The trouble with Hubble

Sunny Vagnozzi

Newton-Kavli Fellow @ University of Cambridge

sunny.vagnozzi@ast.cam.ac.uk www.sunnyvagnozzi.com

sunnyvagnozzi @SunnyVagnozzi

VIA Lecture, Virtual Institute of Astroparticle Physics
17 July 2020

Main take-home messages

- H_0 tension is **not** just a matter of CMB vs Riess *et al.* value...
- ...but of inverse distance ladder vs *several* low-z H_0 measurements
- Solution could be early Universe new physics lowering sound horizon...
- ...but other solutions (including late-time ones) are not excluded yet!
- H_0 tension is **very hard** to solve, we do not yet have a solution

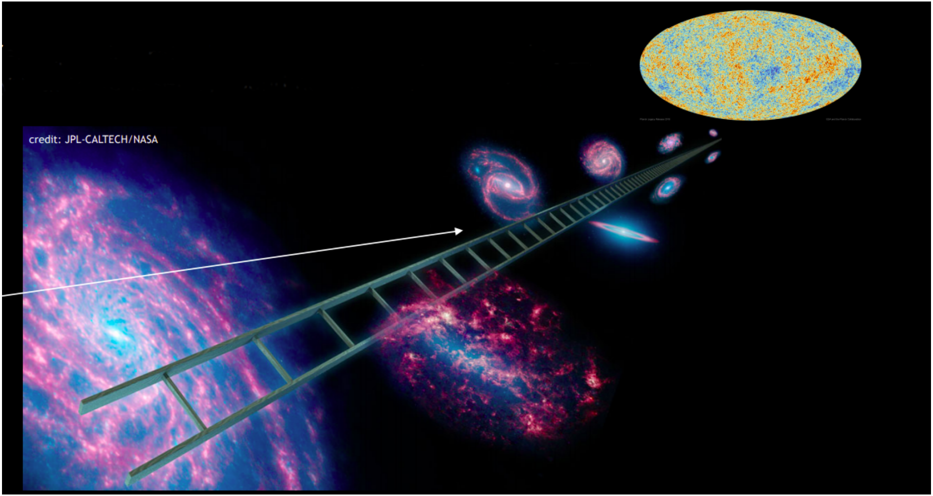
The Hubble constant

H_0: current rate of expansion of the Universe

Why care about H_0?

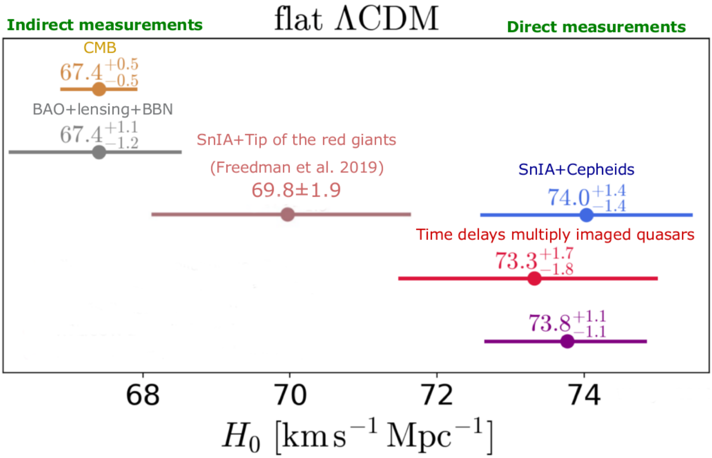
- Allan Sandage, 1970: "*Cosmology can be described as the search for two numbers: the current rate of expansion [H_0] and the deceleration of the expansion [q_0]*"
- Adam Riess, 2019: "*H_0 is the ultimate end-to-end test for ΛCDM*"

H_0 as an end-to-end test



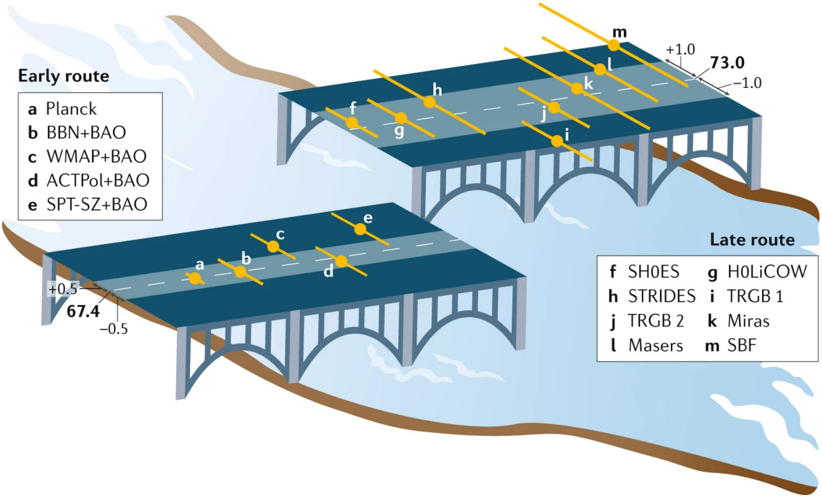
Credits: JPL-Caltech/NASA and Dillon Brout

The trouble



Adapted from Wong et al., arXiv:1907.04869 (to appear in MNRAS), and Silvia Galli

The trouble



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

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 (more of interest to us):

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

Standard candles and standard rulers

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

Fluxes:

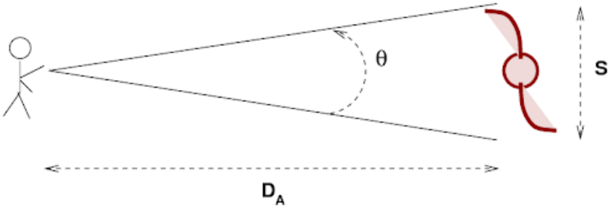
$$d_L = \sqrt{\frac{L}{4\pi f}}$$

L=intrinsic luminosity

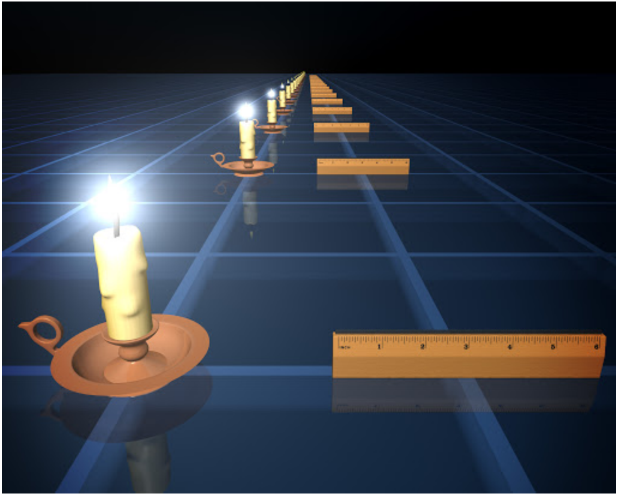
Angles (more of interest to us):

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

s=intrinsic physical size

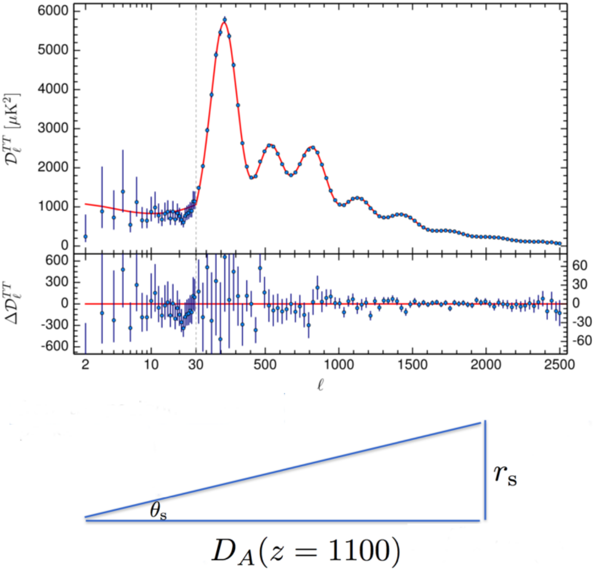


Standard candles and standard rulers



Credits: NASA/JPL-Caltech/R. Hurt (SSC)

The CMB as a (self-calibrated) standard ruler

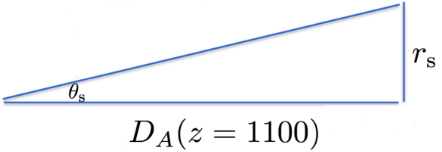


Credits: Planck collaboration and Silvia Galli

The CMB as a (self-calibrated) standard ruler

Steps: See e.g. Knox & Millea's *Hubble Hunter's Guide*, PRD 101 (2020) 043533

- Infer ω_b from even/odd peak height modulation
- Infer ω_m from "potential envelope" effect (early ISW effect)
- Calculate $r_s^\star \sim \int_{z_\star}^{\infty} dz\, c_s(z, \omega_b)/\sqrt{\omega_m(1+z)^3 + \omega_r(1+z)^4}$
- Measure $\theta_s \sim \pi/\Delta\ell$ from peak spacing
- With $r_s^\star$ and θ_s known, infer $D_A^\star = r_s^\star/\theta_s$
- Adjust ω_Λ to match inferred $D_A^\star \sim \int_0^{z_\star} dz/\sqrt{\omega_m(1+z)^3 + \omega_\Lambda}$
- Now $H(z)$ is completely specified, so infer H_0!



Credits: Silvia Galli

Applying the ruler

Units of H_0 always implicitly $\mathrm{km\,s^{-1}\,Mpc^{-1}}$ from now

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

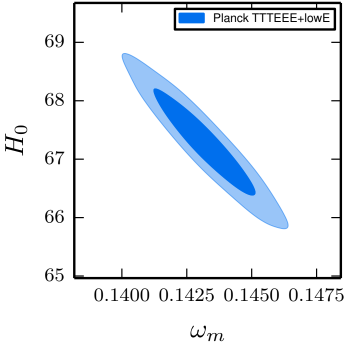
Last-minute news: just confirmed by ACT! ACT collaboration, arXiv:2007.07288

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

The geometrical degeneracy

The real world is not so simple:

$$\ell_{\rm peak} \propto \omega_m^{-0.15} h^{-0.2} \implies \omega_m h^{1.3} \approx \text{const}$$

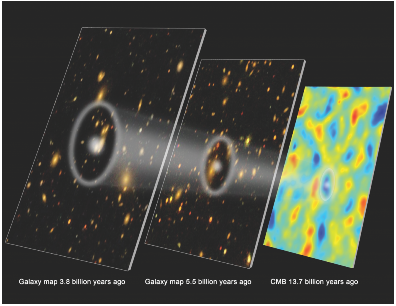


Need some other probe to break this degeneracy to get a more reliable measurement of H_0 (especially in models beyond ΛCDM!)

The role of BAO

Try to measure the same sound horizon feature at different redshifts:

$$\theta_{\rm BAO} \sim \frac{r_s^\star}{D_A(z_{\rm BAO})} \propto \frac{\int_{z_\star}^{\infty} dz\, c_s(z,\omega_b)/\sqrt{\omega_m(1+z)^3+\omega_r(1+z)^4}}{\int_0^{z_{\rm BAO}} dz/\sqrt{\omega_m(1+z)^3+\omega_\Lambda}}$$



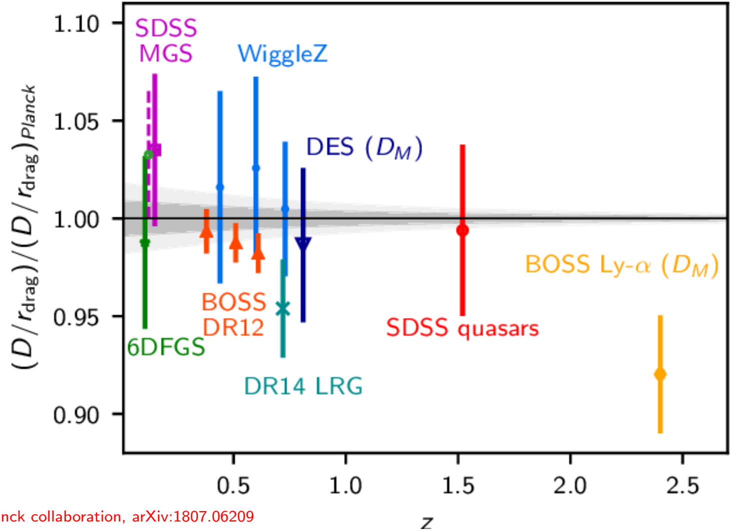
Credits: Eric Huff and the BOSS/SPT collaborations

Note: not really $r_s^\star$ but $r_s^{\rm drag}$, difference irrelevant for the discussion

The role of BAO

- BAO measures a combination of Ω_m and $H_0 r_s$
- Measuring BAO at different redshifts and in parallel/perpendicular directions helps break ω_m-H_0 geometrical degeneracy
- BAO need to be **calibrated** either with prior on r_s (e.g. from CMB)...
- ...or equivalently on ω_b (e.g. from CMB or BBN)...
- ...or with a prior on H_0 (then you infer r_s)
- With r_s calibration can measure H_0, still in the high 60s, *e.g.*:
  - (Gal+Lyα) BAO+BBN: $H_0 = 67.0 \pm 1.2$ Addison *et al.*, ApJ 853 (2018) 119
  - Gal BAO+DES+BBN: $H_0 = 67.4 \pm 1.1$ DES collaboration, MNRAS 480 (2018) 3879
  - Gal BAO+BBN+SNe+θ_s prior: $H_0 = 67.9 \pm 0.8$ Planck collaboration, arXiv:1807.06209
  - (Gal+Lyα) BAO+BBN+voids: $H_0 = 69.0 \pm 1.2$ Nadathur *et al.*, PRL 124 (2020) 221301

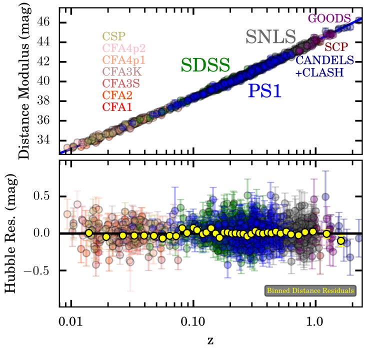
Good agreement between BAO and Planck



Credits: Planck collaboration, arXiv:1807.06209

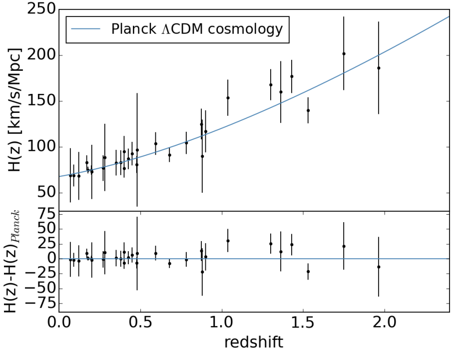
Other late-time guard rails

Uncalibrated high-z SNeIa: constrain slope of $H(z)$



Credits: Scolnic *et al.*, ApJ 859 (2018) 101

Cosmic chronometers: constrain absolute scale of $H(z)$

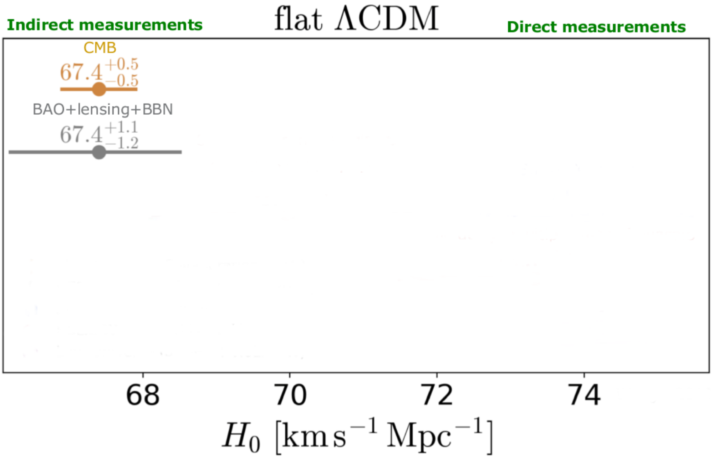


Credits: Moresco *et al.*, JCAP 1612 (2016) 039

Combining CMB and late-time guard rails

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

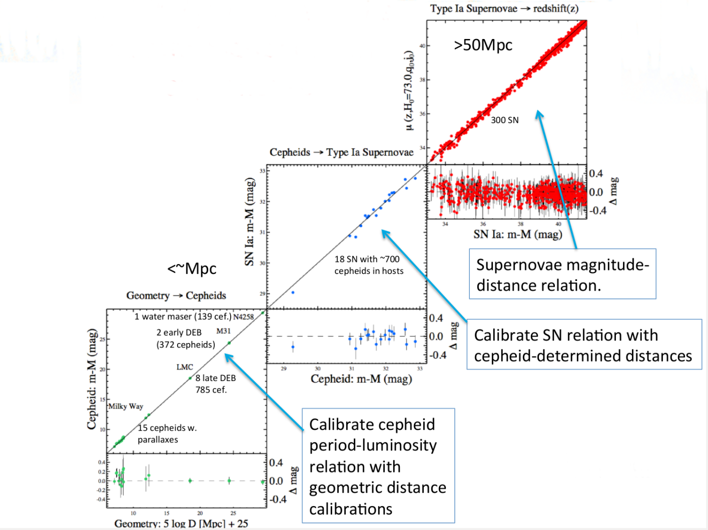
The trouble



Adapted from Wong et al., arXiv:1907.04869 (to appear in MNRAS), and Silvia Galli

Calibrating the local distance ladder with Cepheids

3-rung distance ladder Adapted from Adam Riess and Silvia Galli



Calibrating the local distance ladder with Cepheids

SH0ES team: 5 distance anchors, 19 calibrator SNeIa, ~ 300 SNeIa at $z < 0.15 \rightarrow 1.9\%$ measurement of H_0! Riess *et al.*, ApJ 876 (2019) 85

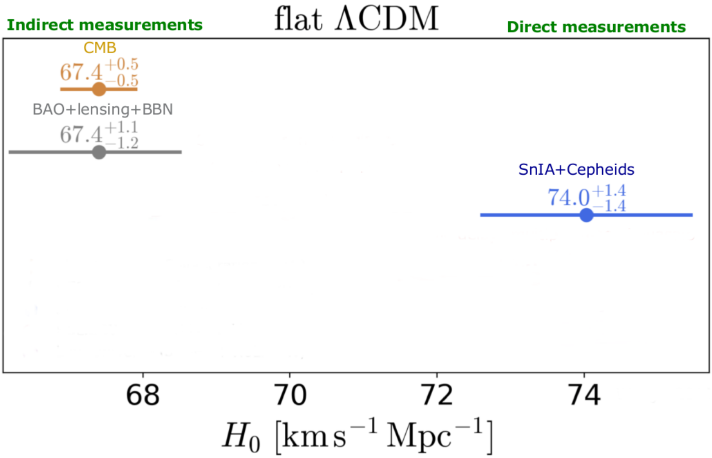
$$H_0 = 74.03 \pm 1.42$$
$$(\textit{Cepheid-calibrated SNeIa})$$

compare against

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

Almost 5σ tension!

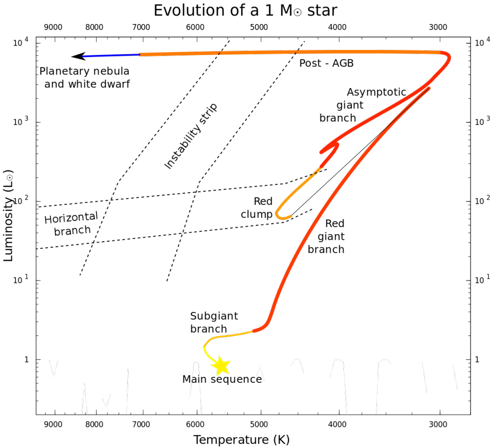
The trouble



Adapted from Wong et al., arXiv:1907.04869 (to appear in MNRAS), and Silvia Galli

Calibrating the local distance ladder with the TRGB

Replace second rung of distance ladder using Tip of the Red Giant Branch (TRGB) as distance indicator instead of Cepheids



Calibrating the local distance ladder with the TRGB

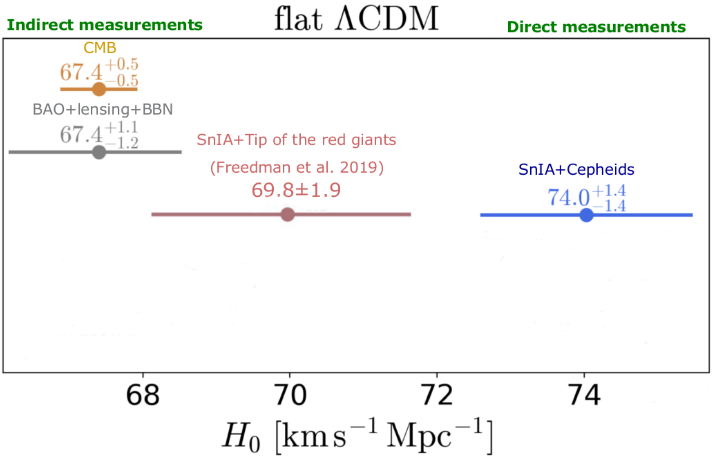
Replace second rung of distance ladder using Tip of the Red Giant Branch (TRGB) as distance indicator instead of Cepheids Freedman *et al.*, ApJ 882 (2019) 34

$$H_0 = 69.8 \pm 1.9$$

(TRGB-calibrated SNeIa)

Criticisms on overestimated extinction raised in Yuan *et al.*, ApJ 886 (2019) 61; addressed in Freedman *et al.*, ApJ 891 (2020) 57

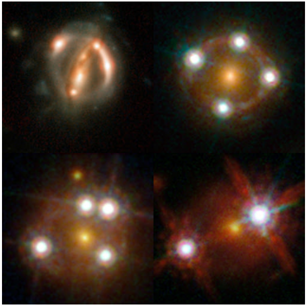
The trouble



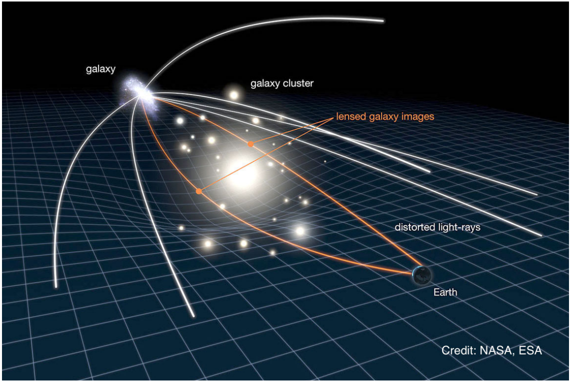
Adapted from Wong et al., arXiv:1907.04869 (to appear in MNRAS), and Silvia Galli

Strong lensing time delays

Arrival time of each of the multiple images of quasars depends on different distances travelled, and hence H_0



Credits: NASA and ESA



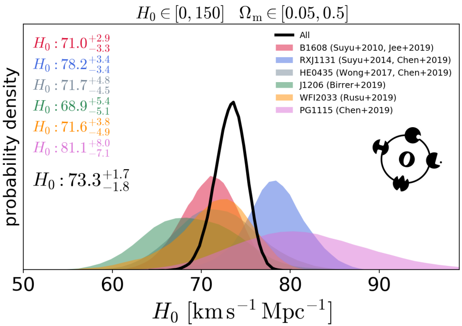
Credits: NASA and ESA

Strong lensing time delays

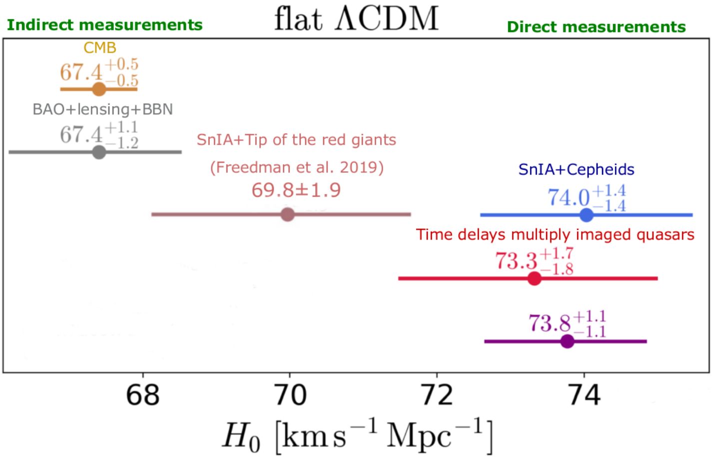
H0LICOW collaboration: Wong et al., arXiv:1907.04869 (to appear in MNRAS)

$$H_0 = 73.3^{+1.7}_{-1.8}$$

(H0LiCOW, 6 lensed quasars)



The trouble

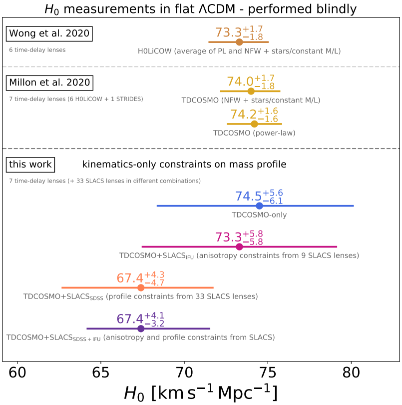


Adapted from Wong et al., arXiv:1907.04869 (to appear in MNRAS), and Silvia Galli

Issues with H0LiCOW?

Unknown lens density profile (mass-sheet degeneracy)? Blum *et al.*, ApJ 892 (2020) L27

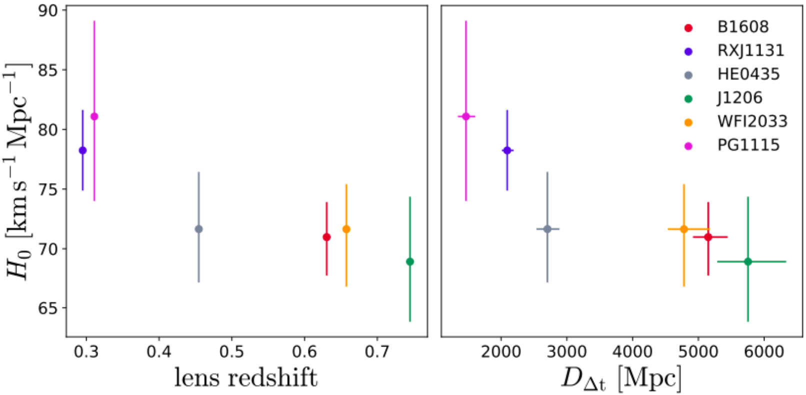
Joint H0LiCOW-SLACS analysis with a Bayesian hierarchical model:



Credits: Birrer et al., arXiv:2007.02941

A curious trend

New physics or systematics? What could this mean?



Wong et al., arXiv:1907.04869 (to appear in MNRAS)

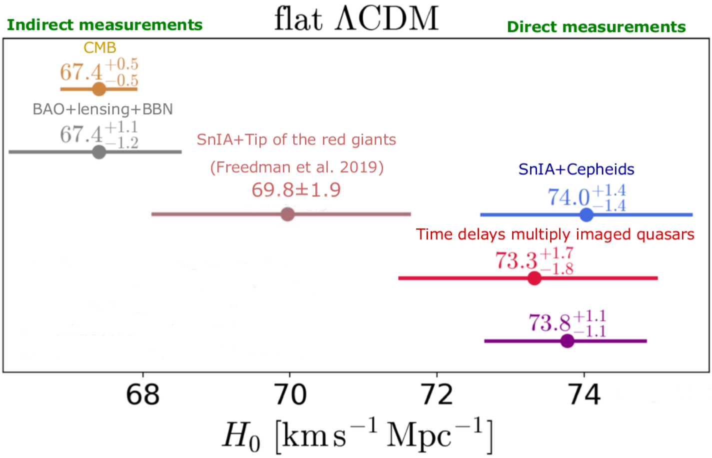
Other late-time measurements

List most certainly not exhaustive (but all in the low 70s):

- Mira variables as SNeIa calibrators: $H_0 \sim 73 \pm 4$ Huang *et al.*, ApJ 857 (2018) 67
- Surface brightness fluctuations: $H_0 \sim 77 \pm 4$ Jensen *et al.*, ApJ 550 (2001) 503
- Water megamasers (single rung): $H_0 \sim 73 \pm 4$ Pesce *et al.*, ApJ 891 (2020) L1
- Revisiting Cepheid-calibrated SNeIa: many examples with H_0 anywhere between 70 and 74 e.g. Efstathiou, MNRAS 440 (2014) 1138; Cardona *et al.*, JCAP 1703 (2017) 056; Zhang *et al.*, MNRAS 471 (2017) 2254; Feeney *et al.*, MNRAS 476 (2017) 3861; Dhawan *et al.*, A&A 609 (2018) A72; Follin & Knox, MNRAS 477 (2017) 4534; and many others
- AGN variability: $H_0 \sim 73 \pm 6$ Hodgson *et al.*, MNRAS 495 (2020) L27
- Black hole shadows: $H_0 \sim 70 \pm 9$ Qi & Zhang, Chin. Phys. C 44 (2020) 055101
- ...and many other examples!

The trouble

What can solve this?



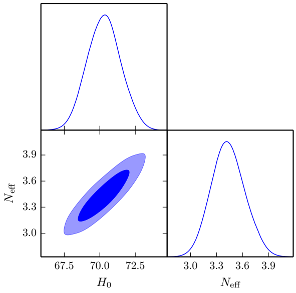
Adapted from Wong et al., arXiv:1907.04869 (to appear in MNRAS), and Silvia Galli

A naïve approach: look at CMB data only

New physics such that higher H_0 required to keep $\theta_s = r_s^\star / D_A^\star$ fixed

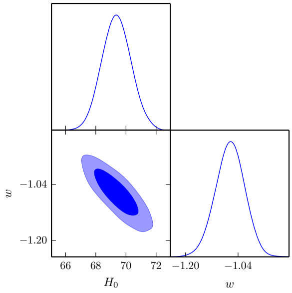
Early-Universe new physics

Prototype: extra relativistic degrees of freedom ($N_{\rm eff} > 3.046$) raise pre-recombination expansion rate



Late-Universe new physics

Prototype: phantom dark energy ($w < -1$) raises post-recombination expansion rate



A naïve approach: look at CMB data only

Most extensions just reduce the tension by enlarging error bars. No simple extension of ΛCDM where H_0 is high from CMB data alone (in most cases H_0 actually becomes lower)!

Table 5. Constraints on standard cosmological parameters from *Planck* TT,TE,EE+lowE+lensing when the base-ΛCDM model is extended by varying additional parameters. The constraint on τ is also stable but not shown for brevity; however, we include H_0 (in km $s^{-1}Mpc^{-1}$) as a derived parameter (which is very poorly constrained from *Planck* alone in the ΛCDM+w_0 extension). Here α_{-1} is a matter isocurvature amplitude parameter, following PCP15. All limits are 68 % in this table. The results assume standard BBN except when varying Y_P independently (which requires non-standard BBN). Varying A_L is not a physical model (see Sect. 6.2).

Parameter(s)	$\Omega_b h^2$	$\Omega_c h^2$	$100\theta_{MC}$	H_0	n_s	$\ln(10^{10}A_s)$
Base ΛCDM	0.02237 ± 0.00015	0.1200 ± 0.0012	1.04092 ± 0.00031	67.36 ± 0.54	0.9649 ± 0.0042	3.044 ± 0.014
r	0.02237 ± 0.00014	0.1199 ± 0.0012	1.04092 ± 0.00031	67.40 ± 0.54	0.9659 ± 0.0041	3.044 ± 0.014
$dn_s/d\ln k$	0.02240 ± 0.00015	0.1200 ± 0.0012	1.04092 ± 0.00031	67.36 ± 0.53	0.9641 ± 0.0044	3.047 ± 0.015
$dn_s/d\ln k, r$	0.02243 ± 0.00015	0.1199 ± 0.0012	1.04093 ± 0.00030	67.44 ± 0.54	0.9647 ± 0.0044	3.049 ± 0.015
$d^2n_s/d\ln k^2, dn_s/d\ln k$.	0.02237 ± 0.00016	0.1202 ± 0.0012	1.04090 ± 0.00030	67.28 ± 0.56	0.9625 ± 0.0048	3.049 ± 0.015
N_{eff}	0.02224 ± 0.00022	0.1179 ± 0.0028	1.04116 ± 0.00043	66.3 ± 1.4	0.9589 ± 0.0084	3.036 ± 0.017
$N_{eff}, dn_s/d\ln k$	0.02216 ± 0.00022	0.1157 ± 0.0032	1.04144 ± 0.00048	65.2 ± 1.6	0.950 ± 0.011	3.034 ± 0.017
Σm_ν	0.02236 ± 0.00015	0.1201 ± 0.0013	1.04088 ± 0.00032	$67.1^{+1.2}_{-0.67}$	0.9647 ± 0.0043	3.046 ± 0.015
$\Sigma m_\nu, N_{eff}$	0.02221 ± 0.00022	$0.1179^{+0.0027}_{-0.0030}$	1.04116 ± 0.00044	$65.9^{+1.8}_{-1.6}$	0.9582 ± 0.0086	3.037 ± 0.017
$m^{eff}_{\nu,\,sterile}, N_{eff}$	$0.02242^{+0.00014}_{-0.00016}$	$0.1200^{+0.0032}_{-0.0020}$	$1.04074^{+0.00033}_{-0.00029}$	$67.11^{+0.63}_{-0.79}$	$0.9652^{+0.0045}_{-0.0056}$	$3.050^{+0.014}_{-0.016}$
α_{-1}	0.02238 ± 0.00015	0.1201 ± 0.0015	1.04087 ± 0.00043	67.30 ± 0.67	0.9645 ± 0.0061	3.045 ± 0.014
w_0	0.02243 ± 0.00015	0.1193 ± 0.0012	1.04099 ± 0.00031	. . .	0.9666 ± 0.0041	3.038 ± 0.014
Ω_K	0.02249 ± 0.00016	0.1185 ± 0.0015	1.04107 ± 0.00032	$63.6^{+2.1}_{-2.3}$	0.9688 ± 0.0047	$3.030^{+0.017}_{-0.015}$
Y_P	0.02230 ± 0.00020	0.1201 ± 0.0012	1.04067 ± 0.00055	67.19 ± 0.63	0.9621 ± 0.0070	3.042 ± 0.016
Y_P, N_{eff}	0.02224 ± 0.00022	$0.1171^{+0.0042}_{-0.0049}$	1.0415 ± 0.0012	$66.0^{+1.7}_{-1.9}$	0.9589 ± 0.0085	3.036 ± 0.018
A_L	0.02251 ± 0.00017	0.1182 ± 0.0015	1.04110 ± 0.00032	68.16 ± 0.70	0.9696 ± 0.0048	$3.029^{+0.018}_{-0.016}$

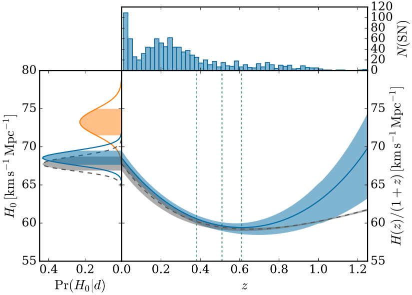
Credits: Planck collaboration, arXiv:1807.06209

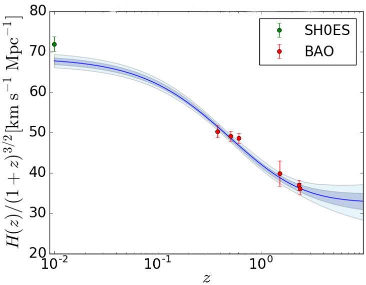
Inverse distance ladder: CMB-independent inferences of H_0

Construct an *inverse distance ladder* from BAO+uncalibrated high-z SNeIa

earlier examples in e.g. Aubourg *et al.*, PRD 92 (2015) 123516; Bernal *et al.*, JCAP 1610 (2016) 019

BAO constrain $H_0 r_s$: anchor $r_s \rightarrow$ infer H_0; anchor $H_0 \rightarrow$ infer r_s



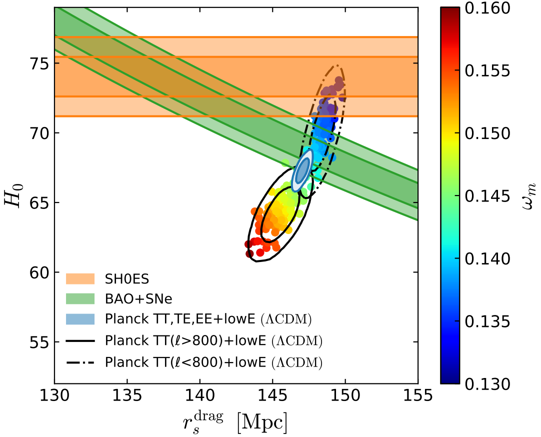


Credits: Feeney *et al.*, PRL 122 (2019) 061105

Credits: Lemos *et al.*, MNRAS 483 (2019) 4803

The H_0 tension as a sound horizon tension

Instructive to look at the r_s-H_0 plane (remember BAO constrain $H_0 r_s$)

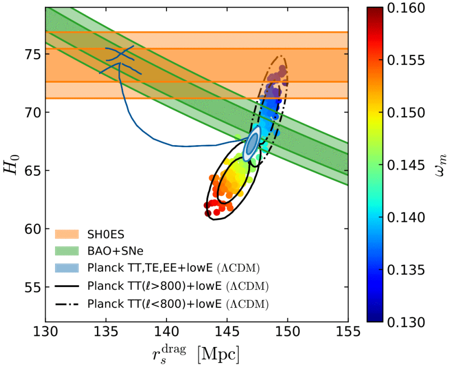


Credits: Knox & Millea's "*Hubble Hunter's Guide*", PRD 101 (2020) 043533

Focusing on H_0 rather than r_s seems to obscure the real story?

The H_0 tension as a sound horizon tension

Solving the H_0/r_s tension would seem to require lowering r_s by $\approx 7\%$ from 147 Mpc to $\sim$ 136 Mpc



Credits: Knox & Millea's "*Hubble Hunter's Guide*", PRD 101 (2020) 043533

This seems to require new physics operating just before recombination!

Solutions to the H_0 tension

What should a good solution to the H_0 tension do?

- Raise the central value of H_0 noticeably *without using SH0ES prior*
- Leave θ_s (mostly) untouched
- Leave θ_d (mostly) untouched
- Fit a wide range of datasets (CMB, BAO, SNeIa, LSS,...)
- Possibly explain other conundra (σ_8 tension? $A_{\rm lens}$ internal tension?)
- Come from a compelling particle/gravity model
- Optional (but not so much): make verifiable predictions...
- ...which later better be verified!

Broad classification of solutions

The good, the bad, and the unlikely

From Knox & Millea's "*Hubble Hunter's Guide*", PRD 101 (2020) 043533

disfavored (yellow line)
highly disfavored (red line)
Holicow disfavored (orange line)

Categories of Solution

	Post-recombination	Pre-recombination
High r_s	1) ~~H(z) wiggles~~ 2) ~~Late-Time photon interactions~~ 3) ~~New physics impacting (some) Cepheids~~	
Low r_s	1) ~~Confusion sowing~~ 2) ~~Post-recombination evolution of BAO feature~~	1) ~~Confusion sowing~~ 2) ~~Sound speed reduction~~ 3) Reduction of conformal time to recombination

Credits: Lloyd Knox

A promising class of solutions: early dark energy

- Scalar field behaving as a cosmological constant just before recombination, then diluting faster than matter
- Many examples in the literature, including particle models Poulin *et al.*, PRL 122 (2019) 221301; Agrawal *et al.*, arXiv:1904.01016; Lin *et al.*, PRD 100 (2019) 063542; Niedermann & Sloth, arXiv:1910.10739; Sakstein & Trodden, PRL 124 (2020) 161301; Zumalacárregui, arXiv:2003.06396; and many others

Featured in Physics | Editors' Suggestion

Early Dark Energy can Resolve the Hubble Tension

Vivian Poulin, Tristan L. Smith, Tanvi Karwal, and Marc Kamionkowski
Phys. Rev. Lett. **122**, 221301 – Published 4 June 2019

Physics See Synopsis: Dark Energy Solution for Hubble Tension

258

More

Article | References | Citing Articles (76) | PDF | HTML | Export Citation

ABSTRACT

Early dark energy (EDE) that behaves like a cosmological constant at early times (redshifts $z \gtrsim 3000$) and then dilutes away like radiation or faster at later times can solve the Hubble tension. In these models, the sound horizon at decoupling is reduced resulting in a larger value of the Hubble parameter H_0 inferred from the cosmic microwave background (CMB). We consider two physical models for this EDE, one involving an oscillating scalar field and another a slowly rolling field. We perform a detailed calculation of the evolution of perturbations in these models. A Markov Chain Monte Carlo search of the parameter space for the EDE parameters, in conjunction with the standard cosmological parameters, identifies regions in which H_0 inferred from *Planck* CMB data agrees with the SH0ES local measurement. In these cosmologies, current baryon acoustic oscillation and supernova data are described as successfully as in the cold dark matter model with a cosmological constant, while the fit to *Planck* data is slightly improved. Future CMB and large-scale-structure surveys will further probe this scenario.

Issue
Vol. 122, Iss. 22 — 7 June 2019

Check for updates

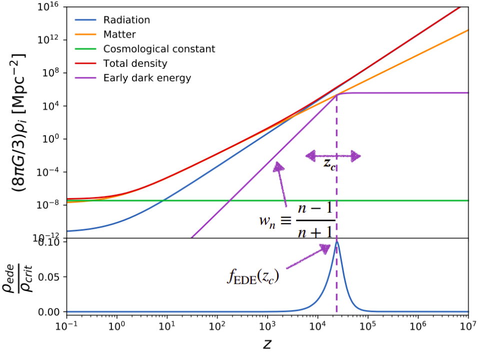
Reuse & Permissions

PHYSICAL

A promising class of solutions: early dark energy

Example: scalar field initially slow-rolls (Hubble friction), then dilutes faster than matter Poulin *et al.*, PRD 98 (2018) 083525; Poulin *et al.*, PRL 122 (2019) 221301

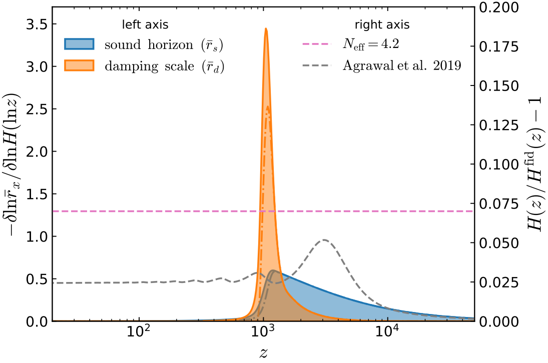
$$V_n(\phi) \propto (1 - \cos\phi)^n \,, \quad \ddot{\phi} + 3H\dot{\phi} + \frac{dV_n(\phi)}{d\phi} = 0$$



Credits: Tanvi Karwal and Vivian Poulin

The difficulties faced by early-time solutions

Generally anything which affects r_s affects damping scale r_d as well!



Credits: Knox & Millea's "*Hubble Hunter's Guide*", PRD 101 (2020) 043533

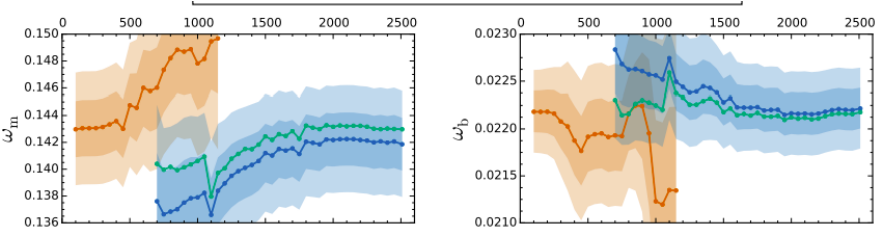
Hard to lower r_s with θ_s/θ_d fixed; excludes the simplest $N_{\rm eff}$ solution (might be saved by exotic neutrino interactions?) Kreisch *et al.*, PRD 101 (2020) 123505

A general feature of early-time solutions?

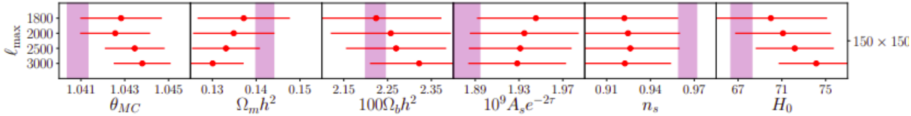
Residuals driving ℓ-dependent inferences of ω_m Knox & Millea, PRD 101 (2020) 043533

Are seeing already seeing hints? Relation to *Planck* $A_{\rm lens}$ internal tension?

See also Addison *et al.*, ApJ 818 (2016) 132



Planck collaboration, A& A 607 (2017) A95



SPT collaboration, ApJ 850 (2017) 101

The difficulties faced by early-time solutions

Problems with early dark energy: Hill *et al.*, arXiv:2003.07355

- At odds with LSS probes (RSD, DES weak lensing, BOSS full-shape power spectrum) due to higher value of Ω_c required to fit *Planck* data
- Not preferred by *Planck* data alone
- Most (if not all) particle physics models extremely fine-tuned
- Inclusion of SH0ES prior in analysis is questionable
- At most brings tension down to $\approx 2.5\sigma$ level

arXiv.org > astro-ph > arXiv:2003.07355

Search... All fields Search

Help | Advanced Search

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 16 Mar 2020 (v1), last revised 8 Apr 2020 (this version, v2)]

Early Dark Energy Does Not Restore Cosmological Concordance

J. Colin Hill, Evan McDonough, Michael W. Toomey, Stephon Alexander

Current cosmological data exhibit a tension between inferences of the Hubble constant, H_0, derived from early and late-universe measurements. One proposed solution is to introduce a new component in the early universe, which initially acts as "early dark energy" (EDE), thus decreasing the physical size of the sound horizon imprinted in the cosmic microwave background (CMB) and increasing the inferred H_0. Previous EDE analyses have shown this model can relax the H_0 tension, but the CMB-preferred value of the density fluctuation amplitude, σ_8, increases in EDE as compared to ΛCDM, increasing tension with large-scale structure (LSS) data. We show that the EDE model fit to CMB and SH0ES data yields scale-dependent changes in the matter power spectrum compared to ΛCDM, including 10% more power at $k = 1$ h/Mpc. Motivated by this observation, we reanalyze the EDE scenario, considering LSS data in detail. We also update previous analyses by including $Planck$ 2018 CMB likelihoods, and perform the first search for EDE in $Planck$ data alone, which yields no evidence for EDE. We consider several data set combinations involving the primary CMB, CMB lensing, SNIa, BAO, RSD, weak lensing, galaxy clustering, and local distance-ladder data (SH0ES). While the EDE component is weakly detected (3σ) when including the SH0ES data and excluding most LSS data, this drops below 2σ when further LSS data are included. Further, this result is in tension with strong constraints imposed on EDE by CMB and LSS data without SH0ES, which show no evidence for this model. We also show that physical priors on the fundamental scalar field parameters further weaken evidence for EDE. We conclude that the EDE scenario is, at best, no more likely to be concordant with all current cosmological data sets than ΛCDM, and appears unlikely to resolve the H_0 tension.

Comments: 36 pages, 23 figures. CLASS_EDE code publicly available at this https URL

Subjects: **Cosmology and Nongalactic Astrophysics (astro-ph.CO)**; General Relativity and Quantum Cosmology (gr-qc); High Energy Physics - Phenomenology (hep-ph); High Energy Physics - Theory (hep-th)

Cite as: arXiv:2003.07355 **[astro-ph.CO]**
(or arXiv:2003.07355v2 **[astro-ph.CO]** for this version)

Bibliographic data

[Enable Bibex (What is Bibex?)]

Submission history

From: Evan McDonough [view email]
[v1] Mon, 16 Mar 2020 17:59:03 UTC (8,465 KB)
[v2] Wed, 8 Apr 2020 23:00:00 UTC (8,444 KB)

Download:

- PDF
- Other formats

(license)

Current browse context:
astro-ph.CO
< prev | next >
new | recent | 2003

Change to browse by:
astro-ph
gr-qc
hep-ph
hep-th

References & Citations

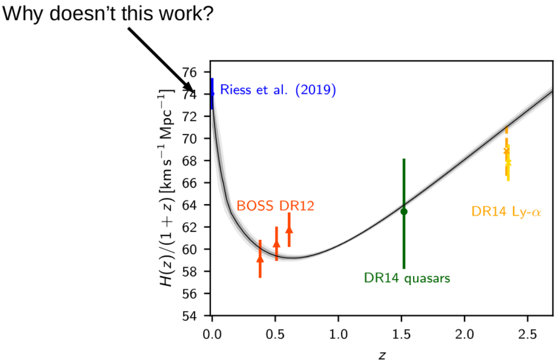
- INSPIRE HEP (refers to | cited by)
- NASA ADS
- Google Scholar
- Semantic Scholar

2 blog links (what is this?)

Export citation

Bookmark

Late-time transitions?



Credits: Marius Millea

Because uncalibrated SNeIa don't allow a high enough slope, and even considering a very late ($z \ll 0.01$) transition doesn't really resolve the source of the tension Benevento *et al.*, PRD 101 (2020) 103517

The difficulties in solving the Hubble tension

- Very hard to fit *all* available precision cosmological data
- Fixing problems produces new problems elsewhere (Whac-a-mole!)
- Use of SH0ES prior in many analyses is questionable
- In most cases central value of H_0 remains quite low, tension relaxed mostly because of larger uncertainties
- Can at most bring tension to $\approx 2.5 - 3\sigma$ level, where it might be considered a statistical fluctuation

An alternative point of view?

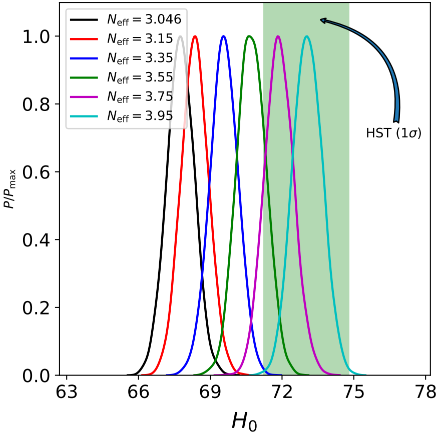
What happens if a theory is able to *fix* beyond-ΛCDM parameters to specific non-standard values?

Example: suppose a particle physics model *predicts* a specific value for $N_{\rm eff}$

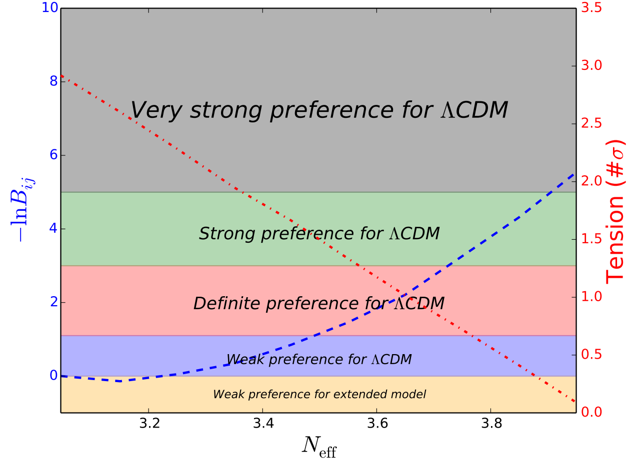
For H_0 coming from CMB+BAO+SNeIa (circa 2018):

$\Delta H_0 \approx 6.2 \Delta N_{\rm eff}$

Vagnozzi, PRD 102 (2020) 023518



An alternative point of view?



Some well-motivated particle models *predict* specific values of $N_{\rm eff}$

Vagnozzi, PRD 102 (2020) 023518

Conclusions

- **Cosmology at crossroads: ΛCDM failing its end-to-end test?**
- H_0 tension is **not** just a matter of CMB vs Riess *et al.* value...
- ...but of inverse distance ladder (CMB+BAO+uncalibrated SNeIa) vs *several* low-z H_0 measurements (including H0LiCOW)
- Solution could be early Universe new physics lowering sound horizon...
- ...but other solutions (including late-time ones) are not excluded yet!
- H_0 tension is **very hard** to solve, we do not yet have a solution
- **Lots of relevant data coming in the next years: the $\mathbf{H_0}$ tension makes this an exciting time to be working on cosmology!**

Conclusions