The present and future of Hubble tension

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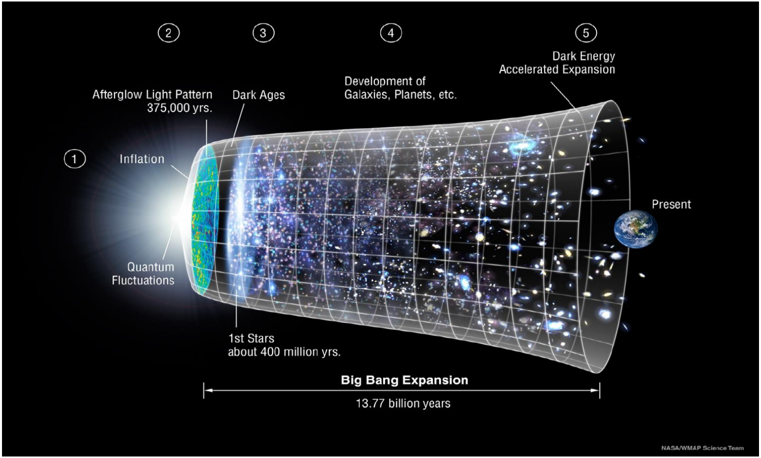
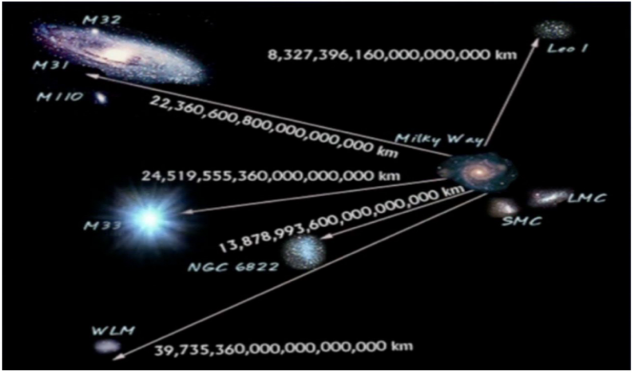
Conclusion

A Cosmologist's wishlist...



....to explain uniquely!!

The grand old man of Observational Cosmology: Hubble (1929)



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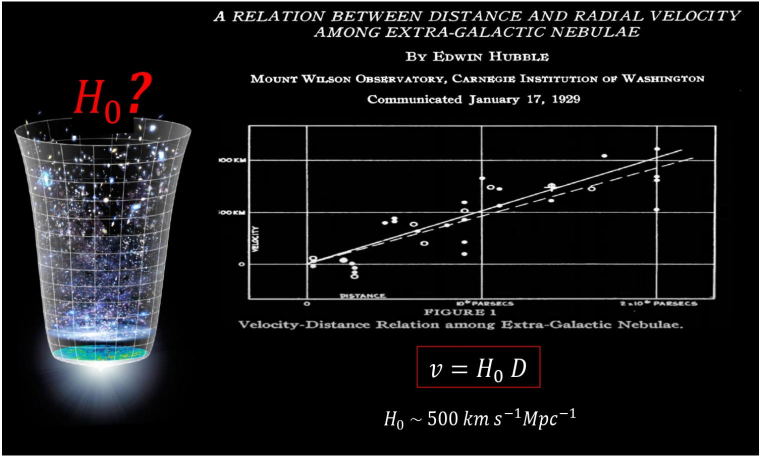
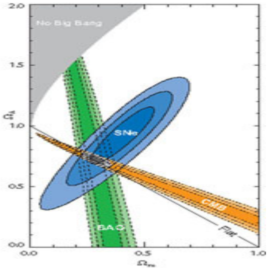
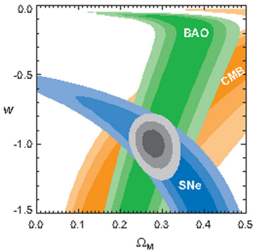
The "coolest" parameter: "The constant" a la Hubble



"The constant" from other observations

CMB, BAO, SNIa...





Universe is accelerating at present $\Rightarrow$
Measure Hubble parameter indirectly (using a cosmological model) from these observations

"The constant" a la Planck and SH0ES

Dataset	Value: km/s/Mpc
WMAP9	69.7 ± 2.1
Riess 2011	72.8 ± 2.4
Planck 2013	67.3 ± 1.2
Efstathiou 2014	70.6 ± 3.3
Planck 2015	67.3 ± 1.0
Riess 2016	73.24 ± 1.74
Plank 2018	67.4 ± 0.5
Riess 2018	74.03 ± 1.42
Riess 2020	73.2 ± 1.3
Riess 2022 (SH0ES)	73.04 ± 1.04

Source of "constant" headache!

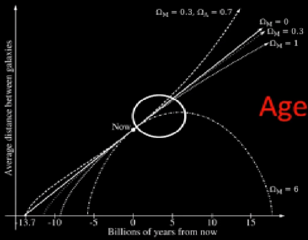
Why does the Hubble constant matter?

$H_0 = H(z=0)$ sets all scales in the Universe and $H(z)$ is related to is expansion history (hence the energy-density content)

It allows us to infer:

- Age of the Universe
- Energy budget of luminous sources
- Masses of galaxies and clusters
- Physical scales of cosmic objects
- Dark matter constraints
- Neutrino mass constraints
- ΛCDM extension parameter(s) constraints
- Et cetera!

The ΛCDM model



$$H_0 \equiv \frac{\dot{a}(t_0)}{a(t_0)}$$

Age = 13.8 Gyr

$$1 + z = \frac{a(t_0)}{a(t_1)}$$

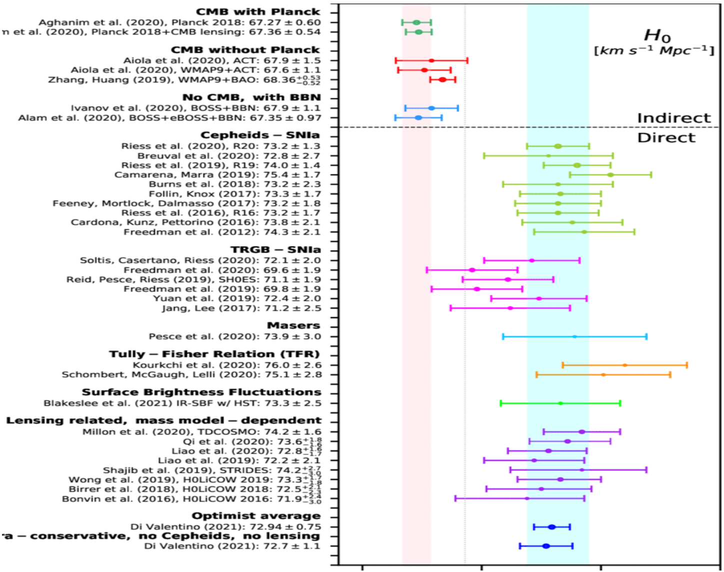
(+)

$$H^2(a) = \left(\frac{\dot{a}}{a}\right)^2 = H_0^2(\Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda)$$

Some other datasets in tension with ΛCDM

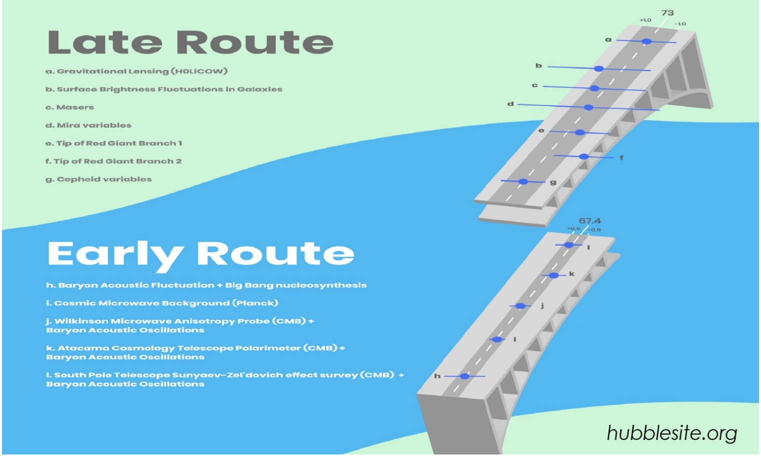
- PAN-STARRS1 data $\rightarrow 2.4\sigma$ Rest et.al., ApJ:2013
- Lyα BAO data ($z = 2.34$) $\rightarrow 2.5\sigma$
- Lensing amplitude $\rightarrow A_L = 1.22 \pm 0.10$ (Planck TT + low P)
- H0LiCOW(lensed quasars) $\rightarrow 4.2\sigma$ Suyu et.al., MNRAS:2016
- H0LiCOW XIII +R18 $\rightarrow 5.3\sigma$ Wong et.al., MNRAS:2020
- .....

Summary of observations so far: Whisker plot

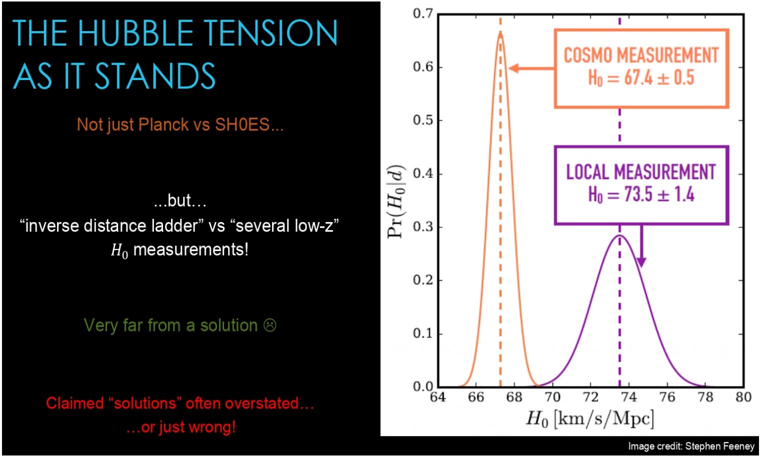


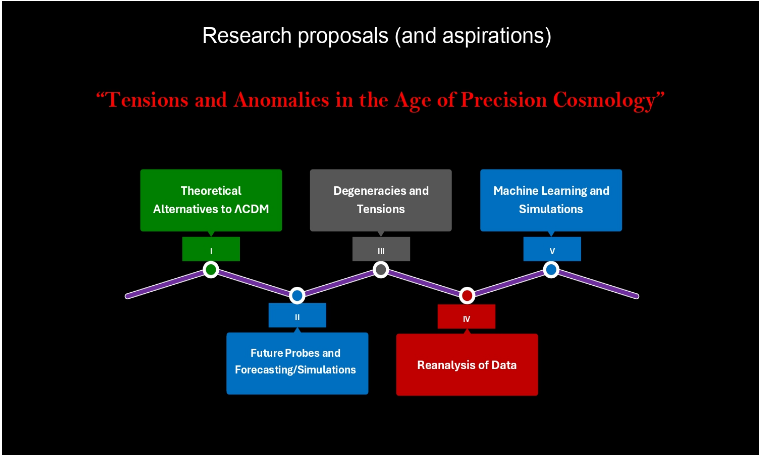
De Valentino et. al., In the realm of Hubble tension, CQG(2021)

Late time vs early time measurements?



Inverse distance ladder vs low redshift measurements



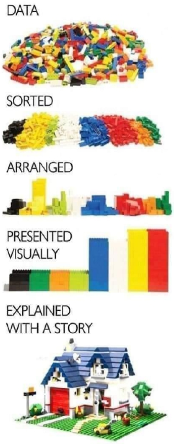


borrowed from Rahul Shah’s thesis proposal

Some beyond-ΛCDM Parametrizations

Models	Additional parameters	Motivation
Chevallier-Polarski-Linder (CPL)	w_0, w_a	Simplest dynamical DE parametrization with redshift-varying EoS to resolve the coincidence problem: $w(z) = w_0 + w_a \frac{z}{1+z}$.
Jassal-Bagla-Padmanabhan (JBP)	w_0, w_a	Phenomenologically chosen redshift-dependent DE EoS: $w(z) = w_0 + w_a \frac{z}{(1+z)^2}$.
Phenomenologically Emergent Dark Energy (PEDE)	–	Redshift-dependent DE density parameter to resolve the H_0 tension: $\Omega(z) = (1 - \Omega_{m0})[1 - \tanh(\log_{10}(1+z))]$.
Vacuum Metamorphosis (VM)	M related to Ω_{m0}	Motivated by non-perturbative effects of quantum gravity where a gravitational phase transition occurs at some critical redshift $z_c = -1 + \frac{3\Omega_{m0}}{4(1-M)}$.
Elaborated Vacuum Metamorphosis (VM-VEV)	M independent of Ω_{m0}	Extension of original VM model allowing a non-vanishing DE component at $z > z_c$, i.e., before the gravitational phase transition.

and there are many more...



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

Disclaimer: we are (almost?) all sinners

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

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

Possible reason in current observations?

- H_0 tension

Bhattacharyya, Alam, Pandey, Das, SP: ApJ:2019

Dataset	Value: km/s/Mpc
WMAP9	69.7 ± 2.1
Riess 2011	72.8 ± 2.4
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- σ_8 ($8h^{-1}$Mpc) tension

Dataset	Value: $S_8 = \sigma_8\sqrt{\Omega_{0m}/0.3}$
Planck 2015	0.851 ± 0.013
Clusters (X-ray)	0.745 ± 0.039
Weak lensing	0.75 ± 0.04
DES Y3 (2021)	0.784 ± 0.013

Generic Parametrization Scheme

- Consider most generic situation: two fluids (DM-DE), interacting, both perturbed
- Write down background and perturbation equations
- Parametrization: $\{w_{DM,eff}, w_{DE,eff}, C^2_{sDM,eff}, C^2_{sDE,eff}\}$
- Boils down to different models for specific choice
  - $w_{DM,eff} = 0, w_{DE,eff} = -1, C^2_{sDM,eff} = 0, C^2_{sDE,eff} = 0$ $\Rightarrow$ ΛCDM
  - $w_{DM,eff} = 0, w_{DE,eff} > -1, C^2_{sDM,eff} = 0, C^2_{sDE,eff} = 1$ $\Rightarrow$ non-phantom, w_zCDM
  - $w_{DM,eff} = 0, w_{DE,eff} < -1, C^2_{sDM,eff} = 0, C^2_{sDE,eff} = 1$ $\Rightarrow$ phantom, w_zCDM
  - $w_{DM,eff} = 0, w_{DE,eff} < -1, C^2_{sDM,eff} = 0, C^2_{sDE,eff} \neq 1$ $\Rightarrow$ modified gravity
  - $w_{DM,eff} \neq 0, w_{DE,eff} = -1, C^2_{sDM,eff} = 0, C^2_{sDE,eff} = 1$ $\Rightarrow$ warm dark matter
  - $w_{DM,eff} \neq 0, w_{DE,eff} < -1 or > -1, C^2_{sDM,eff} \neq 0, C^2_{sDE,eff} \neq 1$ $\Rightarrow$ interacting DM-DE
- Constrain these parameters from data

Parameters (Planck15/ Planck+R16/ Planck+BSH)

Phantom

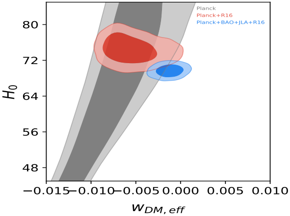
Data	Model	Ω_{0m}	H_0	σ_8	w_0	w_a	$w_{DM,eff}$	$c^2_{sDE,eff}$	χ^2_{bf}	$\chi^2_{\Lambda CDM} - \chi^2_{bf}$
	ΛCDM	$0.30^{+0.02}_{-0.02}$	$68.1^{+1.2}_{-1.2}$	$0.85^{+0.03}_{-0.02}$	-1	0	0	1	781.07	0
Planck	CPLCDM	$0.19^{+0.02}_{-0.04}$	$88.4^{+11.6}_{-3.7}$	$1.02^{+0.08}_{-0.06}$	$-1.5^{+0.3}_{-0.3}$	$-0.13^{+0.27}_{-0.03}$	0	1	779.83	-1.24
	$+w_{DM,eff}$	$0.62^{+0.32}_{-0.59}$	$66.7^{+32.0}_{-11.1}$	$0.80^{+0.27}_{-0.13}$	$-2.0^{+1.0}_{-1.0}$	$-0.45^{+0.48}_{-1.50}$	$-0.0075^{+0.005}_{-0.004}$	1	778.26	-2.81
	$+c^2_{sDE,eff}$	$0.68^{+0.32}_{-0.66}$	$64.9^{+31.7}_{-13.5}$	$0.79^{+0.28}_{-0.14}$	$-2.0^{+1.0}_{-1.0}$	$-0.42^{+0.49}_{-1.58}$	$-0.0078^{+0.005}_{-0.004}$	$1.03^{+0.84}_{-0.45}$	778.88	-2.19
	ΛCDM	$0.29^{+0.01}_{-0.01}$	$69.7^{+1.0}_{-1.0}$	$0.86^{+0.02}_{-0.02}$	-1	0	0	1	786.66	0
Planck	CPLCDM	$0.26^{+0.01}_{-0.01}$	$74.0^{+1.7}_{-1.7}$	$0.90^{+0.02}_{-0.03}$	$-1.1^{+0.1}_{-0.1}$	$-0.27^{+0.46}_{-0.26}$	0	1	782.02	-4.64
+R16	$+w_{DM,eff}$	$0.29^{+0.02}_{-0.02}$	$74.5^{+2.1}_{-2.1}$	$0.88^{+0.03}_{-0.03}$	$-2.0^{+1.0}_{-1.0}$	$-0.96^{+1.10}_{-1.50}$	$-0.005^{+0.001}_{-0.003}$	1	777.65	-9.01
	$+c^2_{sDE,eff}$	$0.29^{+0.02}_{-0.02}$	$74.5^{+2.1}_{-2.2}$	$0.89^{+0.02}_{-0.02}$	$-2.0^{+1.0}_{-1.0}$	$-0.94^{+1.05}_{-1.65}$	$-0.005^{+0.001}_{-0.002}$	$1.03^{+0.96}_{-0.34}$	780.19	-6.47
	ΛCDM	$0.30^{+0.01}_{-0.01}$	$68.5^{+0.6}_{-0.6}$	$0.86^{+0.02}_{-0.02}$	-1	0	0	1	1490.66	0
Planck	CPLCDM	$0.29^{+0.01}_{-0.01}$	$69.8^{+1.0}_{-1.0}$	$0.87^{+0.02}_{-0.02}$	$-1.05^{+0.05}_{-0.01}$	$-0.15^{+0.21}_{-1.10}$	0	1	1490.29	-0.37
+BSH	$+w_{DM,eff}$	$0.30^{+0.01}_{-0.01}$	$69.7^{+1.0}_{-1.0}$	$0.86^{+0.02}_{-0.02}$	$-1.06^{+0.06}_{-0.01}$	$-0.33^{+0.39}_{-0.19}$	$-0.0012^{+0.001}_{-0.001}$	1	1488.14	-2.52
	$+c^2_{sDE,eff}$	$0.30^{+0.01}_{-0.01}$	$69.7^{+1.0}_{-1.0}$	$0.86^{+0.02}_{-0.02}$	$-1.06^{+0.06}_{-0.01}$	$-0.34^{+0.40}_{-0.18}$	$-0.0012^{+0.001}_{-0.001}$	$1.02^{+0.98}_{-1.02}$	1488.83	-1.83

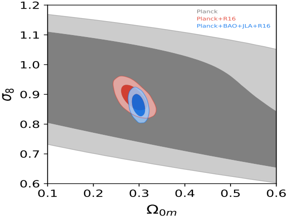
Non-phantom

Data	Model	Ω_{0m}	H_0	σ_8	$w_{0,eff}$	$w_{a,eff}$	$w_{DM,eff}$	$c^2_{sDE,eff}$	χ^2_{bf}	$\chi^2_{\Lambda CDM} - \chi^2_{bf}$
	ΛCDM	$0.30^{+0.02}_{-0.02}$	$68.1^{+1.2}_{-1.2}$	$0.85^{+0.03}_{-0.02}$	-1	0	0	1	781.07	0
Planck	CPLCDM	$0.37^{+0.03}_{-0.05}$	$62.5^{+4.0}_{-2.7}$	$0.80^{+0.04}_{-0.03}$	$-0.82^{+0.14}_{-0.18}$	$0.03^{+0.22}_{-0.22}$	0	1	782.75	1.68
	$+w_{DM,eff}$	$1.06^{+0.31}_{-0.47}$	$44.0^{+4.3}_{-7.5}$	$0.60^{+0.05}_{-0.08}$	$-0.68^{+0.35}_{-0.32}$	$0.16^{+0.36}_{-0.40}$	$-0.012^{+0.004}_{-0.006}$	1	782.63	1.56
	$+c^2_{sDE,eff}$	$1.03^{+0.33}_{-0.43}$	$44.5^{+3.7}_{-8.0}$	$0.60^{+0.04}_{-0.09}$	$-0.68^{+0.05}_{-0.35}$	$0.16^{+0.36}_{-0.40}$	$-0.012^{+0.003}_{-0.006}$	$0.98^{+1.02}_{-0.98}$	780.58	-0.49
	ΛCDM	$0.29^{+0.01}_{-0.01}$	$69.7^{+1.0}_{-1.0}$	$0.86^{+0.02}_{-0.02}$	-1	0	0	1	786.66	0
Planck	CPLCDM	$0.29^{+0.01}_{-0.01}$	$68.6^{+1.3}_{-1.1}$	$0.85^{+0.02}_{-0.02}$	$-0.97^{+0.01}_{-0.03}$	$0.03^{+0.04}_{-0.06}$	0	1	788.97	2.31
+R16	$+w_{DM,eff}$	$0.25^{+0.02}_{-0.02}$	$72.2^{+1.8}_{-1.8}$	$0.89^{+0.03}_{-0.03}$	$-0.92^{+0.01}_{-0.08}$	$0.05^{+0.48}_{-0.13}$	$0.004^{+0.001}_{-0.001}$	1	785.81	-0.85
	$+c^2_{sDE,eff}$	$0.25^{+0.02}_{-0.02}$	$72.2^{+1.8}_{-1.8}$	$0.89^{+0.03}_{-0.03}$	$-0.92^{+0.01}_{-0.08}$	$0.05^{+0.10}_{-0.59}$	$0.004^{+0.001}_{-0.002}$	$1.94^{+0.06}_{-1.94}$	785.73	-0.93
	ΛCDM	$0.30^{+0.01}_{-0.01}$	$68.5^{+0.6}_{-0.6}$	$0.86^{+0.02}_{-0.02}$	-1	0	0	1	1490.66	0
Planck	CPLCDM	$0.30^{+0.01}_{-0.01}$	$67.8^{+0.7}_{-0.7}$	$0.85^{+0.02}_{-0.02}$	$-0.97^{+0.01}_{-0.03}$	$0.04^{+0.04}_{-0.08}$	0	1	1493.36	2.70
+BSH	$+w_{DM,eff}$	$0.30^{+0.01}_{-0.01}$	$68.2^{+0.8}_{-0.8}$	$0.85^{+0.02}_{-0.02}$	$-0.96^{+0.01}_{-0.04}$	$0.10^{+0.07}_{-0.14}$	$0.0012^{+0.001}_{-0.001}$	1	1491.01	0.35
	$+c^2_{sDE,eff}$	$0.30^{+0.01}_{-0.01}$	$68.2^{+0.8}_{-0.8}$	$0.86^{+0.02}_{-0.02}$	$-0.96^{+0.01}_{-0.04}$	$0.09^{+0.06}_{-0.14}$	$0.0012^{+0.001}_{-0.001}$	$0.98^{+1.02}_{-0.98}$	1491.59	0.93

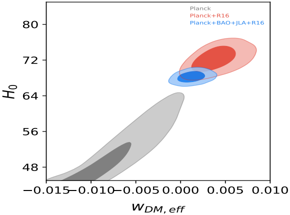
Major results (Planck+BSH)

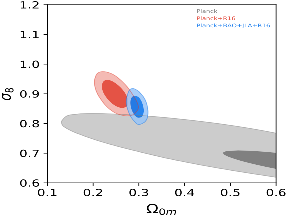
Phantom





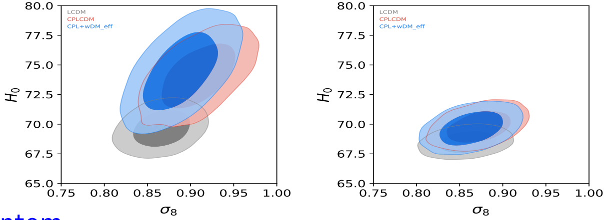
Non-phantom



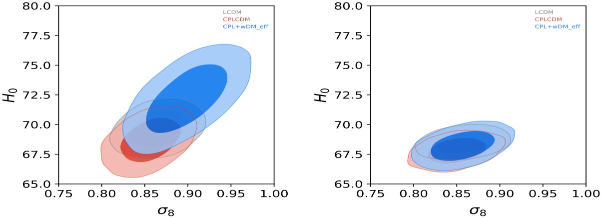


Correlation between H_0 and σ_8 tensions

Phantom



Non-phantom



Strong positive correlation between H_0 and σ_8 is generic to present cosmological data

SO IS IT NEW PHYSICS?

SEE EPIC REVIEW BY VALENTINO+ [2103.01183]

NO THEORETICAL MODIFICATION EXPLAINS TENSION (YET...)

Tension persists

Coupled quint-essence (*Pourtsidou+1604.04222*) — however, that it still exhibits tension with local measurements of the Hubble constant. A full model selection

$M_\nu + N_{eff} + w$ + running + r + A_{lens} (*Di Valentino+1606.0063*) — $w < -1$ now present at just ~ 1.1 sigma. The inclusion of the R16 prior in the Planck+BAO dataset produces a worse fit of $\Delta\chi^2 \sim 4.5$. This is due to the tension at the

Early dark energy (*Karwal+1608.01309*) — In order for the best-fit value of H_0 for a ΛCMD + EE universe to coincide with the local measurement, a value of τ greater than its 5σ Planck-16 value is required. (Such

Dynamical vacuum model dark energy (*Sola+1705.06723*) — definitely favors the Planck range for H_0

Phantom dark energy (*El-Zant+1809.09390*) — The model however faces serious problems when baryon acoustic oscillation data are included. This is true for both

σ_8 tension issues

Holographic DE + sterile ν (*Zhao+1703.08456*) — mic shear; thus we compare our result with the KiDS-450 result. We find a tension at the 1.9σ level between the two. As discussed in the Planck 2015 paper [2], for

DM-ν interactions (*Di Valentino+1710.02559*) — Here we show that it is impossible to solve both tensions simultaneously.

Preliminary

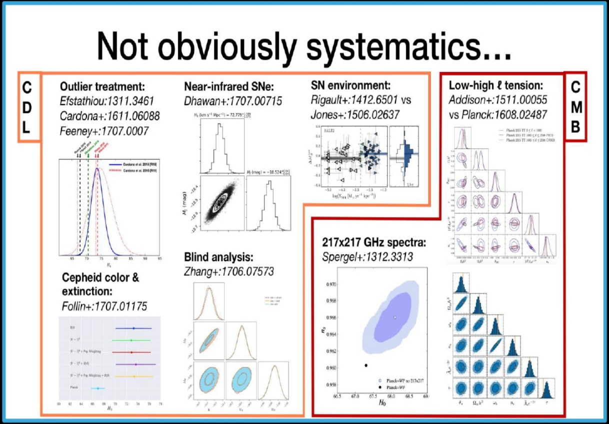
DM-dark rad interactions (*Ko+1608.01083*)
Twin Higgs (*Prilepina+1611.05879*)
Two curvatures (*Santos+1611.01885*)

Evidence prefers LCDM

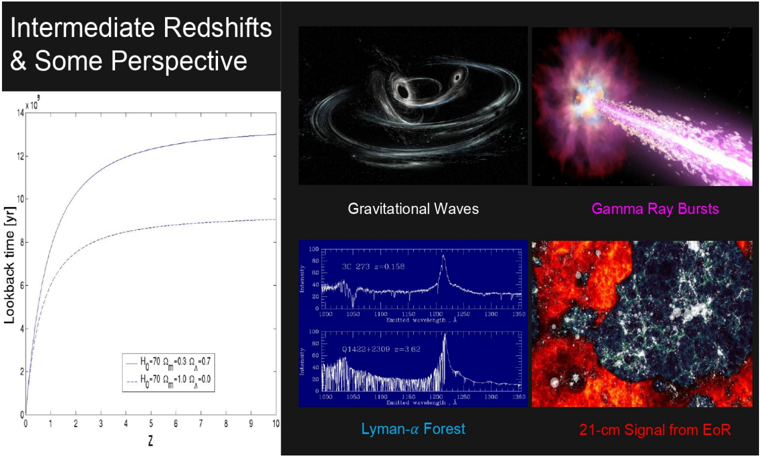
N_{eff} (dark rad) (*Di Bari+1303.6267*)
Sterile ν (*Wyman+1307.7715*)
Non-parametric, time-dependent DE equation of state (*Huang+1606.05965*)
DM-DE interactions + sterile ν (*Kumar+1608.02454*)
Vacuum metamorphosis + N_{eff} + running + M_ν + A_{lens} (*Di Valentino+1710.02153*)
Interacting time-varying DE (*Yang+1809.06883*)
K-mouflage (*Benevento+1809.09958*)
(see also *Verde+SF+1307.2904, Leistedt+1404.5950, Heavens+1704.03467*)

THEN IT MUST BE SYSTEMATICS, RIGHT? NO?

NO PROPOSED SYSTEMATICS EXPLAIN TENSION (YET!)...

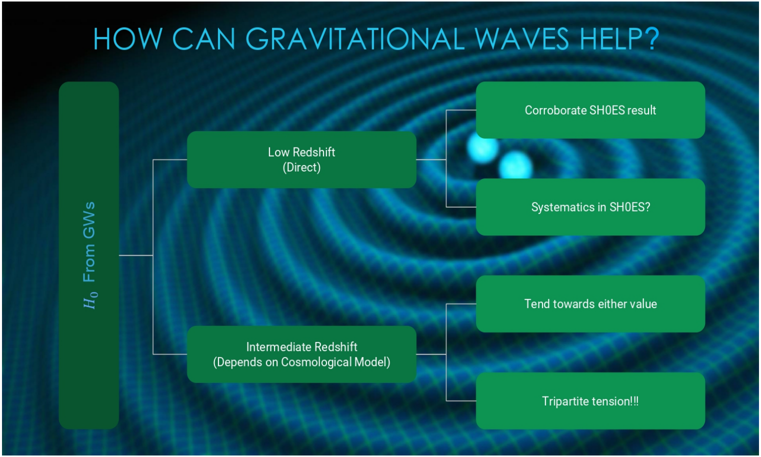


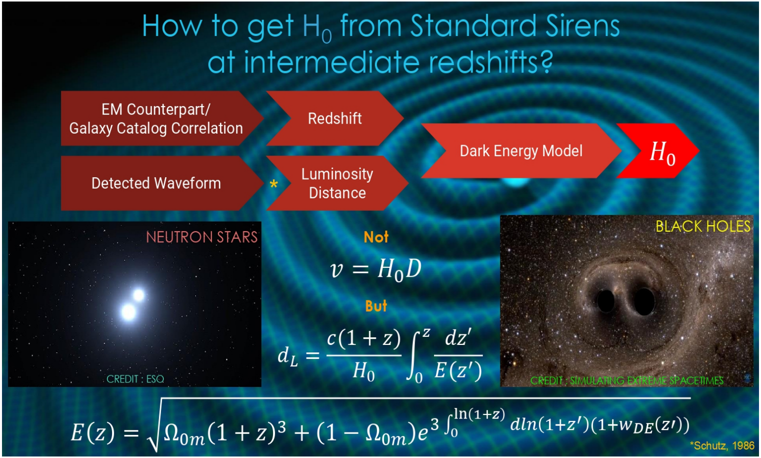
Looking towards future




ET EINSTEIN TELESCOPE
10 km
eLISA
宇宙の始まりを聞く・・・
DECIGO
Cosmic Explorer
and many more…
TMT
SKA
Vera C. Rubin Observatory
JWST
Euclid
Roman Space Telescope

Future prospects: GW missions



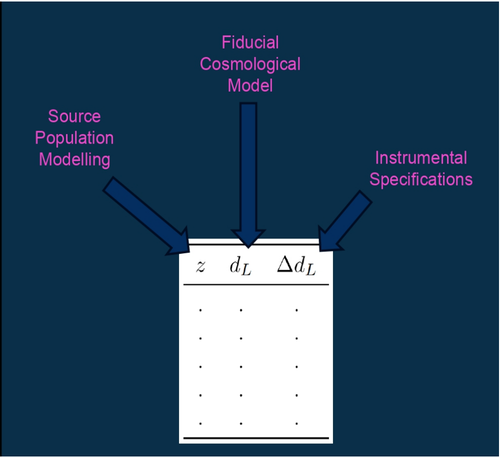

How to get H_0 from Standard Sirens at intermediate redshifts?
EM Counterpart/ Galaxy Catalog Correlation
Redshift
Detected Waveform
*
Luminosity Distance
Dark Energy Model
H_0
NEUTRON STARS
CREDIT : ESO
BLACK HOLES
CREDIT : SIMULATING EXTREME SPACETIMES
Not
$v = H_0 D$
But
$d_L = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{E(z')}$
$E(z) = \sqrt{\Omega_{0m}(1+z)^3 + (1-\Omega_{0m}) e^{3\int_0^{\ln(1+z)} dln(1+z')(1+w_{DE}(z'))}}$
*Schutz, 1986

How to “see” GWs at intermediate redshifts?

Future GW missions!

Wait for / travel to the future? ☹

We can simulate!



Future prospects: GW missions

Baral, Roy, SP, MNRAS:2020
Shah, Bhaumik, Mukherjee, SP, JCAP:2023
Mukherjee, Shah, Bhaumik, SP, ApJ:2024

GW missions under consideration:

- eLISA
- Einstein Telescope

Different approaches used:

A three-pronged approach to forecasting

For a particular model

Fisher Matrix Forecasting	Parameter Estimation using Markov chain Monte Carlo (MCMC)	Non-parametric reconstruction using Gaussian processes (GPs)
Estimate on errors No mean shifts Depends on instrumental specifications	Estimate on errors Can shift mean values Sensitive to assumed cosmological model	Full reconstruction with errors and mean Cannot constrain all parameters Instrument independent and non-parametric

Models under investigation

Choose a fiducial model!

But how?!

"True" Universe unknown. Choose some motivated by H_0 tension?

These may be good representative choices!

Our choices

Baseline Model (6 parameters):
Λ Cold Dark Matter (ΛCDM) [~5.0σ]

Alternative models with 6 parameters:
Phenomenologically Emergent Dark Energy (PEDE) [~1.8σ]
Vacuum Metamorphosis (VM) [~0.8σ]

1-parameter extension:
Elaborated Vacuum Metamorphosis (VM-VEV) [~0.04σ]

2-parameter extensions:
Chevallier-Polarski-Linder (CPL) [~3.7σ]
Jassal-Bagla-Padmanabhan (JBP) [~3.8σ]

RS, A. Bhaumik, P. Mukherjee, S. Pal, JCAP 06 (2023): 038

Current status of $H0$ tension with the models

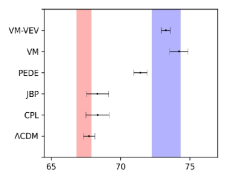
Reinvestigation done by

Shah, Bhaumik, Mukherjee, SP, JCAP:2023

Each model constrained* with current data without late-time measurement prior

Planck2018TTTEEE+lensing + Pantheon + BAO

[PEDE & JBP not as successful for H_0 tension as previously claimed with a different dataset]



With these constraints we simulate ^some different possible future datasets

and move on to *forecasting*

* VM, VM-VEV constraints from Valentino et al. 2020

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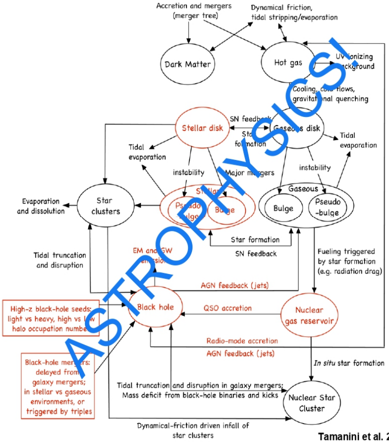
GW source population modelling

Source Population Modelling for MBHBs

- Pop III: A light seed scenario where it is assumed that the first massive black holes grow from stellar remnants of early population III stars, which formed around z ~ 15 − 20 within massive dark matter halos. [~70 events/year]
- No Delay: A heavy seed scenario in which protogalactic disk collapse (e.g., due to bar instabilities) leads to the formation of massive black holes. The MBHB coalescence events are assumed to take place simultaneously with the mergers of their host galaxies, which is a simplistic premise of this model. [~100 events/year]
- Delay: A more realistic heavy seed scenario, in which there is a finite time delay between the merger of a given pair of host galaxies and that of the black holes. The intermediate period leading up to the MBHB merger is governed by a variety of complicated astrophysical processes which non-trivially affect the observable redshift distribution of the MBHB population. [~10 events/year]



Tamanini et al. 2016

Generate realistic mock catalogs

Instrumental Specifications

eLISA	ET
$0.1 < z < 9.0$	$0.07 < z < 2.0$
$\sigma^2_{\rm LISA} = \sigma^2_{\rm delens} + \sigma^2_{\rm v} + \sigma^2_{\rm inst} + \left(\frac{d}{dz}(d_L)\sigma_{\rm photo}\right)^2$	$\sigma^2_{\rm ET} = \sigma^2_{\rm inst} + \sigma^2_{\rm lens}$
*for eLISA configuration L6A2M5N2	

Delensing error

Peculiar velocity error

Instrumental error

Photometric error

Ferreira et al. 2022

Fisher Matrix forecast analysis: eLISA

ΛCDM vs 5 (recent) parametrizations dedicated to H_0 tension

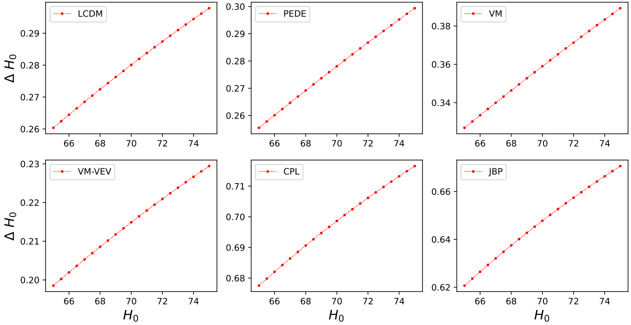


Figure: Dependence of errors estimated by Fisher analysis on the mean value of H_0 (km s^{-1} Mpc^{-1}) for source type No Delay and eLISA mission duration of 10 years.

Parameter estimation using MCMC: eLISA

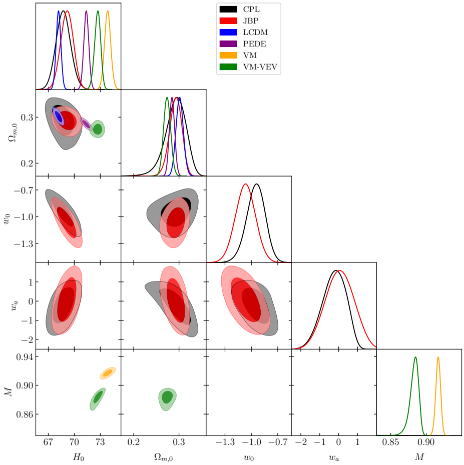
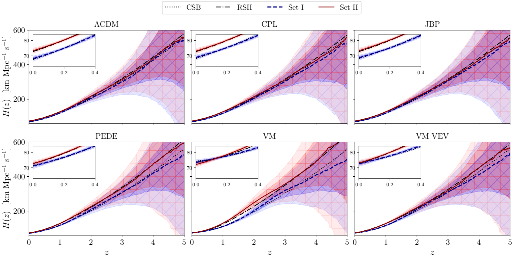


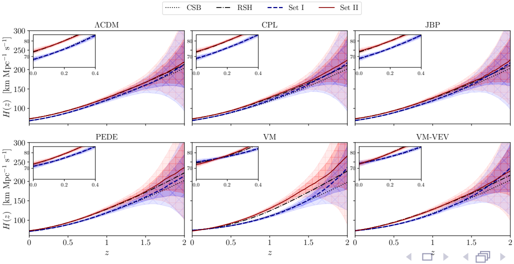
Figure: MCMC contours with No Delay source type for 10 years eLISA mission duration.

$H(z)$ reconstruction using Machine Learning (GP)

eLISA: $\sim$ 10-year run for $0 < z < 5$



ET: $\sim$ 3-year run for $0 < z < 2$



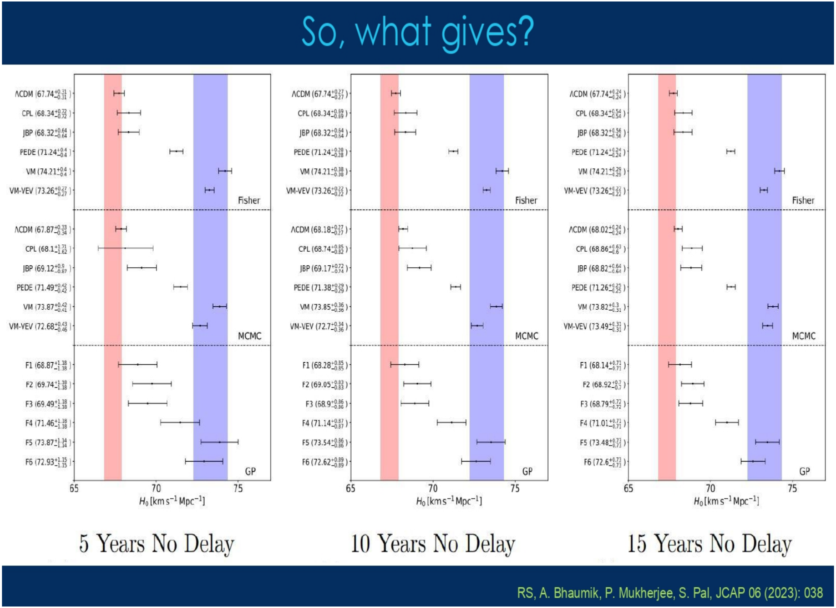
Performance summary: eLISA

Shah, Bhaumik, Mukherjee, SP, JCAP:2023

Method	ΛCDM	CPL	JBP	PEDE	VM	VM-VEV
Current Datasets	4.98σ	3.69σ	3.78σ	1.79σ	0.74σ	0.04σ
Fisher Forecasting	5.20σ	4.15σ	4.11σ	1.91σ	0.84σ	0.04σ
GW MCMC	4.76σ	3.40σ	3.27σ	1.78σ	0.50σ	0.55σ
Gaussian Processes	3.74σ	3.19σ	3.27σ	1.59σ	0.18σ	0.49σ

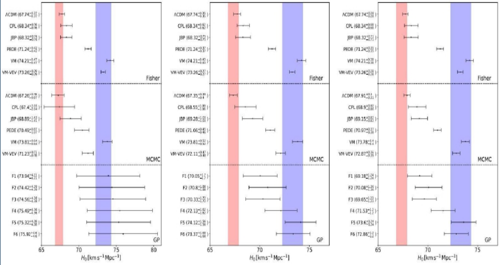
GW missions have some prospects of relaxing the tension for a few parametrizations, do not worsen others...
...but the tension is far from being resolved

Performance summary: eLISA

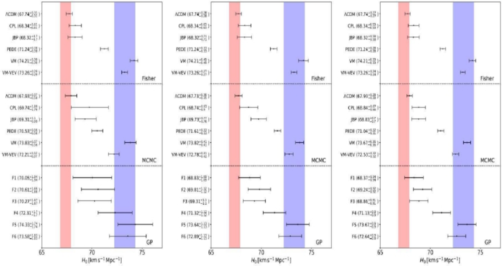


Performance summary: eLISA

So, what gives?



5 Years Delay   10 Years Delay   15 Years Delay



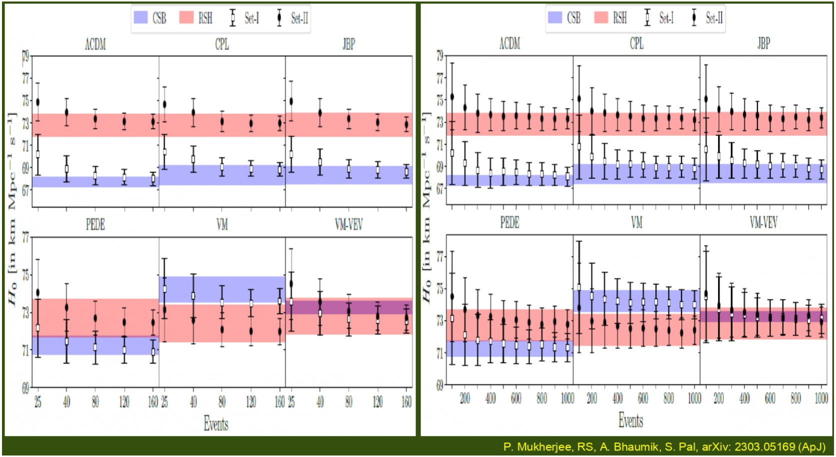
5 Years Pop III   10 Years Pop III   15 Years Pop III

RS, A. Bhaumik, P. Mukherjee, S. Pal, JCAP 06 (2023): 038

Performance summary: ET (GP only)

Mukherjee, Shah, Bhaumik, SP, ApJ:2024

Mock catalogs generated from CSB and RSH fiducials separately



Take-home message: GW

- GW missions have some prospects of relaxing the tension for a few parametrizations, do not worsen others
- Fisher shows eLISA to be more constraining than current data.
- MCMC shows marginally reduced tensions.
- GPs show $H0$ value tending towards late-time value, without any such prior.
- But the tesion is far from being resolved.

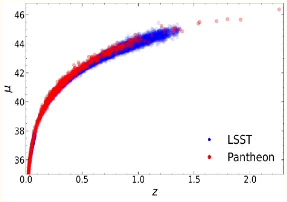
We urge the community to carry out forecasts using different methods so as to comparatively weigh and outweigh the pros and cons of each.

Future prospects: SNIa missions

Prospects of LSST Rubin Observatory

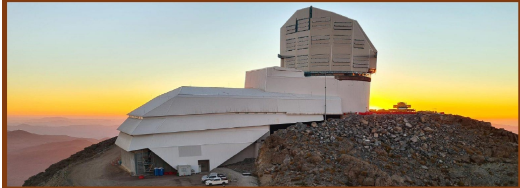
Shah, Mitra, Mukherjee, Pal, SP, arXiv:2305.08786

Pantheon is good. But have you seen through LSST?



Pantheon + CMB + BAO

Models	ΛCDM	CPL
$\Omega_b h^2$	$0.02243^{+0.00014}_{-0.00014}$	$0.02238^{+0.00013}_{-0.00015}$
$\Omega_c h^2$	$0.1192^{+0.00093}_{-0.00094}$	$0.12^{+0.0011}_{-0.0011}$
$100\theta_s$	$1.042^{+0.00029}_{-0.00029}$	$1.042^{+0.00029}_{-0.00030}$
$\ln\left(10^{10}A_s\right)$	$3.048^{+0.014}_{-0.014}$	$3.043^{+0.014}_{-0.015}$
n_s	$0.9672^{+0.0037}_{-0.0038}$	$0.9653^{+0.0039}_{-0.0039}$
τ	$0.05682^{+0.0069}_{-0.0075}$	$0.05356^{+0.0071}_{-0.0073}$
w_0	-	$-0.9573^{+0.075}_{-0.083}$
w_a	-	$-0.2862^{+0.31}_{-0.27}$
H_0	$67.74^{+0.42}_{-0.42}$	$68.32^{+0.83}_{-0.83}$
Ω_{m0}	$0.3102^{+0.0056}_{-0.0056}$	$0.3065^{+0.0078}_{-0.0082}$
$\sigma_{8,0}$	$0.8104^{+0.0060}_{-0.0061}$	$0.8205^{+0.011}_{-0.011}$
χ^2_{min}	3811	3811
$\ln \mathcal{L}_{max}$	1905.5	1905.52

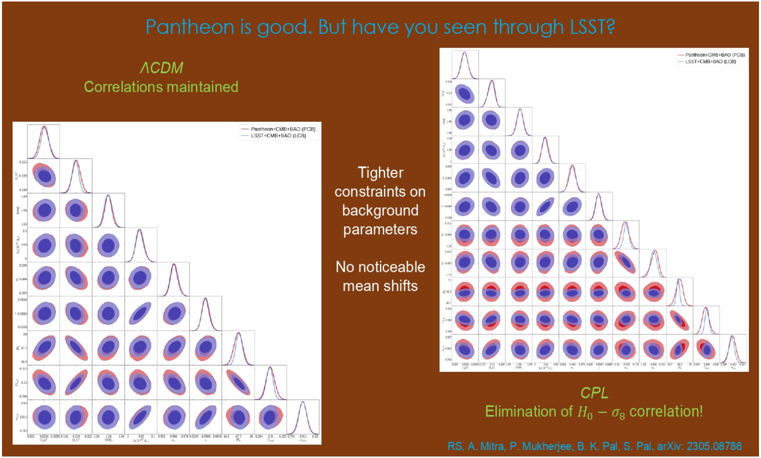


LSSTsim + CMB + BAO

Models	ΛCDM	CPL
$\Omega_b h^2$	$0.02245^{+0.00013}_{-0.00013}$	$0.02238^{+0.00014}_{-0.00015}$
$\Omega_c h^2$	$0.1191^{+0.00074}_{-0.00074}$	$0.1199^{+0.0011}_{-0.0010}$
$100\theta_s$	$1.042^{+0.00028}_{-0.00028}$	$1.042^{+0.0003}_{-0.0003}$
$\ln\left(10^{10}A_s\right)$	$3.05^{+0.014}_{-0.014}$	$3.043^{+0.014}_{-0.014}$
n_s	$0.9676^{+0.0035}_{-0.0035}$	$0.9654^{+0.004}_{-0.004}$
τ	$0.05722^{+0.0069}_{-0.0076}$	$0.05345^{+0.0073}_{-0.0074}$
w_0	-	$-0.9315^{+0.054}_{-0.055}$
w_a	-	$-0.3379^{+0.23}_{-0.22}$
H_0	$67.84^{+0.33}_{-0.34}$	$67.99^{+0.39}_{-0.39}$
Ω_{m0}	$0.3087^{+0.0044}_{-0.0044}$	$0.3094^{+0.0046}_{-0.0044}$
$\sigma_{8,0}$	$0.8101^{+0.0059}_{-0.0060}$	$0.8175^{+0.0086}_{-0.0083}$
χ^2_{min}	2796	2796
$\ln \mathcal{L}_{max}$	1397.74	1397.9

RS, A. Mitra, P. Mukherjee, B. K. Pal, S. Pal, arXiv: 2305.08786

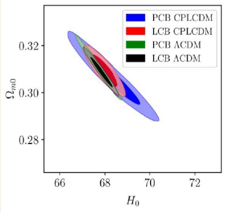
Pantheon vs LSST (+CMB+BAO)

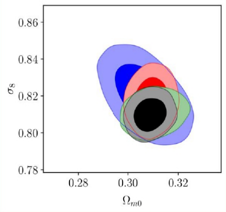


Results with realistically generated mock catalog for LSST.
Other datasets real.

Pantheon vs LSST: any improvements?

Pantheon is good. But have you seen through LSST?

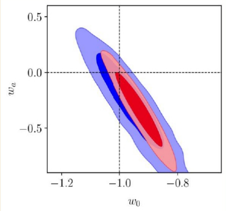


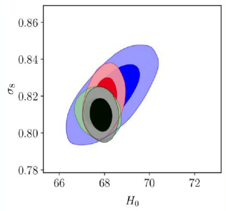


ΛCDM
Correlations maintained

Tighter constraints on background parameters

No noticeable mean shifts





CPL
Elimination of $H_0 - \sigma_8$ correlation!?

RS, A. Mitra, P. Mukherjee, B. K. Pal, S. Pal, arXiv: 2305.08786

Take-home message: SNIa

- Tighter constraints on background parameters, both for ΛCDM and CPL.
- No noticeable mean shift for $H0$.
- Tension is expected to persist with new SNIa data.
- For CPL: $H0 - \sigma_8$ correlations is almost gone!
- Need to test with other models.

Can Cosmic Distance Ladder be reconstrcuted?

LADDER: a deep learning algorithm

Shah, Saha, Mukherjee, Garain, SP, arXiv:2401.17029

- Tranining ANN algorithm: Long-Short Term Memory (LSTM)
- Training dataset used: Pantheon
- Application of trained dataset so far: Pantheon+, BAO, GRB

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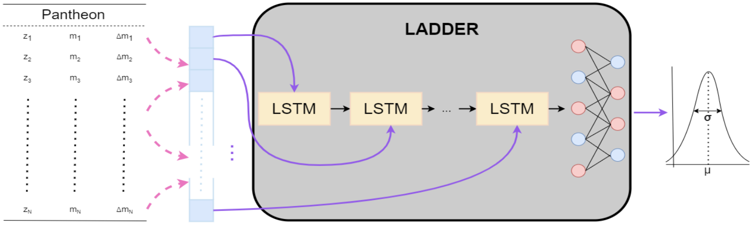
Schematic diagram of LADDER algorithm



LADDER reconstruction of Pantheon+

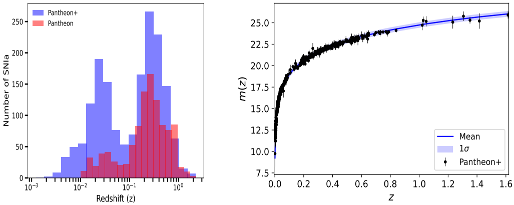


Figure: Redshift distribution (left); Pantheon+ vs reconstructed (right)

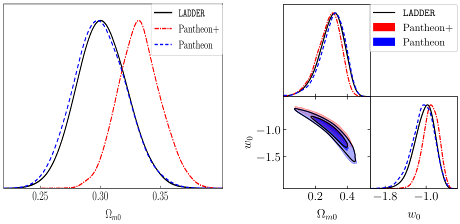


Figure: Cosmological parameters: ΛCDM (left); wCDM (right)

LADDER calibration of BAO (vs CMB ΛCDM-calibration)

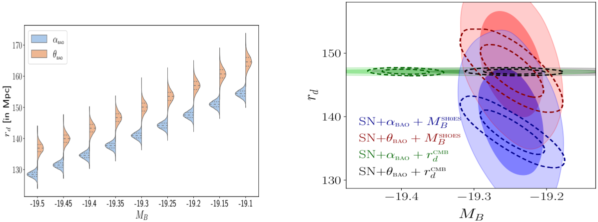
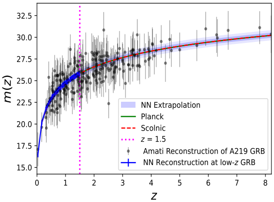


Figure: Angular vs Anisotropic BAO (left); LADDER mean + 1σ uncertainty predictions (right). Colored contours : LADDER predictions, dashed ones : CMB-ΛCDM calibration

Discipancy between Angular vs Anisotropic BAO gone?

LADDER calibration of high-z (GRB) data



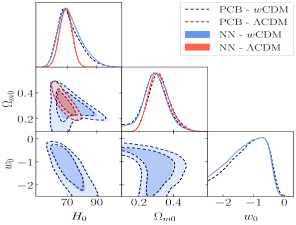


Figure: LADDER calibrated GRB vs other methods (left); Constraints on parameters (CC Hubble + calibrated high-z GRB)

LADDER calibration of high-z (GRB) data

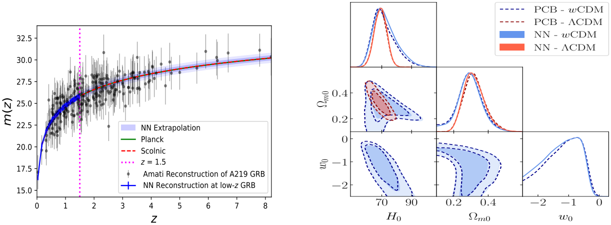


Figure: LADDER calibrated GRB vs other methods (left); Constraints on parameters (CC Hubble + calibrated high-z GRB)

Model	ΛCDM		wCDM	
Calibrator	LADDER	PCB	LADDER	PCB
H_0	$69.203^{+4.050}_{-4.150}$	$68.996^{+4.187}_{-4.095}$	$71.224^{+9.058}_{-6.365}$	$70.265^{+8.989}_{-5.915}$
Ω_{m0}	$0.313^{+0.066}_{-0.055}$	$0.317^{+0.067}_{-0.057}$	$0.289^{+0.068}_{-0.074}$	$0.287^{+0.072}_{-0.085}$
w_0	...	...	$-1.257^{+0.627}_{-0.867}$	$-1.172^{+0.599}_{-0.866}$

Show improvements in mean of $H0$. How seriously one should take GRB?

Take-home message: Distance Ladder reconstruction

- Some interesting results but need to verified with other datasets/ combinations.
- Whether it really helps in addressing Hubble tension is yet to be confirmed.
- Can act a mock data generator (say for GW).
- Major challenge: derivative estimation in d_L'.

Conclusions

The point is not to pocket the truth but to chase it