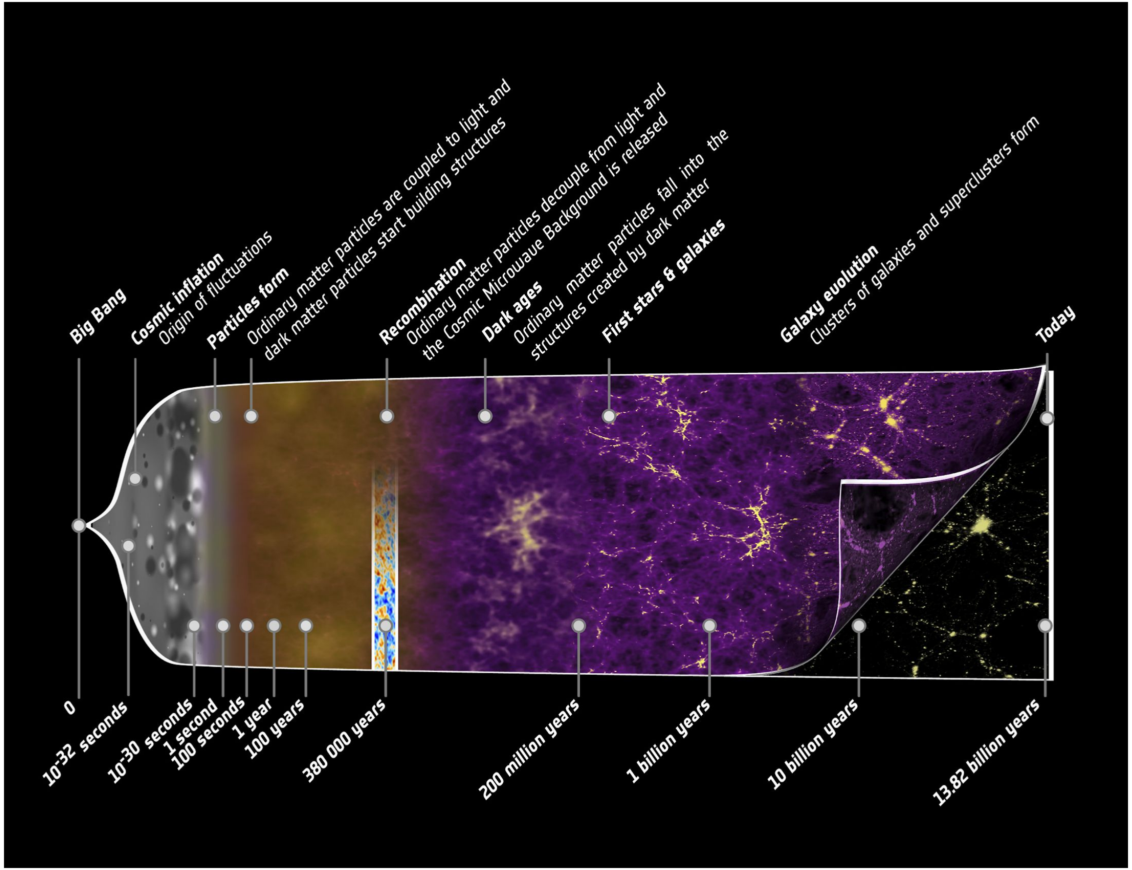
Seminar:

PRECISION COSMOLOGY

10 June 2021 | Matteo Costanzi - University of Trieste / INAF

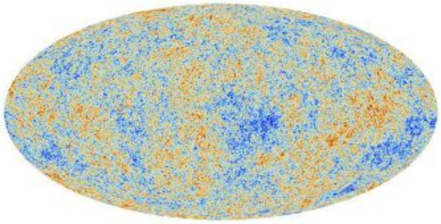
GENERAL FRAMEWORK: ΛCDM MODEL



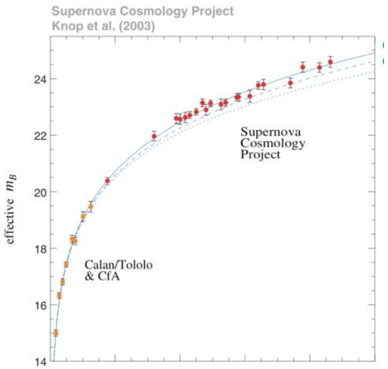
ASSUMPTION OF ΛCDM:

- 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 (Λ)

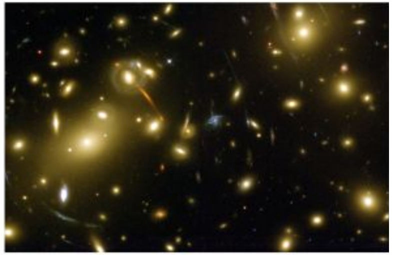
GENERAL FRAMEWORK: COSMOLOGICAL PROBES



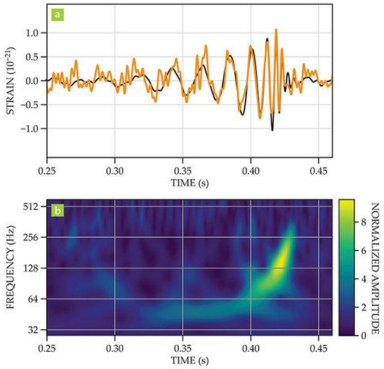
Cosmic Microwave Background and its fluctuations



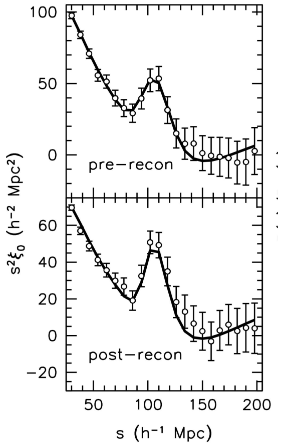
Hubble Diagram (with SNIa)

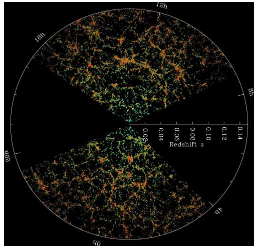


Gravitational lensing

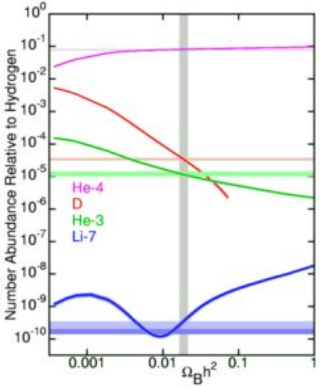


Gravitational waves

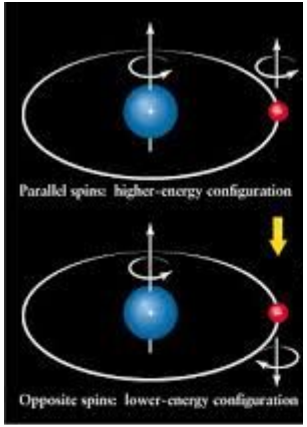




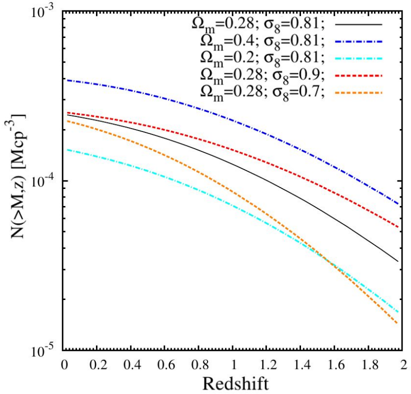
Galaxy Surveys, BAO & RSD



Big Bang nucleosynthesis



21cm Cosmology



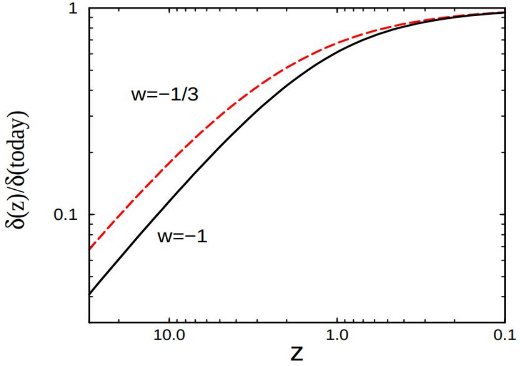
Cluster Cosmology

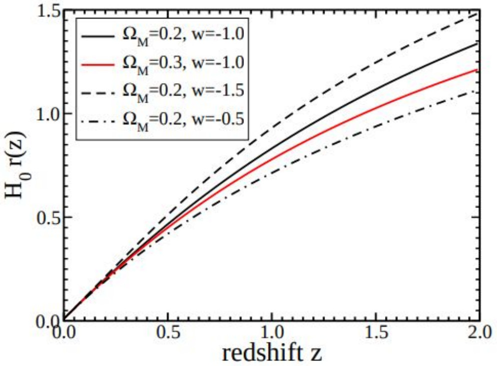
GENERAL FRAMEWORK

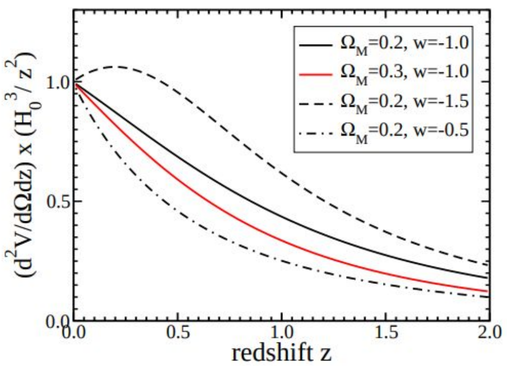
- **What can we measure with cosmological probes:**

Growth of density perturbation

Expansion history

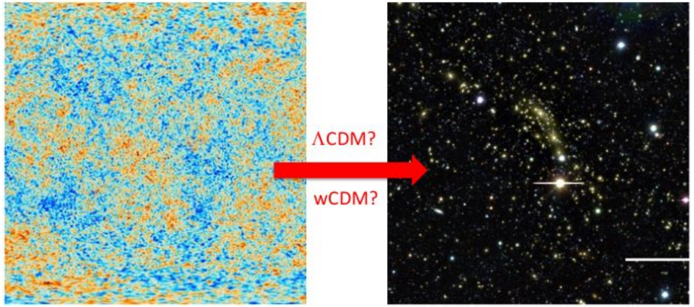






Freiman+08

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

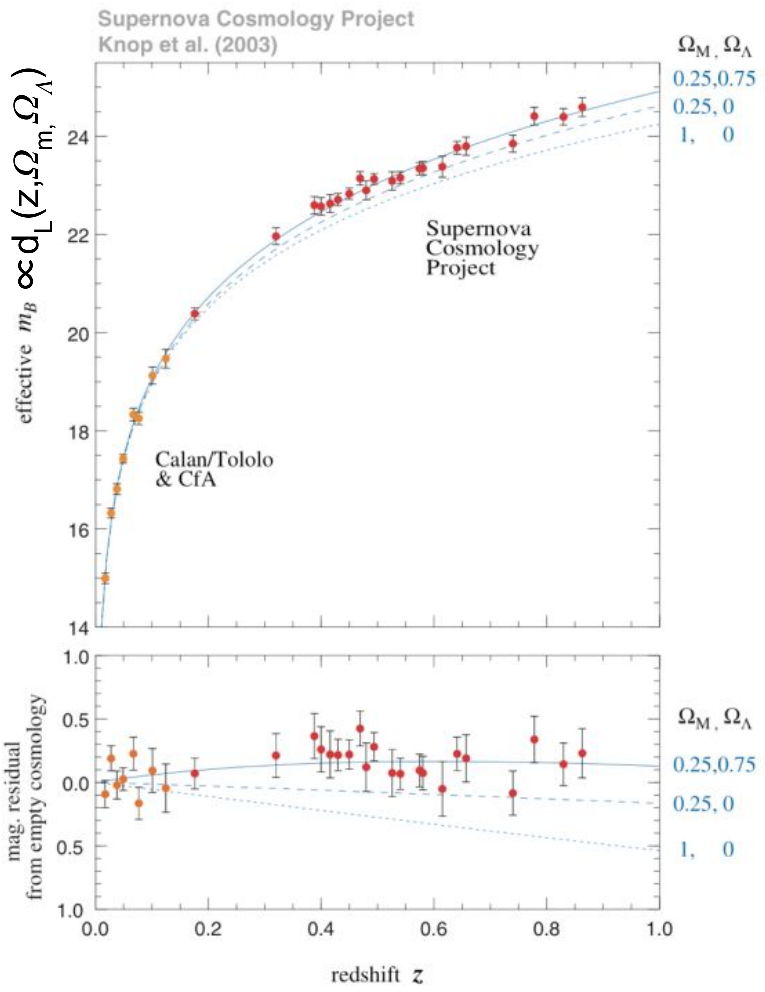
Structure at 13.8 billion years – density contrasts > 10^3

STANDARD CANDLES (SNIa)

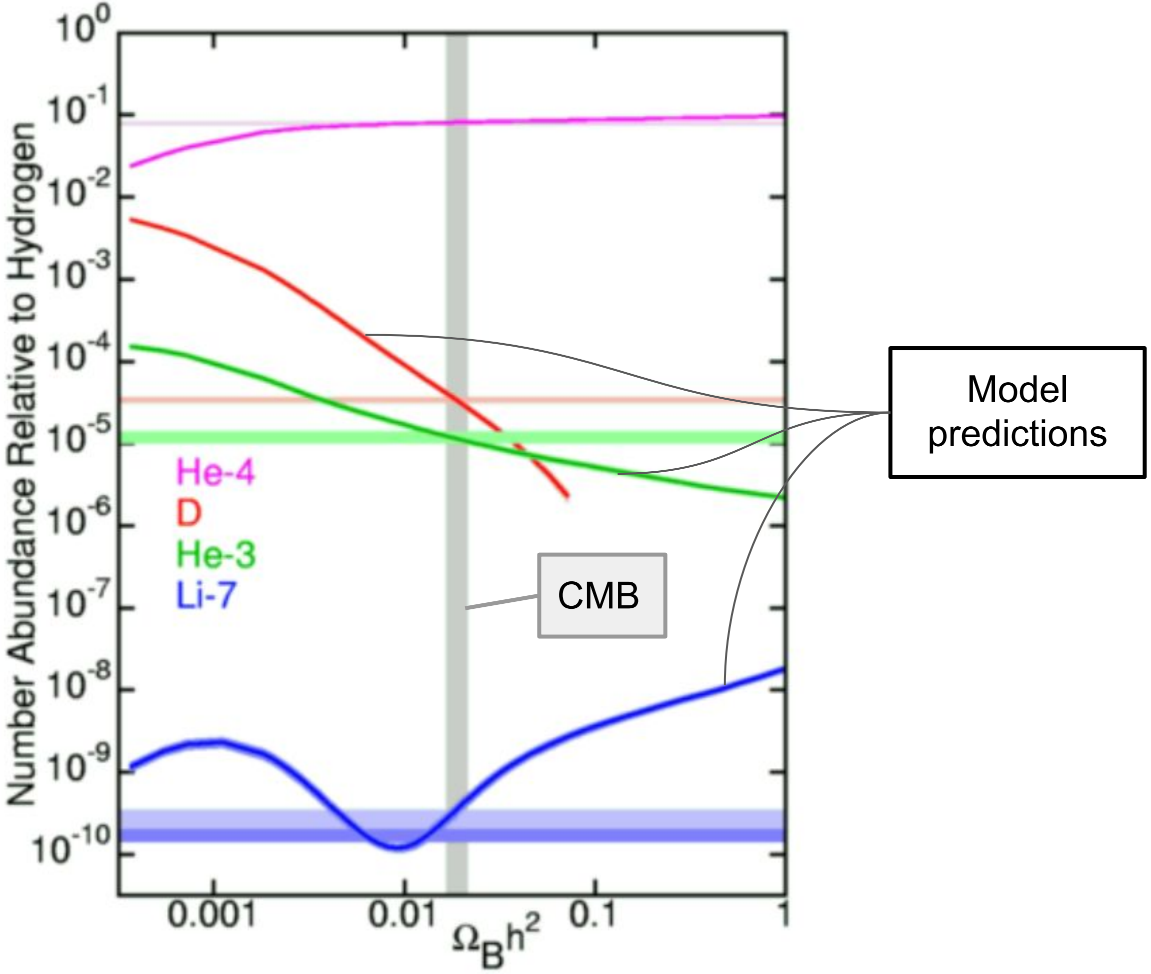
Hubble diagram
(with distand SNe)

$m_1 - m_2 = 2.5 \log10 (f_2/f_1)$

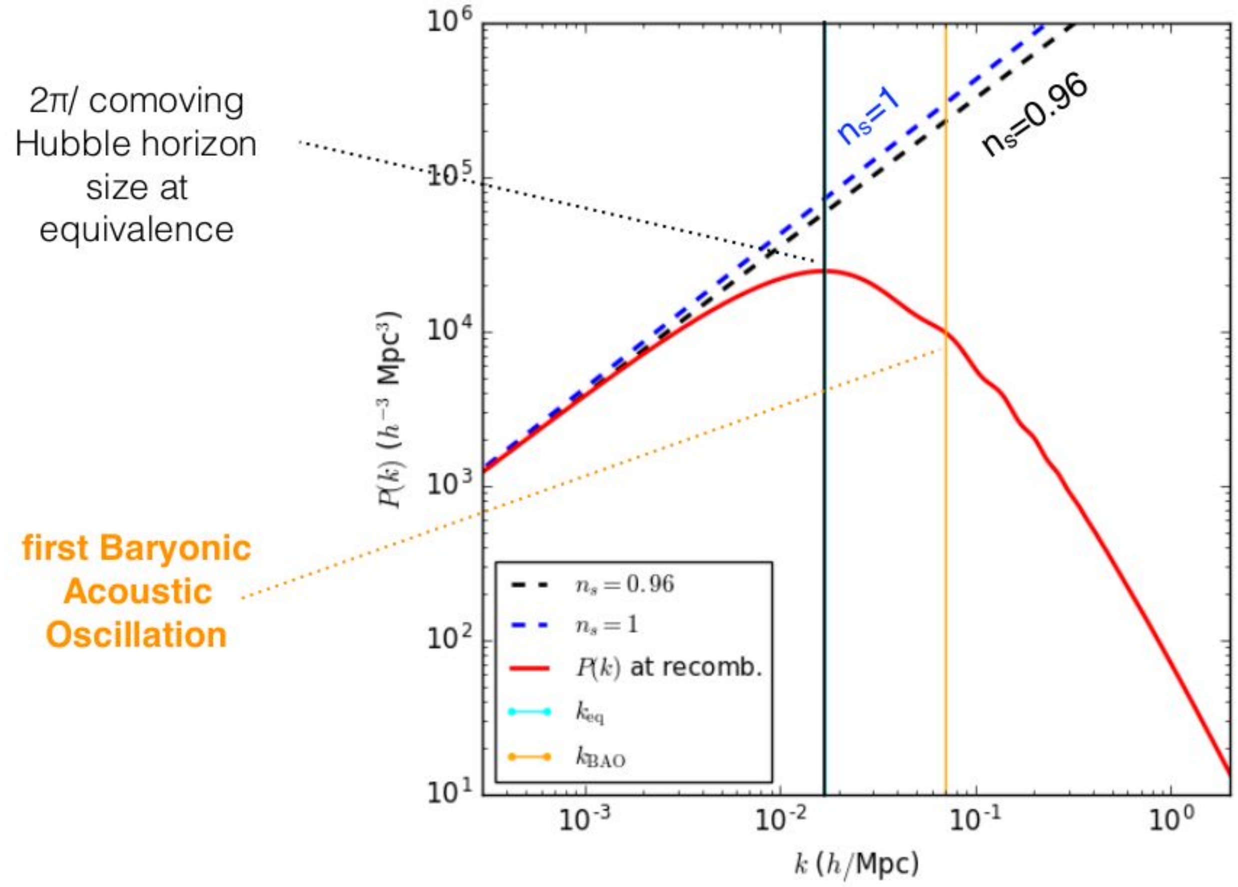
$m - M = 5 \log10 (d_L / 10pc)$



Big Bang Nucleosynthesis



The perturbed Universe



Overdensity field

$$\delta(x) = \frac{\rho(x) - \bar{\rho}}{\bar{\rho}}$$

2 pt. Correlation Function

$$\xi(r) = \langle \delta(x)\delta(x+r) \rangle$$

$\mathscr{F}$ $\mathscr{F}^{-1}$

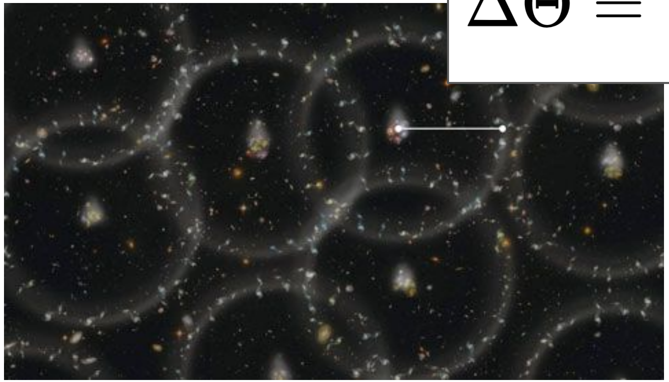
Power spectrum

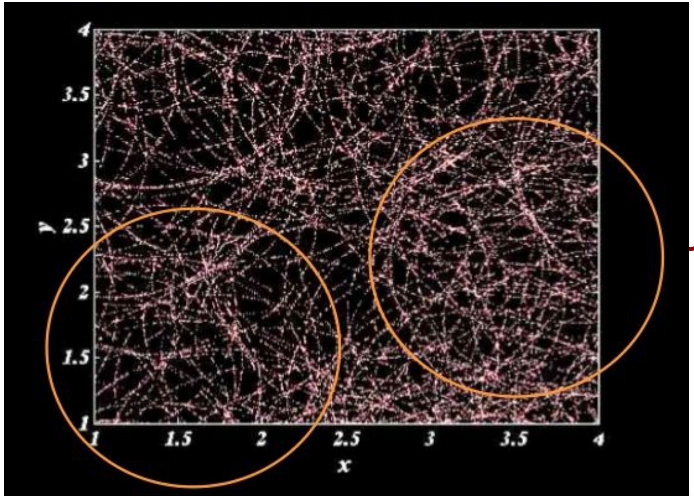
$$P(k) = \langle \tilde{\delta}(k)\tilde{\delta}^*(k') \rangle$$

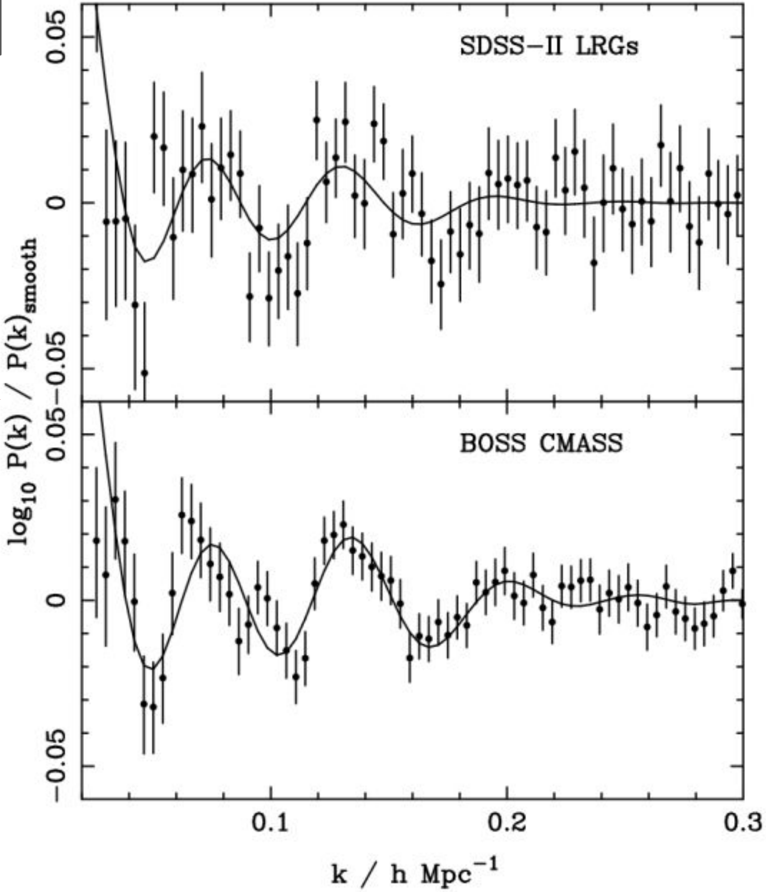
STANDARD RULER (BAO)

$$\Delta\Theta = \frac{R}{d_a(z)}$$

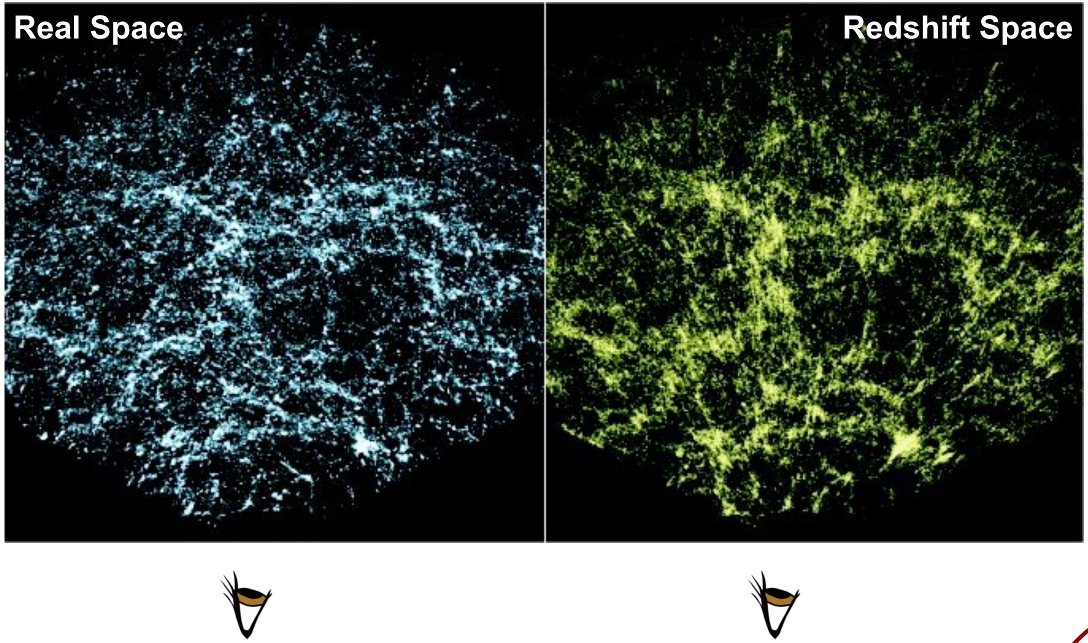
Baryonic acoustic oscillations





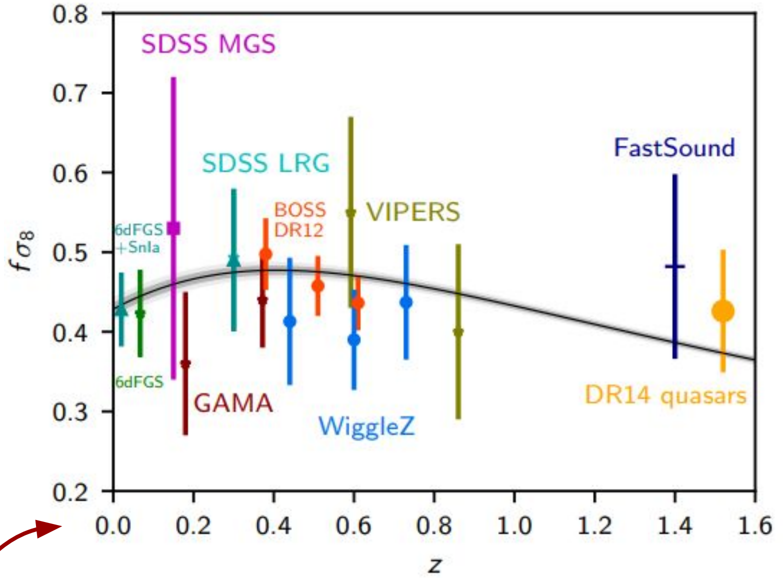


REDSHIFT SPACE DISTORTIONS



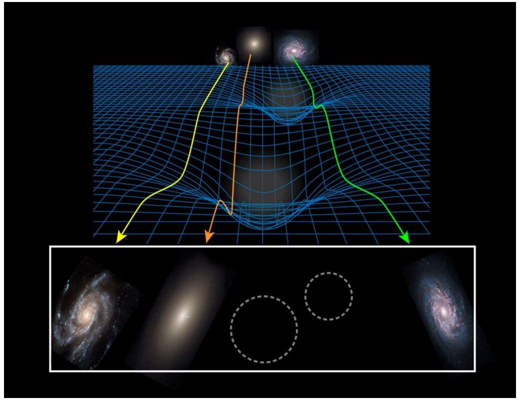
f = growth rate

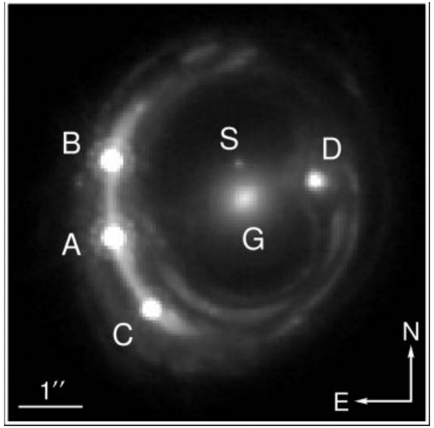
σ_8 = amplitude matter power spectrum on 8 Mpc/h scale

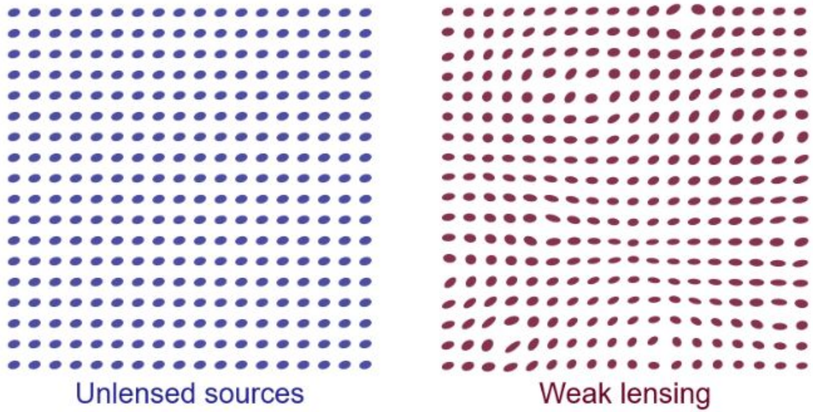


$$r_{\parallel}^{\mathrm{obs}} = r_{\parallel}^{\mathrm{true}} + \frac{v_{\mathrm{pec}}}{aH}$$

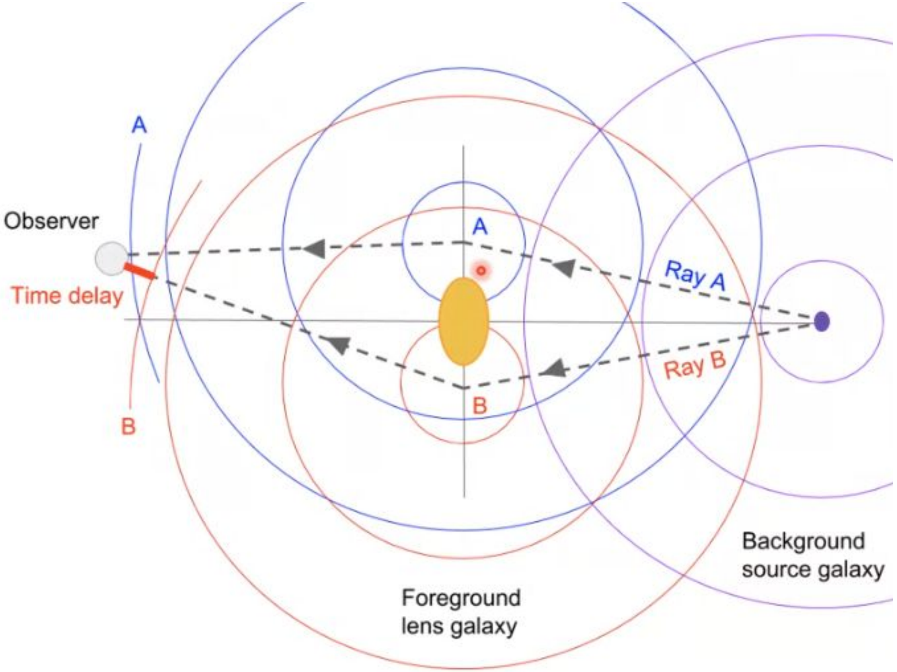
Gravitational (strong and weak) lensing



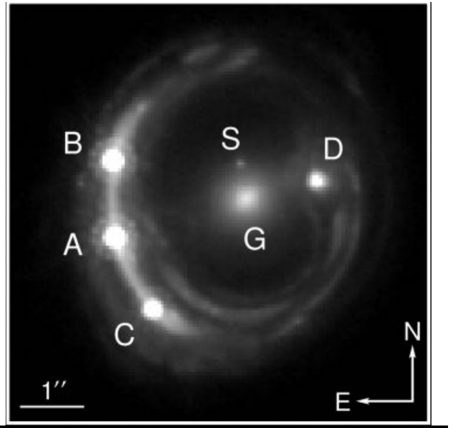




Time delay cosmography



Credit: Tommaso Treu



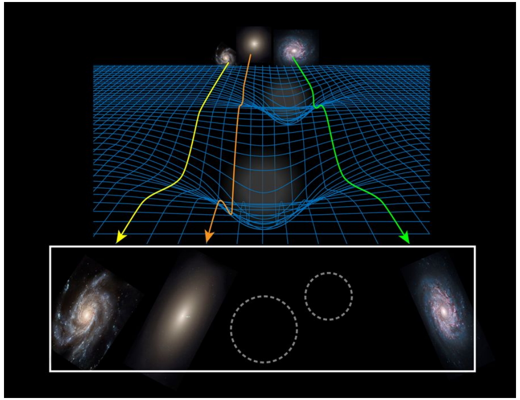
Time delay distance in practice

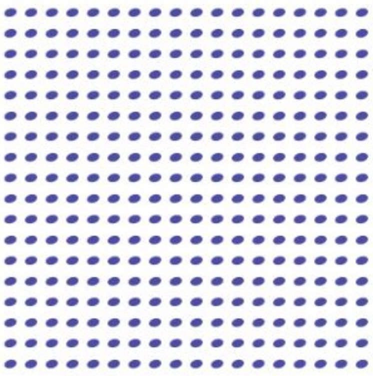
$$\Delta t \propto D_{\Delta t}(z_s, z_d) \propto H_0^{-1} f(\Omega_m, w, ...)$$

Steps:

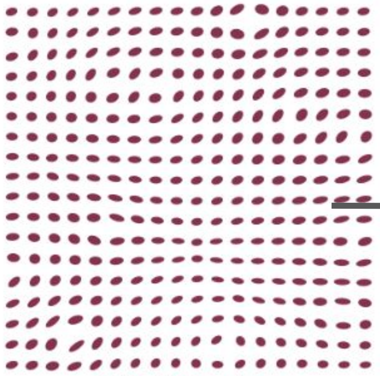
- Measure the time-delay between two images
- Measure and model the potential
- Infer the time-delay distance
- Convert it into cosmlogical parameters

Gravitational (strong and weak) lensing

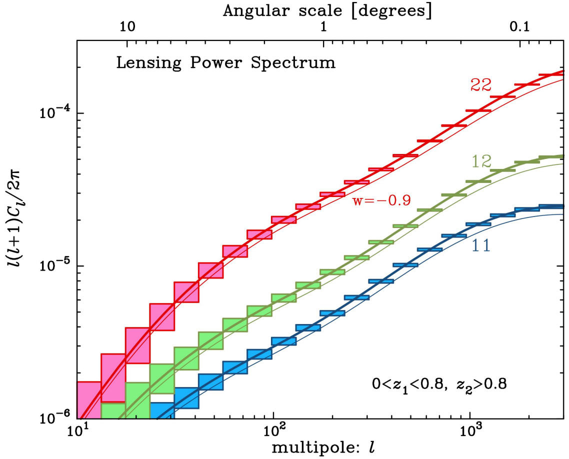




Unlensed sources



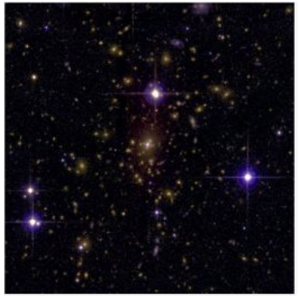
Weak lensing



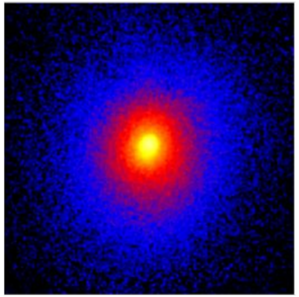
CLUSTER COSMOLOGY

- **Most massive bound objects in the Universe**:
  $M \simeq 10^{13} - 10^{15}\, M_\odot$ and $R \simeq 1 - 5$ Mpc
- **Multi-component systems**:
  galaxies and stars (~5%), ICM (~15%), DM (~80%)

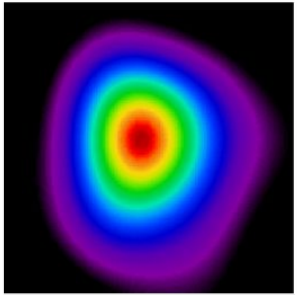
OPTICAL



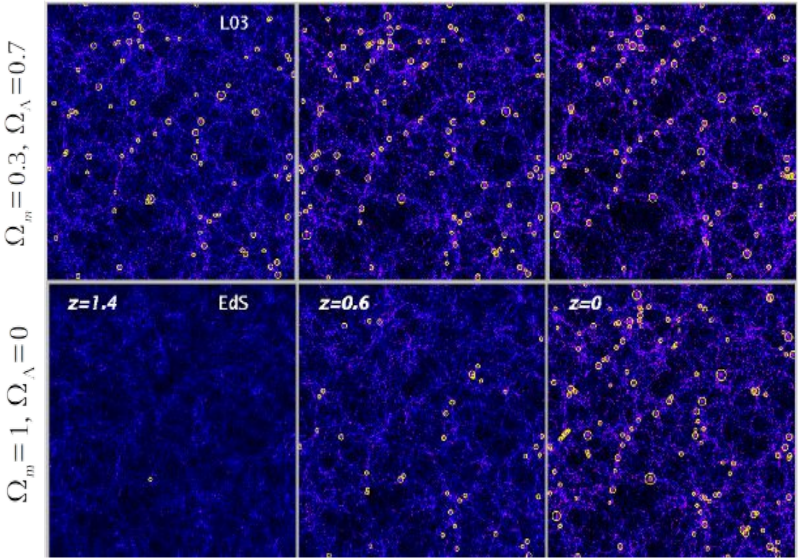
X-RAYS



MICROWAVES



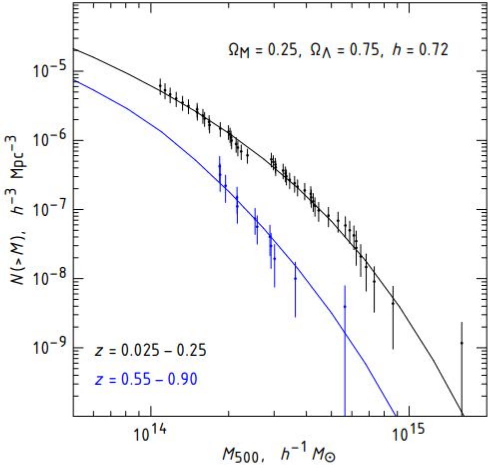
Evolution of the clusters population in 2 simulations

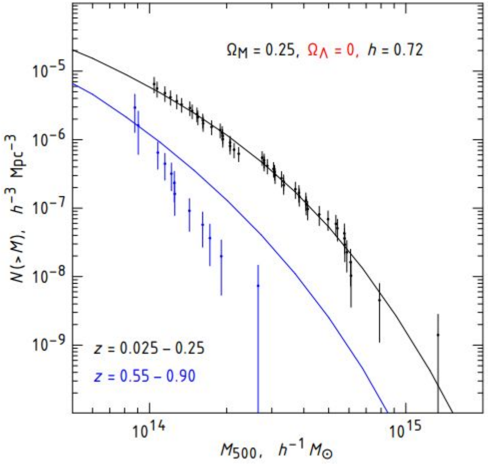


time

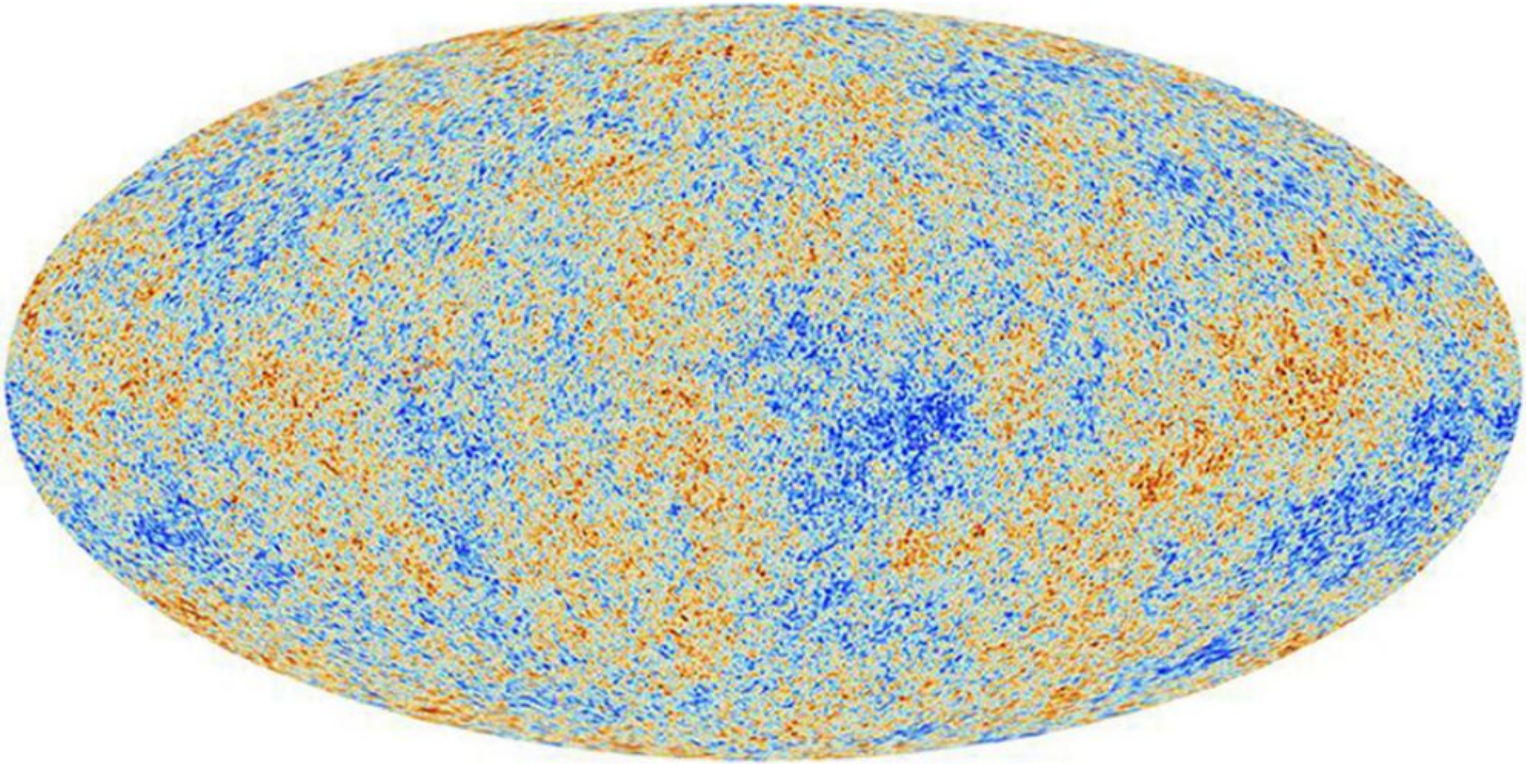
From Borgani, Guzzo 2001

Cluster mass function:



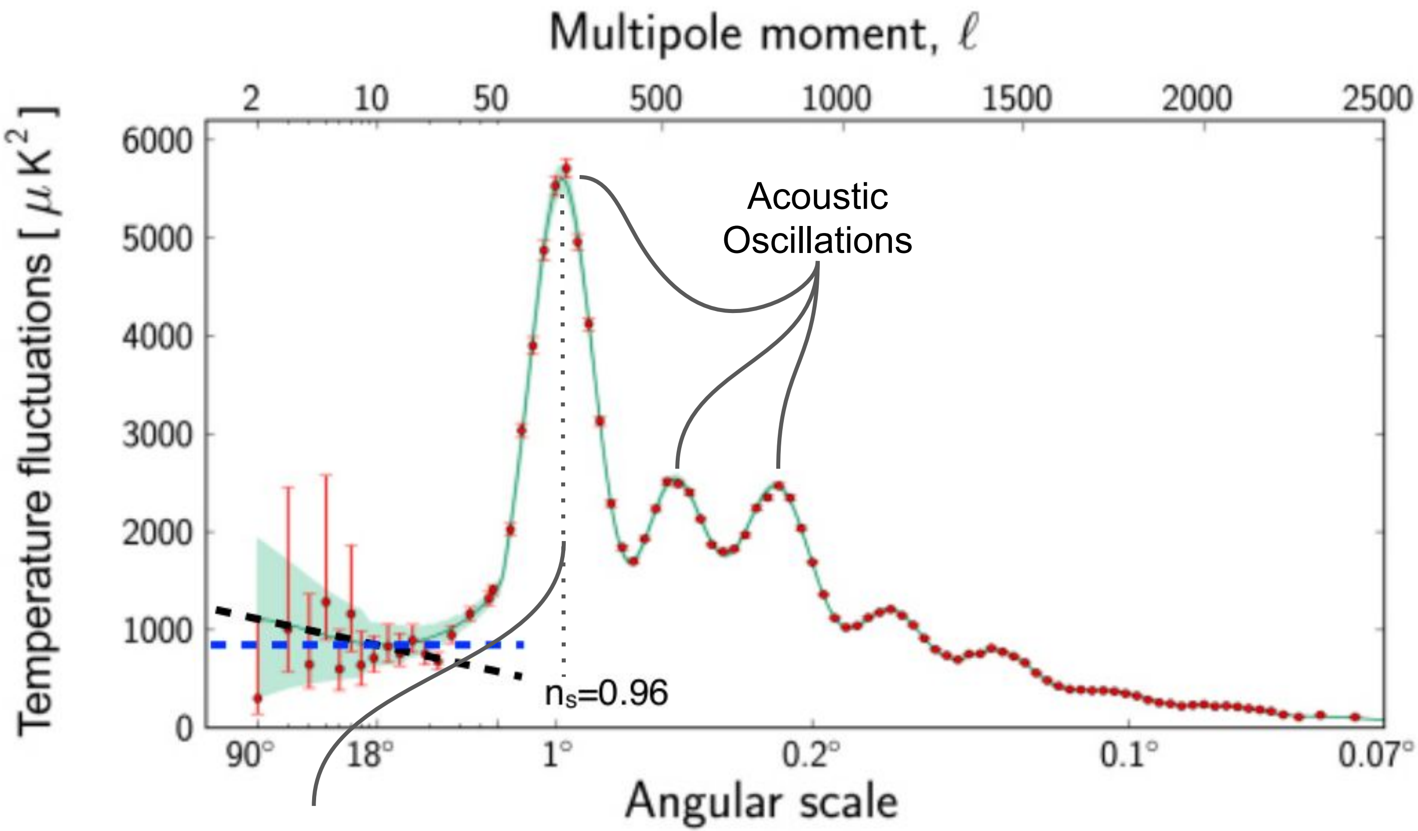


Credits: Vikhlinin+ 2009



Cosmic Microwave
Background and
its fluctuations

CMB Temperature Fluctuation power spectrum

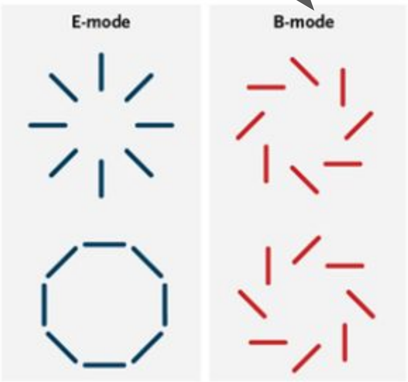


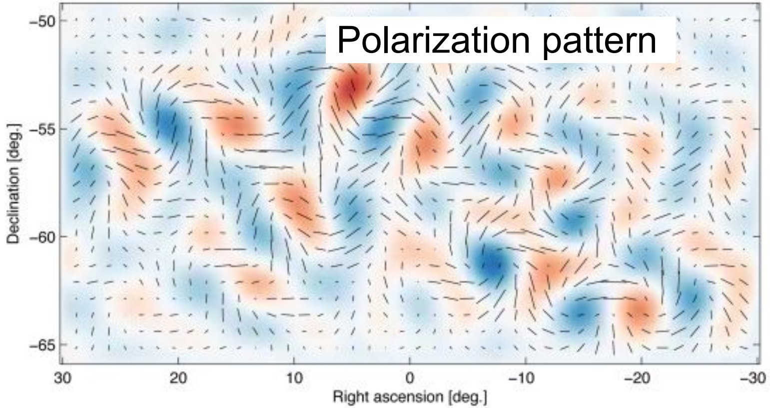
size Hubble radius @ decoupling

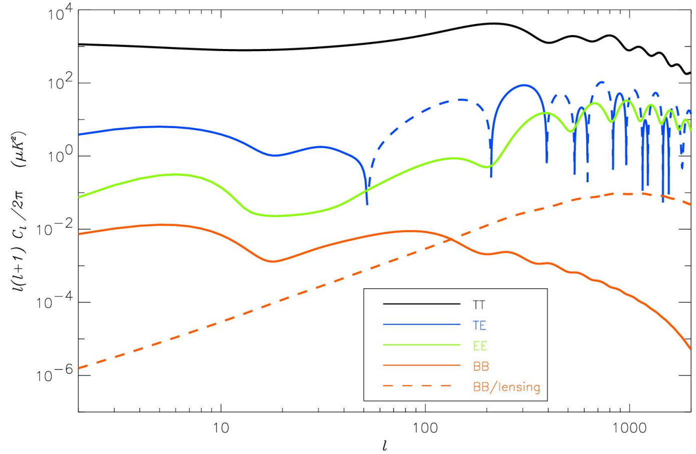
CMB polarization

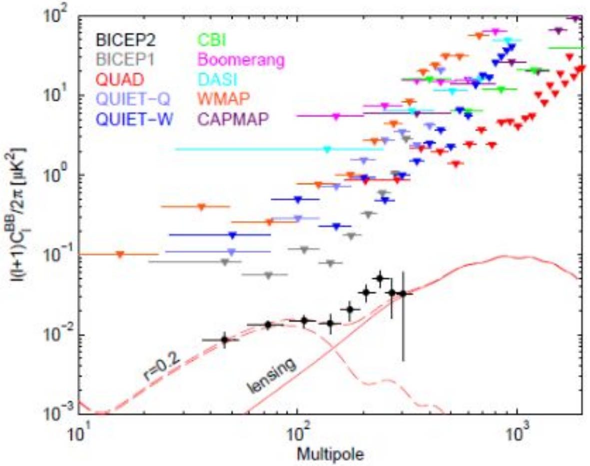
From primordial gravitational waves or lensing

From acoustic density perturbations

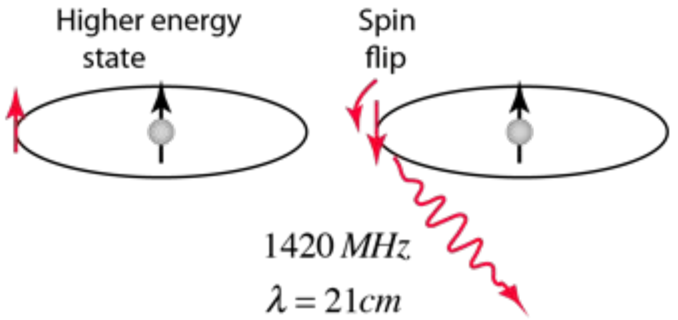


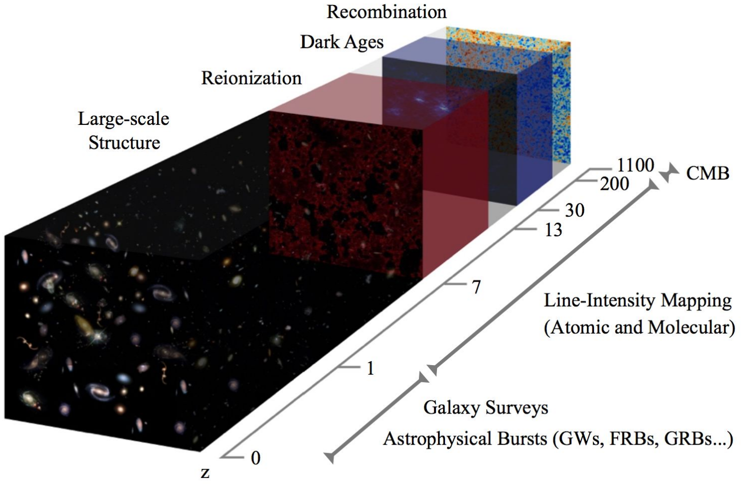




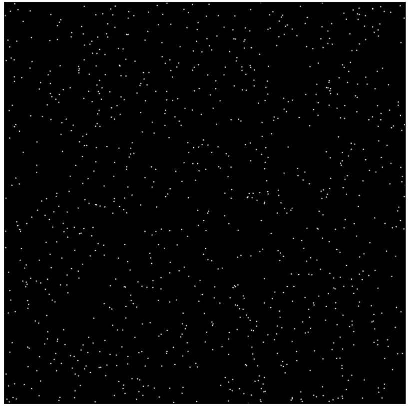


21cm COSMOLOGY

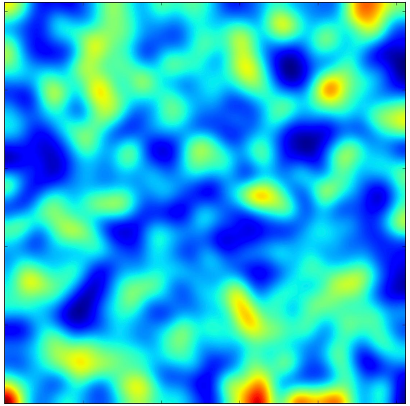




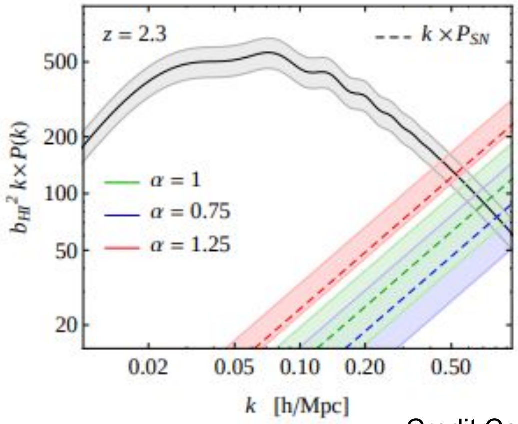
Galaxy distribution



21cm intensity map



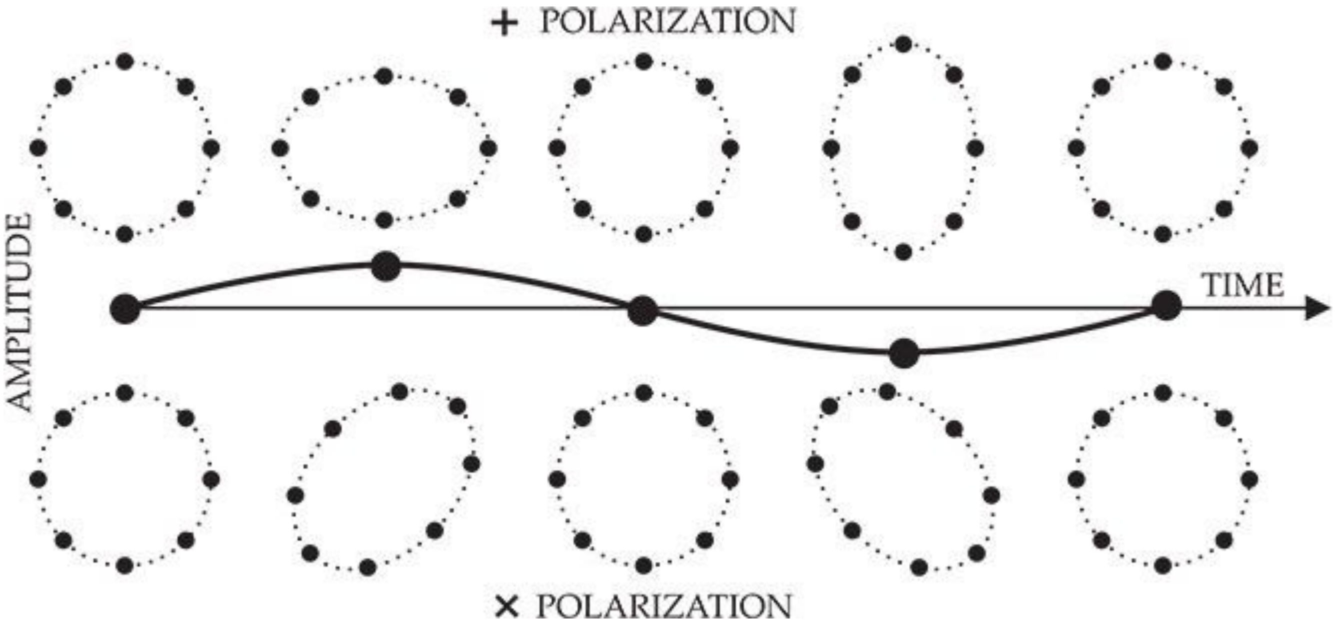
HI power spectrum



Credit Castorina+2016

GRAVITATIONAL WAVES:

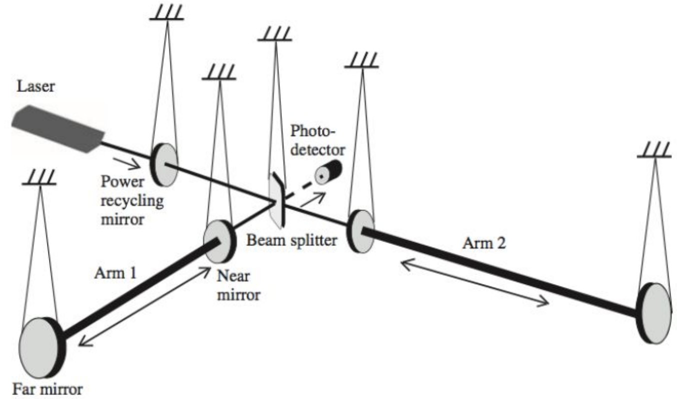
$$\left(-\frac{\partial^2}{\partial t^2} + \nabla^2\right)\bar{h}^{\alpha\beta} = 0.$$

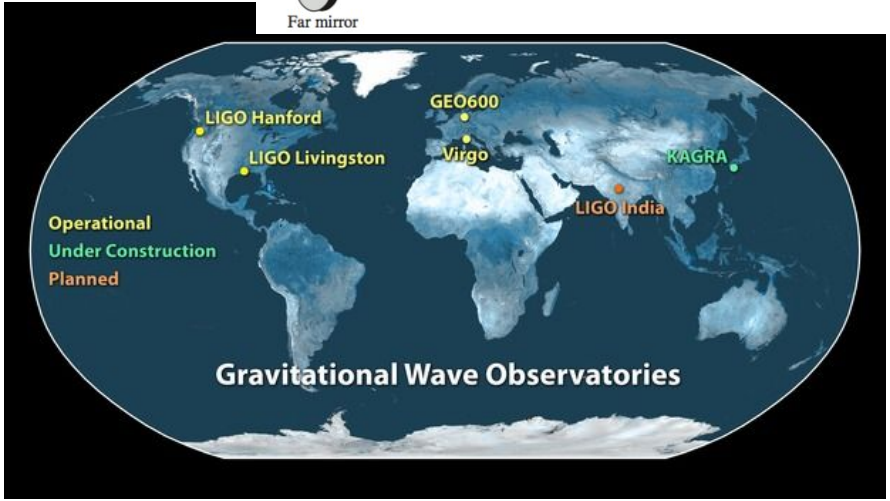


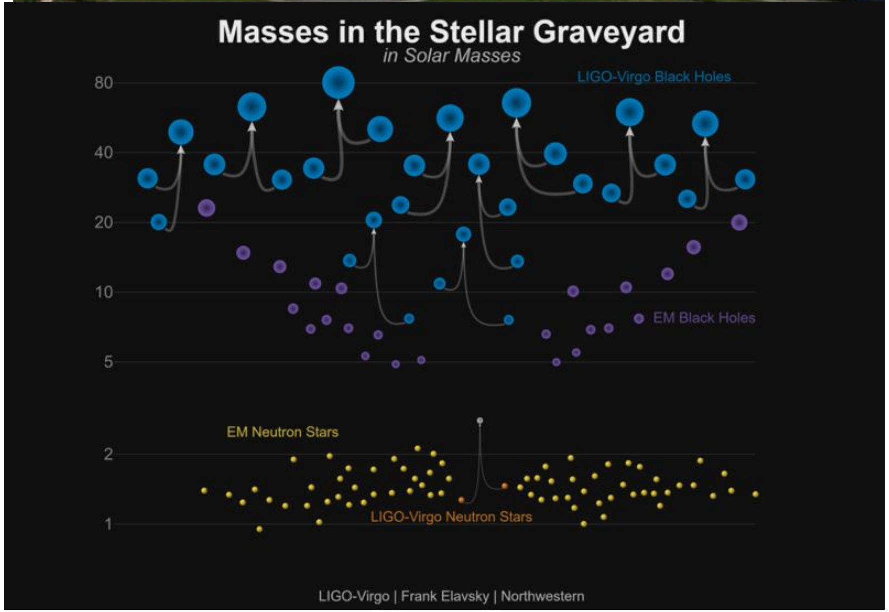
Typical relative deformation:

$$h = \frac{\Delta l}{l} \sim 10^{-21}$$

Laser Interferometer Gravitational-Wave Observatory (LIGO): l~4km → Δl~10^{-16}cm







STANDARD SIRENS:

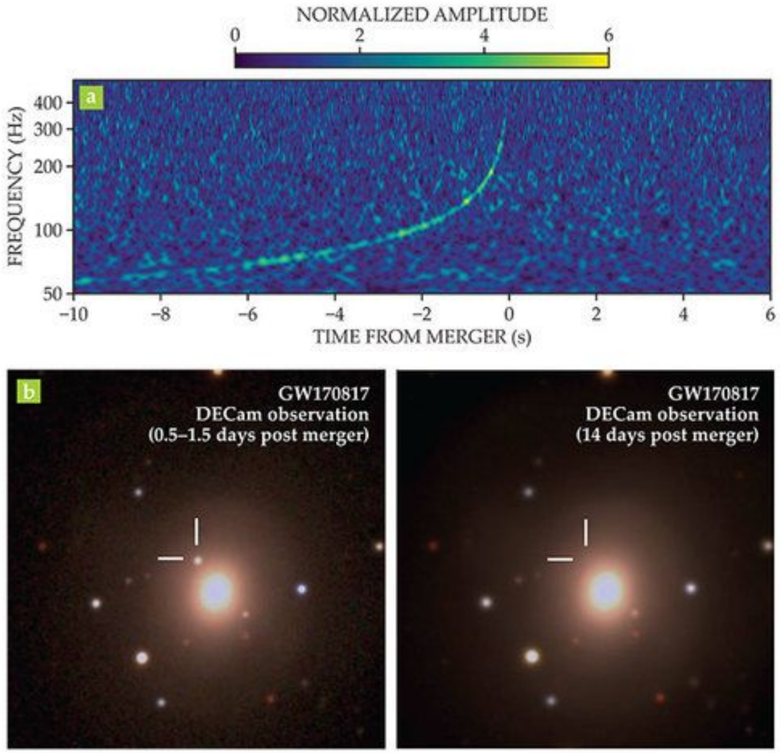
Wave's frequency sweep and amplitude depend on $\mathscr{M} = (m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5}$, and luminosity distance:

$$\frac{d\Omega}{dt} \propto \left(\frac{G\mathcal{M}}{c^3}\right)^{5/3}$$

$$h \propto \frac{1}{D_L}\left(\frac{G\mathcal{M}}{c^3}\right)^{5/3}\Omega^{2/3}$$

- GW170817: Ns-Ns merger

EM transient observed in coincidence with the GW event → Host galaxy identified (NGC 4993)



Cosmography with GW

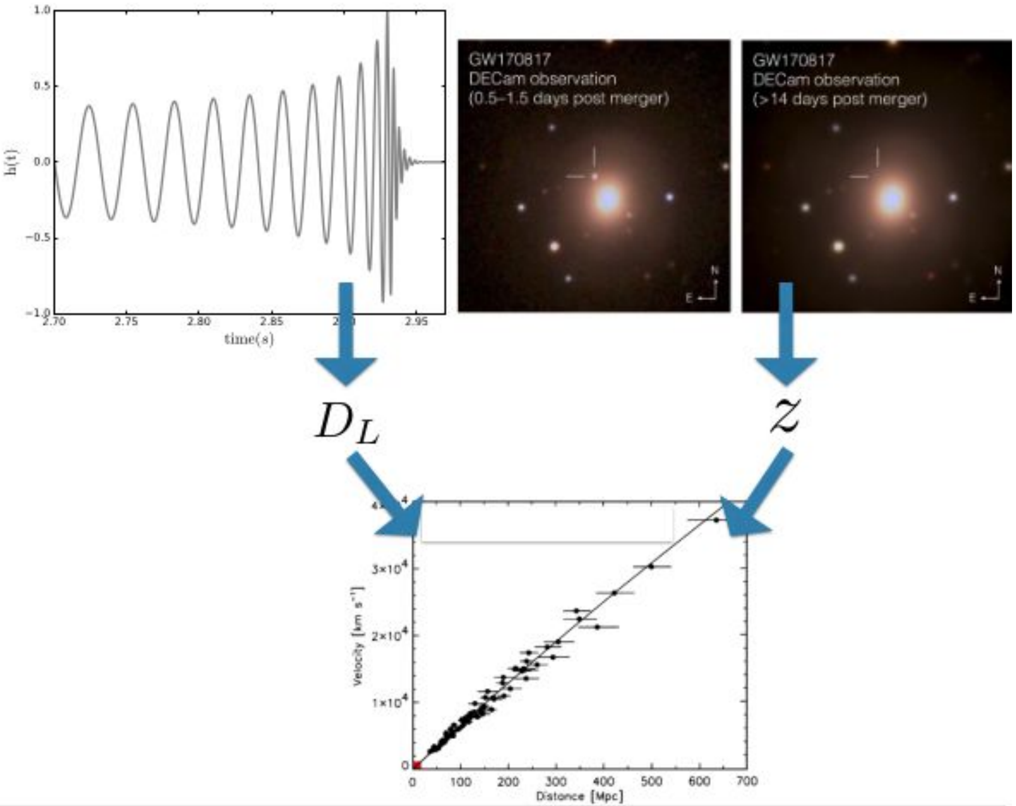
- GW are "self-calibrating" sources (Schutz 1986)

$$h \sim D_L^{-1}$$

  - Direct measurement of luminosity distance
  - "Standard sirens"

- In general, no redshift from GWs (Krolak & Schutz 1987)

$$m_{obs} = m_{src}(1+z)$$



GW170817

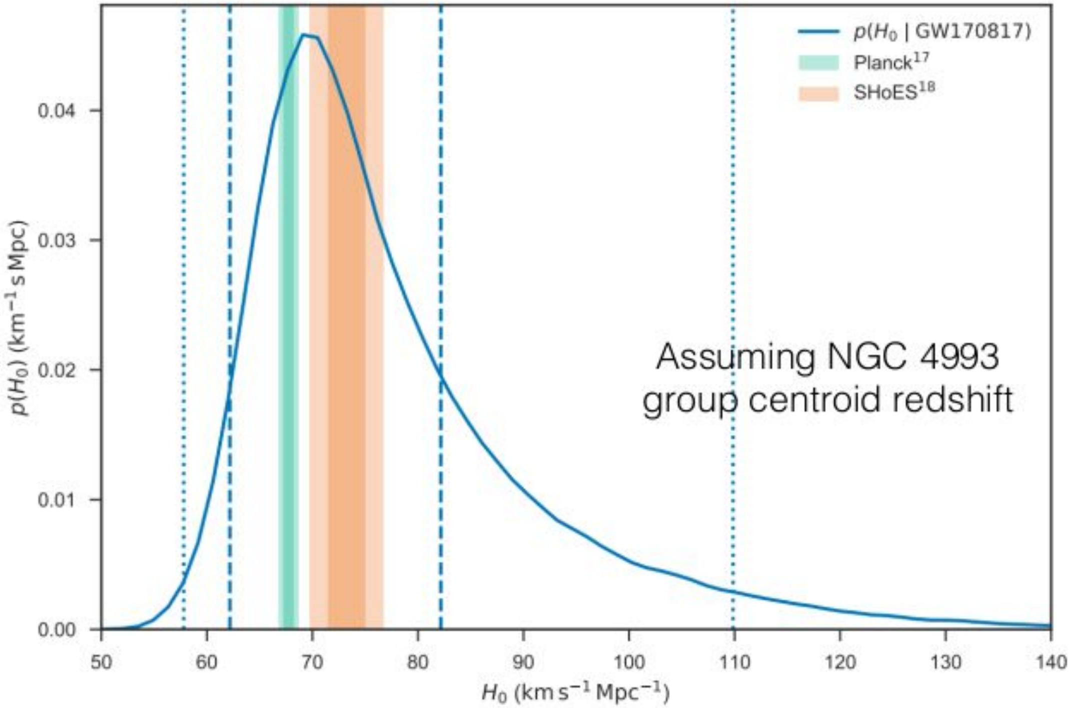
- From GW alone

$$D_L = 44^{+3}_{-7}\,\mathrm{Mpc}$$

- NGC 4993

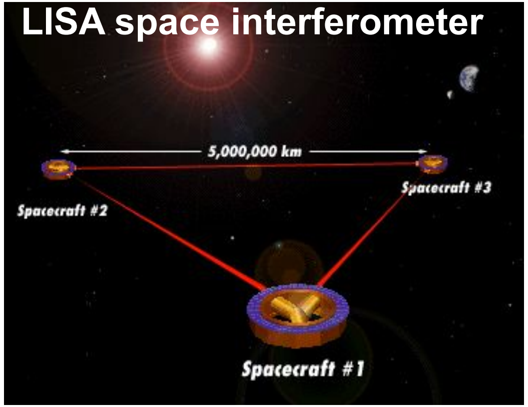
$$z = 0.0098$$

$$H_0 = 70^{+12}_{-8}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$



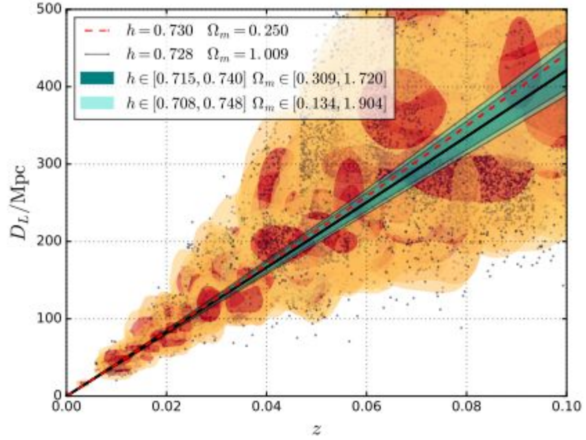
LVC, arXiv:1710.05835

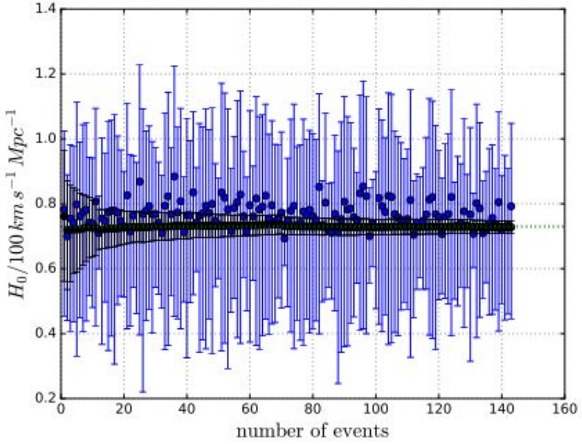
H_0 FROM sBH MERGER



run	LISA design	$\mathcal{R}$ [$yr^{-1}Gpc^{-3}$]	N_{BHB}	$h(68\%)$
$A2_{10}$	N2A2M5L6	12	7	$0.716^{+0.052}_{-0.050}$
$A2_{50}$	N2A2M5L6	34	22	$0.734^{+0.037}_{-0.033}$
$A2_{90}$	N2A2M5L6	70	39	$0.726^{+0.026}_{-0.024}$
$A5_{10}$	N2A5M5L6	12	55	$0.730^{+0.021}_{-0.020}$
$A5_{50}$	N2A5M5L6	34	143	$0.728^{+0.013}_{-0.012}$
$A5_{90}$	N2A5M5L6	70	259	$0.731^{+0.010}_{-0.009}$

Table 1. For each of the instrumental configurations and coalescence rates considered, we report the number of sources observed as well as the 68% credible intervals over h averaged over 10 realisations of the galaxy hosts.



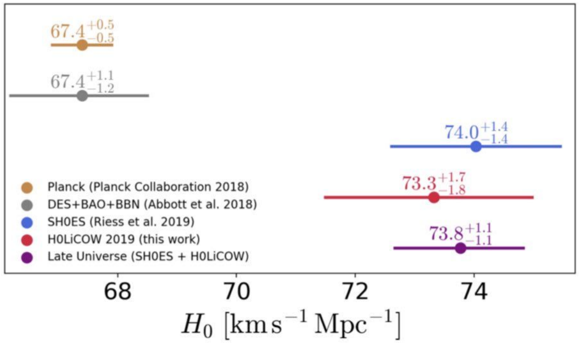


ΛCDM: CURRENT STATUS

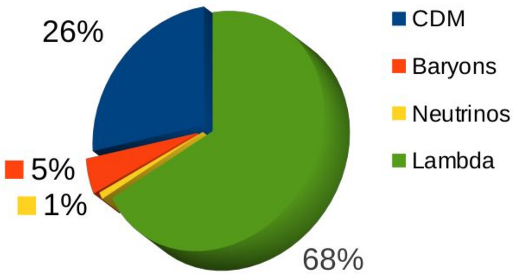
Several cosmological probes point towards a consistent model of flat ΛCDM, but the two dominants components of this model lack a fundamental theory to connect them with the rest of physics:

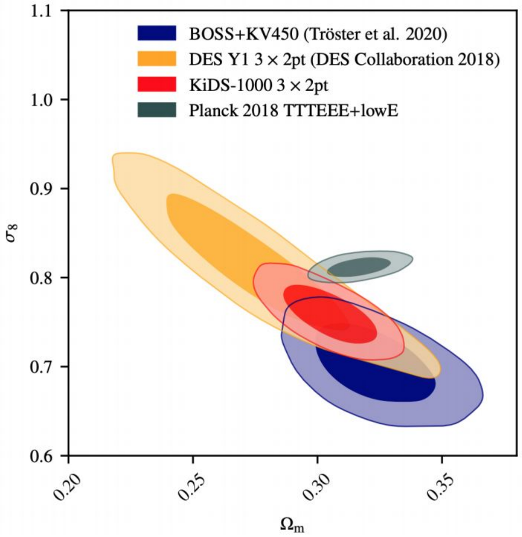
- What is the nature of Dark Matter?
- What is the cause of observed cosmic acceleration?
  - Is it Dark Energy or a modification of general relativity?
  - If it is Dark Energy, is it constant (ΛCDM) or evolving (wCDM)?

Moreover, 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)



The ΛCDM universe

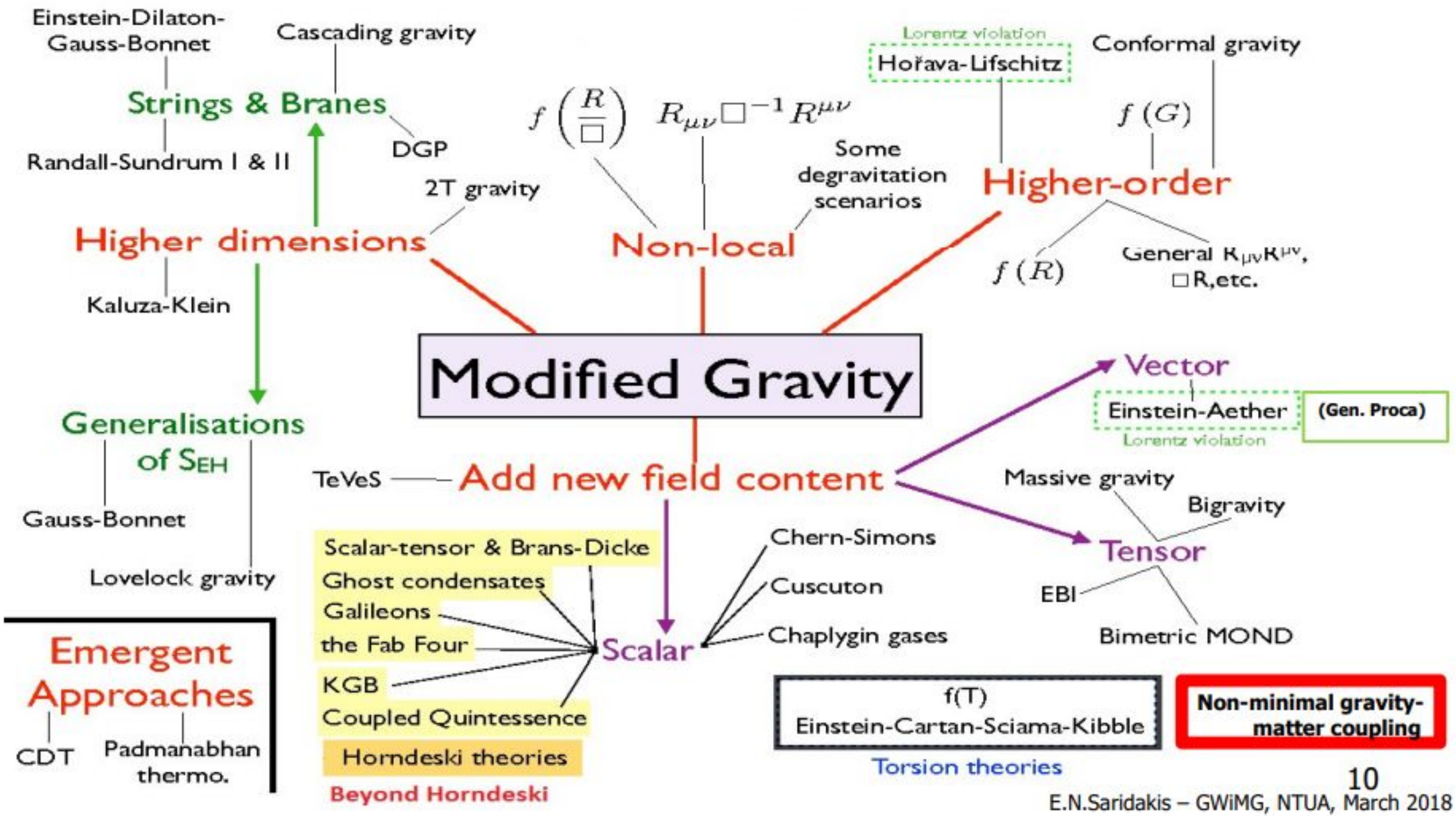




What is dark energy? (R. Bean, arXiv:1003.4468)

Problems with cosmological constant Λ:

- unexplained constant (…but G?)
- fine tuning to have it dominating now (z~0.5), or: $t_{\Lambda} = 1/c\sqrt{\Lambda} \sim H_0^{-1}$
- unnatural value if it is vacuum energy of a field
- string cosmology: 10^{500} vacuum configurations + anthropic principle, but it is predictive?


Modified Gravity
Higher dimensions
Strings & Branes
Einstein-Dilaton-Gauss-Bonnet
Cascading gravity
Randall-Sundrum I & II
DGP
2T gravity
Kaluza-Klein
Generalisations of S_{EH}
Gauss-Bonnet
Lovelock gravity
Non-local
$f\left(\frac{R}{\Box}\right)$
$R_{\mu\nu}\Box^{-1}R^{\mu\nu}$
Some degravitation scenarios
Higher-order
Lorentz violation
Hořava-Lifschitz
Conformal gravity
$f(G)$
$f(R)$
General $R_{\mu\nu}R^{\mu\nu}$, $\Box R$, etc.
Add new field content
TeVeS
Vector
Einstein-Aether
(Gen. Proca)
Lorentz violation
Tensor
Massive gravity
Bigravity
EBI
Bimetric MOND
Scalar
Scalar-tensor & Brans-Dicke
Ghost condensates
Galileons
the Fab Four
KGB
Coupled Quintessence
Horndeski theories
Beyond Horndeski
Chern-Simons
Cuscuton
Chaplygin gases
Emergent Approaches
CDT
Padmanabhan thermo.
f(T)
Einstein-Cartan-Sciama-Kibble
Torsion theories
Non-minimal gravity-matter coupling

Quintessence

$$S_{EH} = \int d^4x\sqrt{-g}\frac{1}{16\pi G}(R - 2\Lambda).$$

$$S = \int d^4x\sqrt{-g}\mathcal{L}, \quad \mathcal{L} = \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)$$

Scalar field potential

$$T^{(\phi)}_{\mu\nu} \equiv -\frac{2}{\sqrt{-g}}\frac{\partial(\sqrt{-g}\mathcal{L})}{\partial g^{\mu\nu}}$$

$$= \partial_\mu\phi\partial_\nu\phi - g_{\mu\nu}\left(\frac{1}{2}g^{\alpha\beta}\partial_\alpha\phi\partial_\beta\phi - V(\phi)\right)$$

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V$$

$$P_\phi = \frac{1}{2}\dot{\phi}^2 - V$$

It is possible to find attractors ⇒ no fine tuning

early dark energy: measurable consequences

f(R) MODEL:

f(R) gravity: This is a class of modified gravity models in which the gravitational action contains a general function $f(R)$ of the Ricci scalar.

$$S = \frac{M_p^2}{2} \int d^4x \sqrt{-g}\, [R + f(R)] + \int d^4x \sqrt{-g}\, \mathcal{L}_{\rm m}[\chi_i, g_{\mu\nu}] \,, \tag{92}$$

Varying the action with respect to the metric gives the Einstein field equations which now contain additional terms on the LHS

$$(1 + f_R)\, R_{\mu\nu} - \frac{1}{2} g_{\mu\nu}\,(R + f) + (g_{\mu\nu}\Box - \nabla_\mu \nabla_\nu)\, f_R = 8\pi G T_{\mu\nu} \,, \tag{93}$$

where $f_R \equiv df/dR$.

The Friedmann equation and acceleration equations are modified,

$$H^2 + \frac{f}{6} + H\dot{f}_R = \frac{8\pi G}{3}\rho \tag{94}$$

$$\frac{\ddot{a}}{a} - H^2 f_R + a^2 \frac{f}{6} + \frac{3}{2} H \dot{f}_R + \frac{1}{2}\ddot{f}_R = -\frac{8\pi G}{6}(\rho + 3P) \,. \tag{95}$$

The extra terms in the acceleration equation are able to reconcile the observed acceleration $\ddot{a} > 0$ with a universe populated by matter with positive pressure.

Observational efforts:

- Detect a gravitational wave background from CMB polarization
- Measure galaxy clustering to constrain the Baryonic Acoustic Oscillations (BAO) and make precision geometry measurements
- Measure the growth of perturbations from Redshift Space Distortions (RSD): test of gravity theory
- Measure gravitational Weak Lensing (WL) from the average distorsion of background galaxies
- Obtain the equation of state of dark energy: is it $w \neq -1$?