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

Colin Hill

Columbia University

Copernicus Webinar
6 June 2023

2109.04451 w/ ACT Collaboration + 2112.10754 w/ La Posta, Louis, Garrido
2210.14339 w/ F. McCarthy
2112.09128 + **2212.08098** w/ M.-X. Lin, E. McDonough, W. Hu
2303.00746 w/ S. Goldstein, V. Irsic, B. Sherwin
2304.03750 w/ B. Bolliet

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“Tensions”

My personal view: observational situation remains unclear

Regardless, the situation has motivated us to think about many types of new physics in the cosmos that we otherwise (likely) would not have

↓

How can we increase H_0 inferred from the CMB and large-scale structure?

…without worsening the S_8 problem (if there is one!)

“Tensions”

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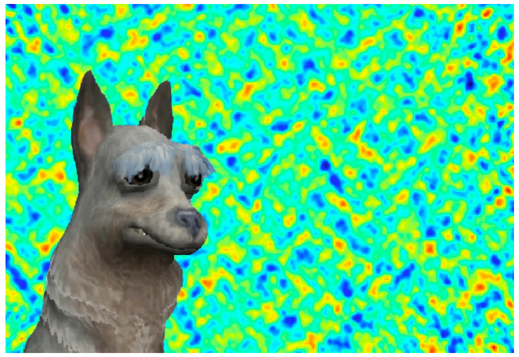
How can we increase H_0 inferred from the CMB and large-scale structure?

…without worsening the S_8 problem (if there is one!)

Late-time (z<few) theoretical modifications are highly constrained by (relative) expansion history data, e.g., BAO distances and SNIa distances

Such models often also conflict with integrated Sachs-Wolfe effect and CMB lensing data (e.g., McCarthy & JCH (2022): 2210.14339)

➡ Viable models modify dynamics at high redshift



Outline

- Classes of Viable Models
- Early Dark Energy
  - Hints? ACT DR4 (+SPT-3G)
  - Challenges —> Early Dark Sector
  - Severe Challenge: Lyman-α Forest
- Post-Recombination Reheating
- Outlook: ACT DR6 + Simons Observatory

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Classes of Models

Viable paths to increase CMB-inferred H_0

- Pre-recombination energy injection (e.g., early dark energy and its variants)

  Poulin+ (2019); Agrawal+ (2019); Lin+ (2019); Smith+ (2020); Knox & Millea (2020); JCH+ (2020); McDonough+ (2021); Lin+ (2022); …

- Modified recombination (e.g., primordial magnetic fields; increased m_e; or decreased ρ_γ)

  Jedamzik & Pogosian (2018); Sekiguchi & Takahashi (2020); Hart & Chluba (2020); Chiang & Slosar (2018); Lee+ (2022) Ivanov+ (2020); JCH & Bolliet (2023)

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- Additional dark radiation species (beyond usual three neutrinos) with non-trivial dynamics/interactions

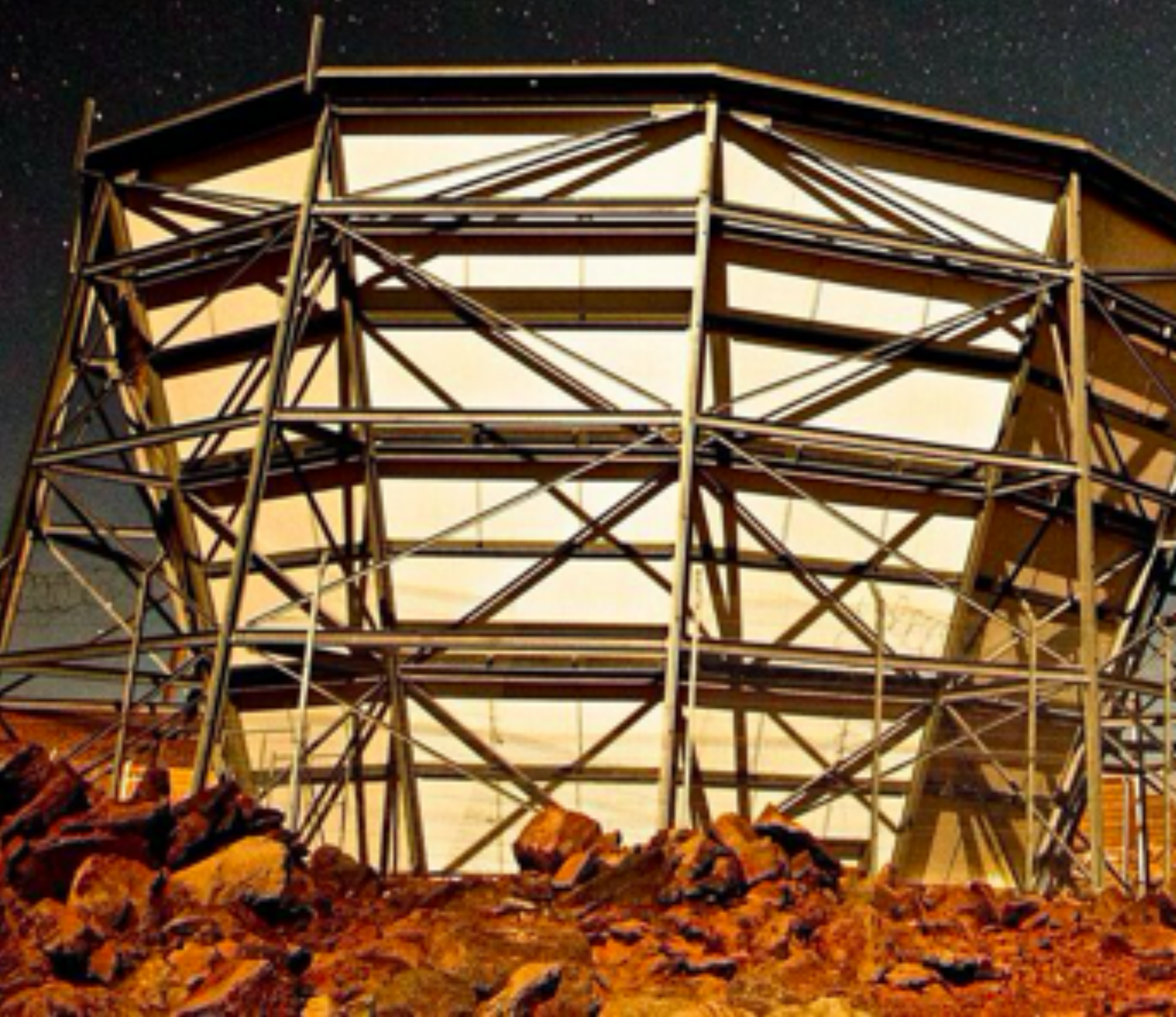
  Buen-Abad+ (2015,2017,2023); Aloni+ (2021,2022); …

- Strong neutrino interactions (delay ν free-streaming)

  Cyr-Racine & Sigurdson (2014); Lancaster+ (2017); Kreisch+ (2019; Escudero & Witte (2019)

If one of these models is actually realized in nature at a level that resolves the Hubble tension, we should soon see unambiguous evidence in CMB+LSS data

H_0 and Searches for New Physics with the Atacama Cosmology Telescope



Aiola, …, JCH, et al. (2020)
Choi, …, JCH, et al. (2020)
JCH et al. (2021)
Thiele, Guan, JCH, Kosowsky, Spergel (2021)
La Posta, Louis, Garrido, JCH (2022)
Kreisch, …, JCH, et al. (2022)

ACT DR4 Cosmology

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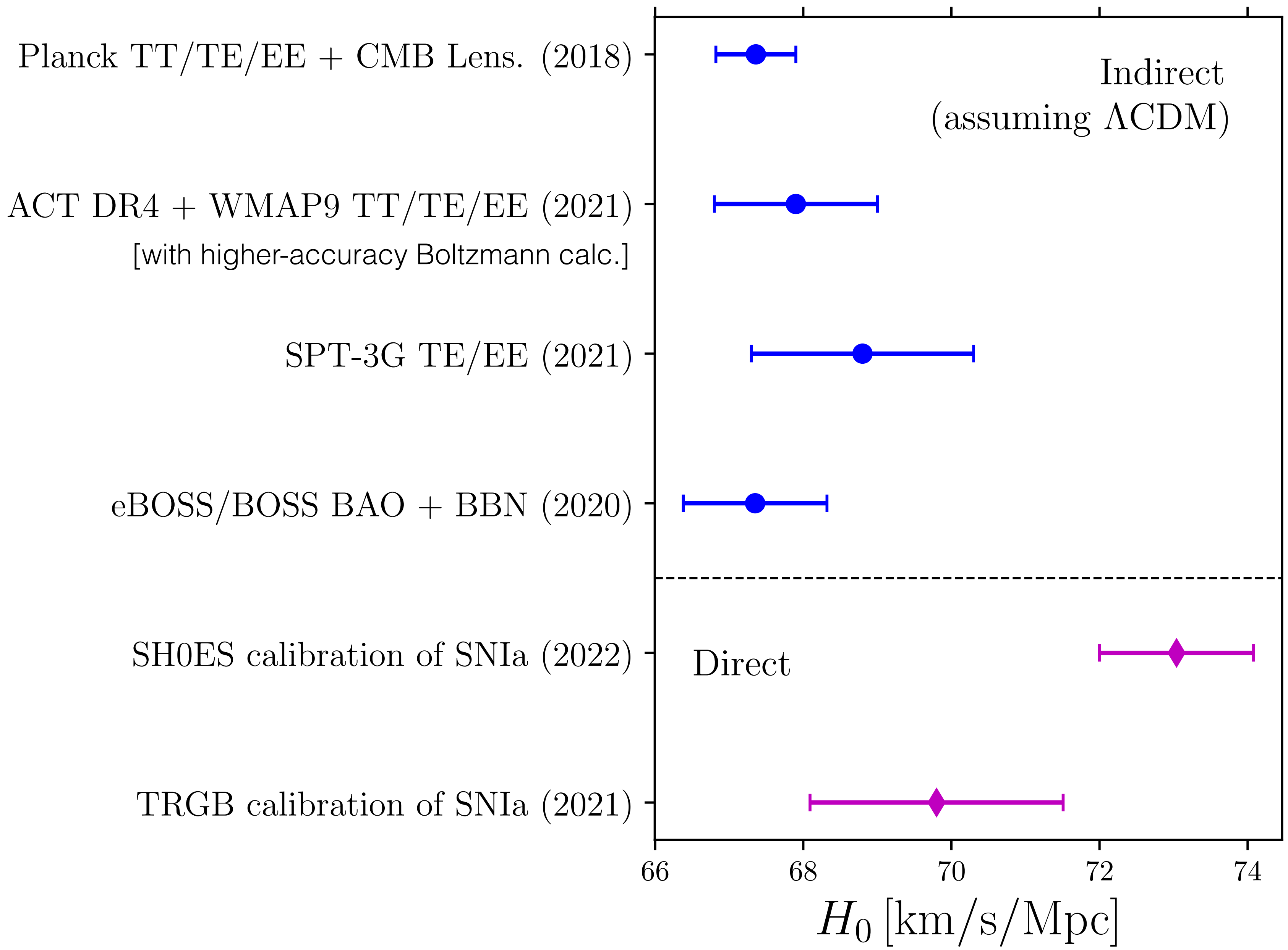

~3.4σ difference between ACT+WMAP (high-acc., ΛCDM) and Cepheid-calibrated SNIa (SH0ES 2022)

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

Aiola et al. (2020); JCH et al. (2021); see also McCarthy, JCH, Madhavacheril (2021)

Classes of Models

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- Modified recombination (e.g., varying m_e)
  —>some models mildly preferred by Planck
  —>most plausible model (baryon clumping due to primordial magnetic fields) is disfavored by ACT DR4
  Thiele, Guan, JCH, Kosowsky, Spergel (2021)

- Additional dark radiation species with non-trivial dynamics/interactions
  —>some models mildly preferred by Planck (strong interactions and/or non-trivial time evolution is crucial)
  —>most such models weakly disfavored by ACT DR4
  Schöneberg & Abellan (2022)

Classes of Models

- Pre-recombination energy injection (e.g., early dark energy and its variants)
  —>not preferred by Planck or LSS data
  —>mild preference in ACT DR4
  JCH et al. (2020); Ivanov, McDonough, JCH, et al. (2020); JCH et al. (2021)

- Strong neutrino interactions (delay ν free-streaming)
  —> disfavored by Planck
  —> mild preference in ACT DR4
  Kreisch, …, JCH, et al. (2022)

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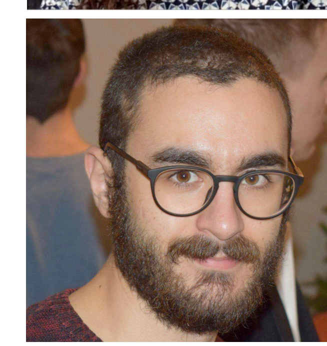
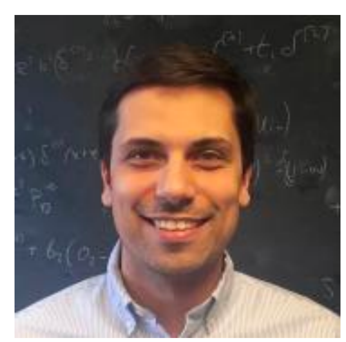
Constraints on Early Dark Energy





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** (2022)

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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

sound speed

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 $\rightarrow$ $\theta_{\rm s}^{\star} = \pi/\Delta\ell \longrightarrow D_A^{\star} = r_{\rm s}^{\star}/\theta_{\rm s}^{\star} \longrightarrow H_0$

$D_A \sim 1/H_0$

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

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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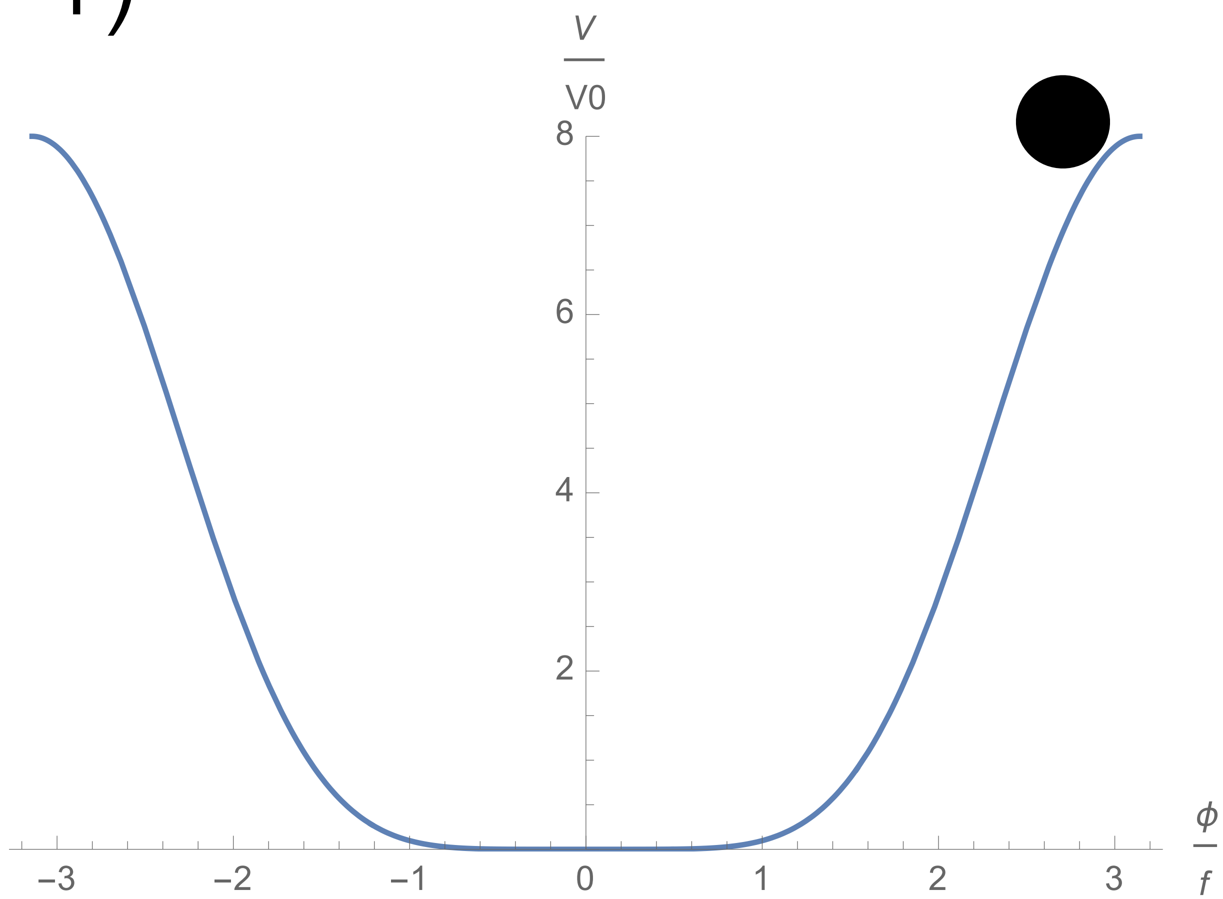
New component: (pseudo)-scalar field ϕ

Idea: field initially frozen on its potential due to Hubble friction — acts as dark energy (equation of state P/ρ=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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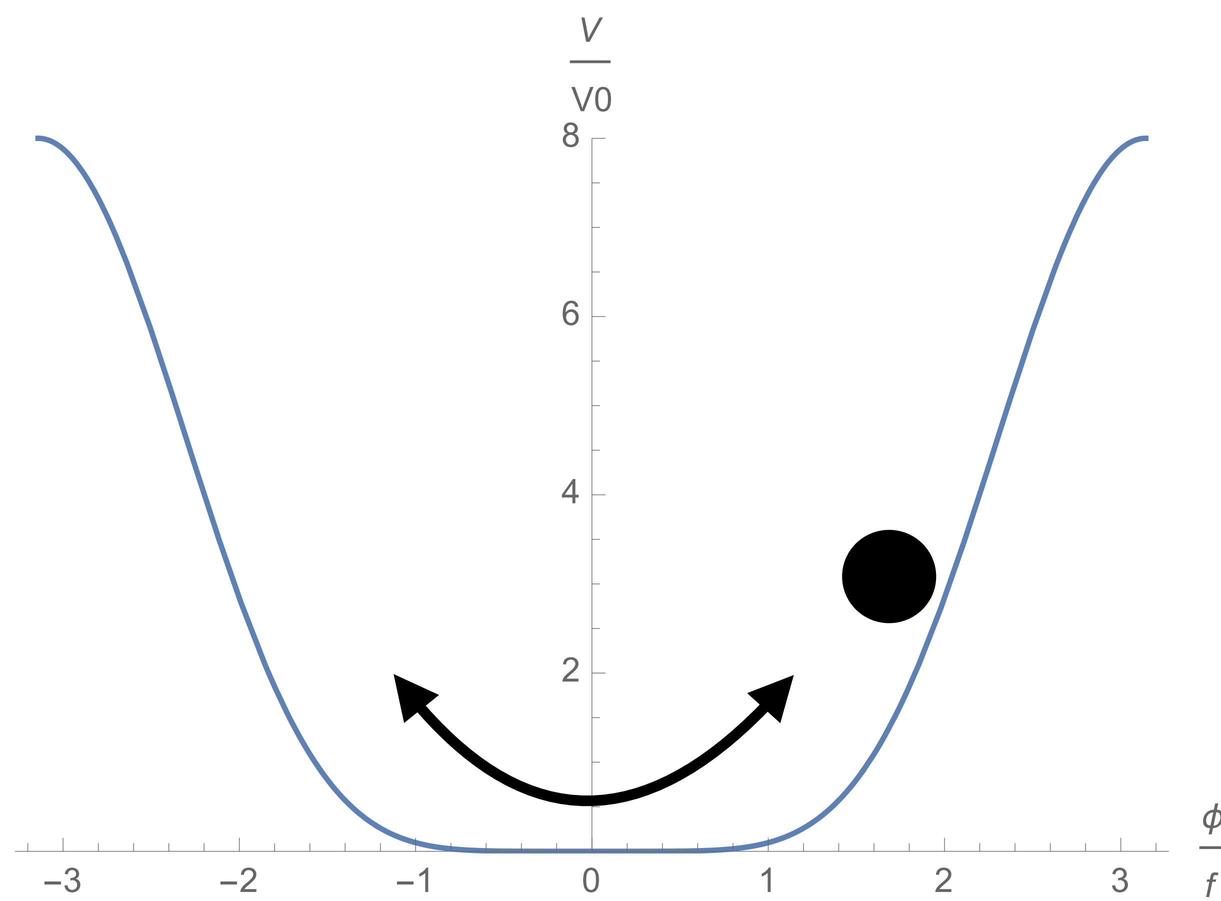
Early Dark Energy

New component: (pseudo)-scalar field ϕ

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

New component: (pseudo)-scalar field ϕ

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

When $H \sim m$ (field mass), it rolls down its potential and oscillates: effective EoS 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} $\longrightarrow$ $w_\phi = \frac{n-1}{n+1}$

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

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

Early Dark Energy

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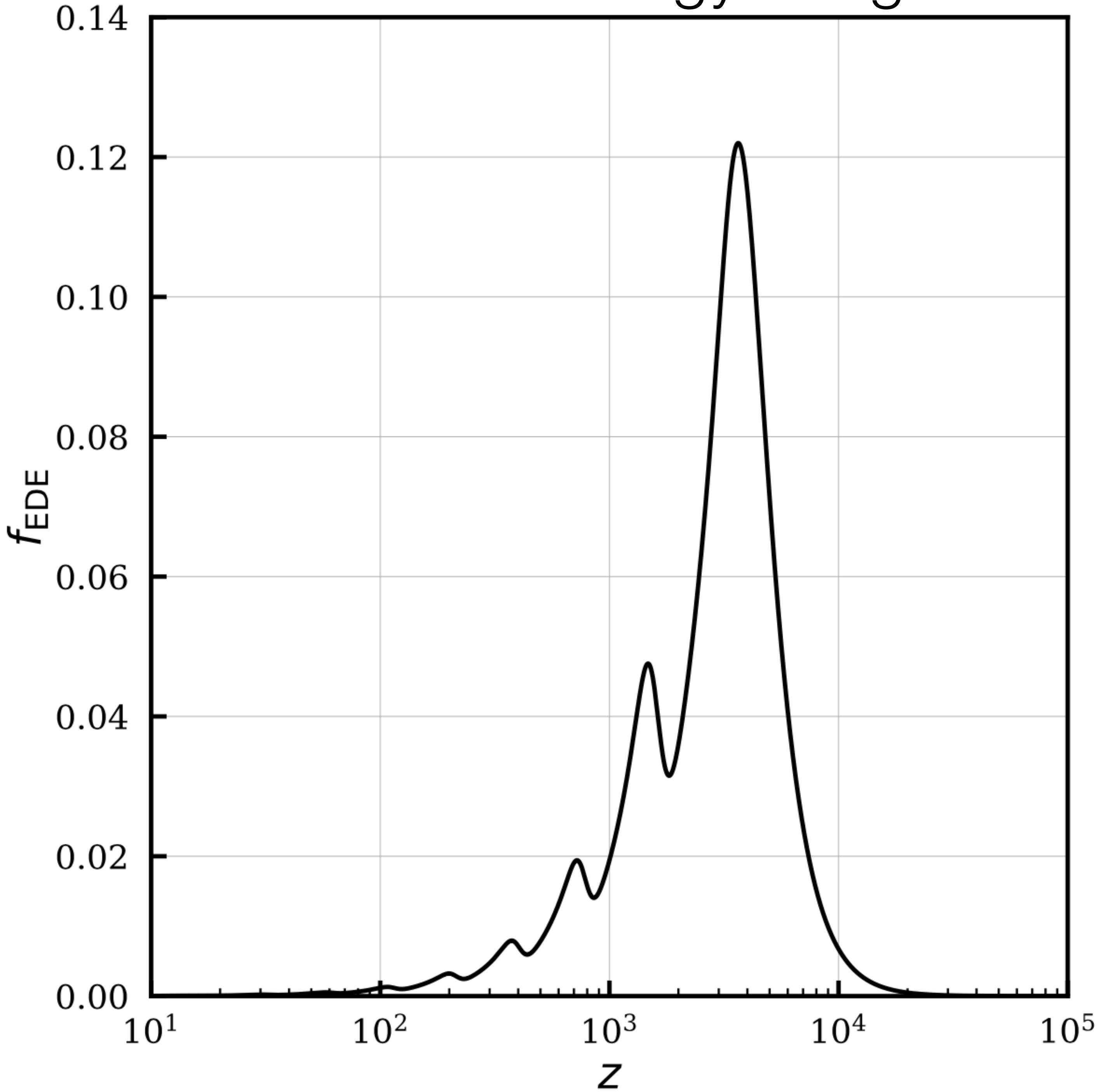
Parameterization

Fractional contribution of EDE to cosmic energy budget



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

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Early Dark Energy

Parameterization

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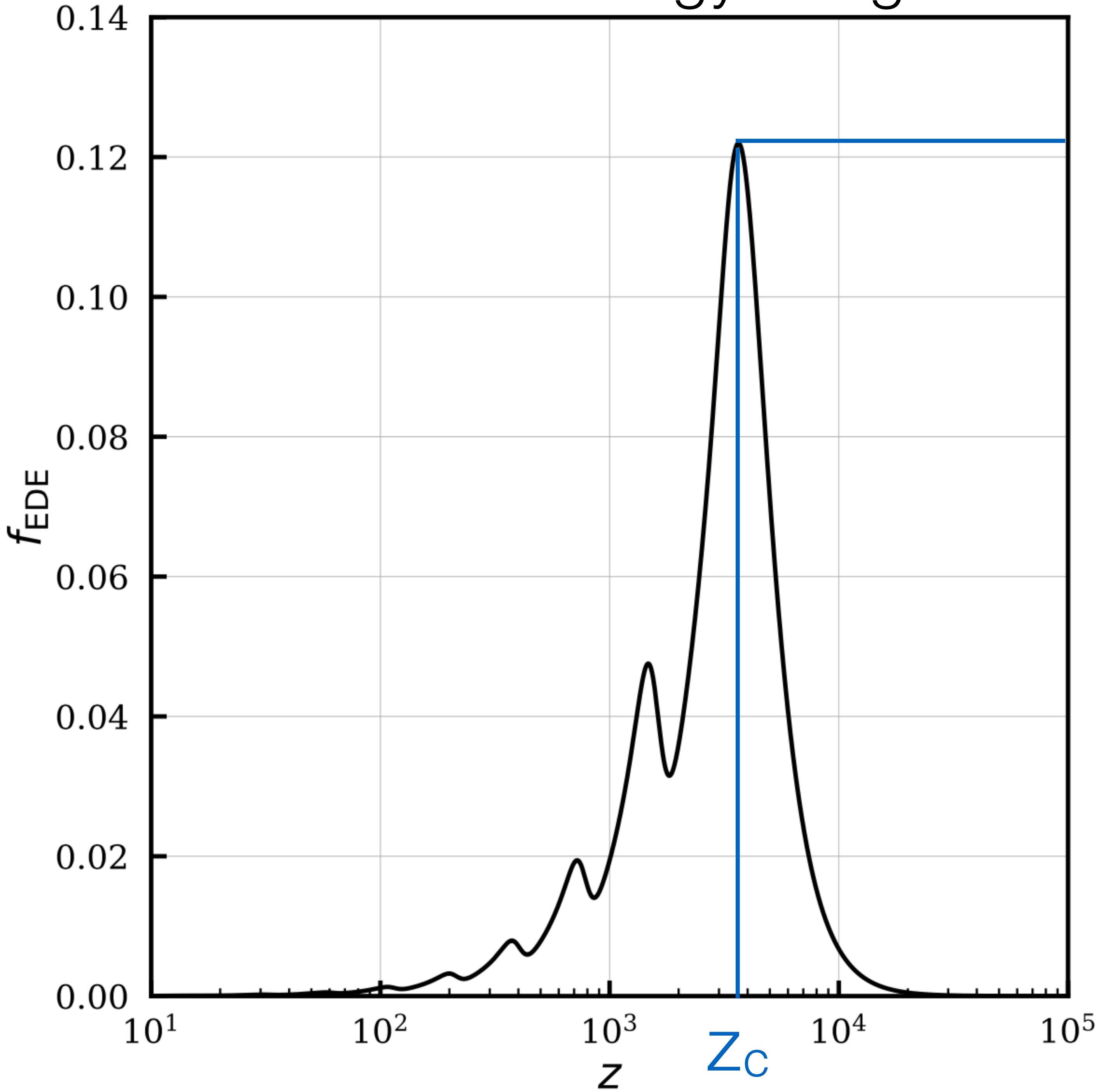

Maximal contribution:

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

which occurs at redshift z_c

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

$\rightarrow$ $\{f_{\rm EDE}, z_c, \theta_i\}$

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

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

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   see also Poulin et al. (2021)

ACT DR4 EDE Results

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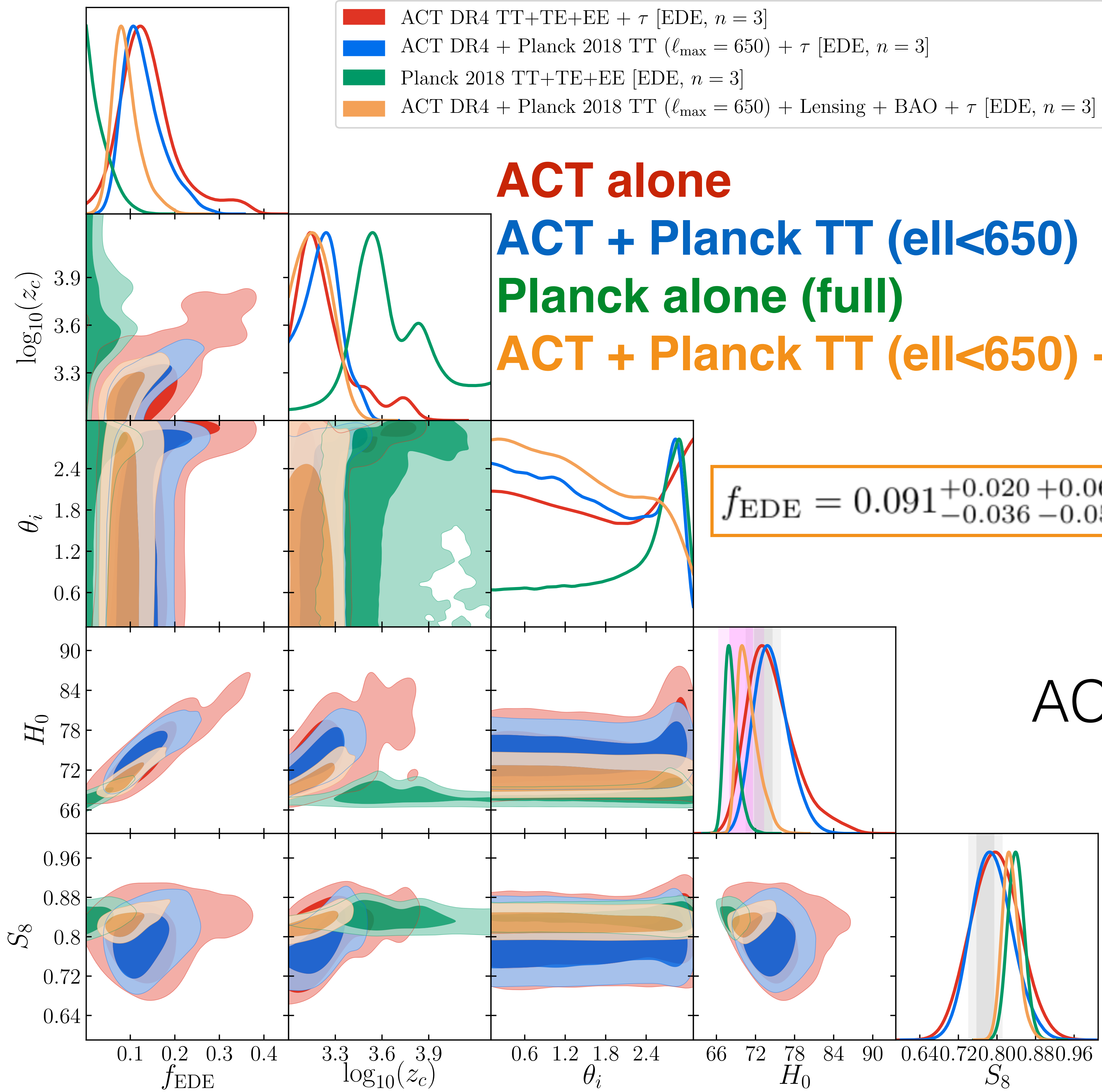

ACT alone

ACT + Planck TT (ell<650)

Planck alone (full)

ACT + Planck TT (ell<650) + CMB Lensing + BAO

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

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

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

ACT DR4 EDE Results

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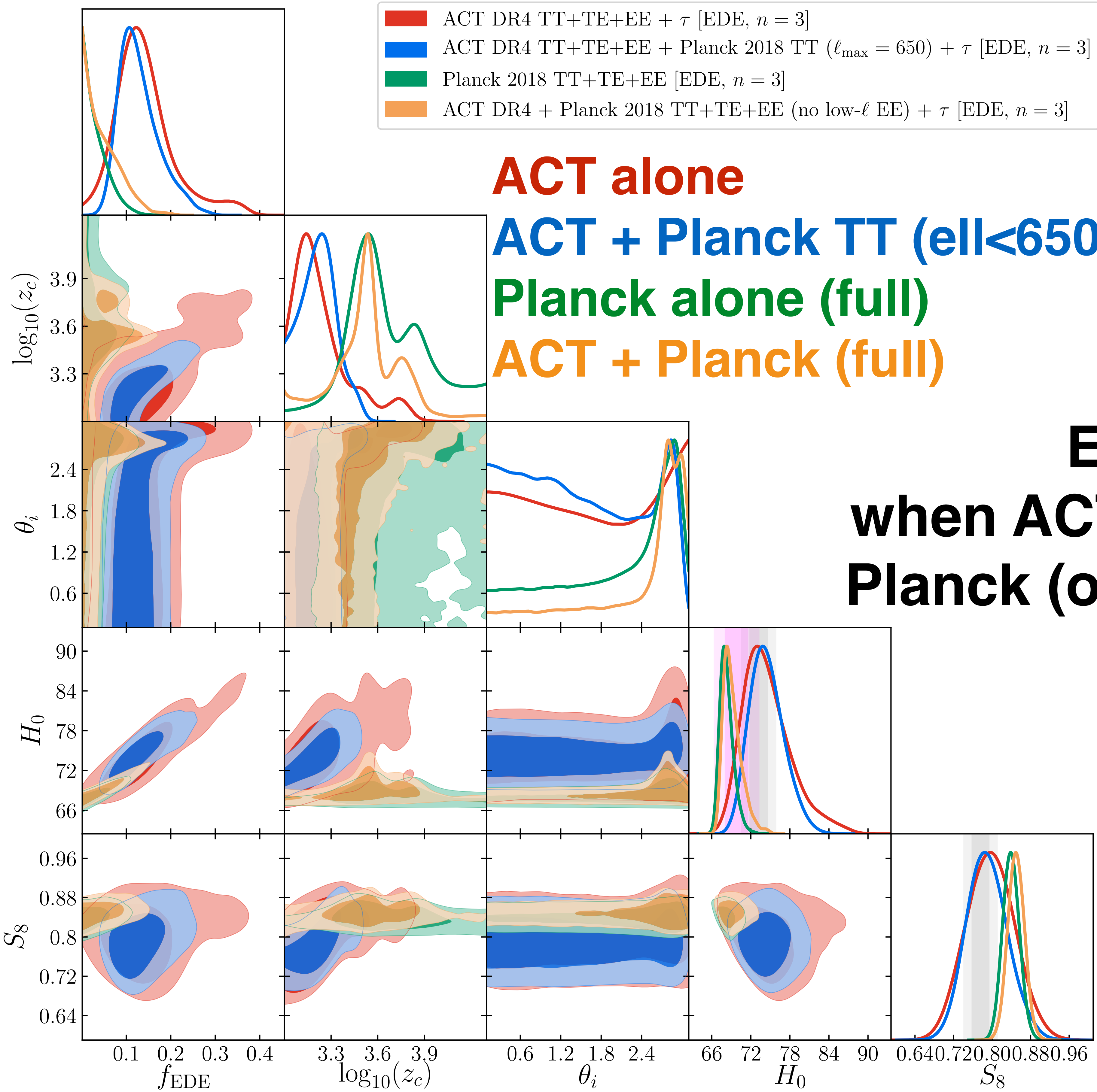

ACT alone

ACT + Planck TT (ell<650)

Planck alone (full)

ACT + Planck (full)

EDE hint 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

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JCH et al. (2021)

Origin of ACT EDE Hint

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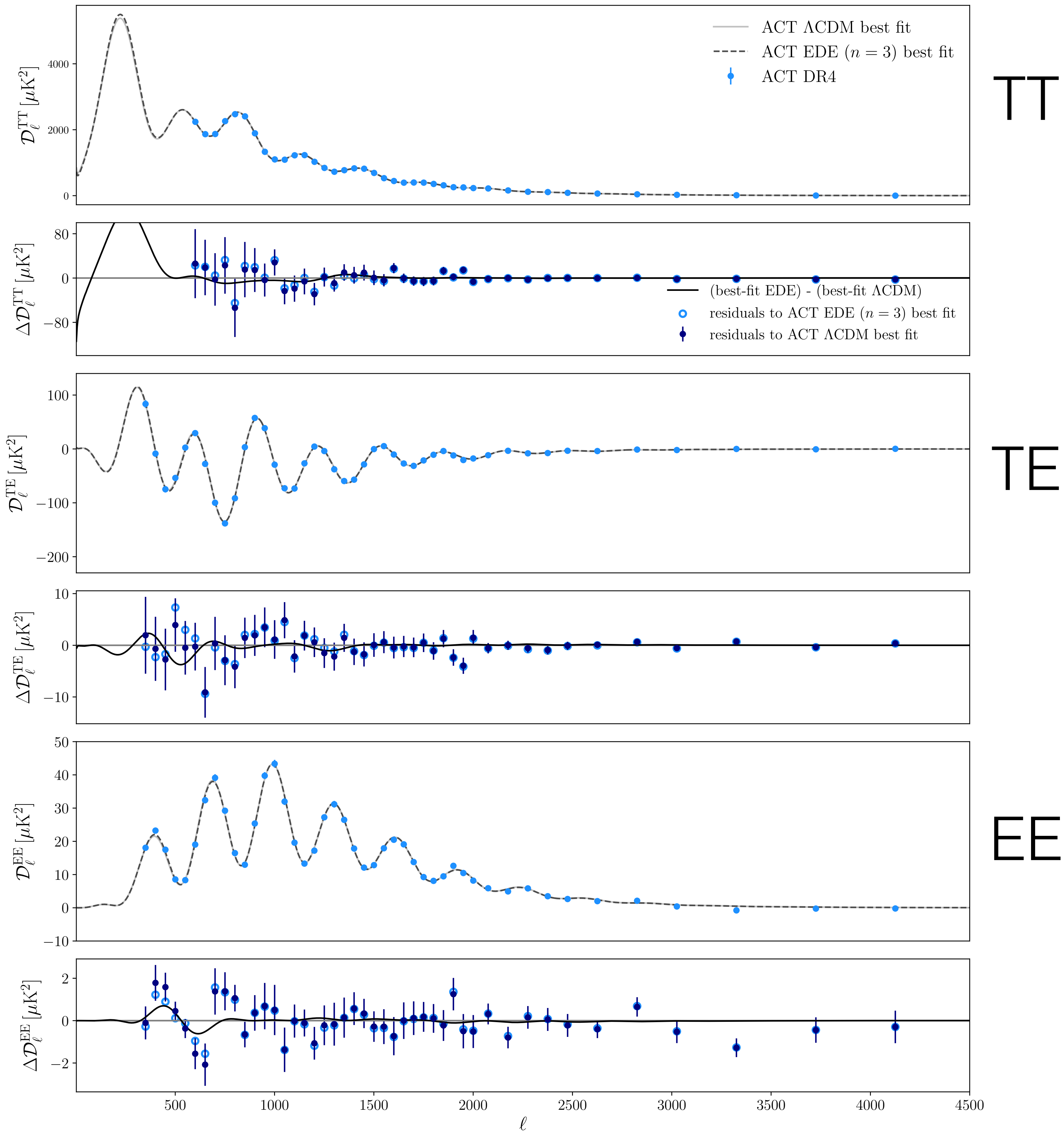
LCDM residuals

EDE residuals



JCH et al. (2021)

Origin of ACT EDE Hint

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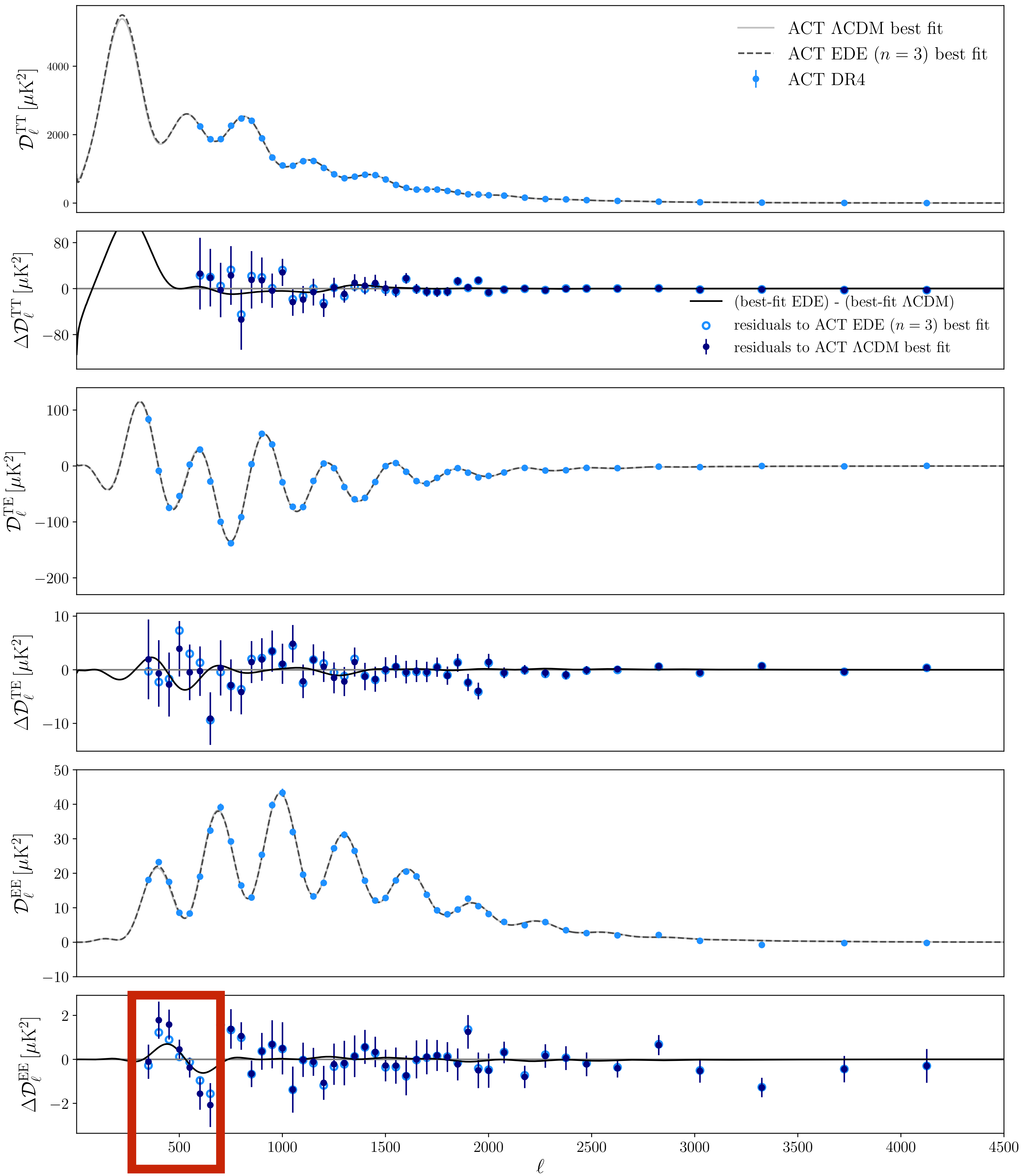
LCDM residuals

EDE residuals



TT

TE

EE

lowest ell bins in EE drive the preference

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

JCH et al. (2021)

Origin of ACT EDE Hint

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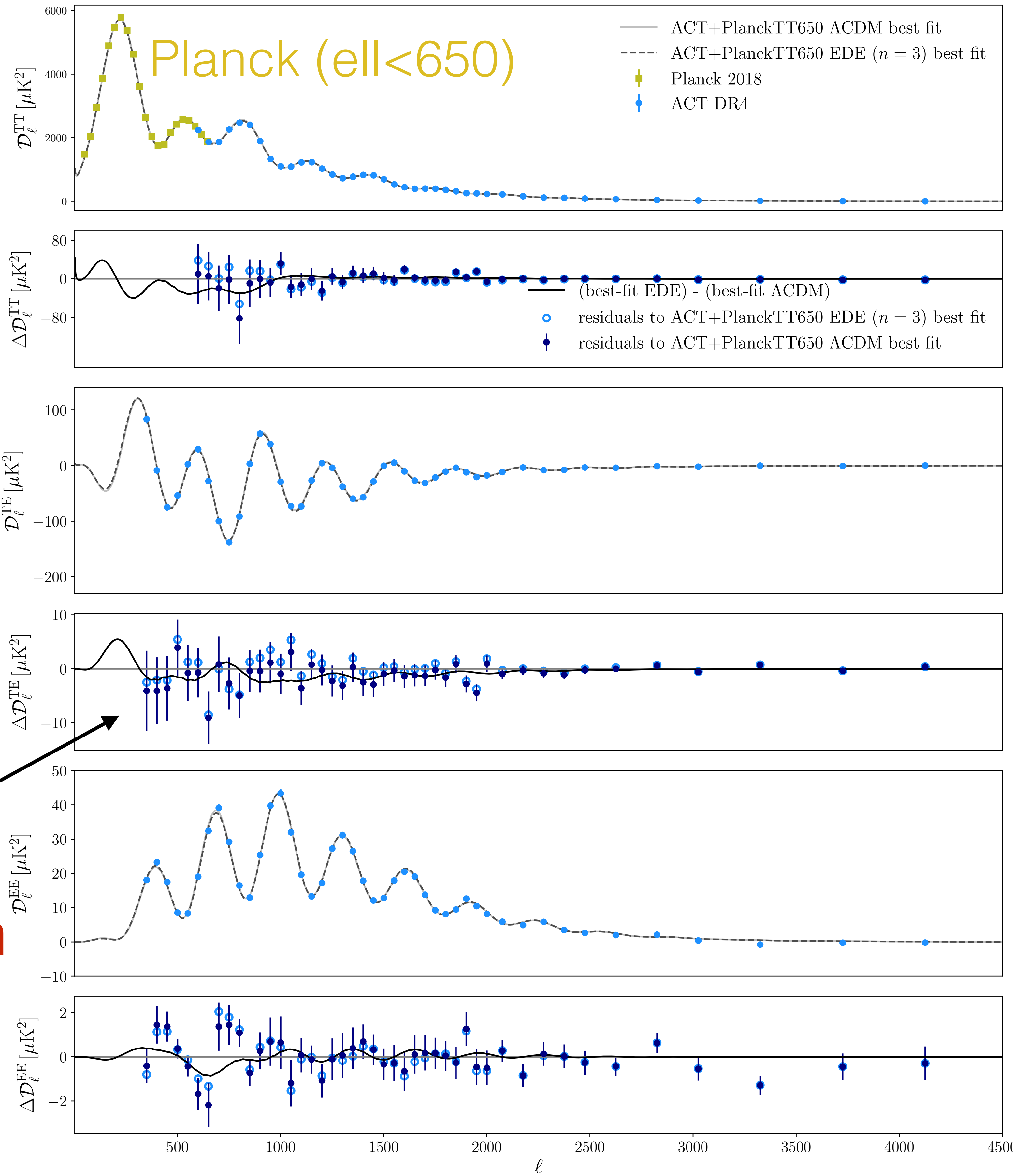
LCDM residuals

EDE residuals

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



TT

TE

EE

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

JCH et al. (2021)

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EDE Puzzles & Problems

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

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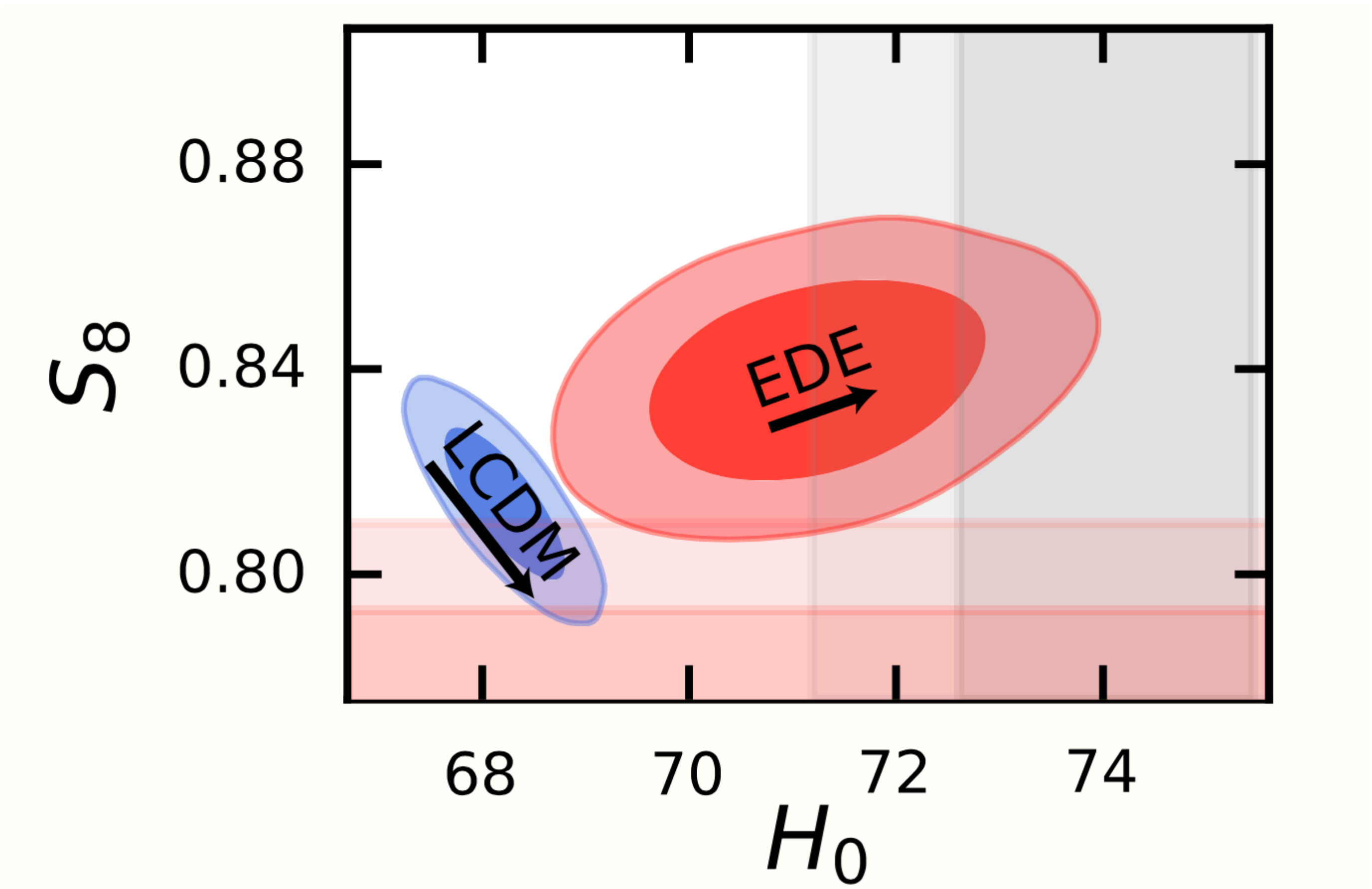
EDE Puzzles & Problems

- 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 increases in the CMB fit 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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EDE Puzzles & Problems

Why do ω_c and n_s increase when fitting EDE to CMB data?

- Recall the integrated Sachs-Wolfe (ISW) effect: grav. potentials decay in a non-matter-dominated universe

- Early ISW arises because radiation is still important at z*

—>Enhanced in an EDE cosmology (because the EDE is not matter)

JCH+ (2020); Vagnozzi+ (2021)

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EDE Puzzles & Problems

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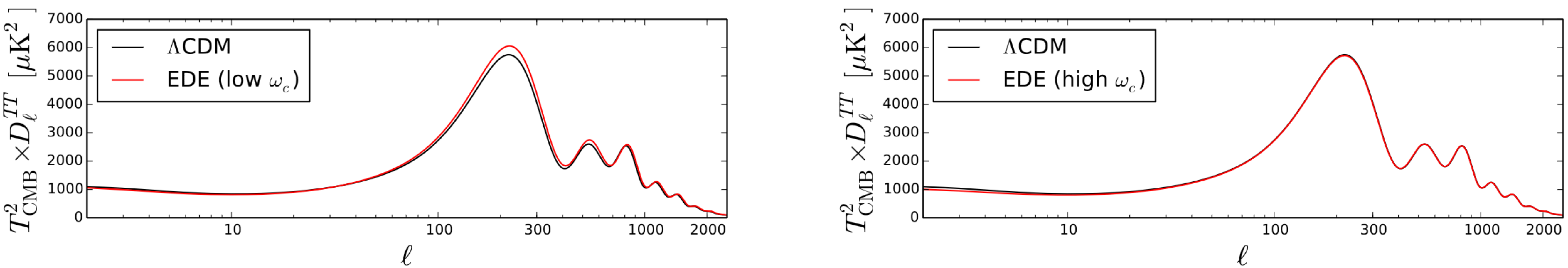

primarily compensated by increasing the CDM density (ω_c), but also by increasing the slope of the power spectrum (n_s)

JCH+ (2020); Vagnozzi+ (2021)

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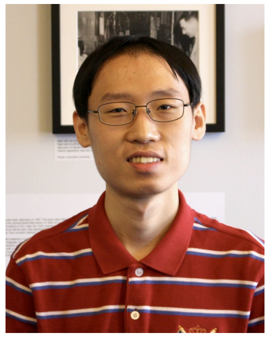
Early Dark Sector

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 seem to be 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 $V(\phi)$

- **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 steep to "trigger" off the EDE-DM coupling

- Solution: flatten $V(\phi)$ into a plateau and choose EDE-DM coupling $m(\phi)$ 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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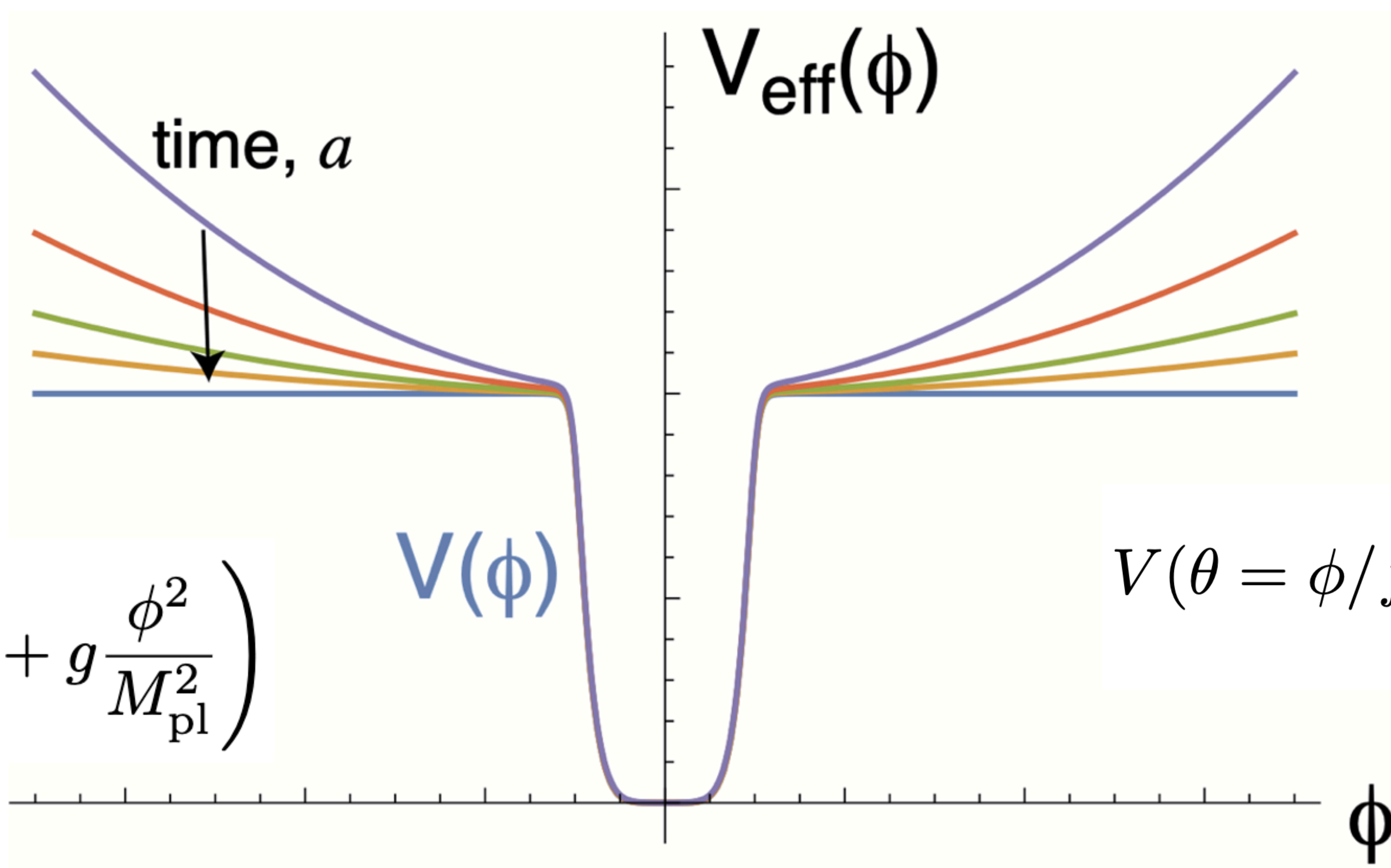

coupling

$$m_{\rm DM}(\phi) = m_0 \left(1 + g\frac{\phi^2}{M_{\rm pl}^2}\right)$$

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

bare potential

Lin, McDonough, JCH, Hu (2022)

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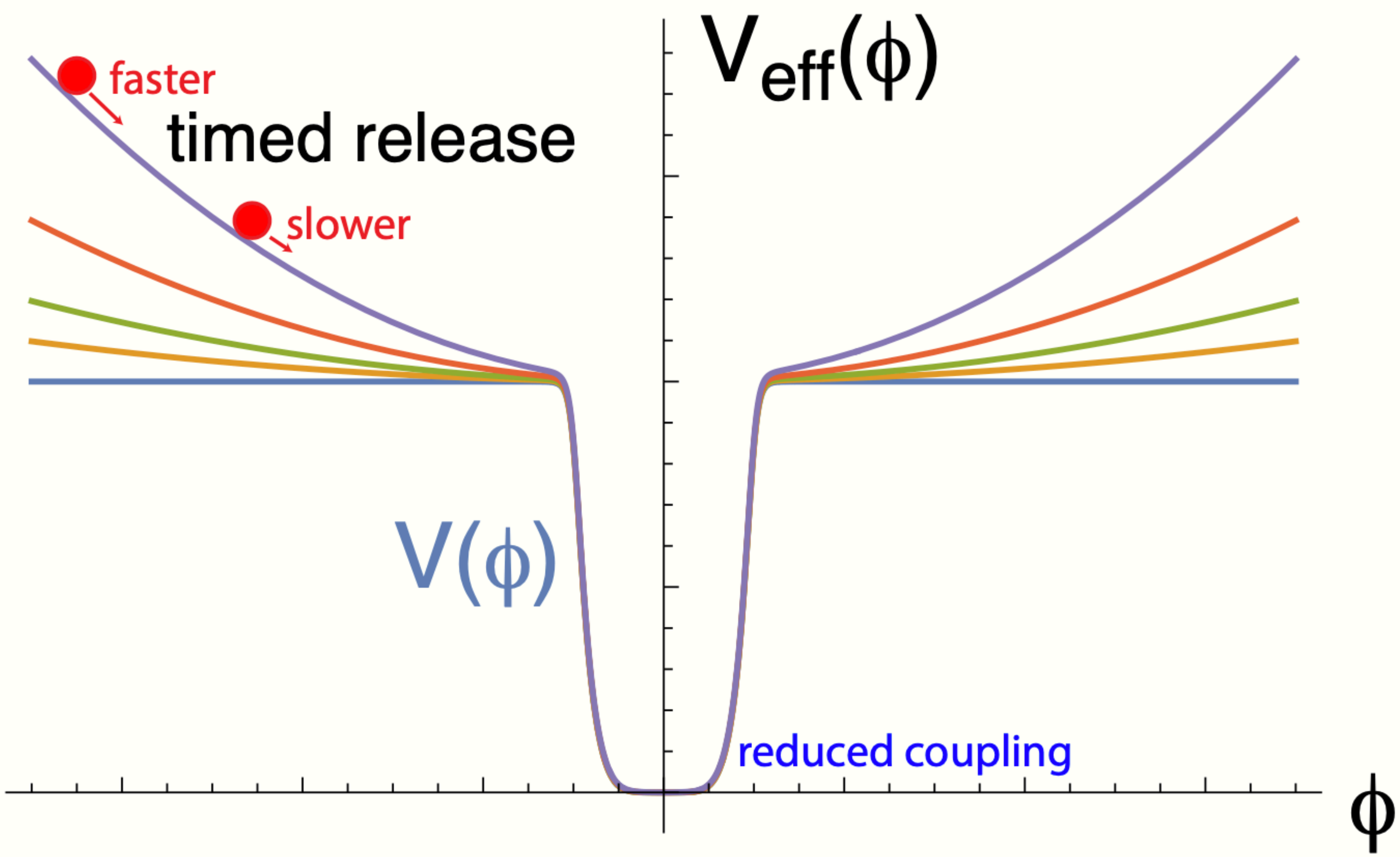
Solution

- Explains coincidence: ϕ starts to roll because of equality
- No initial tuning needed: ϕ rolls to edge of plateau from wide range of initial field values
- No late-time growth problems: for $m(\phi) \sim 1+g\phi^2$, there is no fifth force since $\phi \rightarrow 0$ at late times



Lin, McDonough, JCH, Hu (2022)

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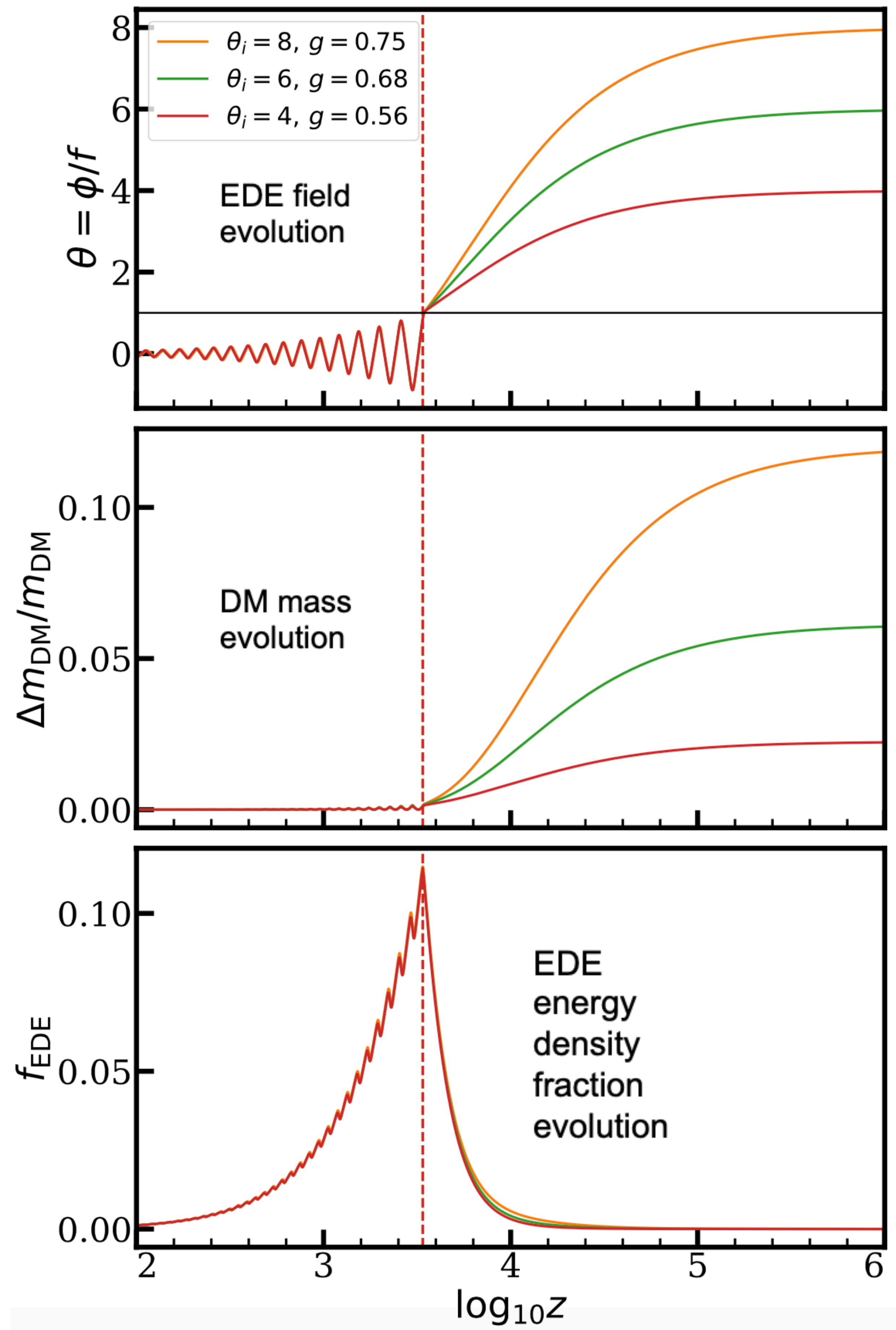
Basic validation: can successfully lower r_s, raise $H_0 \sim 71.2$ km/s/Mpc



Lin, McDonough, JCH, Hu (2022)

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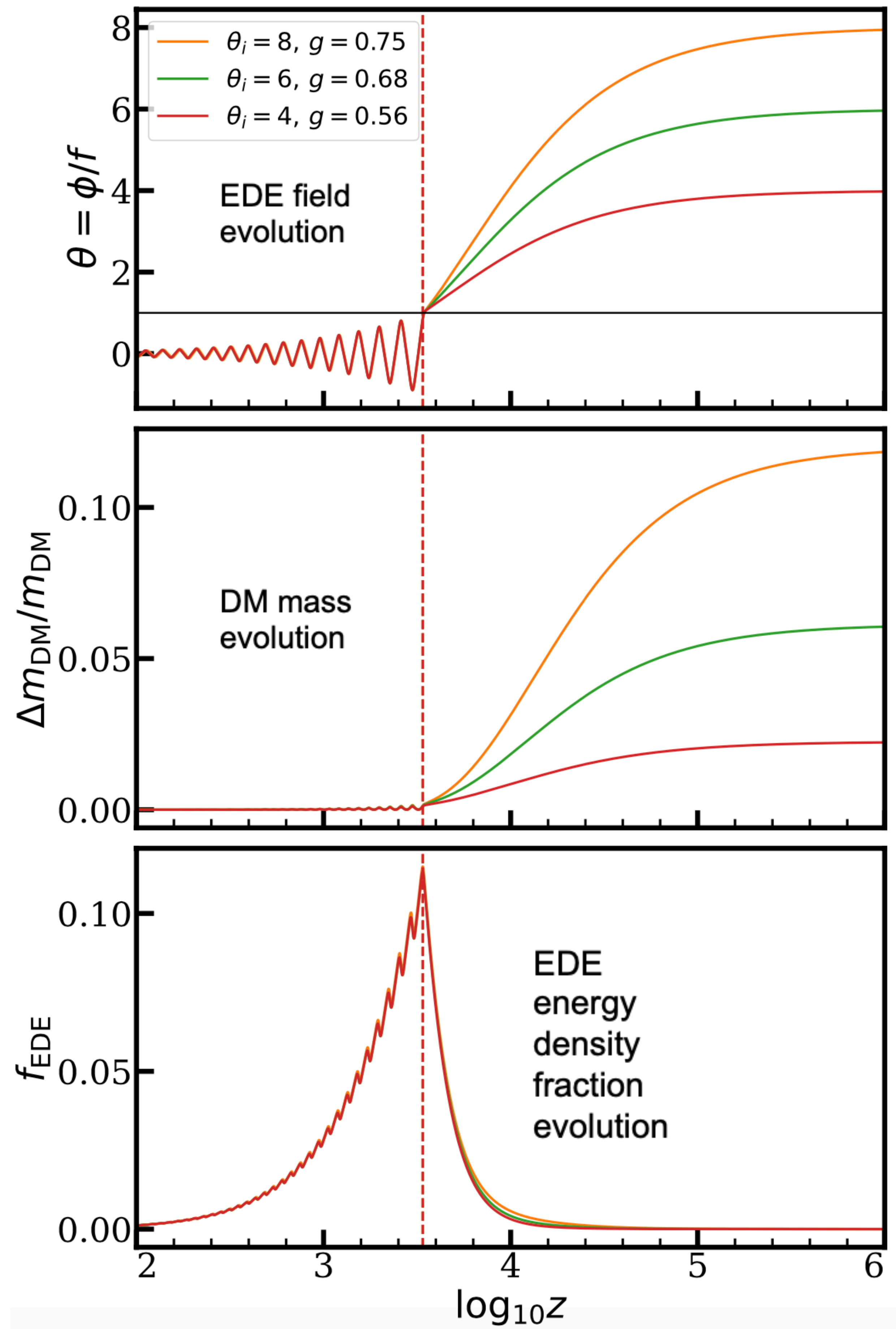
Basic validation: can successfully lower r_s, raise H_0 ~ 71.2 km/s/Mpc

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
n_s	0.9894	0.9843

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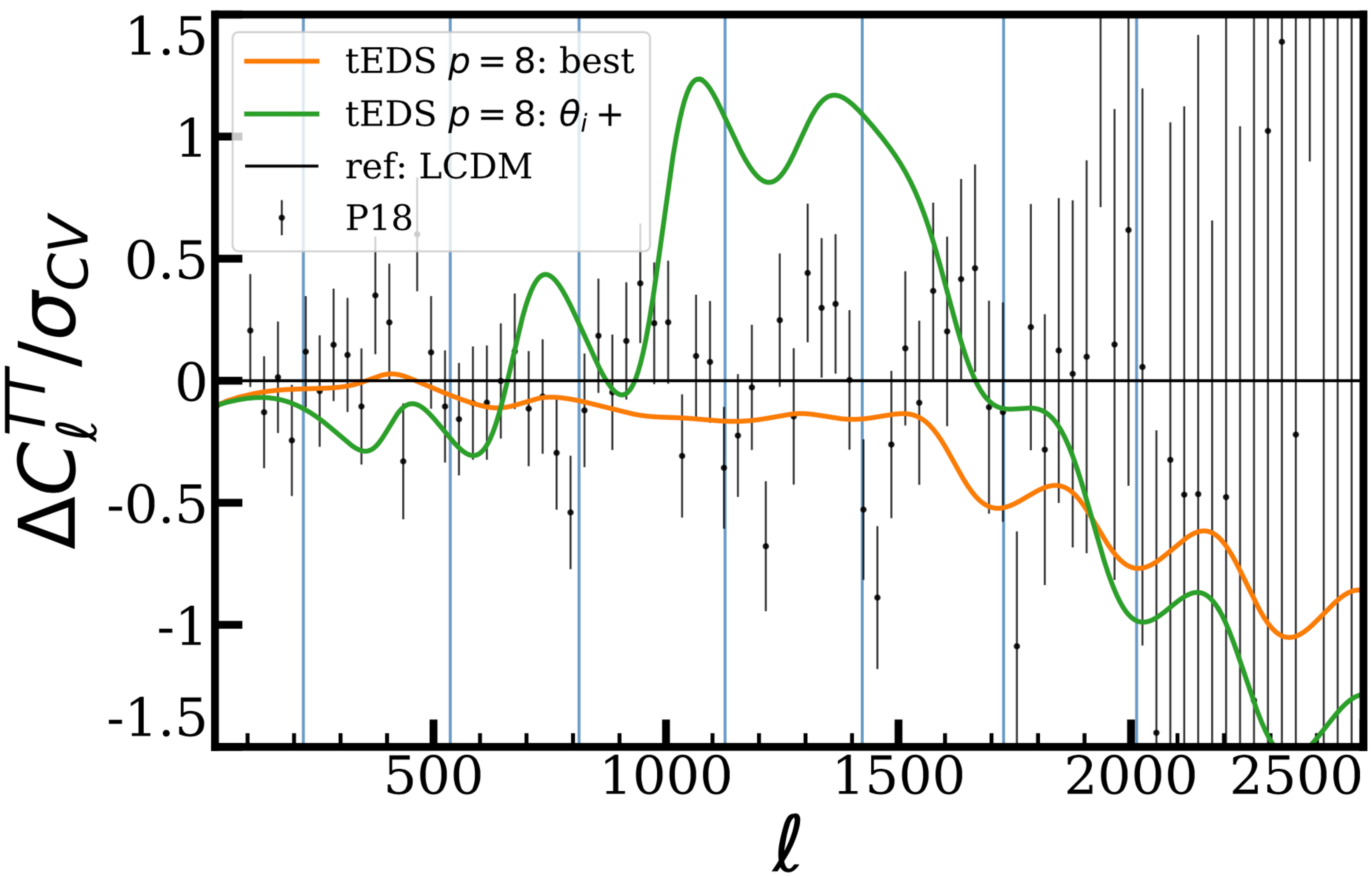
However: excess field fluctuations induced by rolling in $V_{eff}(\phi)$

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

Lin, McDonough, JCH, Hu (2022)

Next: MCMC/further model improvements

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Challenge:
Lyman-α Forest

Goldstein, JCH, Irsic, Sherwin (2023): 2303.00746

Lya Forest

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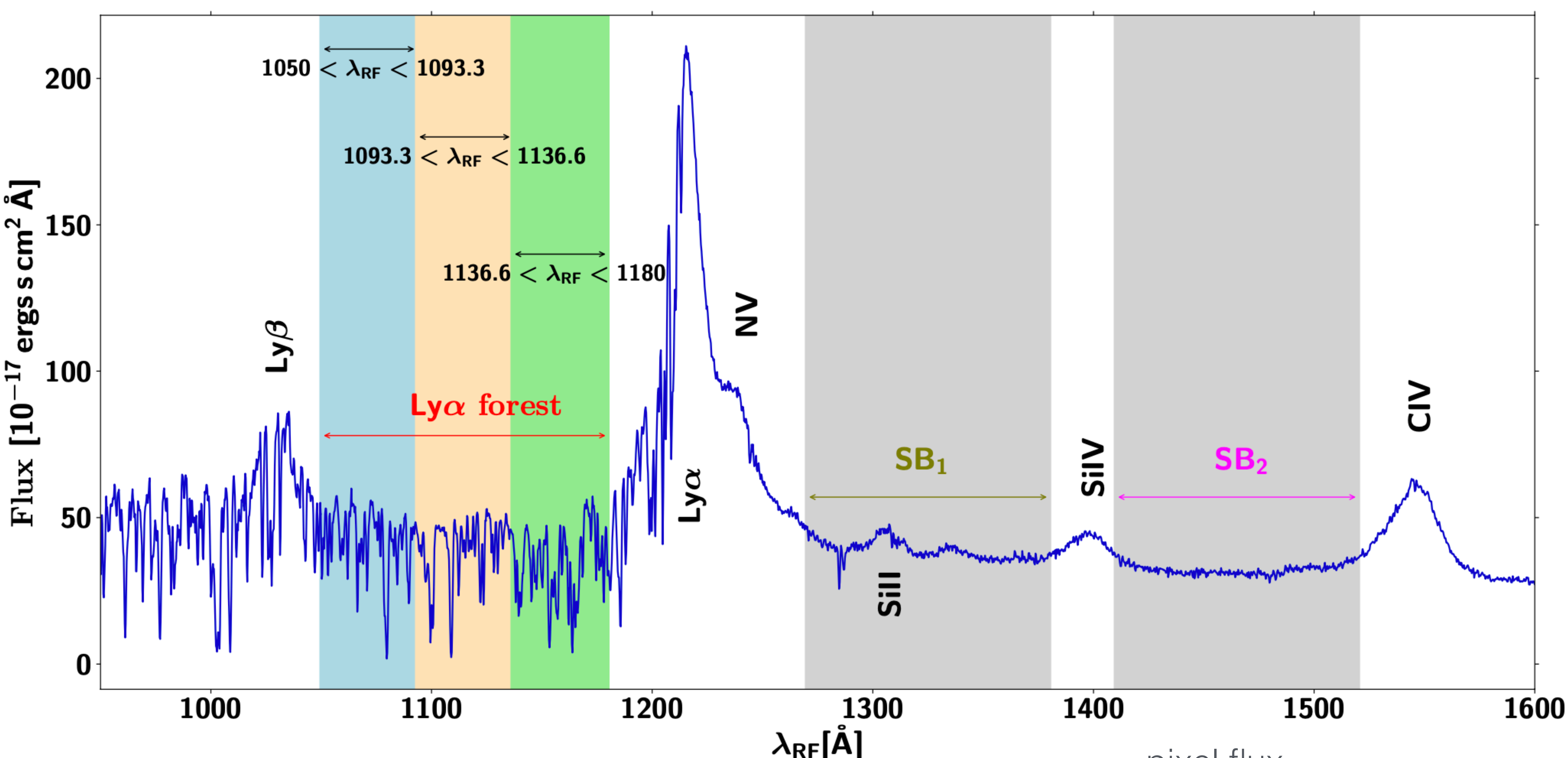
Absorption lines due to HI clouds along the LOS to a distant quasar



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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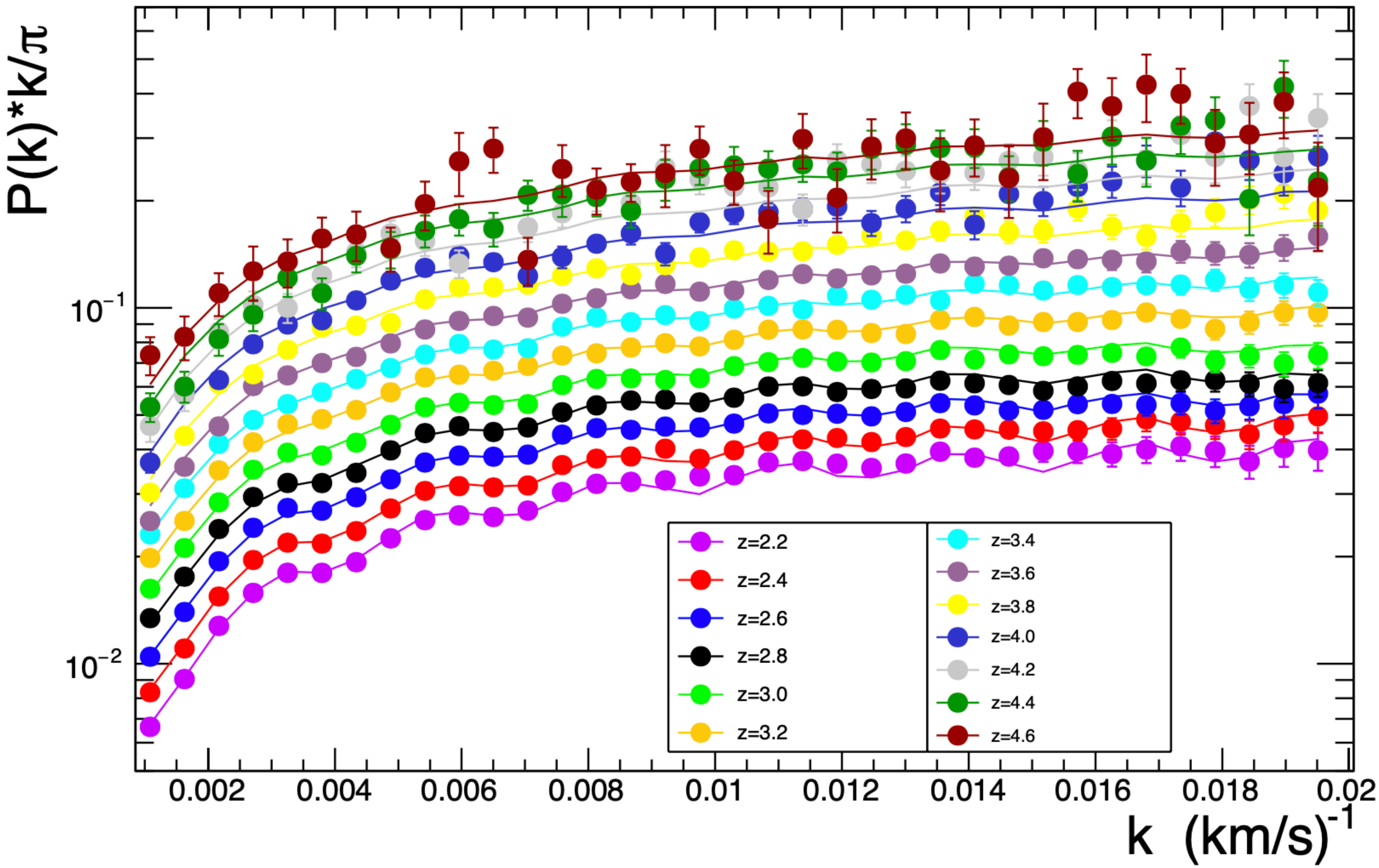
Observable: 1D flux power spectrum

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



k~0.01 s/km ⟷ k~1 h/Mpc at z=3

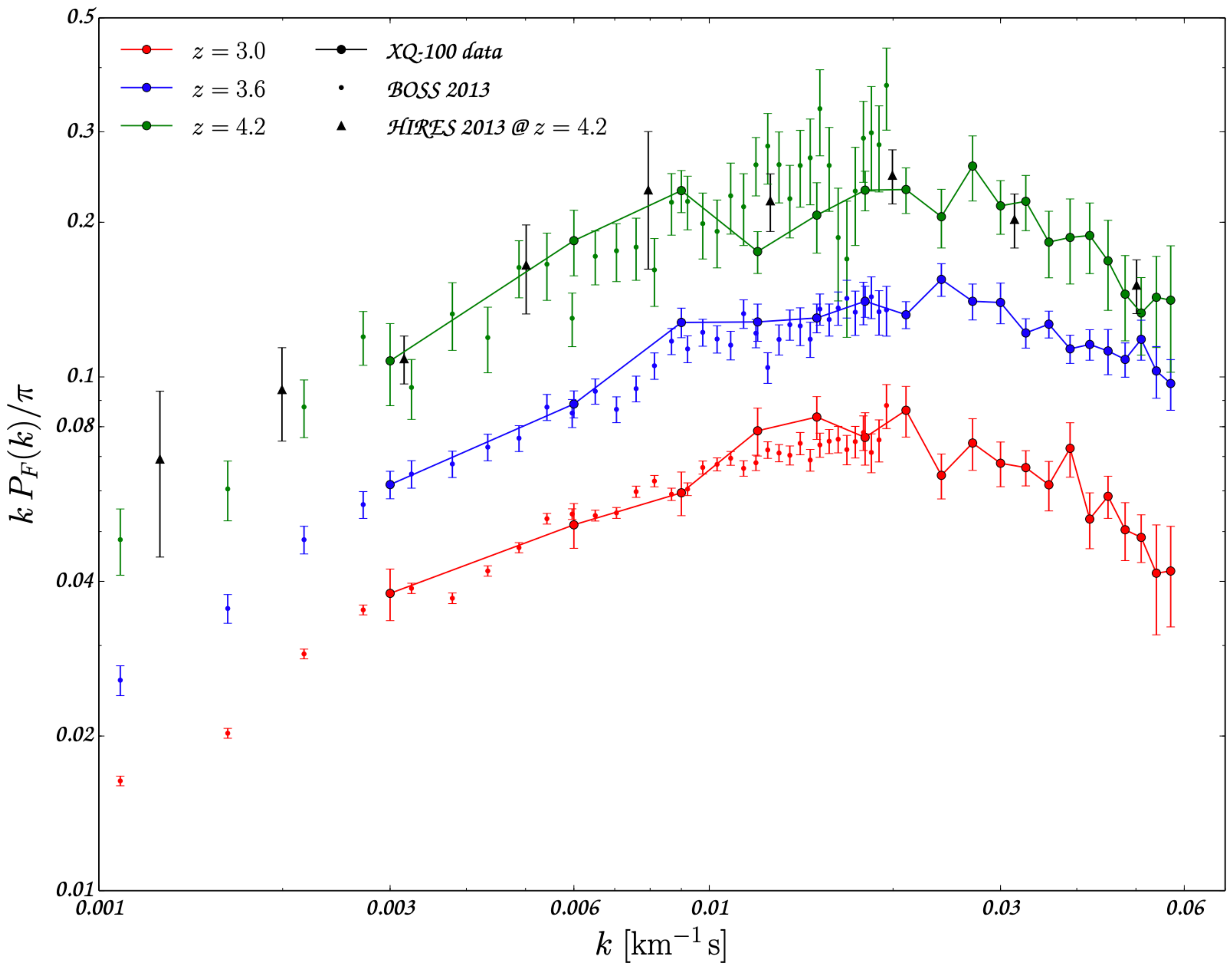
Chabanier et al. (2019)

Lya Forest

Colin Hill
Columbia

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)

Lya Forest

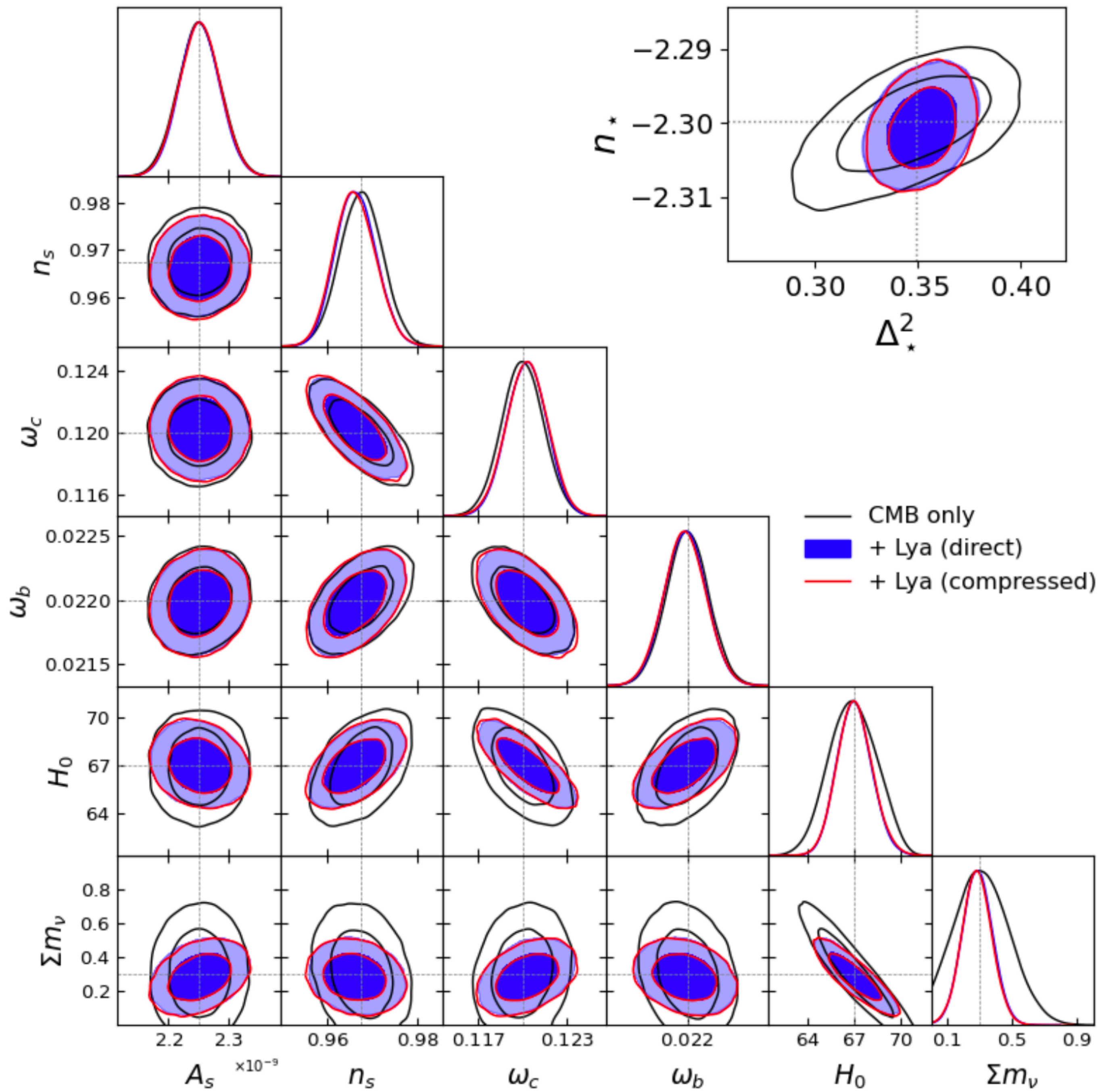
Colin Hill
Columbia

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



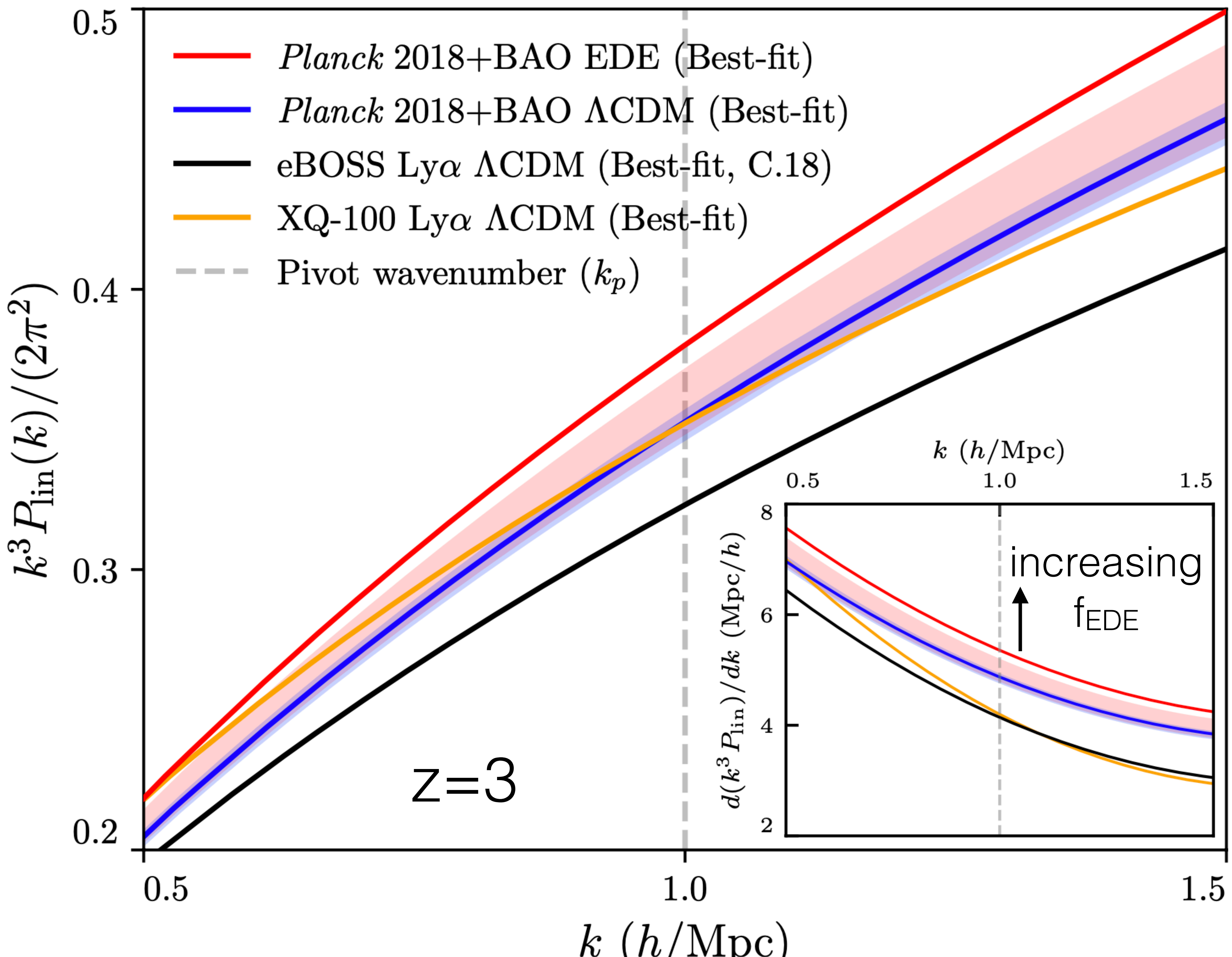
(validation using sims here)

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

Lya Forest

Colin Hill
Columbia

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



Goldstein, JCH, Irsic, & Sherwin (2023): 2303.00746

Origin of EDE Changes to P(k)

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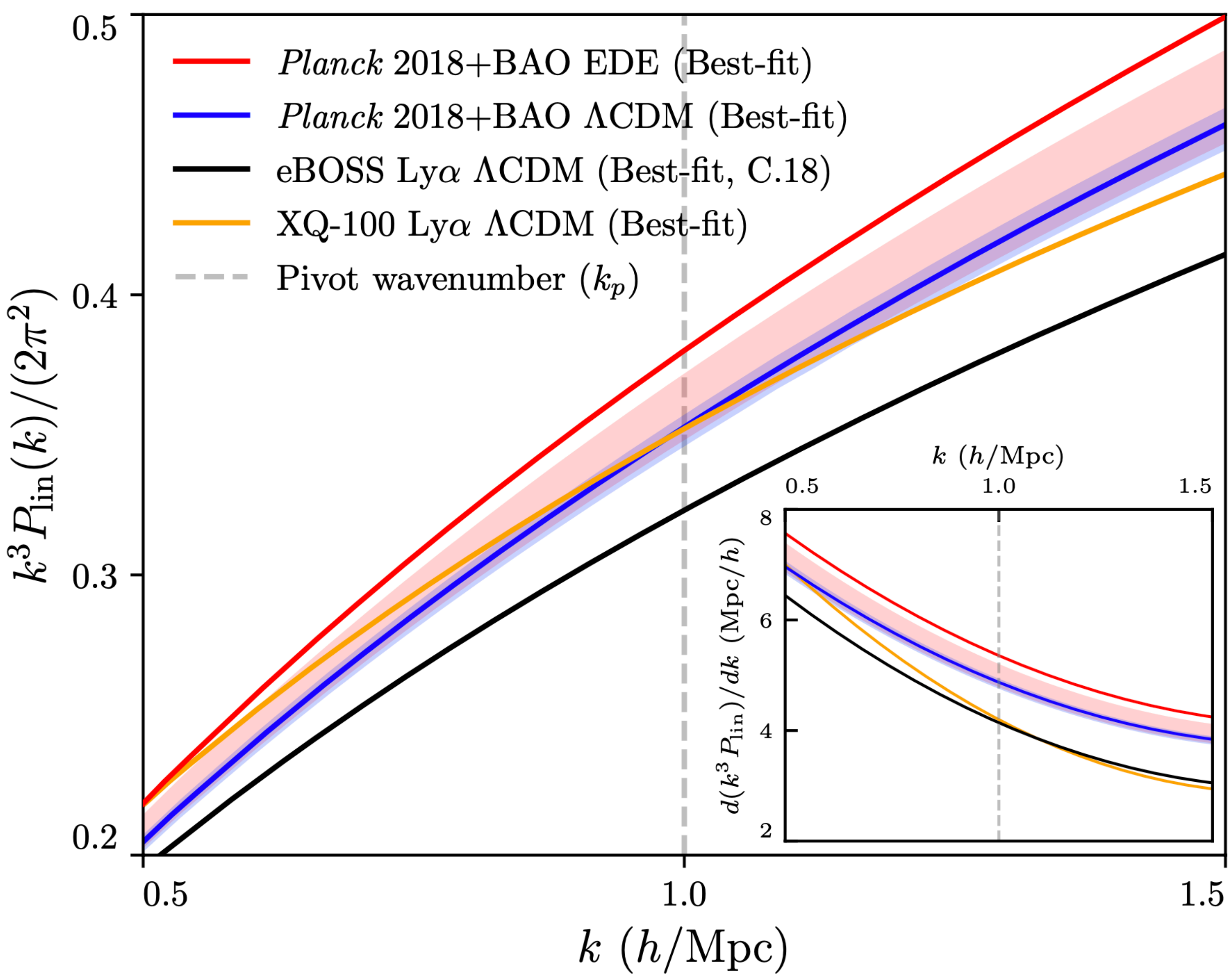
Columbia

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

large increase in ω_{cdm} and increase in n_s

which act to increase P(k) and its slope on Lyα scales

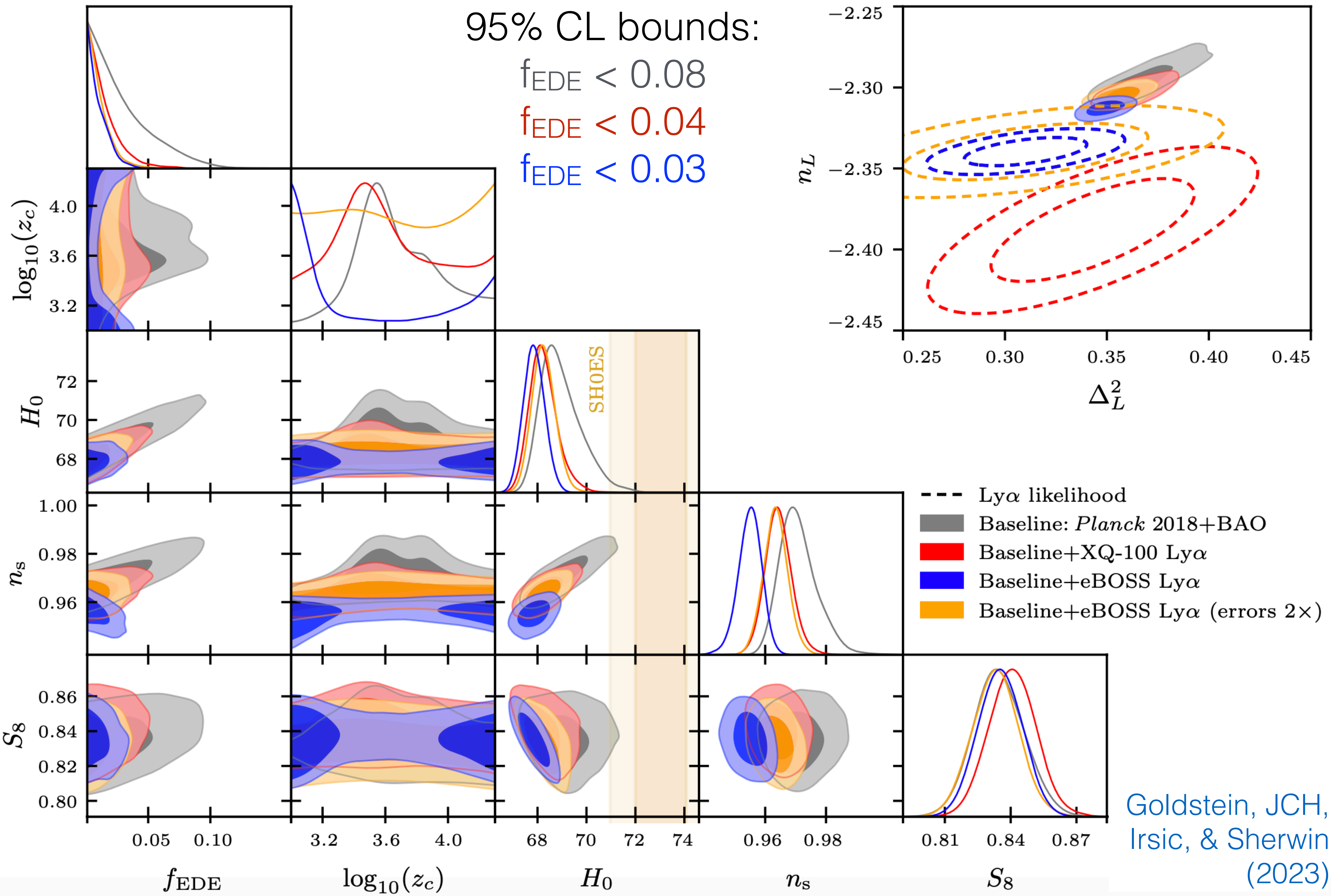


Smith+ (2019); JCH+ (2020); Vagnozzi (2021); Goldstein+ (2023)

Lyα Forest: EDE Constraints

Colin Hill
Columbia

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



Goldstein, JCH, Irsic, & Sherwin (2023)

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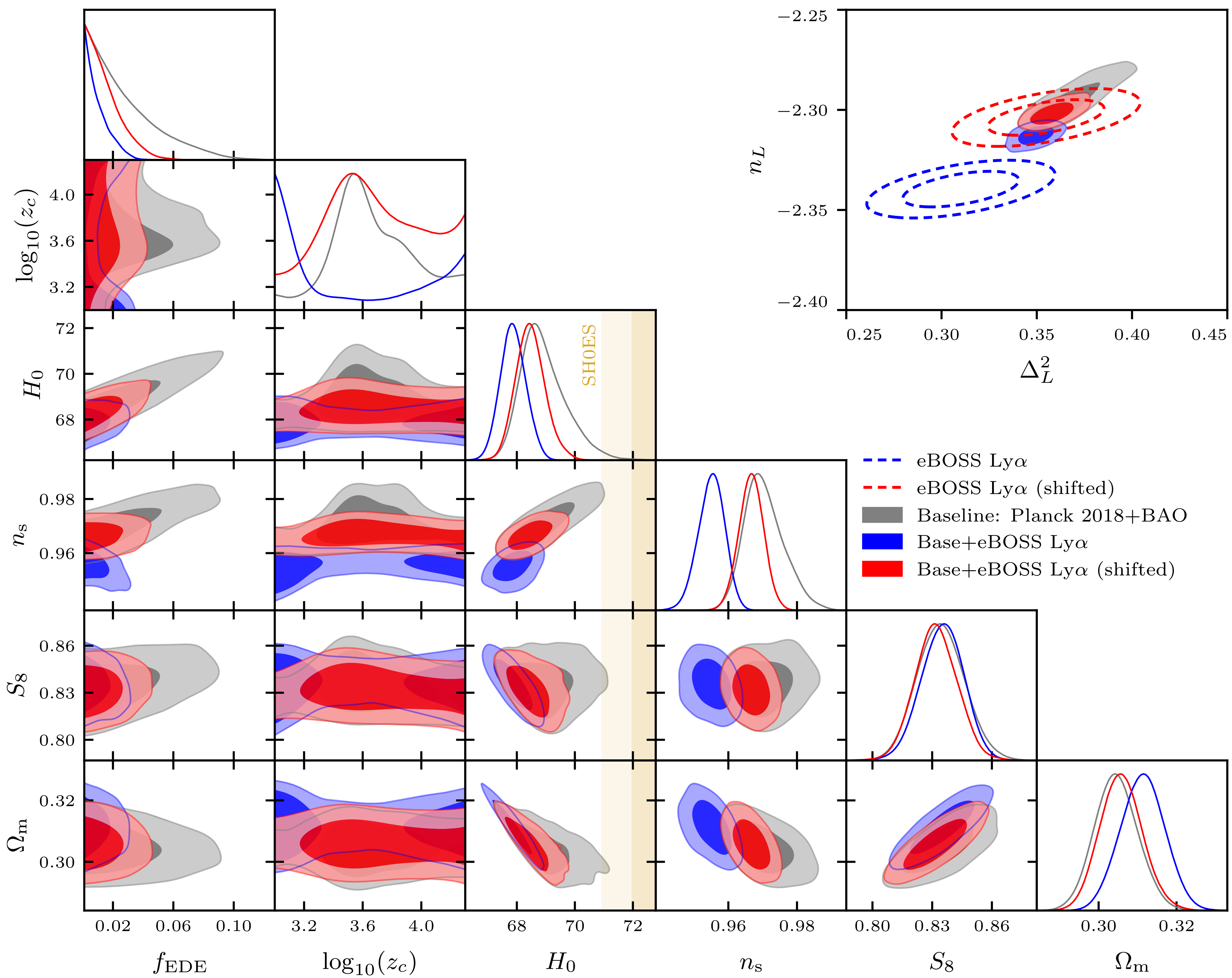
Lyα Forest: EDE Constraints

Constraints are still very tight even if Lyα data are artificially shifted



Goldstein, JCH, Irsic, & Sherwin (2023): 2303.00746

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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 (2023): 2303.00746

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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 (2023): 2303.00746

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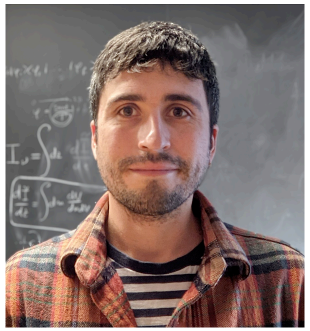
Post-Recombination Reheating (PRR)

JCH & B. Bolliet (2023): 2304.03750



H_0 and $T_{CMB,0}$

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H_0 tension or T_0 tension?

Geometric degeneracy: background and linear perturbation evolution depend (almost) only on parameter combination $H_0 T_{CMB,0}^{1.2}$

- Cosmology would be very different without COBE-FIRAS data!
- Ignoring FIRAS, Planck+SH0ES can be fit with $T_{CMB,0}$ = 2.56 +/- 0.05 K
- BAO breaks degeneracies: Planck + BAO yield $T_{CMB,0}$ = 2.71 +/- 0.02 K
- FIRAS result: $T_{CMB,0}$ = 2.72548 +/- 0.00057 K
- Can we build on this idea while maintaining agreement with FIRAS?

Ivanov, Ali-Haimoud, & Lesgourgues (2020)

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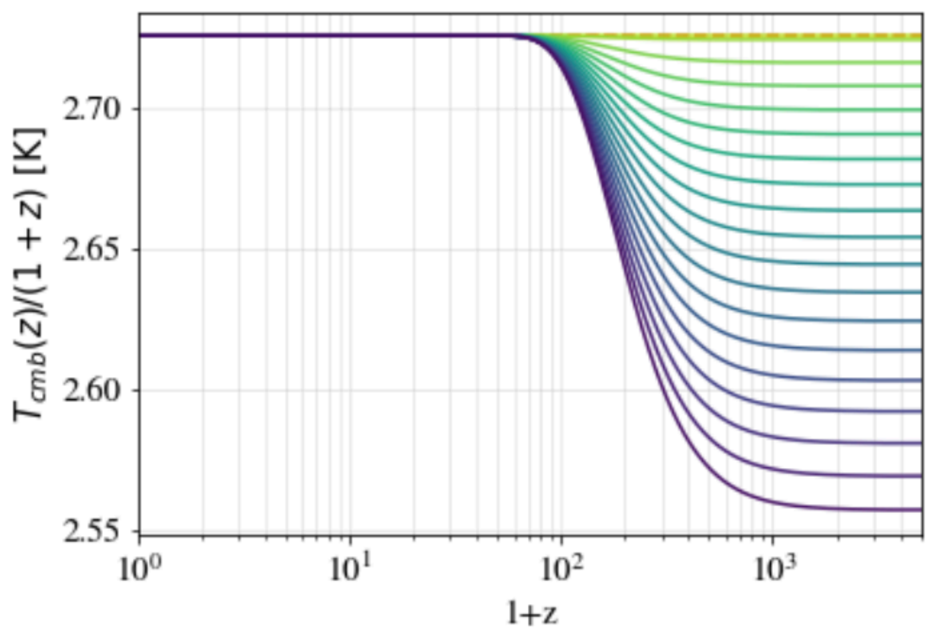
Did the Universe (Slightly) Reheat after Recombination?

- Suppose $T_{CMB}(z^*) < T_{CMB}(z^*)^{\Lambda CDM}$, but a process injects energy at $z < z^*$



Direct constraints on $T_{CMB}(z)$ only exist at z < ~3

Did the Universe (Slightly) Reheat after Recombination?

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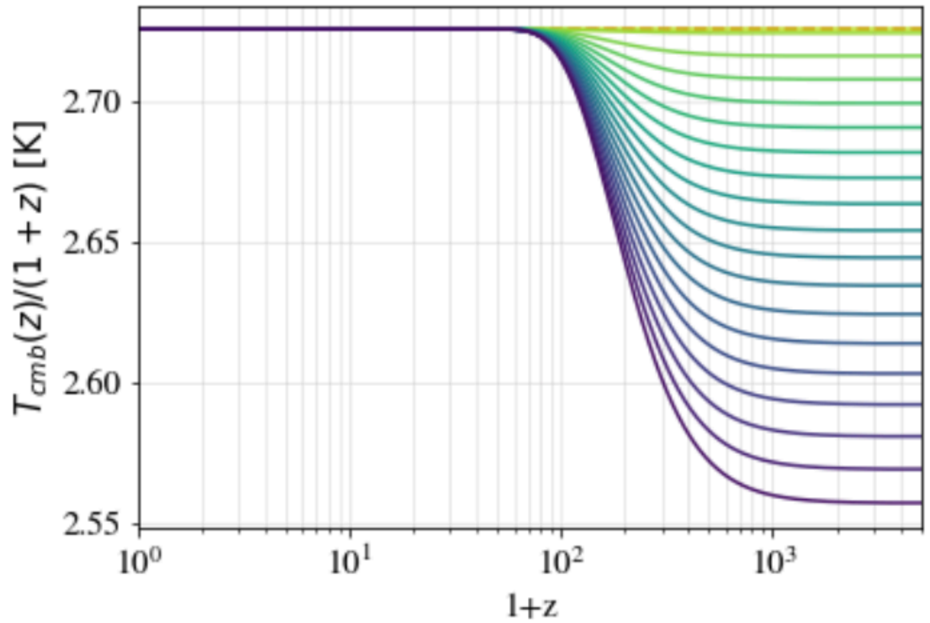
- Suppose $T_{CMB}(z^*) < T_{CMB}(z^*)^{\Lambda CDM}$, but a process injects energy at $z < z^*$



Direct constraints on $T_{CMB}(z)$ only exist at $z < \sim 3$

- To keep k_{eq} fixed, Ω_m must decrease, and hence S_8 decreases
- A conspiracy of integrals leads to higher H_0: the sound horizon is not decreased (in fact it increases due to lower $H(z)$ at early times)

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

- To keep θ_s^* fixed, D_A^* must increase, but since Ω_m decreases, one must increase H_0 to compensate otherwise increased value of the integral:

$$D_A^\star = \int_0^{z_\star} c\,\mathrm{d}z/H(z)$$

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Did the Universe (Slightly) Reheat after Recombination?

Concrete model: sub-component of CDM decays into photons after z*

- Background evolution similar to usual decaying DM->DR:

$$\begin{aligned} \rho'_{\rm DCDM} &= -3aH\rho_{\rm DCDM} - a\Gamma\rho_{\rm DCDM} \\ \rho'_{\gamma} &= -4aH\rho_{\gamma} + a\Gamma\rho_{\rm DCDM}\,, \end{aligned}$$

- New parameters:

  Γ = decay rate
  $\omega_{\rm DCDM,ini}$ = initial decaying CDM density
  ($T_{\rm CMB,ini}$ = initial CMB monopole temperature) — not really new

- Perturbation evolution equations for photons acquire new terms not present in ΛCDM or usual DCDM->DR model

JCH & B. Bolliet (2023): 2304.03750

Did the Universe (Slightly) Reheat after Recombination?

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- Key feature: only a tiny amount of decaying CDM is needed to increase T_{CMB} by the necessary magnitude (e.g., for decay at z=22, only 0.02% of CDM decaying will increase T_{CMB} by 1%)

JCH & B. Bolliet (2023)

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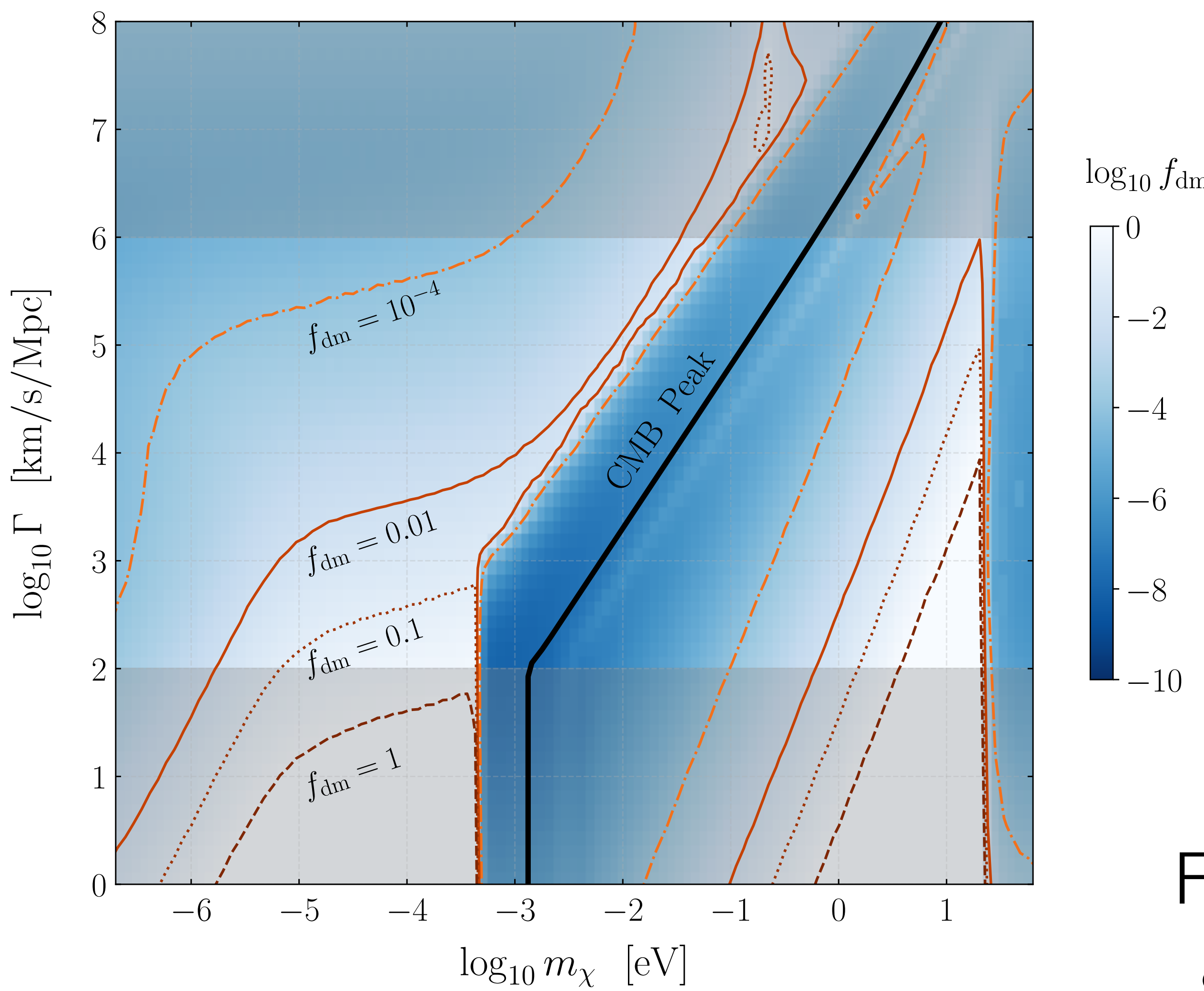
Did the Universe (Slightly) Reheat after Recombination?

- Key feature: only a tiny amount of decaying CDM is needed to increase T_{CMB} by the necessary magnitude (e.g., for decay at z=22, only 0.02% of CDM decaying will increase T_{CMB} by 1%)

- What about spectral distortion constraints?



f_{DM} = fraction of DM that decays

For simplicity here, we assume that injected photons are thermal

JCH & Bolliet (2023); Bolliet, Chluba, & Battye (2021)

PRR Analysis

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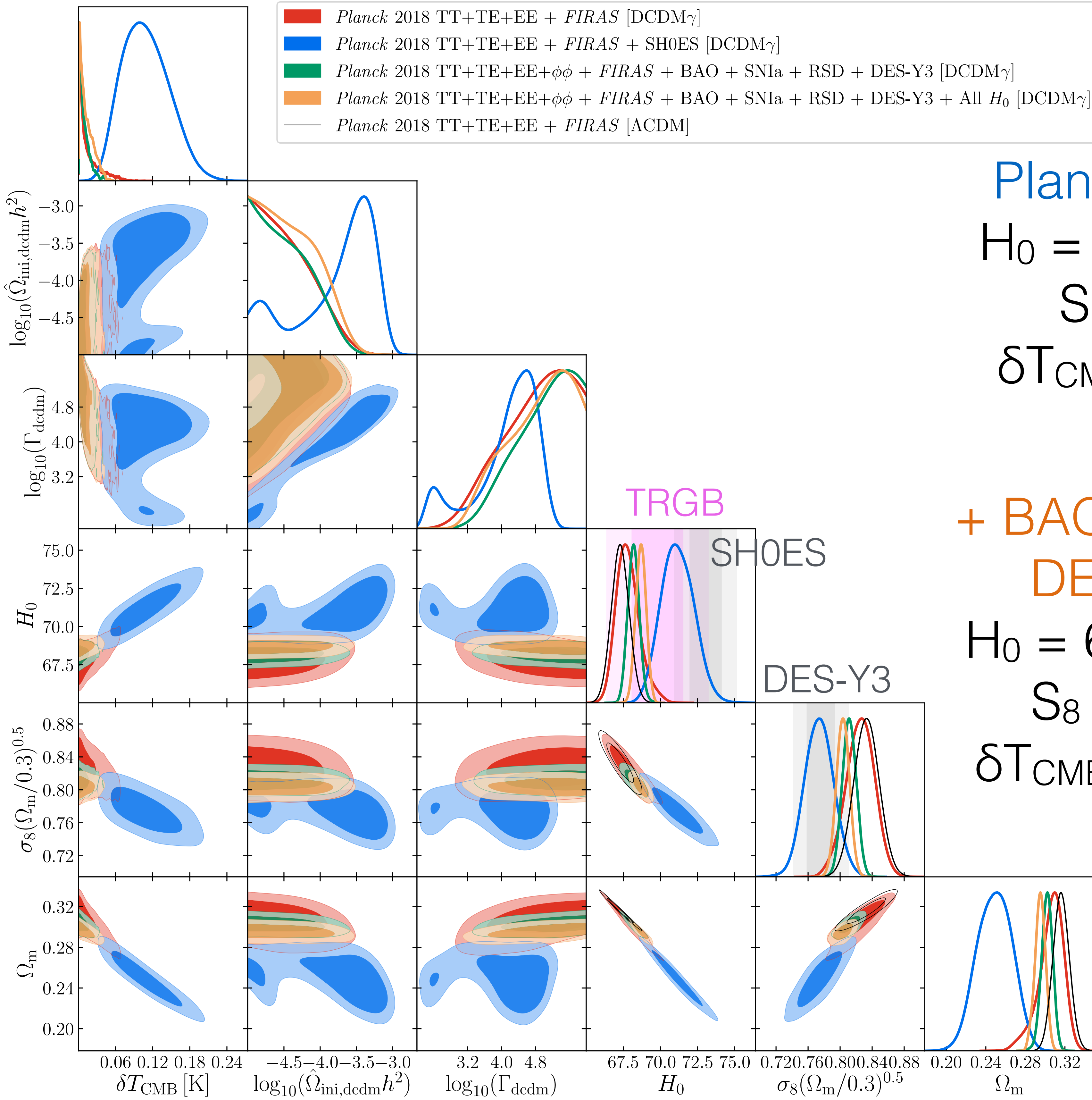

Planck + FIRAS + SH0ES:

H_0 = 71.2 +/- 1.1 km/s/Mpc

S_8 = 0.774 +/- 0.018

δT_{CMB} = 0.109 $^{+0.033}_{-0.044}$ K

+ BAO + SNIa + ϕϕ + RSD + DES-Y3 + MCP + SBF:

H_0 = 68.7 +/- 0.35 km/s/Mpc

S_8 = 0.8035 +/- 0.0081

δT_{CMB} < 0.0342 K [95% CL]

χ^2_{Planck} is as good as that of ΛCDM fit to Planck alone

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PRR Takeaways

- Main obstruction to success of the model: conflict with Ω_m constraint from BAO and SNIa

- One tweak: allow N_{eff} to 'restore' early-universe radiation density back to its normal value, and mitigate decrease in Ω_m (thus giving up S_8 fix and lessening increase in H_0) — such a model fits data better than ΛCDM+N_{eff}, but only slightly

- Most plausible route to avoid SD constraints: suppress the spectrum at frequencies < 60 GHz in early universe (non-trivial)

- Key points:
  - There are large swathes of cosmic history where (semi-)dramatic changes to the model could still lurk
  - Seemingly small changes (δT_{CMB} ~ 10-100 mK) can have big effects
  - We should measure CMB spectral distortions much better than FIRAS! Strong motivation for PIXIE, FOSSIL, BISOU, etc.

JCH & Bolliet (2023)

Next: ACT DR6

(target: later this year)

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Columbia

ACT DR6 Forecasts

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?

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JCH et al. (2021)

Discovering EDE in the CMB?

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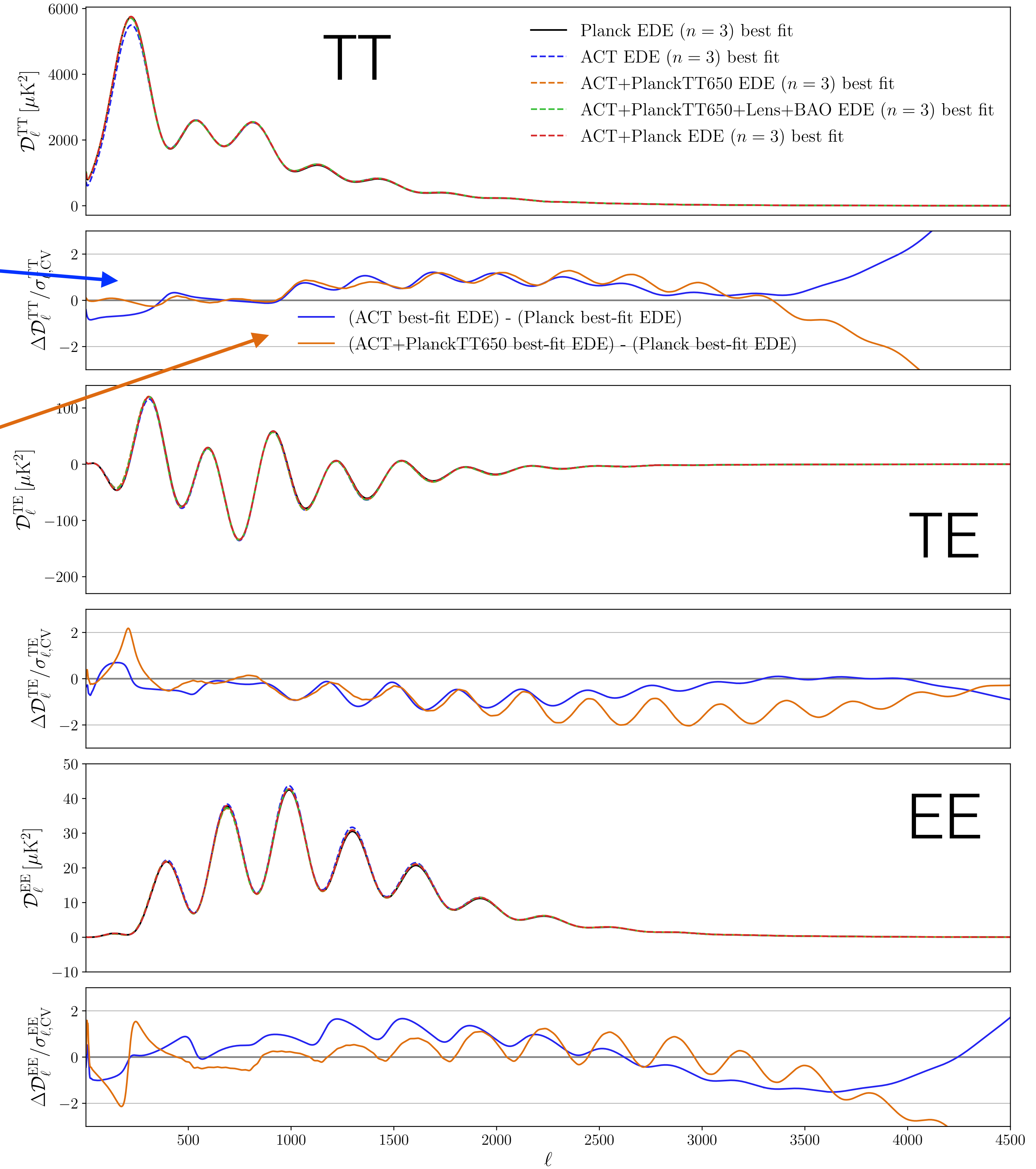
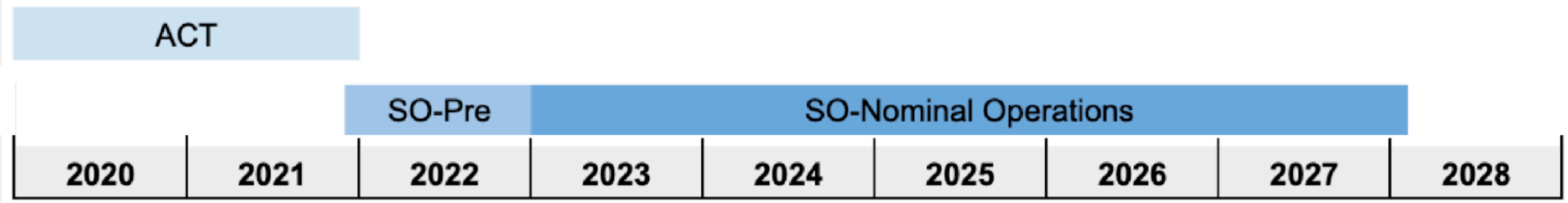
ACT best-fit EDE - Planck EDE

ACT+P18TT650 EDE - Planck EDE



Imminent potential discovery with upcoming ACT DR6 (~2023): the models shown here can be distinguished at ~15-20σ

JCH et al. (2021)



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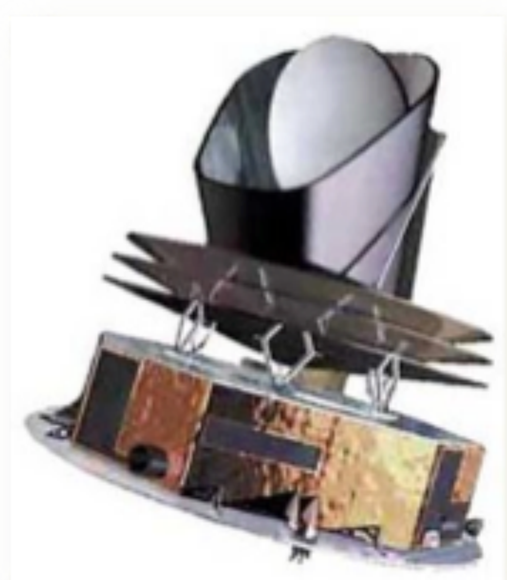
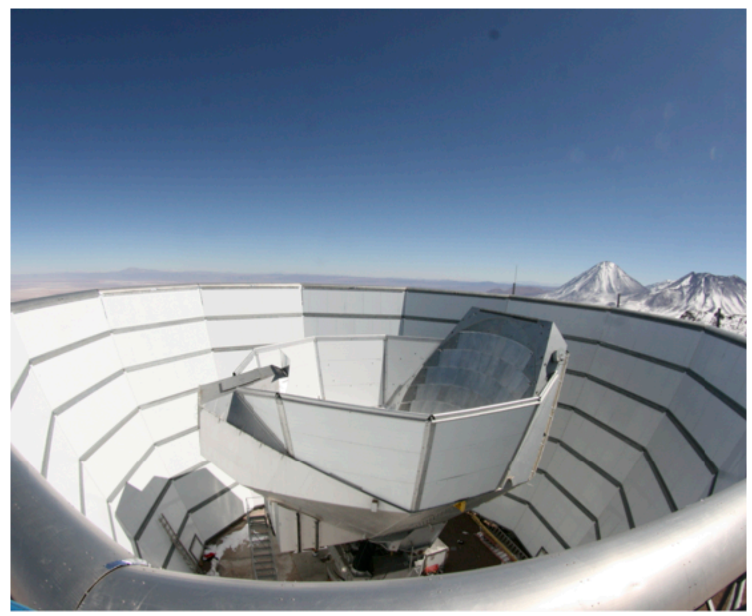
Planck → ACT → **SO** Large Aperture Telescope



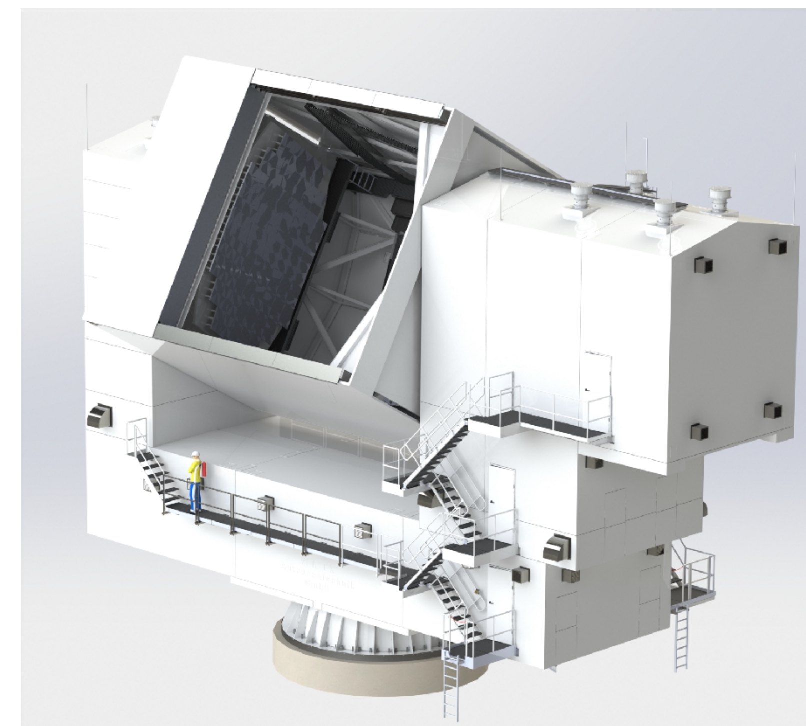
Final data 2018
100% sky

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



Observations until 2022
40% sky
Noise ~3 times < Planck
1.4 — 10 mm (5 bands)
1 — 7' resolution

[South Pole Telescope - same timeframe]



Observations 2024 - ~29
40% sky
Noise ~3 times < ACT
1 — 10 mm (6 bands)
1 — 7' resolution

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

Advanced SO

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NSF News

Detecting faint traces of universe's explosive birth is aim of NSF-supported Advanced Simons Observatory

Funded by NSF in May 2023

- $52.7M NSF investment to double LAT detector count; build robust data pipeline (including transient alerts); build solar array at site to generate 70% of energy for the observatory
- SO observations: 2024-2029
- ASO observations: 2028-2033
- Significant gains in scientific capabilities
- PI: Mark Devlin (Penn)
- Co-PIs: Jo Dunkley (Princeton), Jeff McMahon (Chicago), Suzanne Staggs (Princeton)
- Co-Project Scientists: JCH (Columbia), Susan Clark (Stanford)

Take-Home Messages

1) Cosmic discordance? Observational situation unclear, but viable models will be confirmed or refuted imminently
2) ACT and Planck prefer somewhat different EDE model parameters, with ACT yielding higher f_{EDE} and H_0
3) Challenge: Lyα forest severely constrains canonical EDE
4) 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

Bonus

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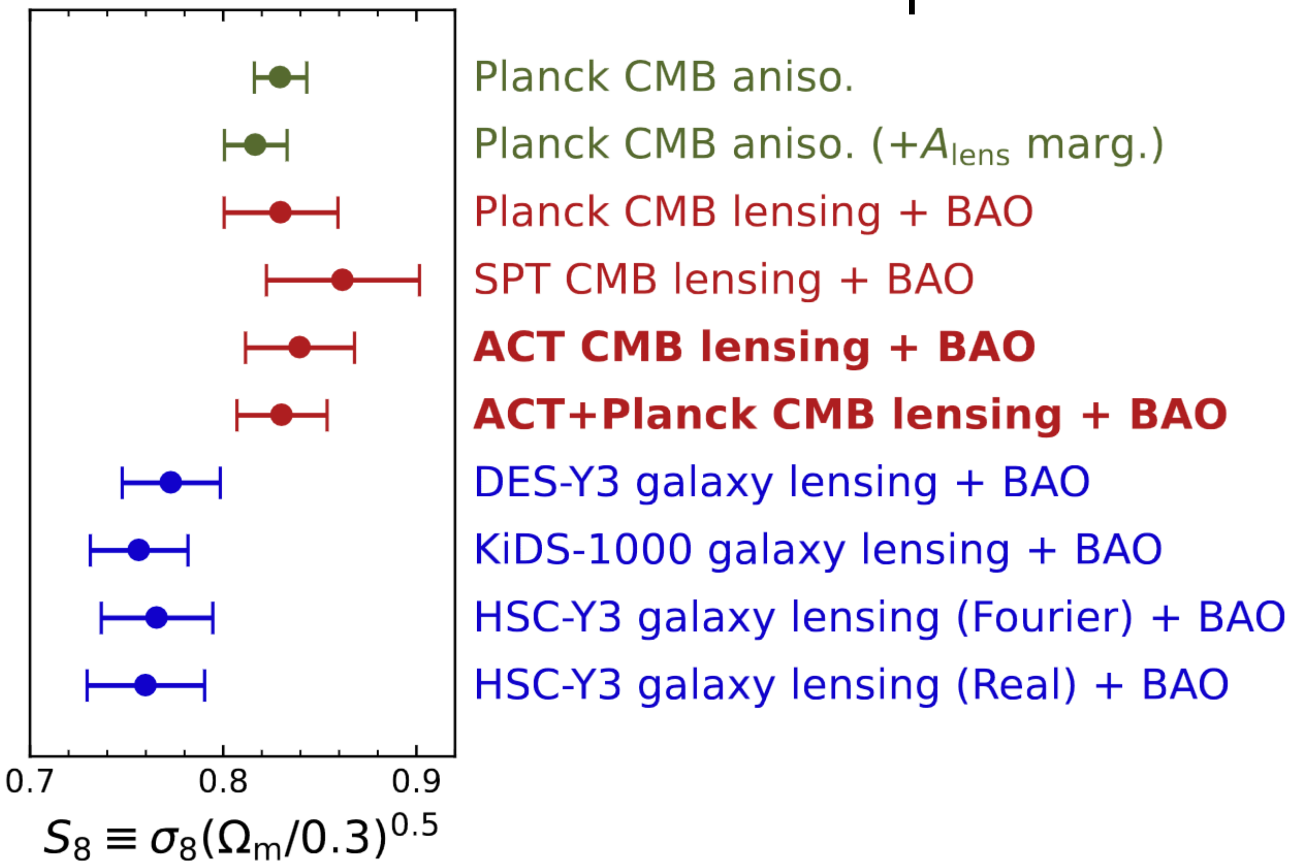
ACT DR6 CMB Lensing

Implications for EDE?



S_8 is not low — reduces discordance with EDE prediction from CMB+SH0ES fit

Madhavacheril et al. (2023); Qu et al. (2023)

ACT DR6 CMB Lensing

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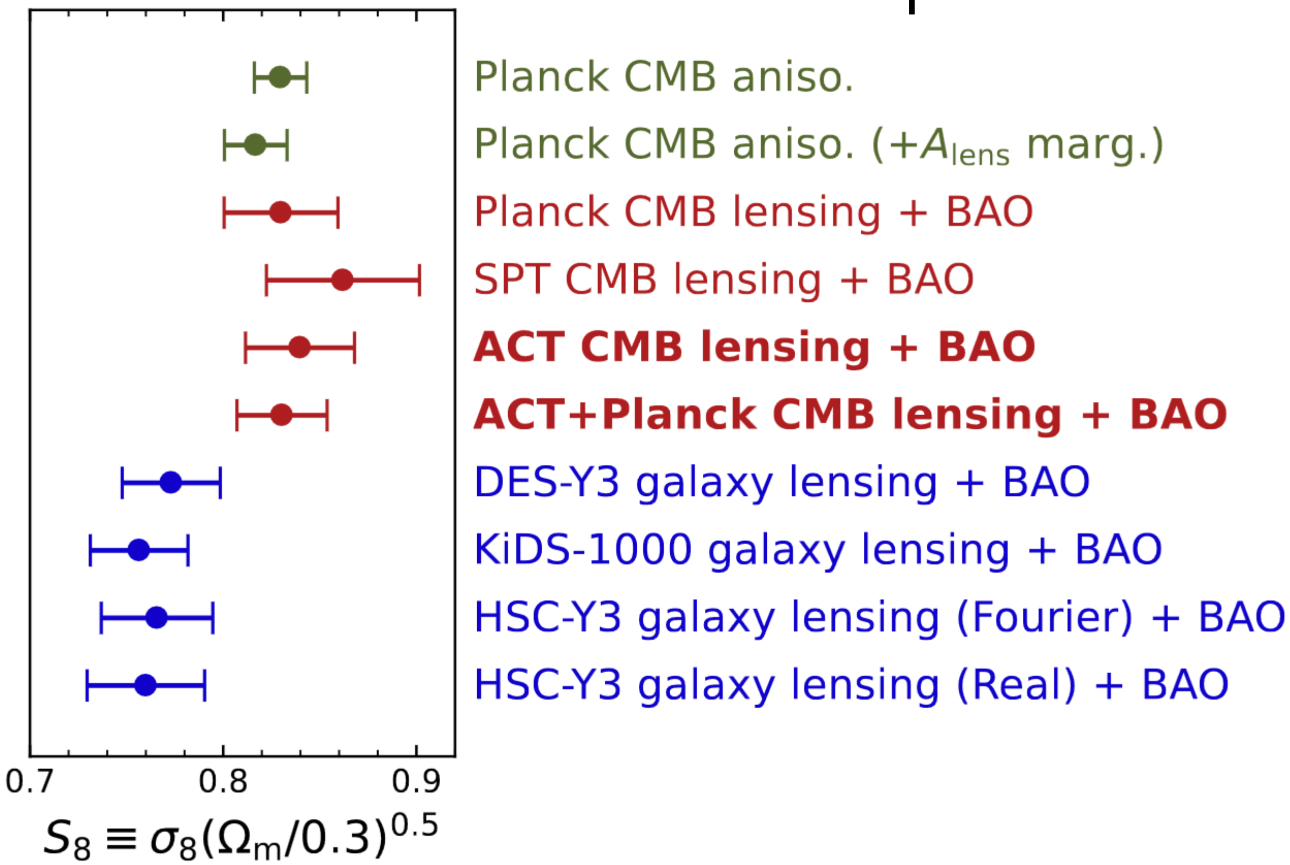
Implications for EDE?

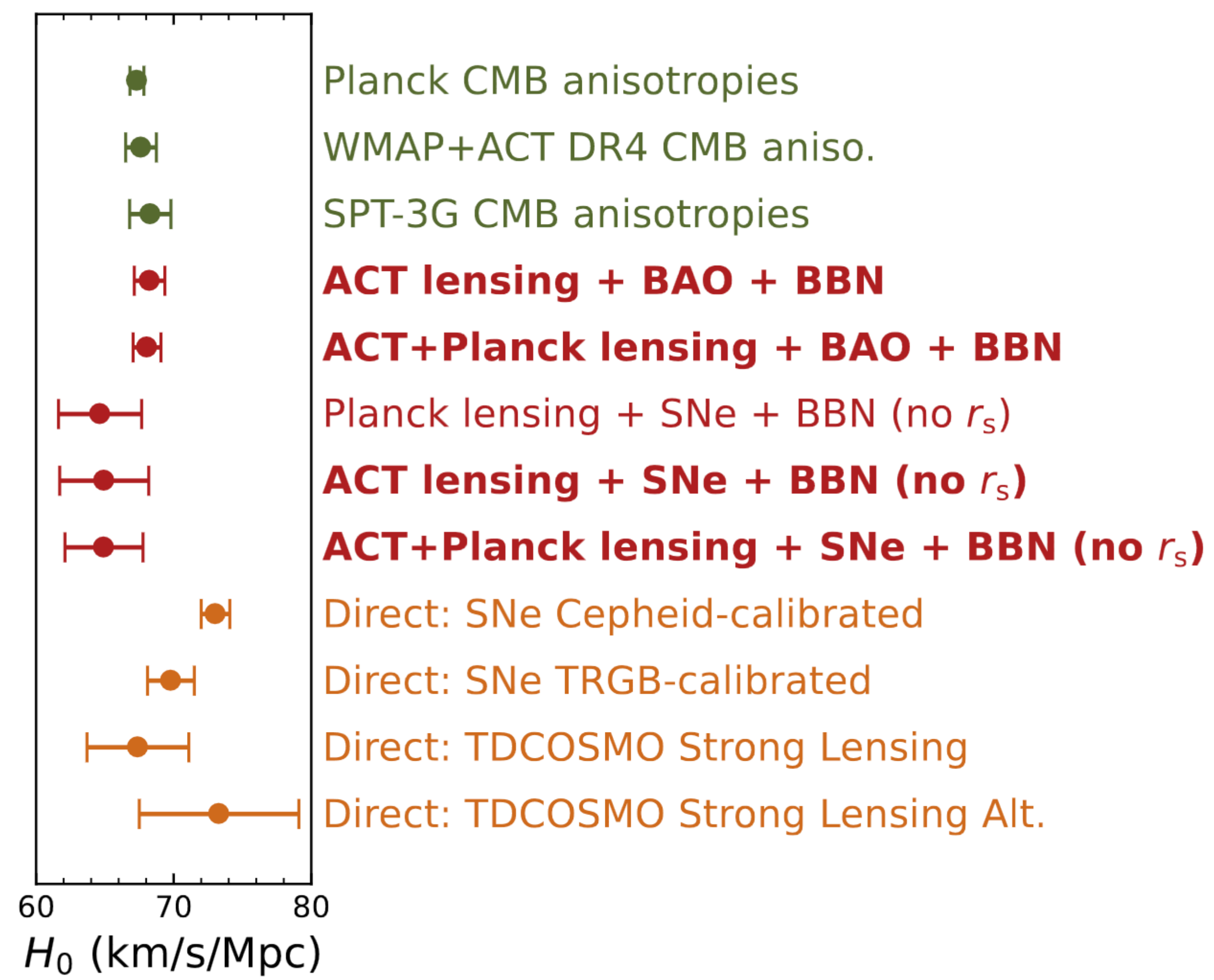


S_8 is not low — reduces discordance with EDE prediction from CMB+SH0ES fit

… But sound-horizon-free H_0 constraint is 3σ lower than SH0ES

$$H_0 = 64.9 \pm 2.8\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Success for ΛCDM at z>z*



Madhavacheril et al. (2023); Qu et al. (2023)

PRR: Particle Physics Model(s)

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Constraints on light particles coupled to photons from, e.g., white dwarfs can be evaded via models with an excited dark matter state

Consider DM with non-zero dipole moment, coupled to SM sector through a kinetically mixed massive dark photon (DP)

The DP allows for transitions between ground and excited states of the DM

If the energy splitting of the states is ~0.1 eV, the excited state is metastable for ~1-10 Myr as we need in the PRR scenario

If m_{DP} > MeV, it is not produced in stars or supernovae

In general our results suggest that cosmological implications of such scenarios should be considered

Most plausible route to avoid SD constraints: suppress the spectrum at frequencies < 60 GHz in early universe (non-trivial)

(e.g.) Baryakhtar+ (2020)

Consistent with SPT-3G?

Analysis using public SPT-3G TE/EE data

https://arxiv.org/abs/2112.10754; Phys. Rev. D 105, 083519

La Posta, Louis, Garrido, **JCH** (2022) ; SPT-3G data from Dutcher et al. (2021)

Consistent with SPT-3G

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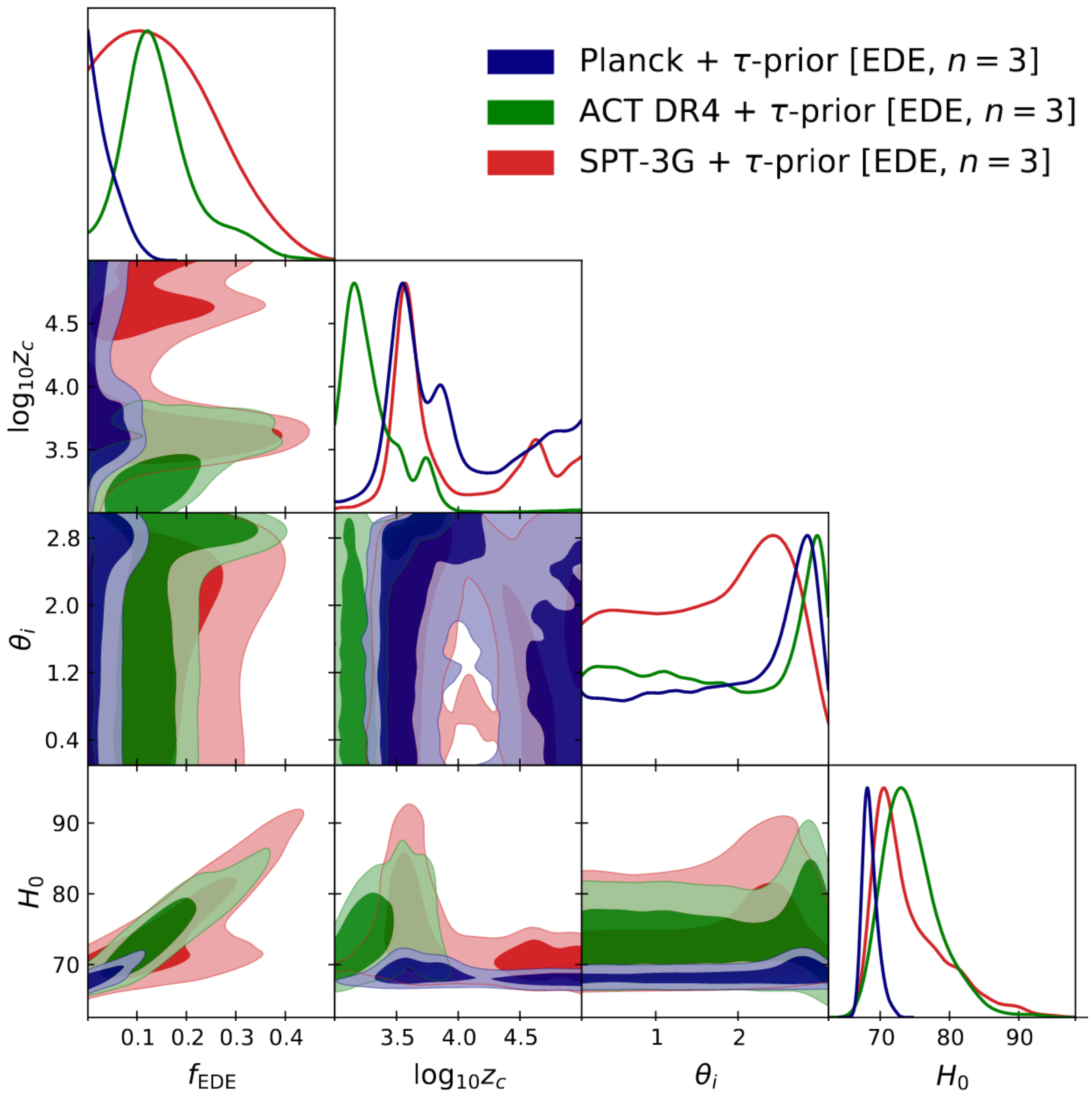
Analysis using public SPT-3G TE/EE data



La Posta, Louis, Garrido, **JCH** (2022) ; SPT-3G data from Dutcher et al. (2021)

Consistent with SPT-3G

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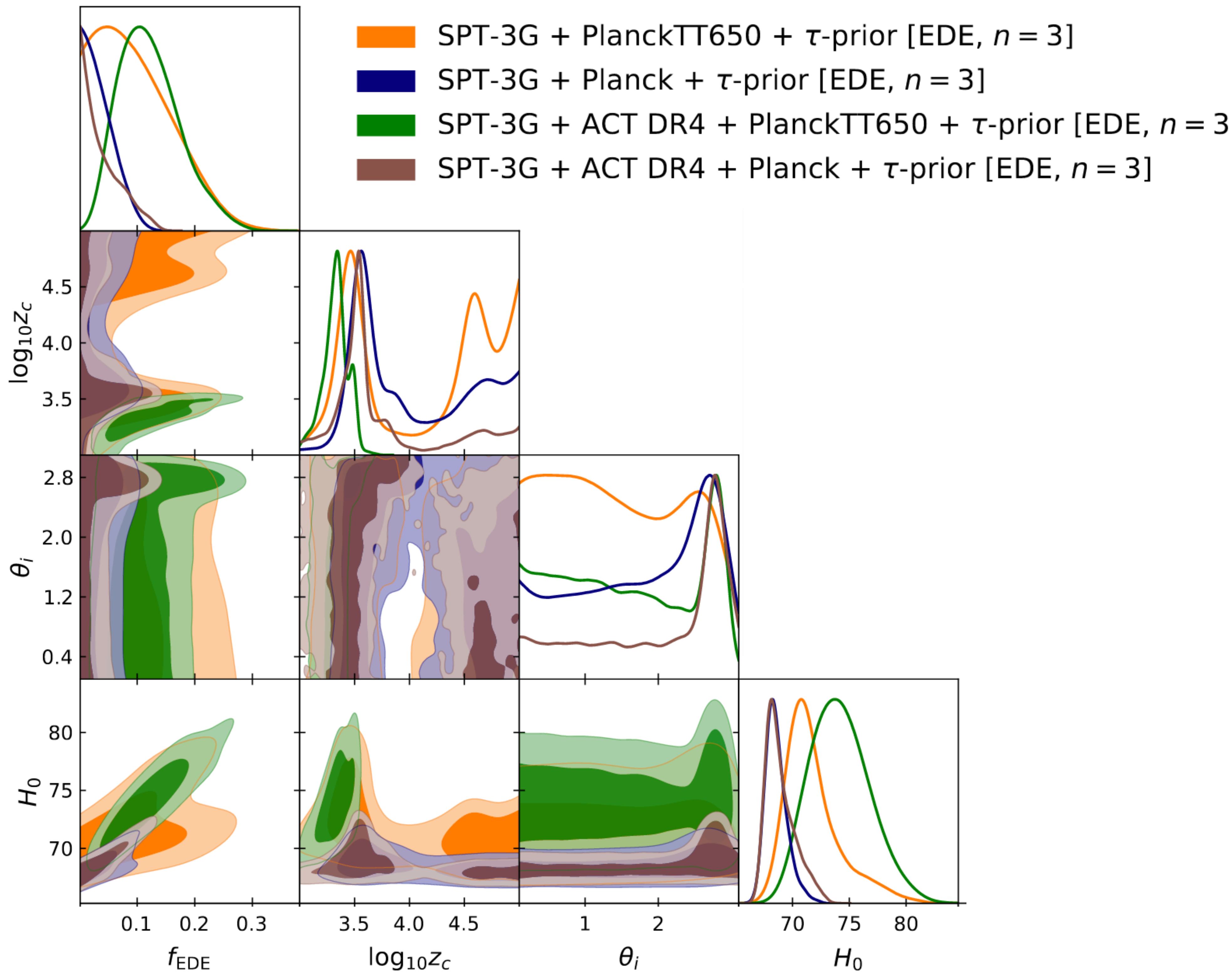

La Posta, Louis, Garrido, JCH (2022) ; SPT-3G data from Dutcher et al. (2021)

Consistent with SPT-3G

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Analysis using public SPT-3G TE/EE data

Inclusion of full Planck TT data still dominates overall constraining power and removes preference for non-zero EDE

Parameters	**SPT-3G + Planck**	**SPT-3G + PlanckTT650 + ACT DR4**	**SPT-3G + Planck + ACT DR4**
$f_{\rm EDE}$	< 0.088	$0.121^{+0.040}_{-0.064}$	< 0.107
H_0 [km/s/Mpc]	$68.6^{+0.7}_{-1.1}$	$74.2^{+2.3}_{-3.0}$	$68.9^{+0.7}_{-1.6}$

2.6σ hint

Upcoming data from ACT + SPT will be very interesting!

La Posta, Louis, Garrido, JCH (2022)

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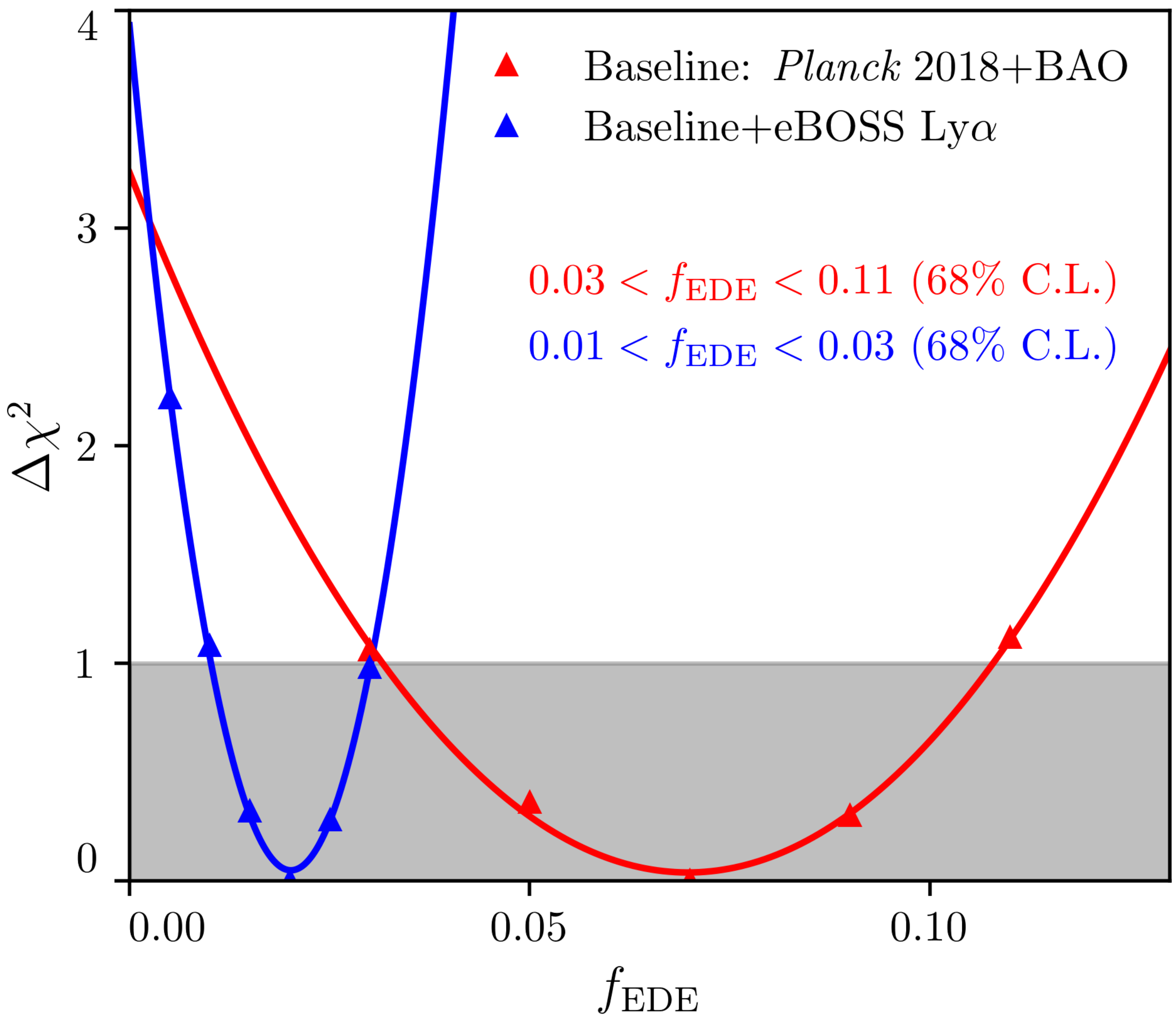
Lyα Forest: EDE Constraints

No biases due to "prior volume effects": profile likelihood analysis yields similarly tight constraints



Goldstein, JCH, Irsic, & Sherwin (2023): 2303.00746

Lyα EDE Validation

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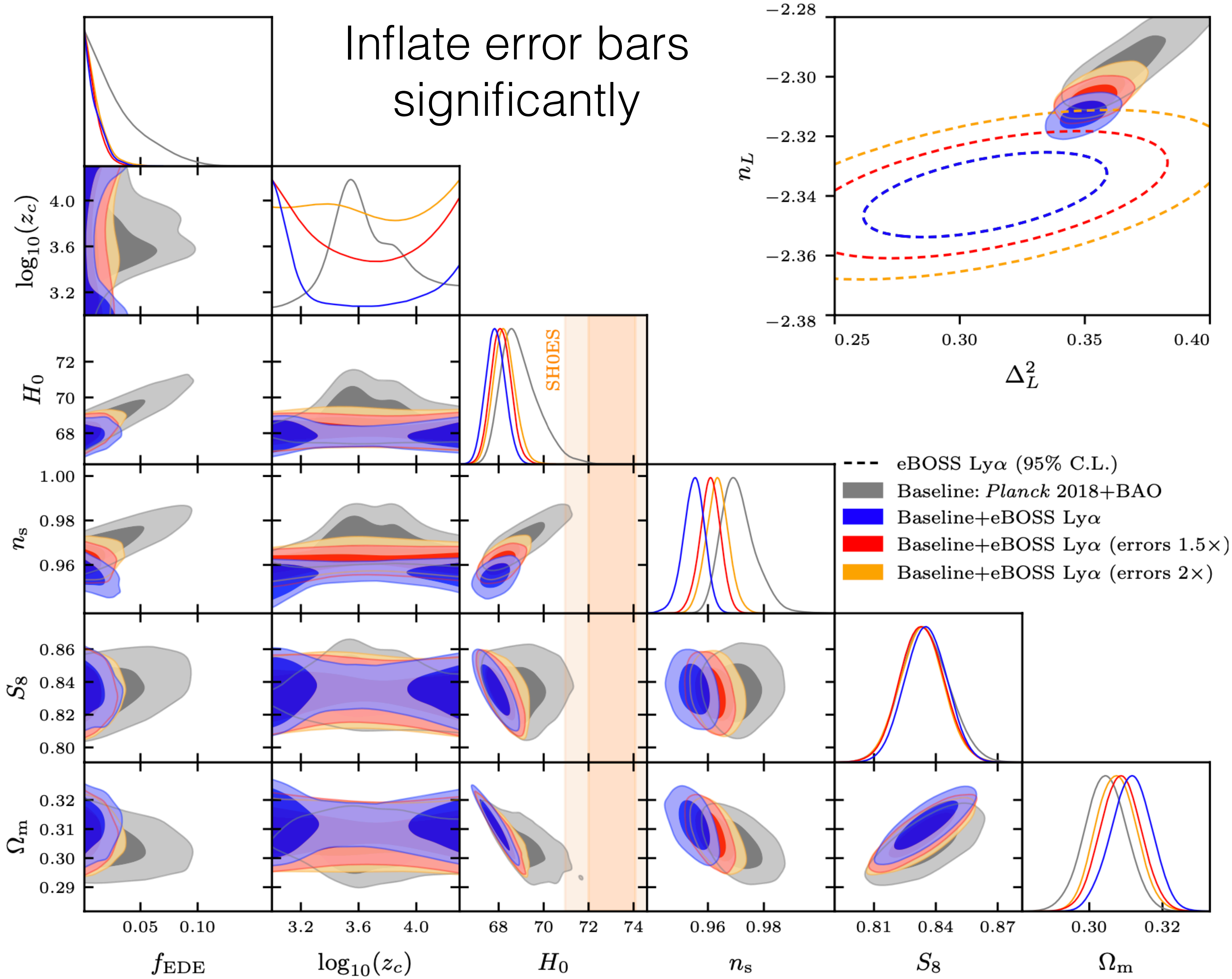
Inflate error bars significantly



Goldstein, JCH, Irsic, & Sherwin (2023)

Lyα EDE Validation

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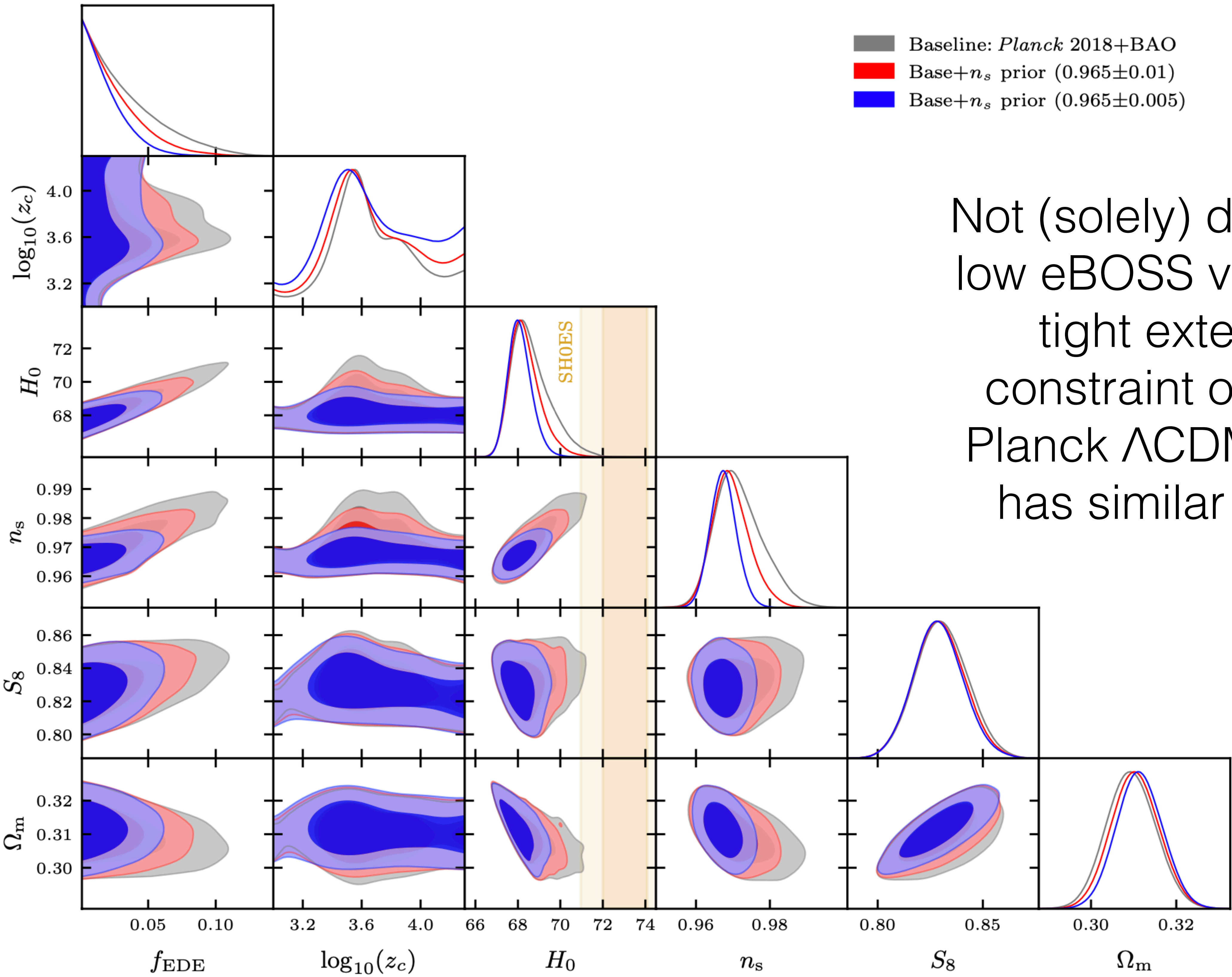


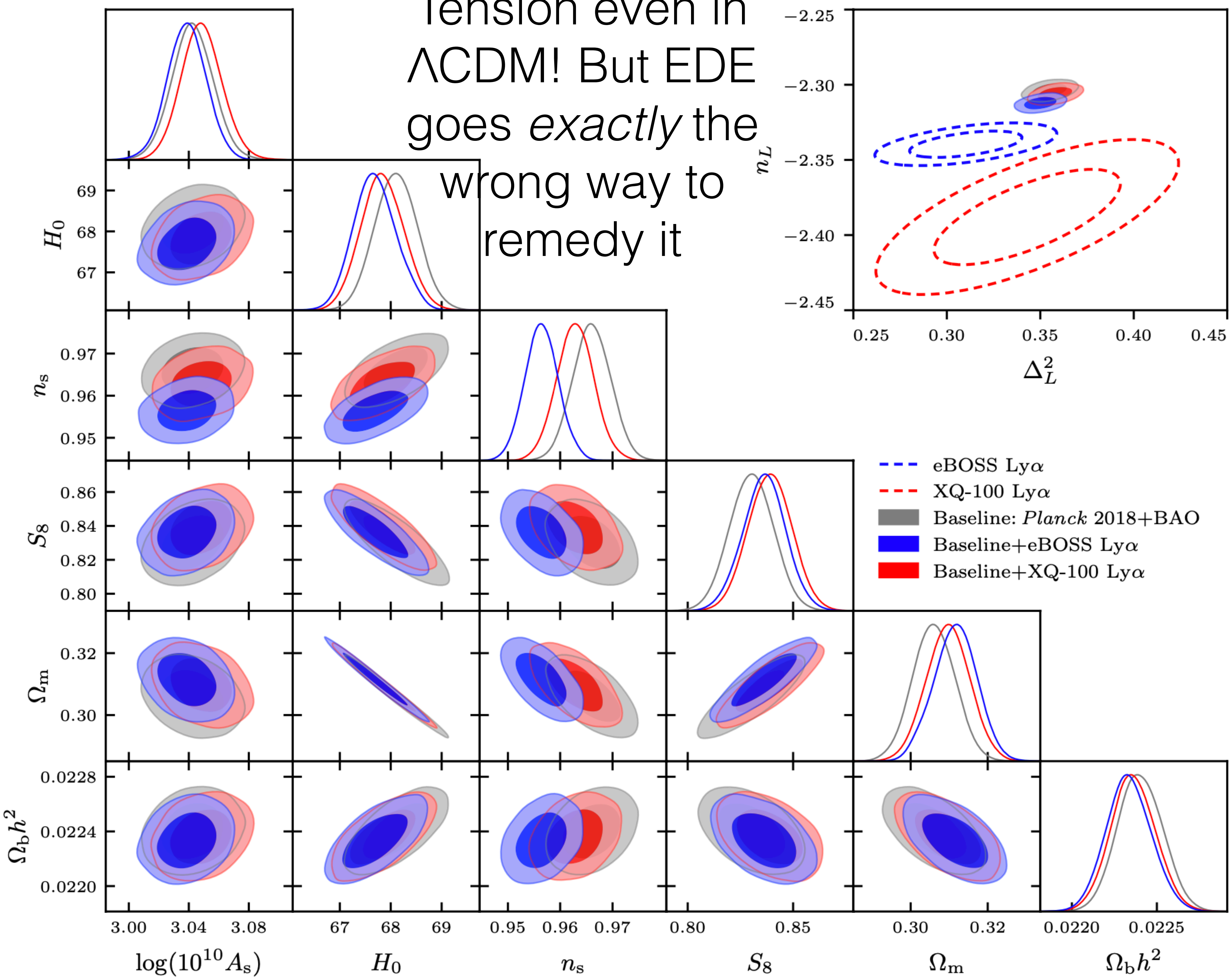
Not (solely) driven by low eBOSS values: a tight external constraint on n_s at Planck ΛCDM value has similar effect

Goldstein, JCH, Irsic, & Sherwin (2023)

Lyα EDE Validation

Colin Hill
Columbia

Tension even in ΛCDM! But EDE goes *exactly* the wrong way to remedy it



Goldstein, JCH, Irsic, & Sherwin (2023)

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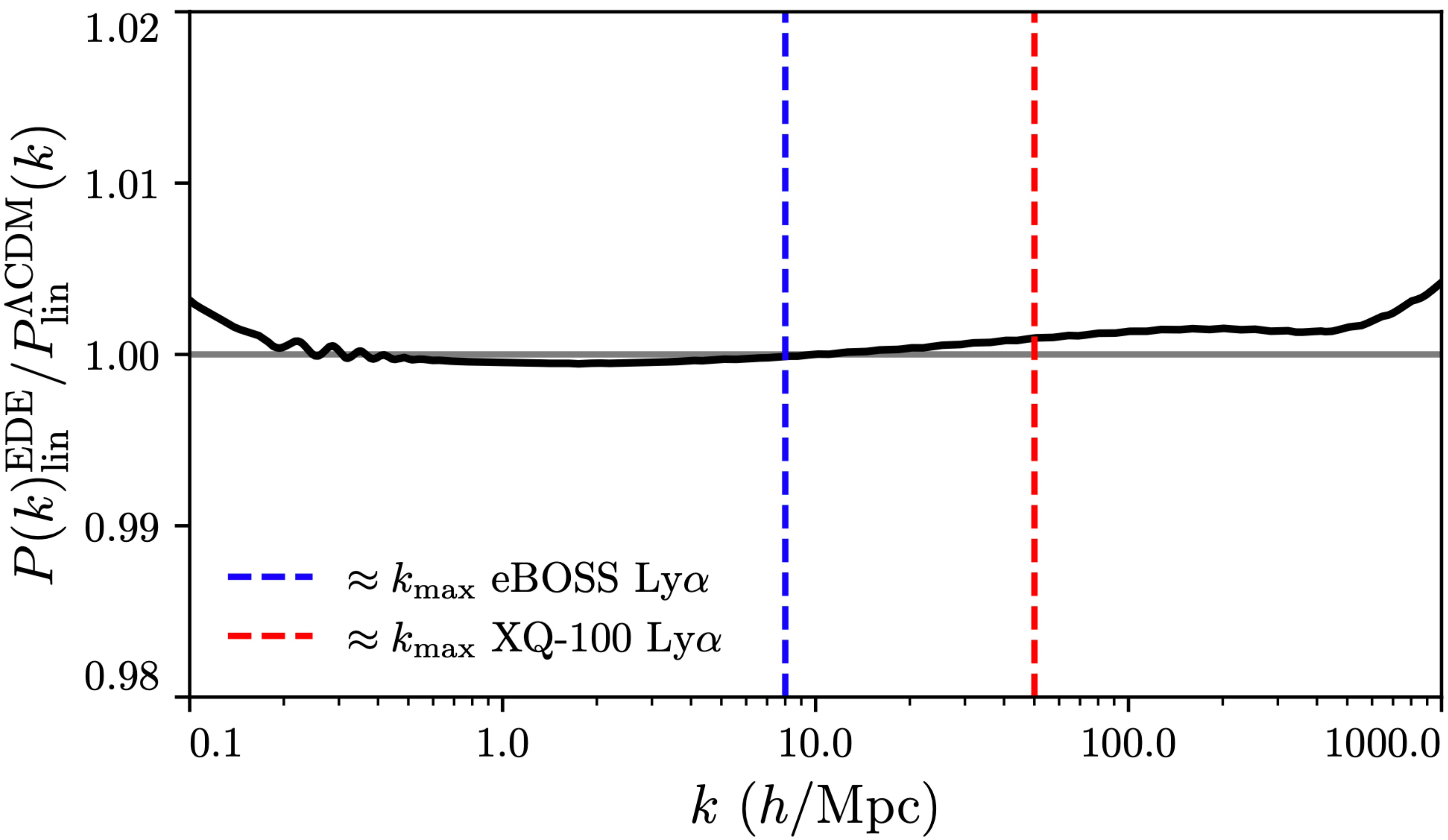
Columbia

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 (2023)

Lyα EDE Validation

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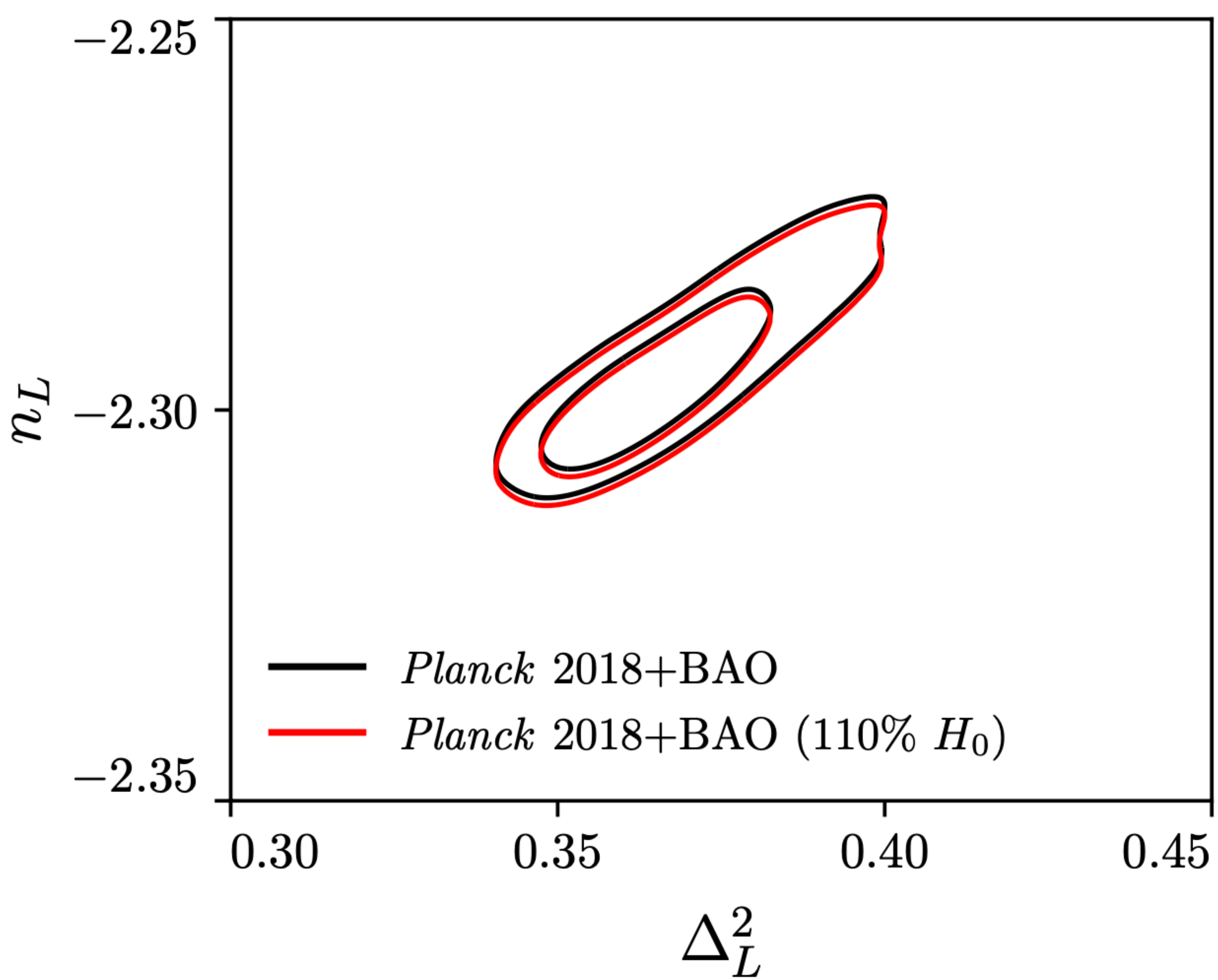
Do the priors used in the Lyα likelihood construction have any impact on the compressed parameter likelihoods used in EDE analysis? No



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

Goldstein, JCH, Irsic, & Sherwin (2023)

Lyα EDE Validation

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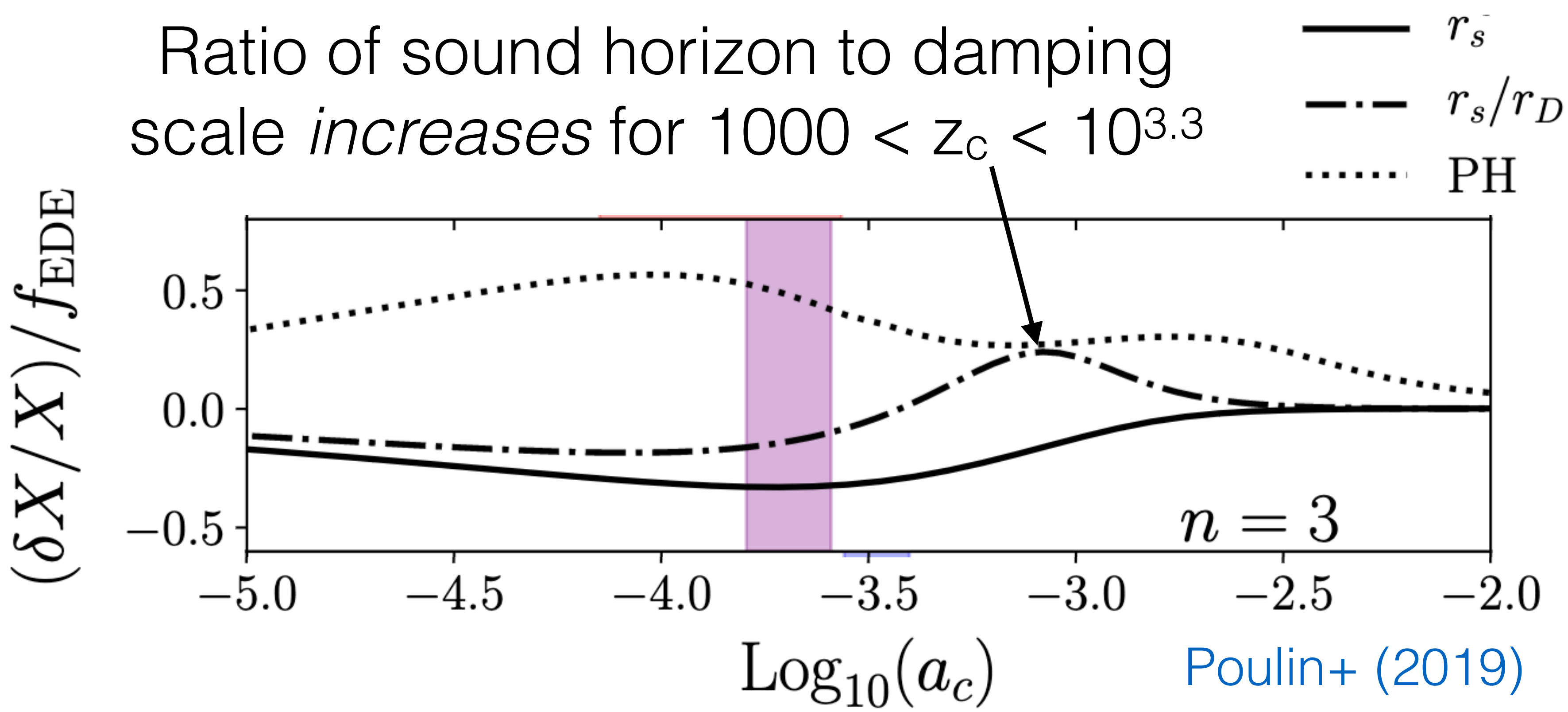
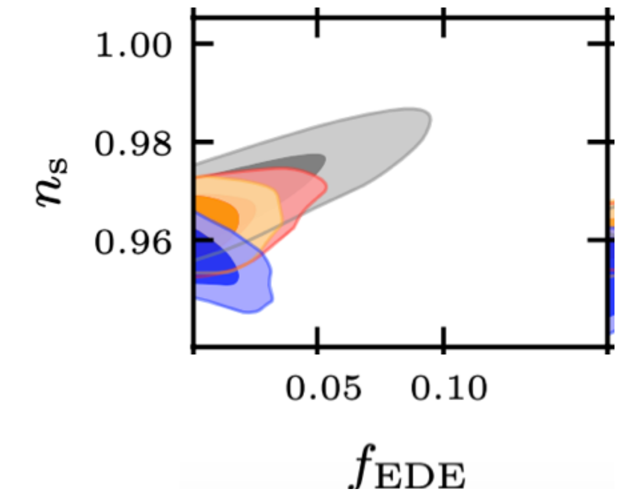
Columbia

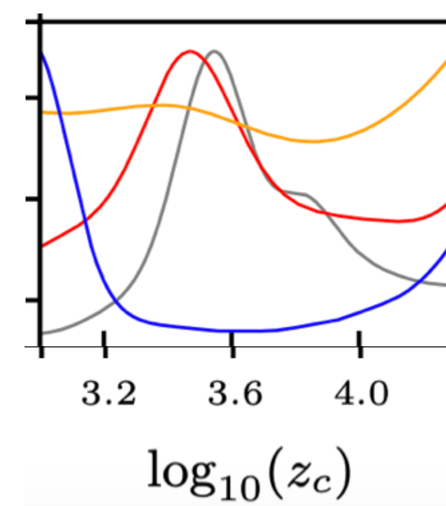
Origin of the n_s - f_{EDE} anti-correlation for the baseline+eBOSS analysis

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



Poulin+ (2019)



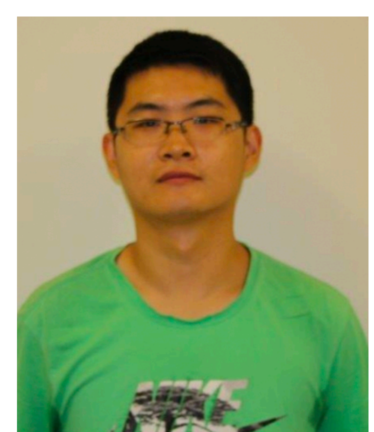


Thus θ_s/θ_d increases; but θ_s is fixed by observations, so θ_d *decreases,* i.e., ell_d increases. Hence less damping at a given ell, so n_s decreases to compensate.

Goldstein, JCH, Irsic, & Sherwin (2023)

Colin Hill
Columbia/CCA

Primordial Magnetic Fields and Baryon Clumping

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

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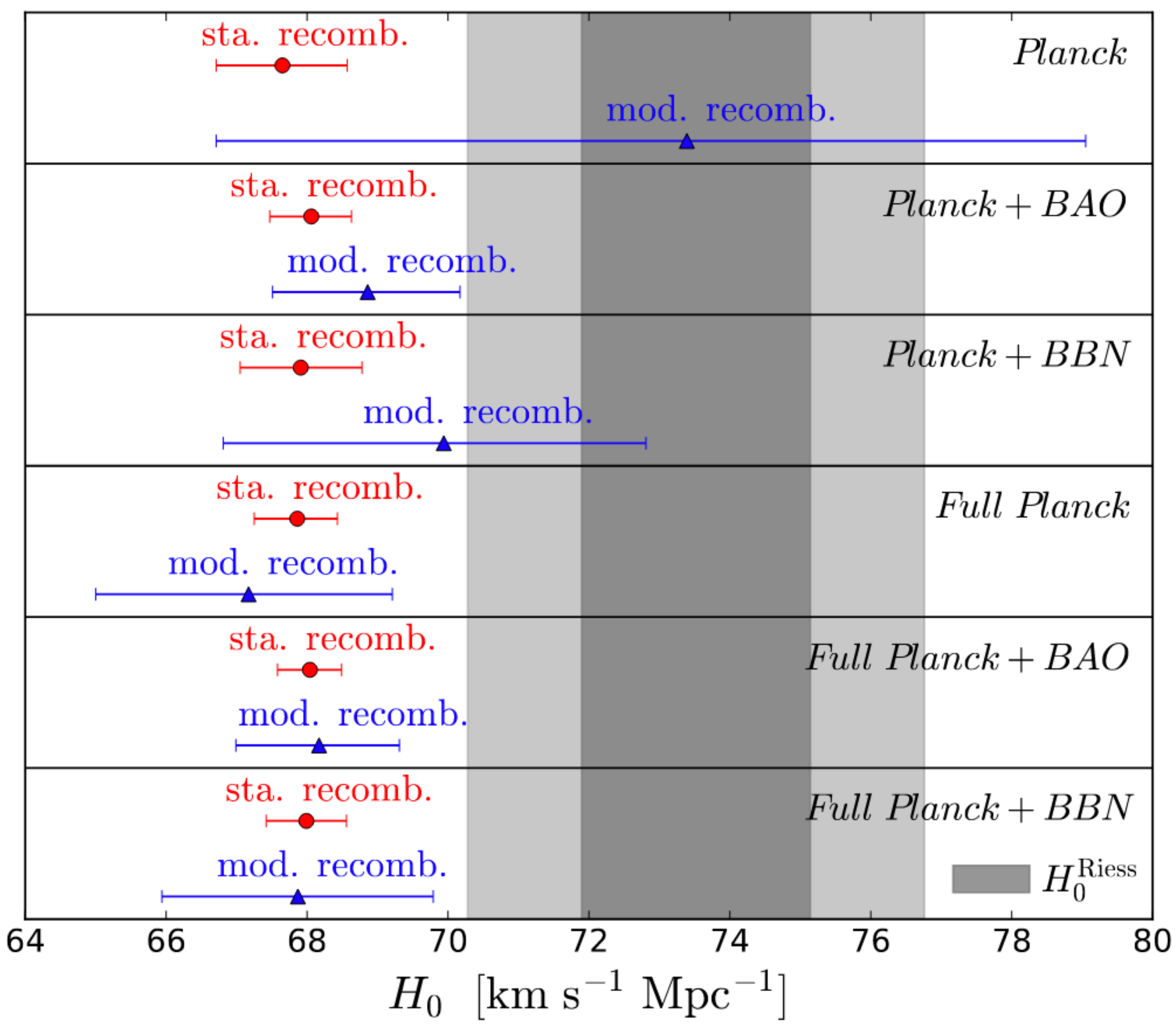
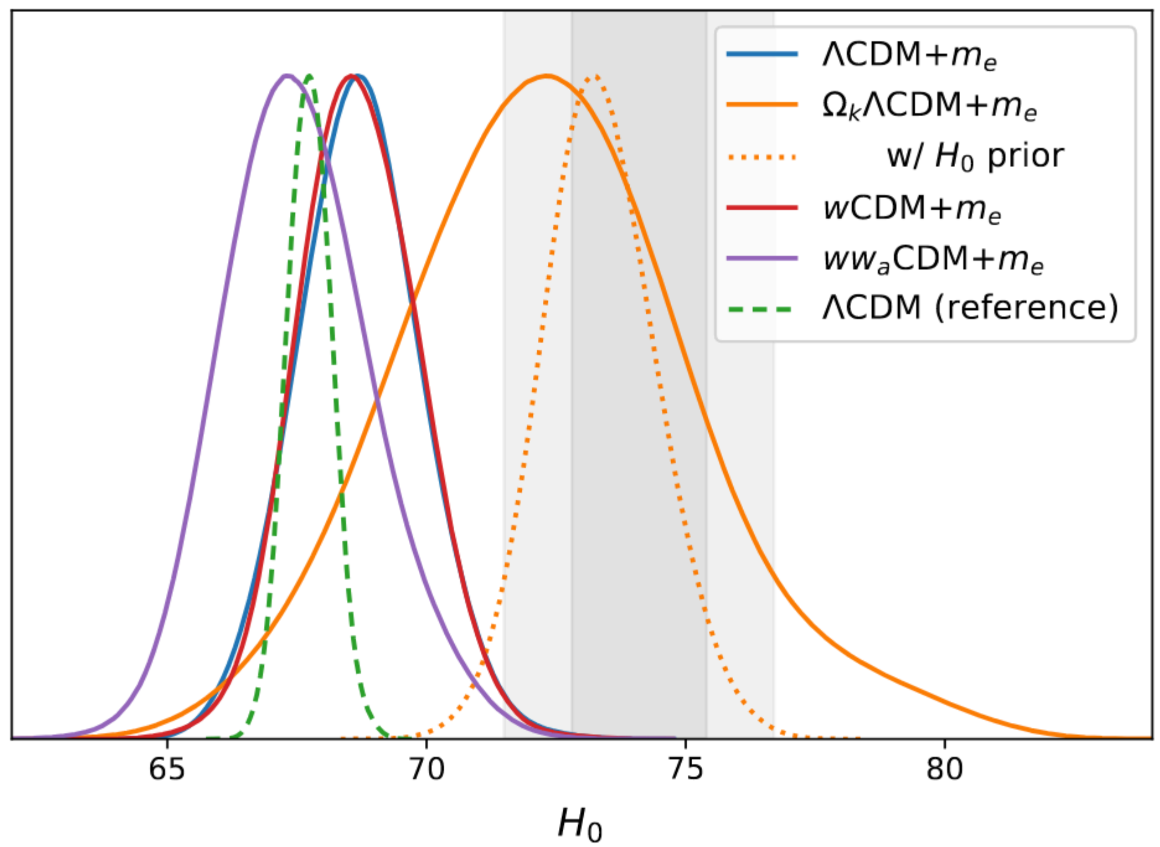
Early Recombination

Success depends on the details of the physical implementation

Phenomenological model



"Physical" model (varying m_e)



Chiang & Slosar (2018); Hart & Chluba (2020); Sekiguchi & Takahashi (2020)

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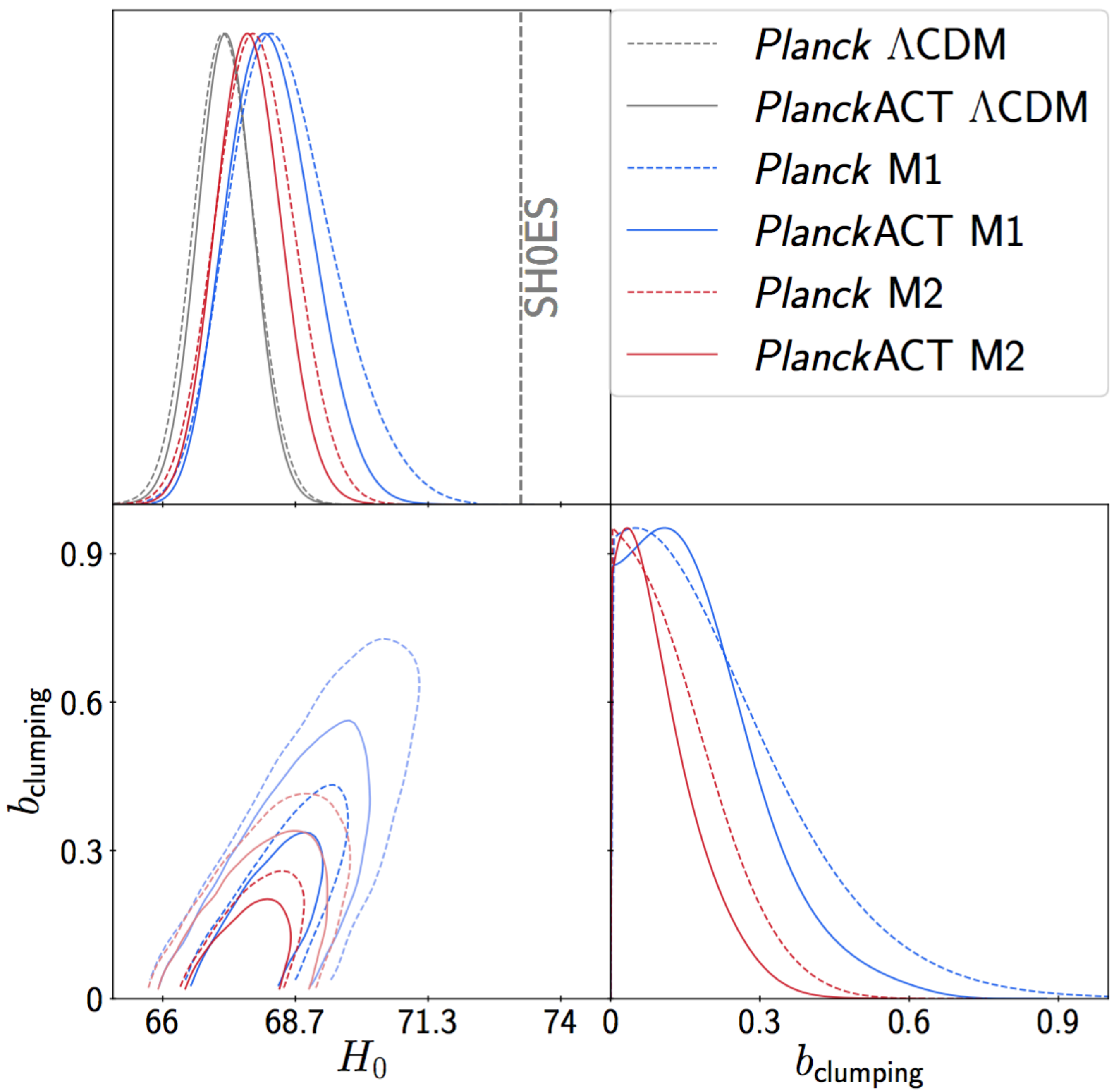
Early Recombination

Success depends on the details of the physical implementation

“Physical” model (primordial magnetic fields) — effectively excluded by ACT DR4



ΛCDM	67.26 ± 0.60
M1	68.18 ± 0.87
M2	67.74 ± 0.71

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

Baryon Clumping

Colin Hill
Columbia/CCA

- 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

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

Baryon Clumping

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- 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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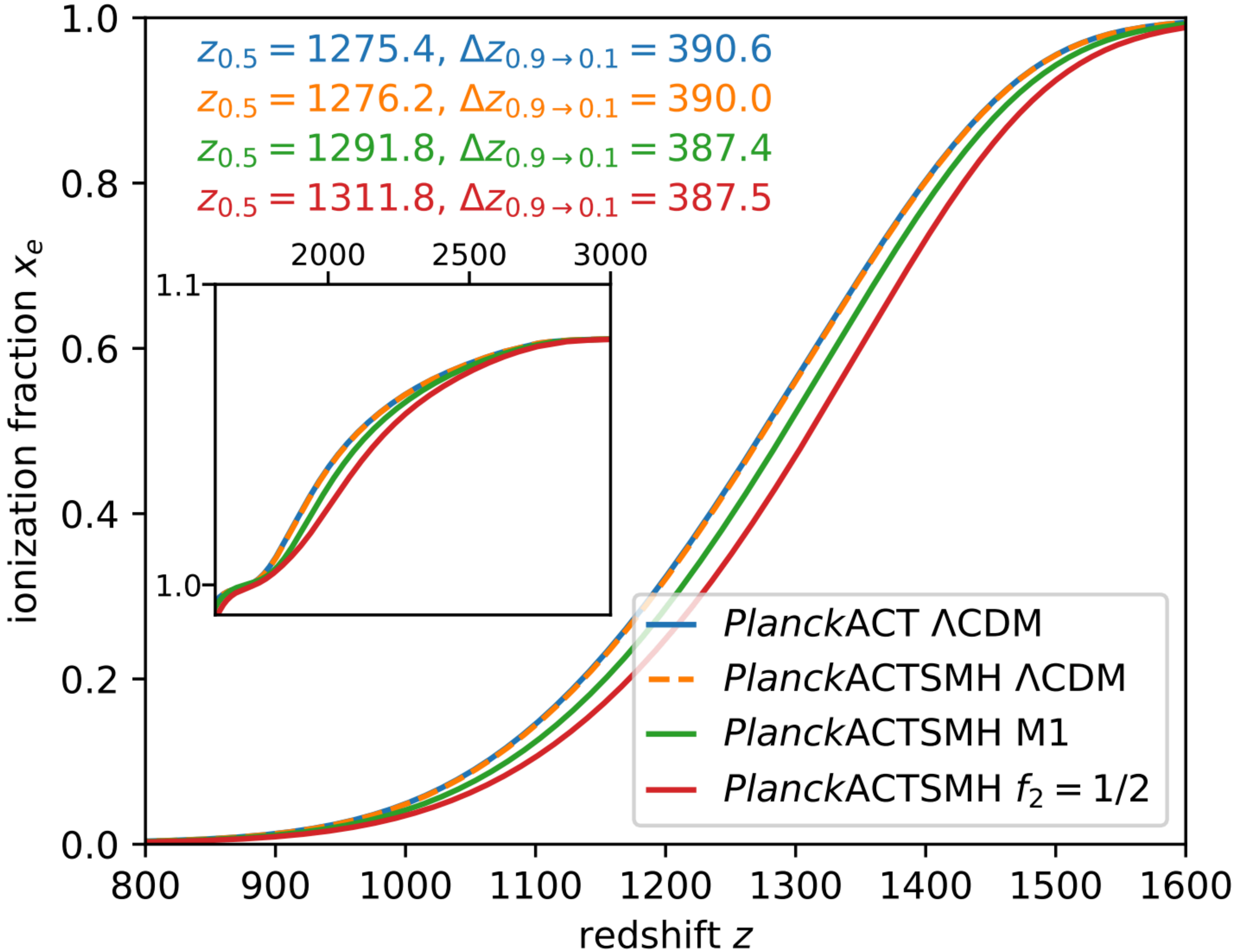
Illustration of the mechanism

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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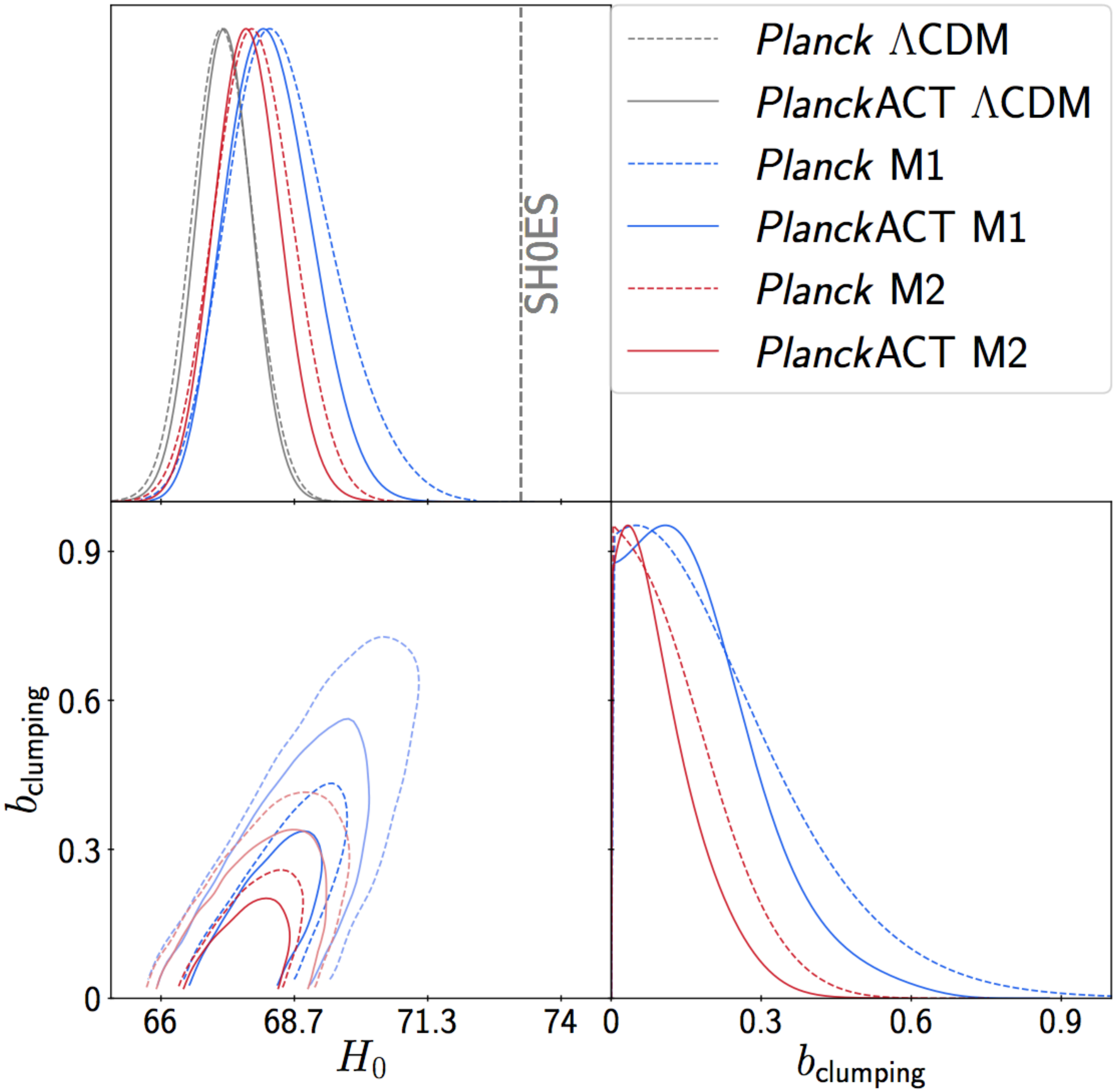

Planck+ACT

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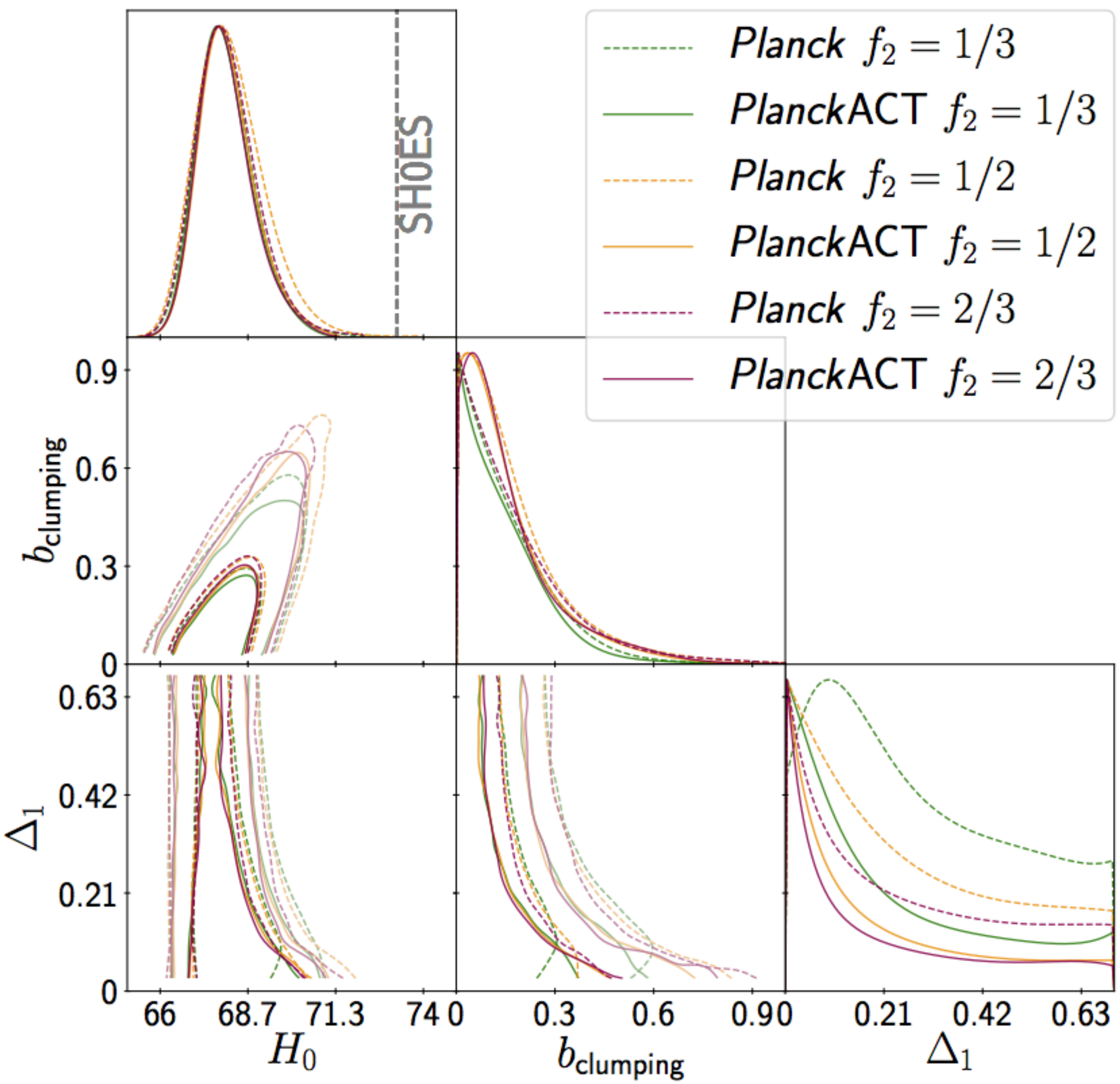
Results persist even in broadened parameter space (more freedom in the small-scale baryon PDF)



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 ΛCDM — 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 (although see Lee & Ali-Haimoud 2021)

Thiele, Guan, **JCH**, Kosowsky, Spergel (2021); see also Galli et al. (2021)

SI Neutrinos

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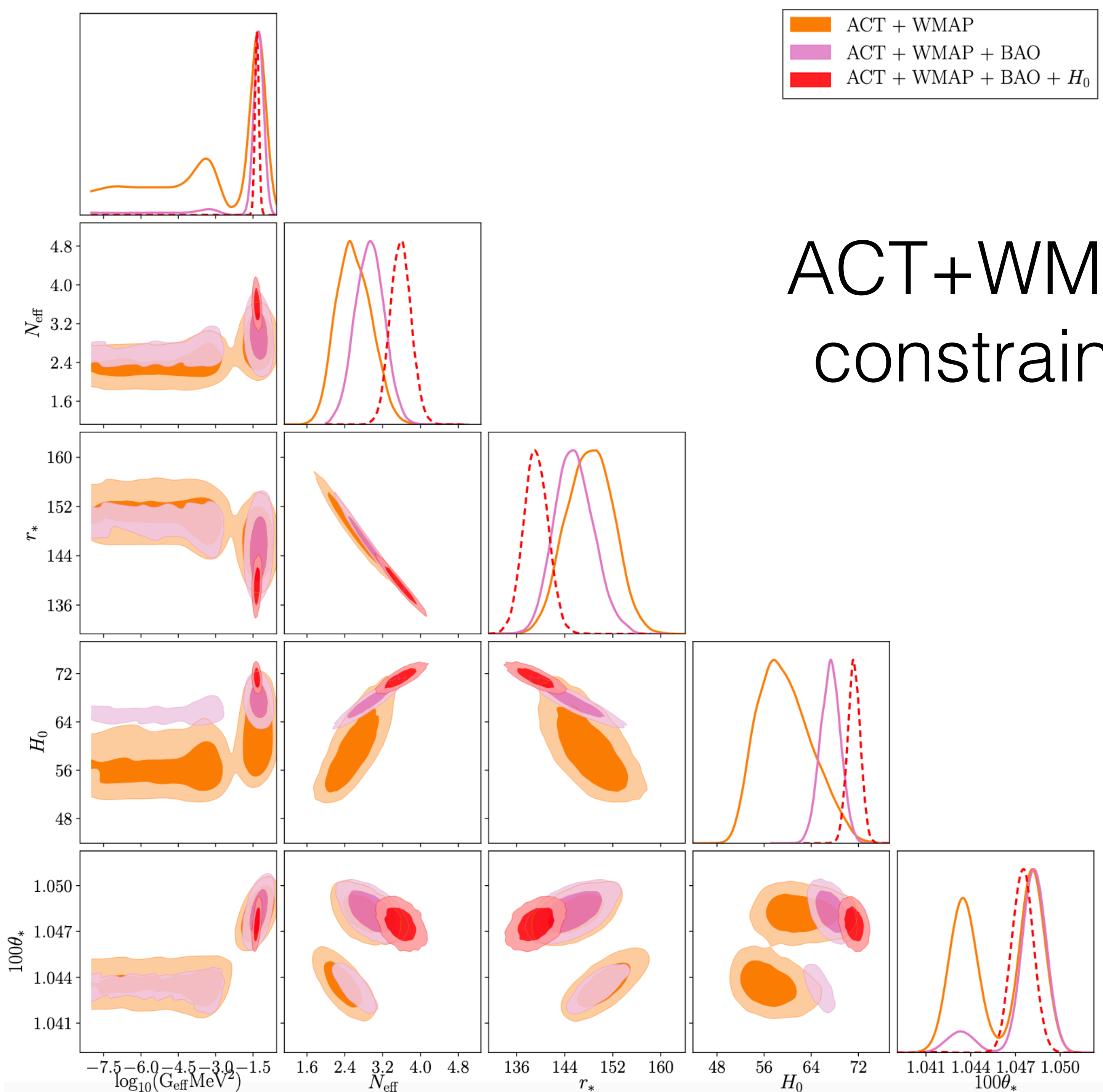
Idea: delay onset of neutrino free-streaming until z ~ z*

$$\dot{\tau}_\nu = -aG_{\rm eff}^2 T_\nu^5 \qquad g_\nu(\tau) \equiv -\dot{\tau}_\nu e^{-\tau_\nu}$$



ACT+WMAP constraints

Kreisch+ (2022); see also earlier work from Kreisch, Cyr-Racine, Dore, Sigurdson, ++

SI Neutrinos

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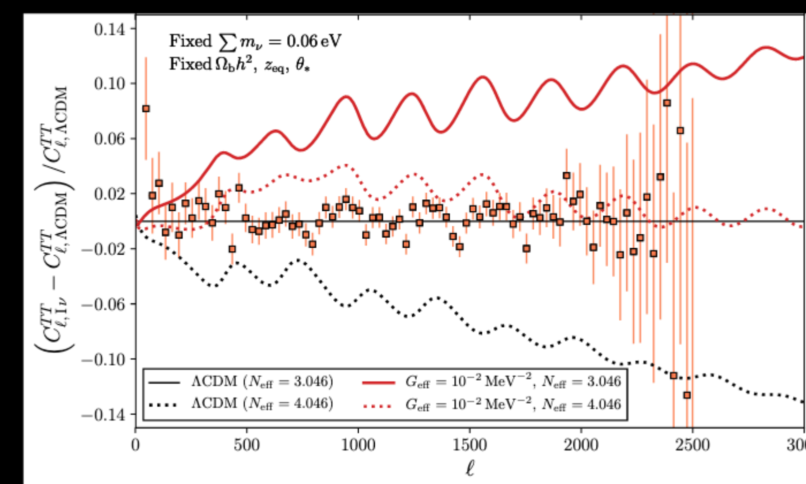
Why does this model work?

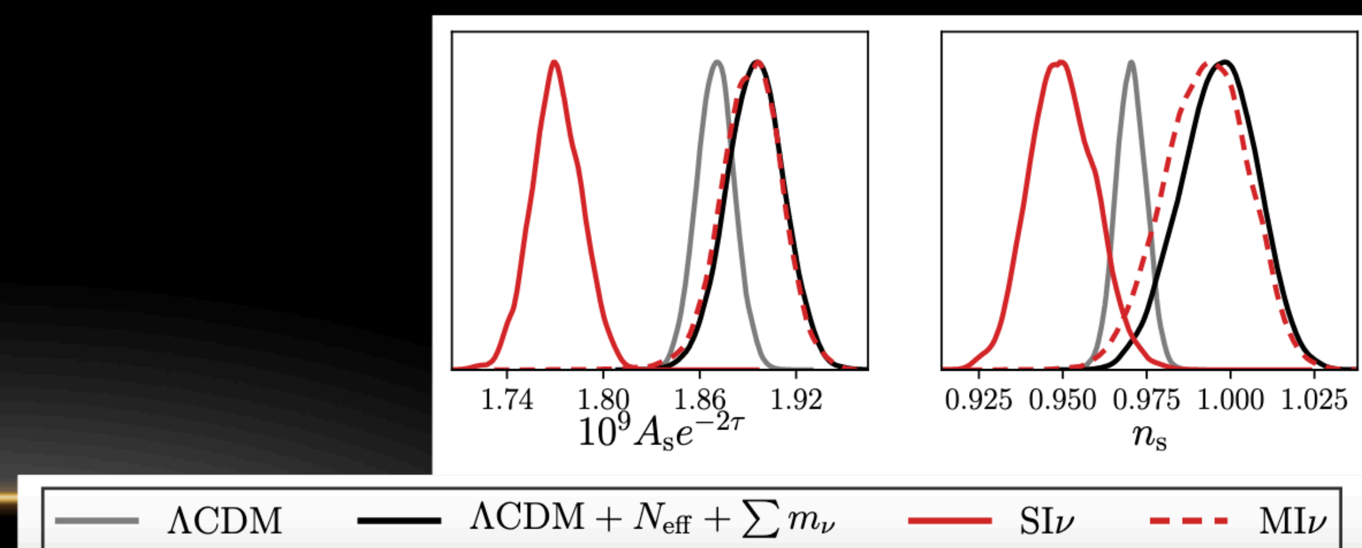
- $N_{\rm eff}$ increases Hubble at early times, hence reducing the sound horizon.

$$r_{\rm s} = \int_0^{a_{\rm d}} da \frac{c_{\rm s}(a)}{a^2 H(a)}$$

- The tightly-coupled neutrinos do not over damp or phase shift the photon-baryon fluctuations.



- Changes in the primordial spectrum of fluctuations (n_s, A_s) absorbs the remainder of the changes.



Slide credit: Francis-Yan Cyr-Racine

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Generalized Dark Matter —> Dark Radiation Conversion

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

F. McCarthy & JCH (2022)

DM —> DR

Colin Hill
Columbia

Analytic ansatz for evolution of 'decaying' dark matter (DDM) density:

$$\rho_\chi(a) = \frac{\rho_\chi^0}{a^3}\left[1 + \zeta \frac{1 - a^\kappa}{1 + (a/a_t)^\kappa}\right]$$

- Assumption: DDM —> massless dark radiation

$$\rho_\phi(a) = \zeta \frac{\rho_\chi^0}{a^3} \frac{(1 + a_t^\kappa)}{(a^\kappa + a_t^\kappa)} \times \left((a^\kappa + a_t^\kappa)\ {}_2F_1\left[1, \frac{1}{\kappa}; 1 + \frac{1}{\kappa}; -\left(\frac{a}{a_t}\right)^\kappa\right] - a_t^\kappa \right)$$

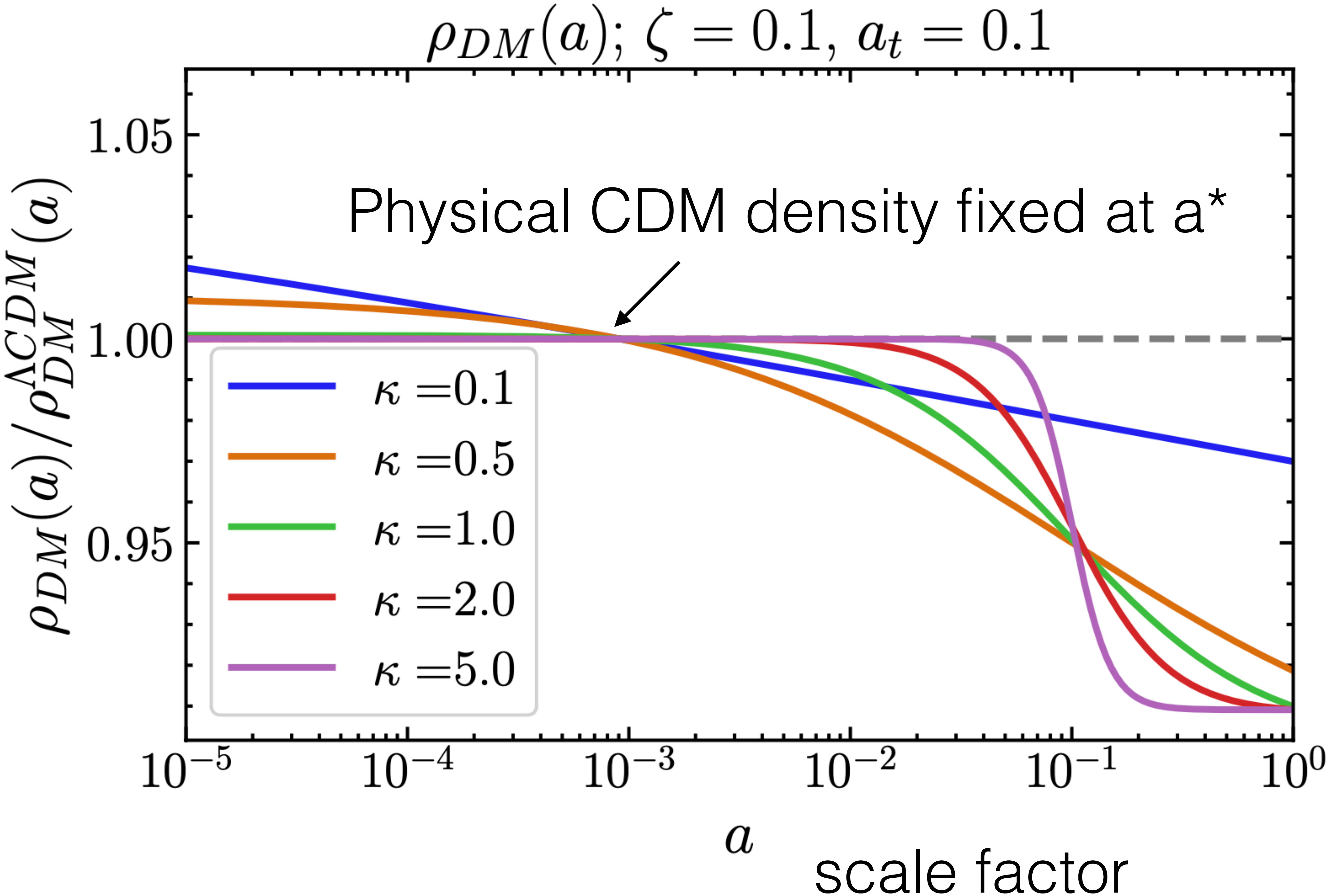
- Comoving DM density decreases by a factor of (1+ζ)
- Transition is centered at $a = a_t$
  - e.g., for $a_t << 10^{-3}$, effects of this model are similar to N_{eff}
- κ determines the rate of the transition
  - e.g., κ=2 —> standard exponential decay with Γ ~ H(a_t)
  - e.g., κ=1 —> Sommerfeld-enhanced annihilation

Bringmann+ (2018)

DM —> DR

Colin Hill
Columbia

Analytic ansatz for DDM density



Bringmann+ (2018); McCarthy & JCH (2022)

DM —> DR

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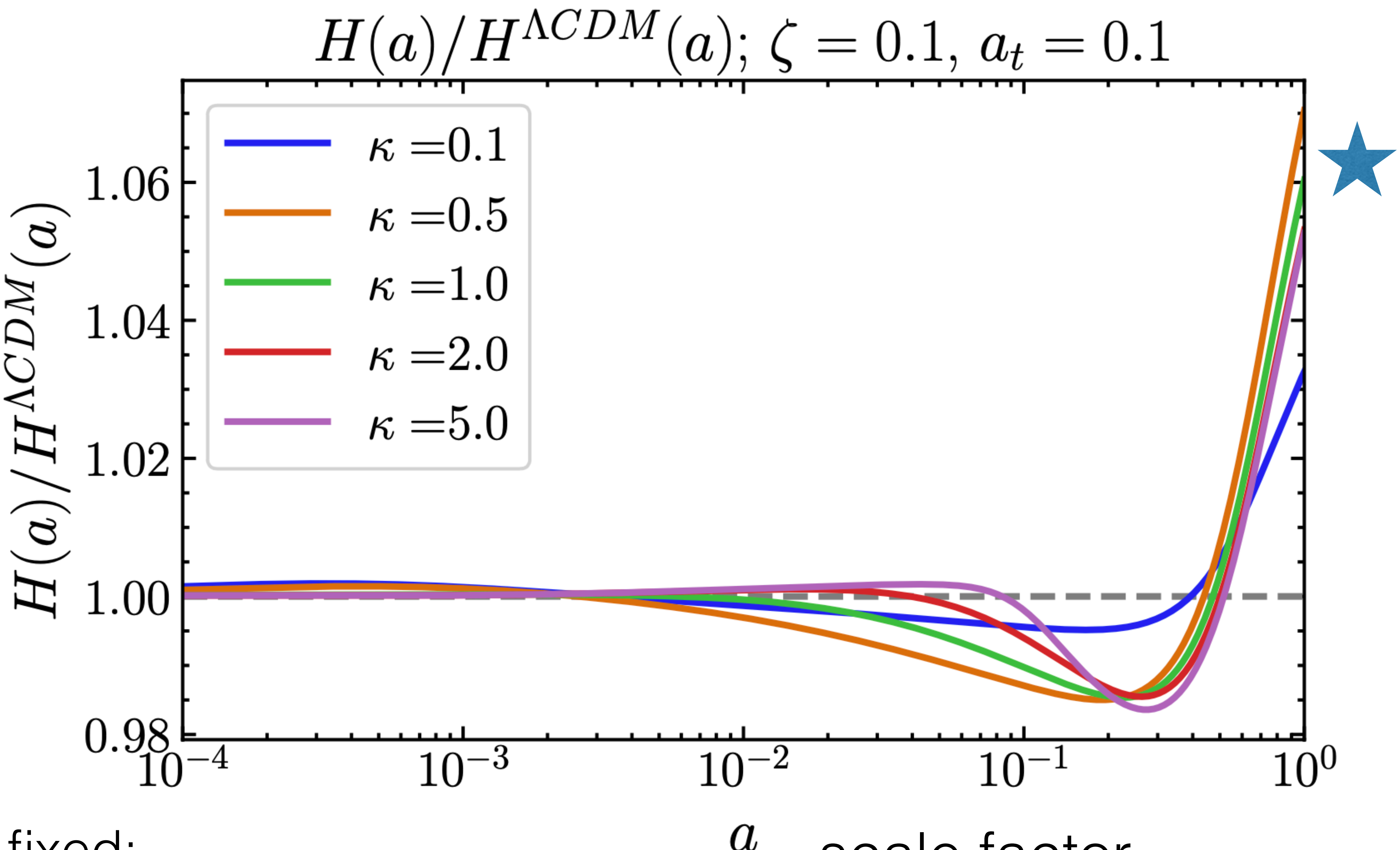
Evolution of Hubble parameter



scale factor

Held fixed:
ω_b, θ^*, A_s, n_s, $\omega_c(z^*)$

Bringmann+ (2018); McCarthy & JCH (2022)

how? z_Λ increases

DM —> DR

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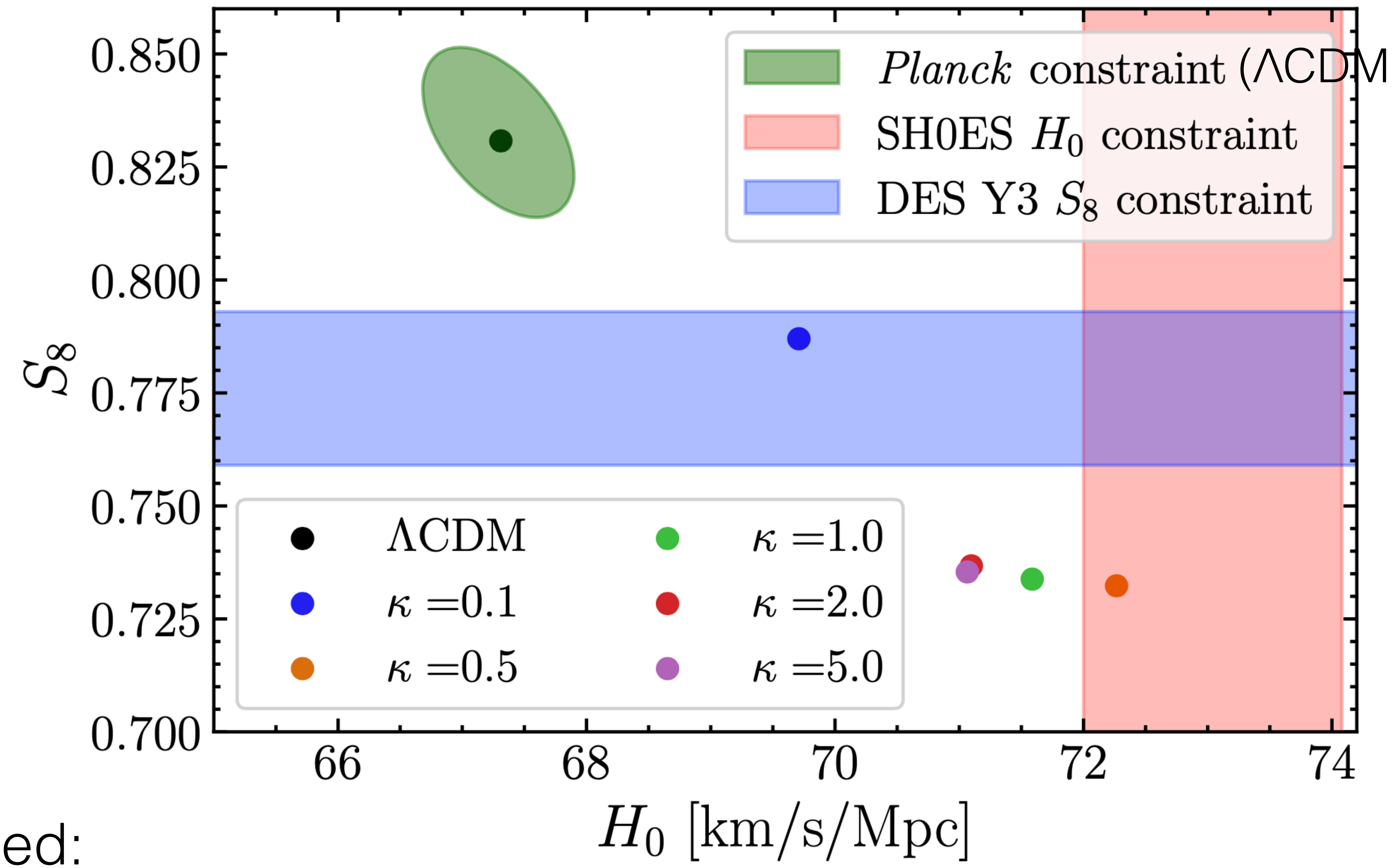
Motivation: such scenarios (can) naturally move both H_0 and S_8 in the "right direction"



Held fixed:
ω_b, θ^*, A_s, n_s, $\omega_c(z^*)$

Bringmann+ (2018); McCarthy & JCH (2022); see also Chen et al. (2021) [DES Collaboration]

DM —> DR

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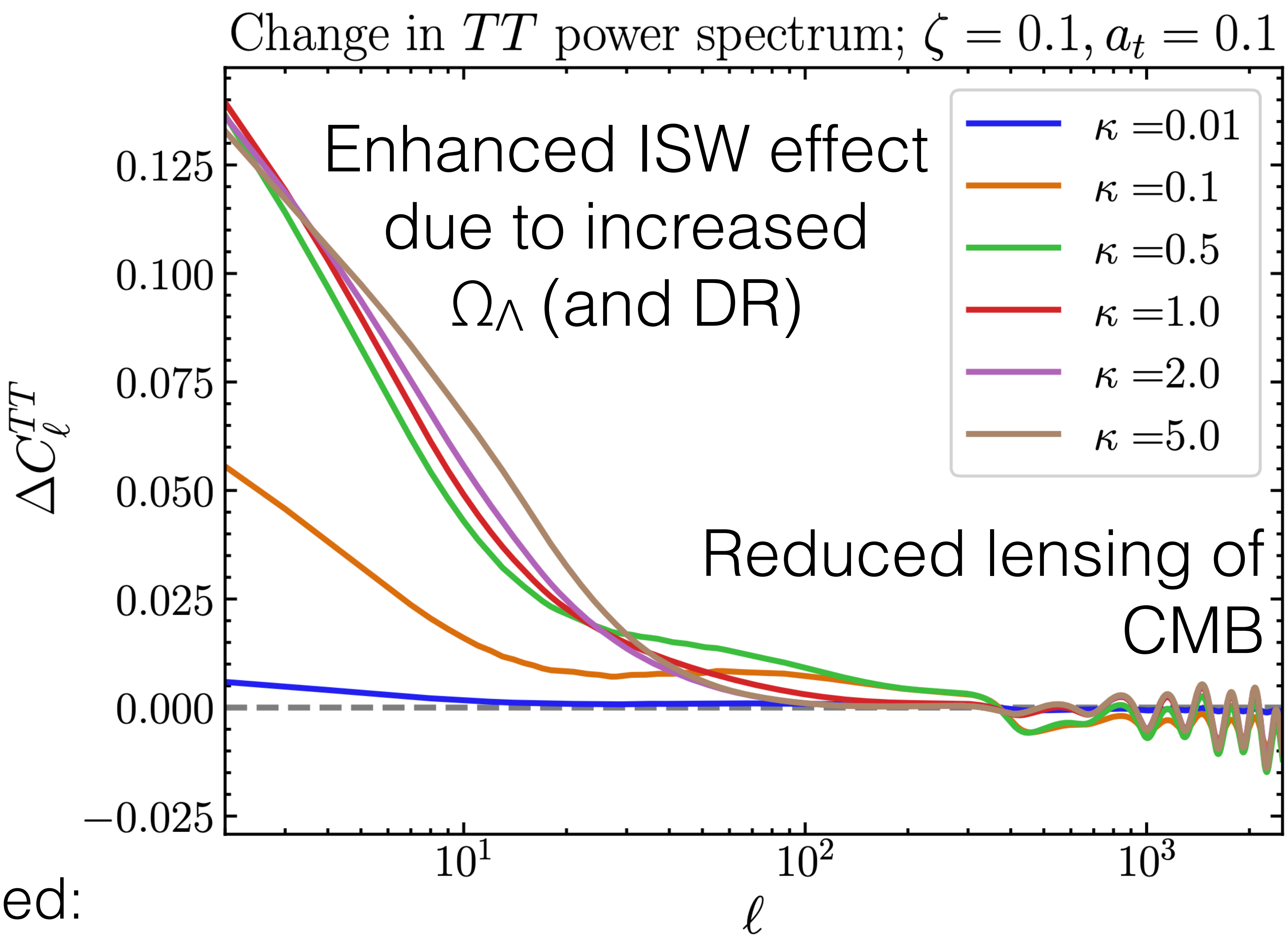
Observables: TT power spectrum



Held fixed:
ω_b, θ^*, A_s, n_s, $\omega_c(z^*)$

Bringmann+ (2018); McCarthy & JCH (2022)

DM —> DR: Results

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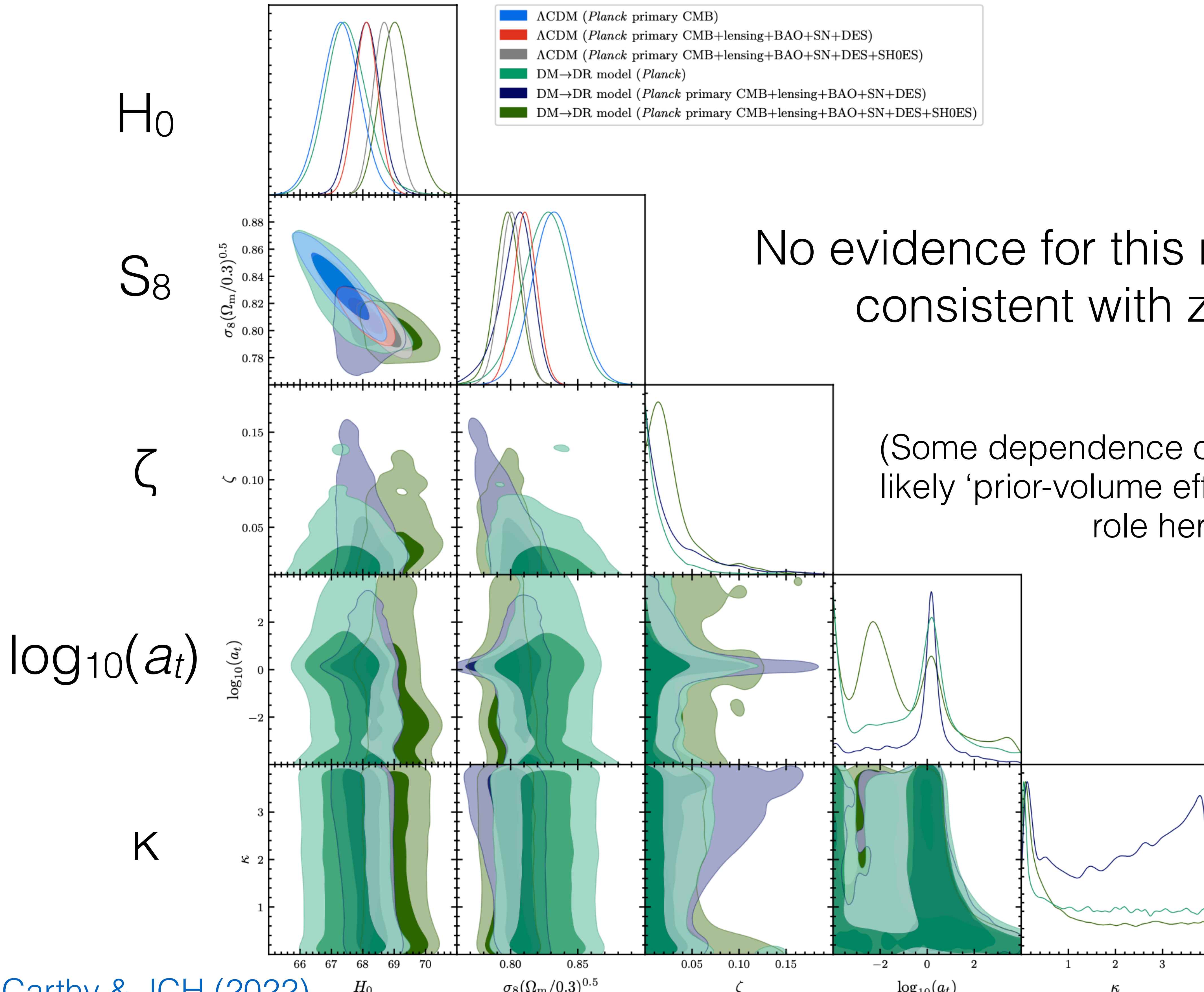

No evidence for this model: ζ consistent with zero

(Some dependence on prior choices; likely 'prior-volume effects' play some role here)

McCarthy & JCH (2022)

DM —> DR

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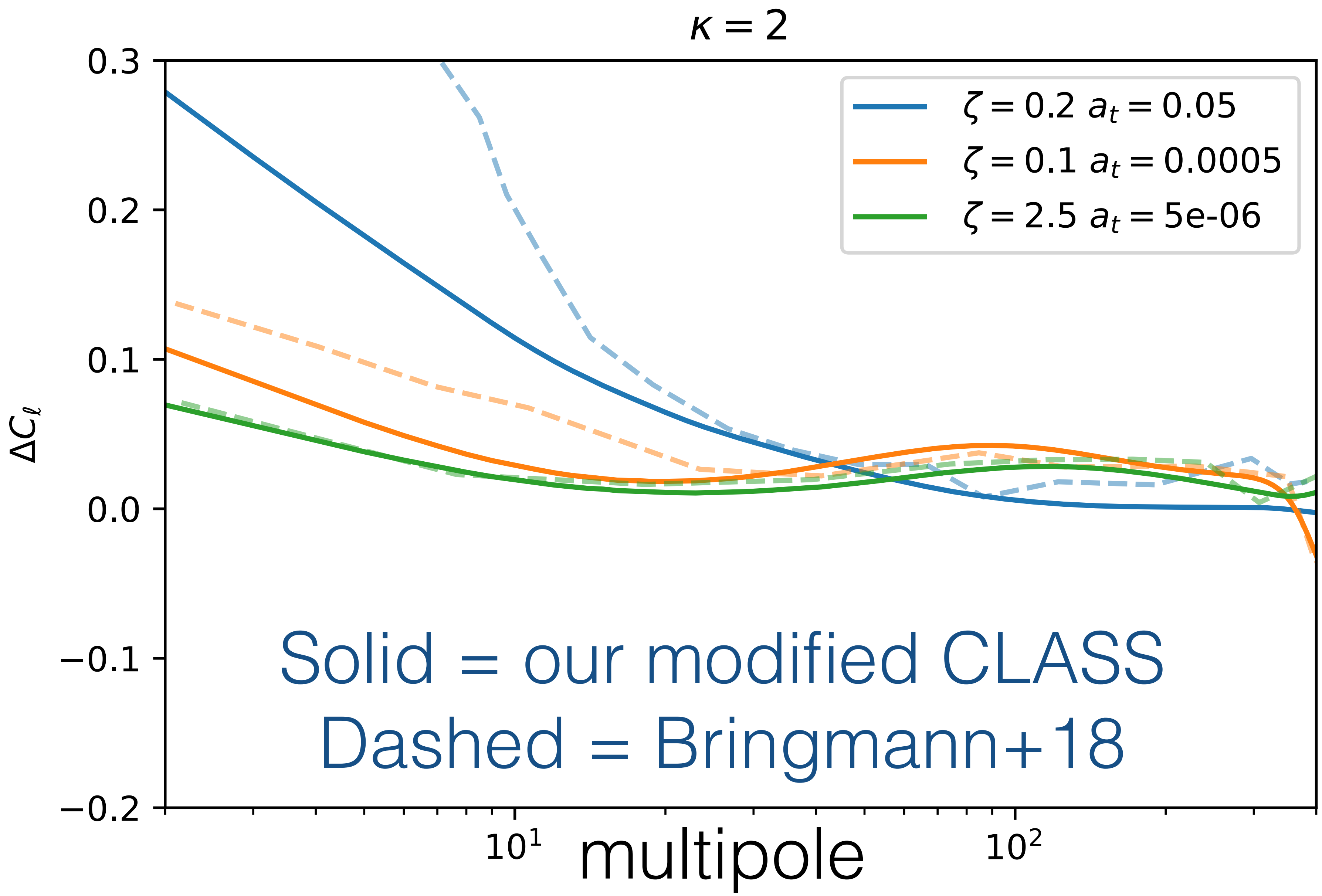
Earlier work (Bringmann+18) found ~2σ hint for this model in Planck15: what changed?
Diffs. in theory calc. (Boltzmann hierarchy for the DR decay products) + datasets/priors



A couple of bugs also found in code used in Chen+21 via cross-check; we have now iterated with A. Chen and D. Huterer and have two independent codes (modified CLASS and modified CAMB) that agree very well

Bringmann+ (2018); McCarthy & JCH (2022); see also Chen et al. (2021) [DES Collaboration]

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DM —> DR

Takeaways

- Fit to Planck TTTEEEκκ + BAO + Pantheon + SH0ES + DES-Y3:
  H_0 = 69.1 +/- 0.5 km/s/Mpc
  S_8 = 0.799 +/- 0.009
  however
  Planck CMB χ^2 is significantly worse than a fit of ΛCDM to Planck ($\Delta\chi^2 \sim +15$)

- Why? Excess ISW signal in low-ell TT and reduced lensing

- Even this very general DM—>DR model lacks sufficient flexibility to accommodate late-time H_0 and S_8 while maintaining good fit to Planck

McCarthy & JCH (2022)

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Columbia

Did the Universe (Slightly) Reheat after Recombination?

Linear perturbation theory

$$\delta'_{\rm DCDM} = -\theta_{\rm DCDM} - m_{\rm cont} - a\Gamma m_\psi \quad (3)$$

$$\theta'_{\rm DCDM} = -\frac{a'}{a}\theta_{\rm DCDM} + k^2 m_\psi \quad (4)$$

$$\delta'_\gamma = -\frac{4}{3}\theta_\gamma - \frac{4}{3}m_{\rm cont} + a\Gamma\frac{\rho_{\rm DCDM}}{\rho_\gamma}\left(\delta_{\rm DCDM} - \delta_\gamma + m_\psi\right) \quad (5)$$

$$\theta'_\gamma = k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) + k^2 m_\psi + a n_e \sigma_{\rm T}\left(\theta_b - \theta_\gamma\right) - \frac{3}{4}a\Gamma\frac{\rho_{\rm DCDM}}{\rho_\gamma}\left(\frac{4}{3}\theta_\gamma - \theta_{\rm DCDM}\right) \quad (6)$$

$$F'_{\gamma,2} = 2\sigma'_\gamma = \frac{8}{15}\theta_\gamma - \frac{3k}{5}F_{\gamma,3} + \frac{8}{15}m_{\rm shear} - \frac{9}{5}a n_e \sigma_{\rm T}\sigma_\gamma + \frac{1}{10}a n_e \sigma_{\rm T}\left(G_{\gamma,0} + G_{\gamma,2}\right) - 2\sigma_\gamma a\Gamma\frac{\rho_{\rm DCDM}}{\rho_\gamma} \quad (7)$$

$$F'_{\gamma,\ell} = \frac{k}{2\ell+1}\left[\ell F_{\gamma,\ell-1} - (\ell+1)F_{\gamma,\ell+1}\right] - a\Gamma F_{\gamma,\ell}\frac{\rho_{\rm DCDM}}{\rho_\gamma} \quad (8)$$

All terms containing Γ in photon perturbation equations are new

Gauge	Synchronous	Newtonian
$m_{\rm cont}$	$h'/2$	$-3\phi'$
m_ψ	0	ψ
$m_{\rm shear}$	$(h' + 6\eta')/2$	0

JCH & B. Bolliet (2023)

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Did the Universe (Slightly) Reheat after Recombination?

"Hat" variables: all cosmological quantities at a given TCMB depend on quantities proportional to baryon-to-photon and dark matter-to-photon number ratios

$$
\begin{aligned}
\hat{\omega}_{\rm b} &\equiv \omega_{\rm b} \left(\frac{T_{\rm CMB,ini}}{T_{\rm FIRAS}}\right)^{-3} \\
\hat{\omega}_{\rm c} &\equiv \omega_{\rm c} \left(\frac{T_{\rm CMB,ini}}{T_{\rm FIRAS}}\right)^{-3} \\
\hat{\omega}_{\rm DCDM,ini} &\equiv \omega_{\rm DCDM,ini} \left(\frac{T_{\rm CMB,ini}}{T_{\rm FIRAS}}\right)^{-3} \\
\hat{A}_{\rm s} &\equiv A_{\rm s} \left(\frac{T_{\rm CMB,ini}}{T_{\rm FIRAS}}\right)^{n_{\rm s}-1} .
\end{aligned}
$$

BBN abundances depend only on $\hat{\omega}_{\rm b}$
Consistency of this parameter with Planck thus maintains (approximate) consistency with BBN [modulo varying Neff, etc.]

Ivanov+ (2020); JCH & Bolliet (2023)

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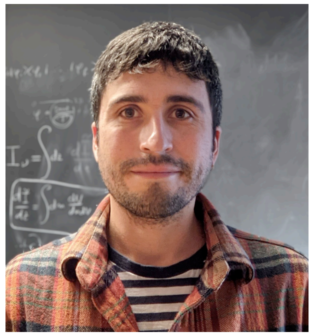
Einstein-Boltzmann Emulators




Bolliet, Spurio Mancini, JCH, Madhavacheril, et al. (2023)

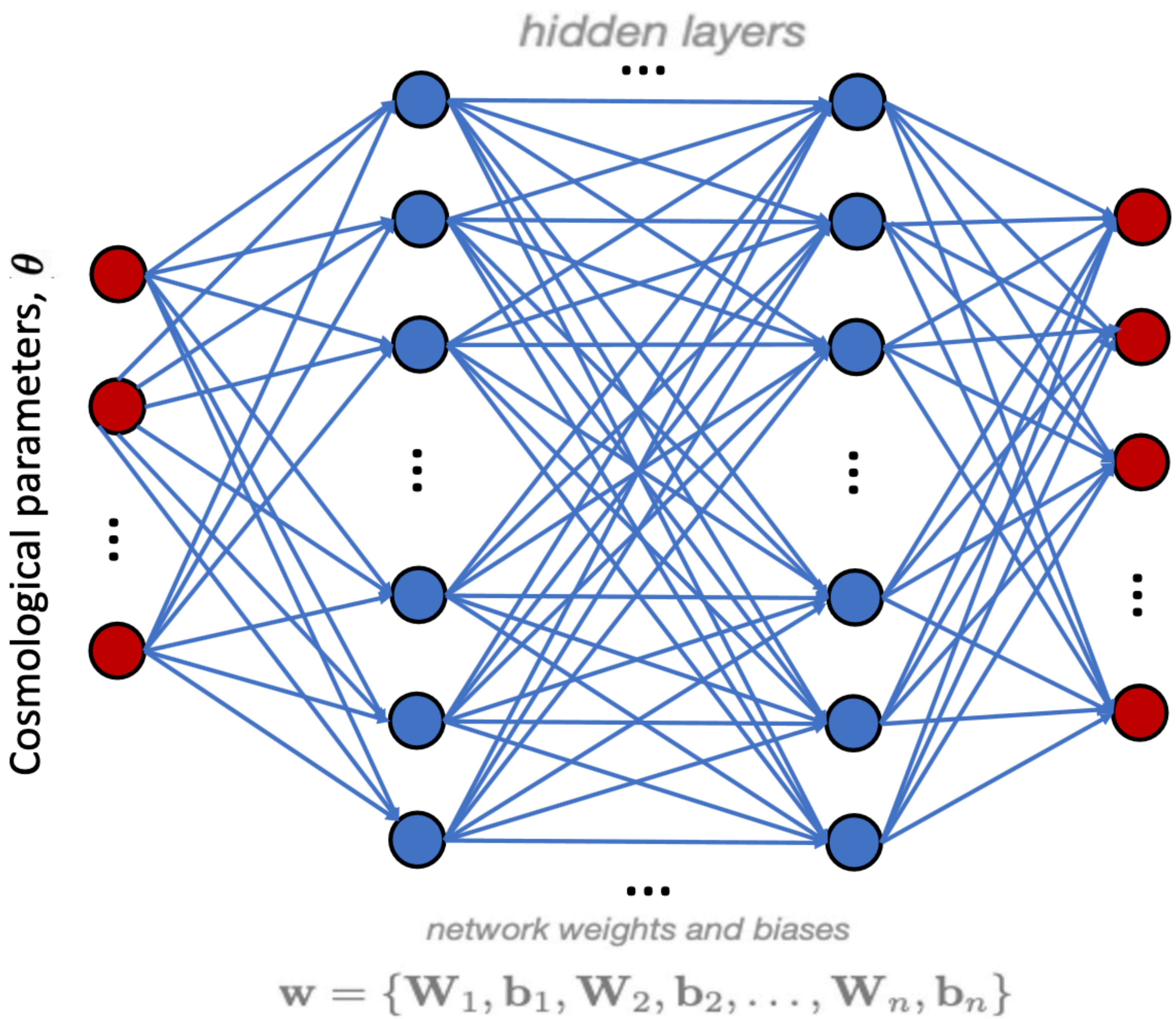
CosmoPower

Colin Hill
Columbia

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

input

ω_b
ω_c
θ_s
A_s
n_s
τ



output

C_l^{TT}
C_l^{TE}
C_l^{EE}
$P(k)$
$H(z)$
…

Spurio Mancini et al. (2022)

Theoretical Accuracy

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Columbia/CCA

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

Theoretical Accuracy

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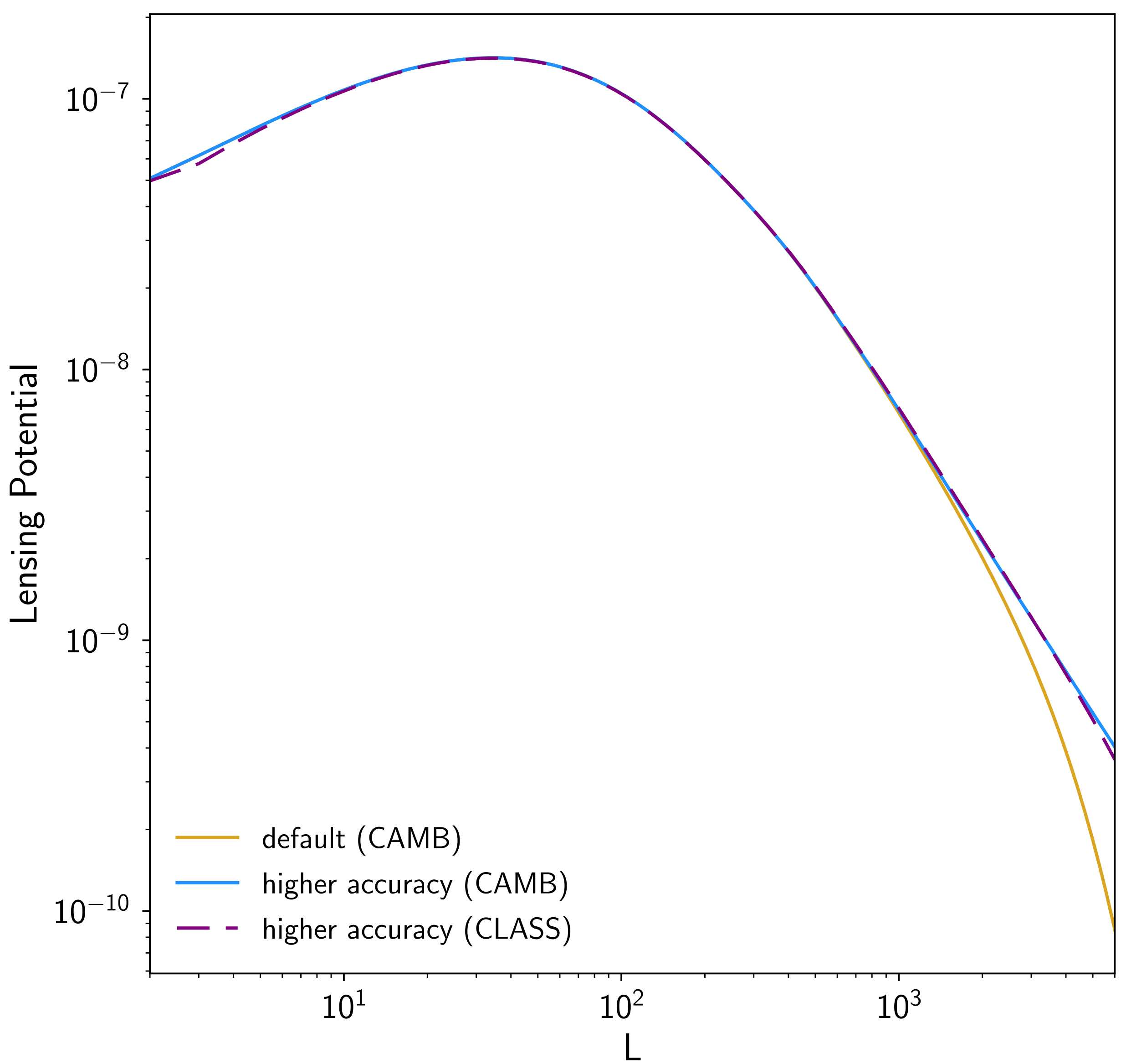

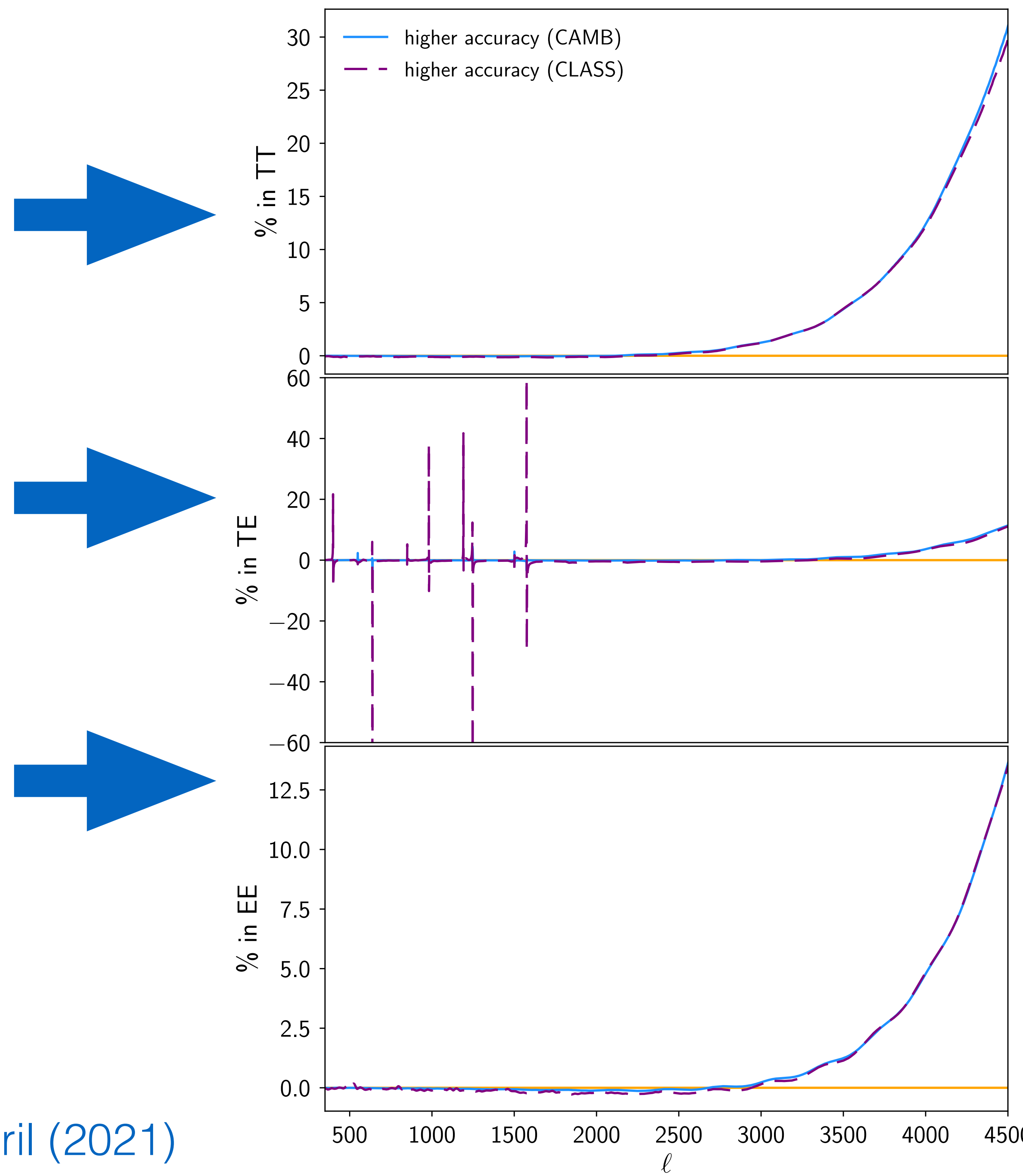

JCH et al. (2021); McCarthy, JCH, Madhavacheril (2021)

Theoretical Accuracy

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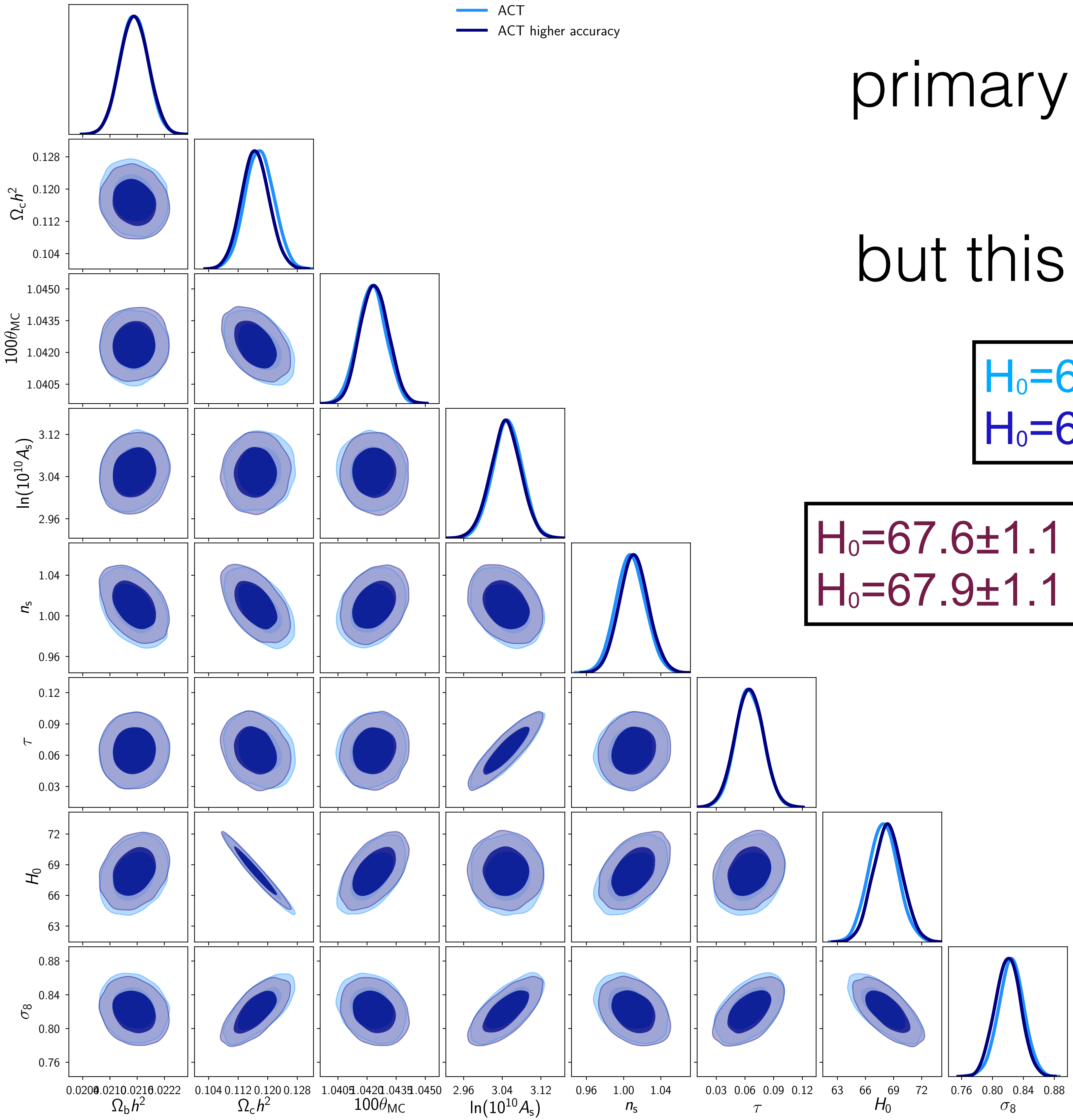
For ACT DR4, this correction shifts some parameters by ~0.2-0.3σ



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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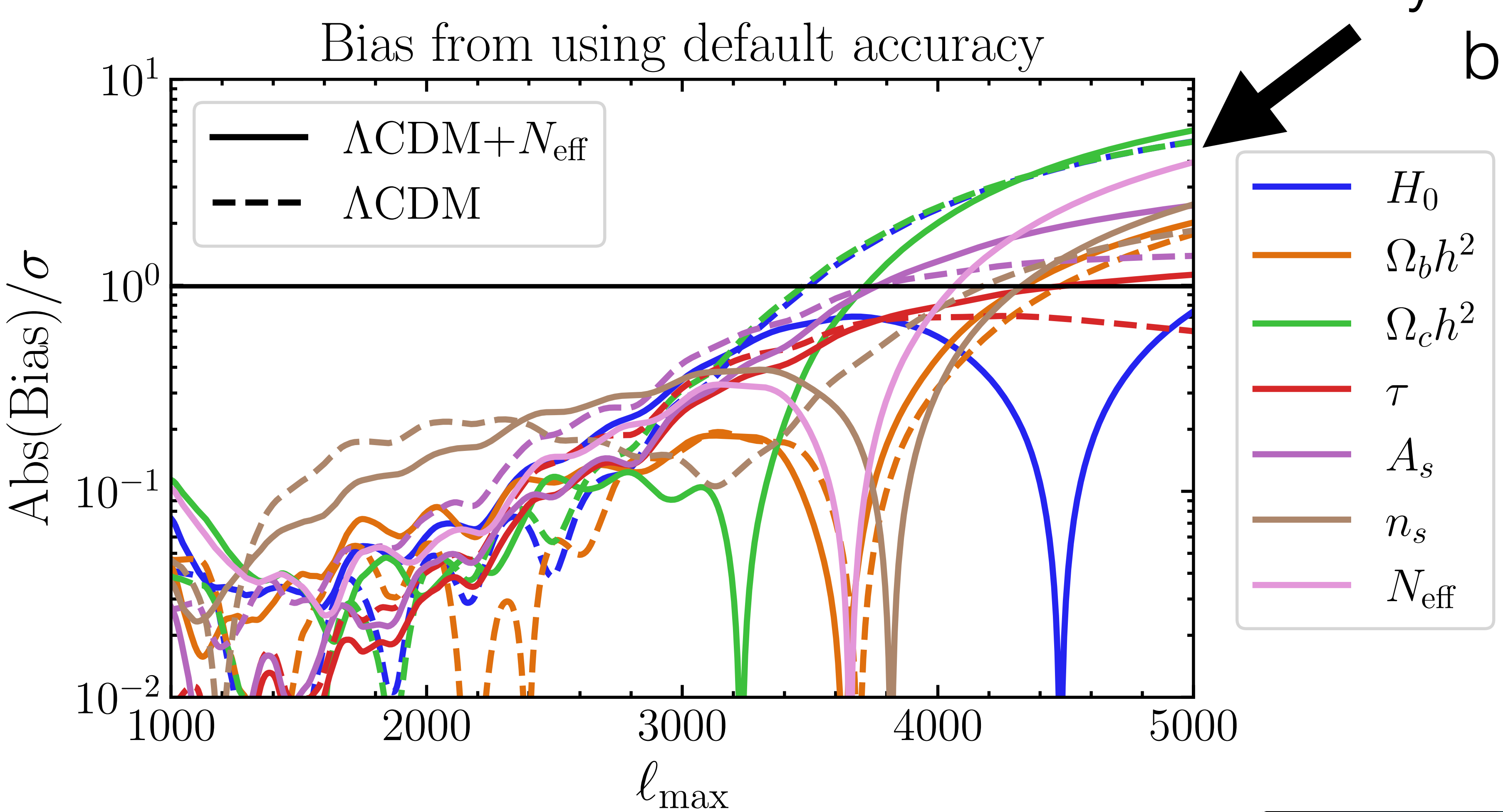
Columbia/CCA

Boltzmann Accuracy

For upcoming experiments, the bias can be very large! Easy to fix: just run CAMB/CLASS with high-accuracy settings (and test them)



very significant bias!

Related: baryonic feedback corrections to CMB lensing also become important in this context

McCarthy, JCH, Madhavacheril (2021): arXiv:2103.05582

CosmoPower++

Colin Hill
Columbia

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. (2023)

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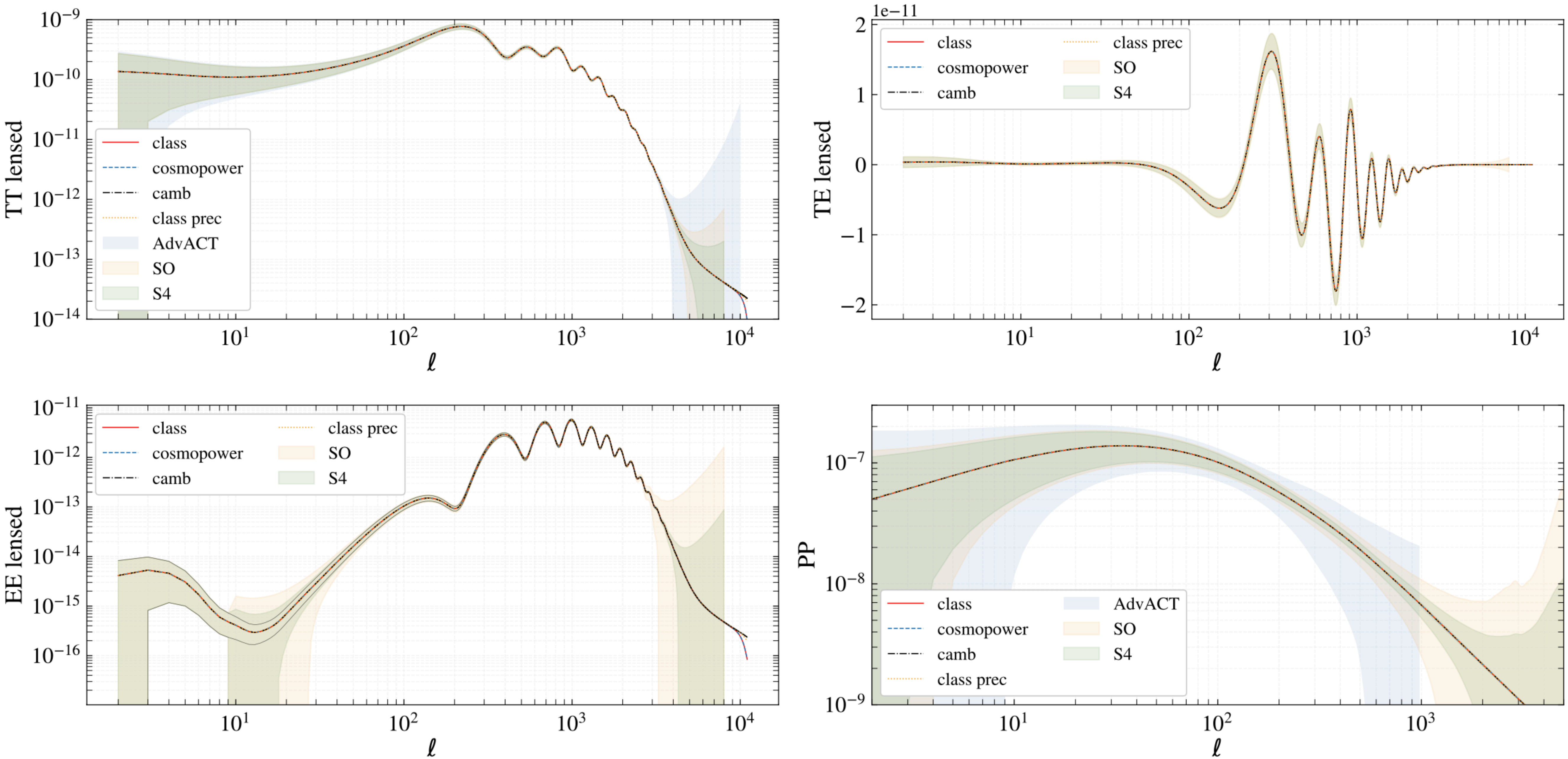
CosmoPower++

It works :-)



Bolliet, Spurio Mancini, JCH, Madhavacheril, et al. (2023)

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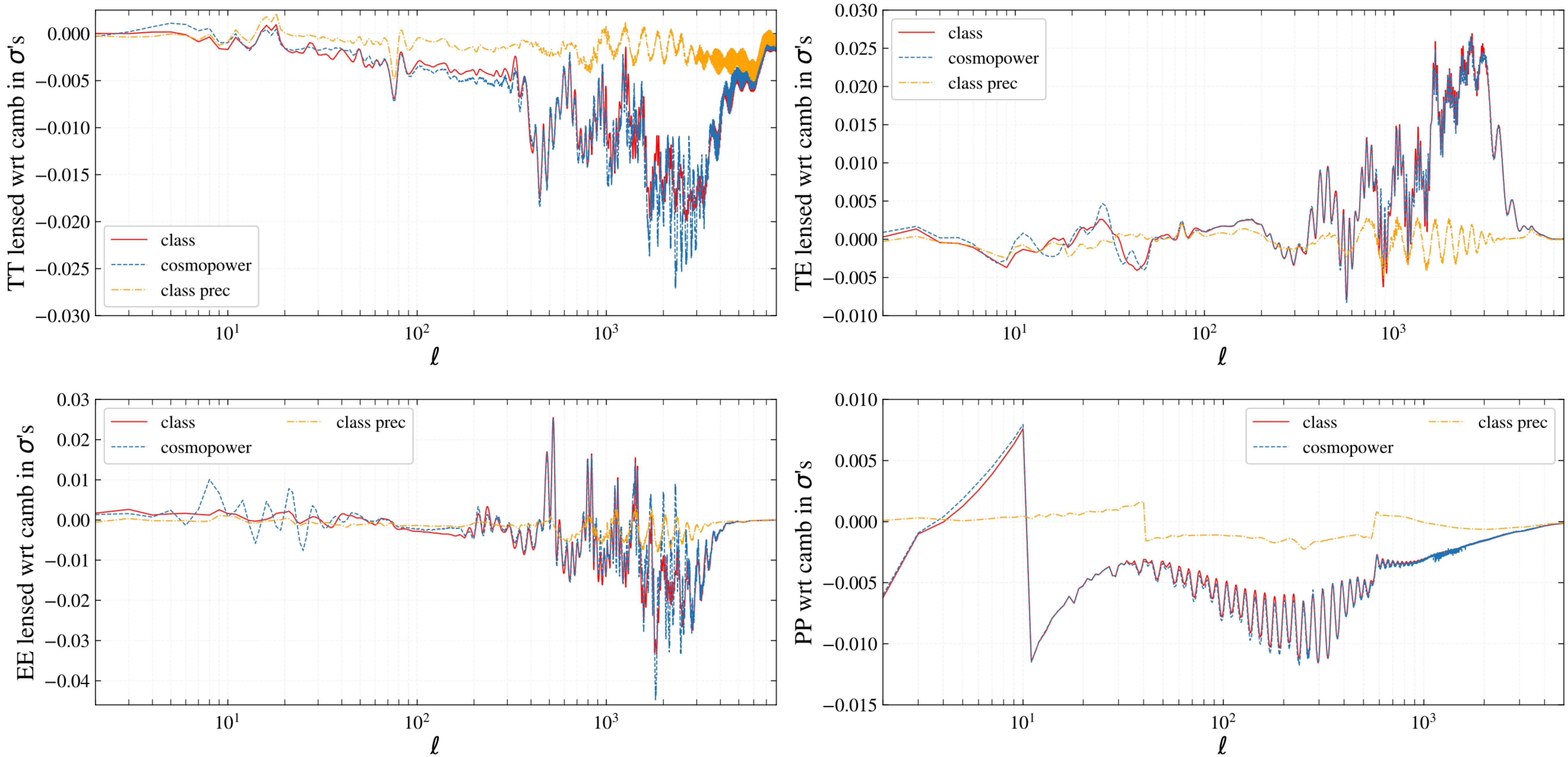
Assess accuracy in terms of forecast CMB-S4 error bars: < 0.05σ!



Bolliet, Spurio Mancini, JCH, Madhavacheril, et al. (2023)

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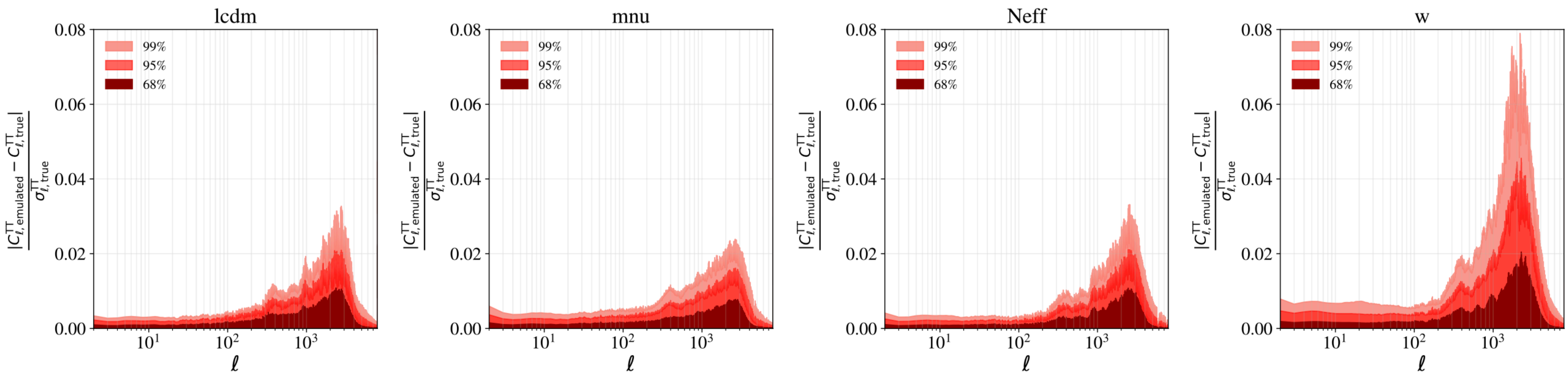
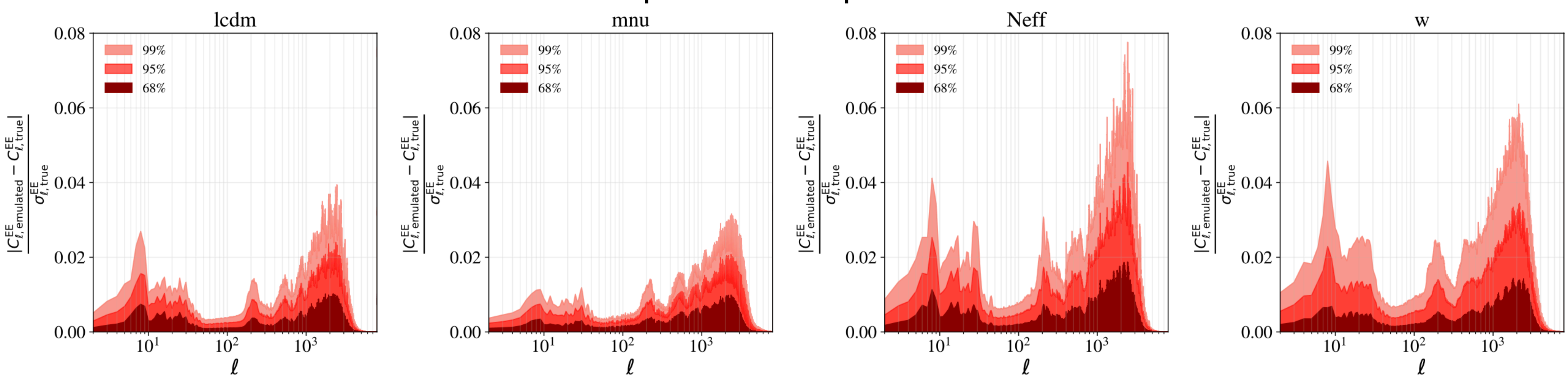
Validation on Test Set

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. (2023)

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ACT DR4 Reproduction

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

ACT DR4 Reproduction

Colin Hill
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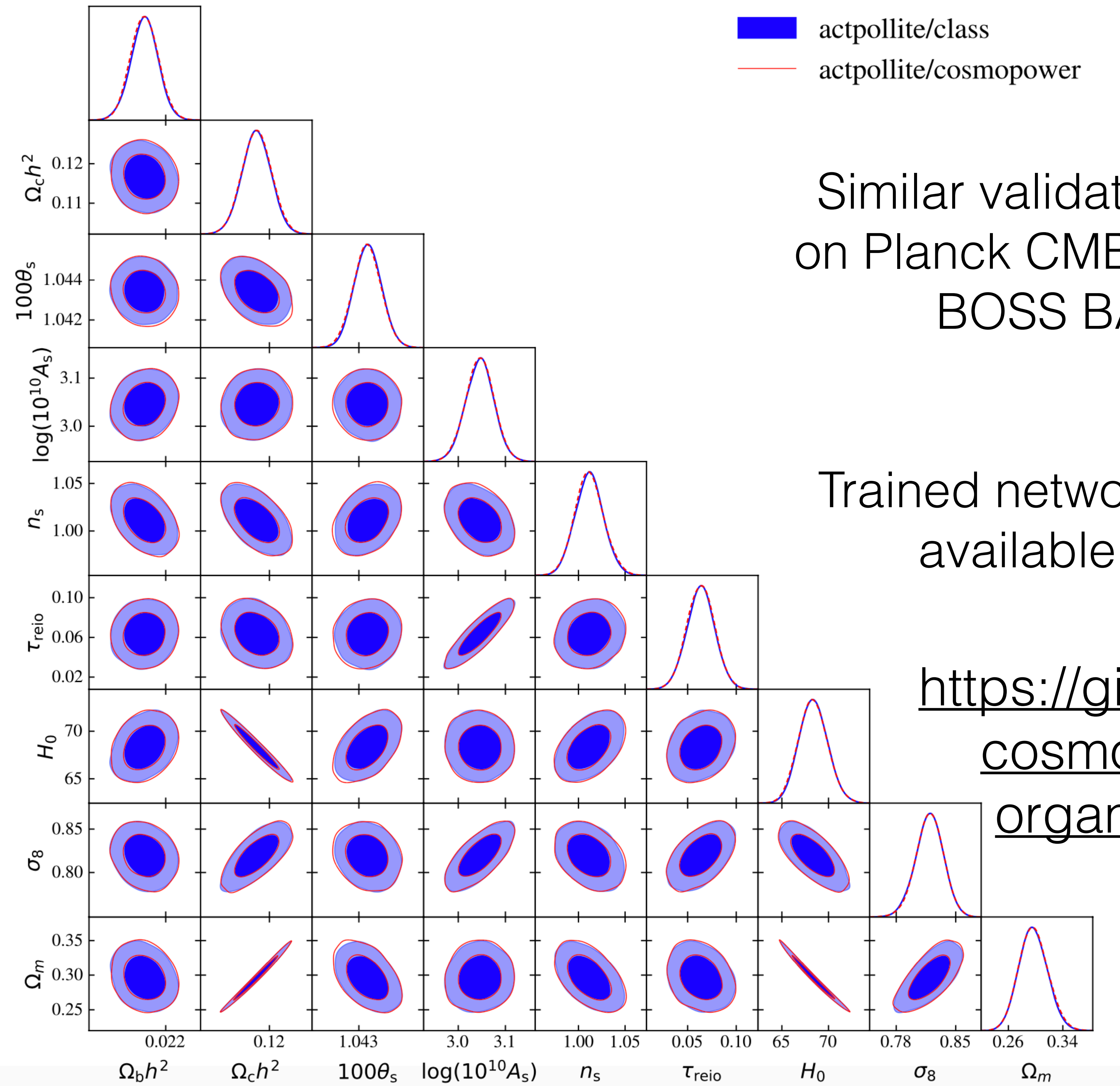

Similar validation performed on Planck CMB, CMB lensing, BOSS BAO+RSD

Trained networks are publicly available via GitHub

https://github.com/cosmopower-organization

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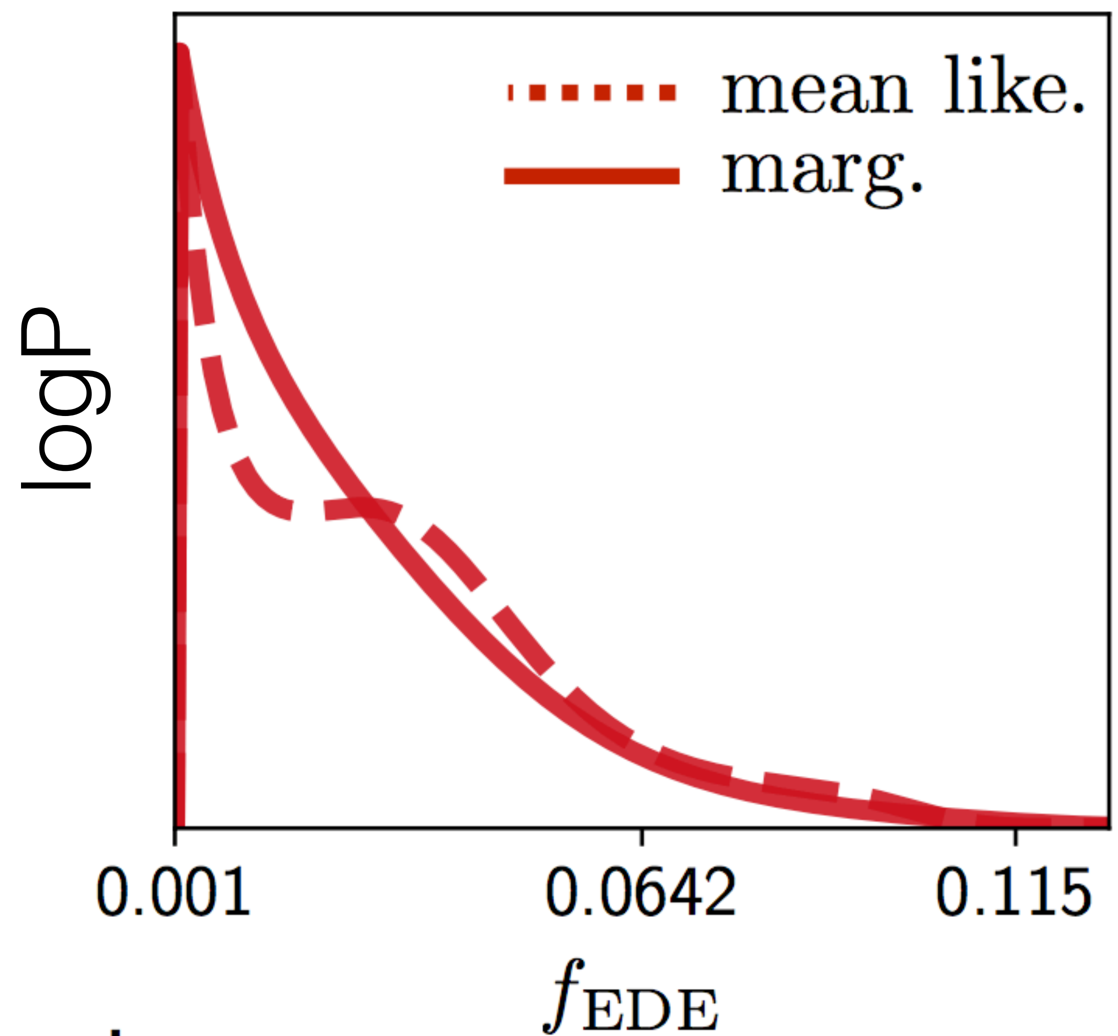
Columbia

Prior Volume Effects?

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



FS+Planck only

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

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

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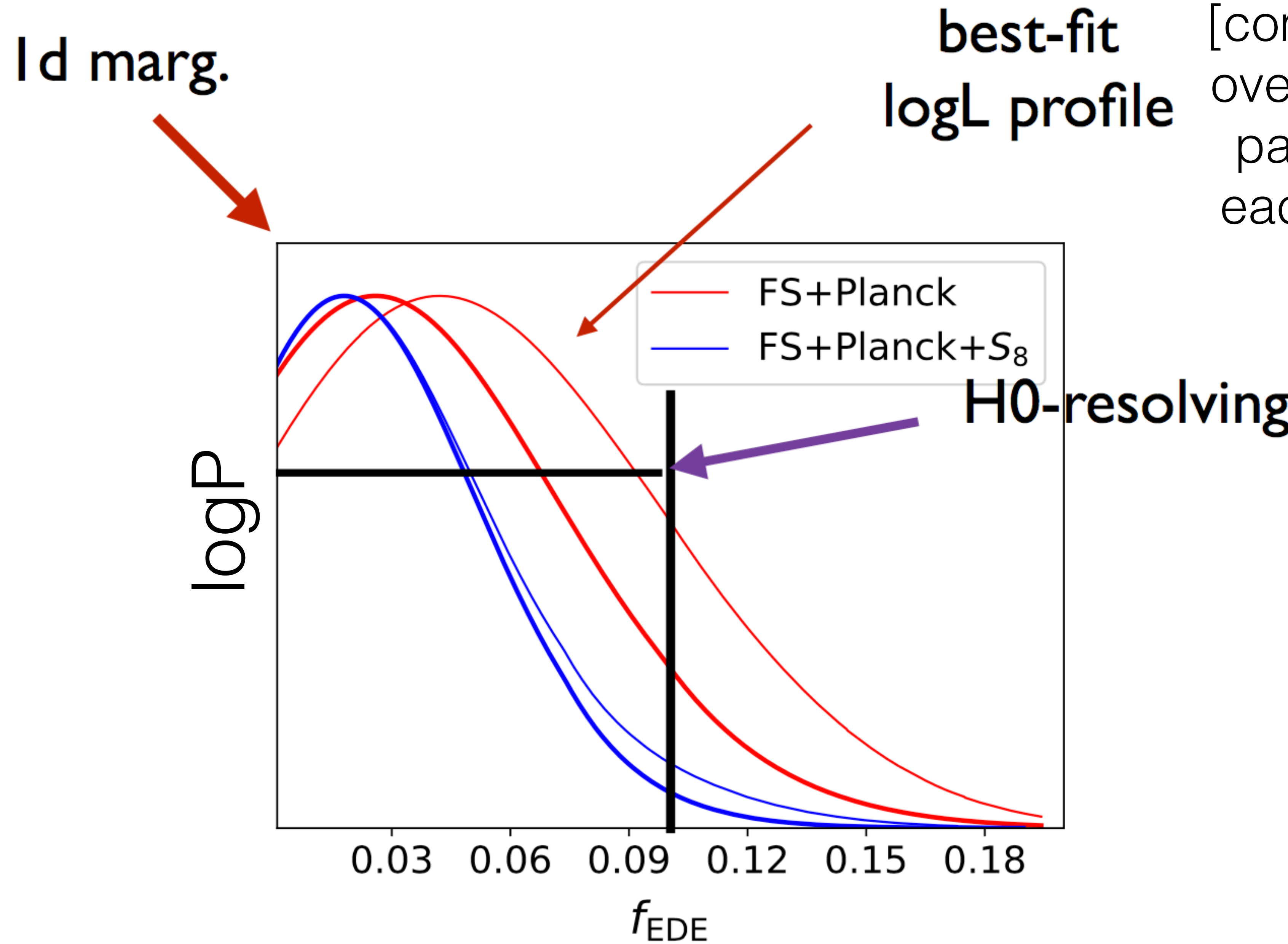
Prior Volume Effects?

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



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

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

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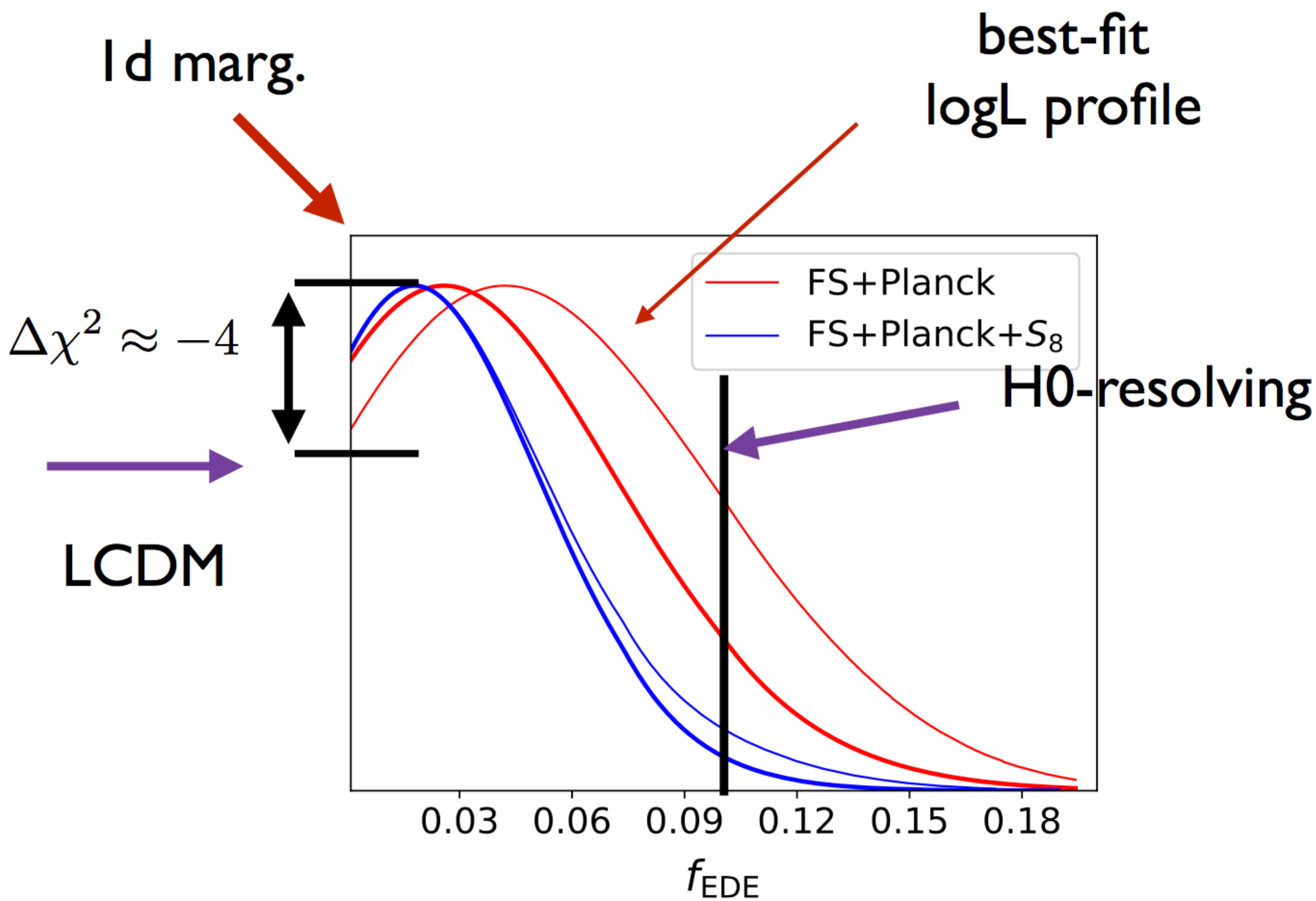
Columbia

Prior Volume Effects?

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



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