Observational Cosmology: Measuring the late Universe

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Cosmological Standard Model - ***ΛCDM Model***

CMB, SNeIa, LSS probes supports:

- Flat Universe with recent accelerated expansion
- Homogeneous and Isotropic in large scales
- General Relativity
- **Dark Energy: cosmological constant Λ**
- **Cold Dark Matter**

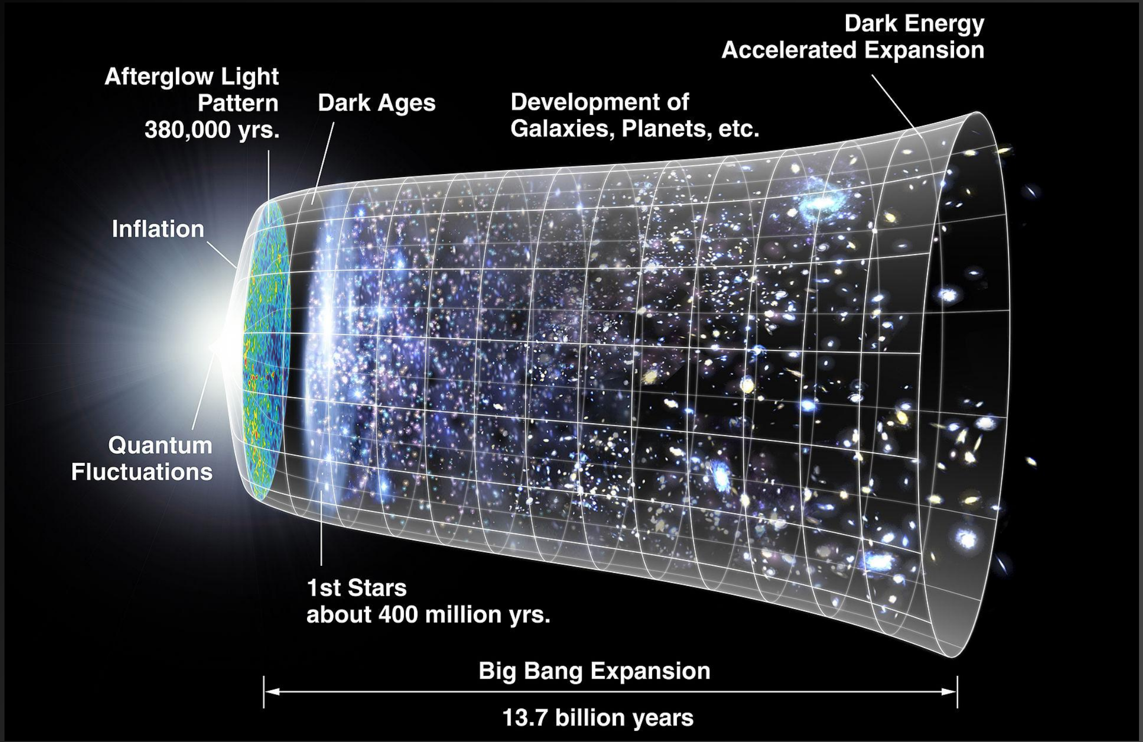


Image Credit: NASA / LAMBDA Archive / WMAP Science Team

Three Big Questions

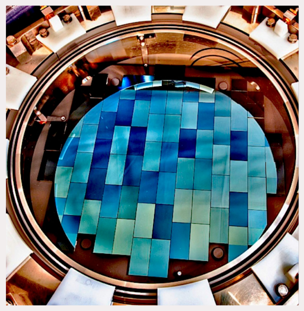
Are the **late Universe** and **early Universe** observations explained by the **same** model?

Do the **growth** of structure and **expansion** measurements agree?

Does the **Dark Energy density changes** with cosmic expansion?

State-of-art Galaxy Surveys

Blanco Telescope (Chile)



DES - The Dark Energy Survey

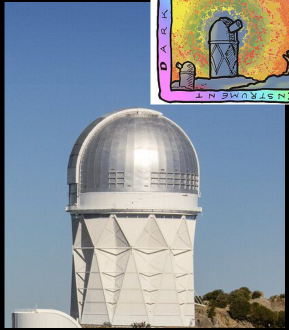
- DECam 570 Mpix
- *Imaging* survey
- 5,000 deg^2
- Operations 2013-2019
- Final Results: 2024/25

Largest map of dark matter distribution so far!

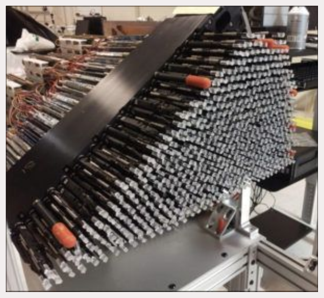
DESI - Dark Energy Spectroscopic Instrument

- 5000 spec. eyes
- *Spectroscopic*
- 14,000 deg^2
- Operations 2021 --
- Year 1 Results: 2024

In 1 year, more spec data measured than all the previous experiments together!



Mayall Telescope (Arizona-USA)

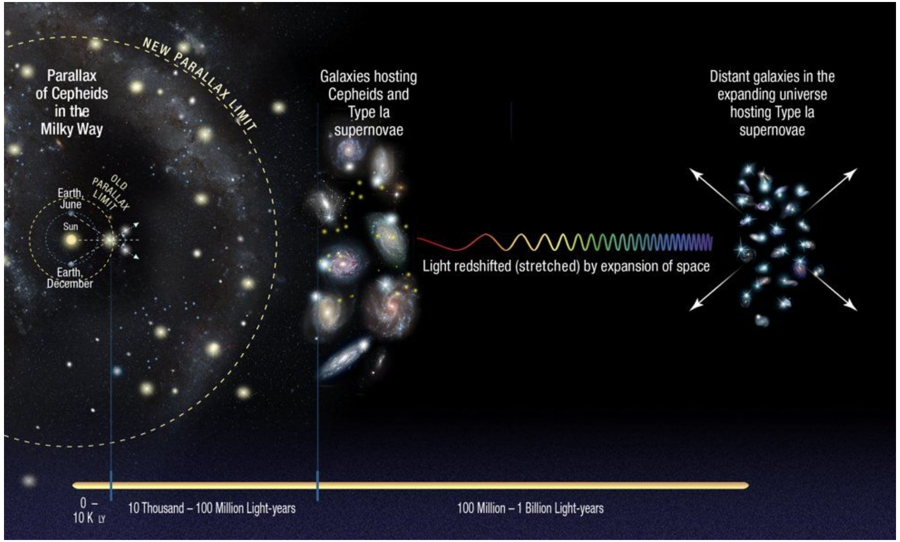


Probing the Expansion: **Standard Candles**

Standard Candles: references with standard(izable) luminosity: $d_L^2 = L/4\pi F$

$$d_L(z|cosmo) = c(1+z)\int_0^z \frac{dz'}{H(z'|cosmo)}$$

- Cepheids:
  - Period-Luminosity relation (Leavitt Law)
- SNe Ia:
  - Luminous and distant
  - Calibration - *cosmic distance ladder*
  - Classification
- Gravitational waves **Standard Sirens**:
  - First time used in 2017
  - Luminosity distance from GW signal
  - Redshift needs to be determined (E.M. counterpart or catalog cross-correlation)



Probing the Expansion: **BAO Standard Ruler**

- At t~0, each overdensity is a source of a spherical pressure wave travelling with speed c_s ~0.57c. When the Universe gets cooler, baryons and radiation decouples from each other (~400,000 years) releasing the Cosmic Microwave Background (CMB).
- Without the support of the radiation, the sound waves halt. The comoving distance travelled by the waves keeps frozen in the matter field.
- We call this imprint the **Baryon Acoustic Oscillation (BAO) feature**. It can be observed as an excess of probability in the galaxy correlation function. The scale of the BAO feature (~147Mpc) sets a **statistical standard ruler**

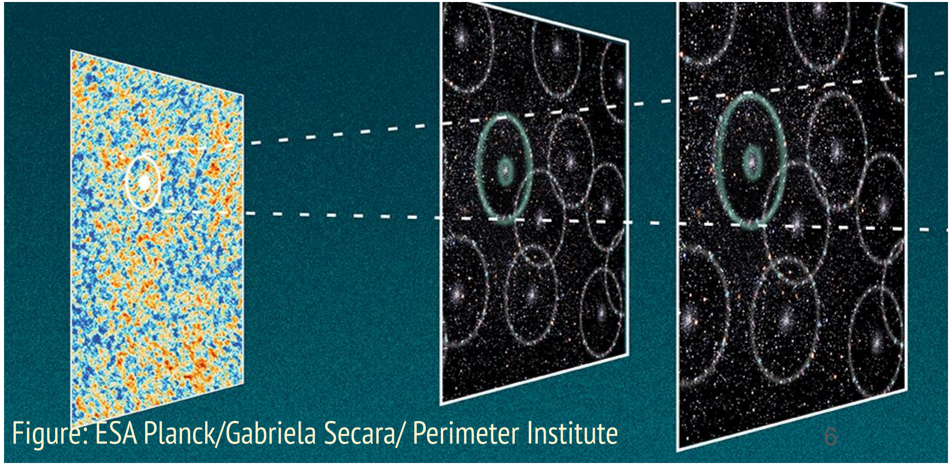
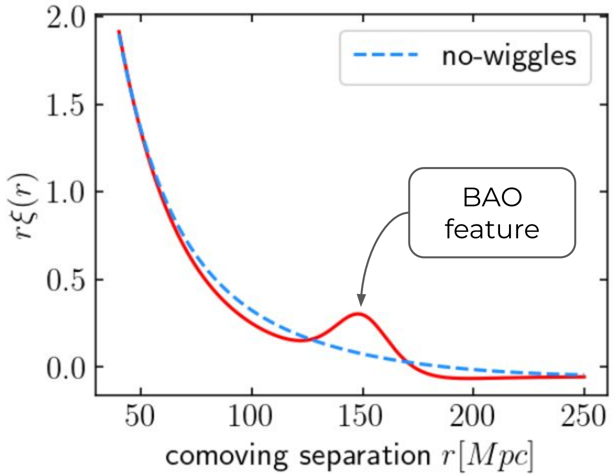


Figure: ESA Planck/Gabriela Secara/ Perimeter Institute



Probing the LSS - **Cosmic Shear and Clustering**

The light from distant **source galaxies** crosses the matter field in their way to us.

The matter potential cause small distortions in the shapes of source galaxies - the **cosmic shear**.

Dark matter field is not visible, but we can trace the total matter distribution using **lens galaxies**.

The distortion of **source galaxies** field has an angular correlation with the **lens field**.

Cosmological model affects predictions from **Correlation Functions/P(k)**: sensitive to *matter content* and how *clumpy* is the universe - $S_8=\sigma_8(\Omega_m/0.3)^{0.5}$

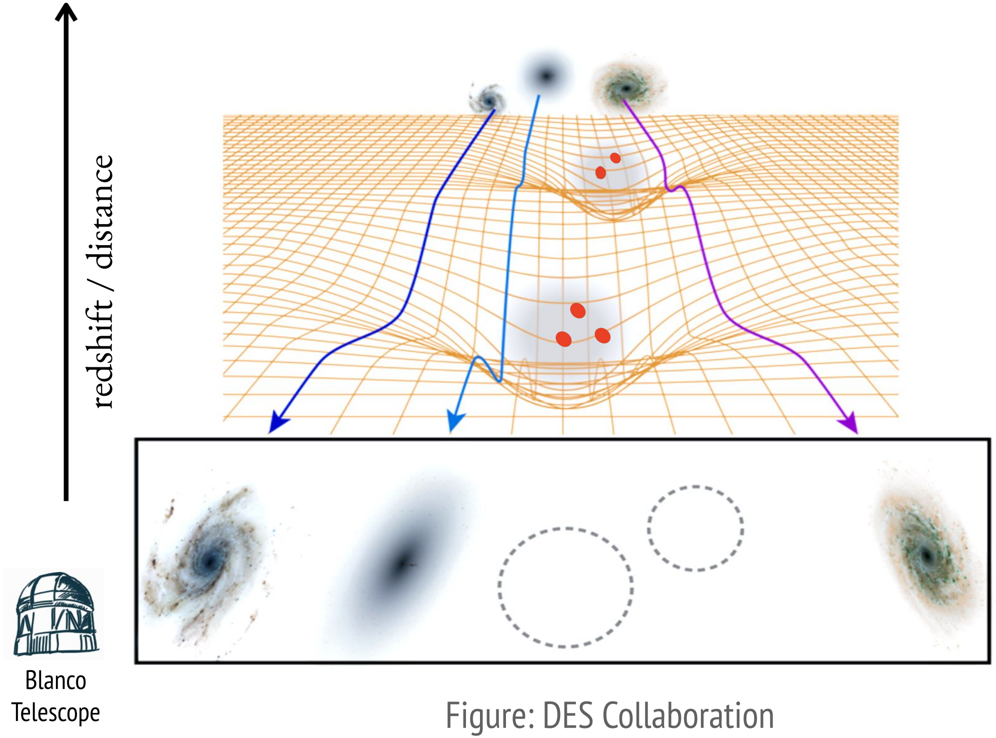
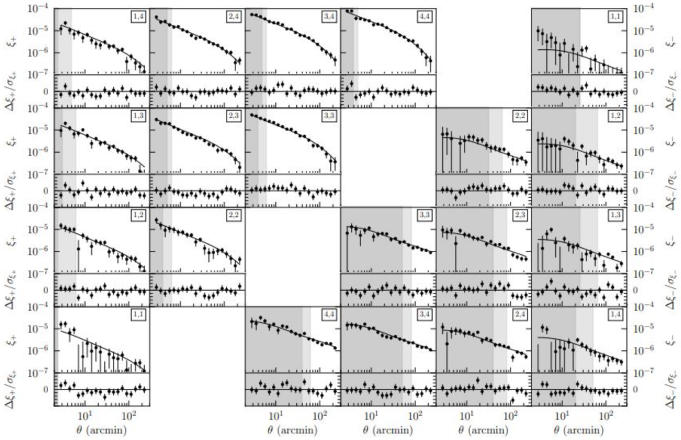


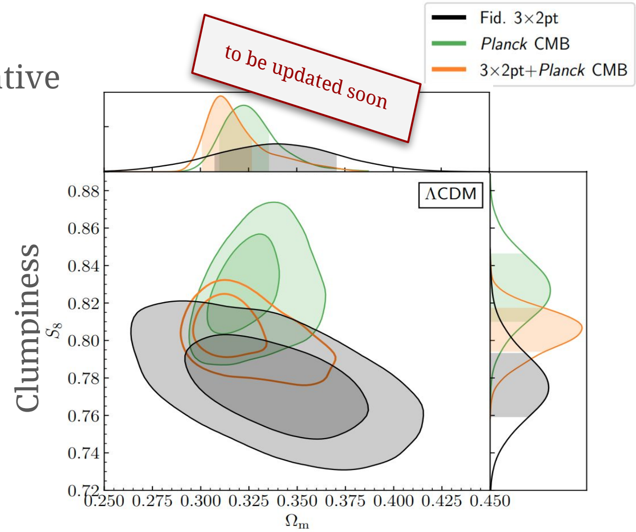
Figure: DES Collaboration

Results: DES Y3 Cosmic Shear & LSS

DES Year 3 combined **3 types** of **2-pt correlation function** (**3x2pt**):

- correlation using **shapes** from *100 million* galaxies and positions from *10.7 million* galaxies
- DES Y3:
  - S_8=0.776±0.017
  - similar precision as CMB experiments: S_8=0.834±0.016
- DES measurement is slightly lower than CMB's one, but with **no** significative tension





Total matter content

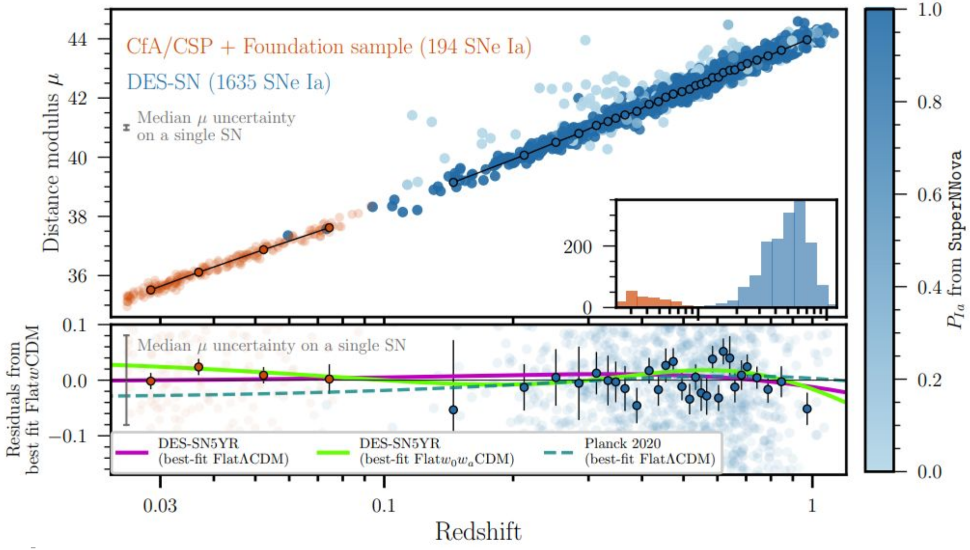
DES Collab., Phys. Rev. D 105, 023520 (2022)

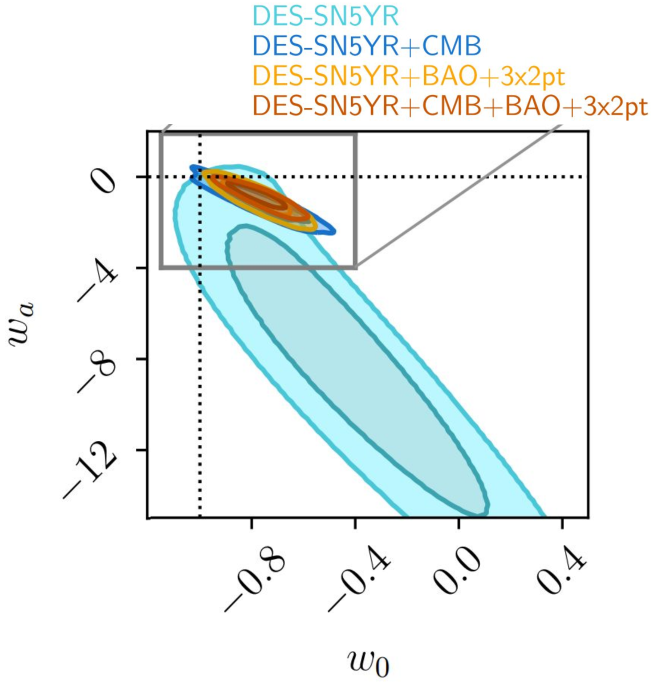
Results: SNe Ia - DES 5 year

- DES SN5YR: 1635 photo-z classified SNe Ia + 207 Low-z sample
- ΛCDM constraint: accelerating expansion confirmed w/ 5.2σ c.l.
- Testing non-constant Dark Energy:

$$\frac{p_{DE}}{\rho_{DE}} = w_0 + w_a \frac{z}{1+z}$$

SNe Ia data **slightly** disfavour cosmological constant



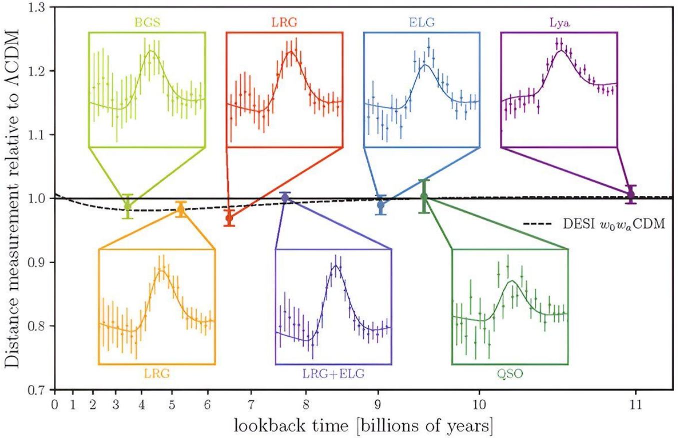


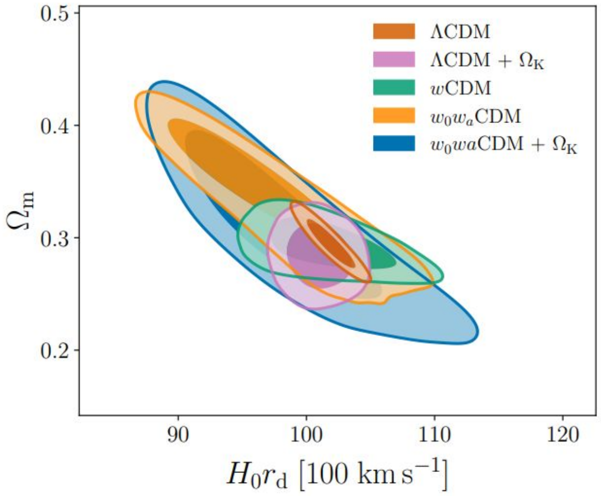
DES Collab., arXiv: 2401.02929 (2024)

Results: DESI BAO - H_0

DESI Year 1: First results from this spectroscopic survey:

- 6 million spectra (LGR, BGS, QSO, Lya) grouped in 7 different redshifts $[0.4<z<4.2]$
- Cosmic expansion:
  - H_0 = 68.52 ±0.62 (BAO+BBN+ θ*)
  - H_0 = 67.97±0.38 (BAO+BBN+ θ*+CMB)
- H0 Tension between SNeIa and BAO+CMB > 4σ

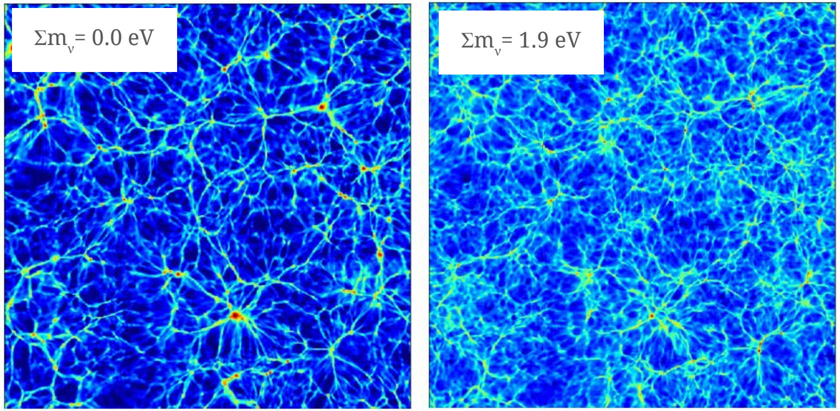




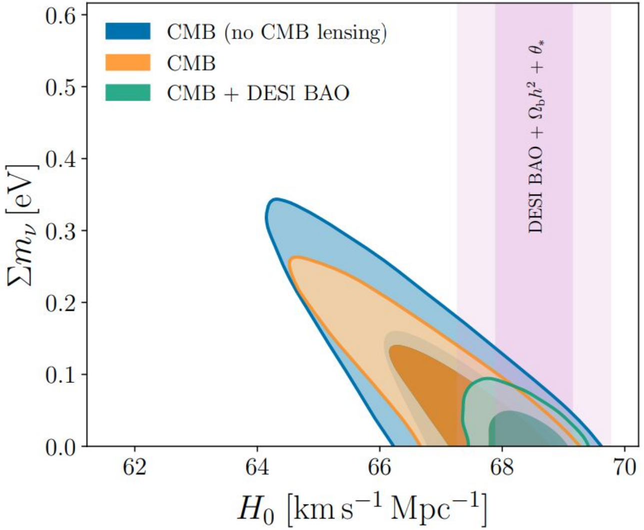
DESI Collab., arXiv: 2404.03002 (2024)

Results: DESI BAO - Neutrinos

- The sum of neutrino masses affect how matter is clustering in the Universe
- DESI BAO: constraints on sum of neutrino masses mnu<0.072 eV (0.95%), assuming LCDM model
  - NH seems to be favoured, but this result **is** dependent on the cosmological model and priors adopted
  - Next DESI Data Release will give significant contribution to neutrino masses bound



Argawal & Feldman, MNRAS 2011

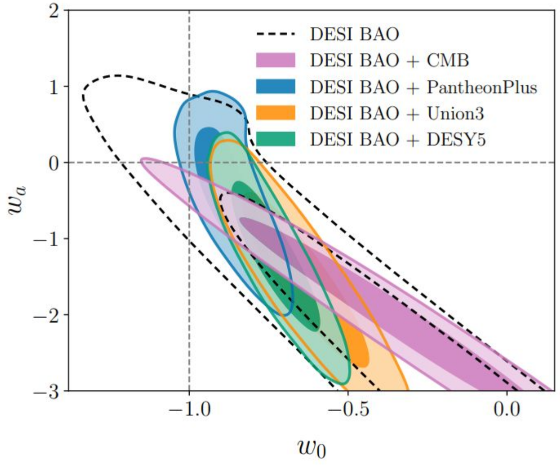


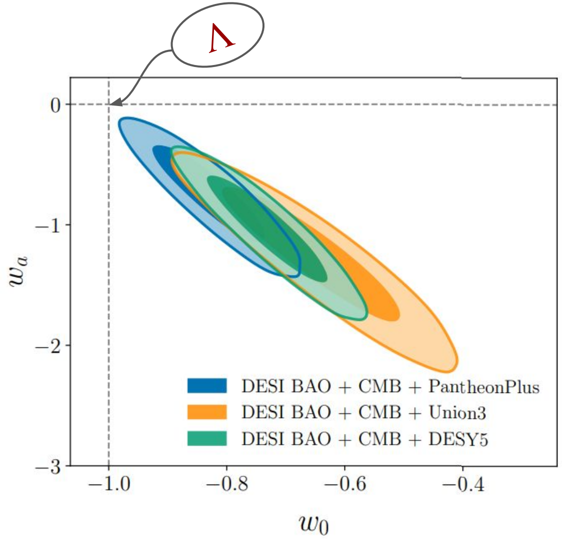
Results: DESI BAO - Is the Dark Energy constant?

Assuming w0-wa parameterization $$\frac{p_{DE}}{\rho_{DE}} = w_0 + w_a \frac{z}{1+z}$$

Tension with **cosmological constant** when combined with different SNe dataset:

- 2.2σ SH0ES
- 3.5σ Union3,
- 3.9σ DES SNY5



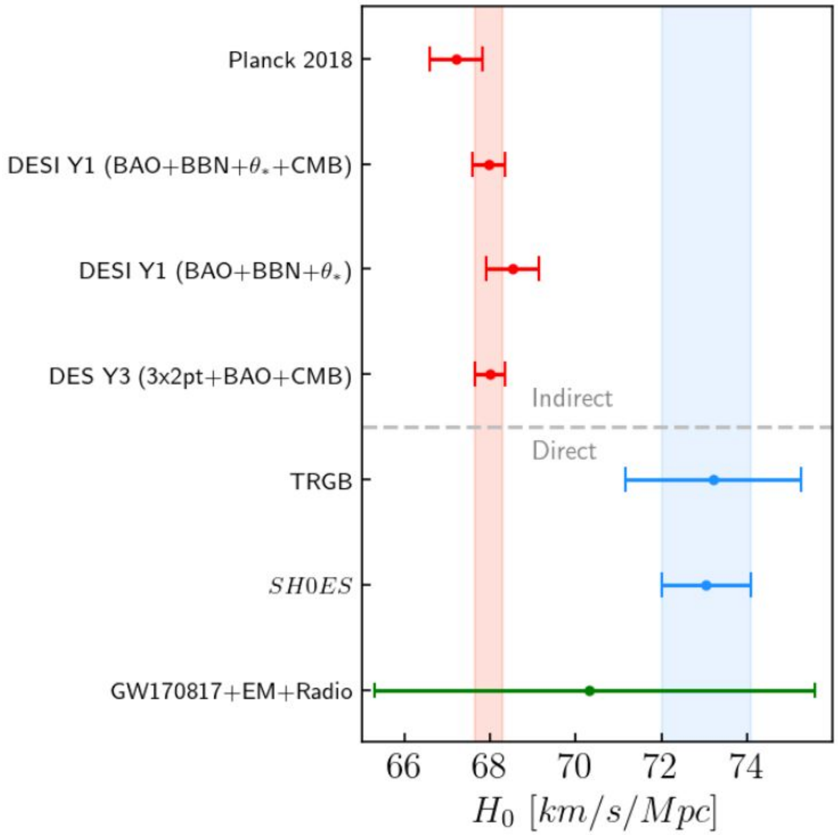


Status of Cosmological Tensions

- S_8 measured from LSS shows **less clustering** than CMB's measurements. However, *results are still compatible*. DES Y6 (3x2pt) final analysis and DESI growth of structure are improving the precision of this measurement and will elucidate if the tension really exists.

- H_0 from direct measurement of recession are **systematically larger** than indirect estimates from LSS.

Calibration, unknown systematics, or new physics?



New Results are Coming Soon

- DES Final Results (2024/2025) (Cosmic Shear, Clusters, BAO, SN)
  - ~Nearly twice number of galaxies than DES Year 3 (presented here)
  - Improvements in modeling and systematics control
  - Combination with DES cluster counts
  - Combined analysis with external probes
- DESI Year 3
  - constraints on neutrino mass, growth of structure, and Dark Energy
- GW standard sirens
  - Ligo, Virgo, Kagra instrument updates
  - Improved strategies for EM counterparts

Exciting new experiments: LSST-Rubin Observatory, Euclid, Roman…

Final Remarks

25 years of the ΛCDM model: a consistent history of the Cosmos. Experiments of different nature agree about the values of most of the cosmological parameters. However

- Tensions between late and early measurements of the **Universe expansion** persists (H_0 tension)
    - GW cosmology is providing independent measurements on H_0, but not in the near future
- Small differences between **how clustered** is the Universe from CMB and LSS probes (S_8 tension)
- Evidences of **non-cosmological constant** dark energy model (to be confirmed)

Observational Cosmology and **HEP:**

- Bounds in the sum neutrino masses
- Constraint on dark energy/Cosmological Constant
- DM astrophysical properties

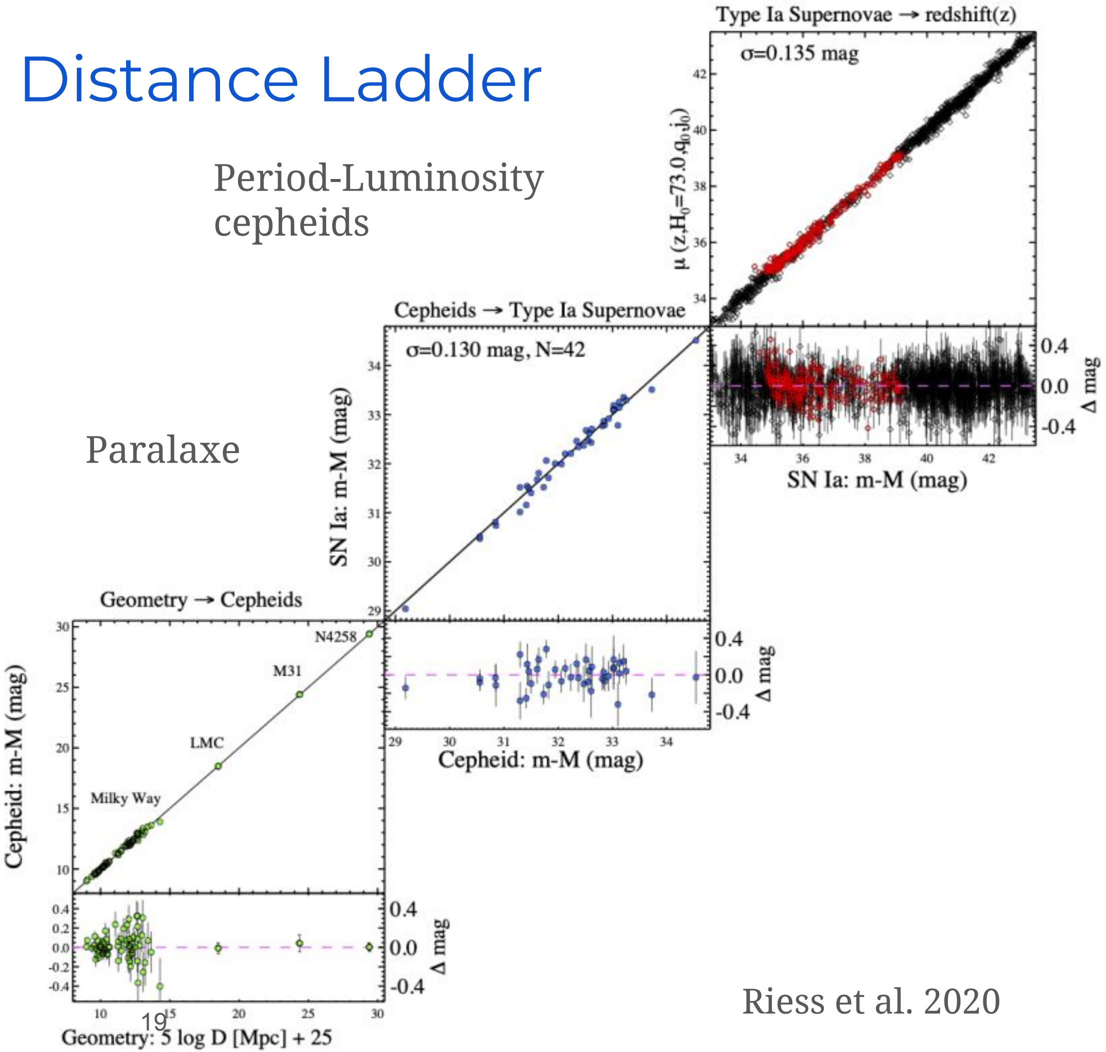
This starting generation of experiments will advance to unveil the **nature of tensions** in the ΛCDM model.

Thanks For Listening!

Cosmic Distance Ladder

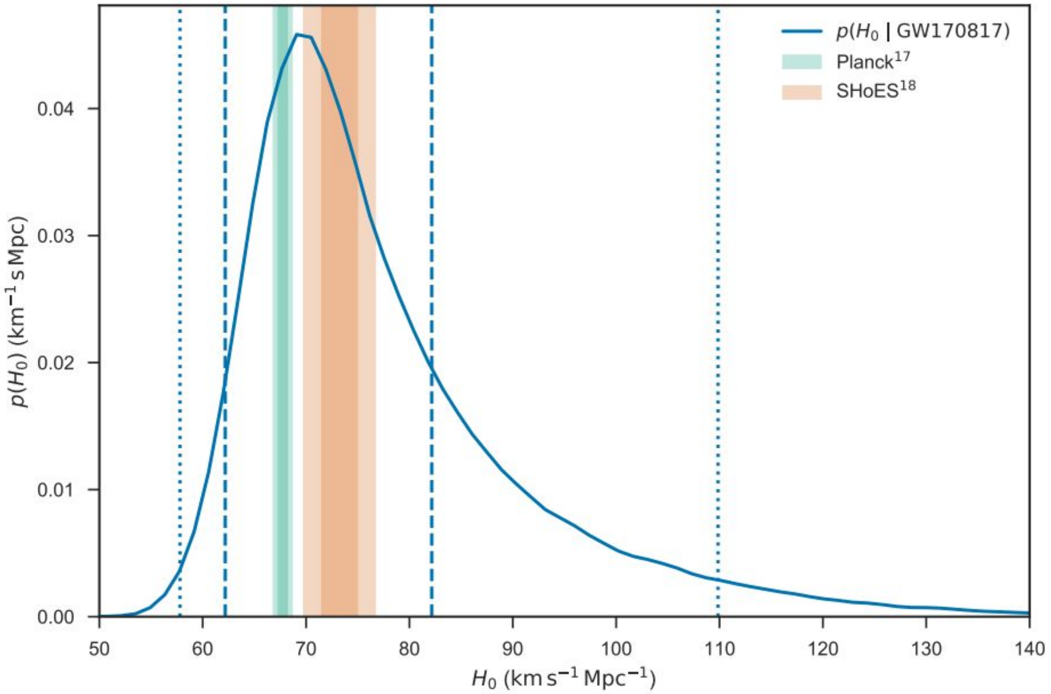
Period-Luminosity
cepheids

Paralaxe



Riess et al. 2020

GW170817 Standard Siren

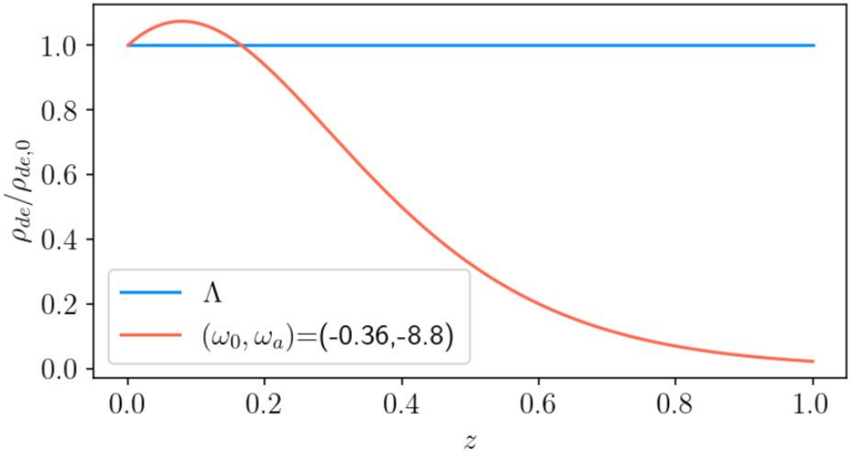


Chevallier-Polarski-Linder Parameterization

dark energy parameterization of EoS:

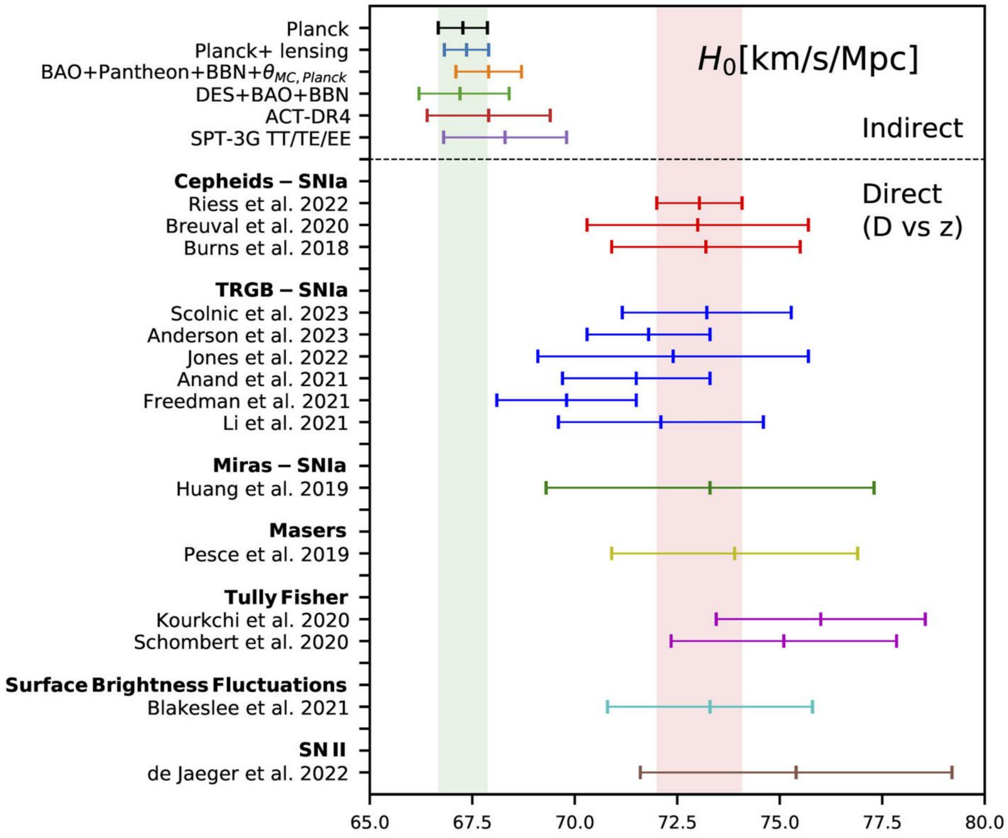
$$w_{de} \equiv \frac{p_{DE}}{\rho_{DE}} = w_0 + w_a \frac{z}{1+z}$$

$$\rho_{de} = \rho_{de,0}(1+z)^{3(1+\omega_0+\omega_a)} e^{-3\omega_a \frac{z}{1+z}}$$

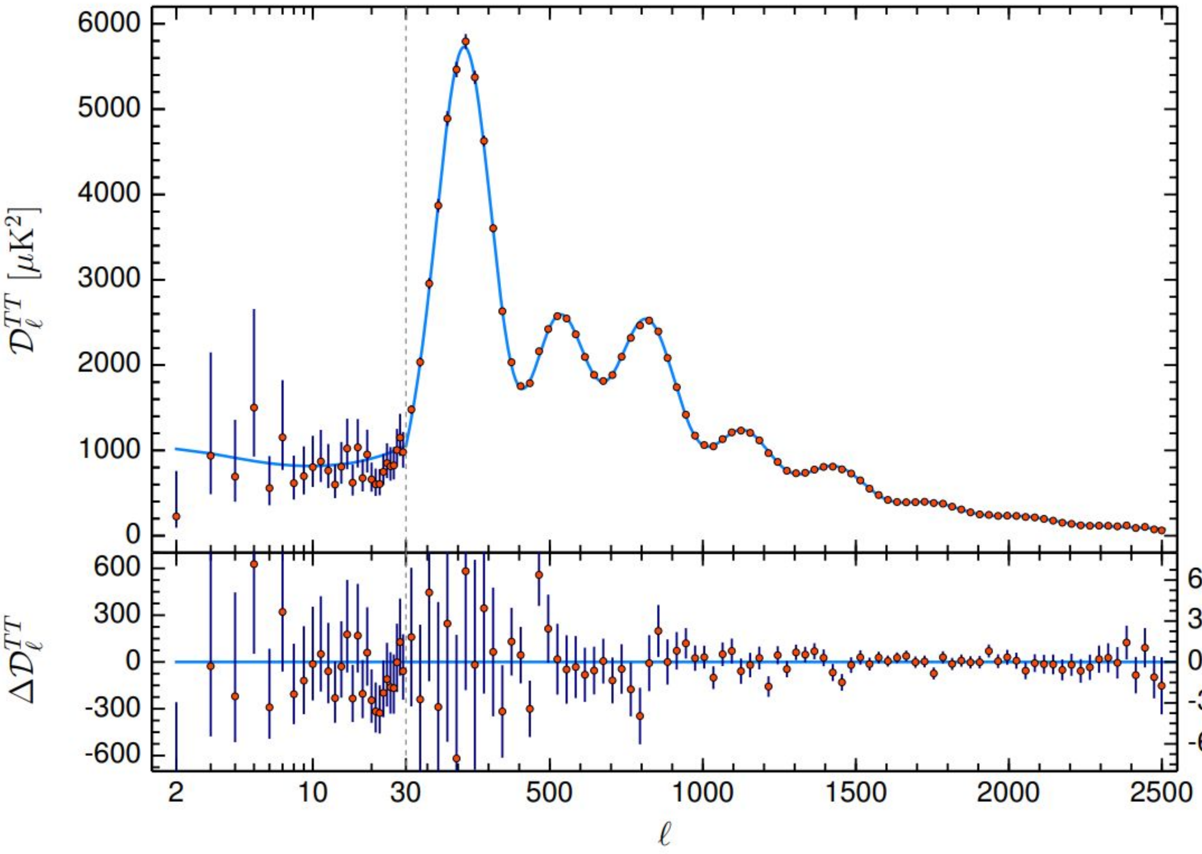


$$H(z) = H_0 \sqrt{\Omega_{de} e^{3\int_0^z \frac{(1+w)}{1+z'} dz'} + \Omega_m (1+z)^3 + \Omega_r (1+z)^4 + \Omega_\nu F(z)}$$

Tensions in H0



Planck 2018



6000
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$\mathcal{D}_\ell^{TT}$ [μK^2]
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