Cosmological Tensions Lecture 3
How (not) to solve the Hubble tension?

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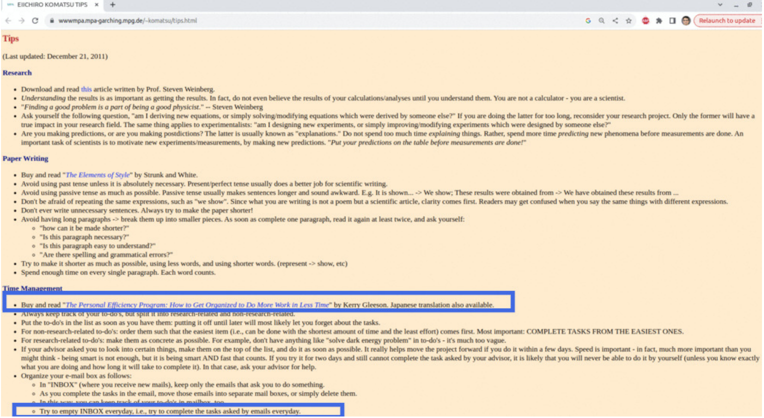
Suggested book

The personal efficiency program, by Kerry Gleeson

(especially the chapters on email and planning)



EIICHIRO KOMATSU TIPS

wwwmpa.mpa-garching.mpg.de/~komatsu/tips.html

Relaunch to update

Tips

(Last updated: December 21, 2011)

Research

- Download and read this article written by Prof. Steven Weinberg.
- *Understanding* the results is as important as getting the results. In fact, do not even believe the results of your calculations/analyses until you understand them. You are not a calculator - you are a scientist.
- "*Finding a good problem is a part of being a good physicist.*" -- Steven Weinberg
- Ask yourself the following question, "am I deriving new equations, or simply solving/modifying equations which were derived by someone else?" If you are doing the latter for too long, reconsider your research project. Only the former will have a true impact in your research field. The same thing applies to experimentalists: "am I designing new experiments, or simply improving/modifying experiments which were designed by someone else?"
- Are you making predictions, or are you making postdictions? The latter is usually known as "explanations." Do not spend too much time *explaining* things. Rather, spend more time *predicting* new phenomena before measurements are done. An important task of scientists is to motivate new experiments/measurements, by making new predictions. "*Put your predictions on the table before measurements are done!*"

Paper Writing

- Buy and read "*The Elements of Style*" by Strunk and White.
- Avoid using past tense unless it is absolutely necessary. Present/perfect tense usually does a better job for scientific writing.
- Avoid using passive tense as much as possible. Passive tense usually makes sentences longer and sound awkward. E.g. It is shown... -> We show; These results were obtained from -> We have obtained these results from ...
- Don't be afraid of repeating the same expressions, such as "we show". Since what you are writing is not a poem but a scientific article, clarity comes first. Readers may get confused when you say the same things with different expressions.
- Don't ever write unnecessary sentences. Always try to make the paper shorter!
- Avoid having long paragraphs -> break them up into smaller pieces. As soon as complete one paragraph, read it again at least twice, and ask yourself:
  - "how can it be made shorter?"
  - "Is this paragraph necessary?"
  - "Is this paragraph easy to understand?"
  - "Are there spelling and grammatical errors?"
- Try to make it shorter as much as possible, using less words, and using shorter words. (represent -> show, etc)
- Spend enough time on every single paragraph. Each word counts.

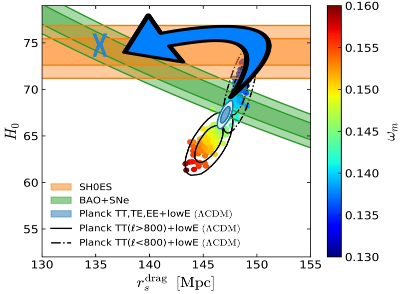
Time Management

- Buy and read "*The Personal Efficiency Program: How to Get Organized to Do More Work in Less Time*" by Kerry Gleeson. Japanese translation also available.
- Always keep track of your to-do's, but split it into research-related and non-research-related.
- Put the to-do's in the list as soon as you have them: putting it off until later will most likely let you forget about the tasks.
- For non-research-related to-do's: order them such that the easiest item (i.e., can be done with the shortest amount of time and the least effort) comes first. Most important: COMPLETE TASKS FROM THE EASIEST ONES.
- For research-related to-do's: make them as concrete as possible. For example, don't have anything like "solve dark energy problem" in to-do's - it's much too vague.
- If your advisor asked you to look into certain things, make them on the top of the list, and do it as soon as possible. It really helps move the project forward if you do it within a few days. Speed is important - in fact, much more important than you might think - being smart is not enough, but it is being smart AND fast that counts. If you try it for two days and still cannot complete the task asked by your advisor, it is likely that you will never be able to do it by yourself (unless you know exactly what you are doing and how long it will take to complete it). In that case, ask your advisor for help.
- Organize your e-mail box as follows:
  - In "INBOX" (where you receive new mails), keep only the emails that ask you to do something.
  - As you complete the tasks in the email, move those emails into separate mail boxes, or simply delete them.
  - In this way, you can keep track of your to-do's in mailbox, too.
  - Try to empty INBOX everyday, i.e., try to complete the tasks asked by emails everyday.

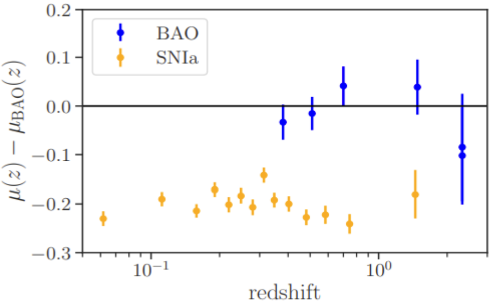
From Eiichiro Komatsu's website, `https://wwwmpa.mpa-garching.mpg.de/~komatsu/tips.html`

What does the Hubble tension really mean?

Reminder: beyond the simplest CMB vs SH0ES interpretation, it is a tension between BAO (r_s) and SNeIa (M_B) calibrators



Knox & Millea, PRD 101 (2020) 043533



Tutusaus, Kunz & Favre, 2311.16862

So we need to change either or both r_s and/or M_B!

A naïve first approach: CMB vs SH0ES

Introduce new physics such that a higher H_0 needed to keep θ_s fixed
$\Longrightarrow$ Most extensions reduce tension by enlarging errors – no simple extension where H_0 high from CMB alone (in most cases H_0 lower)!

Table 5. Constraints on standard cosmological parameters from *Planck* TT,TE,EE+lowE+lensing when the base-ΛCDM model is extended by varying additional parameters. The constraint on τ is also stable but not shown for brevity; however, we include H_0 (in km s^{-1}Mpc^{-1}) as a derived parameter (which is very poorly constrained from *Planck* alone in the ΛCDM+w_0 extension). Here α_{-1} is a matter isocurvature amplitude parameter, following PCP15. All limits are 68 % in this table. The results assume standard BBN except when varying Y_P independently (which requires non-standard BBN). Varying A_L is not a physical model (see Sect. 6.2).

Parameter(s)	$\Omega_b h^2$	$\Omega_c h^2$	$100\theta_{MC}$	H_0	n_s	$\ln(10^{10}A_s)$
Base ΛCDM	0.02237 ± 0.00015	0.1200 ± 0.0012	1.04092 ± 0.00031	67.36 ± 0.54	0.9649 ± 0.0042	3.044 ± 0.014
r	0.02237 ± 0.00014	0.1199 ± 0.0012	1.04092 ± 0.00031	67.40 ± 0.54	0.9659 ± 0.0041	3.044 ± 0.014
$dn_s/d\ln k$	0.02240 ± 0.00015	0.1200 ± 0.0012	1.04092 ± 0.00031	67.36 ± 0.53	0.9641 ± 0.0044	3.047 ± 0.015
$dn_s/d\ln k, r$	0.02243 ± 0.00015	0.1199 ± 0.0012	1.04093 ± 0.00030	67.44 ± 0.54	0.9647 ± 0.0044	3.049 ± 0.015
$d^2n_s/d\ln k^2, dn_s/d\ln k$.	0.02237 ± 0.00016	0.1202 ± 0.0012	1.04090 ± 0.00030	67.28 ± 0.56	0.9625 ± 0.0048	3.049 ± 0.015
N_{eff}	0.02224 ± 0.00022	0.1179 ± 0.0028	1.04116 ± 0.00043	66.3 ± 1.4	0.9589 ± 0.0084	3.036 ± 0.017
$N_{eff}, dn_s/d\ln k$	0.02216 ± 0.00022	0.1157 ± 0.0032	1.04144 ± 0.00048	65.2 ± 1.6	0.950 ± 0.011	3.034 ± 0.017
Σm_ν	0.02236 ± 0.00015	0.1201 ± 0.0013	1.04088 ± 0.00032	$67.1^{+1.2}_{-0.67}$	0.9647 ± 0.0043	3.046 ± 0.015
$\Sigma m_\nu, N_{eff}$	0.02221 ± 0.00022	$0.1179^{+0.0027}_{-0.0030}$	1.04116 ± 0.00044	$65.9^{+1.8}_{-1.6}$	0.9582 ± 0.0086	3.037 ± 0.017
$m^{eff}_{\nu,\,sterile}, N_{eff}$	$0.02242^{+0.00014}_{-0.00016}$	$0.1200^{+0.0032}_{-0.0020}$	$1.04074^{+0.00033}_{-0.00029}$	$67.11^{+0.63}_{-0.79}$	$0.9652^{+0.0045}_{-0.0056}$	$3.050^{+0.014}_{-0.016}$
α_{-1}	0.02238 ± 0.00015	0.1201 ± 0.0015	1.04087 ± 0.00043	67.30 ± 0.67	0.9645 ± 0.0061	3.045 ± 0.014
w_0	0.02243 ± 0.00015	0.1193 ± 0.0012	1.04099 ± 0.00031	. . .	0.9666 ± 0.0041	3.038 ± 0.014
Ω_K	0.02249 ± 0.00016	0.1185 ± 0.0015	1.04107 ± 0.00032	$63.6^{+2.1}_{-2.3}$	0.9688 ± 0.0047	$3.030^{+0.017}_{-0.015}$
Y_P	0.02230 ± 0.00020	0.1201 ± 0.0012	1.04067 ± 0.00055	67.19 ± 0.63	0.9621 ± 0.0070	3.042 ± 0.016
Y_P, N_{eff}	0.02224 ± 0.00022	$0.1171^{+0.0042}_{-0.0049}$	1.0415 ± 0.0012	$66.0^{+1.7}_{-1.9}$	0.9589 ± 0.0085	3.036 ± 0.018
A_L	0.02251 ± 0.00017	0.1182 ± 0.0015	1.04110 ± 0.00032	68.16 ± 0.70	0.9696 ± 0.0048	$3.029^{+0.018}_{-0.016}$

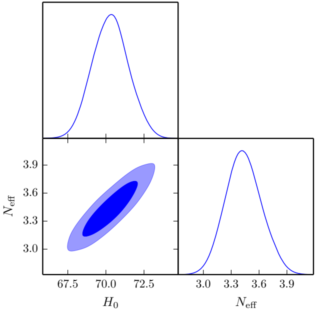
Planck collaboration, A&A 641 (2020) A6

A naïve first approach: CMB vs SH0ES

$$\theta_s = \frac{r_s}{d_A(z_\star)} = \frac{\int_{z_\star}^{\infty} dz' c_s(z')/H(z')}{\int_0^{z_\star} dz''/H(z'')}$$

Early-time new physics
Decreases r_s, then H_0 increases to decrease $d_A(z_\star)$ proportionally

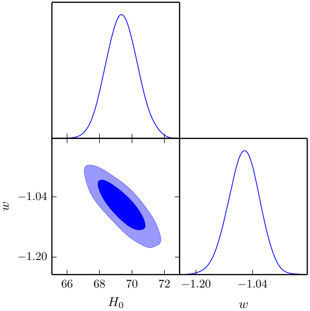
Prototype: $N_{\rm eff} > 3.046$



Vagnozzi, PRD 102 (2020) 023518

Late-time new physics
Keeps r_s and $d_A(z_\star)$ fixed, but $d_A(z < z_\star)$ and thus $H(z < z_\star)$ change so H_0 is higher

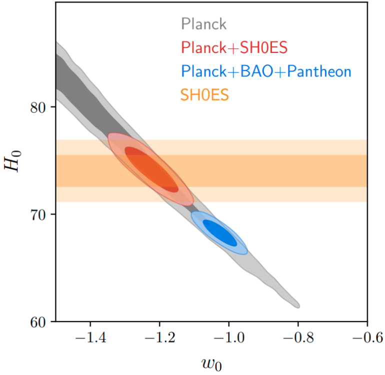
Prototype: $w < -1$



Vagnozzi, PRD 102 (2020) 023518

The problem with late-time modifications

BAO and cosmographic SNeIa data (which help break the geometrical degeneracy) don't want huge late-time modifications to ΛCDM $\rightarrow$ really need to go and fix that sound horizon!



Credits: Vivian Poulin

Keeping θ_s fixed necessary but not sufficient condition for a good model!

Three important scales and angles

Sound horizon at recombination:

$$r_s = \int_{z_\star}^{\infty} dz \, \frac{c_s(z)}{H(z)} \implies \theta_s = \frac{r_s}{d_A(z_\star)}$$

Sound horizon at equality:

$$r_s^{\rm eq} = \int_{z_{\rm eq}}^{\infty} dz \, \frac{c_s(z)}{H(z)} \implies \theta_s^{\rm eq} = \frac{r_s^{\rm eq}}{d_A(z_\star)}$$

Damping scale:

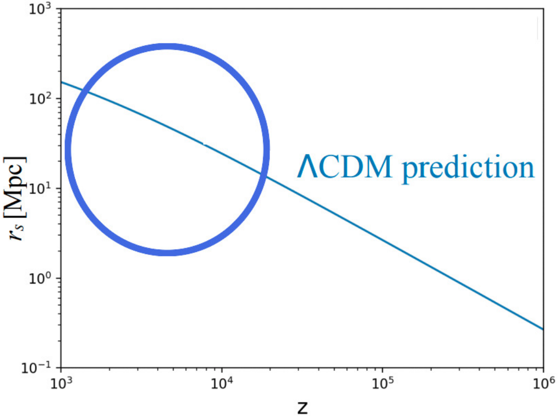
$$r_d = \sqrt{\int_0^{\eta_\star} d\eta \, \frac{1}{6(1+R) n_e \sigma_T a} \left[\frac{R^2}{1+R} + \frac{8}{9} \right]} \implies \theta_d = \frac{r_d}{d_A(z_\star)}$$

Any good model has to keep θ_s, θ_d, $\theta_s^{\rm eq}$ fixed!

Back to the sound horizon

Which knobs do we need to play around with to reduce r_s?

$$r_s = \int_{z_\star}^{\infty} dz \, \frac{c_s(z)}{H(z)} = \sqrt{\frac{3}{8\pi G}} \int_{z_\star}^{\infty} dz \, \frac{c_s(z)}{\sqrt{\rho_{\mathrm{tot}}(z)}}$$



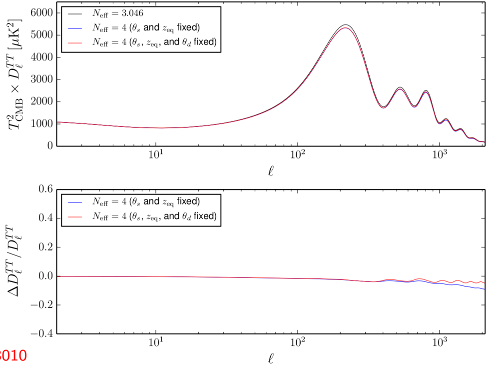
Credits: Vivian Poulin

Increasing the pre-recombination expansion rate

Simplest possibility: effective number of relativistic species $N_{\mathrm{eff}} > 3.044$ (free-streaming dark radiation)

$$\rho_r = \rho_\gamma \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\mathrm{eff}}\right]$$

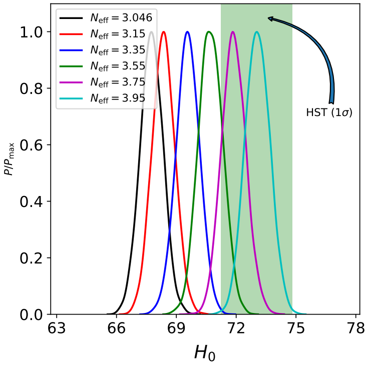
Effect on CMB (increase ω_c and h to keep θ_s fixed, Y_P to keep θ_d fixed)

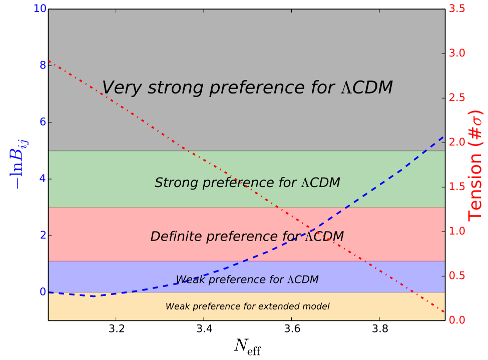


My PhD thesis, arXiv:1907.08010

Why free-streaming dark radiation fails

Need $N_{\rm eff} \gtrsim 4$ to fully solve the tension, completely inconsistent with θ_d (disfavored by *Planck* high-ℓ polarization data)



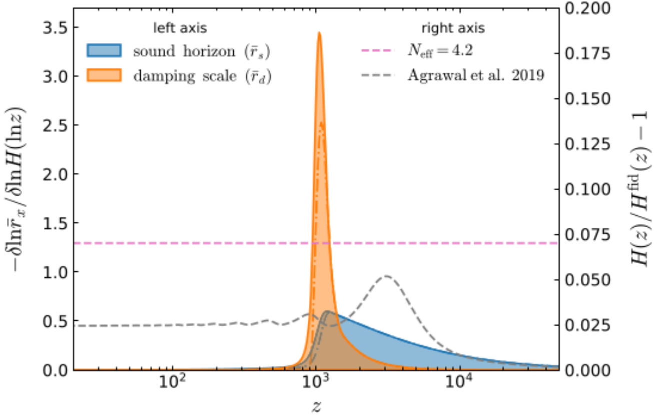


Vagnozzi, PRD 102 (2020) 023518

Possible extensions: self-interacting DR, free-streaming plus self-interacting DR, DR-DR scattering, DR-DM scattering,...

A key difficulty

How do r_s and r_d respond to changes in $H(z)$ before recombination?



Knox & Millea, PRD 101 (2020) 043533

For $N_{\rm eff}$, $\delta r_d/r_d \sim 1/2\,\delta r_s/r_s \implies 1/2$ is the problem!

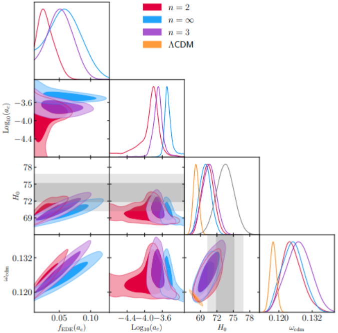
Early dark energy

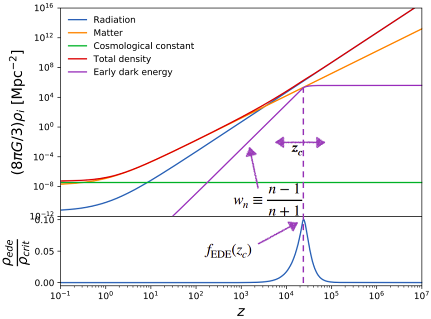
Scalar field initially frozen (Hubble friction), then dilutes faster than matter

$$V_n(\phi) \propto (1 - \cos\phi)^n \,, \quad \ddot{\phi} + 3H\dot{\phi} + \frac{dV_n(\phi)}{d\phi} = 0$$

Effective equation of state:

$$w(z > z_c) \approx -1 \quad w(z > z_c) \approx (n-1)/(n+1) \xrightarrow[n\to\infty]{} 1$$





Poulin *et al.*, PRL 122 (2019) 221301 (left); Credits: Tanvi Karwal & Vivian Poulin (right)

Variants of EDE

Many EDE-like models now exist in the literature! See reviews Poulin, Smith & Karwal, PDU 42 (2023) 101348; Kamionkowski & Riess, ARNPS 73 (2023) 153

Review: VP, Smith, Karwal, 2302.09032 Kamionkowski&Riess 2211.04492

Early dark energy, the Hubble-parameter tension, and the string axiverse

Tanvi Karwal and Marc Kamionkowski
Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218
(Dated: November 8, 2016)

Early Dark Energy Can Resolve The Hubble Tension

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Rock 'n' Roll Solutions to the Hubble Tension

Prateek Agrawal[1], Francis-Yan Cyr-Racine[1,2], David Pinner[1,3], and Lisa Randall[1]
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Acoustic Dark Energy: Potential Conversion of the Hubble Tension

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Early dark energy from massive neutrinos — a natural resolution of the Hubble tension

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Is the Hubble tension a hint of AdS around recombination?

Gen Ye[1*] and Yun-Song Piao[1,2†]
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nstitute of Theoretical Physics, Chinese Academy of Sciences, P.O. Box 2735, Beijing 100190, China

Chain Early Dark Energy: Solving the Hubble Tension and Explaining Today's Dark Energy

Katherine Freese*[1,2,3] and Martin Wolfgang Winkler†[1,2]

Thermal Friction as a Solution to the Hubble Tension

Kim V. Berghaus[1] and Tanvi Karwal[1,2]
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(Dated: November 15, 2019)

Early dark energy from massive neutrinos — a natural resolution of the Hubble tension

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New Early Dark Energy

Florian Niedermann[1,*] and Martin S. Sloth[1,†]
CP^3-Origins, Center for Cosmology and Particle Physics Phenomenology

Scalar-tensor theories of gravity, neutrino physics, and the H_0 tension

Mario Ballardini,[a,b,c,d,1] Matteo Braglia,[a,b,c] Fabio Finelli,[b,c] Daniela Paoletti,[b,c] Alexei A. Starobinsky,[e,f] Caterina Umiltà[g]

Gravity in the Era of Equality: Towards solutions to the Hubble problem without fine-tuned initial conditions

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[2]*Berkeley Center for Cosmological Physics, LBNL and University of California at Berkeley, Berkeley, California 94720, USA*
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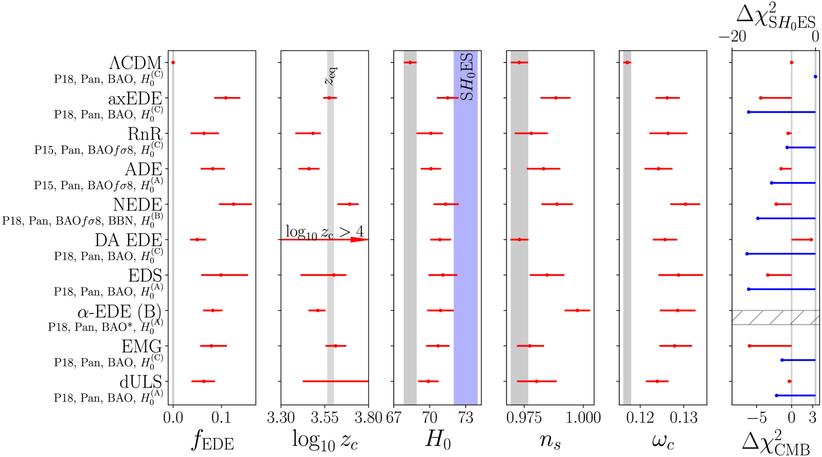
(Dated: June 11, 2020)

Credits: Marc Kamionkowski & Vivian Poulin

Status of EDE models

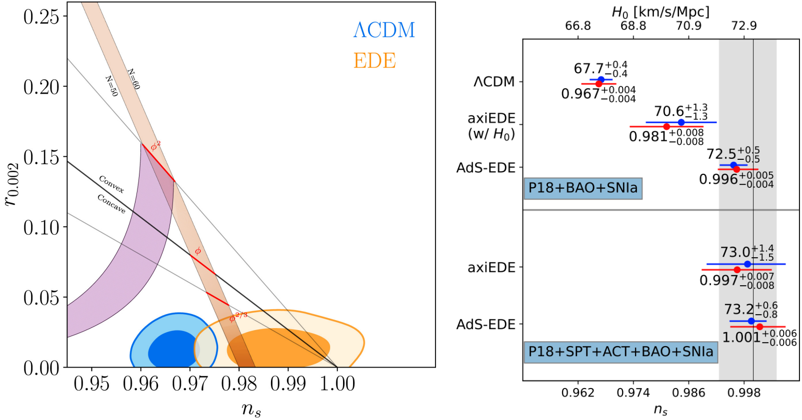


Poulin, Smith & Karwal, PDU 42 (2023) 101348

Interesting model not shown here: AdS-EDE

Implications for inflation

Return of the Harrison-Zel'dovich-Peebles spectrum ($n_s = 1$)? θ_d increase when keeping θ_s fixed can be partially compensated by increasing n_s



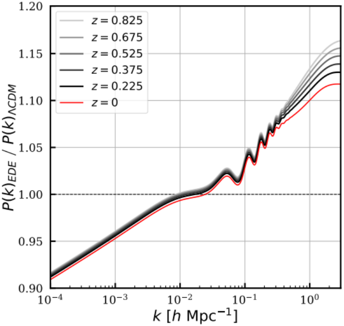
Poulin, Smith & Karwal, PDU 42 (2023) 101348 (left); Ye, Jiang & Piao, PRD 106 (2022) 103528 (right)

Is it too premature to perform inflationary model selection?

Potential problems with EDE

- does not completely absorb shift in θ_d
- requires higher value of ω_c → predicts excess power on small scales (worsens S_8 tension?)
- not preferred by *Planck* CMB data alone
- new coincidence and fine-tuning problems?
- vanilla potential hard to construct theoretically?

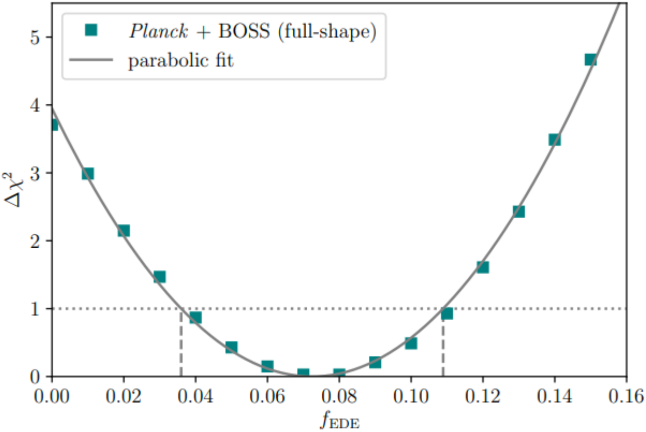
Parameter	ΛCDM	EDE (high ω_c)	EDE (low ω_c)
$100\omega_b$	2.253	2.253	2.253
ω_c	0.1177	0.1322	0.1177
H_0 [km/s/Mpc]	68.21	72.19	72.19
τ	0.085	0.072	0.072
$\ln(10^{10}A_s)$	3.0983	3.0978	3.0978
n_s	0.9686	0.9889	0.9889
$f_{\rm EDE}$	–	0.122	0.122
$\log_{10} z_c$	–	3.562	3.562
θ_i	–	2.83	2.83
n	–	3	3



Hill *et al.*, PRD 102 (2020) 043507

Prior volume effects at play?

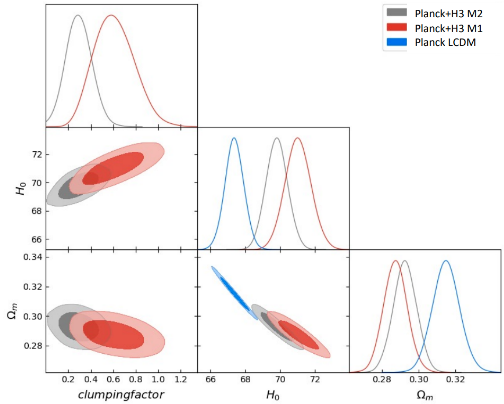
Bayesian constraints on f_{EDE} are potentially affected by prior volume effects $\rightarrow$ useful to look at frequentist methods (e.g. profile likelihood)



Herold, Ferreira & Komatsu, ApJ Lett. 929 (2022) L16

Early recombination from primordial magnetic fields

PMF lead to small-scale ($\sim$kpc) inhomogeneities in baryon density (clumping) $\rightarrow \langle n_e^2 \rangle > \langle n_e \rangle^2 = \langle n_e^2 \rangle_{\rm hom} \rightarrow$ earlier recombination

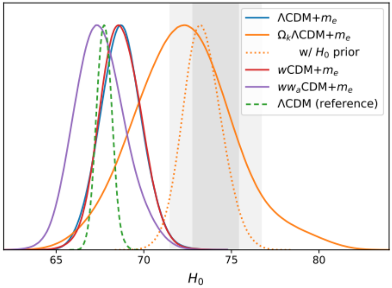


Credits: Levon Pogosian

Clumping factor $b \equiv (\langle n_b^2 \rangle - \langle n_b \rangle^2)/\langle n_b \rangle^2$

Early recombination from varying electron mass

Higher m_e at recombination makes recombination occur earlier ($B \propto m_e$)
Requires small shifts in ω_b and ω_m which can be reabsorbed by $\Omega_K < 0$



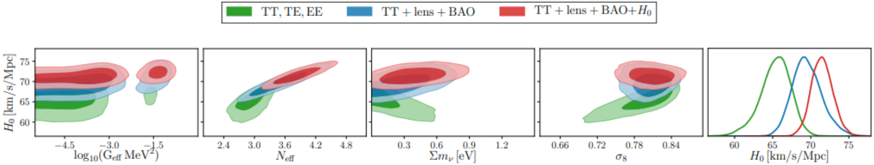
Model	$\Delta N_{\rm param}$	M_B	Gaussian Tension	$Q_{\rm DMAP}$ Tension		$\Delta\chi^2$	ΔAIC		One test passed	
ΛCDM	0	-19.416 ± 0.012	4.4σ	4.5σ	✗	0.00	0.00	✗	✗	
$\Delta N_{\rm ur}$	1	-19.395 ± 0.019	3.6σ	3.8σ	✗	-6.10	-4.10	✗	✗	
SIDR	1	-19.385 ± 0.024	3.2σ	3.3σ	✗	-9.57	-7.57	✓	✓	3
mixed DR	2	-19.413 ± 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 → DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	✗	-0.19	3.81	✗	✗	
DM → DR	2	-19.410 ± 0.011	4.3σ	4.5σ	✗	-0.53	3.47	✗	✗	

Sekiguchi & Takahashi, PRD 103 (2021) 083507 (left); Schöneberg *et al.*, Phys. Rept. 984 (2022) 1

Key point for success: $\sigma_T \propto m_e^{-2}$ breaks $\delta r_d / r_d \sim 1/2\, \delta r_s / r_s$ scaling
$\rightarrow$ θ_d virtually unchanged!

Strongly interacting neutrinos

Free-streaming neutrinos lead to phase shift $\theta_{\text{peak}} \sim \theta_s + 0.6(\rho_\nu/\rho_\gamma)$
Neutrino interactions (4-point with strength G_{eff}) suppress/delay free-streaming: fixed θ_{peak} requires higher θ_s at fixed r_s $\rightarrow$ higher H_0!



Kreisch, Cyr-Racine & Doré, PRD 101 (2020) 123505

Solution requires $N_{\text{eff}} \sim 4$, $M_\nu \sim 0.4\,\text{eV}$, $G_{\text{eff}} \sim 10^{-2}\,\text{MeV}^2$

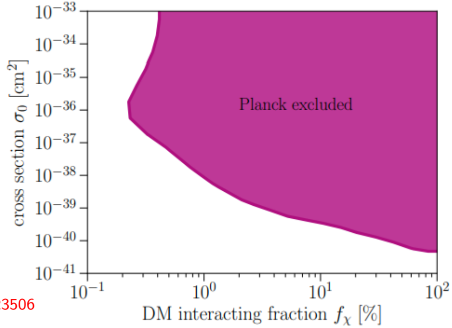
Problem: tension with BBN and laboratory constraints, completely excluded by *Planck* high-ℓ polarization (again problem with damping), disagreement with BAO due to unchanged r_s

Majoron variant (light mediator) solves part of these problems

Sound speed reduction?

$$c_s^2 = \frac{1}{3(1+R)}\,, \quad R = \frac{3\rho_b}{4\rho_\gamma} \to R = \frac{3(\rho_b+\rho_x)}{4\rho_\gamma}?$$

Problem: x tightly coupled to b leads to even-odd peak modulation

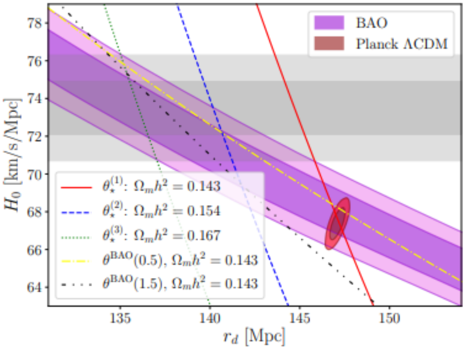


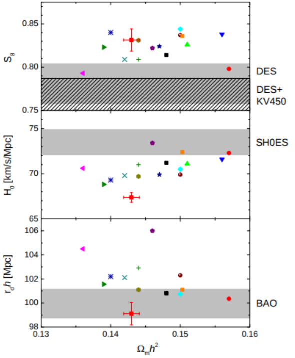
Boddy *et al.*, PRD 98 (2018) 123506

Non-standard DM-γ and/or DM-b interactions can change $c_s(z) \to$ problem: allowed cross-section too small to lead to any visible effect!

Generic problems for early-time modifications

Reducing r_s without touching ω_m can never fully resolve the Hubble tension – higher (lower) ω_m run in tension with WL/LSS (BAO) data





Jedamzik, Pogosian & Zhao, Commun. Phys. 4 (2021) 123

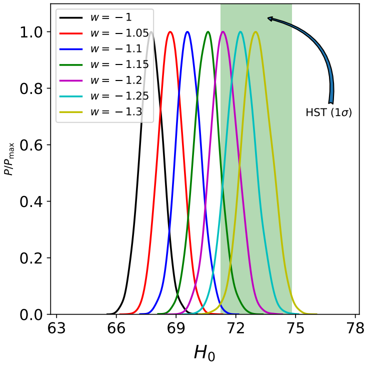
All promising early-time modifications worsen S_8 tension (more tomorrow)

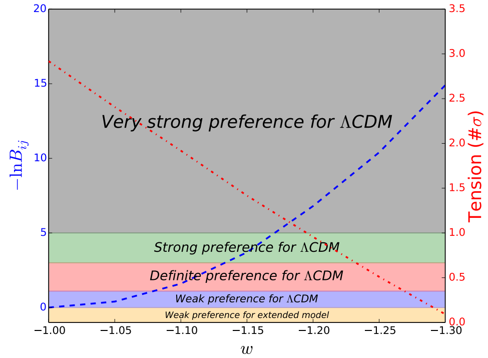
Late-time modifications?

- Late-time wiggles?
  Possible *very much in principle*, unlikely physically and statistically
- Confusion sowing?
  Extremely likely that new late-time physics confuses ω_b and ω_m (would be in very strong tension with BBN and polarization)
- Distance-duality relation violation?
  Only fixes BAO and SNeIa, doesn't fix low H_0 from CMB, cannot explain high H_0 from time delays, challenging for model-building
- Post-recombination evolution of r_s?
  Not impossible, but would lead to large (potentially unobserved?) bulk velocities, disfavored by success of BAO reconstruction

How extreme should late-time modifications be?

Need $w \sim -1.3$ to fully solve the tension, completely inconsistent with BAO and cosmographic SNeIa data





Vagnozzi, PRD 102 (2020) 023518

Late-time modifications: interacting dark energy

Throw in all remotely credible modifications to dark energy ($w \neq -1$, time-varying w, interactions with dark matter,...) *at the same time*

$$\dot{\rho}_c + 3H\rho_c = -\left(\dot{\rho}_{\rm de} + 3H(1+w_{\rm de})\rho_{\rm de}\right) = \xi H \rho_{\rm de}$$

Parameters	Planck	Planck + R19	Planck + lensing	Planck + BAO	Planck + Pantheon	All19
$\Omega_b h^2$	0.0224 ± 0.0002	0.0224 ± 0.0002	0.0224 ± 0.0002	0.0224 ± 0.0001	0.0224 ± 0.00012	0.0224 ± 0.0001
$\Omega_c h^2$	$0.132^{+0.005}_{-0.012}$	$0.133^{+0.006}_{-0.012}$	$0.133^{+0.006}_{-0.012}$	$0.134^{+0.007}_{-0.012}$	$0.134^{+0.006}_{-0.012}$	$0.132^{+0.006}_{-0.012}$
ξ	<0.248	<0.277	<0.258	<0.295	<0.295	<0.288
w	$-1.59^{+0.18}_{-0.33}$	-1.26 ± 0.06	$-1.57^{+0.19}_{-0.32}$	$-1.10^{+0.07}_{-0.04}$	$-1.08^{+0.05}_{-0.04}$	$-1.12^{+0.05}_{-0.04}$
H_0 (km/s/Mpc)	>70.4	74.1 ± 1.4	$85.0^{+10.0}_{-5.0}$	$68.8^{+1.1}_{-1.5}$	68.3 ± 1.0	69.8 ± 0.7
σ_8	0.88 ± 0.08	$0.80^{+0.06}_{-0.04}$	0.87 ± 0.08	0.75 ± 0.05	$0.76^{+0.05}_{-0.04}$	$0.76^{+0.06}_{-0.04}$
S_8	0.74 ± 0.04	0.78 ± 0.03	0.74 ± 0.04	0.79 ± 0.03	0.80 ± 0.03	$0.79^{+0.03}_{-0.02}$
ln B	-1.3	5.6	-1.6	-4.5	-5.2	-2.7
Strength	Positive (ΛCDM)	Very strong (ξpCDM)	Positive (ΛCDM)	Strong (ΛCDM)	Very strong (ΛCDM)	Positive (ΛCDM)

Di Valentino, Melchiorri, Mena & Vagnozzi, PRD 101 (2020) 063502

At best $H_0 \approx 70 \pm 1$: BAO and cosmographic SNeIa very unforgiving!

Late-time modifications: Λ_sCDM

Sign-switching cosmological constant:

$$\Lambda \to \Lambda_s = \Lambda_{s,0}\mathrm{sgn}(z_\dagger - z)$$

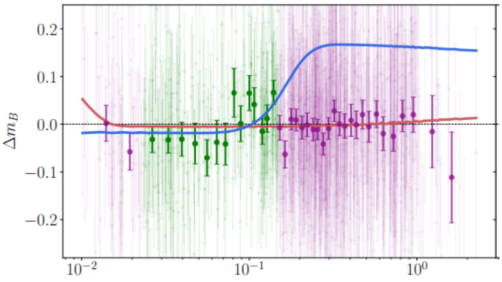
Data set	CMB+Pan		CMB+Pan+Ly-α		CMB+Pan+BAO	
	ΛCDM	Λ_sCDM	ΛCDM	Λ_sCDM	ΛCDM	Λ_sCDM
$10^2\omega_b$	2.240 ± 0.015	2.241 ± 0.014	2.242 ± 0.013	2.241 ± 0.015	2.242 ± 0.013	2.235 ± 0.014
ω_c	0.1197 ± 0.0012	0.1196 ± 0.0011	0.1193 ± 0.0009	0.1196 ± 0.0011	0.1193 ± 0.0009	0.1206 ± 0.0010
$100\theta_s$	1.04191 ± 0.00029	1.04190 ± 0.00028	1.04191 ± 0.00029	1.04190 ± 0.00029	1.04194 ± 0.00028	1.04180 ± 0.00030
$\ln(10^{10}A_s)$	3.047 ± 0.015	3.041 ± 0.014	3.047 ± 0.014	3.040 ± 0.015	3.047 ± 0.015	3.040 ± 0.014
n_s	0.9662 ± 0.0042	0.9668 ± 0.0040	$0.9669^{+0.0039}_{-0.0036}$	0.9668 ± 0.0041	0.9665 ± 0.0037	0.9644 ± 0.0037
τ_{reio}	0.0556 ± 0.0075	0.0533 ± 0.0075	0.0560 ± 0.0069	0.0528 ± 0.0077	0.0561 ± 0.0076	0.0515 ± 0.0073
$z_\dagger$	—	> 1.80 (95% CL)	—	$2.21^{+0.16}_{-0.38}$	—	> 2.13 (95% CL)
M_B [mag]	-19.421 ± 0.014	$-19.363^{+0.021}_{-0.037}$	-19.418 ± 0.011	-19.349 ± 0.028	-19.418 ± 0.012	-19.387 ± 0.015
Ω_m	0.3129 ± 0.0071	$0.2940^{+0.0120}_{-0.0093}$	0.3110 ± 0.0053	0.2899 ± 0.0097	0.3109 ± 0.0056	0.3039 ± 0.0058
ω_m	0.1427 ± 0.0011	0.1427 ± 0.0010	0.1424 ± 0.0008	0.1426 ± 0.0010	0.1424 ± 0.0009	0.1436 ± 0.0010
H_0 [km/s/Mpc]	67.55 ± 0.53	$69.68^{+0.77}_{-1.40}$	67.68 ± 0.40	$70.17^{+0.96}_{-1.10}$	$67.69^{+0.38}_{-0.43}$	$68.74^{+0.49}_{-0.55}$
t_0 [Gyr]	13.79 ± 0.02	$13.65^{+0.06}_{-0.04}$	13.79 ± 0.02	$13.62^{+0.09}_{-0.03}$	13.79 ± 0.02	$13.71^{+0.03}_{-0.02}$
σ_8	$0.8111^{+0.0056}_{-0.0063}$	$0.8167^{+0.0059}_{-0.0067}$	0.8104 ± 0.0060	0.8182 ± 0.0066	0.8101 ± 0.0063	0.8167 ± 0.0062
S_8	0.828 ± 0.013	0.809 ± 0.015	0.825 ± 0.010	0.804 ± 0.014	0.825 ± 0.011	0.822 ± 0.010
$-2\ln\mathcal{L}_{max}$	3807.24	3805.00	3819.36	3806.88	3819.26	3819.06
$\ln\mathcal{Z}$	-1937.82	-1938.02	-1944.53	-1939.75	-1944.51	-1944.76
$\Delta\ln\mathcal{Z}$	0	0.20	4.78	0	0	0.25

Akarsu *et al.*, arXiv:2307.10899

At best $H_0 \approx 70 \pm 1$: BAO and cosmographic SNeIa very unforgiving!

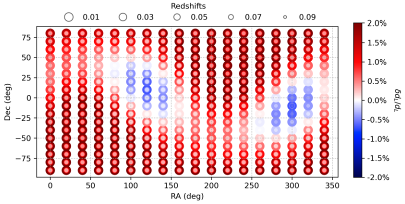
Local structure to the rescue?

"Hubble bubble" of required magnitude excluded by SNeIa



Camarena *et al.*, CQG 39 (2022) 184001

Accounting for Laniakea worsens the tension?

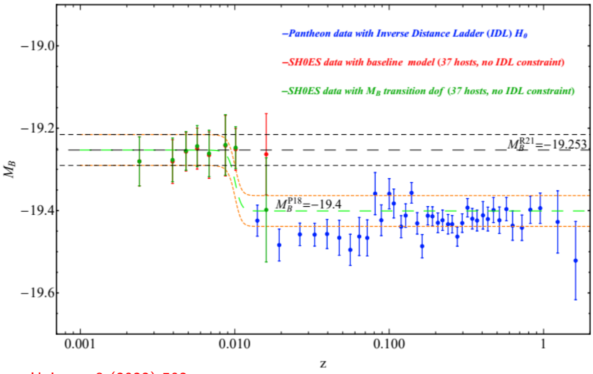


Giani, Howlett, Said, Davis, Vagnozzi, arXiv:2311.00215

Local structure does not seem to help, but can actually make things worse!

Transitions in the SNeIa absolute magnitude

Transition of $\Delta M_B \sim -0.2$ around $z \sim 0.01$ could solve the tension See Marra & Perivolaropoulos, PRD 104 (2021) L021303

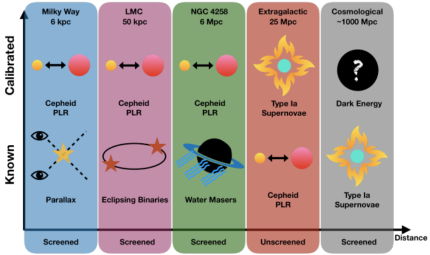


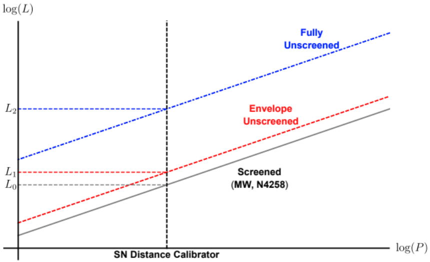
Perivolaropoulos & Skara, Universe 8 (2022) 502

$G_{\text{eff}}/G_N \sim 0.9$ at $z \gtrsim 0.01$, due to modified gravity? Transition ∼70 Myrs ago → dinos disappeared 65 Myrs ago?!?!? see Perivolaropoulos, Universe 8 (2022) 263

Cepheid miscalibration due to screened fifth forces

New gravitational physics can screen a fraction of the Cepheids and therefore bias the SNeIa calibration



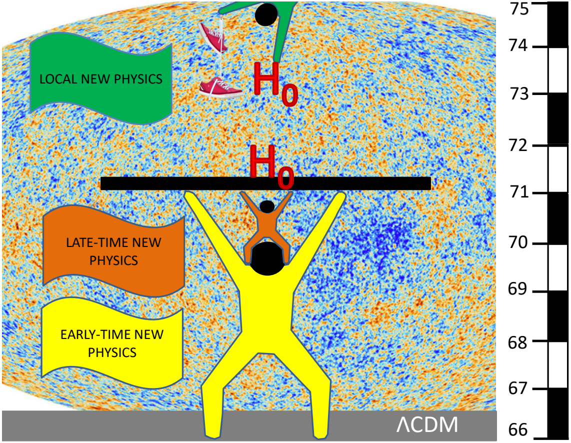


Desmond, Jain & Sakstein, PRD 100 (2019) 043537

This works also for the TRGB (but not for time delays, at least not in an obvious way) See Desmond & Sakstein, PRD 102 (2020) 023007

Combining new physics at different times?

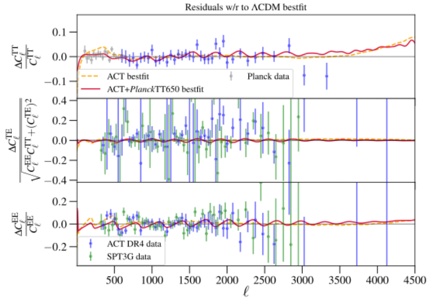
Solution may ultimately require a combination of early-time, late-time, and local new physics

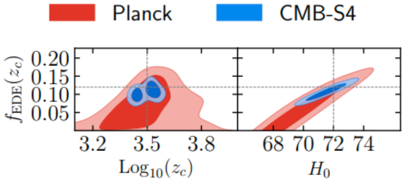


Vagnozzi, Universe 9 (2023) 393; Image credits: Cristina Ghirardini

The good news

Upcoming CMB data should detect proposed early-time modifications at very high significance





Poulin, Smith & Karwal, PDU 42 (2023) 101348 (left); Smith & Poulin, PRD 101 (2020) 063523 (right)

In 10 years, either we'll know one of these models is close to the truth, or we won't be talking about any one of them anymore!

Next lecture

8 December, 10:00-10:50

Is the Hubble tension the only problem with ΛCDM?

Go check out "Betteridge's law"...