The trouble with Hubble, *or*
How (not) to solve the Hubble tension

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Main take-home messages

- H_0 tension is **not** just a matter of CMB vs Riess *et al.* (SH0ES) H_0...
- ...but of inverse distance ladder vs **several** low-z H_0 measurements
- We are very far from a solution, claimed solutions are in the best case overstated, in the worst case wrong

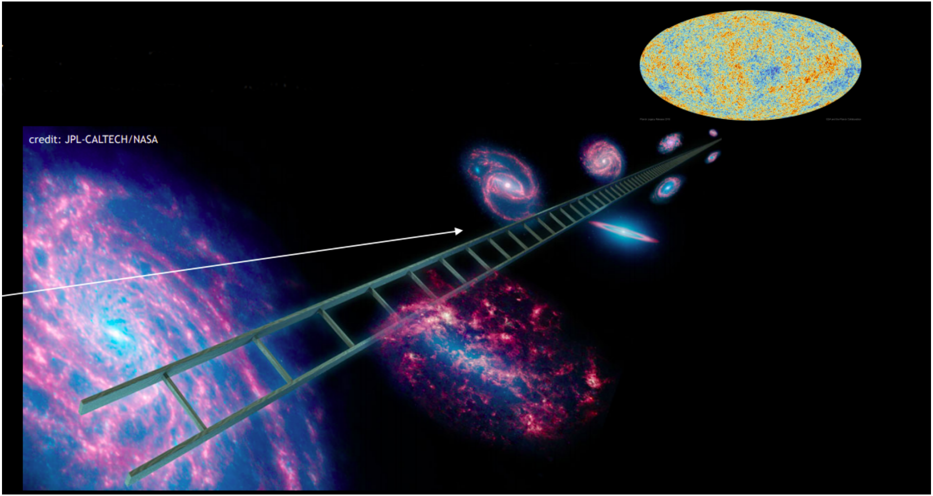
H_0: current rate of expansion of the Universe

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*"

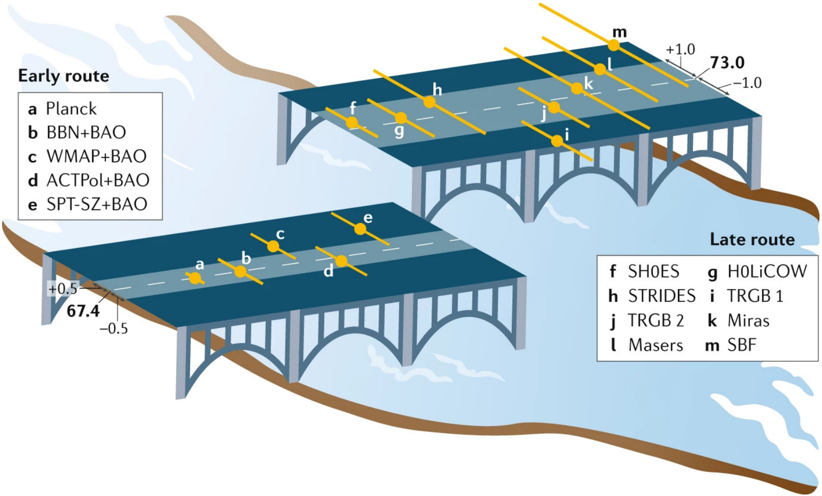
See review by Di Valentino *et al.*, arXiv:2103.01183

H_0 as an end-to-end test



Credits: JPL-Caltech/NASA and Dillon Brout

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:

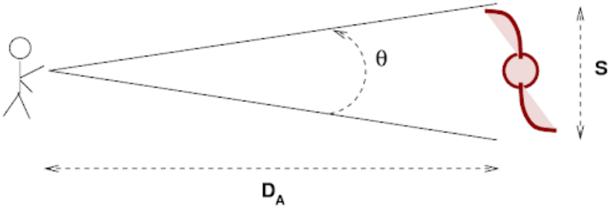
$$d_L = \sqrt{\frac{L}{4\pi f}}$$

L=intrinsic luminosity

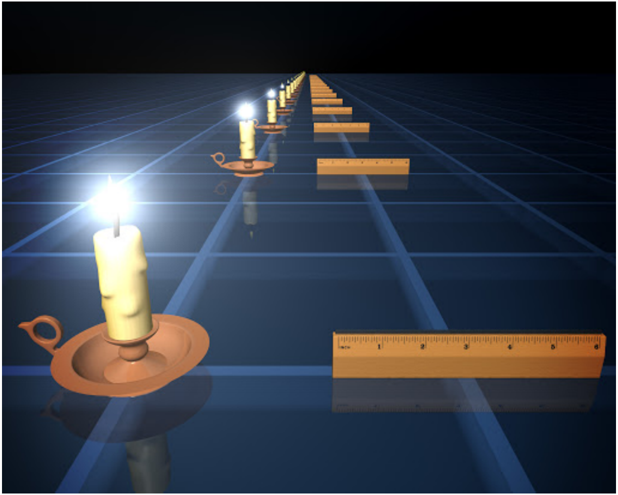
Angles (more of interest to us):

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

s=intrinsic physical size

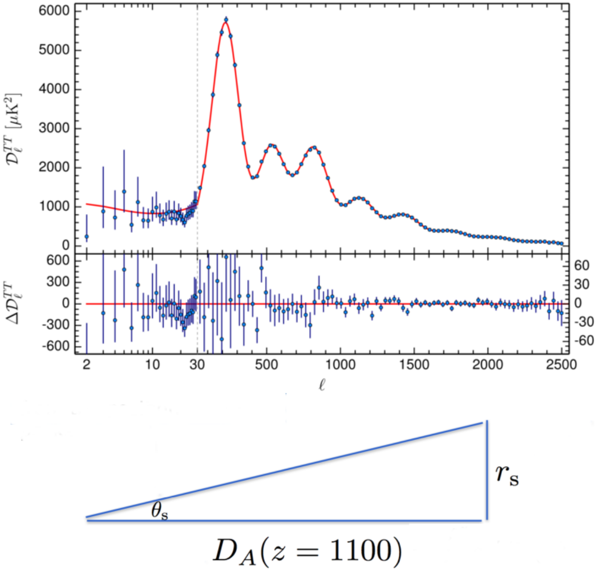


Standard candles and standard rulers



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

The CMB as a (self-calibrated) standard ruler

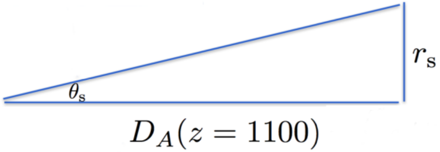


Credits: Planck collaboration and Silvia Galli

The CMB as a (self-calibrated) standard ruler

Steps within ΛCDM: 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)

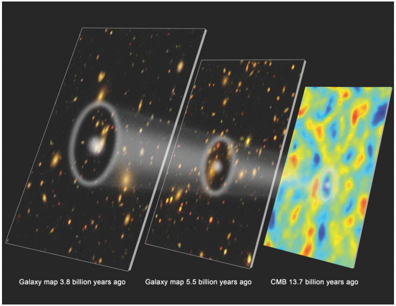
Confirmed by ACT ACT collaboration, JCAP 2012 (2020) 047

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

Late-time guard rails: the role of BAO

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

$$\theta_{\rm BAO} \sim \frac{r_s^\star}{D_A(z_{\rm BAO})}$$



Credits: Eric Huff and the BOSS/SPT collaborations

BAO constrain $H_0 r_s$, stabilizes H_0 constraints from CMB alone, breaks geometrical degeneracy (particularly in models with late-time new physics)

The geometrical degeneracy

How far away is this person (hopefully more than 2m)? d
How tall is this person? h
Only data: angle subtended by this person $\theta \approx h/d$

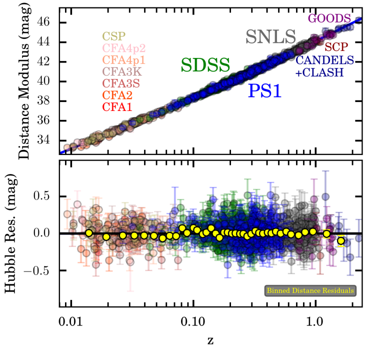
You can't disentangle distance and height from this data alone: geometrical degeneracy!

Breaking the geometrical degeneracy

Answer: roughly 7m away and roughly 3m tall

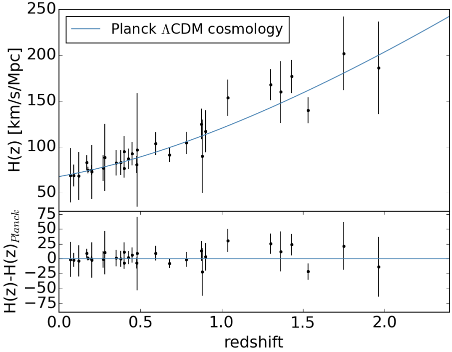
Other late-time guard rails

Uncalibrated Hubble flow SNeIa: constrain slope of $H(z)$



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

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

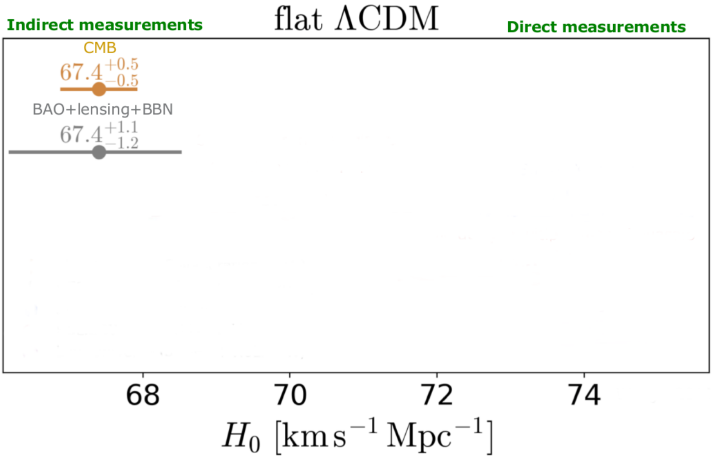


Credits: Moresco *et al.*, JCAP 1612 (2016) 039

Combining CMB and late-time guard rails

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

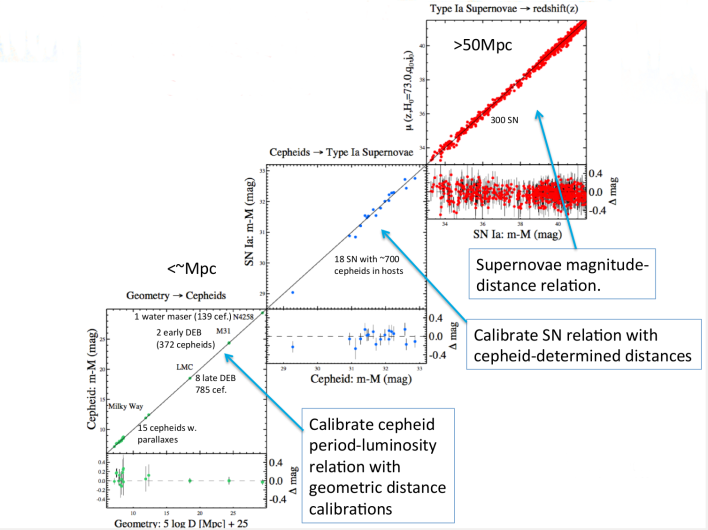
The trouble



Adapted from Wong et al., MNRAS 498 (2020) 1420, 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

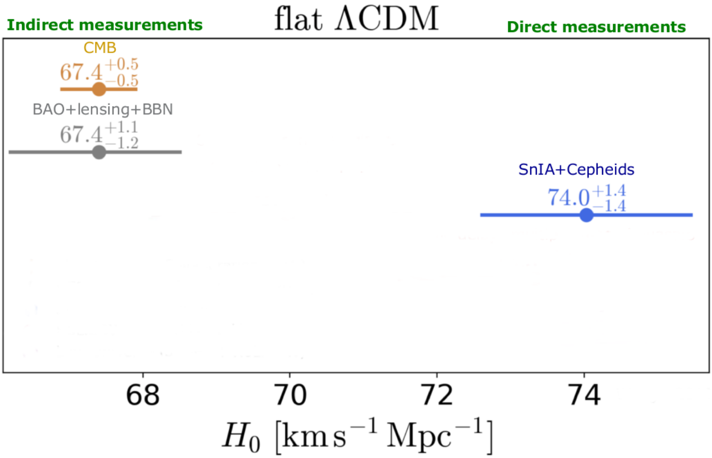
$$H_0 = 74.03 \pm 1.42$$
(Cepheid-calibrated SNeIa, R19)

compare against

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

Almost 5σ tension!

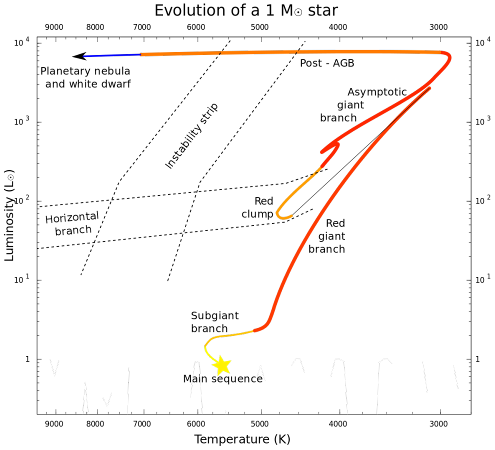
The trouble



Adapted from Wong et al., MNRAS 498 (2020) 1420, 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

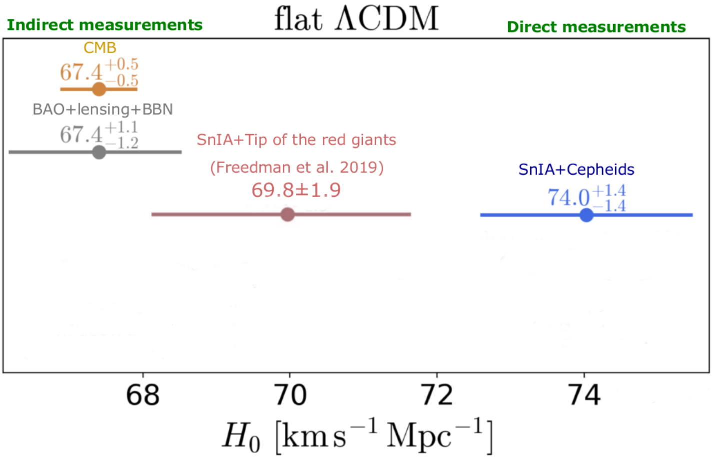
Replace second rung of distance ladder using Tip of the Red Giant Branch (TRGB) as distance indicator instead of Cepheids Freedman *et al.*, ApJ 882 (2019) 34

$$H_0 = 69.8 \pm 1.9$$
(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

Note: uses different SNeIa from SH0ES, $\approx 6\sigma$ calibration offset if one looks at host galaxies with both TRGB and Cepheid distance moduli see Efstathiou, arXiv:2007.10716

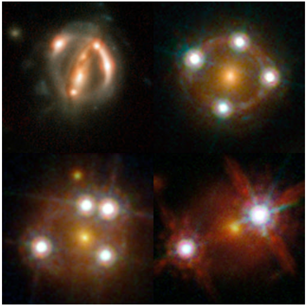
The trouble



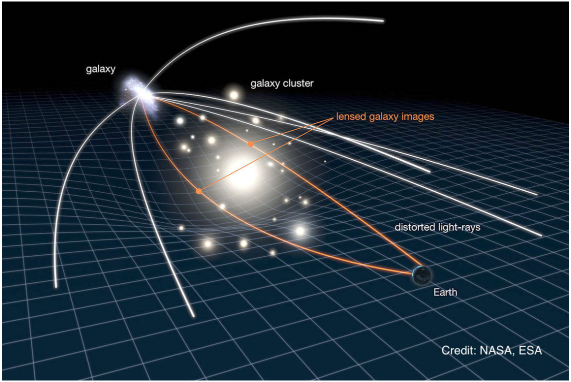
Adapted from Wong et al., MNRAS 498 (2020) 1420, and Silvia Galli

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



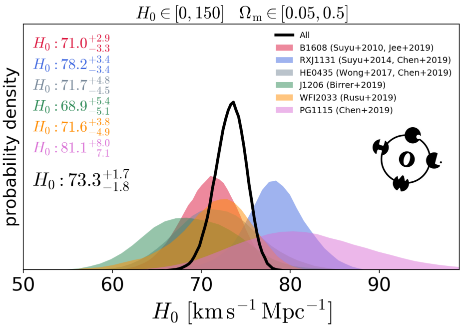
Credits: NASA and ESA

Strong lensing time delays

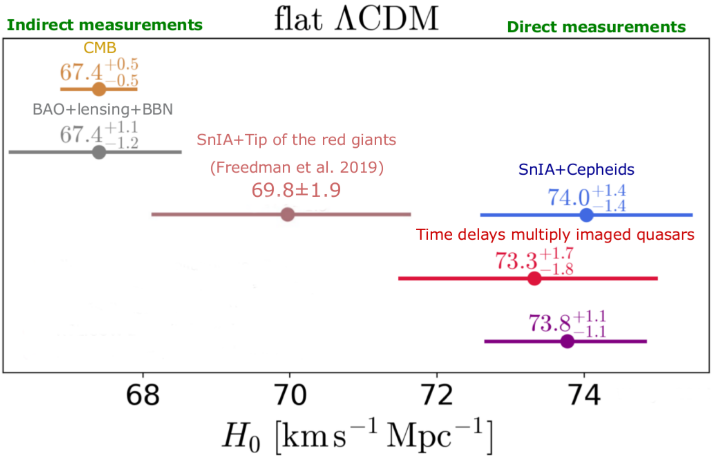
H0LICOW collaboration: Wong et al., MNRAS 498 (2020) 1420

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

(H0LiCOW, 6 lensed quasars)



The trouble

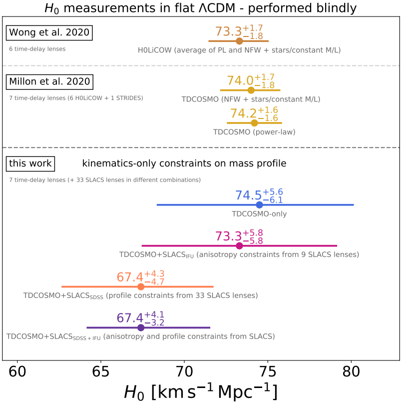


Adapted from Wong et al., MNRAS 498 (2020) 1420, and Silvia Galli

Issues with H0LiCOW?

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

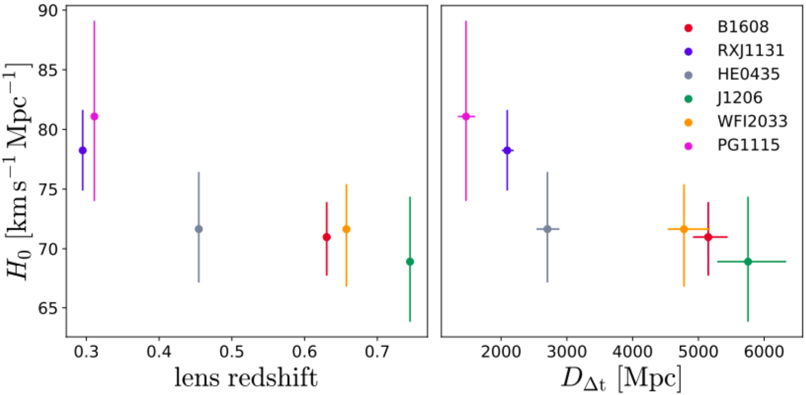
Joint H0LiCOW-SLACS analysis with a Bayesian hierarchical model:



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

A curious trend

New physics or systematics? What could this mean?



Wong et al., MNRAS 498 (2020) 1420

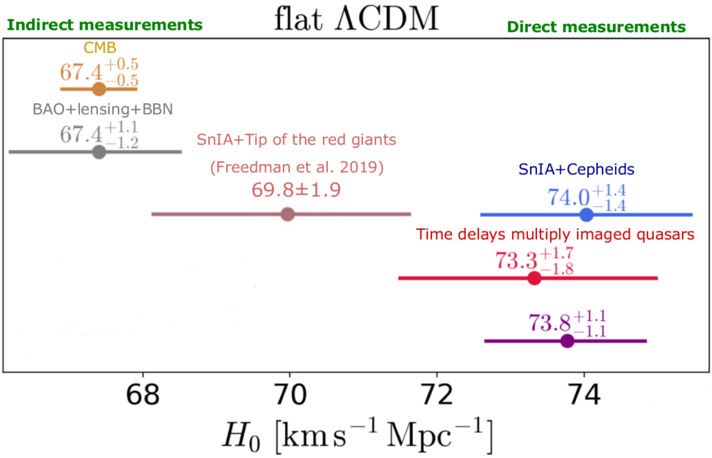
Other late-time measurements

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: $H_0 \sim 73.3 \pm 3.1$ Blakeslee *et al.*, arXiv:2101.02221
- 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
- (Baryonic) Tully-Fisher relation: $H_0 \sim 75.1 \pm 3.8$ Schombert *et al.*, AJ 160 (2020) 71
- 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., MNRAS 498 (2020) 1420, and Silvia Galli

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, Hubble flow SNeIa,...)*
2. Inverse distance ladder (CMB+BAO+Hubble flow SNeIa) vs SH0ES
   $\rightarrow$ *Still wrong, ignores many other late-time measurements besides SH0ES (TRGB, H0LiCOW,...)*
   (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**!

A naïve first approach: CMB vs local measurements 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, A&A 641 (2020) A6

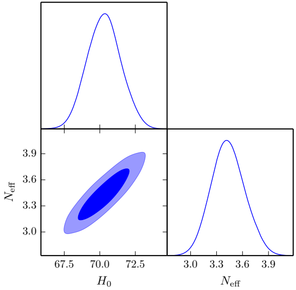
A naïve first approach: CMB vs local measurements only

Exploit CMB parameter degeneracies and introduce new physics such that a higher H_0 is required in order to keep θ_s fixed

$$\theta_s = \frac{r_s(z_{\rm LS})}{D_A(z_{\rm LS})} = \frac{\int_{z_{\rm LS}}^{\infty} \frac{dz'}{H(z')}}{\int_0^{z_{\rm LS}} \frac{dz''}{H(z'')}}$$

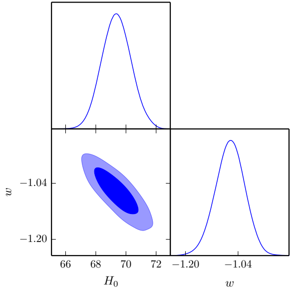
Early-Universe new physics (r_s)

Prototype: $N_{\rm eff} > 3.046$



Late-Universe new physics (D_A)

Prototype: $w < -1$



Focus on late-time new physics

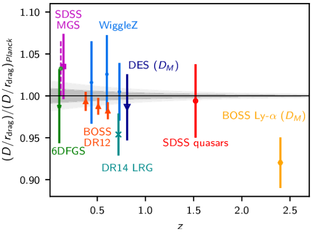
In principle there are late-time scenarios with high H_0 from CMB alone...

- Phantom dark energy or effective phantom phase Di Valentino, Melchiorri & Silk 2016; Zhao, Raveri *et al.* 2017; Di Valentino, Mukherjee & Sen 2020; Alestas, Kazantzidis & Perivolaropoulos 2020
- Interacting dark energy Di Valentino, Melchiorri, Mena, SV 2020
- Decaying dark matter Vattis, Koushiappas & Loeb 2019; Pandey, Karwal & Das 2020
- Decaying (metastable) dark energy Li, Shafieloo, Sahni & Starobinsky 2019; Yang *et al.* 2020
- Emergent dark energy Li & Shafieloo 2019; Pan *et al.* 2020
- Negative dark energy density Poulin *et al.* 2018; Visinelli, SV & Danielsson 2019; Dutta *et al.* 2020
- Vacuum dynamics (running vacuum) Solà, Gomez-Valent & Perez 2017
- Vacuum metamorphosis Di Valentino, Linder & Melchiorri 2018
- Bulk viscosity Yang *et al.* 2019
- Über gravity Khosravi, Baghram, Afshordi & Altamirano 2019
- $+++$

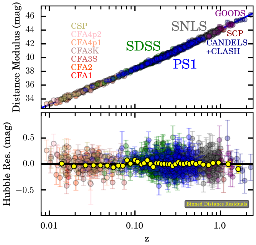
Late-time guard rails

Datasets crucial to break the geometrical degeneracy

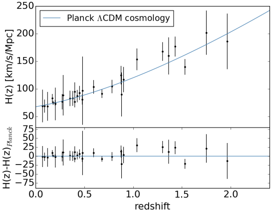
BAO



Hubble flow SNeIa



Cosmic chronometers



Constrain $H(z)r_s$

Constrain $dE(z)/dz$

Constrain $H(z)$

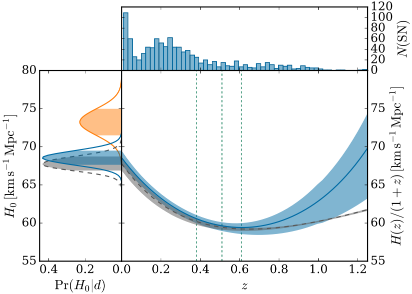
Very little room allowed for deviations from ΛCDM at late times once these datasets are taken into account (with caveats of course)

Inverse distance ladder: CMB-independent inferences of H_0

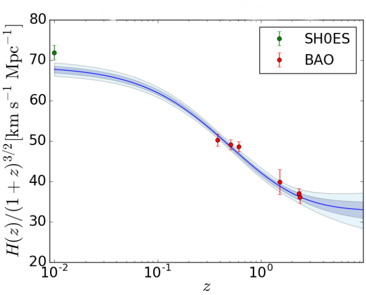
Inverse distance ladder from BAO+uncalibrated Hubble flow SNeIa

earlier examples in e.g. Aubourg *et al.* 2015; Bernal *et al.* 2016

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



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

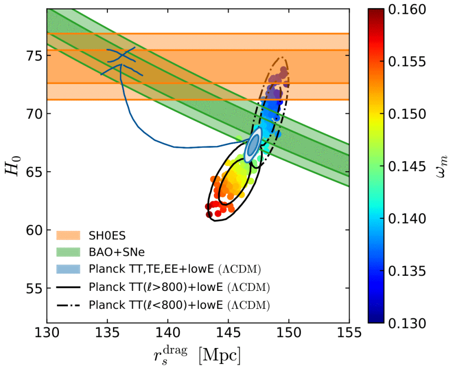


Credits: Lemos *et al.*, MNRAS 483 (2019) 4803

De facto BAO+Hubble flow SNeIa(+CC) almost completely exclude late-time new physics as a solution to the Hubble tension

The Hubble tension as a sound horizon tension

Solving the tension seems to require lowering r_s by $\approx 7\%$



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

This seems to require new physics operating just before recombination!

Ways out of the no-late-time-solutions-no-go-theorem?

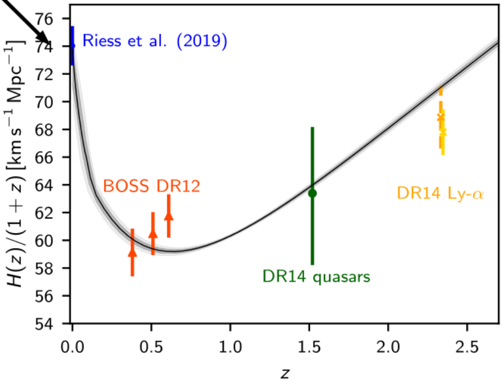
What if we don't want to give up on late-time solutions...yet?

Three approaches: super naïve, headfirst (stubborn?), and clever/cunning

The super naïve approach: late-time transitions?

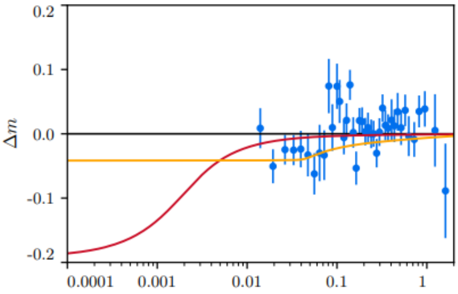
"Hockey-stick dark energy" Name given in Camarena & Marra, arXiv:2101.08641

Why doesn't this work?



Credits: Marius Millea

The super naïve approach: late-time transitions?



Credits: Benevento, Raveri & Hu 2020

- True source of the tension (from the SH0ES side) is $\Delta M_B \approx 0.2$ calibration offset in $0.023 < z < 0.015$ Pantheon SNeIa calibration (distance ladder vs inverse distance ladder) Benevento, Raveri & Hu 2020; Camarena & Marra 2021; Efstathiou 2021
- Even if you changed something at $z < 0.02$, *SH0ES wouldn't know about it*!
- Better to use M_B rather than H_0 prior, or joint calibrator-Hubble flow SNeIa likelihood Dhawan *et al.* 2020; Benevento, Raveri & Hu 2020; Camarena & Marra 2021; Efstathiou 2021

Headfirst approaches: hairdressing dark energy?

Throw in all remotely credible modifications to dark energy ($w \neq -1$, time-varying w, interactions with dark matter,...) *at the same time*

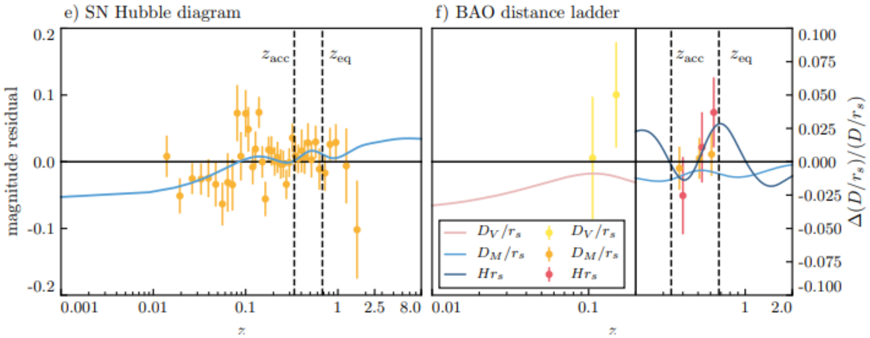
Parameters	Planck	Planck +R19	Planck +lensing	Planck +BAO	Planck + Pantheon	All19
$\Omega_b h^2$	0.0224 ± 0.0002	0.0224 ± 0.0002	0.0224 ± 0.0002	0.0224 ± 0.0001	0.0224 ± 0.00012	0.0224 ± 0.0001
$\Omega_c h^2$	$0.132^{+0.005}_{-0.012}$	$0.133^{+0.006}_{-0.012}$	$0.133^{+0.006}_{-0.012}$	$0.134^{+0.007}_{-0.012}$	$0.134^{+0.006}_{-0.012}$	$0.132^{+0.006}_{-0.012}$
ξ	< 0.248	< 0.277	< 0.258	< 0.295	< 0.295	< 0.288
w	$-1.59^{+0.18}_{-0.33}$	-1.26 ± 0.06	$-1.57^{+0.19}_{-0.32}$	$-1.10^{+0.07}_{-0.04}$	$-1.08^{+0.05}_{-0.04}$	$-1.12^{+0.05}_{-0.04}$
H_0[km/s/Mpc]	> 70.4	74.1 ± 1.4	$85.0^{+10.0}_{-5.0}$	$68.8^{+1.1}_{-1.5}$	68.3 ± 1.0	69.8 ± 0.7
σ_8	0.88 ± 0.08	$0.80^{+0.06}_{-0.04}$	0.87 ± 0.08	0.75 ± 0.05	$0.76^{+0.05}_{-0.04}$	$0.76^{+0.06}_{-0.04}$
S_8	0.74 ± 0.04	0.78 ± 0.03	0.74 ± 0.04	0.79 ± 0.03	0.80 ± 0.03	$0.79^{+0.03}_{-0.02}$
$\ln B$	-1.3	5.6	-1.6	-4.5	-5.2	-2.7
Strength	Positive (ΛCDM)	Very strong (ξpCDM)	Positive (ΛCDM)	Strong (ΛCDM)	Very strong (ΛCDM)	Positive (ΛCDM)

Di Valentino, Melchiorri, Mena & SV, PRD 101 (2020) 063502

The best we can do while not ruining the fit to late-time data is $\approx 70 \pm 1$ ($\approx 2.5\sigma$ tension): BAO and Hubble flow SNeIa data are very unforgiving!

Headfirst approaches: fast wiggles/oscillations in $H(z)$?

Scalar Horndeski model ($\alpha_T = 0$), low-redshift reconstruction with several (≈ 20) extra dof and high-frequency oscillations in $H(z)$



Credits: Raveri, PRD 101 (2020) 083524

Interesting as a proof of principle, but not favored over ΛCDM from a model comparison point of view (and high-frequency oscillations may invalidate BAO data reduction?)

Headfirst approaches: vacuum metamorphosis?

Parker vacuum metamorphosis, well-motivated (nonperturbative) first principles theory Parker & Raval 2000; related to Über gravity, see Khosravi, Baghram, Afshordi & Altamirano 2019

Parameters	CMB	CMB+lensing	CMB+BAO	CMB+Pantheon	CMB+R19	CMB+BAO+Pantheon	CMB+BAO+R19
$\Omega_b h^2$	0.02238 ± 0.00014	0.02242 ± 0.00013	0.02218 ± 0.00012	0.02201 ± 0.00013	0.02221 ± 0.00012	0.02213 ± 0.00012	0.02217 ± 0.00012
$100\theta_{MC}$	1.04091 ± 0.00030	1.04097 ± 0.00029	1.04060 ± 0.00029	1.04033 ± 0.00031	1.04063 ± 0.00029	1.04053 ± 0.00029	1.04060 ± 0.00029
τ	0.0524 ± 0.0078	0.0510 ± 0.0078	$0.0458^{+0.0083}_{-0.0067}$	$0.039^{+0.010}_{-0.007}$	0.0469 ± 0.0075	$0.0449^{+0.0079}_{-0.0065}$	$0.0456^{+0.0083}_{-0.0068}$
M	$0.9363^{+0.0055}_{-0.0044}$	0.9406 ± 0.0034	0.9205 ± 0.0023	$0.8996^{+0.0081}_{-0.0073}$	$0.9230^{+0.0042}_{-0.0036}$	0.9163 ± 0.0023	0.9198 ± 0.0020
$\ln(10^{10} A_s)$	3.041 ± 0.016	3.036 ± 0.015	$3.035^{+0.017}_{-0.014}$	$3.027^{+0.020}_{-0.014}$	3.036 ± 0.016	$3.035^{+0.017}_{-0.014}$	$3.035^{+0.017}_{-0.015}$
n_s	0.9643 ± 0.0039	0.9663 ± 0.0036	0.9572 ± 0.0031	0.9511 ± 0.0036	0.9585 ± 0.0033	0.9560 ± 0.0031	0.9571 ± 0.0031
H_0[km/s/Mpc]	81.1 ± 2.1	82.9 ± 1.5	75.44 ± 0.69	70.1 ± 1.8	76.3 ± 1.2	74.21 ± 0.66	75.22 ± 0.60
σ_8	0.9440 ± 0.0077	0.9392 ± 0.0067	$0.9456^{+0.0082}_{-0.0070}$	$0.9419^{+0.0098}_{-0.0069}$	0.9457 ± 0.0075	$0.9461^{+0.0080}_{-0.0068}$	$0.9457^{+0.0082}_{-0.0073}$
S_8	0.805 ± 0.022	0.783 ± 0.014	0.865 ± 0.010	0.927 ± 0.023	0.856 ± 0.015	0.880 ± 0.010	0.8675 ± 0.0098
Ω_m	$0.218^{+0.010}_{-0.012}$	0.2085 ± 0.0076	0.2510 ± 0.0046	0.291 ± 0.015	$0.2458^{+0.0074}_{-0.0084}$	0.2593 ± 0.0046	0.2525 ± 0.0040
χ^2_{bf}	2767.74	2776.23	2806.22	3874.13	2777.04	3910.01	2808.34
$\Delta\chi^2_{bf}$	−4.91	−5.81	+26.51	+66.63	−14.80	+95.83	+11.29

Credits: Di Valentino, Linder & Melchiorri, Phys. Dark Univ. 30 (2020) 100733

High H_0 from CMB+BAO+Hubble flow SNeIa at the cost of huge $\Delta\chi^2$

We do not solve tensions with concordance cosmology; we do obtain $H_0 \approx 74$ km/s/Mpc from CMB+BAO+SN data in our model, but that is not the point. Discrepancies in Hubble constant

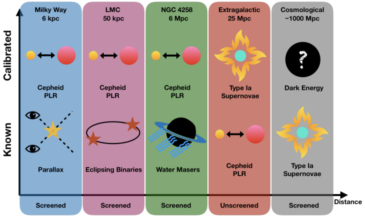
In summary, if one has a very narrow focus, e.g. just on H_0, then one can draw a very different conclusion regarding the attraction of models than if one properly takes into account the array of available data. H_0 *ex machina*, where

Credits: Di Valentino, Linder & Melchiorri, Phys. Dark Univ. 30 (2020) 100733

The clever approach: changing the local calibration

Local measurements are wrong, not because of systematics, but because new physics alters the SNeIa calibration (Cepheids/TRGB) or luminosities:

- Screened fifth forces Desmond, Jain & Sasktein 2019; Desmond & Sakstein 2020
- Late-time transition in G_{eff} Marra & Perivolaropoulos 2021
- Chameleon dark energy? Cai *et al.* 2021



Credits: Desmond, Jain & Sakstein, PRD 100 (2019) 043537

Problem: hard (impossible?) to explain why H0LiCOW finds a high H_0
(Cheap?) Way out: systematics in H0LiCOW? See *e.g.* Birrer *et al.* 2020

Other independent (unlikely) late-time approaches

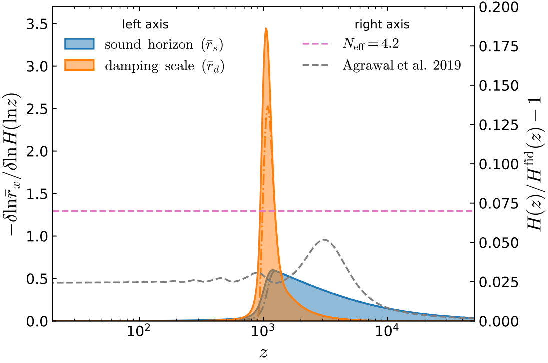
- "Confusion sowing" which confuses our determination of ω_m
- Violation of the Etherington distance-duality relation
- Post-recombination evolution of $r_s^{\rm drag}$
- Note: invoking redshift evolution of intrinsic SNeIa luminosities does not help with the tension and is in any case tightly constrained
  Martinelli & Tutusaus 2019; Rose *et al.* 2020; Di Valentino, Gariazzo, Mena & SV 2020

What if we don't want to give up on late-time solutions...yet?

Late-time solutions cannot be 100% excluded, but are admittedly not so likely, with the possible exception of new physics altering the physics of SNeIa or their calibrators (Cepheids/TRGB)

Early-time solutions

What new physics can lower r_s by $\approx 7\%$?



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

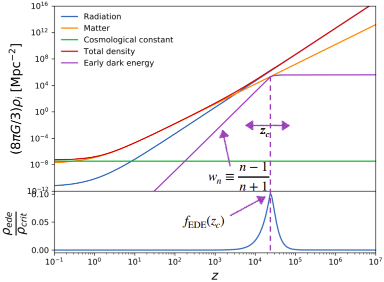
Physics operating just prior to recombination!

Early dark energy: a promising class of solutions?

Example: scalar field initially frozen (Hubble friction), then dilutes faster than matter Karwal & Kamionkowski 2016; Poulin, Smith, Karwal & Kamionkowski 2019

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

Credits: Tanvi Karwal & Vivian Poulin



Many other examples Agrawal, Cyr-Racine, Pinner & Randall *et al.* 2019; Alexander & McDonough 2019; Niederman & Sloth 2019; Sakstein & Trodden 2019; Ye & Piao 2020; and many others...

The trouble with early dark energy

Theory difficulties (not real showstoppers, but worth keeping in mind):

- Fine-tuned mass and initial conditions?
- Fine-tuned potential?
- How to get the right amount of EDE to first appear and then disappear at the right time?

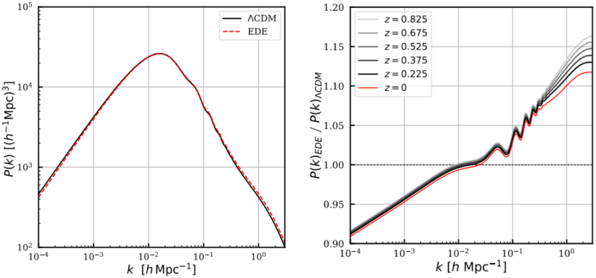
Data difficulties:

- EDE appears to conflict with LSS data (RSD, galaxy clustering)
- EDE worsens the tension with weak lensing measurements (raising σ_8)

The trouble with early dark energy

Problems (essentially related to S_8 discrepancy): Hill *et al.* 2020, Ivanov *et al.* 2020

- higher ω_c required to compensate EDE effects in the CMB...
- which raises σ_8 ($S_8 = \sigma_8\sqrt{\Omega_m/0.3}$), leaves undesired imprints in LSS
- without use of R19 prior H_0 remains low



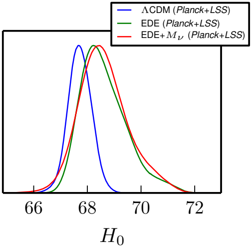
Credits: Ivanov *et al.*, PRD 102 (2020) 103502

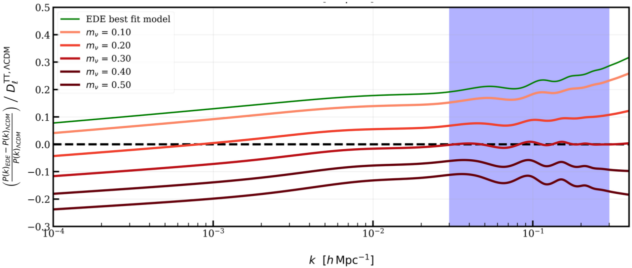
Caveats to CMB+LSS combination for EDE See *e.g.* Murgia *et al.* 2020, Smith *et al.* 2020

What can rescue EDE?

Note: S_8 discrepancy exists already within ΛCDM, presumably whatever solves it would also fix EDE?

Example: neutrino mass (nominally need $M_\nu \sim 0.3\,\mathrm{eV}$ to rescued EDE!)



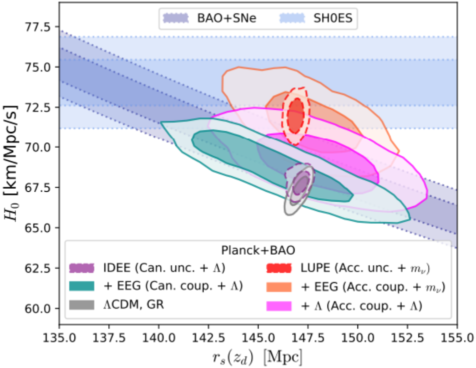


Reeves, SV, Efstathiou, Sherwin, in preparation. Plots credits: Alex Reeves

Other possible ingredients: decaying DM, DM-dark radiation interactions (work in progress)

Early dark energy from modifications of gravity?

Coupled galileon (subset of Horndeski gravity)

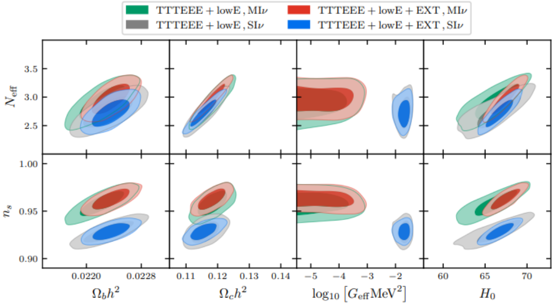


Credits: Zumalacárregui, PRD 102 (2020) 023523

Hard to go beyond $H_0 \approx 70$ without including R19 prior or spoiling fit, other attempts to get EDE from MG face similar problems *e.g.* Braglia *et al.* 2020; García-García, Bellini, SV & Zumalacárregui, in preparation

Non-standard neutrino interactions?

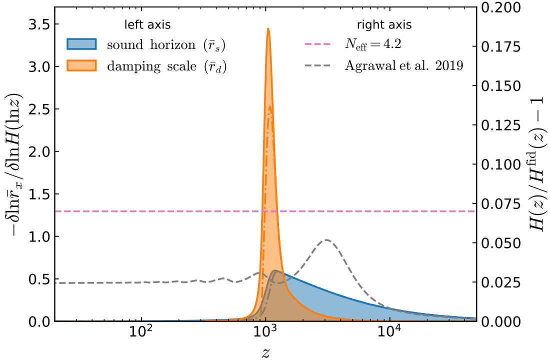
Self-interacting νs reduce or eliminate free-streaming-induced temporal phase shifts of acoustic oscillations, require higher H_0 (and higher $N_{\rm eff}$, $M_\nu \neq 0$) to fit first peak of the CMB Kreisch, Cyr-Racine & Doré, PRD 102 (2020) 123505



Credits: Roy Choudhury, Hannestad & Tram, JCAP 2103 (2021) 084

Problem: recovers low H_0 when CMB polarization data included and/or R19 prior not included Roy Choudhury *et al.*, JCAP 2103 (2021) 084; Brinckmann *et al.*, arXiv:2012.11830

Early-time models in trouble with polarization data?



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

Generally hard to reduce r_s and not modify θ_d (or more precisely θ_s/θ_d)

Other independent (unlikely) early-time approaches

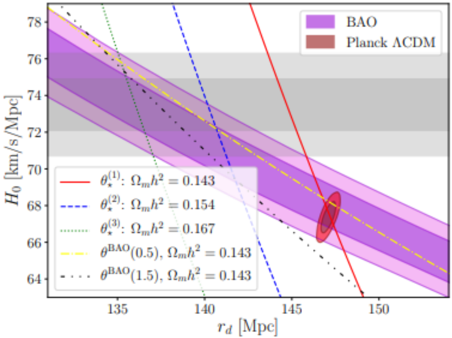
- Reducing photon-baryon plasma sound speed
- Time-varying fundamental constants (α, m_e, *etc.*)
- Photon cooling or conversion
- Making recombination occur earlier Unlikely, with the possible notable exception of the primordial magnetic fields model of Jedamzik & Pogosian 2020; unclear if it still works once BAO+Hubble flow SNeIa data are added (discussed in Supplementary Material), and local H_0 priors removed

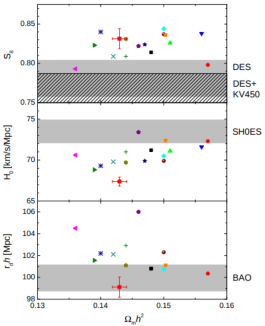
Can early-time approaches solve the Hubble tension?

In principle they are the least unlikely, in practice they face many difficulties, possibly as many (if not more) than late-time approaches

More trouble for early-time models?

Reducing r_s without touching ω_m can never fully resolve the Hubble tension – higher [lower] ω_m run in tension with WL/LSS [BAO] data





Credits: Jedamzik, Pogosian & Zhao, arXiv:2010.04158; see also related results in Lin, Chen & Mack, arXiv:2102.05701

A solution to the tension requires more than just reducing r_s, but probably something on the data side has to give as well (relation to σ_8 tension?)

The difficulties in solving the Hubble tension

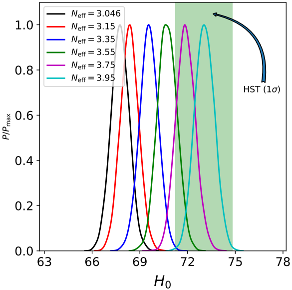
- Very hard to fit *all* available precision cosmological data (sort of an over-constrained algebraic system)
- Fixing problems produces new problems elsewhere (cf. Whac-a-mole!)
- Use of local H_0 prior questionable, [1] often central value of H_0 remains quite low, tension "relaxed" mostly because of larger uncertainties

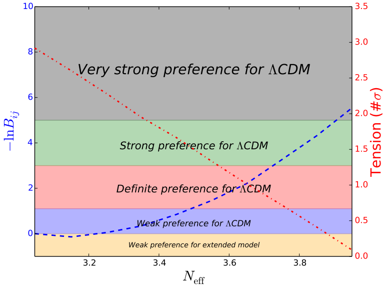
[1] See my blog post www.sunnyvagnozzi.com/blog/top-arxiv-week-26-2020 for an everyday life analogy regarding this point.

What if...?

What if a fundamental particle physics model *predicts* a specific non-standard value for a specific beyond-ΛCDM parameter?

Example circa 2018 (R16 local H_0, no polarization) focused on $N_{\rm eff}$





Vagnozzi, PRD 102 (2020) 023518

There is no "sweet spot" where the Hubble tension is sufficiently reduced and the alternative model is favored over ΛCDM (fit worsens too much)

A laundry-list/bingo table of mistakes in the literature

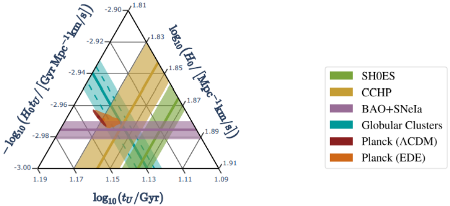
Disclaimer: we are (almost?) all sinners

- Leaving out one or more key datasets: BAO, Hubble flow SNeIa, CMB polarization, (galaxy clustering?)
- Local H_0 prior misuse See warnings in Benevento *et al.* 2020; Camarena & Marra 2021; Efstathiou 2021
- "Solving" the tension just by inflating error bars but not moving the central value of H_0
- Getting a high H_0 at the expense of *a)* worsening other tensions (*e.g.* σ_8), or *b)* a poor $\Delta\chi^2$ (Bayesian evidence prefers ΛCDM)
- (Uncompelling underlying fundamental physics models)

Take-away message: we don't yet have a solution, claimed solutions are in the best case overstated, in the worst case wrong

My personal take on the road ahead

- A mix of early and late new physics (more late than early) [2] will be required
- There is something worth investigating behind the H0LiCOW H_0-z trend
- Important to get BAO experts in the discussion, understand if and to what extent BAO are model-independent with respect to more exotic late-time modifications
- Important to focus on quantities beyond H_0 and r_s, *e.g.* t_U and ω_m, cf. "cosmic triangles" below Bernal *et al.*, arXiv:2102.05066 (credits); Jedamzik, Pogosian & Zhao, arXiv:2010.04158
- We will get to the bottom of this in ≈5 years (but the pandemic will be over first?), the solution will likely teach us something very fundamental



[2] I think backreaction of inhomogeneities can play an important role and potentially invalidate assumptions in the BAO data reduction process (*e.g.* Alcock-Paczynski scaling), see *e.g.* Heinesen, Blake & Wiltshire 2020; Heinesen & Buchert 2020

10 commandments for Hubble hunters

1. I am $H_0 \approx 74$ thy Goal
2. Thou shalt not fail to fit key data (BAO, SNeIa, polarization)...
3. ...or include a local H_0 prior in vain
4. Thou shalt not forget the true source of the tension (from the SH0ES side)
5. Honour H_0's central value, and keep an eye on your $\Delta\chi^2$/Bayesian evidence
6. Thou shalt not murder σ_8/S_8...
7. ...but aim to solve this and other tensions/puzzles at the same time
8. Thy solution shall come from a compelling particle/gravity model...
9. ...which makes verifiable predictions...
10. ...which later better be verified!

Credits: Gustave Doré