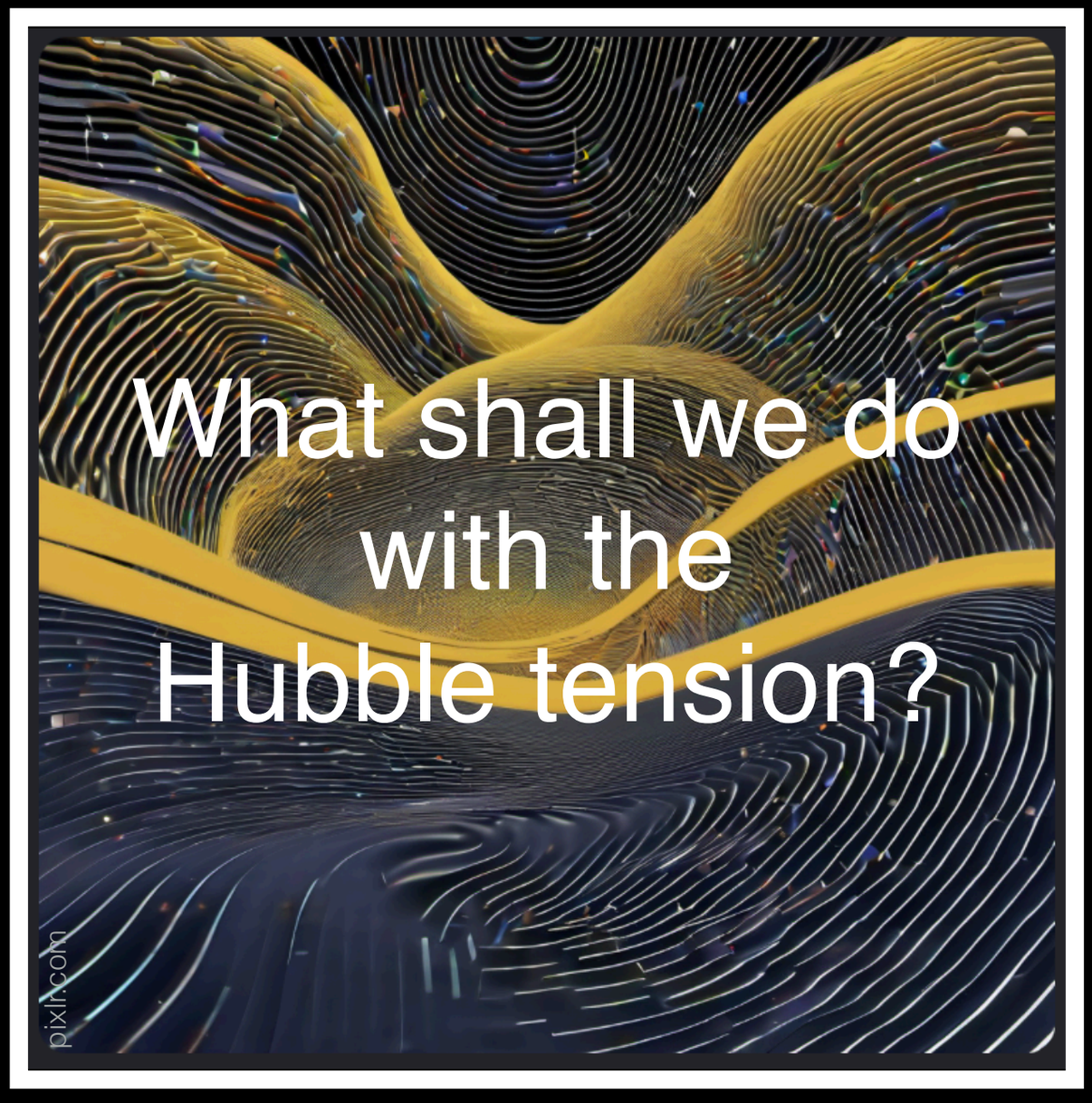
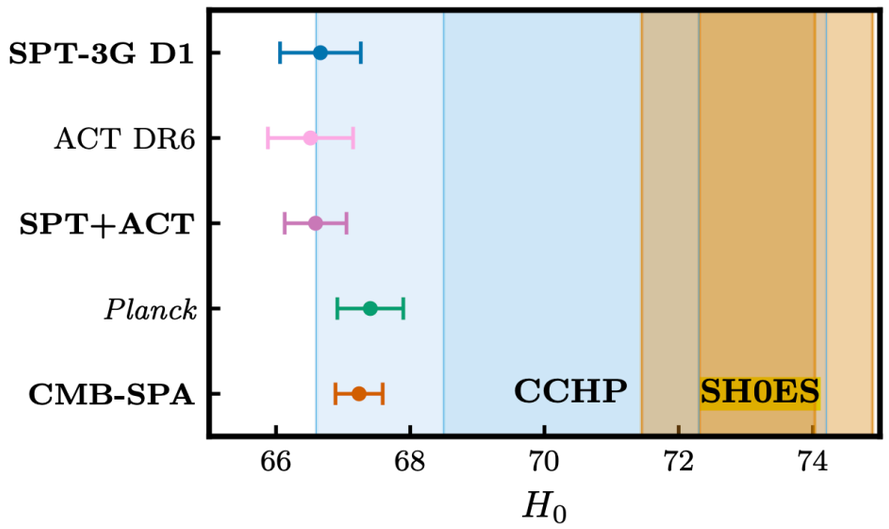
New physics from galaxy clustering, GGI, Florence, 1.10.2025



J. Lesgourgues
Institut für Theoretische Teilchenphysik und Kosmologie (TTK), RWTH Aachen University

Hubble tension



In ΛCDM:

6.4σ between Planck+ ACT+SPT and SH0ES 2024

(Camphuis et al. 2506.20707 vs. Riess et al. 2402.08038)

(may also replace CMB by BBN+BAO,
SH0ES by TRGB, strong lensing, Coma distance...)

So: systematics or new physics?

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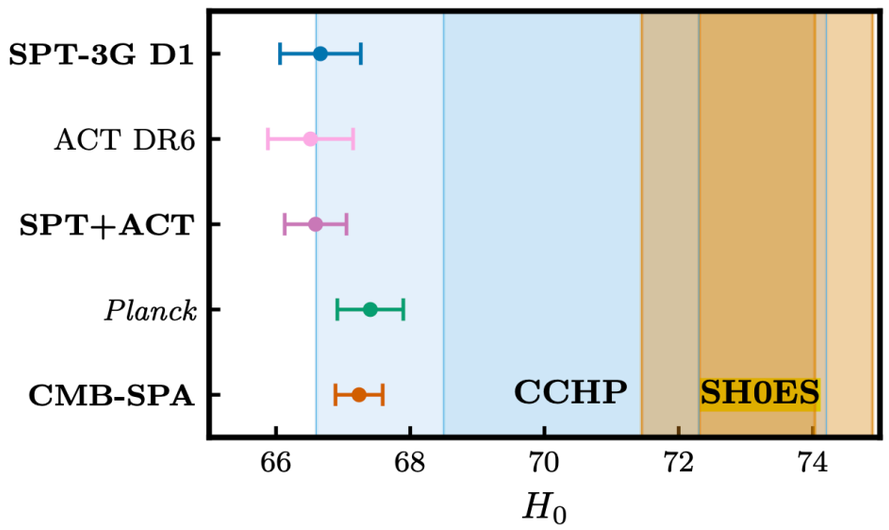
Hubble tension



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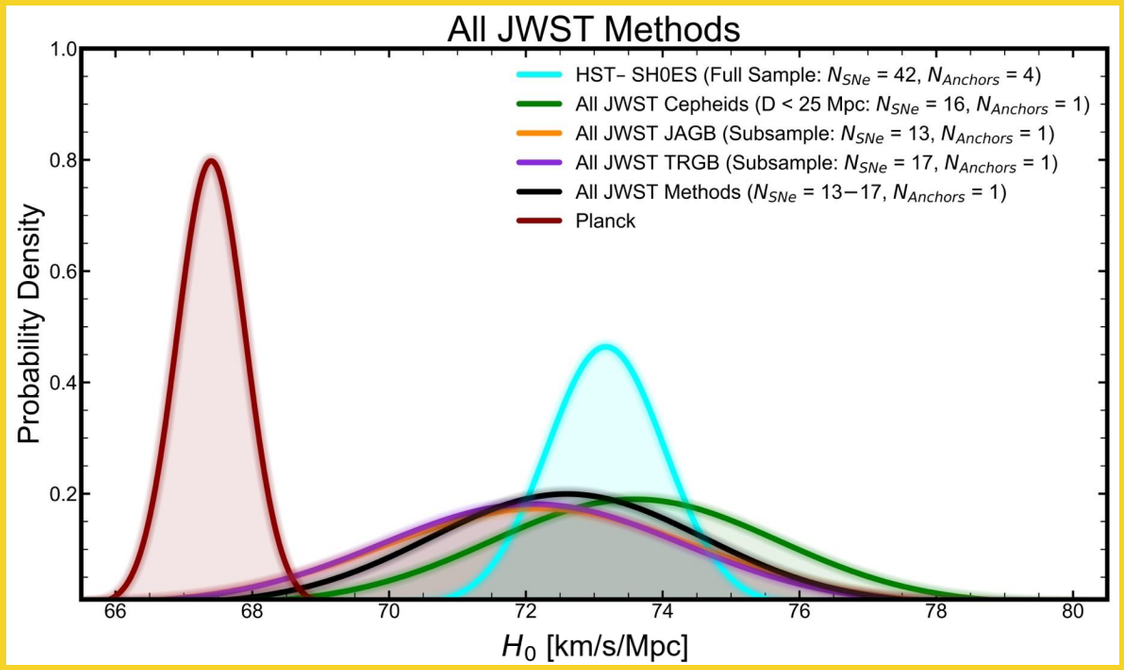
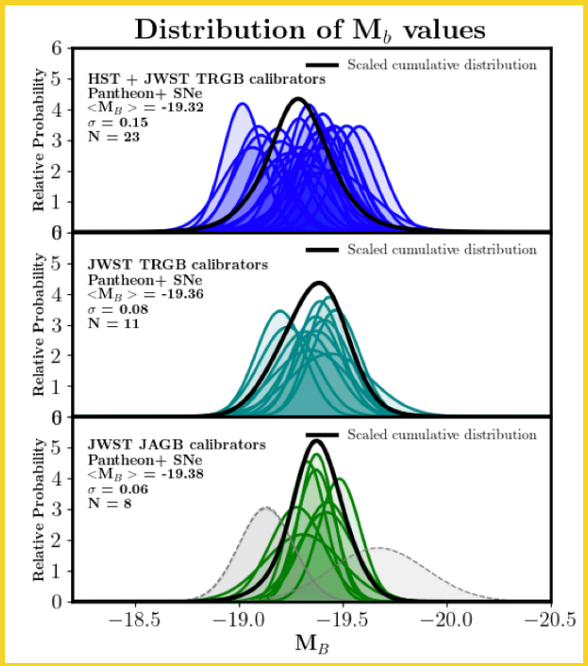
(may also replace CMB by BBN+BAO,
SH0ES by TRGB, strong lensing, Coma distance...)

Summer 2024: preliminary indication from JWST and CCHP that 3 calibration methods (Cepheids, JAGB, TRGB) would give 3 different results (Freedman et al. 2408.06153)...

Disappeared after correcting for selection effects...

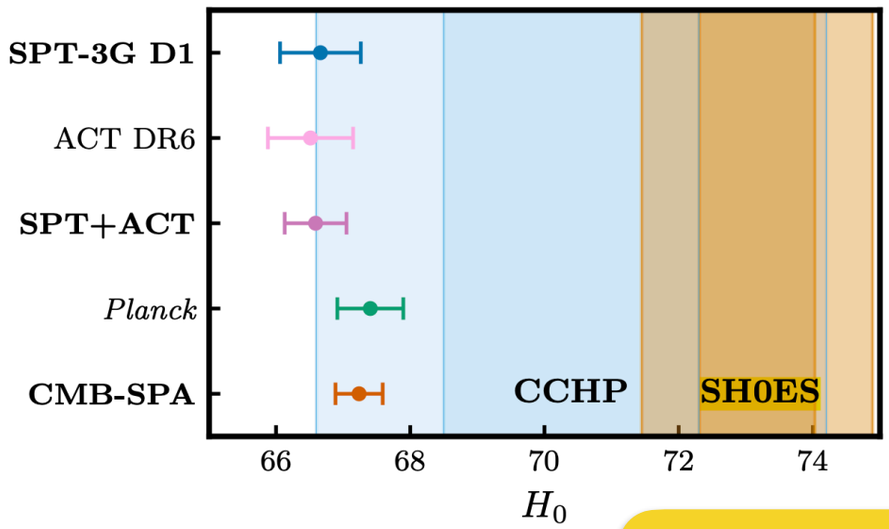


Riess et al. 2408.11770, see also Li et al. 2504.08921



Freedman et al. 2408.06153

Hubble tension



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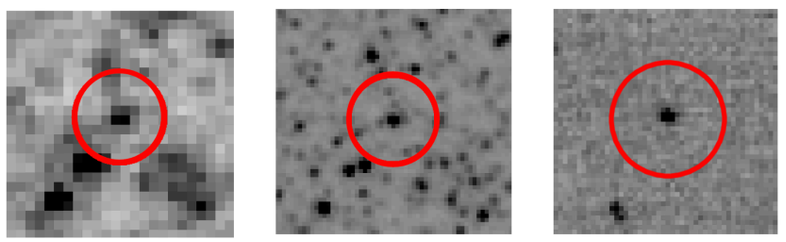
Summer 2024: preliminary indic
would give 3 di
Disappeared afte

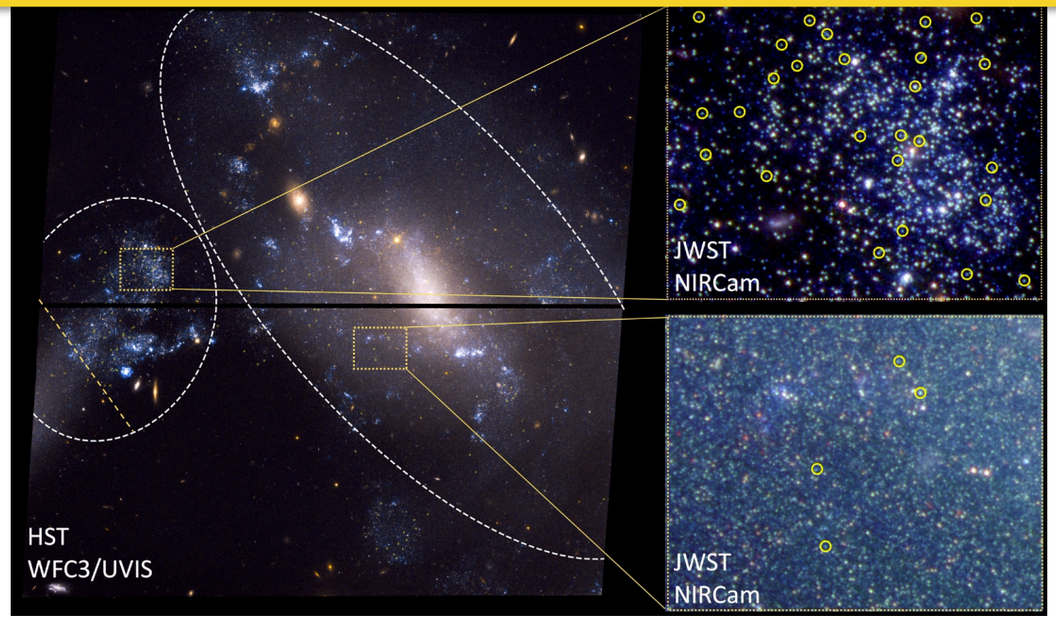
August 2025: independent grou
(Newman et al. 2508.20023)...

Sept. 2025: SHOES compared HST and JWST observations
to exclude crowding as a relevant systematic
(Riess et al. 2509.01677)



HST/host JWST/host JWST/companion

Nice pedagogical update on observational status:
Louise Breuval, CosmoVerse seminar,
"Recent improvements to the cepheid-SNIa distance ladder",
25.09.2025, youyube.com



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A multiplication of tensions ...

Increased s… …rnovae and

…ions:

…on history

$\Rightarrow H_0$, $5-6\sigma$ tension

Increas…

small-scale…

…n?

$\Rightarrow S_8$, $2-$…

with

Small…

going away with Planck PR4, ACT, SPT

Are all astrophysicists underestimating systematics?

Or tensions = different hints of the same new physics?

Assume no unknown systematics in observations:

- What categories of extended cosmology may work?
- Price to pay?
- Are working models elegant or fine-tuned, ad hoc?

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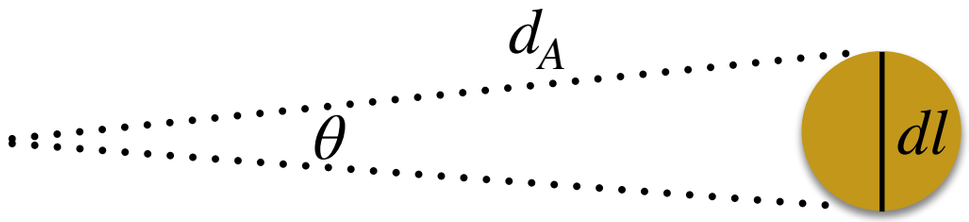
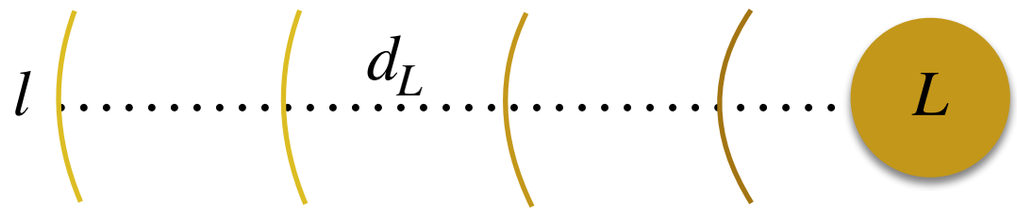
Cosmological distances

Angular diameter distance $d_A \equiv \dfrac{dl}{d\theta}$



Standard ruler

Luminosity distance $d_L \equiv \sqrt{\dfrac{L}{4\pi l}}$



Standard candle

Distance-redshift relation: $d_L(z) \propto (1+z)\, f_k\left(\int_0^z \dfrac{d\tilde{z}}{H(\tilde{z})}\right)$

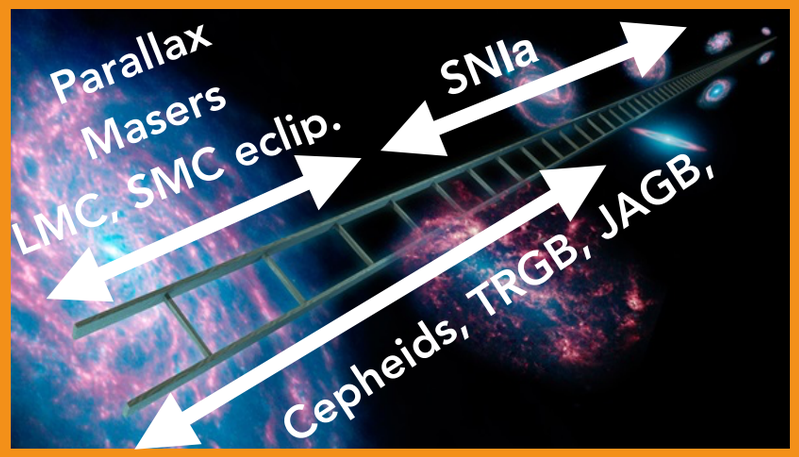
Distance duality relation (Etherington) relation: $d_L(z) = (1+z)^2\, d_A(z)$

(excepted if:

- very non-trivial gravity theories
- photon non-conservation, e.g., decay/oscillation into ALPs)

“Distance ladder” versus “Inverse distance ladders”

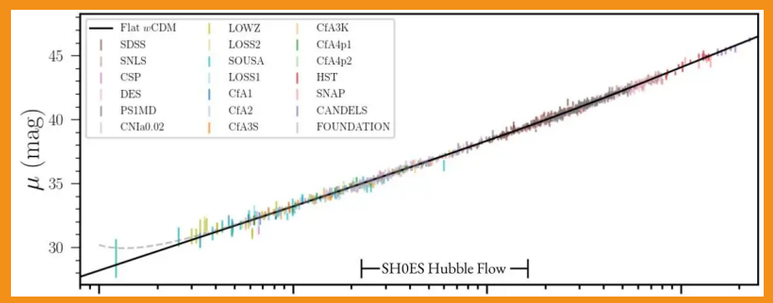
Distance ladders



Standardised SNIa luminosity L

or magnitude M_B

Apparent SNIa luminosity

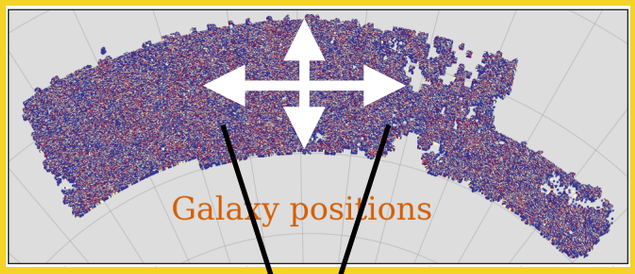


Ratio $d_L(z)/\sqrt{L}$

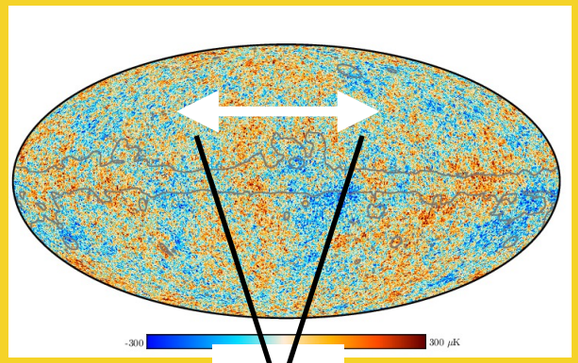
Various cosmological observables sensitive to baryon and matter density (CMB, BBN+BAO, ...)

Sound horizon d_S (model dependent)

Correlation of galaxies

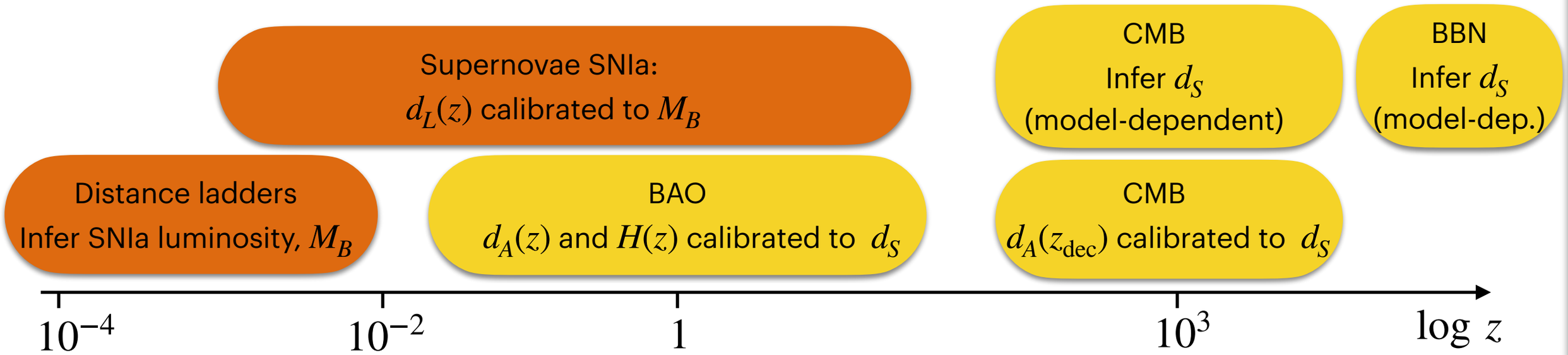


Correlation of CMB anisotropies



Ratio $d_A(z)/d_s$ and product $H(z) \times d_S$

“Distance ladder” versus “Inverse distance ladders”

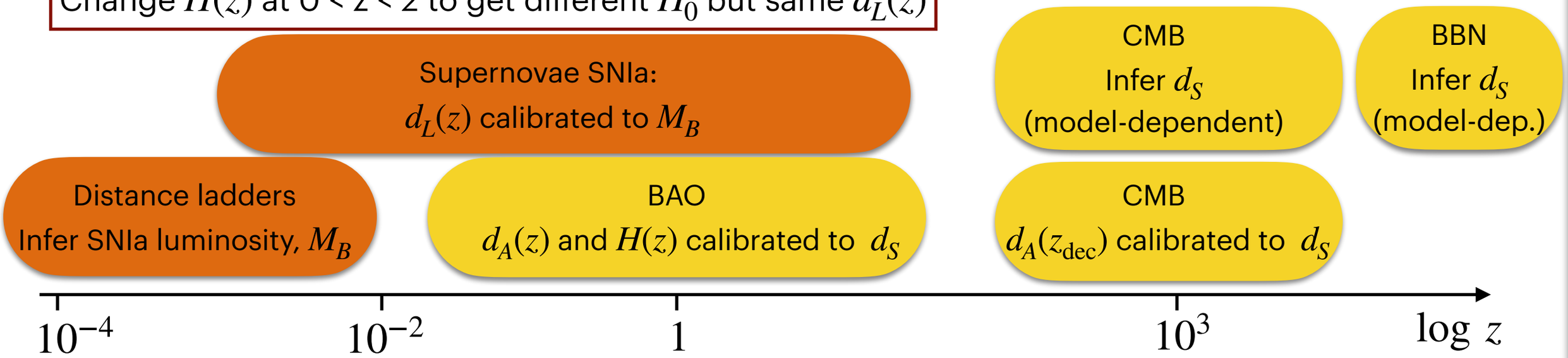


Hubble tension between H_0 = H(z=0) inferred from:

- $d_L(z)$ from supernovae, calibrated to M_B from distance ladders (e.g. SHOES)
- $d_A(z)$ and $H(z)$ from BAO and CMB, calibrated to d_S from CMB (or from BAO+BBN), assuming ΛCDM

Category 1: Modify late background expansion

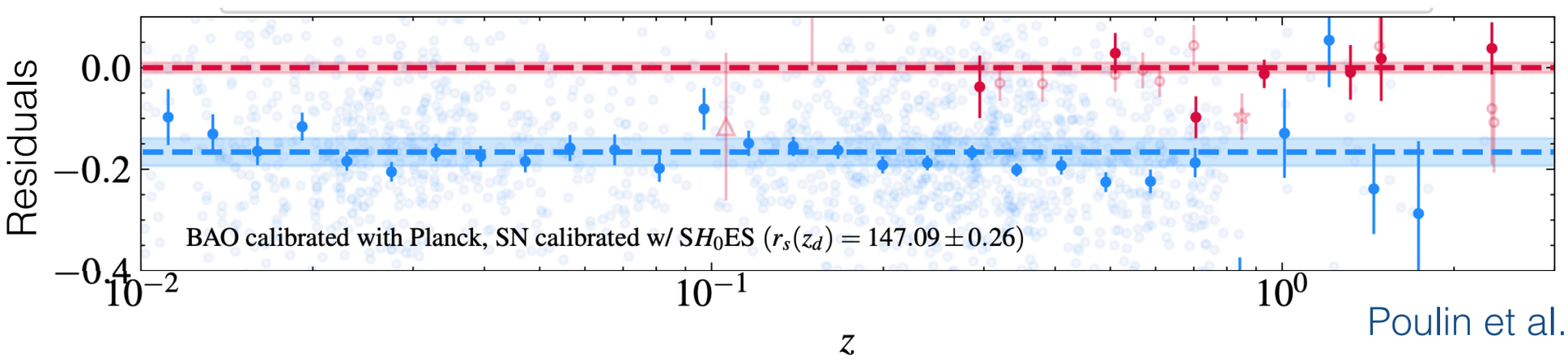
Change $H(z)$ at 0 < z < 2 to get different H_0 but same $d_L(z)$



Issue: over-constrained by overlap between BAO and remote SNIa! As long as:

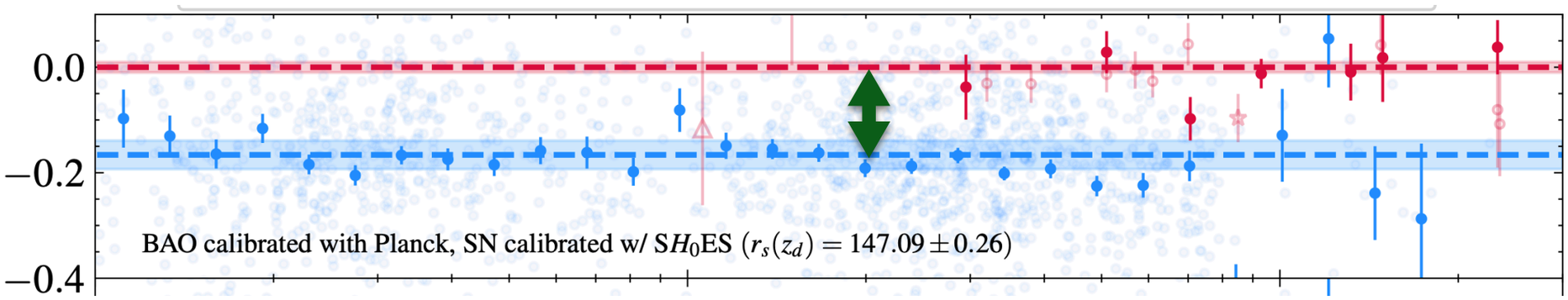
- d_S taken from CMB or BBN+BAO, assuming same early cosmology as in ΛCDM,
- M_B taken from SH0ES

... direct contradiction between $d_L(z) = (1+z)^2 d_A(z)$ on same redshifts!



Poulin et al. 2407.18292

Category 2: Violation of Distance Duality Relation



$(1+z)^2 d_A(z)$ from BAO

$d_L(z)$ from SNIa

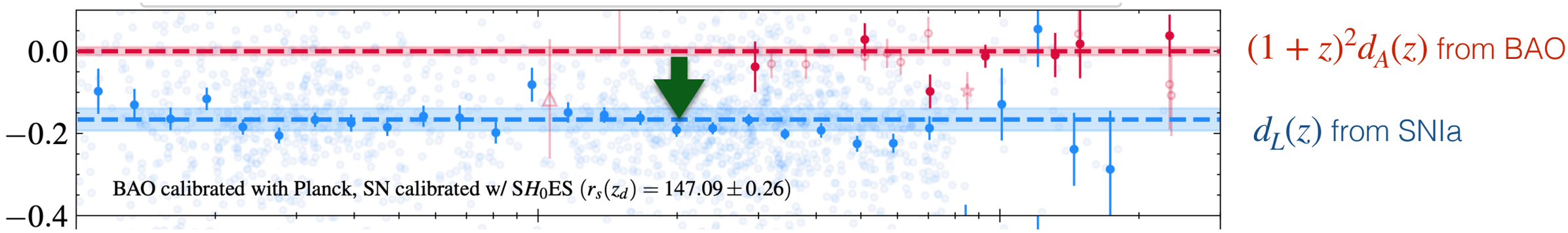
Very unusual gravity theory, or non-conservation of photon number (interaction with axions, gravitons?)

- Constrained by CMB blackbody distribution, quasar spectra, laboratory bounds, supernovae modelling, etc. (Mirrizi et al. astro-ph/0506078)
- Requires photon flux to increase during propagation
- E.g. SN emits photons+axions, then axions convert into photons; expect stronger effect for more distant SNIa
- But data prefers z-independent effect: $d_L(z) = 0.925\,(1+z)^2 d_A(z)$ (equivalent to rescaling of either M_B or d_S) (Teixeira et al. 2504.10464)

Category 3: shift recombination/photon decoupling

Sound horizon $d_S = \int_{z_{\rm dec}}^{\infty} d\tilde{z}\; c_s(\tilde{z})\; H^{-1}(\tilde{z})$

New physics shifts recombination / decoupling to earlier time = larger redshift
$\Rightarrow$ smaller d_s $\Rightarrow$ smaller $d_A(z)$



Recombination temperature and redshift very constrained by Hydrogen atom model

- Inhomogeneous recombination, e.g. primordial magnetic fields (Jedamzik et al. 2503.09599, 2307.05475)
- Time-varying constants, e.g. α, m_e (Hart et al. 1912.03986, Schöneberg et al. 2507.16845)

Additional effects in spectrum of CMB (damped oscillations, early integrated Sachs-Wolfe, ...)

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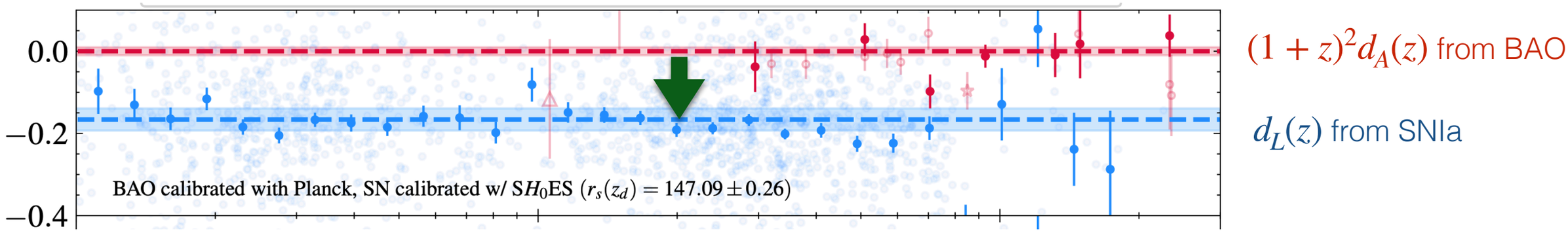
Category 4: Modified early background expansion

Sound horizon $d_S = \int_{z_{\rm dec}}^{\infty} d\tilde{z}\; c_s(\tilde{z})\; H^{-1}(\tilde{z})$

Enhanced expansion due to additional species before recombination/decoupling
$\Rightarrow$ smaller d_s $\Rightarrow$ smaller $d_A(z)$



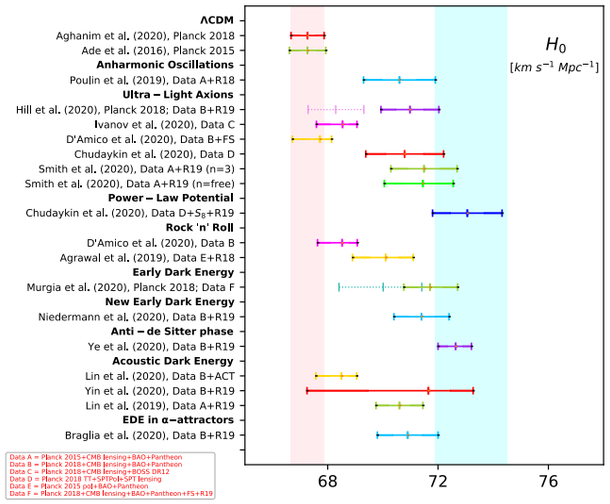
$H(z)$ constrained at BBN temperature (primordial Helium...)

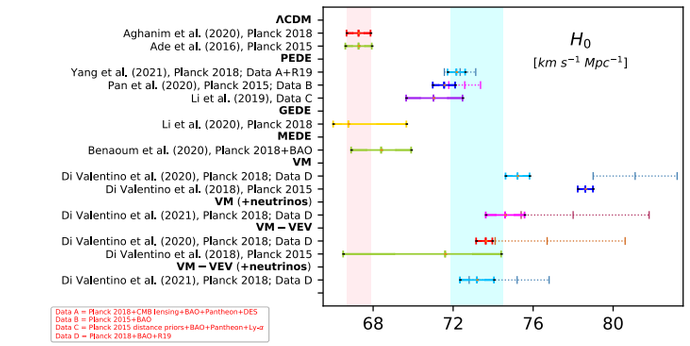
- Stepped dark radiation: entropy release into neutrinos/dark radiation enhancing $N_{\rm eff}$ after BBN (extra radiation may be free-streaming, self-interacting...) (Aloni et al. 2111.00014, ...)
- Early Dark Energy (various implementations; stringy axions, spontaneous symmetry breaking in dark sector, ...) (Karwal et al. 1608.01309, Niedermann et al. 2006.06686 ...)
- Early Modified Gravity (Brans-Dicke) (Ferrari et al. 2501.15298)

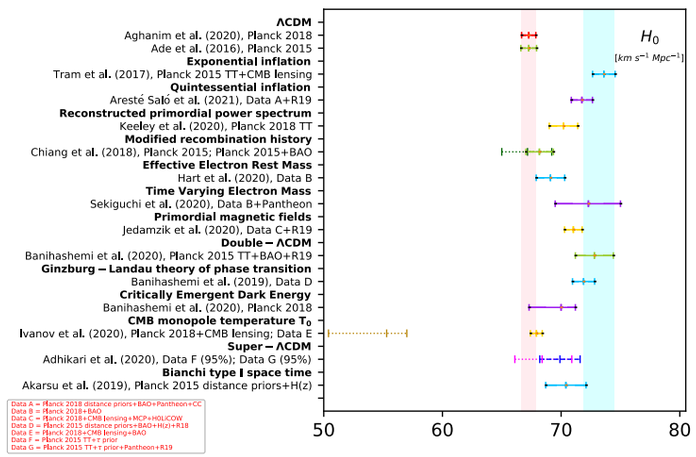
Usually, additional effects in spectrum of CMB and large scale structure...

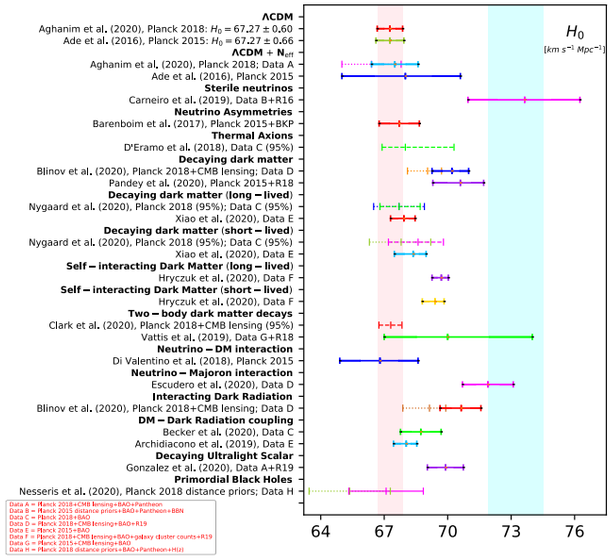
Reviews on existing proposals

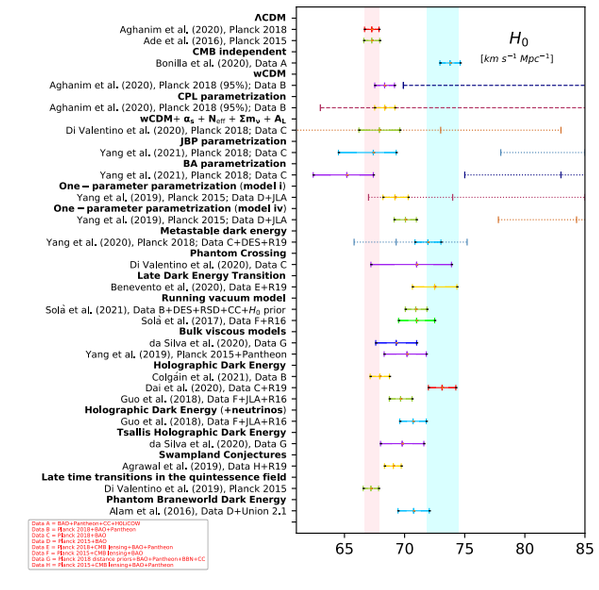
De Valentino et al. 2103.01183, 2504.01669 (CosmoVerse)

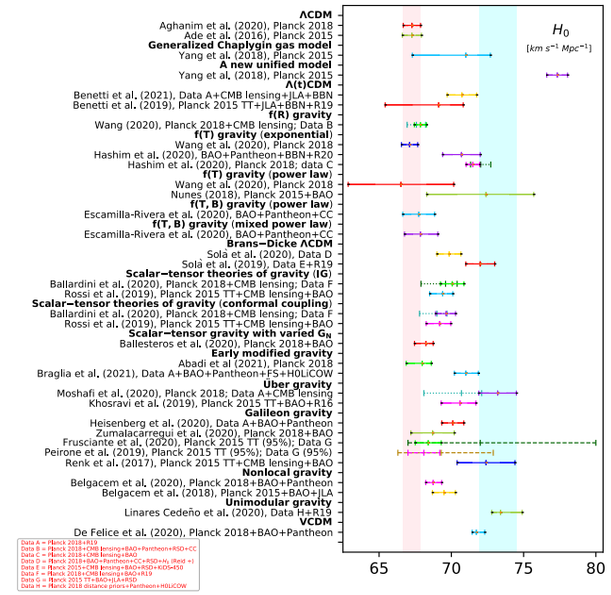












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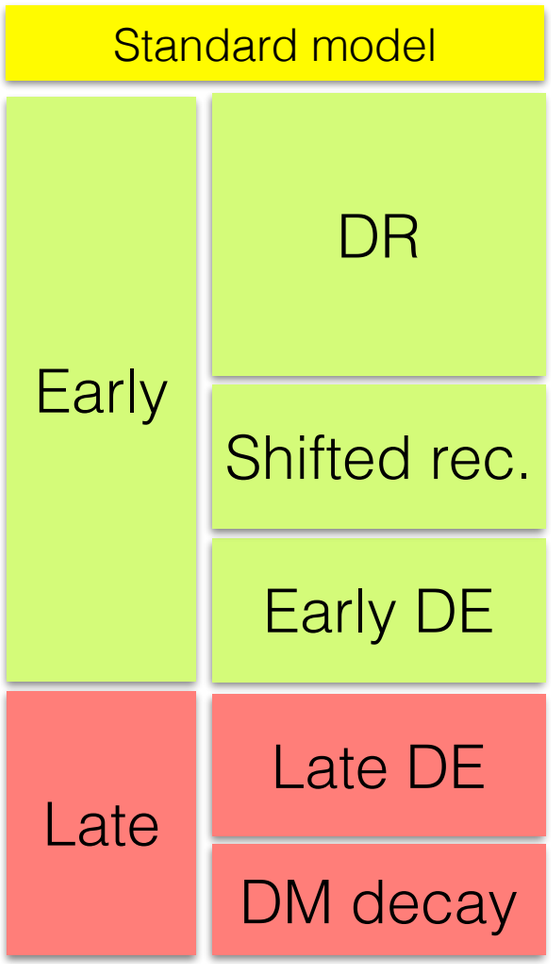
Fair comparison of models

The Hubble Olympics

Schöneberg, Abellan, Pérez, JL, Witte, Poulin, Lesgourgues, 2107.10291, *Phys. Rep. 984 (2022) 1-55*

- Selection of 19 "representative models"; *Planck, BAO till BOSS DR12, Pantheon, SH0ES21*
- Three metrics to quantify the (resolution of the) tension



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	X	0.00	0.00	X	X
$\Delta N_{\rm ur}$	1	-19.395 ± 0.019	3.6σ	3.8σ	X	-6.10	-4.10	X	X
SIDR	1	-19.385 ± 0.024	3.2σ	3.3σ	X	-9.57	-7.57	✓	✓ 3
mixed DR	2	-19.413 ± 0.036	3.3σ	3.4σ	X	-8.83	-4.83	X	X
DR-DM	2	-19.388 ± 0.026	3.2σ	3.1σ	X	-8.92	-4.92	X	X
SIν+DR	3	$-19.440^{+0.037}_{-0.039}$	3.8σ	3.9σ	X	-4.98	1.02	X	X
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	X	-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	X	-4.94	-0.94	X	X
PEDE	0	-19.349 ± 0.013	2.7σ	2.8σ	✓	2.24	2.24	X	X
GPEDE	1	-19.400 ± 0.022	3.6σ	4.6σ	X	-0.45	1.55	X	X
DM $\to$ DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	X	-0.19	3.81	X	X
DM $\to$ DR	2	-19.410 ± 0.011	4.3σ	4.5σ	X	-0.53	3.47	X	X

Table 1: Test of the models based on dataset $\mathcal{D}_{\rm baseline}$ (Planck 2018 + BAO + Pantheon), using the direct measurement of M_b by SH0ES for the quantification of the tension (3rd column) or the computation of the AIC (5th column). Eight models pass at least one of these three tests at the 3σ level.

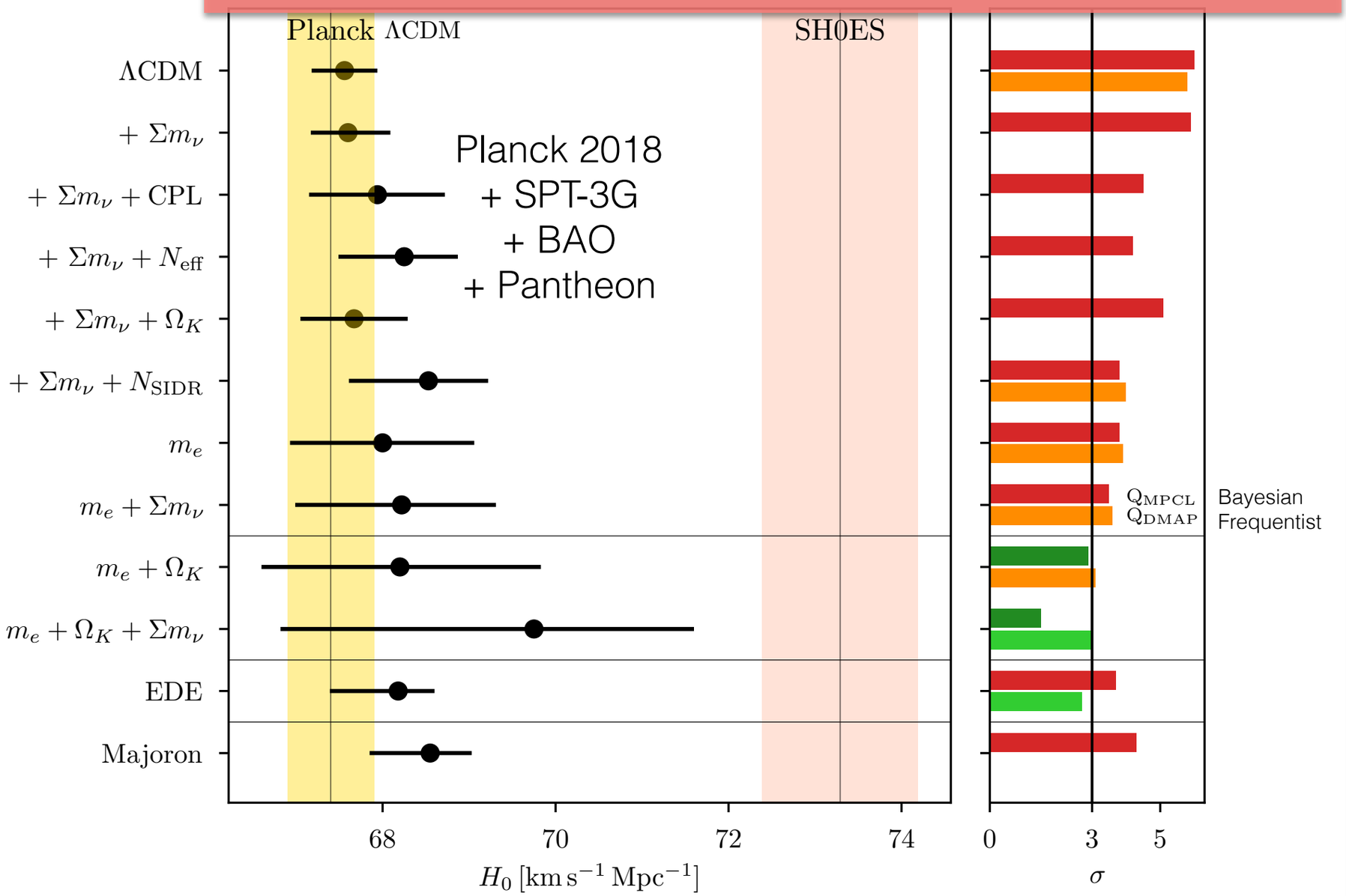
Reviews on existing proposals

Rida Khalife, Bahrami, Guenther, Galli, Lesgourgues, 2312.09814

- Selection of 11 "representative models": +SPT-3G, ACT, BAO till BOSS DR16, SH0ES23
- Four metrics to quantify the (resolution of the) tension

- Getting harder and harder to find theoretical solutions
- Needs complicated ad hoc model
- Even more complicated may work better… e.g. EDE+LDE

Standard model	
Late	Late DE
Early	DR
Late	curvature
Early	DR
	Shifted rec.
	Early DE
	DR

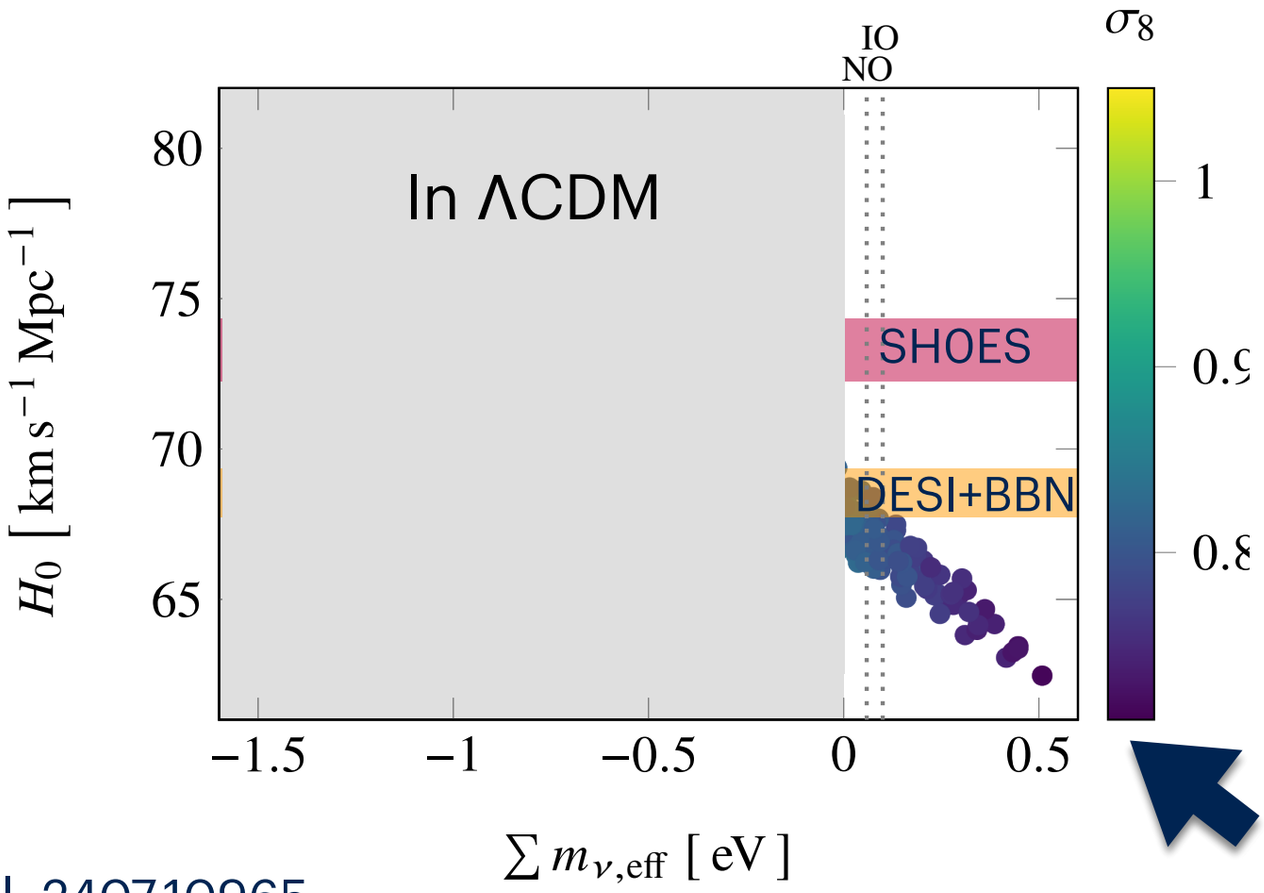


All interpretation of cosmological data gets stuck due to tensions...

For instance, situation with *neutrino mass*...

4 observable effects. Currently, dominant ones:

- Background effect (expansion rate), affected by BAO+SN tension on late expansion history
- CMB lensing effect, affected by slightly unexpected shape of high-l CMB temperature



Push from CMB lensing

Elbers et al. 2407.10965

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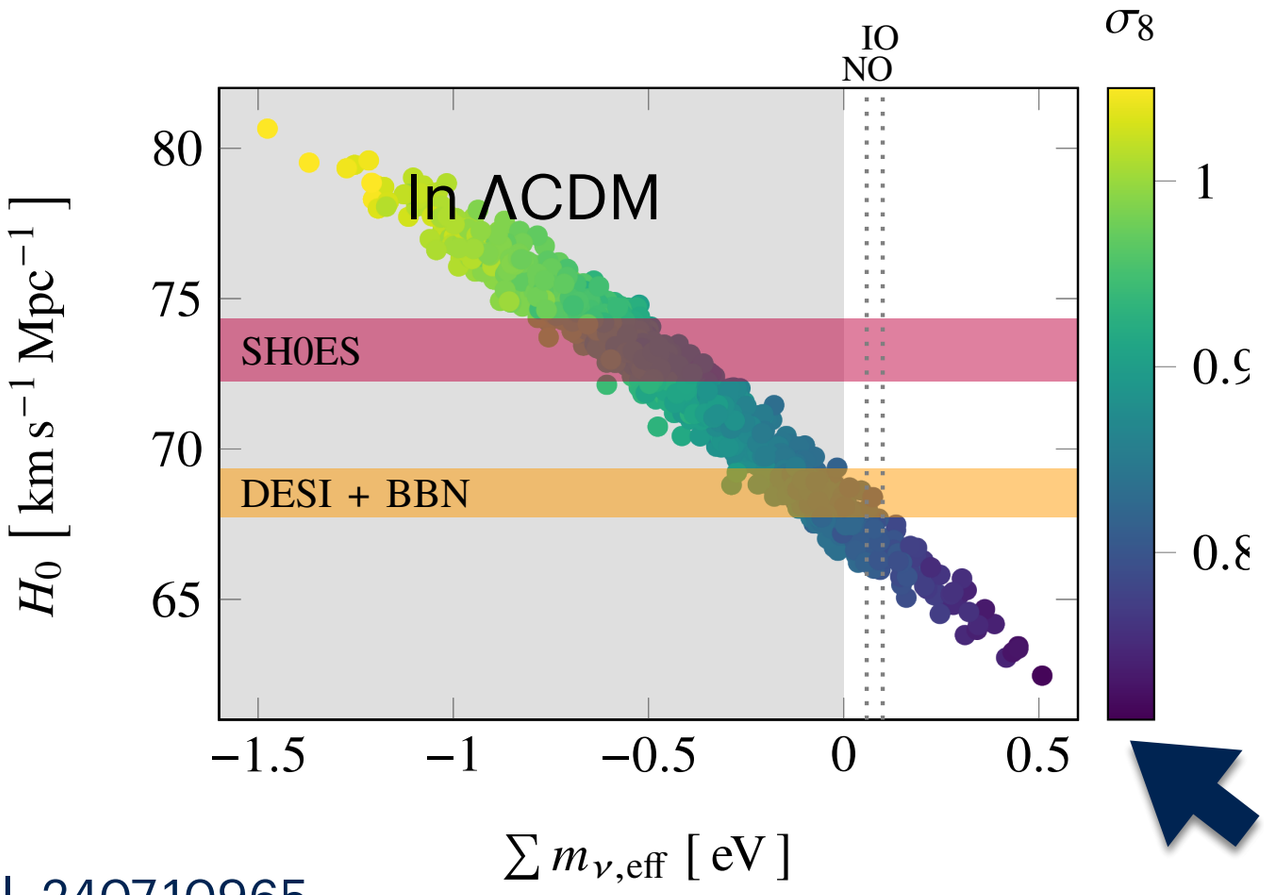


With dynamically DE:
- DESI+BBN moves down
- Mass bound relaxed
- Hubble tension gets worse

Push from CMB lensing

Elbers et al. 2407.10965

So what shall we do?

1. In all areas of observational cosmology relevant for these tensions, reassess systematics:

- Push experts to open their data analysis pipeline, challenge each other's assumptions
- Push experts from other areas of observational cosmology and theorists to learn physics relevant for these observations and enter the debate as challengers or moderators

- Push towards "search for consensus" rather than "deadly competition"

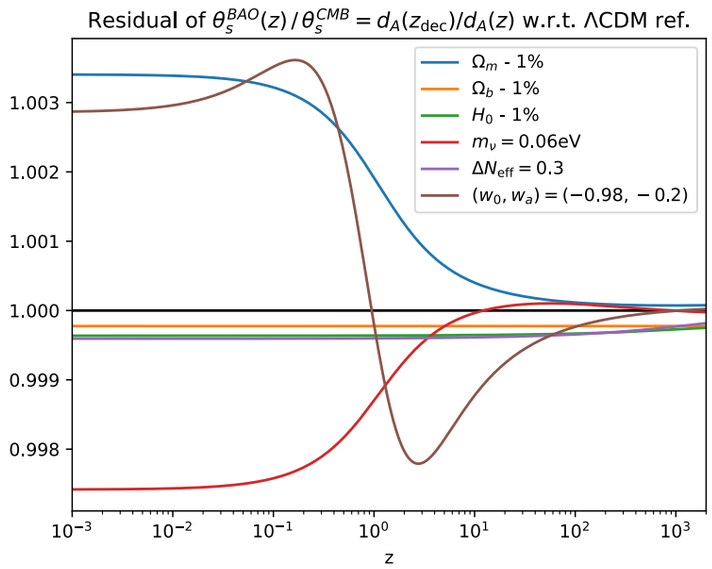
So what shall we do?

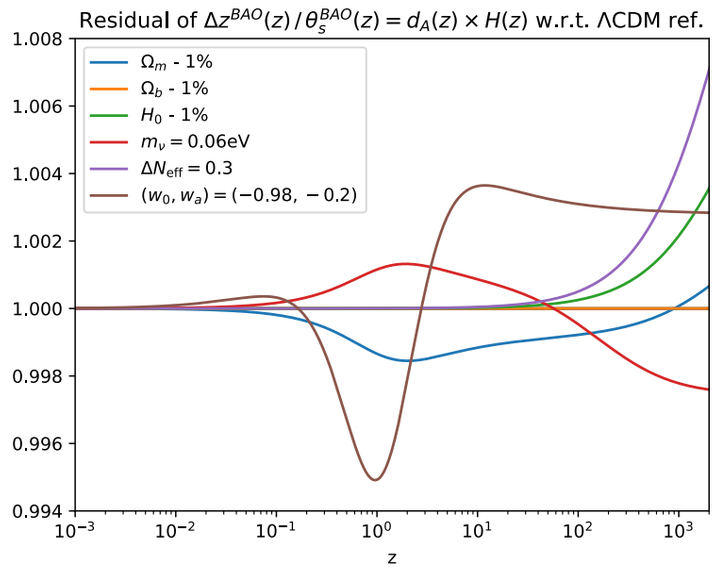
2. As theorists: change prospective w.r.t. global analyses and top-down model fitting

- isolate independent effects of each ingredient in cosmological model
- search for model-independent combinations of observables
- Formulate guardrails on what "cosmological model v2" should have or not have

... and only then search for specific models that work. Maybe combination of several ingredients?

Examples of model-independent combinations:





So what shall we do?

3. As observers: look for independent direct measurements of H_0

- Angular diameter distance to water megamasers in AGNs
- Lensing time-delays (quasars & SNIa)
- Age of objects, cosmic clocks/chronometers
- Full shape of galaxy clustering and weak lensing power spectrum
- Gamma-ray bursts
- Redshift drifts (ELT, SKA, CHIME, HIRAX...)
- Standard sirens ($d_L(z)$ from gravitons!)