Investigating cosmological tensions in low and high redshift observational data

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INFN, Roma

Nov 11, 2023

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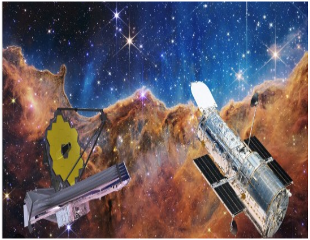
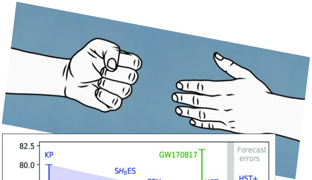
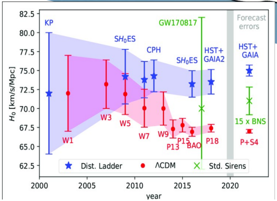
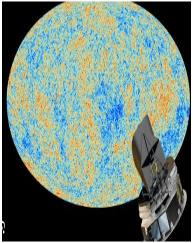
India

Reconciling **JWST, HST** with **Planck**









Outline of the talk ◇

- Introducing Hubble Law
- Tension between Early and Late Universe
- How the late and early universe measurements are done?
- How and why early dark energy was proposed to be a solution to Hubble tension?
- Can early dark energy be a solution to Hubble tension?
- Moving on to Late Universe solutions
- Negative Cosmological Constant proposed as a possible solutions to cosmological tensions
- Can G-Transition in the calibrator box solve Hubble Tension?
- Final Take-away!

Introducing Hubble Law ◇

In 1929, Edwin Hubble using 100-inch Hooker telescope at Mount Wilson discovered that the Universe is expanding.

$$v = H_0 * d$$

velocity　　　　distance

The Hubble constant (H0) is named for astronomer **Edwin Hubble.** And astronomers use this value to make a variety of cosmological estimations, most critically **the expansion rate** and **age of the universe ~ 13.8 Gyr.**

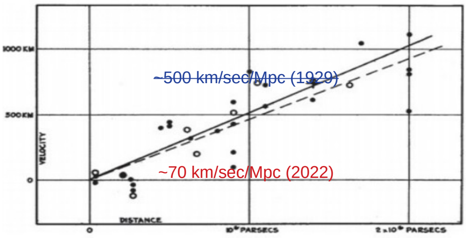
Hubble Law ◇

$$v = H_0 * d$$

velocity distance

v = km/sec
d = Mpc
H0 = km/sec/Mpc

Velocity-Distance Relation among Extra-Galactic Nebulae.



- wrong in 1929 - due to wrong zero point calibration of Standard candles (stars or galaxies).[1]

[1] Contributions: Vesto Slipher and Henrietta Swan Leavitt; Lemaitre, Robertson and Alexander Friedmann

Hubble Law ◇

$$v = H_0 * d$$

velocity distance

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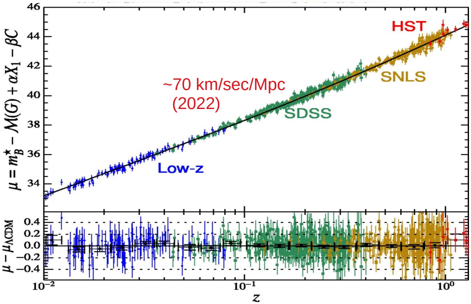


- The slight deviation in shape at large distances is the evidence for acceleration.

by N. A. Bahcall

Hubble Law at comparatively larger distances ◇

$$v = H_0 * d$$

Or

$$cz = H_0 * d_L$$

c= speed of light

z = redshift

d_L = distance

For smaller distances

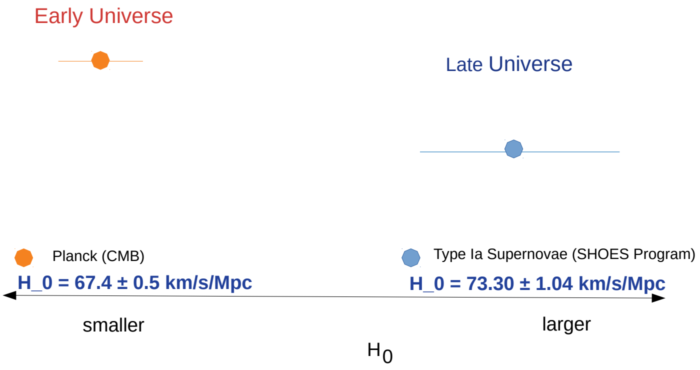
$$d_L = \frac{cz}{H_0}(1 - \frac{q_0 z}{2} + O(z^2))$$

q_0 = deceleration parameter

H_0 = Hubble Constant

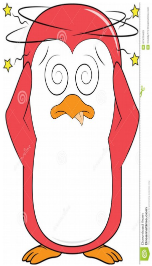
Valid till comparatively larger distances

Current state - Tensions (Hubble Tension) ◇

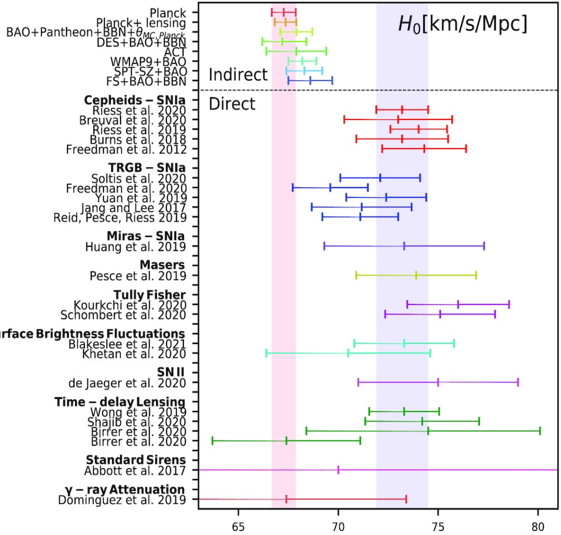


Current state - Tensions (Hubble Tension) ◇

Current state : > 5 sigma tension between Planck and SH0ES 2022

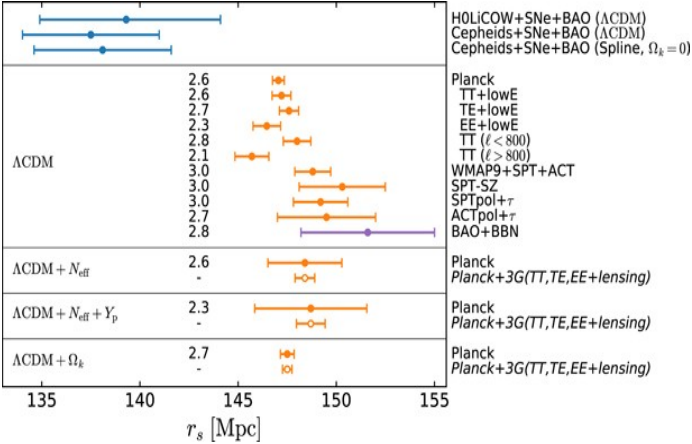


Questions that follow: Is ΛCDM the right theoretical model?



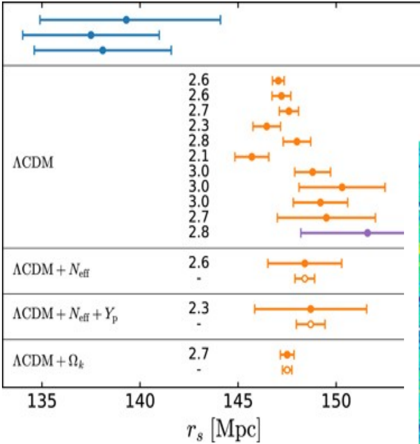
Di Valentino : Mon.Not.Roy.Astron.Soc. 502 (2021)

Price of shift in Hubble Constant is the shift in r_d ◇



Aylor et al. [Astrophys.J. 874 (2019)]

Current state - Tensions (r_d Tension) ◇



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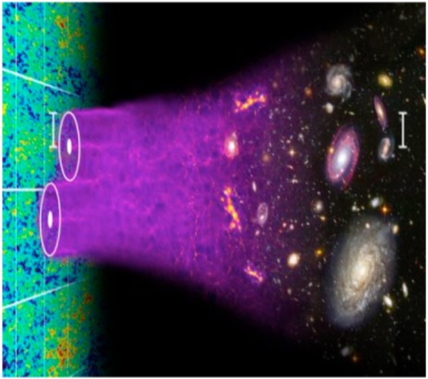


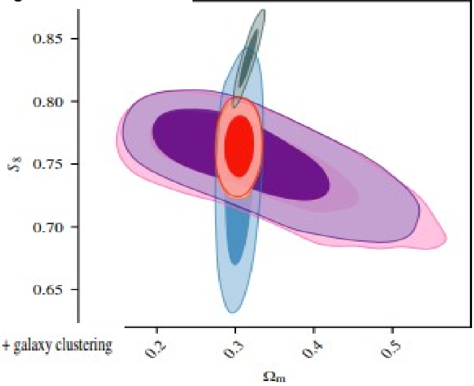
Credit: Blake & Moorfield

Another tension - $S_8 = \sigma_8\sqrt{\Omega_m}$ Tension ◇

Astronomy & Astrophysics manuscript no. KiDS_1000_3x2pt ©ESO 2020
December 9, 2020

KiDS-1000 Cosmology: Multi-probe weak gravitational lensing and spectroscopic galaxy clustering constraints

~ 2-3 σ discrepancy
from Planck



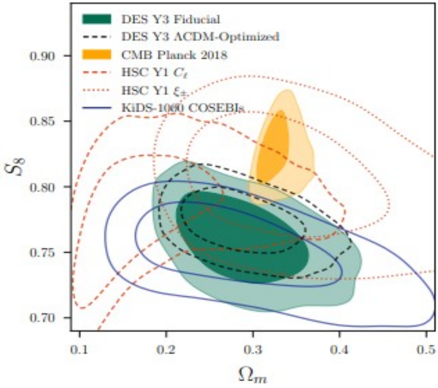
Another tension - $S_8 = \sigma_8\sqrt{\Omega_m}$ Tension ◇

DES-2019-0480
FERMILAB-PUB-21-253-AE

Dark Energy Survey Year 3 Results:
Cosmology from Cosmic Shear and Robustness to Modeling Uncertainty

KiDS and DES in agreement

And both in disagreement with Planck



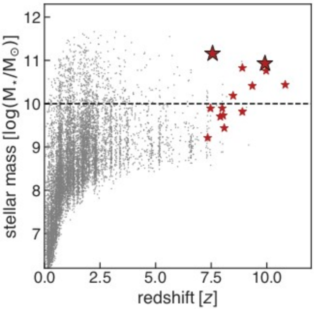
New JWST Observations suggests presence of very massive galaxies at very high redshifts ◇

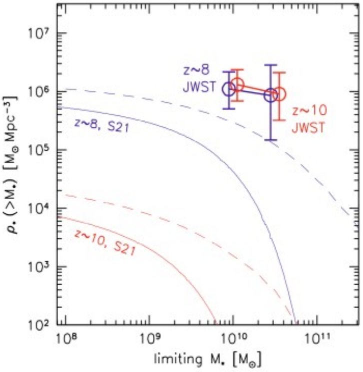
A very early onset of massive galaxy formation

Ivo Labbé[1], Pieter van Dokkum[2], Erica Nelson[3], Rachel Bezanson[4], Katherine A. Suess[5,6], Joel Leja[7,8,9], Gabriel Brammer[10], Katherine Whitaker[10,11], Elijah Mathews[7,8,9], Mauro Stefanon[12,13]

CEERS program – NIRCam

Obeserves galaxies with stellar masses as high as M ∼ 10^11 Ms around z= 7.6





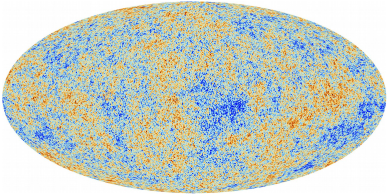
Unlocking the Sigma Spectrum ⋄

Sigma	Their Interpretation
1σ:	Weak Evidence
2σ:	Suggestive Finding
3σ:	Substantial Support
5σ:	Definitive Discovery

Unlocking the Sigma Spectrum ◇

Sigma	Their Interpretation
1σ:	Weak Evidence
2σ:	Suggestive Finding
3σ:	**Substantial Support**
4σ:	**Strong Evidence**
5σ:	Discovery

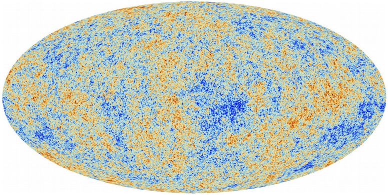
H0 inference from Early and Late Universe ◇



http://www.esa.int/var/esa/storage/images/esa_multimedia/images/2013/03/planck_cmb/12583930-4-eng-GB/Planck_CMB_pillars.jpg

- How do we infer Hubble constant from CMB?

H0 inference from Early and Late Universe ◇



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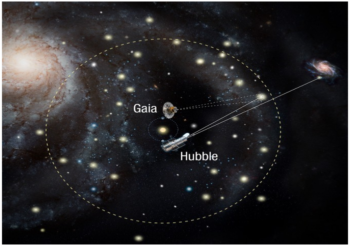
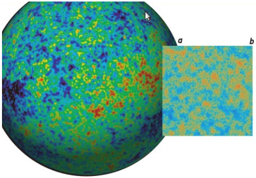
http://www.esa.int/var/esa/storage/images/esa_multimedia/images/2013/03/planck_cmb/12583930-4-eng-GB/Planck_CMB_pillars.jpg

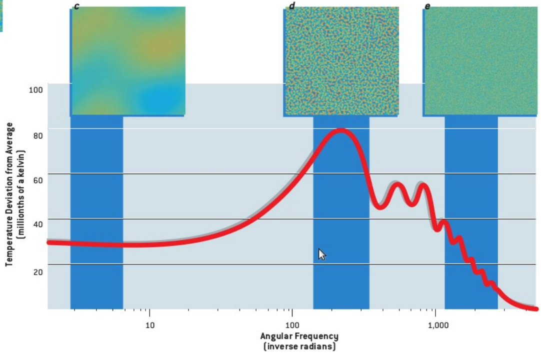
- How do we infer Hubble constant from Late Universe (local measurements) SH0ES?



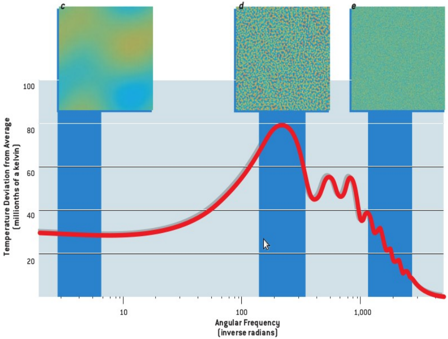
https://mk0astronomynow9oh6g.kinstacdn.com/wp-content/uploads/2018/07/071318_hubble_constant.jpg

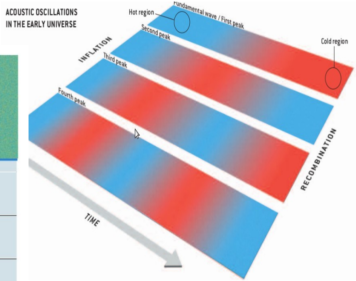
Early Universe: CMB ◇





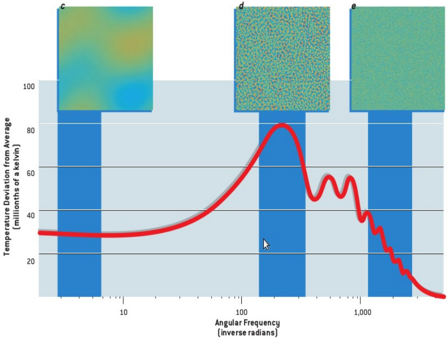
Early Universe: CMB ◇

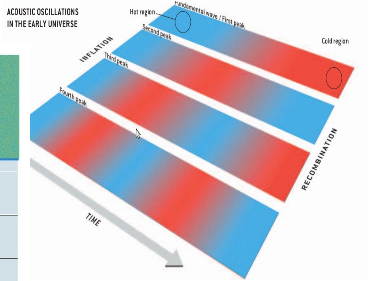




By Wayne Hu and Martin White

Early Universe: CMB ⋄



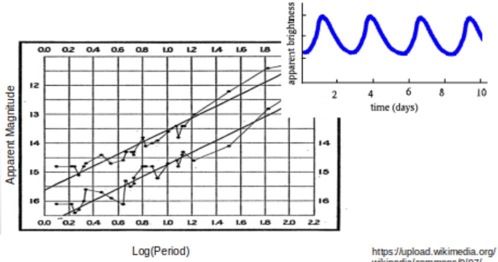


$$r_s^\star = \int_0^{t_\star} \frac{dt}{a(t)}\, c_s(t) = \int_{z_\star}^{\infty} \frac{dz}{H(z)}\, c_s(t),$$

By Wayne Hu and Martin White

Late Universe: Parallex, Cepheids and WFC3 ◇

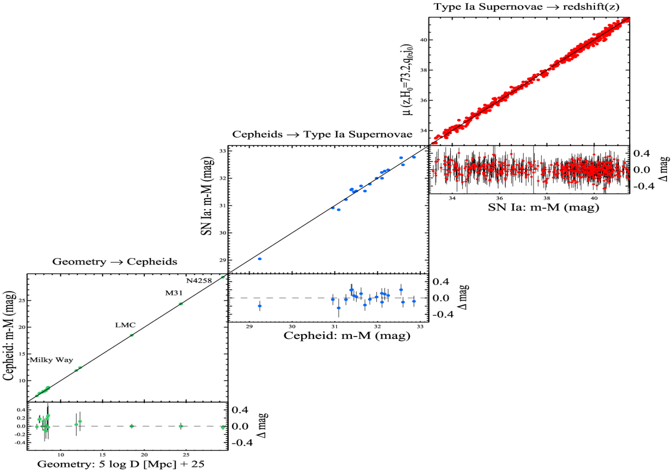
- SHOES (Supernovae, H0, for the Equation of State for Dark Energy)



https://upload.wikimedia.org/wikipedia/commons/9/97/HSLeavittHSCr13Fig2_1912.jpg

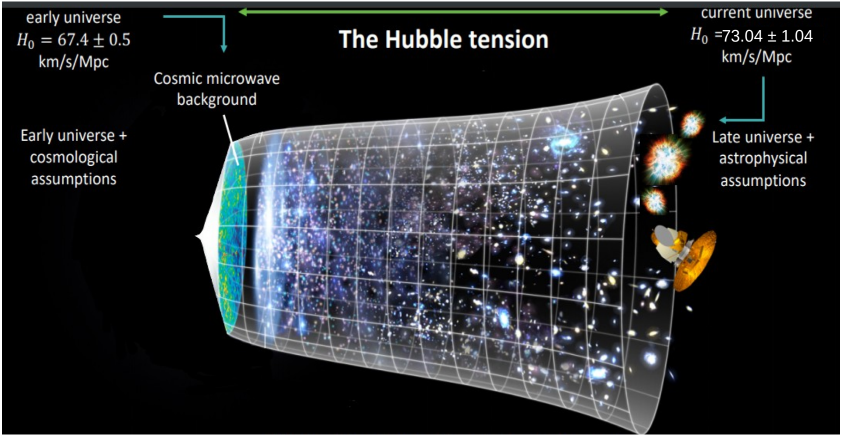
- Cepheids are pulsating stars which fade and brighten at rates that are proportional to their true brightness.
- The distances to the Cepheids using a basic geometrical technique called parallax.
- With Hubble's sharp-eyed Wide Field Camera 3 (WFC3), they extended the parallax measurements further than previously possible, across the Milky Way galaxy

Distance Ladder: Cepheids, Masers, DEBs and Supernovae-Ia ◇

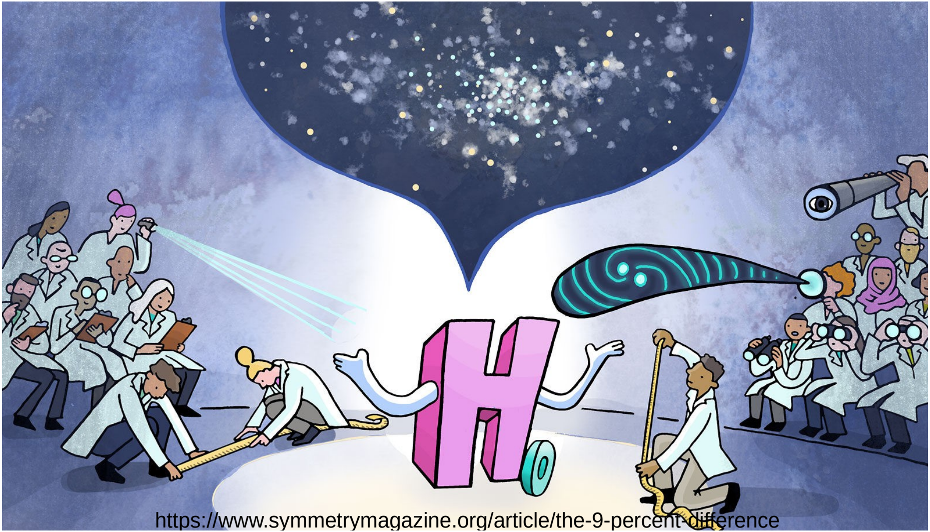


Hubble Tension ◇

> 5 sigma

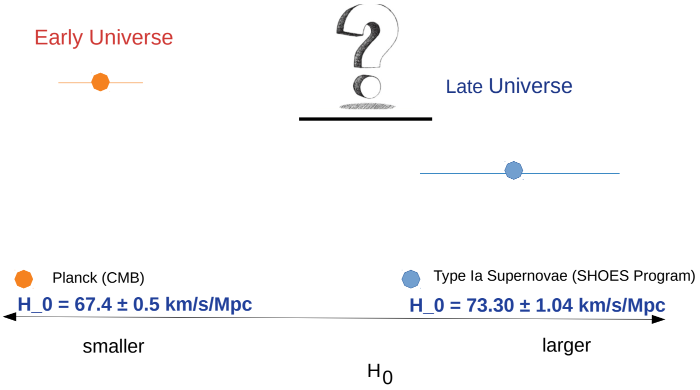


Tension between early and late measurements ◇



https://www.symmetrymagazine.org/article/the-9-percent-difference

Tension signifies Systematic Error or Hint towards New Physics? ◇



New Physics Solutions: Early Type ◇

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

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?

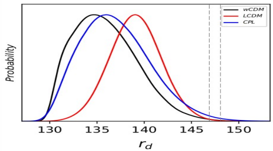
Question : If we fix H_0 to SH0ES value, how much low-redshift data(BAO+Masers+TDSL) shifts the value of Sound Horizon at drag epoch r_d ? ◇

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	$67.37 \pm 0.54 Km/sec/Mpc$	$\Rightarrow$	73.24 ± 1.24 Km/s/M pc.
r_d	$147.26 \pm 0.29 Mpc$	$\Leftarrow$	$139.2 \pm 3.2 Mpc$



$r_d = 147.26 \pm 0.29 Mpc$ (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.

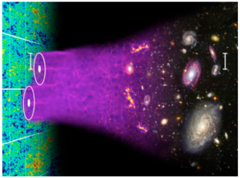
r_d is the Sound Horizon at drag epoch

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

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 ◇

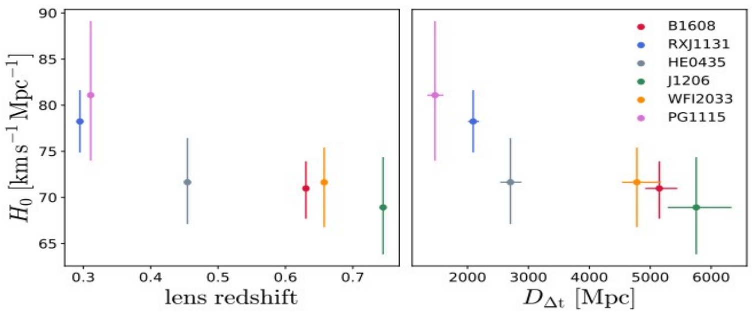


Figure A1. H_0 constraints for the individual H0LiCOW lenses as a function of lens redshift (left) and time-delay distance (right). The trend of smaller H_0 value with increasing lens redshift and with increasing $D_{\Delta t}$ has significance levels of 1.9σ and 1.8σ, respectively.

K. C. Wong et al

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 ≤ 0.7 ⋄

Table: Best-fit values for cosmological parameters

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

⋄ **If we don't do binning,** we get value of H_0 around $69.74^{+1.60}_{-1.56}$ km/sec/Mpc, 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.

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

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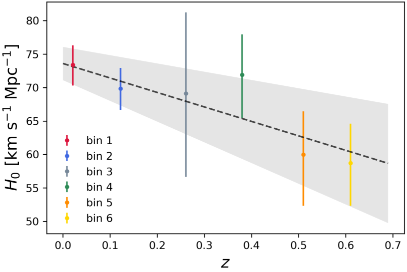
$$\text{bin 5:} \quad \bar{z}_5 = 0.51 \in (0.47, 0.557],$$
$$\text{bin 6:} \quad \bar{z}_6 = 0.61 \in (0.557, 0.7],$$

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

Results ◇

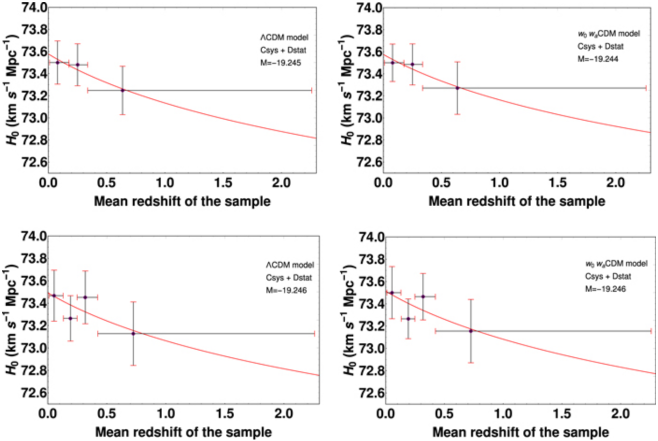
$\bar{z}$	H_0 [$\frac{\text{km}}{\text{s Mpc}}$]	Ω_m	r_d [Mpc]	M
0.021	$73.41^{+3.10}_{-2.88}$	$0.51^{+0.33}_{-0.34}$	...	$-19.26^{+0.09}_{-0.09}$
0.122	$69.85^{+3.17}_{-3.10}$	$0.26^{+0.10}_{-0.09}$	$143.08^{+7.14}_{-6.74}$	$-19.36^{+0.09}_{-0.09}$
0.261	$69.10^{+12.46}_{-12.12}$	$0.27^{+0.20}_{-0.15}$	...	$-19.39^{+0.40}_{-0.33}$
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! ◇



- 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 $H_0 = 73.6 \pm 2.5$ km/sec/Mpc, which is curiously close to H0LiCOW's H_0 determination.

Decreasing Trend of H_0 with redshift is verified by other studies ◇



M. G. Dainotti et al 2021, ApJ 912 150

Conclusions ◇

- Decreasing trend of H_0 with redshift as proposed by H0LICOW is verified.
- If we don't do binning, we get value of H_0 around $69.74^{+1.60}_{-1.56}$ km/sec/Mpc, 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.
- **If the trend is true, Then all the Early Universe Solutions to Hubble Tension will be falsified.**
- **Motivating to find the solution of Hubble Tension in late universe physics**

Other observations ΛCDM can not explain: JWST ◇

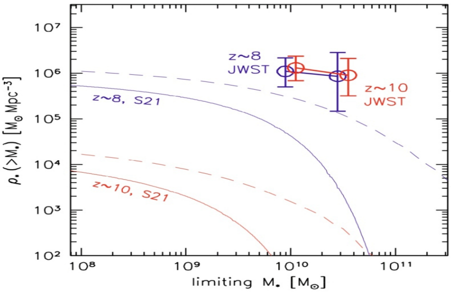


Figure 4: Stellar mass density in *JWST*-selected massive galaxies. The large symbols show the total mass density of the seven galaxies in two redshift bins, $7 < z < 9$ and $9 < z < 11$, and for two limiting masses, $\log(M_*/M_\odot) > 10$ and $\log(M_*/M_\odot) > 10.5$. The lines are derived from Schechter fits to UV-selected samples.[3] Dashed lines are derived from Monte Carlo simulations that perturb the masses of individual galaxies. The perturbations are drawn from a log-normal distribution with a 1σ width of 0.48 dex (a factor of 3). The *JWST*-selected galaxies greatly exceed the expected mass densities of massive galaxies at these redshifts.

2

[2] Labbe et al.

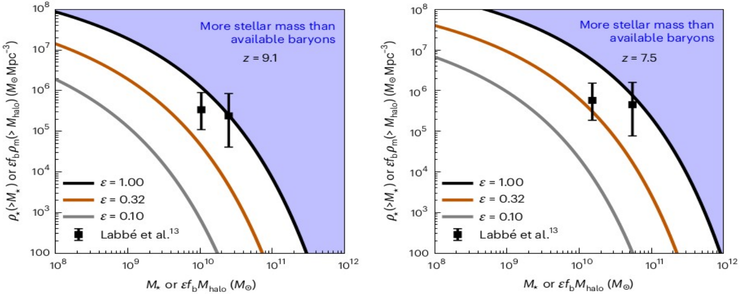
Stress Testing ΛCDM with High-redshift Galaxy Candidates ◇

nature astronomy

Article https://doi.org/10.1038/s41550-023-01937-7

Stress testing ΛCDM with high-redshift galaxy candidates

Boylan et al.



$$\rho_\star(\bar{M}) = \epsilon f_b \int_{z_1}^{z_2} \int_{\bar{M}}^{\infty} \frac{dn}{dM} M dM \frac{dV}{V(z_1, z_2)} ,$$

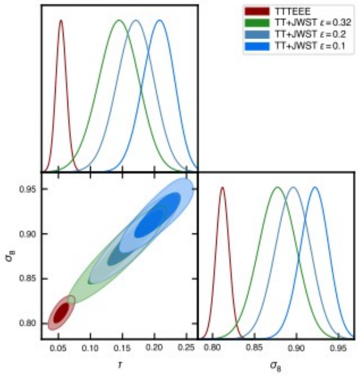
Can present cosmological models explain observations from Early JWST Observations?

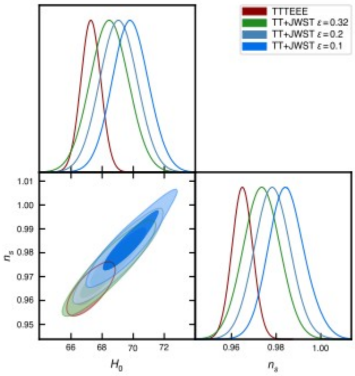
Matteo Forconi, Ruchika, Alessandro Melchiorri

Phys. Rev. D 97,103511(2018)

Question: Does disagreement exist because of CMB polarization measurements?

Does disagreement exist because of CMB polarization measurements? ⋄



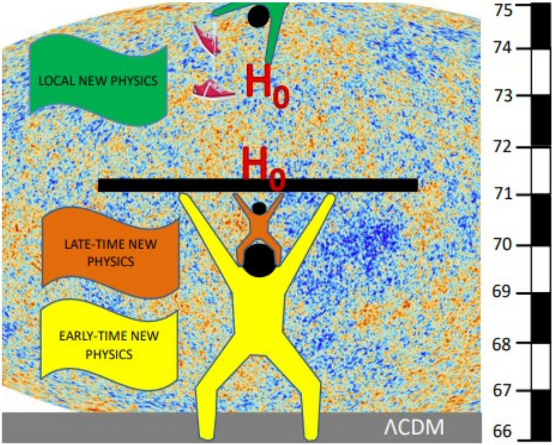


Planck Data Release

$\tau = 0.089^{+0.012}_{-0.014}$ 2013

$\tau = 0.054^{+0.0081}_{-0.0071}$ 2018

Are early universe solutions enough? ◇



SH0ES: Supernova H0 for the Equation of State

UniverseÂ 9Â (2023)Â 9,Â 393,Â

By Sunny Vaganozzi

PC: Cristina Ghirardini

Let's talk about Late time Solutions ...

Cosmolological Model Independent Approach : Cosmography

with Salvatore Capozziello, Anjan Sen

$$H(z) = H_0 + H_{10} z + \frac{H_{20}}{2!} z^2 + \ldots \text{(The Taylor Series expansion)}$$

where $H_{i0} = \frac{d^i H}{dz^i}|_{z=0}$.

$$H(t) = \frac{1}{a}\frac{da}{dt}$$

$$q(t) = -\frac{1}{a}\frac{d^2 a}{dt^2}\left[\frac{1}{a}\frac{da}{dt}\right]^{-2} ; j(t) = \frac{1}{a}\frac{d^3 a}{dt^3}\left[\frac{1}{a}\frac{da}{dt}\right]^{-3}$$

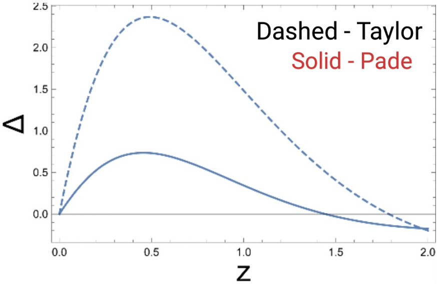
$$s(t) = \frac{1}{a}\frac{d^4 a}{dt^4}\left[\frac{1}{a}\frac{da}{dt}\right]^{-4} ; l(t) = \frac{1}{a}\frac{d^5 a}{dt^5}\left[\frac{1}{a}\frac{da}{dt}\right]^{-5}$$

$$\begin{aligned}
H_1 &= H_{10}/H_0 = 1 + q_0 \\
H_2 &= H_{20}/H_0 = -q_0^2 + j_0 \\
H_3 &= H_{30}/H_0 = 3q_0^2(1 + q_0) - j_0(3 + 4q_0) - s_0 \\
H_4 &= H_{40}/H_0 = -3q_0^2(4 + 8q_0 + 5q_0^2) + j_0(12 + 32q_0 + 25q_0^2 - 4j_0) + s_0(8 + 7q_0) + l_0
\end{aligned}$$

Pade Approxmation ◇

$$H(z) = H_0 + H_{10} z + \frac{H_{20}}{2!} z^2 + \ldots \text{(The Taylor Series expansion)} \quad (1)$$

where $H_{i0} = \frac{d^i H}{dz^i}|_{z=0}$.



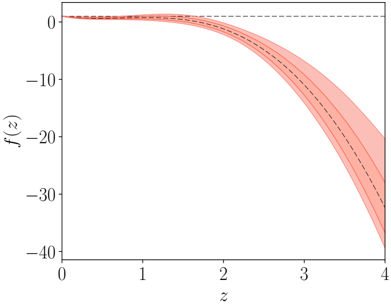
$$E(z) = \frac{H(z)}{H_0} = \frac{1 + P_1 z + P_2 z^2}{1 + Q_1 z + Q_2 z^2} \text{(The Pade Approximation } (P_{2,2})\text{)} \quad (2)$$

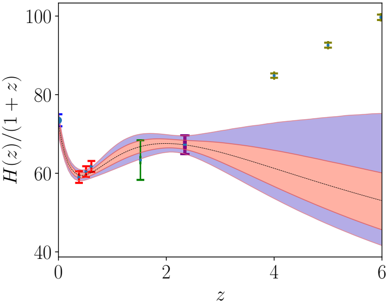
Negative Cosmological Constant is Consistent with Cosmological Data.

with Koushik Dutta, Anirban Roy, Anjan A. Sen, M. M. Sheikh-Jabbari ◇

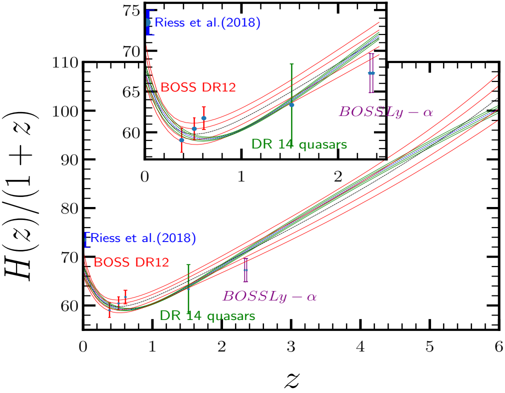
Hubble Parameter Equation can be written as:

$$\frac{H^2}{H_0^2} = \Omega_{m0}(1+z)^3 + (1-\Omega_{m0})f(z) \quad (3)$$



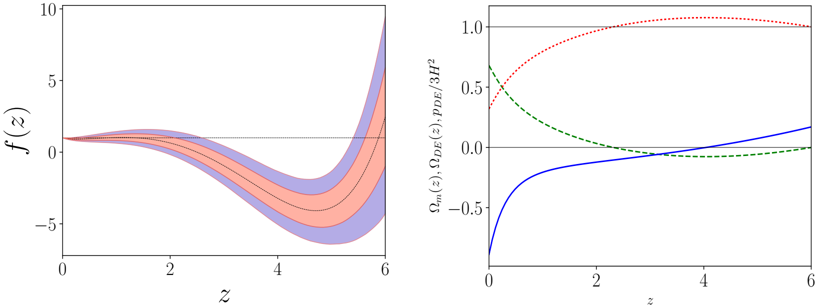


Results ◇



- *Reconstructed Hubble parameter behavior matches with low as well as high redshift data.*

Results with Planck Constraint on H(z) ◇



$$\dot{\rho}(z)|_{z=z_{min}} = 0 \Rightarrow (\rho_{DE} + P_{DE} = 0)$$

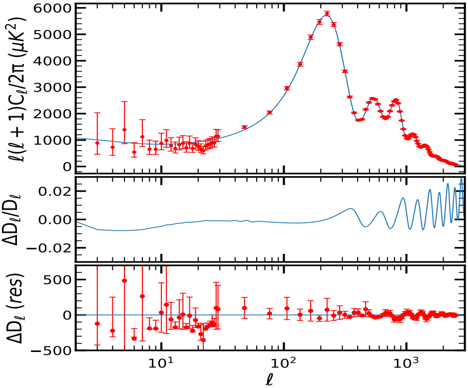
That is, at the minimum, the ρ_{DE} behaves like a cosmological constant.

Possible effects in Structure Formation ⋄

- Due to the presence of -ve Λ and due to spatial flatness, the $\Omega_m > 1$ for certain redshift range. This results more growth of structures due to deeper gravitational potential and the nonlinear regime may start earlier than ΛCDM Universe and there will be more massive galaxies at high redshifts than ΛCDM.

- These are definite prediction and can be verified by upcoming large scale surveys say by *DESI, EUCLID, LSST* using simulations or power spectra.

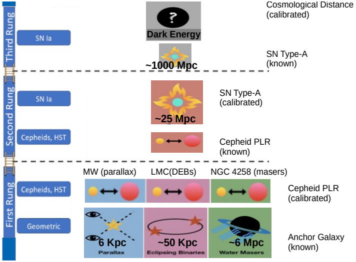
Consistency with Planck's measurement of the CMB anisotropy ◇

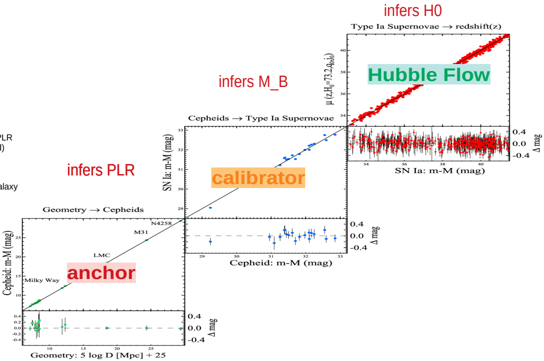


- CMB TT spectra together with Planck data and our Model.

Can a Gravitational Constant Transition at a distance of 10-40 Mpc solve the Hubble Tension?

with Himansh Rathore, Shouvik Roy Choudary, Vikram Rentala ◇



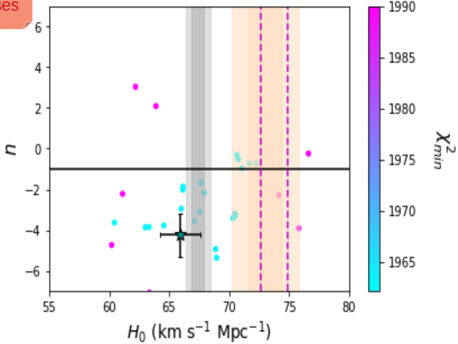


uses parallax   uses PLR from Cepheids   uses M_B of SN Ia

Seems like it does... ◇

We select μt from a list of values between 29 and 32.5 in steps of 0.5, and $\Delta G/G$ as 2%, 4%, 5%, 6%, and 8% and perform MCMC fitting.

40 cases



Riess et al.(2021) - shaded peach band

Planck (2018) - shaded grey band

Our fit (no G Transition) - dashed magenta band

Our fit (with G Transition) - black star

Results and Comparison ◇

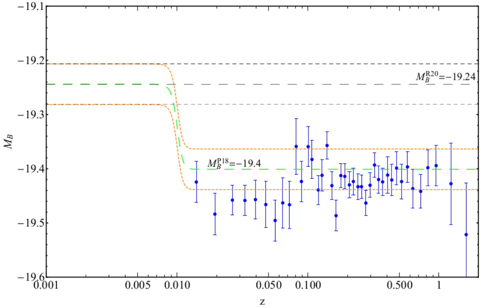
Parameters	Without G-transition	With G-transition
M_H^W	-5.89 ± 0.01	-5.88 ± 0.01
b_W	-3.27 ± 0.01	-3.28 ± 0.01
μ_{LMC}	18.54 ± 0.01	18.54 ± 00.01
$\mu_{NGC4258}$	29.30 ± 0.03	29.30 ± 0.03
M_B	-19.23 ± 0.03	–
M_{B1}	–	-19.20 ± 0.04
M_{B2}	–	-19.47 ± 0.06
n	–	-3.39 ± 0.84
H_0 (kmsec^{-1}Mpc$^-1$)	73.73 ± 1.12	65.90 ± 1.70

Model	χ^2_{min}	d	N	χ^2_{dof}
Without G-transition	1963.19	24	1267	1.579
With G-transition	1962.13	27	1267	1.582

Model	AIC	BIC	ΔAIC	ΔBIC
Without G-transition	2011.19	2134.66	0.0	0.0
With G-transition	2016.13	2155.03	4.94	20.37

Hubble Constant/ Absolute Magnitude tension? ◇

MB = -19.23 \pm 0.03



MB1 = -19.20 \pm 0.04
MB2 = -19.47 \pm 0.06

Marra et al.

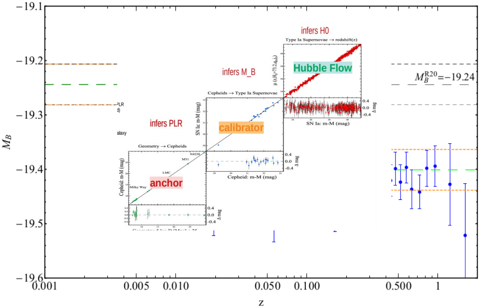
Addresses Hubble Constant / Absolute Magnitude tension.

H0 = 73.73 \pm 1.12 Km/s/Mpc **H0 = 65.90 \pm 1.70 Km/s/Mpc**

$$\log(H_0) = \frac{M_B + 5a_B + 25}{5}$$

Hubble Constant/ Absolute Magnitude tension? ◇

MB = -19.23 \pm 0.03



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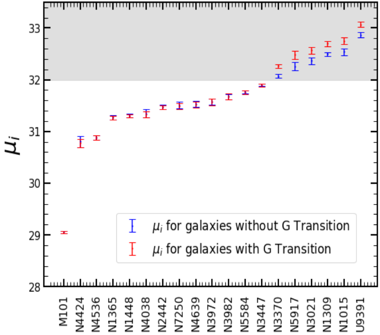
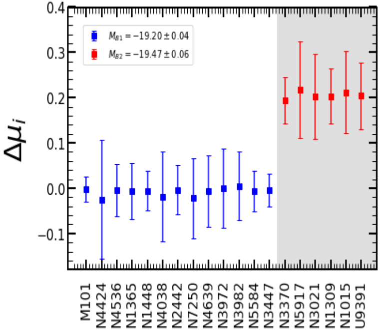
Shift in Distance Modulus in case of G-Transition ◇

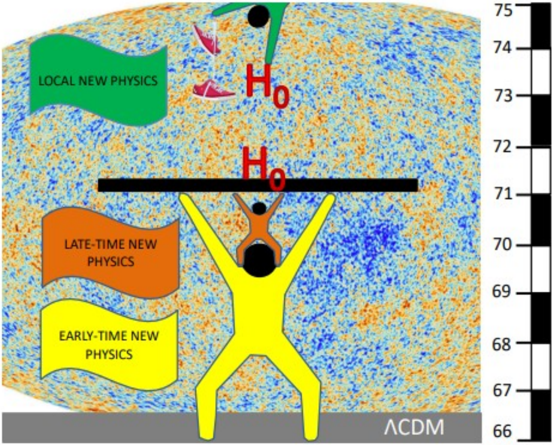




Conclusions◇

We need to work more...

Situation at present! ◇



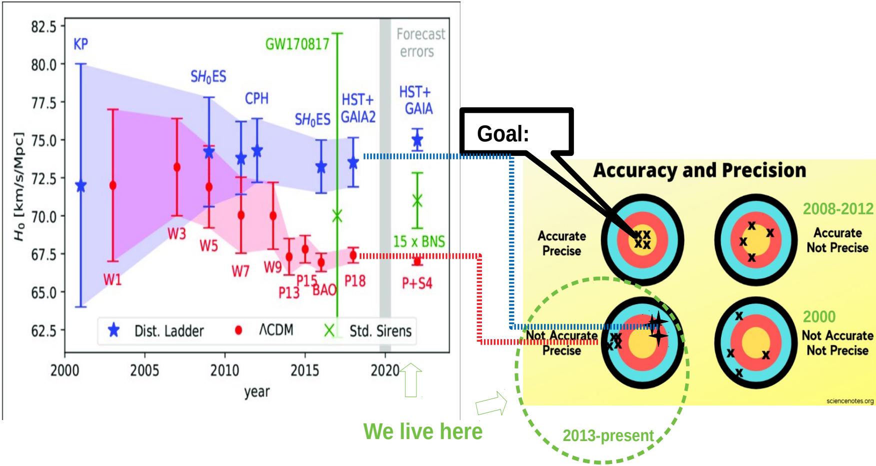
SH0ES: Supernova H0 for the Equation of State

UniverseÂ 9Â (2023)Â 9,Â 393,Â

By Sunny Vaganozzi

PC: Cristina Ghirardini

Situation at present and present Goal!



Beaton et al. 2016

Thanks!

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