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

Sunny Vagnozzi

Newton-Kavli Fellow @ KICC, University of Cambridge

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

sunnyvagnozzi @SunnyVagnozzi

A (Hubble) Tension Headache, 1-3 March 2021

Why haven't we yet found a compelling solution to the Hubble tension?

Important disclaimers:

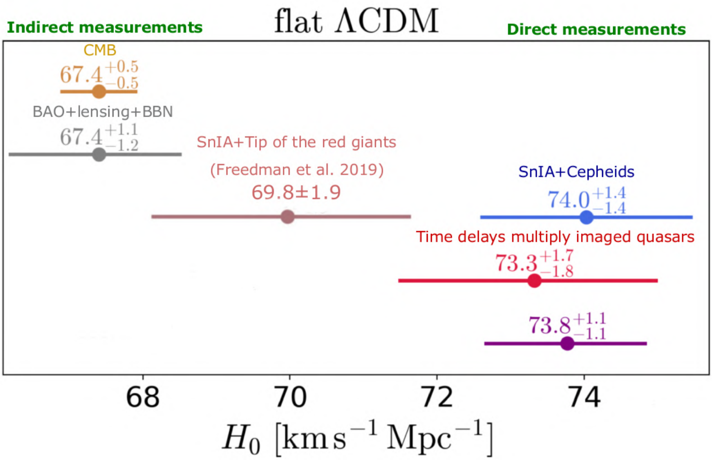
- I will mention specific models and very frequent mistakes in the literature, apologies if your (favourite) model comes up [1]
- I will take Riess *et al.*'s local measurements (R19/R20 *etc.*) for granted, simply because they set a harder task for theorists [2]
- I will assume you know most of the background [3]

[1] This does not violate the conference's Code of Conduct: "*Be kind [...] Be respectful [...] Critique ideas not people.*"

[2] This does not mean I do not respect works which question these measurements, quite the contrary in fact!

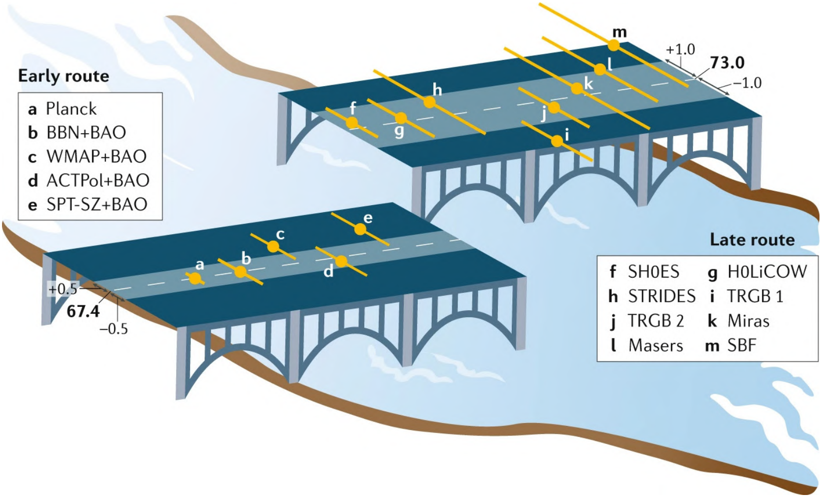
[3] If not, please refer to the excellent overview talks. And if you are wondering, no pun intended.

The trouble



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

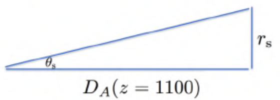
The trouble



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

Early- vs late-time measurements

CMB as a (self-calibrated) standard ruler

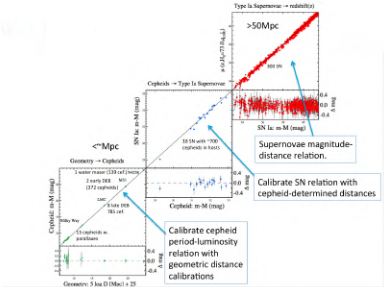


Credits: Silvia Galli

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

$$H_0 = 67.9 \pm 1.5 \textit{ (ACT DR4)}$$

(Cepheid- or TRGB-) Calibrated SNeIa



Credits: Adam Riess and Silvia Galli

$$H_0 = 74.03 \pm 1.42 \textit{ (R19)}$$
$$H_0 = 69.8 \pm 0.8 \pm 1.7 \textit{ (F19)}$$
$$H_0 = 73.2 \pm 1.3 \textit{ (R20)}$$

Ignoring BAO and Hubble-flow SNeIa for the moment (not for long...)

Broad classification of solutions

The good, the bad, and the unlikely

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

disfavored
highly disfavored
Holicow disfavored

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 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

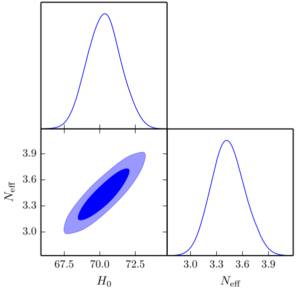
A naïve first approach: CMB vs local measurements only

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

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

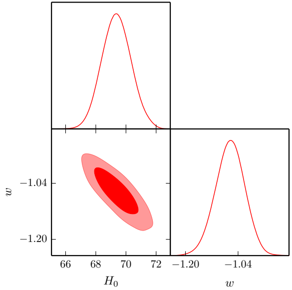
Early-Universe new physics (r_s)

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
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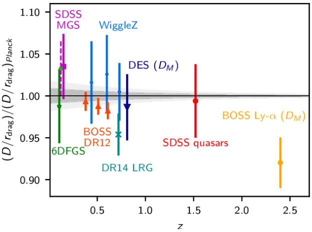
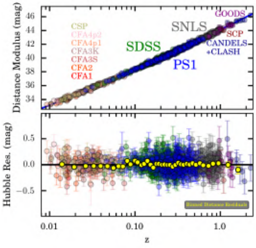
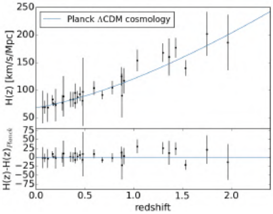
Late-time guard rails

Datasets crucial to break the geometrical degeneracy

BAO | Hubble flow SNeIa | Cosmic chronometers







Constrain $H(z)r_s$ | Constrain $dE(z)/dz$ | Constrain $H(z)$

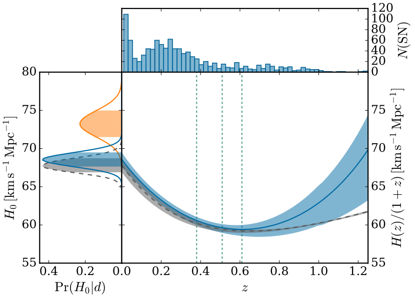
Very little room allowed for deviations from ΛCDM at late times once these datasets are taken into account (with caveats of course)

Inverse distance ladder: CMB-independent inferences of H_0

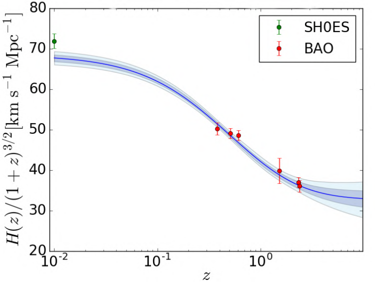
Inverse distance ladder from BAO+uncalibrated Hubble flow SNeIa

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

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



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

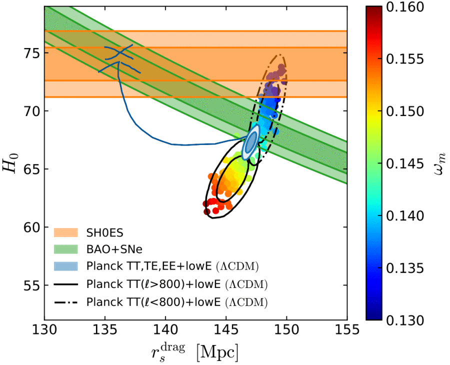


Credits: Lemos *et al.*, MNRAS 483 (2019) 4803

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

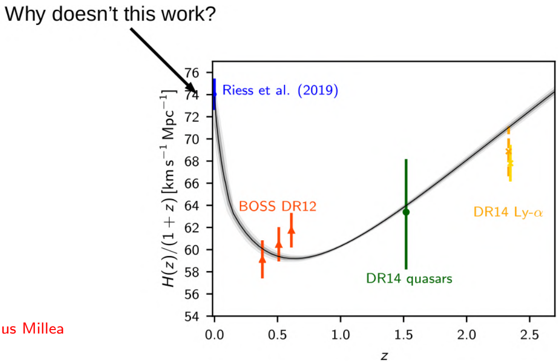
This seems to require new physics operating just before recombination!

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



Credits: Marius Millea

- True source of the tension is $\Delta M_B \approx 0.2$ calibration offset between calibrator SNeIa and Hubble flow SNeIa once the latter are combined with CMB and BAO Benevento, Raveri & Hu 2020; Camarena & Marra 2021
- Better to use M_B prior rather than H_0 prior, or joint calibrator-Hubble flow SNeIa likelihood Dhawan *et al.* 2020; Benevento, Raveri & Hu 2020; Camarena & Marra 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*

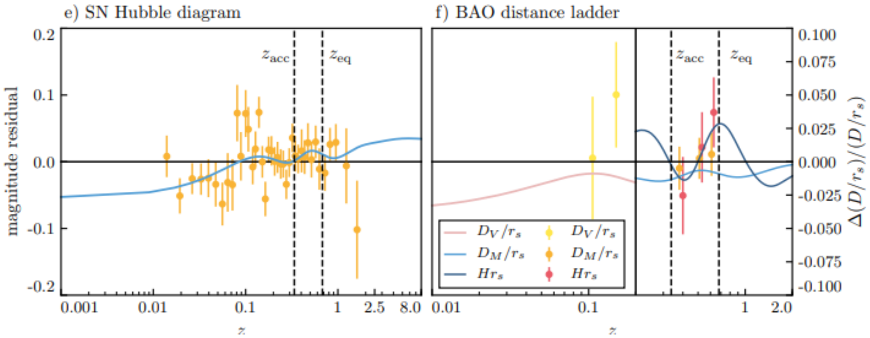
Parameters	Planck	Planck +R19	Planck +lensing	Planck +BAO	Planck + Pantheon	All19
$\Omega_b h^2$	0.0224 ± 0.0002	0.0224 ± 0.0002	0.0224 ± 0.0002	0.0224 ± 0.0001	0.0224 ± 0.00012	0.0224 ± 0.0001
$\Omega_c h^2$	$0.132^{+0.005}_{-0.012}$	$0.133^{+0.006}_{-0.012}$	$0.133^{+0.006}_{-0.012}$	$0.134^{+0.007}_{-0.012}$	$0.134^{+0.006}_{-0.012}$	$0.132^{+0.006}_{-0.012}$
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
$\chi^2_{\rm bf}$	2767.74	2776.23	2806.22	3874.13	2777.04	3910.01	2808.34
$\Delta\chi^2_{\rm bf}$	−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

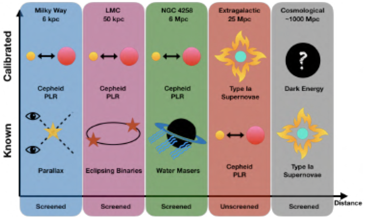
In summary, if one has a very narrow focus, e.g. just on H_0, then one can draw a very different conclusion regarding the attraction of models than if one properly takes into account the array of available data. H_0 *ex machina*, where

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

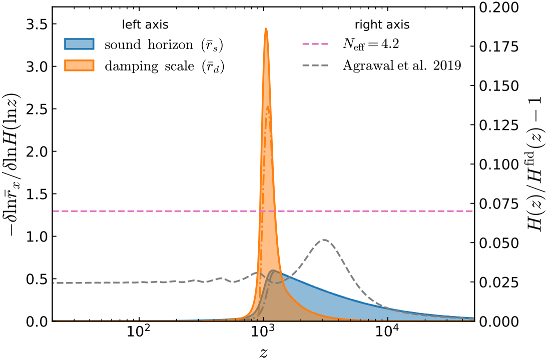
- "Confusion sowing" which confuses our determination of ω_m
- Violation of the Etherington distance-duality relation
- Post-recombination evolution of $r_s^{\rm drag}$
- Note: invoking redshift evolution of intrinsic SNeIa luminosities does not help with the tension and is in any case tightly constrained
  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

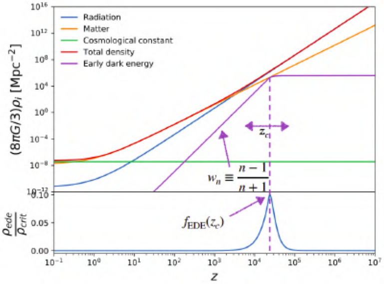
Physics operating just prior to recombination!

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?

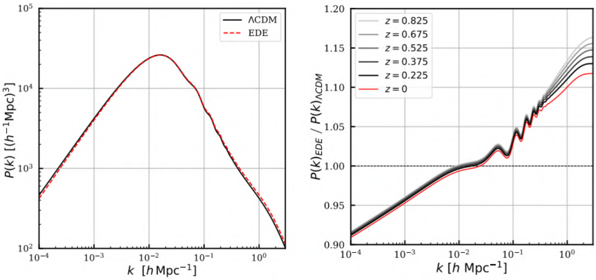
Data difficulties:

- 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: Hill *et al.* 2020, Ivanov *et al.* 2020

- higher ω_c required to compensate EDE effects in the CMB...
- which raises σ_8 and leaves undesired imprints in the LSS
- without use of R19 prior H_0 remains low

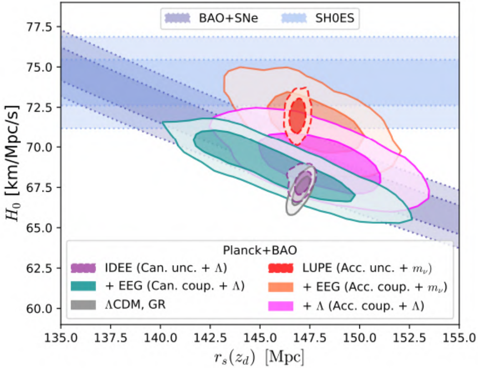


Credits: Ivanov *et al.*, PRD 102 (2020) 103502

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

Early dark energy from modifications of gravity?

Coupled galileon (subset of Horndeski gravity)



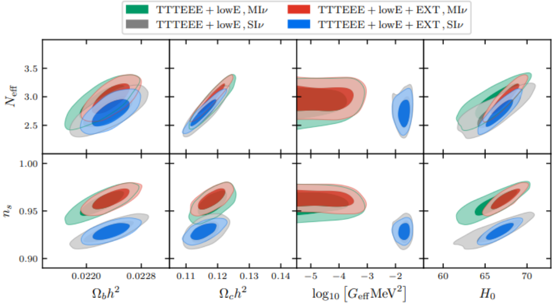
Credits: Zumalacárregui, PRD 102 (2020) 023523

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?

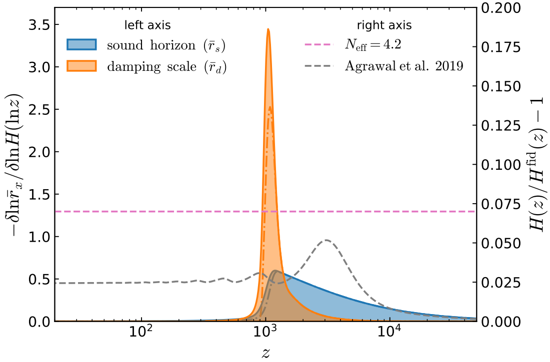
Self-interacting νs reduce or eliminate free-streaming-induced temporal phase shifts of acoustic oscillations, require higher H_0 (and higher $N_{\rm eff}$, $M_\nu \neq 0$) to get the right θ_s Kreisch, Cyr-Racine & Doré, PRD 102 (2020) 123505



Credits: Roy Choudhury, Hannestad & Tram, arXiv:2012.07519 (to appear in JCAP)

Problem: runs into trouble with CMB polarization data $\rightarrow$ low H_0 when CMB polarization data included and/or R19 prior not included

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

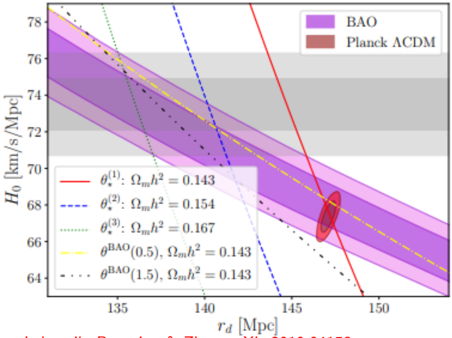
- Reducing photon-baryon plasma sound speed
- Time-varying fundamental constants (α, m_e, *etc.*)
- Photon cooling or conversion
- Making recombination occur earlier Unlikely, with the possible notable exception of the primordial magnetic fields model of Jedamzik & Pogosian 2020; unclear if it still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

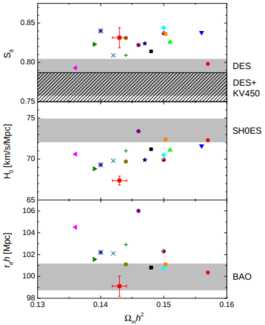
Can early-time approaches solve the Hubble tension?

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

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

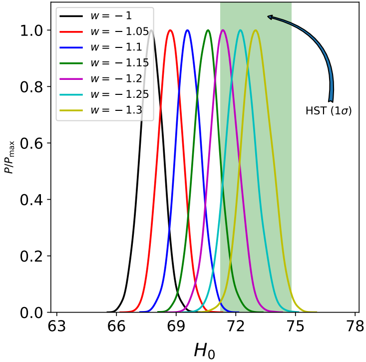
- Very hard to fit *all* available precision cosmological data (sort of an over-constrained algebraic system)
- Fixing problems produces new problems elsewhere (cf. Whac-a-mole!)
- Use of local H_0 prior questionable, [4] often central value of H_0 remains quite low, tension "relaxed" mostly because of larger uncertainties

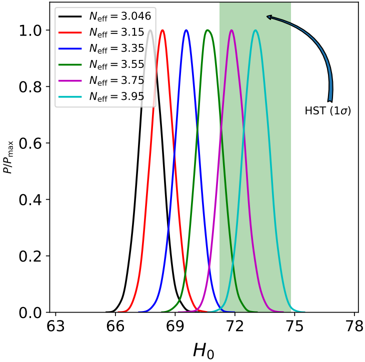
[4] See my blog post www.sunnyvagnozzi.com/blog/top-arxiv-week-26-2020 for an everyday life analogy regarding this point.

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 w and $N_{\rm eff}$

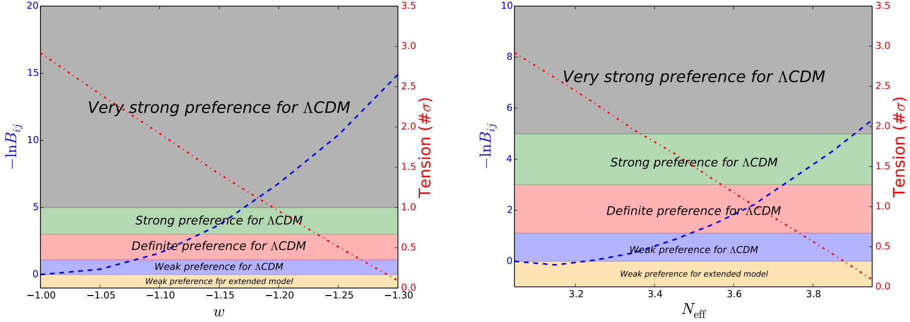




Vagnozzi, PRD 102 (2020) 023518

What if...?

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



Vagnozzi, PRD 102 (2020) 023518

Some (more-or-less-well-motivated) particle physics models *predict* specific values of w and $N_{\rm eff}$ See Section IVD of Vagnozzi, PRD 102 (2020) 023518

A laundry-list of problems/mistakes in the literature

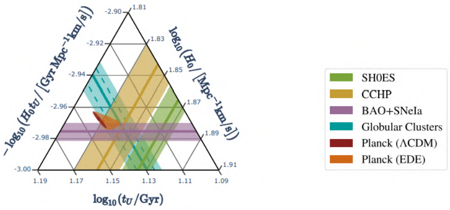
Disclaimer: we are (almost?) all sinners

- Leaving out one or more key datasets: BAO, Hubble flow SNeIa, CMB polarization, (galaxy clustering?)
- Misuse of the local H_0 prior See warnings in Benevento *et al.* 2020; Camarena & Marra 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 solutions, 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) [5] 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



[5] 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. Remember to not just blow up the uncertainty on H_0...
5. ...honour its 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

Conclusions