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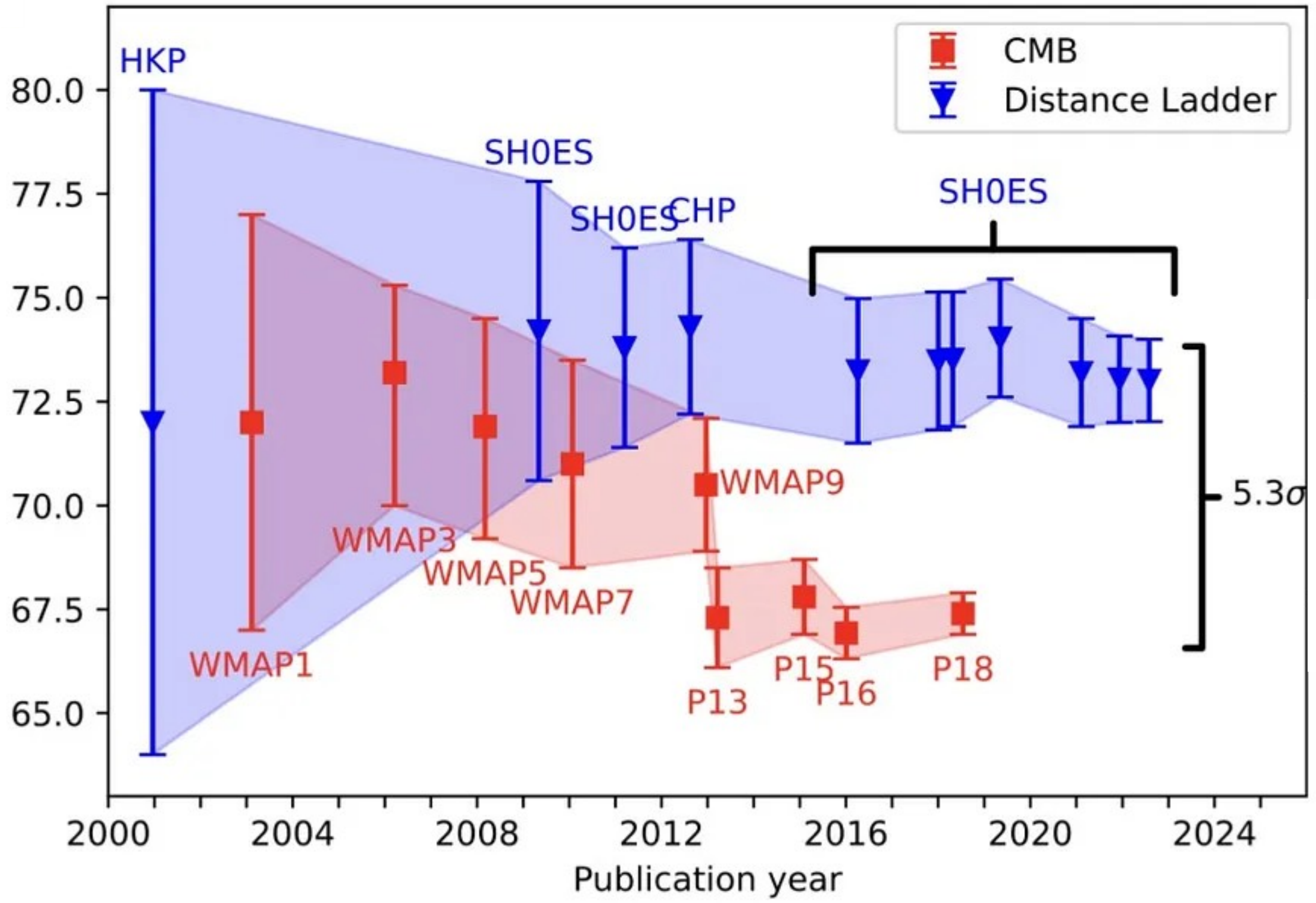
H0 and cosmological tensions: overview of theory solutions



Luca Visinelli

Tsung-Dao Lee Institute & Shanghai Jiao Tong University

July 5, 2024

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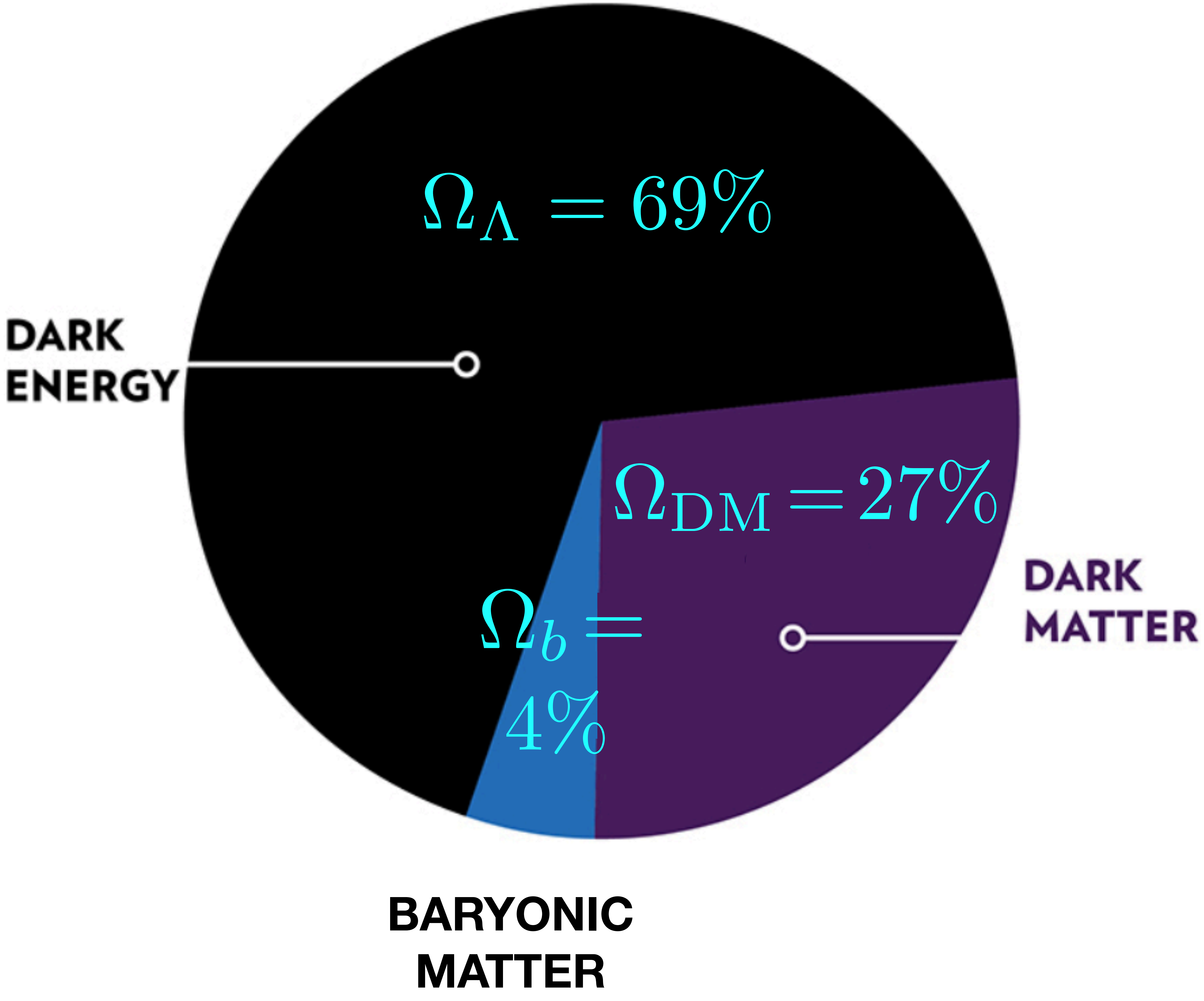
The cosmological concordance model

Luca Visinelli



Credits: NASA

The ΛCDM (Lambda-Cold Dark Matter) model is a concordance model that attempts to capture the key observations about both “early” and “late” Universe.

Key ingredients:

- Standard Model (SM) content: “baryons”, radiation, neutrinos;
- (Cold) pressure-less dark matter;
- Dark energy as a cosmological constant;
- Zero curvature
- Friedmann-Robertson-Walker metric

The Hubble constant: local measurements

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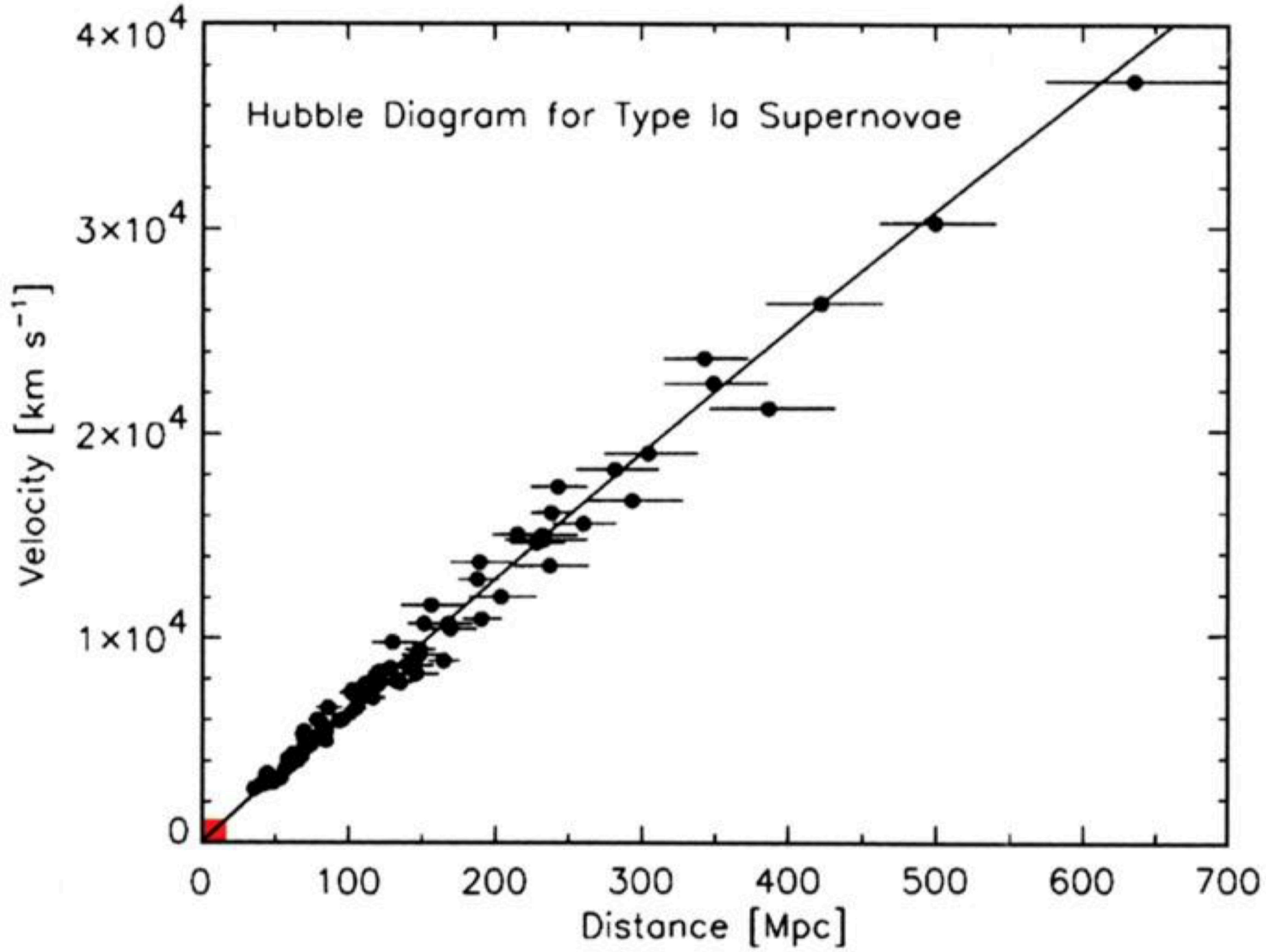
The Hubble constant H_0 yields the expansion rate of the Universe at present time

Historically, H_0 is measured by means of the Hubble law: $v = H_0\, D$

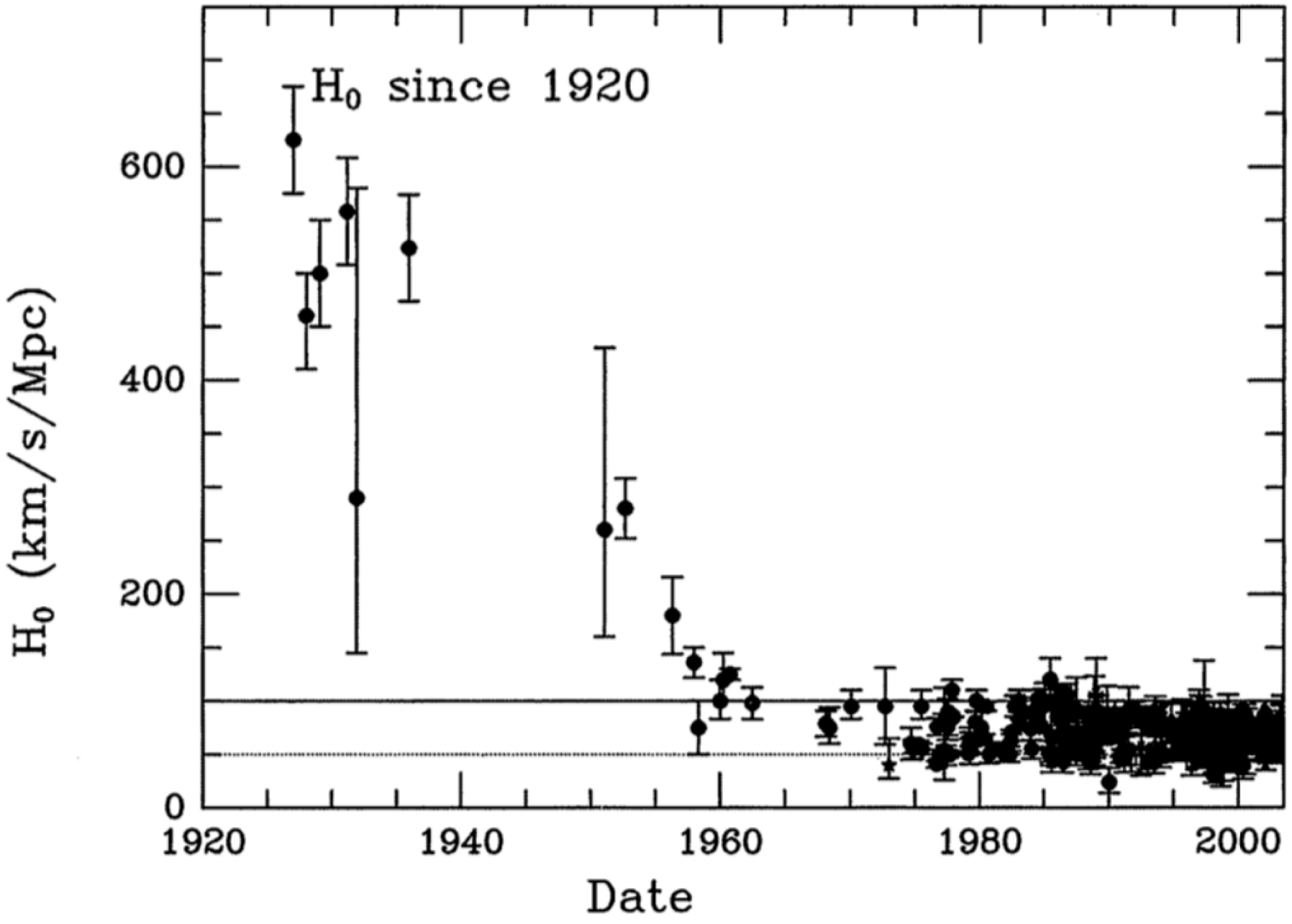
H_0 is the ratio between the luminosity distance and the recessional velocity of known galaxies

E. Hubble 1929; S. Jha PhD thesis 2002

This is an example of a "**local measurement**"



The Hubble constant over time

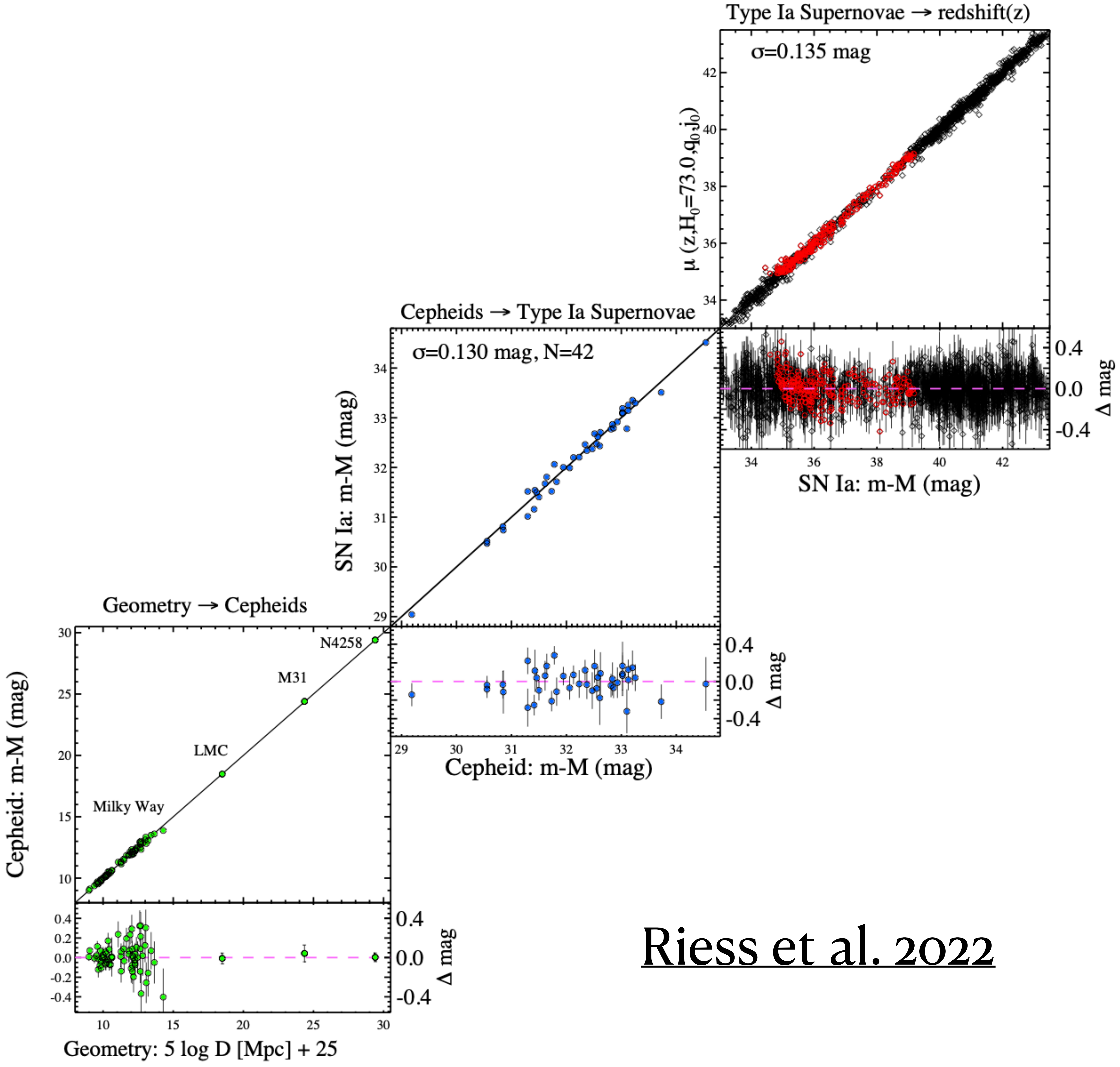


Source: Kirshner 2004

The cosmological distance ladder

The fit is accomplished over the three rungs simultaneously by optimizing a χ^2 statistics to determine the most likely values of the parameters

Combinations of Cepheids+SNe1A, TRGB+SNe1A, or all of the above can be used in the process of calibration



Riess et al. 2022

The Hubble constant: early measurements

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Alternatively, H_0 is found from early Universe measurements + a cosmological model

$$H(z) = H_0\, E(z)$$

Example: in ΛCDM, we find the function:

$$E(z) = [\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_\Lambda]^{1/2}$$

$$\Omega_r + \Omega_m + \Omega_\Lambda = 1$$

These fall under the “**early measurements**” of the Hubble constant

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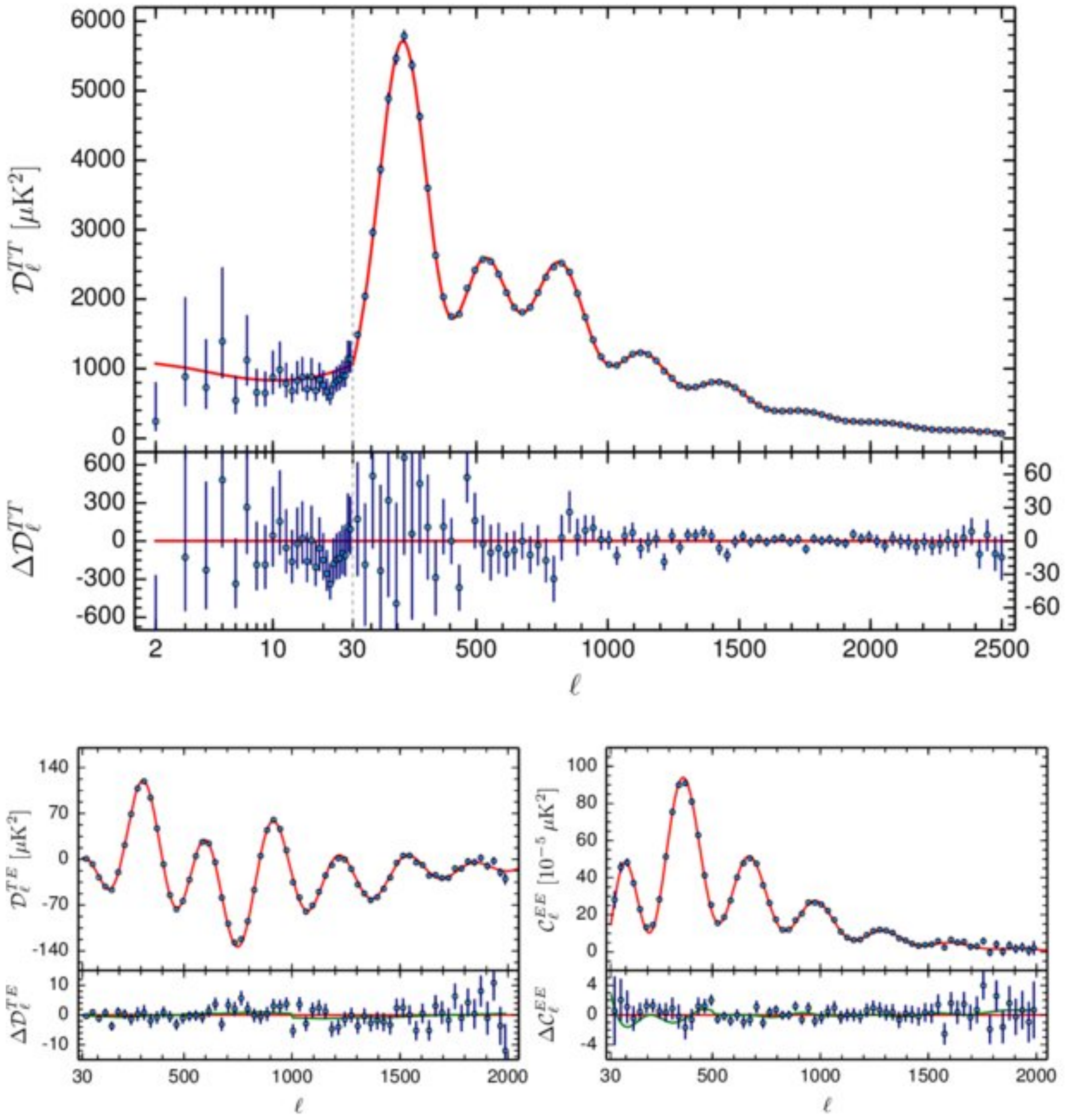
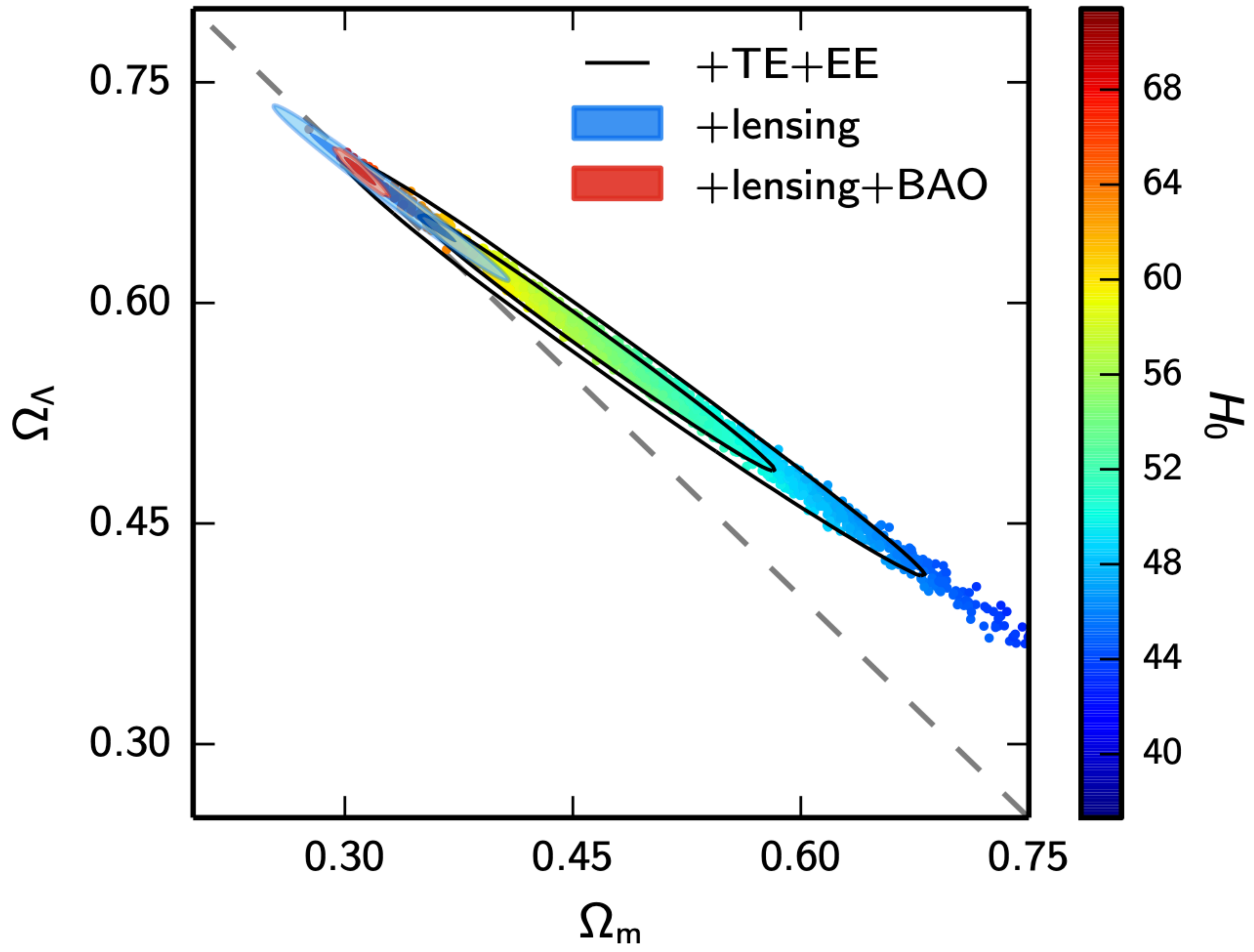
The Hubble constant: early measurements



Planck 2015 CMB power spectra of TT, TE and EE compared with the base ΛCDM fit



Lensing by the inhomogeneous mass distribution along the line of sight between LSS and now helps breaking the geometric degeneracy between Ωm and ΩΛ in the T and E data

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A problem exacerbating in time

SH0ES: The value of H_0 is inferred from Cepheid-calibrated cosmic distance ladder [2112.04510]

$H_0 = (73.04 \pm 1.04)\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

Planck: The value of H_0 is inferred using the ΛCDM model calibrated on early Universe data [1807.06209]

$H_0 = (67.62 \pm 0.47)\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

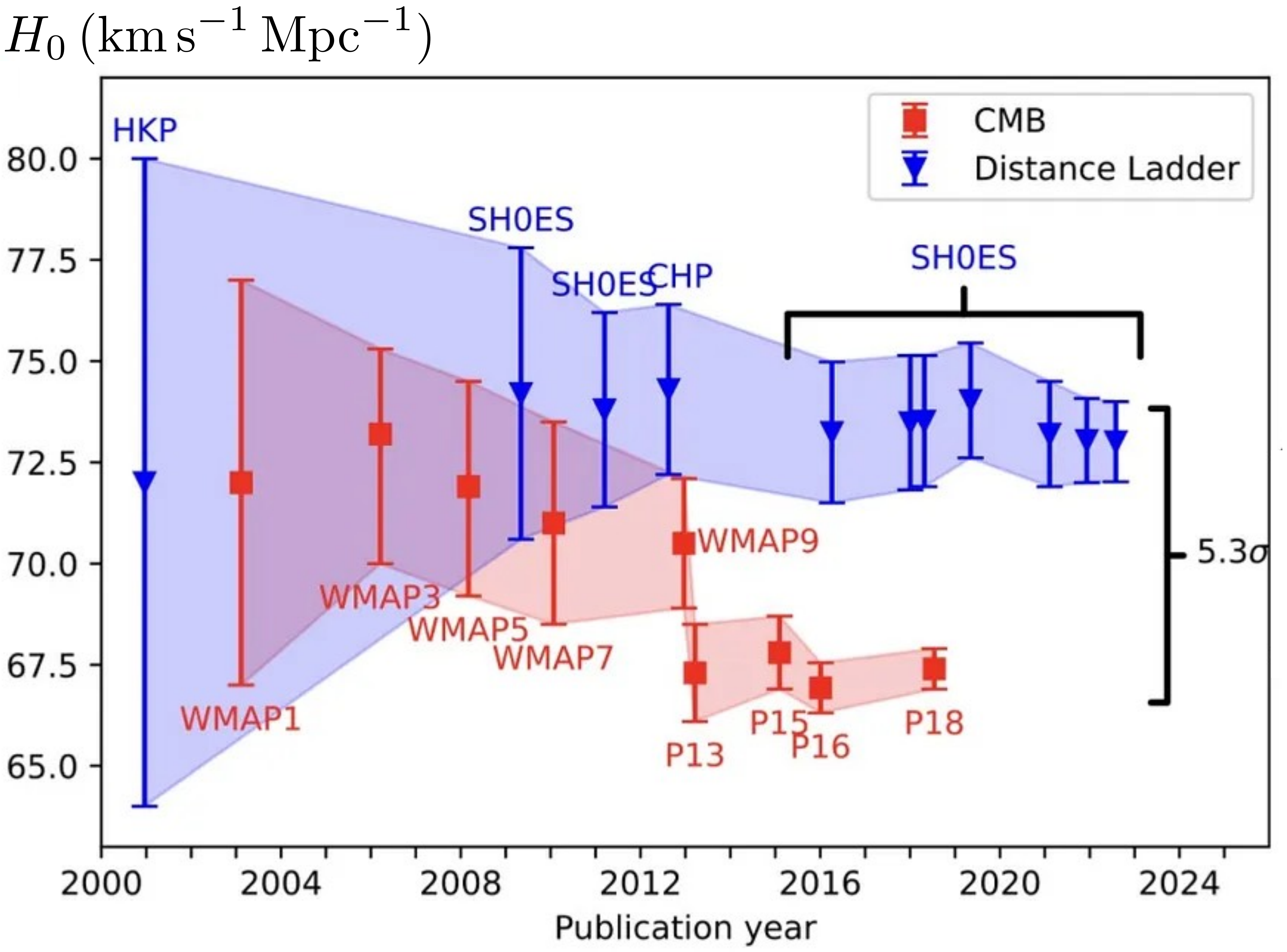

Image Credit: D'arcy Kenworthy

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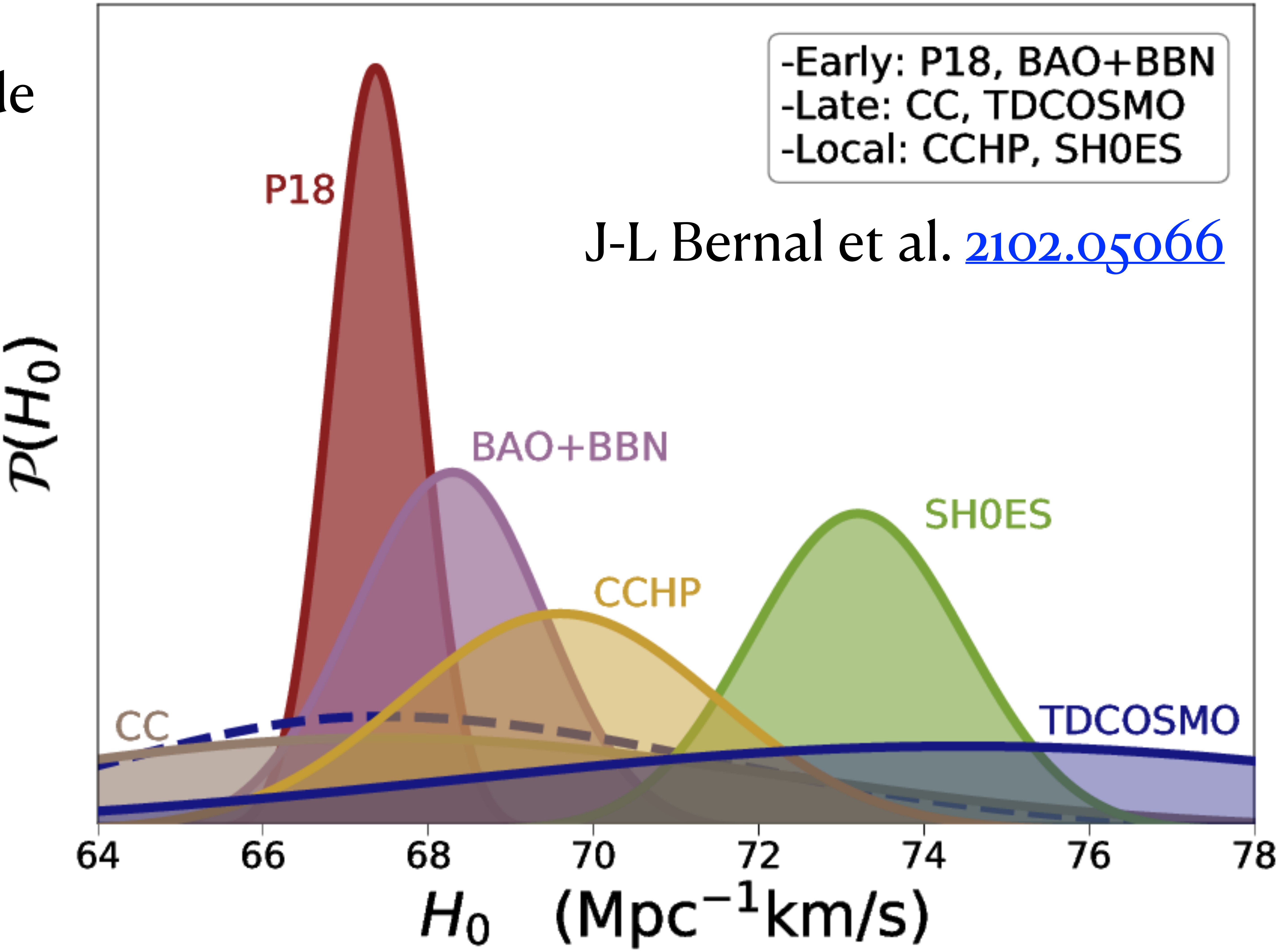
Framing the Hubble tension problem

"The SHoES that fit one pinch another"

Adapted from Carl Jung by Licia Verde

- Planck (P18) 1807.06209
- BAO+BBN prior 1907.11594
- Cosmic chronometers 1805.03595
- Strong- lensing time delays (TDCOSMO) 2007.02941
- Carnegie-Chicago Hubble Program (CCHP) TRGB 2002.01550
- SHoES 21 2012.08534



J-L Bernal et al. 2102.05066

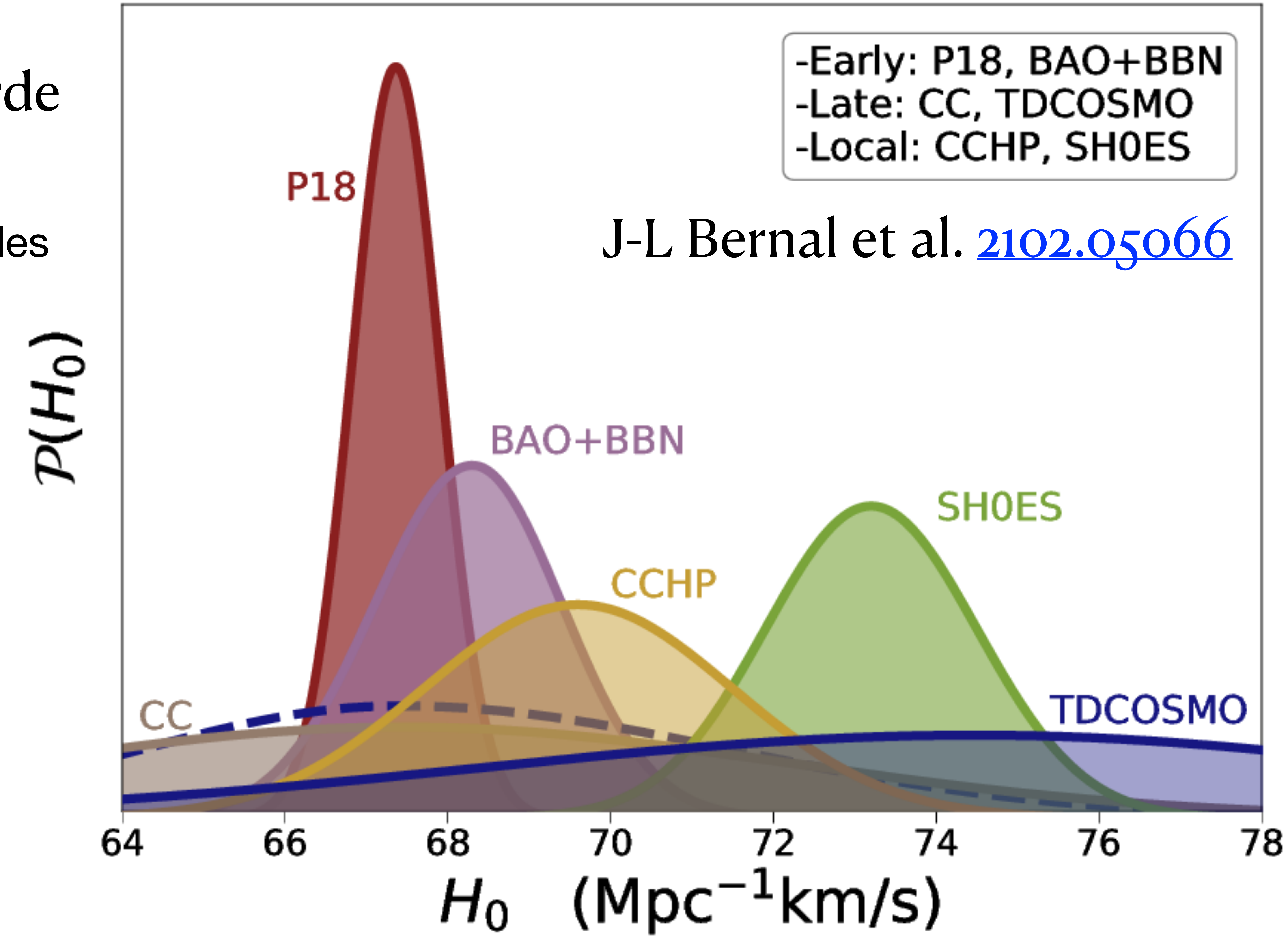
Framing the Hubble tension problem

"The SHoES that fit one pinch another"

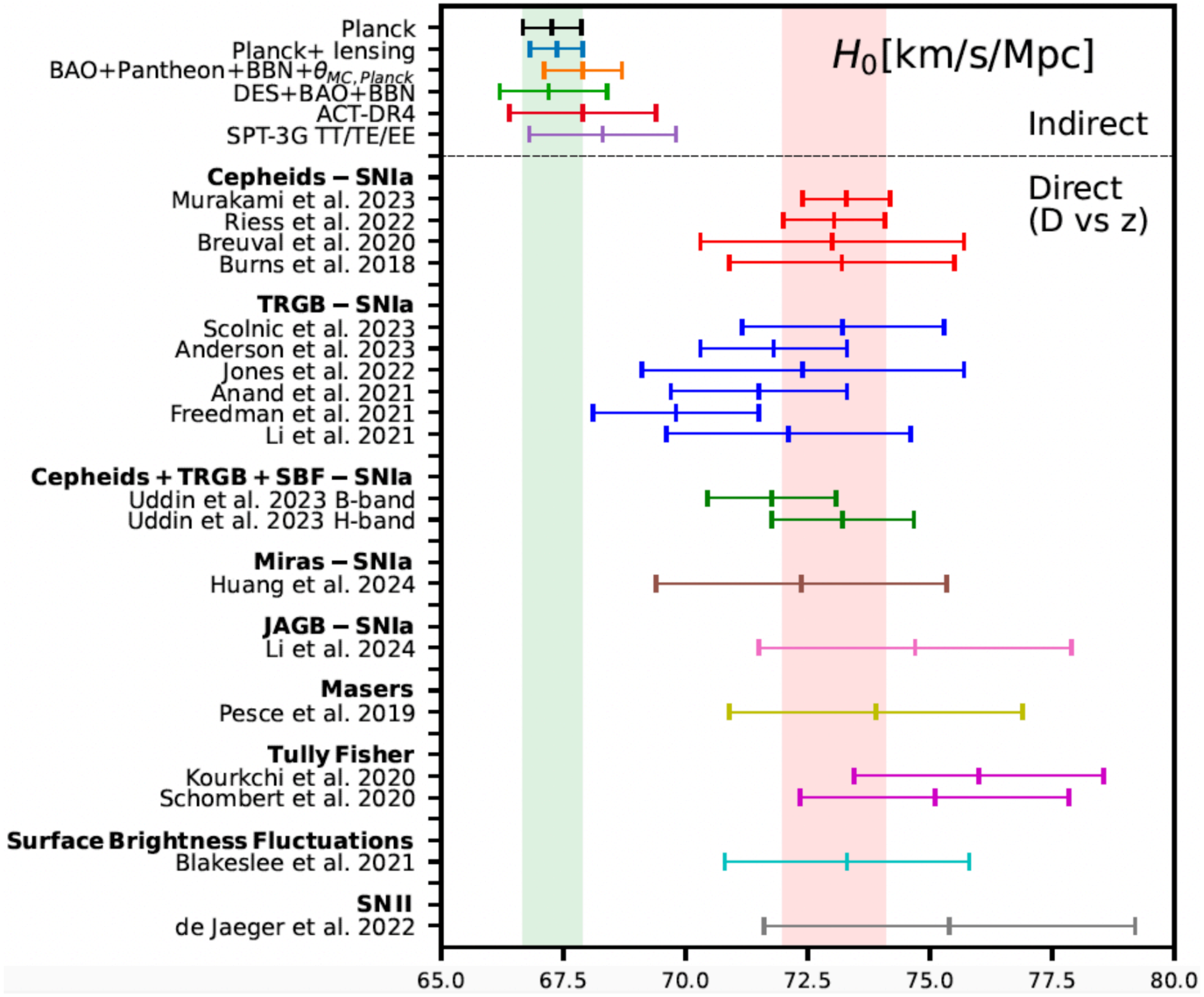
Adapted from Carl Jung by Licia Verde

CC: relative galaxy ages between two ensembles of passively–evolving galaxies at different redshifts measures dz/dt

TDCOSMO: strong lensing time delays at late-time expansion history



H_0 measurements



Di Valentino 2011.00246; 2103.01183

Measurements of H_0 by different astronomical missions over the years

RED: Result from SHoES

GREEN: Results from *Planck* 2018 + ΛCDM model

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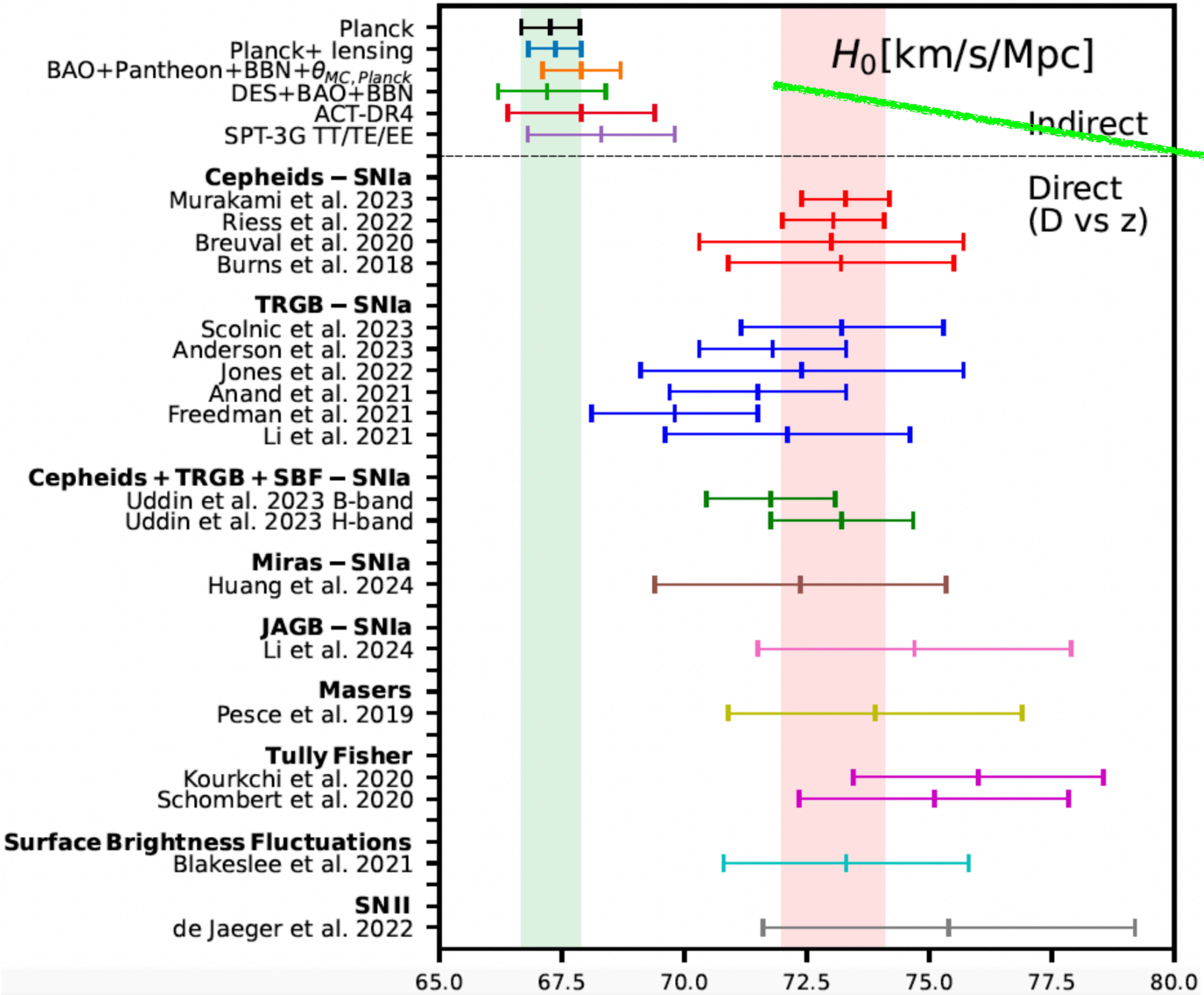
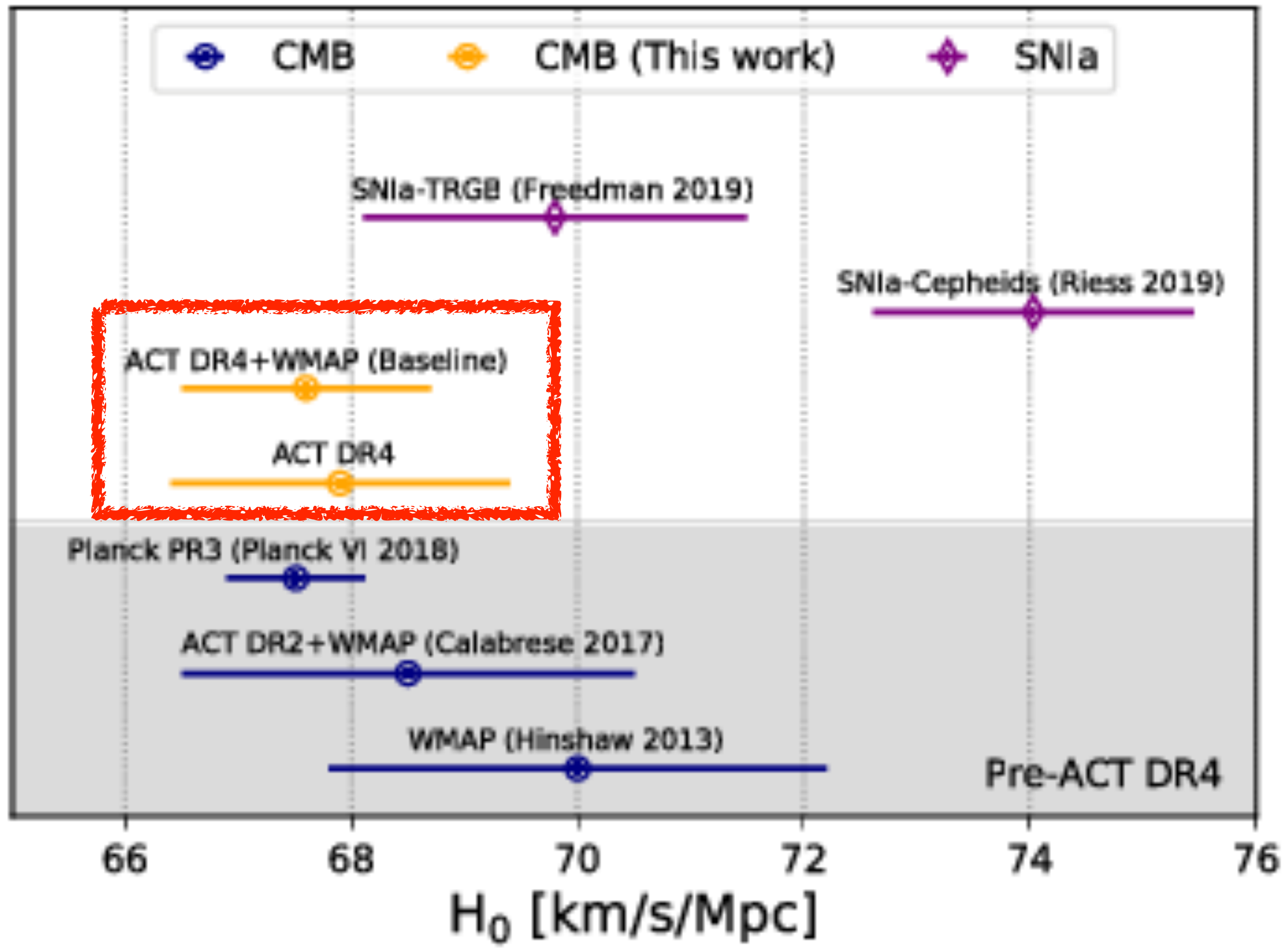
Early-time H_0 measurements



Di Valentino 2011.00246; 2103.01183

Ground-based CMB telescopes obtain results consistent with *Planck*

Atacama Cosmology Telescope (ACT)



2007.07288

Early-time H_0 measurements

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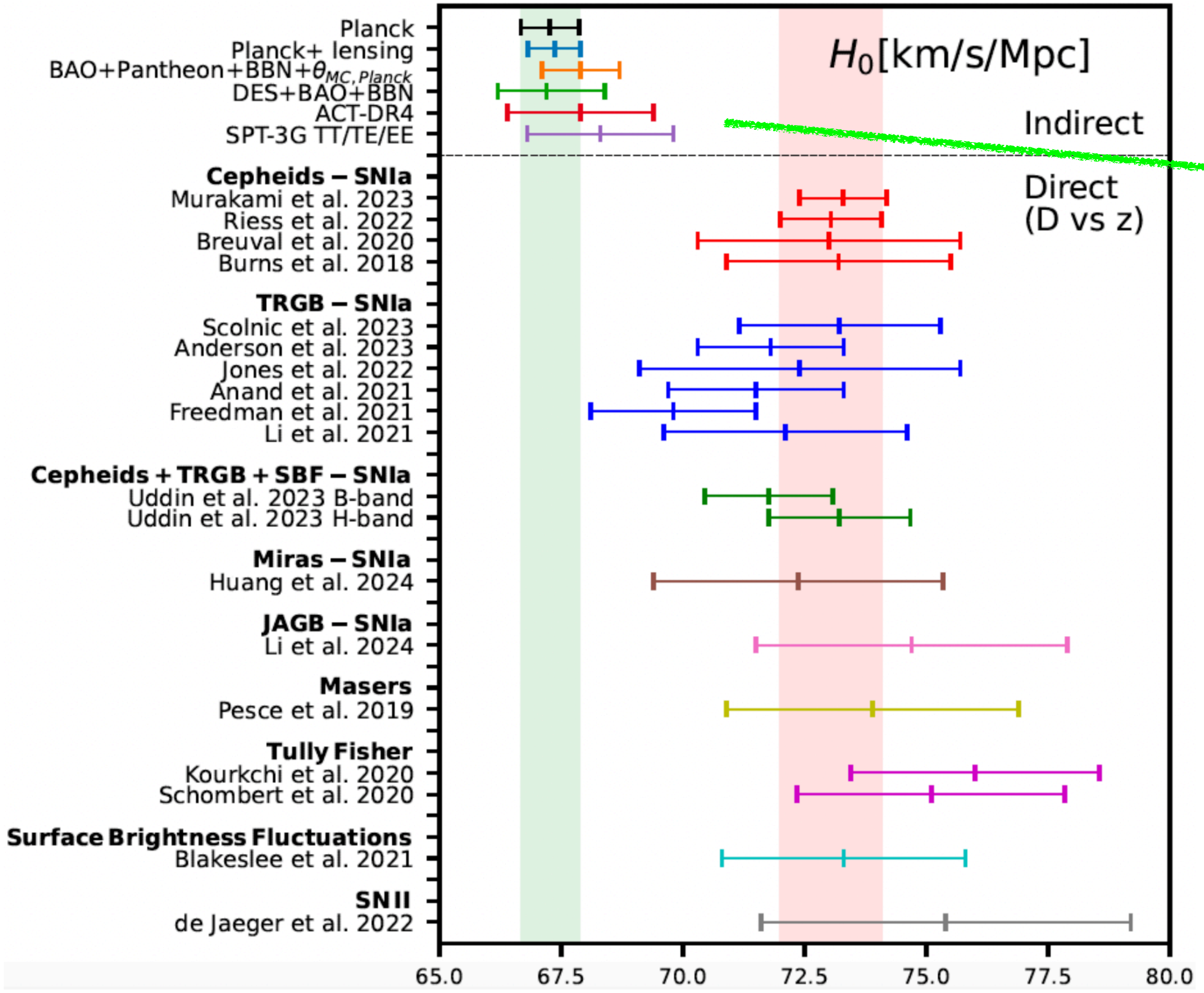
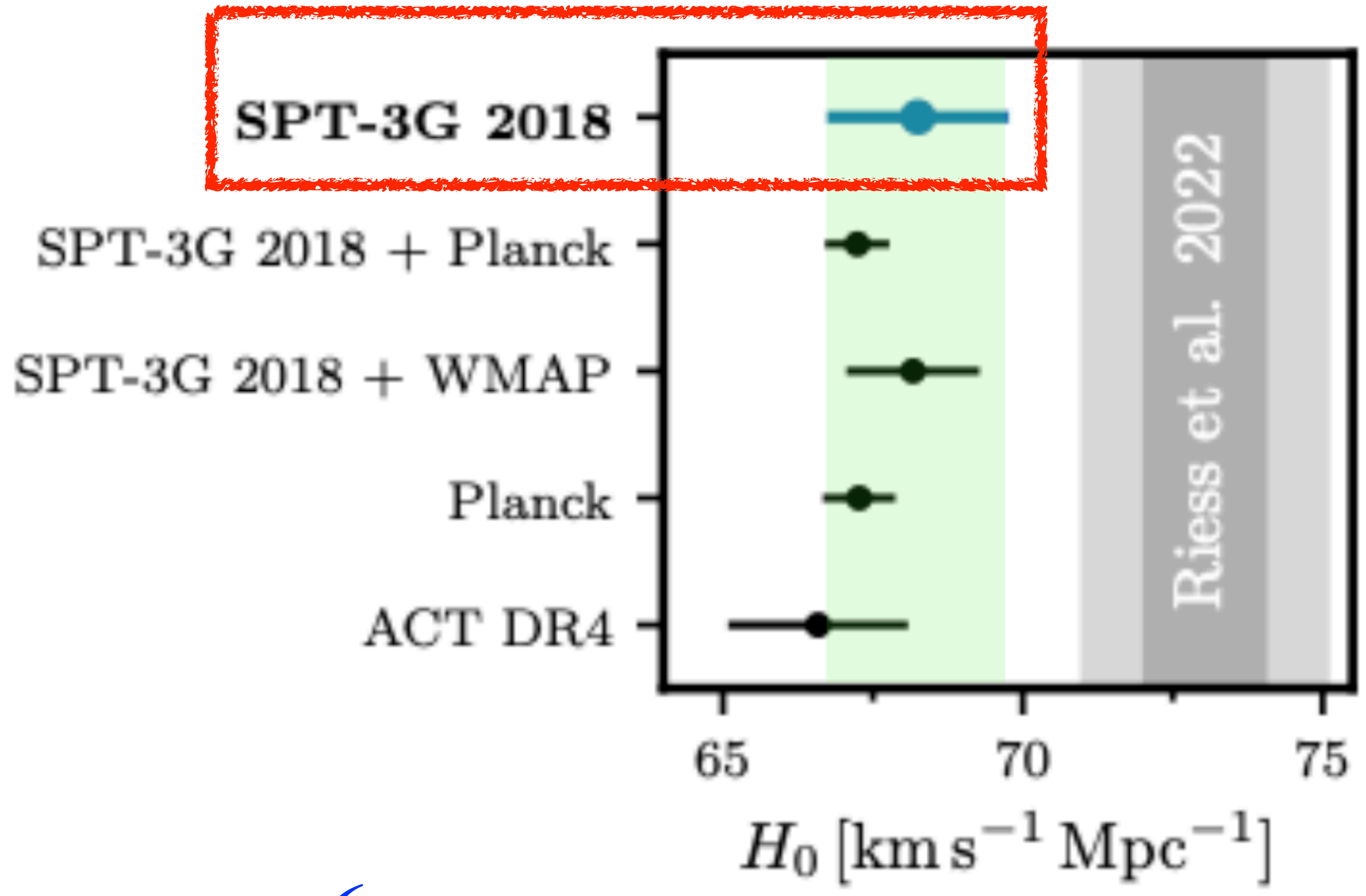


Di Valentino 2011.00246; 2103.01183

Ground-based CMB telescopes obtain results consistent with *Planck*

South Pole Telescope (SPT)



2212.05642

Early-time H_0 measurements

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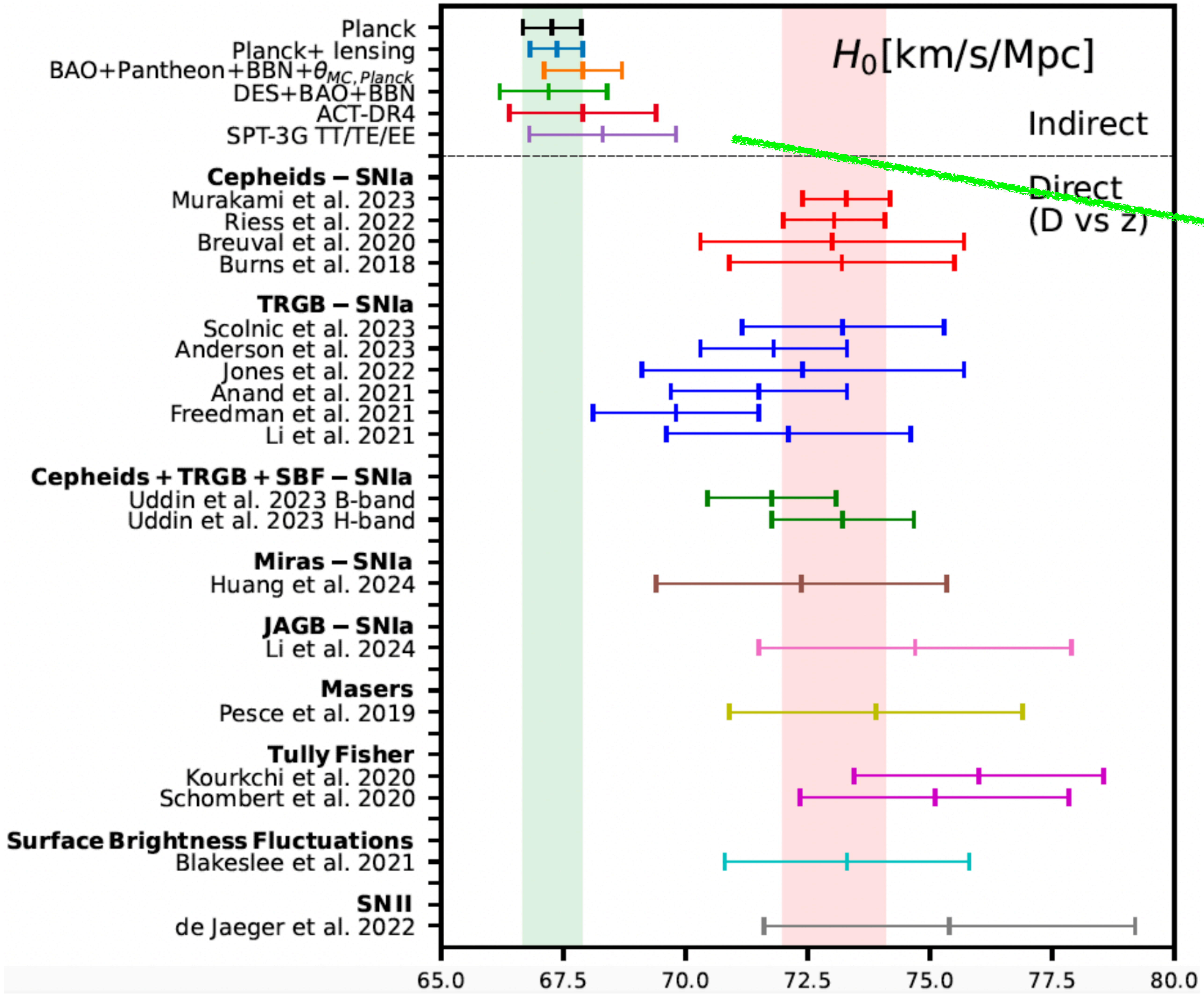
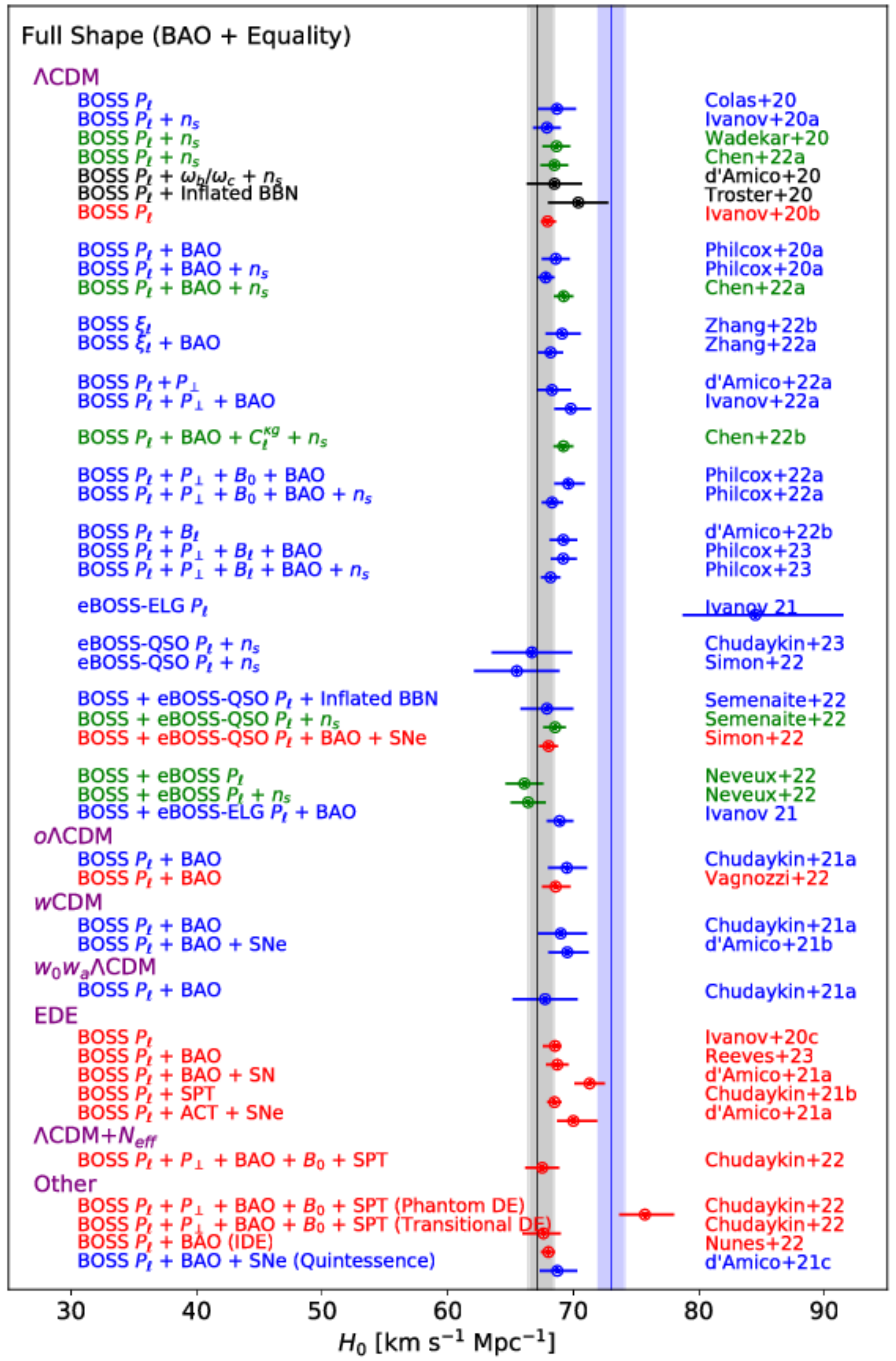


Di Valentino 2011.00246; 2103.01183

Spectroscopic surveys (**BOSS, eBOSS**)

The sound horizon at recombination leads to BAO

Combined with external data from the CMB or BBN



2305.07977

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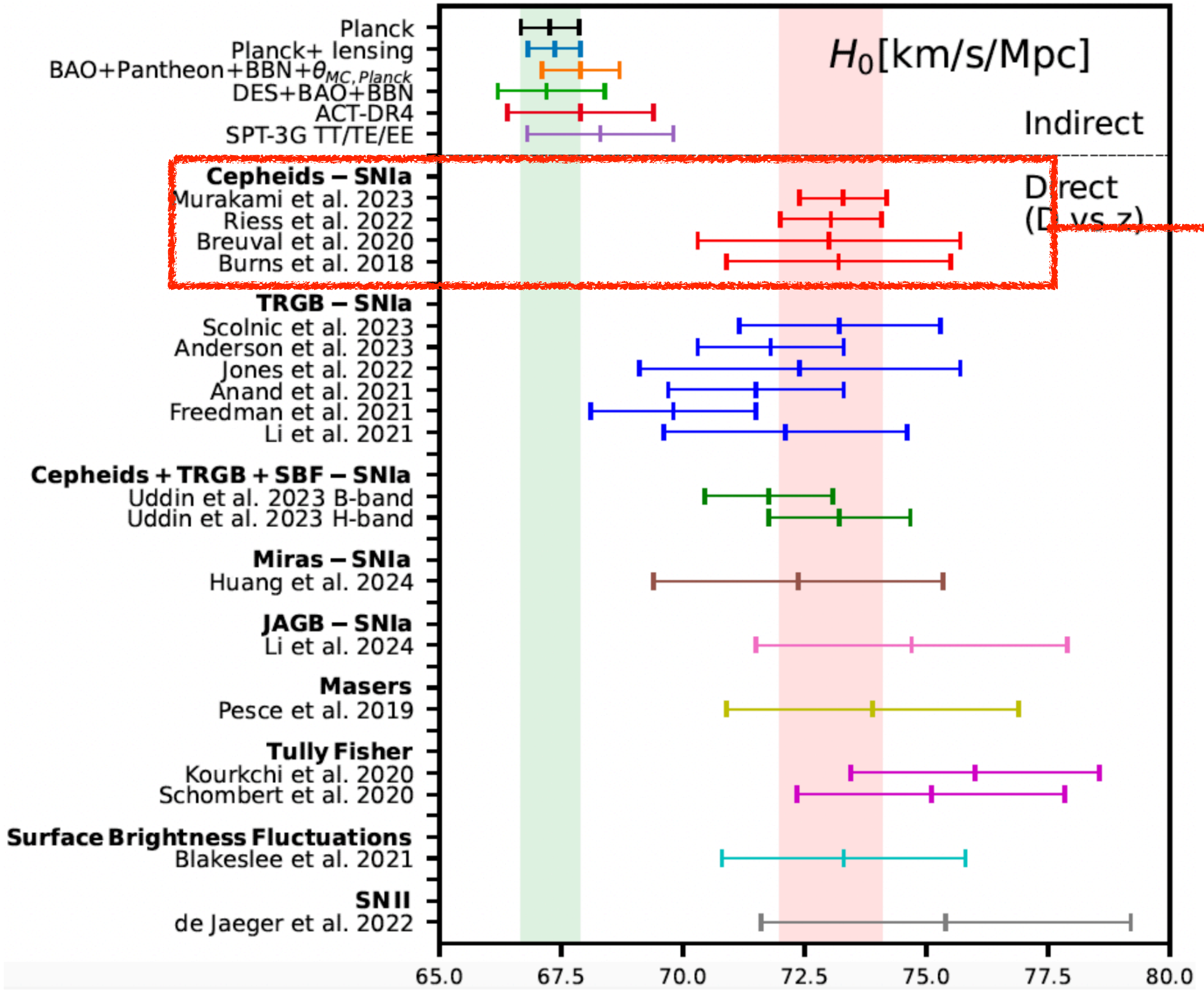
Late-time H_0 measurements



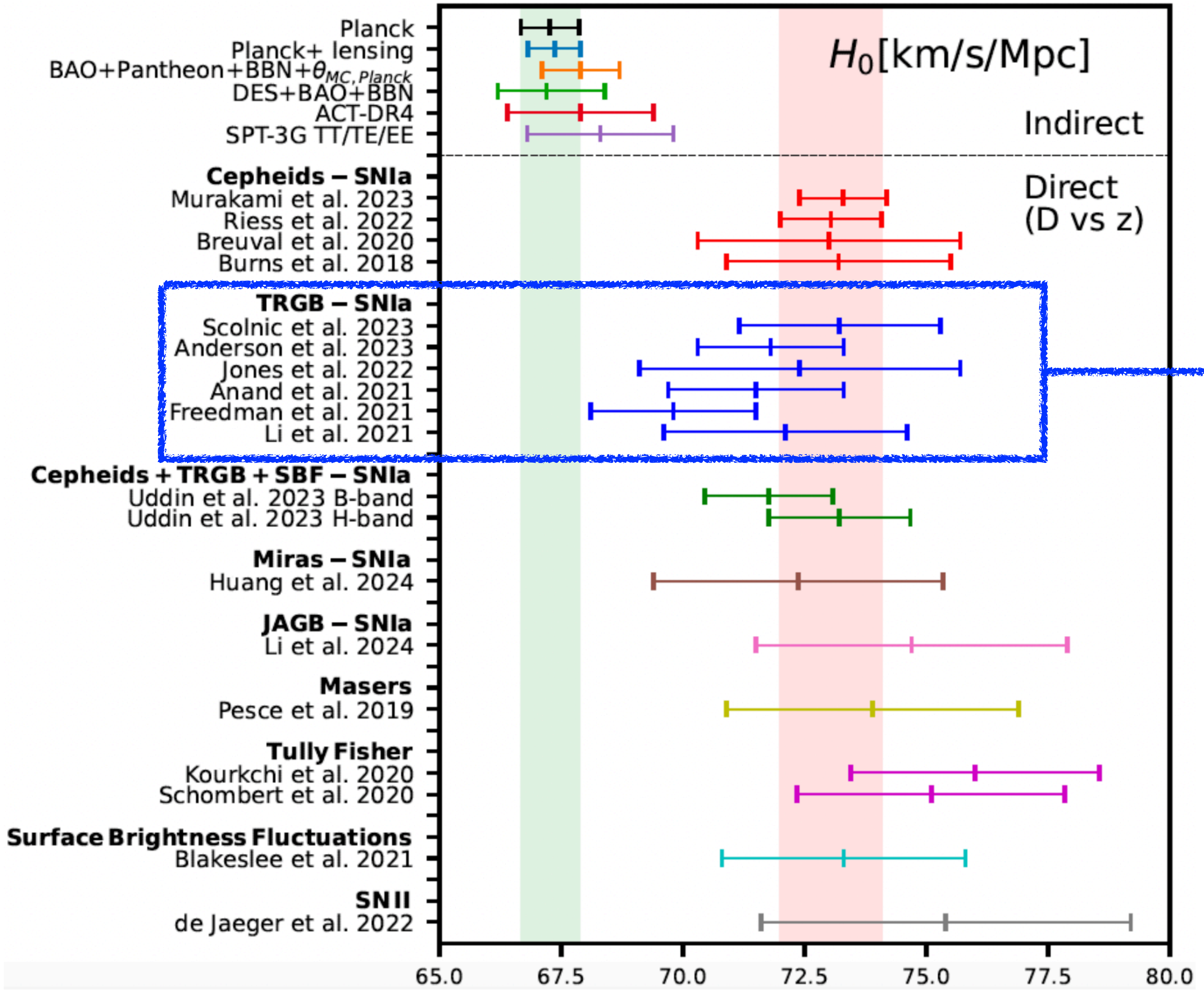
Di Valentino 2011.00246; 2103.01183

Here, Cepheids are used as **standard candles**

SN-1A calibrated with Cepheids
(Murakami+ 2306.00070; Riess+ 2112.04510)

Late-time H_0 measurements

Luca Visinelli



Di Valentino 2011.00246; 2103.01183

Here, TRGB are used as **standard candles**

TRGB: The luminosity of the brightest red-giant-branch stars in a galaxy is a standard candle to gauge the distance to that galaxy

SN-1A calibrated with TRGB (Scolnic+ 2304.06693, Anderson+ 2303.04790, Jones+, Anand+, Freedman+)

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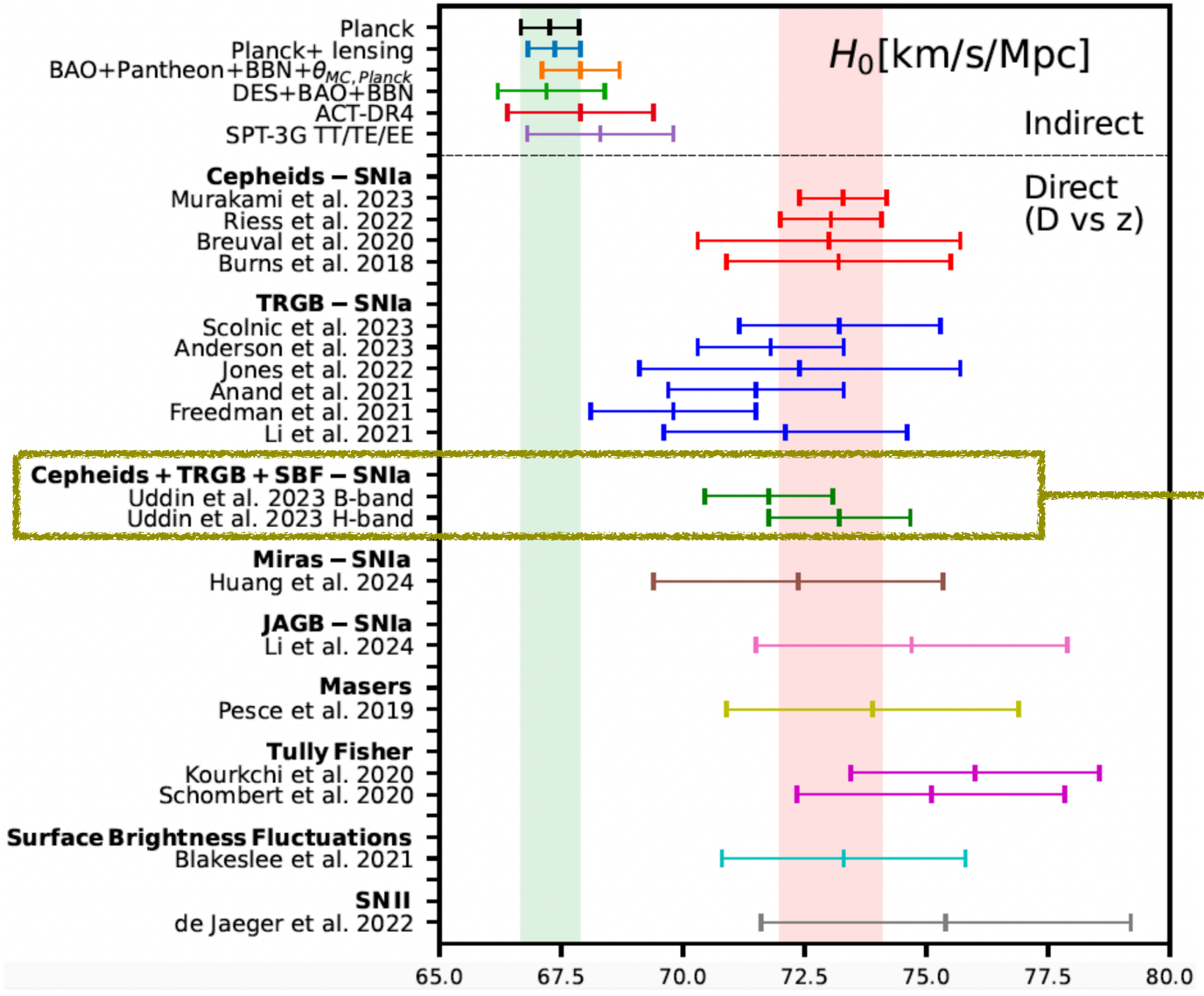
Late-time H_0 measurements



Di Valentino 2011.00246; 2103.01183

Here, TRGB+SBF+Cepheids are used as **standard candles**

SBF measures the variance in the light distribution of a galacy arising from fluctuations in the number & luminosity of individual stars

Carnegie Supernova Project (Uddin+ 2308.01875)

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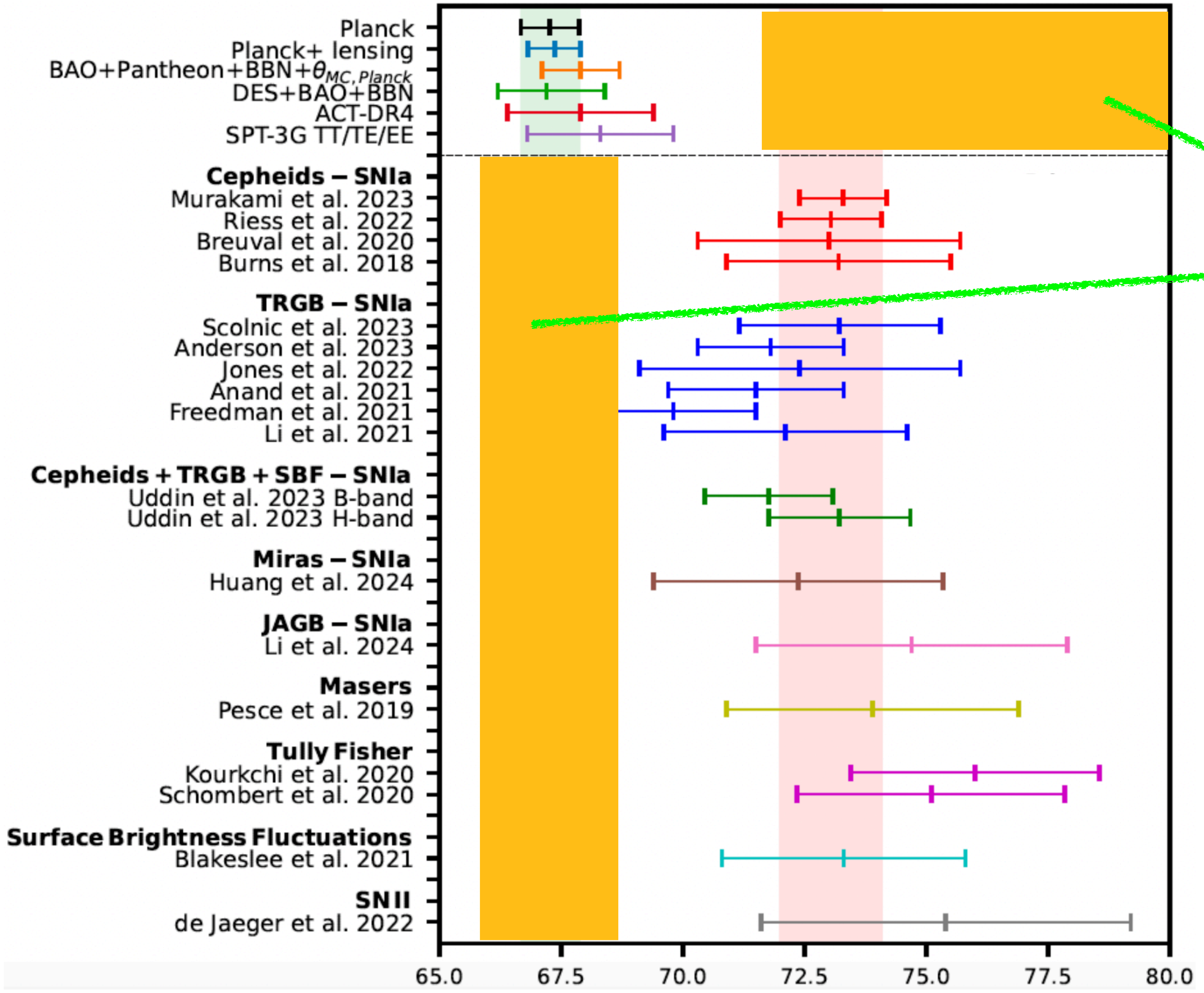
Systematics?



Di Valentino 2011.00246; 2103.01183

No local Universe measurements below the early ones and viceversa

Systematics have been heavily scrutinized

- Efstathiou 2007.10716
- Mortsell+ 2105.11461
- Freedman 2106.15656

Systematics and JWST?

Luca Visinelli

JWST Observations Reject Unrecognized Crowding of Cepheid Photometry as an Explanation for the Hubble Tension at 8σ Confidence

Adam G. Riess,[1,2] Gagandeep S. Anand,[1] Wenlong Yuan,[2] Stefano Casertano,[1] Andrew Dolphin,[3] Lucas M. Macri,[4] Louise Breuval,[2] Dan Scolnic,[5] Marshall Perrin,[1] and Richard I. Anderson[6]

ABSTRACT

We present high-definition observations with the *James Webb Space Telescope* of >1000 Cepheids in a geometric anchor of the distance ladder, NGC 4258, and in 5 hosts of 8 Type Ia supernovae, a far greater sample than previous studies with *JWST*. These galaxies individually contain the largest samples of Cepheids, an average of >150 each, producing the strongest statistical comparison to those previously measured with the *Hubble Space Telescope* in the NIR. They also span the distance range of those used to determine the Hubble constant with *HST*, allowing us to search for a distance-dependent bias in *HST* measurements. The superior resolution of *JWST* negates crowding noise, the largest source of variance in the NIR Cepheid Period-Luminosity relations (Leavitt laws) measured with *HST*. Together with the use of two-epochs to constrain Cepheid phases and three filters to remove reddening, we reduce the dispersion in the Cepheid P–L relations by a factor of 2.5. We find no significant difference in the mean distance measurements determined from *HST* and *JWST*, with a formal difference of -0.01±0.03 mag. This result is independent of zeropoints and analysis variants including metallicity dependence, local crowding, choice of filters, and slope of the relations. We can reject the hypothesis of unrecognized crowding of Cepheid photometry from *HST* that grows with distance as the cause of the "Hubble Tension" at 8.2σ, i.e., greater confidence than that of the Hubble Tension itself. We conclude that errors in photometric measurements of Cepheids across the distance ladder do not significantly contribute to the Tension.

Riess+ 2401.04773

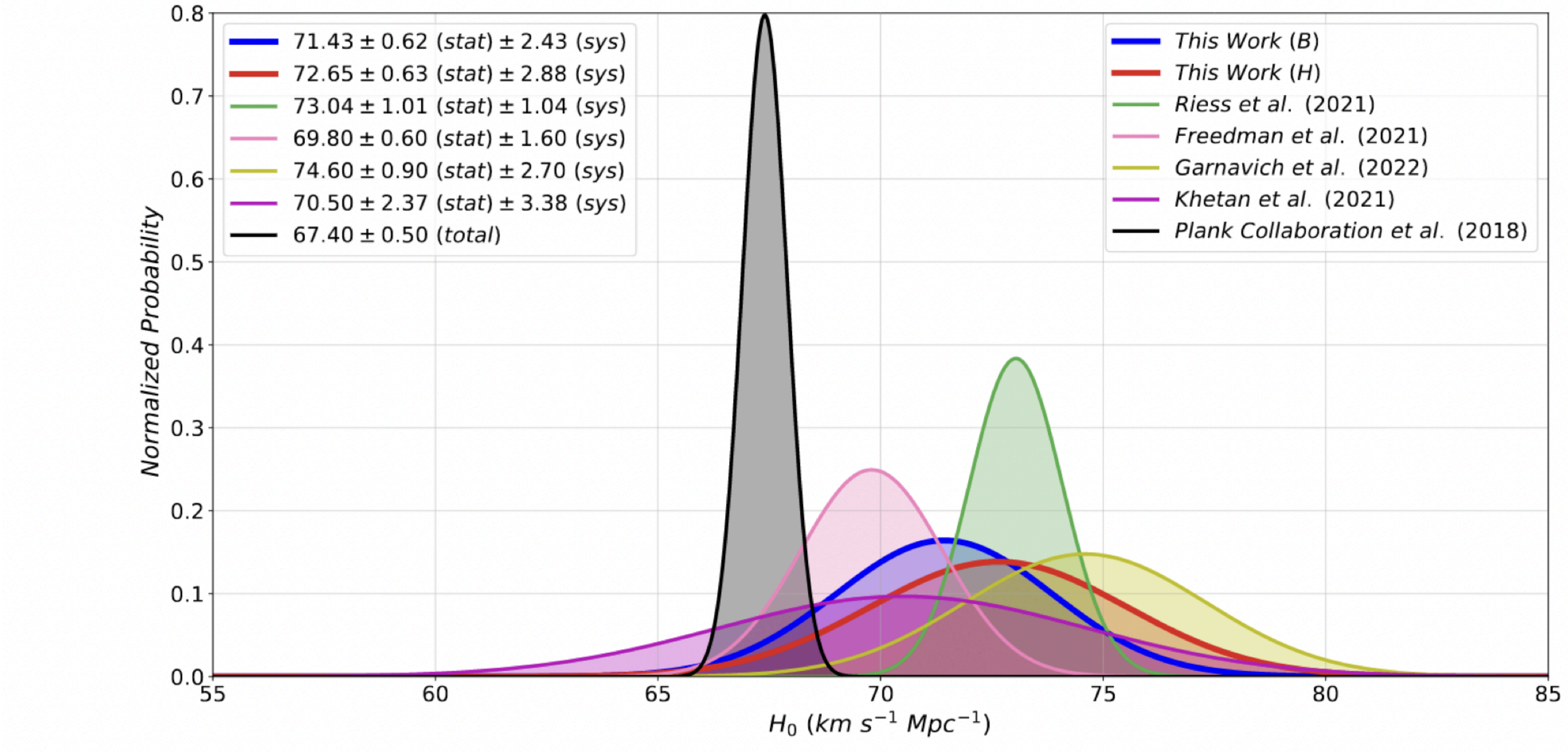


Figure 14. Probability distributions for H_0 for calibrations based on Cepheids [139], the TRGB [25] SBF from [85], compared to recent published values from the literature. The Planck Collaboration value from the CMB [11] shown in grey.

Freedman+ 2309.05618

Abstract: S01.00002 : New JWST Results: Is the Current Tension in Ho Signaling New Physics*
1:57 PM–2:24 PM

← Abstract →

Presenter:
Wendy L Freedman
(University of Chicago)

Author:
Wendy L Freedman
(University of Chicago)

Collaborations:
Barry Madore, In Sung Jang, Taylor Hoyt, Abigail Lee, Kayla Owens

The question of whether there is new physics beyond our current standard model, Lambda Cold Dark Matter (LCDM), is a crucial unresolved issue in cosmology today. Recent measurements of the Hubble constant (Ho) using Cepheids and Type Ia supernovae (SNe) appear to differ significantly (5-sigma) from values inferred from the cosmic microwave background (CMB) fluctuations. This discrepancy, if real, could indicate new physics beyond the standard model. In this talk, I will present new results from a James Webb Space Telescope (JWST) program designed to measure Ho, and aimed at reducing current systematic uncertainties. It utilizes three independent methods for measuring the distances to (the same) nearby galaxies that provide a calibration for SNe: Cepheid variables, Tip of the Red Giant Branch (TRGB) stars and J-Region Asymptotic Giant Branch (JAGB) stars. The Near-Infrared Camera on JWST has four times the resolution and ten times the sensitivity of HST in the near infrared, and is critical for ascertaining whether new physics is required beyond the standard model of cosmology.

*This work is based in part on observations made with the NASA/ESA/CSA James Webb Space Telescope. These observations are associated with JWST program GO-1995.

Examples for possible solutions

Extra relativistic radiation (not viable)

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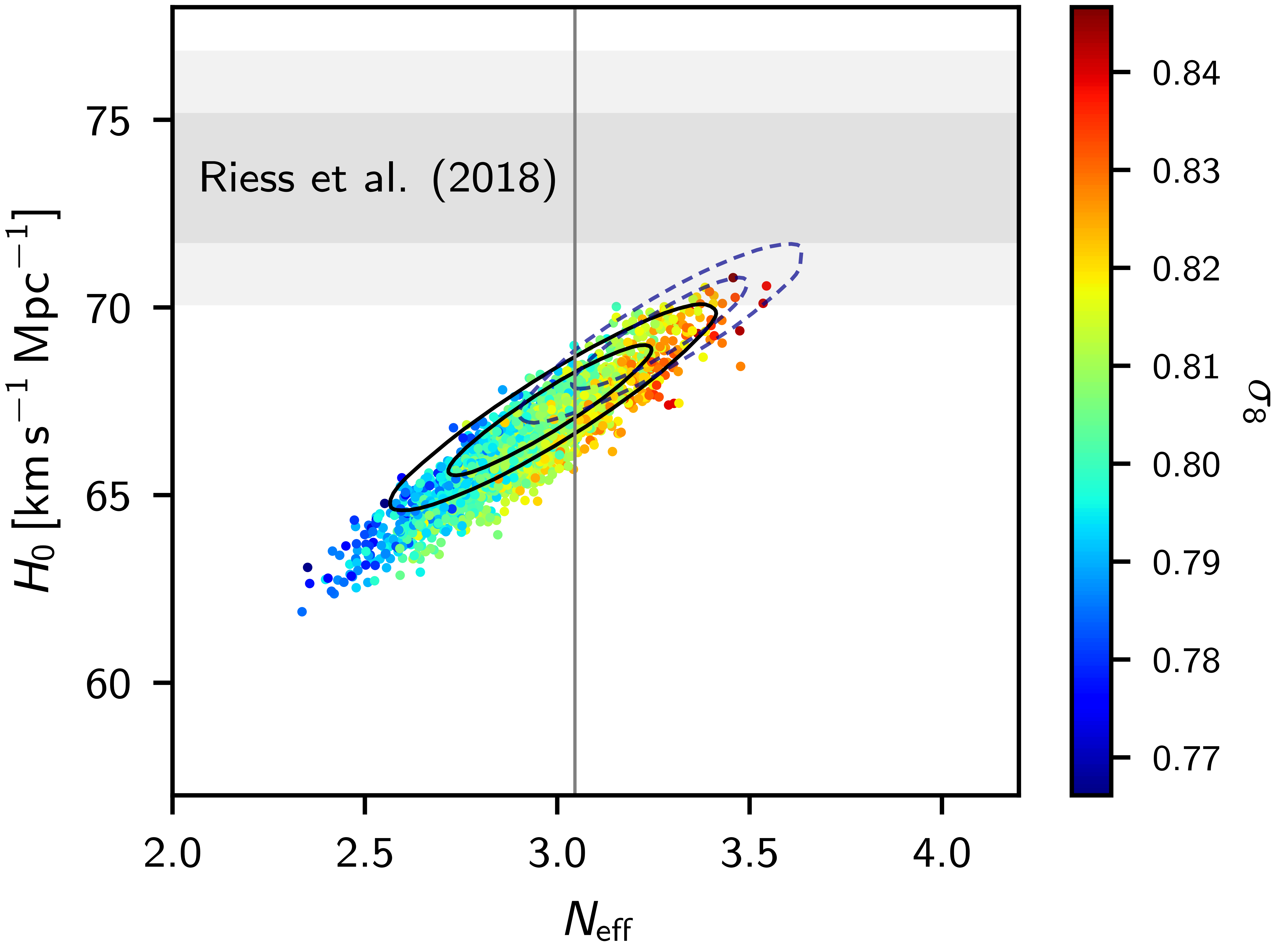

Planck 2018 [1807.06209]

Evolving dark energy (*w*CDM)

Luca Visinelli

$$E(z) = [\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_{\rm DE}(1+z)^{3(1+w)}]^{1/2}$$

Planck-alone data favor a phantom dark energy e.o.s. with $w = -1.58^{+0.52}_{-0.41}$ at 95% C.L.

Parameter	TT+lowE	TT, TE, EE+lowE	TT, TE, EE+lowE+lensing	TT, TE, EE+lowE+lensing+BAO
Ω_K	$-0.056^{+0.044}_{-0.050}$	$-0.044^{+0.033}_{-0.034}$	$-0.011^{+0.013}_{-0.012}$	$0.0007^{+0.0037}_{-0.0037}$
Σm_ν [eV]	< 0.537	< 0.257	< 0.241	< 0.120
$N_{\rm eff}$	$3.00^{+0.57}_{-0.53}$	$2.92^{+0.36}_{-0.37}$	$2.89^{+0.36}_{-0.38}$	$2.99^{+0.34}_{-0.33}$
$Y_{\rm P}$	$0.246^{+0.039}_{-0.041}$	$0.240^{+0.024}_{-0.025}$	$0.239^{+0.024}_{-0.025}$	$0.242^{+0.023}_{-0.024}$
$dn_s/d\ln k$	$-0.004^{+0.015}_{-0.015}$	$-0.006^{+0.013}_{-0.013}$	$-0.005^{+0.013}_{-0.013}$	$-0.004^{+0.013}_{-0.013}$
$r_{0.002}$	< 0.102	< 0.107	< 0.101	< 0.106
w_0	$-1.56^{+0.60}_{-0.48}$	$-1.58^{+0.52}_{-0.41}$	$-1.57^{+0.50}_{-0.40}$	$-1.04^{+0.10}_{-0.10}$

Planck 2018 1807.06209

See also Escamilla+ 2307.14802

However, CMB+BAO data worsen the fit with *w*CDM because the best fit from *Planck* alone fails in recovering $H(z)$ at low redshifts

Locating the CMB acoustic peaks

Luca Visinelli

The angular size of the comoving sound horizon at recombination is

$$\theta_{\rm rec} \equiv \frac{r_{\rm rec}}{D(z_{\rm rec})} \qquad \text{at redshift} \qquad z_{\rm rec} \approx 1100$$

Comoving distance travelled by a sound wave to recombination: $r_{\rm rec} = \int_0^{t_{\rm rec}} {\rm d}t\, \frac{c_s}{a(t)}$

$D(z_{\rm rec})$: comoving distance to recombination, $D(z) = \frac{c}{H_0}\int_0^z \frac{{\rm d}z'}{E(z')}$

The calibration of $r_{\rm rec}$ allows to find the relation between H_0 and ω_m

BAO measurements

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Sound horizon at baryon drag:

$$r_{\rm drag} \approx 1.0184\, r_{\rm rec}$$

BAO measurements at redshifts $z_{\rm obs}$

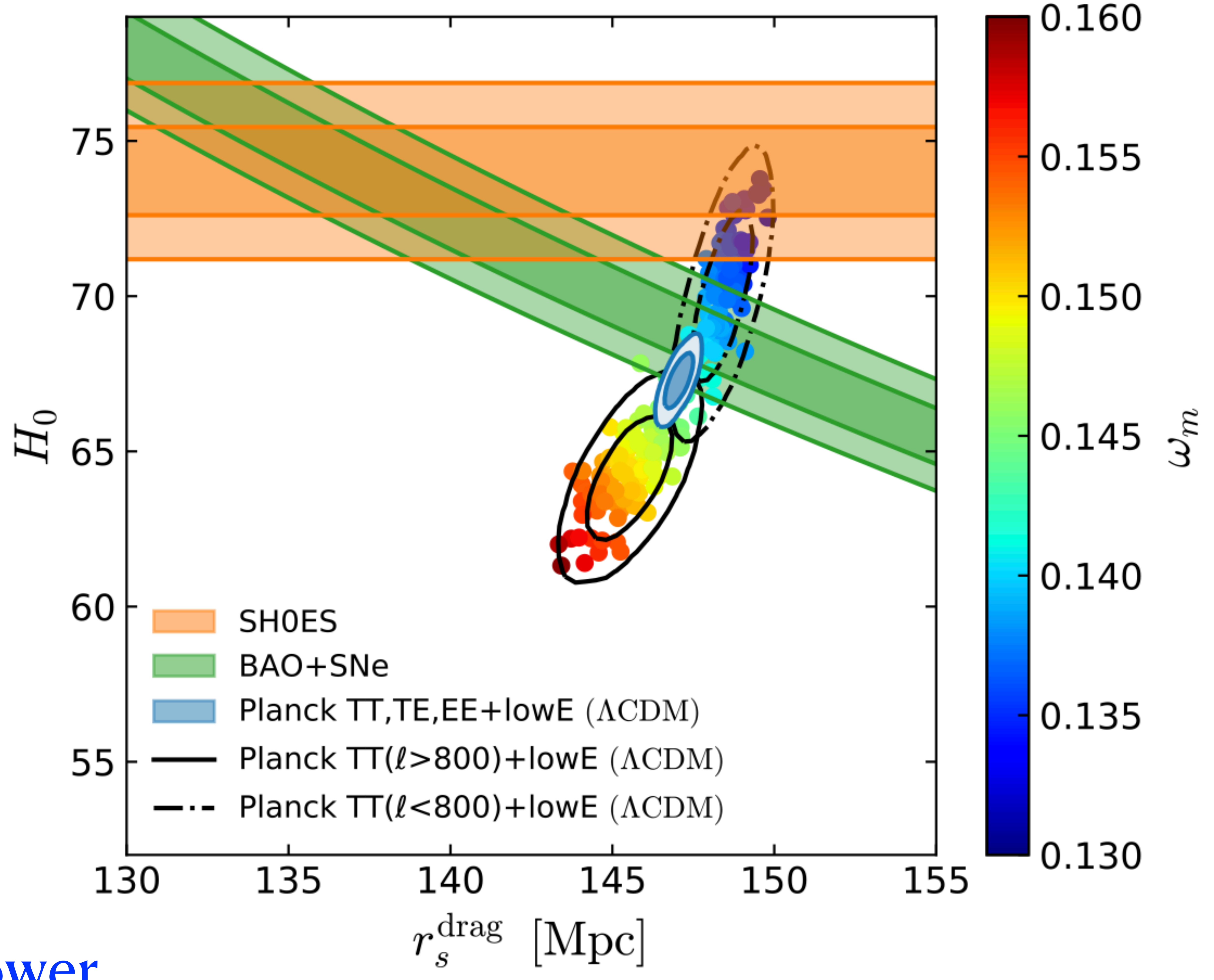
$$\theta(z_{\rm obs}) \equiv \frac{r_{\rm drag}}{D(z_{\rm obs})}$$

BAO+Pantheon measurements constrain the product $H_0\, r_{\rm drag}$

$r_{\rm drag} \sim 147\,{\rm Mpc}$ (*Planck*)

$r_{\rm drag} \sim 137\,{\rm Mpc}$ (SH0ES)

We need to lower $r_{\rm drag}$



Knox & Millea 1908.03663

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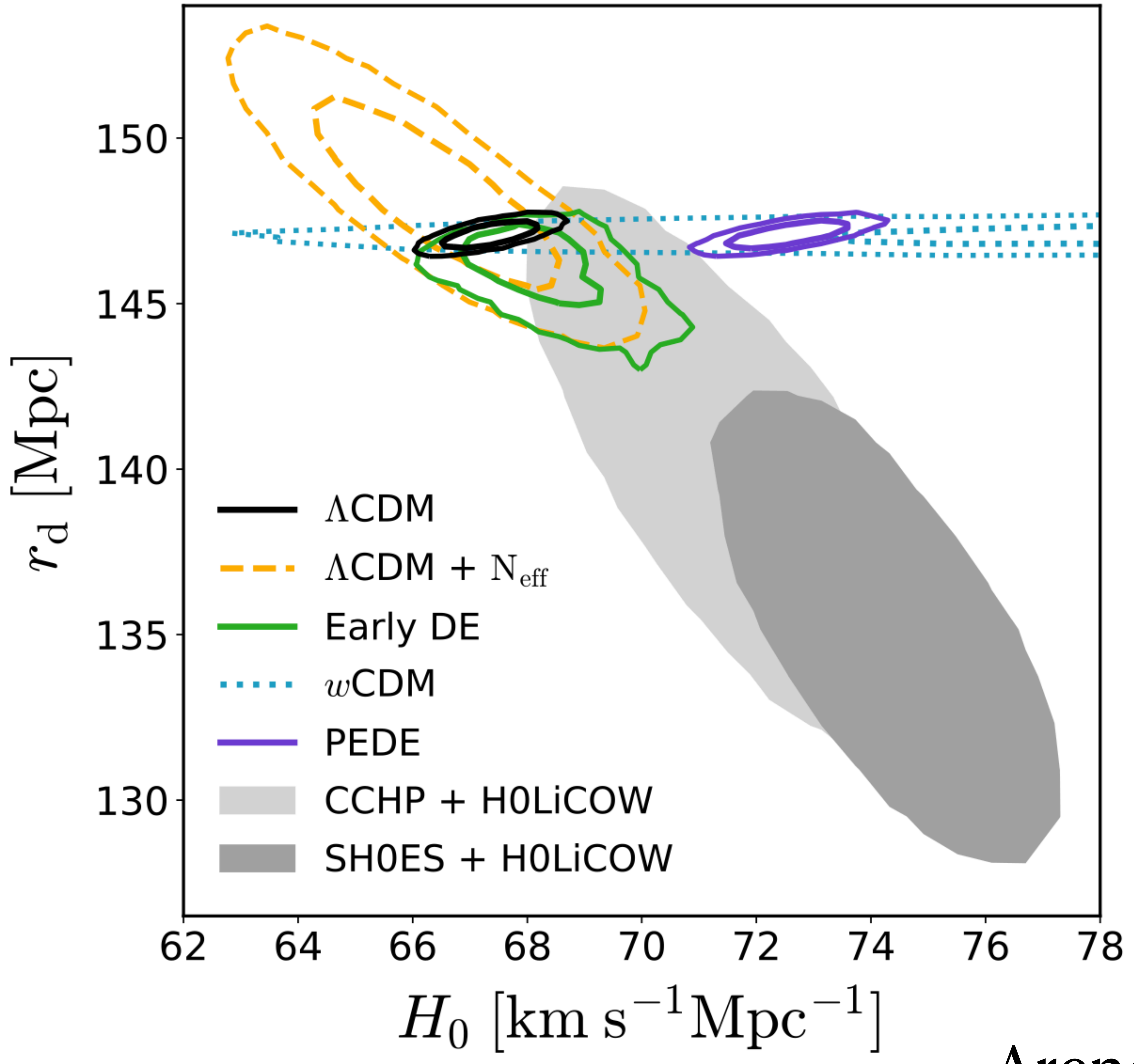
Shortcoming of late-time solutions

Late-time solutions increase H_0 but leave $r_{\rm drag}$ untouched



Arendse+ 1909.07986

Pre-recombination solutions

Decrease the sound horizon by a few % while keeping the features in the damping tail

Examples include:

- Early dark energy (EDE) suppresses the clustering power on small length-scales.

  (Caldwell+ astro-ph/0302505; Doran+ astro-ph/0601544)

  EDE models are constrained by how the damping tail is affected (1608.01309)

Quintessence field with potential

$$V(\phi) \propto (1 - \cos[\phi/f])^n$$

$n = 2$ Radiation

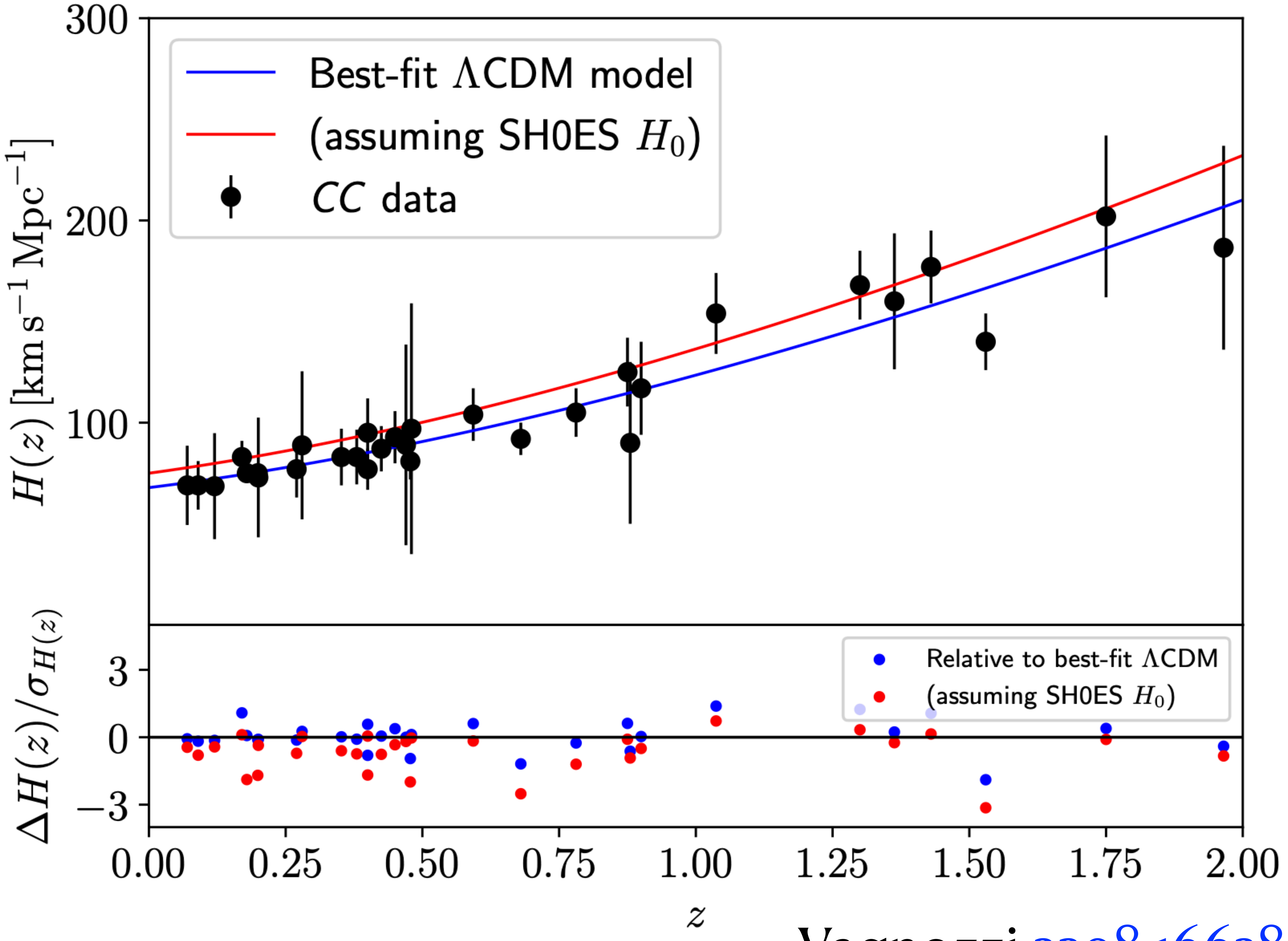
$n \to +\infty$ Kination

1.04149 Parameter	ΛCDM	$n = 2$	$n = 3$	$n = \infty$
$100\ \theta_s$	$1.04198\ (1.04213) \pm 0.0003$	$1.04175\ (1.0414)^{+0.00046}_{-0.00064}$	$1.04138\ (1.0414) \pm 0.0004$	$1.04159\ (1.04149) \pm 0.00035$
$100\ \omega_b$	$2.238\ (2.239) \pm 0.014$	$2.244\ (2.228)^{+0.019}_{-0.022}$	$2.255\ (0.258) \pm 0.022$	$2.257\ (2.277) \pm 0.024$
$\omega_{\rm cdm}$	$0.1179\ (0.1177) \pm 0.0012$	$0.1248\ (0.1281)^{+0.003}_{-0.0041}$	$0.1272\ (0.1299)_{\pm}0.0045$	$0.1248\ (0.1249) \pm 0.0041$
$10^9 A_s$	$2.176\ (2.14) \pm 0.051$	$2.185\ (2.230) \pm 0.056$	$2.176\ (2.177) \pm 0.054$	$2.151\ (2.177) \pm 0.051$
n_s	$0.9686\ (0.9687) \pm 0.0044$	$0.9768\ (0.9828)^{+0.0065}_{-0.0072}$	$0.9812\ (0.9880) \pm 0.0080$	$0.9764\ (0.9795) \pm 0.0073$
$\tau_{\rm reio}$	$0.075\ (0.068) \pm 0.013$	$0.075\ (0.083) \pm 0.013$	$0.068\ (0.068) \pm 0.013$	$0.062\ (0.066) \pm 0.014$
${\rm Log}_{10}(a_c)$	–	$-4.136\ (-3.728)^{+0.57}_{-0.013}$	$-3.737\ (-3.696)^{+0.110}_{-0.094}$	$-3.449\ (-3.509)^{+0.047}_{-0.11}$
$f_{\rm EDE}(a_c)$	–	$0.028\ (0.044)^{+0.011}_{-0.016}$	$0.050\ (0.058)^{+0.024}_{-0.019}$	$0.054\ (0.057)^{+0.031}_{-0.027}$
$r_s(z_{\rm rec})$	$145.05\ (145.1) \pm 0.26$	$141.4\ (139.8)^{+2}_{-1.5}$	$140.3\ (138.9)^{+1.9}_{-2.3}$	$141.6\ (141.3)^{+1.8}_{-2.1}$
S_8	$0.824\ (0.814) \pm 0.012$	$0.826\ (0.836) \pm 0.014$	$0.838\ (0.842) \pm 0.015$	$0.836\ (0.839) \pm 0.015$
H_0	$68.18\ (68.33) \pm 0.54$	$70.3\ (71.1) \pm 1.2$	$70.6\ (71.6) \pm 1.3$	$69.9\ (70) \pm 1.1$

Poulin+ 1811.04083

Is early-time new physics enough?

Luca Visinelli



Vagnozzi 2308.16628

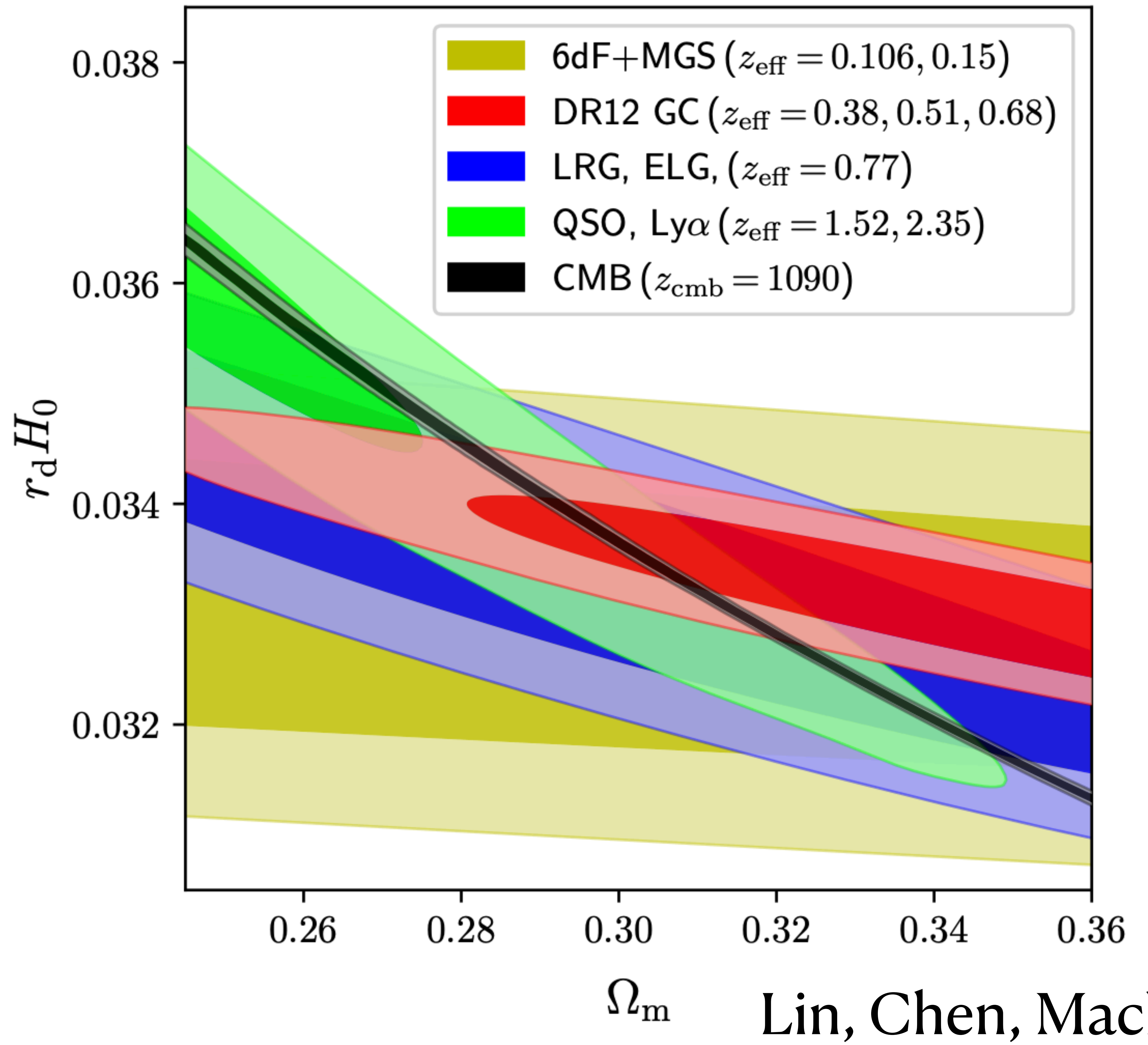
Cosmic Chronometers (CC)

[Jimenez & Loeb astro-ph/0106145]

$$H(z) = -\frac{1}{1+z}\frac{dz}{dt}$$

CC show a residual ~2σ tension with local H_0 measurements within ΛCDM independent of early-Universe physics

Is early-time new physics enough?



Uncalibrated Cosmic Standards (UCS)

[Lin, Mack, Hou, 1910.02978]

A re-analysis of CMB data in combination with other low-redshift observations

Free parameters: Ω_m, $\mathcal{M}$, $r_d H_0$

+ BBN prior on $\Omega_b h^2$

Lin, Chen, Mack, 2102.05701

Is early-time new physics enough?

COSMIC COMPLEMENTARITY: H_0 AND Ω_m FROM COMBINING CMB EXPERIMENTS AND REDSHIFT SURVEYS

Daniel J. Eisenstein, Wayne Hu, and Max Tegmark[1]

Institute for Advanced Study, Princeton, NJ 08540

ARTICLE

Check for updates

https://doi.org/10.1038/s42005-021-00628-x OPEN

Why reducing the cosmic sound horizon alone can not fully resolve the Hubble tension

Karsten Jedamzik[1], Levon Pogosian[2] & Gong-Bo Zhao[3,4]

universe MDPI

Opinion

Seven Hints That Early-Time New Physics Alone Is Not Sufficient to Solve the Hubble Tension

Sunny Vagnozzi [1,2]

Is early-time new physics enough?

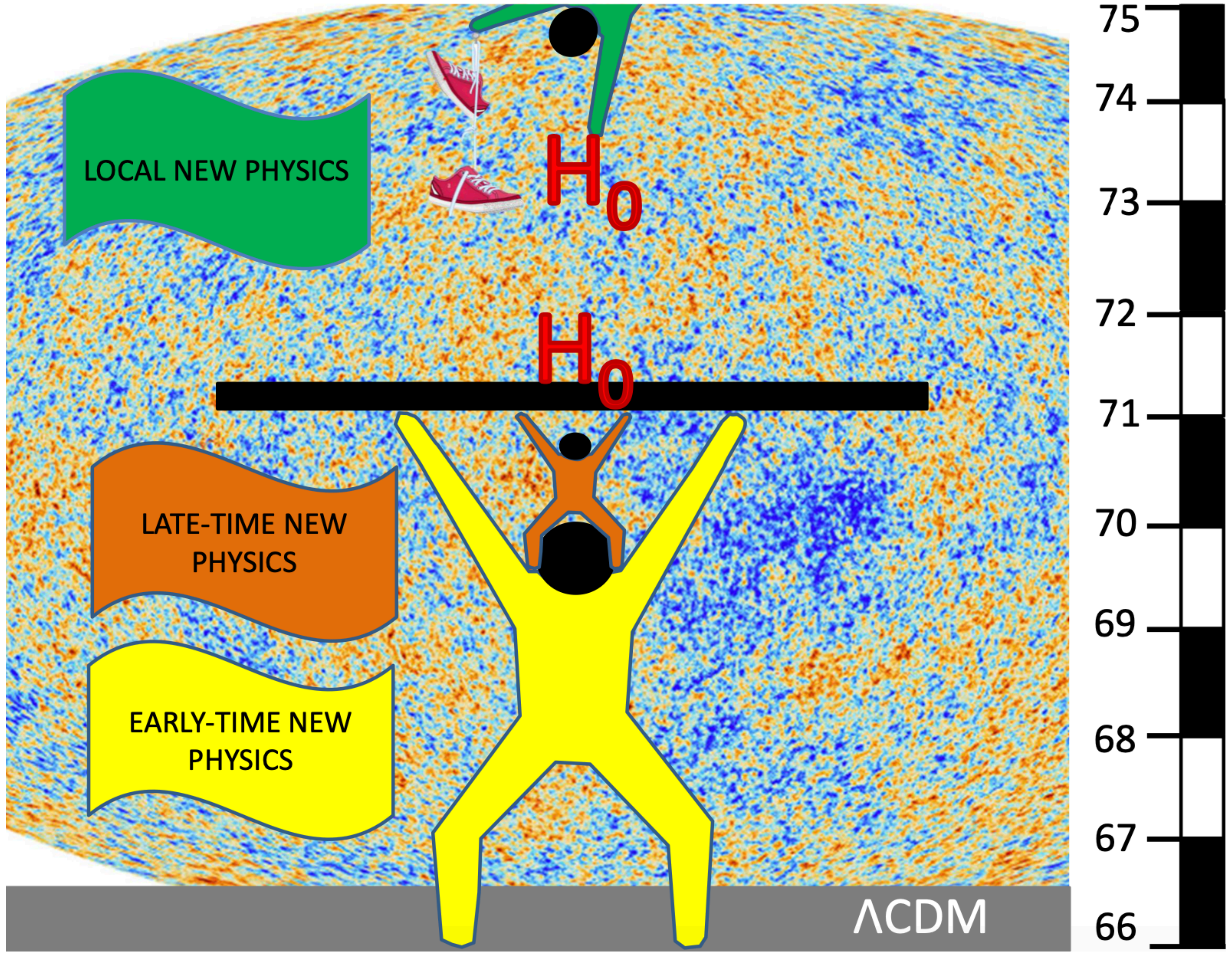


Figure from Vagnozzi 2309.13106

Bonus: please check my latest papers!

Searching for the axion in miniclusters-NS encounters: (out Friday) 2407.XXXXX

Production of light scalars in the Sun: 2406.01691

New PBH bounds from BBN: 2405.18493

Detecting high-frequency GWs prespects: 2403.18610

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Conclusions

- Cosmic tensions likely indicate a problem with the underlying cosmology
and our understanding of the Universe, rather than the presence of systematic effects.

- Many models have been proposed to solve the H_0 tension.
However, the solution might lie in multiple corrections to LCDM at different epochs

- Finding a solution challenging because of additional complications (Thanks E. Di Valentino):
1. The S8 tension;
2. The sound horizon problem;
3. The correlation between parameters;
4. The hidden model dependence of some of the datasets;
5. The Planck $A_{\rm lens}$ problem
6. The role of the optical depth
7. The inconsistency between the different CMB experiments