CosmoVerse:

Addressing observational tensions in cosmology with systematics and fundamental physics (CA21136)

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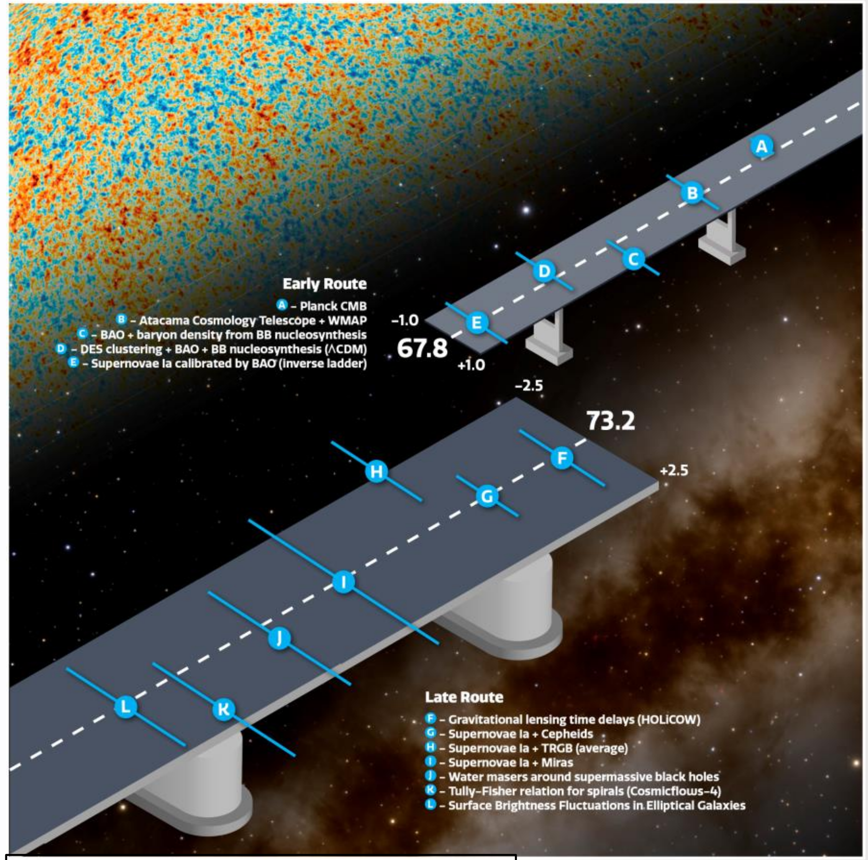
Main take away message

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 low-z measurements**
- We are very far from a solution!



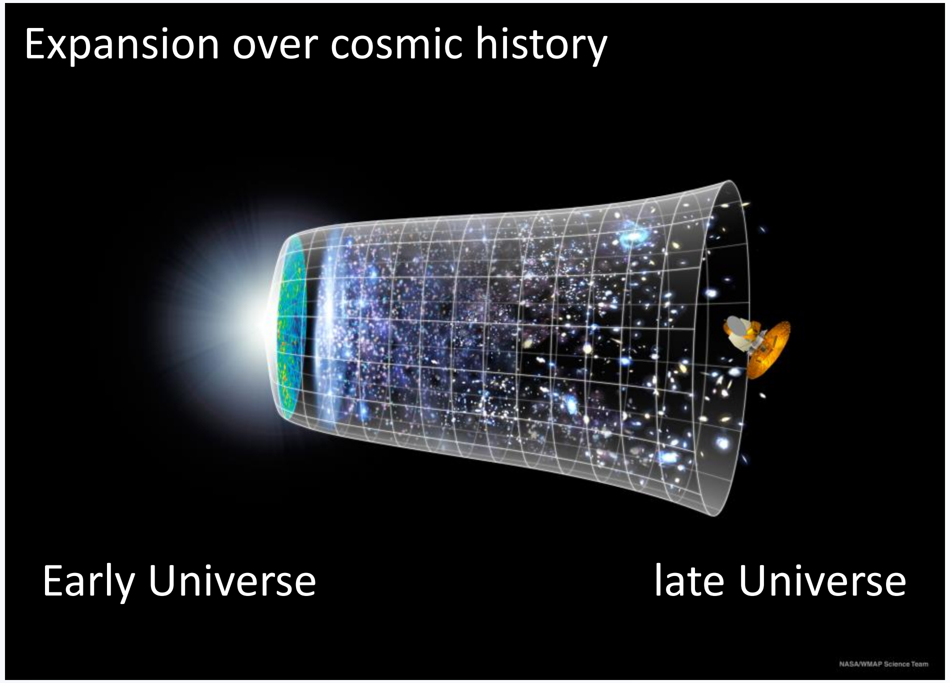
Riess, A. Nat. Rev. Phys. 2 (2020) 10

Why do we need modifications to standard cosmology?

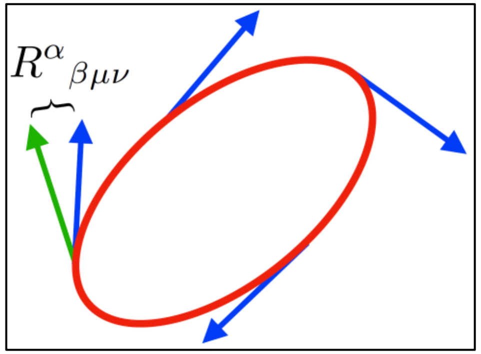
General Relativity and Concordance Cosmology

Einstein-Hilbert action for GR:

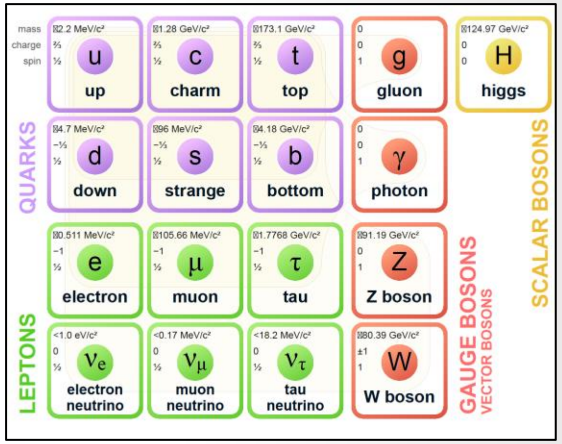
$$S = \frac{1}{16\pi G}\int d^4x\,\sqrt{-g}[\mathcal{R}] + \int d^4x\sqrt{-g}\,\mathcal{L}_m(g_{\mu\nu},\psi)$$



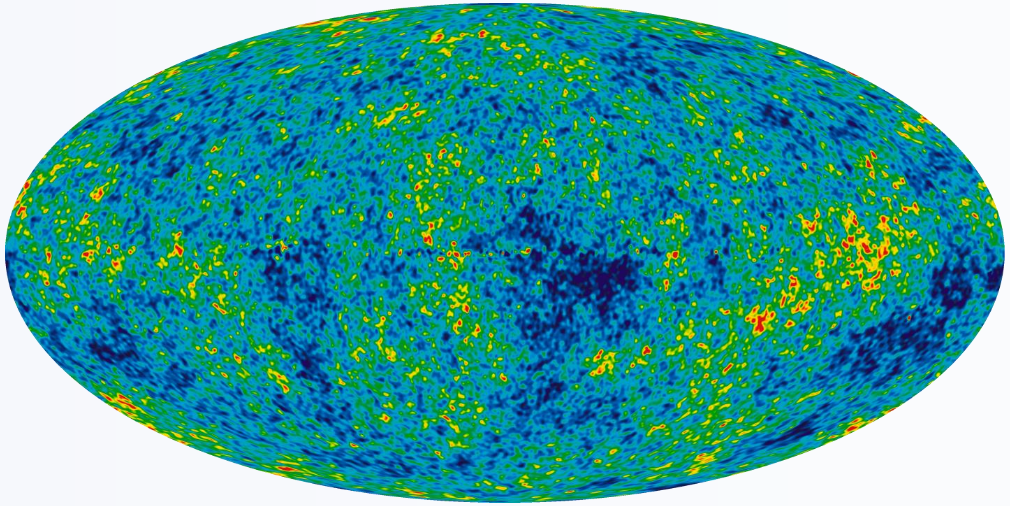
Einstein 1915: **General Relativity (GR)**
Energy-momentum source of curvature
Levi-Civita connection: Zero Torsion, Metricity

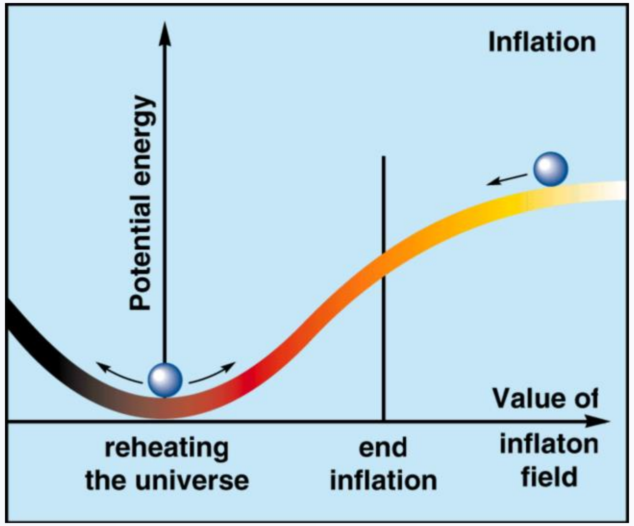


Standard model of particle physics: $SU(3)\times SU(2)\times U(1)$



Early Universe Concordance Cosmology

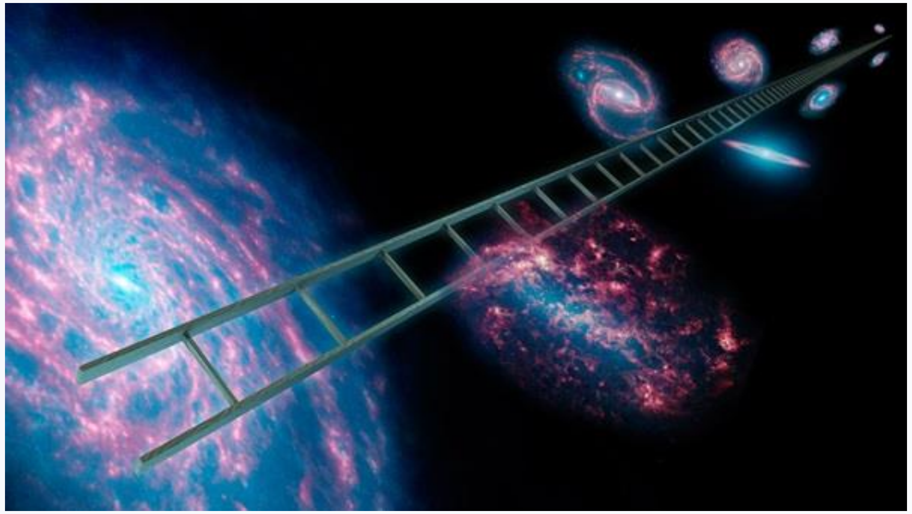




Cosmic inflation
Pros: Horizon and flatness problems
Cons: Fine-tuning

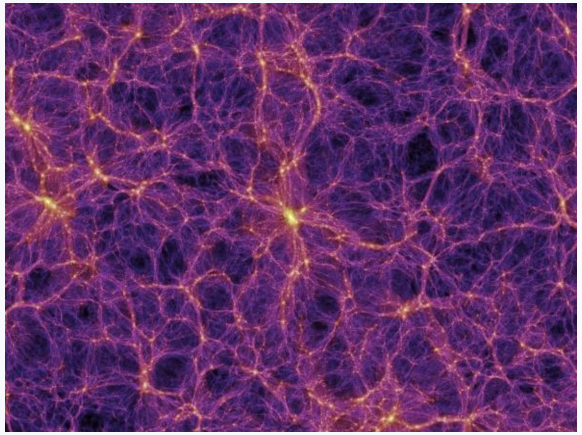
Anomalies and problems:
- The Lithium problem
- Hints of a closed Universe
- Large angular scale anomalies in the CMB
- Anomalously strong ISW effect
- Cosmic dipoles (cosmological principles)
- Lyman-α forest BAO anomalies
- Cosmic birefringence
- Discordance in dark matter abundance at smaller scales

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



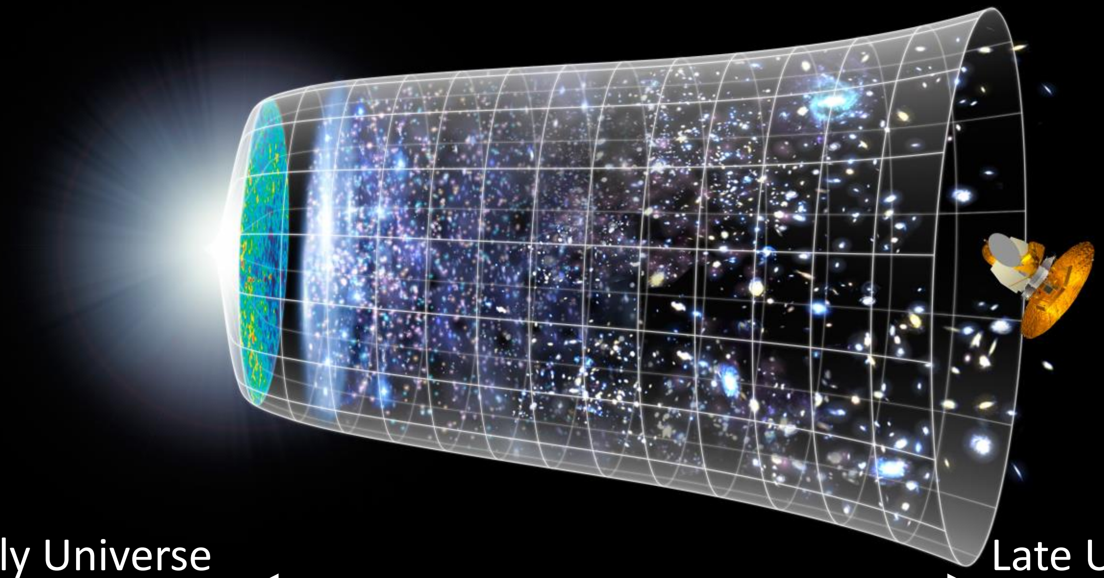
Requirements:
Dark matter
Dark energy

$$S = \frac{1}{16\pi G}\int d^4x\,\sqrt{-g}[\mathcal{R} - 2\Lambda]$$

$$+\int d^4x\sqrt{-g}\mathcal{L}_m(g_{\mu\nu},\psi)$$

The Hubble Tension

Cosmic Tension > 5σ



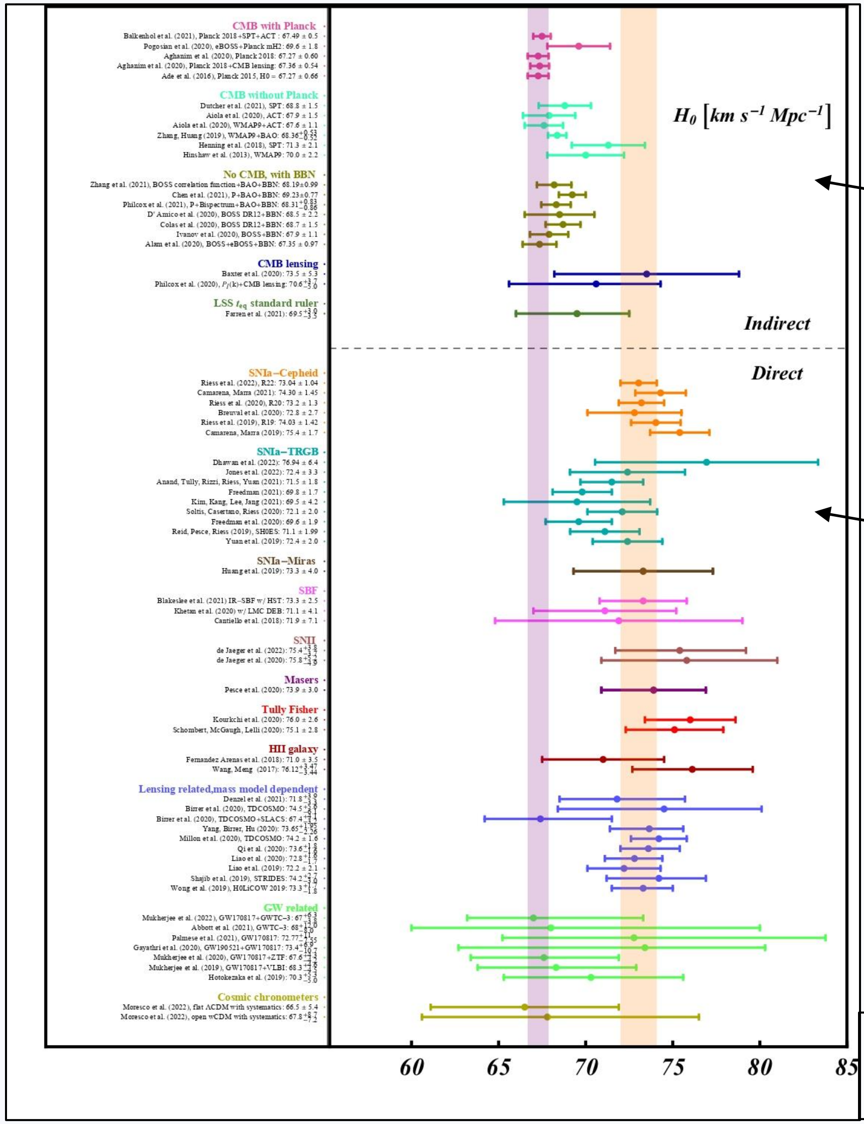
Early Universe estimate ⟷ Late Universe estimate

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

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

NASA/WMAP Science Team

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

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

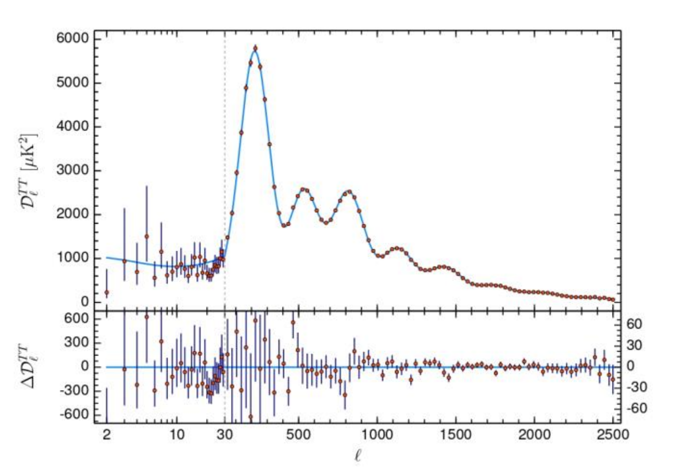
Di Valentino et al. CQG, 38 (2021) 15
Cosmology Intertwined, JHEAp. 2204 (2022) 002

Cosmic Tensions: CMB

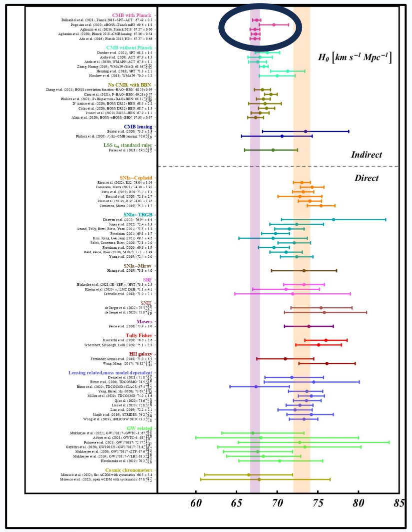
Parameter	Plik best fit	Plik [1]	CamSpec [2]	([2] − [1])/σ_1	Combined
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015	0.02229 ± 0.00015	−0.5	0.02233 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012	0.1197 ± 0.0012	−0.3	0.1198 ± 0.0012
$100\theta_{MC}$	1.040909	1.04092 ± 0.00031	1.04087 ± 0.00031	−0.2	1.04089 ± 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

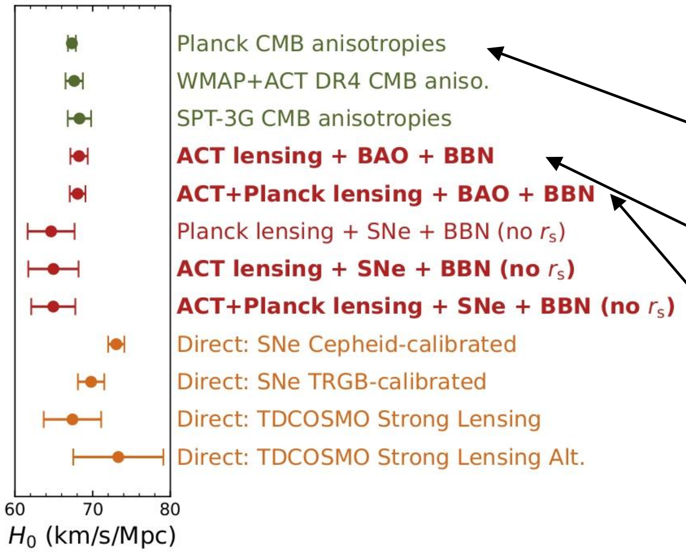
Planck Collaboration, A&A 641 (2020) A6

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





ACT DR6 (2023)

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

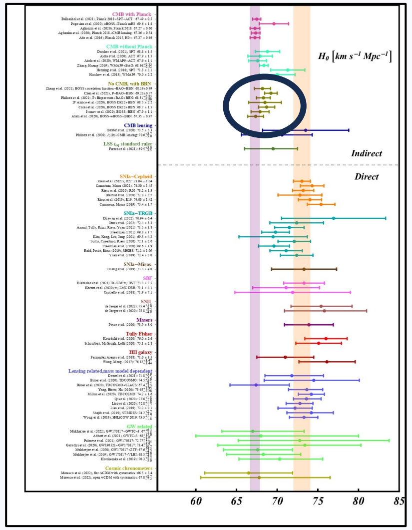
$$H_0^{\mathrm{ACT+BAO+BBN}} = 68.3 \pm 1.1\ \mathrm{km\ s^{-1}Mpc^{-1}}$$

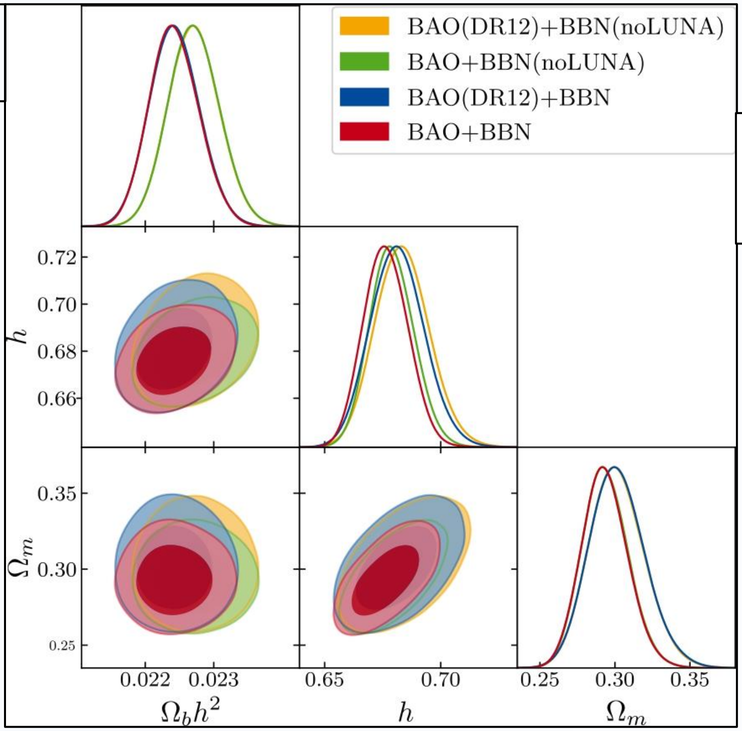
$$H_0^{\mathrm{ACT+P18+BAO+BBN}} = 68.1 \pm 1.0\ \mathrm{km\ s^{-1}Mpc^{-1}}$$

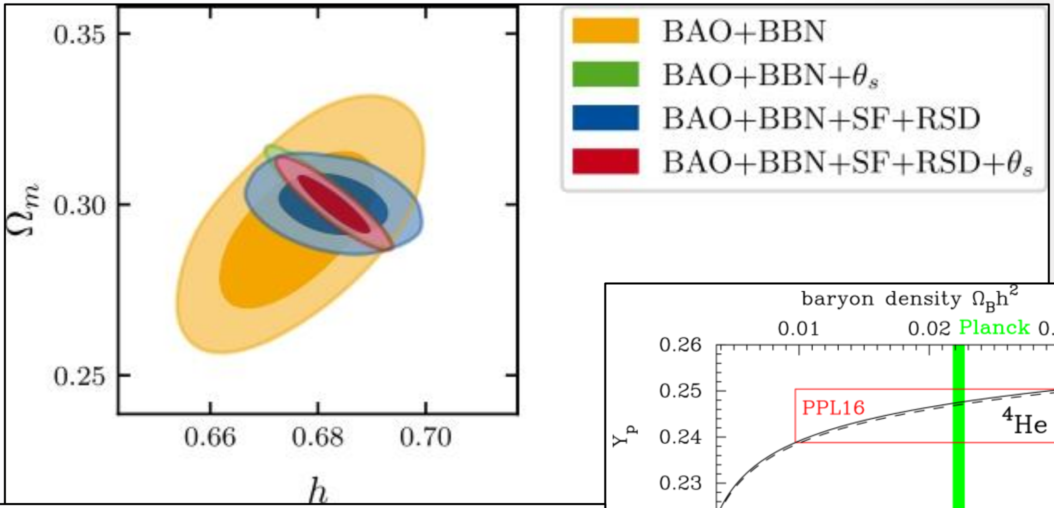
Cosmic Tensions: BBN

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

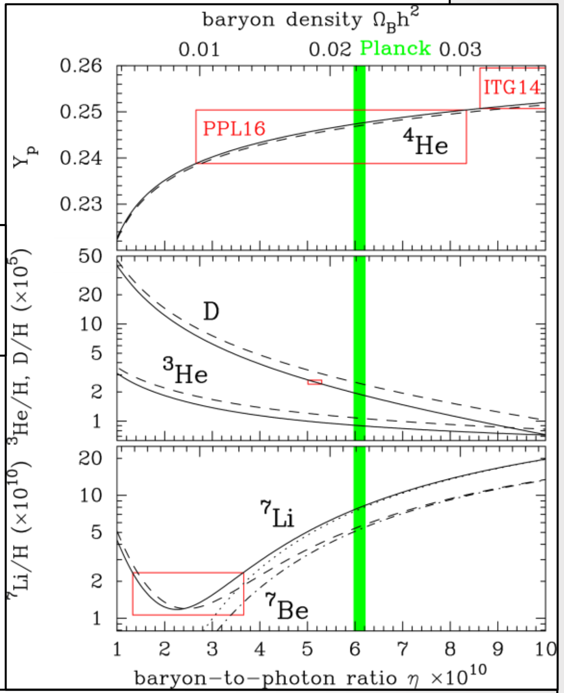






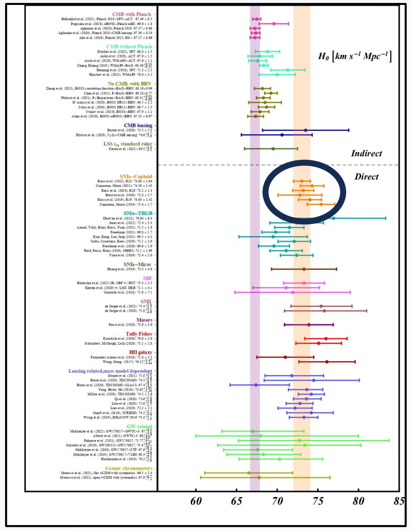
$$H_0^{\mathrm{BAO+BBN}+\theta_s} = 68.16^{+0.48}_{-0.49}\ \mathrm{km\ s^{-1} Mpc^{-1}}$$

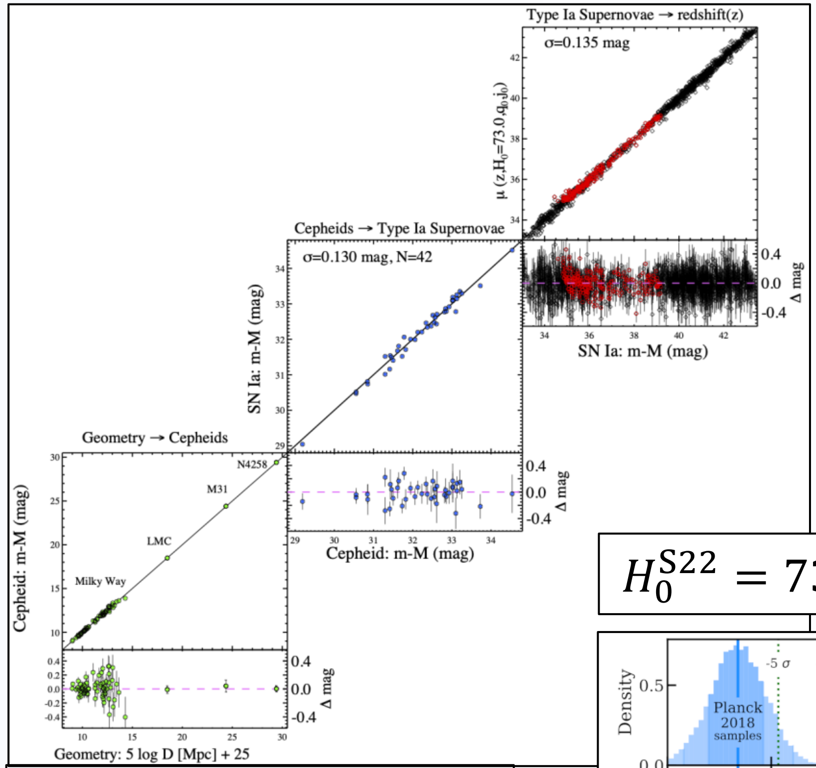
$$\Omega_m^{\mathrm{BAO+BBN}+\theta_s} = 0.3022^{+0.0062}_{-0.0064}$$



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

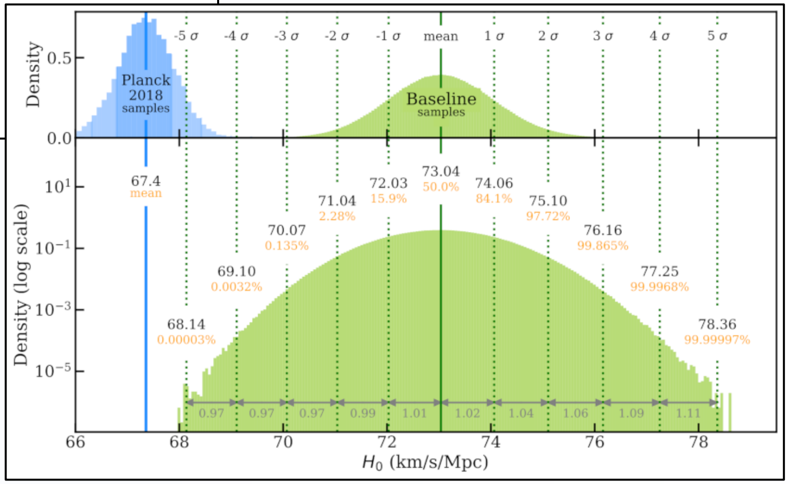
Cosmic Tensions: SH0ES Result



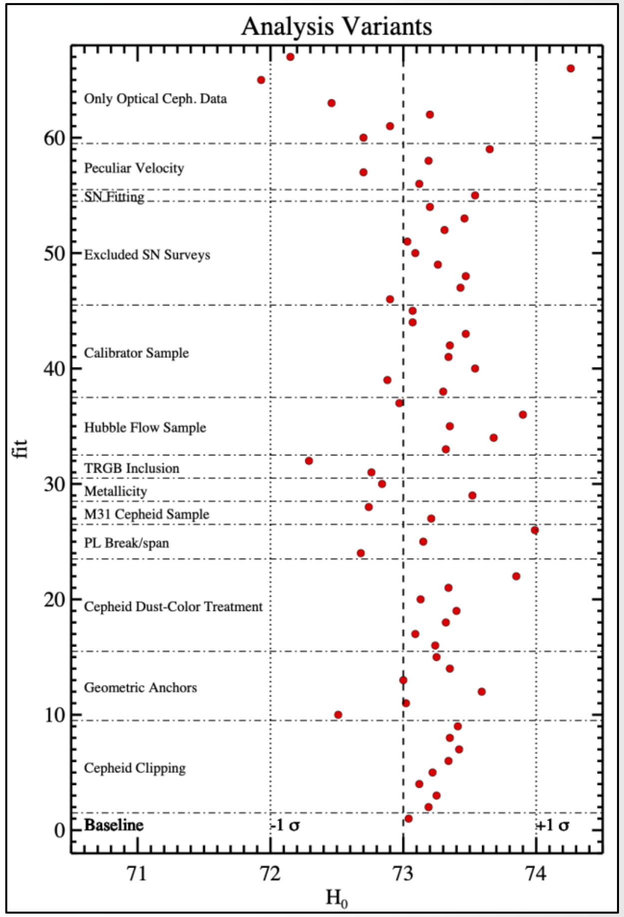


Riess, A. G. et al. ApJL 934 (2022) L7

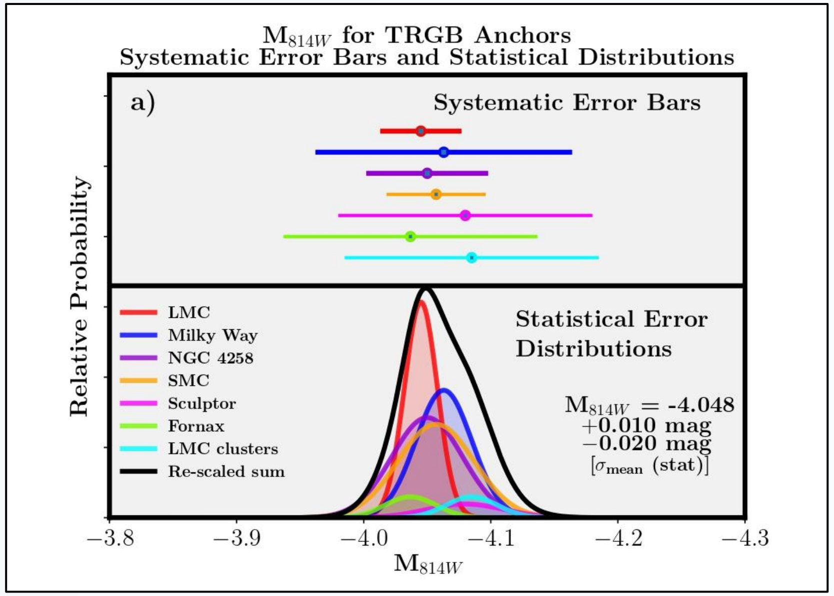
$$H_0^{S22} = 73.04 \pm 1.04 \text{ km s}^{-1}\text{Mpc}^{-1}$$

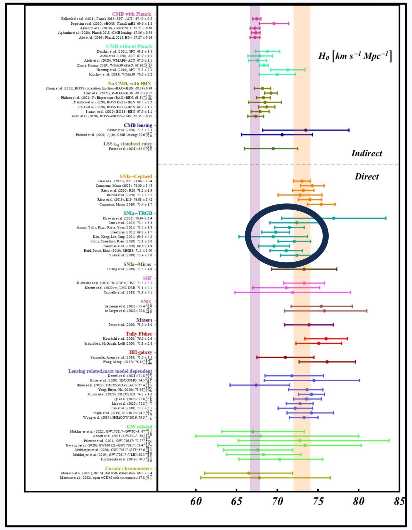


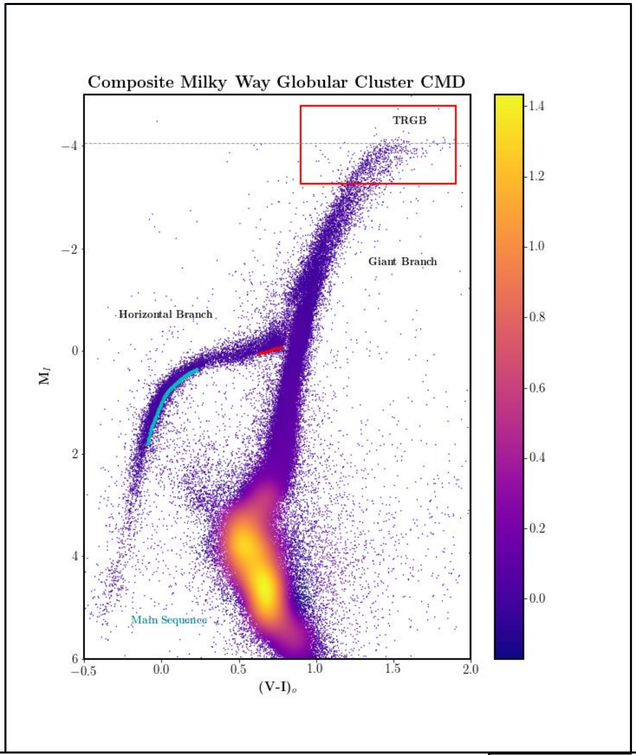
12 variants of analyses

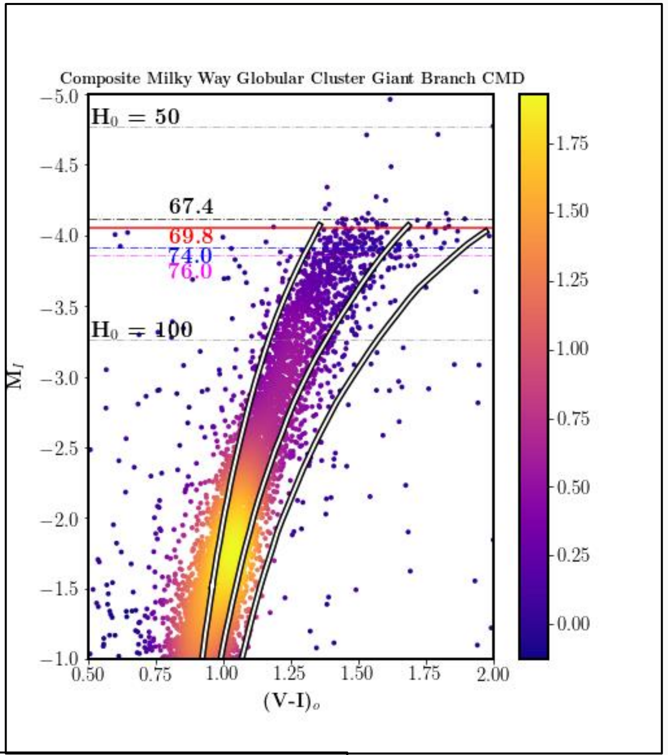


Cosmic Tensions: Tip of the Red Giant Branch



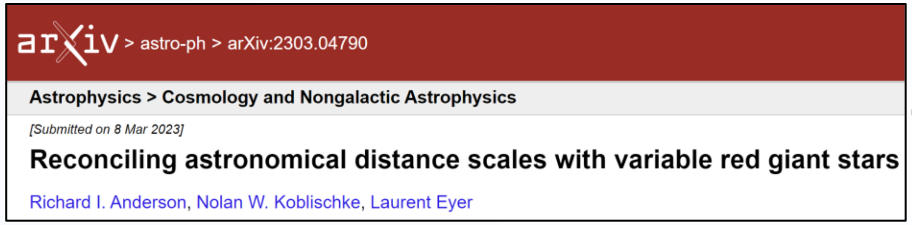






$$H_0^{\mathrm{F22}} = 69.8 \pm 2.10 \text{ km s}^{-1}\text{Mpc}^{-1}$$

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


arXiv > astro-ph > arXiv:2303.04790

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 8 Mar 2023]

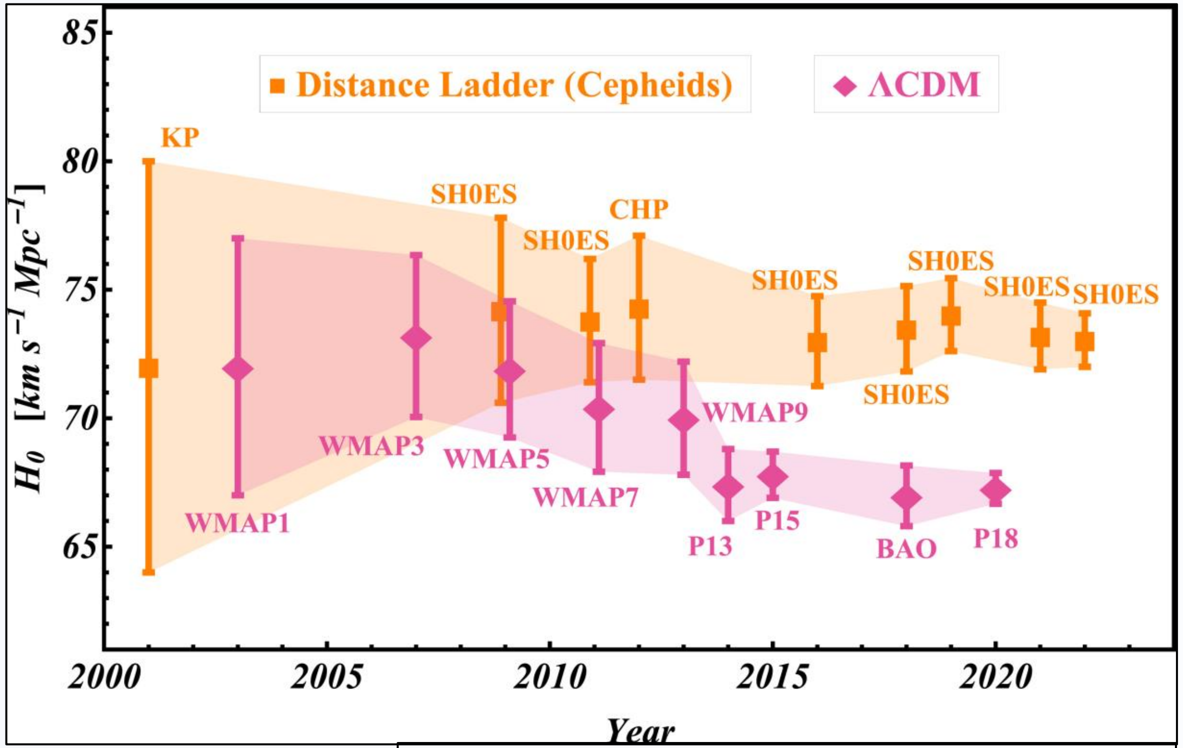
Reconciling astronomical distance scales with variable red giant stars

Richard I. Anderson, Nolan W. Koblischke, Laurent Eyer

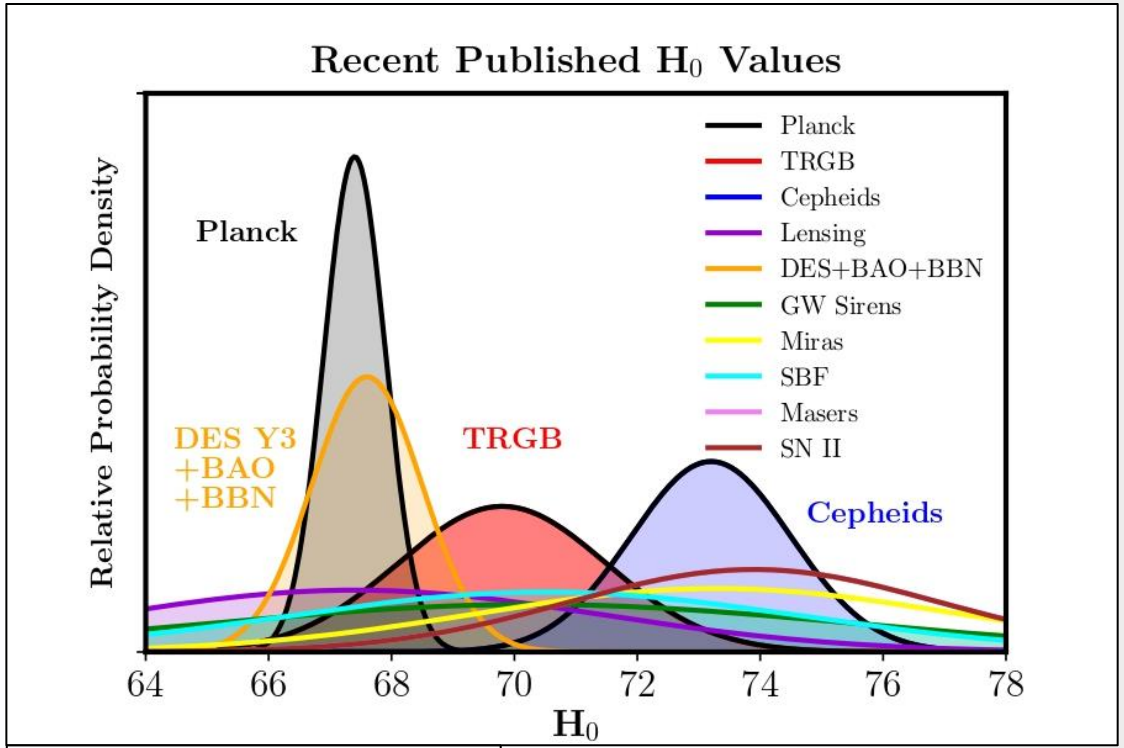
→

$$H_0^{\mathrm{A23}} = 71.8 \pm 1.5 \text{ km s}^{-1}\text{Mpc}^{-1}$$

Cosmic Tensions in recent years



Perivolaropoulos, L.; Skara, F. Challenges for ΛCDM: An update. New Astron. Rev. 95 (2022) 101659.



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

What are possible solutions?

Attempts at a solution

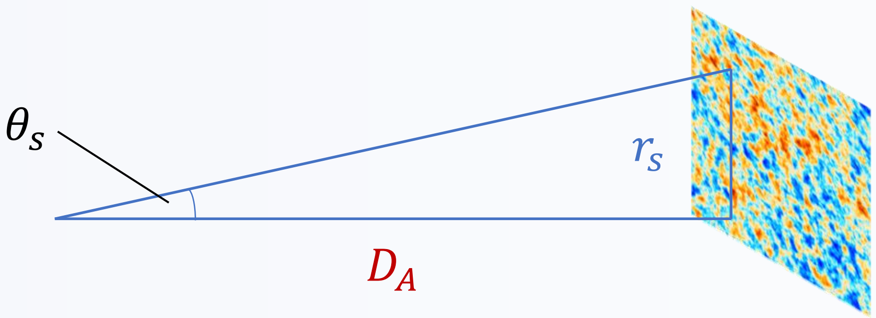
Model	$\Delta N_{\rm param}$	M_B	Gaussian Tension	$Q_{\rm DMAP}$ Tension		$\Delta\chi^2$	ΔAIC		Finalist
ΛCDM	0	-19.416 ± 0.012	4.4σ	4.5σ	✗	0.00	0.00	✗	✗
$\Delta N_{\rm ur}$	1	-19.395 ± 0.019	3.6σ	3.8σ	✗	-6.10	-4.10	✗	✗
SIDR	1	-19.385 ± 0.024	3.2σ	3.3σ	✗	-9.57	-7.57	✓	✓ (3)
mixed DR	2	-19.413 ± 0.036	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 (**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 **r_s**, we can increase **H_0**, or so one would expect

Late-Universe new physics (**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

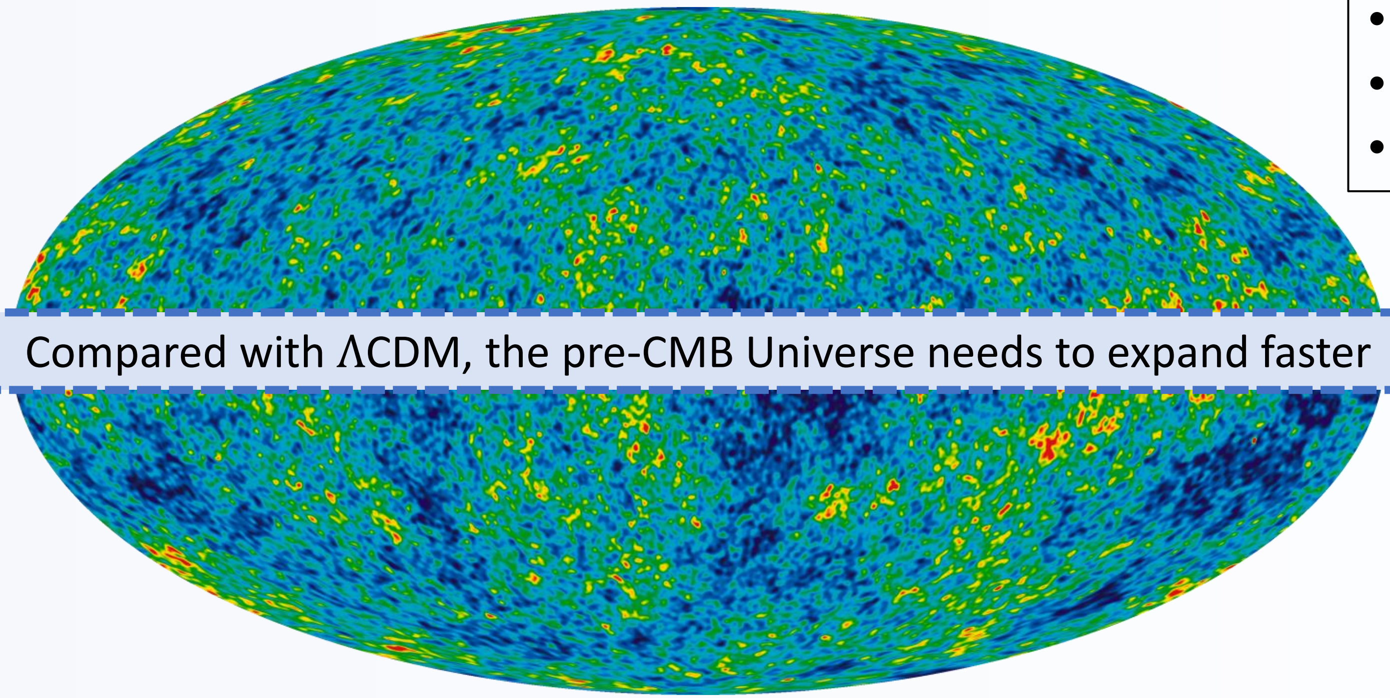
BAO constrain $\theta_s \sim r_s H_0$, anchoring r_s (early Universe) leaves few options for inferring H_0

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 $D_A \propto 1/H_{\text{Late}}(z)$, 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

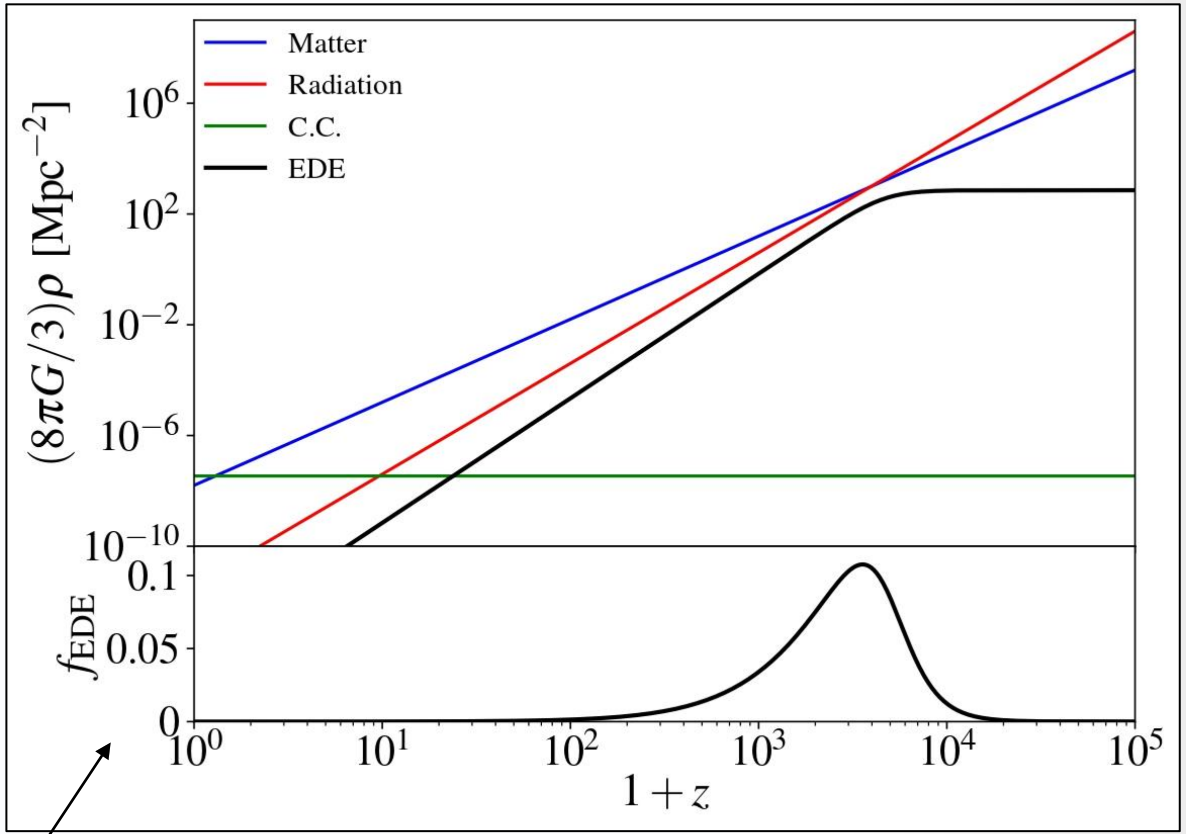
$$w_{\rm EDE}(a) = \frac{1+w_f}{1+(a_c/a)^{3(1+w_f)}} - 1$$

- 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. arXiv:2302.09032

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):**

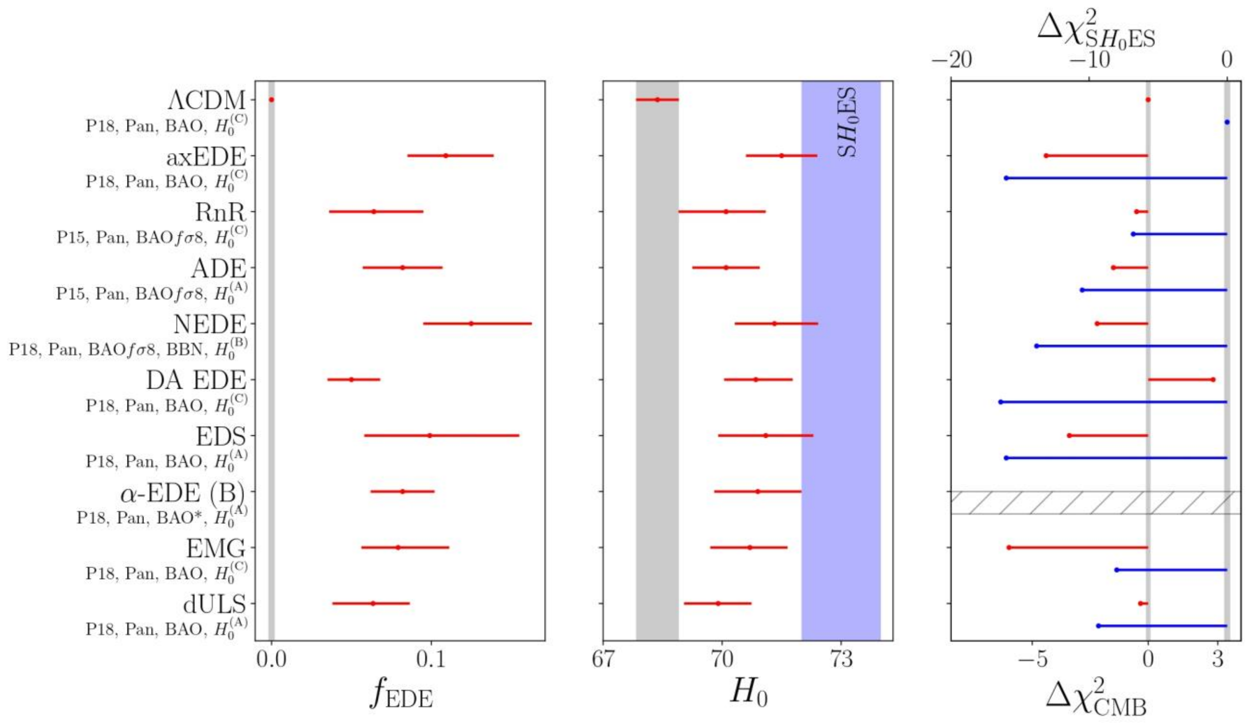
$$V(\psi,\phi) = \frac{\lambda}{4}\psi^4 + \frac{1}{2}\beta M^2\psi^2 - \frac{1}{3}\alpha M\psi^3 + \frac{1}{2}m^2\phi^2 + \frac{1}{2}\gamma\phi^2\psi^2$$

- **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:

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

Evolution of EDE

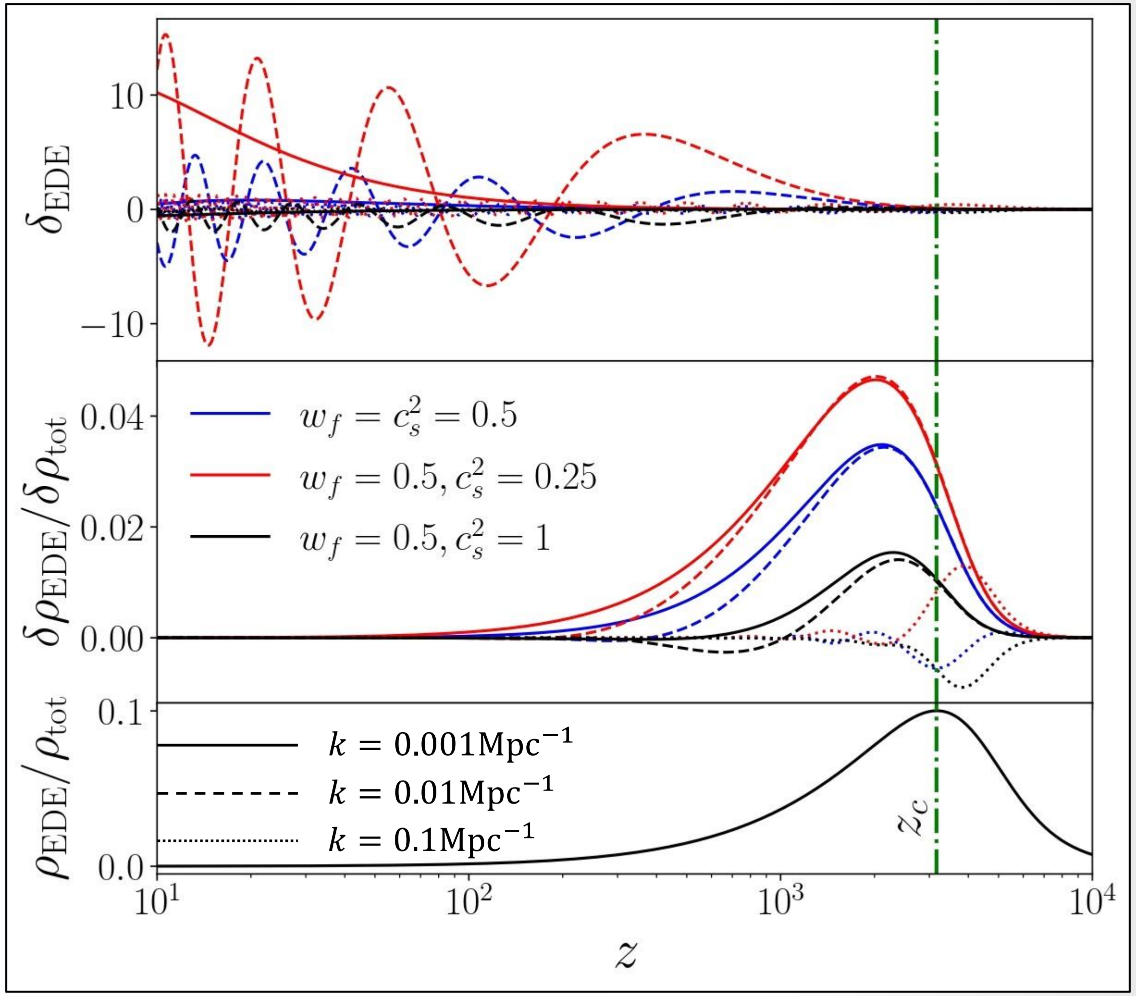
On **subhorizon scales**, the fluid equation takes the form

$$\frac{d^2}{d\eta^2}\left(\frac{\delta_{\rm EDE}}{1+w_{\rm EDE}}\right)$$
$$= -k^2\left(c_s^2\frac{\delta_{\rm EDE}}{1+w_{\rm EDE}}+\psi_{\rm N}\right)-\left(1-3c_a^2\right)\frac{a'}{a}\frac{d}{d\eta}\left(\frac{\delta_{\rm EDE}}{1+w_{\rm EDE}}\right)$$

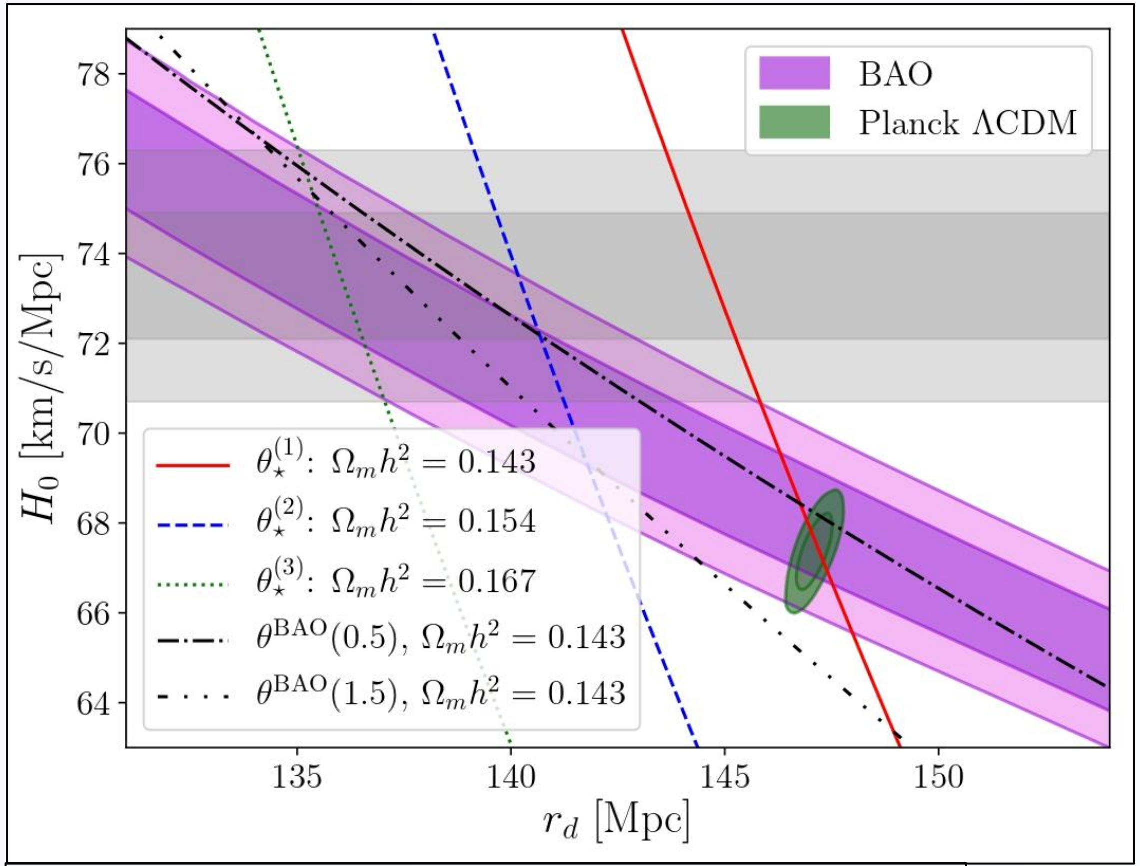
for the fractional EDE perturbation ($\delta_{\rm EDE}$), effective EDE sound speed (c_s^2), Newtonian potential ($\psi_{\rm N}$) and adiabatic EDE sound speed (c_a^2)

General features:

- Larger c_s^2 translates to more resistance in EDE collapse, while smaller c_s^2 give larger overall density perturbations. This sets the frequency of the oscillations
- The sign of $\left(1-3c_a^2\right)$ controls where the amplitude increases (+) or decreases (−)
- EDE modes are counteracted by pressure within the horizon, with stable modes only entering the horizon at $w_{\rm EDE} \simeq -1$



The problem with EDE



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

CMB angular size at recombination:

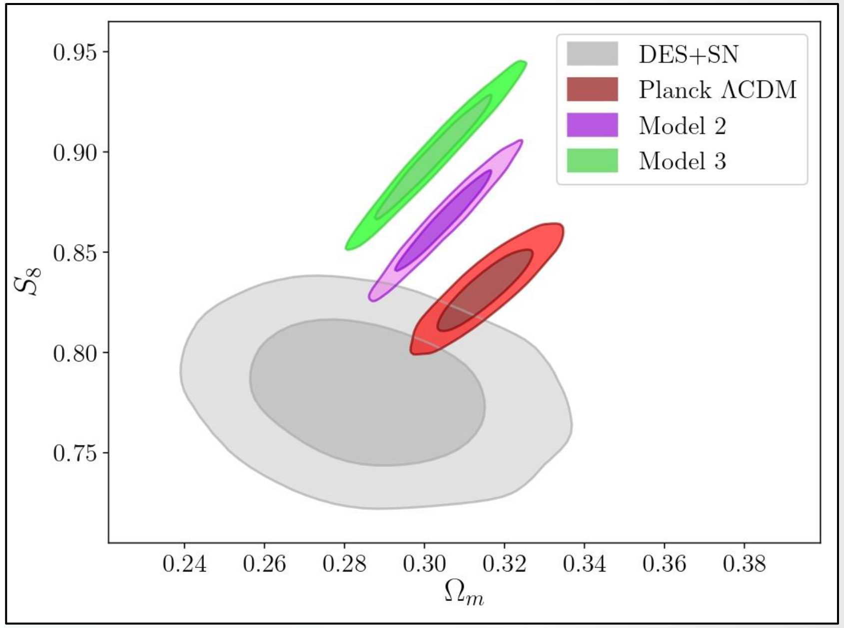
$$\theta_* = \frac{r_s(z_{\rm LS})}{D(z_{\rm LS})}$$

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

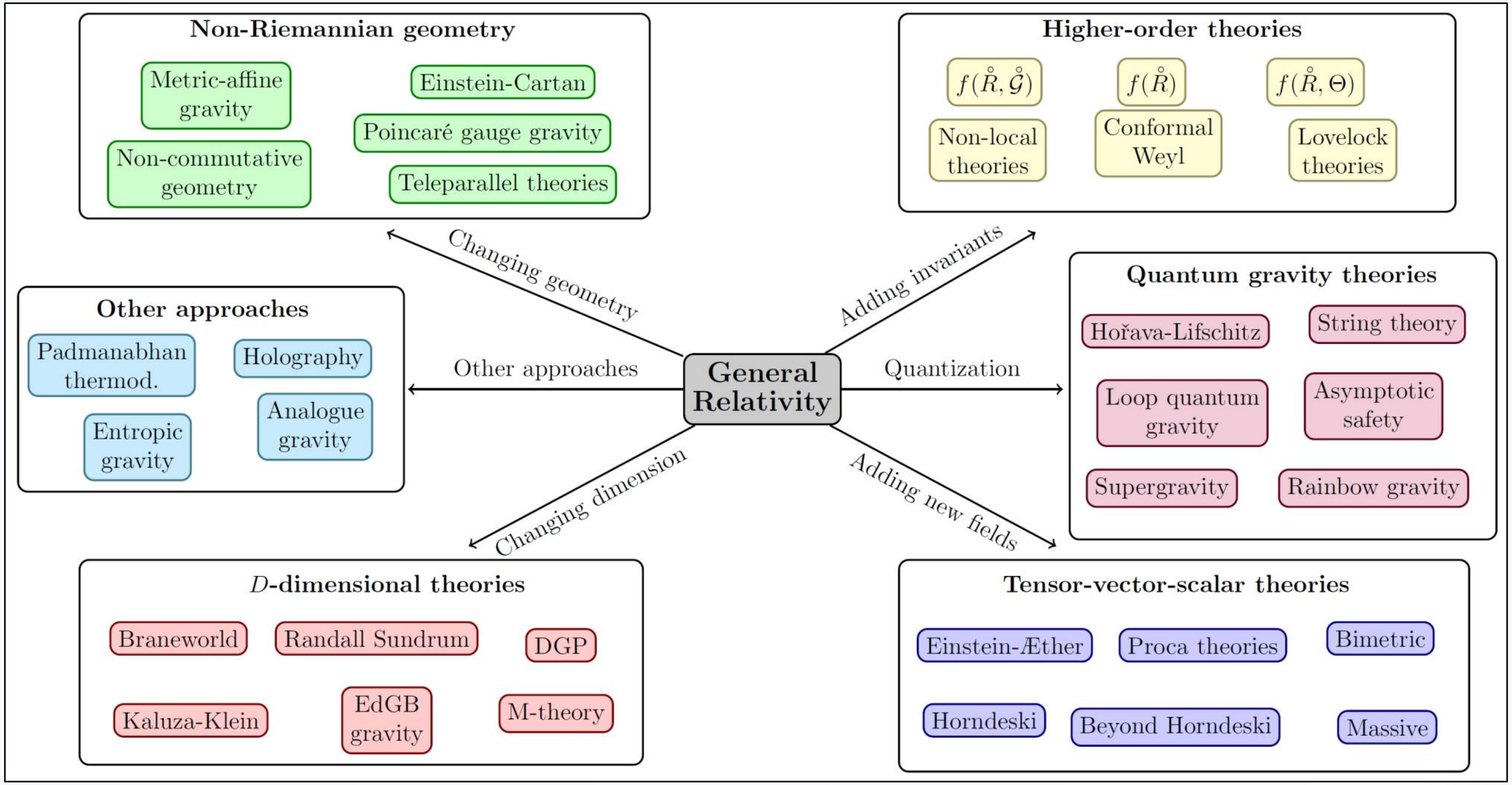
$$E_{\mu\nu} \coloneqq G_{\mu\nu} + \Lambda g_{\mu\nu} = \mathcal{R}_{\mu\nu} - \frac{1}{2}\mathcal{R} g_{\mu\nu} + \Lambda g_{\mu\nu}$$

Consider non-local terms

Take an emergent form of gravity

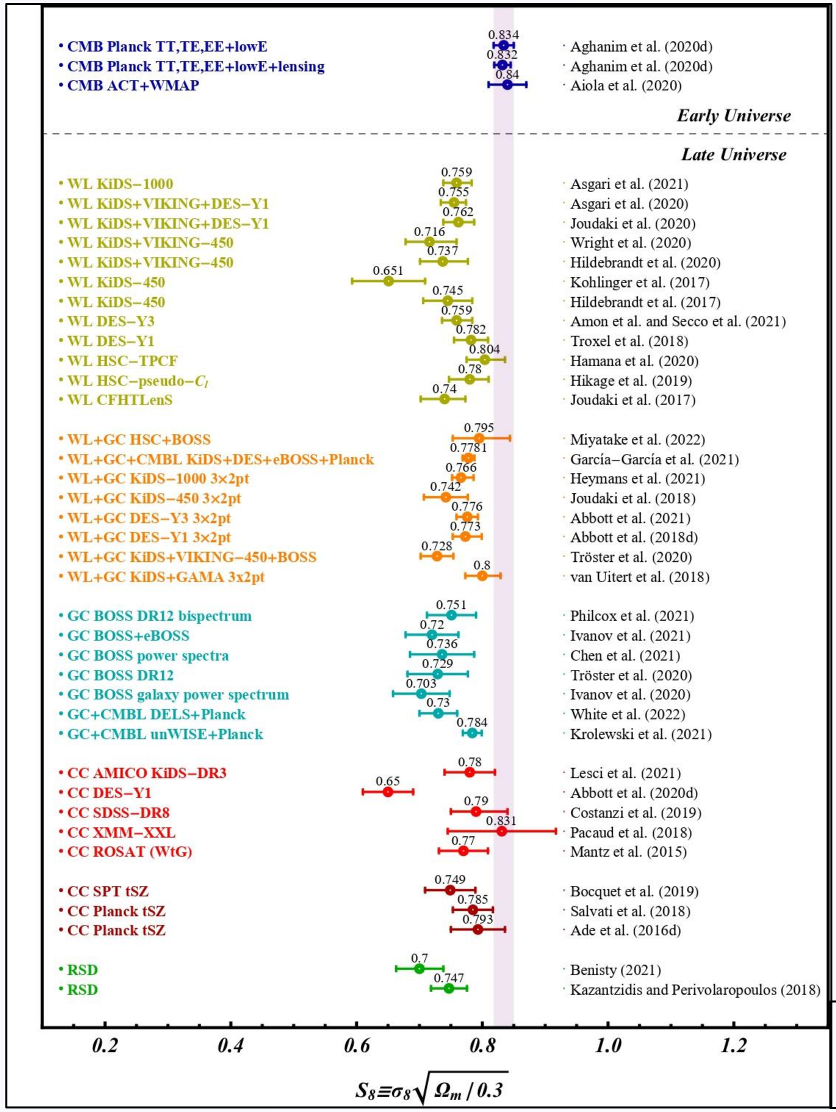
Changing the gravitational connection

The Modified Gravity Landscape



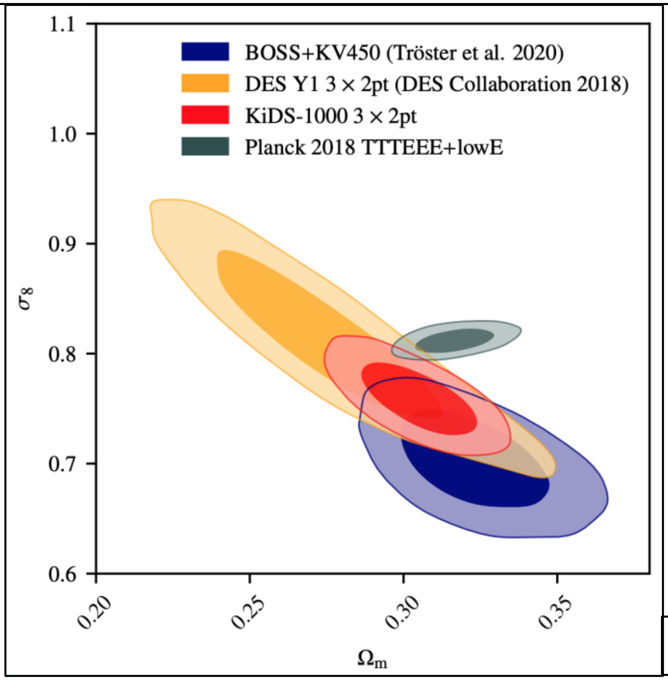
What about other tensions on the rise?

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 $8\ h^{-1}\mathrm{Mpc}$

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



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

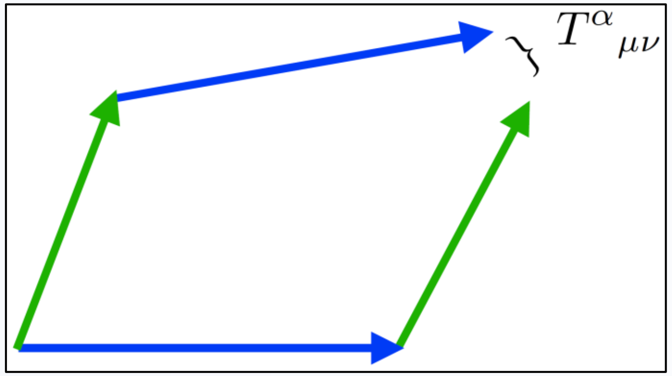
Di Valentino et al. CQG, 38 (2021) 15

Cosmology Intertwined, JHEAp. 2204 (2022) 002

How can machine learning help?

$f(T)$ Teleparallel Gravity

- Tetrad ($e^a{}_\mu$): Relate the tangent space ($g_{\mu\nu} = \eta_{ab} e^a{}_\mu e^b{}_\nu$)
- Use the **teleparallel connection** ($\Gamma^\sigma_{\mu\nu} = e_a{}^\sigma \partial_\nu e^a{}_\mu + e_a{}^\sigma \omega^a{}_{\nu\mu}$) instead of the **Levi-Civita connection gives** $\mathcal{R} = -T + B$
- ***f*(*T*) Gravity:** $S = \frac{1}{16\pi G}\int d^4x\, e[-T + f(T)] + S_{\text{mat}}$
- Taking a flat (**FLRW**) cosmology: $g_{\mu\nu} = \text{diag}\left(-1, a(t)^2, a(t)^2, a(t)^2\right)$
- **Friedmann equations**:



$$H^2 = \frac{8\pi G}{3}\rho_m - \frac{f(T)}{6} + \frac{T}{3} f_T$$

$$\dot{H} = -\frac{4\pi G(\rho_m + p_m)}{1 - f_T - 2T f_{TT}}$$

$$T = 6H^2 = 6\left(\frac{\dot{a}}{a}\right)^2$$

Bahamonde et al. RoPP 86 (2023) 026901

Propagating $f(T(z))$

- The Friedmann equation contains f_T which **need to be eliminated finite difference** methods
- Using a **central differencing** approach (error $\sim \mathcal{O}(\Delta z^2)$), we can assume

$$f'(z_i) \simeq \frac{f(z_{i+1}) - f(z_{i-1})}{z_{i+1} - z_{i-1}}$$

- Therefore, we can remove the $f_T(T) = f'(z)/T'(z)$

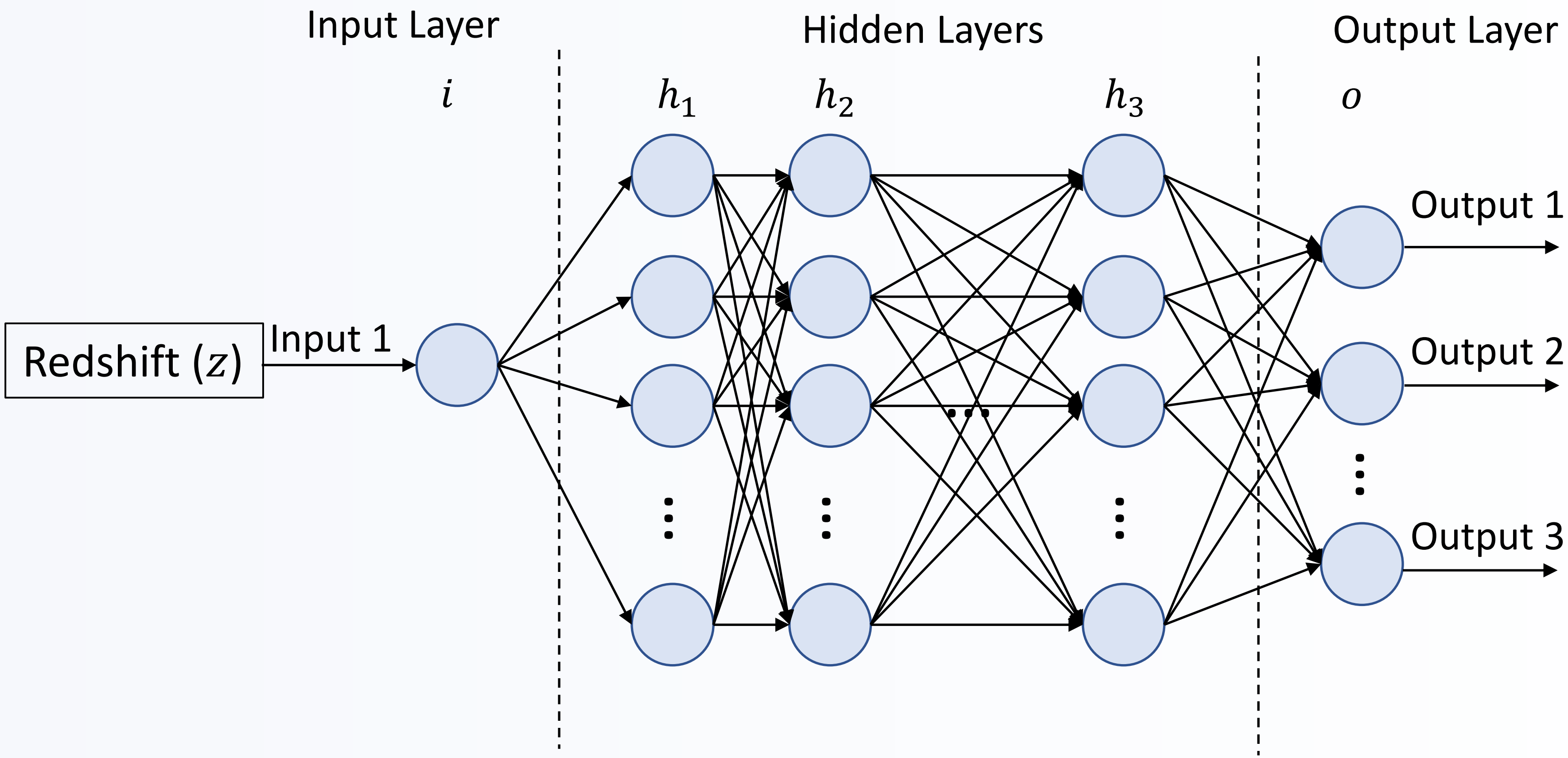
$$H^2 = \frac{8\pi G}{3}\rho_m - \frac{f(T)}{6} + \frac{T}{3}\boldsymbol{f_T}$$

- This then gives a **propagation equation**

$$f(z_{i+1}) = f(z_{i-1}) + 2(z_{i+1} - z_{i-1})\frac{H'(z_i)}{H(z_i)}\left(3H(z_i)^2 + \frac{f(z_i)}{2} - 3H_0^2\Omega_{m_0}(1+z_i)^3\right)$$

Briffa, R. et al. Class. Quantum Grav. 38 (2020) 055007

Artificial Neural Networks (ANNs)

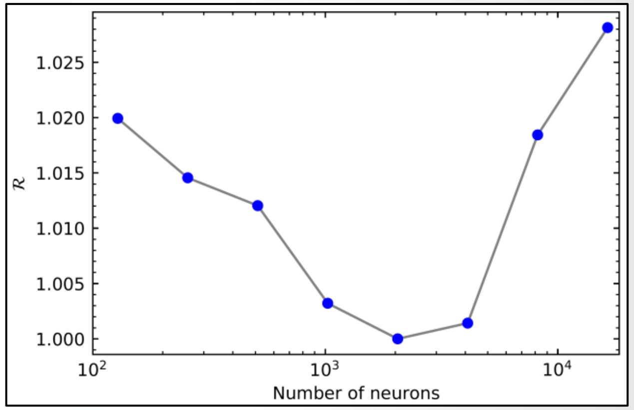


Cosmological parameters (ex. $H(z), \sigma_H(z)$)

Designing the ANN

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

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



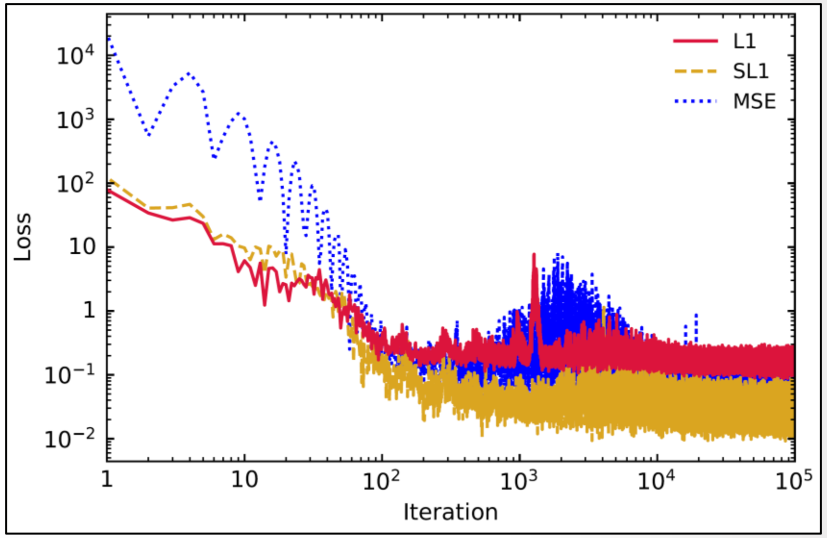
- **Loss** – Balances the **number of iterations** a system needs to predict the observational data

  1. **L1** (Least absolute deviation)

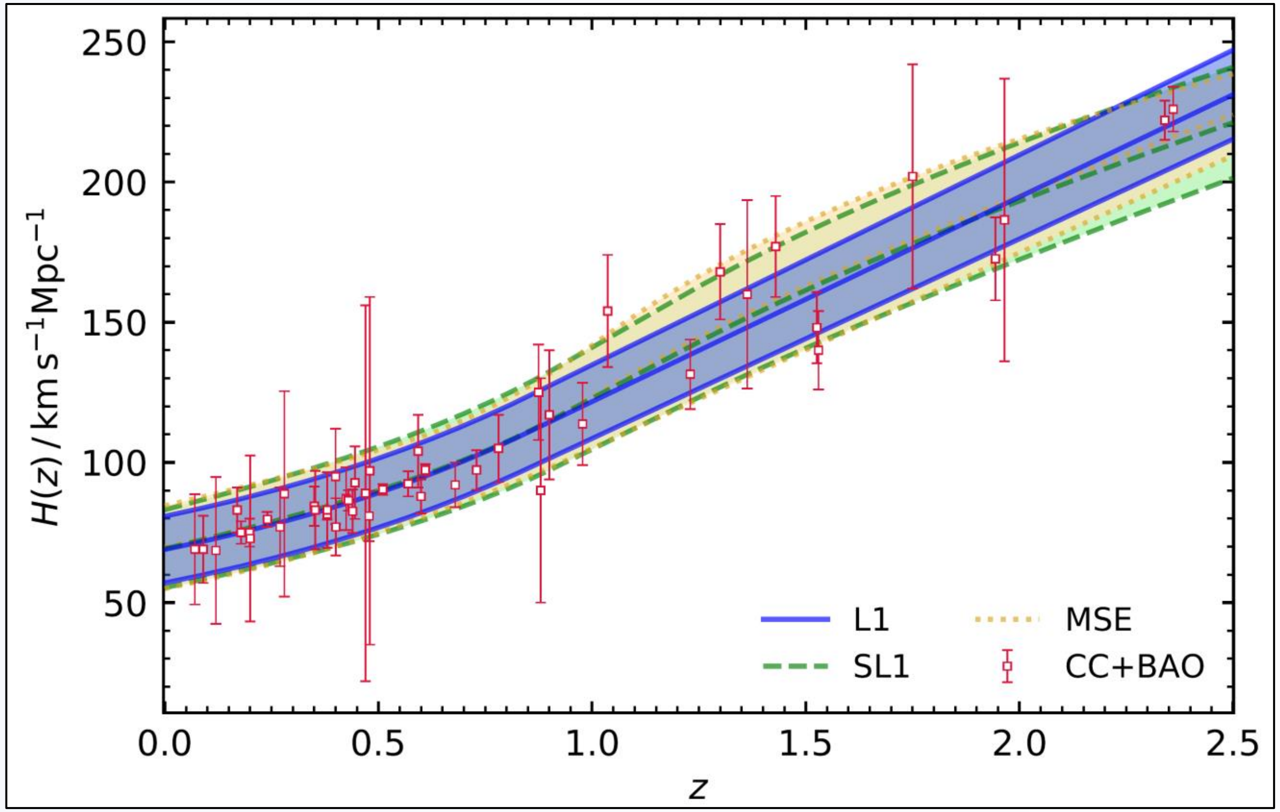
$$\text{L1} = \sum_{i=1}^{N} \left| H_{Obs}(z_i) - H_{pred}(z_i) \right|$$

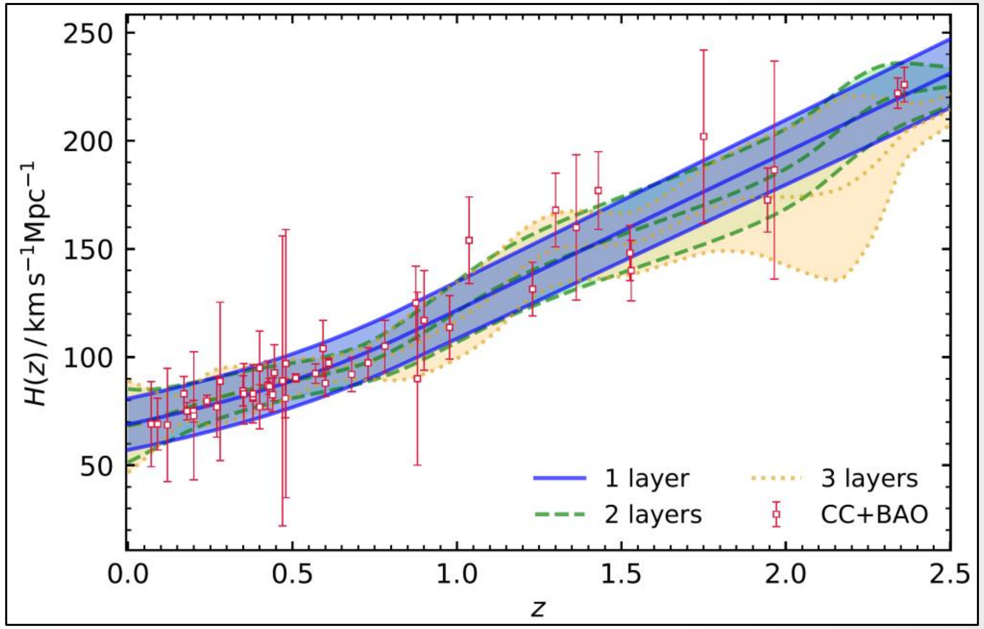
  2. Smoothed L1 (**SL1**)
  3. Mean Square Error (**MSE**)

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



Using the ANN





One layer is preferred

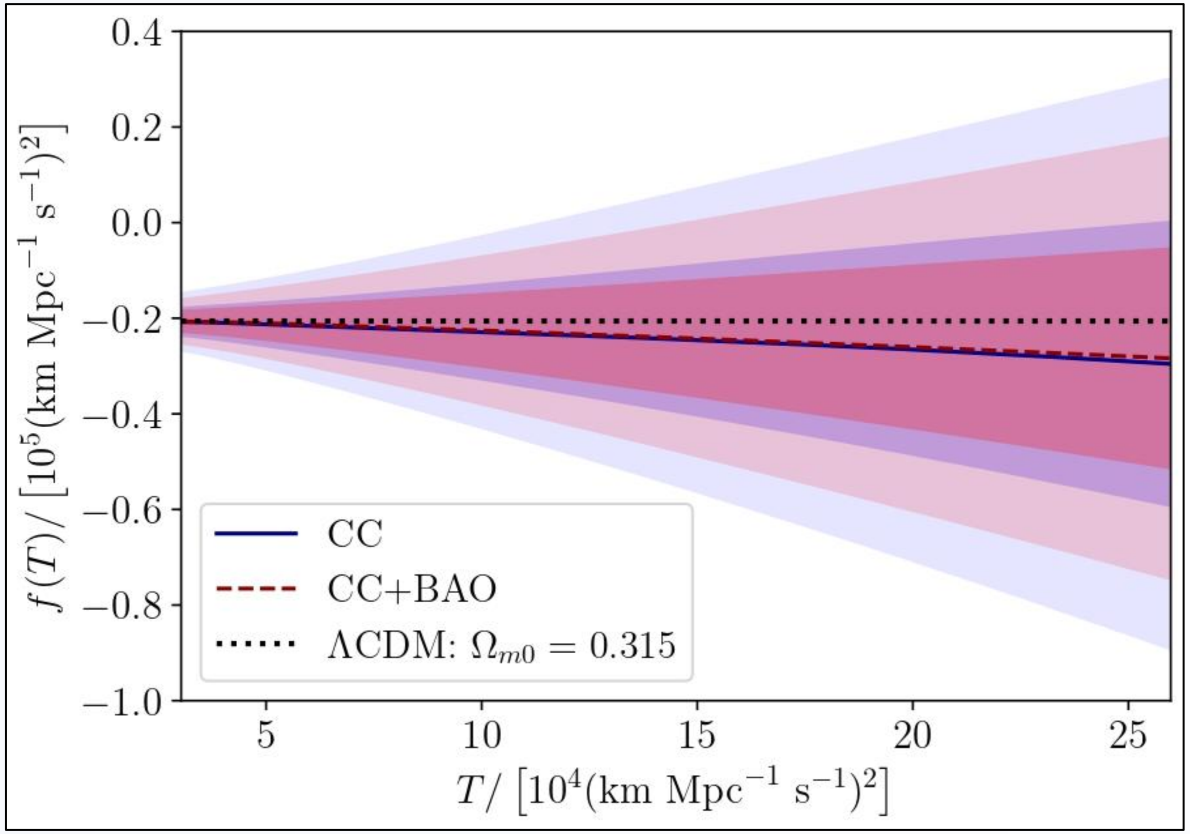
MSE: $H_0 = 69.76 \pm 14.82\ \mathrm{km\,s^{-1}Mpc^{-1}}$

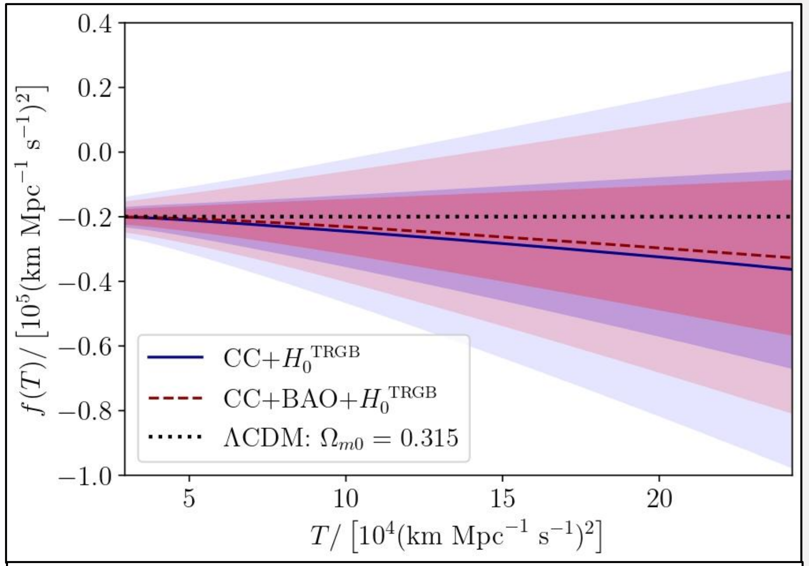
L1: $H_0 = 68.93 \pm 11.90\ \mathrm{km\,s^{-1}Mpc^{-1}}$

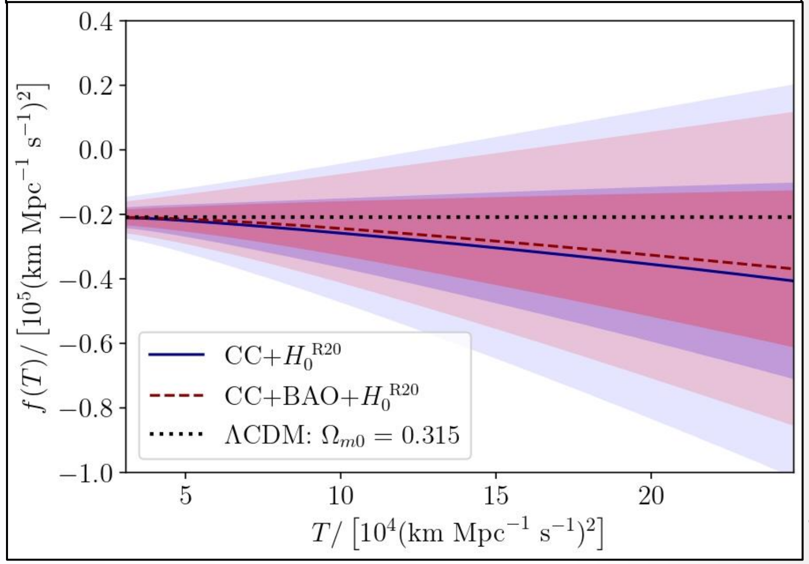
SL1: $H_0 = 69.18 \pm 13.92\ \mathrm{km\,s^{-1}Mpc^{-1}}$

Dialektopoulos, K. et al. JCAP 02 (2022) 023

Propagating f(T)CDM



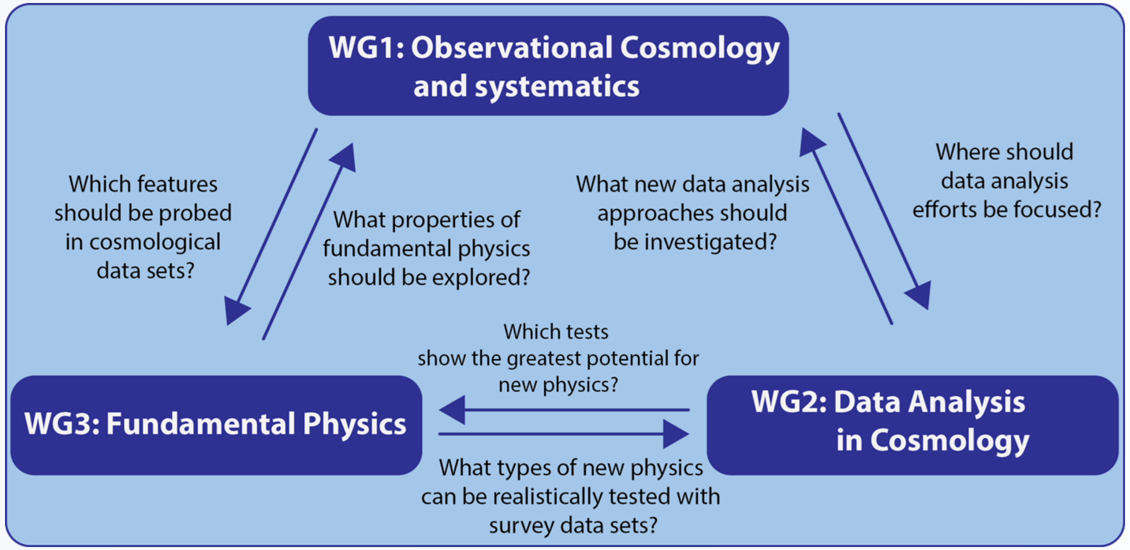




$$H^2 = \frac{8\pi G}{3}\rho_m - \frac{f(T)}{6} + \frac{T}{3}\boldsymbol{f_T}$$

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@Lisbon 2023

Thank You