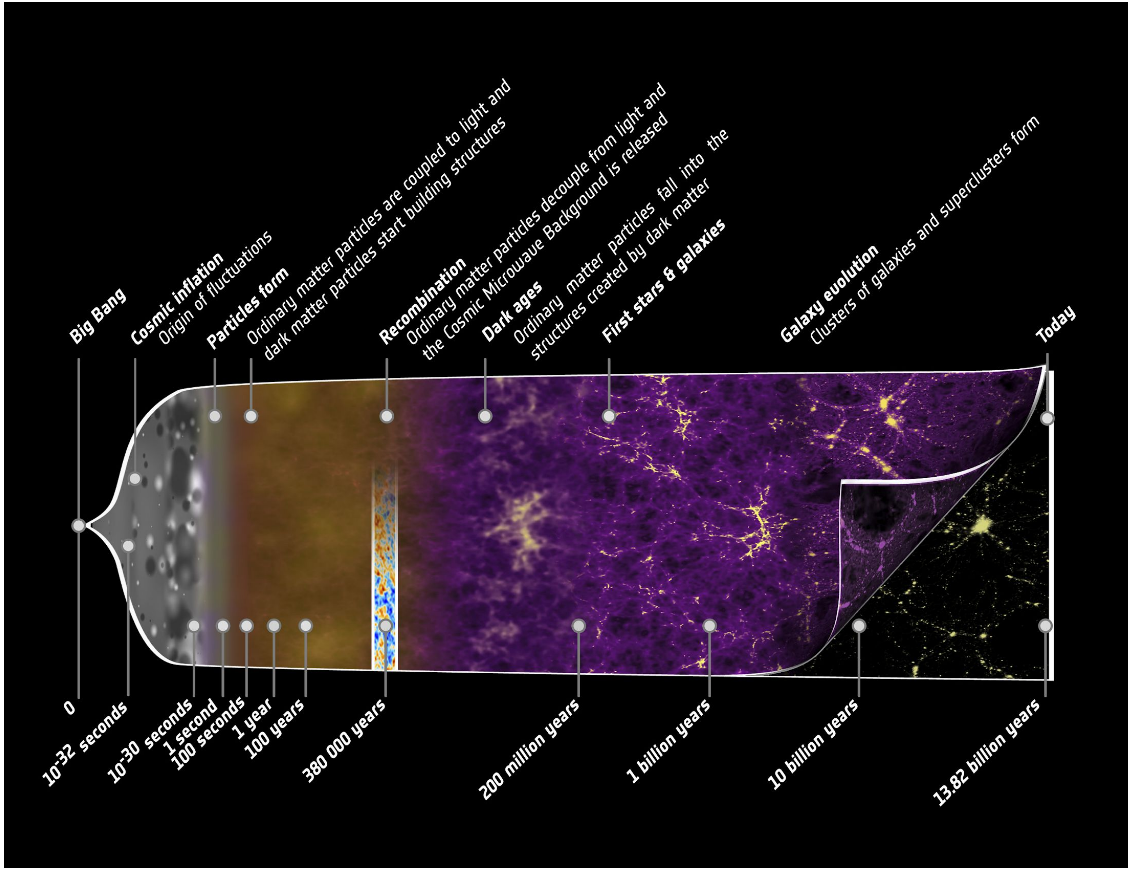
OBSERVATIONAL COSMOLOGY

A.A. 2024/2025 | 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: GENERAL RELATIVITY

Classical (Solar System) Tests

- **Perihelion Precession of Mercury**
  GR explains the 43 arcsec/century discrepancy from Newtonian predictions.

- **Deflection of Light by the Sun**
  Confirmed by Eddington (1919); light bends by 1.75 arcseconds ($\vartheta = 4GM/Rc^2$) near the Sun.

- **Gravitational Redshift**
  Verified in lab (Pound-Rebka experiment) and astrophysical sources. GR correction needed to correct GPS clock (**45 μs / day**)

- **Shapiro Time Delay**
  Signals passing near a massive object take slightly longer to travel.

Astrophysical Tests

- **Binary Pulsars**
  Energy loss via gravitational waves matches GR predictions (e.g. Hulse-Taylor).

- **Detection of Gravitational Wave Signals**

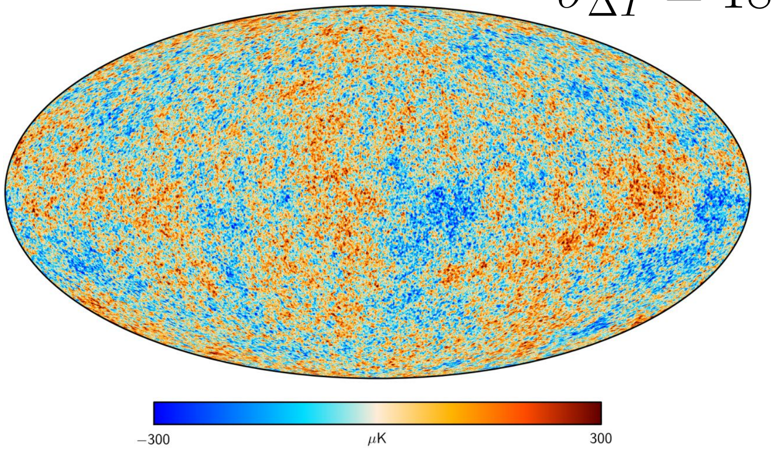
GENERAL FRAMEWORK: COSMOLOGICAL PRINCIPLE

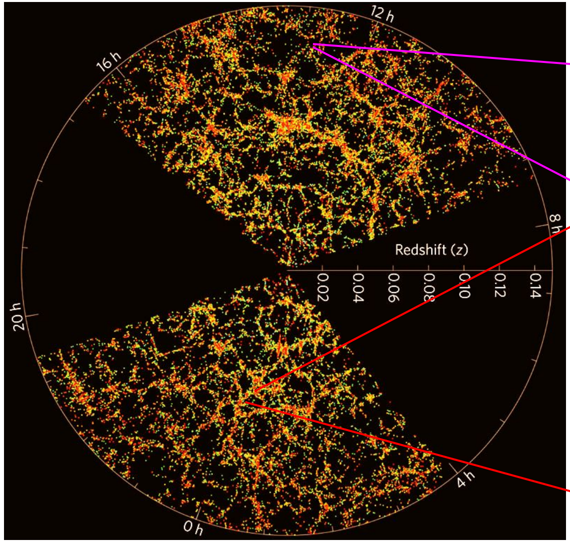
Cosmological principle: **the Universe is isotropic* and homogeneous** on large scale (~100 Mpc/h)**

*** from observation**

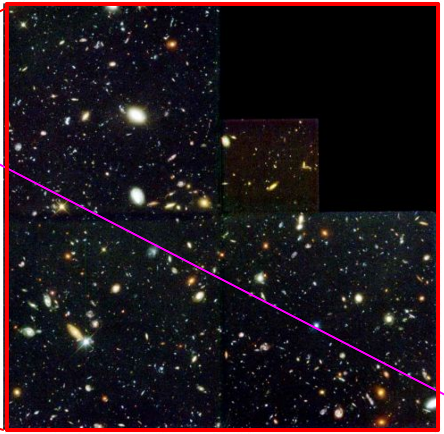
**** Copernican principle**

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

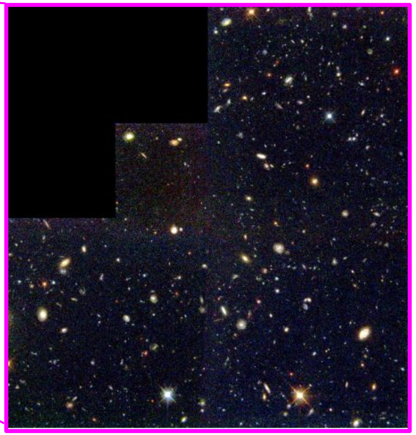




HDF-North



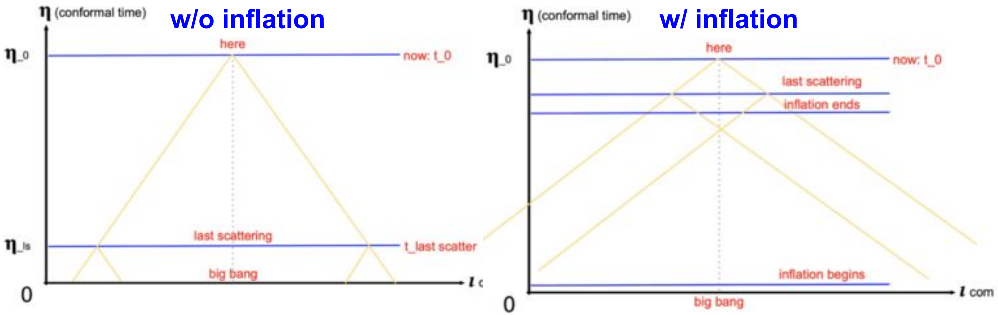
HDF-South



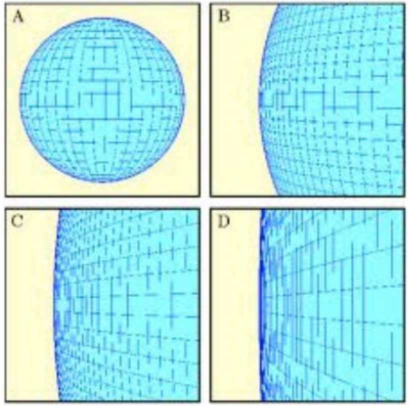
GENERAL FRAMEWORK: INFLATION

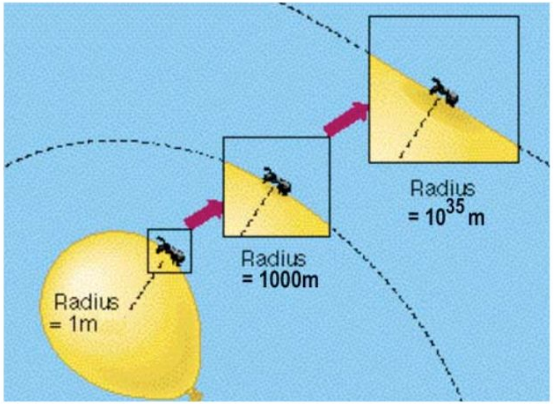
Inflation: **exponential expansion (e-fold~60) happened in the early stages of the Universe (t ≃10^{-37} - 10^{-35}s).**

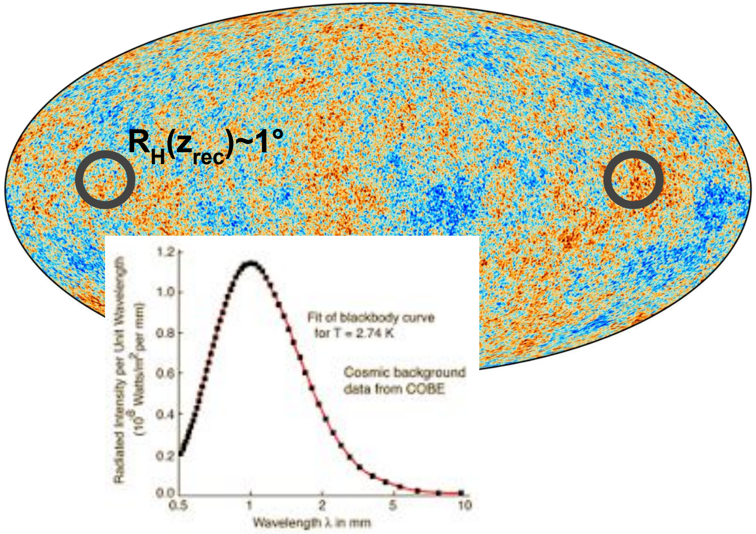
Horizon problem



Flatness problem (today Ω_k ≃ 0)



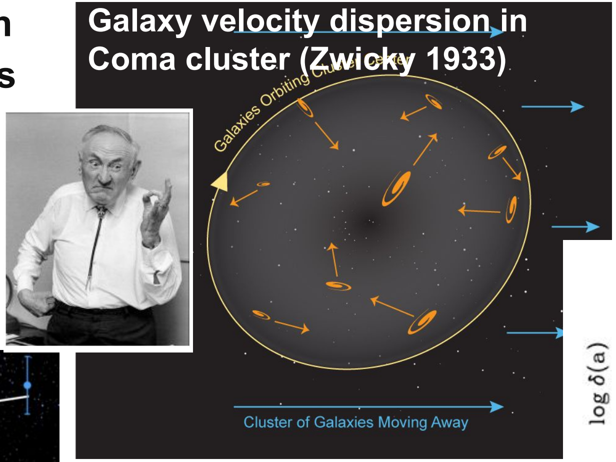


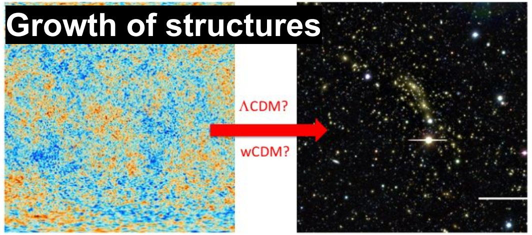


\+ **Magnetic monopole problem: Inflation dilutes the Universe by a factor e^{3N} , with N~60**

GENERAL FRAMEWORK: DARK MATTER

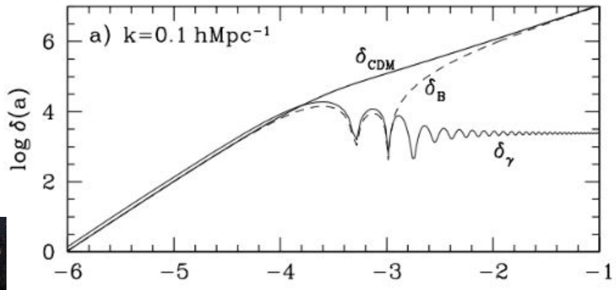
Dark Matter: massive particles which interacts only via gravitational forces

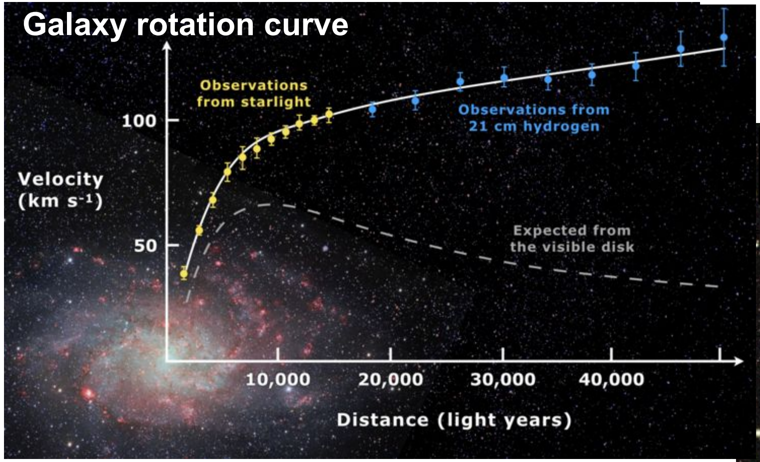


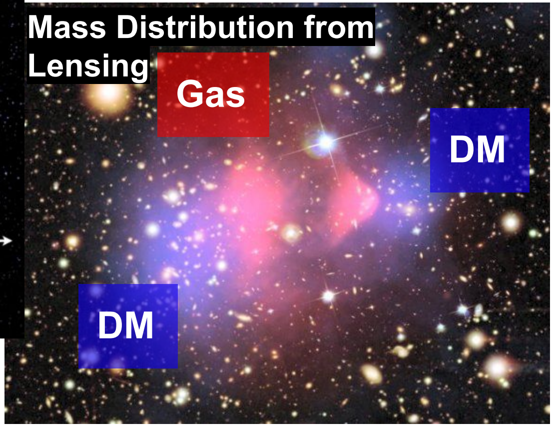


Structure at 380,000 years – 10^{-5} of CMB

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

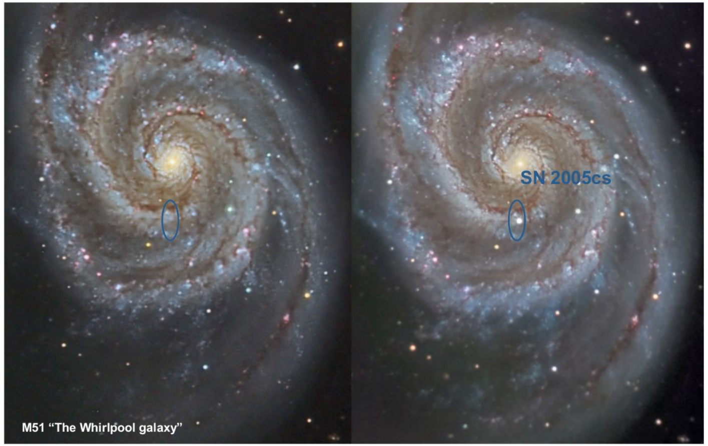


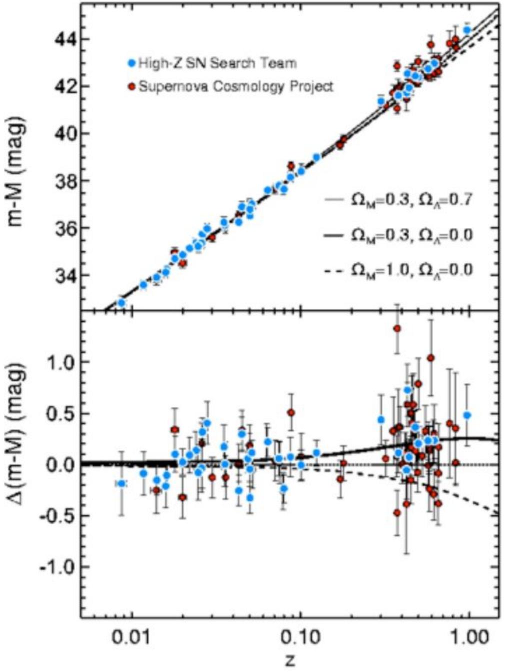


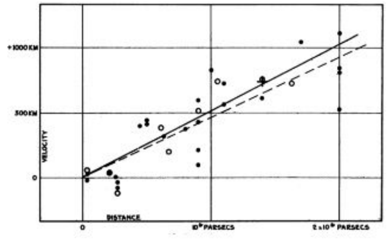


GENERAL FRAMEWORK: ΛCDM MODEL

Accelerated expansion: the Universe is undergoing a phase of accelerated expansion driven by a dark energy component, Λ





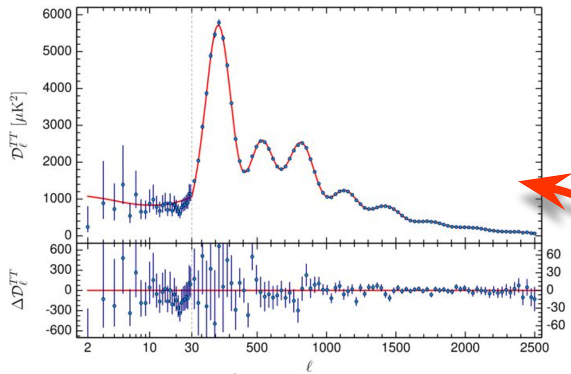


Hubble 1929

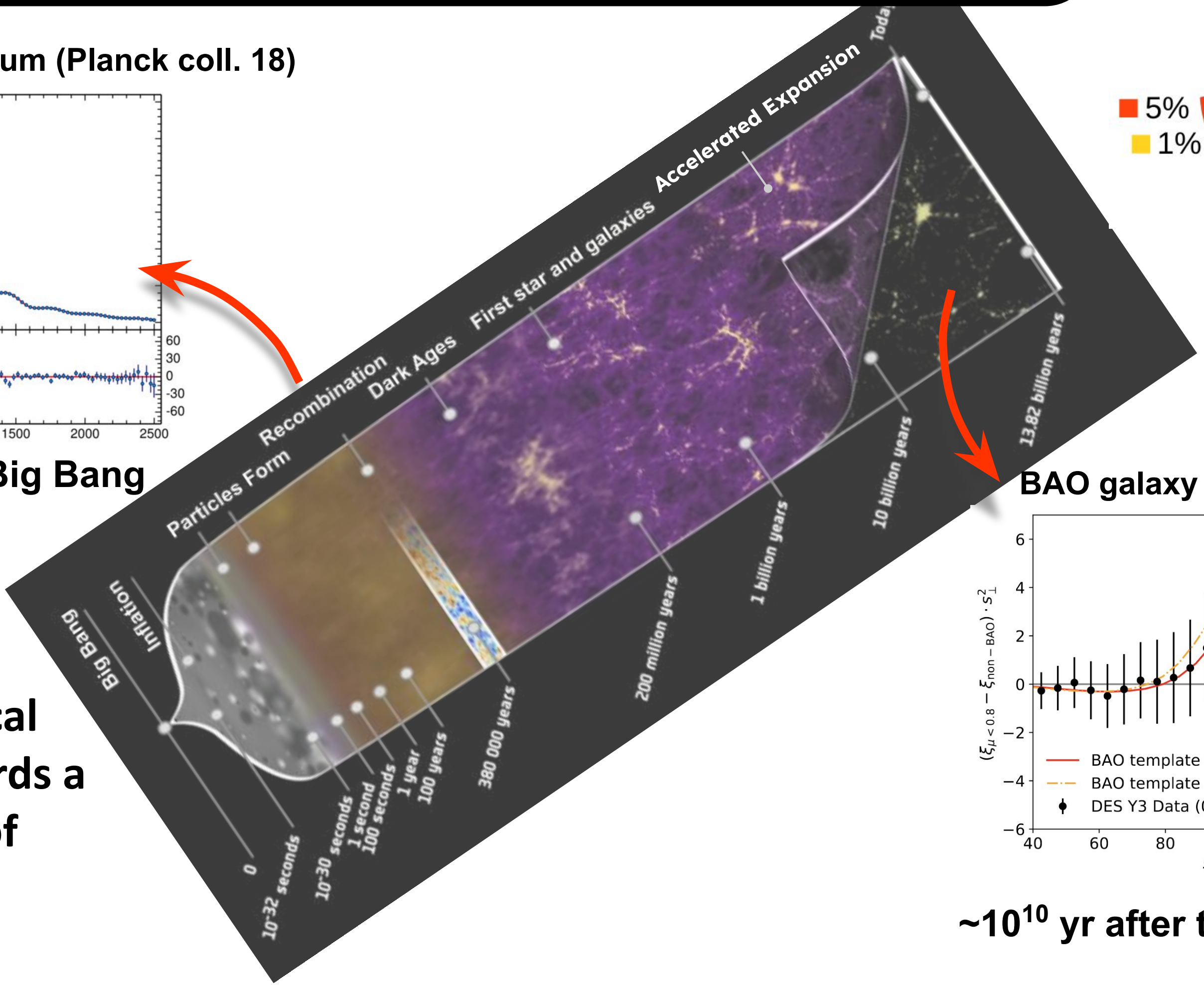
1998/99 High-Z Supernova Search Team and Supernova Cosmology Project found evidence for accelerated expansion of the Universe (2011 Nobel Prize)

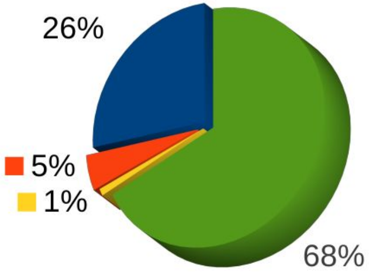
GENERAL FRAMEWORK: CURRENT STATUS

The CMB TT power spectrum (Planck coll. 18)

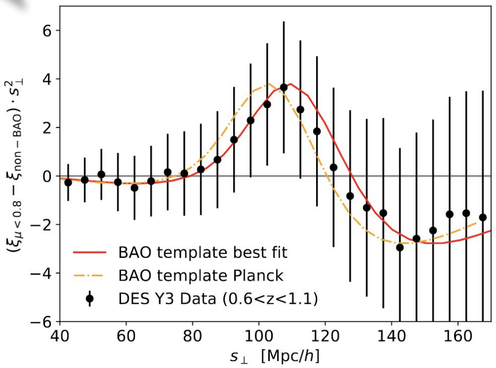


~380.000 yr after the Big Bang





BAO galaxy (DES Coll. 22)



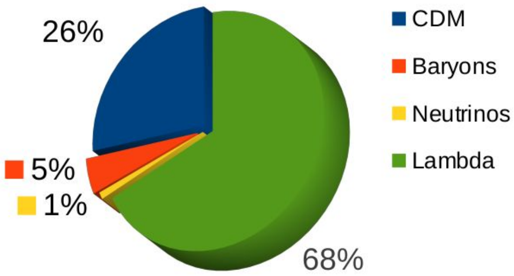
~10^{10} yr after the Big Bang

Several cosmological probes point towards a consistent model of

flat ΛCDM

GENERAL FRAMEWORK: CURRENT STATUS

The ΛCDM universe



The ΛCDM model parameters:

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

Hubble constant

ΛCDM+ν parameters: $\Omega_{\rm m},\ \Omega_{\rm b},\ \Omega_{\nu},\ \sigma_8,\ H_0,\ \tau,\ n_s$

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

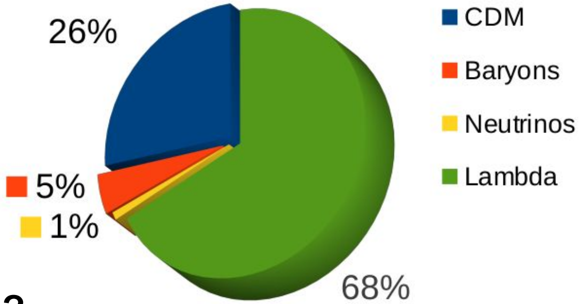
But the two dominants components of this model lack a fundamental theory to connect them with the rest of physics:

- **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 (ΛCDM) or evolving (wCDM)?**
  - **If we interpret DE as vacuum energy, how we do reconcile its value with QFT predictions?**

$$\frac{\rho_{\Lambda \text{ QFT}}}{\rho_{\Lambda \text{ observed}}} \approx 10^{120}$$

- **What is the driver of cosmic inflation?**

The ΛCDM universe

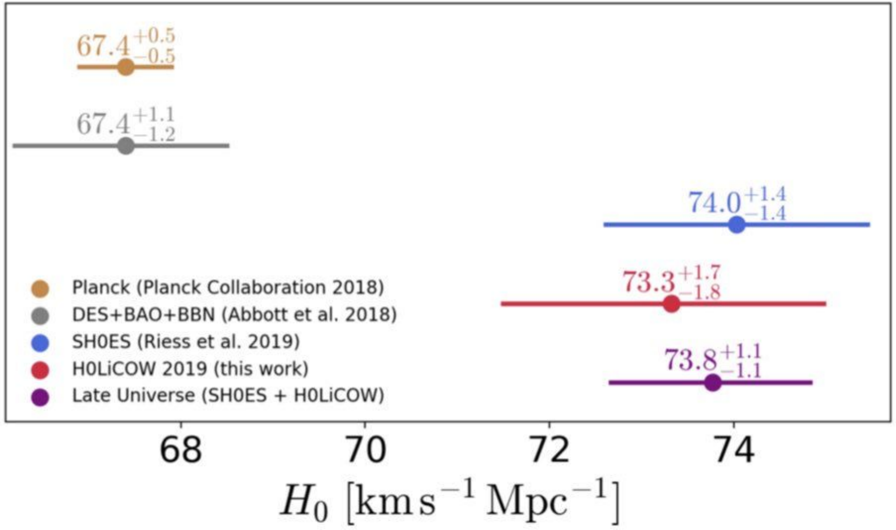


See also: https://arxiv.org/pdf/2405.18307

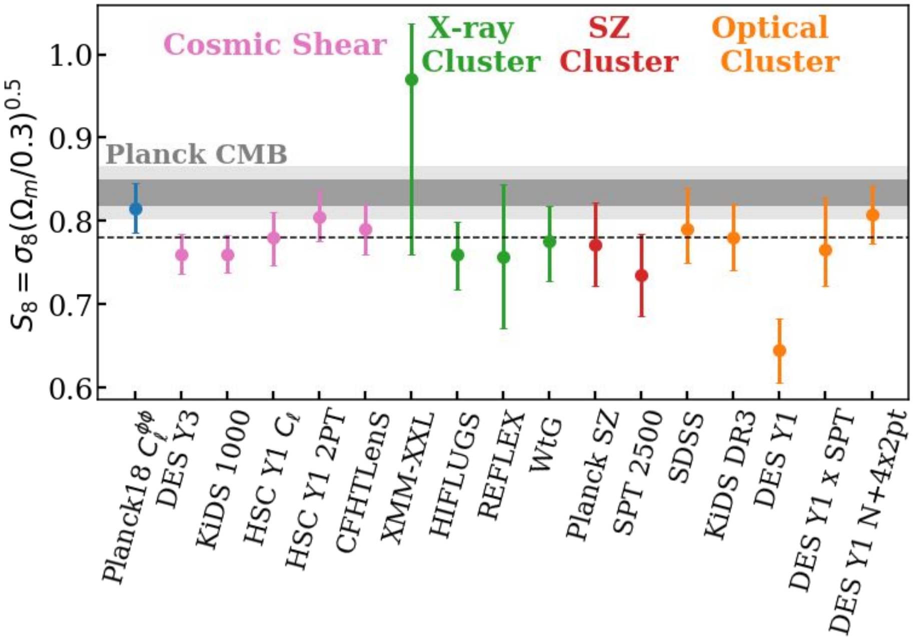
GENERAL FRAMEWORK: CURRENT STATUS

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:



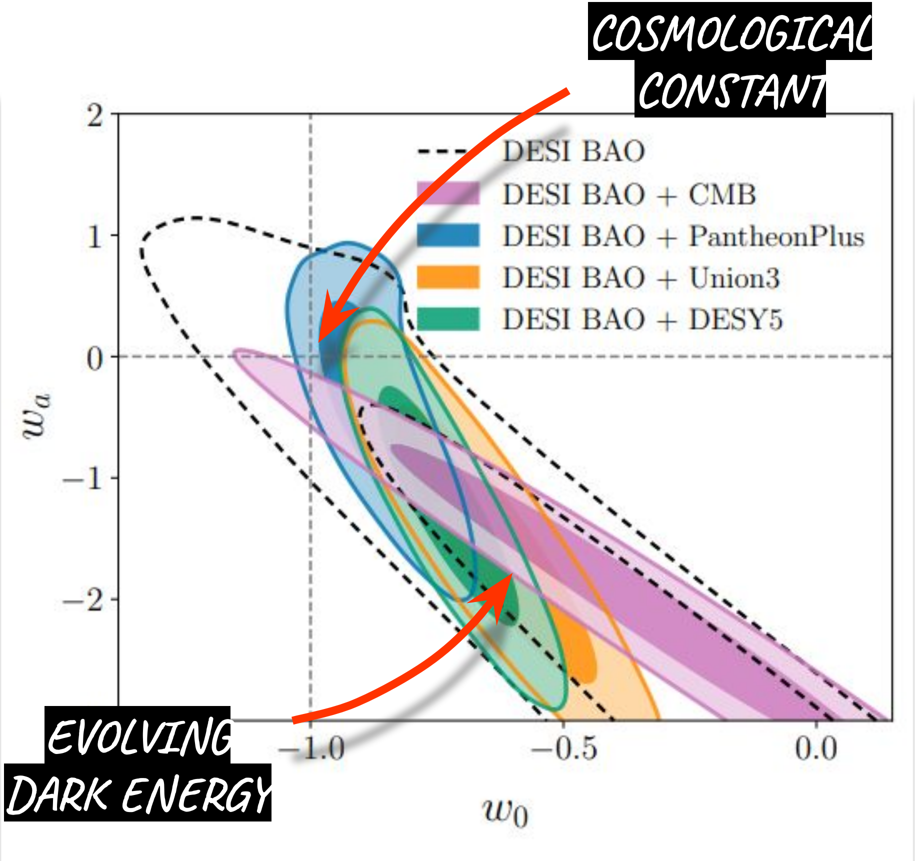
Tension on S_8 (growth of structures)



See also: https://arxiv.org/pdf/2406.12106

GENERAL FRAMEWORK: CURRENT STATUS

Latest results from the spectroscopic survey DESI, in combination with other probes, suggest a dark energy with a time-evolving equation of state parameters ($w_0 w_a$CDM) to solve the ΛCDM tension

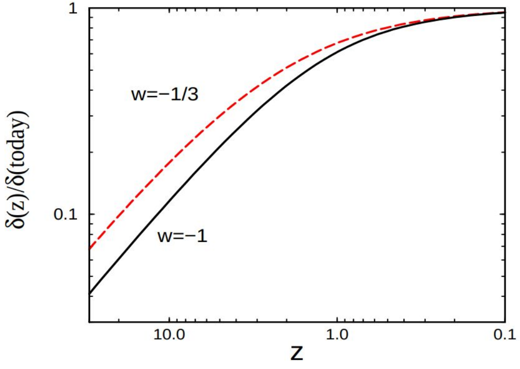


See : https://arxiv.org/pdf/2503.14738

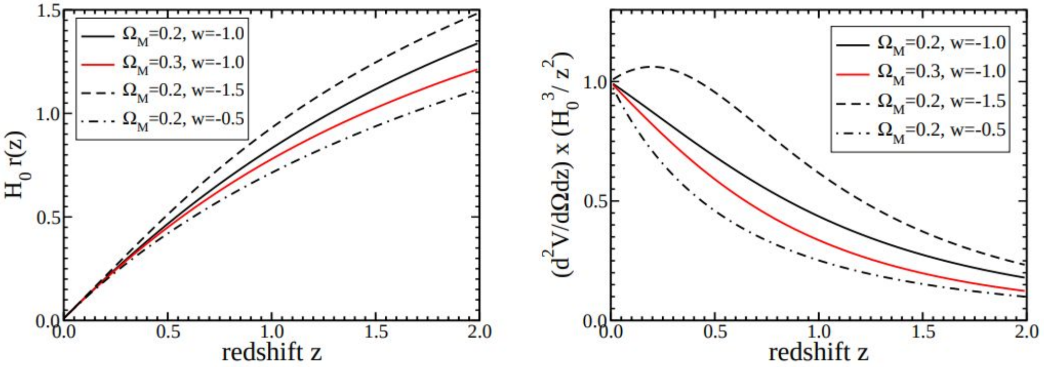
GENERAL FRAMEWORK

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

Growth of density perturbation

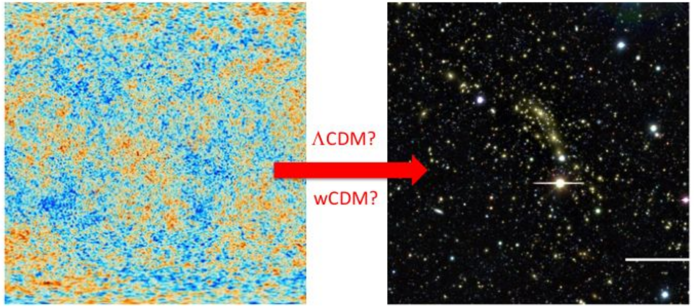


Expansion history



Freiman+08

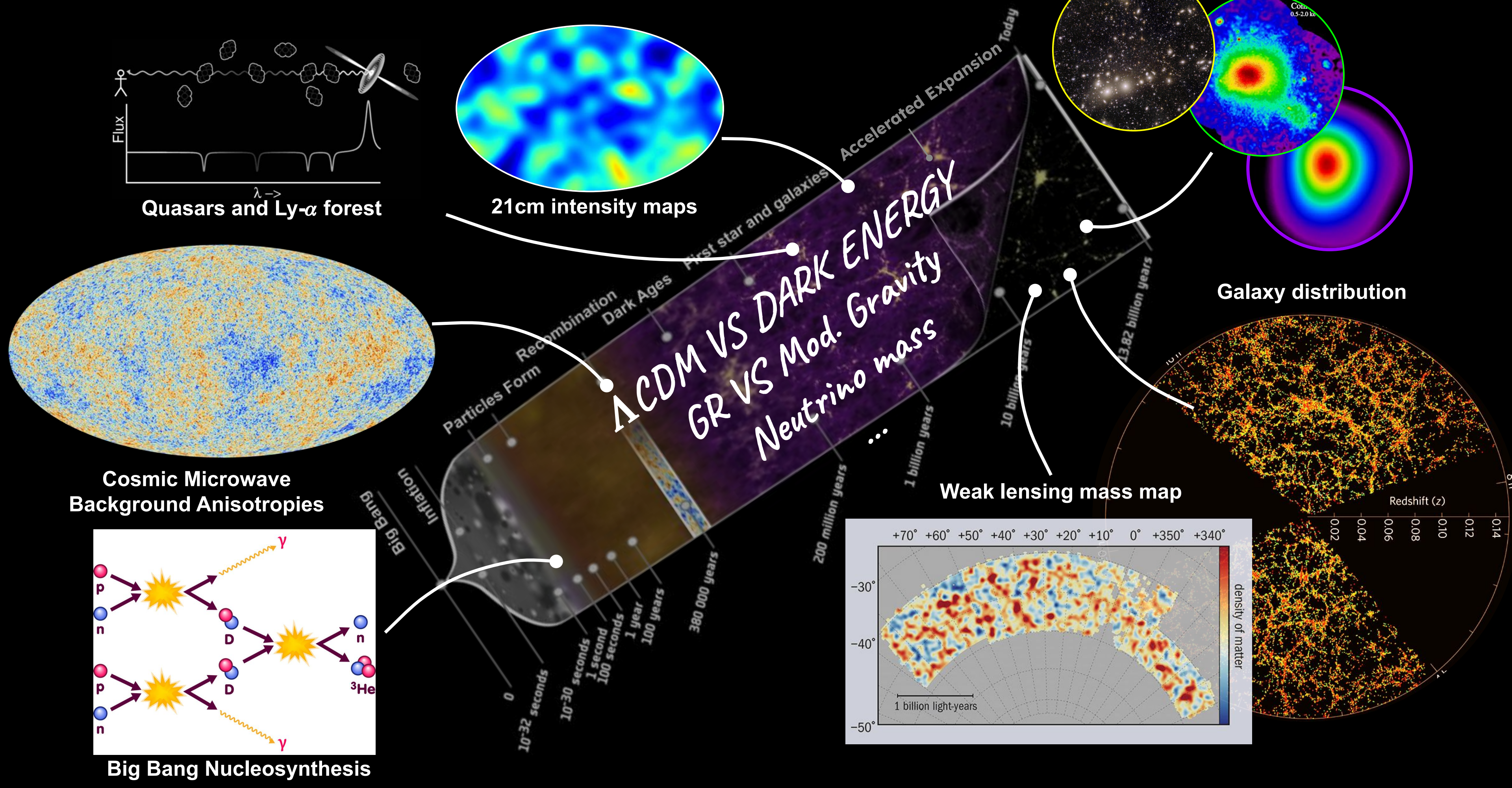
A good strategy is to combine early (i.e. CMB) and late time Universe probes to maximize the redshift leverage, and thus stress test the cosmological models



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

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

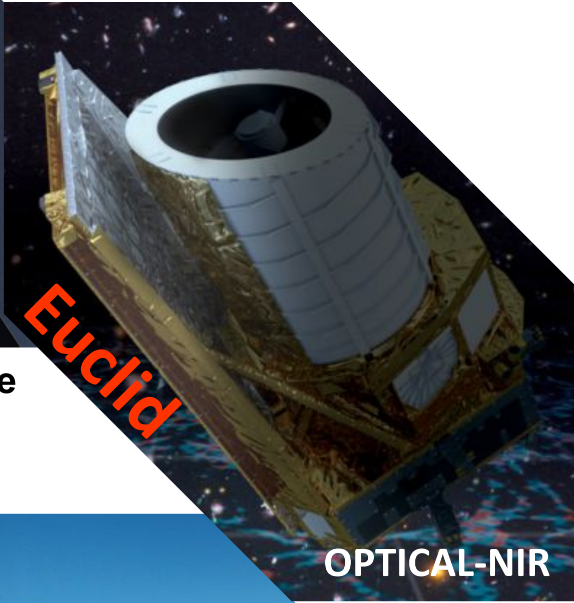
GENERAL FRAMEWORK: COSMOLOGICAL PROBES



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

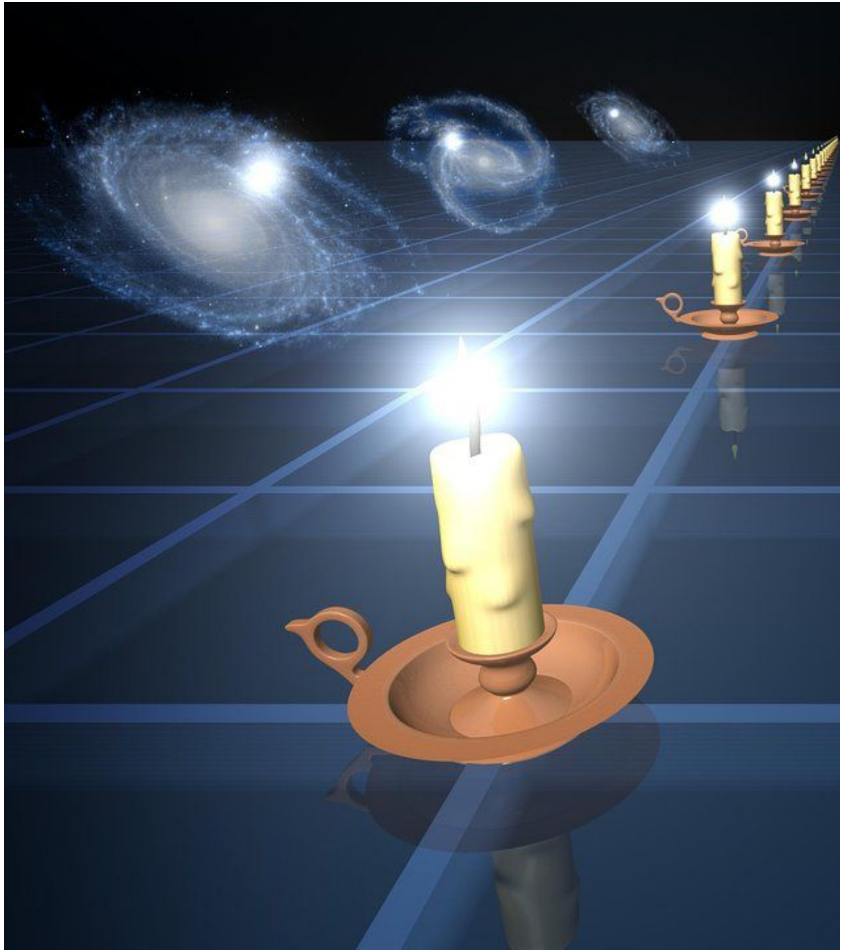
STANDARD CANDLES: SUPERNOVAE IA

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!

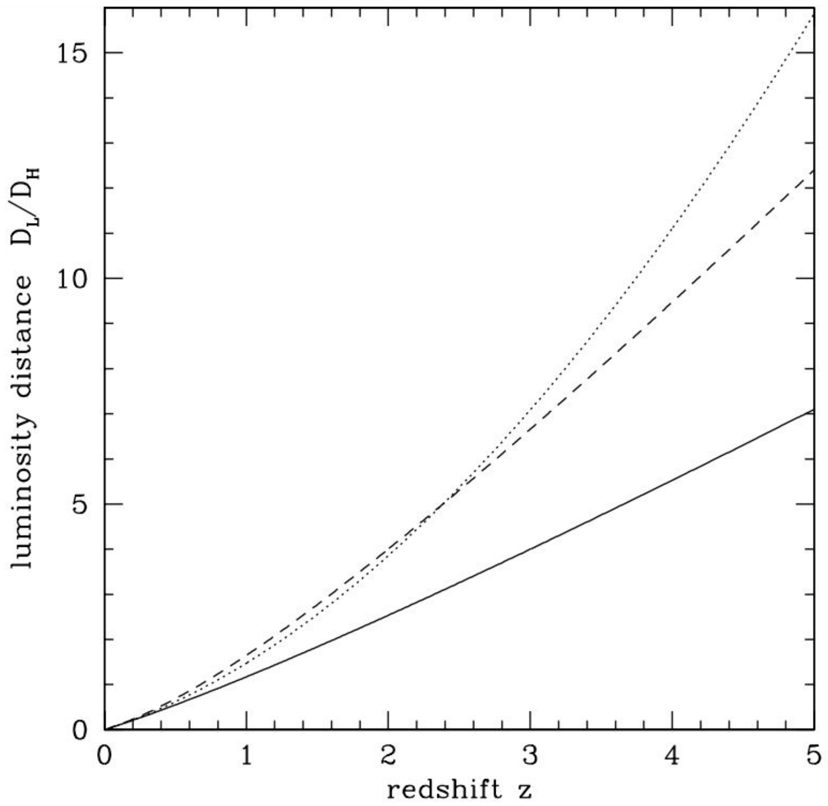


Figure 3: The dimensionless luminosity distance D_L/D_H. The three curves are for the three world models, $(\Omega_M, \Omega_\Lambda) = (1, 0)$, solid; $(0.05, 0)$, dotted; and $(0.2, 0.8)$, dashed.

DISTANCE MODULUS

Apparent magnitude:

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

Distance modulus:

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

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

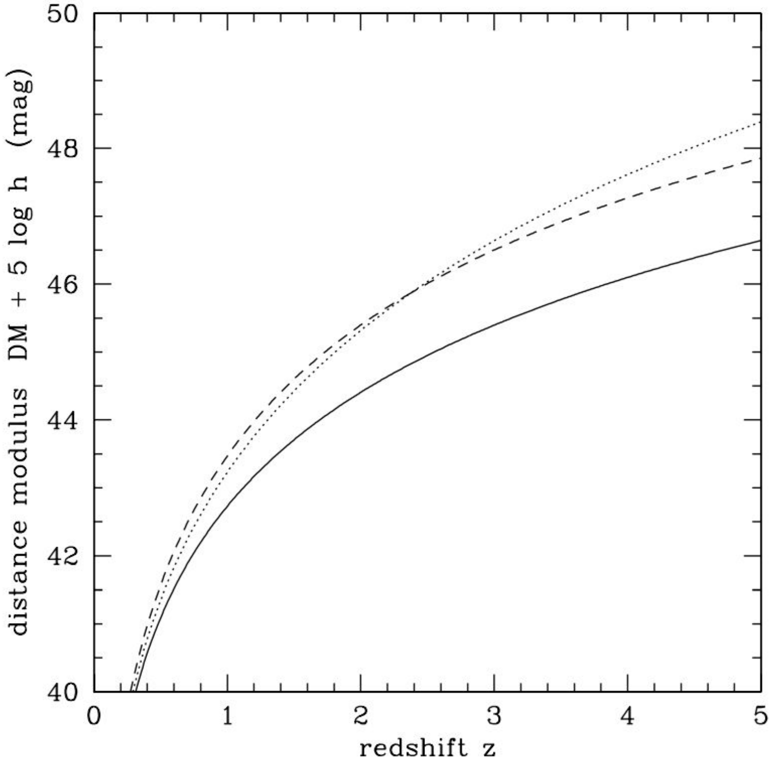


Figure 4: The distance modulus DM. The three curves are for the three world models, $(\Omega_M, \Omega_\Lambda) = (1, 0)$, solid; $(0.05, 0)$, dotted; and $(0.2, 0.8)$, dashed.

CEPHEIDS

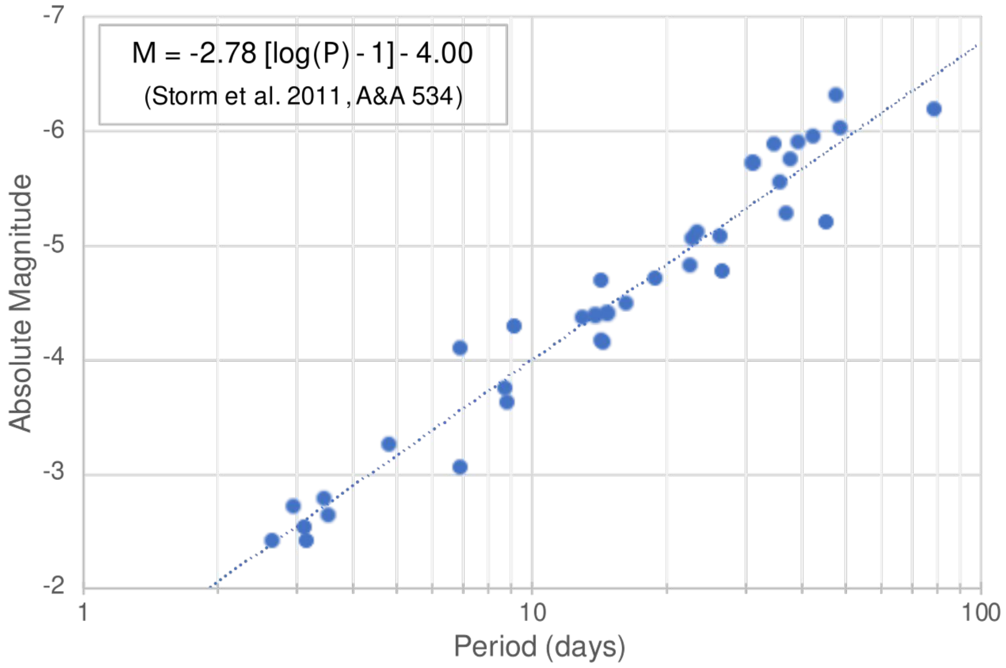
Pulsating stars with a well-defined relationship between their **pulsation period** and **intrinsic luminosity**

Period–Luminosity Relation (Leavitt Law, 1908) allows us to determine their **absolute magnitude**

→ **First standard candle** used in astronomy.

Role in Cosmology:

- Crucial rungs in the **cosmic distance ladder**
- Used to anchor the calibration of **Type Ia Supernovae**



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 ($M_{Ch} \sim 1.4\ M_{\odot}$); after that the star 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

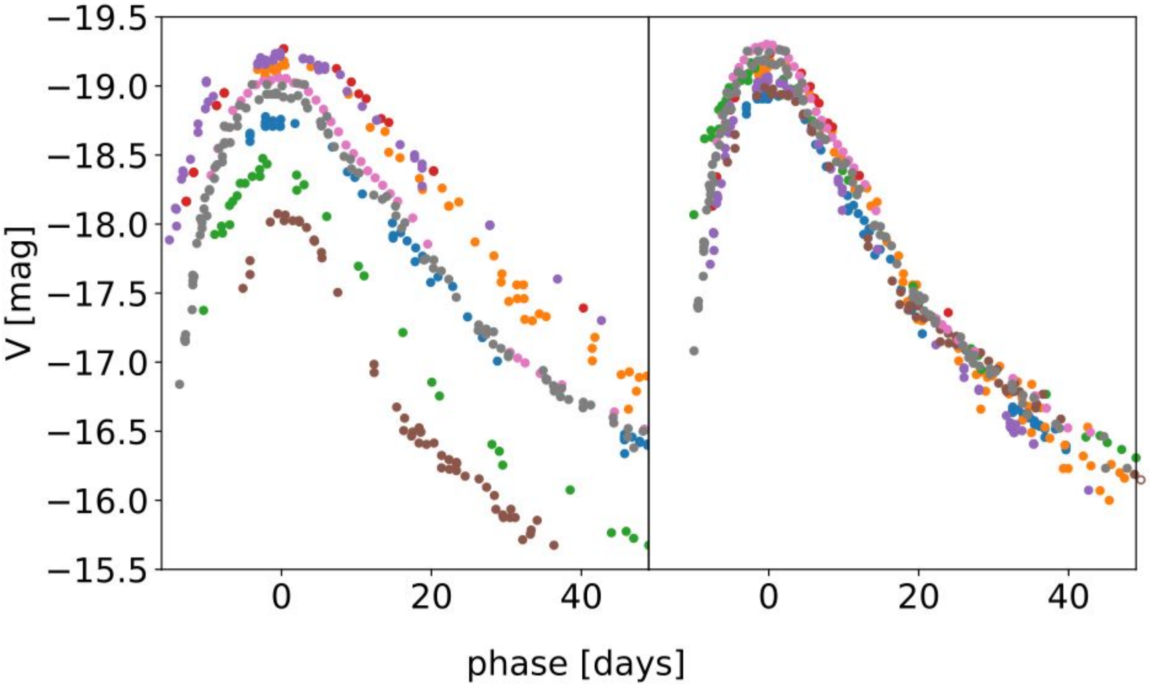


Fig. 6 Illustration of the standardization of SN Ia light curves using the stretch factor. Left panel shows the light curve in absolute V magnitude (corrected for extinction) for a sample on nearby SNe Ia with different decline rates. Right panel: after stretching the time axis to match the luminosity 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

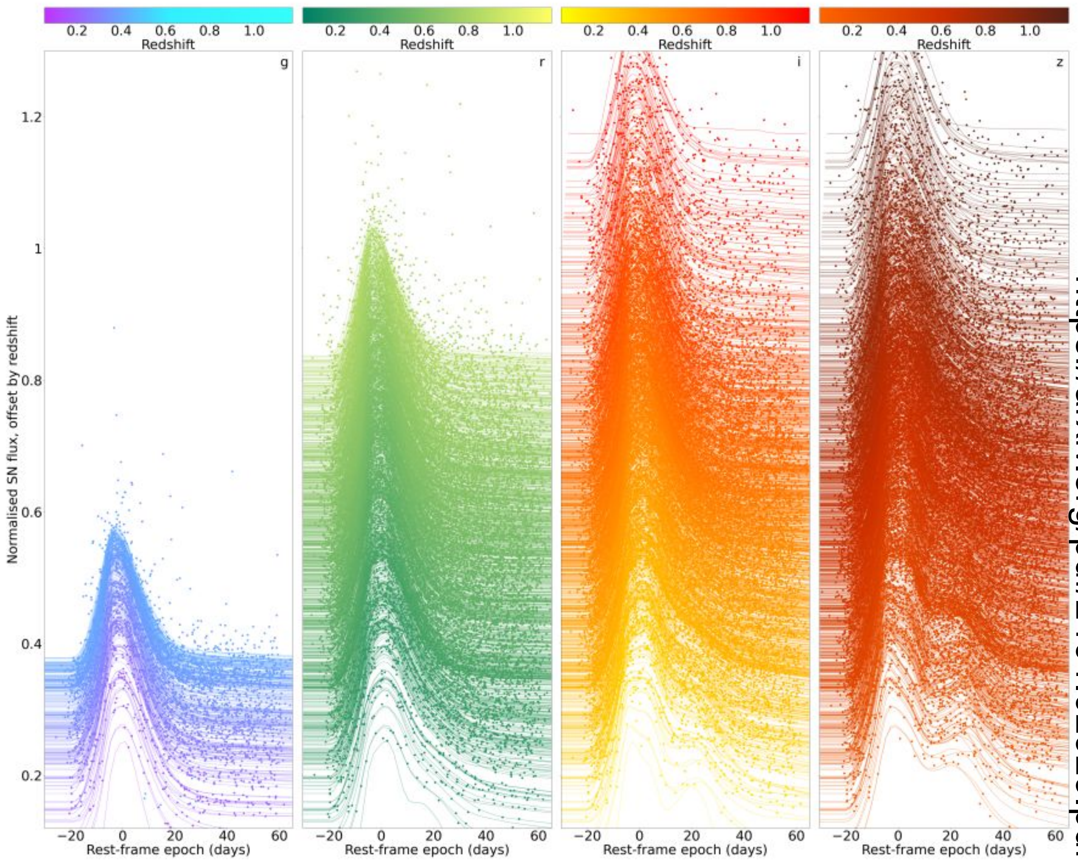


Figure 2. All DES light curves, showing observed magnitudes in g, r, i, and z bands (left to right respectively) normalized by the maximum brightness of each light curve, and with the time-axis de-redshifted to the rest-frame. Each light curve has been arbitrarily offset by their redshift, with higher-redshift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

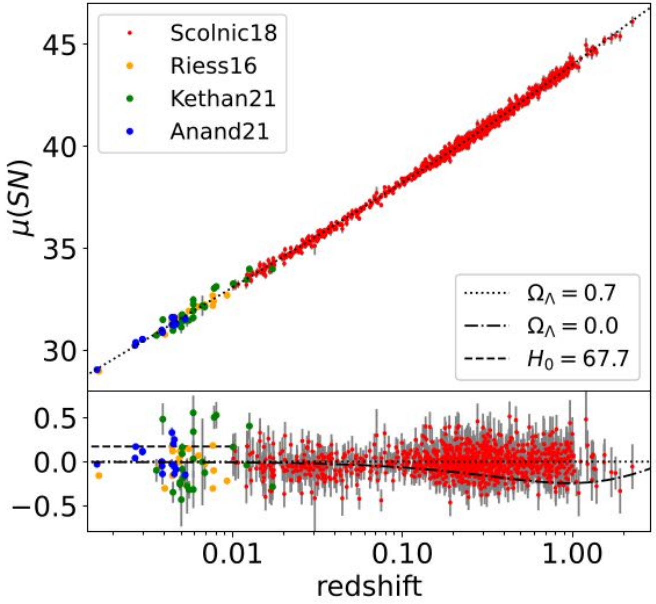
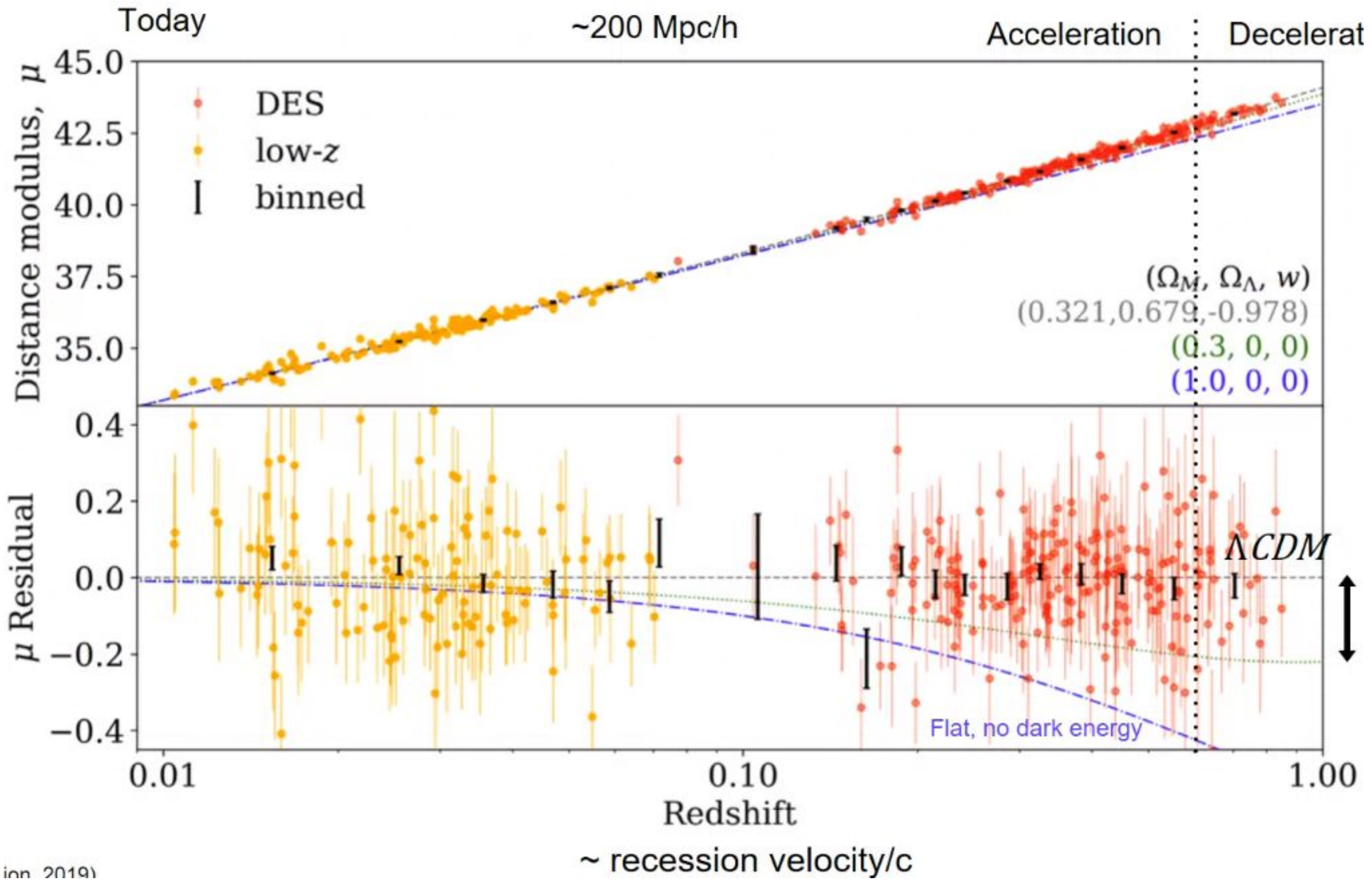


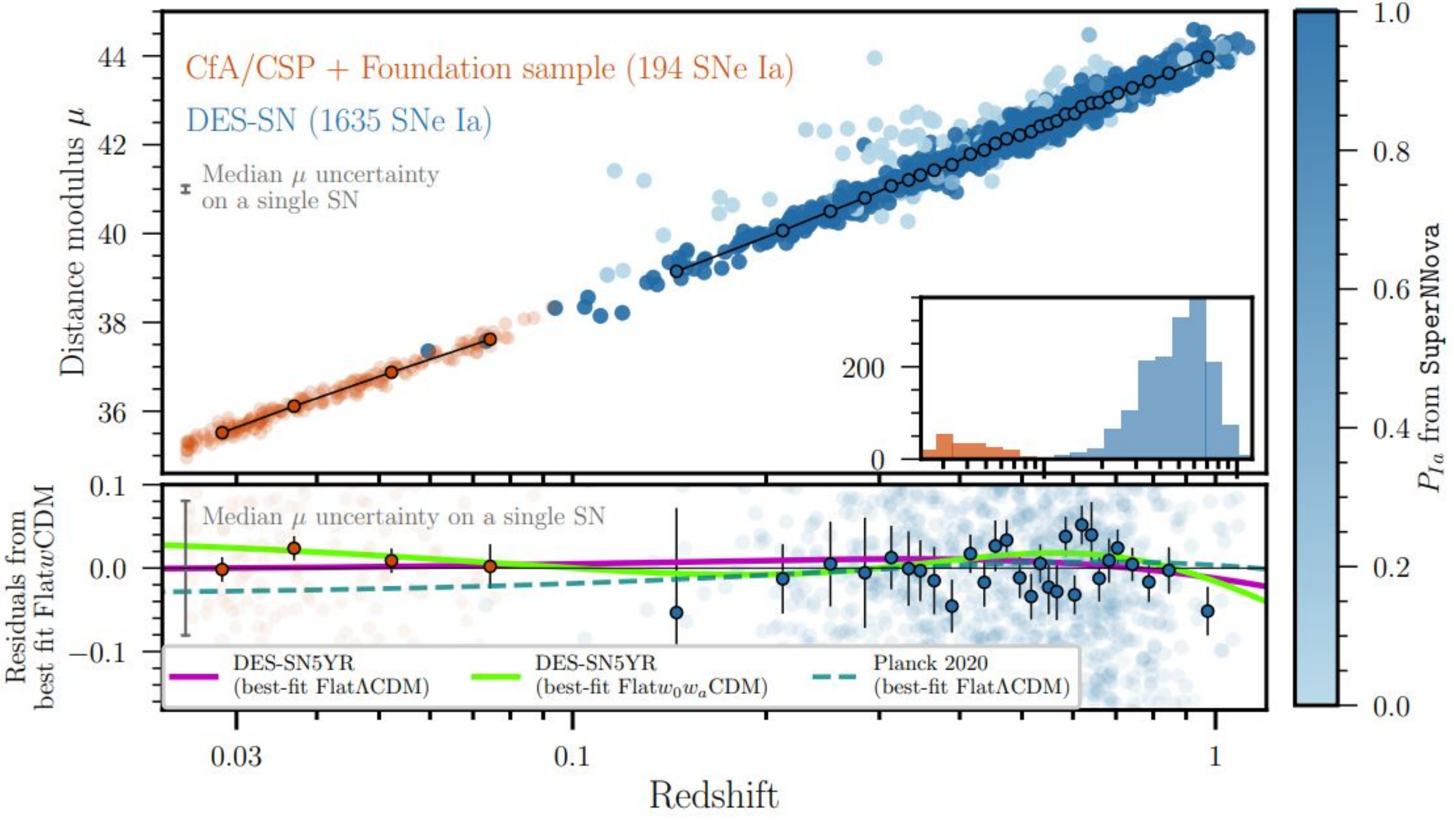
Fig. 8 Hubble diagram for SNe Ia. SNe Ia in the Hubble flow (red points) are from the Pantheon compilation ([179], https://archive.stsci.edu/prepds/ps1cosmo/) whereas low redshift SNe Ia are retrieved from [74] (Riess16, calibrated with Cepheids), [183] (Khetan21, calibrated with SBF) and [184] (Anand21, 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



ion, 2019)

HUBBLE DIAGRAM OF SN Ia



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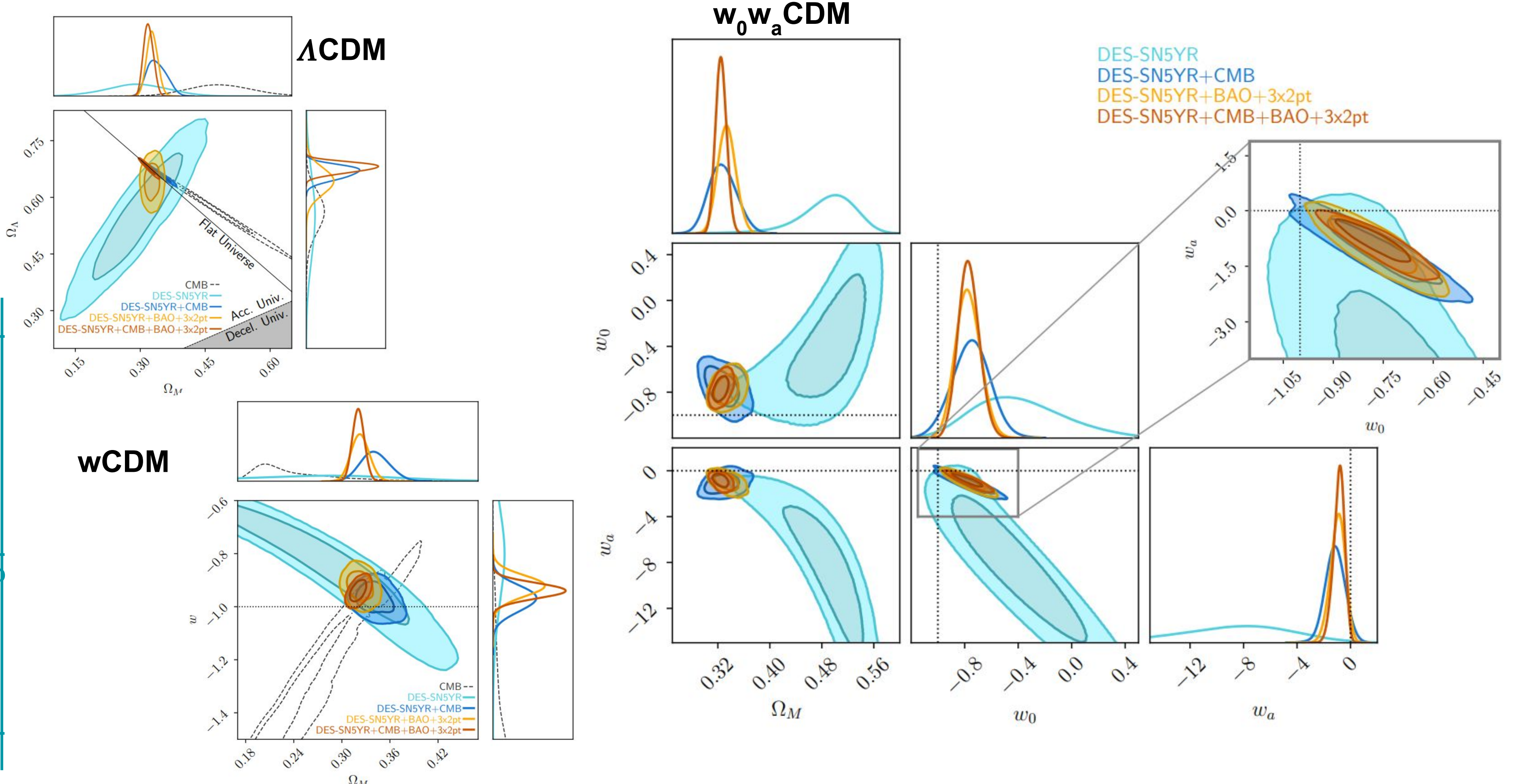
COSMOLOGY WITH SN Ia



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