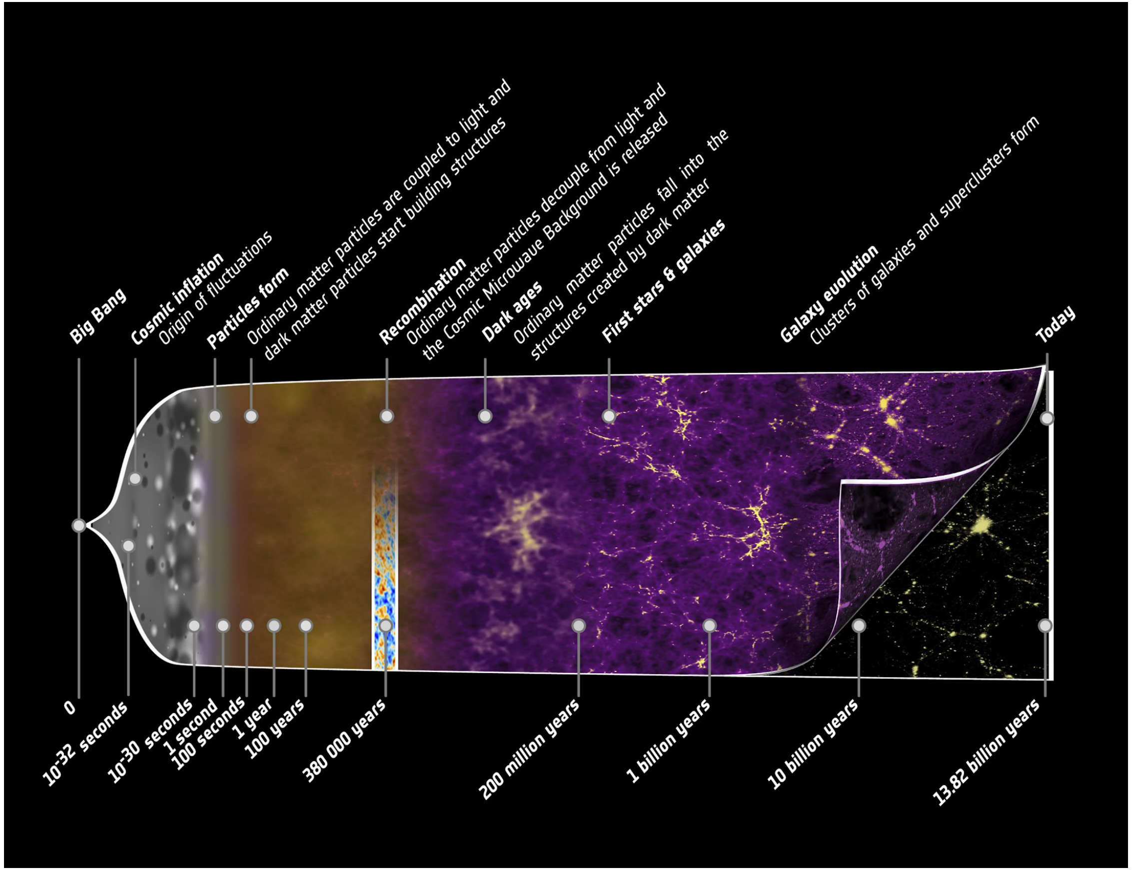
# OBSERVATIONAL COSMOLOGY

**A.A. 2023/2024 | Matteo Costanzi - University of Trieste / INAF**

# GENERAL FRAMEWORK: $\Lambda$CDM MODEL



## ASSUMPTION OF $\Lambda$CDM:

- **Gravity is described by GR**
- **Particles and forces are described by QFT**
- **The cosmological principle is valid**
- **The Universe underwent accelerated expansion at early times (Inflation)**
- **Most matter is made up by a collisionless particle (Dark Matter)**
- **The Universe is undergoing an accelerated expansion ($\Lambda$)**

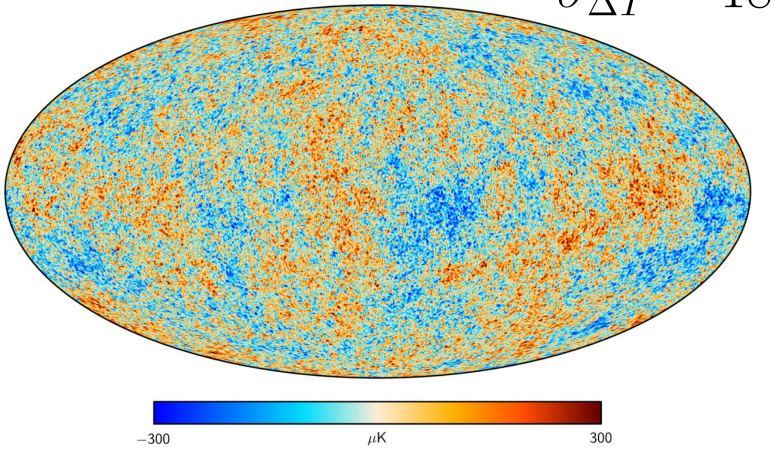
# GENERAL FRAMEWORK: COSMOLOGICAL PRINCIPLE

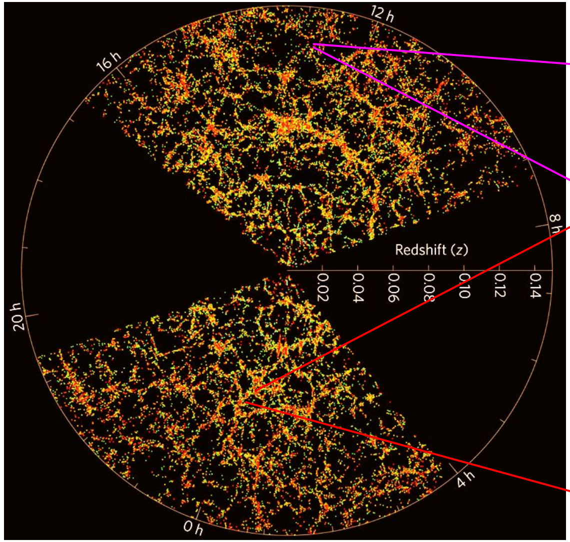
$$\sigma_{\Delta T} = 18\mu K$$

**Cosmological principle:** the Universe is isotropic* and homogeneous** on large scale (~100 Mpc/h)

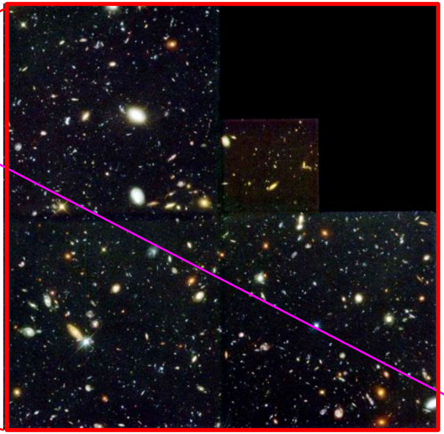
* from observation

** Copernican principle

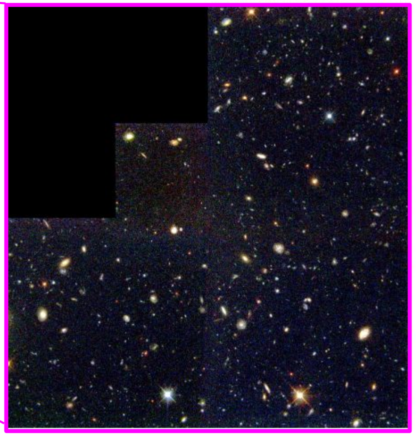




HDF-North



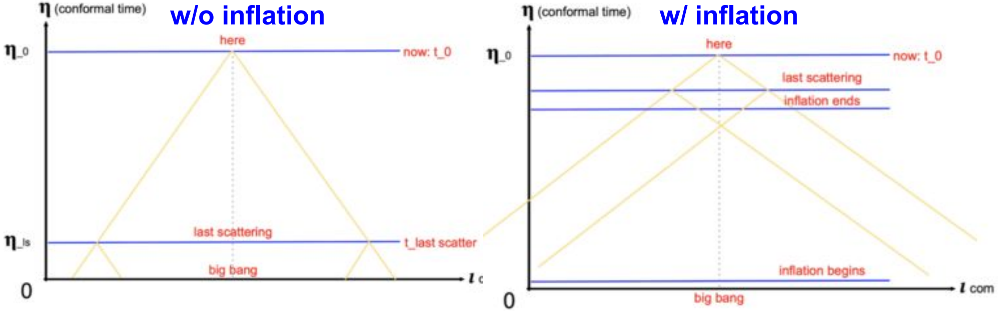
HDF-South



# GENERAL FRAMEWORK: INFLATION

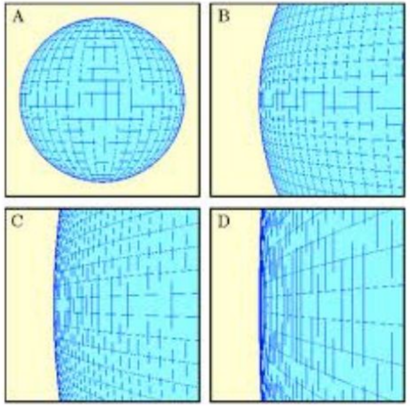
**Inflation:** exponential expansion (e-fold~60) happened in the early stages of the Universe ($t \simeq 10^{-37}$ - $10^{-35}$s).

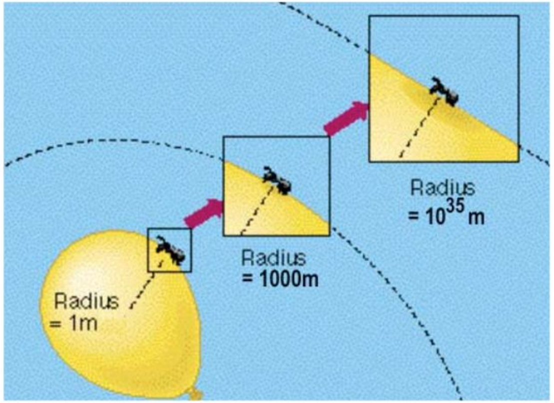
## Horizon problem

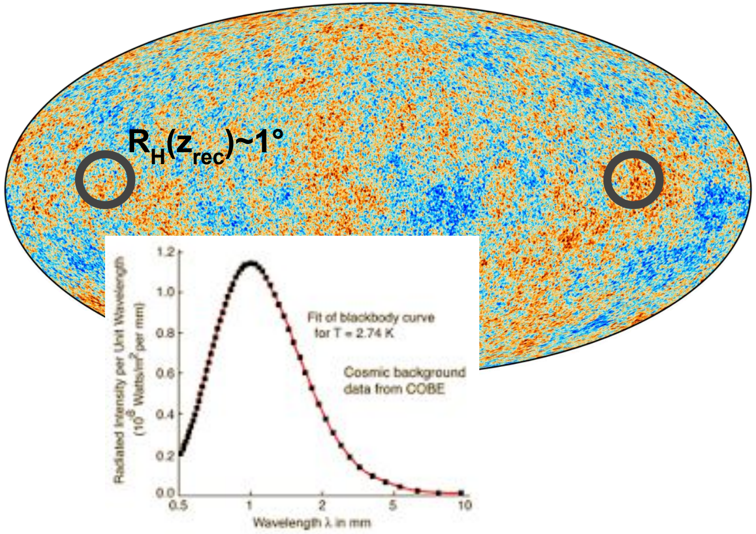

w/o inflation

w/ inflation

## Flatness problem ( today $\Omega_k \simeq 0$ )



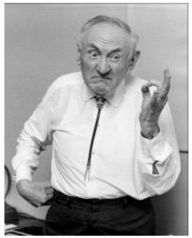


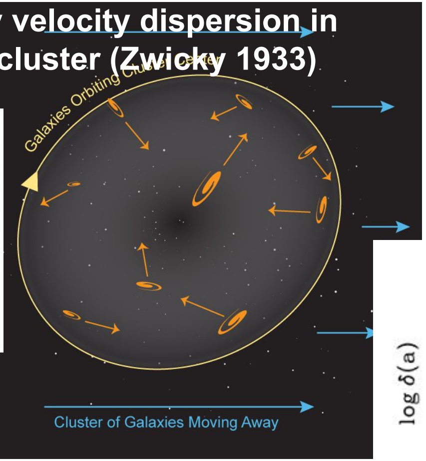

$R_H(z_{rec}) \sim 1°$

\+ Magnetic monopole problem: Inflation dilutes the Universe by a factor $e^{3N}$ , with N~60

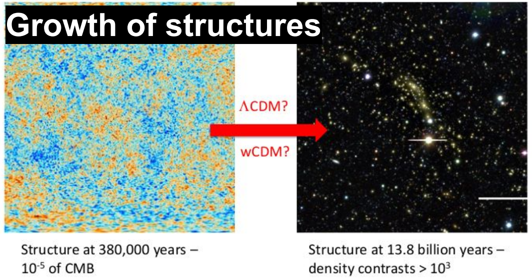
# GENERAL FRAMEWORK: DARK MATTER

**Dark Matter:** massive particles which interacts only via gravitational forces





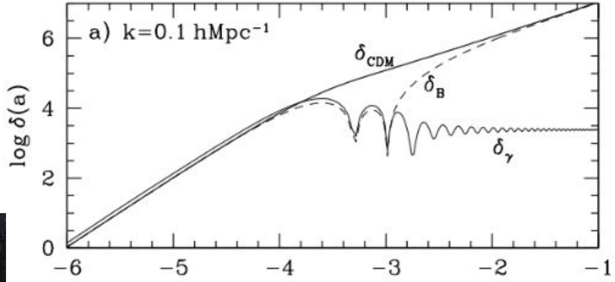
Galaxy velocity dispersion in Coma cluster (Zwicky 1933)

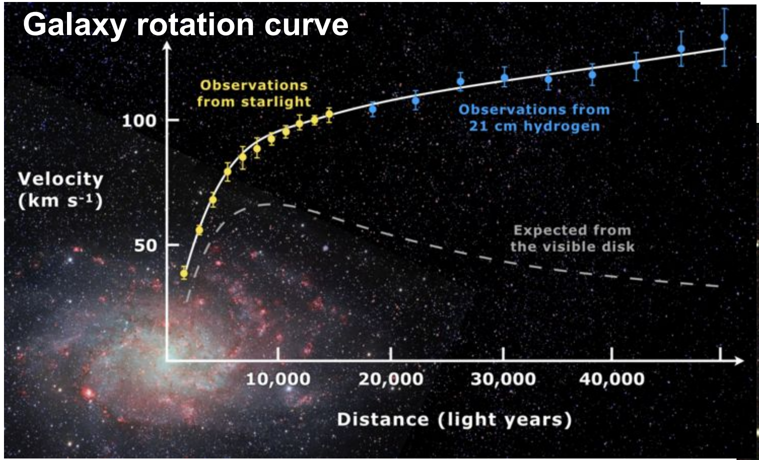


Growth of structures

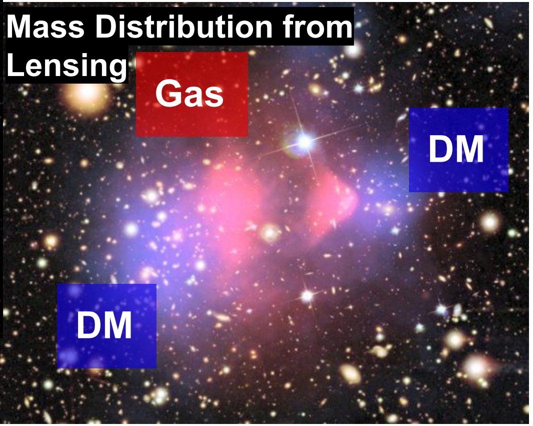
Structure at 380,000 years – $10^{-5}$ of CMB

Structure at 13.8 billion years – density contrasts > $10^3$





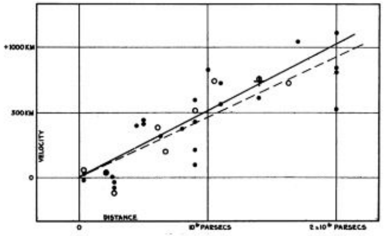
Galaxy rotation curve



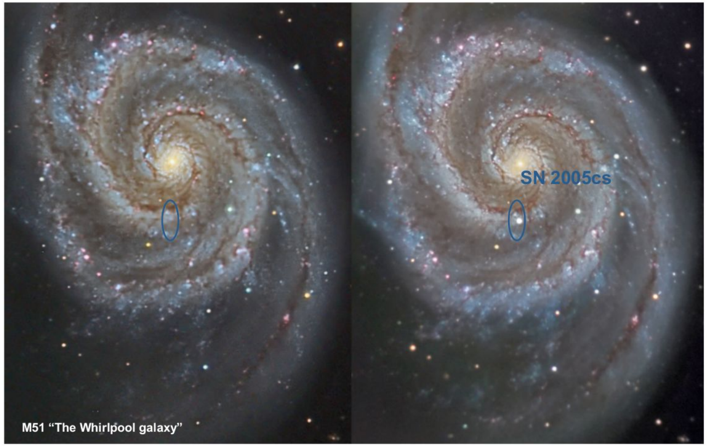
Mass Distribution from Lensing

# GENERAL FRAMEWORK: $\Lambda$CDM MODEL

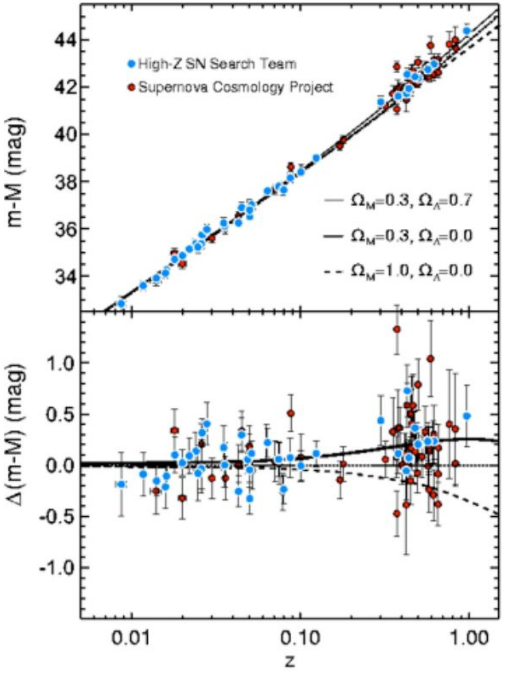
**Accelerated expansion:** the Universe is undergoing a phase of accelerated expansion driven by a dark energy component, $\Lambda$



Hubble 1929



M51 “The Whirlpool galaxy”

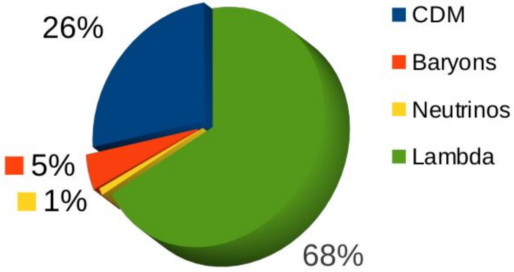


**1998/99 High-Z Supernova Search Team and Supernova Cosmology Project found evidence for accelerated expansion of the Universe (2011 Nobel Prize)**

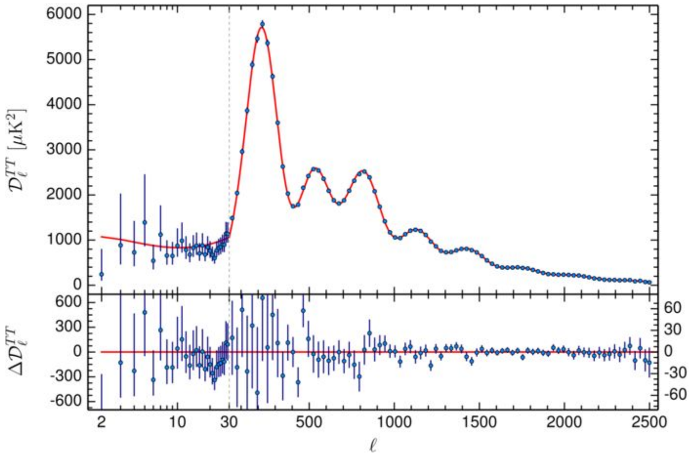
# GENERAL FRAMEWORK: CURRENT STATUS

**Several cosmological probes point towards a consistent model of flat $\Lambda$CDM**

**The $\Lambda$CDM universe**

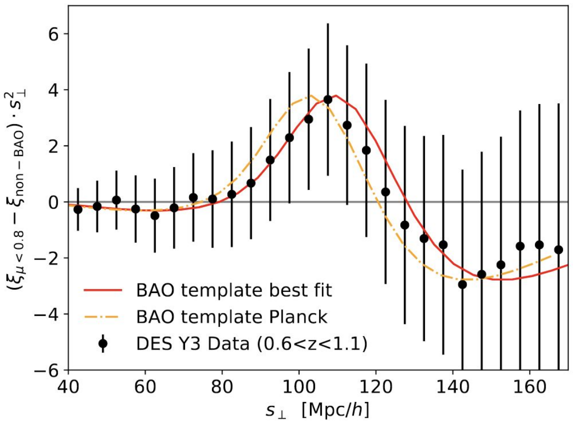


**The CMB TT power spectrum (Planck coll. 18)**



**~380.000 yr after the Big Bang**

**BAO galaxy (DES Coll. 22)**

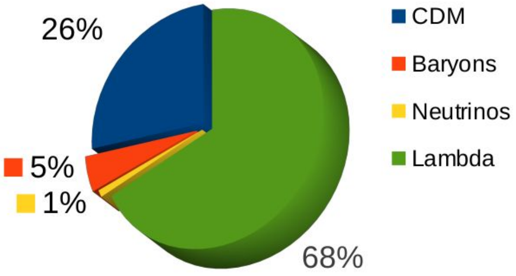


**~$10^{10}$ yr after the Big Bang**

# GENERAL FRAMEWORK: CURRENT STATUS

**Several cosmological probes point towards a consistent model of flat $\Lambda$CDM**

The $\Lambda$CDM universe



**Energy density parameters (total mass, baryons, neutrinos) w.r.t. the critical density of the universe**

**Hubble constant**

**$\Lambda$CDM+$\nu$ parameters:** $\Omega_{\mathrm{m}}, \Omega_{\mathrm{b}}, \Omega_{\nu}, \sigma_8, H_0, \tau, n_s$

**Amplitude of the matter fluctuations on a 8 Mpc/h scale**

**Optical depth**

**Spectral index of primordial fluctuations**

**For a flat Universe:**

$$\Omega_k = 1 - \sum_i \Omega_i = 0$$

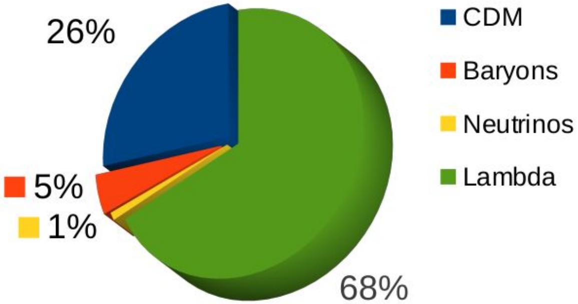
# GENERAL FRAMEWORK: CURRENT STATUS

**But the two dominants components of this model lack a fundamental theory to connect them with the rest of physics:**

- **What is the nature of Dark Matter?**
- **What is the cause of observed cosmic acceleration?**
    - **Is it Dark Energy or a modification of general relativity?**
    - **If it is Dark Energy, is it constant ($\Lambda$CDM) or evolving (wCDM)?**

- **Also, what is the driver of cosmic inflation?**

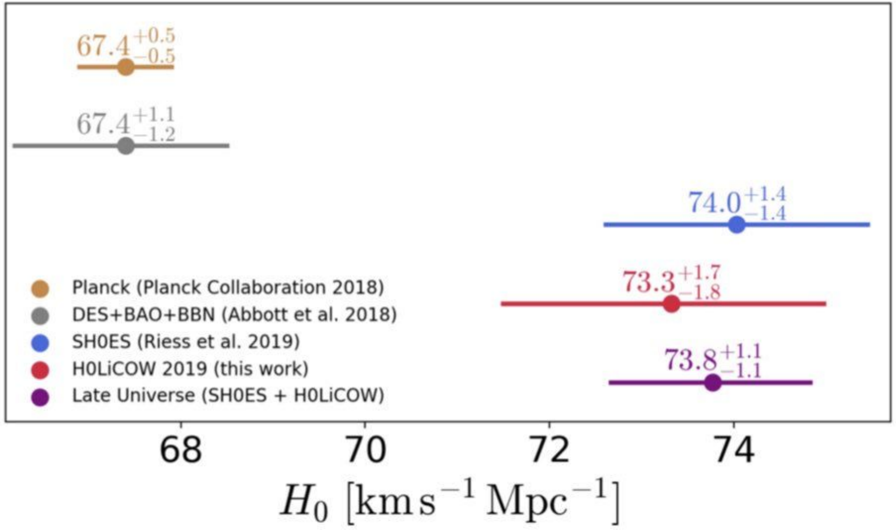
**The $\Lambda$CDM universe**



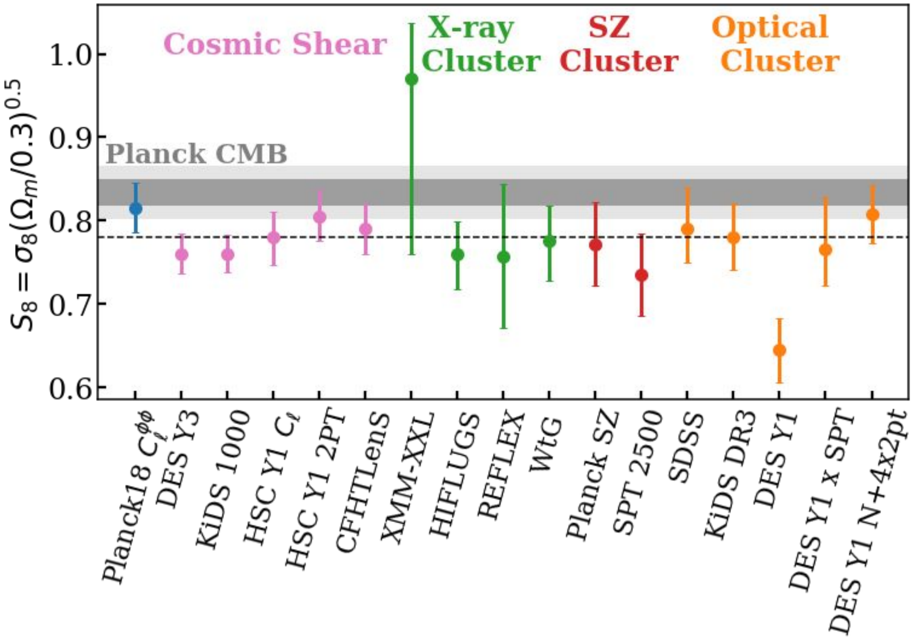
# GENERAL FRAMEWORK: CURRENT STATUS

**Moreover, there are tensions between parameters derived from early Universe probes (e.g. CMB) and low-redshift probes (e.g. SN, cosmic shear, galaxy clustering, cluster of galaxies)**

**Tension on the Hubble's constant:**



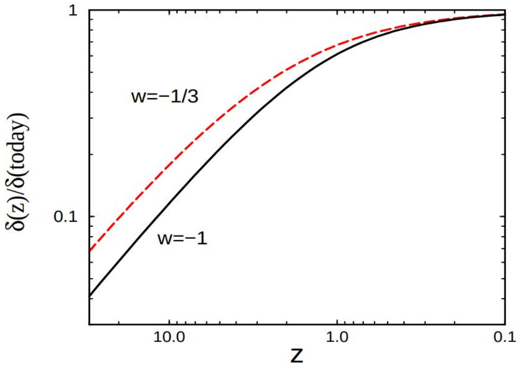
**Tension on $S_8$ (growth of structures)**



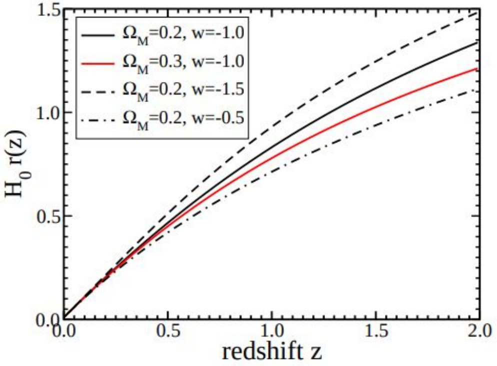
# GENERAL FRAMEWORK

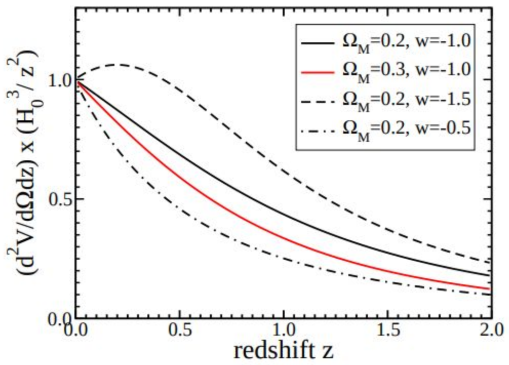
- **What can we measure with cosmological probes:**

**Growth of density perturbation**



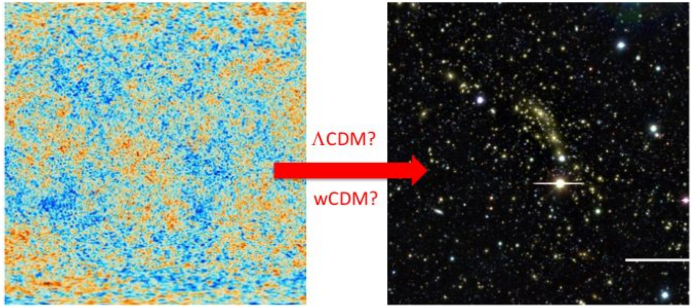
**Expansion history**





**Freiman+08**

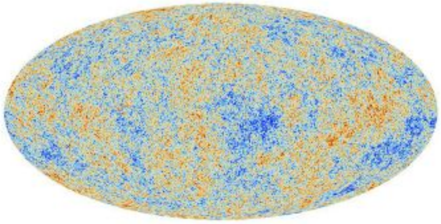
**A good strategy is to combine early (i.e. CMB) and late time Universe probes to maximize the redshift leverage**



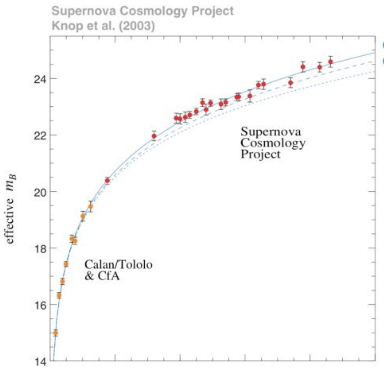
Structure at 380,000 years – $10^{-5}$ of CMB

Structure at 13.8 billion years – density contrasts > $10^3$

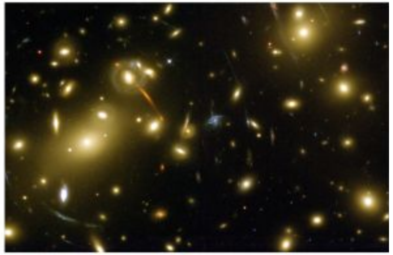
# GENERAL FRAMEWORK: COSMOLOGICAL PROBES



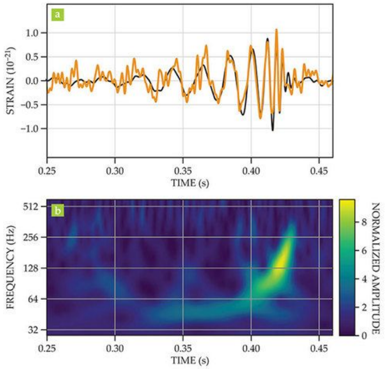
Cosmic Microwave Background and its fluctuations



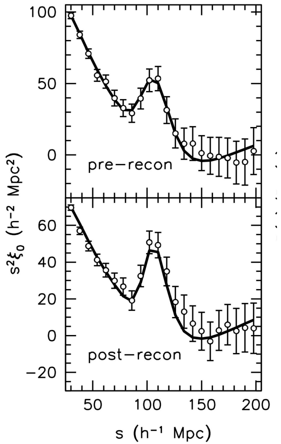
Hubble Diagram (with SNIa)

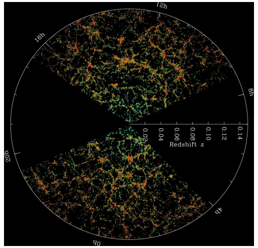


Gravitational lensing

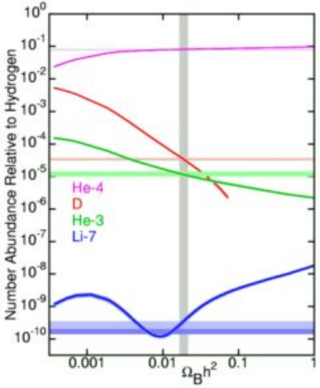


Gravitational waves

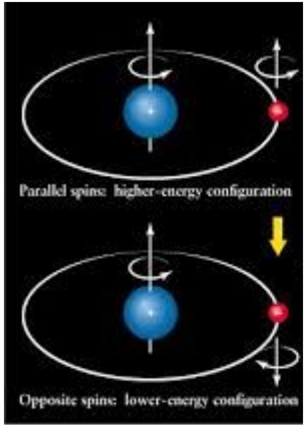




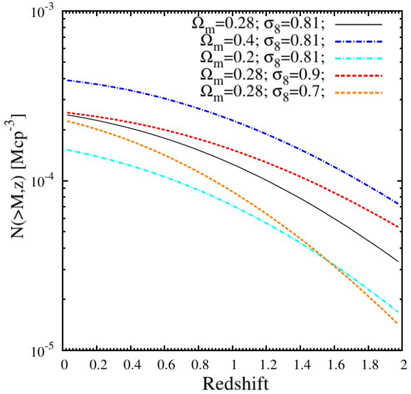
Galaxy Surveys, BAO & RSD



Big Bang nucleosynthesis

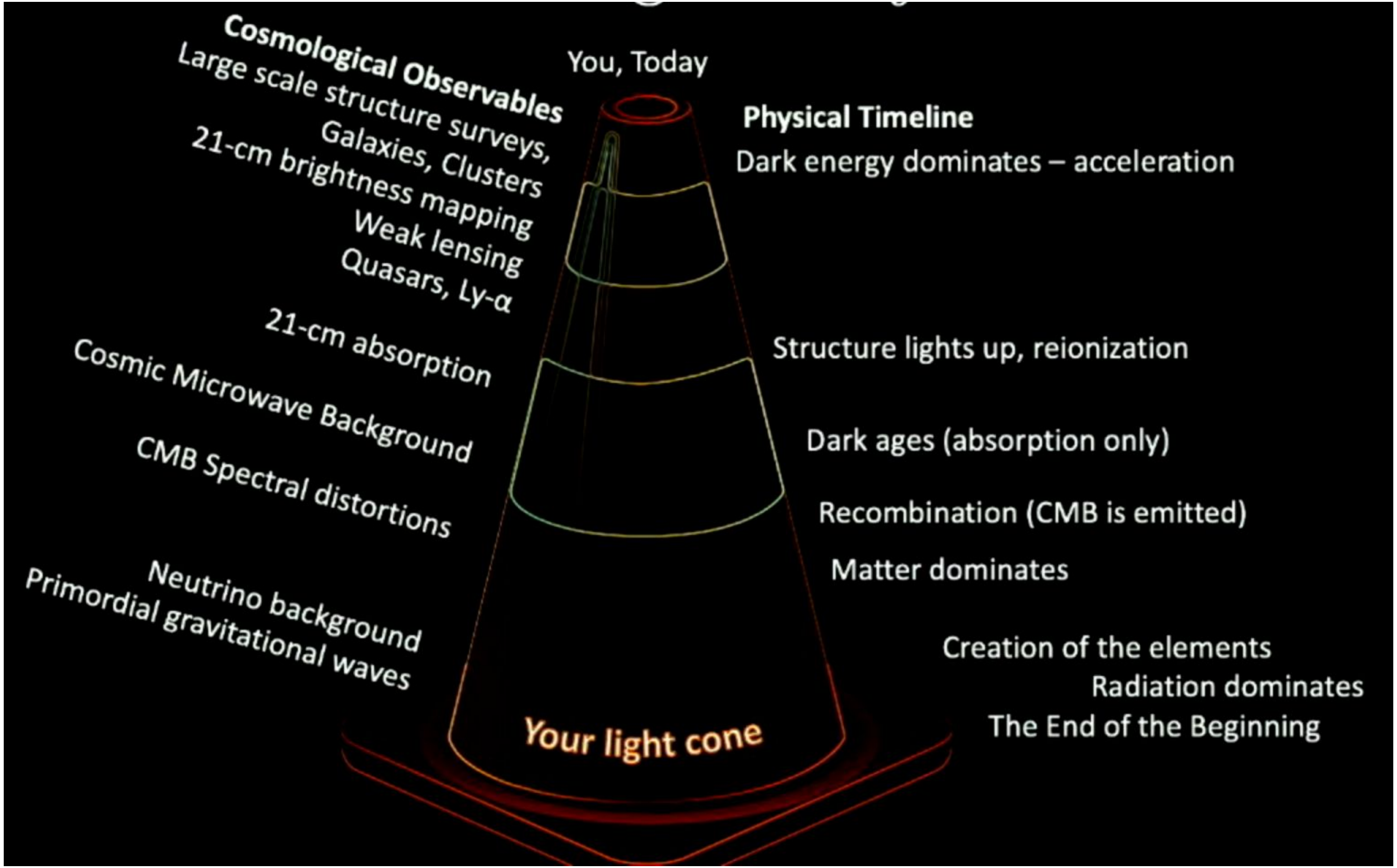


21cm Cosmology



Cluster Cosmology

# GENERAL FRAMEWORK: COSMOLOGICAL PROBES



# GENERAL FRAMEWORK: DARK ENERGY PROBES

**Dark Energy can be probed analysing:**

- **History of the expansion rate of the universe:**
  **SN1a, BAO, weak lensing, cluster counting…**

- **History of the rate of growth structure of the universe:**
  **RSD, weak lensing, LSS distribution, cluster counting…**

**For all the probes but SN1a, large survey are needed, ideally probing large volumes, at different redshifts, and at different wavelengths**

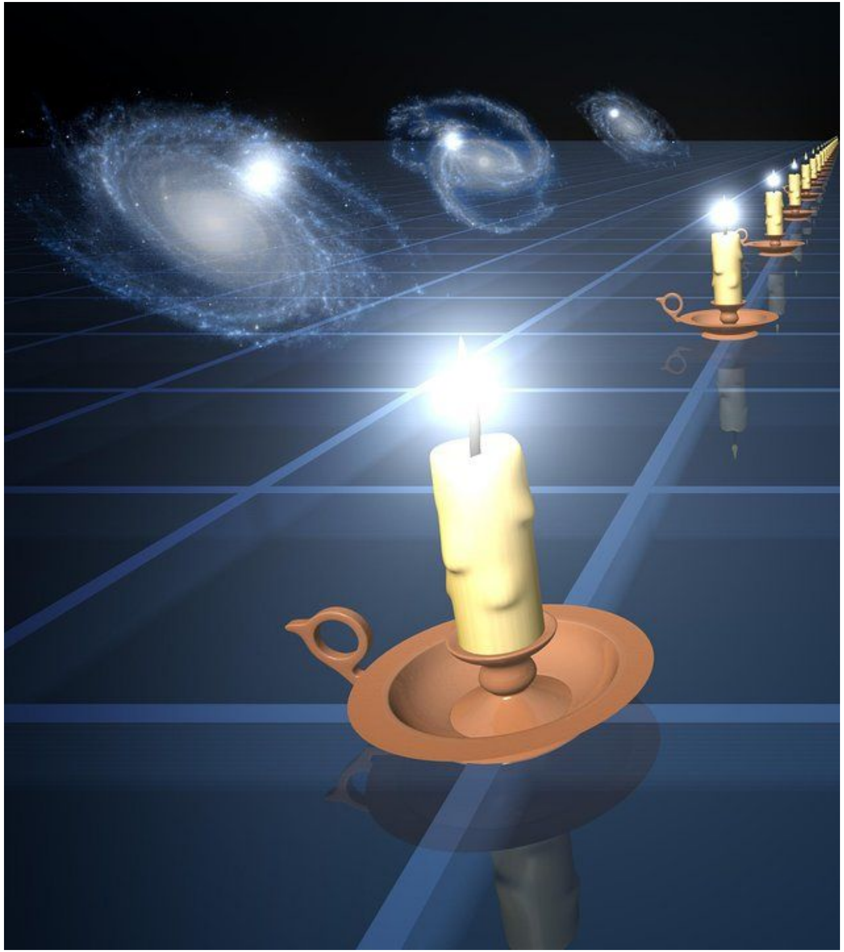
# STANDARD CANDLES: SUPERNOVAE IA

For a short review: https://link.springer.com/article/10.1007/s40766-022-00034-1

# STANDARD CANDLES

**Standard candles: Astronomical objects with known absolute magnitude (i.e. intrinsic luminosity), like variable stars (Cepheid and RR Lyrae), or Type Ia supernovae.**

**Standard candles are valuable cosmological tools since by measuring their apparent magnitude we can determine their (luminosity) distance; by looking at the relation between distance and redshift (Hubble diagram) it is possible to infer cosmological parameters.**



# LUMINOSITY DISTANCE

In an expanding universe, distant galaxies are much dimmer than you would normally expect because the photons of light become stretched and spread out over a wide area.

We define the luminosity distance $D_L$ operationally as the distance that relates the intrinsic (bolometric) luminosity L of an object (e.g. a galaxy) at redshift z to its observed flux f via:

$$f = \frac{L}{4\pi D_L^2}$$

To derive an expression fo $D_L$ we need to consider:

- The Universe's geometry might not be Euclidean
- The energy of each photon is reduced by the redshift effect, i.e. by 1/(1 + z). Therefore, the energy flux of the distant objects is reduced by factor 1/(1 + z)
- Clocks appear to run slower in a distant galaxy by a factor (1 + z); Therefore, photons will arrive at the observer location at a rate reduced by a factor 1/(1 + z) and thus the flux will be reduced by this factor

$$f = \frac{L}{4\pi(1+z)^2 D_M^2}$$

# LUMINOSITY DISTANCE

**For a flat LCDM universe, at late time ($z \ll z_{eq}$):**

$$D_L(z) = (1+z)D_M = (1+z)\frac{c}{H_0}\int_0^z \frac{dz'}{E(z')}$$

$$E(z) = \frac{H(z)}{H_0} = \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$$

**The luminosity distance is a function of cosmological parameters!**

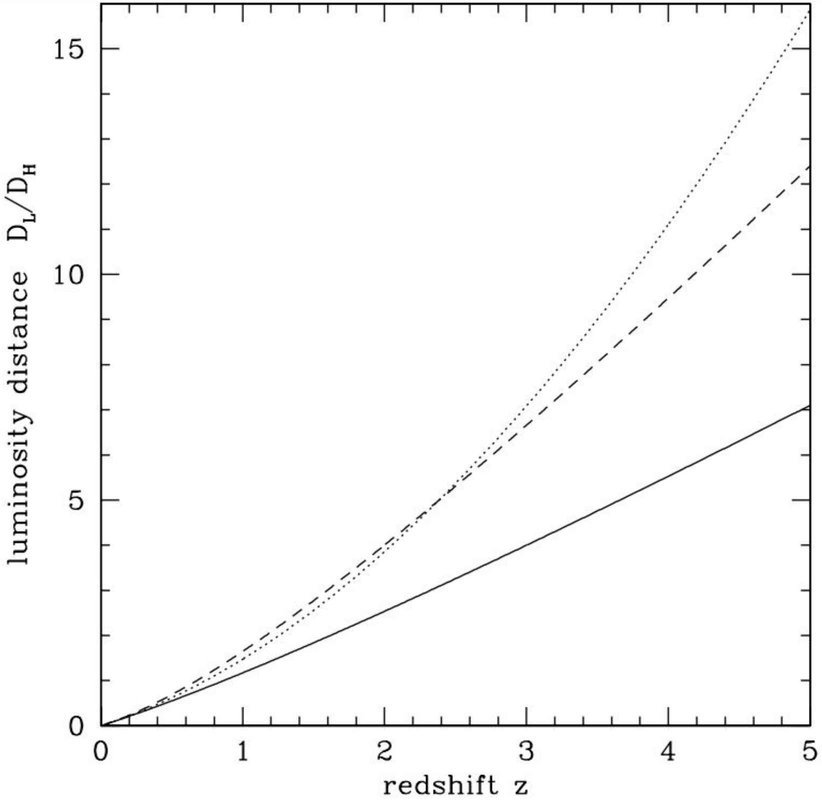


Figure 3: The dimensionless luminosity distance $D_L/D_H$. The three curves are for the three world models, $(\Omega_M, \Omega_\Lambda) = (1, 0)$, solid; $(0.05, 0)$, dotted; and $(0.2, 0.8)$, dashed.

# DISTANCE MODULUS

**Apparent magnitude:**

$$m = -2.5\log_{10}(f) + \text{cost.}$$

**Distance modulus:**

$$\mu = m - M = 5\log_{10}(D_L/10pc)$$

**Absolute magnitude ≡ Apparent magnitude of an object seen from 10 pc**

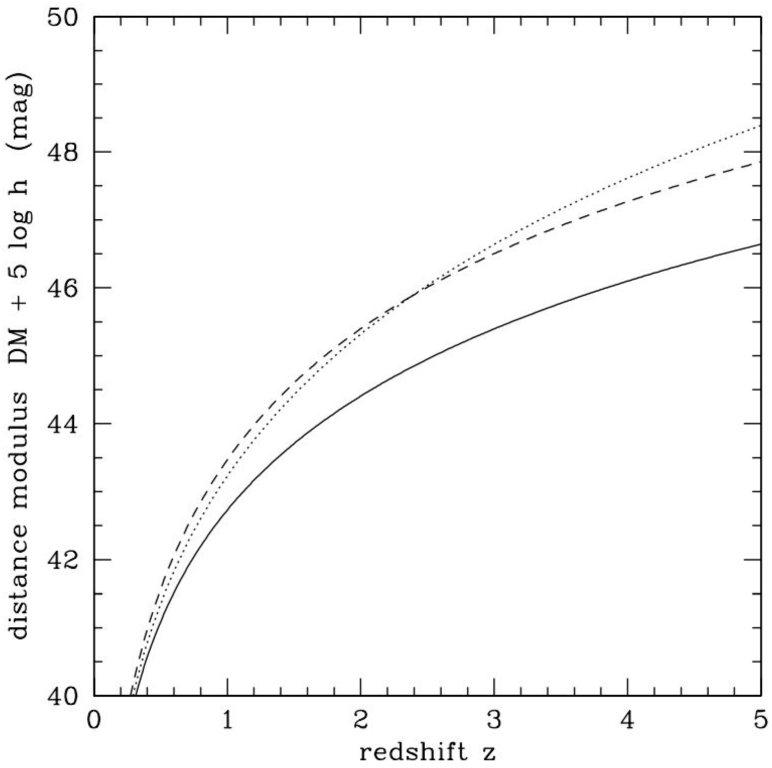


Figure 4: The distance modulus $DM$. The three curves are for the three world models, $(\Omega_{\rm M}, \Omega_\Lambda) = (1, 0)$, solid; $(0.05, 0)$, dotted; and $(0.2, 0.8)$, dashed.

# SUPERNOVAE TYPE Ia

**The progenitor of a SN Ia is a white dwarf in a close binary system, which accrete matter from its companions until it reaches the Chandrasekhar limit ($M_{Ch}$ ~ 1.4 $M_{\odot}$); after that the start is destroyed by an explosive thermonuclear burning that produces iron-peak elements. Having a similar mass at the time of explosion, the SN Ia have a small luminosity dispersion.**

**SN Ia explosions are quite rare events, ~1.0e-4 [yr $Mpc^3]^{-1}$ (~1 per century in our galaxy), but their extremely high luminosity – $M_V$=-19.3, 5 × $10^9$ times brighter than the Sun, typically comparable to the brightness of the entire host galaxy – allows us to detect them at very large distances (z>1)**

# SUPERNOVAE TYPE Ia

**With regards to the luminosity evolution, SNe Ia show the highest homogeneity among SN types. Actually, it is recognised that, strictly speaking, even SNe Ia are not standard candles since they show significant diversity in their absolute magnitudes at maximum (40% scatter in the peak brightness). Standardisation methods have been developed promoting their use as powerful cosmic distance indicators**

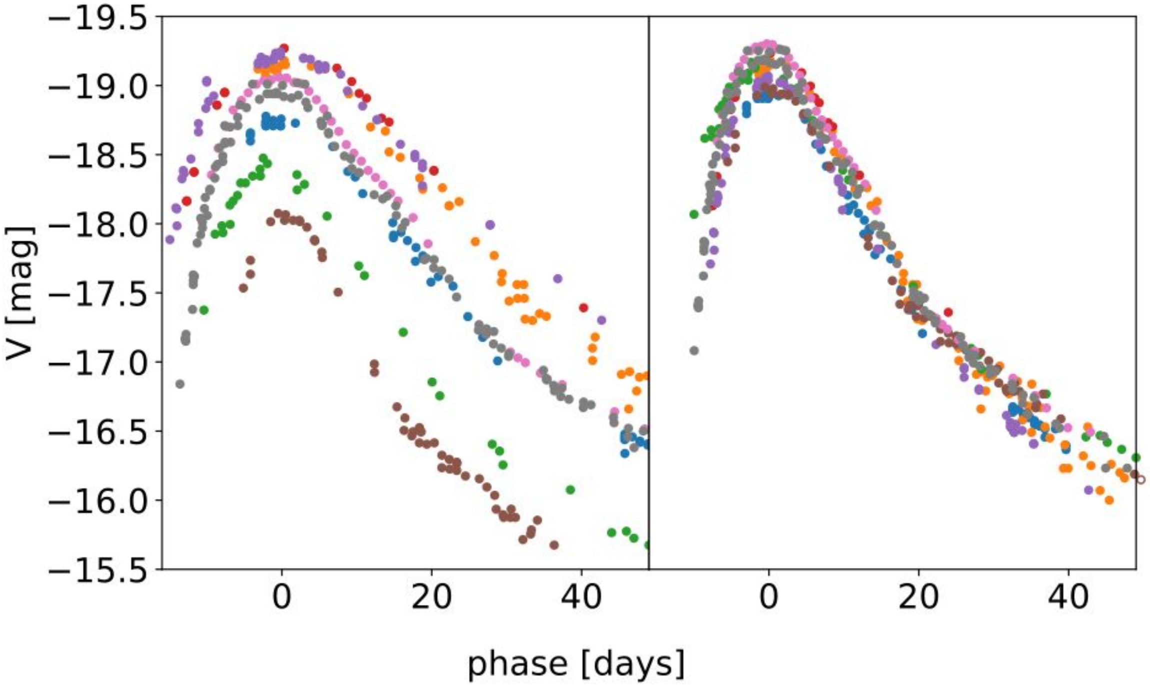


**Fig. 6** Illustration of the standardization of SN Ia light curves using the stretch factor. Left panel shows the light curve in absolute V magnitude (corrected for extinction) for a sample on nearby SNe Ia with different decline rates. Right panel: after stretching the time axis to match the luminosity evolution, the luminosity is scaled based on the light curve evolution-luminosity relation. Data from [100]

# SUPERNOVAE TYPE Ia

**Fortunately, the observed differences in peak luminosities of SNe Ia are very closely correlated with observed differences in the shapes of their light curves: dimmer SNe decline more rapidly after maximum brightness, while brighter SNe decline more slowly.**

**Standardized distance modulus:**

**Fitted parameters**

$$\mu = m - M - \alpha x - \beta c$$

**Stretch parameter**

**Measure of the SN colour**

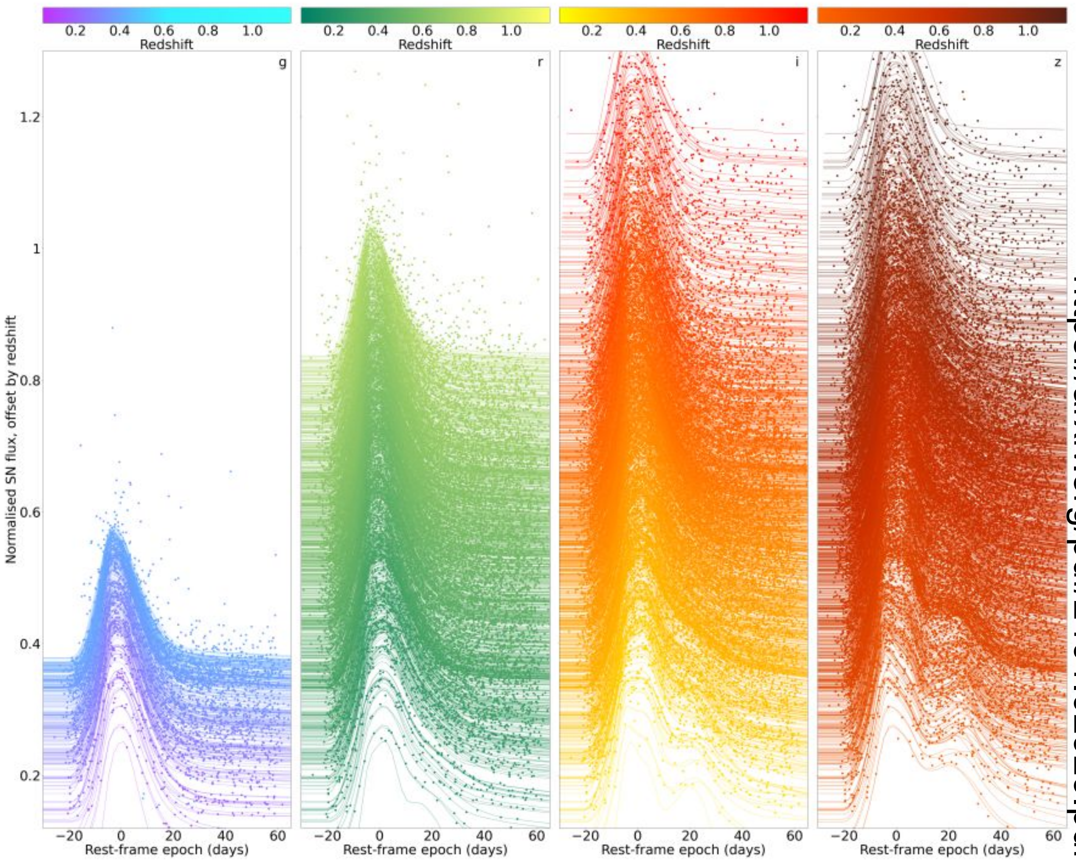


**Figure 2.** All DES light curves, showing observed magnitudes in $g$, $r$, $i$, and $z$ bands (left to right respectively) normalized by the maximum brightness of each light curve, and with the time-axis de-redshifted to the rest-frame. Each light curve has been arbitrarily offset by their redshift, with higher-redshift objects higher on the plot (as labeled on vertical axis). Lines show

https://arxiv.org/pdf/2401.02929.pdf

# HUBBLE DIAGRAM OF SN Ia

- **Studying the evolution of the distance modulus with redshift is it possible to measure $H_0$ and the expansion history of the Universe.**

- **1998/99: High-Z Supernova Search Team and Supernova Cosmology Project found evidence for accelerated expansion of the Universe (Nobel prize 2011)**

- **Precise measurements of the Hubble's constant from SN Ia:**

  **$H_0$ = 73.2 ± 1.3 km/s/Mpc (SH0ES Team, Riess et al 2021)**

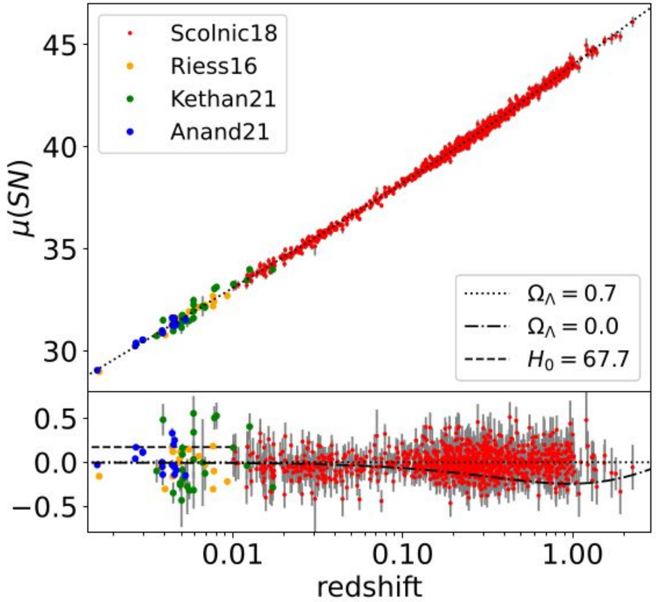
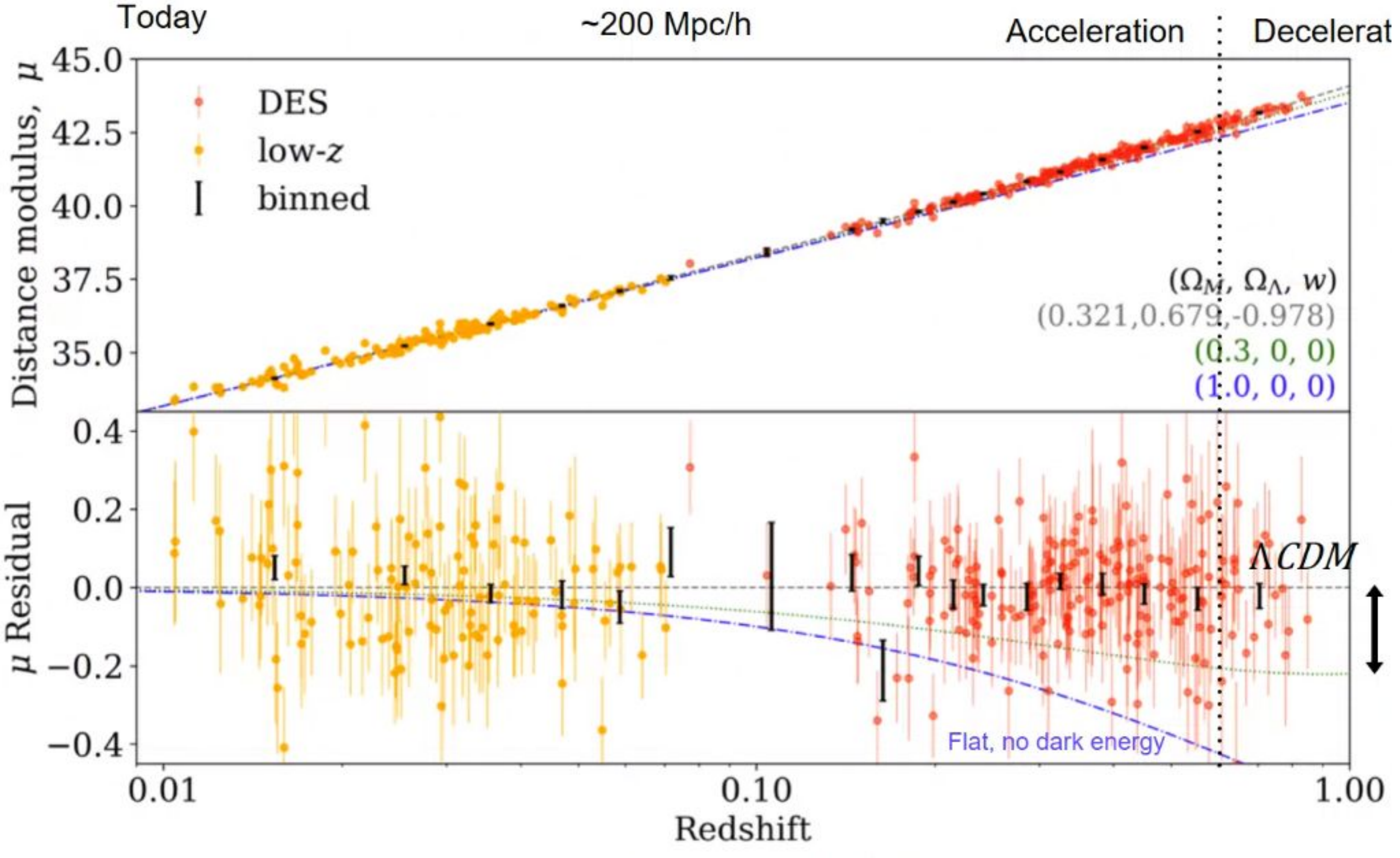


**Fig. 8** Hubble diagram for SNe Ia. SNe Ia in the Hubble flow (red points) are from the Pantheon compilation ([179], https://archive.stsci.edu/prepds/ps1cosmo/) whereas low redshift SNe Ia are retrieved from [74] (Riess16, calibrated with Cepheids), [183] (Khetan21, calibrated with SBF) and [184] (Anand21, calibrated with TRGB). The distance moduli are computed for a flat cosmology with $\Omega_\Lambda = 0.7$ and adopting the [70] calibration of nearby SN Ia ($H_0 = 73.2$). The bottom panel shows the residuals with respect to the adopted cosmology. The dot-dashed line is the expected trend for a null cosmological constant. Instead the dashed line at redshift $z < 0.01$ illustrates the shift of the Planck $H_0$ calibration with respect to local SN Ia calibration

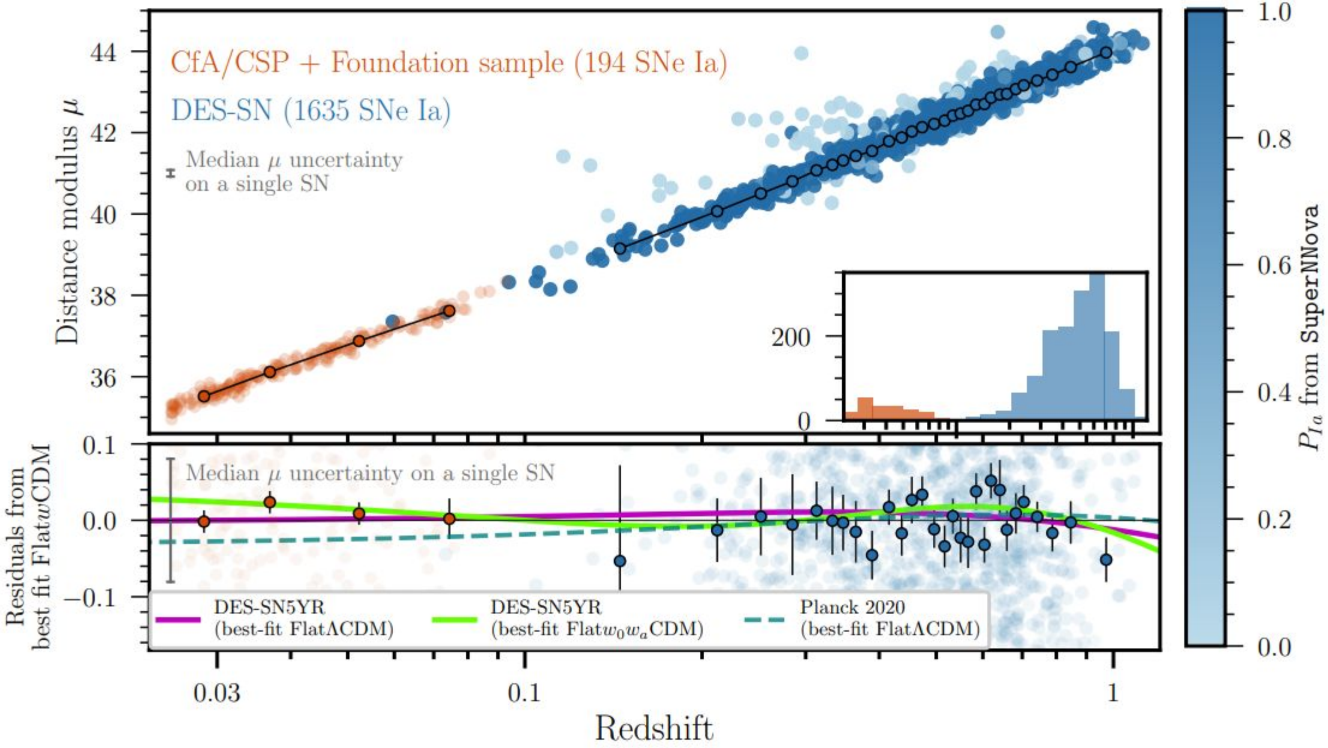
# HUBBLE DIAGRAM OF SN Ia

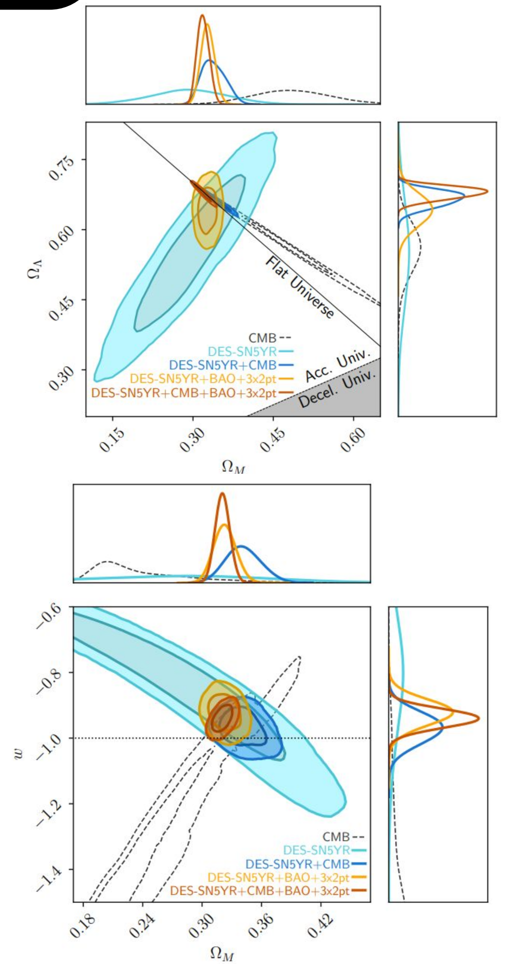


~ recession velocity/c

ion, 2019)

# HUBBLE DIAGRAM OF SN Ia





https://arxiv.org/pdf/2401.02929.pdf

# COSMIC CHRONOMETERS

For a review: https://arxiv.org/pdf/2201.07241.pdf

# STANDARD CLOCKS AND CHRONOMETERS

**Given how the age of the Universe scales as a function of redshift:**

$$t(z) = \frac{1}{H_0}\int_0^z \frac{dz'}{E(z')(1+z')}$$

$$E(z) = \frac{H(z)}{H_0} = \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$$

**finding the oldest objects at each redshift it is possible to use them to constrain the Hubble parameter. In other words, we can use standard clocks – i.e. objects whose absolute age is known – to constrain cosmology.**

**Or we can consider:**

$$H(z) = -\frac{1}{1+z}\frac{dz}{dt}$$

**by measuring the differential age of the Universe (how much the Universe has aged between two redshifts) it is possible to obtain a direct determination of the expansion rate H(z). The main difference here is that instead of looking for some standard clocks, we will be looking for standard chronometers, a homogeneous population of objects with a synchronized formation, i.e. whose clocks started "ticking" at the same time and that are therefore optimal tracers of the differential age evolution of the Universe**

# STANDARD CHRONOMETERS

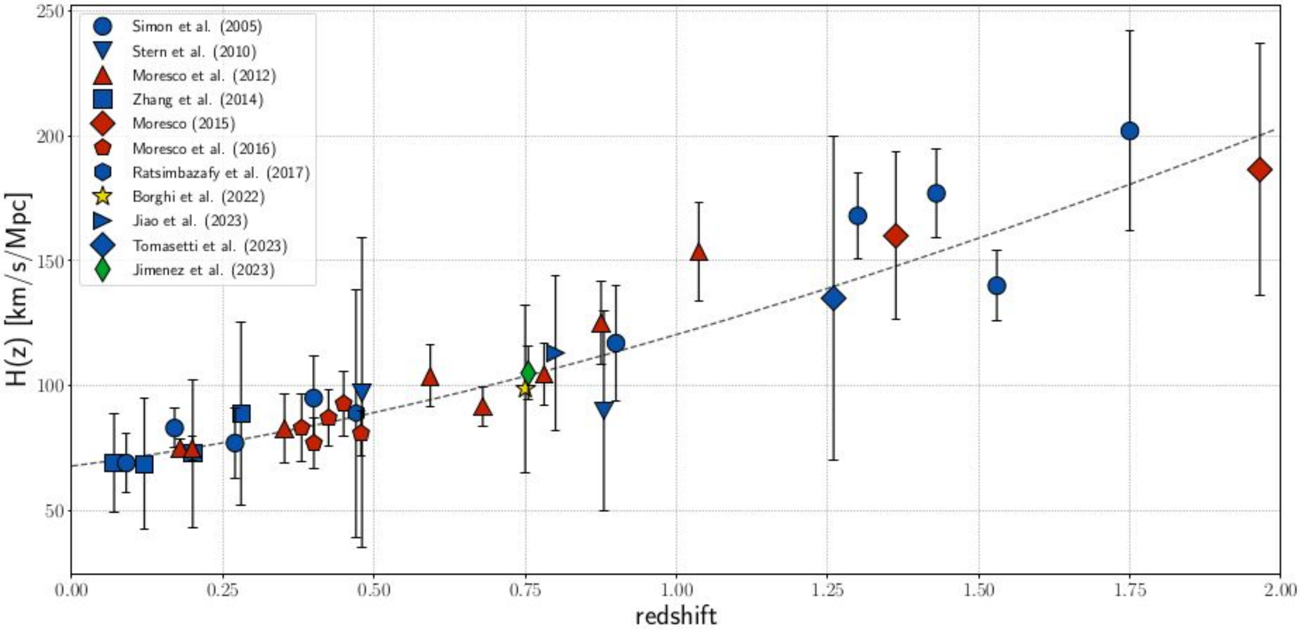
**The pillars of the cosmic chronometers method are:**

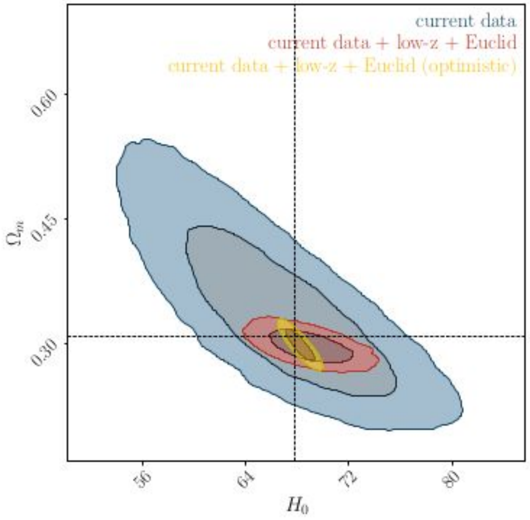
- **Selection of a population of optimal cosmic chronometers, i.e. a population of objects able to trace homogeneously how much the Universe has aged between two redshifts.**

- **Robust measurement of the differential age dt (the advances in spectroscopic surveys makes the measurement of dz remarkably accurate when a spectroscopic redshift is available (typically $\delta z/(1 + z) \lesssim 10^{-3}$).**

**The most elementary objects in the Universe that we can date and that can be found from the local Universe up to high redshifts are galaxies. To apply the cosmic chronometer method, the idea is therefore to find at each redshift the oldest population of galaxies available. Massive passively evolving galaxies are among the best candidates: having formed most of their mass at very high redshifts, in a very quick episode of star formation, and having mostly exhausted their gas reservoir are expected to evolve passively as a function of cosmic time.**

# STANDARD CHRONOMETERS

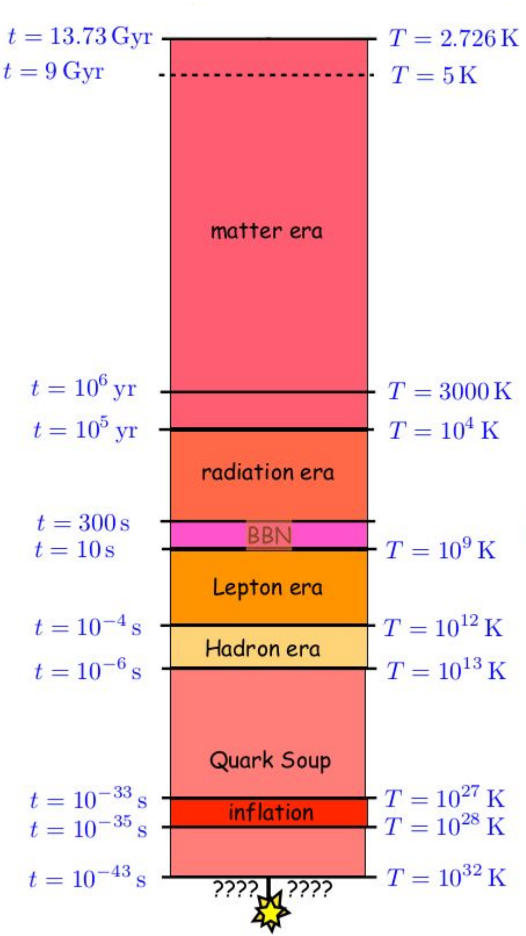




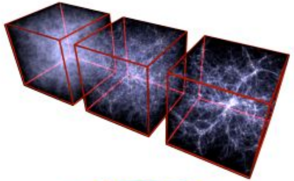
# BIG BANG NUCLEOSYNTHESIS

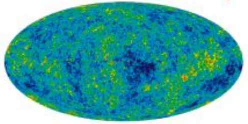
For a review: https://arxiv.org/pdf/astro-ph/0511534.pdf or https://arxiv.org/pdf/astro-ph/0601514.pdf

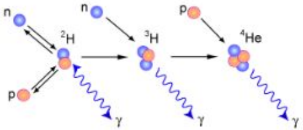
# THERMAL HISTORY OF THE UNIVERSE



| | | | |
|---|---|---|---|
| $t = 13.73\,\mathrm{Gyr}$ | | $T = 2.726\,\mathrm{K}$ | present |
| $t = 9\,\mathrm{Gyr}$ | | $T = 5\,\mathrm{K}$ | Solar system forms |
| | matter era | | structure formation |
| $t = 10^6\,\mathrm{yr}$ | | $T = 3000\,\mathrm{K}$ | recombination --> CMB |
| $t = 10^5\,\mathrm{yr}$ | | $T = 10^4\,\mathrm{K}$ | matter-radiation equality |
| | radiation era | | |
| $t = 300\,\mathrm{s}$ | BBN | | BBN = Big-Bang Nucleosynthesis |
| $t = 10\,\mathrm{s}$ | | $T = 10^9\,\mathrm{K}$ | |
| | Lepton era | | |
| $t = 10^{-4}\,\mathrm{s}$ | | $T = 10^{12}\,\mathrm{K}$ | |
| | Hadron era | | |
| $t = 10^{-6}\,\mathrm{s}$ | | $T = 10^{13}\,\mathrm{K}$ | quark-hadron phase transition |
| | Quark Soup | | |
| $t = 10^{-33}\,\mathrm{s}$ | | $T = 10^{27}\,\mathrm{K}$ | |
| | inflation | | |
| $t = 10^{-35}\,\mathrm{s}$ | | $T = 10^{28}\,\mathrm{K}$ | |
| $t = 10^{-43}\,\mathrm{s}$ | | $T = 10^{32}\,\mathrm{K}$ | |
| | ???? ???? | | Big Bang |







# PRIMORDIAL NUCLEOSYNTHESIS

Primordial nucleosynthesis takes place in the first 3 minutes of life of the Universe, and it is a crucial piece of evidence in favor of standard hot big bang model:

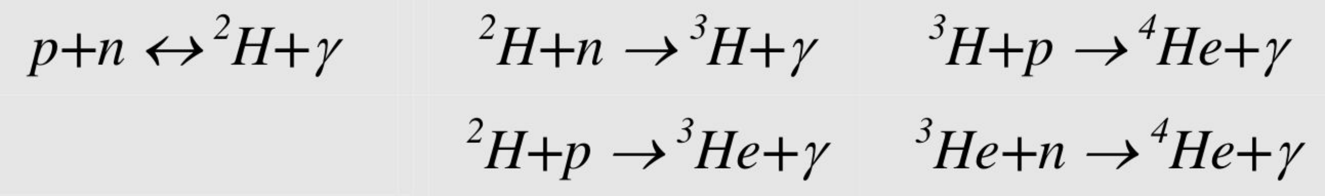
At a temperature of kT>1MeV the rate of weak interactions, $\Gamma_{n\leftrightarrow p}$, is higher than the expansion rate of the universe, H; p, n, e are in equilibrium vai the reactions:

$$\begin{aligned} e^{+} + n &\longleftrightarrow p + \bar{\nu}_e \\ \nu_e + n &\longleftrightarrow p + e^{-} \end{aligned}$$

At temperatures below 1 MeV (t~1 s), neutrinos decouple and the weak interactions are frozen out, $\Gamma_{n\leftrightarrow p} < H$; neutrons and protons cease to interconvert. The equilibrium abundance of neutrons at this temperature is about 1/6 the abundance of protons (due to the slightly larger neutron mass). The neutrons have a finite lifetime ($\tau = 890$ s) that is somewhat larger than the age of the universe at this epoch, t(1 MeV) ≈ 1 s, but they begin to gradually decay into protons and leptons ( $\beta$-decay ) until the neutron-to-proton ratio has dropped to ~1/7.

# PRIMORDIAL NUCLEOSYNTHESIS

**Protons and neutrons can combine to form $^4$He through the chain of reactions:**



| | | |
|---|---|---|
| $p+n \leftrightarrow {}^2H+\gamma$ | ${}^2H+n \rightarrow {}^3H+\gamma$ | ${}^3H+p \rightarrow {}^4He+\gamma$ |
| | ${}^2H+p \rightarrow {}^3He+\gamma$ | ${}^3He+n \rightarrow {}^4He+\gamma$ |

**The bottleneck of these reactions is the formation of Deuterium, which is destroyed by energetic photons, until their number, $n_\gamma^{diss}$, becomes comparable with the number of baryons, $n_b$, at kT~0.1 MeV (T~$10^9$ K). At this epoch, $t_{BBN}$~150s, D is not destroyed and basically all the neutrons which are not decayed forms $^4$He nuclei. The (mass) abundance of $^4$He is determined mainly by:**

- **The temperature at which neutrino decouples and the n-to-p ratio at frozen, $\Gamma_{n\leftrightarrow p} \sim H$, which in turns depends on the total number of neutrino species.**
- **The mean neutron lifetime (~889 s)**
- **The baryon-to-photon ratio , $\eta = n_b / n_\gamma = 2.7 \times 10^{-8}\, \Omega_b h^2$ , which determines $t_{BBN}$**

# PRIMORDIAL NUCLEOSYNTHESIS

**Further reactions lead to the formation of $^{7}$Li:**

$$^{4}He + {}^{3}H \leftrightarrow {}^{7}Li + \gamma \qquad {}^{4}He + {}^{3}He \leftrightarrow {}^{7}Be + \gamma \qquad {}^{7}Be + \gamma \leftrightarrow {}^{7}Li + p$$

**with a relative abundance compare to the hydrogen of ~$10^{-9}$ - $10^{-10}$. Heavier elements cannot be synthesized because:**

**- There are no stable isotopes with mass numbers 5 or 8, in particular $^{8}$Be is unstable.**

**- The density and temperature is too low for the triple-alpha process that could form $^{12}$C to occur.**

**All the other heavier elements (C, N, O, Fe) are formed by thermonuclear processes inside stars**

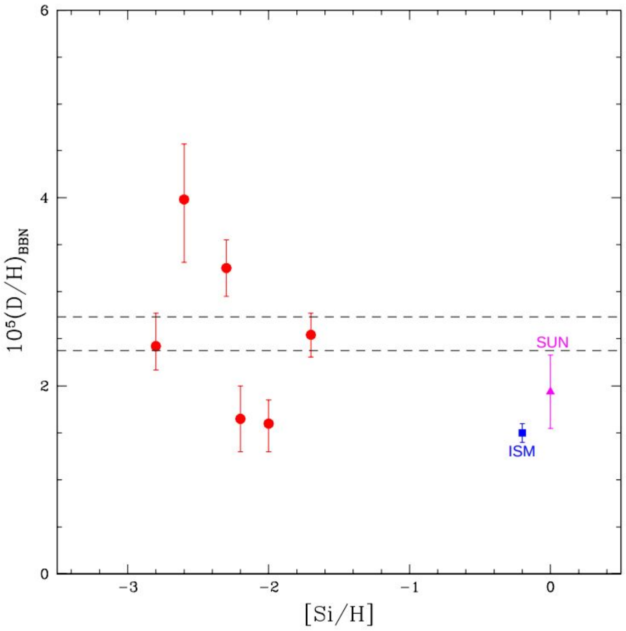
# PRIMORDIAL NUCLEOSYNTHESIS

**Deuterium is the baryometer of choice since its post-BBN evolution is simple (and monotonic!):**

**There are no astrophysical process that produce D and, as the most weakly bound of the light nuclides, any deuterium cycled through stars is burned to 3He. Thus, deuterium observed anywhere, anytime, should provide a lower bound to the primordial D abundance.**

**For "young" systems at high redshift and/or with very low metallicity, which have experienced very limited stellar evolution, the observed D abundance should be close to the primordial value.**

**Thus, although there are observations of deuterium in the solar system and the interstellar medium (ISM) of the Galaxy which provide interesting lower bounds to the primordial abundance, it is the observations of relic D in a few, high redshift, low metallicity, quasars absorption line systems which are of most value in enabling estimates of its primordial abundance**



Deuterium abundance in intergalactic neutral hydrogen clouds at high redshift (observed as absorption lines in quasar spectra). Dashes lines indicate what is expected from WMAP CMB analysis.

# PRIMORDIAL NUCLEOSYNTHESIS

- Observations of $^3$He, are restricted to the solar system and HII region of our Galaxy. The post-BBN evolution of $^3$He, involving competition among stellar production, destruction, and survival, is considerably more complex and model dependent than that of D.

- The post-BBN evolution of $^4$He is quite simple. As gas cycles through generations of stars, hydrogen is burned to helium-4 (and beyond), increasing the $^4$He abundance above its primordial value.  The key data for inferring its primordial abundance are provided by observations of helium and hydrogen emission (recombination) lines from low-metallicity, extragalactic H II regions

- In the post-BBN universe $^7$Li is produced in the Galaxy by cosmic ray spallation and (at least in some) stars. Therefore, in order to probe the BBN yield of $^7$Li, it is necessary to restrict attention to the oldest, most metal-poor halo stars in the halo of our galaxy

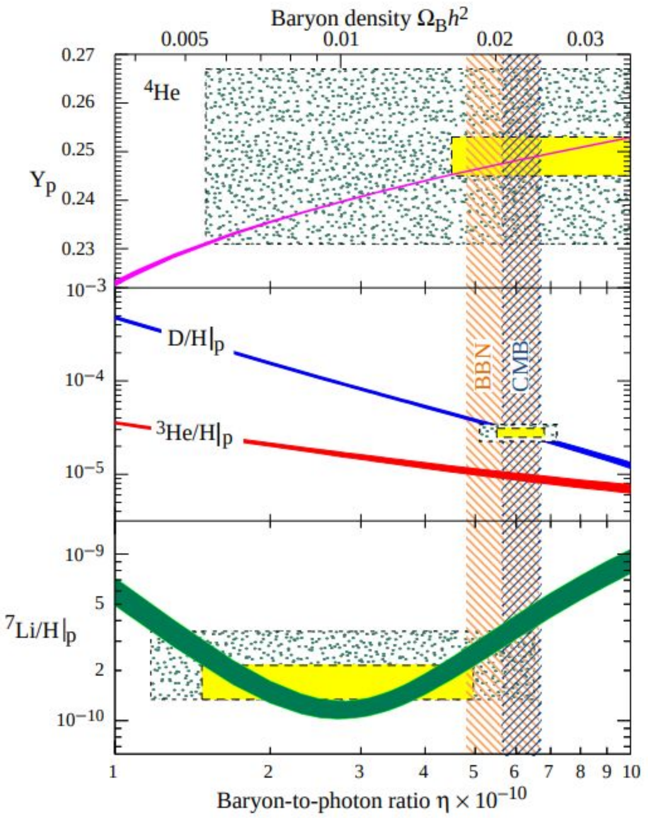


**Figure 1.1:** The abundances of $^4$He, D, $^3$He and $^7$Li as predicted by the standard model of big-bang nucleosynthesis. Boxes indicate the observed light element abundances (smaller boxes: $2\sigma$ statistical errors; larger boxes: $\pm 2\sigma$ statistical and systematic errors). The narrow vertical band indicates the CMB measure of the cosmic baryon density. See full-color version on color pages at end of book.