Hubble Tension Update

Martin Schmaltz, Boston University

Ljubljana, July 3, 2025

CMB, BAO fits to ΛCDM

$$H_0 = 67.24 \pm 0.35$$

(stat.+syst.)
Planck+ACT+SPT2025

Distance ladders

$$H_0 = 73.2 \pm 0.9$$

(stat.+syst.)
SH0ES 2024

6.2σ

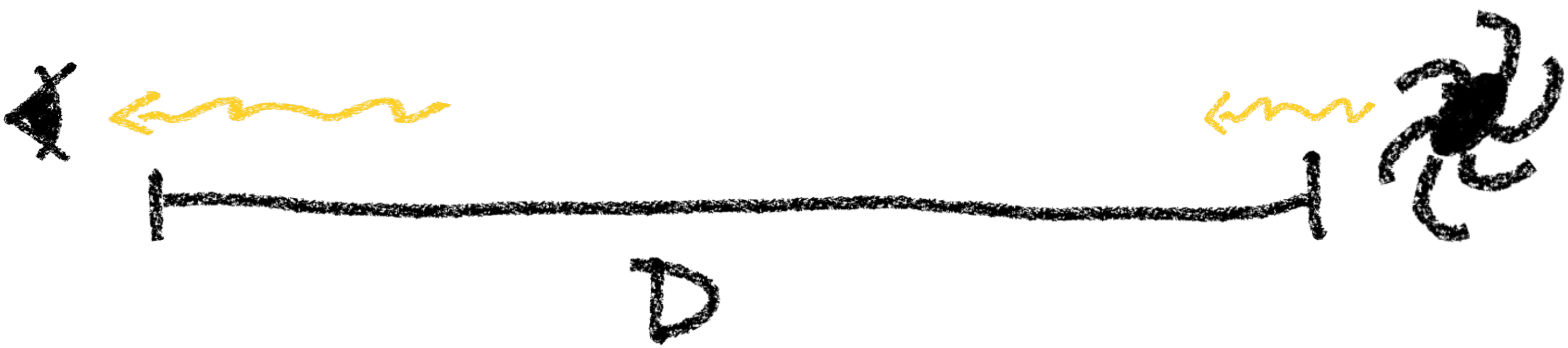
$$p = 3 \times 10^{-10}$$

Outline

- Intro: Hubble's law
- Distance ladders: SH0ES, CCHP, TDCOSMO
- CMB, BAO fit to ΛCDM, sound horizon
- CMB, BAO fit to BSM
- Summary, DESI w0wa

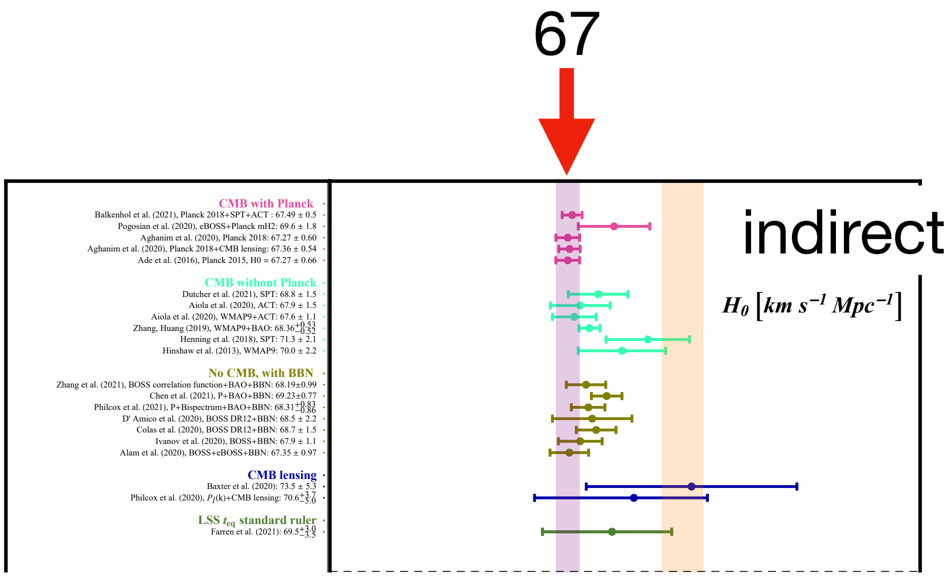
Hubble's Law - definition of H_0

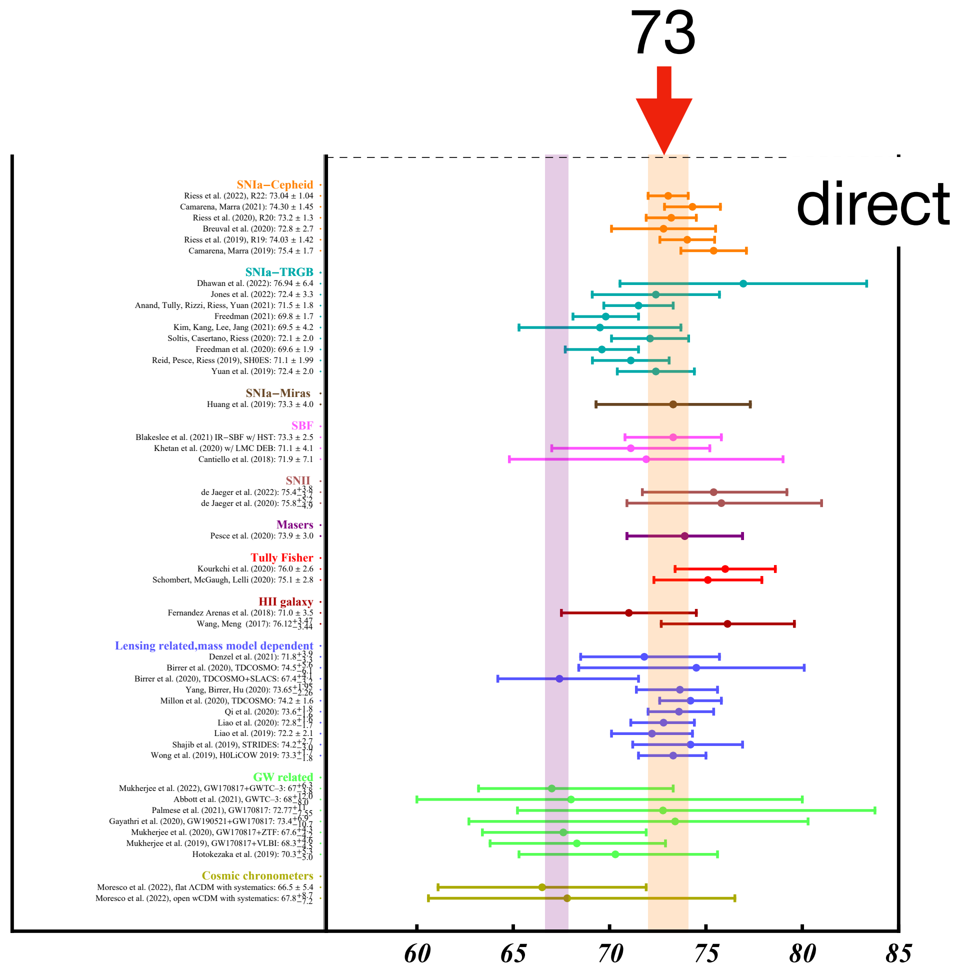
$$H_0 = \frac{v}{D} = \frac{zc}{D} \qquad \frac{\text{easy}}{\text{hard}}$$



Hubble tension

(Snowmass Report 2022)

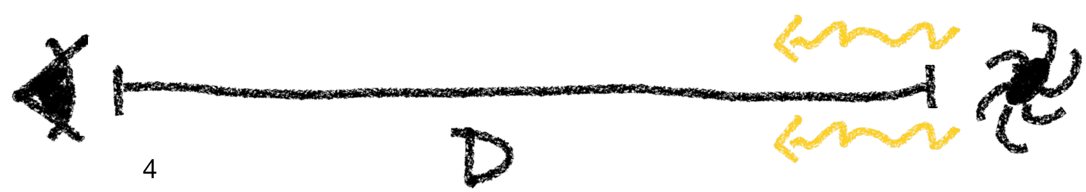




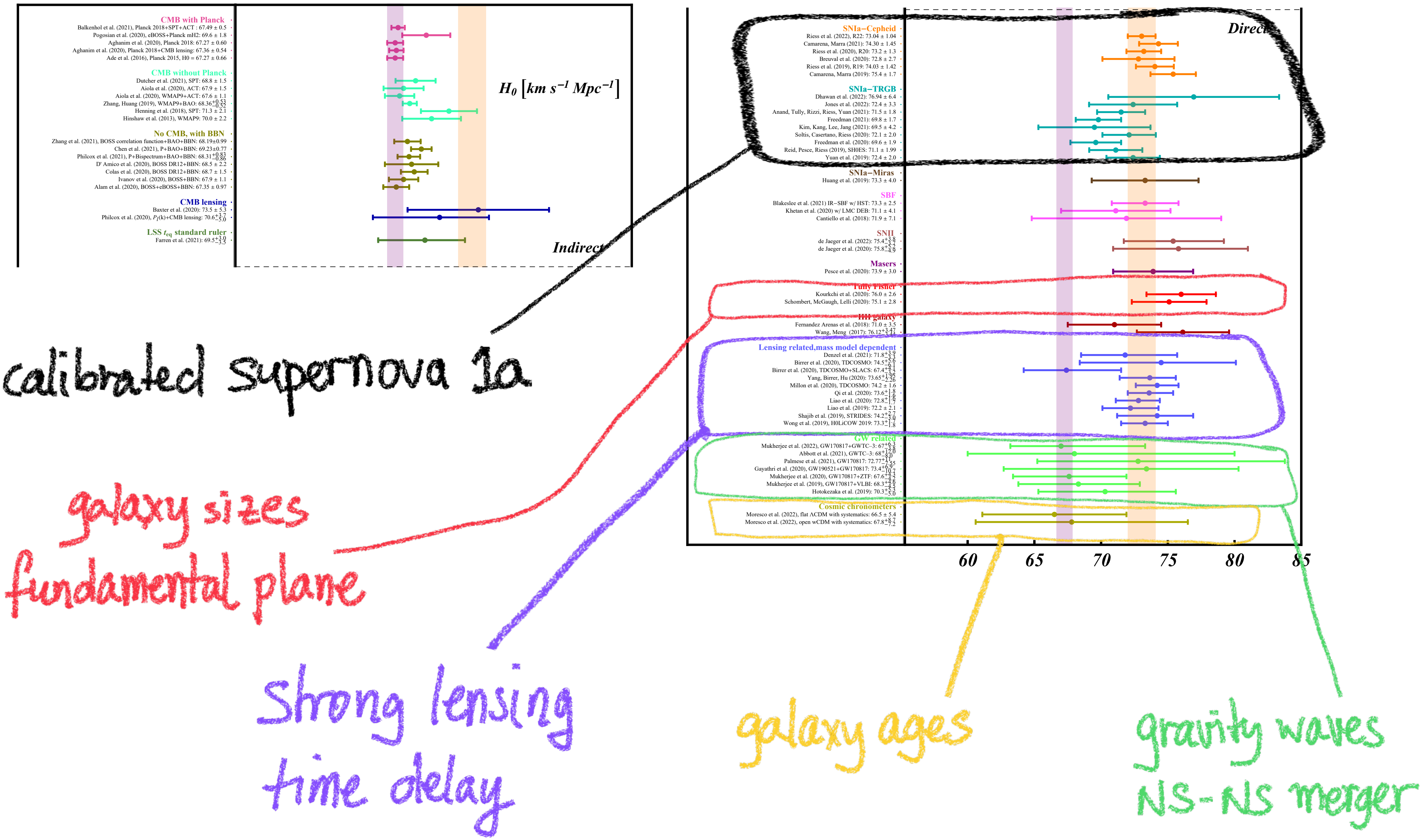
CMB, BAO: "indirect" methods use the sound horizon r_s as ruler to measure D, calculated in ΛCDM

many "direct" methods to determine D

$$H = \frac{v}{D} = \frac{zc}{D}$$

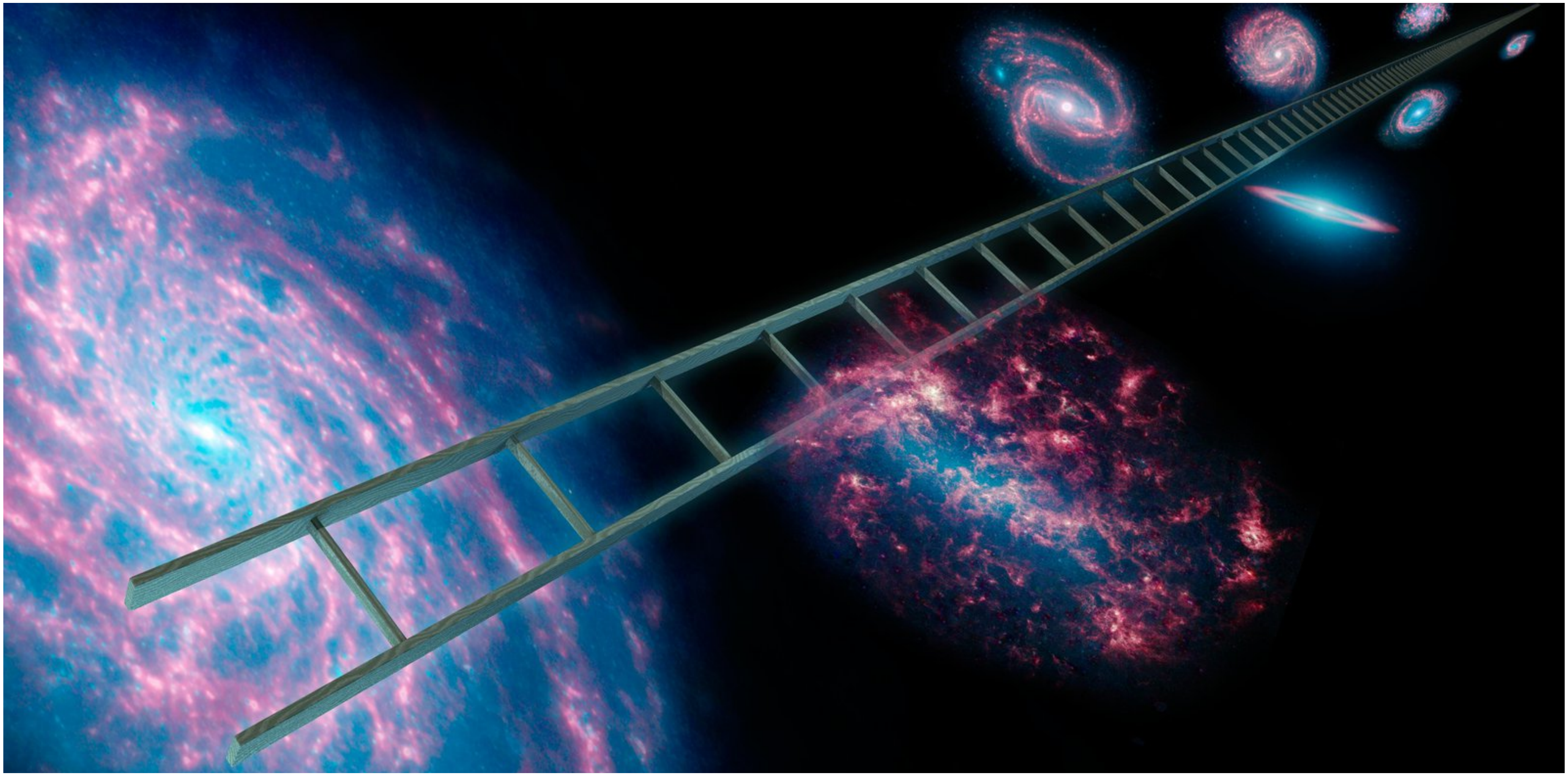


Hubble tension, H_0



Geometry-Cepheids-Supernovae “distance ladder”

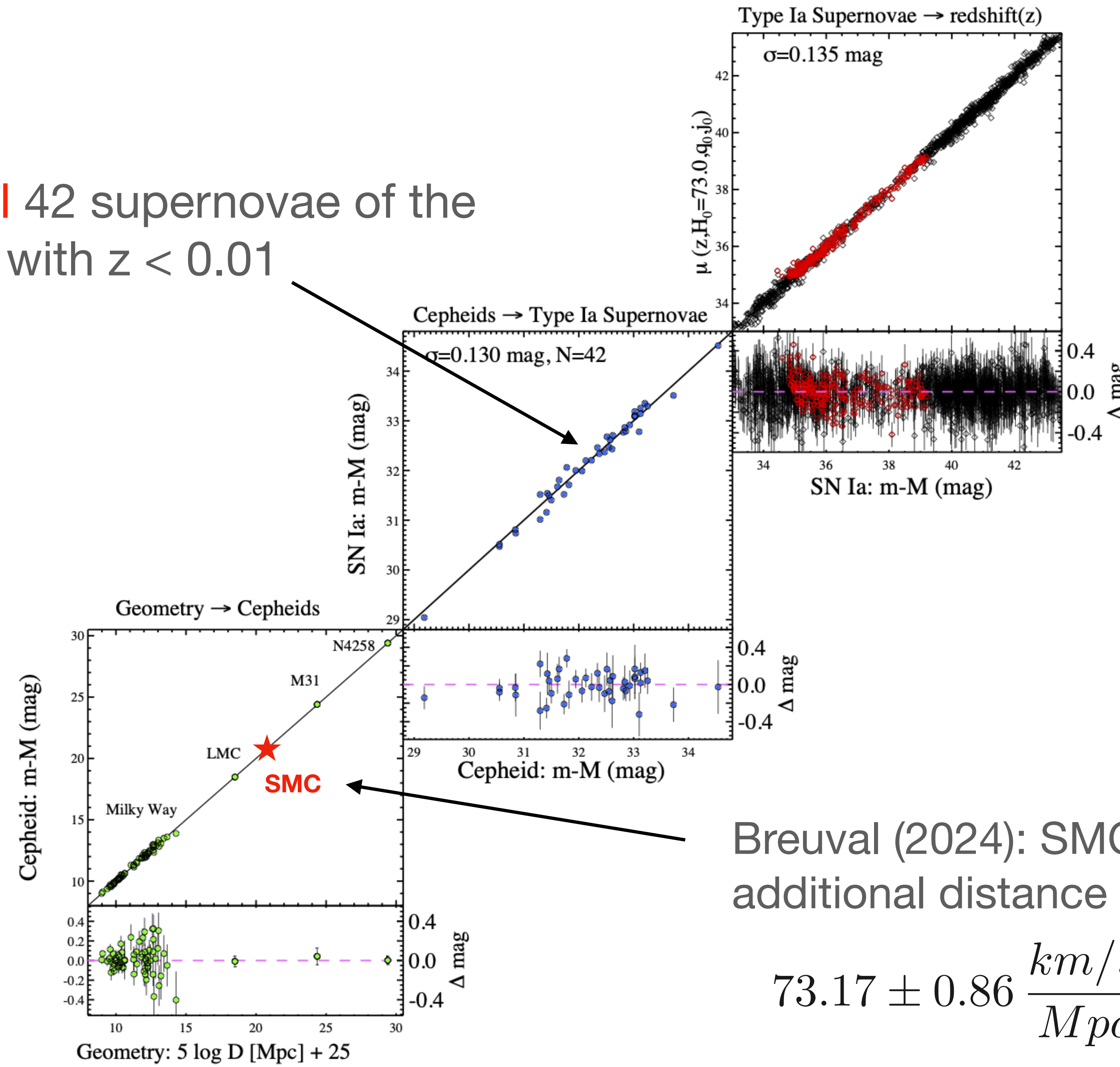
SH_0ES collaboration (Riess et. al.)



JPL/NASA

Geometry > Cepheids > SN1a luminosity calibration

since 2022: all 42 supernovae of the past 40 years with z < 0.01



Breuval (2024): SMC as additional distance anchor

$$73.17 \pm 0.86\,\frac{km/s}{Mpc}$$

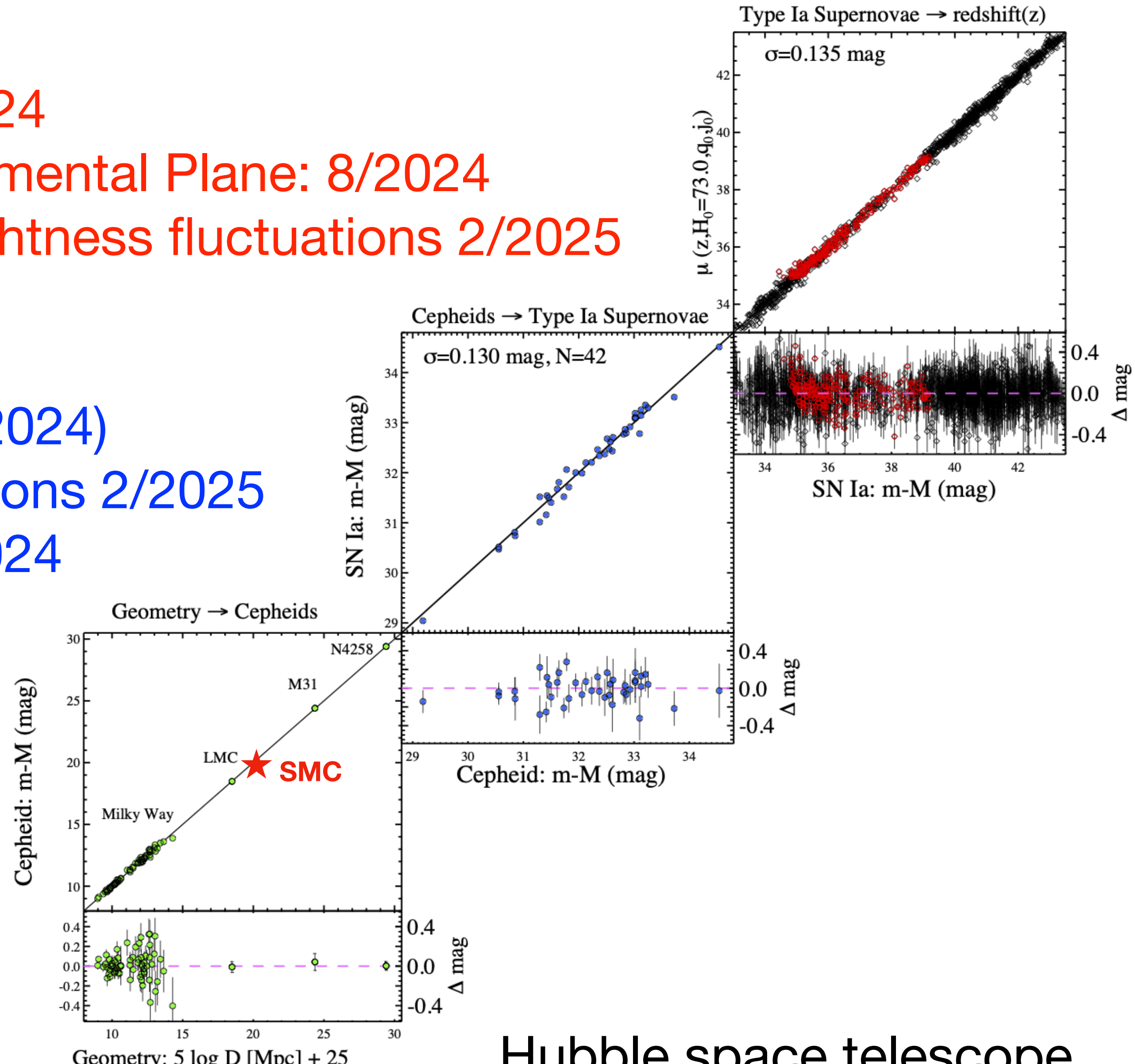
SH$_0$ES Team

Cross-checking all rungs of the distance ladder

- SN 1a
- SN II: 11/2024
- DESI Fundamental Plane: 8/2024
- Surface brightness fluctuations 2/2025

- Cepheids
- TRGB,JAGB (Freedman 8/2024)
- Surface brightness fluctuations 2/2025
- Coma cluster distance 9/2024

- Geometrical distances to: Milky Way, LMC, SMC, Megamasers, M31, N4258

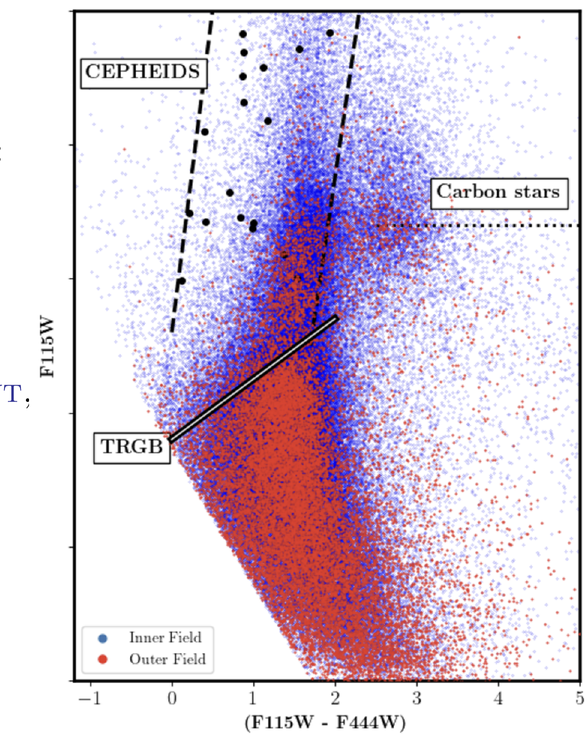


Hubble space telescope cross-checked with JWST

The Freedman vs. Riess tension summer 2024

12 Aug 2024

FREEDMAN ET AL.



Status Report on the Chicago-Carnegie Hubble Program (CCHP): Three Independent Astrophysical Determinations of the Hubble Constant Using the James Webb Space Telescope

*

WENDY L. FREEDMAN,[1] BARRY F. MADORE,[2] IN SUNG JANG,[3,4] TAYLOR J. HOYT, ABIGAIL J. LEE,[3,4,†] AND KAYLA A. OWENS[3,4]

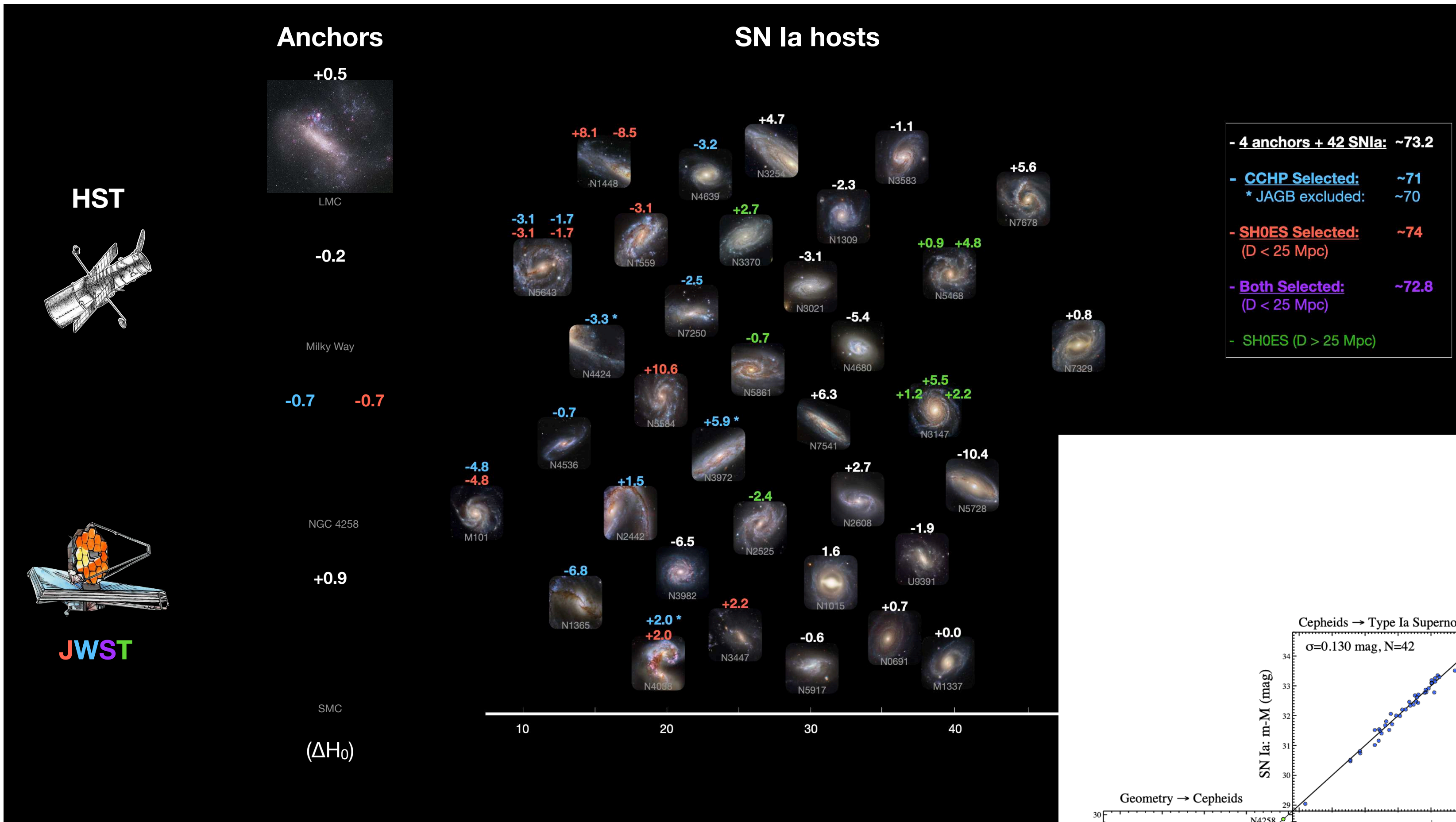
H_0 ~ 70+-2

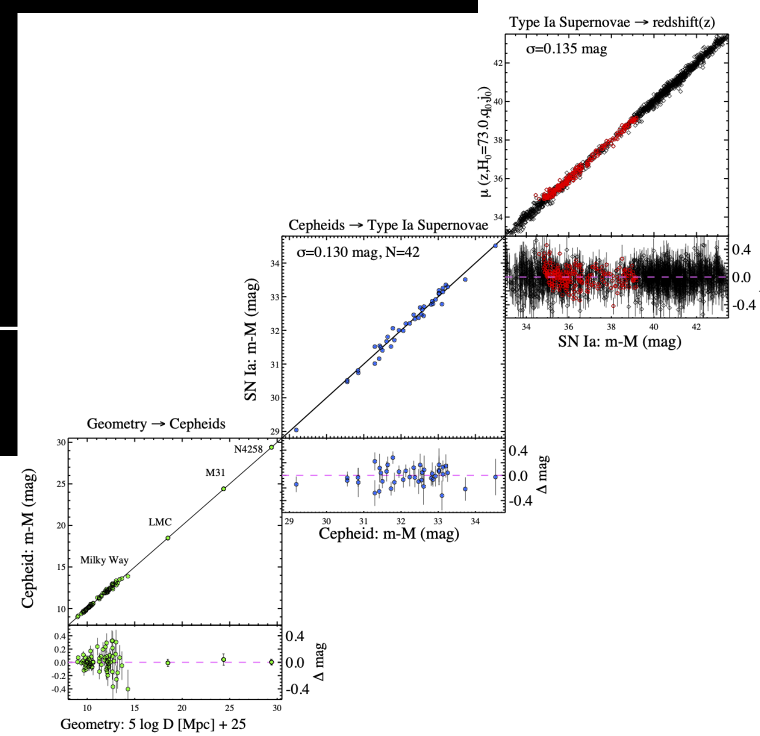
21 Aug 2024

***JWST* Validates *HST* Distance Measurements: Selection of Supernova Subsample Explains Differences in *JWST* Estimates of Local H_0**

ADAM G. RIESS,[1,2] DAN SCOLNIC,[3] GAGANDEEP S. ANAND,[1] LOUISE BREUVAL,[2] STEFANO CASERTANO,[1] LUCAS M. MACRI,[4] SIYANG LI,[2] WENLONG YUAN,[2] CAROLINE D. HUANG,[5] SAURABH JHA,[6] YUKEI S. MURAKAMI,[2] RACHAEL BEATON,[1] DILLON BROUT,[7] TIANRUI WU,[3] GRAEME E. ADDISON,[2] CHARLES BENNETT,[2] RICHARD I. ANDERSON,[8] ALEXEI V. FILIPPENKO,[9] AND ANTHONY CARR[10,11]

Differences in H0 are due to statistical scatter in different subsets of calibrator SN1a



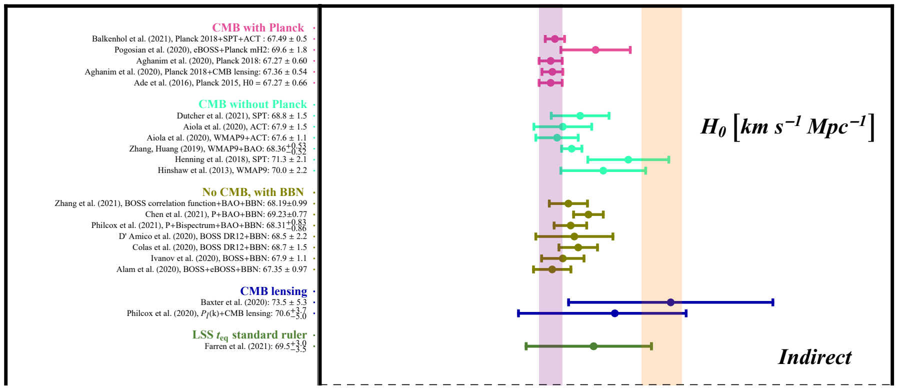


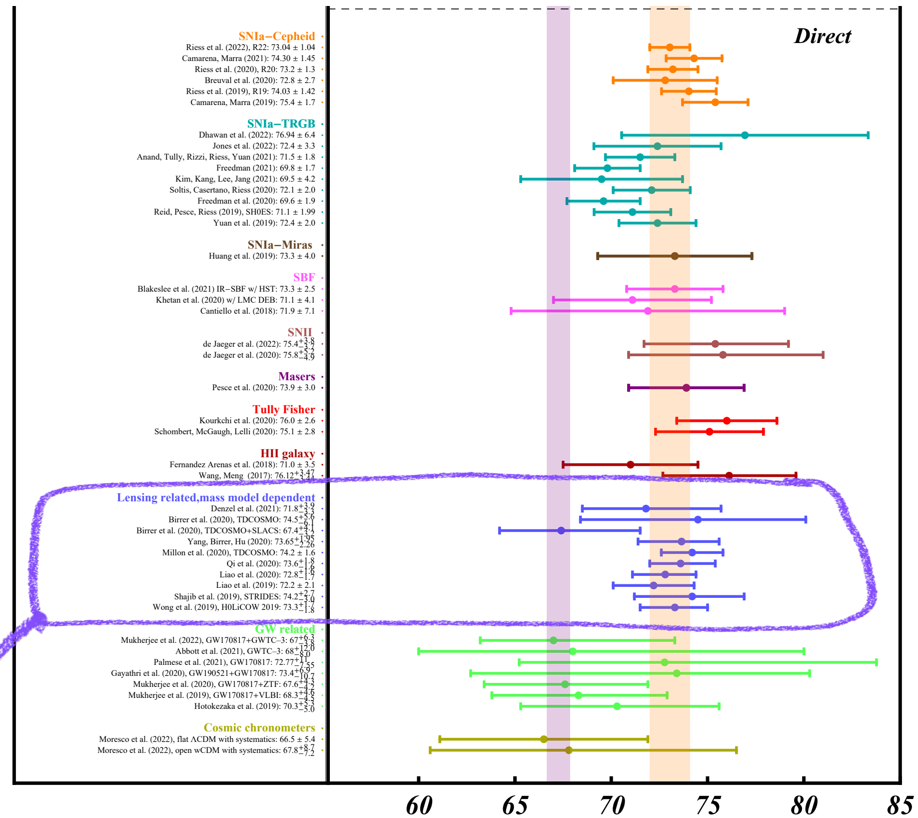
Riess 8/2024

Supernovae 1a bottom line:

- good agreement between Cepheids, TRGB, JAGB
- local H0 = 73.2+-0.9 km/s/Mpc (SH0ES HST 2024)
- cross checks of all rungs of distance ladder ongoing
- new (2025) effort to standardize and combine different groups' methods for rungs of distance ladder into one analysis code

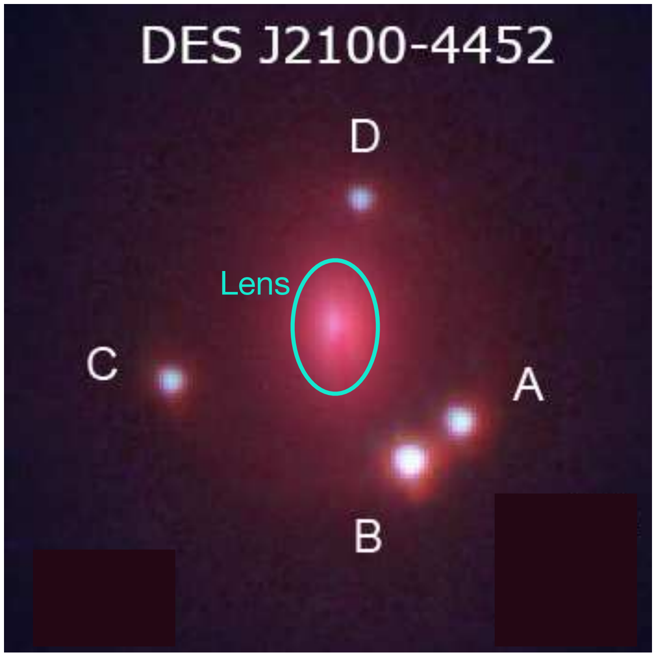
Hubble tension, H_0



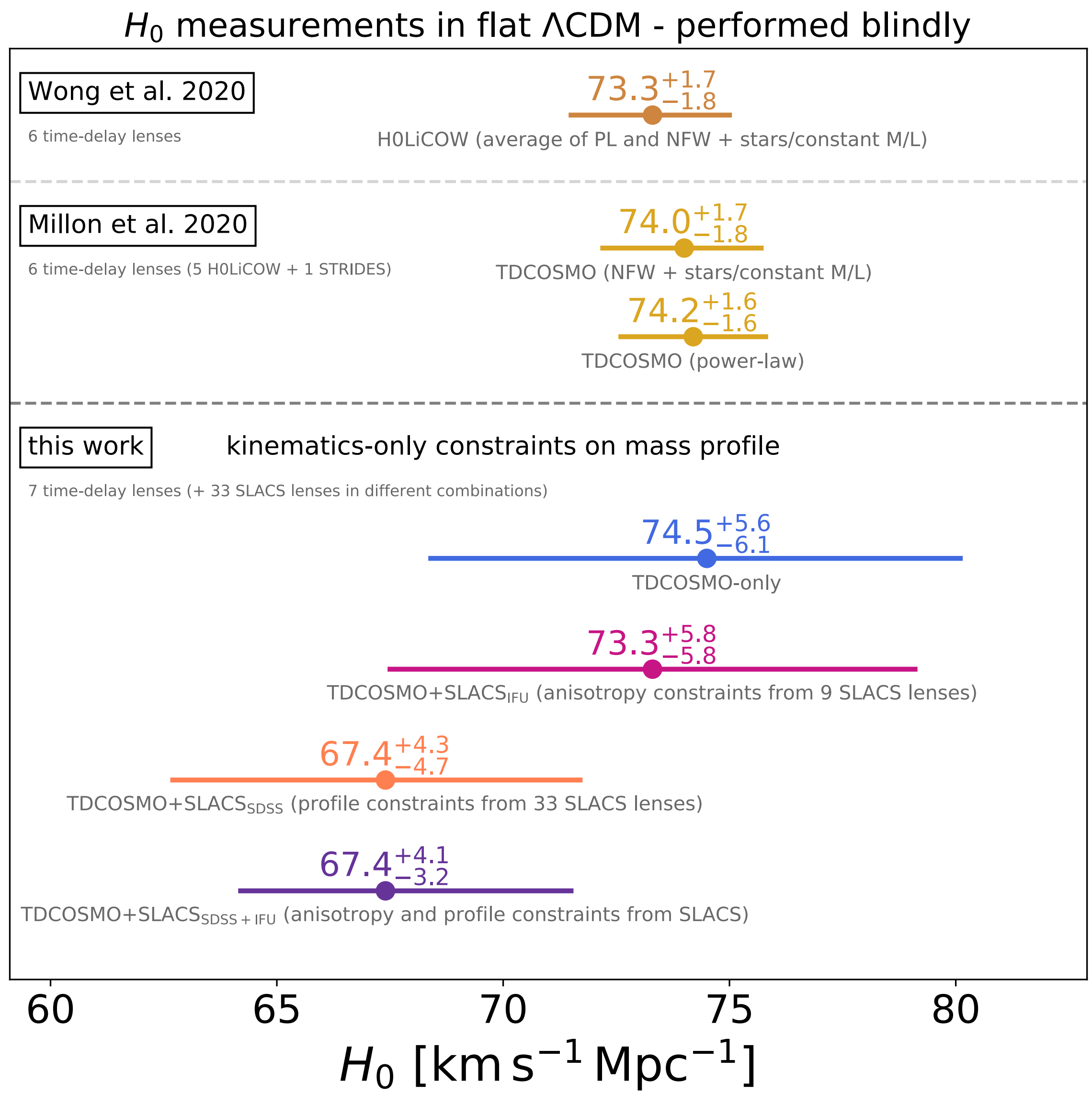


Strong lensing
time delay

Strong lensing time delay -TDCOSMO/HOLICOW

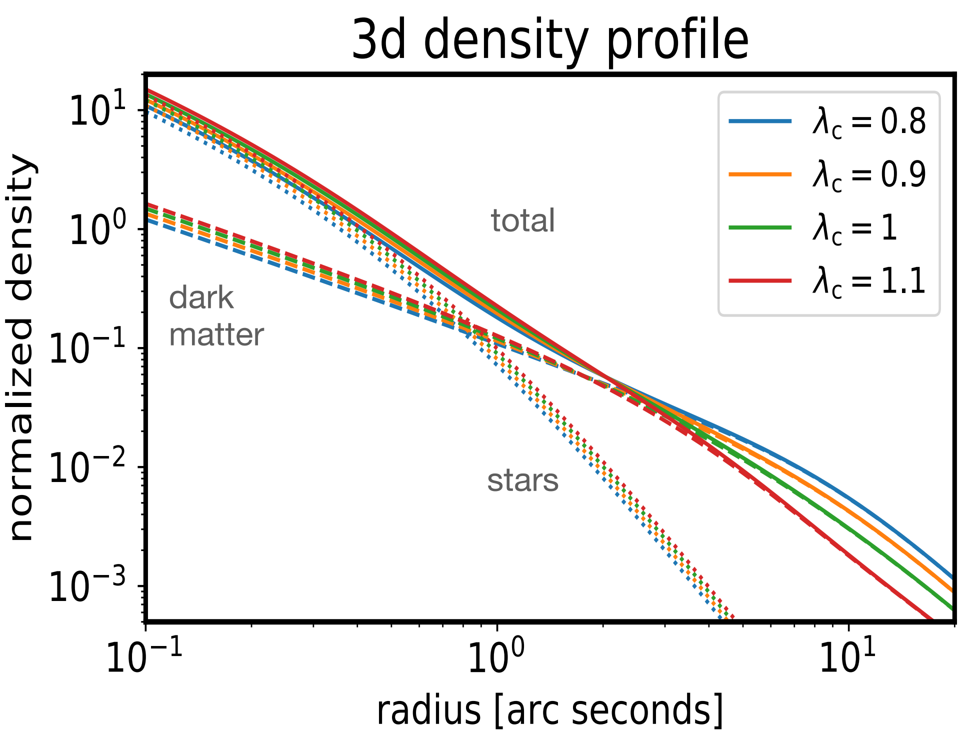


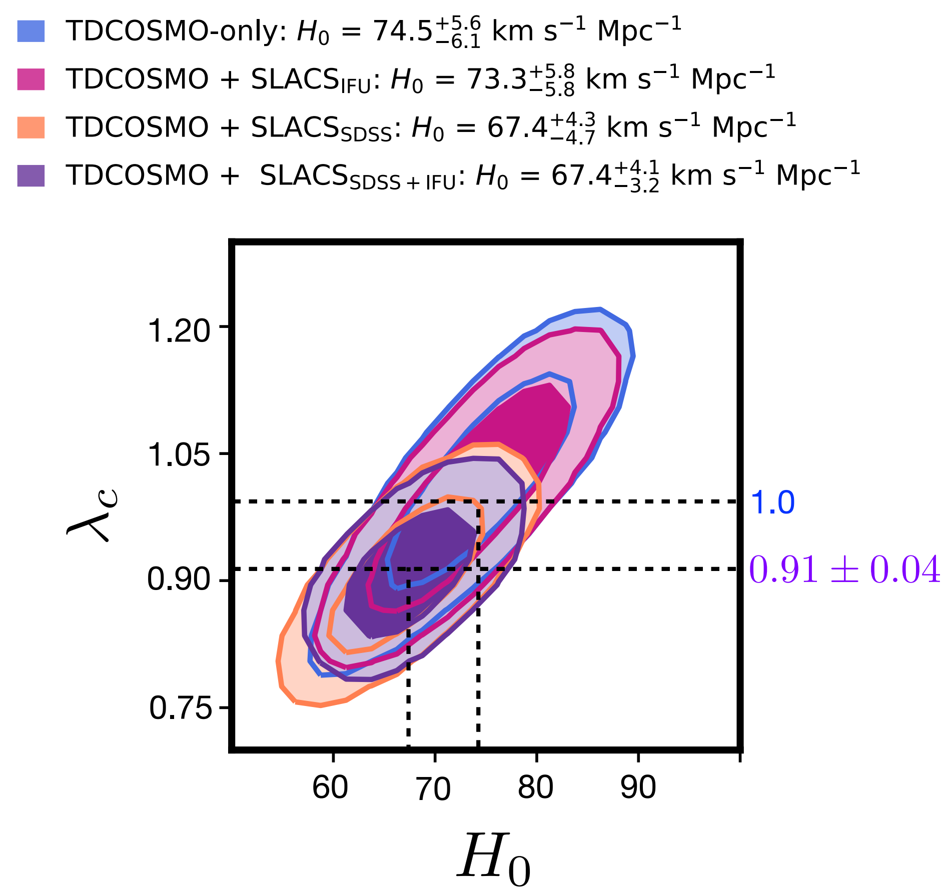
19 Dec 2020



$$H_0 \propto \frac{1}{\Delta t}$$

Approximate “mass-sheet” degeneracy





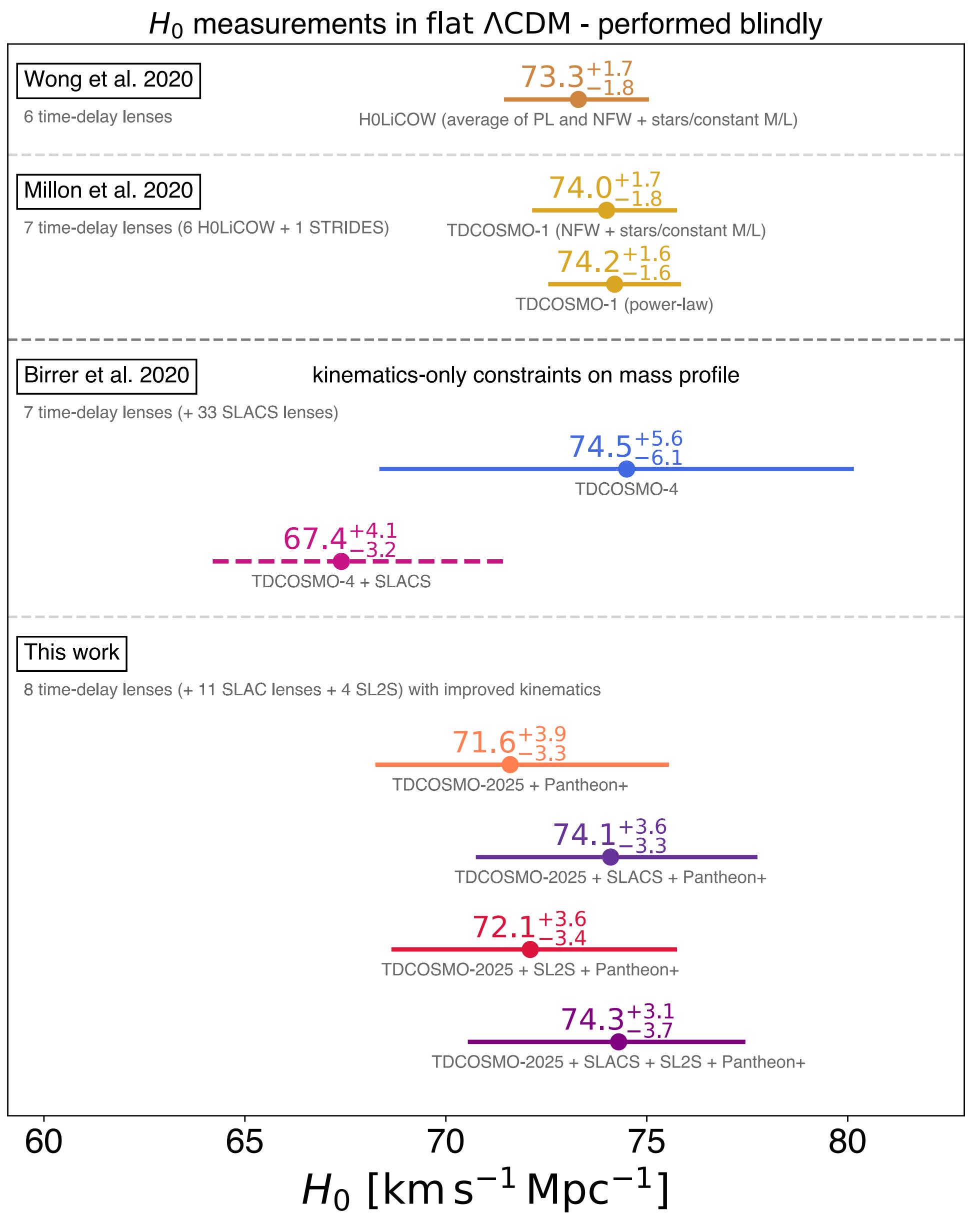
$$H_0 \propto \frac{\lambda_c}{\Delta t}$$

Birrer 2020

Evidence for mass-sheet disappeared

TDCOSMO 2025: Cosmological constraints from strong lensing time delays

25 Jun 2025



local H_0 measurements are not going away

$$H_0 = 73.2 \pm 0.9$$ (stat.+syst.)
SH0ES 2024

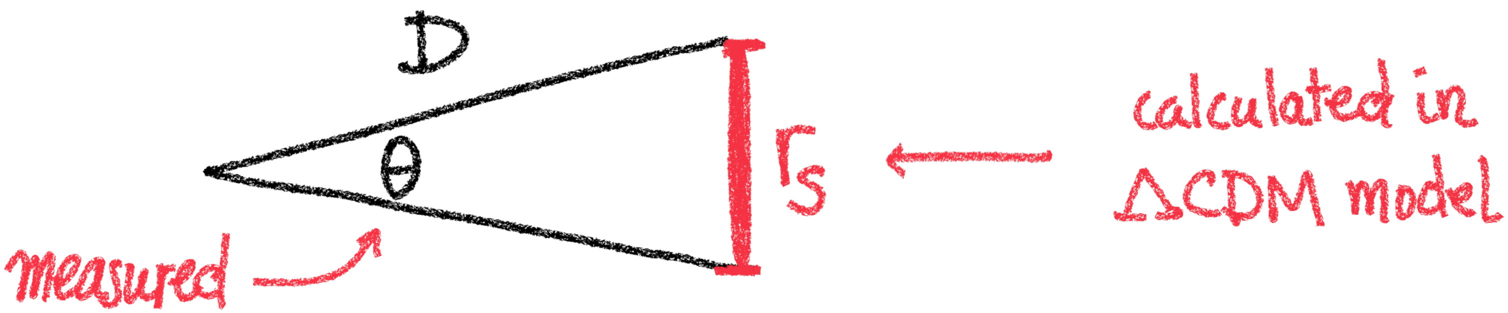
- direct, but depend on Astrophysics,
  many cross-checks and different techniques

- SH0ES is local H_0 , z ~ 0.1,
  other methods extend to z ~ 0.5, overlap with BAO

“Indirect” H_0 from CMB and BAO

$$H_0 = 67.24 \pm 0.35$$ (stat.+syst.)
Planck + ACT 2025 + SPT 2025

CMB and BAO use the sound horizon r_s as a “standard ruler”



$$H_0 \sim \frac{1}{D} \sim \frac{\theta}{r_s}$$

Going beyond ΛCDM to fix Hubble tension

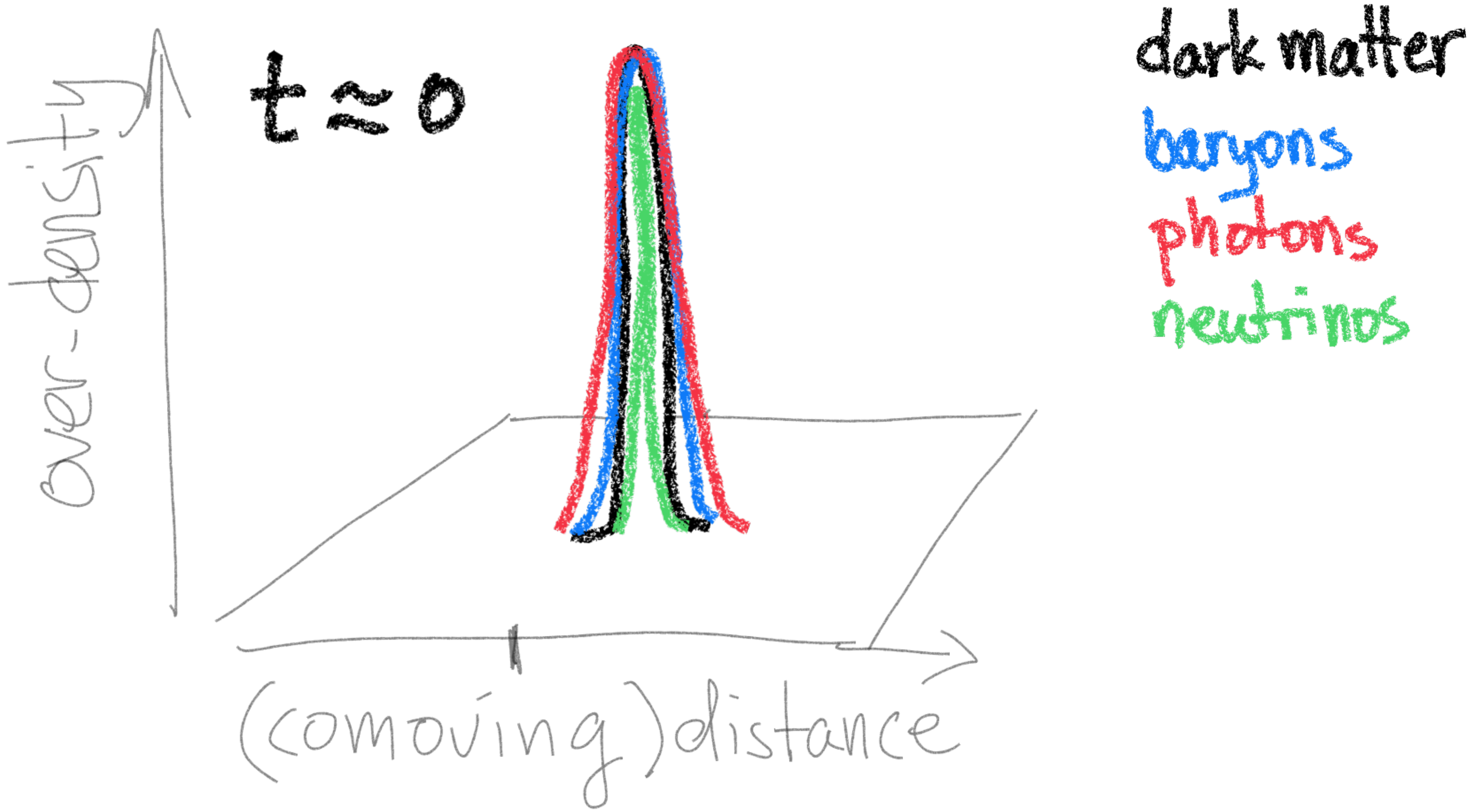
$$H_0^{CMB} = 67.24 \pm 0.35 \qquad H_0^{SH0ES} = 73.1 \pm 0.9$$

17σ in terms of CMB error bar

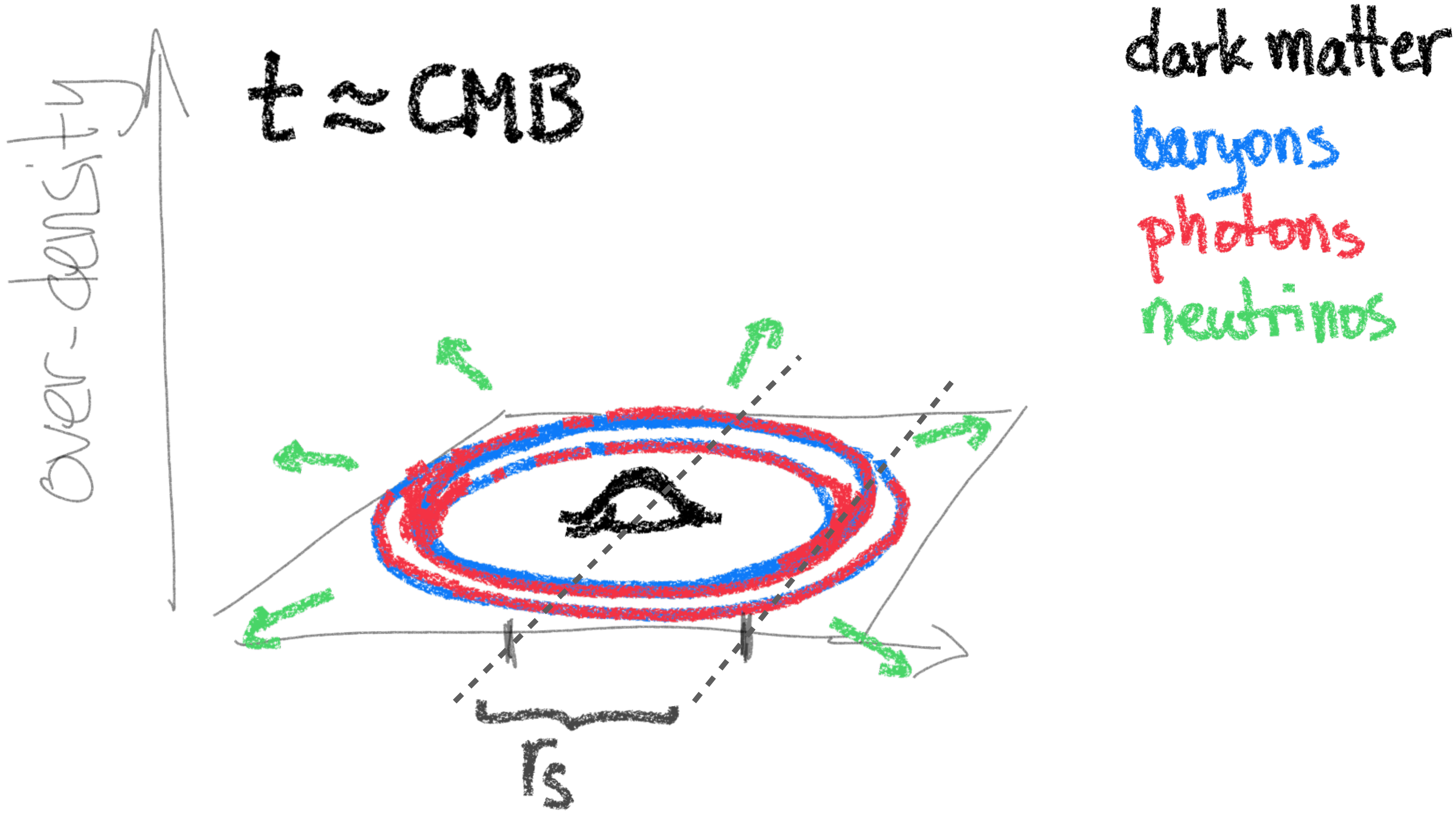
CMB, BAO: $H_0 \propto \frac{1}{r_s}$

to solve Hubble tension
need r_s smaller by 8%

the physics of r_s : primordial over-density



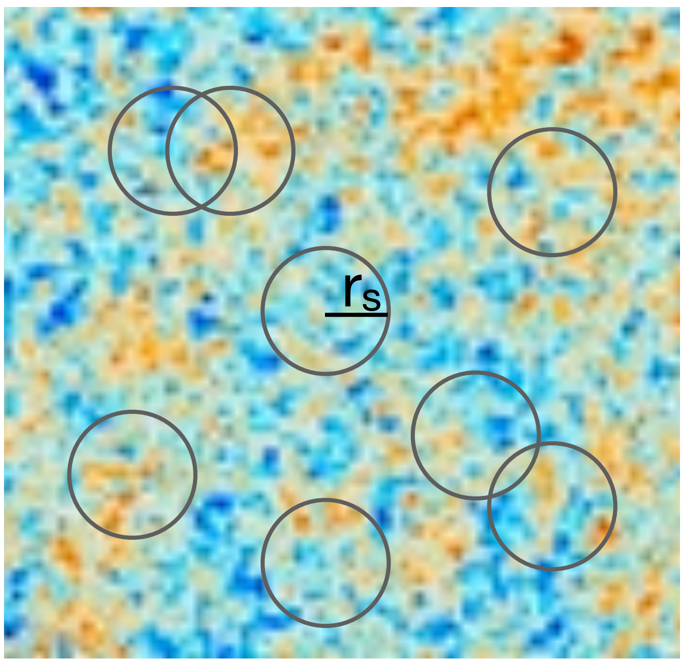
physics of r_s: evolved over-density

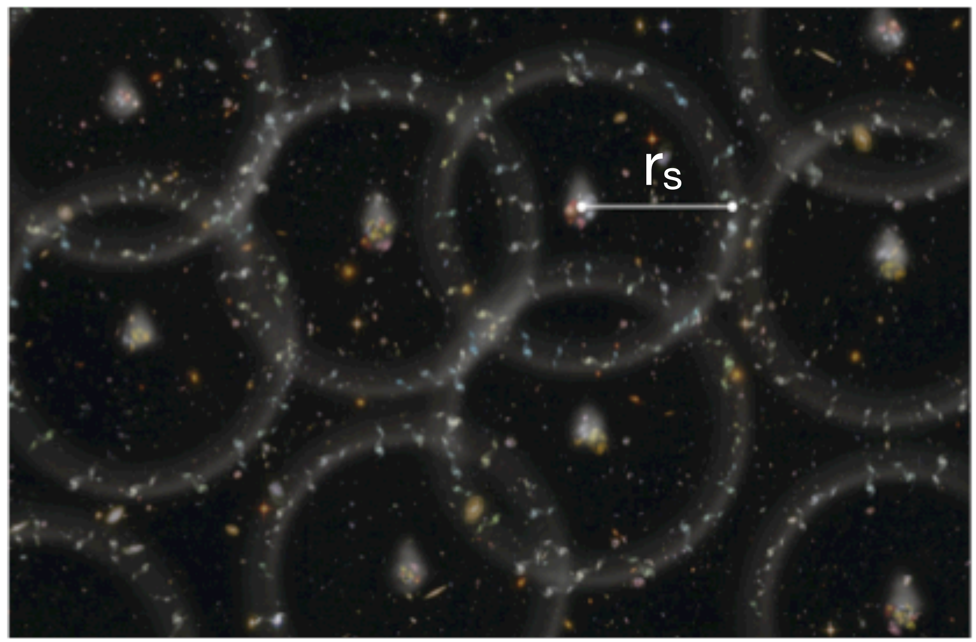


The sound horizon r_s "Circles in the sky"

CMB: correlations in temperature fluctuations

BAO: correlations in galaxy distributions





sound horizon calculation

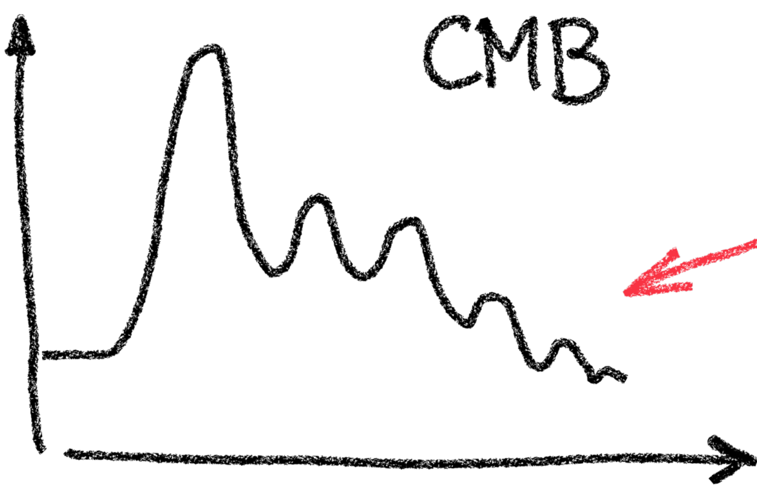
sound speed $1/\sqrt{3}$

$$r_s = \int_0^{\tau_{\rm CMB}} c_s \, d\tau = \int_{z_{\rm CMB}}^{\infty} c_s \frac{dz}{\sqrt{\frac{8\pi G}{3}(\rho_{rad.} + \rho_{mat.})}}$$

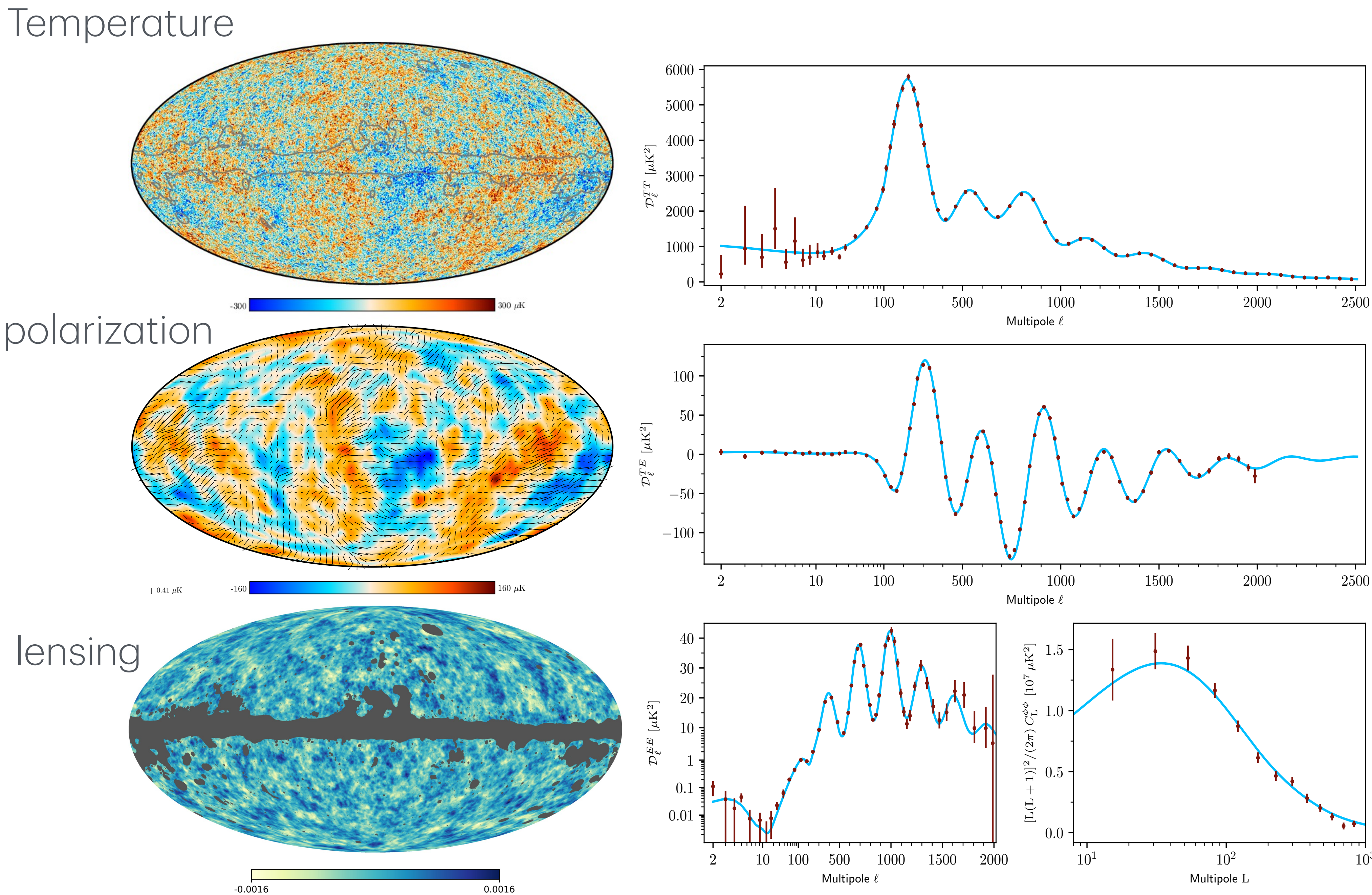
photons
neutrinos

dark matter
baryons

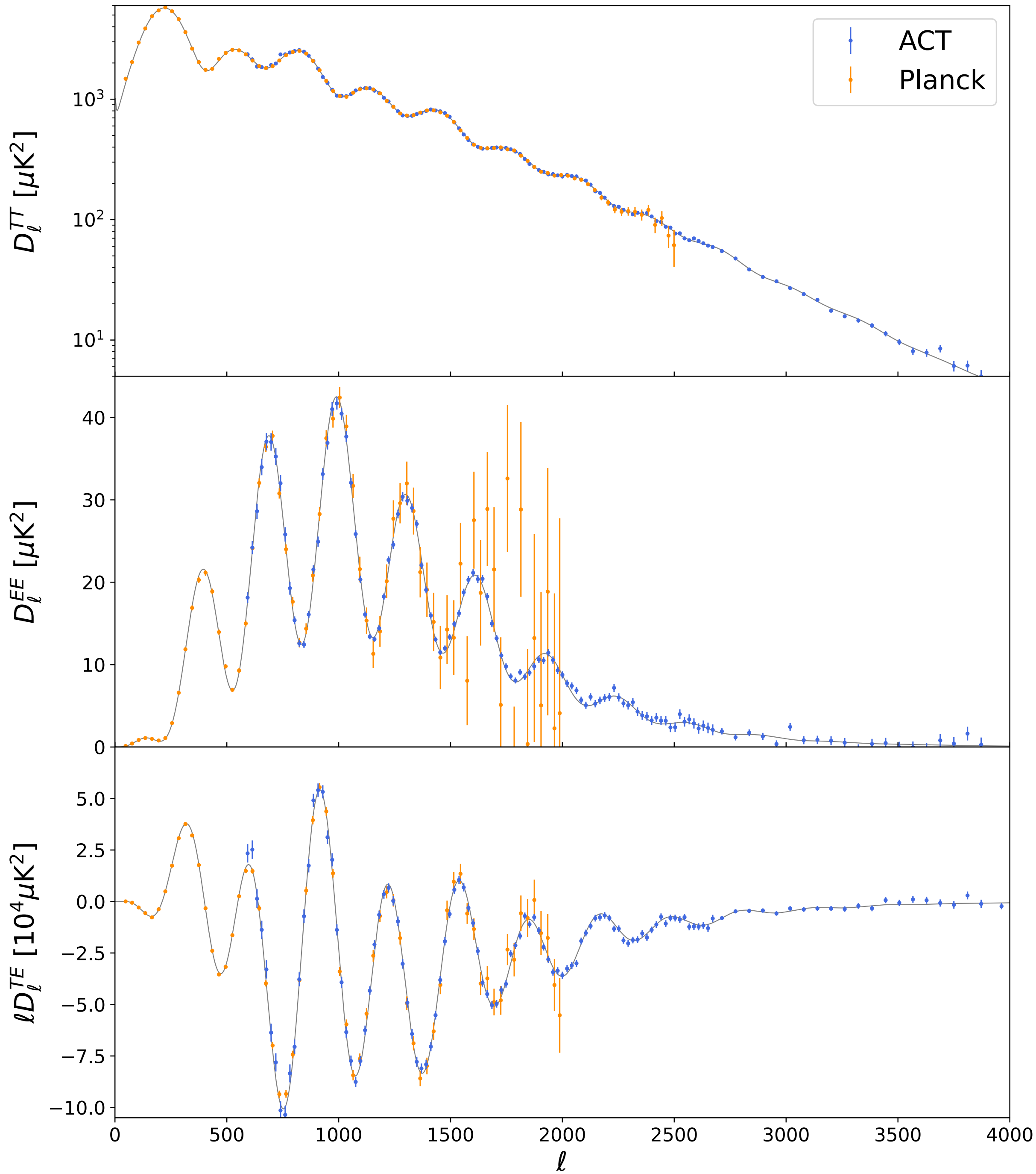
determined by fit to CMB



Planck 2018 results. I.
Overview and the cosmological legacy of _Planck_

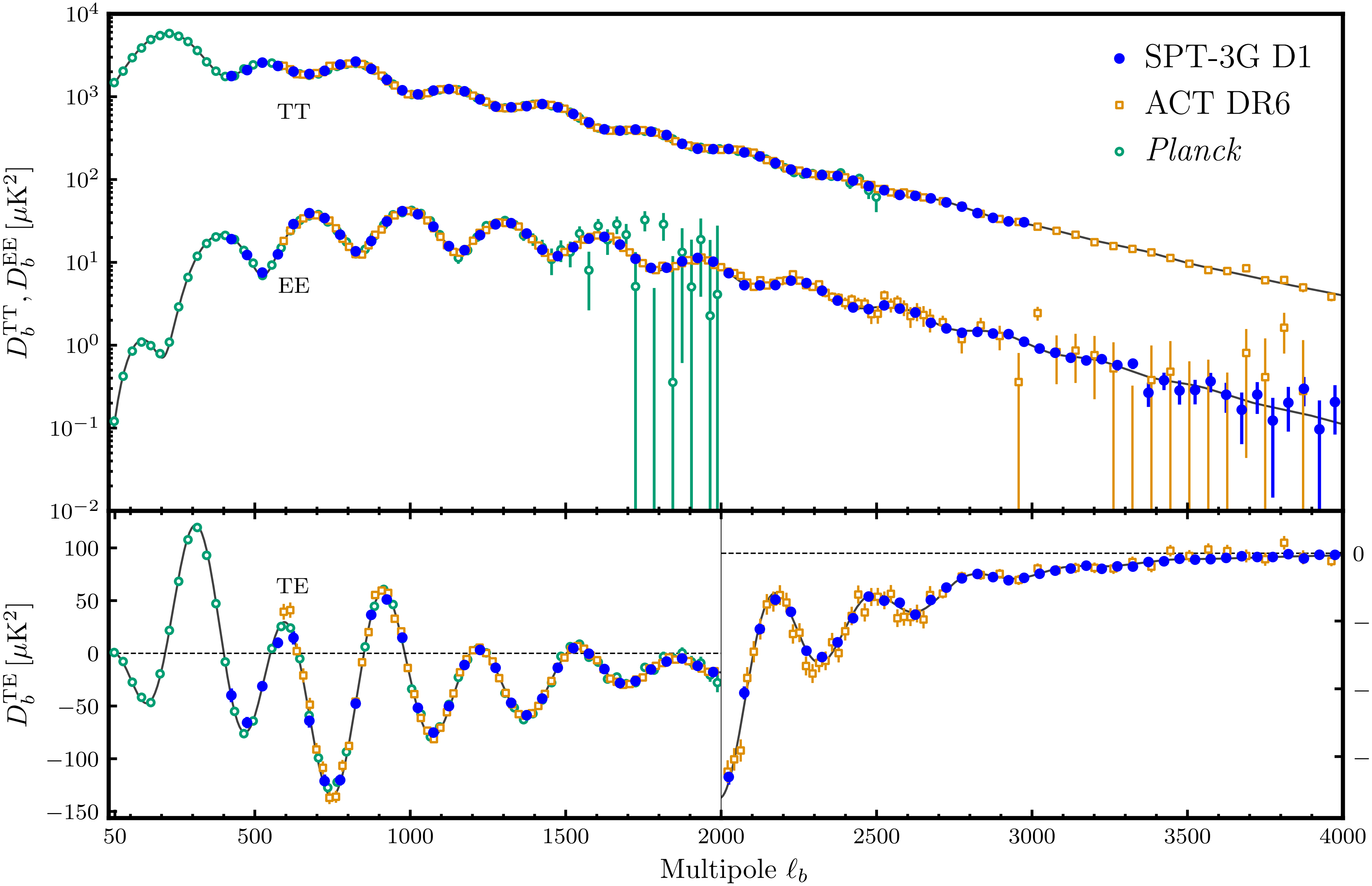


March 18, 2025



SPT-3G D1: CMB temperature and polarization power spectra and cosmology from 2019 and 2020 observations of the SPT-3G Main field

25 Jun 2025



a smaller r_s with additional early energy

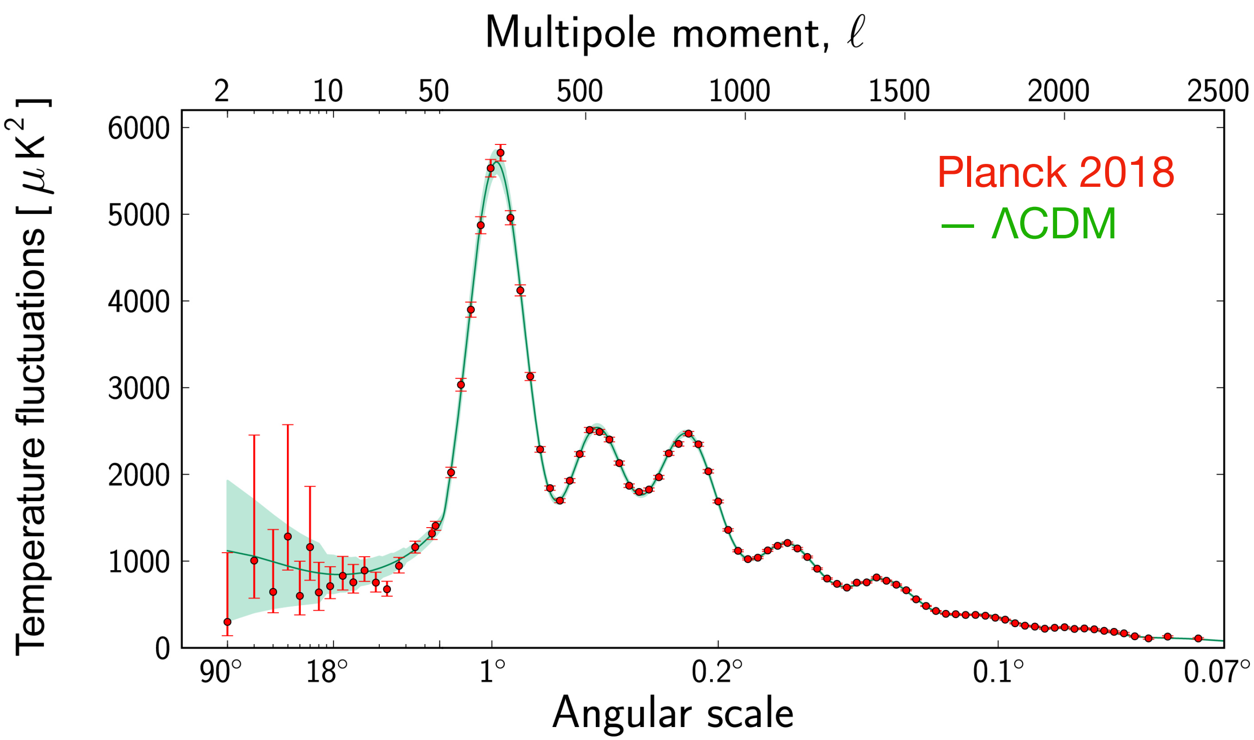
$$r_s = \int_{z_{\rm CMB}}^{\infty} c_s \frac{dz}{\sqrt{\frac{8\pi G}{3}(\rho_{rad.} + \rho_{mat.} + \rho_{early})}}$$

What is early energy?

- early dark energy — Poulin,Smith,Karwal,Kamionkowski (2019)
- dark radiation — Planck 2018
- dark interacting radiation — Baumann,Green (2016); Blinov,MarquesTavares (2020) ⋮
- dark interacting radiation with a step — Aloni,Berlin,Joseph,Schmaltz,Weiner (2022) ⋮

What is early energy?

generic new energy densities at CMB times mess up the CMB



Does it work? maybe, half-way

ACT DR6 **Constraints on Extended Cosmological Models**

18 Mar 2025

- ΔNeff

$$N_{\rm idr} < 0.134 \quad (95\%,\ \text{P-ACT-LB})$$
$$H_0 = 68.59^{+0.41}_{-0.50} \quad (68\%,\ \text{P-ACT-LB}).$$

- EDE

$$f_{\rm EDE} < 0.12 \quad (95\%, \text{P-ACT-LB})$$
$$H_0 = 69.9^{+0.8}_{-1.5} \quad (68\%, \text{P-ACT-LB})$$

- varying m_e + curvature

$$\left.\begin{aligned} m_e/m_{e,0} &= 1.022 \pm 0.016 \\ \Omega_k &= -0.0031 \pm 0.0037 \\ H_0 &= 71.0 \pm 1.7 \end{aligned}\right\} \quad (68\%,\ \text{P-ACT-LB})$$

Summary

- Hubble tension, 6.2σ, and growing
- local "direct" $H_0 = 73.1 \pm 0.9 \quad \frac{km/s}{Mpc}$

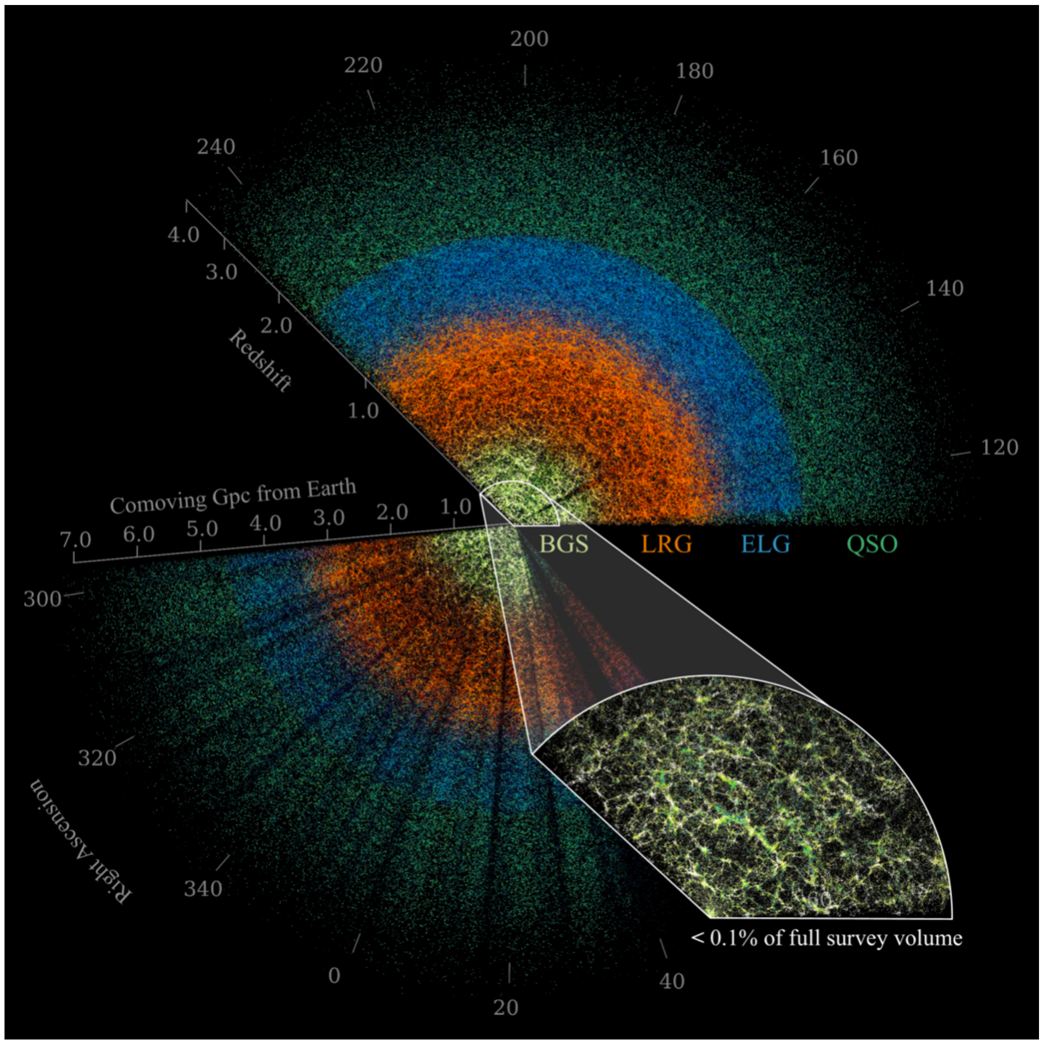
  many cross checks, several methods, bigger error
  more constraints on BSM models
- "indirect" BAO, CMB $H_0 = 67.2 \pm 0.4$

  precise, Planck, ACT, SPT, BAO all agree, rely on sound horizon
  which is sensitive to BSM physics. No full BSM solution yet.
- connection to $w_0 + w_a < -1$

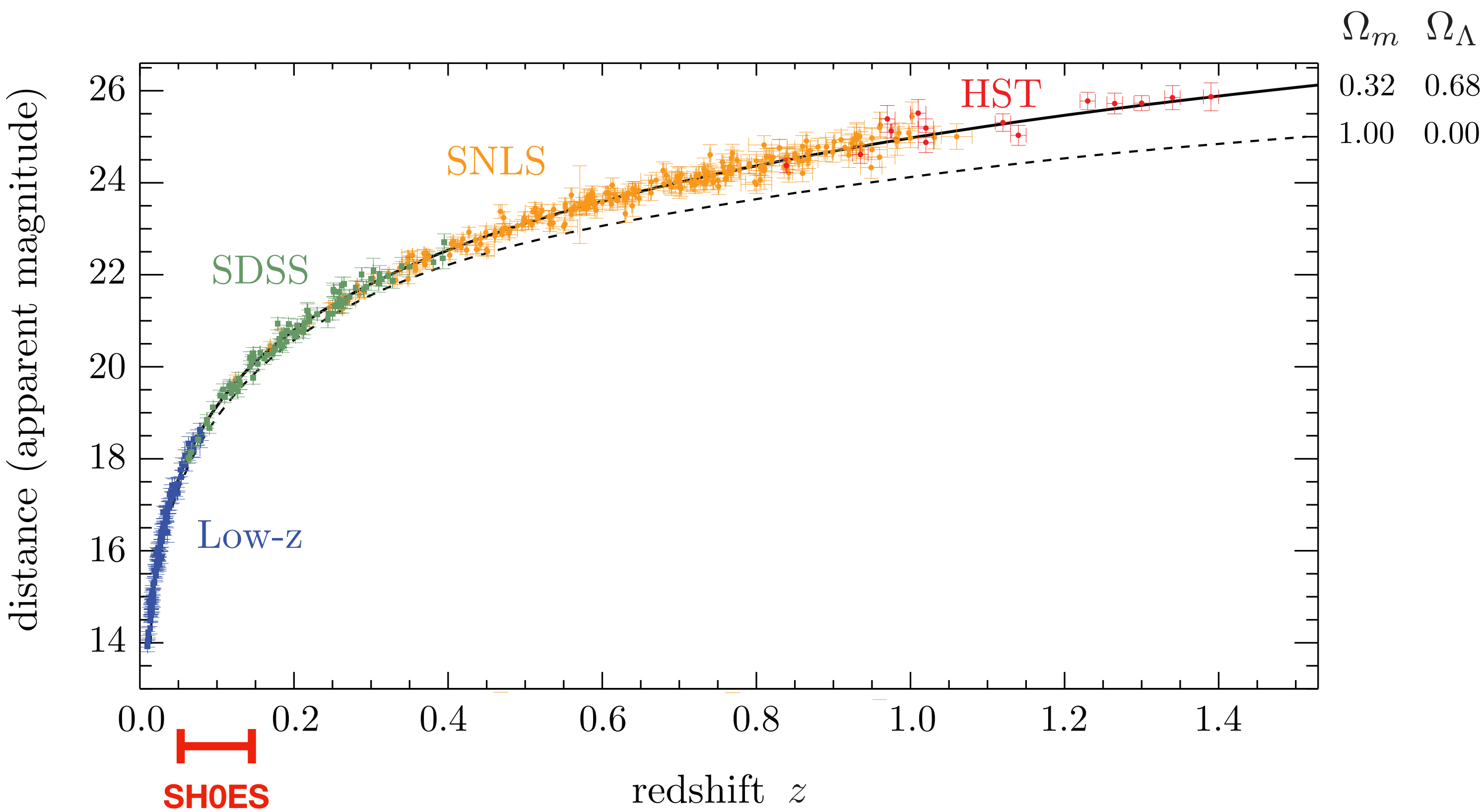
DESI: Evolving "phantom" dark energy

DESI DR2 Results II: Measurements of Baryon Acoustic Oscillations and Cosmological Constraints

26 Mar 2025

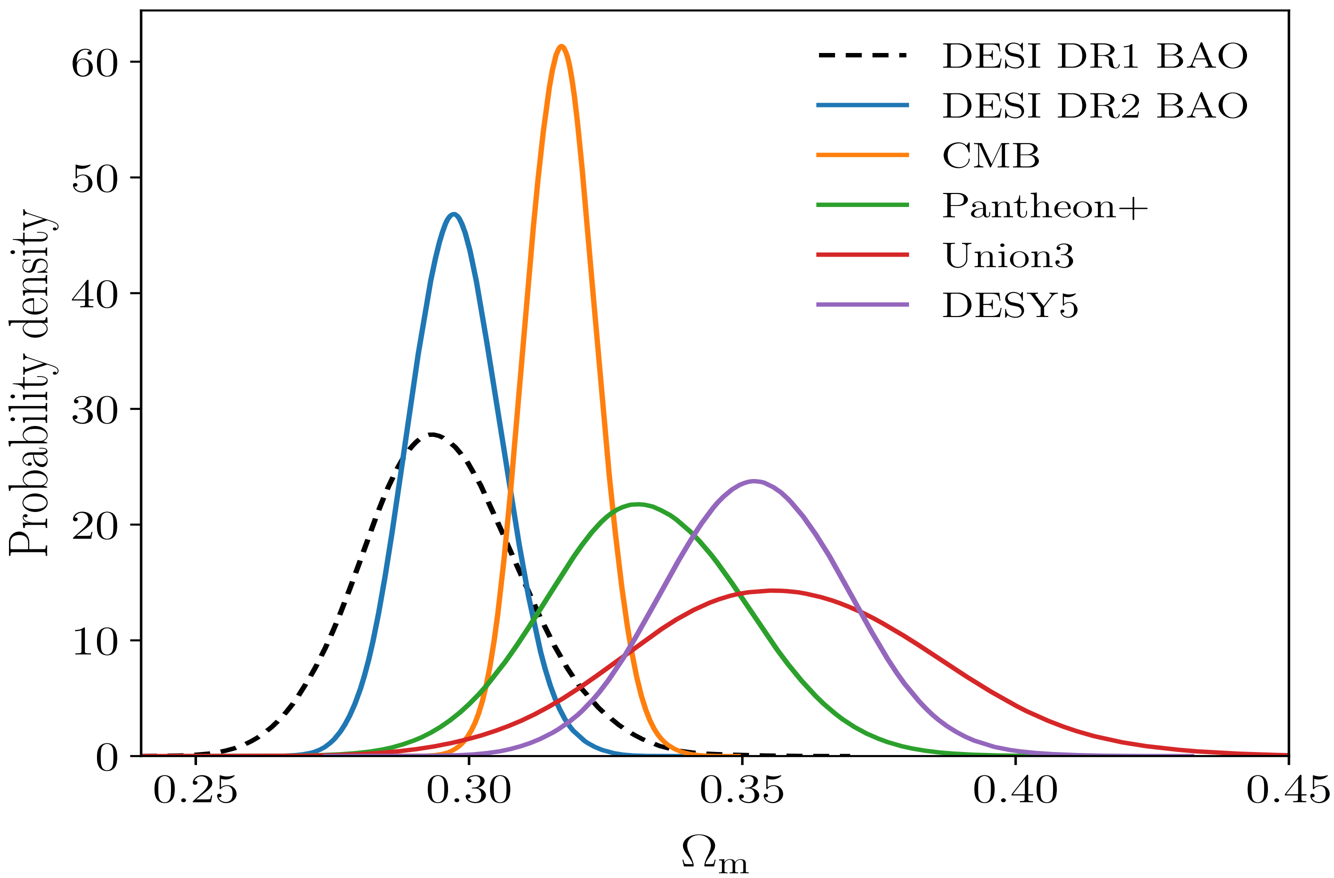


Hubble diagram from Supernovae 1a



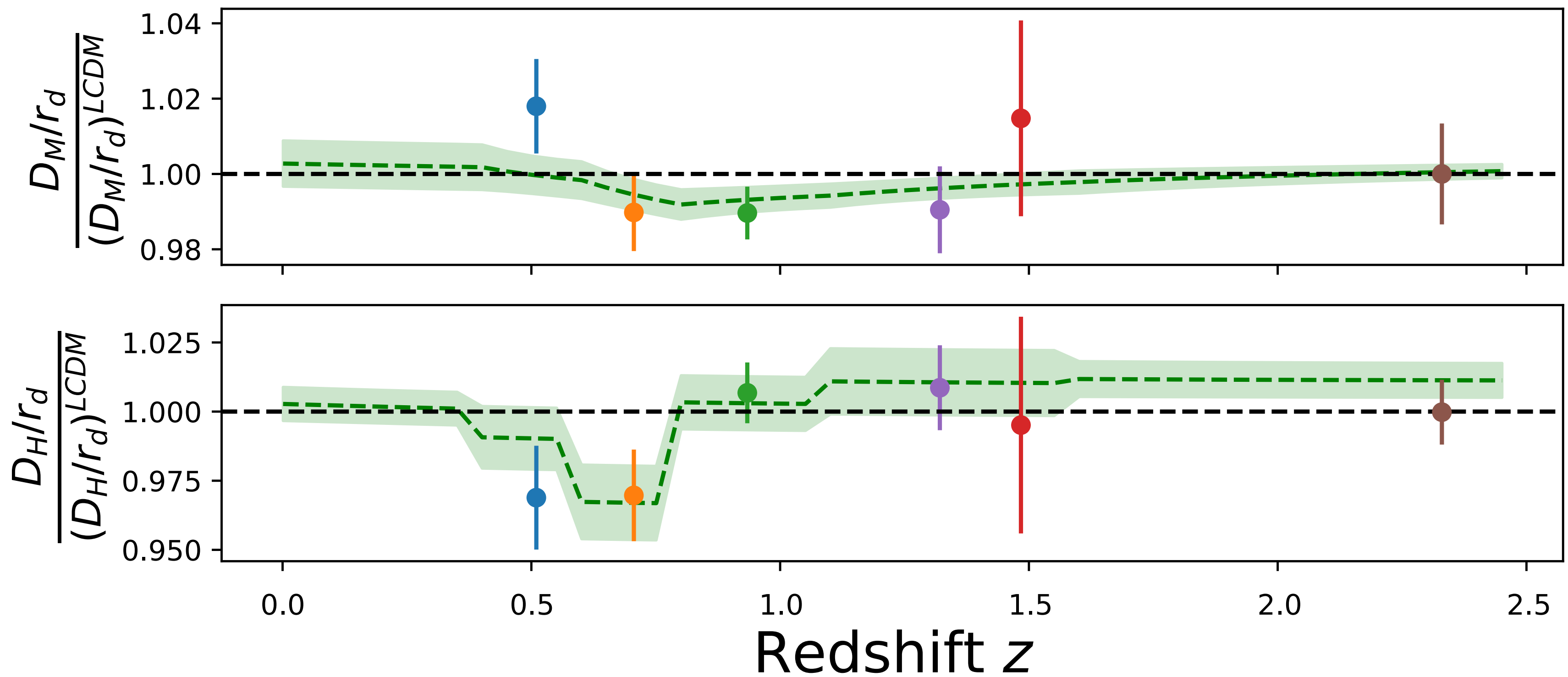
$$d_L = (1+z)\int_0^z \frac{dz'}{H_0\sqrt{\Omega_\Lambda + \Omega_m(1+z')^3}} \xrightarrow{z\to 0} \frac{z}{H_0}$$

$\Omega_\Lambda + \Omega_m = 1$


DESI DR1 BAO
DESI DR2 BAO
CMB
Pantheon+
Union3
DESY5
Probability density
0
10
20
30
40
50
60
0.25
0.30
0.35
0.40
0.45
Ω_m

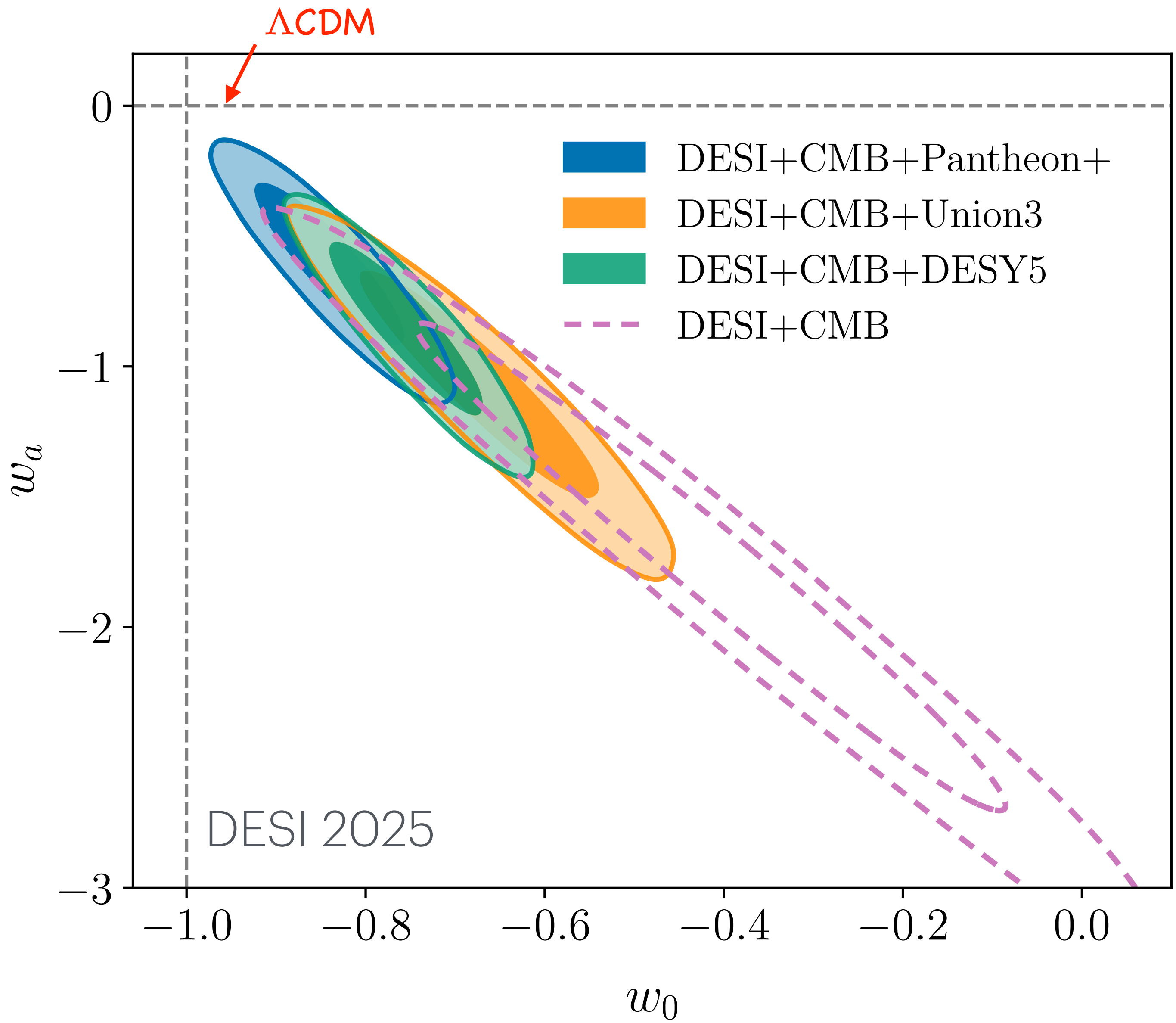
Hubble diagram from BAO-DESI

Bansal,Huterer 2025



$$D \propto \int_0^z \frac{dz'}{H_0\sqrt{\Omega_\Lambda(1+z')^{3(1+w_0+w_a)}e^{-3w_a(1-\frac{1}{1+z'})} + \Omega_m(1+z')^3}}$$

DESI (2025) w0wa fit



dark energy

equation of state:

$w = w_0 + w_a(1 - a)$

H0 measurements require absolute distances

- SH0ES luminosity distances (z~0.1)
- BAO & CMB angular diameter distances (range of z)

SN1a and BAO measurements of H(z) evolution disagree with each other and LCDM for 0<z<2

- disagreement on Ω_m
- evidence for “evolving dark energy” w0wa

is there a connection?

much more data is coming!

CMB: Simons Observatory (first light 2/2025)
Advanced SO (5-10 years)
CMB-S4 (10 years?)

LSS: DESI (Y3 data), Euclid
Vera Rubin Observatory - LSST (2025)

Supernovae: JWST (observing), DES (ongoing), LSST

GW: LIGO 100 NS-NS mergers + optical (2030)
Einstein Telescope (2035?)

Standard Sirens for H0

LIGO: Gravitational waves from neutron star mergers

- reconstruct masses from wave form

  ⇒ GR predicts radiated power

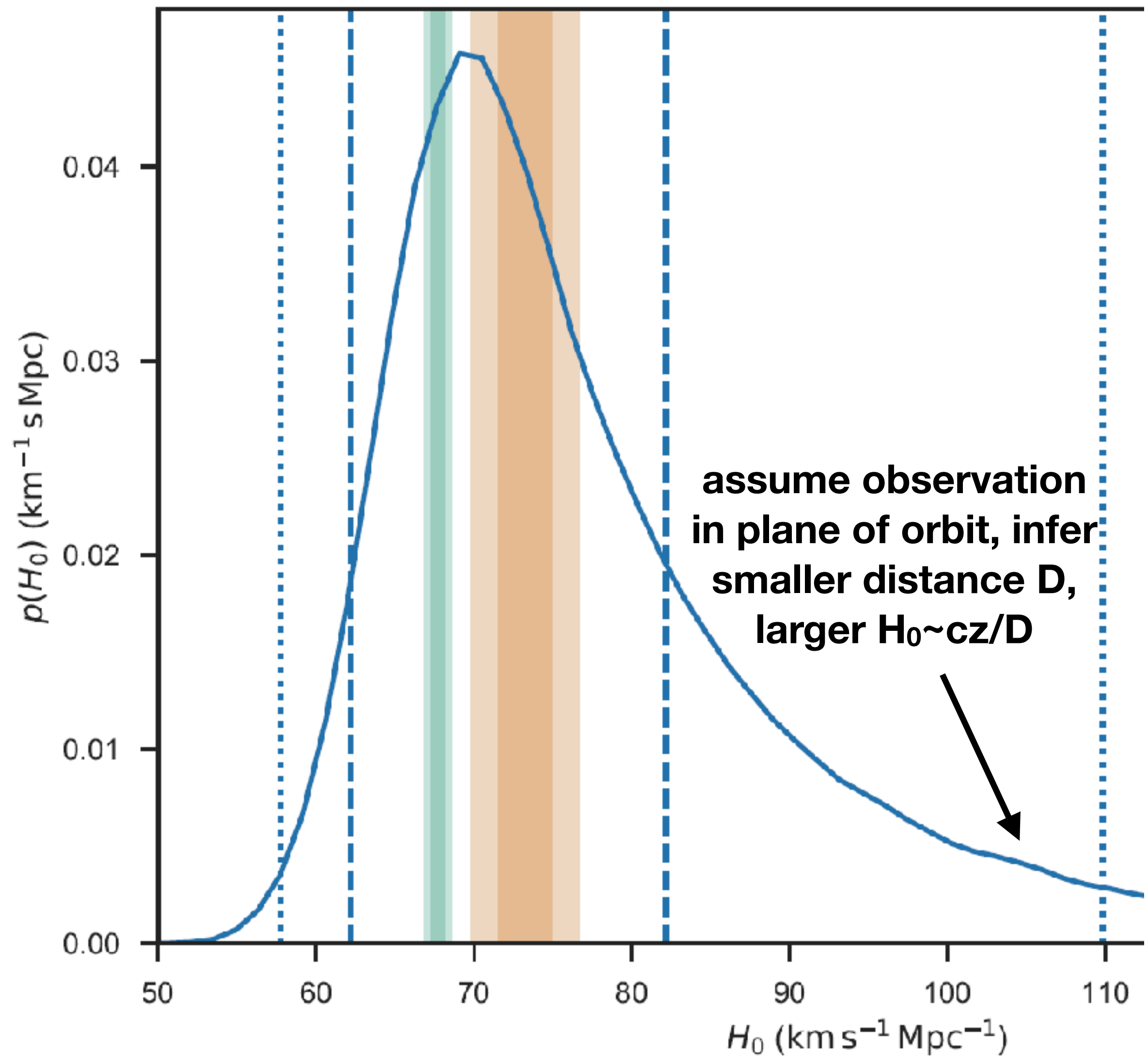
  ⇒ determine D from observed strain

Gravitational Wave Standard Sirens

First Standard Siren Measurement: GW170817

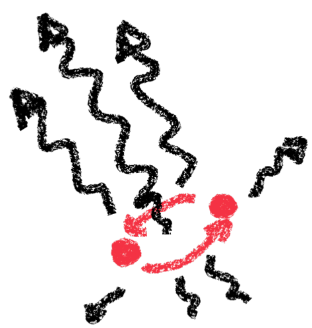
$$H_0 = 70^{+12}_{-8}\ \mathrm{km/s/M}$$

Abbott et al.

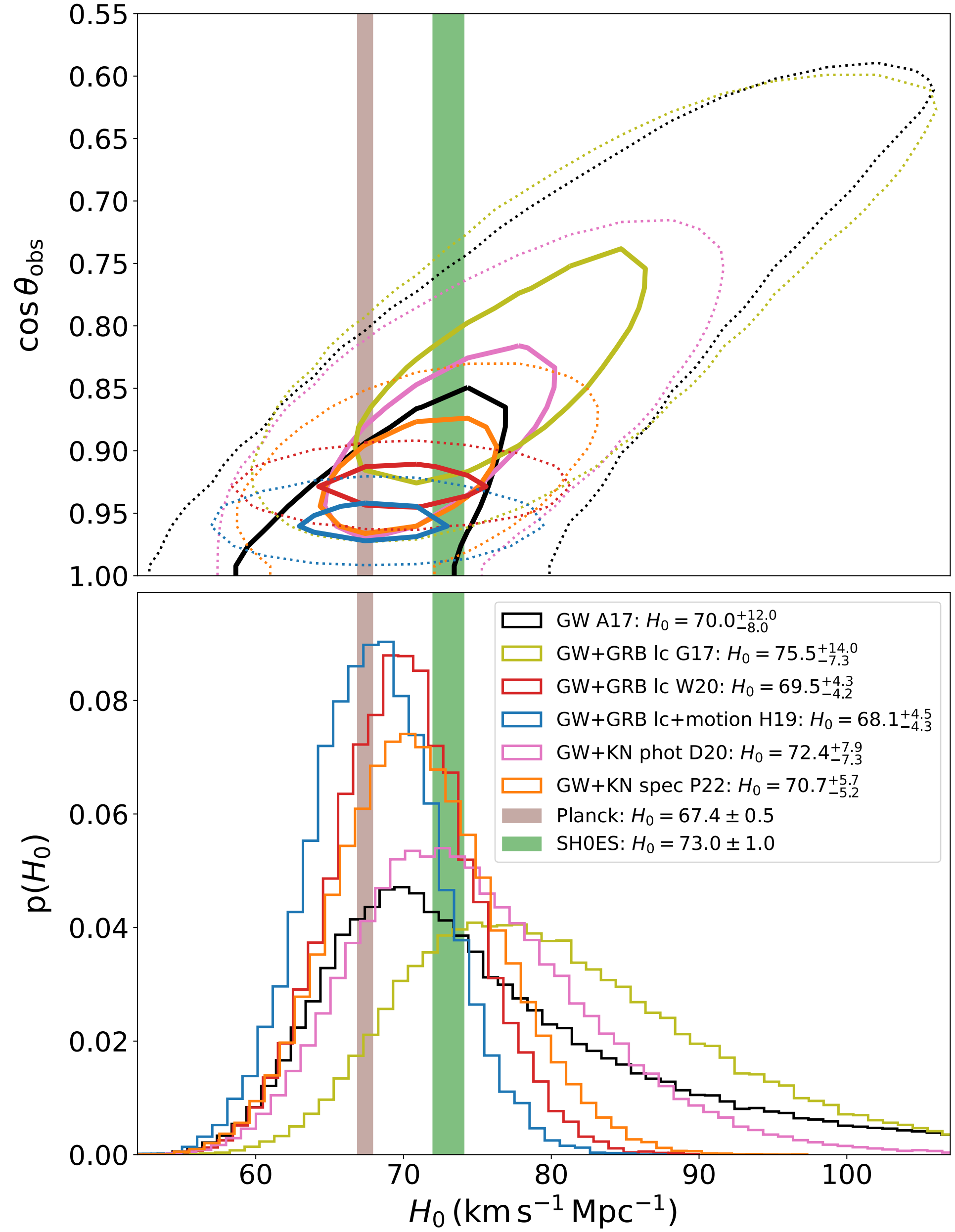


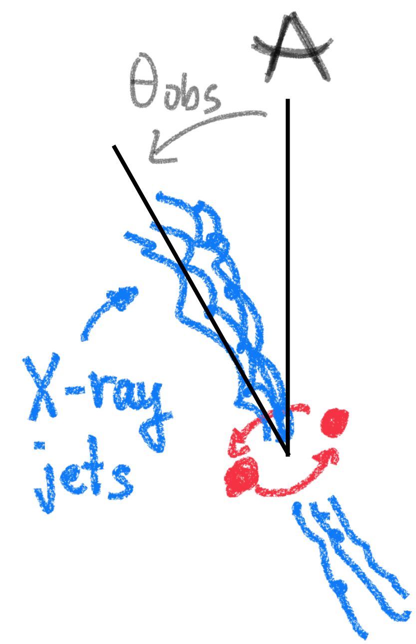
Inclination-distance degeneracy:

radiation is more intense ⊥ to plane of orbits



Improved constraints on H_0 from the BNS merger GW170817 through combination of GW and EM data. (review by Bulla et al 2205.09145)





Extra slides on Hubble from the distance to the Coma cluster

25 Aug 2024

DESI Peculiar Velocity Survey – Fundamental Plane

Khaled Said,[1★] Cullan Howlett,[1] Tamara Davis,[1] John Lucey,[2] Christoph Saulder,[3] Kelly Douglass,
Alex G. Kim,[5] Anthony Kremin,[5] Caitlin Ross,[1] Greg Aldering,[5] Jessica Nicole Aguilar,[5] Steven Ahlen,
Segev BenZvi,[4] Davide Bianchi,[7] David Brooks,[8] Todd Claybaugh,[5] Kyle Dawson,[9] Axel de la Macorra,
Biprateep Dey,[11] Peter Doel,[8] Kevin Fanning,[12,13] Simone Ferraro,[5,14] Andreu Font-Ribera,[15,8]
Jaime E. Forero-Romero,[16,17] Enrique Gaztañaga,[19,20,18] Satya Gontcho A Gontcho,[5] Julien Guy,[5]
Klaus Honscheid,[23,21,22] Robert Kehoe,[24] Theodore Kisner,[5] Andrew Lambert,[5] Martin Landriau,[5]
Laurent Le Guillou,[25] Marc Manera,[26,15] Aaron Meisner,[27] Ramon Miquel,[28,15] John Moustakas,[29]
Andrea Muñoz-Gutiérrez,[10] Adam Myers,[30] Jundan Nie,[31] Nathalie Palanque-Delabrouille,[5,32]
Will Percival,[34,33,35] Francisco Prada,[36] Graziano Rossi,[37] Eusebio Sanchez,[38] David Schlegel,[5]
Michael Schubnell,[39,40] Joseph Harry Silber,[5] David Sprayberry,[27] Gregory Tarlé,[40]
Mariana Vargas Magana,[10] Benjamin Alan Weaver,[27] Risa Wechsler,[41,12,13] Zhimin Zhou,[31] Hu Zou[31]

- Measure velocity dispersion, brightness, and angular sizes of 4191 elliptical galaxies to determine their distances via the "fundamental plane" (relation between velocity dispersion, surface brightness, effective radius)
- Conduct zero-point calibration of distances to the known Coma cluster distance D = 99.1+- 5.8 Mpc

$$H_0 = 76.05 \pm 1.3 * \left[\frac{99.1 \pm 5.8}{D_{Coma}}\right] \text{km/s/Mpc}$$

24 Sep 2024

The Hubble Tension in our own Backyard: DESI and the Nearness of the Coma Cluster

Daniel Scolnic,[1] Adam G. Riess,[2,3] Yukei S. Murakami,[3] Erik R. Peterson,[1] Dillon Brout,[4] Maria Acevedo,[1]
Bastien Carreres,[1] David O. Jones,[5] Khaled Said,[6,7] Cullan Howlett,[6,7] and Gagandeep S. Anand[8]

New supernova based determination of the distance to the Coma cluster D = 98.5+- 2.2 Mpc.

$$H_0 = 76.5 \pm 2.2 \text{ km/s/Mpc}$$

Future: - More SN1a in Coma (currently 12 out of 18 SN1a from 2019-2024)
- Use additional nearby clusters for calibration (Fornax, Virgo, Leo1, …)
- 133,000 ellipticals in fundamental plane relation

Coma cluster distance measurements

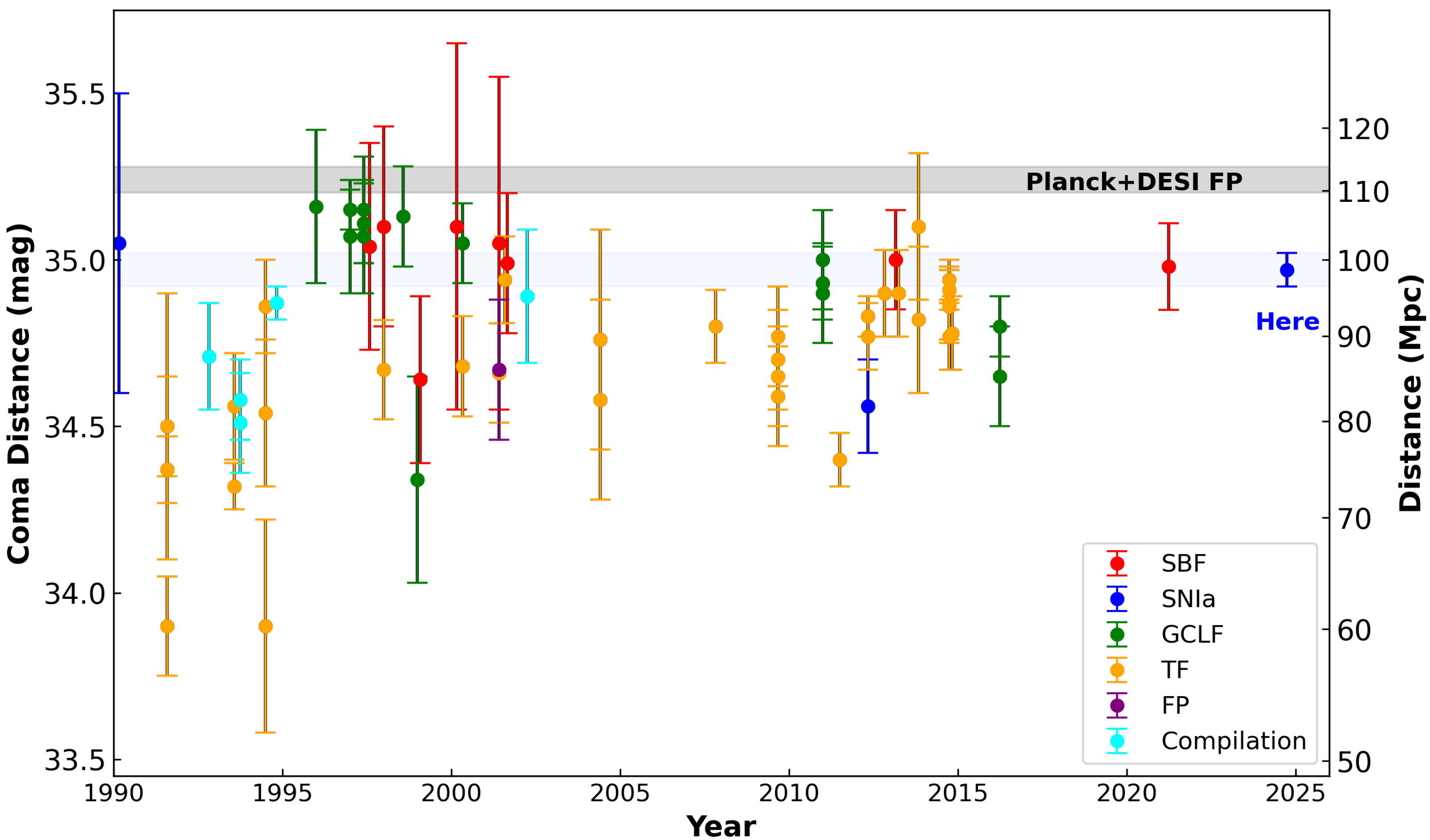


Figure 4. Historical (1990 onward) distance modulus measurements of the Coma cluster (as reviewed in de Grijs & Bono 2020).

Riess 2024