Searching for Cosmological Concordance with New Physics in the Dark Sector: Hints and Challenges

Colin Hill

Columbia University

BCCP/Cosmology Seminar
UC Berkeley
28 February 2023

2109.04451 w/ ACT Collaboration + 2112.10754 w/ La Posta, Louis, Garrido
2210.14339 w/ F. McCarthy
2212.08098 w/ M.-X. Lin, E. McDonough, W. Hu
2303.00746 w/ S. Goldstein, V. Irsic, B. Sherwin
to appear (next week) w/ B. Bolliet, A. Spurio Mancini, ++

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Outline

- Early Dark Energy
  - Hints? ACT DR4 (+SPT-3G)
  - Challenges —>Early Dark Sector
  - Severe Challenge: Lyman-α Forest
- ~~Generalized Dark Matter —> Dark Radiation Conversion~~ [ask me after if interested]
- Einstein-Boltzmann Emulators [if time]

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Early Dark Energy

Motivation: increase CMB-inferred H_0

How does this work?

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

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

scale factor → $a(t)$

sound speed → $c_s(t)$

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

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

physical densities of baryons, CDM, neutrinos, photons

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

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

$D_A \sim 1/H_0$

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

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Early Dark Energy

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

Relevant ingredients in **EDE**: ω_b, ω_m, ω_ν, 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)

Early Dark Energy

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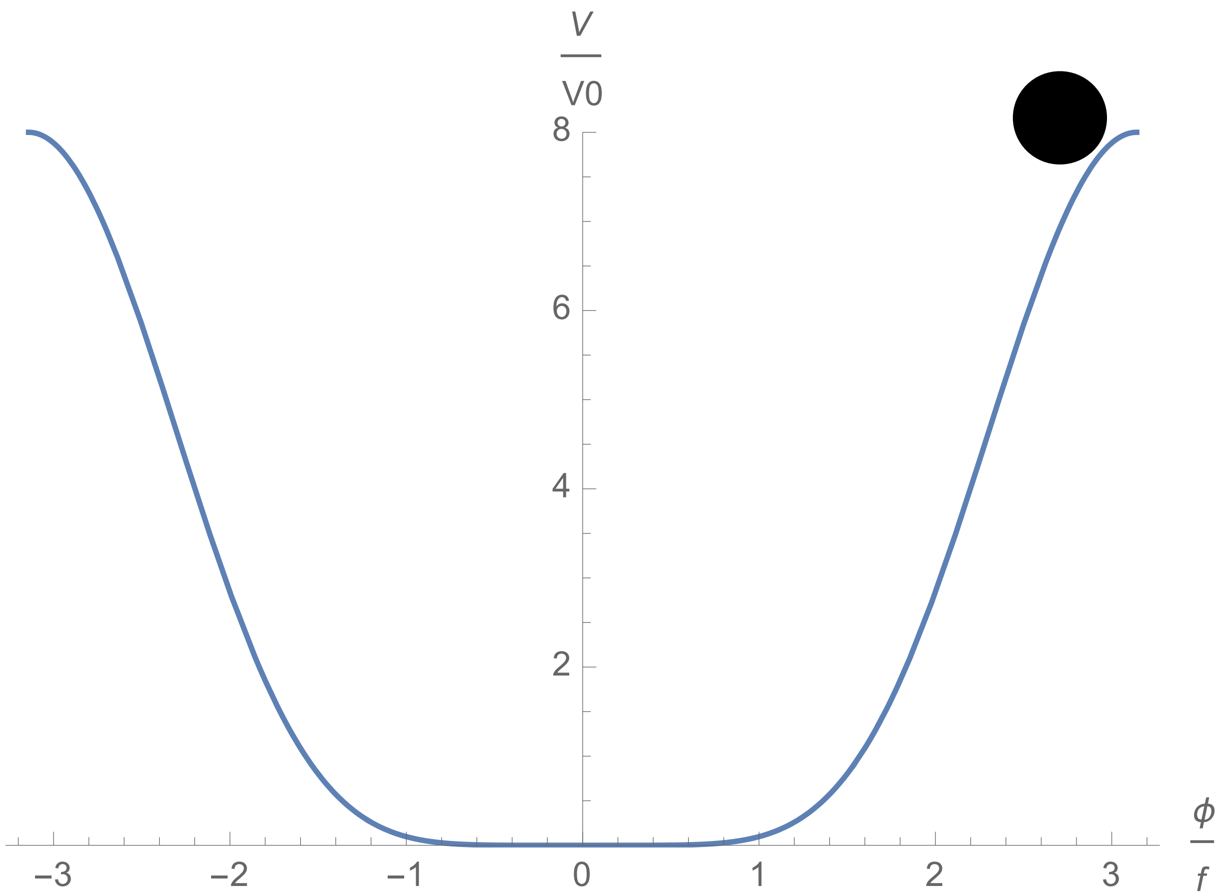
New component: (pseudo)-scalar field ϕ

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



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

$H^2 >> V'' \sim m^2$ initially

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

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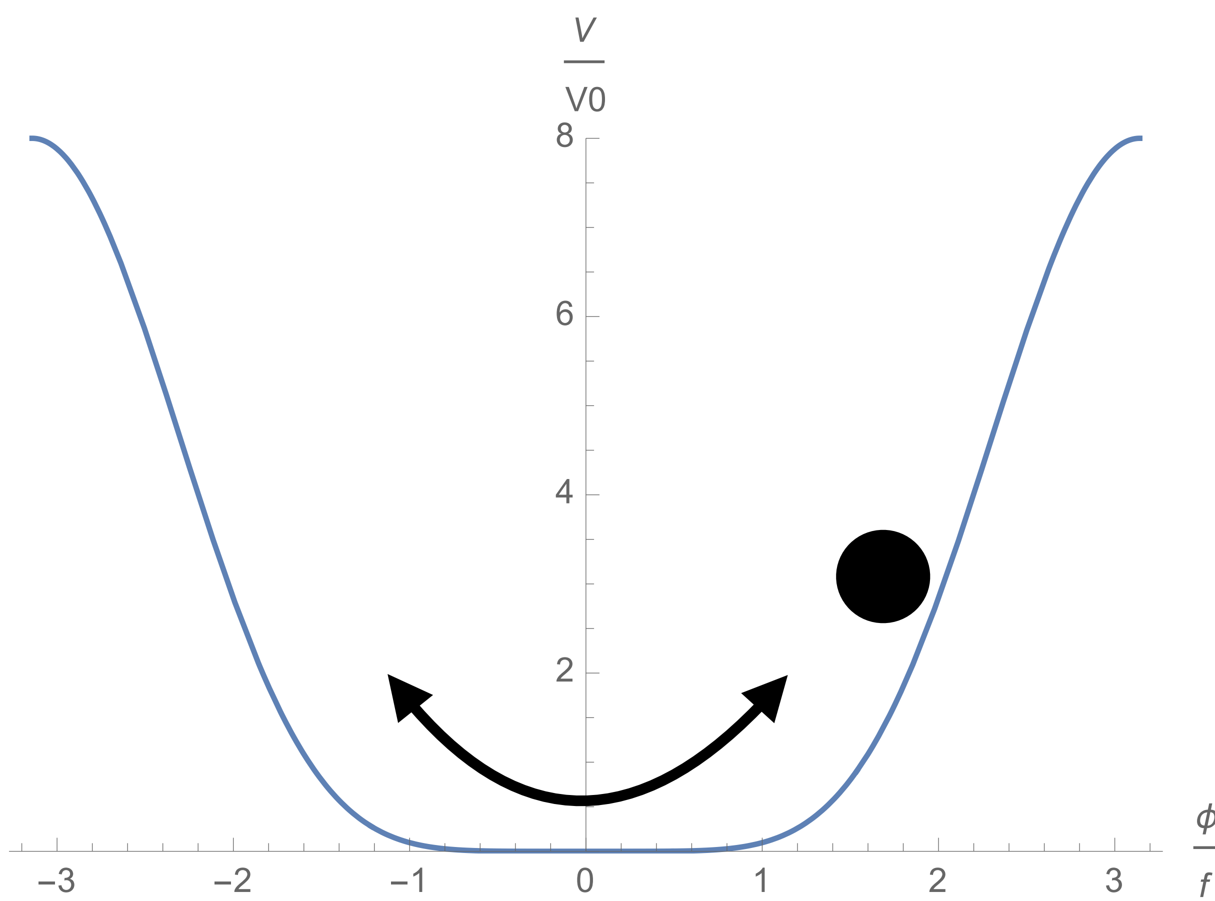
New component: (pseudo)-scalar field ϕ

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



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

↓

$m \sim 10^{-27}$ 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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Early Dark Energy

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

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

Important: need late-time w>0 so that EDE energy density contribution decays faster than matter

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

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Early Dark Energy

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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} ⟶ $w_\phi = \frac{n-1}{n+1}$

m ~ 10^{-27} eV
f ~ $10^{26\text{-}27}$ eV
n >= 2 (we fix to 3 throughout)

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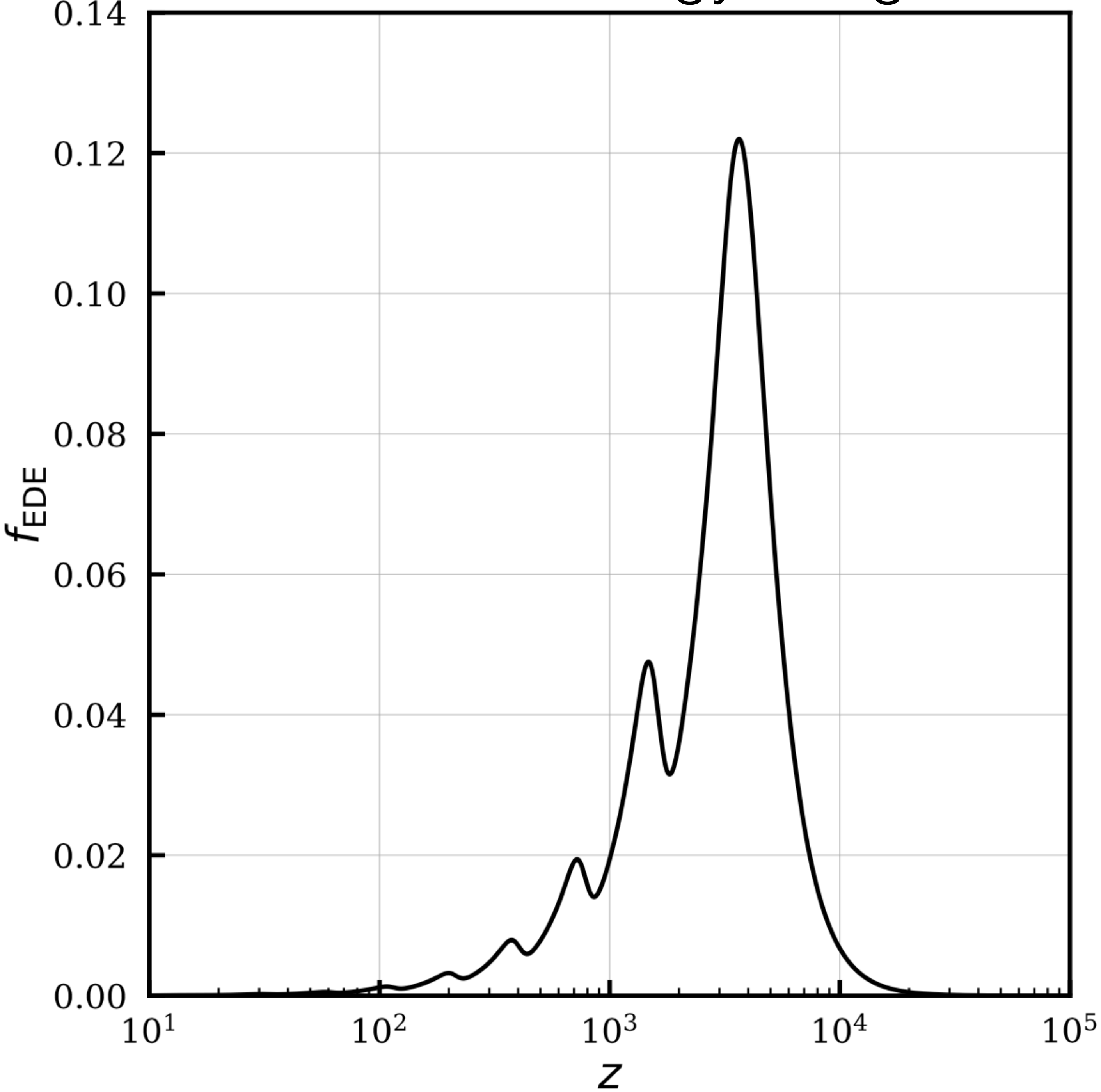
Early Dark Energy

Parameterization

Fractional contribution of EDE
to cosmic energy budget



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

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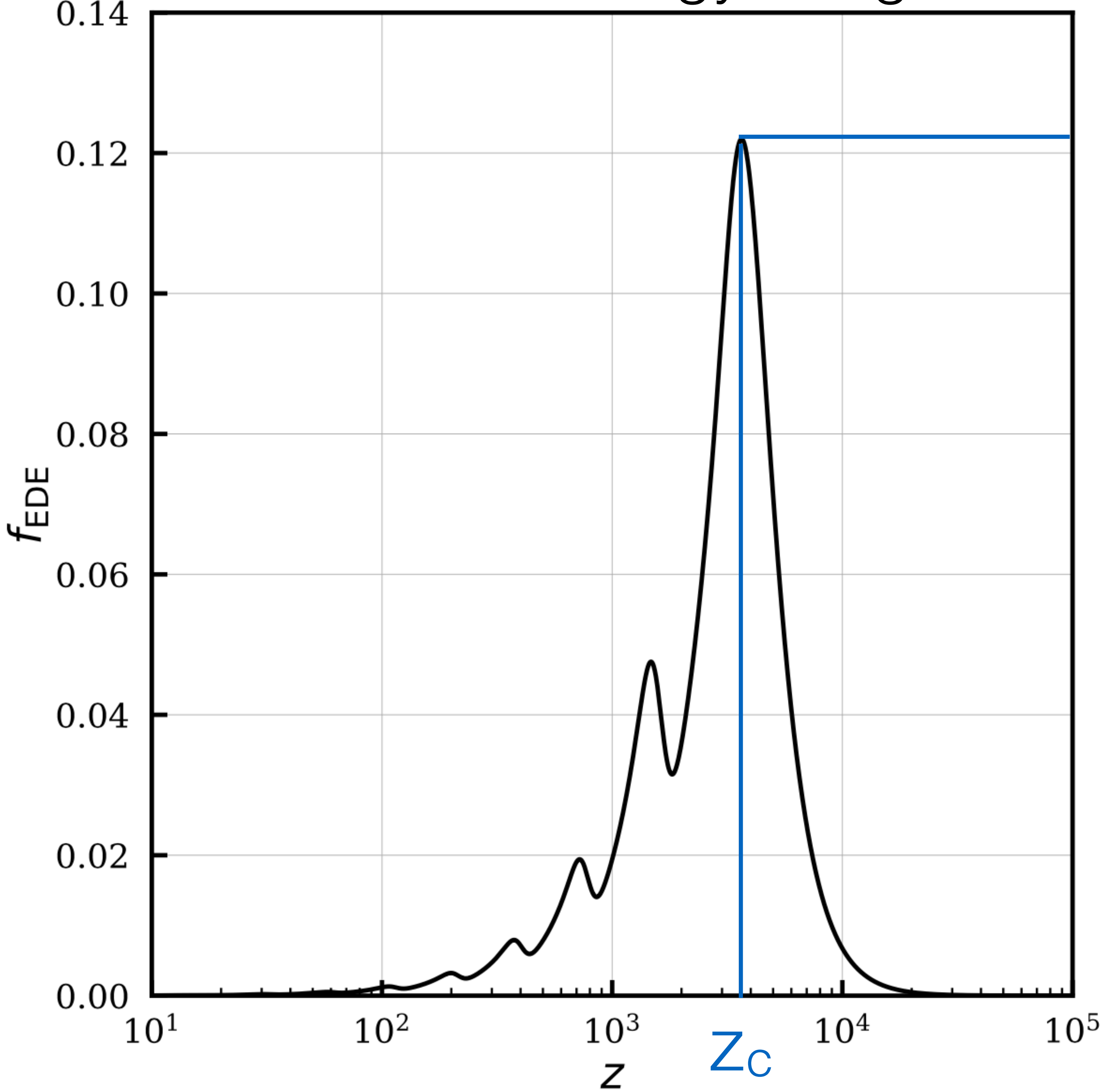
Early Dark Energy

Parameterization

Fractional contribution of EDE to cosmic energy budget



Maximal contribution:

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

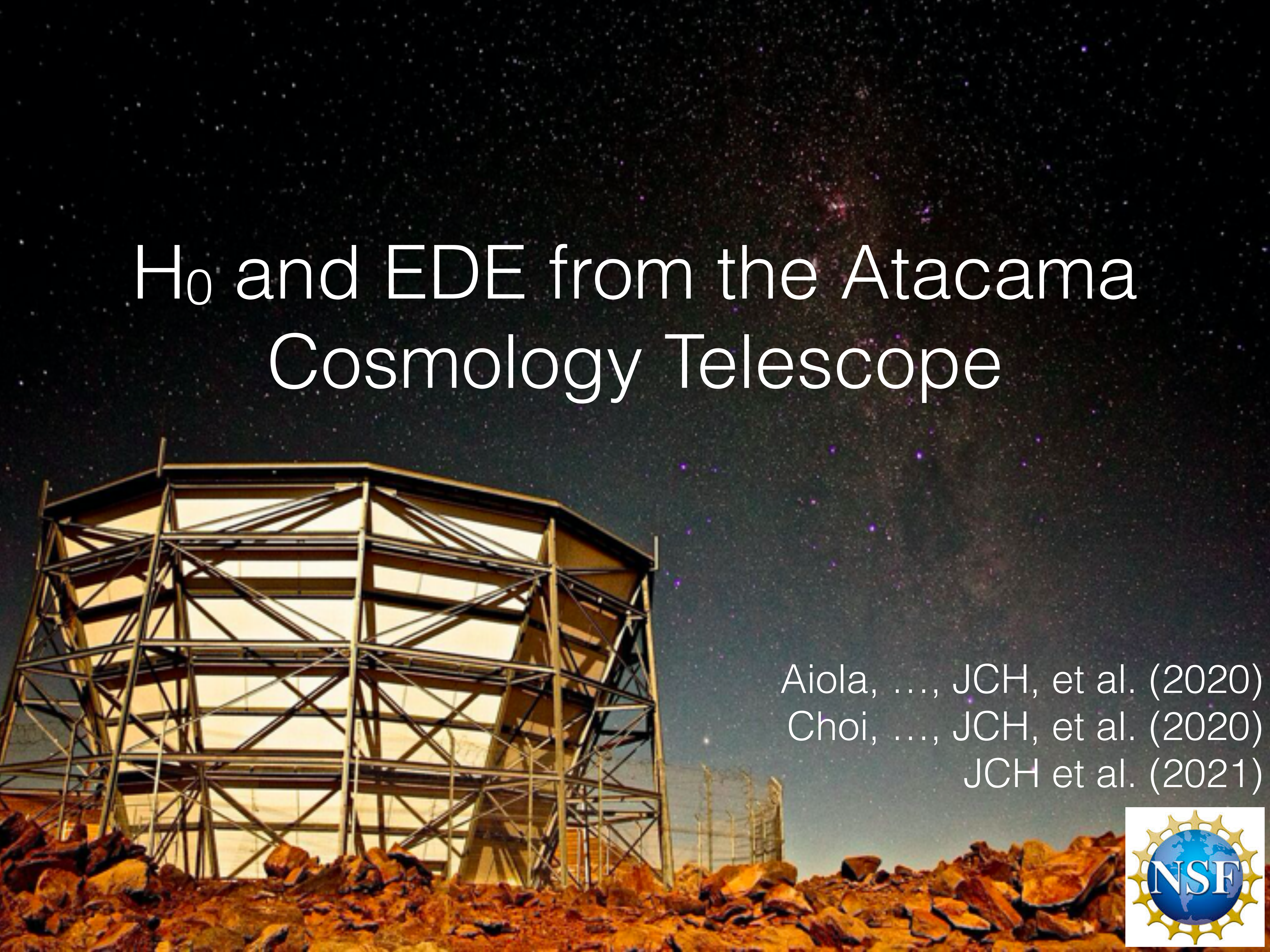
which occurs at redshift z_c

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

→ $\{f_{\mathrm{EDE}}, z_c, \theta_i\}$

N.B.: highly non-linear relation to physical scalar field parameters

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


H_0 and EDE from the Atacama Cosmology Telescope
Aiola, …, JCH, et al. (2020)
Choi, …, JCH, et al. (2020)
JCH et al. (2021)

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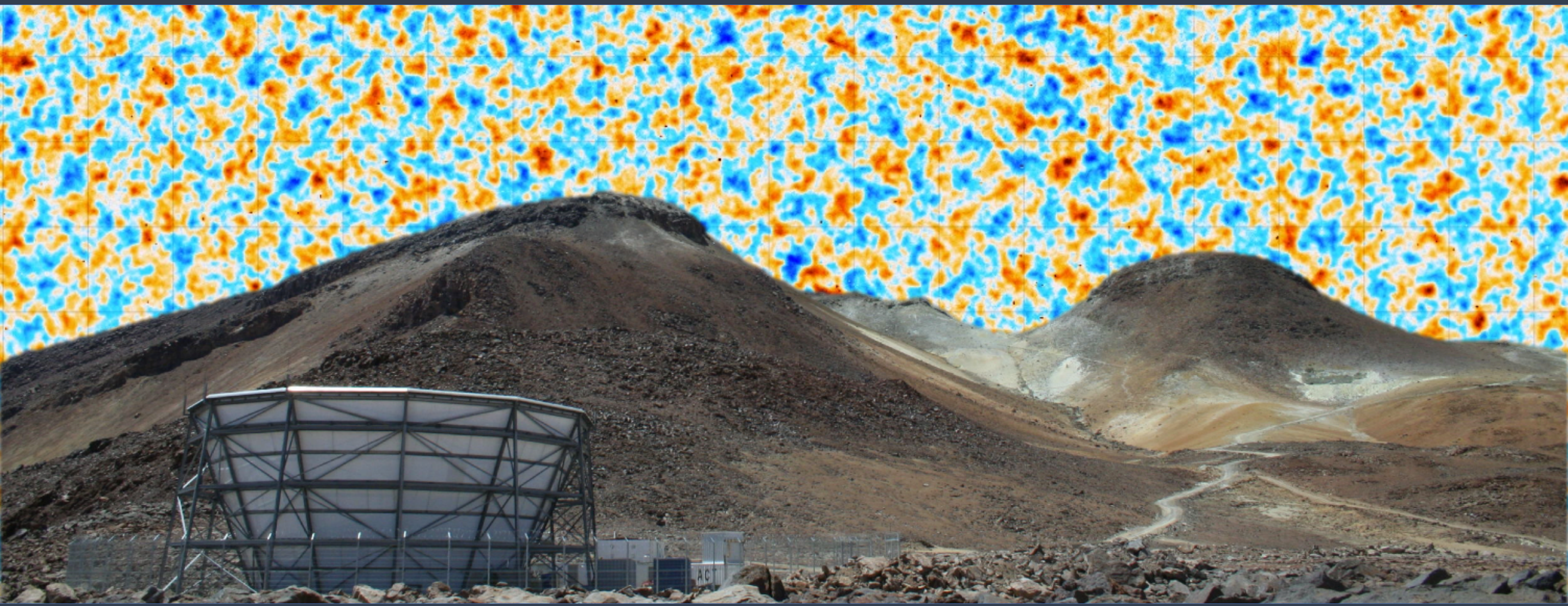
The Atacama Cosmology Telescope



wide-area (~half-sky) multifrequency CMB survey
observations: 2008-2022 (with some gaps for upgrades)

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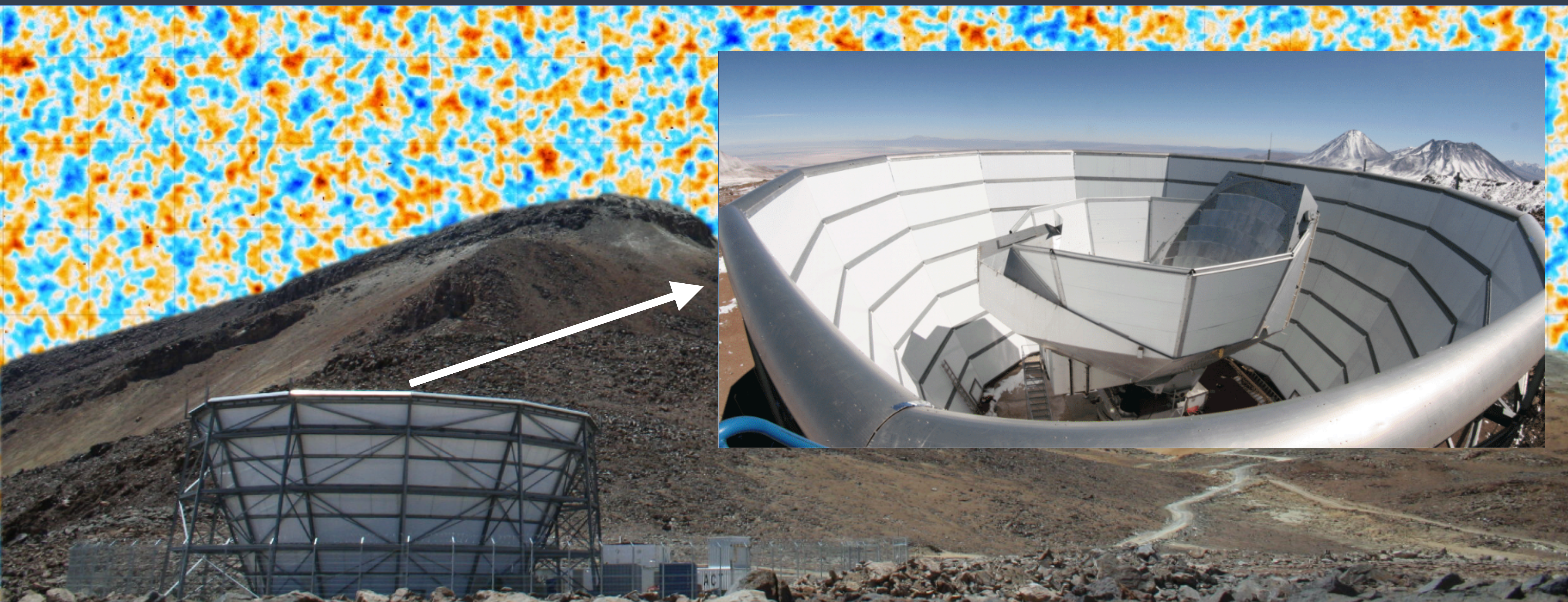
The Atacama Cosmology Telescope



wide-area (~half-sky) multifrequency CMB survey
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The Atacama Cosmology Telescope

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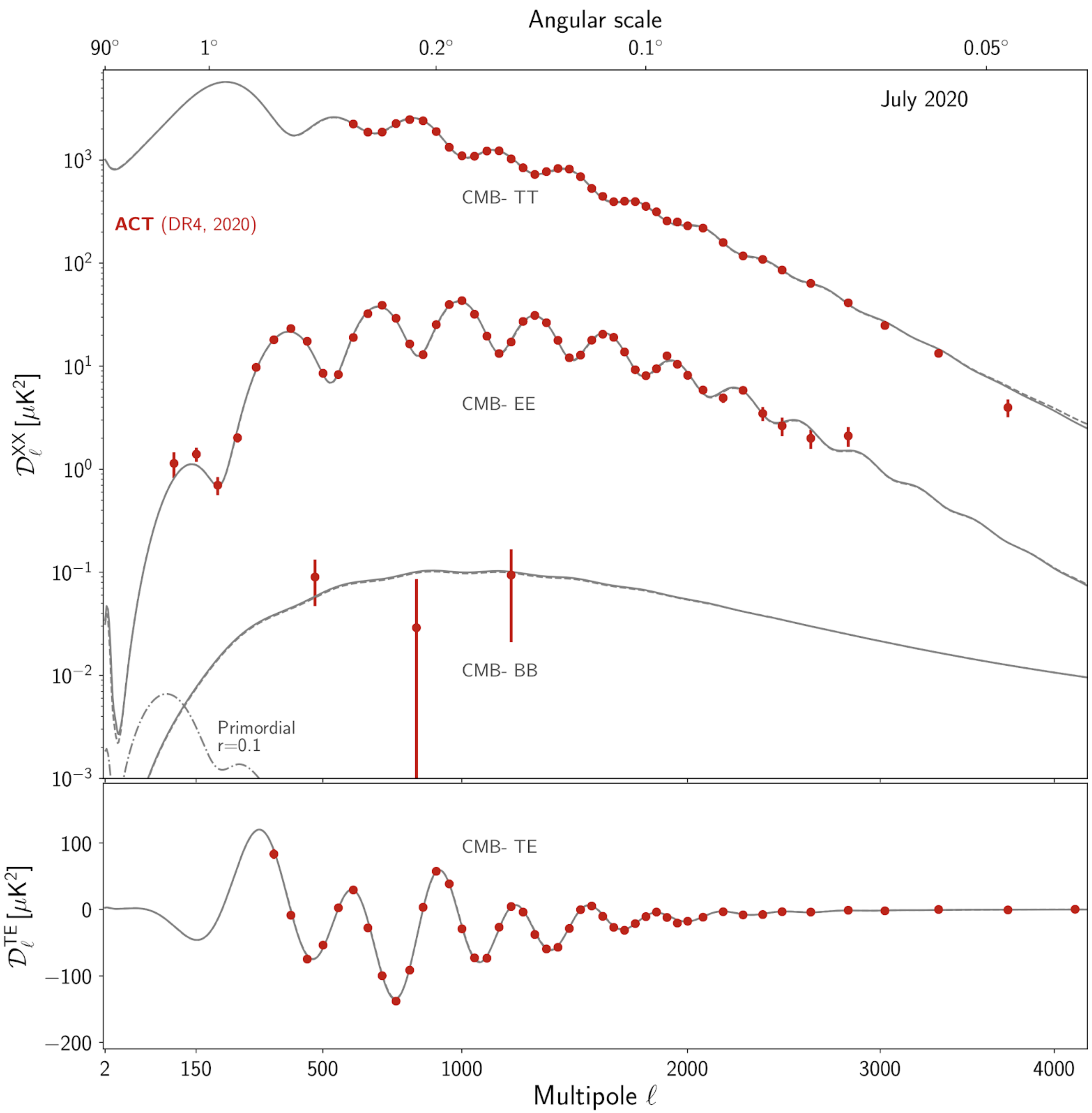
ACT Data Release 4

Foreground-marginalized CMB power spectra



Choi et al. (2020)

ACT Data Release 4

Foreground-marginalized CMB power spectra

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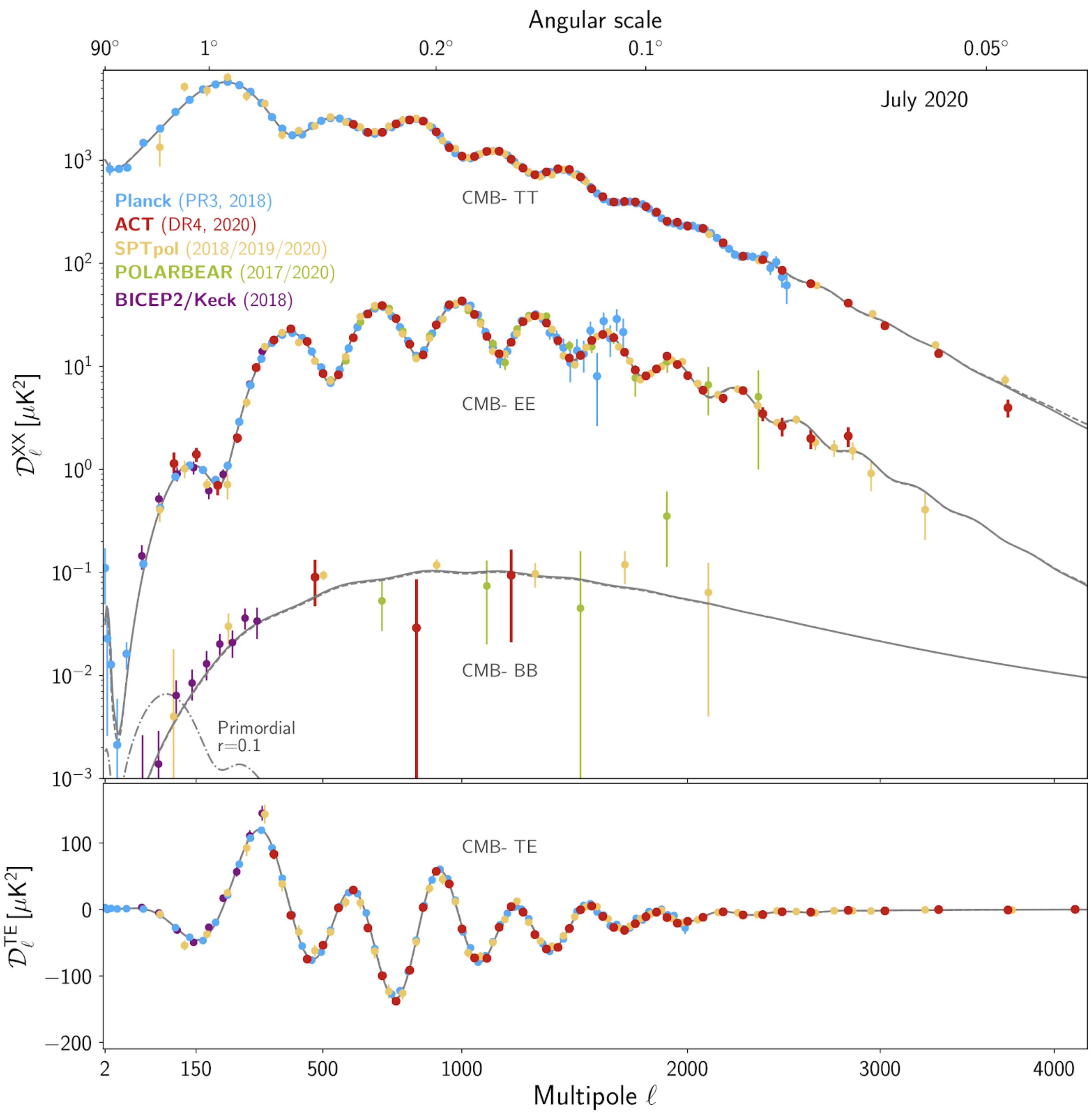

Choi et al. (2020)

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Constraints on Early Dark Energy





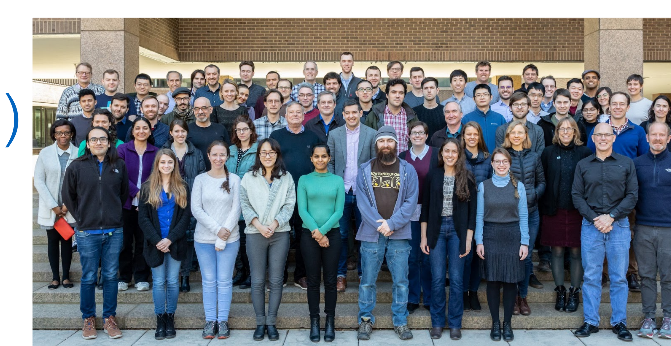


JCH, McDonough, Toomey, Alexander (2020, PRD Editors' Suggestion)

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

JCH, Calabrese, et al. [ACT Collaboration] (2021)

La Posta, Louis, Garrido, **JCH** (2021)



ACT DR4 EDE Analysis

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The Atacama Cosmology Telescope: Constraints on Pre-Recombination Early Dark Energy

JCH et al. (2021) arXiv:2109.04451

ACT DR4 EDE Analysis

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Motivation

- How robust are CMB-derived EDE constraints to the choice of CMB data set?
- What do we find if we replace Planck with ACT or ACT+WMAP?
- ACT and Planck are consistent at 2.5σ in ΛCDM (with consistent H_0~67-68 km/s/Mpc) — what about in EDE?
- N.B. we do not try to assess global concordance of any model w.r.t. all cosmological data in this analysis
- Data sets: ACT, WMAP, Planck, BAO, Planck CMB lensing

Planck TT (ell < 650)

JCH et al. (2021)

See also Poulin et al. (2021)

Pipeline: **CLASS-EDE** (JCH+) + **Cobaya** (Torrado & Lewis)

ACT DR4 EDE Results

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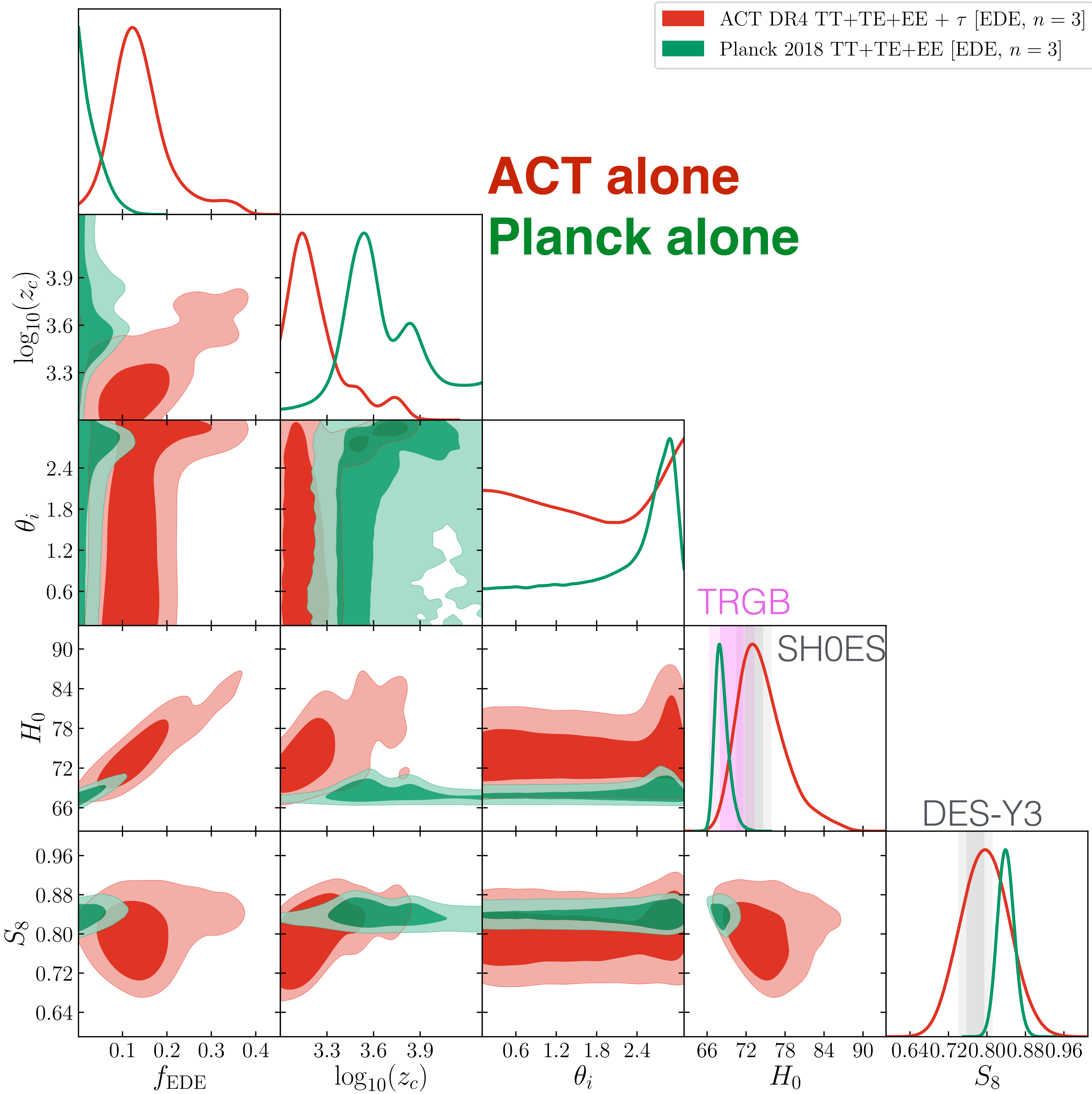

JCH et al. (2021)
JCH et al. (2020)

ACT DR4 EDE Results

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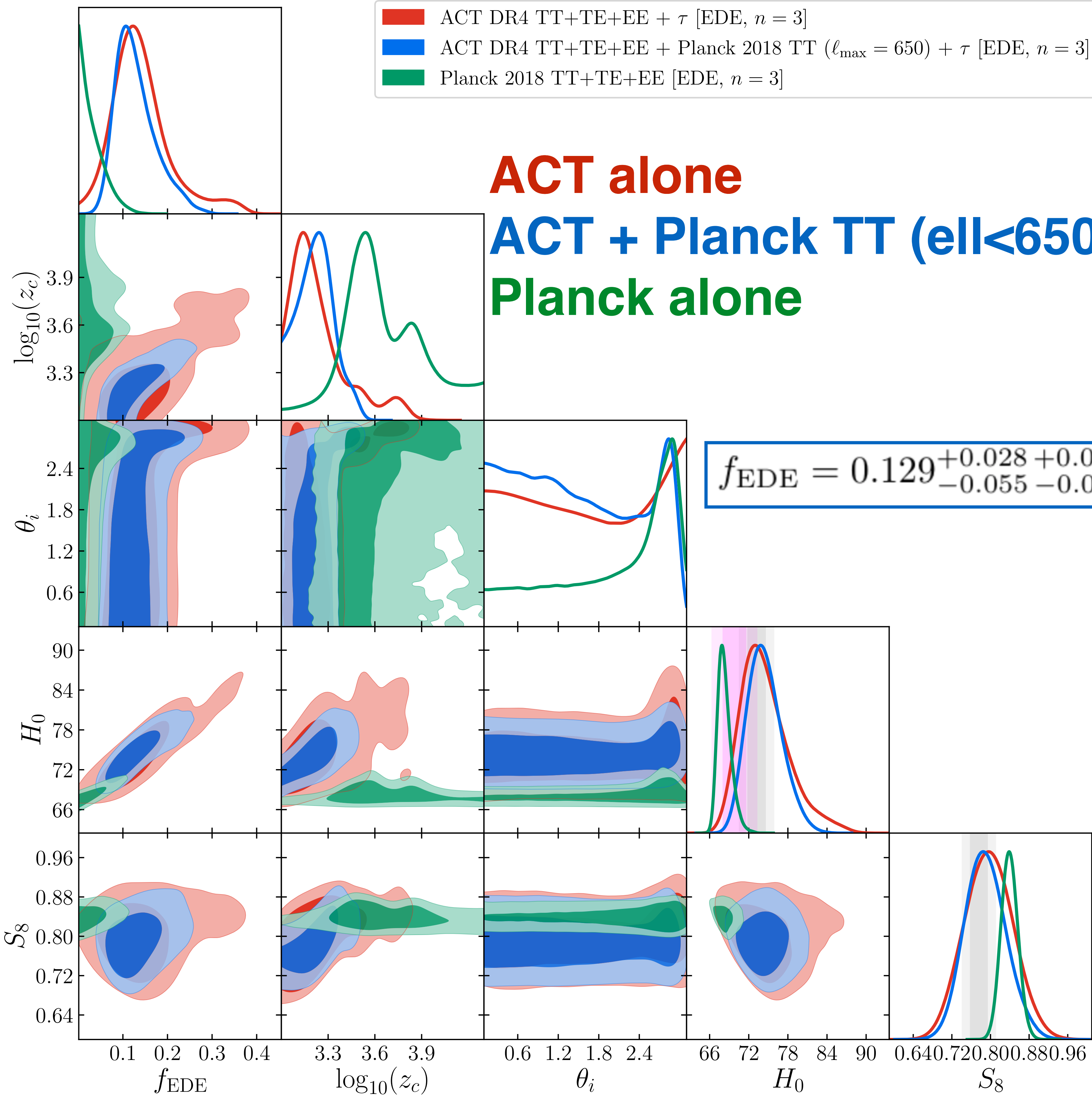

ACT alone

ACT + Planck TT (ell<650)

Planck alone

$$f_{\rm EDE} = 0.129^{+0.028\,+0.099\,+0.14}_{-0.055\,-0.076\,-0.084} \quad (68\%/95\%/99.7\%\ \mathrm{CL})$$

JCH et al. (2021)
JCH et al. (2020)

ACT DR4 EDE Results

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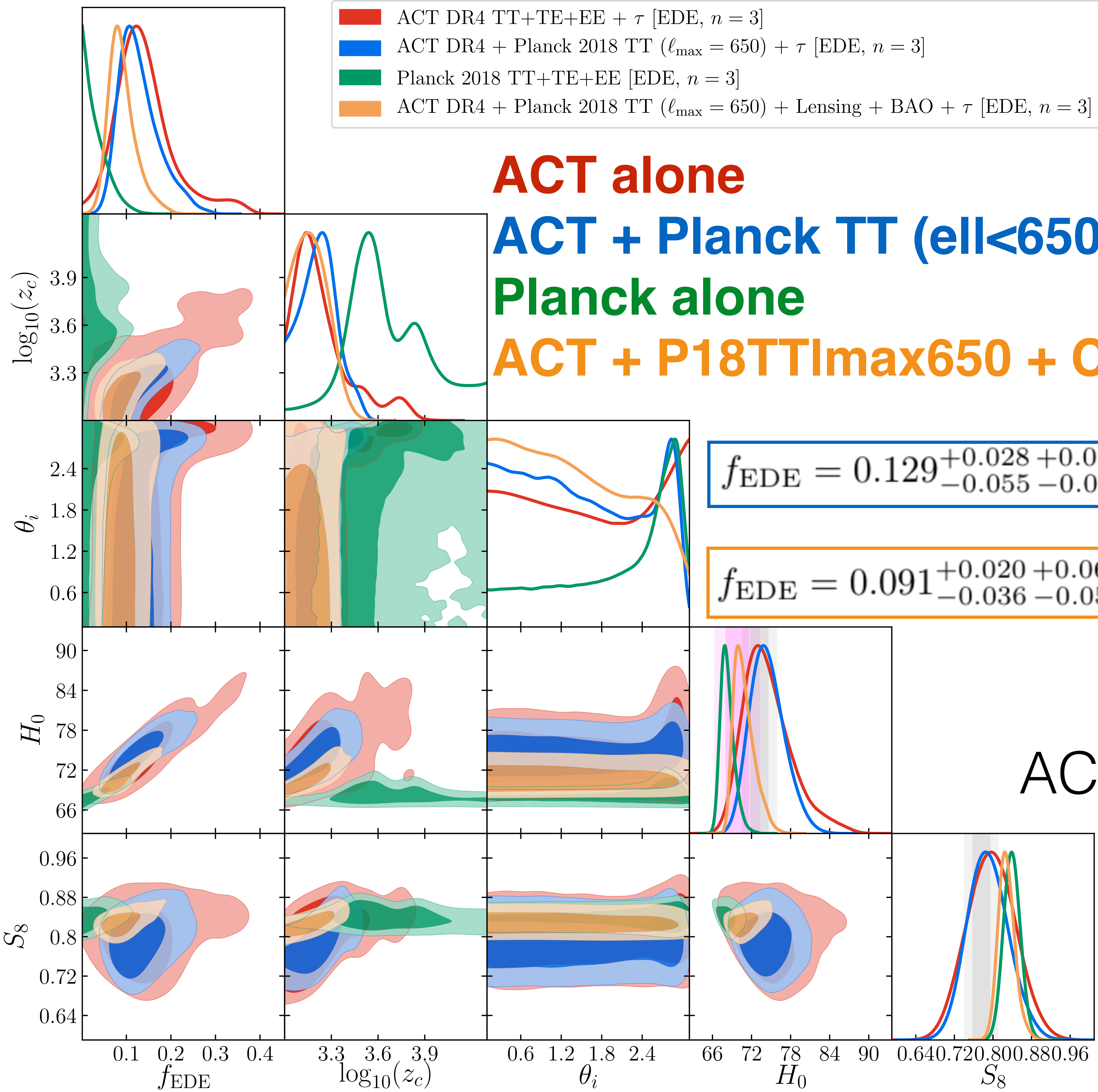

ACT alone

ACT + Planck TT (ell<650)

Planck alone

ACT + P18TTlmax650 + CMB Lensing + BAO

$$f_{\rm EDE} = 0.129^{+0.028}_{-0.055}{}^{+0.099}_{-0.076}{}^{+0.14}_{-0.084} \quad (68\%/95\%/99.7\%\ \text{CL})$$

$$f_{\rm EDE} = 0.091^{+0.020}_{-0.036}{}^{+0.069}_{-0.056}{}^{+0.11}_{-0.063} \quad (68\%/95\%/99.7\%\ \text{CL})$$

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

ACT drives preference for non-zero f_{EDE} (>99.7% CL in joint fits)

ACT DR4 EDE Results

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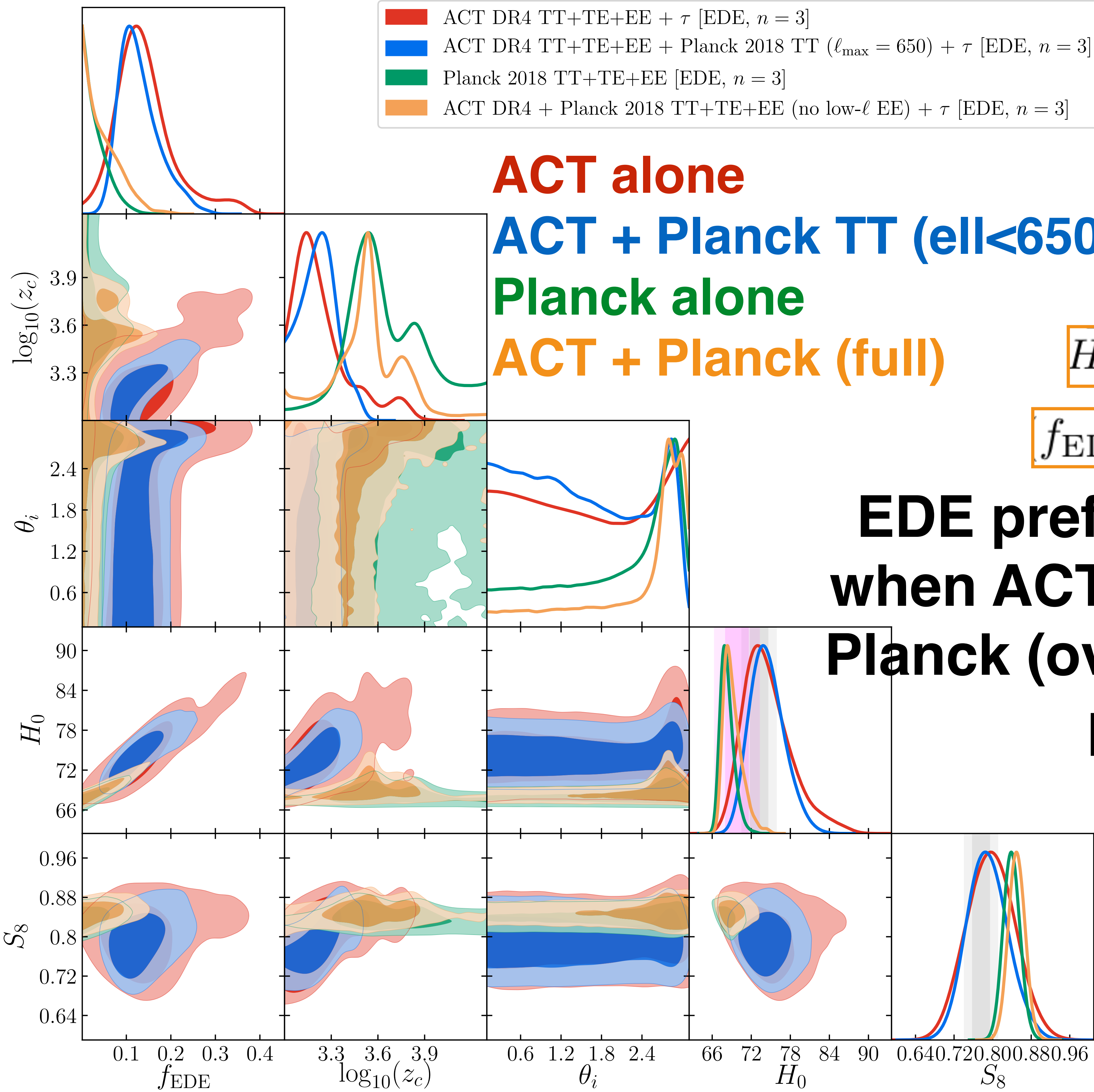

ACT alone

ACT + Planck TT (ell<650)

Planck alone

ACT + Planck (full)

$$H_0 = 69.17^{+0.83}_{-1.70}\ \mathrm{km/s/Mpc}$$

$$f_{\rm EDE} < 0.124 \text{ at } 95\% \text{ CL}$$

EDE preference goes away when ACT is combined with Planck (overall constraining power still Planck-dominated)

JCH et al. (2021)
JCH et al. (2020)

Origin of ACT EDE Hint

JCH et al. (2021)

Origin of ACT EDE Hint

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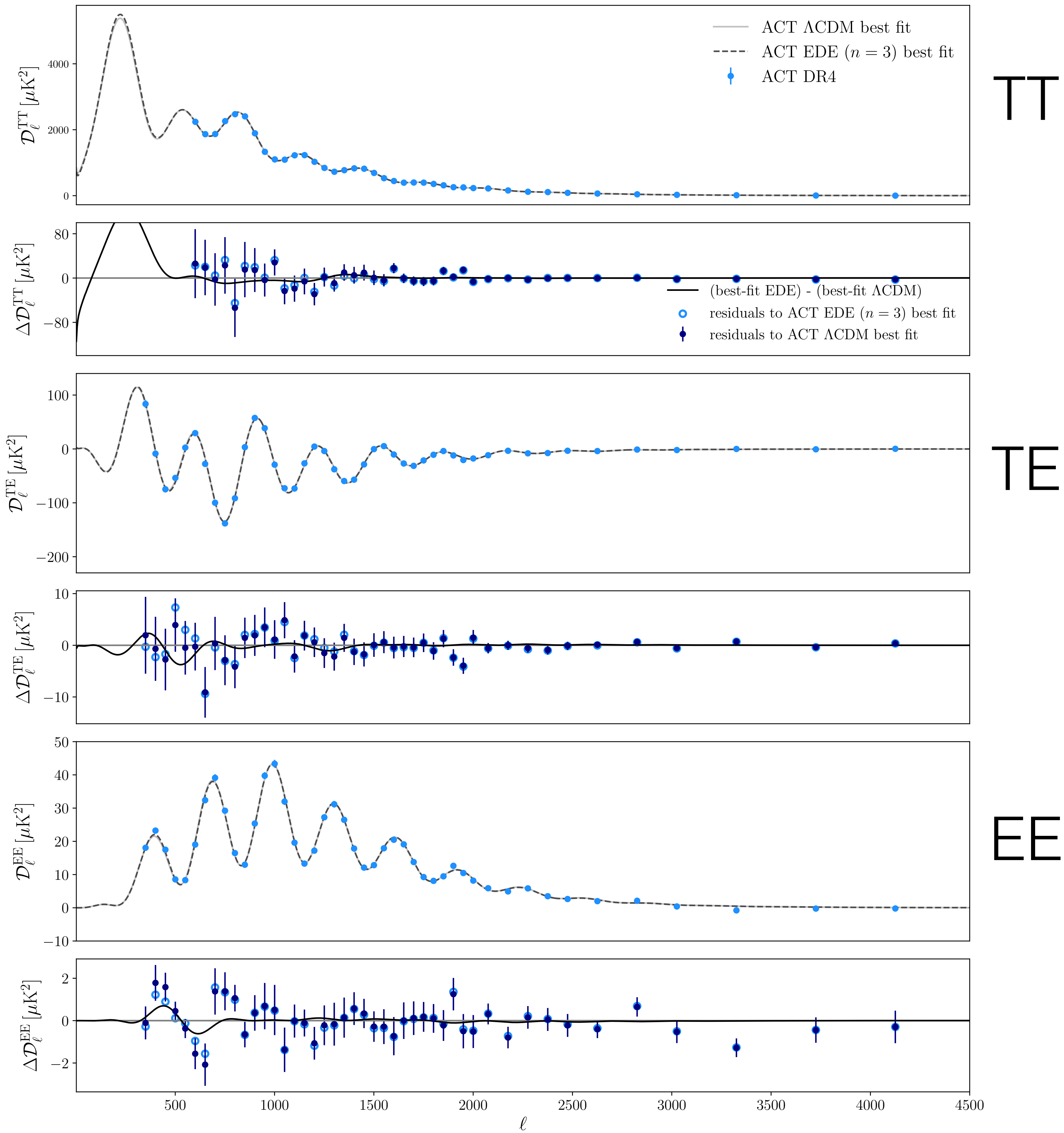
LCDM residuals

EDE residuals



JCH et al. (2021)

Origin of ACT EDE Hint

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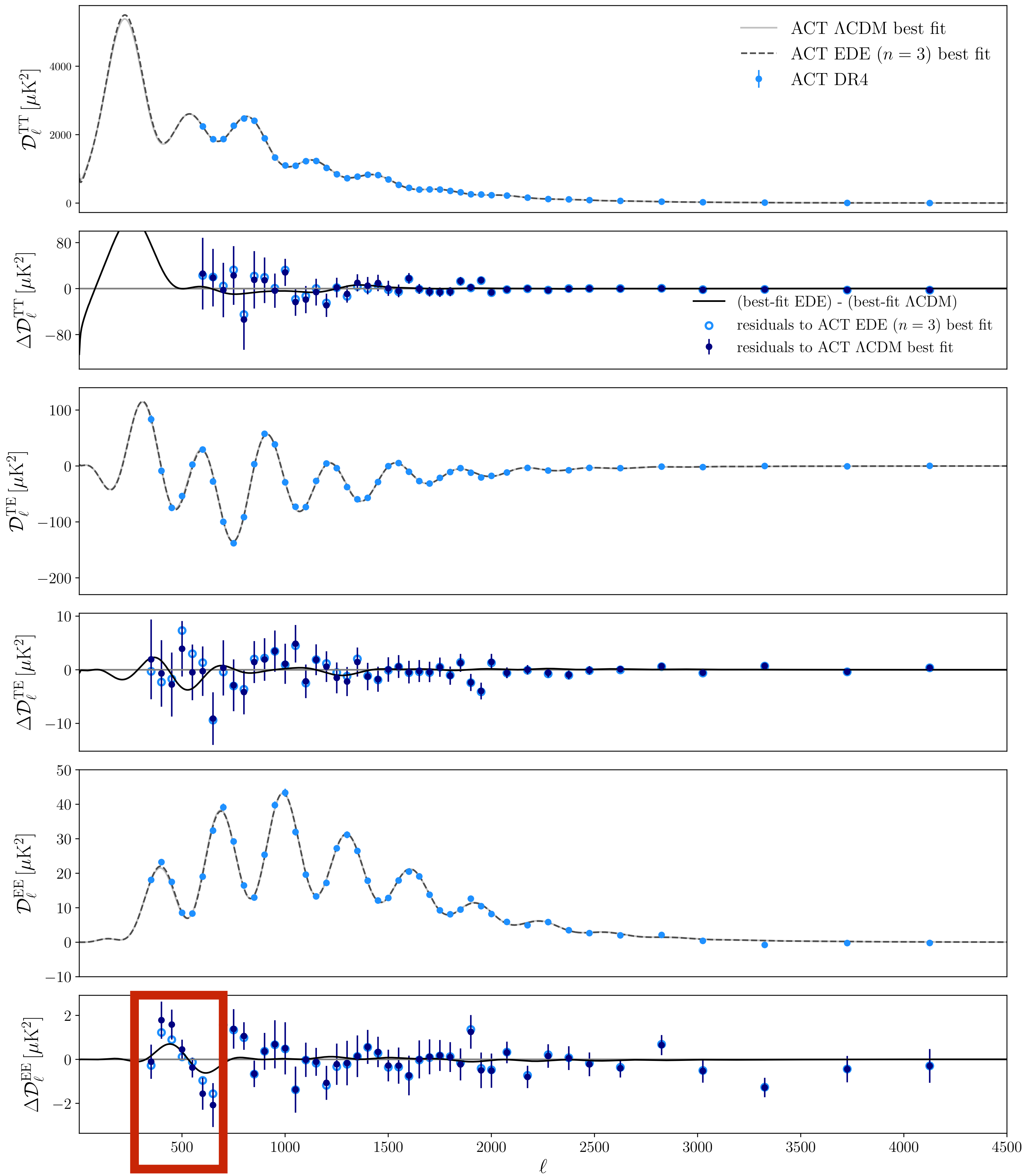
LCDM residuals

EDE residuals

lowest ell bins in EE drive the preference



TT

TE

EE

overall preference ~2.1σ ($\Delta\chi^2$ = -8.7)

JCH et al. (2021)

Origin of ACT EDE Hint

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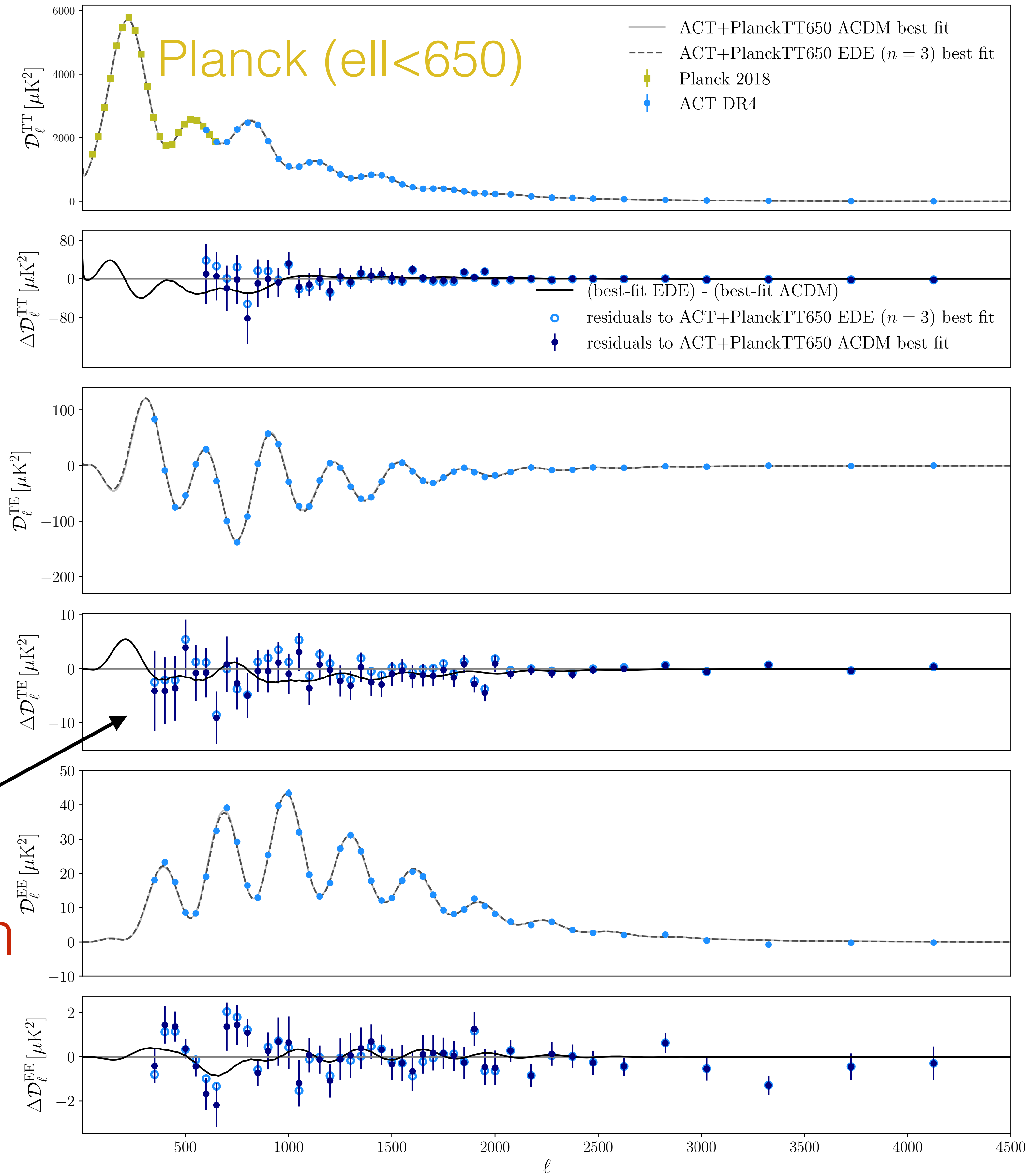
LCDM residuals

EDE residuals

TE plays an important role in driving EDE preference in joint fits



overall preference ~3.2σ ($\Delta\chi^2$ = -15.4)

JCH et al. (2021)

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Next: ACT DR6

(target: later this year)

ACT DR6 Forecasts

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Columbia/CCA

ACT TT + TE + EE : precision cosmology beyond Planck

	ACT DR4	ACT DR4 + WMAP	Planck	Planck + ACT DR6
$\sigma(H_0)$	1.5	1.1	0.5	0.4
$\sigma(n_s)$	0.015	0.006	0.004	0.003
$\sigma(N_{eff})$	0.4	0.3	0.2	0.1

Large improvements in beyond-ΛCDM parameters:
~2x increase in sensitivity to new light relic particles

PRELIMINARY FORECAST

Upcoming ACT DR6 precision cosmology constraints will surpass those from Planck (H_0, N_{eff}, Σm_ν, σ_8, + beyond-ΛCDM models) — stay tuned!

Discovering EDE in the CMB?

JCH et al. (2021)

Discovering EDE in the CMB?

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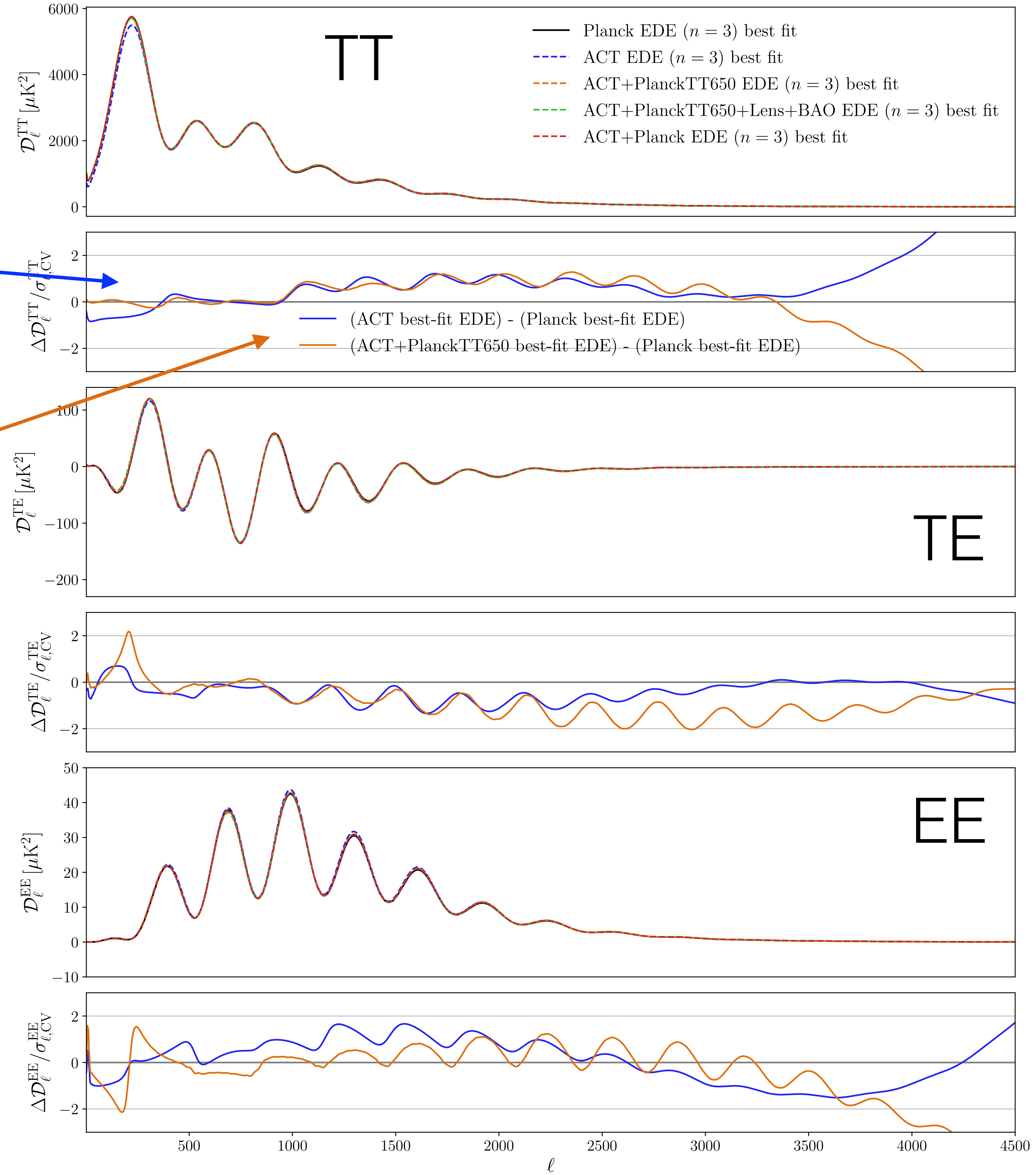
ACT best-fit EDE - Planck EDE

ACT+P18TT650 EDE - Planck EDE

Imminent potential discovery with upcoming ACT DR6 (~2023): the models shown here can be distinguished at ~20σ



JCH et al. (2021)

EDE Puzzles & Problems

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McDonough, Lin, JCH, Hu, Zhou (2021); Lin, McDonough, JCH, Hu (2022); JCH+ (2020); Ivanov+ (2020)

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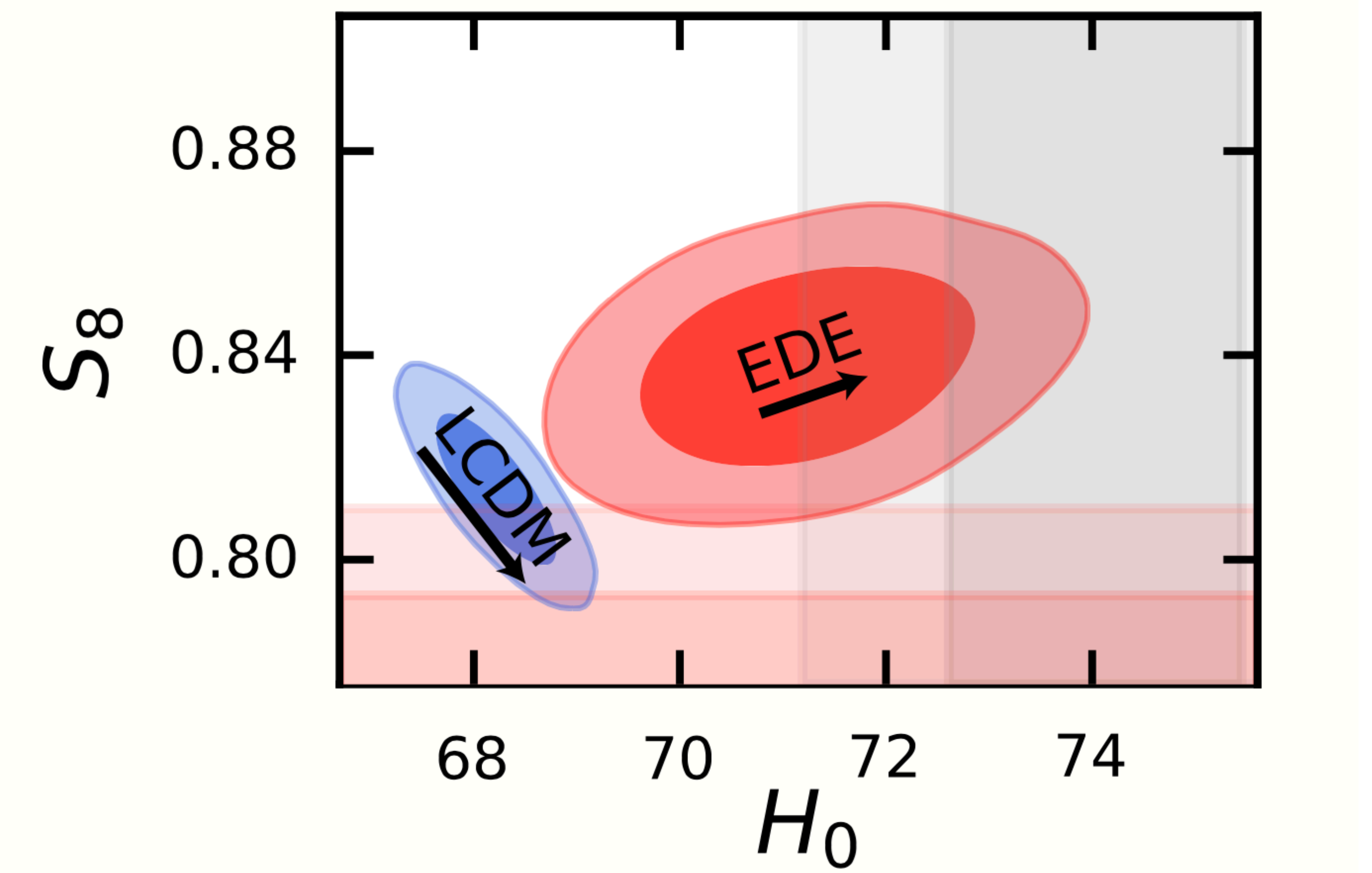
EDE Puzzles & Problems

- Coincidence problem: why should these new dynamics appear near z_{eq}? [—> $V(\phi)$, $V'(\phi)$]
- Initial conditions: axion-like field must start near top of cosine to fit Planck (e.g., Lin, Benevento, Hu, Raveri (2019)) [—>$V''(\phi)$]
- "Tension-trading": H_0 is increased at the cost of adding significantly more dark matter and increasing n_s, hence raising S_8



McDonough, Lin, JCH, Hu, Zhou (2021); Lin, McDonough, JCH, Hu (2022); JCH+ (2020); Ivanov+ (2020)

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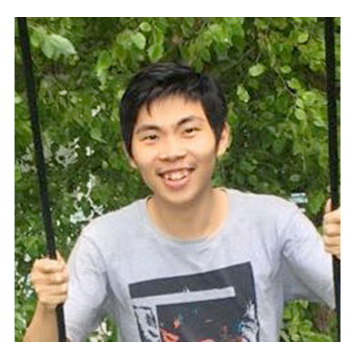
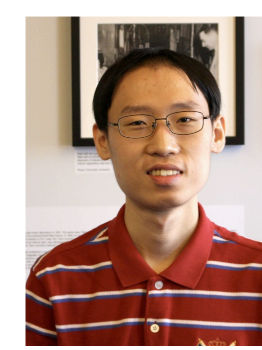
Early Dark Sector

A Dark Matter Trigger for Early Dark Energy Coincidence



2112.09128 w/ Evan McDonough, Meng-Xiang Lin, Wayne Hu, Shengjia Zhou
2212.08098 w/ Lin, McDonough, Hu

Early Dark Sector

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Goal: explain why EDE dynamics at z_c are coincident with z_{eq} by coupling the EDE scalar ϕ to the dark matter, such that DM triggers EDE evolution rather than the bare potential V(ϕ)

- **Field dependent dark matter mass:** $m_{\rm dm}(\phi)$
- **Effective potential:** $V_{\rm eff} = V_0 + m_{\rm dm}(\phi) n_{\rm dm}$

Lin, McDonough, JCH, Hu (2022)

Early Dark Sector

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- **Field dependent dark matter mass:** $m_{\rm dm}(\phi)$
- **Effective potential:** $V_{\rm eff} = V_0 + m_{\rm dm}(\phi) n_{\rm dm}$

- Generically this produces evolution in the DM mass

- Problem for acceptable $\Delta m_{DM}/m_{DM}$ and generic initial conditions: slope of bare potential in axion-like EDE is too high to "trigger" off the EDE-DM coupling

- Solution: flatten V(ϕ) into a plateau and choose clever EDE-DM coupling m(ϕ), such that $V_{eff}(\phi) \sim \rho_{DM}$ and ϕ is released from Hubble friction near z_{eq}

Lin, McDonough, JCH, Hu (2022)

Early Dark Sector

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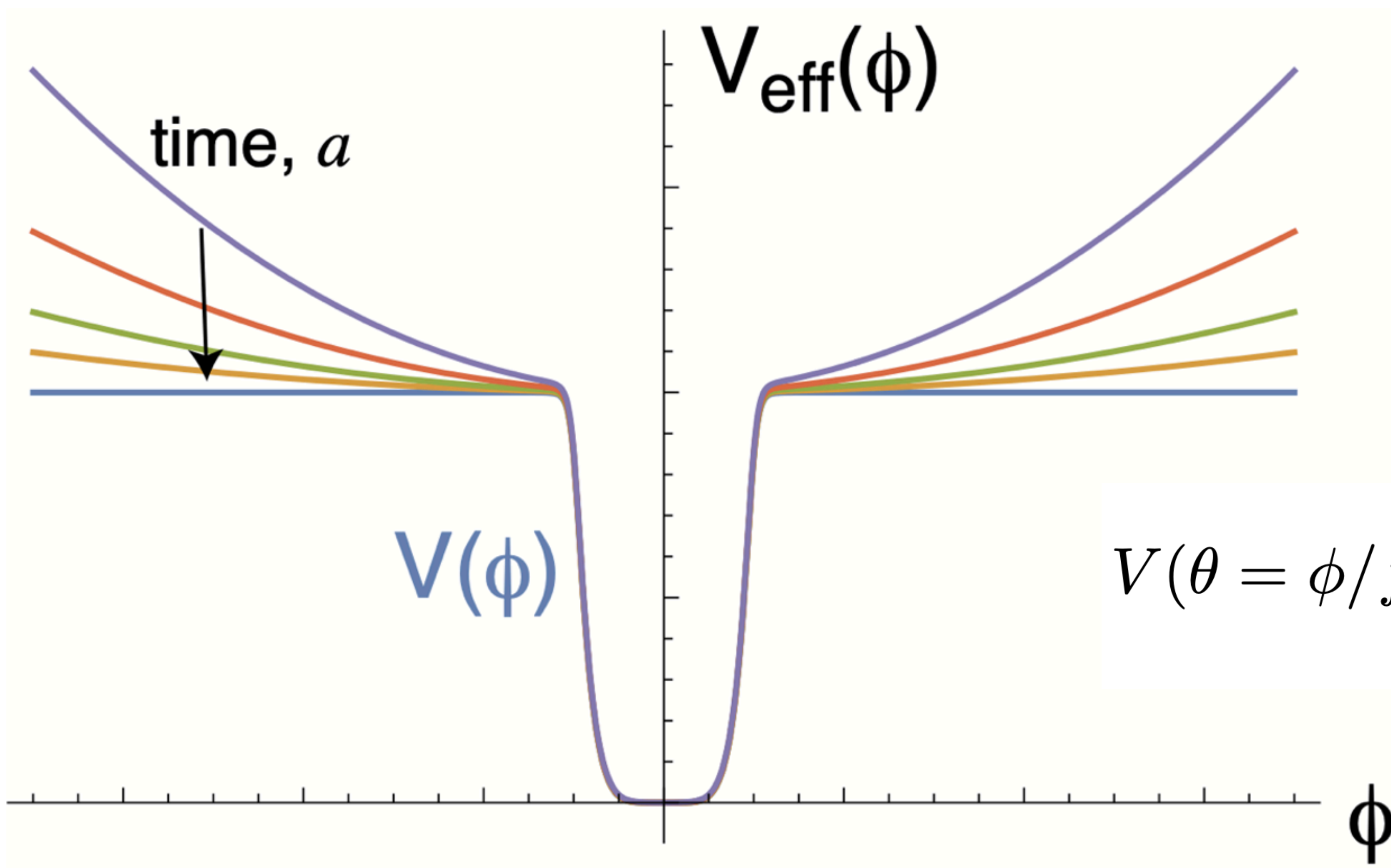
Goal: explain why EDE dynamics at z_c are coincident with z_{eq} by coupling the EDE scalar ϕ to the dark matter, such that DM triggers EDE evolution rather than the bare potential $V(\phi)$

- Solution: flatten $V(\phi)$ into a plateau and choose clever EDE-DM coupling $m(\phi)$, such that $V_{eff}(\phi) \sim \rho_{DM}$ and ϕ is released from Hubble friction near z_{eq}



$$V(\theta = \phi/f) = V_0 \frac{\theta^6}{(1+\theta^{6p})^{\frac{1}{p}}}$$

bare potential

Lin, McDonough, JCH, Hu (2022)

Early Dark Sector

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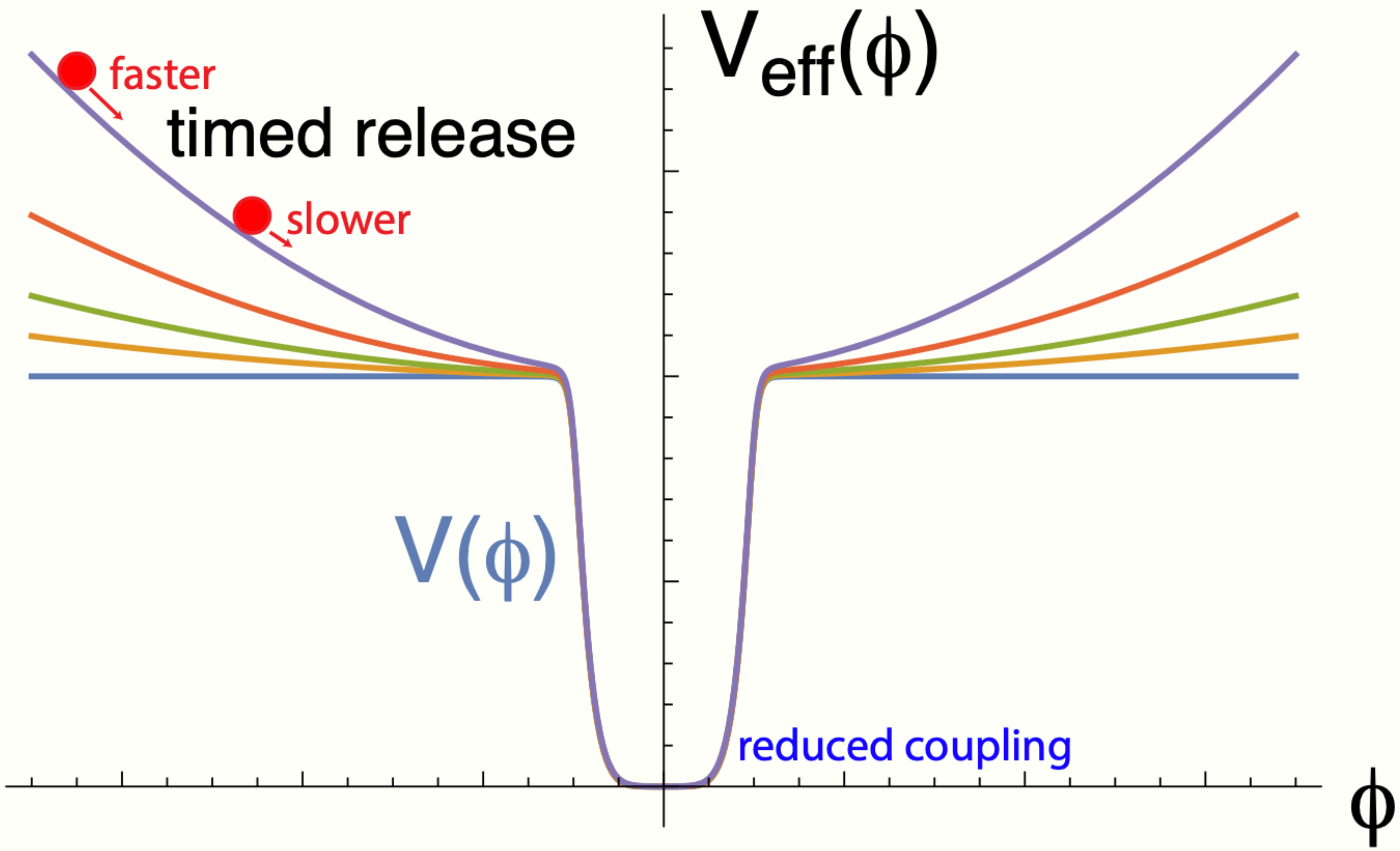
Solution

- Coincidence solved: field starts to roll because of equality
- Initial tuning solved: field will roll to edge of plateau from wide range of initial field positions
- Late growth solved: $m(\phi) \propto 1 + g\phi^2$ suppresses 5th force $\phi \to 0$



Lin, McDonough, JCH, Hu (2022)

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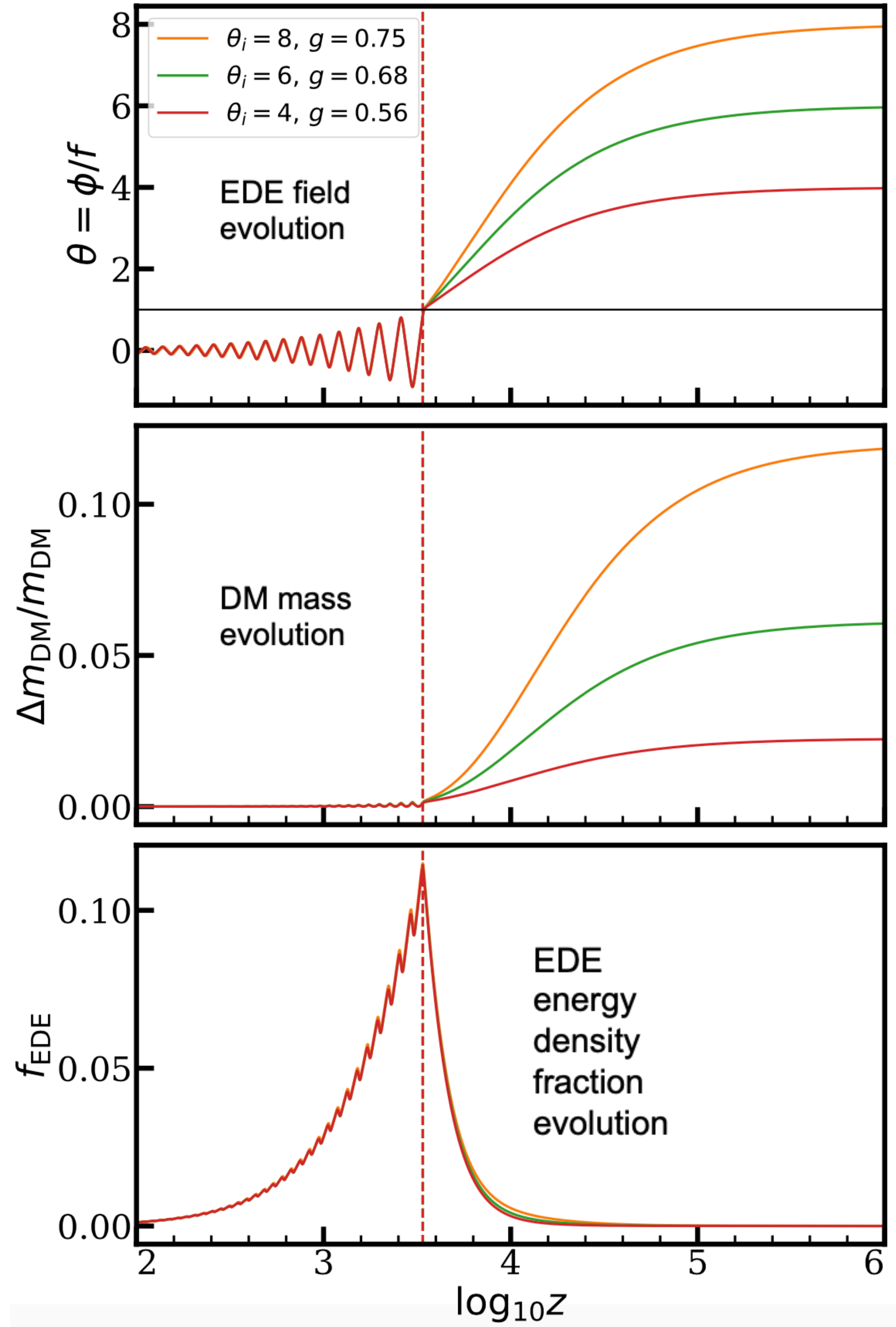
Basic validation: can successfully lower r_s, raise H_0 ~ 71.2 km/s/Mpc



Lin, McDonough, JCH, Hu (2022)

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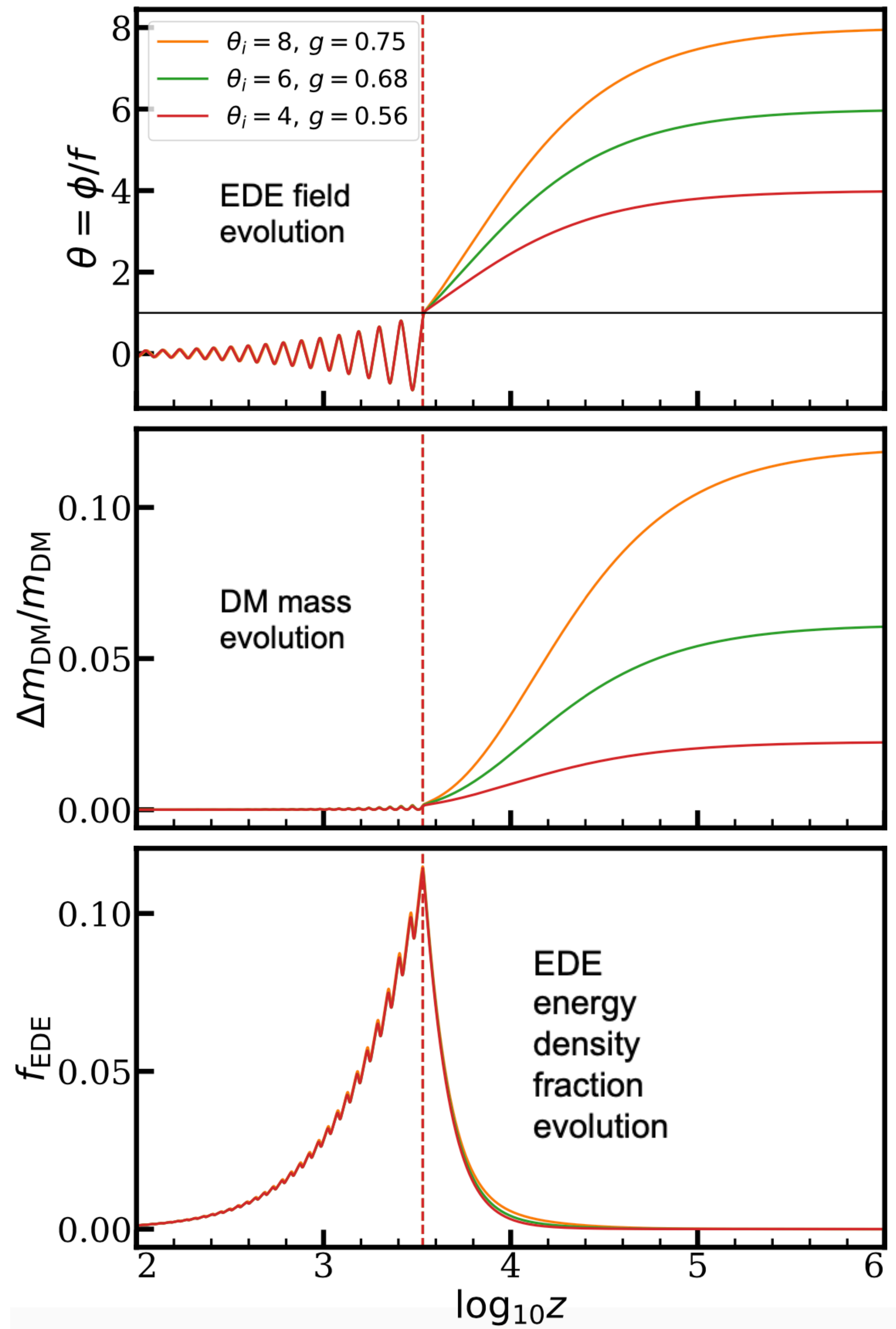
Basic validation: can successfully lower r_s, raise H_0 ~ 71.2 km/s/Mpc

Best-fit parameters to Planck+BAO+SNIa+SH0ES +DES-Y3:

Model	EDE	tEDS(p=8)
$f_{\rm EDE}$	0.108	0.112
$\log_{10} z_c$	3.56	3.83
H_0	71.96	71.21
S_8	0.8236	0.8200

- Goodness-of-fit nearly identical to EDE
- Coincidence problem resolved
- Fine-tuning of initial conditions resolved
- S_8 problem partially ameliorated



Lin, McDonough, JCH, Hu (2022)

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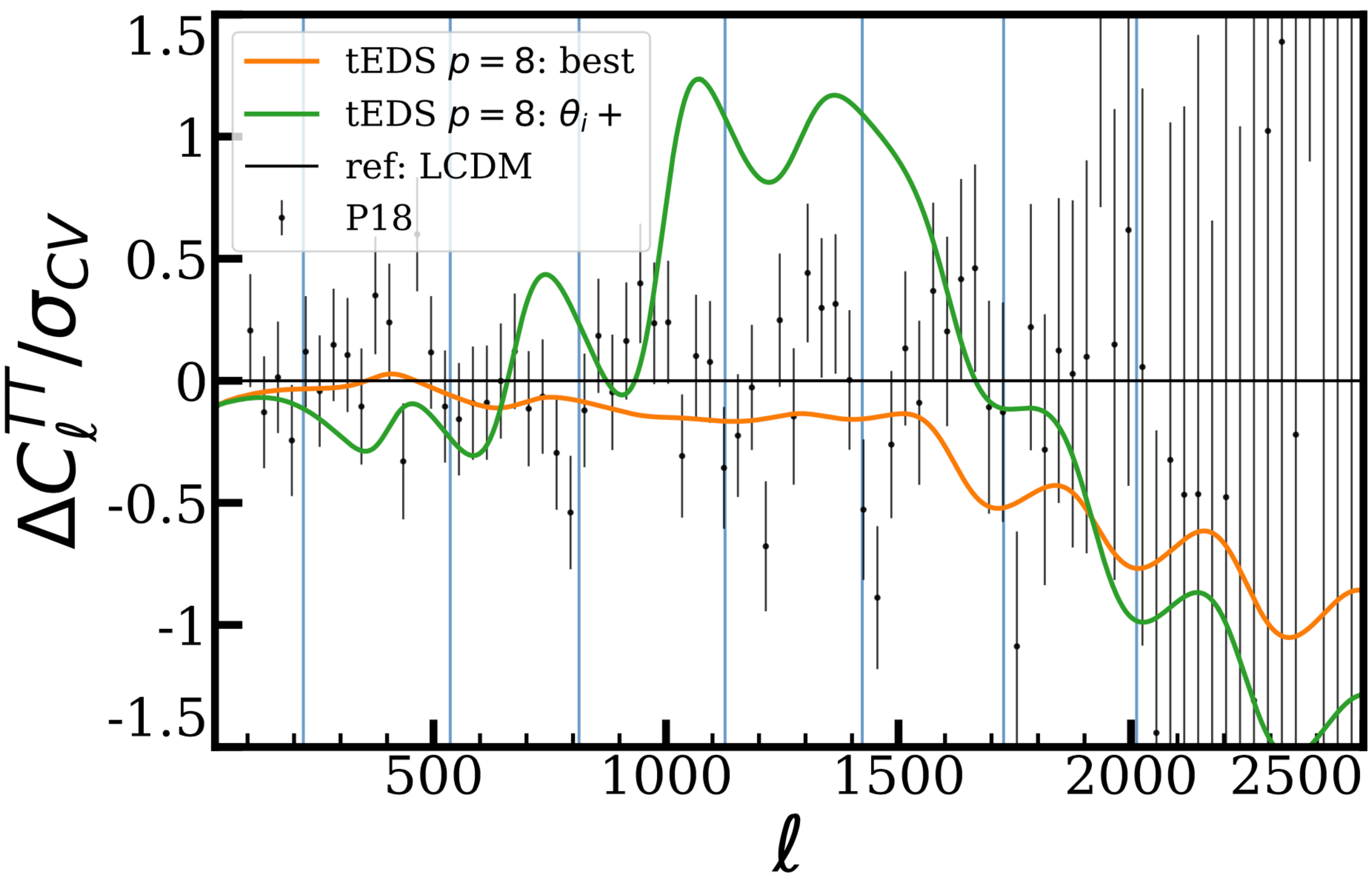
However: excess field fluctuations induced by rolling in $V_{eff}(\phi)$

Consider increase in initial field position (θ_i), hold z_c and $V(\phi)$ fixed



Result: data pick out specific θ_i to achieve dynamical balance

Next: MCMC/further model improvements

Lin, McDonough, JCH, Hu (2022)

Challenge: Lyman-α Forest



Goldstein, JCH, Irsic, Sherwin (to appear)

Lya Forest

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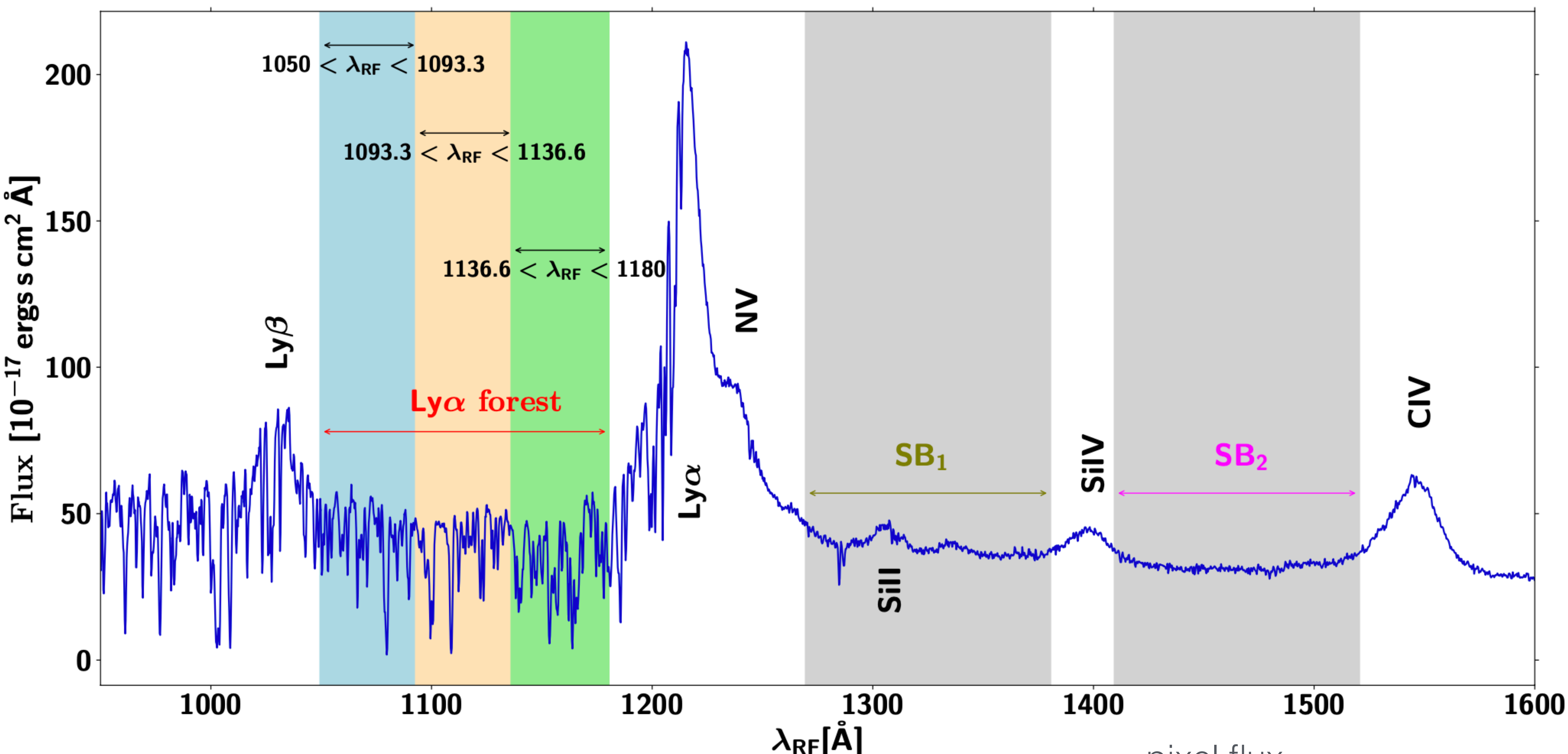
Absorption lines due to HI clouds along the LOS to a distant quasar



pixel flux

$$\delta(\lambda) = \frac{f(\lambda)}{C_q(\lambda)\overline{F}(z_{\mathrm{Ly}\alpha})} - 1$$

quasar continuum   mean trans. flux fraction

Chabanier et al. (2019)

Lya Forest

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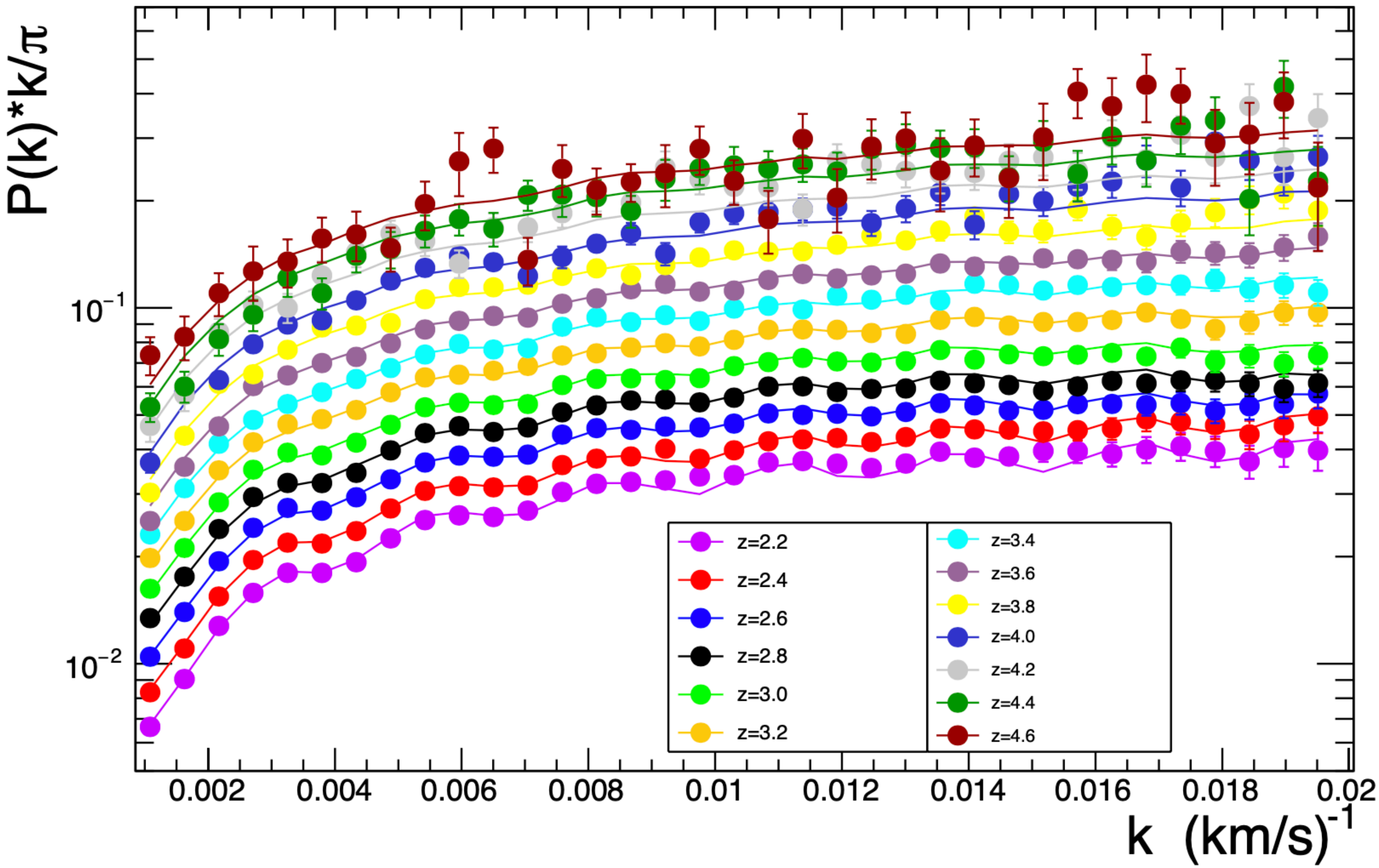
Observable: 1D flux power spectrum

BOSS/eBOSS: ~44,000 quasar spectra (moderate S/N)



k~0.01 s/km ⟷ k~1 h/Mpc at z=3

Chabanier et al. (2019)

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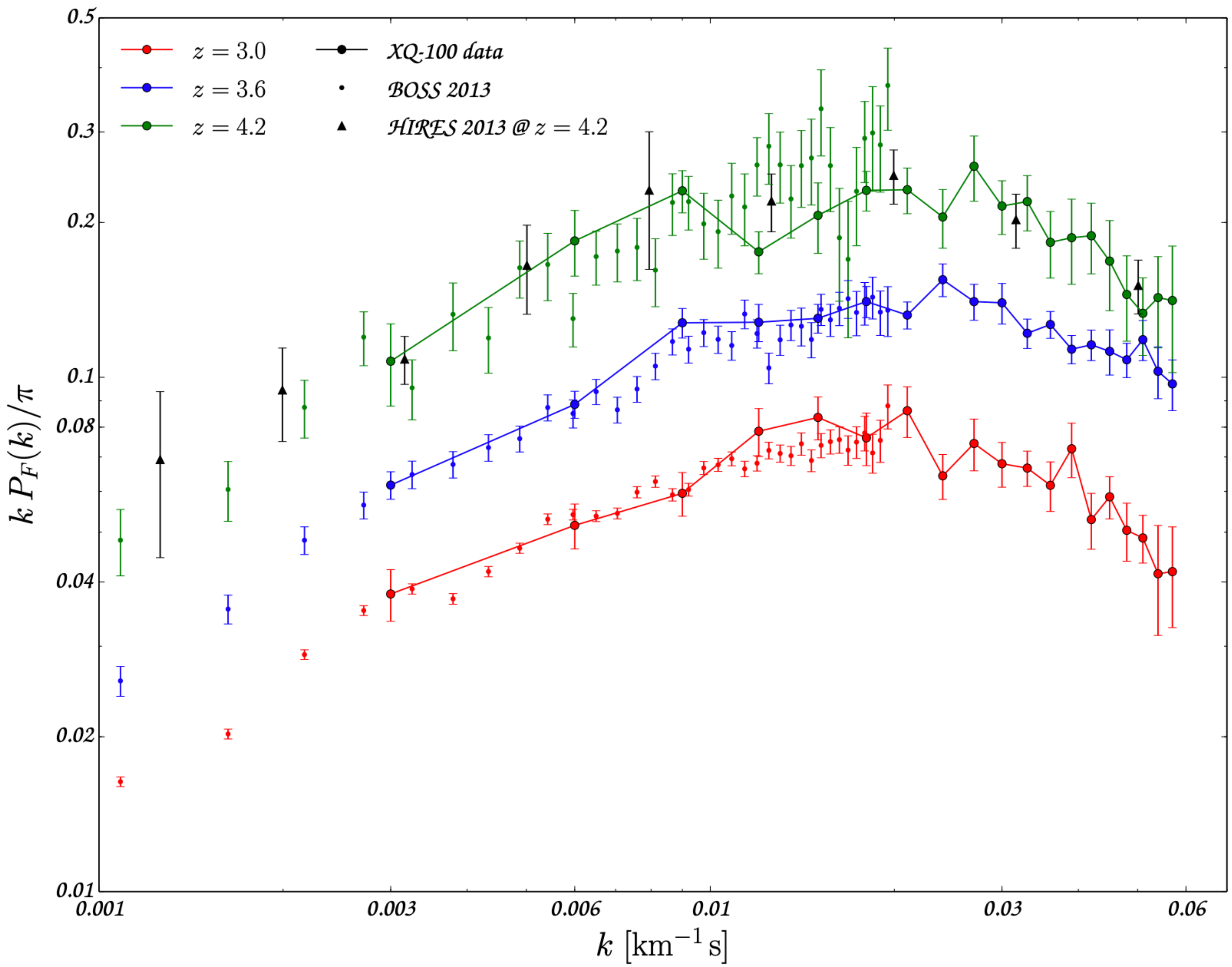
Observable: 1D flux power spectrum

XQ100: 100 quasar spectra (high-S/N)



+ MIKE/ HIRES spectra at z=4.2 - 5.4

Irsic et al. (2017); Viel et al. (2013)

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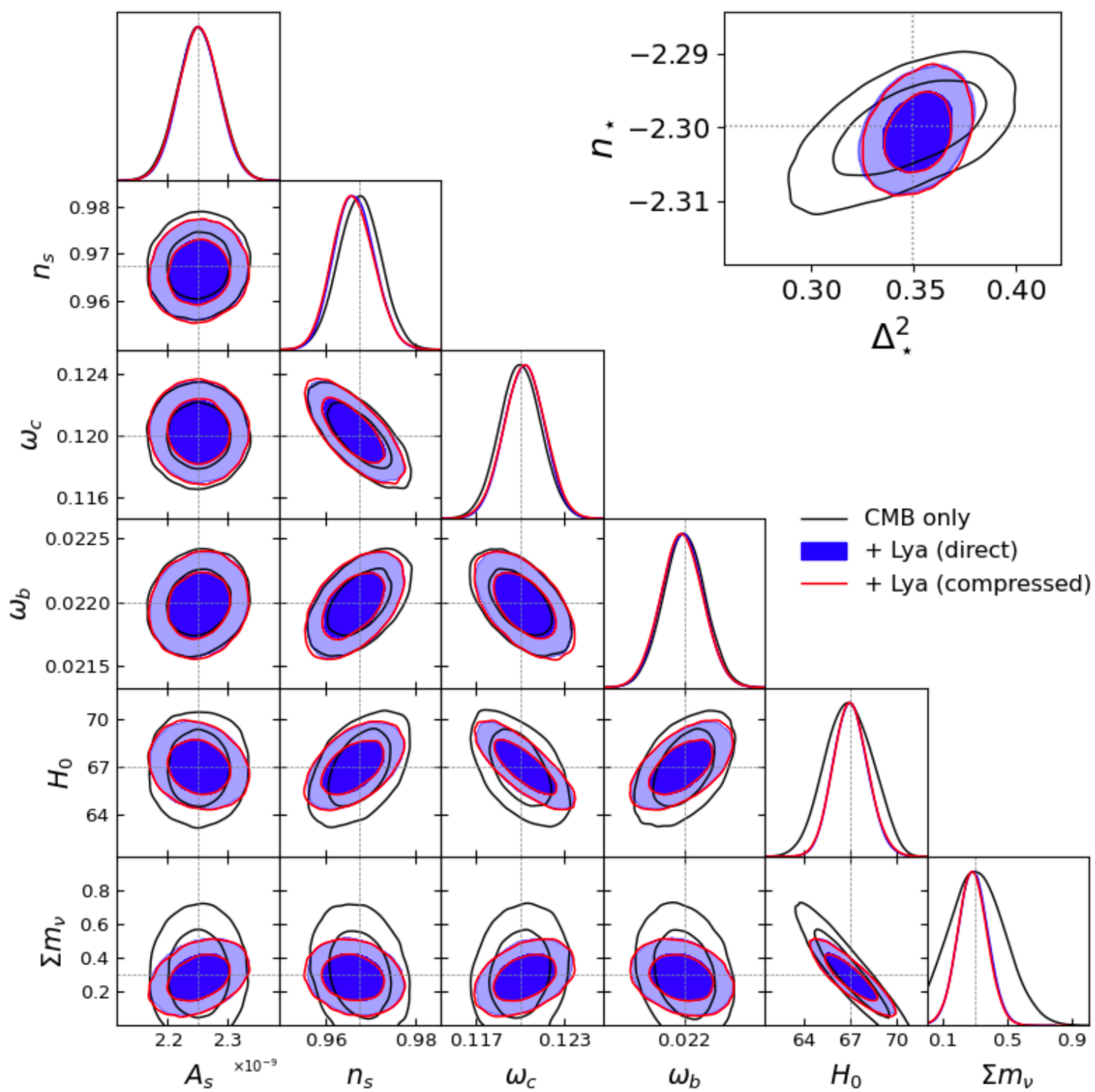
Lya Forest

Information content fully contained in compressed 2D likelihood

amplitude $$\Delta_L^2 \equiv k^3 P_{\rm lin}(k_p, z_p)/(2\pi^2)$$

slope $$n_L \equiv d\ln P_{\rm lin}(k_p, z_p)/d\ln k$$

at k_p = 0.009 s/km and z_p = 3



(validation using sims here)

McDonald et al. (2005); Pedersen, Font-Ribera, & Gnedin (2022)

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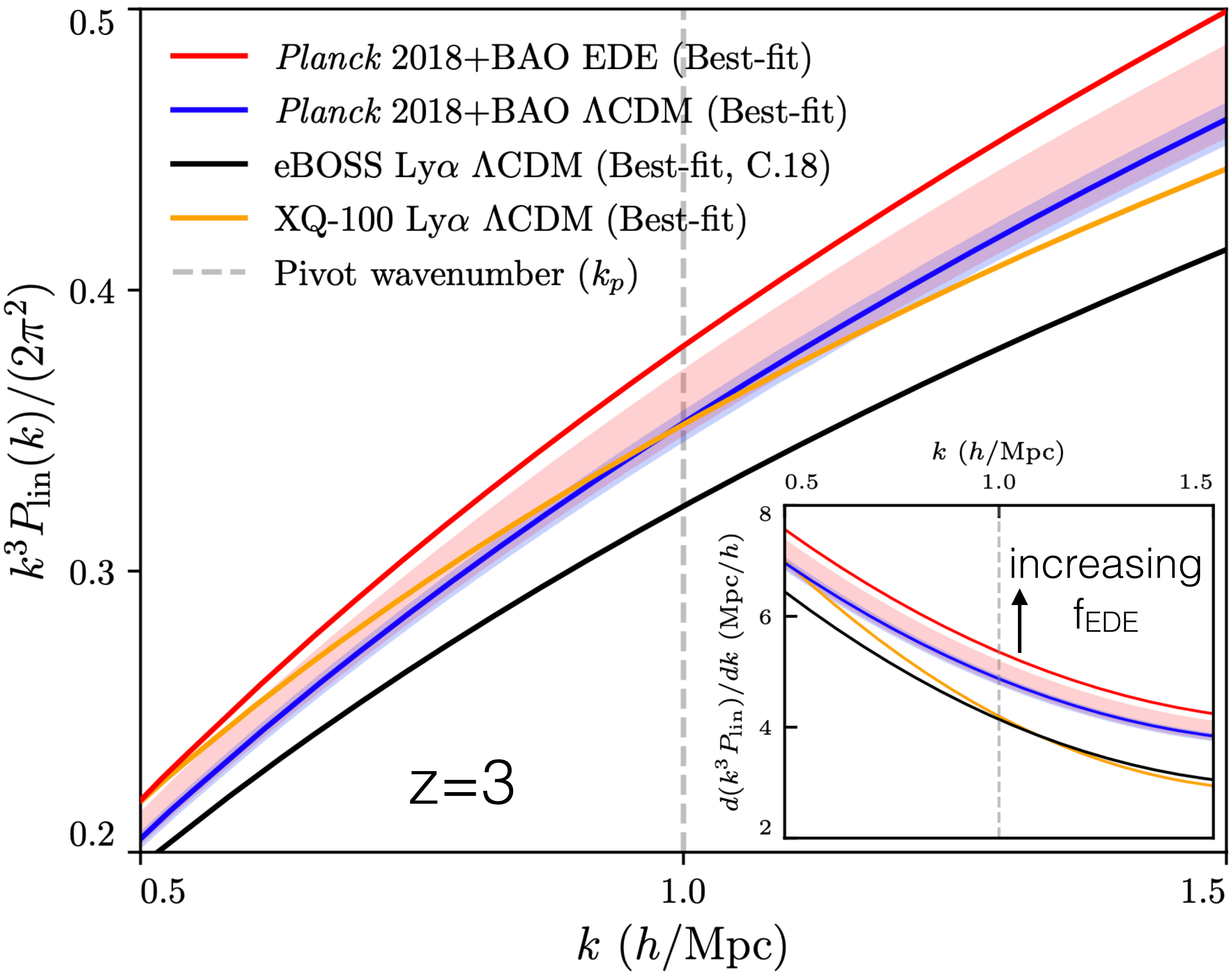
Inconsistent with prediction of EDE model fit to Planck CMB + BAO



Goldstein, JCH, Irsic, & Sherwin (to appear)

Origin of EDE Changes to P(k)

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Why? Parameter shifts necessary to compensate enhanced early ISW effect in EDE cosmologies

Smith+ (2019); JCH+ (2020); Vagnozzi (2021)

Origin of EDE Changes to P(k)

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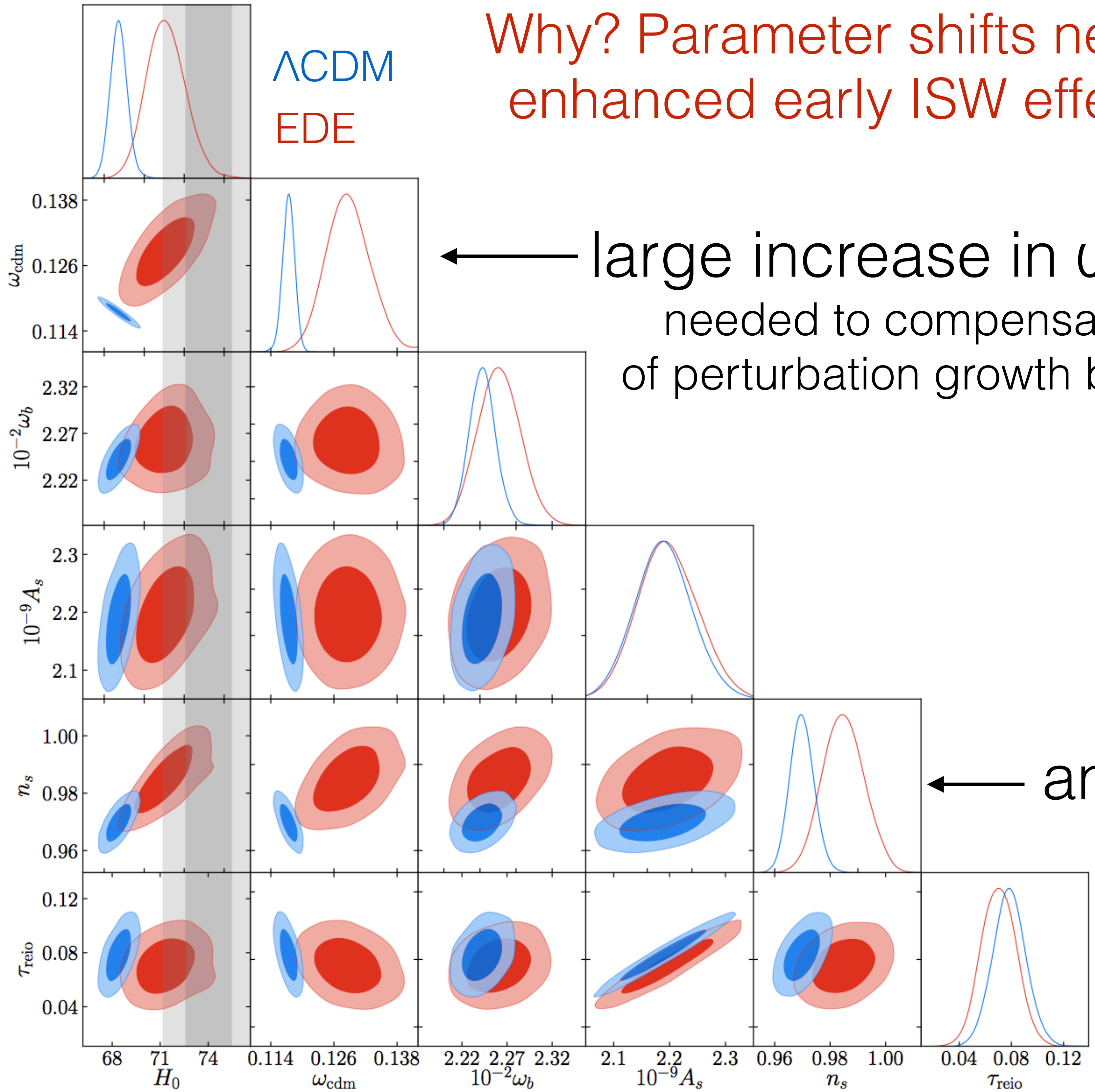
Why? Parameter shifts necessary to compensate enhanced early ISW effect in EDE cosmologies



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

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

← and increase in n_s

fits to Planck + BAO + RSD + SNIa + SH0ES

Smith+ (2019); JCH+ (2020); Vagnozzi (2021)

Lyα Forest: EDE Constraints

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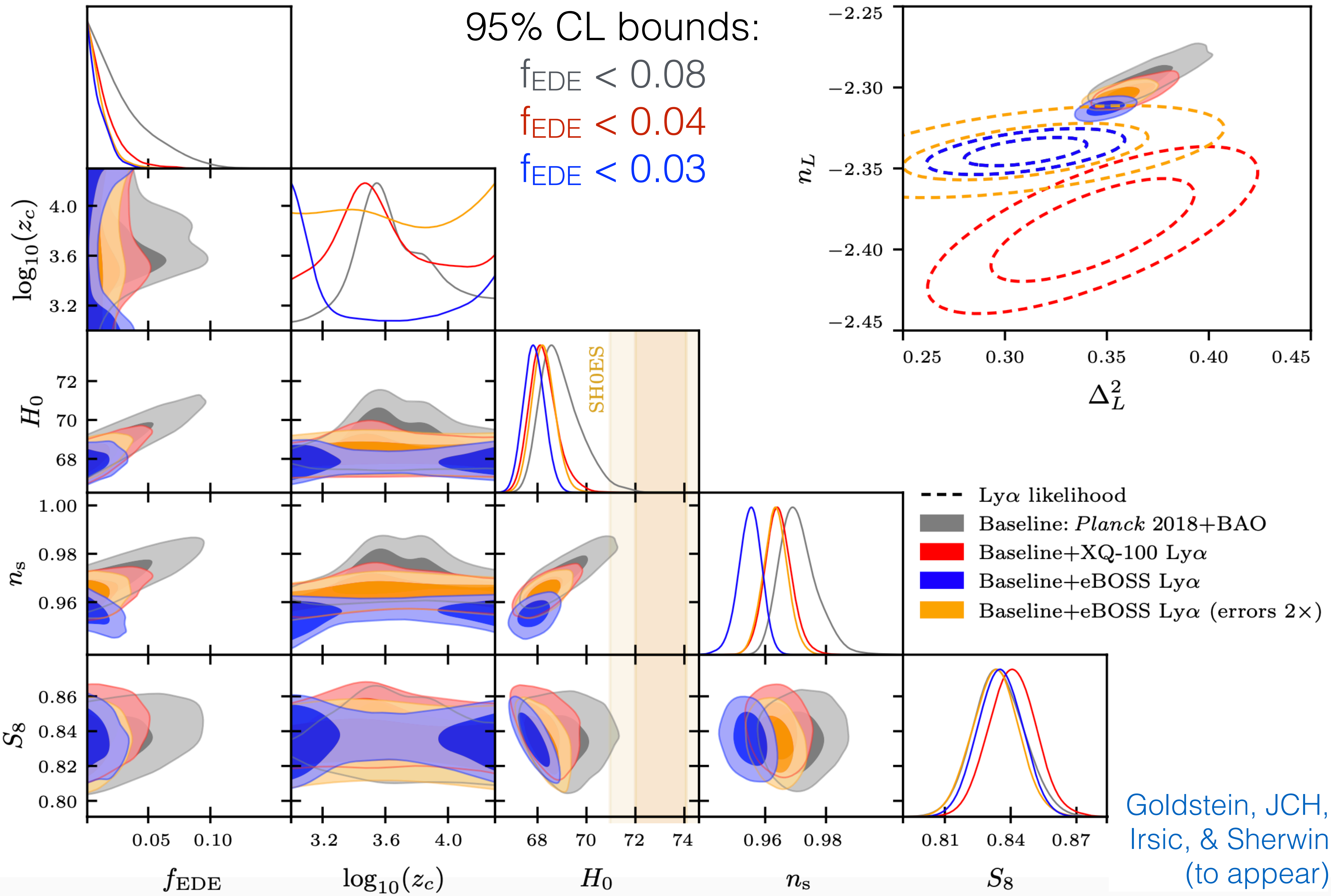
Columbia

95% CL bounds:
$f_{EDE} < 0.08$
$f_{EDE} < 0.04$
$f_{EDE} < 0.03$



Goldstein, JCH, Irsic, & Sherwin (to appear)

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Lyα Forest: EDE Constraints

Taken at face value, Lyα forest excludes EDE resolution of H_0 tension

- Baseline (CMB+BAO): H_0 = 69.0 +0.6 -1.0 (best-fit = 70.1) km/s/Mpc
- Baseline + eBOSS: H_0 = 67.9 +/- 0.4 (best-fit = 67.9) km/s/Mpc
- Baseline + XQ-100: H_0 = 68.2 +0.5 -0.6 (best-fit = 68.2) km/s/Mpc

Goldstein, JCH, Irsic, & Sherwin (to appear)

Lyα Forest: EDE Constraints

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- Baseline + XQ-100: H_0 = 68.2 +0.5 -0.6 (best-fit = 68.2) km/s/Mpc

Even direct inclusion of SH0ES (H_0 = 73.04 +/- 1.04 km/s/Mpc) hardly moves the Lyα EDE posteriors

Note that the hydro simulations used to construct Lyα likelihoods *do* include P(k) that well-represent EDE models

Are the BOSS/eBOSS/XQ100/MIKE/HIRES Lyα data fully secure? There is already some tension w.r.t. Planck even in ΛCDM. Our results motivate close scrutiny!

Goldstein, JCH, Irsic, & Sherwin (to appear)

Generalized Dark Matter —> Dark Radiation Conversion

See
https://arxiv.org/abs/2210.14339

F. McCarthy & JCH (2022)

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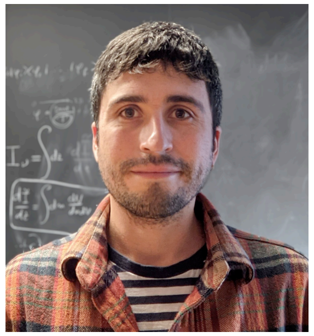
Einstein-Boltzmann Emulators




Bolliet, Spurio Mancini, JCH, Madhavacheril, et al. (to appear)

CosmoPower

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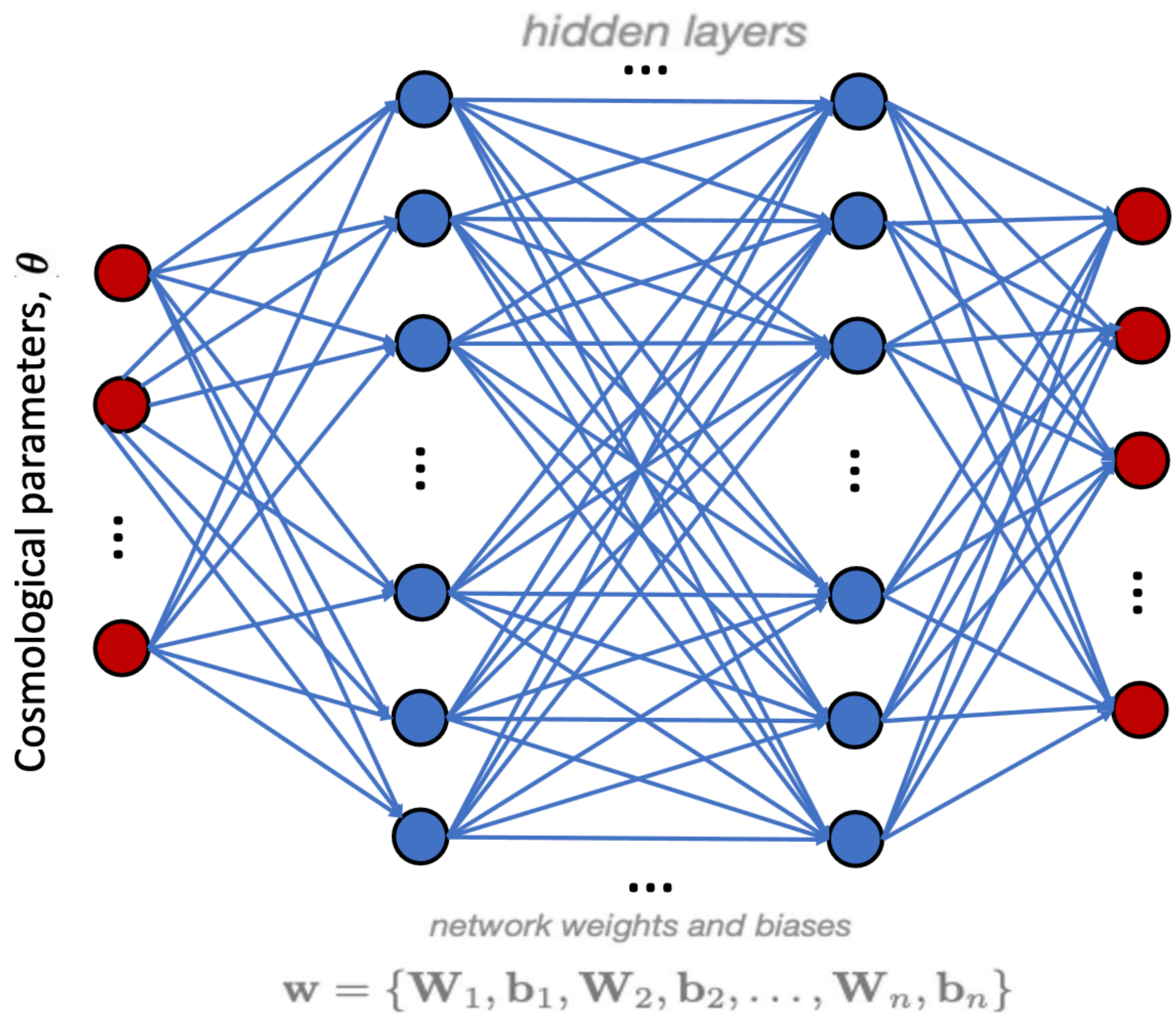
Columbia

Cosmological observables are smooth functions of the input parameters: easy to emulate at high accuracy with modern neural networks



Spurio Mancini et al. (2022)

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Columbia/CCA

Theoretical Accuracy

Are the default accuracy settings in CAMB/CLASS OK for ACT/SO?
Almost, but not quite! Higher accuracy needed in lensing calc.

JCH et al. (2021): arXiv: 2109.04451 ; McCarthy, JCH, Madhavacheril (2021): arXiv:2103.05582

Colin Hill
Columbia/CCA

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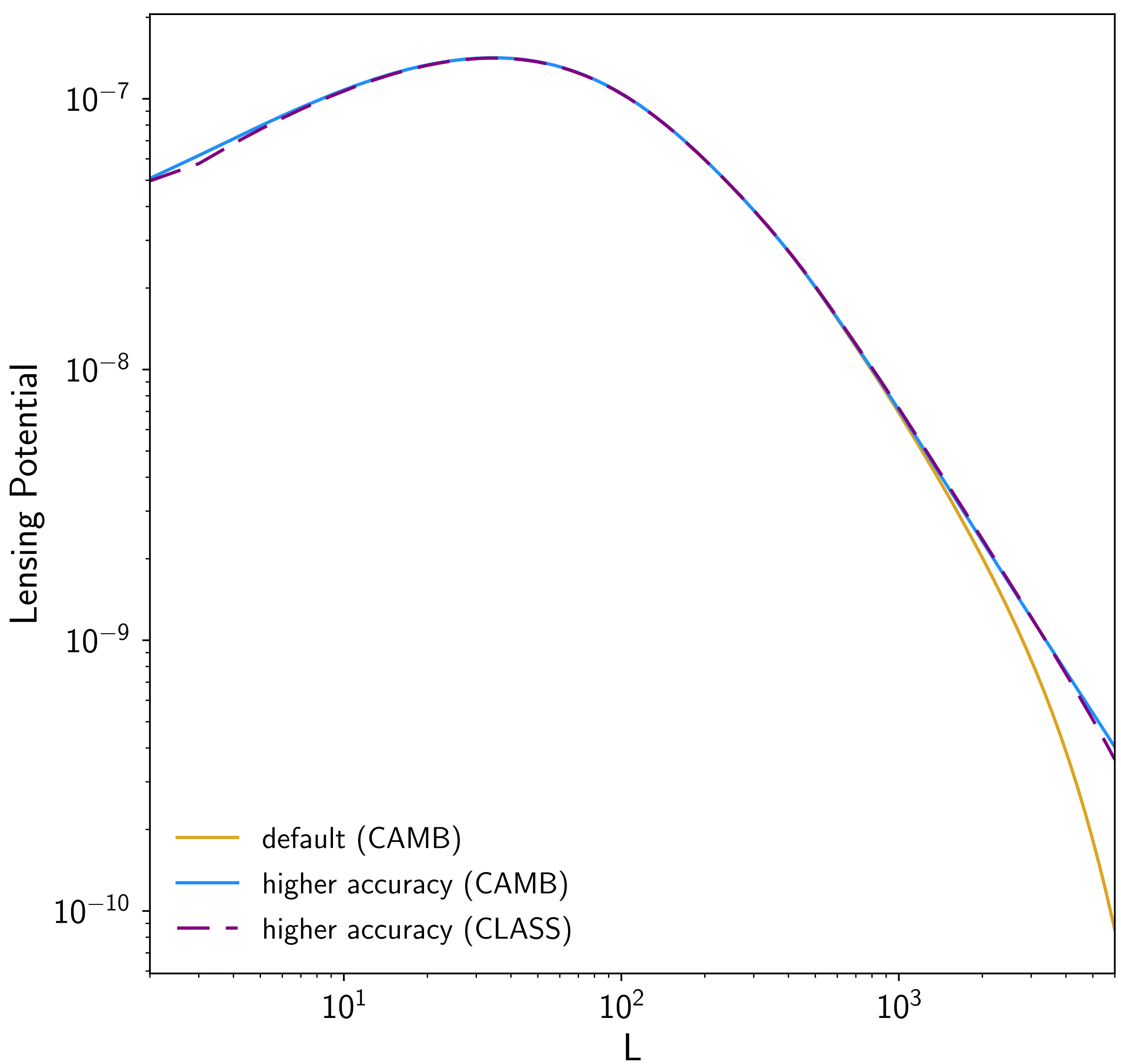

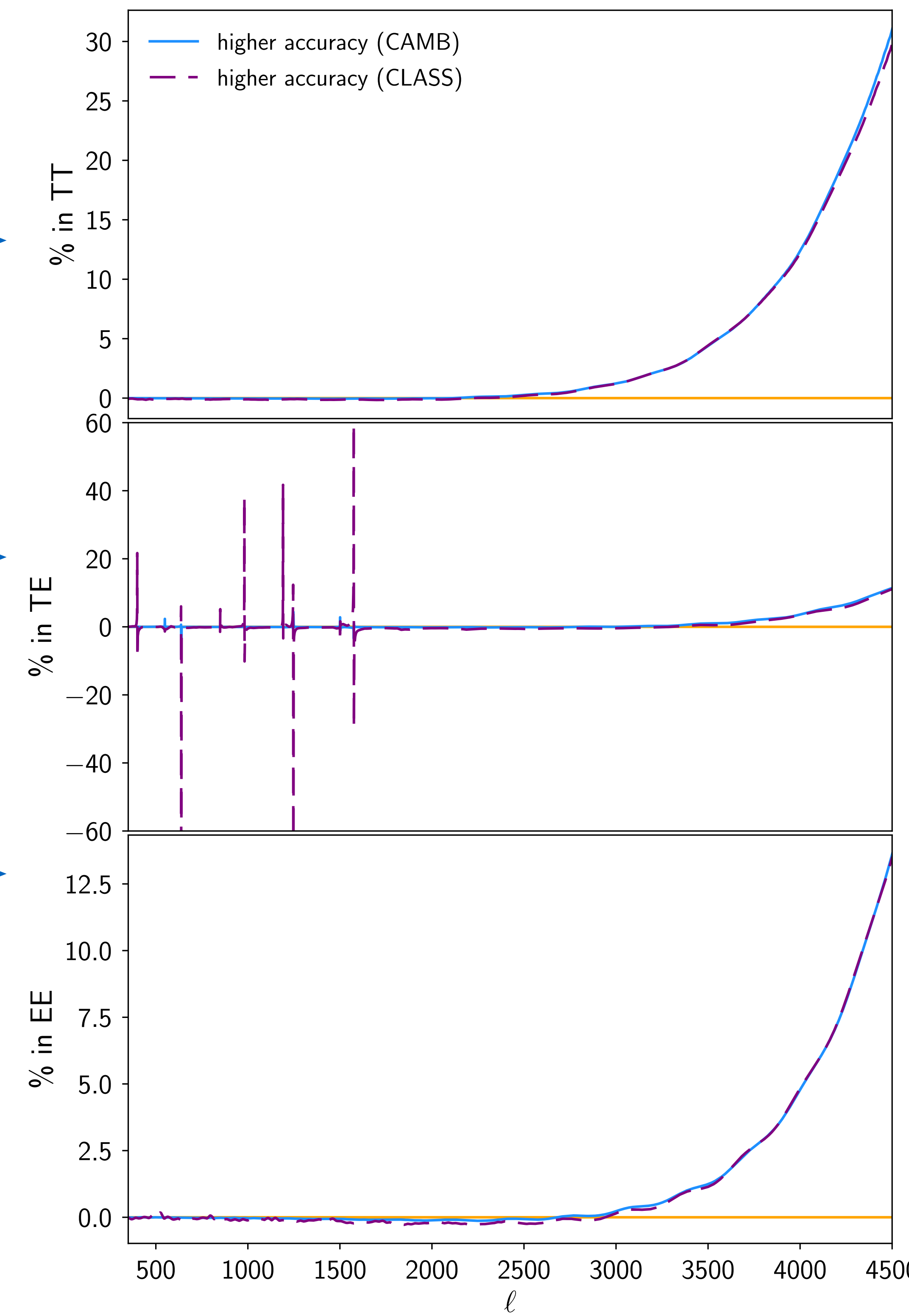

JCH et al. (2021); McCarthy, JCH, Madhavacheril (2021)

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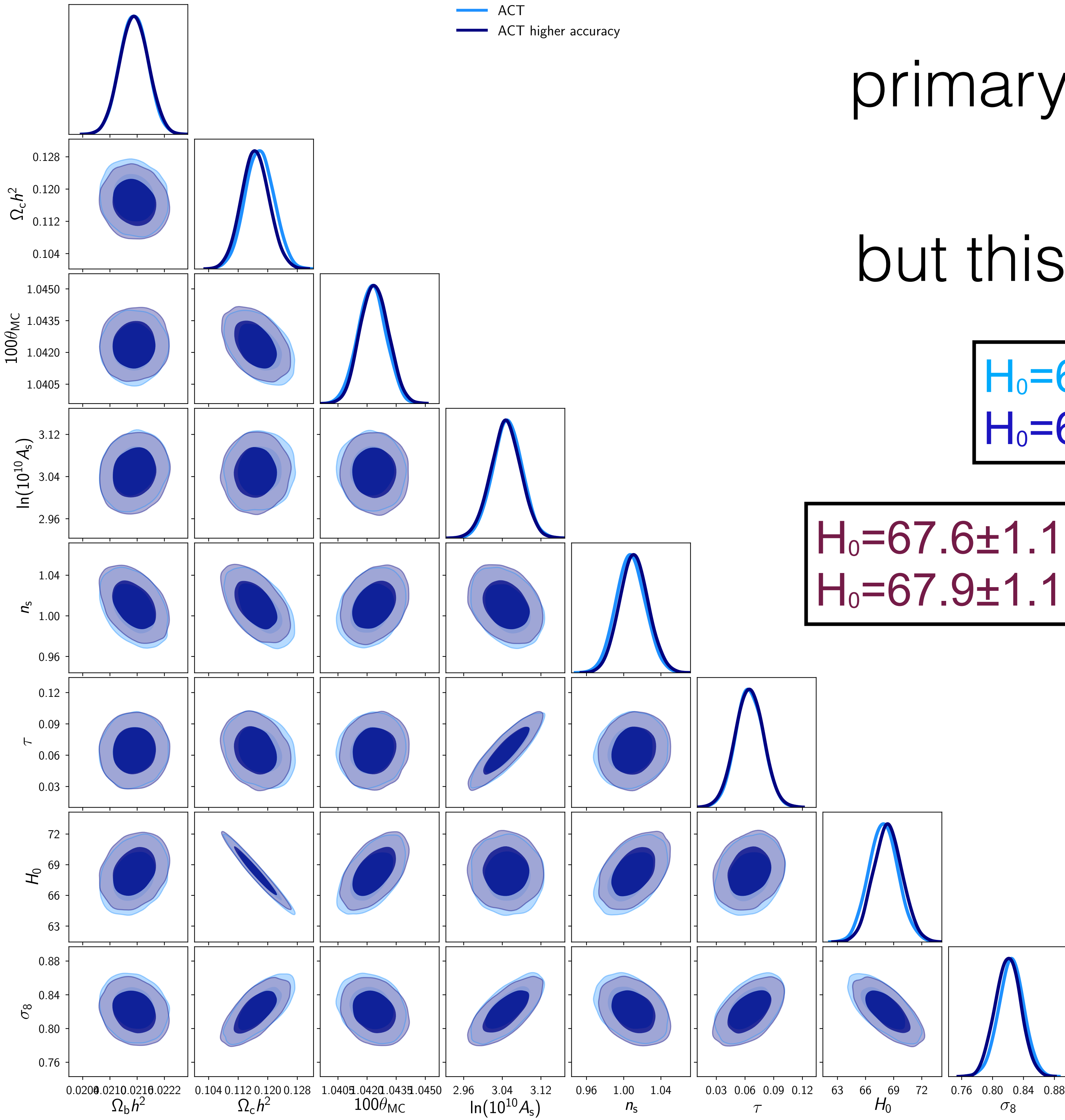
Theoretical Accuracy

For ACT DR4, this correction shifts some parameters by ~0.2-0.3σ



primary parameters affected are $\Omega_c h^2$ and n_s

but this propagates to H_0 and σ_8

H_0=67.9±1.5 km/s/Mpc	*ACT (original)*
H_0=68.4±1.5 km/s/Mpc	*ACT (high-acc.)*

H_0=67.6±1.1 km/s/Mpc	*ACT+WMAP (original)*
H_0=67.9±1.1 km/s/Mpc	*ACT+WMAP (high-acc.)*

JCH et al. (2021)

Can be multi-σ bias for upcoming experiments

McCarthy, JCH, Madhavacheril (2021)

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Columbia

CosmoPower++

Goal: build emulators using very high-precision CLASS calculations — these require 1 minute per evaluation (much slower than default!)

- CMB TT/TE/EE power spectra accurate to < 0.5% at all multipoles < 10^4
- Linear P(k) accurate to < 0.5% at all k < 50 h/Mpc
- Distance-redshift relation; H(z)
- BAO observables
- Derived parameters (σ_8, θ_s, etc.)

- Factor of 100-1000x speedup per Boltzmann call in MCMC
- NNs are fully differentiable (can be used in gradient-based inference)
- Can be run on GPUs for further acceleration

Models run thus far (128,000 parameter sets each):
ΛCDM, +N_{eff}, +M_ν, +w

Bolliet, Spurio Mancini, JCH, Madhavacheril, et al. (to appear)

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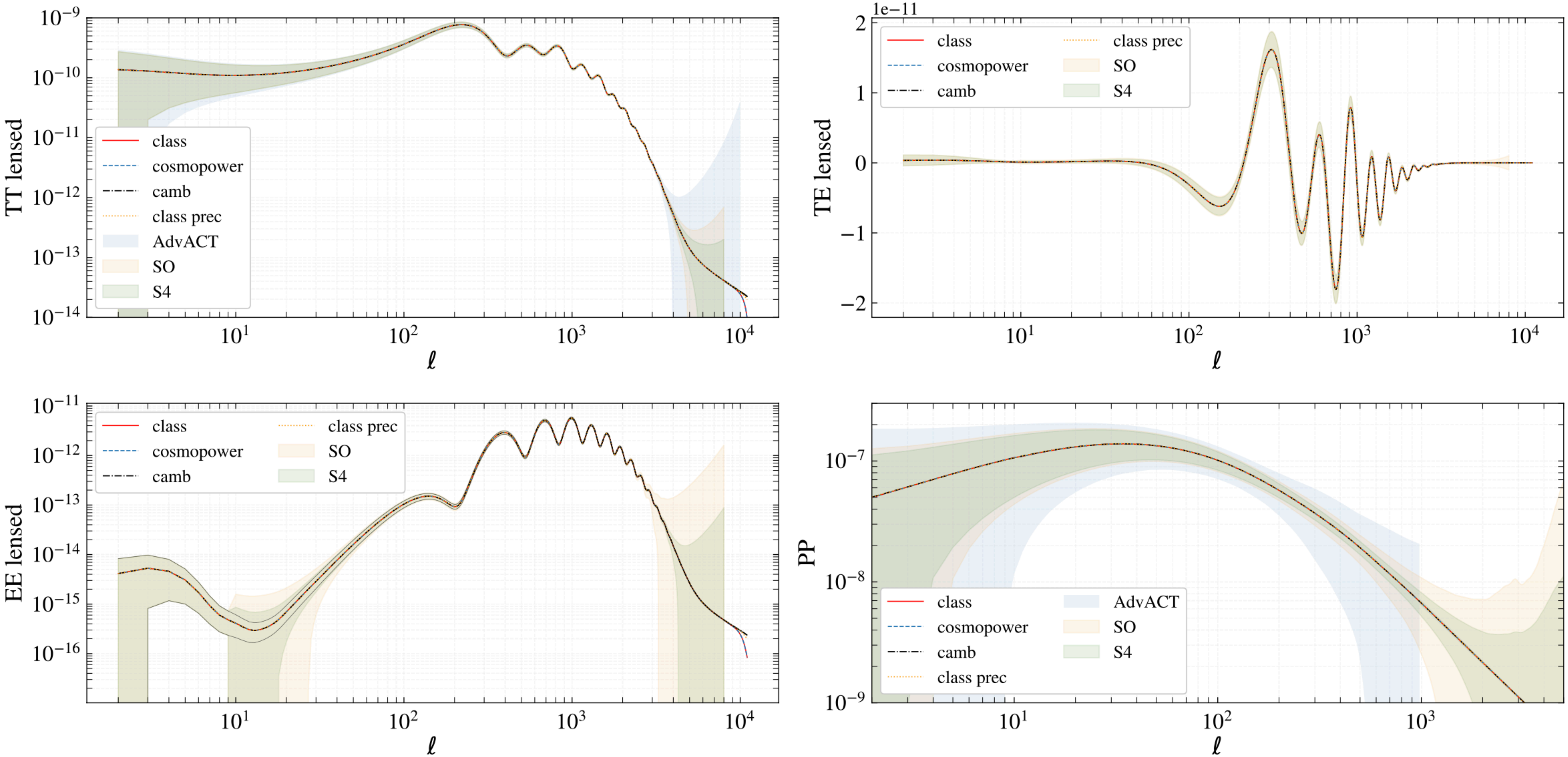
CosmoPower++

It works :-)



Bolliet, Spurio Mancini, JCH, Madhavacheril, et al. (to appear)

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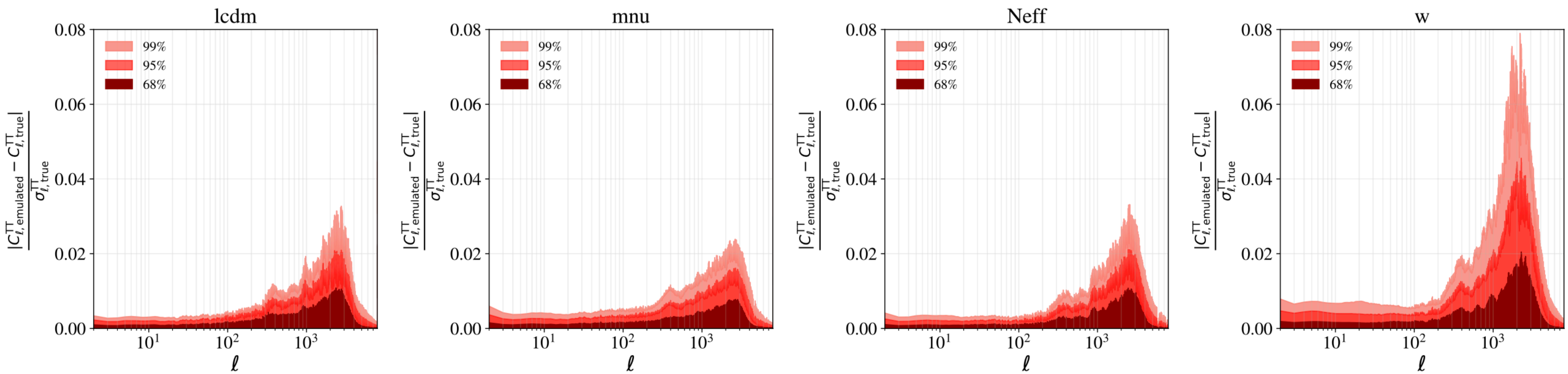
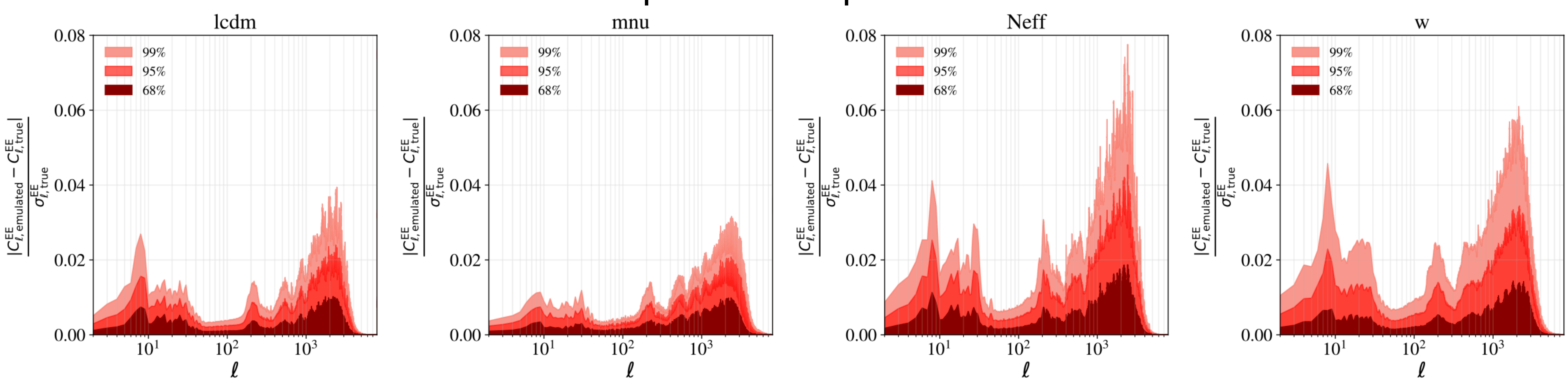
Validation on Test Set

Assess accuracy in terms of forecast CMB-S4 error bars: < 0.07σ!

TT power spectrum



EE power spectrum



Bolliet, Spurio Mancini, JCH, Madhavacheril, et al. (to appear)

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ACT DR4 Reproduction

~few minutes on laptop vs. ~few days on CCA cluster (!)

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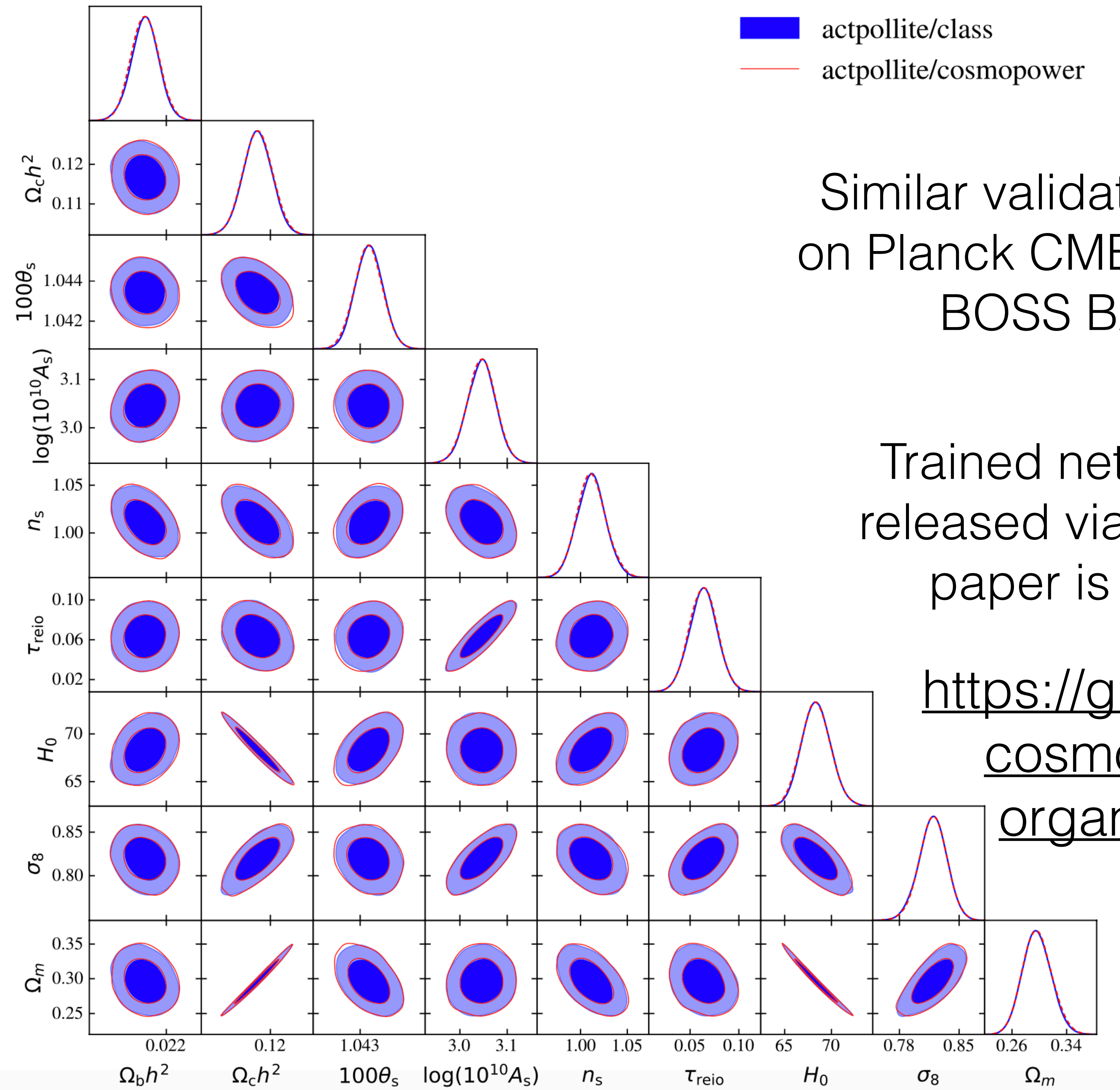


Similar validation performed on Planck CMB, CMB lensing, BOSS BAO+RSD

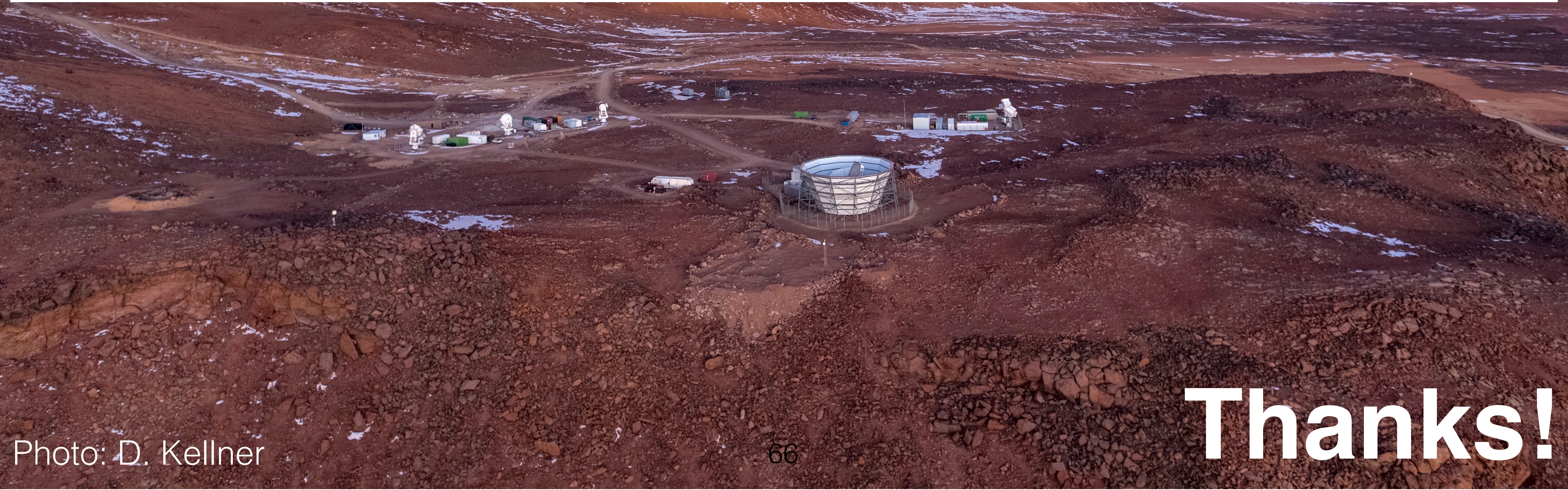
Trained networks will be released via GitHub when paper is submitted!

https://github.com/cosmopower-organization

Bolliet, Spurio Mancini, JCH, Madhavacheril, et al. (to appear)

Take-Home Messages

1) ACT and Planck prefer somewhat different EDE model parameters, with ACT yielding higher f_{EDE} and H_0
2) Early dark sector may help w/ coincidence, ICs, S_8 of EDE
3) Challenge: Lyα forest severely constrains canonical EDE
4) CosmoPower: never wait for MCMCs ever again
5) Early-universe H_0 / S_8 resolutions generically predict clear deviations from ΛCDM in the CMB — imminently testable with ACT DR6, SPT-3G, Simons Observatory



Thanks!

Photo: D. Kellner

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Bonus

Lya EDE Validation

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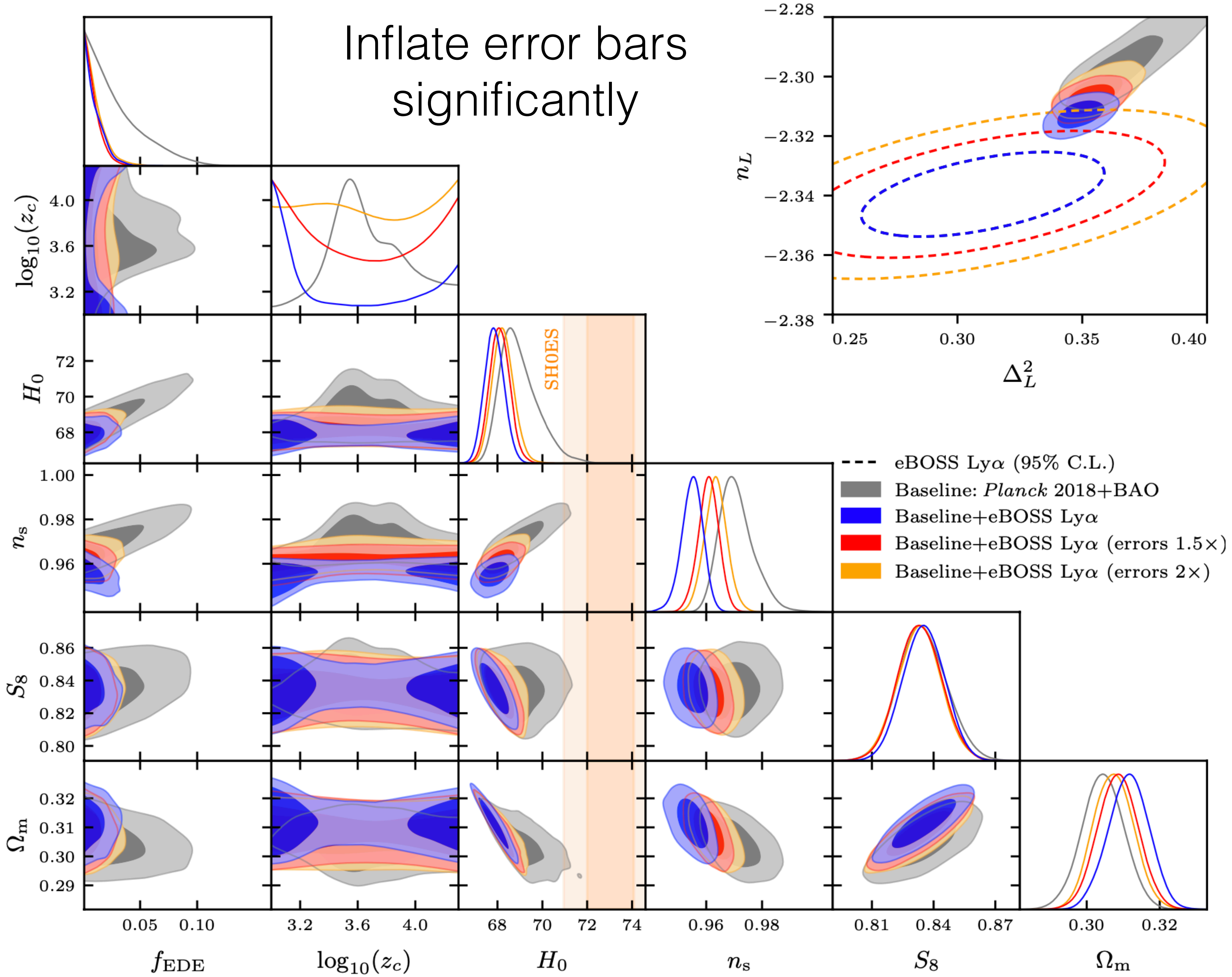
Inflate error bars significantly



Goldstein, JCH, Irsic, & Sherwin (to appear)

Lyα EDE Validation

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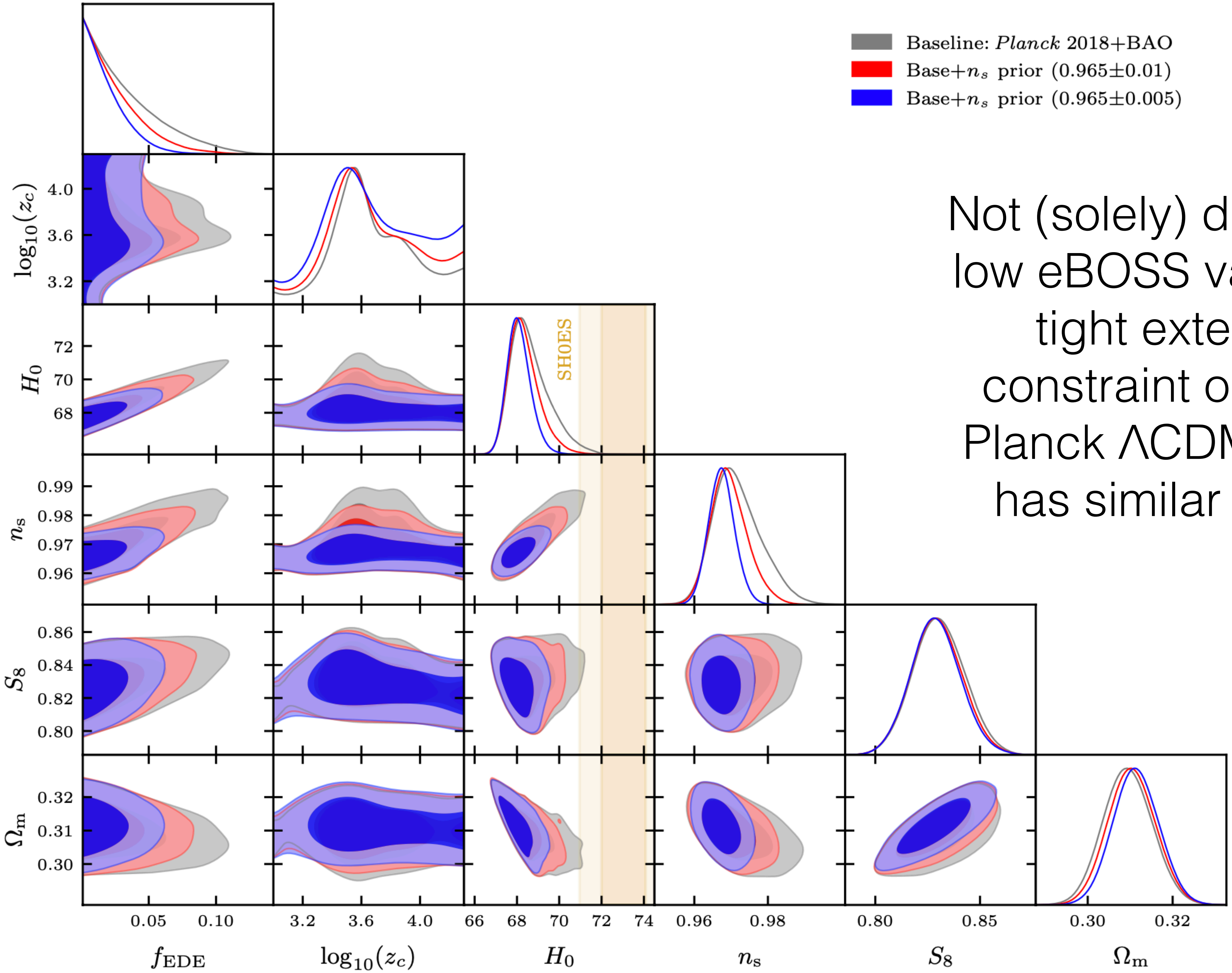

Not (solely) driven by low eBOSS values: a tight external constraint on n_s at Planck ΛCDM value has similar effect

Goldstein, JCH, Irsic, & Sherwin (to appear)

Lyα EDE Validation

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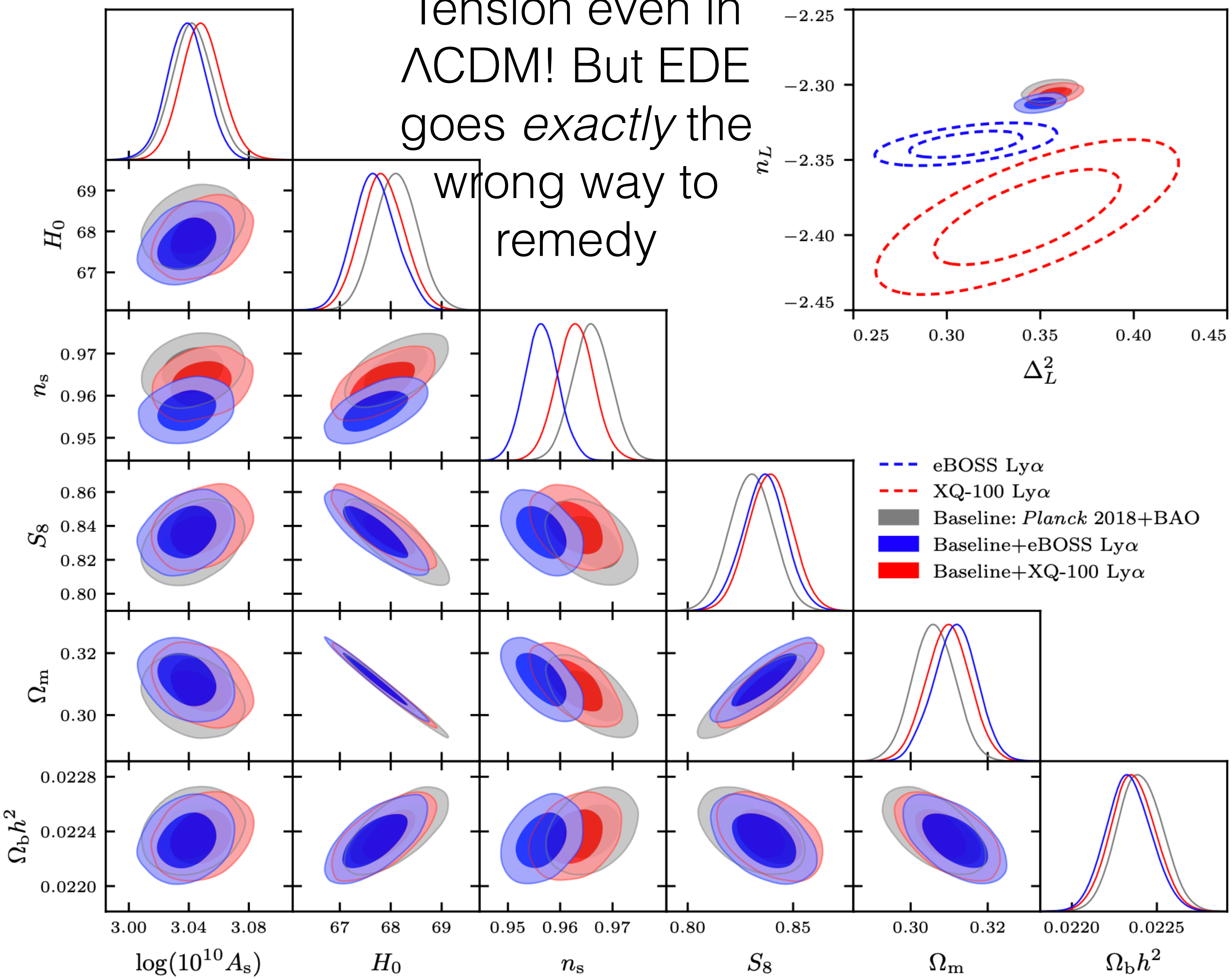

Goldstein, JCH, Irsic, & Sherwin (to appear)

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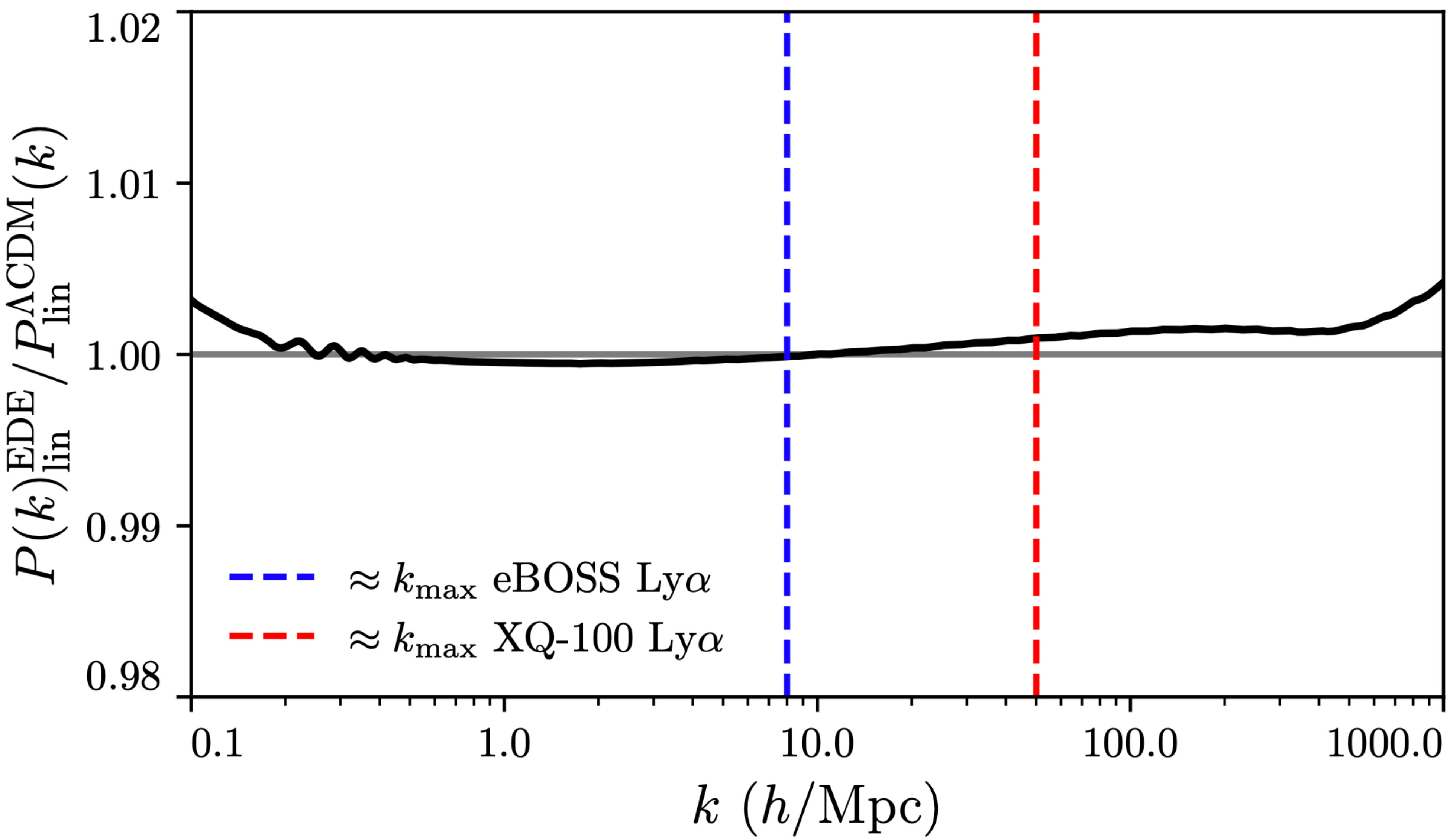
Lyα EDE Validation

Do the hydro sim grids used in the Lyα likelihood construction cover relevant $P_{lin}(k)$ for EDE analysis? Yes

Best-fit baseline EDE P(k) at z=3 can be very accurately mimicked by ΛCDM P(k) with slightly tweaked parameters



Goldstein, JCH, Irsic, & Sherwin (to appear)

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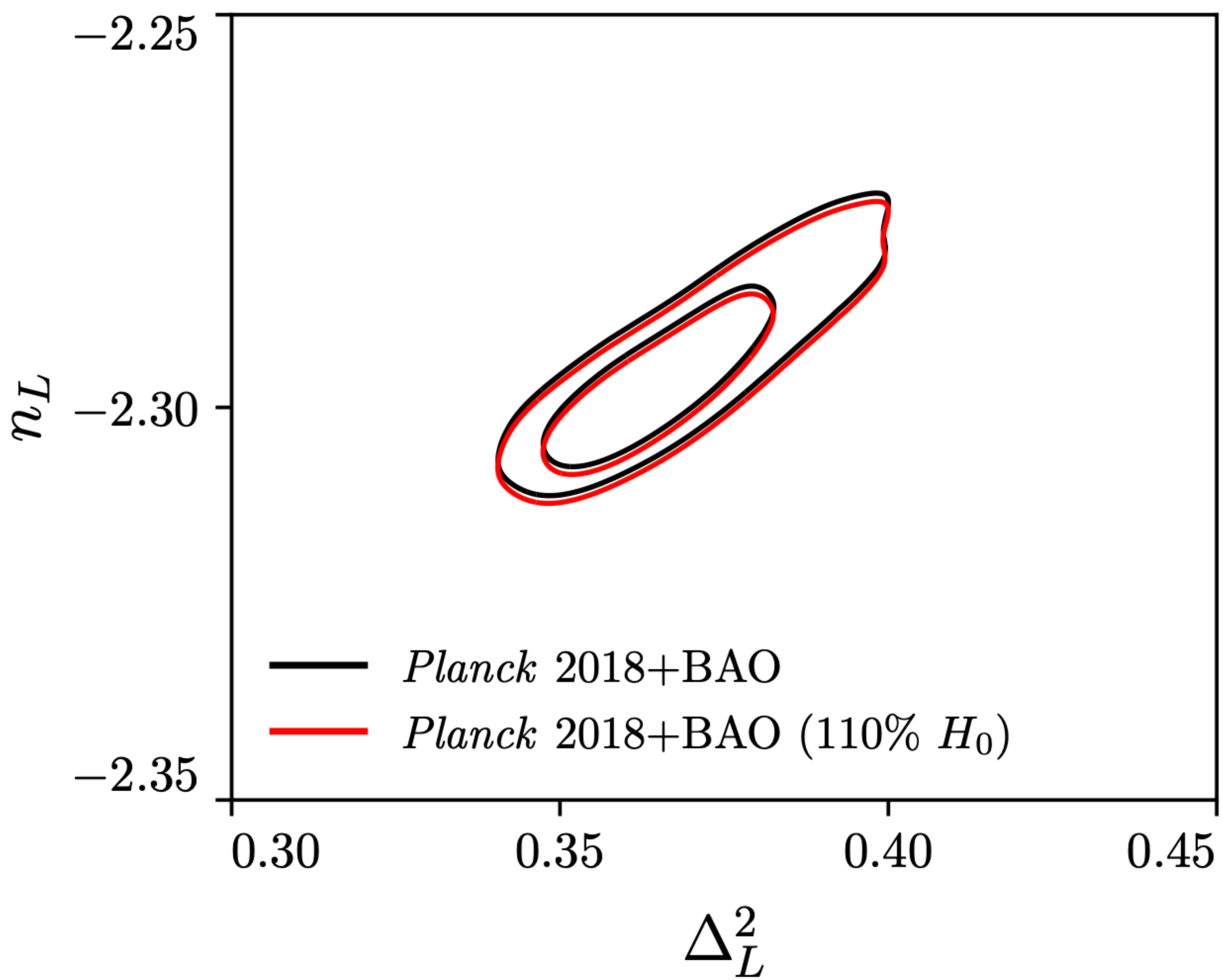
Lyα EDE Validation

Do the priors used in the Lyα likelihood construction have any impact on the compressed parameter likelihoods used in EDE analysis? No



Recomputation of baseline EDE constraints with H_0 increased by 10% for each sample in the chain

Goldstein, JCH, Irsic, & Sherwin (to appear)

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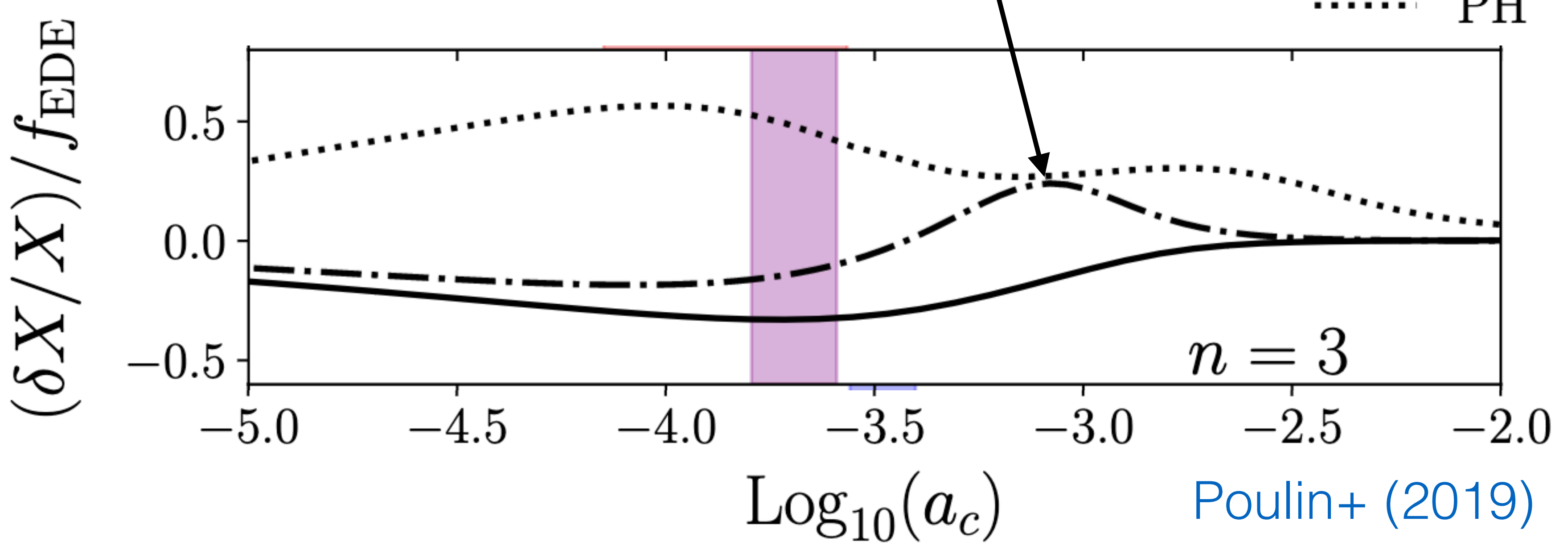
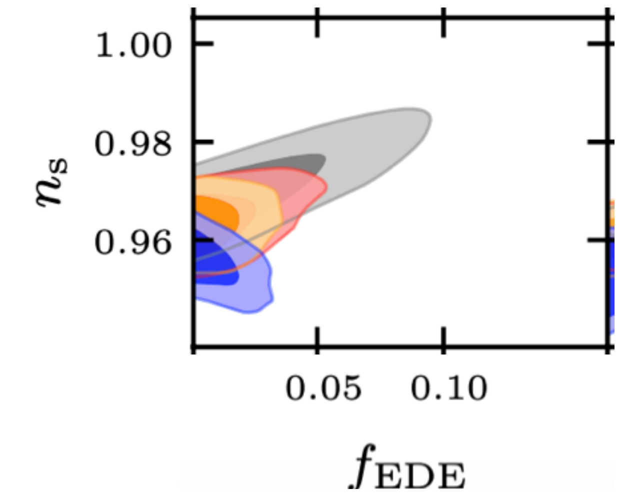
Lya EDE Validation

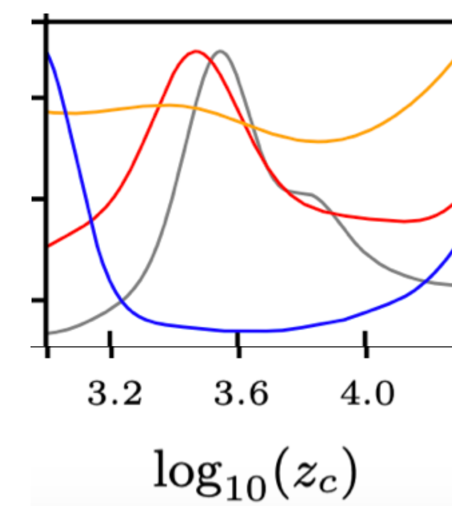
Origin of the n_s - f_{EDE} anti correlation for the baseline+eBOSS analysis

Ratio of sound horizon to damping scale *increases* for $1000 < z_c < 10^{3.3}$



Poulin+ (2019)





Thus θ_s/θ_d increases; but θ_s is fixed by observations, so θ_d *decreases,* i.e., ell_d increases. Hence less damping at a given ell, so n_s decreases to compensate.

Goldstein, JCH, Irsic, & Sherwin (to appear)