

1 Fourier transform

Definition 1.1 (Fourier transform). For $f \in L^1(\mathbb{R}^d, \mathbb{C})$ we call its Fourier transform the function defined by the following formula

$$\widehat{f}(\xi) := (2\pi)^{-\frac{d}{2}} \int_{\mathbb{R}^d} e^{-i\xi \cdot x} f(x) dx. \quad (1.1)$$

We use also the notation $\mathcal{F}f(\xi) = \widehat{f}(\xi)$.

Example 1.2. We have for any $\varepsilon > 0$

$$e^{-\varepsilon \frac{|\xi|^2}{2}} = (2\pi\varepsilon)^{-\frac{d}{2}} \int_{\mathbb{R}^d} e^{-i\xi \cdot x} e^{-\frac{|x|^2}{2\varepsilon}} dx. \quad (1.2)$$

We set also

$$\mathcal{F}^* f(\xi) := (2\pi)^{-\frac{d}{2}} \int_{\mathbb{R}^d} e^{i\xi \cdot x} f(x) dx. \quad (1.3)$$

We have what follows.

Theorem 1.3. *The following facts hold.*

(1) We have $|\widehat{f}(\xi)| \leq (2\pi)^{-\frac{d}{2}} \|f\|_{L^1(\mathbb{R}^d, \mathbb{C})}$. So in particular we have

$$\|\mathcal{F}f\|_{L^\infty(\mathbb{R}^d, \mathbb{C})} \leq (2\pi)^{-\frac{d}{2}} \|f\|_{L^1(\mathbb{R}^d, \mathbb{C})}. \quad (1.4)$$

(2) (Riemann–Lebesgue Lemma) We have $\lim_{\xi \rightarrow \infty} \widehat{f}(\xi) = 0$.

(3) The bounded linear operator $\mathcal{F} : L^1(\mathbb{R}^d, \mathbb{C}) \rightarrow L^\infty(\mathbb{R}^d, \mathbb{C})$ has values in the following space $C_0(\mathbb{R}^d, \mathbb{C}) \subset L^\infty(\mathbb{R}^d, \mathbb{C})$

$$C_0(\mathbb{R}^d, \mathbb{C}) := \{g \in C^0(\mathbb{R}^d, \mathbb{C}) : \lim_{x \rightarrow \infty} g(x) = 0\}. \quad (1.5)$$

(4) \mathcal{F} defines an isomorphism of the space of Schwartz functions $\mathcal{S}(\mathbb{R}^d, \mathbb{C})$ into itself.

(5) \mathcal{F} defines an isomorphism of the space of tempered distributions $\mathcal{S}'(\mathbb{R}^d, \mathbb{C})$ into itself. We have $\mathcal{F}[\partial_{x_j} f] = -i\xi_j \mathcal{F}f$.

(6) For $f, g \in L^1(\mathbb{R}^d, \mathbb{C})$ we have

$$\widehat{f * g}(\xi) = (2\pi)^{\frac{d}{2}} \widehat{f}(\xi) \widehat{g}(\xi).$$

□

Theorem 1.4 (Fourier transform in L^2). *The following facts hold.*

(1) For a function $f \in L^1(\mathbb{R}^d, \mathbb{C}) \cap L^2(\mathbb{R}^d, \mathbb{C})$ we have that $\widehat{f} \in L^2(\mathbb{R}^d, \mathbb{C})$ and $\|\widehat{f}\|_{L^2} = \|f\|_{L^2}$. An operator

$$\mathcal{F} : L^2(\mathbb{R}^d, \mathbb{C}) \rightarrow L^2(\mathbb{R}^d, \mathbb{C}) \quad (1.6)$$

remains defined. For $f \in L^2(\mathbb{R}^d, \mathbb{C})$ for any function $\varphi \in C_c(\mathbb{R}^d, \mathbb{C})$ with $\varphi = 1$ near 0 set

$$\begin{aligned} \mathcal{F}f(\xi) &:= \lim_{\lambda \nearrow \infty} (2\pi)^{-\frac{d}{2}} \int_{\mathbb{R}^d} e^{-i\xi \cdot x} f(x) \varphi(x/\lambda) dx \\ &= \lim_{\lambda \nearrow \infty} (2\pi)^{-\frac{d}{2}} \int_{|x| \leq \lambda} e^{-i\xi \cdot x} f(x) dx. \end{aligned} \quad (1.7)$$

Then (1.7) defines an isometric isomorphism inside $L^2(\mathbb{R}^d, \mathbb{C})$, so in particular we have

$$\|\mathcal{F}f\|_{L^2(\mathbb{R}^d, \mathbb{C})} = \|f\|_{L^2(\mathbb{R}^d, \mathbb{C})}. \quad (1.8)$$

(2) The inverse map is defined by

$$\begin{aligned} \mathcal{F}^*f(x) &= \lim_{\lambda \nearrow \infty} (2\pi)^{-\frac{d}{2}} \int_{\mathbb{R}^d} e^{i\xi \cdot x} f(\xi) \varphi(\xi/\lambda) d\xi \\ &= \lim_{\lambda \nearrow \infty} (2\pi)^{\frac{d}{2}} \int_{|\xi| \leq \lambda} e^{i\xi \cdot x} f(\xi) d\xi. \end{aligned} \quad (1.9)$$

(3) For $f \in L^1(\mathbb{R}^d, \mathbb{C}) \cap L^2(\mathbb{R}^d, \mathbb{C})$ the two definitions (1.1) and (1.7) of \mathcal{F} coincide (by dominated convergence). Similarly, for $f \in L^1(\mathbb{R}^d, \mathbb{C}) \cap L^2(\mathbb{R}^d, \mathbb{C})$ the two definitions (1.3) and (1.9) of \mathcal{F}^* coincide.

The above notions extend naturally to vector fields. So we have a Fourier transform $f \rightarrow \widehat{f}$ from $(L^1(\mathbb{R}^d))^d \rightarrow (C_0(\mathbb{R}^d))^d$, from $(L^2(\mathbb{R}^d))^d \rightarrow (L^2(\mathbb{R}^d))^d$, from $(\mathcal{S}(\mathbb{R}^d))^d \rightarrow (\mathcal{S}(\mathbb{R}^d))^d$ and more generally from $(\mathcal{S}'(\mathbb{R}^d))^d \rightarrow (\mathcal{S}'(\mathbb{R}^d))^d$. Notice that all these maps except the 1st are isomorphisms, and all are one to one maps.

The Fourier transform extends to the spaces $L^p(\mathbb{R}^d, \mathbb{C})$ for $p \in [1, 2]$.

Theorem 1.5 (Hausdorff–Young). For $p \in [1, 2]$ and $f \in L^p(\mathbb{R}^d, \mathbb{C})$ then (1.7) defines a function $\mathcal{F}f \in L^{p'}(\mathbb{R}^d, \mathbb{C})$ where $p' = \frac{p}{p-1}$ and an operator remains defined which satisfies

$$\|\mathcal{F}f\|_{L^{p'}(\mathbb{R}^d, \mathbb{C})} \leq (2\pi)^{-d(\frac{1}{2} - \frac{1}{p'})} \|f\|_{L^p(\mathbb{R}^d, \mathbb{C})}. \quad (1.10)$$

We know already cases $p = 2$ and $p = 1$. This implies that Theorem 1.5 is a consequence of the Marcel Riesz interpolation Theorem, which we discuss now.

Theorem 1.6 (Riesz–Thorin). Let T be a linear map from $L^{p_0}(\mathbb{R}^d) \cap L^{p_1}(\mathbb{R}^d)$ to $L^{q_0}(\mathbb{R}^d) \cap L^{q_1}(\mathbb{R}^d)$ satisfying

$$\|Tf\|_{L^{q_j}} \leq M_j \|f\|_{L^{p_j}} \text{ for } j = 0, 1.$$

Then for $t \in (0, 1)$ and for p_t and q_t defined by

$$\frac{1}{p_t} = \frac{1-t}{p_0} + \frac{t}{p_1}, \quad \frac{1}{q_t} = \frac{1-t}{q_0} + \frac{t}{q_1}$$

we have

$$\|Tf\|_{L^{q_t}} \leq (M_0)^{1-t}(M_1)^t \|f\|_{L^{p_t}} \text{ for } f \in L^{p_0}(\mathbb{R}^d) \cap L^{p_1}(\mathbb{R}^d).$$

Proof of the Hausdorff–Young’s Theorem. We have $\frac{1}{p} = \frac{1-t}{2} + t$ for $t = \frac{2}{p} - 1$. Hence $1-t = 2(1-1/p) = \frac{2}{p'}$ and $\frac{1}{p'} = \frac{1}{2} \frac{2}{p'} + \frac{t}{\infty}$ and

$$\|\mathcal{F}\|_{L^p \rightarrow L^{p'}} \leq (2\pi)^{-\frac{d}{2}t} = (2\pi)^{-\frac{d}{2}(\frac{2}{p}-1)} = (2\pi)^{d(\frac{1}{p}-\frac{1}{2})} = (2\pi)^{d(\frac{1}{2}+\frac{1}{p}-1)} = (2\pi)^{-d(\frac{1}{2}-\frac{1}{p})}.$$

Proof of Riesz–Thorin’s Interpolation Theorem. First of all notice that if $f \in L^a \cap L^b$ with $a < b$ then $f \in L^c$ for any $c \in (a, b)$. To see this recall Hölder

$$\|fg\|_{L^r} \leq \|f\|_{L^p} \|g\|_{L^q} \text{ for } \frac{1}{r} = \frac{1}{p} + \frac{1}{q}$$

Then, since $\frac{1}{c} = \frac{t}{a} + \frac{1-t}{b}$ for $t \in (0, 1)$ from $|f| = |f|^t |f|^{1-t}$ we have

$$\|f\|_{L^c} = \| |f|^t |f|^{1-t} \|_{L^c} \leq \| |f|^t \|_{L^{\frac{a}{t}}} \| |f|^{1-t} \|_{L^{\frac{b}{1-t}}} = \|f\|_{L^a}^t \|f\|_{L^b}^{1-t}.$$

For $p_t = p_0 = p_1 = \infty$ (in fact we can repeat a similar argument for $p_t = p_0 = p_1$ any fixed value in $[1, \infty]$) we then have

$$\|Tf\|_{L^{q_t}} \leq \|Tf\|_{L^{q_1}}^t \|Tf\|_{L^{q_0}}^{1-t} \leq (M_0)^{1-t}(M_1)^t \|f\|_{L^\infty}.$$

So let us suppose $p_t < \infty$. Then it is enough to prove

$$\left| \int Tfg dx \right| \leq (M_0)^{1-t}(M_1)^t \|f\|_{L^{p_t}} \|g\|_{L^{q'_t}} = (M_0)^{1-t}(M_1)^t$$

considering only $\|f\|_{L^{p_t}} = \|g\|_{L^{q'_t}} = 1$ for simple functions $f = \sum_{j=1}^m a_j \chi_{E_j}$ where we can take the E_j to be finite measure sets mutually disjoint. If $q'_t < \infty$ we can also reduce to simple functions $g = \sum_{k=1}^N b_k \chi_{F_k}$ where the F_k are finite measure sets mutually disjoint. The case $q'_t = \infty$ reduces to the case $p_t = \infty$ by duality. In fact, see Remark 16 p. 44 [2],

$$\|T\|_{\mathcal{L}(L^{p_t}, L^1)} = \|T^*\|_{\mathcal{L}(L^\infty, L^{p'_t})}.$$

Notice that if both $p_0 < \infty$ and $p_1 < \infty$ and since we are treating $q_0 = q_1 = 1$, then $\|T\|_{\mathcal{L}(L^{p_j}, L^1)} = \|T^*\|_{\mathcal{L}(L^\infty, L^{p'_j})} \leq M_j$ and so one reduces to the case $p_t = \infty$. If, say, $p_0 = \infty$, then $\|T\|_{\mathcal{L}(L^{p_1}, L^1)} = \|T^*\|_{\mathcal{L}(L^\infty, L^{p'_1})} \leq M_1$ since $p_1 < \infty$, but $\|T\|_{\mathcal{L}(L^{p_0}, L^1)} = \|T^*\|_{\mathcal{L}(L^\infty, (L^\infty)')} \leq M_0$, so in other words, we don’t get a Lebesgue space. However, the

issue is to bound for $f \in L^{p_0} \cap L^\infty$ a $T^*f \in L^1 \cap (L^\infty)' = L^1$ where $\|T^*f\|_{(L^\infty)'} = \|T^*f\|_{L^1}$, so that one can still apply the above argument used for $p_t = \infty$.

Let us turn to the case $p_t < \infty$ and $q'_t < \infty$. For $a_j = e^{i\theta_j}|a_j|$ and $b_k = e^{i\psi_k}|b_k|$ the polar representations, set

$$f_z := \sum_{j=1}^m |a_j|^{\frac{\alpha(z)}{\alpha(t)}} e^{i\theta_j} \chi_{E_j} \text{ with } \alpha(z) := \frac{1-z}{p_0} + \frac{z}{p_1}$$

$$g_z := \sum_{k=1}^N |b_k|^{\frac{1-\beta(z)}{1-\beta(t)}} e^{i\psi_k} \chi_{F_k} \text{ with } \beta(z) := \frac{1-z}{q_0} + \frac{z}{q_1}.$$

Notice that since we are assuming $q'_t < \infty$, then $q_t > 1$ and so $\beta(t) = \frac{1}{q_t} < 1$, so that g_z is well defined. Similarly, since $p_t < \infty$ we have $\alpha(t) = \frac{1}{p_t} > 0$, so also f_z is well defined.

We consider now the function

$$F(z) = \int T f_z g_z dx.$$

Our goal is to prove $|F(t)| \leq M_0^{1-t} M_1^t$.

$F(z)$ is holomorphic in $0 < \operatorname{Re} z < 1$, continuous and bounded in $0 \leq \operatorname{Re} z \leq 1$. Boundedness follows from estimates like

$$\left| |a_j|^{\frac{\alpha(z)}{\alpha(t)}} \right| = |a_j|^{\frac{\alpha(\operatorname{Re} z)}{\alpha(t)}} \text{ which is bounded for } 0 \leq \operatorname{Re} z \leq 1.$$

We have $F(t) = \int T f g dx$ since $f_t = f$ and $g_t = g$.

By the 3 lines lemma, see below, which yields $|F(z)| \leq M_0^{1-\operatorname{Re} z} M_1^{\operatorname{Re} z}$ if the two estimates below are true, our theorem is a consequence of the following two inequalities

$$|F(z)| \leq M_0 \text{ for } \operatorname{Re} z = 0 ;$$

$$|F(z)| \leq M_1 \text{ for } \operatorname{Re} z = 1 .$$

For $z = iy$ we have for $p_0 < \infty$

$$|f_{iy}|^{p_0} = \sum_{j=1}^m \left| |a_j|^{\frac{\alpha(iy)}{\alpha(t)}} \right|^{p_0} \chi_{E_j} = \sum_{j=1}^m \left| |a_j|^{\frac{\frac{1}{p_0} + iy(\frac{1}{p_1} - \frac{1}{p_0})}{\frac{1}{p_t}}} \right|^{p_0} \chi_{E_j}$$

$$= \sum_{j=1}^m \left| |a_j|^{iy p_t (\frac{1}{p_1} - \frac{1}{p_0})} |a_j|^{\frac{p_t}{p_0}} \right|^{p_0} \chi_{E_j} = \sum_{j=1}^m |a_j|^{p_t} \chi_{E_j} = |f|^{p_t}.$$

This implies

$$\|f_{iy}\|_{p_0} = \left(\int_{\mathbb{R}^d} |f_{iy}|^{p_0} dx \right)^{\frac{1}{p_0}} = \left(\int_{\mathbb{R}^d} |f|^{p_t} dx \right)^{\frac{1}{p_0}} = 1. \quad (1.11)$$

Notice that we have also $\|f_{iy}\|_\infty = 1$ when $p_0 = \infty$.

Proceeding similarly, using $1 - \beta(z) = \frac{1-z}{q'_0} + \frac{z}{q'_1}$, for $z = iy$ and $q'_0 < \infty$ we have

$$|g_{iy}|^{q'_0} = \sum_{k=1}^N \left| |b_k|^{\frac{1-\beta(iy)}{1-\beta(t)}} \right|^{q'_0} \chi_{F_k} = \sum_{k=1}^N \left| |b_k|^{\frac{iy(\frac{1}{q'_1} - \frac{1}{q'_0})}{\frac{1}{q'_t}}} \right|^{\frac{q'_0}{q'_t}} \chi_{F_k} = \sum_{j=1}^N |b_k|^{q'_t} \chi_{F_k} = |g|^{q'_t}.$$

This implies

$$\|g_{iy}\|_{q'_0} = \left(\int_{\mathbb{R}^d} |g_{iy}|^{q'_0} dx \right)^{\frac{1}{q'_0}} = \left(\int_{\mathbb{R}^d} |g|^{q'_t} dx \right)^{\frac{1}{q'_0}} = 1. \quad (1.12)$$

Notice that we have also $\|g_{iy}\|_{\infty} = 1$ when $q'_0 = \infty$.

Then

$$|F(iy)| \leq \|Tf_{iy}\|_{q_0} \|g_{iy}\|_{q'_0} \leq M_0 \|f_{iy}\|_{p_0} \|g_{iy}\|_{q'_0} = M_0.$$

By a similar argument

$$\begin{aligned} |f_{1+iy}|^{p_1} &= |f|^{p_1} \\ |g_{1+iy}|^{q'_1} &= |g|^{q'_1}. \end{aligned}$$

Indeed by $\alpha(1+iy) = \frac{1+iy}{p_1} - \frac{iy}{p_0}$

$$\begin{aligned} |f_{1+iy}|^{p_1} &= \sum_{j=1}^m \left| |a_j|^{\frac{\alpha(1+iy)}{\alpha(t)}} \right|^{p_1} \chi_{E_j} = \sum_{j=1}^m \left| |a_j|^{\frac{\frac{1}{p_1} + iy(\frac{1}{p_1} - \frac{1}{p_0})}{\frac{1}{p_t}}} \right|^{p_1} \chi_{E_j} \\ &= \sum_{j=1}^m \left| |a_j|^{\frac{p_t}{p_1}} \right|^{p_1} \chi_{E_j} = \sum_{j=1}^m |a_j|^{p_t} \chi_{E_j} = |f|^{p_t} \end{aligned}$$

and by $1 - \beta(1+iy) = \frac{1+iy}{q'_1} - \frac{iy}{q'_0}$

$$|g_{1+iy}|^{q'_1} = \sum_{k=1}^N \left| |b_k|^{\frac{1-\beta(1+iy)}{1-\beta(t)}} \right|^{q'_1} \chi_{F_k} = \sum_{k=1}^N \left| |b_k|^{\frac{iy(\frac{1}{q'_1} - \frac{1}{q'_0})}{\frac{1}{q'_t}}} \right|^{\frac{q'_1}{q'_t}} \chi_{F_k} = \sum_{j=1}^N |b_k|^{q'_t} \chi_{F_k} = |g|^{q'_t}.$$

Finally

$$|F(1+iy)| \leq \|Tf_{1+iy}\|_{q_1} \|g_{1+iy}\|_{q'_1} \leq M_1 \|f_{1+iy}\|_{p_1} \|g_{1+iy}\|_{q'_1} = M_1 \|f\|_{p_t}^{\frac{p_t}{p_1}} \|g\|_{q'_t}^{\frac{q'_t}{q'_1}} = M_1.$$

□

Here we have used the following lemma.

Lemma 1.7 (Three Lines Lemma). *Let $F(z)$ be holomorphic in the strip $0 < \operatorname{Re} z < 1$, continuous and bounded in $0 \leq \operatorname{Re} z \leq 1$ and such that*

$$\begin{aligned} |F(z)| &\leq M_0 \text{ for } \operatorname{Re} z = 0 ; \\ |F(z)| &\leq M_1 \text{ for } \operatorname{Re} z = 1 . \end{aligned}$$

Then we have $|F(z)| \leq M_0^{1-\operatorname{Re} z} M_1^{\operatorname{Re} z}$ for all $0 < \operatorname{Re} z < 1$.

Proof. Let us start with the special case $M_0 = M_1 = 1$ and set $B := \|F\|_{L^\infty}$. Set $h_\epsilon(z) := (1 + \epsilon z)^{-1}$ with $\epsilon > 0$. Since $\operatorname{Re}(1 + \epsilon z) = 1 + \epsilon x \geq 1$ it follows $|h_\epsilon(z)| \leq 1$ in the strip. Furthermore $\operatorname{Im}(1 + \epsilon z) = \epsilon y$ implies also $|h_\epsilon(z)| \leq |\epsilon y|^{-1}$. Consider now the two horizontal lines $y = \pm B/\epsilon$ and let R be the rectangle $0 \leq x \leq 1$ and $|y| \leq B/\epsilon$. In $|y| \geq B/\epsilon$ we have

$$|F(z)h_\epsilon(z)| \leq \frac{B}{|\epsilon y|} \leq \frac{B}{|\epsilon B/\epsilon|} = 1.$$

On the other hand by the maximum modulus principle

$$\sup_R |F(z)h_\epsilon(z)| = \sup_{\partial R} |F(z)h_\epsilon(z)| \leq 1,$$

where on the horizontal sides the last inequality follows from the previous inequality and on the vertical sides follows from $|F(z)| \leq 1$ for $\operatorname{Re} z = 0, 1$ and from $|h_\epsilon(z)| \leq 1$. Hence in the whole strip $0 \leq x \leq 1$ we have $|F(z)h_\epsilon(z)| \leq 1$ for any $\epsilon > 0$. This implies

$$\lim_{\epsilon \searrow 0} |F(z)h_\epsilon(z)| = |F(z)| \leq 1$$

in the whole strip $0 \leq x \leq 1$.

In the general case $(M_0, M_1) \neq (1, 1)$ set $g(z) := M_0^{1-z} M_1^z$. Notice that

$$\begin{aligned} g(z) &= e^{(1-z)\log M_0} e^{z\log M_1} \Rightarrow |g(z)| = M_0^{1-x} M_1^x \Rightarrow \\ \min(M_0, M_1) &\leq |g(z)| \leq \max(M_0, M_1). \end{aligned}$$

So $F(z)g^{-1}(z)$ satisfies the hypotheses of the case $M_0 = M_1 = 1$ and so $|F(z)| \leq |g(z)| = M_0^{1-\operatorname{Re} z} M_1^{\operatorname{Re} z}$ □

We consider now for $\Delta := \sum_j \frac{\partial^2}{\partial x_j^2}$ and for $f \in \mathcal{S}'(\mathbb{R}^d, \mathbb{C})$ the heat equation

$$u_t - \Delta u = 0, \quad u(0, x) = f(x). \tag{1.13}$$

By applying \mathcal{F} we transform the above problem into

$$\widehat{u}_t + |\xi|^2 \widehat{u} = 0, \quad \widehat{u}(0, \xi) = \widehat{f}(\xi).$$

This yields $\widehat{u}(t, \xi) = e^{-t|\xi|^2} \widehat{f}(\xi)$. Notice that since $\widehat{f} \in \mathcal{S}'(\mathbb{R}^d, \mathbb{C})$ and $e^{-t|\cdot|^2} \in \mathcal{S}(\mathbb{R}^d, \mathbb{C})$ for any $t > 0$, the last product is well defined. Furthermore, we have $\widehat{u}(t, \cdot) \in C^0([0, +\infty), \mathcal{S}'(\mathbb{R}^d, \mathbb{C}))$

and, as a consequence, since \mathcal{F} is an isomorphism of $\mathcal{S}'(\mathbb{R}^d, \mathbb{C})$ also $u(t, \cdot) \in C^0([0, +\infty), \mathcal{S}'(\mathbb{R}^d, \mathbb{C}))$.

We have $e^{-t|\xi|^2} = \widehat{G}(t, \xi)$ with $G(t, x) = (2t)^{-\frac{d}{2}} e^{-\frac{|x|^2}{4t}}$. Then, from $\widehat{u}(t, \xi) = \widehat{G}(t, \xi) \widehat{f}(\xi)$ it follows $u(t, x) = (2\pi)^{-\frac{d}{2}} G(t, \cdot) * f(x)$. In particular, for $f \in L^p(\mathbb{R}^d, \mathbb{C})$, we have

$$u(t, x) = (4\pi t)^{-\frac{d}{2}} \int_{\mathbb{R}^d} e^{-\frac{|x-y|^2}{4t}} f(y) dy.$$

Notice that by (1.2) we have

$$(4\pi t)^{-\frac{d}{2}} \int_{\mathbb{R}^d} e^{-\frac{|x|^2}{4t}} dx = 1.$$

We will write

$$e^{t\Delta} f(x) := (4\pi t)^{-\frac{d}{2}} \int_{\mathbb{R}^d} e^{-\frac{|x-y|^2}{4t}} f(y) dy. \quad (1.14)$$

Notice that for $p \geq 1$ we have $\|e^{t\Delta} f\|_{L^p(\mathbb{R}^d)} \leq \|f\|_{L^p(\mathbb{R}^d)}$ and for $f \in L^1(\mathbb{R}^d)$ and any $x \in \mathbb{R}^d$

$$|e^{t\Delta} f(x)| \leq (4\pi t)^{-\frac{d}{2}} \int_{\mathbb{R}^d} e^{-\frac{|x-y|^2}{4t}} |f(y)| dy \leq (4\pi t)^{-\frac{d}{2}} \int_{\mathbb{R}^d} |f(y)| dy = (4\pi t)^{-\frac{d}{2}} \|f\|_{L^1(\mathbb{R}^d)}. \quad (1.15)$$

We set also $K_t(x) := (4\pi t)^{-\frac{d}{2}} e^{-\frac{|x|^2}{4t}}$. Then $e^{t\Delta} f = K_t * f$. $K_t(x-y)$ is the *Heath Kernel*. As a corollary to the Riesz–Thorin Theorem we obtain the following result.

Corollary 1.8. *For any $q \geq p \geq 1$ and any $f \in L^p(\mathbb{R}^d)$ we have*

$$\|e^{t\Delta} f\|_{L^q(\mathbb{R}^d)} \leq (4\pi t)^{-\frac{d}{2} \left(\frac{1}{p} - \frac{1}{q}\right)} \|f\|_{L^p(\mathbb{R}^d)}. \quad (1.16)$$

Proof. Notice that (1.16) is true for $q = \infty$ and $p = 1$ by (1.15). For $p = q$ can be seen as a consequence of Young’s inequality for convolutions. For $q > p = 1$ Riesz–Thorin and $\frac{1}{q} = \frac{1 - \frac{1}{q}}{\infty} + \frac{\frac{1}{q}}{1}$ yields

$$\|e^{t\Delta}\|_{L^1 \rightarrow L^q} \leq \|e^{t\Delta}\|_{L^1 \rightarrow L^\infty}^{1 - \frac{1}{q}} \|e^{t\Delta}\|_{L^1 \rightarrow L^1}^{\frac{1}{q}} \leq (4\pi t)^{-\frac{d}{2} \left(1 - \frac{1}{q}\right)} = (4\pi t)^{-\frac{d}{2q'}} \text{ with } q' = \frac{q}{q-1}.$$

Next, for $1 < p < q$ we have $\frac{1}{p} = \alpha + \frac{1-\alpha}{q} = \frac{1}{q} + \frac{\alpha}{q'}$ s.t. $\alpha = q' \left(\frac{1}{p} - \frac{1}{q}\right)$. Then

$$\|e^{t\Delta}\|_{L^p \rightarrow L^q} \leq \|e^{t\Delta}\|_{L^1 \rightarrow L^q}^\alpha \|e^{t\Delta}\|_{L^q \rightarrow L^q}^{1-\alpha} \leq (4\pi t)^{-\frac{d}{2q'} \alpha} = (4\pi t)^{-\frac{d}{2} \left(\frac{1}{p} - \frac{1}{q}\right)}.$$

□

Another application of M. Riesz’s Theorem is the following useful tool.

Lemma 1.9 (Young's Inequality). *Let*

$$Tf(x) = \int_{\mathbb{R}^n} K(x, y)f(y)dy$$

where

$$\sup_{x \in \mathbb{R}^n} \int_{\mathbb{R}^n} |K(x, y)|dy < C, \sup_{y \in \mathbb{R}^n} \int_{\mathbb{R}^n} |K(x, y)|dx < C. \quad (1.17)$$

Then

$$\|Tf\|_{L^p(\mathbb{R}^n)} \leq C\|f\|_{L^p(\mathbb{R}^n)} \text{ for all } p \in [1, \infty]$$

Proof. The case $p = 1, \infty$ follow immediately from (1.17). The intermediate cases from Riesz's Theorem. \square

Theorem 1.10. $\rho \in L^1(\mathbb{R}^d)$ be s.t. $\int \rho(x)dx = 1$. Set $\rho_\epsilon(x) := \epsilon^{-d}\rho(x/\epsilon)$. Consider $C_c(\mathbb{R}^d, \mathbb{C})$ and for each $p \in [1, \infty]$ let $\overline{C_c(\mathbb{R}^d, \mathbb{C})}_p$ be the closure of $C_c(\mathbb{R}^d, \mathbb{C})$ in $L^p(\mathbb{R}^d, \mathbb{C})$, so that $\overline{C_c(\mathbb{R}^d, \mathbb{C})}_p = L^p(\mathbb{R}^d, \mathbb{C})$ for $p < \infty$ and $\overline{C_c(\mathbb{R}^d, \mathbb{C})}_\infty = C_0(\mathbb{R}^d, \mathbb{C}) \subsetneq L^\infty(\mathbb{R}^d, \mathbb{C})$. Then for any $f \in \overline{C_c(\mathbb{R}^d, \mathbb{C})}_p$ we have

$$\lim_{\epsilon \searrow 0} \rho_\epsilon * f = f \text{ in } L^p(\mathbb{R}^d, \mathbb{C}). \quad (1.18)$$

In particular we have

$$\lim_{t \searrow 0} e^{t\Delta} f = f \text{ in } L^p(\mathbb{R}^d, \mathbb{C}). \quad (1.19)$$

Proof. Clearly, (1.19) is a special case of (1.18) setting $\epsilon = \sqrt{t}$ and $\rho(x) = (4\pi)^{-\frac{d}{2}}e^{-\frac{|x|^2}{4}}$. To prove (1.18) we start with $f \in C_c(\mathbb{R}^d, \mathbb{C})$. In this case

$$\rho_\epsilon * f(x) - f(x) = \int_{\mathbb{R}^d} (f(x - \epsilon y) - f(x))\rho(y)dy$$

so that, by Minkowski inequality and for $\Delta(y) := \|f(\cdot - y) - f(\cdot)\|_{L^p}$, we have

$$\|\rho_\epsilon * f(x) - f(x)\|_{L^p} \leq \int |\rho(y)|\Delta(\epsilon y)dy.$$

Now we have $\lim_{y \rightarrow 0} \Delta(y) = 0$ and $\Delta(y) \leq 2\|f\|_{L^p}$. So, by dominated convergence we get

$$\lim_{\epsilon \searrow 0} \|\rho_\epsilon * f(x) - f(x)\|_{L^p} = \lim_{\epsilon \searrow 0} \int |\rho(y)|\Delta(\epsilon y)dy = 0.$$

So this proves (1.18) for $f \in C_c(\mathbb{R}^d, \mathbb{C})$. The general case is proved by a density argument. \square

2 Some spaces of functions on L^2 based Sobolev Spaces

We will introduce the *homogeneous* Sobolev spaces $\dot{H}^k(\mathbb{R}^d)$ and we will generalize the standard Sobolev spaces $H^k(\mathbb{R}^d)$. For $\xi \in \mathbb{R}^d$ let $\langle \xi \rangle = \sqrt{1 + |\xi|^2}$ be the *Japanese bracket*. For a tempered distribution u we denote by \widehat{u} its Fourier transform. We consider for $s \in \mathbb{R}$ the space formed by the tempered distributions u

$$H^s(\mathbb{R}^d) \text{ with norm } \|u\|_{H^s(\mathbb{R}^d)} := \|\langle \xi \rangle^s \widehat{u}\|_{L^2(\mathbb{R}^d)} < \infty. \quad (2.1)$$

We consider for $s \in \mathbb{R}$ the space formed by the tempered distributions u s.t. $\widehat{u} \in L^1_{loc}(\mathbb{R}^d)$

$$\dot{H}^s(\mathbb{R}^d) \text{ with norm } \|u\|_{\dot{H}^s(\mathbb{R}^d)} := \|\langle \xi \rangle^s \widehat{u}\|_{L^2(\mathbb{R}^d)} < \infty. \quad (2.2)$$

The following lemma is elementary.

Lemma 2.1. *The following statements are true.*

- $L^2(\mathbb{R}^d) \rightarrow H^s(\mathbb{R}^d)$ defined by $f \rightarrow \mathcal{F}^*\left(\frac{\widehat{f}}{\langle \xi \rangle^s}\right)$ is an isometric isomorphism and all the $H^s(\mathbb{R}^d)$ are Hilbert spaces with inner product $\langle f, g \rangle_{H^s} = \langle \langle \xi \rangle^s \widehat{f}, \langle \xi \rangle^s \widehat{g} \rangle_{L^2}$.
- We have $\mathcal{S}(\mathbb{R}^d) \subseteq \dot{H}^s(\mathbb{R}^d)$ if and only if $s > -d/2$. Furthermore, this embedding is dense.
- The $\dot{H}^s(\mathbb{R}^d)$ have an inner product defined by $\langle f, g \rangle_{\dot{H}^s} = \langle |\xi|^s \widehat{f}, |\xi|^s \widehat{g} \rangle_{L^2}$.

We will use also the following.

Lemma 2.2. *Let $\sigma > -d/2$. Then $C_c^\infty(\mathbb{R}^d)$ is dense in $\dot{H}^\sigma(\mathbb{R}^d)$.*

Proof. It is immediate that $\mathcal{S}(\mathbb{R}^d)$ is dense in $\dot{H}^s(\mathbb{R}^d)$ (because $C_c^\infty(\mathbb{R}^d \setminus \{0\})$ is dense in $L^2(\mathbb{R}^d, |\xi|^{2s} d\xi)$). So it is enough to show that for any $\psi \in \mathcal{S}(\mathbb{R}^d)$ and for $\chi \in C_c^\infty(\mathbb{R}^d, [0, 1])$ a cutoff function with $\chi = 1$ near the origin, then $\chi\left(\frac{x}{n}\right)\psi \xrightarrow{n \rightarrow +\infty} \psi$ in $\dot{H}^\sigma(\mathbb{R}^d)$ for any $\sigma > -d/2$. Indeed recall

$$\widehat{f * g}(\xi) = (2\pi)^{\frac{d}{2}} \widehat{f}(\xi) \widehat{g}(\xi) \text{ so that}$$

$$\begin{aligned} \left\| \chi\left(\frac{x}{n}\right)\psi - \psi \right\|_{\dot{H}^\sigma}^2 &= \int d\xi |\xi|^{2\sigma} \left| \int (2\pi)^{-\frac{d}{2}} n^d \widehat{\chi}(n\eta) \widehat{\psi}(\xi - \eta) d\eta - \widehat{\psi}(\xi) \right|^2 \\ &= \int d\xi |\xi|^{2\sigma} \left| \int (2\pi)^{-\frac{d}{2}} \widehat{\chi}(\eta) \left(\widehat{\psi}\left(\xi - \frac{\eta}{n}\right) - \widehat{\psi}(\xi) \right) d\eta \right|^2. \end{aligned}$$

So

$$\left\| \chi\left(\frac{x}{n}\right)\psi - \psi \right\|_{\dot{H}^\sigma} \leq (2\pi)^{-\frac{d}{2}} \int d\eta |\widehat{\chi}(\eta)| \left(\int |\xi|^{2\sigma} \left| \int \left(\widehat{\psi}\left(\xi - \frac{\eta}{n}\right) - \widehat{\psi}(\xi) \right) d\xi \right|^2 \right)^{\frac{1}{2}}.$$

We split in the right integrating in $|\eta| \leq C$ and in $|\eta| \geq C$, where C is arbitrary. In the integral in $|\eta| \leq C$ we get a sequence that, by dominated convergence, converges to 0. Next, we consider the integral in $|\eta| \geq C$. We can bound it from above by

$$(2\pi)^{-\frac{d}{2}} \int_{|\eta| \geq C} d\eta |\widehat{\chi}(\eta)| \left(\left(\int |\xi|^{2\sigma} \left| \int \widehat{\psi} \left(\xi - \frac{\eta}{n} \right) d\xi \right|^2 d\xi \right)^{\frac{1}{2}} + \|\psi\|_{\dot{H}^\sigma} \right). \quad (2.3)$$

Now we claim that for c independent of η we have

$$\int |\xi|^{2\sigma} \left| \int \widehat{\psi}(\xi - \eta) \right|^2 d\xi \leq c + c|\eta|^{2\sigma}. \quad (2.4)$$

Indeed, we split the integral into regions $|\eta| \ll |\xi|$, $|\eta| \sim |\xi|$ and $|\eta| \gg |\xi|$. We have

$$\int_{|\eta| \gg |\xi|} |\xi|^{2\sigma} \left| \widehat{\psi}(\xi - \eta) \right|^2 d\xi \lesssim \langle \eta \rangle^{-N} \int_{|\eta| \gg |\xi|} |\xi|^{2\sigma} d\xi \lesssim 1.$$

We have

$$\int_{|\eta| \ll |\xi|} |\xi|^{2\sigma} \left| \widehat{\psi}(\xi - \eta) \right|^2 d\xi \lesssim \int_{\mathbb{R}^d} |\xi - \eta|^{2\sigma} \left| \widehat{\psi}(\xi - \eta) \right|^2 d\xi = \|\psi\|_{\dot{H}^\sigma}^2.$$

Finally, for $|\eta| \sim |\xi|$

$$\int_{|\eta| \sim |\xi|} |\xi|^{2\sigma} \left| \widehat{\psi}(\xi - \eta) \right|^2 d\xi \leq \int_{\mathbb{R}^d} |\xi - \eta|^{2\sigma} \left| \widehat{\psi}(\xi) \right|^2 d\xi \lesssim |\eta|^{2\sigma} \int_{\mathbb{R}^d} \left| \widehat{\psi}(\xi) \right|^2 d\xi + \|\psi\|_{\dot{H}^\sigma}^2.$$

So we proved (2.4). Inserting this in (2.3) and taking C sufficiently large we obtain that (2.3) is arbitrarily small. \square

Remark 2.3. We will also consider the space $\dot{H}^\sigma(\mathbb{R}^d) \cap \dot{H}^{1+\sigma}(\mathbb{R}^d)$ for $\sigma > -d/2$. Then, by a similar argument, $C_c^\infty(\mathbb{R}^d)$ is dense in $\dot{H}^\sigma(\mathbb{R}^d) \cap \dot{H}^{1+\sigma}(\mathbb{R}^d)$.

While the $\dot{H}^s(\mathbb{R}^d)$ have an inner product, in general they are not complete topological vector spaces and the following will be important to us.

Proposition 2.4. *For $s < d/2$ the space $\dot{H}^s(\mathbb{R}^d)$ is complete and the Fourier transform establishes an isometric isomorphism $\mathcal{F} : \dot{H}^s(\mathbb{R}^d) \rightarrow L^2(\mathbb{R}^d \setminus \{0\}, |\xi|^{2s} d\xi)$.*

The above proposition is a consequence of the following lemma.

Lemma 2.5. *Let $s < \frac{d}{2}$. Then we have the following facts.*

- $L^2(\mathbb{R}^d \setminus \{0\}, |\xi|^{2s} d\xi) \subset L_{loc}^1(\mathbb{R}^d, d\xi)$
- $L^2(\mathbb{R}^d \setminus \{0\}, |\xi|^{2s} d\xi) \subset \mathcal{S}'(\mathbb{R}^d)$

- The Fourier transform $\mathcal{F} : \mathcal{S}'(\mathbb{R}^d) \rightarrow \mathcal{S}'(\mathbb{R}^d)$ is s.t. $\mathcal{F}(\dot{H}^s(\mathbb{R}^d)) = L^2(\mathbb{R}^d, |\xi|^{2s} d\xi)$ and establishes an isometry between these two spaces.

Proof. Let $g \in L^2(\mathbb{R}^d \setminus \{0\}, |\xi|^{2s} d\xi)$. Obviously $g \in L^1_{loc}(\mathbb{R}^d \setminus \{0\}, d\xi)$. Let now $B = \{\xi \in \mathbb{R}^d : |\xi| \leq 1\}$. Then

$$\begin{aligned} \int_B |g(\xi)| d\xi &\leq \left(\int_B |\xi|^{2s} |g(\xi)|^2 d\xi \right)^{\frac{1}{2}} \left(\int_B |\xi|^{-2s} d\xi \right)^{\frac{1}{2}} \\ &\leq \sqrt{\text{vol}(S^{d-1})} \left(\int_0^1 r^{d-1-2s} dr \right)^{\frac{1}{2}} \|g\|_{L^2(\mathbb{R}^d, |\xi|^{2s} d\xi)} = \sqrt{\frac{\text{vol}(S^{d-1})}{d-2s}} \|g\|_{L^2(\mathbb{R}^d, |\xi|^{2s} d\xi)}. \end{aligned}$$

Next, we check that $L^2(\mathbb{R}^d \setminus \{0\}, |\xi|^{2s} d\xi) \subset \mathcal{S}'(\mathbb{R}^d)$. We split $g = \chi_B g + \chi_{B^c} g$. Then $\chi_B g \in L^1(\mathbb{R}^d, d\xi)$ implies $\chi_B g \in \mathcal{S}'(\mathbb{R}^d)$. On the other hand we have $\chi_{B^c} g \in L^2(\mathbb{R}^d, \langle \xi \rangle^{2s} d\xi)$. This in turn implies $\chi_{B^c} g \in \mathcal{S}'(\mathbb{R}^d)$, where the embedding $L^2(\mathbb{R}^d, \langle \xi \rangle^{2\sigma} d\xi) \subset \mathcal{S}'(\mathbb{R}^d)$ for any $\sigma \in \mathbb{R}$ follows from

$$\begin{aligned} \int_{\mathbb{R}^d} f(\xi) \varphi(\xi) d\xi &= \int_{\mathbb{R}^d} \langle \xi \rangle^\sigma f(\xi) \langle \xi \rangle^{-\sigma} \varphi(\xi) d\xi \leq \|f\|_{L^2(\mathbb{R}^d, \langle \xi \rangle^{2\sigma} d\xi)} \left(\int_{\mathbb{R}^d} \langle \xi \rangle^{-2\sigma} \varphi(\xi) d\xi \right)^{\frac{1}{2}} \\ &\leq \|f\|_{L^2(\mathbb{R}^d, \langle \xi \rangle^{2\sigma} d\xi)} \left(\int_{\mathbb{R}^d} \langle \xi \rangle^{-2\sigma-m} d\xi \right)^{\frac{1}{2}} \|\langle \xi \rangle^m \varphi\|_{L^\infty(\mathbb{R}^d)} \end{aligned}$$

for m chosen s.t. $2\sigma + m > d$. □

Remark 2.6. For $s \geq \frac{d}{2}$ the space $\dot{H}^s(\mathbb{R}^d)$ is not a complete space for the norm indicated.

In particular, the Fourier transform defines an embedding $\dot{H}^s(\mathbb{R}^d) \xrightarrow{\mathcal{F}} L^2(\mathbb{R}^d \setminus \{0\}, |\xi|^{2s} d\xi)$ with image which is strictly contained and dense in $L^2(\mathbb{R}^d \setminus \{0\}, |\xi|^{2s} d\xi)$. The fact that the image is dense can be seen observing that $C_c^\infty(\mathbb{R}^d \setminus \{0\})$ is dense in $L^2(\mathbb{R}^d \setminus \{0\}, |\xi|^{2s} d\xi)$ and we have $\mathcal{F}\dot{H}^s(\mathbb{R}^d) \supseteq C_c^\infty(\mathbb{R}^d \setminus \{0\})$.

For $s = \frac{d}{2} + \varepsilon_0$ with $\varepsilon_0 > 0$, if we pick $f \in C_c^\infty(\mathbb{R}^d)$ with $f(0) \neq 0$, then $\frac{f(\xi)}{|\xi|^{d+\frac{\varepsilon_0}{2}}}$ is a Borel

function not contained in $L^1_{loc}(\mathbb{R}^d, d\xi)$. But $|\xi|^{2s} \left| \frac{f(\xi)}{|\xi|^{d+\frac{\varepsilon_0}{2}}} \right|^2 = \frac{|f(\xi)|^2}{|\xi|^{d-\varepsilon_0}} \in L^1(\mathbb{R}^d, d\xi)$ implies

that $\frac{f(\xi)}{|\xi|^{d+\frac{\varepsilon_0}{2}}} \in L^2(\mathbb{R}^d, |\xi|^{2s} d\xi)$.

For $s = \frac{d}{2}$ consider $f(\xi) = \sum_{k=1}^{\infty} \frac{2^{kd}}{k} \chi_{[3/4, 5/4]}(2^k |\xi|)$. Notice that for each ξ , at most one term

of the sum is non zero, because $[2^{-k} 3/4, 2^{-k} 5/4] \cap [2^{-j} 3/4, 2^{-j} 5/4] = \emptyset$ for $j \neq k$. Indeed, if $j < k$ then

$$2^{-k} 5/4 \leq 2^{-(j-1)} 5/4 < 2^{-j} 3/4 \text{ where the latter follows from } 5 < 6.$$

Then $|\xi|^{\frac{d}{2}} |f(\xi)| \in L^2(\mathbb{R}^d, d\xi)$ since

$$\int_{\mathbb{R}^d} |\xi|^d |f(\xi)|^2 d\xi = \sum_{k=1}^{\infty} \frac{1}{k^2} 2^{2kd} \int_{\mathbb{R}^d} |\xi|^d \chi_{[3/4, 5/4]}(2^k |\xi|) d\xi = \sum_{k=1}^{\infty} \frac{1}{k^2} \int_{\mathbb{R}^d} |\xi|^d \chi_{[3/4, 5/4]}(|\xi|) d\xi < \infty$$

but f , which is supported in the ball $B(0, 5/4)$, is not in $L^1(\mathbb{R}^d, d\xi)$ since otherwise we would have

$$\infty > \int_{\mathbb{R}^d} |f(\xi)| d\xi \geq \sum_{k=1}^n \frac{1}{k} 2^{kd} \int_{\mathbb{R}^d} \chi_{[3/4, 5/4]}(2^k |\xi|) d\xi = \sum_{k=1}^n \frac{1}{k} \int_{\mathbb{R}^d} \chi_{[3/4, 5/4]}(|\xi|) d\xi \xrightarrow{n \rightarrow \infty} \infty.$$

Remark 2.7. For $s \in (0, 1)$ an equivalent definition of $\dot{H}^s(\mathbb{R}^d)$ and of its norm is that

$$u \in L_{loc}(\mathbb{R}^d) \text{ and } \int_{\mathbb{R}^d \times \mathbb{R}^d} \frac{|u(x+y) - u(x)|^2}{|y|^{d+2s}} dx dy < \infty.$$

See [1, Proposition 1.37].

Later on we, when discussing the Navier Stokes Equation, we will deal with vector fields. Given a vector field $u = (u^j)_{j=1}^d \in (\mathcal{S}'(\mathbb{R}^d))^d$ its divergence is

$$\operatorname{div} u = \nabla \cdot u := \sum_{j=1}^d \frac{\partial}{\partial x_j} u^j.$$

Notice that $\widehat{\operatorname{div} u} = -i \sum_{j=1}^d \xi^j \widehat{u}^j$ so that a u is divergence free, that is $\operatorname{div} u = 0$, if and only if $\sum_{j=1}^d \xi^j \widehat{u}^j = 0$.

We have the following elementary representation in $d = 3$.

Lemma 2.8. *For any $u \in \mathcal{D}'(\mathbb{R}^3, \mathbb{R}^3)$ we have*

$$\Delta u = \nabla(\nabla \cdot u) - \nabla \times (\nabla \times u). \quad (2.5)$$

Proof. Obviously, summing on repeated indexes and for $\{\vec{e}_j\}_{j=1}^3$ the standard basis in \mathbb{R}^3 , we have

$$\Delta u = \partial_i \partial_j u_j \vec{e}_i - (\partial_i \partial_j u_j \vec{e}_i - \partial_j \partial_j u_i \vec{e}_i) \quad (2.6)$$

Recalling the tensor ε_{ijk} , defined by $\varepsilon_{123} = 1$, $\varepsilon_{ijk} = 1$ if ijk is an even permutation of 123, $\varepsilon_{ijk} = -1$ if ijk is an odd permutation of 123, $\varepsilon_{ijk} = 0$ if two indexes are equal, we have

$$\begin{aligned} \nabla \times (\nabla \times u) &= \varepsilon_{ijk} \partial_j (\nabla \times u)_k \vec{e}_i = \varepsilon_{ijk} \varepsilon_{ki'j'} \partial_j \partial_{i'} u_{j'} \vec{e}_i \\ &= (\delta_{ii'} \delta_{jj'} - \delta_{ij'} \delta_{ji'}) \partial_j \partial_{i'} u_{j'} \vec{e}_i = \partial_j \partial_{i'} u_j \vec{e}_i - \partial_j \partial_j u_i \vec{e}_i, \end{aligned}$$

where we used the identity $\varepsilon_{ijk} \varepsilon_{ki'j'} = \varepsilon_{ijk} \varepsilon_{i'j'k} = \delta_{ii'} \delta_{jj'} - \delta_{ij'} \delta_{ji'}$ with Kronecker's deltas. The last two displayed formulas prove that (2.5) □

A similar representation is true for $d = 2$.

Lemma 2.9. For any $u \in \mathcal{D}'(\mathbb{R}^2, \mathbb{R}^2)$ we have

$$\Delta u = \nabla(\nabla \cdot u) - \nabla^\perp(\text{curl } u), \quad (2.7)$$

where $\text{curl } u := \partial_1 u_2 - \partial_2 u_1$ and $\nabla^\perp V := (\partial_2 V, -\partial_1 V)$.

Proof. From (2.5) we have

$$\begin{aligned} \Delta u &= \nabla(\nabla \cdot u) - \begin{pmatrix} i & j & k \\ \partial_1 & \partial_2 & \partial_3 \\ 0 & 0 & \partial_1 u_2 - \partial_2 u_1 \end{pmatrix} \\ &= \nabla(\nabla \cdot u) - (i\partial_2(\partial_1 u_2 - \partial_2 u_1) - j\partial_1(\partial_1 u_2 - \partial_2 u_1)). \end{aligned}$$

This gives (2.7). □

Definition 2.10. We call Leray's projector, the operator \mathbb{P} defined by

$$(\mathcal{F}(\mathbb{P}u))^j = \widehat{u}^j - \frac{1}{|\xi|^2} \sum_{k=1}^d \xi_j \xi_k \widehat{u}^k. \quad (2.8)$$

We denote by $H(\mathbb{R}^d)$ the subspace of $L^2(\mathbb{R}^d, \mathbb{R}^d)$ formed by divergence free vector fields. We will also consider $V(\mathbb{R}^d) := H(\mathbb{R}^d) \cap H^1(\mathbb{R}^d, \mathbb{R}^d)$ and $C_{\text{c}}^\infty(\mathbb{R}^d, \mathbb{R}^d) := C_c^\infty(\mathbb{R}^d, \mathbb{R}^d) \cap H(\mathbb{R}^d)$.

A direct and elementary computation yields the following.

Lemma 2.11. We have

$$\mathbb{P}u = -\Delta^{-1} \nabla \times (\nabla \times u) \text{ for } d = 3 \text{ and} \quad (2.9)$$

$$\mathbb{P}u = -\Delta^{-1} \nabla^\perp(\text{curl } u) \text{ for } d = 2. \quad (2.10)$$

Lemma 2.12. $C_{\text{c}}^\infty(\mathbb{R}^d, \mathbb{R}^d)$ is dense in $H(\mathbb{R}^d)$ for any d .

Proof. Let us consider dimension $d = 3$. If $u \in H$ then $u = \nabla \times A$, for $A = -\Delta^{-1} \nabla \times u \in \dot{H}^1(\mathbb{R}^d, \mathbb{R}^d)$. Notice that from Lemma 2.2 we have that $C_c^\infty(\mathbb{R}^d, \mathbb{R}^d)$ is dense in $\dot{H}^1(\mathbb{R}^d, \mathbb{R}^d)$. Since $\dot{H}^1 \ni A \rightarrow \nabla \times A \in L^2$ is a bounded operator, the statement follows. For $d = 2$ the argument is similar and can be generalized to all d . □

Lemma 2.13. $C_{\text{c}}^\infty(\mathbb{R}^d, \mathbb{R}^d)$ is dense in $V(\mathbb{R}^d)$ for any d .

Proof. The argument is similar to the previous one. Let us consider dimension $d = 3$. For $u \in V(\mathbb{R}^d)$ we have $u = \nabla \times A$, for $A = -\Delta^{-1} \nabla \times u \in \dot{H}^1 \cap \dot{H}^2$. But from Remark 2.3 we have that $C_c^\infty(\mathbb{R}^d, \mathbb{R}^d)$ is dense in $\dot{H}^1(\mathbb{R}^d, \mathbb{R}^d) \cap \dot{H}^2(\mathbb{R}^d, \mathbb{R}^d)$. Since $\dot{H}^1 \cap \dot{H}^2 \ni A \rightarrow \nabla \times A \in H^1$ is a bounded operator, the statement follows. We will use this lemma only for $d = 3$. □

For $u \in \dot{H}^k(\mathbb{R}^d)$ and $\lambda > 0$ let us set $\mathbf{P}_\lambda u := \mathcal{F}^*(\chi_{|\xi| \leq \lambda} \mathcal{F}u)$. Notice that this map sends $L^2(\mathbb{R}^d)$ into itself since

$$\|\mathbf{P}_\lambda u\|_{\dot{H}^k(\mathbb{R}^d)} = \|\chi_{|\xi| \leq \lambda} \mathcal{F}u\|_{L^2(\mathbb{R}^d)} \leq \|\chi_{|\xi| \leq \lambda} \mathcal{F}u\|_{L^2(\mathbb{R}^d)} = \|u\|_{\dot{H}^k(\mathbb{R}^d)}.$$

Notice that \mathbf{P}_λ is a projection, that is $\mathbf{P}_\lambda^2 = \mathbf{P}_\lambda$, by

$$\mathbf{P}_\lambda^2 u = \mathbf{P}_\lambda \circ \mathbf{P}_\lambda u = \mathcal{F}^*(\chi_{|\xi| \leq \lambda} \mathcal{F} \mathbf{P}_\lambda u) = \mathcal{F}^*(\chi_{|\xi| \leq \lambda}^2 \mathcal{F}u) = \mathcal{F}^*(\chi_{|\xi| \leq \lambda} \mathcal{F}u) = \mathbf{P}_\lambda u.$$

If $\operatorname{div} u = 0$ then also $\operatorname{div} \mathbf{P}_\lambda u = 0$. Indeed

$$(\operatorname{div} u = 0 \Leftrightarrow \sum_{j=1}^d \xi^j \hat{u}^j = 0) \Rightarrow \mathcal{F}(\operatorname{div} \mathbf{P}_\lambda u) = \sum_{j=1}^d \xi^j \chi_{|\xi| \leq \lambda} \hat{u}^j = \chi_{|\xi| \leq \lambda} \sum_{j=1}^d \xi^j \hat{u}^j = 0,$$

which in turn implies $\operatorname{div} \mathbf{P}_\lambda u = 0$.

2.1 L^p based Sobolev Spaces

The following spaces, for $p \in (1, \infty)$ are formed by tempered distributions u s.t. for $s \in \mathbb{R}$:

$$\dot{\mathcal{W}}^{s,p}(\mathbb{R}^d) \text{ requiring } \hat{u} \text{ in } L_{loc}^1(\mathbb{R}^d) \text{ and with } \|u\|_{\dot{\mathcal{W}}^{s,p}(\mathbb{R}^d)} := \|(|\xi|^s \hat{u})^\vee\|_{L^p(\mathbb{R}^d)}; \quad (2.11)$$

$$\mathcal{W}^{s,p}(\mathbb{R}^d) \text{ defined with } \|u\|_{\mathcal{W}^{s,p}(\mathbb{R}^d)} := \|(\langle \xi \rangle^s \hat{u})^\vee\|_{L^p(\mathbb{R}^d)}. \quad (2.12)$$

We will not use the above spaces except for $p = 2$. The following is true.

Theorem 2.14. *We have*

$$W^{k,p}(\mathbb{R}^d) = \mathcal{W}^{k,p}(\mathbb{R}^d) \text{ for all } p \in (1, \infty) \text{ and all } k \in \mathbb{N}. \quad (2.13)$$

Proof. For this we need the theory of Calderon and Zygmund operators, see later in Sect. 3. \square

For $p = 1$ and $p = \infty$ (2.13) is not true, see [15].

2.2 Hardy Littlewood maximal function

Let $f \in L_{loc}^1(\mathbb{R}^d)$ and consider (for $B(x, r)$ the ball of center x and radius r in \mathbb{R}^d) averages

$$A_r f(x) = \frac{1}{\operatorname{vol}(B(x, r))} \int_{B(x, r)} f(y) dy.$$

Notice that for any $r > 0$ the function $x \rightarrow A_r f(x)$ is continuous. Indeed, fix $\delta_0 > 0$ and consider $\delta x \in B(0, \delta_0)$. Then by the triangular inequality $B(x + \delta x, r) \subset B(x, r + \delta_0)$. So, for $\delta x \in B(0, \delta_0)$

$$A_r f(x) - A_r f(x + \delta x) = \frac{1}{\operatorname{vol}(B(0, 1)) r^d} \int_{B(x, r + \delta_0)} (\chi_{B(x, r) \setminus B(x + \delta x, r)}(y) - \chi_{B(x + \delta x, r) \setminus B(x, r)}(y)) f(y) dy$$

with for any y

$$\left(\chi_{B(x,r)\setminus B(x+\delta x,r)}(y) - \chi_{B(x+\delta x,r)\setminus B(x,r)}(y)\right) \chi_{B(x,r+\delta_0)}(y) f(y) \xrightarrow{|\delta x| \rightarrow 0} 0.$$

By dominated convergence $A_r f(x) - A_r f(x + \delta x) \rightarrow 0$. We define

$$Mf(x) = \sup_{r>0} A_r |f|(x). \quad (2.14)$$

From the definition we conclude that Mf is lower semi continuous that is $\{x : Mf(x) > a\}$ is open for any a . It also obvious that M is sub additive:

$$M(f + g)(x) \leq Mf(x) + Mg(x).$$

We have the following obvious estimate

$$|Mf(x)| \leq |f|_{L^\infty(\mathbb{R}^d)}. \quad (2.15)$$

One important fact is that it is not true that M maps $L^1(\mathbb{R}^d)$ into itself. Indeed if say $K \subset \mathbb{R}^d$ is any compact set and if $B(0, c_0) \supset K$, then since for $|x| > c_0$ we have $B(x, 2|x|) \supset B(0, |x|) \supset K$, we have computing at $r = 2|x|$

$$M\chi_K(x) = \sup_{r>0} \frac{\text{vol}(B(x, r) \cap K)}{\text{vol}(B(0, 1))r^d} \geq \frac{\text{vol}(K)}{\text{vol}(B(0, 1))2^d|x|^d}$$

which shows that $M\chi_K \notin L^1(\mathbb{R}^d)$.

Notice that each $g \in L^1(\mathbb{R}^d)$ satisfies Chebyshev's inequality:

$$\text{vol}(\{x : |g(x)| > \alpha\}) \leq \frac{|g|_{L^1(\mathbb{R}^d)}}{\alpha} \text{ for any } \alpha > 0 \quad (2.16)$$

Indeed (2.16) follows immediately from.

$$|g|_{L^1(\mathbb{R}^d)} = \int_{\mathbb{R}^d} |g(y)| dy \geq \int_{\{x:|g(x)|>\alpha\}} |g(y)| dy \geq \int_{\{x:|g(x)|>\alpha\}} \alpha dy = \alpha \text{vol}(\{x : |g(x)| > \alpha\})$$

If $T : L^1(\mathbb{R}^d) \rightarrow L^1(\mathbb{R}^d)$ satisfies $\|Tf\|_{L^1(\mathbb{R}^d)} \leq A\|f\|_{L^1(\mathbb{R}^d)}$ for all $f \in L^1(\mathbb{R}^d)$ and for a fixed constant A , from (2.16) it is easy to conclude that

$$\text{vol}(\{x : |Tf(x)| > \alpha\}) \leq \frac{A}{\alpha} |f|_{L^1(\mathbb{R}^d)} \text{ for any } \alpha > 0 \text{ and any } f \in L^1(\mathbb{R}^d).$$

Unfortunately we have seen that M does not map $L^1(\mathbb{R}^d)$ into itself. However we will show that it satisfies the last property. Indeed we will prove now that M is weak (1, 1) bounded, that is there exists a constant $A > 0$ (in fact we will prove $A = 3^d$) s.t.

$$\text{vol}(\{x : Mf(x) > \alpha\}) \leq \frac{A}{\alpha} |f|_{L^1(\mathbb{R}^d)} \text{ for any } \alpha > 0. \quad (2.17)$$

To prove this we consider the set $\{x : Mf(x) > \alpha\}$. Then, for any x in this set, there is a ball with center in x , which we denote by B_x , with $\int_{B_x} |f| > \alpha \text{vol}(B_x)$. Pick any compact subset K of the above set, and cover it with such balls B_x . Extract now a finite cover, corresponding to finitely many points x_1, \dots, x_N . We have the following covering result, which we state without proof.

Theorem 2.15 (Vitali's lemma). *Let B_{x_1}, \dots, B_{x_N} be a finite number of balls in \mathbb{R}^d . There exists a subset of balls*

$$\{B_1, \dots, B_m\} \subseteq \{B_{x_1}, \dots, B_{x_N}\} \quad (2.18)$$

with the $B_1 \dots B_m$ pairwise disjoint, s.t.

$$\text{vol}(B_{x_1} \cup \dots \cup B_{x_N}) \leq 3^d \sum_{j=1}^m \text{vol}(B_j). \quad (2.19)$$

We consider balls $B_1 \dots B_m$ as in (2.18) and from

$$K \subset B_{x_1} \cup \dots \cup B_{x_N} \Rightarrow \text{vol}(K) < \text{vol}(B_{x_1} \cup \dots \cup B_{x_N}),$$

from (2.19) and from the definition of the B_{x_j} we get

$$3^{-d} \text{vol}(K) \leq \sum_{j=1}^m \text{vol}(B_j) < \sum_{j=1}^m \frac{1}{\alpha} \int_{B_j} |f| \leq \frac{|f|_1}{\alpha}. \quad (2.20)$$

(2.20) implies $\text{vol}(K) \leq 3^d \alpha^{-1} |f|_1$. By $\text{vol}(\{x : |Mf(x)| > \alpha\}) = \sup_{K \subset \{x : |Mf(x)| > \alpha\}} \text{vol}(K)$ for compact sets K , then (2.20) implies (2.17).

(2.15) and (2.17) imply by the Marcinkiewicz Interpolation Theorem 2.16, proved below,

$$\|Mf\|_{L^p(\mathbb{R}^d)} < A_p \|f\|_{L^p(\mathbb{R}^d)} \text{ for all } p \in (1, \infty]. \quad (2.21)$$

We will use this result in the proof of the Hardy-Littlewood-Sobolev Theorem, and of Sobolev's estimates.

Before introducing the Marcinkiewicz interpolation Theorem, we recall that for a measurable function $g : \mathbb{R}^d \rightarrow \mathbb{R}$ the distribution function is

$$\lambda(\alpha) := \text{vol}(\{x \in \mathbb{R}^d : |g(x)| > \alpha\}).$$

Notice that $\lambda : [0, \infty) \rightarrow [0, \infty]$ is decreasing. This implies that it is measurable.

For a function $g \in L^p(\mathbb{R}^d)$ with $1 \leq p < \infty$ we have

$$\begin{aligned} \int_{\mathbb{R}^d} |g(x)|^p dx &= \int_{\mathbb{R}^d} dx \int_0^{|g(x)|} p \alpha^{p-1} d\alpha = \int_0^\infty d\alpha p \alpha^{p-1} \int_{\{x \in \mathbb{R}^d : |g(x)| > \alpha\}} dx \\ &= \int_0^\infty p \alpha^{p-1} \lambda(\alpha) d\alpha \end{aligned} \quad (2.22)$$

where the 1st equality is elementary, the last follows immediately by the definition of $\lambda(\alpha)$, and the 2nd follows from Tonelli's Theorem applied to the positive measurable function $F(x, \alpha) := |\alpha|^{p-1} \chi_{\mathbb{R}_+}(|g(x)| - \alpha) \chi_{\mathbb{R}_+}(\alpha)$.

Theorem 2.16 (Marcinkiewicz Interpolation). *Let $T : L^1(\mathbb{R}^d) + L^\infty(\mathbb{R}^d) \rightarrow L^1_{loc}(\mathbb{R}^d)$ be a sublinear operator s.t. for two constants A_1 and A_∞ and for all f*

$$\|Tf\|_{L^\infty(\mathbb{R}^d)} \leq A_\infty \|f\|_{L^\infty(\mathbb{R}^d)} \quad (2.23)$$

$$|\{x : |Tf(x)| > \alpha\}| \leq \frac{A_1}{\alpha} \|f\|_{L^1(\mathbb{R}^d)} \text{ for any } \alpha > 0. \quad (2.24)$$

Then for any $p \in (1, \infty)$ there is a constant A_p such that for any $f \in L^p(\mathbb{R}^d)$ we have

$$\|Tf\|_{L^p(\mathbb{R}^d)} \leq A_p \|f\|_{L^p(\mathbb{R}^d)}. \quad (2.25)$$

Proof. Dividing T by a constant, we can assume $A_\infty = 1$. Fix $p \in (1, \infty)$ and $f \in L^p(\mathbb{R}^d)$. For $\alpha > 0$ arbitrary set

$$f_1(x) = \begin{cases} f(x) & \text{if } |f(x)| \geq \frac{\alpha}{2} \\ 0 & \text{otherwise.} \end{cases}$$

Notice that $f_1 \in L^1(\mathbb{R}^d)$ by

$$\int_{\mathbb{R}^d} |f_1(x)| dx = \int_{\{x: |f(x)| \geq \frac{\alpha}{2}\}} |f(x)| dx \leq \frac{2^{p-1}}{\alpha^{p-1}} \int_{\mathbb{R}^d} |f(x)|^p dx.$$

Using (2.23), we get $|Tf(x)| \leq |Tf_1(x)| + \frac{\alpha}{2}$, since $\|f - f_1\|_{L^\infty(\mathbb{R}^d)} \leq \frac{\alpha}{2}$. Then

$$\{x : |Tf(x)| > \alpha\} \subseteq \{x : |Tf_1(x)| > \frac{\alpha}{2}\}.$$

We have, using (2.24),

$$\text{vol}(\{x : |Tf_1(x)| > \frac{\alpha}{2}\}) \leq A_1 \frac{2}{\alpha} \int_{\mathbb{R}^d} |f_1(x)| dx = A_1 \frac{2}{\alpha} \int_{\{x: |f(x)| \geq \frac{\alpha}{2}\}} |f(x)| dx.$$

Substituting $g = Tf$ in (2.22)

$$\begin{aligned} \int_{\mathbb{R}^d} |Tf(x)|^p dx &= \int_0^\infty p\alpha^{p-1} \text{vol}(\{x : |Tf(x)| > \alpha\}) d\alpha \\ &\leq \int_0^\infty p\alpha^{p-1} \text{vol}(\{x : |Tf_1(x)| > \frac{\alpha}{2}\}) d\alpha \leq 2A_1 \int_0^\infty p\alpha^{p-2} \int_{\{x: |f(x)| \geq \frac{\alpha}{2}\}} |f(x)| dx \\ &= 2pA_1 \int_{\mathbb{R}^d} dx |f(x)| \underbrace{\int_0^{2|f(x)|} \alpha^{p-2} d\alpha}_{\frac{2^{p-1}|f(x)|^{p-1}}{p-1}} = \frac{2^p p}{p-1} A_1 \int_{\mathbb{R}^d} |f(x)|^p dx. \end{aligned}$$

□

2.3 Back to Sobolev Embedding

We will use the properties of the Hardy Littlewood Maximal function, and specifically the definition and (2.21), to prove the following important theorem.

Theorem 2.17 (Hardy-Littlewood-Sobolev inequality). *For any*

$$\gamma \in (0, d) \text{ and } 1 < p < q < \infty \text{ with } \frac{1}{p} = \frac{1}{q} + \frac{d - \gamma}{d} \quad (2.26)$$

there exists a constant C s.t.

$$\left\| \int_{\mathbb{R}^d} f(x - y) |y|^{-\gamma} dy \right\|_{L^q(\mathbb{R}^d)} \leq C \|f\|_{L^p(\mathbb{R}^d)}. \quad (2.27)$$

Proof. For an $R > 0$ to be chosen momentarily, we split

$$\int_{\mathbb{R}^d} f(x - y) |y|^{-\gamma} dy = \int_{|y| < R} f(x - y) |y|^{-\gamma} dy + \int_{|y| > R} f(x - y) |y|^{-\gamma} dy.$$

We claim that

$$\left| \int_{|y| < R} f(x - y) |y|^{-\gamma} dy \right| \leq Mf(x) \int_{|y| < R} |y|^{-\gamma} dy = cR^{d-\gamma} Mf(x). \quad (2.28)$$

We assume for a moment this claim and complete the rest of the proof. By Hölder we have

$$\left| \int_{|y| > R} f(x - y) |y|^{-\gamma} dy \right| \leq \|f\|_{L^p(\mathbb{R}^d)} \left\| |y|^{-\gamma} \chi_{\{|y| > R\}} \right\|_{L^{p'}(\mathbb{R}^d)}.$$

We have $|y|^{-\gamma} \chi_{\{|y| > R\}} \in L^{p'}(\mathbb{R}^d)$ exactly if $\gamma p' > d$. The latter inequality is true because

$$\frac{1}{p'} - \frac{\gamma}{d} = -\frac{1}{q} < 0 \Rightarrow \gamma p' - d = \frac{dp'}{q} > 0.$$

In this case

$$\left\| |y|^{-\gamma} \chi_{\{|y| > R\}} \right\|_{L^{p'}(\mathbb{R}^d)} = \left(\text{vol}(\mathbb{S}^{d-1}) \int_{r > R} r^{-\gamma p' + d - 1} dr \right)^{\frac{1}{p'}} = cR^{\frac{d}{p'} - \gamma} = cR^{-\frac{d}{q}}.$$

Hence

$$\left| \int_{\mathbb{R}^d} f(x - y) |y|^{-\gamma} dy \right| \lesssim R^{d-\gamma} Mf(x) + \|f\|_{L^p(\mathbb{R}^d)} R^{-\frac{d}{q}}.$$

Now we choose R so that the two terms on the r.h.s. are equal:

$$\frac{Mf(x)}{\|f\|_{L^p}} = R^{\gamma - d - \frac{d}{q}} = R^{-\frac{d}{p}}.$$

Then we get

$$\begin{aligned} \left| \int_{\mathbb{R}^d} f(x-y)|y|^{-\gamma} dy \right| &\lesssim R^{d-\gamma} Mf(x) + \|f\|_{L^p(\mathbb{R}^d)} R^{-\frac{d}{q}} = 2\|f\|_{L^p(\mathbb{R}^d)} \left(\frac{Mf(x)}{\|f\|_{L^p}} \right)^{\frac{d}{q} \cdot \frac{p}{d}} \\ &= 2(Mf(x))^{\frac{p}{q}} \|f\|_{L^p}^{1-\frac{p}{q}}. \end{aligned}$$

Then

$$\left\| \int_{\mathbb{R}^d} f(x-y)|y|^{-\gamma} dy \right\|_{L^q(\mathbb{R}^d)} \lesssim \|f\|_{L^p}^{1-\frac{p}{q}} \|(Mf)^{\frac{p}{q}}\|_{L^q} = \|f\|_{L^p}^{1-\frac{p}{q}} \|(Mf)\|_{L^p}^{\frac{p}{q}} \lesssim \|f\|_{L^p}.$$

To complete the proof we need the inequality in (2.28). More generally, we prove that if $\Phi \in L^1(\mathbb{R}^d)$ is radial, positive and decreasing, then

$$\left| \int_{\mathbb{R}^d} f(x-y)\Phi(y)dy \right| \leq \int_{\mathbb{R}^d} |f(x-y)|\Phi(y)dy \leq Mf(x) \int_{\mathbb{R}^d} \Phi(y)dy. \quad (2.29)$$

Then (2.28) is just (2.29) for $\Phi(y) = |y|^{-\gamma} \chi_{\{|y|<R\}}$.

Notice that (2.29) is true for radial functions of the form

$$\Phi = \sum_j a_j \chi_{B_j} \quad (2.30)$$

for $a_j > 0$, B_j a ball of center 0. Indeed

$$\sum_j a_j \int_{B_j} |f(x-y)|dy = \sum_j a_j \frac{\text{vol}(B_j)}{\text{vol}(B_j)} \int_{B_j} |f(x-y)|dy \leq \sum_j a_j \text{vol}(B_j) Mf(x) = Mf(x) \int \Phi dy.$$

In the general case the result follows considering a sequence $\Phi_n \xrightarrow{n \rightarrow \infty} \Phi$ a.e. with the Φ_n functions like in (2.30). Then (2.29) follows from Beppo Levi's (or also Lebergue's) monotone convergence theorem. □

For the above proof see [16] p.354, while for the next one see [15] p.73.

Lemma 2.18. *For any $\gamma \in (0, d)$ there exists $c_\gamma > 0$ s.t.*

$$\mathcal{F}(|\cdot|^{-\gamma})(\xi) = c_\gamma |\xi|^{\gamma-d}. \quad (2.31)$$

Proof. It is enough to show that for any $\phi \in \mathcal{S}(\mathbb{R}^d)$ we have

$$\int_{\mathbb{R}^d} |x|^{-\gamma} \phi(x) dx = c_\gamma \int_{\mathbb{R}^d} |\xi|^{\gamma-d} \widehat{\phi}(\xi) d\xi. \quad (2.32)$$

Starting from (1.2) and Plancherel we have

$$\int_{\mathbb{R}^d} \varepsilon^{-\frac{d}{2}} e^{-\frac{|x|^2}{2\varepsilon}} \phi(x) dx = \int_{\mathbb{R}^d} e^{-\varepsilon \frac{|\xi|^2}{2}} \widehat{\phi}(\xi) d\xi.$$

Now we apply to both sides $\int_0^\infty \frac{d\varepsilon}{\varepsilon} \varepsilon^{\frac{d-\gamma}{2}}$ and commuting order of integration we obtain

$$\int_{\mathbb{R}^d} dx \phi(x) \underbrace{\int_0^\infty \varepsilon^{-\frac{\gamma}{2}} e^{-\frac{|x|^2}{2\varepsilon}} \frac{d\varepsilon}{\varepsilon}}_{a_\gamma |x|^{-\gamma}} = \int_{\mathbb{R}^d} d\xi \widehat{\phi}(\xi) \underbrace{\int_0^\infty \varepsilon^{\frac{d-\gamma}{2}} e^{-\varepsilon \frac{|\xi|^2}{2}} \frac{d\varepsilon}{\varepsilon}}_{b_\gamma |\xi|^{\gamma-d}}$$

for appropriate constants a_γ and b_γ . In fact $a_\gamma = 2^{\frac{\gamma}{2}} \Gamma\left(\frac{\gamma}{2} + 1\right)$, $b_\gamma = 2^{\frac{d-\gamma}{2}} \Gamma\left(\frac{d-\gamma}{2}\right)$ and $c_\gamma = \frac{2^{\frac{d-\gamma}{2}} \Gamma\left(\frac{d-\gamma}{2}\right)}{2^{\frac{\gamma}{2}} \Gamma\left(\frac{\gamma}{2} + 1\right)}$. □

Theorem 2.19 (Sobolev Embedding Theorem with fractional derivatives). *Let $p \in (1, \infty)$, $0 < s < \frac{d}{p}$ and $\frac{1}{q} = \frac{1}{p} - \frac{s}{d}$. Then there exists a C s.t. we have*

$$\|f\|_{L^q(\mathbb{R}^d)} \leq C \|f\|_{\mathcal{W}^{s,p}(\mathbb{R}^d)} \text{ for any } f \in \mathcal{S}(\mathbb{R}^d). \quad (2.33)$$

Proof. For $f \in \mathcal{S}(\mathbb{R}^d)$ we have for some fixed c

$$f(x) := (2\pi)^{-\frac{d}{2}} \int_{\mathbb{R}^d} e^{i\xi \cdot x} |\xi|^{-s} \left(|\xi|^s \widehat{f}(\xi) \right) d\xi = c \int_{\mathbb{R}^d} |x-y|^{s-d} g(y) dy \text{ where } \widehat{g}(\xi) = |\xi|^s \widehat{f}(\xi)$$

where we used $\widehat{\varphi * T} = (2\pi)^{\frac{d}{2}} \widehat{\varphi} \widehat{T}$ which holds for $\varphi \in \mathcal{S}(\mathbb{R}^d)$ and $T \in \mathcal{S}'(\mathbb{R}^d)$. Since $g \in L^p(\mathbb{R}^d)$, by the Hardy-Littlewood-Sobolev Theorem we have that $f \in L^q(\mathbb{R}^d)$ for

$$\frac{1}{q} = \frac{1}{p} - \frac{d - (d-s)}{d} = \frac{1}{p} - \frac{s}{d}$$

□

Notice that for $0 < s < \frac{d}{2}$ we know that $\dot{H}^s(\mathbb{R}^d)$ contains $\mathcal{S}(\mathbb{R}^d)$ as a dense subspace, so (2.33) with $p = 2$ extends to all $f \in \dot{H}^s(\mathbb{R}^d)$.

2.4 Assorted inequalities

Lemma 2.20 (Interpolation of Sobolev norms). *For any $s \in [0, 1]$ and any $k = sk_1 + (1-s)k_2$ we have*

$$\|f\|_{\dot{H}^k(\mathbb{R}^d)} \leq \|f\|_{\dot{H}^{k_1}(\mathbb{R}^d)}^s \|f\|_{\dot{H}^{k_2}(\mathbb{R}^d)}^{1-s} \text{ for any } f \in \dot{H}^{k_1}(\mathbb{R}^d) \cap \dot{H}^{k_2}(\mathbb{R}^d). \quad (2.34)$$

In particular, for $s \in [0, 1]$ and any $f \in H^1(\mathbb{R}^d)$

$$\|f\|_{\dot{H}^s(\mathbb{R}^d)} \leq \|f\|_{L^2(\mathbb{R}^d)}^{1-s} \|f\|_{\dot{H}^1(\mathbb{R}^d)}^s \quad (2.35)$$

Proof. (2.35) follows from (2.34) for $k_1 = 1$ and $k_2 = 0$. So let us turn to (2.34). Obviously there is nothing to prove for $s = 0, 1$, so we can assume $s \in (0, 1)$. Notice that for $p = \frac{1}{s}$ we have $p' := \frac{p}{p-1} = \frac{1}{1-s}$. Now, we have

$$\begin{aligned} \|f\|_{\dot{H}^k(\mathbb{R}^d)}^2 &= \int \left(|\xi|^{2sk_1} |\widehat{f}(\xi)|^{2s} \right) \left(|\xi|^{2(1-s)k_2} |\widehat{f}(\xi)|^{2(1-s)} \right) d\xi \\ &\leq \| |\xi|^{2sk_1} |\widehat{f}(\xi)|^{2s} \|_{L^{\frac{1}{s}}(\mathbb{R}^d)} \| |\xi|^{2(1-s)k_2} |\widehat{f}(\xi)|^{2(1-s)} \|_{L^{\frac{1}{1-s}}(\mathbb{R}^d)} \\ &= \| |\xi|^{k_1} |\widehat{f}(\xi)| \|_{L^2(\mathbb{R}^d)}^{2s} \| |\xi|^{k_1} \widehat{f}(\xi) \|_{L^2(\mathbb{R}^d)}^{2(1-s)} = \|f\|_{\dot{H}^{k_1}(\mathbb{R}^d)}^{2s} \|f\|_{\dot{H}^{k_2}(\mathbb{R}^d)}^{2(1-s)}. \end{aligned}$$

□

Lemma 2.21 (Agmon's inequality). *Given a pair $0 < r < d/2 < s$ we have*

$$\|u\|_{L^\infty(\mathbb{R}^d)} \leq \|u\|_{\dot{H}^r(\mathbb{R}^d)}^{\frac{s-d}{s-r}} \|u\|_{\dot{H}^s(\mathbb{R}^d)}^{\frac{d-r}{s-r}}. \quad (2.36)$$

Example 2.22. For instance,

$$\|u\|_{L^\infty(\mathbb{R}^3)} \leq \|\nabla u\|_{L^2(\mathbb{R}^3)}^{\frac{1}{2}} \|\nabla^2 u\|_{L^2(\mathbb{R}^3)}^{\frac{1}{2}}, \quad (2.37)$$

where notice that here we are assuming $\widehat{u} \in L^1_{loc}(\mathbb{R}^3, \mathbb{R}^3)$, which excludes additive constants.

It is well known that $H^{\frac{d}{2}}(\mathbb{R}^d) \not\subset L^\infty(\mathbb{R}^d)$. Indeed, for $\widehat{u}(\xi) := \frac{\langle \xi \rangle^{-d}}{1 + \log \langle \xi \rangle}$ we have $u \in H^{\frac{d}{2}}(\mathbb{R}^d)$. On the other hand we have $\widehat{u} \notin L^1(\mathbb{R}^d)$. We show that $u \notin L^\infty(\mathbb{R}^d)$. Suppose by contradiction that $u \in L^\infty(\mathbb{R}^d)$. Then for $\chi \in C_c^\infty(\mathbb{R}^d, [0, 1])$ with $\int \chi = 1$, radial and decreasing as $|\xi|$ grows,

$$(2\pi)^{-\frac{d}{2}} \int_{\mathbb{R}^d} \chi(\xi/k) \widehat{u}(\xi) d\xi = (2\pi)^{-\frac{d}{2}} \int_{\mathbb{R}^d} k^d \widehat{\chi}(kx) u(x) d\xi \leq (2\pi)^{-\frac{d}{2}} \|u\|_{L^\infty(\mathbb{R}^d)}$$

But then, since $\widehat{\chi}(kx)u(x)$ is an increasing sequence of functions, we have $\chi(\cdot/k)\widehat{u} \xrightarrow{k \rightarrow \infty} \widehat{u}$ in $L^1(\mathbb{R}^d)$ with $\|u\|_{L^1(\mathbb{R}^d)} \leq (2\pi)^{-\frac{d}{2}} \|u\|_{L^\infty(\mathbb{R}^d)}$. This is a contradiction.

Proof of Lemma 2.21. For $R > 0$ we have

$$\begin{aligned} |u(x)| &\leq (2\pi)^{-\frac{d}{2}} \int_{|\xi| < R} |\widehat{u}(\xi)| |\xi|^r |\xi|^{-r} d\xi + (2\pi)^{-\frac{d}{2}} \int_{|\xi| > R} |\widehat{u}(\xi)| |\xi|^s |\xi|^{-s} d\xi \\ &\leq (2\pi)^{-\frac{d}{2}} \|u\|_{\dot{H}^r(\mathbb{R}^d)} \left(\int_{|\xi| < R} |\xi|^{-2r} d\xi \right)^{\frac{1}{2}} + (2\pi)^{-\frac{d}{2}} \|u\|_{\dot{H}^s(\mathbb{R}^d)} \left(\int_{|\xi| > R} |\xi|^{-2s} d\xi \right)^{\frac{1}{2}} \\ &\lesssim \|u\|_{\dot{H}^r(\mathbb{R}^d)} R^{\frac{d}{2}-r} + \|u\|_{\dot{H}^s(\mathbb{R}^d)} R^{\frac{d}{2}-s}. \end{aligned}$$

We choose R so that the two terms are equal, which yields

$$R = \frac{\|u\|_{\dot{H}^s(\mathbb{R}^d)}^{\frac{1}{s-r}}}{\|u\|_{\dot{H}^r(\mathbb{R}^d)}^{\frac{1}{s-r}}},$$

so that $|u(x)| \leq C_d \|u\|_{\dot{H}^r(\mathbb{R}^d)}^{1 - \left(\frac{d}{2} - r\right) \frac{1}{s-r}} \|u\|_{\dot{H}^s(\mathbb{R}^d)}^{\left(\frac{d}{2} - r\right) \frac{1}{s-r}}$.

□

Later in Sect. 11 we will use the following modification of Lemma 2.21.

Lemma 2.23. *Let $U \subset \mathbb{R}^3$ be a bounded open subspace with ∂U a smooth submanifold of \mathbb{R}^3 and suppose $f \in H^k(U)$ with $k \geq 2$. Then for any $r \in [1, 2]$ we have*

$$\|f\|_{L^\infty(U)} \leq C_{k,r} \|f\|_{L^r(U)}^\theta \|f\|_{H^k(U)}^{1-\theta} \quad \text{with } \theta = \frac{r \left(k - \frac{3}{2}\right)}{kr + \frac{3}{2}(2-r)}. \quad (2.38)$$

Proof. We know that there is an appropriate extension operator $H^k(U) \ni f \rightarrow Ef \in H^k(\mathbb{R}^d)$ with $Ef|_U = f$. Then we use

$$\|Ef\|_{H^1(\mathbb{R}^3)} \leq \|Ef\|_{L^2(\mathbb{R}^3)}^{1-\frac{1}{k}} \|Ef\|_{H^k(\mathbb{R}^3)}^{\frac{1}{k}} \quad \text{and} \quad \|Ef\|_{H^2(\mathbb{R}^3)} \leq \|Ef\|_{L^2(\mathbb{R}^3)}^{1-\frac{2}{k}} \|Ef\|_{H^k(\mathbb{R}^3)}^{\frac{2}{k}}$$

and Agmon's

$$\|Ef\|_{L^\infty(\mathbb{R}^3)} \leq \|Ef\|_{H^1(\mathbb{R}^3)}^{\frac{1}{2}} \|Ef\|_{H^2(\mathbb{R}^3)}^{\frac{1}{2}} \leq \|Ef\|_{L^2(\mathbb{R}^3)}^{1-\frac{3}{2k}} \|Ef\|_{H^k(\mathbb{R}^3)}^{\frac{3}{2k}}$$

which yields

$$\|f\|_{L^\infty(U)} \leq c \|f\|_{L^2(U)}^{1-\frac{3}{2k}} \|f\|_{H^k(U)}^{\frac{3}{2k}}.$$

Substitute by Hölder $\|f\|_{L^2(U)} \leq \|f\|_{L^r(U)}^{\frac{r}{2}} \|f\|_{L^\infty(U)}^{1-\frac{r}{2}}$ and then we get

$$\|f\|_{L^\infty(U)} \leq c \|f\|_{L^r(U)}^{\frac{r}{2} \left(1 - \frac{3}{2k}\right)} \|f\|_{L^\infty(U)}^{\left(1 - \frac{r}{2}\right) \left(1 - \frac{3}{2k}\right)} \|f\|_{H^k(U)}^{\frac{3}{2k}}.$$

Solving with respect to $\|f\|_{L^\infty(U)}$ we obtain

$$\|f\|_{L^\infty(U)}^{1 - \left(1 - \frac{r}{2}\right) \left(1 - \frac{3}{2k}\right)} = \|f\|_{L^\infty(U)}^{\frac{r}{2} + \frac{3}{2k} - \frac{3r}{4k}} \leq c \|f\|_{L^r(U)}^{\frac{r}{2} \left(1 - \frac{3}{2k}\right)} \|f\|_{H^k(U)}^{\frac{3}{2k}}.$$

So we get the following, which is the desired result:

$$\|f\|_{L^\infty(U)}^{\frac{r}{2} + \frac{3}{2k} - \frac{3r}{4k}} \leq c_1 \|f\|_{L^r(U)}^{\frac{r}{2} \left(1 - \frac{3}{2k}\right)} \|f\|_{H^k(U)}^{\frac{3}{2k}} = c_1 \|f\|_{L^r(U)}^{\frac{r \left(k - \frac{3}{2}\right)}{kr + 3 - \frac{3r}{2}}} \|f\|_{H^k(U)}^{\frac{3}{kr + 3 - \frac{3r}{2}}}.$$

□

Theorem 2.24 (Gagliardo–Nirenberg). *If $p \in [2, \infty)$ is s.t. $\frac{1}{p} > \frac{1}{2} - \frac{1}{d}$ then there exists C s.t.*

$$\|f\|_{L^p(\mathbb{R}^d)} \leq C \|f\|_{L^2(\mathbb{R}^d)}^{1-s} \|f\|_{\dot{H}^1(\mathbb{R}^d)}^s \text{ where } s = d \left(\frac{1}{2} - \frac{1}{p} \right). \quad (2.39)$$

Proof. By Sobolev, for $\frac{1}{p} = \frac{1}{2} - \frac{s}{d}$ we have

$$\|f\|_{L^p(\mathbb{R}^d)} \leq C \|f\|_{\dot{H}^s(\mathbb{R}^d)}.$$

Here s is like in the statement. Also $s = d \left(\frac{1}{2} - \frac{1}{p} \right) < 1 \Leftrightarrow \frac{1}{2} - \frac{1}{p} < \frac{1}{d}$. Finally, apply (2.35). \square

Remark 2.25. For $p = 4$ and $d = 2, 3$ we have $s = d/4$ and $\|f\|_{L^4(\mathbb{R}^d)} \leq C \|f\|_{L^2(\mathbb{R}^d)}^{1-d/4} \|f\|_{\dot{H}^1(\mathbb{R}^d)}^{d/4}$.

Lemma 2.26 (Gronwall's inequality). *Let $T > 0$, λ and φ two functions in $L^1(0, T)$, both ≥ 0 a.e., and C_1, C_2 two non negative constants. Let $\lambda\varphi \in L^1(0, T)$ and let*

$$\varphi(t) \leq C_1 + C_2 \int_0^t \lambda(s) \varphi(s) ds \text{ for a.e. } t \in (0, T).$$

Then we have

$$\varphi(t) \leq C_1 e^{C_2 \int_0^t \lambda(s) ds} \text{ for a.e. } t \in (0, T).$$

Proof. Set

$$\psi(t) := C_1 + C_2 \int_0^t \lambda(s) \varphi(s) ds.$$

Then $\psi(t)$ is absolutely continuous and so it is differentiable almost everywhere and we have

$$\psi'(t) = C_2 \lambda(t) \varphi(t) \leq C_2 \lambda(t) \psi(t) \text{ for a.e. } t \in (0, T).$$

Also, the function $\psi(t) e^{-C_2 \int_0^t \lambda(s) ds}$ is absolutely continuous with

$$\frac{d}{dt} \left(\psi(t) e^{-C_2 \int_0^t \lambda(s) ds} \right) \leq 0 \text{ for a.e. } t \in (0, T).$$

Then we have

$$\psi(t) \leq e^{C_2 \int_0^t \lambda(s) ds} \psi(0) = C_1 e^{C_2 \int_0^t \lambda(s) ds} \text{ for all } t \in (0, T).$$

Since $\varphi(t) \leq \psi(t)$ a.e., the result follows. \square

3 The Calderon–Zygmund theory

We consider Calderon–Zygmund (CZ) kernels. We will use the following definition.

Definition 3.1. In these notes, we will say that a function $K : \mathbb{R}^d \times \mathbb{R}^d \setminus \Delta \rightarrow \mathbb{C}$ with Δ the diagonal $\{(x, x) : x \in \mathbb{R}^d\}$, is CZ if there exists a fixed constant C s.t. the following conditions hold:

(C–Z1) we have

$$\begin{aligned} |K(x, y)| &\leq \frac{C}{|x - y|^d} \text{ for any } x \neq y \text{ and} \\ |\nabla_{x,y} K(x, y)| &\leq \frac{C}{|x - y|^{d+1}} \text{ for any } x \neq y. \end{aligned} \quad (3.1)$$

(C–Z2) there is an operator T , which satisfies

$$Tf(x) = \int_{\mathbb{R}^d} K(x, y)f(y)dy \text{ for } x \notin \text{supp } f \quad (3.2)$$

and which defines a bounded operator $T : L^2(\mathbb{R}^d) \rightarrow L^2(\mathbb{R}^d)$ with norm bounded by C .

There are many examples.

Example 3.2. 1. Let us consider the operator $R_j = \frac{\partial_j}{\sqrt{-\Delta}}$ which is a well defined bounded operator in $L^2(\mathbb{R}^d)$ since

$$\widehat{R_j f}(\xi) = -i \frac{\xi_j}{|\xi|} \widehat{f}(\xi).$$

Notice that for $K = \mathcal{F}^* \left(-i \frac{\xi_j}{|\xi|} \right)$, we have $R_j f(x) = (2\pi)^{-\frac{d}{2}} K * f(x)$ where for $\varphi \in C_c^\infty(\mathbb{R}^d, [0, 1])$ any function with $\varphi = 1$ in $B(0, a)$ and $\varphi = 0$ outside $B(0, b)$, for some $0 < a < b$, we have

$$K(x) = -i \lim_{R \rightarrow +\infty} (2\pi)^{-\frac{d}{2}} \int_{\mathbb{R}^d} e^{i\xi \cdot x} \frac{\xi_j}{|\xi|} \varphi(\xi/R) d\xi.$$

It is easy to see that for any $x \neq 0$ the above limit converges and that $K(x - y)$ satisfies the inequalities (3.1) for a fixed C . For example, the 1st inequality follows splitting

$$\int_{\mathbb{R}^d} e^{i\xi \cdot x} \frac{\xi_j}{|\xi|} \varphi(\xi|x|) \varphi(\xi/R) d\xi + \int_{\mathbb{R}^d} e^{i\xi \cdot x} \frac{\xi_j}{|\xi|} \varphi(\xi/R) (1 - \varphi(\xi|x|)) d\xi$$

where we bound the absolute value of the 1st integral by

$$\int_{|\xi| \leq \frac{b}{|x|}} d\xi = \frac{b^d \text{vol}(S^{d-1})}{d} \frac{1}{|x|^d}$$

and the absolute value of the 2nd integral by means of an integration by parts using $Le^{i\xi \cdot x} = e^{i\xi \cdot x}$ with $L := \frac{x \cdot \nabla_\xi}{i|x|^2}$, and writing it as

$$\int_{\mathbb{R}^d} e^{i\xi \cdot x} (L^*)^N \left[\frac{\xi_j}{|\xi|} \varphi(\xi/R) (1 - \varphi(\xi|x|)) \right] d\xi.$$

It is now easy to see that

$$\left| (L^*)^N \left[\frac{\xi_j}{|\xi|} \varphi(\xi/R) (1 - \varphi(\xi|x|)) \right] \right| \leq C_N \frac{1}{|x|^N |\xi|^N}.$$

Hence the absolute of the 2nd integral is bounded by

$$C_N \frac{1}{|x|^N} \int_{|\xi| \geq \frac{a}{|x|}} \frac{1}{|\xi|^N} d\xi \leq C'_N \frac{|x|^{N-d}}{a^{N-d} |x|^N} = \frac{C'_N}{a^{N-d}} \frac{1}{|x|^d}.$$

The 2nd inequality in (3.1) can be obtained noticing that

$$\partial_k K(x) = -i \lim_{R \rightarrow +\infty} (2\pi)^{-\frac{d}{2}} \int_{\mathbb{R}^d} e^{i\xi \cdot x} \xi_k \frac{\xi_j}{|\xi|} \varphi(\xi/R) d\xi.$$

When one considers the above inequalities with an additional factor ξ_k inside the integral, one gets the upper bound of the 2nd inequality in (3.1).

The operators R_j are called Riesz transforms.

2. The above discussion works out similarly with operators $\frac{\partial_j}{\sqrt{1-\Delta}}$ and $\frac{\partial^\alpha}{(1-\Delta)^{\frac{k}{2}}}$ with α any multi-index with $|\alpha| \leq k$. In particular, $\frac{\partial_j}{\sqrt{1-\Delta}}$ has symbol $\frac{-i\xi_j}{\langle \xi \rangle}$.
3. Notice that $(\mathbb{P}u)_j = u_j - R_j R_k u_k$, and so in particular it is a CZ operator.
4. Let us consider in \mathbb{R} the Hilbert transform

$$Hf(x) := -\frac{1}{\pi} \lim_{\varepsilon \rightarrow 0^+} \int_{|x-y| > \varepsilon} \frac{f(y)}{x-y} dy = -\frac{1}{\pi} (P.V. \frac{1}{x}) * f \quad (3.3)$$

with $P.V. \frac{1}{x}$ the tempered distribution that acts on a $\phi \in \mathcal{S}(\mathbb{R})$ as $\lim_{\varepsilon \rightarrow 0^+} \int_{|x| > \varepsilon} \frac{\phi(x)}{x} dx$.

Notice that using the Residue theorem we have

$$\lim_{\varepsilon \rightarrow 0^+} \int_{|x| > \varepsilon} e^{-i\xi x} \frac{dx}{x} = -i\pi \text{sign}(\xi)$$

so that

$$\frac{1}{\pi} \mathcal{F}(P.V. \frac{1}{x}) = -i(2\pi)^{-\frac{1}{2}} \text{sign}(\xi).$$

Then

$$\mathcal{F}(Hf)(\xi) = -i \text{sign}(\xi) \widehat{f}(\xi).$$

which implies that (C-Z2) is true. Since (C-Z1) is obvious, we conclude that the Hilbert transform meets the conditions of Definition 3.1.

Remark 3.3. Consider the operator $T_{\mathbb{R}_+} f := \mathcal{F}^* [\chi_{\mathbb{R}_+} \widehat{f}]$. Then $\chi_{\mathbb{R}_+} = 2^{-1}i(-i\text{sign} - i)$ implies $T_{\mathbb{R}_+} = 2^{-1}(I + iH)$. Analogously $T_{\mathbb{R}_-} = 2^{-1}(I - iH)$. Next,

$$T_{(a,+\infty)} = 2^{-1}(I + ie^{iax}He^{-iax}) \text{ and } T_{(-\infty,b)} = 2^{-1}(I - ie^{ibx}He^{-ibx}).$$

Finally

$$T_{(a,b)} = 2^{-1}(T_{(a,+\infty)} - T_{(b,+\infty)}) = 4^{-1}i(e^{iax}He^{-iax} - e^{ibx}He^{-ibx}).$$

Next, if in \mathbb{R}^d we consider the half-plane $x_1 > 0$, then

$$\begin{aligned} \mathcal{F}^* [\chi_{\{x_1>0\}} \widehat{f}] &= 2^{-1}(I + iH_1)f \text{ where} \\ (H_1 f)(x_1, x_2, \dots, x_d) &:= H(f(\cdot, x_2, \dots, x_d))(x_1). \end{aligned}$$

In general, any operator of the form $\mathcal{F}^* [\chi_P \widehat{f}]$ with P a polygon in \mathbb{R}^d can be expressed in terms of the Hilbert transform.

Remark 3.4. Let $p \in (1, \infty)$ and let $L^p(\mathbb{R}, \mathbb{C}) \ni f = \lim_{y \rightarrow 0^+} F(\cdot + iy)$ where

$F : \{x + iy : x \in \mathbb{R}, y > 0\} \rightarrow \mathbb{C}$ is a holomorphic function with $\sup_{y>0} \int_{\mathbb{R}} |F(x + iy)|^p dx < \infty$.

Then, if $u = \text{Re } f$ and $v = \text{Im } f$, we have $v = Hu$ (and, by $H^2 = -1$, $u = -Hv$). We give a brief impressionistic and non-rigorous discussion of how this comes about. Notice that if f is the boundary value in \mathbb{R} of F by Cauchy integral formula we have

$$F(x + iy) = \frac{1}{2\pi i} \int_{\mathbb{R}} \frac{1}{t - x - iy} f(t) dt = \frac{1}{2\pi i} (\cdot - iy * f)(x)$$

where here we assume $f \in \mathcal{S}(\mathbb{R}, \mathbb{C})$. Then for $y \rightarrow 0^+$ by the Sokhotski–Plemelj theorem we get

$$\lim_{y \rightarrow 0^+} \frac{1}{t - iy} = P.V. \cdot \frac{1}{t} + i\pi\delta(t) \text{ in } \mathcal{S}'(\mathbb{R}, \mathbb{C}). \quad (3.4)$$

This implies, assuming here $F \in C^0(\mathbb{R} \times [0, \infty))$, that by $f(x) = \lim_{y \rightarrow 0^+} F(x + iy)$ we have

$$f(x) = \frac{1}{2\pi i} \left(\lim_{\varepsilon \rightarrow 0^+} \int_{|x|>\varepsilon} \frac{f(x)}{x} dx + i\pi f(x) \right),$$

that is $f = iHf$, which is the desired result.

As for (3.4), for $f \in \mathcal{S}(\mathbb{R})$ we have

$$\int_{\mathbb{R}} \frac{f(t)}{t - iy} dt = \int_{\mathbb{R}} \frac{t}{t^2 + y^2} f(t) dt + i \int_{\mathbb{R}} \frac{y}{t^2 + y^2} f(t) dt.$$

By a change of variables, by dominated convergence and by the continuity of f in 0 we have

$$\int_{\mathbb{R}} \frac{y}{t^2 + y^2} f(t) dt = \int_{\mathbb{R}} \frac{1}{t^2 + 1} f(ty) dt \xrightarrow{y \rightarrow 0} \pi f(0).$$

Next we write

$$\int_{\mathbb{R}} \frac{t}{t^2 + y^2} f(t) dt = \int_{|t| \leq y} \frac{t}{t^2 + y^2} f(t) dt + \int_{|t| \geq y} \frac{t}{t^2 + y^2} f(t) dt.$$

We have

$$\left| \int_{|t| \leq y} \frac{t}{t^2 + y^2} f(t) dt \right| = \left| \int_{|t| \leq y} \frac{t}{t^2 + y^2} (f(t) - f(0)) dt \right| \xrightarrow{y \rightarrow 0} 0.$$

Next we write

$$\int_{|t| \geq y} \frac{t}{t^2 + y^2} f(t) dt = \int_{|t| \geq y} \left(\frac{t}{t^2 + y^2} - \frac{1}{t} \right) f(t) dt + \int_{|t| \geq y} \frac{f(t)}{t} dt$$

and observe that, changing variable,

$$\begin{aligned} \int_{|t| \geq y} \left(\frac{t}{t^2 + y^2} - \frac{1}{t} \right) f(t) dt &= \int_{|t| \geq y} \frac{-y^2}{t(t^2 + y^2)} f(t) dt = \int_{|s| \geq 1} \frac{-1}{s(s^2 + 1)} f(sy) dt \\ &\xrightarrow{y \rightarrow 0} -f(0) \int_{|s| \geq 1} \frac{1}{s(s^2 + 1)} dt \end{aligned}$$

by dominated convergence. But the last integral is null. This proves (3.4).

Theorem 3.5. *Consider an operator T as in Definition 3.1. Then for any $p \in (1, \infty)$ the operator T , initially defined in $L^p(\mathbb{R}^d) \cap L^2(\mathbb{R}^d)$, extends into a bounded operator $T : L^p(\mathbb{R}^d) \rightarrow L^p(\mathbb{R}^d)$ with operator norm that depends only on p and C .*

Before proving Theorem 3.5 we need the Calderon–Zygmund decomposition lemma.

Theorem 3.6 (C–Z Decomposition). *For any $f \in L^1(\mathbb{R}^d)$ and any $\alpha > 0$ there exist families of balls B_j , disjoint sets Q_j with $B_j \subseteq Q_j \subseteq 3B_j$ with $\cup_j Q_j = \cup_j 3B_j$ (here $3B_j$ has same center and trice the radius of B_j) functions g and b_j s.t.*

1. $f = g + \sum_j b_j$.
2. $|g(x)| \leq 3^d \alpha$ for a.a. x , $\|g\|_{L^1(\mathbb{R}^d)} \leq (1 + 3^{2d}) \|f\|_{L^1(\mathbb{R}^d)}$.
3. $\text{supp } b_j \subseteq Q_j$, $\int_{\mathbb{R}^d} b_j(x) dx = 0$ and $\sum_j \|b_j\|_{L^1(\mathbb{R}^d)} \leq (1 + 3^{2d}) \|f\|_{L^1(\mathbb{R}^d)}$.
4. $\sum_j \text{vol}(B_j) \leq \frac{3^d}{\alpha} \|f\|_{L^1(\mathbb{R}^d)}$.

Remark 3.7. Notice that in the Calderon–Zygmund decomposition g is the *good* part of f and b_j form the *bad* part of f .

Proof. Define $\Omega = \{x \in \mathbb{R}^d : Mf(x) > \alpha\}$. Here notice that if $\Omega = \emptyset$ then just set $g = f$. For any $x \in \Omega$ there exists a maximal r_x s.t.

$$A_{r_x}|f|(x) := \frac{1}{\text{vol}(B(x, r_x))} \int_{B(x, r_x)} |f(y)| dy = \alpha.$$

Let us consider the family of balls $\{B(x, r_x)\}_{x \in \Omega}$. It contains, by a generalization of Vitali's Lemma, see Theorem 2.15, a maximal family of pairwise disjoint balls $\{B_j\}$ s.t.

$$\Omega \subseteq \cup_{x \in \Omega} B(x, r_x) \subseteq \cup_j (3B_j).$$

Notice that this implies

$$\text{vol}(\cup_{x \in \Omega} B(x, r_x)) \leq \sum_j \text{vol}(3B_j) \leq 3^d \sum_j \text{vol}(B_j) \leq \frac{3^d}{\alpha} \|f\|_{L^1(\mathbb{R}^d)}.$$

It is possible to choose disjoint sets Q_j s.t. $B_j \subseteq Q_j \subseteq 3B_j$ and $\cup_j Q_j = \cup_j (3B_j)$. One way is to choose

$$Q_k = 3B_k \cap C(\cup_{j < k} Q_j) \cap C(\cup_{j > k} B_j) \quad (3.5)$$

with CX the complement of X . Notice indeed that obviously for $k > \ell$ we have

$$Q_k \cap Q_\ell \subseteq C(\cup_{j < k} Q_j) \cap Q_\ell = (\cap_{j < k} CQ_j) \cap Q_\ell \subseteq CQ_\ell \cap Q_\ell = \emptyset.$$

Obviously $Q_k \subseteq 3B_k$.

We have $B_k \cap (\cup_{j > k} B_j) = \emptyset$ and so $B_k \subseteq C(\cup_{j > k} B_j)$. We have $B_k \cap (\cup_{j < k} Q_j) = \emptyset$ because, by (3.5), we have $B_k \cap Q_j = \emptyset$ for any $j < k$. Hence we conclude $B_k \subseteq Q_k$.

Finally we show $\cup_k Q_k = \cup_k 3B_k$. Obviously we have $\cup_k Q_k \subseteq \cup_k 3B_k$. Suppose there exists $x \in \cup_k 3B_k$ with $x \notin \cup_k Q_k$. The latter implies $x \notin \cup_k B_k$, and so $x \in C(\cup_{j > k} B_j)$ for all k , as well as $x \in C(\cup_{j < k} Q_j)$ for all k . But then, since $x \in 3B_\ell$ for some ℓ , it follows that $x \in Q_\ell$. And so we get a contradiction. Hence $\cup_k Q_k = \cup_k 3B_k$.

Now define

$$b_j(x) := \left(f(x) - \text{average}_{Q_j} f \right) \chi_{Q_j}(x)$$

$$g(x) := \begin{cases} \text{average}_{Q_j} f & \text{for } x \in Q_j, \\ f(x) & \text{for } x \notin \cup_j Q_j \end{cases}$$

Then we claim that the statement of the theorem is satisfied. First of all for any $x \in \mathbb{R}^d$ either $x \notin Q_j$ for all j , and so $f(x) = g(x)$ with $b_j(x) = 0$ for all j , or $x \in Q_{j_0}$ for exactly one j_0 , and so $f(x) = g(x) + b_{j_0}(x)$ with $b_j(x) = 0$ for all $j \neq j_0$. This proves the 1st claim.

For $x \notin \cup_j Q_j \supseteq \Omega$ we have $Mf(x) \leq \alpha$. Then, since for a.e. x we have

$$|f(x)| = \lim_{r \rightarrow 0^+} |A_r f(x)| \leq Mf(x)$$

we get $|g(x)| = |f(x)| \leq \alpha$ a.e. in the complement of $\cup_j Q_j$. For $x \in Q_j$ we have

$$|g(x)| = |\text{average}_{Q_j} f| \leq \frac{1}{\text{vol}(Q_j)} \int_{Q_j} |f(y)| dy \leq \frac{1}{\text{vol}(B_j)} \int_{3B_j} |f(y)| dy = \frac{3^d}{\text{vol}(3B_j)} \int_{3B_j} |f(y)| dy < 3^d \alpha.$$

Furthermore we have

$$\begin{aligned} \|g\|_{L^1(\mathbb{R}^d)} &= \int_{\mathbb{R}^d \setminus \cup_j Q_j} |f(x)| dx + \sum_j \int_{Q_j} |g(x)| dx \leq \|f\|_{L^1(\mathbb{R}^d)} + 3^d \alpha \sum_j \text{vol}(3B_j) \\ &\leq (1 + 3^{2d}) \|f\|_{L^1(\mathbb{R}^d)}. \end{aligned}$$

The fact that $\text{supp } b_j \subseteq Q_j$, $\int_{\mathbb{R}^d} b_j(x) dx = 0$ follows immediately by the definition of b_j . We have

$$\begin{aligned} \sum_j \|b_j\|_{L^1(\mathbb{R}^d)} &\leq \|f\|_{L^1(\mathbb{R}^d)} + \sum_j \text{vol}(Q_j) |\text{average}_{Q_j} f| \leq \|f\|_{L^1(\mathbb{R}^d)} + 3^d \alpha \sum_j \text{vol}(Q_j) \\ &\leq (1 + 3^{2d}) \|f\|_{L^1(\mathbb{R}^d)}. \end{aligned}$$

□

Proof of Theorem 3.5. By duality it is enough to consider only $p \in (1, 2]$. Furthermore, since by hypothesis (C-Z2) we know that the case $p = 2$ is true, by Marcinkiewicz Interpolation the statement of Theorem 3.5 results from proving that T is weak-type $(1, 1)$. We need to prove that there exists an $A > 0$ s.t.

$$\text{vol}(\{x : |Tf(x)| > \alpha\}) \leq \frac{A}{\alpha} \|f\|_{L^1(\mathbb{R}^d)} \text{ for any } \alpha > 0 \text{ and any } f \in L^1(\mathbb{R}^d). \quad (3.6)$$

For fixed $\alpha > 0$ and any $f \in L^1(\mathbb{R}^d)$ consider the C-Z decomposition $f = g + \sum_j b_j$. Notice that $|g(x)| \leq 3^d \alpha$ a.e. and $\|g\|_{L^1(\mathbb{R}^d)} \leq (1 + 3^{2d}) \|f\|_{L^1(\mathbb{R}^d)}$ imply $g \in L^2(\mathbb{R}^d)$ with

$$\int_{\mathbb{R}^d} |g|^2 dx \leq C_d \alpha \int_{\mathbb{R}^d} |f| dx \text{ for } C_d = 3^d (1 + 3^{2d})$$

and so by Hypothesis (C-Z2) we have $\|Tg\|_{L^2(\mathbb{R}^d)}^2 \leq C \alpha \|f\|_{L^1(\mathbb{R}^d)}$.

Then by Chebyshev's inequality (2.16) we have

$$\text{vol}(\{x : |(Tg)(x)| > \alpha/2\}) \leq \frac{4 \|Tg\|_{L^2(\mathbb{R}^d)}^2}{\alpha^2} \leq 4C \frac{\|f\|_{L^1(\mathbb{R}^d)}}{\alpha}.$$

We next consider b_j and consider for $x \notin 3B_j$ and for y_j the center of B_j ,

$$Tb_j(x) = \int_{Q_j} K(x, y) b_j(y) dy = \int_{Q_j} (K(x, y) - K(x, y_j)) b_j(y) dy$$

were we used $\text{average}_{Q_j} b_j = 0$. Then by (3.1) we have

$$|Tb_j(x)| \leq \frac{C}{|x - y_j|^{d+1}} \int_{Q_j} |y - y_j| |b_j(y)| dy.$$

Then for $r = \text{radius}(B_j)$

$$\begin{aligned} \int_{\mathbb{R}^d \setminus 3B_j} |Tb_j(x)| dx &\leq \int_{|x-y_j| \geq 3r} dx \frac{C}{|x-y_j|^{d+1}} \int_{|y-y_j| \leq 3r} |y-y_j| |b_j(y)| dy \\ &\leq c_d \frac{C}{3r} \int_{|y-y_j| \leq 3r} |y-y_j| |b_j(y)| dy \leq c_d C \|b_j\|_{L^1(\mathbb{R}^d)}. \end{aligned}$$

Let now $E = \cup_j (3B_j)$. Then for $b = \sum_j b_j$ we have

$$\int_{\mathbb{R}^d \setminus E} |Tb| \leq \sum_j \int_{\mathbb{R}^d \setminus 3B_j} |Tb_j| \leq c_d C \sum_j \|b_j\|_{L^1(\mathbb{R}^d)} \leq c_d C (1 + 3^{2d}) \|f\|_{L^1(\mathbb{R}^d)}.$$

Hence

$$\text{vol}(\{x \notin E : |(Tb)(x)| > \alpha/2\}) \leq \frac{2\|Tb\|_{L^1(\mathbb{R}^d)}}{\alpha} \leq c_d C (1 + 3^{2d}) \frac{\|f\|_{L^1(\mathbb{R}^d)}}{\alpha}.$$

So since

$$\begin{aligned} \text{vol}(\{x \notin E : |Tf(x)| > \alpha\}) &\leq \text{vol}(\{x \notin E : |Tg(x)| > \alpha/2\}) + \text{vol}(\{x \notin E : |(Tb)(x)| > \alpha/2\}) \\ &\leq [4C + c_d C (1 + 3^{2d})] \frac{\|f\|_{L^1(\mathbb{R}^d)}}{\alpha} \end{aligned}$$

and

$$\text{vol}(E) \leq \sum_j \text{vol}(3B_j) \leq 3^d \sum_j \text{vol}(B_j) \leq \frac{3^d}{\alpha} \|f\|_{L^1(\mathbb{R}^d)}$$

we conclude that (3.6) as been proved with $A = 3^d + 4C + c_d C (1 + 3^{2d})$. \square

Now we consider the Proof of Theorem 2.14. We follow [15] from p. 136. Preliminarily, we state the following lemma.

Lemma 3.8. *Suppose $1 < p < \infty$ and $s \geq 1$. Then $f \in \mathcal{W}^{s,p}(\mathbb{R}^d)$ if and only if $f \in \mathcal{W}^{s-1,p}(\mathbb{R}^d)$ and $\partial_{x^j} f \in \mathcal{W}^{s-1,p}(\mathbb{R}^d)$ for all $j = 1, \dots, d$ and furthermore the norms $\|f\|_{\mathcal{W}^{s,p}}$ and $\|f\|_{\mathcal{W}^{s-1,p}} + \sum_{j=1}^d \|\partial_{x^j} f\|_{\mathcal{W}^{s-1,p}}$ are equivalent.*

Proof of Theorem 2.14 assuming Lemma 3.8. Obviously for $k = 0$ we have $\mathcal{W}^{0,p} = W^{0,p} = L^p$.

It is obvious that $f \in W^{k,p}(\mathbb{R}^d)$ if and only if $f \in W^{k-1,p}(\mathbb{R}^d)$ and $\partial_{x^j} f \in W^{k-1,p}(\mathbb{R}^d)$ and that the the norms $\|f\|_{W^{k,p}}$ and $\|f\|_{W^{k-1,p}} + \sum_{j=1}^d \|\partial_{x^j} f\|_{W^{k-1,p}}$ are equivalent. But then Lemma 3.8 guarantees that $\mathcal{W}^{1,p} = W^{1,p}$ with equivalent norms, and so on for all $k \in \mathbb{N}$. \square

Proof of Lemma 3.8. Let us start assuming that $f \in \mathcal{W}^{s,p}(\mathbb{R}^d)$. Then setting $\widehat{g}(\xi) := \langle \xi \rangle^s \widehat{f}(\xi)$ we have $g \in L^p(\mathbb{R}^d)$ by definition of $\mathcal{W}^{s,p}(\mathbb{R}^d)$. Then notice that

$$(\langle \xi \rangle^{s-1} \widehat{f})^\vee = (\langle \xi \rangle^{-1} \widehat{g})^\vee = (2\pi)^{-\frac{d}{2}} \mathcal{J}_{-1} * g$$

where $\mathcal{J}_{-s} = (\langle \xi \rangle^{-1})^\vee$ is easily seen to be an $L^1(\mathbb{R}^d)$ function: this can be seen by an integration by parts argument like in the discussion of the Riesz transforms above. Hence we have

$$\|f\|_{\mathcal{W}^{s-1,p}} \leq (2\pi)^{-\frac{d}{2}} \|\mathcal{J}_{-1}\|_{L^1} \|g\|_{L^p} = (2\pi)^{-\frac{d}{2}} \|\mathcal{J}_{-1}\|_{L^1} \|f\|_{\mathcal{W}^{s,p}}.$$

Next we consider

$$\langle \xi \rangle^{s-1} \widehat{\partial_j f}(\xi) = -i \langle \xi \rangle^{s-1} \xi_j \widehat{f}(\xi) = -i \frac{\xi_j}{\langle \xi \rangle} \widehat{g}(\xi) = \widetilde{R}_j \widehat{g}(\xi),$$

where \widetilde{R}_j is a variant of the Riesz transform considered in the list in Example 3.2. But then, since the Riesz transforms are CZ operators, it follows that

$$\|\partial_j f\|_{\mathcal{W}^{k-1,p}} \leq \|\widetilde{R}_j\|_{L^p \rightarrow L^p} \|g\|_{L^p} = \|\widetilde{R}_j\|_{L^p \rightarrow L^p} \|g\|_{L^p} \|f\|_{\mathcal{W}^{s,p}}.$$

Summing up, we obtained

$$\|f\|_{\mathcal{W}^{s-1,p}} + \sum_{j=1}^d \|\partial_{x_j} f\|_{\mathcal{W}^{s-1,p}} \leq \left((2\pi)^{-\frac{d}{2}} \|\mathcal{J}_{-1}\|_{L^1} + d \|\widetilde{R}_1\|_{L^p \rightarrow L^p} \right) \|f\|_{\mathcal{W}^{s,p}},$$

where we used the fact, easy to show, that $\|\widetilde{R}_j\|_{L^p \rightarrow L^p}$ is constant in j , so that one implication is proved.

Now we consider the opposite implication, assuming $f \in \mathcal{W}^{s-1,p}(\mathbb{R}^d)$ and $\partial_{x_j} f \in \mathcal{W}^{s-1,p}(\mathbb{R}^d)$ for all $j = 1, \dots, d$. Then $\widehat{g}(\xi) := \langle \xi \rangle^{s-1} \widehat{f}(\xi)$ is $g \in L^p(\mathbb{R}^d)$ and, from $\widehat{\partial_{x_j} g}(\xi) = \langle \xi \rangle^{s-1} \widehat{\partial_{x_j} f}(\xi)$, $\partial_{x_j} g \in L^p(\mathbb{R}^d)$ for any j . Now we have

$$\langle \xi \rangle^s \widehat{f} = \langle \xi \rangle \widehat{g} = \langle \xi \rangle^2 \frac{1}{\langle \xi \rangle} \widehat{g} = \frac{1}{\langle \xi \rangle} \widehat{g} - \sum_{j=1}^d \frac{-i\xi_j}{\langle \xi \rangle} (-i\xi_j) \widehat{g}.$$

This means that

$$(\langle \xi \rangle^s \widehat{f})^\vee = (2\pi)^{-\frac{d}{2}} \mathcal{J}_{-1} * g - \sum_{j=1}^d \widetilde{R}_j \partial_{x_j} g$$

and so

$$\begin{aligned} \|f\|_{\mathcal{W}^{s,p}} &\leq (2\pi)^{-\frac{d}{2}} \|\mathcal{J}_{-1}\|_{L^1} \|g\|_{L^p} + \sum_{j=1}^d \|\widetilde{R}_j\|_{L^p \rightarrow L^p} \|\partial_{x_j} g\|_{L^p} \\ &= (2\pi)^{-\frac{d}{2}} \|\mathcal{J}_{-1}\|_{L^1} \|f\|_{\mathcal{W}^{s-1,p}} + \sum_{j=1}^d \|\widetilde{R}_j\|_{L^p \rightarrow L^p} \|\partial_{x_j} f\|_{\mathcal{W}^{s-1,p}}, \end{aligned}$$

which obviously proves the opposite implication and completes the proof of Lemma 3.8. \square

4 Linear heat equation

For Sections 4–5 see [5].

Let $T \in \mathbb{R}_+$ and $f : [0, T] \rightarrow \dot{H}^{s-1}(\mathbb{R}^d, \mathbb{R}^d)$, for $d = 2, 3$, be an external force s.t. $f = \mathbb{P}f$ and consider the following heat equation:

$$\begin{cases} u_t - \nu \Delta u = f \\ \nabla \cdot u = 0 \\ u(0) = u_0 \in \mathbb{P}\dot{H}^s(\mathbb{R}^d, \mathbb{R}^d) \end{cases} \quad (t, x) \in [0, T] \times \mathbb{R}^d \quad (4.1)$$

Definition 4.1. For a fixed $s < d/2$ let $f \in L^2([0, T], \dot{H}^{s-1}(\mathbb{R}^d, \mathbb{R}^d))$ with $f = \mathbb{P}f$. Then u is a solution of (4.1) if

$$u \in L^\infty([0, T], \dot{H}^s(\mathbb{R}^d, \mathbb{R}^d)), \quad \nabla u \in L^2([0, T], \dot{H}^s(\mathbb{R}^d, \mathbb{R}^d \times \mathbb{R}^d)), \quad (4.2)$$

if

$$u \text{ is weakly continuous from } [0, T] \text{ into } \dot{H}^s(\mathbb{R}^d, \mathbb{R}^d) \quad (4.3)$$

(that is, if for any $\psi \in \dot{H}^{-s}(\mathbb{R}^d, \mathbb{R}^d)$ the function $t \rightarrow \langle u(t), \psi \rangle$, which is a well defined function in $L^\infty([0, T], \mathbb{R})$, is in fact in $C^0([0, T], \mathbb{R})$)

and if for any $\Psi \in C_c^\infty([0, T] \times \mathbb{R}^d, \mathbb{R}^d)$ we have

$$\langle u(t), \Psi(t) \rangle_{L^2} = \int_0^t (\nu \langle u(t'), \Delta \Psi(t') \rangle_{L^2} + \langle u(t'), \partial_t \Psi(t') \rangle_{L^2} + \langle f(t'), \Psi(t') \rangle_{L^2}) dt' + \langle u_0, \Psi(0) \rangle_{L^2}. \quad (4.4)$$

The following theorem yields existence, uniqueness and energy estimate for (4.1).

Theorem 4.2. *Problem (4.1) admits exactly one solution in the sense of the above definition. For any t the following energy estimate is satisfied:*

$$\|u(t)\|_{\dot{H}^s}^2 + 2\nu \int_0^t \|\nabla u(t')\|_{\dot{H}^s}^2 dt' = \|u_0\|_{\dot{H}^s}^2 + 2 \int_0^t \langle f(t'), u(t') \rangle_{\dot{H}^s} dt'. \quad (4.5)$$

Furthermore we have

$$u \in C^0([0, T], \dot{H}^s(\mathbb{R}^d, \mathbb{R}^d)) \quad (4.6)$$

and the formula

$$\widehat{u}(t, \xi) = e^{-t\nu|\xi|^2} \widehat{u}_0(\xi) + \int_0^t e^{-(t-t')\nu|\xi|^2} \widehat{f}(t', \xi) dt'. \quad (4.7)$$

Proof. (Uniqueness). It is enough to show that the only solution of the case $u_0 = 0$ and $f = 0$ is $u = 0$. Let u be such a solution. Then

$$\langle u(t), \Psi(t) \rangle_{L^2} = \int_0^t (\nu \langle u(t'), \Delta \Psi(t') \rangle_{L^2} + \langle u(t'), \partial_t \Psi(t') \rangle_{L^2}) dt'.$$

Let $\Psi(t, x) = \psi(x)$ with $\psi \in C_c^\infty(\mathbb{R}^d, \mathbb{R}^d)$. Then the above equality reduces to

$$\langle u(t), \psi \rangle_{L^2} = \nu \int_0^t \langle u(t'), \Delta \psi \rangle_{L^2}. \quad (4.8)$$

We claim that this identity holds for all $\psi \in \dot{H}^{-s}(\mathbb{R}^d, \mathbb{R}^d) \cap \dot{H}^{-s+1}(\mathbb{R}^d, \mathbb{R}^d)$. From Lemma 2.2 we know that $C_c^\infty(\mathbb{R}^d, \mathbb{R}^d)$ is dense in $\dot{H}^{-s}(\mathbb{R}^d, \mathbb{R}^d)$ (here we use $s < d/2$) and in $\dot{H}^{-s+1}(\mathbb{R}^d, \mathbb{R}^d)$ and so the claim follows by density and the fact that

$$\begin{aligned} \langle \cdot, \cdot \rangle_{L^2} : \dot{H}^s(\mathbb{R}^d, \mathbb{R}^d) \times \dot{H}^{-s}(\mathbb{R}^d, \mathbb{R}^d) &\longrightarrow \mathbb{R} \\ L^2([0, T], \dot{H}^{s+1}(\mathbb{R}^d, \mathbb{R}^d)) \times \dot{H}^{-s+1}(\mathbb{R}^d, \mathbb{R}^d) \ni (u(t), \psi) &\longrightarrow \int_0^T \langle u(t'), \Delta \psi \rangle_{L^2} dt' \in \mathbb{R} \end{aligned}$$

are both continuous bilinear forms.

Hence we can conclude that (4.8) is true for all $\psi \in \dot{H}^{-s}(\mathbb{R}^d, \mathbb{R}^d) \cap \dot{H}^{-s+1}(\mathbb{R}^d, \mathbb{R}^d)$. In particular we can replace ψ by $\mathbf{P}_n \psi$ and get

$$\begin{aligned} \langle \mathbf{P}_n u(t), \mathbf{P}_n \psi \rangle_{L^2} &= \int_0^t \nu \mathbf{P}_n \langle u(t'), \Delta \mathbf{P}_n \psi \rangle_{L^2} \leq \nu \|\Delta \mathbf{P}_n \psi\|_{\dot{H}^{-s}} \int_0^t \|\mathbf{P}_n u(t')\|_{\dot{H}^s} dt' \\ &\leq \nu n^2 \|\psi\|_{\dot{H}^{-s}} \int_0^t \|\mathbf{P}_n u(t')\|_{\dot{H}^s} dt' \end{aligned}$$

where the integral $\int_0^t \|\mathbf{P}_n u(t')\|_{\dot{H}^s} dt'$ is well defined by $\mathbf{P}_n u \in L^\infty([0, T], \dot{H}^s(\mathbb{R}^d, \mathbb{R}^d))$. From the above formula

$$\|\mathbf{P}_n u(t)\|_{\dot{H}^s} \leq \nu n^2 \int_0^t \|\mathbf{P}_n u(t')\|_{\dot{H}^s} dt'$$

and hence $\|\mathbf{P}_n u(t)\|_{\dot{H}^s} = 0$ by the Gronwall inequality. This implies $u(t) = 0$ for $t \in [0, T]$.

(Existence). First of all, there exists a sequence (f_n) in $C^0([0, T], \dot{H}^{s-1}(\mathbb{R}^d, \mathbb{R}^d))$ s.t. $f_n \xrightarrow{n \rightarrow +\infty} f$ in $L^2([0, T], \dot{H}^{s-1}(\mathbb{R}^d, \mathbb{R}^d))$. This follows from the density of $C_c^\infty(I, X)$ in $L^p(I, X)$ for $p < \infty$ for I an interval and X a Banach space, see Appendix A.

Applying \mathbf{P}_n to (4.1) and replacing f by f_n we obtain the equation

$$\begin{cases} (u_n)_t - \nu \mathbf{P}_n \Delta u_n = \mathbf{P}_n f_n \\ u_n(0) = \mathbf{P}_n u_0 \end{cases} \quad (4.9)$$

Notice that $\mathbf{P}_n f_n \in C^0([0, T], \dot{H}^s(\mathbb{R}^d, \mathbb{R}^d))$. Since (4.9) is a standard linear equation it admits a solution $u_n \in C^1([0, T], \dot{H}^s(\mathbb{R}^d, \mathbb{R}^d))$. Notice furthermore that $u_n = \mathbf{P}_n u_n$ and so in particular $u_n \in C^0([0, T], \dot{H}^r(\mathbb{R}^d, \mathbb{R}^d))$ for all $r \geq s$.

Furthermore, applying $\langle \cdot, u_n \rangle_{\dot{H}^s}$ to (4.9) and using

$$\begin{aligned} \langle \mathbf{P}_n \Delta u_n, u_n \rangle_{\dot{H}^s} &= - \sum_{k=1}^d \int_{B(0, n)} |\xi|^{2s} \xi_k^2 |\widehat{u}_n(t, \xi)|^2 d\xi = - \sum_{k=1}^d \langle \xi_k \widehat{u}_n, \xi_k \widehat{u}_n \rangle_{L^2(B(0, n), |\xi|^{2s} d\xi)} \\ &= \sum_{k=1}^d \langle \xi_k \widehat{u}_n, \xi_k \widehat{u}_n \rangle_{L^2(\mathbb{R}^d, |\xi|^{2s} d\xi)} = \|\nabla u_n\|_{\dot{H}^s}^2, \end{aligned}$$

we obtain

$$\frac{1}{2} \frac{d}{dt} \|u_n\|_{\dot{H}^s}^2 + \nu \|\nabla u_n\|_{\dot{H}^s}^2 = \langle \mathbf{P}_n f_n, u_n \rangle_{\dot{H}^s}$$

s.t., after integration, we obtain

$$\frac{1}{2} \|u_n(t)\|_{\dot{H}^s}^2 + \nu \int_0^t \|\nabla u_n(t')\|_{\dot{H}^s}^2 dt' = \frac{1}{2} \|\mathbf{P}_n u_0\|_{\dot{H}^s}^2 + \int_0^t \langle \mathbf{P}_n f_n(t'), u_n(t') \rangle_{\dot{H}^s} dt'. \quad (4.10)$$

The difference $u_n - u_{n+\ell}$ solves

$$\begin{cases} (u_n - u_{n+\ell})_t - \nu \mathbf{P}_{n+\ell} \Delta (u_n - u_{n+\ell}) = \mathbf{P}_n f_n - \mathbf{P}_{n+\ell} f_{n+\ell} \\ u_n(0) - u_{n+\ell}(0) = (\mathbf{P}_n - \mathbf{P}_{n+\ell}) u_0 \end{cases}$$

Then, like for (4.10) we get

$$\begin{aligned} & \frac{1}{2} \|u_n(t) - u_{n+\ell}(t)\|_{\dot{H}^s}^2 + \frac{\nu}{2} \int_0^t \|\nabla(u_n - u_{n+\ell})(t')\|_{\dot{H}^s}^2 dt' = \\ & = \frac{1}{2} \|(\mathbf{P}_n - \mathbf{P}_{n+\ell}) u_0\|_{\dot{H}^s}^2 + \int_0^t \langle \mathbf{P}_n f_n(t') - \mathbf{P}_{n+\ell} f_{n+\ell}(t'), (u_n - u_{n+\ell})(t') \rangle_{\dot{H}^s} dt' \\ & \leq \frac{1}{2} \|(\mathbf{P}_n - \mathbf{P}_{n+\ell}) u_0\|_{\dot{H}^s}^2 + \int_0^t \|\mathbf{P}_n f_n(t') - \mathbf{P}_{n+\ell} f_{n+\ell}(t')\|_{\dot{H}^{s-1}} \|\nabla(u_n - u_{n+\ell})(t')\|_{\dot{H}^s} dt' \\ & \leq \frac{1}{2} \|(\mathbf{P}_n - \mathbf{P}_{n+\ell}) u_0\|_{\dot{H}^s}^2 + \frac{1}{2\nu} \int_0^t \|\mathbf{P}_n f_n(t') - \mathbf{P}_{n+\ell} f_{n+\ell}(t')\|_{\dot{H}^{s-1}}^2 dt' + \frac{\nu}{2} \int_0^t \|\nabla(u_n - u_{n+\ell})(t')\|_{\dot{H}^s}^2 dt'. \end{aligned}$$

Hence

$$\begin{aligned} & \|u_n(t) - u_{n+\ell}(t)\|_{\dot{H}^s}^2 + \nu \int_0^t \|\nabla(u_n - u_{n+\ell})(s)\|_{\dot{H}^s}^2 ds \\ & \leq \|(\mathbf{P}_n - \mathbf{P}_{n+\ell}) u_0\|_{\dot{H}^s}^2 + \frac{1}{\nu} \int_0^t \|\mathbf{P}_n f_n(s) - \mathbf{P}_{n+\ell} f_{n+\ell}(s)\|_{\dot{H}^{s-1}}^2 ds. \end{aligned}$$

Since $f_n \xrightarrow{n \rightarrow +\infty} f$ in $L^2([0, T], \dot{H}^{s-1}(\mathbb{R}^d, \mathbb{R}^d))$ implies also $\mathbf{P}_n f_n \xrightarrow{n \rightarrow +\infty} f$ therein, the last inequality implies that (u_n) is Cauchy in $C([0, T], \dot{H}^s(\mathbb{R}^d, \mathbb{R}^d))$ and (∇u_n) is Cauchy in $L^2([0, T], \dot{H}^s(\mathbb{R}^d, \mathbb{R}^d))$. Let u be the limit. Notice that u satisfies (4.2) and (4.6), and so obviously also (4.3).

Taking the limit in (4.10) we see that u satisfies the energy equality (4.5).

Next, we check that u is a weak solution of (4.1) in the sense of Def. 4.1. We apply $\langle \cdot, \Psi(t) \rangle_{L^2}$ to (4.9) with $\Psi \in C_c^\infty([0, \infty) \times \mathbb{R}^d, \mathbb{R}^d)$. Then we have

$$\frac{d}{dt} \langle u_n, \Psi \rangle_{L^2} = \nu \langle \Delta u_n, \Psi \rangle_{L^2} + \langle \mathbf{P}_n f_n, \Psi \rangle_{L^2} + \langle u_n, \partial_t \Psi \rangle_{L^2}.$$

Integrating we have

$$\begin{aligned} \langle u_n(t), \Psi(t) \rangle_{L^2} & = \langle \mathbf{P}_n u_0, \Psi(0) \rangle_{L^2} - \nu \int_0^t \langle u_n(t'), \Delta \Psi(t') \rangle_{L^2} dt' \\ & + \int_0^t \langle \mathbf{P}_n f_n(t'), \Psi(t') \rangle_{L^2} dt' + \int_0^t \langle u_n(t'), \partial_t \Psi(t') \rangle_{L^2} dt'. \end{aligned}$$

Taking the limit for $n \rightarrow \infty$ we get

$$\langle u(t), \Psi(t) \rangle_{L^2} = \langle u_0, \Psi(0) \rangle_{L^2} - \nu \int_0^t \langle u(t'), \Delta \Psi(t') \rangle_{L^2} dt' + \int_0^t \langle f(t'), \Psi(t') \rangle_{L^2} dt' + \int_0^t \langle u(t'), \partial_t \Psi(t') \rangle_{L^2} dt'.$$

which yields (4.4). Hence u is a weak solution of (4.1) in the sense of Def. 4.1.

Next, we prove the Duhamel formula (4.7). Applying the Fourier transform to (4.9)

$$\begin{cases} \partial_t \widehat{u}_n(t, \xi) + \nu \chi_{|\xi| \leq n} |\xi|^2 \widehat{u}_n(t, \xi) = \chi_{|\xi| \leq n} \widehat{f}_n(t, \xi) \\ \widehat{u}_n(0, \xi) = \chi_{|\xi| \leq n} \widehat{u}_0(\xi) \end{cases} \quad (4.11)$$

Notice that $\text{supp} \widehat{u}_n(t, \cdot) \subseteq \{|\xi| \leq n\}$ so that $\chi_{|\xi| \leq n} |\xi|^2 \widehat{u}_n(t, \xi) = |\xi|^2 \widehat{u}_n(t, \xi)$. Then, by the variation of parameters formula

$$\widehat{u}_n(t, \xi) = e^{-t\nu|\xi|^2} \chi_{|\xi| \leq n} \widehat{u}_0(\xi) + \int_0^t e^{-(t-t')\nu|\xi|^2} \chi_{|\xi| \leq n} \widehat{f}_n(t', \xi) dt'. \quad (4.12)$$

Now we know

$$\begin{aligned} \widehat{u}_n(t, \xi) &\xrightarrow{n \rightarrow \infty} \widehat{u}(t, \xi) \text{ in } C([0, T], L^2(\mathbb{R}^d, |\xi|^{2s} d\xi)) \\ \chi_{|\xi| \leq n} \widehat{u}_0(\xi) &\xrightarrow{n \rightarrow \infty} \widehat{u}_0(\xi) \text{ in } L^2(\mathbb{R}^d, |\xi|^{2s} d\xi), \\ \chi_{|\xi| \leq n} \widehat{f}_n(t', \xi) &\xrightarrow{n \rightarrow \infty} \widehat{f}(t', \xi) \text{ in } L^2([0, T] \times \mathbb{R}^d, |\xi|^{2(s-1)} dt d\xi) \end{aligned}$$

Notice that

$$\mathbf{T}g(t, \xi) := \int_0^t e^{-(t-t')\nu|\xi|^2} g(t', \xi) dt'$$

is a bounded operator from $L^2([0, T] \times \mathbb{R}^d, |\xi|^{2(s-1)} dt d\xi)$ into $L^\infty([0, T], L^2(\mathbb{R}^d, |\xi|^{2s} d\xi))$. Indeed for $t \in [0, T]$ and fixed $\xi \in \mathbb{R}^d$ and for $g \in C_c([0, T] \times (\mathbb{R}^d \setminus \{0\}))$

$$|\mathbf{T}g(t, \xi)| \leq \left(\int_0^t e^{-2(t-t')\nu|\xi|^2} dt' \right)^{\frac{1}{2}} \left(\int_0^t |g(t', \xi)|^2 dt' \right)^{\frac{1}{2}} \leq \frac{1}{\sqrt{2\nu}|\xi|} \left(\int_0^t |g(t', \xi)|^2 dt' \right)^{\frac{1}{2}}$$

and so

$$\int_{\mathbb{R}^d} |\xi|^{2s} |\mathbf{T}g(t, \xi)|^2 d\xi \leq \frac{1}{2\nu} \int_{[0, T] \times \mathbb{R}^d} |\xi|^{2(s-1)} |g(t', \xi)|^2 dt' d\xi.$$

This implies

$$\|\mathbf{T}g\|_{L^\infty([0, T], L^2(\mathbb{R}^d, |\xi|^{2s} d\xi))} \leq \sqrt{1/2\nu} \|g\|_{L^2([0, T] \times \mathbb{R}^d, |\xi|^{2(s-1)} dt d\xi)}.$$

Since $C_c([0, T] \times (\mathbb{R}^d \setminus \{0\}))$ is dense in $L^2([0, T] \times \mathbb{R}^d, |\xi|^{2(s-1)} dt d\xi)$ a well defined bounded operator remains defined. Taking the limit for $n \rightarrow \infty$ in (4.12) all terms converge in $L^\infty([0, T], L^2(\mathbb{R}^d, |\xi|^{2s} d\xi))$ to the corresponding terms of

$$\widehat{u}(t, \xi) = e^{-t\nu|\xi|^2} \widehat{u}_0(\xi) + \int_0^t e^{-(t-t')\nu|\xi|^2} \widehat{f}(t', \xi) dt'.$$

□

Remark 4.3. Notice that applying the Fourier transform to (4.7) we get

$$u(t) = e^{t\nu\Delta}u_0 + \int_0^t e^{(t-t')\nu\Delta}f(t')dt'. \quad (4.13)$$

The following theorem yields additional estimates.

Theorem 4.4. *Let f be like in Theorem 4.2 and consider the corresponding solution*

$$u \in C([0, T], \dot{H}^s), \quad \nabla u \in L^2([0, T], \dot{H}^s).$$

Then, additionally, we have

$$\|u(t)\|_{\dot{H}^{s+\frac{2}{p}}} \in L^p([0, T], \mathbb{R}) \text{ for any } p \geq 2. \quad (4.14)$$

Moreover we have

$$V(t) := \left(\int_{\mathbb{R}^d} |\xi|^{2s} \left(\sup_{0 \leq t' \leq t} |\widehat{u}(t', \xi)| \right)^2 d\xi \right)^{\frac{1}{2}} \leq \|u_0\|_{\dot{H}^s} + \frac{1}{(2\nu)^{\frac{1}{2}}} \|f\|_{L^2([0, t], \dot{H}^{s-1})}; \quad (4.15)$$

$$\| \|u\|_{\dot{H}^{s+\frac{2}{p}}} \|_{L^p(0, T)} \leq \nu^{-\frac{1}{p}} \left(\|u_0\|_{\dot{H}^s} + \nu^{-\frac{1}{2}} \|f\|_{L^2([0, T], \dot{H}^{s-1})} \right).$$

Proof. From the Duhamel formula (4.7) and the previous computation

$$|\widehat{u}(t, \xi)| \leq e^{-t\nu|\xi|^2} |\widehat{u}_0(\xi)| + \frac{1}{\sqrt{2\nu}|\xi|} \|\widehat{f}(\cdot, \xi)\|_{L^2(0, t)}.$$

so that

$$|\xi|^s \sup_{0 \leq t' \leq t} |\widehat{u}(t', \xi)| \leq |\xi|^s |\widehat{u}_0(\xi)| + |\xi|^s \frac{1}{\sqrt{2\nu}|\xi|} \|\widehat{f}(\cdot, \xi)\|_{L^2(0, t)}.$$

Taking the $L^2(\mathbb{R}^d, d\xi)$ norm we get

$$V(t) \leq \|u_0(\xi)\|_{L^2(\mathbb{R}^d, |\xi|^{2s} d\xi)} + \frac{1}{\sqrt{2\nu}} \|\widehat{f}\|_{L^2((0, t), L^2(\mathbb{R}^d, |\xi|^{2(s-1)} d\xi))}.$$

and this yields the 1st line in (4.15).

To get the 2nd line in (4.15), from the energy estimate (4.5) we obtain

$$\begin{aligned} \|u(t)\|_{\dot{H}^s}^2 + 2\nu \int_0^t \|\nabla u(t')\|_{\dot{H}^s}^2 dt' &\leq \|u_0\|_{\dot{H}^s}^2 + 2 \int_0^t \frac{1}{\sqrt{\nu}} \|f(t')\|_{\dot{H}^{s-1}} \sqrt{\nu} \|\nabla u(t')\|_{\dot{H}^s} dt' \\ &\leq \|u_0\|_{\dot{H}^s}^2 + \nu \int_0^t \|\nabla u(t')\|_{\dot{H}^s}^2 dt' + \frac{1}{\nu} \int_0^t \|f(t')\|_{\dot{H}^{s-1}}^2 dt'. \end{aligned}$$

This yields

$$\|u(t)\|_{\dot{H}^s}^2 + \nu \int_0^t \|\nabla u(t')\|_{\dot{H}^s}^2 dt' \leq \|u_0\|_{\dot{H}^s}^2 + \frac{1}{\nu} \int_0^t \|f(t')\|_{\dot{H}^{s-1}}^2 dt'.$$

and hence

$$\begin{aligned} \|u\|_{L^\infty([0,T],\dot{H}^s)} &\leq \|u_0\|_{\dot{H}^s} + \nu^{-\frac{1}{2}} \|f\|_{L^2([0,T],\dot{H}^s)} \\ \|u\|_{\dot{H}^{s+1}} \|L^2(0,T)\| &\leq \nu^{-\frac{1}{2}} \left(\|u_0\|_{\dot{H}^s} + \nu^{-\frac{1}{2}} \|f\|_{L^2([0,T],\dot{H}^s)} \right). \end{aligned}$$

So by the interpolation of Sobolev norms Lemma 2.20 for $2 < p < \infty$

$$\begin{aligned} \| \|u\|_{\dot{H}^{s+\frac{2}{p}}} \|L^p(0,T)\| &\leq \| \|u\|_{\dot{H}^s}^{1-\frac{2}{p}} \|\nabla u\|_{\dot{H}^s}^{\frac{2}{p}} \|L^p(0,T)\| \leq \|u\|_{L^\infty([0,T],\dot{H}^s)}^{1-\frac{2}{p}} \| \|\nabla u\|_{\dot{H}^s}^{\frac{2}{p}} \|L^p(0,T)\| \\ &= \|u\|_{L^\infty([0,T],\dot{H}^s)}^{1-\frac{2}{p}} \|\nabla u\|_{L^2([0,T],\dot{H}^s)}^{\frac{2}{p}} \leq \nu^{-\frac{1}{p}} \left(\|u_0\|_{\dot{H}^s} + \nu^{-\frac{1}{2}} \|f\|_{L^2([0,T],\dot{H}^s)} \right). \end{aligned}$$

□

5 The Navier Stokes equation

We will only deal with the Incompressible Navier Stokes (NS) equation:

$$\begin{cases} u_t + u \cdot \nabla u - \nu \Delta u = -\nabla p \\ \nabla \cdot u = 0 \\ u(0, x) = u_0(x) \end{cases} \quad (t, x) \in [0, \infty) \times \mathbb{R}^d \quad (5.1)$$

where $u : [0, \infty) \times \mathbb{R}^d \rightarrow \mathbb{R}^d$ with $u = \sum_{j=1}^d u^j e_j$ with e_j the standard basis of \mathbb{R}^d ,

$$\Delta := \sum_{j=1}^d \frac{\partial^2}{\partial x_j^2}, \quad \nabla \cdot u = \sum_{j=1}^d \frac{\partial}{\partial x_j} u^j, \quad u \cdot \nabla v = \sum_{j=1}^d u^j \frac{\partial}{\partial x_j} v.$$

Here $\nu > 0$ is a fixed constant. We could normalize $\nu = 1$. p is the pressure and its function is simply to absorb the divergence part of the l.h.s. of (5.1).

We can write

$$\begin{aligned} u \cdot \nabla u &= \operatorname{div}(u \otimes u) \text{ for } \operatorname{div}(u \otimes v)^j := \sum_{k=1}^d \partial_k (u^k v^j) \text{ since} \\ \operatorname{div}(u \otimes u)^j &= \sum_{k=1}^d \partial_k (u^k u^j) = \sum_{k=1}^d u^k \partial_k u^j + u^j \underbrace{\operatorname{div} u}_0 = u \cdot \nabla u^j \end{aligned} \quad (5.2)$$

So we rewrite (5.1) and

$$\begin{cases} u_t + \operatorname{div}(u \otimes u) - \nu \Delta u = -\nabla p \\ \nabla \cdot u = 0 \\ u(0, x) = u_0(x) \end{cases} \quad (t, x) \in [0, \infty) \times \mathbb{R}^d \quad (5.3)$$

Definition 5.1 (Weak solutions). Let u_0 be in $L^2(\mathbb{R}^d)$. A vector field $u \in L^2_{loc}([0, \infty) \times \mathbb{R}^d)$ which is weakly continuous as a function from $[0, \infty)$ to $L^2(\mathbb{R}^d, \mathbb{R}^d)$ (we will write $u \in C^0_w([0, \infty), L^2(\mathbb{R}^d, \mathbb{R}^d))$), and what we mean is that $t \rightarrow \langle u(t), \phi \rangle_{L^2} \in C^0([0, \infty), \mathbb{R})$ for any $\phi \in L^2(\mathbb{R}^d, \mathbb{R}^d)$ and s.t. $\operatorname{div} u(t) = 0$ for every t , is a weak solution of (5.3) if for $\Psi \in C_c^\infty([0, \infty) \times \mathbb{R}^d, \mathbb{R}^d)$ with $\operatorname{div} \Psi = 0$ we have

$$\begin{aligned} \langle u(t), \Psi(t) \rangle_{L^2} &= \int_0^t (\nu \langle u(t'), \Delta \Psi(t') \rangle_{L^2} + \langle u(t'), \partial_t \Psi(t') \rangle_{L^2} \\ &\quad - \langle \operatorname{div}(u \otimes u)(t'), \Psi(t') \rangle_{L^2}) dt' + \langle u_0, \Psi(0) \rangle_{L^2}. \end{aligned} \quad (5.4)$$

Remark 5.2. Notice that in Definition 5.1 we could replace the half-line $[0, \infty)$ with a half-line $[t_0, \infty)$ with $t_0 \in \mathbb{R}$. In this sense, observe that any solution in Definition 5.1 solves weakly the NS equation in $[t_0, \infty)$ for $t_0 > 0$ and initial value $u(t_0)$, that is to say, for any for $\Psi \in C_c^\infty([t_0, \infty) \times \mathbb{R}^d, \mathbb{R}^d)$ with $\operatorname{div} \Psi = 0$ we have

$$\begin{aligned} \langle u(t), \Psi(t) \rangle_{L^2} &= \int_{t_0}^t (\nu \langle u(t'), \Delta \Psi(t') \rangle_{L^2} + \langle u(t'), \partial_t \Psi(t') \rangle_{L^2} \\ &\quad - \langle \operatorname{div}(u \otimes u)(t'), \Psi(t') \rangle_{L^2}) dt' + \langle u(t_0), \Psi(t_0) \rangle_{L^2}. \end{aligned} \quad (5.5)$$

Indeed, we can extend any such test function into a $\Psi \in C_c^\infty([0, \infty) \times \mathbb{R}^d, \mathbb{R}^d)$ with $\operatorname{div} \Psi = 0$. Then taking the difference of (5.4) and

$$\begin{aligned} \langle u(t_0), \Psi(t) \rangle_{L^2} &= \int_0^{t_0} (\nu \langle u(t'), \Delta \Psi(t') \rangle_{L^2} + \langle u(t'), \partial_t \Psi(t') \rangle_{L^2} \\ &\quad - \langle \operatorname{div}(u \otimes u)(t'), \Psi(t') \rangle_{L^2}) dt' + \langle u_0, \Psi(0) \rangle_{L^2}, \end{aligned}$$

we obtain exactly (5.5).

Let us now formally take the inner product of the first line of (5.1) with u and integrate in \mathbb{R}^d

$$\frac{1}{2} \frac{d}{dt} \|u\|_{L^2}^2 + \langle u \cdot \nabla u, u \rangle_{L^2} - \nu \langle \Delta u, u \rangle_{L^2} = -\langle \nabla p, u \rangle_{L^2}$$

We have, summing on repeated indexes,

$$\begin{aligned} \langle u \cdot \nabla u, u \rangle_{L^2} &= \int_{\mathbb{R}^d} u^j u^k \partial_j u^k dx = 2^{-1} \int_{\mathbb{R}^d} u^j \partial_j (u^k u^k) dx = -2^{-1} \int_{\mathbb{R}^d} |u|^2 \operatorname{div} u dx = 0 \text{ and} \\ \langle \nabla p, u \rangle_{L^2} &= \int_{\mathbb{R}^d} u^j \partial_j p dx = - \int_{\mathbb{R}^d} p \operatorname{div} u dx = 0. \end{aligned}$$

So, formally (rigorously if u is regular and we can integrate by parts), we get

$$\frac{1}{2} \frac{d}{dt} \|u\|_{L^2}^2 + \nu \|\nabla u\|_{L^2}^2 = 0$$

This in particular yields the following *energy equality*

$$\|u(t)\|_{L^2(\mathbb{R}^d)}^2 + 2\nu \int_0^t \|\nabla u(t')\|_{L^2(\mathbb{R}^d)}^2 dt' = \|u_0\|_{L^2(\mathbb{R}^d)}^2. \quad (5.6)$$

Theorem 5.3 (Leray). *Let $u_0 \in L^2(\mathbb{R}^d)$ for $d = 2, 3$ be divergence free. Then (5.3) admits a weak solution with $u(t) \in L^\infty(\mathbb{R}_+, L^2) \cap L^2_{loc}(\mathbb{R}_+, H^1)$ such that the following energy inequality holds:*

$$\|u(t)\|_{L^2(\mathbb{R}^d)}^2 + 2\nu \int_0^t \|\nabla u(t')\|_{L^2(\mathbb{R}^d)}^2 dt' \leq \|u_0\|_{L^2(\mathbb{R}^d)}^2. \quad (5.7)$$

The proof of Theorem 5.3 is long and will be considered later. Now we consider the following.

Theorem 5.4 (Case $d = 2$). *When $d = 2$ the solution in Theorem 5.3 is unique, it satisfies (5.6) and $u(t) \in C^0([0, \infty), L^2)$.*

Theorem 5.4 depends on Sobolev's Embedding $\dot{H}^{\frac{1}{2}}(\mathbb{R}^2) \hookrightarrow L^4(\mathbb{R}^2)$. Furthermore, we will use the following lemma.

Lemma 5.5. *There exists a constant $C = C_T$ such that for any $u \in L^2((0, T), H^1(\mathbb{R}^d)) \cap H^1((0, T), H^{-1}(\mathbb{R}^d))$ we have $u \in C^0([0, T], L^2(\mathbb{R}^d))$ with*

$$\|u\|_{L^\infty([0, T], L^2(\mathbb{R}^d))} \leq C \left(\|u\|_{L^2((0, T), H^1(\mathbb{R}^d))} + \|\dot{u}\|_{L^2((0, T), H^{-1}(\mathbb{R}^d))} \right). \quad (5.8)$$

Furthermore we have $\|u(t)\|_{L^2}^2 \in AC([0, T])$ with

$$\frac{d}{dt} \|u(t)\|_{L^2}^2 = 2 \langle u(t), \dot{u}(t) \rangle. \quad (5.9)$$

Proof. Let us assume additionally that $u \in C^1([0, T], L^2(\mathbb{R}^d))$. Then for any fixed $t_0 \in [0, T]$ we have

$$\begin{aligned} \|u(t)\|_{L^2}^2 &= \|u(t_0)\|_{L^2}^2 + 2 \int_{t_0}^t \langle u(s), \dot{u}(s) \rangle ds \\ &\leq \|u(t_0)\|_{L^2}^2 + \|u\|_{L^2((0, T), H^1(\mathbb{R}^d))}^2 + \|\dot{u}\|_{L^2((0, T), H^{-1}(\mathbb{R}^d))}^2. \end{aligned} \quad (5.10)$$

We can choose $\|u(t_0)\|_{L^2}^2 = T^{-1} \int_0^T \|u(s)\|_{L^2}^2 ds$ obtaining (5.8) for $C = \sqrt{1 + T^{-1}}$. The general case is obtained by considering a sequence (u_n) in $C^1((0, T), H^1(\mathbb{R}^d))$ converging to u in $L^2((0, T), H^1(\mathbb{R}^d)) \cap H^1((0, T), H^{-1}(\mathbb{R}^d))$. To get such a sequence, we can extend u into a function in $L^2(\mathbb{R}, H^1(\mathbb{R}^d)) \cap H^1(\mathbb{R}, H^{-1}(\mathbb{R}^d))$, and then we can consider $u_n = \rho_{\epsilon_n} * u(t)$ with $\epsilon_n \xrightarrow{n \rightarrow \infty} 0$. Then, by the proof of Proposition A.23 in Appendix A, this sequence satisfies the desired properties.

Then (5.8) implies that (u_n) is a Cauchy sequence in $C^0([0, T], L^2(\mathbb{R}^d))$. The limit is necessarily u , that so satisfies (5.8). Also by a limit, we conclude that u satisfies the equality in (5.10), for any fixed $t_0 \in [0, T]$. This implies $\|u(t)\|_{L^2}^2 \in AC([0, T])$ and formula (5.9). \square

Proof of uniqueness and of $u(t) \in C^0([0, \infty), L^2)$ in 2d. We first claim that for any $d = 2$ solution we have

$$\partial_t u \in L^2((0, T), H^{-1}(\mathbb{R}^2, \mathbb{R}^2)) \text{ for any } T > 0. \quad (5.11)$$

Let us assume this for the moment. Since from (5.7) we have $u \in L^2((0, T), H^1(\mathbb{R}^2, \mathbb{R}^2))$, then $u \in L^2((0, T), H^1(\mathbb{R}^2, \mathbb{R}^2)) \cap H^1((0, T), H^{-1}(\mathbb{R}^2, \mathbb{R}^2))$ for any $T > 0$. By Lemma 5.5 we have $u \in C^0([0, T], L^2)$ for any $T > 0$, and so $u(t) \in C^0([0, \infty), L^2)$.

We now assume that there are two solutions u and v with $u(0) = v(0)$ and we set $w := u - v$. Both u and v satisfy (5.4). We claim that we can take as test function w , obtaining

$$\begin{aligned} \langle u(t), w(t) \rangle &= \int_0^t (-\nu \langle \nabla u, \nabla w \rangle + \langle u, \partial_t w \rangle - \langle \operatorname{div}(u \otimes u), w \rangle_{L^2}) dt' \text{ and} \\ \langle v(t), w(t) \rangle &= \int_0^t (-\nu \langle \nabla v, \nabla w \rangle + \langle v, \partial_t w \rangle - \langle \operatorname{div}(v \otimes v), w \rangle_{L^2}) dt' \end{aligned} \quad (5.12)$$

To prove the claim, notice that there exists a sequence of test functions Ψ_n which converges to w in

$$L^2((0, T), H^1) \cap H^1((0, T), H^{-1}) \cap C([0, T], L^2).$$

This implies that (5.4) with the Ψ_n converge to the above formulas, where we have taken in account $w(0) = 0$ and where we used also estimates like, see Lemma 5.6 below,

$$\begin{aligned} \int_0^t \langle \operatorname{div}(u \otimes u)(t'), w(t') \rangle_{L^2} dt' &\leq C \int_0^t \|\nabla u(t')\|_{L^2} \|u(t')\|_{L^2} \|\nabla w(t')\|_{L^2} dt' \\ &\leq C \|\nabla u\|_{L^2((0, t), L^2)} \|\nabla w\|_{L^2((0, t), L^2)} \|u\|_{L^\infty((0, t), L^2)}, \end{aligned}$$

and an analogous one for the other nonlinear term.

Taking the difference of the two formulas in (5.12), we obtain

$$\|w(t)\|_{L^2}^2 = \int_0^t (-\nu \|\nabla w(t')\|_{L^2}^2 + \langle w(t'), \partial_t w(t') \rangle - \langle \operatorname{div}(u \otimes u)(t') + \operatorname{div}(v \otimes v)(t'), w(t') \rangle_{L^2}) dt'.$$

Formula (5.11) for any solution and Lemma 5.5 imply $\|w(t)\|_{L^2}^2 \in AC([0, T])$ with $\frac{d}{dt} \|w(t)\|_{L^2}^2 = 2\langle w(t), \partial_t w(t) \rangle$. Hence

$$\begin{aligned} \frac{d}{dt} \|w\|_{L^2}^2 + \nu \|\nabla w\|_{L^2}^2 &= \langle \operatorname{div}(v \otimes v) - \operatorname{div}(u \otimes u), w \rangle = \\ &= -\langle \operatorname{div}(w \otimes v) - \operatorname{div}(u \otimes w), w \rangle = -\langle \partial_k(w^k v^j) - \partial_k(u^k w^j), w^j \rangle \\ &= -\langle \partial_k v^j, w^k w^j \rangle \leq \|\nabla v\|_{L^2} \|w\|_{L^4}^2 \leq c \|\nabla v\|_{L^2} \|w\|_{L^2} \|\nabla w\|_{L^2} \\ &\leq \frac{c^2}{\nu} \|\nabla v\|_{L^2}^2 \|w\|_{L^2}^2 + \nu \|\nabla w\|_{L^2}^2, \end{aligned}$$

where in the 3rd line we applied Gagliardo Nirenberg in dimension 2. From the last formula we obtain

$$\begin{aligned} \frac{d}{dt} \|w\|_{L^2}^2 &\leq c_\nu \|\nabla v\|_{L^2}^2 \|w\|_{L^2}^2 \text{ which by Gronwall yields} \\ \|w\|_{L^2}^2 &\leq e^{c_\nu \int_0^t \|\nabla v(t')\|_{L^2}^2 dt'} \|w(0)\|_{L^2}^2 = 0. \end{aligned}$$

To complete the proof we need to prove claim (5.11). We apply (5.4) for $\Psi(t, x) = \phi(x) \in C_{\text{cc}}^\infty(\mathbb{R}^2, \mathbb{R}^2)$ and obtain

$$\langle u(t), \phi \rangle - \langle u(0), \phi \rangle = \int_0^t (\nu \langle \Delta u(t'), \phi \rangle - \langle \mathbb{P} \operatorname{div}(u \otimes u)(t'), \phi \rangle) dt.$$

The above formula extends to any $\phi \in H^1(\mathbb{R}^2, \mathbb{R}^2)$.

We want to use Lemma A.29, which states that if $u, g \in L^1(I, X)$ are such that

$$\langle u(t_2), f \rangle_{XX^*} - \langle u(t_1), f \rangle_{XX^*} = \int_{t_1}^{t_2} \langle g(s), f \rangle_{XX^*} ds \text{ for any } f \in X^*,$$

with X a Banach space, then $\partial_t u = g$ in $\mathcal{D}'(I, X) := \mathcal{L}(\mathcal{D}(I, \mathbb{R}), X)$.

Here we apply Lemma A.29 taking $X = H^{-1}(\mathbb{R}^2, \mathbb{R}^2)$ and its dual $X^* = H^1(\mathbb{R}^2, \mathbb{R}^2)$. Obviously, we have

$$\|\Delta u\|_{L^1((0,T), H^{-1})} \leq \sqrt{T} \|u\|_{L^2((0,T), H^1)}.$$

Notice that the above inequality does not depend on the dimension. The treatment of the nonlinear terms, depends on the dimension and is based on $\dot{H}^{\frac{1}{2}}(\mathbb{R}^2) \hookrightarrow L^4(\mathbb{R}^2)$, which depends on the dimension, and is

$$\begin{aligned} \|\mathbb{P} \operatorname{div}(u \otimes u)\|_{L^1((0,T), H^{-1})} &\leq \sqrt{T} \|u \otimes u\|_{L^2((0,T), L^2)} = \sqrt{T} \| \|u\|_{L^4}^2 \|_{L^2(0,T)} \lesssim \sqrt{T} \| \|u\|_{\dot{H}^{\frac{1}{2}}}^2 \|_{L^2(0,T)} \\ &\leq \sqrt{T} \|u\|_{L^\infty((0,T), L^2)} \|\nabla u\|_{L^2((0,T), L^2)}, \end{aligned}$$

where in the last inequality we used the interpolation $\|u\|_{\dot{H}^{\frac{1}{2}}}^2 \leq \|u\|_{L^2} \|\nabla u\|_{L^2}$.

So we can apply Lemma A.29 obtaining that

$$\partial_t u = -\nu \Delta u + \mathbb{P} \operatorname{div}(u \otimes u) \text{ in } \mathcal{D}'((0, T), H^{-1})$$

and furthermore that (5.11) is true. \square

Notice that if we apply formally the operator \mathbb{P} to equation (5.3) we obtain formally

$$\begin{cases} u_t - \nu \Delta u = \mathcal{Q}_{NS}(u, u) \\ u(0, x) = u_0(x) \end{cases} \quad (t, x) \in [0, \infty) \times \mathbb{R}^d \quad (5.13)$$

where we set

$$\mathcal{Q}_{NS}(u, v) := -\frac{1}{2} \mathbb{P}(\operatorname{div}(u \otimes v)) - \frac{1}{2} \mathbb{P}(\operatorname{div}(v \otimes u)). \quad (5.14)$$

Here notice that

$$\mathbb{P}(\operatorname{div}(u \otimes v))^j = \sum_{l=1}^d \partial_l \left((u^l v^j) - \frac{1}{\Delta} \sum_{k=1}^d \partial_j \partial_k (u^l v^k) \right). \quad (5.15)$$

5.1 Proof of Theorem 5.3

We will need the following elementary lemma.

Lemma 5.6. *Let $d = 2, 3$. Then the trilinear form*

$$(u, v, \varphi) \in (C_c^\infty(\mathbb{R}^d))^d \times (C_c^\infty(\mathbb{R}^d))^d \times (C_c^\infty(\mathbb{R}^d))^d \rightarrow \langle \operatorname{div}(u \otimes v), \varphi \rangle_{L^2} \in \mathbb{R} \quad (5.16)$$

extends into a unique bounded trilinear form $(H^1(\mathbb{R}^d))^d \times (H^1(\mathbb{R}^d))^d \times (H^1(\mathbb{R}^d))^d$ which satisfies for a fixed C

$$\langle \operatorname{div}(u \otimes v), \varphi \rangle_{L^2} \leq C \|\nabla u\|_{L^2}^{\frac{d}{4}} \|\nabla v\|_{L^2}^{\frac{d}{4}} \|u\|_{L^2}^{1-\frac{d}{4}} \|v\|_{L^2}^{1-\frac{d}{4}} \|\nabla \varphi\|_{L^2} \quad (5.17)$$

If furthermore $\operatorname{div} u = 0$ then

$$\langle \operatorname{div}(u \otimes v), v \rangle_{L^2} = 0. \quad (5.18)$$

Proof. Recall that from (5.2) we have $\operatorname{div}(u \otimes v)^j := \sum_{k=1}^d \partial_k(u^k v^j)$. Then for fields like in (5.16) we have

$$\langle \operatorname{div}(u \otimes v), \varphi \rangle_{L^2} = \sum_{j=1}^d \langle \operatorname{div}(u \otimes v)^j, \varphi^j \rangle_{L^2} = \sum_{j=1}^d \left\langle \sum_{k=1}^d \partial_k(u^k v^j), \varphi^j \right\rangle_{L^2} = - \sum_{j=1}^d \sum_{k=1}^d \langle u^k v^j, \partial_k \varphi^j \rangle_{L^2}.$$

Now the r.h.s. can be bounded by

$$|\langle u^k v^j, \partial_k \varphi^j \rangle_{L^2}| \leq \|u^k v^j\|_{L^2} \|\nabla \varphi\|_{L^2} \leq \|u^k\|_{L^4} \|v^j\|_{L^4} \|\nabla \varphi\|_{L^2}.$$

Finally, we apply Gagliardo-Nirenberg inequality writing

$$\|u^k\|_{L^4} \leq C \|\nabla u^k\|_{L^2}^{\frac{d}{4}} \|u^k\|_{L^2}^{1-\frac{d}{4}}.$$

The same holds for v^j . Then we obtain (5.17), obviously with a different C . This implies that the form in (5.16) is continuous and, by density of $C_c^\infty(\mathbb{R}^d)$ in $H^1(\mathbb{R}^d)$, it extends in a unique way.

Next, we write for $\varphi = v$

$$\begin{aligned} \langle \operatorname{div}(u \otimes v), v \rangle_{L^2} &= - \sum_{j=1}^d \sum_{k=1}^d \langle u^k v^j, \partial_k v^j \rangle_{L^2} \\ &= -2^{-1} \sum_{j=1}^d \sum_{k=1}^d \langle u^k, \partial_k (v^j)^2 \rangle_{L^2} = 2^{-1} \sum_{j=1}^d \langle (\operatorname{div} u) v^j, v^j \rangle_{L^2} = 0. \end{aligned}$$

Notice that this formal computation (the Leibnitz rule used for the 2nd equality requires some explaining) is certainly rigorous for $v \in (C_c^\infty(\mathbb{R}^d))^d$. On the other hand inequality (5.17) yields (5.18) by a density argument also for $v \in (H^1(\mathbb{R}^d))^d$. \square

We consider now the following truncation of the NS equation.

$$\begin{cases} (u_n)_t + \mathbf{P}_n \mathbb{P} \operatorname{div}(\mathbf{P}_n u_n \otimes \mathbf{P}_n u_n) - \nu \mathbf{P}_n \Delta u_n = 0 \\ u_n(0, x) = \mathbf{P}_n u_0(x). \end{cases} \quad (t, x) \in [0, \infty) \times \mathbb{R}^d \quad (5.19)$$

Lemma 5.7. *For any n the system (5.3) admits exactly one solution*

$$u_n \in C^\infty([0, \infty), (H^N(\mathbb{R}^d))^d) \text{ for any } N \in \mathbb{N} \cup \{0\}.$$

Furthermore we have $\mathbb{P}u_n = u_n$ and $\mathbf{P}_n u_n = u_n$.

Proof. First of all, we consider for any n local existence. Set

$$F_n(v) := \nu \mathbf{P}_n \Delta v - \mathbf{P}_n \mathbb{P} \operatorname{div}(\mathbf{P}_n v \otimes \mathbf{P}_n v).$$

Then we have

$$\|F_n(v)\|_{(H^N(\mathbb{R}^d))^d} \leq \|\nu(\mathbf{P}_n \Delta)v\|_{(H^N(\mathbb{R}^d))^d} + \|\mathbf{P}_n \mathbb{P} \operatorname{div}(\mathbf{P}_n v \otimes \mathbf{P}_n v)\|_{(H^N(\mathbb{R}^d))^d}$$

with

$$\|\nu(\mathbf{P}_n \Delta)v\|_{(H^N(\mathbb{R}^d))^d} \leq \nu n^{2+N} \|v\|_{(L^2(\mathbb{R}^d))^d}$$

and

$$\begin{aligned} \|\mathbf{P}_n \mathbb{P} \operatorname{div}(\mathbf{P}_n v \otimes \mathbf{P}_n v)\|_{(H^N(\mathbb{R}^d))^d} &\lesssim n^{N+1} \|\mathbf{P}_n v \otimes \mathbf{P}_n v\|_{L^2} \lesssim n^{N+1} \|\mathbf{P}_n v\|_{L^4}^2 \\ &\lesssim n^{N+1} \|\nabla \mathbf{P}_n v\|_{L^2}^{\frac{d}{4}} \|\nabla \mathbf{P}_n v\|_{L^2}^{\frac{d}{4}} \|\mathbf{P}_n v\|_{L^2}^{1-\frac{d}{4}} \|\mathbf{P}_n v\|_{L^2}^{1-\frac{d}{4}} \\ &\lesssim n^{N+1+\frac{d}{2}} \|v\|_{L^2}^2. \end{aligned}$$

So for some constant $C_{n,N}$ we have

$$\|F_n(v)\|_{(H^N(\mathbb{R}^d))^d} \leq C_{n,N} (\|v\|_{(L^2(\mathbb{R}^d))^d} + \|v\|_{(L^2(\mathbb{R}^d))^d}^2).$$

Furthermore, as a sum of a bounded linear operator and a bounded quadratic form each F_n is a locally Lipchitz function. Then for any n and N we know that (5.3) admits a solution $u_n \in C^1([0, T_{n,N}), (H^N(\mathbb{R}^d))^d)$ for some maximal $T_{n,N} > 0$. Furthermore we must have

$$\lim_{t \nearrow T_{n,N}} \|u_n(t)\|_{(H^N(\mathbb{R}^d))^d} = +\infty \text{ if } T_{n,N} < \infty. \quad (5.20)$$

Next we have $u_n = \mathbb{P}u_n$ since applying $1 - \mathbb{P}$ to (5.19)

$$\begin{cases} ((1 - \mathbb{P})u_n)_t - \nu(\mathbf{P}_n \Delta)(1 - \mathbb{P})u_n = 0 \\ (1 - \mathbb{P})u_n(0, x) = 0 \end{cases} \Rightarrow (1 - \mathbb{P})u_n = 0,$$

and $u_n = \mathbf{P}_n u_n$ since applying $1 - \mathbf{P}_n$ to (5.19)

$$\begin{cases} ((1 - \mathbf{P}_n)u_n)_t = 0 \\ (1 - \mathbf{P}_n)u_n(0, x) = 0 \end{cases} \Rightarrow (1 - \mathbf{P}_n)u_n = 0$$

Now we show that the *finite time blow up* in (5.20) cannot occur for any (n, N) (in fact, the following argument proves that also *infinite time blow up*, that is (5.20) but with $T_{n,N} = \infty$, cannot occur).

Let us consider (5.20) first in the case $N = 0$. When we apply $\langle \cdot, u_n \rangle_{L^2}$ to the 1st line in (5.3) and get

$$\frac{1}{2} \frac{d}{dt} \|u_n\|_{L^2}^2 + \langle \mathbf{P}_n \mathbb{P} \operatorname{div}(u_n \otimes u_n), u_n \rangle_{L^2} - \nu \langle \Delta u_n, u_n \rangle_{L^2} = 0.$$

Notice that summing on repeated indexes $\langle \Delta u_n, \varphi \rangle_{L^2} = -\langle \partial_j u_n, \partial_j \varphi \rangle_{L^2}$ for all $\varphi \in (C_0^\infty(\mathbb{R}^d))^d$ and since this is dense in $(H^1(\mathbb{R}^d))^d$ and both sides define bounded functionals in $(H^1(\mathbb{R}^d))^d$, we conclude

$$\nu \langle \Delta u_n, u_n \rangle_{L^2} = -\nu \|\nabla u_n\|_{L^2}^2.$$

Next, using $\mathbb{P}^* = \mathbb{P}$, $\mathbf{P}_n^* = \mathbf{P}_n$ and (5.18), we have

$$\langle \mathbf{P}_n \mathbb{P} \operatorname{div}(u_n \otimes u_n), u_n \rangle_{L^2} = \langle \operatorname{div}(u_n \otimes u_n), u_n \rangle_{L^2} = 0.$$

Hence we conclude

$$\frac{1}{2} \frac{d}{dt} \|u_n\|_{(L^2(\mathbb{R}^d))^d}^2 + \nu \|\nabla u_n\|_{(L^2(\mathbb{R}^d))^{d^2}}^2 = 0$$

and we obtain

$$\|u_n(t)\|_{(L^2(\mathbb{R}^d))^d}^2 + 2\nu \int_0^t \|\nabla u_n(t')\|_{(L^2(\mathbb{R}^d))^{d^2}}^2 dt' = \|\mathbf{P}_n u_0\|_{(L^2(\mathbb{R}^d))^d}^2. \quad (5.21)$$

In particular this yields the bound $\|u_n(t)\|_{L^2} \leq \|\mathbf{P}_n u_0\|_{L^2}$ for all $t \in [0, T_{n,0})$ and by (5.20) we conclude that the lifespan is $T_{n,0} = \infty$ for all $n \in \mathbb{N}$. This proves the case $N = 0$ in Lemma 5.7.

Consider now the case $N \in \mathbb{N}$. If $u_n \in C^1([0, T_{n,N}), (H^N(\mathbb{R}^d))^d)$ with $T_{n,N} < \infty$ is a maximal solution, obviously it is the restriction in $[0, T_{n,N})$ of a solution $u_n \in C^1([0, \infty), (L^2(\mathbb{R}^d))^d)$. On the other hand, the blow up (5.20) is impossible because otherwise we would have

$$\infty = \lim_{t \nearrow T_{n,N}} \|u_n(t)\|_{(H^N(\mathbb{R}^d))^d} \leq n^N \lim_{t \nearrow T_{n,N}} \|u_n(t)\|_{(L^2(\mathbb{R}^d))^d} \leq n^N \|\mathbf{P}_n u_0\|_{L^2} < \infty$$

which is absurd. Hence the lifespan is $T_{n,N} = \infty$ for all $n \in \mathbb{N}$ and $N \in \mathbb{N} \cup \{0\}$. \square

5.1.1 Compactness properties of $\{u_n\}_{n \in \mathbb{N}}$

Now we consider the sequence of solutions $\{u_n\}_{n \in \mathbb{N}}$ of solutions of (5.3). We will prove the following result.

Proposition 5.8. *There exists a $u \in L^\infty(\mathbb{R}_+, (L^2(\mathbb{R}^d))^d) \cap L_{loc}^2(\mathbb{R}_+, H^1(\mathbb{R}^d))^d$ with $\operatorname{div} u = 0$ and a subsequence of $\{u_n\}_{n \in \mathbb{N}}$ such that for any $T > 0$ and any compact subset $K \subset \mathbb{R}^d$ we have (after extracting this subsequence)*

$$\lim_{n \rightarrow \infty} \int_{[0, T] \times K} |u_n(t, x) - u(t, x)|^2 dt dx = 0. \quad (5.22)$$

Moreover, for all vector fields $\Psi \in L^2([0, T], (H^1(\mathbb{R}^d))^d)$ and all $\Phi \in L^2([0, T] \times \mathbb{R}^d, \mathbb{R}^d)$ we have

$$\lim_{n \rightarrow \infty} \int_{[0, T] \times \mathbb{R}^d} (u_n(t, x) - u(t, x)) \cdot \Phi(t, x) dt dx = 0, \quad (5.23)$$

$$\lim_{n \rightarrow \infty} \sum_{j, k=1}^d \int_{[0, T] \times \mathbb{R}^d} \partial_k(u_n^j(t, x) - u^j(t, x)) \partial_k \Psi^j(t, x) dt dx = 0. \quad (5.24)$$

Finally, for any $\psi \in C^0([0, \infty), (H^1(\mathbb{R}^d))^d)$ we have $\langle u_n, \psi \rangle_{(L^2(\mathbb{R}^d))^d} \rightarrow \langle u, \psi \rangle_{(L^2(\mathbb{R}^d))^d}$ in $L_{loc}^\infty([0, \infty))$, that is

$$\lim_{n \rightarrow \infty} \|\langle u_n(t) - u(t), \psi(t) \rangle\|_{L^\infty([0, T])} = 0 \text{ for any } T. \quad (5.25)$$

Proof. Fix an arbitrary $T > 0$ and an arbitrary compact subset K of \mathbb{R}^d .

Claim 5.9. The set formed by the elements of the sequence $\{u_n\}_{n \in \mathbb{N}}$ is relatively compact in $L^2([0, T] \times K, \mathbb{R}^d)$.

Proof of Claim 5.9. Notice that (5.21) implies that $u_n \in L^2([0, T] \times \mathbb{R}^d, \mathbb{R}^d)$ for all n . We will show the following statement, which is equivalent to Claim 5.9.

Claim 5.10. For any $\varepsilon > 0$ there exists a finite family of balls of the space $L^2([0, T] \times K, \mathbb{R}^d)$ which have radius ε and whose union covers the set $\{u_n\}_{n \in \mathbb{N}}$.

Proof of Claim 5.10. First of all, if we want to approximate $\{u_n\}_{n \in \mathbb{N}}$ with $\{\mathbf{P}_{n_0} u_n\}_{n \in \mathbb{N}}$ for a fixed n_0 , we can use the fact that for any n_0 and any n we have

$$\begin{aligned} \|u_n - \mathbf{P}_{n_0} u_n\|_{L^2([0, T] \times \mathbb{R}^d, \mathbb{R}^d)}^2 &= \int_0^T \|u_n - \mathbf{P}_{n_0} u_n\|_{(L^2(\mathbb{R}^d))^d}^2 dt \\ &\leq n_0^{-2} \int_0^T \|\nabla u_n - \nabla \mathbf{P}_{n_0} u_n\|_{(L^2(\mathbb{R}^d))^{d^2}}^2 dt \leq n_0^{-2} \int_0^T \|\nabla u_n\|_{(L^2(\mathbb{R}^d))^{d^2}}^2 dt \leq n_0^{-2} \|u_0\|_{(L^2(\mathbb{R}^d))^d}^2. \end{aligned}$$

Hence we can choose n_0 large enough s.t.

$$\|u_n - \mathbf{P}_{n_0} u_n\|_{L^2([0, T] \times \mathbb{R}^d, \mathbb{R}^d)} < \frac{\varepsilon}{2} \text{ for all } n \in \mathbb{N}. \quad (5.26)$$

Now consider $\{\mathbf{P}_{n_0} u_n\}_{n \in \mathbb{N}}$. Then Claim 5.10 is a consequence of

Claim 5.11. $\{\mathbf{P}_{n_0} u_n\}_{n \in \mathbb{N}}$ is relatively compact in $L^2([0, T] \times K, \mathbb{R}^d)$.

Indeed Claim 5.11 implies that for any $\varepsilon > 0$ there is a finite number of balls $B_{L^2([0, T] \times K, \mathbb{R}^d)}(f_j, \frac{\varepsilon}{2})$ which cover $\{\mathbf{P}_{n_0} u_n\}_{n \in \mathbb{N}}$. Hence by (5.26) we conclude that for any $\varepsilon > 0$ the balls $B_{L^2([0, T] \times K, \mathbb{R}^d)}(f_j, \varepsilon)$ cover $\{u_n\}_{n \in \mathbb{N}}$ and so we get Claim 5.10.

Proof of Claim 5.11. It will be a consequence of the following stronger claim.

Claim 5.12. $\{\mathbf{P}_{n_0} u_n\}_{n \in \mathbb{N}}$ is relatively compact in $C^0([0, T], (L^2(K))^d) \subset L^\infty([0, T], (L^2(K))^d)$.

Proof of Claim 5.12. To get this result we want to apply the Ascoli–Arzela Theorem (for which a sufficient condition for a sequence of continuous functions $f_n : K \rightarrow X$, with K compact and separable metric space and X a complete metric space, to admit a subsequence that converges uniformly to a continuous function $f : K \rightarrow X$ is that it is equicontinuous and $\{f_n(k)\}_n$ is relatively compact for any $k \in K$ ¹). So it is enough to show that $\{\mathbf{P}_{n_0} u_n\}_{n \in \mathbb{N}}$ is a sequence of equicontinuous functions in $C^0([0, T], (L^2(K))^d)$ and that for any $t \in [0, T]$ the sequence $\{\mathbf{P}_{n_0} u_n(t)\}_{n \in \mathbb{N}}$ is relatively compact in $(L^2(K))^d$.

First of all we want to show that $\{\mathbf{P}_{n_0} u_n\}_{n \in \mathbb{N}}$ is a sequence of equicontinuous functions in $C^0([0, T], (L^2(K))^d)$. This will follow from Hölder inequality (since $\frac{4}{d} > 1$ if $d = 2, 3$) and from the following claim.

Claim 5.13. There exists a fixed constant C s.t.

$$\|(\mathbf{P}_{n_0} u_n)_t\|_{L^{\frac{4}{d}}([0, T], (L^2(\mathbb{R}^d))^d)} \leq C \text{ for all } n.$$

Proof of Claim 5.13. We apply \mathbf{P}_{n_0} to (5.3) and we obtain

$$(\mathbf{P}_{n_0} u_n)_t = -\mathbf{P}_{n_0} \mathbf{P}_n \mathbb{P} \operatorname{div}(u_n \otimes u_n) + \nu \mathbf{P}_{n_0} \Delta u_n.$$

We have

$$\|\nu \mathbf{P}_{n_0} \Delta u_n\|_{(L^2(\mathbb{R}^d))^d} \leq \nu n_0^2 \|u_n\|_{(L^2(\mathbb{R}^d))^d} \leq \nu n_0^2 \|u_0\|_{(L^2(\mathbb{R}^d))^d}$$

and, by the Gagliardo-Nirenberg inequality,

$$\begin{aligned} & \|\mathbf{P}_{n_0} \mathbf{P}_n \mathbb{P} \operatorname{div}(u_n \otimes u_n)\|_{(L^2(\mathbb{R}^d))^d} \leq \|\mathbf{P}_{n_0} \operatorname{div}(u_n \otimes u_n)\|_{(L^2(\mathbb{R}^d))^d} \\ &= \sum_{j=1}^d \|\mathbf{P}_{n_0} \sum_{k=1}^d \partial_k (u_n^k u_n^j)\|_{L^2(\mathbb{R}^d)} \leq n_0 \sum_{j,k=1}^d \|u_n^k u_n^j\|_{L^2(\mathbb{R}^d)} \\ &\leq C n_0 \|u_n\|_{(L^4(\mathbb{R}^d))^d}^2 \leq C' n_0 \left(\|\nabla u_n\|_{L^2}^{\frac{d}{4}} \|u_n\|_{L^2}^{1-\frac{d}{4}} \right)^2. \end{aligned}$$

Then we have

$$\begin{aligned} \|(\mathbf{P}_{n_0} u_n)_t\|_{L^{\frac{4}{d}}([0, T], (L^2(\mathbb{R}^d))^d)} &\leq \nu n_0^2 T^{\frac{d}{4}} \|u_0\|_{(L^2(\mathbb{R}^d))^d} \\ &+ C' n_0 \|u_n\|_{L^\infty([0, T], (L^2(\mathbb{R}^d))^d)}^{2(1-\frac{d}{4})} \|\nabla u_n\|_{L^2([0, T], L^2)}^{\frac{d}{2}} \leq C \end{aligned}$$

for some constant C independent of n by the energy equality (5.21) and the fact that $\|\mathbf{P}_n u_0\|_{(L^2(\mathbb{R}^d))^d} \leq \|u_0\|_{(L^2(\mathbb{R}^d))^d}$ for all n .

Hence we have concluded the proof that $\{\mathbf{P}_{n_0} u_n\}_{n \in \mathbb{N}}$ is a sequence of equicontinuous functions in $C^0([0, T], (L^2(\mathbb{R}^d))^d)$.

¹The proof goes as follows. One first considers a dense countable subset \mathcal{N} of K . Then by a diagonal argument, one considers a subsequence $\{f_{n_m}\}$ s.t. $\{f_{n_m}(k)\}$ converges for any $k \in \mathcal{N}$ to a limit that we denote by $f(k)$. Using equicontinuity and the completeness of X it is easy to see that $\{f_{n_m}(k)\}$ converges for any $k \in K$. We denote again by $f(k)$ the limit. Finally, using equicontinuity we conclude that $f : K \rightarrow X$ is continuous

To complete the proof of Claim 5.12 we need to show that for any $t \in [0, T]$ the sequence $\{\mathbf{P}_{n_0} u_n(t)\}_{n \in \mathbb{N}}$ is relatively compact in $(L^2(K))^d$. It is here that we will exploit the fact that K is a compact subspace of \mathbb{R}^d .

We know that $\{\mathbf{P}_{n_0} u_n(t)\}_{n \in \mathbb{N}}$ is a bounded sequence in $(H^1(\mathbb{R}^d))^d$ for any $t \in [0, T]$. This follows immediately from $\|\mathbf{P}_{n_0} u_n(t)\|_{H^1} \leq n_0 \|u_n(t)\|_{L^2} \leq n_0 \|u_0\|_{L^2}$, which follows from the energy inequality (5.21) which guarantees $\|u_n(t)\|_{L^2} \leq \|u_0\|_{L^2}$. We recall now that

Claim 5.14. The restriction map $H^1(\mathbb{R}^d) \rightarrow L^2(K)$ is compact for any compact K .

Sketch of proof Indeed this is equivalent at showing that

$$\mathcal{T}f := \chi_K \mathcal{F}^* \left(\frac{f}{\langle \xi \rangle} \right) \text{ is compact as } L^2(\mathbb{R}^d) \rightarrow L^2(\mathbb{R}^d).$$

We have $\mathcal{T}f = \int \mathcal{K}(x, \xi) f(\xi) d\xi$ with integral kernel $\mathcal{K}(x, \xi) := \chi_K(x) \langle \xi \rangle^{-1} e^{-ix \cdot \xi}$. It is easy to see that $\mathcal{T}_n \xrightarrow{n \rightarrow \infty} \mathcal{T}$ in the operator norm where the \mathcal{T}_n has kernel $\mathcal{K}_n(x, \xi) := \chi_K(x) \langle \xi \rangle^{-1} e^{-ix \cdot \xi} \chi_{B(0, n)}(\xi)$. Since $\mathcal{K}_n \in L^2(\mathbb{R}_x^d \times \mathbb{R}_\xi^d)$, it follows that \mathcal{T}_n is a Hilbert–Schmidt operator, with $\|\mathcal{T}_n\|_{HS} := \|\mathcal{K}_n\|_{L^2(\mathbb{R}_x^d \times \mathbb{R}_\xi^d)}$. It is easy to show that $\|\mathcal{T}_n\|_{L^2 \rightarrow L^2} \leq \|\mathcal{T}_n\|_{HS}$. \mathcal{K}_n is the limit in $L^2(\mathbb{R}_x^d \times \mathbb{R}_\xi^d)$ of elements in $L^2(\mathbb{R}_x^d) \otimes L^2(\mathbb{R}_\xi^d)$. The latter ones are integral kernels of finite rank operators and their operators converge in the Hilbert–Schmidt norm, and so also in the $\|\cdot\|_{L^2 \rightarrow L^2}$ norm, to \mathcal{T}_n . We conclude that there is a sequence of finite rank operators which converges in the operator norm to \mathcal{T} , which then is compact. \square

It follows that $\{\mathbf{P}_{n_0} u_n(t)\}_{n \in \mathbb{N}}$ is relatively compact in $(L^2(K))^d$ for any $t \in [0, T]$.

Hence the hypotheses of the Ascoli–Arzela Theorem have been checked and we can conclude that Claim 5.12, that is the claim that $\{\mathbf{P}_{n_0} u_n\}_{n \in \mathbb{N}}$ is relatively compact in $C^0([0, T], (L^2(K))^d)$, is true.

Hence there exists a subsequence of $\{u_n\}_{n \in \mathbb{N}}$ (and it is not restrictive to assume this is true for the whole sequence) which converges to an $u \in L^2([0, T] \times K, \mathbb{R}^d)$. By a diagonal argument, we can assume that this is true for any compact $K \subset \mathbb{R}^d$ and any $T > 0$. This yields (5.22). Notice that this implies

$$u_n \rightarrow u \text{ in } \mathcal{D}'((0, T) \times \mathbb{R}^d, \mathbb{R}^d). \quad (5.27)$$

We claim now that $u \in L^2([0, T] \times \mathbb{R}^d, \mathbb{R}^d)$ and that

$$u_n \rightharpoonup u \text{ in } L^2([0, T] \times \mathbb{R}^d, \mathbb{R}^d) \quad (5.28)$$

(convergence in the weak topology). Indeed, since from (5.21) we have that $\{u_n\}_{n \in \mathbb{N}}$ is uniformly bounded in $L^2([0, T] \times \mathbb{R}^d, \mathbb{R}^d)$, it follows that up to a subsequence we have $u_n \rightharpoonup v$ for some $v \in L^2([0, T] \times \mathbb{R}^d, \mathbb{R}^d)$. Then (5.27) implies that $v = u$ as distributions in $\mathcal{D}'((0, T) \times \mathbb{R}^d, \mathbb{R}^d)$. This implies that $u \in L^2([0, T] \times \mathbb{R}^d, \mathbb{R}^d)$ with $u = v$.

In particular this implies

$$\lim_{n \rightarrow \infty} \int_{[0, T] \times \mathbb{R}^d} (u_n(t, x) - u(t, x)) \cdot \Phi(t, x) dt dx = 0 \text{ for all } \Phi \in L^2([0, T] \times \mathbb{R}^d, \mathbb{R}^d),$$

that is (5.23). Notice that, for $\Phi(t, x) = \chi(t)\nabla\psi(x)$ we have from the above limit

$$\int_{[0,T]} dt \chi(t) \int_{\mathbb{R}^d} \operatorname{div}_x u(t, x) \psi(x) dx = 0 \text{ for all } \psi \in C_c^\infty(\mathbb{R}^d, \mathbb{R}) \text{ and any } \chi \in C^\infty([0, T], \mathbb{R}),$$

This implies that

$$\int_{\mathbb{R}^d} \operatorname{div}_x u(t, x) \psi(x) dx = 0 \text{ for a.e. } t.$$

In fact, for the argument below, which proves (5.25) and is independent of what we are discussing right here, the integral on the l.h.s. is continuous in t . This integral equals 0 for all t , and not just for a.a. t . Since this is true for all t and for all $\psi \in C_c^\infty(\mathbb{R}^d, \mathbb{R})$, it follows that $\operatorname{div}_x u(t, x) = 0$ for all t .

We now turn to the proof of (5.24).

By (5.21) we know that $\{\nabla u_n\}_{n \in \mathbb{N}}$ is bounded in $L^2((0, T) \times \mathbb{R}^d, \mathbb{R}^d \times \mathbb{R}^d)$. This implies that up to a subsequence there exists $V \in L^2((0, T) \times \mathbb{R}^d, \mathbb{R}^d \times \mathbb{R}^d)$ s.t. $\nabla u_n \rightharpoonup V$. On the other hand (5.28) implies $u_n \rightarrow u$ in $\mathcal{D}'((0, T) \times \mathbb{R}^d)$. This in turn implies $\partial_j u_n \rightarrow \partial_j u$ in $\mathcal{D}'((0, T) \times \mathbb{R}^d, \mathbb{R}^d)$ for any $j = 1, \dots, d$. Hence $\nabla u = V$ in $\mathcal{D}'((0, T) \times \mathbb{R}^d, \mathbb{R}^d \times \mathbb{R}^d)$, $\nabla u \in L^2((0, T) \times \mathbb{R}^d, \mathbb{R}^d \times \mathbb{R}^d)$ and $\nabla u = V$ in $L^2((0, T) \times \mathbb{R}^d, \mathbb{R}^d \times \mathbb{R}^d)$. This proves (5.24).

Notice also that, up to a subsequence, $u_n(t, x) \xrightarrow{n \rightarrow +\infty} u(t, x)$ for almost any (t, x) , see p. 94 [2], and $\nabla u_n \rightharpoonup \nabla u$ as $n \rightarrow +\infty$ in $L^2((0, T) \times \mathbb{R}^d, \mathbb{R}^d \times \mathbb{R}^d)$. We claim that, since we assume we have extracted a subsequence, $u_n(t, x) \xrightarrow{n \rightarrow +\infty} u(t, x)$ for almost any $(t, x) \in \mathbb{R}_+ \times \mathbb{R}^d$, implies that for almost any t we have $u_n(t, x) \xrightarrow{n \rightarrow +\infty} u(t, x)$ for a.e. x . Indeed, if this was not the case, setting $w(t, x) := \limsup_n |u_n(t, x) - u(t, x)|$ there would exist $J \subset \mathbb{R}_+$ with measure $|J| > 0$ and with $\int_{\mathbb{R}^d} w(t, x) dx > 0$ for $t \in J$, which would imply $\int_{\mathbb{R}_+ \times \mathbb{R}^d} w(t, x) dt dx > 0$, and so $w > 0$ on a subset of $\mathbb{R}_+ \times \mathbb{R}^d$ of positive measure. But we know that $w = 0$ a.e. in $\mathbb{R}_+ \times \mathbb{R}^d$ and this proves our claim.

Then the energy inequalities (5.21) imply by Fatou

$$\|u(t)\|_{L^2(\mathbb{R}^d)}^2 + 2\nu \int_0^t \|\nabla u(t')\|_{L^2(\mathbb{R}^d)}^2 dt' \leq \|u_0\|_{L^2(\mathbb{R}^d)}^2, \quad (5.7)$$

where here for the 1st term in the l.h.s. we apply the classical Fatou theorem for a sequence of integrable functions converging pointwise to a function, see [2, Lemma 4.1], while for the 2nd term in the l.h.s. we apply claim (iii) Proposition 3.5 [2]

We turn now to the proof of (5.25).

Fix a function $\psi \in C^0([0, \infty), H^1(\mathbb{R}^d, \mathbb{R}^d))$. For a given n_0 consider

$$g_n(t) := \langle u_n(t), \psi(t) \rangle_{(L^2(\mathbb{R}^d))^d} \text{ and } g_n^{(n_0)}(t) := \langle \mathbf{P}_{n_0} u_n(t), \psi(t) \rangle_{(L^2(\mathbb{R}^d))^d}.$$

Then for any $\epsilon > 0$ and any fixed $T > 0$ there exists n_0 s.t.

$$\|(\mathbf{P}_{n_0} - 1)\psi(t)\|_{L^\infty([0, T], (L^2(\mathbb{R}^d))^d)} < \epsilon.$$

This and $\|u_n(t)\|_{L^\infty([0,T],(L^2(\mathbb{R}^d))^d)} \leq \|u_0\|_{(L^2(\mathbb{R}^d))^d}$ imply

$$\|g_n - g_n^{(n_0)}\|_{L^\infty([0,T])} \leq \|u_0\|_{(L^2(\mathbb{R}^d))^d} \epsilon.$$

Furthermore, for any fixed $T > 0$ there exists a compact K s.t.

$$\|\psi(t)\|_{L^\infty([0,T],(L^2(\mathbb{R}^d \setminus K))^d)} < \epsilon.$$

Then, if we set $g_n^{(n_0,K)}(t) := \langle \mathbf{P}_{n_0} u_n(t), \psi(t) \rangle_{(L^2(K))^d}$ we have

$$\|g_n^{(n_0,K)} - g_n^{(n_0)}\|_{L^\infty([0,T])} \leq \|u_0\|_{(L^2(\mathbb{R}^d))^d} \epsilon.$$

We claim that

$$\mathbf{P}_{n_0} u_n \rightarrow \mathbf{P}_{n_0} u \text{ in } C^0([0,T], (L^2(K))^d). \quad (5.29)$$

Indeed, by Claim 5.12, and by a diagonal argument, we know that there exists a v s.t. $\mathbf{P}_{n_0} u_n \rightarrow v$ in $C^0([0,T], (L^2(K))^d)$ for any T and K . It is easy to conclude that $v \in L^2([0,T] \times \mathbb{R}^d, \mathbb{R}^d)$ and that $\mathbf{P}_{n_0} u_n \rightharpoonup v$ therein. On the other hand, we know that $u_n \rightarrow u$ in $L^2([0,T] \times K, \mathbb{R}^d)$, and that $u_n \rightharpoonup u$ in $L^2([0,T] \times \mathbb{R}^d, \mathbb{R}^d)$. In turn, this implies $\mathbf{P}_{n_0} u_n \rightharpoonup \mathbf{P}_{n_0} u$ in $L^2([0,T] \times \mathbb{R}^d, \mathbb{R}^d)$. But then this implies $v = \mathbf{P}_{n_0} u$ in $L^2([0,T] \times K, \mathbb{R}^d)$, and so we get (5.29).

In turn, (5.29) implies

$$\{g_n^{(n_0,K)}\}_n = \langle \mathbf{P}_{n_0} u_n(t), \psi(t) \rangle_{(L^2(K))^d} \rightarrow \langle \mathbf{P}_{n_0} u(t), \psi(t) \rangle_{(L^2(K))^d} \text{ in } C^0([0,T]).$$

But then also

$$\begin{aligned} & \| \langle u_n(t), \psi(t) \rangle_{(L^2(\mathbb{R}^d))^d} - \langle u(t), \psi(t) \rangle_{(L^2(\mathbb{R}^d))^d} \|_{L^\infty([0,T])} \\ & \leq \| \langle \mathbf{P}_{n_0} u_n(t), \psi(t) \rangle_{(L^2(K))^d} - \langle \mathbf{P}_{n_0} u(t), \psi(t) \rangle_{(L^2(K))^d} \|_{L^\infty([0,T])} + 2 \| u_0 \|_{(L^2(\mathbb{R}^d))^d} \epsilon \\ & + \| \langle u(t), (1 - \mathbf{P}_{n_0}) \psi(t) \rangle_{(L^2(\mathbb{R}^d))^d} \|_{L^\infty([0,T])} + \| \langle u(t), (1 - \chi_K) \psi(t) \rangle_{(L^2(\mathbb{R}^d))^d} \|_{L^\infty([0,T])} \leq \\ & \leq \| \langle \mathbf{P}_{n_0} u_n(t), \psi(t) \rangle_{(L^2(K))^d} - \langle \mathbf{P}_{n_0} u(t), \psi(t) \rangle_{(L^2(K))^d} \|_{L^\infty([0,T])} + 4 \| u_0 \|_{(L^2(\mathbb{R}^d))^d} \epsilon. \end{aligned}$$

Since ϵ is arbitrarily small, it follows that we obtain that g_n converges to $\langle u(t), \psi(t) \rangle_{(L^2(\mathbb{R}^d))^d}$ in $L^\infty([0,T])$, and hence in $C^0([0,T])$. In particular we have shown that $u \in C^0([0,\infty), L_w^2(\mathbb{R}^d, \mathbb{R}^d))$. The proof of Proposition 5.8 is completed. \square

5.1.2 End of the proof of Leray's Theorem 5.3

Proposition 5.8 has provided us with a function

$$u \in L^\infty([0,\infty), L^2(\mathbb{R}^d, \mathbb{R}^d)) \cap L_{loc}^2([0,\infty), H^1(\mathbb{R}^d, \mathbb{R}^d)) \cap C^0([0,\infty), L_w^2(\mathbb{R}^d, \mathbb{R}^d))$$

which satisfies the energy inequality

$$\|u(t)\|_{L^2(\mathbb{R}^d)}^2 + 2\nu \int_0^t \|\nabla u(t')\|_{L^2(\mathbb{R}^d)}^2 dt' \leq \|u_0\|_{L^2(\mathbb{R}^d)}^2. \quad (5.7)$$

Our aim in this section is to prove that u is a weak solution in the sense of Definition 5.1. Let us consider $\Psi \in C^1([0, \infty), H^1(\mathbb{R}^d, \mathbb{R}^d))$ and let us apply to (5.3) the inner product $\langle \cdot, \Psi \rangle_{L^2}$. Then we get

$$\langle (u_n)_t, \Psi \rangle_{(L^2(\mathbb{R}^d))^d} + \langle \mathbf{P}_n \mathbb{P} \operatorname{div}(u_n \otimes u_n), \Psi \rangle_{(L^2(\mathbb{R}^d))^d} - \nu \langle \Delta u_n, \Psi \rangle_{(L^2(\mathbb{R}^d))^d} = 0.$$

Hence

$$\frac{d}{dt} \langle u_n, \Psi \rangle_{(L^2(\mathbb{R}^d))^d} - \langle u_n, \Psi_t \rangle_{(L^2(\mathbb{R}^d))^d} + \langle \operatorname{div}(u_n \otimes u_n), \mathbb{P} \mathbf{P}_n \Psi \rangle_{(L^2(\mathbb{R}^d))^d} + \nu \langle \Delta u_n, \Psi \rangle_{(L^2(\mathbb{R}^d))^d} = 0.$$

So, integrating in t we get

$$\begin{aligned} \int_{\mathbb{R}^d} u_n(t, x) \cdot \Psi(t, x) dx &= \int_{\mathbb{R}^d} \mathbf{P}_n u_0(x) \cdot \Psi(0, x) dx - \int_0^t ds \int_{\mathbb{R}^d} u_n(s, x) \otimes u_n(s, x) : \nabla \mathbb{P} \mathbf{P}_n \Psi(s, x) dx \\ &+ \int_0^t ds \int_{\mathbb{R}^d} u_n(s, x) \cdot \Psi_t(s, x) dx - \nu \sum_{j,k} \int_0^t ds \int_{\mathbb{R}^d} \partial_k u_n^j(s, x) \partial_k \Psi^j(s, x) dx. \end{aligned} \quad (5.30)$$

By (5.25) for any t

$$\lim_{n \rightarrow \infty} \int_{\mathbb{R}^d} u_n(t, x) \cdot \Psi(t, x) dx = \int_{\mathbb{R}^d} u(t, x) \cdot \Psi(t, x) dx. \quad (5.31)$$

By the definition of \mathbf{P}_n we have

$$\lim_{n \rightarrow \infty} \int_{\mathbb{R}^d} \mathbf{P}_n u_0(x) \cdot \Psi(0, x) dx = \int_{\mathbb{R}^d} u_0(x) \cdot \Psi(0, x) dx. \quad (5.32)$$

By (5.23) we have

$$\lim_{n \rightarrow \infty} \int_0^t ds \int_{\mathbb{R}^d} u_n(s, x) \cdot \Psi_t(s, x) dx = \int_0^t ds \int_{\mathbb{R}^d} u(s, x) \cdot \Psi_t(s, x) dx. \quad (5.33)$$

By (5.24) we have

$$\lim_{n \rightarrow \infty} \nu \int_0^t ds \int_{\mathbb{R}^d} \partial_k u_n^j(s, x) \partial_k \Psi^j(s, x) dx = \nu \int_0^t ds \int_{\mathbb{R}^d} \partial_k u^j(s, x) \partial_k \Psi^j(s, x) dx. \quad (5.34)$$

The above limits (5.31)–(5.34) are straightforward consequences of Proposition 5.8. By taking the limit in (5.30), Leray's Theorem will be a consequence of the following claim, which is the delicate point of this part of the proof.

Claim 5.15. We have

$$\lim_{n \rightarrow \infty} \int_0^t ds \int_{\mathbb{R}^d} u_n(s, x) \otimes u_n(s, x) : \nabla \mathbf{P}_n \mathbb{P} \Psi(s, x) dx = \int_0^t ds \int_{\mathbb{R}^d} u(s, x) \otimes u(s, x) : \nabla \mathbb{P} \Psi(s, x) dx. \quad (5.35)$$

Proof of Claim 5.15. The 1st step, algebraic, is to write

$$\begin{aligned} \int_0^t ds \int_{\mathbb{R}^d} u_n(s, x) \otimes u_n(s, x) : \nabla \mathbf{P}_n \mathbb{P} \Psi(s, x) dx &= \int_0^t ds \int_{\mathbb{R}^d} u_n(s, x) \otimes u_n(s, x) : \nabla \mathbb{P} \Psi(s, x) dx \\ &+ \int_0^t ds \int_{\mathbb{R}^d} u_n(s, x) \otimes u_n(s, x) : \nabla \mathbb{P} (\mathbf{P}_n \Psi(s, x) - \Psi(s, x)) dx. \end{aligned}$$

Claim 5.15 will be a consequence of

$$\lim_{n \rightarrow \infty} \int_0^t ds \int_{\mathbb{R}^d} u_n(s, x) \otimes u_n(s, x) : \nabla \mathbb{P} \Psi(s, x) dx = \int_0^t ds \int_{\mathbb{R}^d} u(s, x) \otimes u(s, x) : \nabla \mathbb{P} \Psi(s, x) dx. \quad (5.36)$$

and of

$$\lim_{n \rightarrow \infty} \int_0^t ds \int_{\mathbb{R}^d} u_n(s, x) \otimes u_n(s, x) : \nabla \mathbb{P} (\mathbf{P}_n \Psi(s, x) - \Psi(s, x)) dx = 0. \quad (5.37)$$

In order to prove (5.36)–(5.37) we observe that since $\mathbb{P} \Psi \in C^1([0, \infty), H^1(\mathbb{R}^d, \mathbb{R}^d))$ for any $\varepsilon > 0$ there is a compact set $K \subset \mathbb{R}^d$ s.t.

$$\sup_{s \in [0, T]} \|\nabla \mathbb{P} \Psi(s, \cdot)\|_{L^2(\mathbb{R}^d \setminus K)} < \varepsilon. \quad (5.38)$$

(5.38) is elementary to prove and it is assumed in the sequel. Now we show (5.36).

By Hölder, (5.38), Gagliardo–Nirenberg and the energy equality (5.21) we have

$$\begin{aligned} \left| \int_0^t ds \int_{\mathbb{R}^d \setminus K} u_n(s, x) \otimes u_n(s, x) : \nabla \mathbb{P} \Psi(s, x) dx \right| &\leq \int_0^T ds \|u_n \otimes u_n\|_{L^2(\mathbb{R}^d)} \|\nabla \mathbb{P} \Psi(s)\|_{L^2(\mathbb{R}^d \setminus K)} \\ &\leq T^{\frac{4-d}{4}} \|u_n \otimes u_n\|_{L^{\frac{4}{d}}([0, T], L^2(\mathbb{R}^d))} \|\nabla \mathbb{P} \Psi\|_{L^\infty([0, T], L^2(\mathbb{R}^d \setminus K))} \\ &\leq T^{\frac{4-d}{4}} \| \|u_n\|_{L^4(\mathbb{R}^d)}^2 \| \|_{L^{\frac{4}{d}}(0, T)} \varepsilon \lesssim \varepsilon T^{\frac{4-d}{4}} \| \|u_n\|_{L^2(\mathbb{R}^d)}^{2(1-d/4)} \| \nabla u_n \|_{L^2(\mathbb{R}^d)}^{d/2} \| \|_{L^{\frac{4}{d}}(0, T)} \\ &\lesssim \varepsilon T^{\frac{4-d}{4}} \| \|u_n\|_{L^\infty([0, T], L^2(\mathbb{R}^d))}^{2(1-d/4)} \| \nabla u_n \|_{L^2([0, T], L^2(\mathbb{R}^d))}^{d/2} \leq \varepsilon T^{\frac{4-d}{4}} \| \|u_0\|_{L^2(\mathbb{R}^d)}^2. \end{aligned}$$

Hence, to prove (5.36) it is enough to show for any compact set $K \subset \mathbb{R}^d$

$$\lim_{n \rightarrow \infty} \int_0^t ds \int_K u_n(s, x) \otimes u_n(s, x) : \nabla \mathbb{P} \Psi(s, x) dx = \int_0^t ds \int_K u(s, x) \otimes u(s, x) : \nabla \mathbb{P} \Psi(s, x) dx. \quad (5.39)$$

The limit (5.39) is a consequence of

$$\lim_{n \rightarrow \infty} u_n \otimes u_n = u \otimes u \text{ in } L^1([0, T], L^2(K))$$

which in turn is a consequence of

$$\lim_{n \rightarrow \infty} u_n = u \text{ in } L^2([0, T], L^4(K)). \quad (5.40)$$

Let us consider $\chi \in C_c^\infty(\mathbb{R}^d, [0, 1])$ s.t. $\chi = 1$ in K , $\Omega := \text{supp}\chi$ and with $\|\nabla\chi\|_{L^\infty(\mathbb{R}^d)} \leq 1$. Then by Gagliardo Nirenberg we have

$$\|f\|_{L^4(K)} \leq C\|f\|_{L^2(\Omega)}^{1-d/4}(\|\chi\nabla f\|_{L^2(\mathbb{R}^d)} + \|f\nabla\chi\|_{L^2(\mathbb{R}^d)})^{d/4} \leq C\|f\|_{L^2(\Omega)}^{1-d/4}\|f\|_{H^1(\mathbb{R}^d)}^{d/4}.$$

Using this inequality and Hölder (using $\frac{1}{2} = \frac{4-d}{8} + \frac{d}{8}$):

$$\begin{aligned} \|u - u_n\|_{L^2([0,T], L^4(K))} &\lesssim \| \|u - u_n\|_{L^2(\Omega)}^{1-\frac{d}{4}} \|u - u_n\|_{H^1(\mathbb{R}^d)}^{\frac{d}{4}} \|u - u_n\|_{L^2(0,T)} \\ &\leq \| \|u - u_n\|_{L^2(\Omega)}^{1-\frac{d}{4}} \|u - u_n\|_{L^{\frac{8}{4-d}}(0,T)} \| \|u - u_n\|_{H^1(\mathbb{R}^d)}^{\frac{d}{4}} \|u - u_n\|_{L^{\frac{8}{d}}(0,T)} \\ &= \|u - u_n\|_{L^2([0,T], L^2(\Omega))}^{1-\frac{d}{4}} \|u - u_n\|_{L^2([0,T], H^1(\mathbb{R}^d))}^{\frac{d}{4}} \\ &\leq (2(1 + \sqrt{T})\|u_0\|_{(L^2(\mathbb{R}^d))^d})^{\frac{d}{4}} \|u - u_n\|_{L^2([0,T], L^2(\Omega))}^{1-\frac{d}{4}} \xrightarrow{n \rightarrow +\infty} 0 \end{aligned}$$

where the limit holds because $u_n \xrightarrow{n \rightarrow +\infty} u$ in $L^2([0, T], (L^2(\Omega))^d)$, by Proposition 5.8. This yields (5.40) and so also (5.39).

The proof of (5.37) will follow from the fact that for any $\varepsilon > 0$ there is N s.t. $n \geq N$ implies

$$\sup_{s \in [0, T]} \|\nabla(\mathbf{P}_n - 1)\mathbb{P}\Psi(s)\|_{L^2(\mathbb{R}^d)} < \varepsilon$$

In turn this, like (5.38), is a simple consequence of the fact that $\Psi \in C^1([0, \infty), H^1(\mathbb{R}^d, \mathbb{R}^d))$. To prove (5.37) observe that

$$\begin{aligned} |\text{r.h.s. of (5.37)}| &\leq \|u_n \otimes u_n\|_{L^1([0, T], (L^2(\mathbb{R}^d))^d)} \|\nabla(\mathbf{P}_n - 1)\mathbb{P}\Psi\|_{L^2([0, T], (L^2(\mathbb{R}^d))^d)} \\ &\leq \varepsilon \|u_n\|_{L^2([0, T], (L^4(\mathbb{R}^d))^d)}^2 = \varepsilon \| \|u_n\|_{L^4(\mathbb{R}^d)} \|u_n\|_{L^2(0, T)}^2 \lesssim \varepsilon \| \|u_n\|_{L^2(\mathbb{R}^d)}^{1-d/4} \|\nabla u_n\|_{L^2(\mathbb{R}^d)}^{d/4} \|u_n\|_{L^2(0, T)}^2 \\ &\lesssim \varepsilon \|u_n\|_{L^\infty([0, T], L^2(\mathbb{R}^d))}^{2(1-\frac{d}{4})} \|\nabla u_n\|_{L^2([0, T], L^2(\mathbb{R}^d))}^{\frac{d}{2}} \leq T^{1-\frac{d}{4}} \varepsilon \|u_0\|_{(L^2(\mathbb{R}^d))^d}^2 \xrightarrow{\varepsilon \rightarrow 0} 0 \end{aligned}$$

This completes the proof of Leray's Theorem 5.3. □

Remark 5.16. The solutions we have found don't satisfy only the energy inequality (5.7), but in fact a the more general inequality

$$\|u(t)\|_{L^2(\mathbb{R}^d)}^2 + 2\nu \int_s^t \|\nabla u(t')\|_{L^2(\mathbb{R}^d)}^2 dt' \leq \|u(s)\|_{L^2(\mathbb{R}^d)}^2 \text{ for any } 0 \leq s < t. \quad (5.41)$$

This can be proved exactly like (5.7), exploiting the fact that the sequence u_n satisfies

$$\|u_n(t)\|_{(L^2(\mathbb{R}^d))^d}^2 + 2\nu \int_s^t \|\nabla u_n(t')\|_{(L^2(\mathbb{R}^d))^d}^2 dt' = \|u_n(s)\|_{(L^2(\mathbb{R}^d))^d}^2 \quad (5.42)$$

and then using the weak convergence argument utilized to prove (5.7). Leray's solutions which satisfy (5.41) will be called Leray–Hopf solutions.

Notice this interesting continuity from the right.

Lemma 5.17. *If $u(t)$ is a Leray–Hopf solution for $d = 3$ then for any $s \geq 0$ we have $u(t) \xrightarrow{t \rightarrow s^+} u(s)$ in $L^2(\mathbb{R}^3, \mathbb{R}^3)$.*

Proof. From (5.42) we have $\limsup_{t \rightarrow s^+} \|u(t)\|_{L^2(\mathbb{R}^3)} \leq \|u(s)\|_{L^2(\mathbb{R}^3)}$. On the other hand, since by weak continuity $u(t) \xrightarrow{t \rightarrow s^+} u(s)$, by Fathou’s Lemma we have $\liminf_{t \rightarrow s^+} \|u(t)\|_{L^2(\mathbb{R}^3)} \geq \|u(s)\|_{L^2(\mathbb{R}^3)}$. Hence we have the limit $\lim_{t \rightarrow s^+} \|u(t)\|_{L^2(\mathbb{R}^3)} = \|u(s)\|_{L^2(\mathbb{R}^3)}$. This and $u(t) \xrightarrow{t \rightarrow s^+} u(s)$ yield $u(t) \xrightarrow{t \rightarrow s^+} u(s)$ in $L^2(\mathbb{R}^3, \mathbb{R}^3)$. \square

6 Initial datum in $V(\mathbb{R}^d)$

Theorem 6.1 (Local existence of regular solutions 3d). *There exists a constant $c_\nu > 0$ such that for $u_0 \in V(\mathbb{R}^3)(= H^1(\mathbb{R}^3, \mathbb{R}^3) \cap H(\mathbb{R}^3))$ there exists a $T > c_\nu \|\nabla u_0\|_{L^2}^{-4}$ s.t. one of the Leray’s solutions satisfies $u \in L^\infty([0, T], V)$ and $\nabla^2 u \in L^2([0, T], L^2)$.*

Furthermore, this solution u satisfies the energy equality

$$\|u(t)\|_{L^2(\mathbb{R}^d)}^2 + 2\nu \int_s^t \|\nabla u(t')\|_{L^2(\mathbb{R}^d)}^2 dt' = \|u(s)\|_{L^2(\mathbb{R}^d)}^2 \text{ for any } 0 \leq s < t \leq T. \quad (6.1)$$

Proof. We consider the solution u obtained from the limit of the sequence u_n defined by (5.19), and which we can write as

$$\dot{u}_n + \mathbf{P}_n \mathbb{P} \operatorname{div}(u_n \otimes u_n) - \nu \Delta u_n = 0 \quad , \quad u_n(0, x) = \mathbf{P}_n u_0(x). \quad (6.2)$$

Applying $\langle \cdot, \Delta u_n \rangle$ we obtain

$$\begin{aligned} 2^{-1} \frac{d}{dt} \|\nabla u_n\|_{L^2}^2 + \nu \|\Delta u_n\|_{L^2}^2 &= - \langle \mathbf{P}_n \mathbb{P} \operatorname{div}(u_n \otimes u_n), \Delta u_n \rangle \leq \|\operatorname{div}(u_n \otimes u_n)\|_{L^2} \|\Delta u_n\|_{L^2} \\ &\leq \|u_n\|_{L^\infty} \|\nabla u_n\|_{L^2} \|\Delta u_n\|_{L^2} \leq c \|\nabla u_n\|_{L^2}^{\frac{3}{2}} \|\Delta u_n\|_{L^2}^{\frac{3}{2}} \leq d_\nu \|\nabla u_n\|_{L^2}^6 + \frac{\nu}{2} \|\Delta u_n\|_{L^2}^2, \end{aligned} \quad (6.3)$$

where we used Agmon’s inequality $\|u_n\|_{L^\infty(\mathbb{R}^3)} \leq \|\nabla u_n\|_{L^2(\mathbb{R}^3)}^{\frac{1}{2}} \|\nabla^2 u_n\|_{L^2(\mathbb{R}^3)}^{\frac{1}{2}}$, see (2.37), and Young’s inequality $ab \leq \frac{a^4}{4\lambda^4} + \frac{3}{4}\lambda^{\frac{4}{3}}b^{\frac{4}{3}}$, where we choose λ so that $\frac{3}{4}\lambda^{\frac{4}{3}} = \nu/2$. We obtain

$$\frac{d}{dt} \|\nabla u_n\|_{L^2}^2 + \nu \|\Delta u_n\|_{L^2}^2 \leq d_\nu \|\nabla u_n\|_{L^2}^6.$$

From this we derive

$$\frac{d}{dt} \|\nabla u_n\|_{L^2}^2 \leq d_\nu \|\nabla u_n\|_{L^2}^6 \text{ with } \|\nabla u_n(0)\|_{L^2}^2 = \|\mathbf{P}_n \nabla u_0\|_{L^2}^2. \quad (6.4)$$

Let us consider the ODE

$$\frac{d}{dt}X = d_\nu X^3 \text{ with } X(0) = \|\nabla u_0\|_{L^2}^2.$$

The equation is separable, so the general solution is obtained writing $\frac{dX}{X^3} = d_\nu dt$ and integrating separately, so that

$$-\frac{1}{2X^2} + \frac{1}{2X^2(0)} = d_\nu t \implies X(t) = \frac{X(0)}{\sqrt{1 - 2d_\nu t X^2(0)}} = \frac{\|\nabla u_0\|_{L^2}^2}{\sqrt{1 - 2d_\nu t \|\nabla u_0\|_{L^2}^4}}.$$

We claim that $\|\nabla u_n(t)\|_{L^2}^2 \leq X(t)$ for all n and for all $0 \leq t < (2d_\nu \|\nabla u_0\|_{L^2}^4)^{-1}$. If $X(0) - \|\nabla u_n(0)\|_{L^2}^2 > 0$, then using

$$\frac{d}{dt}(X - \|\nabla u_n\|_{L^2}^2) \geq d_\nu (X - \|\nabla u_n\|_{L^2}^2) (X^2 + X\|\nabla u_n\|_{L^2}^2 + \|\nabla u_n\|_{L^2}^4),$$

we conclude that $X - \|\nabla u_n\|_{L^2}^2 > 0$ since it is increasing. If $X(0) = \|\nabla u_n(0)\|_{L^2}^2$ consider X_ε for $\varepsilon > 0$ the solution with initial datum $X(0) + \varepsilon$. Then, by the above argument we conclude $X_\varepsilon(t) - \|\nabla u_n(t)\|_{L^2}^2 > 0$ for all $0 \leq t < (2d_\nu (\|\nabla u_0\|_{L^2}^2 + \varepsilon))^{-2}$. If by contradiction $X(t_0) - \|\nabla u_n(t_0)\|_{L^2}^2 < 0$ for some $0 < t_0 < (2d_\nu \|\nabla u_0\|_{L^2}^4)^{-1}$ then, using $X_\varepsilon(t_0) \xrightarrow{\varepsilon \rightarrow 0^+} X(t_0)$ and $X_\varepsilon(t_0) - \|\nabla u_n(t_0)\|_{L^2}^2 > 0$ for $\varepsilon > 0$ sufficiently small, we arrive to a contradiction. Hence our claim is true. Notice that the solution at p. 431 [13] of the related Exercise 6.2 [13] is inconclusive.

So there exists a T like in the statement s.t.

$$\|u_n(t)\|_{H^1}^2 + \nu \int_0^t \|u_n(t')\|_{H^2}^2 dt' \leq C_{T, \|u_0\|_{H^1}} \text{ for } t \in [0, T]. \quad (6.5)$$

Recall that we had u_n convergent to u in various ways. By Banach–Alaoglu there exists a subsequence which is $*$ -weakly convergent in $L^\infty([0, T], H^1)$ and is weakly convergent in $L^2([0, T], H^2)$. This and various forms of Fathou lemma, see in [2] Proposition 3.5 for the weak topology and Proposition 3.13 for the $*$ -weak topology, implies that

$$\|u(t)\|_{H^1}^2 + \nu \int_0^t \|u(t')\|_{H^2}^2 dt' \leq C_{T, \|u_0\|_{H^1}} \text{ for } t \in [0, T]. \quad (6.6)$$

We turn to the proof of the energy identity (6.1). We first claim that

$$\operatorname{div}(u \otimes u), \partial_t u \in L^2((0, T), L^2). \quad (6.7)$$

Let us assume this claim. Next, we claim that

$$\int_0^T \langle \partial_t u - \nu \Delta u + \operatorname{div}(u \otimes u), w \rangle dt = 0 \text{ for all } w \in L^2((0, T), H). \quad (6.8)$$

Let us assume also (6.8). Then apply (6.8) for $w = \chi_{[s,t]}u$. Then we get

$$\int_s^t (\langle \partial_t u, u \rangle + \nu \|\nabla u\|_{L^2}^2) dt' = 0$$

where we use $\langle \operatorname{div}(u \otimes u), u \rangle = 0$, from (5.18). Next, we can apply Lemma 5.5 and conclude that $\|u(t)\|_{L^2}^2 \in AC([0, T])$ with $\frac{d}{dt}\|u(t)\|_{L^2}^2 = 2\langle u(t), \dot{u}(t) \rangle$. This yields (6.1).

Let us now prove (6.7). We have

$$\begin{aligned} \|\operatorname{div}(u \otimes u)\|_{L^2((0,T),L^2)} &\lesssim \|\|\nabla u\|_{L^2}\|u\|_{L^\infty}\|_{L^2(0,T)} \leq \|u\|_{L^\infty((0,T),H^1)}\|u\|_{L^2((0,T),L^\infty)} \\ &\lesssim \|u\|_{L^\infty((0,T),H^1)}\|u\|_{L^2((0,T),H^2)} < \infty \end{aligned}$$

using Sobolev's embedding $H^2(\mathbb{R}^3) \hookrightarrow L^\infty(\mathbb{R}^3)$ and (6.6). Next, we apply (5.4) for $\Psi(t, x) = \phi(x) \in C_{c\sigma}^\infty(\mathbb{R}^3, \mathbb{R}^3)$ and obtain

$$\langle u(t), \phi \rangle - \langle u(0), \phi \rangle = \int_0^t (\nu \langle \Delta u(t'), \phi \rangle - \langle \mathbb{P}\operatorname{div}(u \otimes u)(t'), \phi \rangle) dt.$$

This extends to any $\phi \in L^2(\mathbb{R}^3, \mathbb{R}^3)$. Then we can apply Lemma A.29² for $X = L^2(\mathbb{R}^3, \mathbb{R}^3)$, concluding the following, which completes the proof of (6.7):

$$\partial_t u = \nu \Delta u - \mathbb{P}\operatorname{div}(u \otimes u) \text{ in } \mathcal{D}'((0, T), L^2). \quad (6.9)$$

We turn to the proof of (6.8). There exists a sequence of test functions $\Psi_n \rightarrow w$ in $L^2((0, T), H)$, which satisfy

$$\begin{aligned} \langle u(T), \Psi_n(T) \rangle - \langle u_0, \Psi_n(0) \rangle &= \int_0^T (\nu \langle \Delta u(t'), \Psi_n(t') \rangle + \langle u(t'), \partial_t \Psi_n(t') \rangle \\ &\quad - \langle \operatorname{div}(u \otimes u)(t'), \Psi_n(t') \rangle) dt'. \end{aligned}$$

Integration by parts, which can be proved like in [2, Corollary 8.10], yields

$$\langle u(T), \Psi_n(T) \rangle - \langle u_0, \Psi_n(0) \rangle - \int_0^T \langle u(t'), \partial_t \Psi_n(t') \rangle dt' = - \int_0^T \langle \partial_t u, \Psi_n \rangle dt',$$

so that we obtain

$$\int_0^T \langle \partial_t u - \nu \Delta u + \operatorname{div}(u \otimes u), \Psi_n \rangle dt' = 0$$

and for $n \rightarrow \infty$ we obtain (6.8). □

²Recall that Lemma A.29 states that if $u, g \in L^1(I, X)$ are such that

$$\langle u(t_2), f \rangle_{XX^*} - \langle u(t_1), f \rangle_{XX^*} = \int_{t_1}^{t_2} \langle g(s), f \rangle_{XX^*} ds \text{ for any } f \in X^*,$$

with X a Banach space, then $\partial_t u = g$ in $\mathcal{D}'(I, X)$.

Theorem 6.2 (Uniqueness of weak solutions). *Let $u_0 \in V(\mathbb{R}^3)$ and let $u \in L^\infty([0, T], V)$ and $\nabla^2 u \in L^2([0, T], L^2)$ be a solution discussed in the proof of Theorem 6.1. Consider also a weak solution v with initial datum u_0 and satisfying the energy inequality (5.7). Then $u = v$ in $[0, T]$.*

Furthermore, we have $\|\nabla u(t)\|_{L^2} \xrightarrow{t \nearrow T^} \infty$ if the lifespan $T^* = \sup\{T \text{ s.t. } u \in L^\infty([0, T], V)\}$ is $T^* < \infty$.*

Finally, there exists a constant $\varepsilon_\nu > 0$ s.t. if

$$\|\nabla u_0\|_{L^2} \|u_0\|_{L^2} < \varepsilon_\nu \quad (6.10)$$

then the statements in Theorem 6.1 and here are valid for any $T > 0$.

Proof. From (6.8) we have

$$\int_0^T (\langle \partial_t u, v \rangle + \nu \langle \nabla u, \nabla v \rangle + \langle \operatorname{div}(u \otimes u), v \rangle) dt = 0.$$

We claim now that we can treat u as a test function for v , so that

$$\int_0^t (\nu \langle \nabla v, \nabla u \rangle - \langle v, \partial_t u \rangle + \langle \operatorname{div}(v \otimes v), u \rangle) dt' = \|u_0\|_{L^2}^2 - \langle v(t), u(t) \rangle, \quad (6.11)$$

so that adding the two equations we have

$$\int_0^t (2\nu \langle \nabla v, \nabla u \rangle + \langle \operatorname{div}(u \otimes u), v \rangle + \langle \operatorname{div}(v \otimes v), u \rangle) dt' = \|u_0\|_{L^2}^2 - \langle v(t), u(t) \rangle.$$

Let us assume (6.11) and let us continue the proof.

Set $w = v - u$ and substitute in the identities

$$\begin{aligned} 2\nu \langle \nabla v, \nabla u \rangle &= \nu \|\nabla u\|_{L^2}^2 + \nu \|\nabla v\|_{L^2}^2 - \nu \|\nabla w\|_{L^2}^2, \\ \langle v(t), u(t) \rangle &= 2^{-1} \|u(t)\|_{L^2}^2 + 2^{-1} \|v(t)\|_{L^2}^2 - 2^{-1} \|w(t)\|_{L^2}^2, \end{aligned}$$

which are the same as the expansion $(a - b)^2 = a^2 + b^2 - 2ab$, and

$$\langle \operatorname{div}(u \otimes u), v \rangle + \langle \operatorname{div}(v \otimes v), u \rangle = \langle \operatorname{div}(w \otimes w), u \rangle,$$

which follows from

$$\begin{aligned} \langle v^j \partial_j v^k, u^k \rangle + \langle u^j \partial_j u^k, v^k \rangle &= \langle v^j \partial_j v^k, u^k \rangle - \langle u^j \partial_j v^k, u^k \rangle = \langle w^j \partial_j v^k, u^k \rangle \\ &= \langle w^j \partial_j w^k, u^k \rangle + \langle w^j \partial_j u^k, u^k \rangle = \langle w^j \partial_j w^k, u^k \rangle = \langle \operatorname{div}(w \otimes w), u \rangle. \end{aligned}$$

Then rearranging, we obtain the equality

$$\begin{aligned} 2^{-1} \|w(t)\|_{L^2}^2 + \int_0^t (\nu \|\nabla w\|^2 - \langle \operatorname{div}(w \otimes w), u \rangle) dt' \\ = 2^{-1} \|u(t)\|_{L^2}^2 + \int_0^t \nu \|\nabla u\|^2 - 2^{-1} \|u_0\|_{L^2}^2 \end{aligned} \quad (6.12)$$

$$+ 2^{-1} \|v(t)\|_{L^2}^2 + \int_0^t \nu \|\nabla v\|^2 - 2^{-1} \|v_0\|_{L^2}^2 \leq 0, \quad (6.13)$$

where the inequality follows from the Energy identity (6.1) and the Energy inequality (5.7). Then

$$\begin{aligned} \|w(t)\|_{L^2}^2 + 2\nu \int_0^t \|\nabla w\|^2 dt' &\leq 2 \int_0^t \langle \operatorname{div}(w \otimes w), u \rangle dt' \\ &\leq 2 \int_0^t \|u\|_{L^\infty} \|\nabla w\|_{L^2} \|w\|_{L^2} dt' \leq \frac{1}{\nu} \int_0^t \|u\|_{H^2}^2 \|w\|_{L^2}^2 dt' + \nu \int_0^t \|\nabla w\|_{L^2}^2 dt'. \end{aligned}$$

Absorbing, as usual, the very last term in the 2nd term of the l.h.s., we obtain

$$\|w(t)\|_{L^2}^2 \leq \frac{1}{\nu} \int_0^t \|u\|_{H^2}^2 \|w\|_{L^2}^2 dt'$$

which, by Gronwall, yields

$$\|w(t)\|_{L^2}^2 \leq e^{\frac{1}{\nu} \int_0^t \|u\|_{H^2}^2 dt'} \|w(0)\|_{L^2}^2 = 0.$$

Next, suppose the T^* in the statement of the lemma is $T^* < \infty$. If there is no blow up, there exists $C > 0$ and a $t' < T^*$ with $\|\nabla u(t')\|_{L^2}^4 < C$ and $T^* - t' < c_\nu/C$ (that because there are a C , a sequence $t_n \xrightarrow{n \nearrow \infty} T^*$ with $\|\nabla u(t_n)\|_{L^2}^4 < C$). In particular, for \mathbf{v} a solution as of Theorem 6.1 with initial value $\mathbf{v}(t') = u(t')$, we have $\mathbf{v} \in L^\infty((t', t' + c_\nu/C), V)$. But by the uniqueness $\mathbf{v} = u$ in $[t', T^*)$, so u extends into a solution in $u \in L^\infty([0, t' + c_\nu/C], V)$, $u \in L^2([0, t' + c_\nu/C], H^2)$, yielding a contradiction. Therefore, we must have $\|\nabla u(t)\|_{L^2} \xrightarrow{t \nearrow T^*} \infty$ if $T^* < \infty$.

We now need to address formula (6.11). We have $u \in H^1((0, t), L^2)$ for $t \in (0, T)$, see (6.7), $u \in L^\infty((0, t), H^1)$ and $u \in L^2((0, t), H^2)$, see (6.6), and we can consider a sequence of test functions $\Psi_n \xrightarrow{\rightarrow \infty} u$ in all these spaces. Starting from

$$\int_0^t (\nu \langle \nabla v, \nabla \Psi_n \rangle - \langle v, \partial_t \Psi_n \rangle + \langle \operatorname{div}(v \otimes v), \Psi_n \rangle) dt' = \langle u_0, \Psi_n(0) \rangle - \langle v(t), \Psi_n(t) \rangle,$$

for $n \nearrow \infty$ it is easy to see that all the terms linear in v converge to the corresponding ones in (6.11). Also the nonlinear term converges, as a consequence of

$$\begin{aligned} \int_0^t \langle \operatorname{div}(u \otimes u), \Psi_n - u \rangle_{L^2} dt' &\leq C \int_0^t \|\nabla u\|_{L^2} \|u\|_{L^2} \|\Psi_n - u\|_{L^\infty} dt' \\ &\leq C \|\nabla u\|_{L^2((0, t), L^2)} \|u\|_{L^\infty((0, t), L^2)} \|\Psi_n - u\|_{L^2((0, t), H^2)} \end{aligned}$$

by Sobolev's embedding $H^2(\mathbb{R}^3) \hookrightarrow L^\infty(\mathbb{R}^3)$.

We finally turn to the proof of the last statement of the theorem, that is the global regularity for small initial data, that is $T^* = \infty$. From (6.8) we obtain for any $T \in (0, T^*)$

$$\int_0^T \langle \partial_t u - \nu \Delta u + \operatorname{div}(u \otimes u), -\Delta u \rangle dt = 0$$

that is

$$\int_0^T (\langle \partial_t \nabla u, \nabla u \rangle + \nu \|\Delta u\|_{L^2}^2 - \langle \operatorname{div}(u \otimes u), \Delta u \rangle) dt = 0$$

Now, notice that $\nabla u \in L^2([0, T], H^1)$ and $\partial_t \nabla u \in L^2([0, T], H^{-1})$. Then we can apply Lemma 5.5 obtaining that $\|\nabla u\|_{L^2}^2 \in AC([0, T])$ with $\frac{d}{dt} \|\nabla u\|_{L^2}^2 = 2 \langle \partial_t \nabla u, \nabla u \rangle$. Proceeding as in (6.3), adjusting Young's inequality $ab \leq \frac{a^8}{8} + \frac{7b^7}{8}$ and using interpolation to get the last line, we have

$$\begin{aligned} \frac{d}{dt} \|\nabla u\|_{L^2}^2 + 2\nu \|\Delta u\|_{L^2}^2 &= 2 \langle \operatorname{div}(u \otimes u), \Delta u \rangle \leq c \|\nabla u\|_{L^2}^{\frac{3}{2}} \|\Delta u\|_{L^2}^{\frac{3}{2}} = c \|\nabla u\|_{L^2}^{\frac{1}{2}} \|\nabla u\|_{L^2} \|\Delta u\|_{L^2}^{\frac{3}{2}} \\ &\leq c \|u\|_{L^2}^{\frac{1}{4}} \|\nabla u\|_{L^2} \|\Delta u\|_{L^2}^{\frac{7}{4}} \leq C_\nu \|u\|_{L^2}^2 \|\nabla u\|_{L^2}^8 + \nu \|\Delta u\|_{L^2}^2 \\ &\leq C_\nu \|u\|_{L^2}^4 \|\nabla u\|_{L^2}^4 \|\Delta u\|_{L^2}^2 + \nu \|\Delta u\|_{L^2}^2, \end{aligned}$$

so that

$$\frac{d}{dt} \|\nabla u\|_{L^2}^2 \leq \|\Delta u\|_{L^2}^2 (C_\nu \|u\|_{L^2}^4 \|\nabla u\|_{L^2}^4 - \nu).$$

Since from (6.1) we have $\frac{d}{dt} \|u\|_{L^2}^2 = -2\nu \|\nabla u\|_{L^2}^2$, $\|u\|_{L^2}$ is decreasing. We have, using Leibnitz rule for products of AC functions, see Corollary 8.10 [2],

$$\frac{d}{dt} (\|u\|_{L^2}^2 \|\nabla u\|_{L^2}^2) \leq \|u\|_{L^2}^2 \|\Delta u\|_{L^2}^2 (C_\nu \|u\|_{L^2}^4 \|\nabla u\|_{L^2}^4 - \nu) - 2\nu \|\nabla u\|_{L^2}^4.$$

If $\|u\|_{L^2}^4 \|\nabla u\|_{L^2}^4 \leq \nu C_\nu^{-1}$ then $\|u\|_{L^2}^2 \|\nabla u\|_{L^2}^2$ is strictly decreasing in any interval $[0, T]$ with $T \in (0, T^*)$, and so also in $[0, T^*)$. Then

$$\frac{d}{dt} \|\nabla u\|_{L^2}^2 + \nu \|\Delta u\|_{L^2}^2 \leq C_\nu \|u_0\|_{L^2}^4 \|\nabla u_0\|_{L^2}^4 \|\Delta u\|_{L^2}^2 \leq \varepsilon_\nu^4 \|\Delta u\|_{L^2}^2$$

so that, if $\varepsilon_\nu^4 \leq \nu/2$, we get

$$\frac{d}{dt} \|\nabla u\|_{L^2}^2 + \frac{\nu}{2} \|\Delta u\|_{L^2}^2 \leq 0 \text{ in } [0, T^*)$$

and so also

$$\|\nabla u(t)\|_{L^2}^2 + \frac{\nu}{2} \int_0^t \|\Delta u\|_{L^2}^2 dt' \leq \|\nabla u_0\|_{L^2}^2 \text{ in } [0, T^*) .$$

This obviously contradicts the blow up $\|\nabla u(t)\|_{L^2} \xrightarrow{t \nearrow T^*} \infty$ if $T^* < \infty$, and hence $T^* = \infty$. This completes the proof of the global existence of small solutions. \square

Theorem 6.3 (Global existence of regular solutions 2d). *For any $u_0 \in V(\mathbb{R}^2) (= H^1(\mathbb{R}^2, \mathbb{R}^2) \cap H(\mathbb{R}^2))$ we have $u \in L^\infty([0, T], V)$ and $\nabla^2 u \in L^2([0, T], L^2)$ for all $T > 0$.*

Proof. The fact that locally for some $T > 0$ we have $u \in L^\infty([0, T], V)$ and $\nabla^2 u \in L^2([0, T], L^2)$ and that we have $\|\nabla u(t)\|_{L^2} \xrightarrow{t \nearrow T^*} \infty$ whenever the lifespan $T^* = \sup\{T \text{ s.t. } u \in L^\infty([0, T], V)\}$ is $T^* < \infty$, can be proved as above and is skipped here. So we need to prove $T^* = \infty$ by showing there cannot be finite time blow up. Now we consider

$$\begin{aligned} \frac{d}{dt} \|\nabla u\|_{L^2}^2 + 2\nu \|\Delta u\|_{L^2}^2 &= 2 \langle \operatorname{div}(u \otimes u), \Delta u \rangle \lesssim \|u\|_{L^4} \|\nabla u\|_{L^4} \|\Delta u\|_{L^2} \\ &\lesssim \|u\|_{\dot{H}^{\frac{1}{2}}} \|\nabla u\|_{\dot{H}^{\frac{1}{2}}} \|\Delta u\|_{L^2} \leq (\|u\|_{L^2} \|\nabla u\|_{L^2})^{\frac{1}{2}} (\|\nabla u\|_{L^2} \|\nabla^2 u\|_{L^2})^{\frac{1}{2}} \|\Delta u\|_{L^2} \\ &\lesssim \|u\|_{L^2}^{\frac{1}{2}} \|\nabla u\|_{L^2} \|\Delta u\|_{L^2}^{\frac{3}{2}} \leq c_\nu \|u\|_{L^2}^2 \|\nabla u\|_{L^2}^4 + \nu \|\Delta u\|_{L^2}^2, \end{aligned}$$

where we used Young's inequality $ab \leq \frac{a^4}{4\lambda^4} + \frac{3\lambda^{\frac{4}{3}} b^{\frac{4}{3}}}{4}$ adjusting λ . By absorbing the last term in the 2nd term of the l.h.s. we obtain

$$\frac{d}{dt} \|\nabla u\|_{L^2}^2 + \nu \|\Delta u\|_{L^2}^2 \leq c_\nu \|u\|_{L^2}^2 \|\nabla u\|_{L^2}^2 \|\nabla u\|_{L^2}^2 \leq c_\nu \|u\|_{L^2}^2 \|\nabla u\|_{L^2}^2 \left(\|\nabla u\|_{L^2}^2 + \nu \int_0^t \|\Delta u(s)\|_{L^2}^2 ds \right).$$

From Gronwall's inequality we obtain

$$\|\nabla u\|_{L^2}^2 + \nu \int_0^t \|\Delta u(s)\|_{L^2}^2 ds \leq e^{c_\nu \|u\|_{L^\infty(0, \infty), L^2}^2 \int_0^t \|\nabla u\|_{L^2}^2 ds} \|\nabla u_0\|_{L^2}^2$$

which yields the desired result. \square

Theorem 6.4 (Higher spacial regularity). *Let $u \in L^\infty([0, T], V)$ with $\nabla^2 u \in L^2([0, T], L^2)$ be a solution like in Theorem 6.1 or Theorem 6.3. Suppose that $u_0 \in V \cap H^m(\mathbb{R}^d)$ with $m \geq 2$. Then $u \in L^\infty([0, T], H^m(\mathbb{R}^d))$ and $u \in L^2([0, T], H^{m+1}(\mathbb{R}^d))$.*

Proof. We can go back to the framework of Theorem 6.1 with the sequence of regularizations. We claim that we can generalize (6.5) into

$$\|u_n(t)\|_{H^k}^2 + \nu \int_0^t \|u_n(t')\|_{H^{k+1}}^2 dt' \leq C_{k, T, \|u_0\|_{H^k}} \text{ in } [0, T] \text{ for all } 1 \leq k \leq m. \quad (6.14)$$

We have already case $k = 1$. Suppose $2 \leq k \leq m$ and we have case $k - 1$. We apply $\langle \cdot, u_n \rangle_{H^k}$ to

$$\dot{u}_n + \mathbf{P}_n \mathbb{P} \operatorname{div}(u_n \otimes u_n) - \nu \Delta u_n = 0 \quad , \quad u_n(0, x) = \mathbf{P}_n u_0(x).$$

and obtain

$$\begin{aligned} 2^{-1} \frac{d}{dt} \|u_n\|_{H^k} + \nu \|\nabla u_n\|_{H^k}^2 &= - \langle \mathbf{P}_n \mathbb{P} \operatorname{div}(u_n \otimes u_n), u_n \rangle_{H^k} \leq \|\operatorname{div}(u_n \otimes u_n)\|_{H^k} \|u_n\|_{H^k} \\ &\leq \|u_n\|_{H^k} \|\nabla u_n\|_{H^k} \|u_n\|_{H^k} \leq \frac{1}{2\nu} \|u_n\|_{H^k}^4 + \frac{\nu}{2} \|\nabla u_n\|_{H^k}^2, \end{aligned}$$

where we used the fact that, since $k > d/2$ for $d = 2, 3$, H^k is an algebra. So

$$\frac{d}{dt} \|u_n\|_{H^k} + \nu \|\nabla u_n\|_{H^k}^2 \leq \frac{1}{\nu} \|u_n\|_{H^k}^2 \|u_n\|_{H^k}^2.$$

From this and Gronwall we read

$$\|u_n(t)\|_{H^k} + \nu \int_0^t \|\nabla u_n\|_{H^k}^2 ds \leq e^{\frac{1}{\nu} \int_0^t \|u_n\|_{H^k}^2 ds} \|u_0\|_{H^k}^2 \leq C_{k,T} \|u_0\|_{H^k}^2 \text{ in } [0, T].$$

Recall that we had u_n convergent to u in various ways. We can take a subsequence, which by Banach–Alaoglu is $*$ -weakly convergent in $L^\infty([0, T], H^k)$ and is weakly convergent in $L^2([0, T], H^{k+1})$. This implies that

$$\|u(t)\|_{H^k}^2 + \nu \int_0^t \|u(t')\|_{H^{k+1}}^2 dt' \leq C_{k,T} \|u_0\|_{H^k}^2 \text{ in } [0, T] \text{ for all } 1 \leq k \leq m. \quad (6.15)$$

□

Corollary 6.5. *Let $u \in L^\infty([0, T], V)$ with $\nabla^2 u \in L^2([0, T], L^2)$ be a solution like in Theorem 6.1 or Theorem 6.3. Then, for any m we have $u \in C^\infty((0, T], H^m(\mathbb{R}^d))$.*

Proof. We have seen in Theorem 6.1 that u solves distributionally the NS equation, see (6.9) and that $\partial_t u \in L^2((0, T), L^2)$, see (6.7), and we know $u \in L^2([0, T], H^2)$. Obviously $u \in H^1((0, T), L^2) \cap L^2([0, T], H^2)$ is equivalent to $\langle \sqrt{-\Delta} \rangle u \in L^2([0, T], H^1) \cap H^1([0, T], H^{-1})$. The latter, by Lemma 5.5, implies $\langle \sqrt{-\Delta} \rangle u \in C^0([0, T], L^2)$. Equivalent conclusion is $u \in C^0([0, T], H^1)$. Then,

$$\begin{aligned} &\text{for any } t_n \in (0, T), u \text{ is the unique solution in } L^\infty([t_n, T], V) \cap L^2([t_n, T], H^2) \\ &\text{of NS with initial values } u(t_n). \end{aligned} \quad (6.16)$$

Now, for any $\epsilon > 0$ there exists a $t_2 \in (0, \epsilon)$ s.t. $u(t_2) \in H^2$ and applying (6.16) and Theorem 6.4, we conclude $u \in L^\infty([t_2, T], H^2(\mathbb{R}^d))$ and $u \in L^2([t_2, T], H^3(\mathbb{R}^d))$. So there exists $t_3 \in (t_2, \epsilon)$ s.t. $u(t_3) \in H^3$, and proceeding by induction we get that for any n there exists $t_n \in (0, \epsilon)$ s.t. $u(t_n) \in H^n$, so that $u \in L^\infty([t_n, T], H^n(\mathbb{R}^d)) \cap L^2([t_n, T], H^{n+1}(\mathbb{R}^d))$. Recalling $\partial_t u = \nu \Delta u - \mathbb{P} \operatorname{div}(u \otimes u)$ in $\mathcal{D}'((0, T), L^2)$, from $u \in L^\infty([t_{m+2}, T], H^{m+2}(\mathbb{R}^d))$ we derive $\partial_t u \in L^\infty([t_{m+2}, T], H^m)$ and so $u \in C^0([t_{m+2}, T], H^m)$. So we conclude $u \in C^0([\epsilon, T], H^m)$ for any m and, by the arbitrariness of $\epsilon > 0$, $u \in C^0((0, T], H^m)$ for any m . Notice that this implies $\partial_t u = \nu \Delta u - \mathbb{P} \operatorname{div}(u \otimes u)$ in $C^0((0, T], H^m)$ for any m . In other words $u \in C^1((0, T], H^m)$ for any m . It is easy to conclude, proceeding by induction, that we have $u \in C^\infty((0, T], H^m)$ and that for all j

$$\partial_t^j u = \nu \Delta \partial_t^{j-1} u - \mathbb{P} \sum_{k=0}^{j-1} \binom{j-1}{k} \operatorname{div}(\partial_t^k u \otimes \partial_t^{j-1-k} u).$$

□

Notice that the proof of Lemma 7.4 [13] is incomplete, because it is based on the last displayed formula of p. 152 [13], where the uniformity in n is left untreated both in the text and in the exercises, and seems non trivial.

6.1 Structure of the singular set

We consider a digression on the singular set of Leray–Hopf solutions in $d = 3$.

Lemma 6.6 (Compactness of Singular Set). *Given a Leray–Hopf solution u there exists a $T_* \geq 0$ such that $u \in C^\infty((T_*, +\infty) \times \mathbb{R}^3, \mathbb{R}^3)$.*

Proof. Since $u \in L^\infty(\mathbb{R}_+, L^2)$ and $\nabla u \in L^2(\mathbb{R}_+, L^2)$, we know that there is a $T^* > 0$ s.t. $\|\nabla u(T^*)\|_{L^2} \|u(T^*)\|_{L^2} < \varepsilon_\nu$, with $\varepsilon_\nu > 0$ the constant in (6.10). From Remark 5.2 we know that u is a weak solution of the NS in $[T^*, \infty)$ with initial value $u(T^*) \in V$. By the smallness condition (6.10) in Theorem 6.1 we know that there exists a solution $v \in L^\infty([T^*, \infty), V)$ and $\nabla^2 v \in L^2([T^*, \infty), L^2)$ of the NS with initial value $u(T^*) \in V$. Notice that, as a Leray–Hopf solution, see Remark 5.16, in particular u satisfies the energy inequality

$$\|u(t)\|_{L^2(\mathbb{R}^d)}^2 + 2\nu \int_s^t \|\nabla u(t')\|_{L^2(\mathbb{R}^d)}^2 dt' \leq \|u(T^*)\|_{L^2(\mathbb{R}^d)}^2 \text{ for any } T^* < t.$$

By the Uniqueness theorem of weak solutions 6.2, we know that $u = v$ in $[T^*, \infty)$. Finally, from Corollary 6.5 we know $u \in C^\infty((T_*, +\infty) \times \mathbb{R}^3, \mathbb{R}^3)$. □

Definition 6.7. Consider a Leray–Hopf solution u . We say that a time $t_0 \geq 0$ is regular if there exists a neighborhood I of t_0 in $[0, \infty)$ with $\nabla u \in L^\infty(I, L^2)$. If t_0 is not regular, it is called singular. We denote by \mathcal{R} the set of regular times, and by \mathcal{T} the set of singular times.

It is quite obvious that \mathcal{R} is open in $[0, \infty)$, and hence that \mathcal{T} is closed. From Lemma 6.6 we know that \mathcal{T} is compact.

In this section we consider two simple results about \mathcal{T} , one about box–counting dimension and the other about Hausdorff measure.

Let us start with the box–counting dimension.

Definition 6.8. Consider a compact subspace X of \mathbb{R}^d and for any $\epsilon > 0$ denote by $N(X, \epsilon)$ the smallest number of open balls of radius ϵ needed to cover X . Then the (upper) box–counting dimension of X is

$$\dim_B(X) := \limsup_{\epsilon \rightarrow 0^+} (-\log_\epsilon N(X, \epsilon)) = \limsup_{\epsilon \rightarrow 0^+} \frac{\log N(X, \epsilon)}{-\log \epsilon}. \quad (6.17)$$

Lemma 6.9. *For a compact subspace X of \mathbb{R}^d we have $\dim_B(X) = \dim'_B(X)$, where*

$$\dim'_B(X) := \limsup_{\epsilon \rightarrow 0^+} \frac{\log M(X, \epsilon)}{-\log \epsilon}$$

with $M(X, \epsilon)$ the largest number of disjoint open balls of radius ϵ with centers at points of X .

Proof. First of all, we have $M(X, \epsilon) \leq N(X, \epsilon)$ (so that $\dim_B(X) \geq \dim'_B(X)$). Indeed, let us consider a family of disjoint balls $\{D(x_j, \epsilon)\}_{j=1}^{M(X, \epsilon)}$, with $x_j \in X$. If $\{D(y_k, \epsilon)\}_{j=1}^{N(X, \epsilon)}$ is a cover of X , it is also a cover of $\{x_1, \dots, x_{M(X, \epsilon)}\}$. It is not possible to have a $D(y_k, \epsilon)$ which contains two distinct $x_i \neq x_j$, because this would imply $|x_i - x_j| < 2\epsilon$, while we know that $|x_i - x_j| \geq 2\epsilon$. So $M(X, \epsilon) \leq N(X, \epsilon)$.

Next, we have $M(X, \epsilon/3) \geq N(X, \epsilon)$. This follows by the proof of Vitali's lemma, Theorem 2.15. In fact, given a cover $\{D(x_j, \epsilon/3)\}$ of X , we know that we can extract a family of disjoint balls, which we will label as $\{D(x_j, \epsilon/3)\}_{j=1}^L$, such that $\{D(x_j, \epsilon)\}_{j=1}^L$ is a cover of X . Then $M(X, \epsilon/3) \geq L \geq N(X, \epsilon)$. So

$$\begin{aligned} \dim'_B(X) &\leq \dim_B(X) \leq \limsup_{\epsilon \rightarrow 0^+} \frac{\log M(X, \epsilon/3)}{-\log \epsilon} = \limsup_{\epsilon \rightarrow 0^+} \frac{\log M(X, \epsilon/3)}{-\log \epsilon/3} \frac{-\log \epsilon/3}{-\log \epsilon/3 - \log 3} \\ &= \dim'_B(X). \end{aligned}$$

□

Example 6.10. 1. $\dim_B([0, 1]^d) = d$, $\dim_B([0, 1]^j \times \{0\}^{d-j}) = j$.

2. We have $\dim_B S_k = \frac{1}{k+1}$ for $S_k = \{n^{-k} : n \in \mathbb{N}\}$, $k > 0$, see [13].

3. For C the usual Cantor ternary set, we have $\dim_B(C) = \frac{\log(2)}{\log(3)}$.

Lemma 6.11. *Let $K(\epsilon)$ be either $M(X, \epsilon)$ or $N(X, \epsilon)$. Then*

1. *if $d' \in (0, \dim_B(X))$ there is a sequence $\epsilon_j \rightarrow 0$ s.t. $K(\epsilon_j) \geq \epsilon_j^{-d'}$ while*

2. *if $d'' > \dim_B(X)$ there is $\epsilon_0 > 0$ s.t. $K(\epsilon) \leq \epsilon^{-d''}$ for all $\epsilon \in (0, \epsilon_0)$.*

Proof. By the properties of \limsup there exists a sequence $\epsilon_j \rightarrow 0$ s.t. $-\log_{\epsilon_j} K(\epsilon_j) \rightarrow \dim_B(X)$. So, if $d' < \dim_B(X)$, we have $\log_{\epsilon_j} K(\epsilon_j) < -d'$, that is $K(\epsilon_j) > \epsilon_j^{-d'}$ for $j \gg 1$.

Let now $d'' > \dim_B(X)$. Then we claim $K(\epsilon) \leq \epsilon^{-d''}$ for all $\epsilon \in (0, \epsilon_0)$ for an appropriate $\epsilon_0 > 0$. If this is false, there exists a sequence $\epsilon_j \rightarrow 0$ s.t. $K(\epsilon_j) > \epsilon_j^{-d''}$. Then $\frac{\log K(\epsilon_j)}{-\log \epsilon_j} > d''$.

But then $\dim_B(X) = \limsup_{\epsilon \rightarrow 0^+} \frac{\log K(\epsilon)}{-\log \epsilon} \geq \liminf_j \frac{\log K(\epsilon_j)}{-\log \epsilon_j} \geq d'' > \dim_B(X)$.

□

Now we have the following result.

Proposition 6.12. *Given a Leray–Hopf solution u of NS in $d = 3$, then $\dim_B(\mathcal{T}) \leq 1/2$.*

Proof. Fix $\epsilon > 0$ and let us consider a family of disjoint 1–dimensional balls $\{D(t_j, \epsilon)\}_{j=1}^{M(\mathcal{T}, \epsilon)}$, with $t_j \in \mathcal{T}$, with $t_1 < \dots < t_{M(\mathcal{T}, \epsilon)}$. For c_ν the constant in Theorem 6.1, we claim that

$$t_j - t \geq c_\nu \|\nabla u(t)\|_{L^2}^{-4} \text{ for } t \in (t_j - \epsilon, t_j), \quad (6.18)$$

where we set $\|\nabla u(t)\|_{L^2} = \infty$ in the 0 measure set of points t where $u(t) \notin H^1$. Notice that for $u(t) \notin H^1$, (6.18) is obviously true. To prove (6.18) observe that if there exists a t for

which (6.18) is false, then we would have $t_j - t < c_\nu \|\nabla u(t)\|_{L^2}^{-4}$, which automatically implies that $\|\nabla u(t)\|_{L^2} < \infty$ and $u(t) \in H^1$. But then, by Theorem 6.1, there exists a solution $v \in L^\infty([t, t+T], H^1)$ to the NS with $v(t) = u(t)$ and with $T > c_\nu \|\nabla u(t)\|_{L^2}^{-4} > t_j - t$. This means that $t_j \in (t, t+T)$. But since u is a Leray–Hopf solution, by Theorem 6.2 we have $u = v$ in $[t, t+T)$. But then we get a contradiction to $t_j \in \mathcal{T}$.

From (6.18) we obtain $\|\nabla u(t)\|_{L^2}^2 \geq \frac{\sqrt{c_\nu}}{\sqrt{t_j - t}}$ in $(t_j - \epsilon, t_j)$. For T sufficiently large, such that u is smooth in (T, ∞) , using the energy inequality

$$\begin{aligned} \|u_0\|_{L^2(\mathbb{R}^d)}^2 &\geq 2\nu \int_0^T \|\nabla u(t)\|_{L^2(\mathbb{R}^3)}^2 dt \geq 2\nu \sum_{j=1}^{M(\mathcal{T}, \epsilon)} \int_{t_j - \epsilon}^{t_j} \|\nabla u(t)\|_{L^2(\mathbb{R}^3)}^2 dt \\ &\geq 2\nu \sqrt{c_\nu} \sum_{j=1}^{M(\mathcal{T}, \epsilon)} \int_{t_j - \epsilon}^{t_j} \frac{1}{\sqrt{t_j - t}} dt = 4\nu \sqrt{c_\nu} M(\mathcal{T}, \epsilon) \sqrt{\epsilon}. \end{aligned}$$

So $M(\mathcal{T}, \epsilon) < \frac{\|u_0\|_{L^2(\mathbb{R}^d)}^2}{4\nu \sqrt{c_\nu}} \epsilon^{-\frac{1}{2}}$ which, implies

$$\dim_B(\mathcal{T}) = \limsup_{\epsilon \rightarrow 0^+} \frac{\log M(\mathcal{T}, \epsilon)}{-\log \epsilon} \leq \lim_{\epsilon \rightarrow 0^+} \frac{\log \left(\frac{\|u_0\|_{L^2(\mathbb{R}^d)}^2}{4\nu \sqrt{c_\nu}} \epsilon^{-\frac{1}{2}} \right)}{-\log \epsilon} = \frac{1}{2}.$$

□

Definition 6.13. Given a subset $X \subset \mathbb{R}^d$ set for $s > 0$ and $\delta > 0$

$$\mu_{s, \delta}(X) = \inf \left\{ \sum_{j=1}^{\infty} (\text{diam } (U_j))^s : \{U_j\}_{j=1}^{\infty} \text{ is an open cover of } X \text{ with } \text{diam } (U_j) \leq \delta \text{ for all } j \right\}$$

Notice that $\mu_{s, \delta}(X)$ is decreasing in δ . Then we call s -dimensional Hausdorff measure of X the number

$$\mathcal{H}^s(X) = \lim_{\delta \rightarrow 0^+} \mu_{s, \delta}(X).$$

The Hausdorff measure of X is

$$\dim_H(X) = \inf\{s > 0 : \mathcal{H}^s(X) = 0\}.$$

Remark 6.14. Notice that $\mu_{s, \delta}(X) = \mu'_{s, \delta}(X)$ if we set

$$\begin{aligned} \mu'_{s, \delta}(X) = \inf \left\{ \sum_{j=1}^{\infty} (\text{diam } (U_j))^s : \{U_j\}_{j=1}^{\infty} \text{ is an open cover of } X \right. \\ \left. \text{with } \text{diam } (U_j) \leq \delta \text{ for all } j \text{ and all the } U_j \text{ are convex} \right\}. \end{aligned}$$

Indeed, any open set is contained in an open convex set with the same diameter.

Lemma 6.15. *We have $\dim_H(X) \leq \dim_B(X)$.*

Proof. Let $d = \dim_B(X)$ and $s > d$. Let $s > z > d$. Then, by Lemma 6.11 there is $\epsilon_0 > 0$ s.t. $N(X, \epsilon) \leq \epsilon^{-z}$ for all $\epsilon \in (0, \epsilon_0)$. Since we can cover X with $N(X, \epsilon)$ balls of radius ϵ , we have

$$\sum_{j=1}^{N(X, \epsilon)} (2\epsilon)^s = 2^s N(X, \epsilon) \epsilon^s \leq 2^s \epsilon^{s-z} \xrightarrow{\epsilon \rightarrow 0^+} 0$$

$\implies \mathcal{H}^s(X) = 0$. This implies $\dim_H(X) := \inf\{s > 0 : \mathcal{H}^s(X) = 0\} \leq \dim_B(X)$.

Lemma 6.16 (Isodiametric Inequality). *The Lebesgue measure of an open convex set in \mathbb{R}^d of diameter D is at most the volume $c_d D^d$ of the ball of radius $D/2$.*

See [7, Sect. 2.2]. □

Theorem 6.17. *In \mathbb{R}^d , for \mathcal{L}^d the Lebesgue measure, $\mathcal{L}^d = c_d \mathcal{H}^d$.*

Proof. Here we will only prove $\mathcal{L}^d(K) \leq c_d \mathcal{H}^d(K)$ for any $K \subset \subset \mathbb{R}^d$. Given $\epsilon > 0$, we can cover $K \subseteq \cup_{j=1}^{\infty} U_j$ with U_j open convex sets and with $\sum_{j=1}^{\infty} (\text{diam } (U_j))^d \leq \mathcal{H}^d(K) + \epsilon$. Then

$$|K| \leq \sum_{j=1}^{\infty} |U_j| \leq c_d \sum_{j=1}^{\infty} (\text{diam } (U_j))^d \leq c_d (\mathcal{H}^d(K) + \epsilon). \text{ This implies } \mathcal{L}^d(K) \leq c_d \mathcal{H}^d(K).$$

Proposition 6.18. *Given a Leray–Hopf solution u of NS in $d = 3$, then $\mathcal{H}^{1/2}(\mathcal{T}) = 0$.*

Proof. Since $\mathcal{H}^1(\mathcal{T}) = 0$, we can cover \mathcal{T} by a finite or a numerable family of disjoint intervals $\{[t_k, t_k + \epsilon_k]\}_{k \in \mathbb{N}}$ with $\sum \epsilon_k < \delta$ for any preassigned $\delta > 0$. Possibly picking $\epsilon_k = 0$, we can assume that $t_k + \epsilon_k \in \mathcal{T}$. Indeed, if $[t_k, t_k + \epsilon_k] \cap \mathcal{T} = \emptyset$ we can discard the interval, while if $\exists t'_k \in [t_k, t_k + \epsilon_k] \cap \mathcal{T}$, then we can replace $[t_k, t_k + \epsilon_k]$ with $[t_k, t'_k]$. By the discussion in Proposition 6.12 we have $\|\nabla u(t)\|_{L^2}^2 \geq \frac{\sqrt{c_\nu}}{\sqrt{t_k + \epsilon_k - t}}$ in $[t_k, t_k + \epsilon_k]$. Then

$$\int_{\cup_k [t_k, t_k + \epsilon_k]} \|\nabla u(t)\|_{L^2}^2 dt \geq \sqrt{c_\nu} \sum_{k=1}^{\infty} \int_{t_k}^{t_k + \epsilon_k} \frac{dt}{\sqrt{t_k + \epsilon_k - t}} = 2\sqrt{c_\nu} \sum_{k=1}^{\infty} \sqrt{\epsilon_k}.$$

But, by absolute integrability, the l.h.s. can be made smaller than any given $\epsilon > 0$. Then $\mathcal{H}^{1/2}(\mathcal{T}) = 0$. □

6.2 Serrin's condition

We have the following theorem.

Theorem 6.19. *Let u be a solution in $d = 3$ of the type in Leray's Theorem 5.3 and suppose that*

$$u \in L^r((0, T), L^s(\mathbb{R}^3)) \text{ where } \frac{2}{r} + \frac{3}{s} = 1, \text{ with } r \geq 2 \text{ and } s \geq 3. \quad (6.19)$$

Then $u \in C^\infty((0, T] \times \mathbb{R}^3, \mathbb{R}^3)$ and u is in $[\epsilon, T]$ for any $\epsilon \in (0, T)$ also a solution in the sense of Theorem 6.1. Furthermore, if v is another solution of the type in Leray's Theorem 5.3 satisfying Serrin's condition, for possibly different exponents (still with $s > 3$) in $(0, T)$ and with the same initial value, we have $u = v$ in $[0, T]$.

Remark 6.20. The case $L^\infty((0, T), L^3(\mathbb{R}^3))$ is relatively recent [6] and will not be considered here.

Proof. Let us start by assuming $u_0 \in V$. Then we know that there exists $T^* > 0$ s.t. $u \in L^\infty([0, T_1], V)$ if $T_1 \in (0, T^*)$ and that $u \in C^\infty((0, T^*) \times \mathbb{R}^3, \mathbb{R}^3)$. So for the regularity part of the lemma, it is enough to show that $T < T^*$. Suppose the opposite, that is $\infty > T \geq T^*$. Then, recall that there is the blow up $\|\nabla u(t)\|_{L^2} \xrightarrow{t \nearrow T^*} \infty$.

We have in $[0, T^*)$, by (6.8),

$$\frac{d}{dt} \|\nabla u\|_{L^2}^2 + 2\nu \|\Delta u\|_{L^2}^2 = 2 \langle \operatorname{div}(u \otimes u), \Delta u \rangle \leq c \|u\|_{L^s} \|\nabla u\|_{L^{\frac{2s}{s-2}}} \|\Delta u\|_{L^2},$$

where $\frac{1}{s} + \frac{s-2}{2s} + \frac{1}{2} = 1$ and where $s > 3$ implies $\frac{2s}{s-2} \in [2, 6)$. Then, by Hölder's (we use $\frac{s-2}{2s} = \frac{s-3}{3} + \frac{3}{6}$ and $\|f\|_{L^{\frac{2s}{s-2}}} \leq \|f\|_{L^{\frac{s-3}{s}}} \|f\|_{L^{\frac{3}{s}}}$) and Young's (using $1 = \frac{s-3}{2s} + \frac{s+3}{2s}$) inequalities and by Sobolev's immersion $\dot{H}^1(\mathbb{R}^3) \hookrightarrow L^6(\mathbb{R}^3)$, we obtain

$$\begin{aligned} c \|u\|_{L^s} \|\nabla u\|_{L^{\frac{2s}{s-2}}} \|\Delta u\|_{L^2} &\leq c \|u\|_{L^s} \|\nabla u\|_{L^{\frac{s-3}{s}}}^{\frac{s-3}{s}} \|\nabla u\|_{L^6}^{\frac{3}{s}} \|\Delta u\|_{L^2} \\ &\leq c' \|u\|_{L^s} \|\nabla u\|_{L^{\frac{s-3}{s}}}^{\frac{s-3}{s}} \|\Delta u\|_{L^2}^{\frac{s+3}{s}} \leq c'' \left(\|u\|_{L^s} \|\nabla u\|_{L^{\frac{s-3}{s}}} \right)^{\frac{2s}{s-3}} + \nu \left(\|\Delta u\|_{L^{\frac{s-3}{s}}} \right)^{\frac{2s}{s+3}}. \end{aligned}$$

Then we conclude

$$\frac{d}{dt} \|\nabla u\|_{L^2}^2 \leq \frac{d}{dt} \|\nabla u\|_{L^2}^2 + \nu \|\Delta u\|_{L^2}^2 \leq c'' \|u\|_{L^s}^{\frac{2s}{s-3}} \|\nabla u\|_{L^2}^2$$

which, by Gronwall's inequality, in $[0, T^*)$ yields

$$\|\nabla u(t)\|_{L^2}^2 \leq \|\nabla u(0)\|_{L^2}^2 e^{c'' \int_0^t \|u(t')\|_{L^s}^{\frac{2s}{s-3}} dt'} \leq \|\nabla u(0)\|_{L^2}^2 e^{c'' \|u\|_{L^r(0, T), L^s}^{\frac{2s}{s-3}}}.$$

But this contradicts the blow up and shows that $T^* > T$. Hence the regularity $u \in C^\infty((0, T] \times \mathbb{R}^3, \mathbb{R}^3)$ is proved when $u_0 \in V$. More generally, if $u_0 \notin V$, we can consider

a sequence $t_n \searrow 0$ with $u(t_n) \in V$, from this and the uniqueness Theorem 6.2 conclude $u \in C^\infty((t_n, T] \times \mathbb{R}^3, \mathbb{R}^3)$ for all n , and hence also $u \in C^\infty((0, T] \times \mathbb{R}^3, \mathbb{R}^3)$. The statement that u in $[\epsilon, T]$, for any $\epsilon \in (0, T)$, is also a solution in the sense of Theorem 6.1, has been assumed implicitly in this proof, but is easily proved using Theorem 6.2.

Next, we turn to the discussion of the uniqueness in the present theorem. Se let us consider a solution v like in the statement. We claim that u can be used as test function for v and v can be used as a test function of u in the formula (5.4).

Assuming the claim, we have

$$\begin{aligned} \int_0^t (\nu \langle \nabla v, \nabla u \rangle - \langle v, \partial_t u \rangle + \langle \operatorname{div}(v \otimes v), u \rangle) dt' &= \|u_0\|_{L^2}^2 - \langle v(t), u(t) \rangle \text{ and} \\ \int_0^t (\nu \langle \nabla v, \nabla u \rangle - \langle \partial_t v, u \rangle + \langle \operatorname{div}(u \otimes u), v \rangle) dt' &= \|u_0\|_{L^2}^2 - \langle v(t), u(t) \rangle. \end{aligned}$$

We can write the above as

$$\begin{aligned} \int_0^t (\nu \langle \nabla v, \nabla u \rangle - \langle v, \partial_t u \rangle + \langle \operatorname{div}(v \otimes v), u \rangle) dt' &= \|u_0\|_{L^2}^2 - \langle v(t), u(t) \rangle \text{ and} \\ \int_0^t (\nu \langle \nabla v, \nabla u \rangle + \langle v, \partial_t u \rangle + \langle \operatorname{div}(u \otimes u), v \rangle) dt' &= 0 \end{aligned}$$

where in the 2nd equality we have used the fact that $u, v \in C^\infty((0, T], L^2)$, which follows from the 1st part of the proof, integration by parts with the information that $u(t) \xrightarrow{t \rightarrow 0^+} u_0$ and $v(t) \xrightarrow{t \rightarrow 0^+} u_0$ in $L^2(\mathbb{R}^3, \mathbb{R}^3)$, which can be proved using the proof of Lemma 5.17 for all solutions like in Leray's Theorem 5.3. Now we are exactly in the same situation of Theorem 6.2. Proceeding with the same algebraic manipulations, we arrive to

$$\begin{aligned} 2^{-1} \|w(t)\|_{L^2}^2 + \int_0^t (\nu \|\nabla w\|^2 - \langle \operatorname{div}(w \otimes w), u \rangle) dt' \\ = 2^{-1} \|u(t)\|_{L^2}^2 + \int_0^t \nu \|\nabla u\|^2 - 2^{-1} \|u_0\|_{L^2}^2 \end{aligned} \quad (6.20)$$

$$+ 2^{-1} \|v(t)\|_{L^2}^2 + \int_0^t \nu \|\nabla v\|^2 - 2^{-1} \|v_0\|_{L^2}^2 \leq 0, \quad (6.21)$$

where the inequality follows from the fact that both u and v satisfy the Energy Inequality (5.7), and so the last two lines are both ≤ 0 .

Therefore we get for $w = v - u$

$$\|w(t)\|_{L^2}^2 + 2 \int_0^t \nu \|\nabla w\|^2 dt' \leq 2 \int_0^t \langle \operatorname{div}(w \otimes w), u \rangle dt'$$

Like above in the proof of this theorem, we bound

$$\begin{aligned} 2 \operatorname{div}(w \otimes w), u &\leq c \|u\|_{L^s} \|w\|_{L^{\frac{2s}{s-2}}} \|\nabla w\|_{L^2} \\ &\leq c \|u\|_{L^s} \|w\|_{L^{\frac{s-3}{s}}}^{\frac{s-3}{s}} \|\nabla w\|_{L^{\frac{s+3}{s}}}^{\frac{s+3}{s}} \leq c' \|u\|_{L^s}^r \|w\|_{L^2}^2 + \nu \|\nabla w\|_{L^2}^2 \text{ where } r = \frac{2s}{s-3}. \end{aligned}$$

Then

$$\|w(t)\|_{L^2}^2 \leq c'' \int_0^t \|u(t')\|_{L^s}^r \|w(t')\|_{L^2}^2 dt'$$

implies by Gronwall $w(t) \equiv 0$ in $[0, T]$, proving uniqueness.

Now we have to prove the claim that v (and u) can be used as test functions in (5.4). Suppose that v is a weak solution like in Leray's Theorem satisfying the Serrin condition and let u be a weak solution like in Leray's Theorem. We know that $v \in C^\infty([\epsilon, T])$ for any $\epsilon \in (0, T)$. So, for $t \in (\epsilon, T)$ we get

$$\int_\epsilon^t \langle u, \partial_t v \rangle dt' = \langle u(\epsilon), v(\epsilon) \rangle - \langle u(t), v(t) \rangle + \nu \int_\epsilon^t \langle \nabla u(t'), \nabla v(t') \rangle dt' + \int_\epsilon^t \langle \operatorname{div}(u \otimes u), v \rangle dt'.$$

Let us consider now the limit $\epsilon \rightarrow 0^+$. We know by the right continuity Lemma 5.17 that $u(\epsilon) \xrightarrow{\epsilon \rightarrow 0^+} u_0$ and $v(\epsilon) \xrightarrow{\epsilon \rightarrow 0^+} v_0$ in $L^2(\mathbb{R}^3, \mathbb{R}^3)$ so that

$$(\langle u(\epsilon), v(\epsilon) \rangle - \langle u(t), v(t) \rangle) \xrightarrow{\epsilon \rightarrow 0^+} (\langle u_0, v_0 \rangle - \langle u(t), v(t) \rangle).$$

Next, $u, v \in L^2((0, t), H^1)$ implies

$$\int_\epsilon^t \langle \nabla u(t'), \nabla v(t') \rangle dt' \xrightarrow{\epsilon \rightarrow 0^+} \int_0^t \langle \nabla u(t'), \nabla v(t') \rangle dt'.$$

Finally, we show that

$$\lim_{\epsilon \rightarrow 0^+} \int_\epsilon^t \langle \operatorname{div}(u \otimes u), v \rangle dt' \text{ exists and is finite.} \quad (6.22)$$

The above limits are sufficient to prove

$$\int_0^t \langle u, \partial_t v \rangle dt' = \langle u_0, v_0 \rangle - \langle u(t), v(t) \rangle + \nu \int_0^t \langle \nabla u(t'), \nabla v(t') \rangle dt' + \int_0^t \langle \operatorname{div}(u \otimes u), v \rangle dt',$$

and hence the claim. To prove (6.22) it is sufficient to show that

$$I := \int_0^t |\langle \operatorname{div}(u \otimes u), v \rangle| dt' < \infty.$$

We bound, using $r' = \frac{2s}{s+3}$,

$$\begin{aligned} I &\lesssim \int_0^t \|v\|_{L^s} \|u\|_{L^{\frac{s-3}{s}}}^{\frac{s-3}{s}} \|\nabla u\|_{L^{\frac{s+3}{s}}}^{\frac{s+3}{s}} dt' \lesssim \int_0^t \|v\|_{L^s}^r dt' + \int_0^t \|u\|_{L^{\frac{(s-3)r'}{s}}}^{\frac{(s-3)r'}{s}} \|\nabla u\|_{L^{\frac{(s+3)r'}{s}}}^{\frac{(s+3)r'}{s}} dt' \\ &\leq \|v\|_{L^r((0,t), L^s)}^r + \|u\|_{L^\infty(\mathbb{R}_+, L^2)}^{\frac{2s-6}{s+3}} \int_0^t \|\nabla u\|_{L^2}^2 dt < \infty. \end{aligned}$$

□

7 Well posedness in Sobolev spaces

In Sections 7–9 we follow [1]. The theory is mostly due to T.Kato. The approach will be different and the results will partially overlap with the ones in previous sections. To explain the approach we go back to equation (5.13) and observe that if $\mathcal{Q}_{NS}(u, u)$ is a force like the f in (4.1), we can interpret the solutions of (5.13) as solutions of a linear heat equation (4.1). More specifically, if we denote by $B(u, v)$ the weak solution of

$$\begin{cases} \partial_t B(u, v) - \nu \Delta B(u, v) = \mathcal{Q}_{NS}(u, v) \\ B(u, v)|_{t=0} = 0. \end{cases} \quad (7.1)$$

then, when we are within the scope of the theory of Sect. 4, the solutions of (5.13) can be rewritten as

$$u = e^{\nu t \Delta} u_0 + B(u, u). \quad (7.2)$$

In fact in Sections 7–9, for us the Navier Stokes equation will be equation (7.2). In Sect. 9 we will give an explicit formula to the operator $B(u, v)$. It is an integral operator whose integral kernel is the so called Oseen kernel. We will try to solve the problem by means of a fixed point argument. Specifically, we will look for an appropriate Banach space X_T of functions defined in $[0, T] \times \mathbb{R}^d$, for a subspace $\mathcal{E} \subset \mathcal{S}'(\mathbb{R}^d, \mathbb{R}^d)$ such that $u_0 \in \mathcal{E}$ implies $e^{\nu t \Delta} u_0 \in X_T$ and furthermore $\|e^{\nu t \Delta} u_0\|_{X_T} \xrightarrow{T \rightarrow 0^+} 0$, and we will use the following general and abstract lemma.

Lemma 7.1. *Let X be a Banach space and $B : X^2 \rightarrow X$ a continuous bilinear map. Let $\alpha < \frac{1}{4\|B\|}$ where $\|B\| = \sup_{\|x\|=\|y\|=1} \|B(x, y)\|$. Then for any $x_0 \in X$ in $D_X(0, \alpha)$ (the open ball of center 0 and radius α in X) there exists a unique $x \in \overline{D}_X(0, 2\alpha)$ s.t. $x = x_0 + B(x, x)$.*

Proof. We consider the map

$$x \rightarrow x_0 + B(x, x). \quad (7.3)$$

We will frame this as a fixed point problem in $\overline{D}_X(0, 2\alpha)$.

First of all, we claim that the map (7.3) leaves $\overline{D}_X(0, 2\alpha)$ invariant. Indeed

$$\|x_0 + B(x, x)\| \leq \|x_0\| + \|B(x, x)\| \leq \|x_0\| + \|B\| \|x\|^2 \leq \alpha \underbrace{(1 + 4\|B\|\alpha)}_{<1} < 2\alpha.$$

Next, we check that the map (7.3) is a contraction. Indeed

$$\|B(x, x) - B(y, y)\| \leq \|B(x - y, x)\| + \|B(y, x - y)\| \leq 4\alpha \|B\| \|x - y\|$$

where $4\alpha \|B\| < 1$. So the map (7.3) has a unique fixed point in $\overline{D}_X(0, 2\alpha)$. \square

In this section we will discuss the case $X = X_T = L^4([0, T], \dot{H}^{\frac{d-1}{2}}(\mathbb{R}^d, \mathbb{R}^d))$ and space of initial data $\dot{H}^{\frac{d-1}{2}-1}(\mathbb{R}^d, \mathbb{R}^d)$ and use the above lemma to prove the following well posedness result.

Theorem 7.2. For any $u_0 \in \dot{H}^{\frac{d}{2}-1}(\mathbb{R}^d, \mathbb{R}^d)$ there exists a T and a solution of (7.2) with $u \in L^4([0, T], \dot{H}^{\frac{d-1}{2}}(\mathbb{R}^d, \mathbb{R}^d))$. This solution is unique. Furthermore we have

$$u \in C([0, T], \dot{H}^{\frac{d}{2}-1}(\mathbb{R}^d, \mathbb{R}^d)), \nabla u \in L^2([0, T], \dot{H}^{\frac{d}{2}-1}(\mathbb{R}^d, \mathbb{R}^d \times \mathbb{R}^d)). \quad (7.4)$$

Let T_{u_0} be the lifespan of the solution. Then:

(1) there exists a c s.t.

$$\|u_0\|_{\dot{H}^{\frac{d}{2}-1}(\mathbb{R}^d, \mathbb{R}^d)} \leq c\nu \Rightarrow T_{u_0} = \infty;$$

(2) if $T_{u_0} < \infty$ then

$$\int_0^{T_{u_0}} \|u(t)\|_{\dot{H}^{\frac{d-1}{2}}(\mathbb{R}^d, \mathbb{R}^d)}^4 dt = \infty. \quad (7.5)$$

(3) if $T_{u_0} < \infty$ then

$$\int_0^{T_{u_0}} \|\nabla u(t)\|_{\dot{H}^{\frac{d}{2}-1}(\mathbb{R}^d, \mathbb{R}^d \times \mathbb{R}^d)}^2 dt = \infty. \quad (7.6)$$

Moreover, if u and v are solutions, then

$$\begin{aligned} & \|u(t) - v(t)\|_{\dot{H}^{\frac{d}{2}-1}(\mathbb{R}^d, \mathbb{R}^d)}^2 + \nu \int_0^t \|\nabla(u - v)(s)\|_{\dot{H}^{\frac{d}{2}-1}(\mathbb{R}^d, \mathbb{R}^d \times \mathbb{R}^d)}^2 ds \\ & \leq \|u_0 - v_0\|_{\dot{H}^{\frac{d}{2}-1}(\mathbb{R}^d, \mathbb{R}^d)}^2 e^{C\nu^{-3} \int_0^t \left(\|u(t')\|_{\dot{H}^{\frac{d-1}{2}}(\mathbb{R}^d, \mathbb{R}^d)}^4 + \|v(t')\|_{\dot{H}^{\frac{d-1}{2}}(\mathbb{R}^d, \mathbb{R}^d)}^4 \right) dt'} \end{aligned} \quad (7.7)$$

where C is a fixed constant.

Remark 7.3. Notice that the following transformation preserves the solutions of the Navier Stokes equation:

$$u(t, x) \mapsto u_\lambda(t, x) := \lambda u(\lambda^2 t, \lambda x), \quad (7.8)$$

Furthermore, notice that the norms of u in the spaces in (7.4) coincide with the analogous norms of u_λ in the interval $[0, T/\lambda^2]$. Notice also that the norm of $u_0(x)$ in $\dot{H}^{\frac{d}{2}-1}(\mathbb{R}^d, \mathbb{R}^d)$ coincides with the norm of $u_0(x/\lambda)$ in the same space. So the space $\dot{H}^{\frac{d}{2}-1}$ is an example of space *critical* for the Navier Stokes equation. One obvious consequence of this is the following: there exists no function $T(\cdot) : [0, +\infty) \rightarrow (0, +\infty]$ s.t. $T_{u_0} \geq T(\|u_0\|_{\dot{H}^{\frac{d}{2}-1}})$ for all $u_0 \in \dot{H}^{\frac{d}{2}-1}$.

Remark 7.4. While for $d = 2$ the solutions provided by Theorem 7.2 are exactly Leray's solutions, for $d = 3$ we could have $u_0 \in (\dot{H}^{\frac{1}{2}}(\mathbb{R}^3))^3$ with $u_0 \notin (L^2(\mathbb{R}^3))^3$. The corresponding solutions of the Navier Stokes equations provided by Theorem 7.2 are not Leray's solutions.

Remark 7.5. We will prove in Sect. 9 that the solutions provided by Theorem 7.2 are in $C^\infty((0, T) \times \mathbb{R}^d, \mathbb{R}^d)$.

Remark 7.6. Notice that the finite lifespan (7.5) is relevant only for $d = 3$. Furthermore, if $T_{u_0} < \infty$, it has been shown that

$$\|u\|_{L^\infty([0, T_{u_0}], (\dot{H}^1(\mathbb{R}^3))^3)} = \infty,$$

but the proof is a much harder.

We will assume for the moment Theorem 7.2 and prove the following.

8 Proof of Theorem 7.2

This section is devoted to the proof of this theorem. First we have the following lemma.

Lemma 8.1. *Let $d = 2, 3$. There exists a constant $C > 0$ s.t.*

$$\|\mathcal{Q}_{NS}(u, v)\|_{\dot{H}^{\frac{d}{2}-2}(\mathbb{R}^d, \mathbb{R}^d)} \leq C \|u\|_{\dot{H}^{\frac{d-1}{2}}(\mathbb{R}^d, \mathbb{R}^d)} \|v\|_{\dot{H}^{\frac{d-1}{2}}(\mathbb{R}^d, \mathbb{R}^d)}. \quad (8.1)$$

Proof. If $d = 2$ we have

$$\begin{aligned} \|\mathcal{Q}_{NS}(u, v)\|_{\dot{H}^{-1}} &\leq \sum_{j,k=1}^2 \left(\|\partial_k(u^k v^j)\|_{\dot{H}^{-1}} + \|\partial_k(v^k u^j)\|_{\dot{H}^{-1}} \right) \\ &\leq 2 \sum_{j,k} \|u^k v^j\|_{L^2} \leq C \|u\|_{L^4} \|v\|_{L^4} \leq C \|u\|_{\dot{H}^{\frac{1}{2}}} \|v\|_{\dot{H}^{\frac{1}{2}}} \end{aligned}$$

by the Sobolev embedding $\dot{H}^{\frac{1}{2}}(\mathbb{R}^2) \subset L^4(\mathbb{R}^2)$, since $\frac{1}{4} = \frac{1}{2} - \frac{1}{2}$. This yields (8.1) for $d = 2$. For $d = 3$

$$\begin{aligned} \|\mathcal{Q}_{NS}(u, v)\|_{\dot{H}^{-\frac{1}{2}}(\mathbb{R}^3)} &\leq \sum_{j,k} \left(\|\partial_k(u^k v^j)\|_{\dot{H}^{-\frac{1}{2}}(\mathbb{R}^3)} + \|\partial_k(v^k u^j)\|_{\dot{H}^{-\frac{1}{2}}(\mathbb{R}^3)} \right) \\ &\lesssim \|(\nabla u)v\|_{\dot{H}^{-\frac{1}{2}}(\mathbb{R}^3)} + \|u\nabla v\|_{\dot{H}^{-\frac{1}{2}}(\mathbb{R}^3)} \lesssim \|(\nabla u)v\|_{L^{\frac{3}{2}}(\mathbb{R}^3)} + \|u\nabla v\|_{L^{\frac{3}{2}}(\mathbb{R}^3)} \end{aligned}$$

where we are using the Sobolev embedding $\dot{H}^{\frac{1}{2}}(\mathbb{R}^3) \subset L^3(\mathbb{R}^3)$ (since $\frac{1}{3} = \frac{1}{2} - \frac{1}{3}$) which in turn by duality implies $L^{\frac{3}{2}}(\mathbb{R}^3) \subset \dot{H}^{-\frac{1}{2}}(\mathbb{R}^3)$.

Hence, by $\frac{2}{3} = \frac{1}{2} + \frac{1}{6}$ and Hölder,

$$\|\mathcal{Q}_{NS}(u, v)\|_{\dot{H}^{-\frac{1}{2}}(\mathbb{R}^3)} \lesssim \|\nabla u\|_{L^2(\mathbb{R}^3)} \|v\|_{L^6(\mathbb{R}^3)} + \|u\|_{L^6(\mathbb{R}^3)} \|\nabla v\|_{L^2(\mathbb{R}^3)} \leq 2 \|u\|_{\dot{H}^1(\mathbb{R}^3)} \|v\|_{\dot{H}^1(\mathbb{R}^3)}.$$

This yields (8.1) for $d = 3$. \square

A straightforward consequence of Lemma 8.1 is the following for C the constant in Lemma 8.1.

Lemma 8.2. *Let $d = 2, 3$. Then for $u, v \in L^4([0, T], (\dot{H}^{\frac{d-1}{2}}(\mathbb{R}^d, \mathbb{R}^d)))$ we have*

$$\|\mathcal{Q}_{NS}(u, v)\|_{L^2([0, T], \dot{H}^{\frac{d}{2}-2}(\mathbb{R}^d, \mathbb{R}^d))} \leq C \|u\|_{L^4([0, T], \dot{H}^{\frac{d-1}{2}}(\mathbb{R}^d, \mathbb{R}^d))} \|v\|_{L^4([0, T], \dot{H}^{\frac{d-1}{2}}(\mathbb{R}^d, \mathbb{R}^d))} \quad (8.2)$$

□

Proof of Theorem 7.2. By Theorem 4.4 we have for $s = \frac{d}{2} - 1$ and $p = 4$

$$\begin{aligned} \|B(u, v)\|_{L^4([0, T], \dot{H}^{\frac{d-1}{2}})} &= \| \|B(u, v)\|_{\dot{H}^{s+\frac{2}{p}}} \|_{L^p(0, T)} \lesssim \frac{1}{\nu^{\frac{1}{p}+\frac{1}{2}}} \|\mathcal{Q}_{NS}(u, v)\|_{L^2([0, T], \dot{H}^{s-1})} \\ &= \nu^{-\frac{3}{4}} \|\mathcal{Q}_{NS}(u, v)\|_{L^2([0, T], \dot{H}^{\frac{d}{2}-2})} \leq C \nu^{-\frac{3}{4}} \|u\|_{L^4([0, T], \dot{H}^{\frac{d-1}{2}})} \|v\|_{L^4([0, T], \dot{H}^{\frac{d-1}{2}})}. \end{aligned} \quad (8.3)$$

So in the Banach space $X = L^4([0, T], \dot{H}^{\frac{d-1}{2}})$ we have $\|B\| \leq C \nu^{-\frac{3}{4}}$. Obviously this is the same as $\frac{\nu^{\frac{3}{4}}}{4C} \leq \frac{1}{4\|B\|}$. Our strategy is to prove

$$\|e^{\nu t \Delta} u_0\|_{L^4([0, T], \dot{H}^{\frac{d-1}{2}})} < \frac{\nu^{\frac{3}{4}}}{4C} \leq \frac{1}{4\|B\|} \quad (8.4)$$

where $e^{\nu t \Delta} u_0$ plays the role of x_0 in the abstract Lemma 7.1.

If (8.4) happens, that is if the l.h.s. of (8.4) is less than an $\alpha < \frac{1}{4\|B\|}$, then by Lemma 7.1 we can conclude that problem (7.2) admits a unique solution in $L^4([0, T], \dot{H}^{\frac{d-1}{2}})$ with norm less than $2\alpha < \frac{\nu^{\frac{3}{4}}}{2C}$.

We consider two distinct proofs of (8.4). The 1st, simpler, is valid only if $\|u_0\|_{\dot{H}^{\frac{d}{2}-1}}$ is sufficiently small and shows that (8.4) holds for all T . In the second proof, which is general, we drop the assumption that $\|u_0\|_{\dot{H}^{\frac{d}{2}-1}}$ is small, and we prove (8.4) for T sufficiently small.

Step 1: small initial data. By Theorem 4.4 we have for $s = \frac{d}{2} - 1$ and $p = 4$

$$\|e^{\nu t \Delta} u_0\|_{L^4([0, T], \dot{H}^{\frac{d-1}{2}})} = \| \|e^{\nu t \Delta} u_0\|_{\dot{H}^{s+\frac{2}{p}}} \|_{L^p(0, T)} \leq \nu^{-\frac{1}{p}} \|u_0\|_{\dot{H}^s} = \nu^{-\frac{1}{4}} \|u_0\|_{\dot{H}^{\frac{d}{2}-1}}. \quad (8.5)$$

So, if $\|u_0\|_{\dot{H}^{\frac{d}{2}-1}} < \frac{\nu}{4C}$ then (8.4) is true for any $T > 0$. In particular $T_{u_0} = \infty$ and we have just proved (1) in Theorem 7.2.

Step 2: possibly large initial data. Now we consider the case when $u_0 \in \dot{H}^{\frac{d}{2}-1}(\mathbb{R}^d)$ is possibly large. We consider a low-high energy decomposition: $u_0 = \mathbf{P}_\rho u_0 + \chi_{\sqrt{-\Delta} \geq \rho} u_0$ where we pick $\rho = \rho_{u_0}$ large enough so that

$$\|\chi_{\sqrt{-\Delta} \geq \rho} u_0\|_{\dot{H}^{\frac{d}{2}-1}} < \frac{\nu}{8C}.$$

Then by (8.5) we get

$$\begin{aligned} \|e^{\nu t \Delta} u_0\|_{L^4([0, T], \dot{H}^{\frac{d-1}{2}})} &\leq \|e^{\nu t \Delta} \chi_{\sqrt{-\Delta} \geq \rho} u_0\|_{L^4([0, T], \dot{H}^{\frac{d-1}{2}})} + \|e^{\nu t \Delta} \mathbf{P}_\rho u_0\|_{L^4([0, T], \dot{H}^{\frac{d-1}{2}})} \\ &< \frac{\nu^{\frac{3}{4}}}{8C} + \|e^{\nu t \Delta} \mathbf{P}_\rho u_0\|_{L^4([0, T], \dot{H}^{\frac{d-1}{2}})} \end{aligned} \quad (8.6)$$

where we made the high energy contribution small by the choice of ρ large.

We now exploit the fact that we have the freedom to choose T small, in order to make the contribution to (8.6) small too. Indeed we have

$$\begin{aligned}
& \|e^{\nu t \Delta} \mathbf{P}_\rho u_0\|_{L^4([0, T], \dot{H}^{\frac{d-1}{2}})} = \|e^{\nu t \Delta} \chi_{[0, \rho]}(\sqrt{-\Delta}) u_0\|_{L^4([0, T], \dot{H}^{\frac{d-1}{2}})} \\
& = \|e^{\nu t \Delta} \chi_{[0, \rho]}(\sqrt{-\Delta}) \sqrt{\rho} \frac{(-\Delta)^{\frac{1}{4}}}{\sqrt{\rho}} u_0\|_{L^4([0, T], \dot{H}^{\frac{d}{2}-1})} \\
& \leq \sqrt{\rho} \|e^{\nu t \Delta} \chi_{[0, \rho]}(\sqrt{-\Delta}) u_0\|_{L^4([0, T], \dot{H}^{\frac{d}{2}-1})} = \sqrt{\rho} \|e^{\nu t \Delta} \mathbf{P}_\rho u_0\|_{L^4([0, T], \dot{H}^{\frac{d}{2}-1})} \\
& \leq (\rho^2 T)^{\frac{1}{4}} \|e^{\nu t \Delta} \mathbf{P}_\rho u_0\|_{L^\infty([0, T], \dot{H}^{\frac{d}{2}-1})} \leq (\rho^2 T)^{\frac{1}{4}} \|\mathbf{P}_\rho u_0\|_{\dot{H}^{\frac{d}{2}-1}} \leq (\rho^2 T)^{\frac{1}{4}} \|u_0\|_{\dot{H}^{\frac{d}{2}-1}} \leq \frac{\nu^{\frac{3}{4}}}{8C}
\end{aligned}$$

if we choose T small enough so that the last inequality holds, that is if we choose T such that

$$T \leq \left(\frac{\nu^{\frac{3}{4}}}{8\rho^{\frac{1}{2}} C \|u_0\|_{\dot{H}^{\frac{d}{2}-1}}} \right)^4, \quad (8.7)$$

then all terms in the r.h.s. of (8.6) have been made small enough s.t.

$$\|e^{\nu t \Delta} u_0\|_{L^4([0, T], \dot{H}^{\frac{d-1}{2}})} < \frac{\nu^{\frac{3}{4}}}{4C} \leq \frac{1}{4\|B\|},$$

that is we obtained (8.4).

We have proved the 1st sentence in the statement of Theorem 7.2.

Now we turn to the proof that a solution $u \in L^4([0, T], \dot{H}^{\frac{d-1}{2}})$ satisfies (7.4).

By (8.1) we have $\mathcal{Q}_{NS}(u, u) \in L^2([0, T], \dot{H}^{\frac{d}{2}-2})$. Then it must be remarked that by its definition $B(u, u)$ is a solution in the sense of Definition 4.1 of the Heat Equation written above (7.2). Similarly, by Theorem 4.2 also $e^{\nu t \Delta} u_0$ is a solution of the homogeneous Heat Equation with initial value u_0 . Hence, since u satisfies (7.2), then u is the solution of the Heat Equation (5.13), where the latter can be framed in terms of the theory in Sect. 4 for $s = \frac{d}{2} - 1$. Then by Theorem 4.2 we have $u \in C^0([0, T], \dot{H}^{\frac{d}{2}-1})$ and $\nabla u \in L^2([0, T], \dot{H}^{\frac{d}{2}})$. This yields (7.4).

We turn now to the proof of (7.7). We consider two solutions u and v , and set $w = u - v$. Then

$$\begin{cases} w_t - \nu \Delta w = \mathcal{Q}_{NS}(w, u + v) \\ w(0) = u_0 - v_0 \end{cases}$$

where we used the symmetry $\mathcal{Q}_{NS}(u, v) = \mathcal{Q}_{NS}(v, u)$ and

$$\mathcal{Q}_{NS}(u - v, u + v) = \mathcal{Q}_{NS}(u, u) - \mathcal{Q}_{NS}(v, v) + \underbrace{\mathcal{Q}_{NS}(u, v) - \mathcal{Q}_{NS}(v, u)}_0.$$

By the energy estimate (4.5) for $s = \frac{d}{2} - 1$ we have

$$\Delta_w := \|w(t)\|_{\dot{H}^{\frac{d}{2}-1}}^2 + 2\nu \int_0^t \|\nabla w(t')\|_{\dot{H}^{\frac{d}{2}-1}}^2 dt' = \|w_0\|_{\dot{H}^{\frac{d}{2}-1}}^2 + 2 \int_0^t \langle \mathcal{Q}_{NS}(w, u + v), w \rangle_{\dot{H}^{\frac{d}{2}-1}}(t') dt'.$$

Claim 8.3. We have

$$\langle \mathcal{Q}_{NS}(a, b), c \rangle_{\dot{H}^{\frac{d}{2}-1}} \leq C \|a\|_{\dot{H}^{\frac{d-1}{2}}} \|b\|_{\dot{H}^{\frac{d-1}{2}}} \|c\|_{\dot{H}^{\frac{d}{2}}}. \quad (8.8)$$

Proof. Indeed, trading derivatives we have

$$\langle \mathcal{Q}_{NS}(a, b), c \rangle_{\dot{H}^{\frac{d}{2}-1}} \leq \|\mathcal{Q}_{NS}(a, b)\|_{\dot{H}^{\frac{d}{2}-2}} \|c\|_{\dot{H}^{\frac{d}{2}}}$$

and by (8.1) we have

$$\|\mathcal{Q}_{NS}(a, b)\|_{\dot{H}^{\frac{d}{2}-2}} \leq C \|a\|_{\dot{H}^{\frac{d-1}{2}}} \|b\|_{\dot{H}^{\frac{d-1}{2}}}.$$

This proves Claim 8.3.

Now for $N(t) := \|u(t)\|_{\dot{H}^{\frac{d-1}{2}}} + \|v(t)\|_{\dot{H}^{\frac{d-1}{2}}}$ by Claim 8.3 we have

$$\Delta_w \leq \|w_0\|_{\dot{H}^{\frac{d}{2}-1}}^2 + 2 \int_0^t \|w(t')\|_{\dot{H}^{\frac{d-1}{2}}} N(t') \|\nabla w(t')\|_{\dot{H}^{\frac{d}{2}-1}} dt'.$$

By the interpolation estimate in Lemma 2.20 we have

$$\|w(t')\|_{\dot{H}^{\frac{d-1}{2}}} \leq \|w(t')\|_{\dot{H}^{\frac{d}{2}-1}}^{\frac{1}{2}} \|\nabla w(t')\|_{\dot{H}^{\frac{d}{2}-1}}^{\frac{1}{2}}.$$

This implies

$$\Delta_w \leq \|w_0\|_{\dot{H}^{\frac{d}{2}-1}}^2 + 2 \int_0^t \|w(t')\|_{\dot{H}^{\frac{d}{2}-1}}^{\frac{1}{2}} N(t') \|\nabla w(t')\|_{\dot{H}^{\frac{d}{2}-1}}^{\frac{3}{2}} dt'.$$

Using the inequality $ab \leq \frac{1}{4}a^4 + \frac{3}{4}b^{\frac{4}{3}}$, which follows by

$$\log(ab) = \frac{1}{4} \log(a^4) + \frac{3}{4} \log(b^{\frac{4}{3}}) \leq \log\left(\frac{1}{4}a^4 + \frac{3}{4}b^{\frac{4}{3}}\right),$$

we get

$$\begin{aligned} \text{the integrand} &= \left(\|w(t')\|_{\dot{H}^{\frac{d}{2}-1}}^{\frac{1}{2}} N(t') \nu^{-\frac{3}{4}} \left(\frac{3}{4}\right)^{\frac{3}{4}} \right) \left(\frac{4}{3} \nu \|\nabla w(t')\|_{\dot{H}^{\frac{d}{2}-1}}^2 \right)^{\frac{3}{4}} \\ &\leq \frac{3^3}{4^4 \nu^3} \|w(t')\|_{\dot{H}^{\frac{d}{2}-1}}^2 N^4(t') + \nu \|\nabla w(t')\|_{\dot{H}^{\frac{d}{2}-1}}^2. \end{aligned}$$

Then

$$\Delta_w \leq \|w_0\|_{\dot{H}^{\frac{d}{2}-1}}^2 + \frac{3^3}{4^4 \nu^3} \int_0^t \|w(t')\|_{\dot{H}^{\frac{d}{2}-1}}^2 N^4(t') dt' + \nu \int_0^t \|\nabla w(t')\|_{\dot{H}^{\frac{d}{2}-1}}^2 dt'.$$

In other words, by the definition of Δ_w

$$\begin{aligned} & \|w(t)\|_{\dot{H}^{\frac{d}{2}-1}}^2 + 2\nu \int_0^t \|\nabla w(t')\|_{\dot{H}^{\frac{d}{2}-1}}^2 dt' \\ & \leq \|w_0\|_{\dot{H}^{\frac{d}{2}-1}}^2 + \frac{3^3}{4^4\nu^3} \int_0^t \|w(t')\|_{\dot{H}^{\frac{d}{2}-1}}^2 N^4(t') dt' + \cancel{\nu \int_0^t \|\nabla w(t')\|_{\dot{H}^{\frac{d}{2}-1}}^2 dt'} \end{aligned}$$

so that, if we set

$$X(t) := \|w(t)\|_{\dot{H}^{\frac{d}{2}-1}}^2 + \nu \int_0^t \|\nabla w(t')\|_{\dot{H}^{\frac{d}{2}-1}}^2 dt'$$

we have

$$\begin{aligned} X(t) & \leq \|w_0\|_{\dot{H}^{\frac{d}{2}-1}}^2 + \frac{3^3}{4^4\nu^3} \int_0^t \|w(t')\|_{\dot{H}^{\frac{d}{2}-1}}^2 N^4(t') dt' \\ & \leq \|w_0\|_{\dot{H}^{\frac{d}{2}-1}}^2 + \frac{3^3}{4^4\nu^3} \int_0^t X(t') N^4(t') dt'. \end{aligned}$$

So by Gronwall's inequality

$$\|w(t)\|_{\dot{H}^{\frac{d}{2}-1}}^2 + \nu \int_0^t \|\nabla w(t')\|_{\dot{H}^{\frac{d}{2}-1}}^2 dt' \leq \|w_0\|_{\dot{H}^{\frac{d}{2}-1}}^2 \exp\left(\frac{3^3}{4^4\nu^3} \int_0^t N^4(t') dt'\right).$$

This proves the stability inequality (7.7)

We now consider the blow up criterion (7.5). Suppose that $u(t)$ is a solution in $[0, T]$ with

$$\int_0^T \|u(t)\|_{\dot{H}^{\frac{d-1}{2}}}^4 dt < \infty.$$

Notice that then $u \in L^4([0, T], \dot{H}^{\frac{d-1}{2}})$ and

$$\|\mathcal{Q}_{NS}(u, u)\|_{L^2([0, T], \dot{H}^{\frac{d}{2}-2})} \leq C \|u\|_{L^4([0, T], \dot{H}^{\frac{d-1}{2}})}^2. \quad (8.9)$$

We claim that we can extend $u(t)$ beyond T .

Claim 8.4. There exists a $\tau > 0$ s.t. u extends in a solution in $L^4([0, T + \tau], \dot{H}^{\frac{d-1}{2}}(\mathbb{R}^d, \mathbb{R}^d))$.

First of all we set

$$g(\xi) := \sup_{0 \leq t' \leq T} |\widehat{u}(t', \xi)|.$$

Claim 8.5. We have $|\xi|^{\frac{d}{2}-1} g \in L^2(\mathbb{R}^d)$.

Proof of Claim 8.5. By (4.15) for $s = \frac{d}{2} - 1$ and by (8.1) we have

$$\begin{aligned} \|\xi^{\frac{d}{2}-1}g\|_{L^2} &= \left(\int_{\mathbb{R}^d} |\xi|^{d-2} \left(\sup_{0 \leq t' \leq t} |\widehat{u}(t', \xi)| \right)^2 d\xi \right)^{\frac{1}{2}} \\ &\leq \|u_0\|_{\dot{H}^{\frac{d}{2}-1}} + \frac{1}{(2\nu)^{\frac{1}{2}}} \|\mathcal{Q}_{NS}\|_{L^2([0, T], \dot{H}^{\frac{d}{2}-2})} \\ &\leq \|u_0\|_{\dot{H}^{\frac{d}{2}-1}} + \frac{C}{(2\nu)^{\frac{1}{2}}} \|u\|_{L^4([0, T], \dot{H}^{\frac{d-1}{2}})}^2 < \infty. \end{aligned}$$

This proves Claim 8.5.

Proof of Claim 8.4. Claim 8.5 implies

$$\int_{|\xi| \geq \rho} |\xi|^{d-2} |g(\xi)|^2 d\xi \xrightarrow{\rho \rightarrow +\infty} 0.$$

Thus there exists $\rho > 0$ s.t for any preassigned $c > 0$

$$\int_{|\xi| \geq \rho} |\xi|^{d-2} |\widehat{u}(t, \xi)|^2 d\xi < (c\nu)^2 \text{ for all } t \in [0, T].$$

Now, recalling the splitting in high and low energies in the proof of the 1st sentence in the statement of Theorem 7.2, there exists a fixed $\tau > 0$ s.t. the lifespan of the solution with initial datum $u(t)$ is bounded below by τ independently of $t \in [0, T]$. Indeed there exists a $c_1 > 0$ independent from $t \in [0, T]$ s.t.

$$\left(\frac{\nu^{\frac{3}{4}}}{8\rho^{\frac{1}{2}} C \|u(t)\|_{\dot{H}^{\frac{d}{2}-1}}} \right)^4 > c_1 > 0.$$

This follows from the fact that

$$\|u(t)\|_{\dot{H}^{\frac{d}{2}-1}} \leq \|\xi^{\frac{d}{2}-1}g\|_{L^2} < \infty$$

So we can take $\tau = c_1$. Then $T_{u_0} \geq T + \tau$ and this yields Claim 8.4.

Let us now discuss the blow up criterion (7.6). Suppose that $T_{u_0} < \infty$ and that

$$C_{L^2} := \int_0^{T_{u_0}} \|\nabla u(t)\|_{\dot{H}^{\frac{d}{2}-1}}^2 dt < \infty. \quad (8.10)$$

Since we have (7.5) and

$$L^4([0, T], \dot{H}^{\frac{d-1}{2}}(\mathbb{R}^d, \mathbb{R}^d)) \subseteq L^\infty([0, T], \dot{H}^{\frac{d}{2}-1}(\mathbb{R}^d, \mathbb{R}^d)) \cap L^2([0, T], \dot{H}^{\frac{d}{2}}(\mathbb{R}^d, \mathbb{R}^d))$$

it follows that since we must have (7.5), then (8.10) implies that

$$\lim_{T \rightarrow T_{u_0}} \|u(t)\|_{L^\infty([0, T], \dot{H}^{\frac{d}{2}-1})} = \infty \quad (8.11)$$

For $0 \leq t \leq T < T_{u_0}$ we have, by (8.8) and interpolation,

$$\begin{aligned}
& \|u(t)\|_{\dot{H}^{\frac{d}{2}-1}}^2 + 2\nu \int_0^t \|\nabla u(t')\|_{\dot{H}^{\frac{d}{2}-1}}^2 dt' = \|u(t_1)\|_{\dot{H}^{\sigma_s}}^2 + 2 \int_0^t \langle Q(u(t'), u(t')), u(t') \rangle_{\dot{H}^{\frac{d}{2}-1}} dt' \\
& \leq \|u(0)\|_{\dot{H}^{\frac{d}{2}-1}}^2 + C'_d \int_0^t \|u(t')\|_{\dot{H}^{\frac{d-1}{2}}}^2 \|\nabla u(t')\|_{\dot{H}^{\frac{d}{2}-1}} dt' \\
& \leq \|u(0)\|_{\dot{H}^{\frac{d}{2}-1}}^2 + C_d \int_0^t \|u(t')\|_{\dot{H}^{\frac{d}{2}-1}} \|\nabla u(t')\|_{\dot{H}^{\frac{d}{2}-1}}^2 dt'
\end{aligned} \tag{8.12}$$

and so

$$\|u\|_{L^\infty([0,T], \dot{H}^{\frac{d}{2}-1})}^2 \leq \|u(0)\|_{\dot{H}^{\frac{d}{2}-1}}^2 + C_d C_{L^2} \|u\|_{L^\infty([0,T], \dot{H}^{\frac{d}{2}-1})}.$$

But this means that

$$\|u\|_{L^\infty([0,T], \dot{H}^{\frac{d}{2}-1})} \leq \frac{1}{2} C_d C_{L^2} + \frac{1}{2} \sqrt{C_d^2 C_{L^2}^2 + 4 \|u(0)\|_{\dot{H}^{\frac{d}{2}-1}}^2} < \infty,$$

contradicting (8.11). This contradiction proves the blow up criterion (7.6).

The proof of Theorem 7.2 is completed. \square

Theorem 7.2 yields also an alternative proof of Leray's Theorem 5.4 for $d = 2$.

Corollary 8.6. *In the case $d = 2$, Theorem 7.2 implies Leray's Theorem 5.4 for $d = 2$*

Proof. By the Leray's Theorem 5.3 we know that given a divergence free $u_0 \in L^2(\mathbb{R}^2, \mathbb{R}^2)$ there are weak solutions in the sense of Leray with $u \in L^\infty([0, \infty), L^2(\mathbb{R}^2, \mathbb{R}^2))$ and $\nabla u \in L^2([0, \infty), L^2(\mathbb{R}^2, \mathbb{R}^4))$. Interpolating, for each such a solution we have

$$\| \|u\|_{\dot{H}^{\frac{1}{2}}} \|u\|_{L_t^4} \leq \| \|u\|_{L^2}^{\frac{1}{2}} \|\nabla u\|_{L^2}^{\frac{1}{2}} \|u\|_{L_t^4} \leq \|u\|_{L_t^\infty L^2}^{\frac{1}{2}} \|\nabla u\|_{L_t^2 L^2}^{\frac{1}{2}}$$

and so we obtain also $u \in L^4([0, \infty), \dot{H}^{\frac{1}{2}}(\mathbb{R}^2, \mathbb{R}^2))$.

By Lemma 8.2 we know that this implies

$$\mathcal{Q}_{NS}(u, u) \in L^2([0, \infty), \dot{H}^{-1}(\mathbb{R}^2, \mathbb{R}^2)).$$

Notice that the right hand side of (5.13) satisfies the hypothesis of the force term in the linear heat equation (4.1). As a weak solution of the Navier Stokes equation in the sense of Definition 5.1, u is then also a solution of the linear heat equation (4.1) in the sense of Definition 4.1. This means that it is also a solution of (7.2). Since by Theorem 7.2 such solution is a unique, we conclude that the solution of Leray's Theorem 5.3 in the case $d = 2$ is unique. Furthermore by Theorem 7.2 we know also that $u \in C^0([0, \infty), L^2(\mathbb{R}^2, \mathbb{R}^2))$.

We now turn to the energy identity. By Leray's Theorem 5.3 we know that

$$\|u(t)\|_{L^2(\mathbb{R}^2)}^2 + 2\nu \int_0^t \|\nabla u(t')\|_{L^2(\mathbb{R}^2)}^2 dt' \leq \|u_0\|_{L^2(\mathbb{R}^2)}^2.$$

We want now to prove that \leq can be replaced by $=$ in this formula. As we have mentioned above, u solves in the sense of Definition 4.1 the problem

$$\partial_t u - \nu \Delta u = \mathcal{Q}_{NS}(u, u) \text{ with } \mathcal{Q}_{NS}(u, u) \in L^2(\mathbb{R}_+, \dot{H}^{-1}(\mathbb{R}^2, \mathbb{R}^2)),$$

Then, by Theorem 4.2 for $s = 0$ the identity (4.5) yields

$$\|u(t)\|_{L^2}^2 + 2\nu \int_0^t \|\nabla u(t')\|_{L^2}^2 dt' = \|u_0\|_{L^2}^2 + 2 \int_0^t \langle \mathcal{Q}_{NS}(u(t'), u(t')), u(t') \rangle_{L^2} dt'.$$

By Lemma 5.6 we have the cancelation

$$\langle \mathcal{Q}_{NS}(u, u), u \rangle = \langle \mathbb{P}(\operatorname{div}(u \otimes u)), u \rangle = \langle \operatorname{div}(u \otimes u), u \rangle = 0.$$

This completes the proof, by giving the energy identity. \square

9 The case of initial data in $L^3(\mathbb{R}^3)$

It is possible to prove the following theorem.

Theorem 9.1. *For any divergence free $u_0 \in L^3(\mathbb{R}^3, \mathbb{R}^3)$ there is a $T > 0$ and a unique solution $u \in C^0([0, T], L^3(\mathbb{R}^3, \mathbb{R}^3))$ of*

$$u = e^{\nu t \Delta} u_0 + B(u, u). \quad (7.2)$$

Furthermore there exists a $\varepsilon_{3, \nu} > 0$ s.t. for $\|u_0\|_{L^3} < \varepsilon_{3, \nu}$ we have $T = \infty$. Furthermore, if $u_0 \in \dot{H}^{1/2}(\mathbb{R}^3, \mathbb{R}^3)$, the life span is the same of Theorem 7.2.

Exercise 9.2. Prove that the mapping $\dot{H}^{1/2}(\mathbb{R}^3, \mathbb{R}^3) \rightarrow L^3(\mathbb{R}^3, \mathbb{R}^3)$ is not surjective.

Exercise 9.3. Prove that the subspace of divergence free vector fields in $\dot{H}^{1/2}(\mathbb{R}^3, \mathbb{R}^3)$ is closed in $\dot{H}^{1/2}(\mathbb{R}^3, \mathbb{R}^3)$. Prove the same for with $\dot{H}^{1/2}(\mathbb{R}^3, \mathbb{R}^3)$ replaced by $L^3(\mathbb{R}^3, \mathbb{R}^3)$.

Exercise 9.4. Prove that the Sobolev embedding from the subspace of divergence free vector fields in $\dot{H}^{1/2}(\mathbb{R}^3, \mathbb{R}^3)$ to the subspace of divergence free vector fields in $L^3(\mathbb{R}^3, \mathbb{R}^3)$ is not surjective.

Exercise 9.5. Pick a divergence free u_0 belonging to $L^3(\mathbb{R}^3, \mathbb{R}^3)$ but not to $\dot{H}^{1/2}(\mathbb{R}^3, \mathbb{R}^3)$. Show that there exists a sequence of divergence free vector fields $\{u_0^{(n)}\}$ in $\dot{H}^{1/2}(\mathbb{R}^3, \mathbb{R}^3)$ with $u_0^{(n)} \rightarrow u_0$ in $L^3(\mathbb{R}^3, \mathbb{R}^3)$. Show also that $\|u_0^{(n)}\|_{\dot{H}^{1/2}} \rightarrow \infty$.

Exercise 9.6. Show that it is possible to define divergence free sequences $\{v_0^{(n)}\}$ in $\dot{H}^{1/2}(\mathbb{R}^3, \mathbb{R}^3)$ with $\|v_0^{(n)}\|_{\dot{H}^{1/2}} \rightarrow \infty$ and $\|v_0^{(n)}\|_{L^3} \rightarrow 0$.

Remark 9.7. For a sequence such as in Exercise 9.6, for $n \gg 1$ the corresponding solutions of the NS equation are globally defined in time by Theorem 9.13, while Theorem 7.2 is able to guarantee only on short intervals of time.

To prove Theorem 9.13 we will apply the abstract Lemma 7.1 in an appropriate Banach space X . The striking fact though, is that the space X will not be of the form $C^0([0, T], L^3(\mathbb{R}^3, \mathbb{R}^3))$. This because if X where this space, then the bilinear form B defined by (7.1) is known not to be continuous. It turns out that to get the right Banach space X , has required a certain degree of imagination and insight.

Definition 9.8 (Kato's Spaces). For $p \in [d, \infty]$ and $T \in (0, \infty)$ we set

$$K_p(T) := \{u \in C^0((0, T], L^p(\mathbb{R}^d, \mathbb{R}^d)) : \|u\|_{K_p(T)} := \sup_{t \in (0, T]} (\nu t)^{\frac{d}{2} \left(\frac{1}{d} - \frac{1}{p} \right)} \|u(t)\|_{L^p} < \infty\} \quad (9.1)$$

and for $p \in [1, d)$

$$K_p(T) := \{u \in C^0([0, T], L^p(\mathbb{R}^d, \mathbb{R}^d)) : \|u\|_{K_p(T)} := \sup_{t \in (0, T]} (\nu t)^{\frac{d}{2} \left(\frac{1}{d} - \frac{1}{p} \right)} \|u(t)\|_{L^p} < \infty\}. \quad (9.2)$$

We denote by $K_p(\infty)$ the spaces defined as above, with $(0, T]$ replaced by $(0, \infty)$.

We recall that the solution of the heat equation $u_t - \nu \Delta u = 0$ is $e^{t\nu \Delta} f = K_t * f$ where $K_t(x) := (4\pi\nu t)^{-\frac{d}{2}} e^{-\frac{|x|^2}{4t\nu}}$. Notice that $K_t(x) = (\nu t)^{-\frac{d}{2}} K((\nu t)^{-\frac{1}{2}} x)$, where $K(x) := (4\pi)^{-\frac{d}{2}} e^{-\frac{|x|^2}{4}}$ and where $\widehat{K}(\xi) = e^{-|\xi|^2}$.

Notice that for $u_0 \in L^d(\mathbb{R}^d)$ and $p \geq d$ we have from (1.16),

$$\|e^{t\nu \Delta} u_0\|_{L^p(\mathbb{R}^d)} \leq (4\pi\nu t)^{\frac{d}{2} \left(\frac{1}{p} - \frac{1}{d} \right)} \|u_0\|_{L^d(\mathbb{R}^d)} \quad \text{for all } p \geq d, \quad (9.3)$$

it can be proved that $e^{t\nu \Delta} u_0 \in C(\mathbb{R}_+, L^p)$, and so $e^{t\nu \Delta} u_0 \in K_p(\infty)$.

Lemma 9.9. *Let $u_0 \in L^d(\mathbb{R}^d, \mathbb{R}^d)$ and $p > d$. Then*

$$\lim_{T \rightarrow 0} \|e^{t\nu \Delta} u_0\|_{K_p(T)} = 0. \quad (9.4)$$

Proof. For any $\epsilon > 0$ there exists $\phi \in L^d(\mathbb{R}^d, \mathbb{R}^d) \cap L^p(\mathbb{R}^d, \mathbb{R}^d)$ s.t. $\|u_0 - \phi\|_{L^d} < \epsilon$. Then by (9.3) we have

$$\|u_0 - \phi\|_{K_p(T)} \leq (4\pi\nu T)^{\frac{d}{2} \left(\frac{1}{p} - \frac{1}{d} \right)} \epsilon.$$

Since $\|e^{t\nu \Delta} \phi\|_{L^p} \leq \|\phi\|_{L^p}$, it follows

$$\|e^{t\nu \Delta} u_0\|_{K_p(T)} = \sup_{t \in (0, T]} (\nu t)^{\frac{d}{2} \left(\frac{1}{d} - \frac{1}{p} \right)} \|e^{t\nu \Delta} u_0\|_{L^p} \leq (\nu T)^{\frac{d}{2} \left(\frac{1}{d} - \frac{1}{p} \right)} \|\phi\|_{L^p} \xrightarrow{T \rightarrow 0} 0.$$

□

Lemma 9.10. *Let p, q and r satisfy*

$$\begin{aligned} 0 < \frac{1}{p} + \frac{1}{q} &\leq 1 \\ \frac{1}{r} &\leq \frac{1}{p} + \frac{1}{q} < \frac{1}{d} + \frac{1}{r} \end{aligned} \tag{9.5}$$

Then the bilinear map B defined in (7.1) maps $K_p(T) \times K_q(T) \rightarrow K_r(T)$ and there is a constant C independent from T s.t.

$$\|B(u, v)\|_{K_r(T)} \leq C \|u\|_{K_p(T)} \|v\|_{K_q(T)}. \tag{9.6}$$

To prove Lemma 9.10 we consider for any $m = 1, \dots, d$ the problem

$$\begin{cases} (L_m f)_t - \nu \Delta L_m f = \mathbb{P} \partial_m f \\ L_m f(0, x) = 0 \end{cases} \tag{9.7}$$

($L_m f$ is by definition the solution of the above heat equation). Then by (4.7) and (5.15) for c_{ijk} the constants s.t. $\widehat{\mathbb{P}u}^i = \sum_{j,k=1}^d c_{ijk} \xi_j \xi_k |\xi|^{-2} \widehat{u}^k$, we have

$$\widehat{L_m f^i}(t, \xi) = \sum_{j,k=1}^d c_{ijk} \int_0^t e^{-(t-t')\nu|\xi|^2} \xi_j \xi_k \xi_m |\xi|^{-2} \widehat{f}^k(t', \xi) dt'. \tag{9.8}$$

This means, for $\Gamma_{jkm}(t, x)$ the inverse Fourier transform of $e^{-t\nu|\xi|^2} \xi_j \xi_k \xi_m |\xi|^{-2}$,

$$L_m f^i(t) = \sum_{j,k=1}^d c_{ijk} \int_0^t \Gamma_{jkm}(t-t') * \widehat{f}^k(t') dt'. \tag{9.9}$$

We claim the following.

Claim 9.11. We have for a fixed $C > 0$

$$|\Gamma_{jkm}(t, x)| \leq C(\sqrt{\nu t} + |x|)^{-d-1}. \tag{9.10}$$

Proof. It is elementary that $\Gamma_{jkm}(t, x) = (\nu t)^{-\frac{d+1}{2}} \Gamma_{jkm}((\nu t)^{-1/2} x)$ with $\widehat{\Gamma}_{jkm}(x) = e^{-|\xi|^2} \xi_j \xi_k \xi_m |\xi|^{-2}$. Then (9.10) is a consequence of

$$|\Gamma_{jkm}(x)| \leq C(1 + |x|)^{-d-1}. \tag{9.11}$$

It is straightforward that $\Gamma_{jkm} \in C^\infty(\mathbb{R}^{d+1}) \cap L^\infty(\mathbb{R}^{d+1})$, because of the rapid decay to 0 at infinity of $e^{-|\xi|^2} \xi_j \xi_k \xi_m |\xi|^{-2}$. Hence, to prove (9.11) it suffices to consider $|x| \gg 1$. For χ_0 a smooth cutoff of compact support equal to 1 near 0 and with $\chi_1 := 1 - \chi_0$, we set

$$\begin{aligned} \Gamma_{jkm}(x) &= (2\pi)^{-\frac{d}{2}} \int_{\mathbb{R}^d} e^{-i\xi \cdot x} \chi_0(|x|\xi) e^{-|\xi|^2} \xi_j \xi_k \xi_m |\xi|^{-2} d\xi \\ &\quad + (2\pi)^{-\frac{d}{2}} \int_{\mathbb{R}^d} e^{-i\xi \cdot x} \chi_1(|x|\xi) e^{-|\xi|^2} \xi_j \xi_k \xi_m |\xi|^{-2} d\xi \end{aligned}$$

The 1st term in the r.h.s. is

$$\lesssim \int_{|\xi| \leq |x|^{-1}} |\xi| d\xi \sim |x|^{-d-1}.$$

We next consider the other term, which we split as

$$(2\pi)^{-\frac{d}{2}} \int_{\mathbb{R}^d} e^{-i\xi \cdot x} \chi_1(|x|\xi) \chi_0(\xi) e^{-|\xi|^2} \xi_j \xi_k \xi_m |\xi|^{-2} d\xi \quad (9.12)$$

$$+ (2\pi)^{-\frac{d}{2}} \int_{\mathbb{R}^d} e^{-i\xi \cdot x} \chi_1(\xi) e^{-|\xi|^2} \xi_j \xi_k \xi_m |\xi|^{-2} d\xi. \quad (9.13)$$

Notice that the last line is $O(|x|^{-N})$ for any N . Indeed, $\chi_1(\xi) e^{-|\xi|^2} \xi_j \xi_k \xi_m |\xi|^{-2} \in \mathcal{S}(\mathbb{R}^d)$, and so also its Fourier transform (9.13) is rapidly decreasing.

Let us consider the term in (9.12). Set $L := i \frac{x}{|x|^2} \cdot \nabla_\xi$ and notice that $Le^{-i\xi \cdot x} = e^{-i\xi \cdot x}$. Then, the term in (9.12) is

$$(2\pi)^{-\frac{d}{2}} \int_{\mathbb{R}^d} e^{-i\xi \cdot x} L^{d+2} \left(\chi_1(|x|\xi) e^{-|\xi|^2} \xi_j \xi_k \xi_m |\xi|^{-2} \right) d\xi.$$

The absolute value of the integrand is for fixed C

$$\left| L^{d+2}(\dots) \right| \leq C|x|^{-d-2} |\xi|^{-d-1}.$$

Here we used that in the support of $\nabla_\xi(\chi_1(|x|\xi))$ we have $|x| \sim |\xi|^{-1}$. So the last integral is bounded

$$\lesssim |x|^{-d-2} \int_{1 \geq |\xi| \geq |x|^{-1}} |\xi|^{-d-1} d\xi \sim |x|^{-d-2} |x| = |x|^{-d-1}.$$

This completes the proof of Claim 9.11. □

Completion of proof of Lemma 9.10. By (9.10) we have by Young's inequality for convolutions and Hölder's inequality for the tensor product of u and v the bound (here $\frac{1}{a} = 1 + \frac{1}{r} - \frac{1}{\beta}$ and $\frac{1}{\beta} = \frac{1}{p} + \frac{1}{q}$)

$$\begin{aligned} \|B(u, v)\|_{L^r} &\leq C_1 \sum_{j,m,k} \int_0^t \|\Gamma_{j,m,k}(t-t')\|_{L^a} \|u(t') \otimes v(t')\|_{L^\beta} dt' \\ &\leq C_1 \sum_{j,m,k} \int_0^t \|\Gamma_{j,m,k}(t-t')\|_{L^a} \|u(t')\|_{L^p} \|v(t')\|_{L^q} dt' \\ &\lesssim \int_0^t (t-t')^{-\frac{1}{2} - \frac{d}{2} \left(\frac{1}{p} + \frac{1}{q} - \frac{1}{r} \right)} (t')^{-\frac{d}{2} \left(\frac{2}{d} - \frac{1}{p} - \frac{1}{q} \right)} dt' \|u\|_{K_p(t)} \|v\|_{K_q(t)} \end{aligned} \quad (9.14)$$

where in the 3rd line we used

$$\begin{aligned}
\|\Gamma_{j,m,k}(t-t')\|_{L^a(\mathbb{R}^d)} &\lesssim \left\| (\sqrt{t-t'} + |x|)^{-d-1} \right\|_{L^a(\mathbb{R}^d)} = (t-t')^{-\frac{d+1}{2}} \left\| \left(1 + \frac{|x|}{\sqrt{t-t'}} \right)^{-d-1} \right\|_{L^a(\mathbb{R}^d)} \\
&= (t-t')^{-\frac{d+1}{2}} (t-t')^{\frac{d}{2a}} \left\| (1+|x|)^{-d-1} \right\|_{L^a(\mathbb{R}^d)} \sim (t-t')^{-\frac{d+1}{2} + \frac{d}{2} \left(1 + \frac{1}{r} - \frac{1}{p} - \frac{1}{q} \right)} \\
&= (t-t')^{-\frac{1}{2} - \frac{d}{2} \left(\frac{1}{p} + \frac{1}{q} - \frac{1}{r} \right)}.
\end{aligned}$$

We then conclude

$$\|B(u, v)\|_{L^r} \leq C t^{-\frac{d}{2} \left(\frac{1}{d} - \frac{1}{r} \right)} \|u\|_{K_p(t)} \|v\|_{K_q(t)} \quad (9.15)$$

where we used the fact that $\forall \alpha, \beta \in (-\infty, 1)$ we have

$$\int_0^t (t-t')^{-\alpha} (t')^{-\beta} dt' = C(\alpha, \beta) t^{1-\alpha-\beta} \text{ for all } t > 0 \text{ and for } C(\alpha, \beta) := \int_0^1 (1-t')^{-\alpha} (t')^{-\beta} dt'. \quad (9.16)$$

and

$$\begin{aligned}
\frac{1}{2} + \frac{d}{2} \left(\frac{1}{p} + \frac{1}{q} - \frac{1}{r} \right) + \frac{d}{2} \left(\frac{2}{d} - \frac{1}{p} - \frac{1}{q} \right) &= \frac{1}{2} + \frac{d}{2} \left(\frac{2}{d} - \frac{1}{r} \right) = \frac{1}{2} + 1 - \frac{d}{2r} \\
&= 2 - \frac{1}{2} - \frac{d}{2r} = 1 + 1 - \frac{d}{2r} = 1 + \frac{d}{2} \left(\frac{1}{d} - \frac{1}{r} \right).
\end{aligned}$$

Notice that in the inequalities in (9.5) we need:

- $\frac{1}{\beta} := \frac{1}{p} + \frac{1}{q} \leq 1$ in order for $u \otimes v$ to belong to the Lebesgue space $L^\beta(\mathbb{R}^d)$;
- $0 < \frac{1}{p} + \frac{1}{q}$ is needed because otherwise in (9.14) we get $(t')^{-1}$ and the integral is undefined;
- $\frac{1}{r} \leq \frac{1}{p} + \frac{1}{q}$ is needed for $a \geq 1$;
- $\frac{1}{p} + \frac{1}{q} < \frac{1}{d} + \frac{1}{r}$ is needed to get $-\frac{1}{2} - \frac{d}{2} \left(\frac{1}{p} + \frac{1}{q} - \frac{1}{r} \right) > -1$ in the exponent of $(t-t')$ in (9.14).

□

We have the following fact.

Proposition 9.12. *For any $p \in (d, \infty]$ there exists a constant $\varepsilon_{p\nu} > 0$ s.t. if*

$$\|e^{t\Delta} u_0\|_{K_p(T)} < \varepsilon_{p\nu} \quad (9.17)$$

then there exists and is unique u in the ball of center 0 and radius $2\varepsilon_{p\nu}$ in $K_p(T)$ which satisfies (7.2).

Proof. Setting $r = q = p$, we see that for $p > d$ we have $B : K_p(T) \times K_p(T) \rightarrow K_p(T)$ is bounded and with norm that admits a finite upper bound independent from T . The proof follows then from the abstract Lemma 7.1. \square

Theorem 9.13. *For any $u_0 \in L^d(\mathbb{R}^d, \mathbb{R}^d)$ there is a $T > 0$ and solution $u \in C^0([0, T], L^d(\mathbb{R}^d, \mathbb{R}^d))$ of (7.2) which is unique. Furthermore there exists a $\varepsilon_d > 0$ s.t. for $\|u_0\|_{L^d} < \varepsilon_{d\nu}$ we have $T = \infty$. In the case $d = 2$, in particular, all solutions are defined for all $T > 0$.*

Proof. We have $e^{t\Delta}u_0 \in K_p(T)$ for any $p > d$, see (9.3). Furthermore, $\|e^{t\Delta}u_0\|_{K_p(T)} \xrightarrow{T \rightarrow 0} 0$ for $p > d$ by Lemma 9.9. Then we can apply Proposition 9.12 concluding that there exists a solution u of (7.2) in $K_{2d}(T)$ for $T > 0$ small enough. Applying Lemma 9.10 for $p = q = 2d$ and $r = d$ we get $B(u, u) \in C^0([0, T], L^d)$, and so $u \in C^0([0, T], L^d)$.

We assume now that there are two solutions u_1 and u_2 in $C^0([0, T], L^d)$. We already know the uniqueness for $d = 2$, so we will focus uniquely on the case $d = 3$.

Setting $u_{21} = u_2 - u_1$ and $w_j = B(u_j, u_j)$ we have

$$\begin{cases} \partial_t u_{21} - \nu \Delta u_{21} = f_{21} & \text{with} \\ u_{21}(0) = 0 \end{cases}$$

$$f_{21} = 2Q(e^{\nu t \Delta} u_0, u_{21}) + Q(w_2, u_{21}) + Q(w_1, u_{21}).$$

By $L^{\frac{3}{2}}(\mathbb{R}^3) \hookrightarrow \dot{H}^{-\frac{1}{2}}(\mathbb{R}^3)$, which is the dual of Sobolev's Embedding $\dot{H}^{\frac{1}{2}}(\mathbb{R}^3) \hookrightarrow L^3(\mathbb{R}^3)$, we have

$$\|Q(u, v)\|_{\dot{H}^{-\frac{3}{2}}(\mathbb{R}^3)} \leq \|u \otimes v\|_{\dot{H}^{-\frac{1}{2}}(\mathbb{R}^3)} \lesssim \|u \otimes v\|_{L^{\frac{3}{2}}(\mathbb{R}^3)} \leq \|u\|_{L^3} \|v\|_{L^3}.$$

Then, by (4.5) and entering the definition of f_{21}

$$\begin{aligned} & \|u_{21}(t)\|_{\dot{H}^{-\frac{1}{2}}}^2 + 2\nu \int_0^t \|\nabla u_{21}(t')\|_{\dot{H}^{-\frac{1}{2}}}^2 dt' \leq 2 \int_0^t \langle f_{21}(t'), u_{21}(t') \rangle_{\dot{H}^{-\frac{1}{2}}} dt' \\ & \leq 4 \int_0^t \|Q(e^{\nu t' \Delta} u_0, u_{21})\|_{\dot{H}^{-\frac{3}{2}}} \|\nabla u_{21}(t')\|_{\dot{H}^{-\frac{1}{2}}} dt' \\ & + 2 \int_0^t \|Q(w_2, u_{21}) + Q(w_1, u_{21})\|_{\dot{H}^{-\frac{3}{2}}} \|\nabla u_{21}(t')\|_{\dot{H}^{-\frac{1}{2}}} dt'. \end{aligned} \quad (9.18)$$

We bound the last line with, for $j = 1, 2$,

$$\begin{aligned} & 2 \int_0^t \|Q(w_j, u_{21})\|_{\dot{H}^{-\frac{3}{2}}} \|\nabla u_{21}(t')\|_{\dot{H}^{-\frac{1}{2}}} dt' \lesssim \|w_j\|_{K_3(t)} \int_0^t \|u_{21}(t')\|_{L^3} \|\nabla u_{21}(t')\|_{\dot{H}^{-\frac{1}{2}}} dt' \\ & \lesssim \|w_j\|_{K_3(t)} \int_0^t \|\nabla u_{21}(t')\|_{\dot{H}^{-\frac{1}{2}}}^2 dt', \end{aligned} \quad (9.19)$$

where in the last line we used Sobolev's Embedding $\dot{H}^{\frac{1}{2}}(\mathbb{R}^3) \hookrightarrow L^3(\mathbb{R}^3)$.

So, the last line of (9.18) is

$$\lesssim (\|w_1\|_{K_3(t)} + \|w_2\|_{K_3(t)}) \int_0^t \|\nabla u_{21}(t')\|_{\dot{H}^{-\frac{1}{2}}}^2 dt'. \quad (9.20)$$

We split now

$$u_0 = u_0^{(1)} + u_0^{(2)} \text{ with } \|u_0^{(1)}\|_{L^3} < \epsilon \text{ and } u_0^{(2)} \in L^6 \cap L^3$$

and we bound similarly to (9.19)

$$\int_0^t \|Q(e^{\nu t'} \Delta u_0^{(1)}, u_{21})\|_{\dot{H}^{-\frac{3}{2}}} \|\nabla u_{21}(t')\|_{\dot{H}^{-\frac{1}{2}}} dt' \lesssim \|u_0^{(1)}\|_{L^3} \int_0^t \|\nabla u_{21}(t')\|_{\dot{H}^{-\frac{1}{2}}}^2 dt'.$$

Finally, we bound

$$\begin{aligned} & \int_0^t \|Q(e^{\nu t'} \Delta u_0^{(2)}, u_{21})\|_{\dot{H}^{-\frac{3}{2}}} \|\nabla u_{21}(t')\|_{\dot{H}^{-\frac{1}{2}}} dt' \\ & \leq \int_0^t \|e^{\nu t'} \Delta u_0^{(2)} \otimes u_{21}\|_{\dot{H}^{-\frac{1}{2}}} \|\nabla u_{21}(t')\|_{\dot{H}^{-\frac{1}{2}}} dt' \lesssim \int_0^t \|e^{\nu t'} \Delta u_0^{(2)} \otimes u_{21}\|_{L^{\frac{3}{2}}} \|\nabla u_{21}(t')\|_{\dot{H}^{-\frac{1}{2}}} dt' \\ & \leq \int_0^t \|e^{\nu t'} \Delta u_0^{(2)}\|_{L^6} \|u_{21}\|_{L^2} \|\nabla u_{21}\|_{\dot{H}^{-\frac{1}{2}}} dt' \leq \|u_0^{(2)}\|_{L^6} \int_0^t \|u_{21}\|_{\dot{H}^{-\frac{1}{2}}}^{\frac{1}{2}} \|\nabla u_{21}\|_{\dot{H}^{-\frac{1}{2}}}^{\frac{3}{2}} dt'. \end{aligned}$$

So we get

$$\begin{aligned} & \|u_{21}(t)\|_{\dot{H}^{-\frac{1}{2}}}^2 + 2\nu \int_0^t \|\nabla u_{21}(t')\|_{\dot{H}^{-\frac{1}{2}}}^2 dt' \lesssim \left(\|w_1\|_{K_3(t)} + \|w_2\|_{K_3(t)} + \|u_0^{(1)}\|_{L^3} \right) \int_0^t \|\nabla u_{21}(t')\|_{\dot{H}^{-\frac{1}{2}}}^2 dt' \\ & + \frac{3}{4\mathbf{C}^{\frac{4}{3}}} \int_0^t \|\nabla u_{21}(t')\|_{\dot{H}^{-\frac{1}{2}}}^2 dt' + \frac{\mathbf{C}^4}{4} \|u_0^{(2)}\|_{L^6}^4 \int_0^t \|u_{21}\|_{\dot{H}^{-\frac{1}{2}}}^2 dt'. \end{aligned}$$

Taking \mathbf{C} large, and t small, so that $\|w_1\|_{K_3(t)} + \|w_2\|_{K_3(t)} + \|u_0^{(1)}\|_{L^3} < 3\epsilon$ with ϵ sufficiently small, we obtain

$$\|u_{21}(t)\|_{\dot{H}^{-\frac{1}{2}}}^2 + \nu \int_0^t \|\nabla u_{21}(t')\|_{\dot{H}^{-\frac{1}{2}}}^2 dt' \lesssim \frac{\mathbf{C}^4}{4} \|u_0^{(2)}\|_{L^6}^4 \int_0^t \|u_{21}\|_{\dot{H}^{-\frac{1}{2}}}^2 dt'.$$

Gronwall's Inequality implies that $u_{21}(t') = 0$ for all $t' \in [0, t]$ with $t > 0$ sufficiently small. The above argument shows that the set

$$\{t \in [0, T) : u_{21} \equiv 0 \text{ in } [0, t]\} \quad (9.21)$$

is open (and, obviously, non empty) in $[0, T)$. On the other hand, since $u_{21} \in C^0([0, T), L^3(\mathbb{R}^3, \mathbb{R}^3))$, the set in (9.21) is also closed in $[0, T)$. Hence, since it is non empty because it contains 0, it coincides with $[0, T)$.

Next we turn to the global existence for small data. This follows $\|e^{t\nu\Delta} u_0\|_{K_{2d}(\infty)} \leq C_d \|u_0\|_{L^d(\mathbb{R}^d)}$ and Proposition 9.12 when $C_d \|u_0\|_{L^d(\mathbb{R}^d)} < \varepsilon_{2d\nu}$. \square

Remark 9.14. Let $u_0 \in \dot{H}^{\frac{1}{2}}(\mathbb{R}^3, \mathbb{R}^3)$. Then it can be proved that if $T_3 > 0$ is the lifespan of the corresponding solution $u \in C^0([0, T_3), L^3(\mathbb{R}^3, \mathbb{R}^3))$ provided by Theorem 9.13 and if $T_{u_0} > 0$ is the lifespan of the solution provided by Theorem 7.2, we have $T_3 = T_{u_0}$. We will prove the simpler result in Proposition 9.15.

Proposition 9.15. *Let $u_0 \in \dot{H}^{\frac{1}{2}}(\mathbb{R}^3, \mathbb{R}^3)$. There there exists $\epsilon_{3\nu} > 0$ s.t. for $\|u_0\|_{L^3(\mathbb{R}^3)} < \epsilon_{3\nu}$ and if $T_{u_0} > 0$ is the lifespan of the solution provided by Theorem 7.2, we have $T_{u_0} = \infty$.*

Proof. Taking $\epsilon_{3\nu} > 0$ sufficiently small we can assume by Theorem 9.13 that $u \in C^0([0, \infty), L^3)$. In fact, if it is sufficiently small we can prove $\|u\|_{L^\infty([0, \infty), L^3)} < C_\nu \|u_0\|_{L^3}$ for a fixed $C_\nu > 0$. Suppose that $T_{u_0} < \infty$. Then by Theorem 7.2 we have the blow up

$$\lim_{T \nearrow T_{u_0}} \int_0^T \|\nabla u(t)\|_{\dot{H}^{\frac{1}{2}}}^2 dt = \infty. \quad (9.22)$$

By Theorem 7.2 and by (4.5), for $0 < t \leq T < T_{u_0}$ we have

$$\|u(t)\|_{\dot{H}^{\frac{1}{2}}}^2 + 2\nu \int_0^t \|\nabla u(t')\|_{\dot{H}^{\frac{1}{2}}}^2 dt' = \|u_0\|_{\dot{H}^{\frac{1}{2}}}^2 + 2 \int_0^t \langle u(t') \cdot \nabla u(t'), u(t') \rangle_{\dot{H}^{\frac{1}{2}}} dt'. \quad (9.23)$$

By Sobolev's Embedding $\dot{H}^{\frac{1}{2}}(\mathbb{R}^3, \mathbb{R}^3) \hookrightarrow L^3(\mathbb{R}^3, \mathbb{R}^3)$ we obtain

$$|\langle u \cdot \nabla u, u \rangle_{\dot{H}^{\frac{1}{2}}}| = |\langle u \cdot \nabla u, \nabla u \rangle_{L^2}| \leq \|u\|_{L^3} \|\nabla u\|_{L^3}^2 \leq C \|u\|_{L^3} \|\nabla u\|_{\dot{H}^{\frac{1}{2}}}^2.$$

Then

$$\begin{aligned} \|u(t)\|_{\dot{H}^{\frac{1}{2}}}^2 + 2\nu \int_0^t \|\nabla u(t')\|_{\dot{H}^{\frac{1}{2}}}^2 dt' &\leq \|u_0\|_{\dot{H}^{\frac{1}{2}}}^2 + C \|u\|_{L^\infty(\mathbb{R}_+, L^3)} \int_0^t \|\nabla u(t')\|_{\dot{H}^{\frac{1}{2}}}^2 dt' \\ &\leq \|u_0\|_{\dot{H}^{\frac{1}{2}}}^2 + C_\nu C \|u_0\|_{L^3} \int_0^t \|\nabla u(t')\|_{\dot{H}^{\frac{1}{2}}}^2 dt'. \end{aligned}$$

So, for $C_\nu C \|u_0\|_{L^3} < \nu$, we get

$$\|u(t)\|_{\dot{H}^{\frac{1}{2}}}^2 + \nu \int_0^t \|\nabla u(t')\|_{\dot{H}^{\frac{1}{2}}}^2 dt' \leq \|u_0\|_{\dot{H}^{\frac{1}{2}}}^2,$$

which contradicts (9.22). □

We will prove now the following.

Lemma 9.16. *The solutions $u \in C^0([0, T], L^d(\mathbb{R}^d, \mathbb{R}^d))$ in Theorem 9.13 are in $C^\infty((0, T) \times \mathbb{R}^d, \mathbb{R}^d)$.*

Proof. A proof of this lemma is in [11, Proposition 15.1], but it uses Besov spaces so here we modify the argument. We know the result already for $d = 2$, so we consider only $d = 3$. We notice that $e^{t\Delta} u_0 \in K_r(\infty)$ for all $r \geq d$ and $e^{t\Delta} u_0 \in C^\infty((0, T) \times \mathbb{R}^d, \mathbb{R}^d)$. We already know that, for $S > 0$ sufficiently small, we have $u \in K_{2d}(S)$, see the proof of Theorem 9.13. Then, using Lemma 9.10 we conclude that $B(u, u) \in K_r(S)$ for any $r \in [d, \infty)$ (notice $\frac{1}{p} + \frac{1}{q} < \frac{1}{d} + \frac{1}{r}$ in (9.5), where $p = q = 2d$ in our case). So $u \in K_r(S)$ for all $r \in [d, \infty)$. But then, applying again Lemma 9.10, we conclude that $u \in K_r(S)$ for all $r \in [d, \infty)$, and in particular $u \in L^\infty([t_0, S], L^r(\mathbb{R}^d))$ for any $t_0 \in (0, S)$ and any $r \in [d, \infty)$. Let us fix an

$r \in (2d, \infty)$ and let us prove by induction that $u \in L^\infty([t_0, S], W^{\frac{k}{2}, r}(\mathbb{R}^d))$ for all $k \in \mathbb{N} \cup \{0\}$. We have shown this for $k = 0$, and let us suppose by induction that it is true for some k . Then we will show $u \in L^\infty([t_1, S], W^{\frac{k+1}{2}, r}(\mathbb{R}^d))$ for any $t_0 < t_1 < S$. We can write

$$u(t) = e^{(t-t_0)\Delta}u(t_0) - \int_{t_0}^t e^{(t-s)\Delta}\mathbb{P}\nabla \cdot (u \otimes u)ds. \quad (9.24)$$

We know that $e^{(t-t_0)\Delta}u(t_0) \in C^\infty([t_1, S], W^{\frac{k+1}{2}, r}(\mathbb{R}^d))$ for all k , so we focus on the integral. We write

$$\begin{aligned} & \|(-\Delta)^{\frac{1}{4}} \int_{t_0}^t e^{(t-s)\Delta}\mathbb{P}\nabla \cdot (u \otimes u)ds\|_{W^{\frac{k}{2}, r}} \lesssim \int_{t_0}^t \|(-\Delta)^{-\frac{1}{2}}\nabla \cdot e^{(t-s)\Delta}(-\Delta)^{\frac{3}{4}}(u \otimes u)\|_{W^{\frac{k}{2}, r}} ds \\ & \leq C_{d,r} \int_{t_0}^t (t-s)^{-\frac{3}{4}} \|e^{(t-s)\Delta}(-(t-s)\Delta)^{\frac{3}{4}}(u \otimes u)\|_{W^{\frac{k}{2}, r}} ds \\ & \leq C'_{d,r,S,k} \int_{t_0}^t (t-s)^{-\frac{3}{4}} \|u \otimes u\|_{W^{\frac{k}{2}, r}} ds \leq C''_{d,r,S,k} \int_{t_0}^t (t-s)^{-\frac{3}{4}} \|u\|_{W^{\frac{k}{2}, r}}^2 ds \\ & = 4C'''_{d,r,S,k} (t-t_0)^{\frac{1}{4}} \|u\|_{L^\infty([t_0, S], W^{\frac{k}{2}, r}(\mathbb{R}^d))}^2, \end{aligned}$$

where we exploited the Calderon Zygmund theory (for example, Theorem 3 at p. 96 in [15], and the relation between the constants B and A_p in that statement where, from the proof, $A_p = A_p(B)$). Next, for $k = 0$ we use Hölder's inequality to bound

$$C'_{d,r,S,0} \int_{t_0}^t (t-s)^{-\frac{3}{4}} \|u \otimes u\|_{L^r} ds \leq C'_{d,r,S,0} \int_{t_0}^t (t-s)^{-\frac{3}{4}} \|u\|_{L^{2r}}^2 ds \leq C''_{d,r,S,0} (t-t_0)^{\frac{1}{4}} \|u\|_{L^\infty([t_0, S], L^{2r}(\mathbb{R}^d))}^2$$

while for $k \geq 1$ we use the fact that $W^{\frac{k}{2}, r}(\mathbb{R}^d)$ is an algebra to bound

$$\begin{aligned} & C'_{d,r,S,k} \int_{t_0}^t (t-s)^{-\frac{3}{4}} \|u \otimes u\|_{W^{\frac{k}{2}, r}} ds \leq C''_{d,r,S,k} \int_{t_0}^t (t-s)^{-\frac{3}{4}} \|u\|_{W^{\frac{k}{2}, r}}^2 ds \\ & = 4C'''_{d,r,S,k} (t-t_0)^{\frac{1}{4}} \|u\|_{L^\infty([t_0, S], W^{\frac{k}{2}, r}(\mathbb{R}^d))}^2. \end{aligned}$$

Now we use a general result of the theory of semigroups which guarantees that for $f \in L^1((0, T), X)$, where X is a Banach space where $e^{t\Delta}$ is a contraction semigroup, then

$$v(t) := - \int_{t_0}^t e^{(t-s)\Delta} f(s) ds$$

satisfies $\partial_t v = \Delta v + f(t)$ in $\mathcal{D}'((t_0, T), X)$, see [3, Proposition 4.1.6 (ii)]. In our case, since $u \in L^\infty([t_0, S], W^{k,r}(\mathbb{R}^d))$ for all k and appropriate $r < \infty$, and $f = -\mathbb{P}\nabla \cdot (u \otimes u)$, we have $v' = \Delta v + f(t)$ in $\mathcal{D}'((t_0, T), W^{k,r})$, since $e^{t\Delta}$ is a contraction semigroup in any space $W^{k,r}$ for $r < \infty$.

Furthermore, the Hille–Yosida–Phillips Theorem, see [3, Theorem 3.1.1], guarantees that $\partial_t e^{t\Delta}u(t_0) = \Delta e^{t\Delta}u(t_0)$ in $\mathcal{D}'((t_0, T), W^{k,r})$ for all k and our $r < \infty$.

Summing up, we obtain that

$$\partial_t u = \Delta u - \mathbb{P}\nabla \cdot (u \otimes u) \text{ in } \mathcal{D}'((0, S), W^{k,r}(\mathbb{R}^d)) \text{ for all } k. \quad (9.25)$$

Since the r.h.s. is in $L^\infty((t_0, S), W^{k,r}(\mathbb{R}^d))$ for all k , it follows that $u \in W^{1,\infty}((t_0, S), W^{k,r}(\mathbb{R}^d))$ for all k , which fed again in (9.25) yields $u \in W^{2,\infty}((t_0, S), W^{k,r}(\mathbb{R}^d))$, by applying Leibnitz rule like in Brezis [2, Corollary 8.10]. By induction, proceeding iteratively we get $u \in W^{l,\infty}((t_0, S), W^{k,r}(\mathbb{R}^d))$ for all l and k , and so the statement. \square

10 Vorticity

We recall the following.

Lemma 10.1. *Suppose that $f \in \mathcal{S}(\mathbb{R}^3)$. Then $u \in \mathcal{S}'(\mathbb{R}^3)$ satisfies $-\Delta u = f$ if and only if*

$$u = K * f + h \text{ with } K(x) := \frac{1}{4\pi|x|} \quad (10.1)$$

and $h(x)$ a harmonic polynomial.

Proof. Notice that $-\Delta h = 0$ requires $|\xi|^2 \widehat{h} = 0$, that is, $\text{supp} \widehat{h} = \{0\}$. But $\text{supp} \widehat{h} = \{0\}$ implies $\widehat{h} = \sum_{|\alpha| \leq k} a_\alpha \partial_\xi^\alpha \delta$, with k the order of \widehat{h} and a_α arbitrary constants, see [9, Theorem 2.3.4]. Then h is a degree k harmonic polynomial.

Next, let us consider the tempered distribution given by $\widehat{v} = \frac{1}{|\xi|^2} \widehat{f}$. Now, recall from Lemma 2.18, that

$$\mathcal{F}(|\cdot|^{-\gamma})(\xi) = \frac{2^{\frac{d-\gamma}{2}} \Gamma\left(\frac{d-\gamma}{2}\right)}{2^{\frac{\gamma}{2}} \Gamma\left(\frac{\gamma}{2} + 1\right)} |\xi|^{\gamma-d}.$$

So, for example, for $\gamma = 2$ and $d = 3$, using $\Gamma(2) = 1$ and $\Gamma(1/2) = \sqrt{\pi}$, we get $\mathcal{F}^{-1}(|\xi|^{-2}) = \sqrt{\frac{\pi}{2}} \frac{1}{|x|}$. Recalling also the formula $\widehat{f * g} = (2\pi)^{\frac{3}{2}} \widehat{f} \widehat{g}$, we get

$$v = \frac{1}{(2\pi)^{\frac{3}{2}}} \sqrt{\frac{\pi}{2}} \frac{1}{|x|} * f = \frac{1}{4\pi} \frac{1}{|x|} * f.$$

By linearity, $u \in \mathcal{S}'(\mathbb{R}^3)$ satisfies $-\Delta u = f$ exactly if it is like in (10.1). \square

If we consider a field $u \in \mathcal{S}'(\mathbb{R}^3, \mathbb{R}^3)$, then its vorticity is $\omega := \nabla \times u$.

Lemma 10.2. *Let $u \in W^{1,p}(\mathbb{R}^3, \mathbb{R}^3)$ with $p \in (1, 3)$ and with $\text{div} u = 0$. Then*

$$u = T\omega, \quad (10.2)$$

where

$$T\omega := -\frac{1}{4\pi} \int_{\mathbb{R}^3} \frac{x-y}{|x-y|^3} \times \omega(y) dy. \quad (10.3)$$

Proof. First of all, for divergent free vector-fields we have the identity $-\Delta u = \nabla \times \omega$.

Let us now assume $\omega \in C_c^\infty(\mathbb{R}^3, \mathbb{R}^3)$. Then we claim

$$\frac{1}{|x|} * \partial_j \omega_k = \left(\partial_j \frac{1}{|x|} \right) * \omega_k. \quad (10.4)$$

Indeed, by applying the divergence theorem, we have

$$\begin{aligned} \frac{1}{|x|} * \partial_j \omega_k &= - \lim_{\epsilon \rightarrow 0^+} \int_{|x-y| \geq \epsilon} \omega_k(y) \partial_{y_j} \frac{1}{|x-y|} dy + \lim_{\epsilon \rightarrow 0^+} \int_{|x-y| = \epsilon} \frac{x_j - y_j}{|x-y|^2} \omega_k(y) dS \\ &= - \int_{\mathbb{R}^3} \omega_k(y) \partial_{y_j} \frac{1}{|x-y|} dy = \left(\partial_j \frac{1}{|x|} \right) * \omega_k. \end{aligned}$$

Still for $\omega \in C_c^\infty(\mathbb{R}^3, \mathbb{R}^3)$, from $-\Delta u = \nabla \times \omega$, from Lemma 10.1 and (10.4) we have

$$\begin{aligned} u &= \vec{e}_i \epsilon_{ijk} \frac{1}{4\pi} \frac{1}{|x|} * \partial_j \omega_k + h = \vec{e}_i \epsilon_{ijk} \frac{1}{4\pi} \left(\partial_j \frac{1}{|x|} \right) * \omega_k + h \\ &= - \vec{e}_i \epsilon_{ijk} \frac{1}{4\pi} \frac{x_j}{|x|^3} * \omega_k + h = T\omega + h, \end{aligned}$$

where the components of h are harmonic polynomials. From the Hardy-Littlewood-Sobolev inequality, we have $\|T\omega\|_{L^q(\mathbb{R}^3)} \leq c\|\omega\|_{L^p(\mathbb{R}^3)}$ for $\frac{1}{q} = \frac{1}{p} - \frac{1}{3}$, if $1 < p < 3$. Since also $u \in L^q(\mathbb{R}^3, \mathbb{R}^3)$ it follows that also $h \in L^q(\mathbb{R}^3, \mathbb{R}^3)$ which, given that the coordinates of h are polynomials, implies $u = K * (\nabla \times \omega) = T\omega$ in the case $\omega \in C_c^\infty(\mathbb{R}^3, \mathbb{R}^3)$. For the general case, let $C_c^\infty(\mathbb{R}^3, \mathbb{R}^3) \ni \tilde{\omega}_n \xrightarrow{n \rightarrow \infty} \omega$ in $L^p(\mathbb{R}^3, \mathbb{R}^3)$. Then $u_n = T\tilde{\omega}_n \rightarrow \tilde{u} \in L^q(\mathbb{R}^3, \mathbb{R}^3)$, with $\tilde{u} = T\omega$. Notice that

$$\nabla \cdot u_n = \nabla \cdot T\omega_n = \nabla \cdot [(-\Delta)^{-1}(\nabla \times \tilde{\omega}_n)] = (-\Delta)^{-1} [\nabla \cdot (\nabla \times \tilde{\omega}_n)] = (-\Delta)^{-1} 0 = 0.$$

This implies, in particular, that $\nabla \cdot \tilde{u} = 0$.

Next notice that \mathbb{P} , which is a Calderon-Zygmund operator, is a bounded operator inside $L^p(\mathbb{R}^3, \mathbb{R}^3)$. Thus, for

$$\tilde{\omega}_n = \tilde{\omega}_n^{(1)} + \tilde{\omega}_n^{(2)}, \text{ with } \tilde{\omega}_n^{(1)} := \mathbb{P}\omega_n \text{ and } \tilde{\omega}_n^{(2)} := (1 - \mathbb{P})\omega_n,$$

we have $\tilde{\omega}_n^{(1)} \xrightarrow{n \rightarrow \infty} \omega$ and $\tilde{\omega}_n^{(2)} \xrightarrow{n \rightarrow \infty} 0$ in $L^p(\mathbb{R}^3, \mathbb{R}^3)$. We have

$$-\Delta u_n = \nabla \times \tilde{\omega}_n^{(1)} = \nabla \times \omega_n, \text{ where } \omega_n := \nabla \times u_n.$$

From the formula $\mathbb{P}\diamond = -\Delta^{-1}\nabla \times (\nabla \times \diamond)$, see (2.9), we obtain $\tilde{\omega}_n^{(1)} = \mathbb{P}\tilde{\omega}_n^{(1)} = \mathbb{P}\omega_n = \omega_n$. Hence we have proved that $\nabla \times u_n = \tilde{\omega}_n^{(1)}$. Taking the limit in this last equation, we obtain $\nabla \times u = \omega$, since $\nabla \times u_n \xrightarrow{n \rightarrow \infty} \nabla \times u$ in a distributional sense, and $\tilde{\omega}_n^{(1)} \xrightarrow{n \rightarrow \infty} \omega$ in $L^p(\mathbb{R}^3, \mathbb{R}^3)$. Hence we conclude that $\nabla \times u = \nabla \times \tilde{u}$.

We can finish the proof in two ways. The first is to observe that $\Delta(u - \tilde{u}) = 0$, so that by Lemma 10.1 we have $u - \tilde{u} = h$, where the components of h are harmonic polynomials. But since both $u, \tilde{u} \in L^q(\mathbb{R}^3, \mathbb{R}^3)$, we get $h \in L^q(\mathbb{R}^3, \mathbb{R}^3)$ and, as above, $h = 0$.

The second way to finish is to use again formula (2.9) and to conclude $u = \mathbb{P}u = \mathbb{P}\tilde{u} = \tilde{u}$. \square

Notice that for any $u \in \mathcal{S}'(\mathbb{R}^3, \mathbb{R}^3)$ we have $\nabla \cdot \omega = 0$. Indeed

$$\nabla \cdot (\nabla \times u) = (\epsilon_{ijk} \partial_i \partial_j) u_k = 0 u_k = 0$$

by $\partial_i \partial_j = \partial_j \partial_i$ and by $\epsilon_{ijk} = -\epsilon_{jik}$.

As we know, a solution of NS formally satisfies

$$u_t - \nu \Delta u + u \cdot \nabla u = -\nabla p.$$

Notice that if u is regular,

$$(u \cdot \nabla)u = 2^{-1} \nabla |u|^2 - u \times \omega, \quad (10.5)$$

since indeed $(u \cdot \nabla)u = e_i u_j \partial_j u_i$, $2^{-1} \nabla |u|^2 = e_i u_j \partial_i u_j$ and

$$\begin{aligned} u \times (\nabla \times u) &= e_i \epsilon_{ijk} u_j (\nabla \times u)_k = e_i \epsilon_{ijk} \epsilon_{i'j'k} u_j \partial_{i'} u_{j'} = e_i (\delta_{ii'} \delta_{jj'} - \delta_{ij'} \delta_{ji'}) u_j \partial_{i'} u_{j'} \\ &= e_i u_j \partial_i u_j - e_i u_j \partial_j u_i. \end{aligned}$$

Summing up, we obtain (10.5).

From (10.5) we obtain

$$\nabla \times ((u \cdot \nabla)u) = -\nabla \times (u \times \omega) = (u \cdot \nabla)\omega - (\omega \cdot \nabla)u, \quad (10.6)$$

from $\operatorname{div} u = \operatorname{div} \omega = 0$ and

$$\begin{aligned} \nabla \times (u \times \omega) &= e_i \epsilon_{ijk} \partial_j (u \times \omega)_k = e_i \epsilon_{ijk} \epsilon_{i'j'k} (\omega_{j'} \partial_j u_{i'} + u_{i'} \partial_j \omega_{j'}) = e_i (\delta_{ii'} \delta_{jj'} - \delta_{ij'} \delta_{ji'}) (\omega_{j'} \partial_j u_{i'} + u_{i'} \partial_j \omega_{j'}) \\ &= e_i (\omega_j \partial_j u_i + u_i \partial_j \omega_j) - e_i (\omega_i \partial_j u_j + u_j \partial_j \omega_i) = e_i \omega_j \partial_j u_i - e_i u_j \partial_j \omega_i. \end{aligned}$$

Then, applying $\nabla \times$ to the NS, we formally obtain

$$\omega_t - \nu \Delta \omega + (u \cdot \nabla)\omega = (\omega \cdot \nabla)u. \quad (10.7)$$

If we apply $\langle \cdot, \phi \rangle_{L^2_{tx}}$ to (10.7) with $\phi(t, x)$ a function in $C_c^\infty((0, \infty) \times \mathbb{R}^3, \mathbb{R}^3)$, then, exploiting $\nabla_x \cdot u = \nabla_x \cdot \omega = 0$, (10.7) implies

$$\int_0^\infty (\langle \omega, \partial_t \phi \rangle + \nu \langle \omega, \Delta \phi \rangle + \langle \omega, u \cdot \nabla \phi \rangle - \langle u, \omega \cdot \nabla \phi \rangle) dt' \text{ for all } \phi \in C_c^\infty((0, \infty) \times \mathbb{R}^3, \mathbb{R}^3), \quad (10.8)$$

which is the weak form of the vorticity equation. The above discussion is purely heuristic, but we have the following.

Lemma 10.3. *Let u be Leray Hopf solution of the NS, in the sense of Definition 5.1, with $u \in L^\infty(\mathbb{R}_+, L^2)$ and $\nabla u \in L^2(\mathbb{R}_+, L^2)$ and consider the vorticity ω . Then, the pair (u, ω) satisfies (10.8).*

Proof. For $\phi \in C_c^\infty((0, \infty) \times \mathbb{R}^3, \mathbb{R}^3)$ we have $\nabla \times \phi \in C_{c,\sigma}^\infty((0, \infty) \times \mathbb{R}^3, \mathbb{R}^3)$. So, by (5.4), we have

$$\int_{\mathbb{R}_+} (-\nu \langle u, \Delta \nabla \times \phi \rangle - \langle u, \nabla \times \partial_t \phi \rangle + \langle (u \cdot \nabla)u, \nabla \times \phi \rangle) dt' = 0.$$

Integrating by parts, we have $\langle u, \Delta \nabla \times \phi \rangle = -\langle \omega, \Delta \phi \rangle$ and $\langle u, \nabla \times \partial_t \phi \rangle = -\langle \omega, \partial_t \phi \rangle$. Notice that for $u(t) \in H^1$, formula (10.5) is true, and if $u(t) \in H^2$, then formula (10.6) is true. This means that if $u(t) \in H^2$, for that value of t we have

$$\langle (u \cdot \nabla)u, \nabla \times \phi \rangle = \langle \omega, (u \cdot \nabla)\phi \rangle - \langle u, (\omega \cdot \nabla)\phi \rangle.$$

By the discussion in Sect. 6.1 and the discussion of regular solution in (6), $u(t) \in H^2$ for a.e. $t \in \mathbb{R}_+$. This yields (10.8). \square

Lemma 10.4. *Let B be a bounded open subset of \mathbb{R}^3 , consider a divergence free vector-field $u \in L^r(B, \mathbb{R}^3)$ with $\nabla u \in L^p(B)$, where $r \in [1, \infty]$ and $1 < p < \infty$. Let Ω be an open subset of B with $\overline{\Omega} \subset\subset B$ and with boundary \cdot . Then*

$$u(x) = T(\chi_\Omega \omega) + h(x) \text{ for all } x \in \Omega, \quad (10.9)$$

where h is a harmonic vector-field in Ω .

Proof. We can start by defining h by formula (10.9). Let us consider an open ball \mathbb{B}_1 in Ω , and another ball $\overline{\mathbb{B}}_1 \subset\subset \mathbb{B}_2 \subset \overline{\mathbb{B}}_2 \subset\subset \Omega$. Then let $\varphi \in C_c^\infty(\Omega, [0, 1])$, with $\varphi|_{\mathbb{B}_2} = \chi_{\mathbb{B}_2}$. Then we write

$$\begin{aligned} \tilde{u} &:= T\nabla \times (\varphi u) = T(\varphi \omega) + T(\nabla \varphi \times u) \\ &= T(\chi_\Omega \omega) + \tilde{h} \text{ where } \tilde{h} = T((\varphi - \chi_\Omega)\omega) + T(\nabla \varphi \times u). \end{aligned}$$

Notice that \tilde{h} is harmonic inside \mathbb{B}_1 . Indeed,

$$\Delta \tilde{h} = -\frac{1}{4\pi} \Delta \int_{B \setminus \mathbb{B}_2} \frac{x-y}{|x-y|^3} \times \omega(y) (\varphi(y) - \chi_\Omega(y)) dy - \frac{1}{4\pi} \Delta \int_{B \setminus \mathbb{B}_2} \frac{x-y}{|x-y|^3} \times (\nabla \varphi(y) \times u(y)) dy = 0$$

by $\Delta_x \frac{x-y}{|x-y|^3} = 0$ (this follows from $\Delta r^{-2} = (\partial_r^2 + \frac{2}{r})r^{-2} = 0$ for $r \neq 0$, and then applying ∇ to this equation), for $x \neq y$ and by differentiation with respect to a parameter in an integral. In \mathbb{B}_2 we have

$$\nabla \times (u - \tilde{u}) = \nabla \times (\varphi u - T\nabla \times (\varphi u)) = 0, \quad (10.10)$$

where the 1st equality follows from $u = \varphi u$ in \mathbb{B}_2 and from the definition of \tilde{u} , and where the 2nd equality follows from

$$\mathbb{P}(\varphi u) = T\nabla \times \mathbb{P}(\varphi u) = T\nabla \times (\varphi u) \quad (10.11)$$

where for the 1st equality we apply Lemma 10.2 to $\mathbb{P}(\varphi u)$. This we can do because by $u \in L^r(B, \mathbb{R}^3)$ with $\nabla u \in L^p(B)$, if the boundary ∂B is smooth, by Poincaré–Wirtinger inequality we have

$$\|u - |B|^{-1} \int_B u\|_{L^p(B)} \leq C_B \|\nabla u\|_{L^p(B)}.$$

If the boundary ∂B is not smooth, we can simply replace B by another open domain B' s.t. $\bar{\Omega} \subset\subset B' \subset \bar{B}' \subset\subset B$ with $\partial B'$ is smooth.

Then $u \in W^{1,p}(B, \mathbb{R}^3)$. Obviously also $\varphi u \in W^{1,p}(\mathbb{R}^3, \mathbb{R}^3)$ and so also $\varphi u \in W^{1,p}(B, \mathbb{R}^3)$. If $p \in (1, 3)$ Lemma 10.2 applies to $\mathbb{P}(\varphi u)$. If $p \geq 3$, then $\mathbb{P}(\varphi u) \in W^{1,a}(B, \mathbb{R}^3)$ for any $a \leq p$. This proves (10.11) and completes the proof of (10.10).

From (10.10) and from the usual identity

$$\Delta(u - \tilde{u}) = \nabla(\nabla \cdot (u - \tilde{u})) - \nabla \times (\nabla \times (u - \tilde{u}))$$

we obtain $\Delta(u - \tilde{u})$ in \mathbb{B}_2 . So $u - \tilde{u} = h_1$ with h_1 harmonic in \mathbb{B}_2 . So $u = \tilde{u} + h_1$. Thus we conclude that $u = \tilde{u} + h_1 = T(\chi_\Omega \omega) + h$ with $h := \tilde{h} + h_1$ harmonic vector-field in \mathbb{B}_1 . This implies the statement of the lemma. \square

Recall that, for Ω an open subset of \mathbb{R}^d , the space $C^{k,\alpha}(\Omega)$ with $\alpha \in (0, 1)$ is the subspace of $C^k(\Omega) \cap W^{k,\infty}(\Omega)$ defined by the functions f satisfying the additional conditions

$$\sup_{|\mu|=k} \sup_{x \neq y \text{ in } \Omega} \frac{|\partial^\mu f(x) - \partial^\mu f(y)|}{|x - y|^\alpha} < \infty.$$

Let B_R a ball of radius R and a fixed center(which we can take to be 0) in \mathbb{R}^3 .

Lemma 10.5. *Let $u \in L^\infty((0, T), L^2(B_R))$. Then, for any $R' < R$ we have:*

1. for $\beta \in [2, \infty]$ and $k \in \{0, 1, \dots\}$, $\omega \in L^\beta((0, T), W^{k,\infty}(B_R)) \Rightarrow u \in L^\beta((0, T), W^{k,\infty}(B_{R'}))$;
2. for $\alpha \in (0, 1)$ and $k \in \{0, 1, 2, \dots\}$, $\omega \in L^\beta((0, T), C^{k,\alpha}(B_R)) \Rightarrow u \in L^\beta((0, T), C^{k+1,\alpha'}(B_{R'}))$ for any $\alpha' \in (0, \alpha)$.

Proof. The proof of the first statement is elementary. We consider only case $k = 0$. We fix $R'' \in (R', R)$. Then, by Lemma 10.4 we have

$$u(x) = -\frac{1}{4\pi} \int_{B_{R''}} \frac{x - y}{|x - y|^3} \times \omega(y) dy + h(x) \text{ for all } x \in B_{R''},$$

Since h is harmonic in $B_{R''}$, it follows that $h \in L^\beta((0, T), W^{n,\infty}(B_{R''}))$. Next, for $x \in B_R$ we have

$$\left| \int_{B_{R''}} \frac{x - y}{|x - y|^3} \times \omega(y) dy \right| \leq \int_{B_{R''}} \frac{1}{|x - y|^2} dy \|\omega\|_{L^\infty(B_R)} \leq \int_{B_{2R''}(x)} \frac{1}{|x - y|^2} dy \|\omega\|_{L^\infty(B_R)} = c_3 R'' \|\omega\|_{L^\infty(B_R)}.$$

The 2nd claim in the statement of Lemma 10.5 is more delicate. It is not restrictive to consider only $k = 0$. Using the above discussion, we don't need to worry about h . We consider $\varphi \in C_c^\infty(B_{R''}, [0, 1])$, with $\varphi|_{B_{R'}} = \chi_{B_{R'}}$. Then is

$$u(x) = \int_{B_{R''}} \frac{x-y}{|x-y|^3} \times \omega(y) dy = \int_{B_{R''}} \frac{x-y}{|x-y|^3} \times \omega(y)\varphi(y) dy + \int_{B_{R''}} \frac{x-y}{|x-y|^3} \times \omega(y)(1-\varphi(y)) dy$$

and it is elementary to see, that the 2nd integral on the r.h.s. is smooth in $B_{R'}$. We look then at the 1st integral on the r.h.s. and we absorb φ in ω , simply assuming $\omega \in C_c^{0,\alpha}(B_R)$ and let us consider

$$v(x) := \int_{\mathbb{R}^3} \frac{x-y}{|x-y|^3} \times \omega(y) dy.$$

We have the following lemma.

Lemma 10.6. *Let K be smooth in $\mathbb{R}^d \setminus \{0\}$, homogeneous of degree $-(d-1)$. Then*

$$\langle \partial_j K, \psi \rangle = P.V. \int_{\mathbb{R}^d} \partial_j K(y) \psi(y) dy - c_j \psi(0) \text{ for all } \psi \in C_c^\infty(\mathbb{R}^d), \quad (10.12)$$

where $c_j = \int_{|x|=1} K(x) x_j dS$.

Proof. We have

$$\begin{aligned} -\langle K, \partial_j \psi \rangle &= -\lim_{\epsilon \rightarrow 0^+} \int_{|y| \geq \epsilon} K(y) \partial_j \psi(y) dy = \lim_{\epsilon \rightarrow 0^+} \int_{|y| \geq \epsilon} \partial_j K(y) \psi(y) dy + \lim_{\epsilon \rightarrow 0^+} \int_{|y|=\epsilon} K(y) \psi(y) \frac{y_j}{|y|} dS \\ &= P.V. \int_{\mathbb{R}^d} \partial_j K(y) \psi(y) dy + \psi(0) \int_{|y|=1} K(y) y_j dS. \end{aligned}$$

□

Exercise 10.7. For K like in Lemma 10.6, that is smooth in $\mathbb{R}^d \setminus \{0\}$ and homogeneous of degree $-(d-1)$, we have $\int_{|x|=1} \partial_j K(x) dS = 0$ for any j . Show this in two ways. First way, by using the information that $P.V. \partial_j K \in \mathcal{S}'(\mathbb{R}^d)$. Second way, by a direct computation of the integral $\int_{|x|=1} \partial_j K(x) dS$.

ANSWER. Let us look only at the 2nd approach. It is enough to consider $j = d$. Let us consider cylindrical coordinates

$$\begin{aligned} x_d &= x_d \\ (x_1, \dots, x_{d-1}) &= r\omega \text{ with } r > 0 \text{ and } \omega \in S^{d-2} \end{aligned}$$

Then, for $x_d = \rho \cos \phi$ and $r = \rho \sin \phi$,

$$\begin{aligned} \int_{|x|=1} \partial_d K(x) dS &= \int_{S^{d-2}} dS(\omega) \int_{\substack{x_d^2+r^2=1 \\ r>0}} r^{d-2} \partial_d K d\ell = \int_{S^{d-2}} dS(\omega) \int_0^\pi \sin^{d-2}(\phi) (\cos \phi \partial_\rho K - \sin \phi \partial_\phi K) d\phi \\ &= - \int_{S^{d-2}} dS(\omega) \int_0^\pi ((d-1) \sin^{d-2}(\phi) \cos \phi K + \sin^{d-1}(\phi) \partial_\phi K) d\phi \\ &= - \int_{S^{d-2}} dS(\omega) \sin^{d-1}(\phi) K \Big|_{\phi=0}^{\phi=\pi} = 0 \text{ by } \sin(0) = \sin(\pi) = 0. \end{aligned}$$

Here we used $\partial_{x_a} K = \cos \phi \partial_\rho K - \frac{\sin \phi}{\rho} \partial_\phi K$. \square

Returning to the proof of Lemma 10.5, we can assume initially that $\omega \in C_c^\infty(B_R)$. Then from Lemma 10.6 it is easy to conclude that

$$\nabla v(x) = P.V. \int_{\mathbb{R}^3} \nabla_x \frac{x-y}{|x-y|^3} \times \omega(y) dy + L\omega(x) = P.V. \int_{\mathbb{R}^3} \nabla_y \frac{y-x}{|y-x|^3} \times \omega(y) dy + L\omega(x),$$

with L some fixed linear operator in \mathbb{R}^3 . Obviously $\|L\omega\|_{C^{0,\alpha}(B_{R'})} \leq \|L\| \|\omega\|_{C^{0,\alpha}(B_R)}$, so the key term we need to bound is the P.V.

Let us define $H_{ik}(y-x)$ by

$$\vec{e}_i H_{ik}(y-x) \omega_k(y) = \vec{e}_i \varepsilon_{ijk} \frac{y_j - x_j}{|x-y|^3} \omega_k(y).$$

Then

$$\partial_a v(x) = \vec{e}_i P.V. \int_{\mathbb{R}^3} \partial_{y_a} H_{ik}(y-x) \omega_k(y) dy.$$

An elementary computation shows that

$$K_{ik}^{(a)}(x) := \partial_{x_a} H_{ik}(x) = \varepsilon_{iak} \frac{1}{|x|^3} - 3\varepsilon_{ijk} \frac{x_j x_a}{|x|^5}.$$

These functions are homogeneous degree -3 and satisfy

$$\begin{aligned} \int_{|x|=1} K_{ik}^{(a)}(x) dS &= \varepsilon_{iak} \int_{|x|=1} \frac{1}{|x|^3} dS - 3\varepsilon_{ijk} \int_{|x|=1} \frac{x_j x_a}{|x|^5} dS = 4\pi\varepsilon_{iak} - 3\varepsilon_{iak} \int_{|x|=1} x_3^2 dS \\ &= 4\pi\varepsilon_{iak} - 6\pi\varepsilon_{iak} \int_0^\pi \cos^2(\phi) \sin(\phi) d\phi = 4\pi\varepsilon_{iak} - 6\pi\varepsilon_{iak} \frac{\cos^3(\phi)}{3} \Big|_0^\pi = -4\pi\varepsilon_{iak} - 6\pi\varepsilon_{iak} \left(-\frac{2}{3}\right) = 0. \end{aligned}$$

We claim now that for any $\alpha' \in (0, \alpha)$ there is a constant $C_{\alpha'}$ s.t. for all $x, x' \in B_{R'}$

$$\left| P.V. \int_{\mathbb{R}^3} K_{ik}^{(a)}(y) \omega(x-y) dy - P.V. \int_{\mathbb{R}^3} K_{ik}^{(a)}(y) \omega(x'-y) dy \right| \leq C_{\alpha'} \|\omega\|_{C_c^{0,\alpha}(B_R)} |x-x'|^{\alpha'}. \quad (10.13)$$

This will prove the second claim in the statement of Lemma 10.5 for $\omega \in C_c^\infty(B_R)$, but in fact by density this will extend to all $\omega \in C_c^{0,\alpha}(B_R)$.

The l.h.s. of (10.13) can be written as

$$\left| P.V. \int_{\mathbb{R}^3} K_{ik}^{(a)}(y) (\omega(x'-y) - \omega(x') - \omega(x-y) + \omega(x)) dy \right|$$

by the cancelation $\int_{|x|=1} K_{ik}^{(a)}(x) dS = 0$. It is elementary that

$$|\omega(x'-y) - \omega(x') - \omega(x-y) + \omega(x)| \leq 2\|\omega\|_{C_c^{0,\alpha}(B_R)} \min\{|y|^\alpha, |x'-x|^\alpha\}.$$

Then

$$\begin{aligned}
& \left| P.V. \int_{\mathbb{R}^3} K_{ik}^{(a)}(y) \omega(x' - y) dy - P.V. \int_{\mathbb{R}^3} K_{ik}^{(a)}(y) \omega(x - y) dy \right| \\
& \lesssim \|\omega\|_{C_c^{0,\alpha}(B_R)} \int_{B_{2R}} \frac{1}{|y|^3} \min\{|y|^\alpha, |x' - x|^\alpha\} dy \\
& \lesssim \|\omega\|_{C_c^{0,\alpha}(B_R)} \left(\int_0^{|x'-x|} |y|^{\alpha-1} d|y| + |x' - x|^\alpha \int_{|x'-x|}^{2R} |y|^{-1} d|y| \right) \approx \|\omega\|_{C_c^{0,\alpha}(B_R)} |x' - x|^\alpha |\log |x' - x||.
\end{aligned}$$

□

We end this section with a result not particularly related to the rest of the section, but which will be useful in the sequel.

Lemma 10.8. *Given a field $u \in L^r(\mathbb{R}^3, \mathbb{R}^3)$ for $r \in (2, \infty)$ there is a unique solution $p \in L^{\frac{r}{2}}(\mathbb{R}^3)$ of the equation*

$$-\Delta p = \partial_i \partial_j (u_i u_j) \quad (10.14)$$

which is given by

$$p = \frac{\partial_i}{\sqrt{-\Delta}} \frac{\partial_j}{\sqrt{-\Delta}} (u_i u_j) = R_i R_j (u_i u_j). \quad (10.15)$$

It satisfies

$$\|p\|_{L^{\frac{r}{2}}} \leq C_r \sum_{i,j} \|u_i u_j\|_{L^{\frac{r}{2}}} \leq C_r \|u\|_{L^r}^2. \quad (10.16)$$

Proof. The discussion is similar to that in Lemma 10.2. The estimates follow by the estimates on Riesz transformations. □

Proposition 10.9. *Consider a weak solution u of NS in $d = 3$ with $u \in L^\infty(\mathbb{R}_+, L^2) \cap L^2(\mathbb{R}_+, \dot{H}^1)$ and define the pressure $p \in L^1(\mathbb{R}_+, L^3)$ by the equation (10.14). Then u is a distributional solution in $\mathbb{R}_+ \times \mathbb{R}^3$ of the equation*

$$u_t + u \cdot \nabla u - \nu \Delta u = -\nabla p \quad (10.17)$$

Proof. Recall that u satisfies equation (5.4), and thus, in particular,

$$\int_{\mathbb{R}_+} (\nu \langle u, \Delta \Psi \rangle + \langle u, \partial_t \Psi \rangle - \langle \operatorname{div}(u \otimes u), \Psi \rangle) dt' = 0 \text{ for all } \Psi \in C_{\text{co}}^\infty(\mathbb{R}_+ \times \mathbb{R}^3, \mathbb{R}^3).$$

Exploiting Remark 2.3, which states that $C_{\text{co}}^\infty(\mathbb{R}^3, \mathbb{R}^3)$ is dense in V , we claim that

$$\text{for any } T > 0 \text{ the space } C_{\text{co}}^\infty((0, T) \times \mathbb{R}^3, \mathbb{R}^3) \text{ is dense in } C_c^1((0, T), V). \quad (10.18)$$

To prove (10.18), consider $\Phi \in C_c^1((0, T), V)$ and its derivative $\dot{\Phi} \in C_c^0((0, T), V)$. For any given $\epsilon > 0$, let $0 < t_0 < t_1 < \dots < t_M < T$, with $\dot{\Phi} = 0$ outside $[t_0, t_M]$, and $\|\dot{\Phi}(t) - \dot{\Phi}(s)\|_{H^1} < \epsilon$ for $t, s \in [t_{j-1}, t_j]$, for any $j = 1, \dots, M$. For a $\delta > 0$ to be fixed later, let $\tilde{\Psi}(t_j) \in C_{c\sigma}^\infty(\mathbb{R}^3, \mathbb{R}^3)$ s.t. $\|\tilde{\Psi}(t_j) - \dot{\Phi}(t_j)\|_{H^1} < \delta$ for all $j = 1, \dots, M$ and define $\tilde{\Psi}(t) = \frac{t_j - t}{t_j - t_{j-1}} \tilde{\Psi}(t_{j-1}) + \frac{t - t_{j-1}}{t_j - t_{j-1}} \tilde{\Psi}(t_j)$ for $t \in [t_{j-1}, t_j]$ and $\tilde{\Psi} = 0$ outside $[t_0, t_M]$. Then $\|\tilde{\Psi}(t) - \dot{\Phi}(t)\|_{H^1} < \delta$ for all $t \in [0, T]$. We also have

$$\left\| \int_0^T \tilde{\Psi}(t) dt \right\|_{H^1} \leq T\delta$$

For $\theta \in C_c^0((0, T), [0, 1])$ a cutoff with $\int_0^1 \theta(t) dt = 1$, let

$$\hat{\Psi}(t) = \tilde{\Psi}(t) - \theta(t) \int_0^T \tilde{\Psi}(t) dt$$

Then

$$\|\hat{\Psi}(t) - \dot{\Phi}(t)\|_{H^1} < \delta(T + 1)$$

and for $\hat{\Psi}(t) := \int_0^t \hat{\Psi}(t') dt' \in C_c^1((0, T), V)$ we have $\hat{\Psi}(t) \in C_{c\sigma}^\infty(\mathbb{R}^3, \mathbb{R}^3)$ for any t and

$$\|\hat{\Psi}(t) - \Phi(t)\|_{H^1} < \delta(T + 1)T.$$

Next, taking a cutoff $\rho \in C_c^\infty(\mathbb{R}, [0, 1])$ with $\int_{\mathbb{R}} \rho(t) dt = 1$, we can assume that $\Psi(t) := \rho_h * \hat{\Psi}(t)$ is in $C_c^\infty((0, T), V)$ and that

$$\|\hat{\Psi}(t) - \Psi(t)\|_{C_c^1([0, T], V)} < \delta.$$

Then $\|\Phi(t) - \Psi(t)\|_{C_c^1([0, T], V)} \leq \delta(T + 1)^2 + \delta < \epsilon$, if we pick $\delta > 0$ small enough. This completes the proof of (10.18), since clearly $\Psi \in C_{c\sigma}^\infty((0, T) \times \mathbb{R}^3, \mathbb{R}^3)$.

By (10.18), we claim that

$$\int_{\mathbb{R}_+} (-\nu \langle \nabla u, \nabla \Phi \rangle + \langle u, \partial_t \Phi \rangle - \langle \mathbb{P} \operatorname{div}(u \otimes u), \Phi \rangle) dt' = 0 \text{ for all } \Phi \in C_c^1(\mathbb{R}_+, V), \quad (10.19)$$

which, in particular, implies

$$\int_{\mathbb{R}_+} (\nu \langle u, \Delta \Phi \rangle + \langle u, \partial_t \Phi \rangle - \langle \mathbb{P} \operatorname{div}(u \otimes u), \Phi \rangle) dt' = 0 \text{ for all } \Phi \in C_c^\infty((0, T) \times \mathbb{R}^3, \mathbb{R}^3). \quad (10.20)$$

To get (10.19) consider a sequence $C_{c\sigma}^\infty((0, T) \times \mathbb{R}^3, \mathbb{R}^3) \ni \Phi_n \xrightarrow{n \rightarrow \infty} \Phi$ in $C_c^1([0, T], V)$, for T appropriately large s.t. $\operatorname{supp} \Phi \subset (0, T) \times \mathbb{R}^3$. Then, obviously

$$\int_0^T (-\nu \langle \nabla u, \nabla \Phi_n \rangle + \langle u, \partial_t \Phi_n \rangle) dt' \xrightarrow{n \rightarrow \infty} \int_0^T (-\nu \langle \nabla u, \nabla \Phi \rangle + \langle u, \partial_t \Phi \rangle) dt'$$

and

$$\begin{aligned} \int_0^T |\langle \mathbb{P} \operatorname{div}(u \otimes u), \Phi - \Phi_n \rangle| &\leq \|u \otimes u\|_{L^1((0,T),L^2)} \|\Phi_n - \Phi\|_{C_c^0([0,T],V)} \leq \|u\|_{L^2((0,T),L^4)}^2 \|\Phi_n - \Phi\|_{C_c^0([0,T],V)} \\ &\leq \|\nabla u\|_{L^2((0,T),L^2)}^{\frac{3}{2}} \|u\|_{L^2((0,T),L^2)}^{\frac{1}{2}} \|\Phi_n - \Phi\|_{C_c^0([0,T],V)} \xrightarrow{n \rightarrow \infty} 0. \end{aligned}$$

So, by taking the limit with $n \nearrow \infty$, we obtain (10.19).

Now, looking at (10.20), we can write $\mathbb{P} \operatorname{div}(u \otimes u) = \operatorname{div}(u \otimes u) - (1 - \mathbb{P}) \operatorname{div}(u \otimes u)$. So, by a direct computation which uses $\mathbb{P}v = v + \vec{e}_i R_i R_j v_j$, we have

$$\begin{aligned} \langle \mathbb{P} \operatorname{div}(u \otimes u), \Phi \rangle &= \langle \operatorname{div}(u \otimes u), \Phi \rangle + \langle R_i R_j \partial_k (u^k u^j), \Phi_i \rangle = \langle \operatorname{div}(u \otimes u), \Phi \rangle + \langle \partial_i R_j R_k (u^k u^j), \Phi_i \rangle \\ &= \operatorname{div}(u \otimes u), \Phi \rangle + \langle \nabla p, \Phi \rangle. \end{aligned}$$

So, plugging in the previous equation, we get the desired result:

$$\int_{\mathbb{R}_+} (\nu \langle u, \Delta \Phi \rangle + \langle u, \partial_t \Phi \rangle - \langle \operatorname{div}(u \otimes u), \Phi \rangle - \langle \nabla p, \Phi \rangle) dt' = 0 \text{ for all } \Phi \in C_c^\infty(\mathbb{R}_+ \times \mathbb{R}^3, \mathbb{R}^3).$$

Remark 10.10. Notice that the related remarks at the bottom of p. 116 [13] are based on an incorrect Helmholtz–Weyl decomposition of vector fields in $\mathcal{S}(\mathbb{R}^d, \mathbb{R}^d)$. Notice in particular that the solution of exercise 5.2 in p. 429 is wrong.

11 Local Serrin regularity

In this section we will prove the following result.

Theorem 11.1. *Consider u , a weak solution of NS in $d = 3$ with $u \in L^\infty(\mathbb{R}_+, L^2) \cap L^2(\mathbb{R}_+, \dot{H}^1)$ and suppose that, for an open subspace $U \subseteq \mathbb{R}^3$, we have*

$$u \in L^r((0, T), L^s(U)) \text{ where } \frac{2}{r} + \frac{3}{s} = 1, \text{ with } r \geq 2 \text{ and } s \geq 3, \quad (11.1)$$

excluding case $(r, s) = (0, 3)$. Then for any open $\Omega \subset \bar{\Omega} \subset\subset U$ and any $t_0 \in (0, T]$ $u \in L^\infty((t_0, T), H^k(\Omega))$ for any $k = 0, 1, \dots$ and $u \in C_t^{0,\gamma}([t_0, T], C_x^0(\bar{\Omega}))$ for any $\gamma \in (0, 1/2)$.

Remark 11.2. More generally, for any k there exists a $\gamma \in (0, 1)$ with $u \in C_t^{0,\gamma}([t_0, T], C_x^k(\bar{\Omega}))$.

The case $(r, s) = (0, 3)$ is also true, but is not discussed here.

Theorem 11.1 will be obtained as a consequence of Theorem 11.6, see below, which requires a definition.

Definition 11.3. We say that u is a local weak solution of NS in $(a, b) \times U$ if

1. $u \in L^\infty((a, b), L^2(U))$ and $\nabla u \in L^2((a, b), L^2(U))$ and
2. u satisfies

$$\int_a^b (\langle u, \Delta \Psi \rangle + \langle u, \partial_t \Psi \rangle - \langle \operatorname{div}(u \otimes u), \Psi \rangle) dt' = 0 \text{ for all } \Psi \in C_{cc}^\infty((a, b) \times U, \mathbb{R}^3).$$

Notice that weak solutions in $[0, \infty) \times \mathbb{R}^3$ are local weak solutions in $(a, b) \times U$ for any $a \geq 0$. The viceversa is not true.

Example 11.4 (Serrin's example). Notice that $u(t, x) = \alpha(t)\nabla\psi(x)$, with $\psi : U \rightarrow \mathbb{R}$ harmonic and $\alpha \in L^1(\mathbb{R}_+) \cap L^\infty(\mathbb{R}_+)$ is a local weak solution of NS. Obviously $\langle \alpha\psi, \Delta\Psi \rangle = \langle \alpha\Delta\psi, \Psi \rangle = 0$. Also

$$\langle \operatorname{div}(u \otimes u), \Psi \rangle = \alpha^2 \langle \partial_j \psi \partial_j \partial_k \psi, \Psi_k \rangle = 2^{-1} \alpha^2 \sum_j \langle \partial_k (\partial_j \psi)^2, \Psi_k \rangle = -\alpha^2 \langle |\nabla\psi|^2, \nabla \cdot \Psi \rangle = 0.$$

Finally, by $\nabla \cdot \Psi = 0$,

$$\langle u, \partial_t \Psi \rangle = \alpha^2 \langle \nabla\psi, \partial_t \Psi \rangle = 0.$$

Definition 11.5 (Parabolic cylinders). Given $(t_0, x_0) \in \mathbb{R} \times \mathbb{R}^3$ for any $R > 0$ we will denote by $Q_R^*(t_0, x_0)$ the set

$$Q_R^*(t_0, x_0) = \left(t_0 - \frac{R^2}{2}, t_0 + \frac{R^2}{2} \right) \times B_R(x_0)$$

and with $Q_R(t_0, x_0)$ the set

$$Q_R(t_0, x_0) = (t_0 - R^2, t_0) \times B_R(x_0).$$

Notice the relation

$$Q_R^*(t_0, x_0) = Q_R \left(t_0 + \frac{R^2}{2}, x_0 \right). \quad (11.2)$$

In this section we will use pairs (q', q) of indexes, where q' is not the dual index of q .

The main technical result of this section is the following.

Theorem 11.6. *Consider a local weak solution u in a parabolic cylinder $Q_R(t_0, x_0)$. Then, if*

$$u \in L^{q'} L^q(Q_R(t_0, x_0)) \text{ where } \frac{2}{q'} + \frac{3}{q} \leq 1, \text{ for } q' \geq 2 \text{ and } q \geq 3, \quad (11.3)$$

u is smooth in the x variable in $\overline{Q_{R'}}(t_0, x_0)$ for any $R' \in (0, R)$.

We will not prove the case $(q', q) = (\infty, 3)$, which is more complicated and was proved some time after the other cases in [6]. Notice that, in view of Example 11.4, we cannot get any regularity in t . On the other hand, we will see later how to recover the Hölder regularity for the weak solutions of the NS in Theorem 11.1.

Theorem 11.6 is, in the case $(q', q) \neq (\infty, 3)$, a consequence of the following theorem. Indeed given any point $(a, s) \in Q_R(t_0, x_0)$ we have for $Q_\rho(s, a) \subset Q_R(t_0, x_0)$

$$\|u\|_{L^{q'} L^q(Q_\rho(s, a))} \leq \|u\|_{L^{q'} L^q((s-\rho^2, s) \times B_R(t_0))} \xrightarrow{\rho \rightarrow 0} 0$$

by $q' < \infty$.

Theorem 11.7. *There exists an $\epsilon_{q'q} > 0$ such that if u is a local weak solution in a parabolic cylinder $Q_R(t_0, x_0)$ s.t. u satisfies (11.3), with*

$$\|u\|_{L^{q'}L^q(Q_R(t_0, x_0))} < \epsilon_{q'q}, \quad (11.4)$$

then u is in $L_t^\infty H_x^k(Q_{R'}(t_0, x_0))$ for any $R' \in (0, R)$ and $k \in \mathbb{N}$.

Considering that the condition of u being smooth in Theorem 11.6 is a local condition, it is natural that, in the case $(q', q) \neq (\infty, 3)$, around each point of the cylinder in Theorem 11.6, we can consider a sufficiently small cylinder where (11.4) is satisfied, etc.

We will prove Theorem 11.7 also in the case $(q', q) = (\infty, 3)$. The proof will exploit the vorticity and the following result on the linear heat equation.

Proposition 11.8. *Assume that*

$$\begin{cases} 1 \leq l \leq r \leq \infty, & 1 \leq l' \leq r' < \infty \\ \frac{d}{l} + \frac{2}{l'} \leq \frac{d}{r} + \frac{2}{r'} + 2 \end{cases} \quad (11.5)$$

or, if $r' = \infty$,

$$\begin{cases} 1 \leq l \leq r \leq \infty, & 1 \leq l' \leq r' = \infty \\ \frac{d}{l} + \frac{2}{l'} < \frac{d}{r} + \frac{2}{r'} + 2. \end{cases} \quad (11.6)$$

Then there exists a fixed constant $c(d, l, l', r, r')$ s.t.

$$\left\| \int_a^t e^{\Delta(t-t')} f dt' \right\|_{L^{r'}L^r((a,b) \times \mathbb{R}^d)} < c(d, l, l', r, r') \|f\|_{L^{l'}L^l((a,b) \times \mathbb{R}^d)}. \quad (11.7)$$

We will use an analogous version involving the gradient of f .

Proposition 11.9. *Assume that*

$$\begin{cases} 1 \leq l \leq r \leq \infty, & 1 \leq l' \leq r' < \infty \\ \frac{d}{l} + \frac{2}{l'} \leq \frac{d}{r} + \frac{2}{r'} + 1 \end{cases} \quad (11.8)$$

or, if $r' = \infty$,

$$\begin{cases} 1 \leq l \leq r \leq \infty, & 1 \leq l' \leq r' = \infty \\ \frac{d}{l} + \frac{2}{l'} < \frac{d}{r} + \frac{2}{r'} + 1 \end{cases} \quad (11.9)$$

then there exists a fixed constant $c(d, l, l', r, r')$ s.t.

$$\left\| \int_a^t e^{\Delta(t-t')} \nabla f dt' \right\|_{L^{r'}L^r((a,b) \times \mathbb{R}^d)} < c(d, l, l', r, r') \|f\|_{L^{l'}L^l((a,b) \times \mathbb{R}^d)}. \quad (11.10)$$

Next, we will use the following regularity result, see Appendix B for the proof.

Proposition 11.10. *Assume that $W_t - \Delta W = \partial f$ in $Q_R(t_0, x_0)$ and $W(t_0 - R^2) \equiv 0$. Assume f vanishes outside $\overline{Q}_{\rho_s R}(t_0, x_0)$ for an $\rho_s \in (0, 1)$. Then, for any $\rho_i \in (0, \rho_s)$:*

1. $f \in L^\infty L^\infty(Q_R(t_0, x_0)) \Rightarrow W \in L_t^\infty C_x^{0,\alpha}(\overline{Q}_{\rho_i R}(t_0, x_0))$ for any $\alpha \in (0, 1)$;

2. $f \in L^\infty W^{k,\infty}(Q_R(t_0, x_0)) \Rightarrow W \in L_t^\infty C_x^{k,\alpha}(\overline{Q}_{\rho_i R}(t_0, x_0))$ for any $\alpha \in (0, 1)$;
3. $f \in L^\infty C^{0,\alpha}(Q_R(t_0, x_0))$ for an $\alpha \in (0, 1) \Rightarrow \nabla W \in L_t^\infty L_x^\infty(\overline{Q}_{\rho_i R}(t_0, x_0))$;
4. $f \in L^\infty C^{k,\alpha}(Q_R(t_0, x_0))$ for an $\alpha \in (0, 1) \Rightarrow \nabla^{k+1} W \in L_t^\infty L_x^\infty(\overline{Q}_{\rho_i R}(t_0, x_0))$.

Finally, we will use the following regularity result.

Proposition 11.11. *Assume that $W_t - \Delta W = f$ in $Q_R(t_0, x_0)$ and $W(t_0 - R^2) \equiv 0$. Assume f vanishes outside $\overline{Q}_{\rho_s R}(t_0, x_0)$ for an $\rho_s \in (0, 1)$. Then, for any $\rho_i \in (0, \rho_s)$:*

1. $f \in L^\infty L^\infty(Q_R(t_0, x_0)) \Rightarrow W \in L_t^\infty C_x^{1,\alpha}(\overline{Q}_{\rho_i R}(t_0, x_0))$ for any $\alpha \in (0, 1)$;
2. $f \in L^\infty W^{k,\infty}(Q_R(t_0, x_0)) \Rightarrow W \in L_t^\infty C_x^{k+1,\alpha}(\overline{Q}_{\rho_i R}(t_0, x_0))$ for any $\alpha \in (0, 1)$;
3. $f \in L^\infty C^{0,\alpha}(Q_R(t_0, x_0))$ for an $\alpha \in (0, 1) \Rightarrow \nabla^2 W \in L_t^\infty L_x^\infty(\overline{Q}_{\rho_i R}(t_0, x_0))$;
4. $f \in L^\infty C^{k,\alpha}(Q_R(t_0, x_0))$ for an $\alpha \in (0, 1) \Rightarrow \nabla^{k+2} W \in L_t^\infty L_x^\infty(\overline{Q}_{\rho_i R}(t_0, x_0))$.

For the proofs of Propositions 11.8–11.11 we refer to [13].

The proof of Theorem 11.7 is divided in two parts. The first is the following.

Proposition 11.12. *Consider a local weak solution u in a parabolic cylinder $Q_R(t_0, x_0)$. Then, if*

$$u \in L^{q'} L^q(Q_R(t_0, x_0)) \text{ where } \frac{2}{q'} + \frac{3}{q} < 1, \quad (11.11)$$

u is smooth in the x variable in $\overline{Q_{R'}(t_0, x_0)}$ for any $R' \in (0, R)$.

Proof. It is enough to prove that u is smooth in the x variable in $\overline{Q_{R/2}(t_0, x_0)}$. To proceed we observe that an analogue of Lemma 10.3 shows that the pair (u, ω) satisfies the following analogue of (10.8):

$$\int_0^\infty (\langle \omega, \partial_t \Phi \rangle + \langle \omega, \Delta \Phi \rangle + \langle \omega, u \cdot \nabla \Phi \rangle - \langle u, \omega \cdot \nabla \Phi \rangle) dt' \text{ for all } \Phi \in C_c^\infty(Q_R(t_0, x_0), \mathbb{R}^3). \quad (11.12)$$

We define $W = \phi \omega$ with a cutoff $\phi \in C_c^\infty(\mathbb{R}^4, [0, 1])$ with $\text{supp} \phi \cap (\overline{Q}_R(t_0, x_0)) \subseteq \overline{Q_{\rho_l R}(t_0, x_0)}$, with $\phi = 1$ in $\overline{Q_{\rho_i R}(t_0, x_0)}$, where ρ_i and ρ_l will be chosen later, they depend on the pair (q', q) and satisfy $1/2 < \rho_i < \rho_l < 1$. Then, in a weak sense, the weak formulation of (11.12) implies a weak form of

$$W_t - \Delta W = (W \cdot \nabla)u - \phi(u \cdot \nabla)\omega + (\phi_t - \Delta \phi)\omega - 2\nabla \phi \cdot \nabla \omega.$$

Writing $-2\nabla\phi\cdot\nabla\omega_i = -2\partial_j(\omega_i\partial_j\phi) + 2\omega_i\Delta\phi$, the above equation can be conveniently written as

$$\partial_t W_i - \Delta W_i = \partial_j(W_j u_i - W_i u_j) - 2\partial_j(\omega_i\partial_j\phi) \quad (11.13)$$

$$+ (\phi_t + \Delta\phi)\omega_i - \partial_j\phi(\omega_j u_i - \omega_i u_j). \quad (11.14)$$

The proof of Proposition 11.12 is divided in two parts. In the first, we will prove that $\omega \in L^\infty L^\infty(Q_{3R/4}(t_0, x_0))$. Let us assume this and see the conclusion of Proposition 11.12.

The rather standard second part of the proof of Proposition 11.12, starts by noticing that Lemma 10.5 implies, for $k = 0$, $u \in L_t^\infty W_x^{k,\infty}(Q_{R'_k}(t_0, x_0))$ for any $R'_k \in (R/2, 3R/4)$. Having $u, \omega \in L_t^\infty W_x^{k,\infty}(Q_{R'_k}(t_0, x_0))$ we can fix an arbitrary $R''_k \in (R/2, R'_k)$. Then let us consider a cutoff $\phi \in C_c^\infty(\mathbb{R}^4, [0, 1])$ with $\text{supp}\phi \cap \overline{Q_{3R/4}(t_0, x_0)} \subseteq \overline{Q_{R'_k}(t_0, x_0)}$ and with $\phi = 1$ in $\overline{Q_{R''_k}(t_0, x_0)}$. For $W = \phi\omega$ we have the above equation. Applying Propositions 11.10–11.11 in $Q_{R'_k}(t_0, x_0)$ we obtain $W \in L_t^\infty C_x^{k,\alpha}(\overline{Q_{R'_k}(t_0, x_0)})$, that is $\omega \in L_t^\infty C_x^{k,\alpha}(\overline{Q_{R'_k}(t_0, x_0)})$ from $\phi = 1$ in $\overline{Q_{R''_k}(t_0, x_0)}$, for any $\alpha \in (0, 1)$. Then Lemma 10.5 implies $u \in L_t^\infty C_x^{k,\alpha}(\overline{Q_{R''_k}(t_0, x_0)})$ for any $R''_k \in (R/2, R'_k)$ and for any $\alpha \in (0, 1)$. Now we fix $R_k^{(4)} \in (R/2, R''_k)$ and a cutoff $\phi \in C_c^\infty(\mathbb{R}^4, [0, 1])$ with $\text{supp}\phi \cap \overline{Q_{3R/4}(t_0, x_0)} \subseteq \overline{Q_{R_k^{(4)}}(t_0, x_0)}$ with $\phi = 1$ in $\overline{Q_{R_k^{(4)}}(t_0, x_0)}$. For $W = \phi\omega$ we have the above equation. Applying Propositions 11.10–11.11 in $Q_{R_k^{(4)}}(t_0, x_0)$ we obtain $\nabla^{k+1}W \in L_t^\infty L_x^\infty(\overline{Q_{R_k^{(4)}}(t_0, x_0)})$ combined with $W \in L_t^\infty C_t^{k,\alpha}(\overline{Q_{R_k^{(4)}}(t_0, x_0)})$. Thus $\nabla^{k+1}\omega \in L_t^\infty L_x^\infty(\overline{Q_{R_k^{(4)}}(t_0, x_0)})$ and $\omega \in L_t^\infty C_x^{k,\alpha}(\overline{Q_{R_k^{(4)}}(t_0, x_0)})$. For $R'_{k+1} = R_k^{(4)}$, we can repeat the argument with k replaced by $k + 1$. By induction there is a decreasing sequence $\{R_n\}$ with $R_n > R/2$ with $u \in L_t^\infty C^n(\overline{Q_{R_n}(t_0, x_0)})$ for any $n \in \mathbb{N}$.

We now start the proof of $\omega \in L^\infty L^\infty(Q_{3R/4}(t_0, x_0))$. We start by assuming $\omega \in L^{m'} L^m(Q_R(t_0, x_0))$ for some (m', m) . This is certainly true for $(m', m) = (2, 2)$. Obviously, we assume $(m', m) \neq (\infty, \infty)$, since otherwise there is nothing to prove. As we did above, we consider $W = \phi\omega$ with a cutoff $\phi \in C_c^\infty(\mathbb{R}^4, [0, 1])$ with $\text{supp}\phi \cap \overline{Q_R(t_0, x_0)} \subseteq \overline{Q_{\rho_l R}(t_0, x_0)}$ and with $\phi = 1$ in $\overline{Q_{\rho_l R}(t_0, x_0)}$. Notice that $W \in L^{m'} L^m((t_0 - R^2, t_0) \times \mathbb{R}^3)$.

Using Propositions 11.8–11.9, we have

$$\|W\|_{L^{r'} L^r} \lesssim \|Wu\|_{L^{a'} L^a} + \|\omega\nabla\phi\|_{L^{m'} L^m} + \|(\phi_t + \Delta\phi)\omega\|_{L^{l'} L^l} + \|\omega u \nabla\phi\|_{L^{l'} L^l} \quad (11.15)$$

where

$$\begin{cases} 1 \leq a \leq r \leq \infty, & 1 \leq a' \leq r' \leq \infty \\ \frac{3}{a} + \frac{2}{a'} < \frac{3}{r} + \frac{2}{r'} + 1 \end{cases}, \quad \begin{cases} 1 \leq m \leq r \leq \infty, & 1 \leq m' \leq r' \leq \infty \\ \frac{3}{m} + \frac{2}{m'} < \frac{3}{r} + \frac{2}{r'} + 1 \end{cases} \quad (11.16)$$

$$\begin{cases} 1 \leq l \leq r \leq \infty, & 1 \leq l' \leq r' \leq \infty \\ \frac{3}{l} + \frac{2}{l'} < \frac{3}{r} + \frac{2}{r'} + 2 \end{cases}.$$

Now we have to choose the indexes. Recall that $u \in L^{q'} L^q(Q_R(t_0, x_0))$, see (11.3). We consider

$$\frac{1}{l} = \frac{1}{a} = \frac{1}{q} + \frac{1}{m} \quad \text{and} \quad \frac{1}{l'} = \frac{1}{a'} = \frac{1}{q'} + \frac{1}{m'}. \quad (11.17)$$

Here notice that from $\frac{2}{q} + \frac{3}{q'} < 1$ obviously we have $q > 2$ and $q' > 3$, to that from $m \geq 2$ and $m' \geq 2$, we have $l \geq 1$ and $l' \geq 1$.

Inequalities (11.16) become

$$\begin{aligned}\frac{3}{m} + \frac{3}{q} + \frac{2}{m'} + \frac{2}{q'} &< \frac{3}{r} + \frac{2}{r'} + 1, \\ \frac{3}{m} + \frac{2}{m'} &< \frac{3}{r} + \frac{2}{r'} + 1 \\ \frac{3}{m} + \frac{3}{q} + \frac{2}{m'} + \frac{2}{q'} &< \frac{3}{r} + \frac{2}{r'} + 2,\end{aligned}$$

where obviously the 1st implies the other two. Then we have

$$\|W\|_{L^{r'}L^r} \lesssim \|W\|_{L^{m'}L^m} \|u\|_{L^{q'}L^q} + \|u\|_{L^{q'}L^q} \|\omega\|_{L^{m'}L^m} + \|\omega\|_{L^{m'}L^m}. \quad (11.18)$$

In fact we get $\|W\|_{L^{r'}L^r((t_0-R^2, t_0) \times \mathbb{R}^3)} \lesssim \|\omega\|_{L^{m'}L^m(Q_R(t_0, x_0))}$, where

$$\frac{3}{m} - \frac{3}{r} + \frac{2}{m'} - \frac{2}{r'} < 1 - \frac{3}{q} - \frac{2}{q'}. \quad (11.19)$$

Since by hypothesis the r.h.s. in (11.19) is strictly positive and (m', m) are given, we can find $m \leq r$ and $m' \leq r'$, not both equal, so that (11.25) is true. In fact this can be written in a systematic way, setting $\chi := \frac{1}{6} \left(1 - \frac{3}{q} - \frac{2}{q'}\right)$ and defining

$$r = \begin{cases} \frac{m}{1-\chi m} & \text{if } m\chi < 1 \\ \infty & \text{if } m\chi \geq 1 \end{cases} \quad \text{and} \quad r' = \begin{cases} \frac{m'}{1-\chi m'} & \text{if } m'\chi < 1 \\ \infty & \text{if } m'\chi \geq 1. \end{cases} \quad (11.20)$$

With these choices we have $\frac{3}{m} - \frac{3}{r} \leq 3\chi$ and $\frac{2}{m'} - \frac{2}{r'} \leq 2\chi$, so that $\frac{3}{m} - \frac{3}{r} + \frac{2}{m'} - \frac{2}{r'} \leq 5\chi < 1 - \frac{3}{q} - \frac{2}{q'}$. Then we have obtained

$$\omega \in L^{m'}L^m(Q_R(t_0, x_0)) \implies \omega \in L^{\frac{m'}{1-\chi m'}}L^{\frac{m}{1-\chi m}}(Q_{\rho_i R}(t_0, x_0)).$$

We repeat this argument until both exponents are (∞, ∞) . Notice that if we repeat the procedure k times, we reach $\omega \in L^{\frac{m'}{1-k\chi m'}}L^{\frac{m}{1-k\chi m}}(Q_{\rho_i^k R}(t_0, x_0))$, since, for $km < 1$,

$$\frac{\frac{m}{1-(k-1)\chi m}}{1 - \chi \frac{m}{1-(k-1)\chi m}} = \frac{m}{1 - (k-1)\chi m - \chi m} = \frac{m}{1 - k\chi m}.$$

It is clear that, after a finite number k of iterations, with k dependent on the initial pairs (m', m) and (q', q) , the procedure has to stop because, for example, either we get to $\chi \frac{m}{1-k\chi m} \geq 1$ or $1 - k\chi m < 0$. But $1 - k\chi m < 0$ cannot occur if $0 < \chi \frac{m}{1-(k-1)\chi m} < 1$ in the previous iterate. Hence at some point we get to $\chi \frac{m}{1-k\chi m} \geq 1$, so that from that iterate on, we have $r = \infty$. For r' the same argument is true. So, after a finite number of iterate, we obtain the pair (∞, ∞) . We also choose $3/4 < \rho_i < \rho_l < 1$ so that $\rho_i^k > 3/4$ for all the finitely many iterates. □

Now we consider the 2nd part of the proof of Theorem 11.7.

Proposition 11.13. *There exists an $\epsilon_{q'q} > 0$ such that if u is a local weak solution in a parabolic cylinder $Q_R(t_0, x_0)$ which satisfies (11.3) with $\frac{2}{q'} + \frac{3}{q} = 1$ and if*

$$\|u\|_{L^{q'}L^q(Q_R(t_0, x_0))} < \epsilon_{q'q}, \quad (11.21)$$

then u is smooth in the x variable in $Q_{R'}(t_0, x_0)$ for any $R' \in (0, R)$.

The proof consists in finding $\beta' > 2$ s.t. $u \in L^{\beta'}L^\infty(Q_{R'}(t_0, x_0))$ for any $R' \in (0, R)$. Then we can apply Proposition 11.12.

Notice that we can normalize and consider $R = 1$, thanks to scaling. It would be reasonable to proceed as in the proof of Proposition 11.12, starting with $\omega \in L^{m'}L^m(Q_R(t_0, x_0))$ and then reaching $\omega \in L^{\beta'}L^\infty(Q_{R'}(t_0, x_0))$, and then to apply Lemma 10.5.

So we could consider (11.15)

$$\begin{cases} 1 \leq a \leq r \leq \infty, & 1 \leq a' \leq r' < \infty \\ \frac{3}{a} + \frac{2}{a'} = \frac{3}{r} + \frac{2}{r'} + 1 \end{cases}, \quad \begin{cases} 1 \leq m \leq r \leq \infty, & 1 \leq m' \leq r' < \infty \\ \frac{3}{m} + \frac{2}{m'} \leq \frac{3}{r} + \frac{2}{r'} + 1 \end{cases} \\ \begin{cases} 1 \leq l \leq r \leq \infty, & 1 \leq l' \leq r' < \infty \\ \frac{3}{l} + \frac{2}{l'} \leq \frac{3}{r} + \frac{2}{r'} + 2 \end{cases}. \end{cases} \quad (11.22)$$

Next, in analogy to (11.17) we could consider

$$\frac{1}{l} = \frac{1}{q} + \frac{1}{m} \text{ and } \frac{1}{l'} = \frac{1}{q'} + \frac{1}{m'}, \quad (11.23)$$

while we need to take, here $\frac{1}{r} + \frac{1}{q} \leq 1$ (because $r \geq 2$ and $q \geq 3$) and $\frac{1}{r'} + \frac{1}{q'} \leq 1$,

$$\frac{1}{a} = \frac{1}{q} + \frac{1}{r} \text{ and } \frac{1}{a'} = \frac{1}{q'} + \frac{1}{r'}. \quad (11.24)$$

Here the point is that if we chose exactly (11.17), we would be forced, from

$$0 \leq \frac{3}{m} - \frac{3}{r} + \frac{2}{m'} - \frac{2}{r'} \leq 1 - \frac{3}{q} - \frac{2}{q'} = 0$$

and from $m \leq r$ and $m' \leq r'$, to have exactly $(m, m') = (r, r')$. So (11.23), gives us a little more of flexibility. Indeed (11.22) reduce to

$$\begin{cases} 1 \leq m \leq r \leq \infty, & 1 \leq m' \leq r' < \infty \\ \frac{3}{m} - \frac{3}{r} + \frac{2}{m'} - \frac{2}{r'} \leq 1 \end{cases} \quad (11.25)$$

and we can certainly pick $m \leq r$ and $m' \leq r'$ appropriate and not both equalities if (m', m) is not of the form (β', ∞) with $\beta' > 0$.

Then we obtain, in $Q_R(t_0, x_0)$,

$$\|W\|_{L^{r'}L^r} \lesssim \|W\|_{L^{r'}L^r} \|u\|_{L^{q'}L^q} + \|u\|_{L^{q'}L^q} \|\omega\|_{L^{m'}L^m} + \|\omega\|_{L^{m'}L^m} \lesssim \|W\|_{L^{r'}L^r} \|u\|_{L^{q'}L^q} + \|\omega\|_{L^{m'}L^m}. \quad (11.26)$$

Then, from $\|u\|_{L^{q'}L^q} < \epsilon_{q'q}$, for $\epsilon_{q'q}$ small enough we would absorb the $\|W\|_{L^{r'}L^r}\|u\|_{L^{q'}L^q}$ into the l.h.s., obtaining

$$\|W\|_{L^{r'}L^r(Q_R(t_0,x_0))} \lesssim \|\omega\|_{L^{m'}L^m(Q_R(t_0,x_0))}. \quad (11.27)$$

Then we could improve until we get to the desired (β', ∞) . In fact, for $\chi = 1/6$, we can proceed like in (11.20) obtaining $\frac{3}{m} - \frac{3}{r} \leq 3\chi$ and $\frac{2}{m'} - \frac{2}{r'} \leq 2\chi$, so that $\frac{3}{m} - \frac{3}{r} + \frac{2}{m'} - \frac{2}{r'} \leq 5\chi < 1$. After a finite number of iterates, we would get to (β', ∞) and stop.

The above argument is however just formal, because it assumes implicitly that $\|W\|_{L^{r'}L^r} < \infty$. To perform rigorously the argument, we consider a mollification, both in space and time. We still can consider the equation (11.13)–(11.14) for W . Now consider

$$\begin{aligned} \partial_t W_i^\epsilon - \Delta W_i^\epsilon &= \partial_j (W_j^\epsilon u_i^\epsilon - W_i^\epsilon u_j^\epsilon) - 2\partial_j (\omega_i \partial_j \phi) \\ &\quad + (\phi_t + \Delta \phi) \omega_i^\epsilon - \partial_j \phi (\omega_j^\epsilon u_i^\epsilon - \omega_i^\epsilon u_j^\epsilon), \end{aligned} \quad (11.28)$$

where W_i^ϵ is an unknown and the $(u^\epsilon, \omega^\epsilon) := \rho_\epsilon * (u, \omega)$ and $W_i^\epsilon(t_0 - R^2) = 0$, where we extend $(\omega, u) = 0$ in $\mathbb{R}^4 \setminus Q_R(t_0, x_0)$.

Now the previous argument works, and we obtain for a fixed c (notice that in the equation, ω^ϵ appears with factors involving ϕ which live in $Q_R(t_0, x_0)$)

$$\|W^\epsilon\|_{L^{r'}L^r((t_0-R^2,t_0)\times\mathbb{R}^3)} \leq c\|\omega^\epsilon\|_{L^{m'}L^m((t_0-R^2,t_0)\times\mathbb{R}^3)}.$$

There exists a sequence $\epsilon_n \xrightarrow{n \rightarrow \infty} 0$, such that $W^{\epsilon_n} \rightharpoonup \overline{W}$ in $L^{r'}L^r((t_0 - R^2, t_0) \times \mathbb{R}^3)$, and we have

$$\|\overline{W}\|_{L^{r'}L^r((t_0-R^2,t_0)\times\mathbb{R}^3)} \leq c\|\omega\|_{L^{m'}L^m(Q_R(t_0,x_0))}. \quad (11.29)$$

Now we have to establish that $\overline{W} = W$ in $L^{r'}L^r((t_0 - R^2, t_0) \times \mathbb{R}^3)$ to obtain

$$\|W\|_{L^{r'}L^r(Q_R(t_0,x_0))} \leq c\|\omega\|_{L^{m'}L^m(Q_R(t_0,x_0))}.$$

and so, restricting the domain in the left

$$\|W\|_{L^{r'}L^r(Q_{\rho_i R}(t_0,x_0))} \leq c\|\omega\|_{L^{m'}L^m(Q_R(t_0,x_0))}.$$

Once we do this, we conclude that the formal argument leading to (11.27) is correct.

The first step to prove $\overline{W} = W$, is to show that \overline{W} is a weak solution of (11.13)–(11.14). Taking a test function $\psi \in C_c^\infty([t_0 - R^2, t_0] \times \mathbb{R}^3, \mathbb{R}^3)$, from (11.28) we have

$$\begin{aligned} 0 &= \int_{t_0-R^2}^{t_0} (\langle W_i^{\epsilon_n}, \partial_t \psi_i \rangle + \langle W_i^{\epsilon_n}, \Delta \psi_i \rangle) dt' - \int_{t_0-R^2}^{t_0} \langle W_j^{\epsilon_n} u_i^{\epsilon_n} - W_i^{\epsilon_n} u_j^{\epsilon_n}, \partial_j \psi_i \rangle dt' \\ &\quad + 2 \int_{t_0-R^2}^{t_0} \langle \omega_i^{\epsilon_n} \partial_j \phi, \partial_j \psi_i \rangle dt' + \int_{t_0-R^2}^{t_0} \langle (\phi_t + \Delta \phi) \omega_i^{\epsilon_n}, \partial_j \psi_i \rangle dt' + \int_{t_0-R^2}^{t_0} \langle \partial_j \phi (\omega_j^{\epsilon_n} u_i^{\epsilon_n} - \omega_i^{\epsilon_n} u_j^{\epsilon_n}), \psi_i \rangle dt'. \end{aligned}$$

Taking the limit $n \rightarrow \infty$ we get

$$0 = \int_{t_0-R^2}^{t_0} (\langle \overline{W}_i, \partial_t \psi_i \rangle + \langle \overline{W}_i, \Delta \psi_i \rangle) dt' - \lim_{n \rightarrow +\infty} \int_{t_0-R^2}^{t_0} \langle W_j^{\epsilon_n} u_i^{\epsilon_n} - W_i^{\epsilon_n} u_j^{\epsilon_n}, \partial_j \psi_i \rangle dt' \\ + 2 \int_{t_0-R^2}^{t_0} \langle \omega_i \partial_j \phi, \partial_j \psi_i \rangle dt' + \int_{t_0-R^2}^{t_0} \langle (\phi_t + \Delta \phi) \omega_i, \partial_j \psi_i \rangle dt' + \int_{t_0-R^2}^{t_0} \langle \partial_j \phi (\omega_j u_i - \omega_i u_j), \psi_i \rangle dt'.$$

Now we show that

$$\lim_{n \rightarrow +\infty} \int_{t_0-R^2}^{t_0} \langle W_j^{\epsilon_n} u_i^{\epsilon_n} - W_i^{\epsilon_n} u_j^{\epsilon_n}, \partial_j \psi_i \rangle dt' = \int_{t_0-R^2}^{t_0} \langle W_j u_i - W_i u_j, \partial_j \psi_i \rangle dt'.$$

We have

$$\int_{t_0-R^2}^{t_0} \langle W_j^{\epsilon_n} u_i^{\epsilon_n}, \partial_j \psi_i \rangle dt' = \int_{t_0-R^2}^{t_0} \langle W_j^{\epsilon_n} u_i, \partial_j \psi_i \rangle dt' + \int_{t_0-R^2}^{t_0} \langle W_j^{\epsilon_n} (u_i^{\epsilon_n} - u_i), \partial_j \psi_i \rangle dt'.$$

But now

$$\int_{t_0-R^2}^{t_0} \langle W_j^{\epsilon_n} u_i, \partial_j \psi_i \rangle dt' \xrightarrow{n \rightarrow \infty} \int_{t_0-R^2}^{t_0} \langle \overline{W}_j u_i, \partial_j \psi_i \rangle dt'$$

while

$$\left| \int_{t_0-R^2}^{t_0} \langle W_j^{\epsilon_n} (u_i^{\epsilon_n} - u_i), \partial_j \psi_i \rangle dt' \right| \leq C \|W_j^{\epsilon_n}\|_{L^{r'} L^r((t_0-R^2, t_0) \times \mathbb{R}^3)} \|u_i^{\epsilon_n} - u_i\|_{L^{q'} L^q((t_0-R^2, t_0) \times \mathbb{R}^3)} \\ \leq C' \|\omega^{\epsilon_n}\|_{L^{r'} L^r((t_0-R^2, t_0) \times \mathbb{R}^3)} \|u_i^{\epsilon_n} - u_i\|_{L^{q'} L^q((t_0-R^2, t_0) \times \mathbb{R}^3)} \\ \leq C' \|\omega\|_{L^{r'} L^r((t_0-R^2, t_0) \times \mathbb{R}^3)} \|u_i^{\epsilon_n} - u_i\|_{L^{q'} L^q((t_0-R^2, t_0) \times \mathbb{R}^3)} \xrightarrow{n \rightarrow \infty} 0.$$

Notice that here $\frac{1}{r} + \frac{1}{q} \leq 1$ (because $r \geq 2$ and $q \geq 3$) and $\frac{1}{r'} + \frac{1}{q'} \leq 1$ (because $r' \geq 2$ and $q' \geq 2$) justify the above use of Hölder inequality.

So we conclude that for any $\psi \in C_c^\infty([t_0 - R^2, t_0) \times \mathbb{R}^3, \mathbb{R}^3)$

$$0 = \int_{t_0-R^2}^{t_0} (\langle \overline{W}_i, \partial_t \psi_i \rangle + \langle \overline{W}_i, \Delta \psi_i \rangle) dt' - \int_{t_0-R^2}^{t_0} \langle \overline{W}_j, u_i - \overline{W}_i u_j, \partial_j \psi_i \rangle dt' \\ + 2 \int_{t_0-R^2}^{t_0} \langle \omega_i \partial_j \phi, \partial_j \psi_i \rangle dt' + \int_{t_0-R^2}^{t_0} \langle (\phi_t + \Delta \phi) \omega_i, \partial_j \psi_i \rangle dt' + \int_{t_0-R^2}^{t_0} \langle \partial_j \phi (\omega_j u_i - \omega_i u_j), \psi_i \rangle dt'.$$

This implies that $\overline{W} \in L^{r'} L^r([t_0 - R^2, t_0) \times \mathbb{R}^3, \mathbb{R}^3)$ is a distributional solution of (11.13)–(11.14) with initial datum $\overline{W}(t_0 - R^2) = 0$, see Takahashi [17]. Then, taking the difference between the equations of \overline{W} and W , we have

$$\partial_t(W_i - \overline{W}_i) - \Delta(W_i - \overline{W}_i) = \partial_j((W_j - \overline{W}_j)u_i - (W_i - \overline{W}_i)u_j) \text{ with } (W - \overline{W})(t_0 - R^2) = 0$$

in a weak sense, that is for any $\psi \in C_c^\infty([t_0 - R^2, t_0] \times \mathbb{R}^3, \mathbb{R}^3)$

$$0 = \int_{t_0 - R^2}^{t_0} (\langle W_i - \overline{W}_i, \partial_t \psi_i \rangle + \langle W_i - \overline{W}_i, \Delta \psi_i \rangle) dt' - \int_{t_0 - R^2}^{t_0} \langle (W_j - \overline{W}_j)u_i - (W_i - \overline{W}_i)u_j, \partial_j \psi_i \rangle dt'.$$

We can apply Propositions 11.8–11.9 to $\overline{W} - W$, see Takahashi [17]. For

$$\frac{3}{l} + \frac{2}{l'} \leq \frac{3}{r} + \frac{2}{r'} + 1 = \frac{3}{r} + \frac{2}{r'} + \frac{3}{q} + \frac{2}{q'},$$

we have

$$\begin{aligned} \|W - \overline{W}\|_{L^{r'} L^r(Q_R(t_0, x_0))} &\lesssim \|(W - \overline{W})u\|_{L^{l'} L^l(Q_R(t_0, x_0))} \\ &\lesssim \|W - \overline{W}\|_{L^{r'} L^r(Q_R(t_0, x_0))} \|u\|_{L^{q'} L^q(Q_R(t_0, x_0))} \leq \epsilon_{q'q} \|W - \overline{W}\|_{L^{r'} L^r(Q_R(t_0, x_0))}, \end{aligned}$$

where we are free to choose a $L^{r'} L^r(Q_R(t_0, x_0))$ s.t. both W and \overline{W} belong to it. We exploited the fact that $\|u\|_{L^{q'} L^q((t_0 - R^2, t_0) \times \mathbb{R}^3)} = \|u\|_{L^{q'} L^q(Q_R(t_0, x_0))}$ and, in the left hand side, that $\|W - \overline{W}\|_{L^{r'} L^r(Q_R(t_0, x_0))} \leq \|W - \overline{W}\|_{L^{r'} L^r((t_0 - R^2, t_0) \times \mathbb{R}^3)}$.

Now we exploit that $\epsilon_{q'q}$ is small, to conclude that $W = \overline{W}$ in $Q_R(t_0, x_0)$. This completes the proof of Proposition 11.13. \square

End of the proof of Theorem 11.1. By Theorem 11.6, in particular by its proof, we know that $\Delta u \in L^\infty[t_0, T], L^\infty(\Omega)$ for $\Omega \subset \overline{\Omega} \subset\subset U$ and for any $t_0 \in (0, T)$. Next, we claim that

$$u \cdot \nabla u + \nabla p \in L^{\frac{2r}{4r-3}}((0, T), L^r(\mathbb{R}^3)) \text{ for all } 1 < r \leq 3/2. \quad (11.30)$$

Assuming (11.30), it follows from (10.17) that $u \in W^{1, \frac{2r}{4r-3}}(t_0, T), L^r(\Omega)$. We know that elements of $W^{1, \frac{2r}{4r-3}}((t_0, T), L^r(\Omega))$ are classes of functions and that, by Sobolev's inequality, one of the elements of this class is in $C^{0, \alpha}([t_0, T], L^r(\Omega))$ for $\alpha = 1 - \frac{4r-3}{2r} = \frac{3-2r}{2r}$. In fact, by $u \in C^0([0, T], L_w^2(\mathbb{R}^3))$, it is easy to conclude that $u \in C^{0, \alpha}([t_0, T], L^r(\Omega))$, so that

$$\|u(t) - u(s)\|_{L^r(\Omega)} \leq c|t - s|^\alpha \text{ for } t_0 \leq s < t \leq T. \quad (11.31)$$

Next, by the variation of Agmon's inequality in (2.38), for almost any pair (t, s) in (t_0, T) we have

$$\begin{aligned} \|u(t) - u(s)\|_{L^\infty(\Omega)} &\leq C_{\Omega, k, r} \|u(t) - u(s)\|_{L^r(\Omega)}^\theta \|u(t) - u(s)\|_{H^k(\Omega)}^{1-\theta} \text{ with } \theta = \frac{r(k - \frac{3}{2})}{kr + \frac{3}{2}(2-r)} \\ &\leq C'_{k, r} |t - s|^{\alpha\theta} = C'_{k, r} |t - s|^{\frac{3-2r}{2} \frac{(k - \frac{3}{2})}{kr + \frac{3}{2}(2-r)}}. \end{aligned} \quad (11.32)$$

Then, for any $\gamma < 1/2$ we can find $r \in (1, 3/2)$ and $k \in \mathbb{N}$ s.t. $\gamma = \alpha\theta$ so that

$$\|u(t) - u(s)\|_{L^\infty(\Omega)} \leq C_\gamma |t - s|^\gamma \text{ for almost any pair } (t, s) \text{ in } (t_0, T). \quad (11.33)$$

Notice that (11.31) and (11.33), together imply that (11.33) must be true for all pairs (t, s) in (t_0, T) and on Ω . Hence we have proved that $u \in C_t^{0,\gamma}([t_0, T], C_x^0(\Omega))$. In fact, this extends to an element of $C_t^{0,\gamma}([t_0, T], C_x^0(\bar{\Omega}))$, and by the continuity $u \in C^0([0, T], L_w^2(\mathbb{R}^3))$ we conclude that the extension in $C_t^{0,\gamma}([t_0, T], C_x^0(\bar{\Omega}))$ is exactly u . With this the proof of Theorem 11.1 is completed except for (11.30).

To prove (11.30) notice first of all that a weak solution satisfies

$$u \in L^s((0, T), L^r(\mathbb{R}^3)) \text{ for all } \frac{2}{s} + \frac{3}{r} = 3/2. \quad (11.34)$$

Indeed the case $(s, r) = (\infty, 2)$ follows from $u \in L^\infty(\mathbb{R}_+, L^2(\mathbb{R}^3))$ and case $(s, r) = (2, 6)$ from $\nabla u \in L^2(\mathbb{R}_+, L^2(\mathbb{R}^3))$ and Sobolev's embedding. The intermediate cases are obtained by Hölder inequality. Next, by Hölder inequality we get

$$\|u \cdot \nabla u\|_r \leq \|\nabla u\|_2 \|u\|_{\frac{2r}{2-r}},$$

where $\frac{2r}{2-r} \leq 6 \Leftrightarrow r \leq 3/2$. Now, since the pair $\left(\frac{2r}{3r-3}, \frac{2r}{2-r}\right)$ satisfies the condition in (11.34), we obtain

$$\|u \cdot \nabla u\|_{L^{\frac{2r}{4r-3}}((0, T), L^r)} \leq \|\nabla u\|_{L^2(\mathbb{R}_+, L^2)} \|u\|_{L^{\frac{2r}{3r-3}}((0, T), L^{\frac{2r}{2-r}})}.$$

The same is true for $\mathbb{P}(u \cdot \nabla u)$ and for $\nabla p = (1 - \mathbb{P})(u \cdot \nabla u)$, proving (11.30). This proves $u \in C_t^{0,\gamma}([t_0, T], C_x^0(\bar{\Omega}))$ for any $\gamma \in (0, 1/2)$ and any $t_0 \in (0, T)$ and any open $\Omega \subset \bar{\Omega} \subset\subset U$. \square

Remark 11.14. Notice that it is easy to prove

$$\|\nabla f\|_{L^\infty(\Omega)} \leq C \|f\|_{L^r(\Omega)}^\theta \|f\|_{H^k(\Omega)}^{1-\theta}$$

for appropriate θ and in fact more generally

$$\|\nabla^l f\|_{L^\infty(\Omega)} \leq C \|f\|_{L^r(\Omega)}^{\theta_l} \|f\|_{H^k(\Omega)}^{1-\theta_l}$$

for appropriate θ_l with $l \leq L$ and $k - L$ sufficiently large. Then, one can repeat the argument and prove $u \in C_t^{0,\gamma}([t_0, T], C_x^{L-2}(\bar{\Omega}))$ for L arbitrary and appropriate $\gamma \in (0, 1)$ and for any $t_0 \in (0, T)$ and any open $\Omega \subset \bar{\Omega} \subset\subset U$. This yields the result stated in Remark 11.2.

12 Local energy inequality

We will later need *suitable* weak solutions.

Proposition 12.1 (Global suitable weak solutions). *Consider $u_0 \in L^2(\mathbb{R}^3, \mathbb{R}^3)$ and a Leray–Hopf solution u proved to exist in Sect. 5. Then u satisfies the following Local*

Energy Inequality:

$$\begin{aligned}
2 \int_0^T \int_{\mathbb{R}^3} |\nabla u|^2 \varphi dx ds &\leq \int_0^T \int_{\mathbb{R}^3} |u|^2 (\varphi_t + \Delta \varphi) dx ds \\
+ \int_0^T \int_{\mathbb{R}^3} (|u|^2 + 2p)(u \cdot \nabla) \varphi dx ds &\text{ for all } \varphi \in C_c^\infty((0, T) \times \mathbb{R}^3, [0, +\infty)),
\end{aligned} \tag{12.1}$$

where p is defined by (10.15).

Proof. Consider the sequence

$$\begin{cases} (\partial_t - \Delta)u_n + \mathbf{P}_n \operatorname{div}(u_n \otimes u_n) = \mathbf{P}_n \nabla p_n & (t, x) \in [0, \infty) \times \mathbb{R}^d \\ u_n(0, x) = \mathbf{P}_n u_0(x). \end{cases}$$

where $p_n = R_i R_j (u_n^i u_n^j)$. We apply to the above equation $\langle \cdot, \varphi u_n \rangle$. Then

$$\begin{aligned}
\frac{1}{2} \frac{d}{dt} \langle |u_n|^2, \varphi \rangle - \frac{1}{2} \langle |u_n|^2, \partial_t \varphi \rangle - \langle \Delta u_n, \varphi u_n \rangle + \langle (u_n \cdot \nabla) u_n, \varphi u_n \rangle \\
= \langle \nabla p_n, \varphi u_n \rangle + \langle (\mathbf{P}_n - 1) \nabla p_n, \varphi u_n \rangle - \langle (\mathbf{P}_n - 1)(u_n \cdot \nabla) u_n, \varphi u_n \rangle.
\end{aligned}$$

We have

$$\begin{aligned}
- \langle \Delta u_n, \varphi u_n \rangle &= \langle |\nabla u_n|^2, \varphi \rangle + \langle \partial_j u_n, u_n \partial_j \varphi \rangle = \langle |\nabla u_n|^2, \varphi \rangle + 2^{-1} \langle \partial_j |u_n|^2, \partial_j \varphi \rangle \\
&= \langle |\nabla u_n|^2, \varphi \rangle - 2^{-1} \langle |u_n|^2, \Delta \varphi \rangle.
\end{aligned}$$

We have

$$\langle \nabla p_n, \varphi u_n \rangle = \langle \partial_j p_n, \varphi u_n^j \rangle = \langle p_n, (u_n \cdot \nabla) \varphi \rangle.$$

Finally,

$$\langle (u_n \cdot \nabla) u_n, \varphi u_n \rangle = \langle (u_n \cdot \nabla) u_n, \varphi u_n \rangle = -2^{-1} \langle |u_n|^2, (u_n \cdot \nabla) \varphi \rangle$$

So, integrating we obtain

$$\begin{aligned}
2 \int_0^T \langle |\nabla u_n|^2, \varphi \rangle dt &= 2 \int_0^T \langle |u_n|^2, \partial_t \varphi + \Delta \varphi \rangle dt + \int_0^T \langle |u_n|^2 + 2p_n, (u_n \cdot \nabla) \varphi \rangle dt \\
+ \int_0^T (\langle (\mathbf{P}_n - 1) \nabla p_n, \varphi u_n \rangle - \langle (\mathbf{P}_n - 1)(u_n \cdot \nabla) u_n, \varphi u_n \rangle) dt
\end{aligned}$$

which, up to error terms in the last line, is formula (12.1) for the solutions of the truncated problems. So now we will take the limit for $n \nearrow \infty$ in this equality.

We have

$$\int_0^T \langle |u_n|^2, \partial_t \varphi + \Delta \varphi \rangle dt \xrightarrow{n \rightarrow \infty} \int_{\mathbb{R}_+} \langle |u|^2, \partial_t \varphi + \Delta \varphi \rangle dt$$

because $u_n \xrightarrow{n \rightarrow \infty} u$ in $L^2((0, T) \times K, \mathbb{R}^3)$ for any compact set $K \subset \subset \mathbb{R}^3$ and any $T > 0$. We have

$$\int_0^T \langle |\nabla u|^2, \varphi \rangle dt \leq \liminf_{n \rightarrow \infty} \int_0^T \langle |\nabla u_n|^2, \varphi \rangle dt$$

by $\nabla u_n \xrightarrow{n \rightarrow \infty} \nabla u$ in $L^2(\mathbb{R}_+ \times \mathbb{R}^3)$. Next, we claim

$$\lim_{n \rightarrow +\infty} \int_0^T (\langle |u_n|^2, (u_n \cdot \nabla)\varphi \rangle dt - \langle |u|^2, (u \cdot \nabla)\varphi \rangle) dt = 0. \quad (12.2)$$

Indeed, the difference of the two terms is a sum of various terms. We bound a typical one:

$$\left| \int_0^T \langle u_n - u, u_n (u_n \cdot \nabla)\varphi \rangle dt \right| \lesssim \|u_n - u\|_{L_t^2 L_x^4(\Omega)} \|u_n\|_{L_t^\infty L_x^2(\Omega)} \|u_n\|_{L_t^2 L_x^4(\Omega)} \leq C_\Omega \|u_n - u\|_{L_t^2 L_x^4(\Omega)}$$

for $\Omega = \text{supp}\varphi$ and where $\|u_n\|_{L_t^\infty L_x^2(\Omega)} \|u_n\|_{L_t^2 L_x^4(\Omega)} \leq C_\Omega$ by the energy equality (5.21). By (5.40) we have $\|u_n - u\|_{L_t^2 L_x^4(\Omega)} \xrightarrow{n \rightarrow \infty} 0$ and so, treating analogously the other similar terms, we get the desired limit (12.2). Similarly, for the pressure we have

$$\lim_{n \rightarrow +\infty} \int_0^T (\langle p_n, (u_n \cdot \nabla)\varphi \rangle dt - \langle p, (u \cdot \nabla)\varphi \rangle) dt = 0. \quad (12.3)$$

Next we show

$$\lim_{n \rightarrow +\infty} \int_0^T (\langle (\mathbf{P}_n - 1)\nabla p_n, \varphi u_n \rangle - \langle (\mathbf{P}_n - 1)(u_n \cdot \nabla)u_n, \varphi u_n \rangle) dt = 0. \quad (12.4)$$

It is enough to consider one of the two terms inside the integral. We can write

$$\int_0^T \langle (\mathbf{P}_n - 1)\nabla p_n, \varphi u_n \rangle dt = \int_0^T \langle \nabla p_n, (\mathbf{P}_n - 1)\varphi u \rangle dt + \int_{\mathbb{R}_+} \langle (\mathbf{P}_n - 1)\nabla p_n, \varphi (u_n - u) \rangle dt.$$

Both terms in the r.h.s. will converge to 0. The 2nd because of $\|u_n - u\|_{L_t^2 L_x^4(\Omega)} \xrightarrow{n \rightarrow \infty} 0$ and the first because $(\mathbf{P}_n - 1) \xrightarrow{n \rightarrow \infty} 0$ strongly in a reasonable chosen space³. So in the limit we obtain (12.1). □

³This is an insidious point and here the proof breaks down. It can be easily fixed though, redefining the \mathbf{P}_n which here are $\mathbf{P}_n = \chi_{[-1,1]} \left(\frac{\sqrt{-\Delta}}{n} \right)$ and using instead, here as well as earlier in these notes, the operators $\psi \left(\frac{\sqrt{-\Delta}}{n} \right)$ with $\psi \in C_c^\infty(\mathbb{R}, [0, 1])$, with $\psi = 1$ near the origin. Here the problem is that the operators $\mathbf{P}_n = \chi_{[-1,1]} \left(\frac{\sqrt{-\Delta}}{n} \right)$, by C.Feffermann [8] (see also [16]), for $d \geq 2$ is bounded from $L^p(\mathbb{R}^d)$ into itself only if $p = 2$. No such problem exists in the case of $\psi \left(\frac{\sqrt{-\Delta}}{n} \right)$, which is always bounded with a bound independent on n

Proposition 12.2 (Alternative local energy inequality). *Suppose that u s.t. $u \in L^\infty((a, b), L^2(U))$ and $\nabla u \in L^2((a, b), L^2(U))$ also the Local Energy Inequality:*

$$\begin{aligned} 2 \int_a^b \int_{\mathbb{R}^3} |\nabla u|^2 \varphi dx ds &\leq \int_a^b \int_{\mathbb{R}^3} |u|^2 (\varphi_s + \Delta \varphi) dx ds \\ &+ \int_a^b \int_{\mathbb{R}^3} (|u|^2 + 2p)(u \cdot \nabla) \varphi dx ds \text{ for all } \varphi \in C_c^\infty((a, b) \times U, [0, +\infty)), \end{aligned} \quad (12.5)$$

where p is defined by (10.15). Then u satisfies for all $t \in (a, b)$ also

$$\begin{aligned} \int_{\mathbb{R}^3} |u(t)|^2 \phi(t) dx + 2 \int_a^t \int_{\mathbb{R}^3} |\nabla u|^2 \phi dx ds &\leq \int_a^t \int_{\mathbb{R}^3} |u|^2 (\phi_s + \Delta \phi) dx ds \\ &+ \int_a^t \int_{\mathbb{R}^3} (|u|^2 + 2p)(u \cdot \nabla) \phi dx ds \text{ for all } \phi \in C_c^\infty((a, b) \times U, [0, +\infty)). \end{aligned} \quad (12.6)$$

Proof. We start from (12.5) and we consider $\varphi_\epsilon(s, x) = \phi(s, x) \chi\left(\frac{t-s}{\epsilon}\right)$ where $\chi \in C^\infty(\mathbb{R}, [0, 1])$ satisfies $\chi = 0$ in \mathbb{R}_- and $\chi = 1$ in $[1, \infty)$. Notice that

$$\chi'\left(\frac{t-s}{\epsilon}\right) = 0 \text{ for } s \leq t - \epsilon \text{ and } s \geq t \text{ and } \int_{t-\epsilon}^t \epsilon^{-1} \chi'\left(\frac{t-s}{\epsilon}\right) ds = -\chi\left(\frac{t-s}{\epsilon}\right) \Big|_{s=t-\epsilon}^t = \chi(1) - \chi(0) = 1.$$

We have

$$\partial_s \varphi_\epsilon(s, x) = \partial_s \phi(s, x) \chi\left(\frac{t-s}{\epsilon}\right) - \phi(s, x) \epsilon^{-1} \chi'\left(\frac{t-s}{\epsilon}\right).$$

So when we enter this information in (12.5) with $\varphi = \varphi_\epsilon$, we obtain

$$\begin{aligned} \int_a^b \int_{\mathbb{R}^3} |u|^2 \phi(s) \epsilon^{-1} \chi'\left(\frac{t-s}{\epsilon}\right) ds + 2 \int_a^b \int_{\mathbb{R}^3} |\nabla u|^2 \phi \chi\left(\frac{t-s}{\epsilon}\right) dx ds &\leq \int_a^b \int_{\mathbb{R}^3} |u|^2 \chi\left(\frac{t-s}{\epsilon}\right) (\phi_s + \Delta \phi) dx ds \\ &+ \int_a^b \int_{\mathbb{R}^3} (|\nabla u|^2 + 2p) \chi\left(\frac{t-s}{\epsilon}\right) (u \cdot \nabla) \phi dx ds. \end{aligned}$$

Taking limit $\epsilon \searrow 0$ we get

$$\begin{aligned} \lim_{\epsilon \searrow 0} \int_a^b \int_{\mathbb{R}^3} |u|^2 \phi(s) \epsilon^{-1} \chi'\left(\frac{t-s}{\epsilon}\right) ds dx + 2 \int_0^t \int_{\mathbb{R}^3} |\nabla u|^2 \phi dx ds &\leq \int_0^t \int_{\mathbb{R}^3} |u|^2 (\phi_s + \Delta \phi) dx ds \\ &+ \int_0^t \int_{\mathbb{R}^3} (|\nabla u|^2 + 2p)(u \cdot \nabla) \phi dx ds \end{aligned}$$

where we have applied dominated convergence, leaving aside the most crucial limit. We have

$$\int_a^b \int_{\mathbb{R}^3} |u|^2 \phi(s) \epsilon^{-1} \chi'\left(\frac{t-s}{\epsilon}\right) ds dx = \int_{t-\epsilon}^t ds \epsilon^{-1} \chi'\left(\frac{t-s}{\epsilon}\right) \int_{\mathbb{R}^3} |u(s, x)|^2 \phi(s, x) dx.$$

Now, we have

$$\int_{t-\epsilon}^t ds \epsilon^{-1} \chi' \left(\frac{t-s}{\epsilon} \right) \int_{\mathbb{R}^3} |u(s, x)|^2 \phi(s, x) dx \xrightarrow{\epsilon \searrow 0} \int_{\mathbb{R}^3} |u(t, x)|^2 \phi(t, x) dx \text{ in } L^p(\mathbb{R})$$

for any $1 \leq p < \infty$, by $u \in L^\infty((a, b), L^2(U))$, $\phi \in C_c^\infty((a, b) \times U, [0, +\infty))$ and, finally, by Theorem 1.10. Then, there is a sequence $\epsilon_n \searrow 0$, s.t. for a.e. t we have

$$\int_{t-\epsilon_n}^t ds \epsilon_n^{-1} \chi' \left(\frac{t-s}{\epsilon_n} \right) \int_{\mathbb{R}^3} |u(s, x)|^2 \phi(s, x) dx \xrightarrow{n \nearrow \infty} \int_{\mathbb{R}^3} |u(t, x)|^2 \phi(t, x) dx \text{ for a.e. } t \in \mathbb{R},$$

see in the proof of Theorem A.19. □

13 A first result of Caffarelli, Kohn and Nirenberg

Definition 13.1 (Suitable pairs). A pair (u, p) is suitable in $(a, b) \times U$ if:

1. $u \in L^\infty((a, b), L^2(U, \mathbb{R}^3))$ and $\nabla u \in L^2((a, b) \times U)$ and is divergence free, and $p \in L^{3/2}((a, b) \times U, \mathbb{R})$;
2. $-\Delta p = \partial_i \partial_j (u_i u_j)$;
3. u satisfies for all $t \in (a, b)$ the local energy inequality

$$\begin{aligned} & \int_{\mathbb{R}^3} |u(t)|^2 \phi(t) dx + 2 \int_a^t \int_{\mathbb{R}^3} |\nabla u|^2 \phi dx ds \leq \int_a^t \int_{\mathbb{R}^3} |u|^2 (\phi_t + \Delta \phi) dx ds \quad (13.1) \\ & + \int_a^t \int_{\mathbb{R}^3} (|u|^2 + 2p)(u \cdot \nabla) \phi dx ds \text{ for all } \phi \in C_c^\infty((a, b) \times U, [0, +\infty)). \end{aligned}$$

In this section we will prove the following theorem.

Theorem 13.2. *There exists absolute constants $\epsilon_0^* > 0$ and $c_M > 0$ s.t. if (u, p) is a suitable weak solution of the NS with*

$$R^{-2} \int_{Q_R(t_0, x_0)} \left(|u|^3 + |p|^{\frac{3}{2}} \right) dt dx < \epsilon_0 \quad (13.2)$$

for an $R > 0$ and for a $\epsilon_0 \in (0, \epsilon_0^*]$, then $\|u\|_{L^\infty(Q_{R/2}(t_0, x_0))} \leq c_M \epsilon_0^{\frac{1}{3}}$.

Notice that, in view of Theorem 11.1, u would be smooth in x and Hölder continuous in t inside $Q_{R/2}(t_0, x_0)$. The proof of Theorem 13.2 is rather articulated. Before proving it we will discuss a consequence. Notice that Theorem 13.2 says that for an $R > 0$ and for a $\epsilon_0 \in (0, \epsilon_0^*]$

$$R^{-2} \int_{Q_R(t_0 + \frac{R^2}{8}, x_0)} \left(|u|^3 + |p|^{\frac{3}{2}} \right) dt dx < \epsilon_0 \implies \|u\|_{L^\infty(Q_{R/2}(t_0 + \frac{R^2}{8}, x_0))} \leq c_M \epsilon_0^{\frac{1}{3}}. \quad (13.3)$$

Notice that $Q_{R/2} \left(t_0 + \frac{R^2}{8}, x_0 \right) = \left(t_0 + \frac{R^2}{8} - \frac{R^2}{4}, t_0 + \frac{R^2}{8} \right) \times B_{R/2}(x_0)$ is a neighborhood of (t_0, x_0)

Definition 13.3. A point $(t, x) \in \mathbb{R}_+ \times \mathbb{R}^3$ is called a regular point of a weak solution u if there exists a neighborhood of (t, x) in $\mathbb{R}_+ \times \mathbb{R}^3$ such that $u \in L^\infty(U, \mathbb{R}^3)$. If not regular, a point $(t, x) \in \mathbb{R}_+ \times \mathbb{R}^3$ is called singular.

A simple consequence of Theorem 13.2 is the following result.

Proposition 13.4. *Given a suitable Leray–Hopf weak solution u , then the set of singular points S of u is bounded in $[0, \infty \times \mathbb{R}^3$.*

Proof. We already know that there exists T s.t. $u \in C^\infty((T, \infty) \times \mathbb{R}^3, \mathbb{R}^3)$. Now we will show that there is an $R_0 > 0$ s.t. $S \subset [0, T] \times B(0, R_0)$. Theorem 13.2 implies that if $(t, x) \in S$, then

$$r^{-2} \int_{Q_R(t+\frac{R^2}{8}, x)} \left(|u|^3 + |p|^{\frac{3}{2}} \right) \geq \epsilon_0 \text{ for all } R > 0.$$

From

$$\|u\|_{L^3(Q_R(t+\frac{R^2}{8}, x))} \leq \|u\|_{L^{\frac{10}{3}}(Q_R(t+\frac{R^2}{8}, x))} |Q_R \left(t + \frac{R^2}{8}, x \right)|^{\frac{1}{30}} = \|u\|_{L^{\frac{10}{3}}(Q_R(t+\frac{R^2}{8}, x))} \left(\frac{4\pi}{3} \right)^{\frac{1}{30}} 2^{-\frac{1}{6}} R^{\frac{1}{6}}$$

and

$$\|p\|_{L^{\frac{3}{2}}(Q_R(t+\frac{R^2}{8}, x))} \leq \|p\|_{L^{\frac{5}{3}}(Q_R(t+\frac{R^2}{8}, x))} |Q_R \left(t + \frac{R^2}{8}, x \right)|^{\frac{1}{15}} = \|p\|_{L^{\frac{5}{3}}(Q_R(t+\frac{R^2}{8}, x))} \left(\frac{4\pi}{3} \right)^{\frac{1}{15}} 2^{-\frac{1}{3}} R^{\frac{1}{3}},$$

we get

$$\int_{Q_R(t+\frac{R^2}{8}, x)} \left(|u|^{\frac{10}{3}} + |p|^{\frac{5}{3}} \right) \geq C\epsilon_0^{\frac{10}{9}} R^{\frac{5}{3}} \text{ for all } R > 0. \quad (13.4)$$

But we also know that $u \in L^{\frac{10}{3}}((0, T) \times \mathbb{R}^3, \mathbb{R}^3)$ and $p \in L^{\frac{5}{3}}((0, T) \times \mathbb{R}^3, \mathbb{R}^3)$. If S is unbounded, then for any R there is a sequence (t_n, x_n) in $[0, 2T] \times \mathbb{R}^3$ where $\left(t_n + \frac{R^2}{8}, x_n \right) \cap \left(t_m + \frac{R^2}{8}, x_m \right) = \emptyset$, we have $Q_R \left(t_n + \frac{R^2}{8}, x_n \right) \subset [0, 2T] \times \mathbb{R}^3$ for any n and

$$\int_{Q_R(t_n+\frac{R^2}{8}, x_n)} \left(|u|^{\frac{10}{3}} + |p|^{\frac{5}{3}} \right) \geq C\epsilon_0^{\frac{10}{9}} R^{\frac{5}{3}}.$$

But then we get a contradiction

$$\infty > \int_{[0, 2T] \times \mathbb{R}^3} \left(|u|^{\frac{10}{3}} + |p|^{\frac{5}{3}} \right) \geq \sum_n \int_{Q_R(t_n+\frac{R^2}{8}, x_n)} \left(|u|^{\frac{10}{3}} + |p|^{\frac{5}{3}} \right) = +\infty.$$

□

Another corollary is the following.

Proposition 13.5. *Given a suitable Leray–Hopf weak solution u and any compact subspace $K \subset\subset \mathbb{R}_+ \times \mathbb{R}^3$, then the set of singular points S satisfies $\dim_B(S \cap K) \leq 5/3$.*

Proof. Suppose this is false, so that we have that $\dim_B(S \cap K) > 5/3$ in a case, and let $\dim_B(S \cap K) > d > 5/3$. Then, by Lemma 6.11 there is a sequence $\epsilon_j \rightarrow 0$ s.t. $M(S \cap K, \epsilon_j) \geq \epsilon_j^{-d}$, where $M(S \cap K, \epsilon_j)$ the largest number of disjoint open balls of radius ϵ_j with centers at points of $S \cap K$. Now for $\epsilon \in (0, 1)$ we have

$$B_\epsilon(t, x) \supset Q_{\epsilon/2}^*(t, x) = Q_{\epsilon/2}(t + \epsilon^2/8, x) = \left(t - \frac{\epsilon^2}{4}, t + \frac{\epsilon^2}{4}\right) \times B_{\epsilon/2}(x),$$

indeed, for any $(s, y) \in Q_{\epsilon/2}^*(t, x)$ we have for

$$\sqrt{(t-s)^2 + (y-x)^2} < \sqrt{\frac{\epsilon^4}{16} + \frac{\epsilon^2}{4}} \leq \sqrt{\frac{\epsilon^4}{16} + \frac{\epsilon^2}{4}} < 2^{-\frac{1}{2}}\epsilon.$$

For any j , fix $M_j := M(S \cap K, \epsilon_j)$ open balls of radius ϵ_j with centers at points of $S \cap K$. Then, we get a contradiction:

$$\infty > \int_{[0, 2T] \times \mathbb{R}^3} \left(|u|^{\frac{10}{3}} + |p|^{\frac{5}{3}}\right) \geq \sum_{l=1}^{M_j} \int_{Q_{\epsilon_j/2}(t_l + \epsilon^2/8, x_l)} \left(|u|^{\frac{10}{3}} + |p|^{\frac{5}{3}}\right) \geq c\epsilon_j^{-d} \epsilon_j^{\frac{5}{3}} \xrightarrow{j \nearrow \infty} \infty.$$

□

We now turn to the proof of Theorem 13.2. Following [13] we proceed by outlining twice the argument, with increasing precision, before giving a full proof in the third try. First of notice that, by scaling invariance of the NS and of the estimate (13.6), it is enough to take $R = 1$. Furthermore, we can take $t_0 = 0$ and $x_0 = 0$.

13.1 First outline

We oversimplify and we assume that there is no pressure in the local energy inequality (12.6), so that the latter is for $s \in (a, b)$ of the form

$$\begin{aligned} \int_{\mathbb{R}^3} |u(s)|^2 \phi(s) dx + 2 \int_a^s \int_{\mathbb{R}^3} |\nabla u|^2 \phi \leq \int_a^s \int_{\mathbb{R}^3} |u|^2 (\partial_t + \Delta) \phi \\ + \int_a^s \int_{\mathbb{R}^3} |u|^2 (u \cdot \nabla) \phi \text{ for all } \phi \in C_c^\infty((a, b) \times U, [0, +\infty)). \end{aligned} \quad (13.5)$$

Then using (13.5) it is possible to prove rigorously the following.

Proposition 13.6. *There exists absolute constants $\epsilon_0^* > 0$ s.t. if u satisfies (13.5) and*

$$R^{-2} \int_{Q_R(t_0, x_0)} |u|^3 dt dx < \epsilon_0 \quad (13.6)$$

for an $R > 0$ and for a $\epsilon_0 \in (0, \epsilon_0^*]$, then $\|u\|_{L^\infty(Q_{R/2}(t_0, x_0))} \leq \epsilon_0^{\frac{1}{3}}$.

First we give a heuristic argument picking $R = 1$ and $(t_0, x_0) = (0, 0)$. We will prove that for any $(s, a) \in Q_{1/2}(0, 0)$ we have

$$2^{5n} \int_{Q_{2^{-n}}(s, a)} |u|^3 dt dx < \epsilon_0^{\frac{2}{3}} \text{ for all } n \in \mathbb{N} \quad (13.7)$$

Then by Lebesgue's Differentiation Theorem, this will imply $\|u\|_{L^\infty(Q_{R/2}(t_0, x_0))} \leq \epsilon_0^{\frac{1}{3}}$. We will consider an appropriate sequence of cutoffs ϕ_n . They are chosen so that $(\partial_t + \Delta)\phi_n \approx 0$. Here let us assume $(\partial_t + \Delta)\phi_n = 0$. In fact the ϕ_n 's will almost be fundamental solutions of the backwards heat equation, but not quite. This, unfortunately, imposes some constraints on them. In fact, they will satisfy estimates of the form

$$\begin{aligned} \phi_n &\sim 2^n \text{ in } Q_{2^{-n}}(s, a) \text{ and} \\ |\nabla \phi_n| &\leq \begin{cases} C2^{2n} & \text{in } Q_{2^{-n}}(s, a) \\ C2^{-2n}2^{4k} & \text{in } Q_{2^{-k}}(s, a) \setminus Q_{2^{-(k+1)}}(s, a). \end{cases} \end{aligned} \quad (13.8)$$

We assume by induction that

$$2^{2k} \int_{Q_{2^{-k}}(s, a)} |u|^3 dt dx < \epsilon_0^{\frac{2}{3}} 2^{-3k} \text{ for all } k \leq n.$$

Using (13.5) we have for $t \in (s - 2^{-2n}, s)$

$$\begin{aligned} &\int_{B_{2^{-n}}(a)} |u(t)|^2 2^n dx + 2 \iint_{Q_{2^{-n}}(s, a) \cap \{t' < t\}} |\nabla u|^2 2^n dx dt' \leq \iint_{Q_{2^{-1}}(s, a)} |u|^3 |\nabla \phi_n| dx dt' \\ &= \sum_{k=1}^{n-1} \iint_{Q_{2^{-k}}(s, a) \setminus Q_{2^{-(k+1)}}(s, a)} |u|^3 |\nabla \phi_n| dx dt' + \iint_{Q_{2^{-n}}(s, a)} |u|^3 |\nabla \phi_n| dx dt' \end{aligned}$$

where we decomposed the domain of integration on the r.h.s.

$$Q_{2^{-1}}(s, a) = (Q_{2^{-1}}(s, a) \setminus Q_{2^{-2}}(s, a)) \cup (Q_{2^{-2}}(s, a) \setminus Q_{2^{-3}}(s, a)) \cup \dots \cup (Q_{2^{-(n-1)}}(s, a) \setminus Q_{2^{-n}}(s, a)) \cup Q_{2^{-n}}(s, a).$$

Now, using (13.8) we obtain for $t \in (s - 2^{-2n}, s)$

$$\begin{aligned} &2^n \int_{B_{2^{-n}}(a)} |u(t)|^2 dx + 2^n 2 \iint_{Q_{2^{-n}}(s, a) \cap \{t' < t\}} |\nabla u|^2 dx dt' \leq \\ &\leq C \sum_{k=1}^{n-1} 2^{-2n} 2^{4k} \iint_{Q_{2^{-k}}(s, a)} |u|^3 dx dt' + C2^{2n} \iint_{Q_{2^{-n}}(s, a)} |u|^3 dx dt' \\ &\leq C2^{-2n} \sum_{k=1}^{n-1} 2^{-k} \epsilon_0^{\frac{2}{3}} + C2^{-3n} \epsilon_0^{\frac{2}{3}} = C2^{-2n} \epsilon_0^{\frac{2}{3}} \sum_{k=1}^n 2^{-k} < C2^{-2n} \epsilon_0^{\frac{2}{3}}. \end{aligned}$$

From this for $t \in (s - 2^{-2n-2}, s)$ we get

$$2^{n+1} \int_{B_{2^{-n-1}}(a)} |u(t)|^2 dx + 2^{n+1} 2 \iint_{Q_{2^{-n-1}}(s, a)} |\nabla u|^2 dx dt < 2^3 C2^{-2(n+1)} \epsilon_0^{\frac{2}{3}}.$$

Now we need the following lemma.

Lemma 13.7. *There exists a constant $C_0 > 0$ such that for any $s \in \mathbb{R}$, $r > 0$ and $a \in \mathbb{R}^3$ and any u s.t.*

$$u \in L^\infty((s-r^2, s), L^2(B_r(a))) \text{ and } \nabla u \in L^2(Q_r(s, a)),$$

then

$$r^{-2} \int_{Q_r(s, a)} |u|^3 dx \leq C_0 \left[r^{-1} \sup_{s-r^2 < t < s} \int_{B_r(a)} |u(t)|^2 dx + r^{-1} \int_{Q_r(s, a)} |\nabla u|^2 dt dx \right]^{\frac{3}{2}}. \quad (13.9)$$

Proof. By scaling, it is sufficient to consider $r = 1$, and by translation invariance we can consider $(s, a) = (0, 0)$. By Hölder inequality $\|u\|_{L^3(B_1)} \leq \|u\|_{L^6(B_1)}^{\frac{1}{2}} \|u\|_{L^2(B_1)}^{\frac{1}{2}}$ and by Sobolev's inequality $\|u\|_{L^6(B_1)} \leq c_0 \|u\|_{L^2(B_1)} + c_0 \|\nabla u\|_{L^2(B_1)}$. Then $\|u\|_{L^3(B_1)} \leq c_0^{\frac{1}{2}} \left(\|u\|_{L^2(B_1)} + \|\nabla u\|_{L^2(B_1)}^{\frac{1}{2}} \|u\|_{L^2(B_1)}^{\frac{1}{2}} \right)$ and so, by $(\alpha + \beta)^q \leq 2^{q-1} (\alpha^q + \beta^q)$ for $q \geq 1$ and for $\alpha, \beta \in \mathbb{R}_+$ (this by the convexity of $t \rightarrow t^q$)

$$\begin{aligned} \int_{B_1} |u|^3 dx &\leq c_0^{\frac{3}{2}} \left(\|u\|_{L^2(B_1)} + \|\nabla u\|_{L^2(B_1)}^{\frac{1}{2}} \|u\|_{L^2(B_1)}^{\frac{1}{2}} \right)^3 \\ &\leq 4c_0^{\frac{3}{2}} \left(\|u\|_{L^2(B_1)}^3 + \|\nabla u\|_{L^2(B_1)}^{\frac{3}{2}} \|u\|_{L^2(B_1)}^{\frac{3}{2}} \right). \end{aligned}$$

Then, by Hölder,

$$\begin{aligned} \int_{Q_1} |u|^3 dx &\leq 4c_0^{\frac{3}{2}} \int_{-1}^0 \|\nabla u\|_{L^2(B_1)}^{\frac{3}{2}} \|u\|_{L^2(B_1)}^{\frac{3}{2}} + 4c_0^{\frac{3}{2}} \int_{-1}^0 \|u\|_{L^2(B_1)}^3 \\ &\leq 4c_0^{\frac{3}{2}} \|\|\nabla u\|_{L^2(B_1)}\|_{L^{\frac{4}{3}}(-1,0)}^{\frac{3}{2}} \|\|u\|_{L^2(B_1)}\|_{L^4(-1,0)}^{\frac{3}{2}} + 4c_0^{\frac{3}{2}} \int_{-1}^0 \|u\|_{L^2(B_1)}^3 \\ &= 4c_0^{\frac{3}{2}} \|\|\nabla u\|_{L^2(B_1)}\|_{L^2(-1,0)}^{\frac{3}{2}} \|\|u\|_{L^2(B_1)}\|_{L^6(-1,0)}^{\frac{3}{2}} + 4c_0^{\frac{3}{2}} \int_{-1}^0 \|u\|_{L^2(B_1)}^3 \\ &= 4c_0^{\frac{3}{2}} \|\|\nabla u\|_{L^2(Q_1)}\|_{L^2(Q_1)}^{\frac{3}{2}} \left(\sup_{-1 < t < 0} \|u\|_{L^2(B_1)} \right)^{\frac{3}{2}} + 4c_0^{\frac{3}{2}} \left(\sup_{-1 < t < 0} \|u\|_{L^2(B_1)} \right)^3 \\ &= 4c_0^{\frac{3}{2}} \|\|\nabla u\|_{L^2(Q_1)}\|_{L^2(Q_1)}^{\frac{3}{2}} \left(\sup_{-1 < t < 0} \|u\|_{L^2(B_1)}^2 \right)^{\frac{3}{4}} + 4c_0^{\frac{3}{2}} \left(\sup_{-1 < t < 0} \|u\|_{L^2(B_1)}^2 \right)^{\frac{3}{2}} \\ &\leq 2c_0^{\frac{3}{2}} \|\|\nabla u\|_{L^2(Q_1)}\|_{L^2(Q_1)}^3 + 6c_0^{\frac{3}{2}} \left(\sup_{-1 < t < 0} \|u\|_{L^2(B_1)}^2 \right)^{\frac{3}{2}} \leq 6c_0^{\frac{3}{2}} \left[\|\|\nabla u\|_{L^2(Q_1)}\|_{L^2(Q_1)}^3 + \left(\sup_{-1 < t < 0} \|u\|_{L^2(B_1)}^2 \right)^{\frac{3}{2}} \right] \\ &\leq 6c_0^{\frac{3}{2}} \left[\|\|\nabla u\|_{L^2(Q_1)}\|_{L^2(Q_1)}^2 + \sup_{-1 < t < 0} \|u\|_{L^2(B_1)}^2 \right]^{\frac{3}{2}}, \end{aligned}$$

where in the last step we use $\alpha^q + \beta^q \leq (\alpha + \beta)^q$ for $q \geq 1$ and for $\alpha, \beta \in \mathbb{R}_+$ ⁴. Then we are done, for $C_0 = 6c_0^{\frac{3}{2}}$. □

Then, applying the lemma, for $\epsilon_0 < (2^{\frac{9}{2}}C_0C^{\frac{3}{2}})^{-3}$,

$$2^{2n+2} \iint_{Q_{2^{-n-1}}(s,a)} |u|^3 \leq C_0 \left[2^3 C 2^{-2(n+1)} \epsilon_0^{\frac{2}{3}} \right]^{\frac{3}{2}} = 2^{\frac{9}{2}} C_0 C^{\frac{3}{2}} 2^{-3(n+1)} \epsilon_0 < 2^{-3(n+1)} \epsilon_0^{\frac{2}{3}}$$

where C is a fixed constant, dependent on the ϕ_n .

13.2 Proof of Proposition 13.6

It is worth, first of all, so see the definition of the cutoffs ϕ_n , in order to make sense of the bounds like in (13.9).

Lemma 13.8. *There exists a constant $C_1 > 1$ and for any fixed $(s, a) \in \mathbb{R}^4$ a sequence $\phi_n \in C_c^\infty((s - 1/9, s + 2^{-(n+1)}) \times B_{1/3}(a))$ such that for all $n \geq 2$ we have the following facts:*

- (i) $C_1^{-1}2^n \leq \phi_n \leq C_12^n$ and $|\nabla\phi_n| \leq C_12^{2n}$ in $Q_{2^{-n}}(s, a)$;
- (ii) $\phi_n \leq C_12^{-2n}2^{3k}$ and $|\nabla\phi_n| \leq C_12^{-2n}2^{4k}$ in $Q_{2^{-(k-1)}}(s, a) \setminus Q_{2^{-k}}(s, a)$;
- (iii) $\text{supp}\phi_n \cap ((-\infty, s] \times \mathbb{R}^3) \subset \overline{Q_{1/3}(s, a)}$;
- (iv) $|(\partial_t + \Delta)\phi_n| \leq C_12^{-2n}$ in $(-\infty, s] \times \mathbb{R}^3$.

Proof. It is enough to consider $(s, a) = (0, 0)$. Then

$$\phi_n(t, x) = 2^{-2n}\theta_n(t, x) = 2^{-2n}\chi_n(t, x)\psi_n(t, x). \quad (13.10)$$

Here we choose ψ_n such that

$$(\partial_t + \Delta)\psi_n(t, x) = 0 \text{ for } t < 2^{-2n} \text{ and with initial value } \psi_n(2^{-2n}, x) = \delta(x). \quad (13.11)$$

Recalling $K_t(x) = (4\pi t)^{-\frac{3}{2}}e^{-\frac{|x|^2}{4t}}$ satisfies $(\partial_t - \Delta)K_t(x) = 0$ for $t > 0$ and $K_t(x)|_{t=0} = \delta(x)$. Then $K_{-t}(x)$ solves the analogue of problem 13.11 but with the condition $K_{-t}(x)|_{t=0} = \delta(x)$. Finally, by translation invariance we find

$$\psi_n(t, x) = K_{2^{-2n}-t}(x) = (4\pi(2^{-2n} - t))^{-\frac{3}{2}}e^{-\frac{|x|^2}{4(2^{-2n}-t)}}. \quad (13.12)$$

⁴This follows from $\left(\frac{\alpha}{\alpha+\beta}\right)^q + \left(\frac{\beta}{\alpha+\beta}\right)^q \leq \frac{\alpha}{\alpha+\beta} + \frac{\beta}{\alpha+\beta} = 1$ for $q \geq 1$.

Notice that the constant factor $(4\pi)^{-\frac{3}{2}}$ is not important in the discussion. We have

$$\begin{aligned}\psi_n(t, x) &= (4\pi(2^{-2n} - t))^{-\frac{3}{2}} e^{-\frac{|x|^2}{4(2^{-2n}-t)}} \leq (4\pi(2^{-2n} - t))^{-\frac{3}{2}} \\ &\leq (4\pi 2^{-2n})^{-\frac{3}{2}} = (4\pi)^{-\frac{3}{2}} 2^{3n} \text{ in } Q_{2^{-n}} = (-2^{-2n}, 0) \times B_{2^{-n}}\end{aligned}\quad (13.13)$$

$$\begin{aligned}\psi_n(t, x) &= (4\pi(2^{-2n} + |t|))^{-\frac{3}{2}} e^{-\frac{|x|^2}{4(2^{-2n}+|t|)}} \\ &\geq (4\pi(2^{-2n} + 2^{-2n}))^{-\frac{3}{2}} e^{-\frac{2^{-2n}}{4(2^{-2n}+2^{-2n})}} = (8\pi)^{-\frac{3}{2}} e^{-\frac{1}{8}} 2^{3n} \text{ in } Q_{2^{-n}}.\end{aligned}\quad (13.14)$$

Next,

$$\nabla\psi_n(t, x) = -2^{-1}\pi^{-\frac{3}{2}}(4(2^{-2n} - t))^{-\frac{5}{2}} e^{-\frac{|x|^2}{4(2^{-2n}-t)}} x$$

so that

$$|\nabla\psi_n(t, x)| \leq 2^{-6}\pi^{-\frac{3}{2}} 2^{5n} 2^{-n} = 2^{-6}\pi^{-\frac{3}{2}} 2^{4n} \text{ in } Q_{2^{-n}}. \quad (13.15)$$

Keeping in mind the factor 2^{-2n} in (13.10), (13.13)–(13.15) explain (i). We will see of course the full estimate of ϕ_n shortly.

Next, still focusing on $\nabla\psi_n(t, x)$ only, observe that

$$Q_{2^{-(k-1)}} \setminus Q_{2^{-k}} = (-2^{-2(k-1)}, -2^{-2k}) \times B_{2^{-(k-1)}} \cup [-2^{-2k}, 0) \times (B_{2^{-(k-1)}} \setminus B_{2^{-k}}).$$

Now, in $(-2^{-2(k-1)}, -2^{-2k}) \times B_{2^{-(k-1)}}$ we have

$$\begin{aligned}\psi_n(t, x) &= (4\pi(2^{-2n} + |t|))^{-\frac{3}{2}} e^{-\frac{|x|^2}{4(2^{-2n}+|t|)}} \leq (4\pi(2^{-2n} + 2^{-2k}))^{-\frac{3}{2}} \\ &\leq (4\pi 2^{-2k})^{-\frac{3}{2}} = (4\pi)^{-\frac{3}{2}} 2^{3k},\end{aligned}\quad (13.16)$$

while in $[-2^{-2k}, 0) \times (B_{2^{-(k-1)}} \setminus B_{2^{-k}})$ we have

$$\begin{aligned}\psi_n(t, x) &= (4\pi(2^{-2n} + |t|))^{-\frac{3}{2}} e^{-\frac{|x|^2}{4(2^{-2n}+|t|)}} \leq (4\pi(2^{-2n} + |t|))^{-\frac{3}{2}} e^{-\frac{2^{-2k}}{4(2^{-2n}+|t|)}} \\ &= (4\pi)^{-\frac{3}{2}} 2^{3k} \left(\frac{2^{-2k}}{2^{-2n} + |t|} \right)^{\frac{3}{2}} e^{-\frac{2^{-2k}}{4(2^{-2n}+|t|)}} \leq (4\pi)^{-\frac{3}{2}} 2^{3k} \sup_{\alpha \geq 0} \alpha^{\frac{3}{2}} e^{-\frac{\alpha}{4}}.\end{aligned}\quad (13.17)$$

Turning to $\nabla\psi_n(t, x)$, in $(-2^{-2(k-1)}, -2^{-2k}) \times B_{2^{-(k-1)}}$ we have

$$\begin{aligned}|\nabla\psi_n(t, x)| &= 2^{-1}\pi^{-\frac{3}{2}}(4(2^{-2n} + |t|))^{-\frac{5}{2}} e^{-\frac{|x|^2}{4(2^{-2n}+|t|)}} |x| \leq \pi^{-\frac{3}{2}} (82^{-2k})^{-\frac{5}{2}} 2^{-k} \\ &= \pi^{-\frac{3}{2}} (8)^{-\frac{5}{2}} 2^{4k},\end{aligned}\quad (13.18)$$

and in $[-2^{-2k}, 0) \times (B_{2^{-(k-1)}} \setminus B_{2^{-k}})$ we have

$$\begin{aligned}|\nabla\psi_n(t, x)| &= 2^{-1}\pi^{-\frac{3}{2}}(4(2^{-2n} + |t|))^{-\frac{5}{2}} e^{-\frac{|x|^2}{4(2^{-2n}+|t|)}} |x| \leq 2^{-1}\pi^{-\frac{3}{2}}(4(2^{-2n} + |t|))^{-\frac{5}{2}} e^{-\frac{2^{-2k}}{4(2^{-2n}+|t|)}} 2^{-(k-1)} \\ &= 4^{-\frac{5}{2}} \pi^{-\frac{3}{2}} 2^{4k} \left(\frac{2^{-2k}}{2^{-2n} + |t|} \right)^{\frac{5}{2}} e^{-\frac{2^{-2k}}{4(2^{-2n}+|t|)}} \leq 4^{-\frac{5}{2}} \pi^{-\frac{3}{2}} 2^{4k} \sup_{\alpha \geq 0} \alpha^{\frac{5}{2}} e^{-\frac{\alpha}{4}}.\end{aligned}\quad (13.19)$$

Keeping in mind the factor 2^{-2n} in (13.10), (13.17)–(13.19) explain (ii).

If we chose $\chi_n(t, x) \equiv 1$ in (13.10), that is if we chose $\phi_n(t, x) = 2^{-2n}\psi_n(t, x)$, we would then have (i),(ii) and (vi), but obviously we would not have (iii). We define

$$\chi_n(t, x) = X(x)T_n(t) \text{ where}$$

$$X(x) = \begin{cases} 1 & \text{in } B_{1/4} \\ 0 & \text{outside } B_{1/3} \end{cases} \text{ and } T_n(t) = \begin{cases} 1 & \text{for } t \in (-1/16, 0) \\ 0 & \text{for } t < -1/9 \text{ and } t > 2^{-2n-1}, \end{cases} \quad (13.20)$$

with $T_n|_{(-\infty, 0]} = T$ independent of n , and they are $X \in C_c^\infty(\mathbb{R}^3, [0, 1])$ and $T_n \in C_c^\infty(\mathbb{R}, [0, 1])$. Now $\text{supp}\chi_n \subseteq \overline{Q_{1/3}} \cup [0, 2^{-2n-1}] \times B_{1/3}$, and so clearly the ϕ_n in (13.10) satisfies (iii). Notice now that

$$\nabla\theta_n(t, x) = \psi_n(t, x)\nabla\chi_n(t, x) + \chi_n(t, x)\nabla\psi_n(t, x).$$

Then $|\chi_n\nabla\psi_n| \leq |\nabla\psi_n|$ and the previous estimates apply, while $|\psi_n\nabla\chi_n| \leq |\psi_n\nabla X| \leq c\psi_n$ is smaller. Hence our ϕ_n in (13.10) satisfies (i) and (ii).

Finally, we have

$$(\partial_t + \Delta)\phi_n(t, x) = 2^{-2n}\psi_n(t, x)(\partial_t + \Delta)\chi_n(t, x) + 22^{-2n}\nabla\chi_n(t, x) \cdot \nabla\psi_n(t, x). \quad (13.21)$$

Here is important to observe that $\chi_n = 1$ in $Q_{1/4}$ and $\chi_n = 0$ in $(-\infty, 0] \times \mathbb{R}^3$ outside $Q_{1/3}$. This means that the terms in (13.21) need to be bounded only in $Q_{1/3} \setminus Q_{1/4} \subset Q_{1/2} \setminus Q_{1/4}$, where $\psi_n \leq (4\pi)^{-\frac{3}{2}}2^6$, by (13.16), and where $|\nabla\psi_n| \leq c_02^8$, by (13.17)–(13.18). From $|\nabla\chi_n| \leq |\nabla X| \leq c$, it follows that the 2nd term in the r.h.s. of (13.21) satisfies the desired estimate. The same is true for the 1st, since

$$|(\partial_t + \Delta)\chi_n(t, x)| \leq |T_n'| + |\Delta X| \leq |T'| + |\Delta X| \leq c_1$$

and so

$$|\psi_n(\partial_t + \Delta)\chi_n| \leq c_1|\psi_n|_{Q_{1/2} \setminus Q_{1/4}} \leq c_1(8\pi)^{-\frac{3}{2}}2^6.$$

□

Proof of Proposition 13.6. We proceed by induction proving by induction

A'_n

$$2^{5n} \int_{Q_{2^{-n}}(s, a)} |u|^3 dt dx < \epsilon_0^{\frac{2}{3}} \text{ for all } n \geq 4 \quad (13.22)$$

B_n

$$2^n \sup_{s-2^{-2n} < t < s} \int_{B_{2^{-n}}(a)} |u(t)|^2 dx + 2^n \iint_{Q_{2^{-n}}(s, a)} |\nabla u|^2 \leq C_B 2^{-2n} \epsilon_0^{\frac{2}{3}}. \quad (13.23)$$

We already saw how $B_n \implies A'_n$ by Lemma 13.7. Now we prove A'_4 and how $A'_4, \dots, A'_n \implies B_{n+1}$.

We start with A'_n for $n \leq 4$. We have the following, which uses the hypothesis (13.6) for $R = 1$ and $(t_0, x_0) = (0, 0)$ and which proves A'_n for $n \leq 4$: for any $(s, a) \in Q_{1/2}(0, 0)$

$$2^{5n} \int_{Q_{2^{-n}}(s, a)} |u|^3 dt dx \leq 2^{20} \int_{Q_1(0, 0)} |u|^3 dt dx \leq 2^{20} \epsilon_0 < \epsilon_0^{\frac{2}{3}} \text{ for } 2^{20} \epsilon_0^{\frac{1}{3}} < 1, \text{ that is for } \epsilon_0 < 2^{-15}.$$

Now we show that $A'_1, \dots, A'_n \implies B_{n+1}$. We consider, for $t \leq 0$,

$$\begin{aligned} & \int_{B_1} |u(t)|^2 \phi_n(t) + 2 \int_{-1}^t \int_{B_1} |\nabla u|^2 \phi_n \leq \int_{-1/9}^t \int_{B_{1/3}} |u|^2 (\partial_t + \Delta) \phi_n \\ & + \int_{-1/9}^t \int_{B_{1/3}} |u|^2 (u \cdot \nabla) \phi_n, \end{aligned}$$

where we exploited that $\text{supp} \phi_n(x) \subset \text{supp} X \subset \overline{B}_{1/3}$ and $\text{supp} \phi_n(t) \subset \text{supp} T_n \subset (-1/9, 2^{-2n-1})$.

Let us focus now on one term of the l.h.s. at a time.

For $s - 2^{-2n} < t < s$ and restricting to $a = 0$, we have

$$\begin{aligned} C_1^{-1} 2^n \int_{B_{2^{-n}}} |u(t)|^2 & \leq \int_{B_{2^{-n}}} |u(t)|^2 \phi_n(t) \leq \int_{-1/9}^t \int_{B_{1/3}} |u|^2 (\partial_t + \Delta) \phi_n + \int_{-1/9}^t \int_{B_{1/3}} |u|^2 (u \cdot \nabla) \phi_n \\ & \leq C_1 2^{-2n} \int_{-1/9}^s \int_{B_{1/3}} |u|^2 + \int_{-1/9}^s \int_{B_{1/3}} |u|^3 |\nabla \phi_n|. \end{aligned}$$

and similarly

$$2C^{-1} 2^n \int_{s-2^{-2n}}^t \int_{B_{2^{-n}}} |\nabla u|^2 \leq 2 \int_{-1/9}^t \int_{B_1} |\nabla u|^2 \phi_n \leq C_1 2^{-2n} \int_{-1/9}^s \int_{B_{1/3}} |u|^2 + \int_{-1/9}^s \int_{B_{1/3}} |u|^3 |\nabla \phi_n|,$$

so that

$$\begin{aligned} & C_1^{-1} 2^n \sup_{s-2^{-2n} < t < s} \int_{B_{2^{-n}}} |u(t)|^2 + C^{-1} 2^n \int_{s-2^{-2n}}^t \int_{B_{2^{-n}}} |\nabla u|^2 \\ & \leq \frac{3}{2} C_1 2^{-2n} \int_{-1/9}^s \int_{B_{1/3}} |u|^2 + \frac{3}{2} \int_{-1/9}^s \int_{B_{1/3}} |u|^3 |\nabla \phi_n|. \end{aligned} \quad (13.24)$$

Now we examine the 1st term in the r.h.s. of (13.24), for which by $s \leq 0$ we have

$$\begin{aligned} & \frac{3}{2} C_1 2^{-2n} \int_{-1/9}^s \int_{B_{1/3}} |u|^2 \leq \frac{3}{2} C_1 2^{-2n} \iint_{Q_{1/3}(s, 0)} |u|^2 \\ & \leq \frac{3}{2} C_1 2^{-2n} |Q_{1/3}|^{1/3} \|u\|_{L^3(Q_{1/3}(s, 0))}^2 \leq \frac{3}{2} C_1 2^{-2n} |Q_{1/3}|^{1/3} \|u\|_{L^3(Q_1(0, 0))}^2 \\ & < C_1 2^{-2n} \frac{3}{2} \left(3^{-5} \frac{4\pi}{3} \right)^{1/3} \epsilon_0^{2/3} = C_1 2^{-2n} \frac{3}{2 \cdot 3^2} (4\pi)^{1/3} \epsilon_0^{2/3} < C_1 2^{-2n} \epsilon_0^{2/3} < C_1 2^{-2n} \epsilon_0^{2/3}, \end{aligned} \quad (13.25)$$

where we used $\|u\|_{L^3(Q_1(0,0))} < \epsilon_0^{1/3}$ from hypothesis (13.6) for $R = 1$ and $(t_0, x_0) = (0, 0)$ and $\sqrt[3]{4\pi}/6 < 1$.

We consider now the 2nd term in the r.h.s. of (13.24). We have, by $s \leq 0$

$$\begin{aligned}
& \int_{-1/9}^s \int_{B_{1/3}} |u|^3 |\nabla \phi_n| \leq \iint_{Q_{1/3}(s,0)} |u|^3 |\nabla \phi_n| \leq \iint_{Q_{1/2}(s,0)} |u|^3 |\nabla \phi_n| \\
& = \sum_{k=2}^n \iint_{Q_{2^{-(k-1)}(s,0)} \setminus Q_{2^{-k}}(s,0)} |u|^3 |\nabla \phi_n| + \iint_{Q_{2^{-n}}(s,0)} |u|^3 |\nabla \phi_n| \\
& \leq \sum_{k=2}^n C_1 2^{-2n} 2^{4k} \iint_{Q_{2^{-(k-1)}(s,0)} \setminus Q_{2^{-k}}(s,0)} |u|^3 + C_1 2^{2n} \iint_{Q_{2^{-n}}(s,0)} |u|^3 \\
& \leq \sum_{k=2}^n C_1 2^{-2n} 2^{4k} \iint_{Q_{2^{-(k-1)}(s,0)}} |u|^3 + C_1 2^{2n} \iint_{Q_{2^{-n}}(s,0)} |u|^3 = \sum_{k=1}^n C_1 2^{-2n} 2^{4k} \iint_{Q_{2^{-k}}(s,0)} |u|^3 \\
& \leq C_1 2^{-2n} \epsilon_0^{\frac{2}{3}} \sum_{k=1}^n 2^{-k} = C_1 2^{-2n} \epsilon_0^{\frac{2}{3}} 2^{-1} \sum_{k=0}^{n-1} 2^{-k} < C_1 2^{-2n} \epsilon_0^{\frac{2}{3}} 2^{-1} 2 = C_1 2^{-2n} \epsilon_0^{\frac{2}{3}}.
\end{aligned}$$

So, returning to (13.24), we have proved

$$2^n \sup_{s-2^{-2n} < t < s} \int_{B_{2^{-n}}} |u(t)|^2 + 2^n \int_{-1}^s \int_{B_{2^{-n}}} |\nabla u|^2 \leq 3C_1^2 2^{-2n} \epsilon_0^{\frac{2}{3}}.$$

Then

$$2^{n+1} \sup_{s-2^{-2(n+1)} < t < s} \int_{B_{2^{-n-1}}} |u(t)|^2 + 2^{n+1} \iint_{Q_{2^{-n-1}}(s,0)} |\nabla u|^2 \leq 2^3 3C_1^2 2^{-2(n+1)} \epsilon_0^{\frac{2}{3}}$$

and this proves the induction argument for $C_B = 24C_1^2$. \square

13.3 Proof of Theorem 13.2

In the proof of Theorem 13.2, the presence of the pressure complicates the discussion. As before, we normalize to the case $Q_1(0,0)$. We proceed by induction proving the following:

A_n

$$2^{2n} \int_{Q_{2^{-n}}(s,a)} |u|^3 + 2^{\frac{3}{2}n} \int_{Q_{2^{-n}}(s,a)} |p - (p)_{B_{2^{-n}}(a)}|^{\frac{3}{2}} < 2^{-3n} \epsilon_0^{\frac{2}{3}} \text{ for all } n \in \mathbb{N}; \quad (13.26)$$

B_n

$$2^n \sup_{s-2^{-2n} < t < s} \int_{B_{2^{-n}}(a)} |u(t)|^2 dx + 2^n \iint_{Q_{2^{-n}}(s,a)} |\nabla u|^2 \leq C_B 2^{-2n} \epsilon_0^{\frac{2}{3}}. \quad (13.27)$$

We prove A_1 , then $A_1, \dots, A_n \implies B_{n+1}$ and, finally, $B_2, \dots, B_n \implies A_n$.

Step 1: proof of A_n for $n \leq 4$. We use, for $(p)_{B_r(a)}$ =average of p in $B_r(a) = |B_r(a)|^{-1} \int_{B_r(a)} p$,

$$\begin{aligned} \int_{Q_r(s,a)} |(p)_{B_r(a)}|^q &\leq \int_{Q_r(s,a)} (|p|)_{B_r(a)}^q = \int_{s-r^2}^s \frac{4\pi}{3} r^3 (|p|)_{B_r(a)}^q \\ &= \int_{s-r^2}^s \frac{4\pi}{3} r^3 \left(\frac{1}{\frac{4\pi}{3} r^3} \int_{B_r(a)} |p| \right)^q \leq \int_{s-r^2}^s \frac{4\pi r^3}{3} \frac{1}{\frac{4\pi}{3} r^3} \int_{B_r(a)} |p|^q = \int_{Q_r(s,a)} |p|^q, \end{aligned}$$

where in the 1st inequality we used the obvious fact that $|(p)_{B_r(a)}| \leq (|p|)_{B_r(a)}$ and the 2nd inequality follows by $q \geq 1$ and the Jensen inequality. Using $(\alpha + \beta)^q \leq 2^{q-1}(\alpha^q + \beta^q)$ for $q \geq 1$ and for $\alpha, \beta \in \mathbb{R}_+$ (this by the convexity of $t \rightarrow t^q$), we obtain

$$\begin{aligned} 2^{2n} \int_{Q_{2^{-n}}(s,a)} |u|^3 + 2^{\frac{3}{2}n} \int_{Q_{2^{-n}}(s,a)} |p - (p)_{B_{2^{-1}}(a)}|^{\frac{3}{2}} &\leq 2^{2n} \int_{Q_{2^{-1}}(s,a)} |u|^3 + 2^{\frac{3}{2}n + \frac{1}{2}} \int_{Q_{2^{-n}}(s,a)} \left(|p|^{\frac{3}{2}} + |(p)_{B_{2^{-1}}(a)}|^{\frac{3}{2}} \right) \\ &\leq 2^{2n} \int_{Q_{2^{-n}}(s,a)} |u|^3 + 2^{\frac{3}{2}n + \frac{3}{2}} \int_{Q_{2^{-n}}(s,a)} |p|^{\frac{3}{2}} \leq 2^{2n + \frac{3}{2}} \int_{Q_1(0,0)} \left(|u|^3 + |p|^{\frac{3}{2}} \right) \leq 2^{2n + \frac{3}{2}} \epsilon_0 < 2^{-3n} \epsilon_0^{\frac{2}{3}} \end{aligned}$$

for $2^{5n + \frac{3}{2}} \epsilon_0 < 2^{-15}$ for $n \leq 4$.

Step 2: proof of $A_1, \dots, A_n \implies B_{n+1}$. We consider, for $t \leq 0$,

$$\begin{aligned} \int_{B_1} |u(t)|^2 \phi_n(t) + 2 \int_{-1}^t \int_{B_1} |\nabla u|^2 \phi_n &\leq \int_{-1}^t \int_{B_1} |u|^2 (\partial_t + \Delta) \phi_n \\ + \int_{-1}^t \int_{B_1} (|u|^2 + 2p)(u \cdot \nabla) \phi_n, \end{aligned}$$

and we conclude

$$\begin{aligned} C_1^{-1} 2^n \sup_{s-2^{-2n} < t < s} \int_{B_{2^{-n}}(a)} |u(t)|^2 + 2C_1^{-1} 2^n \int_{Q_{2^{-n}}(s,a)} |\nabla u|^2 \\ \leq \frac{3}{2} C_1 2^{-2n} \int_{-1/9}^s \int_{B_{1/3}(a)} |u|^2 + \frac{3}{2} \int_{-1/9}^s \int_{B_{1/3}(a)} |u|^3 |\nabla \phi_n| + 3 \int_{-1/9}^s \int_{B_{1/3}(a)} pu \cdot \nabla \phi_n \\ =: I_1 + I_2 + I_3. \end{aligned}$$

We have already seen, in (13.25), that $I_1 \leq C_1 2^{-2n} \epsilon_0^{2/3}$ and, in the inequality after (13.25), that $I_2 \leq \frac{3}{2} C_1 2^{-2n} \epsilon_0^{\frac{2}{3}}$.

We now focus on I_3 . We consider a sequence $\chi_k \in C_c^\infty((-\infty, s] \times \mathbb{R}^3, [0, 1])$ for $k = 1, \dots, n$, with $\chi_k = 1$ in $Q_{\frac{7}{8}2^{-k}}(s, a)$ and $\text{supp} \chi_k \cap Q_1(s, a) \subset Q_{2^{-k}}(s, a)$ and $|\nabla \chi_k| \leq 2^k 16$. It is enough to pick $\chi_k(t, x) = T(2^{2k}(t-s))X(2^k(x-a))$ with $X(y) = 1$ for $|y| \leq \frac{7}{8}$ and $X(y) = 0$ for $|y| \geq 1$ and with $T(l) = 1$ for $|l| \leq \frac{7^2}{8^2}$ and $T(l) = 0$ $|l| \geq 1$.

Now we write

$$\begin{aligned}
I_3 &= 3 \int_{-1/9}^s \int_{B_{1/3}(a)} pu \cdot \nabla \phi_n = 3 \sum_{k=1}^{n-1} \int_{Q_{1/3}(s,a)} pu \cdot \nabla [\phi_n (\chi_k - \chi_{k+1})] + 3 \int_{Q_{1/3}(s,a)} pu \cdot \nabla [\phi_n \chi_n] \\
&= 3 \sum_{k=1}^{n-1} \int_{Q_{1/3}(s,a)} \left(p - (p)_{B_{2^{-k}}(a)} \right) u \cdot \nabla [\phi_n (\chi_k - \chi_{k+1})] + 3 \int_{Q_{1/3}(s,a)} \left(p - (p)_{B_{2^{-n}}(a)} \right) u \cdot \nabla [\phi_n \chi_n] \\
&= 3 \sum_{k=1}^{n-1} \int_{Q_{2^{-k}}(s,a)} \left(p - (p)_{B_{2^{-k}}(a)} \right) u \cdot \nabla [\phi_n (\chi_k - \chi_{k+1})] + 3 \int_{Q_{2^{-n}}(s,a)} \left(p - (p)_{B_{2^{-n}}(a)} \right) u \cdot \nabla [\phi_n \chi_n],
\end{aligned}$$

where we used $\text{supp} \chi_k \cap \overline{Q_1(s,a)} \subset \overline{Q_{2^{-k}}(s,a)}$. Then we have

$$|I_3| \leq 3 \sum_{k=1}^{n-1} \int_{Q_{2^{-k}}(s,a)} \left| p - (p)_{B_{2^{-k}}(a)} \right| |u| |\nabla [\phi_n (\chi_k - \chi_{k+1})]| + 3 \int_{Q_{2^{-n}}(s,a)} \left| p - (p)_{B_{2^{-n}}(a)} \right| |u| |\nabla [\phi_n \chi_n]|.$$

Now we use the bounds

$$\begin{aligned}
|(\chi_k - \chi_{k+1}) \nabla \phi_n| &\leq (\chi_{Q_{2^{-k}}(s,a) \setminus Q_{2^{-k-1}}(s,a)} + \chi_{Q_{2^{-k-1}}(s,a) \setminus Q_{2^{-k-2}}(s,a)}) |\nabla \phi_n| \\
&\leq C_1 2^{-2n} 2^{4(k+1)} + C_1 2^{-2n} 2^{4(k+2)},
\end{aligned}$$

$$\chi_n |\nabla \phi_n| \leq \chi_{Q_{2^{-n}}(s,a)} |\nabla \phi_n| \leq C_1 2^{2n},$$

$$\begin{aligned}
|\phi_n (\nabla \chi_k - \nabla \chi_{k+1})| &\leq \phi_n \left(162^k \chi_{Q_{2^{-k}}(s,a) \setminus \frac{7}{8} Q_{2^{-k}}(s,a)} + 162^{k+1} \chi_{Q_{2^{-k-1}}(s,a) \setminus \frac{7}{8} Q_{2^{-k-1}}(s,a)} \right) \\
&\leq \phi_n \left(162^k \chi_{Q_{2^{-k}}(s,a) \setminus Q_{2^{-k-1}}(s,a)} + 162^{k+1} \chi_{Q_{2^{-k-1}}(s,a) \setminus Q_{2^{-k-2}}(s,a)} \right) \\
&\leq 162^k C_1 2^{-2n} 2^{3(k+1)} + 162^{k+1} C_1 2^{-2n} 2^{3(k+2)}
\end{aligned}$$

and, finally

$$|\phi_n \nabla \chi_n| \leq \phi_n 16 \chi_{Q_{2^{-n}}(s,a) \setminus \frac{7}{8} Q_{2^{-n}}(s,a)} \leq \phi_n 16 \chi_{Q_{2^{-n}}(s,a)} \leq 16 C_1 2^n.$$

Then, for an appropriate c'_0 , we have

$$\begin{aligned}
|I_3| &\leq c'_0 C_1 \sum_{k=1}^{n-1} 2^{-2n} 2^{4k} \int_{Q_{2^{-k}}(s,a)} |p - (p)_{B_{2^{-k}}(a)}| |u| + c'_0 C_1 2^{2n} \int_{Q_{2^{-n}}(s,a)} |p - (p)_{B_{2^{-n}}(a)}| |u| \\
&= c'_0 C_1 2^{-2n} \sum_{k=1}^n 2^{4k} \int_{Q_{2^{-k}}(s,a)} |p - (p)_{B_{2^{-k}}(a)}| |u| \\
&\leq c'_0 C_1 2^{-2n} \sum_{k=1}^n 2^{\frac{7}{3}k} 2^{\frac{2}{3}k} \|u\|_{L^3(Q_{2^{-k}}(s,a))} 2^k \|p - (p)_{B_{2^{-k}}(a)}\|_{L^{\frac{3}{2}}(Q_{2^{-k}}(s,a))} \\
&\leq c_0 C_1 2^{-2n} \sum_{k=1}^n 2^{\frac{7}{3}k} \left(2^{2k} \int_{Q_{2^{-k}}(s,a)} |u|^3 + 2^{\frac{3}{2}k} \int_{Q_{2^{-k}}(s,a)} |p - (p)_{B_{2^{-n}}(a)}|^{\frac{3}{2}} \right) \\
&\leq c'_0 C_1 2^{-2n} \sum_{k=1}^n 2^{-\frac{2}{3}k} \epsilon_0^{\frac{2}{3}} \leq c'_0 2^{-2n} C_1 \epsilon_0^{\frac{2}{3}} \frac{1}{2^{\frac{2}{3}} - 1}.
\end{aligned}$$

So we have shown that A_1, \dots, A_n imply

$$I_1 + I_2 + I_3 \leq C_1 (1 + 2 + c_0) 2^{-2n} \epsilon_0^{\frac{2}{3}} \text{ for } c_0 = \frac{c'_0}{2^{\frac{2}{3}} - 1}.$$

Then

$$2^n \sup_{s-2^{-2n} < t < s} \int_{B_{2^{-n}}(a)} |u(t)|^2 + 2^{2n} \int_{Q_{2^{-n}}(s,a)} |\nabla u|^2 \leq (1 + 2 + c_0) C_1^2 2^{-2n} \epsilon_0^{\frac{2}{3}}$$

and so also

$$\begin{aligned}
&2^{n+1} \sup_{s-2^{-2n-2} < t < s} \int_{B_{2^{-n}}(a)} |u(t)|^2 + 2^{n+1} \int_{Q_{2^{-n-1}}(s,a)} |\nabla u|^2 \\
&\leq 2(1 + 2 + c_0) C_1^2 2^{-2(n+1)} \epsilon_0^{\frac{2}{3}}.
\end{aligned}$$

So, if we set $C_B = 2(1 + 2 + c_0) C_1^2$ we have $A_1, \dots, A_n \implies B_{n+1}$.

Proof of $B_2, \dots, B_n \implies A_n$.

Recall that we need the bound

$$2^{2n} \int_{Q_{2^{-n}}(s,a)} |u|^3 + 2^{\frac{3}{2}n} \int_{Q_{2^{-n}}(s,a)} |p - (p)_{B_{2^{-n}}(a)}|^{\frac{3}{2}} < 2^{-3n} \epsilon_0^{\frac{2}{3}}.$$

The first term in this formula can be bounded using (13.9), that is, using B_n

$$\begin{aligned}
2^{2n} \int_{Q_{2^{-n}}(s,a)} |u|^3 &\leq C_0 \left[2^n \sup_{s-2^{-2n} < t < s} \int_{B_{2^{-n}}(a)} |u(t)|^2 + 2^n \int_{Q_{2^{-n}}(s,a)} |\nabla u|^2 \right]^{\frac{3}{2}} \\
&\leq C_0 \left[C_B 2^{-2n} \epsilon_0^{\frac{2}{3}} \right]^{\frac{3}{2}} = \frac{1}{4} 4 C_0 C_B^{\frac{3}{2}} 2^{-3n} \epsilon_0 < \frac{1}{4} 2^{-3n} \epsilon_0^{\frac{2}{3}} \text{ for } \epsilon_0 < 4^{-3} C_0^{-3} C_B^{-\frac{9}{2}}.
\end{aligned}$$

To finish, we will prove

$$2^{\frac{3}{2}n} \int_{Q_{2^{-n}}(s,a)} |p - (p)_{B_{2^{-n}}(a)}|^{\frac{3}{2}} < \frac{3}{4} 2^{-3n} \epsilon_0^{\frac{2}{3}}. \quad (13.28)$$

To this effect we will use the formula, valid for $0 < r \leq \rho/2$,

$$\begin{aligned} r^{-\frac{3}{2}} \int_{Q_r(s,a)} |p - (p)_{B_r(a)}|^{\frac{3}{2}} &< C_2 r^{-\frac{3}{2}} \int_{Q_{2r}(s,a)} |u|^3 \\ &+ C_2 r^5 \left[\sup_{s-r^2 < t < s} \int_{2r < |y-a| < \rho} \frac{|u(t)|^2}{|y-a|^4} \right]^{\frac{3}{2}} \\ &+ C_2 \frac{r^3}{\rho^{\frac{9}{2}}} \int_{Q_\rho(s,a)} \left(|u|^3 + |p|^{\frac{3}{2}} \right). \end{aligned} \quad (13.29)$$

We apply this formula for $r = 2^{-n}$ and $\rho = 1/2$, to get

$$\begin{aligned} 2^{\frac{3}{2}n} \int_{Q_{2^{-n}}(s,a)} |p - (p)_{B_{2^{-n}}(a)}|^{\frac{3}{2}} &< C_2 2^{\frac{3}{2}n} \int_{Q_{2^{-(n-1)}}(s,a)} |u|^3 \\ &+ C_2 2^{-5n} \left[\sup_{s-2^{-2n} < t < s} \int_{2^{-(n-1)} < |y-a| < 1/2} \frac{|u(t)|^2}{|y-a|^4} \right]^{\frac{3}{2}} \\ &+ C_2 2^{\frac{9}{2}} 2^{-3n} \int_{Q_{1/2}(s,a)} \left(|u|^3 + |p|^{\frac{3}{2}} \right). \end{aligned} \quad (13.30)$$

Then we estimate the three terms on the r.h.s.

For the first, we have, using inequality (13.9),

$$\begin{aligned} C_2 2^{\frac{3}{2}n} \int_{Q_{2^{-(n-1)}}(s,a)} |u|^3 &= 4C_2 2^{-\frac{1}{2}n} 2^{2(n-1)} \int_{Q_{2^{-(n-1)}}(s,a)} |u|^3 \\ &\leq 4C_2 C_0 2^{-\frac{1}{2}n} \left[2^{n-1} \sup_{s-2^{-2(n-1)} < t < s} \int_{B_{2^{-(n-1)}}(a)} |u(t)|^2 dx + 2^{n-1} \int_{Q_{2^{-(n-1)}}(s,a)} |\nabla u|^2 \right]^{\frac{3}{2}} \\ &\leq 4C_2 C_0 2^{-\frac{1}{2}n} \left[C_B 2^{-2(n-1)} \epsilon_0^{\frac{2}{3}} \right]^{\frac{3}{2}} = \frac{1}{4} 16C_2 C_0 C_B^{\frac{3}{2}} 2^{-\frac{1}{2}n} 2^{-3(n-1)} \epsilon_0 \leq \left(32C_2 C_0 C_B^{\frac{3}{2}} \epsilon_0^{\frac{1}{3}} \right) \frac{1}{4} 2^{-3n} \epsilon_0^{\frac{2}{3}} < \frac{1}{4} 2^{-3n} \epsilon_0^{\frac{2}{3}}. \end{aligned} \quad (13.31)$$

The last term in (13.30) is bounded using $\int_{Q_1(0,0)} \left(|u|^3 + |p|^{\frac{3}{2}} \right) < \epsilon_0$, which yields

$$C_2 2^{\frac{9}{2}} 2^{-3n} \int_{Q_{1/2}(s,a)} \left(|u|^3 + |p|^{\frac{3}{2}} \right) \leq \left(4C_2 2^{\frac{9}{2}} 2^{-3n} \epsilon_0^{\frac{1}{3}} \right) \frac{1}{4} 2^{-3n} \epsilon_0^{\frac{2}{3}} < \frac{1}{4} 2^{-3n} \epsilon_0^{\frac{2}{3}}. \quad (13.32)$$

We consider now the middle term in (13.30). We have

$$\begin{aligned}
& \sup_{s-2^{-2n}<t<s} \int_{2^{-(n-1)}<|y-a|<1/2} \frac{|u(t)|^2}{|y-a|^4} = \sup_{s-2^{-2n}<t<s} \sum_{k=2}^{n-1} \int_{2^{-k}<|y-a|<2^{-(k-1)}} \frac{|u(t)|^2}{|y-a|^4} \\
& \leq 2^4 \sum_{k=2}^{n-1} 2^{4(k-1)} \sup_{s-2^{-2(k-1)}<t<s} \int_{B_{2^{-(k-1)}}(a)} |u(t)|^2 = 2^4 \sum_{k=1}^{n-2} 2^{4k} \sup_{s-2^{-2k}<t<s} \int_{B_{2^{-k}}(a)} |u(t)|^2 \\
& \leq 2^4 C_B \epsilon_0^{\frac{2}{3}} \sum_{k=1}^{n-2} 2^k \leq 2^4 C_B \epsilon_0^{\frac{2}{3}} 2^n.
\end{aligned}$$

Then

$$\begin{aligned}
& C_2 2^{-5n} \left[\sup_{s-2^{-2n}<t<s} \int_{2^{-(n-1)}<|y-a|<1/2} \frac{|u(t)|^2}{|y-a|^4} \right]^{\frac{3}{2}} \\
& \leq C_2 2^{-5n} \left[2^4 C_B \epsilon_0^{\frac{2}{3}} 2^n \right]^{\frac{3}{2}} < \frac{1}{4} \left(2^6 C_2 C_B^{\frac{3}{2}} \epsilon_0^{\frac{1}{3}} \right) 2^{-2n} \epsilon_0^{\frac{2}{3}} < \frac{1}{4} 2^{-2n} \epsilon_0^{\frac{2}{3}}.
\end{aligned} \tag{13.33}$$

So, summing up (13.31)–(13.33), we get (13.28), and this ends the proof of $B_2, \dots, B_n \implies A_n$. \square

We will prove now formula (13.29).

Lemma 13.9. *There exists C_2 such that for $p \in L^{\frac{3}{2}}(Q_\rho)$ and $u \in L^3(Q_\rho) \cap L^\infty((-\rho^2, 0), L^2(B_\rho))$ and for $-\Delta p = \partial_i \partial_j (u_i u_j)$ in Q_ρ , then for any $0 < r < \rho/2$ we have*

$$\begin{aligned}
& r^{-\frac{3}{2}} \int_{Q_r} |p - (p)_{B_r}|^{\frac{3}{2}} < C_2 r^{-\frac{3}{2}} \int_{Q_{2r}} |u|^3 \\
& + C_2 r^5 \left[\sup_{-r^2 < t < 0} \int_{2r < |y| < \rho} \frac{|u(t, y)|^2}{|y|^4} \right]^{\frac{3}{2}} \\
& + C_2 \frac{r^3}{\rho^{\frac{9}{2}}} \int_{Q_\rho} (|u|^3 + |p|^{\frac{3}{2}}).
\end{aligned} \tag{13.34}$$

Proof. We will start by assuming $u \in L^\infty((-\rho^2, 0), C^N(B_\rho))$ with $N \gg 1$. This in turn implies that $p(t) \in L^{\frac{3}{2}}((-\rho^2, 0), C^k(B_{\rho'}))$ for a large $k < N$ and for $\rho' < \rho$: this is analogous to Lemma 10.5 valid for the pair (u, ω) .

Let now $\phi \in C_c^\infty(\mathbb{R}^3, [0, 1])$ with

$$\phi(x) = \begin{cases} 1 & \text{in } B_{3\rho/4} \\ 0 & \text{outside } B_\rho \end{cases}$$

with $|\nabla\phi| \leq c\rho^{-1}$ and $|\partial_i\partial_j\phi| \leq c\rho^{-2}$. Then, like in Lemma 10.2, we have

$$\begin{aligned}
\phi p &= (-\Delta)^{-1}(-\Delta)\phi p = \frac{1}{4\pi|x|} * ((-\Delta)\phi p) = \frac{1}{4\pi|x|} * (-\phi\Delta p - p\Delta\phi - 2\nabla\phi \cdot \nabla p) \\
&= \frac{1}{4\pi|x|} * (\phi\partial_i\partial_j(u_i u_j) - p\Delta\phi - 2\nabla\phi \cdot \nabla p) \\
&= \frac{1}{4\pi|x|} * (\partial_i\partial_j(\phi u_i u_j) - \partial_i(u_i u_j \partial_j\phi) - \partial_j(u_i u_j \partial_i\phi) + u_i u_j \partial_j\partial_i\phi - p\Delta\phi - 2\nabla \cdot (p\nabla\phi) + 2p\Delta\phi) \\
&= \partial_i \frac{1}{4\pi|x|} * (\partial_j(\phi u_i u_j) - 2u_i u_j \partial_i\phi - 2p\partial_j\phi) + \frac{1}{4\pi|x|} * (u_i u_j \partial_j\partial_i\phi + p\Delta\phi) \\
&= -\frac{x_i}{4\pi|x|^3} * (\partial_j(\phi u_i u_j) - 2u_i u_j \partial_i\phi - 2p\partial_j\phi) + \frac{1}{4\pi|x|} * (u_i u_j \partial_j\partial_i\phi + p\Delta\phi)
\end{aligned}$$

Now we can apply Lemma 10.6 and conclude that

$$\phi p = -\frac{1}{4\pi} P.V. \left(\frac{\delta_{ij}}{|x|^3} - \frac{3x_i x_j}{|x|^5} \right) * (\phi u_i u_j) + \frac{x_i}{4\pi|x|^3} * (2u_i u_j \partial_i\phi + 2p\partial_j\phi) + \frac{1}{4\pi|x|} * (u_i u_j \partial_j\partial_i\phi + p\Delta\phi).$$

We have $p = \phi p$ in $Q_{3\rho/4}$. We write

$$\begin{aligned}
p_{11} &= -\frac{1}{4\pi} P.V. \left(\left(\frac{\delta_{ij}}{|x|^3} - \frac{3x_i x_j}{|x|^5} \right) \right) * (\chi_{B_{2r}} \phi u_i u_j) \\
p_{12} &= -\frac{1}{4\pi} P.V. \left(\left(\frac{\delta_{ij}}{|x|^3} - \frac{3x_i x_j}{|x|^5} \right) \right) * ((1 - \chi_{B_{2r}}) \phi u_i u_j).
\end{aligned}$$

Then

$$\|p_{11}\|_{L^{\frac{3}{2}}(B_r)} \leq C \sum_{i,j} \|\phi u_i u_j\|_{L^{\frac{3}{2}}(B_{2r})} \leq C \sum_{i,j} \|u_i u_j\|_{L^{\frac{3}{2}}(B_{2r})} \leq C' \|u\|_{L^3(B_{2r})}^2.$$

and so also

$$\|p_{11} - (p_{11})_{B_r}\|_{L^{\frac{3}{2}}(Q_r)} \leq 2C' \|u\|_{L^3(Q_{2r})}^2$$

which is equivalent to

$$\int_{Q_r} |p_{11} - (p_{11})_{B_r}|^{\frac{3}{2}} \leq (2C')^{\frac{3}{2}} \int_{Q_{2r}} |u|^3.$$

Next, we observe that by mean value there exists $x_0(t) \in B_r$ so that $(p_{12})_{B_r} = p_{21}(x_0(t))$

$$p_{12}(t, x) - (p_{12})_{B_r}(t) = \int_0^1 \nabla p(t, s(x - x_0(t)) + x_0(t)) \cdot (x - x_0(t)) ds$$

and so

$$\begin{aligned}
\|p_{12} - (p_{12})_{B_r}\|_{L^{\frac{3}{2}}(Q_r)} &\leq 2r \int_0^1 ds \|\nabla p(s(x - x_0(t)) + x_0(t))\|_{L^{\frac{3}{2}}(Q_r)} \leq 2r |Q_r|^{\frac{2}{3}} \|\nabla p_{12}\|_{L^\infty(Q_r)} \\
&= 2r (4\pi/3)^{\frac{2}{3}} r^{\frac{10}{3}} \frac{1}{4\pi} \left\| \nabla \left(\frac{\delta_{ij}}{|x|^3} - \frac{3x_i x_j}{|x|^5} \right) * ((1 - \chi_{B_{2r}}) \phi u_i u_j) \right\|_{L^\infty(Q_r)} \\
&\leq Cr^{\frac{13}{3}} \left\| \int_{\rho > |y| \geq 2r} \frac{1}{|x - y|^4} |u(t, y)|^2 dy \right\|_{L^\infty(Q_r)} \leq 2^4 Cr^{\frac{13}{3}} \left\| \int_{\rho > |y| \geq 2r} \frac{1}{|y|^4} |u(t, y)|^2 dy \right\|_{L^\infty(Q_r)},
\end{aligned}$$

where we used $|x - y| = |y| \left(1 - \frac{|x|}{|y|}\right) \geq |y|2^{-1}$.

So we conclude

$$\int_{Q_r} |p_{12} - (p_{12})_{B_r}|^{\frac{3}{2}} \leq 2^6 C^{\frac{3}{2}} r^{\frac{3}{2}} r^5 \left(\sup_{-r^2 < t < 0} \int_{\rho > |y| \geq 2r} \frac{1}{|y|^4} |u(t, y)|^2 dy \right)^{\frac{3}{2}}.$$

Now we set

$$p_2 = p_{21} + p_{22} = \frac{x_i}{2\pi|x|^3} * u_i u_j \partial_i \phi + \frac{x_i}{4\pi|x|^3} * p \partial_j \phi.$$

Then, also from $|\nabla \phi| \leq c\rho^{-1}$, $\text{supp}|\nabla \phi| \subseteq B_\rho \setminus B_{3\rho/4}$ and

$$|x - y| = |y| \left(1 - \frac{|x|}{|y|}\right) \geq |y| \left(1 - \frac{r}{\frac{3}{4}\rho}\right) \geq |y| \left(1 - \frac{\frac{1}{2}\rho}{\frac{3}{4}\rho}\right) = |y| \left(1 - \frac{2}{3}\right) = \frac{|y|}{3},$$

we obtain

$$\begin{aligned}
\|p_{21} - (p_{21})_{B_r}\|_{L^{\frac{3}{2}}(B_r)} &\leq 2r |B_r|^{\frac{2}{3}} \|\nabla p_{21}\|_{L^\infty(B_r)} \leq Cr^3 \rho^{-1} \int_{\frac{3}{4}\rho \leq |y| \leq \rho} \frac{|u(y)|^2}{|x - y|^3} dy \\
&\leq 3^3 Cr^3 \rho^{-1} \int_{\frac{3}{4}\rho \leq |y| \leq \rho} \frac{|u(y)|^2}{|y|^3} dy \leq 4^3 Cr^3 \rho^{-4} \int_{\frac{3}{4}\rho \leq |y| \leq \rho} |u(y)|^2 dy \\
&\leq 4^3 Cr^3 \rho^{-4} |\{\frac{3}{4}\rho \leq |y| \leq \rho\}|^{\frac{1}{3}} \left(\int_{\frac{3}{4}\rho \leq |y| \leq \rho} |u(y)|^3 dy \right)^{\frac{2}{3}} \leq C' Cr^3 \rho^{-3} \left(\int_{\frac{3}{4}\rho \leq |y| \leq \rho} |u(y)|^3 dy \right)^{\frac{2}{3}}.
\end{aligned}$$

Then

$$\int_{Q_r} |p_{21} - (p_{21})_{B_r}|^{\frac{3}{2}} \leq (C')^{\frac{3}{2}} r^{\frac{9}{2}} \rho^{-\frac{9}{2}} \int_{Q_\rho} |u|^3 dy.$$

By the exact same argument,

$$\int_{Q_r} |p_{22} - (p_{22})_{B_r}|^{\frac{3}{2}} \leq (C')^{\frac{3}{2}} r^{\frac{9}{2}} \rho^{-\frac{9}{2}} \int_{Q_\rho} |p|^{\frac{3}{2}} dy.$$

Finally we set

$$p_3 = p_{31} + p_{32} = \frac{1}{4\pi|x|} * (u_i u_j \partial_j \partial_i \phi) + \frac{1}{4\pi|x|} * (p \Delta \phi).$$

They can be treated like p_{21} and p_{22} , due to $|\partial_i \partial_j \phi| \leq c\rho^{-2}$. Indeed, for example

$$\begin{aligned} \|p_{31} - (p_{31})_{B_r}\|_{L^{\frac{3}{2}}(B_r)} &\leq 2r|B_r|^{\frac{2}{3}} \|\nabla p_{31}\|_{L^\infty(B_r)} \leq Cr^3 \rho^{-2} \int_{\frac{3}{4}\rho \leq |y| \leq \rho} \frac{|u(y)|^2}{|x-y|^2} dy \\ &\leq 3^2 Cr^3 \rho^{-2} \int_{\frac{3}{4}\rho \leq |y| \leq \rho} \frac{|u(y)|^2}{|y|^2} dy \leq 4^2 Cr^3 \rho^{-4} \int_{\frac{3}{4}\rho \leq |y| \leq \rho} |u(y)|^2 dy \\ &\leq C' Cr^3 \rho^{-3} \left(\int_{\frac{3}{4}\rho \leq |y| \leq \rho} |u(y)|^3 dy \right)^{\frac{2}{3}} \text{ etc.} \end{aligned}$$

All the above estimates have been obtained by assuming $u \in L_t^\infty C_x^N(\overline{Q_\rho})$. In general, we consider a sequence $L^\infty((-\rho^2, 0), C_x^N(\overline{B_\rho})) \ni u_n \xrightarrow{n \rightarrow \infty} u$, with the convergence occurring in $L^3(Q_\rho) \cap L^\infty((-\rho^2, 0), L^2(B_\rho))$. □

14 A second result of Caffarelli, Kohn and Nirenberg

In this section we will the following theorem.

Theorem 14.1. *There exists absolute constants $\epsilon_1 > 0$ s.t. if (u, p) is a suitable weak solution of the NS in $Q_R(t_0, x_0)$ for some $R > 0$ and we have either*

$$\limsup_{r \rightarrow 0} \frac{1}{r} \int_{Q_r(t_0, x_0)} |\nabla u|^2 < \epsilon_1 \text{ or} \tag{14.1}$$

$$\limsup_{r \rightarrow 0} \frac{1}{r} \sup_{t_0 - r^2 < t < t_0} \int_{B_r(x_0)} |u|^2 < \epsilon_1, \tag{14.2}$$

then $u \in L^\infty(Q_\rho(t_0, x_0))$ for some $\rho \in (0, R)$.

Specifically, we will show that

$$(2\rho)^{-2} \int_{Q_{2\rho}(t_0, x_0)} \left(|u|^3 + |p|^{\frac{3}{2}} \right) dt dx < \epsilon_0^*, \tag{14.3}$$

with ϵ_0^* the small positive constant in Theorem 13.2. Then, the conclusion follows from Theorem 13.2.

Like in the previous section, we will at first prove a simplified version of this theorem, where there is no pressure.

14.1 A simplified result, without pressure

We oversimplify and we assume that there is no pressure in the local energy inequality (12.6), so that, as before in (13.5) we have

$$\begin{aligned} & \int_{B_R(x_0)} |u(s)|^2 \phi(s) dx + 2 \int_{t_0-R^2}^s \int_{B_R(x_0)} |\nabla u|^2 \phi \leq \int_{t_0-R^2}^s \int_{B_R(x_0)} |u|^2 (\partial_t + \Delta) \phi \quad (14.4) \\ & + \int_{t_0-R^2}^s \int_{B_R(x_0)} |u|^2 (u \cdot \nabla) \phi \text{ for all } \phi \in C_c^\infty(Q_R(t_0, x_0), [0, \infty)). \end{aligned}$$

Then using (14.4) it is possible to prove rigorously the following.

Proposition 14.2. *There exists an absolute constant $\epsilon_1 > 0$ such that if for some $R > 0$*

$$u \in L^\infty((t_0 - R^2, t_0), L^2(B_R(x_0), \mathbb{R}^3)) \text{ and } \nabla u \in L^2(Q_R(t_0, x_0)) \quad (14.5)$$

and u satisfies (14.4) then, if u satisfies either (14.1) or (14.2), there exists $\rho \in (0, R)$ s.t.

$$\rho^{-2} \int_{Q_\rho(t_0, x_0)} |u|^3 < \epsilon_0^*. \quad (14.6)$$

Before proving Proposition 14.2 we give a sketch. First of all, we can assume $(t_0, x_0) = (0, 0)$. Next, suppose that (14.1) is true and define

$$\tilde{E}(r) = \frac{1}{r} \sup_{-r^2 < t < 0} \int_{B_r} |u|^2.$$

Then it will be shown that there exists a fixed $\theta \in (0, 1)$ s.t. $\tilde{E}(\theta r) \leq 2^{-1} \epsilon_1 + 2^{-1} \tilde{E}(r)$ for all $r \in (0, r_0]$ for $r_0 > 0$ small enough. Then

$$\tilde{E}(\theta^n r) \leq 2^{-1} \epsilon_1 + 2^{-1} \tilde{E}(\theta^{n-1} r) \leq (2^{-1} + 2^{-2}) \epsilon_1 + 2^{-2} \tilde{E}(\theta^{n-2} r) \leq \sum_{j=1}^n 2^{-j} \epsilon_1 + 2^{-n} \tilde{E}(r)$$

so that, assuming that $\tilde{E}(r)$ is uniformly bounded in $(0, r_0]$, then picking n sufficiently large, we find that there exists an $r_1 > 0$ s.t. $\tilde{E}(r) < 2\epsilon_1$ for all $r \in (0, r_1]$. Then, by (13.9)

$$\begin{aligned} r^{-2} \int_{Q_r} |u|^3 dx & \leq C_0 \left[r^{-1} \sup_{-r^2 < t < 0} \int_{B_r} |u(t)|^2 dx + r^{-1} \int_{Q_r} |\nabla u|^2 \right]^{\frac{3}{2}} \leq C_0 [3\epsilon_1]^{\frac{3}{2}} \\ & = C_0 3^{\frac{3}{2}} \epsilon_1^{\frac{3}{2}} < \epsilon_0^* \text{ for } \epsilon_1 \in \left(0, C_0^{-\frac{2}{3}} 3^{-1} (\epsilon_0^*)^{\frac{2}{3}} \right). \end{aligned}$$

The proof of Proposition 14.2 exploits the following lemma.

Lemma 14.3. *There exists a constant $C_3 \geq 1$ such that, for any fixed $r > 0$ and $\theta \in (0, 1/2]$, there exists $\phi \in C_c^\infty(\mathbb{R}^4, [0, \infty))$ such that $\text{supp } \phi \cap \overline{Q_1} \subseteq \overline{Q_r}$,*

$$\phi \geq C_3^{-1} (\theta r)^{-1} \text{ in } Q_{\theta r} \text{ and} \quad (14.7)$$

$$0 \leq \phi \leq C_3 (\theta r)^{-1}, \quad |\nabla \phi| \leq C_3 (\theta r)^{-2} \text{ and } |(\partial_t + \Delta) \phi| \leq C_3 \theta^2 r^{-3} \text{ in } Q_r. \quad (14.8)$$

Proof. We write

$$\phi(t, x) = (\theta r)^2 \vartheta(t, x) \psi(t, x). \quad (14.9)$$

Here we choose ψ such that

$$(\partial_t + \Delta)\psi(t, x) = 0 \text{ for } t < (\theta r)^2 \text{ and with initial value } \psi((\theta r)^2, x) = \delta(x). \quad (14.10)$$

Then we know that

$$\psi(t, x) = K_{(\theta r)^2 - t}(x) = (4\pi((\theta r)^2 - t))^{-\frac{3}{2}} e^{-\frac{|x|^2}{4((\theta r)^2 - t)}}. \quad (14.11)$$

Then we have

$$\begin{aligned} \psi(t, x) &= (4\pi((\theta r)^2 - t))^{-\frac{3}{2}} e^{-\frac{|x|^2}{4((\theta r)^2 - t)}} \leq (4\pi((\theta r)^2 - t))^{-\frac{3}{2}} \\ &\leq (4\pi(\theta r)^2)^{-\frac{3}{2}} = (4\pi)^{-\frac{3}{2}} (\theta r)^{-3} \text{ in } Q_r = (-r^2, 0) \times B_r \end{aligned} \quad (14.12)$$

$$\begin{aligned} \psi(t, x) &= (4\pi((\theta r)^2 + |t|))^{-\frac{3}{2}} e^{-\frac{|x|^2}{4((\theta r)^2 + |t|)}} \\ &\geq (4\pi 2(\theta r)^2)^{-\frac{3}{2}} e^{-\frac{\theta^2 r^2}{4(\theta r)^2}} = (8\pi)^{-\frac{3}{2}} e^{-\frac{1}{4}} (\theta r)^{-3} \text{ in } Q_{\theta r}. \end{aligned} \quad (14.13)$$

Next,

$$\begin{aligned} \nabla \psi(t, x) &= -2^{-1} \pi^{-\frac{3}{2}} (4((\theta r)^2 - t))^{-\frac{5}{2}} e^{-\frac{|x|^2}{4((\theta r)^2 - t)}} x \\ &= -2^{-1} \pi^{-\frac{3}{2}} (4((\theta r)^2 - t))^{-2} e^{-\frac{|x|^2}{4((\theta r)^2 - t)}} \frac{x}{\sqrt{4((\theta r)^2 - t)}} \end{aligned}$$

so in Q_r

$$|\nabla \psi(t, x)| \leq 2^{-6} \pi^{-\frac{3}{2}} (\theta r)^{-4} e^{-\frac{|x|^2}{4((\theta r)^2 - t)}} \frac{|x|}{\sqrt{4((\theta r)^2 - t)}} \leq 2^{-6} \pi^{-\frac{3}{2}} (\theta r)^{-4} \sup_{\alpha \geq 0} \alpha e^{-\alpha^2}. \quad (14.14)$$

We define, for $X \in C_c^\infty(\mathbb{R}^3, [0, 1])$ and $T, \eta \in C_c^\infty(\mathbb{R}, [0, 1])$,

$$\begin{aligned} \vartheta(t, x) &= X(x/r) T(t/r^2) \eta(t) \text{ where} \\ X(x) &= \begin{cases} 1 & \text{in } B_{1/2} \\ 0 & \text{outside } B_1 \end{cases} \text{ and } T(t) = \begin{cases} 1 & \text{for } t \in (-1/4, 1/4) \\ 0 & \text{for } |t| \geq 1, \end{cases} \end{aligned} \quad (14.15)$$

and

$$\eta(t) = \begin{cases} 1 & \text{for } t \leq r^2/4 \\ 0 & \text{for } t \geq r^2/2 \end{cases}$$

Now we check if (14.9) satisfies the desired results. First of all, in Q_1 we have $\phi(t, x) \neq 0$ only if $X(x/r) \neq 0$, that is only if $|x| > 1$, and $T(t/r^2) \neq 0$, that is only if $-r^2/4 < t < 0$. Hence it is true that $\text{supp} \phi \cap Q_1 \subseteq Q_r$.

Now, let us look at the estimates. In $Q_{\theta r}$ we have

$$\phi(t, x) = (\theta r)^2 X(x/r) T(t/r^2) \eta(t) \psi(t, x) = (\theta r)^2 \psi(t, x) \geq (8\pi)^{-\frac{3}{2}} e^{-\frac{1}{8}} (\theta r)^{-1},$$

yielding (14.7) and in Q_r we have

$$\phi(t, x) = (\theta r)^2 X(x/r) T(t/r^2) \eta(t) \psi(t, x) \leq (\theta r)^2 \psi(t, x) \leq (4\pi)^{-\frac{3}{2}} (\theta r)^{-1},$$

so yielding the first estimate in (14.8).

Turning to the gradient, we have

$$\nabla \phi(t, x) = (\theta r)^2 \psi(t, x) T(t/r^2) \eta(t) r^{-1} \nabla X(x/r) + (\theta r)^2 T(t/r^2) \eta(t) r^{-1} X(x/r) \nabla \psi(t, x).$$

In Q_r we have

$$(\theta r)^2 \psi(t, x) T(t/r^2) \eta(t) r^{-1} |\nabla X(x/r)| \leq \|\nabla X\|_{L^\infty} (\theta r)^2 \psi(t, x) \leq \|\nabla X\|_{L^\infty} (4\pi)^{-\frac{3}{2}} (\theta r)^{-1},$$

and

$$(\theta r)^2 T(t/r^2) \eta(t) r^{-1} X(x/r) |\nabla \psi(t, x)| \leq (\theta r)^2 |\nabla \psi(t, x)| \leq C \theta^{-2} r^{-2}.$$

Finally, we have

$$\begin{aligned} (\partial_t + \Delta) \phi(t, x) &= (\theta r)^2 \psi(t, x) (\partial_t + \Delta) (X(x/r) T(t/r^2) \eta(t)) \\ &\quad + 2(\theta r)^2 r^{-1} T(t/r^2) \eta(t) \nabla X(x/r) \cdot \nabla \psi(t, x). \end{aligned}$$

In Q_r , using $|(\nabla X)(x/r)| \neq 0 \implies 1/2 \leq |x/r| \leq 1$, we have

$$\begin{aligned} 2r^{-1} (\theta r)^2 T(t/r^2) \eta(t) |(\nabla X)(x/r) \cdot \nabla \psi(t, x)| &\leq \theta^2 r |(\nabla X)(x/r)| 2^{-6} \pi^{-\frac{3}{2}} \theta^{-5} r^{-4} e^{-\frac{1}{24\theta^2} \frac{|x|}{r}} \\ &\leq 2^{-6} \theta^2 \pi^{-\frac{3}{2}} r^{-3} \|\nabla X\|_{L^\infty} \sup_{\theta > 0} \theta^{-5} e^{-\frac{1}{24\theta^2}} \leq C \theta^2 r^{-3}. \end{aligned}$$

Finally, in Q_r , using also $T'(t/r^2) \neq 0 \implies 1/4 \leq |t/r^2| \leq 1$

$$\begin{aligned} (\theta r)^2 \psi(t, x) |(\partial_t + \Delta) (X(x/r) T(t/r^2) \eta(t))| &= (\theta r)^2 \psi(t, x) |(\partial_t + \Delta) (X(x/r) T(t/r^2))| \\ &\leq (\theta r)^2 (4\pi((\theta r)^2 + |t|))^{-\frac{3}{2}} e^{-\frac{|x|^2}{4((\theta r)^2 + |t|)}} r^{-2} (X(x/r) |T'(t/r^2)| + T(t/r^2) |(\Delta X)(x/r)|) \\ &\leq \theta^2 (4\pi)^{-\frac{3}{2}} (1/4)^{-\frac{3}{2}} \|T'\|_{L^\infty(\mathbb{R})} + \theta^2 (4\pi)^{-\frac{3}{2}} (\theta r)^{-3} e^{-\frac{1}{24\theta^2}} \|\Delta X\|_{L^\infty} \leq C \theta^2 r^{-3}. \end{aligned}$$

□

Proof of Proposition 14.2. In the proof it is enough to consider $(t_0, x_0) = (0, 0)$. Then, applying (14.4) for the ϕ of Lemma 14.3, we get

$$\begin{aligned} \int_{B_1} |u(t)|^2 \phi(t) + 2 \int_{-1}^t \int_{B_1} |\nabla u|^2 \phi &\leq \int_{-1}^t \int_{B_1} |u|^2 (\partial_t + \Delta) \phi \\ &\quad + \int_{-1}^t \int_{B_1} \left(|u|^2 - (|u|^2)_{B_r} \right) (u \cdot \nabla) \phi. \end{aligned}$$

Using the estimates in Lemma 14.3, we obtain

$$\begin{aligned}
& \frac{1}{\theta r} \int_{B_{\theta r}} |u(t)|^2 + \frac{1}{\theta r} \int_{-(\theta r)^2}^t \int_{B_{\theta r}} |\nabla u|^2 \leq C_3^2 \theta^2 r^{-3} \int_{Q_r} |u|^2 \\
& + C_3^2 \theta^{-2} r^{-2} \int_{Q_r} \left| |u|^2 - (|u|^2)_{B_r} \right| |u| \\
& \leq C_3^2 \theta^2 r^{-3} |Q_r|^{\frac{1}{3}} \|u\|_{L^3(Q_r)}^2 + C_3^2 \theta^{-2} r^{-2} \int_{Q_r} \left| |u|^2 - (|u|^2)_{B_r} \right| |u| \\
& = C_3^2 \theta^2 r^{-3 + \frac{5}{3}} \left(\frac{4\pi}{3} \right)^{\frac{1}{3}} \|u\|_{L^3(Q_r)}^2 + C_3^2 \theta^{-2} r^{-2} \int_{Q_r} \left| |u|^2 - (|u|^2)_{B_r} \right| |u| \\
& \leq 2C_3^2 \theta^2 \left(r^{-2} \int_{Q_r} |u|^3 \right)^{\frac{2}{3}} + C_3^2 \theta^{-2} r^{-2} \int_{Q_r} \left| |u|^2 - (|u|^2)_{B_r} \right| |u|.
\end{aligned}$$

Now we have

$$\begin{aligned}
\int_{B_r} \left| |u|^2 - (|u|^2)_{B_r} \right| |u| & \leq \| |u|^2 - (|u|^2)_{B_r} \|_{L^{\frac{3}{2}}(B_r)} \|u\|_{L^3(B_r)} \leq C_4 \|\nabla |u|^2\|_{L^1(B_r)} \|u\|_{L^3(B_r)} \\
& \leq 2C_4 \|u\|_{L^2(B_r)} \|\nabla u\|_{L^2(B_r)} \|u\|_{L^3(B_r)},
\end{aligned}$$

where we used the Poincaré inequality

$$\| |u|^2 - (|u|^2)_{B_r} \|_{L^{\frac{3}{2}}(B_r)} \leq C_4 \|\nabla |u|^2\|_{L^1(B_r)},$$

see [10] Theorem 8.11, where, by scale invariance, the constant C_4 does not depend on r . Then, from Hölder with $\frac{1}{6} + \frac{1}{2} + \frac{1}{3} = 1$

$$\begin{aligned}
& \int_{Q_r} \left| |u|^2 - (|u|^2)_{B_r} \right| |u| \leq 2C_4 \|\nabla u\|_{L^2(Q_r)} \|u\|_{L^3(Q_r)} \| \|u\|_{L^2(B_r)} \|_{L^6(-r^2, 0)} \\
& \leq 2r^{\frac{1}{3}} C_4 \|\nabla u\|_{L^2(Q_r)} \|u\|_{L^3(Q_r)} \sup_{-r^2 < t < 0} \|u\|_{L^2(B_r)} \\
& = 2C_4 r^2 \left(r^{-2} \int_{Q_r} |u|^3 \right)^{\frac{1}{3}} \left(r^{-1} \int_{Q_r} |\nabla u|^2 \right)^{\frac{1}{2}} \left(r^{-1} \sup_{-r^2 < t < 0} \int_{B_r} |u(t)|^2 \right)^{\frac{1}{2}}.
\end{aligned}$$

Then we conclude

$$\begin{aligned}
& \frac{1}{\theta r} \int_{B_{\theta r}} |u(t)|^2 + \frac{1}{\theta r} \int_{-(\theta r)^2}^t \int_{B_{\theta r}} |\nabla u|^2 \leq 2C_3^2 \theta^2 \left(r^{-2} \int_{Q_r} |u|^3 \right)^{\frac{2}{3}} \\
& + 2C_4 C_3^2 \theta^{-2} \left(r^{-2} \int_{Q_r} |u|^3 \right)^{\frac{1}{3}} \left(r^{-1} \int_{Q_r} |\nabla u|^2 \right)^{\frac{1}{2}} \left(r^{-1} \sup_{-r^2 < t < 0} \int_{B_r} |u(t)|^2 \right)^{\frac{1}{2}} \\
& \leq 2C_3^2 \theta^2 \left(r^{-2} \int_{Q_r} |u|^3 \right)^{\frac{2}{3}} \\
& + C_3^2 \theta^2 \left(r^{-2} \int_{Q_r} |u|^3 \right)^{\frac{2}{3}} + 4C_4^2 C_3^2 \theta^{-6} \left(r^{-1} \int_{Q_r} |\nabla u|^2 \right) \left(r^{-1} \sup_{-r^2 < t < 0} \int_{B_r} |u(t)|^2 \right).
\end{aligned}$$

Then, using the inequality

$$r^{-2} \int_{Q_r} |u|^3 \leq C_0 \left[r^{-1} \sup_{-r^2 < t < 0} \int_{B_r} |u(t)|^2 + r^{-1} \int_{Q_r} |\nabla u|^2 \right]^{\frac{3}{2}}, \quad (14.16)$$

we obtain

$$\begin{aligned}
& \max \left(\sup_{-(\theta r)^2 < t < 0} \frac{1}{\theta r} \int_{B_{\theta r}} |u(t)|^2, \frac{1}{\theta r} \int_{-(\theta r)^2}^t \int_{B_{\theta r}} |\nabla u|^2 \right) \\
& \leq 3C_3^2 C_0^{\frac{2}{3}} \theta^2 \left[r^{-1} \sup_{-r^2 < t < 0} \int_{B_r} |u(t)|^2 + r^{-1} \int_{Q_r} |\nabla u|^2 \right] \\
& + 4C_4^2 C_3^2 \theta^{-6} \left(r^{-1} \sup_{-r^2 < t < 0} \int_{B_r} |u(t)|^2 \right) \left(r^{-1} \int_{Q_r} |\nabla u|^2 \right).
\end{aligned} \quad (14.17)$$

Now we assume either (14.1) or (14.2). For definiteness we assume (14.1), that is

$$\limsup_{r \rightarrow 0} \frac{1}{r} \int_{Q_r} |\nabla u|^2 < \epsilon_1$$

but, assuming instead (14.2), that is

$$\limsup_{r \rightarrow 0} \frac{1}{r} \sup_{t_0 - r^2 < t < t_0} \int_{B_r} |u|^2 < \epsilon_1,$$

the argument is the same, due to the symmetry with respect to the above quantities. Then for r sufficiently small, we have

$$\frac{1}{r} \int_{Q_r} |\nabla u|^2 < 2\epsilon_1.$$

Then we have

$$\begin{aligned} \sup_{-(\theta r)^2 < t < 0} \frac{1}{\theta r} \int_{B_{\theta r}} |u(t)|^2 &\leq 3C_3^2 C_0^{\frac{2}{3}} \theta^2 \left[r^{-1} \sup_{-r^2 < t < 0} \int_{B_r} |u(t)|^2 + 2\epsilon_1 \right] \\ &+ 8C_4^2 C_3^2 \theta^{-6} \epsilon_1 \left(r^{-1} \sup_{-r^2 < t < 0} \int_{B_r} |u(t)|^2 \right). \end{aligned}$$

Setting now

$$\tilde{E}(r) := \frac{1}{r} \sup_{-r^2 < t < 0} \int_{B_r} |u|^2.$$

we have

$$\tilde{E}(\theta r) \leq 6C_3^2 C_0^{\frac{2}{3}} \theta^2 \epsilon_1 + \left(3C_3^2 C_0^{\frac{2}{3}} \theta^2 + 8C_4^2 C_3^2 \theta^{-6} \epsilon_1 \right) \tilde{E}(r).$$

Now if we use $\theta \leq 1/2$ so small that $6C_3^2 C_0^{\frac{2}{3}} \theta^2 < 1/2$ and $\epsilon_1 > 0$ so small that $8C_4^2 C_3^2 \theta^{-6} \epsilon_1 < 1/4$, we obtain

$$\tilde{E}(\theta r) \leq \frac{1}{2} \epsilon_1 + \frac{1}{2} \tilde{E}(r) \text{ for all } r \in (0, r_0] \text{ for } r_0 > 0 \text{ small enough.} \quad (14.18)$$

This implies

$$\tilde{E}(\theta^n r) \leq \epsilon_1 + 2^{-n} \tilde{E}(r). \quad (14.19)$$

We assume now

$$\limsup_{r \rightarrow 0} \tilde{E}(r) < \infty. \quad (14.20)$$

Then (14.20) implies $\tilde{E}(r) \leq C_5 < \infty$ for $r \in (0, r_1]$. Then (14.19) implies $\tilde{E}(\theta^n r) \leq \epsilon_1 + 2^{-n} C_5 \leq 2\epsilon_1$ for $n > \log_2(C_5 \epsilon_1^{-1})$ and $0 < r < \min\{r_0, r_1\}$. This implies $\tilde{E}(r) \leq 2\epsilon_1$ for $0 < r < r_2$, with $r_2 = \theta^{n_0} \min\{r_0, r_1\}$, for a fixed $n_0 > \log_2(C_5 \epsilon_1^{-1})$. Inserting $\tilde{E}(r) \leq 2\epsilon_1$ and (14.1) in (14.16) we obtain

$$r^{-2} \int_{Q_r} |u|^3 \leq C_0 3^{3/2} \epsilon_1^{\frac{3}{2}} < \epsilon_0^* \text{ for } \epsilon_1 < 3(C_0^{-1} \epsilon_0^*)^{\frac{2}{3}}, \quad (14.21)$$

yielding (14.6). To complete the proof of Proposition 14.2, we need to prove (14.20). If (14.20) is false, there exists $R_n \searrow 0$ with $\tilde{E}(R_n) \nearrow \infty$. Using (14.18),

$$\tilde{E}(R_n) \leq \frac{1}{2} \epsilon_1 + \frac{1}{2} \tilde{E}(\theta^{-1} R_n) \leq \epsilon_1 + 2^{-m_n} \tilde{E}(\theta^{-m_n} R_n)$$

for $m_n := \left\lceil \left\lfloor \frac{\log(R_n/r_0)}{\log\theta} \right\rfloor \right\rceil$ which is the largest m_n s.t. $\theta^{-m_n}R_n \leq r_0$, so that we have $\theta r_0 \leq \theta^{-m_n}R_n \leq r_0$. This implies

$$\tilde{E}(R_n) \leq \frac{1}{2}\epsilon_1 + \frac{1}{2}\tilde{E}(\theta^{-1}R_n) \leq \epsilon_1 + 2^{-1} \sup_{\theta r_0 \leq r \leq r_0} \tilde{E}(r)$$

which, from $\tilde{E}(R_n) \xrightarrow{n \rightarrow \infty} \infty$, implies $\sup_{\theta r_0 \leq r \leq r_0} \sup_{-r^2 < t < 0} \int_{B_r} |u|^2 = \infty$. But then, this would imply $u \notin L^\infty((-R^2, 0), L^2(B_R, \mathbb{R}^3))$, contradicting the hypothesis (14.5). \square

14.2 Proof of Theorem 14.1

We can focus on the case $(t_0, x_0) = (0, 0)$. Then using (13.1) like in Sect. 14.1, we have

$$\begin{aligned} & \int_{B_1} |u(t)|^2 \phi(t) + 2 \int_{-1}^t \int_{B_1} |\nabla u|^2 \phi \leq \int_{-1}^t \int_{B_1} |u|^2 (\partial_t + \Delta) \phi \\ & + \int_{-1}^t \int_{B_1} \left(|u|^2 - (|u|^2)_{B_r} \right) (u \cdot \nabla) \phi + \int_{-1}^t \int_{B_1} p(u \cdot \nabla) \phi, \end{aligned}$$

with the test function from Lemma 14.3. Then, by Lemma 14.3 we get

$$\begin{aligned} & \frac{1}{\theta r} \int_{B_{\theta r}} |u(t)|^2 + \frac{1}{\theta r} \int_{-(\theta r)^2}^t \int_{B_{\theta r}} |\nabla u|^2 \leq C_3^2 \theta^2 r^{-3} \int_{Q_r} |u|^2 \\ & + C_3^2 \theta^{-2} r^{-2} \int_{Q_r} \left| |u|^2 - (|u|^2)_{B_r} \right| |u| + C_3^2 \theta^{-2} r^{-2} \int_{Q_r} |p| |u|. \end{aligned}$$

Now, by the discussion in Sect. 14.1, see (14.17), we have

$$\begin{aligned} & \frac{1}{\theta r} \int_{B_{\theta r}} |u(t)|^2 + \frac{1}{\theta r} \int_{-(\theta r)^2}^t \int_{B_{\theta r}} |\nabla u|^2 \leq 3C_3^2 C_0^{\frac{2}{3}} \theta^2 \left[r^{-1} \sup_{-r^2 < t < 0} \int_{B_r} |u(t)|^2 + r^{-1} \int_{Q_r} |\nabla u|^2 \right] \\ & + 4C_4^2 C_3^2 \theta^{-6} \left(r^{-1} \sup_{-r^2 < t < 0} \int_{B_r} |u(t)|^2 \right) \left(r^{-1} \int_{Q_r} |\nabla u|^2 \right) + C_3^2 \theta^{-2} r^{-1} \int_{Q_r} |p| |u|. \end{aligned}$$

We focus now on the additional term

$$\begin{aligned} & C_3^2 \theta^{-2} r^{-2} \int_{Q_r} |p| |u| \leq C_3^2 \theta^{-2} r^{-2} \|u\|_{L^3(Q_r)} \|p\|_{L^{\frac{3}{2}}(Q_r)} = C_3^2 \theta \left(r^{-2} \int_{Q_r} |u|^3 \right)^{\frac{1}{3}} \theta^{-3} \left(r^{-2} \int_{Q_r} |p|^{\frac{3}{2}} \right)^{\frac{2}{3}} \\ & \leq C_3^2 \theta^2 \left(r^{-2} \int_{Q_r} |u|^3 \right)^{\frac{2}{3}} + C_3^2 \theta^{-6} \left(r^{-2} \int_{Q_r} |p|^{\frac{3}{2}} \right)^{\frac{4}{3}}. \end{aligned}$$

So if we apply (14.16), we obtain

$$\begin{aligned} & \max \left(\frac{1}{\theta r} \int_{B_{\theta r}} |u(t)|^2, \frac{1}{\theta r} \int_{-(\theta r)^2}^t \int_{B_{\theta r}} |\nabla u|^2 \right) \leq 4C_3^2 C_0^{\frac{2}{3}} \theta^2 \left[r^{-1} \sup_{-r^2 < t < 0} \int_{B_r} |u(t)|^2 + r^{-1} \int_{Q_r} |\nabla u|^2 \right] \\ & + 4C_4^2 C_3^2 \theta^{-6} \left(r^{-1} \sup_{-r^2 < t < 0} \int_{B_r} |u(t)|^2 \right) \left(r^{-1} \int_{Q_r} |\nabla u|^2 \right) + C_3^2 \theta^{-6} \left(r^{-2} \int_{Q_r} |p|^{\frac{3}{2}} \right)^{\frac{4}{3}}. \end{aligned}$$

Now introduce the estimate

$$\begin{aligned} \left((\theta r)^{-2} \int_{Q_{\theta r}} |p|^{\frac{3}{2}} \right)^{\frac{4}{3}} &\leq 2C_5^{\frac{4}{3}} \theta^{-2} \left(r^{-1} \sup_{-r^2 < t < 0} \int_{B_r} |u(t)|^2 \right) \left(r^{-1} \int_{Q_r} |\nabla u|^2 \right) \\ &\quad + 2C_5^{\frac{4}{3}} \theta^{\frac{4}{3}} \left(r^{-2} \int_{Q_r} |p|^{\frac{3}{2}} \right)^{\frac{4}{3}}. \end{aligned} \quad (14.22)$$

We need now to exploit one of (14.1)–(14.2). We choose

$$\limsup_{r \rightarrow 0} \frac{1}{r} \int_{Q_r} |\nabla u|^2 < \epsilon_1. \quad (14.23)$$

Then, for $r_0 > 0$ small enough, we have

$$\frac{1}{r} \int_{Q_r} |\nabla u|^2 < 2\epsilon_1 \text{ for } r \in (0, r_0]. \quad (14.24)$$

Then we have

$$\begin{aligned} \frac{1}{\theta r} \int_{B_{\theta r}} |u(t)|^2 &\leq 4C_3^2 C_0^{\frac{2}{3}} \theta^2 \left[r^{-1} \sup_{-r^2 < t < 0} \int_{B_r} |u(t)|^2 + 2\epsilon_1 \right] \\ &\quad + 8C_4^2 C_3^2 \theta^{-6} \epsilon_1 \left(r^{-1} \sup_{-r^2 < t < 0} \int_{B_r} |u(t)|^2 \right) + C_3^2 \theta^{-6} \left(r^{-2} \int_{Q_r} |p|^{\frac{3}{2}} \right)^{\frac{4}{3}} \end{aligned}$$

and

$$\left((\theta r)^{-2} \int_{Q_{\theta r}} |p|^{\frac{3}{2}} \right)^{\frac{4}{3}} \leq 4C_5^{\frac{4}{3}} \epsilon_1 \theta^{-2} \left(r^{-1} \sup_{-r^2 < t < 0} \int_{B_r} |u(t)|^2 \right) + 2C_5^{\frac{4}{3}} \theta^{\frac{4}{3}} \left(r^{-2} \int_{Q_r} |p|^{\frac{3}{2}} \right)^{\frac{4}{3}}.$$

Then we obtain

$$\begin{aligned} &\frac{1}{\theta r} \int_{B_{\theta r}} |u(t)|^2 + \theta^{-7} \left((\theta r)^{-2} \int_{Q_{\theta r}} |p|^{\frac{3}{2}} \right)^{\frac{4}{3}} \\ &\leq 4C_3^2 C_0^{\frac{2}{3}} \theta^2 \left[r^{-1} \sup_{-r^2 < t < 0} \int_{B_r} |u(t)|^2 + 2\epsilon_1 \right] \\ &\quad + 8C_4^2 C_3^2 \theta^{-6} \epsilon_1 \left(r^{-1} \sup_{-r^2 < t < 0} \int_{B_r} |u(t)|^2 \right) + C_3^2 \theta \theta^{-7} \left(r^{-2} \int_{Q_r} |p|^{\frac{3}{2}} \right)^{\frac{4}{3}} \\ &\quad + 4C_5^{\frac{4}{3}} \epsilon_1 \theta^{-9} \left(r^{-1} \sup_{-r^2 < t < 0} \int_{B_r} |u(t)|^2 \right) + 2C_5^{\frac{4}{3}} \theta^{\frac{4}{3}} \theta^{-7} \left(r^{-2} \int_{Q_r} |p|^{\frac{3}{2}} \right)^{\frac{4}{3}}. \end{aligned}$$

Setting

$$E(r) := \frac{1}{r} \int_{B_r} |u(t)|^2 + \theta^{-7} \left(r^{-2} \int_{Q_r} |p|^{\frac{3}{2}} \right)^{\frac{4}{3}},$$

we obtain

$$E(\theta r) \leq 8C_3^2 C_0^{\frac{2}{3}} \theta^2 \epsilon_1 + \left(4C_3^2 C_0^{\frac{2}{3}} \theta^2 + 8C_4^2 C_3^2 \theta^{-6} \epsilon_1 + C_3^2 \theta + 4C_5^{\frac{4}{3}} \epsilon_1 \theta^{-9} + 2C_5^{\frac{4}{3}} \theta^{\frac{4}{3}} \right) E(r).$$

Choosing θ small enough, we can assume $8C_3^2 C_0^{\frac{2}{3}} \theta^2 < 1/2$ and $C_3^2 \theta + 2C_5^{\frac{4}{3}} \theta^{\frac{4}{3}} < 1/5$, so that

$$E(\theta r) \leq 5^{-1} \epsilon_1 + \left(\frac{3}{10} + 8C_4^2 C_3^2 \theta^{-6} \epsilon_1 + 4C_5^{\frac{4}{3}} \epsilon_1 \theta^{-9} \right) E(r).$$

We choose ϵ_1 so that $8C_4^2 C_3^2 \theta^{-6} \epsilon_1 + 4C_5^{\frac{4}{3}} \epsilon_1 \theta^{-9} < 1/5$. Then we obtain

$$E(\theta r) \leq 2^{-1} \epsilon_1 + 2^{-1} E(r).$$

Then, proceeding as in Sect. 14.1, if we know that $\limsup_{r \rightarrow 0} E(r) < \infty$, we conclude $E(r) \leq 2\epsilon_1$ for $0 < r < r_2$ for some appropriately small r_2 . Then we get

$$r^{-2} \int_{Q_r} |u|^3 \leq C_0 3^{3/2} \epsilon_1^{\frac{3}{2}} < 2^{-1} \epsilon_0^* \text{ for } \epsilon_1 < 3 \left(2^{-1} C_0^{-1} \epsilon_0^* \right)^{\frac{2}{3}}, \quad (14.25)$$

Similarly

$$r^{-2} \int_{Q_r} |p|^{\frac{3}{2}} \leq \theta^{\frac{21}{4}} E^{\frac{3}{4}}(r) \leq \theta^{\frac{21}{4}} 2^{\frac{3}{4}} \epsilon_1^{\frac{3}{4}} < 2^{-1} \epsilon_0^* \text{ for } \epsilon_1 < 2^{-7} 2^{-\frac{28}{3}} (\epsilon_0^*)^{\frac{4}{3}}.$$

Then we get (14.3). To complete the proof, up to (14.22), we need to show $\limsup_{r \rightarrow 0} E(r) < \infty$. By the argument in (14.1), having $\limsup_{r \rightarrow 0} E(r) = \infty$ would imply

$$\sup_{\theta r_0 \leq r \leq r_0} \left[\sup_{-r^2 < t < 0} \int_{B_r} |u|^2 + \int_{Q_r} |p|^{\frac{3}{2}} \right] = \infty.$$

But this would imply either $u \notin L^\infty((-R^2, 0), L^2(B_R, \mathbb{R}^3))$ or $p \notin L^{3/2}(Q_R, \mathbb{R})$, contradicting the hypotheses. □

Finally, we state the lemma needed for (14.22).

Lemma 14.4. *There exists C_5 such that for $p \in L^{\frac{3}{2}}(Q_r)$ and $u \in L^3(Q_r) \cap L^\infty((-r^2, 0), L^2(B_r))$ and for $-\Delta p = \partial_i \partial_j (u_i u_j)$ in Q_r , then for any $0 < \theta < 1/2$ we have*

$$\begin{aligned} (\theta r)^{-2} \int_{Q_{\theta r}} |p|^{\frac{3}{2}} &\leq C_5 \theta^{-3/2} \left(r^{-1} \sup_{-r^2 < t < 0} \int_{B_r} |u(t)|^2 \right)^{\frac{3}{4}} \left(r^{-1} \int_{Q_r} |\nabla u|^2 \right)^{\frac{3}{4}} \\ &\quad + C_5 \theta r^{-2} \int_{Q_r} |p|^{\frac{3}{2}}. \end{aligned} \quad (14.26)$$

Proof. By scaling, it suffices to consider case $r = 1$. We will start by assuming $u \in C^\infty(\overline{Q_1})$. This in turn implies that $p(t) \in L^{\frac{3}{2}}((-1, 0)), C^k(B_1)$ for all k . Let now $\phi \in \mathbb{C}_c^\infty(\mathbb{R}^3, [0, 1])$ with

$$\phi(x) = \begin{cases} 1 & \text{in } B_{3/4} \\ 0 & \text{outside } B_{4/5}. \end{cases}$$

Let $U_{ij} = u_i(u_j - (u_j)_1)$ where $(u_j)_r = (u_j)_{B_r} = v|B_r v|^{-1} \int_{B_r} u_j$. Notice that $-\Delta p = \partial_i \partial_j U_{ij}$. Then, by Lemma 10.1, we have

$$\begin{aligned} \phi p &= (-\Delta)^{-1}(-\Delta)\phi p = \frac{1}{4\pi|x|} * ((-\Delta)\phi p) = \frac{1}{4\pi|x|} * (-\phi\Delta p - p\Delta\phi - 2\nabla\phi \cdot \nabla p) \\ &= \frac{1}{4\pi|x|} * (\phi\partial_i\partial_j U_{ij} - p\Delta\phi - 2\nabla\phi \cdot \nabla p) \\ &= \frac{1}{4\pi|x|} * (\partial_i\partial_j(\phi U_{ij}) - \partial_i(U_{ij}\partial_j\phi) - \partial_j(U_{ij}\partial_i\phi) + U_{ij}\partial_j\partial_i\phi - p\Delta\phi - 2\nabla \cdot (\nabla\phi p) + 2p\Delta\phi) \\ &= \partial_i \frac{1}{4\pi|x|} * (\partial_j(\phi U_{ij}) - 2U_{ij}\partial_i\phi - 2p\partial_j\phi) + \frac{1}{4\pi|x|} * (U_{ij}\partial_j\partial_i\phi + p\Delta\phi) \\ &= -\frac{x_i}{4\pi|x|^3} * (\partial_j(\phi U_{ij}) - 2U_{ij}\partial_i\phi - 2p\partial_j\phi) + \frac{1}{4\pi|x|} * (U_{ij}\partial_j\partial_i\phi + p\Delta\phi) \end{aligned}$$

Like in Lemma 13.9 we conclude

$$\phi p = -\frac{1}{4\pi} P.V. \left(\frac{\delta_{ij}}{|x|^3} - \frac{3x_i x_j}{|x|^5} \right) * (\phi U_{ij}) + \frac{x_i}{4\pi|x|^3} * (2U_{ij}\partial_i\phi + 2p\partial_j\phi) + \frac{1}{4\pi|x|} * (U_{ij}\partial_j\partial_i\phi + p\Delta\phi).$$

We have $p = \phi p$ in Q_θ . We write

$$p_1 = -\frac{1}{4\pi} P.V. \left(\left(\frac{\delta_{ij}}{|x|^3} - \frac{3x_i x_j}{|x|^5} \right) \right) * (\phi U_{ij}).$$

Then

$$\begin{aligned} \|p_1\|_{L^{\frac{3}{2}}(B_\theta)} &\leq C \sum_{i,j} \|\phi U_{ij}\|_{L^{\frac{3}{2}}(\mathbb{R}^3)} \leq C \sum_{i,j} \|u_i(u_j - (u_j)_1)\|_{L^{\frac{3}{2}}(B_{4/5})} \leq C' \|u\|_{L^2(B_1)} \|u_j - (u_j)_1\|_{L^6(B_1)} \\ &\leq C \|u\|_{L^2(B_1)} \|\nabla u\|_{L^2(B_1)}. \end{aligned}$$

Next, we write

$$p_2 = \frac{x_i}{4\pi|x|^3} * U_{ij}\partial_i\phi = \frac{1}{2\pi} \int_{3/4 \leq |y| \leq 4/5} \frac{x_i - y_i}{4\pi|x-y|^3} U_{ij}\partial_i(y)\phi(y).$$

Then, using Yang's inequality,

$$\|p_2\|_{L^{\frac{3}{2}}(B_\theta)} \lesssim \left\| \frac{1}{|x|^2} \right\|_{L^1(1/4 \leq |x| \leq 2)} \|u_i(u_j - (u_j)_1)\|_{L^{\frac{3}{2}}(B_{4/5})} \leq C \|u\|_{L^2(B_1)} \|\nabla u\|_{L^2(B_1)}.$$

Similarly, for

$$p_3 = \frac{1}{4\pi|x|} * U_{ij} \partial_j \partial_i \phi$$

we have

$$\|p_3\|_{L^{\frac{3}{2}}(B_\theta)} \lesssim \left\| \frac{1}{|x|} \right\|_{L^1(1/4 \leq |x| \leq 2)} \|u_i(u_j - (u_j)_1)\|_{L^{\frac{3}{2}}(B_{4/5})} \leq C \|u\|_{L^2(B_1)} \|\nabla u\|_{L^2(B_1)}.$$

For

$$p_4 = \frac{1}{4\pi|x|} * p \Delta \phi$$

we have

$$\|p_4\|_{L^{\frac{3}{2}}(B_\theta)} \leq c\theta^2 \|p_4\|_{L^\infty(B_\theta)} \lesssim \theta^2 \|p\|_{L^1(B_1)} \leq C\theta^2 \|p\|_{L^{\frac{3}{2}}(B_1)}$$

and, similarly, for

$$p_5 = \frac{x_i}{4\pi|x|^3} * 2p \partial_j \phi$$

we have

$$\|p_5\|_{L^{\frac{3}{2}}(B_\theta)} \leq C\theta^2 \|p\|_{L^{\frac{3}{2}}(B_1)}.$$

Thus, we have

$$\|p\|_{L^{\frac{3}{2}}(B_\theta)} \leq C \|u\|_{L^2(B_1)} \|\nabla u\|_{L^2(B_1)} + C\theta^2 \|p\|_{L^{\frac{3}{2}}(B_1)}$$

and so

$$\begin{aligned} \|p\|_{L^{\frac{3}{2}}(Q_\theta)}^{\frac{3}{2}} &\leq C \int_{-\theta^2}^0 \|u\|_{L^2(B_1)}^{\frac{3}{2}} \|\nabla u\|_{L^2(B_1)}^{\frac{3}{2}} dt + C\theta^3 \|p\|_{L^{\frac{3}{2}}(Q_1)}^{\frac{3}{2}} \\ &\leq C \| \|u\|_{L^2(B_1)}^{\frac{3}{2}} \| \|\nabla u\|_{L^2(B_1)}^{\frac{3}{2}} \|_{L^{4/3}(-\theta^2, 0)} + C\theta^3 \|p\|_{L^{\frac{3}{2}}(Q_1)}^{\frac{3}{2}} \\ &\leq C \| \|u\|_{L^2(B_1)} \|_{L^6(-\theta^2, 0)}^{\frac{3}{2}} \|\nabla u\|_{L^2(Q_1)}^{\frac{3}{2}} + C\theta^3 \|p\|_{L^{\frac{3}{2}}(Q_1)}^{\frac{3}{2}} \\ &\leq C\theta^{2\frac{1}{6} - \frac{3}{2}} \|u\|_{L^\infty((-\theta^2, 0), L^6(B_1))}^{\frac{3}{2}} \|\nabla u\|_{L^2(Q_1)}^{\frac{3}{2}} + C\theta^3 \|p\|_{L^{\frac{3}{2}}(Q_1)}^{\frac{3}{2}}, \end{aligned}$$

that is

$$\begin{aligned} \int_{Q_\theta} |p|^{\frac{3}{2}} &\leq C\theta^{1/2} \left(\sup_{-1 < t < 0} \int_{B_1} |u(t)|^2 \right)^{\frac{3}{4}} \left(\int_{Q_1} |\nabla u|^2 \right)^{\frac{3}{4}} \\ &\quad + C\theta^3 \int_{Q_r} |p|^{\frac{3}{2}}, \end{aligned}$$

which is (14.26) for $r = 1$.

□

A Appendix. On the Bochner integral

For this part see [3]. Let X be a Banach space.

Definition A.1 (Strong measurability). Let I be an interval. A function $f : I \rightarrow X$ is strongly measurable if there exists a set E of measure 0 and a sequence $(f_n(t))$ in $C_c(I, X)$ s.t. $f_n(t) \rightarrow f(t)$ for any $t \in I \setminus E$.

Remark A.2. Notice that when $\dim X < \infty$ a function is measurable (in the sense that $f^{-1}(B)$ is measurable for any Borel set B) if and only if it is strongly measurable in the above sense. Indeed if f is strongly measurable in the above sense then as a point wise limit of measurable functions f is measurable, see Theorem 1.14 p. 14 Rudin [14]. Viceversa if f is measurable, then f is strongly measurable in the above sense, see the Corollary to Lusin's Theorem in Rudin [14] p. 54.

Example A.3. Consider $\{x_j\}_{j=1}^n$ in X and $\{A_j\}_{j=1}^n$ measurable sets in I with $|A_j| < \infty$ and with $A_j \cap A_k = \emptyset$ for $j \neq k$. Then we claim that the *simple* function

$$f(t) := \sum_{j=1}^n x_j \chi_{A_j}(t) : I \rightarrow X \quad (\text{A.1})$$

is measurable. Indeed, see Rudin [14] p. 54, there are sequences $\{\varphi_{j,k}\}_{k \in \mathbb{N}}$ in $C_c^0(I, \mathbb{R})$ with $\varphi_{j,k}(t) \xrightarrow{k \rightarrow \infty} \chi_{A_j}(t)$ a.e. and hence

$$C_c^0(I, \mathbb{R}) \ni f_k(t) := \sum_{j=1}^n x_j \varphi_{j,k}(t) \xrightarrow{k \rightarrow \infty} f(t) \text{ a.e. in } I.$$

Proposition A.4. *If (f_n) is a sequence of strongly measurable functions from I to X convergent a.e. to a $f : I \rightarrow X$, then f is strongly measurable.*

Proof. There is an E with $|E| = 0$ s.t. $f_n(t) \xrightarrow{n \rightarrow \infty} f(t)$ for any $t \in I \setminus E$. Consider for any n a sequence $C_c(I, X) \ni f_{n,k} \xrightarrow{k \rightarrow \infty} f_n$ a.e. We will suppose first that $|I| < \infty$. By applying Egorov Theorem to $\{\|f_{n,k} - f_n\|\}_{k \in \mathbb{N}}$ there is $E_n \subset I$ with $|E_n| \leq 2^{-n}$ s.t. $\|f_{n,k} - f_n\| \xrightarrow{k \rightarrow \infty} 0$ uniformly in $I \setminus E_n$. Let $k(n)$ be s.t. $\|f_{n,k(n)} - f_n\| < 1/n$ in $I \setminus E_n$ and set $g_n = f_{n,k(n)}$. Set $F := E \cup (\bigcap_m \bigcup_{n>m} E_n)$. Then $|F| = 0$. Indeed for any m

$$|F| \leq |E| + \sum_{n=m}^{\infty} |E_n| \leq |E| + \sum_{n=m}^{\infty} 2^{-n} \xrightarrow{m \rightarrow \infty} 0.$$

Let $t \in I \setminus F$. Since $t \notin E$ we have $f_n(t) \xrightarrow{n \rightarrow \infty} f(t)$. Furthermore, for n large enough we have $t \in I \setminus E_n$. Indeed

$$t \notin \bigcap_m \bigcup_{n>m} E_n \Rightarrow \exists m \text{ s.t. } t \notin \bigcup_{n>m} E_n \Rightarrow t \notin E_n \forall n > m.$$

Then $\|g_n(t) - f_n(t)\| < 1/n$ and $g_n(t) \xrightarrow{n \rightarrow \infty} f(t)$. So $f(t)$ is measurable in the case $|I| < \infty$. Now we consider the case $|I| = \infty$. We express $I = \cup_n I_n$ for an increasing sequence of intervals with $|I_n| < \infty$. Consider for any n a sequence $C_c(I_n, X) \ni f_{n,k} \xrightarrow{k \rightarrow \infty} f$ a.e. in I_n . Then by Egorov Theorem to $\|f_{n,k} - f_n\|$ there is $E_n \subset I_n$ with $|E_n| \leq 2^{-n}$ s.t. $f_{n,k} \xrightarrow{k \rightarrow \infty} f_n$ uniformly in $I_n \setminus E_n$. Let $k(n)$ be s.t. $\|f_{n,k(n)} - f_n\| < 1/n$ in $I_n \setminus E_n$ and set $g_n = f_{n,k(n)}$. Then defining F like above, the remainder of the proof works exactly like for the case $|I| < \infty$. \square

Example A.5. Consider a sequence $\{x_j\}_{j \in \mathbb{N}}$ in X and a sequence $\{A_j\}_{j \in \mathbb{N}}$ of measurable sets in I with $|A_j| < \infty$ and with $A_j \cap A_k = \emptyset$ for $j \neq k$. Then we claim

$$f(t) := \sum_{j=1}^{\infty} x_j \chi_{A_j}(t) \quad (\text{A.2})$$

is measurable. Indeed if we set $f_n(t) := \sum_{j=1}^n x_j \chi_{A_j}(t)$, then we have $\lim_{n \rightarrow \infty} f_n(t) = f(t)$

for any t , since if $t \notin \cup_{j=1}^{\infty} A_j$ both sides are 0, and if $t \in A_{n_0}$ then for $n \geq n_0$ we have $f_n(t) = x_{n_0} = f(t)$. Hence by Proposition A.4 the function f is measurable.

When the sum in (A.2) is finite then the function f is called *simple*.

Example A.6. Consider a sequence $\{x_j\}_{j \in \mathbb{N}}$ in X and a sequence $\{A_j\}_{j \in \mathbb{N}}$ of measurable sets in I where again $A_j \cap A_k = \emptyset$ for $j \neq k$ but we allow $|A_j| = \infty$. Then

$$f(t) := \sum_{j=1}^{\infty} x_j \chi_{A_j}(t) \quad (\text{A.3})$$

is measurable. To see this consider $f_n(t) = \chi_{[-n,n]}(t) f(t)$. Then

$$f_n(t) = \sum_{j=1}^{\infty} x_j \chi_{A_j \cap [-n,n]}(t)$$

and by Example A.5 we know that each $f_n(t)$ is strongly measurable. Since $f_n(t) \rightarrow f(t)$ for any $t \in I$ we conclude by Proposition A.4 that f is strongly measurable.

Another natural definition of measurability is the following one.

Definition A.7 (Weak measurability). Let I be an interval. A function $f : I \rightarrow X$ is weakly measurable if for any $x' \in X'$ the function $t \rightarrow \langle x', f(t) \rangle_{X', X}$ is a measurable function $I \rightarrow \mathbb{R}$.

Obviously, strongly measurable implies weakly measurable. Let us explore the vice-versa.

Definition A.8. Let I be an interval. A function $f : I \rightarrow X$ is *almost separably valuable* if there exists a 0 measure set $N \subset I$ s.t. $f(I \setminus N)$ is separable.

The following lemma shows that strongly measurable functions are almost separably valuable.

Lemma A.9. *If $f : I \rightarrow X$ is strongly measurable with $(f_n(t))$ a sequence in $C_c(I, X)$ s.t. $f_n(t) \rightarrow f(t)$ for any $t \in I \setminus E$ for a 0 measure set $E \subset I$ then $f(I \setminus E)$ is separable and there exists a separable Banach subspace $Y \subseteq X$ with $f(I \setminus E) \subseteq Y$.*

Proof. First of all $f_n(I \cap \mathbb{Q})$ is a countable dense set in $f_n(I)$. So $f_n(I)$ is separable. In a separable metric space any subspace is separable. So $f_n(I \setminus E)$ is separable. The closed vector space Y generated by $\cup_n f_n(I \setminus E)$ is separable. Indeed let $C \subseteq \cup_n f_n(I \setminus E)$ be a countable set dense in $\cup_n f_n(I \setminus E)$. Let $\text{Span}_{\mathbb{Q}}(C)$ be the vector space on \mathbb{Q} generated by C . Then $\text{Span}_{\mathbb{Q}}(C)$ is dense in Y . For $C = \{x_1, x_2, \dots\}$ we have $\text{Span}_{\mathbb{Q}}(C) = \cup_{n=1}^{\infty} \text{Span}_{\mathbb{Q}}(\{x_1, \dots, x_n\})$. This proves that $\text{Span}_{\mathbb{Q}}(C)$ is countable and that Y is separable. \square

Example A.10. Let X be a Hilbert space with an orthonormal basis $\{e_t\}_{t \in \mathbb{R}}$. Then the map $f : \mathbb{R} \rightarrow X$ given by $f(t) = e_t$ is not strongly measurable. This follows from the fact that it is not almost separably valuable.

On the other hand if $x \in X$ then $t \rightarrow \langle f(t), x \rangle$ is different from 0 only on a countable subset of \mathbb{R} , and as such it is measurable. Hence f is weakly measurable.

Notice however that if $C \subset [0, 1]$ is the standard Cantor set (which has 0 measure and has same cardinality of \mathbb{R}) and if $\{\tilde{e}_t\}_{t \in C}$ is another basis of X , then the map

$$g(t) = \begin{cases} \tilde{e}_t & \text{for } t \in C \text{ and} \\ 0 & \text{otherwise} \end{cases}$$

is weakly measurable (like f and for the same reasons) and is almost separably valuable. Pettis Theorem, which we prove below, implies that $g : \mathbb{R} \rightarrow X$ is strongly measurable.

The following lemma will be used for Pettis Theorem.

Lemma A.11. *Let X be a separable Banach space and let S' be the unit ball of the dual X' . Then X' is separable for the weak topology $\sigma(X', X)$, see Brezis [2] p.62, that is there exists a sequence $\{x'_n\}$ in S' s.t. for any $x' \in S'$ there exists a subsequence $\{x'_{n_k}\}$ s.t. for any $x \in X$ we have $\lim_{k \rightarrow \infty} \langle x'_{n_k}, x \rangle_{X'X} = \langle x', x \rangle_{X'X}$.*

Proof. Let $\{x_n\}$ be dense in X . For any n consider

$$F_n : S' \rightarrow \mathbb{R}^n \text{ defined by } F_n(x') := (\langle x', x_1 \rangle_{X'X}, \dots, \langle x', x_n \rangle_{X'X}).$$

Since \mathbb{R}^n is separable, and so is $F_n(S')$, there exists a sequence $\{x'_{n,k}\}_k$ s.t. $\{F_n(x'_{n,k})\}_k$ is dense in $F_n(S')$. Obviously $\{x'_{n,k}\}_{n,k}$ can be put into a sequence. For any $x' \in S'$ for any n there is a k_n s.t. $|\langle x' - x'_{n,k_n}, x_i \rangle_{X'X}| < 1/n$ for all $i \leq n$. This implies that for any fixed i we have $\lim_{n \rightarrow \infty} \langle x'_{n,k_n}, x_i \rangle_{X'X} = \langle x', x_i \rangle_{X'X}$. By density this holds for any $x \in X$. \square

Proposition A.12 (Pettis's Theorem). *Consider $f : I \rightarrow X$. Then f is strongly measurable if and only if it is weakly measurable and almost separable valuable.*

Proof. The necessity has been already proved, so we focus on the sufficiency only. By modifying f we can assume that $f(I)$ is separable. By replacing X by a smaller space, we can assume that X is separable.

Fix now $x \in X$. Then we claim that $t \rightarrow \|f(t) - x\|$ is measurable. Indeed for any $a > 0$

$$\{t \in I : \|f(t) - x\| \leq a\} = \cap_{x' \in S'} \{t \in I : |\langle x', f(t) - x \rangle_{X'X}| \leq a\}.$$

Using the fact that S' is separable in the weak topology $\sigma(X', X)$ and the notation in Lemma A.11, we have

$$\{t \in I : \|f(t) - x\| \leq a\} = \cap_{n \in \mathbb{N}} \{t \in I : |\langle x'_n, f(t) - x \rangle_{X'X}| \leq a\}.$$

Since the set in the r.h.s. is measurable, we conclude that $t \rightarrow \|f(t) - x\|$ is measurable and so our claim is correct.

Consider now $n \geq 1$. Since $f(I)$ is separable there is a sequence of balls $\{B(x_j, \frac{1}{n})\}_{j \geq 0}$ whose union contains $f(I)$. Set now

$$\begin{cases} \omega_0^{(n)} := \{t : f(t) \in B(x_0, \frac{1}{n})\}, \\ \omega_j^{(n)} := \{t : f(t) \in B(x_j, \frac{1}{n})\} \setminus \cup_{k < j} \omega_k^{(n)} \end{cases}$$

and

$$f_n(t) := \sum_{j=0}^{\infty} x_j \chi_{\omega_j^{(n)}}(t).$$

Notice that $\cup_{j \geq 0} \omega_j^{(n)} = I$ and they are pairwise disjoint and measurable. By Example A.6 we know that $f_n : I \rightarrow X$ is strongly measurable. Furthermore, for any $t \in I$ there is a j s.t. $t \in \omega_j^{(n)}$ and this implies

$$\frac{1}{n} > \|f(t) - x_j\| = \|f(t) - f_n(t)\|.$$

In other words, $\|f(t) - f_n(t)\| \leq 1/n$ for any $t \in I$. Then $f_n(t) \rightarrow f(t)$ for any t , and so by Proposition A.4 the function $f : I \rightarrow X$ is strongly measurable. \square

Example A.13. Consider the map $f : (0, 1) \rightarrow L^\infty(0, 1)$ defined by $t \xrightarrow{f} \chi_{(0,t)}$. This map is not almost separable valued. Indeed $t \neq s$ implies $\|f(t) - f(s)\|_\infty = 1$. If f was almost separable valued then there would exist a 0 measure subset E in $(0, 1)$ and a countable set $\mathcal{N} = \{t_n\}_n$ in $(0, 1) \setminus E$ such that for any $t \in (0, 1) \setminus (E \cup \mathcal{N})$ there would exist a subsequence n_k with $f(t_{n_k}) \xrightarrow{k \rightarrow \infty} f(t)$ in $L^\infty(0, 1)$. But this is impossible since $\|f(t) - f(t_{n_k})\|_\infty = 1$. On the other hand $f : (0, 1) \rightarrow L^2(0, 1)$ defined in the same way, is strongly measurable. First of, since $L^2(0, 1)$ is separable, it is almost separable valued. Next for any given any $w \in L^2(0, 1)$ we have

$$\langle f(t), w \rangle_{L^2(0,1)} = \int_0^t w(x) dx$$

which is a continuous, and hence measurable, function. So f is also weakly measurable and hence it is strongly measurable by Pettis Theorem.

Recall that in Remark A.2 we mentioned another possible notion of measurability, that is that $f : I \rightarrow X$ could be defined as measurable if $f^{-1}(A)$ is a measurable set for any open subset $A \subseteq X$. We have the following fact.

Proposition A.14. *Consider $f : I \rightarrow X$. Then f is strongly measurable \Leftrightarrow it almost separably valuable and $f^{-1}(A)$ is a measurable set for any open subset $A \subseteq X$.*

Proof. The " \Leftarrow " follows from the fact that for any \mathfrak{a} open subset of \mathbb{R} and for any $x' \in X$ the set $A = \{x \in X : \langle x, x' \rangle_{X, X'} \in \mathfrak{a}\}$ is open and for $g(t) := \langle f(t), x' \rangle_{X, X'}$ we have $f^{-1}(A) = g^{-1}(\mathfrak{a})$. So the latter being measurable it follows that g is measurable and hence f is weakly measurable. Hence by Pettis Theorem we conclude that f is strongly measurable.

We now assume that f is strongly measurable. We know from Lemma A.9 that f is almost separably valuable. Let U be an open subset of X . Let $(f_n)_n$ be a sequence in $C_c^0(I, X)$ with $f_n(t) \xrightarrow[n \rightarrow \infty]{m} f(t)$ a.e. outside a 0 measure set $E \subset I$. Let $U_r = \{x \in X : \text{dist}(x, U^c) > r\}$. Then

$$f^{-1}(U) \setminus E = (\cup_{m \geq 1} \cup_{n \geq 1} \cap_{k \geq n} f_k^{-1}(U_{\frac{1}{m}})) \setminus E. \quad (\text{A.4})$$

To check this, notice that if t belongs to the left hand side, then $f(t) \in U_{\frac{1}{m_0}}$ for some m_0 and, since $f_n(t) \xrightarrow[n \rightarrow \infty]{m} f(t)$, for n large we have $f_k(t) \in U_{\frac{1}{m_1}}$ if $k \geq n$ for $m_1 > m_0$ preassigned. Viceversa if t belongs to the right hand side, then there exist n and m s.t. $f_k(t) \in U_{\frac{1}{m}}$ for all $k \geq n$. Then by $f_k(t) \xrightarrow[k \rightarrow \infty]{m} f(t)$ it follows that $f(t) \in \overline{U_{\frac{1}{m}}}$ with the latter a subset of U . This proves (A.4). Since the r.h.s. is a measurable set, this completes the proof. \square

Definition A.15 (Bochner integrability). A strongly measurable function $f : I \rightarrow X$ is Bochner-integrable if there exists a sequence $(f_n(t))$ in $C_c(I, X)$ s.t.

$$\lim_{n \rightarrow \infty} \int_I \|f_n(t) - f(t)\|_X dt = 0. \quad (\text{A.5})$$

Notice that $\|f_n(t) - f(t)\|_X$ is measurable.

Example A.16. Consider the situation of Example A.13 of a Hilbert space X with an orthonormal basis $\{e_t\}_{t \in \mathbb{R}}$ and the map $f : \mathbb{R} \rightarrow X$, which we saw is not strongly measurable and hence is not Bochner-integrable. Notice that f is Riemann integrable in any compact interval $[a, b]$ with $\int_a^b f(t) dt = 0$.

To see this recall that the Riemann integral is, if it exists, the limit

$$\int_a^b f(t) dt = \lim_{|\Delta| \rightarrow 0} \sum_{I_j \in \Delta} f(t_j) |I_j| \text{ with } t_j \in I_j \text{ arbitrary}$$

where Δ varies among all possible decompositions of $[a, b]$ and $|\Delta| = \max_{I \in \Delta} |I|$. We have

$$\| \sum_{I_j \in \Delta} e_{t_j} |I_j| \|^2 = \sum_{j, k} \langle e_{t_j}, e_{t_k} \rangle |I_j| |I_k| \leq 2 \sum_j |I_j| |\Delta| = 2 |\Delta| (b - a) \xrightarrow{|\Delta| \rightarrow 0} 0.$$

Proposition A.17. *Let $f : I \rightarrow X$ be Bochner-integrable. Then there exists an $x \in X$ s.t. if $(f_n(t))$ is a sequence in $C_c(I, X)$ satisfying (A.5) then we have*

$$\lim_{n \rightarrow \infty} x_n = x \text{ where } x_n := \int_I f_n(t) dt. \quad (\text{A.6})$$

Proof. First of all we check that x_n is Cauchy. This follows immediately from (A.5) and from

$$\begin{aligned} \|x_n - x_m\|_X &= \left\| \int_I (f_n(t) - f_m(t)) dt \right\|_X \leq \int_I \|f_n(t) - f_m(t)\|_X dt \\ &\leq \int_I \|f_n(t) - f(t)\|_X dt + \int_I \|f(t) - f_m(t)\|_X dt. \end{aligned}$$

Let us set $x = \lim x_n$. Let $(g_n(t))$ be another sequence in $C_c(I, X)$ satisfying (A.5). Then $\lim \int_I g_n = x$ by

$$\begin{aligned} \left\| \int_I g_n(t) dt - x \right\|_X &= \left\| \int_I (g_n(t) - f_n(t)) dt + \int_I f_n(t) dt - x \right\|_X \\ &\leq \int_I \|g_n(t) - f_n(t)\|_X dt + \left\| \int_I f_n(t) dt - x \right\|_X \\ &\leq \int_I \|g_n(t) - f(t)\|_X dt + \int_I \|f_n(t) - f(t)\|_X dt + \left\| \int_I f_n(t) dt - x \right\|_X. \end{aligned}$$

□

Definition A.18. Let $f : I \rightarrow X$ be Bochner-integrable and let $x \in X$ be the corresponding element obtained from Proposition A.17. Then we set $\int_I f(t) dt = x$.

Theorem A.19 (Bochner's Theorem). *Let $f : I \rightarrow X$ be strongly measurable. Then f is Bochner-integrable if and only if $\|f\|$ is Lebesgue integrable. Furthermore, we have*

$$\left\| \int_I f(t) dt \right\| \leq \int_I \|f(t)\| dt. \quad (\text{A.7})$$

Proof. Let f be Bochner-integrable. Then there is a sequence $(f_n(t))$ in $C_c(I, X)$ satisfying (A.5). We have $\|f\| \leq \|f_n\| + \|f - f_n\|$. Since both functions in the r.h.s. are Lebesgue integrable and $\|f\|$ is measurable it follows that $\|f\|$ is Lebesgue integrable.

Conversely let $\|f\|$ be Lebesgue integrable. Then there exist a sequence $(g_n(t))$ in $C_c(I, \mathbb{R})$ and $g \in L^1(I)$ s.t. $\int_I |g_n(t) - \|f(t)\|| dt \rightarrow 0$ and $|g_n(t)| \leq g(t)$. In fact it is possible to choose such a sequence so that $\|g_n - g_m\|_{L^1(I)} < 2^{-n}$ for any n and any $m \geq n$ (just by extracting an appropriate subsequence from a starting g_n ⁵). Then if we set

$$S_N(t) := \sum_{n=1}^N |g_n(t) - g_{n+1}(t)| \quad (\text{A.8})$$

⁵Suppose we start with a given $\{g_n\}$. Then for any 2^{-n} there exists N_n s.t. $n_1, n_2 > N_n$ implies $\|g_{n_1} - g_{n_2}\|_{L^1(I)} < 2^{-n}$. Let now $\{\varphi(n)\}$ be a strictly increasing sequence in \mathbb{N} s.t. $\varphi(n) > N_n$ for any n . Then $\|g_{\varphi(n)} - g_{\varphi(m)}\|_{L^1(I)} < 2^{-n}$ for any pair $m > n$. Rename $g_{\varphi(n)}$ as g_n .

we have $\|S_N\|_{L^1(I)} \leq 1$. Since $\{S_N(t)\}_{N \in \mathbb{N}}$ is increasing, the limit $S(t) := \lim_{n \rightarrow +\infty} S_n(t)$ remains defined, is finite a.e. and $\|S\|_{L^1(I)} \leq 1$. Then $|g_n(t)| \leq |g_1(t)| + S(t) =: g(t)$ everywhere, where $g \in L^1(I)$. Notice that $\lim_{n \rightarrow \infty} g_n(t)$ is convergent almost everywhere (it convergent in all points where $\lim_{n \rightarrow +\infty} S_n(t)$ is convergent). By dominated convergence it follows that this limit holds also in $L^1(I)$ and hence it is equal to $\|f\|$. Let $(f_n(t))$ in $C_c(I, X)$ s.t. $f_n(t) \rightarrow f(t)$ a.e. (this sequence exists by the strong measurability of $f(t)$). Set

$$u_n(t) := \frac{|g_n(t)|}{\|f_n(t)\| + \frac{1}{n}} f_n(t).$$

Notice that $(u_n(t))$ is in $C_c(I, X)$. We have

$$\|u_n(t)\| \leq \frac{|g_n(t)| \|f_n(t)\|}{\|f_n(t)\| + \frac{1}{n}} \leq |g_n(t)| \leq g(t).$$

We have (where the 2nd equality holds because because $\lim_{n \rightarrow \infty} g_n(t) = \|f(t)\|$ and $\lim_{n \rightarrow \infty} \|f_n(t)\| = \|f(t)\|$ a.e.)

$$\lim_{n \rightarrow \infty} u_n(t) = \lim_{n \rightarrow \infty} \frac{|g_n(t)|}{\|f_n(t)\| + \frac{1}{n}} f_n(t) = \lim_{n \rightarrow \infty} f_n(t) = f(t) \text{ a.e..}$$

Then we have

$$\lim_{n \rightarrow \infty} \|u_n(t) - f(t)\| = 0 \text{ a.e. with } \|u_n(t) - f(t)\| \leq g(t) + \|f(t)\| \in L^1(I).$$

By dominated convergence we conclude

$$\lim_{n \rightarrow \infty} \int_I \|u_n(t) - f(t)\| dt = 0.$$

This implies that f is Bochner-integrable. Finally, we have

$$\left\| \int_I f(t) dt \right\| = \lim_{n \rightarrow \infty} \left\| \int_I u_n(t) dt \right\| \leq \lim_{n \rightarrow \infty} \int_I \|u_n(t)\| dt = \int_I \|f(t)\| dt.$$

□

Corollary A.20 (Dominated Convergence). *Consider a sequence $(f_n(t))$ of Bochner-integrable functions $I \rightarrow X$, $g : I \rightarrow \mathbb{R}$ Lebesgue integrable and let $f : I \rightarrow X$. Suppose that*

$$\begin{aligned} \|f_n(t)\| &\leq g(t) \text{ for all } n \\ \lim_{n \rightarrow \infty} f_n(t) &= f(t) \text{ for almost all } t. \end{aligned}$$

Then f is Bochner-integrable with $\int_I f(t) = \lim_n \int_I f_n(t)$.

Proof. By Dominated Convergence in $L^1(I, \mathbb{R})$ we have $\int_I \|f(t)\| = \lim_n \int_I \|f_n(t)\|$. By Proposition A.4, as a pointwise limit a.e. of a sequence of strongly measurable functions, f is strongly measurable. By Bochner's Theorem f is Bochner-integrable. By the triangular inequality

$$\limsup_n \left\| \int_I (f(t) - f_n(t)) \right\| \leq \lim_n \int_I \|f(t) - f_n(t)\| = 0$$

where the last inequality follows from $\|f(t) - f_n(t)\| \leq \|f(t)\| + \|f_n(t)\|$ and the standard Dominated Convergence. \square

Definition A.21. Let $p \in [1, \infty]$. We denote by $L^p(I, X)$ the set of equivalence classes of strongly measurable functions $f : I \rightarrow X$ s.t. $\|f(t)\| \in L^p(I, \mathbb{R})$. We set $\|f\|_{L^p(I, X)} := \|\|f\|\|_{L^p(I, \mathbb{R})}$.

Proposition A.22. $(L^p(I, X), \|\cdot\|_{L^p})$ is a Banach space.

Proof. The proof is similar to the case $X = \mathbb{R}$, see [2].

(**Case** $p = \infty$). Let (f_n) be Cauchy sequence in $L^\infty(I, X)$. For any $k \geq 1$ there is a N_k s.t.

$$\|f_n - f_m\|_{L^\infty(I, X)} \leq \frac{1}{k} \text{ for all } n, m \geq N_k.$$

So there exists an $E_k \subset I$ with $|E_k| = 0$ s.t.

$$\|f_n(t) - f_m(t)\|_X \leq \frac{1}{k} \text{ for all } n, m \geq N_k \text{ and for all } t \in I \setminus E_k.$$

Set $E := \cup_k E_k$. Then for any $t \in I \setminus E$ the sequence $(f_n(t))$ is convergent. So a function $f(t)$ remains defined with

$$\|f_n(t) - f(t)\|_X \leq \frac{1}{k} \text{ for all } n \geq N_k \text{ and for all } t \in I \setminus E. \quad (\text{A.9})$$

By Proposition A.4 the function f is strongly measurable. By (A.9) we have $f \in L^\infty(I, X)$ and

$$\|f_n - f\|_{L^\infty(I, X)} \leq \frac{1}{k} \text{ for all } n \geq N_k$$

and so $f_n \rightarrow f$ in $L^\infty(I, X)$.

(**Case** $p < \infty$). Let (f_n) be Cauchy sequence in $L^p(I, X)$ and let (f_{n_k}) be a subsequence with

$$\|f_{n_k} - f_{n_{k+1}}\|_{L^p(I, X)} \leq 2^{-k}.$$

Set now

$$g_l(t) = \sum_{k=1}^l \|f_{n_k}(t) - f_{n_{k+1}}(t)\|_X$$

Then

$$\|g_l\|_{L^p(I, \mathbb{R})} \leq 1.$$

By monotone convergence we have that $(g_l(t))_l$ converges a.e. to a $g \in L^p(I, \mathbb{R})$. Furthermore, for $2 \leq k < l$

$$\|f_{n_k}(t) - f_{n_l}(t)\|_X = \sum_{j=k}^{l-1} \|f_{n_j}(t) - f_{n_{j+1}}(t)\|_X \leq g(t) - g_{k-1}(t).$$

Then a.e. the sequence $(f_{n_k}(t))$ is Cauchy in X for a.e. t and so it converges for a.e. t to some $f(t)$. By Proposition A.4 the function f is strongly measurable. Furthermore,

$$\|f(t) - f_{n_k}(t)\|_X \leq g(t).$$

It follows that $f - f_{n_k} \in L^p(I, X)$, and so also $f \in L^p(I, X)$. Finally we claim $\|f - f_{n_k}\|_{L^p(I, X)} \rightarrow 0$. First of all we have $\|f(t) - f_{n_k}(t)\|_X \rightarrow 0$ for a.e. t and

$$\|f(t) - f_{n_k}(t)\|_X^p \leq g^p(t)$$

by dominated convergence we obtain that $\|f - f_{n_k}\|_X \rightarrow 0$ in $L^p(I, \mathbb{R})$. Hence $f_{n_k} \rightarrow f$ in $L^p(I, X)$. \square

Proposition A.23. $C_c^\infty(I, X)$ is a dense subspace of $L^p(I, X)$ for $p < \infty$.

Proof. We split the proof in two parts. We first show that $C_c^0(I, X)$ is a dense subspace of $L^p(I, X)$ for $p < \infty$. For $p = 1$ this follows from the definition of integrable functions in Definition A.15. For $1 < p < \infty$ going through the proof of Bochner's Theorem A.19, the functions u_n considered in that proof can be taken to belong to $C_c^0(I, X)$ and converge to f in $L^p(I, X)$.

The second part of the proof consists in showing that $C_c^\infty(I, X)$ is a dense subspace of $C_c^0(I, X)$ inside $L^p(I, X)$ for $p < \infty$. Let $f \in C_c^0(I, X)$. We consider $\rho \in C_c^\infty(\mathbb{R}, [0, 1])$ s.t. $\int \rho(x) dx = 1$. Set $\rho_\epsilon(x) := \epsilon^{-1} \rho(x/\epsilon)$. Then for $\epsilon > 0$ small enough $\rho_\epsilon * f \in C_c^\infty(I, X)$. We extend both f and $\rho_\epsilon * f$ on \mathbb{R} setting them 0 in $\mathbb{R} \setminus I$. In this way $\rho_\epsilon * f \in C_c^\infty(\mathbb{R}, X)$ and $f \in C_c^0(\mathbb{R}, X)$ and it is enough to show that $\rho_\epsilon * f \xrightarrow{\epsilon \rightarrow 0^+} f$ in $L^p(\mathbb{R}, X)$.

We have

$$\rho_\epsilon * f(t) - f(t) = \int_{\mathbb{R}} (f(t - \epsilon s) - f(s)) \rho(s) ds$$

so that, by Minkowski inequality and for $\Delta(s) := \|f(\cdot - s) - f(\cdot)\|_{L^p}$, we have

$$\|\rho_\epsilon * f(t) - f(t)\|_{L^p} \leq \int |\rho(s)| \Delta(\epsilon s) ds.$$

Now we have $\lim_{s \rightarrow 0} \Delta(s) = 0$ and $\Delta(s) \leq 2\|f\|_{L^p}$. So, by dominated convergence we get

$$\lim_{\epsilon \searrow 0} \|\rho_\epsilon * f - f\|_{L^p} = \lim_{\epsilon \searrow 0} \int |\rho(s)| \Delta(\epsilon s) ds = 0.$$

So

$$\lim_{\epsilon \searrow 0} \rho_\epsilon * f = f \text{ in } L^p(\mathbb{R}, X). \tag{A.10}$$

\square

Proceeding as in the previous proof, we can prove the following.

Proposition A.24. Let $p \in [1, \infty)$ and $f \in L^p(\mathbb{R}, X)$. Set

$$T_h f(t) = h^{-1} \int_t^{t+h} f(s) ds \text{ for } t \in \mathbb{R} \text{ and } h \neq 0.$$

Then $T_h f \in L^p(\mathbb{R}, X) \cap L^\infty(\mathbb{R}, X) \cap C^0(\mathbb{R}, X)$ and $T_h f \xrightarrow{h \rightarrow 0} f$ in $L^p(\mathbb{R}, X)$ and for almost every t . □

Definition A.25. We denote by $\mathcal{D}'(I, X)$ the space $\mathcal{L}(\mathcal{D}(I, \mathbb{R}), X)$.

Corollary A.26. Let $f \in L^1_{loc}(I, X)$ be such that $f = 0$ in $\mathcal{D}'(I, X)$. Then $f = 0$ a.e.

Proof. First of all we have $\int_J f dt = 0$ for any $J \subset I$ compact. Indeed, let $(\varphi_n) \in \mathcal{D}(I)$ with $0 \leq \varphi_n \leq 1$ and $\varphi_n \rightarrow \chi_J$ a.e. Then

$$\int_J f dt = \lim_{n \rightarrow +\infty} \int_J \varphi_n f dt = 0$$

where we applied Dominated Convergence for the last equality.

Set now $\bar{f}(t) = f(t)$ in J and $\bar{f}(t) = 0$ outside J . Then $T_h \bar{f} = 0$ for all $h > 0$. Then $\bar{f}(t) = 0$ for a.e. t . So $f(t) = 0$ for a.e. $t \in J$. This implies $f(t) = 0$ for a.e. $t \in \mathbb{R}$. □

Corollary A.27. Let $g \in L^1_{loc}(I, X)$, $t_0 \in I$, and $f \in C(I, X)$ given by $f(t) = \int_{t_0}^t g(s) ds$. Then:

- (1) $f' = g$ in $\mathcal{D}'(I, X)$;
- (2) f is differentiable a.e. with $f' = g$ a.e.

Proof. It is not restrictive to consider the case $I = \mathbb{R}$ and $g \in L^1(\mathbb{R}, X)$. We have

$$T_h g(t) = h^{-1} \int_t^{t+h} g(s) ds = \frac{f(t+h) - f(t)}{h}.$$

By Proposition A.24 $T_h g \xrightarrow{h \rightarrow 0} g$ for almost every t . This yields (2).

For $\varphi \in \mathcal{D}(\mathbb{R})$ we have

$$\langle f', \varphi \rangle = - \int_{\mathbb{R}} f(t) \varphi'(t) dt.$$

Furthermore

$$\lim_{h \rightarrow 0} \frac{\varphi(t+h) - \varphi(t)}{h} = \varphi'(t) \text{ in } L^\infty(\mathbb{R}).$$

So

$$\begin{aligned} \langle f', \varphi \rangle &= - \lim_{h \rightarrow 0} \int_{\mathbb{R}} f(t) \frac{\varphi(t+h) - \varphi(t)}{h} dt = - \lim_{h \rightarrow 0} \int_{\mathbb{R}} \varphi(t) \frac{f(t-h) - f(t)}{h} dt \\ &= - \lim_{h \rightarrow 0} \int_{\mathbb{R}} \varphi(t) T_{-h} g(t) dt = \langle g, \varphi \rangle. \end{aligned}$$

□

Definition A.28. Let $p \in [1, \infty]$. We denote by $W^{1,p}(I, X)$ the space formed by the $f \in L^p(I, X)$ s.t. $f' \in \mathcal{D}(I, X)$ is also $f' \in L^p(I, X)$ and we set $\|f\|_{W^{1,p}} = \|f\|_{L^p} + \|f'\|_{L^p}$.

Lemma A.29. Let $u, g \in L^1(I, X)$ be such that

$$\langle u(t_2), f \rangle_{XX^*} - \langle u(t_1), f \rangle_{XX^*} = \int_{t_1}^{t_2} \langle g(s), f \rangle_{XX^*} ds \text{ for any } f \in X^*.$$

Then $\partial_t u = g$ in $\mathcal{D}'(I, X)$.

Proof. We immediately obtain $\langle u(t), f \rangle_{XX^*} \in AC(I)$ with derivative $\partial_t \langle u(t), f \rangle_{XX^*} = \langle g(t), f \rangle_{XX^*}$. For any $\varphi \in \mathcal{D}(I)$ and any $f \in X^*$

$$\left\langle - \int_I u(t) \varphi'(t) dt, f \right\rangle_{XX^*} = - \int_I \langle u(t), f \rangle_{XX^*} \varphi'(t) dt = \int_I \langle g(t), f \rangle_{XX^*} \varphi(t) dt = \left\langle \int_I g(t) \varphi(t) dt, f \right\rangle_{XX^*}$$

which yields

$$- \int_I u(t) \varphi'(t) dt = \int_I g(t) \varphi(t) dt \text{ for all } \varphi \in \mathcal{D}(I)$$

and so $\partial_t u = g$ in $\mathcal{D}'(I, X)$. □

B Appendix. A little more on the heat equation

We will will Proposition 11.10. v

Proposition B.1. Assume that $W_t - \Delta W = \partial_j f$ in Q_1 . Assume f vanishes outside \overline{Q}_{ρ_s} for an $\rho_s \in (0, 1)$ and that $W(-1, x) \equiv 0$. Then, for any $\rho_i \in (0, \rho_s)$:

1. $f \in L_t^\infty L_x^\infty(Q_1) \Rightarrow W \in L_t^\infty C_x^{0,\alpha}(\overline{Q}_{\rho_i})$ for any $\alpha \in (0, 1)$;
2. $f \in L_t^\infty W_x^{k,\infty}(Q_1) \Rightarrow W \in L_t^\infty C_x^{k,\alpha}(\overline{Q}_{\rho_i})$ for any $\alpha \in (0, 1)$;
3. $f \in L_t^\infty C_x^{0,\alpha}(Q_1)$ for an $\alpha \in (0, 1) \Rightarrow \nabla W \in L^\infty(\overline{Q}_{\rho_i})$;
4. $f \in L_t^\infty C_x^{k,\alpha}(Q_1)$ for an $\alpha \in (0, 1) \Rightarrow \nabla^{k+1} W \in L^\infty(\overline{Q}_{\rho_i})$.

Proof. It is enough to prove the 1st and 3rd claim. Let us start with the 1st claim. First of all

$$\begin{aligned} W(t, x) &= (4\pi)^{-\frac{3}{2}} \int_{-1}^t ds \int_{\mathbb{R}^3} (t-s)^{-\frac{3}{2}} e^{-\frac{|x-y|^2}{4(t-s)}} \partial_j f(s, y) dy \\ &= (4\pi)^{-\frac{3}{2}} \int_{-1}^t ds \int_{\mathbb{R}^3} e^{-\frac{|x-y|^2}{4(t-s)}} \frac{x_j - y_j}{2(t-s)^{1+\frac{3}{2}}} f(s, y) dy. \end{aligned}$$

Then

$$W(t, x) - W(t, z) = (4\pi)^{-\frac{3}{2}} \int_{-1}^t ds \int_{\mathbb{R}^3} \left[e^{-\frac{|x-y|^2}{4(t-s)}} \frac{x_j - y_j}{2(t-s)^{\frac{5}{2}}} - e^{-\frac{|z-y|^2}{4(t-s)}} \frac{z_j - y_j}{2(t-s)^{\frac{5}{2}}} \right] f(s, y) dy.$$

Introducing

$$\xi = \frac{x}{(t-s)^{\frac{1}{2}}}, \quad \eta = \frac{y}{(t-s)^{\frac{1}{2}}}, \quad \rho = \frac{z}{(t-s)^{\frac{1}{2}}}$$

we have

$$W(t, x) - W(t, z) = 2^{-1}(4\pi)^{-\frac{3}{2}} \int_{-1}^t ds \int_{\mathbb{R}^3} (t-s)^{-1/2} \left[e^{-\frac{|\xi-\eta|^2}{4}} (\xi_j - \eta_j) - e^{-\frac{|\rho-\eta|^2}{4}} (\rho_j - \eta_j) \right] f(s, (t-s)^{1/2}\eta) d\eta.$$

Then

$$\begin{aligned} & \frac{W(t, x) - W(t, z)}{|x-z|^\alpha} \\ &= 2^{-1}(4\pi)^{-\frac{3}{2}} \int_{-1}^t ds \int_{\mathbb{R}^3} (t-s)^{-1/2-\alpha/2} \frac{e^{-\frac{|\xi-\eta|^2}{4}} (\xi_j - \eta_j) - e^{-\frac{|\rho-\eta|^2}{4}} (\rho_j - \eta_j)}{|\xi - \rho|^\alpha} f(s, (t-s)^{1/2}\eta) d\eta. \end{aligned}$$

Now split the domain of integration in two parts. In the first part $|\xi - \rho| \geq 1$. When this holds we bound the integral by

$$\begin{aligned} & C \int_{-1}^t ds \int_{\mathbb{R}^3} (t-s)^{-1/2-\alpha/2} \left(e^{-\frac{|\xi-\eta|^2}{4}} |\xi - \eta| + e^{-\frac{|\rho-\eta|^2}{4}} |\rho - \eta| \right) d\eta \|f\|_{L_{t,x}^\infty} \\ & \leq 2C \int_{-1}^t ds (t-s)^{-1/2-\alpha/2} \int_{\mathbb{R}^3} e^{-\frac{|\eta|^2}{4}} |\eta| d\eta \|f\|_{L_{t,x}^\infty}. \end{aligned}$$

In the region where $|\xi - \rho| < 1$ we bound from above the integral by

$$\begin{aligned} & \int_{-1}^t ds \int_{\mathbb{R}^3} (t-s)^{-1/2-\alpha/2} \left| \frac{e^{-\frac{|\xi-\eta|^2}{4}} (\xi_j - \eta_j) - e^{-\frac{|\rho-\eta|^2}{4}} (\rho_j - \eta_j)}{|\xi - \rho|} \right| |f(s, (t-s)^{1/2}\eta)| d\eta \\ & \leq \int_{-1}^t ds \int_{\mathbb{R}^3} (t-s)^{-1/2-\alpha/2} \sup_{\tau \in [0,1]} \left| \partial_\tau \left(e^{-\frac{|\rho+\tau(\xi-\rho)-\eta|^2}{4}} (\rho_j + \tau(\xi_j - \rho_j) - \eta_j) \right) \right| d\eta \|f\|_{L_{t,x}^\infty} \\ & \leq \int_{-1}^t ds \int_{\mathbb{R}^3} (t-s)^{-1/2-\alpha/2} \sup_{\tau \in [0,1]} \left(e^{-\frac{|\tau(\xi-\rho)-\eta|^2}{4}} + e^{-\frac{|\tau(\xi-\rho)-\eta|^2}{4}} |\tau(\xi - \rho) - \eta|^2 \right) d\eta \|f\|_{L_{t,x}^\infty} \\ & \leq \int_{-1}^t ds \int_{|\eta| \leq 2} (t-s)^{-1/2-\alpha/2} (1+9) d\eta \|f\|_{L_{t,x}^\infty} \\ & + \int_{-1}^t ds \int_{\mathbb{R}^3} (t-s)^{-1/2-\alpha/2} \left(e^{-\frac{|\eta|^2}{8}} + 2e^{-\frac{|\eta|^2}{8}} |\eta|^2 \right) d\eta \|f\|_{L_{t,x}^\infty} \leq C \|f\|_{L_{t,x}^\infty}. \end{aligned}$$

We now consider the 3rd statement. For $\epsilon > 0$ we consider

$$W_\epsilon(t, x) = \int_{-1}^{t-\epsilon} ds \int_{\mathbb{R}^3} e^{-\frac{|x-y|^2}{4(t-s)}} \frac{x_j - y_j}{(t-s)^{1+\frac{3}{2}}} f(s, y) dy.$$

Then

$$\begin{aligned} \partial_k W_\epsilon(t, x) &= \int_{-1}^{t-\epsilon} ds \int_{\mathbb{R}^3} e^{-\frac{|x-y|^2}{4(t-s)}} \left[\frac{\delta_{jk}}{(t-s)^{1+\frac{3}{2}}} - \frac{(x_j - y_j)(x_k - y_k)}{2(t-s)^{2+\frac{3}{2}}} \right] f(s, y) dy \\ &= \int_{-1}^{t-\epsilon} ds \int_{\mathbb{R}^3} e^{-\frac{|x-y|^2}{4(t-s)}} \left[\frac{\delta_{jk}}{(t-s)^{1+\frac{3}{2}}} - \frac{(x_j - y_j)(x_k - y_k)}{2(t-s)^{2+\frac{3}{2}}} \right] |x-y|^\alpha \frac{f(s, y) - f(s, x)}{|x-y|^\alpha} dy. \end{aligned}$$

So, using

$$\xi = \frac{x}{(t-s)^{\frac{1}{2}}}, \quad \eta = \frac{y}{(t-s)^{\frac{1}{2}}},$$

$$\begin{aligned} |\partial_k W_\epsilon(t, x)| &\leq \|f\|_{L^\infty((-1,0), C_x^{0,\alpha})} \int_{-1}^{t-\epsilon} ds \int_{\mathbb{R}^3} e^{-\frac{|\xi-\eta|^2}{4}} |\delta_{jk} - 2^{-1}(\xi_j - \eta_j)(\xi_k - \eta_k)| \frac{|\xi - \eta|^\alpha}{(t-s)^{1-\alpha/2}} d\eta \\ &\leq C \|f\|_{L^\infty((-1,0), C_x^{0,\alpha})} \text{ for } C = \sup_{t \in (-1,0)} \int_{-1}^t ds \int_{\mathbb{R}^3} e^{-\frac{|\eta|^2}{4}} (1 + |\eta|^2) \frac{|\eta|^\alpha}{(t-s)^{1-\alpha/2}} d\eta. \end{aligned}$$

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