Title: A New Constraint on Early Dark Energy using the Profile Likelihood

Speakers: Laura Herold

Series: Cosmology & Gravitation

Date: January 17, 2023 - 1:00 PM

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Abstract: A dark energy-like component in the early universe, known as early dark energy (EDE), is a proposed solution to the Hubble tension. In this talk, I will describe how a frequentist profile likelihood yields important complementary information compared to a Bayesian MCMC analysis. While in an MCMC analysis, the EDE model is clearly disfavoured by Cosmic Microwave Background and large-scale structure data, a profile likelihood analysis prefers consistently larger amounts of EDE and with that a Hubble constant consistent with the SH0ES measurement for the same data sets. The difference between MCMC and profile likelihood can be explained by prior volume effects in the MCMC analysis. I will discuss how frequentist and Bayesian methods can give important complementary information in the context of beyond-LCDM models.

Zoom link: https://pitp.zoom.us/j/97257428766?pwd=ckx4ajRsQVRQUnpXaGEvZEtEWW9ldz09

A new constraint on Early Dark Energy using the profile likelihood

based on ***LH, Ferreira (arXiv:2210.16296),***
LH, Ferreira, Komatsu (ApJ.L. **929 (2022) 1, L16*)***

Jan. 17, 2023 — Perimeter Institute

Laura Herold (MPA)

MAX PLANCK INSTITUTE
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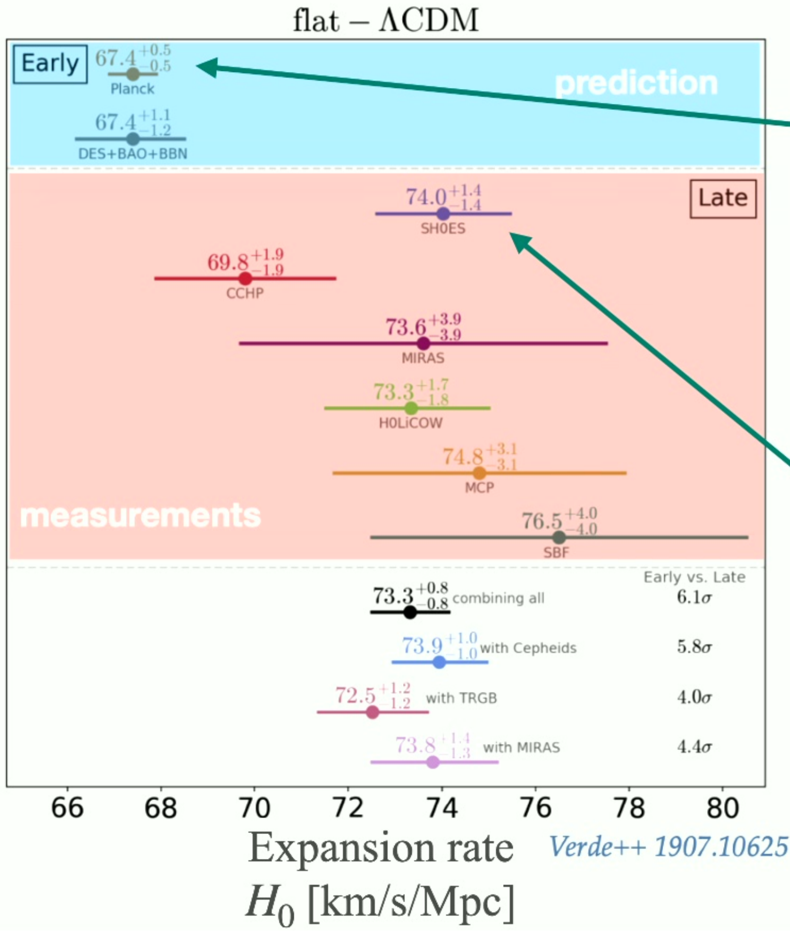
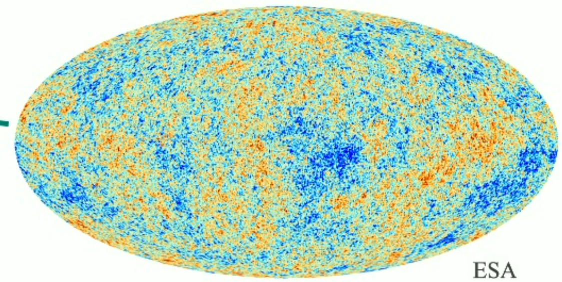
The Hubble tension



Verde++ 1907.10625



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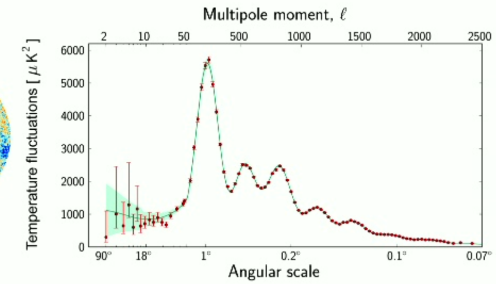

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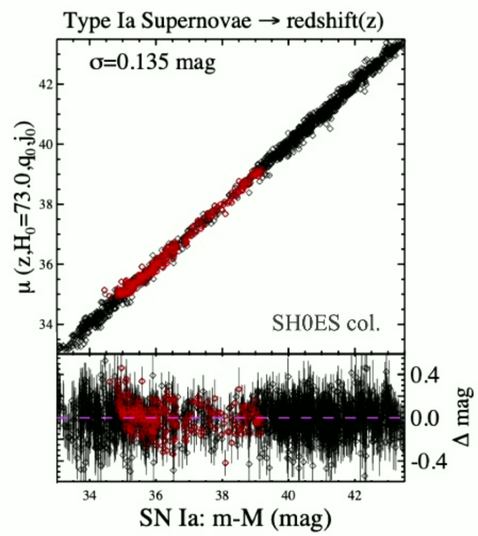
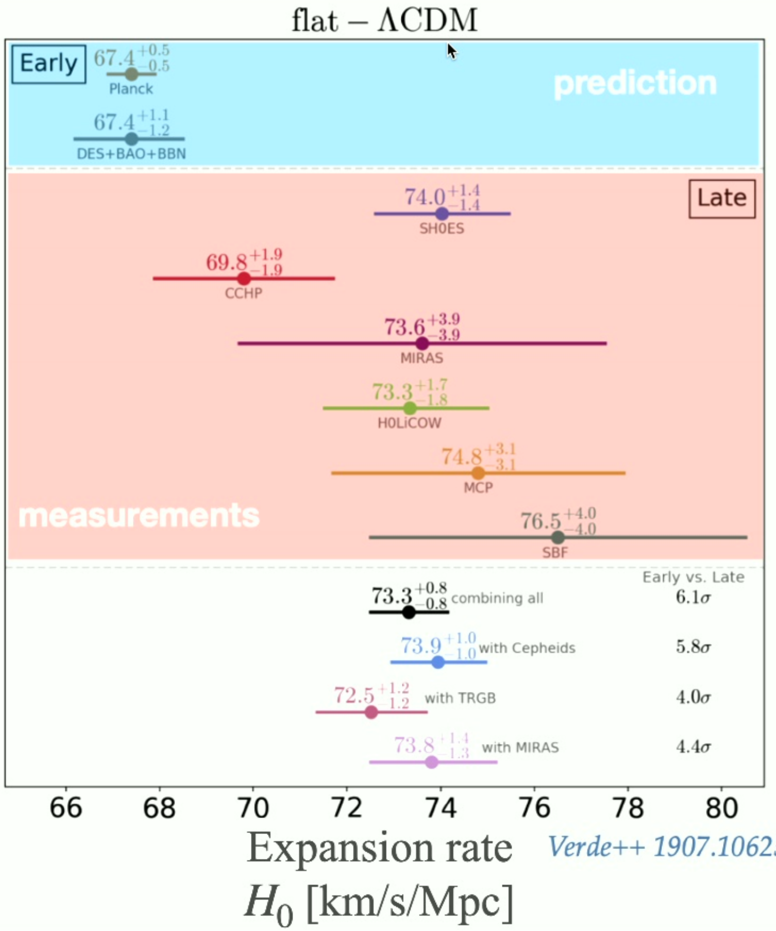


The Hubble tension



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Most recent SH0ES results:

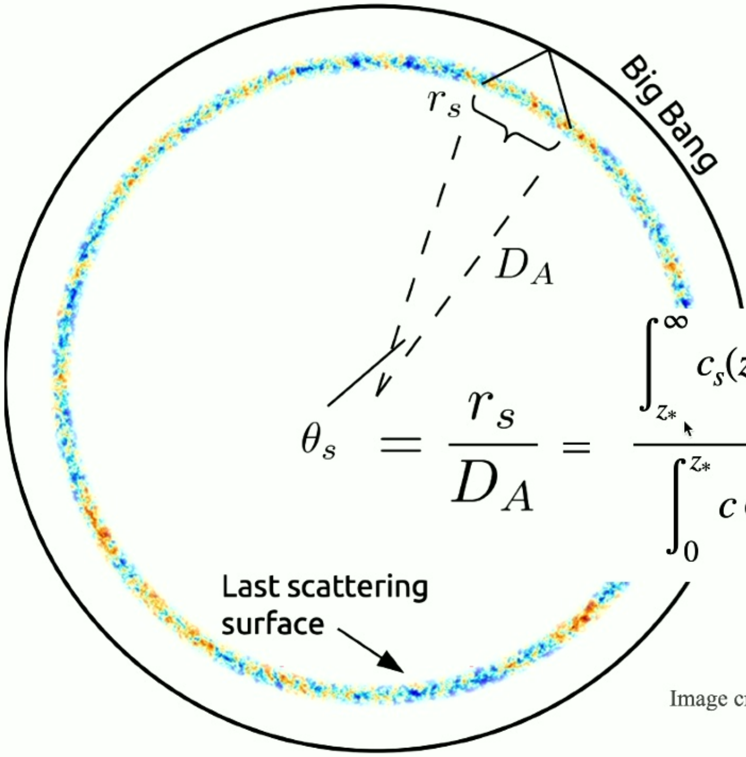
$H_0 = 73.04 \pm 1.04$ km/s/Mpc

$\rightarrow$ 5σ tension with *Planck*

Not only tension between two experiments but:
direct and indirect measurements

Systematics or new physics?

Solutions to the Hubble tension



$$\theta_s = \frac{r_s}{D_A} = \frac{\int_{z_*}^{\infty} c_s(z)\,\mathrm{d}z\,/\,H(z)}{\int_0^{z_*} c\,\mathrm{d}z\,/\,H(z)}$$

Image credit: Marius Millea

Angular scale of sound horizon θ_s measured with 0.03% precision by *Planck.*

Early-time solutions:
Modify r_s

Late-time solutions:
Modify D_A

Early Dark Energy (EDE)

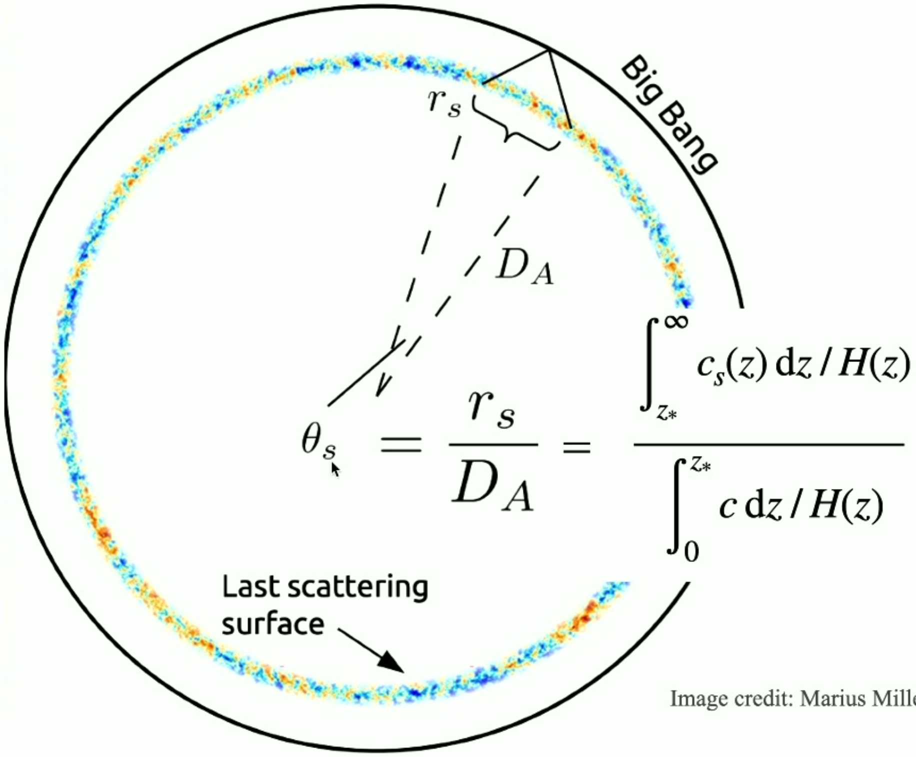


Image credit: Marius Millea

Idea of EDE:

Angular scale of sound horizon θ_s measured with 0.03% precision by *Planck.*

↓

Introducing an additional component before recombination reduces the sound horizon r_s.

↓ θ_s fixed

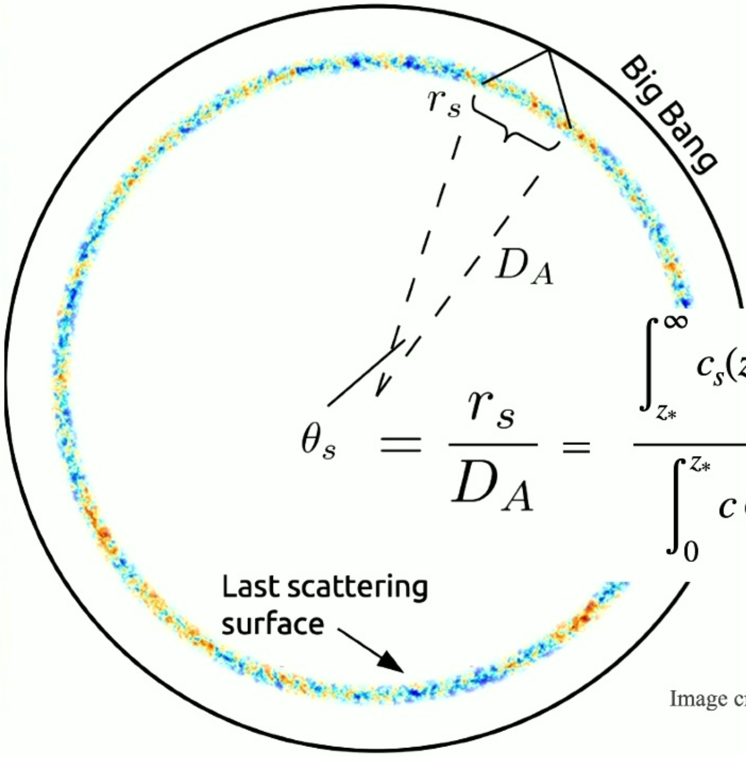
Angular diameter distance D_A decreases.

↓ $H(z) = H_0\sqrt{\Omega_m(z) + \Omega_r(z) + \Omega_\Lambda}$

H_0 increases.

Early Dark Energy (EDE)

Kamionkowski et al. 2014, Karwal & Kamionkowski 2016, Caldwell & Devulder 2018, Poulin et al. 2019



$$\theta_s = \frac{r_s}{D_A} = \frac{\int_{z_*}^{\infty} c_s(z)\,\mathrm{d}z\,/\,H(z)}{\int_0^{z_*} c\,\mathrm{d}z\,/\,H(z)}$$

Image credit: Marius Millea

Requirements:

1) It starts becoming relevant just before recombination z_*.

2) It behaves like dark energy at early times.

3) Its energy density dilutes faster than matter after z_*.

Early Dark Energy (EDE)

Kamionkowski et al. 2014, Karwal & Kamionkowski 2016, Caldwell & Devulder 2018, Poulin et al. 2019

Canonical EDE model: scalar field ϕ with potential

$$V(\phi) = V_0 \left[1 - \cos(\phi/f)\right]^n$$

Free parameters:

m: mass of $\phi \rightarrow V_0 = m^2 f^2$,

f: decay constant,

$\theta_i \equiv \phi_i/f$: initial value of the field,

$n = 3$: shown to fulfil EDE requirements.

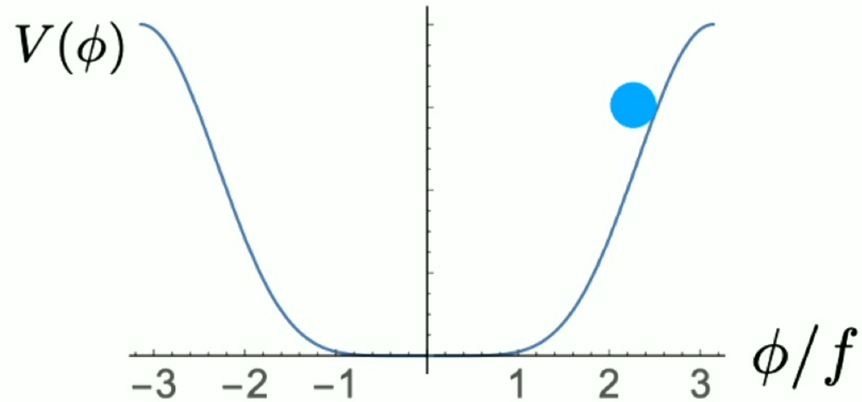


Image credit: Tristan Smith

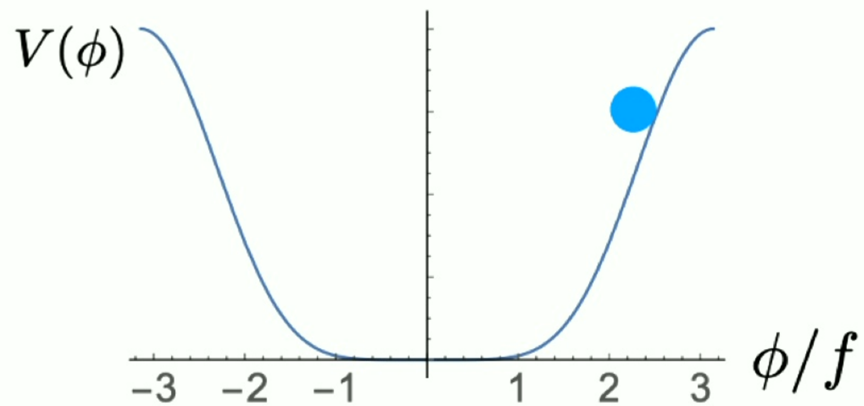
$\rightarrow$ Field inspired by axion ($n = 1$) with extremely small mass $\sim 10^{-27}$eV

Early Dark Energy (EDE)

Kamionkowski et al. 2014, Karwal & Kamionkowski 2016, Caldwell & Devulder 2018, Poulin et al. 2019

Dynamics: $$\ddot{\phi} + 3H\dot{\phi} + \frac{\mathrm{d}V(\phi)}{\mathrm{d}\phi} = 0$$

- Initially: Hubble friction dominates: ϕ frozen —> behaves as DE
- At z_c: Hubble friction < mass term: ϕ starts oscillating and decays faster than matter



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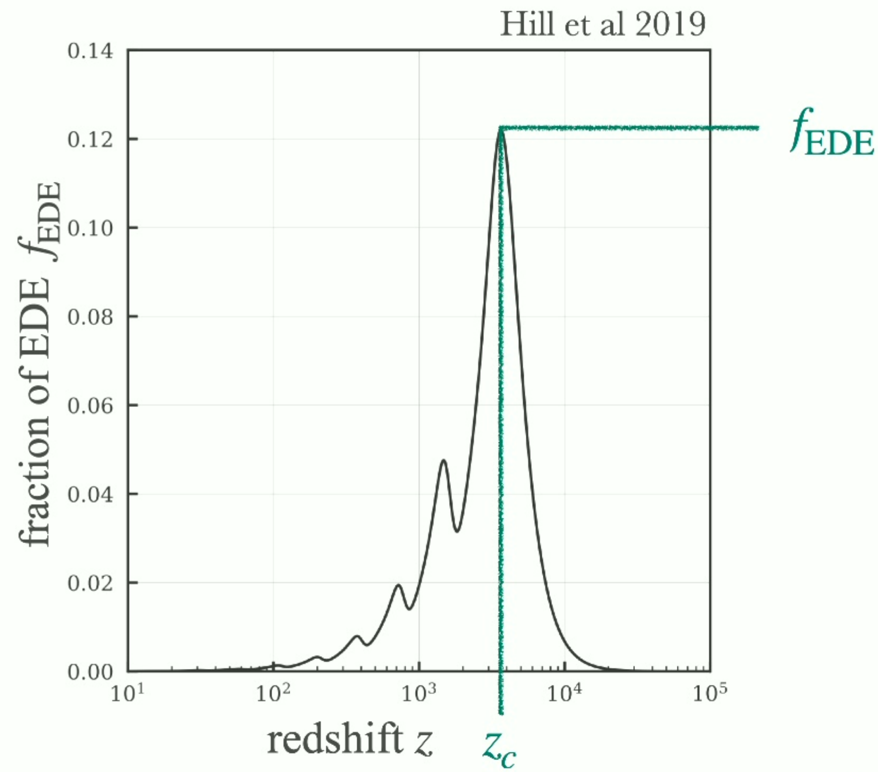
From m, f, θ_i one can calculate:
$f_{\rm EDE}$, z_c, θ_i (3 additional parameters to ΛCDM)



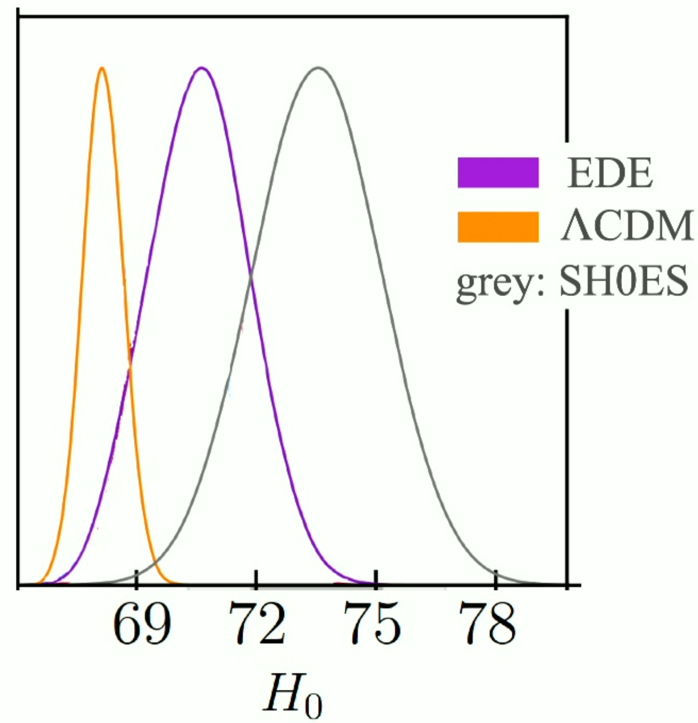
15 - Laura Herold - MPA

EDE can solve the H_0 tension

Poulin, Smith, Karwal, Kamionkowski, 2019

Data sets: Planck + 6dFGS + BOSS DR12 BAO/ RSD + Pantheon + SH0ES 2016

- $f_{\rm EDE} = 0.107^{+0.035}_{-0.030}$ (mean $\pm 1\sigma$)
- $H_0 = 71.49 \pm 1.20$ km/s/Mpc



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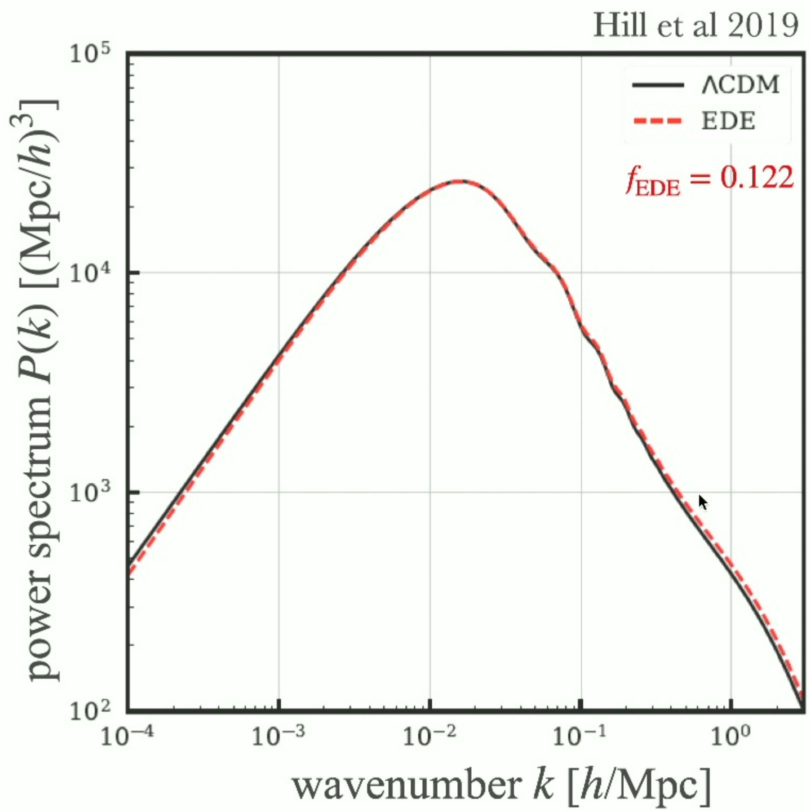
- $f_{\mathrm{EDE}} = 0.107^{+0.035}_{-0.030}$ (mean $\pm 1\sigma$)
- $H_0 = 71.49 \pm 1.20$ km/s/Mpc
- Also other parameters shift:
  EDE suppresses growth of perturbations at early times
  $\rightarrow$ ω_{CDM} and n_s increase
  $\rightarrow$ σ_8 increases, worsening the so-called σ_8 discrepancy

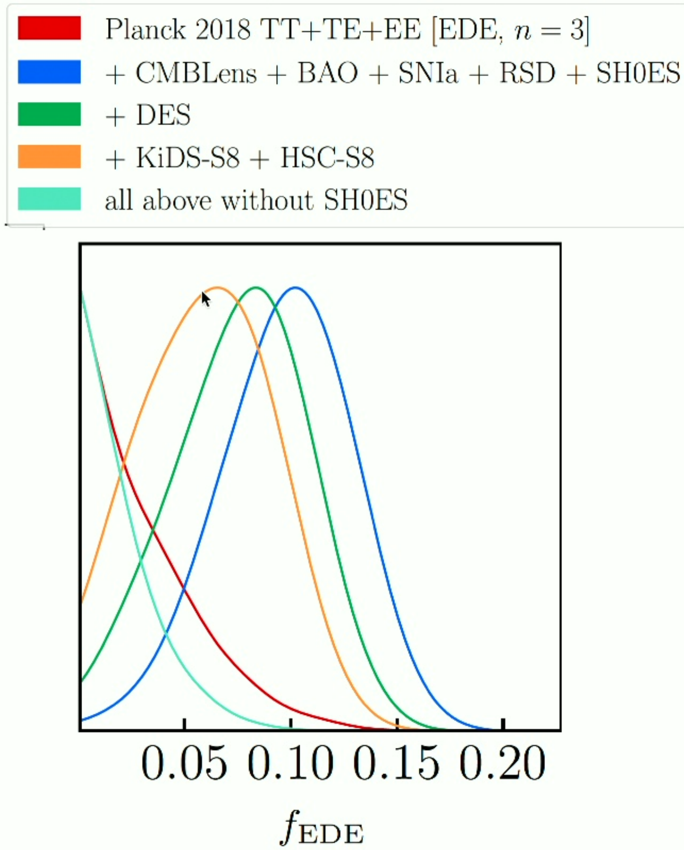


Adding LSS data: EDE is ruled out?

Hill, McDonough, Troomey, Alexander, 2020

Data sets: Planck + 6dFGS + BOSS DR12 BAO/RSD + Pantheon ~~+ SH0ES 2016~~ + DES + KiDS + HSC

- $f_{\rm EDE} < 0.06$ (95% C.L.)
- $H_0 = 68.92^{+0.57}_{-0.59}$ km/s/Mpc
- No SH0ES → no preference for EDE

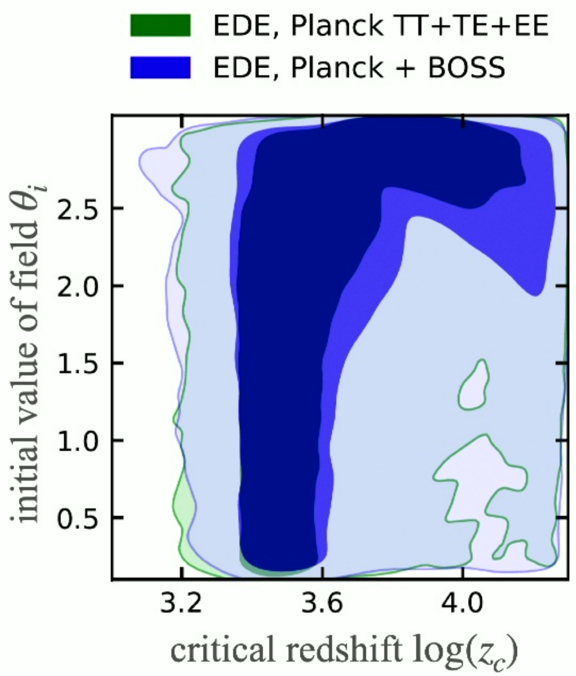


Prior volume / projection / marginalisation effects

…appear if the posterior is influenced by the prior volume.
Reasons:

- Model has too many parameters / data is not constraining.
- Posterior is very non-Gaussian.
- Parameter structure of the model generates large volume differences.

Ivanov et al. 2020



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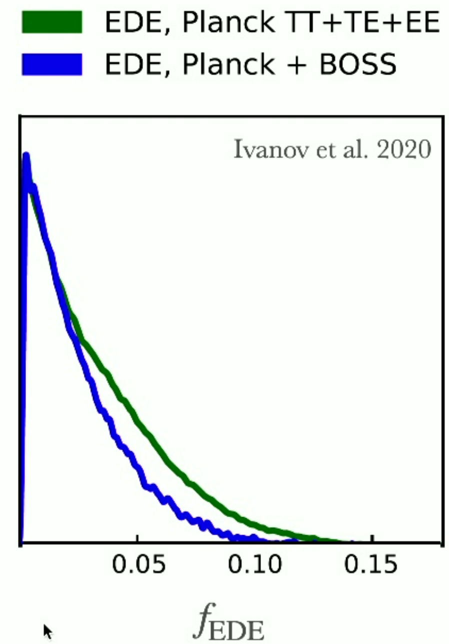

$f_{\rm EDE} \approx 0$: all values of z_c, θ_i unconstrained (ΛCDM limit)

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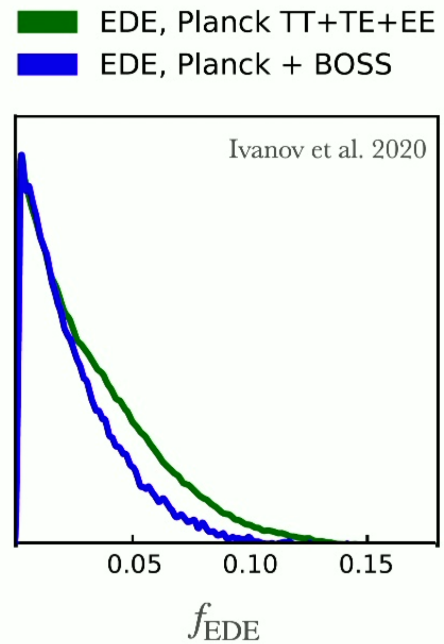
→ Bias in the marginalised posterior.



$f_{\rm EDE} \approx 0$: all values of z_c, θ_i unconstrained (ΛCDM limit)

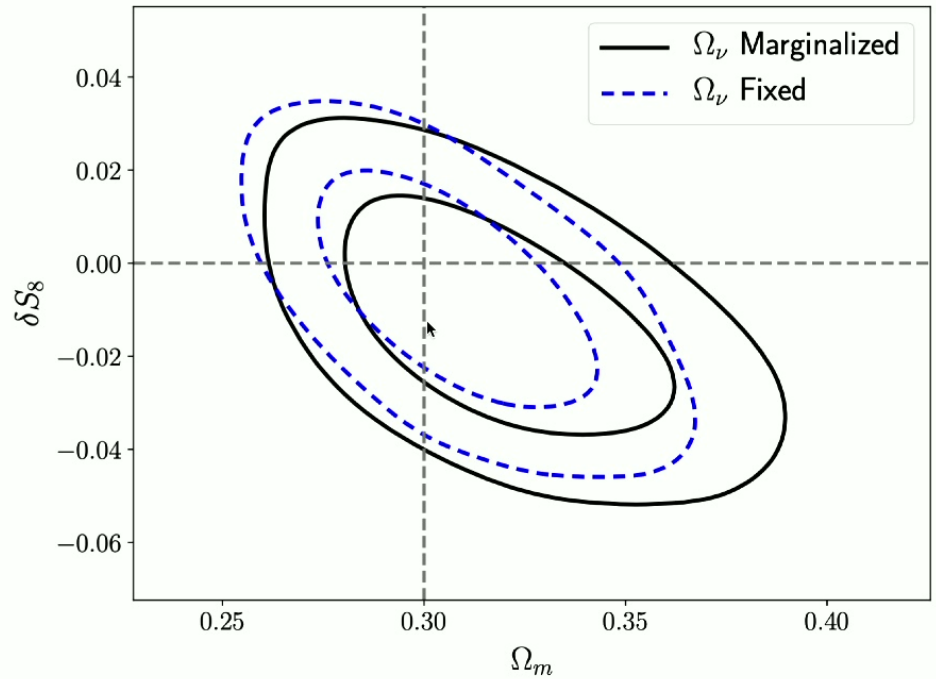
Aside: volume effects in the literature

Krause et al. (DES collaboration): Y3 analysis paper

- Ω_ν is poorly constrained by 3×2pt analysis
- "Shift in 2D contours indicates a projection effect from marginalising over an under-constrained parameter that is correlated with the parameters shown."

→ Fix Ω_ν

3x2pt simulated ΛCDM

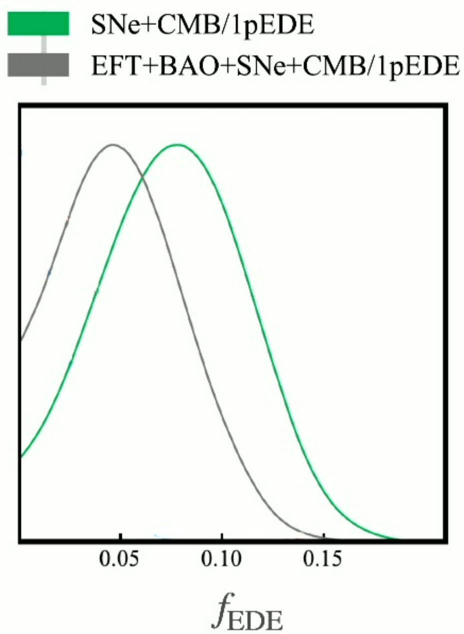


EDE is not ruled out by LSS?

Smith, Poulin, Bernal, Boddy, Kamionkowski, Murgia, 2020; Niedermann, Sloth, 2019 (for NEDE)

Data sets: Planck + BOSS DR12 BAO + full-shape analysis + Pantheon

- fixing z_c, θ_i to bestfit to *Planck* — "1-parameter model"
- $f_{\mathrm{EDE}} = 0.072 \pm 0.034$ (mean $\pm 1\sigma$)
- Same data set, but different conclusion than Ivanov et al., D'Amico et al., suspect volume effects



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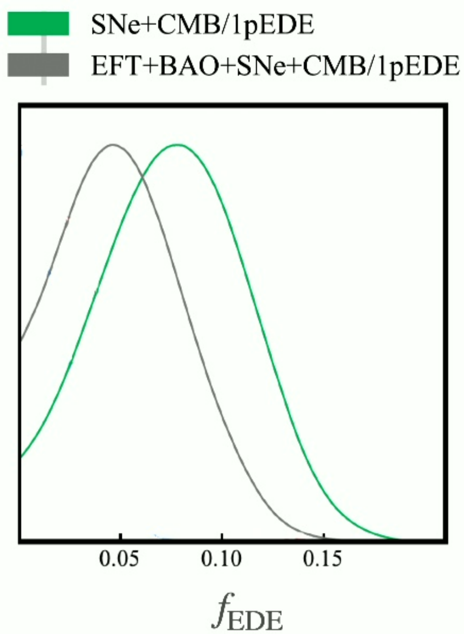


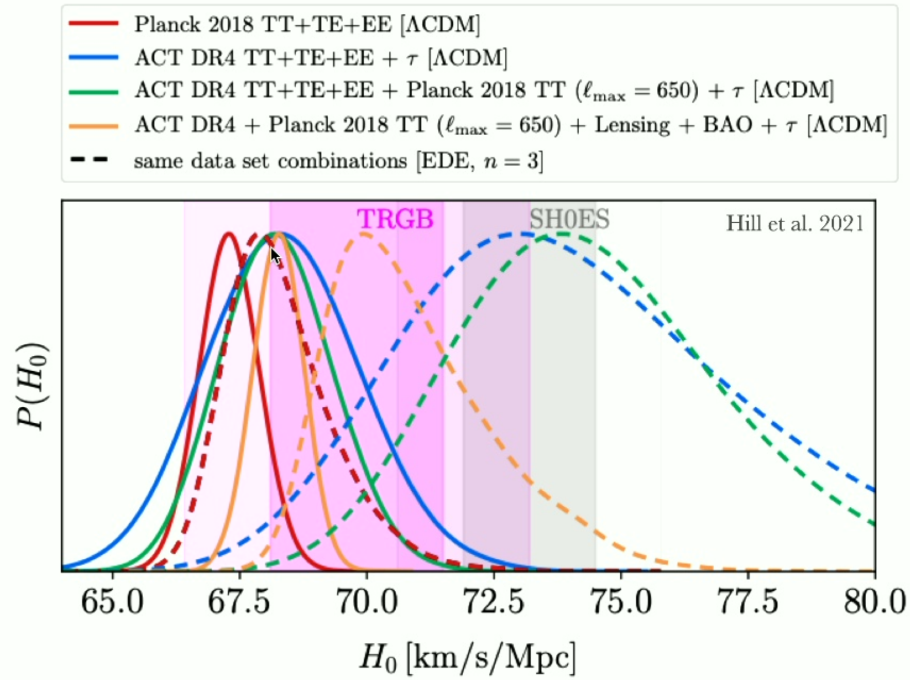
However: Not a full Bayesian analysis — How does $f_{\rm EDE}$ depend on choice of z_c, θ_i?

Results from ACT

Hill et al. 2021, Poulin et al. 2021

Data sets: ACT DR4 + large-scale *Planck* TT+lensing + BOSS BAO (yellow line)

- prefers the EDE model over ΛCDM by 2-3 σ
- $H_0 = 70.9^{+1.0}_{-2.0}$ km/s/Mpc, $f_{\rm EDE} = 0.091^{+0.020}_{-0.036}$
- Driven by ACT *TE+EE* power spectra



Status of EDE

Is EDE ruled out or not?

- When including SH0ES (full MCMC): EDE solves the tension!
- CMB, galaxy clustering, weak lensing (full MCMC): EDE is ruled out!
- CMB, galaxy clustering, weak lensing (1-parameter MCMC): EDE solves the tension!
- (CMB from ACT: EDE solves the tension!)

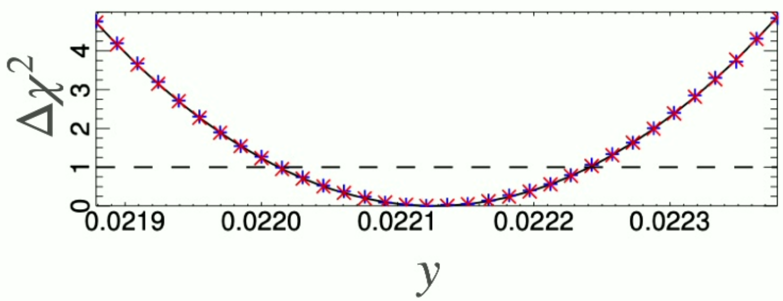
Profile likelihood — method

Profile likelihood:

- Fix parameter y of interest to different values, minimize χ^2 w.r.t. all other parameters
- for Gaussian distribution this gives parabola in $\Delta\chi^2$

Confidence interval:

- Read off 1σ at the intersection with $\Delta\chi^2 = 1$ *(Neyman construction)*
- At a physical boundary: Feldman-Cousins prescription



Example: Planck col. XVI, 2014

Comparison to MCMC

MCMC (Bayesian statistics):

- Includes prior knowledge as priors: $P(M \mid D) \sim \mathscr{L}(D \mid M) \cdot P(M)$.
- Identifies bulk volumes that fit data well.

\- Problem: If data is not constraining enough, can be subject to prior effects. Solution: Use more/better data, less free parameters.

Profile Likelihood (Frequentist statistics):

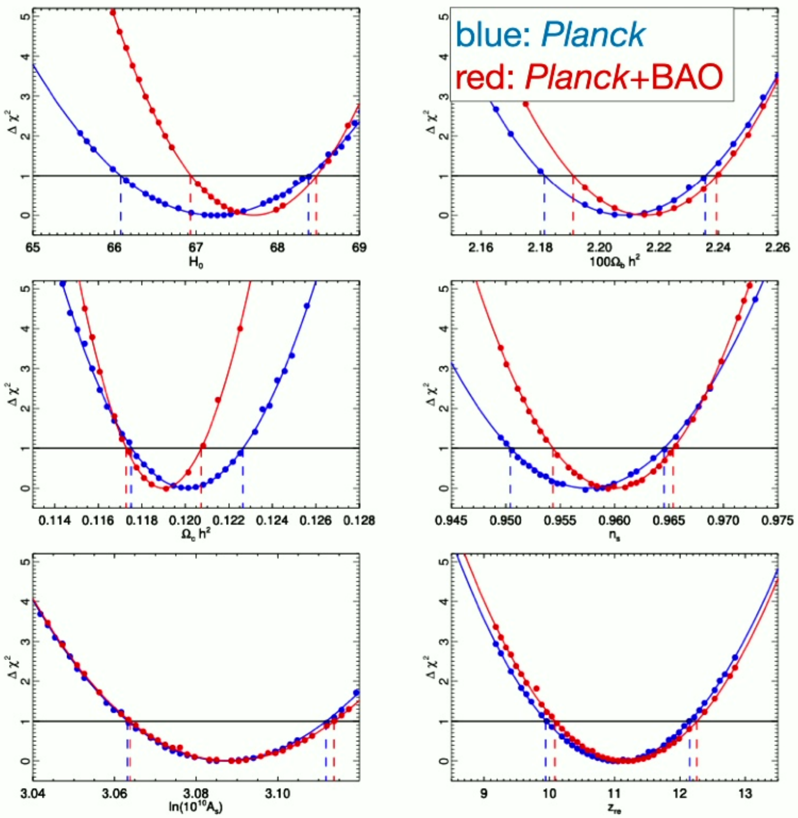
- Only based on the likelihood $\mathscr{L}(D \mid M)$ or on $\chi^2 = -2\log(\mathscr{L})$.
- No posterior, no prior dependence.

\- Problem: Can prefer cosmology with very small parameter volume — "fine tuning". Solution: Construct physically motivated model.

→ Verify results from MCMC

Profile likelihood — examples

***Planck* col. XVI, 2013**



→ Use profile likelihood to verify *Planck* ΛCDM results from MCMC

Parameter	CMB MCMC	CMB Profile-likelihood	CMB+BAO MCMC	CMB+BAO Profile-likelihood
H_0	67.3 ± 1.2	67.2 ± 1.2	67.8 ± 0.8	67.7 ± 0.8
$100\omega_b$	2.207 ± 0.027	2.208 ± 0.027	2.214 ± 0.024	2.215 ± 0.024
ω_c	0.1198 ± 0.0026	0.1201 ± 0.0026	0.1187 ± 0.0017	0.1190 ± 0.0017
n_s	0.9585 ± 0.0070	0.9575 ± 0.0071	0.9608 ± 0.0054	0.9598 ± 0.0055
$\ln(10^{10}A_s)$	3.090 ± 0.025	3.087 ± 0.025	3.091 ± 0.025	3.088 ± 0.025
z_{re}	11.2 ± 1.1	11.0 ± 1.1	11.2 ± 1.1	11.2 ± 1.1

Consistent results for all ΛCDM parameters

Profile likelihood — results

Compute profile likelihood in f_{EDE} and H_0:

1) Maximise likelihood (for f_{EDE} / H_0 fixed to different values)

2) Fit parabola to $\Delta\chi^2$ as a function of f_{EDE}/H_0

3) Construct confidence interval via Feldman-Cousins prescription

Profile likelihood — results

LH, Ferreira (arXiv:2210.16296)

Step 1 — Compute profile likelihoods for different data sets

Model: CLASS-PT_EDE — combined CLASS-PT **(Chudaykin et al. 2020)** and CLASS_EDE **(Hill et al. 2020)**

Data sets:

- Planck 2018 TT, TE, EE, lowℓ, lensing ***- Planck col. VI 2020***
- BOSS DR12 full-shape power spectrum (EFT of LSS) ***- Alam et al. 2017***
- DES Gaussian likelihood: $S_8 = 0.776 \pm 0.017$ ***- Abott et al. 2022***
- SH0ES Gaussian likelihood: $H_0 = 73.04 \pm 1.04$ km/s/Mpc ***- Riess et al. 2021***

Baseline data set: Planck + BOSS

Carrasco++ 2012, Baumann++ 2012, Carrasco++ 2014, Alam++ 2017, Chudaykin++ 2020

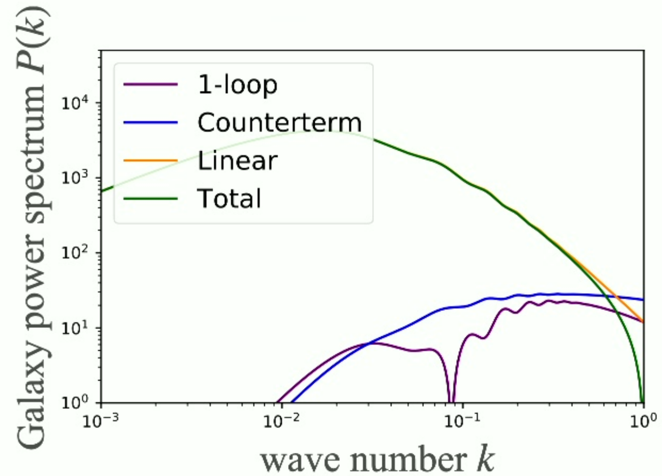
Full-shape BOSS analysis based on the Effective field theory of LSS (CLASS_PT)

- The galaxy power spectrum multipoles have the form

$$P_{g,\ell}(k) = P^{\text{tree}}_{g,\ell}(k) + P^{1-\text{loop}}_{g,\ell}(k) + P^{\text{noise}}_{g,\ell}(k) + P^{\text{ctr}}_{g,\ell}(k)$$

- With 8 nuisance parameters:

$$\underbrace{b_1,\, b_2,\, b_{\mathcal{G}_2},\, b_{\Gamma_3}}_{\text{galaxy bias parameters}},\, \underbrace{c_0,\, c_2,\, c_4}_{\text{counterterms}},\, \underbrace{P_{\text{shot}}}_{\text{shot noise}}$$



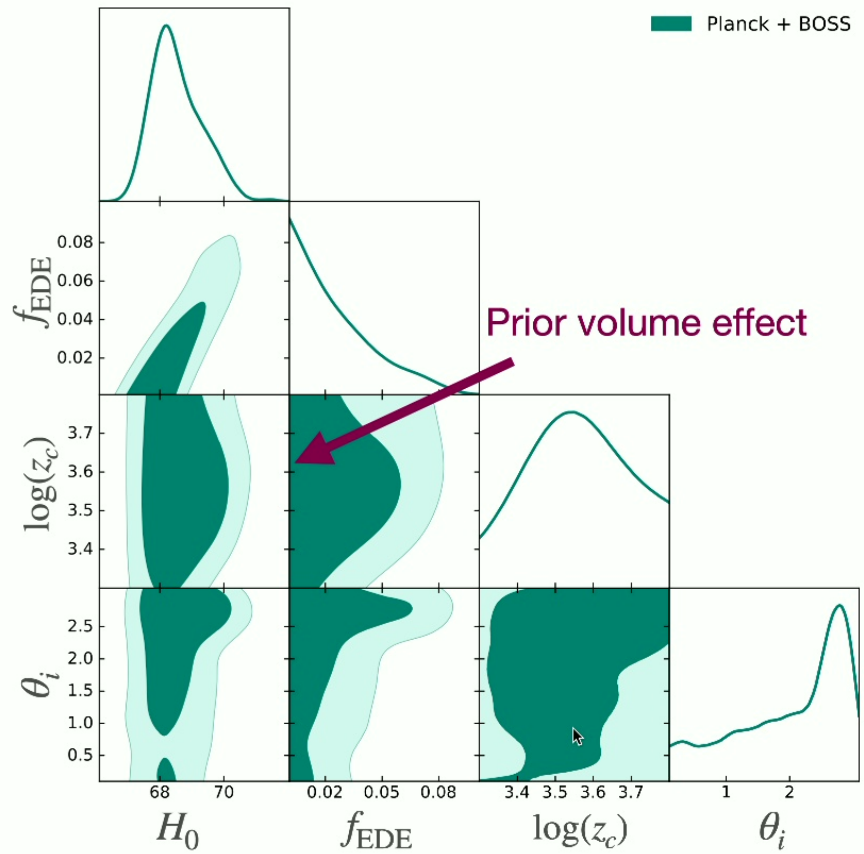
- Note: Update in the BOSS window-function treatment included here **(Beutler&McDonald 2021)**

Planck + BOSS (baseline data set)

LH, Ferreira (arXiv:2210.16296)

MCMC results:

- $f_{\rm EDE} < 0.072$ (95% C.L.), $H_0 = 68.55^{+0.62}_{-1.06}$ km/s/Mpc
- z_c and θ_i not well constrained



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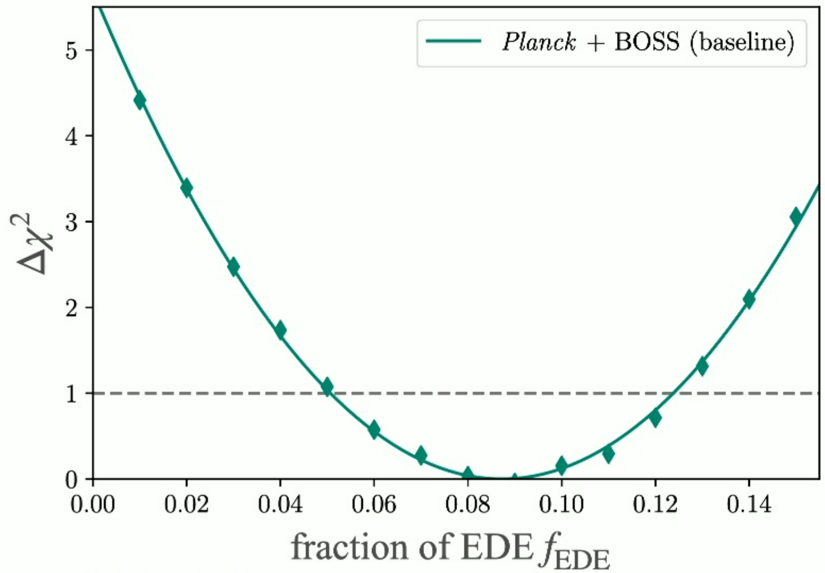
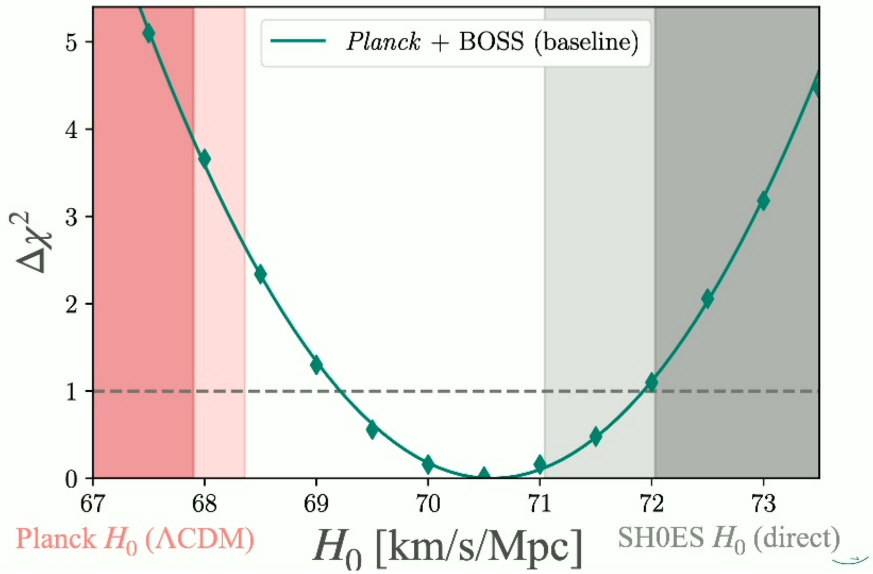
Profile likelihood results:

- $f_{\rm EDE} = 0.087 \pm 0.037$,
  $H_0 = 70.57 \pm 1.36$ km/s/Mpc
- Consistency with SH0ES at $1.4\,\sigma$
- However: S_8 tension worsens slightly
  (ΛCDM: 0.828, EDE: 0.840, DES: 0.776)



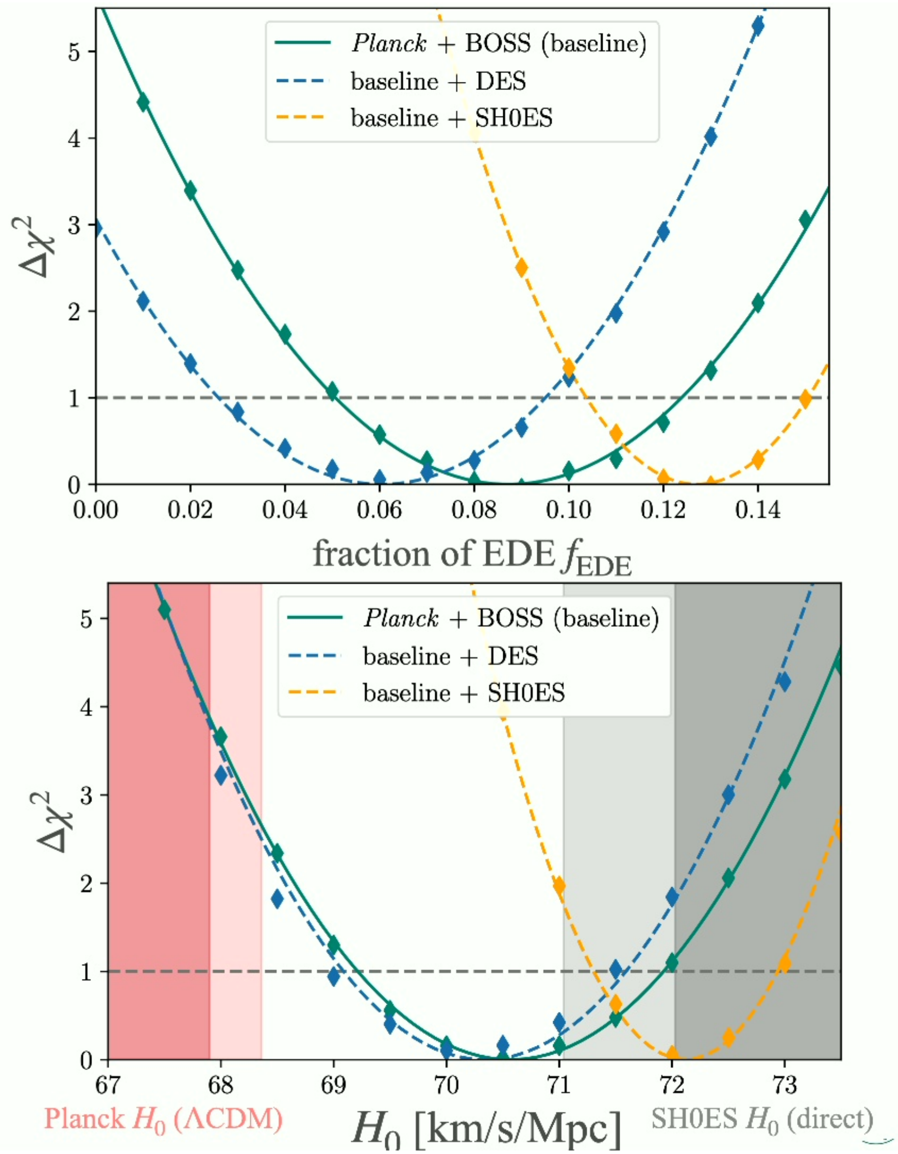


Baseline + DES

LH, Ferreira (arXiv:2210.16296)

Baseline+DES ($S_8 = 0.776 \pm 0.017$):

- $f_{\mathrm{EDE}} = 0.061^{+0.035}_{-0.034}$, $H_0 = 70.28 \pm 1.33$ km/s/Mpc
- Consistency with SH0ES at $1.6\,\sigma$
- Including weak lensing reduces f_{EDE} and H_0 slightly but does not rule out EDE
- Prior volume effect seems to be the dominating effect (compared to clustering enhancement)



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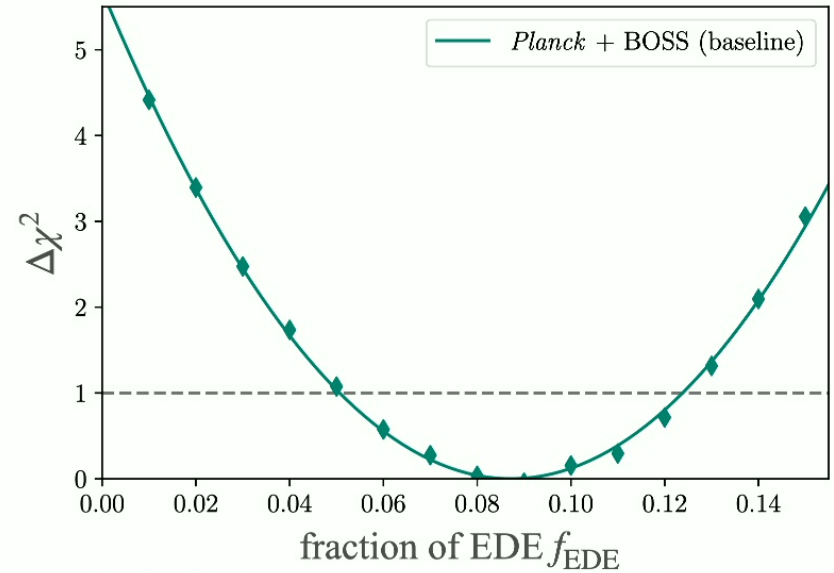
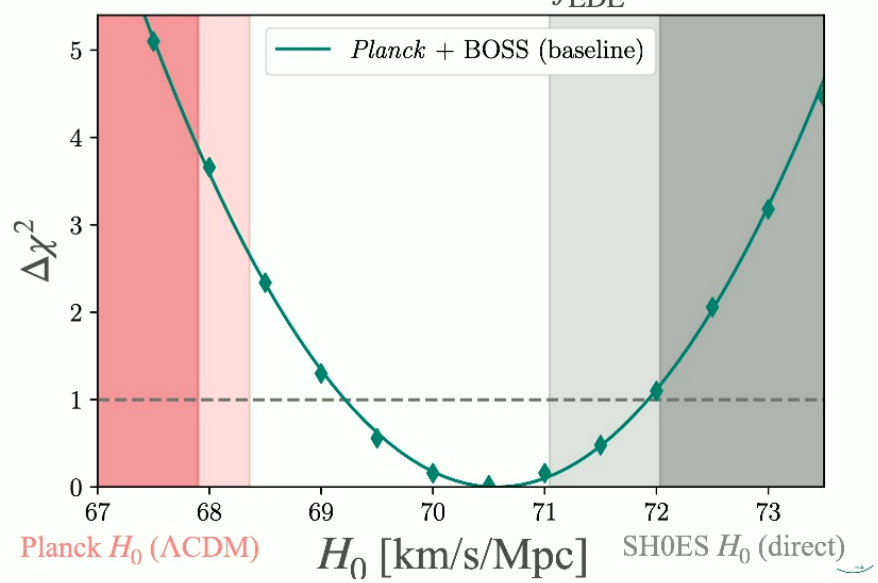


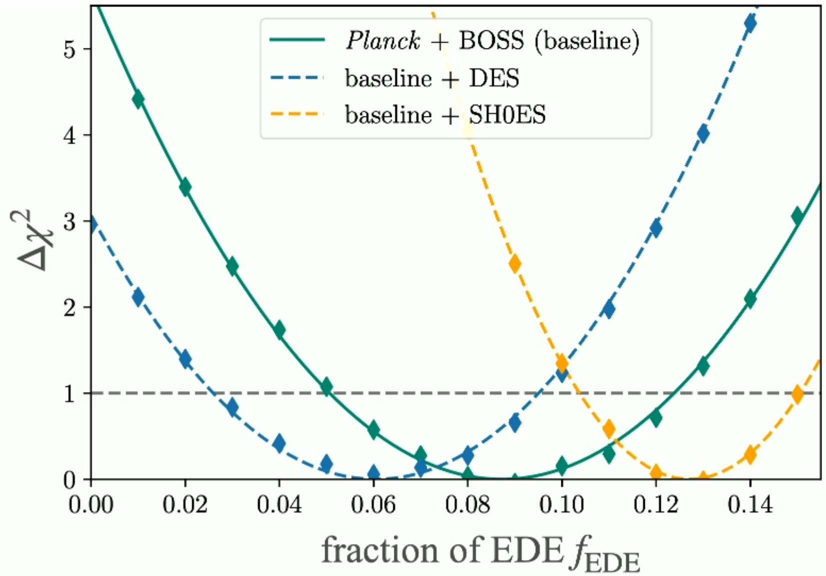


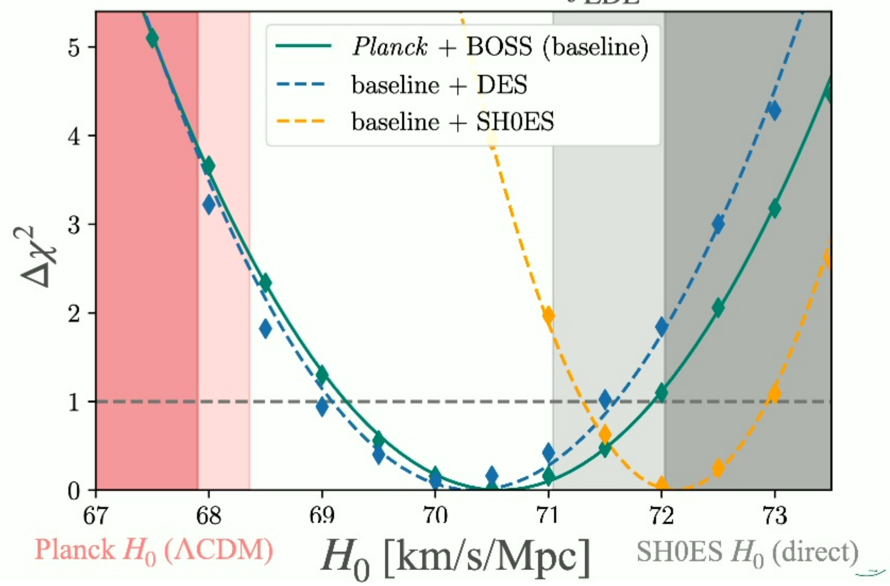
Baseline + SH0ES

LH, Ferreira (arXiv:2210.16296)

Baseline+SH0ES
($H_0 = 73.04 \pm 1.04$ km/s/Mpc):

- Since we find that H_0 for the baseline data set is in agreement with SH0ES, we can combine both data sets
- $f_{\rm EDE} = 0.127 \pm 0.023$,
  $H_0 = 72.12 \pm 0.82$ km/s/Mpc
- Consistency with SH0ES at $0.69\,\sigma$



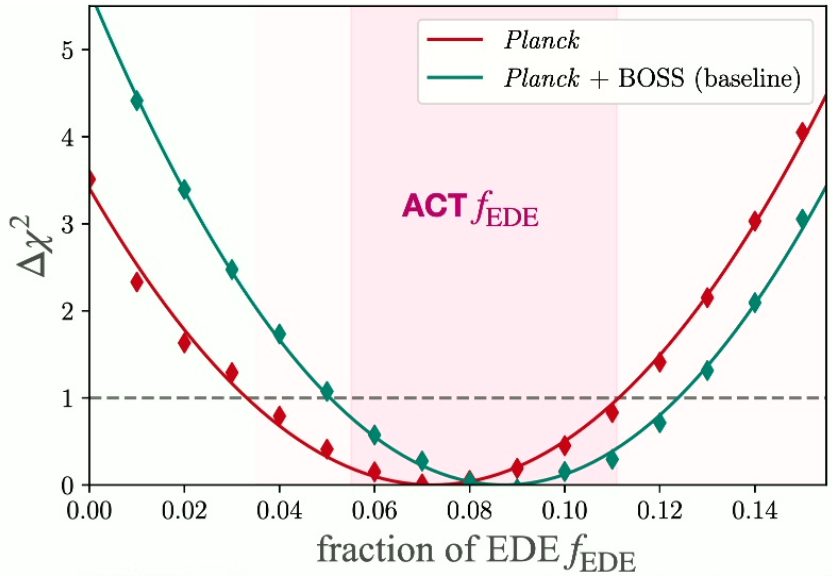


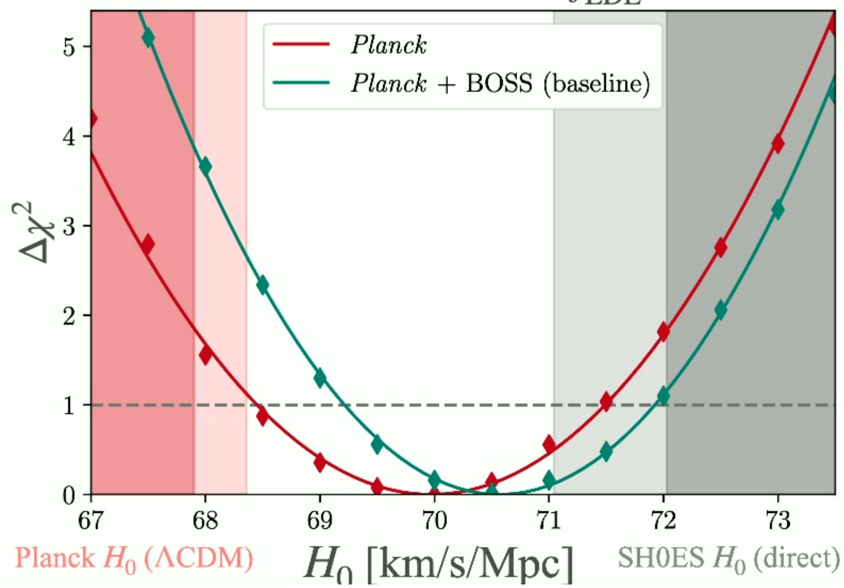
Planck only

LH, Ferreira (arXiv:2210.16296)

Planck only:

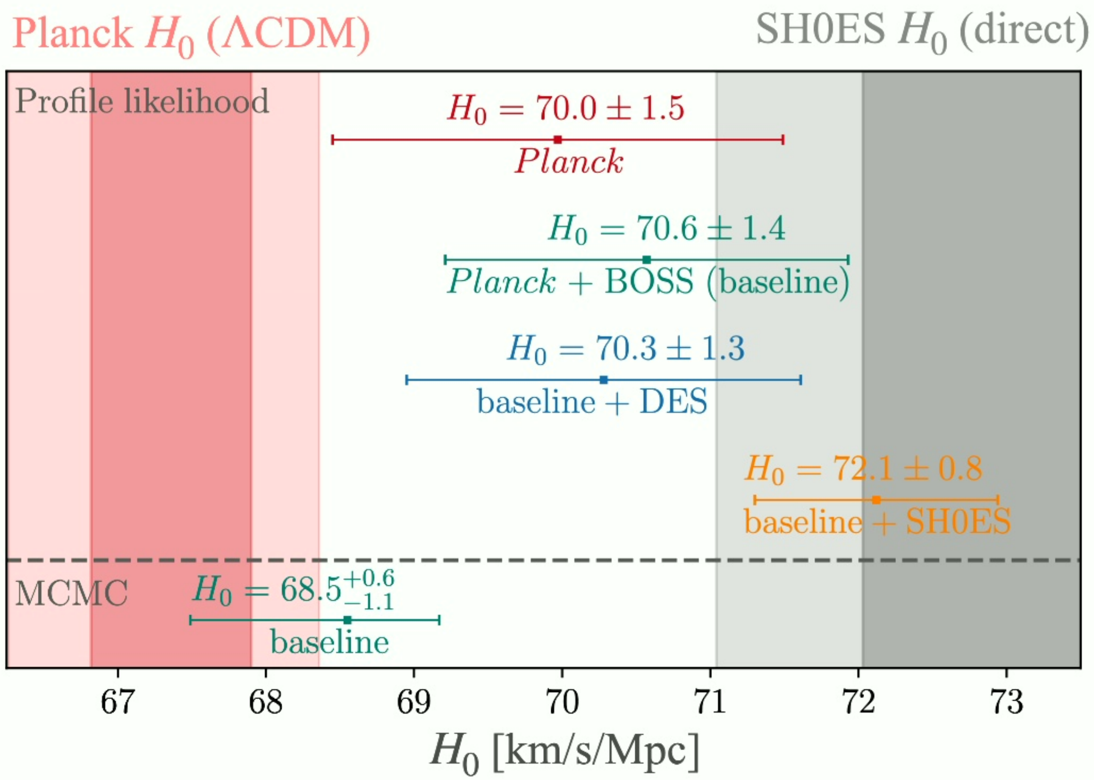
- $f_{\rm EDE} = 0.072 \pm 0.039,$
  $H_0 = 69.97 \pm 1.52$ km/s/Mpc
- Agreement with SH0ES at $1.7\,\sigma$
- Agrees with recent MCMC results from the Atacama cosmology telescope (ACT):
  $f_{\rm EDE} = 0.091^{+0.020}_{-0.036}$ (Hill++ 2022)





Profile likelihood — results

LH, Ferreira (arXiv:2210.16296)



Results:

- Evidence for prior volume effects.
- H_0 in EDE model within $1.7\,\sigma$ of SH0ES measurement for all data sets (incl. galaxy clustering, weak lensing).
- EDE viable solution to Hubble tension.

Model comparison

LH, Ferreira (arXiv:2210.16296)

Data set	$\chi^2(\Lambda\text{CDM})$	$\chi^2(\text{EDE})$	$\Delta\chi^2$	Δ AIC
Planck	2774.24	2770.72	−3.52	+2.48
Planck+BOSS (base)	3045.65	3039.98	−5.67	+0.33
Baseline + DES	3052.06	3049.13	−2.93	+3.07
Baseline + SH0ES	3068.44	3042.08	−26.36	−20.36

Data sets **Δchi^2** **Akaike Information Criterion**

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Mild preference for ΛCDM

Clear preference for EDE

Result:

For all data sets: EDE is a similarly good model as ΛCDM (penalising extra parameters)

Table of content

The idea behind EDE

Does EDE solve the Hubble tension?

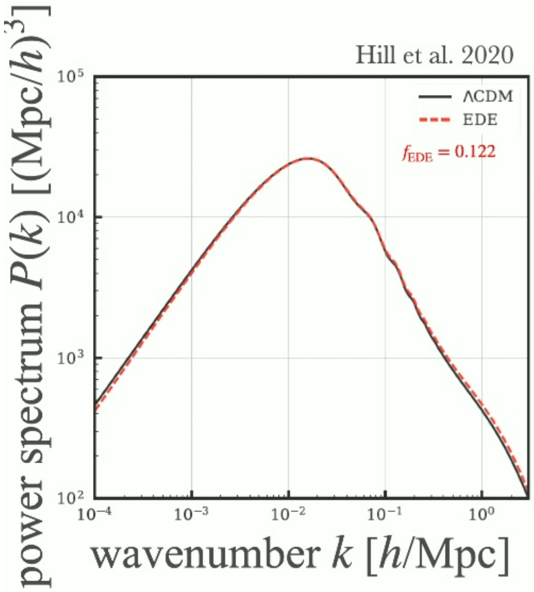
New constraint with the profile likelihood

Short extra section: What about the S_8 tension?

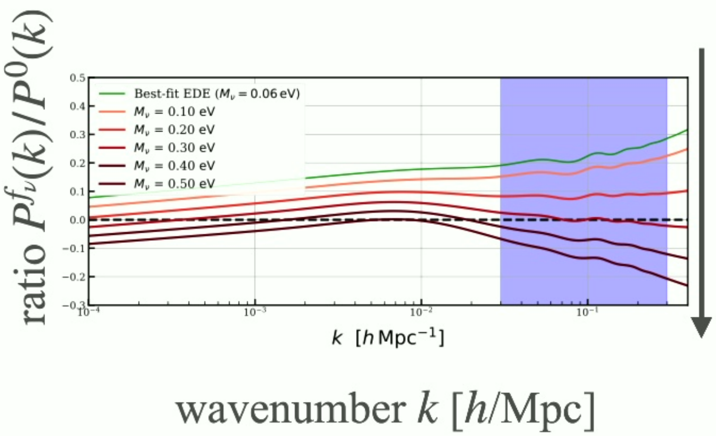
*based on A. Reeves, **LH**, S. Vagnozzi, B. D. Sherwin, E. G. M. Ferreira (arXiv:2207.01501)*

Massive neutrinos and EDE

*A. Reeves, **LH**, S. Vagnozzi, B. D. Sherwin, E. G. M. Ferreira (arXiv:2207.01501)*



Higher f_{EDE}: stronger enhancement of clustering at small scales

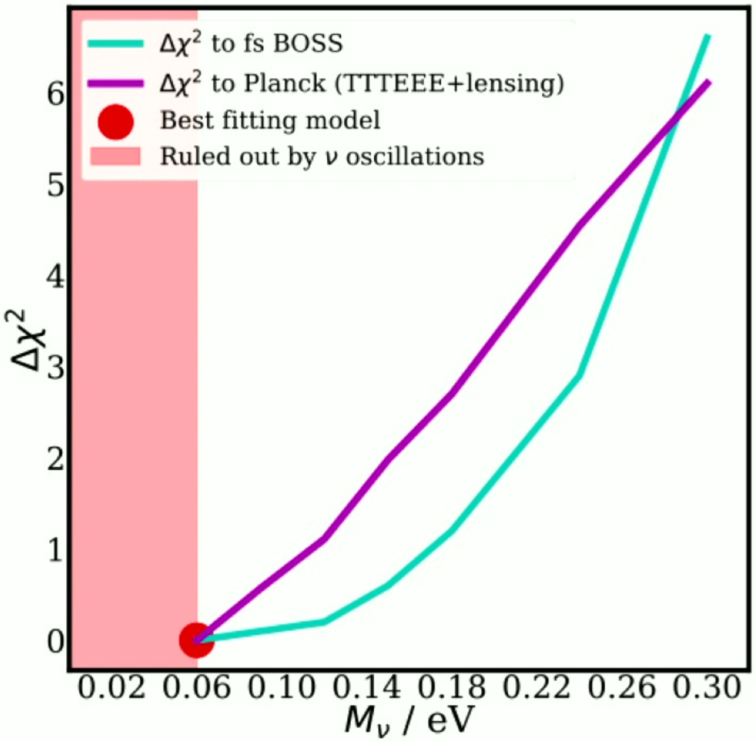


Higher M_ν: stronger suppression of clustering at small scales

Could higher neutrino masses **compensate the worsening of the S_8-tension** in EDE cosmologies?

Massive neutrinos and EDE

*A. Reeves, **LH**, S. Vagnozzi, B. D. Sherwin, E. G. M. Ferreira (arXiv:2207.01501)*



Profile likelihood analysis in M_ν with $f_{\rm EDE}$, θ_i, z_c free:

- Bestfit: $M_\nu = 0.06$ eV, $f_{\rm EDE} = 0.077$ (no preference for larger M_ν in EDE cosmologies)
- Positive correlation between M_ν and $f_{\rm EDE}$
- To reduce S_8 to the ΛCDM limit: Need $M_\nu = 0.24$ eV ($H_0 = 70.1$ km/s/Mpc) but worsens $\Delta\chi^2 = 7.5$
- Constraining power from BAO data

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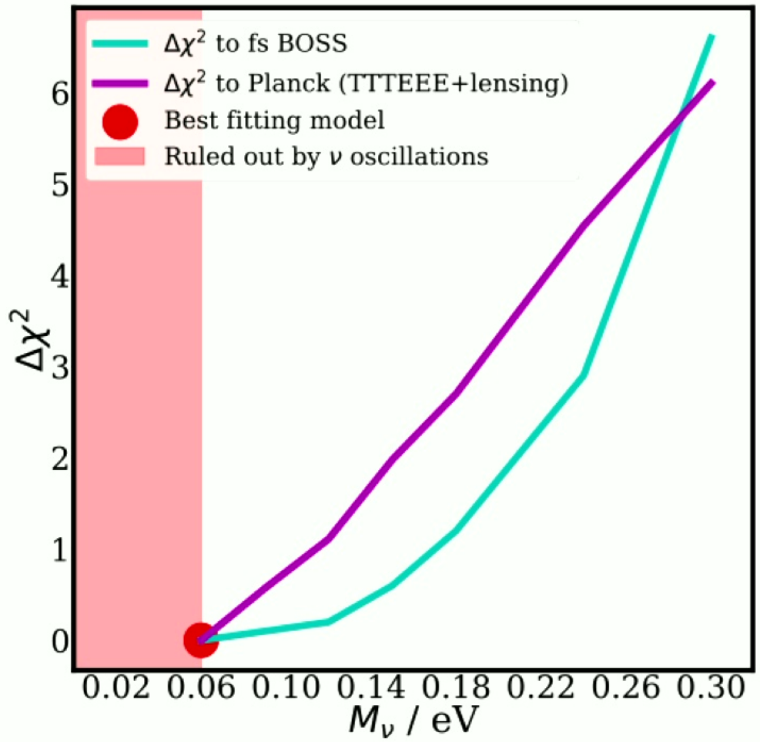

Profile likelihood analysis in M_ν with f_{EDE}, θ_i, z_c free:

- Bestfit: $M_\nu = 0.06$ eV, $f_{\mathrm{EDE}} = 0.077$ (no preference for larger M_ν in EDE cosmologies)
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If S_8 tension persists, this is a problem for EDE.
→ Requires an independent (late-time) solution.

Summary

Prior volume effects

Important for beyond-ΛCDM models with many parameters, e.g. EDE, decaying DM (see 2211.01935, E. Holm, **LH,** S. Hannestad, A. Nygaard, T. Tram)

Profile likelihood

EDE is viable solution to the Hubble tension (not ruled out by LSS)

Frequentist + Bayesian methods are complementary

Both have different shortcomings (fine tuning vs. prior volume effects)

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Thank you!