Cosmological Tensions Lecture 2
Measuring the Hubble constant – the Hubble tension

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How to measure H_0?

Always a good idea in cosmology:
measure distances to measure the expansion rate

Luminosity distance:

$$d_L(z) = (1+z)\frac{1}{H_0\sqrt{\Omega_K}}\sinh\left[H_0\sqrt{\Omega_K}\int_0^z \frac{dz'}{H(z')}\right]$$

Angular diameter distance:

$$d_A(z) = \frac{1}{1+z}\frac{1}{H_0\sqrt{\Omega_K}}\sinh\left[H_0\sqrt{\Omega_K}\int_0^z \frac{dz'}{H(z')}\right]$$

Standard candles and standard rulers

In practice "infer distances" = "measure fluxes or angles"

Fluxes:

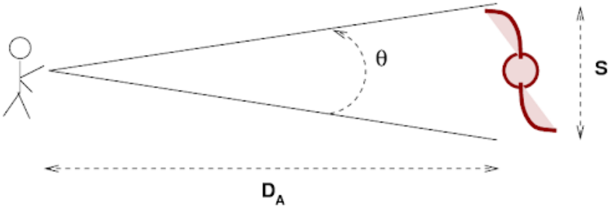
$$d_L = \sqrt{\frac{L}{4\pi F}}$$

L=intrinsic luminosity

Angles:

$$d_A = \frac{s}{\theta}$$

s=intrinsic physical size



Measuring H_0 via the local distance ladder

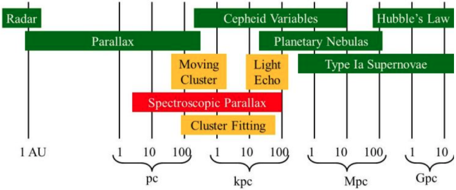
Only strictly empirical (cosmology model-independent) way to measure H_0

Idea: measure d-z relation, extract H_0 from intercept

Difficulty 1: need to extend distance ladder into the Hubble flow so measured z is predominantly cosmological (no $v_{\rm pec}$...but not too far else parameters such as Ω_m start to matter)

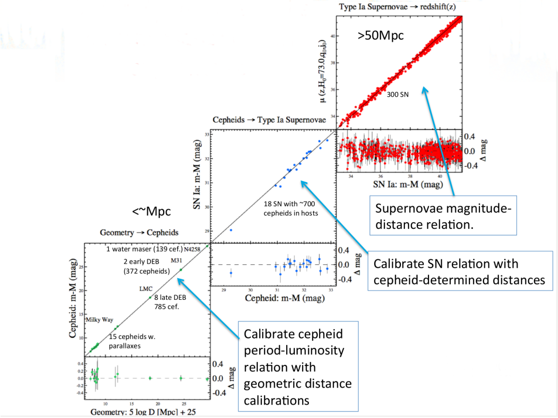
Difficulty 2: each distance indicator has limited range of applicability

Solution: combine different distance indicators in different rungs, as long as two consecutive indicators have a (even limited) range of overlap



Credits: Tabitha Dillinger

Best known 3-rung distance ladder: Cepheid-calibrated SNeIa



Credits: adapted from Adam Riess and Silvia Galli

Applying the ladder

Units of H_0 always implicitly km/s/Mpc from now

SH0ES analysis: 75 MW Cepheids with *Gaia* EDR3 parallaxes (plus other geometric distances), >90 Cepheids, 42 calibrator SNeIa in 37 SNeIa+Cepheid hosts, 277 SNeIa in $0.0233 < z < 0.15$
$\implies$ 1.4% measurement of H_0!

$$H_0 = 73.04 \pm 1.04$$

(Cepheid-calibrated SNeIa, R22)

Riess *et al.*, ApJ Lett. 934 (2022) L7

Notes:

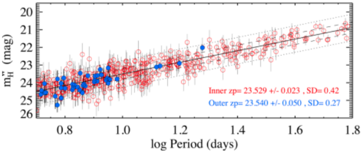
- need intermediate rung as SNeIa are rare events, not enough of them in the local Universe for direct parallax calibration
- Cepheids are standard candles through period-luminosity relation

Dissecting the local distance ladder

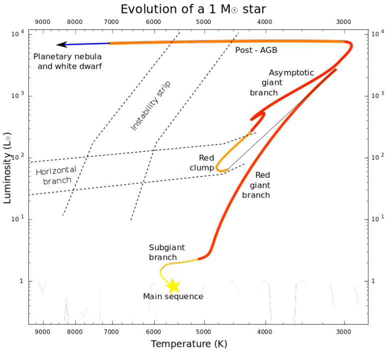
Calibrator (second rung)

Tip of the Red Giant Branch (TRGB)

Cepheids



Riess *et al.*, ApJ Lett. 934 (2022) L7



Different reanalyses fall between 72.8 and 74.3

CCHP analysis: $H_0 = 69.8 \pm 0.8 \pm 1.7$ Freedman *et al.*, ApJ 882 (2019) 34

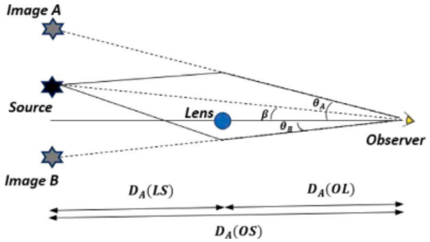
Later reanalyses fall between 69.6 and 76.9

Dissecting the local distance ladder

- *2^{nd} rung* – Cepheids vs TRGB: currently most credible contenders, but no complete consensus on TRGB See review by Freedman, ApJ 919 (2021) 16
- *2^{nd} rung* – Mira variables (Miras; highly-evolved low-mass AGB stars) as SNeIa calibrators: $H_0 = 73.3 \pm 4.0$ Huang *et al.*, ApJ 889 (2020) 5
- *2^{nd} rung* – Surface brightness fluctuations (SBFs) as SNeIa calibrators: $H_0 = 70.50 \pm 2.37 \pm 3.38$ Khetan *et al.*, A&A 647 (2021) A72
- *$2^{nd}/3^{rd}$ rung* – Cepheid- and TRGB-calibrated SBFs: $H_0 = 73.3 \pm 0.7 \pm 2.4$ Blakeslee *et al.*, ApJ 911 (2021) 65
- *$2^{nd}/3^{rd}$ rung* – Cepheid- and TRGB-calibrated SNeII: $H_0 = 75.4 \pm 3.7$ de Jaeger *et al.*, MNRAS 514 (2022) 4620
- *$2^{nd}/3^{rd}$ rung* – Cepheid- and TRGB-calibrated baryonic Tully-Fisher relation: $H_0 = 75.1 \pm 2.5 \pm 1.5$ Schombert *et al.*, AJ 160 (2020) 71
- *Only 2 rungs* – *d*-*z* relation for $z \lesssim 0.01$ Cepheids: $H_0 = 73.1 \pm 2.4$ Kenworthy *et al.*, ApJ 935 (2022) 83
- *No rungs* – Water megamasers (stimulated emission from water rotational transition levels): $H_0 = 73.9 \pm 3.0$ Pesce *et al.*, ApJ Lett. 891 (2020) L1
- *Other possibilities* – GW standard sirens (with or without EM counterpart), γ-ray attenuation, HII galaxies, BH shadows,...

Strong lensing time-delay cosmography

Completely independent of the local distance ladder (but not completely cosmology model-independent, depends on Ω_m, w, Ω_K, etc.)



Perivolaropoulos & Skara, New Astron. Rev. 95 (2022) 101659

$$\Delta t = D_{\Delta t}\Delta\phi_L \propto \frac{1+z_L}{c}\frac{d_A(OL)d_A(OS)}{d_A(LS)} \propto \frac{1}{H_0}$$

Main difficulty: mass-sheet degeneracy!

Strong lensing time-delay cosmography

$$H_0 = 73.3 \pm 1.8 \textit{ (TDCOSMO, seven quasar time-delay lenses)}$$

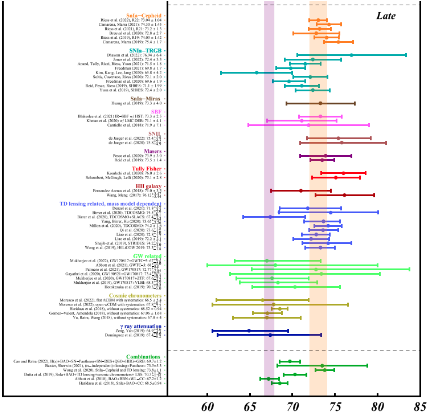
Birrer *et al.*, A&A 643 (2020) A165

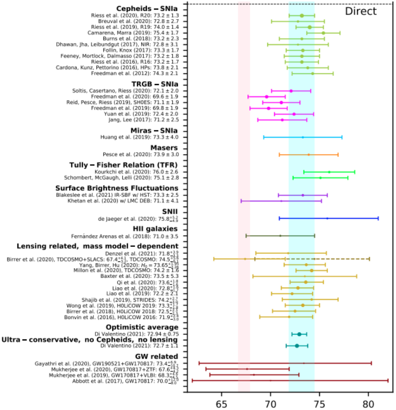
Attempting to break the mass-sheet degeneracy:

$$H_0 = 67.4 \pm 3.7 \textit{ (TDCOSMO+SLACS)}$$

Birrer *et al.*, A&A 643 (2020) A165

Local measurements summary

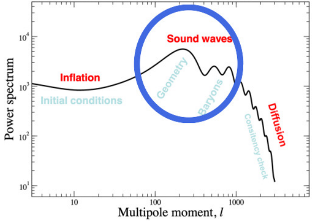


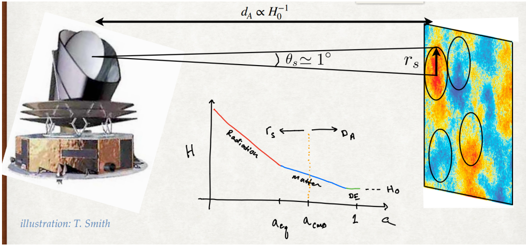


Adapted from Perivolaropoulos & Skara, New Astron. Rev. 95 (2022) 101659

Adapted from Di Valentino *et al.*, Class. Quant. Grav. 38 (2021) 153001

The CMB as a (self-calibrated) standard ruler

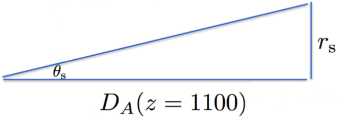




Credits: Planck collaboration and Silvia Galli (left); Tristan Smith and Vivian Poulin (right)

$$\theta_s = \frac{r_s}{d_A(z_\star)} = 0.010411 \pm \underline{\underline{0.000003}} \quad (!!!)$$

Note: θ_s measured exquisitely, but r_s and d_A are model-dependent!



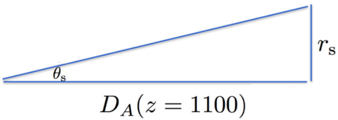
Credits: Silvia Galli

Steps to apply the CMB ruler

Within ΛCDM:

$$\theta_s = \frac{r_s}{d_A(z_\star)}\,, \qquad r_s \simeq \int_{z_\star}^{\infty} dz\, \frac{c_s(z,\omega_b,\omega_r)}{\sqrt{(\omega_c+\omega_b)(1+z)^3+\omega_r(1+z)^4}}$$

- ω_r: exquisitely measured from $T_{\rm CMB}$ (e.g. COBE)
- $c_s(z) = (1+3\rho_b/4\rho_\gamma)^{-1}$
- ω_b: infer from relative height of odd and even peaks, further improvement from damping tail
- ω_c: infer from early ISW effect (first peak height), potential envelope, further improvement from lensing-induced peak smoothing



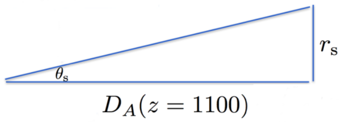
Credits: Silvia Galli

Steps to apply the CMB ruler

Within ΛCDM:

$$\theta_s = \frac{r_s}{d_A(z_\star)}\,, \qquad d_A(z_\star) \simeq 3 \int_0^{z_\star} dz \, \frac{1}{\sqrt{\omega_\Lambda + \omega_m (1+z)^3 + \omega_r(z)}} \, \text{Gpc}$$

- $\omega_r(z)$: already known as before
- $\omega_m = \omega_c + \omega_b$: both terms already known as before
- θ_s: inferred from peak spacing, $\theta_s \simeq \pi/\Delta\ell = \pi/(\ell_{p+1} - \ell_p)$
- ω_Λ: only remaining free parameter, to fix from $d_A(z_\star) = r_s \Delta\ell/\pi$
- Once ω_Λ is known, the whole evolution of $H(z)$ is known, including $H(z=0) = H_0$!

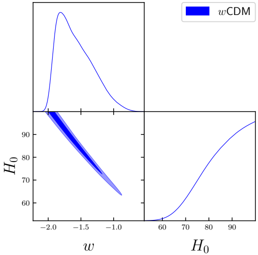


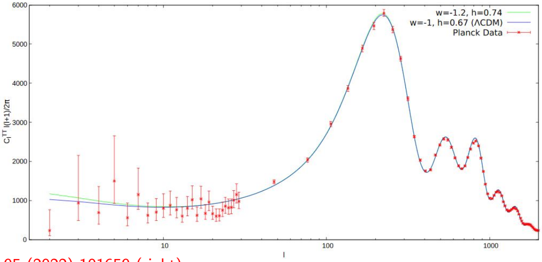
Credits: Silvia Galli

Applying the CMB ruler: some important observations

- In ΛCDM, with all other *physical* densities fixed by early-Universe considerations, H_0 controls only the physical amount of dark energy
- In ΛCDM there is enough information/sufficiently few free parameters to constrain H_0 from the CMB...
- but this is *not* (necessarily) true in extensions of ΛCDM, especially late-time extensions (geometrical degeneracy)

Example: $w \neq -1$, H_0 unconstrained from CMB alone (just lower limit)





Perivolaropoulos & Skara, New Astron. Rev. 95 (2022) 101659 (right)

Applying the ruler

$$H_0 = 67.27 \pm 0.60$$
$$(Planck\ 2018\ TTTEEE{+}lowE)$$

Planck collaboration, A&A 641 (2020) A6

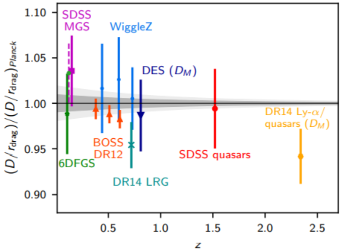
$$H_0 = 67.9 \pm 1.5$$
$$(ACT\ DR4)$$

ACT collaboration, JCAP 2012 (2020) 047

Late-time guard rails

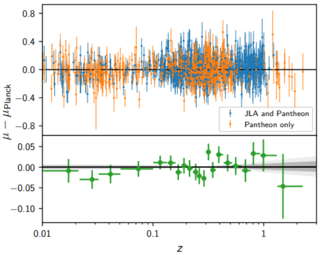
It is important to "stabilize" CMB-only constraints with late-time datasets, *especially when going beyond ΛCDM at late times*!

BAO



Planck collaboration, A&A 641 (2020) A6

Cosmological/high-z SNeIa



Planck collaboration, A&A 641 (2020) A6

These are in *very good* agreement with the expansion history inferred from *Planck* within ΛCDM (so in ΛCDM mostly a consistency check)!

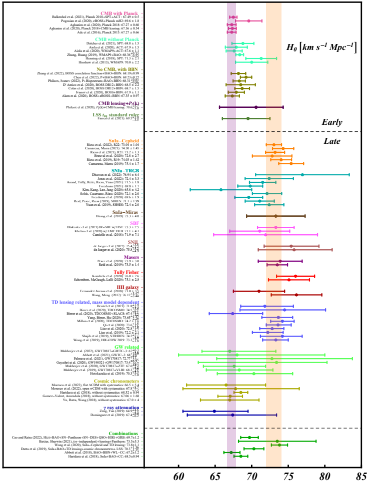
Combining CMB and late-time guard rails

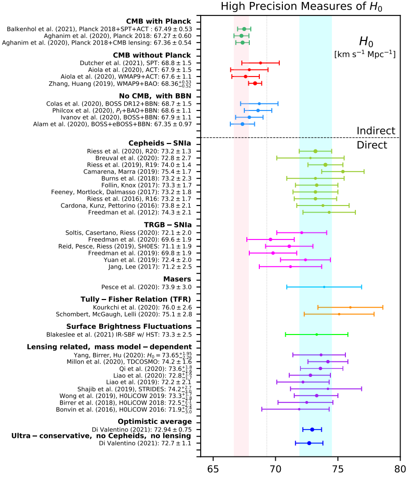
Combination consistent with CMB-only value of H_0 within ΛCDM, important sanity check!

$$H_0 = 67.72 \pm 0.40 \; (CMB{+}BAO{+}uncalibrated\ SNeIa)$$

Planck collaboration, A&A 641 (2020) A6

Hubble tension summary





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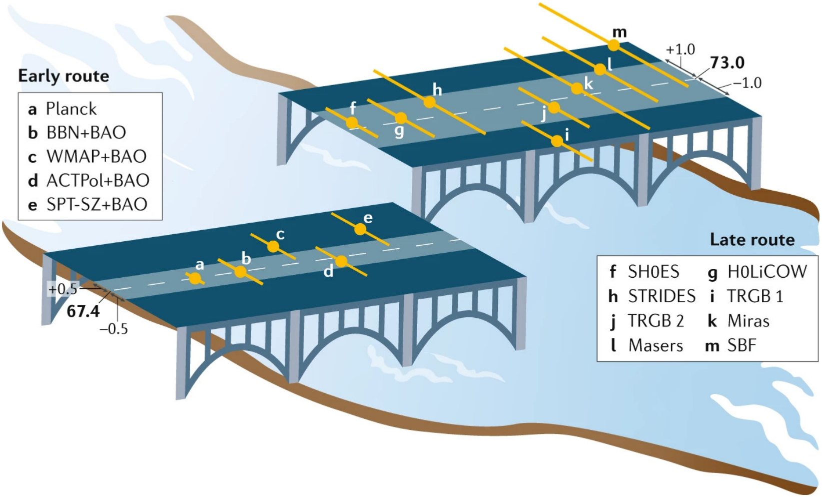
Adapted from Di Valentino *et al.*, Class. Quant. Grav. 38 (2021) 153001

Hubble tension summary



Credits: Riess, Nat. Rev. Phys. 2 (2020) 10

Systematics?

Cepheid-calibrated distance ladder:

- systematics in 1st rung distances
- extinction
- metallicity
- crowding/blending
- environmental dependence of Cepheid/SNeIa properties
- unknown unknowns...

CMB:

- beam systematics
- foregrounds
- instrumental systematics (e.g. half-wave plate systematics)
- atmosphere
- bandpass variability
- unknown unknowns...

If systematics are the answer, why do they conspire to make early-vs-late discrepancy consistent *across so many independent measurements*?

Inverse distance ladder

BAO measure $r_s/d \propto r_s H_0 \implies$ BAO can be calibrated with H_0 or r_s!

Classical distance ladder

- Determine H_0 from N-rung distance ladder
- Calibrate SNeIa d_L with H_0
- From BAO d_A in the same z range infer r_s

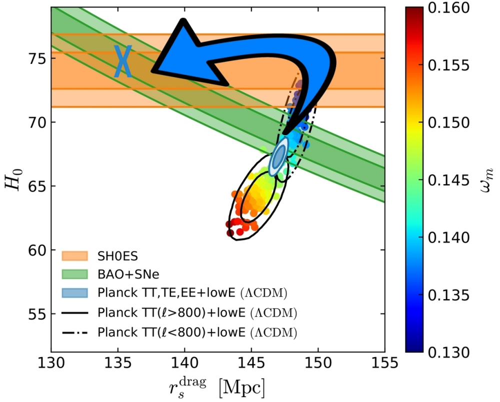
Inverse distance ladder

- Calibrate BAO with r_s prior (model-dependent)
- Transfer BAO calibration to SNeIa d_L in the same z range
- Extrapolate to $z = 0$ to infer H_0

If model-dependent r_s prior (CMB-dependent or not, more later) is correct, H_0 from inverse distance ladder and classical distance ladder should agree!

What does the tension mean?

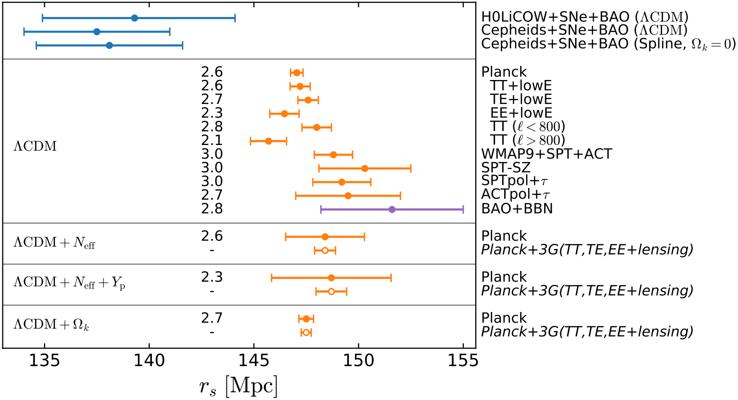
Useful to look at r_s-H_0 plane



Knox & Millea, PRD 101 (2020) 043533

BAO data tell us that r_s has to decrease by $\simeq 7\%$! $r_s h \sim 100\,\mathrm{Mpc} \implies$ good fit with $r_s \sim 147$ and $H_0 \sim 67$ (ΛCDM) or $r_s \sim 136$ and $H_0 \sim 73$

H_0 tension or r_s tension?

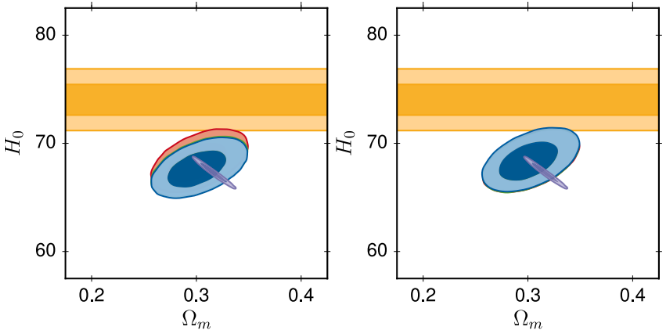


Aylor *et al.*, ApJ 874 (2019) 4

r_s inferred from distance ladder systematically lower than ΛCDM-based inferences for any dataset combination!

CMB- and SNeIa-free determinations of H_0

Can determine H_0 completely free of CMB data: BBN prior on ω_b used to calibrate r_s assuming pre-recombination $H(z)$, then infer H_0 from BAO

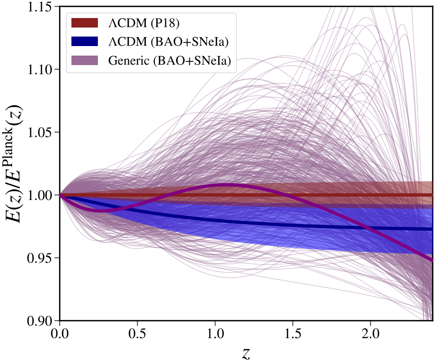


Schöneberg, Lesgourgues & Hooper, JCAP 1910 (2019) 029

Larger error bars, but tension (assuming ΛCDM at early times) remains regardless of BBN model, determinations of Y_P and Y_{DP}, and BAO data

Reconstructing the late-time expansion history

BAO (sparse in redshift) and uncalibrated SNeIa (dense in redshift) highly complementary



Bernal *et al.*, PRD 103 (2021) 103533

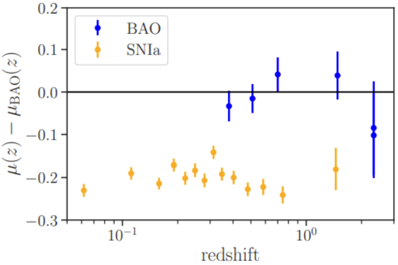
BAO+uncalibrated SNeIa very strongly constrain $H(z)$ or $E(z)$, do not allow more than 10% deviations from ΛCDM at $z \lesssim 2$

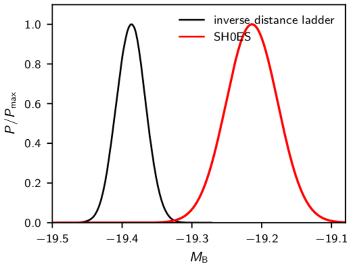
Tension between calibrators

The tension is between calibrators!

BAO: $\theta_s(z) = \frac{r_s}{d_A(z)}$

SNeIa: $\mu(z) = 5 \log_{10} d_L(z) + M_B$



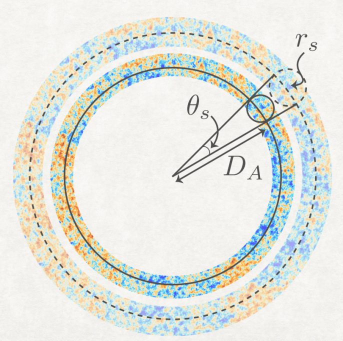


Tutusaus, Kunz & Favre, 2311.16862 (left); Efstathiou, MNRAS 505 (2021) 3866 (right)

Without change in calibration, BAO d_A and SNeIa d_L *in an overlapping redshift range* are incompatible!

Is the CMB closer to us?

With θ_s fixed, lower r_s implies lower d_A



Credits: Tristan Smith and Vivian Poulin

- Is the CMB closer to us?
- Are the spots in the CMB smaller than what we expect within ΛCDM?

What is the Hubble tension, really?

3 different interpretations in order of increasing "correctness"

The Hubble tension is the mismatch between:

1. CMB vs SH0ES
   $\rightarrow$ *"Too wrong", ignores stabilizing role of late-time datasets (BAO, uncalibrated SNeIa,...)*

2. Inverse distance ladder (CMB+BAO+uncalibrated SNeIa) vs SH0ES
   $\rightarrow$ *Still wrong, ignores many other local/late-time measurements besides SH0ES (TRGB, strong lensing time delays,...)*
   (at this level the Hubble tension is best thought of as a M_B tension)

3. Inverse distance ladder vs **several** low-z H_0 measurements
   $\rightarrow$ **most correct interpretation of the Hubble tension**!

Next lecture

7 December, 11:30-12:20

How to solve the Hubble tension?

Early dark energy, varying electron mass, primordial magnetic fields, phantom dark energy, M_B transitions, and all that!