A Growing Universe... and Tension
Cosmology With Low-Redshift Observations: Any Signal For New Physics at Early Times?

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Feb 5, 2022

Reference: Phys. Rev. D 97,103511(2018)
Jarah Evslin, Anjan A Sen, Ruchika
Reference: Phys. Rev. D 102.103525(2020)
C. Krishnan, E. O Colgain, Ruchika, A. A. Sen, Sheikh-Jabbari and T. Yang

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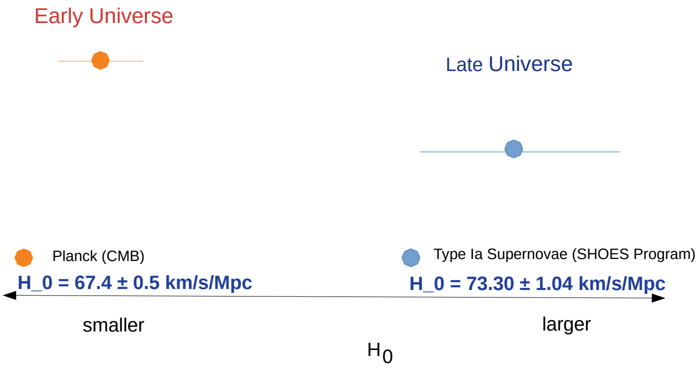
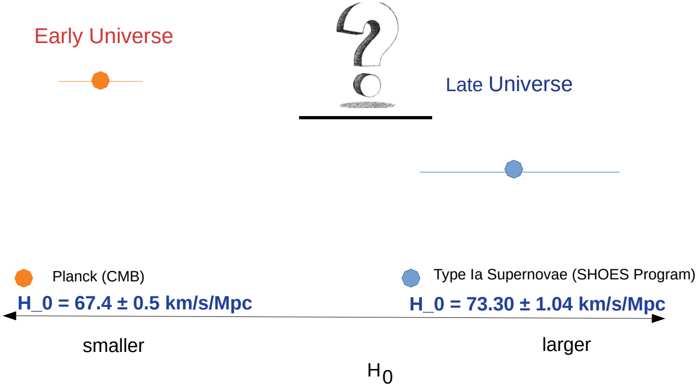
Outline of the talk ◇

- How Early Dark Energy was proposed to be a solution to Hubble Tension?
- Is Early Dark Energy a solution to Hubble Tension?

Tension between Early and Late Universe ◇



Tension between Early and Late Universe ◇



The Price of Shifting the Hubble Constant.

Jarah Evslin, Anjan A Sen, Ruchika

Phys. Rev. D 97,103511(2018)

Question: How Early Dark Energy was proposed to be a solution to Hubble Tension?

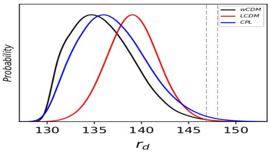
Question : If we fix H_0 to SH0ES value, how much low-redshift data(BAO+Masers+TDSL) shifts the value of Sound Horizon at drag epoch r_d ? ◇

Maximum Likelihood values and 1D marginalised 68% confidence intervals of parameters for respective models.
Taking value of $H_0 = 73.24 \pm 1.24$ Km/s/M pc.

	Ω_m0	r_d	w_0	w_a
ΛCDM	0.295 ± 0.019	139.2 ± 3.2	N/A	N/A
wCDM	0.277 ± 0.027	135.3 ± 3.8	-0.76 ± 0.14	N/A
CPL	0.241 ± 0.084	136.4 ± 3.9	-0.77 ± 0.17	0.44 ± 0.53

Also, $H_0 = 136.41 \pm 3.82$ confirmed model independently by Salvatore et al.(2018).

	Planck		Local Measurements
H_0	$67.37 \pm 0.54 Km/sec/Mpc$	⇒	73.24 ± 1.24 Km/s/M pc.
r_d	$147.26 \pm 0.29 Mpc$	⇐	$139.2 \pm 3.2 Mpc$



$r_d = 147.26 \pm 0.29 Mpc$ (Planck)

- ΛCDM: 2.52 σ away from Planck
- wCDM : 3.14 σ away from Planck
- CPL : 2.79 σ away from Planck

So, our results are quite model independent.
So, The Price of shift in Hubble constant is the shift in r_d.

Answer: The shift in value of sound horizon is more than 2 σ away than Planck inferred r_d value.

Interpretation: How Early Dark Energy was a proposed solution to Hubble Tension? ◇

BAO together with measurement of H_0 by Strong Lensing and Local Distance Ladder, give r_d which is significantly smaller than that from Planck-2018 for LCDM.

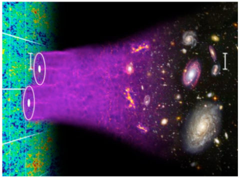
r_d is the Sound Horizon at drag epoch

$$r_d = \int_0^{t(zd)} c_s(1+z)dt$$

Physics: sound waves in early Universe propagate until radiation and matter decouple.

Lower r_d as compared to Planck suggets:

◇ changing z_d
◇ modifying the speed of sound
◇ changing the age of universe at drag epoch
◇ changing primodial fluctuations



Credit: Blake & Moorfield

Conclusion ◇

◇ Along with Hubble Tension, there is a similar tension involving sound horizon at drag epoch from low-redshift and Planck measurements.

◇ It does not depend on dark energy behaviour.

◇ Solution: One needs to modify the early Universe cosmology.

Is there an early Universe solution to Hubble tension?

Chethan Krishnan, Eoin Ó Colgáin, Ruchika, Anjan A. Sen, M. M. Sheikh-Jabbari, Tao Yang

Phys. Rev. D 102, 103525(2020)

Question: Is Early Dark Energy a solution to Hubble Tension?

H0LiCOW XIII. A 2.4% measurement of H0 from lensed quasars ◇

H0LiCOW XIII: A 2.4% measurement of H_0 23

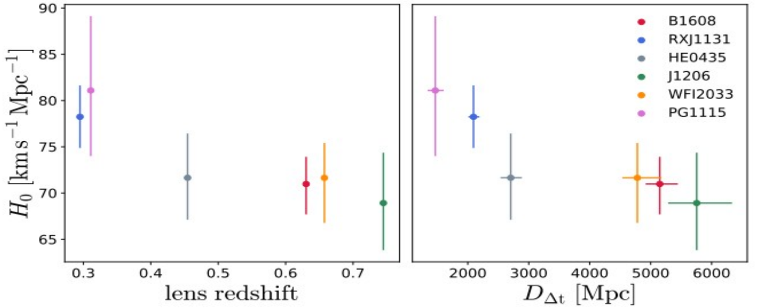


Figure A1. H_0 constraints for the individual H0LiCOW lenses as a function of lens redshift (left) and time-delay distance (right). The trend of smaller H_0 value with increasing lens redshift and with increasing $D_{\Delta t}$ has significance levels of 1.9σ and 1.8σ, respectively.

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Why is it interesting? ◇

If the H0LiCOW result is substantiated, Implications are as follows:

◇ First, this trend cannot be explained by keeping ΛCDM and adjusting the sound horizon using early Universe physics , since this will only raise and lower the trend

◇ Thus may be staring at preliminary evidence for a new cosmology at late times

Data Sets Used: $\diamond$

- Isotropic BAO measurements by the 6dF survey ($z = 0.106$), SDSS-MGS survey ($z = 0.15$)
- Anisotropic BAO measurement by BOSS-DR12 at $z = 0.38, 0.51, 0.61$
- Angular diameter distances from megamaser hosting galaxies: UGC 3789, NGC 6264, NGC 6323, NGC 5765b, CGCG 074-064 and NGC 4258 in the range $0.002 \leq z \leq 0.034$
- Cosmic chronometer (CC) data for $z \leq 0.7$
- We incorporate 924 Type Ia SNe from the Pantheon dataset in the range $0.01 < z \leq 0.7$ [32], including both the statistical and systematic uncertainties.

Constraints while taking datasets $\leq$ 0.7 $\diamond$

Table: Best-fit values for cosmological parameters

H_0 $[\frac{\mathrm{km}}{\mathrm{s\ Mpc}}]$	Ω_m	r_d [Mpc]	M
$69.74^{+1.60}_{-1.56}$	$0.30^{+0.02}_{-0.02}$	$144.83^{+3.44}_{-3.34}$	$-19.36^{+0.05}_{-0.05}$

$\diamond$ **If we don't do binning,** we get value of H_0 around $69.74^{+1.60}_{-1.56}$, So now it is conceivable that the Planck result for flat ΛCDM is an "averaged" value, which is essentially a *coarse-grained* value for H_0.

And then we introduce the bining! ⋄

Bin	Data
1	Masers, SNe
2	iso BAO, SNe, CC
3	SNe, CC
4-6	aniso BAO, SNe, CC

TABLE I: Summary of the data in each bin.

$$\text{bin 1:} \quad \bar{z}_1 = 0.021 \in (0, 0.029],$$
$$\text{bin 2:} \quad \bar{z}_2 = 0.122 \in (0.029, 0.21],$$
$$\text{bin 3:} \quad \bar{z}_3 = 0.261 \in (0.21, 0.321].$$
$$\text{bin 4:} \quad \bar{z}_4 = 0.38 \in (0.321, 0.47],$$
$$\text{bin 5:} \quad \bar{z}_5 = 0.51 \in (0.47, 0.557],$$
$$\text{bin 6:} \quad \bar{z}_6 = 0.61 \in (0.557, 0.7],$$

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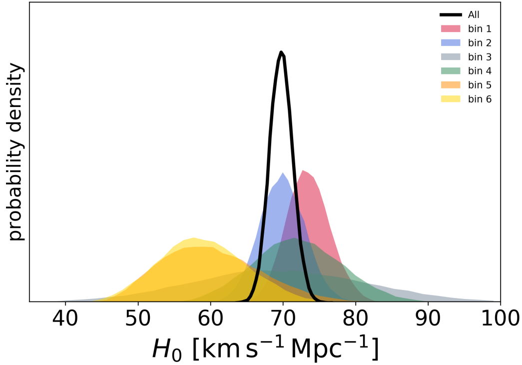
$$\bar{z}_i = \frac{\sum_k^{N_i} z_k (\sigma_k)^{-2}}{\sum_k^{N_i} (\sigma_k)^{-2}},$$

Results ◇

$\bar{z}$	H_0 $[\frac{km}{s\ Mpc}]$	Ω_m	r_d [Mpc]	M
0.021	$73.41^{+3.10}_{-2.88}$	$0.51^{+0.33}_{-0.34}$	–	$-19.26^{+0.09}_{-0.09}$
0.122	$69.85^{+3.17}_{-3.10}$	$0.26^{+0.10}_{-0.09}$	$143.08^{+7.14}_{-6.74}$	$-19.36^{+0.09}_{-0.09}$
0.261	$69.10^{+12.46}_{-12.12}$	$0.27^{+0.20}_{-0.15}$	–	$-19.39^{+0.40}_{-0.33}$
0.38	$71.90^{+6.42}_{-6.03}$	$0.22^{+0.11}_{-0.09}$	$143.94^{+9.94}_{-8.91}$	$-19.33^{+0.15}_{-0.15}$
0.51	$59.98^{+7.64}_{-6.45}$	$0.37^{+0.12}_{-0.10}$	$164.05^{+17.66}_{-15.92}$	$-19.65^{+0.23}_{-0.23}$
0.61	$58.72^{+6.40}_{-5.87}$	$0.44^{+0.12}_{-0.10}$	$161.04^{+13.31}_{-11.55}$	$-19.59^{+0.18}_{-0.17}$

Decreasing Trend of H_0 with redshift is verified! ◇



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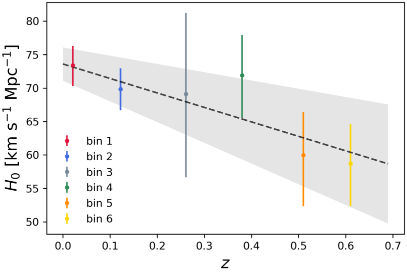

- We fit the same linear regression through the data with the original binned H_0 values and find that the slope of the data falls 2.1 σ (which is 1.7 σ in H0LiCOW) away from the slope of the null hypothesis.
- Concretely, we find the intercept $H_0 = 73.6 \pm 2.5$, which is curiously close to H0LiCOW's H_0 determination.

Conclusions ◇

- Decreasing trend of H_0 with redshift as proposed by H0LICOW is verified.
- If the trend is true, Then all the Early Universe Solutions to Hubble Tension will be falsified.
- If we don't do binning we get value of H_0 around $69.74^{+1.60}_{-1.56}$, So now it is conceivable that the Planck result for flat ΛCDM is an "averaged" value, which is essentially a *coarse-grained* value for H_0.

THANK YOU!