Hubble Tension Update

Martin Schmaltz, Boston University

Moriond EW, March 28, 2025

CMB, BAO fits to ΛCDM

$$H_0 = 67.5 \pm 0.5$$

(stat.+syst.)
Planck,ACT,SPT

Distance ladders

$$H_0 = 73.2 \pm 0.9$$

(stat.+syst.)
SH0ES 2024

5.7σ

$$p = 6.16 \times 10^{-9}$$

Outline

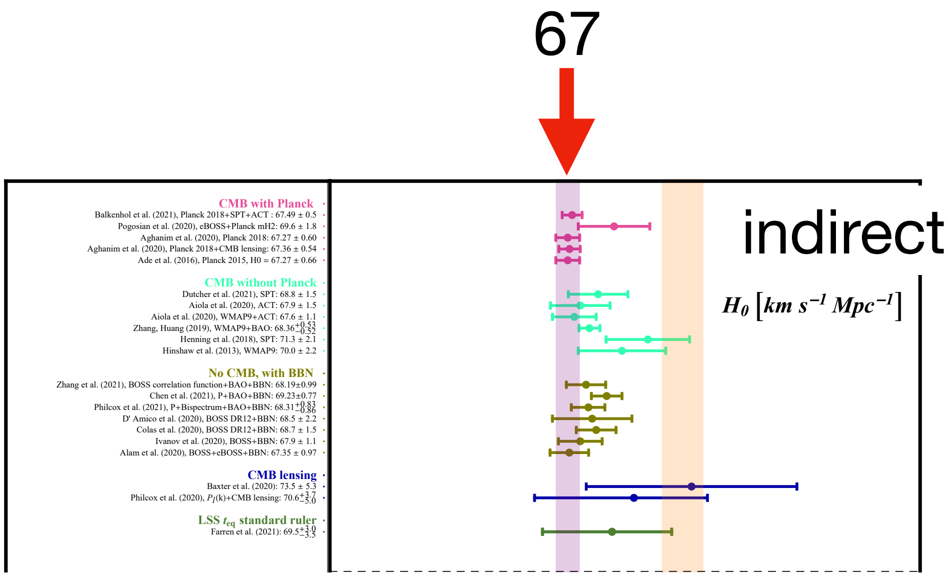
- Intro: Hubble's law
- Distance ladders, SH0ES
- CMB, BAO fit to ΛCDM, sound horizon
- CMB, BAO fit to BSM
- Summary

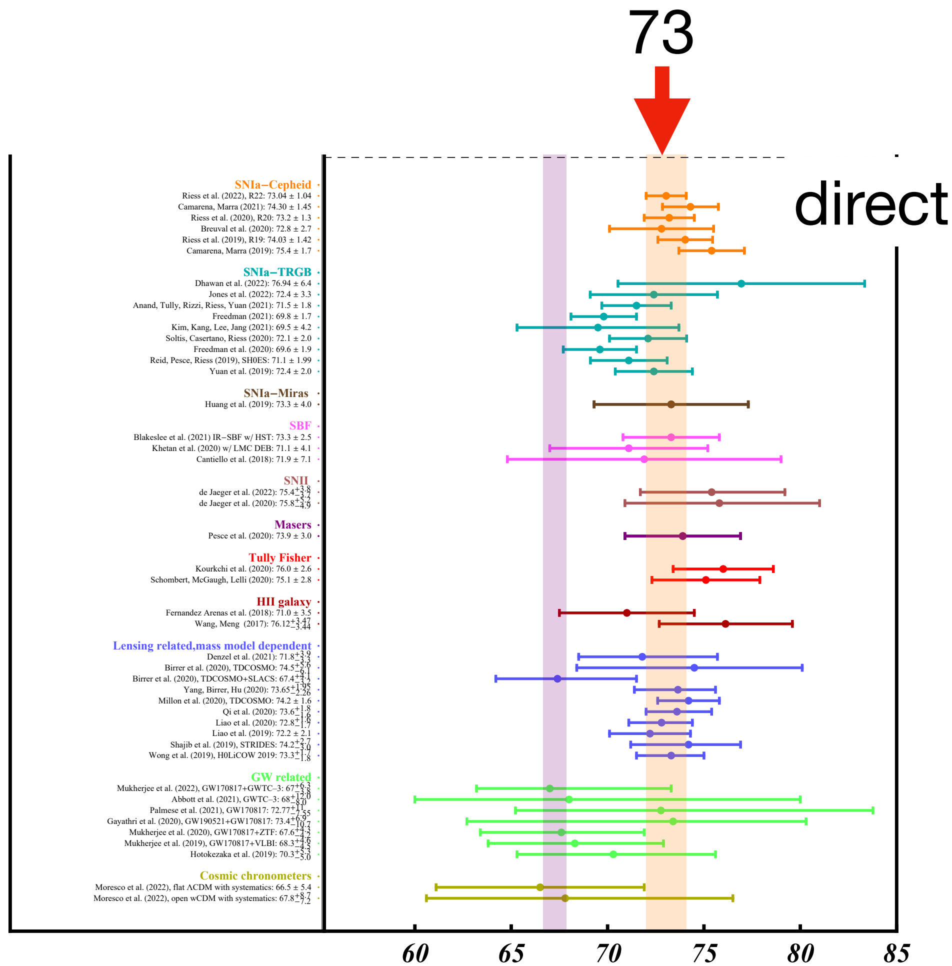
Hubble's Law - definition of H_0

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

Hubble tension

(Snowmass Report 2022)

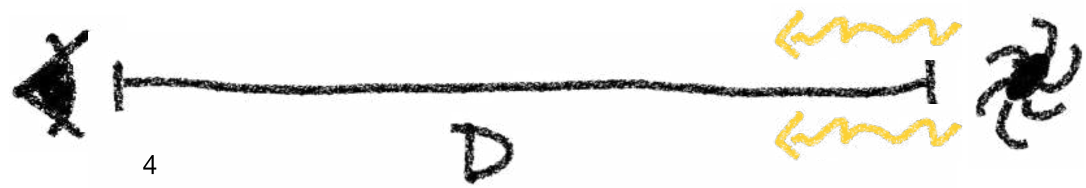




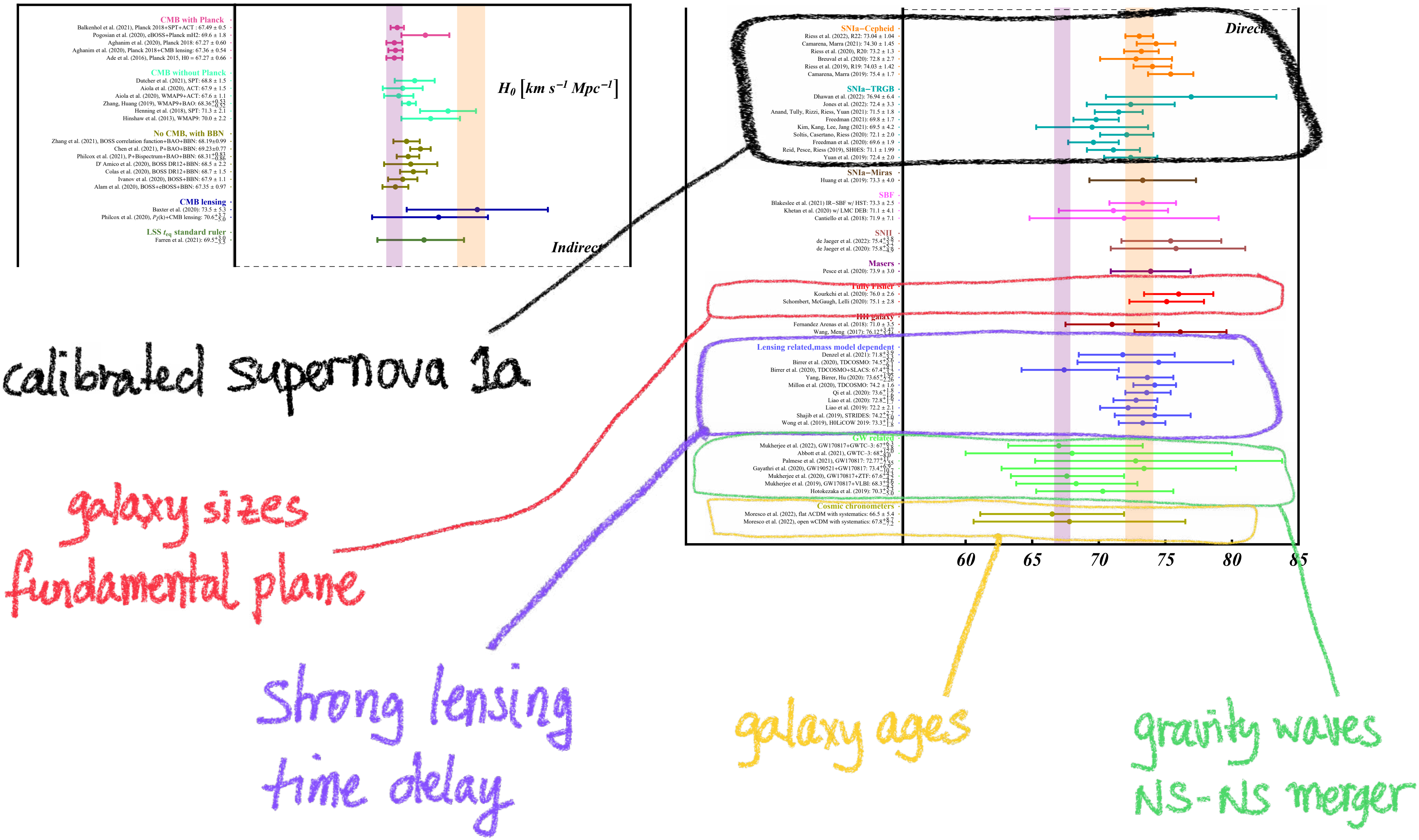
CMB, BAO: “indirect” methods use the sound horizon r_s as ruler to measure D, calculated in ΛCDM

many “direct” methods to determine D

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

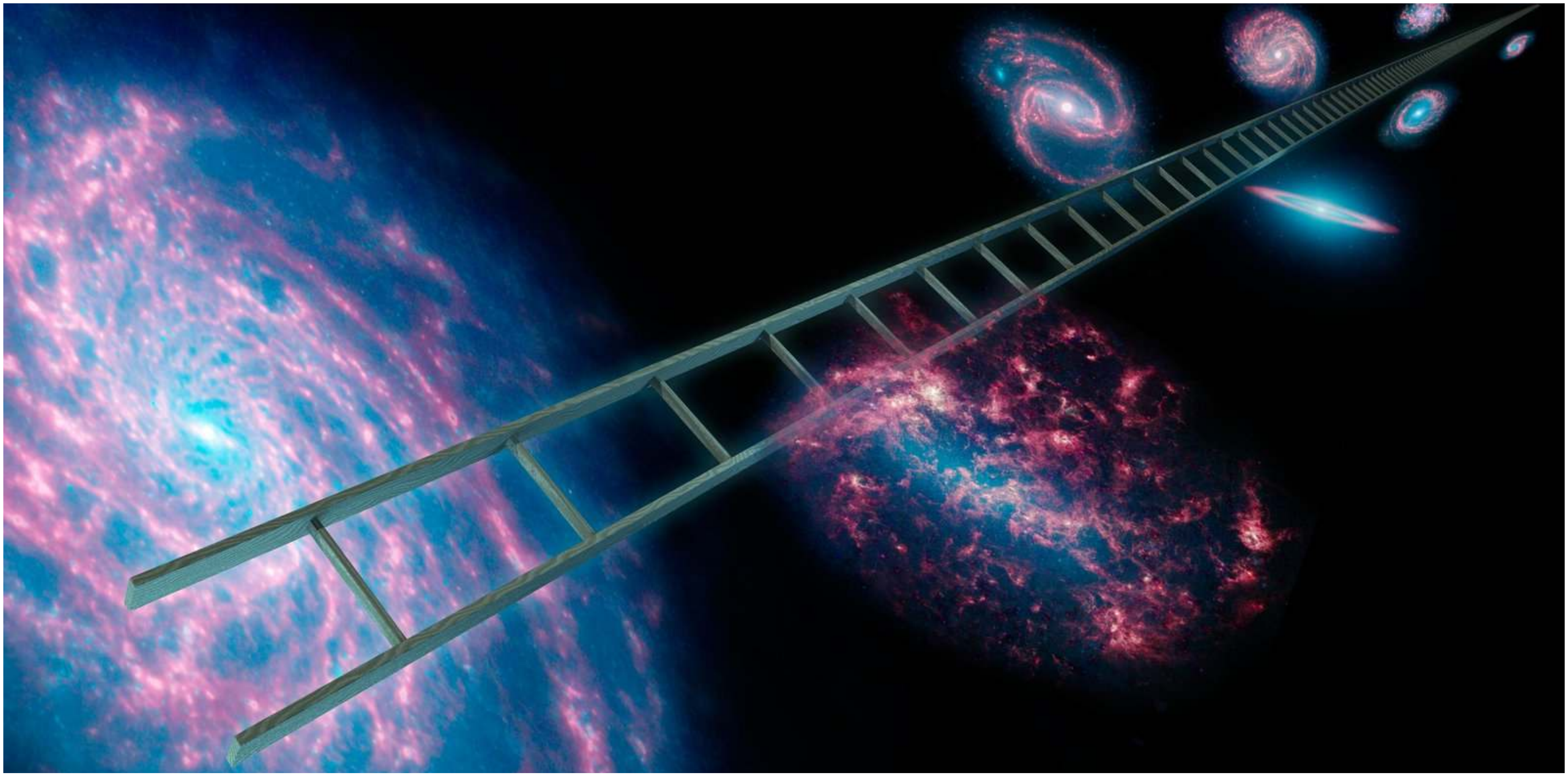


Hubble tension, H_0



Geometry-Cepheids-Supernovae "distance ladder"

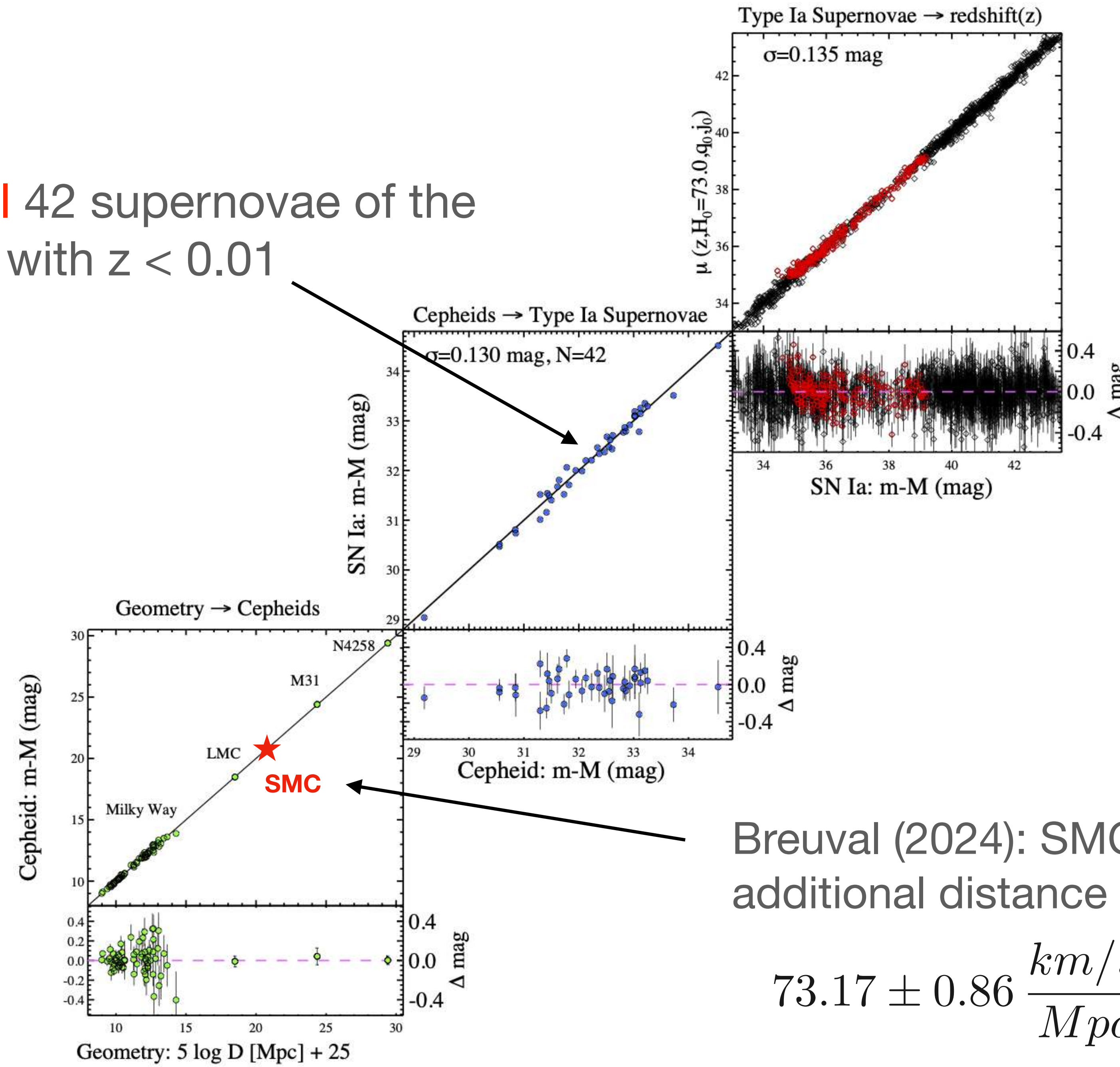
SH_0ES collaboration (Riess et. al.)



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

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

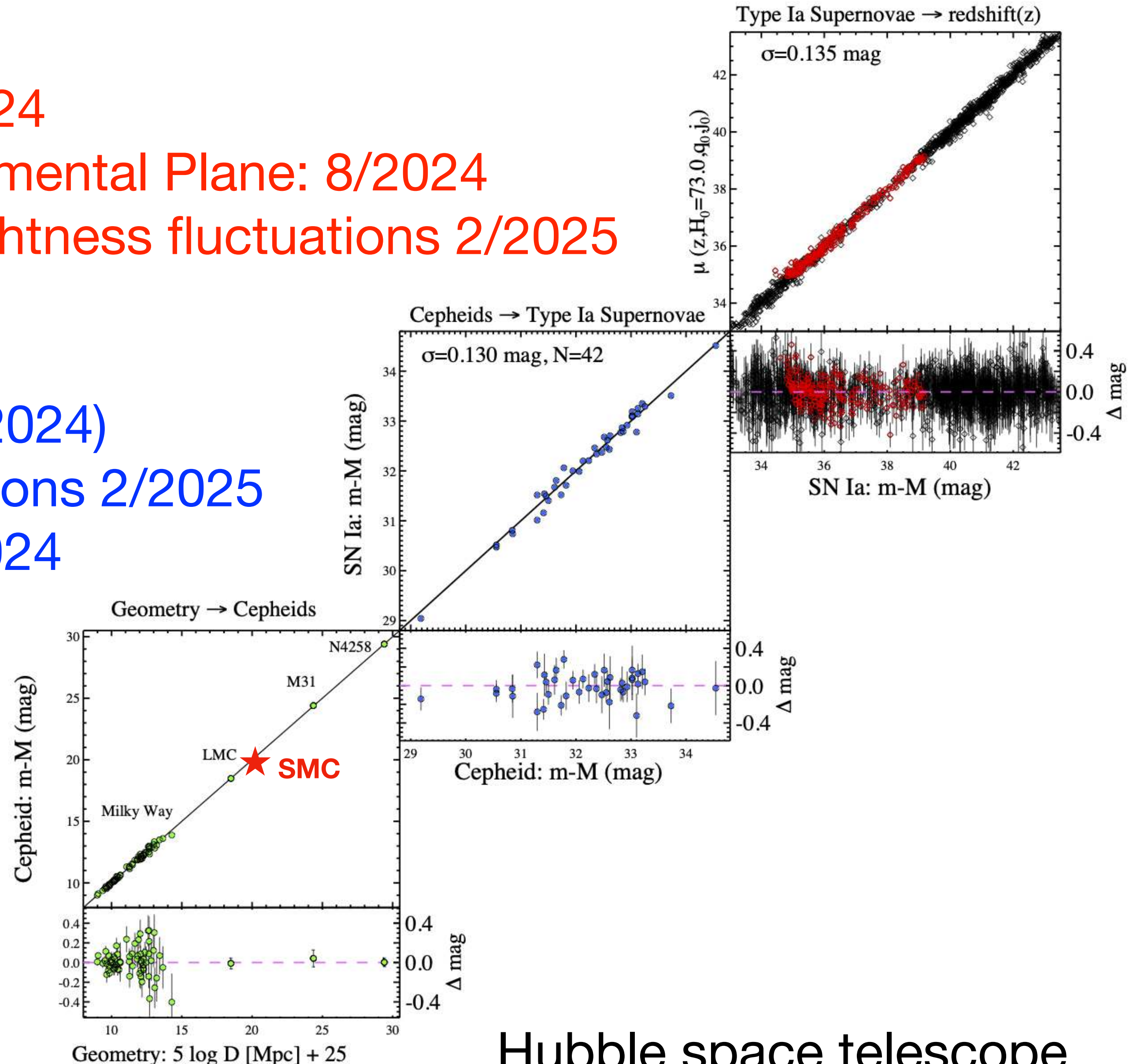
SH$_0$ES Team

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 last summer

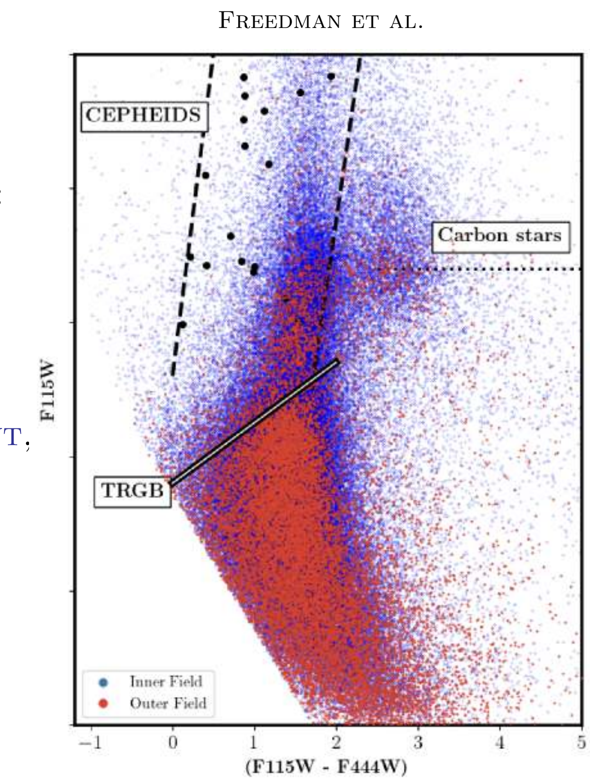
12 Aug 2024

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]

$H_0 \sim 70 \pm 2$

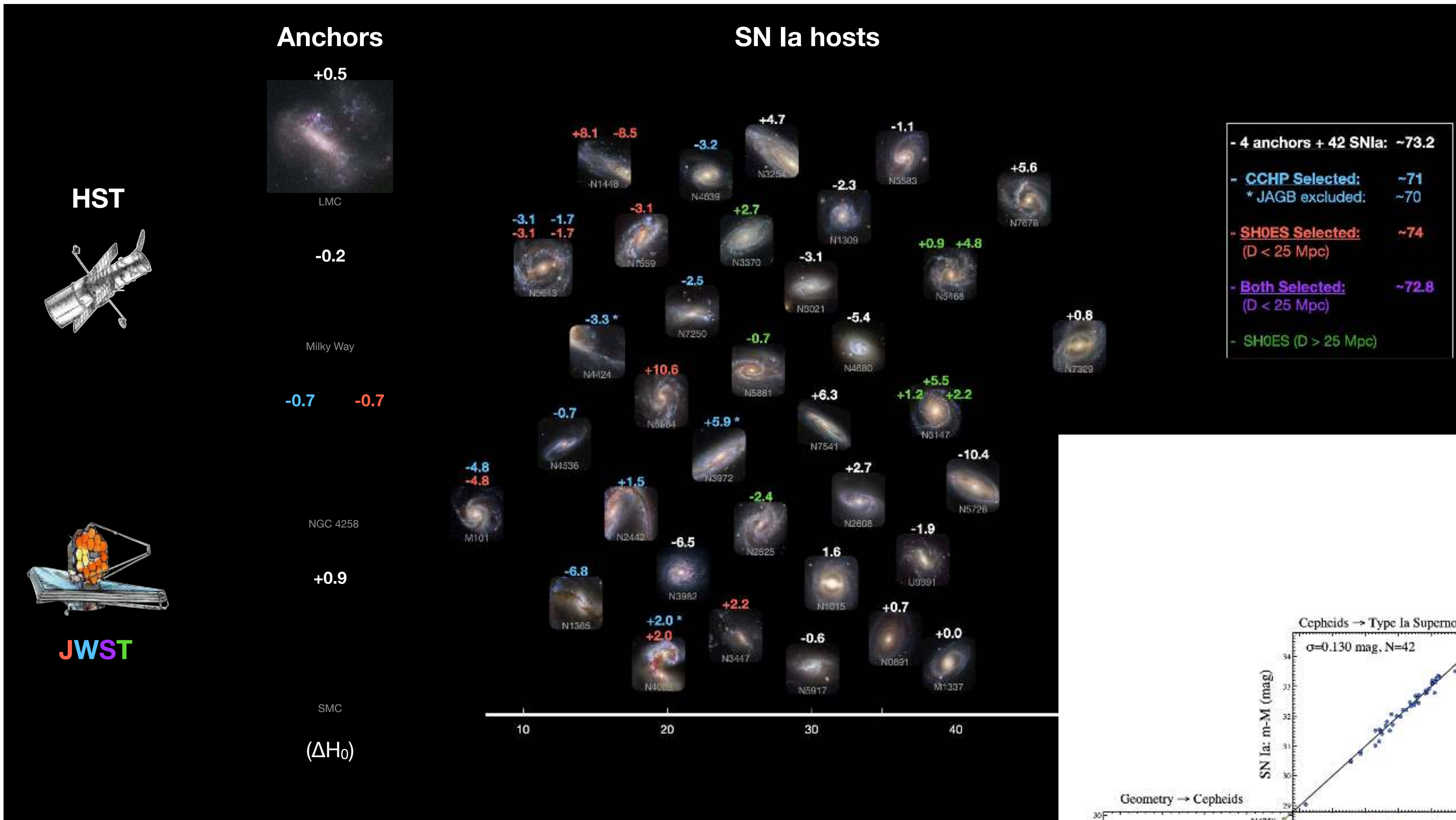


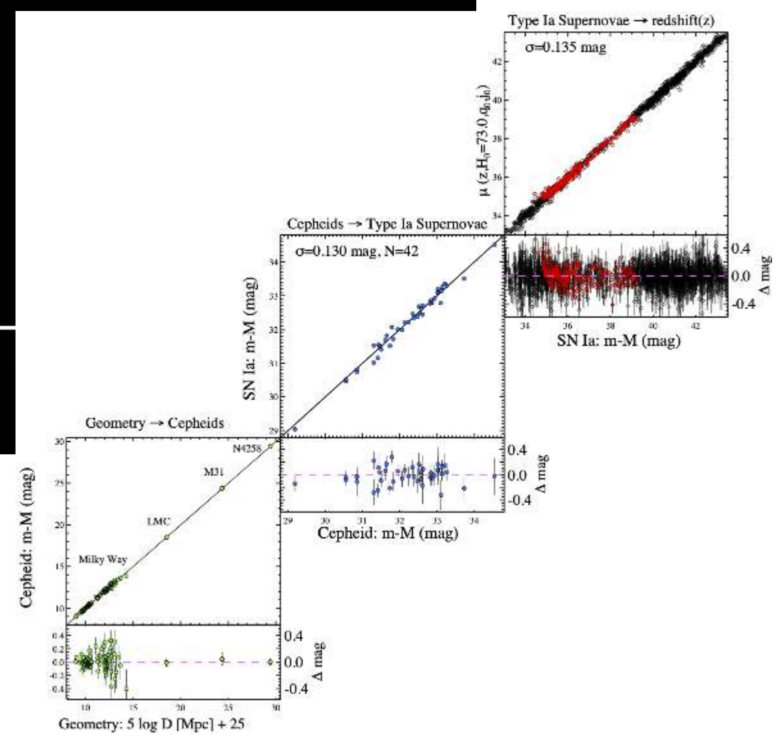
21 Aug 2024

***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 selection of hosts of calibration SN1a



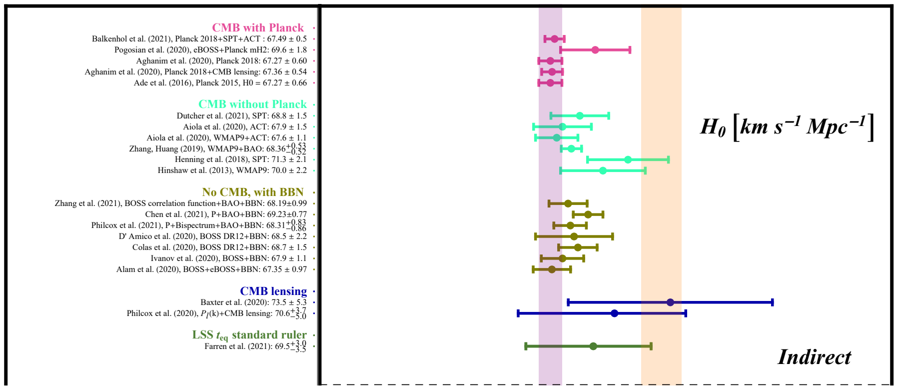


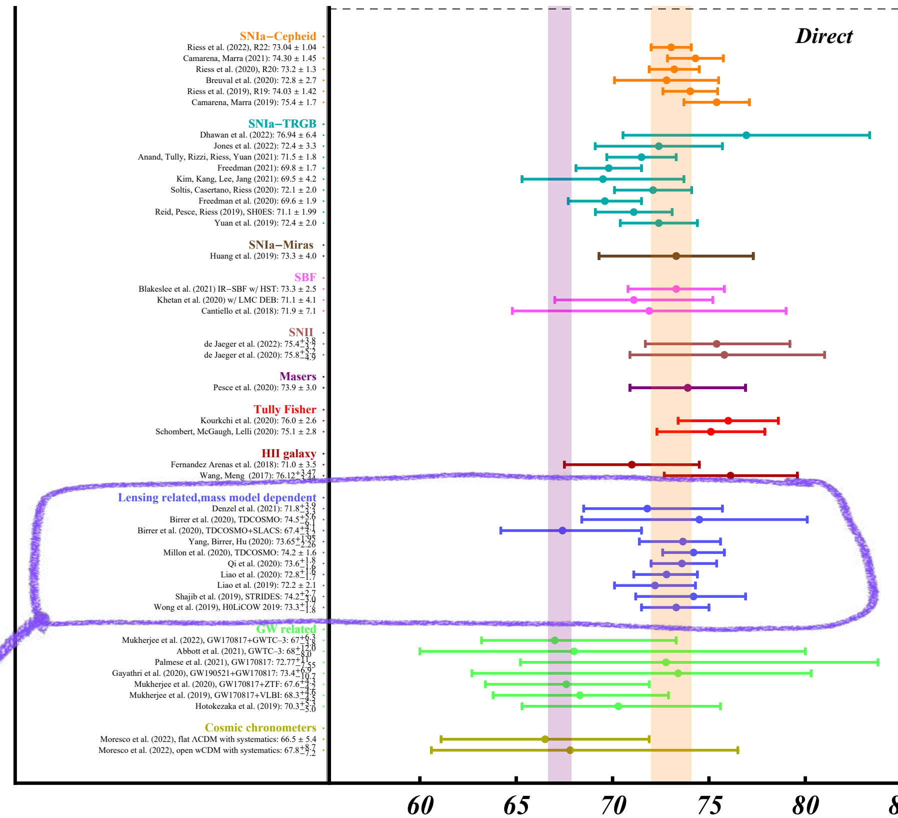
Riess 8/2024

Supernovae 1a bottom line:

- good agreement between Cepheids, TRGB, JAGB
- cross checks of all rungs of distance ladder ongoing
- local H0 = 73.2+-0.9 km/s/Mpc (SH0ES HST 2024)

Hubble tension, H_0





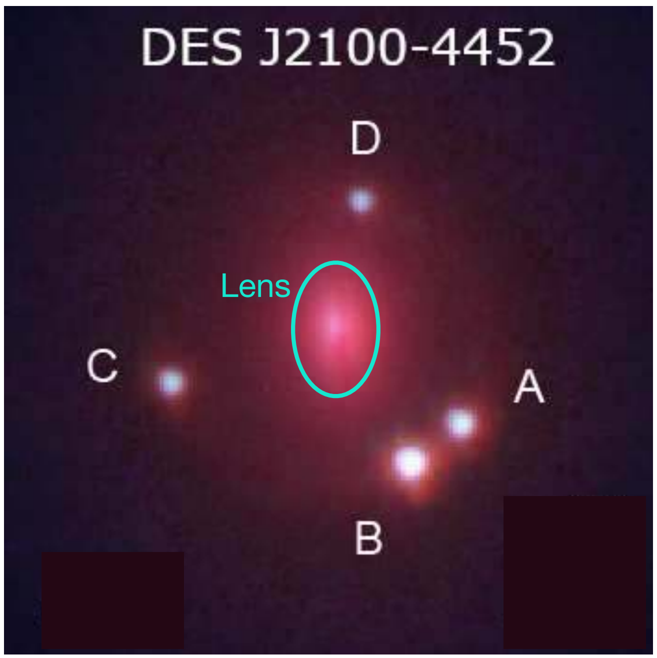
Strong lensing time delay

Strong lensing time delay -TDCOSMO/HOLICOW

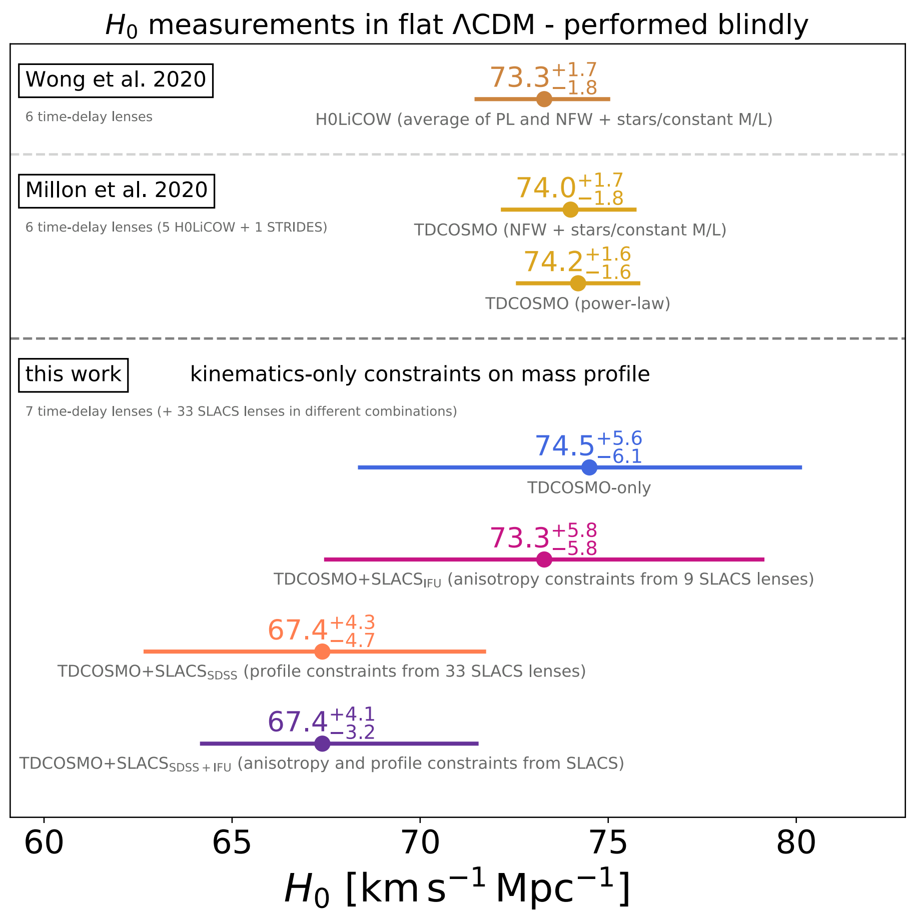
19 Dec 2020

TDCOSMO IV: Hierarchical time-delay cosmography - joint inference of the Hubble constant and galaxy density profiles

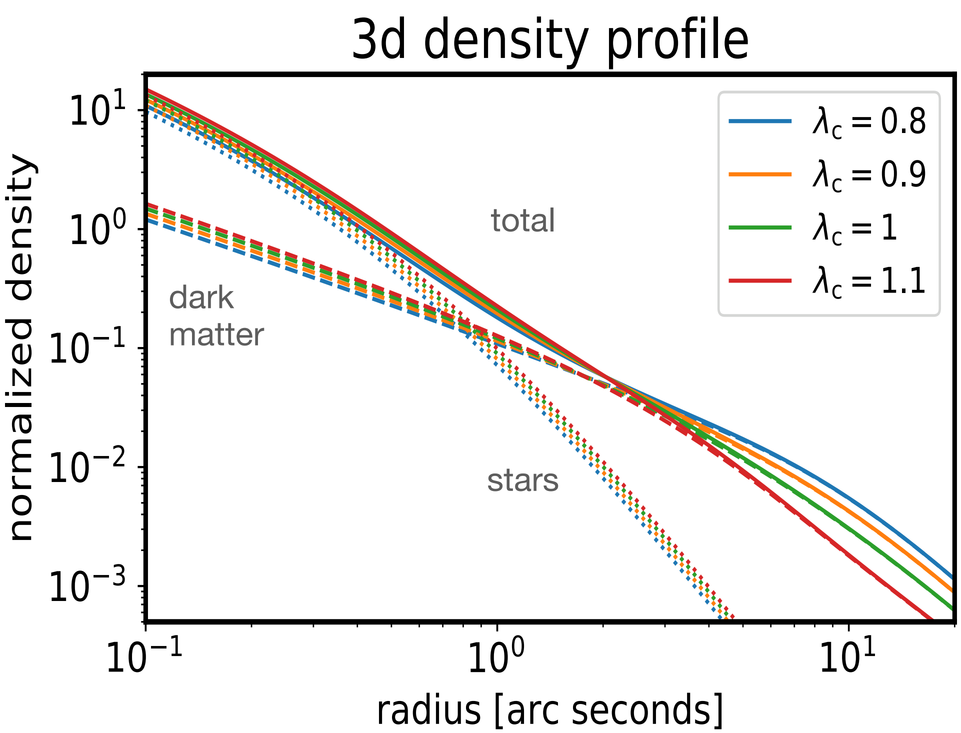
S. Birrer[1,⋆], A. J. Shajib[2], A. Galan[3], M. Millon[3], T. Treu[2], A. Agnello[4], M. Auger[5,6], G. C.-F. Chen[7], L. Christensen[4], T. Collett[8], F. Courbin[3], C. D. Fassnacht[7,9], L. V. E. Koopmans[10], P. J. Marshall[1], J.-W. Park[1], C. E. Rusu[11], D. Sluse[12], C. Spiniello[13,14], S. H. Suyu[15,16,17], S. Wagner-Carena[1], K. C. Wong[18], M. Barnabè, A. S. Bolton[19], O. Czoske[20], X. Ding[2], J. A. Frieman[21,22], and L. Van de Vyvere[12]

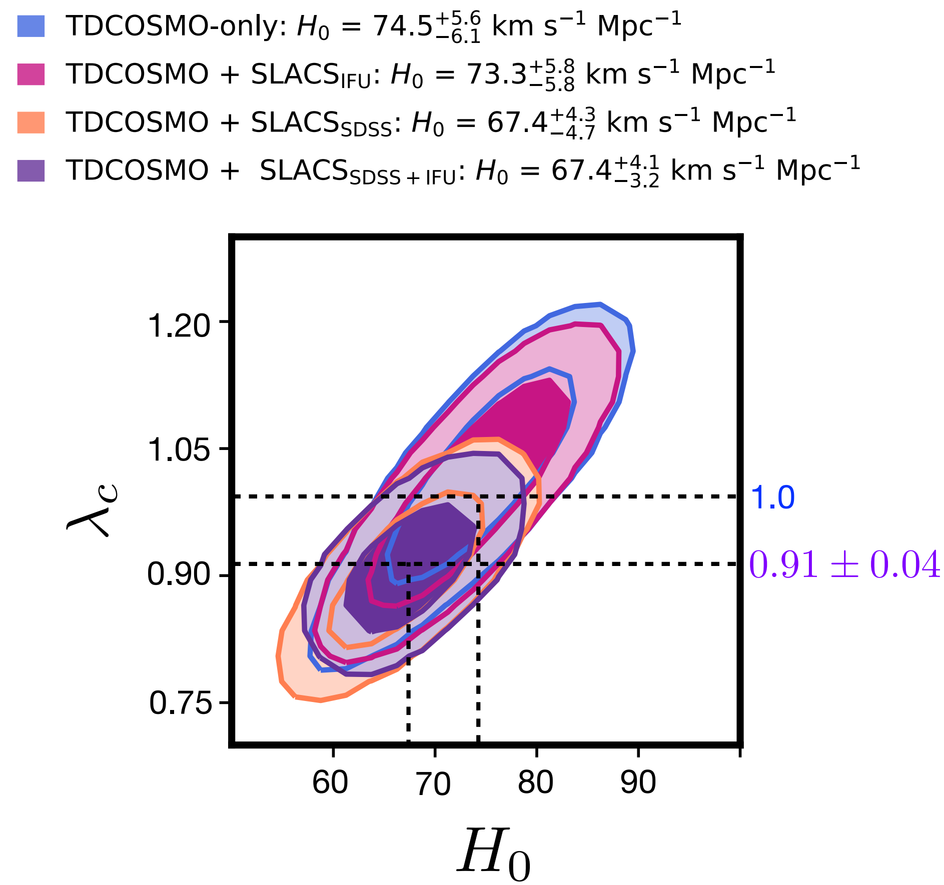


$$H_0 \propto \frac{1}{\Delta t}$$



Approximate “mass-sheet” degeneracy





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

Birrer 2020

Evidence for mass-sheet disappeared

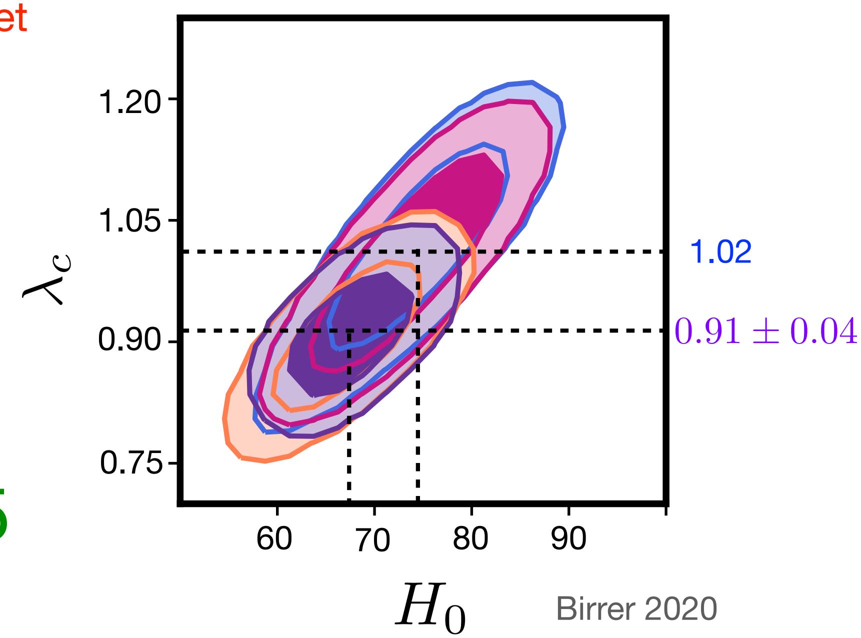
19 Aug 2024

Project Dinos II: Redshift evolution of dark and luminous matter density profiles in strong-lensing elliptical galaxies across $0.1 < z < 0.9$

William Sheu,[1*] Anowar J. Shajib,[2,3†] Tommaso Treu,[1] Alessandro Sonnenfeld,[4] Simon Birrer,[5]
Michele Cappellari,[6] Lindsay J. Oldham,[7] Chin Yi Tan[2,8]

- 21 elliptical galaxy-galaxy lenses reconstructed with dynamical observations
- consistent with NFW density profiles and no mass sheet

$$\lambda_c = 1.02 \pm 0.01$$



Birrer 2020

paper stops short of a new H_0,
but we can predict TDCosmo2025

$$H_0 = 74.5 \pm (2\,?)$$

local H_0 measurements are not going away

$$H_0 = 73.2 \pm 0.9$$

(stat.+syst.)
SH0ES 2024

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

- SH0ES is local H_0, $z < 0.1$,
  other methods extend to $z \sim 0.5$, overlap with BAO
  late solutions can only do a small part

- meeting in Bern this week on standardizing analysis pipelines for local H_0 measurements. They have no snow :(

"Indirect" H_0 from CMB and BAO

$$H_0 = 67.6 \pm 0.5$$ (stat.+syst.)
Planck + ACT 2025

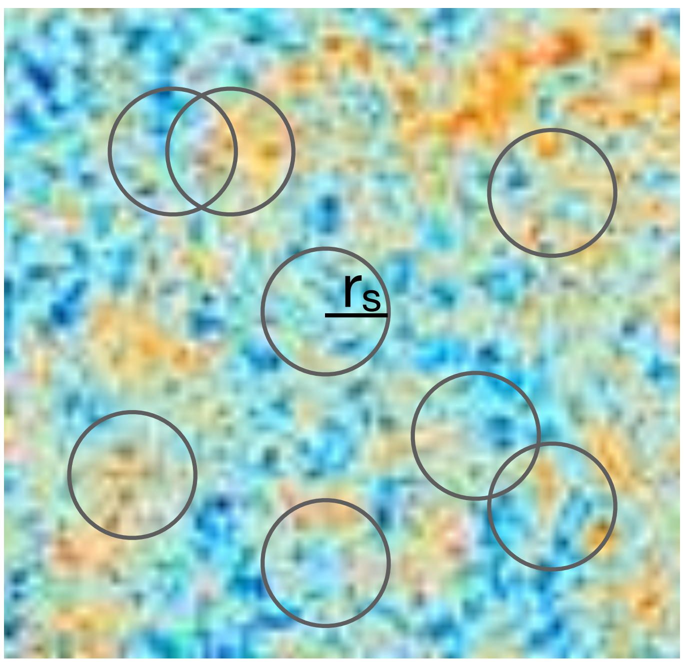
CMB and BAO use the sound horizon r_s as a "standard ruler"

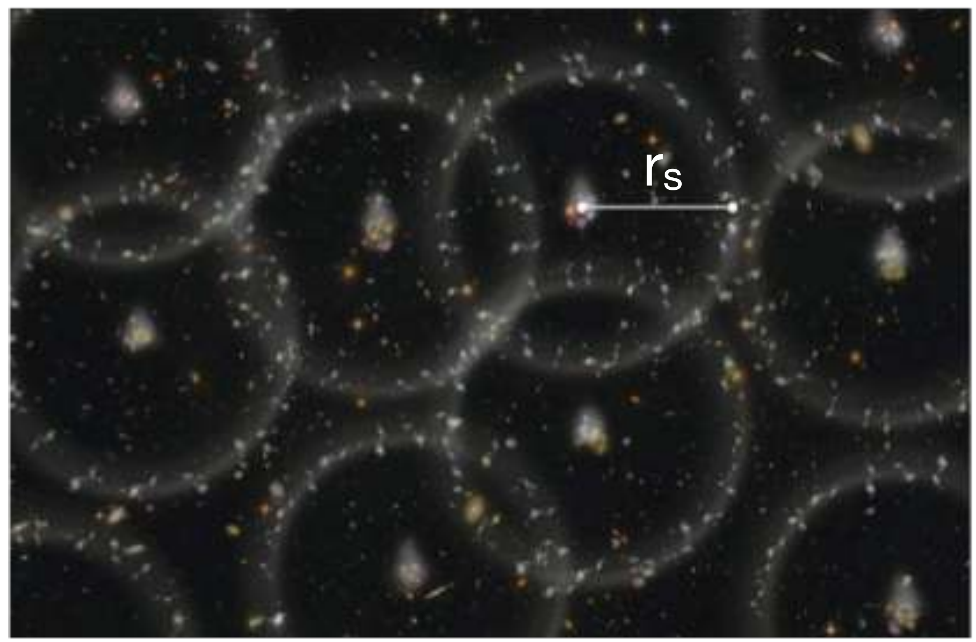
$$H_0 \sim \frac{1}{D} \sim \frac{\theta}{r_s}$$

The sound horizon r_s "Circles in the sky"

CMB : correlations in temperature fluctuations

BAO : correlations in galaxy distributions





sound horizon calculation

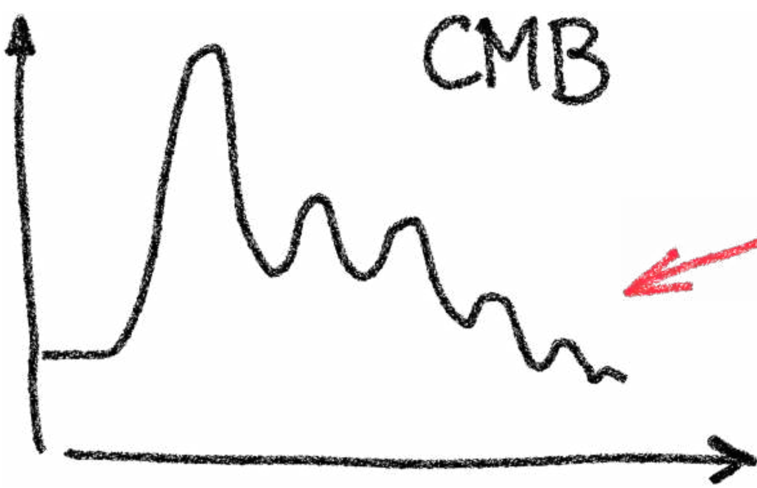
sound speed $1/\sqrt{3}$

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

photons
neutrinos

dark matter
baryons

determined by fit to CMB



Going beyond ΛCDM to fix Hubble tension

$H_0^{CMB} = 67.6 \pm 0.5$ $H_0^{Riess} = 73.1 \pm 0.9$

11σ 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%

a smaller r_s with additional early energy

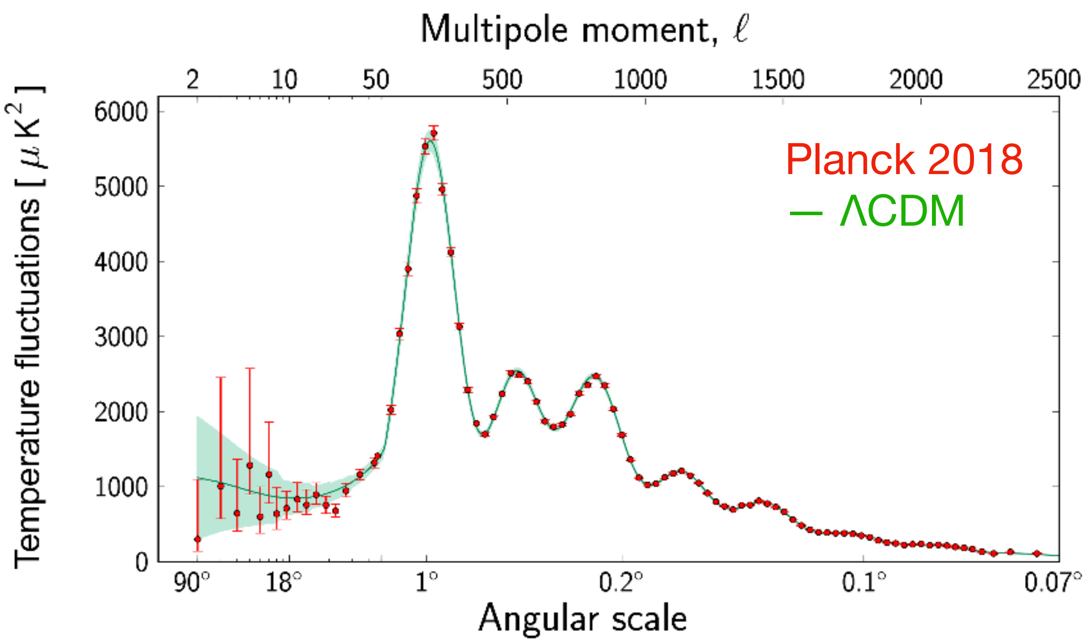
$$r_s = \int_{z_{\rm CMB}}^{\infty} c_s \frac{dz}{\sqrt{\frac{8\pi G}{3}(\rho_{rad.} + \rho_{mat.} + \rho_{early})}}$$

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!

ACT DR6 Constraints on Extended Cosmological Models

18 Mar 2025

- ΔN_{eff}

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

- 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, 5.7σ, and growing

- local "direct" $H_0 \simeq 73 \pm 1 \ \mathrm{km\,s^{-1} Mpc^{-1}}$

  many cross checks, several methods, bigger error
  more constraints on BSM models

- "indirect" BAO, CMB $H_0 \simeq 67.5 \pm 0.5$

  precise, Planck, ACT, SPT, BAO all agree, rely on sound horizon
  which is sensitive to BSM physics. No compelling solution yet.

- connection to $S_8, w_0 + w_a < -1$

  $m_\nu^2 < 0?$

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), TRGB (ongoing)

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

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

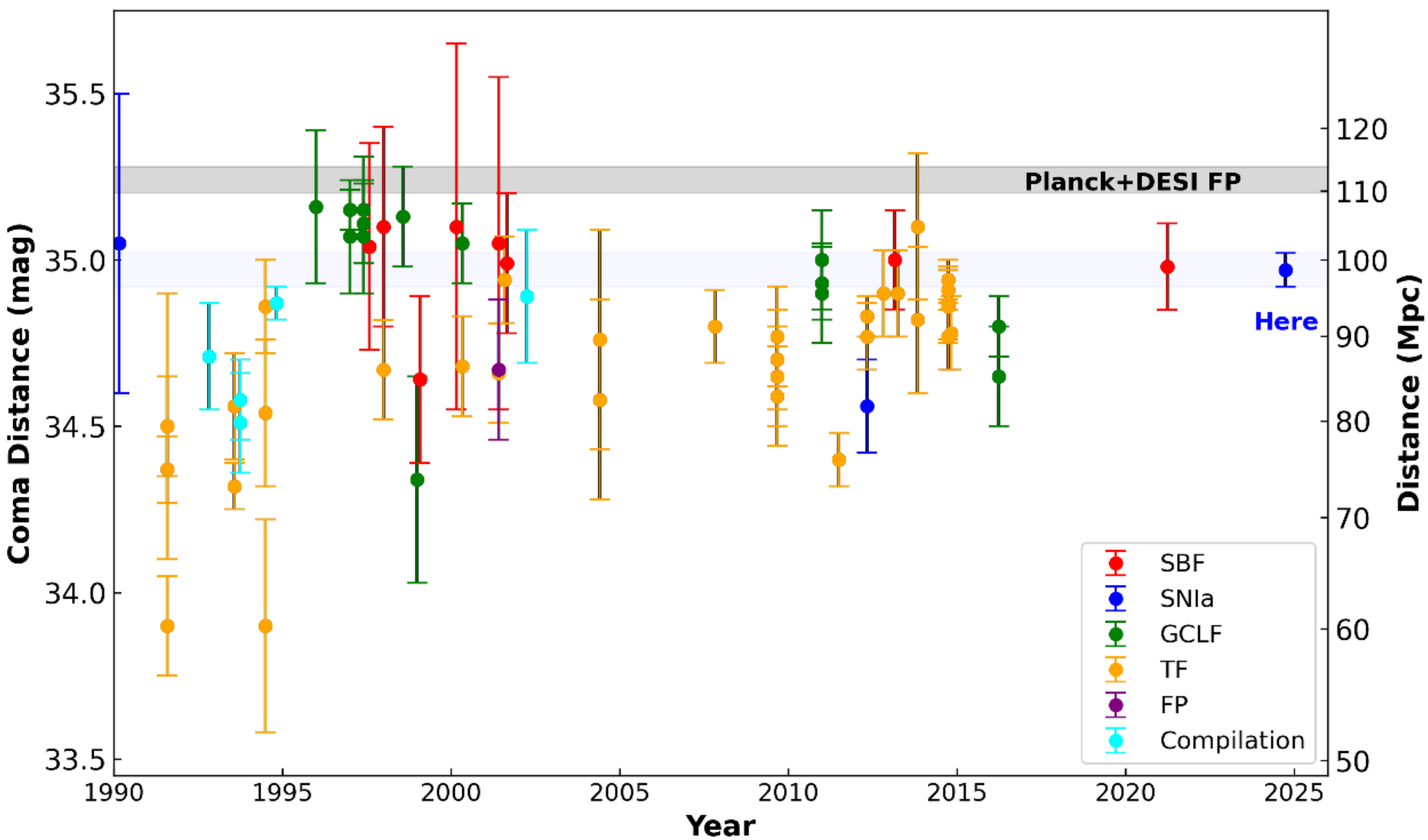


Figure 4. Historical (1990 onward) distance modulus measurements of the Coma cluster (as reviewed in de Grijs & Bono 2020).

Riess 2024