Prior effects and the cosmological tensions

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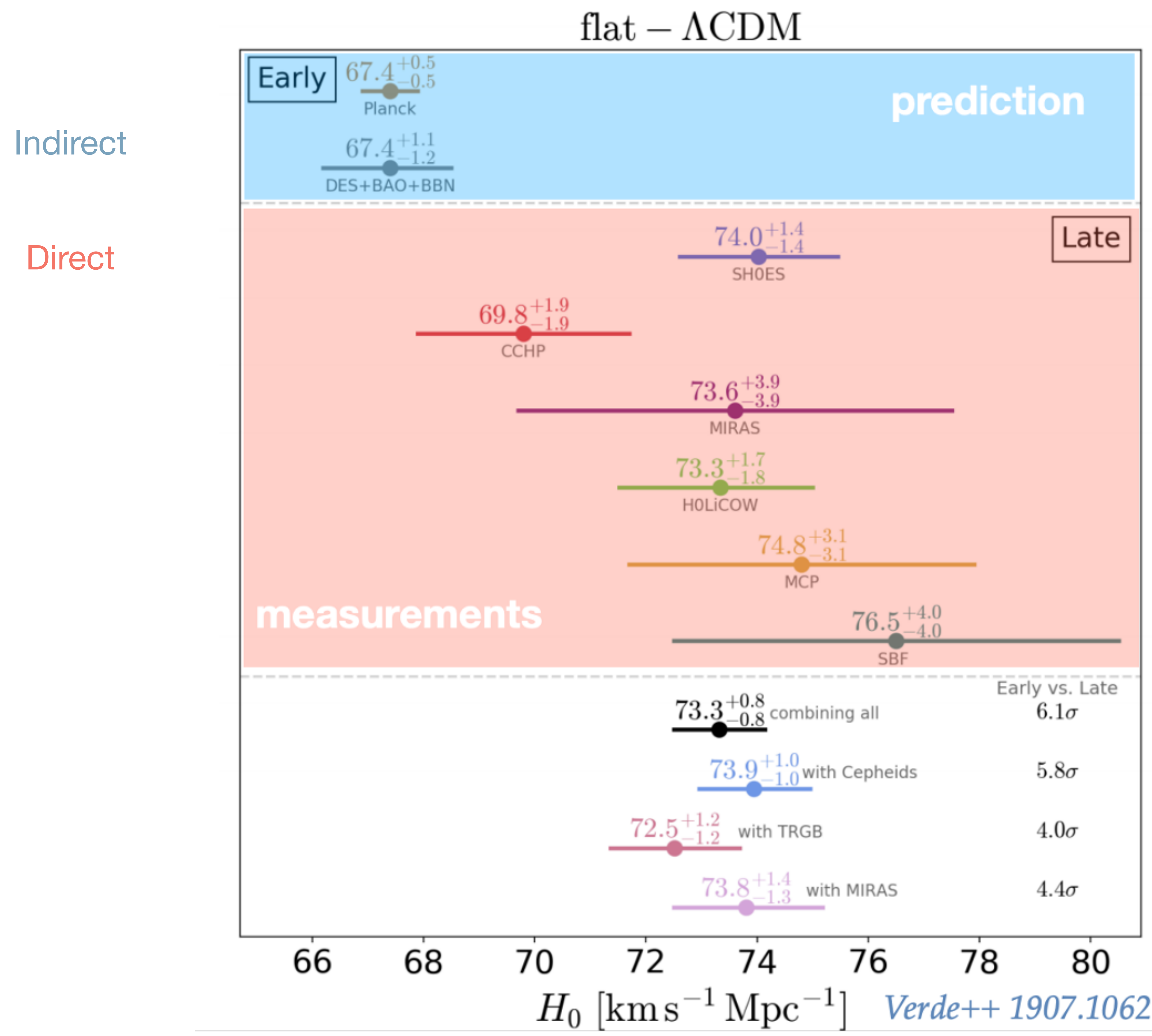
Dark Energy from Fundamental Theories to Observations

13/September/2023

Hubble tension



Verde++ 1907.10625

→ Depends on the cosmological model

New SHOES result (*Riess et al 2021*):

$$H_0 = 73.04 \pm 1.04\,\mathrm{km/s/Mpc}$$

5σ tension with Planck!

↓

$$H_0 = 67.71 \pm 0.40\,\mathrm{km/s/Mpc}$$

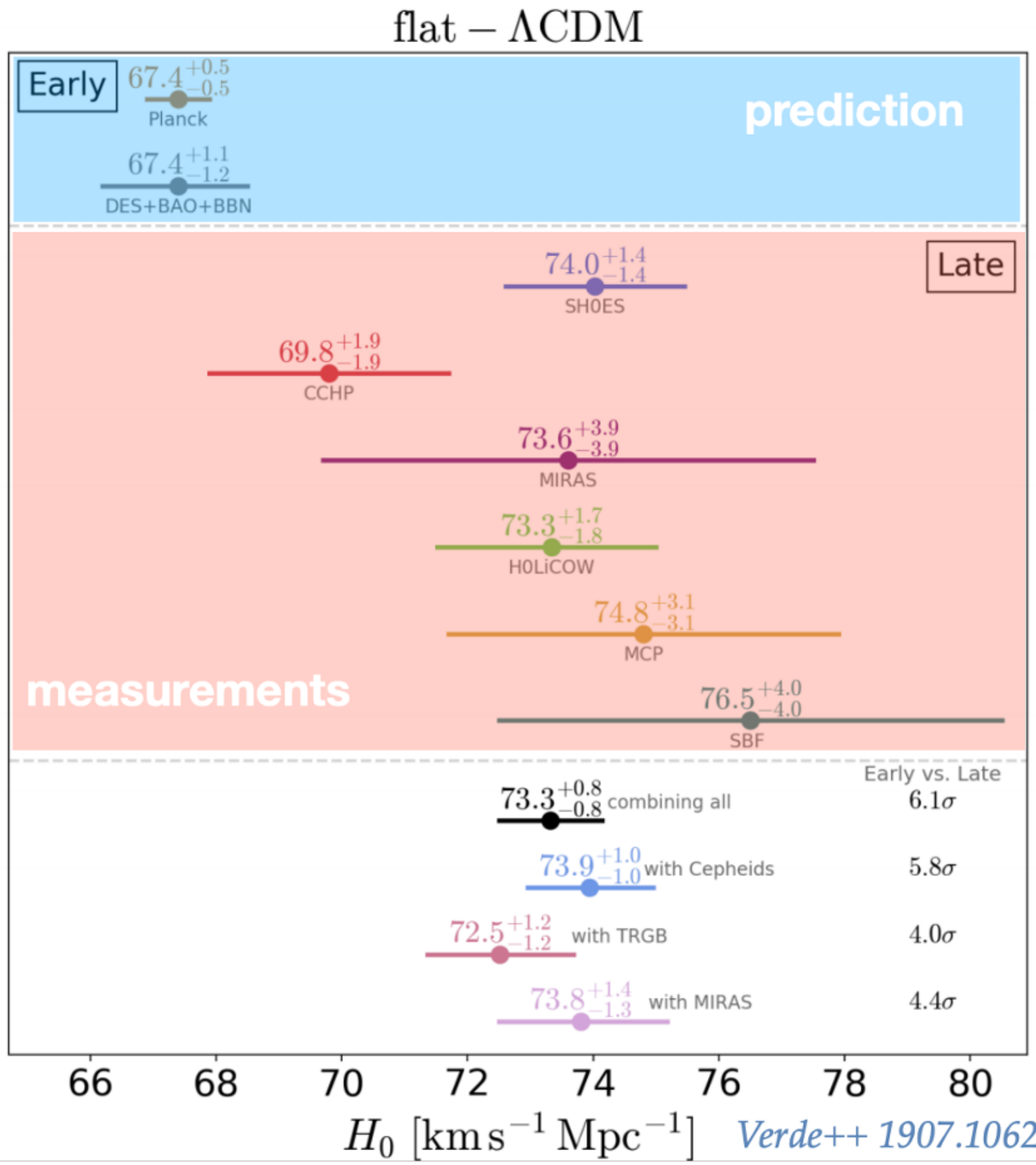
(Planck+BAO+Sn)

Systematics or new physics?

Hubble tension

Indirect

Direct



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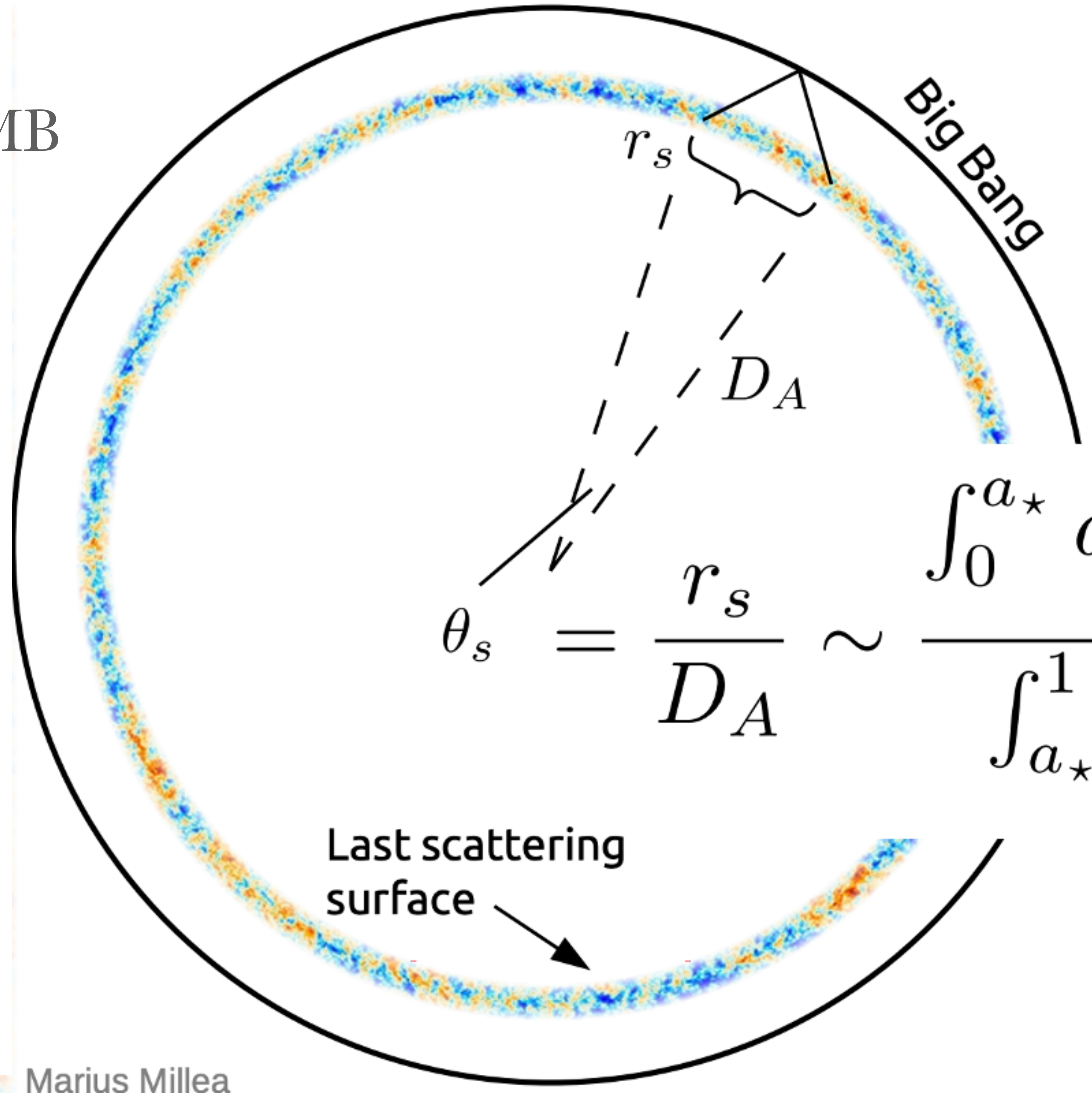
Systematics or new physics?

Measuring H0

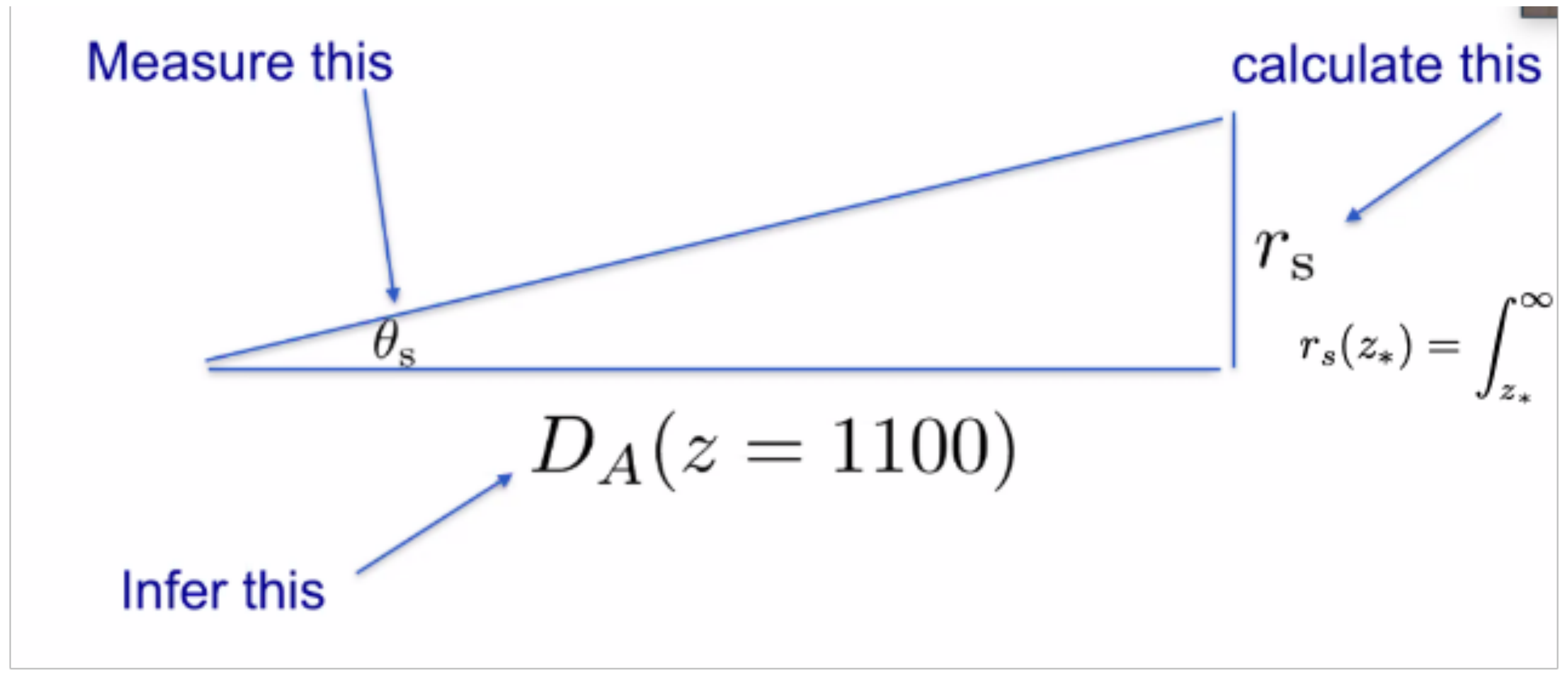
INDIRECT

CMB



$$\theta_s = \frac{r_s}{D_A} \sim \frac{\int_0^{a_\star} da \frac{c_s(a;\omega_b)}{\sqrt{\omega_m a^{-3} + \omega_r a^{-4}}}}{\int_{a_\star}^{1} da \frac{1}{\sqrt{\omega_m a^{-3} + \omega_\Lambda}}}$$

Marius Millea



L. Knox

$r_s(z_*) \rightarrow$ Sound horizon at lss

$D_A(z_*) \rightarrow$ Angular diameter distance

$\theta_s(z_*) \rightarrow$ Angular scale of the sound horizon

Measured with a 0.03% precision by *Planck* 2018

How to solve the ***H0 tension?***

Introducing new physics

INDIRECT

r_s: *pre-recombination* physics ⟶ depend on physical densities (b, r, cdm, ν)

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

Measured with a 0.03% precision by *Planck* 2018

D_A: *post-recombination* physics ⟶ information on H0

$r_s(z_*) \rightarrow$ Sound horizon at lss

$D_A(z_*) \rightarrow$ Angular diameter distance

$\theta_s(z_*) \rightarrow$ Angular scale of the sound horizon

Early vs late time solutions to the Hubble tension

To increase H_0:

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

Measured with a 0.03% precision by *Planck* 2018

LATE UNIVERSE SOLUTIONS

Change only late time physics: early universe unaffected

Little room for changes in the physics (?)

Shown to not solve the tension, only alleviates!

EARLY UNIVERSE SOLUTIONS

Change only early time physics, late time almost unaffected

$\theta_s(z_*)$: decrease $r_s(z_*)$ $\Longrightarrow$ decreases $D_A(z_*)$

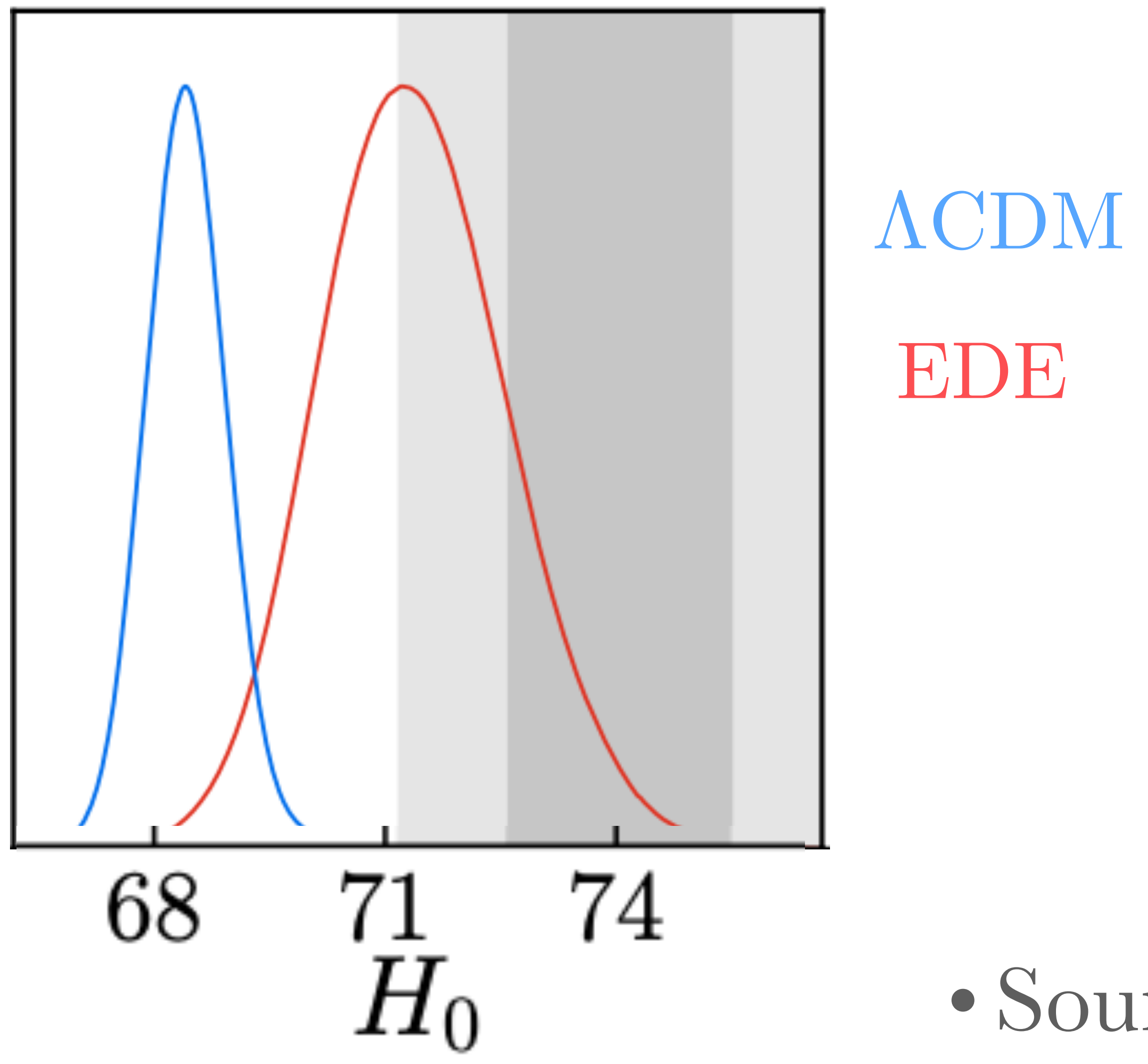
Fixed

$\Downarrow$

Increases H_0

Verde + (2019),Poulin (2019), Agrawal + (2019), Lin +(2019), Smith + (2019), Knox and Milea (2019)

Early time solutions to the Hubble tension



$\theta_s(z_*)$: decrease $r_s(z_*)$ $\Longrightarrow$ decreases $D_A(z_*)$ $\Longrightarrow$ Increases H_0

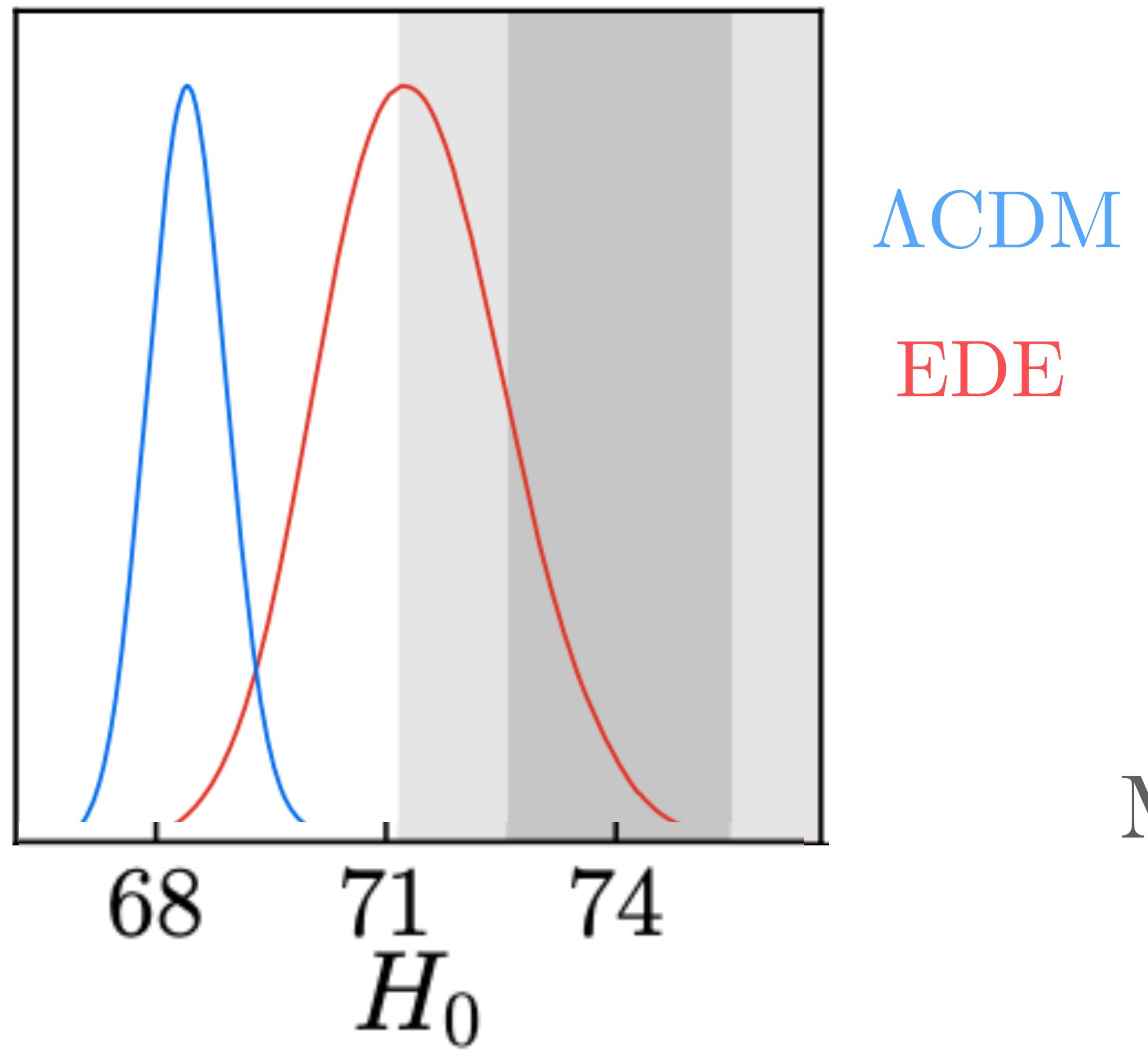
Fixed

$$r_s(z_*) = \int_{z_*}^{\infty} \frac{dz}{H(z)} c_s(t)$$

- Sound horizon at last scattering dominated by contributions near the lower bound of the integral
- Sensitive to H(z) at times shortly after recombination

$\Longrightarrow$ If we decrease r_s by 10 Mpc (keeping r_s/r_d and r_s/r_{eq} fixed) we can *solve the H_0 tension*

Early time solutions to the Hubble tension



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Fixed

$\Longrightarrow$ If we decrease r_s by 10 Mpc (keeping r_s/r_d and r_s/r_{eq} fixed) we can *solve the H_0 tension*

Many ideas on how to do this:

$$r_s(z_*) = \int_{z_*}^{\infty} \frac{dz}{H(z)} c_s(t)$$

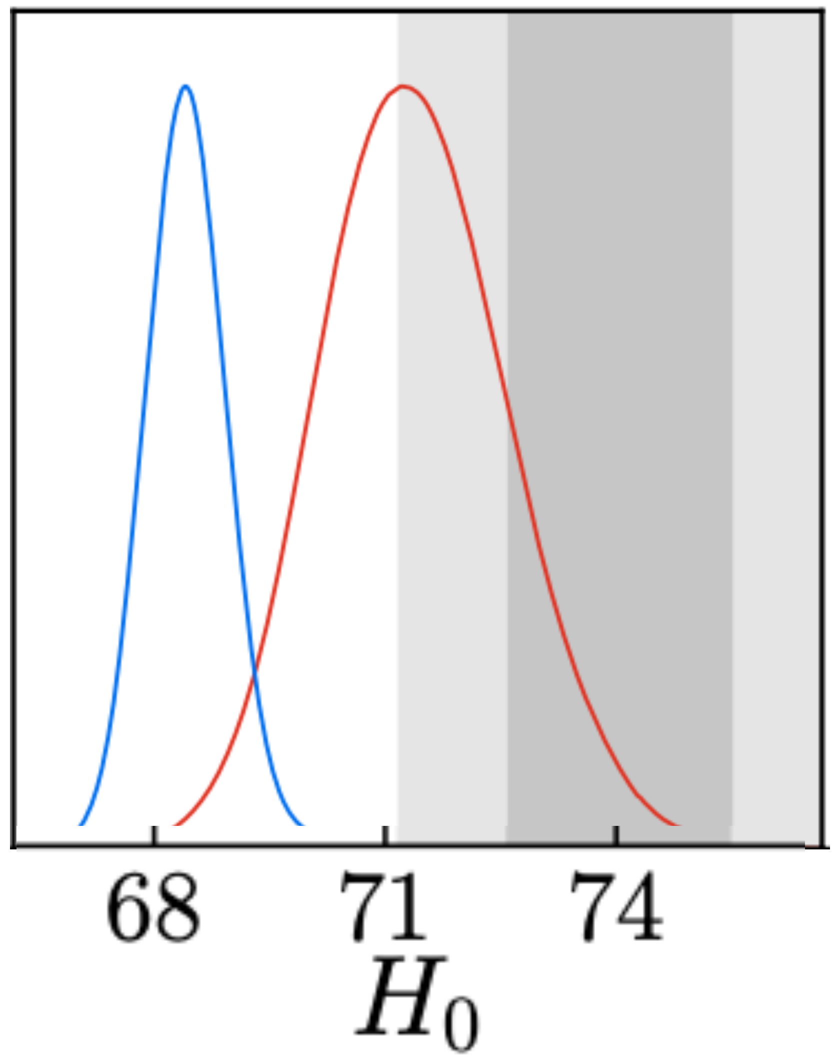
Change $H(z)$: increasing $H(z)$ before recombination with additional components

- Light Relics
- Early Dark Energy *(Karwal+ 2016, …)*

Change z_*: change recombination physics - primordial B *(Jedamzik + 2020)*; change m_e or m_e, Ω_k *(Sekiguchi+ 2020)*

Change c_s *(e.g. Boddy + 2018)*

Early time solutions to the Hubble tension



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The H_0 Olympics: A fair ranking of proposed models, Schöneberg + (2021)

	ΔN_p	
Majoron	3	2
primordial B	1	3
varying m_e	1	1
varying $m_e+\Omega_k$	2	1
EDE	3	2
NEDE	3	2
EMG	3	2

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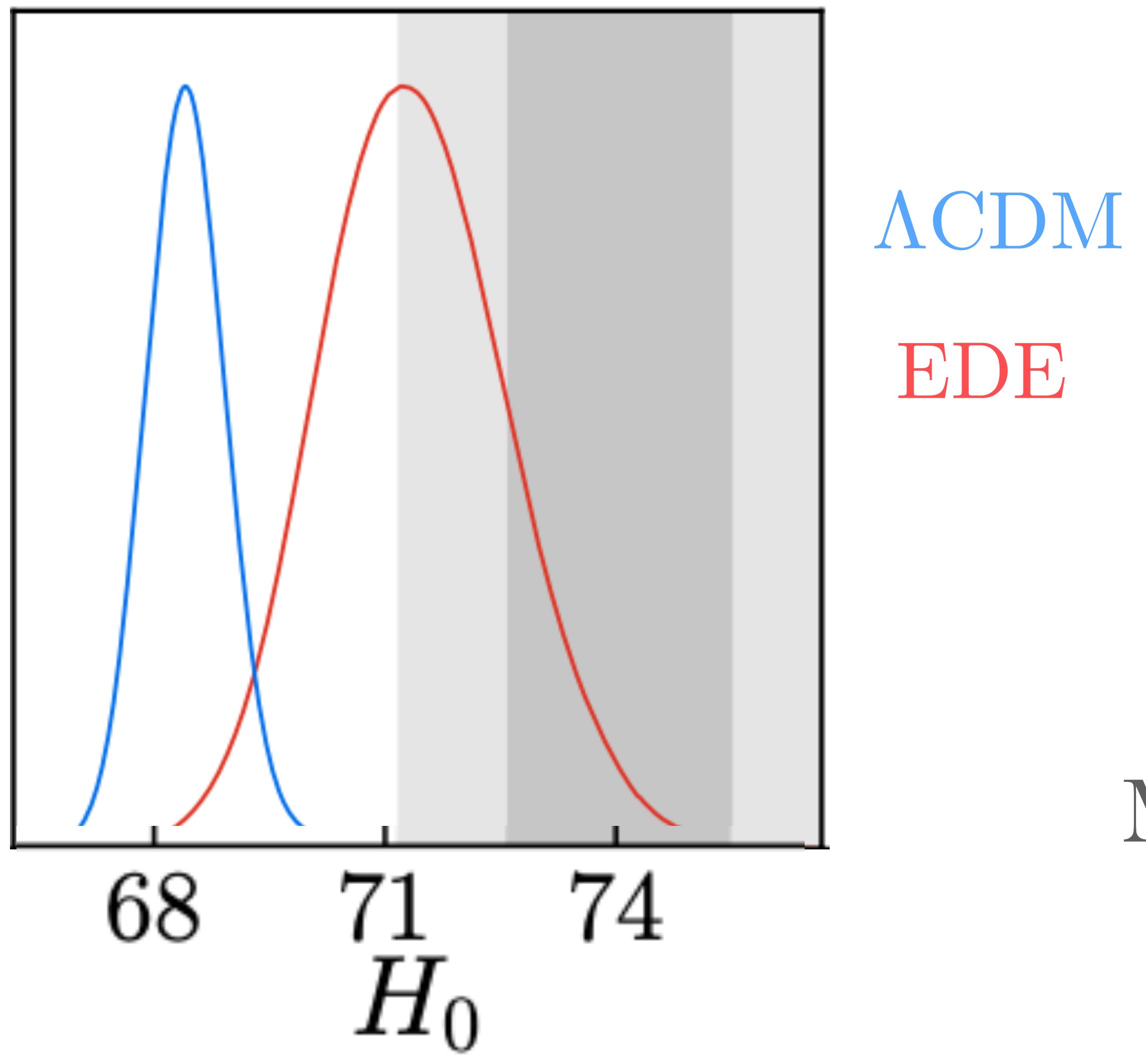
Change c_s *(e.g. Boddy + 2018)*

Early time solutions to the Hubble tension



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Change $H(z)$: increasing $H(z)$ before recombination with additional components

- Light Relics
- Early Dark Energy

Hubble hunter's guide, Knox & Milea (2019)

Change z_*: change recombination physics - primordial B *(Jedamzik + 2020)*; change m_e or m_e, Ω_k *(Sekiguchi+ 2020)*

Change c_s *(e.g. Boddy + 2018)*

Early dark energy

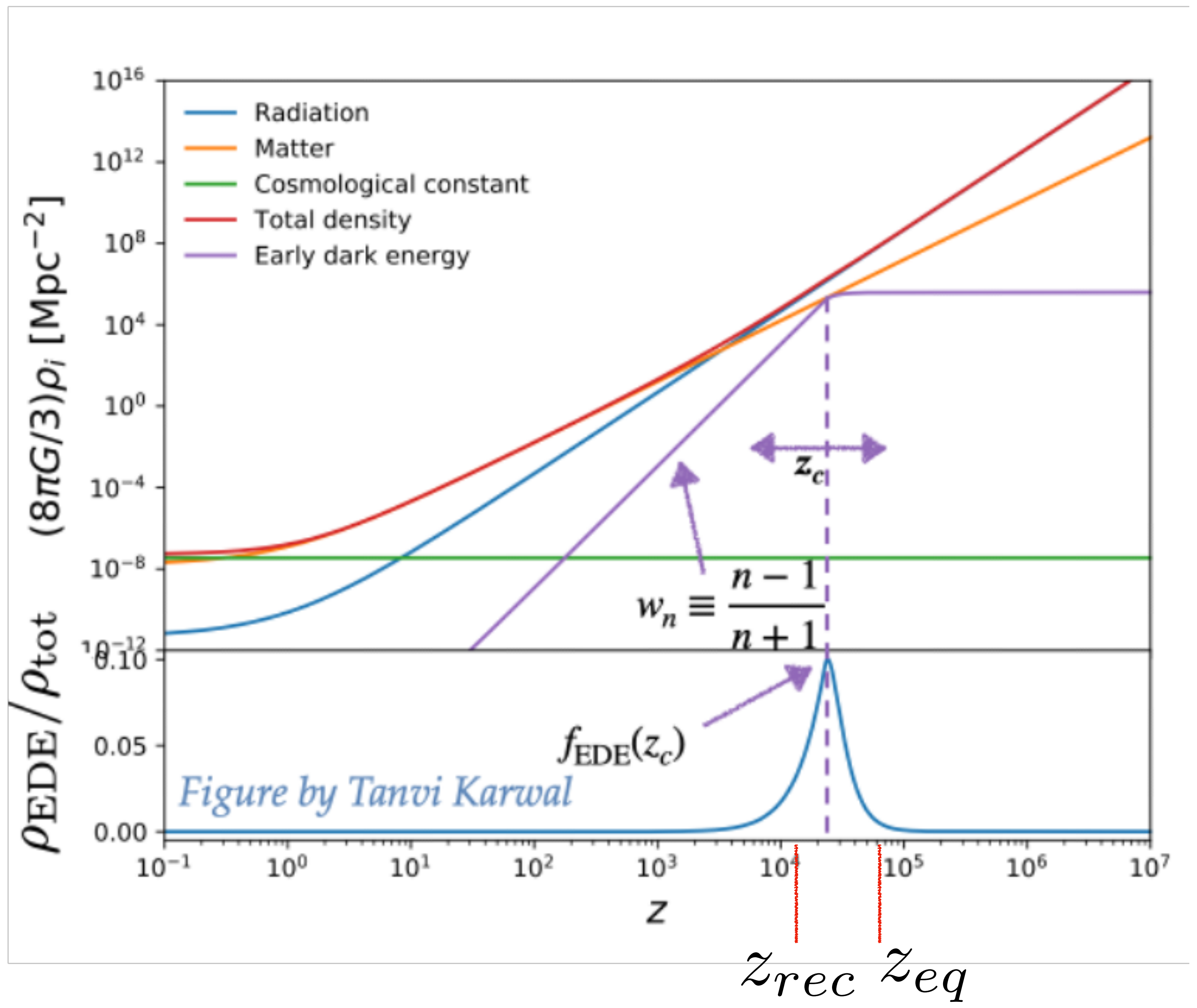
Based on Laura Herold, EF 2210.1629
& Laura Herold, EF and Eiichiro Komatsu 2112.12140,
& A. Reeves, L. Herold, S. Vagnozzi , B. Sherwin, EF 2207.01501

Early dark energy

Idea: add an extra component (to increase $H(z)$) that starts acting around equality, behaves as DE and dilutes faster than matter

This can be done by adding a pseudo-scalar field in FRW:

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



Early dark energy

Idea: add a component that starts acting around equality, behaves as DE and dilutes faster than matter

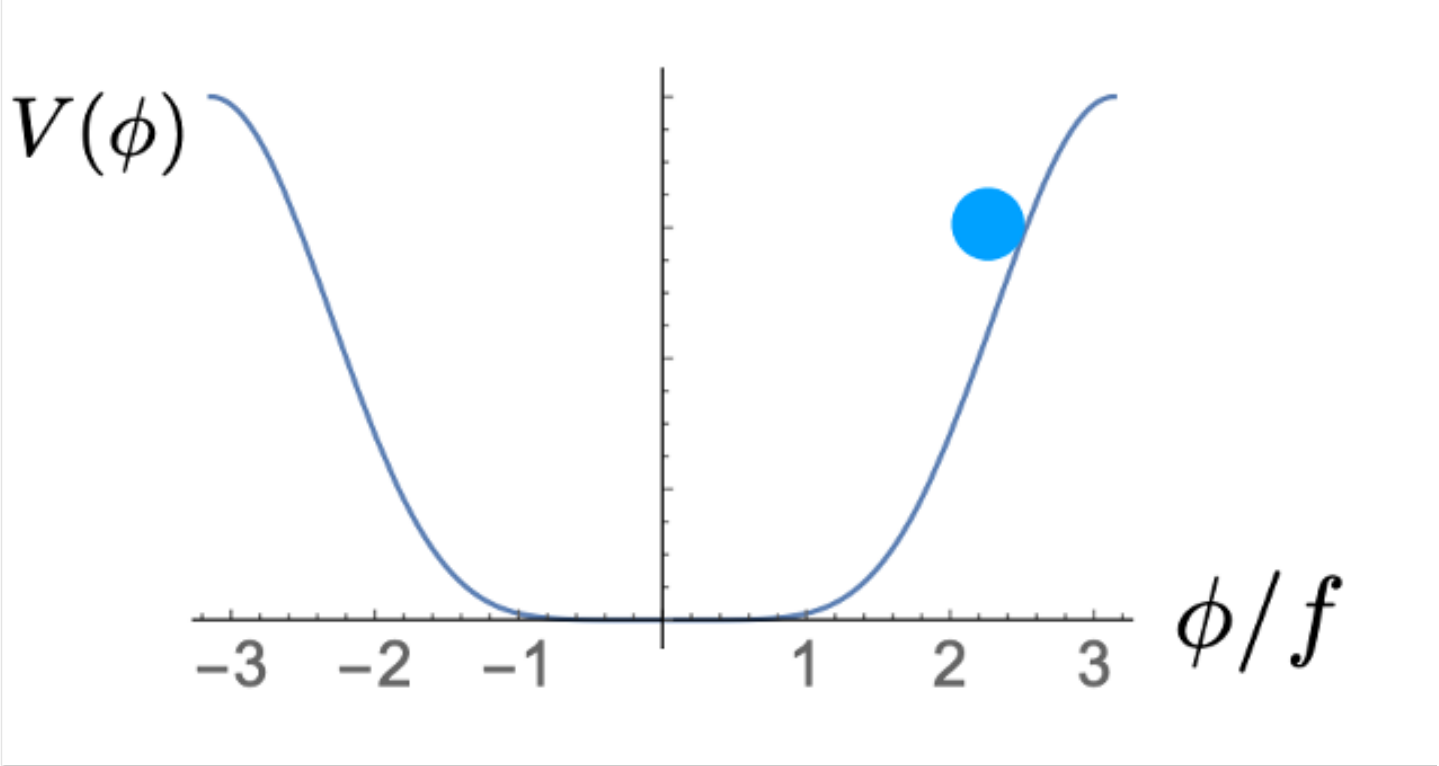
acting around equality → ϕ_i

behaves as DE → Initially frozen, Slow-rolls

This can be done by adding a pseudo-scalar field in FRW:

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

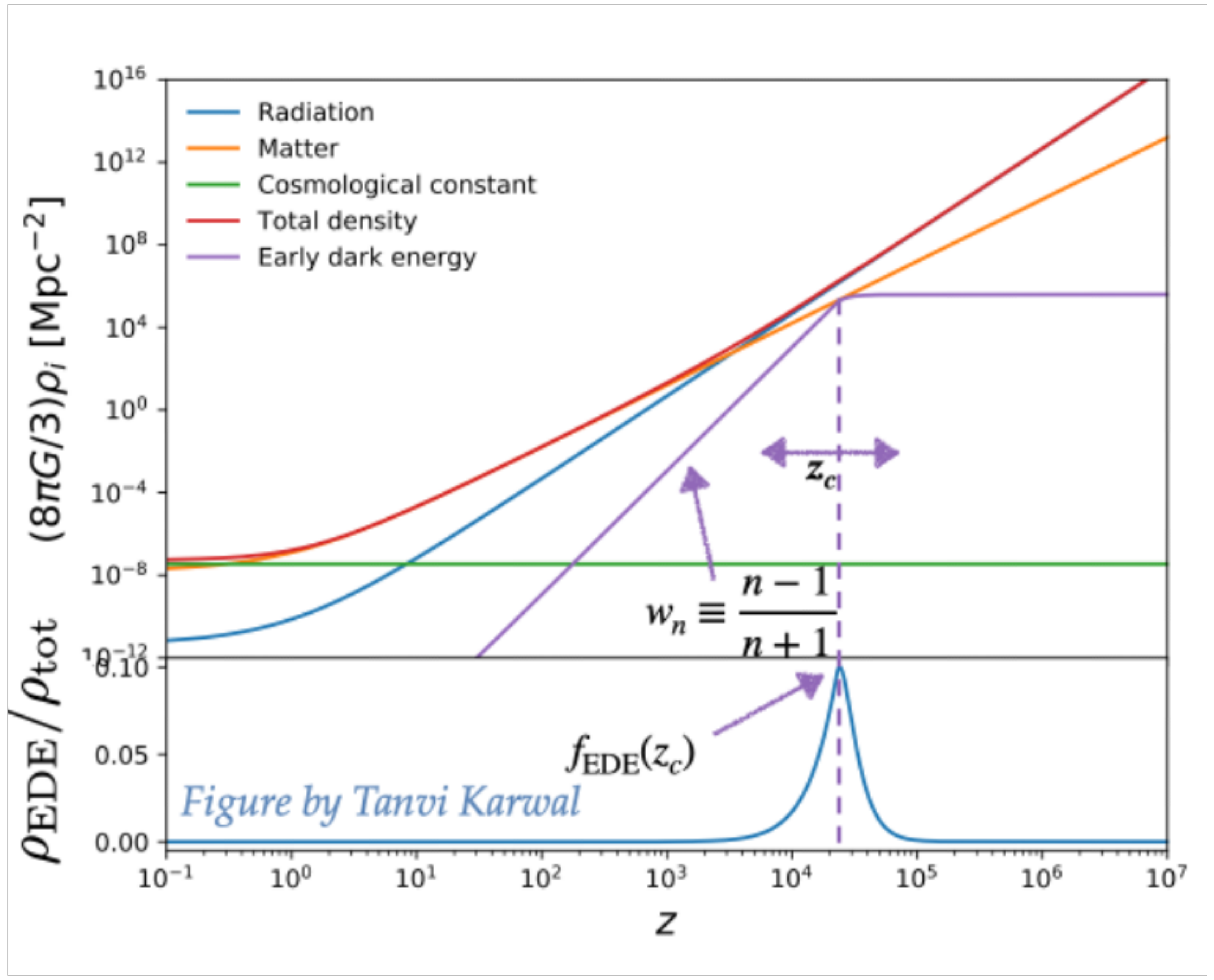
Canonical EDE (toy model)



Credit: Tristan Smith

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

$$\begin{cases} w = -1\,, & \text{for } z > z_c \\ w = \frac{n-1}{n+1}\,, & \text{for } z < z_c \end{cases}$$



$$\begin{cases} \rho_{EDE}(z > z_c) = \rho_{EDE}(z_c) \\ \rho_{EDE}(z < z_c) = \rho^0_{EDE}\,(1+z)^{3(w_n+1)} \end{cases}$$

Early dark energy

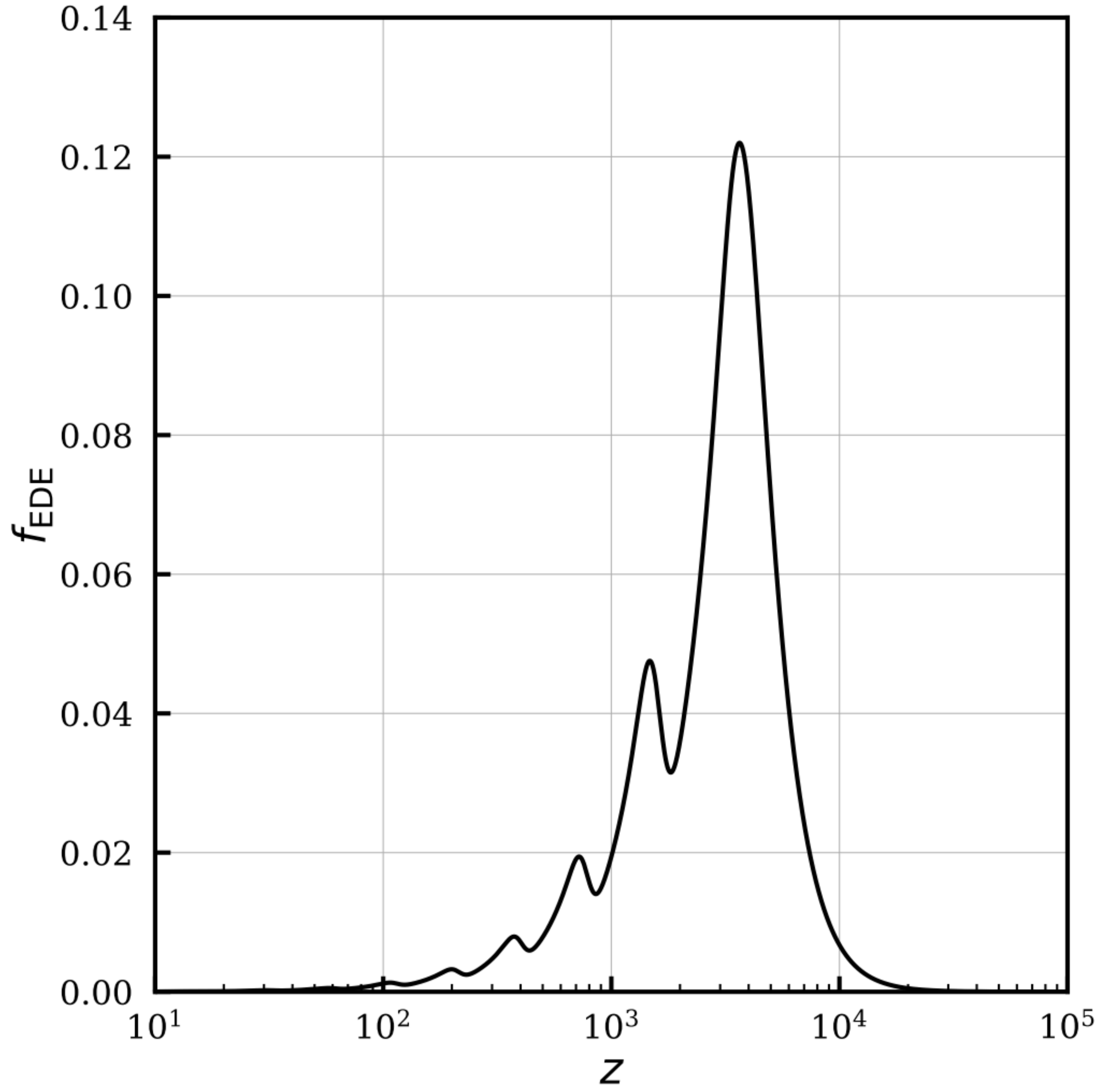
$$V(\phi) = V_0 \, [1 - \cos(\phi/f)]^n$$

3 free parameters: $\{m, f, n\}$ + IC: ϕ_i

- V_0 or m $(V_0 = m^2 f^2)$: the field is ultra-light $m \sim H(z_{eq})$ $\sim 10^{-27}$ eV
- f (spont. sym. breaking scale)
- n : controls the decay → needs to be hidden at late times

$$n \geq 2 \;\; (w \geq 1/3)$$

Hill et al 2019



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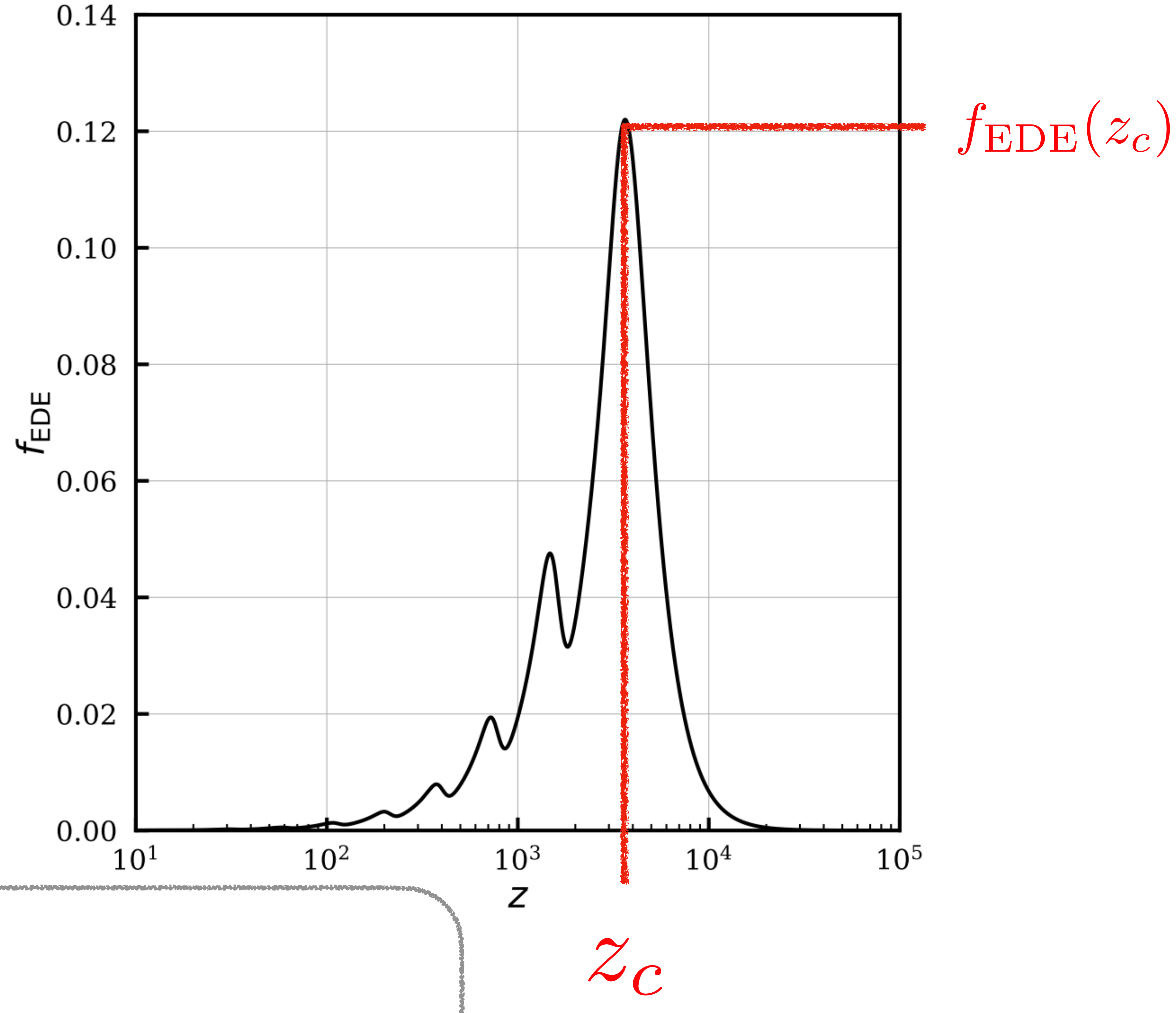

Phenomenological parameters $\{f_{\rm EDE}(z_c),\, z_c,\, n,\, \theta_i = \phi_i/f\}$

$$f_{\rm EDE}(z_c) \equiv \frac{\rho_{\rm EDE}}{\rho_{\rm tot}}\Big|_{z_c} = \frac{\rho_{\rm EDE}}{(3M_{pl}^2 H^2)}\Big|_{z_c} \simeq \frac{V(\theta_i)}{\rho_{\rm tot}(z_c)} = \frac{m^2 f^2}{\rho_{\rm tot}(z_c)}(1 - \cos\theta_i)$$

Early dark energy

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

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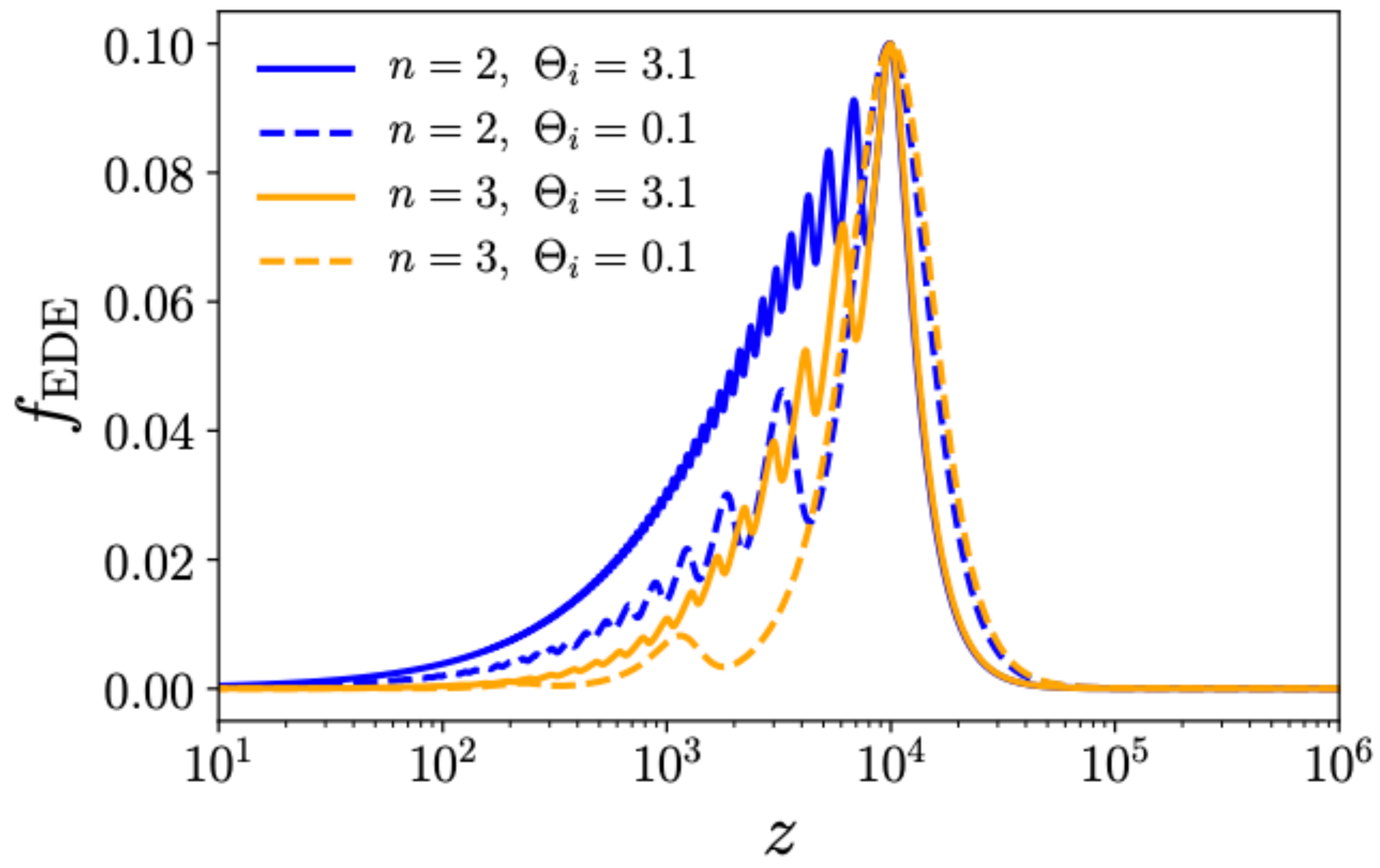
Smith et al 2019



Phenomenological parameters $\{f_{\rm EDE}(z_c),\ z_c,\ n,\ \theta_i = \phi_i/f\}$

$$f_{\rm EDE}(z_c) \equiv \left.\frac{\rho_{\rm EDE}}{\rho_{\rm tot}}\right|_{z_c} = \left.\frac{\rho_{\rm EDE}}{(3M_{pl}^2 H^2)}\right|_{z_c}$$

We usually fix $n = 3$

$$\Longrightarrow \{f_{\rm EDE}(z_c),\ z_c,\ \theta_i\}$$

Matteo Braglia et al 2020, Adrià Gómez-Valent et al 2021, …

Early dark energy

Does EDE really solves the H_0 tension?

Early dark energy can resolve the Hubble tension

2019

EDE from CMB

V. Poulin, T. Smith, T. Karwal,
M. Kamionkowski, 2019

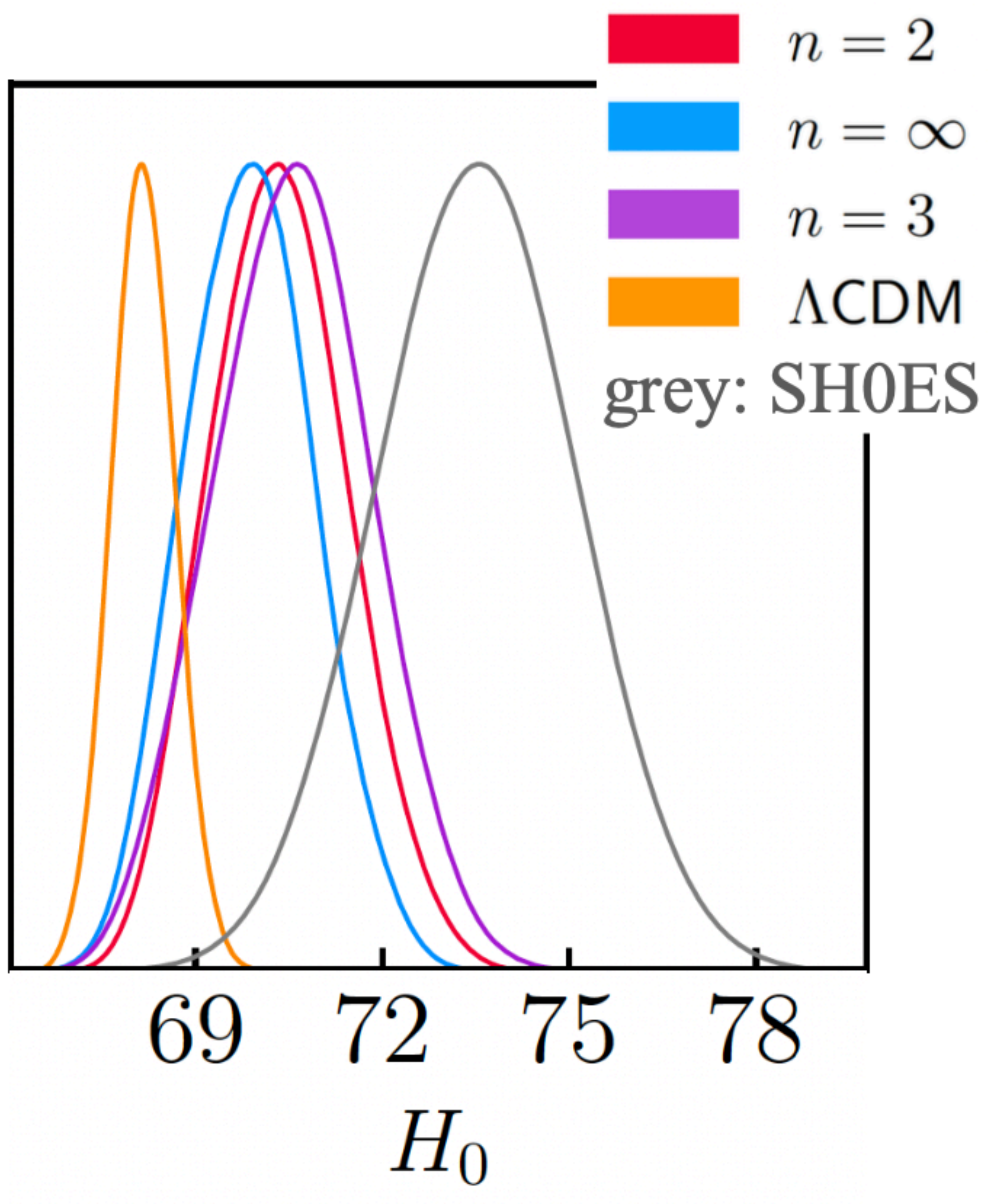
- For: *Planck + BOSS DR12 BAO/RSD + 6dFGS + Pantheon* + *SHOES 2016*

$$H_0 = 71.49 \pm 1.20\,\mathrm{km/s/Mpc}$$

Solves the tension!

$$f_{\rm EDE} = 0.107^{+0.035}_{-0.030}$$

$\uparrow f_{\rm EDE}$ $\uparrow H_0$



$w_{cdm} = \Omega_{cdm}\, h^2$

Early dark energy can resolve the Hubble tension

2019

V. Poulin, T. Smith, T. Karwal,
M. Kamionkowski, 2019

EDE from CMB

- For: *Planck + BOSS DR12 BAO/RSD + 6dFGS + Pantheon* + *SHOES 2016*

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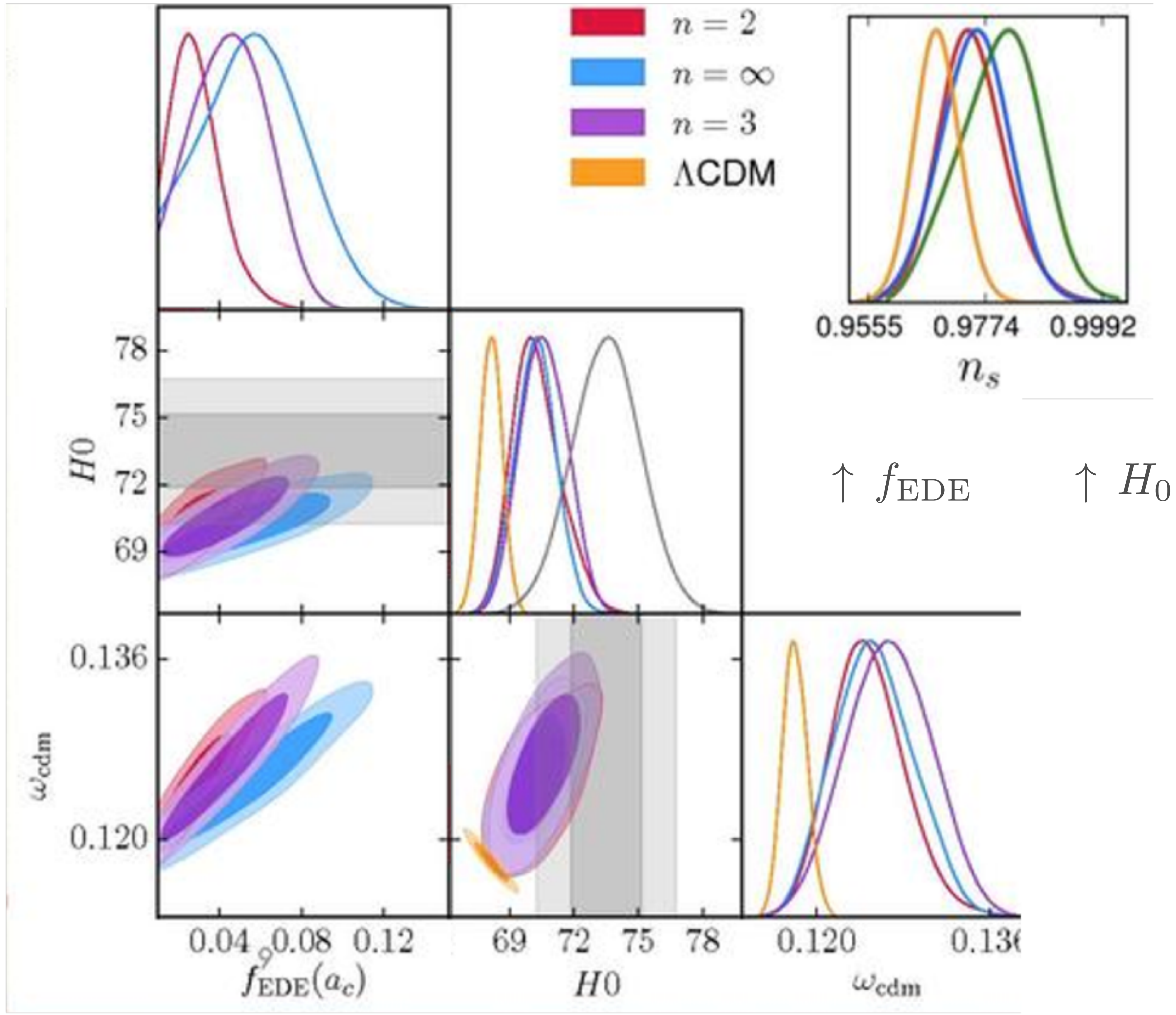
Solves the tension!



$\uparrow f_{\rm EDE}$ $\uparrow H_0$

But with:
- More DM
- Higher n_s

$$w_{cdm} = \Omega_{cdm}\, h^2$$

Early dark energy does NOT *restore cosmological concordance*

EDE from LSS

2020

Use LSS to constrain EDE

- CMB: *Planck* 2018 TT, TE, EE
- LSS
  - *Planck* lensing
  - "Compressed" likelihood
    - BAO
  - Weak lensing from KIDS+VIKING-450 + HSC

Early Dark Energy Does Not Restore Cosmological Concordance

J. Colin Hill,[1,2] Evan McDonough,[3] Michael W. Toomey,[4] and Stephon Alexander[3]

Uniform prior in the phenomenological parameters

$$f_{\rm EDE}, z_c, \theta_i$$

Early dark energy does NOT *restore cosmological concordance*

EDE from **LSS**

- For: *Planck + BOSS DR12 BAO/RSD + 6dFGS + Pantheon* + ~~*SHOES 2016*~~ + *DES + KiDS + VIKING*

Constraints on EDE ($n = 3$) for varying data sets

Parameter	*Planck* 2018 TT+TE+EE	*Planck* 2018 TT+TE+EE, CMB lensing, BAO, RSD, SNIa, and SH0ES	*Planck* 2018 TT+TE+EE, CMB lensing, BAO, RSD, SNIa, SH0ES, and DES-Y1	*Planck* 2018 TT+TE+EE, CMB lensing, BAO, RSD, SNIa, SH0ES, DES-Y1, and HSC, KiDS (S_8)	*Planck* 2018 TT+TE+EE, CMB lensing, BAO, RSD, SNIa, DES-Y1, and HSC, KiDS (S_8) (no SH0ES)
$\boldsymbol{f}_{\mathbf{EDE}}$	< 0.087	0.098 ± 0.032	$0.077^{+0.032}_{-0.034}$	$0.062^{+0.032}_{-0.033}$	< 0.060
H_0 [km/s/Mpc]	$68.29^{+1.02}_{-1.00}$	70.98 ± 1.05	$70.75^{+1.05}_{-1.09}$	$70.45^{+1.05}_{-1.08}$	$68.92^{+0.57}_{-0.59}$

"Concordance" of EDE:
$f_{\rm EDE} \sim 10\,\% > 0$ at 3.1σ

Hubble tension $\rightarrow 1.7\sigma$

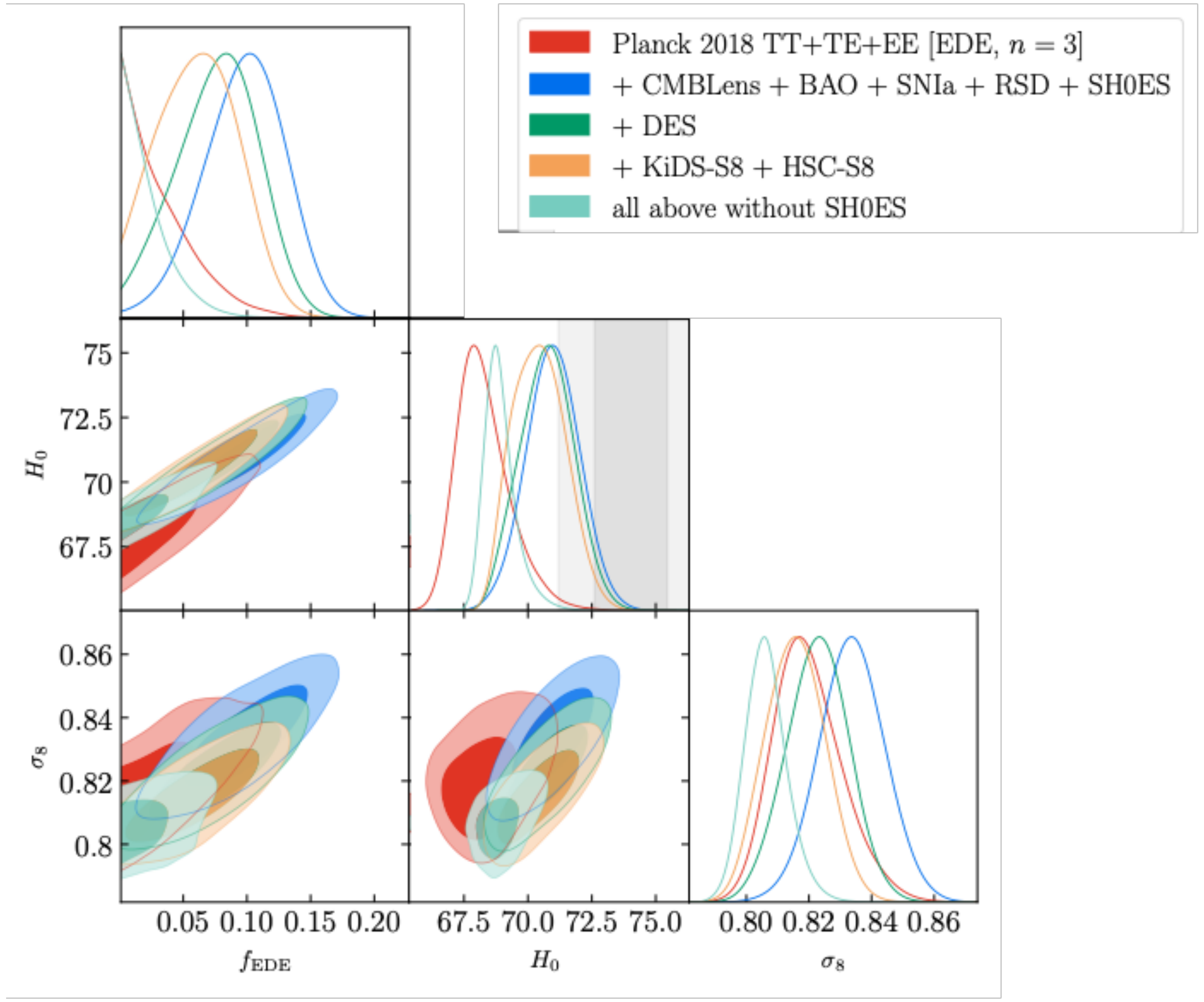
$\Longrightarrow$ Without SHOES, EDE **not** preferred by Planck CMB alone
$f_{\rm EDE} < 0.087$

$$H_0 = 68.92^{+0.57}_{-0.59}\ {\rm km/s/Mpc}$$

$\left(H_0^{\Lambda{\rm CDM}} = 68.33 \pm 0.36\,{\rm km/s/Mpc}\right)$

$f_{\rm EDE} < 0.06$ (95 % CL)

3.3σ tension with SHOES !!



Weak lensing strongly constraints σ_8, and EDE

No SHOES $\longrightarrow$ No solution to H_0 !

Early dark energy does NOT *restore cosmological concordance*

EDE from LSS

2020

Constraining Early Dark Energy with Large-Scale Structure

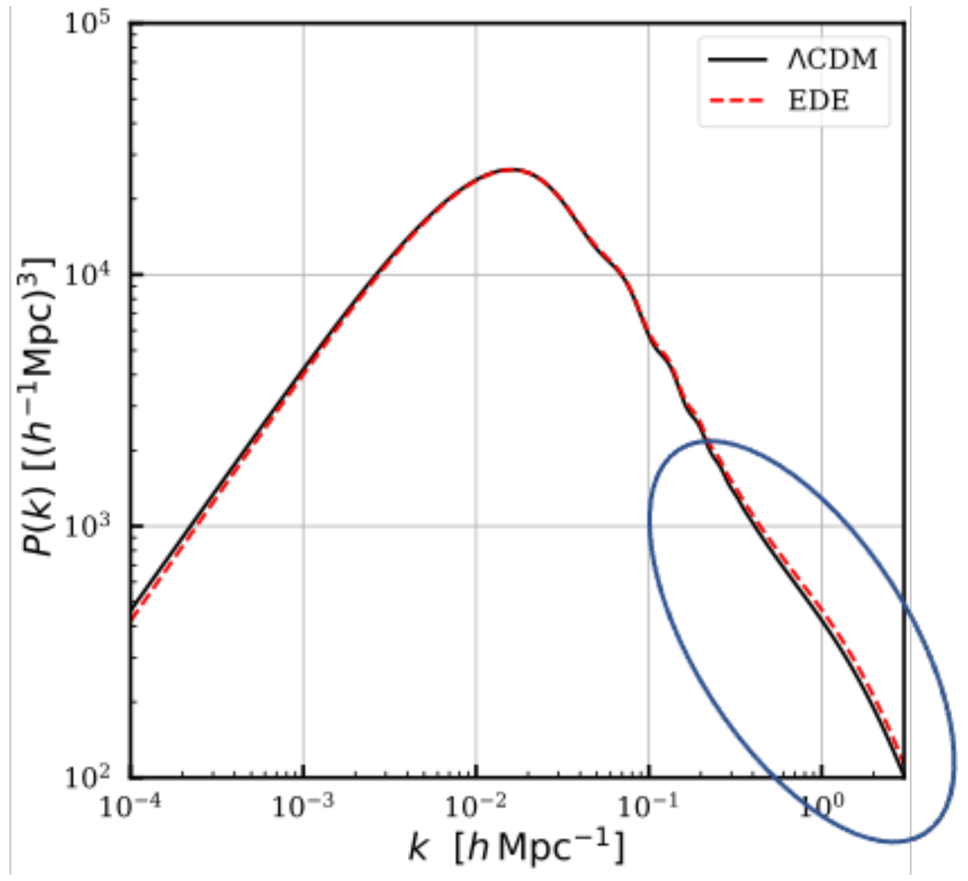
Mikhail M. Ivanov,[1,2] Evan McDonough,[3] J. Colin Hill,[4,5] Marko Simonović,[6]
Michael W. Toomey,[7] Stephon Alexander,[7] and Matias Zaldarriaga[8]

Use LSS to constrain EDE

- CMB: *Planck* 2018 TT, TE, EE
- LSS
  - *Planck* lensing
  - "Compressed" likelihood
    - BAO
  - Weak lensing from KIDS+VIKING-450 + HSC
  - FULL SHAPE OF THE PS ⟵

    Allows to model the galaxy PS up to mildly non-linear scales ($k \sim 0.5\, h/\mathrm{Mpc}$)

More DM changes the matter power spectrum on small scales ⟶ full-shape analysis can constrain small scale clustering



* Similar results in D'Amico, Senatore, Zhang, Zheng 2020

Early dark energy does NOT *restore cosmological concordance*

EDE from LSS

- For: *Planck* + *BOSS DR12 BAO/RSD* + ~~*SHOES 2016*~~ + *full-shape of PS*

Constraints from *Planck* 2018 data + BOSS DR12

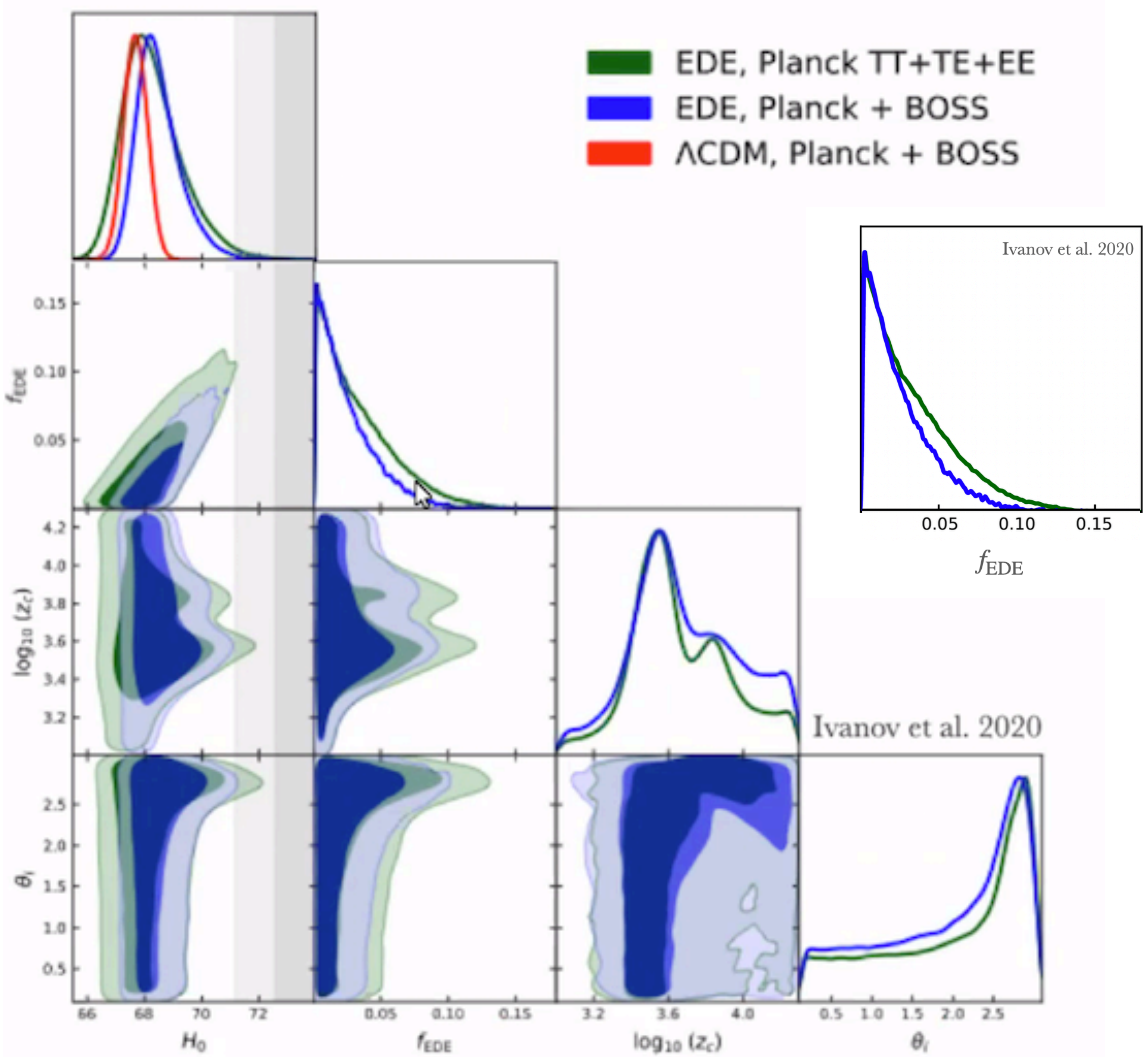
Parameter	ΛCDM	EDE ($n = 3$)
$\boldsymbol{f_{\rm EDE}}$	–	$< 0.072\,(0.047)$
H_0 [km/s/Mpc]	$67.70\,(67.56)\ \pm 0.42$	$68.54\,(68.83)^{+0.52}_{-0.95}$
$\Omega_{\rm m}$	$0.3105\,(0.3112)^{+0.0053}_{-0.0058}$	$0.3082\,(0.3120)^{+0.0056}_{-0.0057}$

$$H_0 = 68.54^{+0.52}_{-0.95}\ \mathrm{km/s/Mpc}$$

$f_{\rm EDE} < 0.072$ (95 % CL)

3.6σ tension with SHOES !!

Adding S_8 prior $\longrightarrow$ $f_{\rm EDE} < 0.058$



Early dark energy does NOT *restore cosmological concordance*

EDE from LSS

2020

Early Dark Energy Does Not Restore Cosmological Concordance

J. Colin Hill,[1,2] Evan McDonough,[3] Michael W. Toomey,[4] and Stephon Alexand

Constraining Early Dark Energy with Large-Scale Structure

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Main messages:

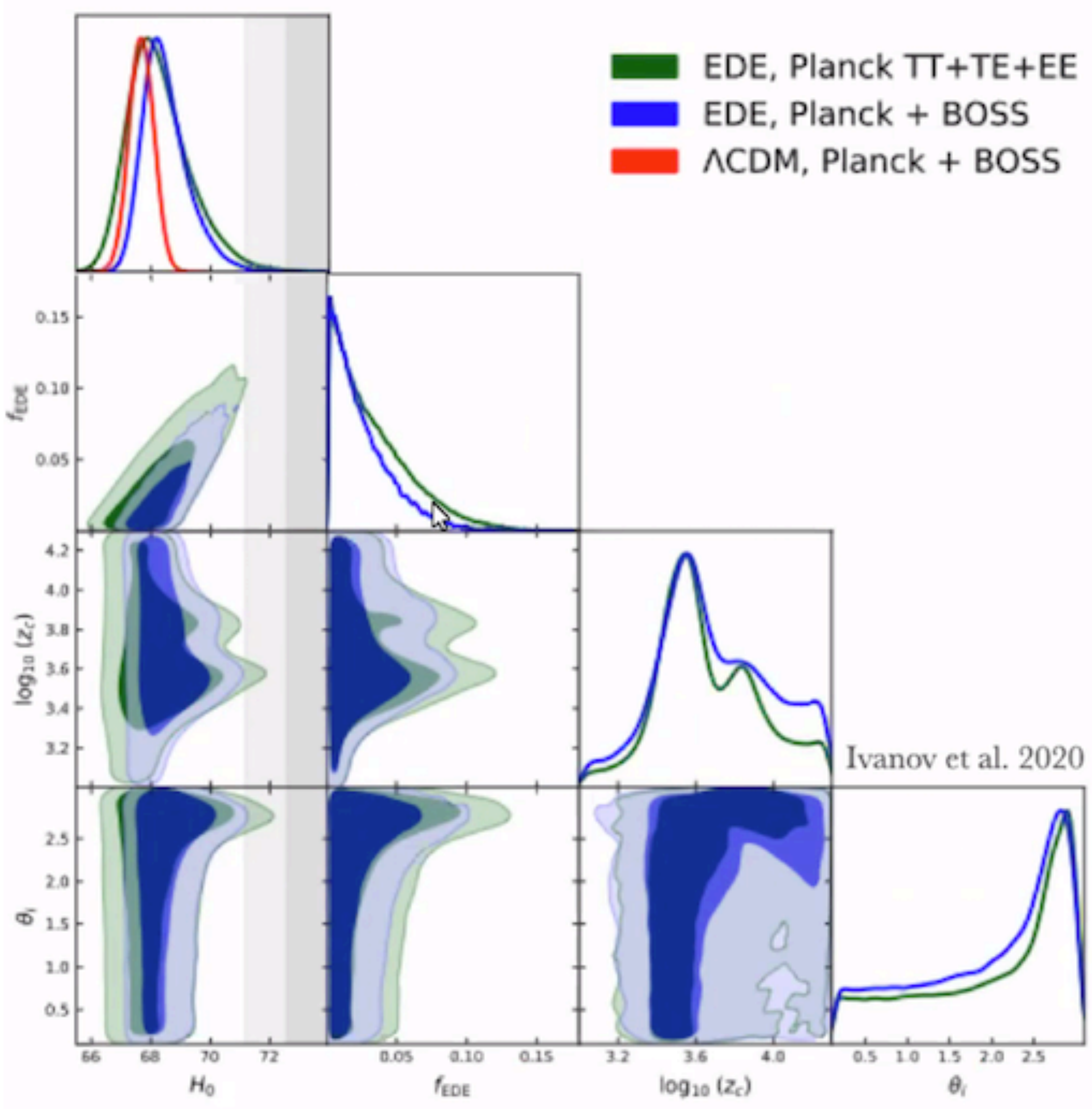
- EDE to solve the H0 tension it must fit a wide set of cosmological data sets available, not just a subset (e.g CMB).
- **No evidence** for EDE from CMB (*Planck*) alone or CMB+LSS (no SHOES) ⟶ in tension with SHOES
  - Reason: higher H_0 requires higher f_{EDE}, which increases CDM ⟶ worse fit to LSS data
- Get H0 consistent with SHOES without including SHOES *(only include the local SH0ES prior if you are sure your model can go a good way towards solving the H0 tension).*

Early dark energy does NOT solve Hubble tension!

Wait…

Not all groups agree with this result

- Previous result can be a consequence of choice of priors of the EDE parameters



Ivanov et al. 2020

Volume effects: $f_{\rm EDE} \to 0$, any value of $\log(z_c)$ and θ_i, degenerate with ΛCDM

↓

Marginalization: preference for $f_{\rm EDE} \sim 0$

- $\log(z_c)$ and θ_i are not well constrained by data

→ Ivanov et al checked for volume effects in their paper, finding no evidence

Wait…

Not all groups agree with this result

Volume effects?

- For: *Planck* + *BOSS DR12 BAO/RSD* + ~~*SHOES 2016*~~ + *Pantheon* + *full-shape of PS*

Same data set as in Ivanov et al and D'Amico et al!

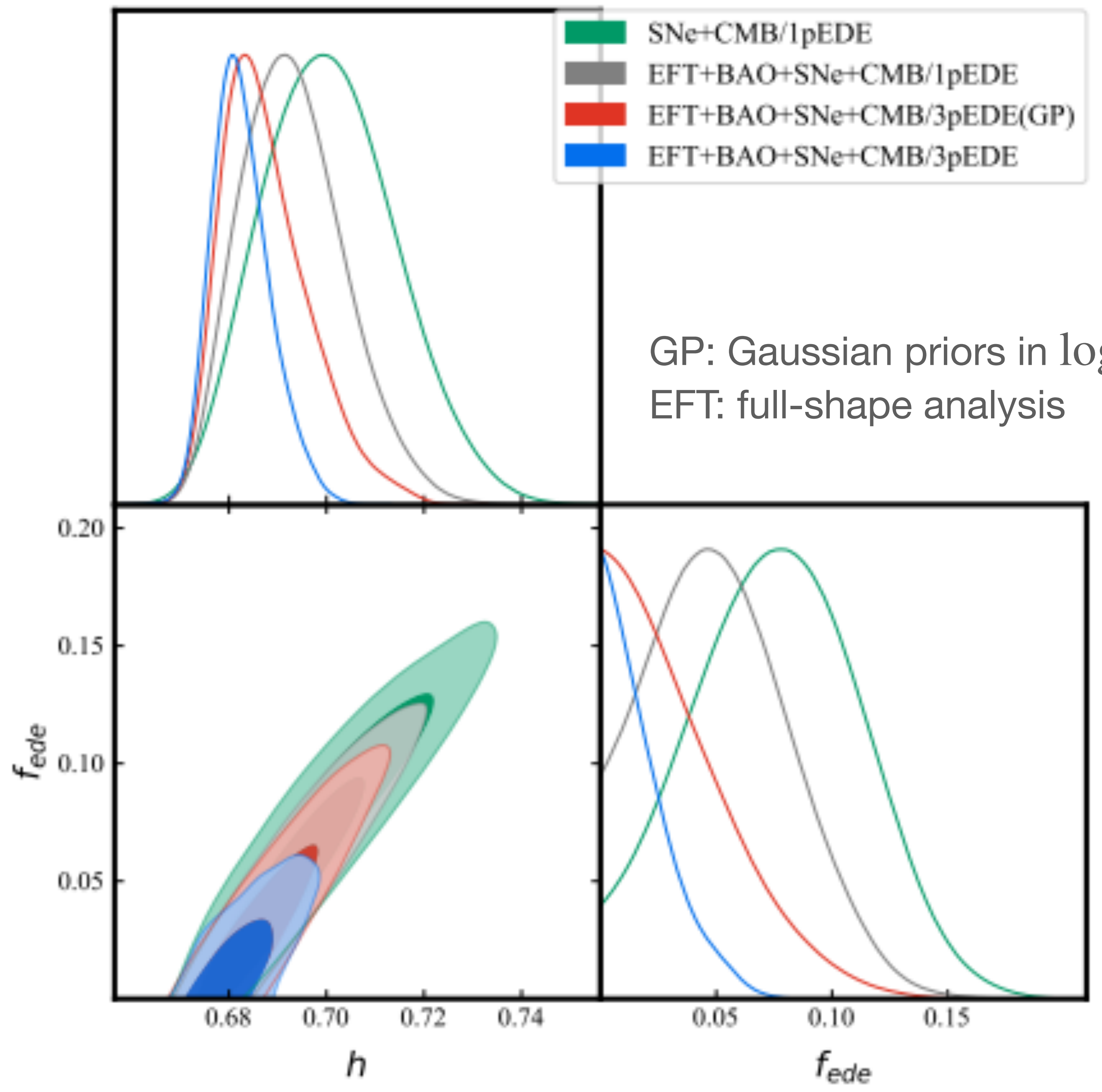
Attempt to mitigate volume effects by considering a *1 parameter model* EDE: only $f_{\rm EDE}$ free with $\log(z_c) = 3.569$ and $\theta_i = 2.775$

$$f_{\rm EDE} = 0.72 \pm 0.034$$

Conclusion: - 1pEDE allows for large $f_{\rm EDE}$
- Potential resolution to the Hubble tension
- Volume effects?

BUT, this is not the full analysis (1 parameter only)
Dependence on the values of z_c and θ_i ?

Early dark energy is ***NOT*** excluded by current LSS data
T. Smith et al (2020)
Niedermann, Sloth (2019)



GP: Gaussian priors in $\log(z_c)$ and θ_i
EFT: full-shape analysis

Summary - status

Early time solutions to the Hubble tension

$\theta_s(z_*)$: $\downarrow r_s(z_*) \implies \downarrow D_A(z_*) \implies \uparrow H_0$

Fixed

Early dark energy

2019

EDE can resolve the Hubble tension

CMB + SHOES

$H_0 = 71.49 \pm 1.20\,\mathrm{km/s/Mpc}$

2020

EDE cannot resolve the Hubble tension

CMB + LSS (including FS)

$H_0 = 68.54^{+0.52}_{-0.95}\,\mathrm{km/s/Mpc}$

3.6σ tension with SHOES !!

EDE can resolve the Hubble tension

CMB + LSS (FS) - 1pm

2021

(Maybe) EDE is back

ACT (+ Planck + BAO)

$H_0 = 70.9^{+1.0}_{-2.0}\,\mathrm{km/s/Mpc}$

??

The status of EDE is still open. Many open questions:

- Why those results do not agree?
- Volume effects?
- Systematics in ACT?
- New window function for FS

Prior volume effects

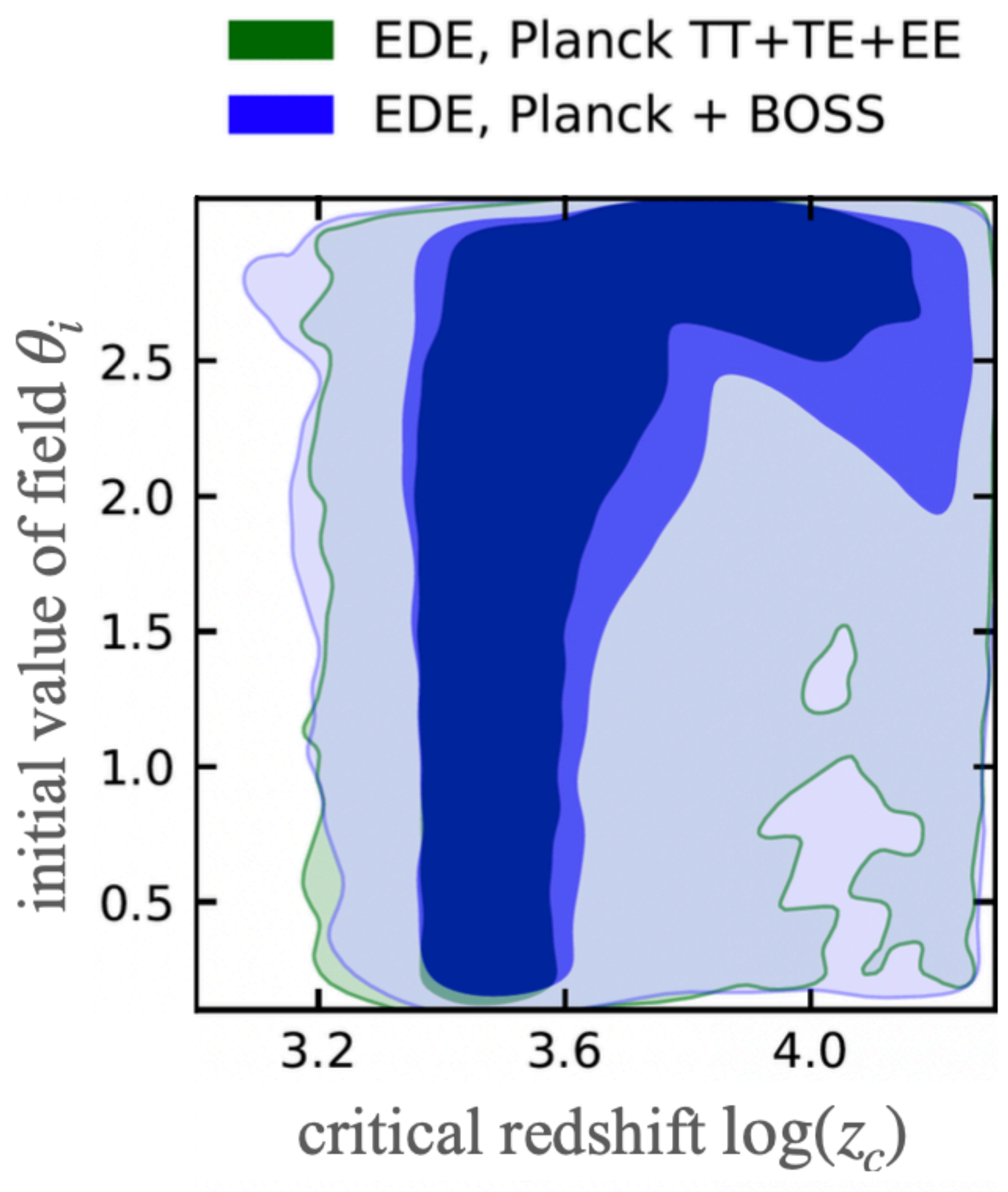
Bayesian marginalization of the full-dimensional posterior involves integrating out the nuisance dimensions

Since in addition to the value of the posterior, an integral is sensitive to the volume in these directions

→ Large parameter regions (of possibly non-maximal posterior values) are emphasized compared to smaller regions (of possibly larger posterior values).

Inescapable feature of the Bayesian method!!

(volume effect can occur even with flat priors)



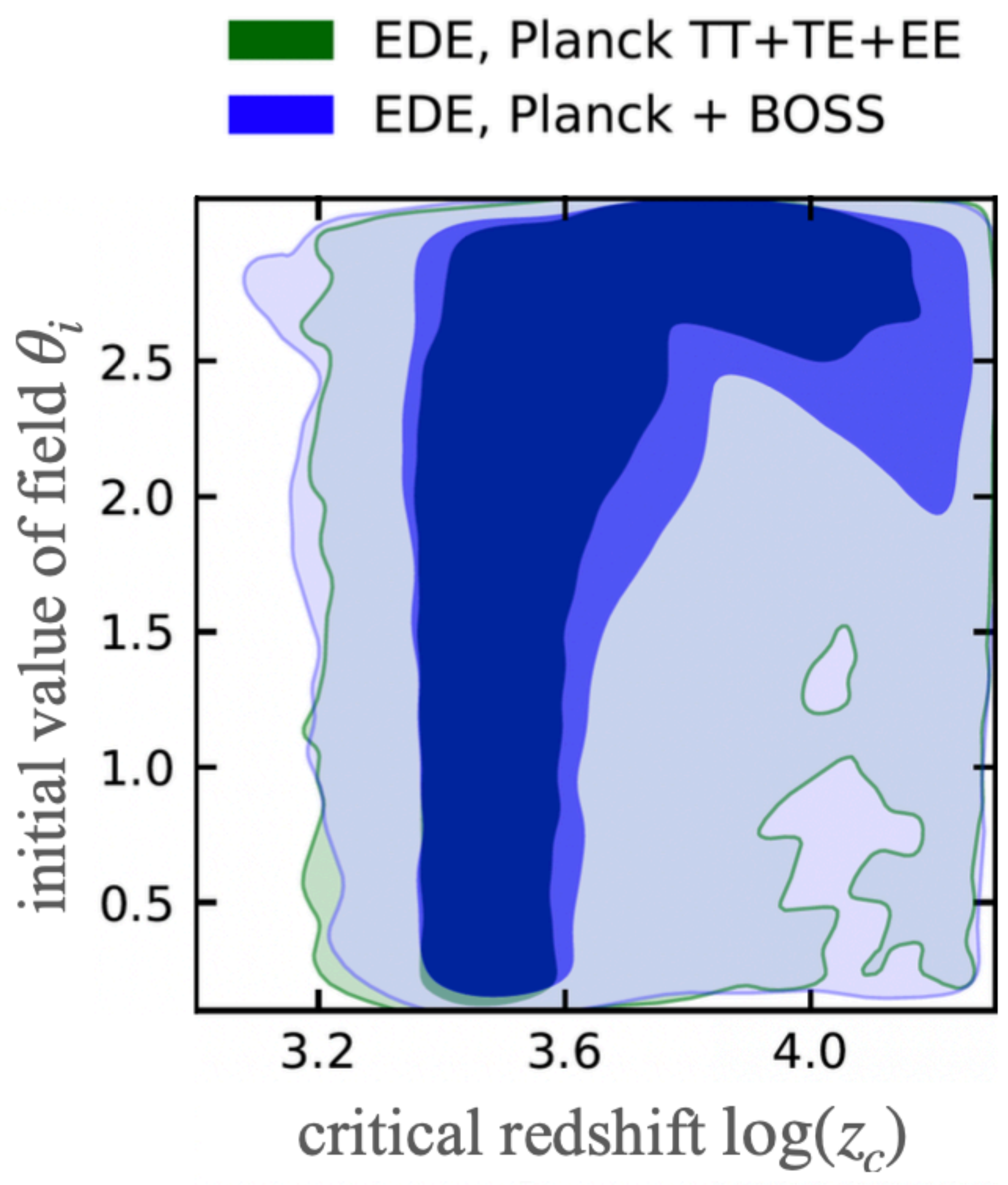
Ivanov et al. 2020

Prior volume effects

Prior volume effects or marginalization effects: ...appear if the posterior is dominated by the prior volume

When they appears:

- 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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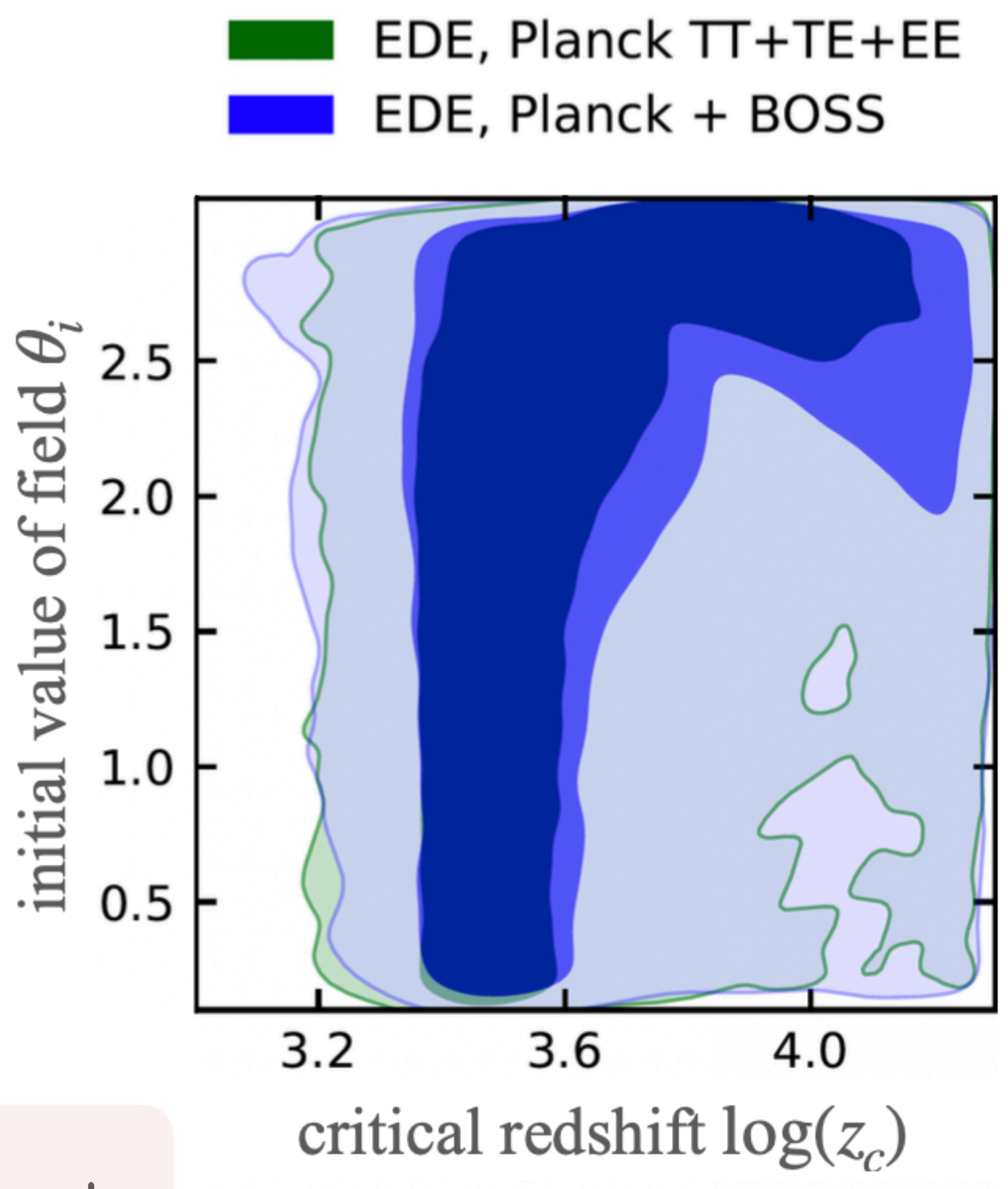
⟶ Bias* in the marginalized posterior

** offset induced by a projection effect*



Ivanov et al. 2020

Relevant to study the extent to which one's results are affected by volume effects!

Prior volume effects

Prior volume effects or marginalization effects: ...appear if the posterior is dominated by the prior volume

When they appears:

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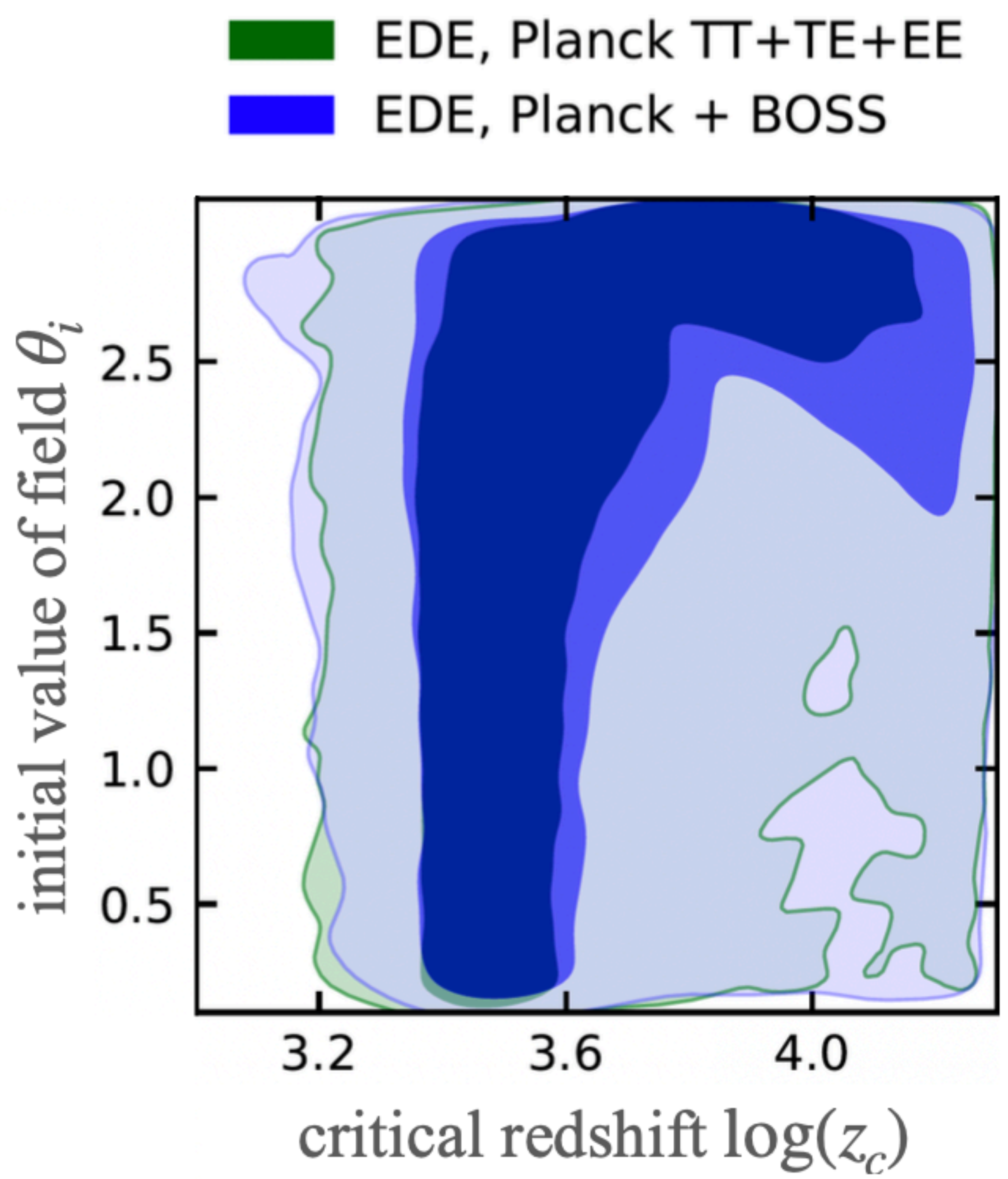
- Posterior is very non-Gaussian.
- Parameter structure of the model generates large volume differences.



Ivanov et al. 2020

Other effects:

Prior weight effect: non-flat priors will affect the posterior in a direct way when they do not align with the likelihood. This can manifest in, for example, a shift of the posterior peak or a scaling of its width.

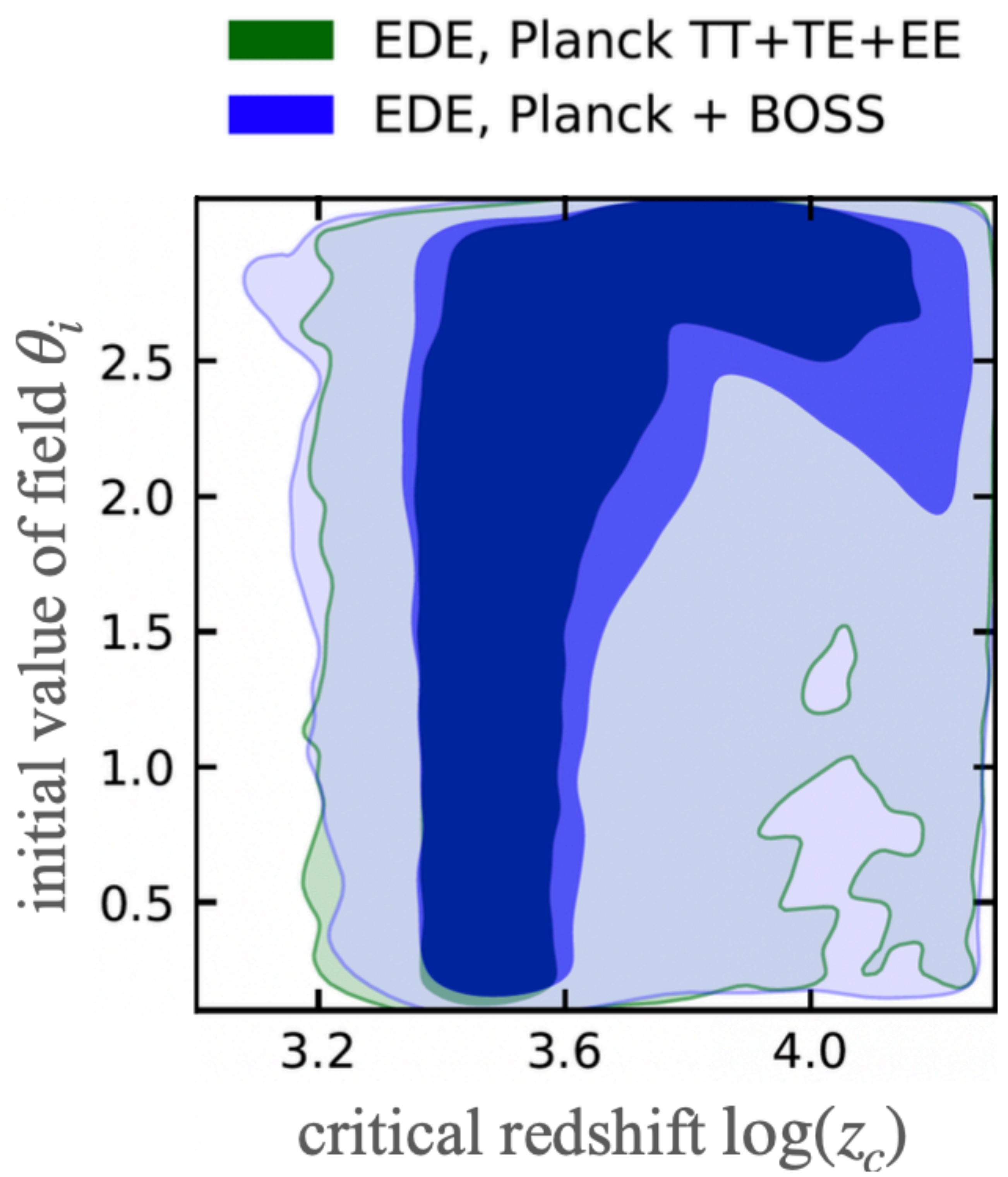
Prior volume effects

Prior volume effects or marginalization effects: ...appear if the posterior is dominated by the prior volume

When they appears:

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

$\longrightarrow$ Bias in the marginalized posterior



Ivanov et al. 2020

Idea: Profile likelihood not subjected to volume effects

Profile likelihood

Motivation:

Frequentist method for comparison with Bayesian to check for prior or marginalization effects

What is the profile likelihood $L(\theta)$ or $\chi^2(\theta)$?

Profile likelihood is a method in frequentist statistics, that allows to treat nuisance parameters

By splitting the full parameter space Θ into two categories:

- θ of N parameters
- ν of M (nuisance) parameters

⇒ Profile likelihood of θ is obtained by **maximization** over all parameters in the complementary set of (nuisance) parameters ν for **fixed** $\boldsymbol{\theta}$

Nuisance parameters

$$L(\boldsymbol{\theta}) = \max_{\boldsymbol{\nu}} \underbrace{L(\boldsymbol{\theta}, \boldsymbol{\nu})}_{\text{Full likelihood function}},$$

Full likelihood function

Profile likelihood

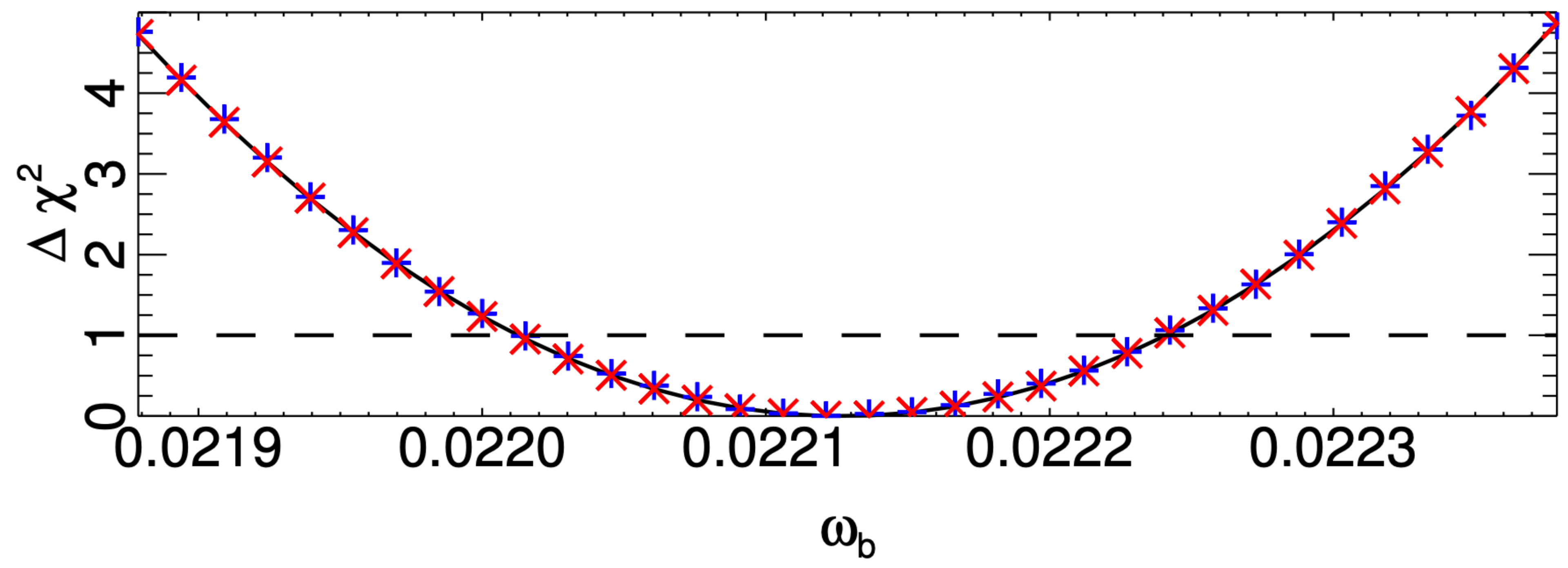
Motivation:

Frequentist method for comparison with Bayesian to check for prior or marginalization effects

What is the profile likelihood $\chi^2(\theta)$?

- Fix the parameters of interested θ to different values
- Maximize the likelihood L (minimizes $\chi^2 = -2 \ln L$) wrt to the other parameters for different values of the parameter of interest
- For Gaussian distribution this gives a parabola → fit a parabola

Planck intermediate results XVI, 2014



Confidence interval:

- A confidence region, can be extracted from the likelihood ratio statistic: $\Delta\chi^2(\theta) = \chi^2(\theta) - \chi^2_{\rm min} = -2\ln(\mathscr{L}/\mathscr{L}_{\rm max})$
- For parabolic $\chi^2(\theta)$, and one dof, the c.i. is given by:

  $\Delta\chi^2 = 1, 2.7, 3.84$ for 68, 90 and 95%, respectively $\longrightarrow$ Neyman construction

$\chi^2_{\rm min}$ is obtained from global maximum likelihood estimate given the entire set of parameters

Profile likelihood

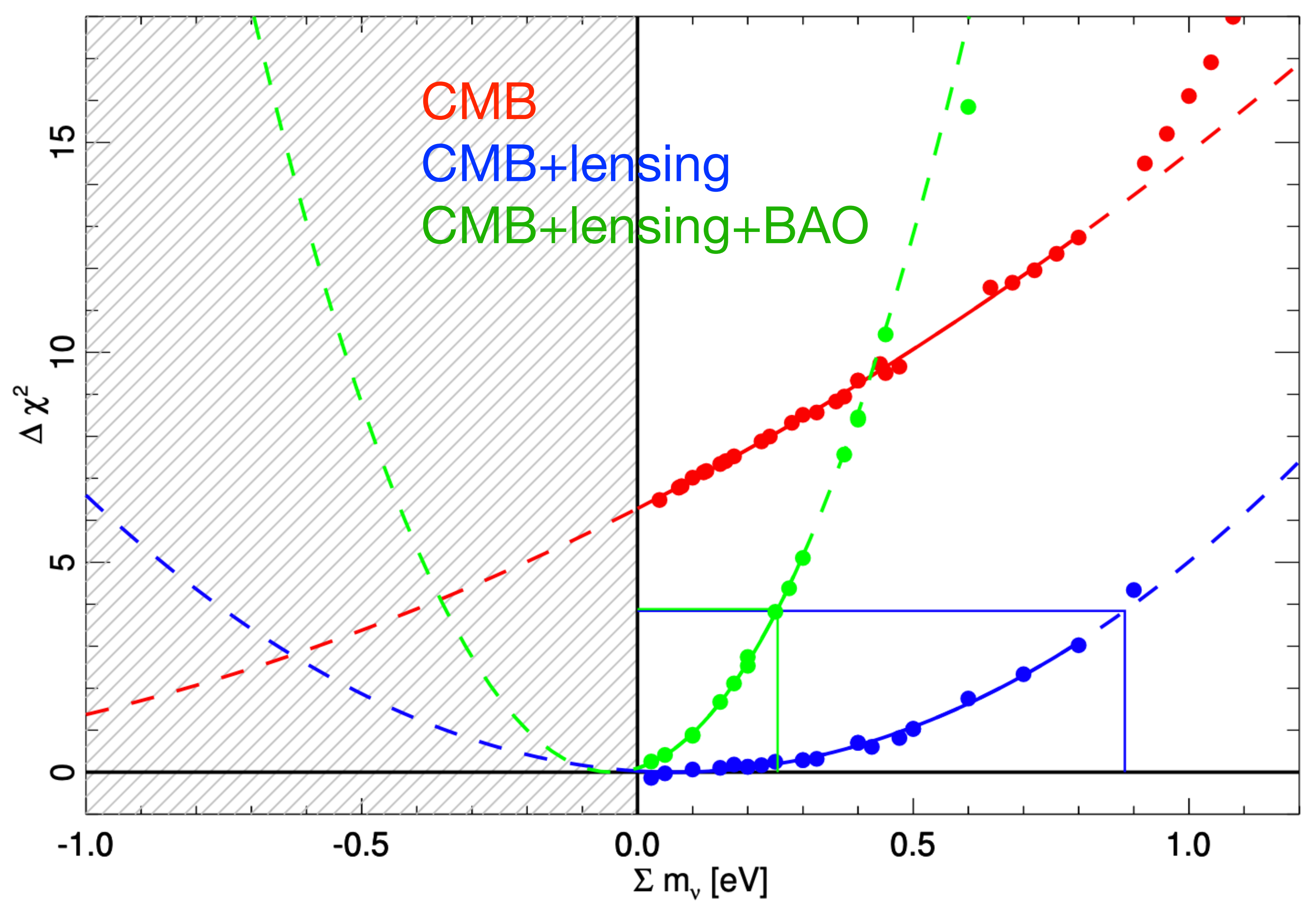
Advantages:

- Not affected by volume effects (no priors)
- Invariant under reparametrizations (since $L(\theta)$ is a MLE)
- Allows construction of confidence intervals close to boundaries

Disadvantages:

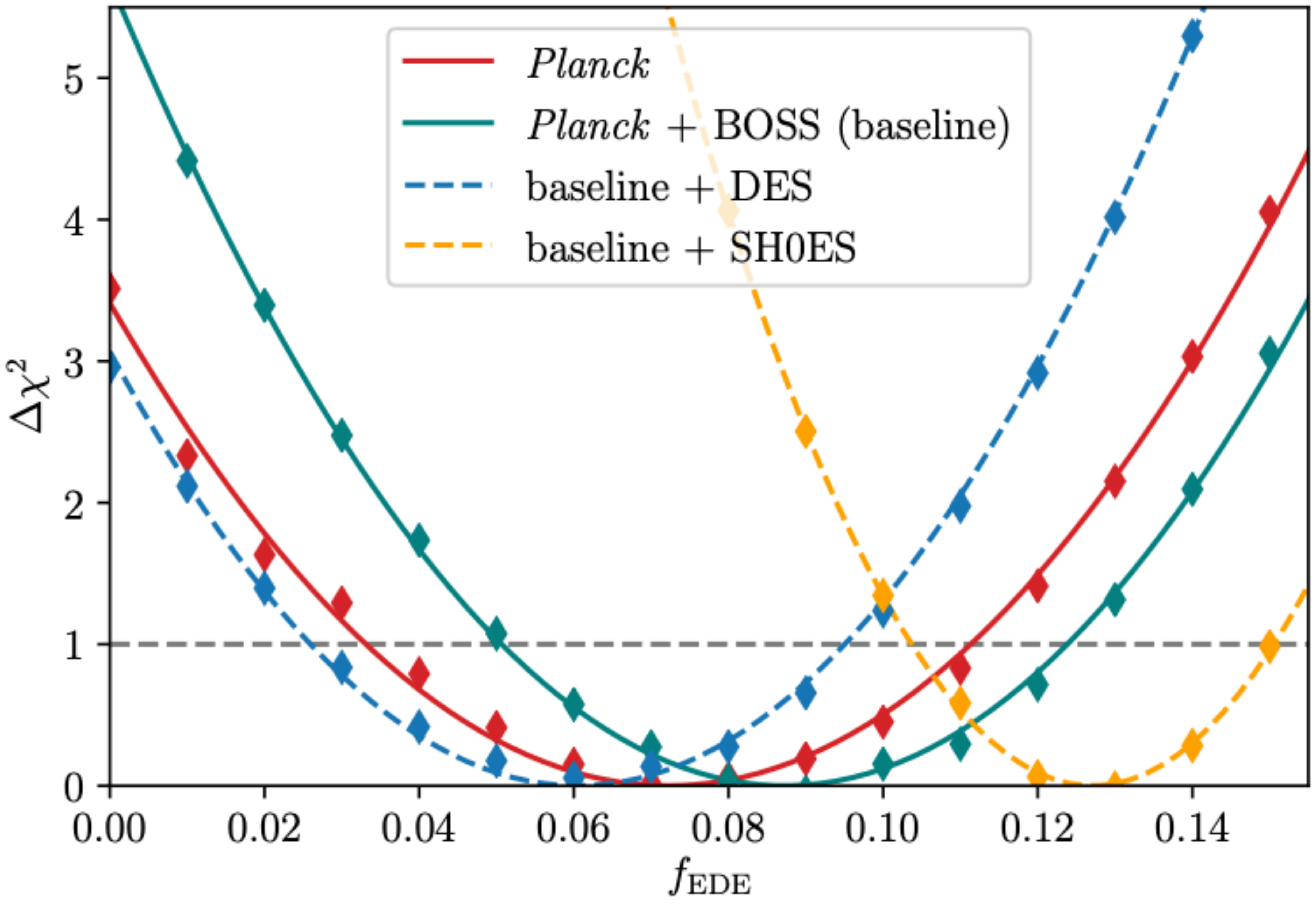
- Computationally expensive

"Larger confidence intervals"



Planck intermediate results XVI, 2014

Profile likelihood for $f_{\rm EDE}$



$$f_{\rm EDE}^{\rm (base)} = 0.087 \pm 0.037$$
(68%CL)

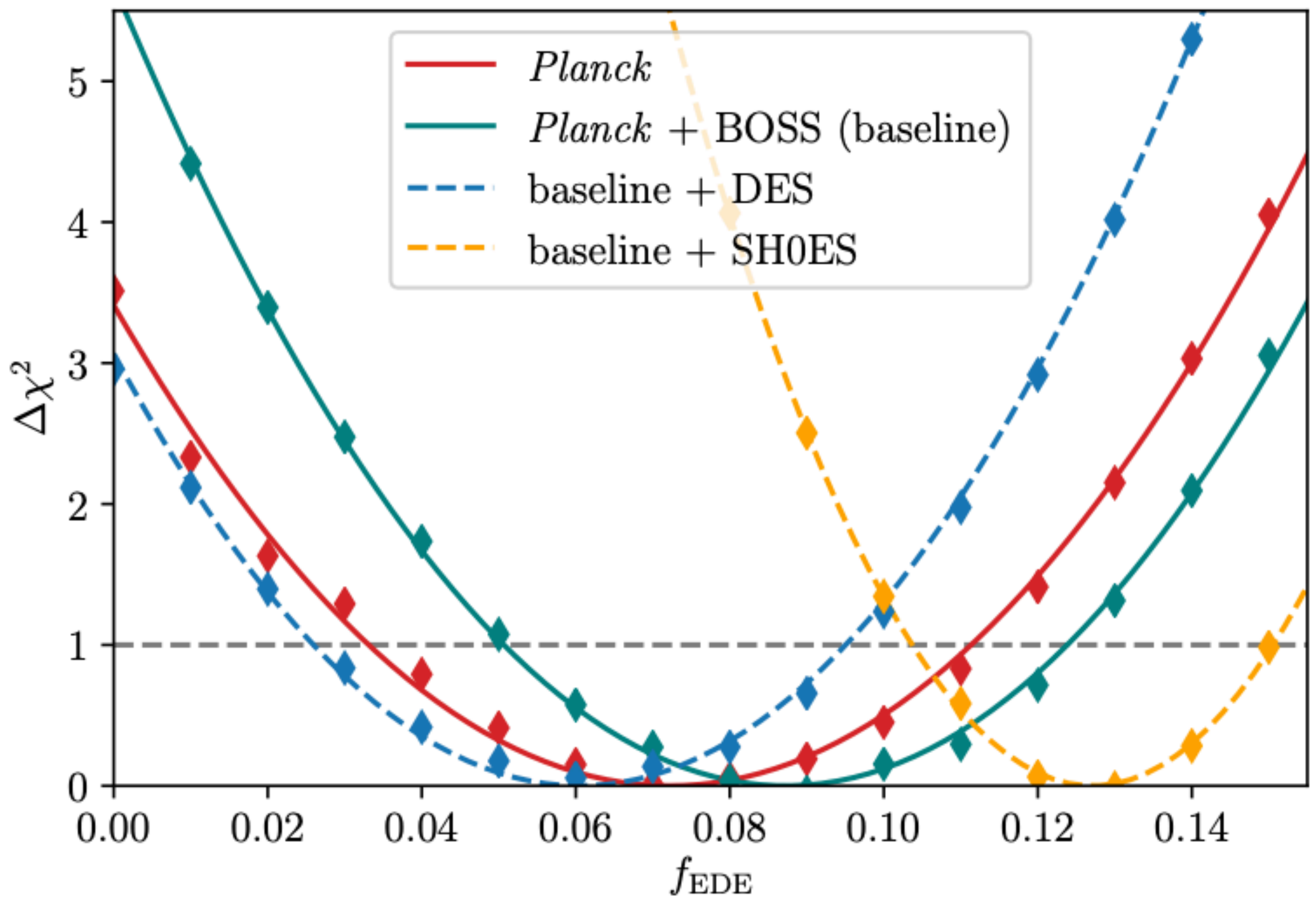
Old window function

$$f_{\rm EDE} = 0.072 \pm 0.036$$

Baseline: Planck+BOSS FS

Profile likelihood for $f_{\rm EDE}$

Check for *volume effects:*
comparison to previous results



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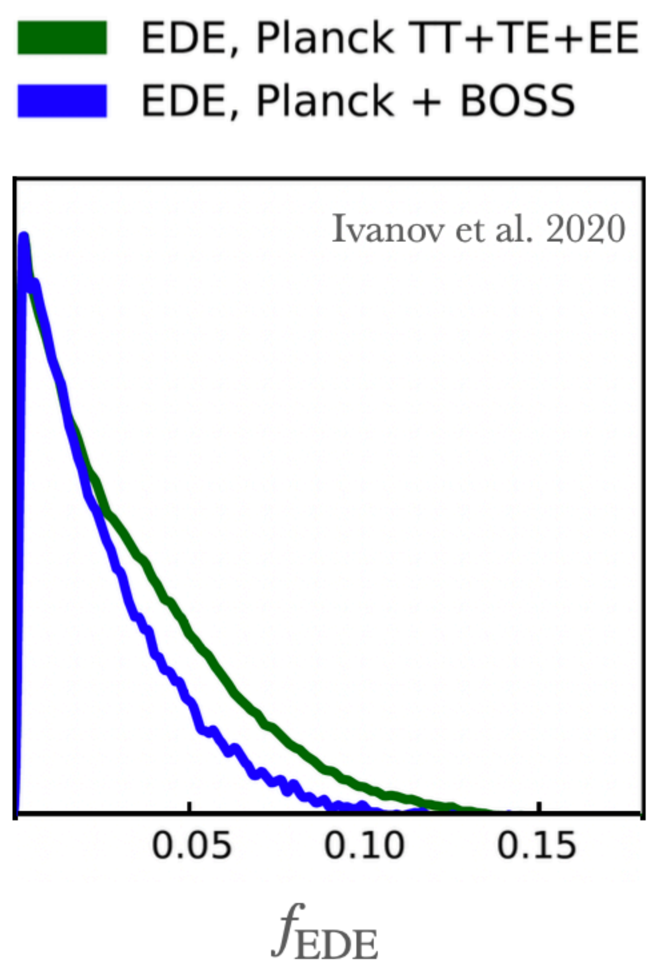
Baseline: Planck+BOSS FS

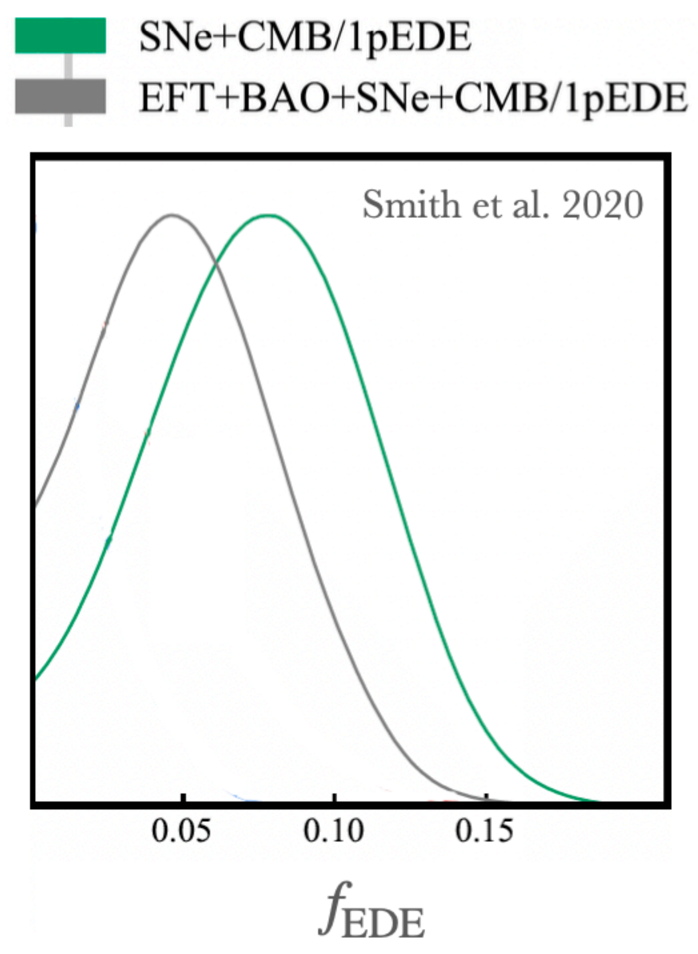


3-parameter model

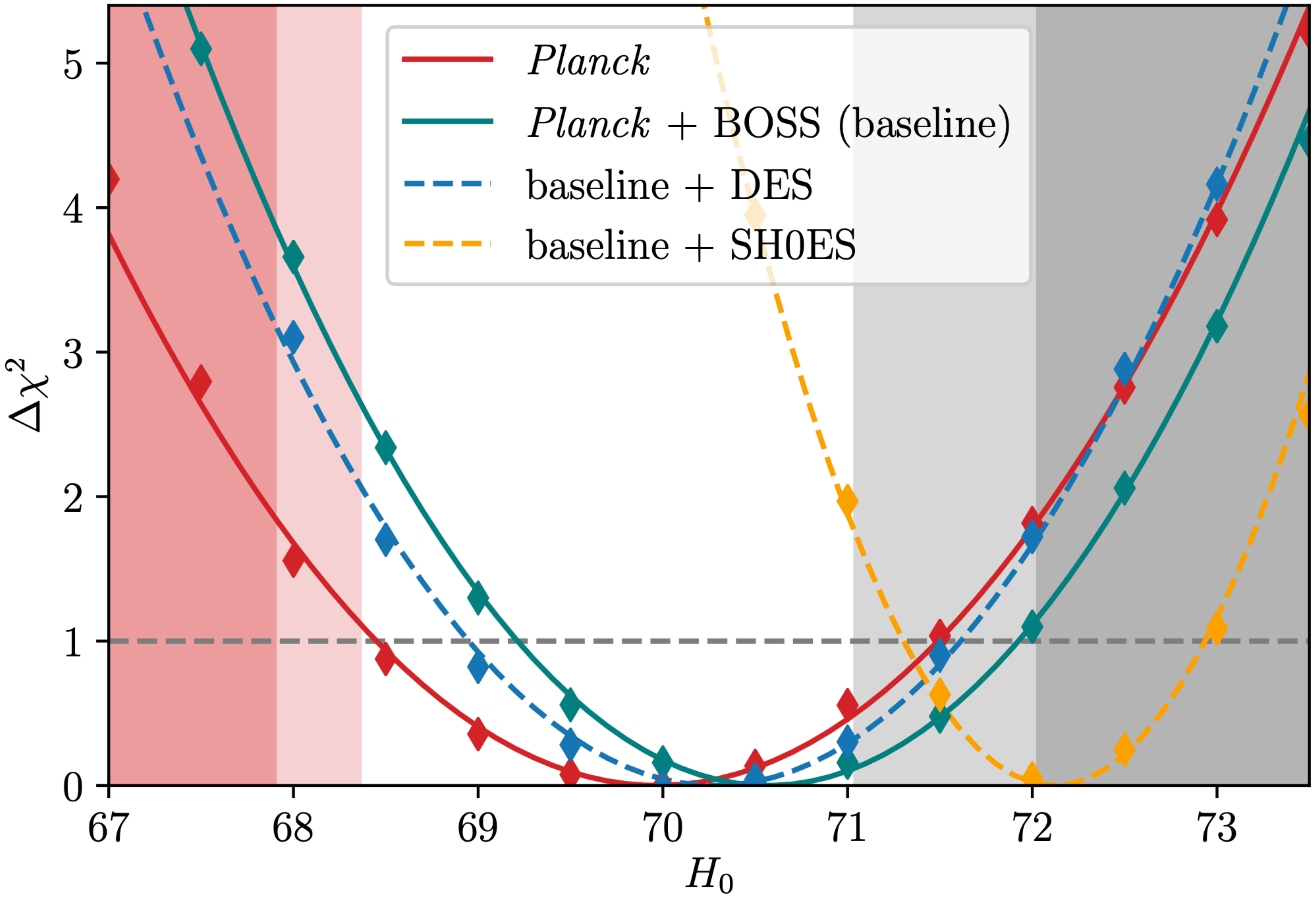
$$f_{\rm EDE} < 0.072 \quad (95\%CL)$$

1-parameter model

$$f_{\rm EDE} = 0.072 \pm 0.034$$
$(68\%CL)$



Profile likelihood for H0

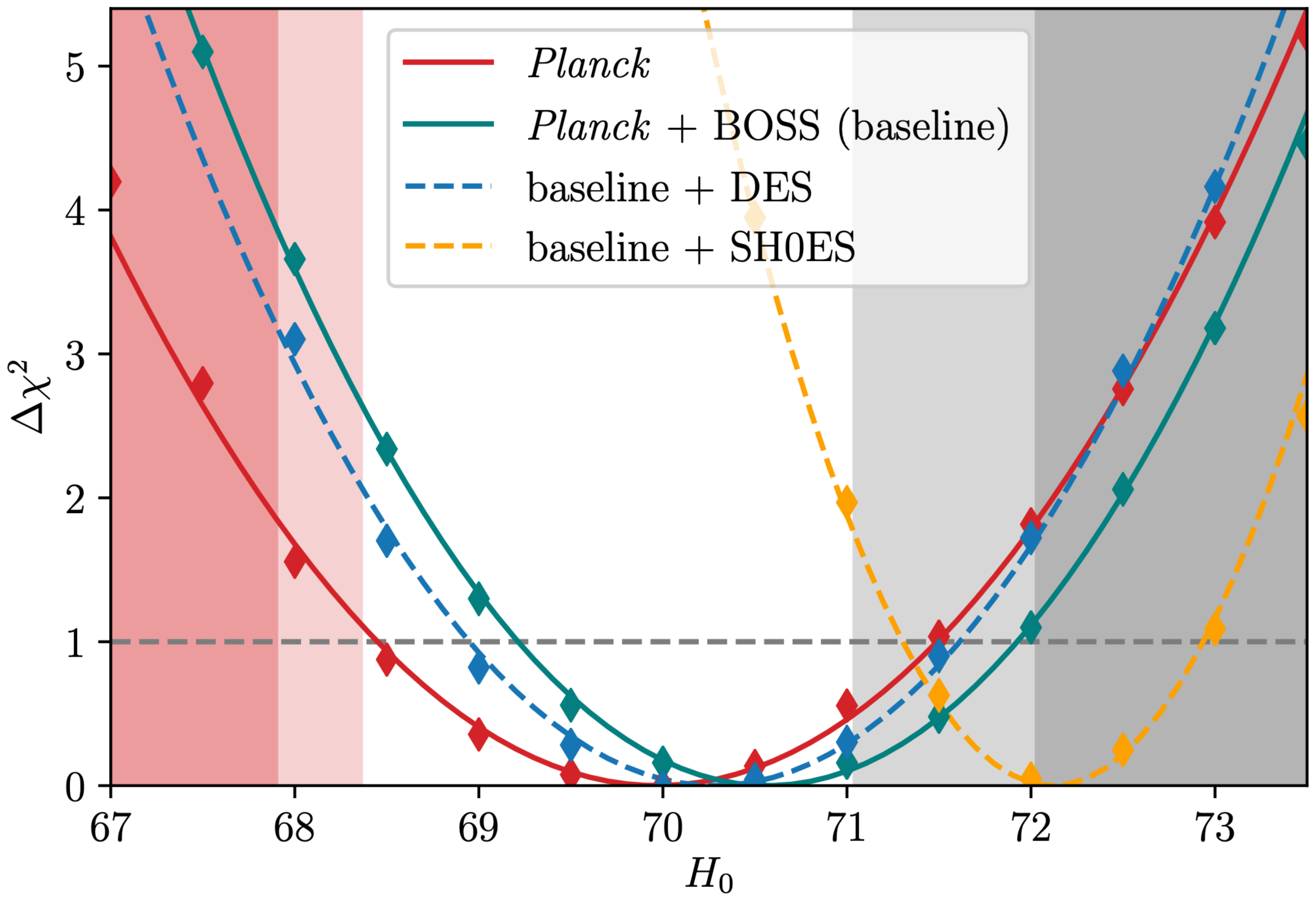


$$H_0^{\mathrm{EDE,(base)}} = 70.57 \pm 1.36$$
(68%CL)

Consistent with SHOES at 1.4σ !

Baseline: Planck+BOSS FS

Profile likelihood for H0



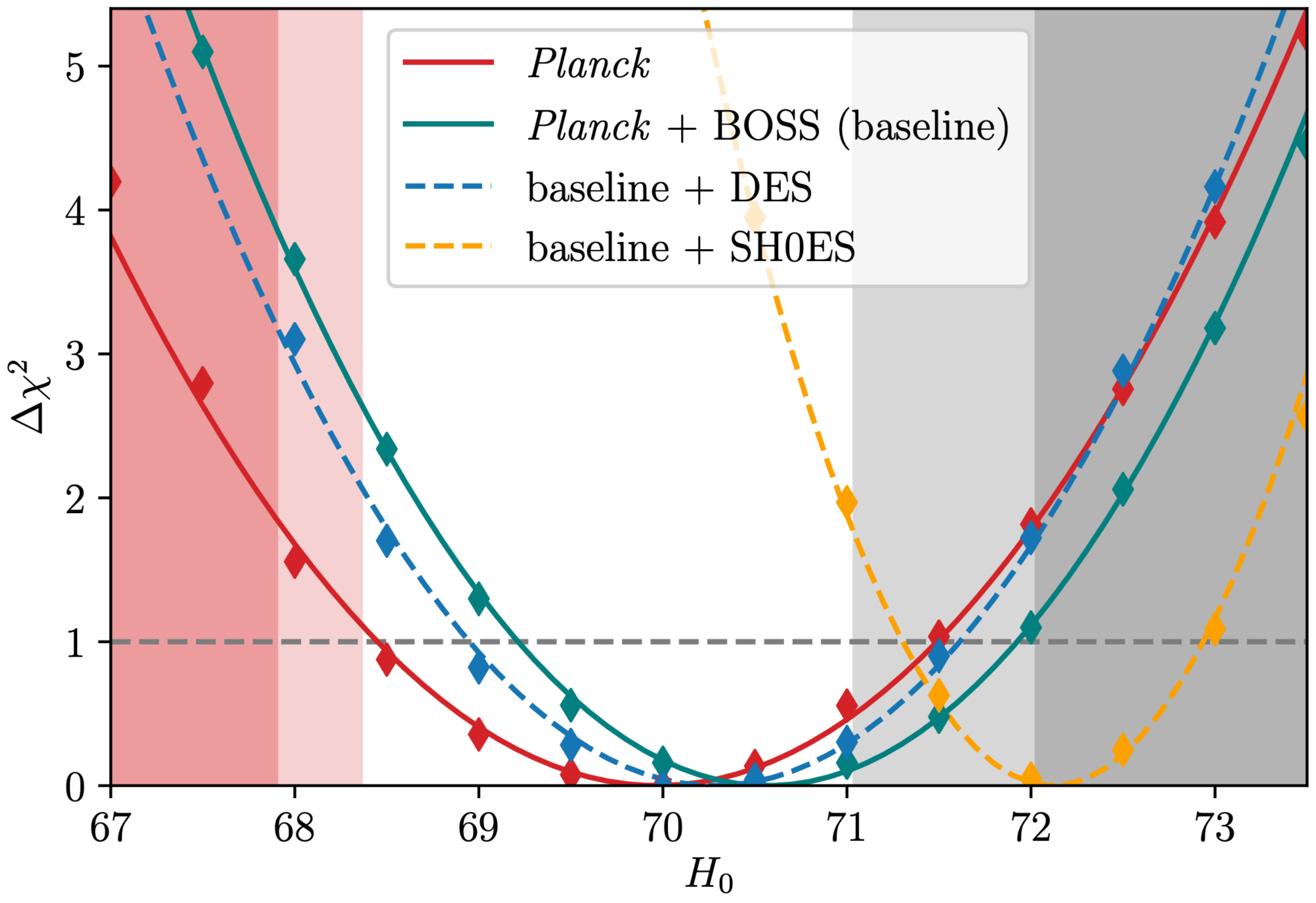
Data set	$\chi^2(\Lambda\mathrm{CDM})$	$\chi^2(\mathrm{EDE})$	$\Delta\chi^2$	f_{EDE}	H_0 (consistency w. SH0ES)
Planck	2774.24	2770.72	−3.52	0.072 ± 0.039	69.97 ± 1.52 ($1.7\,\sigma$)
Planck+BOSS (base)	3045.65	3039.98	−5.67	0.087 ± 0.037	70.57 ± 1.36 ($1.4\,\sigma$)
Baseline + DES	3052.06	3049.13	−2.93	$0.061^{+0.035}_{-0.034}$	70.28 ± 1.33 ($1.6\,\sigma$)
Baseline + SH0ES	3068.44	3042.08	−26.36	0.127 ± 0.023	72.12 ± 0.82 ($0.69\,\sigma$)

Consistent with SHOES at $< 1.4\sigma$!

EDE can solve the H0 tension

Baseline: Planck+BOSS FS

Profile likelihood for H0



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Baseline

ΛCDM $S_8 = 0.828$

$EDE(f_{\text{EDE}} = 0.09)$ $S_8 = 0.840$

Baseline + DES

ΛCDM $S_8 = 0.812$

$EDE(f_{\text{EDE}} = 0.06)$ $S_8 = 0.817$

DES

ΛCDM $S_8 = 0.0.776 \pm 0.017$

Baseline: Planck+BOSS FS

Going back to the behavior of EDE

EDE from CMB

C. Hill, E. McDonough, M. Toomey, S. Alexander, 2020

EDE fits the CMB power spectra remarkable well.

BUT this comes at the cost of shifting some cosmological parameters from the LCDM best-fit

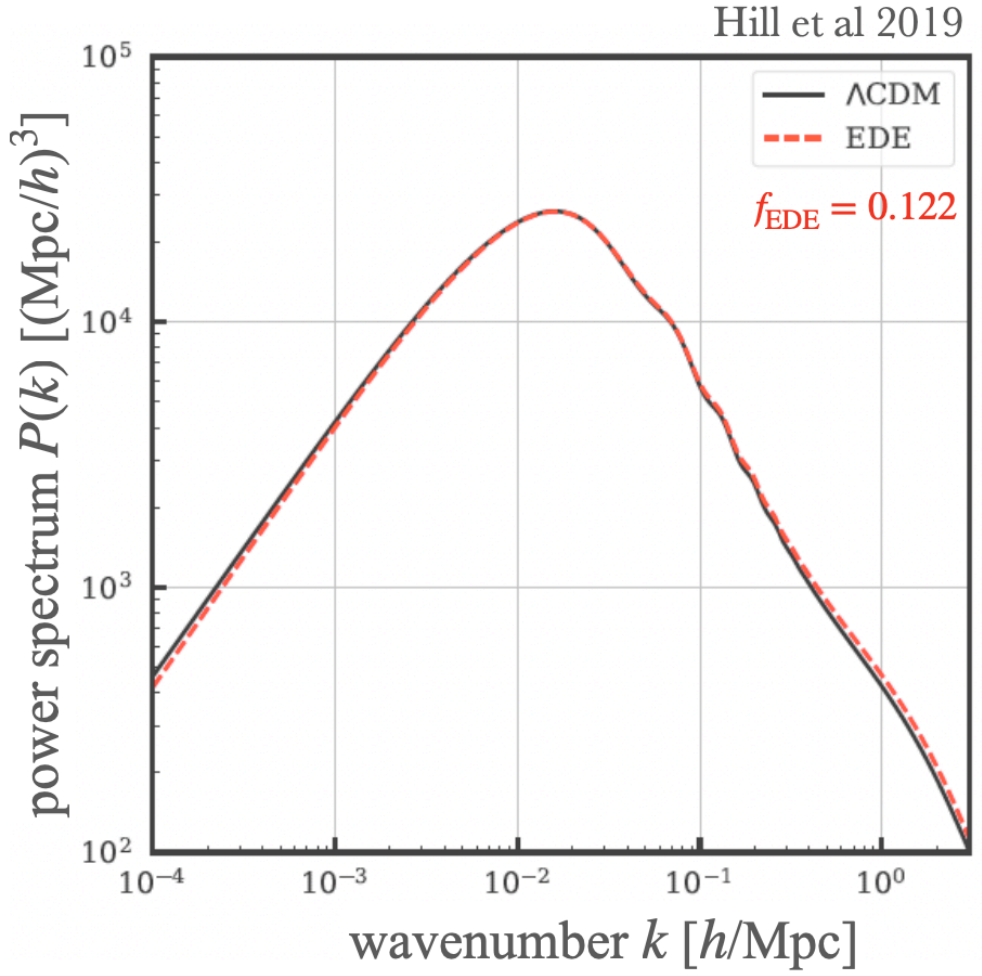
EDE

$$H_0 = 71.00\,\mathrm{km/s/Mpc}, \quad 100\omega_b = 2.262$$
$$\omega_{\rm cdm} = 0.12955, \quad \ln 10^{10} A_s = 3.067,$$
$$n_s = 0.9829, \quad \tau_{\rm reio} = 0.0552$$
$$f_{\rm EDE} = 0.101 \;,\; \log_{10}(z_c) = 3.56 \;,\; \theta_i = 2.78.$$

LCDM

$$H_0 = 68.02\,\mathrm{km/s/Mpc} \quad 100\omega_b = 2.250,$$
$$\omega_{\rm cdm} = 0.11860 \quad \ln 10^{10} A_s = 3.050,$$
$$n_s = 0.9690$$

Hill et al 2019



Shifts leave an imprint on cosmological observables:

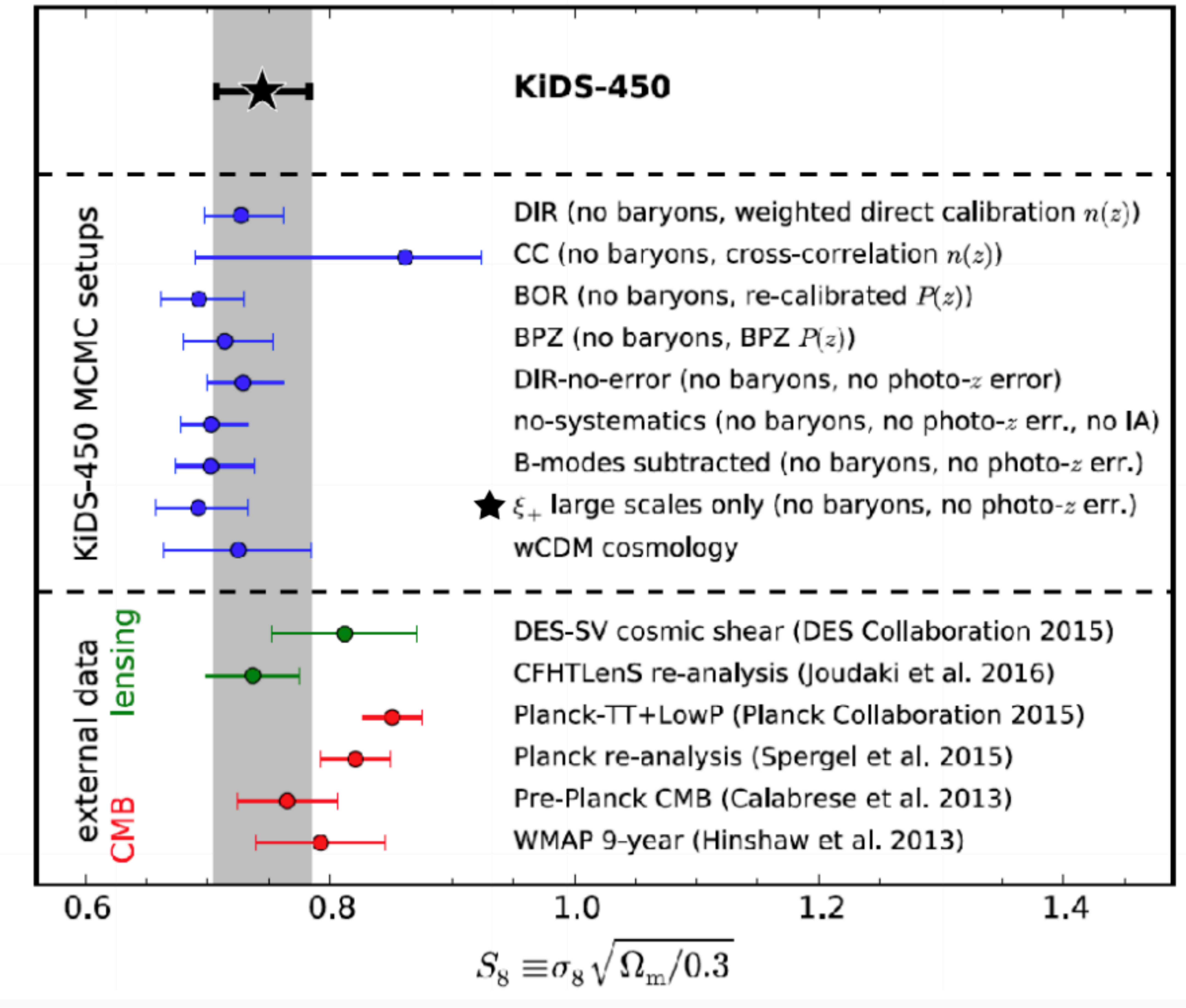
- EDE makes the growth of perturbations less efficient at the time of CMB
- This is compensated by increasing amount of CDM (higher σ_8 → higher S_8 → higher $f\sigma_8$)
  - After EDE decays, large amount of CDM remains and enhances structure formation at late times.
  - Worsens the S_8 **tension**!

Important to use LSS observables to constrain the amount of CDM CDM (w_{cdm})

S_8 *tension ?*

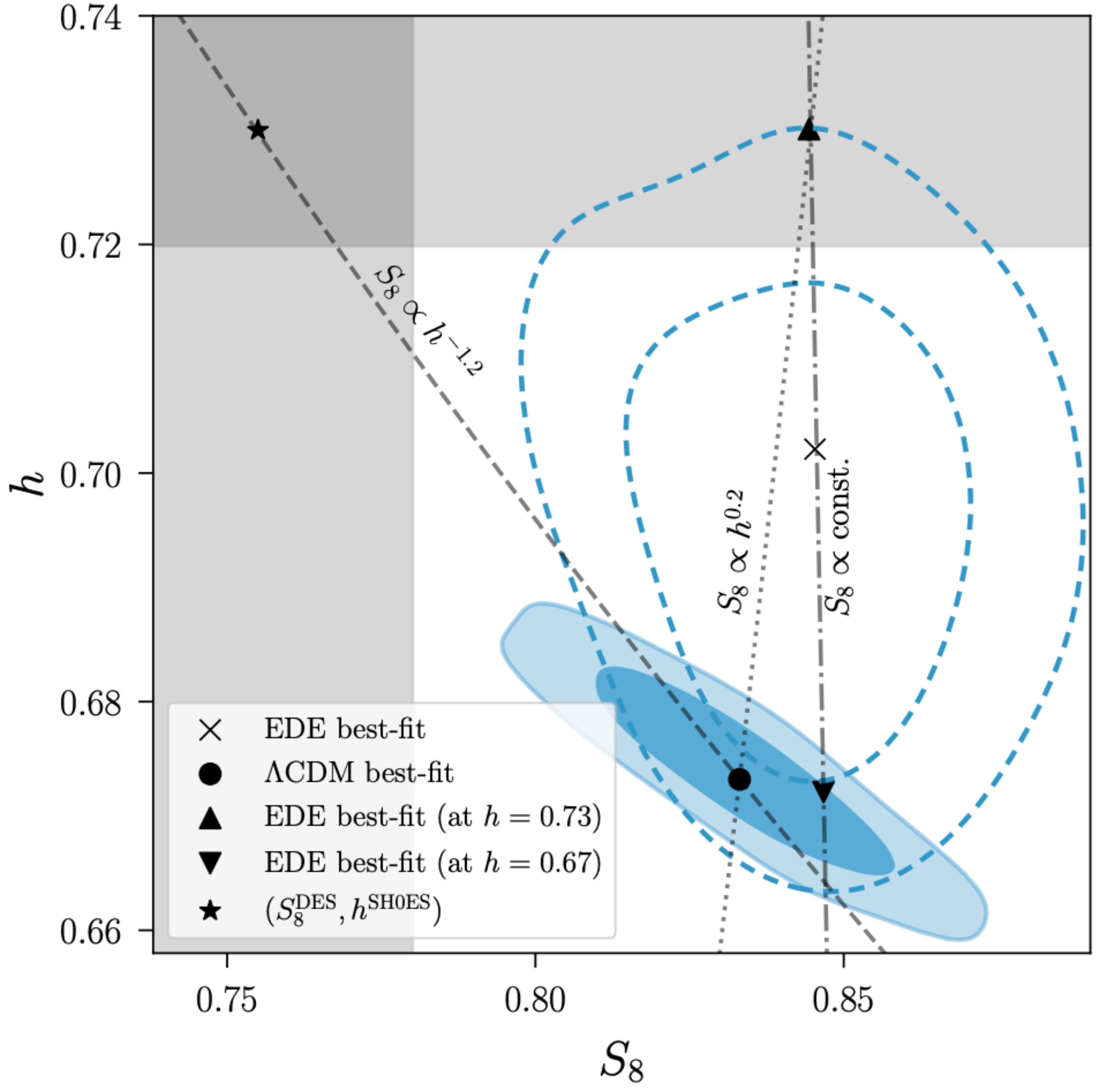
σ_8: RMS fluctuation of the linear density field within a spherical top-hat of radius 8 Mpc/h

$$S_8 \equiv \sigma_8 \sqrt{\Omega_m/0.3}$$



S_8 *tension ?*

EDE makes the S_8 tension to go towards the wrong direction, worsening the tension

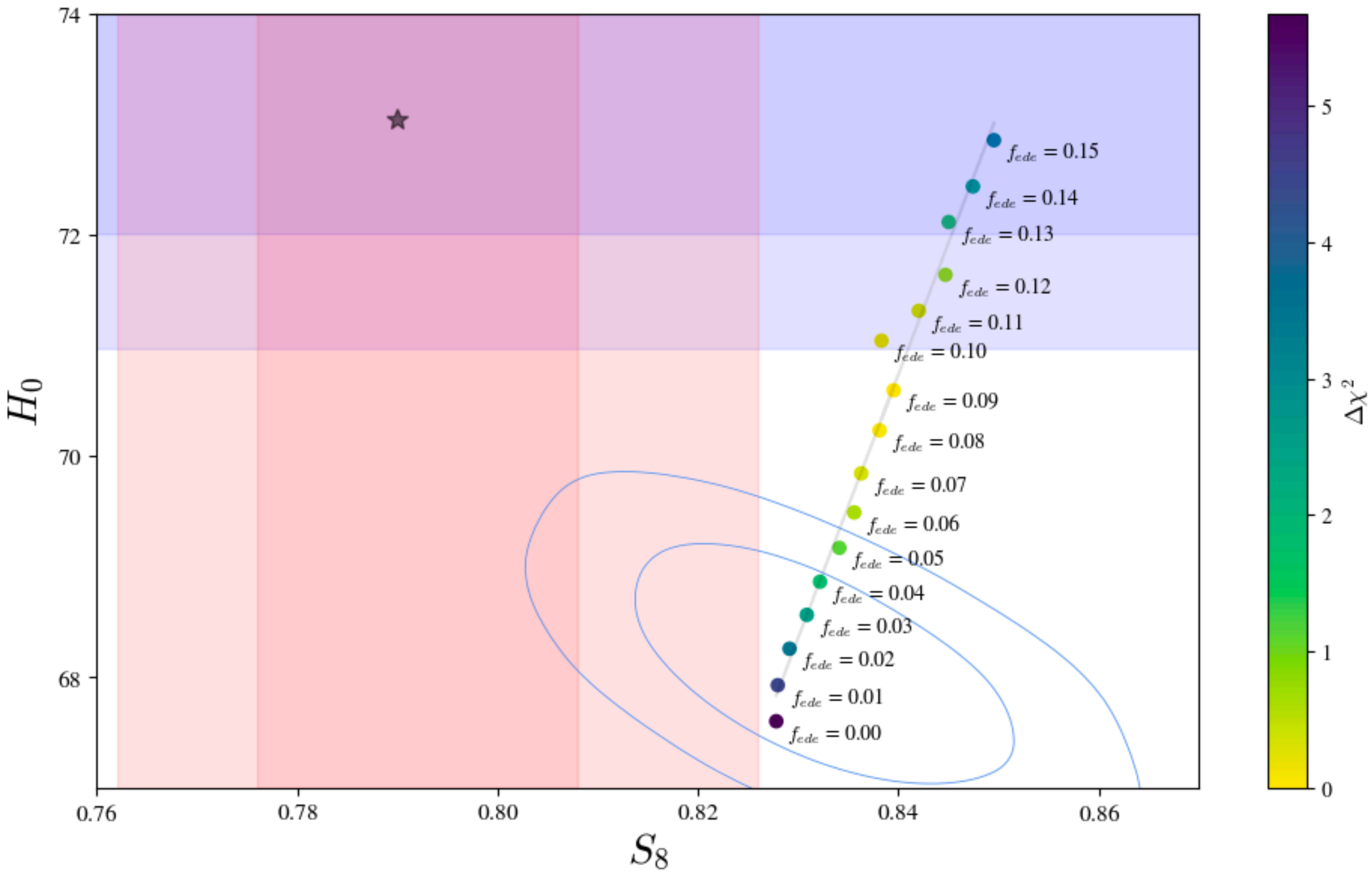


Lucas Secco et al., 2022

S_8 *tension ?*

EDE makes the S_8 tension to go towards the wrong direction, worsening the tension

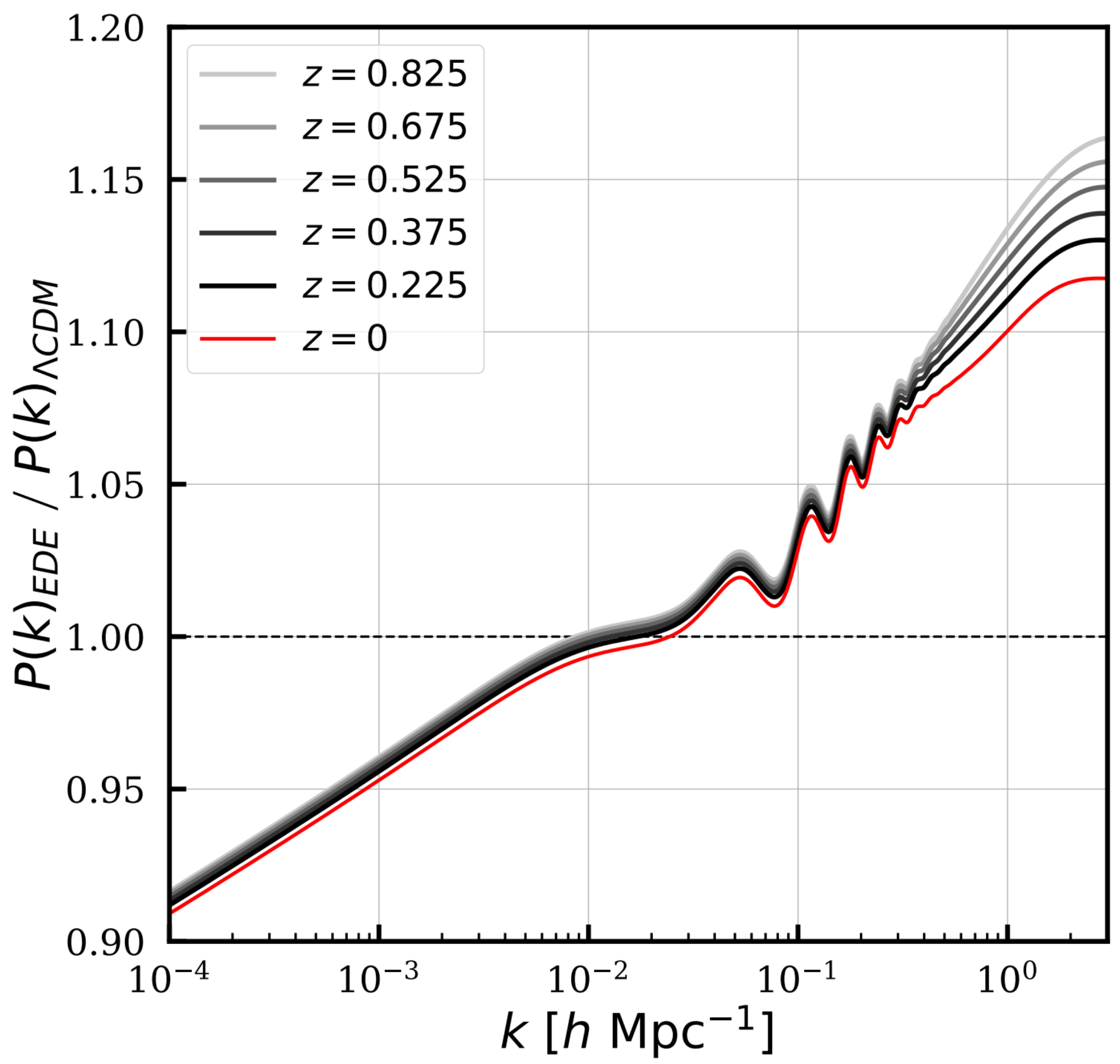
PRELIMINARY



To appear: in collaboration with Mico Benetti, Laura Herold, Leila Graef & Igor Pedreira

Can neutrinos increase *EDE?*

Solve S8 (or at least not make it worse)?

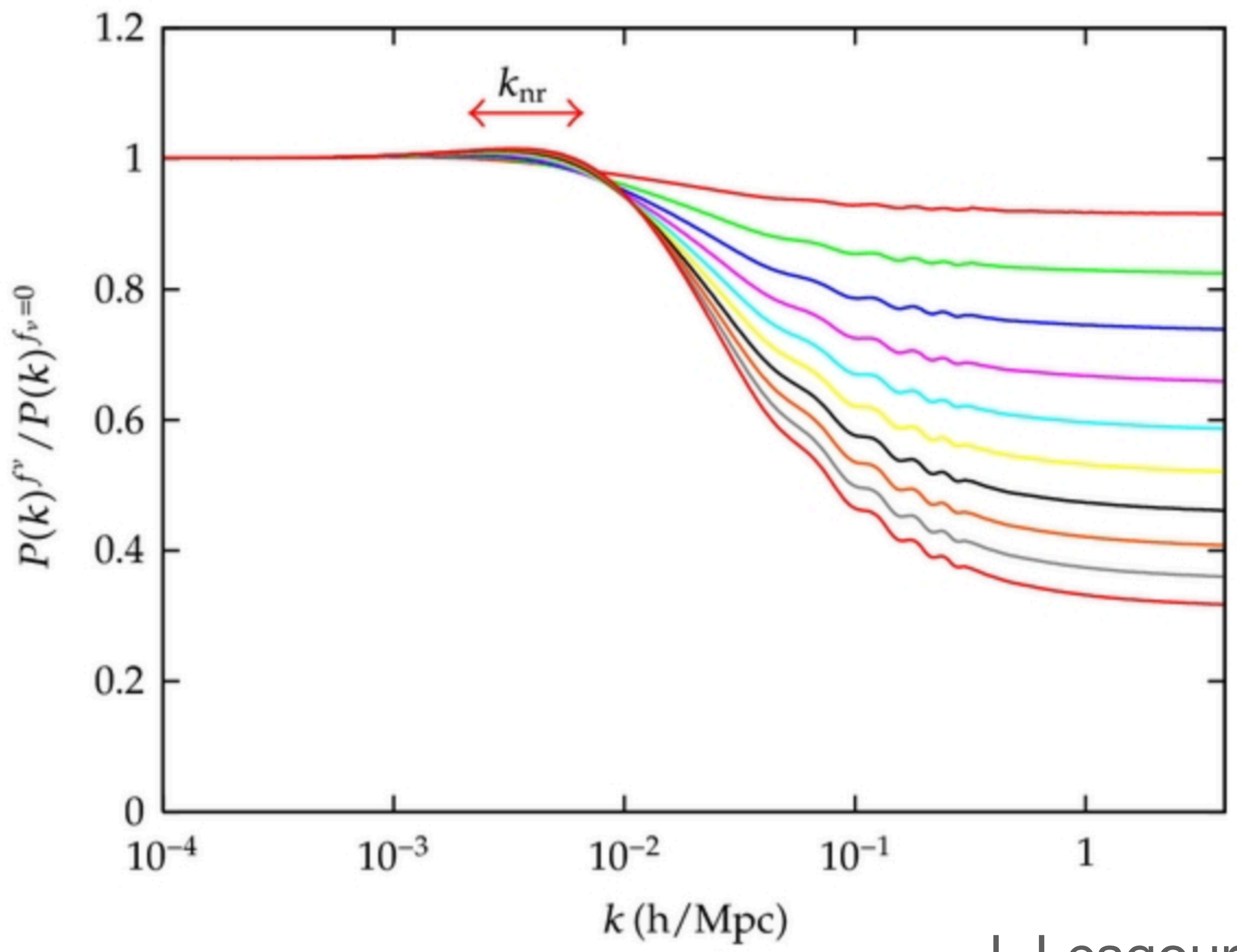


Hill et al. 2020

In collaboration with Laura Herold, Alex Reeves, Sunny Vagnozzi and Blake Sherwin

EDE:

Higher f_{EDE} ⟶ More DM



J. Lesgourgues et al. 2012

Neutrinos:

- Suppress structure formation on small scales
- Shift in the BAO peak

Influence of a higher neutrino mass sum Mν on EDE?

Can neutrinos increase EDE?

EDE + neutrinos

In collaboration with Alex Reeves, Laura Herold, Sunny Vagnozzi and Blake Sherwin

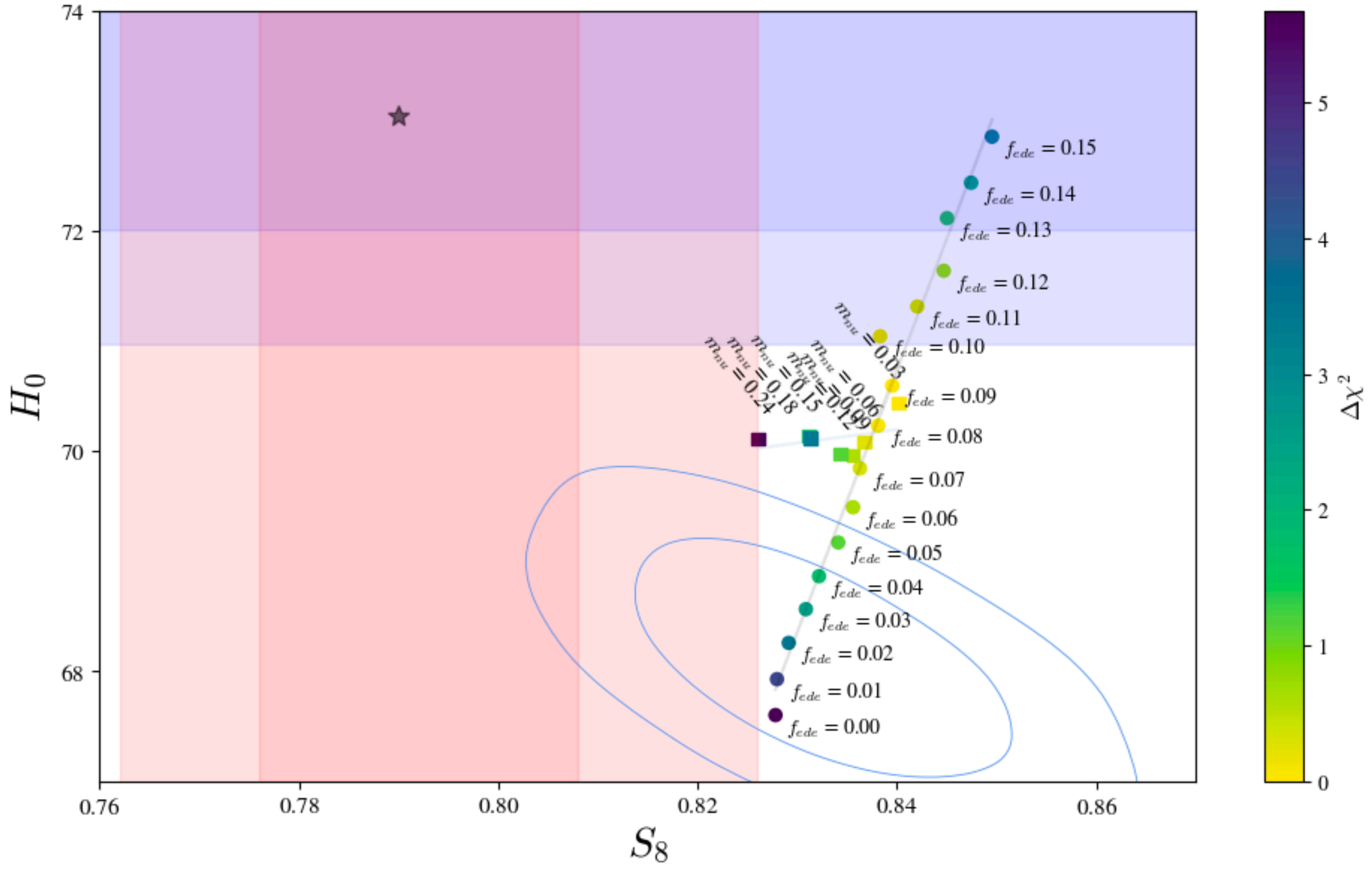
Individual best-fit χ^2 contributions								
Likelihood \ Model	ΛCDM	$\mathrm{EDE}_{0.06}$	$\mathrm{EDE}_{0.09}$	$\mathrm{EDE}_{0.12}$	$\mathrm{EDE}_{0.15}$	$\mathrm{EDE}_{0.18}$	$\mathrm{EDE}_{0.24}$	$\mathrm{EDE}_{0.3}$
BOSS (BAO+FS)	297.2	295.3	295.4	295.5	295.9	296.5	298.2	301.9
Planck TTTEEE	2345.5	2342.6	2343.2	2343.7	2345.1	2345.5	2347.2	2348.3
Planck lowE	396.3	396.1	396.4	396.8	396.5	397.0	397.3	397.7
Planck lowl	23.2	21.9	21.7	21.5	21.3	21.2	21.1	21.1
Planck lensing	8.8	9.47	9.34	9.18	9.15	9.07	9.01	9.07
Total χ^2 (S21)	3071.0	3065.4	3065.9	3066.7	3067.9	3069.3	3072.9	3078.1
(Migrad)	3078.6	3070.7	3072.7	3073.0	3073.4	3076.0	3076.5	3088.3
Best-fit parameters								
H_0 [km/s/Mpc]	67.59	70.08	69.96	69.97	70.12	70.12	70.11	69.42
σ_8	0.811	0.828	0.824	0.820	0.814	0.811	0.802	0.787
Ω_m	0.312	0.306	0.309	0.311	0.312	0.315	0.319	0.325
ω_c	0.120	0.127	0.128	0.128	0.129	0.130	0.131	0.130
f_{EDE}	–	0.077	0.082	0.089	0.099	0.107	0.117	0.110

- Positive correlation between M_ν and f_{EDE}
- EDE can increase H0 but at the cost of increasing σ_8, high neutrino masses slow down structure formation and decrease S8
- **EDE+M_ν model can alleviate the Hubble tension to the same amount as the EDE model without worsening the S8 discrepancy.**

S_8 *tension ?*

PRELIMINARY

EDE + neutrinos at least doesn't make the tension worse



To appear: in collaboration with Mico Benetti, Laura Herold, Leila Graef & Igor Pedreira

Profile likelihood: general

- Using profile likelihood and other complimentary statistical methods is going to be more and more important in cosmology:
    - Beyond LCDM model

      Ex.: EDE, decaying DM, nEDE, …
    - New observables or systematics

      Ex.: full-shape (nuisance parameters), clusters, …

→ **extra dofs**

Important new analysis to be incorporated in observational collaborations!

Ex.: Euclid
PFS and LiteBIRD?

Refs:

- Herold + Ferreira, 2022; + Komatsu, 2021
- Campetti, Komatsu, 2022
- Cosmology with 6 parameters in the Stage-IV era: efficient marginalisation over nuisance parameters, Hadzhiyska et al, 2023
- Other works to come…

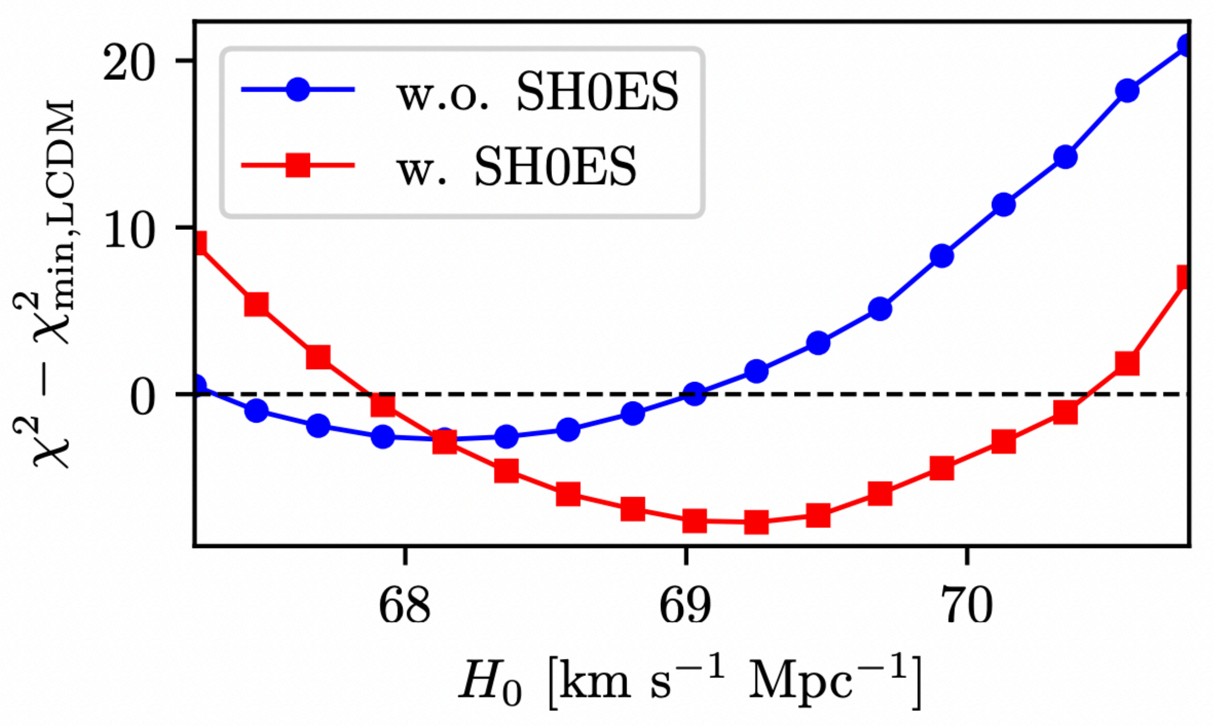
Other beyond LCDM models…

- Decaying dark matter

Holm et al. 2022

(See also (Holm et al. 2022 - DWDM)

- Previous MCMC analysis find a strong preference for either very long-lived or very short-lived dark matter.



This work:

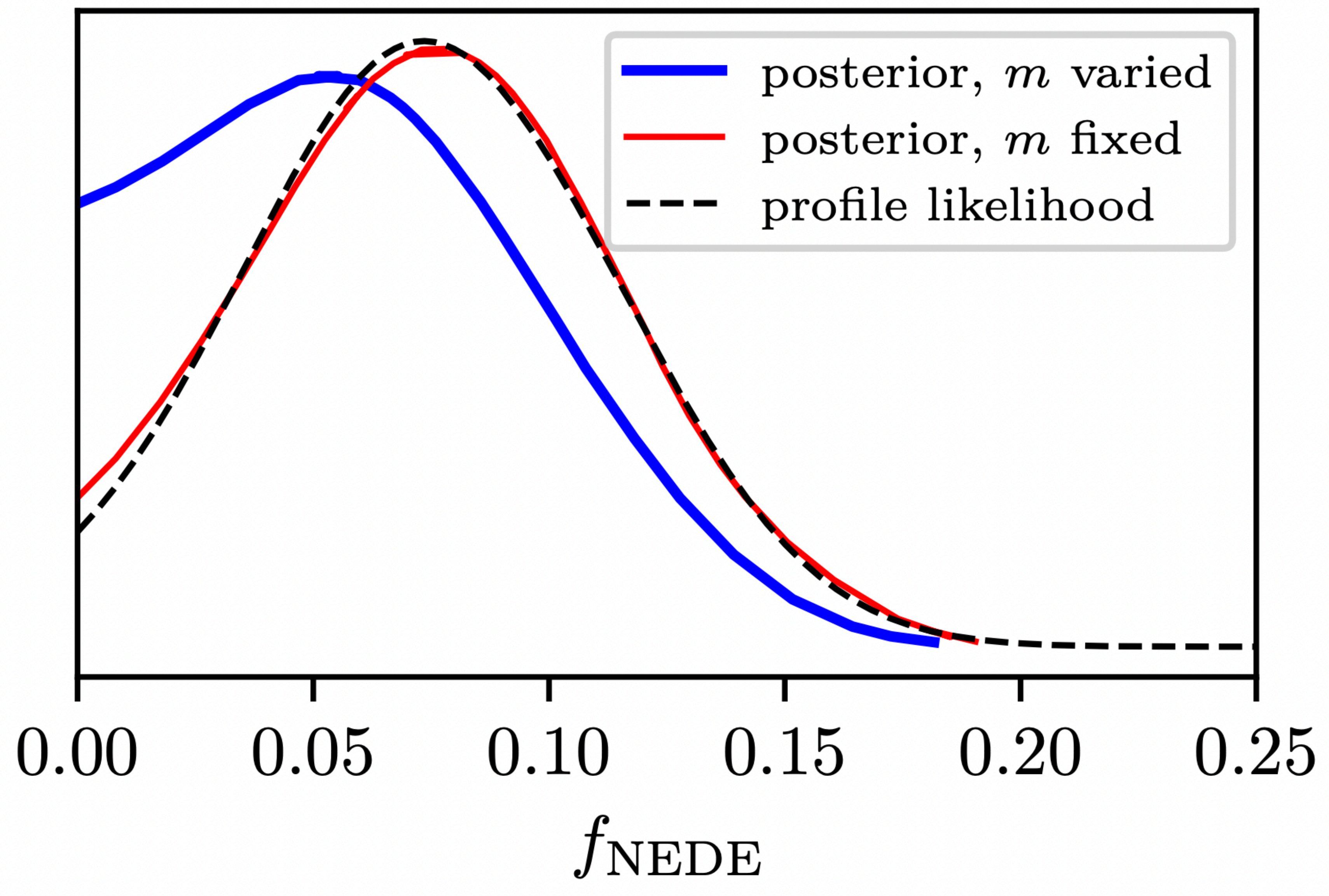
- This preference is due to volume effects - drives the model towards the standard ΛCDM limit
- Using profile likelihoods, they instead find that best-fitting parameters are in an intermediate regime - ~3% of cold dark matter decays just prior to recombination.

- New EDE

Cruz et al. 2023

$$\{f_{\mathrm{NEDE}}, z_{\mathrm{decay}}, w_{\mathrm{NEDE}}\}$$

- Stronger evidence for NEDE with PL, than MCMC



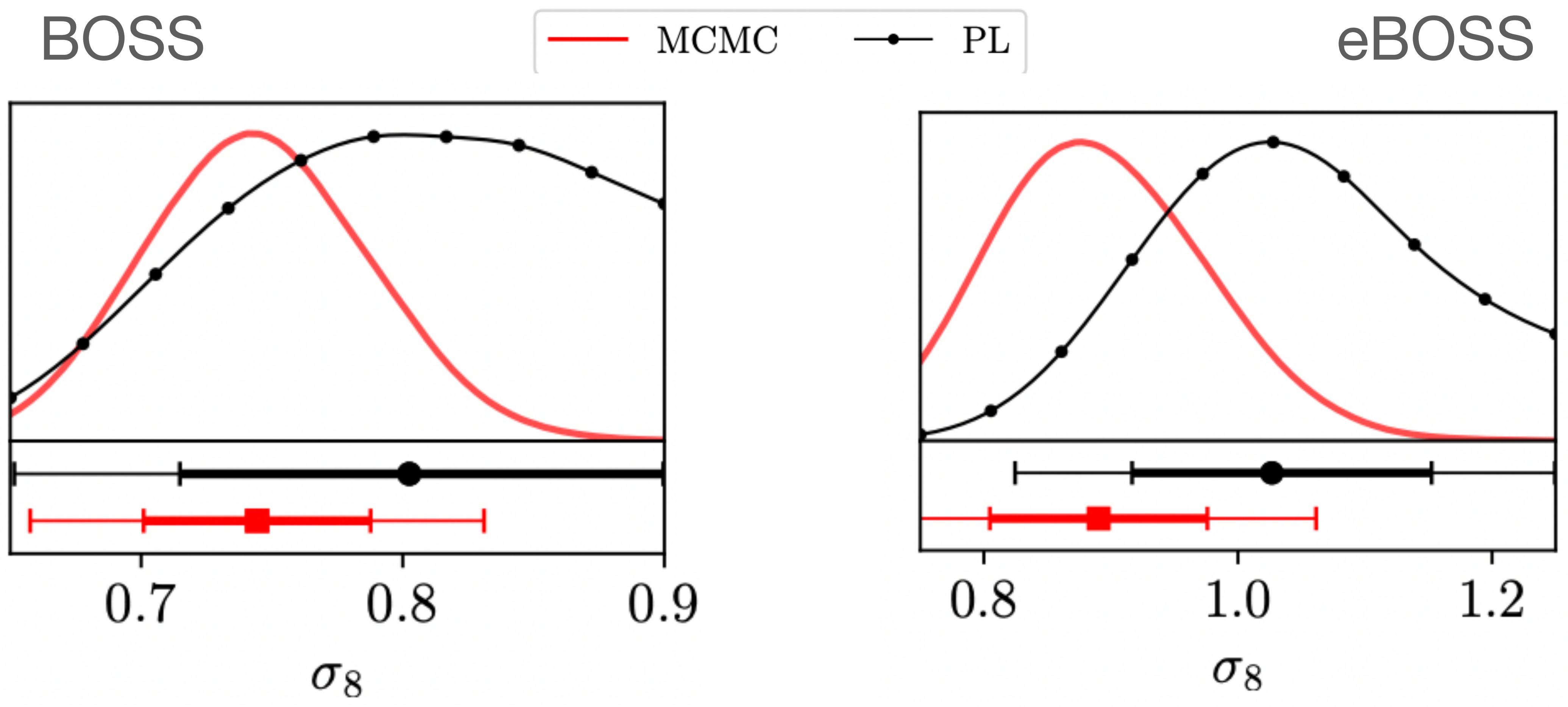
- Shows that fixing the trigger mass an s an appropriate method of avoiding volume effects

Prior effects in EFTofLSS analyses of full-shape BOSS and eBOSS data

E.Holm, L. Herold, T. Simon, EF, S. Hannestad, V. Poulin, T. Tram 2023

- Previous MCMC analysis have shown that the constraints from BOSS full-shape data using EFTofLSS depend on the choice of prior on the EFT nuisance parameters

- We explore this prior dependence using profile likelihood for BOSS, eBOSS and Planck



Shift of 1σ (BOSS)

1.6σ (eBOSS)

Widening of intervals by factors of 1.9 (BOSS)

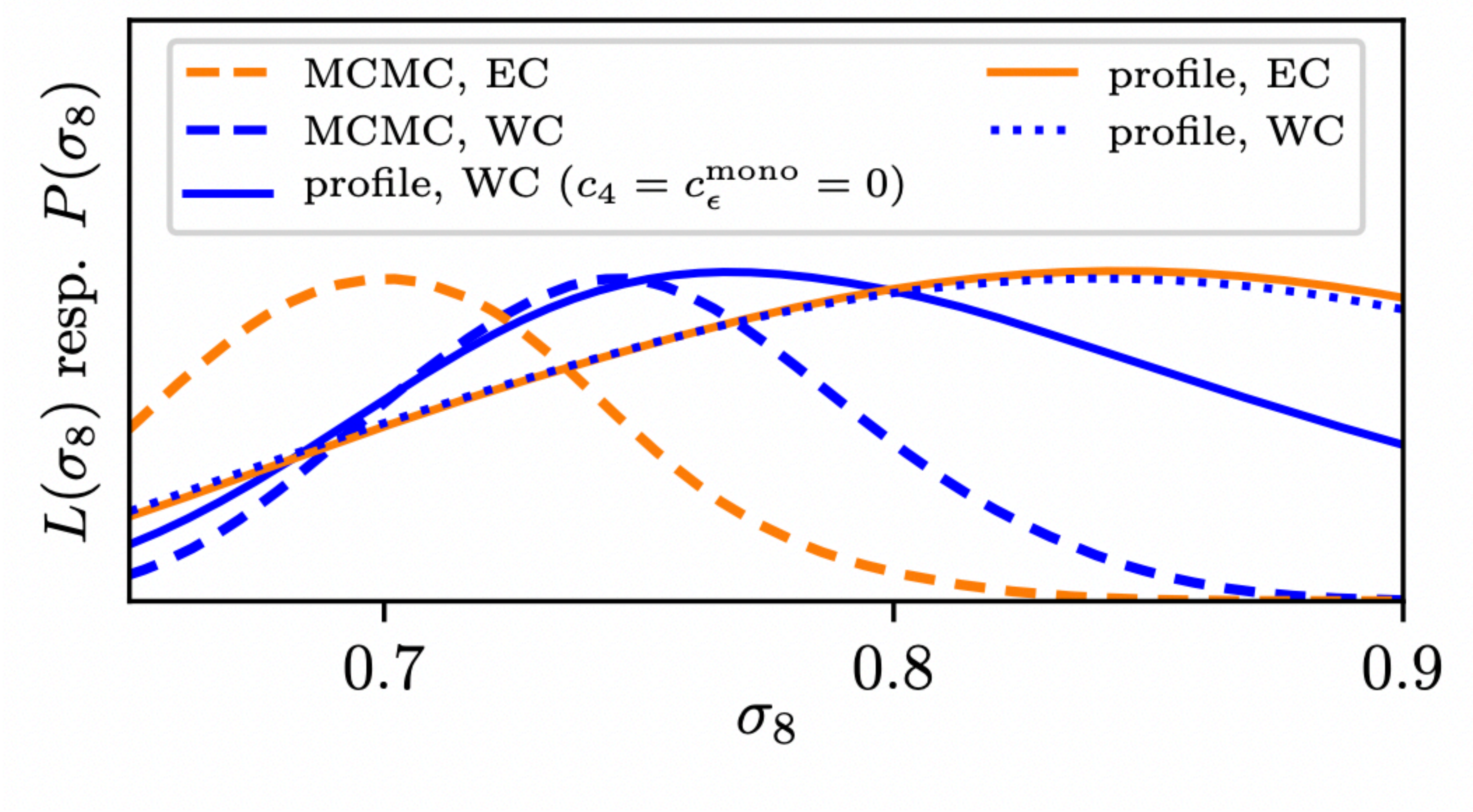
1.6 (eBOSS)

- We find that the priors on the EFT parameters in the Bayesian inference are informative and that prior volume effects are important.

Prior effects in *EFTofLSS analyses of full-shape BOSS and eBOSS data*

E.Holm, L. Herold, T. Simon, EF, S. Hannestad, V. Poulin, T. Tram 2023

- EC vs. WC parametrizations and comparison to MCMC



Marginalized MCMC posteriors (dashed) and profile likelihoods (solid) of σ8 within the WC (blue) and EC parametrizations (orange), for BOSS+BAO data

Prior effects in *EFTofLSS analyses of full-shape BOSS and eBOSS data*

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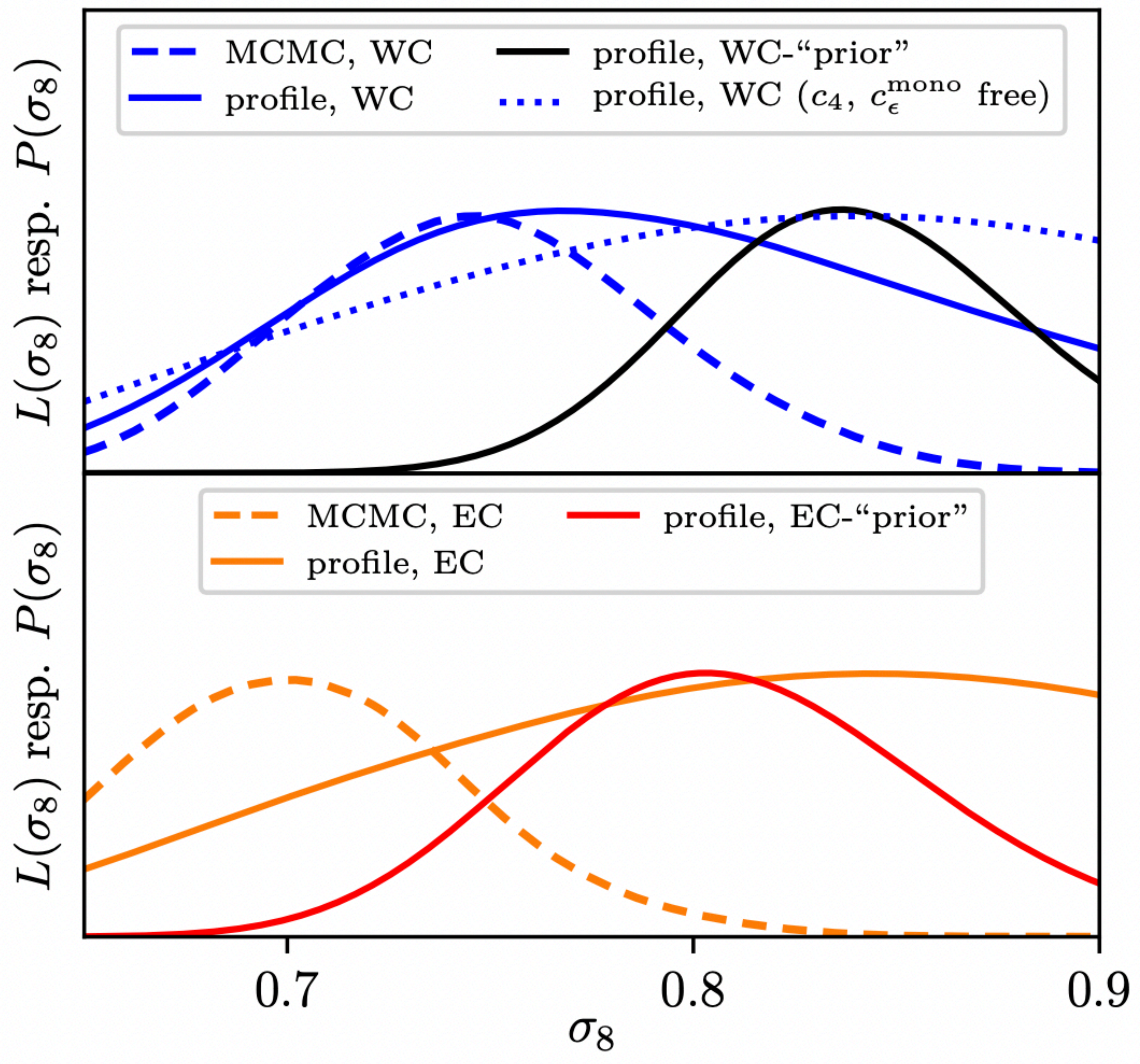

Marginalized MCMC posteriors (dashed) and profile likelihoods (solid) of σ8 within the WC (blue) and EC parametrizations (orange), for BOSS+BAO data, *including profile likelihoods with Gaussian data likelihoods on the EFT parameters*

Other σ_8 estimates

- DES x KIDS analysis

DES Y3 + KIDS-1000: CONSISTENT COSMOLOGY COMBINING COSMIC SHEAR SURVEYS

Dark Energy Survey and Kilo-Degree Survey Collaboration:
T. M. C. Abbott,[1] M. Aguena,[2] A. Alarcon,[3] O. Alves,[4] A. Amon,[5,6] F. Andrade-Oliveira,[4] M. Asgari,[7] S. Avila,[8] D. Bacon,[9]
K. Bechtol,[10] M. R. Becker,[3] G. M. Bernstein,[11] E. Bertin,[12,13] M. Bilicki,[14] J. Blazek,[15] S. Bocquet,[16] D. Brooks,[17]
P. Burger,[18] D. L. Burke,[19,20] H. Camacho,[21,2] A. Campos,[22] A. Carnero Rosell,[23,2,24] M. Carrasco Kind,[25,26] J. Carretero,[8]
F. J. Castander,[27,28] R. Cawthon,[29] C. Chang,[30,31] R. Chen,[32] A. Choi,[33] C. Conselice,[34,35] J. Cordero,[34] L. N. da Costa,[2]
M. E. S. Pereira,[36] R. Dalal,[37] C. Davis,[19] J. T. A. de Jong,[38,39] J. DeRose,[40] S. Desai,[41] H. T. Diehl,[42] S. Dodelson,[22,43]
P. Doel,[17] C. Doux,[11,44] A. Drlica-Wagner,[30,42,31] A. Dvornik,[45] K. Eckert,[11] T. F. Eifler,[46,47] J. Elvin-Poole,[48] S. Everett,[47]
X. Fang,[49,46] I. Ferrero,[50] A. Ferté,[20] B. Flaugher,[42] O. Friedrich,[6] J. Frieman,[42,31] J. García-Bellido,[51] M. Gatti,[11]
G. Giannini,[8] B. Giblin,[52,53] D. Gruen,[16] R. A. Gruendl,[25,26] G. Gutierrez,[42] I. Harrison,[54] W. G. Hartley,[55] K. Herner,[42]
C. Heymans,[53,45] H. Hildebrandt,[45] S. R. Hinton,[56] H. Hoekstra,[38] D. L. Hollowood,[57] K. Honscheid,[58,59] H. Huang,[46,60]
E. M. Huff,[47] D. Huterer,[4] D. J. James,[61] M. Jarvis,[11] N. Jeffrey,[17] T. Jeltema,[57] B. Joachimi,[62] S. Joudaki,[63] A. Kannawadi,[64]
E. Krause,[46] K. Kuehn,[65,66] K. Kuijken,[38] N. Kuropatkin,[42] P.-F. Leget,[19] P. Lemos,[67,68,69,70] S. Li,[38] X. Li,[71,72] A. R. Liddle,[73]
M. Lima,[74,2] C. Lin,[45,75] H. Lin,[42] N. MacCrann,[76] C. Mahony,[45] J. L. Marshall,[77] J. McCullough,[19] J. Mena-Fernández,[78]
F. Menanteau,[25,26] R. Miquel,[79,8] J. J. Mohr,[80,16] J. Muir,[81] J. Myles,[82,19,20] N. Napolitano,[83] A. Navarro-Alsina,[84]
R. L. C. Ogando,[85] A. Palmese,[22] S. Pandey,[11] Y. Park,[86] M. Paterno,[42] J. A. Peacock,[53] D. Petravick,[25] A. Pieres,[2,85]
A. A. Plazas Malagón,[87] A. Porredon,[58,59,53] J. Prat,[30,31] M. Radovich,[88] M. Raveri,[89] R. Reischke,[45] R. P. Rollins,[34]
A. K. Romer,[90] A. Roodman,[19,20] E. S. Rykoff,[19,20] S. Samuroff,[15] C. Sánchez,[11] E. Sanchez,[78] J. Sanchez,[91] P. Schneider,[18]
L. F. Secco,[31] I. Sevilla-Noarbe,[78] H. Shan,[92,93,94] E. Sheldon,[95] T. Shin,[96] C. Sifón,[97] M. Smith,[98] M. Soares-Santos,[4]
B. Stölzner,[45] E. Suchyta,[99] M. E. C. Swanson, G. Tarle,[4] D. Thomas,[9] C. To,[58] M. A. Troxel,[32] T. Tröster,[100]

Identified and quantified the marginalization (prior volume or projection) effects given some choices in the analysis.
Using MAP (maximum a posteriori)

Projection effects

With the increase statistical power of new observations that have the goal to lead to a more precise determination of the cosmological parameters, new systematic effects are present leading to a larger number of nuisance parameter that also need to be fitted in the data analysis.

This **inflation of the number of parameters** can lead to difficulties in the statistical analysis and ***bias*** the inference of cosmological parameters.

For the standard MCMC analysis these are:

Ex.: Prior volume effects, weight volume effects, … ⟶ Inescapable feature of the Bayesian method!

Relevant to study the extent to which one's results are affected by volume effects!

Need complementary statistical methods to deal with that, like for example, the profile likelihood

Prior/marginalization effects

Inflation in the number of nuisance parameters or beyond LCDM parameters that enter the statistical analysis leading to possible marginalization or prior volume effects in standard MCMC analysis

Inherent from Bayesian analysis. When strong, can influence inferred parameters

Early Dark Energy

Volume effects are important: full MCMC result differs from the profile likelihood

PL analysis: $H_0^{\mathrm{EDE,(base)}} = 70.57 \pm 1.36$

Compatible with SHOES at 1.4σ

EDE can resolve the Hubble tension!

Summary

Complementary statistical methods necessary for current and future parameter inference analysis - profile likelihood


Thank you!