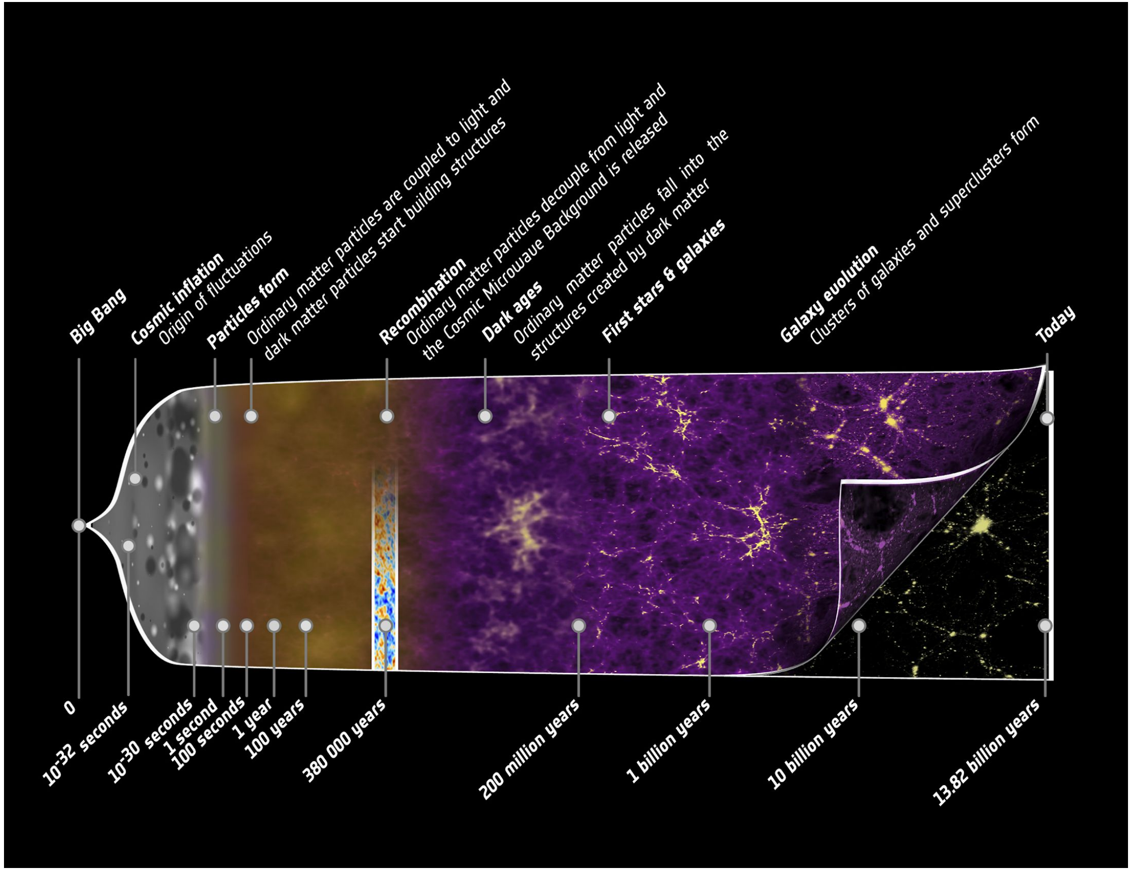
OBSERVATIONAL COSMOLOGY:

COSMOLOGICAL PROBES

A.A. 2025/2026 | 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)

See e.g.: https://arxiv.org/pdf/2509.12121

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 laboratory (Pound-Rebka experiment) and using 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 toward us compared to light traveling along unperturbed paths.

Astrophysical Tests

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

- **Detection of Gravitational Wave Signals**

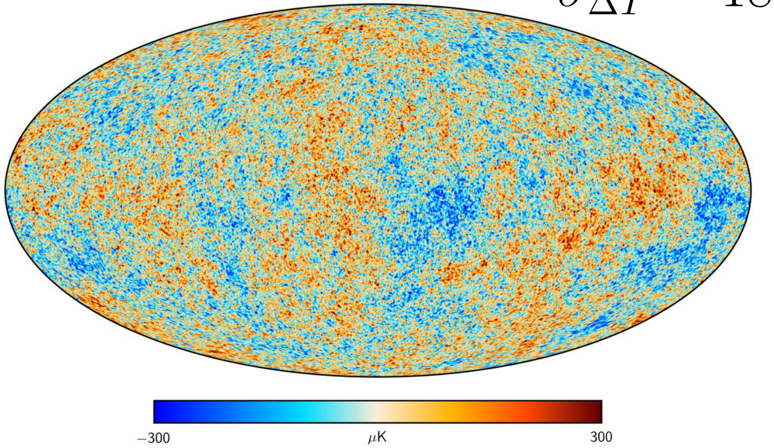
GENERAL FRAMEWORK: COSMOLOGICAL PRINCIPLE

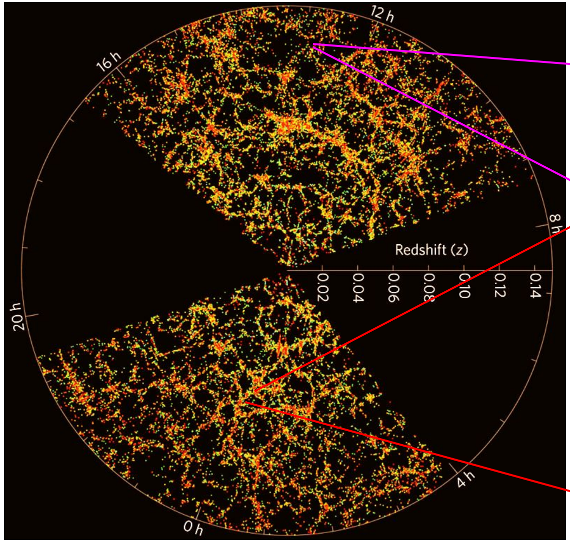
Cosmological principle: the Universe is isotropic* and homogeneous** on large scale (~100 Mpc/h)

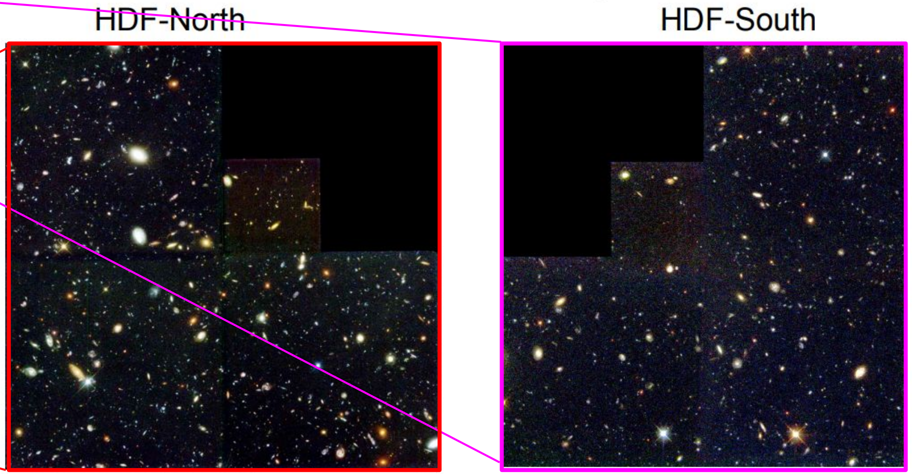
* from observation

** Copernican principle

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



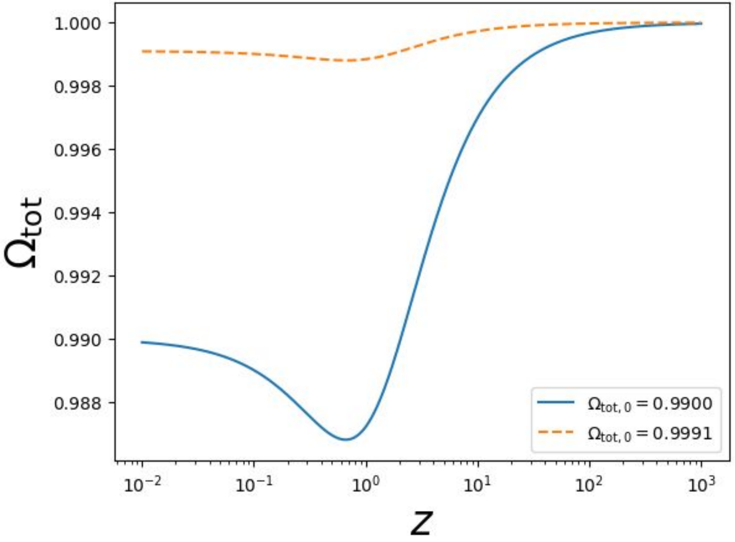


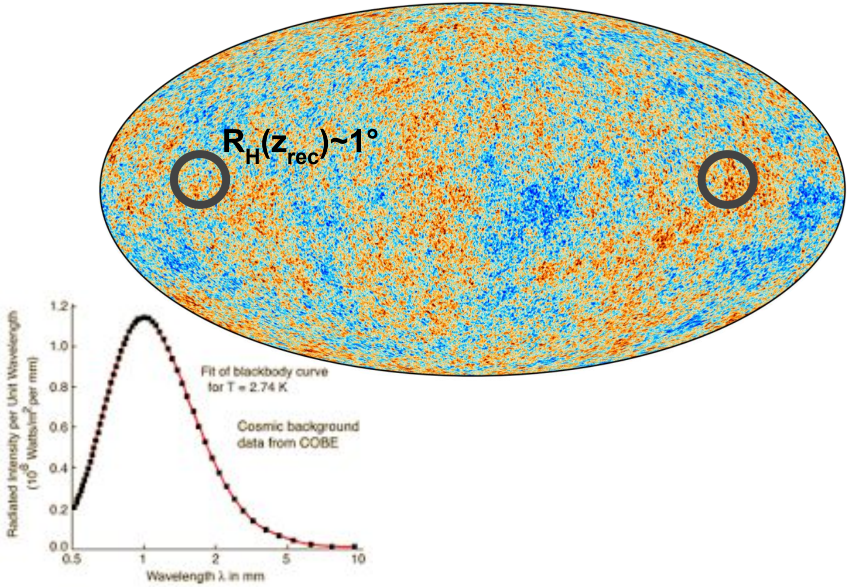


GENERAL FRAMEWORK: INFLATION

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 $\Omega_k \simeq 0$)
- Magnetic monopole problem





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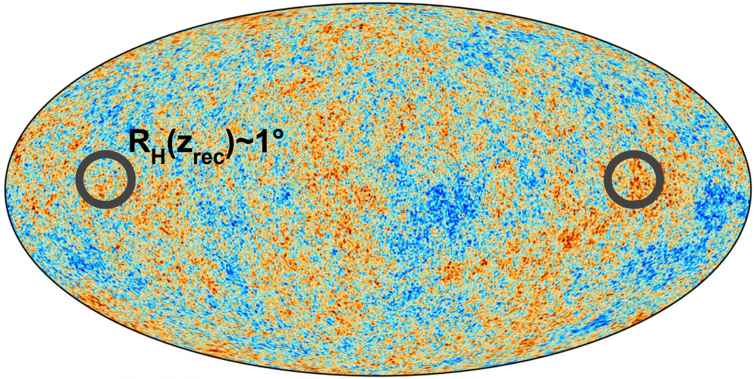
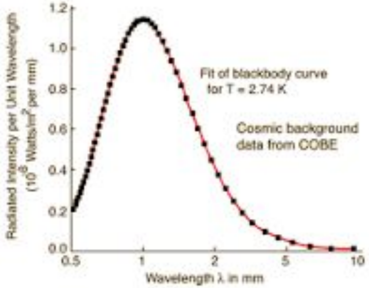
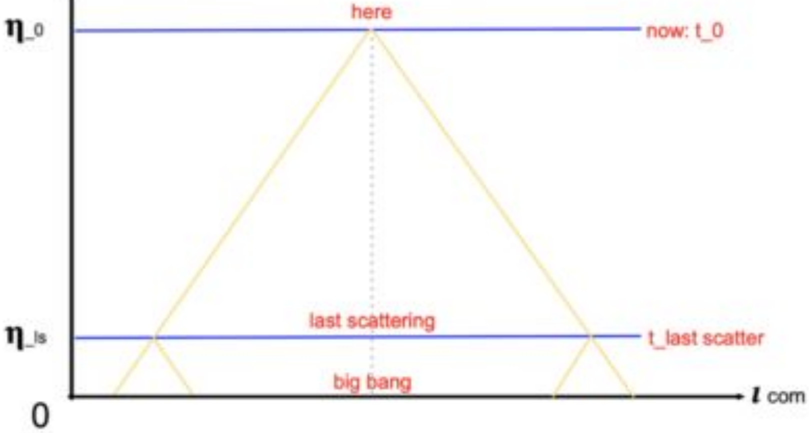
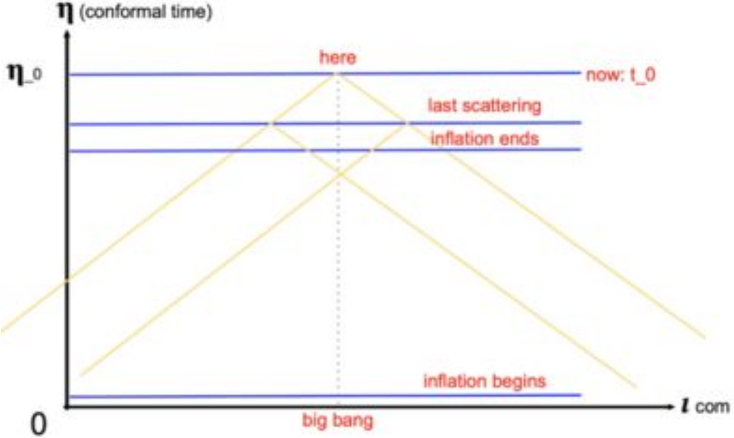




w/o inflation



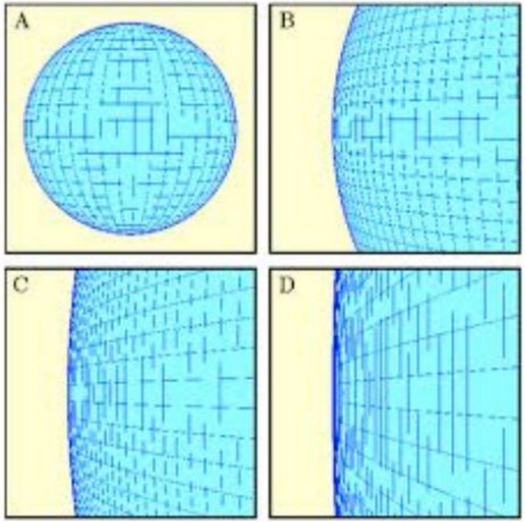
w/ inflation

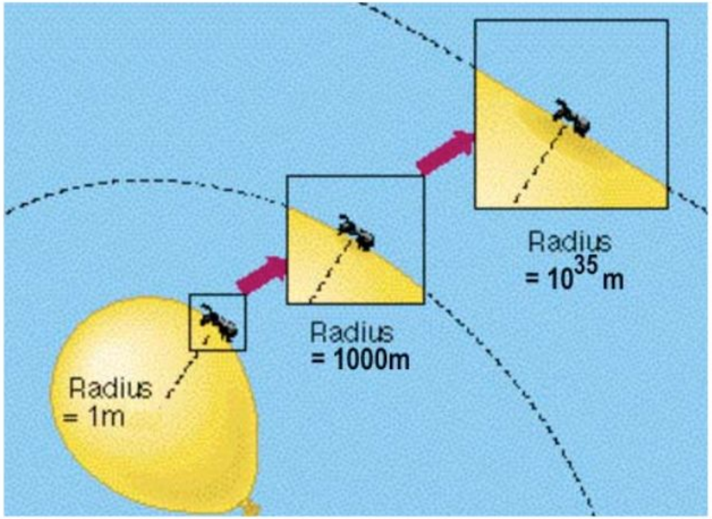


GENERAL FRAMEWORK: INFLATION

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

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

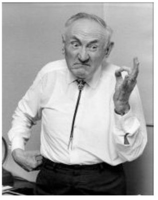




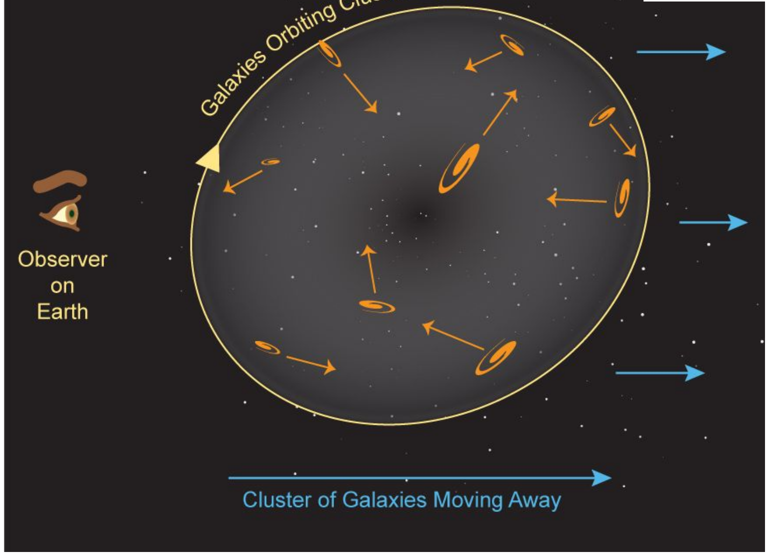
\+ Magnetic monopole problem: Inflation dilutes the Universe by a factor e^{3N} , with N~60

GENERAL FRAMEWORK: DARK MATTER

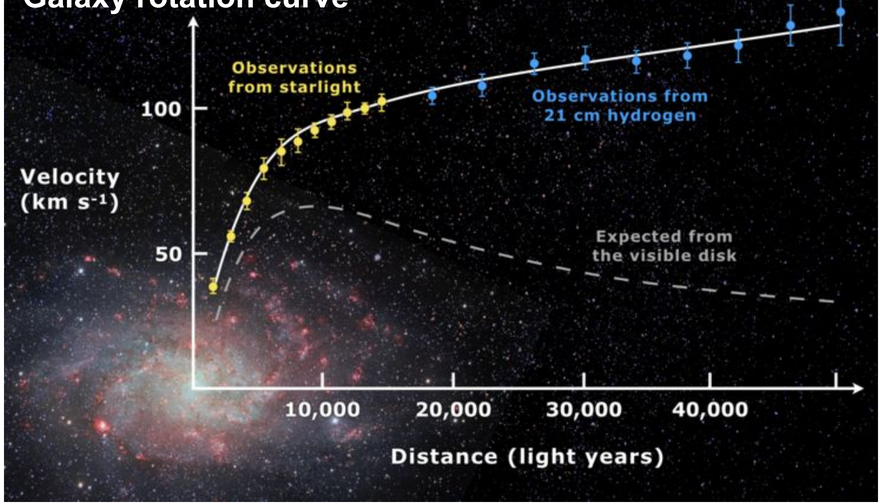
Dark Matter: massive particles which interacts only via gravitational forces



Galaxy velocity dispersion in Coma cluster (Zwicky 1933)



Galaxy rotation curve



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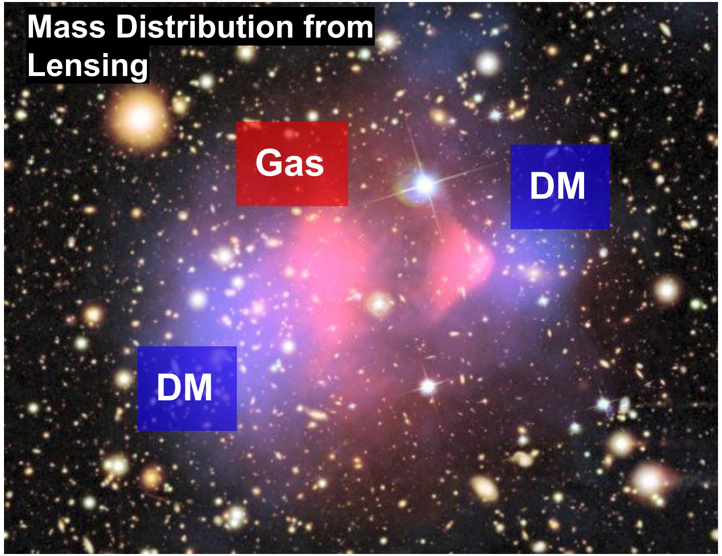
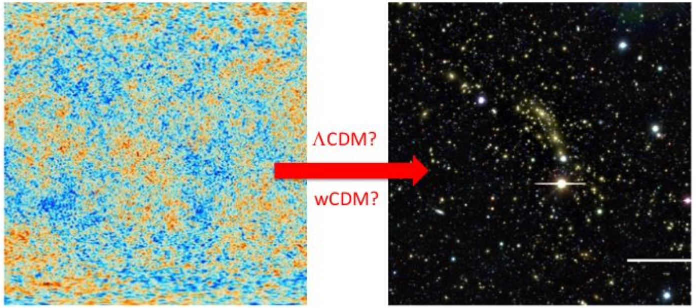
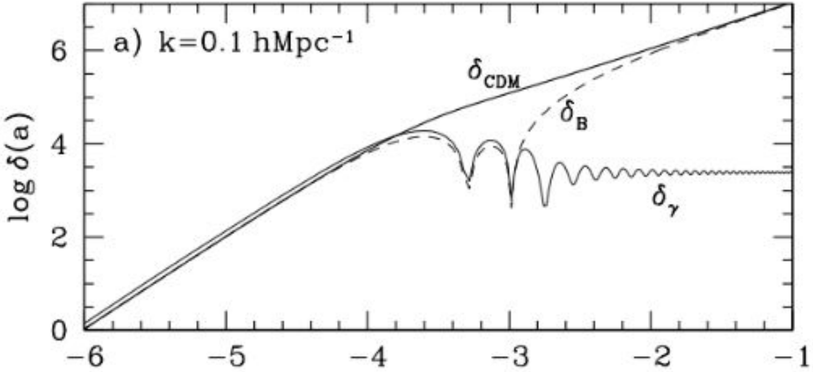


Growth of structures



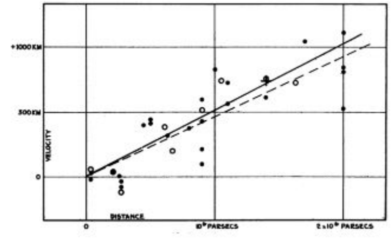
Structure at 380,000 years – 10^{-5} of CMB

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

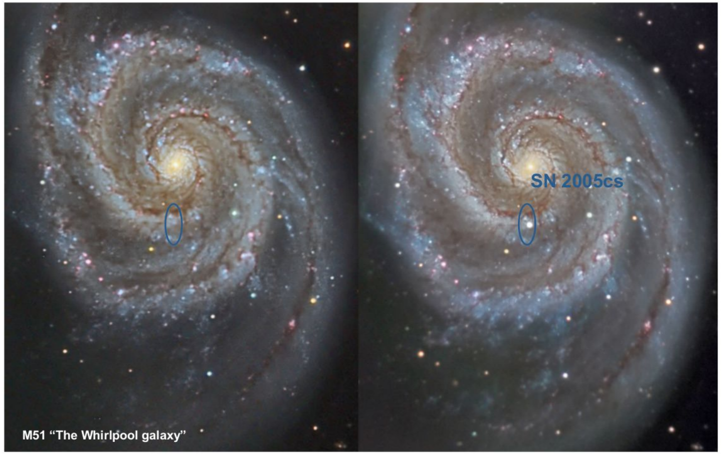


GENERAL FRAMEWORK: ΛCDM MODEL

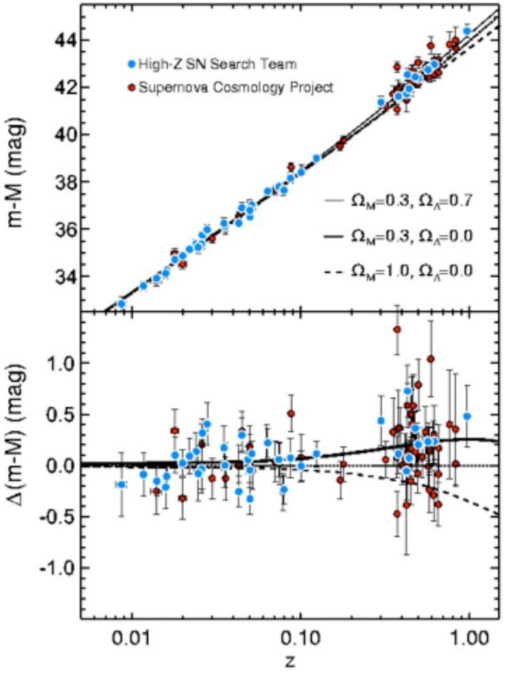
Accelerated expansion: the Universe is undergoing a phase of accelerated expansion driven by a dark energy component, Λ



Hubble 1929



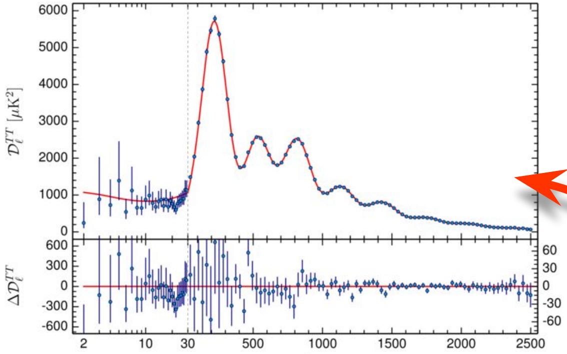
M51 “The Whirlpool galaxy”



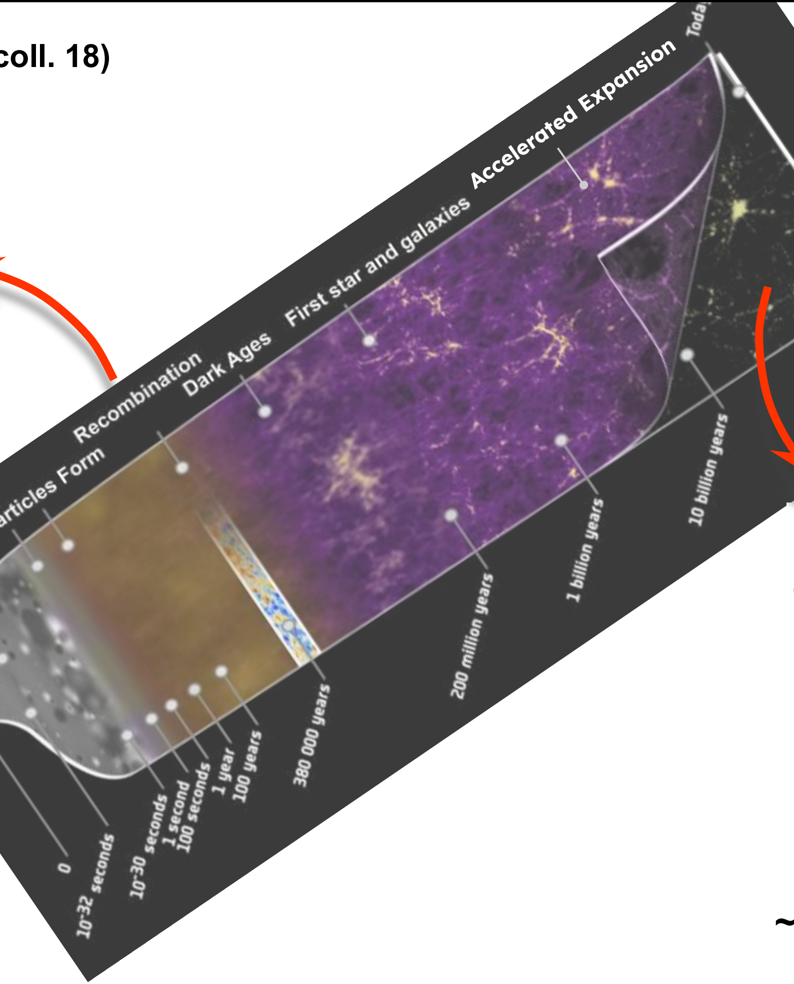
1998/99 High-Z Supernova Search Team and Supernova Cosmology Project found evidence for accelerated expansion of the Universe (2011 Nobel Prize)

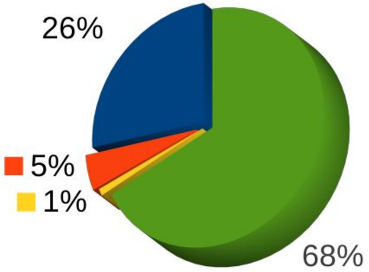
GENERAL FRAMEWORK: CURRENT STATUS

The CMB TT power spectrum (Planck coll. 18)

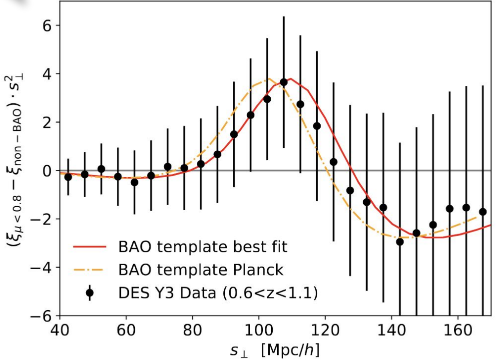


~380.000 yr after the Big Bang





BAO galaxy (DES Coll. 22)



~10^{10} yr after the Big Bang

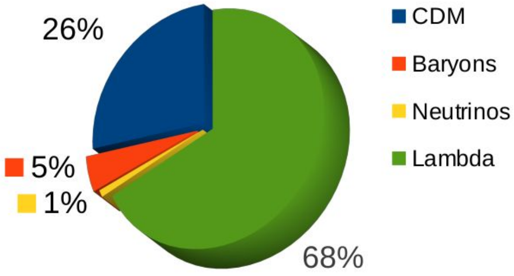
Several cosmological probes point towards a consistent model of

flat ΛCDM

GENERAL FRAMEWORK: CURRENT STATUS

The ΛCDM model parameters:

The ΛCDM universe



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

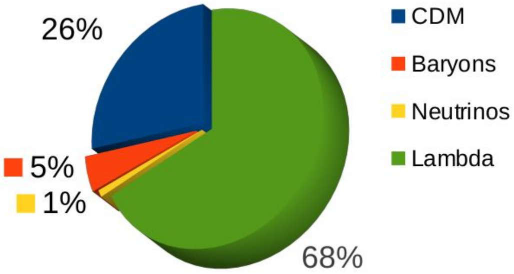
Optical depth

Spectral index of primordial fluctuations

For a flat Universe: $$\Omega_k = 1 - \sum_i \Omega_i = 0$$

GENERAL FRAMEWORK: CURRENT STATUS

The ΛCDM universe



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?**

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

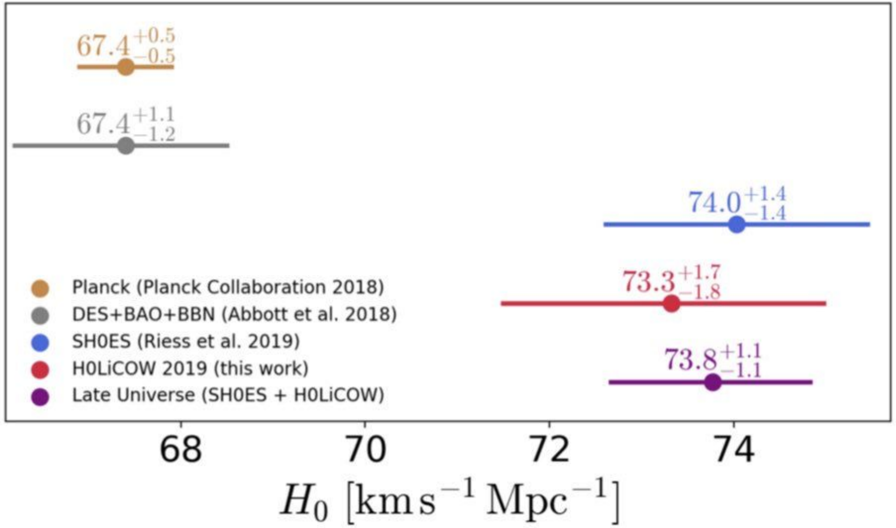
- **What is the driver of cosmic inflation?**

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

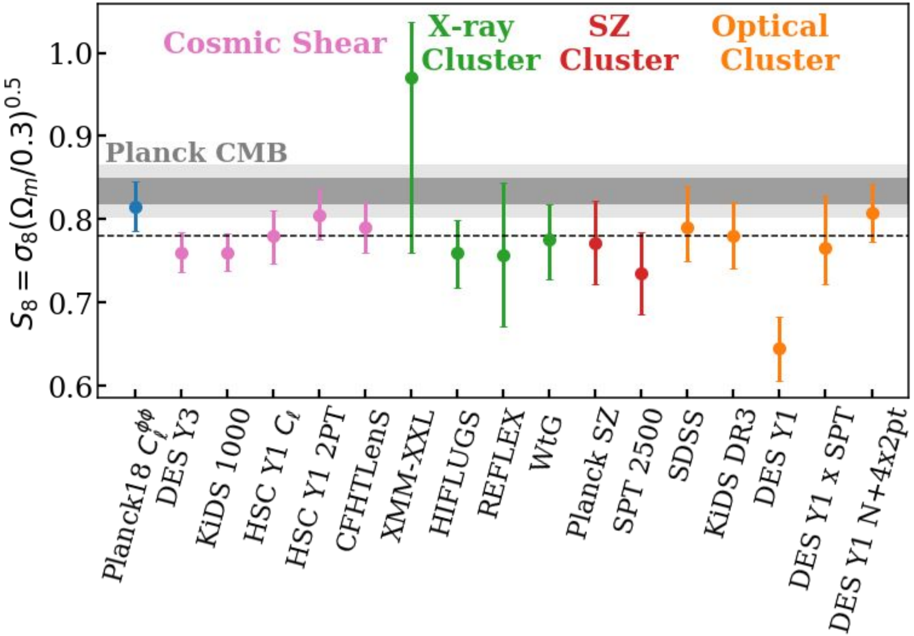
GENERAL FRAMEWORK: CURRENT STATUS

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:



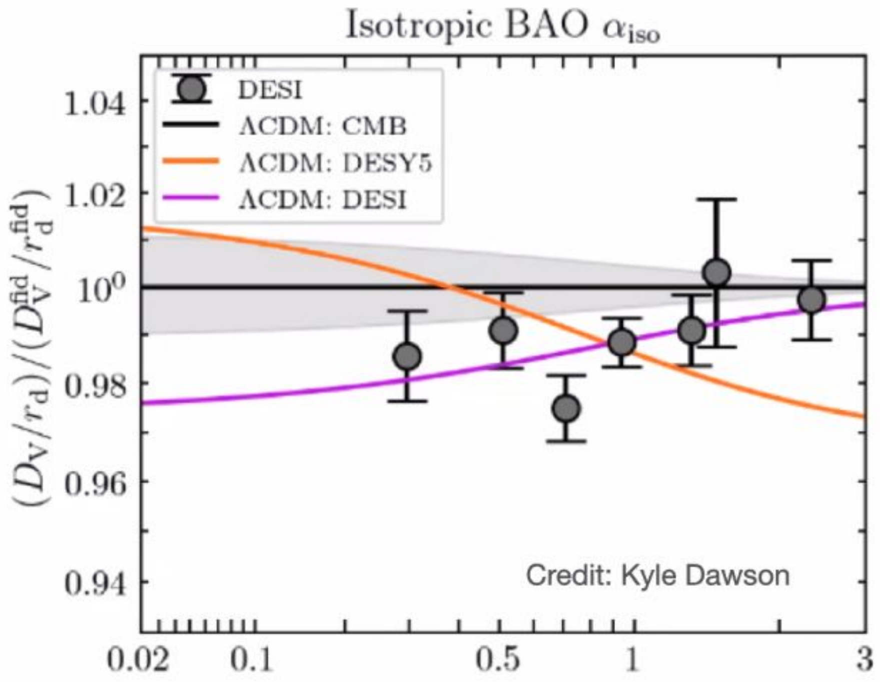
Tension on S_8 (growth of structures)



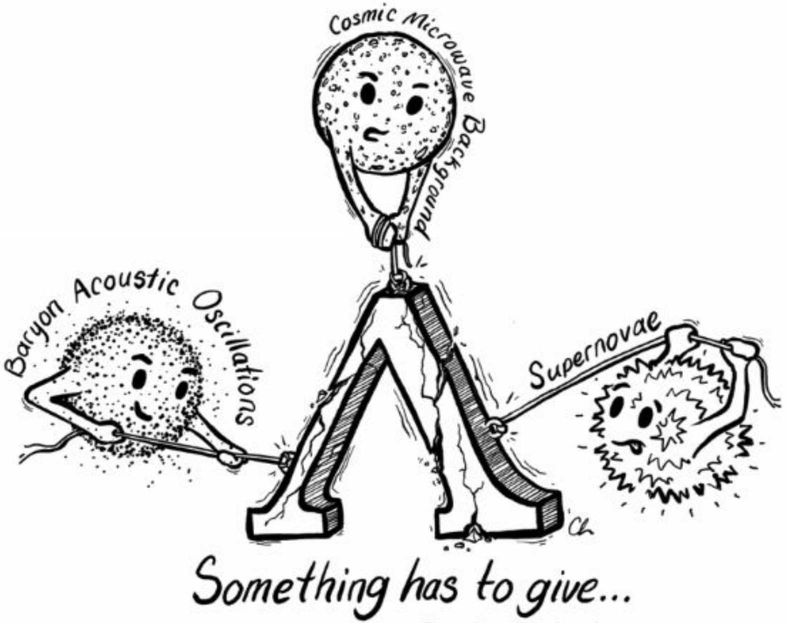
See also: https://arxiv.org/pdf/2406.12106

GENERAL FRAMEWORK: CURRENT STATUS

Recent measurements of the distance-redshift relation challenge the "concordant" model!



Credit: Kyle Dawson

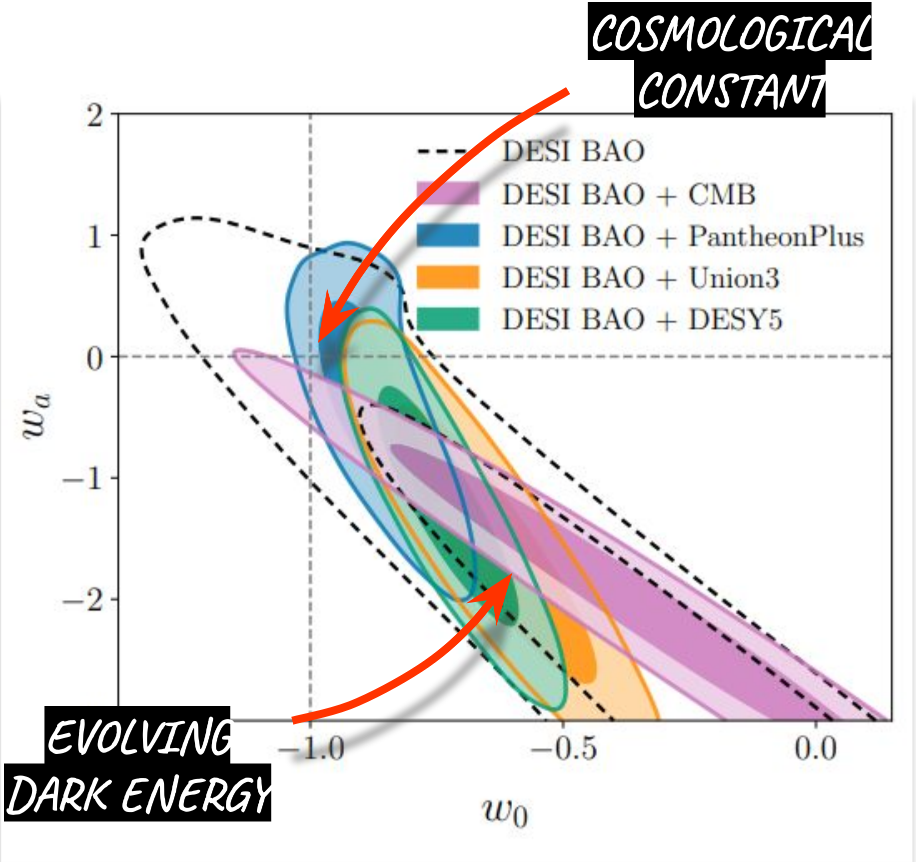


Something has to give...

Credit: Claire Lamman

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_0w_aCDM) to solve the ΛCDM tension



COSMOLOGICAL CONSTANT

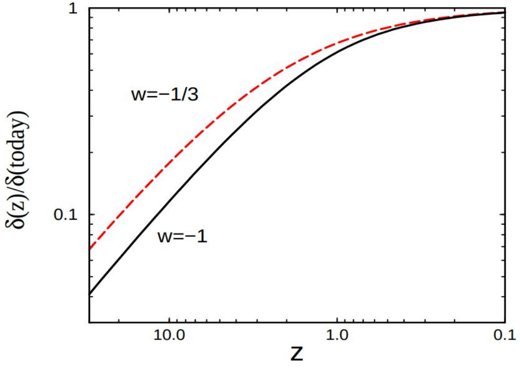
EVOLVING DARK ENERGY

See : https://arxiv.org/pdf/2503.14738
See also: https://arxiv.org/pdf/2603.05472
See also: Looking beyond lambda
See also: The Limits of Cosmology

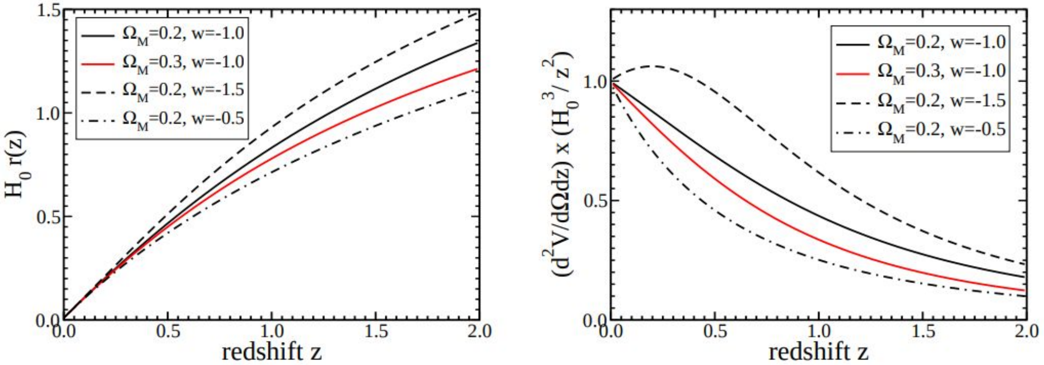
GENERAL FRAMEWORK

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

Growth of density perturbation

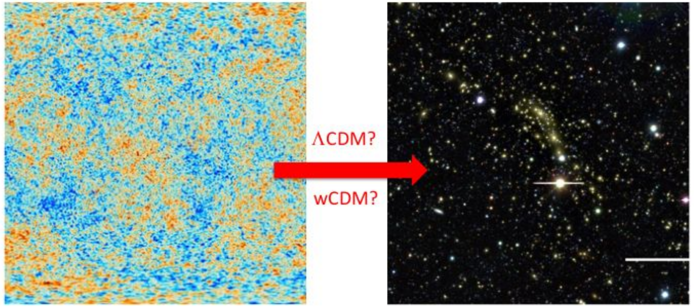


Expansion history



Freiman+08

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



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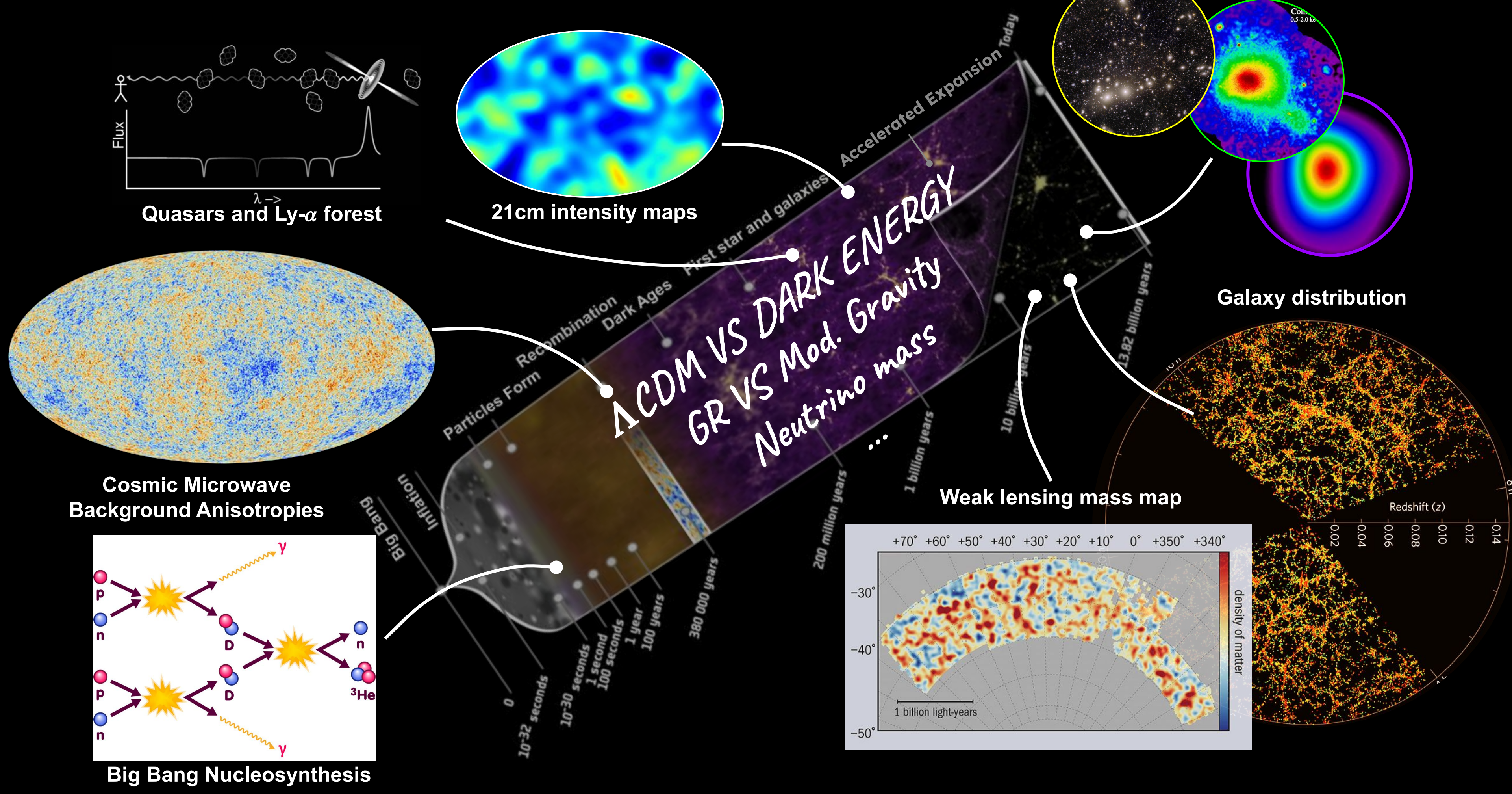
GENERAL FRAMEWORK: COSMOLOGICAL PROBES



ΛCDM VS DARK ENERGY
GR VS Mod. Gravity
Neutrino mass
…

Quasars and Ly-α forest

21cm intensity maps

Galaxy Clusters

Cosmic Microwave Background Anisotropies

Galaxy distribution

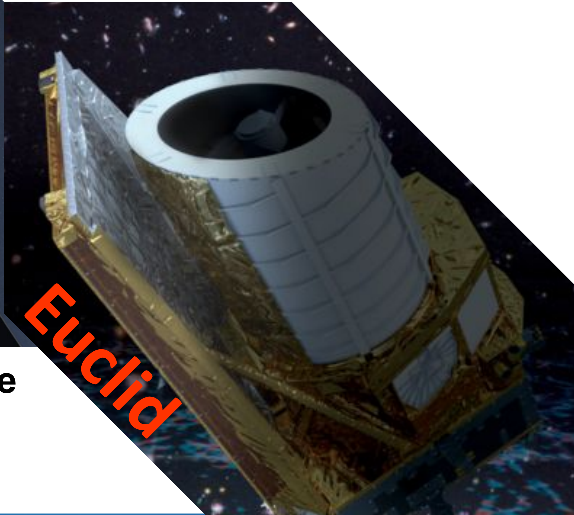
Weak lensing mass map

Big Bang Nucleosynthesis

GENERAL FRAMEWORK: DARK ENERGY PROBES

Dark Energy can be probed analysing:

- History of the expansion rate of the universe: SN Ia, BAO, weak lensing, cluster counting…
- History of the growth rate of 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

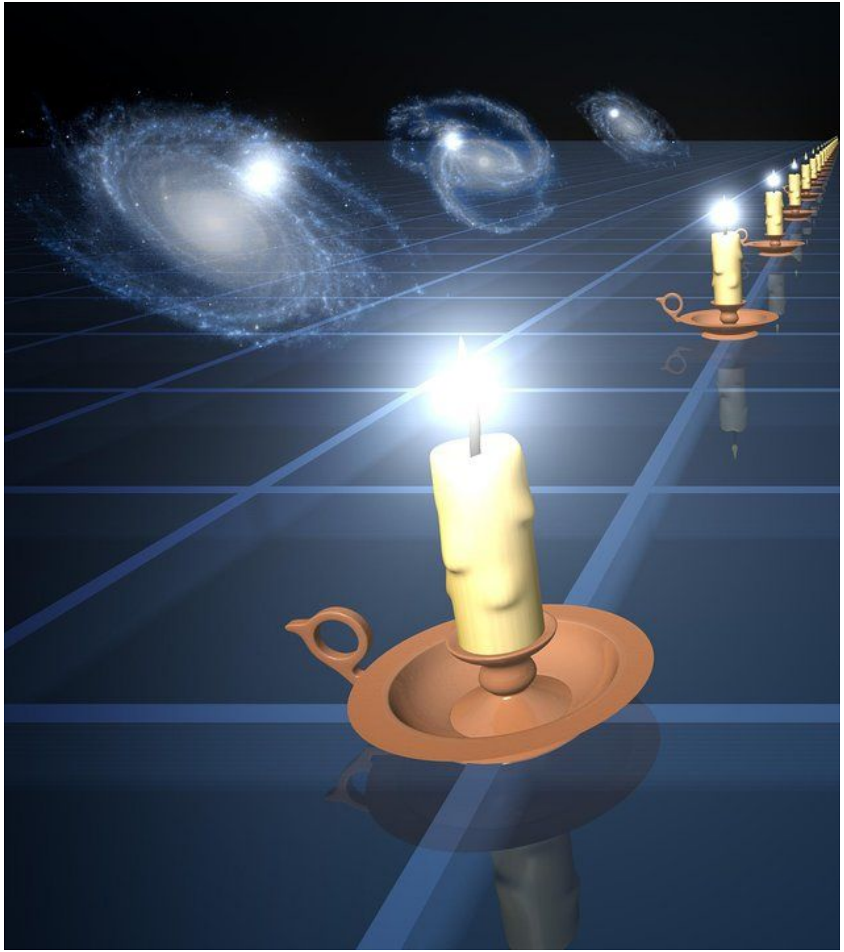
STANDARD CANDLES: SUPERNOVAE IA

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!

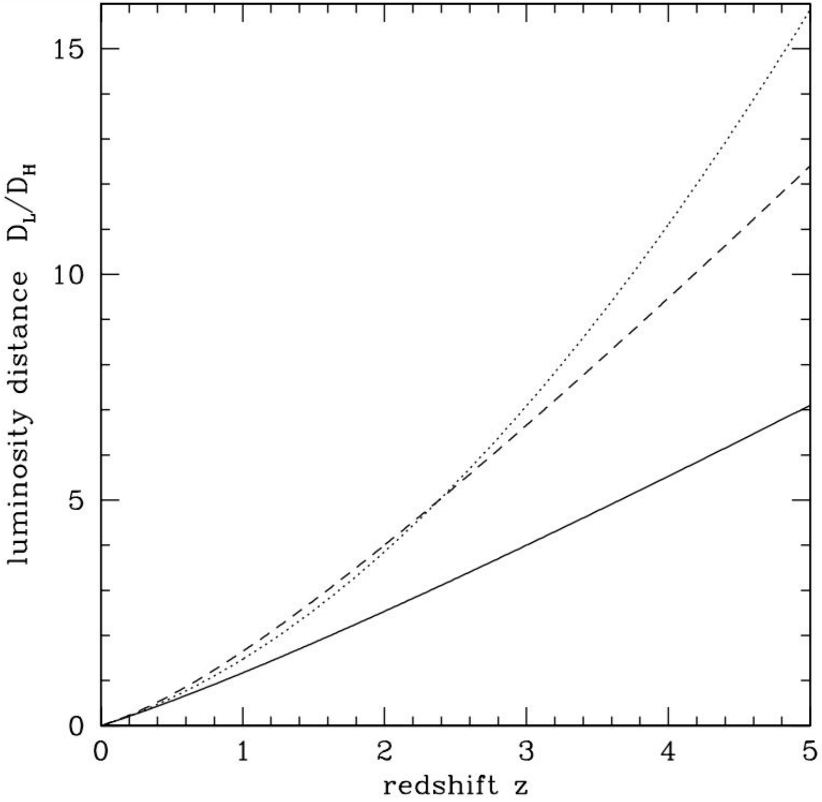


Figure 3: The dimensionless luminosity distance D_L/D_H. The three curves are for the three world models, $(\Omega_M, \Omega_\Lambda) = (1, 0)$, solid; $(0.05, 0)$, dotted; and $(0.2, 0.8)$, dashed.

DISTANCE MODULUS

Apparent magnitude:

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

Distance modulus:

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

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

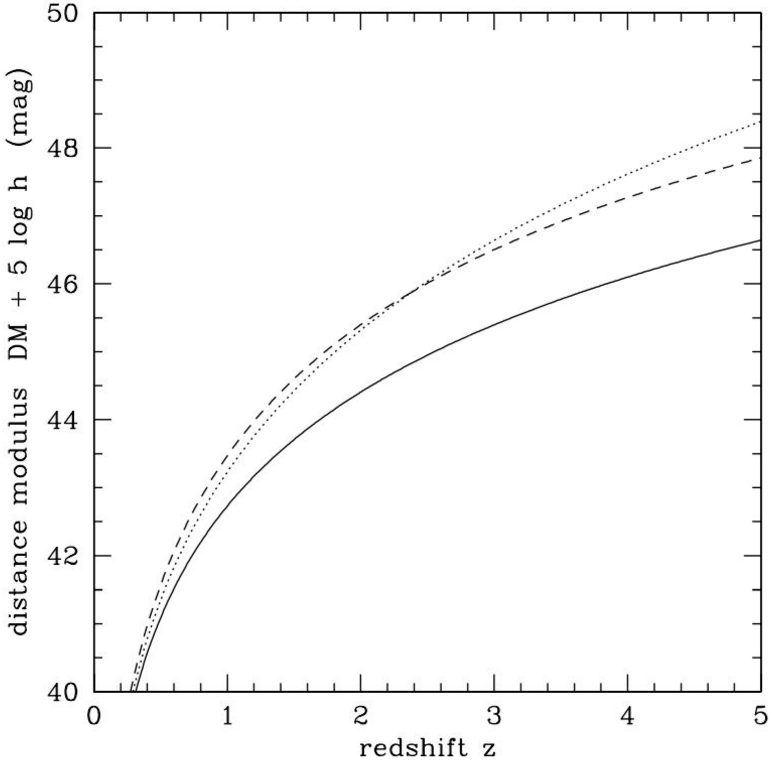


Figure 4: The distance modulus DM. The three curves are for the three world models, $(\Omega_M, \Omega_\Lambda) = (1, 0)$, solid; $(0.05, 0)$, dotted; and $(0.2, 0.8)$, dashed.

STANDARD CANDLE: CEPHEIDS

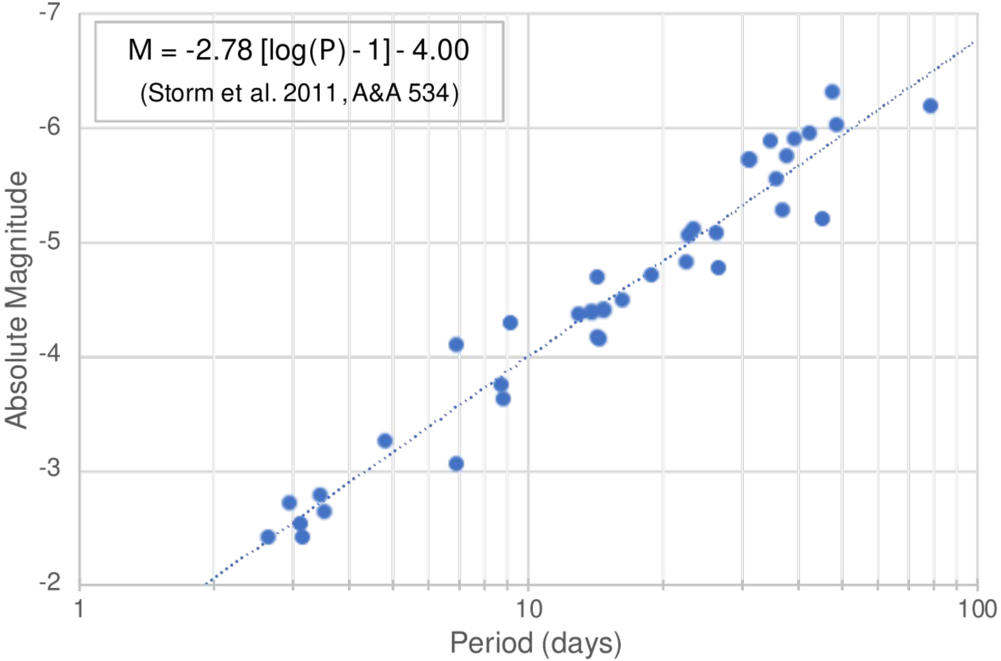
Pulsating stars with a well-defined relationship between their **pulsation period** and **intrinsic luminosity**

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**



STANDARD CANDLE: 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

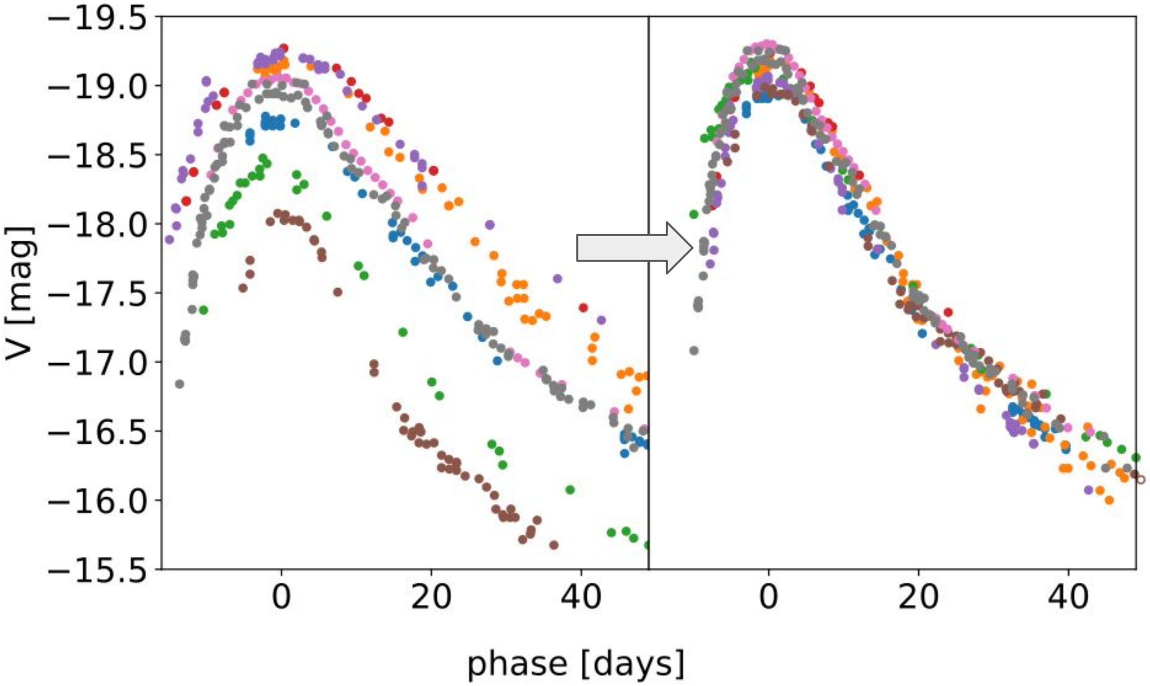


Fig. 6 Illustration of the standardization of SN Ia light curves using the stretch factor. Left panel shows the light curve in absolute V magnitude (corrected for extinction) for a sample on nearby SNe Ia with different decline rates. Right panel: after stretching the time axis to match the luminosity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

SUPERNOVAE TYPE Ia

Standardisation: 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

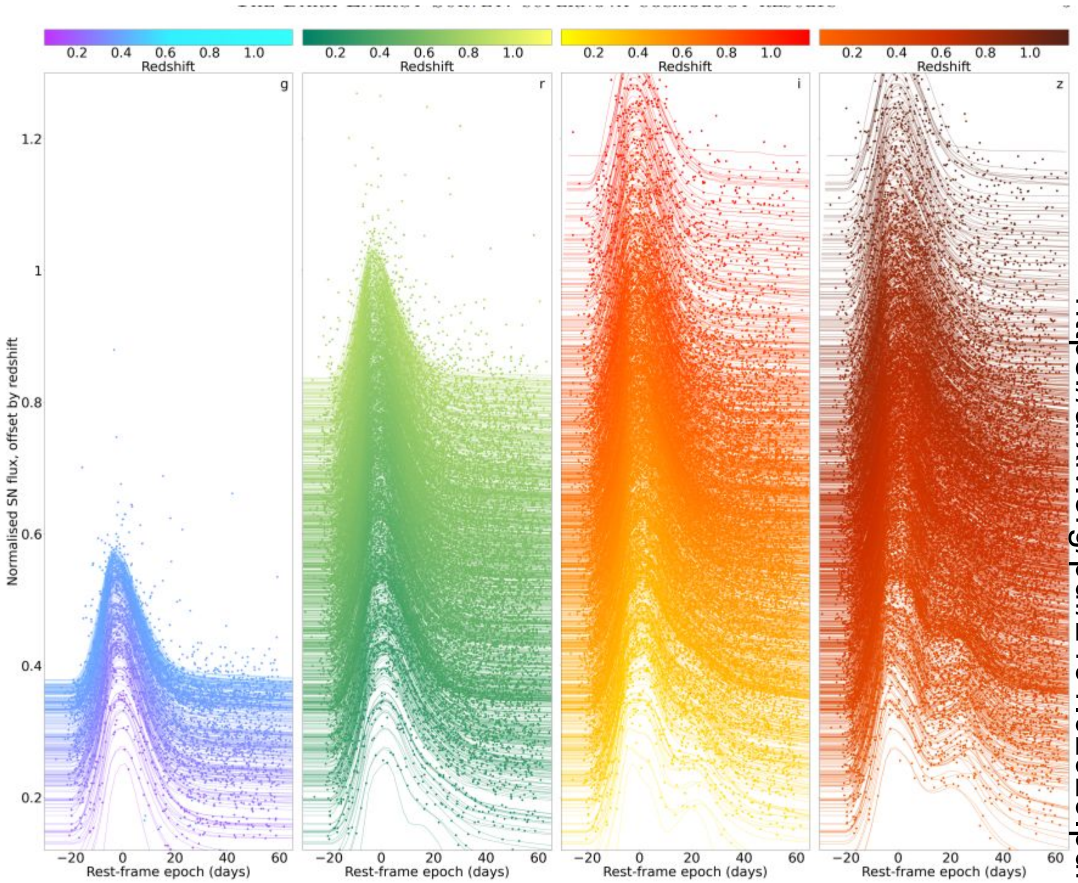


Figure 2. All DES light curves, showing observed magnitudes in g, r, i, and z bands (left to right respectively) normalized by the maximum brightness of each light curve, and with the time-axis de-redshifted to the rest-frame. Each light curve has been arbitrarily offset by their redshift, with higher-redshift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

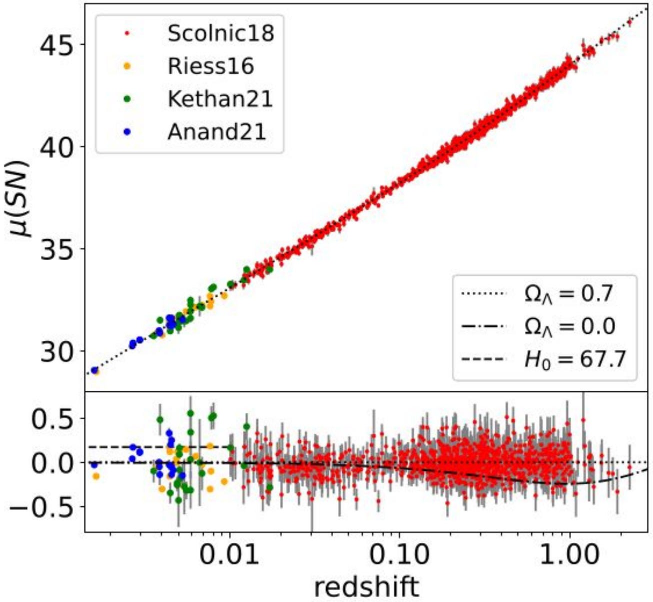
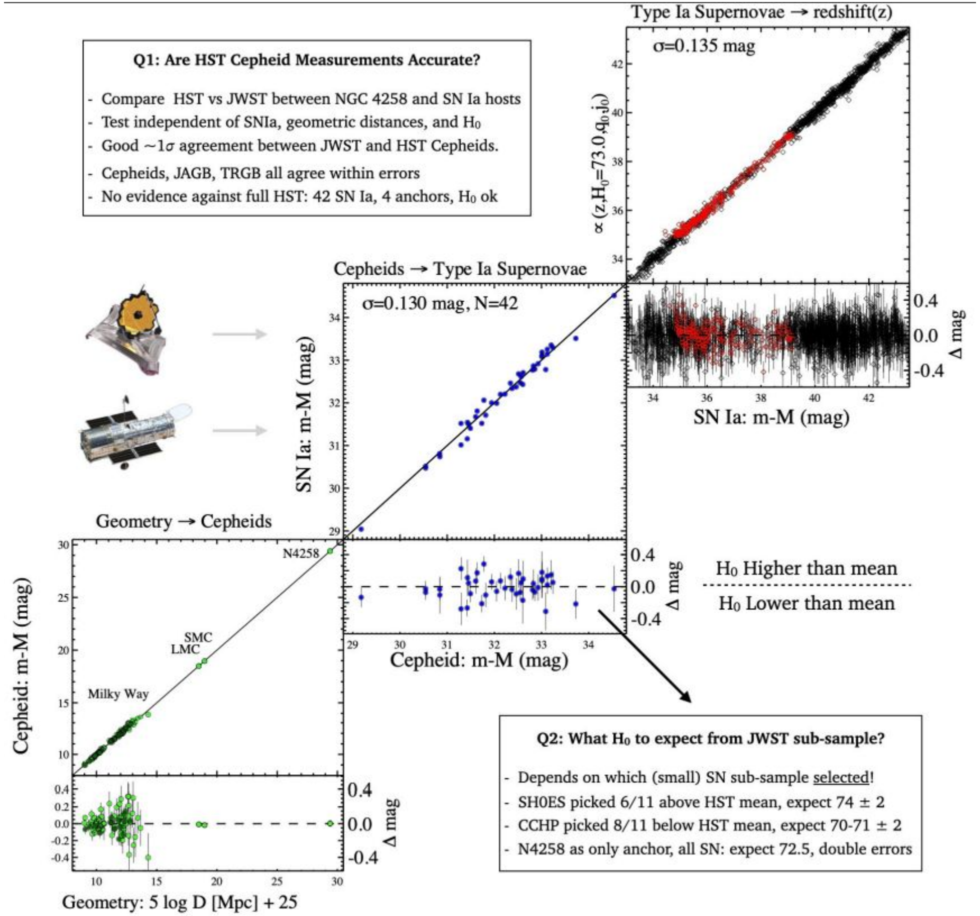


Fig. 8 Hubble diagram for SNe Ia. SNe Ia in the Hubble flow (red points) are from the Pantheon compilation ([179], https://archive.stsci.edu/prepds/ps1cosmo/) whereas low redshift SNe Ia are retrieved from [74] (Riess16, calibrated with Cepheids), [183] (Khetan21, calibrated with SBF) and [184] (Anand21,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

H_0 AND LOW REDSHIFT ANCHORS



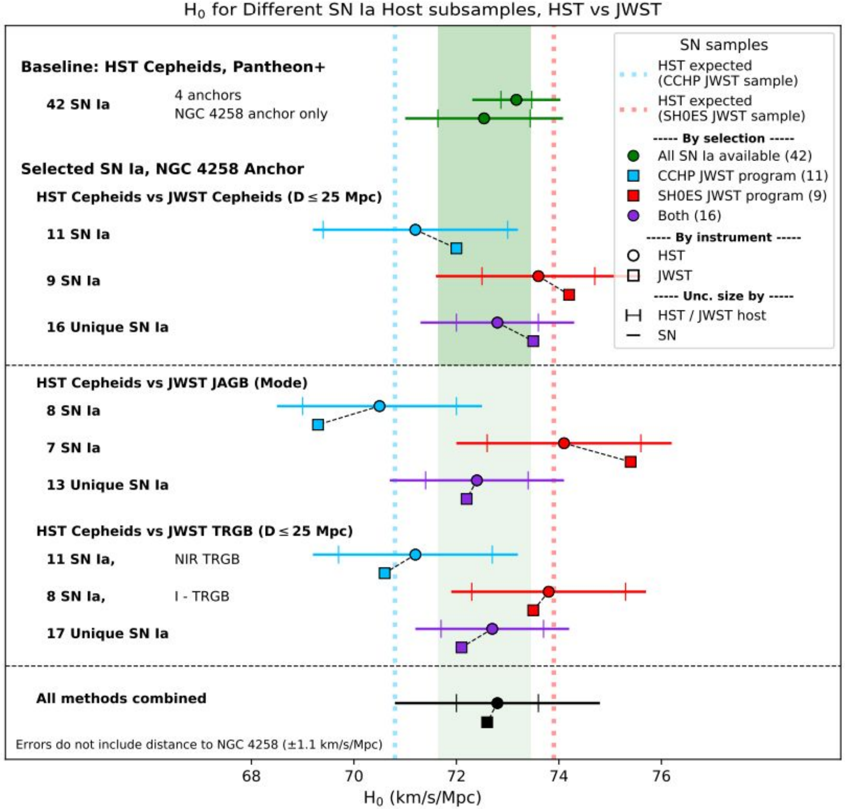
Q1: Are HST Cepheid Measurements Accurate?

- Compare HST vs JWST between NGC 4258 and SN Ia hosts
- Test independent of SNIa, geometric distances, and H_0
- Good ~1σ agreement between JWST and HST Cepheids.
- Cepheids, JAGB, TRGB all agree within errors
- No evidence against full HST: 42 SN Ia, 4 anchors, H_0 ok

Q2: What H_0 to expect from JWST sub-sample?

- Depends on which (small) SN sub-sample selected!
- SH0ES picked 6/11 above HST mean, expect 74 ± 2
- CCHP picked 8/11 below HST mean, expect 70-71 ± 2
- N4258 as only anchor, all SN: expect 72.5, double errors

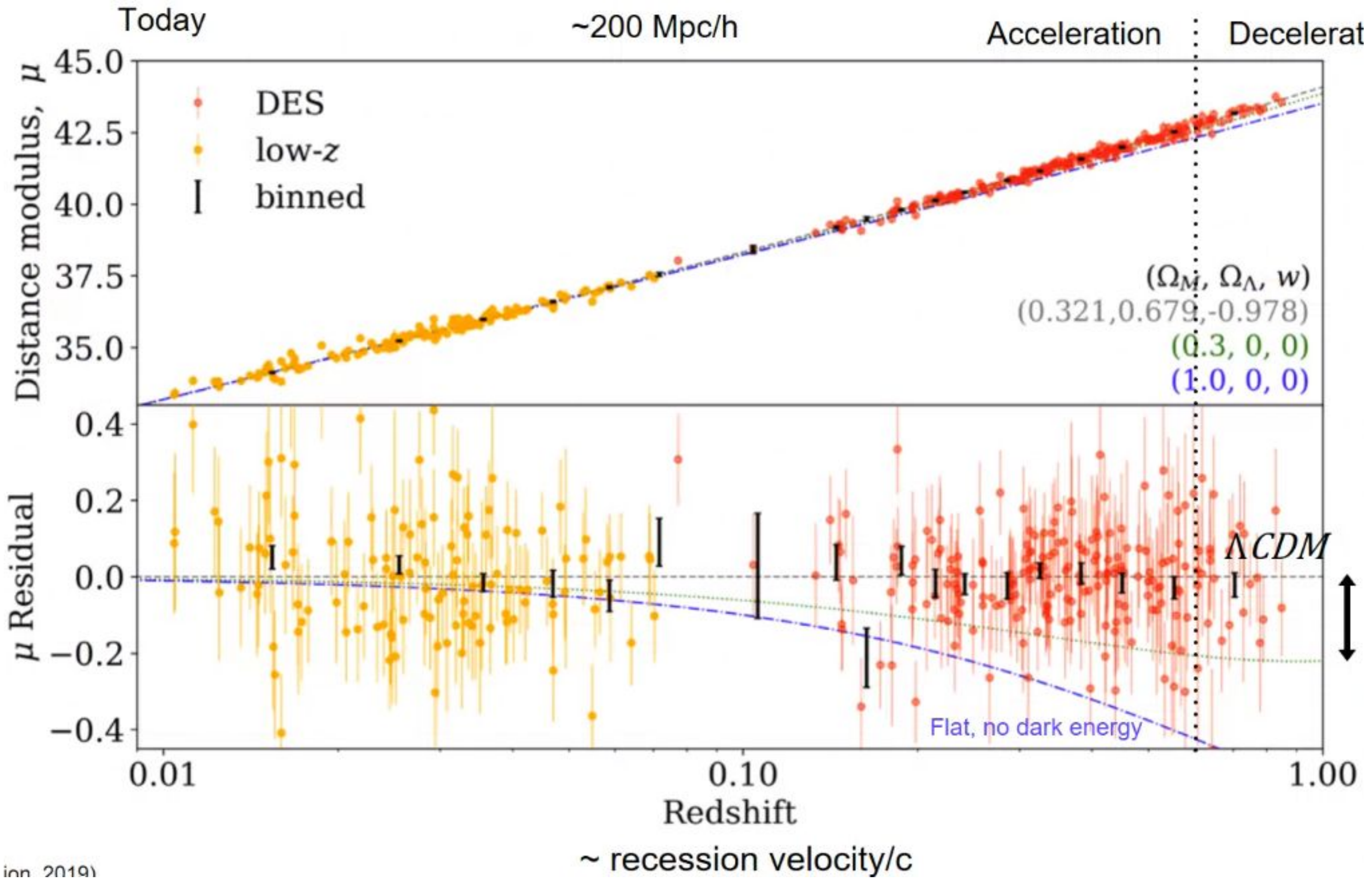
Riess et al 2025 https://arxiv.org/pdf/2408.11770



H_0 for Different SN Ia Host subsamples, HST vs JWST

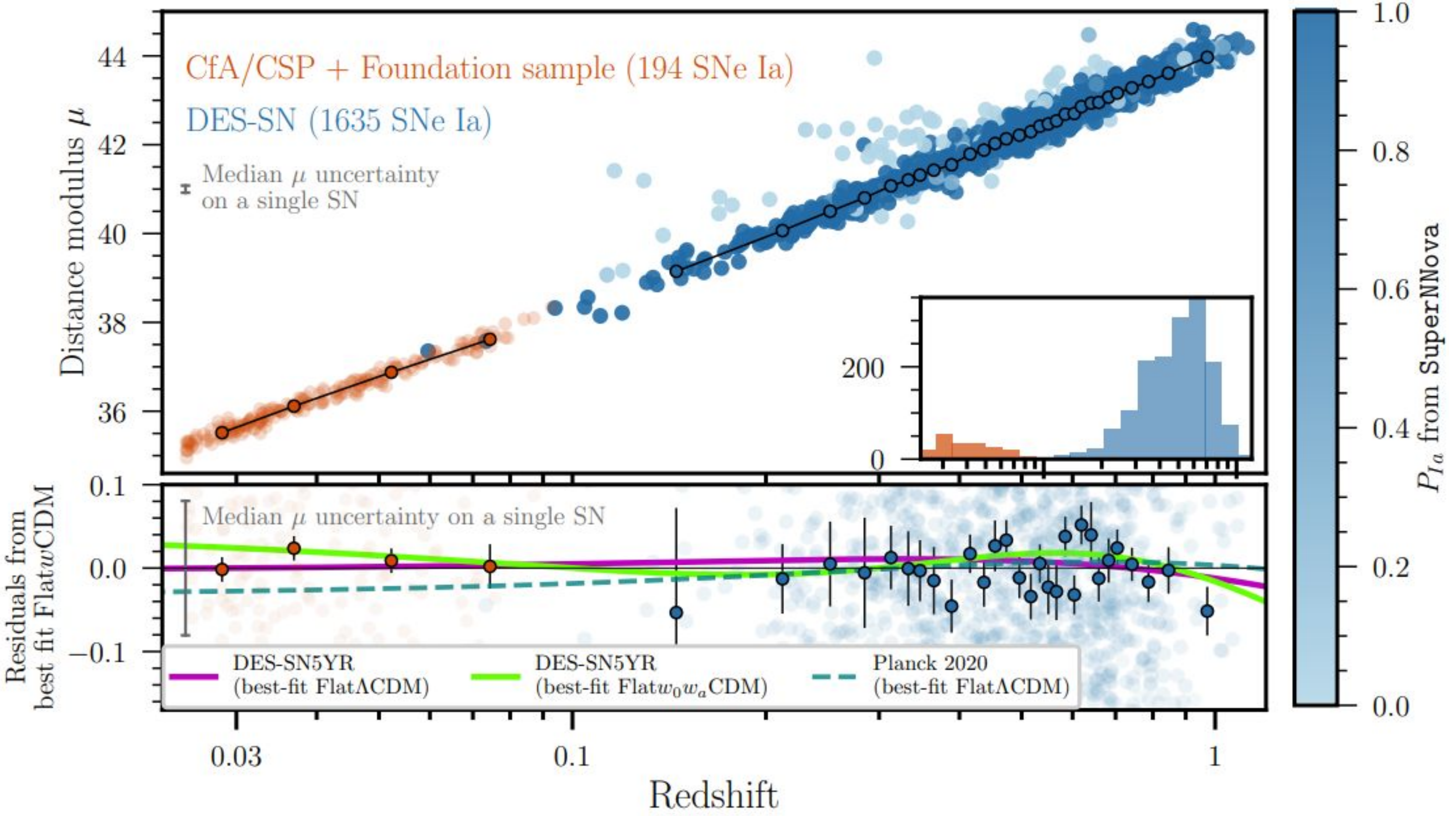
See also: https://arxiv.org/pdf/2408.06153

HUBBLE DIAGRAM OF SN Ia



ion, 2019)

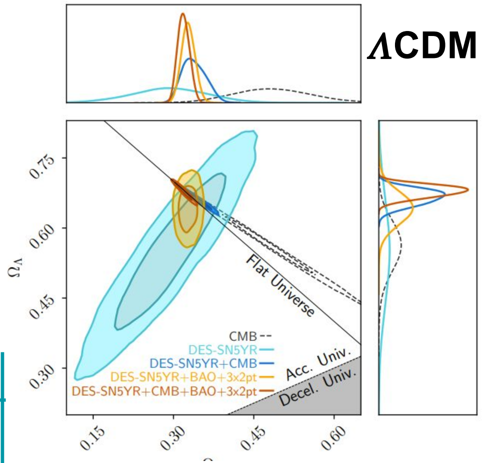
HUBBLE DIAGRAM OF SN Ia: DES Y6 RESULTS

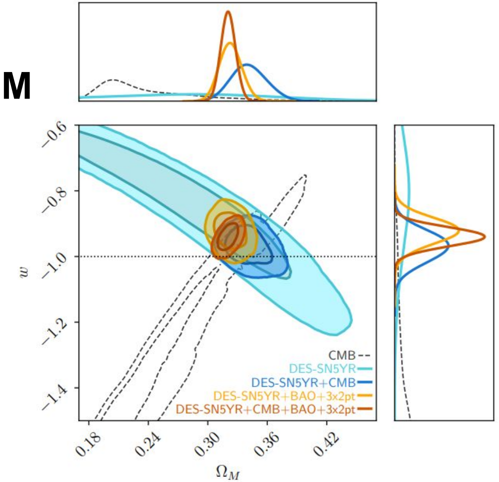


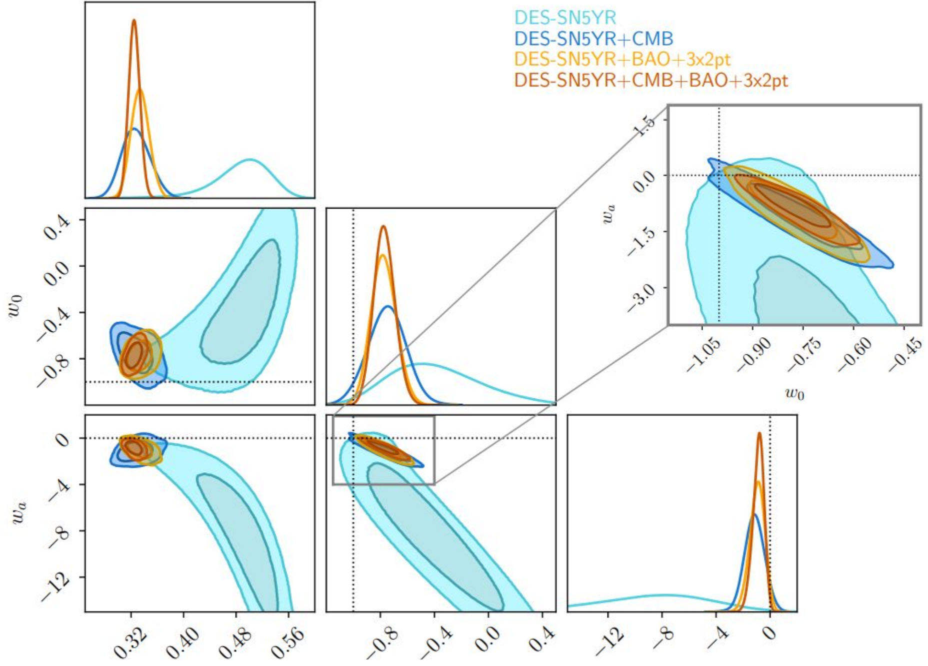
https://arxiv.org/pdf/2401.02929.pdf

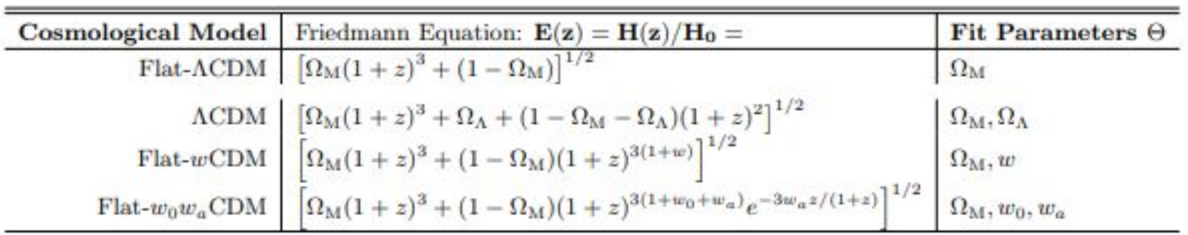
COSMOLOGY WITH SN Ia: DES Y6 RESULTS

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


ΛCDM


wCDM


w_0w_aCDM



Cosmological Model	Friedmann Equation: $\mathbf{E(z) = H(z)/H_0}$ =	Fit Parameters Θ
Flat-ΛCDM	$\left[\Omega_M(1+z)^3 + (1-\Omega_M)\right]^{1/2}$	Ω_M
ΛCDM	$\left[\Omega_M(1+z)^3 + \Omega_\Lambda + (1-\Omega_M-\Omega_\Lambda)(1+z)^2\right]^{1/2}$	Ω_M, Ω_Λ
Flat-wCDM	$\left[\Omega_M(1+z)^3 + (1-\Omega_M)(1+z)^{3(1+w)}\right]^{1/2}$	Ω_M, w
Flat-w_0w_aCDM	$\left[\Omega_M(1+z)^3 + (1-\Omega_M)(1+z)^{3(1+w_0+w_a)}e^{-3w_a z/(1+z)}\right]^{1/2}$	Ω_M, w_0, w_a

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 → 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 (>90%) at very high redshifts (z> 2-3), 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.

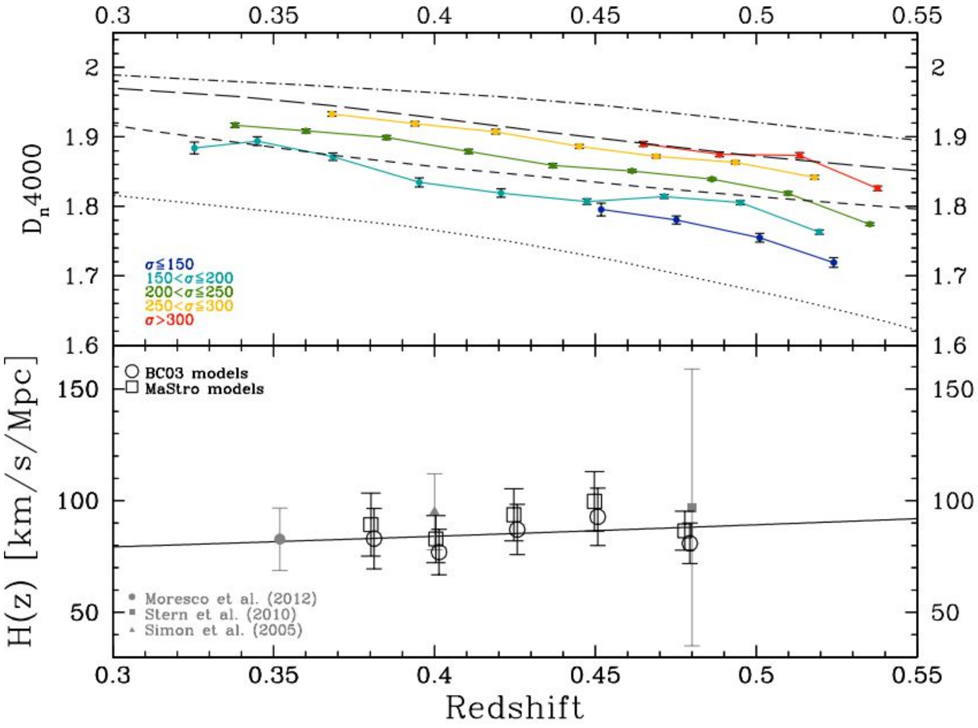
STANDARD CHRONOMETERS

When observed at cosmic times considerably later than their formation epoch, the age evolution of ETGs stars serves a clock that is synchronized with the evolution of cosmic time.

To minimize the dependence of the age estimate on evolutionary stellar population synthesis (EPS) models, one can study a direct observable of galaxy spectra, the 4000 ˚A break (D4000).

$$D_n4000 = A(SFH, Z/Z_\odot) \cdot \text{age} + B,$$

$$H(z) = -\frac{1}{1+z} A(SFH, Z/Z_\odot) \frac{dz}{dD_n4000}$$



https://arxiv.org/pdf/1601.01701

STANDARD CHRONOMETERS

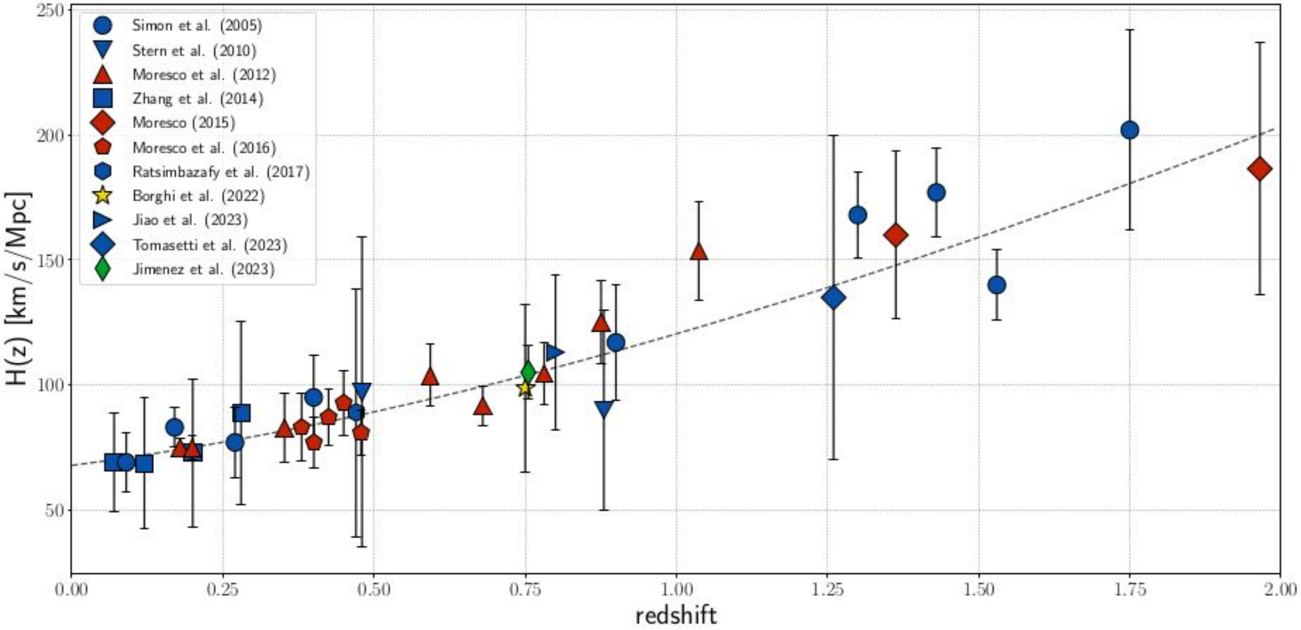
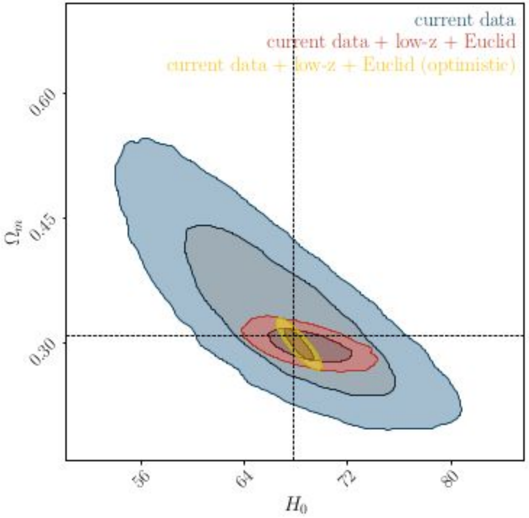


Figure 5: Hubble parameter measurements obtained with the CC method. Different colors refer to different methods adopted to estimate dt, as presented in Tab. 1. The dashed line shows the flat ΛCDM cosmological model from Planck Collaboration et al. (2020a) as a pure illustrative reference.

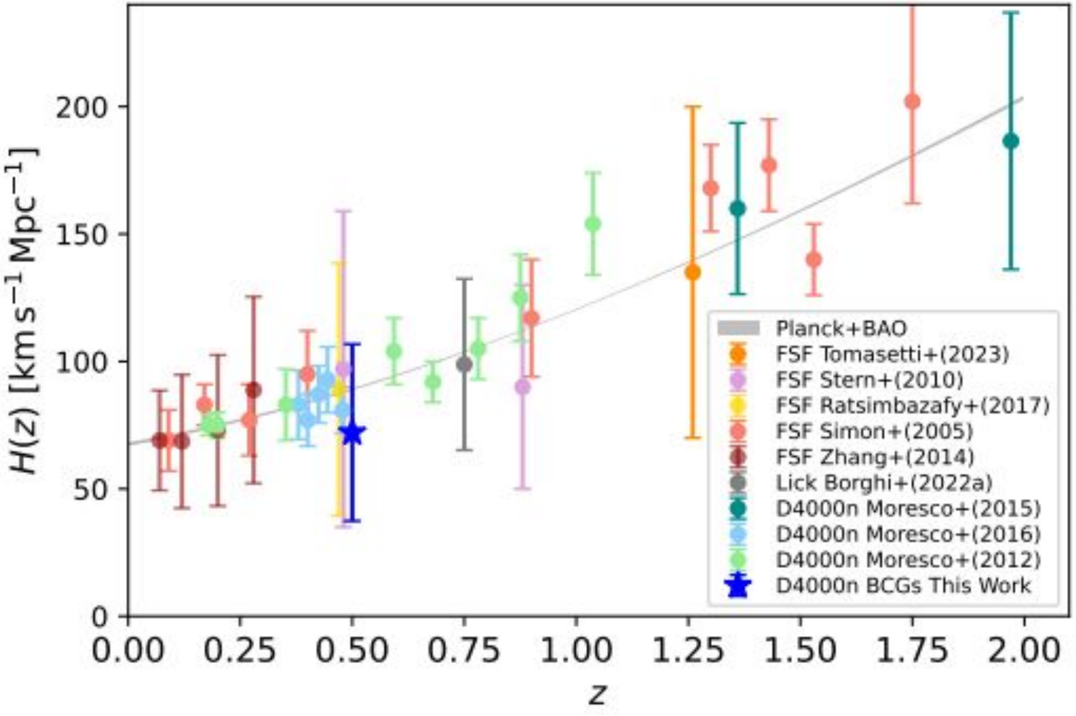


STANDARD CHRONOMETERS

BCG are the most massive and oldest galaxies in the universe located at the centers of massive galaxy clusters.

Because BCGs formed their stars very early and very quickly (z > 2), they represent a much more **homogeneous and "pure"** population, reducing the risk of contamination of the sample

An independent estimate of H(z) at z = 0.5 from the stellar ages of brightest cluster galaxies (BCG)
https://arxiv.org/pdf/2506.03836
See also: https://arxiv.org/pdf/2512.02109



STANDARD CLOCKS AND CHRONOMETERS

Advantages

- **Model-independent**: No assumption on the underlying cosmological model.
- Complementary to other probes like **BAO**, **SNe Ia**, and **CMB**.
- Useful at **intermediate redshifts (z ~ 0.1–2)**, where other probes are sparse.

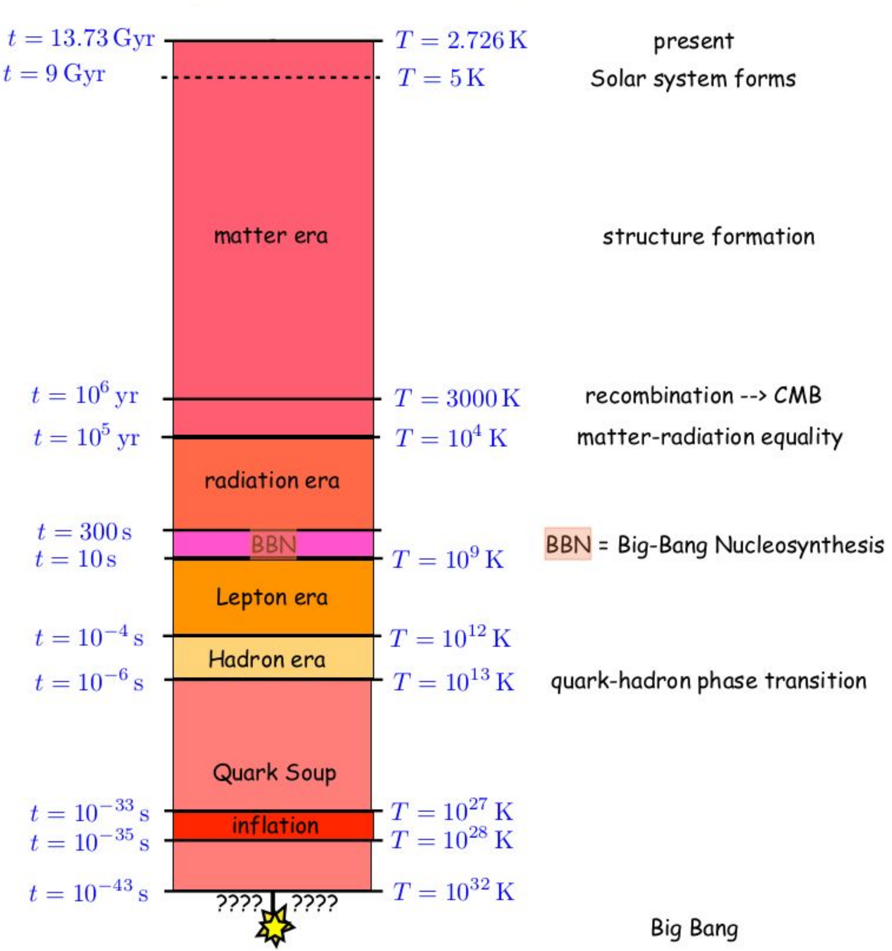
Challenges

- Requires accurate age-dating of galaxies (affected by metallicity, star formation history).
- Systematics in stellar population modeling must be controlled.

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

$t = 10\,\mathrm{s}$ — $T = 10^9\,\mathrm{K}$ — BBN = Big-Bang Nucleosynthesis

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

$t = 10^{-33}\,\mathrm{s}$ — $T = 10^{27}\,\mathrm{K}$

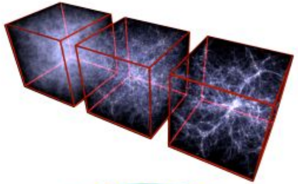
inflation

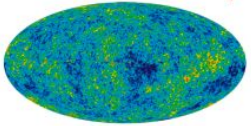
$t = 10^{-35}\,\mathrm{s}$ — $T = 10^{28}\,\mathrm{K}$

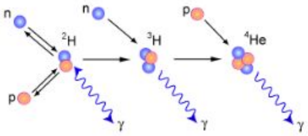
$t = 10^{-43}\,\mathrm{s}$ — $T = 10^{32}\,\mathrm{K}$

???? ????

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 (τ = 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 (β-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:

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

$$ {}^2H+p \rightarrow {}^3He+\gamma \qquad {}^3He+n \rightarrow {}^4He+\gamma$$

The bottleneck of these reactions is the formation of Deuterium, ^{2}H:

- **D is destroyed by energetic photons, until their number density, n_γ^{diss}, becomes comparable with the number density 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.**

PRIMORDIAL NUCLEOSYNTHESIS

The primordial (mass) abundance of ^{4}He, Y_{He}, is determined mainly by:

- The temperature at which neutrino decouples and the n-to-p ratio frozen, $\Gamma_{n\leftrightarrow p} \sim H$, which in turns depends on the total number of neutrino species.

- The mean neutron lifetime (~889 s), which determines the neutron-to-proton ratio after neutrino decoupling

- The baryon-to-photon ratio , $\eta = n_b / n_\gamma = 2.7 \times 10^{-8}\, \Omega_b h^2$, which determines the time t_{BBN} after which D is not efficiently destroyed

PRIMORDIAL NUCLEOSYNTHESIS

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

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

with a relative abundance compared 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

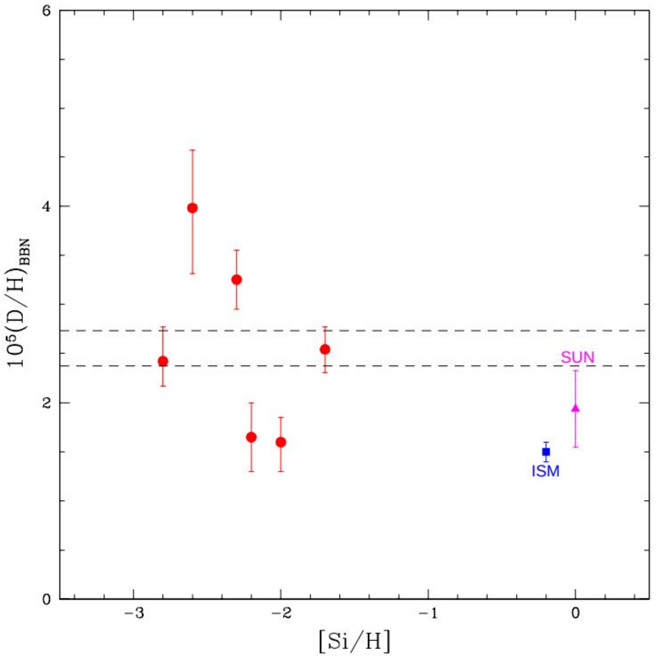
PRIMORDIAL NUCLEOSYNTHESIS

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 ^{3}He. 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

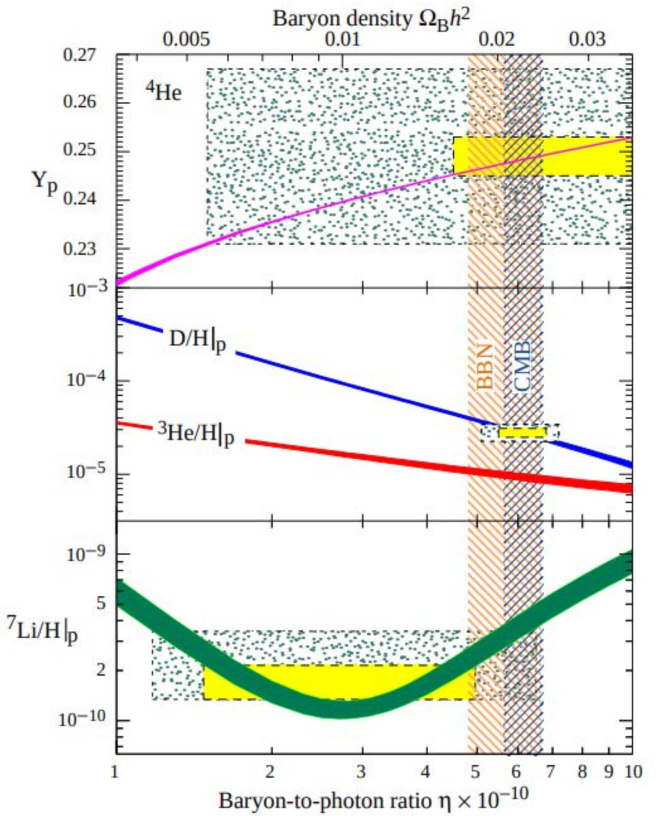


Figure 1.1: The abundances of ^{4}He, D, ^{3}He and ^{7}Li as predicted by the standard model of big-bang nucleosynthesis. Boxes indicate the observed light element abundances (smaller boxes: 2σ statistical errors; larger boxes: $\pm 2\sigma$ statistical and systematic errors). The narrow vertical band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

PRIMORDIAL NUCLEOSYNTHESIS

- **^{7}Li problem: BBN predictions** (based on the standard ΛCDM model and baryon density from the CMB) **overestimate the primordial abundance of ^{7}Li** by a factor of **~3** compared to what we **observe in old, metal-poor (Population II) stars** in the galactic halo:

$$\left(\frac{^7\mathrm{Li}}{\mathrm{H}}\right)_{\mathrm{BBN}} \sim 5 \times 10^{-10} \qquad \left(\frac{^7\mathrm{Li}}{\mathrm{H}}\right)_{\mathrm{obs}} \sim 1.6 \times 10^{-10}$$

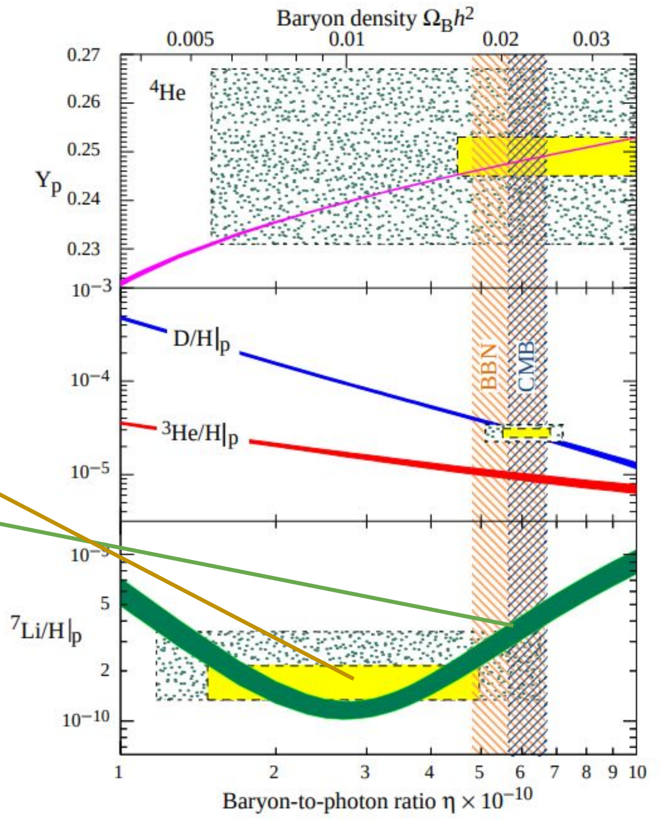


Figure 1.1: The abundances of ^{4}He, D, ^{3}He and ^{7}Li as predicted by the standard model of big-bang nucleosynthesis. Boxes indicate the observed light element abundances (smaller boxes: 2σ statistical errors; larger boxes: $\pm 2\sigma$ statistical and systematic errors). The narrow vertical band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

Proposed Solutions (none fully successful yet):

- **Astrophysical**: ^{7}Li depletion in stars (e.g. diffusion, mixing, destruction)

  → but no known stellar process explains the uniform low abundance in old stars (Spite plateau).

- **Nuclear physics**: Re-evaluating nuclear reaction rates (e.g., ^{7}Be destruction)

  → but updated measurements haven't fixed the problem.

See e.g.: https://arxiv.org/pdf/1801.08023

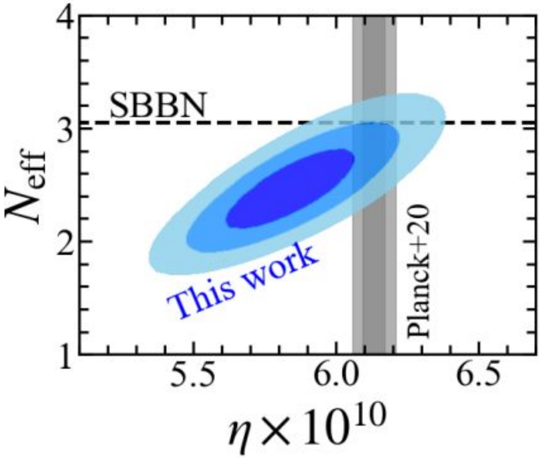
PRIMORDIAL NUCLEOSYNTHESIS

The effective number of relativistic species, Neff, quantifies contributions from particles other than photons to the radiation energy density in the early Universe

$$\rho_{\rm rad} = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

The presence of additional radiation, i.e. N_{eff}>3.046, directly affects the expansion history and perturbation evolution in the early Universe, hence N_{eff} modifies the cosmic microwave background and alters the abundances of light elements forged during Big Bang nucleosynthesis

Determination of the Primordial Helium Abundance based on Suburau observation of extremely-poor metal galaxies: https://arxiv.org/abs/2506.24050



https://arxiv.org/pdf/2603.13226

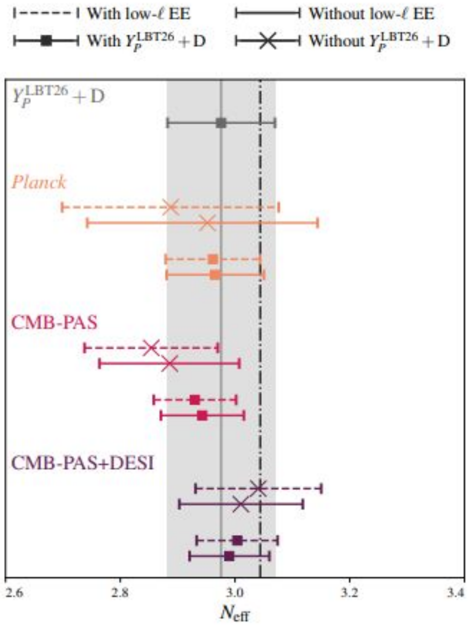


FIG. 1. Comparison of $N_{\rm eff}$ constraints from dataset combinations considered here. For each dataset, we show the one-dimensional marginalized posterior mean and the 68% two-tailed confidence limits. The gray constraint uses only primordial helium and deuterium abundance measurements. For the remaining datasets, the × and the square denote constraints excluding and including primordial helium and deuterium abundance measurements, respectively. The measurements with solid (dashed) error bars exclude (include) *Planck* low-ℓ EE measurements. The vertical dot-dashed line shows the Standard Model prediction, $N_{\rm eff} = 3.044$.