Exploring Cosmological Concordance with ACT DR4, Planck, and Beyond

Colin Hill

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Flatiron Institute - Center for Computational Astrophysics

Marcel Grossman Conference, July 2021

2105.03003 w/ L. Thiele, Y. Guan, A. Kosowsky, D. Spergel
2003.07355 w/ E. McDonough, M. Toomey, S. Alexander
2006.11235 w/ ↗ + M. Ivanov, M. Simonovic, M. Zaldarriaga

2007.07288+2007.07289 w/ ACT Collab.

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Outline

- H_0 from the Atacama Cosmology Telescope
- Baryon Clumping / Primordial Magnetic Field H_0 Tension Resolution: Constraints from ACT
- Searching for Early Dark Energy as an H_0 Tension Resolution: Planck + LSS Data
- Outlook: Advanced ACT and Simons Observatory

H_0 from the Atacama Cosmology Telescope

Aiola, …, JCH, et al. (2020)
Choi, …, JCH, et al. (2020)

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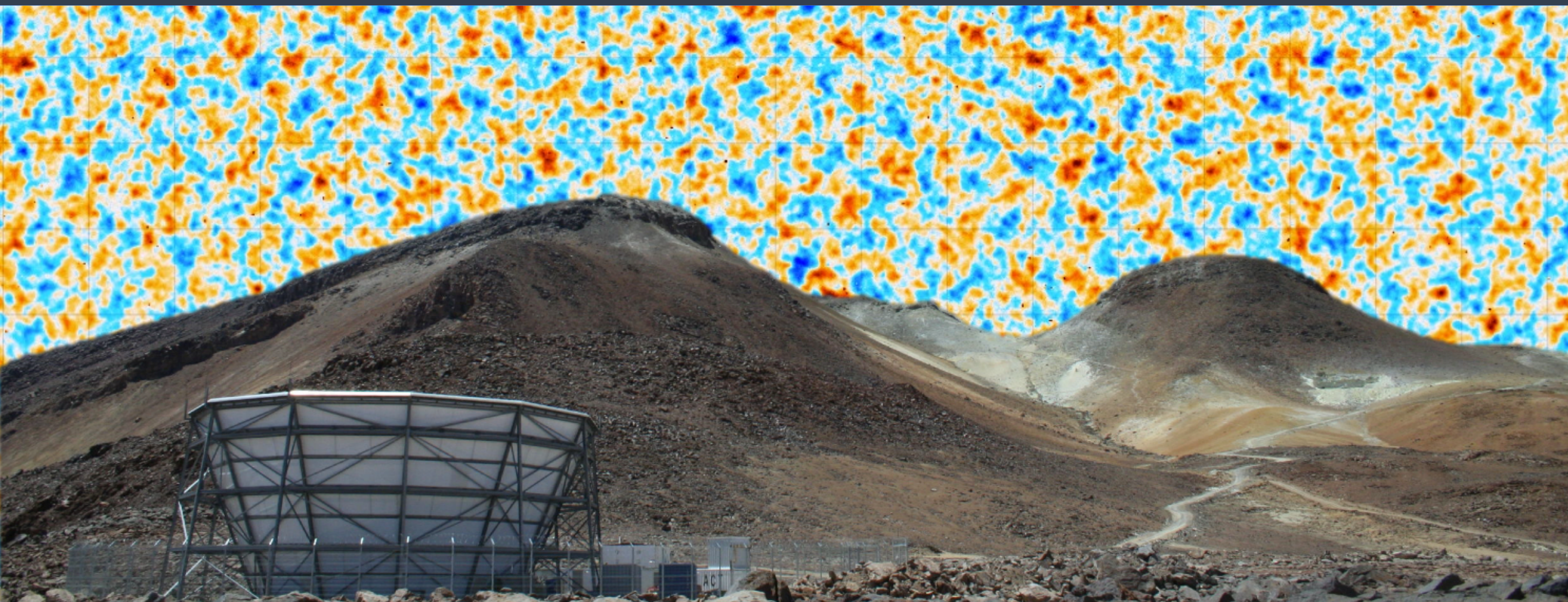
The Atacama Cosmology Telescope



wide-area (~half-sky) multifrequency CMB survey
observations: 2008-2021 (with some gaps for upgrades)

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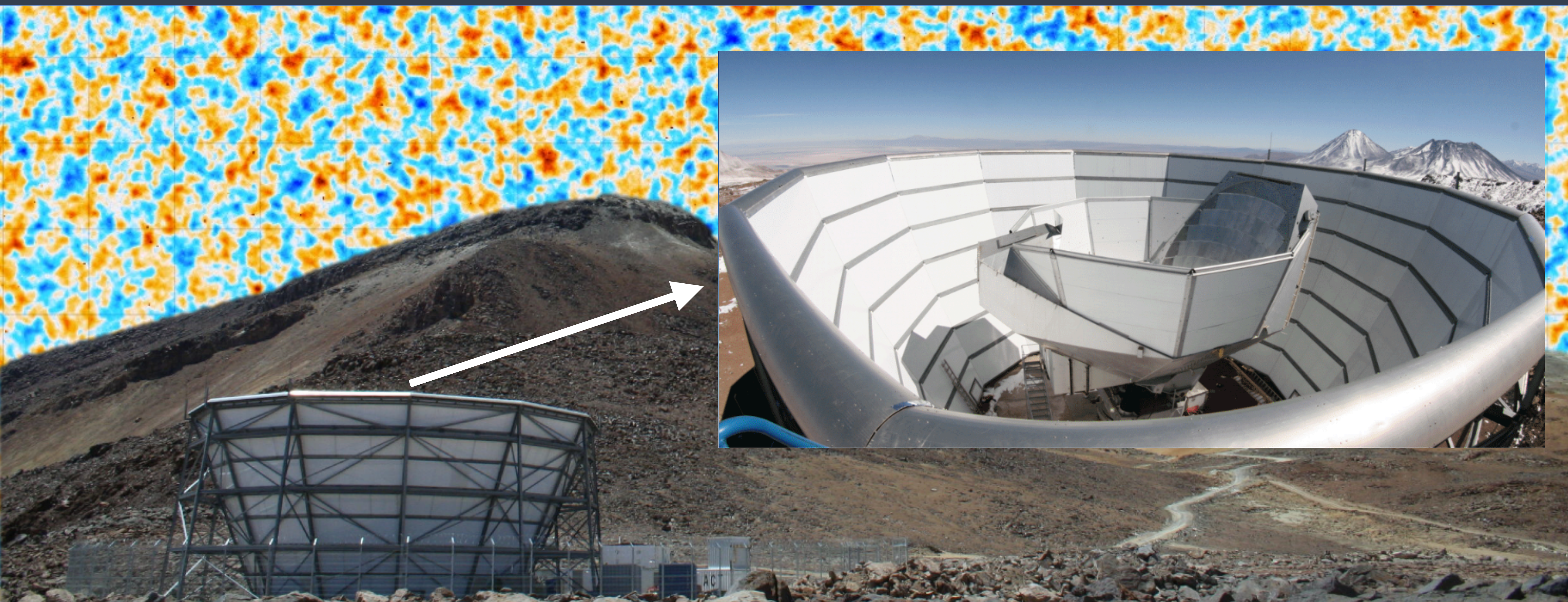
The Atacama Cosmology Telescope



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The Atacama Cosmology Telescope

wide-area (~half-sky) multifrequency CMB survey
observations: 2008-2021 (with some gaps for upgrades)

ACT Data Release 4

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this talk

- Aiola et al. 2020 – Maps, data products, and parameters

- Choi et al. 2020 – Power spectra, consistency tests, and baseline parameters

- Naess et al. 2020 – 17,000 deg^2 high-resolution maps from combined ACT+Planck data

- Madhavacheril, JCH, et al. 2020 – Component-separated maps: CMB and thermal Sunyaev-Zel'dovich effect (Compton-y)

- Darwish et al. 2020 – Reconstructed gravitational lensing maps and cross-correlation with BOSS galaxies

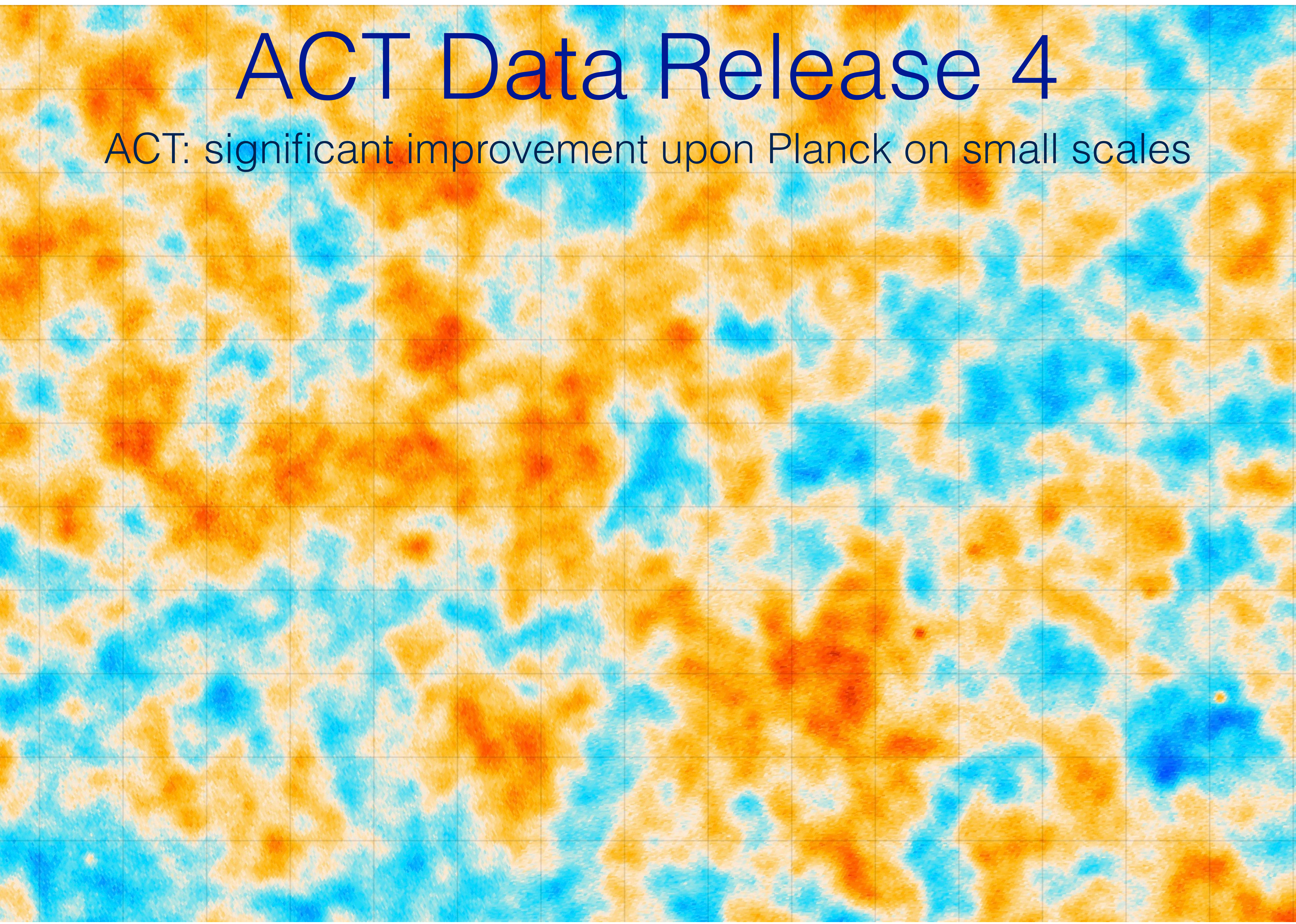
- and a lot more! (e.g., catalog of >4000 SZ-selected clusters)

https://act.princeton.edu/publications

https://lambda.gsfc.nasa.gov/product/act/

ACT Data Release 4

ACT: significant improvement upon Planck on small scales



Sky intensity at 2mm (150 GHz): Planck   30x22 deg^2 patch   Naess et al. (2020)

ACT Data Release 4

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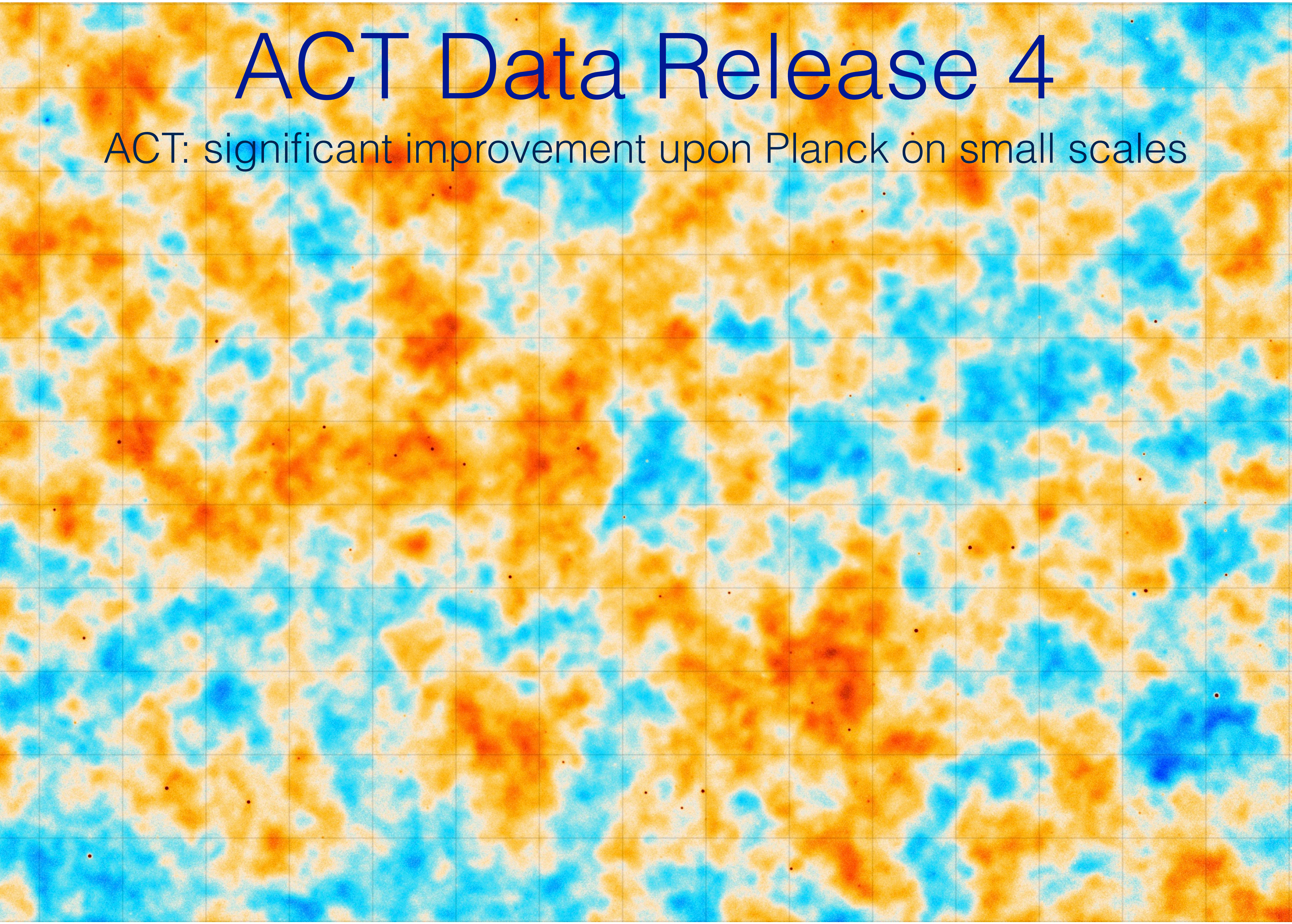

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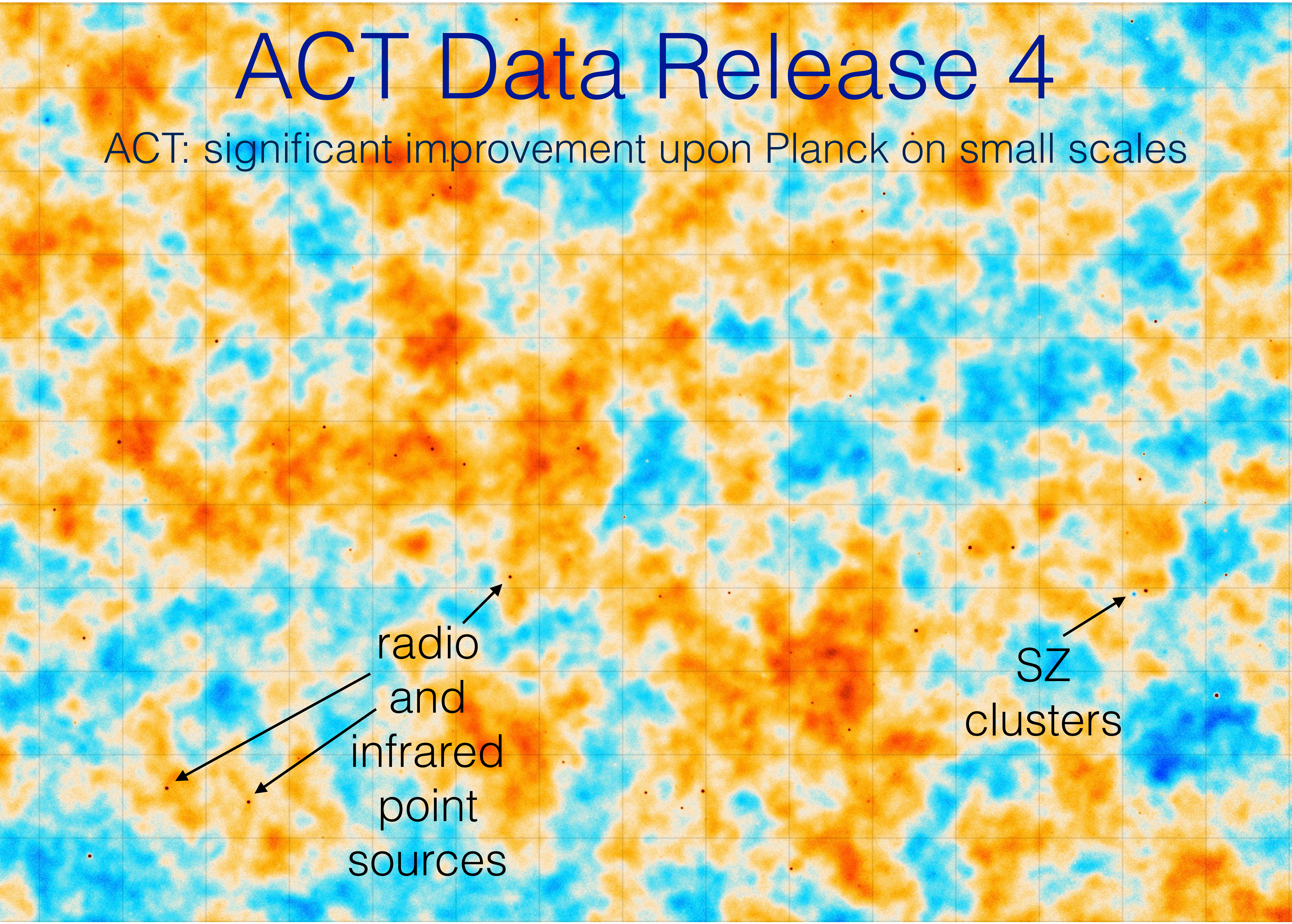

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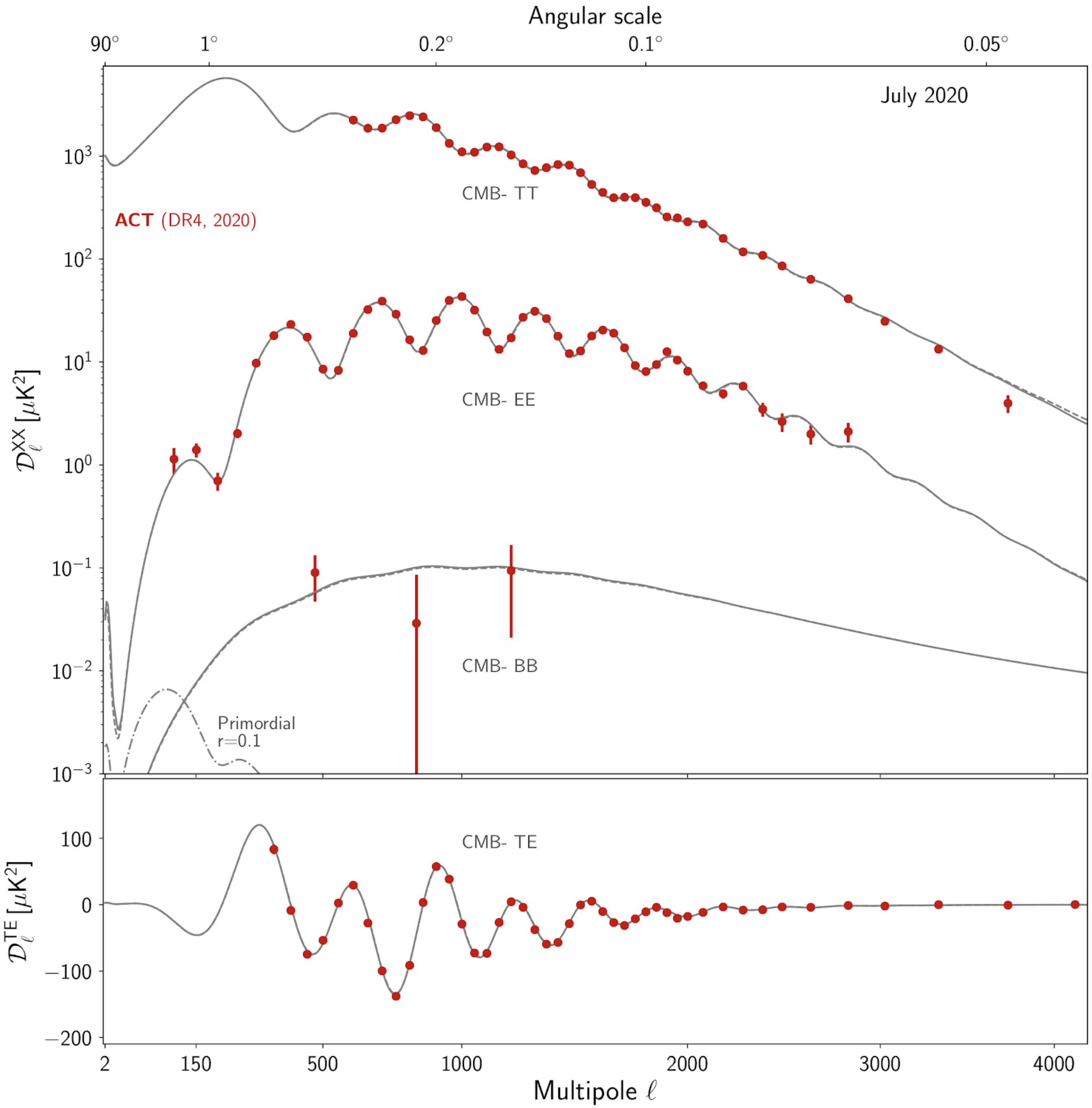
Foreground-marginalized CMB power spectra



Choi et al. (2020)

ACT Data Release 4

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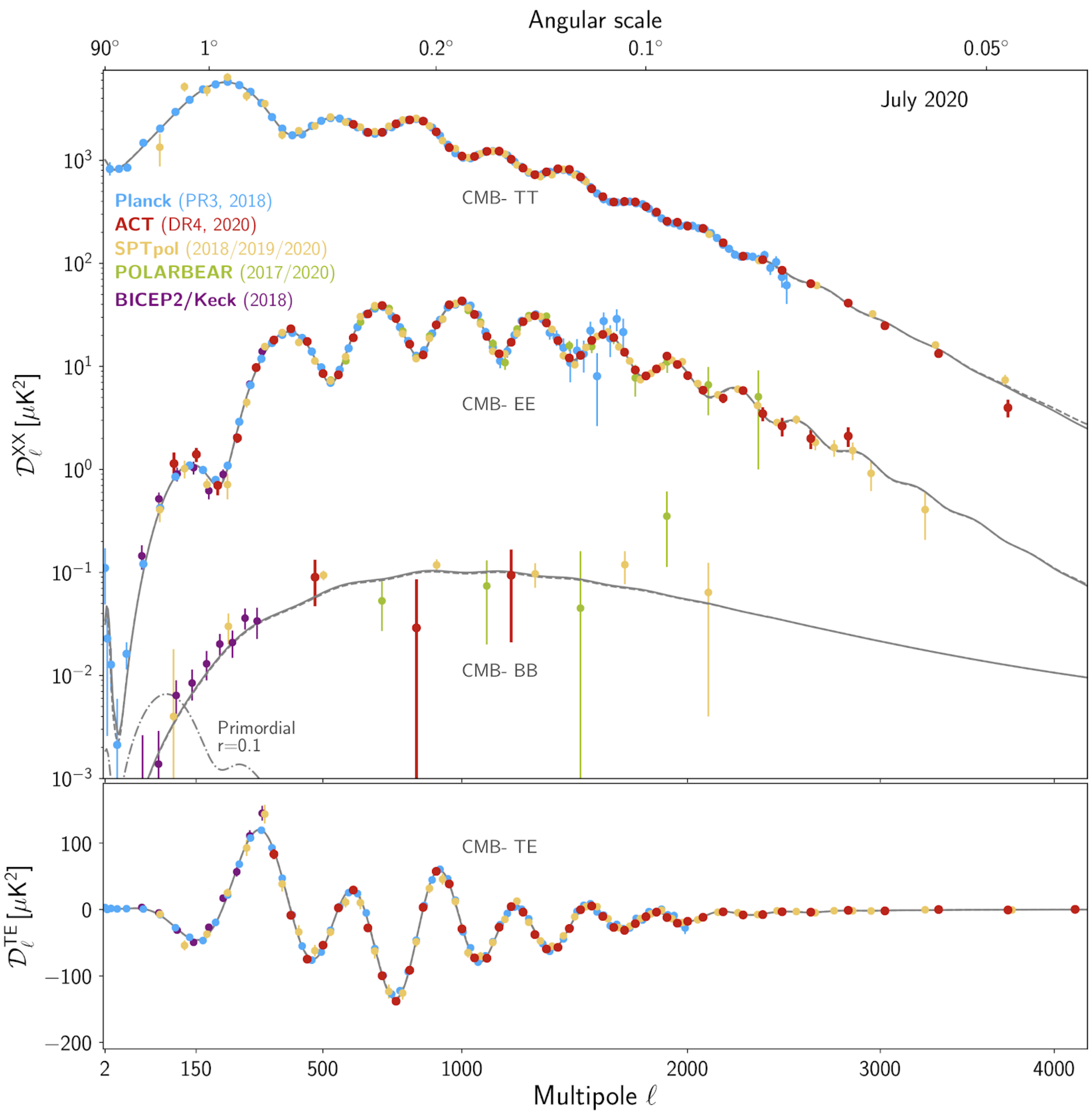

Choi et al. (2020)

ACT DR4 Cosmology

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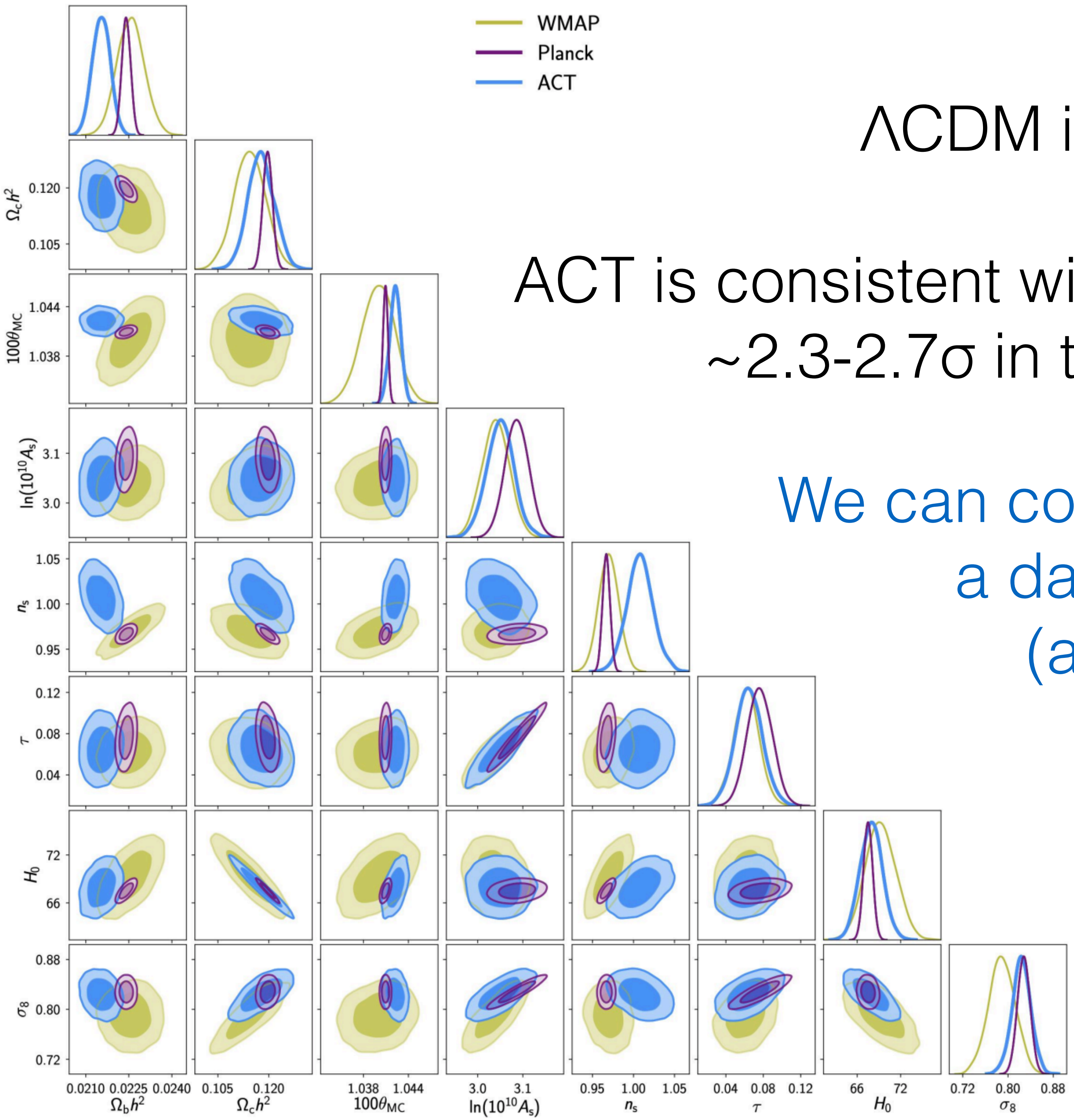
ACT: completely independent check of WMAP and Planck results



ΛCDM is a good fit to the ACT data

ACT is consistent with WMAP and Planck within ~2.3-2.7σ in the ΛCDM parameter space

We can combine ACT+WMAP to form a data set with statistical power (almost) approaching Planck

Aiola et al. (2020); Choi et al. (2020)

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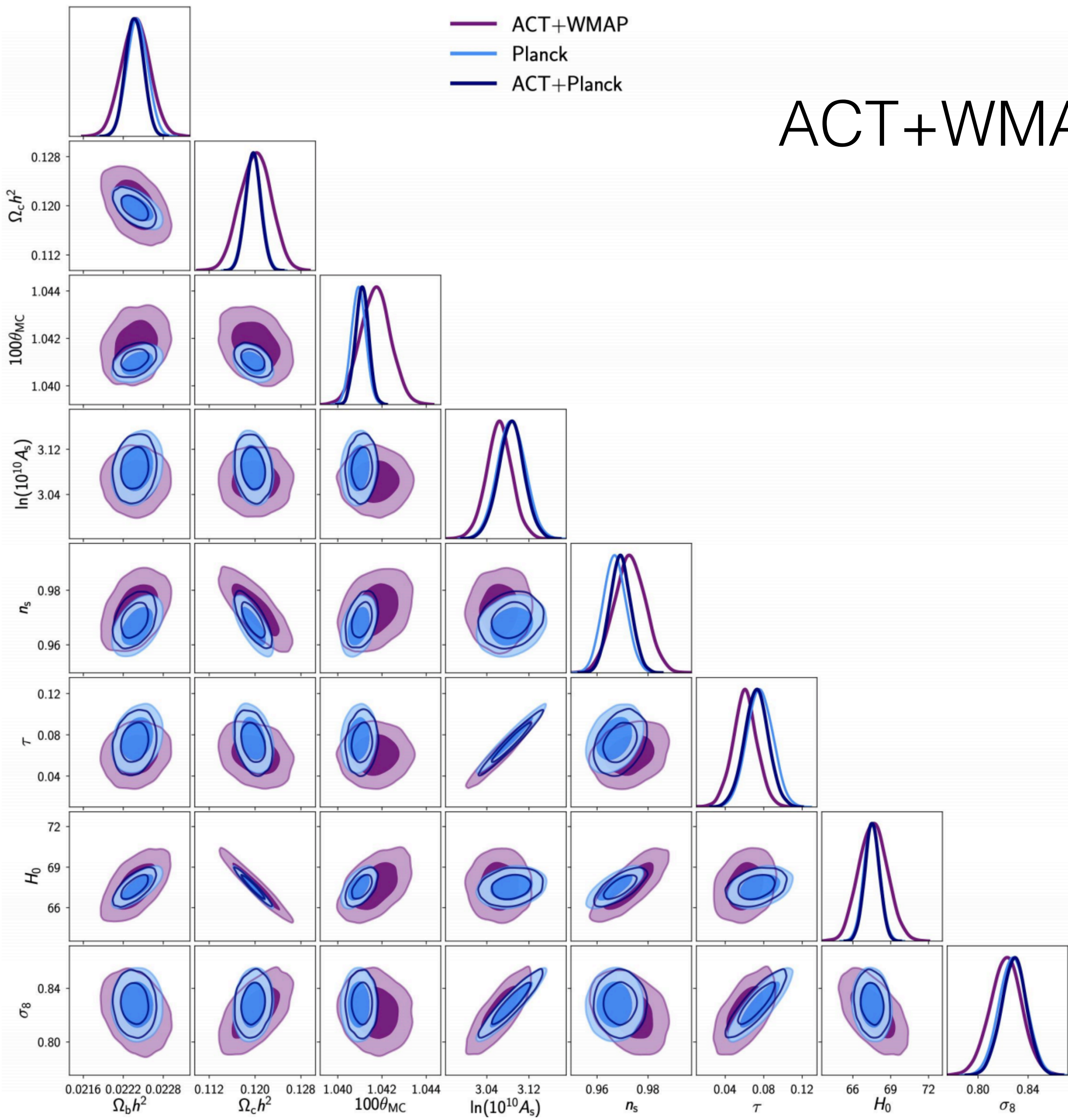
ACT+WMAP: completely independent check of Planck results



ACT+WMAP is in excellent agreement with Planck

Aiola et al. (2020); Choi et al. (2020)

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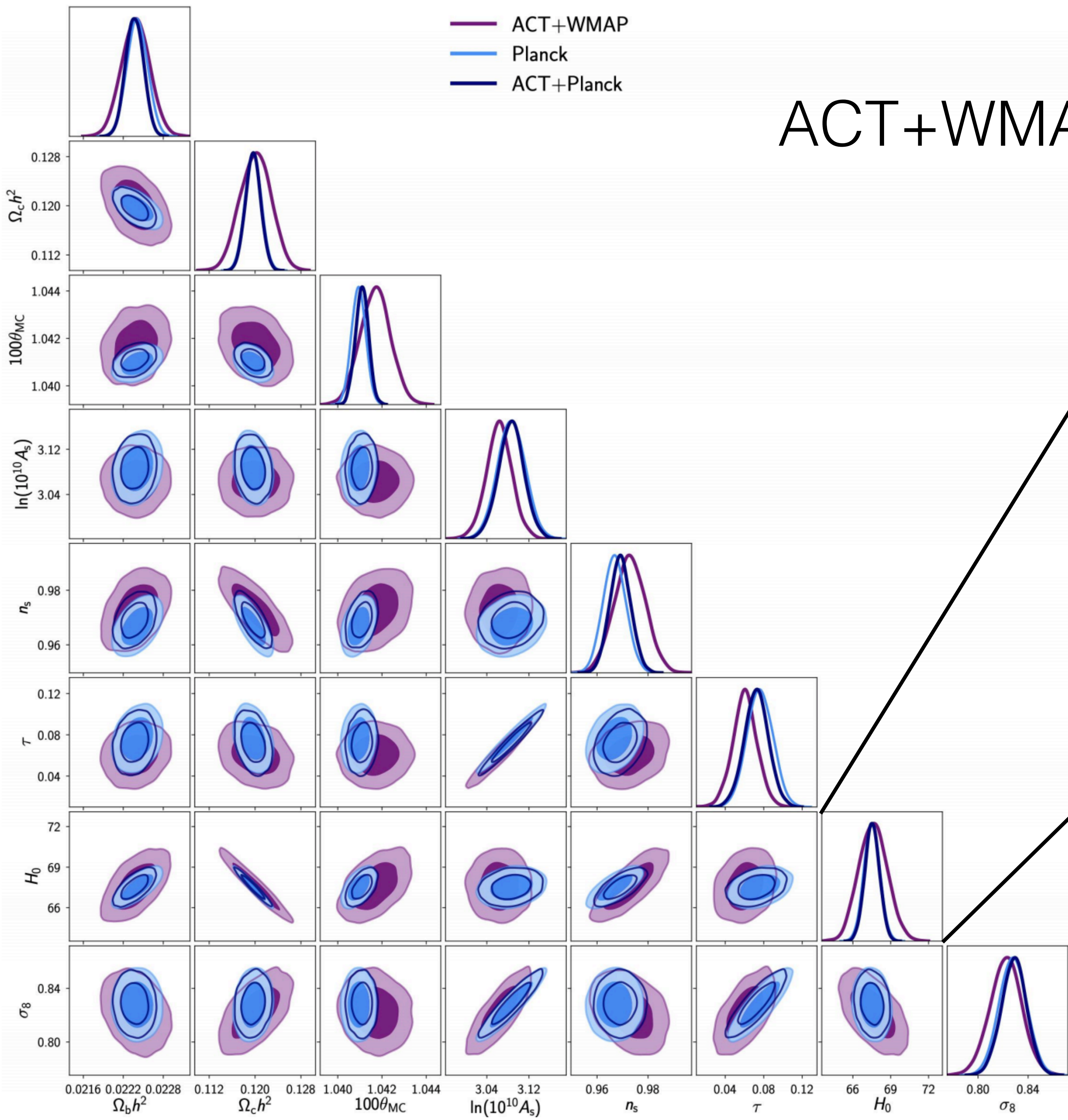
ACT DR4 Cosmology

ACT+WMAP: completely independent check of Planck results



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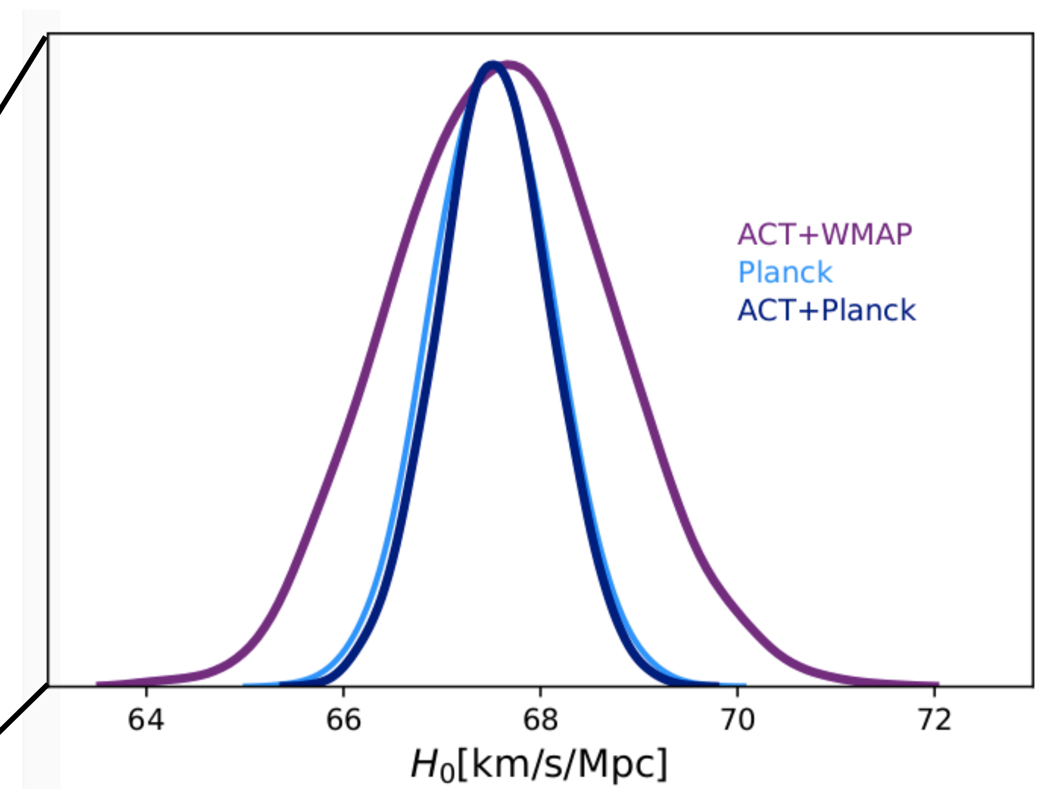

H_0=67.6±1.1 km/s/Mpc	*ACT+WMAP*
H_0=67.9±1.5 km/s/Mpc	*ACT*
H_0=67.5±0.6 km/s/Mpc	*Planck*

Aiola et al. (2020); Choi et al. (2020)

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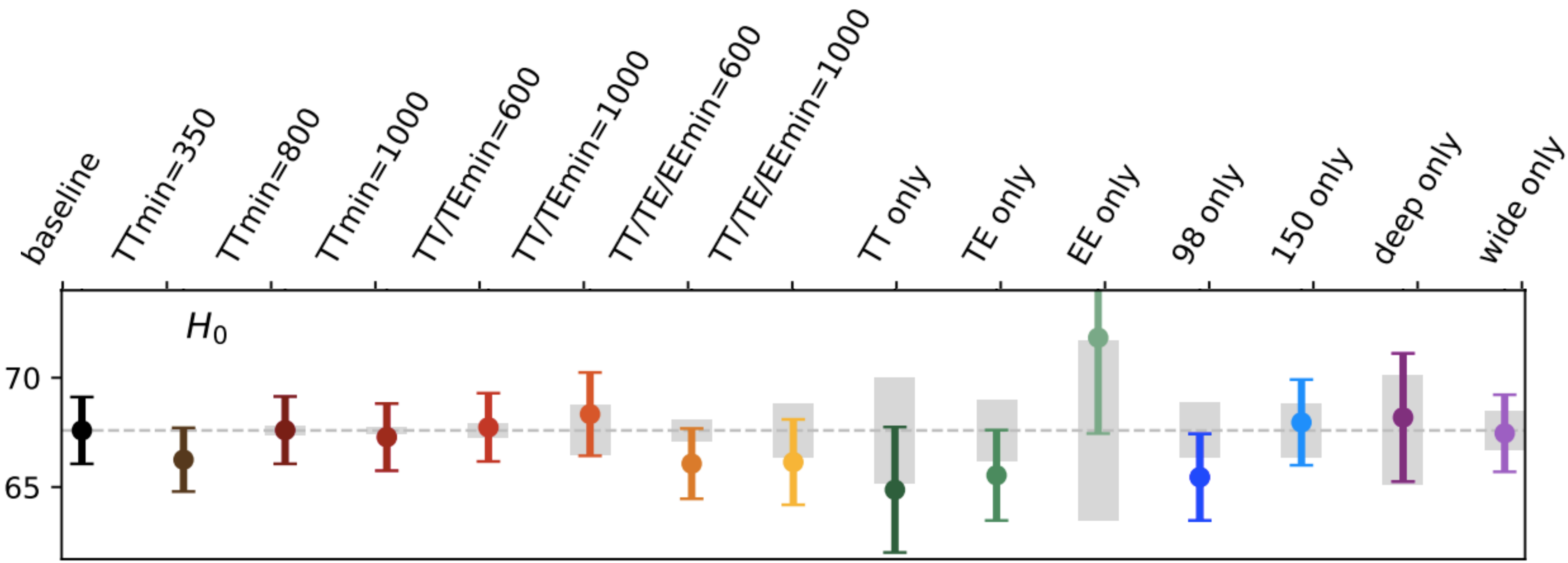
ACT DR4 Cosmology

H_0 results are stable for a wide range of analysis choices



Aiola et al. (2020); Choi et al. (2020)

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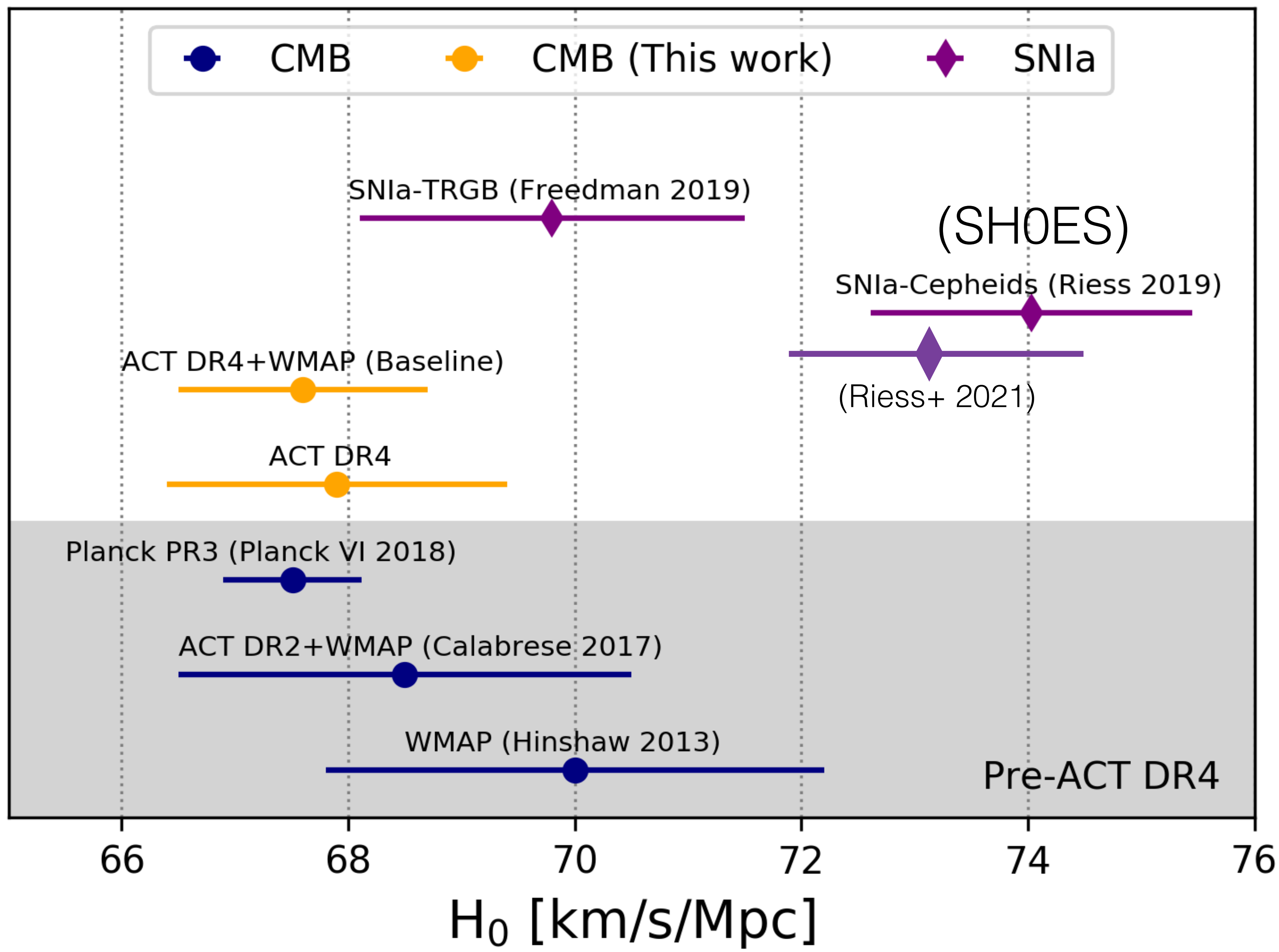
ACT DR4 Cosmology



~4σ disagreement between ACT+WMAP and Cepheid-calibrated SNIa (2019), ~3.3σ using SH0ES 2021

Agreement within ~1σ between ACT+WMAP and TRGB-calibrated SNIa

Aiola et al. (2020)

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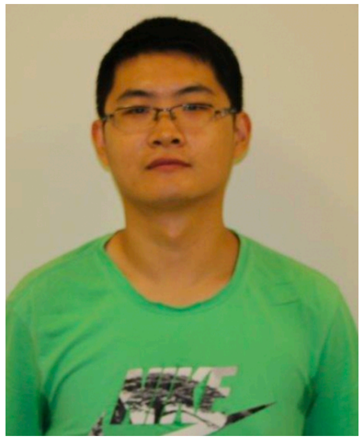
Baryon Clumping / Primordial Magnetic Field H_0 Tension Resolution: Constraints from ACT

2105.03003 w/ L. Thiele, Y. Guan, A. Kosowsky, D. Spergel

Baryon Clumping

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- Basic idea: push recombination to earlier time, thus yielding a decreased sound horizon (and higher H_0 from CMB data)

- Recombination rate: $\dot{n}_e \propto -n_e^2$

- Thus, small-scale clumping s.t. $\langle n_e^2 \rangle > \langle n_e \rangle^2$ yields faster recombination and smaller r_s

- This is naturally achieved with primordial magnetic fields, which can dynamically sustain large inhomogeneities on small scales (otherwise suppressed by diffusion/Silk damping) — but we can agnostically consider “baryon clumping” on small scales in general

Jedamzik & Abel (2011); Jedamzik & Pogosian (2020)

Baryon Clumping

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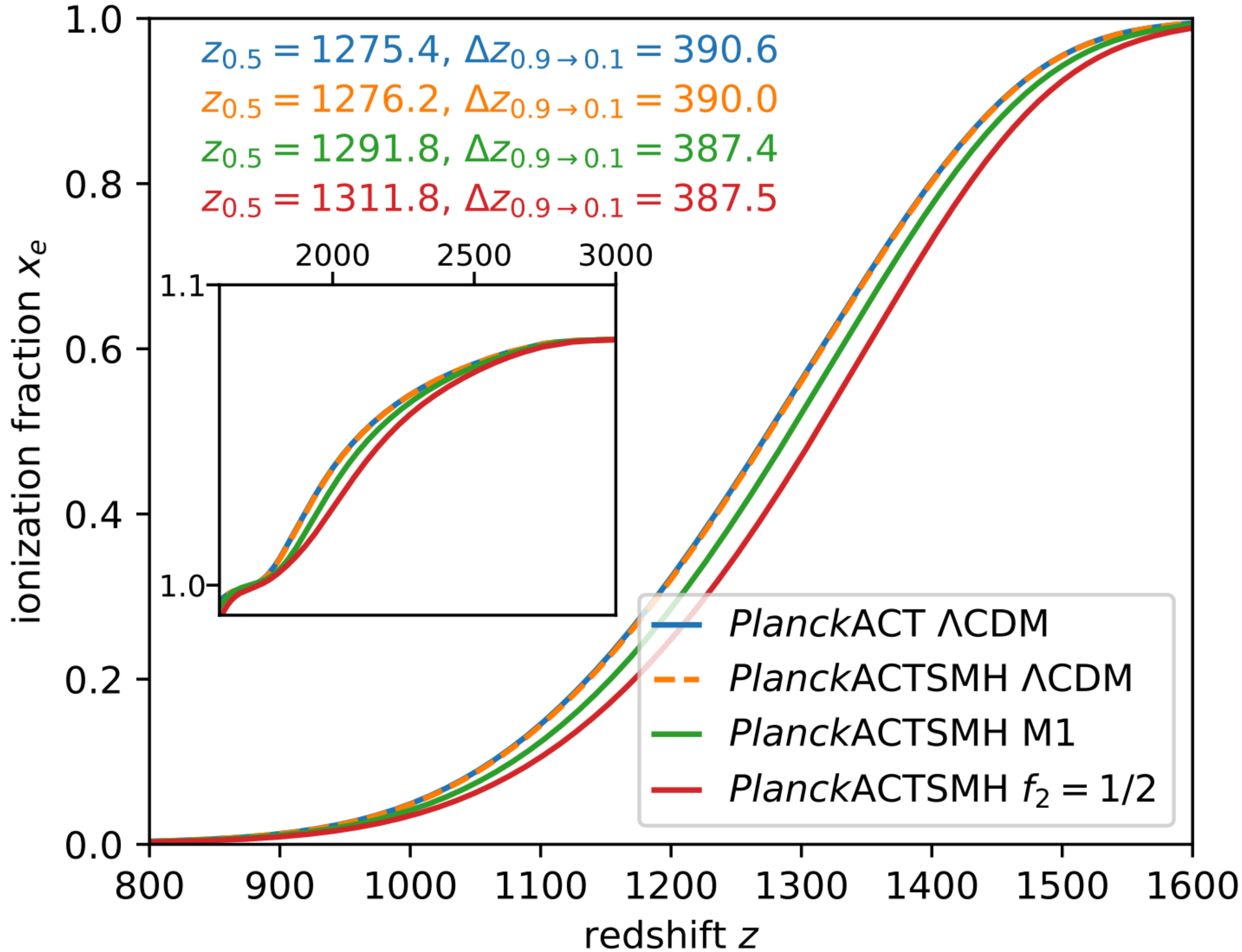
Illustration of the mechanism

Ionization history of the universe



Jedamzik & Abel (2011); Jedamzik & Pogosian (2020); Thiele, Guan, **JCH**, Kosowsky, Spergel (2021)

Baryon Clumping

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ACT: independent test of this scenario with high-ell CMB data, probing scales that Planck does not (and higher S/N in TE + EE)

Thiele, Guan, **JCH**, Kosowsky, Spergel (2021)

Baryon Clumping

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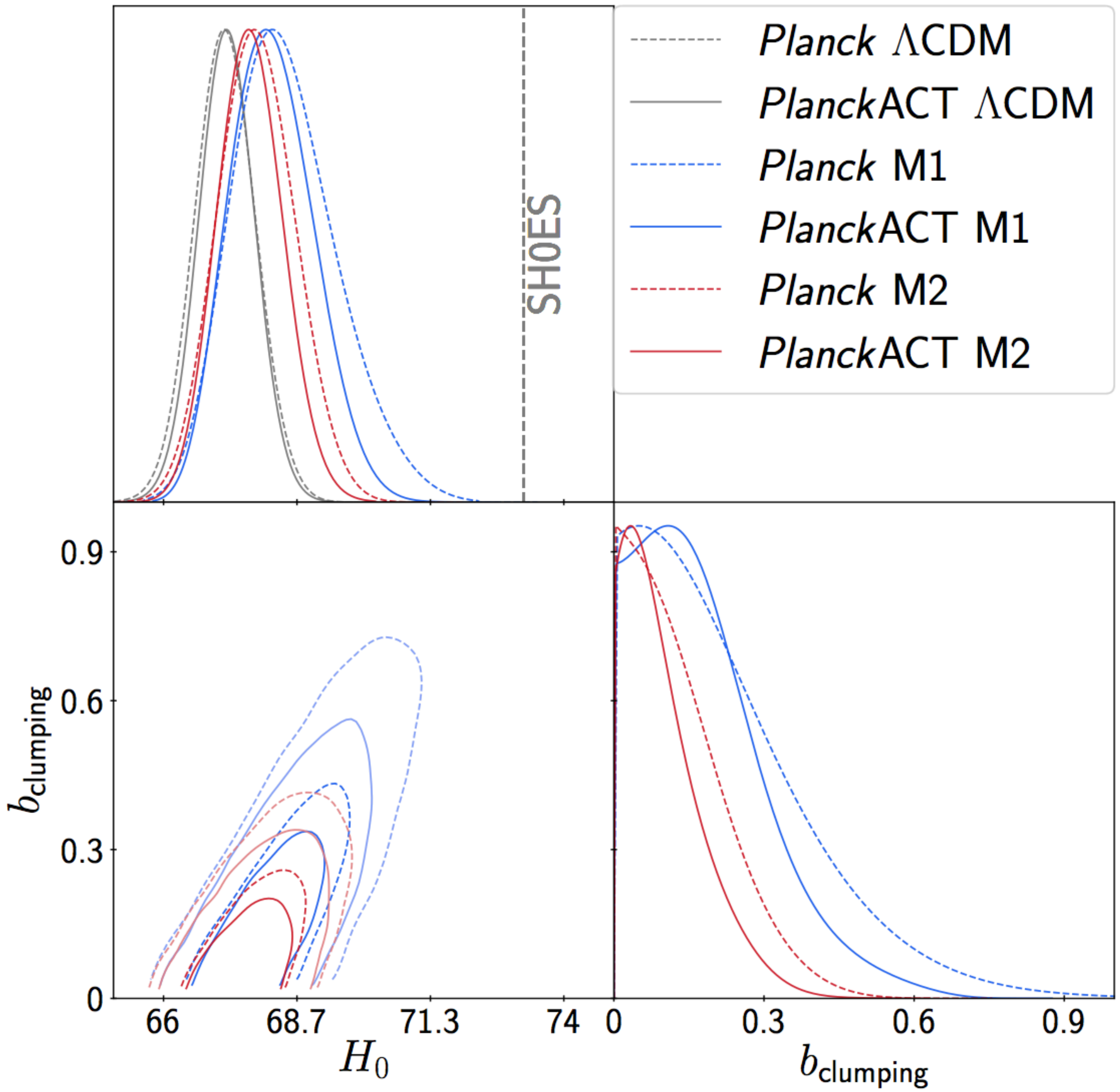

Planck+ACT

model	H_0 [km/s/Mpc]	b
ΛCDM	67.26 ± 0.60	–
M1	68.18 ± 0.87	<0.42
M2	67.74 ± 0.71	<0.26

no relief of tension with SH0ES — one should thus be wary of combining

Thiele, Guan, **JCH**, Kosowsky, Spergel (2021)

Baryon Clumping

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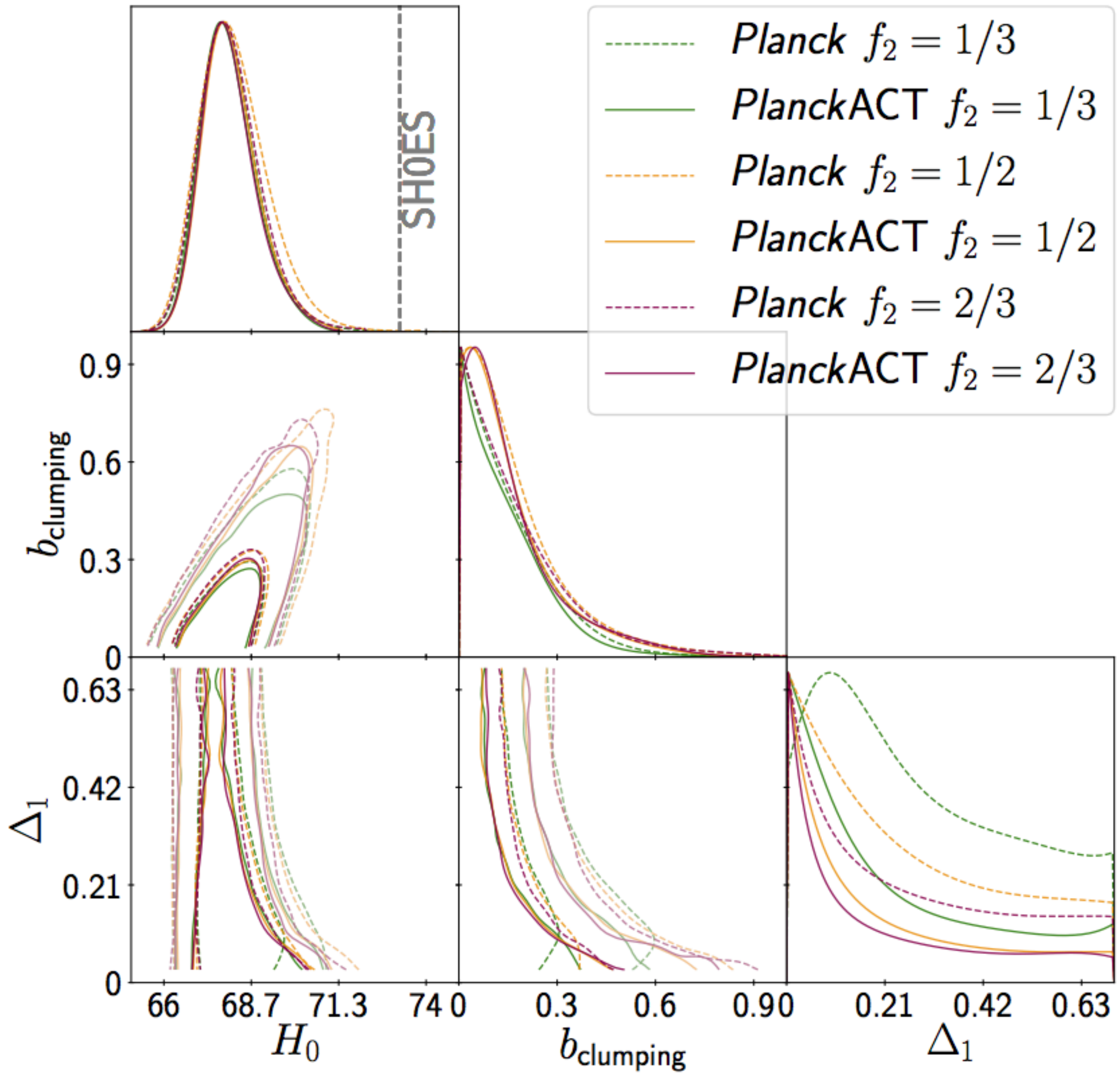
Results persist even in broadened parameter space (more freedom in the small-scale baryon PDF)



Thiele, Guan, **JCH**, Kosowsky, Spergel (2021)

Baryon Clumping

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Takeaways and Outlook

- Baryon clumping models not preferred by ACT + Planck (or ACT + Planck + BAO)

- CMB H_0 still in tension with SH0ES even in the context of this model, so one should be wary of combining likelihoods — if one tries to do so, the CMB χ^2 worsens by ~6-7 relative to LCDM — thus the model does not appear to restore concordance

- Perhaps further model extensions could help — e.g., time-dependence in the small-scale baryon PDF (as would be expected in more realistic PMF models)

Thiele, Guan, **JCH**, Kosowsky, Spergel (2021)

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Early Dark Energy and Cosmological Concordance






JCH, McDonough, Toomey, Alexander (2020, PRD Editors' Suggestion)

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

Early Dark Energy

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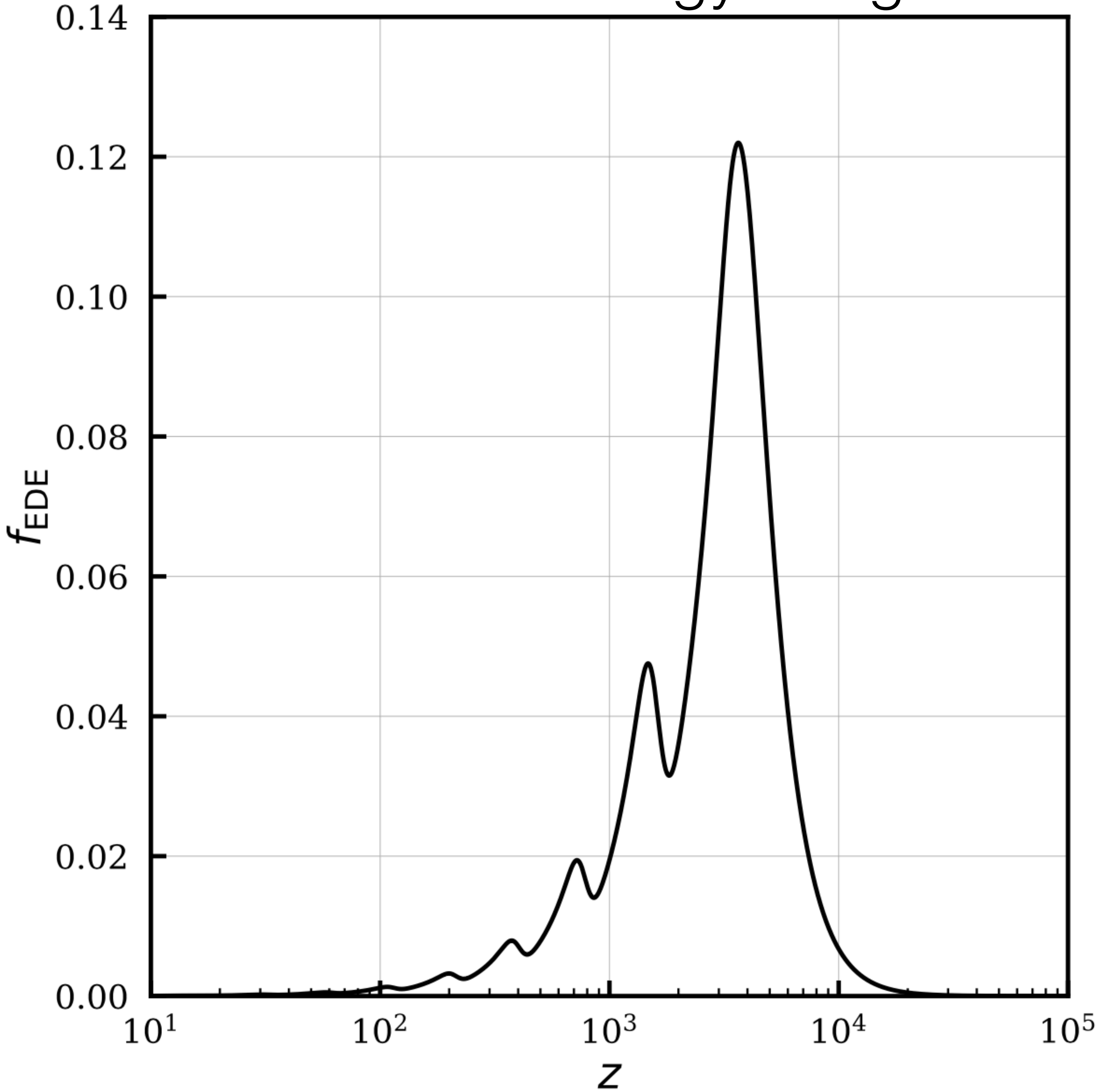
Parameterization

Fractional contribution of EDE to cosmic energy budget



Motivation:
decrease the size of the sound horizon imprinted in the CMB

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

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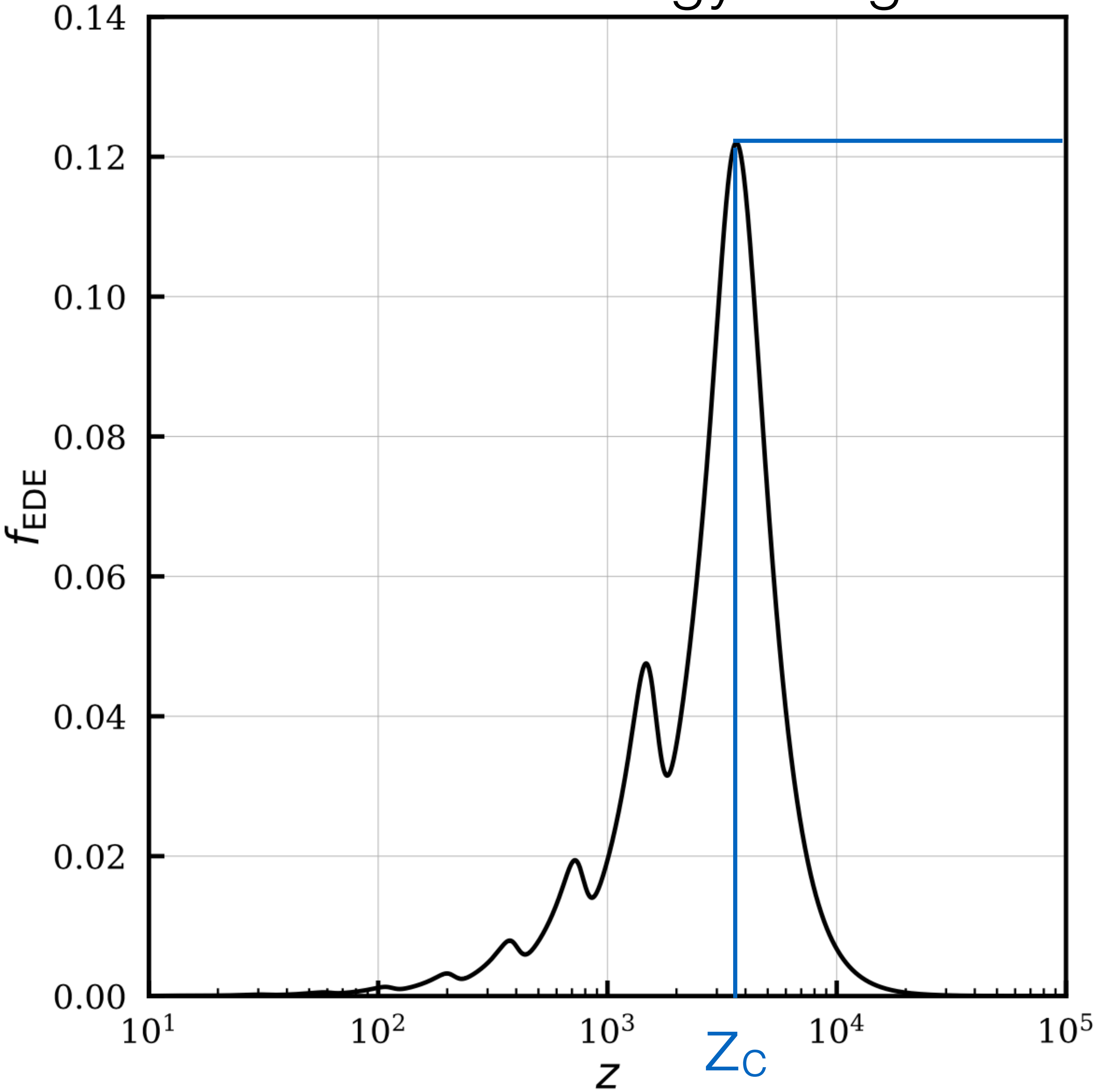
Early Dark Energy

Parameterization

Fractional contribution of EDE to cosmic energy budget



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 physical scalar field parameters

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

Early Dark Energy

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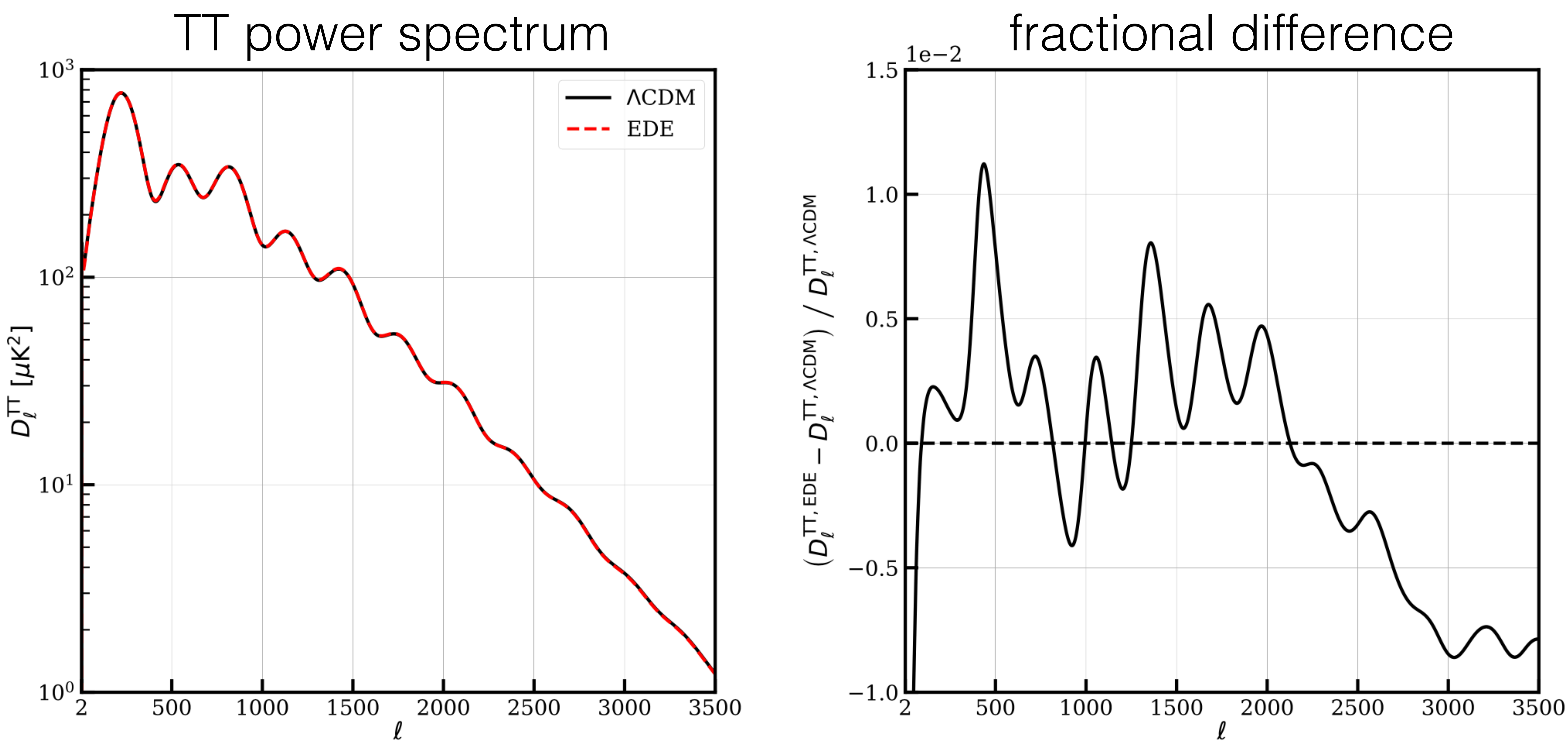
It maintains a good fit to CMB power spectrum data with higher H_0



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

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

caused by decrease in r_s

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

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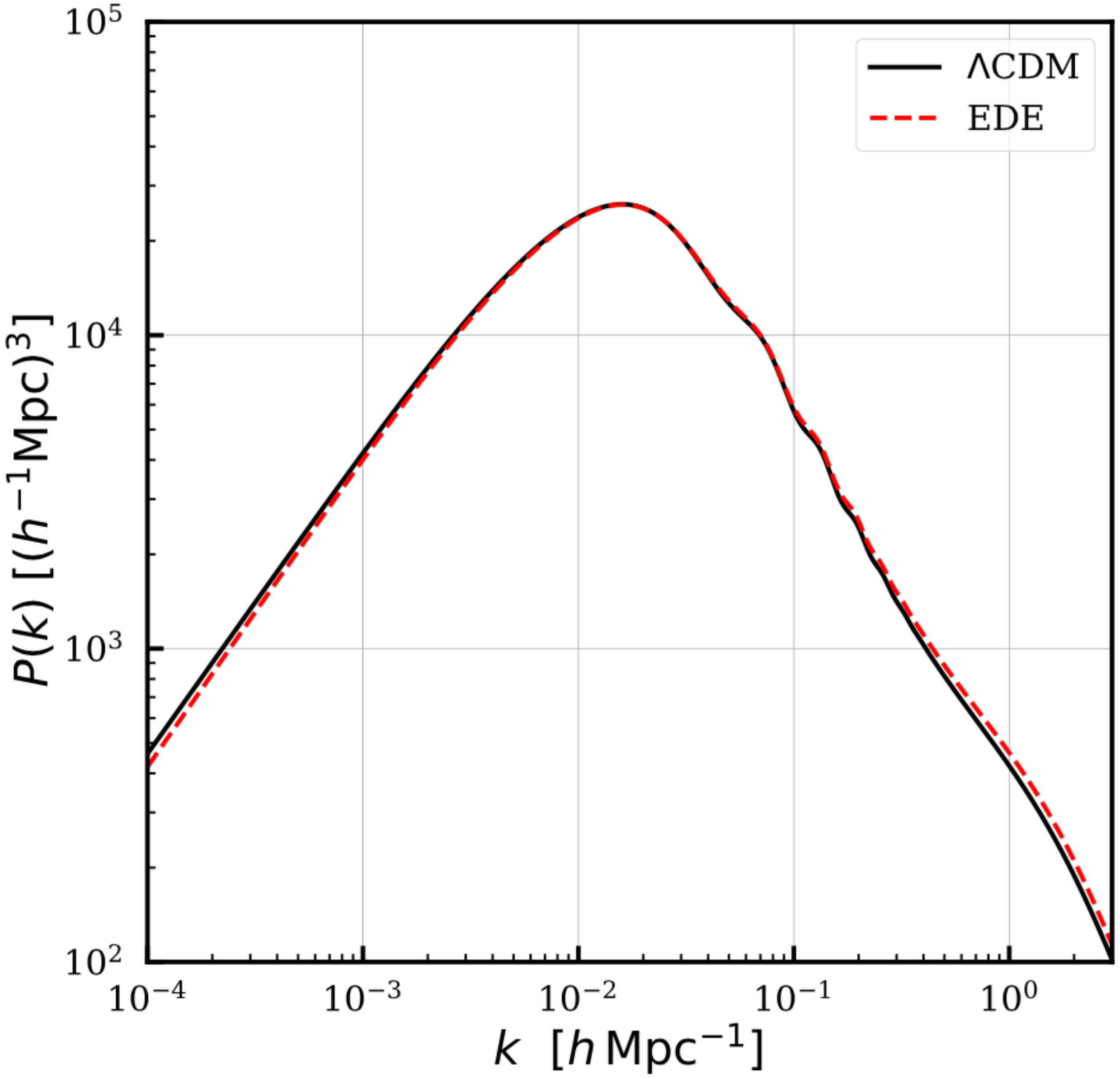
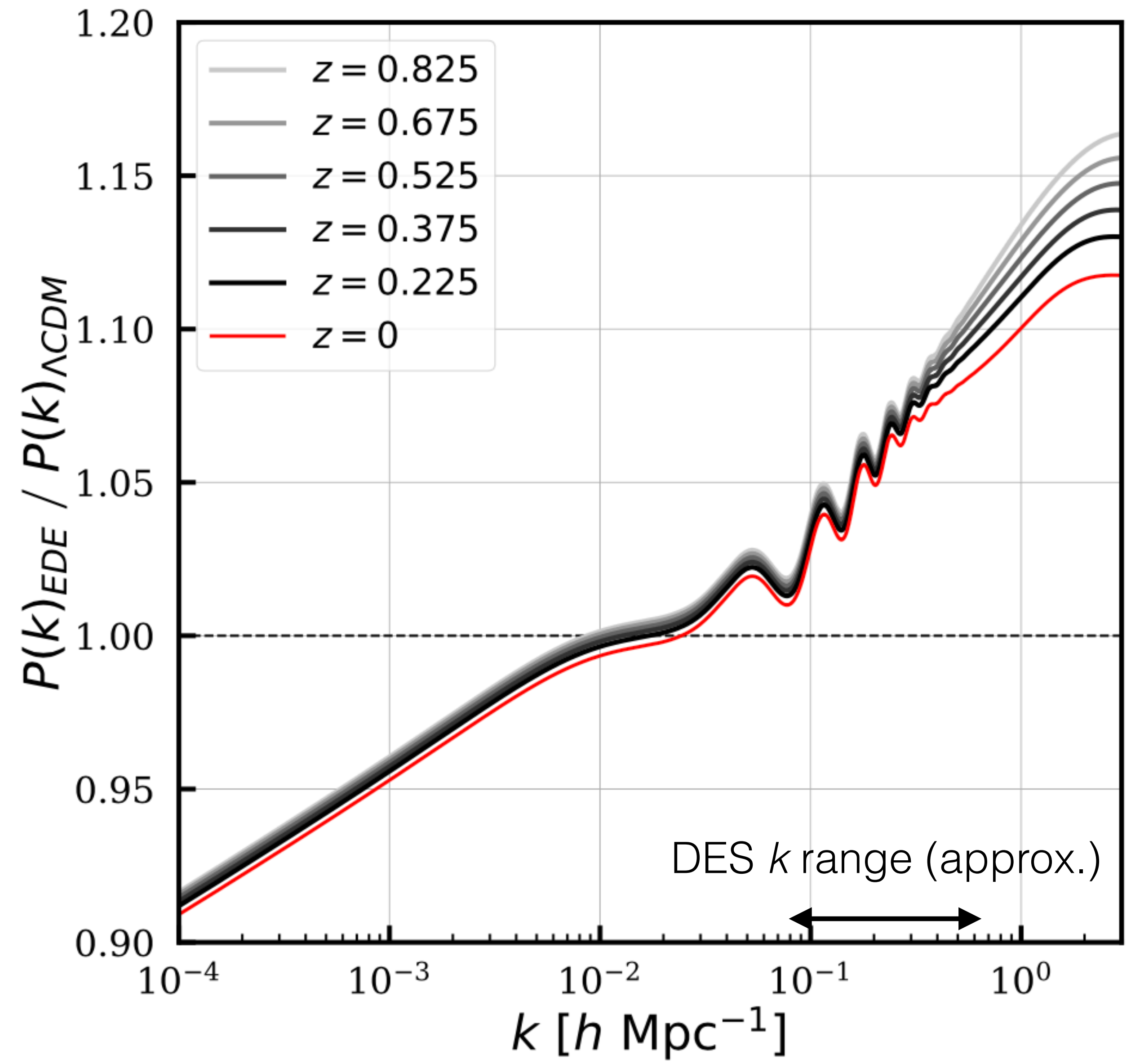
LSS in EDE Model

Changes to P(k), matter density fluctuation power spectrum

matter power spectrum



ratio



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

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

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

Parameter Shifts in EDE

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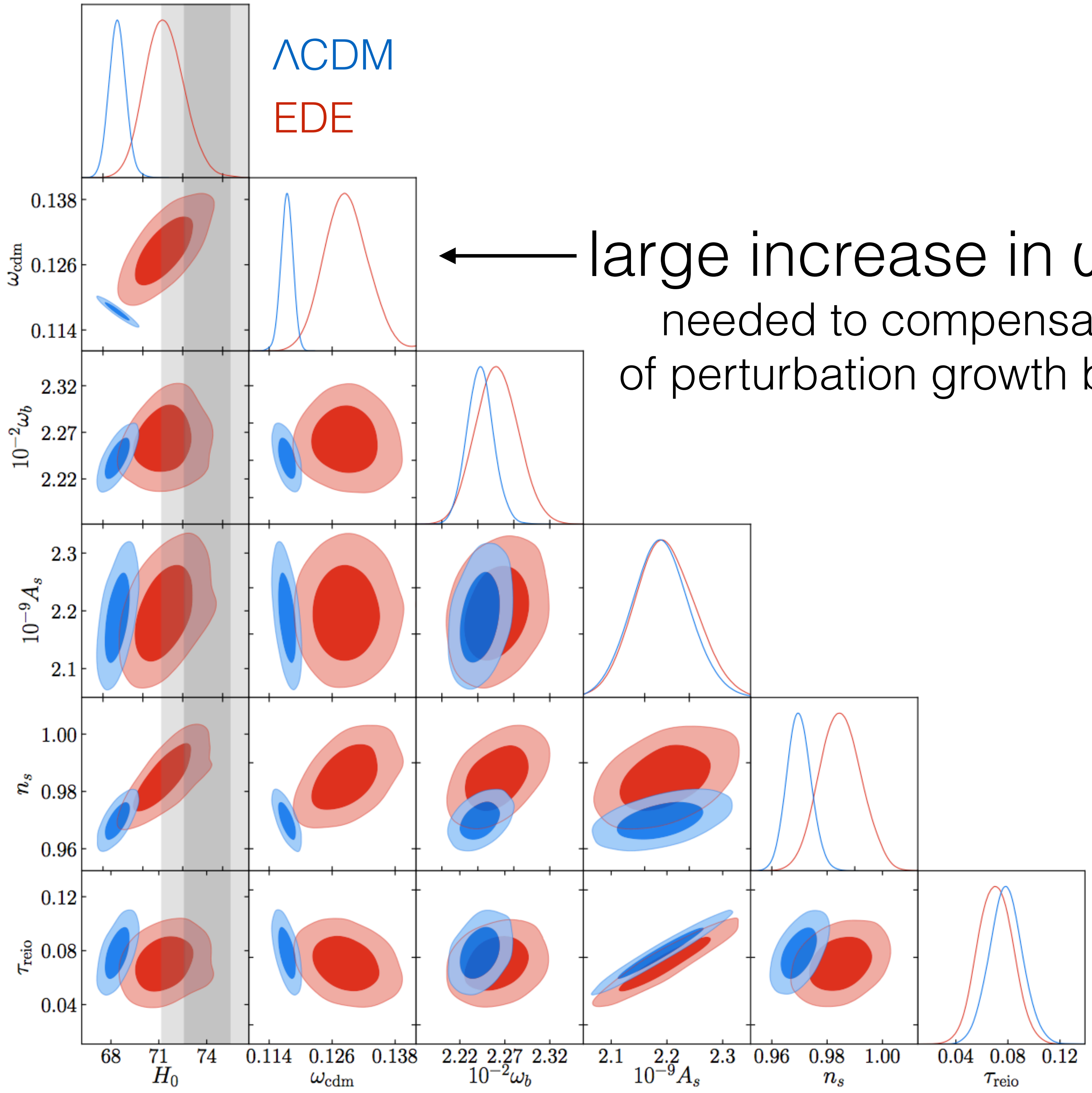

large increase in ω_{cdm}

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

Smith+ (2019)

Parameter Shifts in EDE

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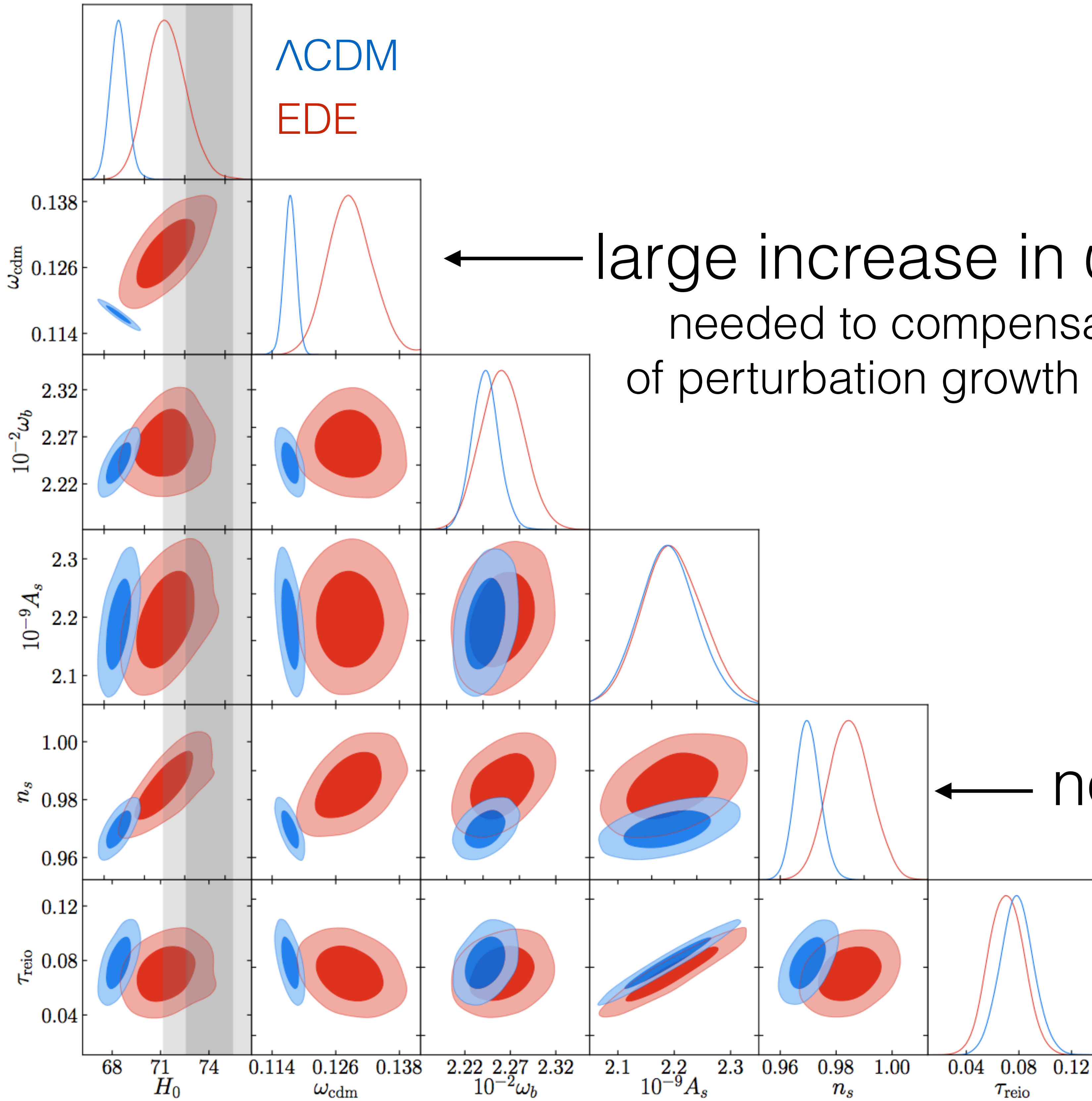

← large increase in ω_{cdm}

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

← noticeable increase in n_s

implication: increase in σ_8 and Ω_m

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

Smith+ (2019)

Global Analysis (no SH0ES)

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

JCH+ (2020)

Global Analysis (no SH0ES)

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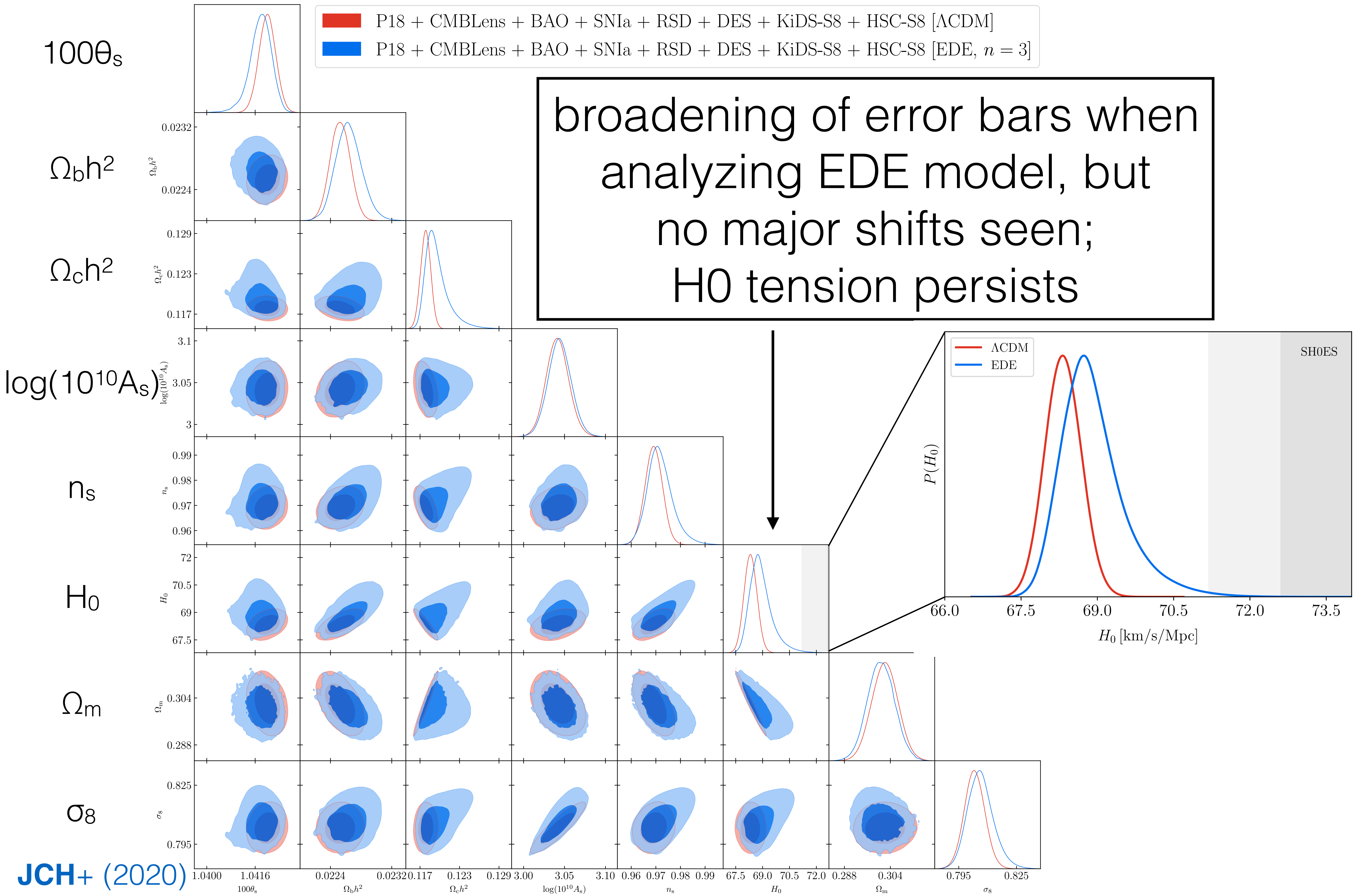
broadening of error bars when analyzing EDE model, but no major shifts seen; H0 tension persists



JCH+ (2020)

Global Analysis (no SH0ES)

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Strong upper limit on existence of EDE component

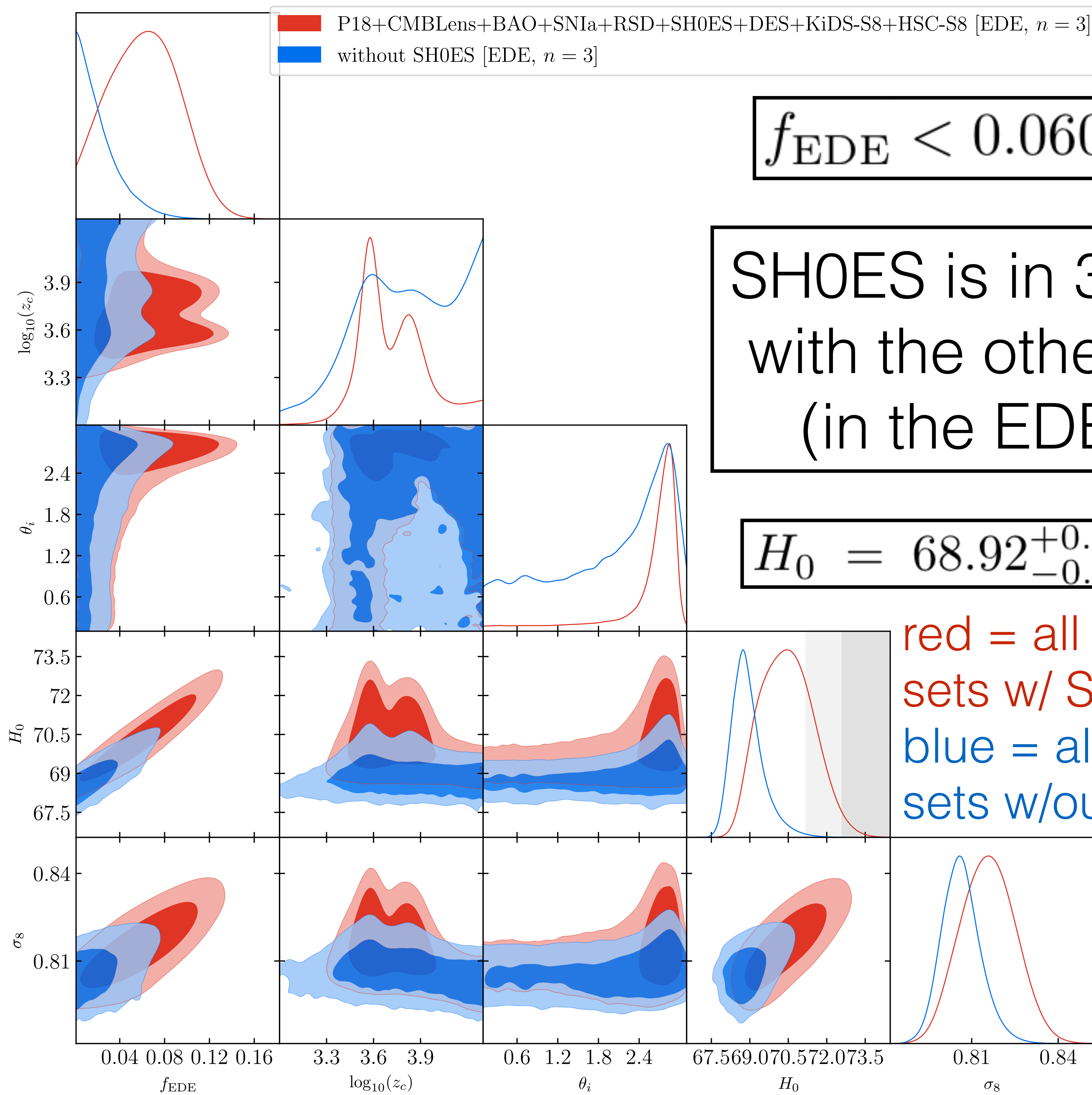
f_{EDE}

$\log_{10}(z_c)$

θ_i

H_0

σ_8



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

SH0ES is in 3.3σ tension with the other data sets (in the EDE model!)

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

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

JCH+ (2020)

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

Ivanov, McDonough, JCH+ (2020)

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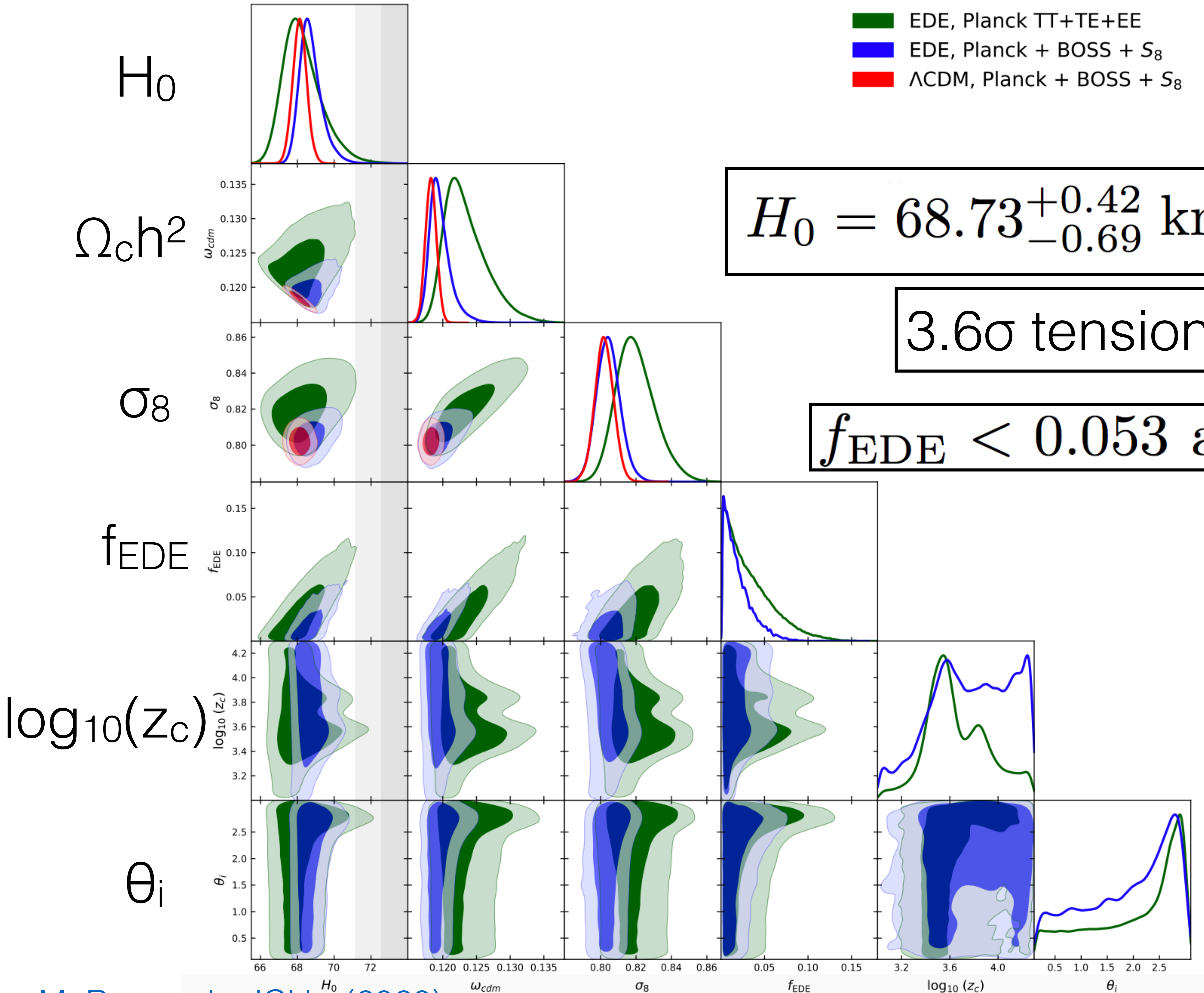
Planck + BOSS (EFT) + DES/HSC/KiDS (S_8)



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

3.6σ tension w/ SH0ES

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

Ivanov, McDonough, JCH+ (2020)

Additional Constraining Power of EFT

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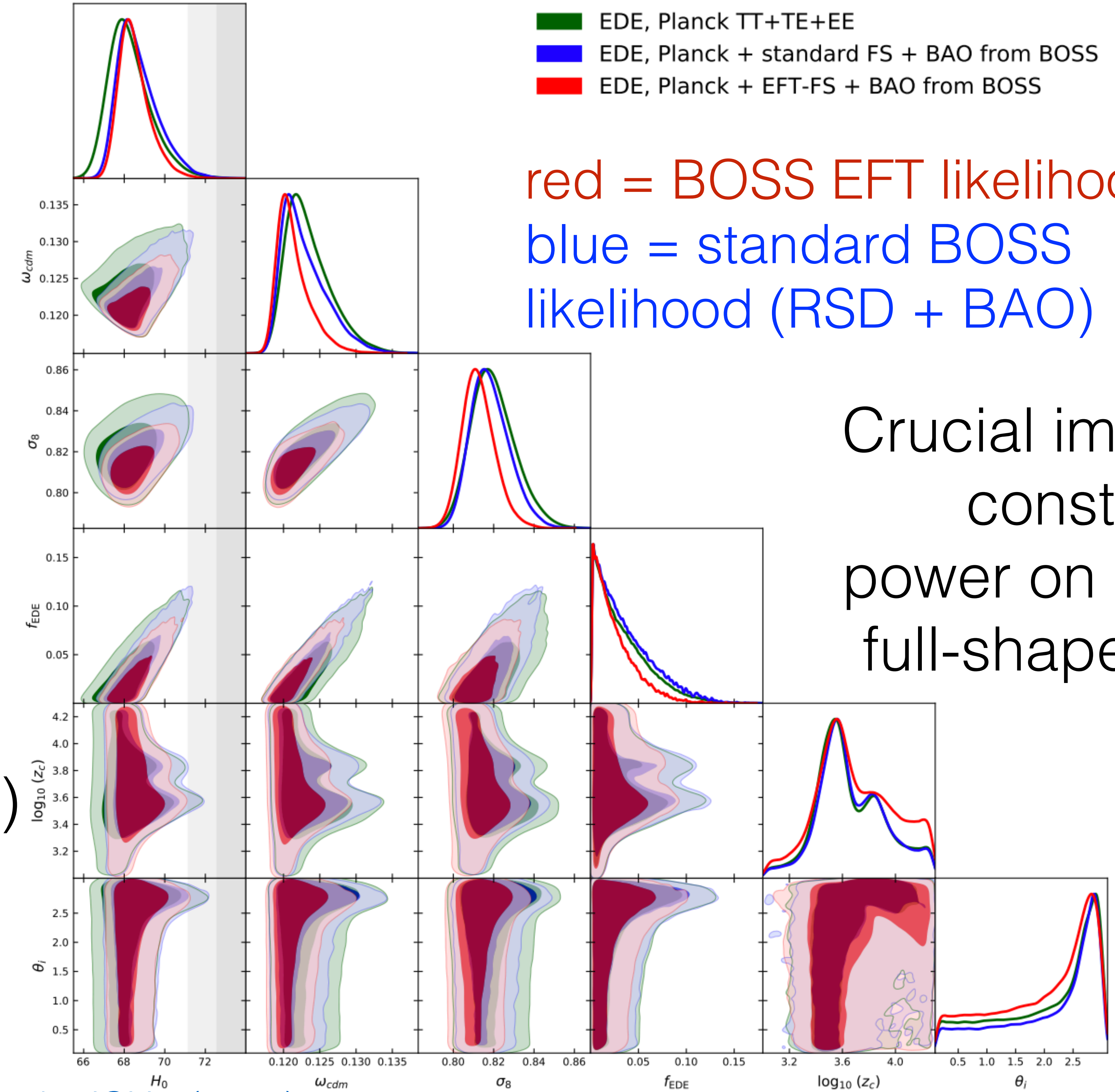

red = BOSS EFT likelihood

blue = standard BOSS likelihood (RSD + BAO)

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

Ivanov, McDonough, JCH+ (2020)

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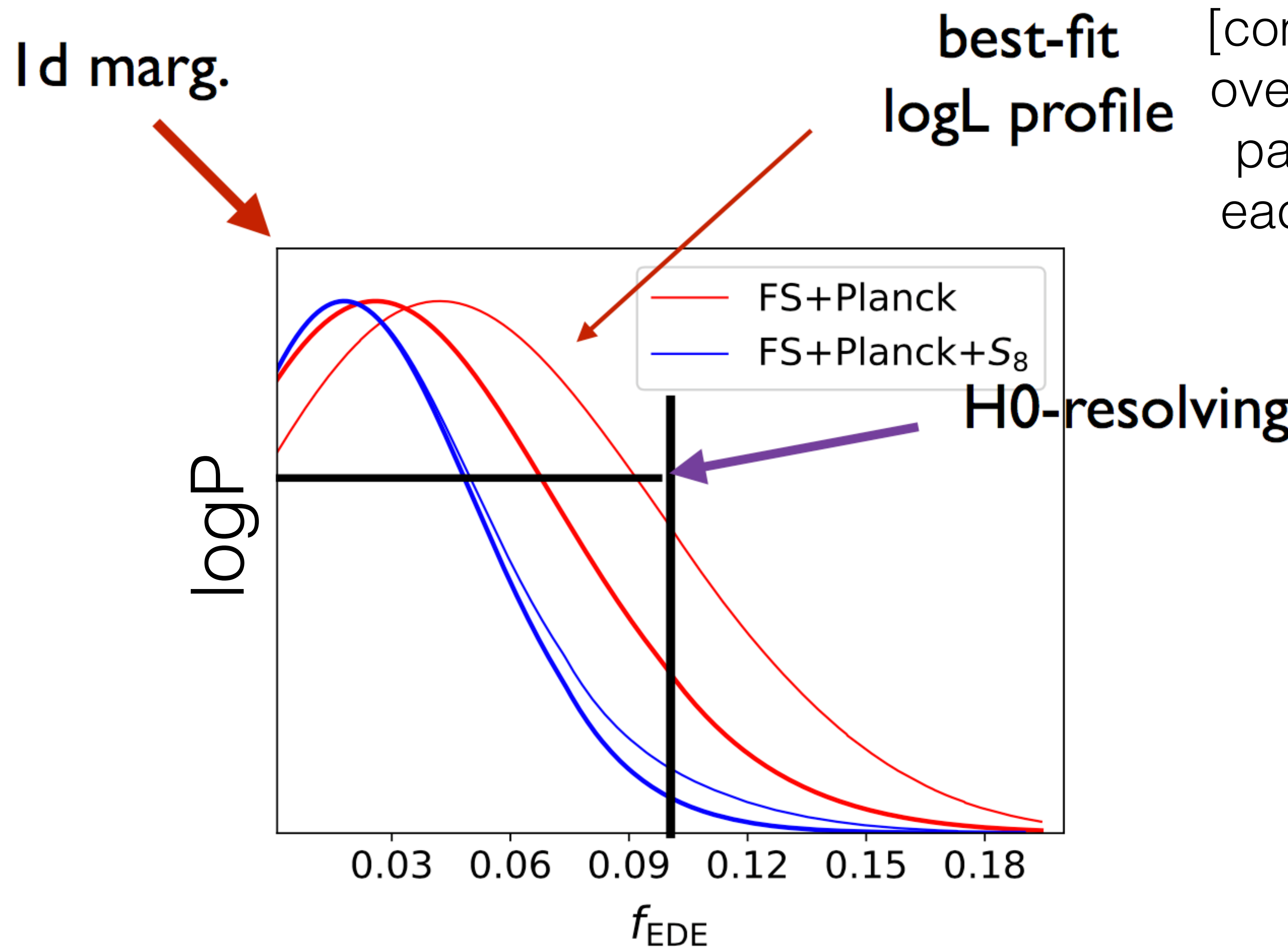
Prior Volume Effects?

non-preference for H0-resolving EDE is robust in either frequentist or Bayesian methodology



[compute best-fit over all the other parameters, at each $f_{\rm EDE}$ value]

Ivanov, McDonough, JCH+ (2020) — see Appendices B and C for detailed discussion of these points

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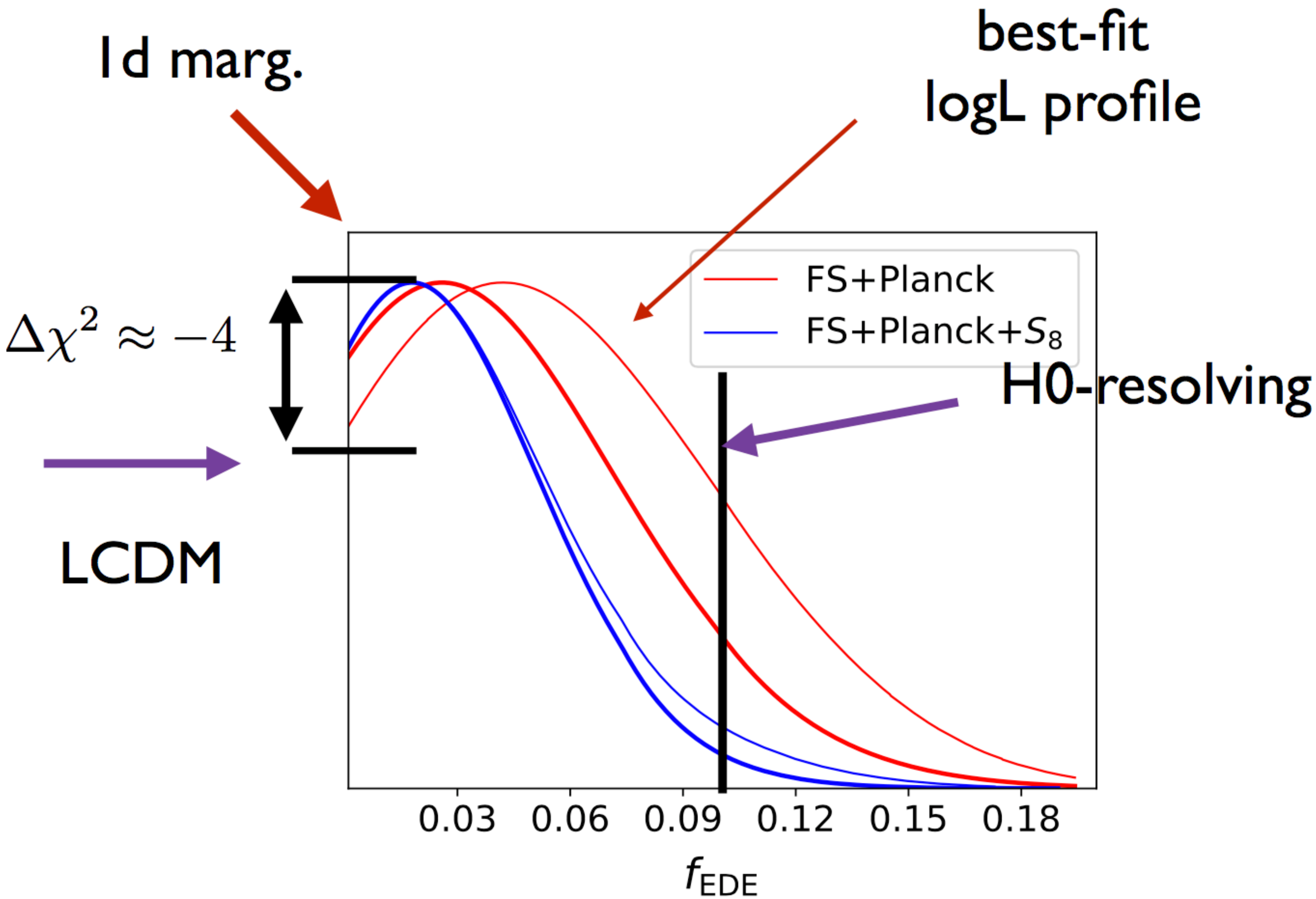

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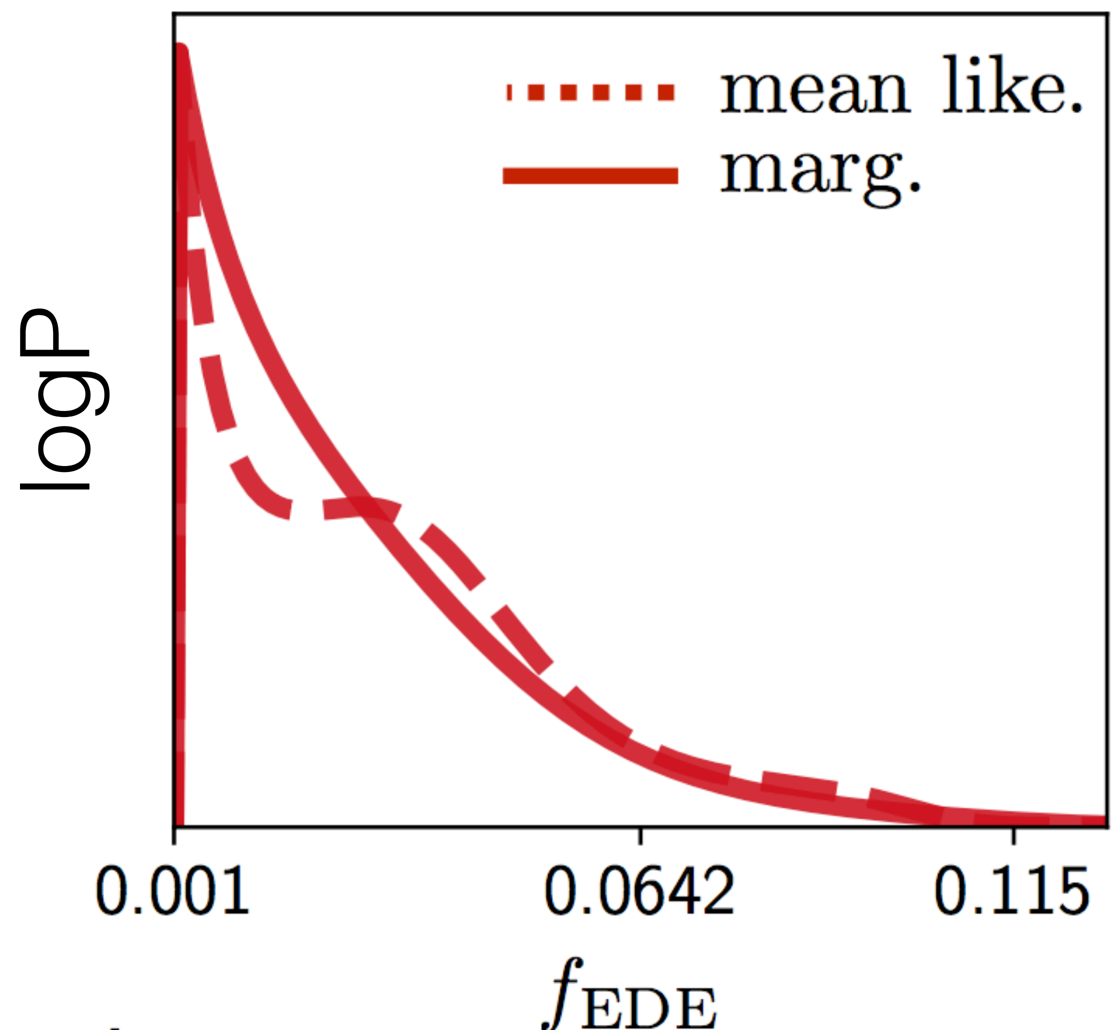

mean like. = [compute average log(likelihood), averaging over all the other parameters, at each f_{EDE} value]

FS+Planck only

Ivanov, McDonough, JCH+ (2020) — see Appendices B and C for detailed discussion of these points

Outlook: Advanced ACT and Simons Observatory

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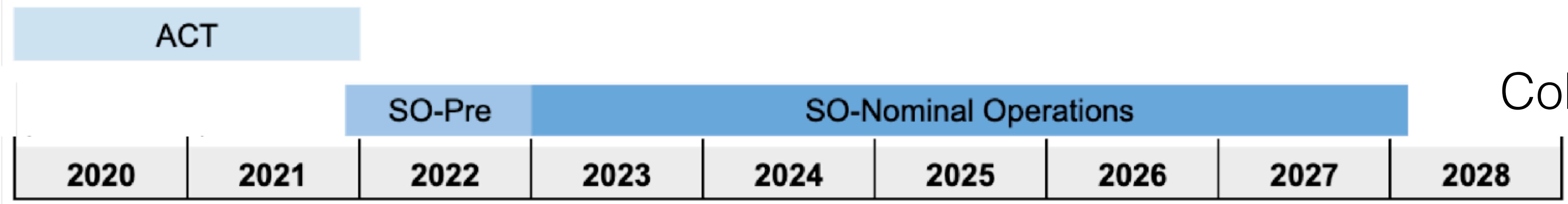
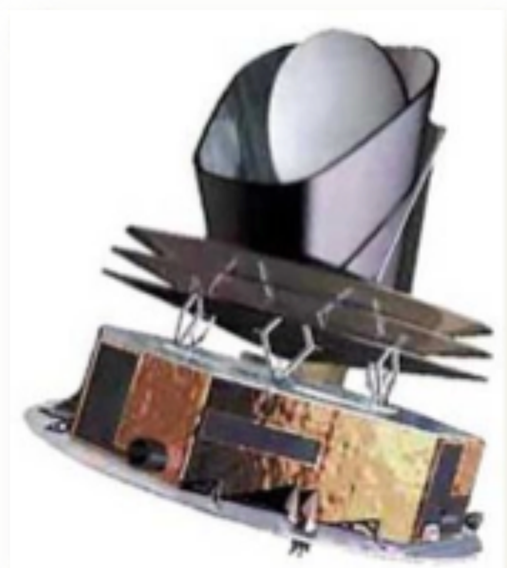
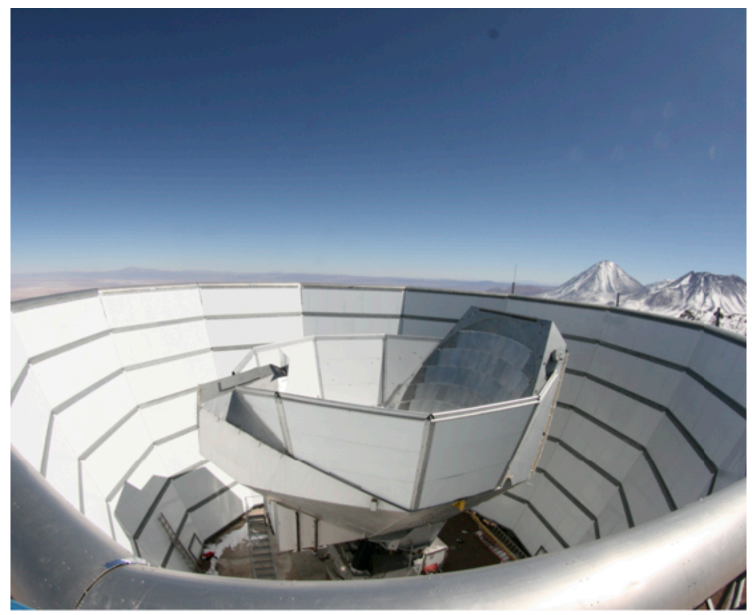


Planck → **Advanced ACT**





Final data 2018
100% sky

0.35 — 10 mm (9 bands)
5 — 33' resolution

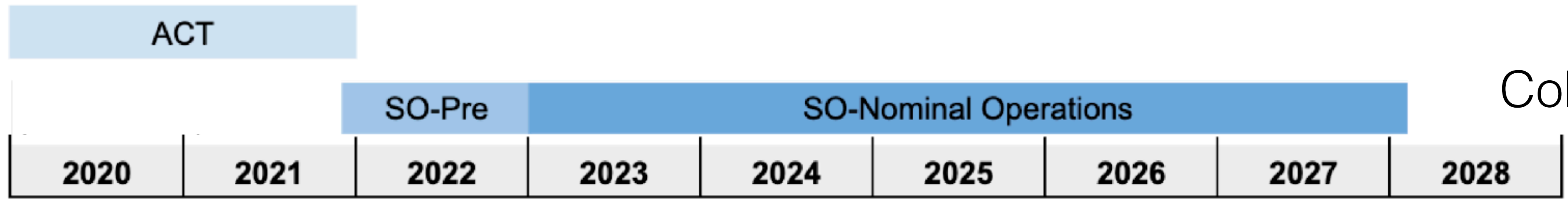
Observations until 2021
40% sky
Noise ~3 times < Planck
1.4 — 10 mm (5 bands)
1 — 7' resolution

[South Pole Telescope - same timeframe]

ACT DR4 only comprises data collected through 2016 — we have >4x as much data already on disk, collected through 2020, and we are still going!

$\sigma(H_0)$ ~ 0.5 km/s/Mpc

(in ΛCDM model)



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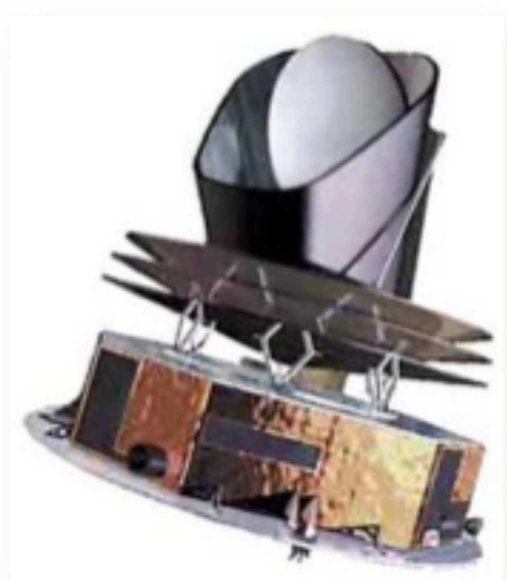
Planck → ACT → SO Large Aperture Telescope

σ(H_0) ~ 0.3 km/s/Mpc



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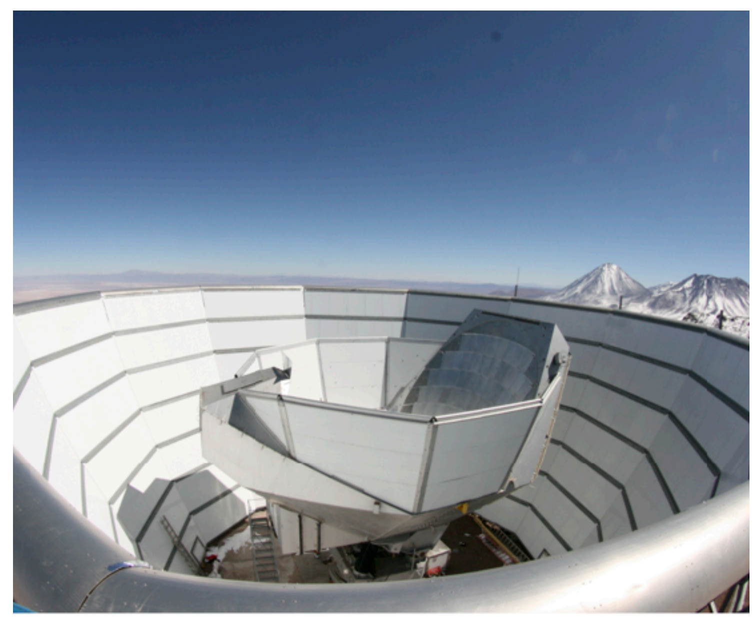

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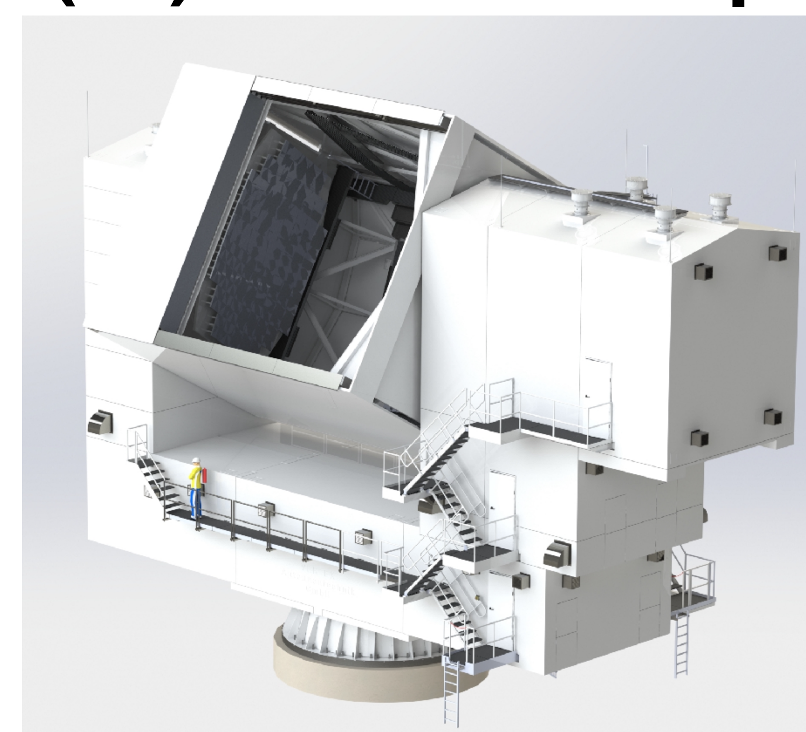

Observations 2023-28
40% sky
Noise ~3 times < ACT
1 — 10 mm (6 bands)
1 — 7’ resolution

[CMB-S4 would start observing after this, with multiple telescopes]

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Take-Home Messages

1) ACT DR4 confirms H_0 from Planck; systematics ruled out
2) ACT+Planck do not prefer small-scale baryon clumping (e.g., from PMFs) as an H_0 tension resolution
3) EDE model to resolve H_0 tension fails to match LSS data
4) Early-universe H_0 resolutions predict clear deviations from ΛCDM in the CMB — imminently testable with ACT+SO

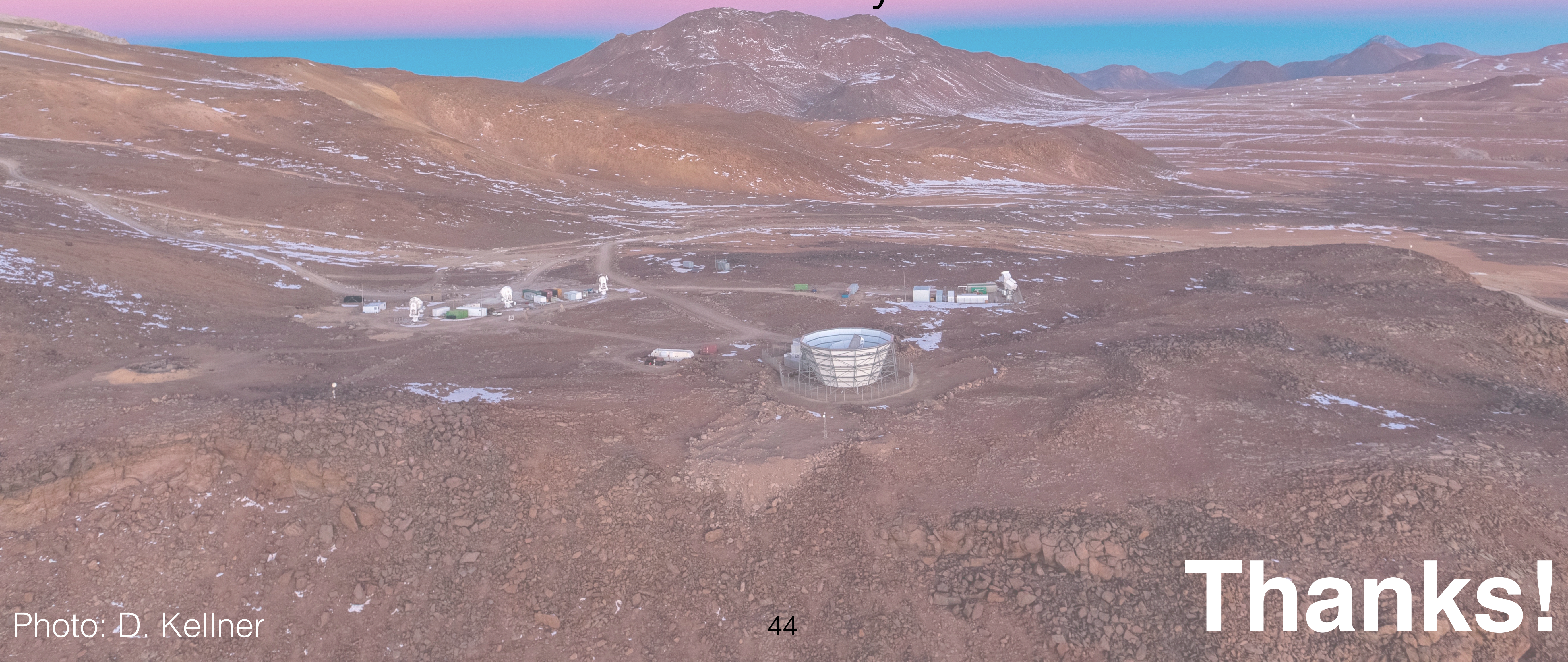

Photo: D. Kellner

Thanks!

Bonus

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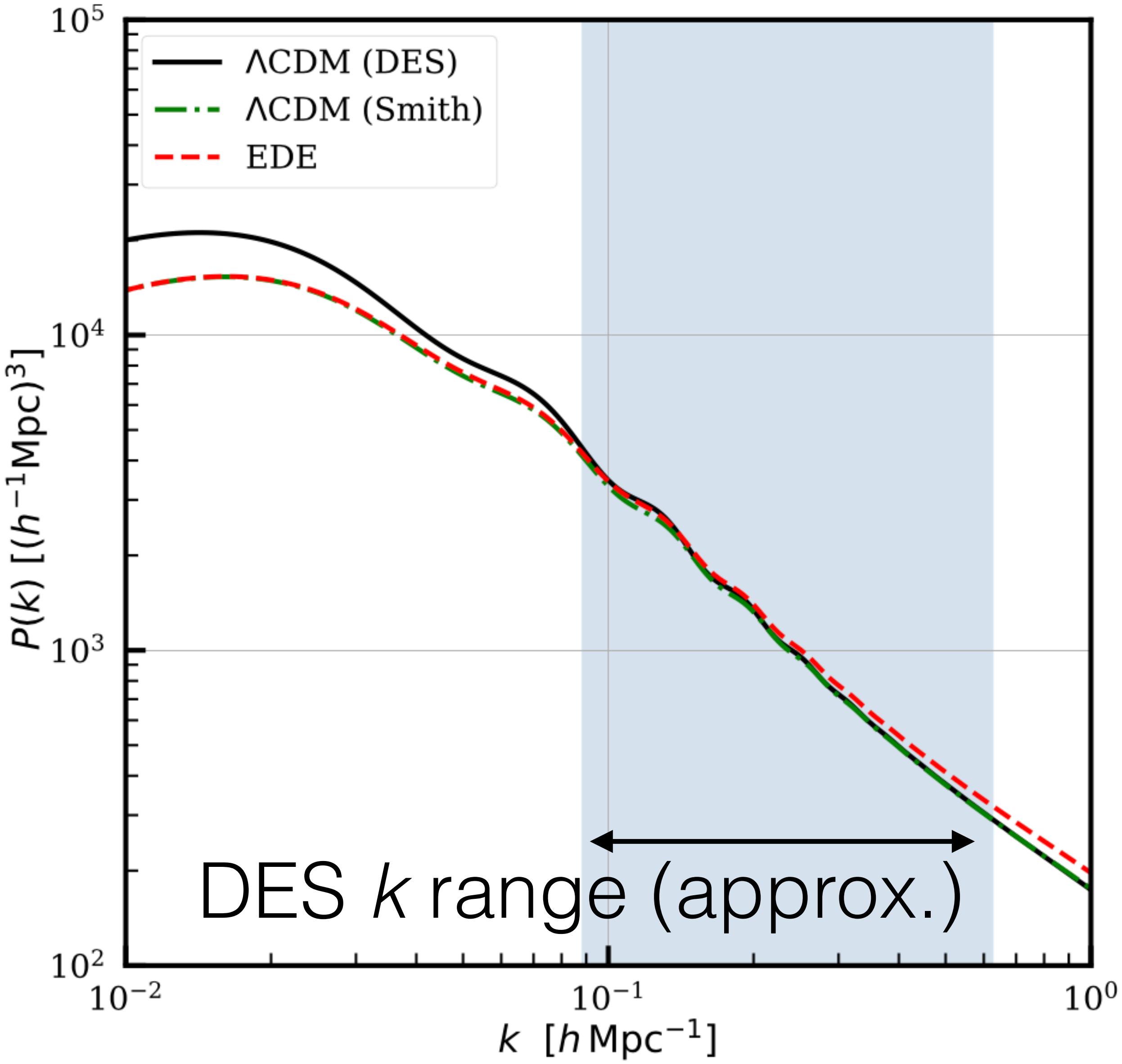
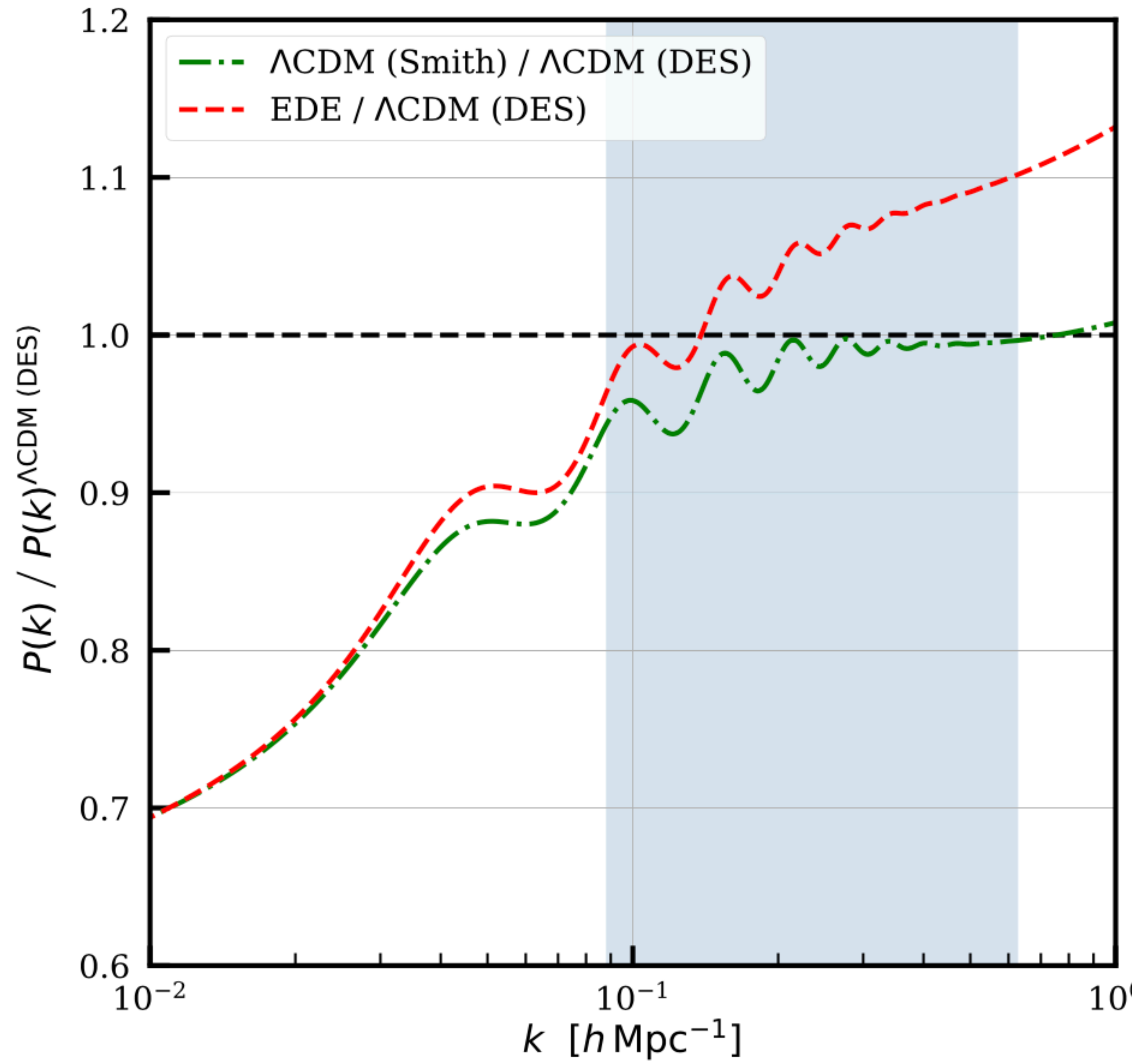
LSS in EDE Model

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

Summary

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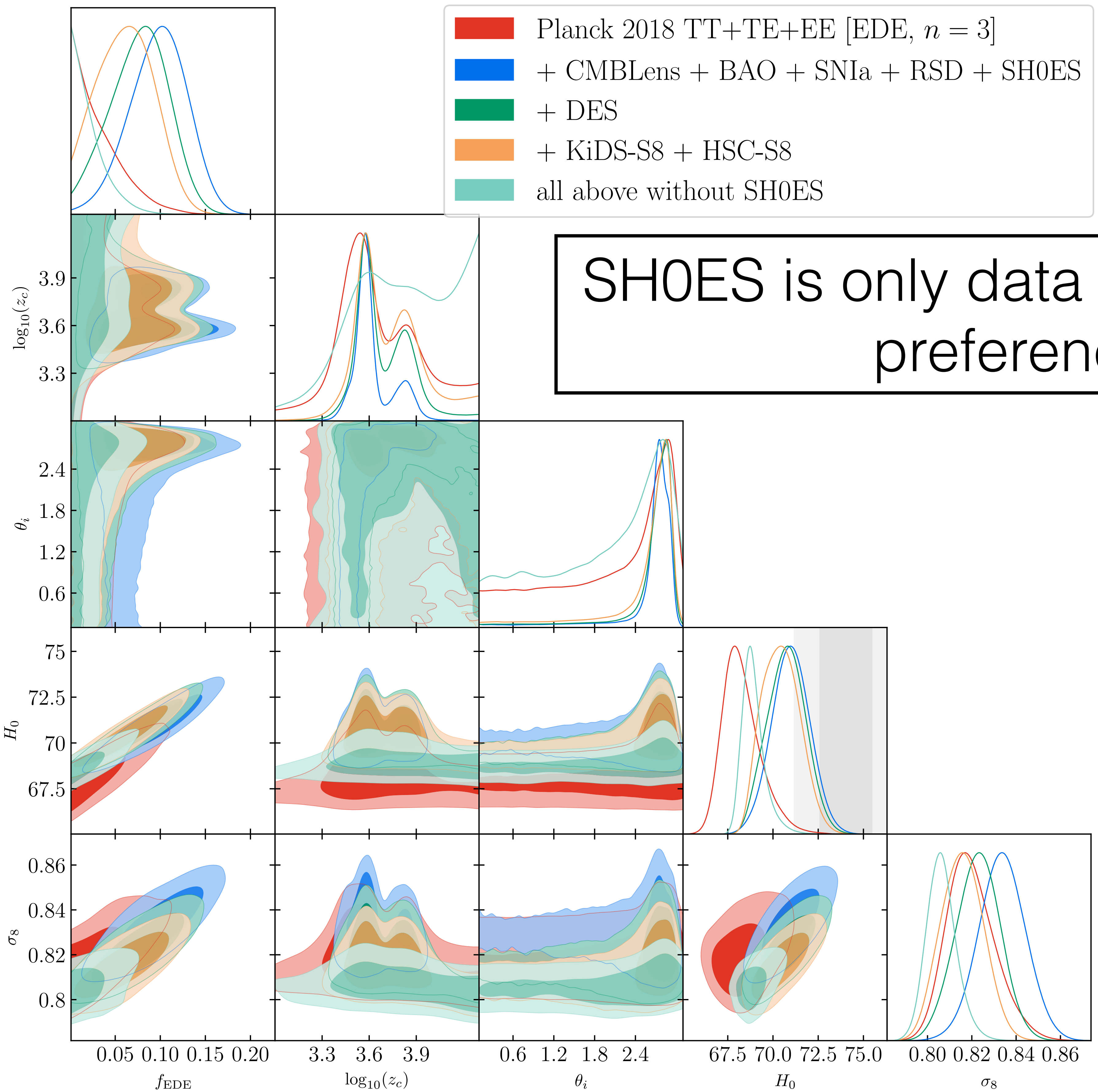
SH0ES is only data set driving preference for EDE



JCH+ (2020)

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EDE in Primary CMB?

Fit to Planck 2018 TT+TE+EE data alone

JCH+ (2020)

EDE in Primary CMB? No

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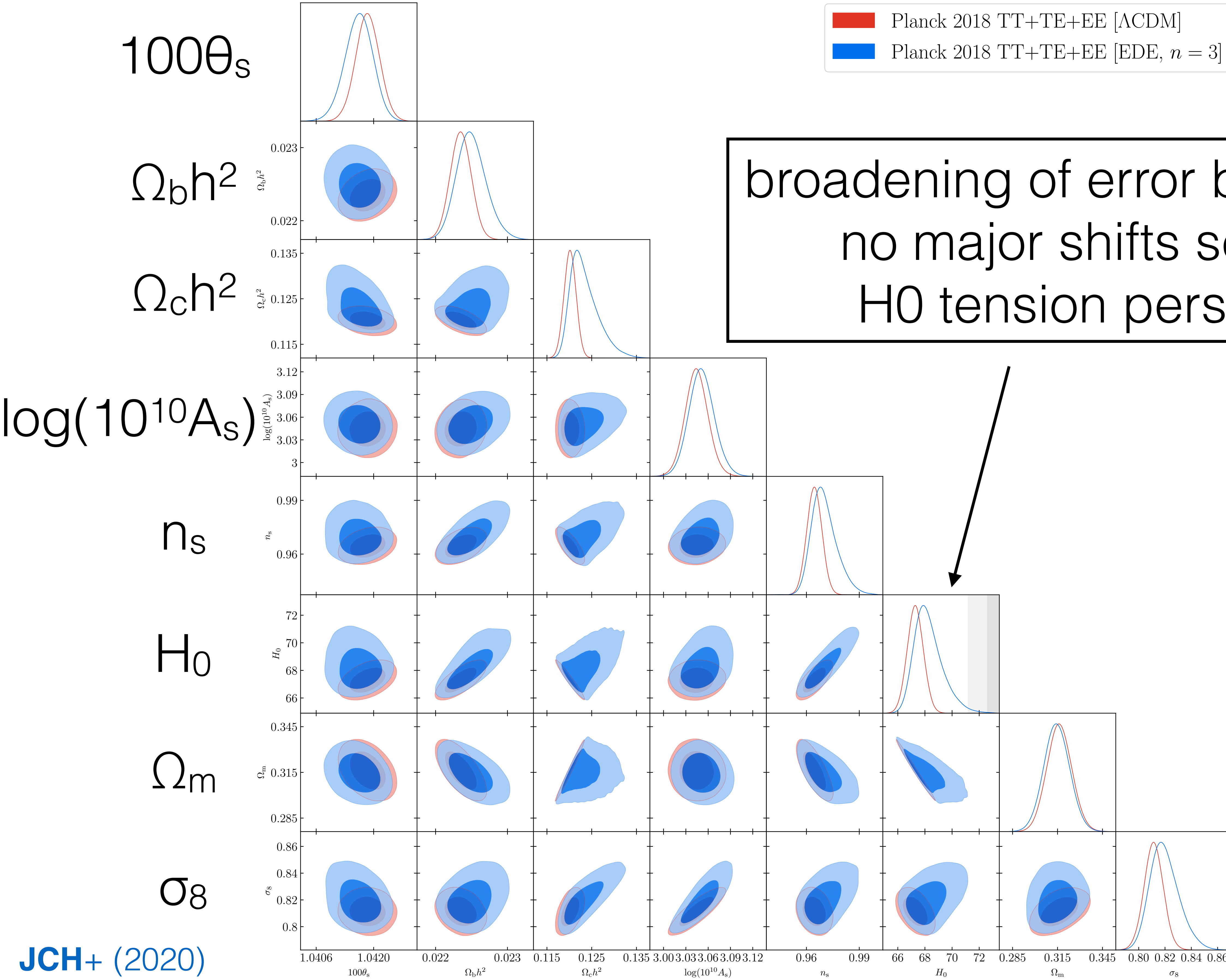

broadening of error bars, but no major shifts seen; H0 tension persists

JCH+ (2020)

Primary CMB Alone

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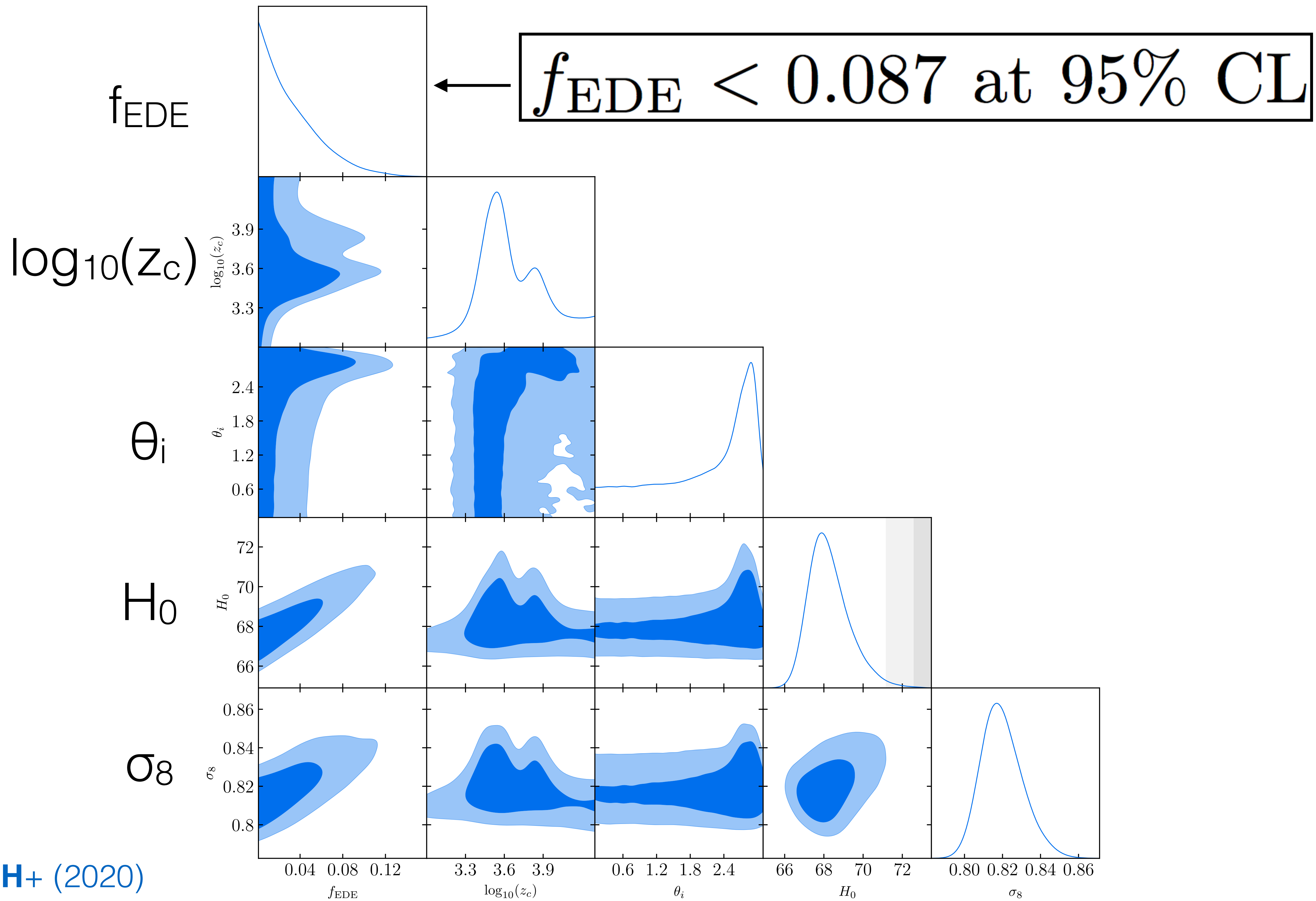
Planck primary CMB data show no evidence for EDE component



JCH+ (2020)

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Reproduce Earlier Results

Fit to Planck + BAO + SH0ES + SNIa + RSD

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

Reproduce Earlier Results

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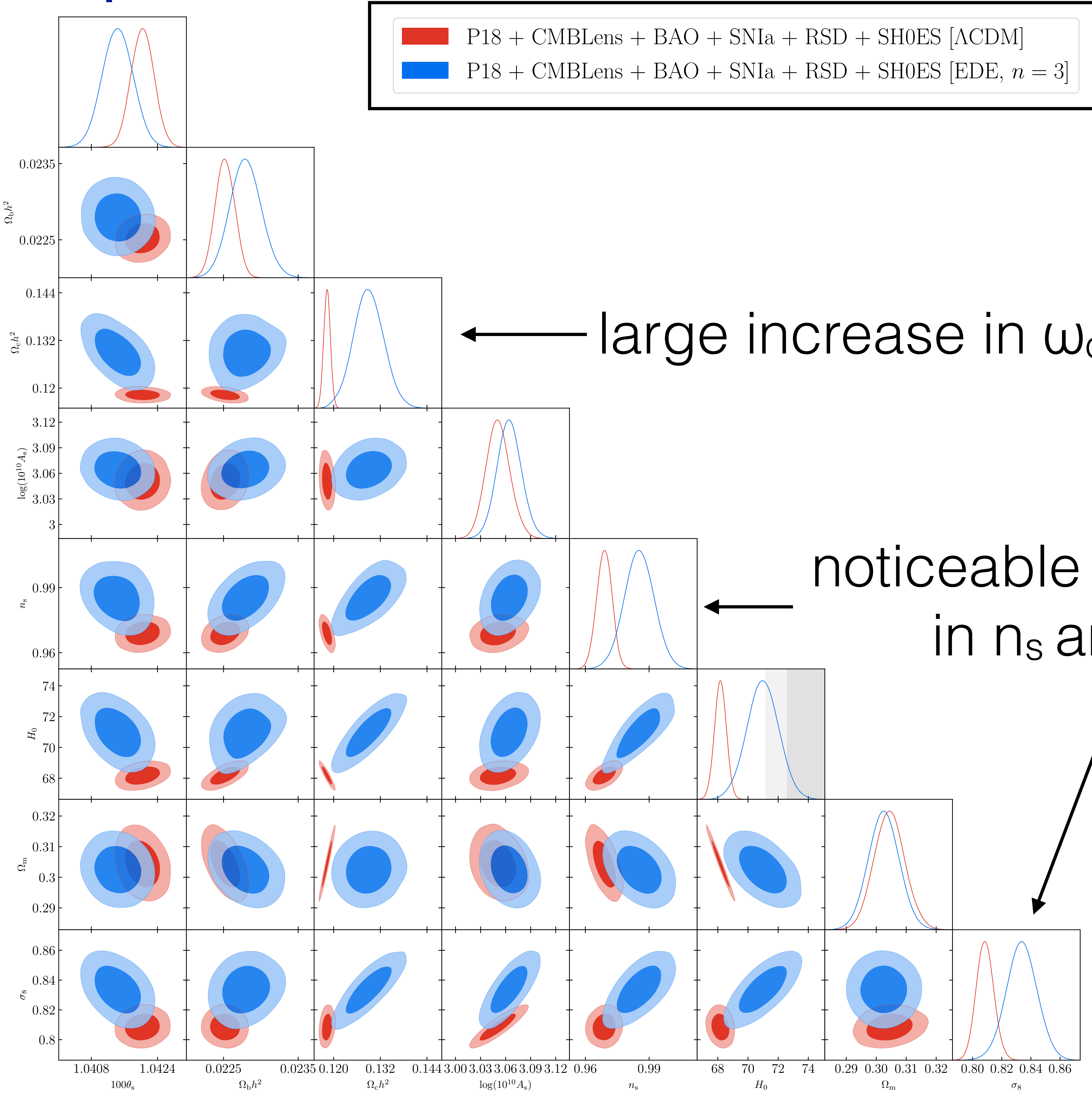

large increase in ω_{cdm}

noticeable increases in n_s and σ_8

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

Reproduce Earlier Results

Colin Hill
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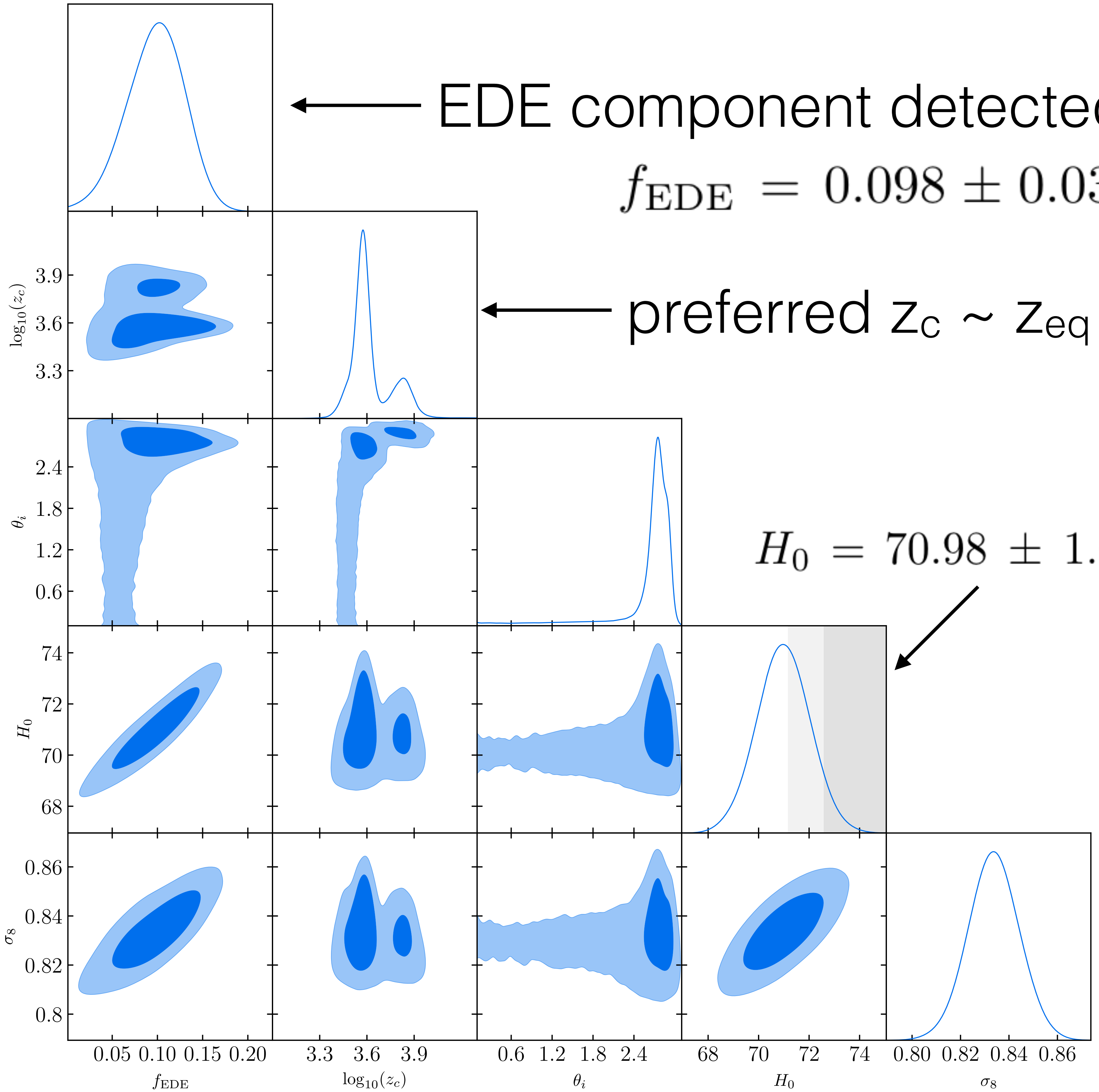

EDE component detected at ~3σ

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

preferred $z_c \sim z_{eq}$

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

JCH+ (2020)

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Inclusion of LSS Data

Fit to "everything" *including* DES, HSC, KiDS

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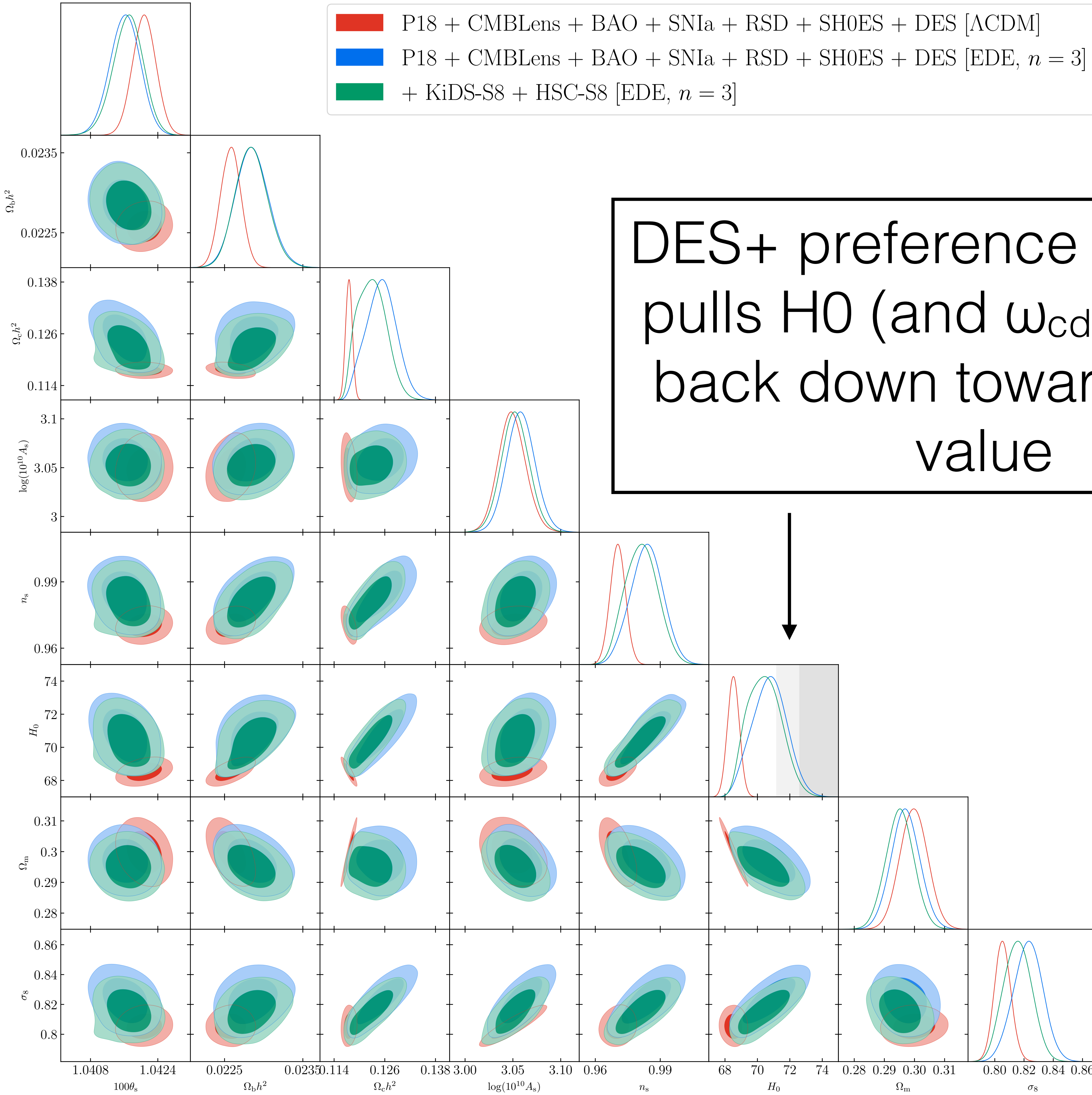
Inclusion of LSS Data



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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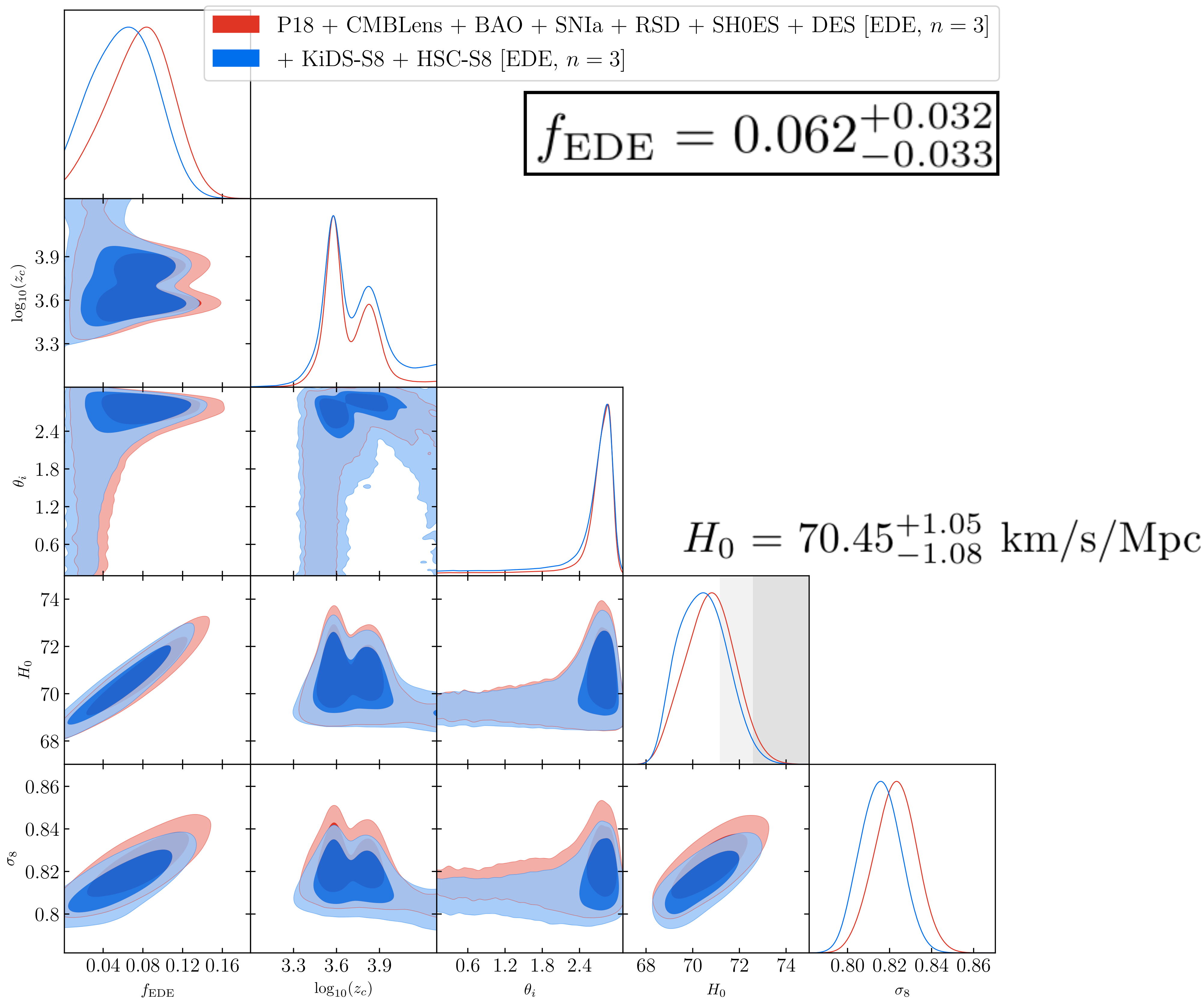
Inclusion of LSS Data

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



JCH+ (2020)

Analysis without SH0ES

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

JCH+ (2020)

Analysis without SH0ES

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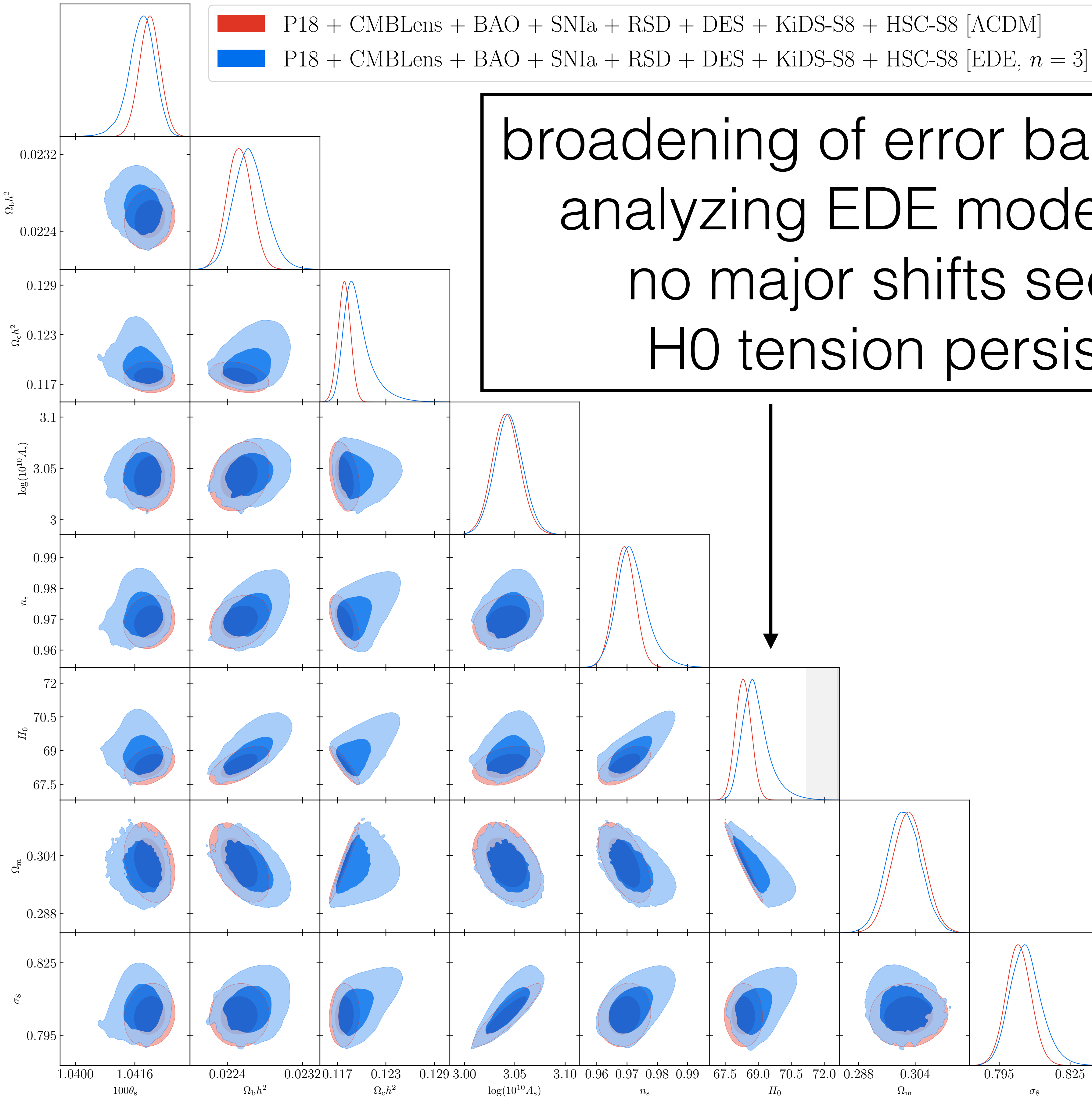

broadening of error bars when analyzing EDE model, but no major shifts seen; H0 tension persists

JCH+ (2020)

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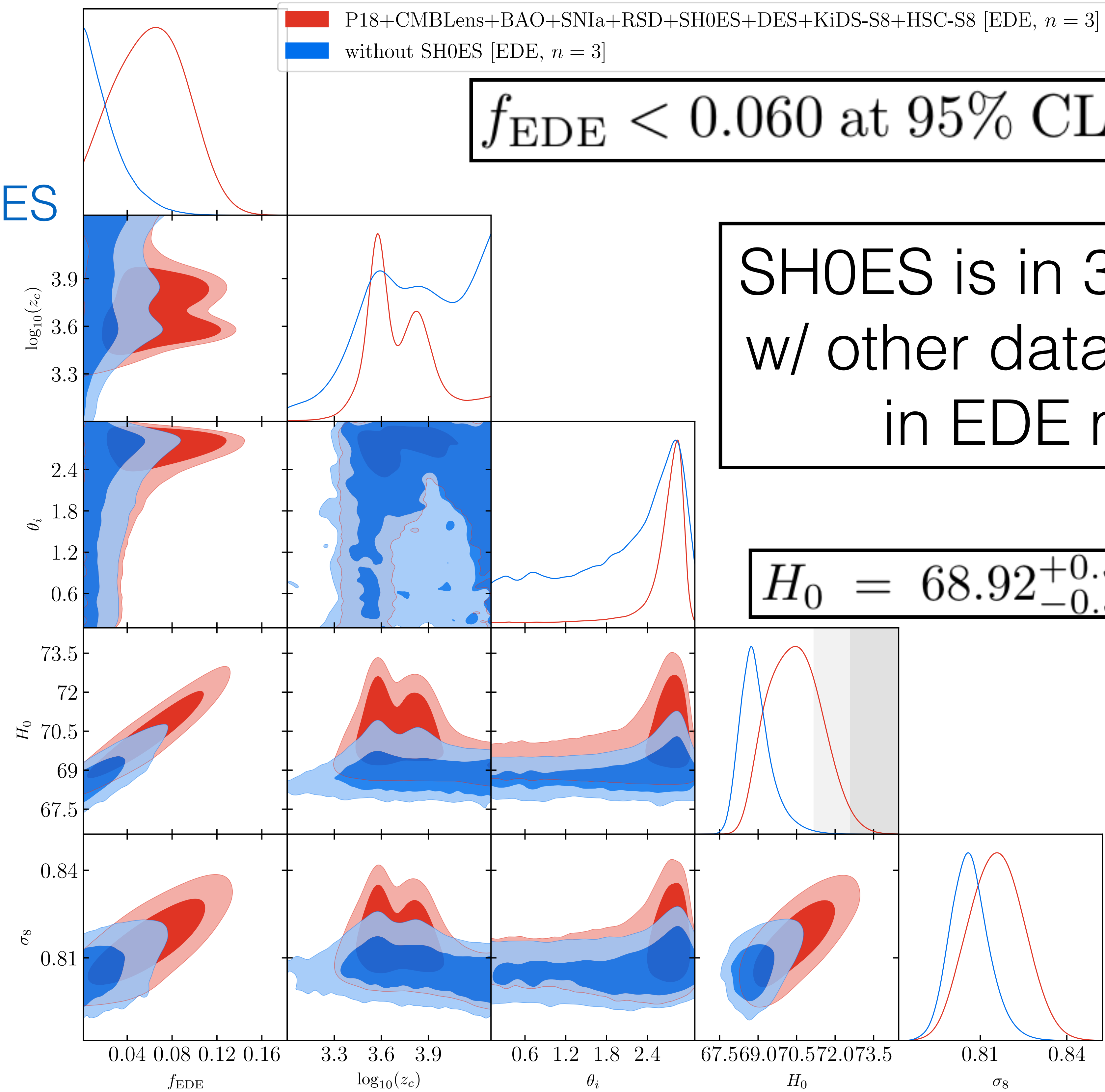
Analysis without SH0ES

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)

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

JCH+ (2020)

Physical Priors

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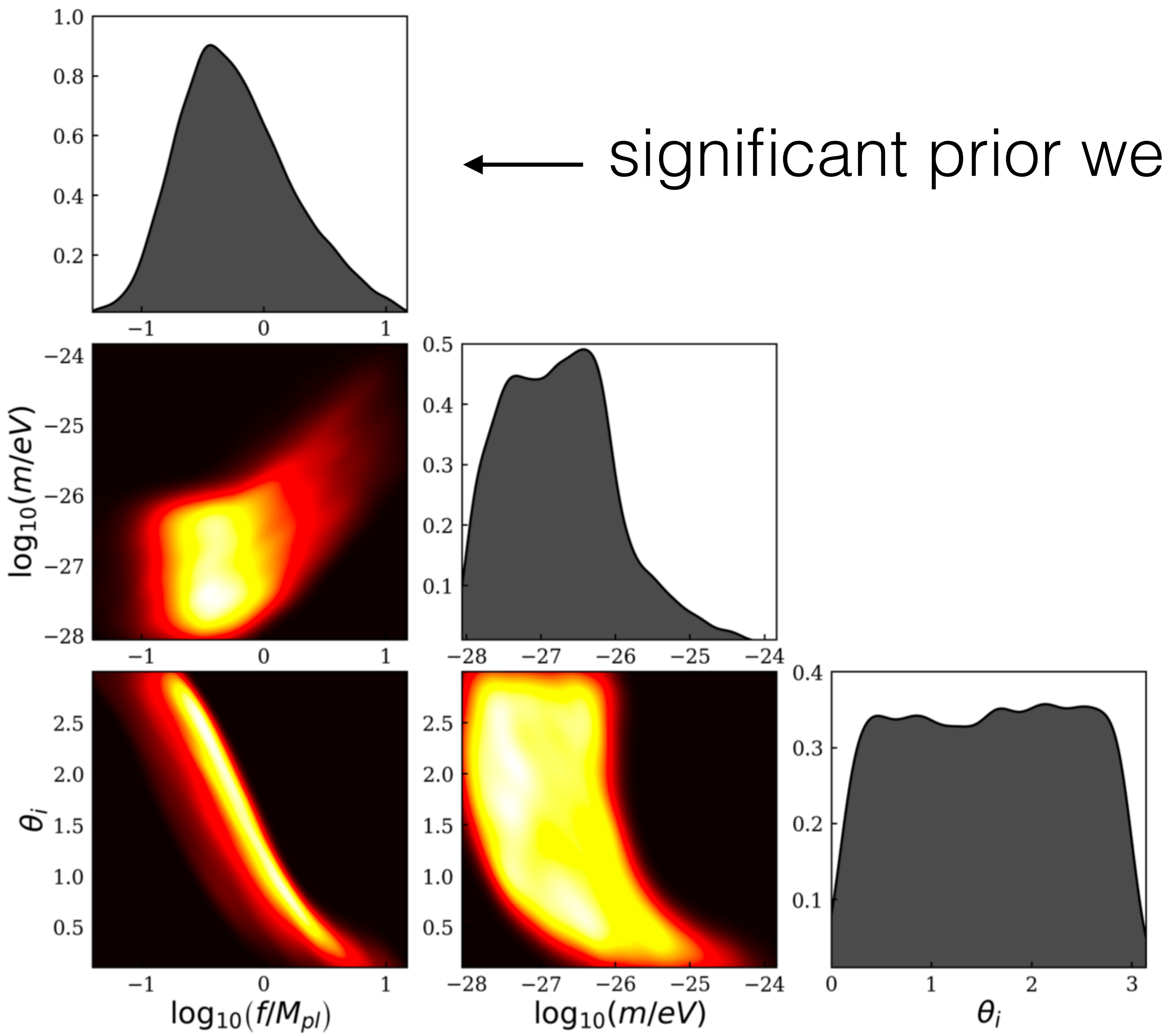
Uniform priors on f_{EDE} and $\log(z_c)$ are very non-uniform on physical scalar field parameters f and m



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

JCH+ (2020)

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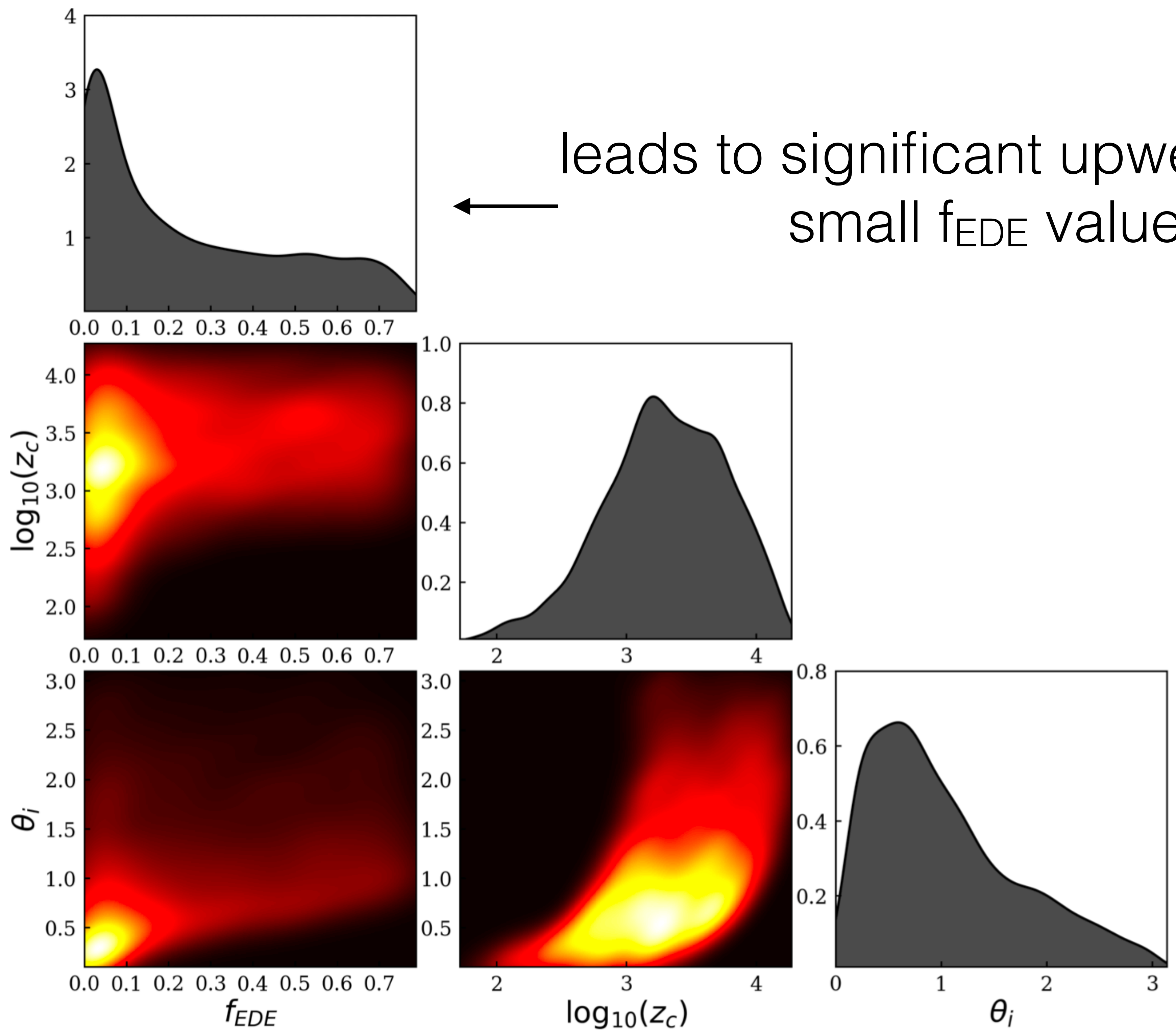
Physical Priors

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



leads to significant upweighting of small f_{EDE} values

JCH+ (2020)

Primary CMB Alone, Revisited

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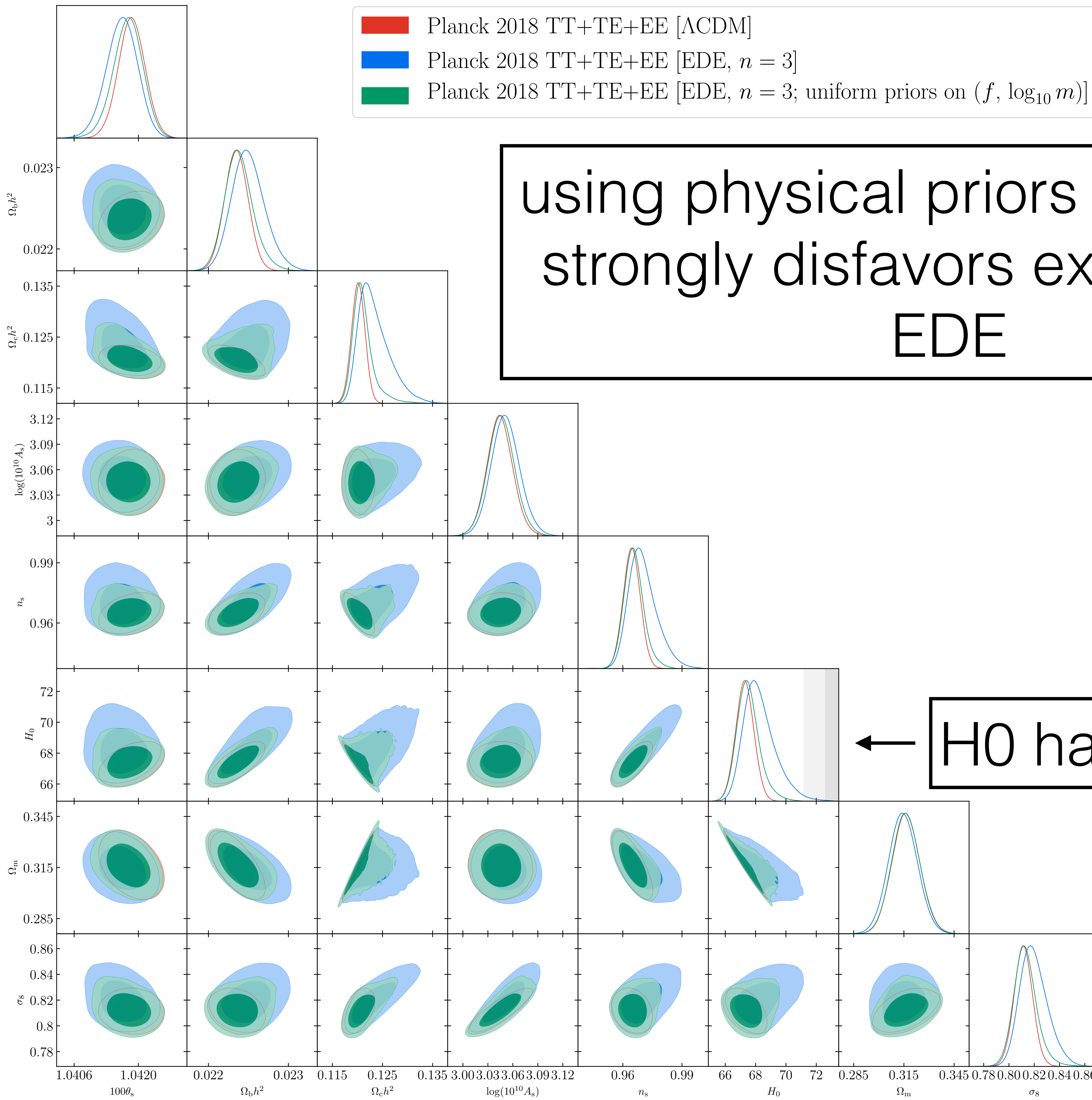

using physical priors even more strongly disfavors existence of EDE

← H0 hardly moves

JCH+ (2020)

Validation of S_8 Procedure

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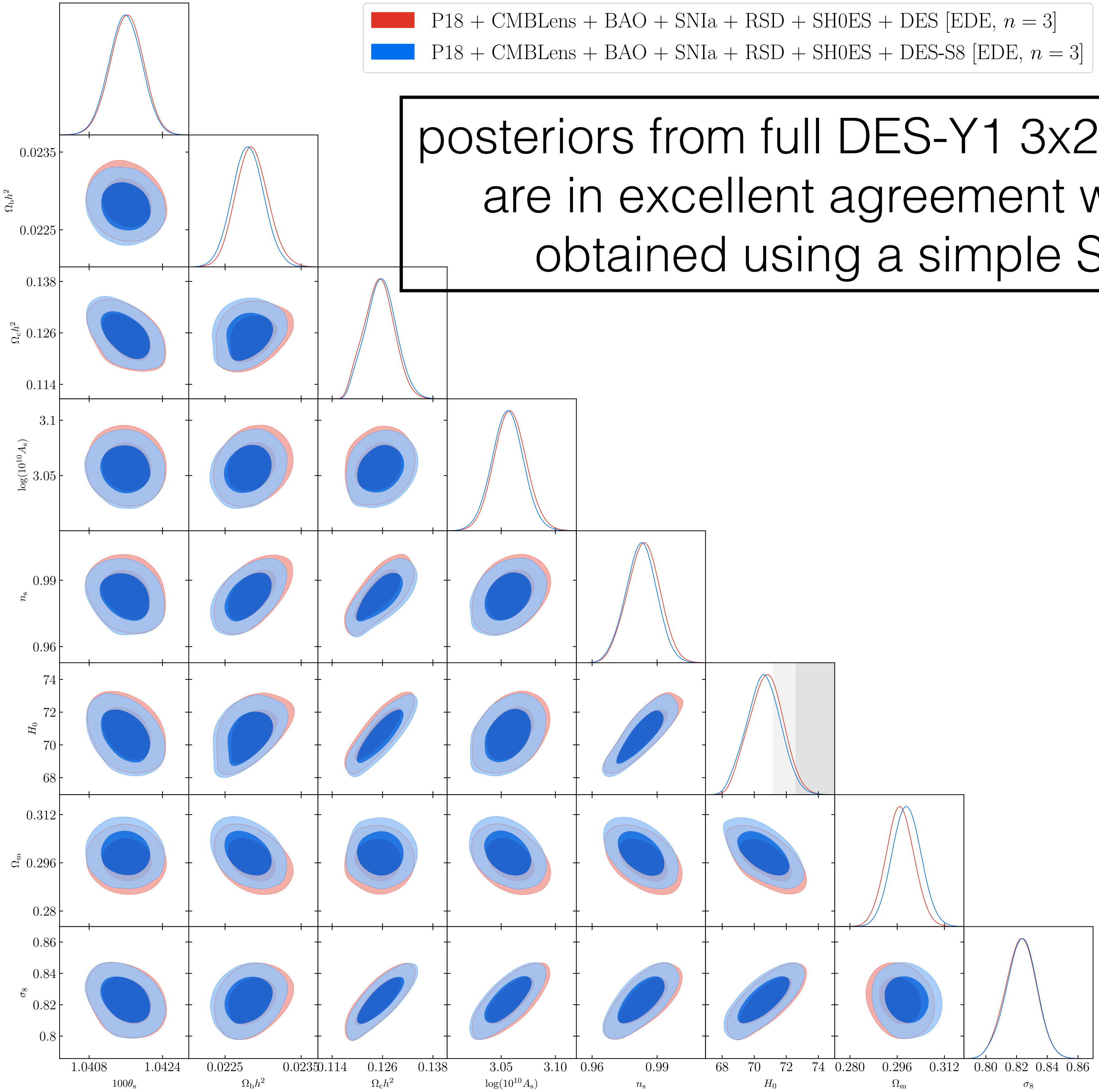

posteriors from full DES-Y1 3x2pt likelihood are in excellent agreement with those obtained using a simple S8 prior

JCH+ (2020)

Validation of S_8 Procedure

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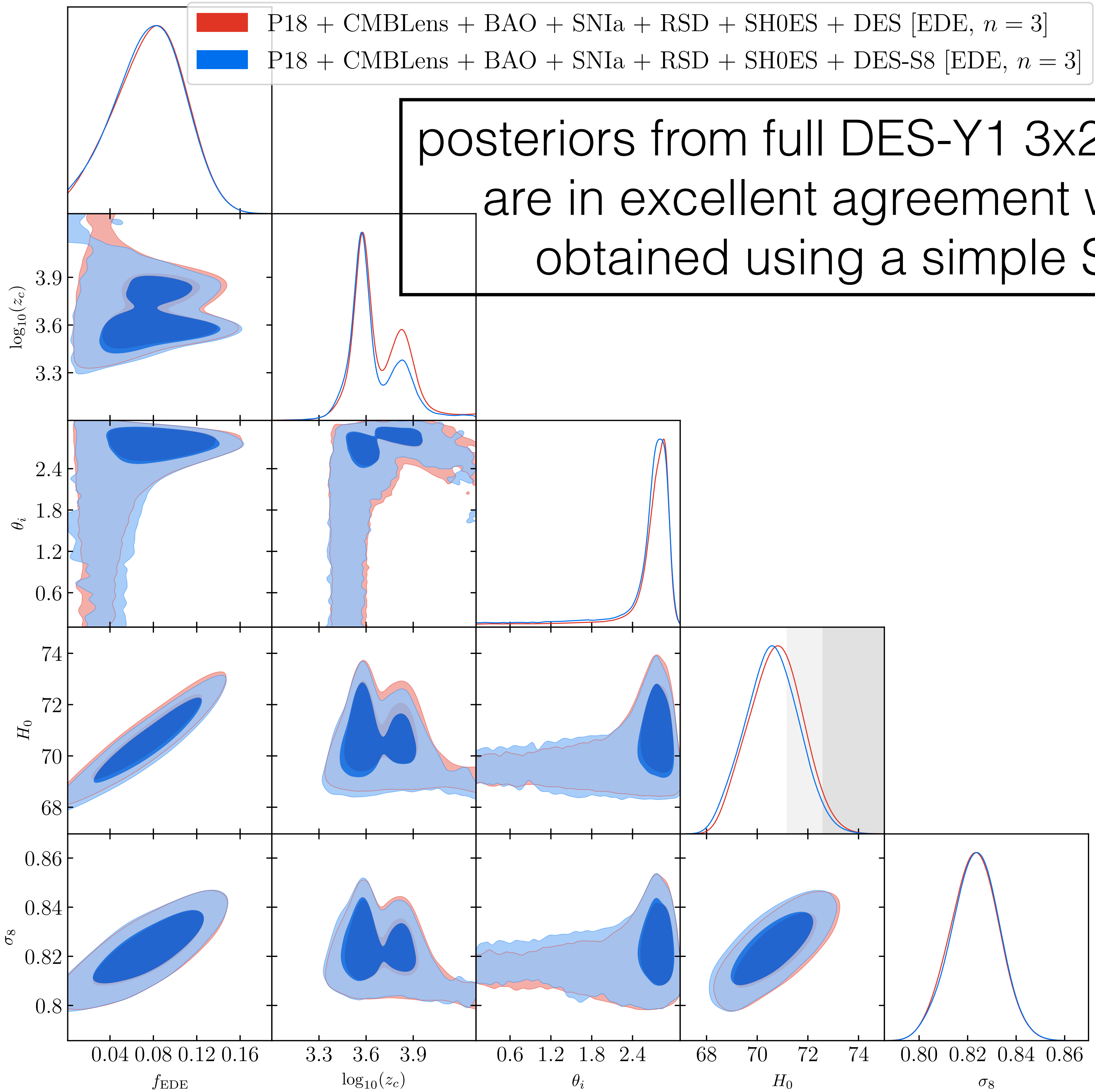

posteriors from full DES-Y1 3x2pt likelihood are in excellent agreement with those obtained using a simple S8 prior

JCH+ (2020)

Summary

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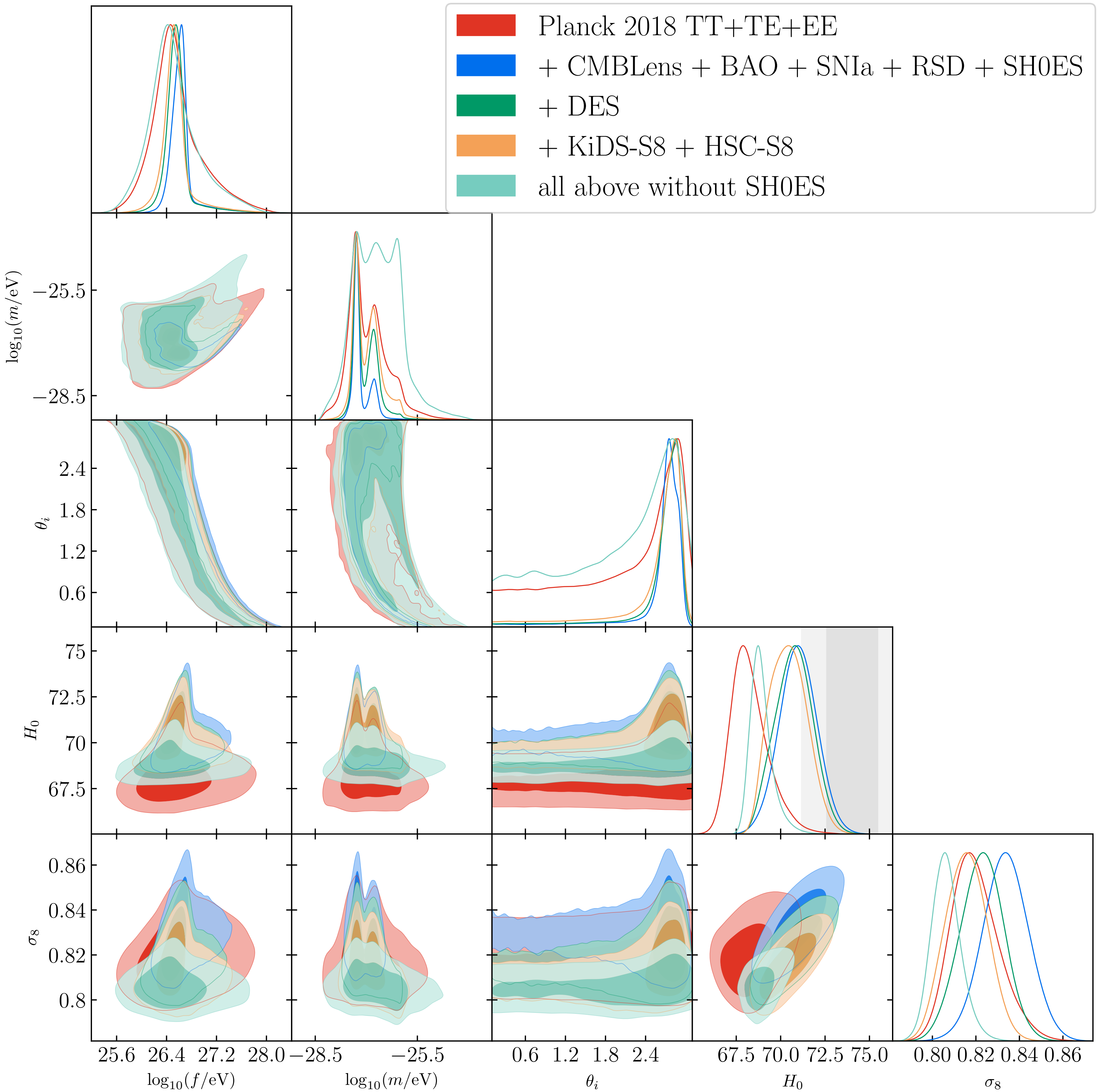

JCH+ (2020)

EDE in the EFTofLSS

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Fractional difference between fiducial EDE and LCDM models

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

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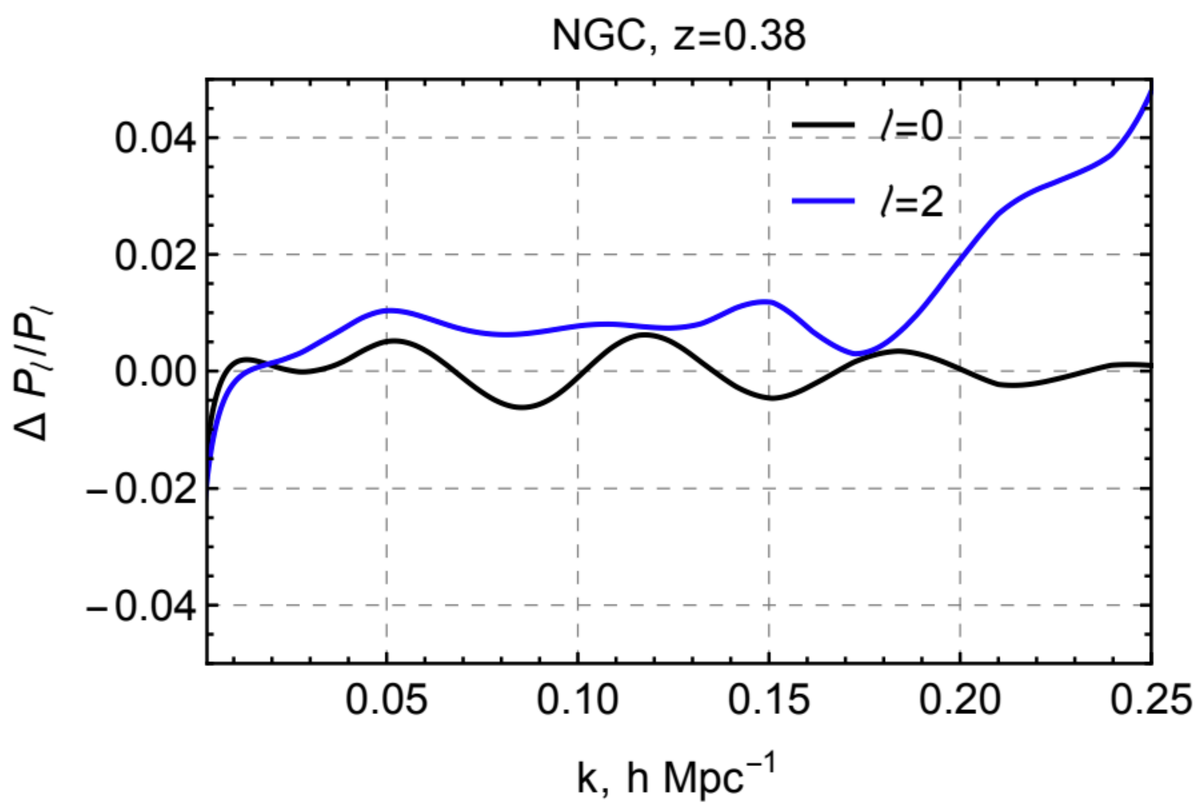
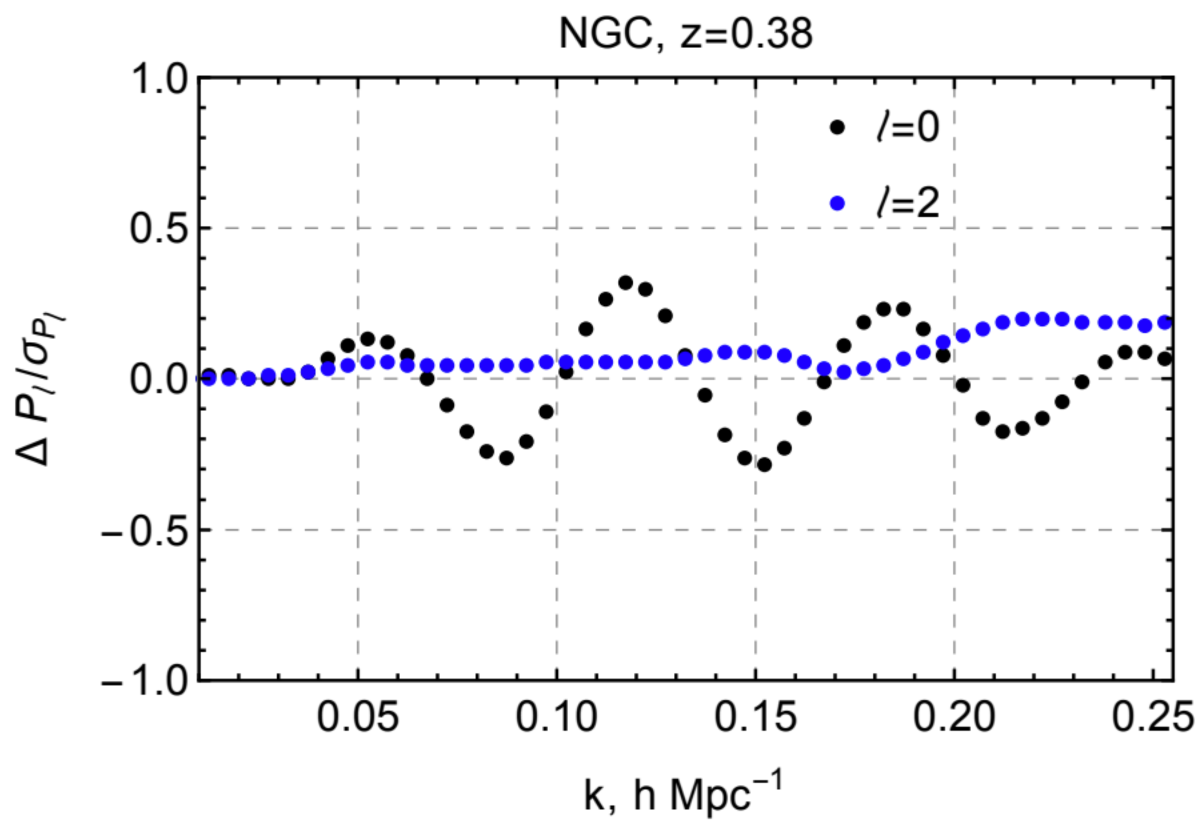
EDE in the EFTofLSS

Fractional difference between fiducial EDE and LCDM models





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)

Planck + BOSS (EFT)

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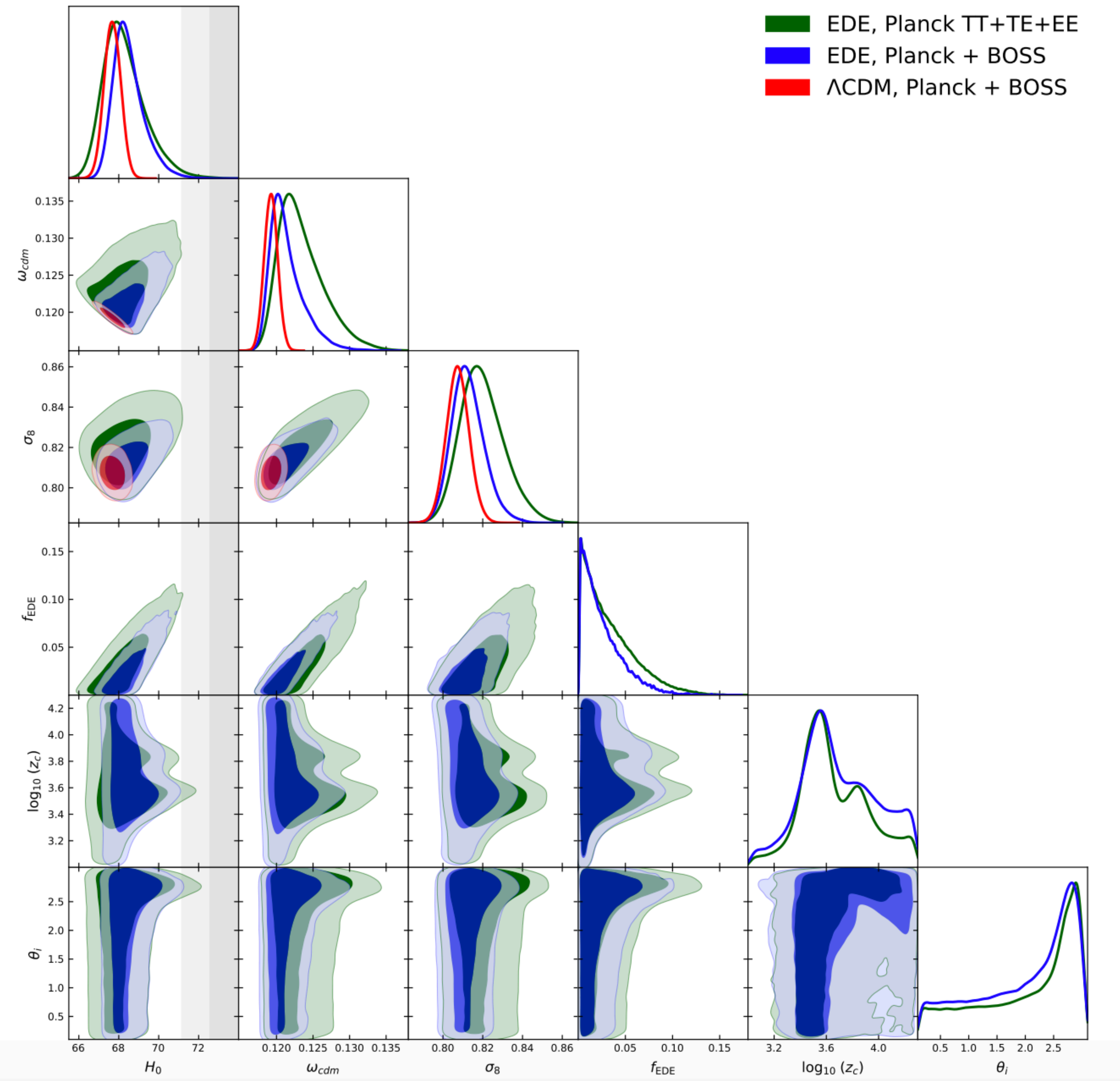

Ivanov, McDonough, **JCH**+ (2020)

Tables

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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)
$\boldsymbol{f_{\rm EDE}}$	< 0.087	0.098 ± 0.032	$0.077^{+0.032}_{-0.034}$	$0.062^{+0.032}_{-0.033}$	< 0.060
$\mathbf{log_{10}(z_c)}$	$3.66^{+0.28}_{-0.24}$	$3.63^{+0.17}_{-0.10}$	$3.69^{+0.18}_{-0.15}$	$3.73^{+0.20}_{-0.19}$	> 3.28
$\boldsymbol{\theta_i}$	> 0.36	$2.58^{+0.29}_{-0.09}$	$2.58^{+0.32}_{-0.15}$	$2.49^{+0.40}_{-0.38}$	> 0.35
H_0 [km/s/Mpc]	$68.29^{+1.02}_{-1.00}$	70.98 ± 1.05	$70.75^{+1.05}_{-1.09}$	$70.45^{+1.05}_{-1.08}$	$68.92^{+0.57}_{-0.59}$
σ_8	$0.8198^{+0.0109}_{-0.0107}$	0.8337 ± 0.0105	$0.8228^{+0.0099}_{-0.0101}$	0.8157 ± 0.0096	0.8064 ± 0.0065

JCH+ (2020)

Tables

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Constraints from *Planck* 2018 data only: TT+TE+EE

Parameter	ΛCDM	EDE ($n = 3$)
$\ln(10^{10} A_s)$	$3.044\,(3.055)\ \pm 0.016$	$3.051\,(3.056)\ \pm 0.017$
n_s	$0.9645\,(0.9659)\ \pm 0.0043$	$0.9702\,(0.9769)^{+0.0071}_{-0.0069}$
$100\theta_s$	$1.04185\,(1.04200)\ \pm 0.00029$	$1.04164\,(1.04168)\ \pm 0.00034$
$\Omega_b h^2$	$0.02235\,(0.02244)\ \pm 0.00015$	$0.02250\,(0.02250)\ \pm 0.00020$
$\Omega_c h^2$	$0.1202\,(0.1201)\ \pm 0.0013$	$0.1234\,(0.1268)^{+0.0031}_{-0.0030}$
τ_{reio}	$0.0541\,(0.0587)\ \pm 0.0076$	$0.0549\,(0.0539)\ \pm 0.0078$
$\log_{10}(z_c)$	–	$3.66\,(3.75)^{+0.28}_{-0.24}$
f_{EDE}	–	$< 0.087\,(0.068)$
θ_i	–	$> 0.36\,(2.96)$
H_0 [km/s/Mpc]	$67.29\,(67.44)\ \pm 0.59$	$68.29\,(69.13)^{+1.02}_{-1.00}$
Ω_m	$0.3162\,(0.3147)\ \pm 0.0083$	$0.3145\,(0.3138)\ \pm 0.0086$
σ_8	$0.8114\,(0.8156)\ \pm 0.0073$	$0.8198\,(0.8280)^{+0.0109}_{-0.0107}$
S_8	$0.8331\,(0.8355)\ \pm 0.0159$	$0.8393\,(0.8468)\ \pm 0.0173$
$\log_{10}(f/\mathrm{eV})$	–	$26.57\,(26.36)^{+0.39}_{-0.36}$
$\log_{10}(m/\mathrm{eV})$	–	$-26.94\,(-26.90)^{+0.58}_{-0.53}$

χ^2 statistics from *Planck* 2018 data only: TT+TE+EE

Datasets	ΛCDM	EDE
Planck 2018 low-ℓ TT	23.4	22.1
Planck 2018 low-ℓ EE	397.2	396.0
Planck 2018 high-ℓ TT+TE+EE	2344.9	2343.3
Total χ^2	2765.5	2761.4
$\Delta\chi^2$		-4.1

JCH+ (2020)

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Tables

Constraints from *Planck* 2018 TT+TE+EE + CMB Lensing, BAO, SNIa, SH0ES, and RSD

Parameter	ΛCDM	EDE ($n = 3$)
$\boldsymbol{\ln(10^{10} A_s)}$	$3.051\,(3.047)\ \pm 0.014$	$3.064\,(3.058)\ \pm 0.015$
$\boldsymbol{n_s}$	$0.9689\,(0.9686)\ \pm 0.0036$	$0.9854\,(0.9847)^{+0.70}_{-0.69}$
$\boldsymbol{100\theta_s}$	$1.04204\,(1.04209)\ \pm 0.00028$	$1.04144\,(1.04119)\ \pm 0.00037$
$\boldsymbol{\Omega_b h^2}$	$0.02252\,(0.02249)\ \pm 0.00013$	$0.02280\,(0.02286)\ \pm 0.00021$
$\boldsymbol{\Omega_c h^2}$	$0.11830\,(0.11855)\ \pm 0.00085$	$0.12899\,(0.12999)\ \pm 0.00390$
$\boldsymbol{\tau_{reio}}$	$0.0590\,(0.0566)\ \pm 0.0072$	$0.0573\,(0.0511)\ \pm 0.0071$
$\boldsymbol{\log_{10}(z_c)}$	–	$3.63\,(3.59)^{+0.17}_{-0.10}$
$\boldsymbol{f_{EDE}}$	–	$0.098\,(0.105) \pm 0.032$
$\boldsymbol{\theta_i}$	–	$2.58\,(2.71)^{+0.29}_{-0.09}$
H_0 [km/s/Mpc]	$68.17\,(68.07)\ \pm 0.39$	$70.98\,(71.15) \pm 1.05$
Ω_m	$0.3044\,(0.3058)\ \pm 0.0051$	$0.3025\,(0.3032)\ \pm 0.0051$
σ_8	$0.8086\,(0.8081)\ \pm 0.0060$	$0.8337\,(0.8322) \pm 0.0105$
S_8	$0.8145\,(0.8158)\ \pm 0.0099$	$0.8372\,(0.8366) \pm 0.0127$
$\log_{10}(f/\text{eV})$	–	$26.64\,(26.63)^{+0.08}_{-0.15}$
$\log_{10}(m/\text{eV})$	–	$-27.15\,(-27.27)^{+0.34}_{-0.22}$

JCH+ (2020)

Tables

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χ^2 statistics from the fit to *Planck* 2018 TT+TE+EE + CMB Lensing, BAO, SNIa, SH0ES, and RSD

Datasets	ΛCDM	EDE
CMB TT, EE, TE:		
Planck 2018 low-ℓ TT	22.8	21.4
Planck 2018 low-ℓ EE	396.4	395.8
Planck 2018 high-ℓ TT+TE+EE	2346.8	2346.9
LSS:		
Planck CMB lensing	8.9	9.5
BAO (6dF)	0.0015	0.000002
BAO (DR7 MGS)	1.6	1.7
BAO+RSD (DR12 BOSS)	5.9	6.5
Supernovae:		
Pantheon	1034.8	1034.8
SH0ES	17.6	4.1
Total χ^2	3834.8	3820.7
$\Delta\chi^2$		-14.1

JCH+ (2020)

Tables

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Constraints from *Planck* 2018 TT+TE+EE + CMB Lensing, BAO, SNIa, SH0ES, RSD, and DES-Y1

Parameter	ΛCDM	EDE ($n = 3$)
$\ln(10^{10} A_s)$	3.049 (3.049) $\pm$ 0.014	3.058 (3.064) $\pm$ 0.015
n_s	0.9704 (0.9698) $\pm$ 0.0035	0.9838 (0.9909)$^{+0.0074}_{-0.0075}$
$100\theta_s$	1.04208 (1.04183) $\pm$ 0.00028	1.04162 (1.04172) $\pm$ 0.00036
$\Omega_b h^2$	0.02258 (0.02260) $\pm$ 0.00013	0.02285 (0.02304) $\pm$ 0.00021
$\Omega_c h^2$	0.11752 (0.11810) $\pm$ 0.00078	0.1251 (0.1254)$^{+0.0035}_{-0.0037}$
τ_{reio}	0.0590 (0.0584) $\pm$ 0.0072	0.0581 (0.0626) $\pm$ 0.0072
$\log_{10}(z_c)$	–	3.69 (3.84)$^{+0.18}_{-0.15}$
f_{EDE}	–	0.077 (0.088)$^{+0.032}_{-0.034}$
θ_i	–	2.58 (2.89)$^{+0.32}_{-0.15}$
H_0 [km/s/Mpc]	68.52 (68.24) $\pm$ 0.36	70.75 (71.05)$^{+1.05}_{-1.09}$
Ω_m	0.2998 (0.3035) $\pm$ 0.0046	0.2970 (0.2954) $\pm$ 0.0047
σ_8	0.8054 (0.8067) $\pm$ 0.0057	0.8228 (0.8263)$^{+0.0099}_{-0.0101}$
S_8	0.8051 (0.8115) $\pm$ 0.0087	0.8186 (0.8199) $\pm$ 0.0109
$\log_{10}(f/\text{eV})$	–	26.57 (26.47)$^{+0.11}_{-0.16}$
$\log_{10}(m/\text{eV})$	–	−27.03 (−26.76)$^{+0.33}_{-0.32}$

JCH+ (2020)

Tables

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χ^2 statistics from the fit to *Planck* 2018 TT+TE+EE + CMB Lensing, BAO, SNIa, SH0ES, RSD, and DES-Y1

Datasets	ΛCDM	EDE
CMB TT, EE, TE:		
Planck 2018 low-ℓ TT	22.7	20.5
Planck 2018 low-ℓ EE	396.8	397.7
Planck 2018 high-ℓ TT+TE+EE	2347.6	2350.2
LSS:		
Planck CMB lensing	9.0	9.6
BAO (6dF)	0.0001	0.04
BAO (DR7 MGS)	1.8	2.4
BAO+RSD (DR12 BOSS)	5.9	6.9
DES-Y1	507.8	508.7
Supernovae:		
Pantheon	1034.8	1034.8
SH0ES	16.6	4.4
Total χ^2	4343.0	4335.2
$\Delta\chi^2$		-7.8

JCH+ (2020)

Tables

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Constraints from *Planck* 2018 TT+TE+EE + CMB Lensing, BAO, SNIa, SH0ES, RSD, DES-Y1, KiDS-S_8, and HSC-S_8

Parameter	ΛCDM	EDE ($n = 3$)
$\ln(10^{10} A_s)$	3.046 ± 0.014	3.053 ± 0.014
n_s	0.9710 ± 0.0035	$0.9814^{+0.0075}_{-0.0077}$
$100\theta_s$	1.04209 ± 0.00028	1.04169 ± 0.00036
$\Omega_b h^2$	0.02260 ± 0.00013	0.02285 ± 0.00020
$\Omega_c h^2$	0.11718 ± 0.00075	$0.1230^{+0.0034}_{-0.0035}$
τ_{reio}	0.0581 ± 0.0070	0.0574 ± 0.0071
$\log_{10}(z_c)$	−	$3.73^{+0.20}_{-0.19}$
f_{EDE}	−	$0.062^{+0.032}_{-0.033}$
θ_i	−	$2.49^{+0.40}_{-0.38}$
H_0 [km/s/Mpc]	68.67 ± 0.35	$70.45^{+1.05}_{-1.08}$
Ω_m	0.2978 ± 0.0044	0.2952 ± 0.0046
σ_8	0.8032 ± 0.0055	0.8157 ± 0.0096
S_8	0.8002 ± 0.0082	0.8090 ± 0.0100
$\log_{10}(f/\text{eV})$	−	$26.55^{+0.13}_{-0.18}$
$\log_{10}(m/\text{eV})$	−	$-26.94^{+0.39}_{-0.40}$

Constraints from *Planck* 2018 TT+TE+EE + CMB Lensing, BAO, SNIa, RSD, DES-Y1, KiDS-S_8, and HSC-S_8 (No-SH0ES)

Parameter	ΛCDM	EDE ($n = 3$)
$\ln(10^{10} A_s)$	3.041 ± 0.014	3.044 ± 0.014
n_s	0.9692 ± 0.0035	0.9718 ± 0.0049
$100\theta_s$	1.04200 ± 0.00028	$1.04177^{+0.00035}_{-0.00033}$
$\Omega_b h^2$	0.02253 ± 0.00013	0.02264 ± 0.00017
$\Omega_c h^2$	0.11785 ± 0.00076	0.1196 ± 0.0016
τ_{reio}	0.0552 ± 0.0069	0.0558 ± 0.0069
$\log_{10}(z_c)$	−	> 3.28
f_{EDE}	−	< 0.060
θ_i	−	> 0.35
H_0 [km/s/Mpc]	68.33 ± 0.36	$68.92^{+0.57}_{-0.59}$
Ω_m	0.3021 ± 0.0045	0.3008 ± 0.0047
σ_8	0.8032 ± 0.0053	0.8064 ± 0.0065
S_8	0.8060 ± 0.0082	0.8074 ± 0.0089
$\log_{10}(f/\text{eV})$	−	$26.52^{+0.38}_{-0.36}$
$\log_{10}(m/\text{eV})$	−	$-26.67^{+0.65}_{-0.69}$

JCH+ (2020)

Tables

Colin Hill
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Constraints from *Planck* 2018 data only (TT+TE+EE)
with uniform priors on f and $\log_{10}(m)$

Parameter	EDE ($n = 3$)
$\ln(10^{10} A_s)$	$3.046\,(3.042)\ \pm 0.016$
n_s	$0.9657\,(0.9626)^{+0.0048}_{-0.0049}$
$100\theta_s$	$1.04177\,(1.04184)\ \pm 0.00032$
$\Omega_b h^2$	$0.02238\,(0.02222)\ \pm 0.00017$
$\Omega_c h^2$	$0.1212\,(0.1218)^{+0.0017}_{-0.0019}$
τ_{reio}	$0.0541\,(0.0532)\ \pm 0.0075$
$f/(10^{27}\,\mathrm{eV})$	$2.25\,(0.80)^{+2.49}_{-1.96}$
$\log_{10}(m/\mathrm{eV})$	$-26.98\,(-26.11)^{+0.66}_{-0.64}$
θ_i	$< 2.31\,(0.15)$
H_0 [km/s/Mpc]	$67.53\,(66.63)^{+0.71}_{-0.73}$
Ω_m	$0.3162\,(0.3258)\ \pm 0.0083$
σ_8	$0.8132\,(0.8153)^{+0.0086}_{-0.0089}$
S_8	$0.8349\,(0.8497)\ \pm 0.0166$
$\log_{10}(z_c)$	$< 3.89\,(3.16)$
f_{EDE}	$< 0.041\,(0.0003)$
$\log_{10}(f/\mathrm{eV})$	$27.07\,(26.92)\ \pm 0.60$

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Tables

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Constraints from *Planck* 2018 data + BOSS DR12

Parameter	ΛCDM	EDE ($n=3$)
$\ln(10^{10}A_s)$	$3.043\,(3.034)\ \pm 0.014$	$3.047\,(3.049)\ \pm 0.014$
n_s	$0.9656\,(0.9655)\ \pm 0.0037$	$0.9696\,(0.9717)^{+0.0046}_{-0.0068}$
$100\theta_s$	$1.04185\,(1.04200)\ \pm 0.00029$	$1.04172\,(1.04126)\ \pm 0.00032$
$\Omega_b h^2$	$0.02241\,(0.02233)\ \pm 0.00014$	$0.02255\,(0.02245)\ \pm 0.00018$
$\Omega_{cdm} h^2$	$0.1192\,(0.1191)^{+0.00087}_{-0.00095}$	$0.1215\,(0.1243)^{+0.0013}_{-0.0029}$
τ_{reio}	$0.0546\,(0.0503)^{+0.0065}_{-0.0072}$	$0.0553\,(0.0543)^{+0.0069}_{-0.0075}$
$\log_{10}(z_c)$	–	$3.71\,(3.52)^{+0.26}_{-0.33}$
f_{EDE}	–	$< 0.072\,(0.047)$
θ_i	–	$2.023(2.734)^{+1.1}_{-0.34}$
H_0 [km/s/Mpc]	$67.70\,(67.56)\ \pm 0.42$	$68.54\,(68.83)^{+0.52}_{-0.95}$
Ω_m	$0.3105\,(0.3112)^{+0.0053}_{-0.0058}$	$0.3082\,(0.3120)^{+0.0056}_{-0.0057}$
σ_8	$0.8077\,(0.8039)\ \pm 0.0058$	$0.8127\,(0.8195)^{+0.0072}_{-0.0091}$
S_8	$0.822\,(0.819)\ \pm 0.010$	$0.824\,(0.827)\ \pm 0.011$

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Constraints from *Planck* 2018 data + BOSS DR12 + S_8 from DES+KV-450+HSC

Parameter	ΛCDM	EDE ($n = 3$)
$\ln(10^{10} A_\mathrm{s})$	$3.036\,(3.039)\ \pm 0.014$	$3.038\,(3.034)\ \pm 0.014$
n_s	$0.9674\,(0.9727)\ \pm 0.0037$	$0.9696\,(0.9621)^{+0.0042}_{-0.0051}$
$100\theta_\mathrm{s}$	$1.041945\,(1.041966)\ \pm 0.00030$	$1.04178\,(1.04176)\ \pm 0.00035$
$\Omega_\mathrm{b} h^2$	$0.02249\,(0.02273)\ \pm 0.00013$	$0.02259\,(0.02243)^{+0.00016}_{-0.00018}$
$\Omega_\mathrm{cdm} h^2$	$0.1182\,(0.1157) \pm 0.00081$	$0.11958\,(0.11951)^{+0.00096}_{-0.0018}$
τ_reio	$0.0527\,(0.0591) \pm 0.0067$	$0.0535\,(0.0521)^{+0.0069}_{-0.0075}$
$\log_{10}(z_c)$	–	$3.77\,(4.24)^{+0.51}_{-0.33}$
f_EDE	–	$< 0.0526\,(0.0115)$
θ_i	–	$1.91(1.55)^{+1.2}_{-0.47}$
H_0 [km/s/Mpc]	$68.13\,(69.28)\ \pm 0.38$	$68.73\,(67.92)^{+0.42}_{-0.69}$
Ω_m	$0.3046\,(0.2859) \pm 0.0049$	$0.3024\,(0.3091) \pm 0.0050$
σ_8	$0.80204\,(0.7947)\ \pm 0.0053$	$0.8044\,(0.8023)^{+0.0060}_{-0.0069}$
S_8	$0.8082\,(0.7810)\ \pm 0.0086$	$0.8075\,(0.8143)\ \pm 0.0092$

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