Università degli Studi di Napoli Federico II

Cosmology and Cosmography

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XXIV SIGRAV Conference
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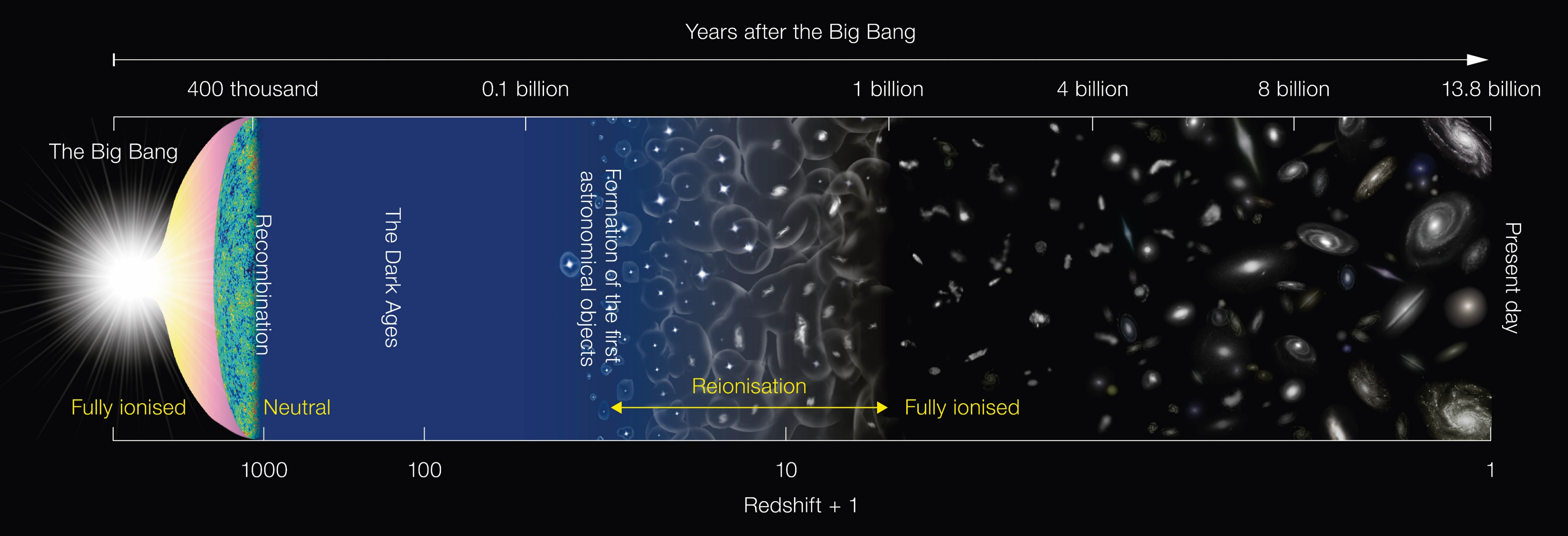
Outline

- Cosmology – current state
- Open questions in cosmology
- New approach: Cosmograpy

Recombination: charged electrons and protons first became bound to form electrically neutral hydrogen atoms

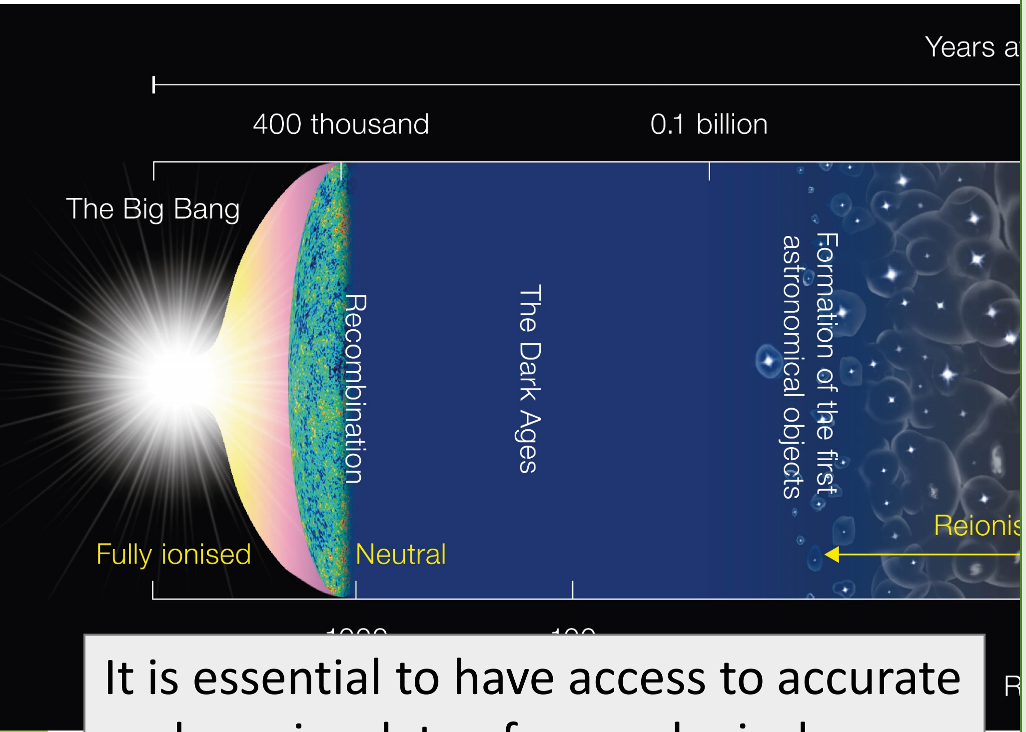
Reionization (hydrogen): Objected started to condense are now enough energetic to re-ionize neutral hydrogen → the universe reverted from being neutral to (once again) being ionized



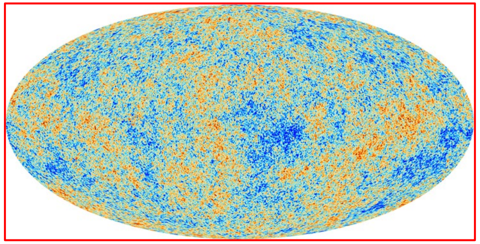
Dark ages: electrons of neutral hydrogen absorb photons of wavelengths by rising to an excited state → the universe became trasparent at the other wavelenght

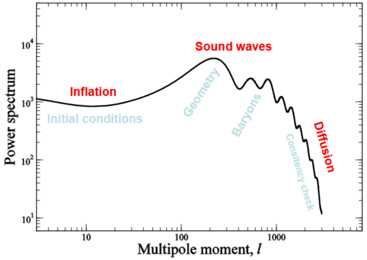
Cosmological analysis are conducted with the use of four fundamental factors:

- the formulation of a self-consistent theory
- the translation of this theory into codes and algorithms capable of producing simulations and observational predictions
- the comparison of these predictions with observational data using algorithms capable of exploring parametric space and thus giving constraints on the parameters of the theory
- the use of reliable statistical tools for a proper model comparison, that allow to infer conclusions with physical significance



It is essential to have access to accurate and precise data of cosmological observables, independent and also cover different cosmological scales

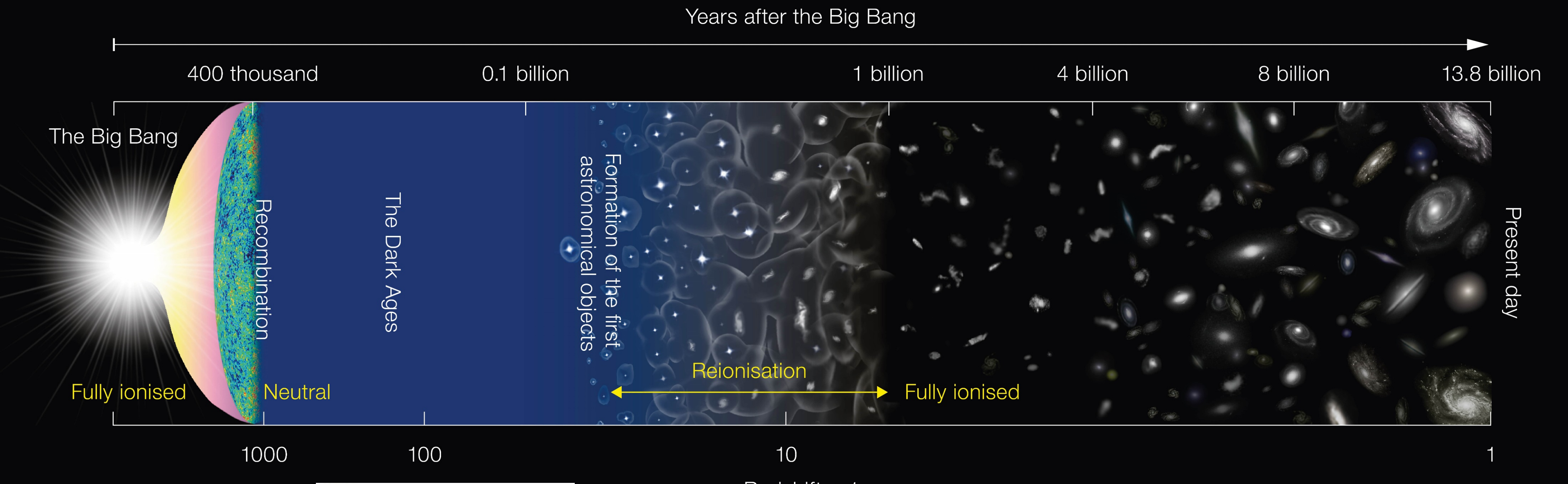


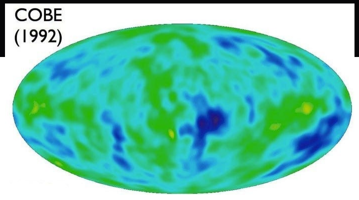


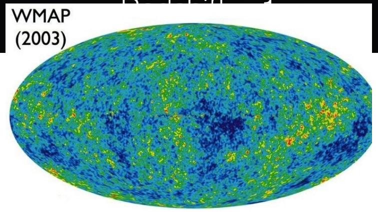
z= 1100 → CMB

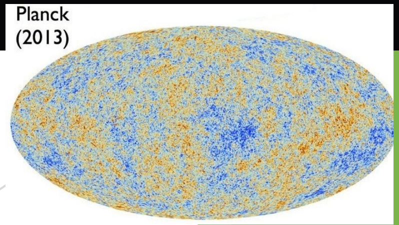
probe initial perturbation physics (initial conditions!)

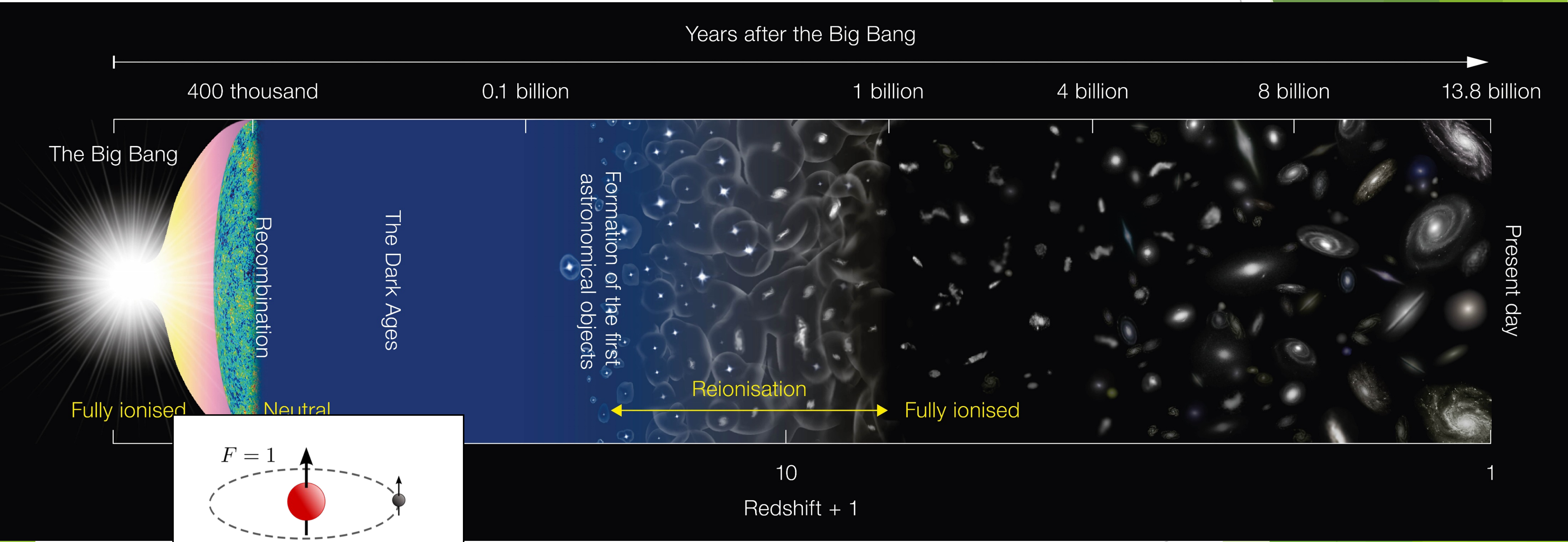
ALSO, it probe physics at several universe epoch

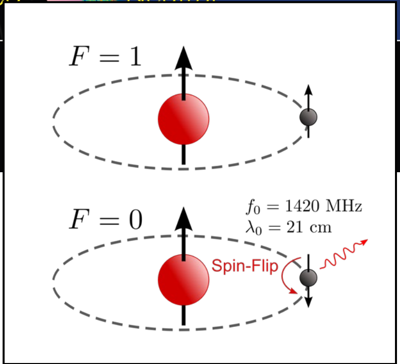




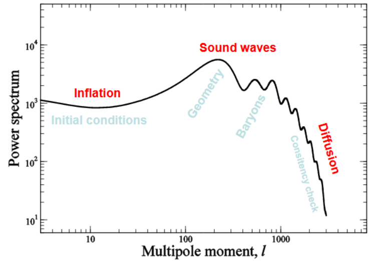




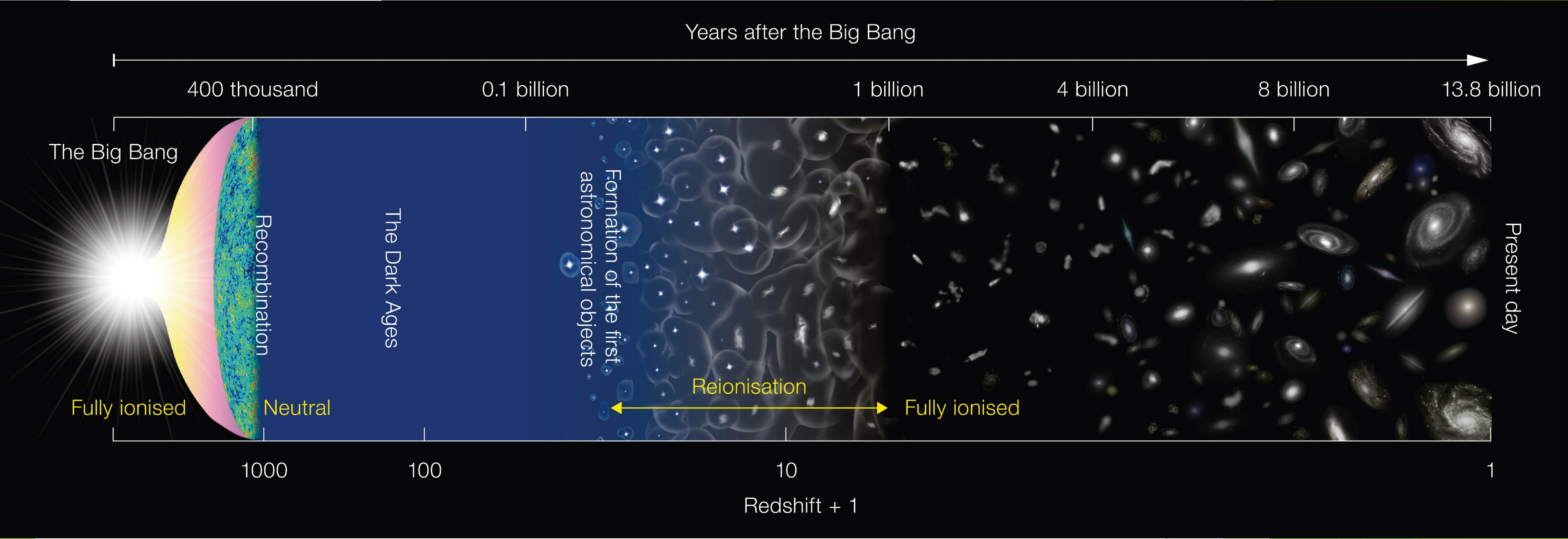




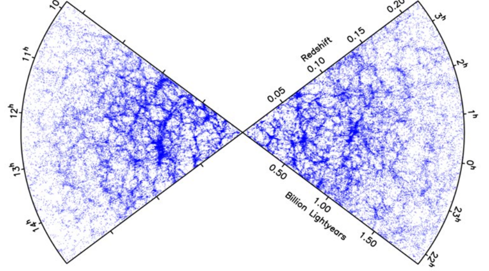
→ **21 cm (or H I line):** due to atomic transition of an electron between the two hyperfine levels of the hydrogen 1s ground state. Today, it is observed in radio astronomy



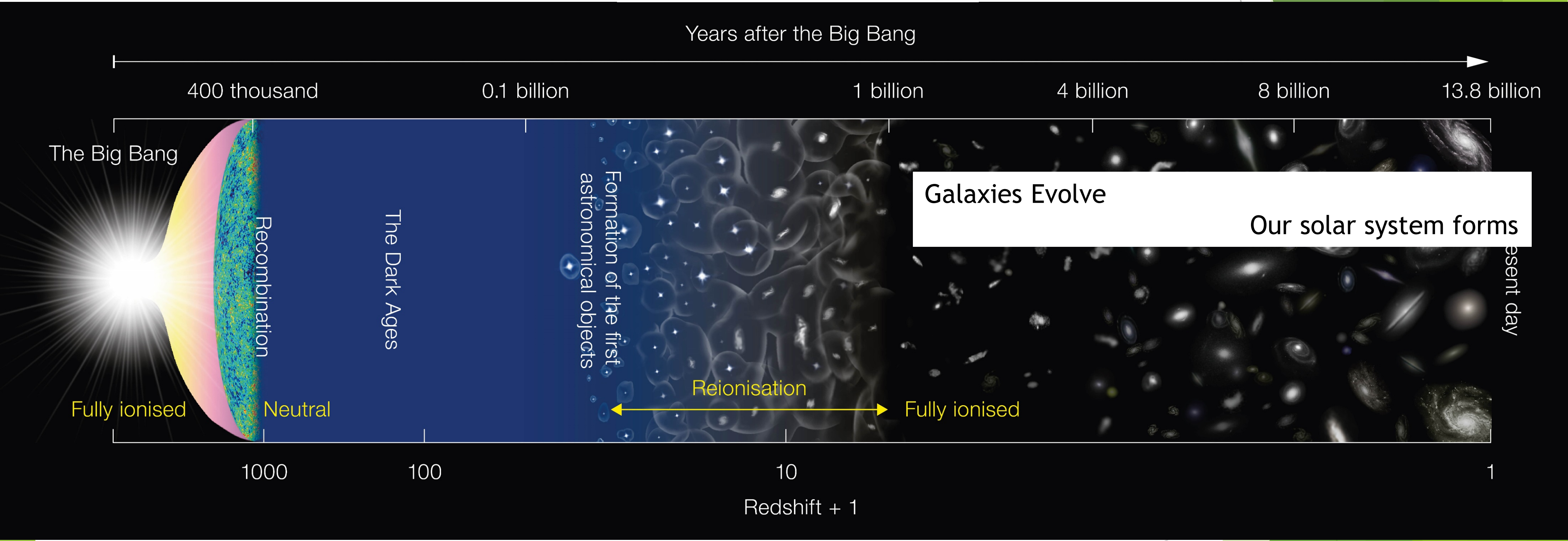
$z = 11$ ⟶ Thomson scattering of CMB on free electrons (whose density is decreasing..) : leave its mark on the CMB anisotropy map, introducing secondary anisotropies → electron column density at the time of reionization can be determined→ the **age of the universe when reionization occurred** can then be calculated.



$z = 6$ ⟶ Lyman alpha forest : absorption lines in the spectra of distant galaxies and quasars arising from the Lyman-alpha electron transition of the neutral hydrogen atom. It probe the **end of the reionization of the universe**

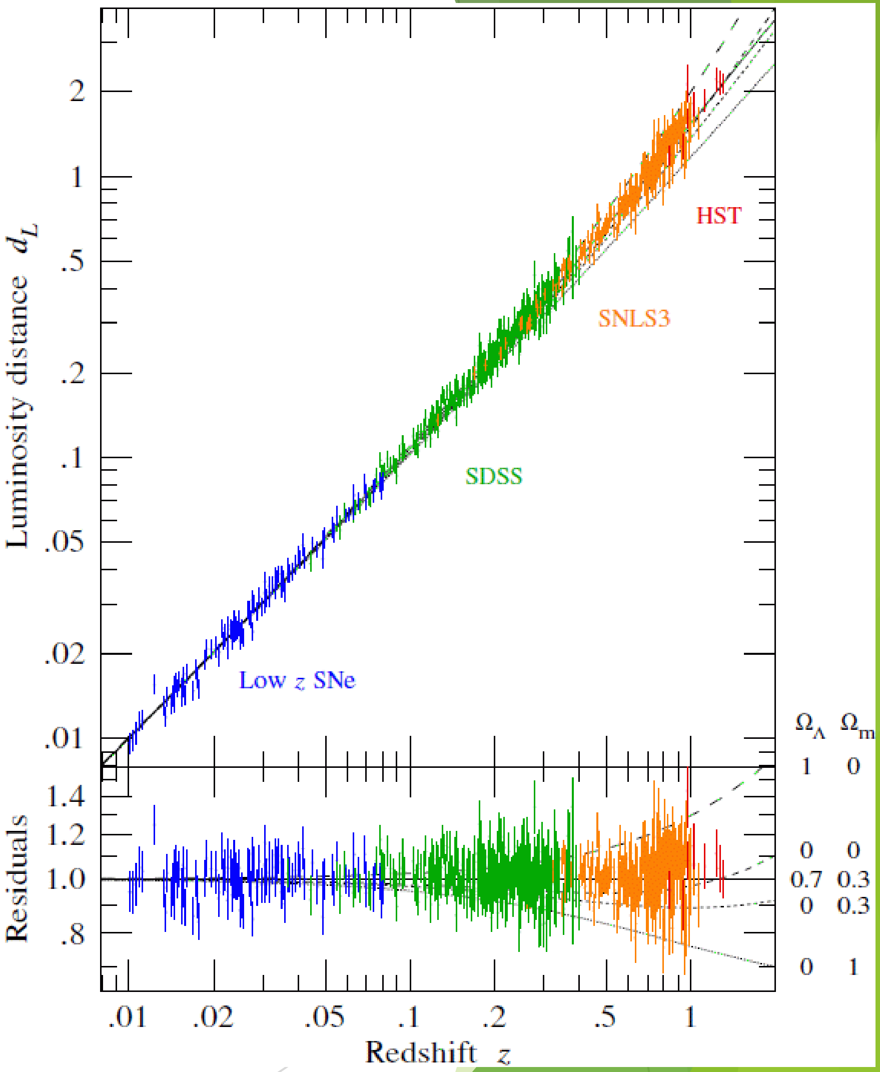


- Large Scale Structure
- Galaxies
- Galaxy Clusters
- Cosmic Web

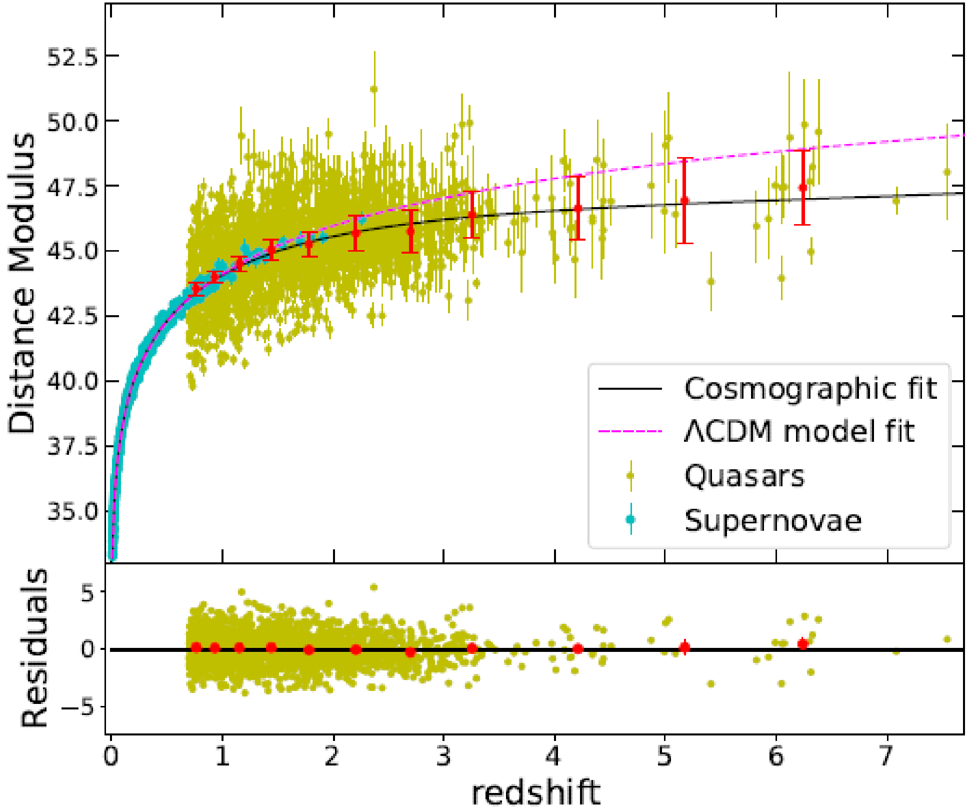


- Standard candles: measure the luminosity distance as a function of redshift.
- Standard rulers: measure the angular diameter distance as a function of redshift.
- Lensing
- Gravitational waves

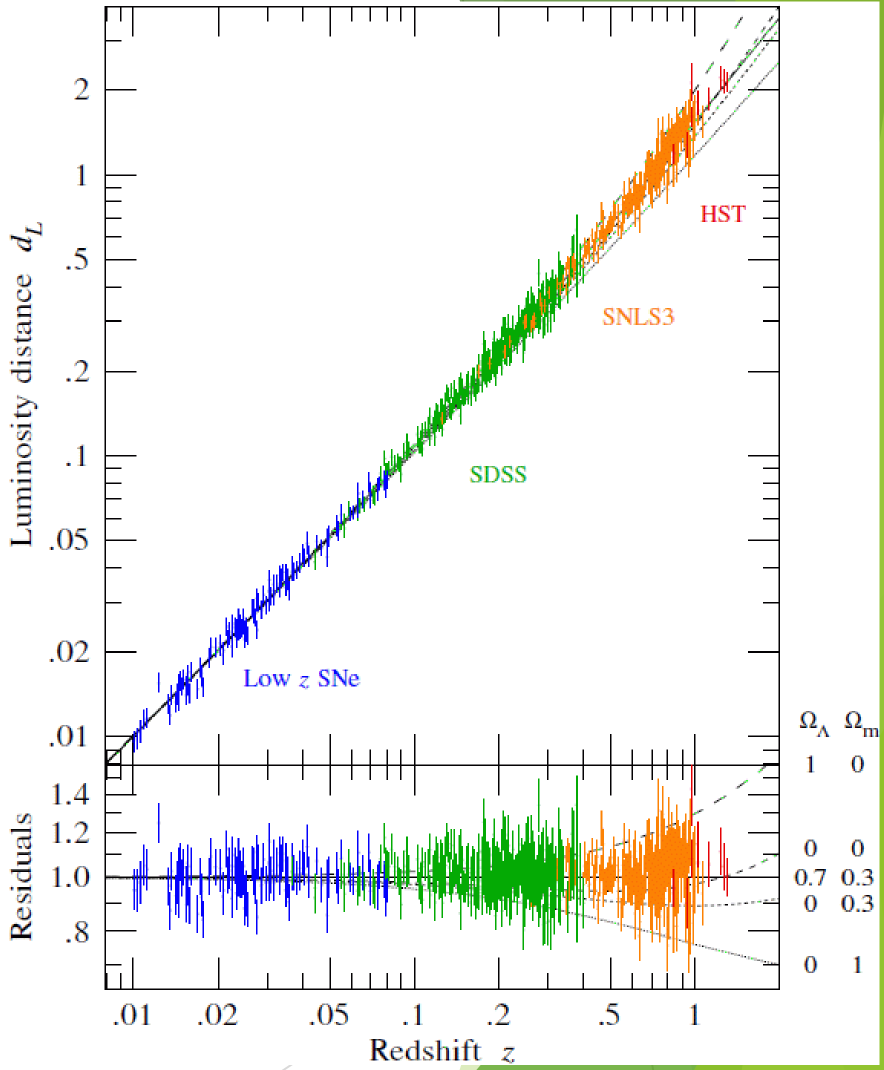
SNe, Quasars and GRB



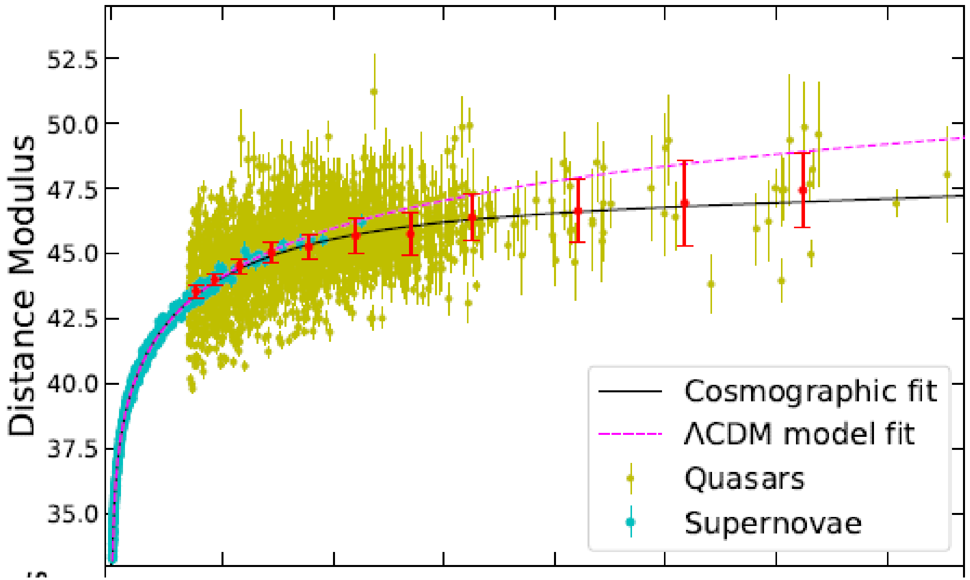
Credit: M. Betoule et al. A&A 568 (2014)

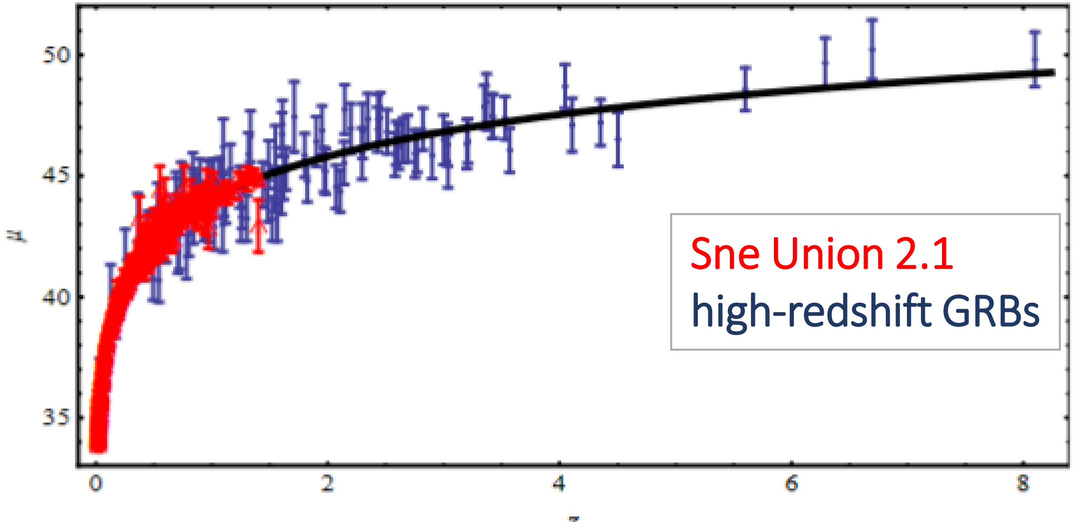


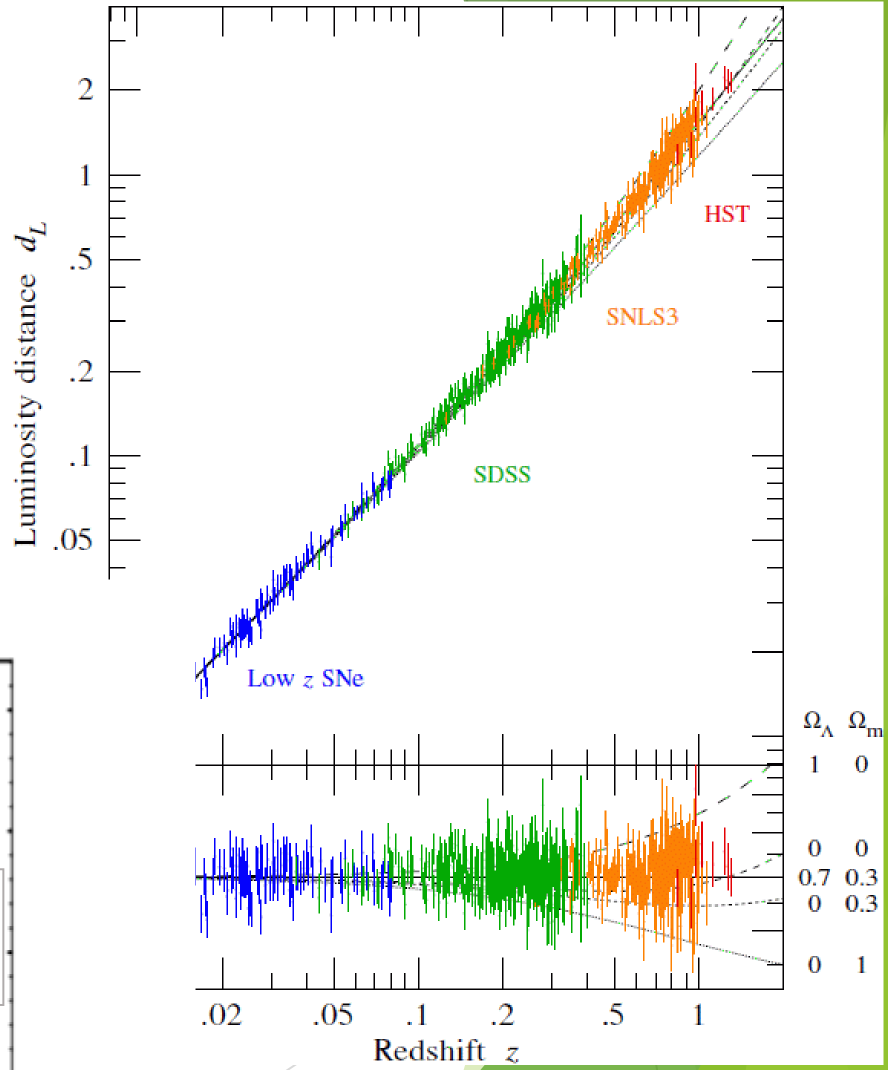
Credit: G. Bargiacchi, G. Risaliti, M. Benetti, S. Capozziello, E. Lusso, A. Saccardi, M. Signorini A&A, 649, A65 (2021)



Credit: M. Betoule et al. A&A 568 (2014)



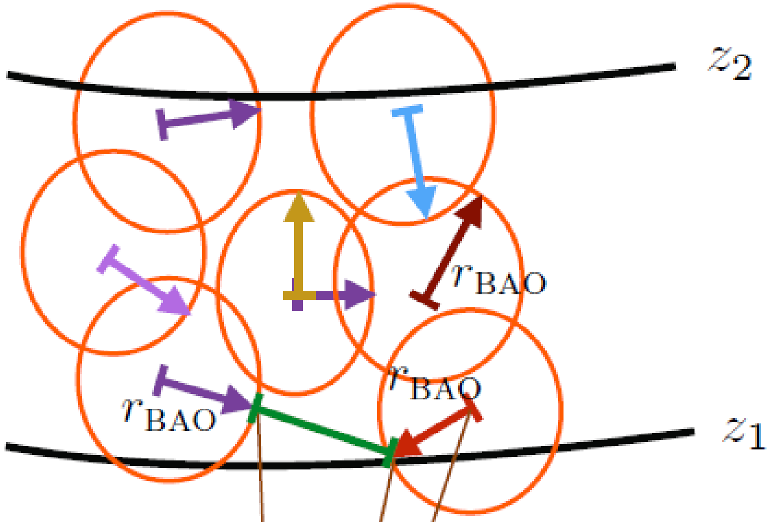




Credit: E. Piedipalumbo, P. Scudellaro, G. Esposito, C. Rubano, Gen. Rel. and Gravit. 44, 10 (2012)

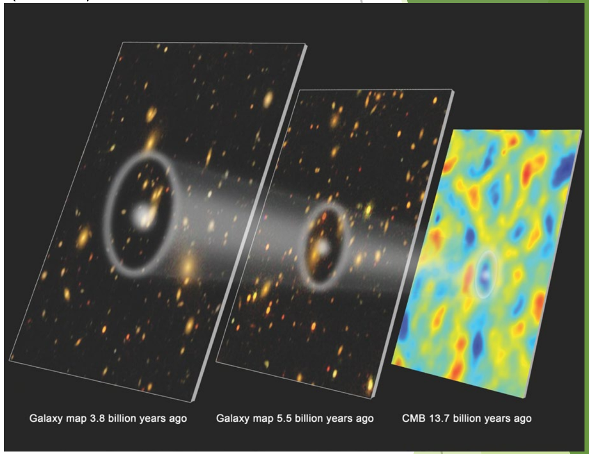
Barionic Acoustic Oscillation

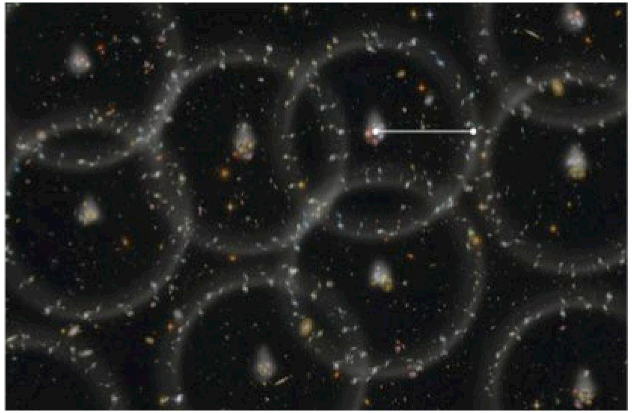
- **The transverse baryonic acoustic scale from the SDSS DR11 galaxies**, G. C. Carvalho et al. Astroparticle Physics119, 10243 (2020)
- **Baryon Acoustic Oscillations from the SDSS DR10 galaxies angular correlation function** G. C. Carvalho et al. PRD. **93**, 023530 (2016)

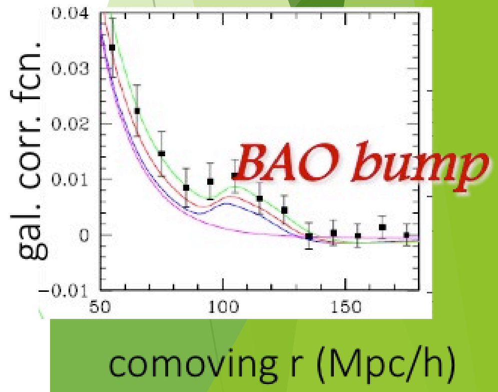


$$r_{\mathrm{BAO}}^{\mathrm{radial}} = \frac{c}{H(z)} \Delta z$$

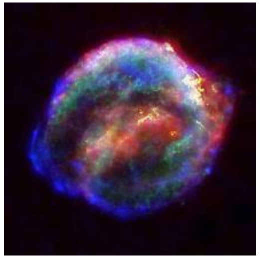
$$r_{\mathrm{BAO}}^{\mathrm{transv}} = \theta_{\mathrm{BAO}}\, D_A\,(1+z)$$





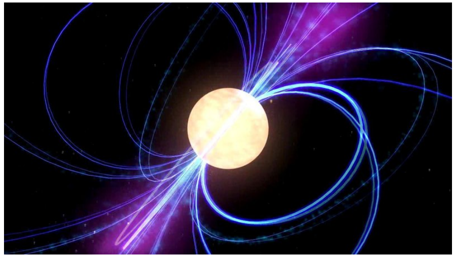


Gravitational Waves



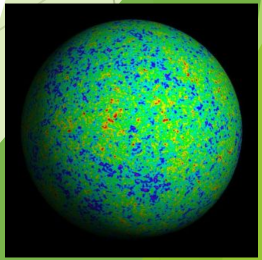
Supernova: Explosion caused by the collapse of an old, burnt-out star
- Produces a burst of gravitational radiation, *if it is non-symmetric!*

Neutron star: A city-sized atomic nucleus!
- Can spin at up to 600 cycles per second
- Emits continuous gravitational radiation (again, if it is non-symmetric)

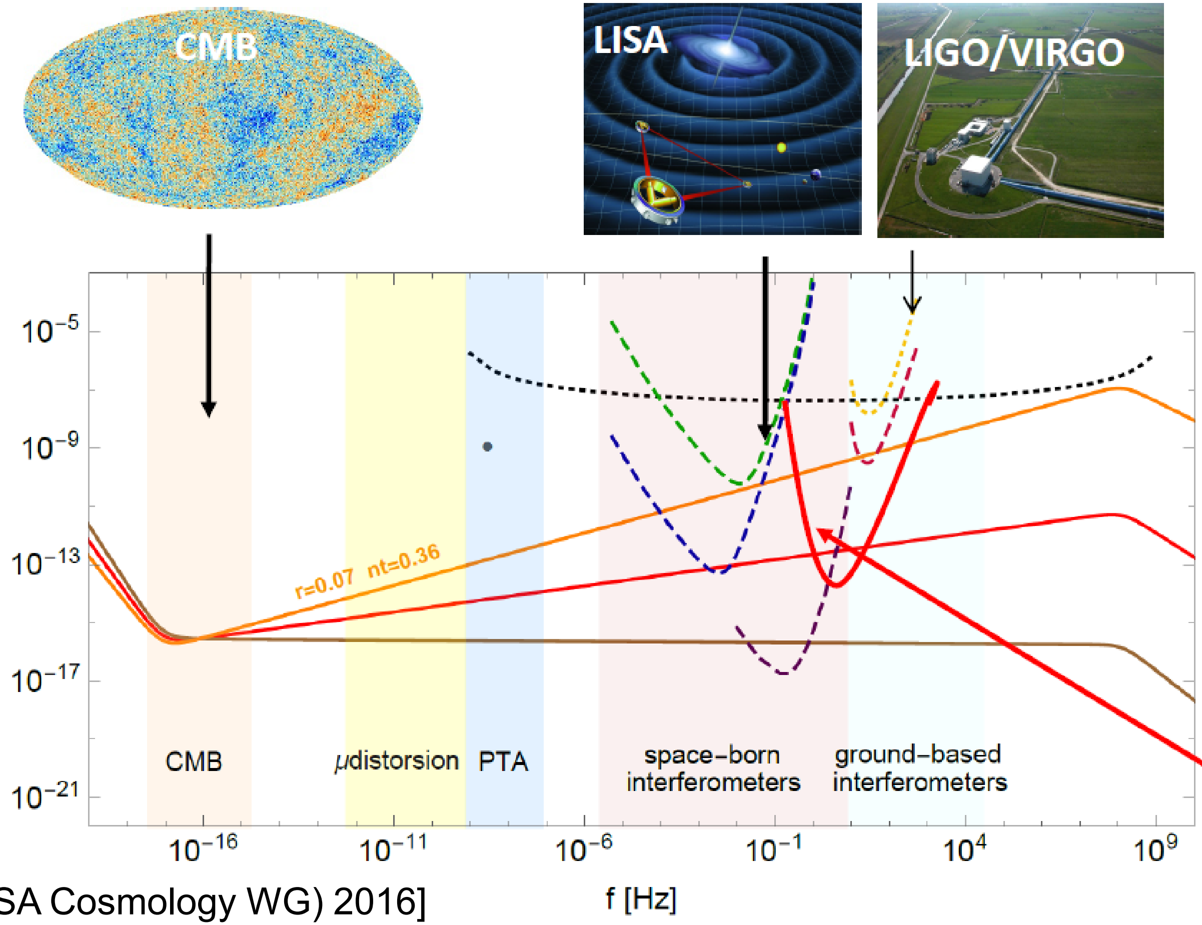


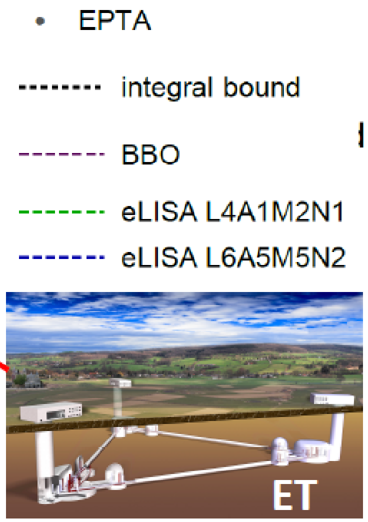
Merging compact binary: Collision of two stellar remnants (neutron stars or *black holes*)

Primordial background: Leftover radiation from the beginning of the Universe
- Tells us about the state of the Universe immediately after the Big Bang!
- Sounds like "noise" with a characteristic spectrum



Gravitational Waves





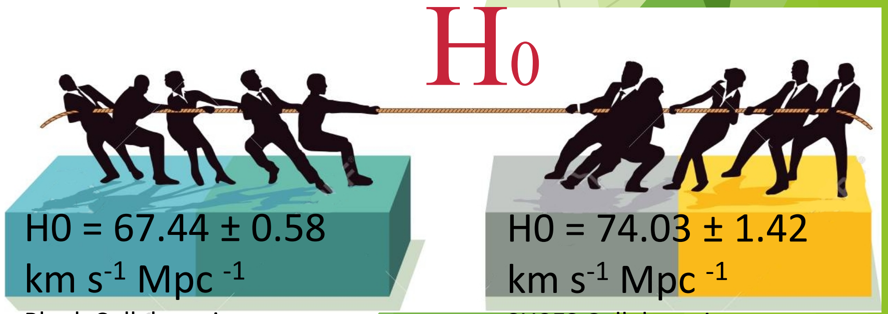
[Bartolo et al, (LISA Cosmology WG) 2016]
[Guzzetti, Bartolo, Liguori, Matarrese 2016]
[Caprini and Figueroa, 2018]

Open questions

- Did the universe have an inflationary period? How did it happen? What stopped it? What is the level of non-gaussianities?

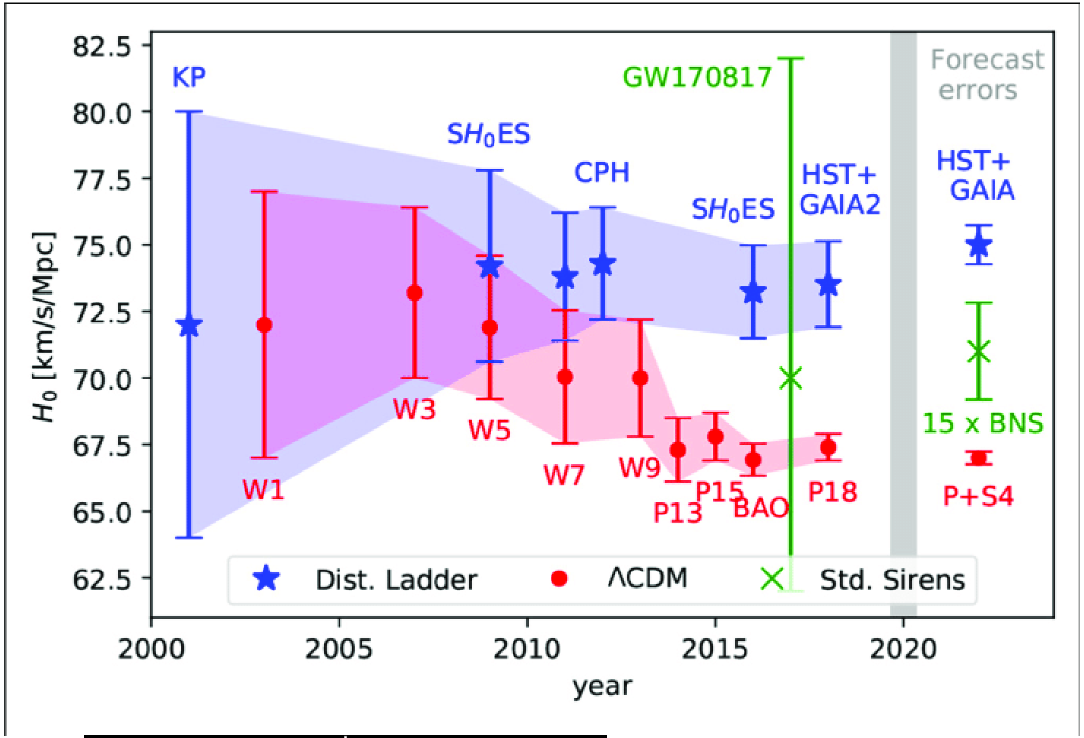
- Does gravity behave like General Relativity even at horizon size scales? Is it necessary to consider Modified Gravity?
- Do we actually need physics beyond the Standard Model (SM) of particle physics?
- What dark energy and dark matter are? Do we need them?

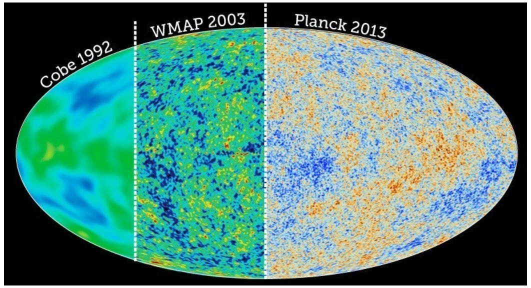
- What is the origin of the tension in the observed and inferred values of H0 and $\sigma 8$? Is this a crisis of the standard model?



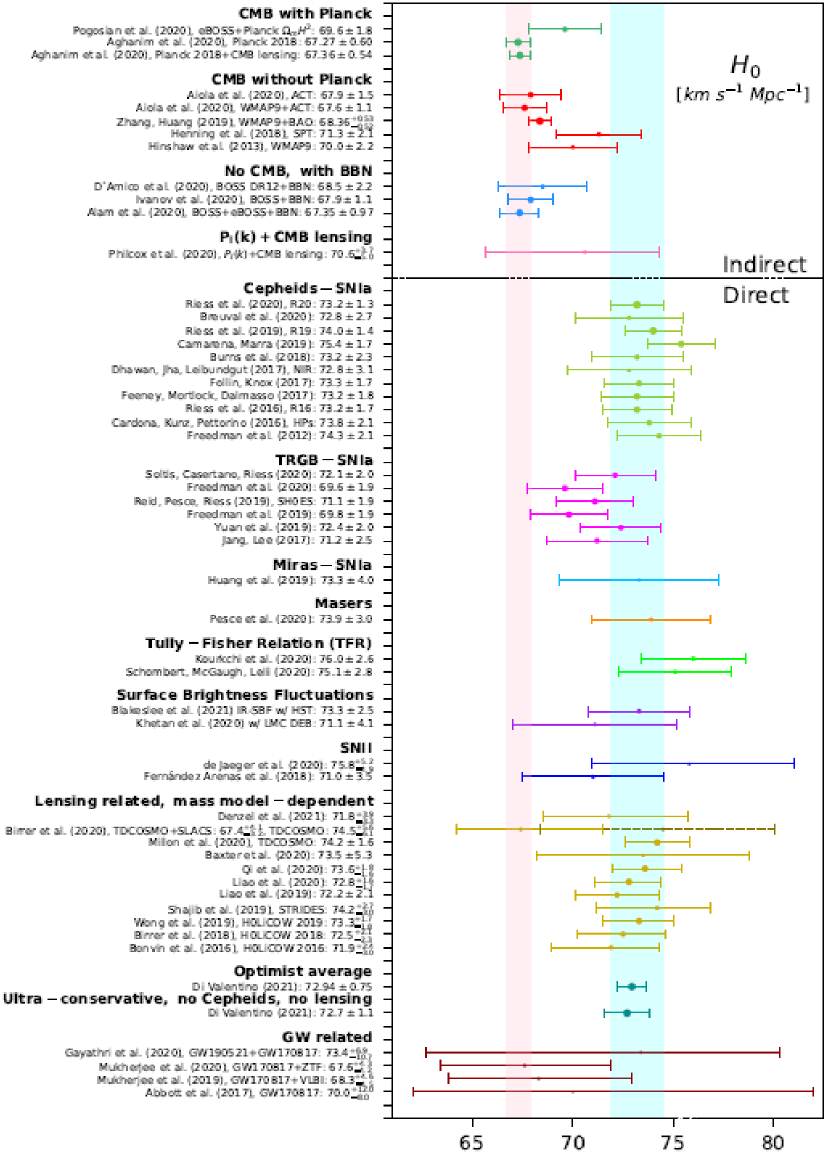
Plank Collaboration

SH0ES Collaboration





Credit: Di Valentino et al 2021



Explored Solutions:

- ✓ radical departures from conventional cosmology:

  i.e. Modified Gravity models in which gravity changes with redshift, such that the H0 estimate from CMB can have larger values today

- ✓ changes to the physics of the early universe that alters the value of the sound horizon:

  i.e Extra relativistic degrees of freedom at recombination or Decaying dark matter or interacting ν

- ✓ changes to the physics at late times:

  i.e Interacting dark energy (IDE) models, where DM and DE share interactions other than gravitational

Adopt a parametric approach to describe the data →

address the problem in model-independent way with the aim of obtaining important clues on which to construct the theory →

Cosmography !

D_L = luminosity distance
D(z) = comoving angular diameter distance

Cosmography

$$D_L = (1+z)D(z)$$

Low redshift approximation

$$v(z) = H_0 D(z)$$

$$z \sim \frac{v(z)}{c}$$

$$D_L = (1+z)\frac{zc}{H_0}$$

$$z = \frac{a(t_0)}{a(t_e)} - 1$$

$$a(t) = 1 + \sum_{k=1}^{\infty} \frac{1}{k!} \frac{d^k a}{dt^k}\bigg|_{t=t_0} (t-t_0)^k$$

Cosmography

$$H(t) \equiv \frac{1}{a}\frac{da}{dt} \qquad j(t) \equiv \frac{1}{aH^3}\frac{d^3a}{dt^3}$$

$$q(t) \equiv -\frac{1}{aH^2}\frac{d^2a}{dt^2} \qquad s(t) \equiv \frac{1}{aH^4}\frac{d^4a}{dt^4}$$

$$D_L(z) = \frac{zc}{H_0}\Big[1 + \frac{z}{2}(1-q_0) - \frac{z^2}{6}\left(1 - q_0 - 3q_0^2 + j_0\right) + \frac{z^3}{24}\left(2 - 2q_0 - 15q_0^2 - 15q_0^3 + 5j_0 + 10q_0j_0 + s_0\right) + \mathcal{O}(z^4)\Big]$$

$$a(t) = 1 + \sum_{k=1}^{\infty} \frac{1}{k!}\frac{d^ka}{dt^k}\Big|_{t=t_0}(t-t_0)^k$$

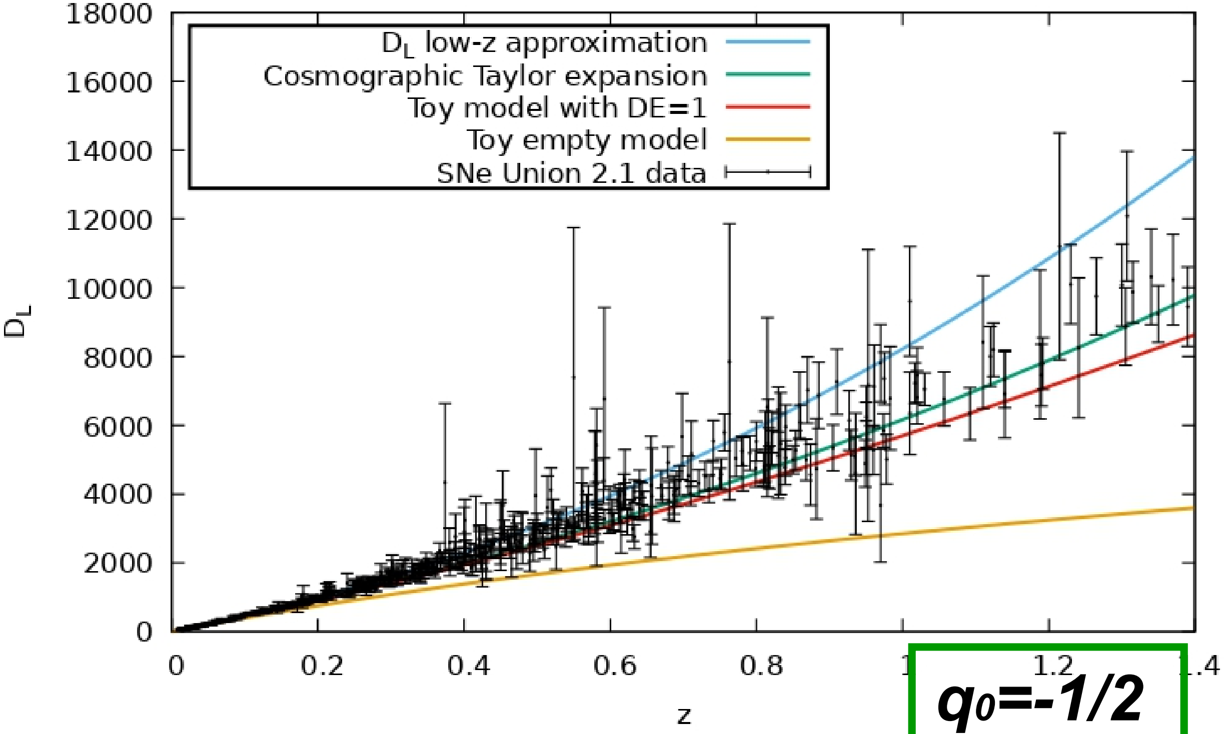
Low redshift approximation

$$v(z) = H_0 D(z)$$

$$z \sim \frac{v(z)}{c}$$

$$D_L = (1+z)\frac{zc}{H_0}$$

Cosmography



Low redshift approximation

$$v(z) = H_0 D(z)$$

$$z \sim \frac{v(z)}{c}$$

$$D_L = (1+z)\frac{zc}{H_0}$$

$q_0=-1/2$
$j_0=s_0=0$

$$D_L(z) = \frac{zc}{H_0}\Big[1 + \frac{z}{2}(1-q_0) - \frac{z^2}{6}\left(1 - q_0 - 3q_0^2 + j_0\right) + \frac{z^3}{24}\left(2 - 2q_0 - 15q_0^2 - 15q_0^3 + 5j_0 + 10q_0 j_0 + s_0\right) + \mathcal{O}(z^4)\Big]$$

Cosmography – Padé polinomials

$$P_{n,m}(z) = \frac{\sum_{i=0}^{n} a_i z^i}{1 + \sum_{j=1}^{m} b_j z^j} \longleftarrow a(t) = 1 + \sum_{k=1}^{\infty} \frac{1}{k!} \frac{d^k a}{dt^k}\bigg|_{t=t_0} (t - t_0)^k$$

Extended Gravity Cosmography,
Capozziello et al. Int. J. Mod. Phys. D 28, 1930016 (2019)

Cosmography – Padé polinomials

$$P_{n,m}(z) = \frac{\sum_{i=0}^{n} a_i z^i}{1 + \sum_{j=1}^{m} b_j z^j}$$

$P_{2,2}$

$$\boxed{\frac{H(z)}{H_0} = \frac{P_0 + P_1 z + P_2 z^2}{1 + Q_1 z + Q_2 z^2}}$$

$$P_0 = 1$$
$$P_1 = H_1 + Q_1$$
$$P_2 = \frac{H_2}{2} + Q_1 H_1 + Q_2$$
$$Q_1 = \frac{-6H_1H_4 + 12H_2H_3}{24H_1H_3 - 36H_2^2}$$
$$Q_2 = \frac{3H_2H_4 - 4H_3^2}{24H_1H_3 - 36H_2^2}$$

$$H_1 = H_{10}/H_0 = 1 + q_0$$
$$H_2 = H_{20}/H_0 = -q_0^2 + j_0$$
$$H_3 = H_{30}/H_0 = 3q_0^2(1 + q_0) - j_0(3 + 4q_0) - s_0$$
$$H_4 = H_{40}/H_0 = \ldots$$

Extended Gravity Cosmography,
Capozziello et al. Int. J. Mod. Phys. D 28, 1930016 (2019)

Model independent constraints on dark energy evolution from low-redshift observations, Capozziello et al. Mon. Not. Roy. Astron. Soc. 484, 4484 (2019)

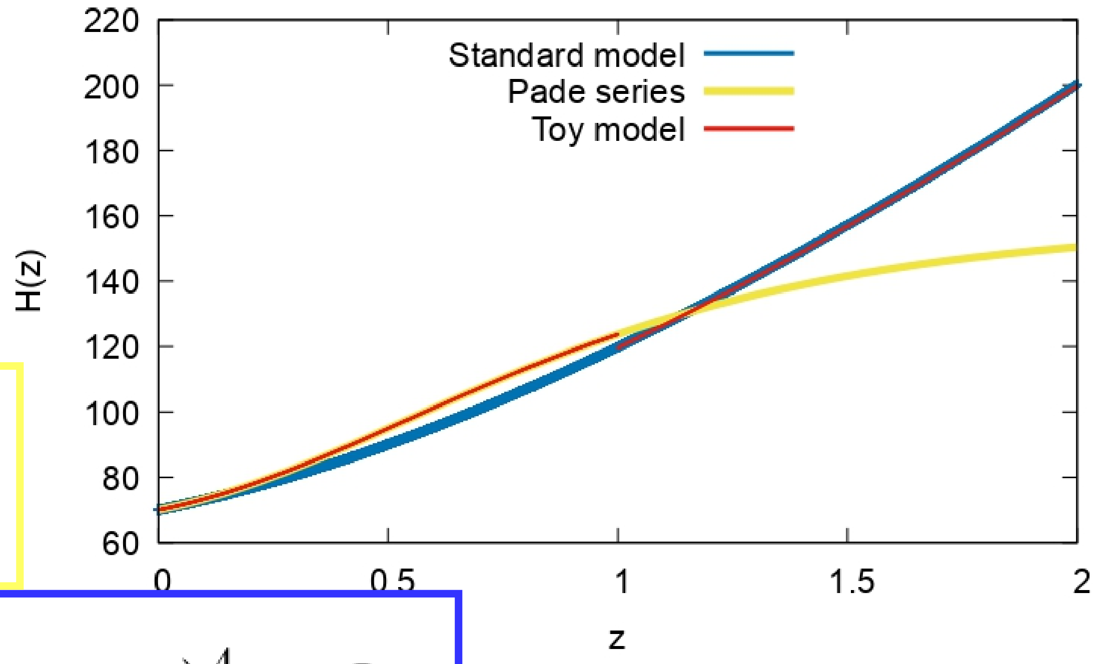
Cosmography

Connecting early and late epochs by f(z)CDM cosmography, M. Benetti and S. Capozziello, JCAP, **12** 008 (2019).

$q_0=-0.6$
$j_0=2$
$s_0=0$

$\Omega_m = 0.3$
$\Omega_r = 0$
$\Omega_\Lambda = 0.7$

$$\frac{H(z)}{H_0} = \frac{P_0 + P_1 z + P_2 z^2}{1 + Q_1 z + Q_2 z^2}$$



$$\frac{H(z)}{H_0} = \Omega_m (1+z)^3 + \Omega_r (1+z)^4 + \Omega_\Lambda$$

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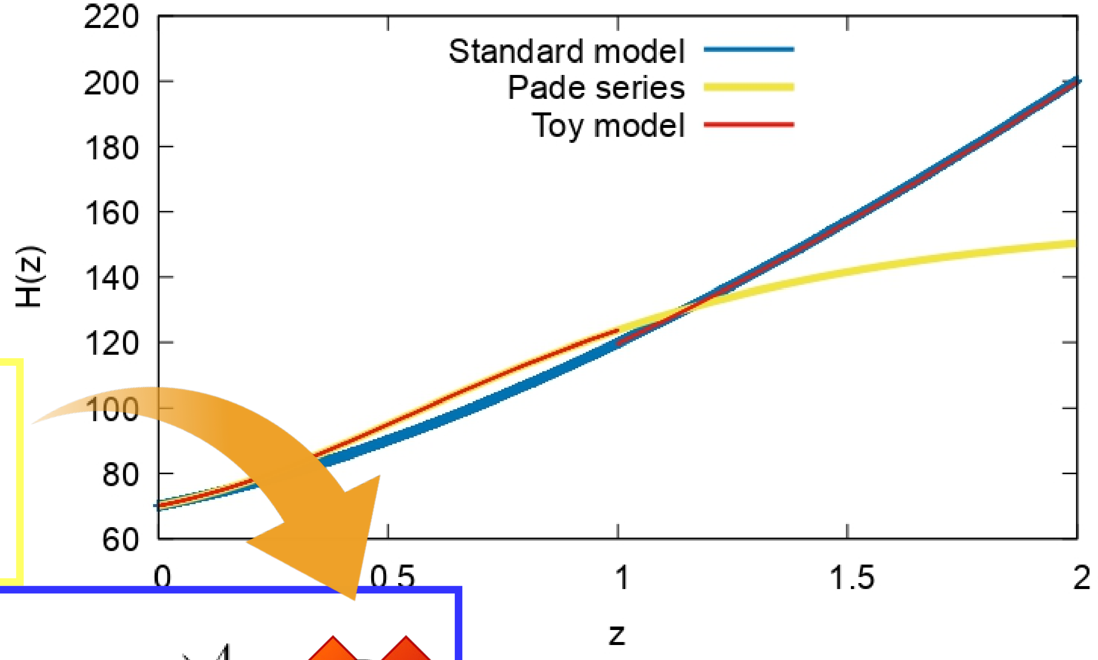


$$\frac{H(z)}{H_0} = \frac{P_0 + P_1 z + P_2 z^2}{1 + Q_1 z + Q_2 z^2}$$

$$\frac{H(z)}{H_0} = \Omega_m (1+z)^3 + \Omega_r (1+z)^4 + \cancel{\Omega_\Lambda}$$

Analysis

- f(z)CDM model truncated to 2° order → q_0
- f(z)CDM model truncated to 3° → q_0 and j_0
- f(z)CDM model truncated to 4° order → q_0, j_0, s_0

Dataset

- Cosmic Microwave Background (CMB)
- Baryon Acoustic Oscillation (BAO)
- Supernovae Type Ia (Pantheon sample)

$$H(t) \equiv \frac{1}{a}\frac{da}{dt} \qquad j(t) \equiv \frac{1}{aH^3}\frac{d^3a}{dt^3}$$

$$q(t) \equiv -\frac{1}{aH^2}\frac{d^2a}{dt^2} \qquad s(t) \equiv \frac{1}{aH^4}\frac{d^4a}{dt^4}$$

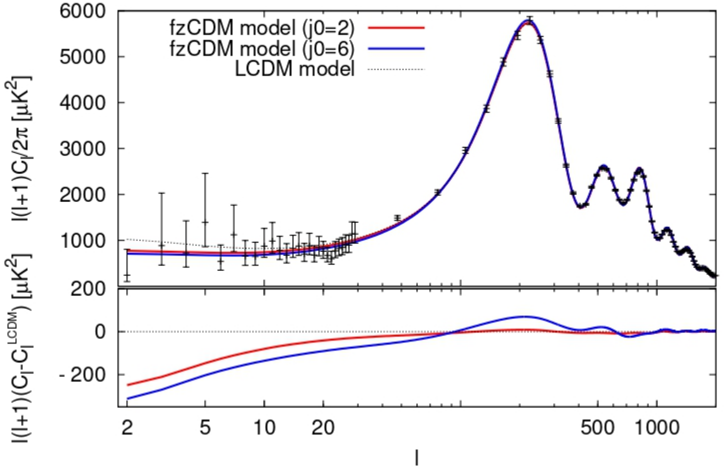
Cosmography + cosmological model

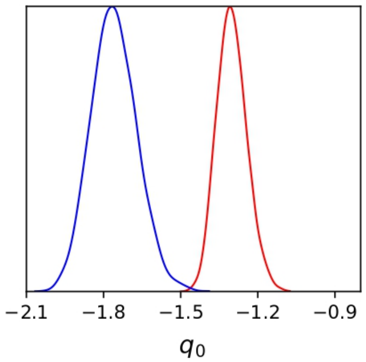
f(z)CDM model truncated to 2°

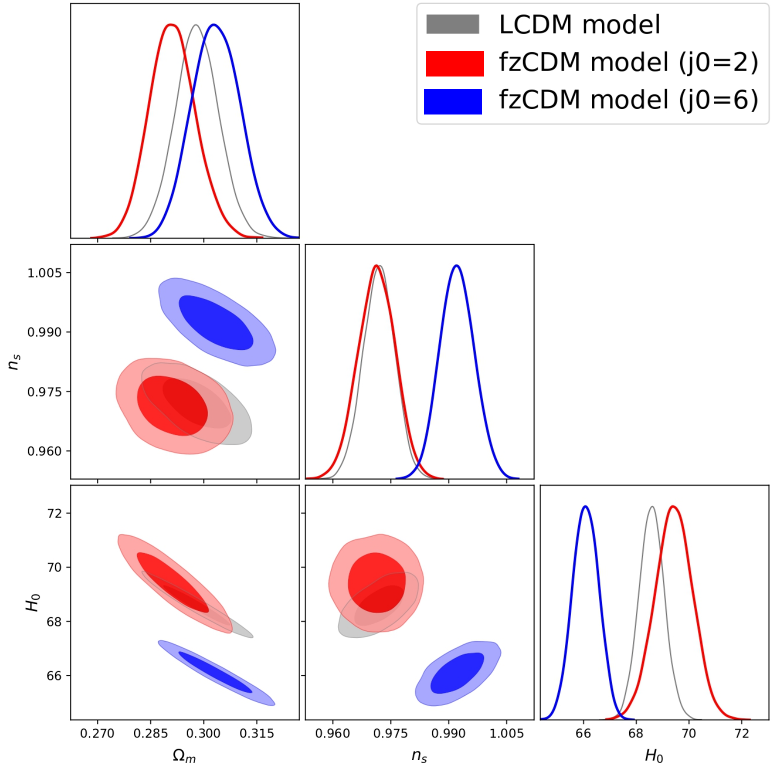
We note:

- dependence of Ωm value with cosmographic parameters

- non-negligible effect of the cosmographic parameters on the CMB temperature anisotropy power spectrum







Cosmography + cosmological model

We note:

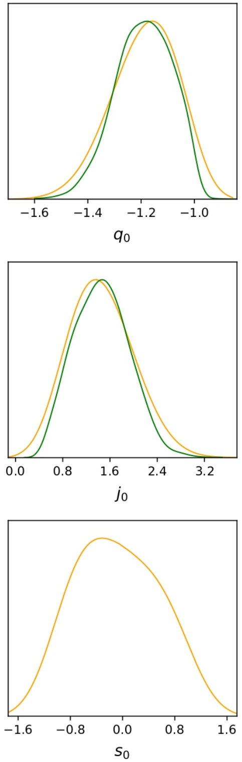
- good parameter constraints on q_0 and j_0, while s_0 needs further data accuracy.

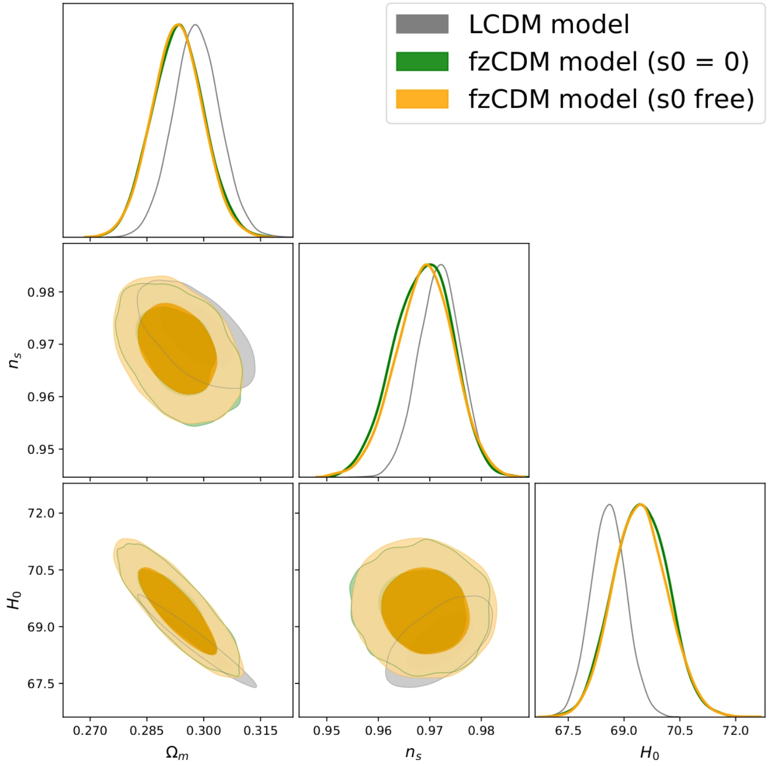
f(z)CDM model truncated t0 3°

$q_0 = -1.2 \pm 0.1$
$j_0 = 1.5 \pm 0.5$
$s_0 = 0$

f(z)CDM model truncated to 4°

$q_0 = -1.2 \pm 0.1$
$j_0 = 1.5 \pm 0.5$
$s_0 = -0.1 \pm 0.6$





Cosmography + cosmological model

We note:

- f(z)CDM model truncated at third order show $\Delta\chi^2 \sim 7$ with respect to vanilla ΛCDM model → can this be interpreted as a requirement to consider higher orders, with respect to the General Relativity theory, to properly describe the data?

Connecting early and late epochs by f(z)CDM cosmography, M. Benetti and S. Capozziello, JCAP, **12** 008 (2019).

Thanks for your attention