

Seven hints that early-time new physics alone is not sufficient to solve the Hubble tension

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STAR – Babeş-Bolyai University (UBB), 22 June 2023



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The Hubble constant

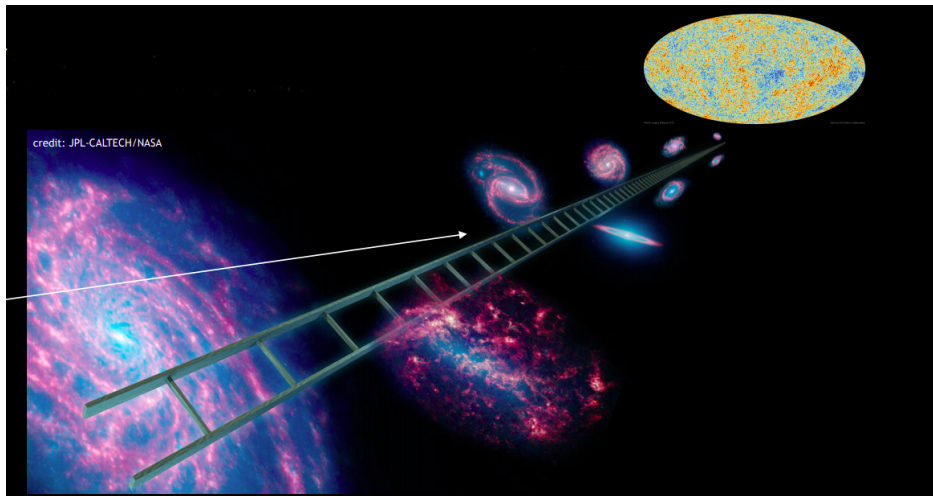
H_0 : current rate of expansion of the Universe

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 Λ CDM”*

See review by Di Valentino et al., CQG 38 (2021) 153001

H_0 as an end-to-end test



How to measure H_0 ?

Always a good idea in cosmology:

measure distances to measure the expansion rate

Luminosity distance:

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

Angular diameter distance:

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

Standard candles and standard rulers

In practice “infer distances” = “measure fluxes or angles”

Fluxes:

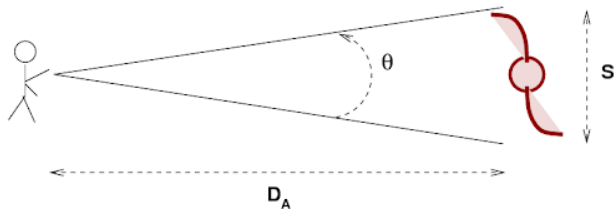
$$d_L = \sqrt{\frac{L}{4\pi f}}$$

L =intrinsic luminosity

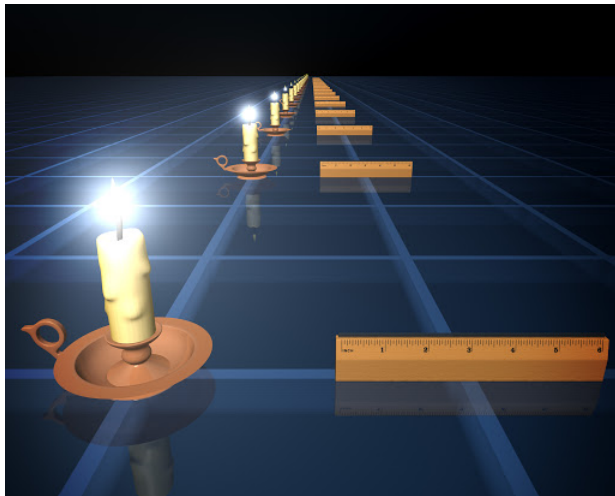
Angles:

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

s =intrinsic physical size



Standard candles and standard rulers



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

The CMB as a (self-calibrated) standard ruler

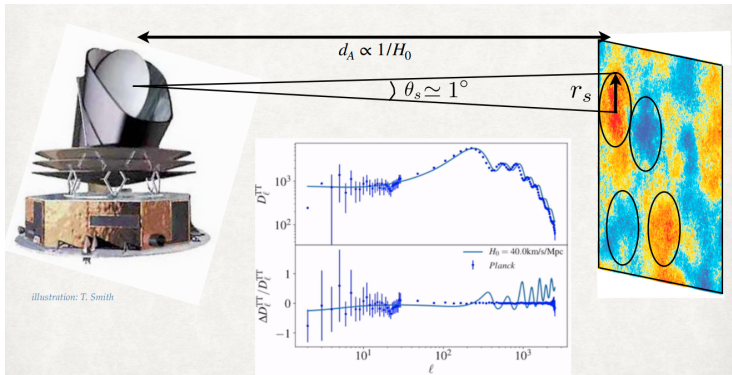
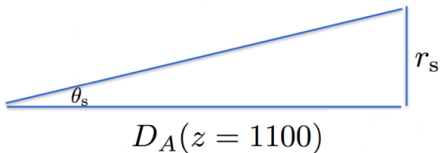


illustration: T. Smith



Credits: Tristan Smith and Vivian Poulin (above), Silvia Galli (below)

Applying the ruler

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

$$H_0 = 67.27 \pm 0.60$$

(Planck 2018 TTTEEE+lowE)

Planck collaboration, A&A 641 (2020) A6

Confirmed by ACT

$$H_0 = 67.9 \pm 1.5$$

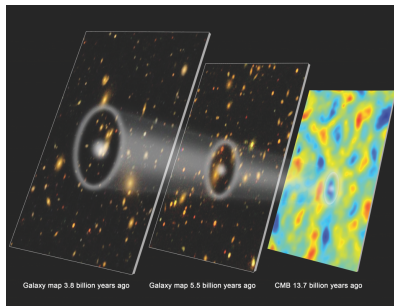
(ACT DR4)

ACT collaboration, JCAP 2012 (2020) 047

Late-time guard rails: the role of BAO

Can measure the sound horizon feature at different redshifts:

$$\theta_{\text{BAO}} \sim \frac{r_s(z_*)}{d_A(z_{\text{BAO}})}$$

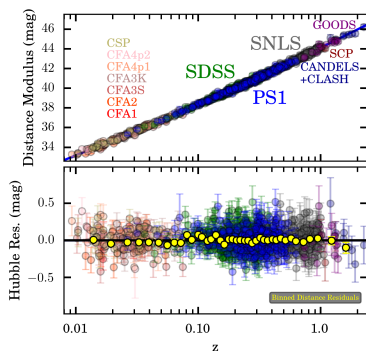


Credits: Eric Huff and the BOSS/SPT collaborations

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

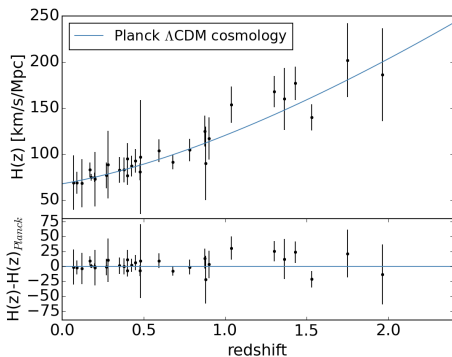
Other late-time guard rails

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



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

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



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

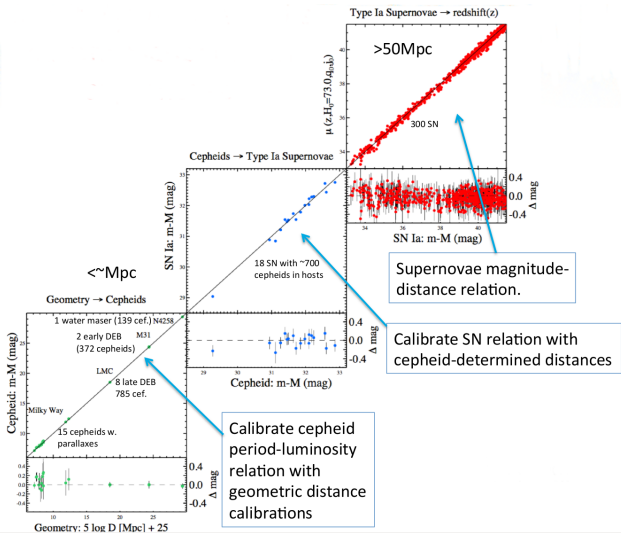
Combining CMB and late-time guard rails

$$H_0 = 67.72 \pm 0.40$$

(CMB+BAO+uncalibrated SNeIa)

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

PantheonPlus+SH0ES: several distance anchors, 42 calibrator SNeIa,
~ 300 SNeIa at $z < 0.15 \rightarrow 1.4\%$ measurement of H_0 ! Riess et al., ApJL 934 (2022) L7

$$H_0 = 73.04 \pm 1.04$$

(Cepheid-calibrated SNeIa, R22)

compare against

$$H_0 = 67.72 \pm 0.40$$

(CMB+BAO+uncalibrated SNeIa)

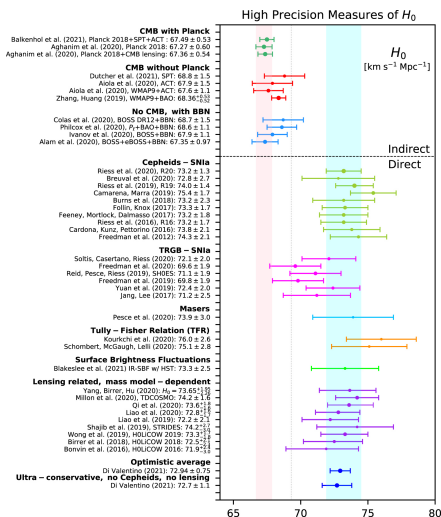
Almost 5σ tension!

The trouble

Several other inferences of H_0 beyond those discussed earlier, which make the tension more (or less) severe

Overall trend:

- “early-time” model-dependent measurements prefer low H_0
- “late-time” direct measurements prefer high H_0



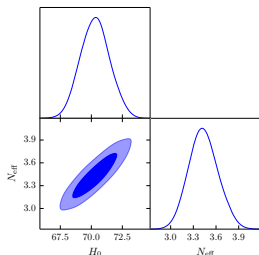
Di Valentino et al., CQG 38 (2021) 153001

A naïve first approach: CMB vs local measurements only

$$\theta_s = \frac{r_s(z_*)}{d_A(z_*)} = \frac{\int_{z_*}^{\infty} \frac{dz'}{H(z')}}{\int_0^{z_*} \frac{dz''}{H(z'')}}$$

Early-Universe new physics

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

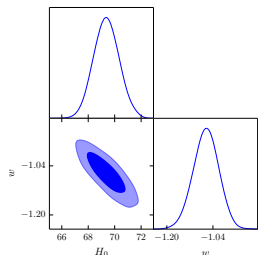


SV, PRD 102 (2020) 023518

$r_s(z_*)$ and $d_A(z_*)$ decrease at fixed θ_s , H_0 increases to decrease $d_A(z_*)$

Late-Universe new physics

Prototype: $w < -1$

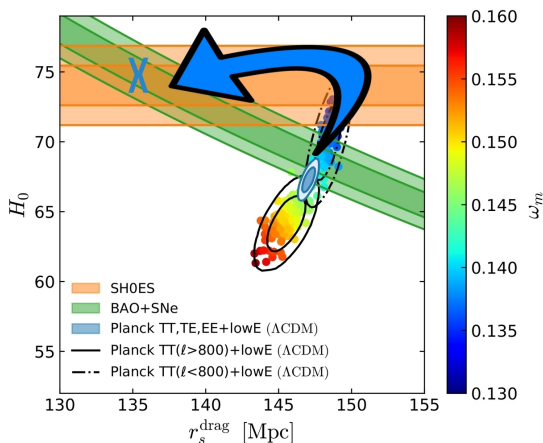


SV, PRD 102 (2020) 023518

$r_s(z_*)$ and $d_A(z_*)$ fixed so θ_s fixed, $d_A(z < z_*)$ decreases to increase H_0

Hubble tension no-go theorem

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



Knox & Millea, PRD 101 (2020) 043533

This would seem to require early-time (pre-recombination) new physics!

Hubble tension no-go theorem?


...yet, we still haven't been able to construct a model truly fixing H_0 (empirically, early-Universe new physics only seems to get to $H_0 \sim 70$)

Is early-time new physics the end of the story?

Perhaps not...

Opinion

Seven hints that early-time new physics alone is not sufficient to solve the Hubble tension

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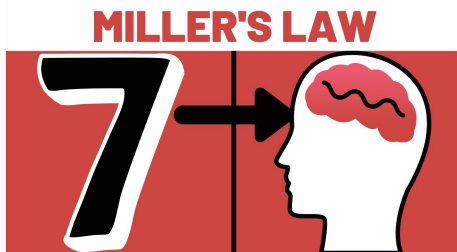
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Seven hints

- **A**ges of the oldest astrophysical objects
- **B**aryon Acoustic Oscillations r_d - H_0 degeneracy slope
- **C**osmic chronometers
- **D**escending trends observed in a wide range of low- z datasets
- **E**arly integrated Sachs-Wolfe effect and its restrictions on early-time new physics
- **F**ractional matter density (Ω_m) constraints from uncalibrated cosmic standards
- **G**alaxy power spectrum r_d - and k_{eq} -based determinations of H_0

Why seven? (*Why not?*) Miller, Psychol. Rev. 63 (1956) 81



Hint 1: Ages of the oldest astrophysical objects

Historically (1960s-1998) high- z OAOs provided the first hints for the existence of dark energy ($\Omega \neq 1$, $\Omega_\Lambda > 0$)

A 3.5-Gyr-old galaxy at redshift 1.55

James Dunlop, John Peacock, Hyron Spinrad, Arjun Dey, Raul Jimenez, Daniel Stern & Rogier Windhorst

Nature **381**, 581–584 (1996) | [Cite this article](#)

Conflict over the age of the Universe

M. Bolte & C. J. Hogan

Nature **376**, 399–402 (1995) | [Cite this article](#)

The observational case for a low-density Universe with a non-zero cosmological constant


J. P. Ostriker & Paul J. Steinhardt

Nature **377**, 600–602 (1995) | [Cite this article](#)

What can OAOs do for cosmology in the 2020s?

Hint 1: Ages of the oldest astrophysical objects

$$t_U(z) = \int_z^\infty \frac{dz'}{(1+z')H(z')} \propto \frac{1}{H_0}$$

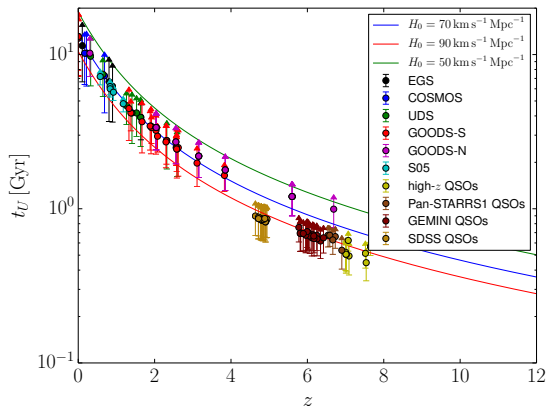
- OAOs cannot be older than the Universe \rightarrow **upper limit on H_0**
- $t_U(z)$ integral insensitive to early-time cosmology
- \rightarrow **late-time Λ CDM consistency test independent of early times!**
- **Ages of astrophysical objects at $z > 0$ hard to estimate robustly** 

Usefulness in relation to the H_0 tension:

- Contradiction between OAOs upper limit on H_0 and local H_0 measurements could indicate the need for non-standard late-time ($z \lesssim 10$) physics, or non-standard local physics
- Conclusions completely independent of pre-recombination physics

Hint 1: Ages of the oldest astrophysical objects

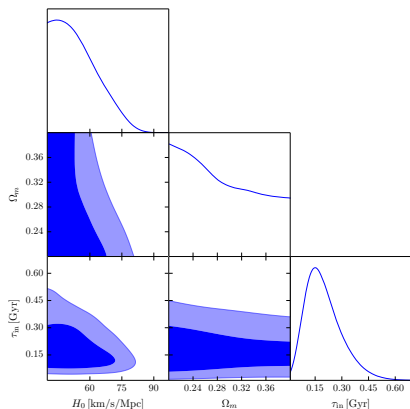
Age-redshift diagram up to $z \sim 8$



Hint 1: Ages of the oldest astrophysical objects

Assume Λ CDM at late times, constrain H_0 , Ω_m , and incubation time τ_{in}

Prior for τ_{in} following Jiménez *et al.*, JCAP 1903 (2019) 043; Valcin *et al.*, JCAP 2012 (2020) 022



CAVEAT – If the OAOs ages are reliable, possible explanations are:

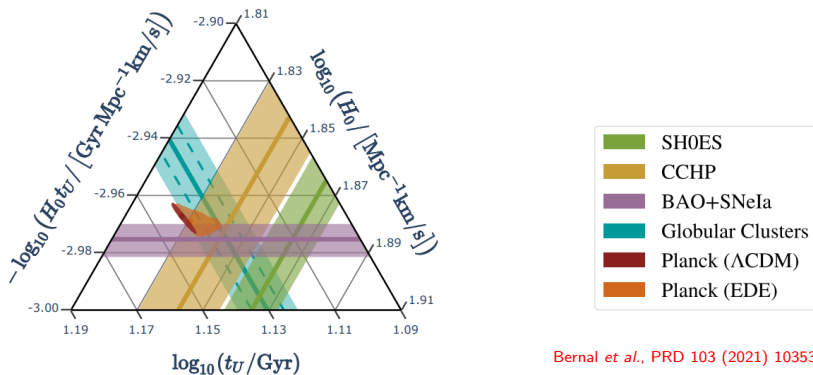
- #1: Λ CDM may not be the end of the story at $z \lesssim 10$
- #2: Nothing wrong with Λ CDM at $z \lesssim 10$, need new physics on local scales
- #3: Just a boring 2σ fluke or systematics?

SV, Pacucci & Loeb, JHEAp 36 (2022) 27

$H_0 < 73.2$ (95% C.L.)

Hint 1: OAOs

Cosmic triangles: current cosmological data within a given model are over-constrained, look at quantities beyond H_0 and r_d (e.g. Ω_m , t_U)



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

If high $t_U(z=0)$ measured reliably and with small uncertainties, models with high H_0 and standard low- z physics disfavored

Hint 2: BAO r_d - H_0 degeneracy slope

CMB and BAO constrain respectively:

$$\theta_\star \equiv \frac{r_\star}{D(z_\star)}, \quad \theta_d(z_{\text{obs}}) \equiv \frac{r_d}{D(z_{\text{obs}})}$$

Two sound horizons closely related:

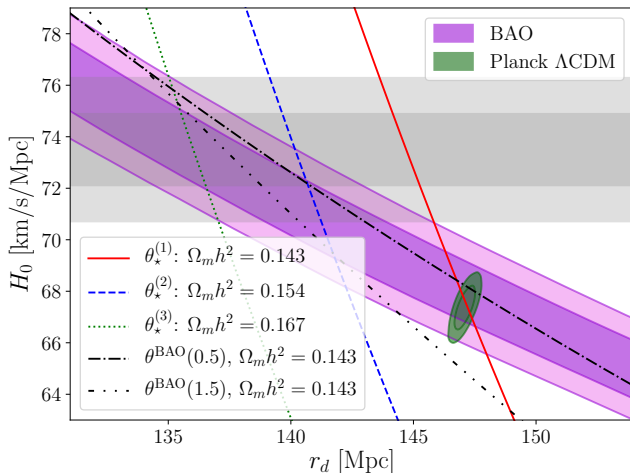
$$r_d \approx 1.0184 r_\star$$

For given ω_m , imposing $\theta_\star = \text{const}$ and $\theta_d(z_{\text{obs}}) = \text{const}$ defines a degeneracy line in the r_d - H_0 plane with very different slopes for CMB and BAO (steeper for CMB, because $z_\star \gg z_{\text{obs}}$)

Q: what happens if H_0 is raised, while *only* lowering r_d ...?

Hint 2: BAO r_d - H_0 degeneracy slope

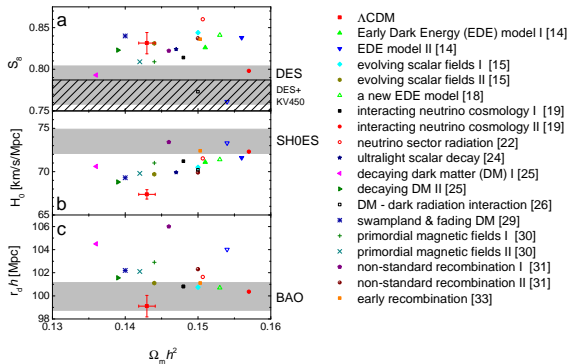
A: quickly run into trouble with BAO and/or WL data if ω_m is unchanged, but even changing ω_m cannot bring agreement with both!



Hint 2: BAO r_d-H_0 degeneracy slope

Lower $\omega_m \implies$ tension with BAO data

Higher $\omega_m \implies$ tension with WL data (worsen S_8 tension)



Jedamzik, Pogosian & Zhao, *Commun. Phys.* 4 (2021) 123

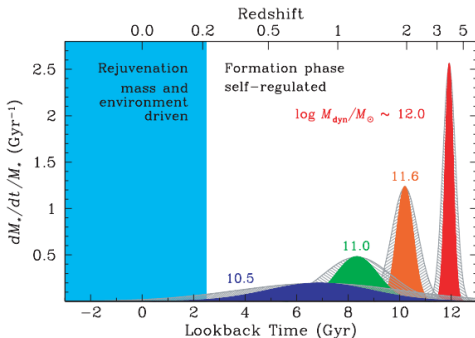
New physics which *only* reduces r_s is not enough!

Hint 3: Cosmic chronometers

Take two ensembles of galaxies that formed around the same time and are separated by a small redshift interval Δz around z_{eff} : Jiménez & Loeb, ApJ 573 (2002) 37

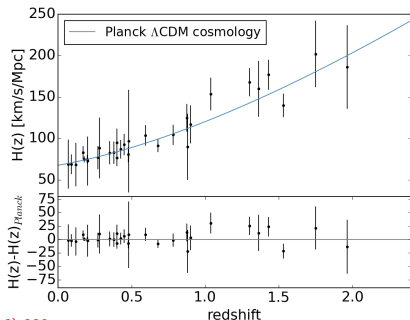
$$\frac{dt}{dz} = -\frac{1}{(1+z)H(z)} \implies H(z_{\text{eff}}) = -\frac{1}{1+z_{\text{eff}}} \frac{\Delta z}{\Delta t}$$

Use massive, early-time, passively-evolving galaxies (evolving on a much longer timescale than their age differences)



Hint 3: Cosmic chronometers

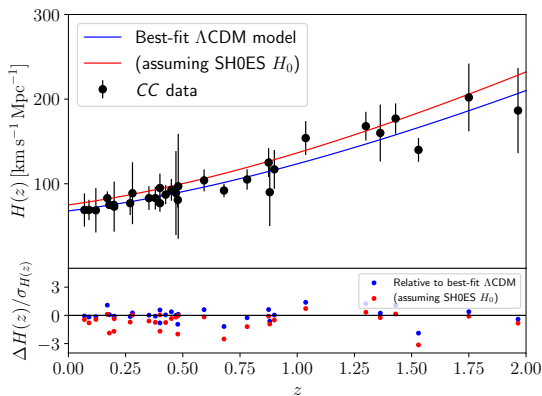
- CCs are completely (cosmological) model-independent
- CCs can be used to infer *cosmological*/*non-local* value of H_0
- Analyzing CC requires no assumptions on early-Universe physics
- Contradiction between CCs value of H_0 (assuming Λ CDM) and local H_0 measurements could indicate the need for non-standard late-time ($z \lesssim 2$) physics beyond Λ CDM, or non-standard local physics



Hint 3: Cosmic chronometers

Early-time-independent consistency test of Λ CDM: assuming Λ CDM holds at late times, from CC alone infer $H_0 = 67.5 \pm 3.0$

- Central value in excellent agreement with *Planck*
- Almost 2σ “tension” with local Cepheid-calibrated SNIa H_0
- Preference for low H_0 not driven by any specific datapoint



Hint 4: Descending trends

Mathematically speaking, dynamical models (e.g. Λ CDM) break down if values of (constant) fitting parameters pick up time dependence

Integrate 1st Friedmann equation with $w_{\text{eff}}(z)$ prescribed (in FLRW):

$$H_0 = H(z) \exp \left[-\frac{3}{2} \int_0^z dz' \frac{1 + w_{\text{eff}}(z')}{1 + z'} \right]$$

$H(z) \sim$ data $w_{\text{eff}}(z')$: prescribed model

H_0 : inferred fitting parameter (here mathematically integration constant)

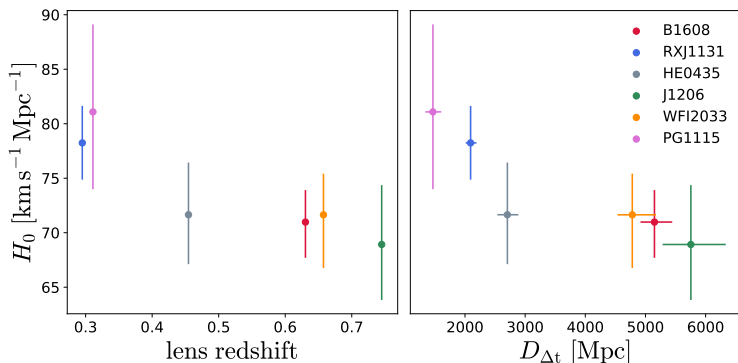
If input $w_{\text{eff}}(z)$ and data “disagree”, H_0 picks up z -dependence and “runs”
at all redshifts Krishnan et al., PRD 103 (2021) 103509

If H_0 tension physical, z -evolution of H_0 at intermediate z inevitable!

Hint 4: Descending trends

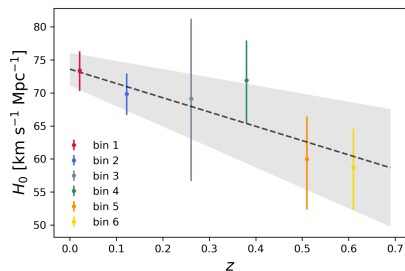
- Has such a z -evolution already been observed in current data?
- Has it been observed in independent datasets with a common trend?
- Are there mundane explanations for its size and direction?

Perhaps most famous example observed in H0LiCOW data ($\sim 2\sigma$)

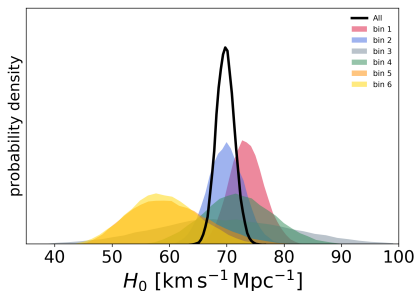


Hint 4: Descending trends

Combination of (binned) low- z datasets: megamaser distances, CCs, isotropic BAO, *Pantheon* SNeIa (r_d treated as free parameter)



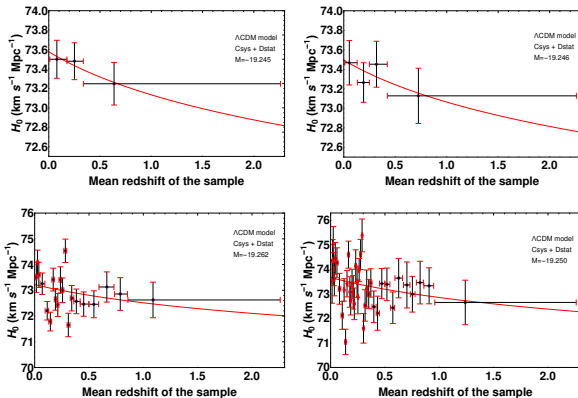
Krishnan *et al.*, PRD 102 (2020) 103525



$\sim 2.1\sigma$ significance, slope consistent with H0LiCOW, by construction independent of early-Universe physics

Hint 4: Descending trends

(Binned) *Pantheon* SNeIa



Dainotti *et al.*, *ApJ* 912 (2021) 150

$\sim 2\sigma$ significance, well fit by $H(z) = H_0(1+z)^{-\alpha}$, with $\alpha \sim 10^{-2}$

Hint 4: Descending trends

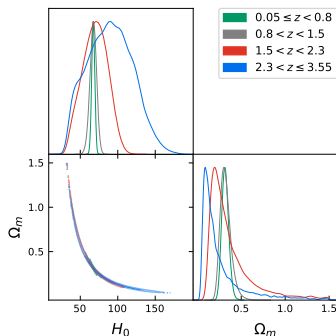
Similar trends (descending H_0 and/or increasing Ω_m) observed in many different dataset combinations:

- *PantheonPlus+SH0ES* SNela [Jia, Hu & Wang, A&A 674 \(2023\) A45](#)
- *PantheonPlus* SNela [Malekjani et al., arXiv:2301.12725](#)
- *Pantheon* SNela [Horstmann, Pietschke & Schwarz, A&A 668 \(2022\) A34](#)
- *CC+Pantheon* SNela+QSOs [Ó Colgáin et al., arXiv:2206.11447](#)
- QSOs [Risaliti & Lusso, Nat. Astron. 3 \(2019\) 272](#)
- $f\sigma_8$ measurements: S_8 increasing with redshift [Adil et al., arXiv:2303.06928](#)
- ...and others!

Question: could this be expected even within Λ CDM? (naïve guess: at high z lose sensitivity to DE, so expect $\Omega_m \uparrow \implies H_0 \downarrow$)

Hint 4: Descending trends

Forecast with mock data matching expected sensitivity of DESI



Ó Colgáin, Sheikh-Jabbari & Solomon, PDU 40 (2023) 101216

- Slight trend actually in the *opposite* direction
- Trend seen at z *smaller* than those where one expects to see it
- Expected size in any case *much smaller* than what is observed

Taken seriously, descending trends indicate need for new late-time physics

Hint 5: Early ISW effect

Around recombination: Universe not fully matter dominated \implies residual decay of gravitational potentials \implies eISW effect sources anisotropies

$$\Theta = \int_0^{\eta_0} d\eta \left[\underbrace{\propto g(\Theta_0 + \Psi)}_{\text{Sachs-Wolfe}} + \underbrace{\propto g v_b \frac{d}{d\eta}}_{\text{Doppler}} + \underbrace{\propto e^{-\tau} (\dot{\Psi} - \dot{\Phi})}_{\text{ISW}} + \underbrace{\propto (g\Pi + [g\ddot{\Pi}])}_{\text{Polarization}} \right] j_\ell(k\Delta\eta)$$

$$\Theta_\ell^{\text{ISW}}(k) = \underbrace{\int_0^{\eta_m} d\eta e^{-\tau} (\dot{\Psi} - \dot{\Phi}) j_\ell(k\Delta\eta)}_{\text{early ISW}} + \underbrace{\int_{\eta_m}^{\eta_0} d\eta e^{-\tau} (\dot{\Psi} - \dot{\Phi}) j_\ell(k\Delta\eta)}_{\text{late ISW}}$$

(A substantial amount of) New physics increasing $H(z)$ around z_{eq}/z_* *should* leave an imprint on the eISW effect!

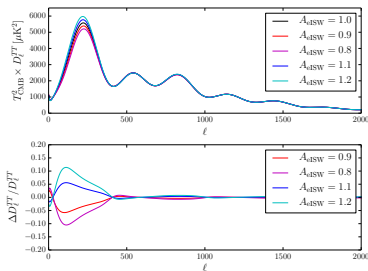
Why is there no clear sign of early-time new physics in CMB data alone?

Hint 5: Early ISW effect

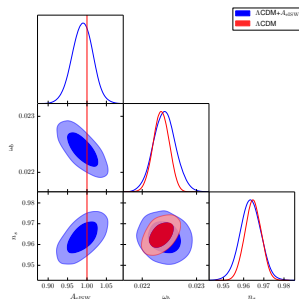
$$\Theta_{\ell}^{\text{eISW}}(k) = A_{\text{eISW}} \int_0^{\eta_m} d\eta e^{-\tau} (\dot{\Psi} - \dot{\Phi}) j_{\ell}(k\Delta\eta)$$

Consistency check: within Λ CDM, data consistent with $A_{\text{eISW}} = 1$?

Yes! $A_{\text{eISW}} = 0.988 \pm 0.027$ (other parameters stable to within $\lesssim 0.3\sigma$)



SV, PRD 104 (2021) 063524



SV, PRD 104 (2021) 063524

Hint 5: Early ISW effect

High H_0 EDE fit to CMB requires increased $\omega_c \rightarrow$ worsens S_8 tension?

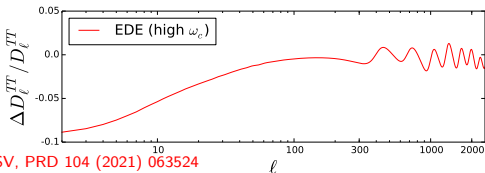
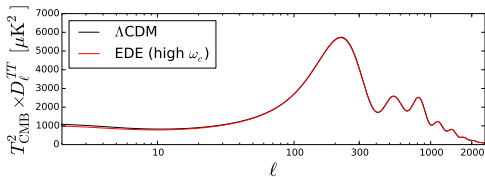
Hill *et al.*, PRD 102 (2020) 043507; Ivanov *et al.*, PRD 102 (2020) 103502; D'Amico *et al.*, JCAP 2105 (2021) 072; see partial rebuttals in: Murgia *et al.*, PRD 103 (2021) 063502; Smith *et al.*, PRD 103 (2021) 123542

Editors' Suggestion

Early dark energy does not restore cosmological concordance

J. Colin Hill, Evan McDonough, Michael W. Toomey, and Stephon Alexander
Phys. Rev. D 102, 043507 – Published 5 August 2020

Parameter	Λ CDM	EDE (high ω_c)	EDE (low ω_c)
$100\omega_b$	2.253	2.253	2.253
ω_c	0.1177	0.1322	0.1177
H_0 [km/s/Mpc]	68.21	72.19	72.19
τ	0.085	0.072	0.072
$\ln(10^{10} A_s)$	3.0983	3.0978	3.0978
n_s	0.9686	0.9889	0.9889
f_{EDE}	–	0.122	0.122
$\log_{10} z_c$	–	3.562	3.562
θ_i	–	2.83	2.83
n	–	3	3

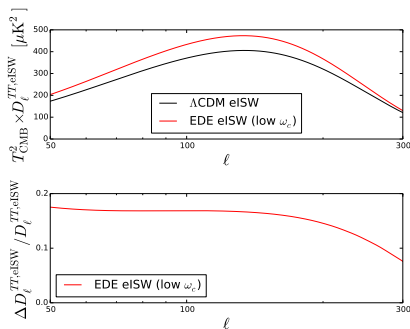


SV, PRD 104 (2021) 063524

Hint 5: Early ISW effect

Let's extract only eISW contribution to temperature anisotropies...

Low ω_c

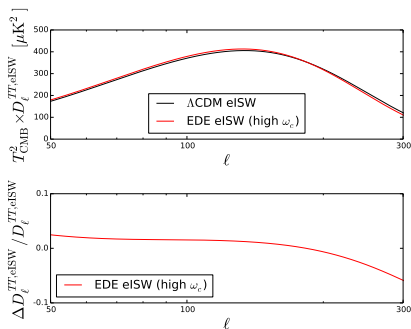


SV, PRD 104 (2021) 063524

Almost 20% eISW excess!

Problem generic to models increasing pre-recombination $H(z)$

High ω_c



SV, PRD 104 (2021) 063524

No more than \lesssim 3-5% eISW excess

Hint 6: Ω_m constraints from EUPIUCS

Beneficial to look at joint H_0 - Ω_m constraints rather than just projected H_0 constraints [Lin, Mack & Hou, ApJL 904 \(2020\) L22](#)

Can we determine Ω_m :

- At a level competitive with the CMB model-dependent value?
- Free from early-Universe assumptions (as with BAO+SNela)?

$\Delta r H_0$ small & insensitive to early-Universe physics [Lin, Chen & Mack, ApJ 920 \(2021\) 159](#)

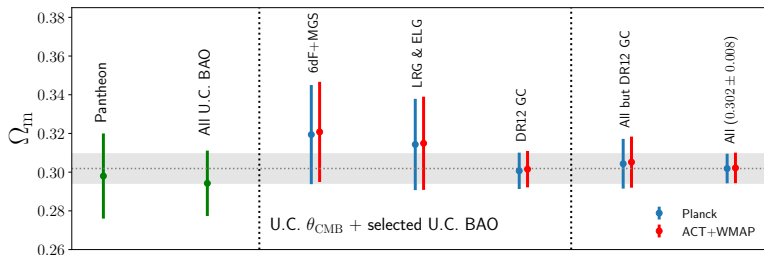
$$\Delta r H_0 \equiv (r_d - r_\star) H_0 = \int_{z_d}^{z_\star} dz \frac{c_s(z)}{E(z)} \quad (z_d - z_\star) \sim 30$$

Combine θ_\star (CMB) and θ_d (BAO) in almost early Universe-independent way, with long lever arm to constrain Ω_m at level competitive with CMB: Early Universe Physics Insensitive Uncalibrated Cosmic Standards (UCS)

Hint 6: Ω_m constraints from EUPIUCS

Data: θ_* (*Planck*+ACT+WMAP), θ_d (eBOSS), CMB priors on z_* and Δz_s , BBN prior on $\Omega_b h^2$

Parameters: Ω_m , \mathcal{M} , $r_d H_0$, h (weak dependence)



Lin, Chen & Mack, *ApJ* 920 (2021) 159

Purely geometrical, early Universe-independent value: $\Omega_m = 0.302 \pm 0.008$

For comparison $\Omega_m = 0.310 \pm 0.006$ in Λ CDM using full CMB information

Hint 6: Ω_m constraints from EUPIUCS

Constraints not exactly along Ω_m direction, weak Ω_m - h degeneracy

$$\left(\frac{\Omega_m}{0.3}\right) \left(\frac{h}{0.7}\right)^{-0.08} = 1.0060 \pm 0.0258$$

Combine UCS with several early Universe-independent late-time, non-local measurements to infer H_0 in an early Universe-independent way

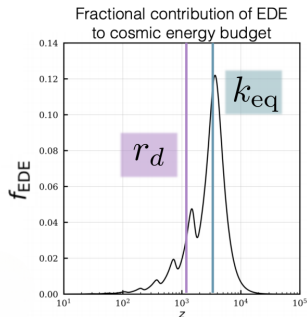
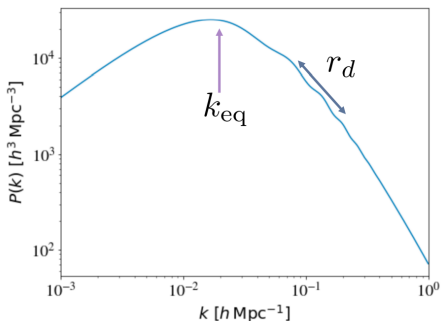
Methods	H_0 (km s ⁻¹ Mpc ⁻¹)		n - σ from R21	
	Without θ_{cmb}	With θ_{cmb}	Without θ_{cmb}	With θ_{cmb}
UCS and individual nonlocal observation				
Cosmic chronometers				
Current public data	69.1 \pm 1.7	68.8 \pm 1.6	1.9 σ	2.1σ
Extra systematic	69.4 \pm 2.3	69.2 \pm 2.1	1.4 σ	1.6σ
Extra systematic, conservative	69.3 \pm 3.4	68.9 \pm 3.3	1.1 σ	1.2σ
γ -ray optical depth	66.2 \pm 3.5	66.1 \pm 3.4	1.9 σ	2.0σ
Cosmic age				
$t_U = 13.5 \pm 0.27$ Gyr	70.2 \pm 1.7	69.8 \pm 1.5	1.4 σ	1.7σ
$t_U = 13.5 \pm 0.33$ Gyr	70.3 \pm 2.1	69.8 \pm 1.9	1.2 σ	1.5σ
CMB lensing+DES+BBN	68.8 \pm 2.4	68.6 \pm 2.0	1.6 σ	1.9σ
UCS and joint nonlocal observations ^a				
All nonlocal observations	69.1 \pm 1.5	68.8 \pm 1.3	2.0 σ	2.4σ
Nonlocal observations without cosmic age	68.3 \pm 1.9	68.1 \pm 1.6	2.1 σ	2.5σ
Nonlocal observations without LSS	69.1 \pm 1.6	68.8 \pm 1.5	2.0 σ	2.2σ

Lin, Chen & Mack, ApJ 920 (2021) 159

Residual $\approx 2\sigma$ tension can have nothing to do with early-Universe physics: need late-time new physics and/or local new physics (systematics very unlikely given consistency among independent probes)

Hint 7: r_s - and k_{eq} -based constraints on H_0 from $P(k)$

Two scales in $P(k)$, both standard rulers



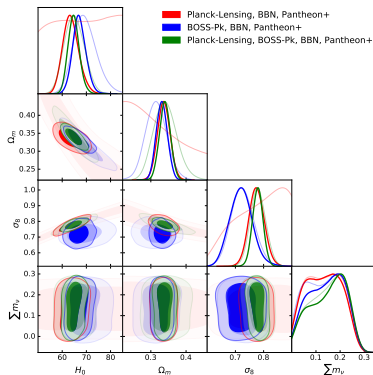
Credits: Oliver Philcox

- $k_{\text{eq}} = \sqrt{2\Omega_m H_0 z_{\text{eq}}}$ sets peak and overall shape ($z_{\text{eq}} \approx 3500$)
- r_d sets BAO frequency ($z_* \approx 1100$)

Both can be used to infer H_0 : in the presence of a substantial amount of new physics, no reason two values should agree!

Hint 7: r_s - and k_{eq} -based constraints on H_0 from $P(k)$

Can analyze $P(k)$ data removing (most) r_d information (effectively marginalizing over r_d), similarly CMB lensing also sensitive to k_{eq}



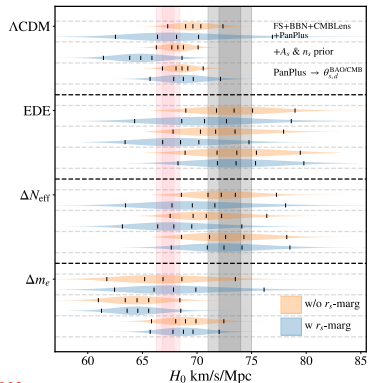
Philcox *et al.*, PRD 106 (2022) 063530

$H_0 = 64.8^{+2.2}_{-2.5}$ (only k_{eq} info): agrees with Λ CDM r_d -based value of H_0 , disfavors significant amount of early-time new physics?

Hint 7: r_s - and k_{eq} -based constraints on H_0 from $P(k)$

Caveats:

- Current error bars still quite large
- r_d vs r_d -marginalized comparison model-dependent...
- ...and (Ω_m) prior-dependent



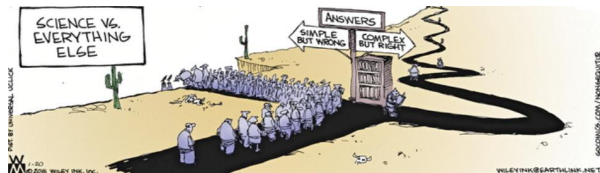
Smith, Poulin & Simon, arXiv:2208.12992

Future data should improve discriminatory power!

Where to from here? Some scattered thoughts

- Empirically: early-time physics only seems to reach $H_0 \sim 70$ (no external priors)
- Idea: combine early-time and late-time (both non-local) and local new physics?
- Direction of late-time physics: lower $d_A(z)$ at $z > 0$ (phantom/interacting DE?)
- BAO and high- z SNeIa actually can tolerate w as low as ~ -1.07 (even $-1.10?$), $\Delta H_0 \sim -20(1 + w)$, so this can help as much as $\Delta H_0 \sim 1.5$ [SV, PRD 102 \(2020\) 023518](#)
- If there is *also* some local new physics lowering local H_0 , maybe don't need non-local H_0 to go all the way up to ~ 74 after all? (two can meet halfway)
- Early-time new physics probably still need to do the lion's share of the job...
- Early+late: can two models decouple, both "push" non-local H_0 up separately, combining their tension-solving virtues "in phase" / "constructively"?

Objection: wouldn't this violate Occam's razor? (my opinion ↓)



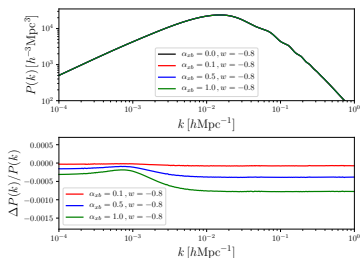
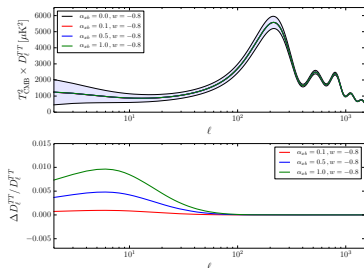
Where to from here? What about the S_8 tension?

Early times: a relatively successful early-time model (EDE and variants, $\Delta m_e, \dots$)

Late times: scattering-type new physics (at 1st order does not affect background but only perturbations) involving DM and/or DE \rightarrow decouple S_8 -solving effects from H_0 -solving ones, combine the two constructively?

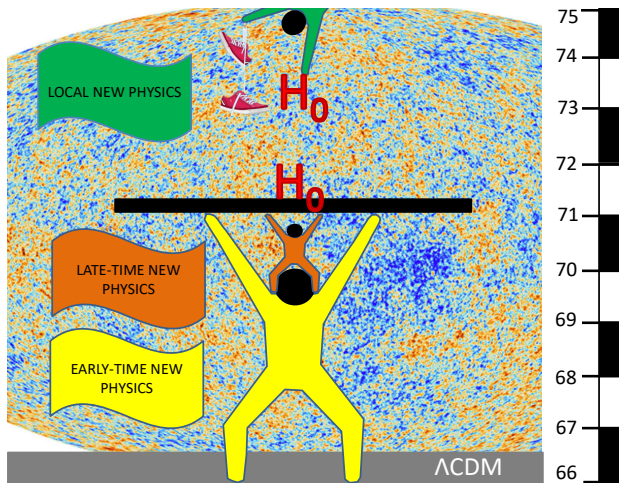
Example: DE-baryon scattering

$$\begin{aligned}\dot{\theta}_b &= -\mathcal{H}\theta_b + c_s^2 k^2 \delta_b + \frac{4\rho_\gamma}{3\rho_b} a n_e \sigma_T (\theta_\gamma - \theta_b) + (1 + w_x) \frac{\rho_x}{\rho_b} a n_e \sigma_{xb} (\theta_x - \theta_b) \\ \dot{\theta}_x &= -\mathcal{H}(1 - 3c_s^2)\theta_x + \frac{c_s^2 k^2}{1 + w_x} \delta_x + a n_e \sigma_{xb} (\theta_b - \theta_x)\end{aligned}$$



Where to from here?

Pictorial representation of what I think could be a promising scenario




Conclusions

- Seve(ral/n) hints that early-time new physics alone cannot solve the Hubble tension
- My opinion: will probably need a combination of early-time and late-time (both non-local) and local new physics, non-local and local H_0 might not need to meet at ~ 74 but halfway
- “Decoupling” of early- and late-time tension-solving effects may also help S_8 : I find scattering-type models particularly promising

Stay tuned for more details soon!

Opinion

Seven hints that early-time new physics alone is not sufficient to solve the Hubble tension

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