An overview of cosmological tensions - Addressing systematics and fundamental physics solutions

Jackson Levi Said

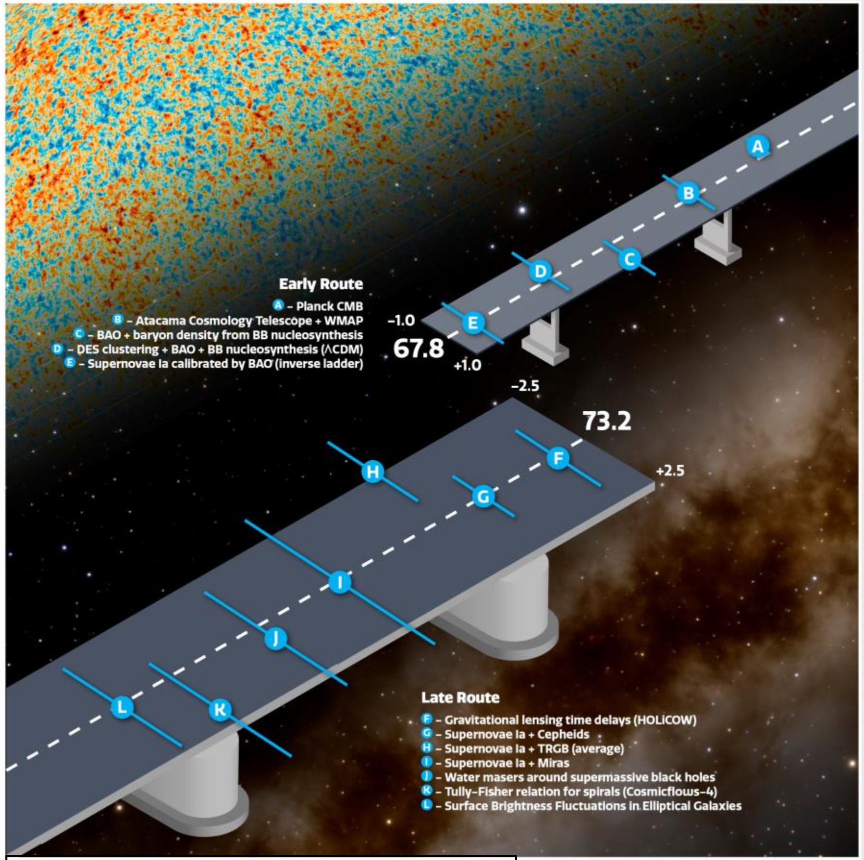
Institute of Space Sciences and Astronomy, University of Malta

Main take away message

Why care about the Hubble constant?

Adam Riess (2019): “H_0 is the ultimate end-to-end test for ΛCDM”

- The H_0 tension is more than just a **tension between CMB and the SH0ES** measurement
- Its also a tension between the **inverse distance ladder and high-z measurements**
- We are very far from a solution!



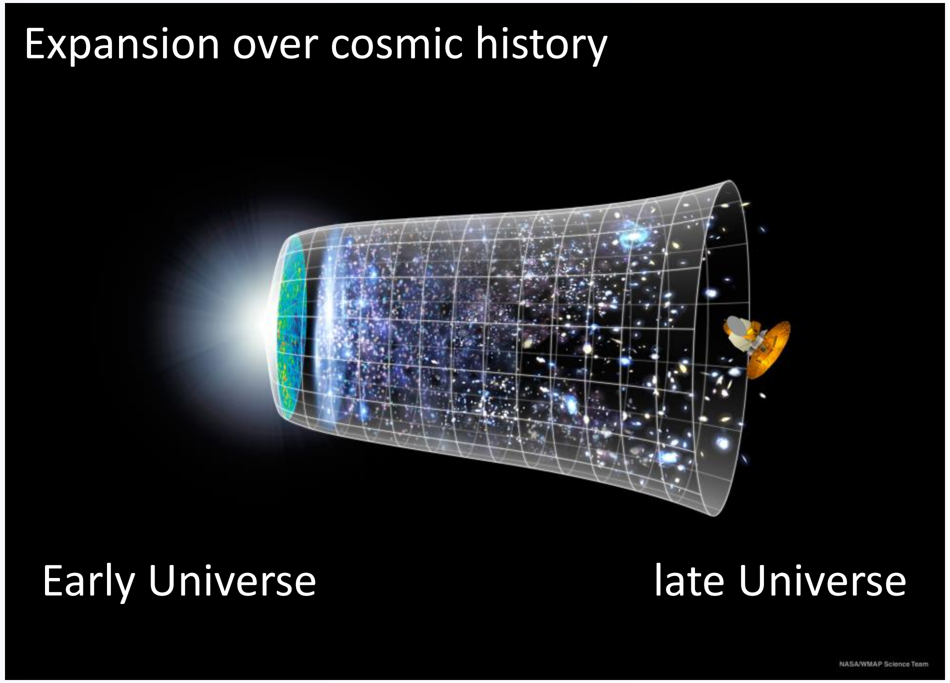
Riess, A. Nat. Rev. Phys. 2 (2020) 10

Why do we need modifications to standard cosmology?

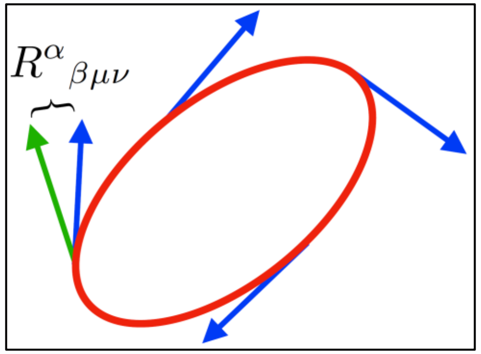
General Relativity and Concordance Cosmology

ΛCDM action:

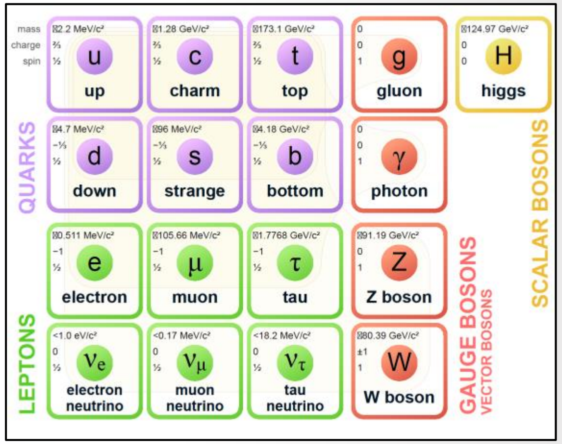
$$S = \frac{1}{16\pi G}\int d^4x\,\sqrt{-g}[\mathcal{R} - 2\Lambda] + \int d^4x\sqrt{-g}\,\mathcal{L}_m(g_{\mu\nu},\psi)$$



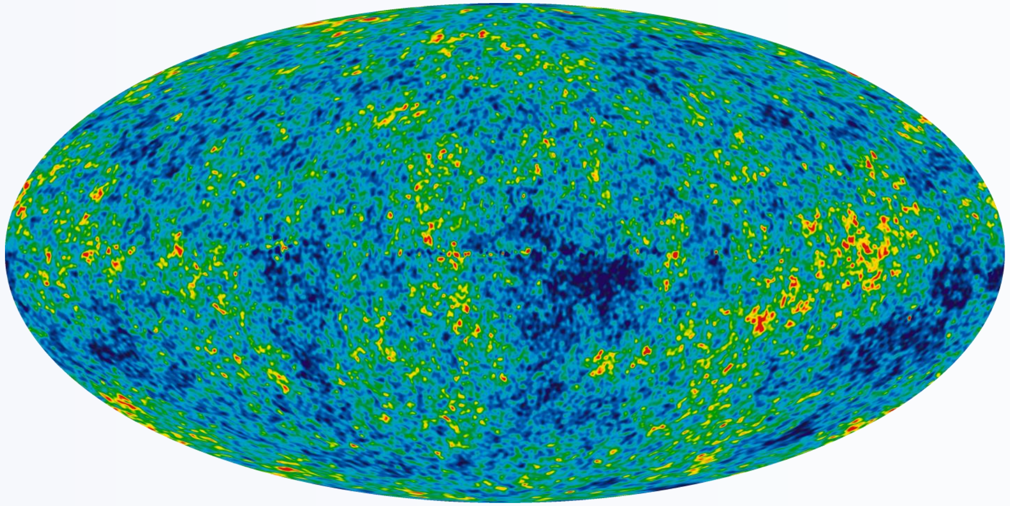
Einstein 1915: **General Relativity (GR)**
Energy-momentum source of curvature
Levi-Civita connection: Zero Torsion, Metricity



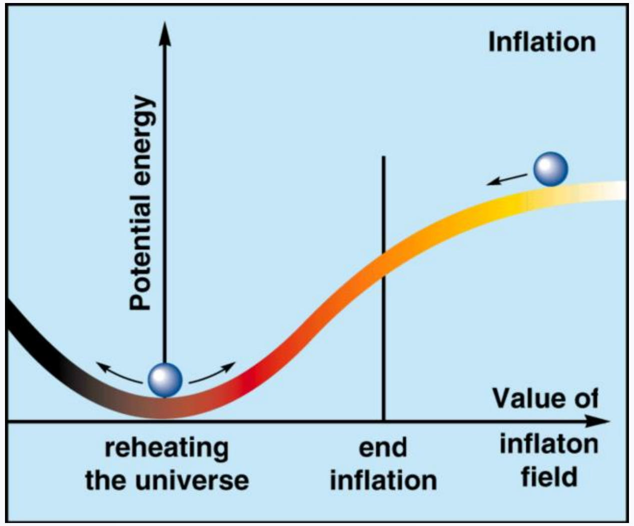
Standard model of particle physics:
$SU(3) \times SU(2) \times U(1)$



Early Universe Concordance Cosmology

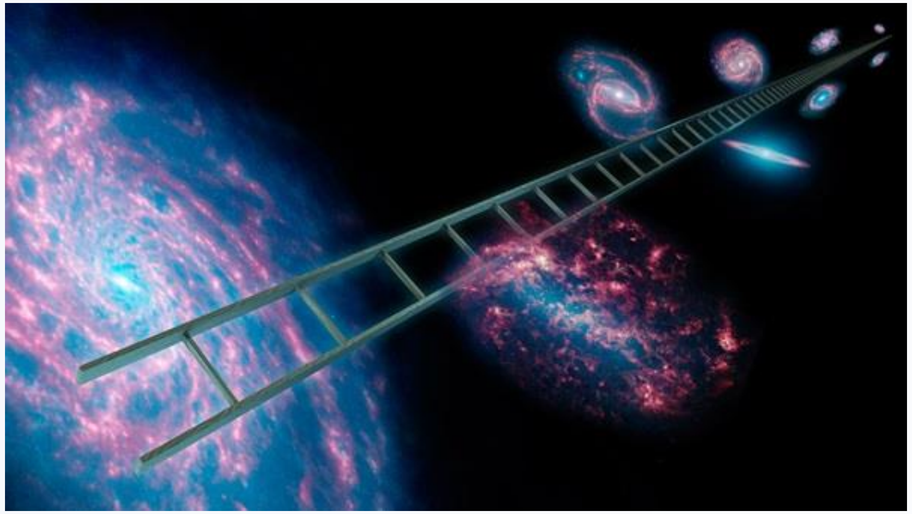


Anomalies and problems:
- The Lithium problem
- Hints of a closed Universe
- Large angular scale anomalies in the CMB
- Anomalously strong ISW effect
- Cosmic dipoles (cosmological principle)
- Lyman-α forest BAO anomalies
- Cosmic birefringence
- Discordance in dark matter abundance at smaller scales

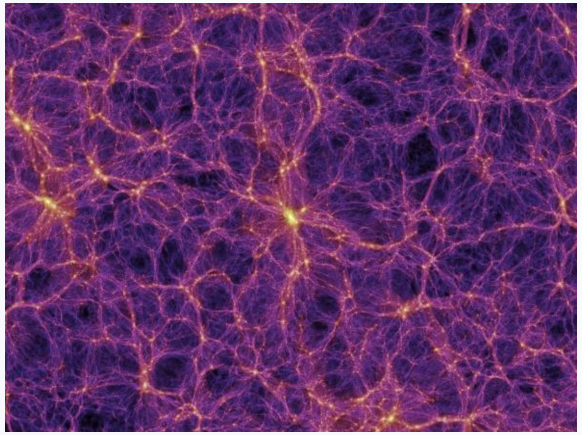


Cosmic inflation
Pros: Horizon and flatness problems
Cons: Fine-tuning

Late Universe Concordance Cosmology



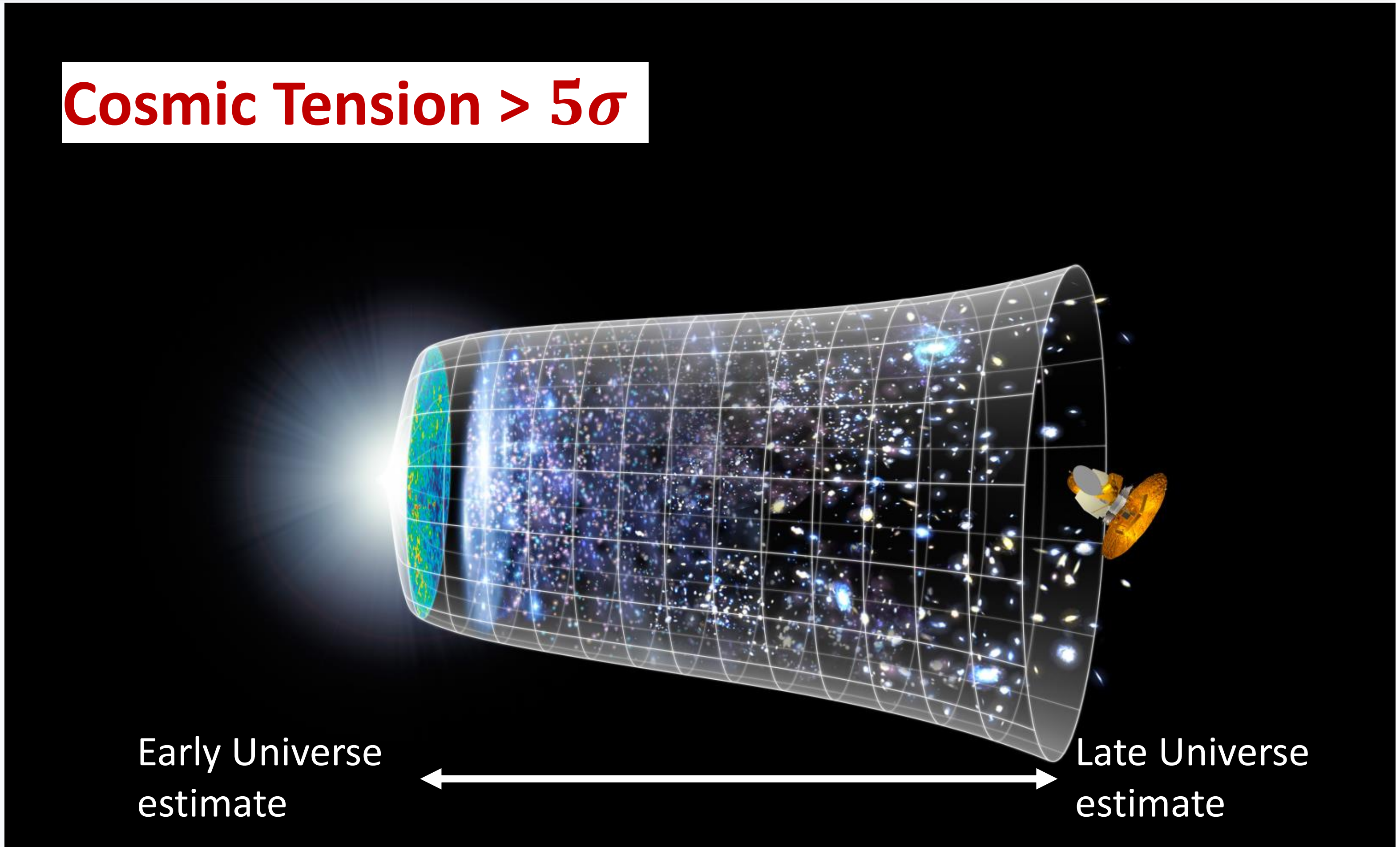
Anomalies and problems:
- Cold dark matter problems (core-cusp, missing satellites, satellite plane alignment)
- Dark energy in fundamental physics
- Oscillations of best-fit parameters across the sky
- Baryonic Tully-Fisher Relation



Requirements:
Dark matter
Dark energy

$$S = \frac{1}{16\pi G} \int d^4x \sqrt{-g}[\mathcal{R} - 2\Lambda]$$
$$+ \int d^4x \sqrt{-g} \mathcal{L}_m(g_{\mu\nu}, \psi)$$

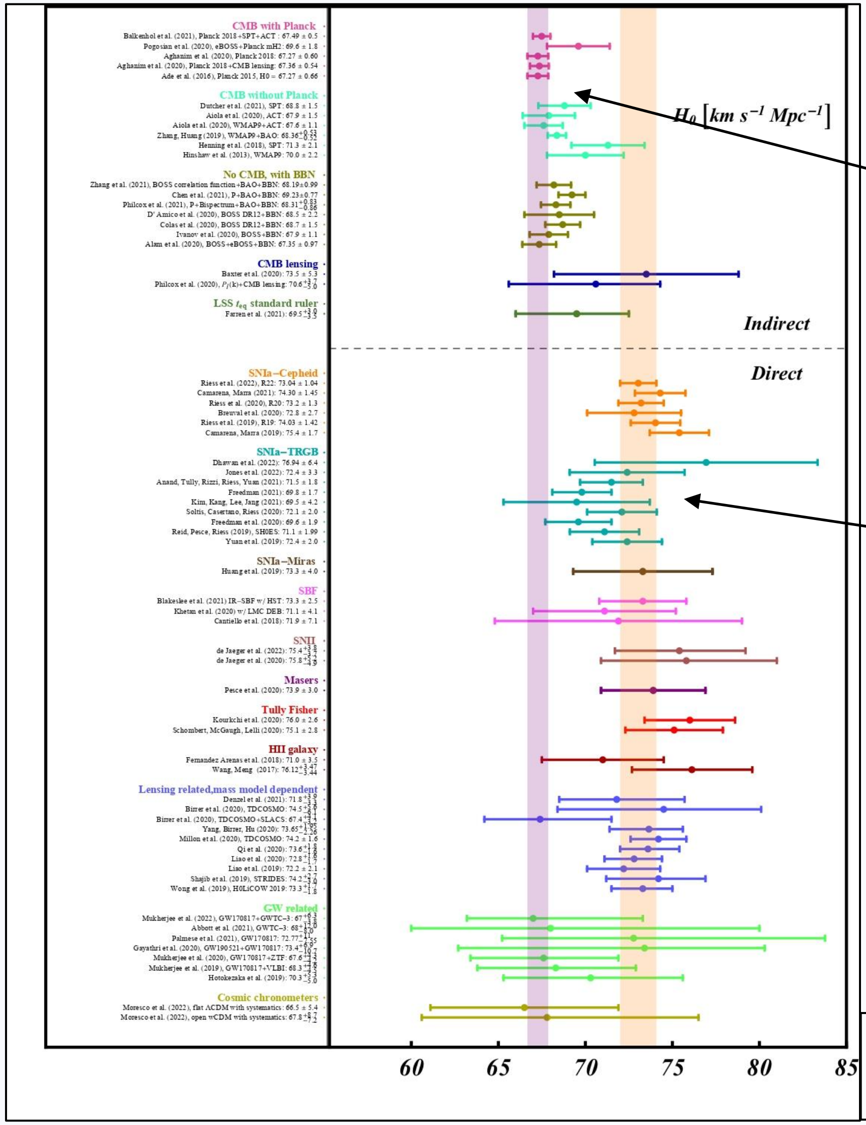
The Hubble Tension



$H_0^{\mathrm{P18}} = 67.27 \pm 0.60\ \mathrm{km\ s^{-1}Mpc^{-1}}$

$H_0^{\mathrm{S22}} = 73.04 \pm 1.04\ \mathrm{km\ s^{-1}Mpc^{-1}}$

Cosmic Tensions



Indirect measures predict H_0 using ΛCDM

$$r_s = \int_{z_{\rm LS}}^{\infty} \frac{c_s(z', \rho_b)}{H(z')} \mathrm{d}z'$$

Direct measures estimate H_0 using astrophysics

$$d_L(z) = (1+z) \int_0^z \frac{\mathrm{d}z'}{H(z')}$$

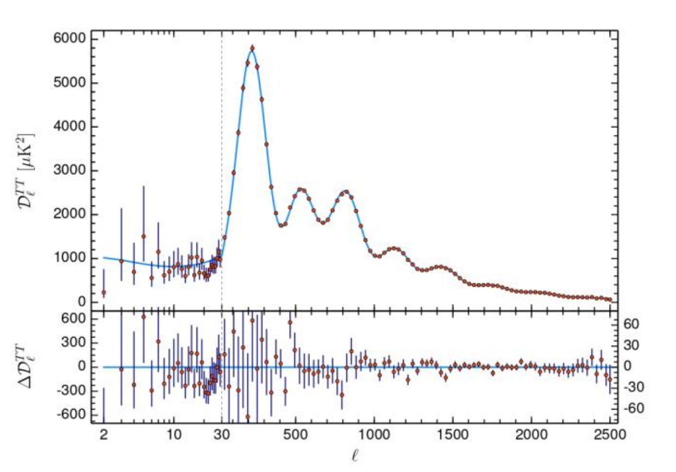
Di Valentino et al. CQG, 38 (2021) 15
Cosmology Intertwined JHEAp. 2204 (2022) 002

Cosmic Tensions: CMB

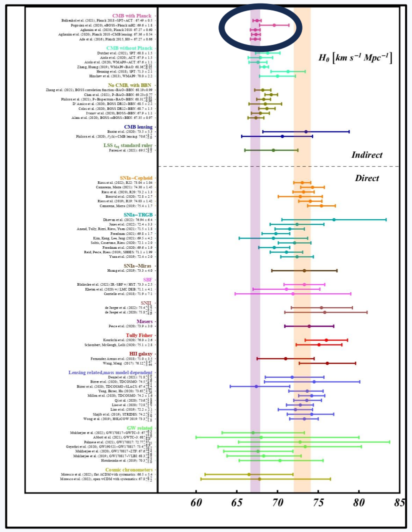
Parameter	Plik best fit	Plik [1]	CamSpec [2]	([2] − [1])/σ_1	Combined
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015	0.02229 ± 0.00015	−0.5	0.02233 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012	0.1197 ± 0.0012	−0.3	0.1198 ± 0.0012
$100\theta_{MC}$	1.040909	1.04092 ± 0.00031	1.04087 ± 0.00031	−0.2	1.04089 ± 0.00031
τ	0.0543	0.0544 ± 0.0073	$0.0536^{+0.0069}_{-0.0077}$	−0.1	0.0540 ± 0.0074
$\ln(10^{10}A_s)$	3.0448	3.044 ± 0.014	3.041 ± 0.015	−0.3	3.043 ± 0.014
n_s	0.96605	0.9649 ± 0.0042	0.9656 ± 0.0042	+0.2	0.9652 ± 0.0042
$\Omega_m h^2$	0.14314	0.1430 ± 0.0011	0.1426 ± 0.0011	−0.3	0.1428 ± 0.0011
H_0 [km s^{-1}Mpc^{-1}]	67.32	67.36 ± 0.54	67.39 ± 0.54	+0.1	67.37 ± 0.54
Ω_m	0.3158	0.3153 ± 0.0073	0.3142 ± 0.0074	−0.2	0.3147 ± 0.0074
Age [Gyr]	13.7971	13.797 ± 0.023	13.805 ± 0.023	+0.4	13.801 ± 0.024
σ_8	0.8120	0.8111 ± 0.0060	0.8091 ± 0.0060	−0.3	0.8101 ± 0.0061
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$	0.8331	0.832 ± 0.013	0.828 ± 0.013	−0.3	0.830 ± 0.013
z_{re}	7.68	7.67 ± 0.73	7.61 ± 0.75	−0.1	7.64 ± 0.74
$100\theta_*$	1.041085	1.04110 ± 0.00031	1.04106 ± 0.00031	−0.1	1.04108 ± 0.00031
r_{drag} [Mpc]	147.049	147.09 ± 0.26	147.26 ± 0.28	+0.6	147.18 ± 0.29

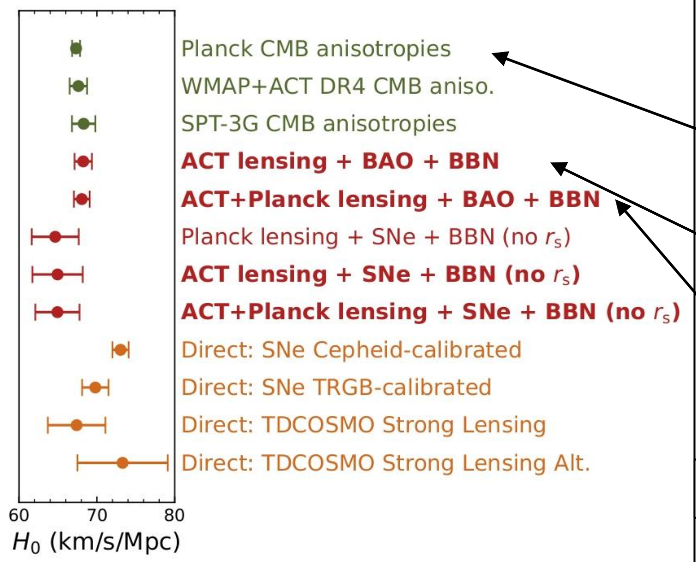
Planck Collaboration A&A 641 (2020) A6

ΛCDM is a six parameter model:
- Baryon density ($\Omega_m h^2$)
- Cosmological dark matter density ($\Omega_c h^2$)
- Acoustic scale angle ($100\theta_{MC}$)
- Reionization optical depth (τ)
- Primordial power spectrum amplitude ($\ln(10^{10}A_s)$)
- Primordial spectral index (n_s)



Spectrum of CMB temperature anisotropies from Planck





$$H_0^{P18} = 67.4 \pm 0.5 \text{ km s}^{-1}\text{Mpc}^{-1}$$

$$H_0^{ACT+BAO+BBN} = 68.3 \pm 1.1 \text{ km s}^{-1}\text{Mpc}^{-1}$$

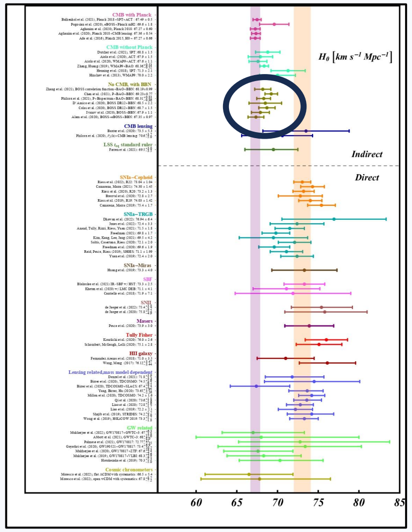
$$H_0^{ACT+P18+BAO+BBN} = 68.1 \pm 1.0 \text{ km s}^{-1}\text{Mpc}^{-1}$$

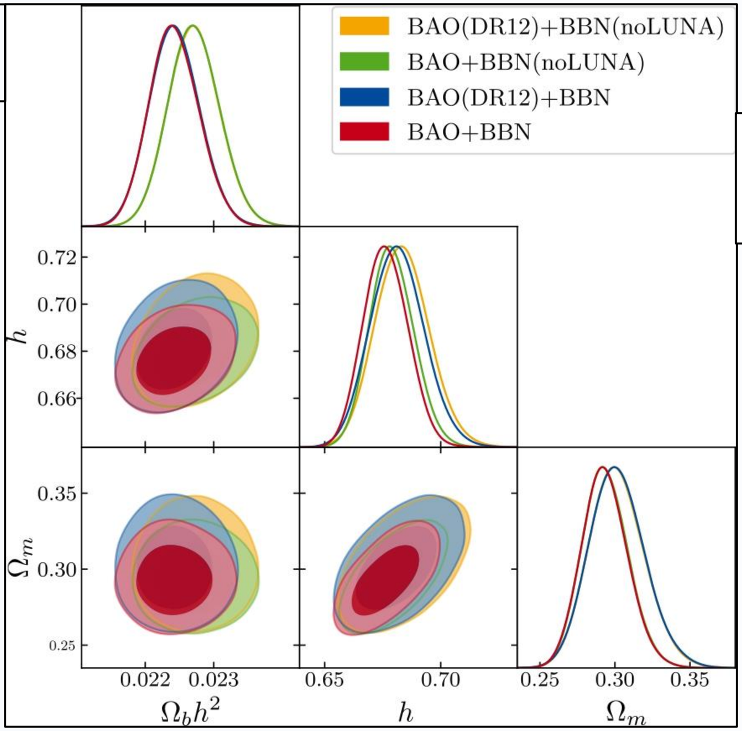
ACT Collaboration Astrophys. J. 962 (2024) 2, 113

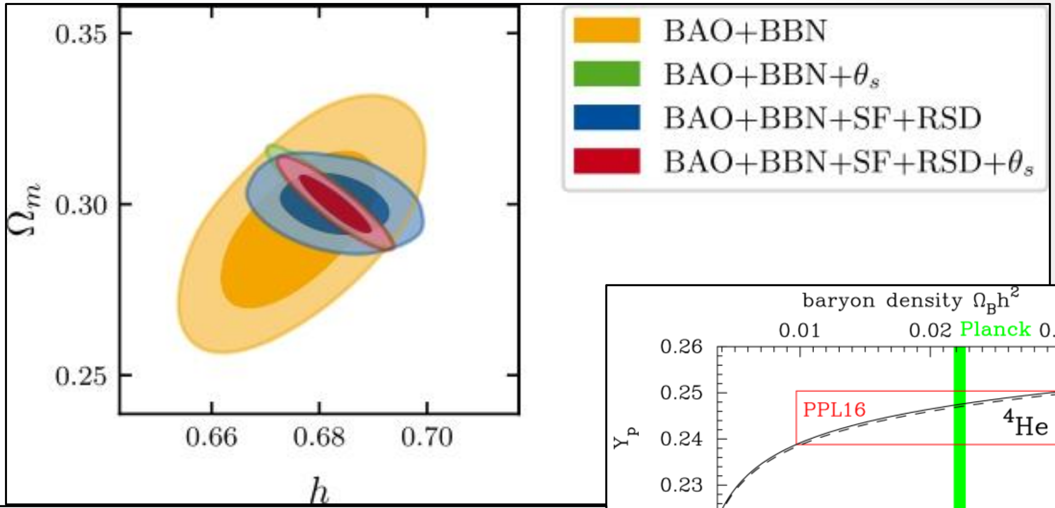
Cosmic Tensions: BBN

Data Sets	H_0 [km s^{-1} Mpc^{-1}]	$\Omega_{m,0}$
BAO (DR12)+BBN (noLUNA)	$68.36^{+1.13}_{-1.25}$	$0.302^{+0.018}_{-0.020}$
BAO+BBN (noLUNA)	$67.90^{+0.92}_{-1.03}$	$0.294^{+0.015}_{-0.016}$
BAO (DR12)+BBN	$68.14^{+1.13}_{-1.24}$	$0.302^{+0.017}_{-0.020}$
BAO+BBN	$67.64^{+0.97}_{-1.03}$	$0.293^{+0.015}_{-0.016}$

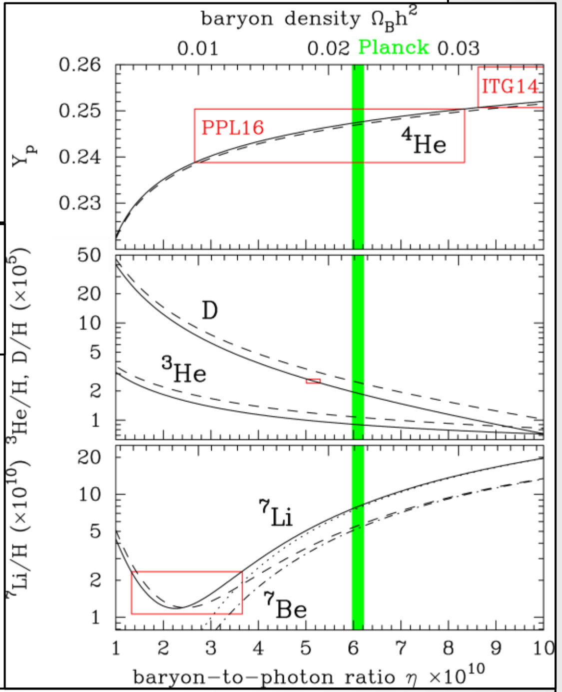
Schöneberg, N. et al
JCAP 11 (2022) 039





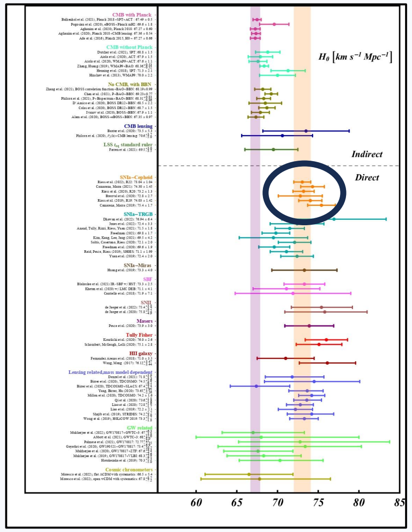


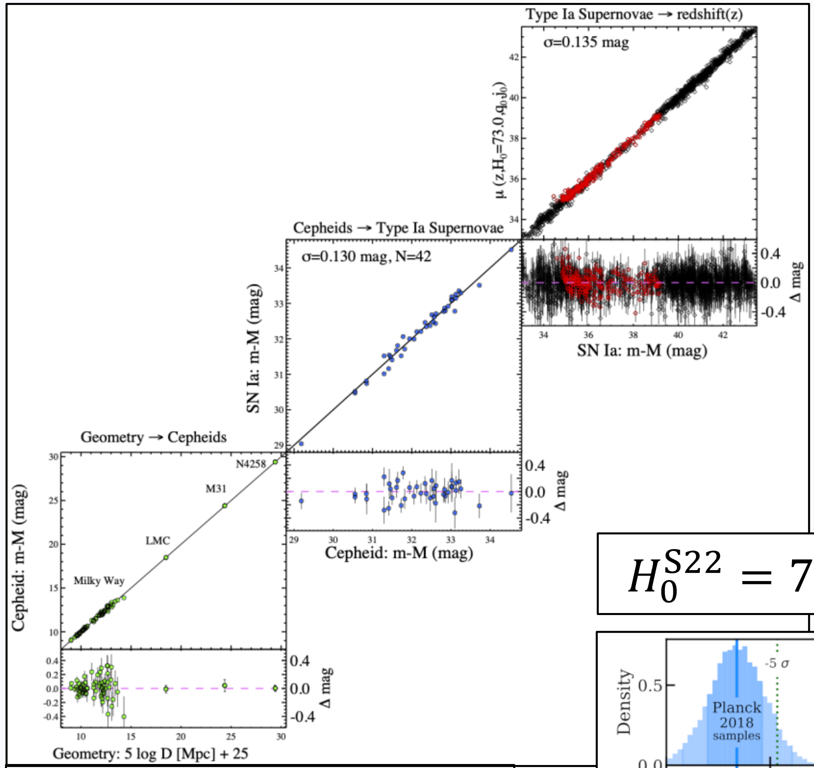
$$H_0^{\mathrm{BAO+BBN}+\theta_s} = 68.16^{+0.48}_{-0.49}\ \mathrm{km\ s^{-1}Mpc^{-1}}$$
$$\Omega_m^{\mathrm{BAO+BBN}+\theta_s} = 0.3022^{+0.0062}_{-0.0064}$$



Sasankan, N. et al Phys. Rev. D 101 (2020) 123532

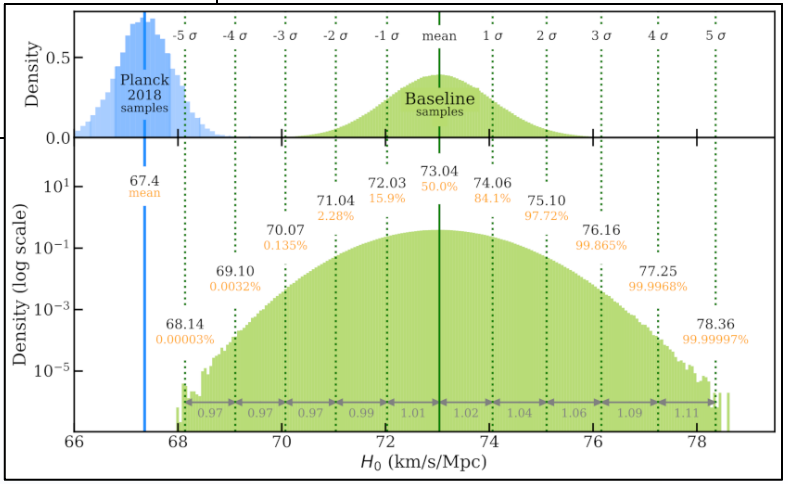
Cosmic Tensions: SH0ES Result



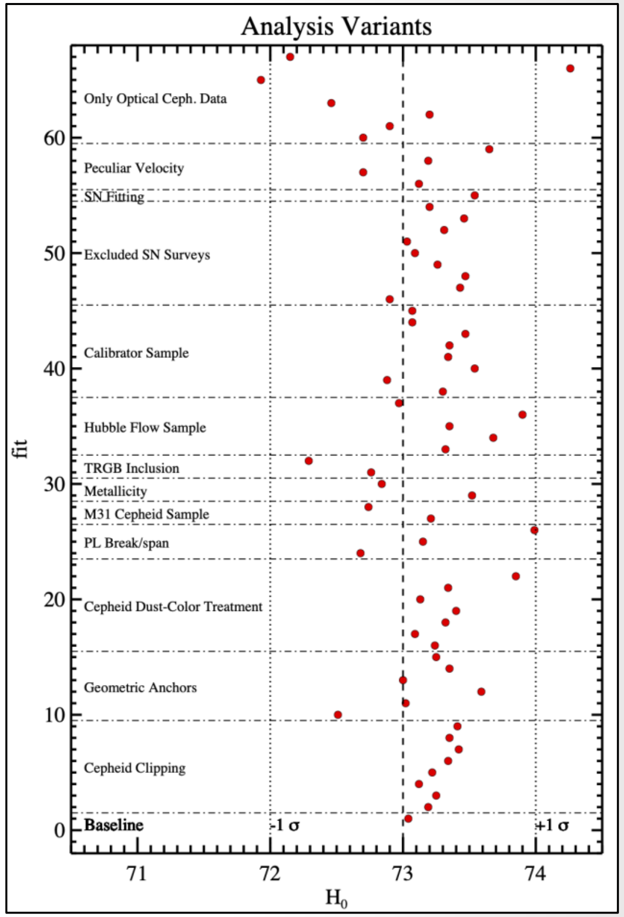


Riess, A. G. et al. ApJL 934 (2022) L7

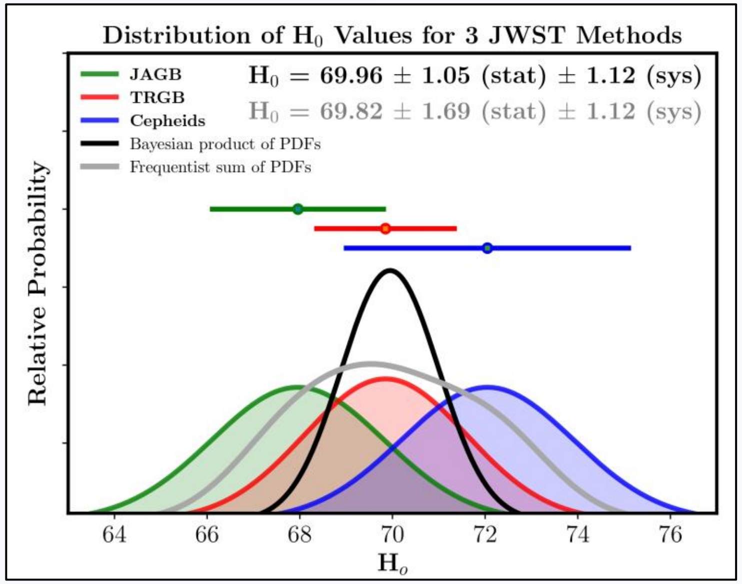
$$H_0^{S22} = 73.04 \pm 1.04 \text{ km s}^{-1}\text{Mpc}^{-1}$$

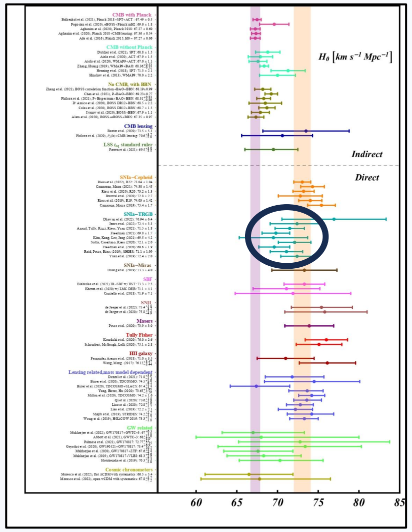


12 variants of analyses

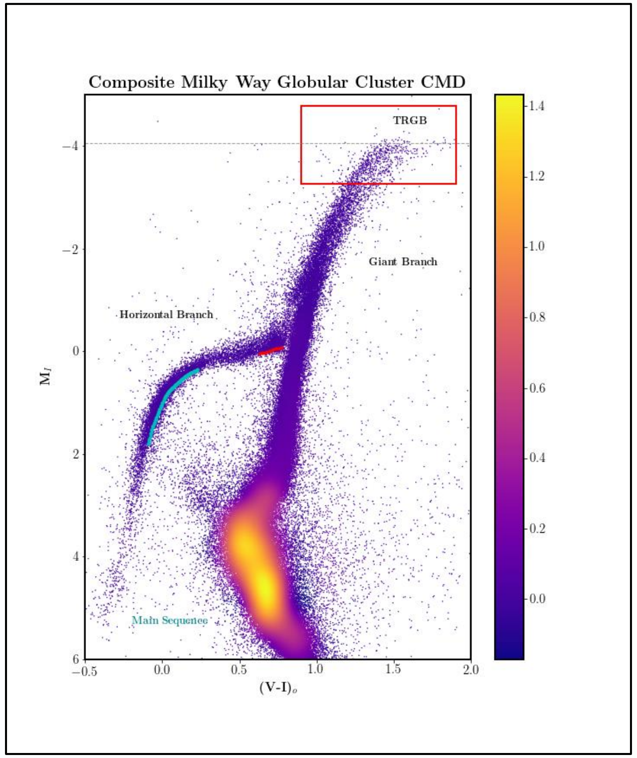


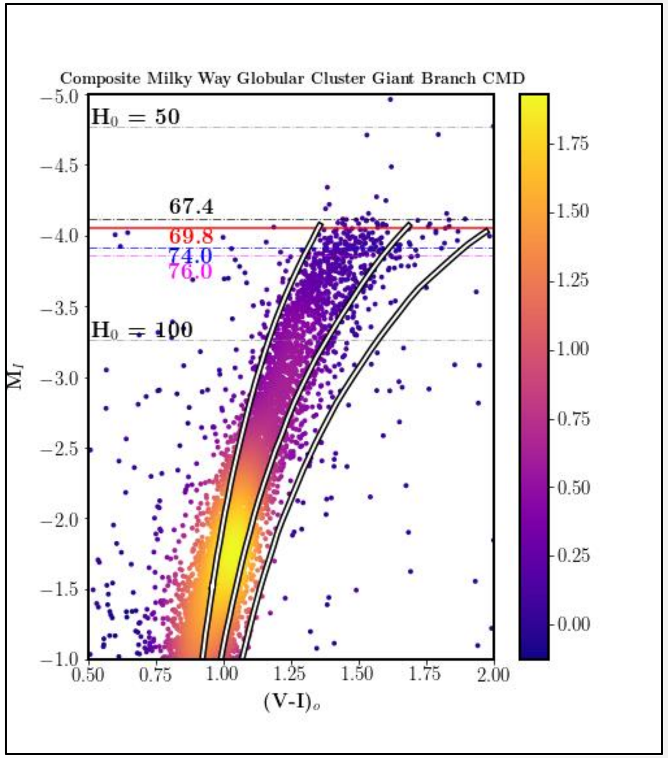
Cosmic Tensions: Tip of the Red Giant Branch



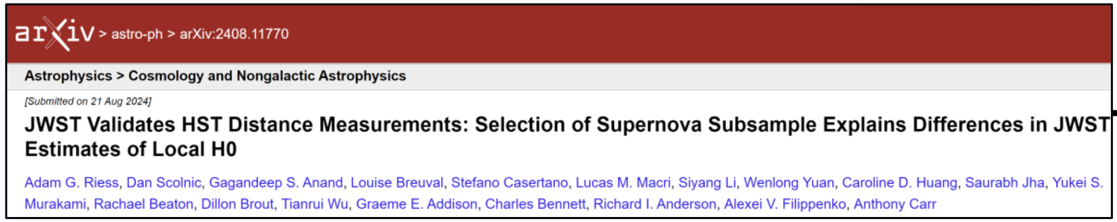


Freedman, W. L. et al.
arXiv:2408.06153





Freedman, W. et al. L. ApJ 919
(2021) 16


arXiv > astro-ph > arXiv:2408.11770

Astrophysics > Cosmology and Nongalactic Astrophysics

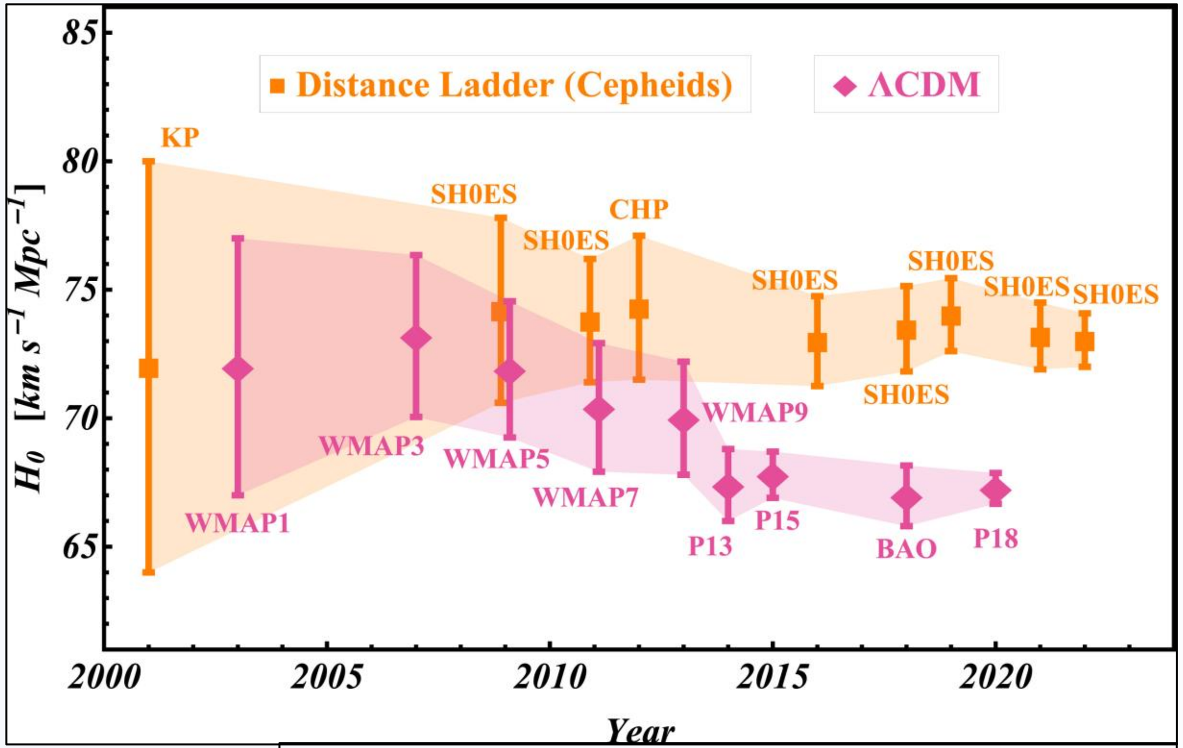
[Submitted on 21 Aug 2024]

JWST Validates HST Distance Measurements: Selection of Supernova Subsample Explains Differences in JWST Estimates of Local H0

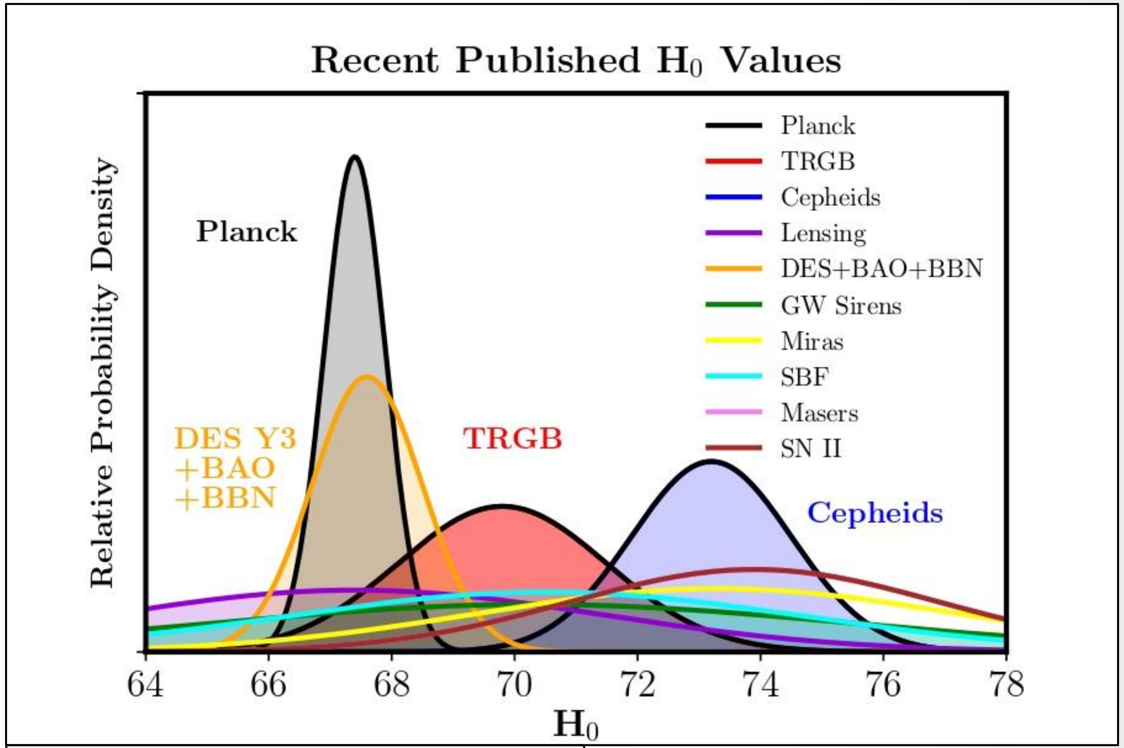
Adam G. Riess, Dan Scolnic, Gagandeep S. Anand, Louise Breuval, Stefano Casertano, Lucas M. Macri, Siyang Li, Wenlong Yuan, Caroline D. Huang, Saurabh Jha, Yukei S. Murakami, Rachael Beaton, Dillon Brout, Tianrui Wu, Graeme E. Addison, Charles Bennett, Richard I. Anderson, Alexei V. Filippenko, Anthony Carr

$$H_0^{\mathrm{A23}} = 72.1 \pm 2.2\ \mathrm{km\ s^{-1} Mpc^{-1}}$$

Cosmic Tensions in recent years



Perivolaropoulos, L.; Skara, F. New Astron. Rev. 95 (2022) 101659.



Freedman, W. et al. L. ApJ 919 (2021) 16

What are possible solutions?

Attempts at a solution

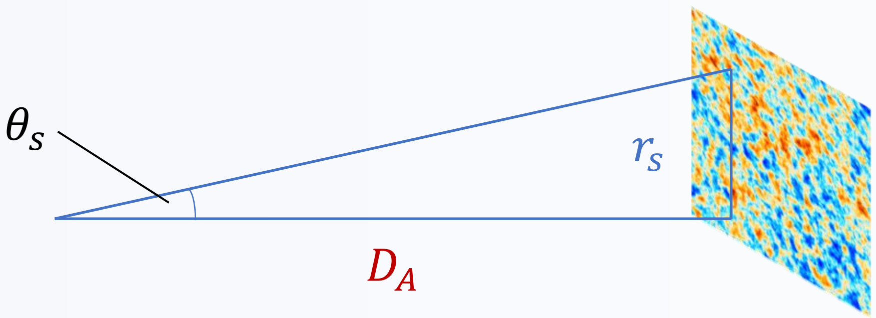
Model	ΔN_{param}	M_B	Gaussian Tension	Q_{DMAP} Tension		$\Delta\chi^2$	ΔAIC		Finalist
ΛCDM	0	-19.416 ± 0.012	4.4σ	4.5σ	✗	0.00	0.00	✗	✗
ΔN_{ur}	1	-19.395 ± 0.019	3.6σ	3.8σ	✗	-6.10	-4.10	✗	✗
SIDR	1	-19.385 ± 0.024	3.2σ	3.3σ	✗	-9.57	-7.57	✓	✓ 3
mixed DR	2	-19.413 ± 0.036	3.3σ	3.4σ	✗	-8.83	-4.83	✗	✗
DR-DM	2	-19.388 ± 0.026	3.2σ	3.1σ	✗	-8.92	-4.92	✗	✗
SIν+DR	3	$-19.440^{+0.037}_{-0.039}$	3.8σ	3.9σ	✗	-4.98	1.02	✗	✗
Majoron	3	$-19.380^{+0.027}_{-0.021}$	3.0σ	2.9σ	✓	-15.49	-9.49	✓	✓ 2
primordial B	1	$-19.390^{+0.018}_{-0.024}$	3.5σ	3.5σ	✗	-11.42	-9.42	✓	✓ 3
varying m_e	1	-19.391 ± 0.034	2.9σ	2.9σ	✓	-12.27	-10.27	✓	✓ 1
varying m_e+Ω_k	2	-19.368 ± 0.048	2.0σ	1.9σ	✓	-17.26	-13.26	✓	✓ 1
EDE	3	$-19.390^{+0.016}_{-0.035}$	3.6σ	1.6σ	✓	-21.98	-15.98	✓	✓ 2
NEDE	3	$-19.380^{+0.023}_{-0.040}$	3.1σ	1.9σ	✓	-18.93	-12.93	✓	✓ 2
EMG	3	$-19.397^{+0.017}_{-0.023}$	3.7σ	2.3σ	✓	-18.56	-12.56	✓	✓ 2
CPL	2	-19.400 ± 0.020	3.7σ	4.1σ	✗	-4.94	-0.94	✗	✗
PEDE	0	-19.349 ± 0.013	2.7σ	2.8σ	✓	2.24	2.24	✗	✗
GPEDE	1	-19.400 ± 0.022	3.6σ	4.6σ	✗	-0.45	1.55	✗	✗
DM $\to$ DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	✗	-0.19	3.81	✗	✗
DM $\to$ DR	2	-19.410 ± 0.011	4.3σ	4.5σ	✗	-0.53	3.47	✗	✗

The H_0 Olympics:

1. What tension does a model have with the SH0ES result using a baseline Planck 2018 + BAO + Pantheon best fit?
2. How does the inclusion of the SH0ES measurement impact this fit?
3. Does this inclusion make the best fit better than ΛCDM or worse?

Schöneberg, N. et al. Phys. Rept., 984 (2022) 1

Early vs local measurement approaches



$$\theta_s = \frac{r_s(z_{\rm LS})}{D_A(z_{\rm LS})} = \frac{\int_{z_{\rm LS}}^{\infty} c_s(z,\rho_b) H^{-1}(z') dz'}{\int_0^{z_{\rm LS}} H^{-1}(z') dz'}$$

Early-Universe new physics ($\boldsymbol{r_s}$)

- Considering the angular size of the sound horizon

$$\theta_s \sim \frac{r_s}{1/H(z_{\rm late})} \sim r_s H_0$$

By decreasing $\boldsymbol{r_s}$, we can increase $\boldsymbol{H_0}$, or so one would expect

Late-Universe new physics ($\boldsymbol{D_A}$)

- Keep early Hubble evolution unchanged and modify late-time evolution of $H(z)$

This is very difficult to do provided BAO, SnIa and CC data

Late-Universe new physics

Possible late-Universe solutions with new physics (that give high H_0 values with CMB):

- Graduated Dark Energy Akarsu, Ö., Barrow, J. D., Escamilla, L. A., and Vazquez, J. A. 2020
- Late-time interacting dark sector Gariazzo, S., Di Valentino, E., Mena, O., and Nunes, R. C. 2022
- Decaying dark matter Vattis, K., Koushiappas, S. M., Loeb, A 2020
- Decaying dark energy Li, X., Shafieloo, A., Sahni, V., and Starobinsky, A. A. 2019
- Negative dark energy density Poulin V., Boddy, K. K., Bird, S., and Kamionkowski, M 2018
- Phenomenologically Emergent Dark Energy Li, X., and Shafieloo, A. 2020
- Running vacuum models Sola J., Gomez-Valent, A., and de Cruz Perez, J. 2017

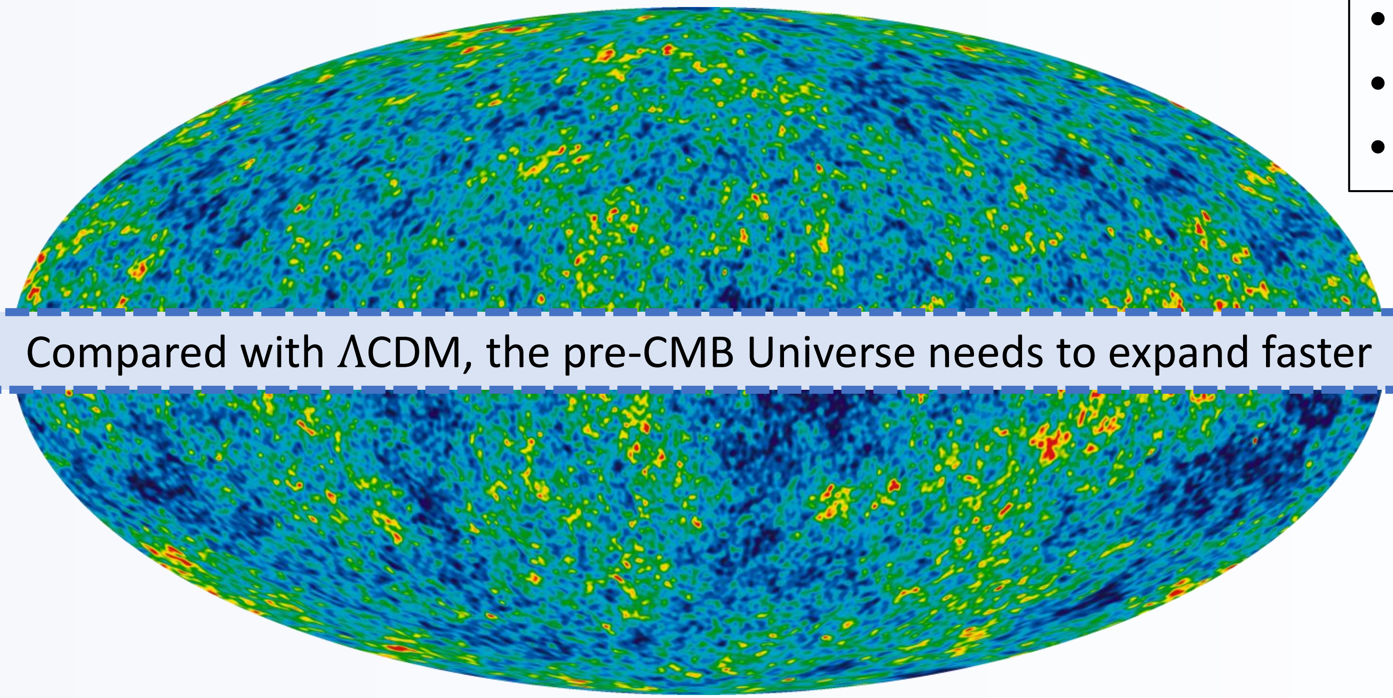
BAO constrain $\theta_s \sim r_s H_0$, anchoring r_s (early Universe) leaves few options for inferring H_0

Early-Universe new physics

Early-Universe physics concept:

- Fix θ_s (CMB peaks unchanged) so that $r_s \sim 1/H_0$
- Lower r_s which will increase pre-CMB expansion rate
- Do not change $D_A \propto 1/H_{\mathrm{Late}}(z)$, so modifications in the late Universe are not needed

- Recombination takes place sooner
- Sound waves travel a shorter distance (small r_s)
- The early Universe cools faster



Compared with ΛCDM, the pre-CMB Universe needs to expand faster

Early Universe Dark Energy (EDE)

- **Motivation**: Decrease the sound horizon by an early Universe dark component that is active up to roughly matter-radiation equality

- EDE continuity equation implies energy evolution

$$\rho_{\rm EDE}(a) = \rho_{\rm EDE,0}\, e^{3\int_a^1 [1+w_{\rm EDE}(a)]da/a}$$

This defines the **EDE density parameter** $f_{\rm EDE} = \rho_{\rm EDE}/\rho_{\rm Crit}$

- This can be parametrized through the EoS

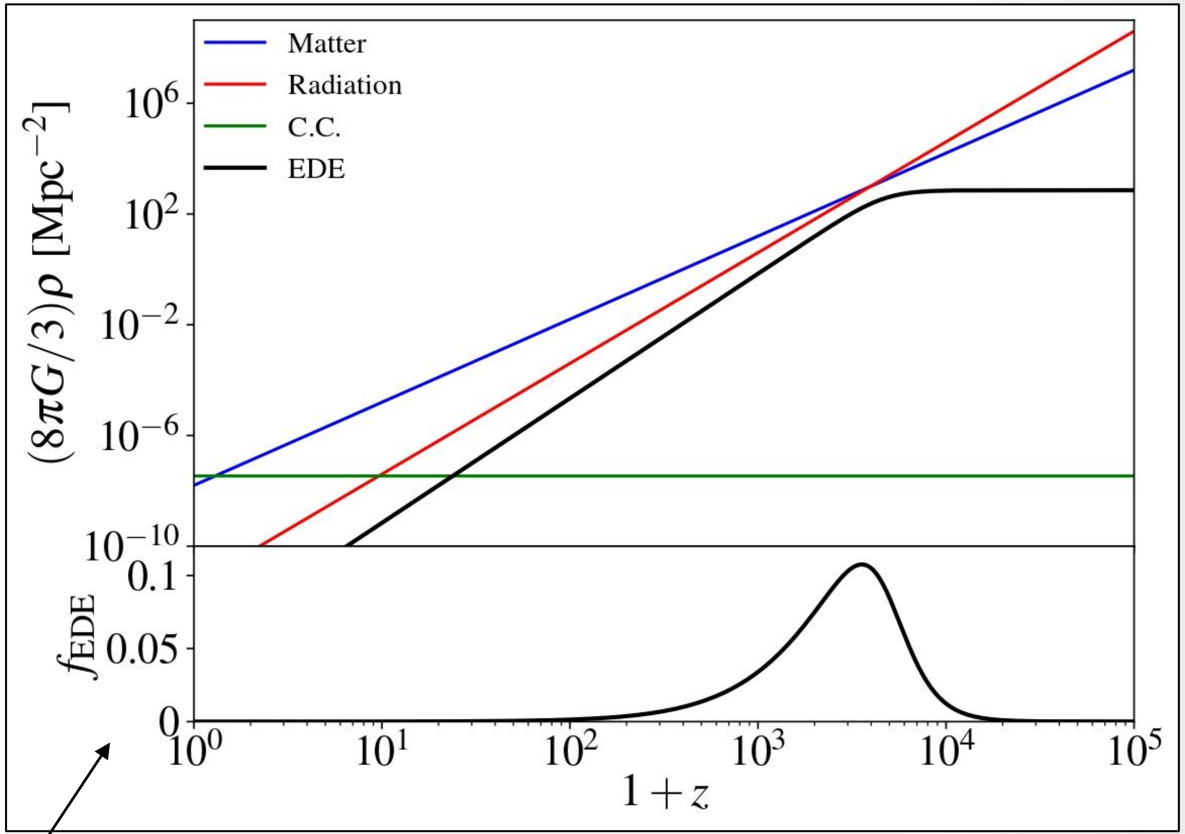
$$w_{\rm EDE}(a) = \frac{1+w_f}{1+(a_c/a)^{3(1+w_f)}} - 1$$

- The **critical scale factor** sets the scale for EDE:

$a \ll a_c \ \rightarrow$ cosmic expansion with $w_{\rm EDE} \rightarrow -1$

$a \gg a_c \ \rightarrow$ Dilutes as $a^{-3(1+w_f)}$

Example: $V(\phi) = \phi^{2n} \Rightarrow w_f = (n-1)/(n+1)$



Representative example: $f_{\rm EDE,max} = 0.1$ at $z_c \simeq 3500$ ($w_{\rm EDE} \rightarrow 1/2$ afterwards)

Poulin, V., Smith, T. L., and Karwal, T. Phys.Dark Univ. 42 (2023) 101348

EDE Models

- **Axion-like EDE (axEDE):**

$$V = m^2 f^2 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]^n$$

- **Rock 'n Roll EDE (RnR EDE):**

$$V = V_0 \left(\frac{\phi}{M_{\rm Pl}}\right)^{2n} + V_\Lambda$$

- **Acoustic EDE (ADE):**

$$1 + w_{\rm ADE} = \frac{1 + w_f}{\left[1 + (a_c/a)^{3(1+w_f)/p}\right]^p}$$

- **New EDE (NEDE):**

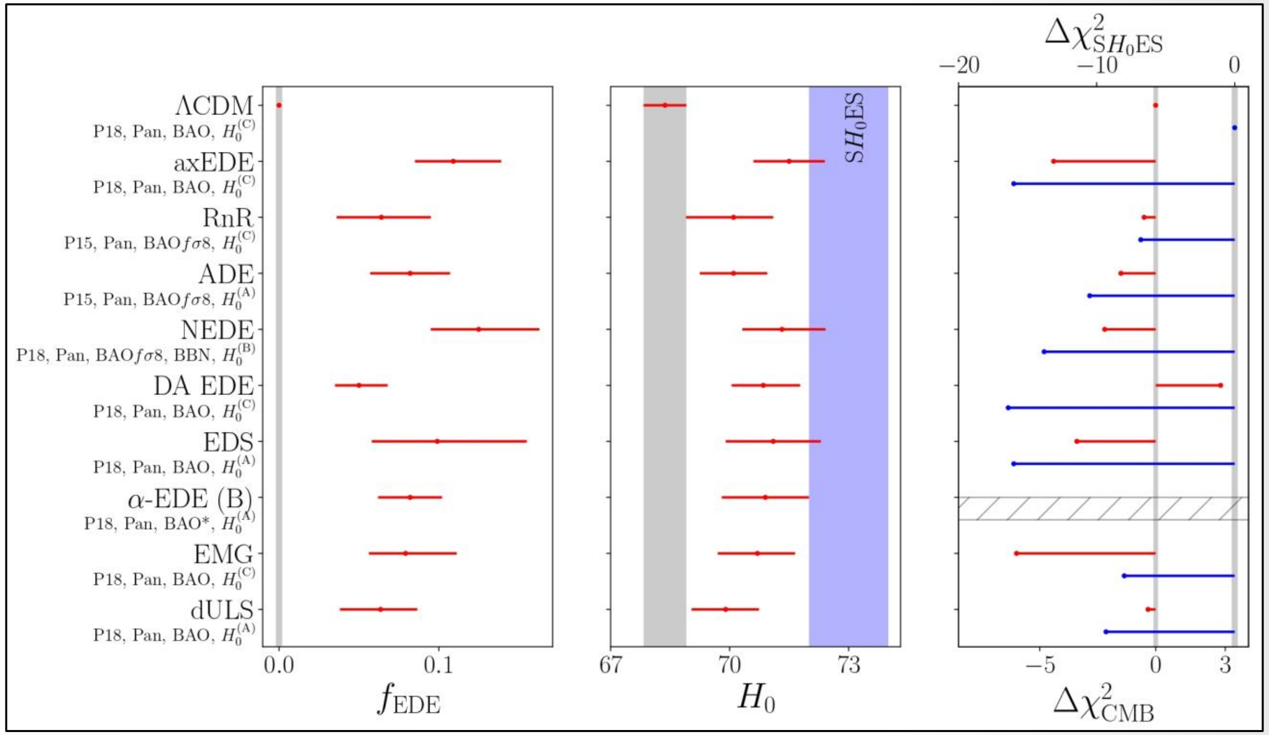
$$V(\psi, \phi) = \frac{\lambda}{4}\psi^4 + \frac{1}{2}\beta M^2 \psi^2 - \frac{1}{3}\alpha M \psi^3 + \frac{1}{2} m^2 \phi^2 + \frac{1}{2}\gamma \phi^2 \psi^2$$

- **EDE coupled to DM (EDS):**

$$V(\phi, a) = V(\phi) + \rho_{\rm DM}(a)$$

- **α –attractors EDE (α –EDE):**

$$V = \Lambda + V_0 \frac{(1+\beta)^{2n} \tanh\left(\phi/\sqrt{6\alpha} M_{\rm Pl}\right)^{2p}}{\left[1 + \beta \tanh\left(\phi/\sqrt{6\alpha} M_{\rm Pl}\right)\right]^{2n}}$$

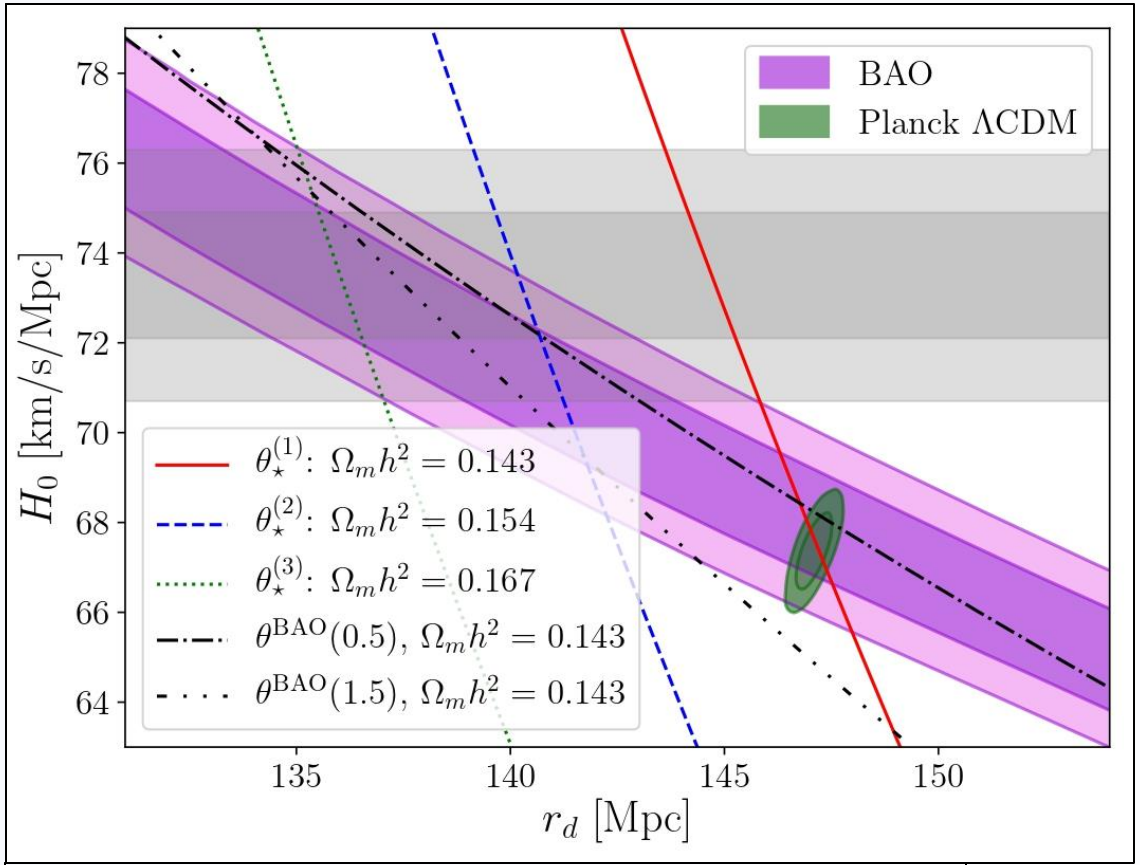


$\Delta\chi^2_{\rm SH0ES}$
$\Delta\chi^2_{\rm CMB}$

Klein-Gordon equation of motion:

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV(\phi)}{d\phi} = 0$$

The problem with EDE



Jedamzik, K., Pogosian, L. and Zhao, G. B. Commun. Phys. 4 (2021) 123

CMB angular size at recombination:

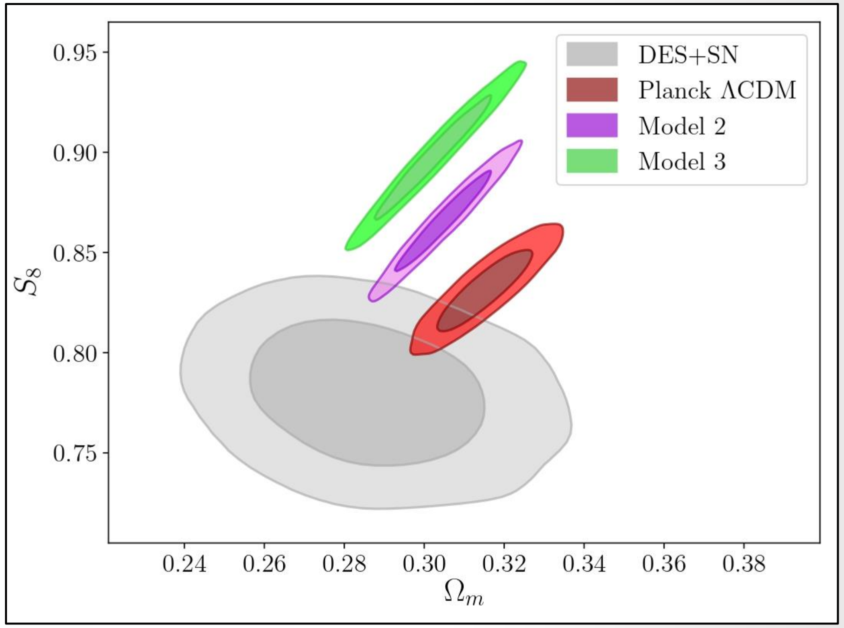
$$\theta_* = \frac{r_s(z_{\rm LS})}{D(z_{\rm LS})}$$

Transverse BAO angular scale:

$$\theta^{\rm BAO}(z_{\rm Obs}) = \frac{r_{\rm d}}{D(z_{\rm Obs})}$$

Model 2:
Fits BAO and CMB peaks at $\Omega_{\rm m} h^2 = 0.155$

Model 3:
Fits BAO, CMB peaks and SH0ES result at $\Omega_{\rm m} h^2 = 0.167$



Modified Gravity through Lovelock's Theorem

Adding new fields (scalar, vector, tensor)

Adding more than second-order derivatives of the metric

Use more/less than four dimensions of spacetime

Lovelock's Theorem

For **second order** vacuum field equations $E_{\mu\nu} = 0$, if $E_{\mu\nu}$ is a function of the metric $g_{\mu\nu}$, then

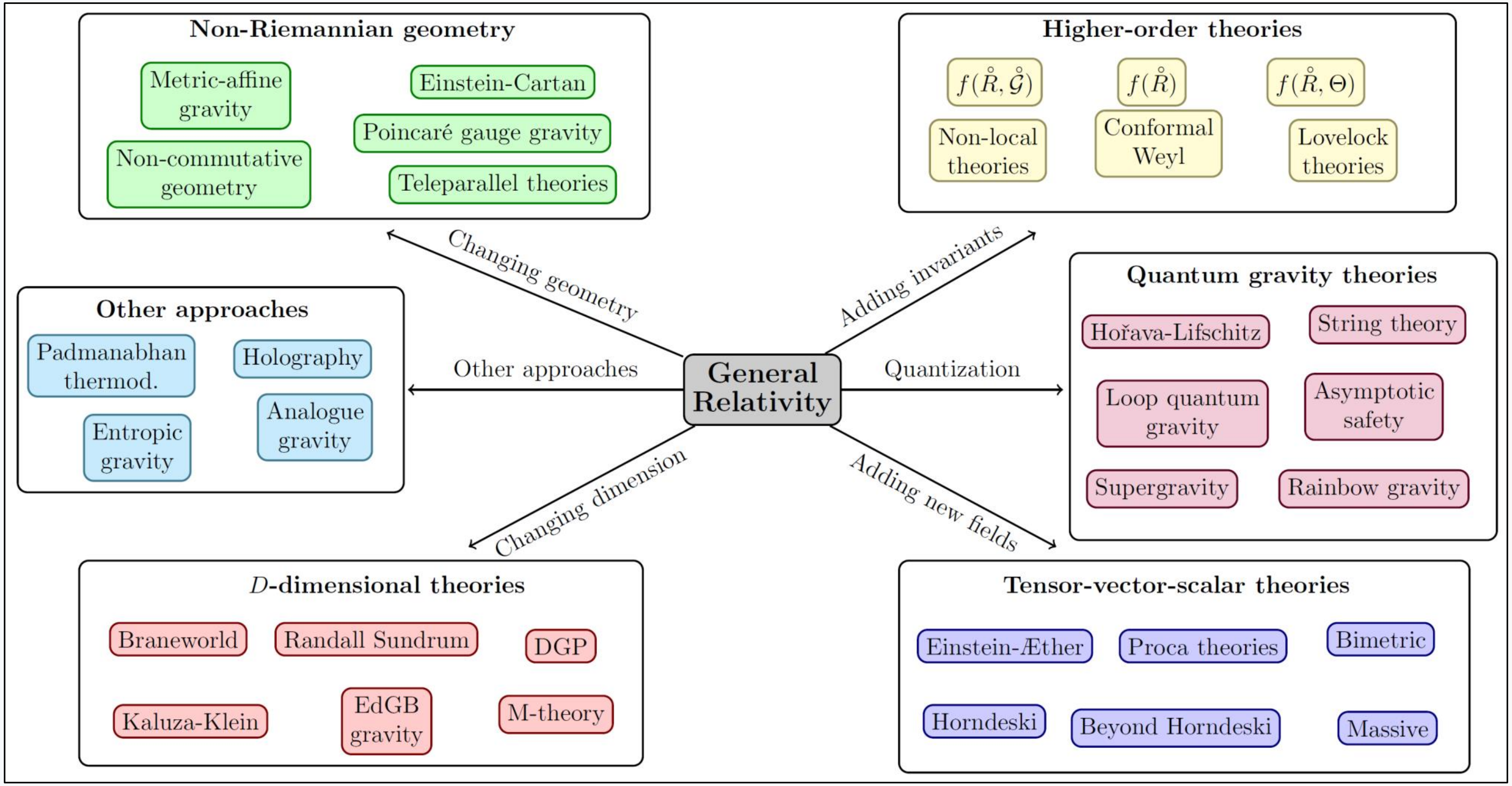
$$E_{\mu\nu} \coloneqq G_{\mu\nu} + \Lambda g_{\mu\nu} = \mathcal{R}_{\mu\nu} - \frac{1}{2}\mathcal{R} g_{\mu\nu} + \Lambda g_{\mu\nu}$$

Consider non-local terms

Take an emergent form of gravity

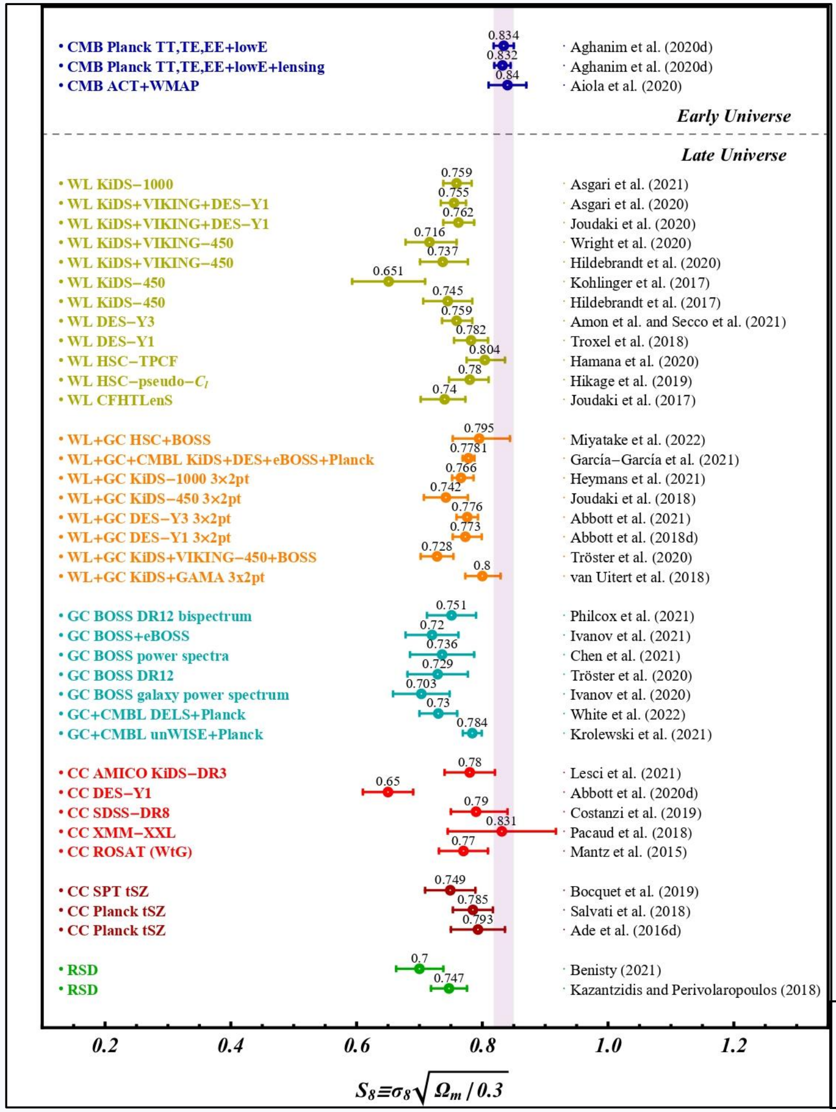
Changing the gravitational connection

The Modified Gravity Landscape



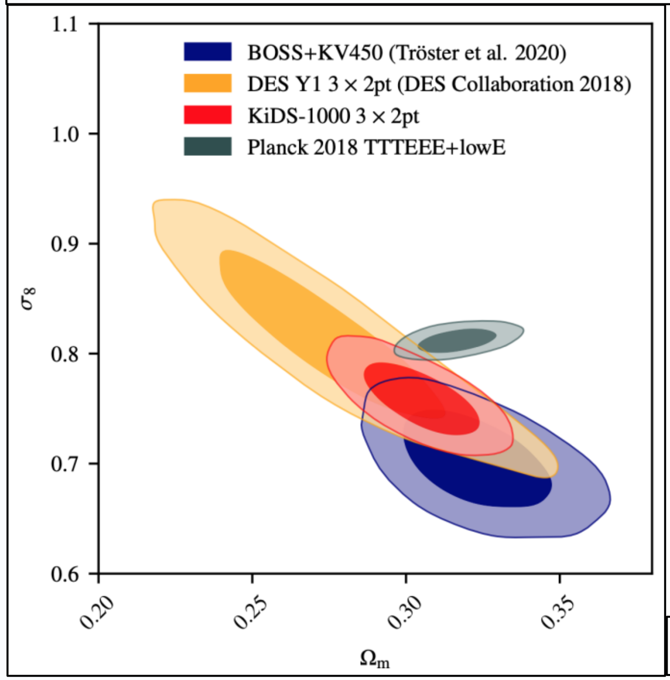
What about other tensions on the rise?

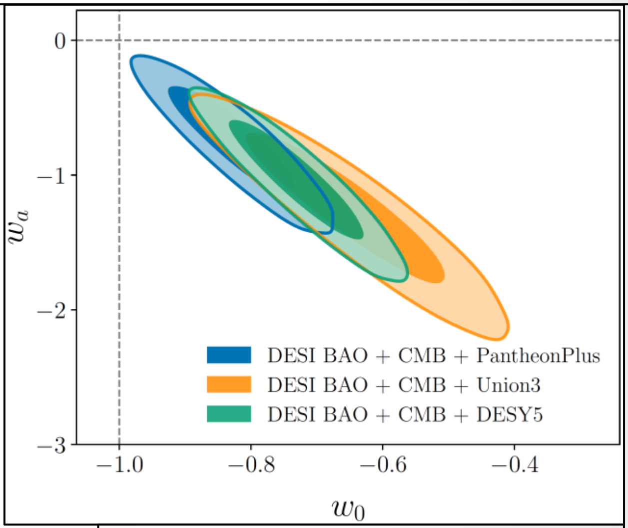
S_8 Tension



Large scale structure is nicely represented by S_8 which combines the matter density and matter density fluctuations on the scale of $8\ h^{-1}\mathrm{Mpc}$

$$S_{8,0} = \sigma_{8,0} \sqrt{\frac{\Omega_{\mathrm{m},0}}{0.3}}$$





DESI Collaboration, arXiv:2404.03002

Haymans, C. et al. A&A 646 (2021) A140

Di Valentino et al. CQG, 38 (2021) 15

Cosmology Intertwined, JHEAp. 2204 (2022) 002

How can machine learning help?

Horndeski Gravity

Horndeski Gravity: Produces the most **general second-order theory** that contains only **one scalar field** (in **standard gravity**)

$$S = \frac{1}{16\pi G}\int d^4x\,\sqrt{-g}\left[\mathcal{L}_2 + \mathcal{L}_3 + \mathcal{L}_4 + \mathcal{L}_5\right]$$

where

$$\mathcal{L}_2 = G_2(\phi, X)$$
$$\mathcal{L}_3 = G_3(\phi, X)\Box\phi$$
$$\mathcal{L}_4 = G_4(\phi, X)R + G_{4,X}(\phi, X)\left[(\Box\phi)^2 - \phi_{;\mu\nu}\phi^{;\mu\nu}\right]$$
$$\mathcal{L}_5 = G_5(\phi, X)G_{\mu\nu}\phi^{;\mu\nu} - \frac{1}{6}G_{5,X}(\phi, X)\left[(\Box\phi)^3 + 2\phi_{;\mu}{}^{\nu}\phi_{;\nu}{}^{\alpha}\phi_{;\alpha}{}^{\mu} - 3\phi_{;\mu\nu}\phi^{;\mu\nu}\Box\phi\right]$$

Example classes of models

Quintessence models

$$G_2 = X - V(\phi), G_3 = C,$$
$$G_4 = 1/2, G_5 = 0$$

Background equations:

$$3H^2 = \rho + \frac{\dot{\phi}^2}{2} + V(\phi)$$

$$2\,\dot{H} + 3H^2 = -p - \frac{\dot{\phi}^2}{2} + V(\phi)$$

$$\ddot{\phi} + 3H\,\dot{\phi} + V'(\phi) = 0$$

Equation of State parameter:

$$w_\phi = \frac{\dot{\phi}/2 - V}{\dot{\phi}/2 + V}$$

Designer Horndeski models

$$G_2 = K(X), G_3 = G(X),$$
$$G_4 = 1/2, G_5 = 0$$

Background equations:

$$3H^2 = \rho - K(X) + 2XK_X + 3H\dot{\phi}^2 G_X$$
$$2\,\dot{H} + 3H^2 = -p - K(X) + 2X\,\ddot{\phi}G_X$$

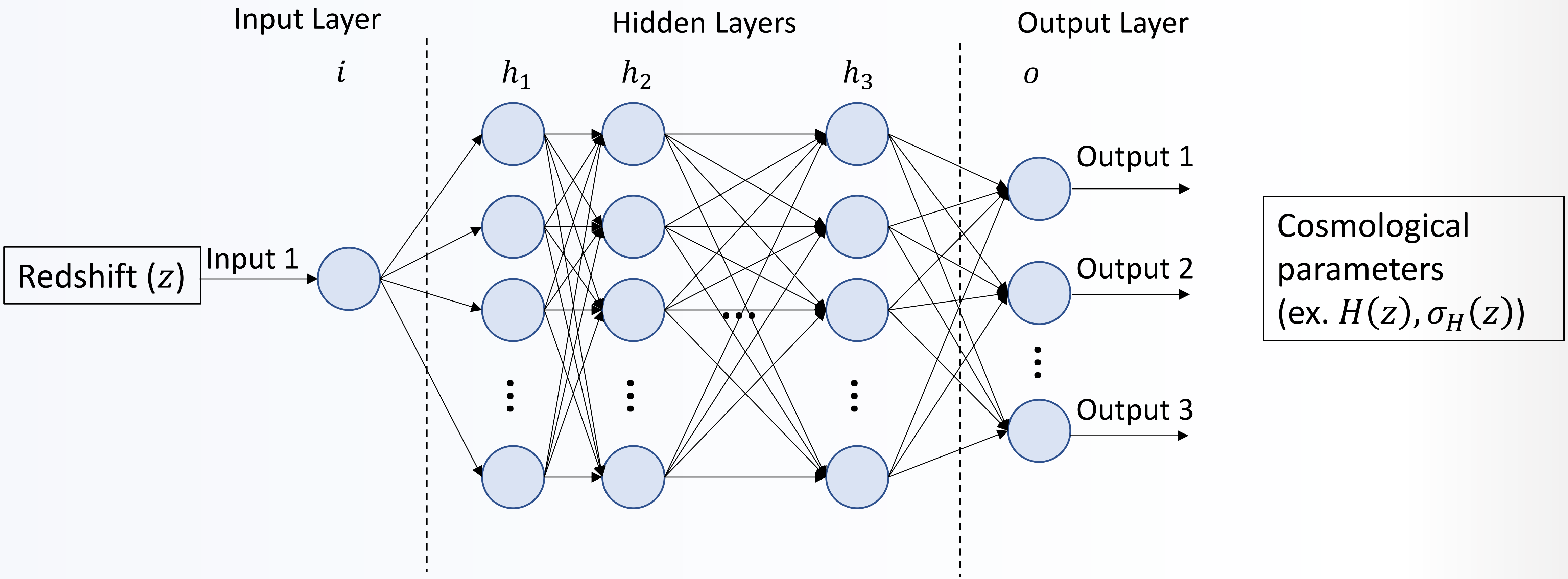
$$\ddot{\phi}\left[\dot{\phi}\left(3H\left(G_{XX}\,\dot{\phi}^2 + G_X\right) + K_{XX}\,\dot{\phi}\right) + K_X\right]$$
$$+ 3\,\dot{\phi}\left(G_X\,\dot{H}\,\dot{\phi} + 3G_X H^2\,\dot{\phi} + HK_X\right) = 0$$

Equation of State parameter:

$$w_\phi = -1 + \frac{J\sqrt{2X}\left(H^2 - H_0^2(1-\Omega_m)\right)}{3H_0^4\Omega_m(1-\Omega_m)} - \frac{2J\sqrt{2X}\left(\dot{\phi}K_X + 3H\,\dot{\phi}^2 G_X\right)(1+z)HH'}{9H_0^4\Omega_m(1-\Omega_m)}$$

where $J = \dot{\phi}K_X + 3H\,\dot{\phi}^2 G_X$

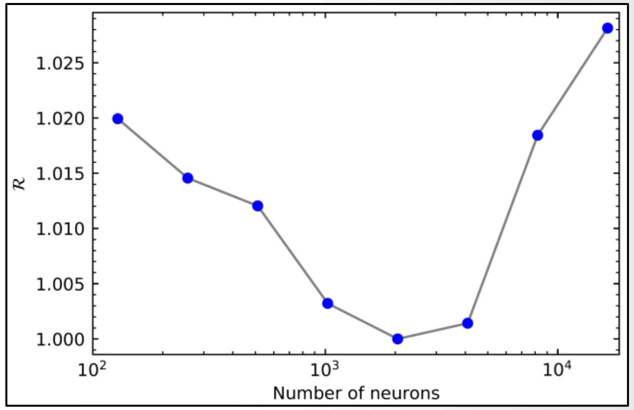
Artificial Neural Networks (ANNs)



Designing the ANN

- **Risk** – Optimizes the **number of hidden layers and neurons** in an ANN

$$\text{risk} = \sum_{i=1}^{N} (\text{Bias}_i^2 + \text{Variance}_\text{i}) = \sum_{i=1}^{N} \left(\left[H_{Obs}(z_i) - H_{pred}(z_i) \right]^2 + \sigma_H^2(z_i) \right)$$

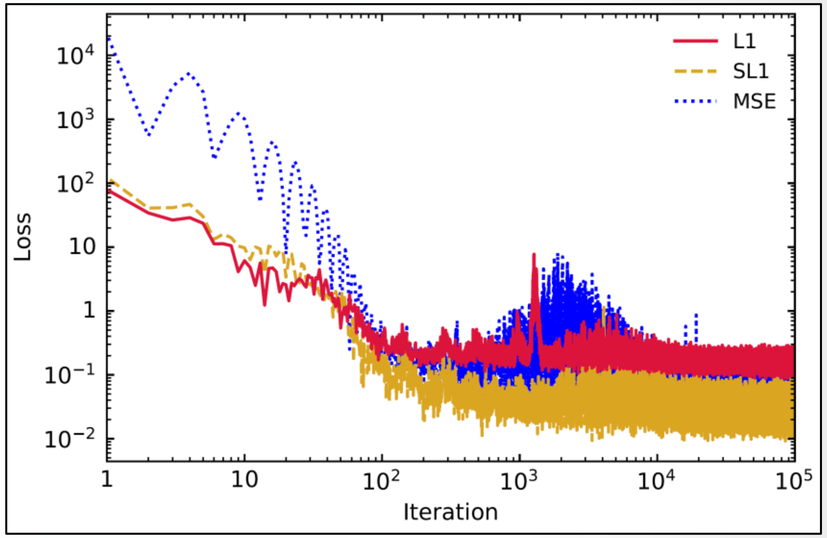


- **Loss** – Balances the **number of iterations** a system needs to predict the observational data
  1. **L1** (Least absolute deviation)

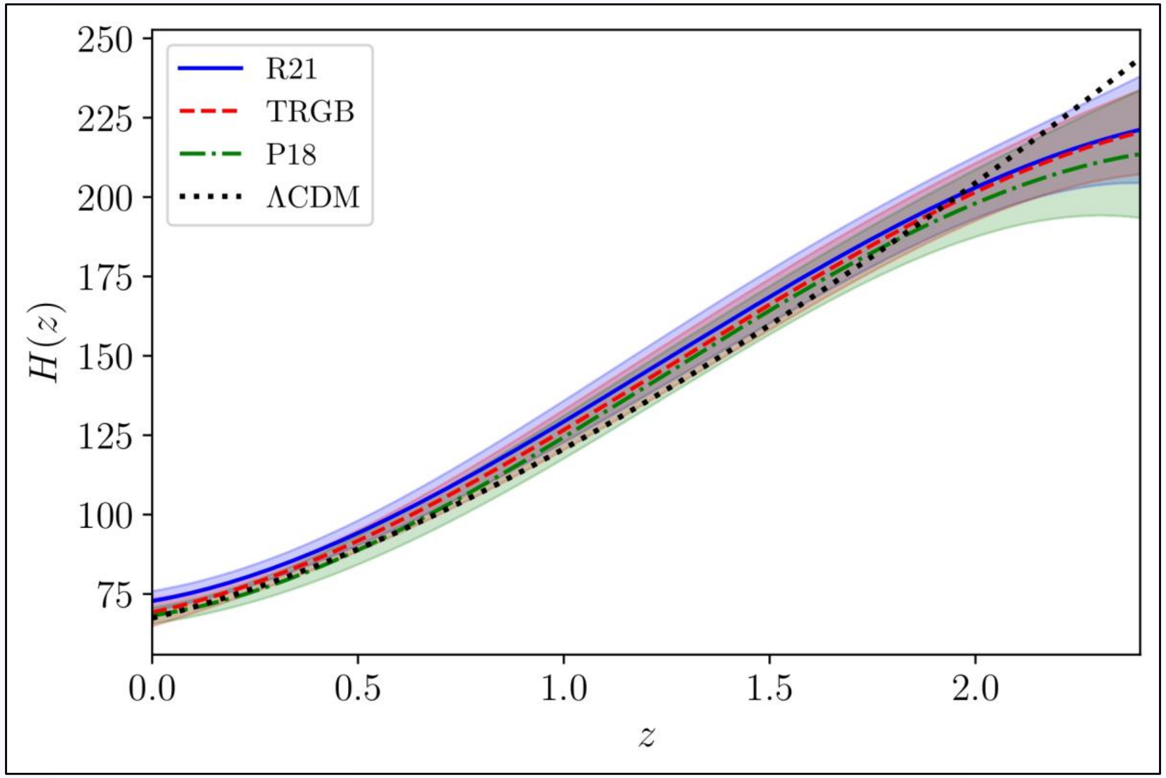
$$\text{L1} = \sum_{i=1}^{N} \left| H_{Obs}(z_i) - H_{pred}(z_i) \right|$$

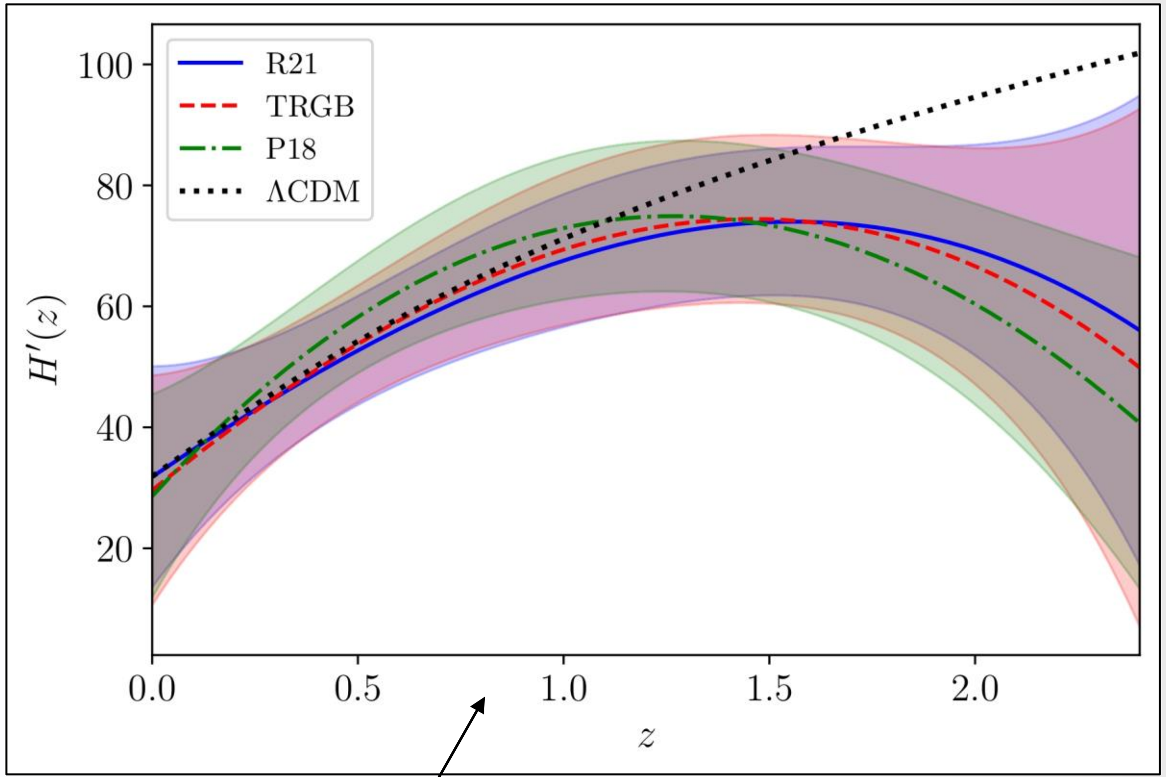
  2. Smoothed L1 (**SL1**)
  3. Mean Square Error (**MSE**)

$$\text{MSE} = \frac{1}{N} \sum_{i=1}^{N} \left(H_{Obs}(z_i) - H_{pred}(z_i) \right)^2$$



Using the ANN



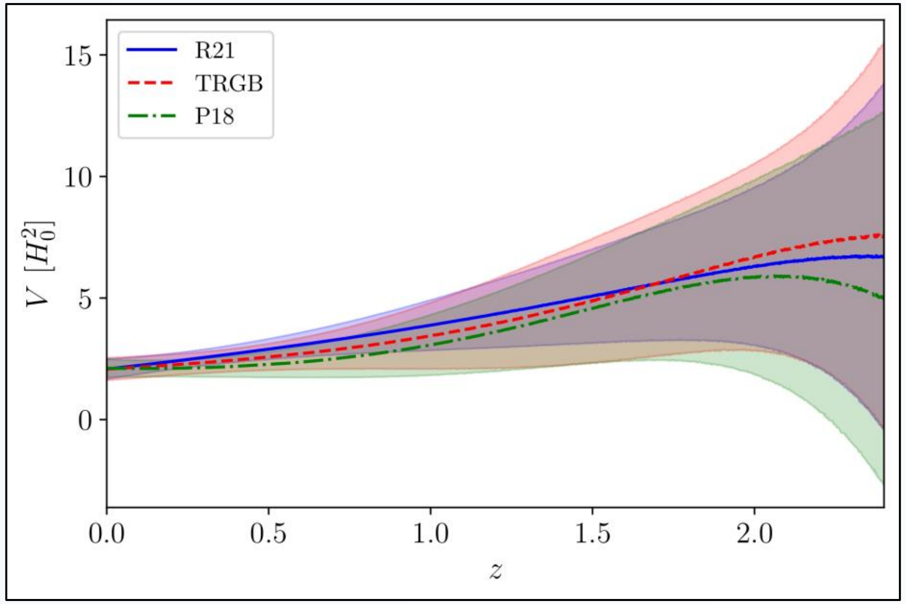


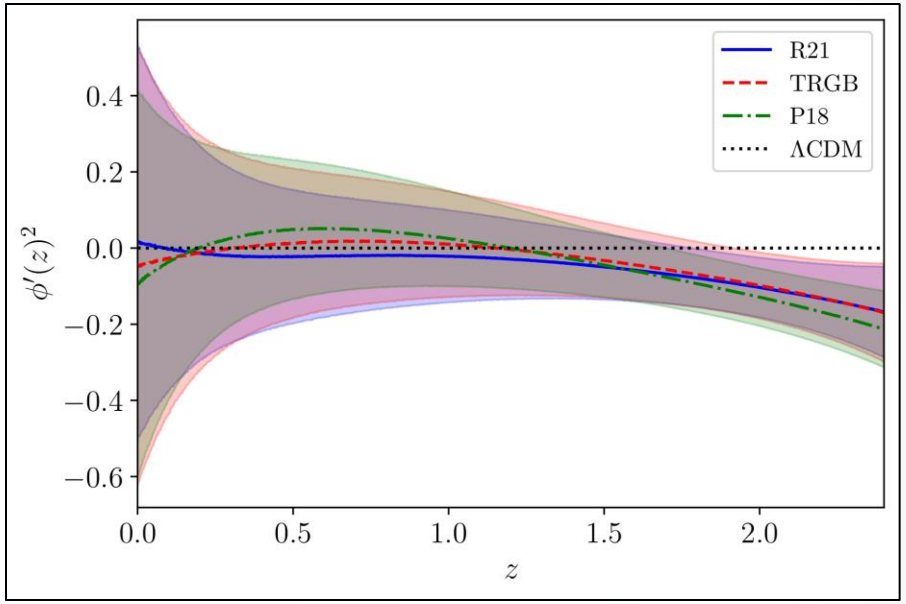
One layer is preferred

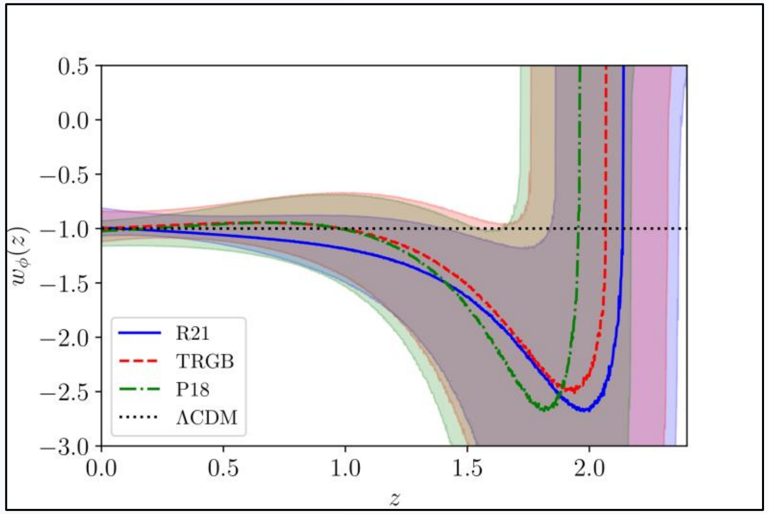
Monte Carlo routine used to determine uncertainties on $H'(z)$

Dialektopoulos, K. et al. Phys. Dark Univ. 43 (2024) 101383

Quintessence Models

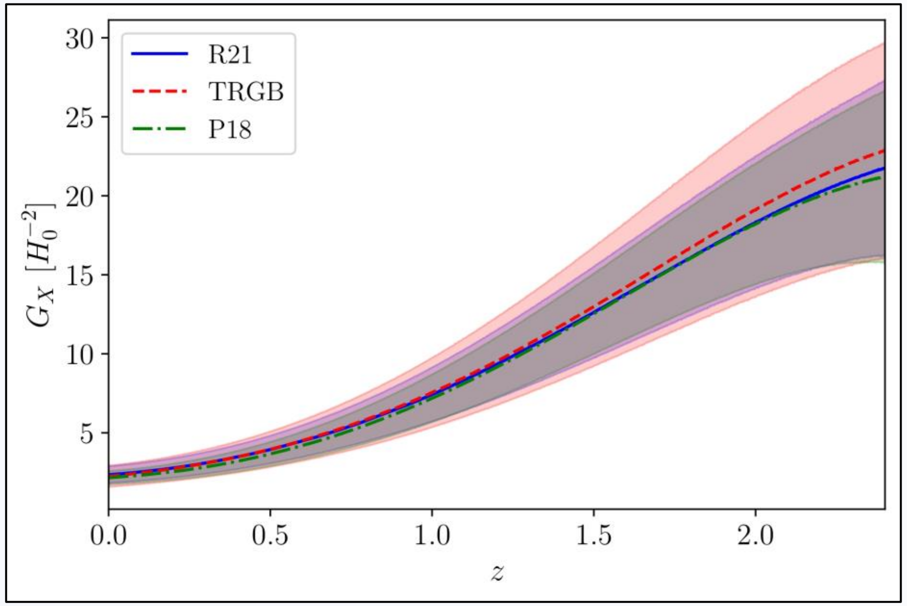


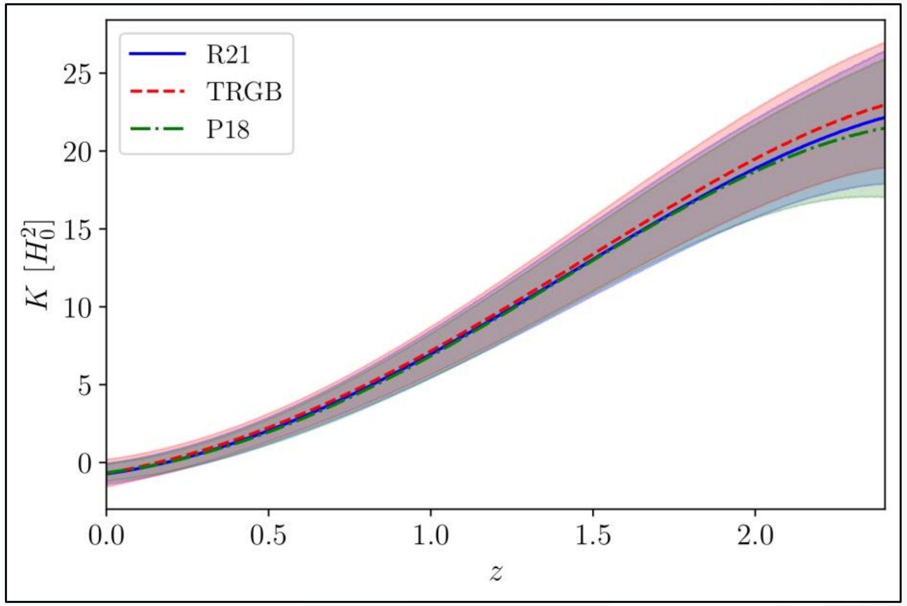


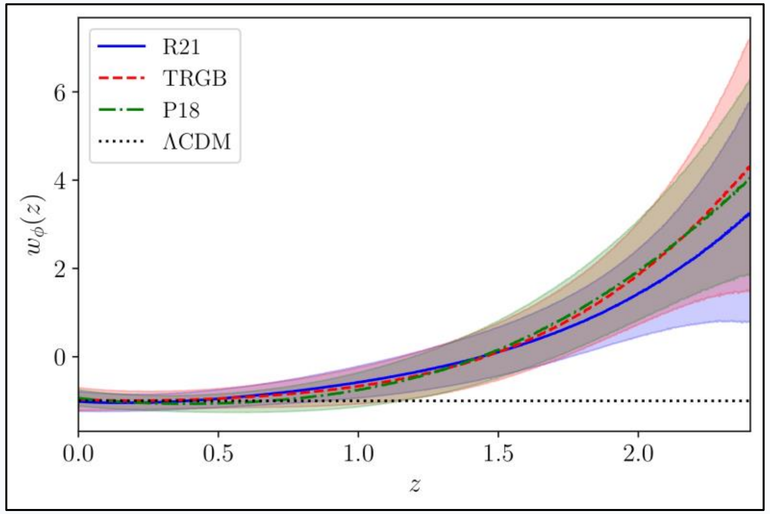


$$V(\phi) = \dot{H} + 3H^2 - \frac{\rho - p}{2}$$
$$\dot{\phi}^2 = -2\dot{H} - (\rho - p)$$

Designer Horndeski Models







$$K = -3H_0^2(1-\Omega_m) + \frac{J\sqrt{2X}H^2}{3H_0^2\Omega_m} - \frac{J\sqrt{2X}(1-\Omega_m)}{\Omega_m}$$

$$G_X = -\frac{2JH'(X)}{3H_0^2\Omega_m}$$

Using machine learning to probe systematics

SNaI Distances

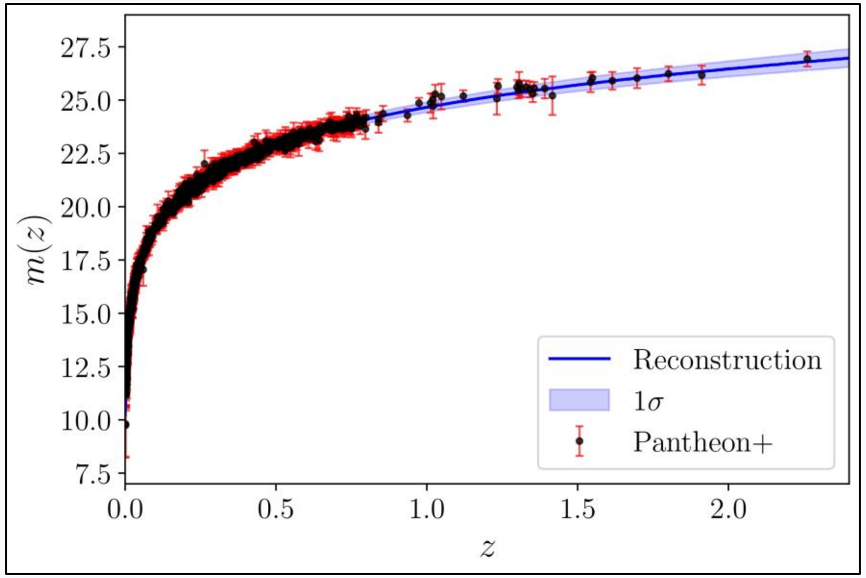
Apparent Magnitude:

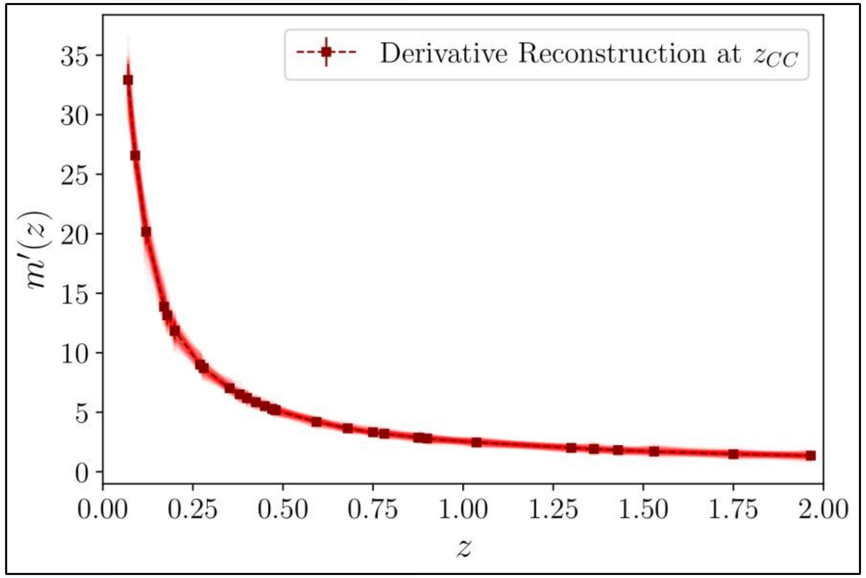
$$m(z) = 5\log_{10}\left[\frac{d_L(z)}{1\ \mathrm{Mpc}}\right] + 25 + M_B$$

$$H(z) = \frac{c\,(1+z)^2}{(1+z)d_L'(z) - d_L(z)}$$

Luminosity distance: $d_L(z) = c\,(1+z)\int_0^z \frac{dz'}{H(z')}$

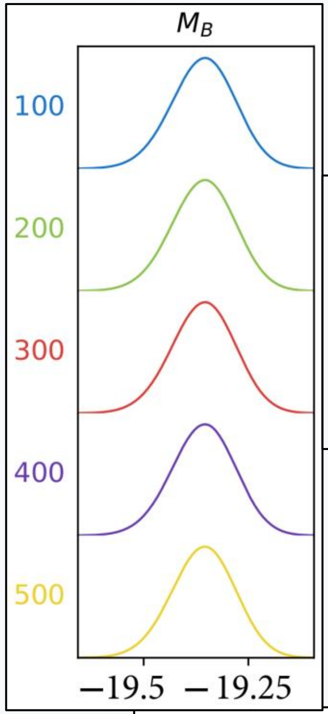
Absolute magnitude





Mukherjee et al., JCAP, Accepted [arXiv:2402.10502]

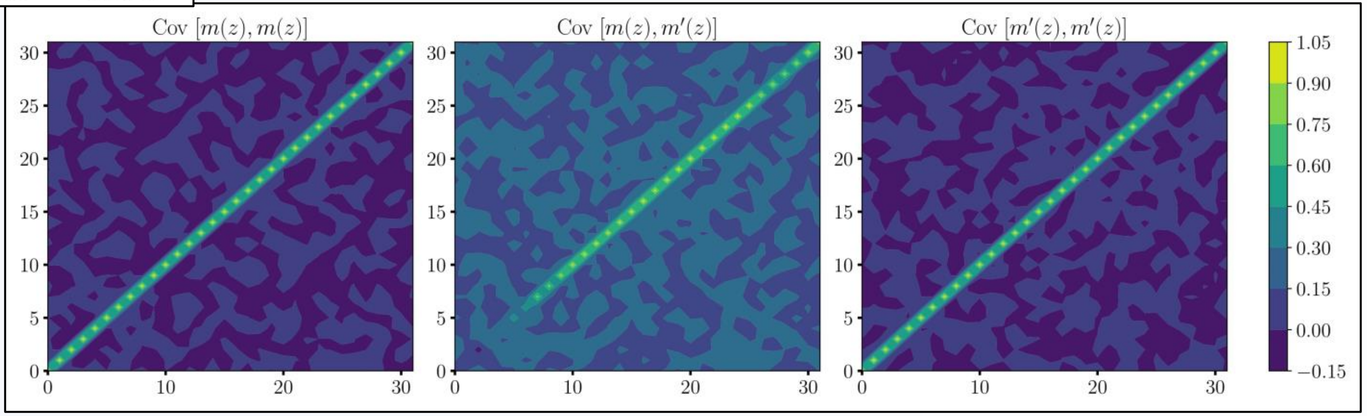
ANN-Driven constraints on M_B

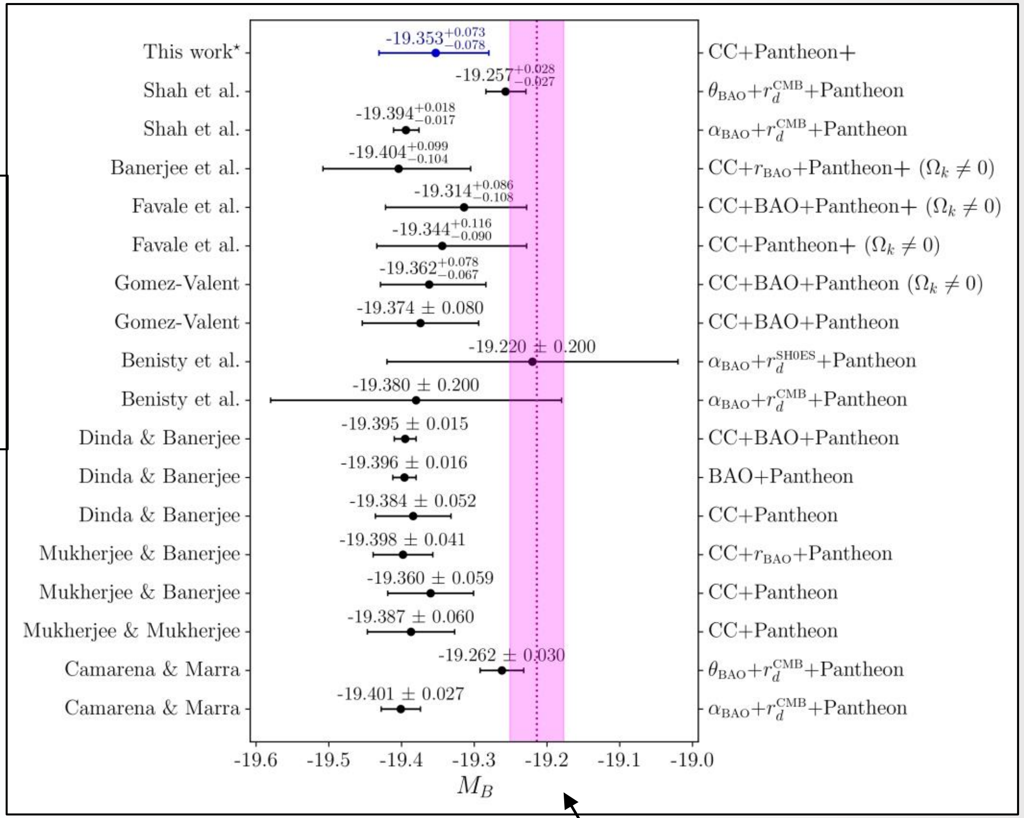


MCMC log-likelihood:

$$\log \mathcal{L}(M_B) = -\frac{\chi^2}{2} - \frac{1}{2}\log|\Sigma| - \frac{N}{2}\log 2\pi$$

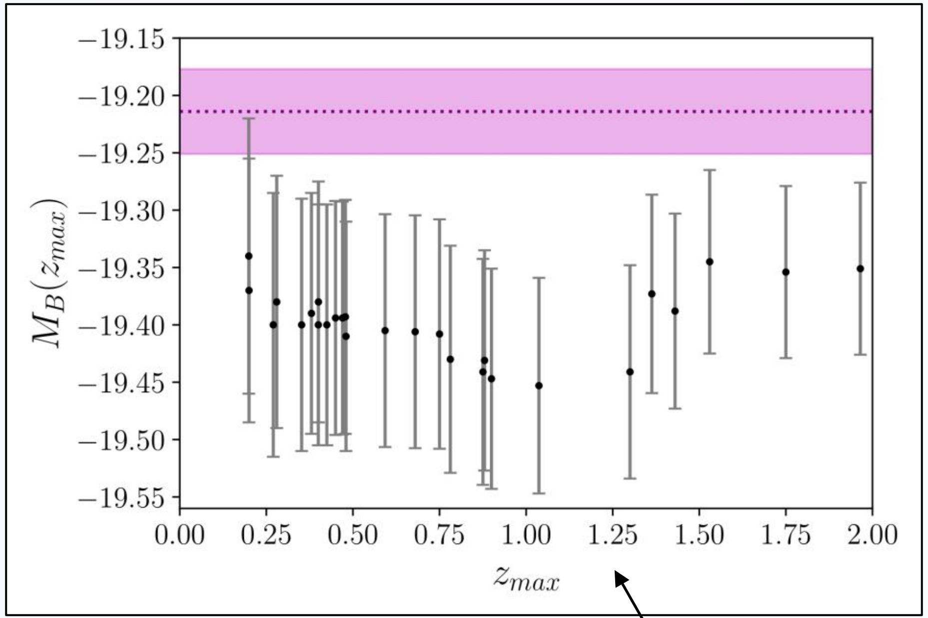
$$\chi^2(M_B) = \Sigma_{i,j}[H_{\rm CC}(z_i) - H_{\rm ANN}(z_i)]{\rm Cov}_{ij}^{-1}[H_{\rm CC}(z_i) - H_{\rm ANN}(z_i)]$$



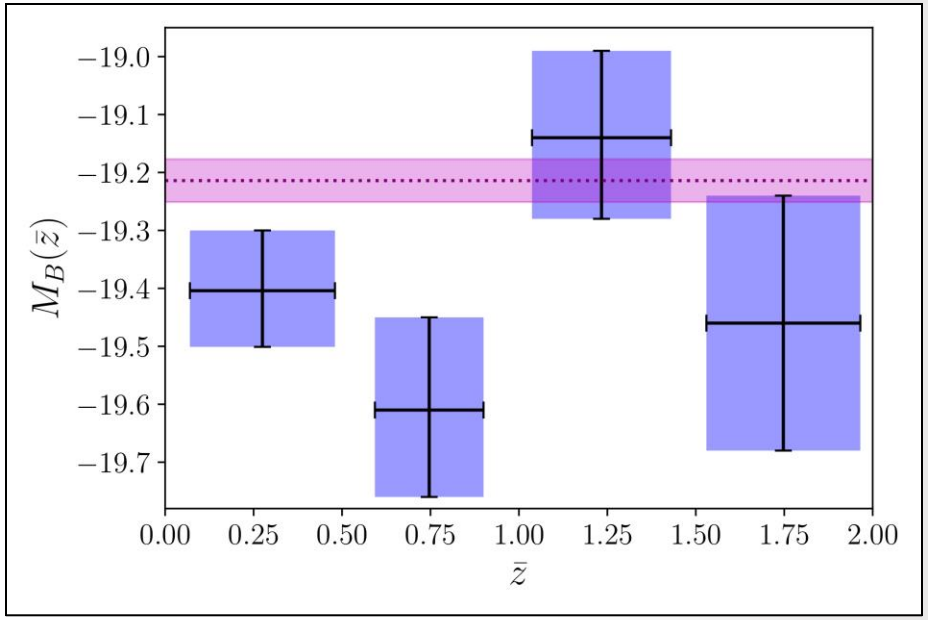


SH0ES Team (S22) $M_B = -19.214 \pm 0.037$

A possible late-time transition of M_B



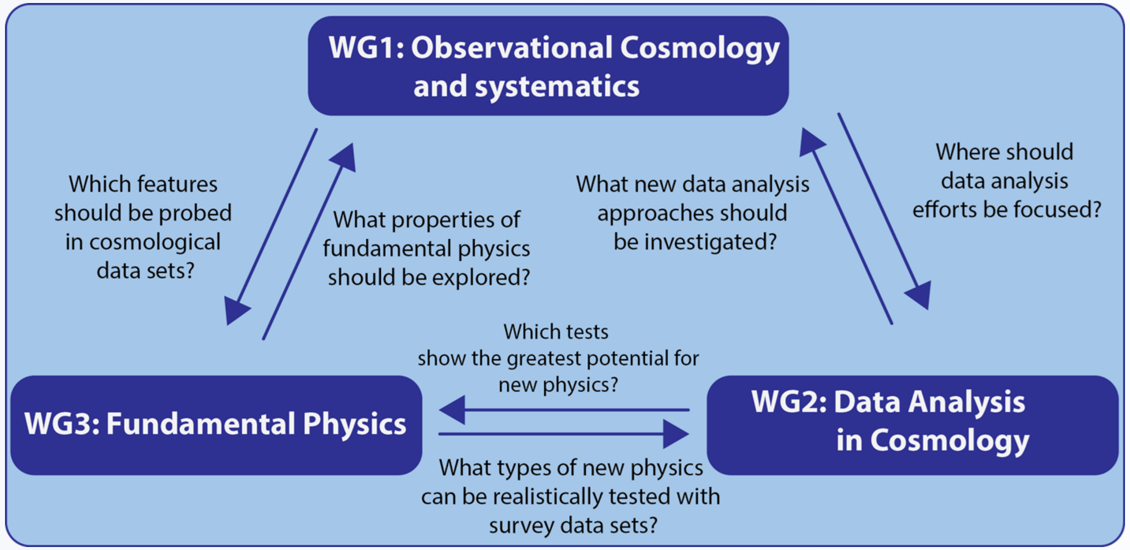
$\bar{z}$	$M_B(\bar{z})$
0.275	$-19.404^{+0.097}_{-0.104}$
0.746	$-19.61^{+0.15}_{-0.16}$
1.234	$-19.14^{+0.14}_{-0.15}$
1.748	$-19.46 \pm 0.22$$



Mild indication of transition at $z \approx 1$

What are we doing in CosmoVerse?

CA21136 CosmoVerse



Main Challenge: Understand the nature of cosmic tensions and probe possible solutions using novel statistical approaches and fundamental physics

CosmoVerse@Krakow 2024

CosmoVerse@Lisbon 2023

CA21136 CosmoVerse – Current Activities

CosmoVerse White Paper: Addressing observational tensions in cosmology with systematics and fundamental physics
(Dated: September 5, 2024)

https://shorturl.at/MeIaD

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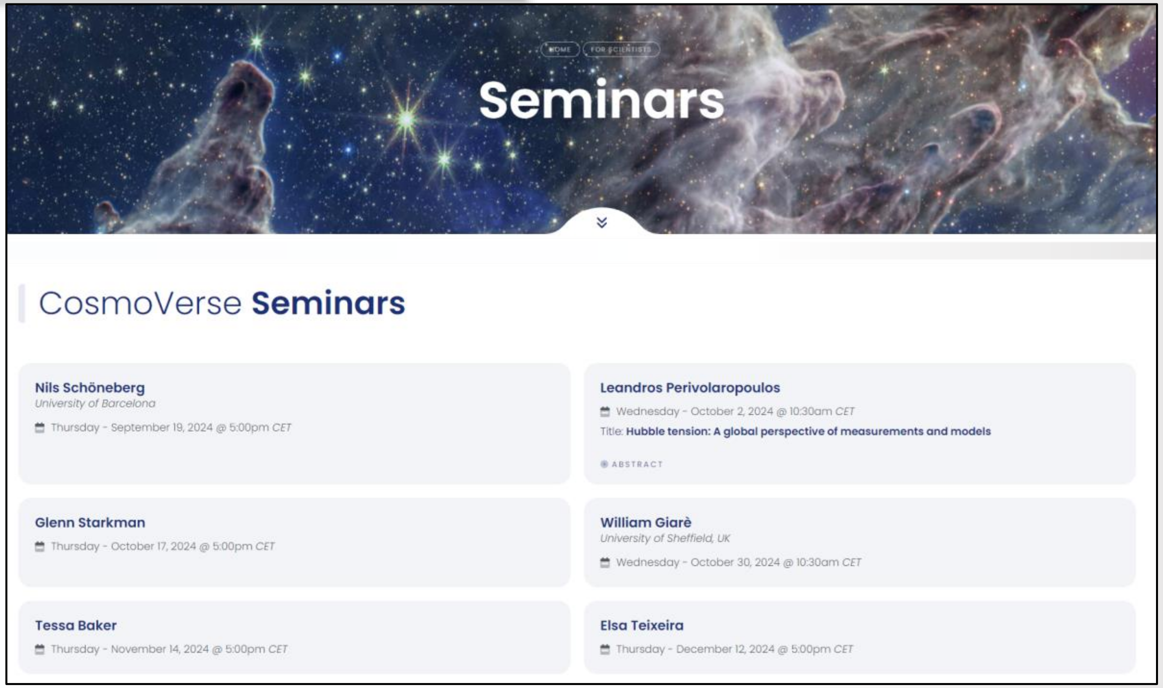
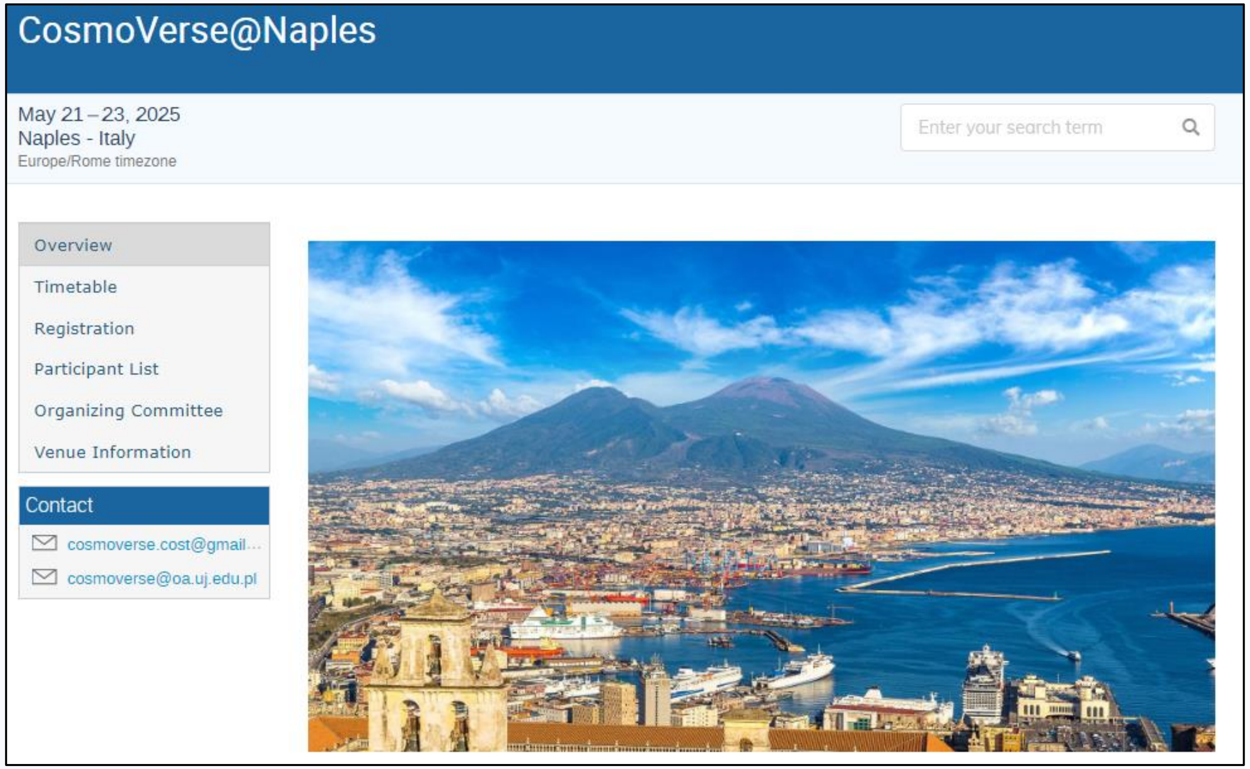


https://cosmoversetensions.eu

CA21136 CosmoVerse - 2025



CosmoVerseWorkshop@Naples 2025 – 21-23 May

CosmoVerse@Istanbul 2025 – 24-26 June

Thank You