Constraining Early Dark Energy with Large Scale Structure

Evan McDonough
(Brown ➔)   MIT   (➔ Chicago KICP)

[Ivanov, EM, Hill, Simonovic, Toomey, Alexander, Zaldarriaga] [arXiv:2006.11235]

[Hill, EM, Toomey, Alexander] [arXiv:2003.07355] [PRD]

[EM, Alexander] [arXiv:1904.08912] [PLB]

Bourses postdoctorales Banting Postdoctoral Fellowships

Government of Canada

"Cosmological Complementarity and the Dark Universe"

The Hubble tension

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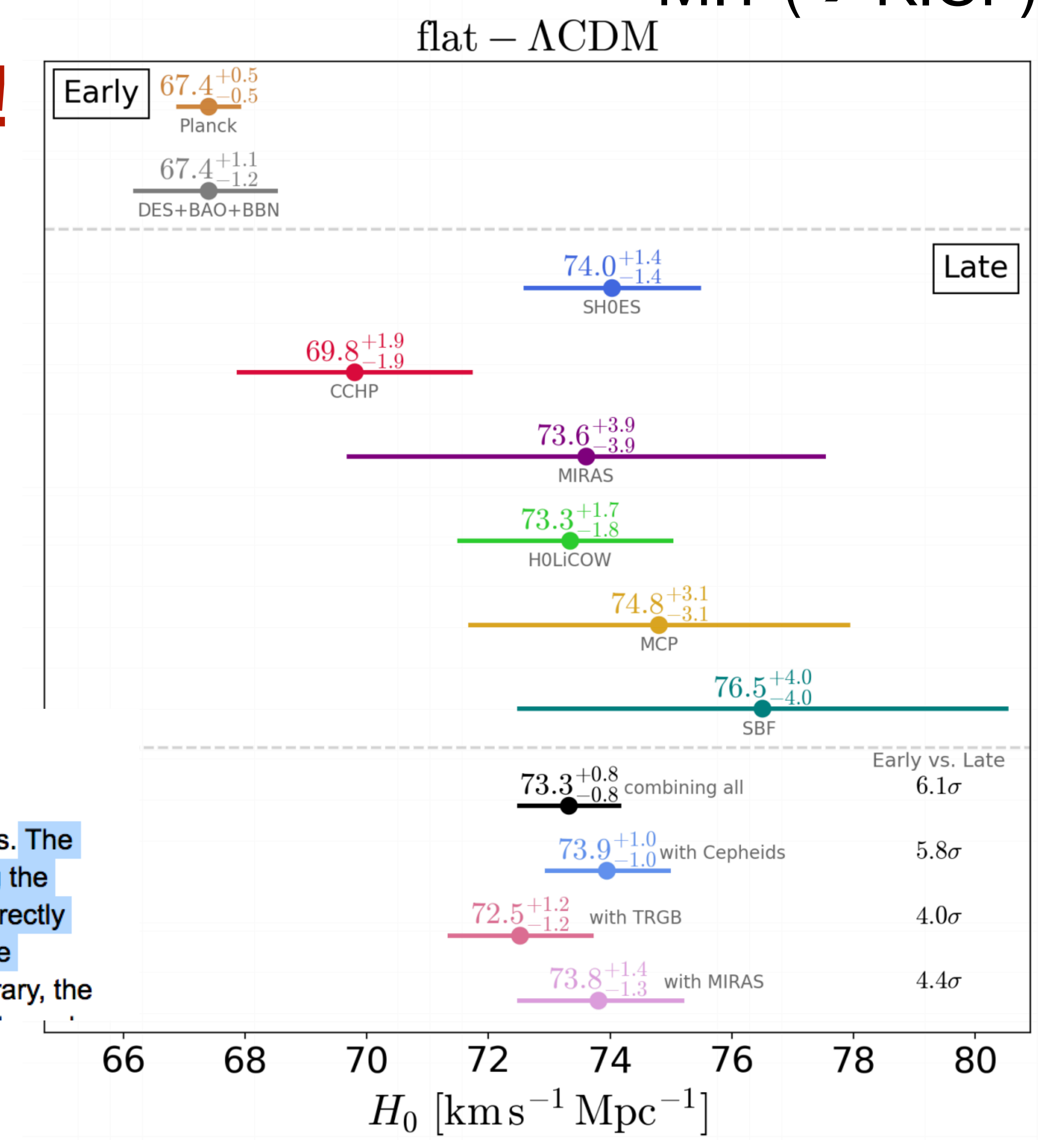
= CMB vs SH0ES? No!

Assessing Uncertainties in Hubble's Constant Across the Universe

The tension in the Hubble constant is the one of the potentially most consequential open problems of present-day astrophysics. The early-Universe H0 value inferred from high-precision measurements of the Cosmic Microwave Background (CMB) – assuming the ΛCDM concordance model – differs by 9.4 ± 2.1% (4.4σ) from the cosmology-independent present-day H0 value measured directly using a well-calibrated, empirical cosmic distance ladder composed of classical Cepheid variable stars and type-Ia supernovae (SNIa). Despite intense scrutiny, no straightforward resolutions of the Hubble tension have as yet been identified. On the contrary, the



Large Scale Structure

Combining Full-Shape and BAO Analyses of Galaxy Power Spectra: A 1.6% CMB-independent constraint on H0

Oliver H.E. Philcox (Princeton U., Astrophys. Sci. Dept.), Mikhail M. Ivanov (New York U., CCPP and Moscow, INR), Marko Simonović (CERN), Matias Zaldarriaga (Princeton, Inst. Advanced Study) (Feb 10, 2020)

Published in: *JCAP* 05 (2020) 032 • e-Print: 2002.04035 [astro-ph.CO]

$$(\text{Result}: H_0 = 68.6 \pm 1.1\ \text{km/s/Mpc})$$

See also:

Ivanov+ 1909.05277, D'Amico+ 1909.05271, Tröster+ 1909.11006

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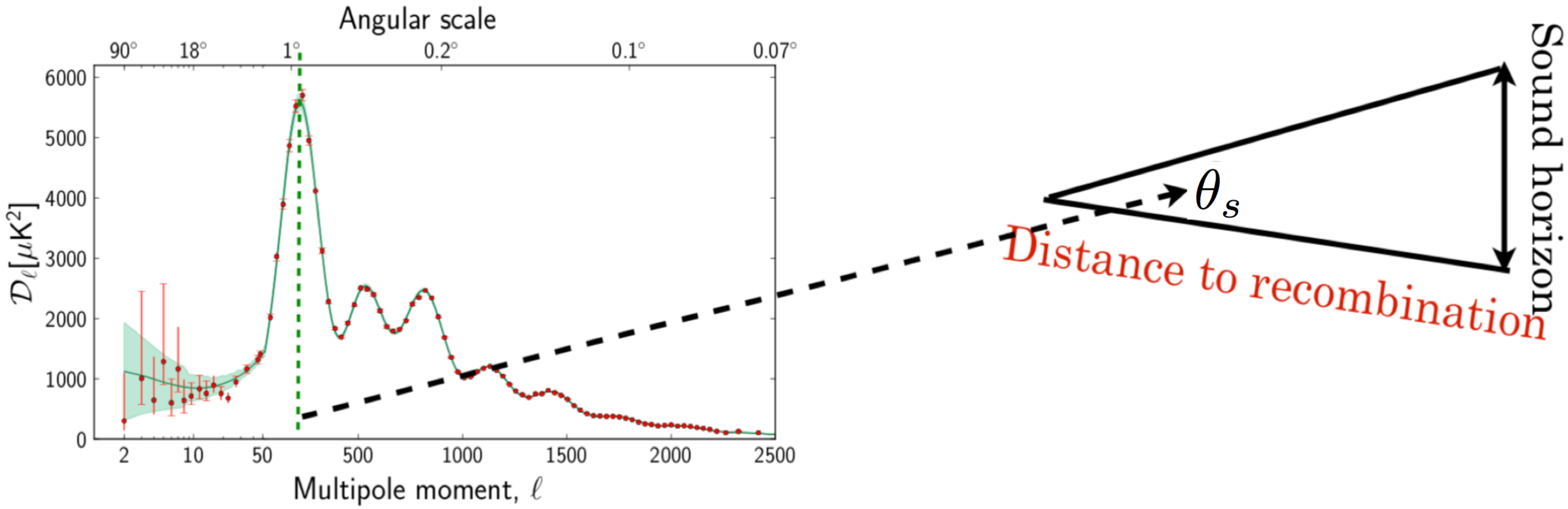
Early Universe Solutions: Appease the CMB



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

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

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

Planck 2018 results. VI. Cosmological parameters

The angular acoustic scale is measured to $0.03\,\%$ precision, with $100\theta_* = 1.0411 \pm 0.0003$.

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[Poulin+ 1811.04083]
[Smith+ 1908.06995]

Early Dark Energy

The canonical model

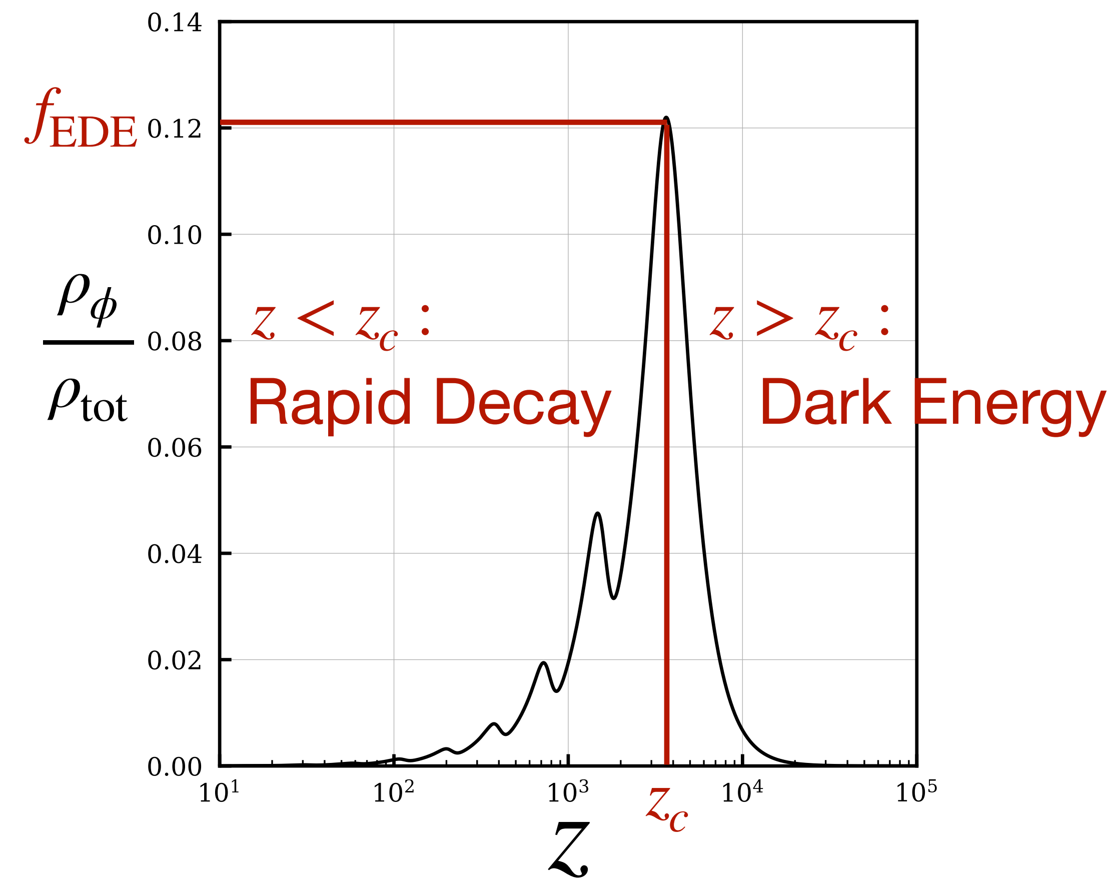
$$V(\phi) = m^2 f^2 \left(1 - \cos\frac{\phi}{f}\right)^n$$

Ultralight: $m \sim H(z_{eq}) \sim 10^{-27}\text{eV}$

10% of the universe at $z \sim z_{eq}$: $f \lesssim M_{\text{pl}}$

Hidden from Late Universe: $n \geq 2 \quad (w \geq 1/3)$

Parameterization



Many Models!

Example: Trigger Field Models:

Two-field destabilization [EM, Alexander] [arXiv:1904.08912]
1st order PT [Niedermann & Sloth, 1910.10739]
Neutrinos [Sakstein & Trodden, 1911.11760)]

See also:
non-minimal coupling [Gonzalez, Mark P. Hertzberg, Rompineve]
decay into gauge fields [Ballesteros, Notari, Rompineve] [Berghaus,Karwal]

A Recipe for the CMB

(CLASS-EDE code on GitHub)

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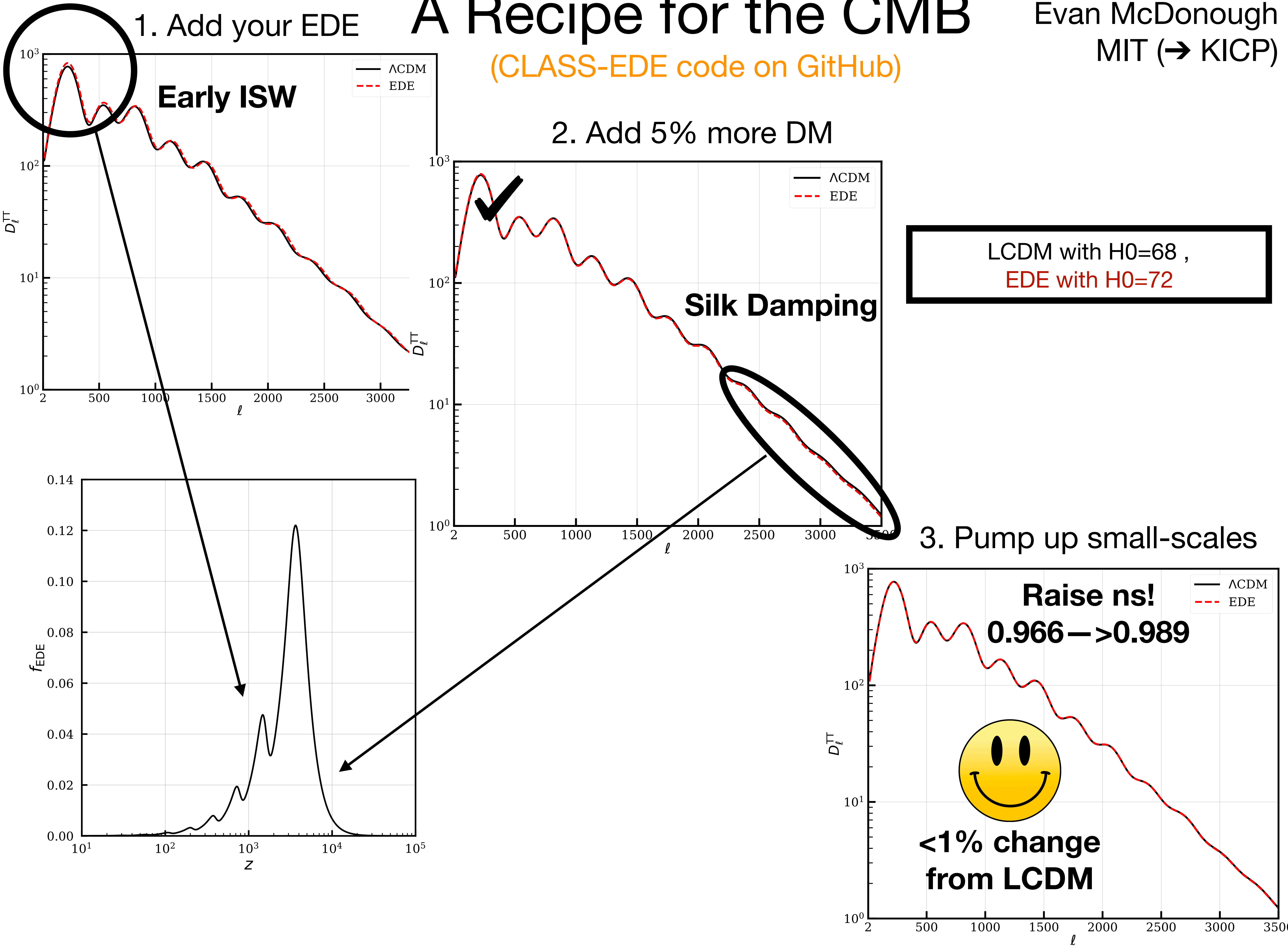

(CLASS-EDE code on GitHub)

Large Scale Structure

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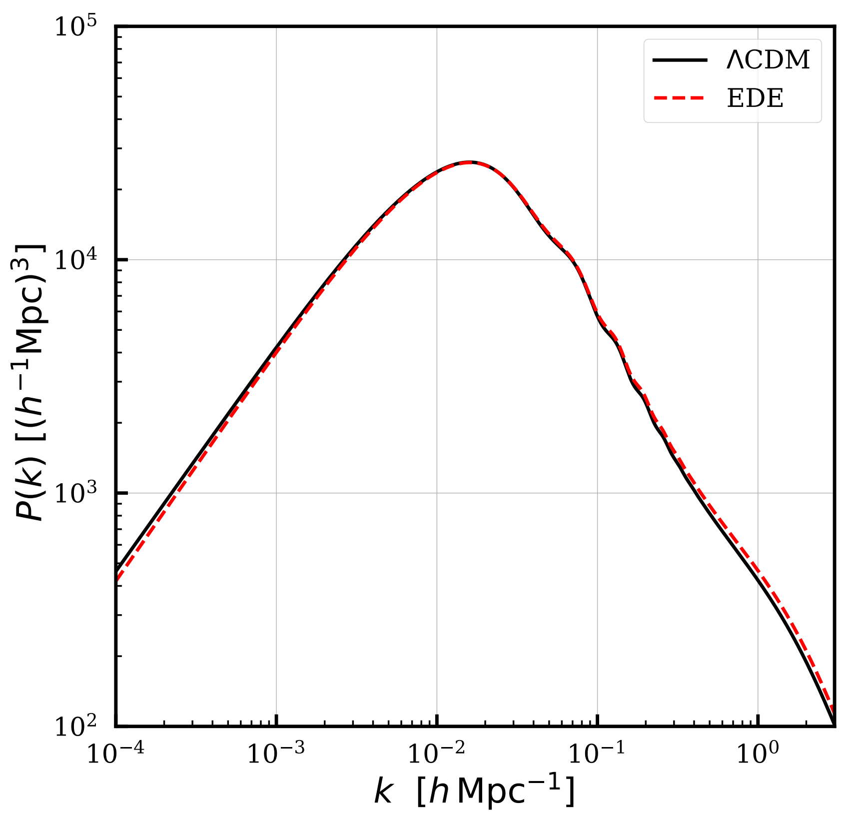
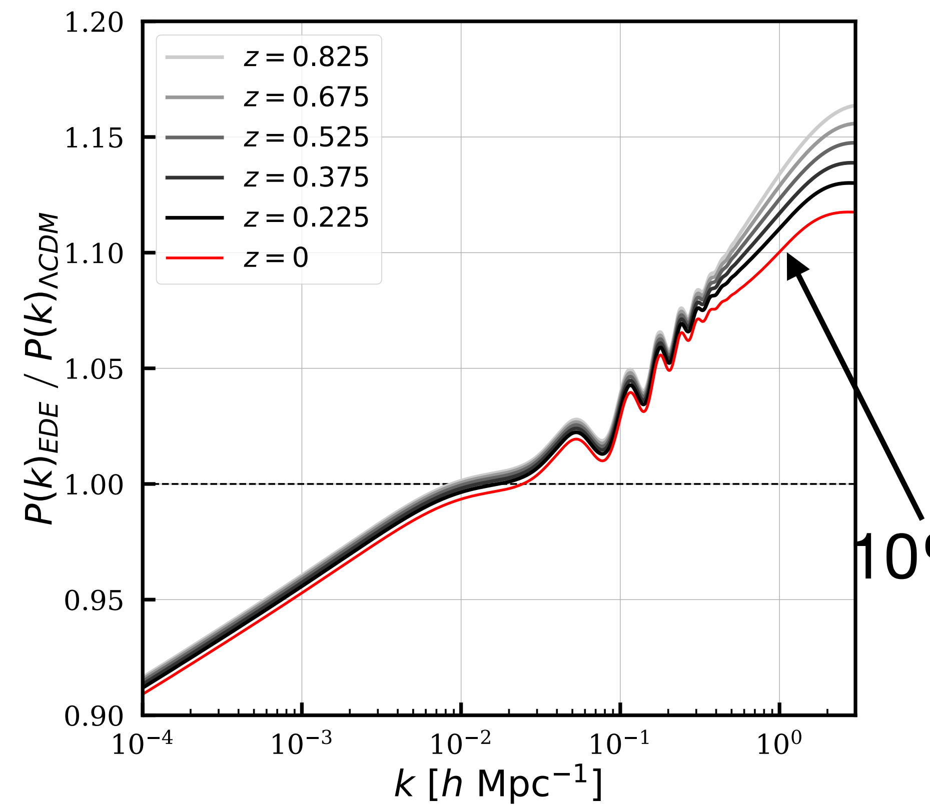
More than 1 or 2 numbers!

Changes in LCDM params boost P(k) on small scales.

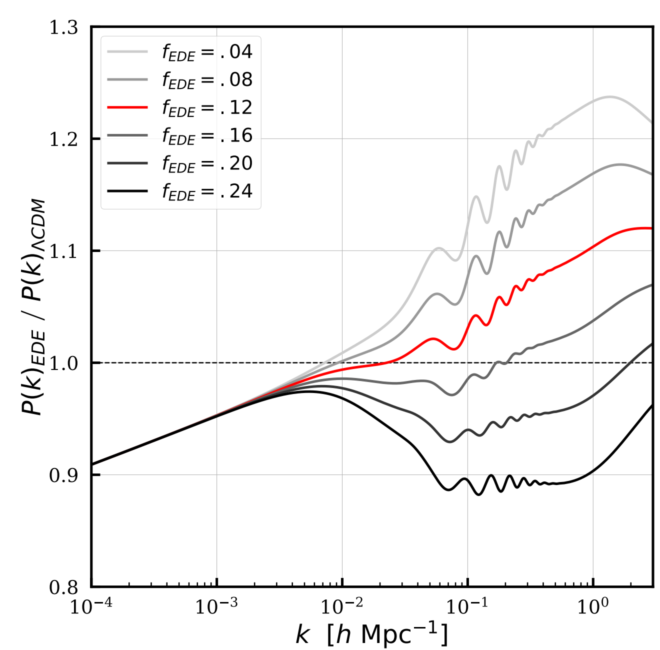


Impact is worse at ‘high’ redshift



10% change

The EDE itself acts to *suppress* modes inside the horizon before EDE decays



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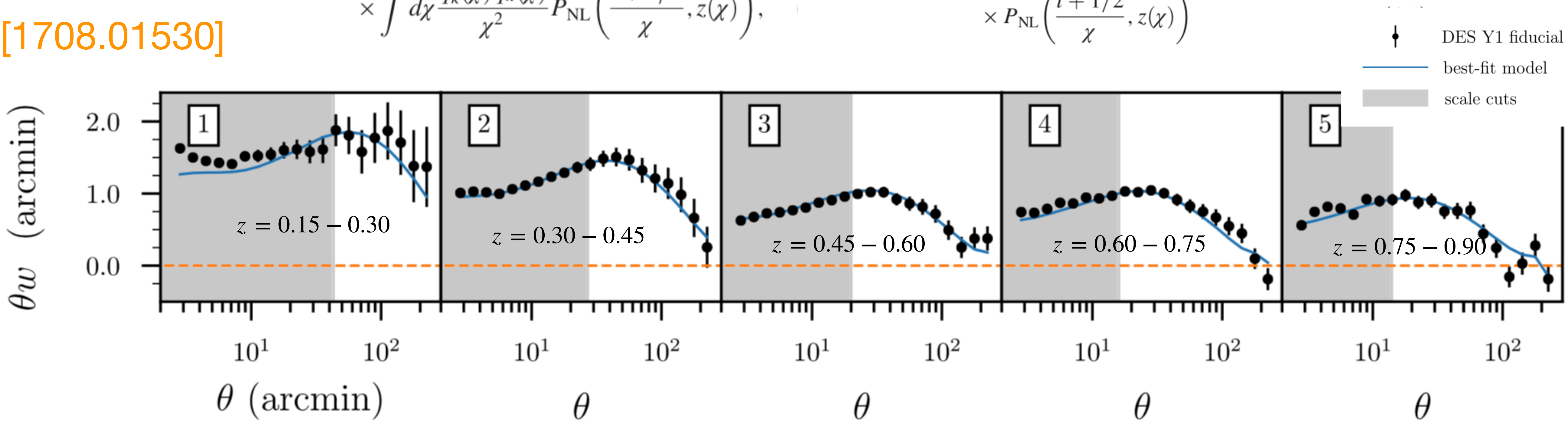
LSS Data
Case Study: The Dark Energy Survey

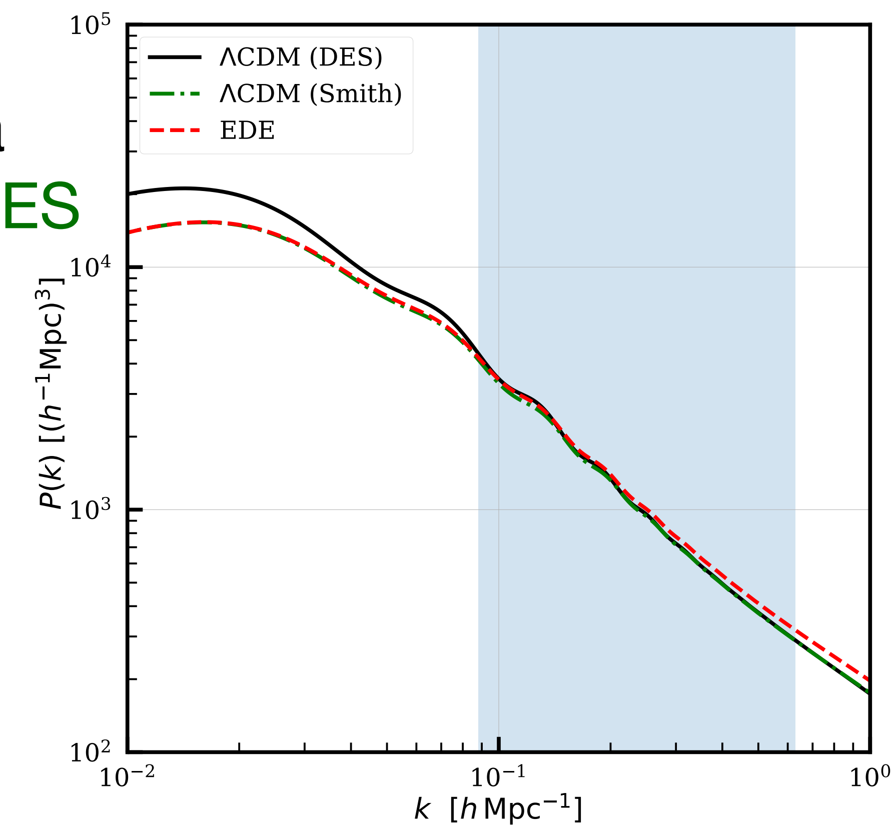
$$\xi^{ij}_{+/-}(\theta) = (1+m^i)(1+m^j)\int \frac{dll}{2\pi} J_{0/4}(l\theta) \times \int d\chi \frac{q^i_\kappa(\chi) q^j_\kappa(\chi)}{\chi^2} P_{\rm NL}\left(\frac{l+1/2}{\chi}, z(\chi)\right),$$

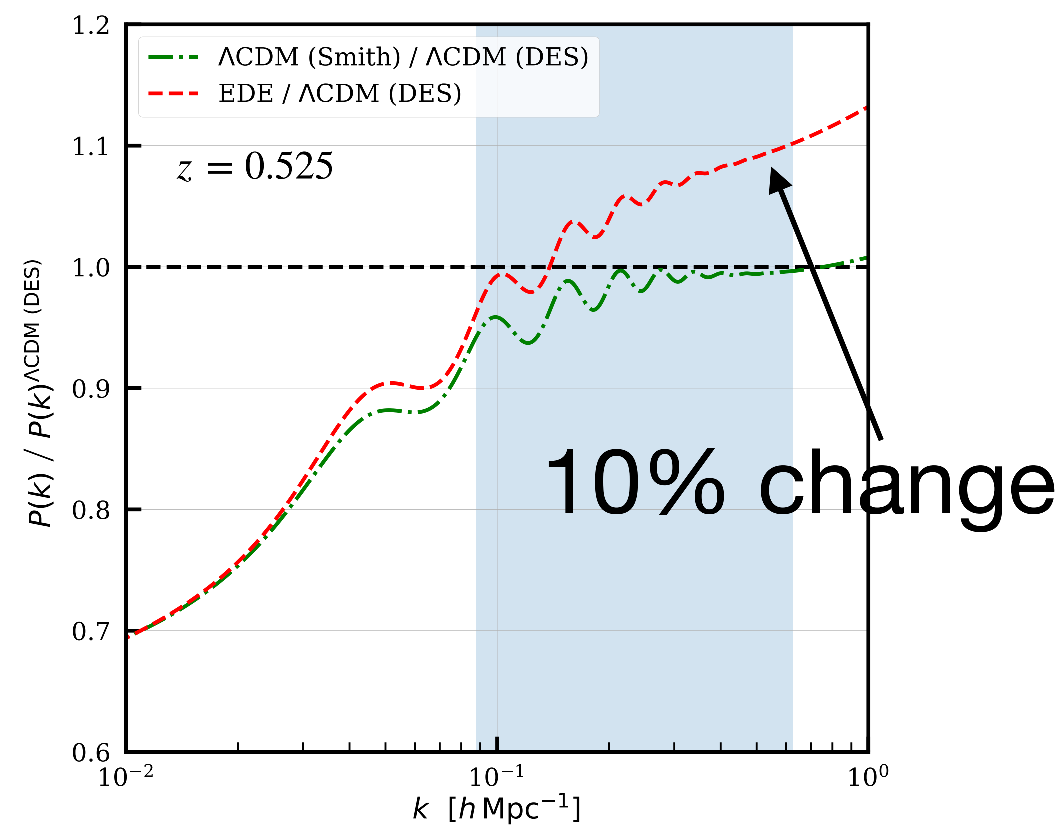
$$w^i(\theta) = \int \frac{dll}{2\pi} J_0(l\theta) \int d\chi \frac{q^i_{\delta_g}\left(\frac{l+1/2}{\chi},\chi\right) q^j_{\delta_g}\left(\frac{l+1/2}{\chi},\chi\right)}{\chi^2} \times P_{\rm NL}\left(\frac{l+1/2}{\chi}, z(\chi)\right)$$

[1708.01530]



Compare P(k):
Inferred from DES data
LCDM fit to CMB, SH0ES
EDE fit CMB, SH0ES





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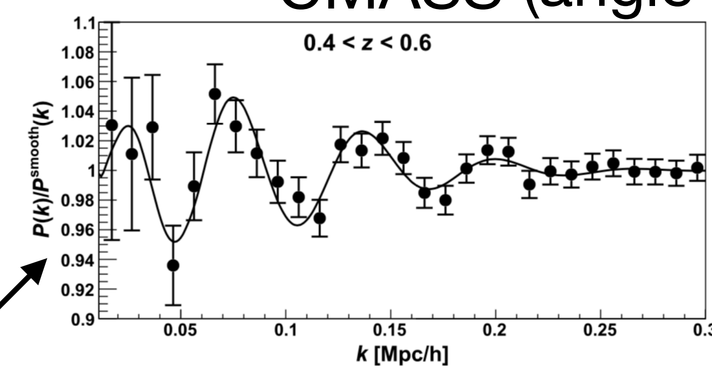
Let's get to work. Data Sets:

CMB Temperature and Polarization: Planck 2018 TT, TE, EE

Large Scale Structure:

CMASS (angle averaged)



- Planck 2018 lensing
- BAO:
  - 6dF galaxy survey
  - SDSS DR7 main galaxy sample
  - SDSS DR12 BOSS LOWZ+CMASS
- Redshift Space Distortions BOSS DR12 → $\delta_{\mathrm{g,RSD}}(\boldsymbol{k}) = \left[b_1 + f\mu_k^2\right]\delta_{\mathrm{m}}(\boldsymbol{k})$
- Dark Energy Survey 3x2pt
- S8 from HSC, KiDS $(S_8 \equiv \sigma_8\sqrt{\Omega_m/0.3})$

Supernovae: Pantheon: relative luminosity of 1048 SNeIa in 0.01 < z < 2.3

SH0ES 2019: $H_0 = 74.03 \pm 1.42\,\mathrm{km/s/Mpc}$

Chains available on Flatiron Servers:

https://users.flatironinstitute.org/~chill/H20_data/

Results: Tight Constraint, No Concordance

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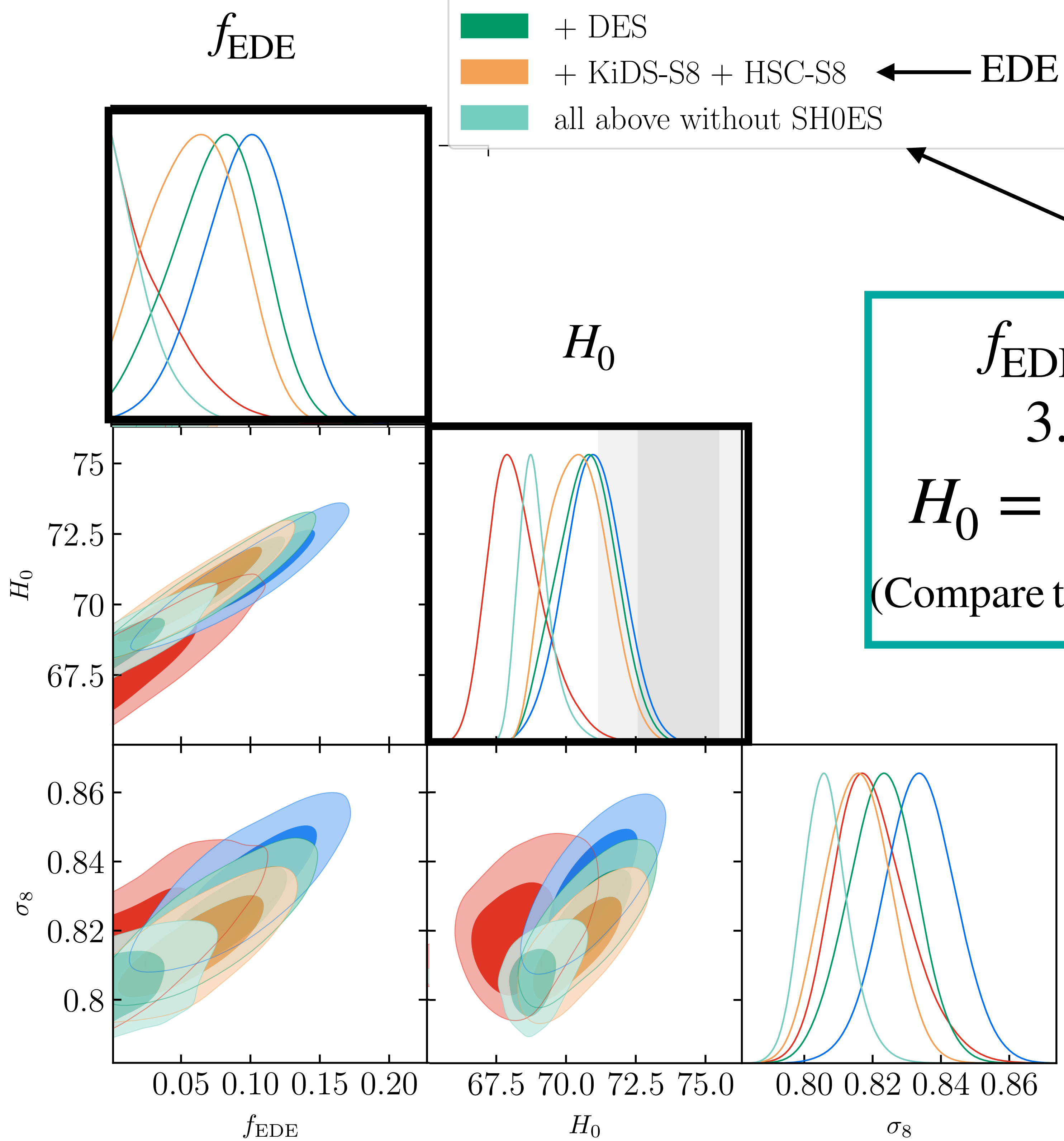

Peak "proof" of EDE:
H_0 tension $= 1.7\sigma$
$f_{\rm EDE} \sim 10\,\% > 0$ at 3.1σ

$f_{\rm EDE} < 0.060$ (95 % CL)
3.3σ tension SH0ES
$H_0 = 68.92^{+0.57}_{-0.59}$ km/s/Mpc
(Compare to $H_0^{\Lambda{\rm CDM}} = 68.33 \pm 0.36$ km/s/Mpc)

Chains available on Flatiron Servers:
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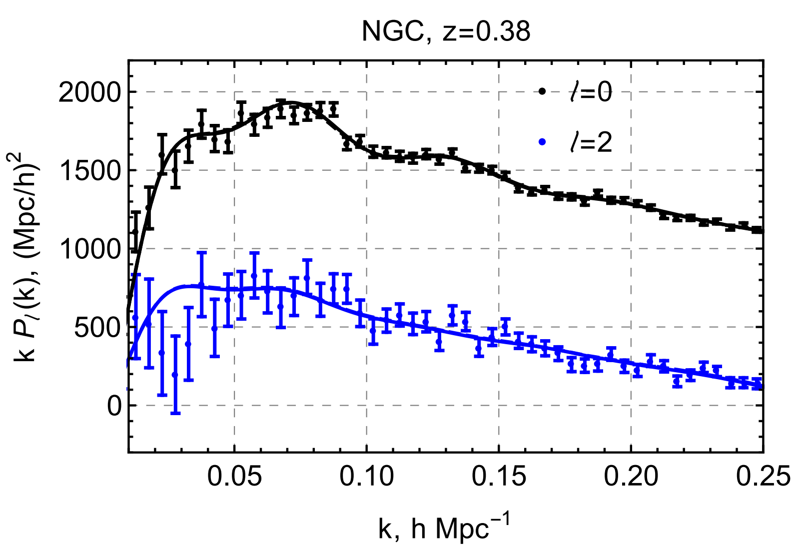
A more careful analysis of LSS?

Modeling of non-non-linear P(k):
Use of "Fitting Formulas" for Non-Linear Matter Power Spectrum?
e.g. HALOFIT, HMCODE

Calibrated to N-body simulations of LCDM!

Cosmology-Dependence of BOSS Likelihood?

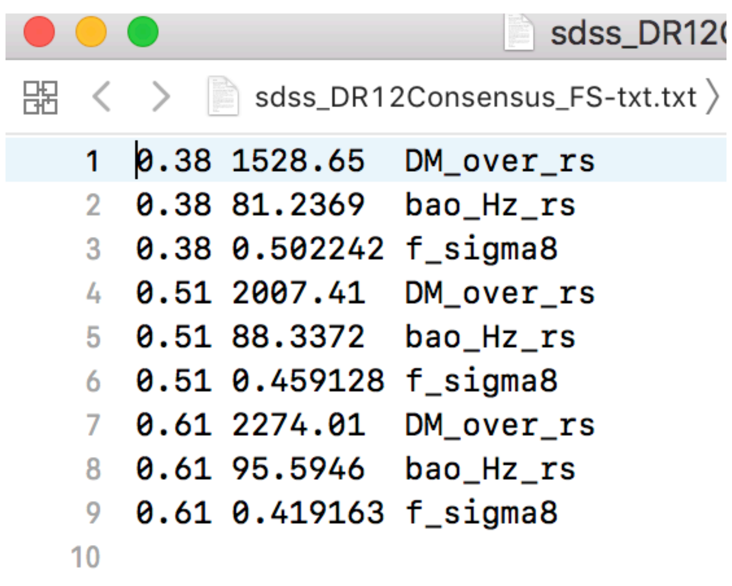
3D P(k) Data



Fiducial LCDM
Cosmology
[Planck priors]

Likelihood

$f\sigma_8$


sdss_DR12Consensus_FS-txt.txt

```
1  0.38 1528.65   DM_over_rs
2  0.38 81.2369   bao_Hz_rs
3  0.38 0.502242  f_sigma8
4  0.51 2007.41   DM_over_rs
5  0.51 88.3372   bao_Hz_rs
6  0.51 0.459128  f_sigma8
7  0.61 2274.01   DM_over_rs
8  0.61 95.5946   bao_Hz_rs
9  0.61 0.419163  f_sigma8
10
```

+ covariances, etc.

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The Effective Field Theory of Large Scale Structure "EFT of LSS"

[Carrasco, Hertzberg, Senatore, 1206.2926.]
[Baumann, Nicolis, Senatore, Zaldarriaga, 1004.2488]

$$\langle [\tau^{ij}]_\Lambda \rangle_{\delta_l} = p_b \delta^{ij} + \rho_b \left[c_s^2 \delta_l \delta^{ij} - \frac{c_{bv}^2}{Ha} \delta^{ij} \partial_k v_l^k - \frac{3}{4} \frac{c_{sv}^2}{Ha} \left(\partial^j v_l^i + \partial^i v_l^j - \frac{2}{3} \delta^{ij} \partial_k v_l^k \right) \right] + \ldots$$

$$\eta = 3\rho_b c_{sv}^2/(4H), \; \zeta = \rho_b c_{bv}^2/H$$

Lots of Important Developments:

Biased Tracers in Redshift Space in the EFT of Large-Scale Structure

Ashley Perko, Leonardo Senatore, Elise Jennings, Risa H. Wechsler

The Effective Field Theory of Large-Scale Structure (EFTofLSS) provides a novel formalism that is able to accurately predict the clustering of large-scale structure (LSS) in the mildly non-linear regime. Here we provide the first computation of the power spectrum of biased tracers in redshift space at one loop order, and we make the associated code publicly available. We compare the multipoles $\ell = 0, 2$ of the redshift-space halo power spectrum, together with the real-space matter and halo power

$$\delta_g = b_1 \delta + \frac{b_2}{2} \delta^2 + b_{\mathcal{G}_2} \mathcal{G}_2 \, ,$$

$$P_{g,\ell}(k) \equiv \frac{2\ell+1}{2} \int_{-1}^{1} d\mu \, P_g(k,\mu) \mathcal{P}_\ell(\mu) \, ,$$

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

Nuisance Parameters, marginalized over in Bayesian analysis

Recent Successes:

1. CMB-independent measurement of DM density, H0
2. Neutrino Masses

[Ivanov, Simonovic. Zaldarriaga, 1909.05277]
[D'Amico+1909.05271]

Results: Planck + BOSS Data

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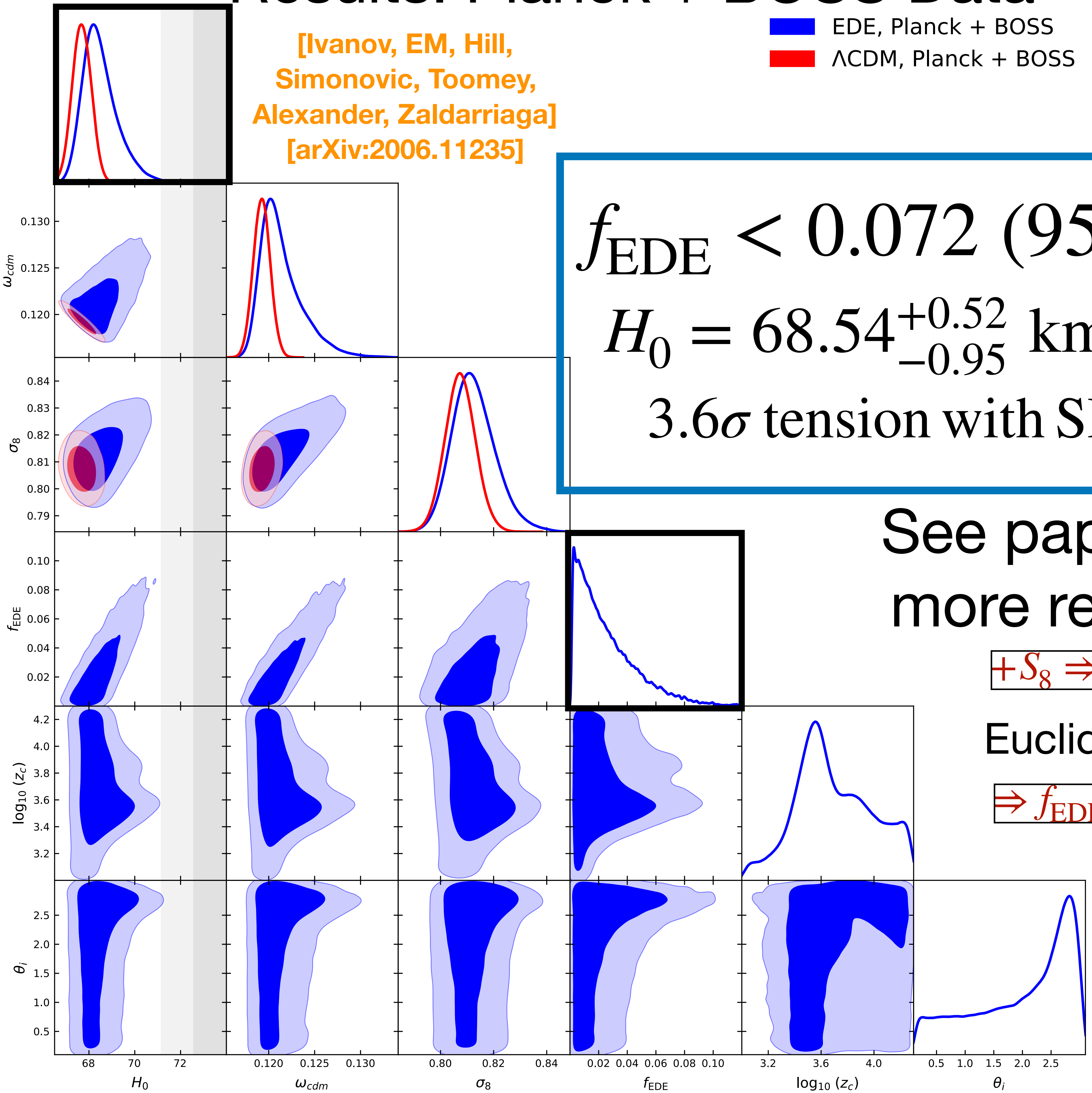
[Ivanov, EM, Hill, Simonovic, Toomey, Alexander, Zaldarriaga] [arXiv:2006.11235]



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

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

3.6σ tension with SH0ES

See paper for more results:

$+S_8 \Rightarrow f_{\rm EDE} < 0.053$

Euclid forecast:

$\Rightarrow f_{\rm EDE} < 0.012$

See also D'Amico+ [arXiv:2006.12420]

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Where to go from here?

Ways forward for the Hubble tension:

- Early+Late Hybrid Resolutions
- Interacting Dark Sectors

Apply New Technology to **Ultralight Axion Dark Matter**
(e.g. Constraint on fraction of DM)

LSS Constraints on BSM Physics

Thanks!

Extra Slides

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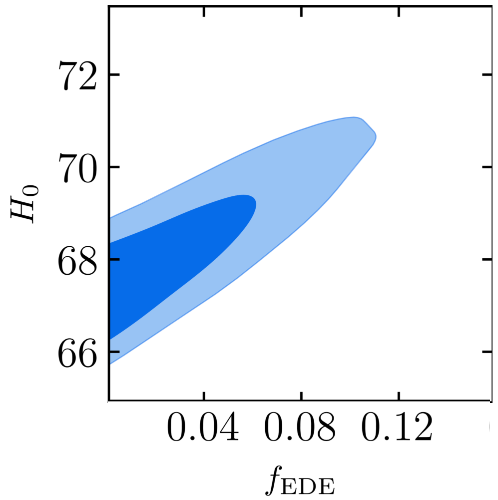
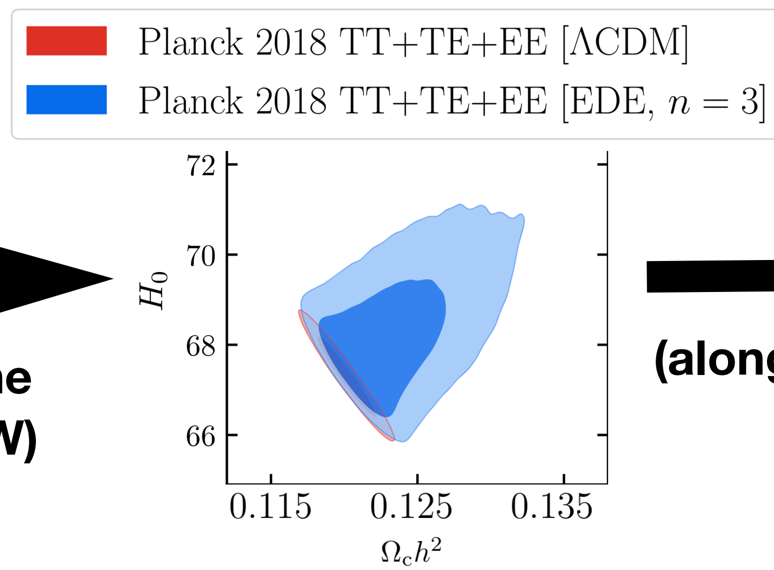
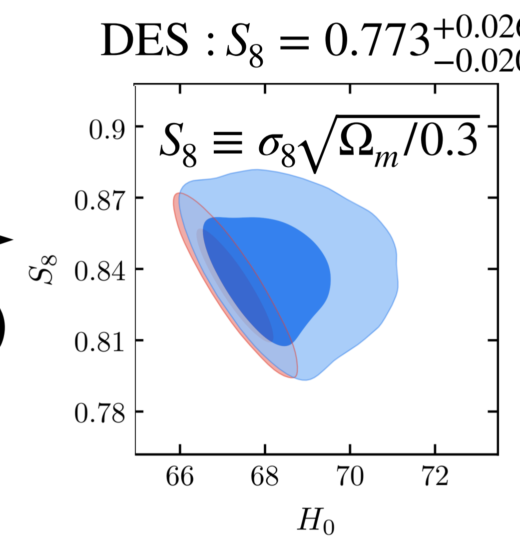
Summary



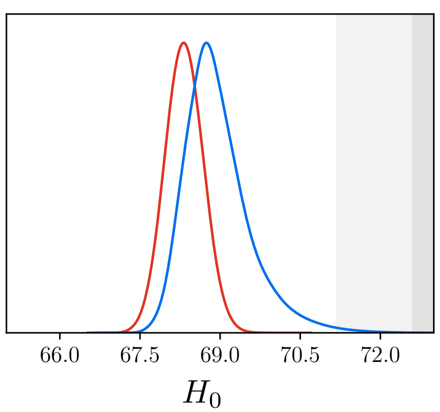
(undo the Early ISW)



(along with n_s)



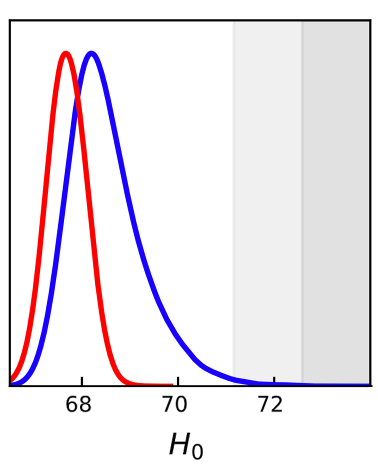
What say ye, Large Scale Structure?



P18 + CMBLens + BAO + SNIa + RSD + DES + KiDS-S8 + HSC-S8 [ΛCDM]
P18 + CMBLens + BAO + SNIa + RSD + DES + KiDS-S8 + HSC-S8 [EDE, $n = 3$]

$$H_0 = 68.96^{+0.55}_{-0.58} \text{ km/s/Mpc}$$
3.3σ tension with SH0ES

[Hill, EM, Toomey, Alexander]
[arXiv:2003.07355]



EDE, Planck + BOSS (EFT)
ΛCDM, Planck + BOSS (EFT)

$$H_0 = 68.54^{+0.52}_{-0.95} \text{ km/s/Mpc}$$
3.6σ tension with SH0ES

[Ivanov, EM, Hill, Simonovic, Toomey, Alexander, Zaldarriaga]
[arXiv:2006.11235]

See also D'Amico+
[arXiv:2006.12420]

LSS breaks the degeneracies of the EDE model

Chains available on Flatiron Servers:
https://users.flatironinstitute.org/~chill/H20_data/

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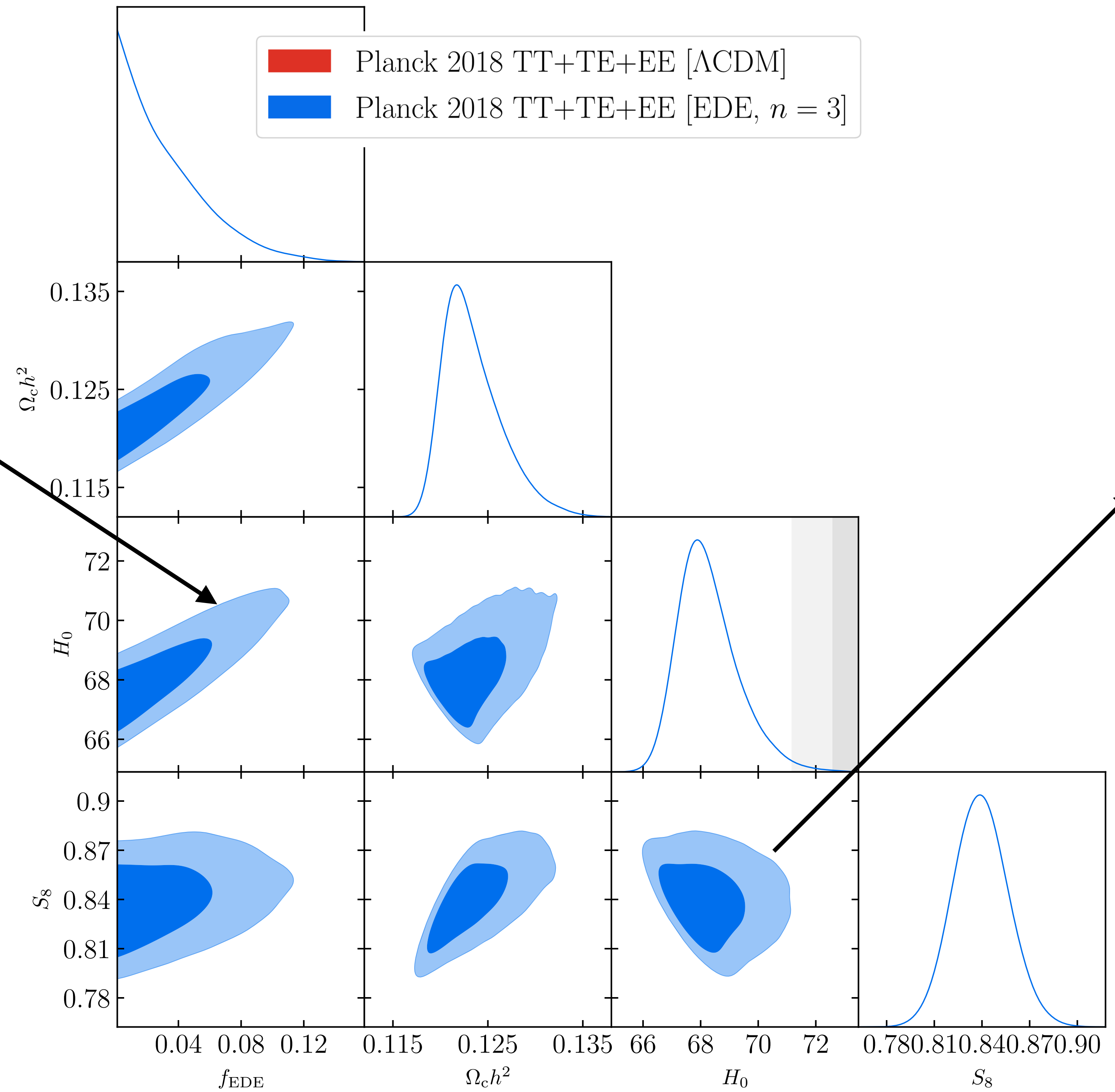
(The First Ever) EDE Fit To CMB:

New Degeneracies

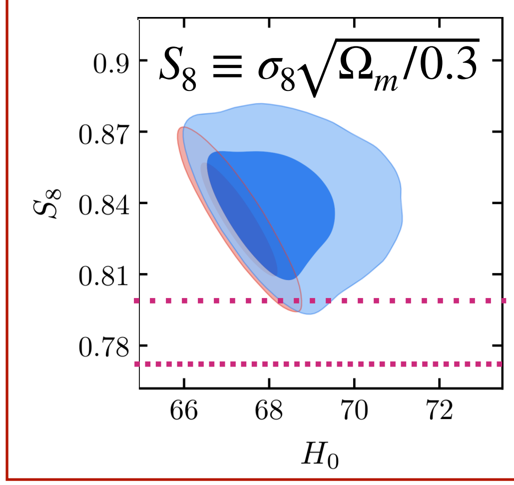
Hope for a resolution!

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

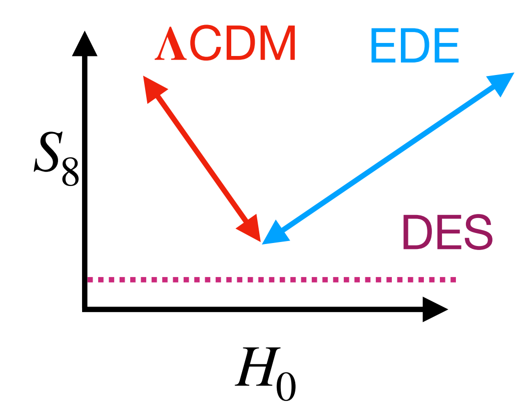


$S_8 = 0.773^{+0.026}_{-0.020}$

But note!



Artists Rendering:



Results: Tight Constraint, No Concordance

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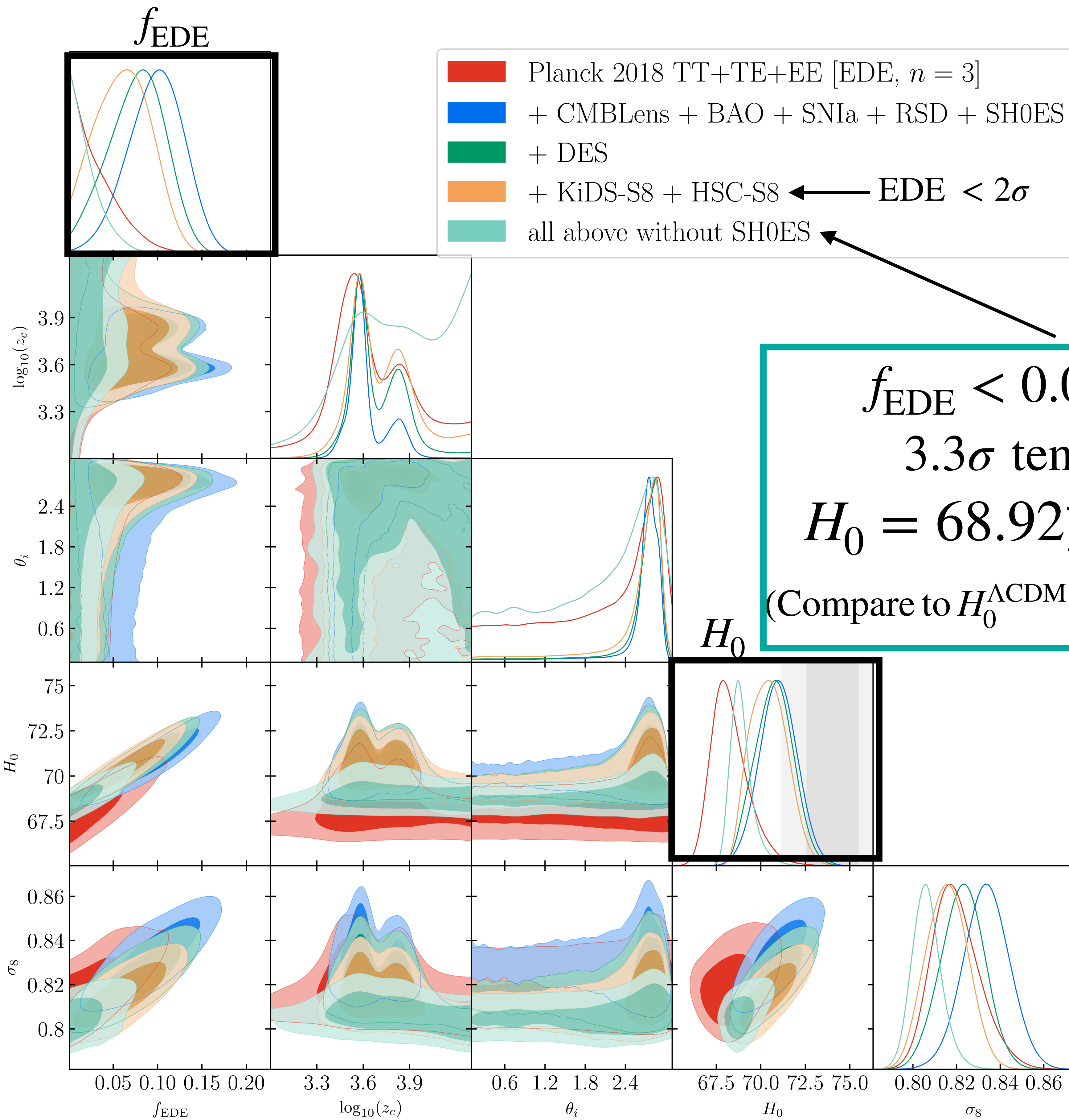

Peak “proof” of EDE:
H_0 tension $= 1.7\sigma$
$f_{\rm EDE} \sim 10\,\% > 0$ at 3.1σ

$$f_{\rm EDE} < 0.060 \ (95\,\%\ {\rm CL})$$

3.3σ tension SH0ES

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

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

Chains available on Flatiron Servers: https://users.flatironinstitute.org/~chill/H20_data/

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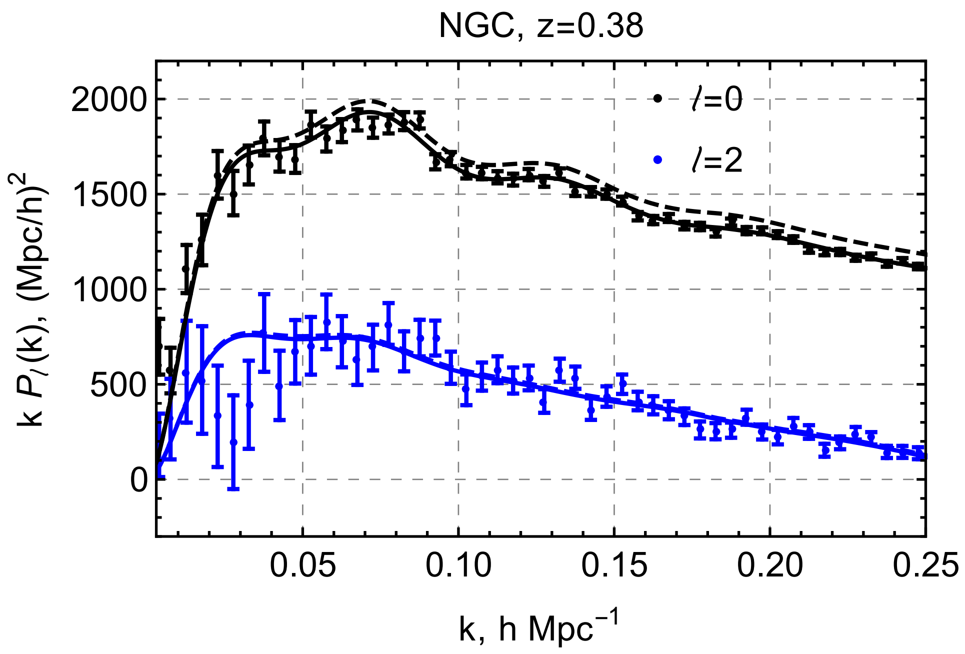
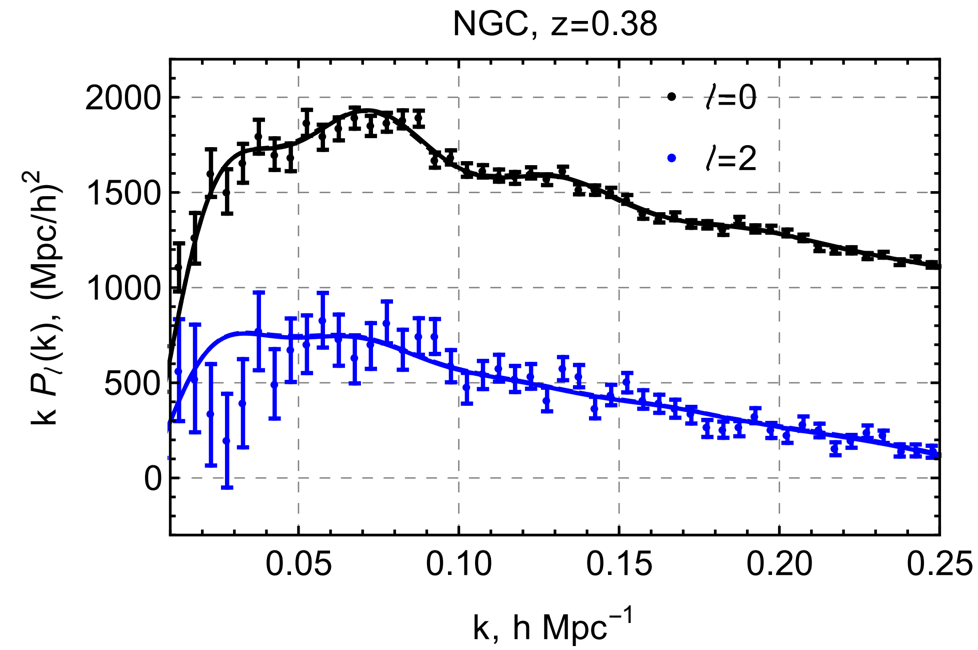
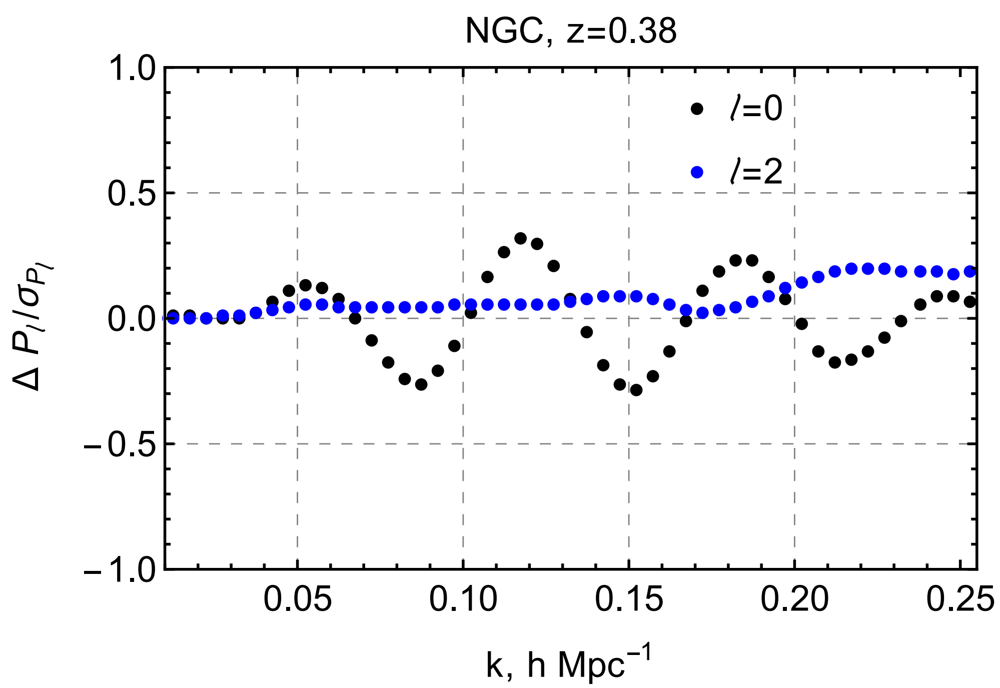
EDE Meets BOSS Data



Marginalize over EFT params



EDE vs LCDM:



Results 1: BOSS Data

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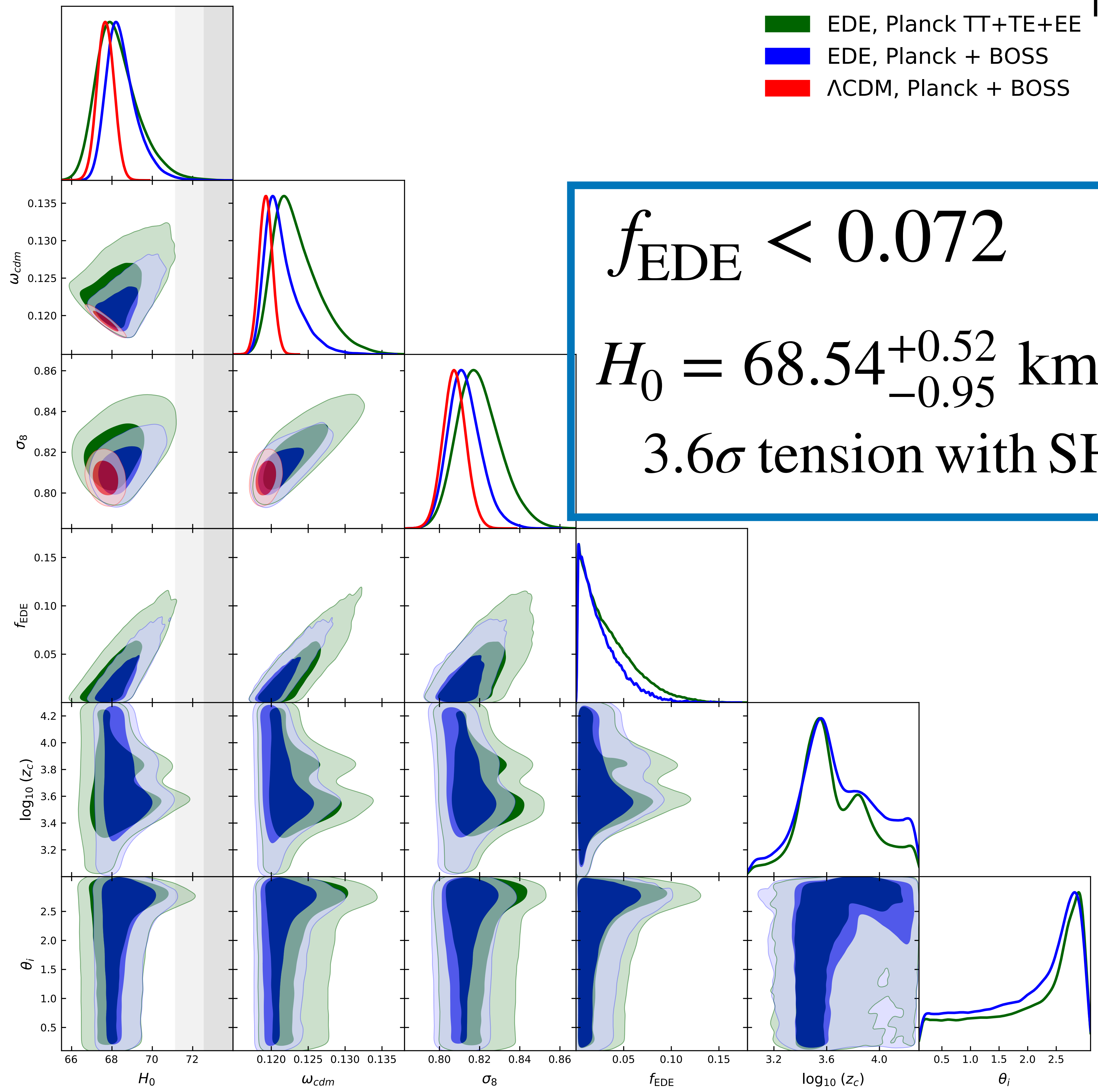

$$f_{\rm EDE} < 0.072$$

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

3.6σ tension with SH0ES

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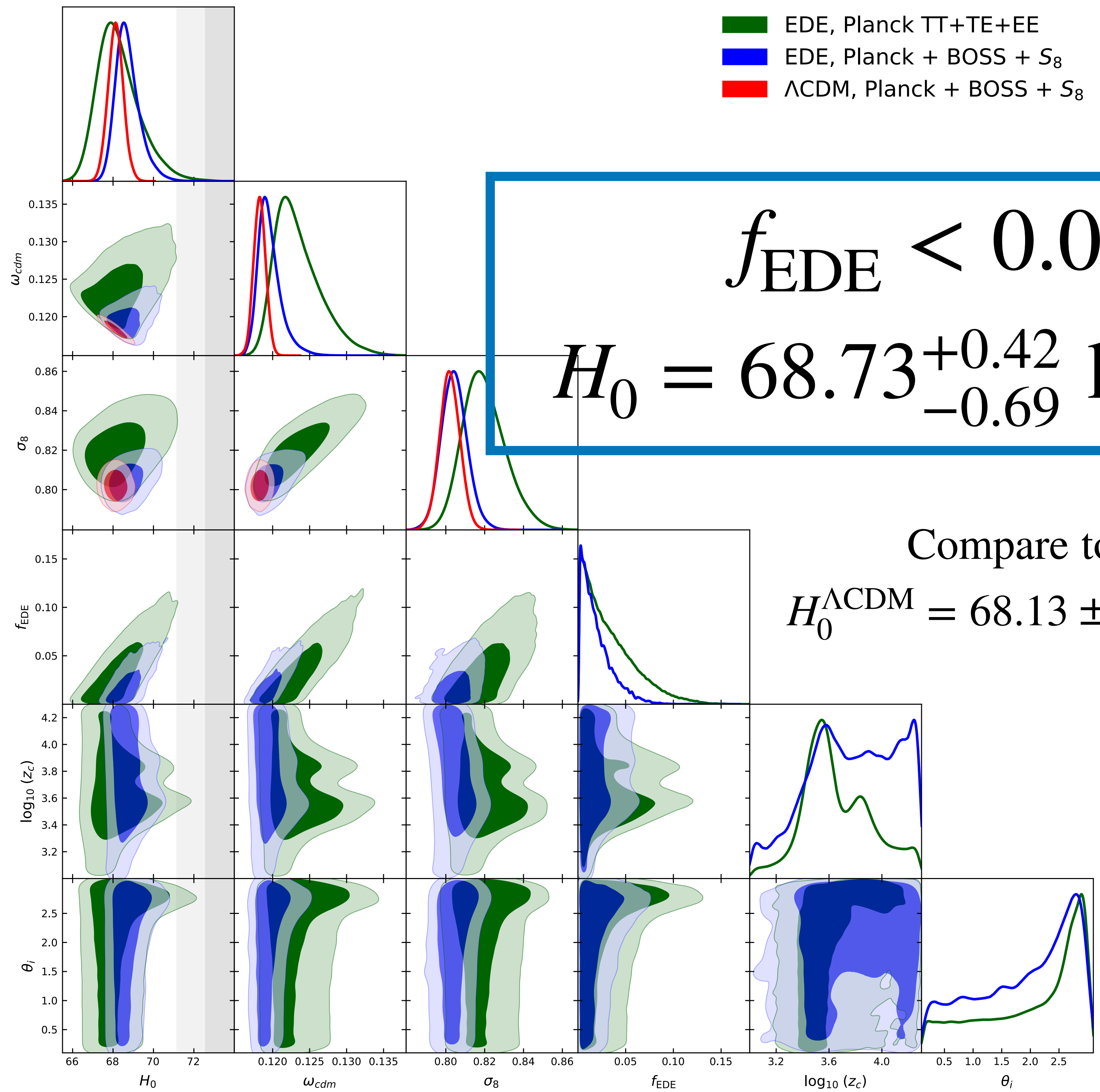
Results 2: BOSS Data + Prior on S8 from DES, HSC, KiDS



$$f_{\rm EDE} < 0.053$$

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

Compare to ΛCDM :

$$H_0^{\Lambda\rm CDM} = 68.13 \pm 0.38\ \rm km/s/Mpc$$

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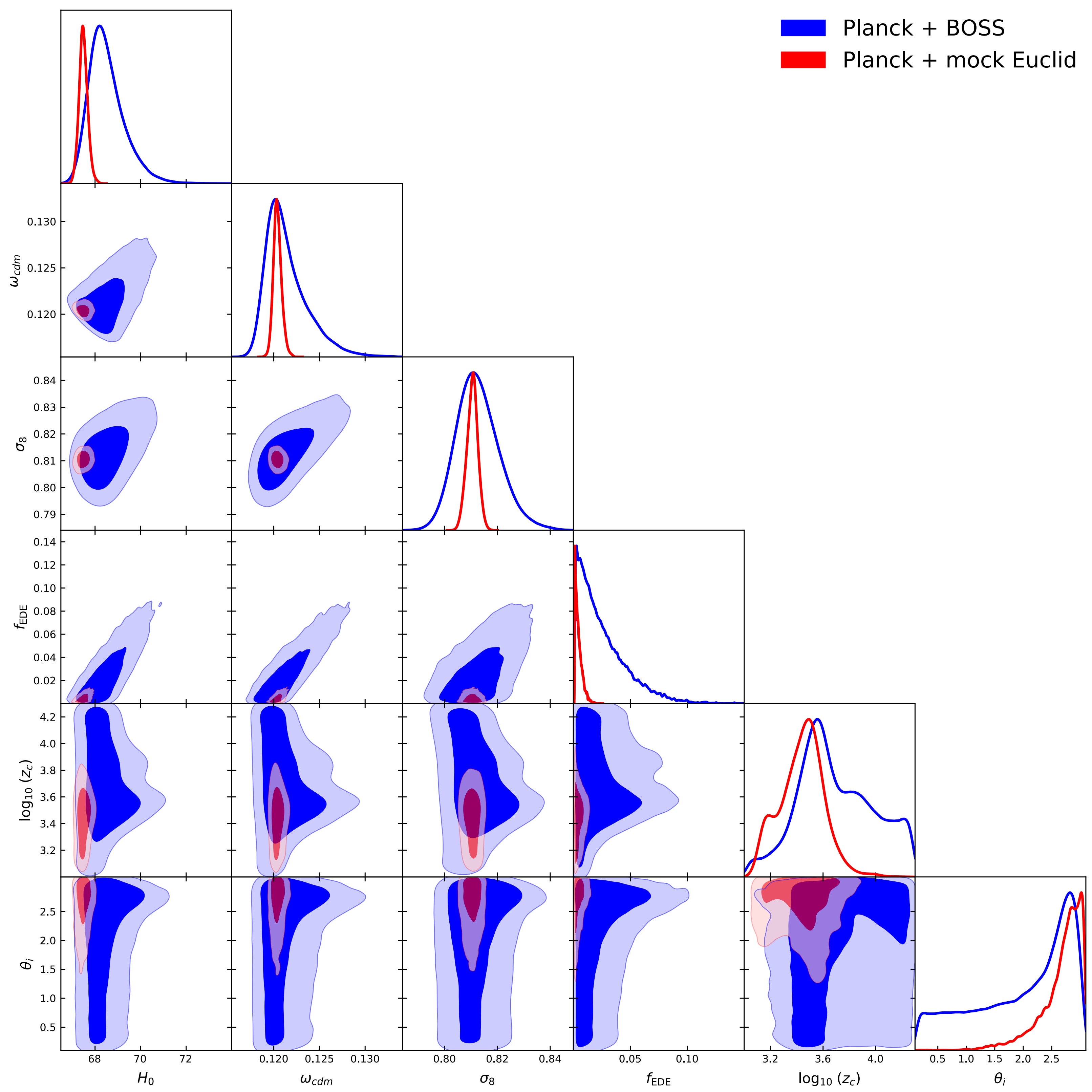
Euclid Forecast



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A note on Pantheon

Not calibrated! —> No absolute luminosity

Priors I fEDE, zc vs f, m

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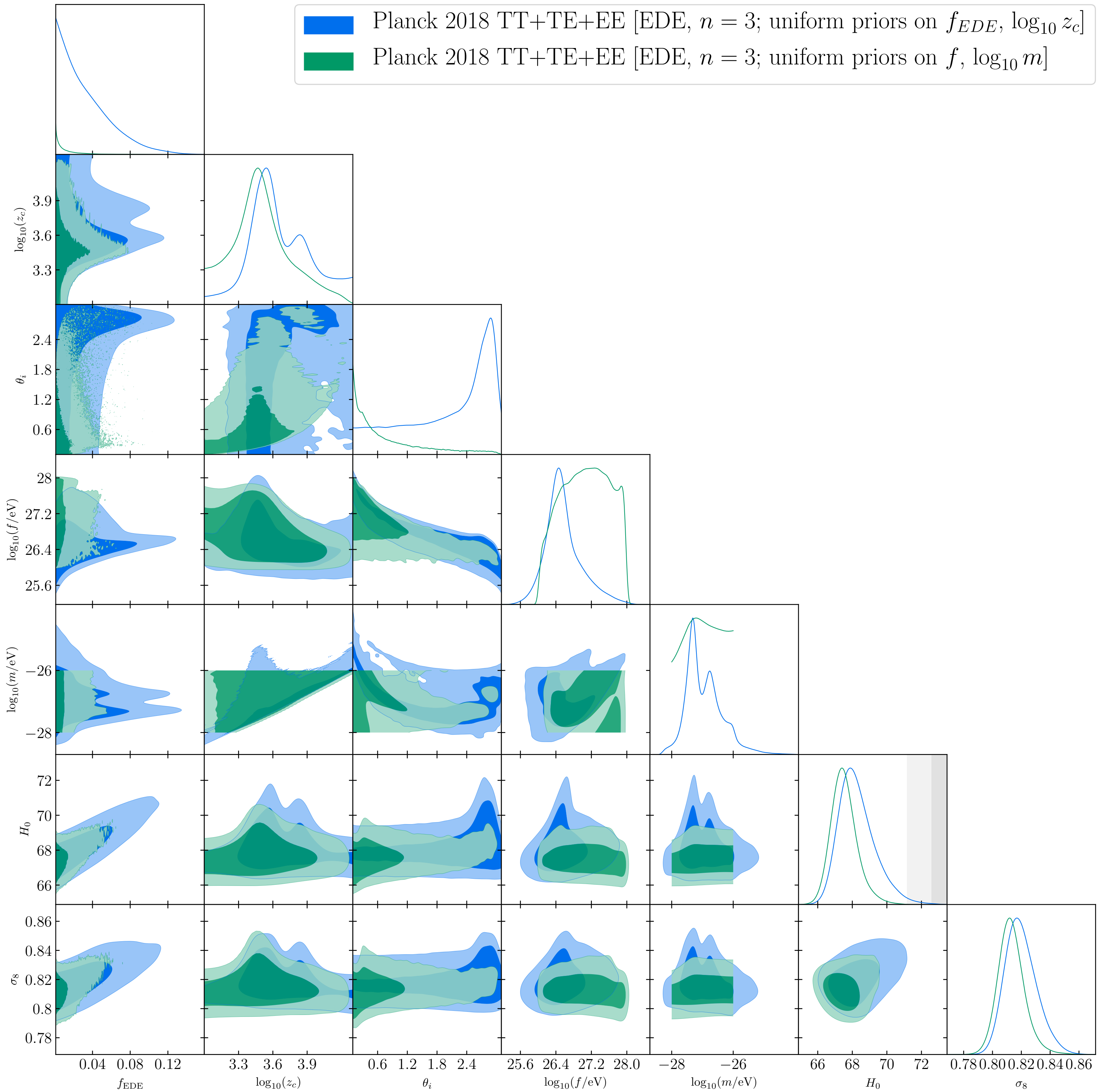

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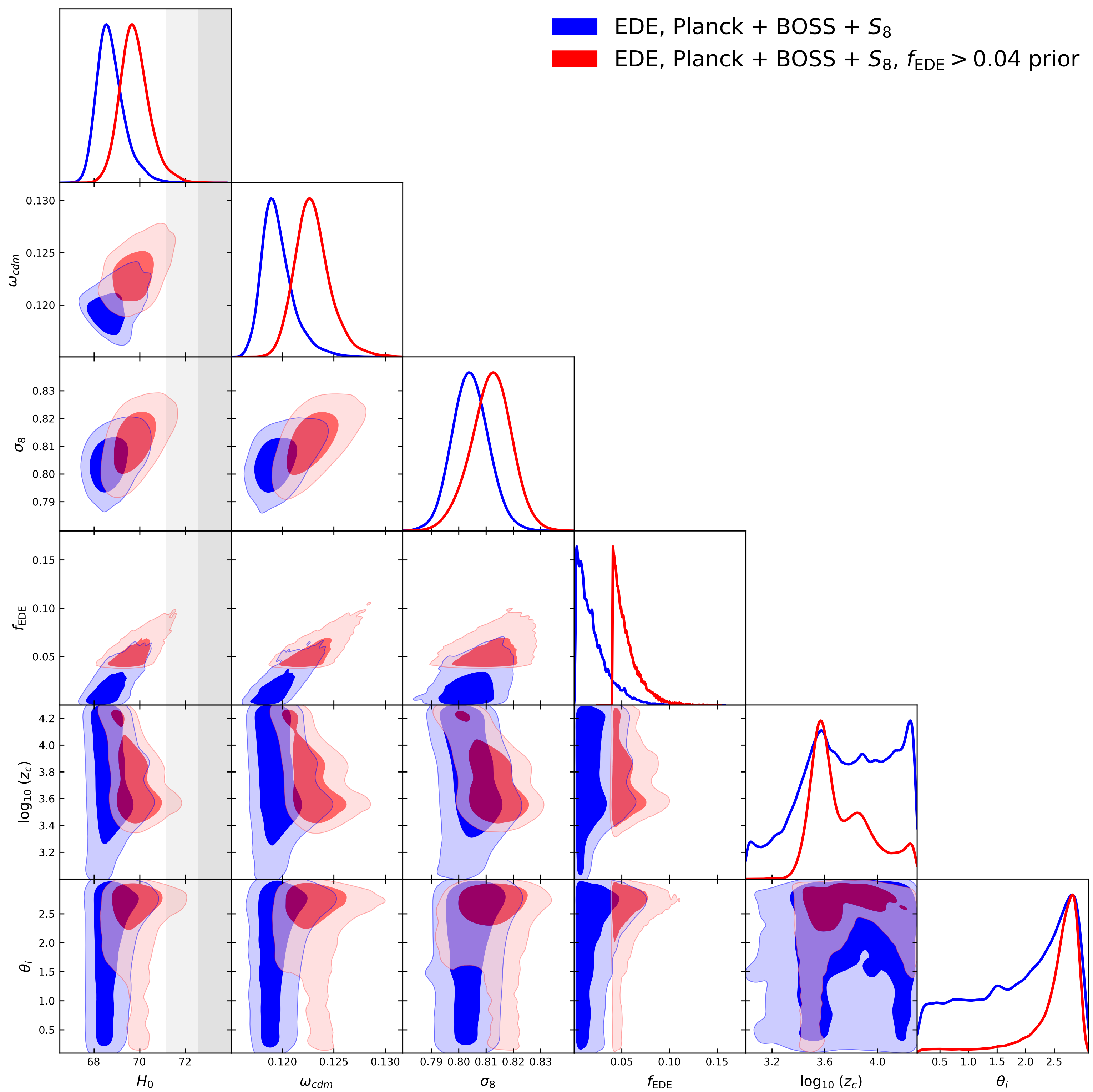
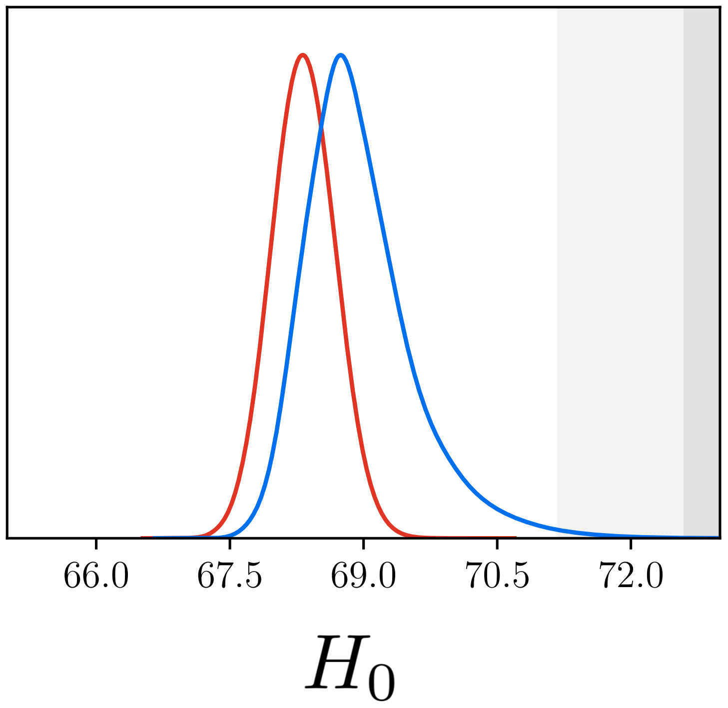
Priors II



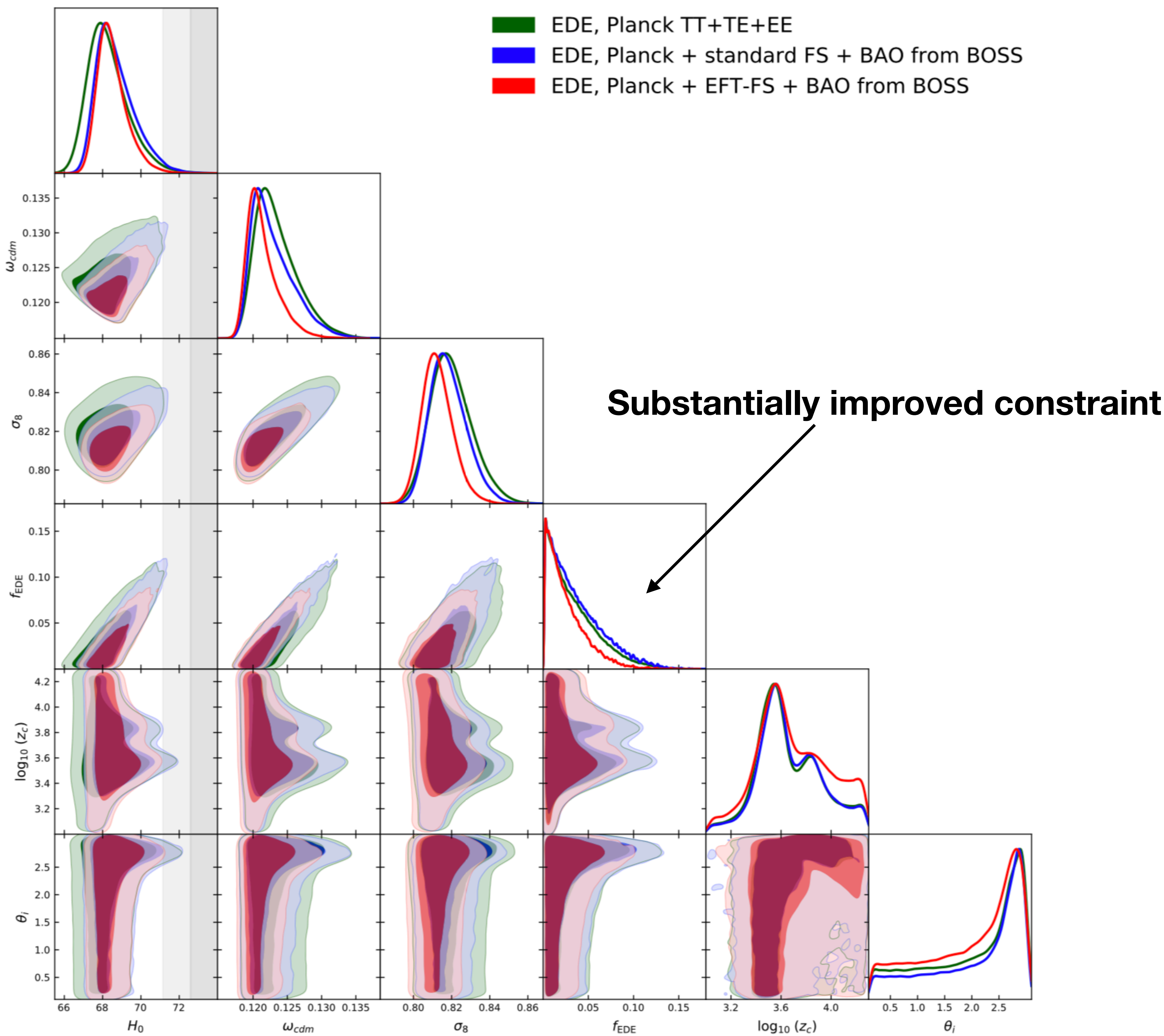
Priors III

E. Walking Barefoot: EDE without SH0ES

To complete our analysis of constraints on EDE from these data sets and data set combinations, we consider the cosmological constraints when the SH0ES measurement $H_0 = 74.03 \pm 1.42\,\mathrm{km/s/Mpc}$ [15] is excluded from the combined data set. We impose an additional inverse-Gaussian H_0 prior on the results of Sec. VI C to effectively remove the SH0ES likelihood, which itself is effectively a prior on H_0. The resulting posterior distributions correspond to the fit of the ΛCDM or EDE model to *Planck* 2018 primary CMB, *Planck* 2018 CMB lensing, BAO data from 6dF, SDSS DR7, and SDSS DR12, Pantheon SNIa, SDSS DR12 RSD, DES-Y1 3x2pt data, and the KiDS and HSC S_8 priors. Note that the original MCMC sampling for these constraints was performed with the SH0ES likelihood included, which obviates the concerns related to parameter-space volume effects expressed in, e.g., [26]. For a complementary discussion of this issue, see Appendix B of [91].



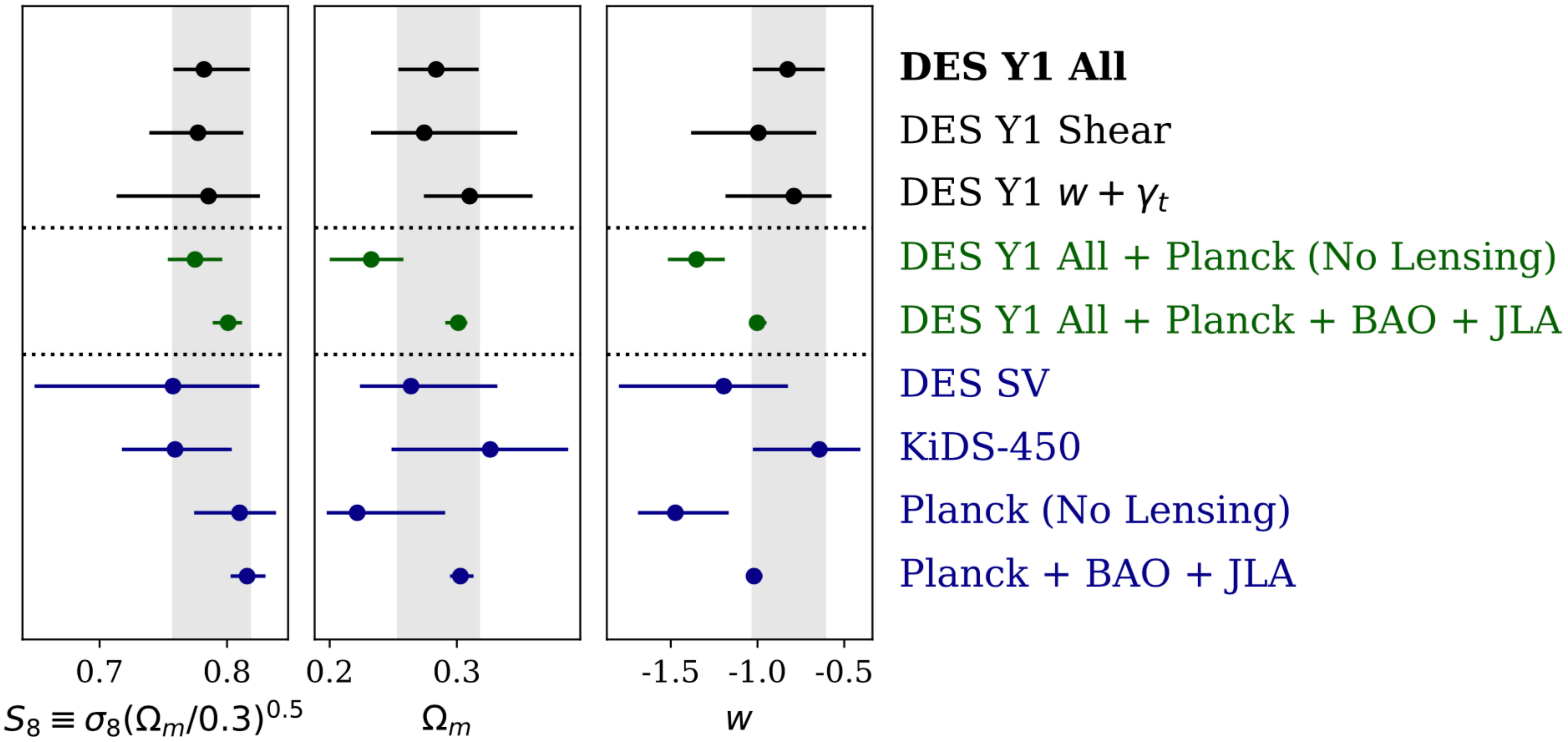
3.3σ tension with SH0ES



EDE, Planck TT+TE+EE
EDE, Planck + standard FS + BAO from BOSS
EDE, Planck + EFT-FS + BAO from BOSS
Substantially improved constraint
ω_{cdm}
σ_8
$f_{\rm EDE}$
$\log_{10}(z_c)$
θ_i
H_0

BAO measurement of H0

DM weakly dependent on H0



DES Y1 All
DES Y1 Shear
DES Y1 $w + \gamma_t$
DES Y1 All + Planck (No Lensing)
DES Y1 All + Planck + BAO + JLA
DES SV
KiDS-450
Planck (No Lensing)
Planck + BAO + JLA
0.7
0.8
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$
0.2
0.3
Ω_m
-1.5
-1.0
-0.5
w