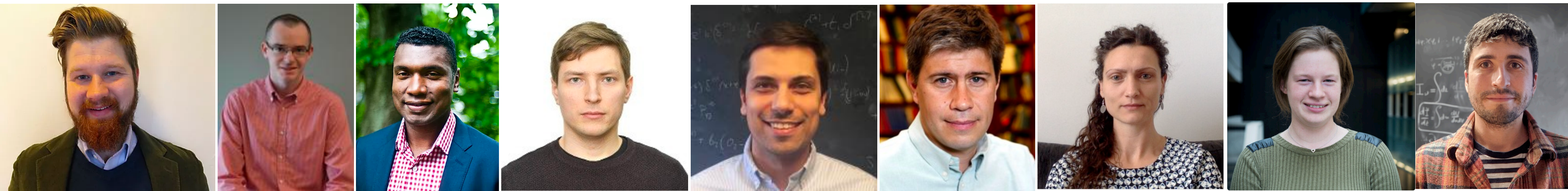
Toward Cosmological Concordance with New Physics in the Dark Sector

Colin Hill
Columbia University
Flatiron Institute - Center for Computational Astrophysics

“Tensions in Cosmology” @ Corfu
8 September 2022

2003.07355 w/ E. McDonough, M. Toomey, S. Alexander
2006.11235 w/ EM,MT,SA + M. Ivanov, M. Simonovic, M. Zaldarriaga
2109.04451 w/ ACT Collaboration
2112.09128 w/ EM, W. Hu, M.-X. Lin, S. Zhou + work in prep.
2112.10754 w/ A. La Posta, T. Louis, X. Garrido
to appear w/ F. McCarthy + to appear with B. Bolliet



Outline

- Early Dark Energy: ACT DR4 (+SPT-3G)
- —>Early Dark Sector
- Post-Recombination Reheating
- ~~Generalized Dark Matter —> Dark Radiation Conversion~~

Colin Hill
Columbia/CCA

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

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

scale
factor

sound
speed

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

Colin Hill
Columbia/CCA

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

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

Relevant ingredients in 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:

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

$D_A \sim 1/H_0$

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

Early Dark Energy

Colin Hill
Columbia/CCA

Motivation: increase CMB-inferred H_0

How does this work?

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

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

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)

Colin Hill
Columbia/CCA

Early Dark Energy

New component: (pseudo)-scalar field ϕ

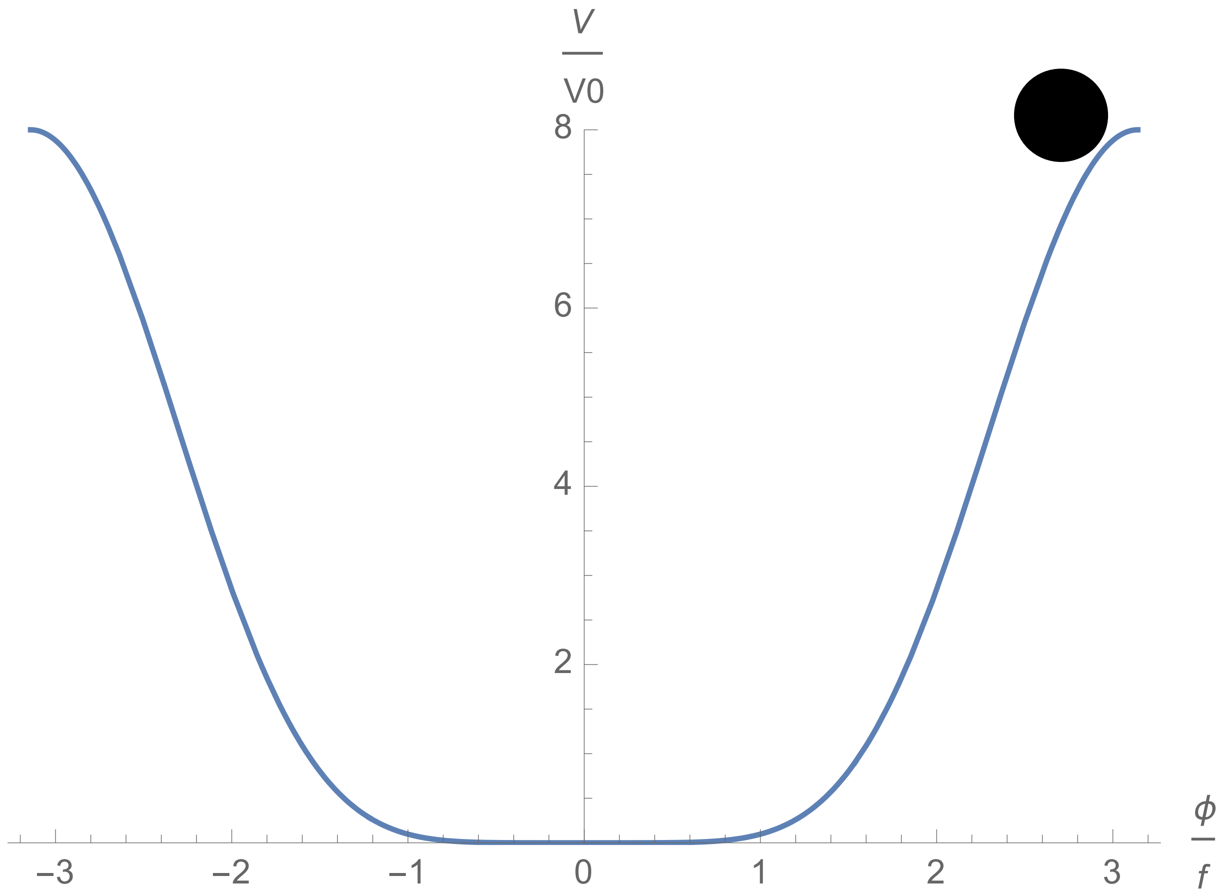
Poulin+ (2019); Agrawal+ (2019); Lin+ (2019); Smith+ (2019)

Colin Hill
Columbia/CCA

Early Dark Energy

New component: (pseudo)-scalar field ϕ

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



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

H >> m
initially

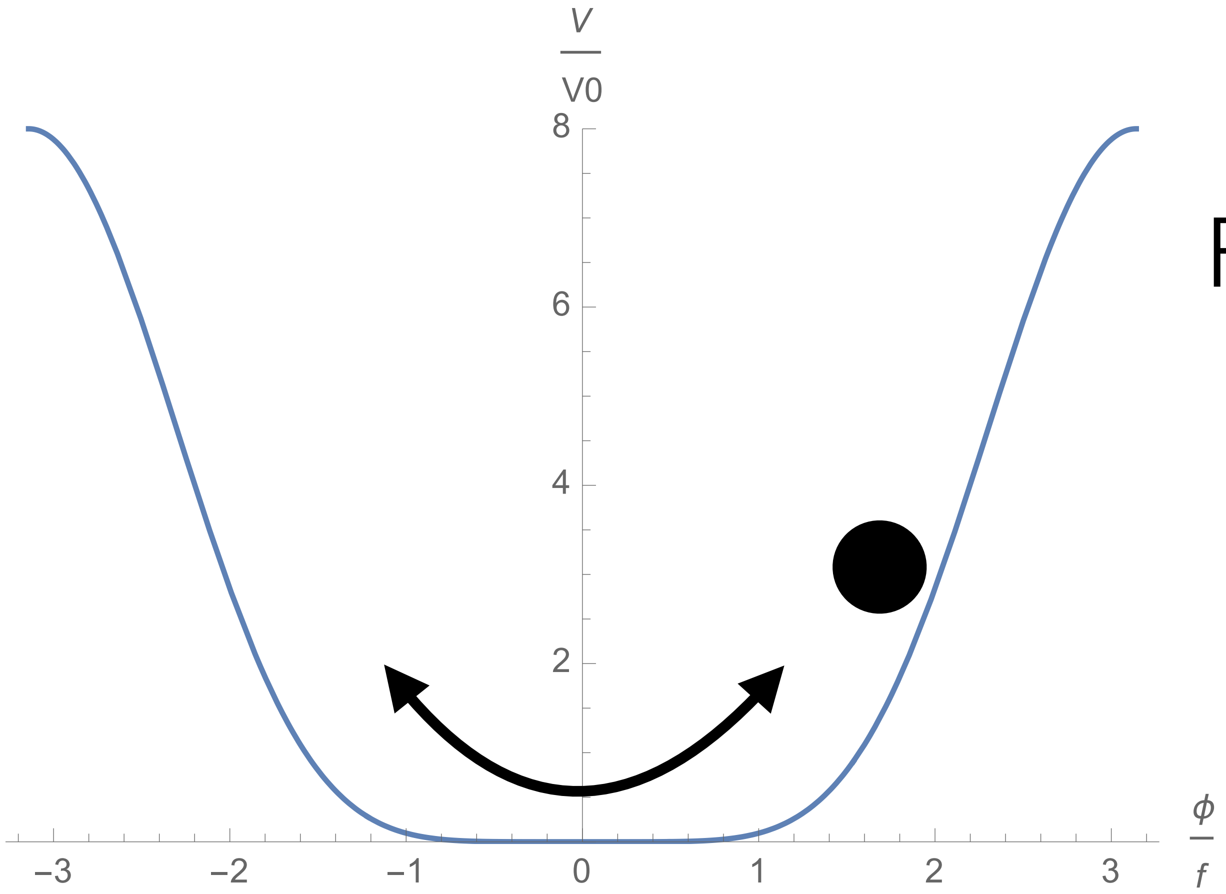
Poulin+ (2019); Agrawal+ (2019); Lin+ (2019); Smith+ (2019)

Colin Hill
Columbia/CCA

Early Dark Energy

New component: (pseudo)-scalar field ϕ

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



For EDE, this must occur near ~z_{CMB}

↓

m ~ 10^{-27} eV

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

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

Colin Hill
Columbia/CCA

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 ~ 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)

Colin Hill
Columbia/CCA

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 ~ 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

Canonical EDE Potential:

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

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

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

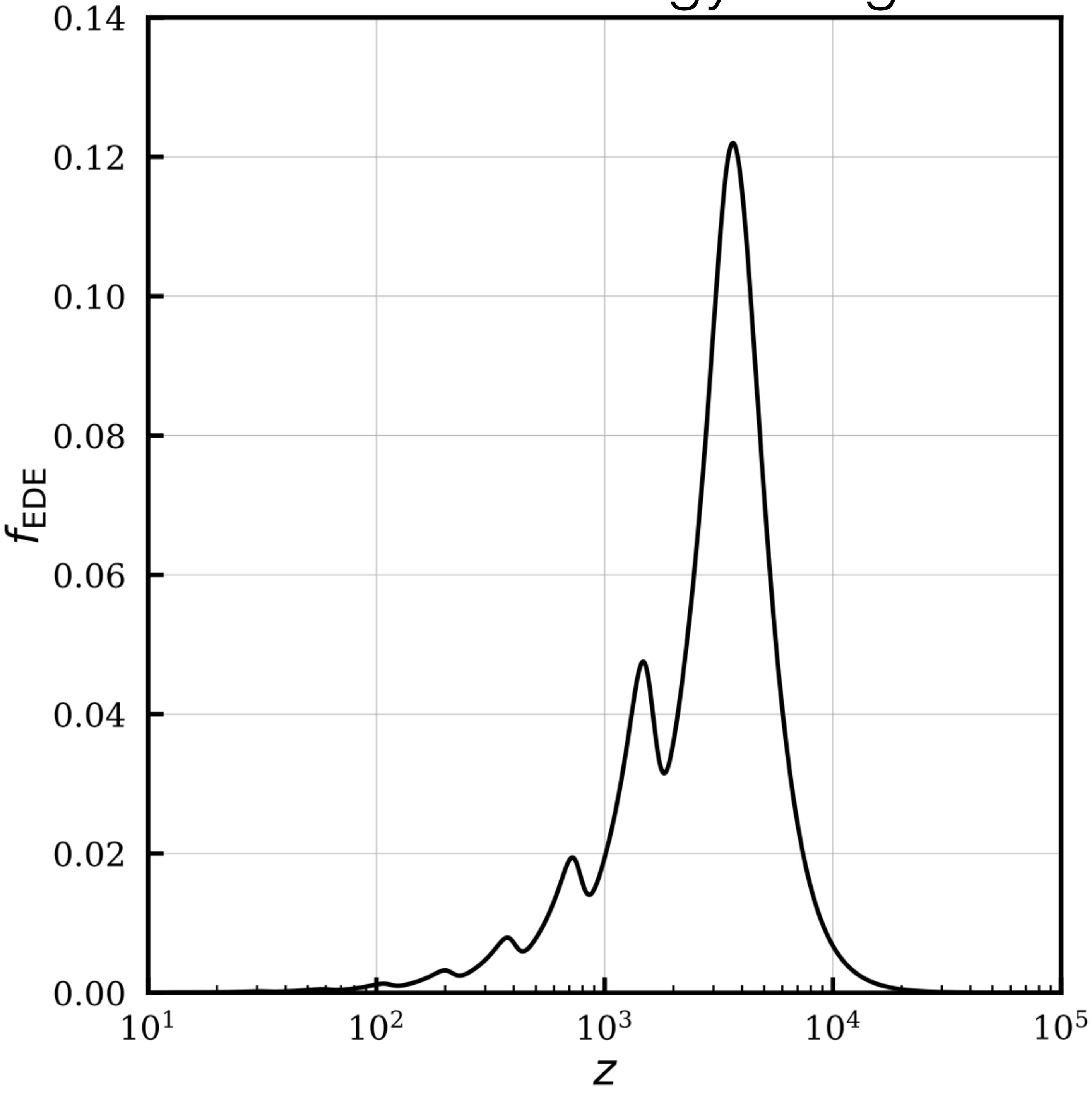
Poulin+ (2019); Agrawal+ (2019); Lin+ (2019); Smith+ (2019)

Colin Hill
Columbia/CCA

Early Dark Energy

Parameterization

Fractional contribution of EDE to cosmic energy budget



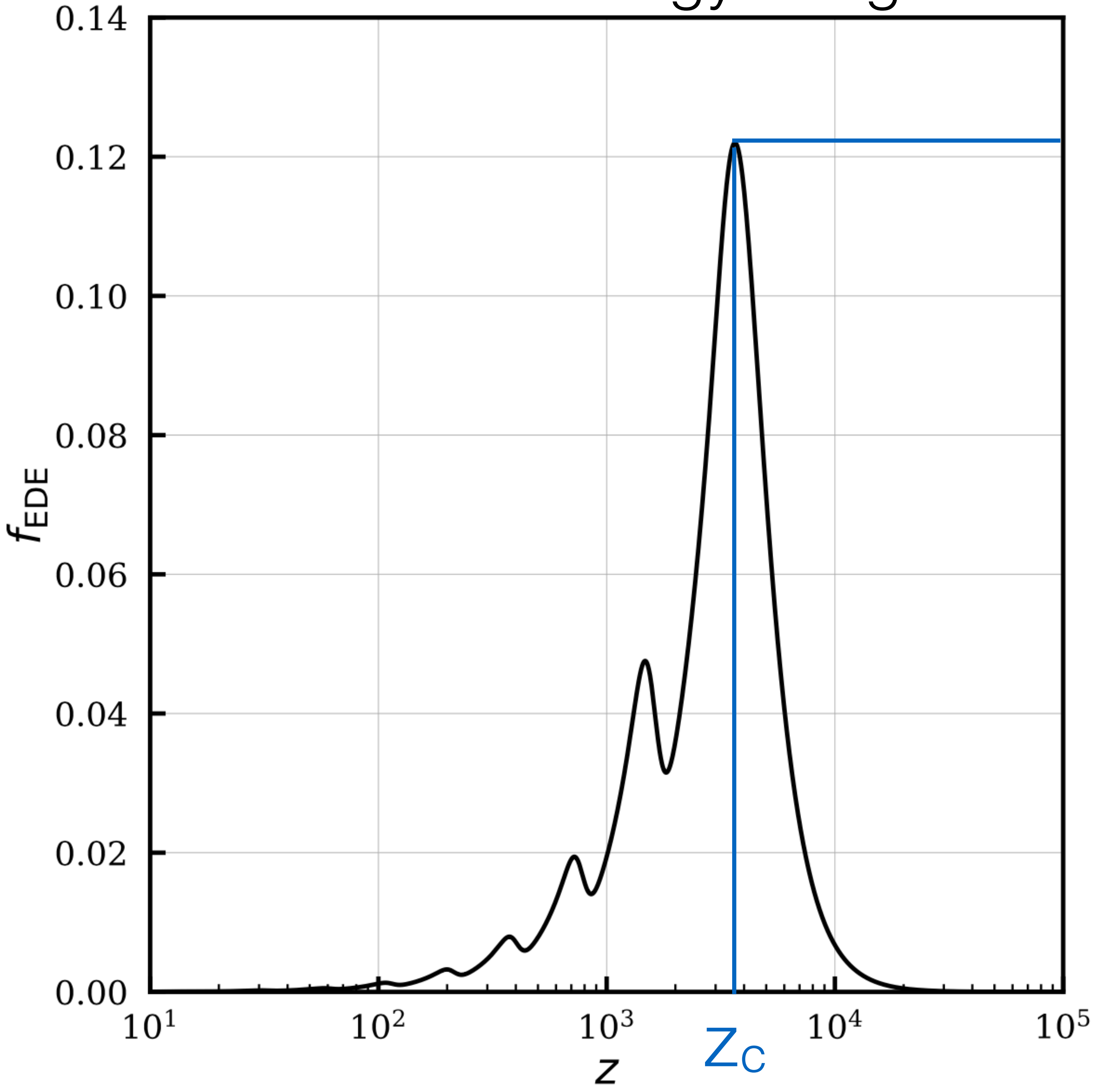
Poulin+ (2019); Agrawal+ (2019); Lin+ (2019); Smith+ (2019); **JCH**+ (2020)

Colin Hill
Columbia/CCA

Early Dark Energy

Parameterization

Fractional contribution of EDE to cosmic energy budget



Maximal contribution:

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

which occurs at redshift z_c

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

→ $\{f_{\rm EDE}, z_c, \theta_i\}$

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

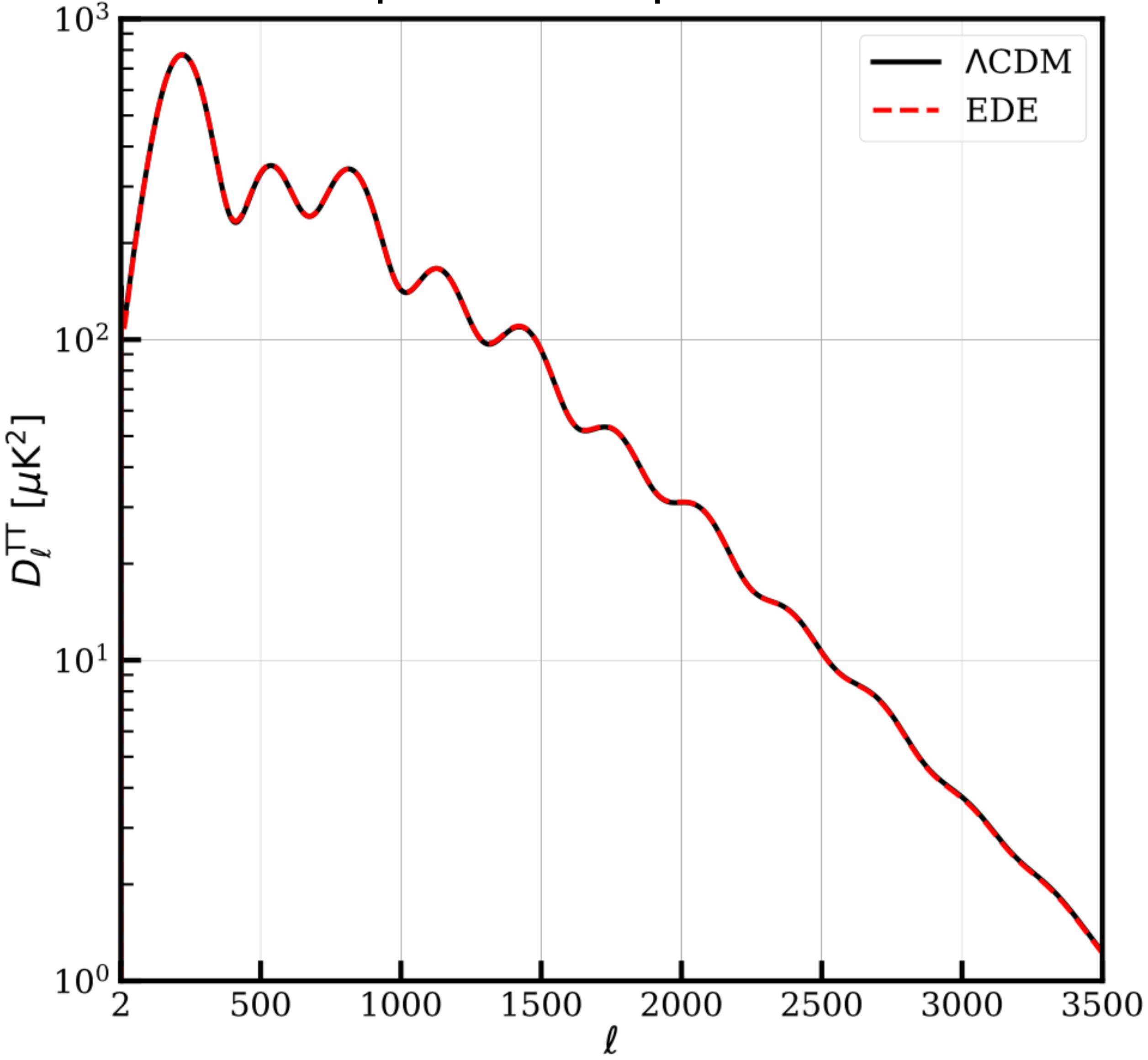
Poulin+ (2019); Agrawal+ (2019); Lin+ (2019); Smith+ (2019); **JCH**+ (2020)

Colin Hill
Columbia/CCA

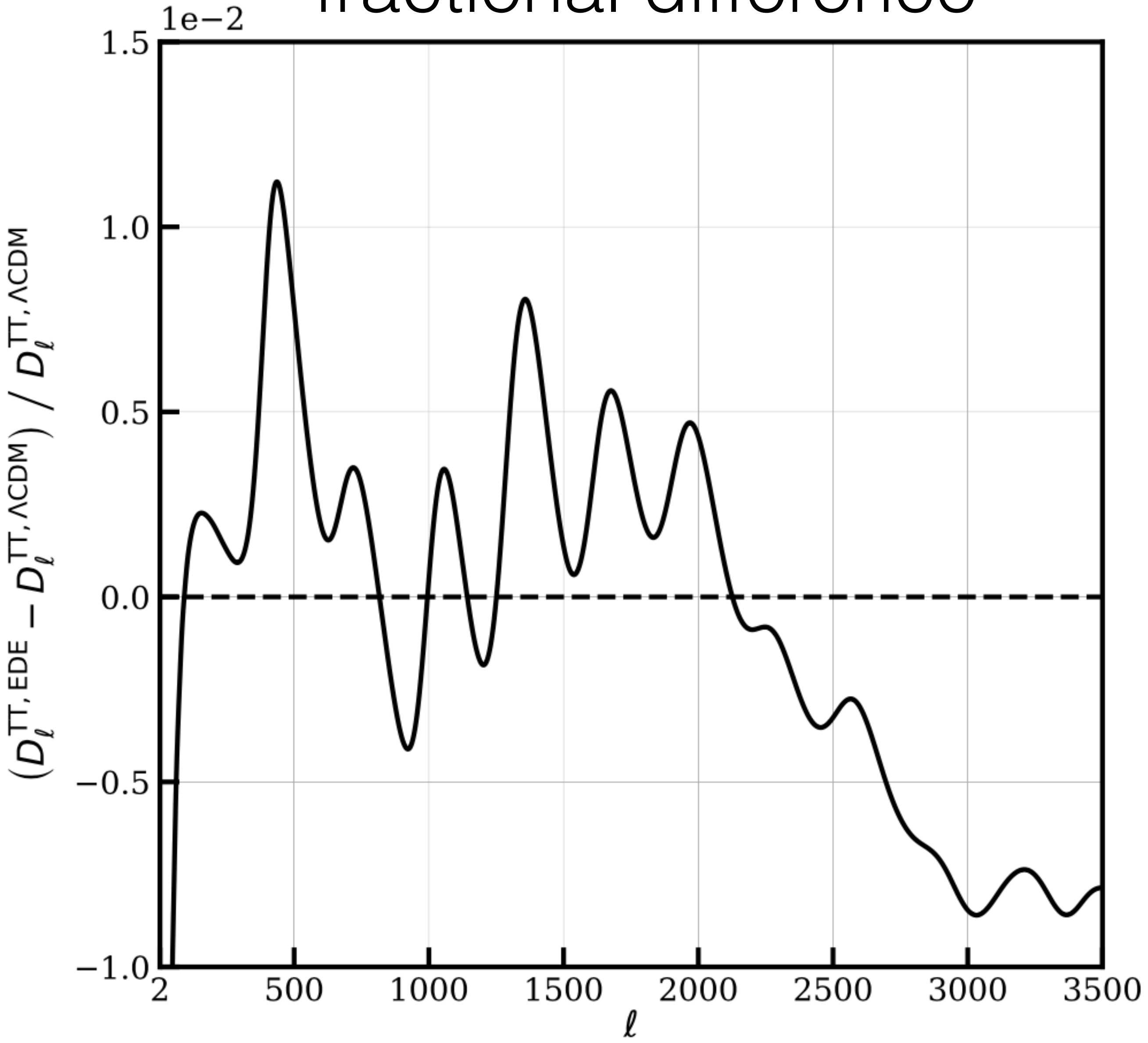
Early Dark Energy

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

TT power spectrum



fractional difference



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

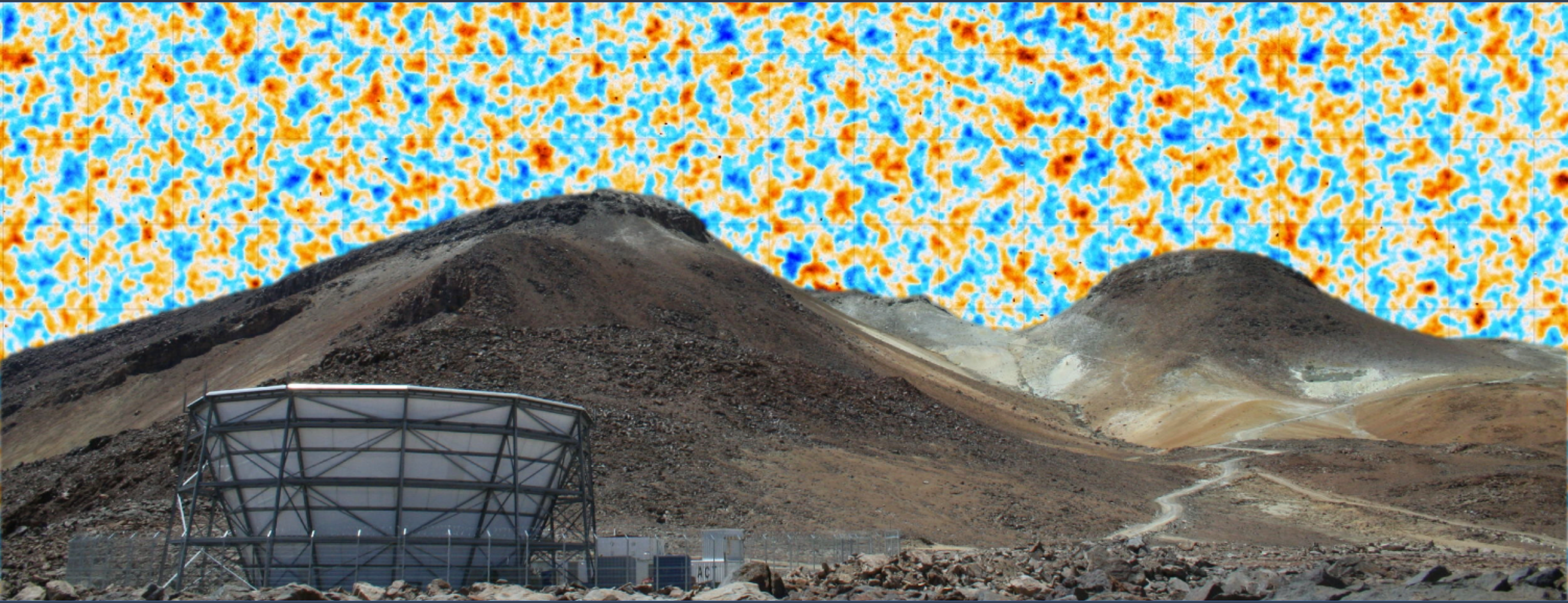
EDE model here has H_0 = 72.19 km/s/Mpc

caused by decrease in r_s

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

Colin Hill
Columbia/CCA

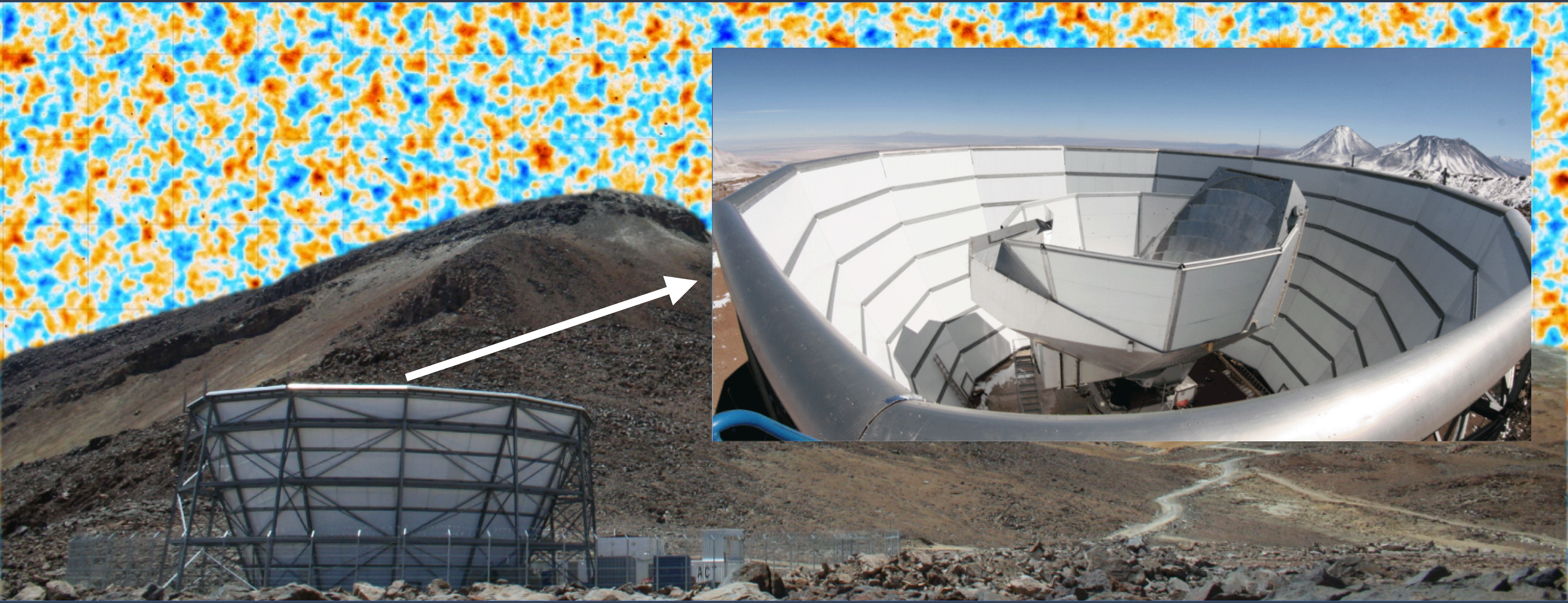
The Atacama Cosmology Telescope



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

Colin Hill
Columbia/CCA

The Atacama Cosmology Telescope



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

Colin Hill
Columbia/CCA

The Atacama Cosmology Telescope

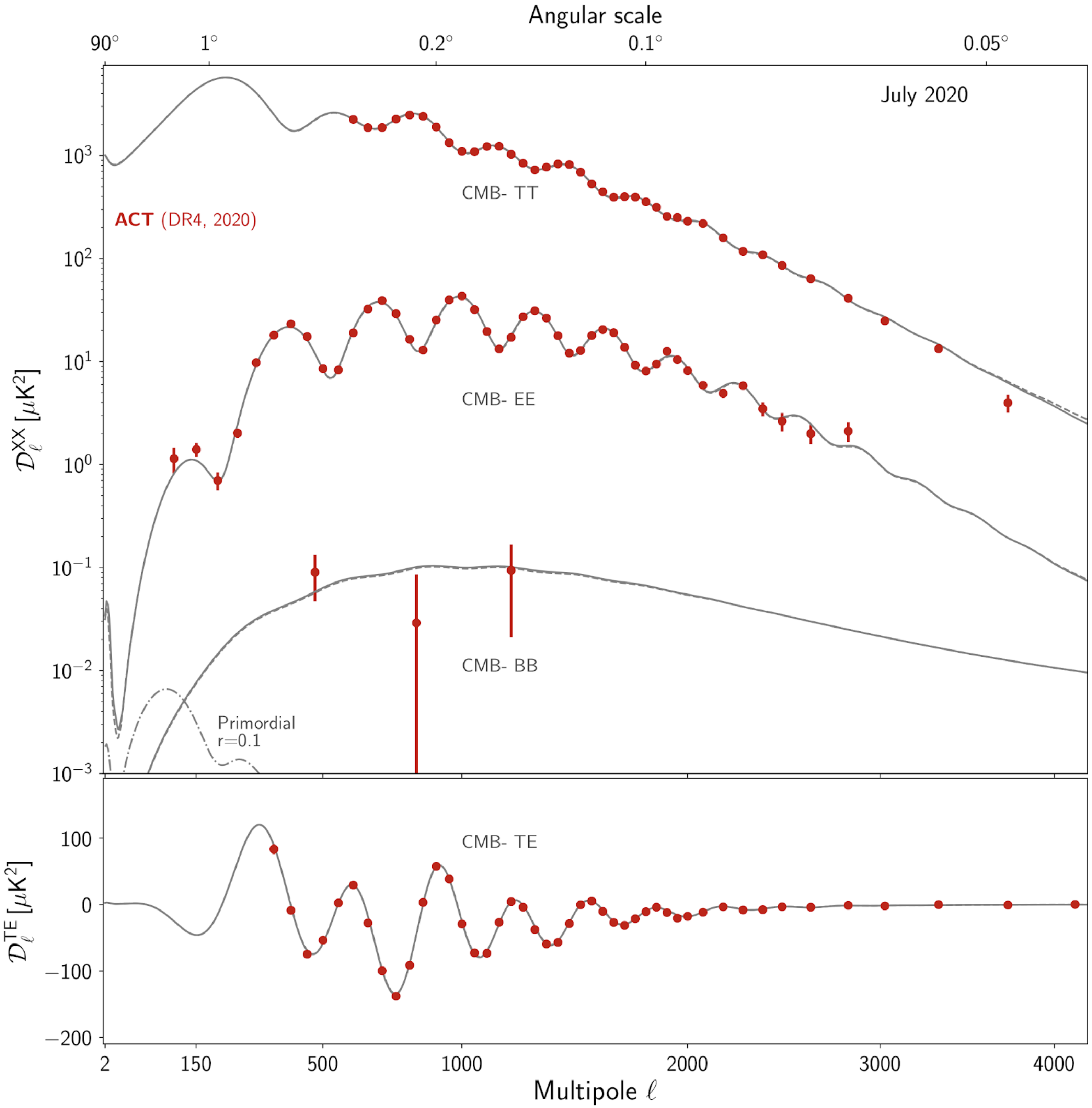
Princeton, March 2019

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

Colin Hill
Columbia/CCA

ACT Data Release 4

Foreground-marginalized CMB power spectra

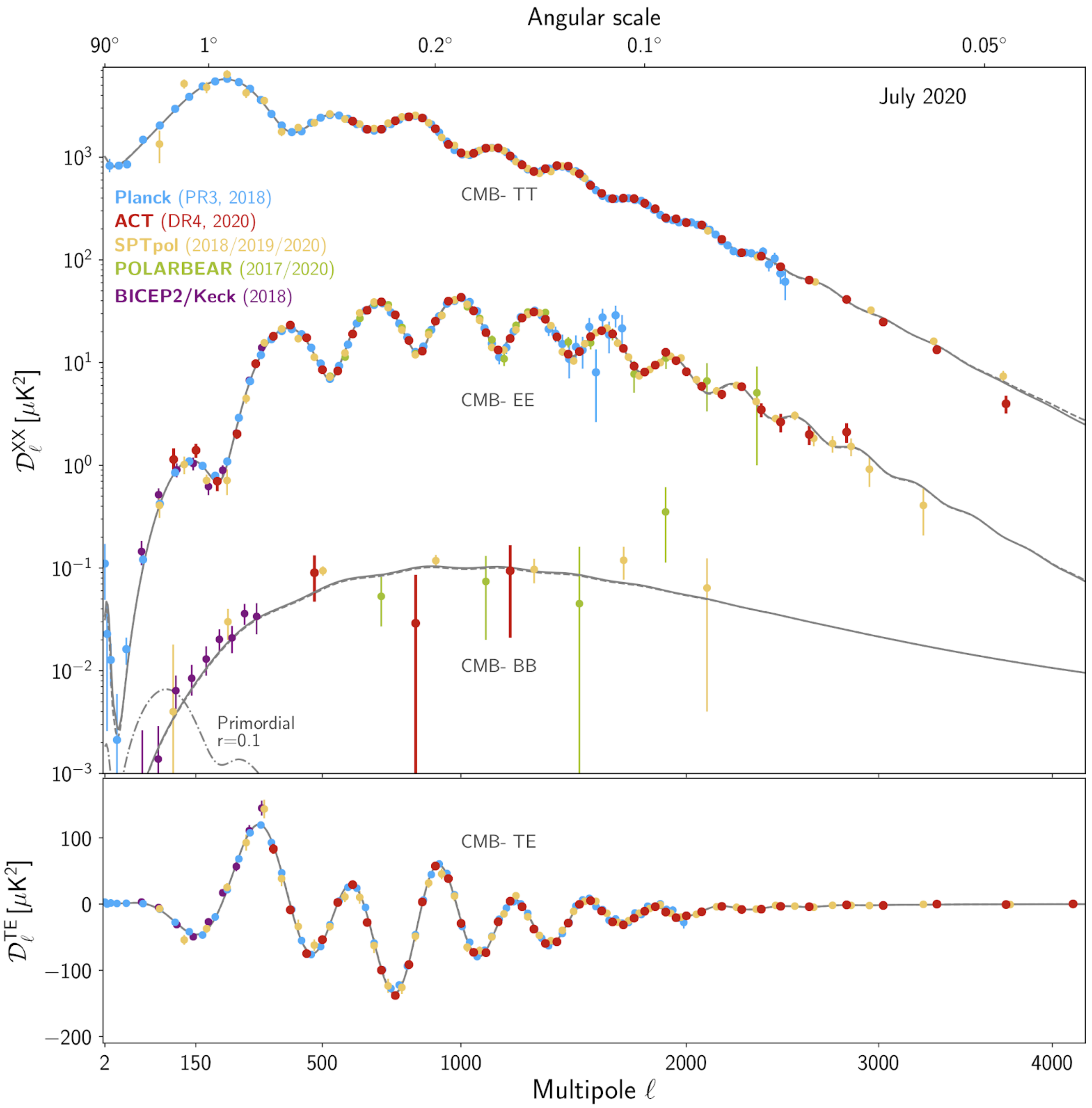


Choi et al. (2020)

ACT Data Release 4

Colin Hill
Columbia/CCA

Foreground-marginalized CMB power spectra



Choi et al. (2020)

Colin Hill
Columbia/CCA

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)

Colin Hill
Columbia/CCA

ACT DR4 EDE Analysis

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

JCH et al. (2021) arXiv:2109.04451

ACT DR4 EDE Analysis

Colin Hill
Columbia/CCA

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)

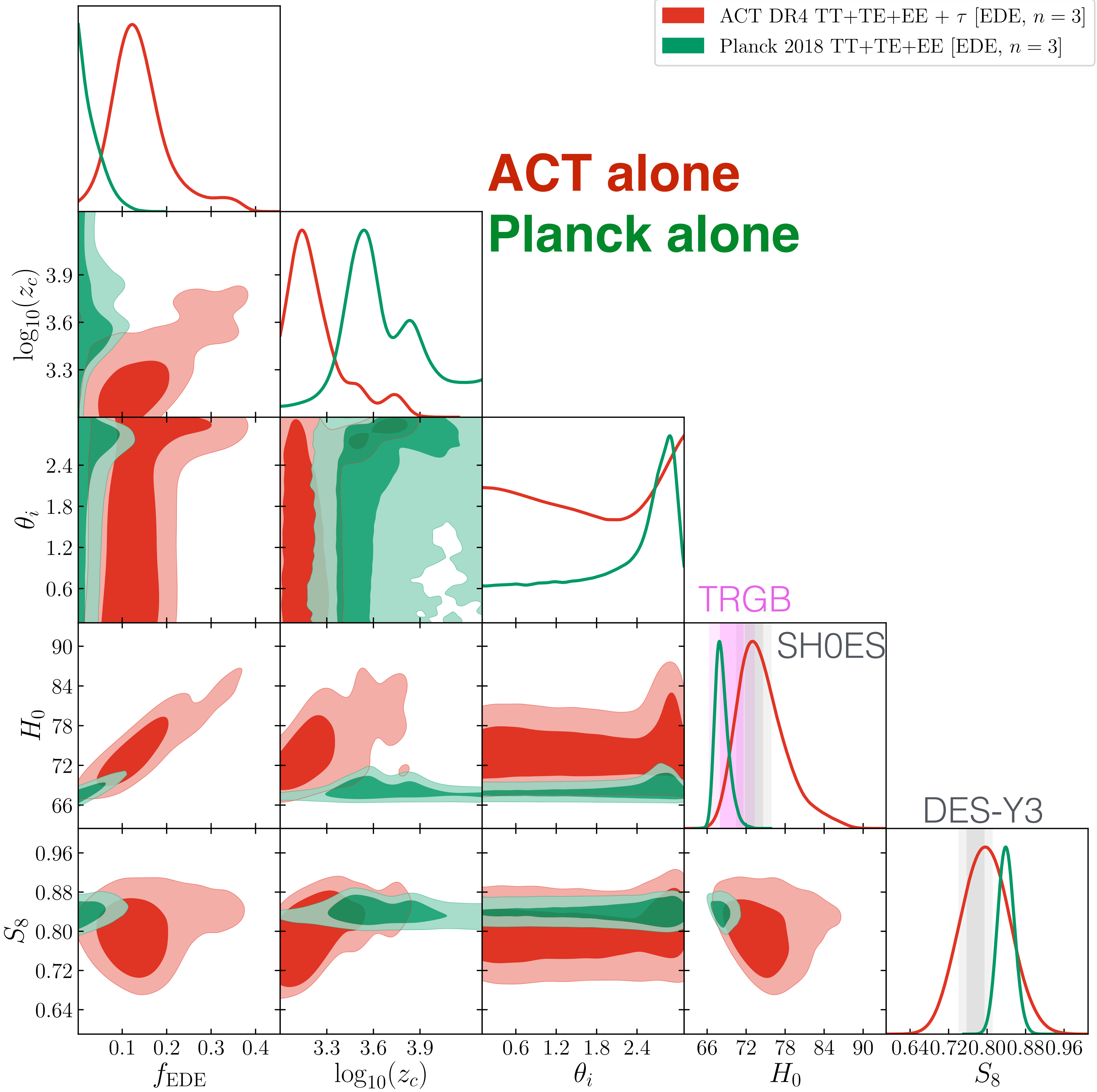
JCH et al. (2021)

See also Poulin et al. (2021)

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

ACT DR4 EDE Results

Colin Hill
Columbia/CCA



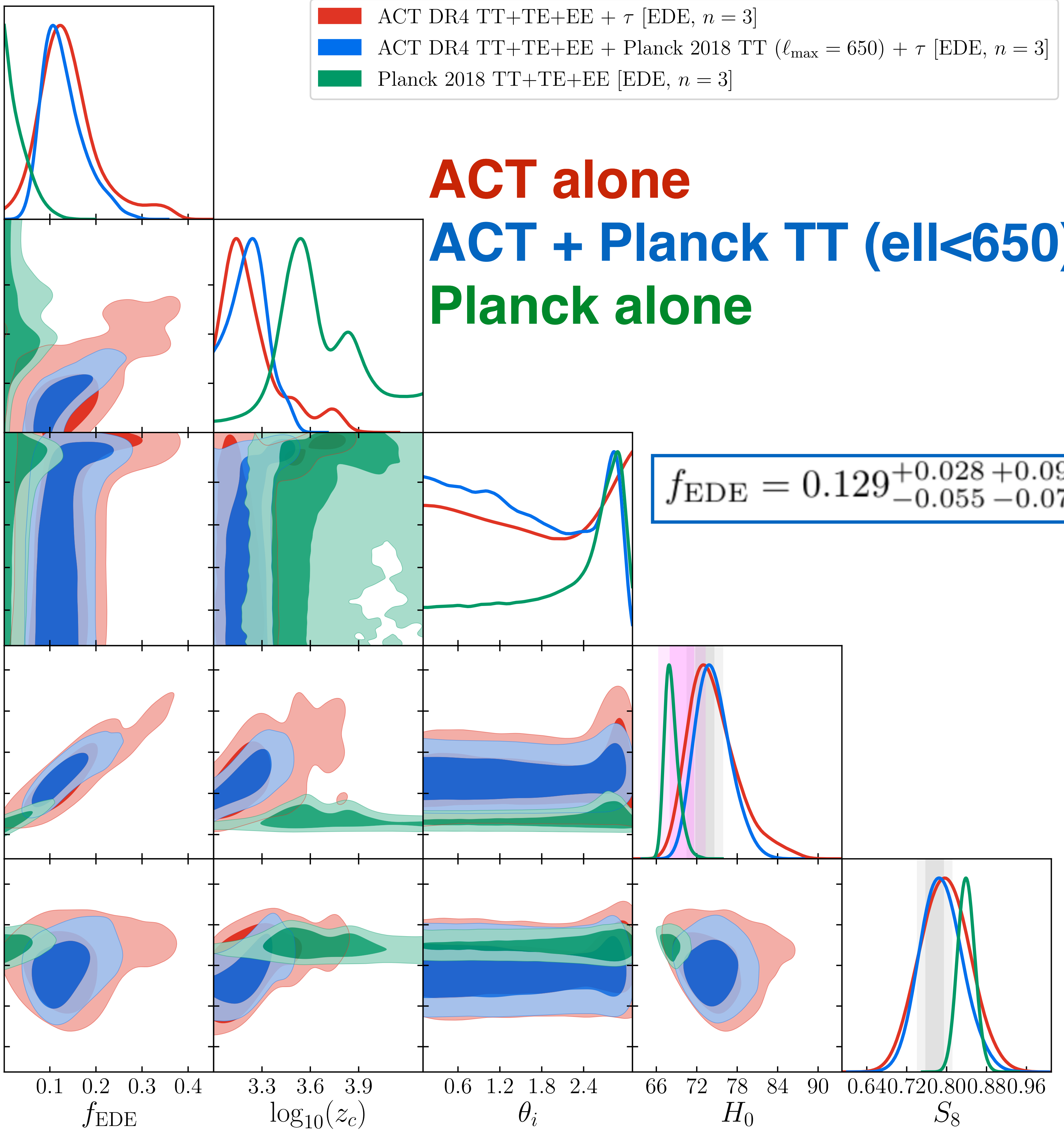
ACT alone

Planck alone

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

ACT DR4 EDE Results

Colin Hill
Columbia/CCA



ACT alone

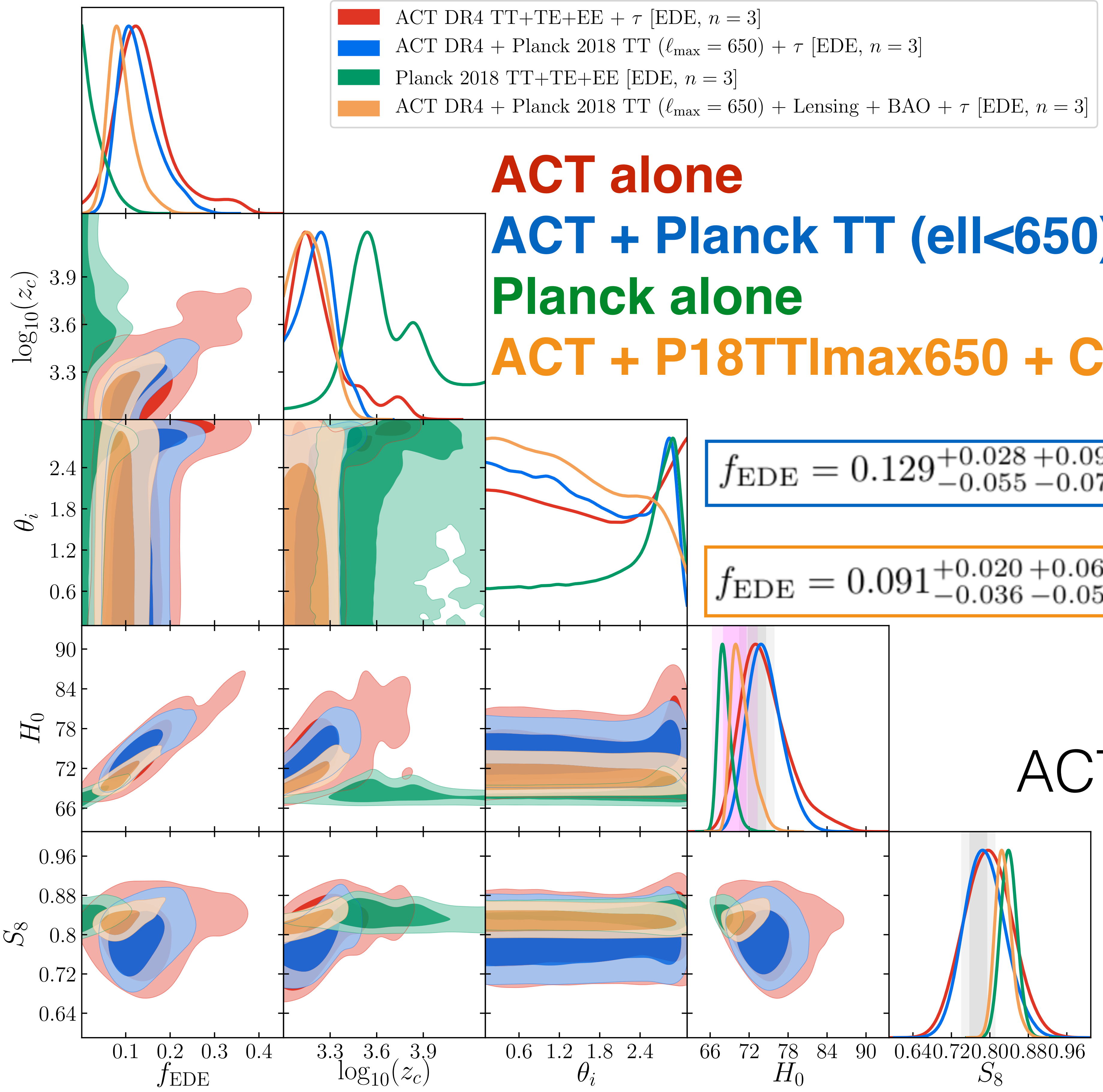
ACT + Planck TT (ell<650)

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



ACT alone

ACT + Planck TT (ell<650)

Planck alone

ACT + P18TTlmax650 + CMB Lensing + BAO

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

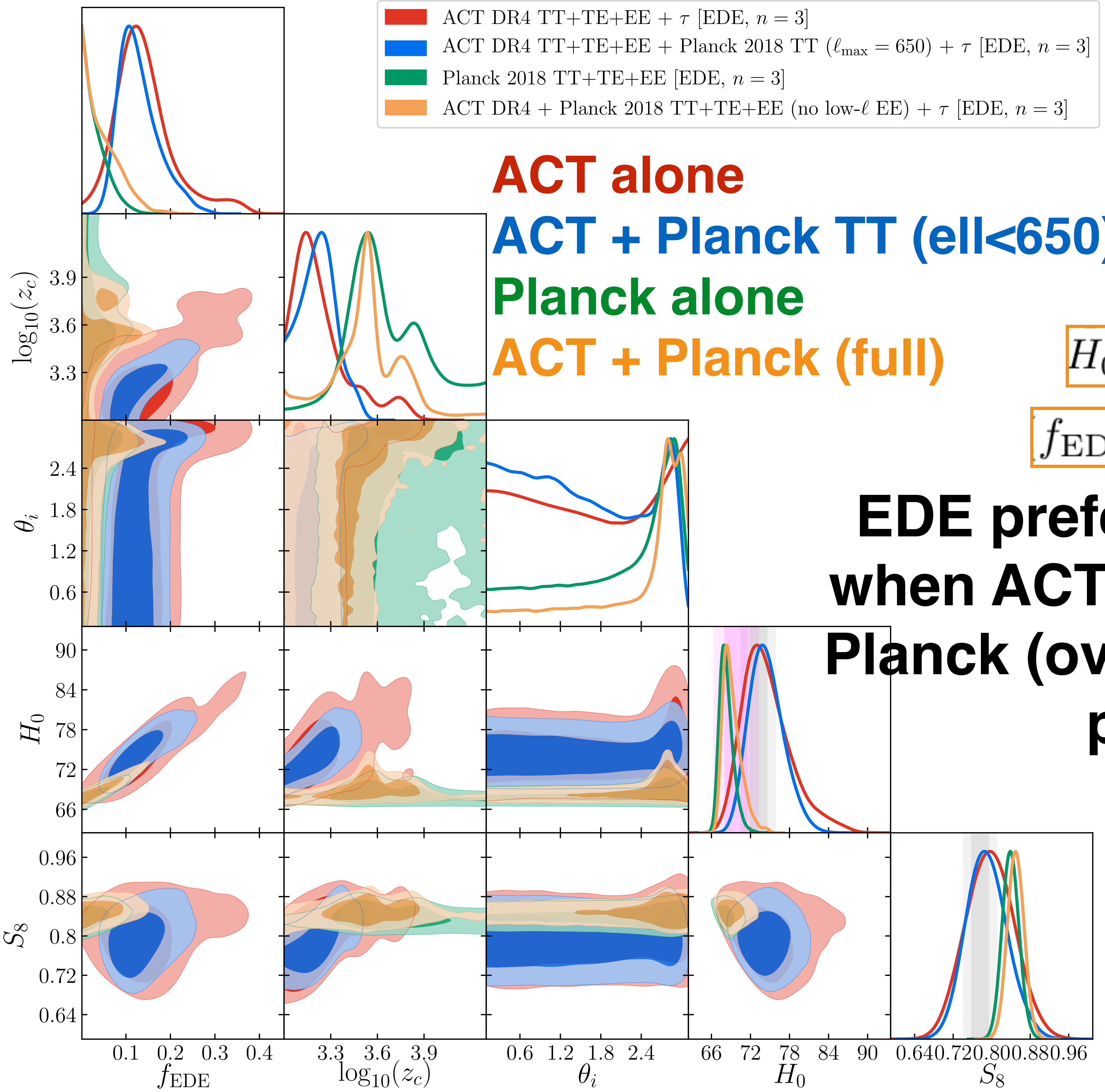
$$f_{\rm EDE} = 0.091^{+0.020\,+0.069\,+0.11}_{-0.036\,-0.056\,-0.063} \quad (68\%/95\%/99.7\%\ \mathrm{CL})$$

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

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

ACT DR4 EDE Results

Colin Hill
Columbia/CCA



ACT alone

ACT + Planck TT (ell<650)

Planck alone

ACT + Planck (full)

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

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

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 Preference

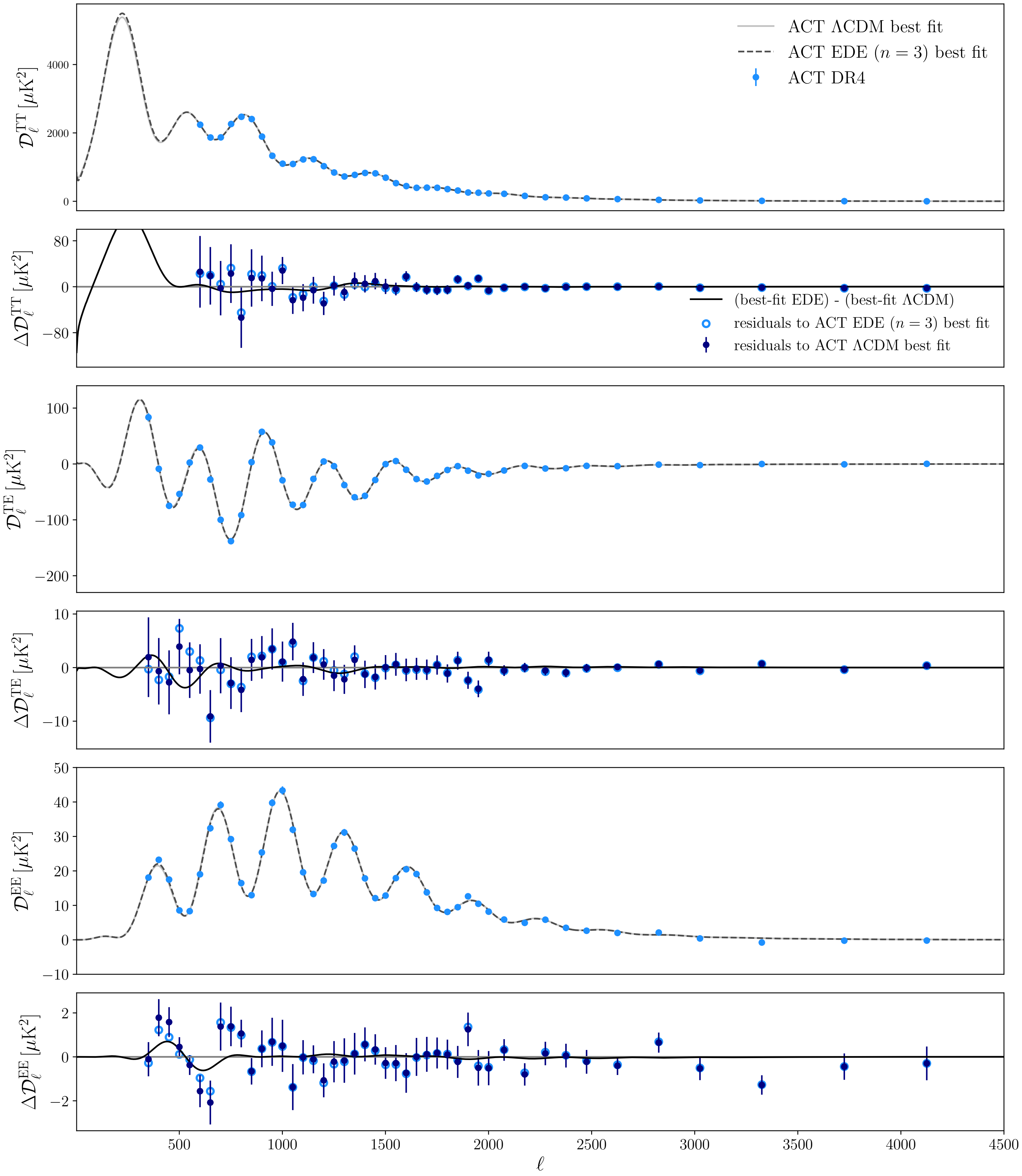
JCH et al. (2021)

Origin of ACT EDE Preference

Colin Hill
Columbia/CCA

LCDM residuals

EDE residuals



TT

TE

EE

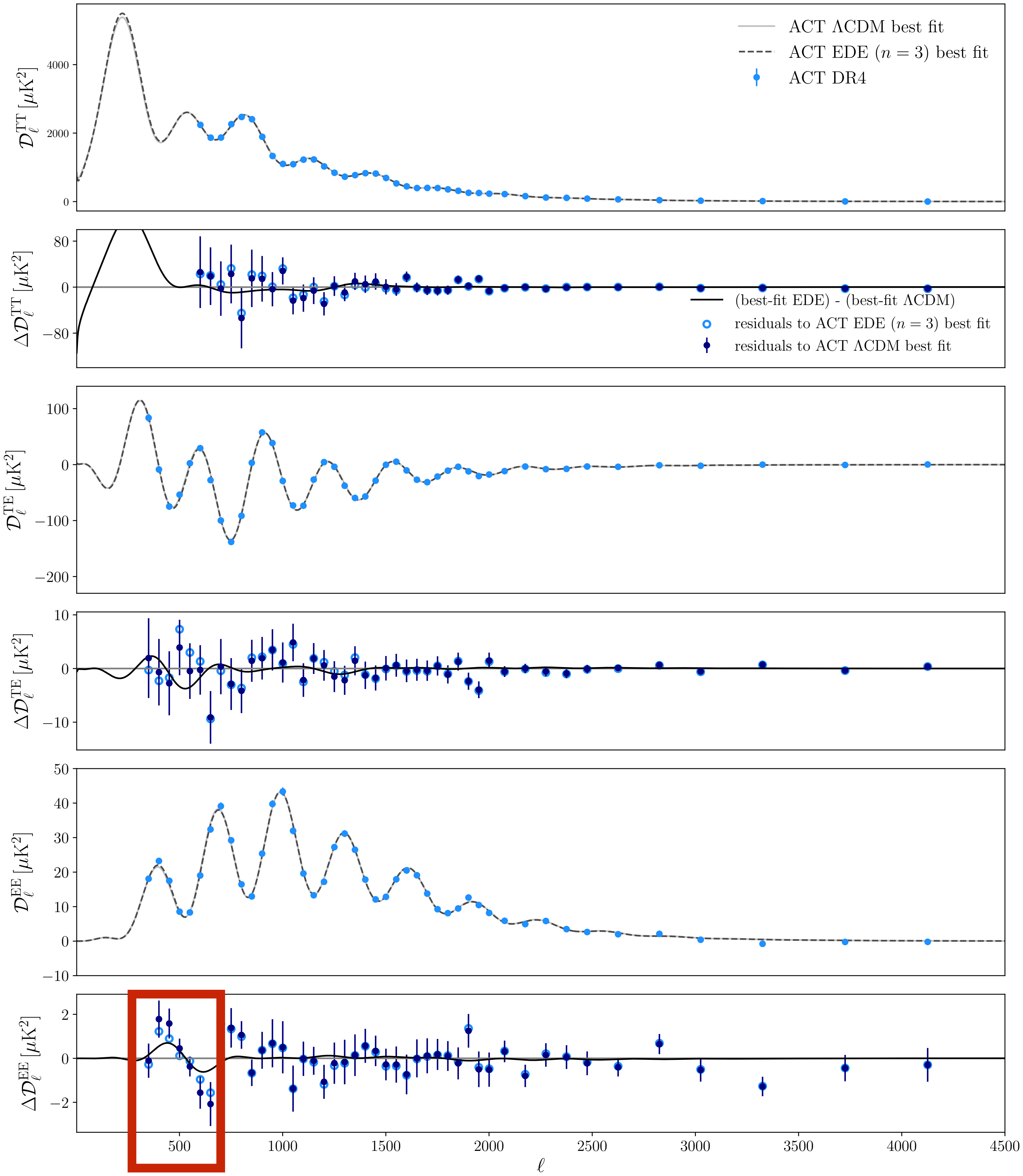
JCH et al. (2021)

Origin of ACT EDE Preference

Colin Hill
Columbia/CCA

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)

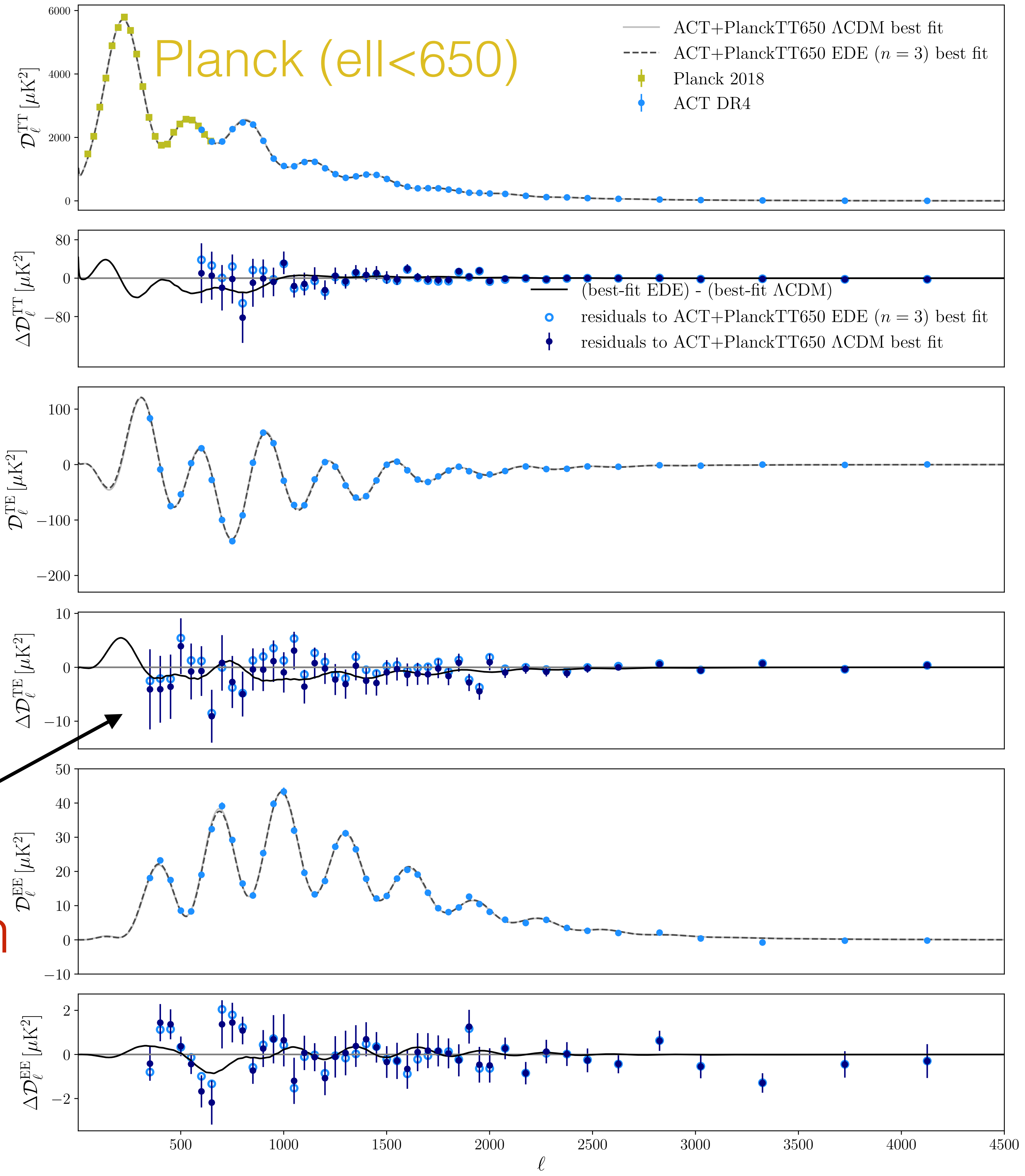
Origin of ACT EDE Preference

Colin Hill
Columbia/CCA

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)

Consistent with SPT-3G?

Analysis using public SPT-3G TE/EE data

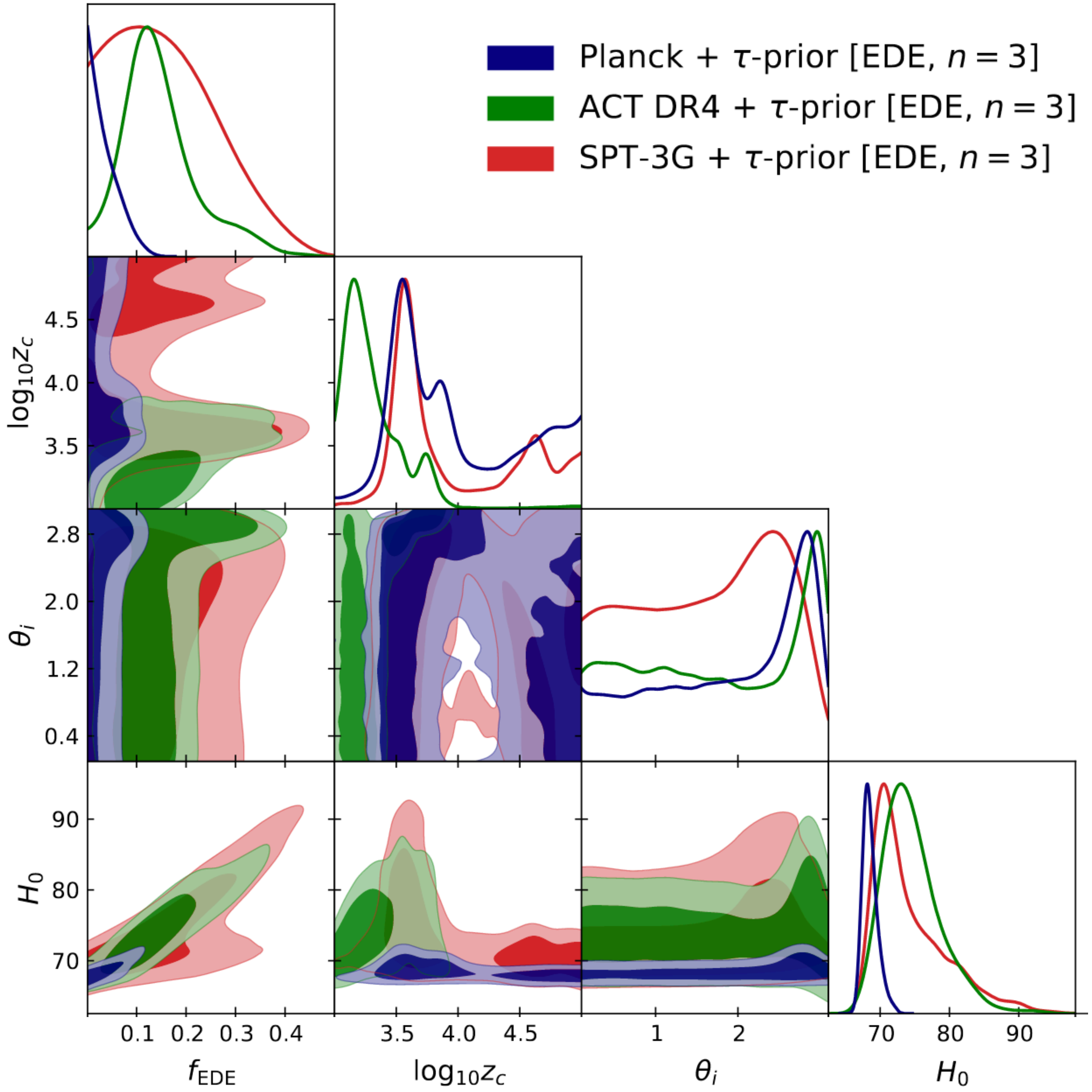
https://arxiv.org/abs/2112.10754; Phys. Rev. D 105, 083519

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

Consistent with SPT-3G

Colin Hill
Columbia/CCA

Analysis using public SPT-3G TE/EE data

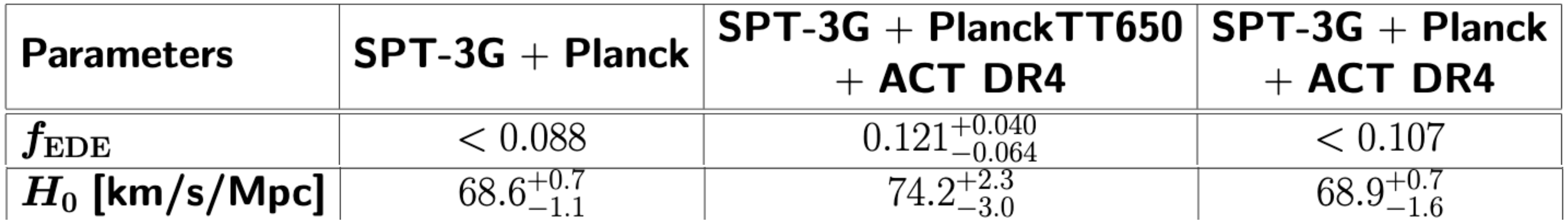


La Posta, Louis, Garrido, **JCH** (2021) ; SPT-3G data from Dutcher et al. (2021)

Consistent with SPT-3G

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** (2021)

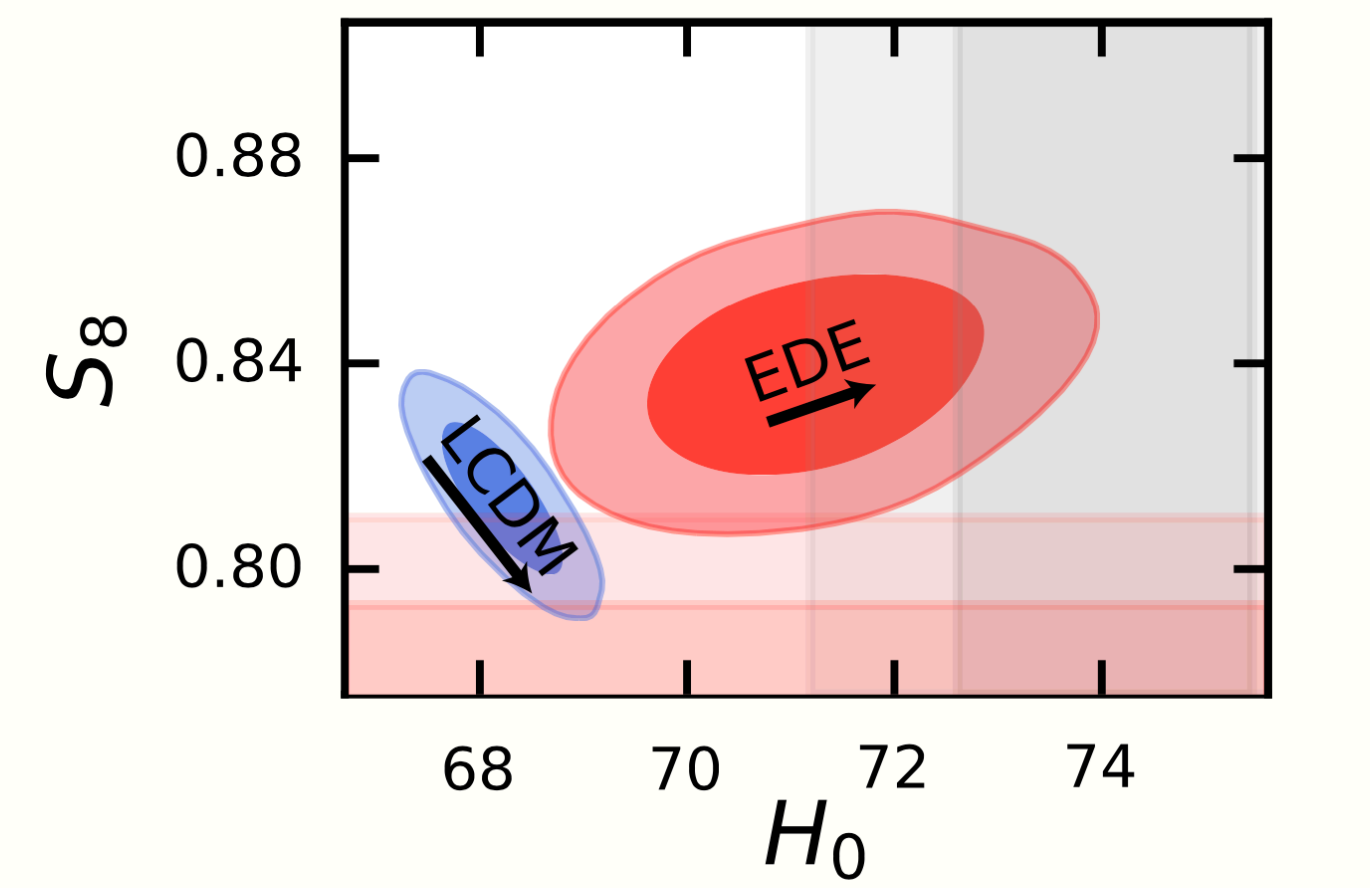
Colin Hill
Columbia/CCA

EDE Puzzles & Problems

McDonough, Lin, JCH, Hu, Zhou (2021); Lin, McDonough, JCH, Hu (in prep.); JCH+ (2020); Ivanov+ (2020)

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, hence raising S_8



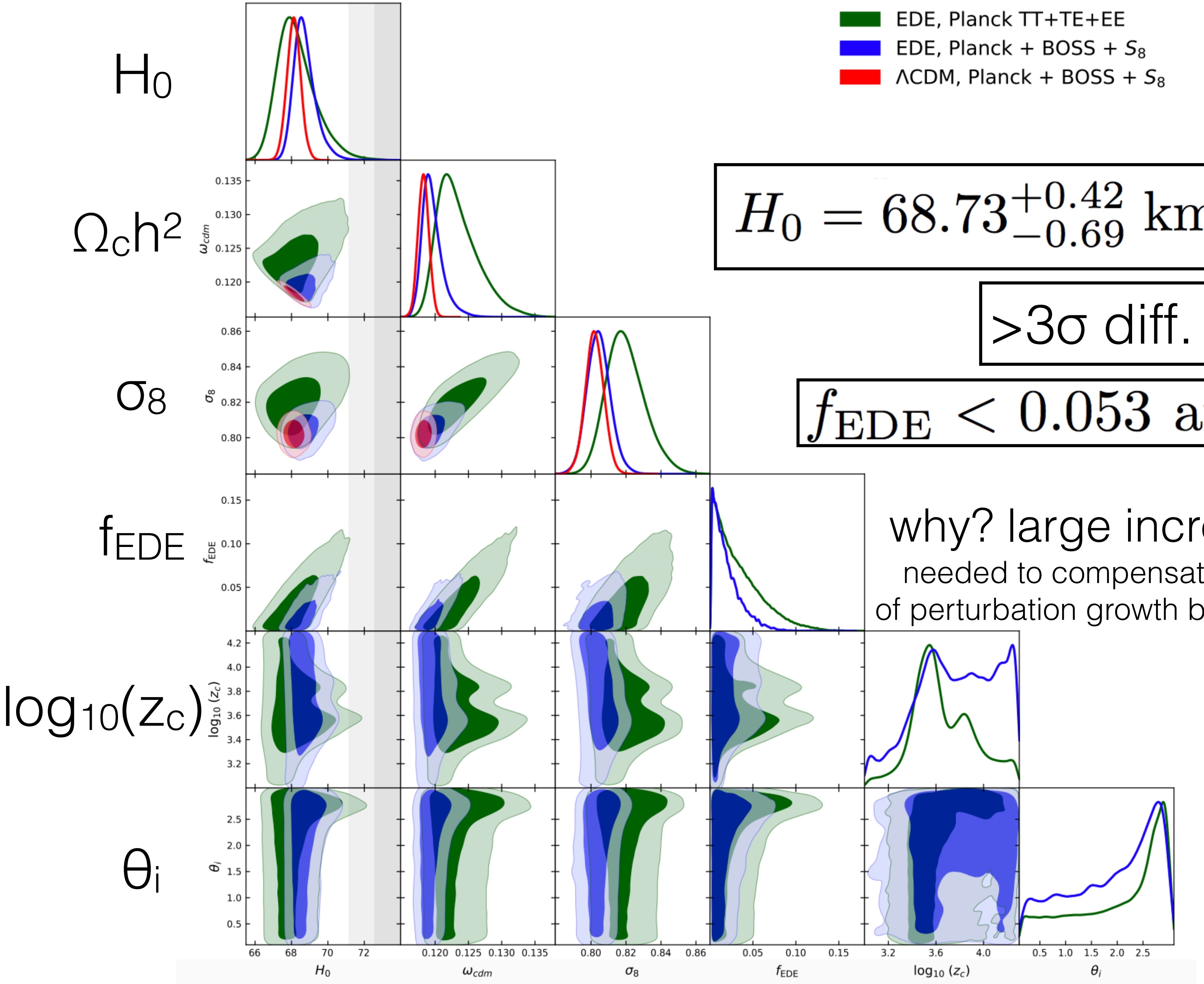
McDonough, Lin, JCH, Hu, Zhou (2021); Lin, McDonough, JCH, Hu (in prep.); JCH+ (2020); Ivanov+ (2020)

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

Ivanov, McDonough, JCH+ (2020)

Colin Hill
Columbia/CCA

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



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

>3σ diff. w/ SH0ES

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

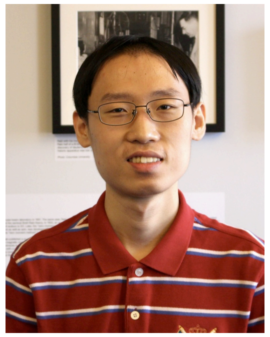
why? large increase in ω_{cdm}
needed to compensate for suppression
of perturbation growth by EDE (“early ISW”)

Ivanov, McDonough, JCH+ (2020); see also D’Amico+ (2020), Smith+(2021), Simon+ (2022)

Colin Hill
Columbia/CCA

Early Dark Sector



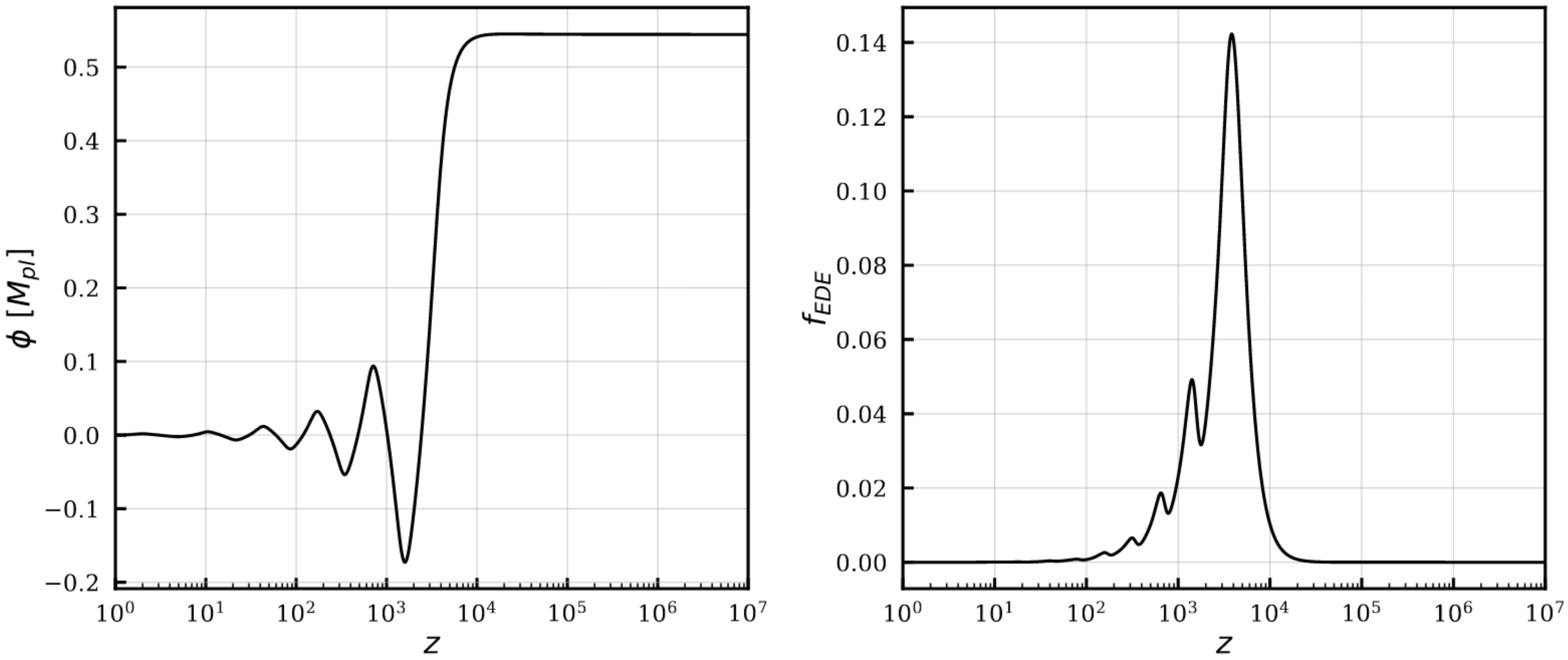



2112.04510 w/ Evan McDonough, Meng-Xiang Lin, Wayne Hu, Shengjia Zhou
+ in prep. w/ Lin, McDonough, Hu

Early Dark Sector

Colin Hill
Columbia/CCA

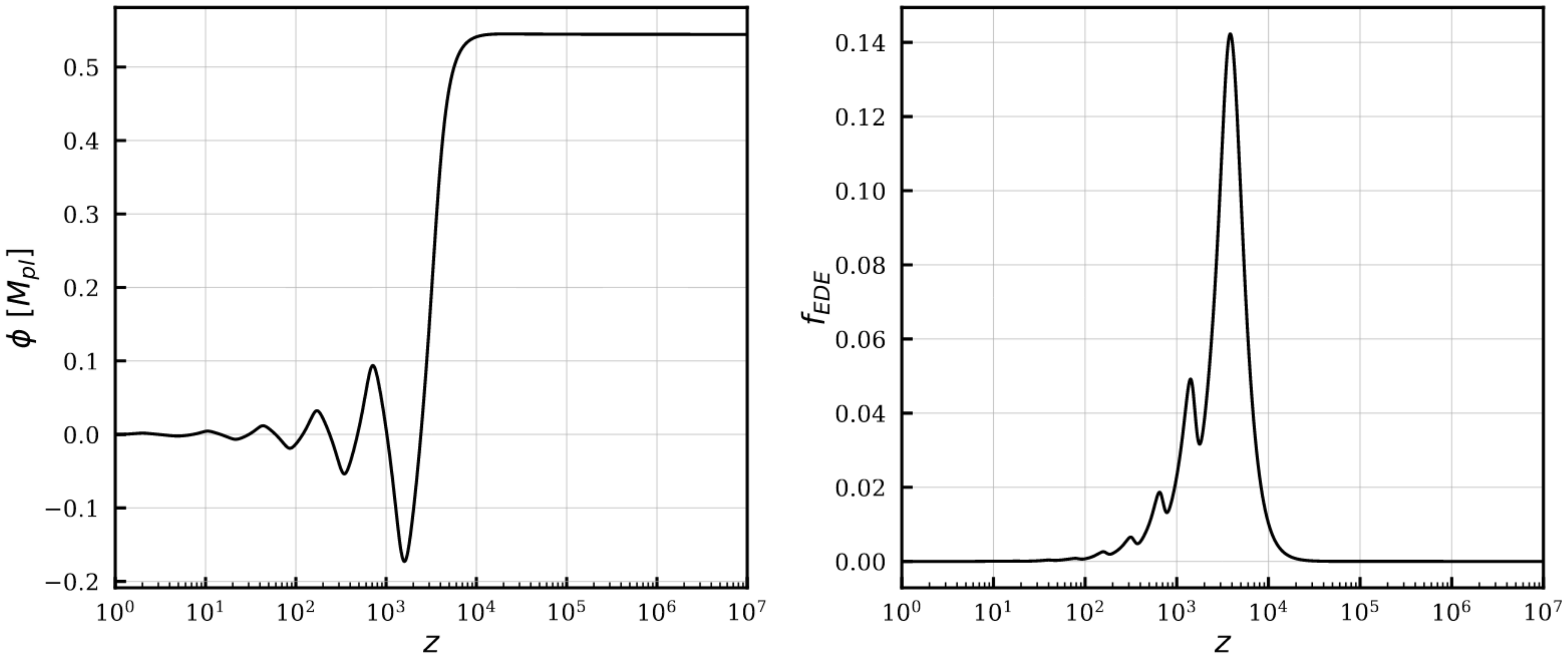
Theoretical motivation: in H_0-tension-resolving EDE models, the scalar ϕ generically undergoes a Planckian field excursion



McDonough, Lin, JCH, Hu, Zhou (2021)

Early Dark Sector

Theoretical motivation: in H_0-tension-resolving EDE models, the scalar ϕ generically undergoes a Planckian field excursion



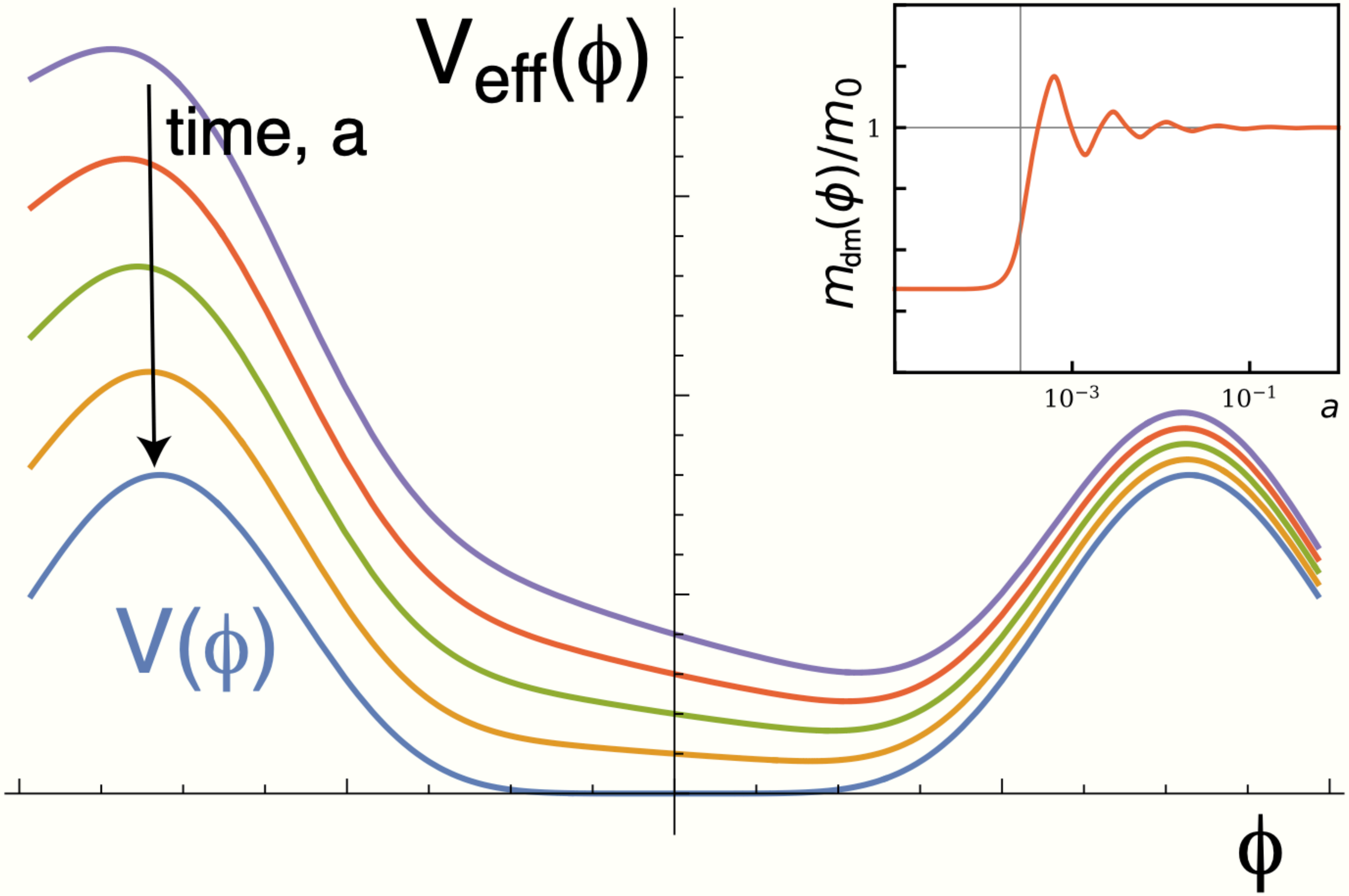
- Swampland distance conjecture (SDC) [Vafa, Ooguri]: breakdown of EFT that occurs at Planckian field excursions is encoded in an exponential sensitivity of the mass spectrum of the effective theory —> suggests $m_{DM} \sim e^{\phi/M_{pl}}$

McDonough, Lin, JCH, Hu, Zhou (2021)

Early Dark Sector

Colin Hill
Columbia/CCA

- Field dependent dark matter mass: $m_{\rm dm}(\phi) = m_0 e^{c\phi}$
- Effective potential: $V_{\rm eff} = V_0 + m_{\rm dm}(\phi) n_{\rm dm}$



McDonough, Lin, JCH, Hu, Zhou (2021)

Early Dark Sector

Effects on growth of structure (holding $\Omega_c h^2$ fixed)

- $c<0$ ($c>0$): DM mass lighter (heavier) at $z>z_c$, and thus matter-radiation equality occurs later (earlier), leading to less (more) growth by today

McDonough, Lin, JCH, Hu, Zhou (2021)

Early Dark Sector

Colin Hill
Columbia/CCA

Effects on growth of structure (holding $\Omega_c h^2$ fixed)

- $c<0$ ($c>0$): DM mass lighter (heavier) at $z>z_c$, and thus matter-radiation equality occurs later (earlier), leading to less (more) growth by today
- On small scales, ϕ mediates a fifth force that scales as $\sim c^2$ and enhances growth

$$G_{\rm eff} = G_N \left(1 + \frac{2c^2k^2}{k^2 + a^2 d^2V/d\phi^2}\right)$$

$$\xrightarrow[\text{high-k limit}]{} \quad G_{\rm eff} = G_N(1+2c^2)$$

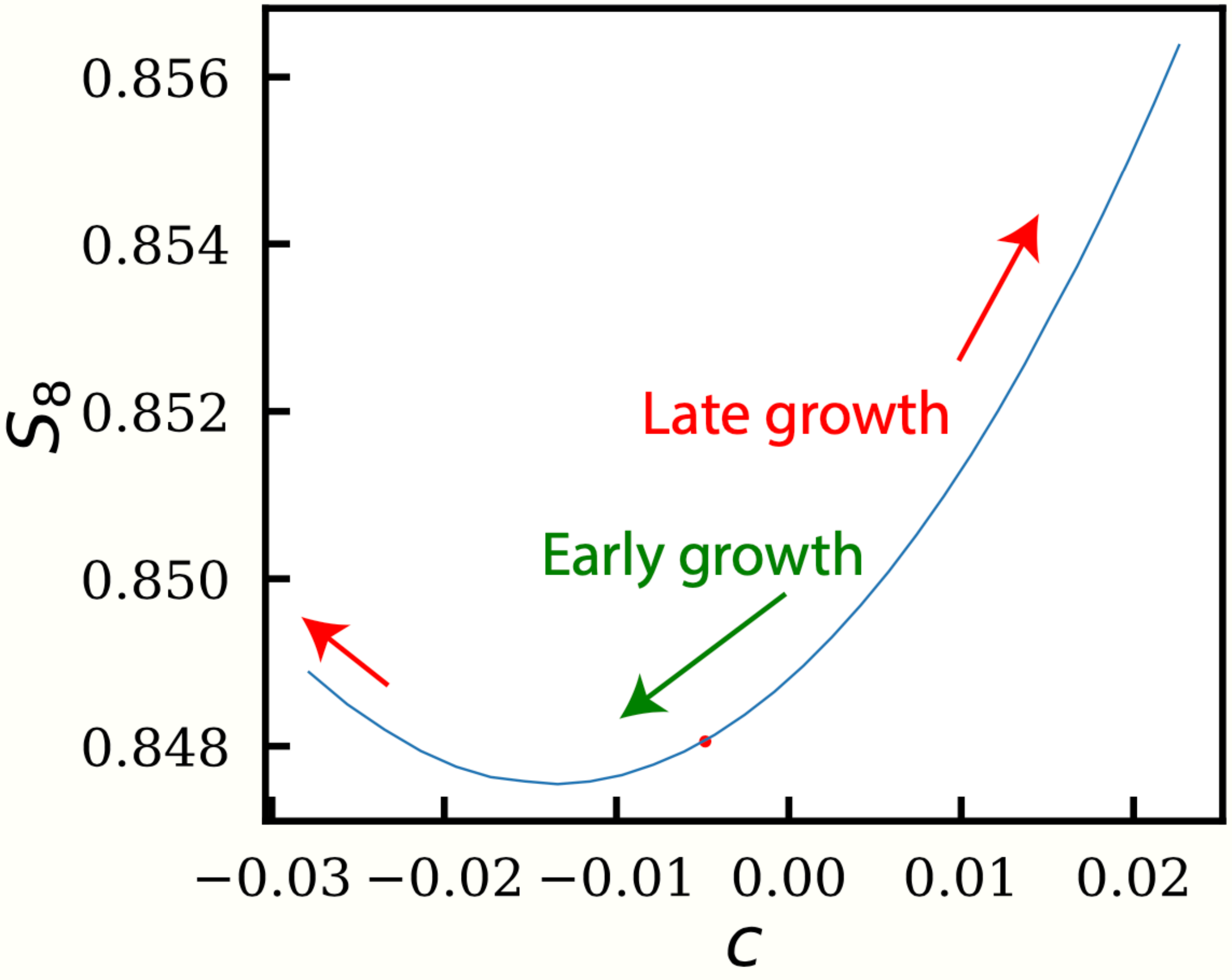
McDonough, Lin, JCH, Hu, Zhou (2021)

Early Dark Sector

Colin Hill
Columbia/CCA

Competing S_8 effects

- Early: linear in c and $c < 0$ reduces S_8
- Late: quadratic in c and all c enhances S_8



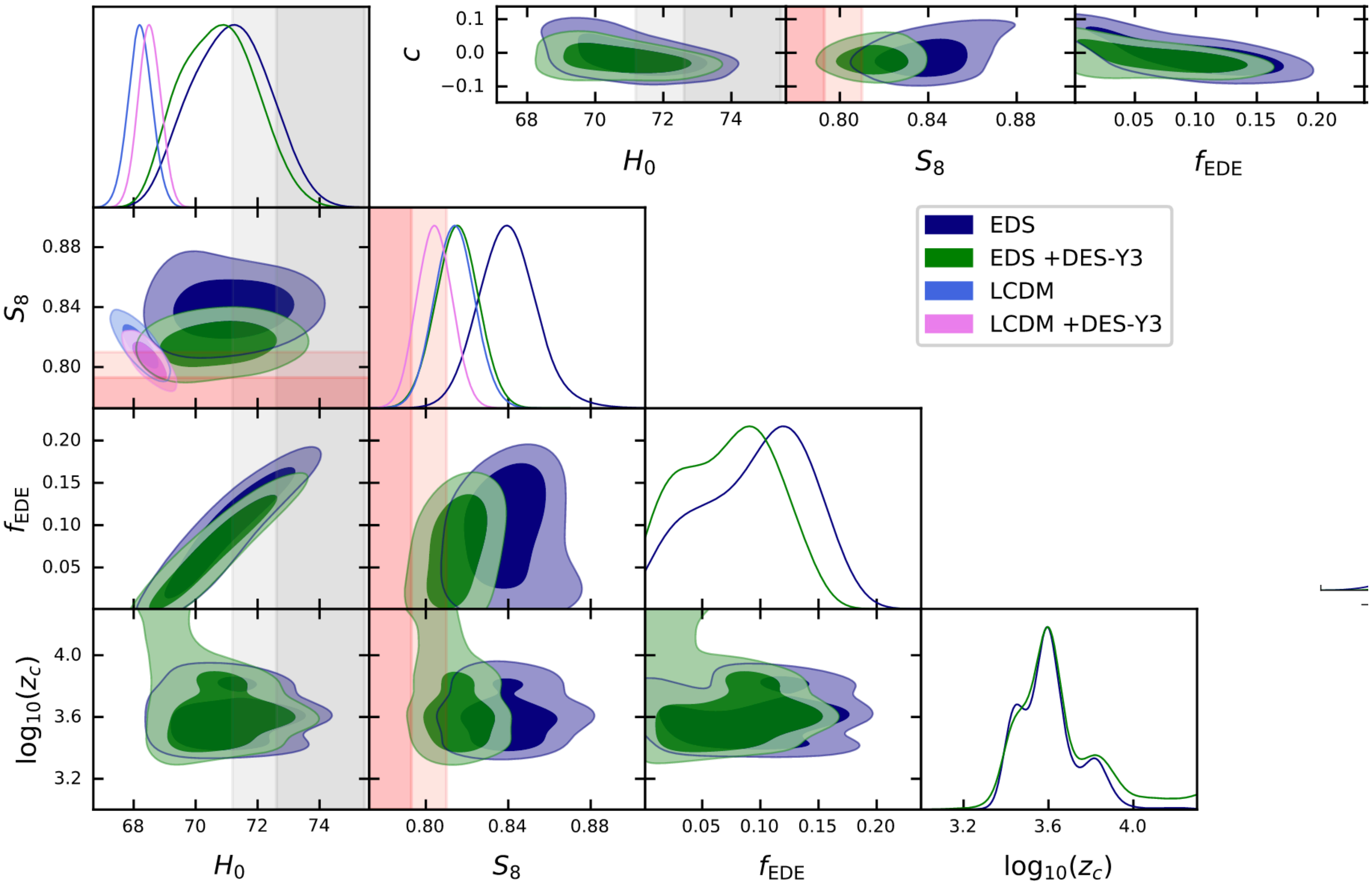
- Combination: only small ability to lower S_8

McDonough, Lin, JCH, Hu, Zhou (2021)

Early Dark Sector

Colin Hill
Columbia/CCA

Additional low-S8, high-H0 parameter space is now allowed: we've reduced the "tension of tensions", but fit does not substantially improve over ΛCDM



Data sets = Planck + BAO + SNIa + SH0ES (+DES)

McDonough, Lin, JCH, Hu, Zhou (2021)

Early Dark Sector 2

Colin Hill
Columbia/CCA

Can we perhaps solve (at least) the EDE “coincidence” and initial-conditions problems?

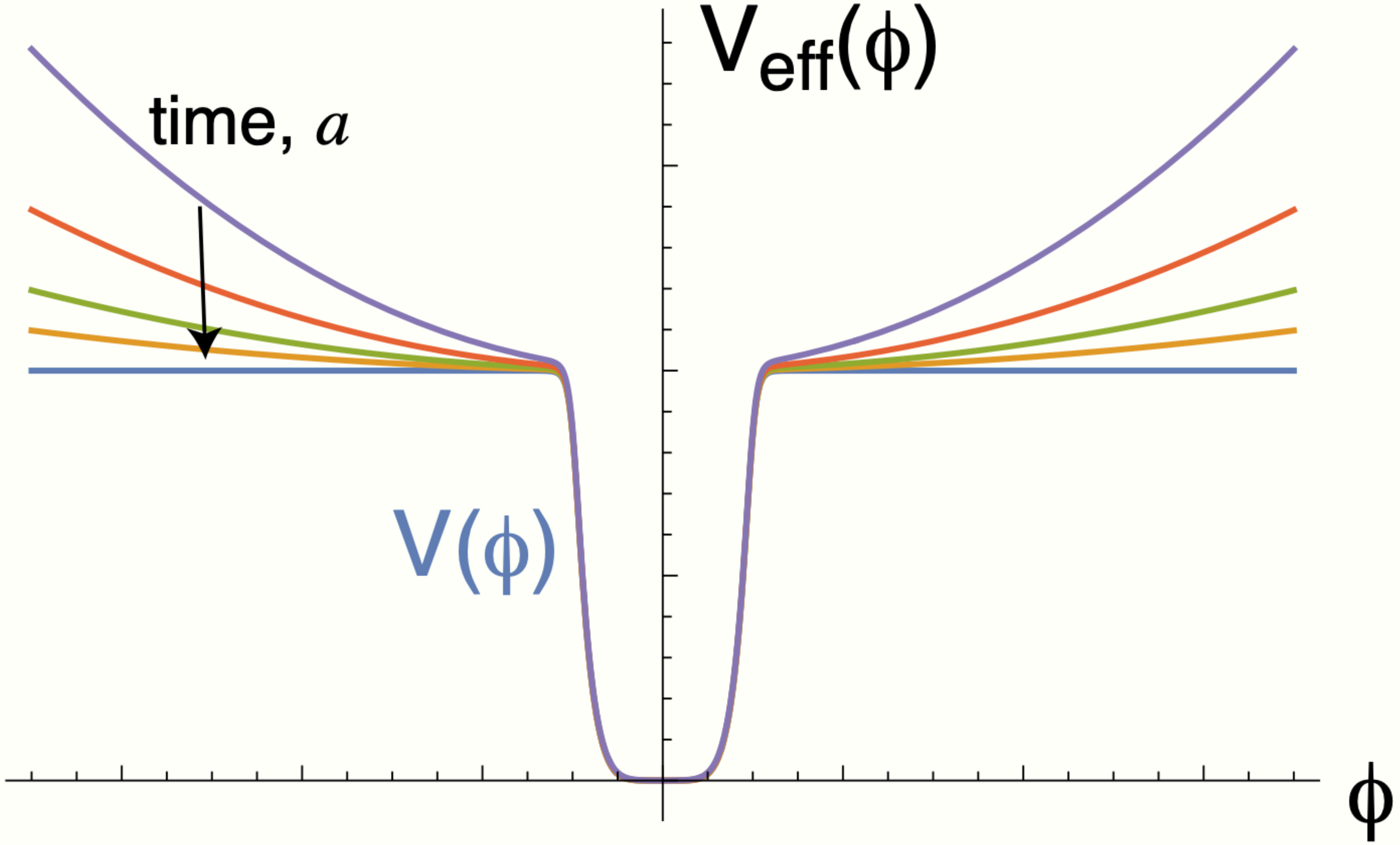
Lin, McDonough, JCH, Hu (in prep.)

Early Dark Sector 2

Colin Hill
Columbia/CCA

Toy solution

- Problem for acceptable $\Delta m_{\rm dm}/m_{\rm dm}$ and generic initial conditions, slope of bare potential too high to trigger off coupling
- Flatten the bare potential into a plateau and change $m(\phi)$, $V_{\rm eff} \propto \rho_{\rm dm}$ and overcomes Hubble drag near equality

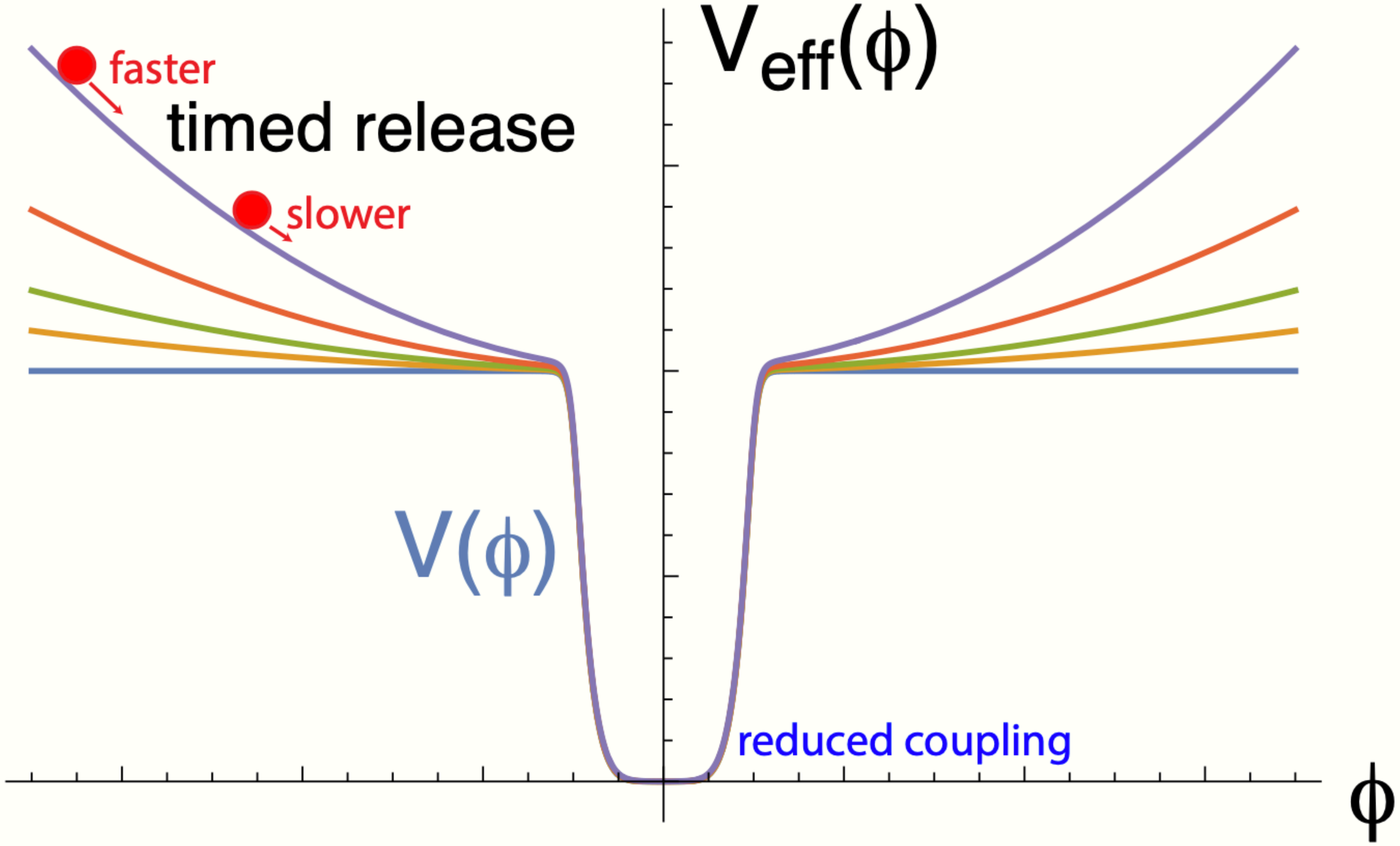


Lin, McDonough, JCH, Hu (in prep.)

Early Dark Sector 2

Toy 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 $\phi \to 0$

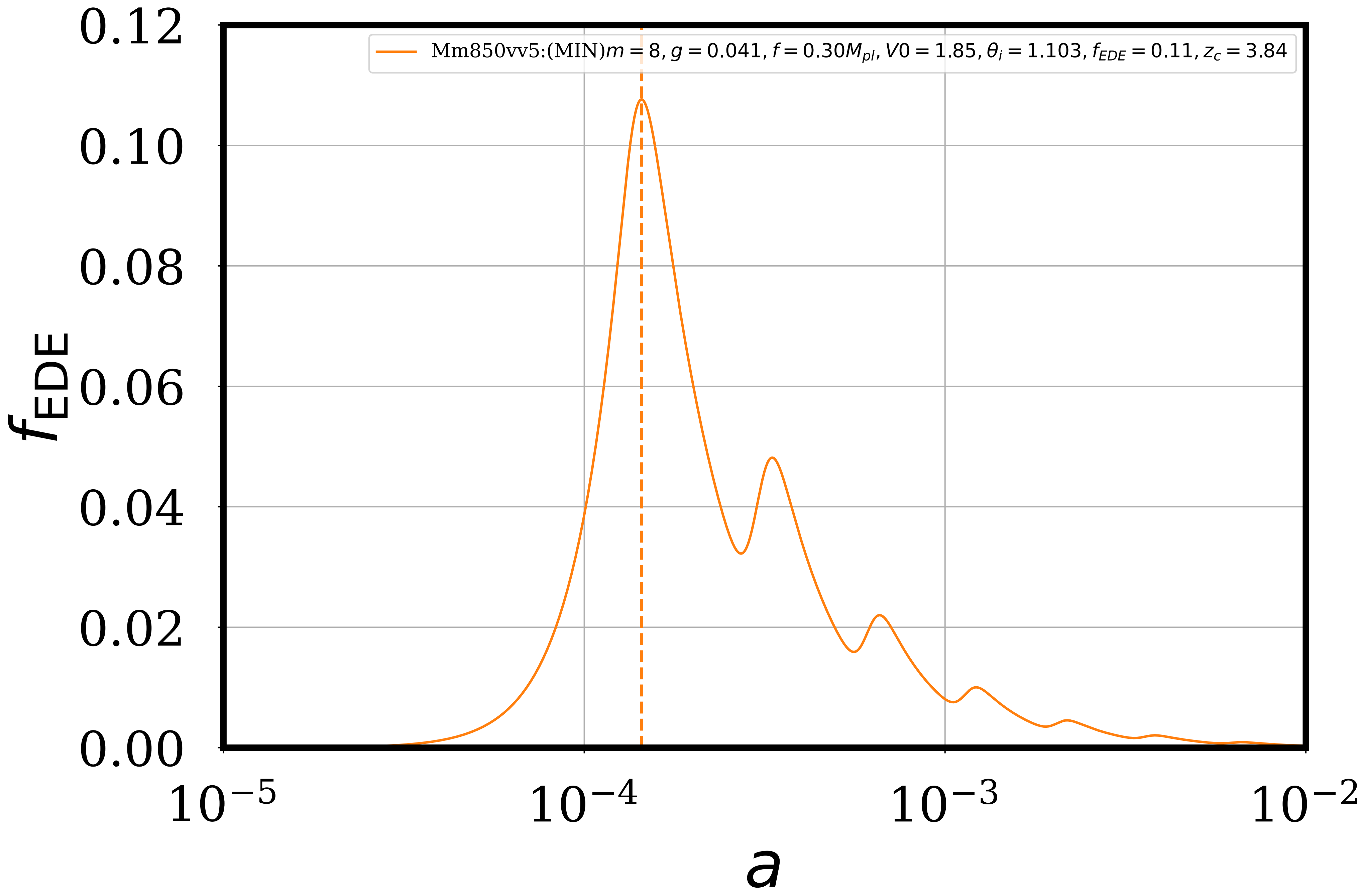


Lin, McDonough, JCH, Hu (in prep.)

Early Dark Sector 2

Colin Hill
Columbia/CCA

Basic validation: can successfully lower r_s, raise H_0 ~ 70.5 km/s/Mpc

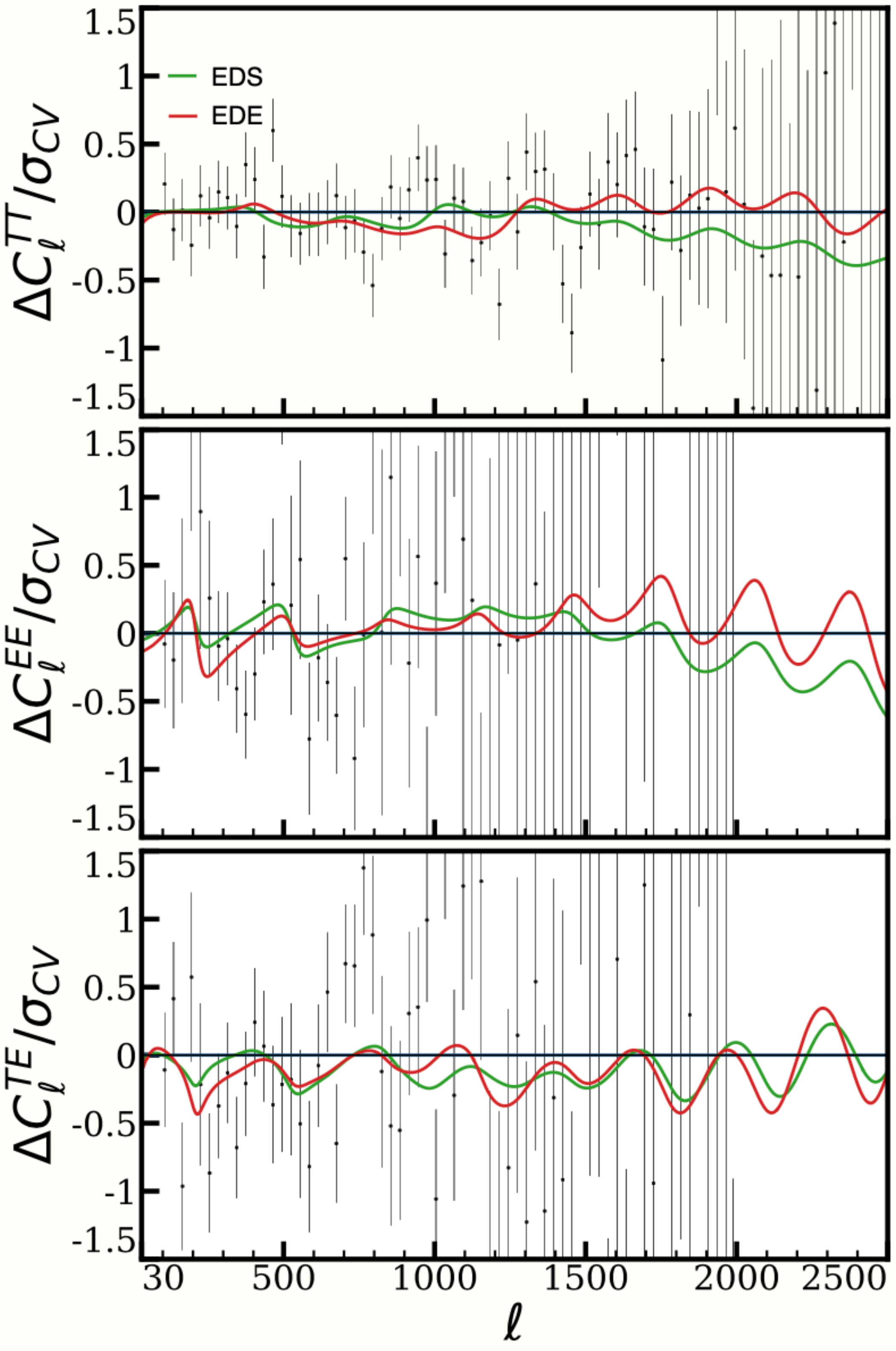


Lin, McDonough, JCH, Hu (in prep.)

Early Dark Sector 2

However:

- Simple toy model achieves $H_0 > 70$ (better fit than ΛCDM but not as good as EDE)
- Even larger H_0 produces too large changes to gravitational driving for CMB acoustic modes around $\ell \sim 500$ (See also Lin, Hu, Raveri 2009.08974)
- Potentially related to A_L anomaly (TT peaks too smooth)
- Incidental or fundamental? rolling in the effective



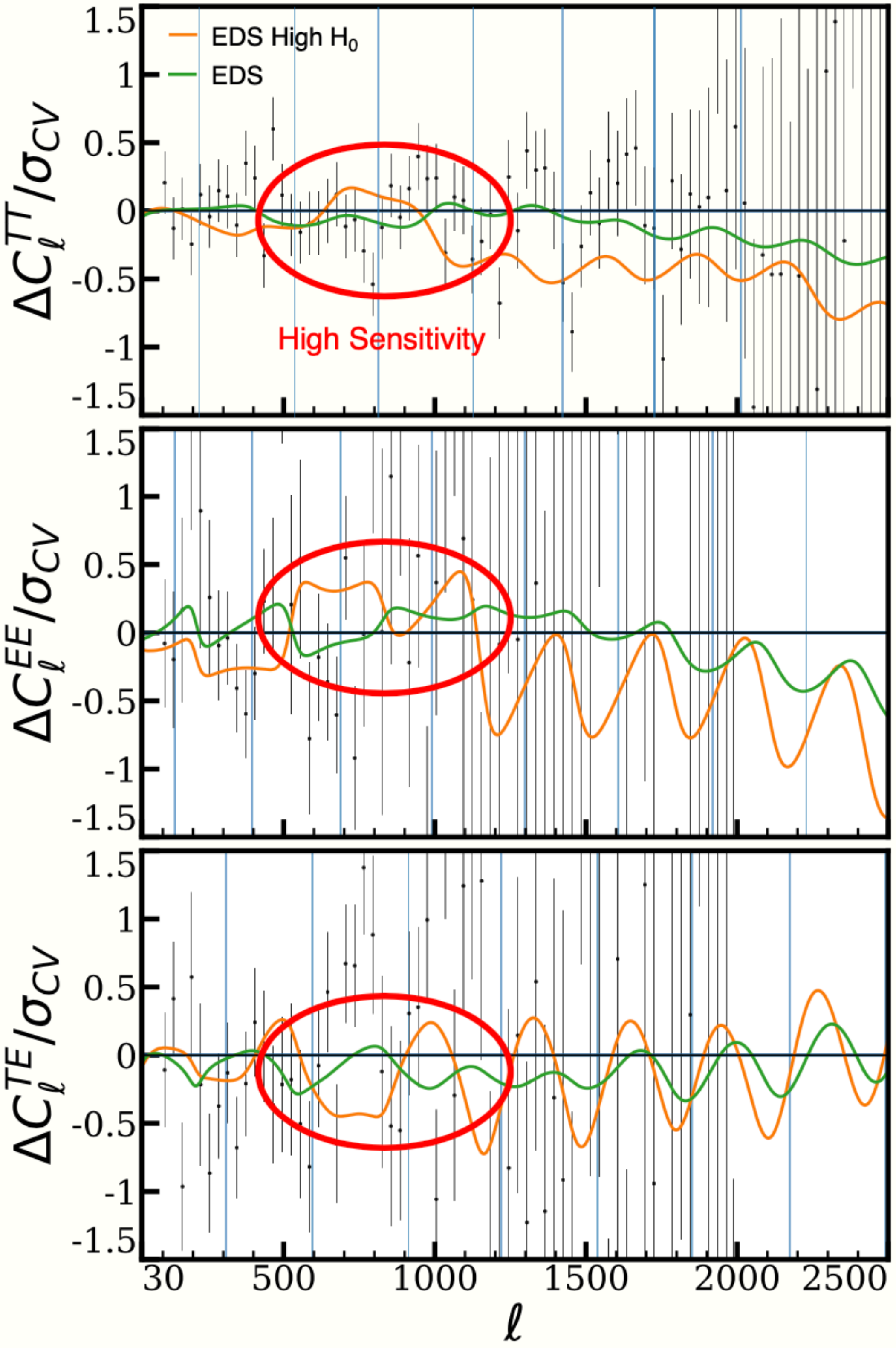
Lin, McDonough, JCH, Hu (in prep.)

Early Dark Sector 2

Colin Hill
Columbia/CCA

However:

- Simple toy model achieves $H_0 > 70$ (better fit than ΛCDM but not as good as EDE)
- Even larger H_0 produces too large changes to gravitational driving for CMB acoustic modes around $\ell \sim 500$ (see also Lin, Hu, Raveri 2009.08974)
- Potentially related to $A_{\rm L}$ anomaly (TT peaks too smooth)
- Incidental or fundamental? rolling in the effective potential produces problematic field fluctuations



W.I.P.

Next: ACT DR6

Colin Hill
Columbia/CCA

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

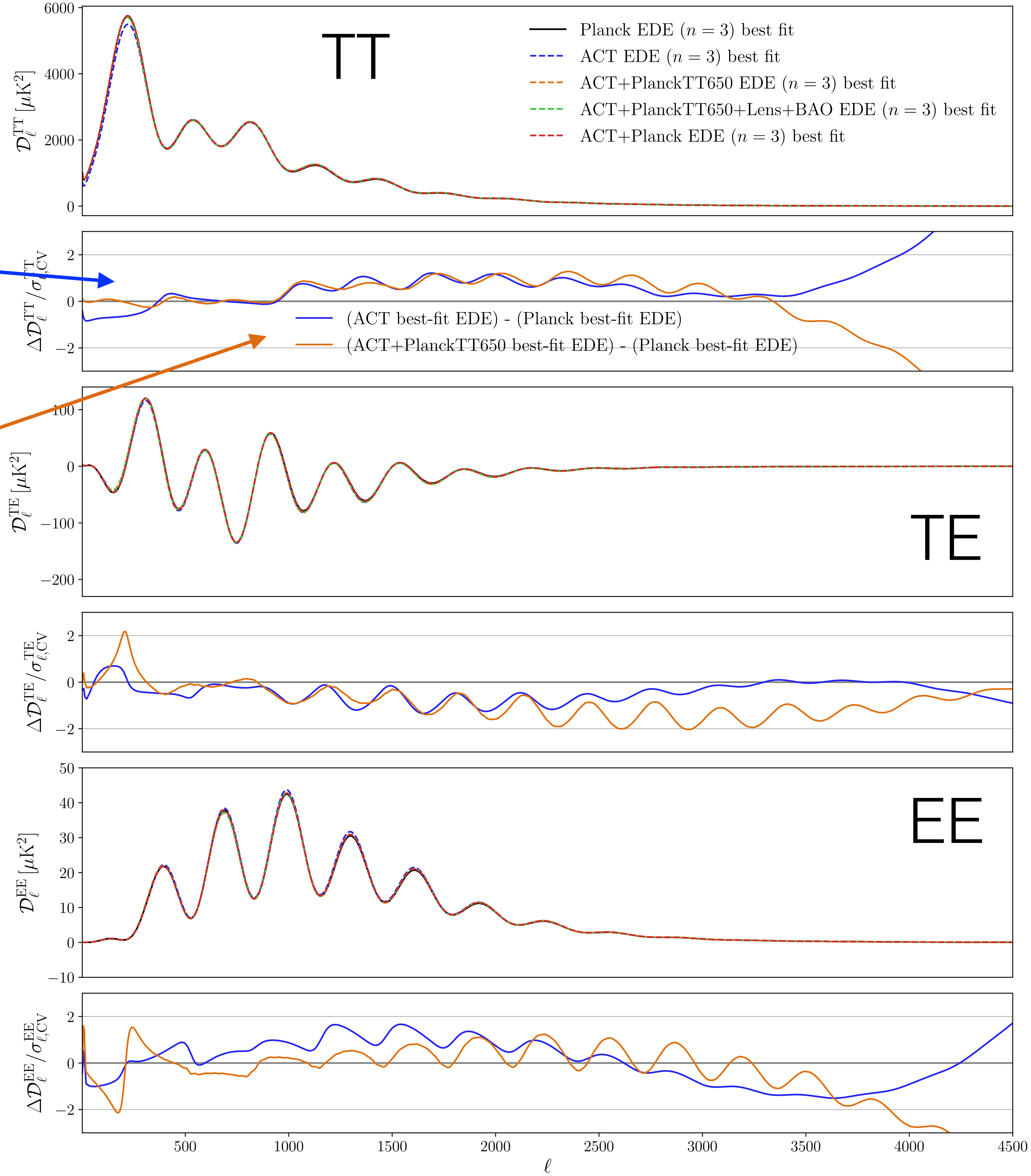
JCH et al. (2021)

Discovering EDE in the CMB

Colin Hill
Columbia/CCA

ACT best-fit EDE -
Planck EDE

ACT+P18TT650 EDE -
Planck EDE

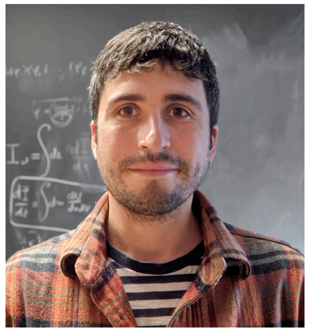


Imminent potential discovery with upcoming ACT DR6 (~2023): the models shown here can be distinguished at ~20σ

JCH et al. (2021)

Post-Recombination Reheating (PRR)

JCH & B. Bolliet (to appear)



H_0 and $T_{CMB,0}$

H_0 tension or T_0 tension?

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

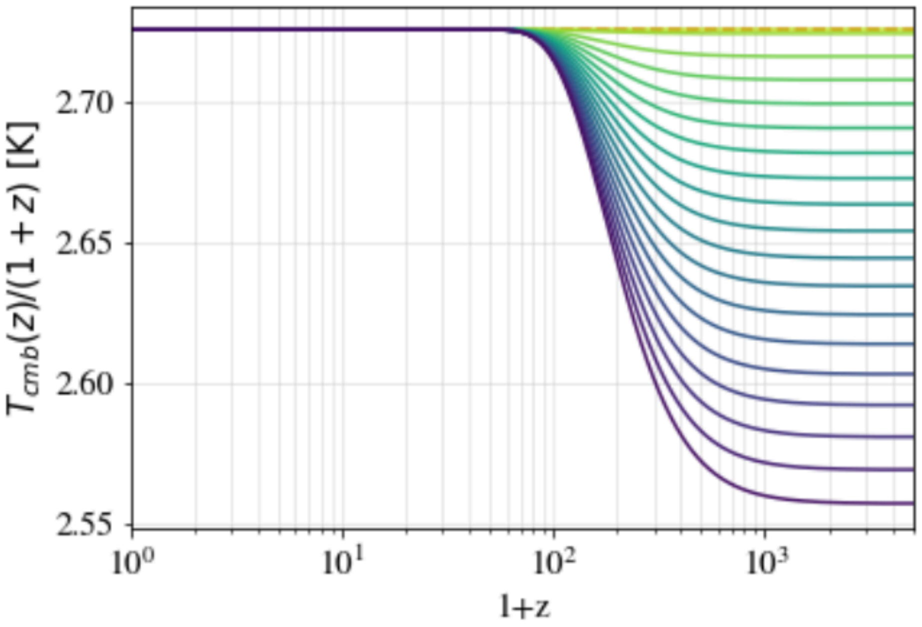
- Cosmology would be very different without COBE-FIRAS!
- Ignoring FIRAS, Planck+SH0ES can be fit with $T_{CMB,0}$ = 2.56 +/- 0.05 K
- BAO breaks degeneracies: Planck + BAO yield $T_{CMB,0}$ = 2.71 +/- 0.02 K
- FIRAS result: $T_{CMB,0}$ = 2.72548 +/- 0.00057 K
- Can we build on this idea while maintaining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

Ivanov, Ali-Haimoud, & Lesgourgues (2020)

Colin Hill
Columbia/CCA

Did the Universe (Slightly) Reheat after Recombination?

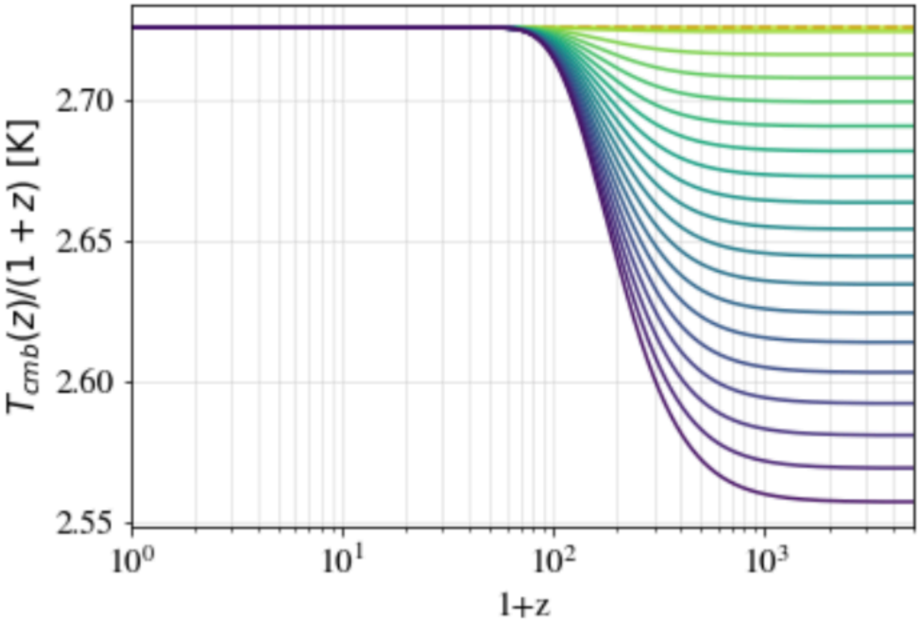
- Suppose $T_{CMB}(z^*) < T_{CMB}(z^*)^{\Lambda CDM}$, but a process injects energy at $z < z^*$



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

Did the Universe (Slightly) Reheat after Recombination?

- 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

- 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 z^{*} increases, one must increase H_0 to compensate otherwise increased value of the integrand:

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

- To keep k_{eq} fixed, Ω_m must decrease, and hence S_8 decreases

Did the Universe (Slightly) Reheat after Recombination?

Colin Hill
Columbia/CCA

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 & Bolliet (to appear)

Colin Hill
Columbia/CCA

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%)

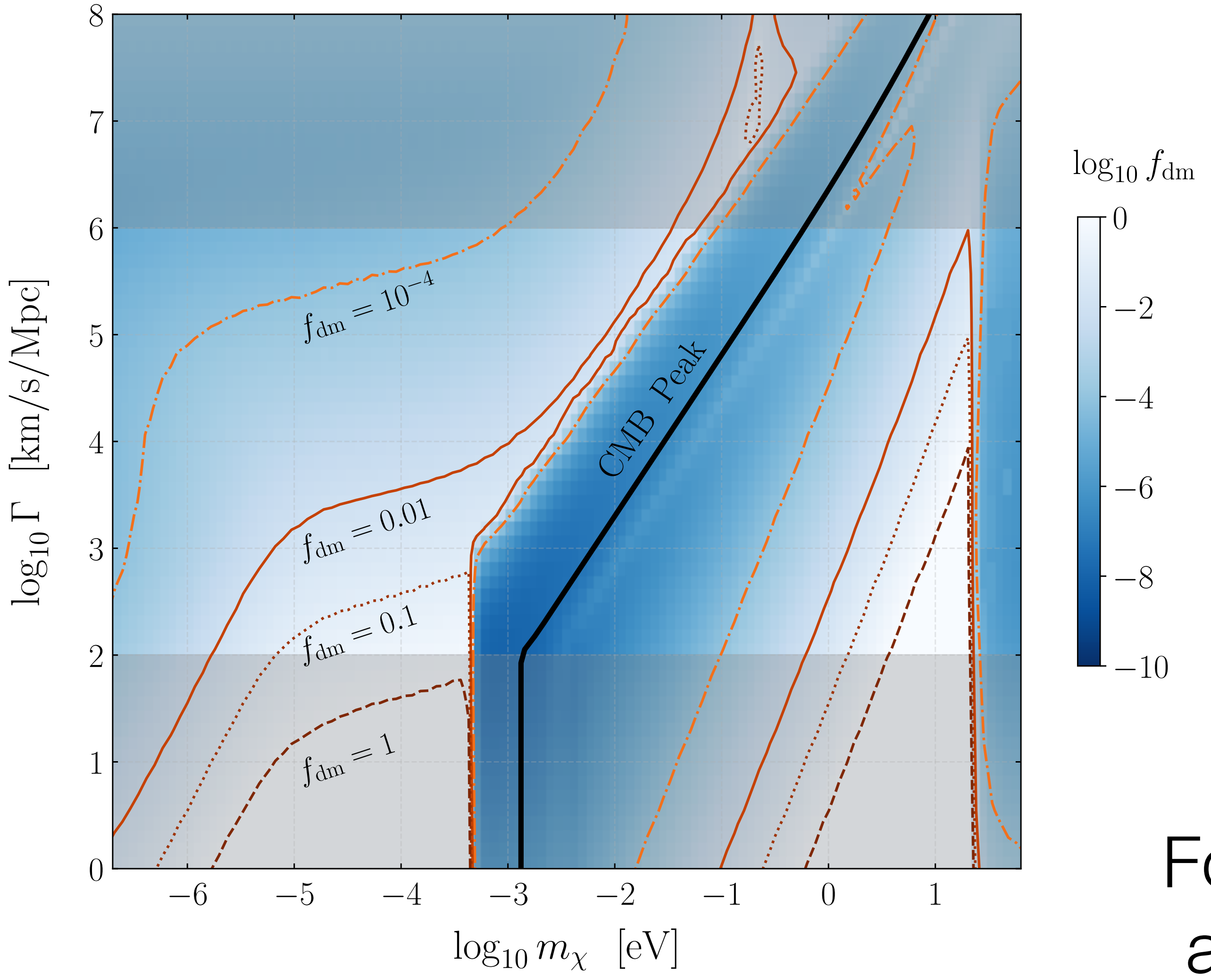
JCH & Bolliet (to appear)

Colin Hill
Columbia/CCA

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?

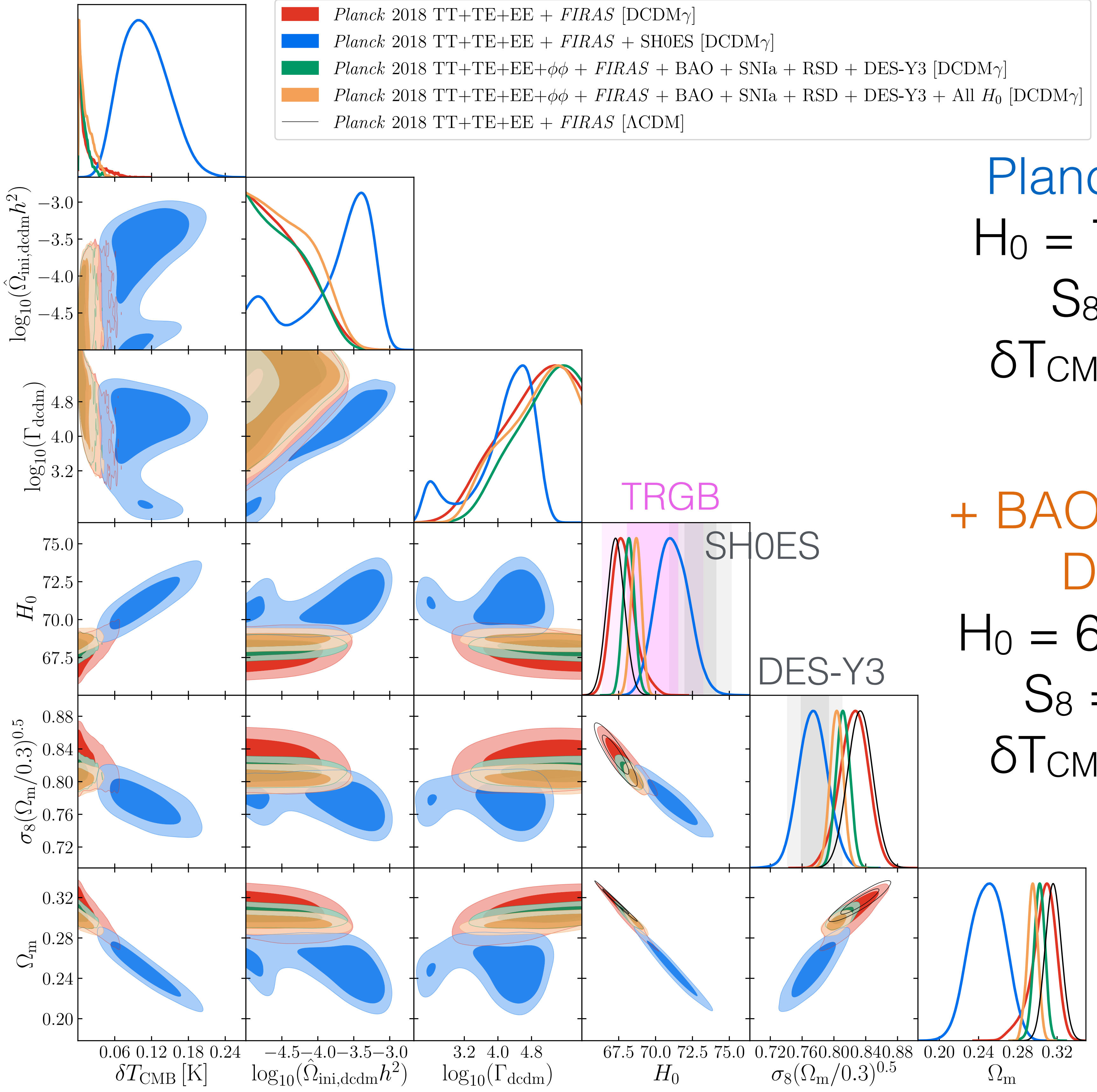


f_{DM} = fraction of DM that decays

For simplicity here, we assume that injected photons are thermal

JCH & Bolliet (to appear); Bolliet, Chluba, & Battye (2021)

PRR Analysis



Planck + FIRAS + SH0ES:

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

S_8 = 0.774 +/- 0.018

$\delta T_{CMB} = 0.109^{+0.033}_{-0.044}$ K

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

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

S_8 = 0.8035 +/- 0.0081

$\delta T_{CMB} = 0.013^{+0.004}_{-0.013}$ K

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

Colin Hill
Columbia/CCA

PRR Analysis

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)

- Such a model fits data better than ΛCDM+N_{eff}, but not dramatically

- 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 need to measure CMB spectral distortions much better than FIRAS! Strong motivation for PIXIE, FOSSIL, BISOU +++

JCH & Bolliet (to appear)

Take-Home Messages

1) ACT and Planck prefer somewhat different EDE model parameters, with ACT yielding higher H_0
2) Early dark sector may help w/ S_8, coincidence, ICs of EDE
3) Small post-recombination reheating is allowed by data and moves H_0 and S_8 in the 'right direction'
4) Early(ish)-universe H_0 / S_8 resolutions generically predict clear deviations from ΛCDM in the CMB — imminently testable with ACT DR6

Photo: D. Kellner

Thanks!

Bonus

ACT DR4 Cosmology

Colin Hill
Columbia/CCA

ACT: completely independent check of WMAP and Planck results

ΛCDM Parameter Refresher:

- baryon density
- cold dark matter density
- angular acoustic scale
- primordial fluctuation amplitude
- primordial spectral index
- optical depth (reionization)

Derived Parameters:

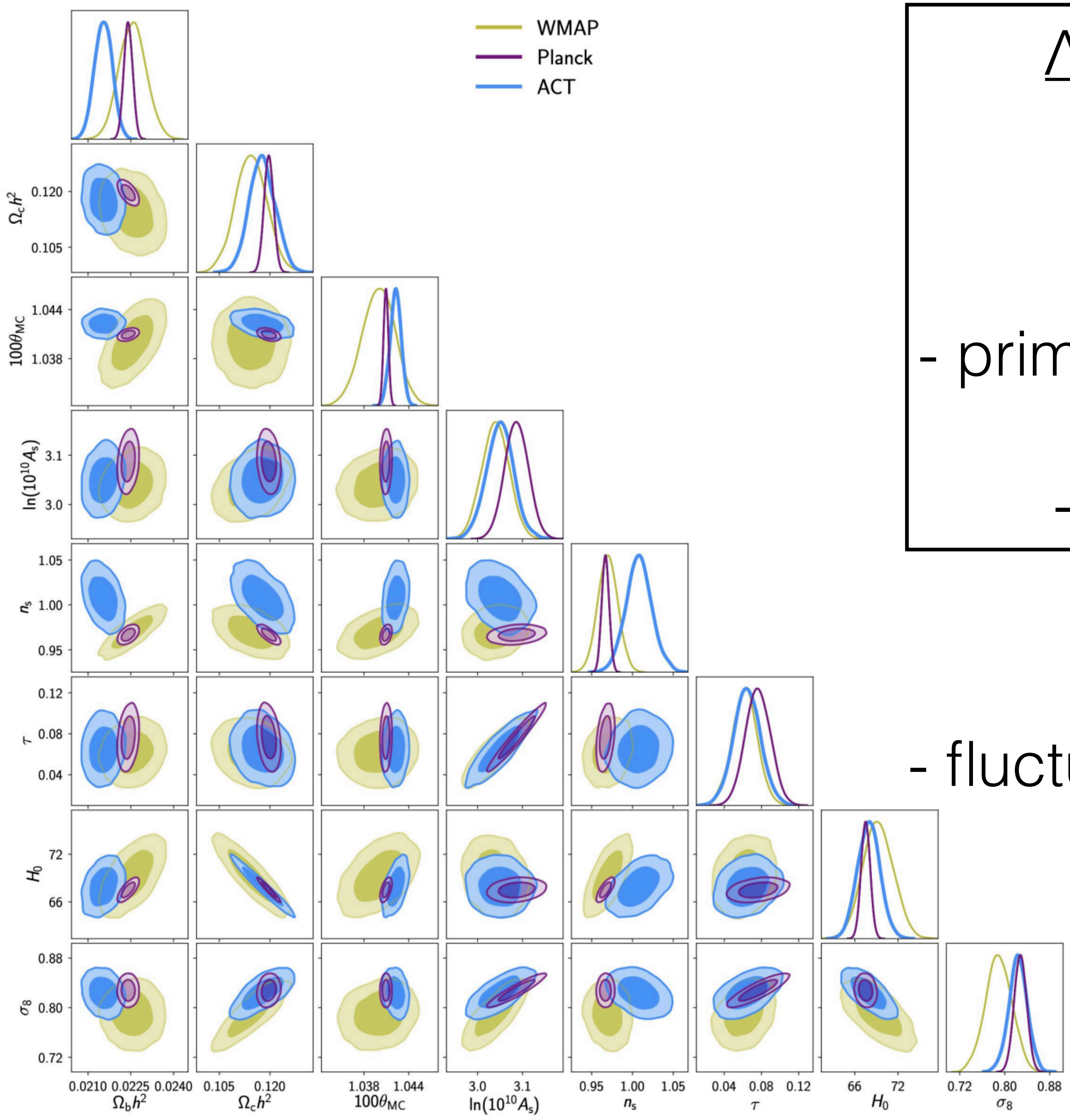
- Hubble constant (H_0)
- fluctuation amplitude at z=0 (σ_8)

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

Colin Hill
Columbia/CCA

ACT DR4 Cosmology

ACT: completely independent check of WMAP and Planck results



ΛCDM Parameter Refresher:

- baryon density
- cold dark matter density
- angular acoustic scale
- primordial fluctuation amplitude
- primordial spectral index
- optical depth (reionization)

Derived Parameters:

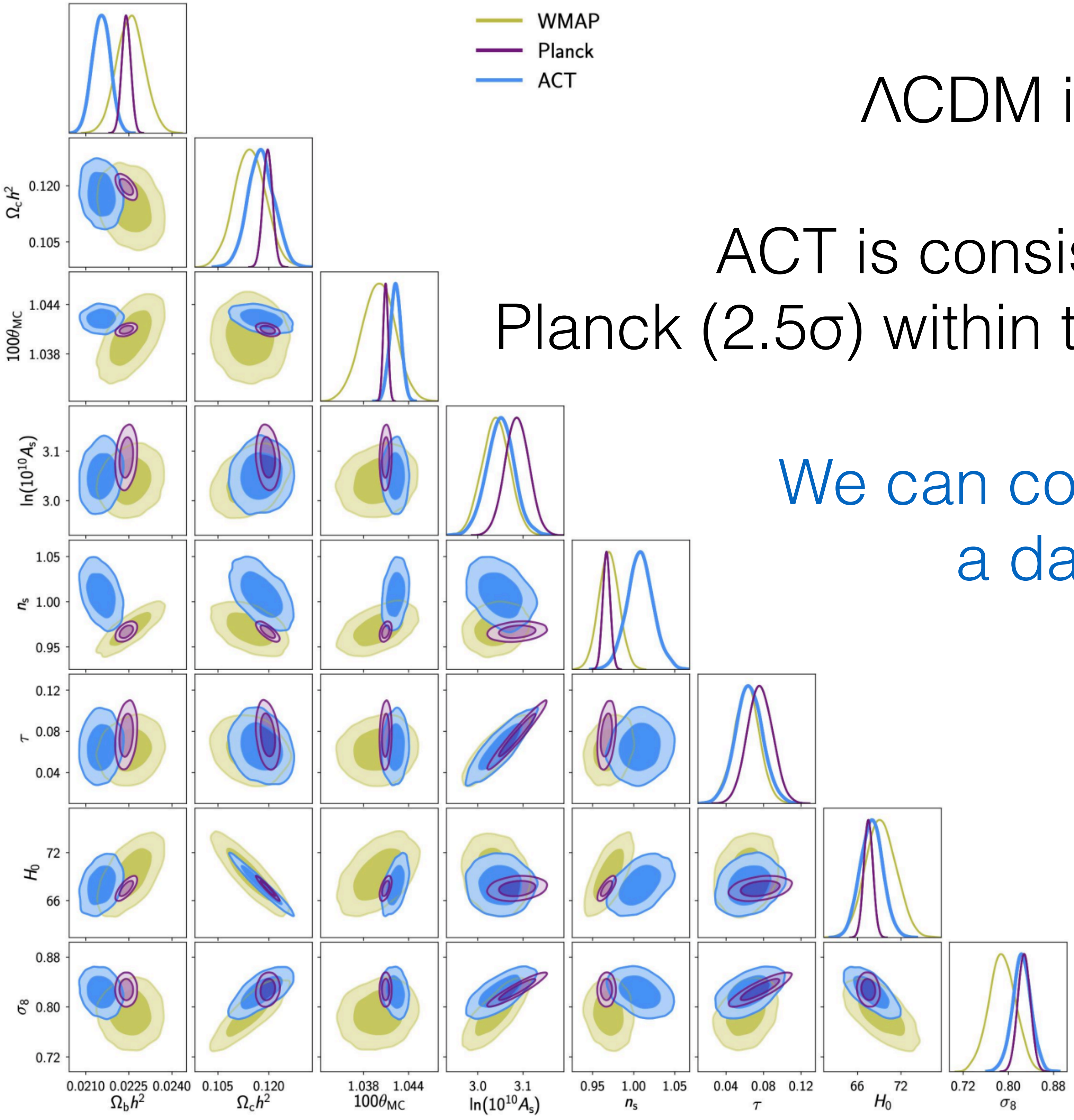
- Hubble constant (H_0)
- fluctuation amplitude at z=0 (σ_8)

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

ACT DR4 Cosmology

Colin Hill
Columbia/CCA

ACT: completely independent check of WMAP and Planck results



ΛCDM is a good fit to the ACT data

ACT is consistent with WMAP (2.4σ) and Planck (2.5σ) within the ΛCDM parameter space

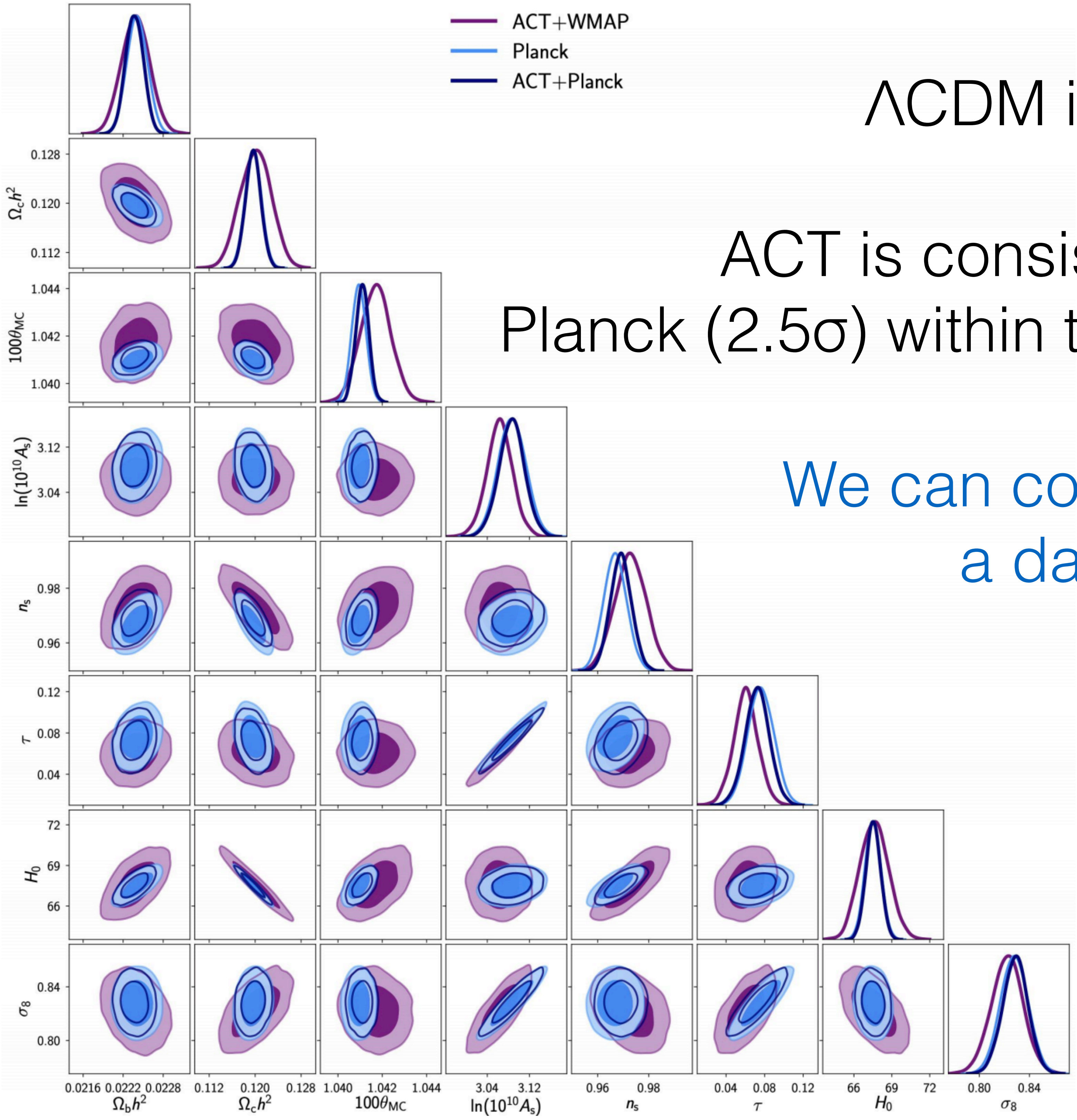
We can combine ACT+WMAP to form a data set with statistical power approaching Planck

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

ACT DR4 Cosmology

Colin Hill
Columbia/CCA

ACT(+WMAP): completely independent check of Planck results



ΛCDM is a good fit to the ACT data

ACT is consistent with WMAP (2.4σ) and Planck (2.5σ) within the ΛCDM parameter space

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

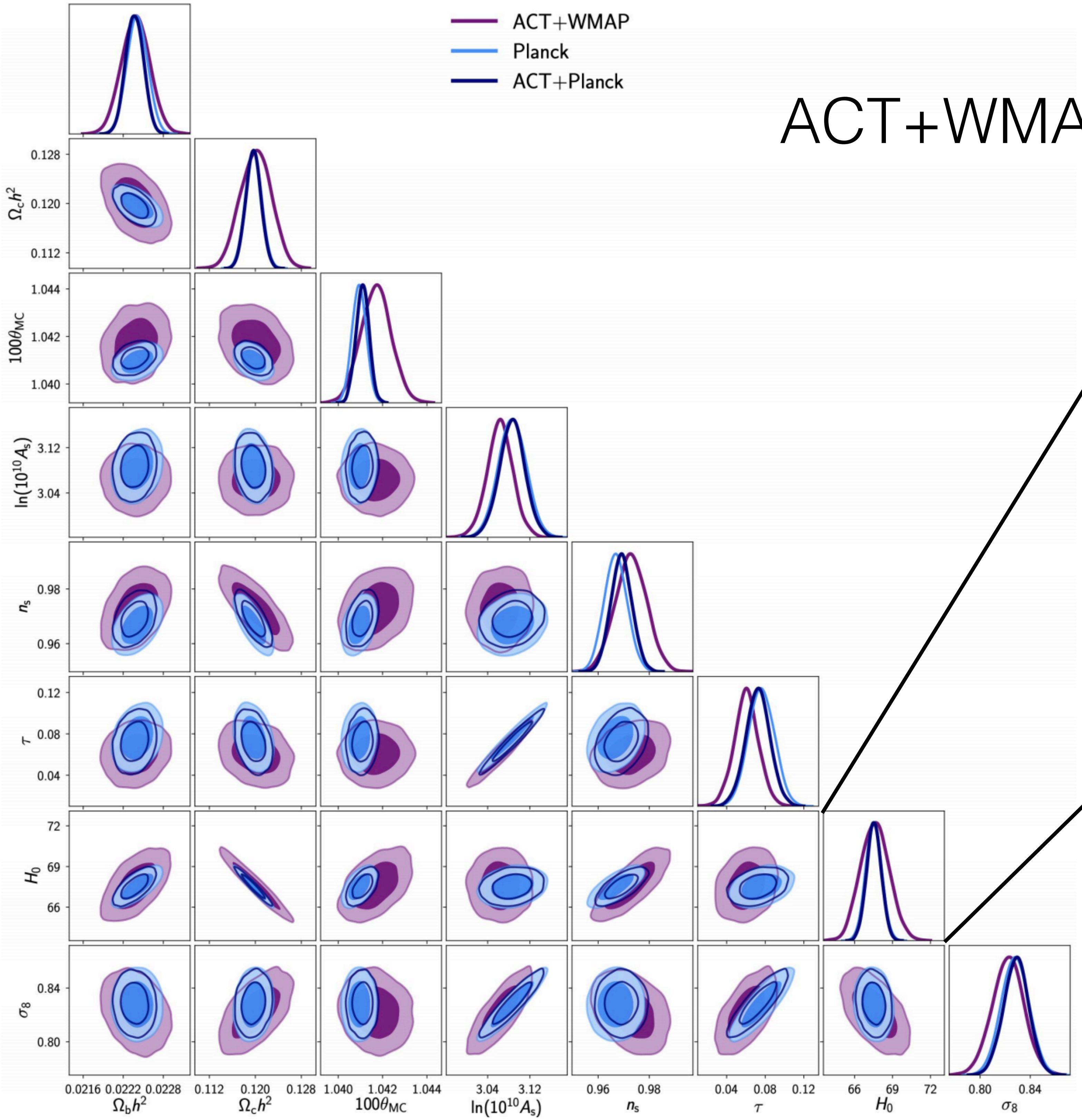
ACT+WMAP is in excellent agreement with Planck (within ΛCDM)

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

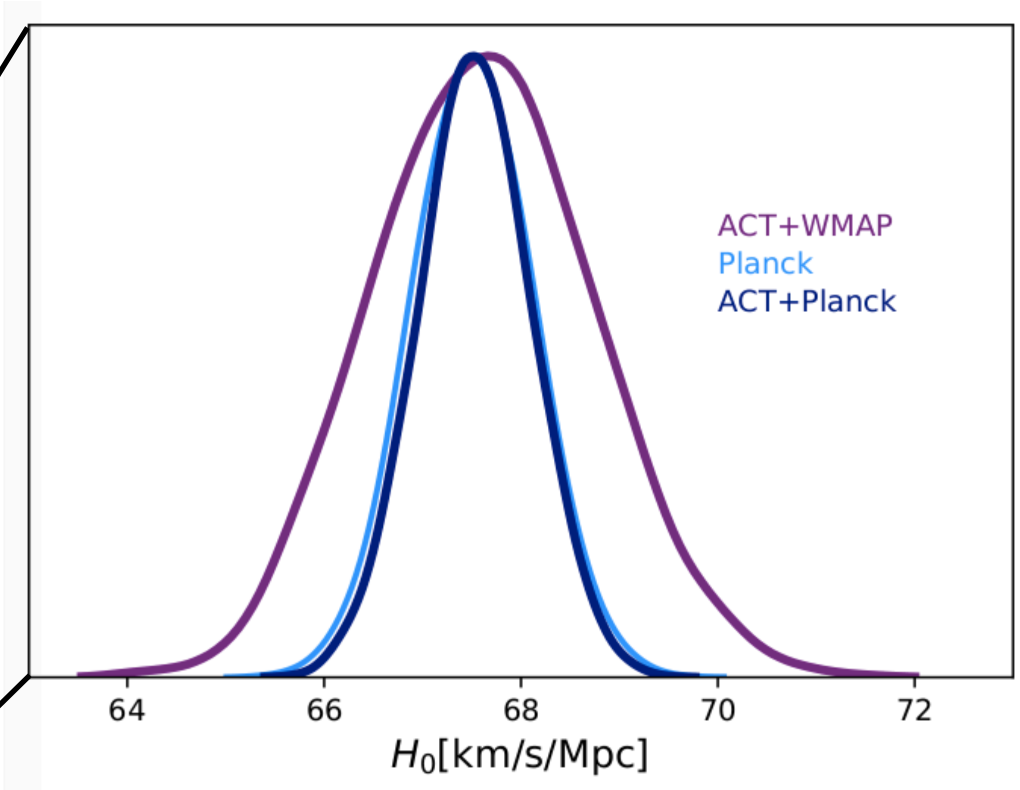
Colin Hill
Columbia/CCA

ACT DR4 Cosmology

ACT(+WMAP): completely independent check of Planck results



ACT+WMAP is in excellent agreement with Planck (within ΛCDM)



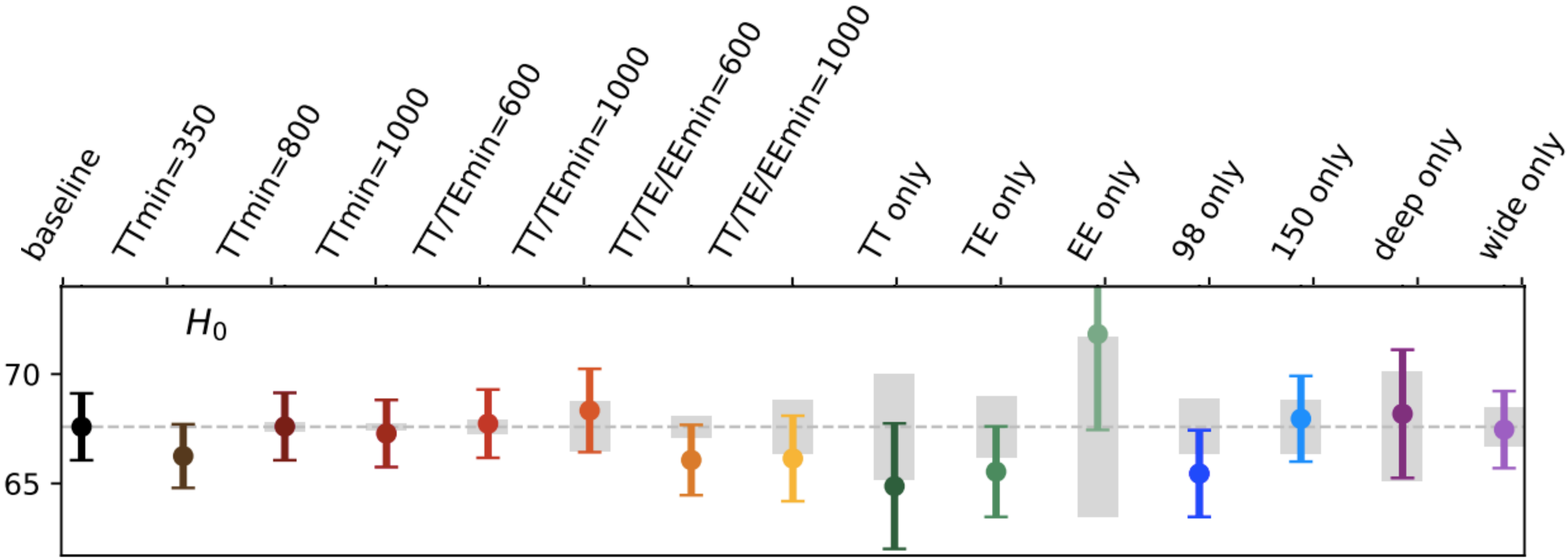
H_0=67.6±1.1 km/s/Mpc	*ACT+WMAP*
H_0=67.9±1.5 km/s/Mpc	*ACT*
H_0=67.5±0.6 km/s/Mpc	*Planck*

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

Colin Hill
Columbia/CCA

ACT DR4 Cosmology

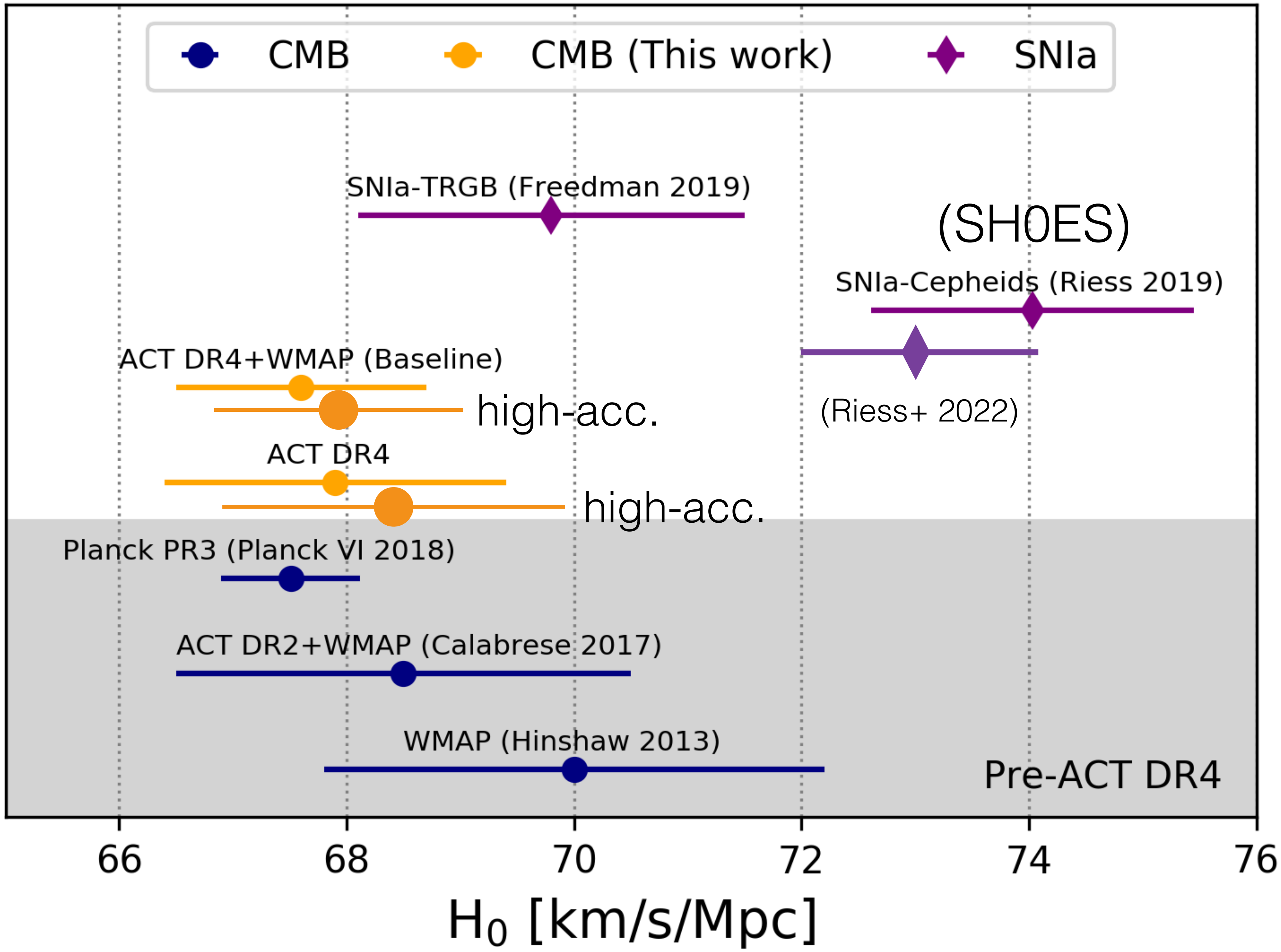
H_0 results are stable for a wide range of analysis choices



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

ACT DR4 Cosmology

Colin Hill
Columbia/CCA



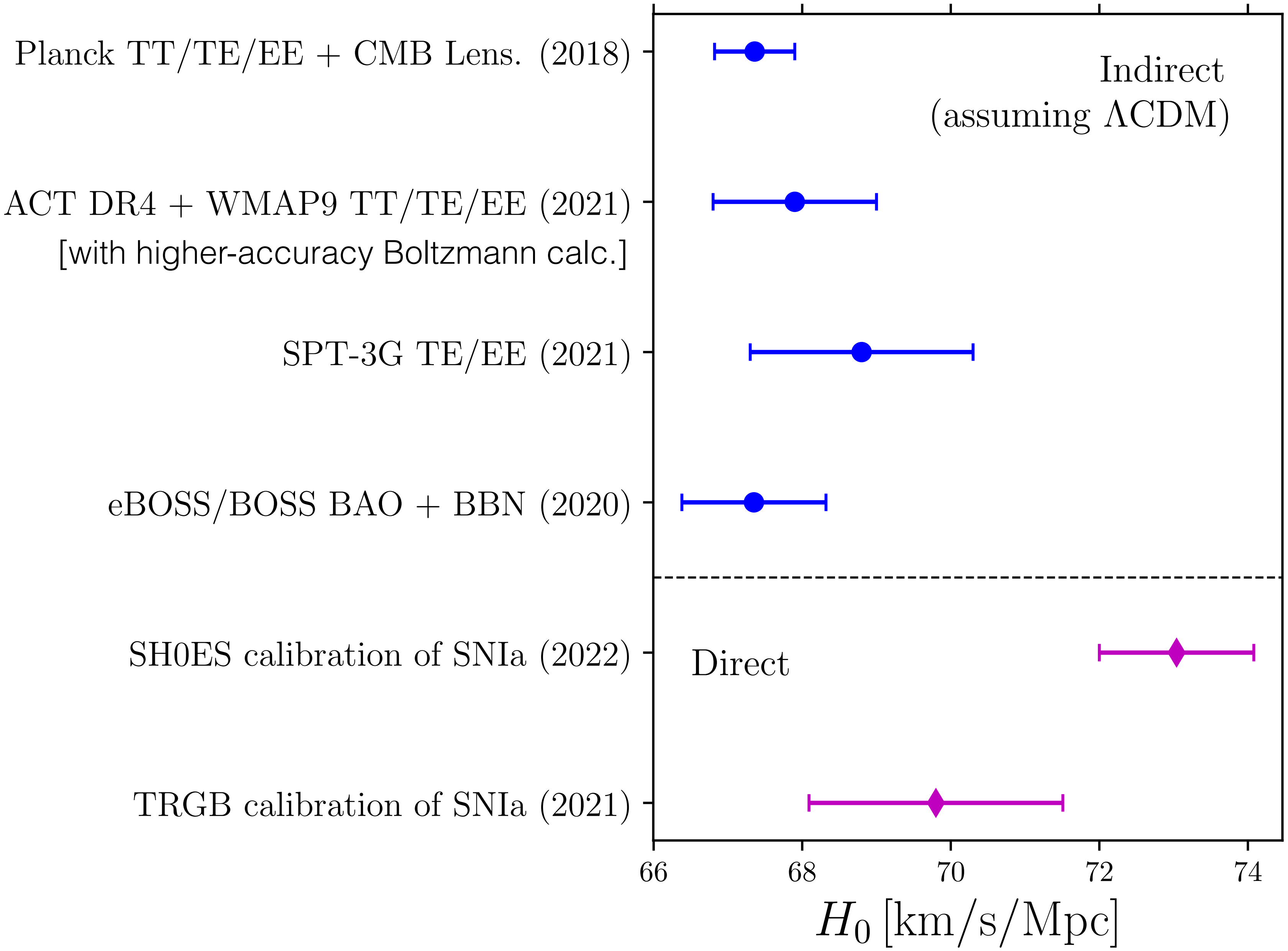
~3.4σ difference between ACT+WMAP (high-acc., ΛCDM) and Cepheid-calibrated SNIa (SH0ES 2022)

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

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

ACT DR4 Cosmology

Colin Hill
Columbia/CCA



~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)

Colin Hill
Columbia/CCA

Did the Universe (Slightly) Reheat after Recombination?

Linear perturbation theory

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

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

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

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

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

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

All terms containing Γ in photon perturbation equations are new

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

JCH & Bolliet (to appear)

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

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

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

Ivanov+ (2020); JCH & Bolliet (to appear)

Colin Hill
Columbia/CCA

Did the Universe
(Slightly) Reheat after Recombination?

Constraints on light particles coupled to photons from, e.g., white dwarf lifetimes can be evaded by formulating the model using 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

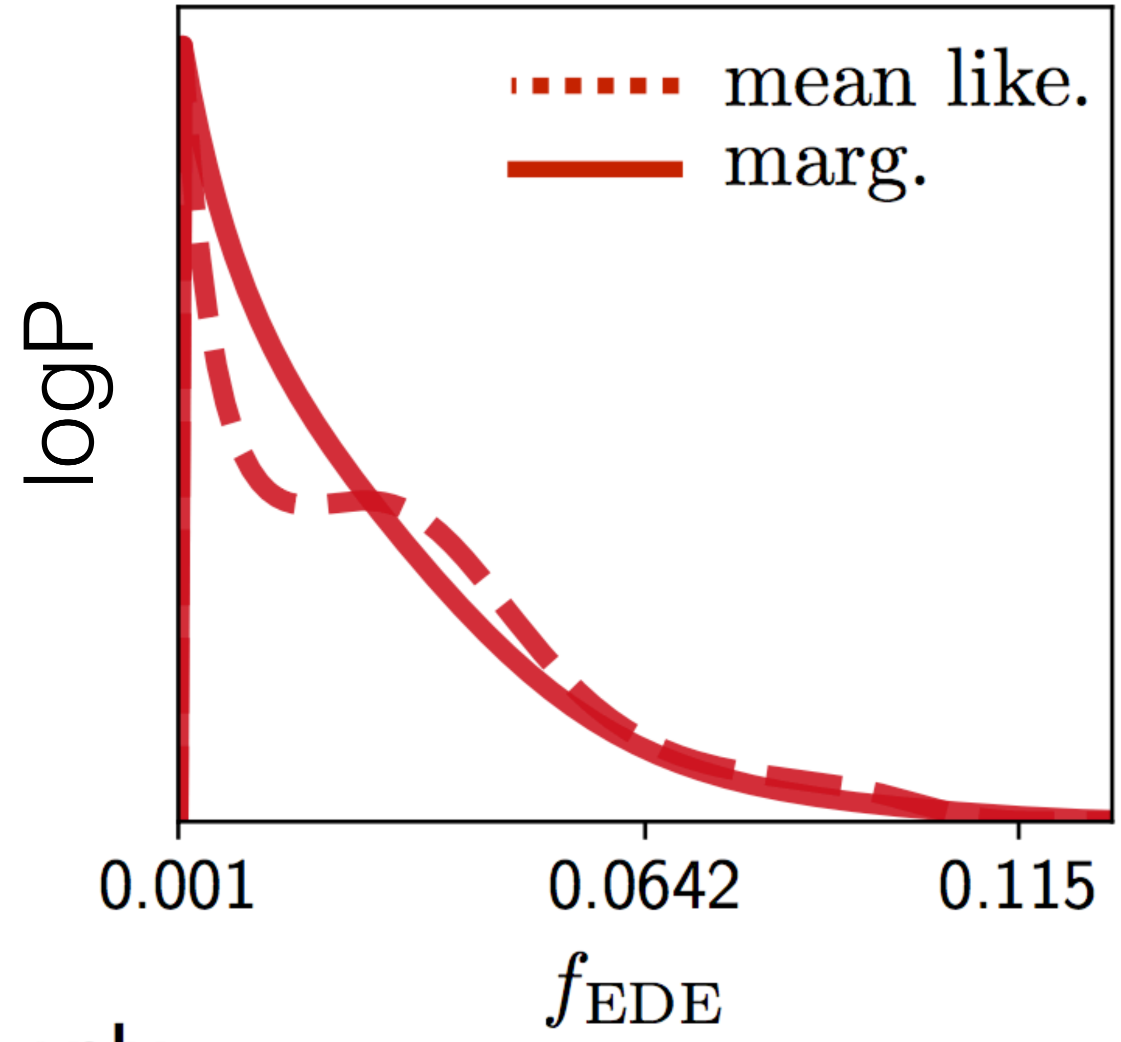
If m_{DP} > MeV, it is not produced in stars or supernovae

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

(e.g.) Baryakhtar+ (2020)

Prior Volume Effects?

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



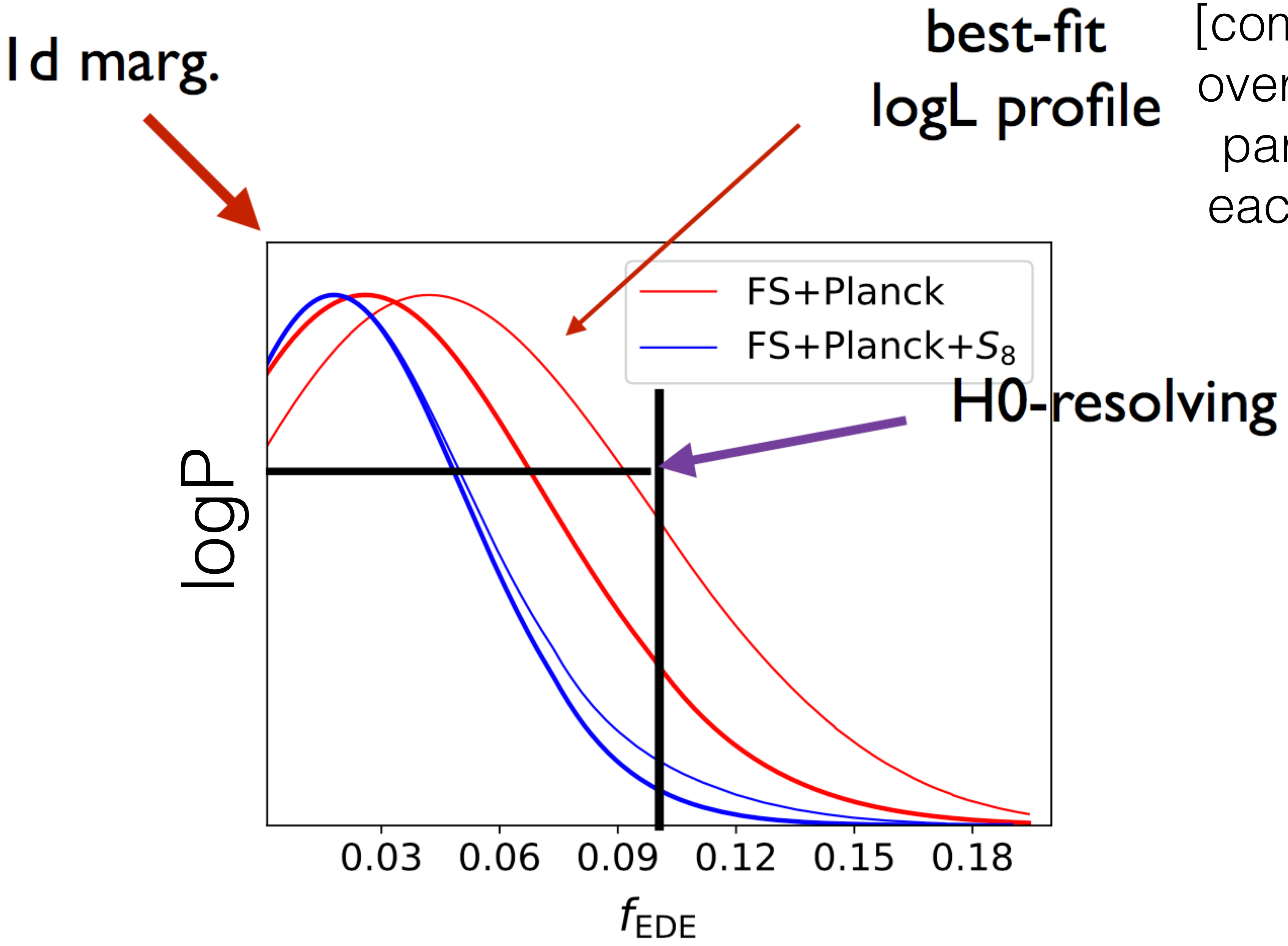
mean like. = [compute average log(likelihood), averaging over all the other parameters, at each f_{EDE} value]

FS+Planck only

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

Prior Volume Effects?

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

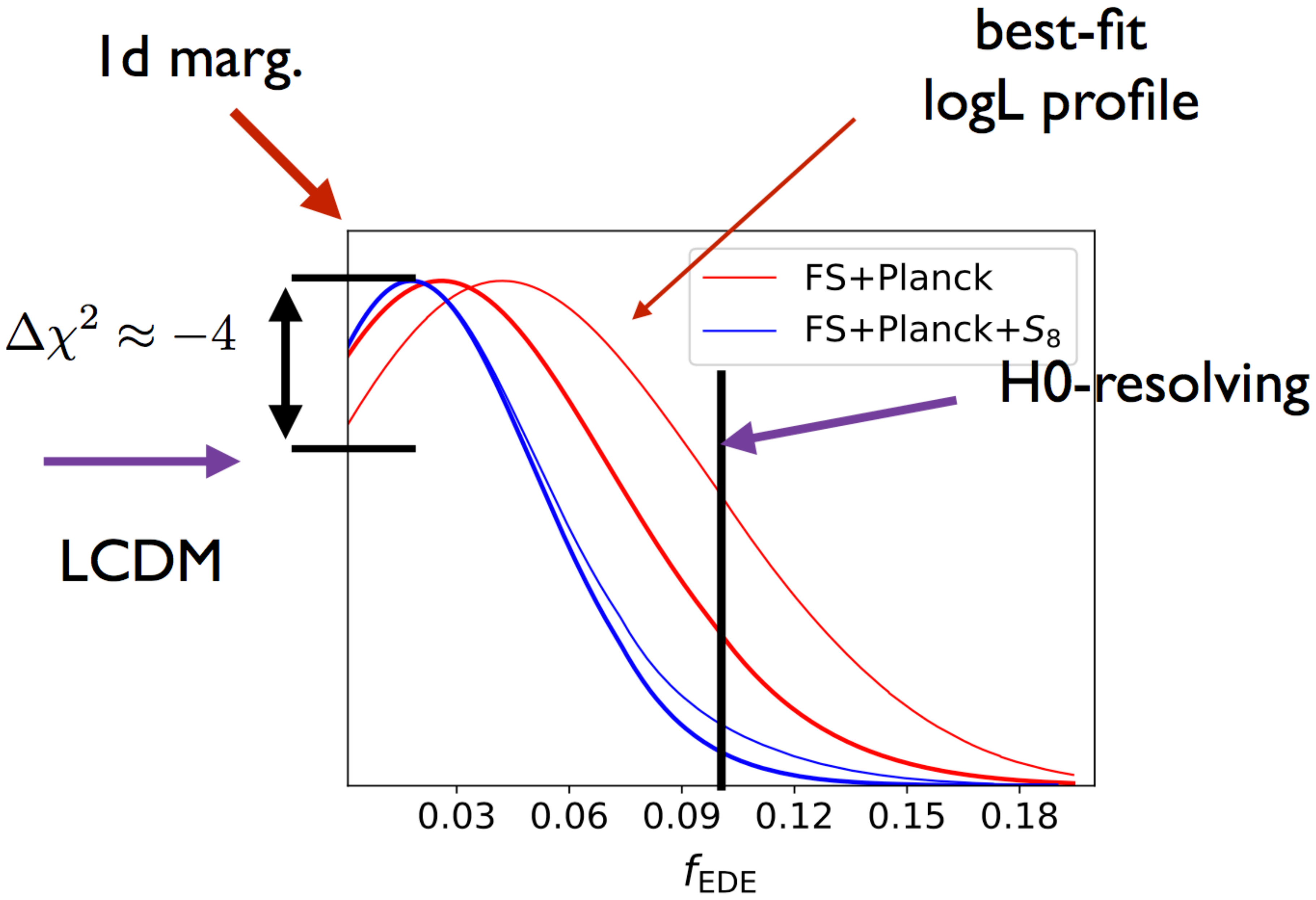


[compute best-fit over all the other parameters, at each $f_{\rm EDE}$ value]

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

Prior Volume Effects?

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



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