Early Dark Energy and Cosmological Concordance

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Cosmology from Home
August 2020

2003.07355 w/ E. McDonough, M. Toomey, S. Alexander
2006.11235 w/ ↗ + M. Ivanov, M. Simonovic, M. Zaldarriaga

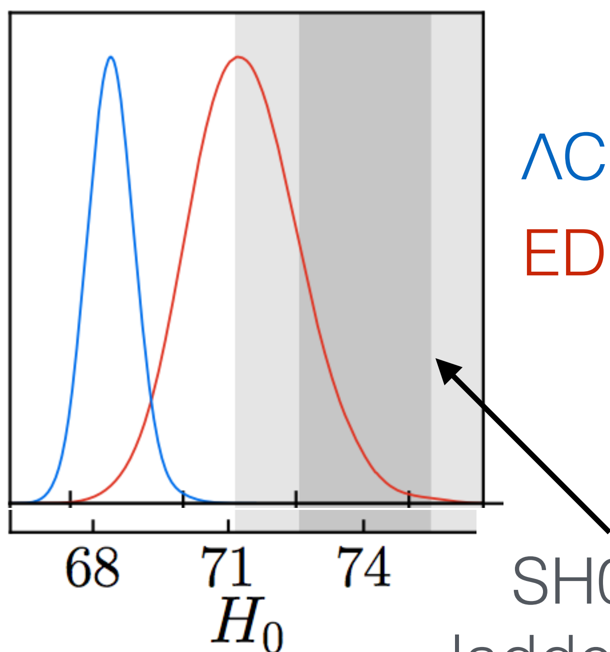





Early Dark Energy

Motivation: resolve the H0 tension

Smith+ (2019)



ΛCDM model fit to Planck+BAO+SNIa+SH0ES+…

EDE model fit to Planck+BAO+SNIa+SH0ES+…

SH0ES distance
ladder H0 constraint

Poulin+ (2019); Agrawal+ (2019); Lin+ (2019); Smith+ (2019)

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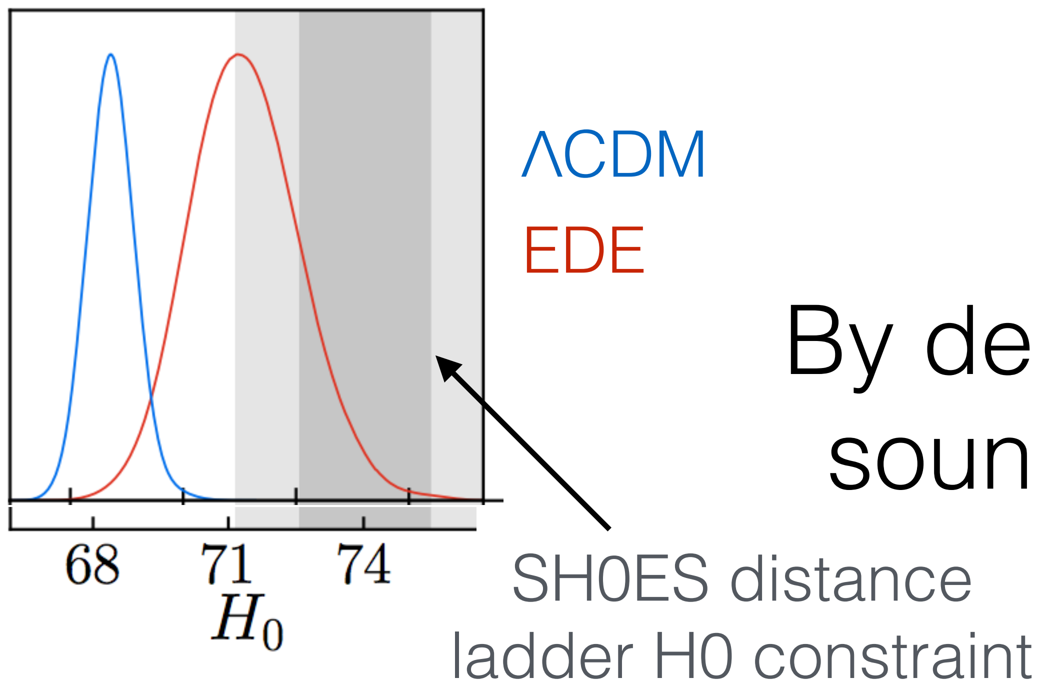

How does this work?

By decreasing the physical size of the sound horizon imprinted in the CMB

$$r_s^\star = \int_0^{t_\star} \frac{dt}{a(t)}\, c_s(t) = \int_{z_\star}^{\infty} \frac{dz}{H(z)}\, c_s(t)$$

Poulin+ (2019); Agrawal+ (2019); Lin+ (2019); Smith+ (2019)

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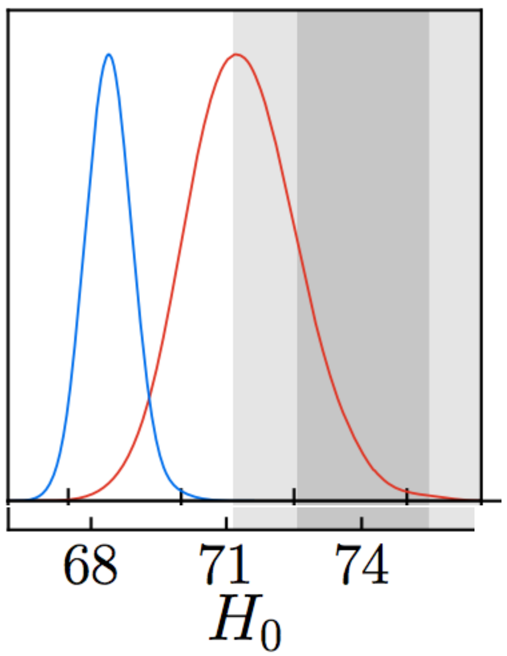

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Relevant ingredients in ΛCDM: ω_b, ω_{cdm}, ω_γ

physical density of baryons, CDM, photons

Angular sound horizon is (approx.) related to peak spacing:

measured → $\theta_s^\star = \pi/\Delta\ell \longrightarrow D_A^\star = r_s^\star/\theta_s^\star \longrightarrow H_0$

$$D_A = \int_0^{z_*} \frac{dz}{H(z)}$$

Poulin+ (2019); Agrawal+ (2019); Lin+ (2019); Smith+ (2019); Knox & Millea (2019)

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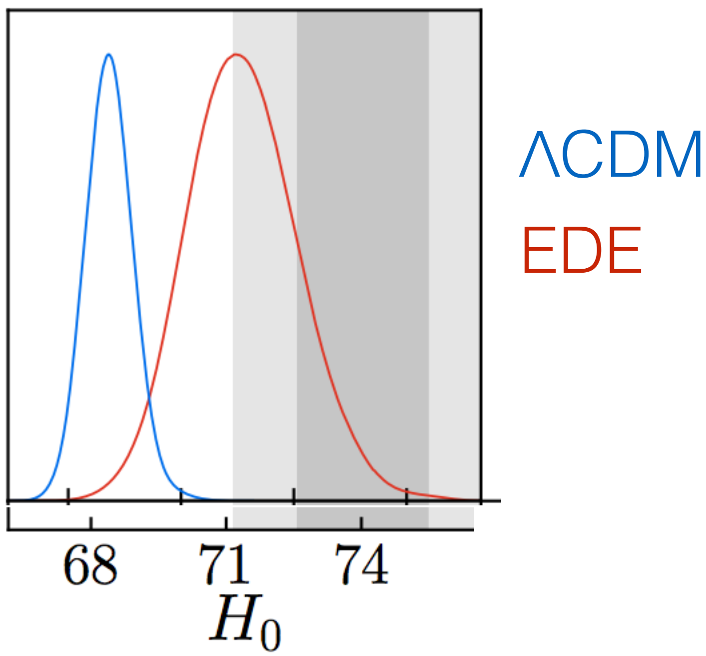

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Relevant ingredients in **EDE**: ω_b, ω_m, ω_γ **+ EDE parameters**

Angular sound horizon is (approx.) related to peak spacing:

$$\theta_s^\star = \pi/\Delta\ell \longrightarrow D_A^\star = r_s^\star/\theta_s^\star \longrightarrow H_0$$

Poulin+ (2019); Agrawal+ (2019); Lin+ (2019); Smith+ (2019); Knox & Millea (2019)

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Early Dark Energy

New component: (pseudo)-scalar field ϕ

Poulin+ (2019); Agrawal+ (2019); Lin+ (2019); Smith+ (2019)

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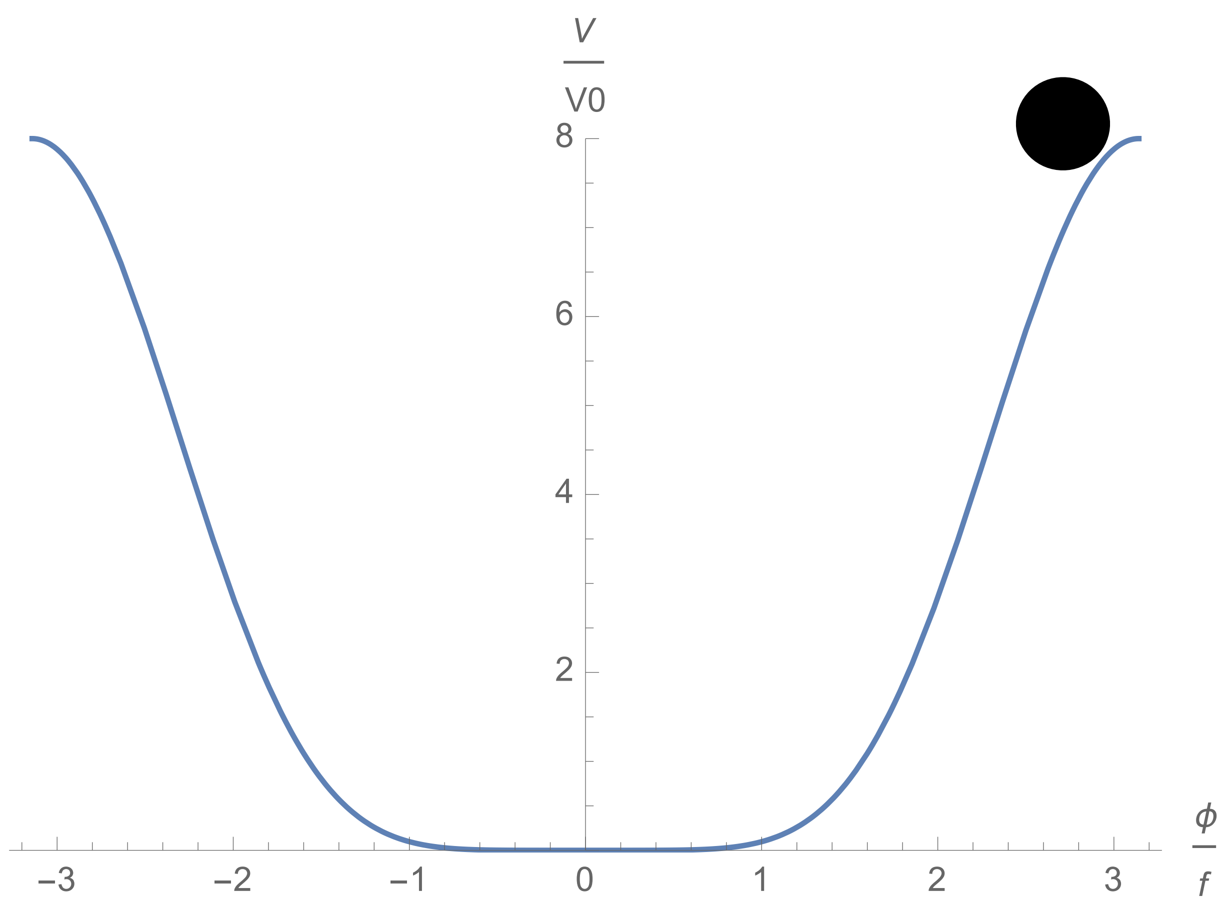
Early Dark Energy

New component: (pseudo)-scalar field ϕ

Idea: field initially frozen on its potential due to Hubble friction — acts as dark energy (equation of state w=-1)



$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

H >> m initially

Poulin+ (2019); Agrawal+ (2019); Lin+ (2019); Smith+ (2019)

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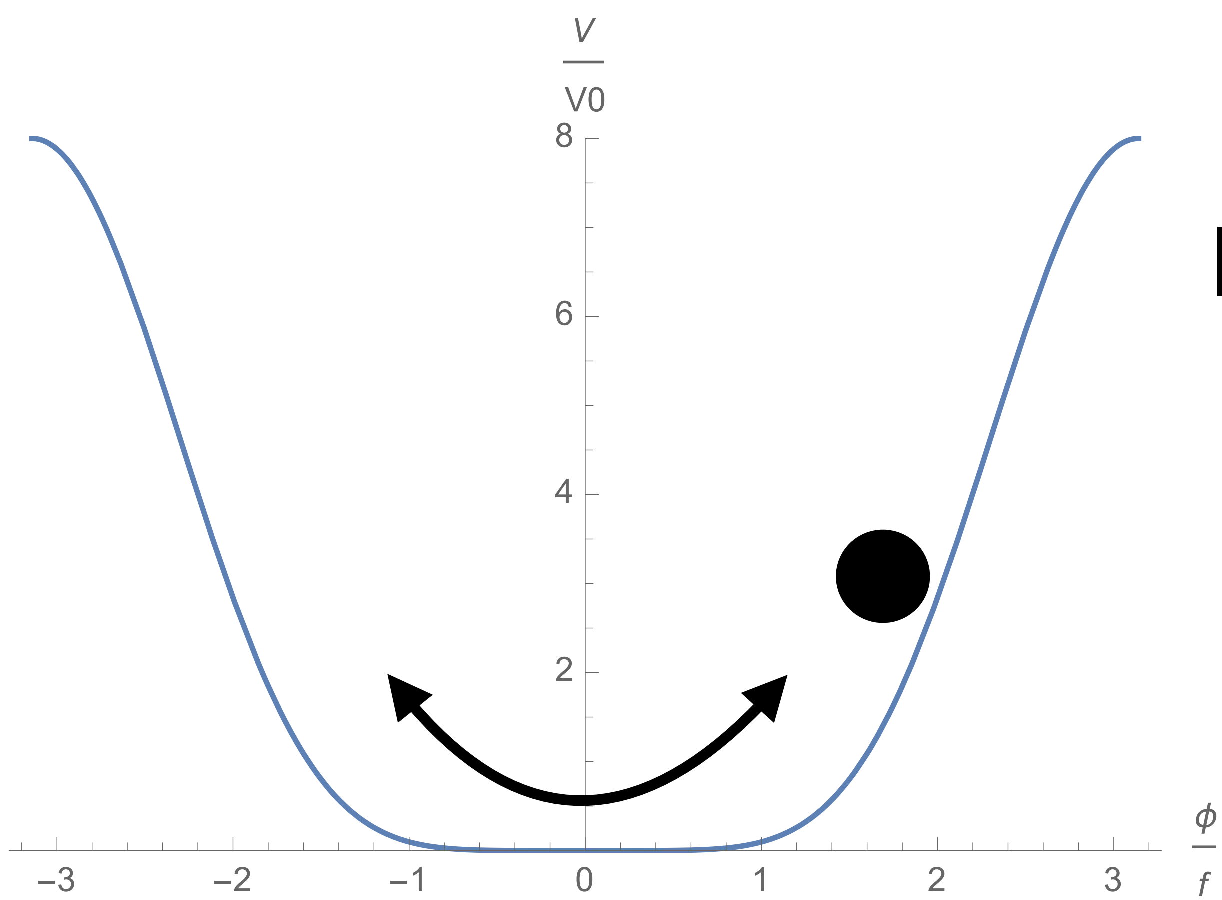
New component: (pseudo)-scalar field ϕ

When H ~ m (field mass), it rolls down its potential and oscillates: effective w will depend on potential



For EDE, this must occur near $\sim z_{CMB}$

↓

m ~ 10^{-27} eV

e.g., $\phi(t) = \phi_i a^{-3/2} \cos(mt)$ if $V(\phi) = m^2\phi^2/2$

Poulin+ (2019); Agrawal+ (2019); Lin+ (2019); Smith+ (2019)

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Poulin+ (2019); Agrawal+ (2019); Lin+ (2019); Smith+ (2019)

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Canonical EDE Potential:

$$V(\phi) = m^2 f^2 \left(1 - \cos\left(\phi/f\right)\right)^n$$

Near minimum, V ~ ϕ^{2n} $\longrightarrow$ $w_\phi = \frac{n-1}{n+1}$

We assume n=3 throughout

Poulin+ (2019); Agrawal+ (2019); Lin+ (2019); Smith+ (2019)

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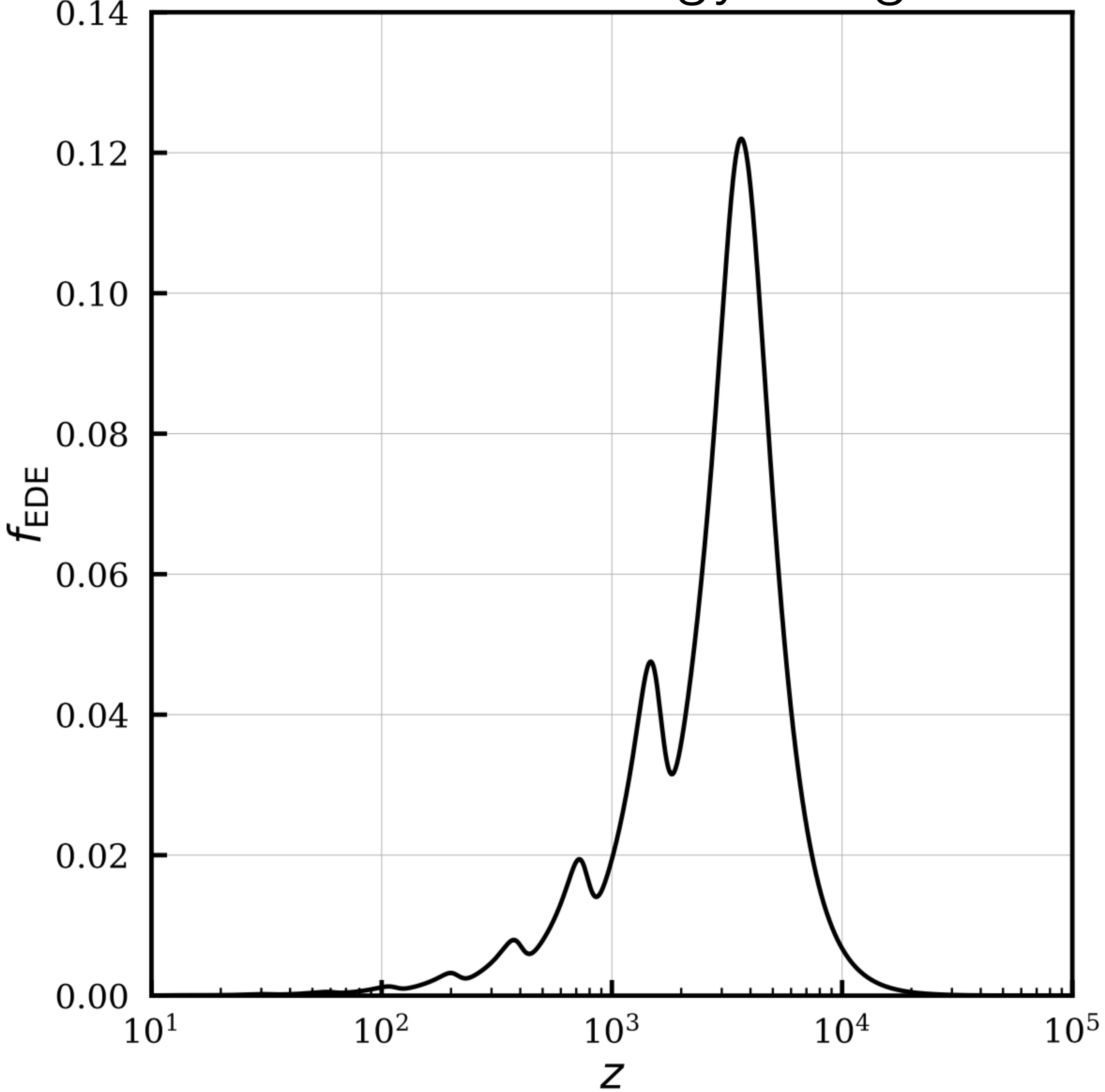
Parameterization

Fractional contribution of EDE to cosmic energy budget



Poulin+ (2019); Agrawal+ (2019); Lin+ (2019); Smith+ (2019); JCH+ (2020)

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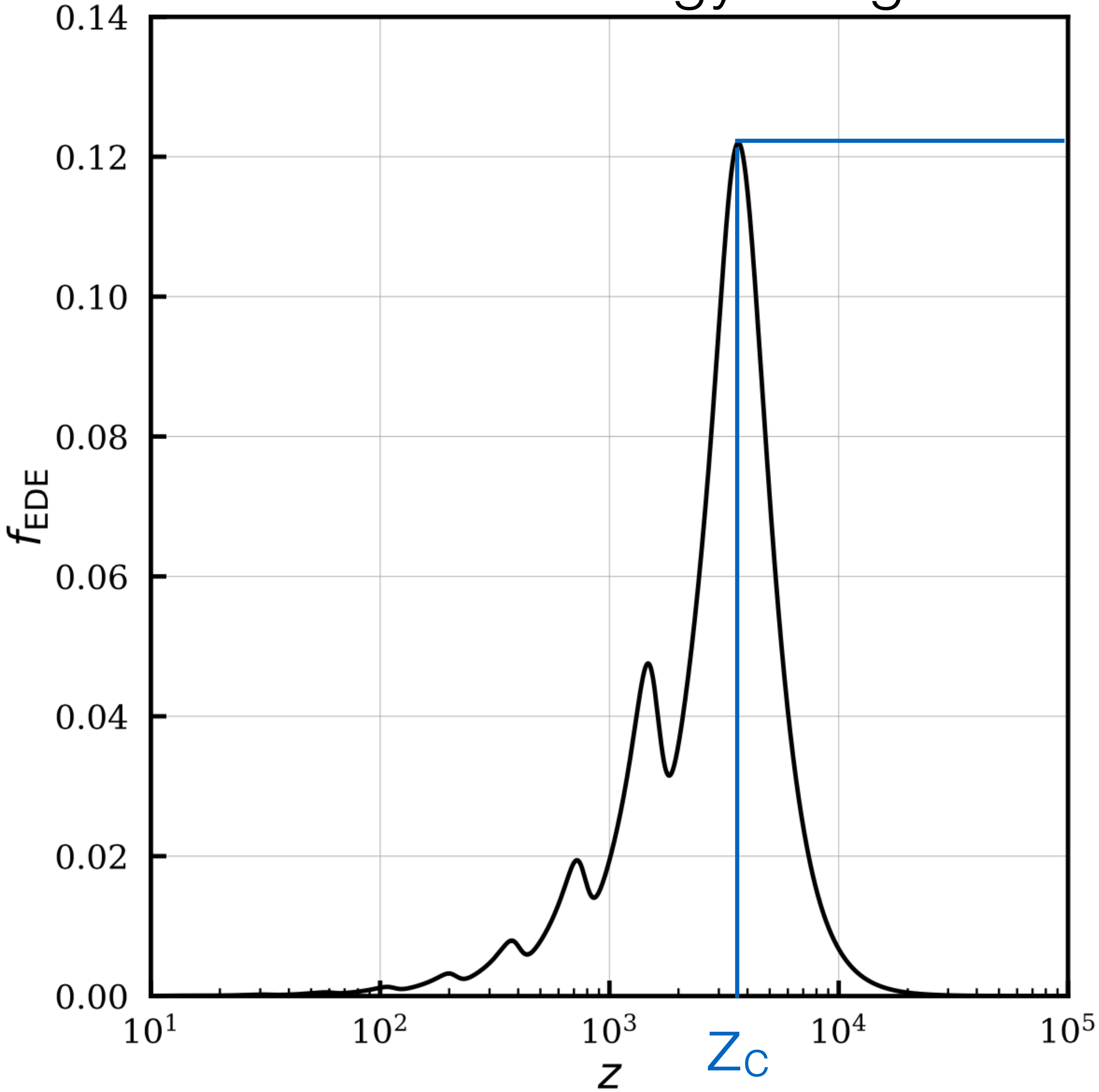

Maximal contribution:

$$f_{\rm EDE}(z_c) \equiv (\rho_{\rm EDE}/3M_{pl}^2 H^2)|_{z_c}$$

which occurs at redshift z_c

Final parameter: $\theta_i = \phi_i/f$
(initial field displacement)

→ $\{f_{\rm EDE}, z_c, \theta_i\}$

N.B: highly non-linear relation to scalar field parameters *f* and *m*

Poulin+ (2019); Agrawal+ (2019); Lin+ (2019); Smith+ (2019); JCH+ (2020)

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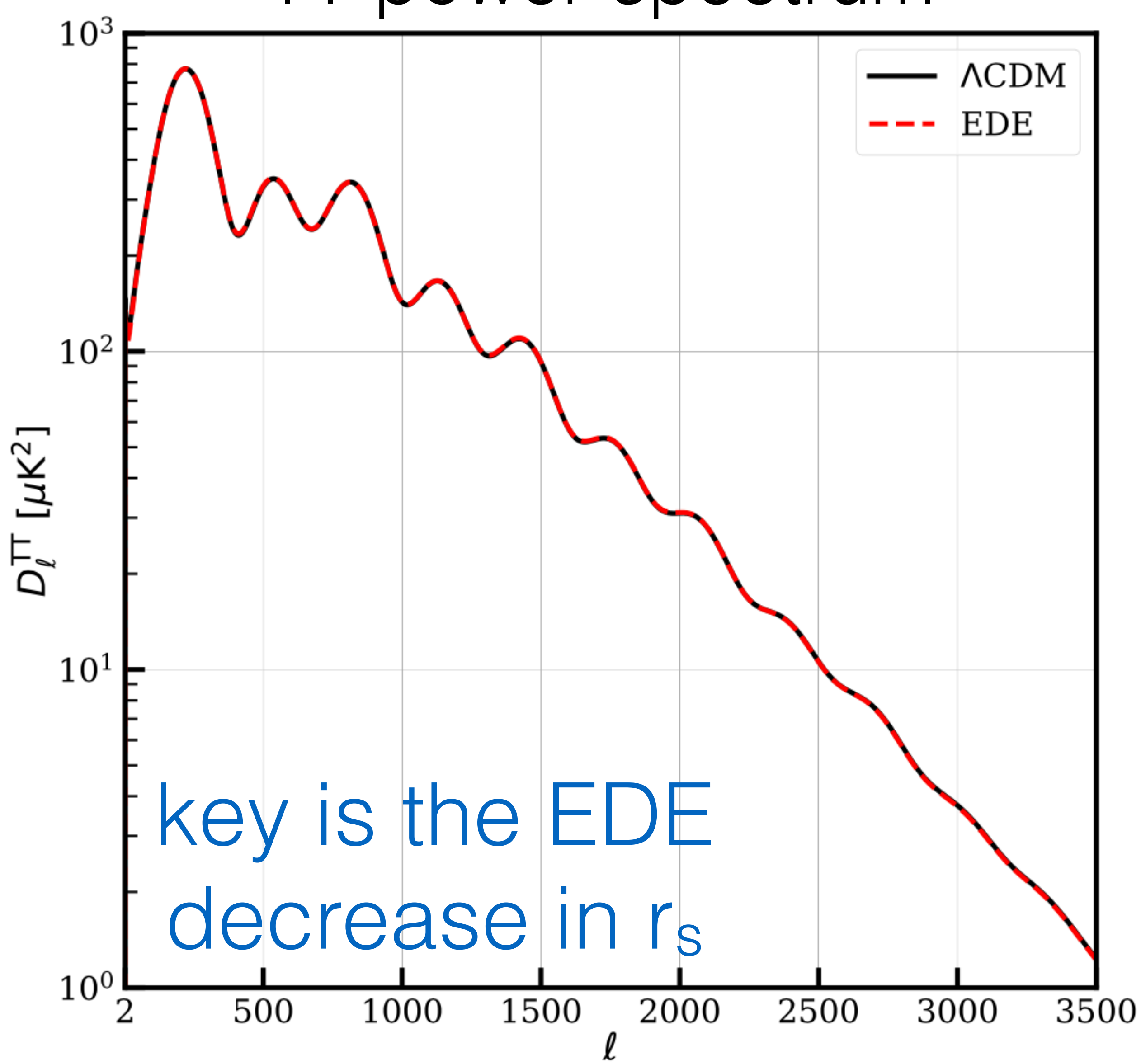
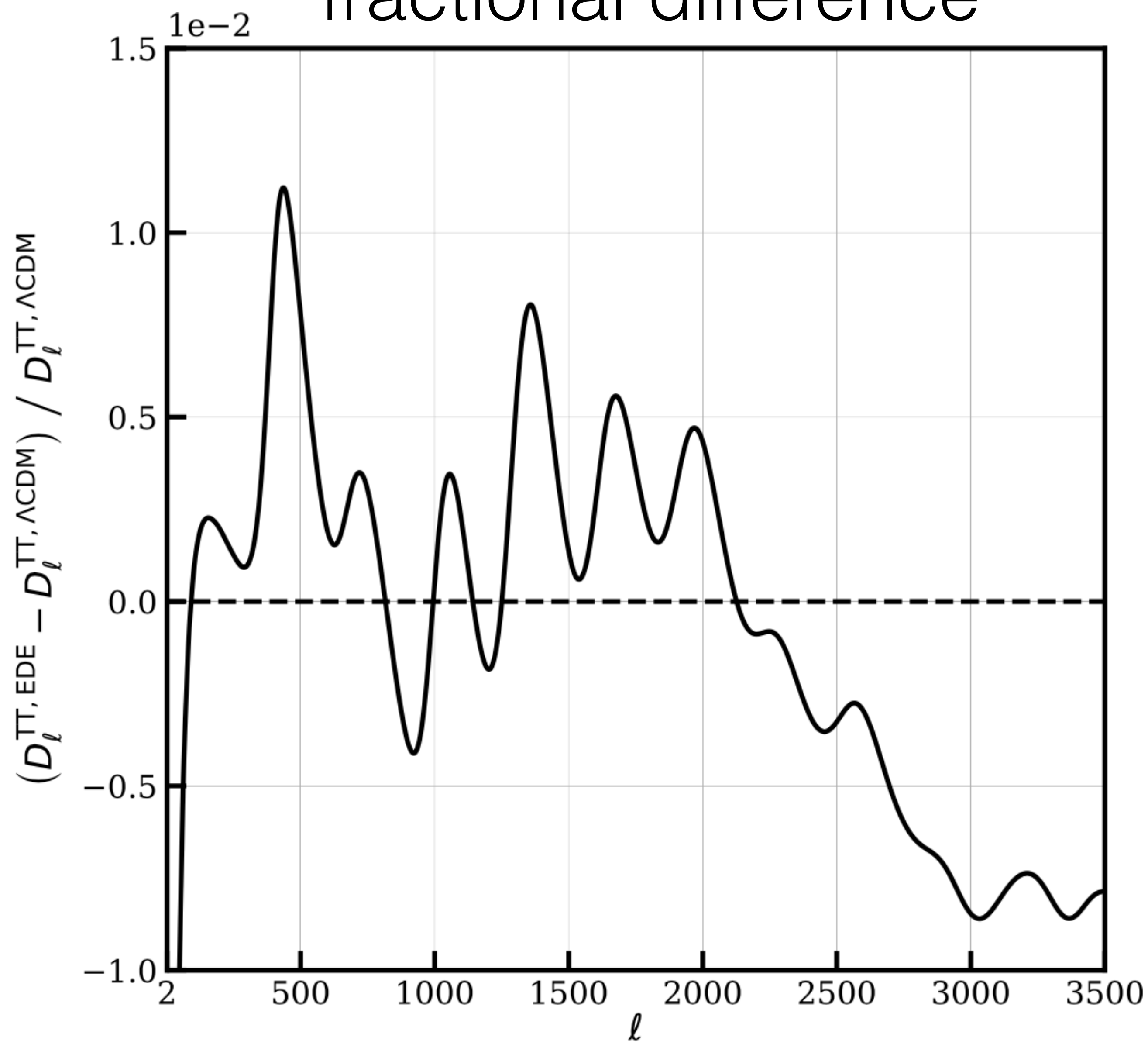
It maintains a good fit to CMB power spectrum data with higher H_0





ΛCDM model here has H_0 = 68.21 km/s/Mpc

EDE model here has H_0 = 72.19 km/s/Mpc

But other parameters also shift! particularly $\Omega_c h^2$ and n_s

JCH+ (2020)

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What about large-scale structure?

Interestingly, no one had made a plot of the matter power spectrum P(k)

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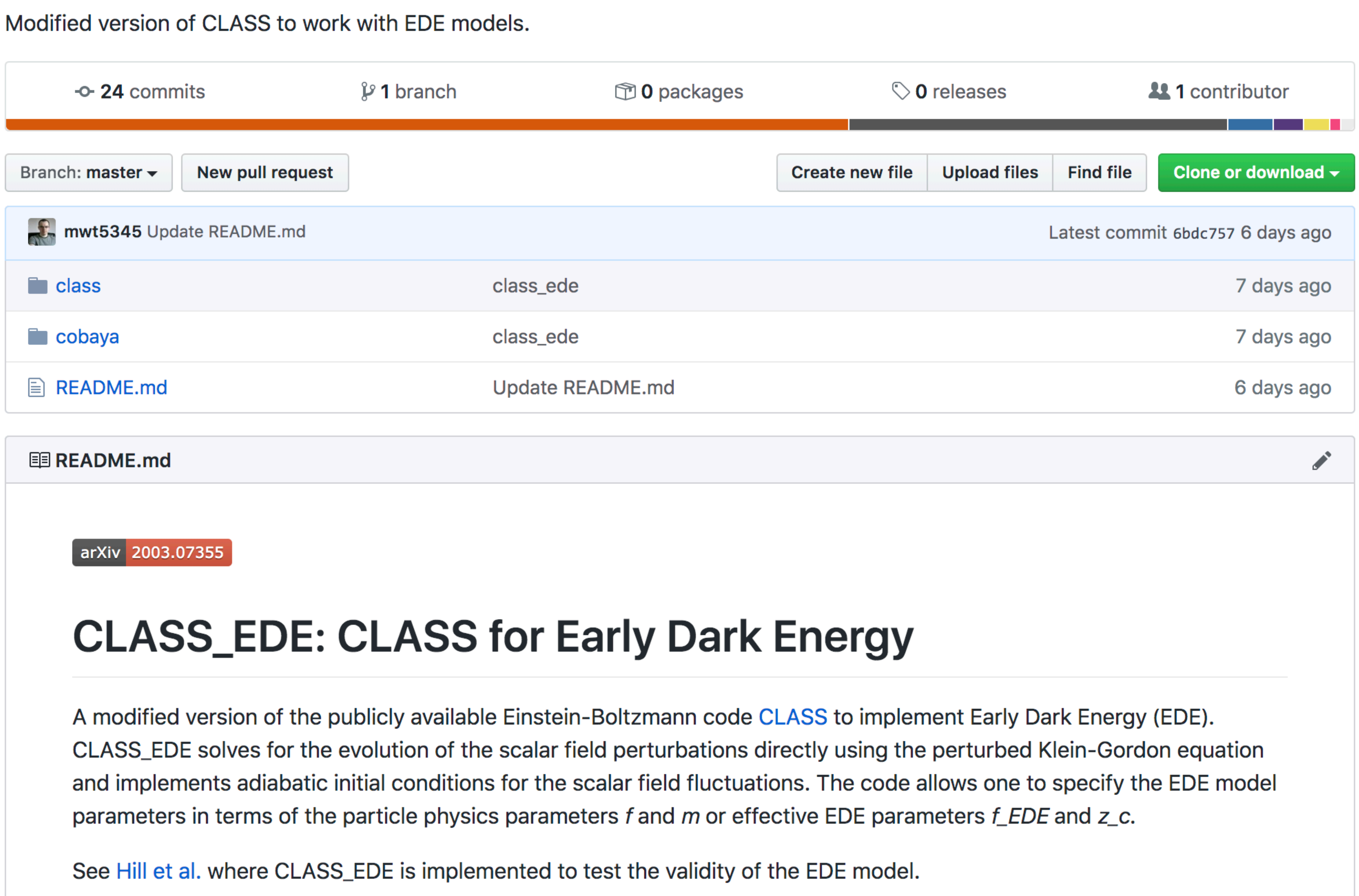
What about LSS?

Interestingly, no one had made a plot of P(k)

So we set out to do this — and now you can too:
https://github.com/mwt5345/class_ede



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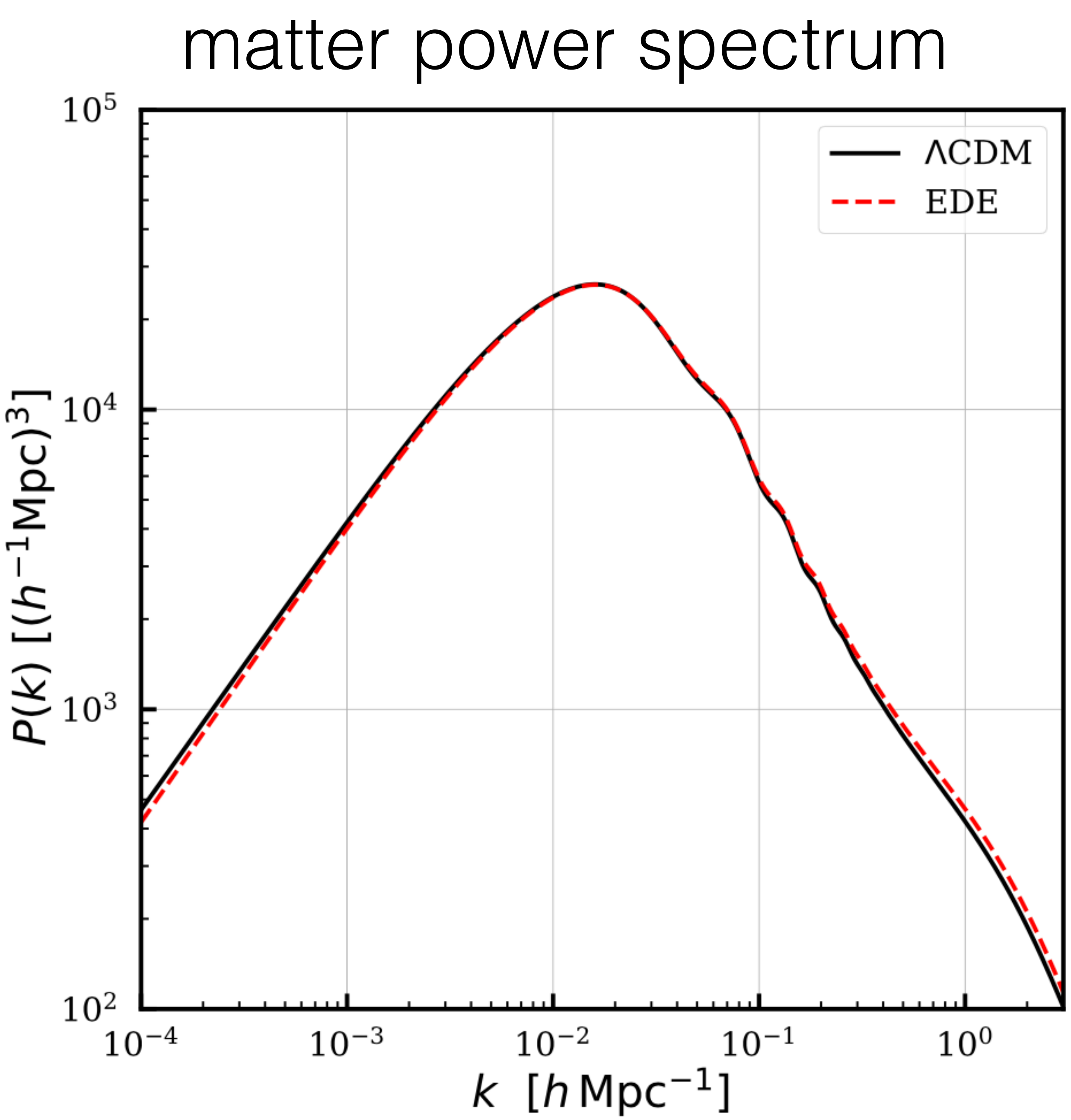

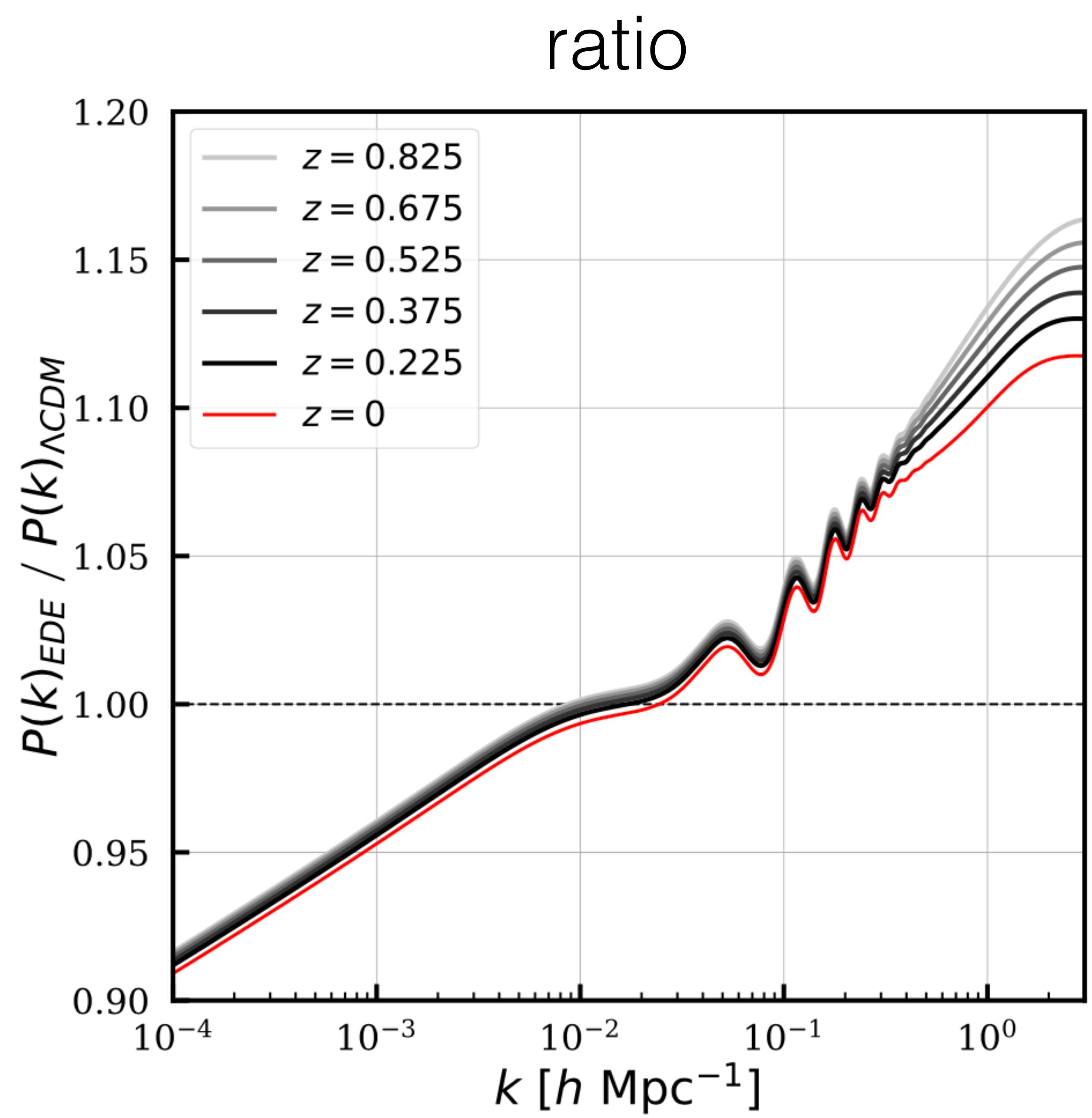

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JCH+ (2020) computed with CLASS_EDE: https://github.com/mwt5345/class_ede

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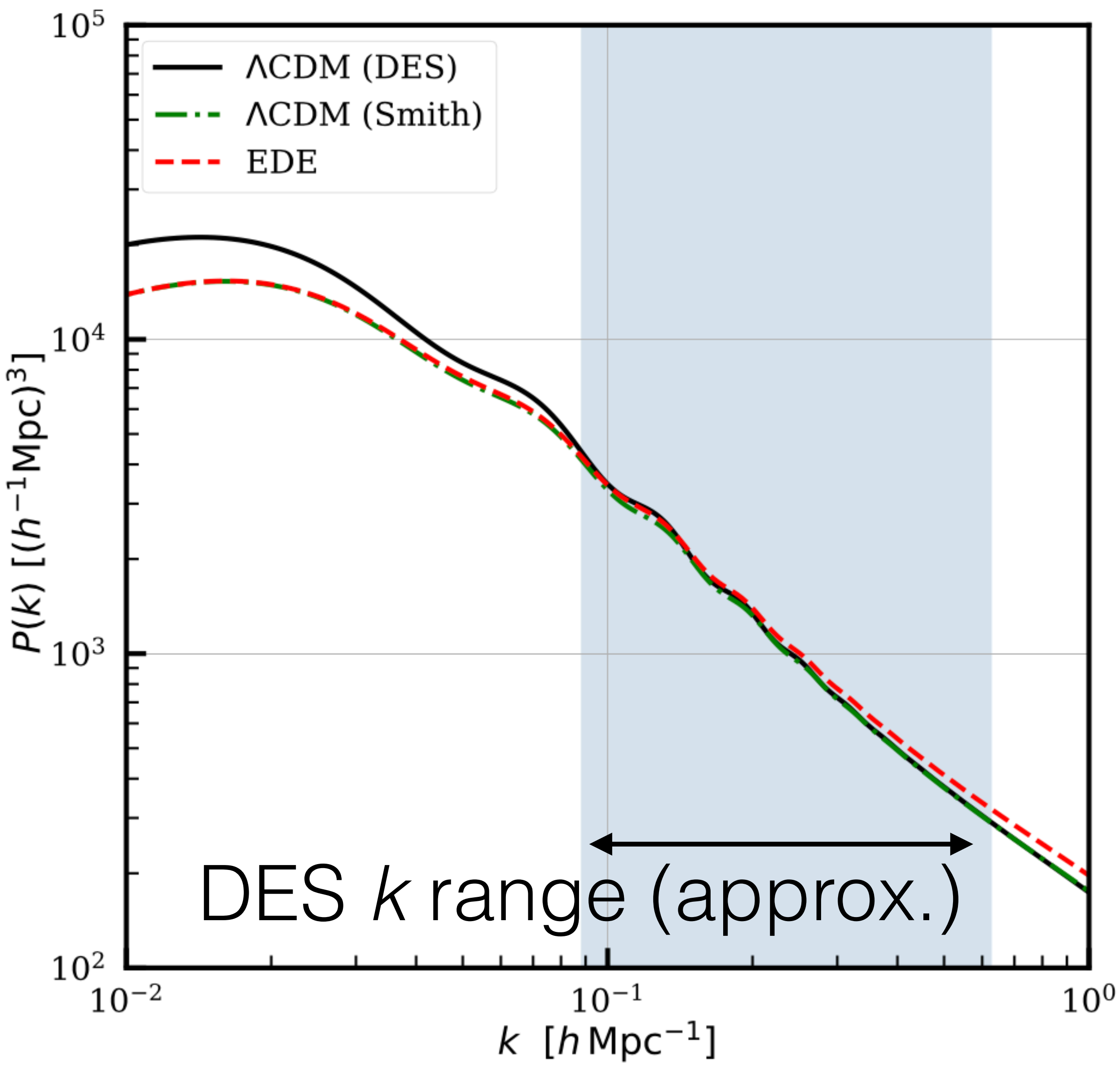
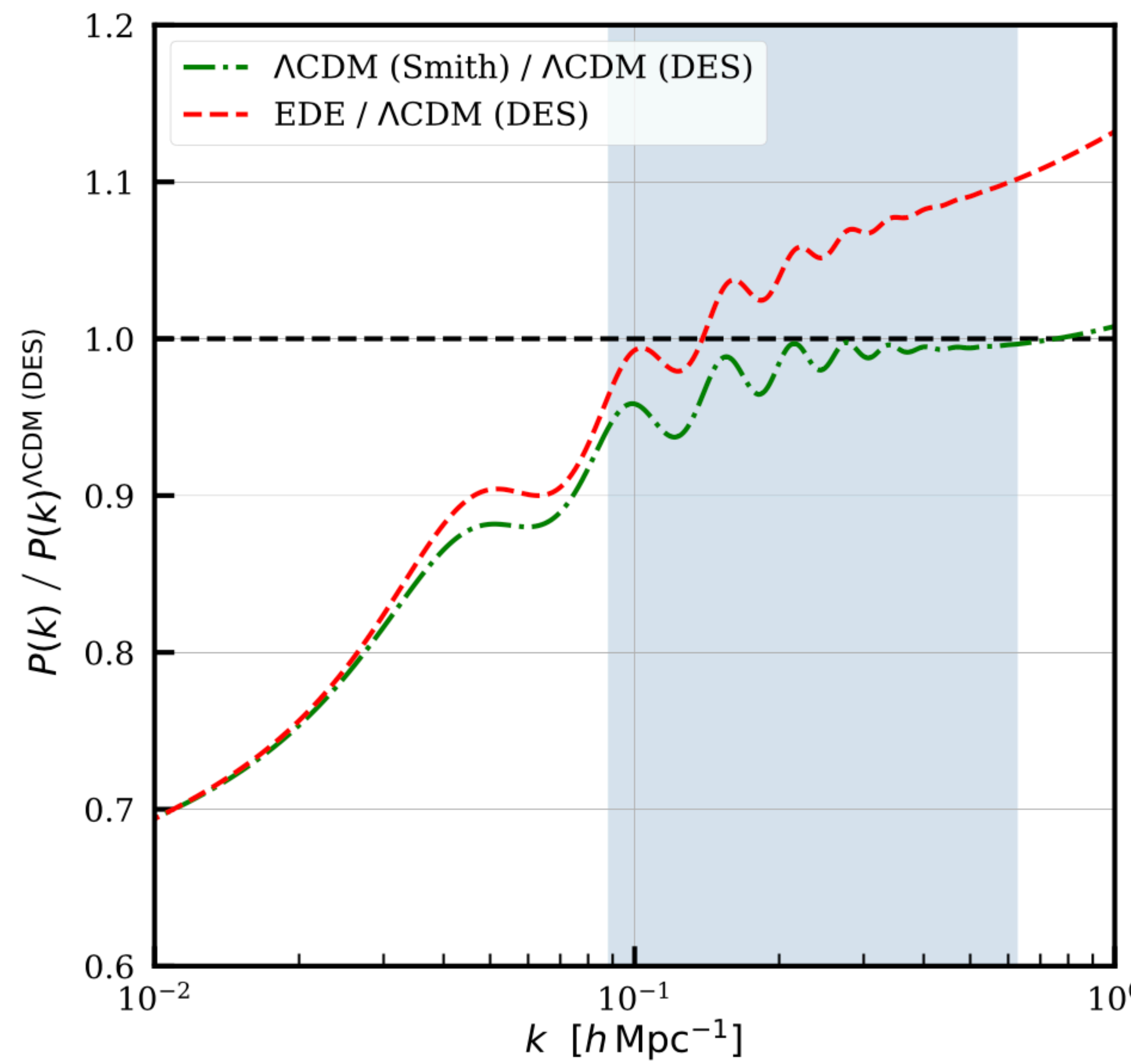
What about LSS?

5-10% differences in a wavenumber range that is well-measured

matter power spectrum at z=0.525



ratio



What drives these differences? Shifts in other ΛCDM parameters that are required to preserve the fit to CMB data in the EDE model

JCH+ (2020) computed with CLASS_EDE: https://github.com/mwt5345/class_ede

Parameter Shifts

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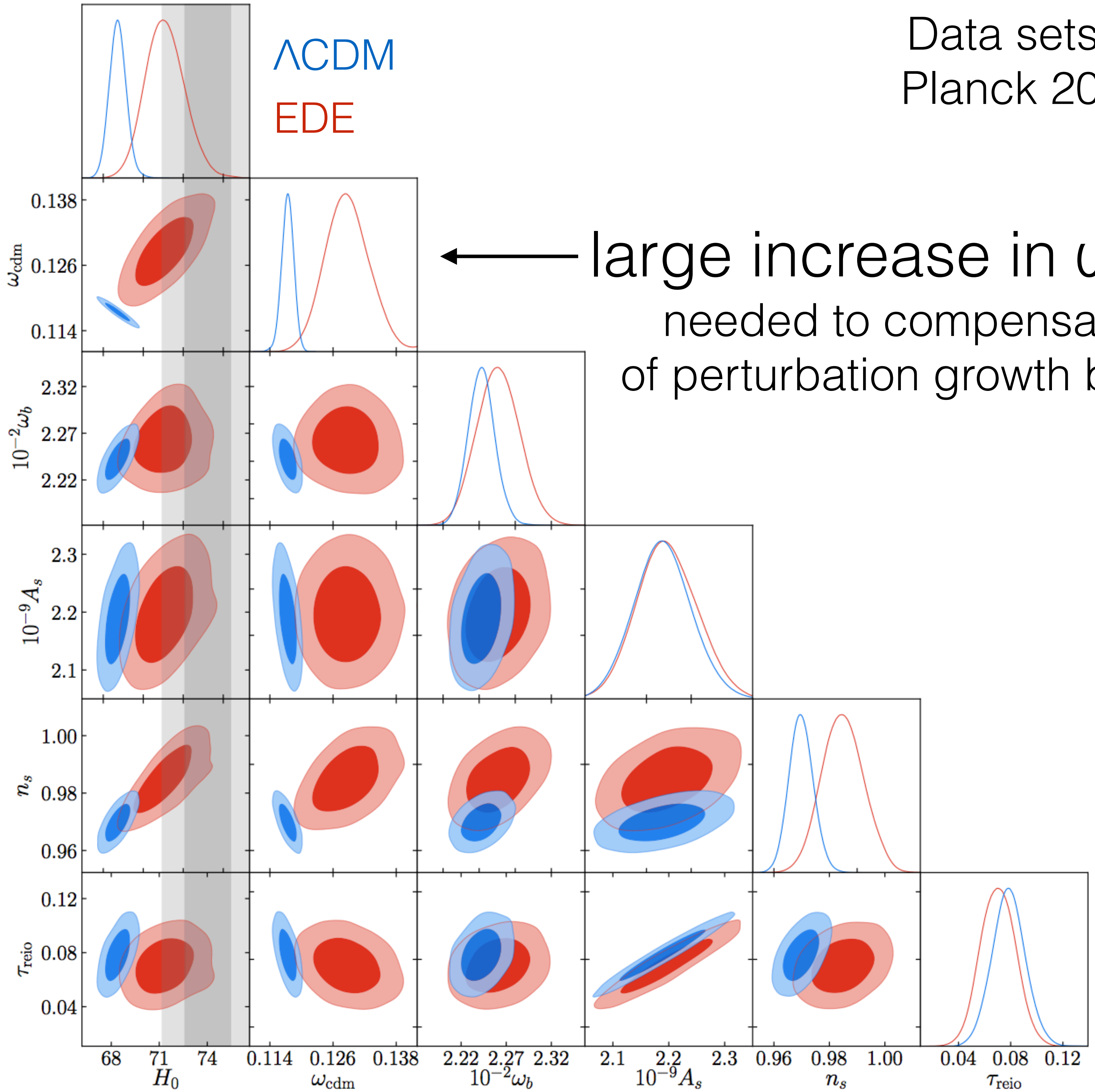
Data sets fit here: Planck 2015 TT/TE/EE; Planck 2015 lensing; SH0ES; BAO; SNIa; BOSS RSD



← large increase in $\omega_{\rm cdm}$

needed to compensate for suppression of perturbation growth by EDE ("early ISW")

Smith+ (2019)

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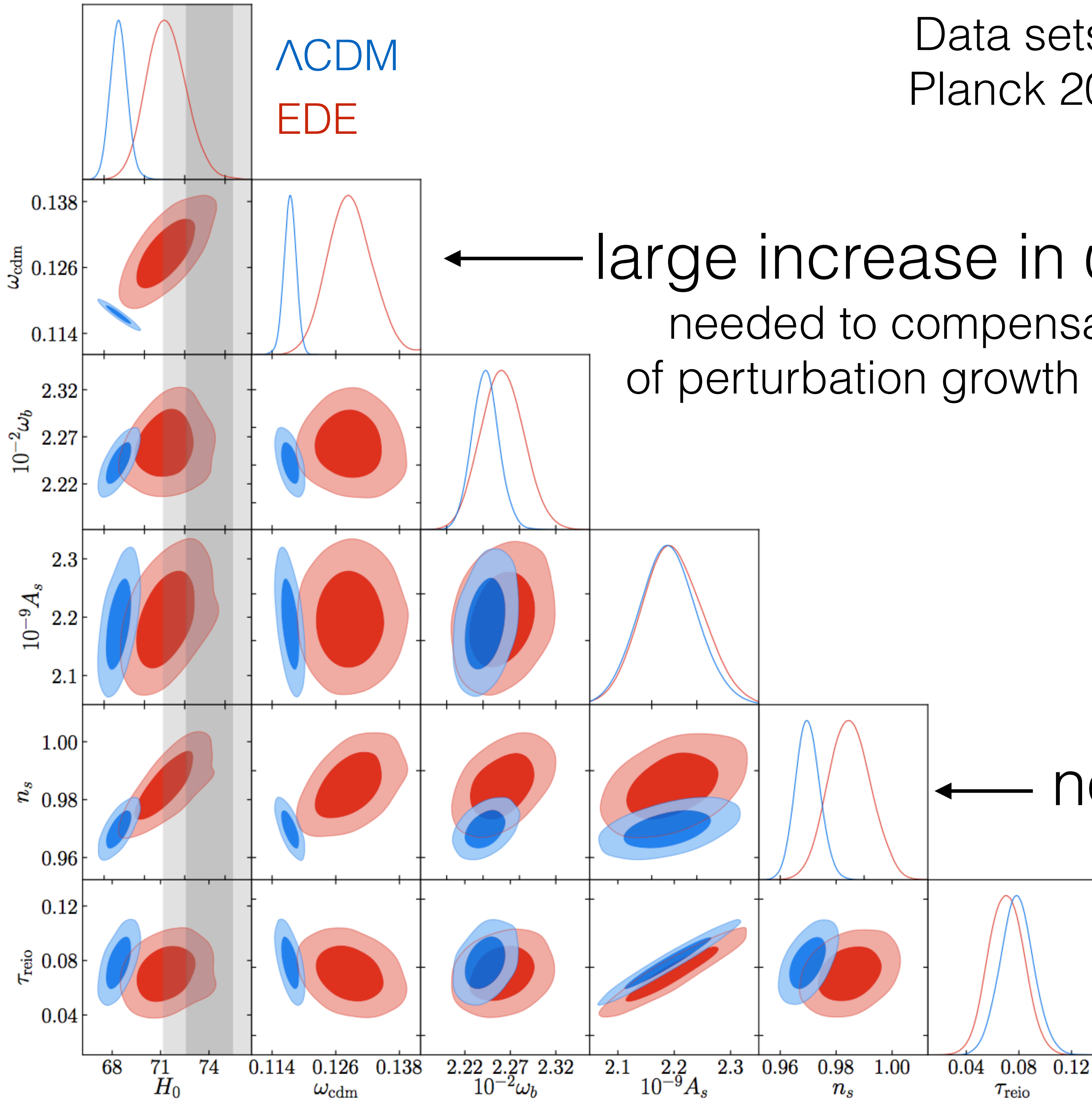

← large increase in $\omega_{\rm cdm}$
needed to compensate for suppression of perturbation growth by EDE ("early ISW")

← noticeable increase in n_s

implication for P(k)

amplitude of P(k) $\sigma_8(\Omega_m/0.3)^{0.5} = S_8 = 0.842\ (0.843) \pm 0.019$

Smith+ (2019)

What about LSS?

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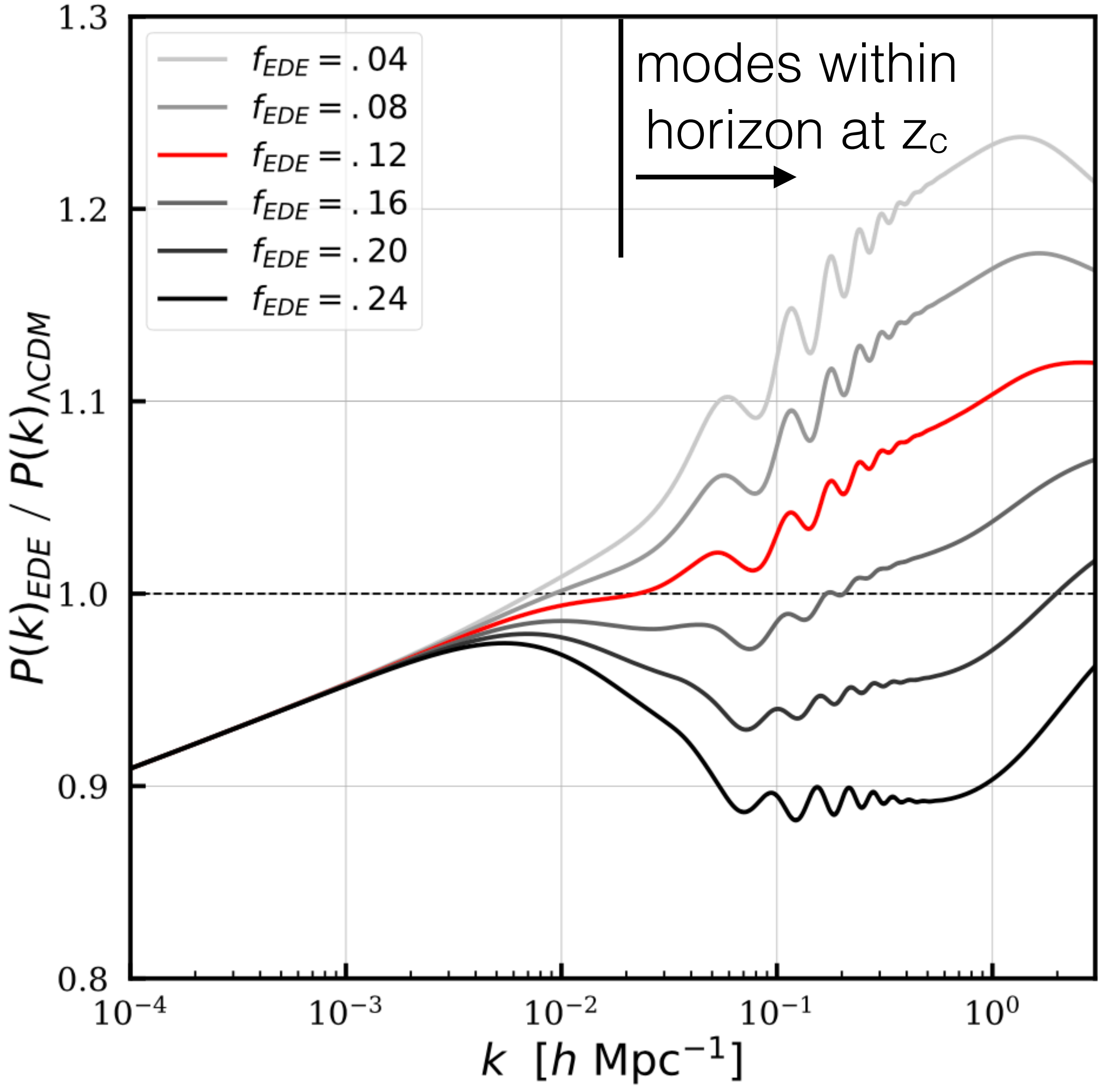
There are also interesting physical effects due to the EDE itself

varying amount of EDE



more EDE: more suppression

JCH+ (2020) computed with CLASS_EDE: https://github.com/mwt5345/class_ede

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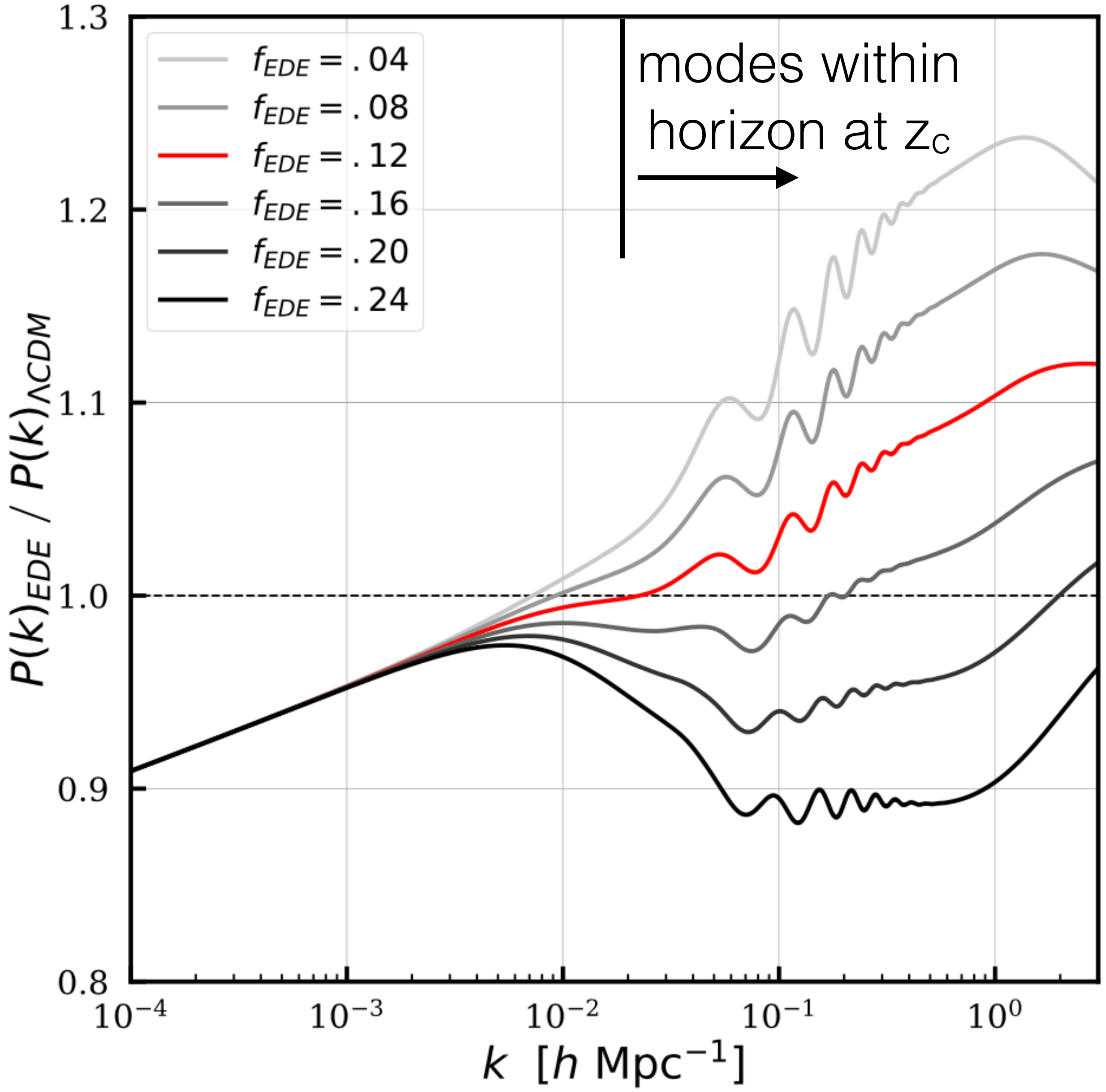
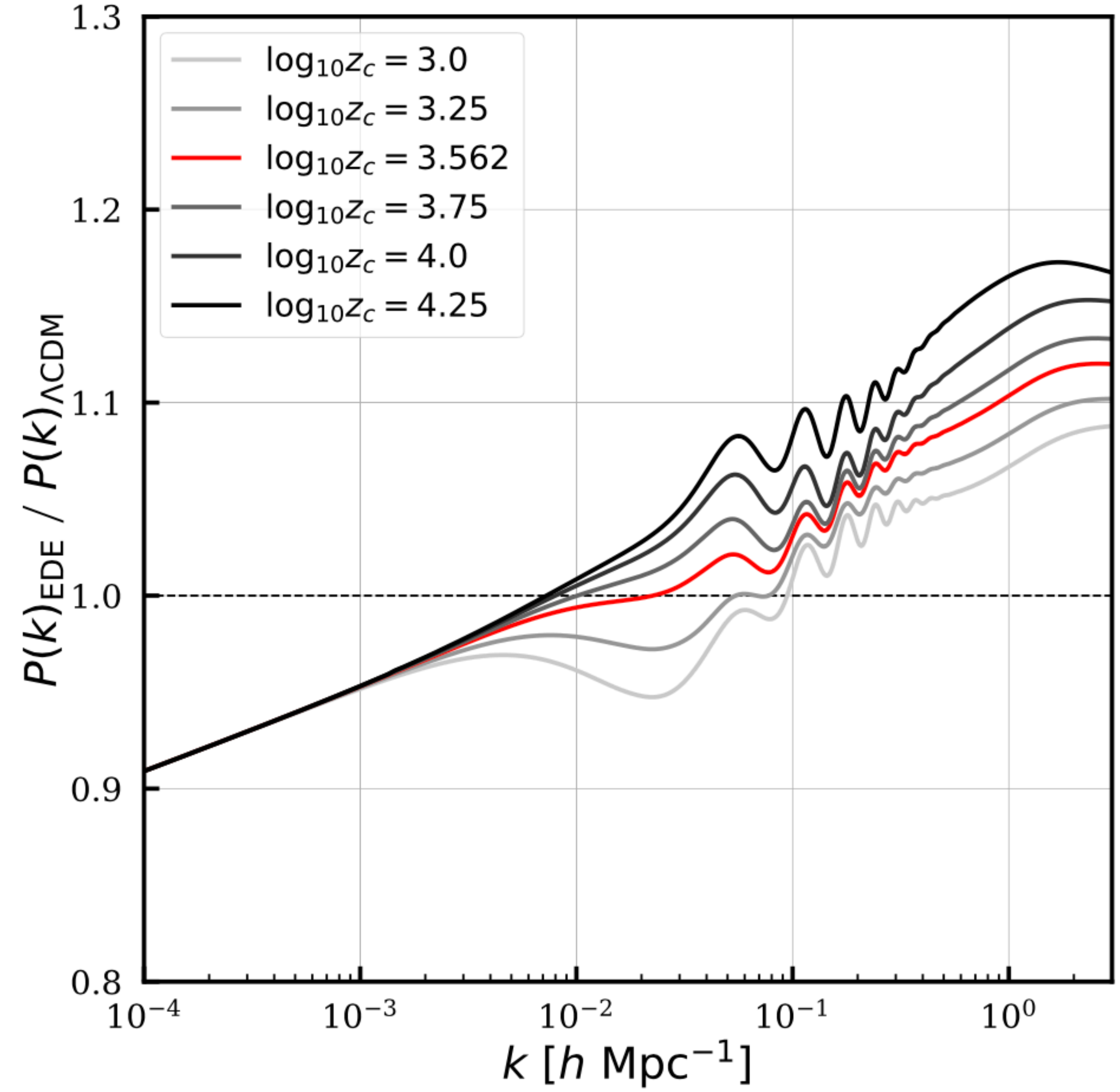


more EDE: more suppression

varying critical redshift



lower z_c: effects at lower k

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Updated EDE Analysis Including Large-Scale Structure Data Sets

JCH, McDonough, Toomey, Alexander (2020)

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Data Sets

- Planck 2018 CMB TT/TE/EE power spectra
- Planck 2018 CMB lensing
- SH0ES 2019: H_0 = 74.03 +/- 1.42 km/s/Mpc
- Baryon acoustic oscillations:
  - 6dF
  - SDSS DR7 Main Galaxy Sample
  - SDSS DR12 BOSS LOWZ + CMASS
- Type Ia supernovae (Pantheon)
- Redshift-space distortions: SDSS DR12 BOSS
- Dark Energy Survey "3x2pt" (gg, gκ, κκ) full likelihood
- S_8 constraints from HSC and KiDS

not considered in previous work

Sampled via MCMC with Cobaya

JCH+ (2020); Cobaya by A. Lewis and J. Torrado: https://github.com/CobayaSampler/cobaya

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EDE in Primary CMB?

Fit to Planck 2018 TT+TE+EE data alone

EDE in Primary CMB? No

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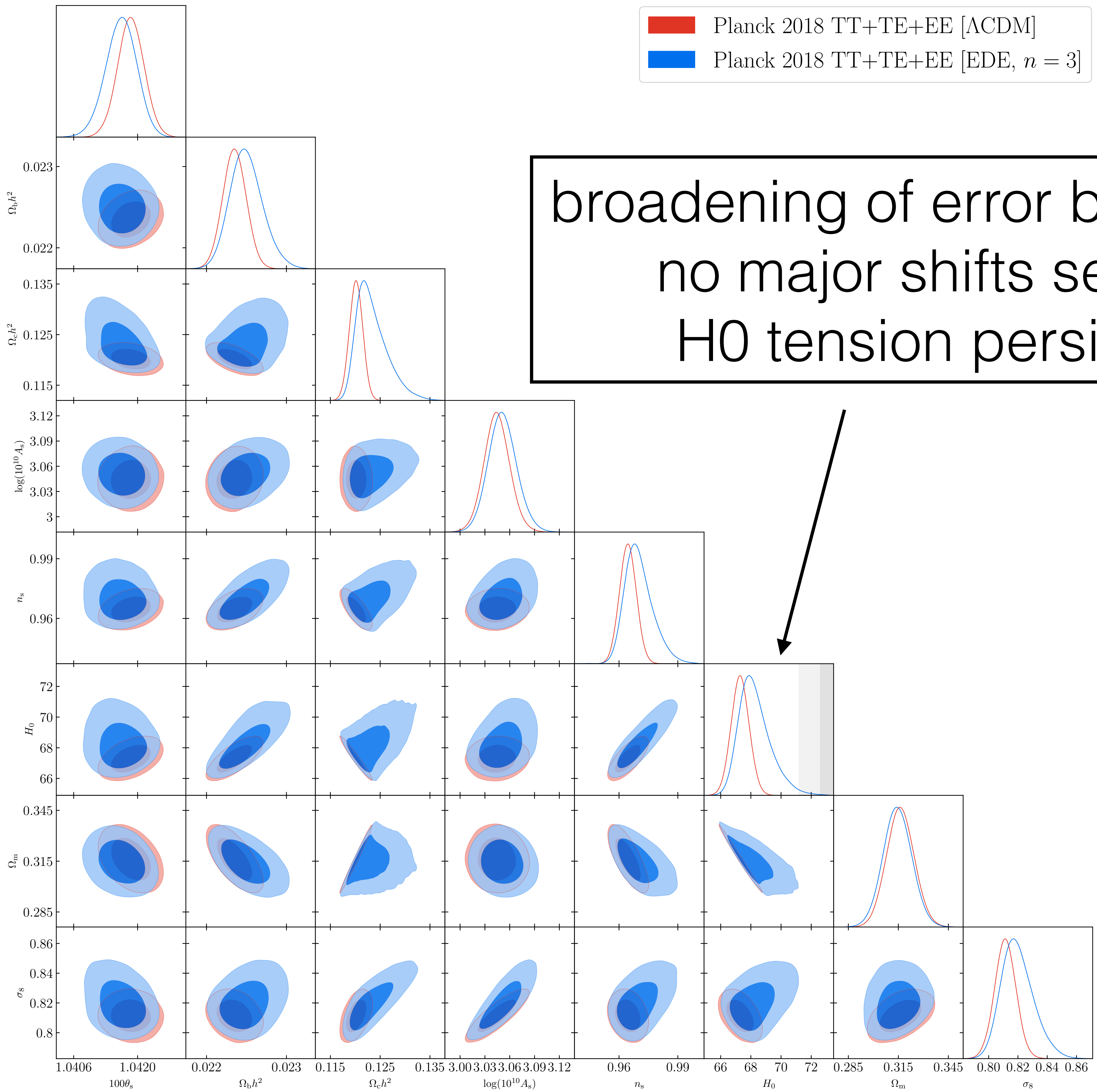

broadening of error bars, but no major shifts seen; H0 tension persists

JCH+ (2020)

Primary CMB Alone

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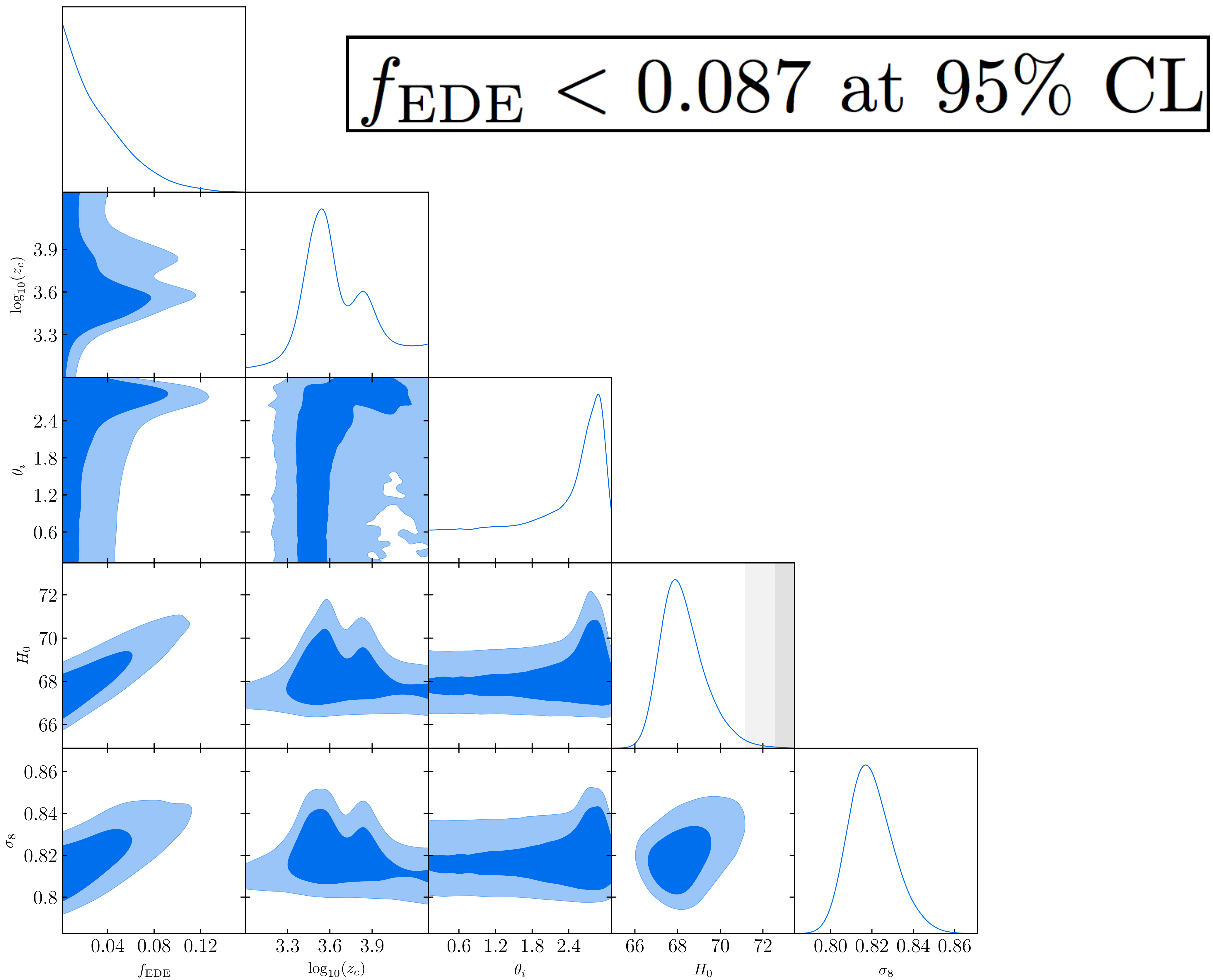
Planck primary CMB data show no evidence for EDE component



JCH+ (2020)

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Global Analysis (no SH0ES)

Fit to “everything” *including* DES, HSC, KiDS but *without* SH0ES

JCH+ (2020)

Global Analysis (no SH0ES)

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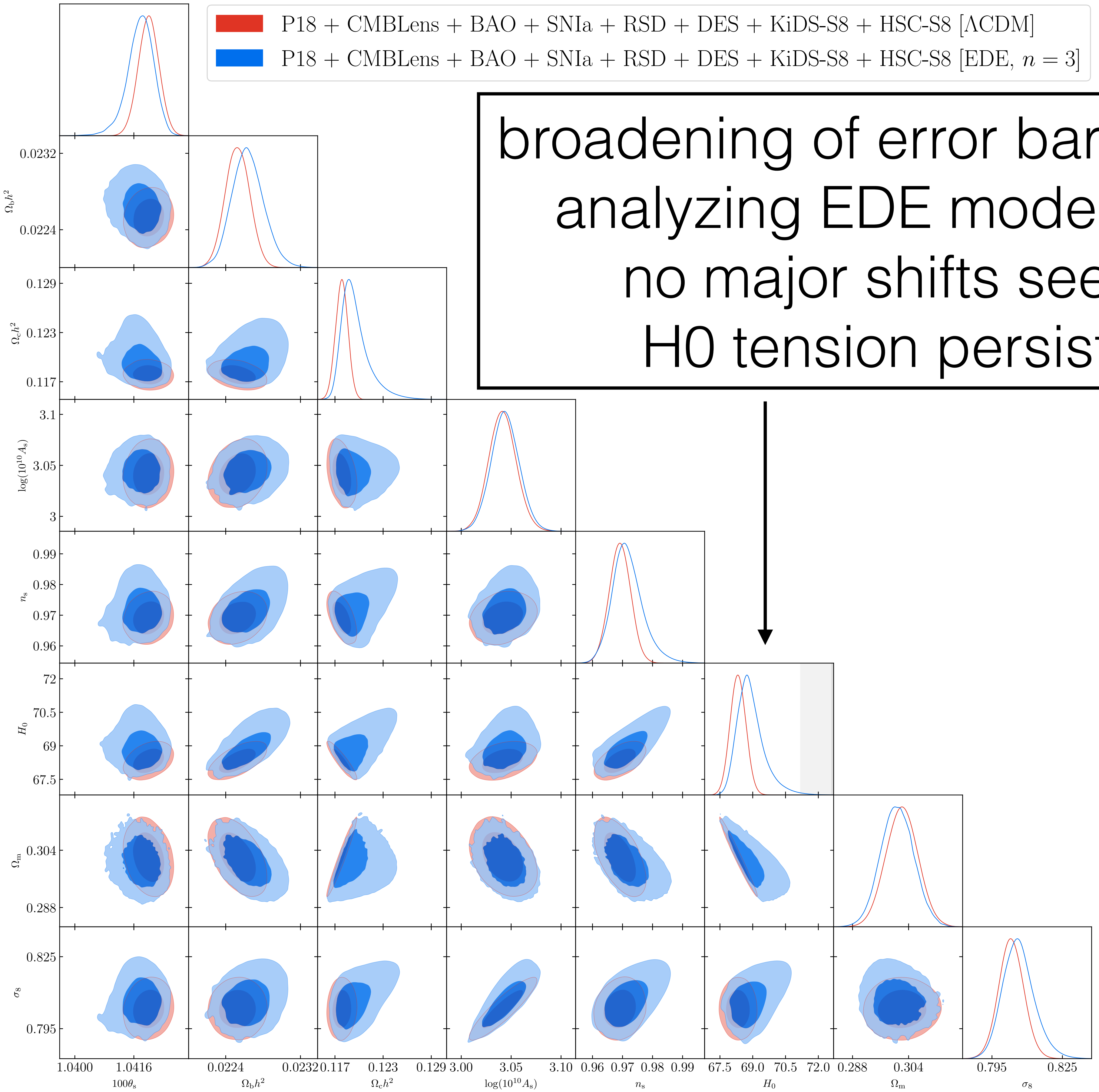

broadening of error bars when analyzing EDE model, but no major shifts seen; H0 tension persists

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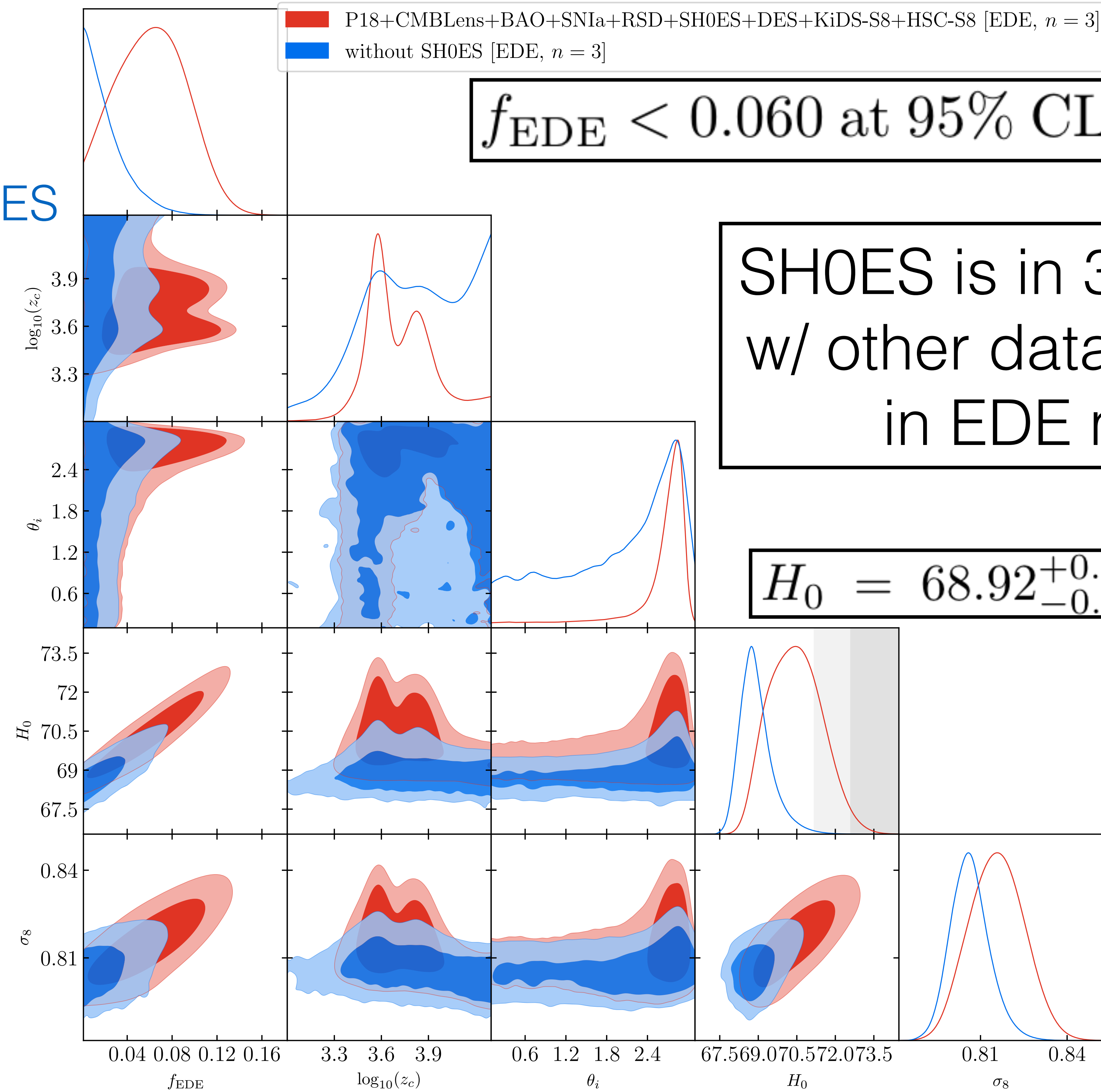
Global Analysis (no SH0ES)

Strong upper limit on existence of EDE component

red = all data sets w/ SH0ES
blue = all data sets w/out SH0ES



$f_{\rm EDE} < 0.060$ at 95% CL

SH0ES is in 3.3σ tension w/ other data sets (even in EDE model)

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

JCH+ (2020)

Summary

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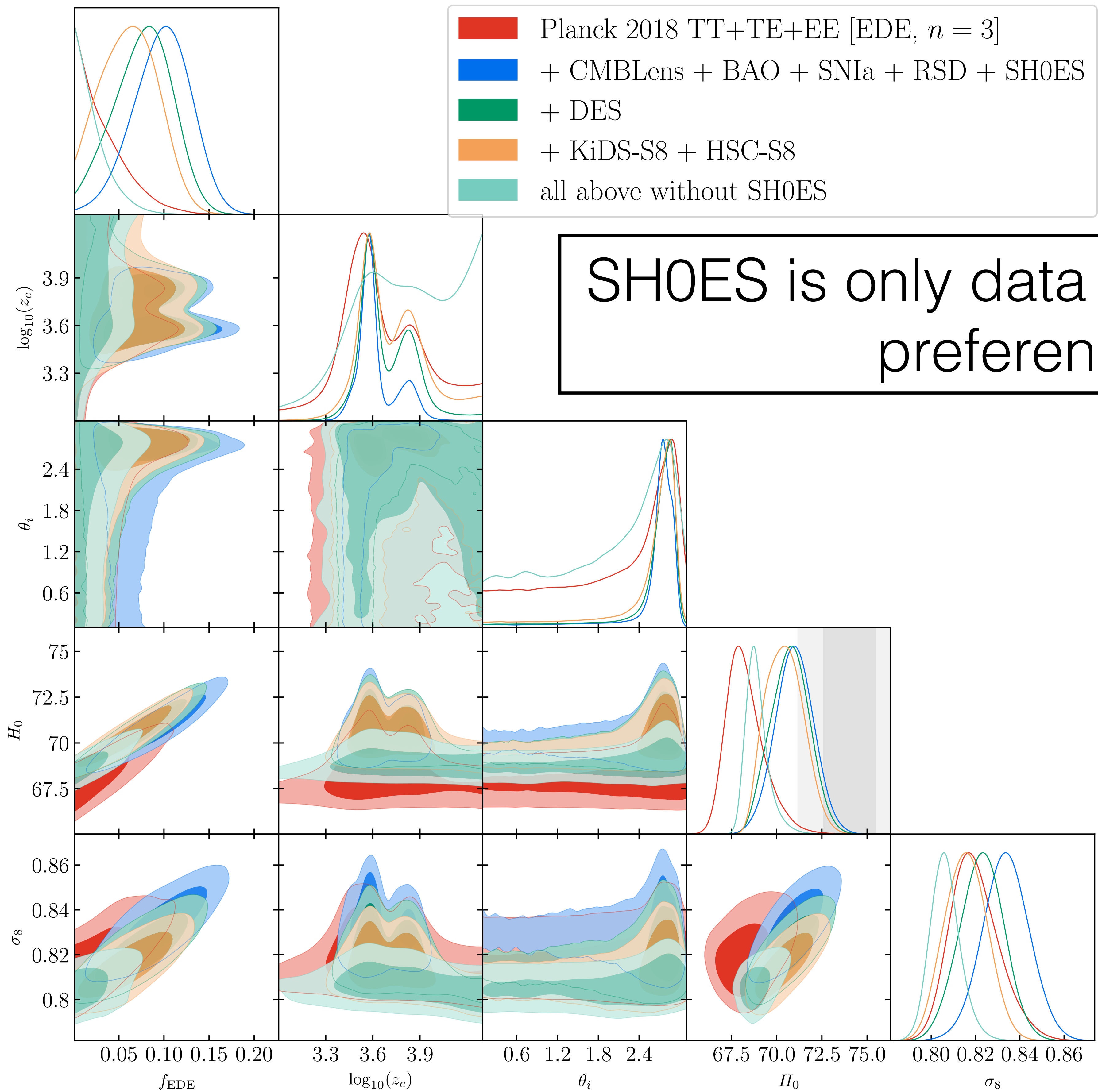

SH0ES is only data set driving preference for EDE

JCH+ (2020)

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EDE Analysis in the Effective Field Theory of Large-Scale Structure

Ivanov, McDonough, **JCH**, Simonovic, Toomey, Alexander, Zaldarriaga (2020)

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EDE in the EFTofLSS

- Goal of EFT: first-principles calculation of redshift-space galaxy power spectrum (e.g., BOSS, DESI) a la CMB
- Our previous analysis (and others') implicitly used BOSS RSD that assumed standard LCDM early-universe physics

Ivanov, McDonough, **JCH**, Simonovic, Toomey, Alexander, Zaldarriaga (2020)

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- Goal of EFT: first-principles calculation of redshift-space galaxy power spectrum (e.g., BOSS, DESI) a la CMB
- Our previous analysis (and others') implicitly used BOSS RSD that assumed standard LCDM early-universe physics
- Moreover, standard BOSS RSD likelihood does not use the full shape info encoded in the galaxy power spectrum
- Punchline of our new analysis: the one-loop EFT-based full-shape likelihood is much more powerful for constraining EDE than the standard BOSS ($f\sigma_8$ + BAO) likelihood, and further tightens bounds on EDE

Ivanov, McDonough, **JCH**, Simonovic, Toomey, Alexander, Zaldarriaga (2020)

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EDE in the EFTofLSS

Fractional difference between fiducial EDE and LCDM models

Ivanov, McDonough, **JCH**, Simonovic, Toomey, Alexander, Zaldarriaga (2020)

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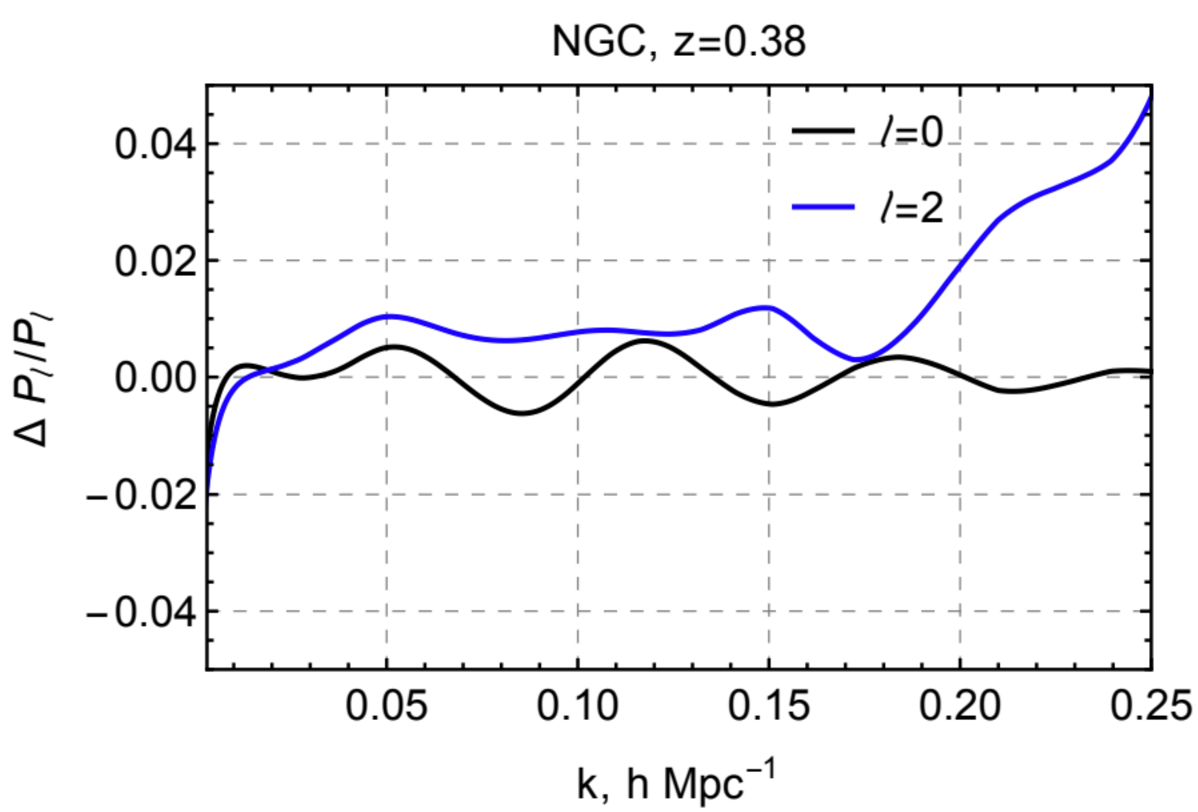

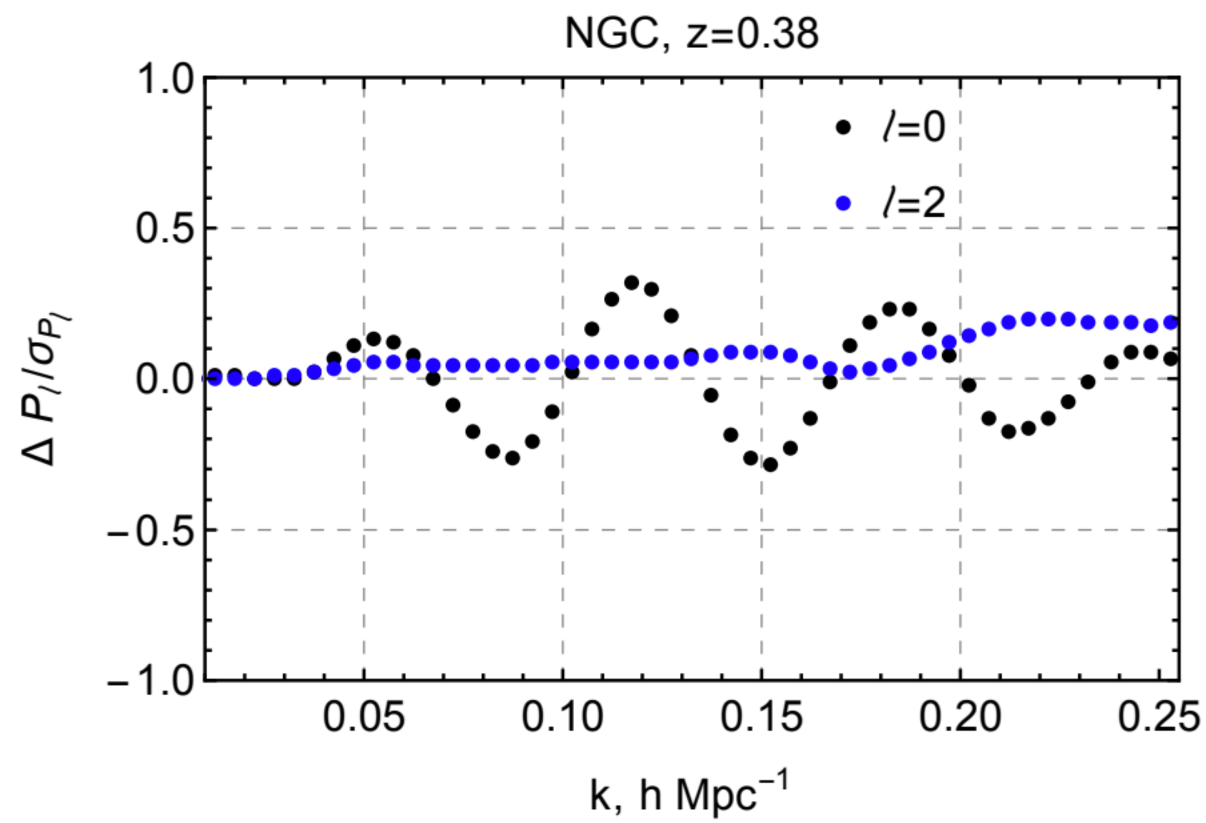

All nuisance parameters have been separately fit in each model, so differences seen here are due to cosmology

Biggest discrepancy: shape and position of the BAO wiggles in the monopole

Ivanov, McDonough, **JCH**, Simonovic, Toomey, Alexander, Zaldarriaga (2020)

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Planck + BOSS (EFT) + DES/HSC/KiDS (S_8)

Ivanov+ (2020)

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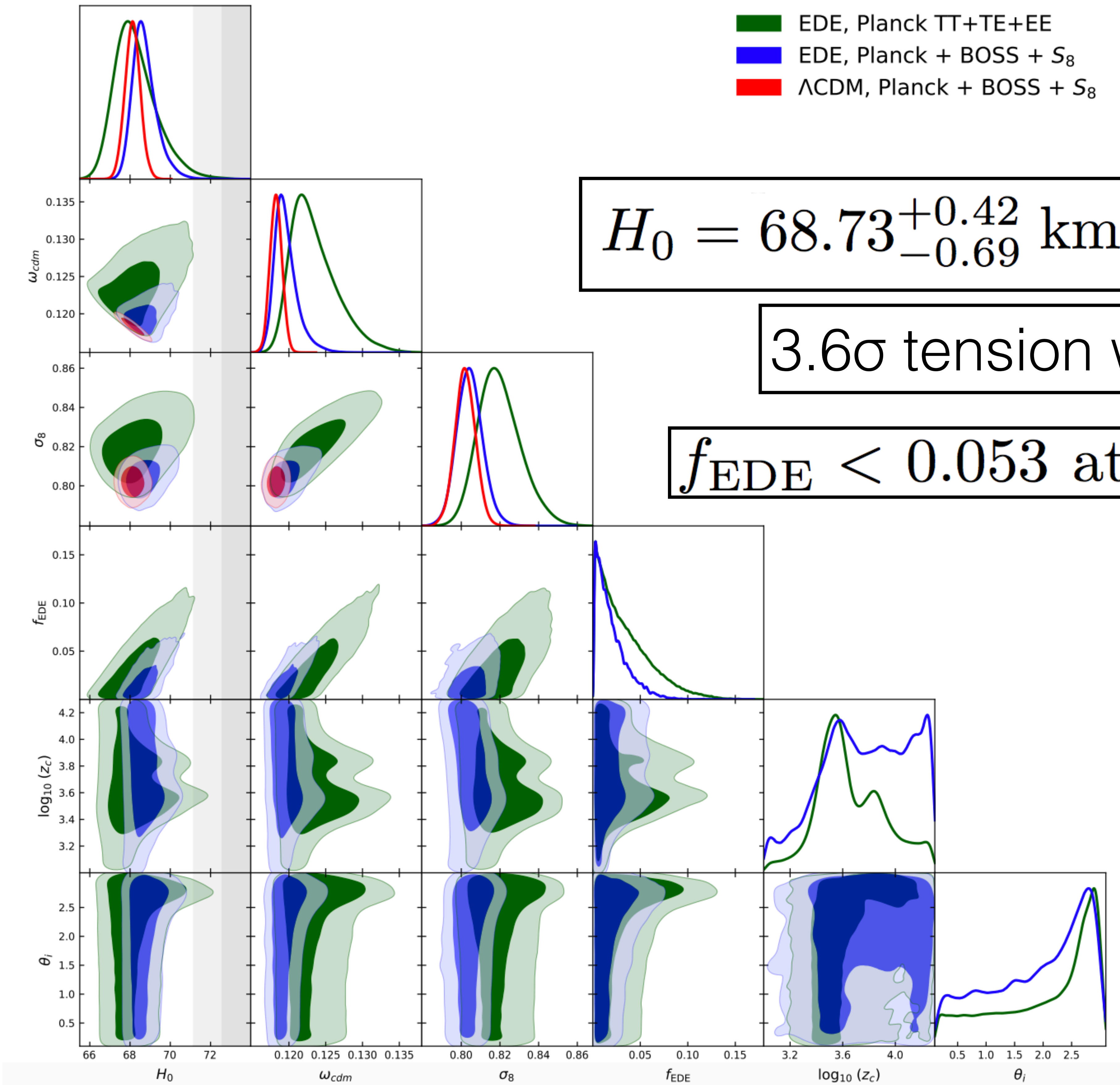
Planck + BOSS (EFT) + DES/HSC/KiDS (S_8)



$$H_0 = 68.73^{+0.42}_{-0.69}\ \mathrm{km/s/Mpc}$$

3.6σ tension w/ SH0ES

$$f_{\rm EDE} < 0.053\ \text{at}\ 95\%\ \text{CL}$$

Ivanov+ (2020)

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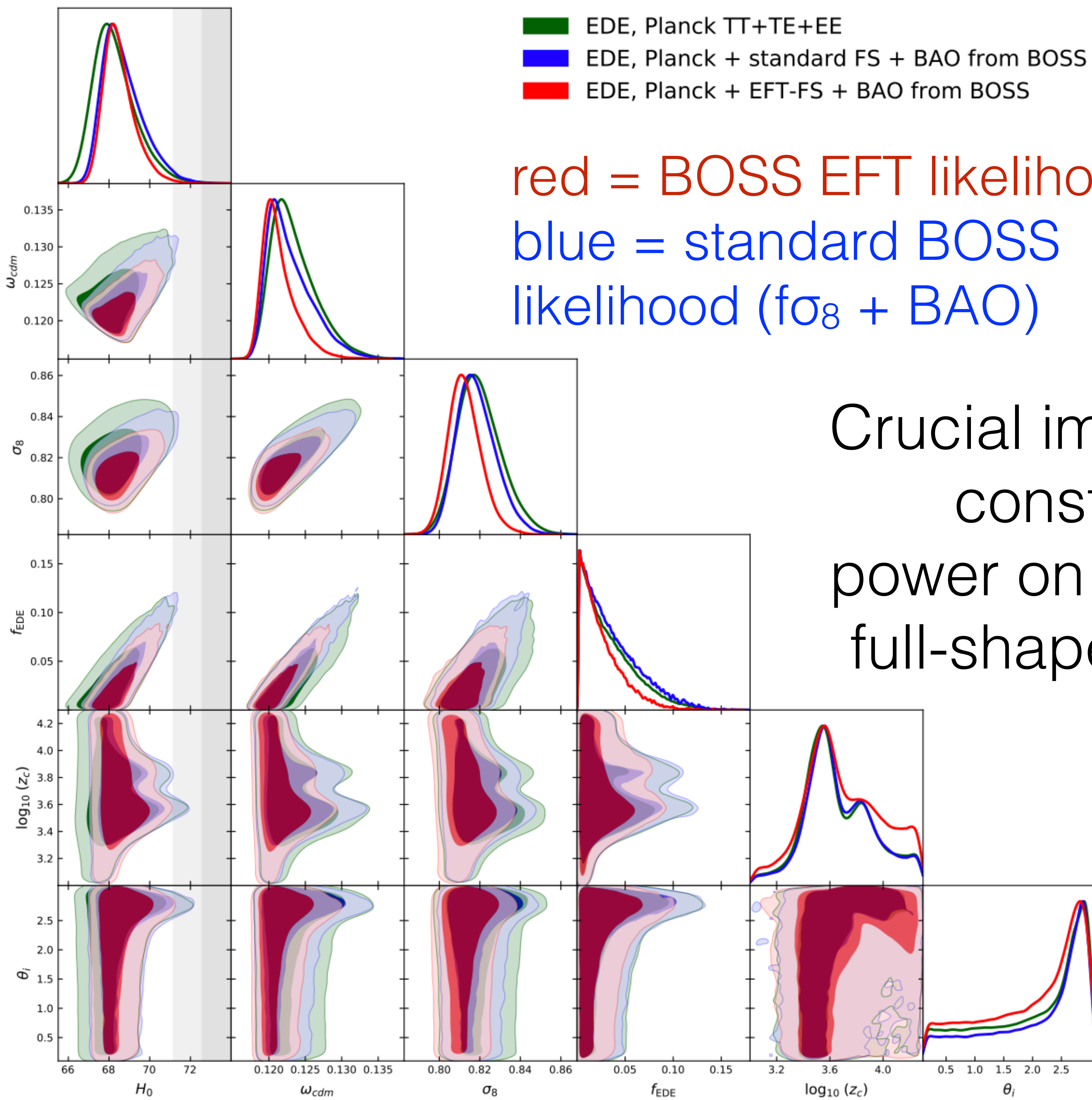
Additional Constraining Power of EFT



red = BOSS EFT likelihood

blue = standard BOSS likelihood ($f\sigma_8$ + BAO)

Crucial improvement: constraining power on ω_{cdm} in EFT full-shape likelihood

Ivanov+ (2020)

Summary

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- No evidence for EDE component seen in CMB-only or CMB+LSS data; strong upper limits obtained
- SH0ES constraint is in tension, even in this model
- Basic problem: higher H_0 requires higher f_{EDE}, which increases ω_{cdm}, σ_8, S_8 and hence worsens fit to LSS data
- In short: EDE model does not restore concordance
- Use of physical priors (on scalar field parameters) further weakens evidence for EDE (see bonus slides if interested)

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- Theorists: back to the drawing board
- Data analysts: w/ new results from TDCOSMO and CCHP (TRGB), perhaps the case for H0 tension has weakened

Bonus

Validation of S_8 Procedure

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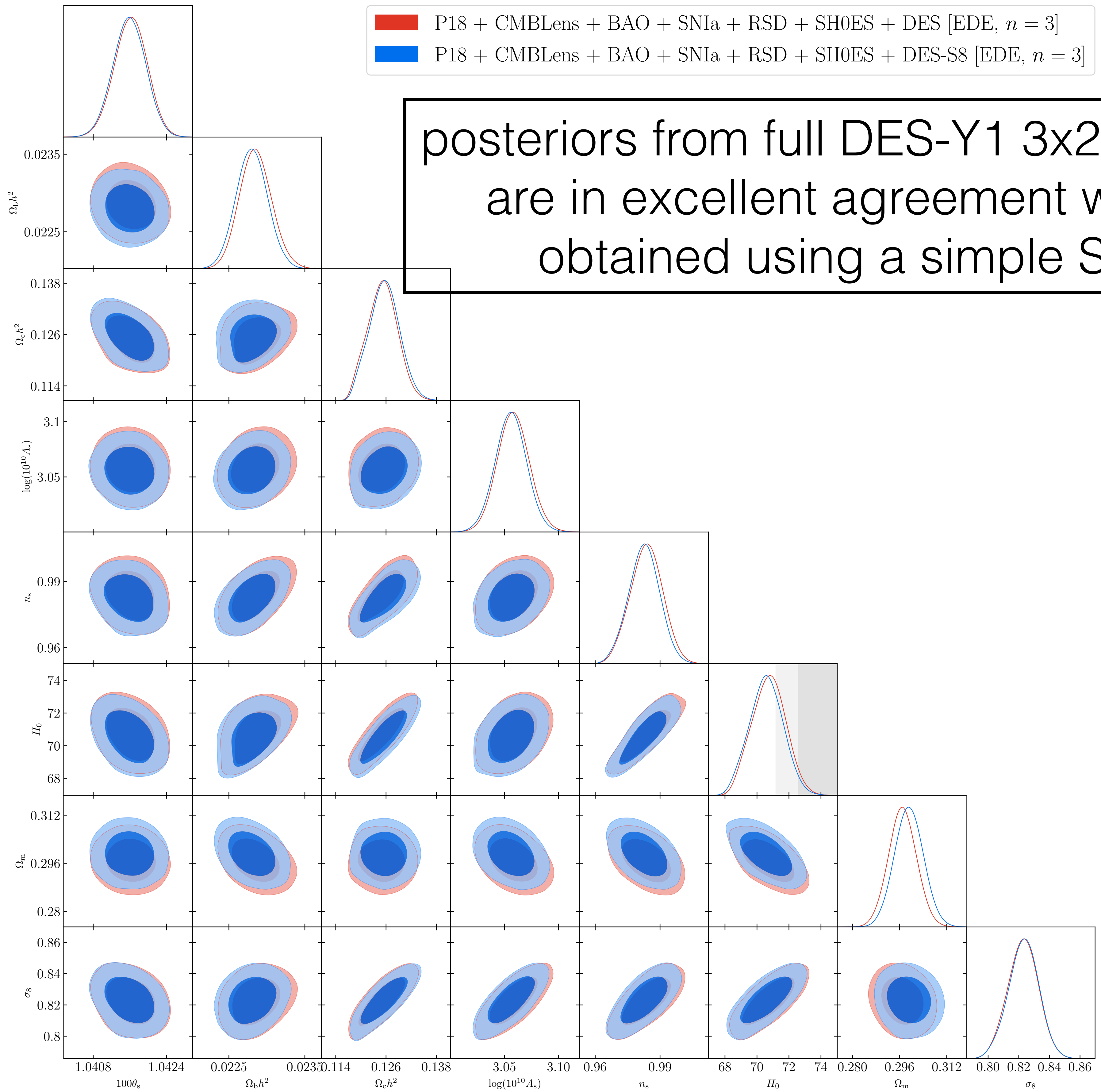

posteriors from full DES-Y1 3x2pt likelihood are in excellent agreement with those obtained using a simple S8 prior

JCH+ (2020)

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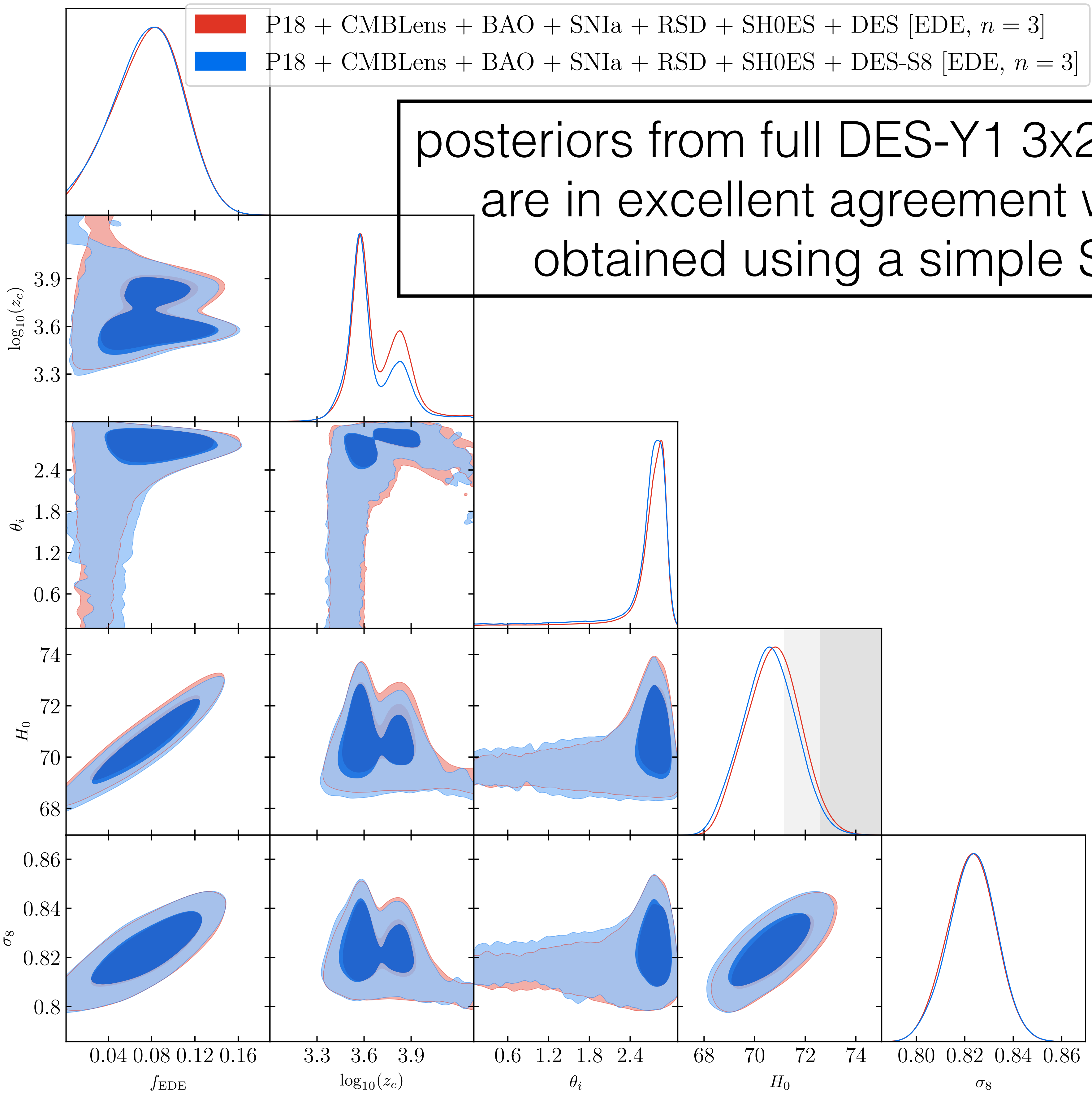

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JCH+ (2020)

Reproduce Earlier Results

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Fit to Planck 2018 (+ lensing) + BAO + SH0ES + SNIa + RSD

JCH+ (2020),
Poulin+ (2019),
Smith+ (2019)

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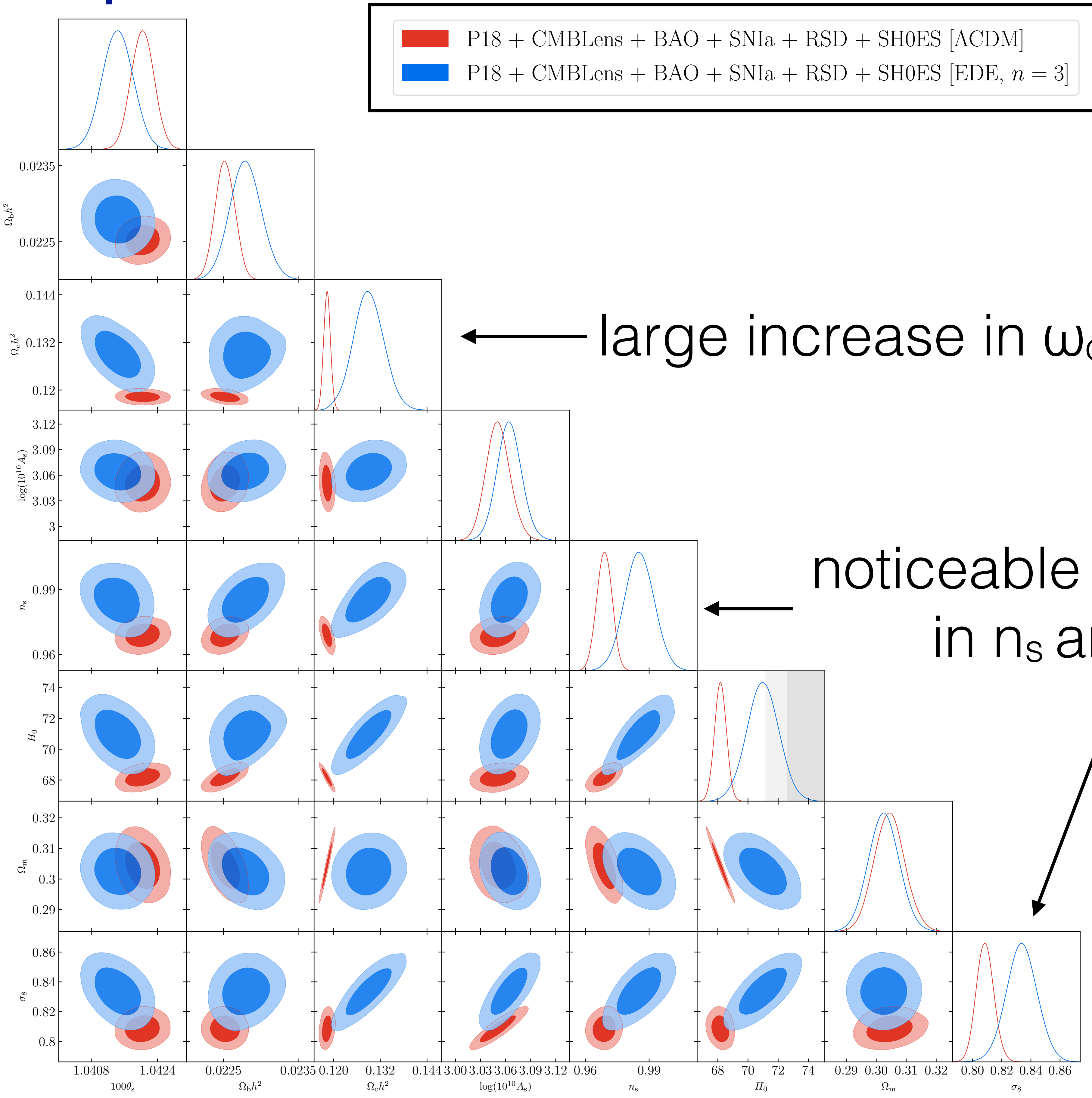

large increase in ω_{cdm}

noticeable increases in n_s and σ_8

JCH+ (2020), Poulin+ (2019), Smith+ (2019)

Reproduce Earlier Results

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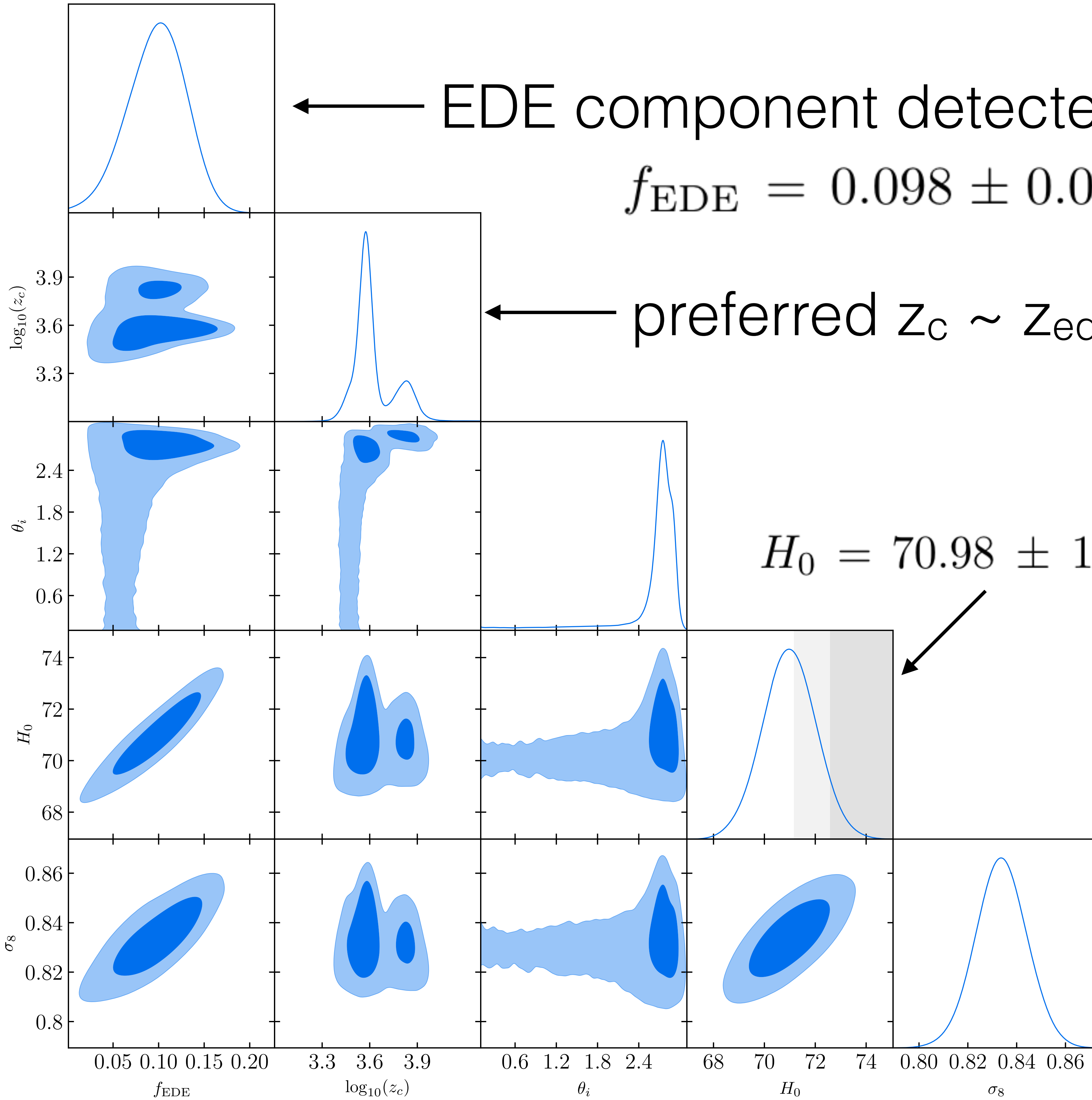

EDE component detected at ~3σ

$$f_{\rm EDE} = 0.098 \pm 0.032$$

preferred $z_c \sim z_{eq}$

$$H_0 = 70.98 \pm 1.05\,{\rm km/s/Mpc}$$

JCH+ (2020)

Inclusion of LSS Data

Fit to “everything” including DES, HSC, KiDS and SH0ES

JCH+ (2020)

Inclusion of LSS Data

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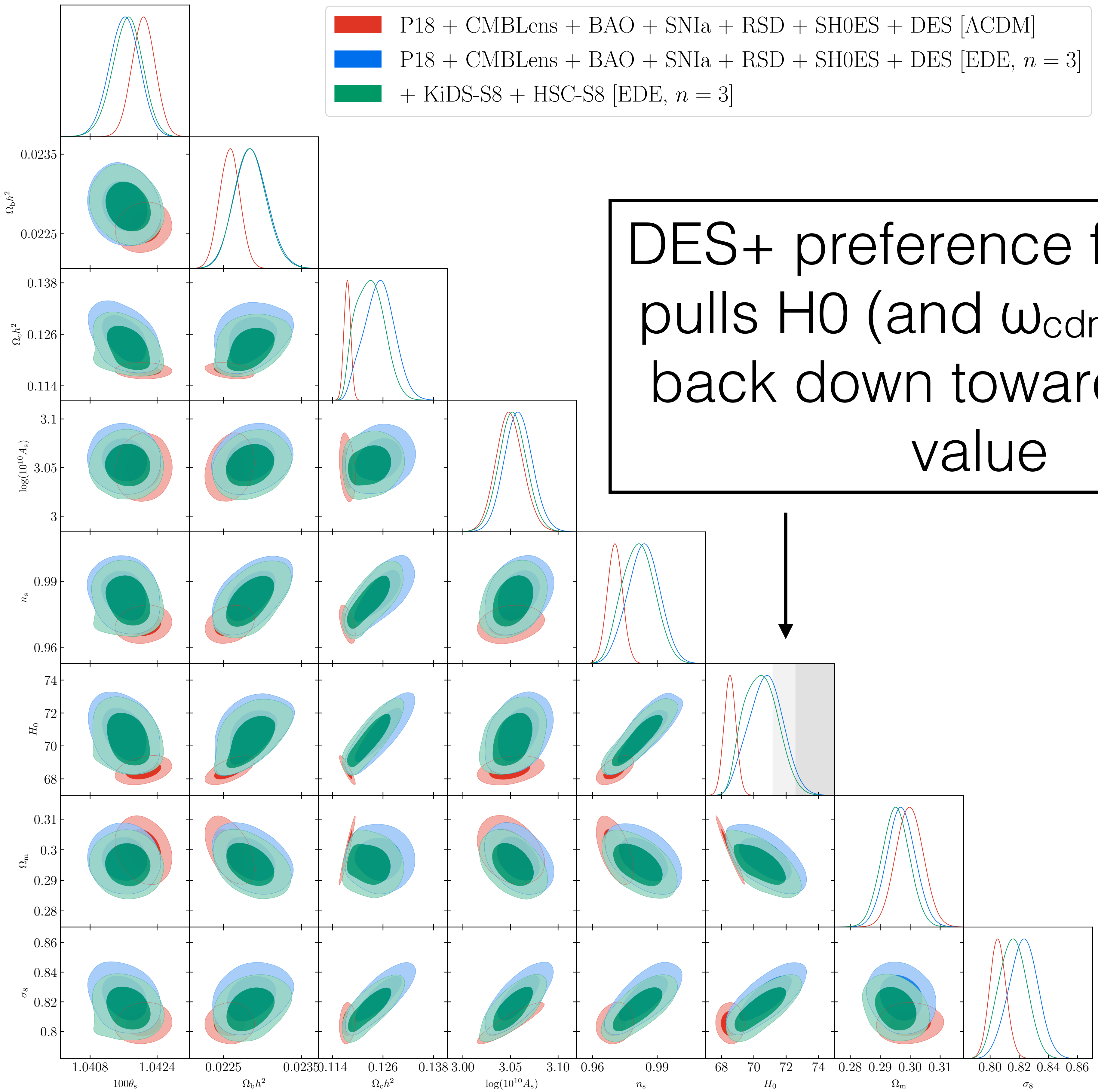

DES+ preference for low S_8 pulls H0 (and ω_{cdm} and n_s) back down toward ΛCDM value

JCH+ (2020)

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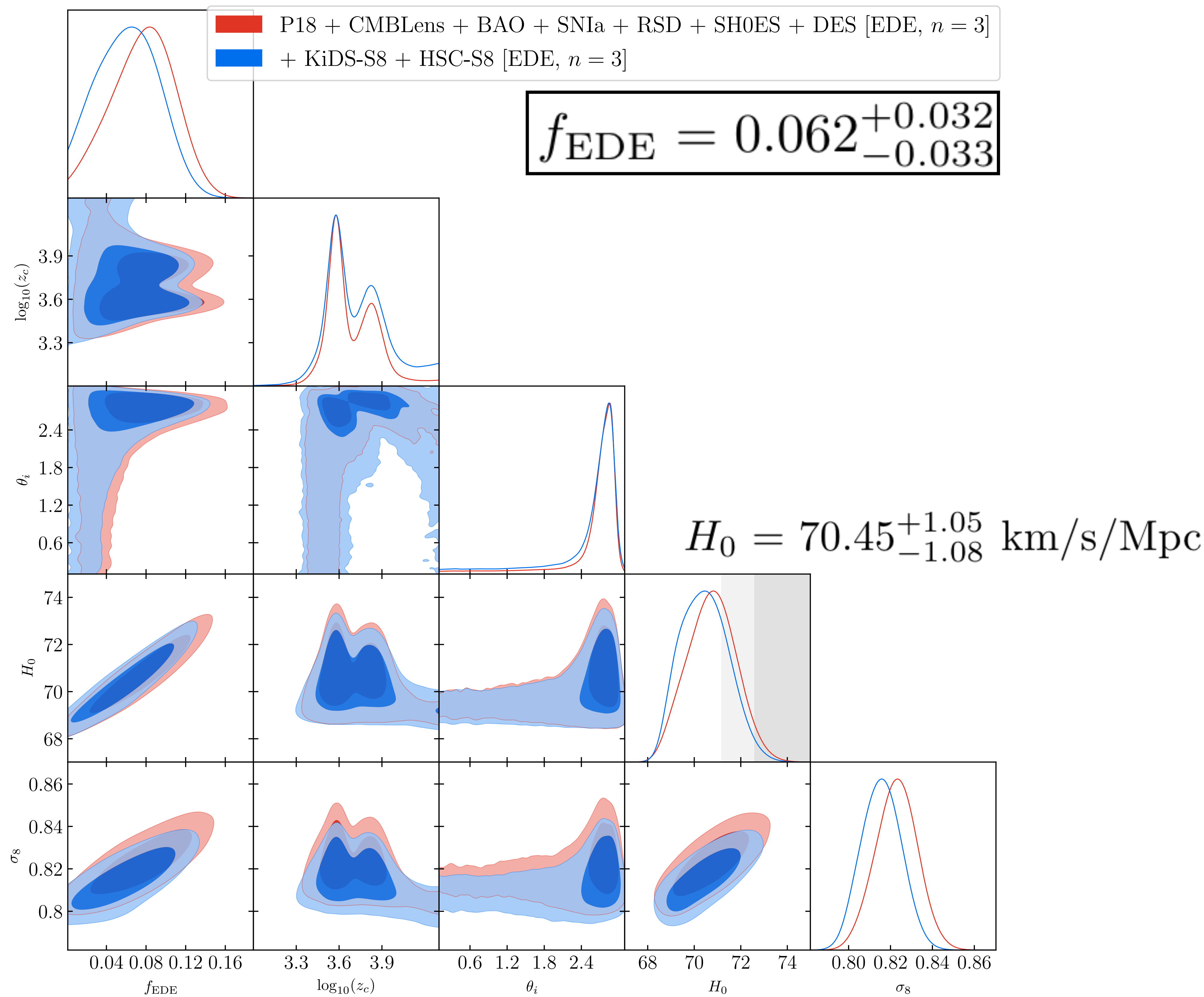
Inclusion of LSS Data

Inclusion of LSS data leads to non-detection of EDE component



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Physical Priors

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Uniform priors on f_{EDE} and $\log(z_c)$ are very non-uniform on physical scalar field parameters f and m

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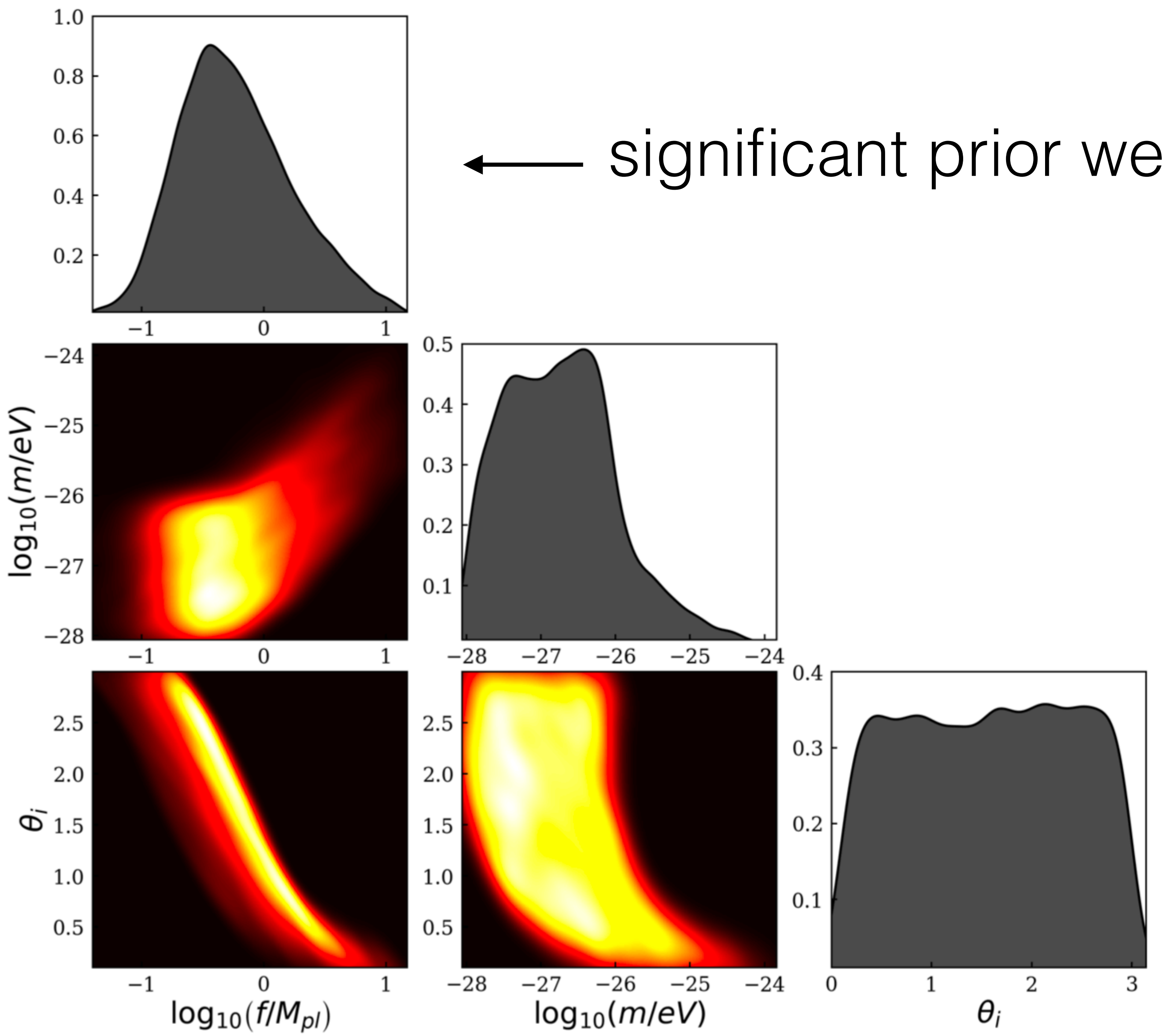
Physical Priors

Uniform priors on f_{EDE} and $\log(z_c)$ are very non-uniform on physical scalar field parameters f and m



← significant prior weight at f > M_{Pl}!

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Physical Priors

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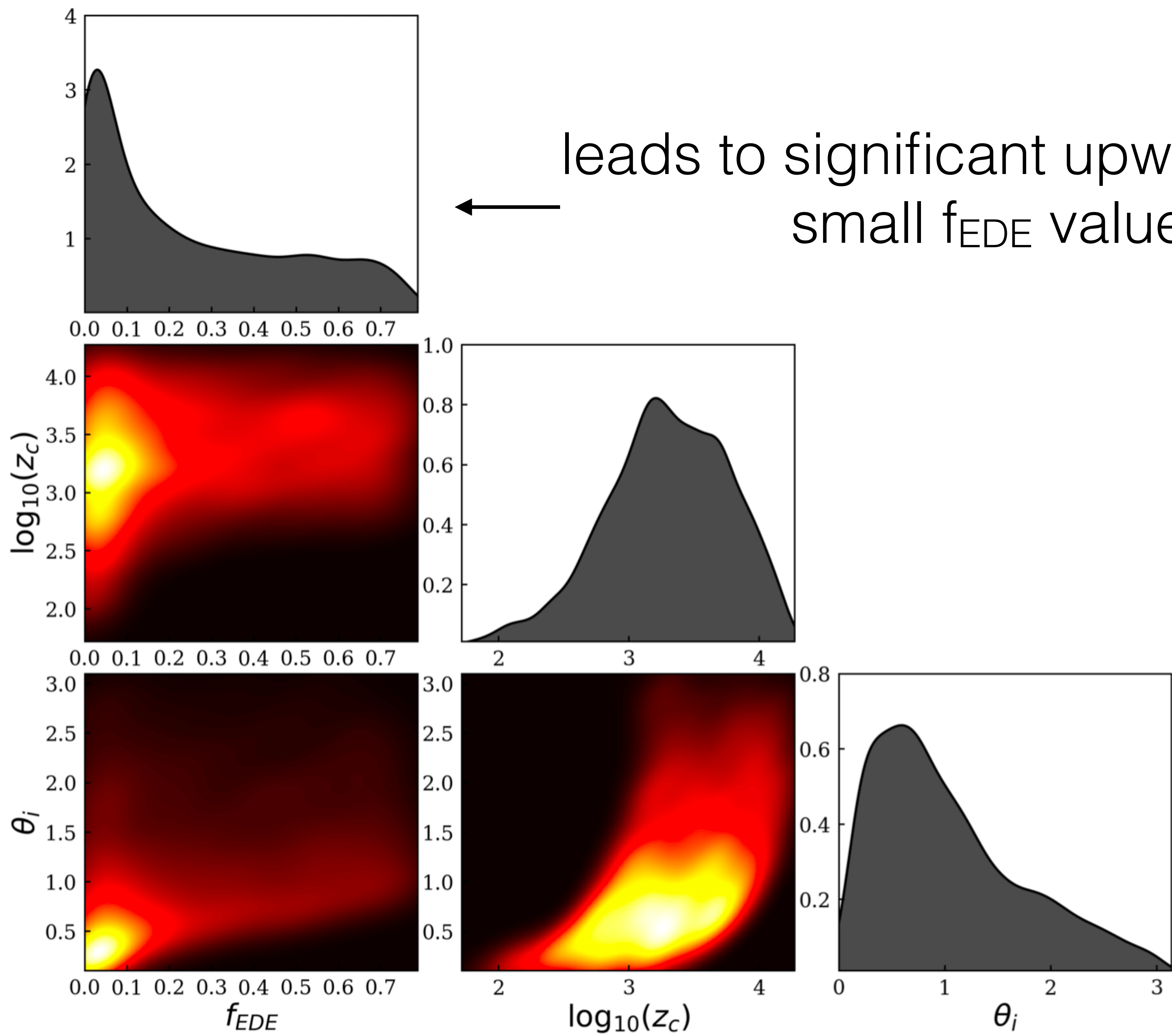
What if we use uniform priors on f and log(m) instead?



leads to significant upweighting of small f_{EDE} values

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Primary CMB Alone, Revisited

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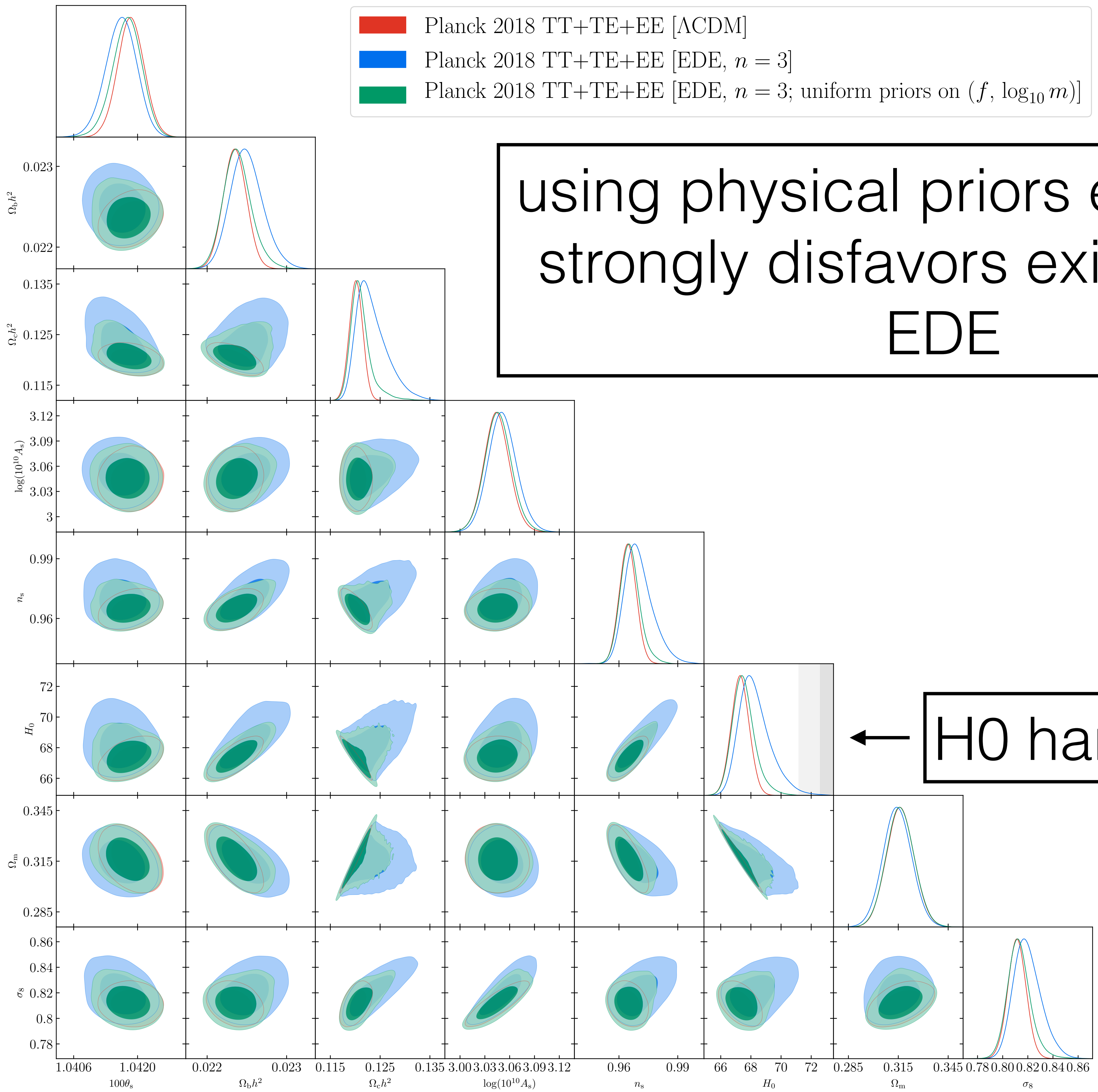

using physical priors even more strongly disfavors existence of EDE

← H0 hardly moves

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Summary (log(f) and log(m))

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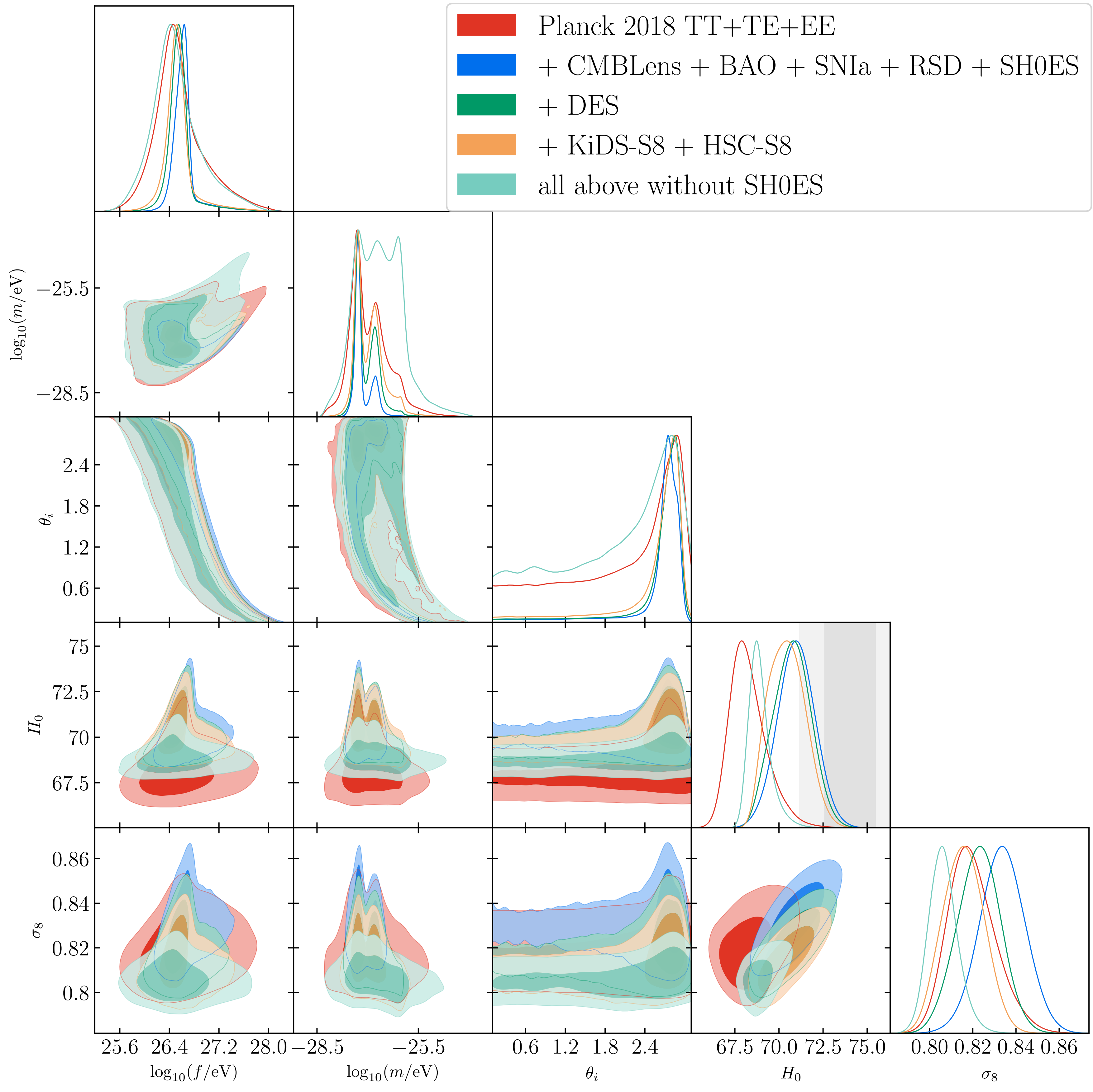

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Prior Volume Effects?

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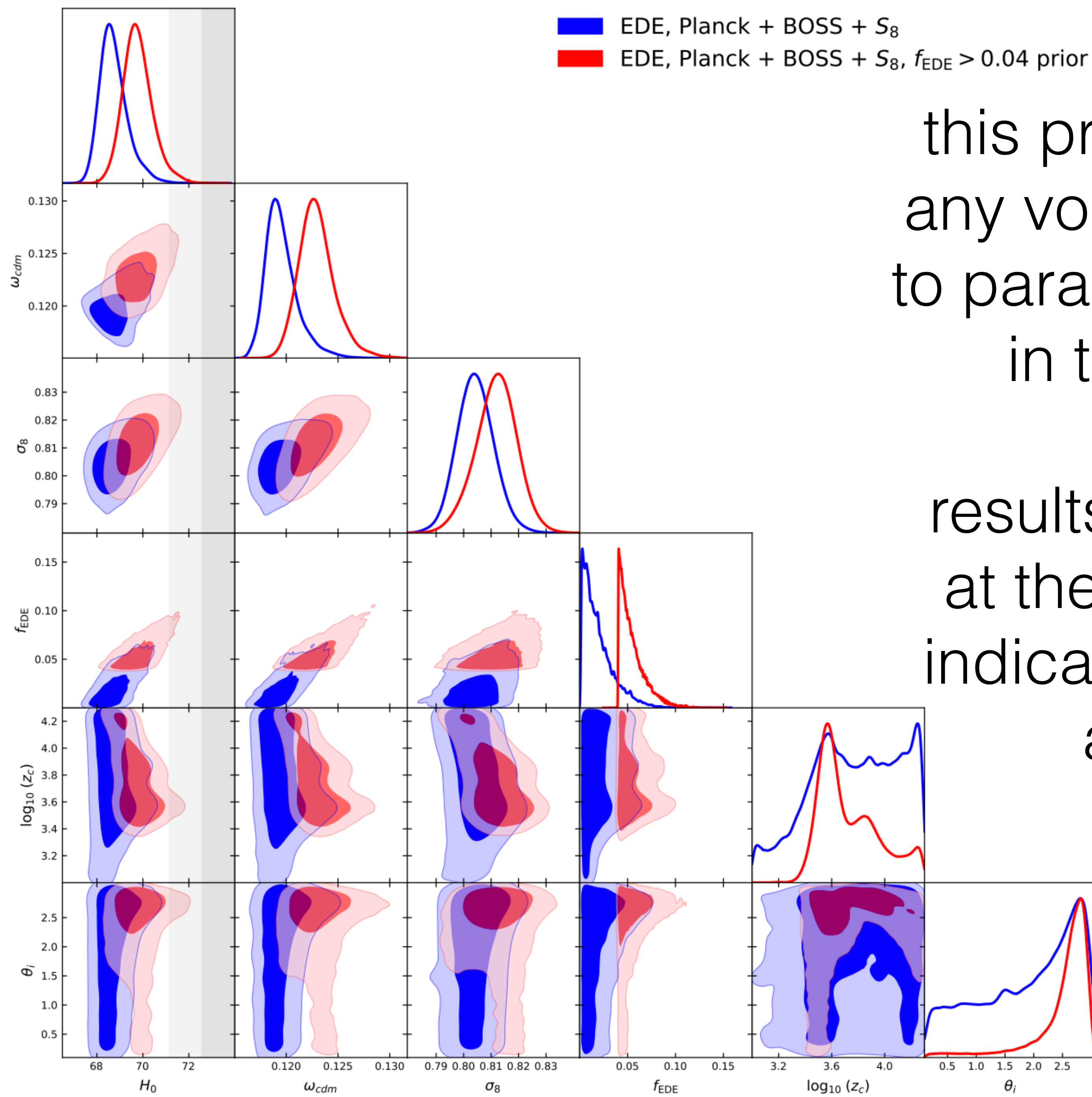
Could standard MCMC approach somehow "miss" preference for EDE model due to prior volume effects? We find no evidence for this

Re-run of Planck + BOSS + S8 analysis with $f_{EDE} > 0.04$ prior



this prior would eliminate any volume effects related to parameter degeneracies in the f_{EDE} -> 0 limit

results still peak strongly at the f_{EDE} lower bound, indicating volume effects are negligible

also confirmed with a direct χ^2 test

Ivanov+ (2020)