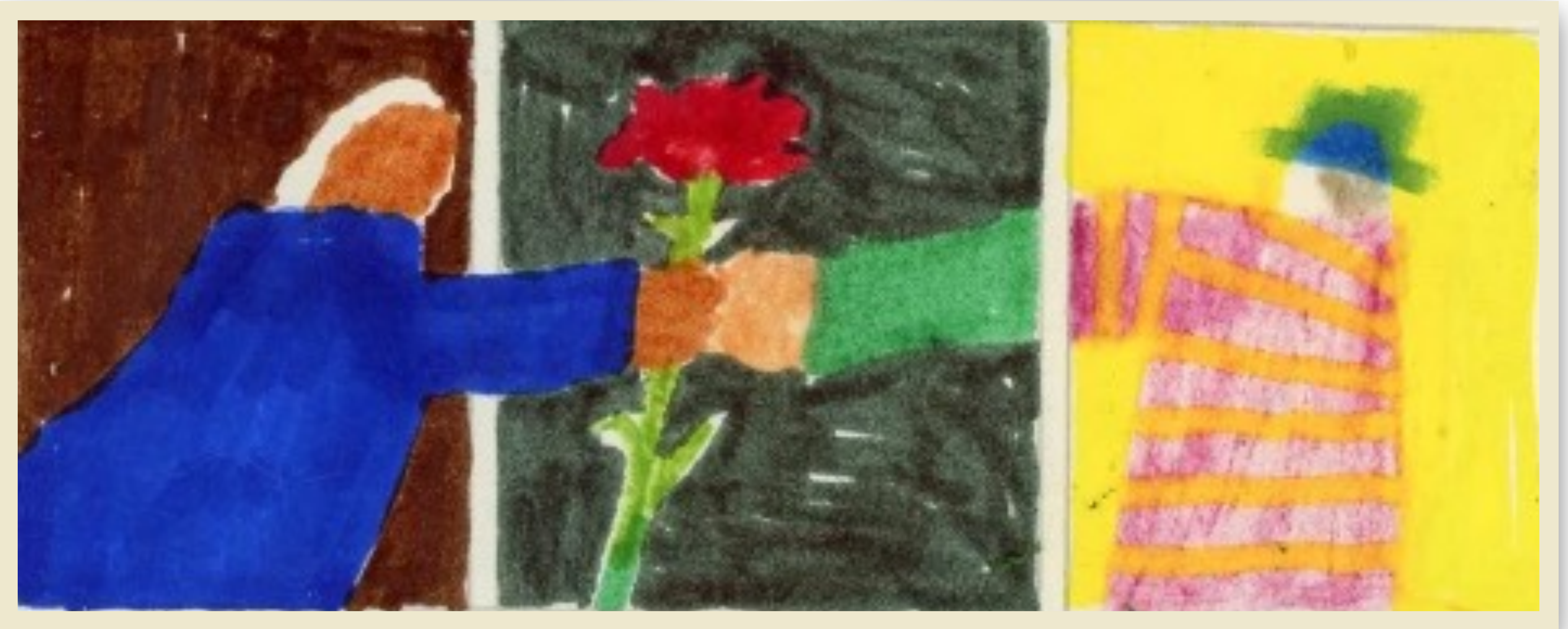
MOMENTUM-TRANSFER COUPLING BETWEEN DARK MATTER AND EARLY DARK ENERGY



Illustrations: Inês Viegas Oliveira (ivoliveira.com)

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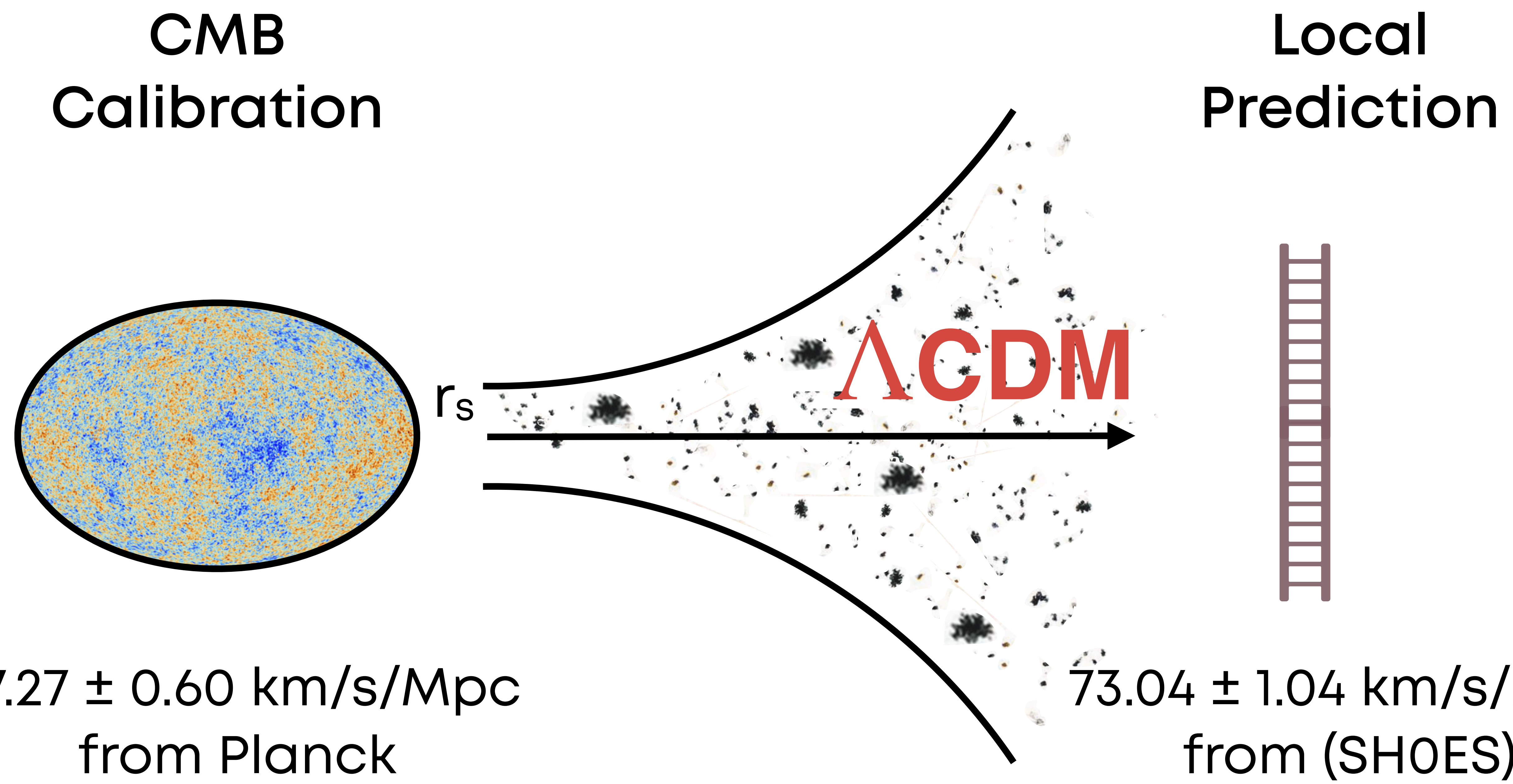
- Based on 2608.xxxxx with Adèle Poudou, Thomas Montandon, Tristan L. Smith and Vivian Poulin

SUPPORTED BY FUNDING FROM THE EUROPEAN RESEARCH COUNCIL (ERC) UNDER THE EUROPEAN UNION’S HORIZON-ERC-2022 (GRANT AGREEMENT NO. 101076865)


Cosmic Tensions

The Hubble tension



67.27 ± 0.60 km/s/Mpc
from Planck

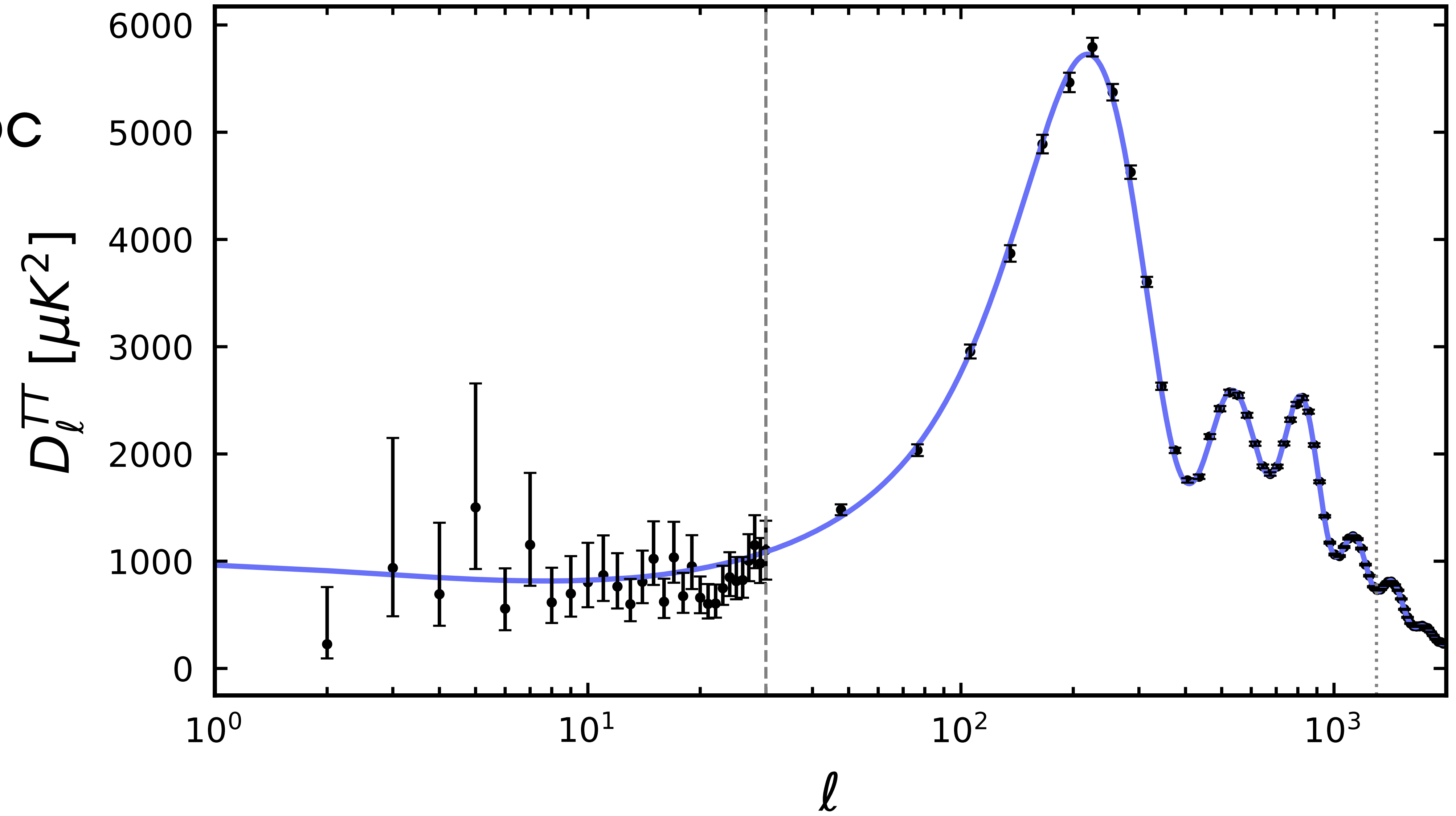
73.04 ± 1.04 km/s/Mpc
from (SH0ES)

CMB: $r_s = \int_{z_*}^{\infty} \mathrm{d}z\, c_s(z)\, H^{-1}(z),$

$$\theta_s(z) = \frac{r_s(z_*)}{D_A(z)},\ D_A(z_*) \propto 1/H_0$$

SN1a: $m(z) = 5\log_{10}\left(D_L(z)\right) + M_b$

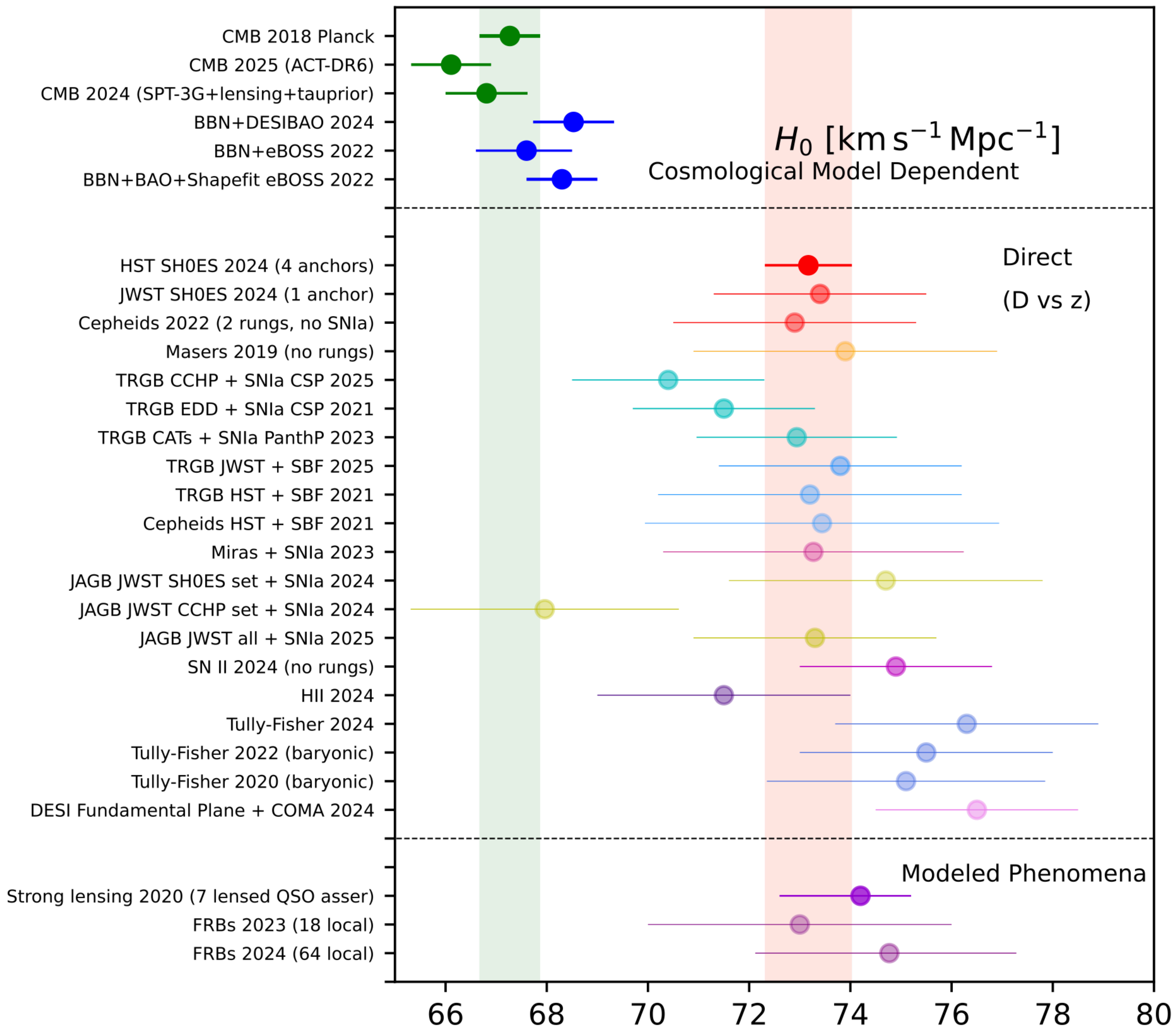
Mismatch between early- and late-Universe estimations of H_0



The Hubble Tension

Incompatible values for H_0 from the CMB and from direct local distance ladder measurements

- ~5σ tension between Planck 2018 and SH_0ES:
  - CMB (Planck): $H_0 = 67.27 \pm 0.60$ km/s/Mpc
  - SNe (R22): $H_0 = 73.04 \pm 1.04$ km/s/Mpc
- The CMB data assumes the ΛCDM model
- DESI BAO (+BBN+CMB): $H_0 = 68.45 \pm 0.47$ km/s/Mpc
  [DESI Collaboration DR2 2025: arXiv:2503.14738]
- Confirmed and reinforced by joint analysis of local estimators (7.1σ with Planck+SPT+ACT):
- Distance Network: $H_0 = 73.50 \pm 0.81$ km/s/Mpc [H0DN Collaboration 2025: arXiv:2510.23823]
- Different hints of new physics or various underestimated systematics?

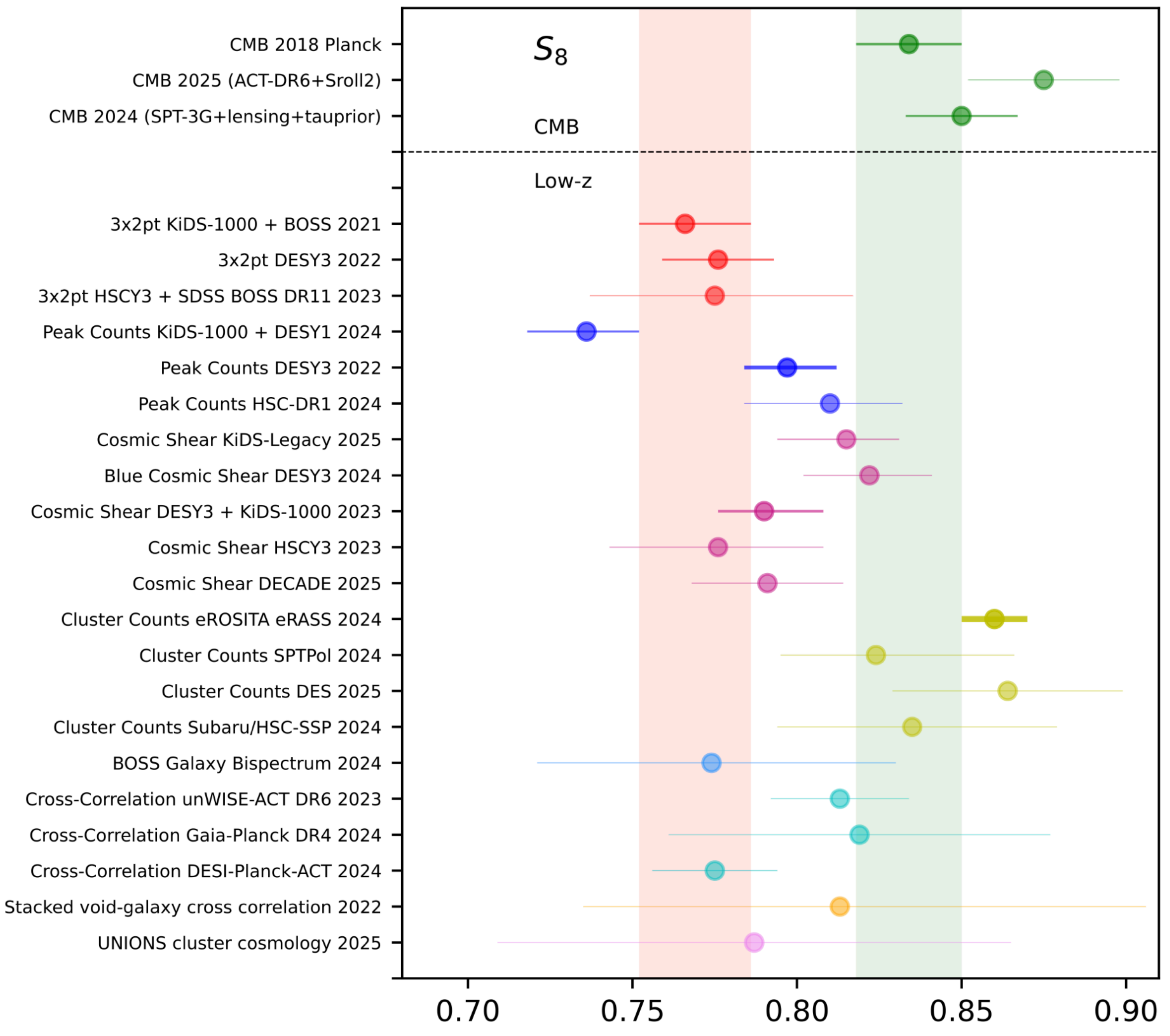


[Cosmoverse white paper: arxiv:2504.01669]

The S8 Tension

Discrepancy between CMB data and lensing surveys on combined quantity $S_8 = \sigma_8\sqrt{\Omega_m/0.3}$

- ~ 3σ tension between Planck 2018 CMB data and KiDS-1000 combination of Cosmic Shear and Galaxy Clustering:
  - CMB (Planck 2018): $S_8 = 0.832 \pm 0.013$
  - Cosmic Shear (DES-Y3): $S_8 = 0.759^{+0.025}_{-0.023}$
- eRosita (eRASS1): $S_8 = 0.86 \pm 0.01$ [Ghirardini et al. 2024]
- Could signal changes in clustering of matter (nature of CDM)
- Kids-Legacy ($S_8 = 0.815^{+0.016}_{-0.021}$) find possible resolution with Planck but not for the other measurements (improved redshift distribution estimation and calibration, as well as new survey area and improved image reduction)



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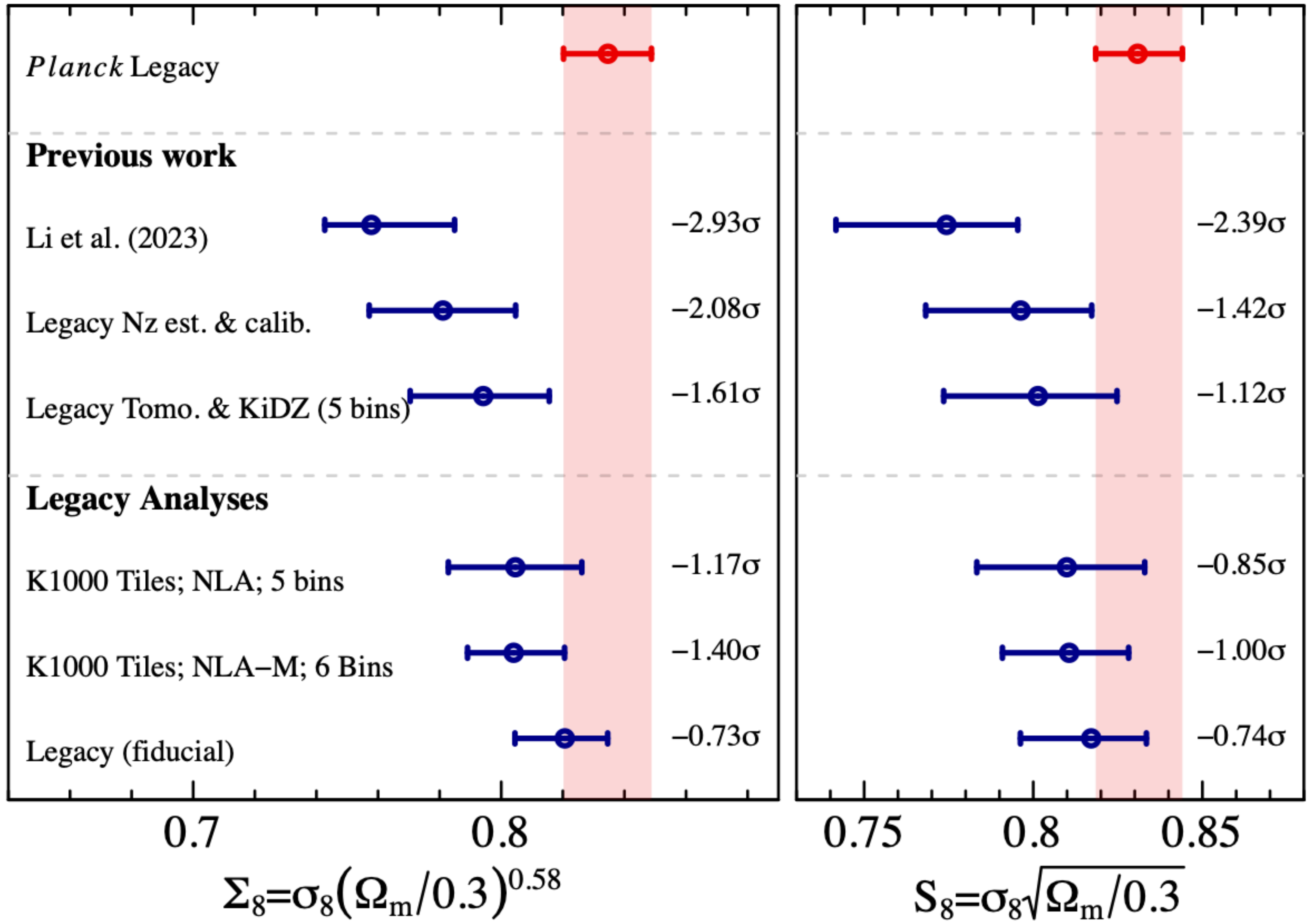
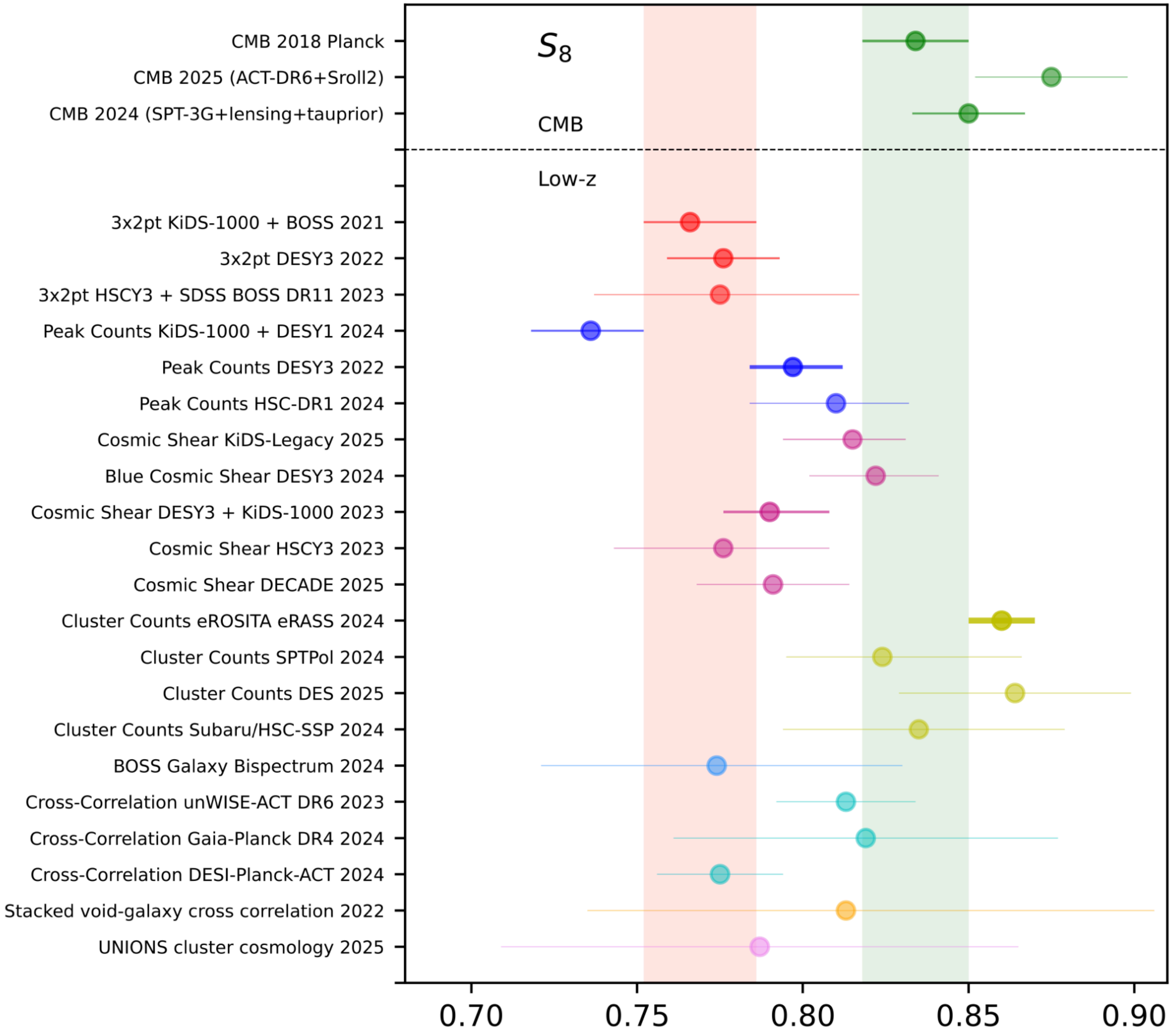
The S_8 Tension





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[A.H. Wright, et al., (Kids Legacy), arxiv:2503.19441]

[Cosmoverse white paper: arxiv:2504.01669]

Beyond the Standard Model: Models of Early Dark Energy

Early dark energy

- Early-time slowly-rolling canonical scalar field ϕ with self-interacting potential $V(\phi)$ that later dilutes faster than matter

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

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V_n(\phi), \quad p_\phi = \frac{1}{2}\dot{\phi}^2 - V_n(\phi)$$

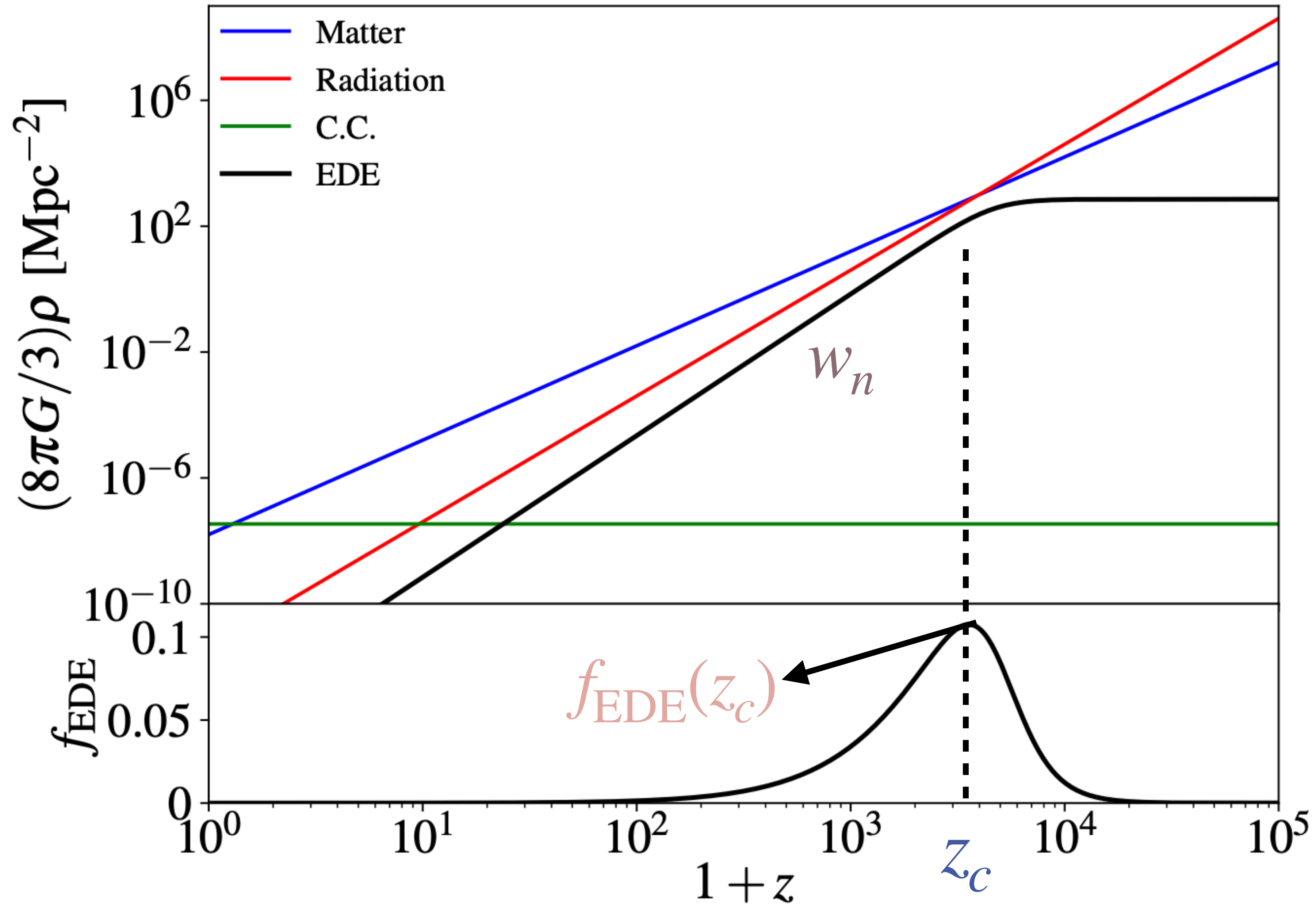
$$V_n(\phi) = m^2 f^2 \left(1 - \cos\frac{\phi}{f}\right)$$

- Phenomenology specified by $f_{\mathrm{EDE}}(z_c)$, z_c, w_n, $\theta_i = \phi_i/f_{\mathrm{EDE}}$

$$\begin{cases} z > z_c \Rightarrow w_n = -1 \\ z < z_c \Rightarrow w_n = (n-1)/(n+1) \end{cases}$$

- To address the Hubble tension (n=3) we need

$$f_{\mathrm{EDE}} \sim 10\,\% \;\Rightarrow H_0 \sim 72\ \mathrm{km\,s^{-1}\,Mpc^{-1}},\ S_8 \sim 0.84$$



[Poulin et al, arxiv: 2302.09032]

Early dark energy

- Any pre-recombination new physics that reduces r_s must decrease Ω_m or increase $\omega_m \equiv \Omega_m h^2$ to increase H_0 and still preserve the CMB peak positions

Measured

$$\theta_s(z) = \frac{r_s(z_*)}{D_A(z)}$$

Assumed from ΛCDM

$$D_A(z) \equiv \int_0^z \frac{dz'}{H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)} + \cdots}}$$

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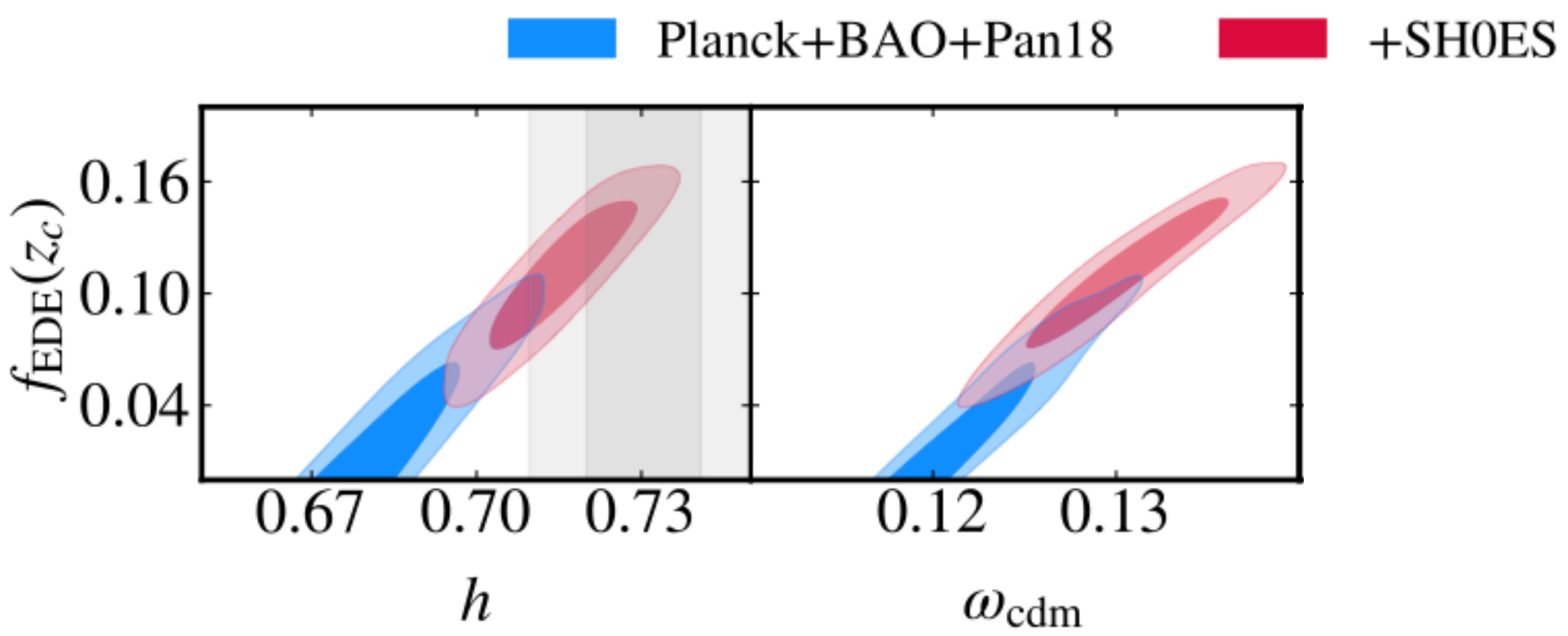

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- Under a ΛCDM-like this comes at a cost: suppression of growth at early times leads to increasing the small scale clustering σ_8

- The EDE parameter region that resolves the H_0 tension therefore worsens the S_8tension

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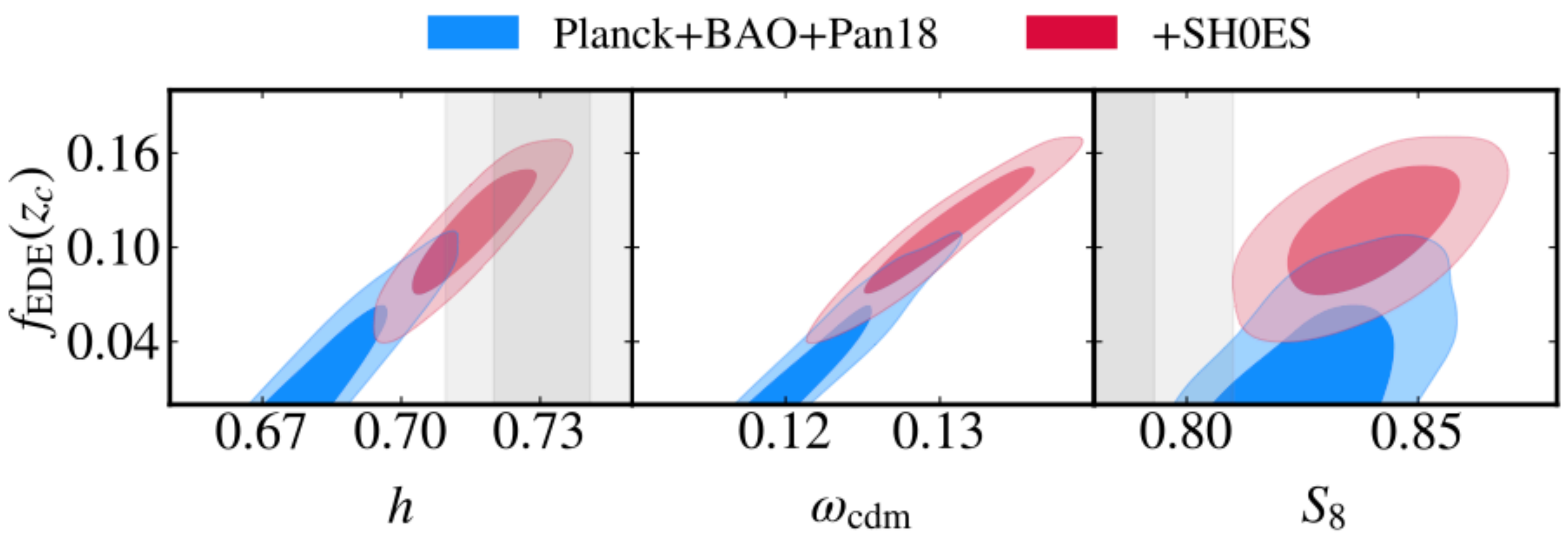
$$H_0 \uparrow \Rightarrow \Omega_X(z) \downarrow \Rightarrow \uparrow \sigma_8$$



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- Can we suppress structure growth during and after the EDE epoch, while preserving the reduction of the sound-horizon?

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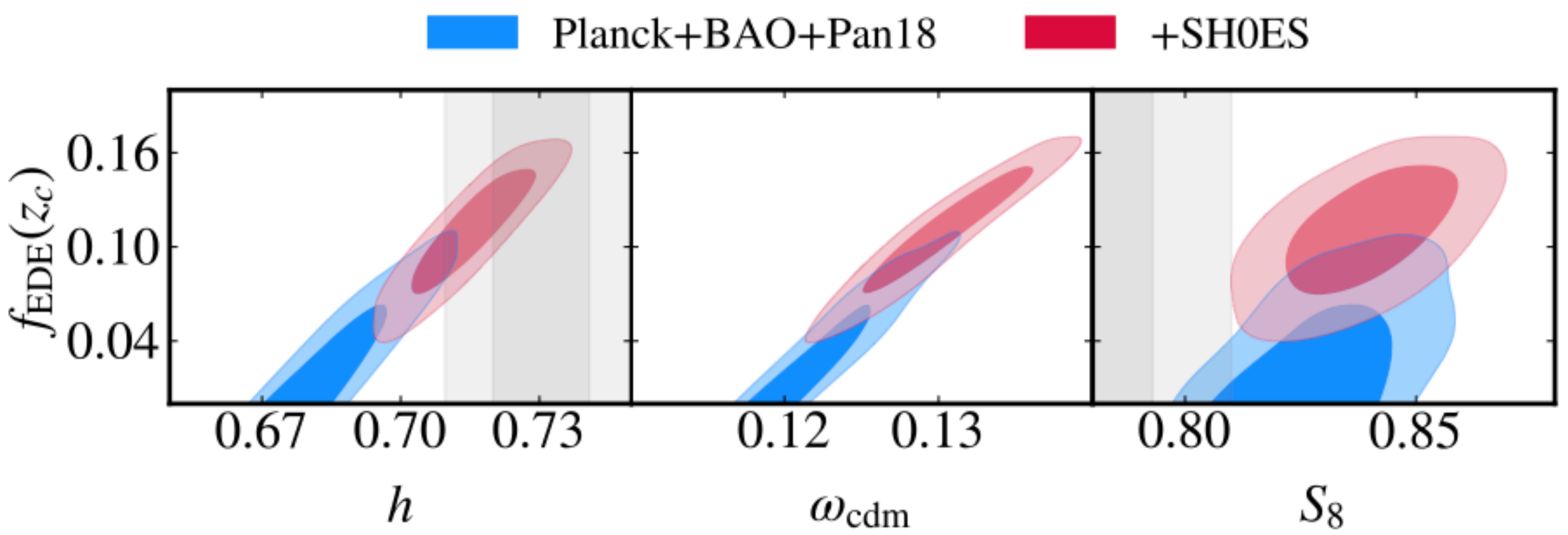

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- Can we suppress structure growth during and after the EDE epoch, while preserving the reduction of the sound-horizon?
  Drag from momentum couplings with DM?

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Measured

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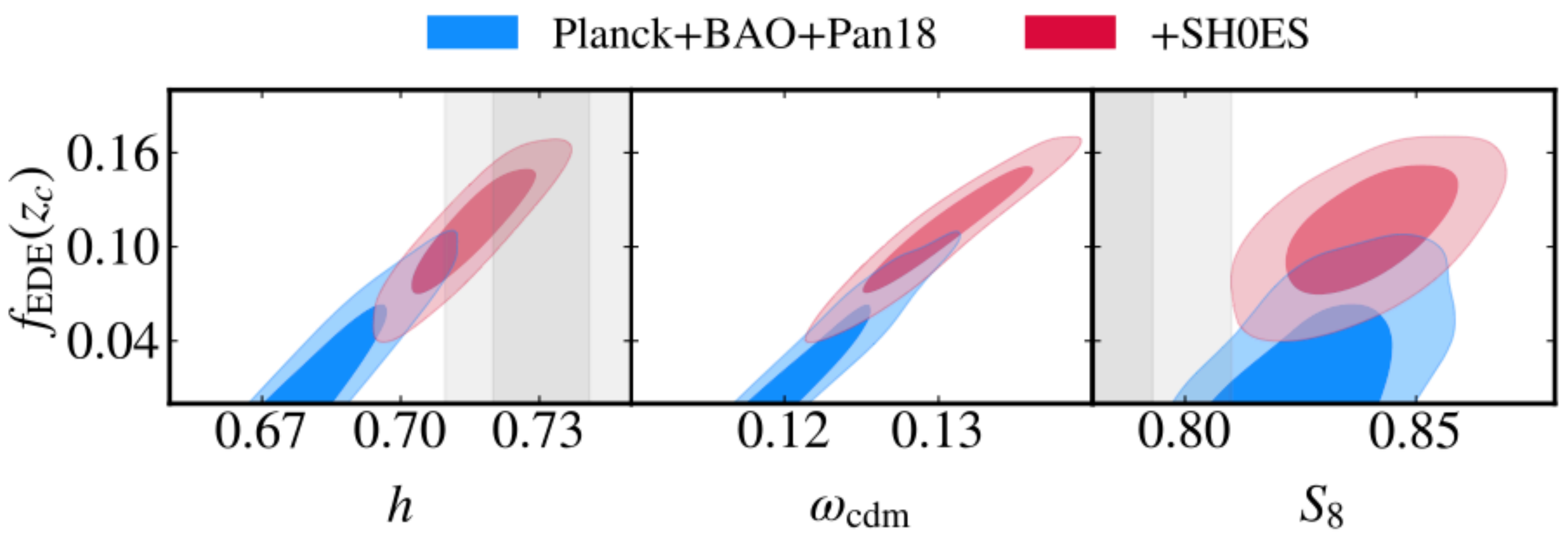


Momentum couplings between early dark energy and dark matter

Momentum transfer interaction

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}R - \int d^4x\sqrt{-g}L(h^I_\mu, \phi, \phi_\mu), \quad L = L(n, Y, Z, \phi)$$

[Pourtsidou et al., arxiv:1307.0458]

- Type-3 models with $L(n,Y,Z,\phi) = Y + V(\phi) + \beta Z^2$ with $Y = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi$ and $Z = u^\mu\partial_\mu\phi$ in FLRW

$$\rho^{(\phi)} = \left(\frac{1}{2} - \beta\right)\frac{\dot\phi^2}{a^2} + V(\phi), \qquad P^{(\phi)} = \left(\frac{1}{2} - \beta\right)\frac{\dot\phi^2}{a^2} - V(\phi)$$

$$\ddot\phi + 2\mathscr{H}\dot\phi + \left(1 - 2\beta\right)^{-1} a^2 V_\phi = 0$$

$$\dot\rho_{\rm CDM} + 3\mathscr{H}\rho_{\rm CDM} = 0, \qquad \dot\rho_\phi + 3\mathscr{H}(\rho_\phi + P_\phi) = 0$$

- CDM number density is conserved with no background energy transfer between CDM and EDE

Momentum transfer interaction

- Linear perturbations in the synchronous gauge

$$ds^2 = -a^2 d\tau^2 + a^2 \left[(1 + \frac{1}{3} h)\gamma_{ij} + D_{ij}\nu \right] dx^i dx^j$$

- Non-standard dark energy perturbations

$$\theta_\phi = \frac{1}{(2\beta - 1)Z} \left(\frac{\delta\phi}{a} + 2\beta Z \theta_{\mathrm{CDM}} \right)$$

$$\delta\rho_\phi = -Za^{-2}(1-2\beta)\,\delta\phi + V_\phi\,\delta\phi,$$
$$\delta P_\phi = -Za^{-2}(1-2\beta)\,\delta\phi - V_\phi\,\delta\phi$$

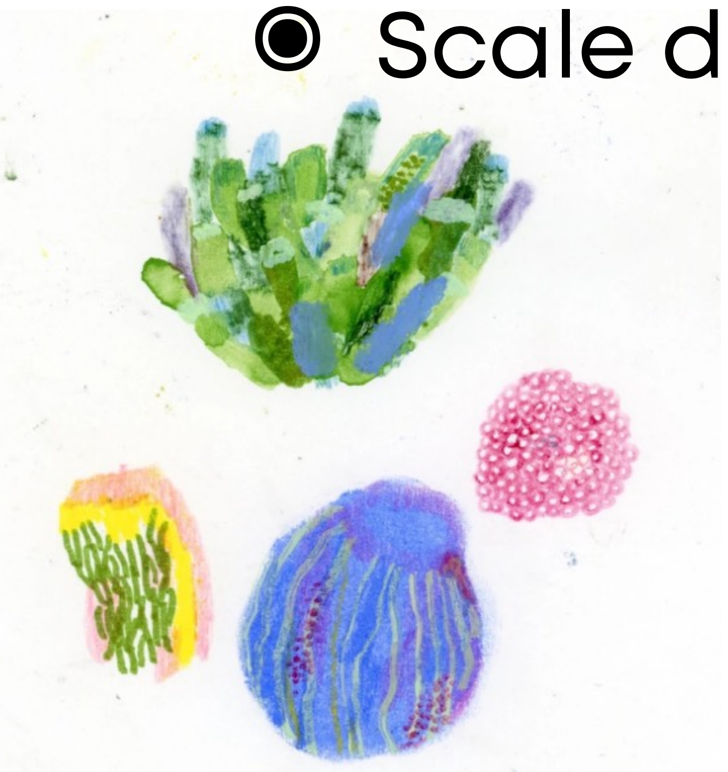
- Standard perturbed continuity equation but Type 3 momentum-transfer contribution in the Euler equation

$$\dot{\delta}_{\mathrm{CDM}} = -k^2\theta_{\mathrm{CDM}} - \frac{1}{2}\dot{h},$$

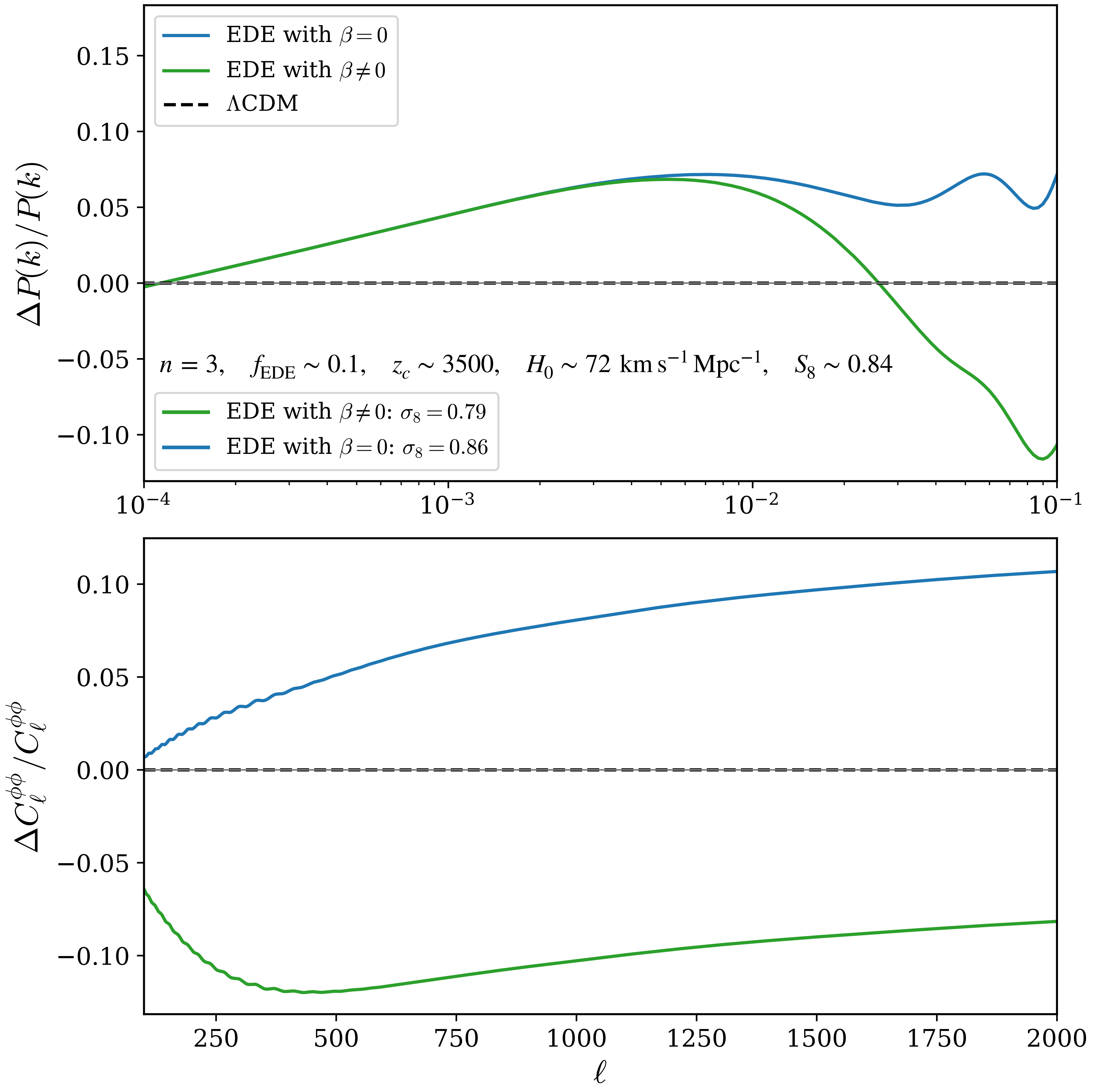
$$\dot{\theta}_{\mathrm{CDM}} = -\mathcal{H}\theta_{\mathrm{CDM}} + \frac{\left(6\mathcal{H}\beta Z + 2\beta\dot{Z}\right)\delta\phi + 2\beta Z\delta\dot{\phi}}{a\left(\rho_{\mathrm{CDM}} - 2\beta Z^2\right)}$$

- Scale dependent modifications to KG equation

$$(1-2\beta)\left(\delta\ddot{\phi} + 2\mathcal{H}\delta\dot{\phi}\right) + (k^2 + a^2V_{\phi\phi})\delta\phi + \frac{1}{2}(1-2\beta)\dot{\phi}\,\dot{h} - 2\beta\dot{\phi}k^2\theta_{\mathrm{CDM}} = 0$$



Observational Signatures



[Figure credit: Youri Carloni]

- Best-fit EDE model from Planck+SH0ES analyses with $\beta = 0$ (no coupling) and $\beta = -0.5$
- Scale-dependent reduction of matter power for modes that contribute most to σ_8 and large-scale normalisation is practically unchanged
- Type 3 structure: interaction in the CDM velocity equation provides mechanism to lower S_8 relative to uncoupled EDE

$$\dot{\theta}_{\rm CDM} = -\mathcal{H}\theta_{\rm CDM} + \frac{\left(6\mathcal{H}\beta Z + 2\beta\dot{Z}\right)\delta\phi + 2\beta Z\delta\dot{\phi}}{a\left(\rho_{\rm CDM} - 2\beta Z^2\right)}$$

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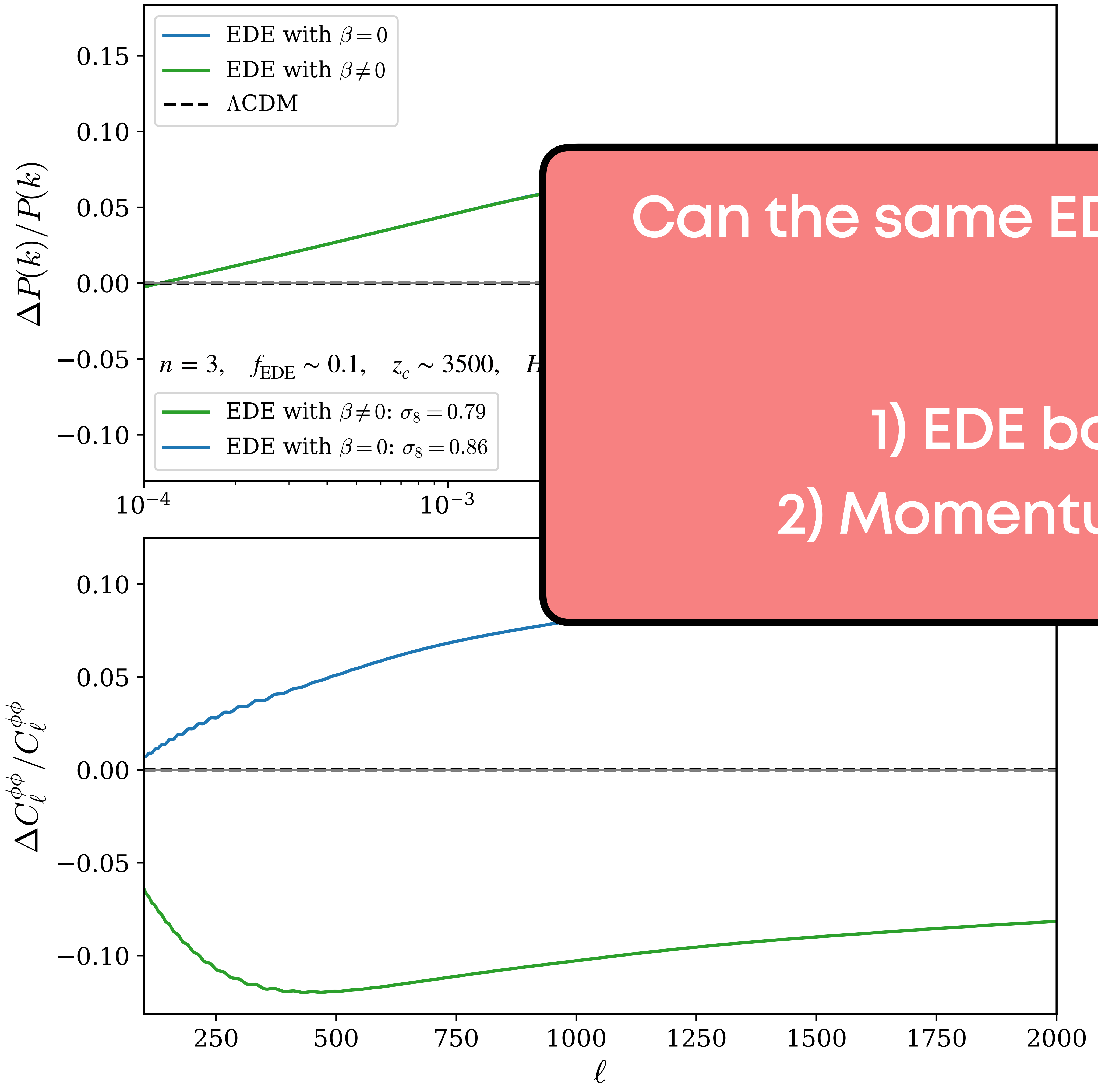


[Figure credit: Youri Carloni]

- Best-fit EDE model from Planck+SH0ES …) and $\beta = -0.5$

… matter power … to σ_8 and … actically

… the CDM velocity equation provides mechanism to lower S_8 relative to uncoupled EDE

Can the same EDE field address both H_0 and S_8 tensions?

1) EDE background: $r_s \downarrow \Rightarrow H_0 \uparrow$

2) Momentum coupling: $P(k) \downarrow \Rightarrow S_8 \downarrow$

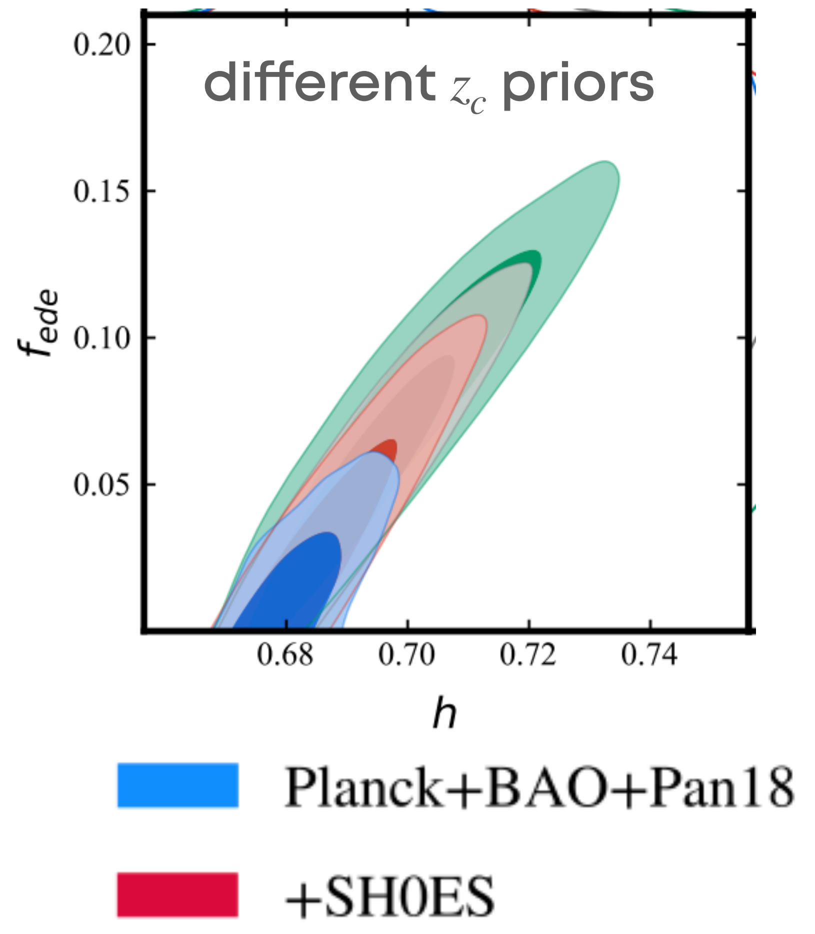
$$\dot{\theta}_{\rm CDM} = -\mathcal{H}\theta_{\rm CDM} + \frac{\left(6\mathcal{H}\beta Z + 2\beta\dot{Z}\right)\delta\phi + 2\beta Z\delta\dot{\phi}}{a\left(\rho_{\rm CDM} - 2\beta Z^2\right)}$$

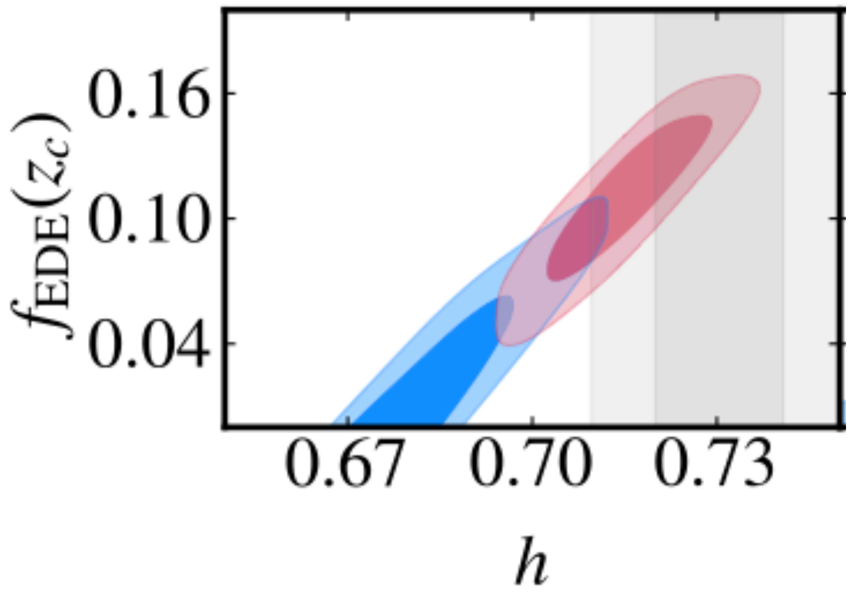
Bayesian or Frequentist?

- Prior volume effects if: too many parameters; poorly constraining data; non-Gaussian posteriors; volume effects in parameters sampled

- When $f_{\rm EDE} \to 0$ all the EDE parameters (z_c, θ_i) become degenerate with ΛCDM and there is a bias in the marginalised posteriors

- We have no theory informed priors on EDE





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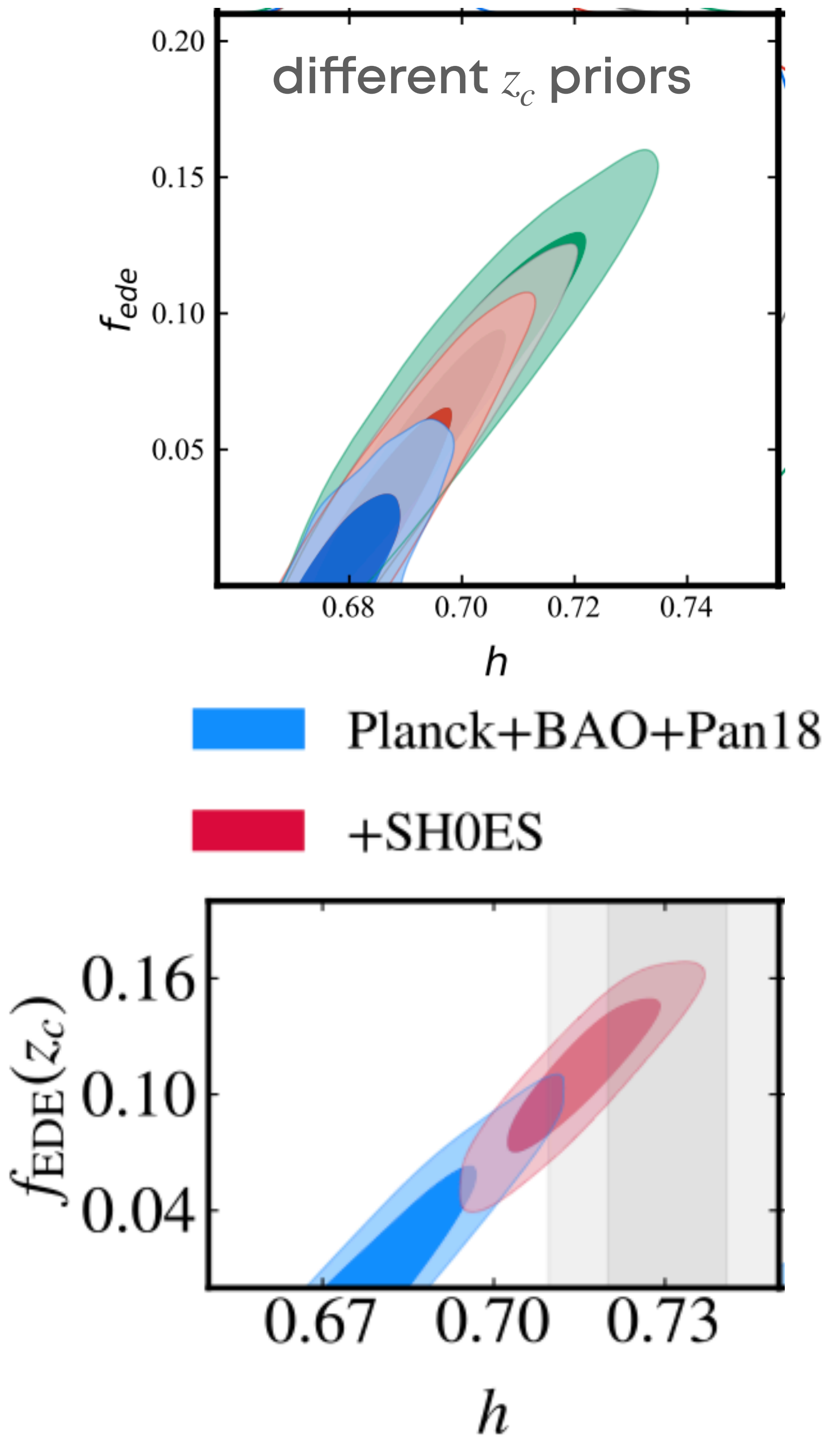
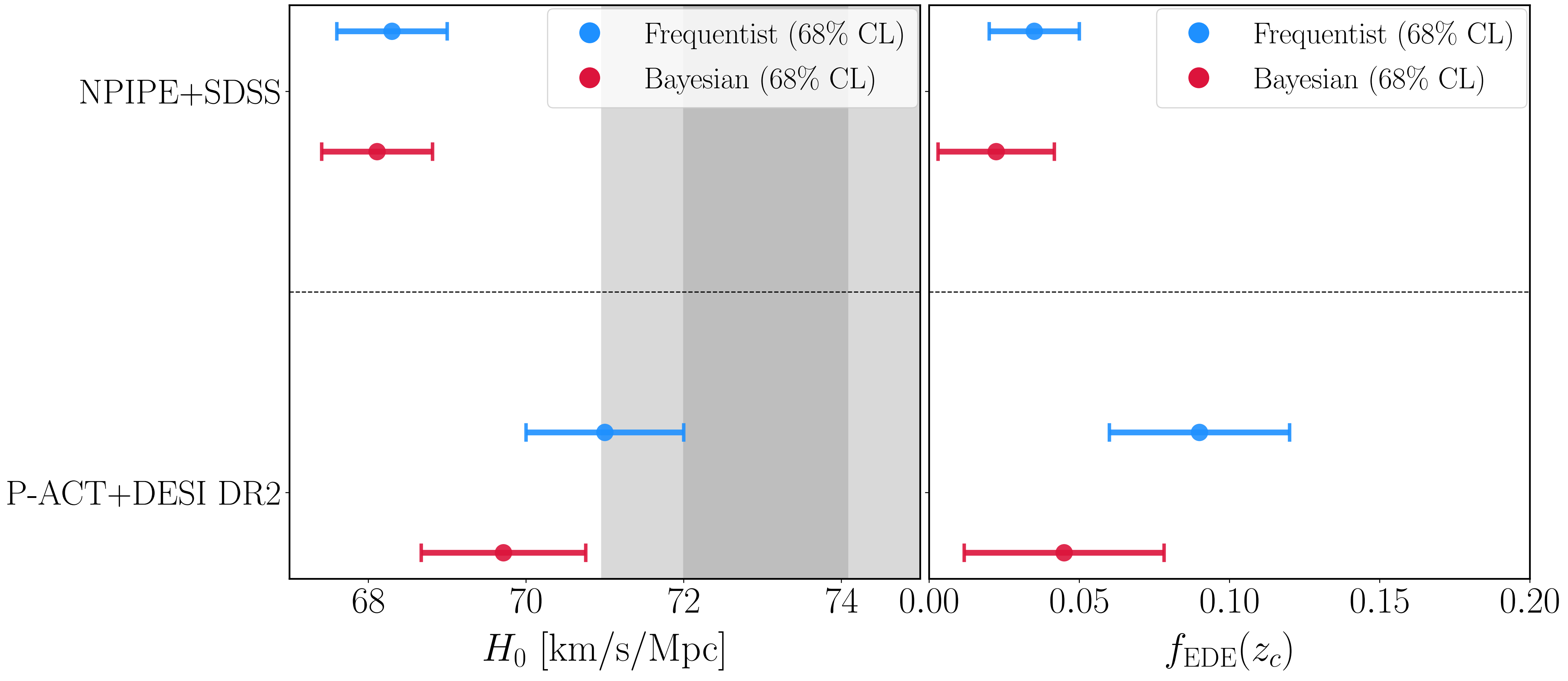
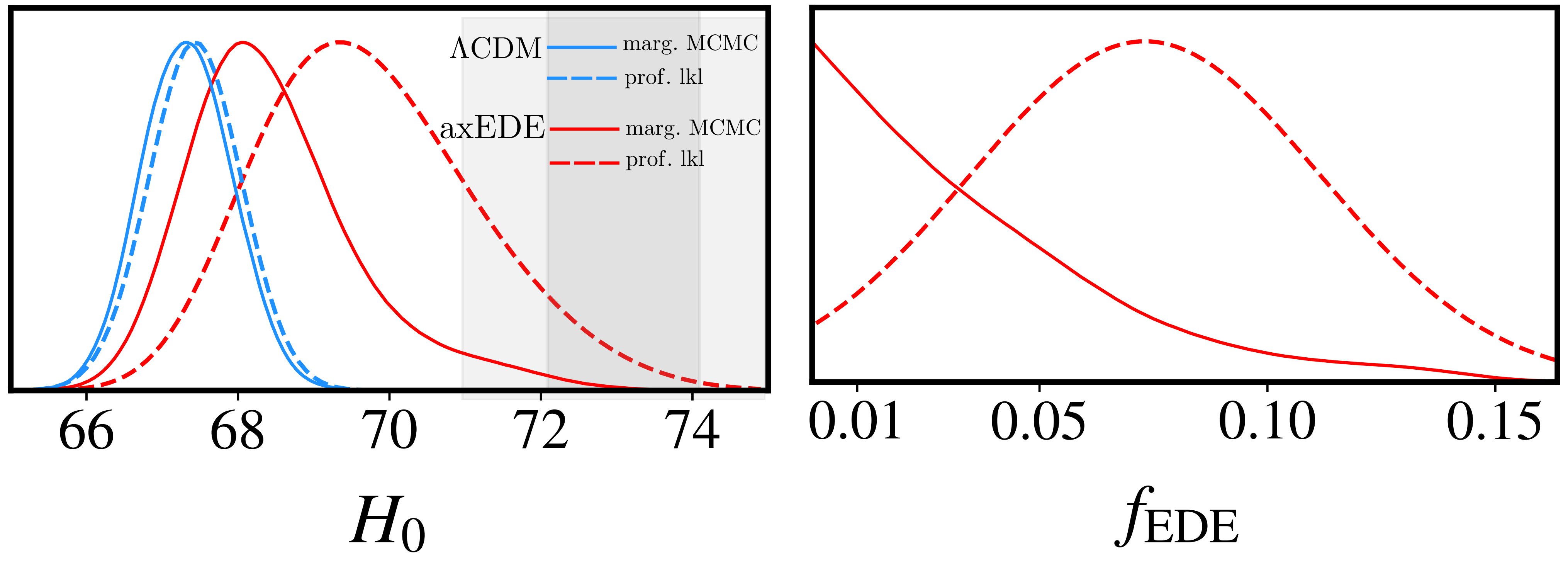
- When $f_{\rm EDE} \to 0$ all the EDE parameters (z_c, θ_i) become degenerate with Λ CDM and there is a bias in the marginalised posteriors
- We don't have theory informed priors on EDE
- Remove the prior volume effects with a profile likelihood analysis





[Poulin et al, arxiv: 2505.08051]



[Herold et al, arxiv: 2210.16296]

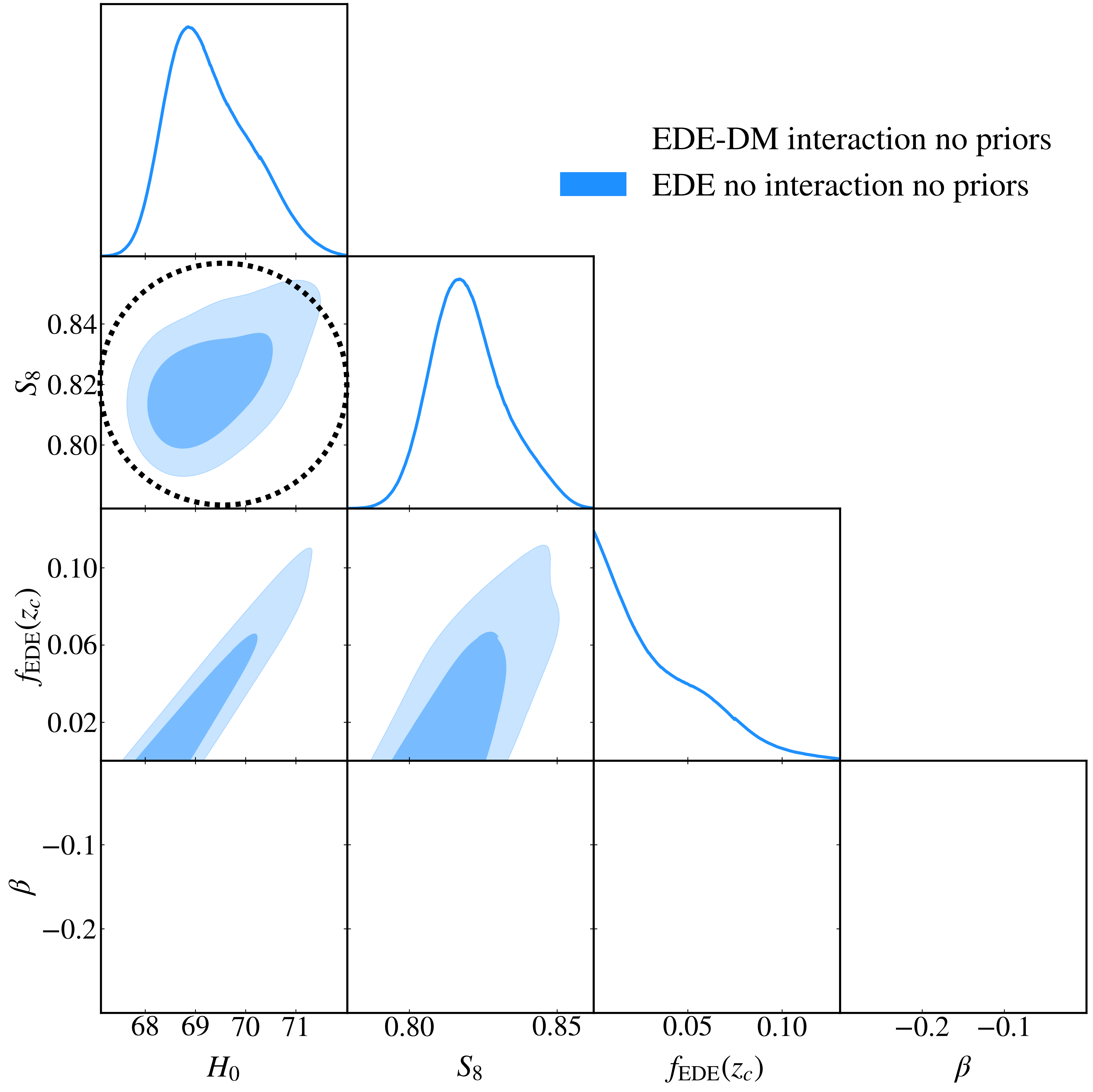
Methodology

- Baseline Planck 2018, Pantheon+, DESI DR1 BAO
- Optional Gaussian priors "on H_0" ($M_B = -19.253 \pm 0.027$ from SH0ES) and $S_8 = 0.790^{+0.018}_{-0.014}$ (from a combination of cosmic shear surveys from DES Y3 and KiDS-1000)
- Conduct both Bayesian and Frequentist analyses
- Consider two prior choices:
    - Linear uniform priors on β and $f_{\rm EDE}$: degeneracy between the amount of EDE and the strength of the coupling
    - Logarithmic uniform prior on the product $x \equiv \log_{10}(\beta f_{\rm EDE})$: directly samples the physical amplitude of the interaction and reduces the prior-volume dilution in the $(\beta, f_{\rm EDE})$ case

Planck 2018: [Aghanim et al.: Astron.Astrophys. 641 (2020) A6]
DESI DR2: [Abdul-Karim et al. Phys. Rev. D 112, 083515 (2025(]
PantheonPlus: [Brout et al: Astrophys. J. 938 (2022) 110]
SH0ES prior: [Riess et al: Astrophys. J. Lett. 934 (2022) 1 L7]
S8 prior: [Abbott et al: The Open Journal of Astrophysics 6 (2023)]

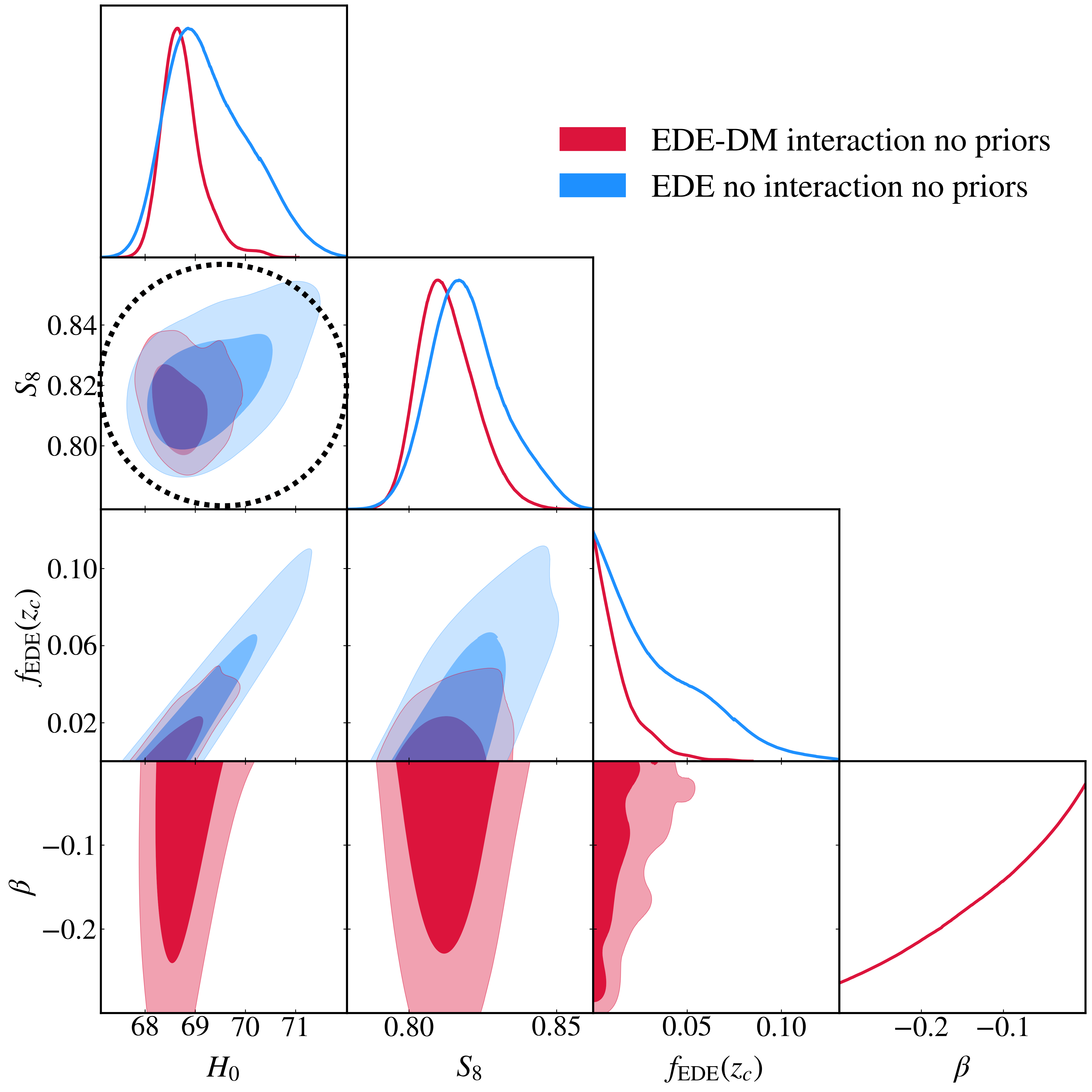
Linear case

- No additional priors: EDE can raise H_0 for larger $f_{\rm EDE}$ relative to ΛCDM, but also raises S_8



Linear case

- No additional priors: EDE can raise H_0 for larger $f_{\rm EDE}$ relative to ΛCDM, but also raises S_8
- Turning on the coupling suppresses structure growth and moves S_8 down
- However: the posterior shifts away from the high-H_0 region preferred by a large EDE fraction



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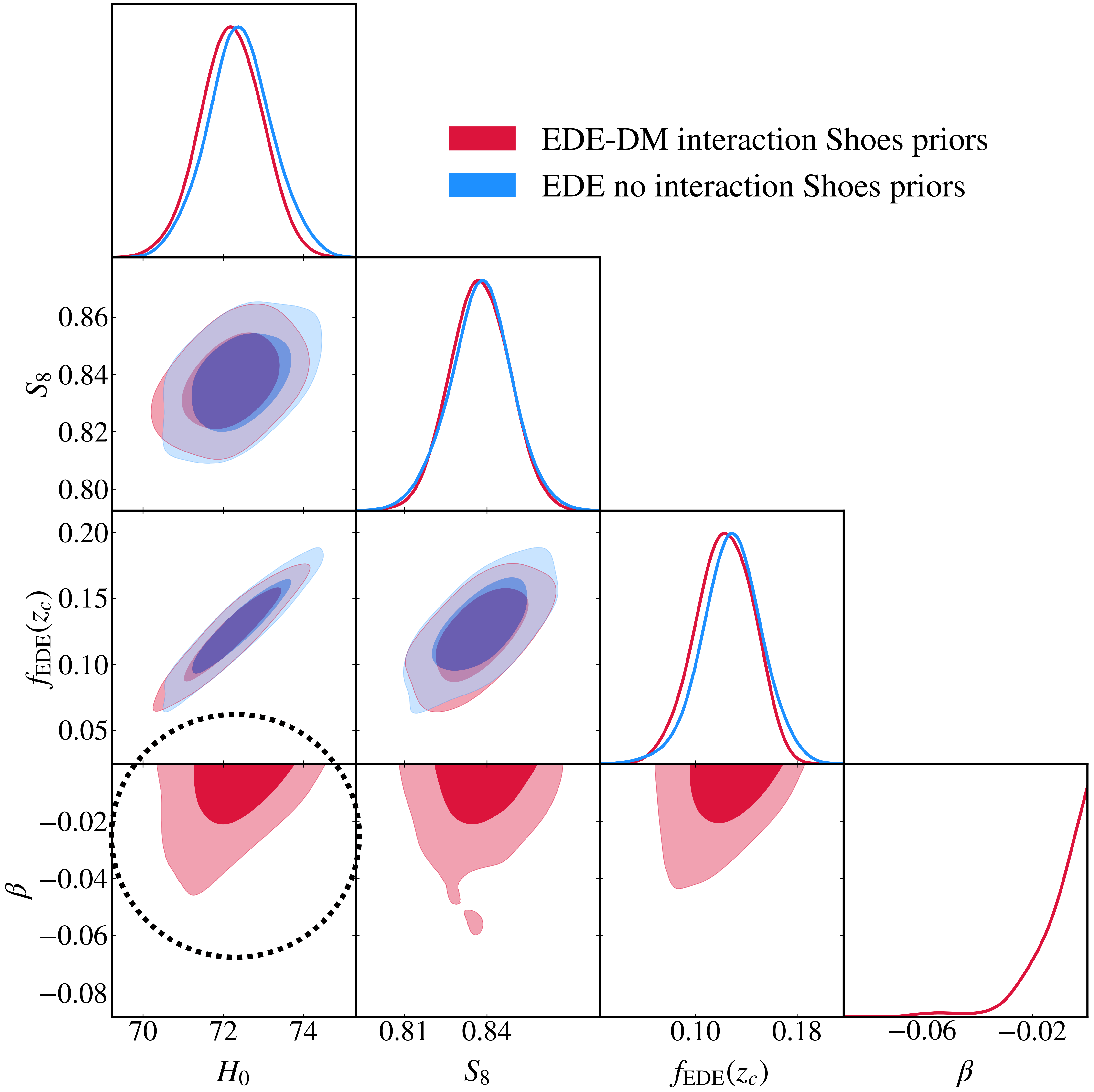
- Adding the SH0ES H_0 prior favours a larger EDE fraction and hence a larger S_8
- However: a coupling strong enough to compensate this increase is disfavoured as it departs from the high-H_0 EDE solution



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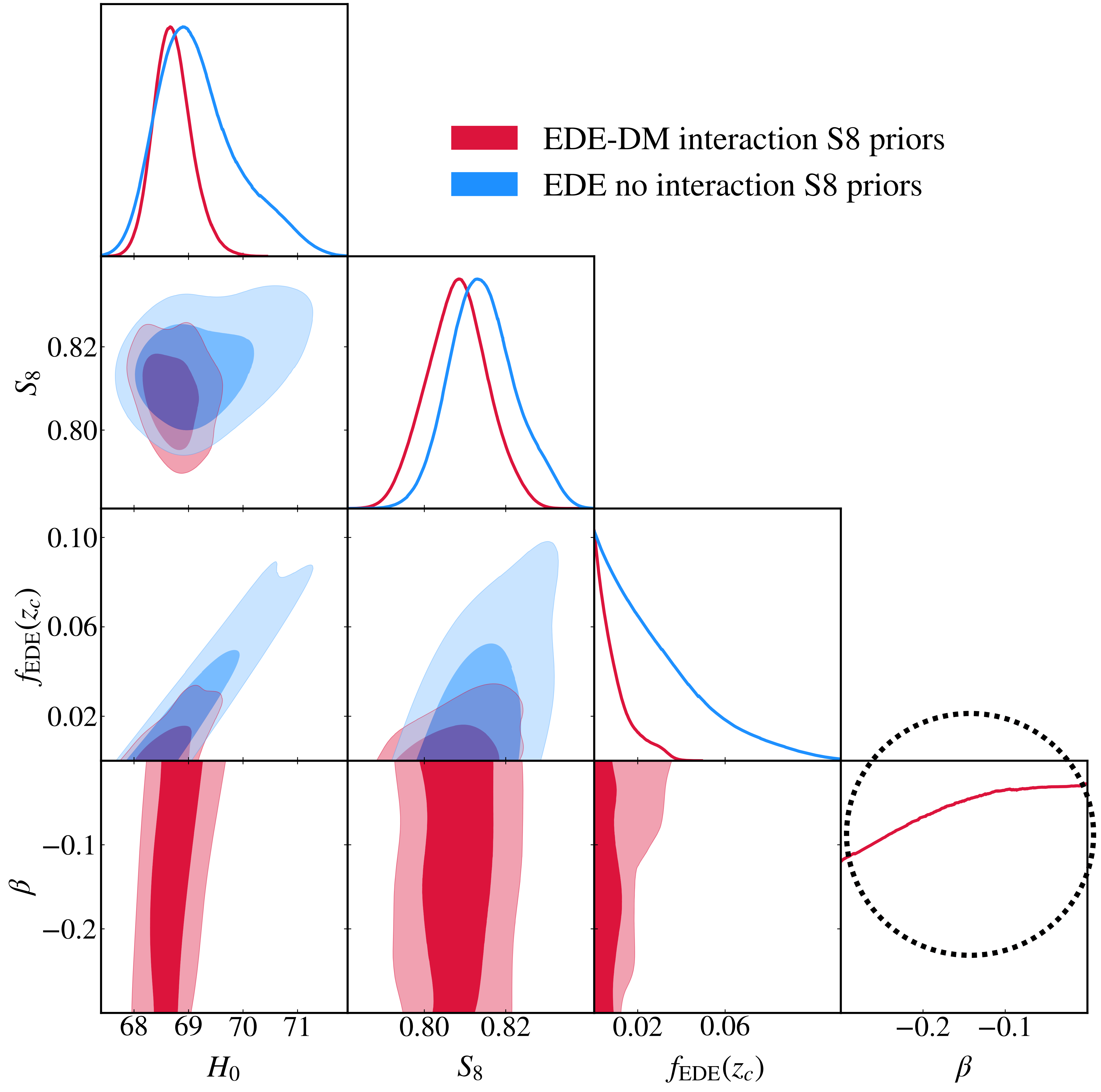
- S_8 prior: S_8 is smaller for the model with interaction, but the coupling is not detected



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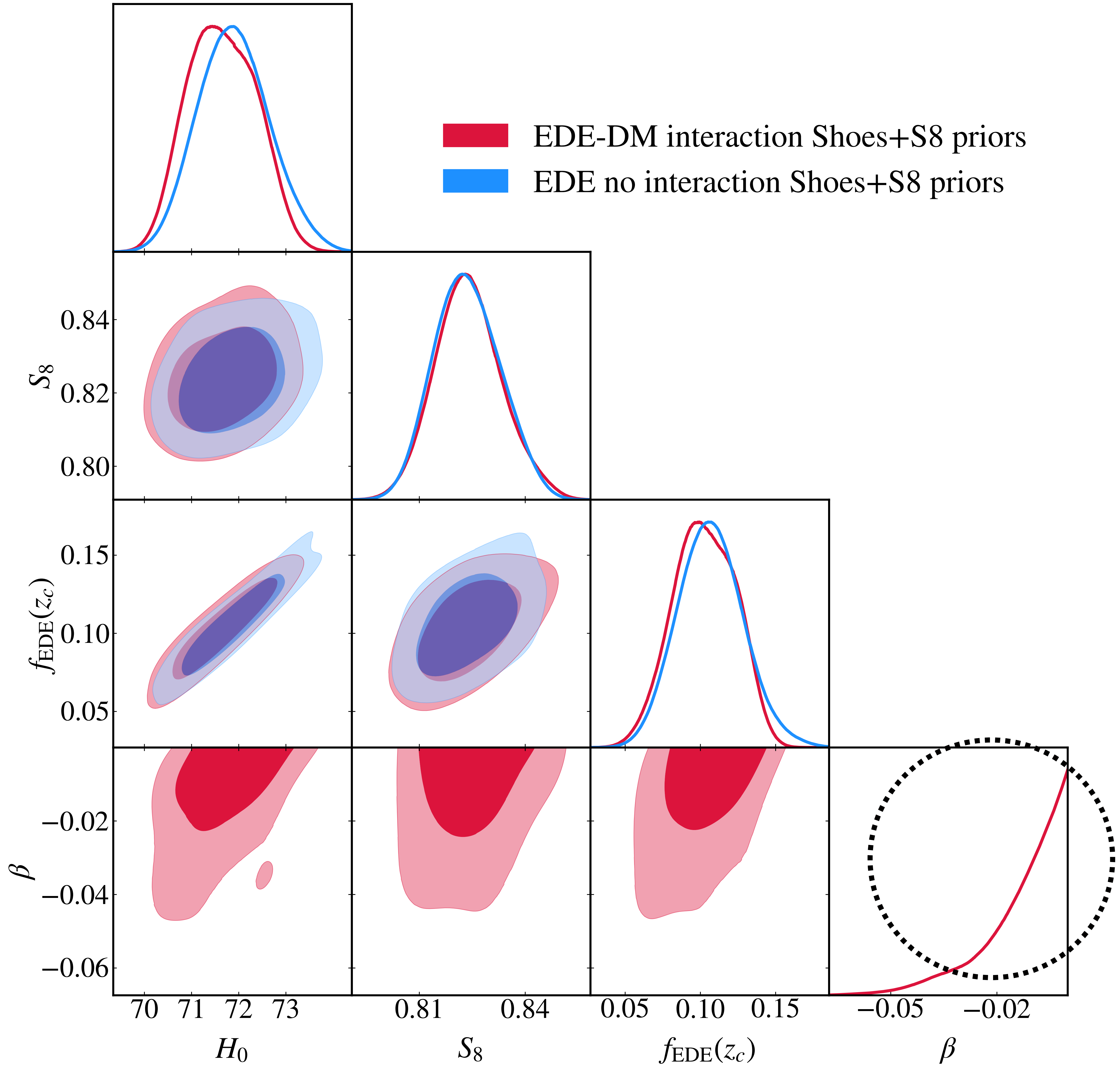
- H_0 and S_8 priors: the posterior is dominated by SH0ES prior and the coupling has no effect



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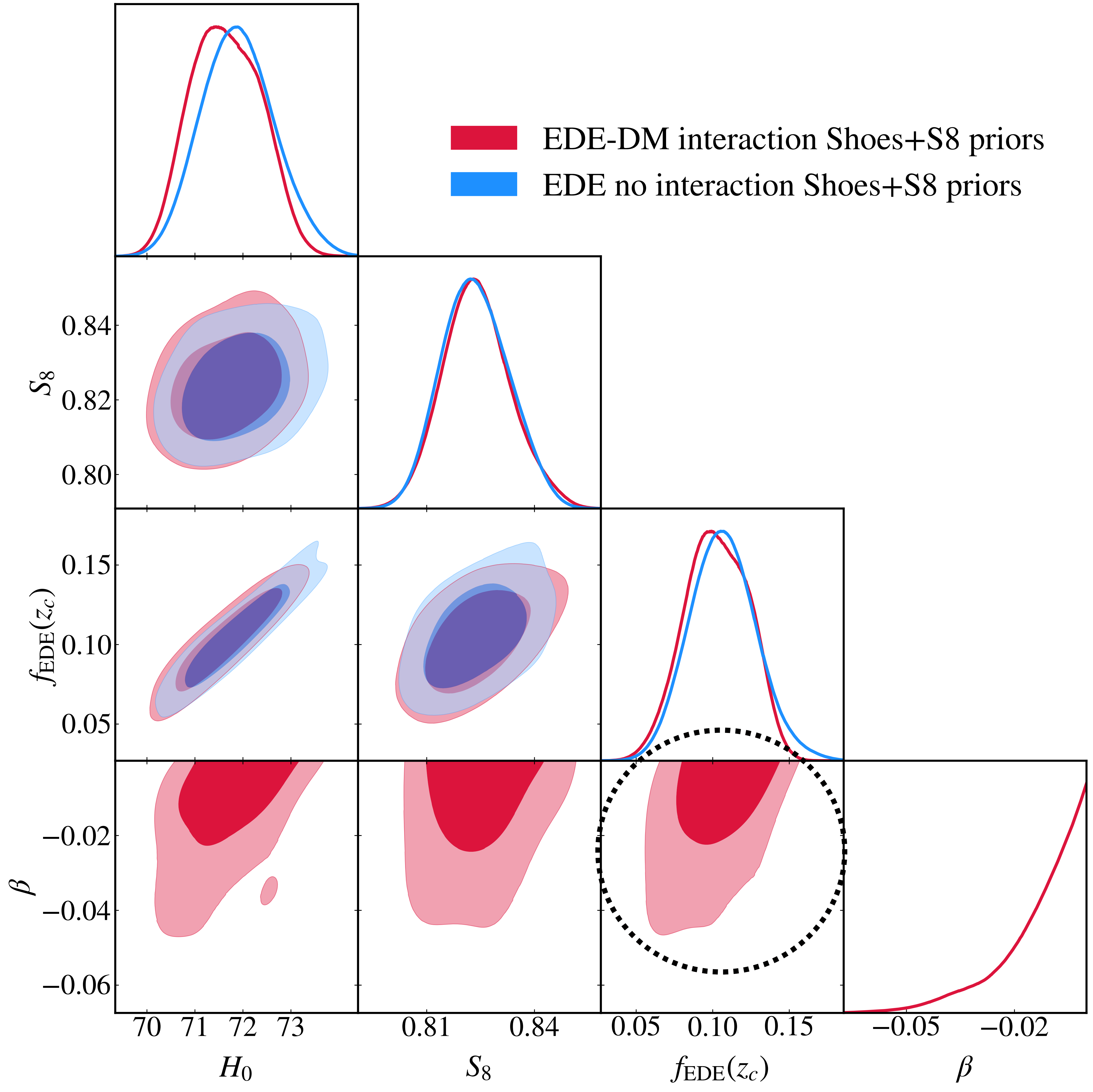
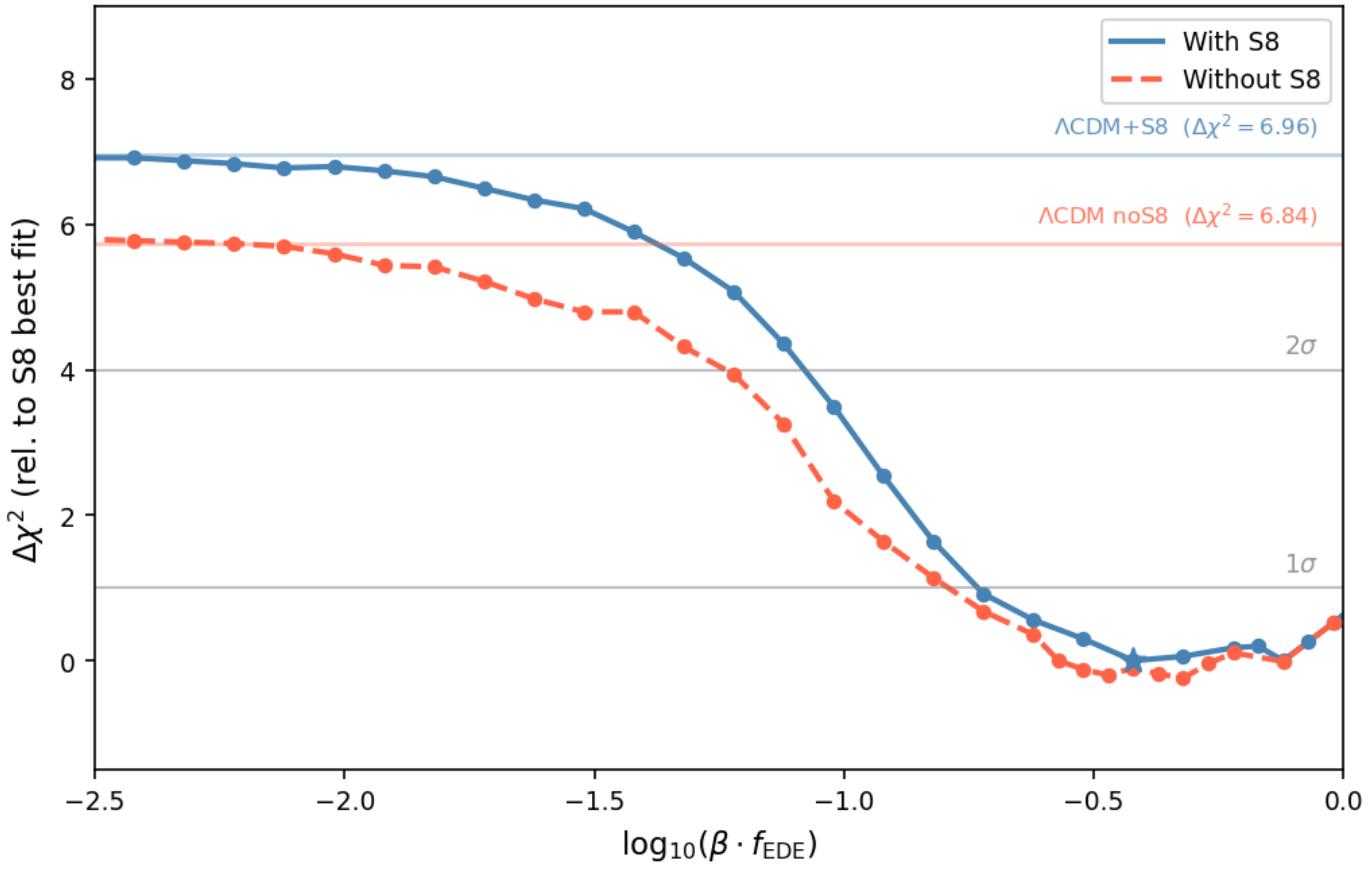
- Turning on the coupling suppresses structure growth and moves S_8 down
- However: the posterior shifts away from the high-H_0 region preferred by a large EDE fraction
- H_0 and S_8 priors: the posterior is dominated by SH0ES prior and the coupling has no effect
- Cannot reduce S_8 while maintaining high H_0: the coupling strength needed to reduce S_8 requires small $f_{\rm EDE}$, which undermines the H_0 gain



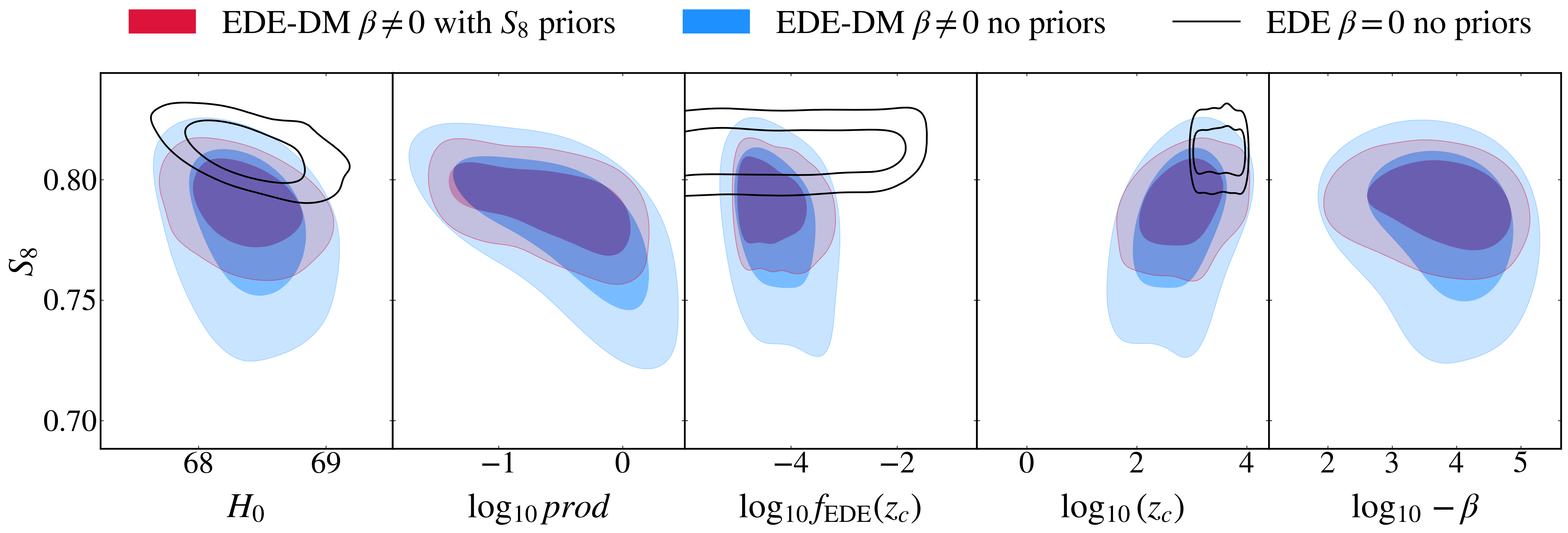
Prior volume effect: profile likelihood

- Use $x = \log_{10}(\beta f_{\rm EDE})$ which captures the physical amplitude of the coupling
- Map the likelihood landscape with a prior-independent profile scan to get informed priors
- Well-defined interior minimum at $x_{\rm min} \approx -0.42$, with best-fit $S_8 = 0.789$ and $\log_{10}(z_c) \approx 2.35$
- The momentum coupling EDE improves the total fit by $\Delta\chi^2 \sim 7$ with and without the S8 prior
- The improvement is mostly from Planck CMB data - driven by the effect of the coupling in the DM perturbations for small EDE fraction?



Logarithmic product case

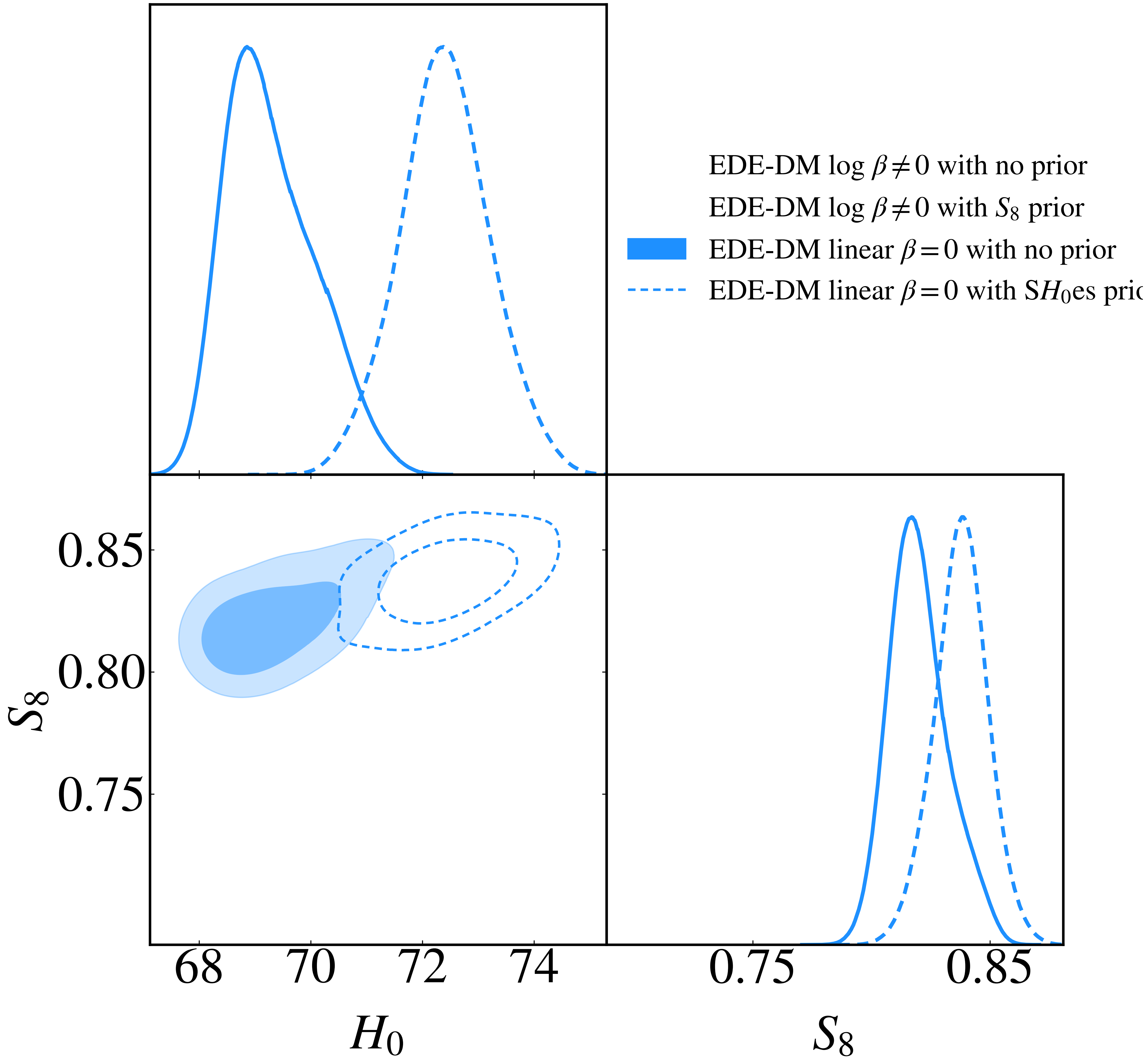
- Sampling on the effective coupling $x \equiv f_{\rm EDE}\beta$ reveals a preference for small $f_{\rm EDE}$ and large β
- Large β can lower S_8 but no contribution to the expansion rate from EDE so no increase in H_0
- SH0ES prior targets high f_{EDE} which would erase detection of β and leave S_8 unchanged



Take-away result

The model contains two useful regimes that do not overlap

1. EDE-dominated regime: the EDE field reduces r_s and can raise the CMB-inferred value of H_0, at the cost of increasing $\omega_{\rm cdm}$ which increases S_8



Take-away result

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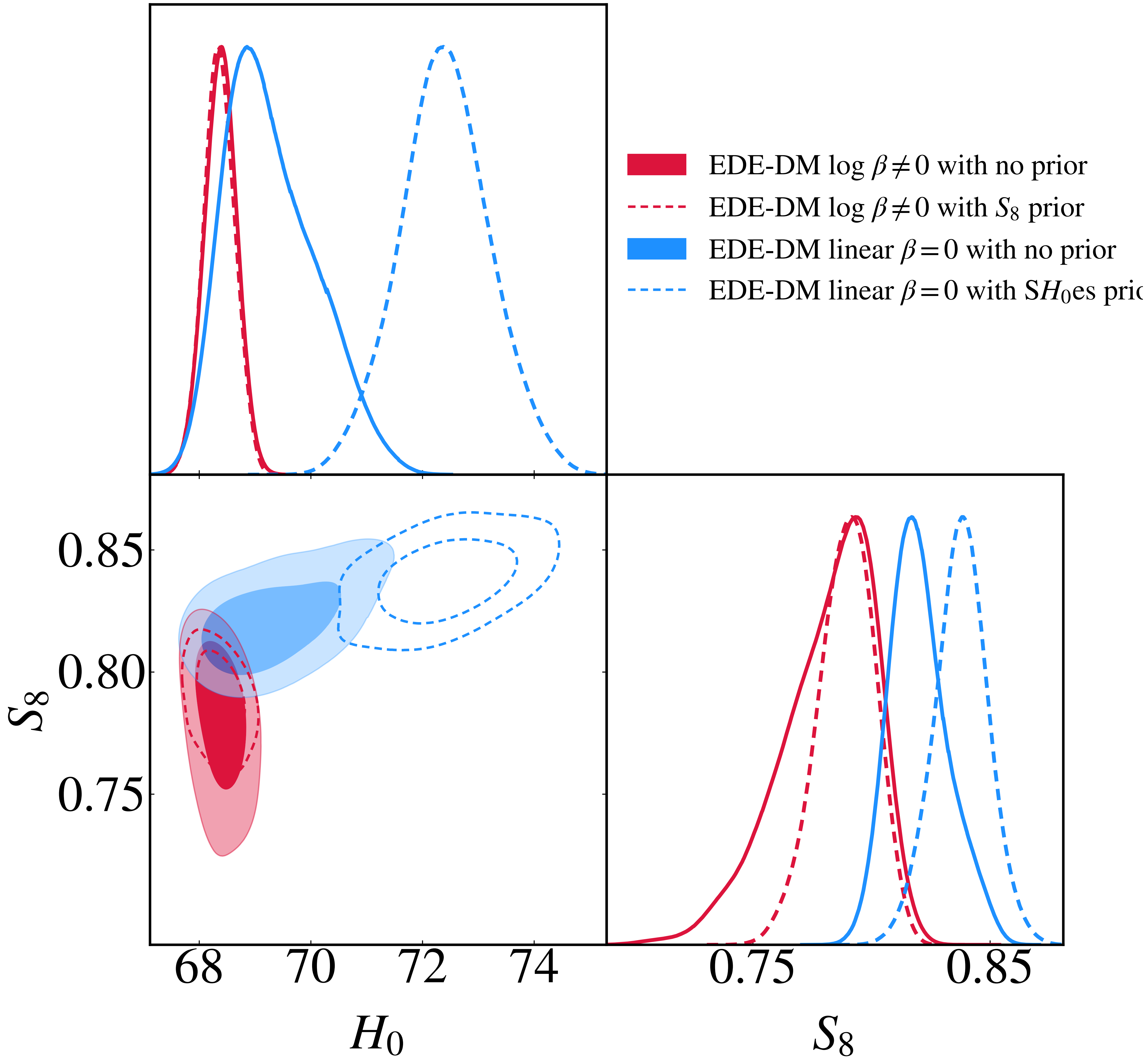

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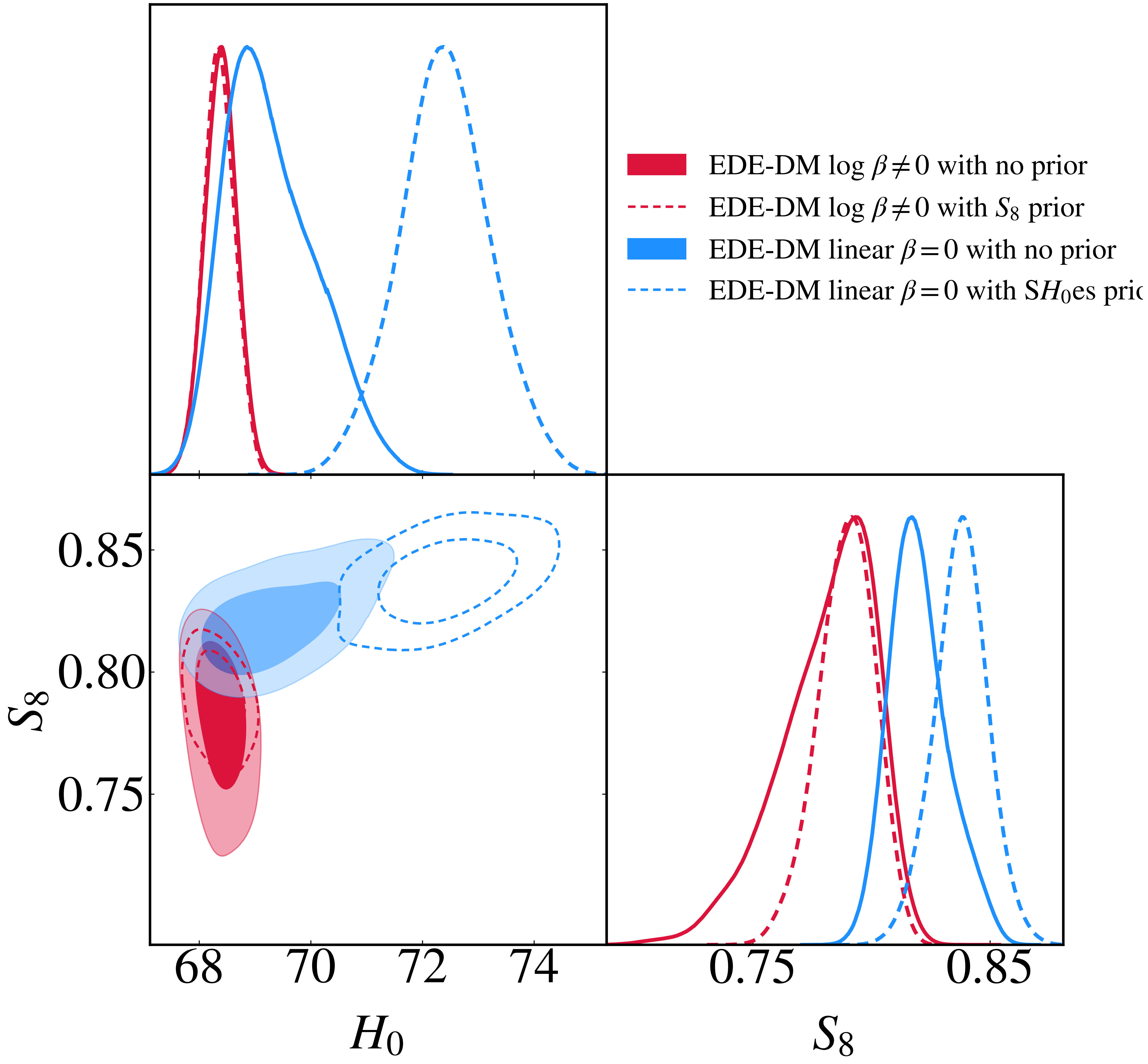
- Same behaviour found for dark-fluid EDE models with drag-like term: general conflict if the same EDE component is asked both to shrink the sound horizon and to suppress late-time clustering [Simon et al: arxiv:2410.21459]

- In the single-field EDE model, the lower-S_8 and the high-H_0 branches are different regions of parameter space: should separate the field behaviours?



Conclusions

- Type 3 momentum-transfer coupling between CDM and an axion-like EDE field with no energy exchange but which modifies the CDM Euler equation and EDE perturbations

- The model contains two useful regimes that do not overlap:

  i) EDE-dominated regime for $f_{\rm EDE} \sim 0.1$ which raise CMB-inferred $H_0 \Rightarrow \omega_{\rm cdm} \uparrow \Rightarrow S_8 \uparrow$

  ii) Coupled regime for $f_{\rm EDE} \sim \mathcal{O}(10^{-4})$ suppress structure growth S_8 but doesn't change H_0

- Frequentist profile likelihood gives a detection for effective coupling $x \equiv \log_{10}(\beta f_{\rm EDE}) \approx -0.42$ with $S_8 = 0.789$ and $\log_{10}(z_c) \approx 2.35$ and $\Delta\chi^2 \approx 7$

- The CDM-EDE momentum-transfer model can ease the S_8 tension or help with the H_0 tension, but not both at the same time

- Future direction: separate the two physical roles, e.g. a multi-axion EDE scenario with one uncoupled axion transitioning near MR equality ($r_s^* \downarrow, H_0 \uparrow$) and a second axion transitioning later and coupled to CDM to suppress growth

Thank you for your attention!

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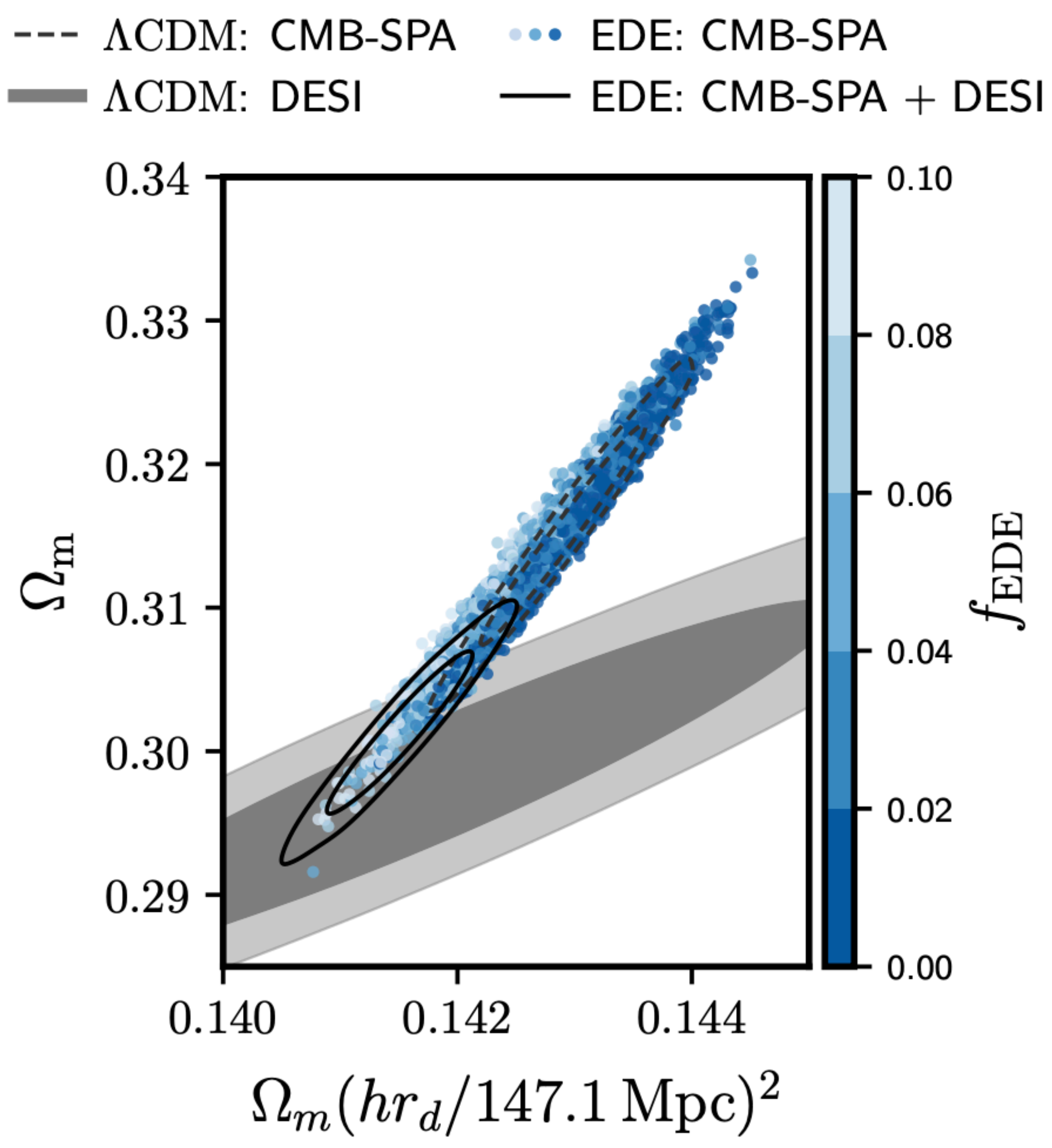
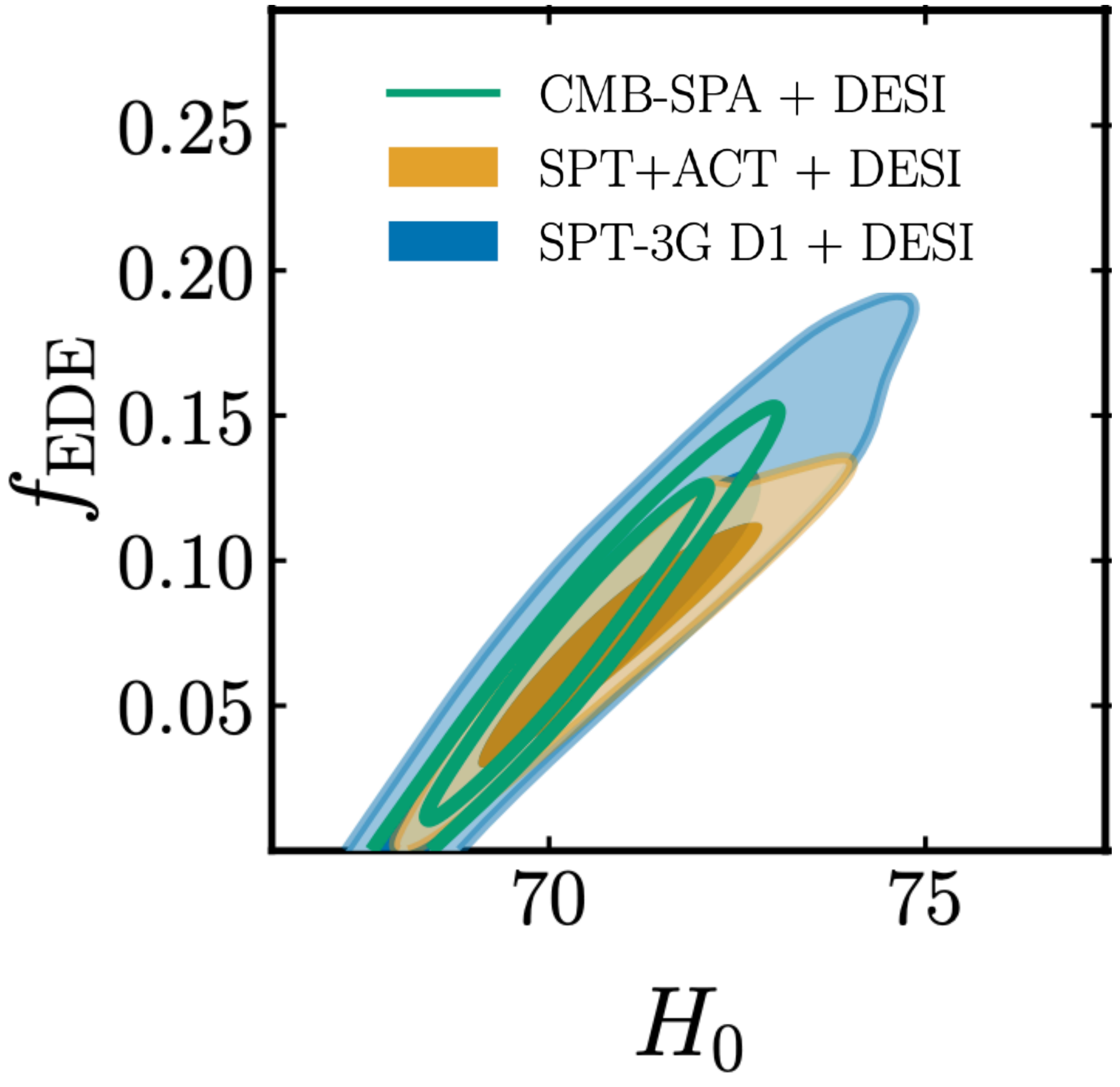
Early dark energy

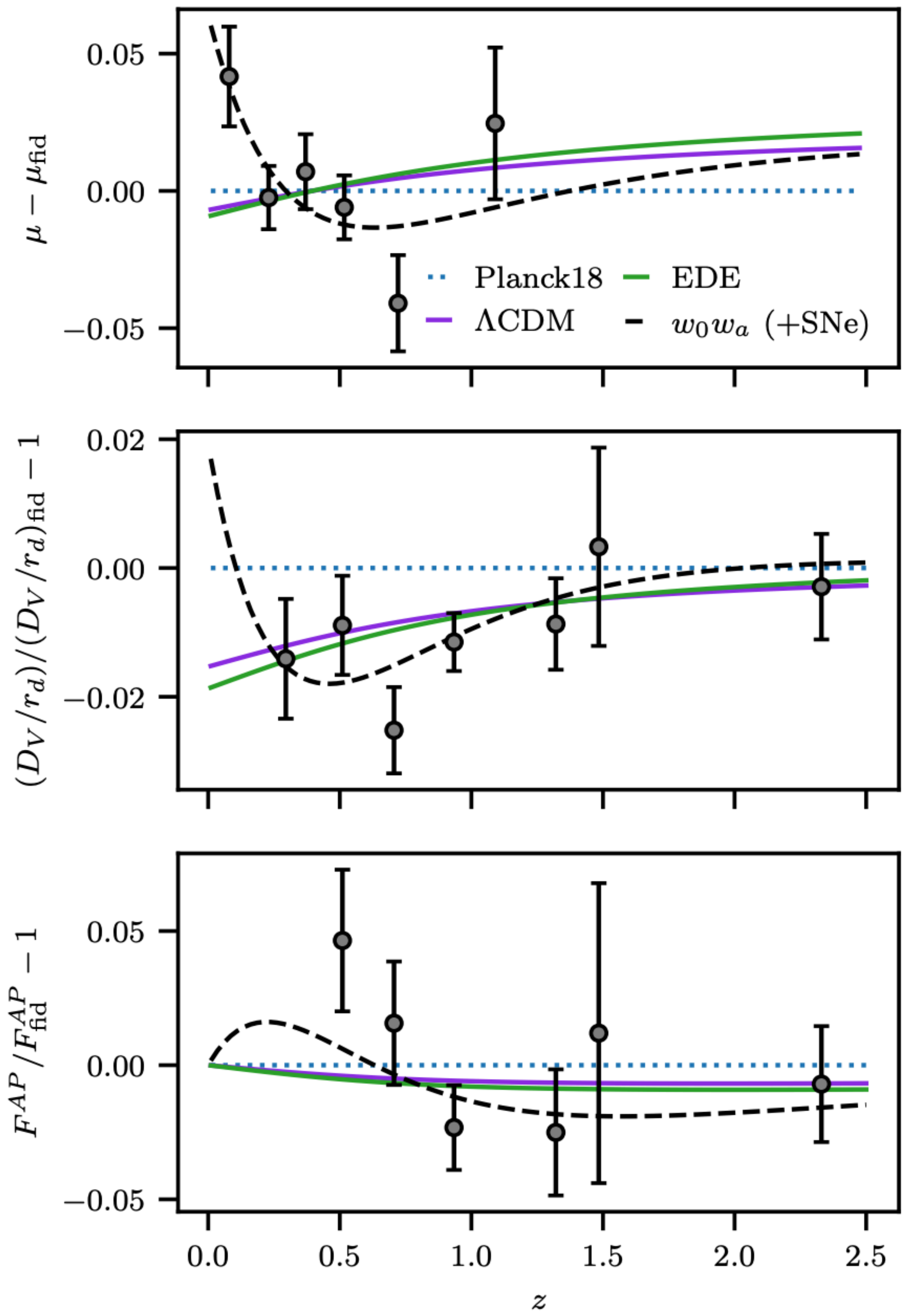
- Reduces the CMB/DESI tension but disfavored by high-Ω_m from SN1a

Data	ΛCDM - EDE	ΛCDM - w_0w_a
CMB+BAO	7.4	13
+SNe	7.5	19
+SNe+CCHP	8.7	14
+SNe+SH0ES	26	-4.6





[Khalife et al SPT-3G D1, arxiv:2507.23355]



[DESI DR2 Results 2025, arxiv:2503.14738]

Bayesian credible interval

1. Central quantity: posterior

$$P(\boldsymbol{\theta}\,|\,\boldsymbol{x}) \sim \mathscr{L}(\boldsymbol{x}\,|\,\boldsymbol{\theta}) \cdot \pi(\boldsymbol{\theta})$$

2. Nuisance parameters $\boldsymbol{\theta} = (\mu, \boldsymbol{\nu})$: integration/marginalization:

$$P(\mu\,|\,\boldsymbol{x}) = \int d\boldsymbol{\nu}\, P(\mu, \boldsymbol{\nu}\,|\,\boldsymbol{x})$$

3. Method: MCMC

→ **Prior dependence, prior volume effects**

Freq. confidence interval

1. Central quantity is the likelihood: $\mathscr{L}(\boldsymbol{x}\,|\,\boldsymbol{\theta})$
   - Prior not necessary (additional likelihood)

2. Nuisance parameters: optimization/profiling

$$PL(\mu) \sim \max_{\nu} \mathscr{L}(x\,|\,\mu, \nu)$$

3. Method: Neyman construction
   - Limit of a large data set (asymptotic limit): profile likelihood

(Test asymptotic limit for Planck & ΛCDM; LH, Ferreira, Heinrich 2024)

→ **Only considers $\mathscr{L}$: "fine tuned"**

Profile likelihood

Profile likelihood:

conditional MLE

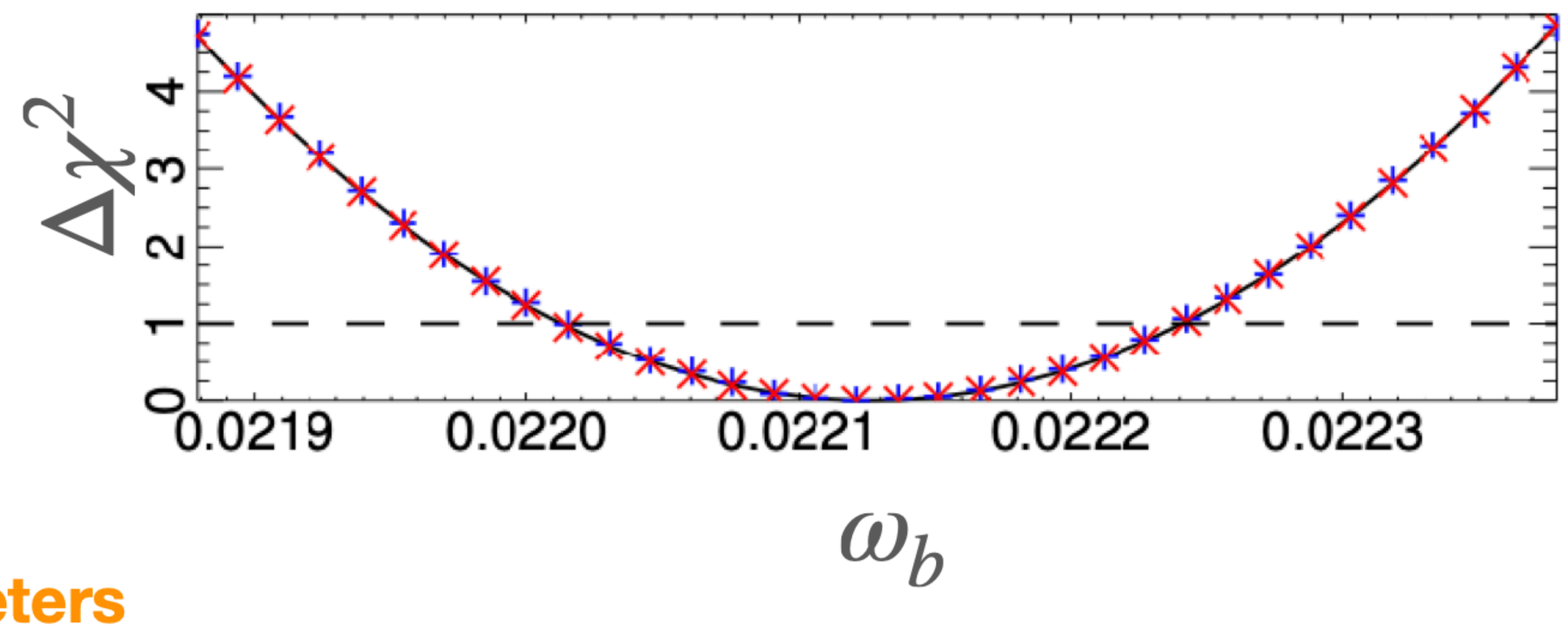
$$\Delta\chi^2(\theta) = -2\log\left(\frac{\mathcal{L}(\theta,\hat{\hat{\boldsymbol{\nu}}})}{\mathcal{L}(\hat{\theta},\hat{\boldsymbol{\nu}})}\right)$$

parameter of interest

MLE

nuisance parameters

Example: Planck col. XVI, 2013



Graphical method:

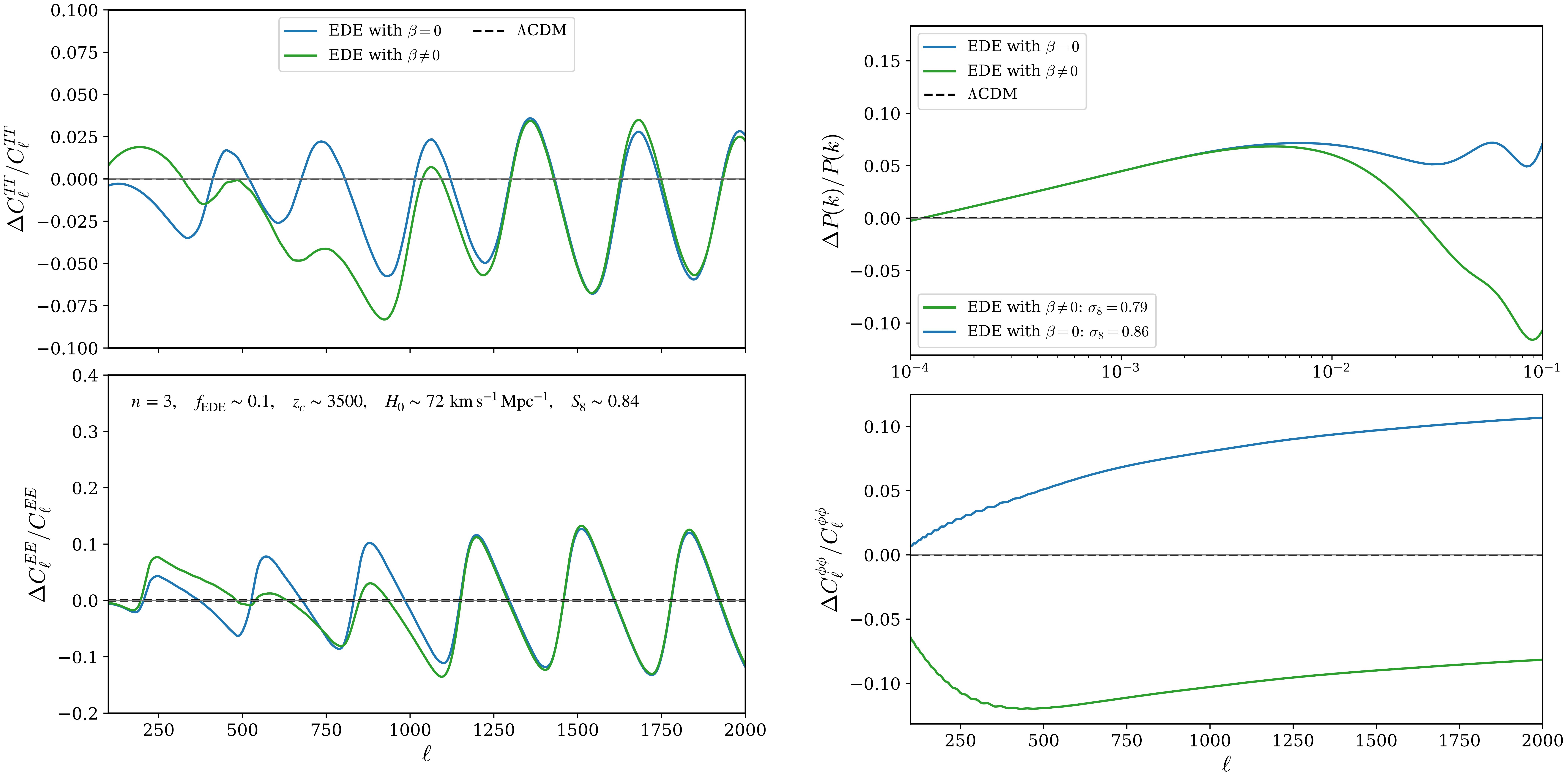
- Read off 1σ at the intersection with $\Delta\chi^2 = 1$
- Read off 2σ at the intersection with $\Delta\chi^2 = 4$, etc.
- Near physical boundary: boundary-corrected PL construction **(Feldman&Cousins, 1997)**

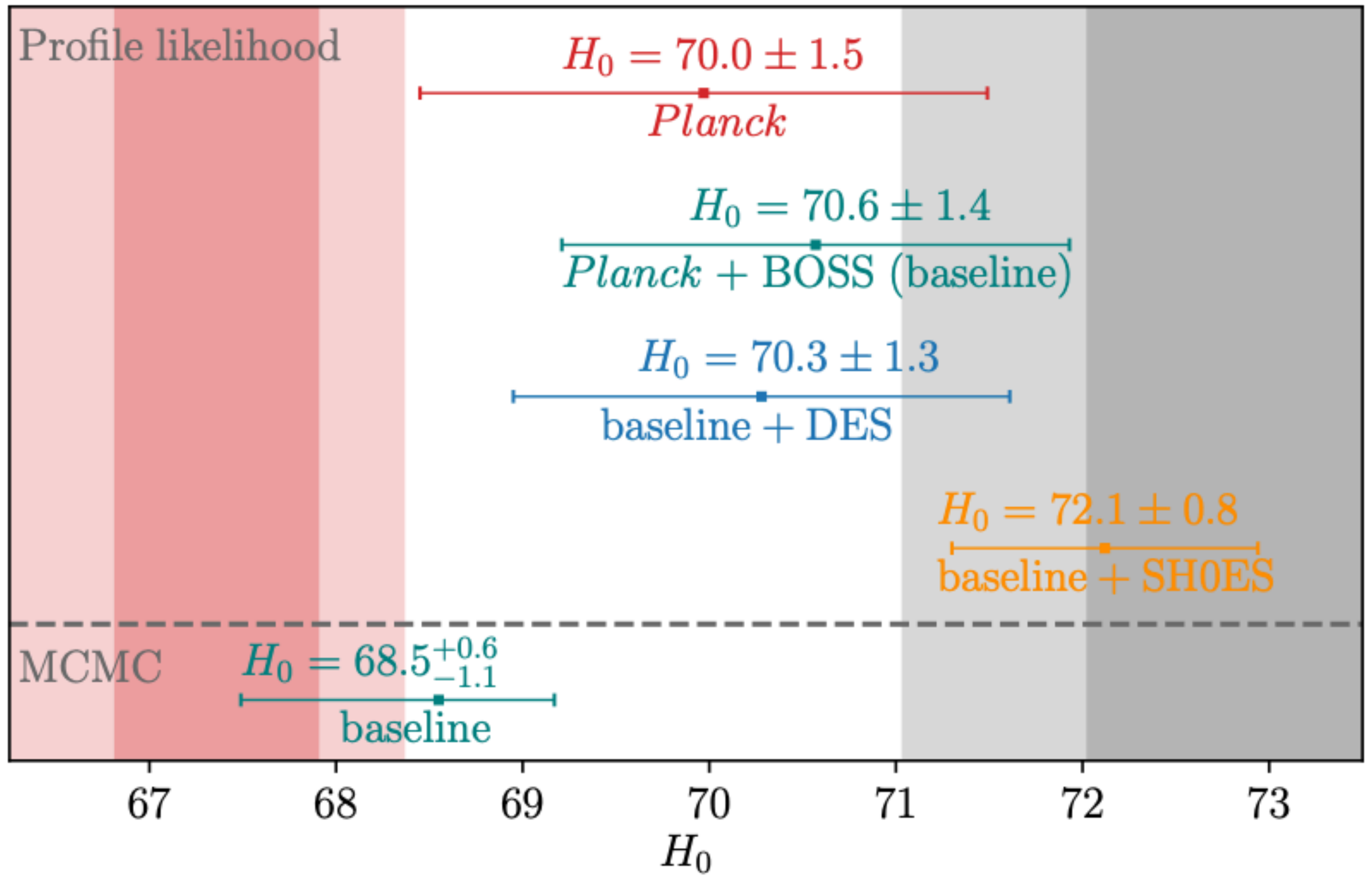
Methodology

- Baseline Planck 2018, Pantheon+, DESI DR1 BAO
- Optional Gaussian priors on H_0 ($M_B = -19.253 \pm 0.027$ from SH0ES) and $S_8 = 0.790^{+0.018}_{-0.014}$ (from a combination of cosmic shear surveys from DES Y3 and KiDS-1000)
- Conduct both Bayesian and Frequentist analyses
- Consider two prior choices:
  - Linear uniform priors on β and $f_{\rm EDE}$: displays the degeneracy between the amount of EDE and the strength of the momentum transfer
  - Logarithmic uniform prior on the product $x \equiv \log_{10}(\beta f_{\rm EDE})$: directly samples the physical amplitude of the interaction and reduces the prior-volume dilution present in the two-parameter linear case

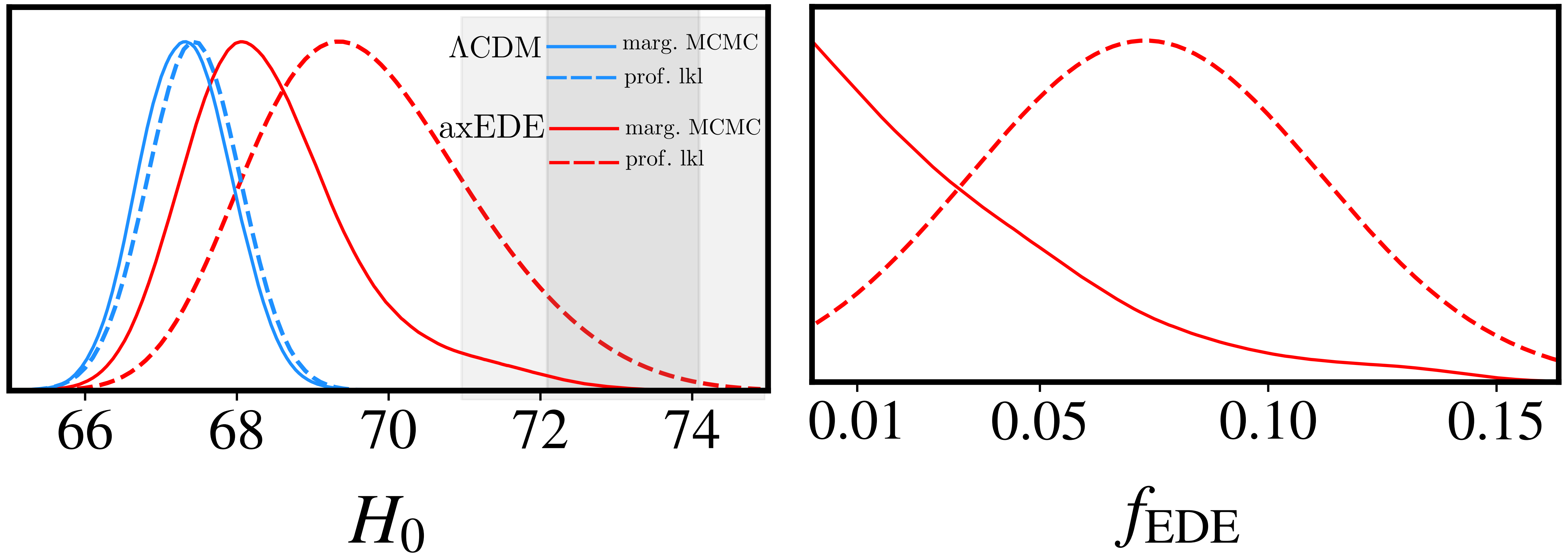
Planck 2018: [Aghanim et al.: Astron.Astrophys. 641 (2020) A6]
DESI: [A. G. Adame et al. (DESI), (2024), JCAP 02, 021 (2025)]
PantheonPlus: [Brout et al: Astrophys. J. 938 (2022) 110]
SH0ES prior: [Riess et al: Astrophys. J. Lett. 934 (2022) 1 L7]
S8 prior: [Abbott et al: The Open Journal of Astrophysics 6 (2023)]

Observational Signatures





[Herold et al, arxiv: 2210.16296]



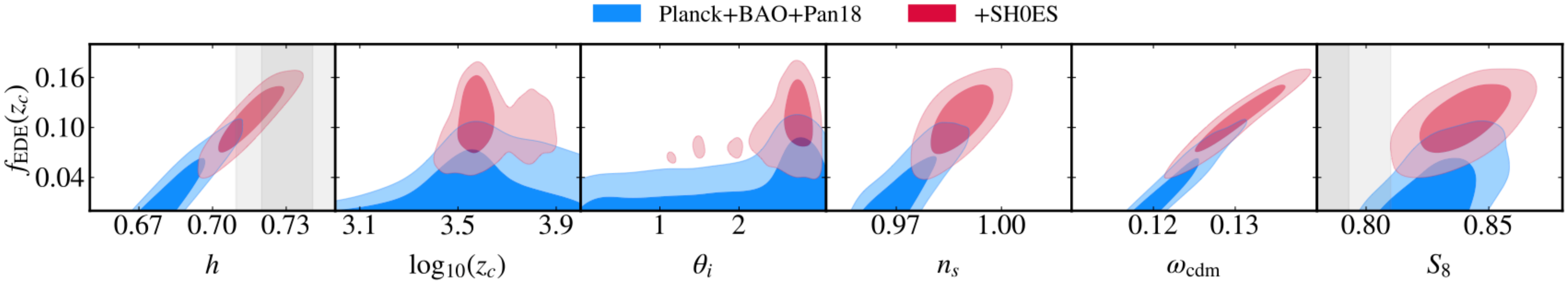
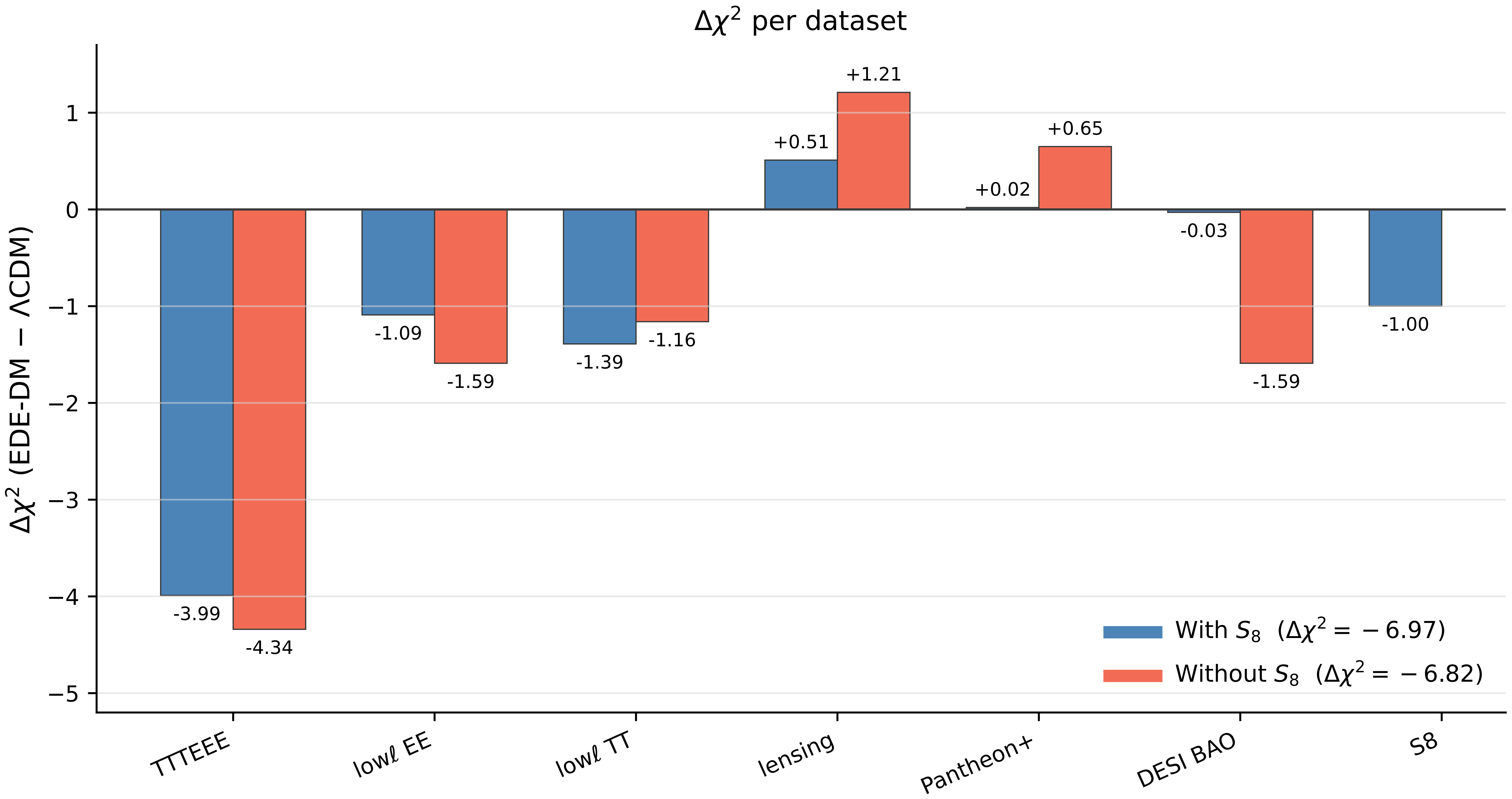


TABLE I. χ^2 for each runs with linear priors on β and f_{EDE}

	With EDE-DM interactions ($\beta \neq 0$)	Without EDE-DM interactions ($\beta = 0$)
No priors	4198.59	4198.74
SH_0es priors	4199.74	4200.30
S_8 priors	4201.11	4200.45
SH_0es + S_8 priors	4206.21	4206.30

TABLE II. χ^2 for each runs with logarithmic prior on product of β and f_{EDE}

	With EDE-DM interactions ($\beta \neq 0$)	Without EDE-DM interactions ($\beta = 0$)
No priors	3802.03	3803.73
SH_0es priors	3803.29	3803.23
S_8 priors	3802.68	3807.83
SH_0es + S_8 priors	3809.68	3809.55


$\Delta\chi^2$ per dataset
$\Delta\chi^2$ (EDE-DM − ΛCDM)
1
0
−1
−2
−3
−4
−5
-3.99
-4.34
-1.09
-1.59
-1.39
-1.16
+0.51
+1.21
+0.02
+0.65
-0.03
-1.59
-1.00
TTTEEE
lowℓ EE
lowℓ TT
lensing
Pantheon+
DESI BAO
S8
With S_8 ($\Delta\chi^2 = -6.97$)
Without S_8 ($\Delta\chi^2 = -6.82$)