Cosmological Constraints from ACT DR6 Power Spectra

Colin Hill

Columbia University

mm Universe
Chicago
26 June 2025

Calabrese & JCH, et al: 2503.14454
Louis et al: 2503.14452
Naess et al: 2503.14451
Beringue, Surrao, JCH, et al: 2506.06274

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ACT Power Spectra: Maps, Data, and Modeling

See Adri's talk from Monday morning session

Naess, Guan, Duivenvoorden, Hasselfield, Wang, et al. (2025), 2503.14451
Louis, La Posta, Atkins, Jense, et al. (2025), 2503.14452
Beringue, Surrao, JCH, et al. (2025), 2506.06274

CMB State of the Art

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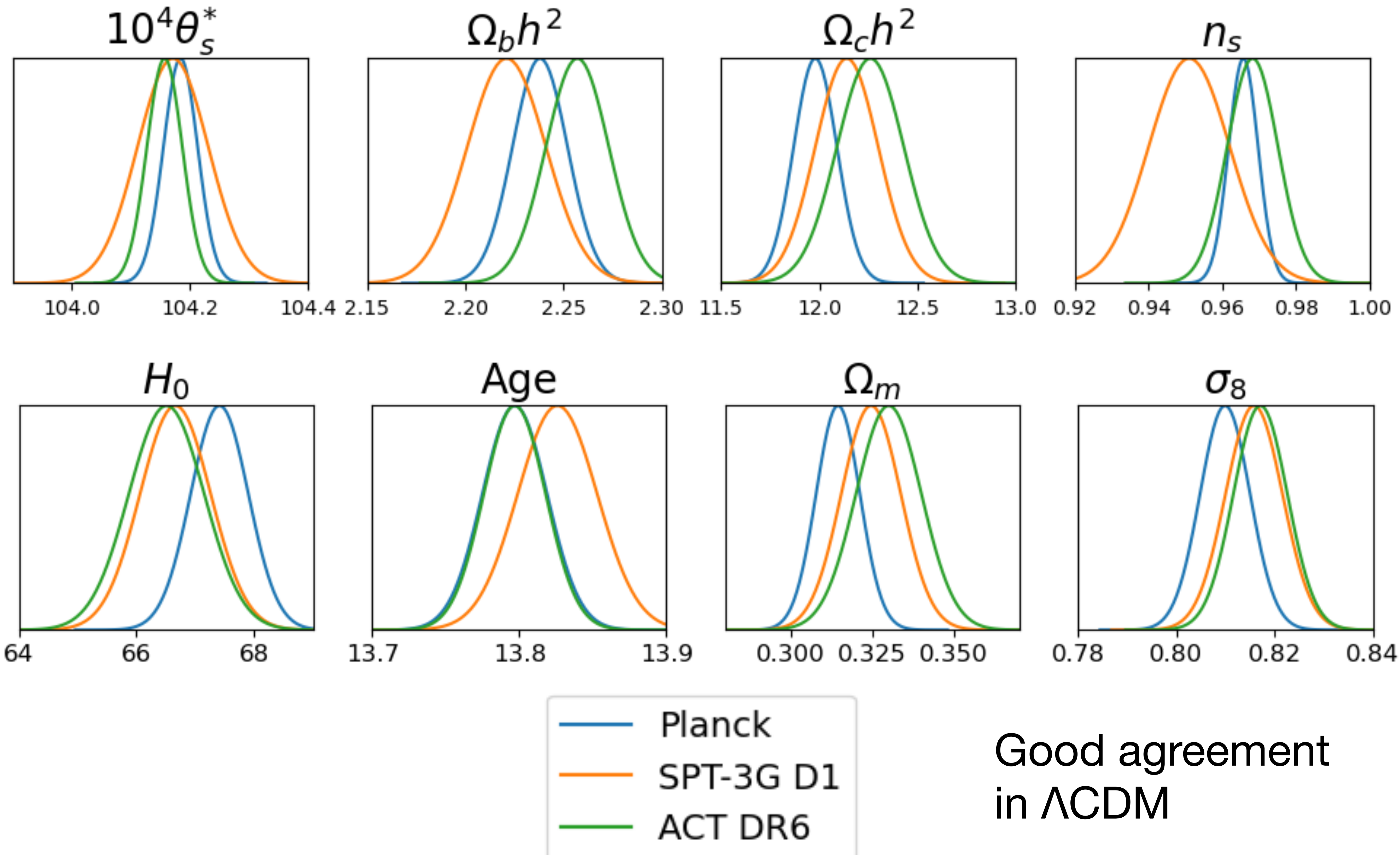
New since Monday: SPT-3G D1



Good agreement in ΛCDM

Multifrequency Power Spectra

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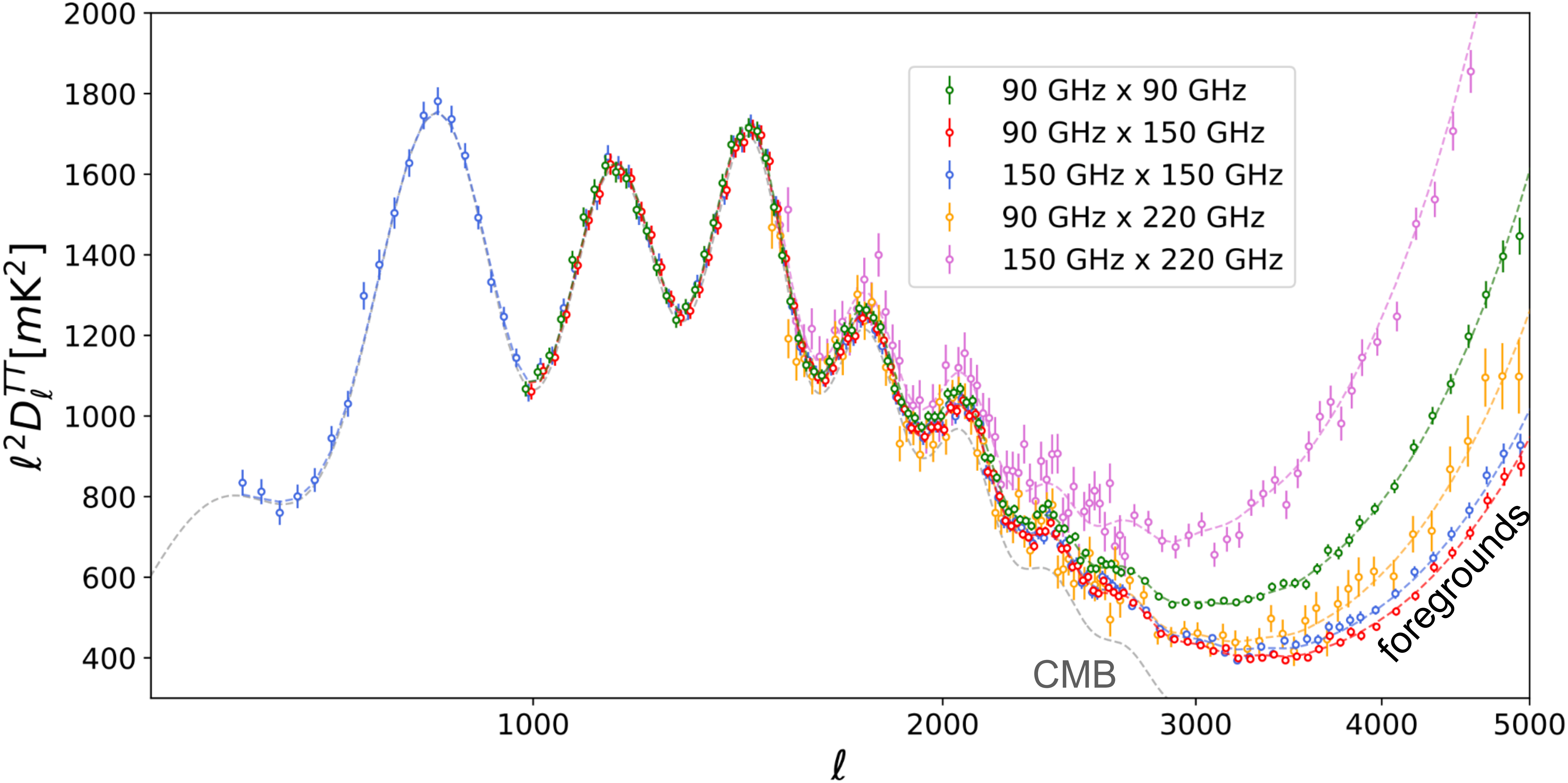
The CMB is not the only astrophysical signal that we observe

Foregrounds distinguished by non-blackbody frequency dependence



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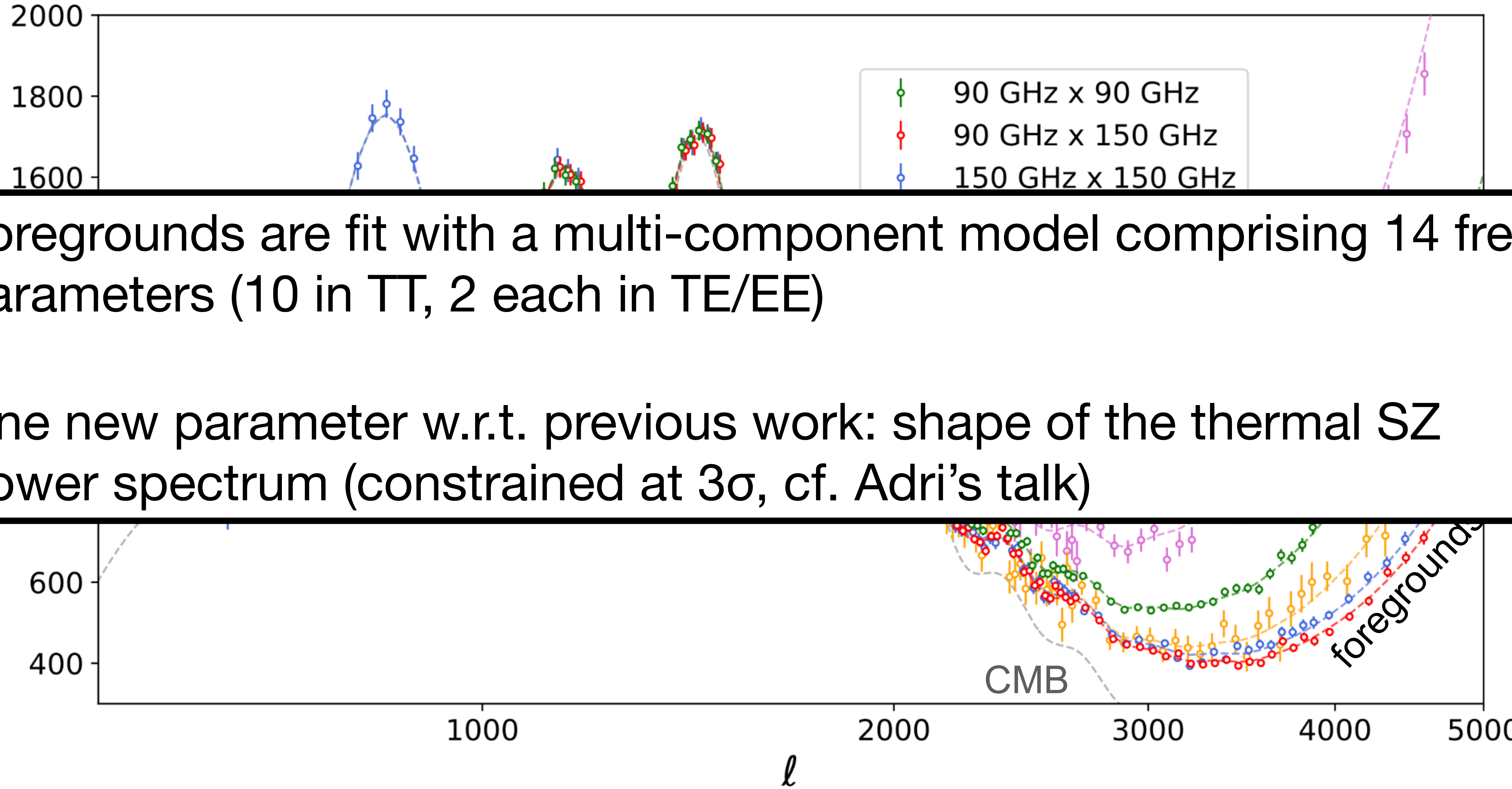
Multifrequency Power Spectra

The CMB is not the only astrophysical signal that we observe

Foregrounds distinguished by non-blackbody frequency dependence



Foregrounds are fit with a multi-component model comprising 14 free parameters (10 in TT, 2 each in TE/EE)

One new parameter w.r.t. previous work: shape of the thermal SZ power spectrum (constrained at 3σ, cf. Adri’s talk)

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Reionization kSZ

		P-ACT	ACT	
Louis et al.:	a_{kSZ}	2.0 ± 0.9	$1.5^{+0.7}_{-1.1}$	kSZ amplitude at ell=3000

Beringue, Surrao, JCH, et al. (2025), 2506.06274

Reionization kSZ

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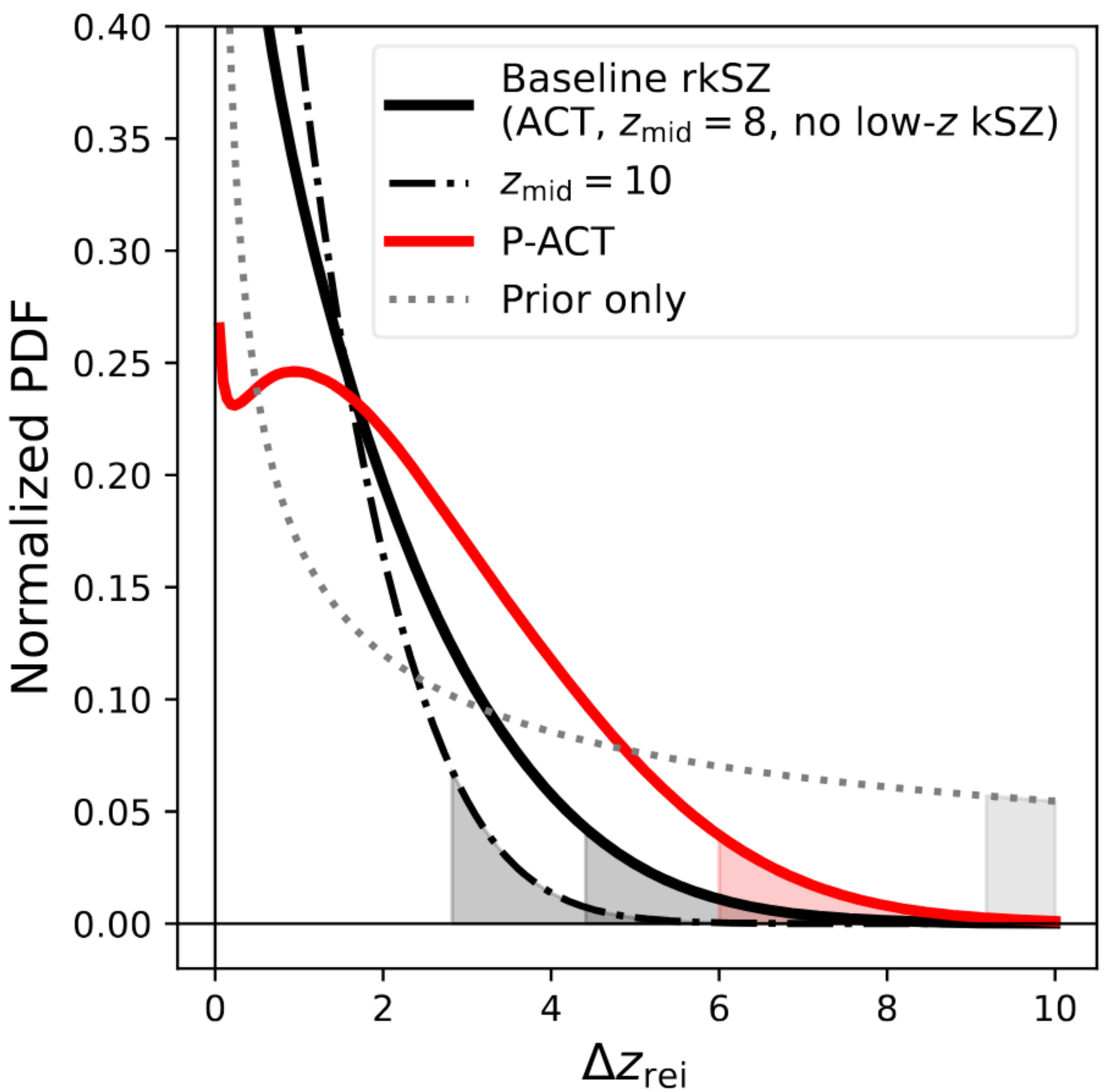
Louis et al.:		P-ACT	ACT
	$a_{\rm kSZ}$	2.0 ± 0.9	$1.5^{+0.7}_{-1.1}$

kSZ amplitude at ell=3000

Convert into constraint on duration of reionization using Battaglia+13 model:



Model	95% Upper Limit
Baseline rkSZ (ACT, B13 param., $z_{\rm mid} = 8$, no low-z kSZ)	$\Delta z_{\rm rei} < 4.4$
$z_{\rm mid} = 10$	$\Delta z_{\rm rei} < 2.9$
P-ACT	$\Delta z_{\rm rei} < 6.0$
low-z kSZ: $\log(T_{\rm AGN}) = 8.0$	$\Delta z_{\rm rei} < 2.5$
low-z kSZ: $\log(T_{\rm AGN}) = 7.6$	$\Delta z_{\rm rei} < 0.7$

Beringue, Surrao, JCH, et al. (2025), 2506.06274

Talk to Darby here!

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Beyond ΛCDM

(just a small sampling — see the paper!)

Notation:
P = Planck
ACT = ACT
L = ACT+Planck CMB lensing
B = BAO [DESI DR1, or DR2 where indicated]

Calabrese & JCH, Jense, La Posta, et al. (2025), 2503.14454

Primordial Power Spectrum

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Constraints on scale dependence of primordial curvature perturbation power spectrum

$$n_s = 0.9660 \pm 0.0046 \text{ (W-ACT)}$$
$$= 0.9651 \pm 0.0044 \text{ (Planck)},$$

Independent confirmation of $n_s < 1$ at 7σ

Primordial Power Spectrum

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Constraints on scale dependence of primordial curvature perturbation power spectrum

$$n_s = 0.9660 \pm 0.0046 \text{ (W-ACT)}$$
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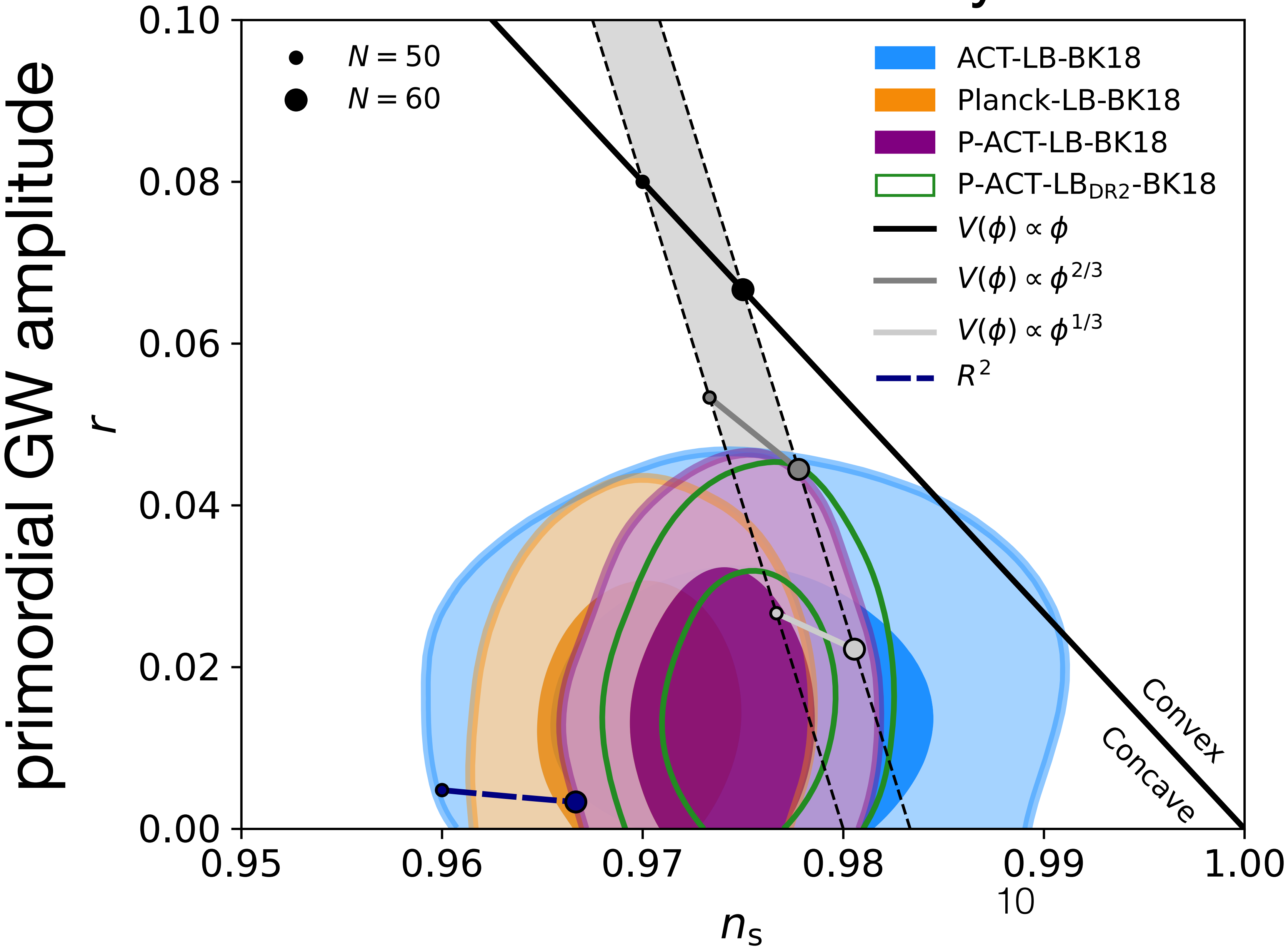
constraints on inflationary models



Primordial Power Spectrum

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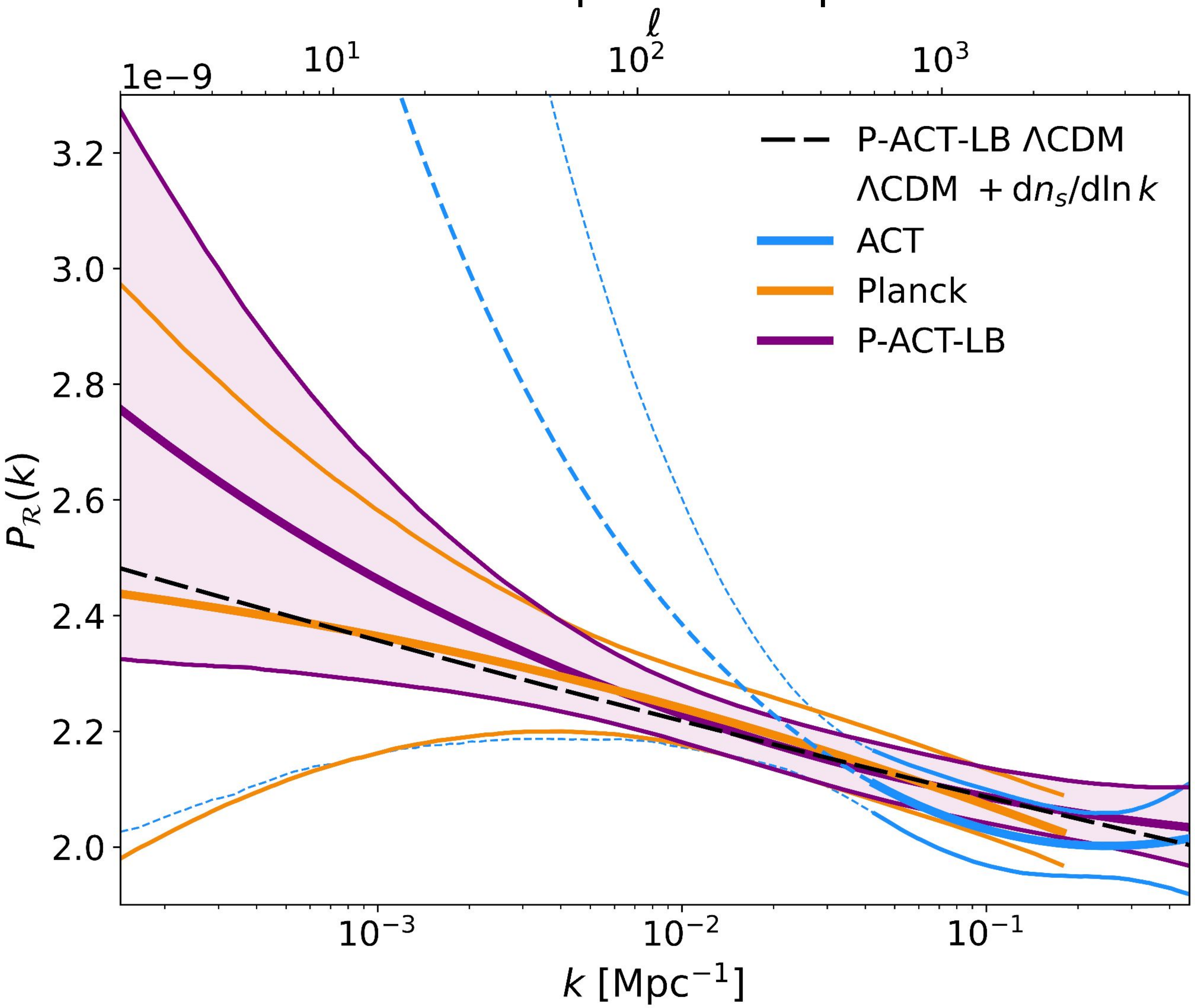
Primordial power spectrum



+ No evidence of departure from simple power-law

$$dn_s/d\ln k = 0.0062 \pm 0.0052$$ (P-ACT-LB)

(30% tighter than previous CMB+LSS constraints)

+ tightened constraints on primordial isocurvature perturbations — no deviation from adiabaticity detected

New Light, Relativistic Particles

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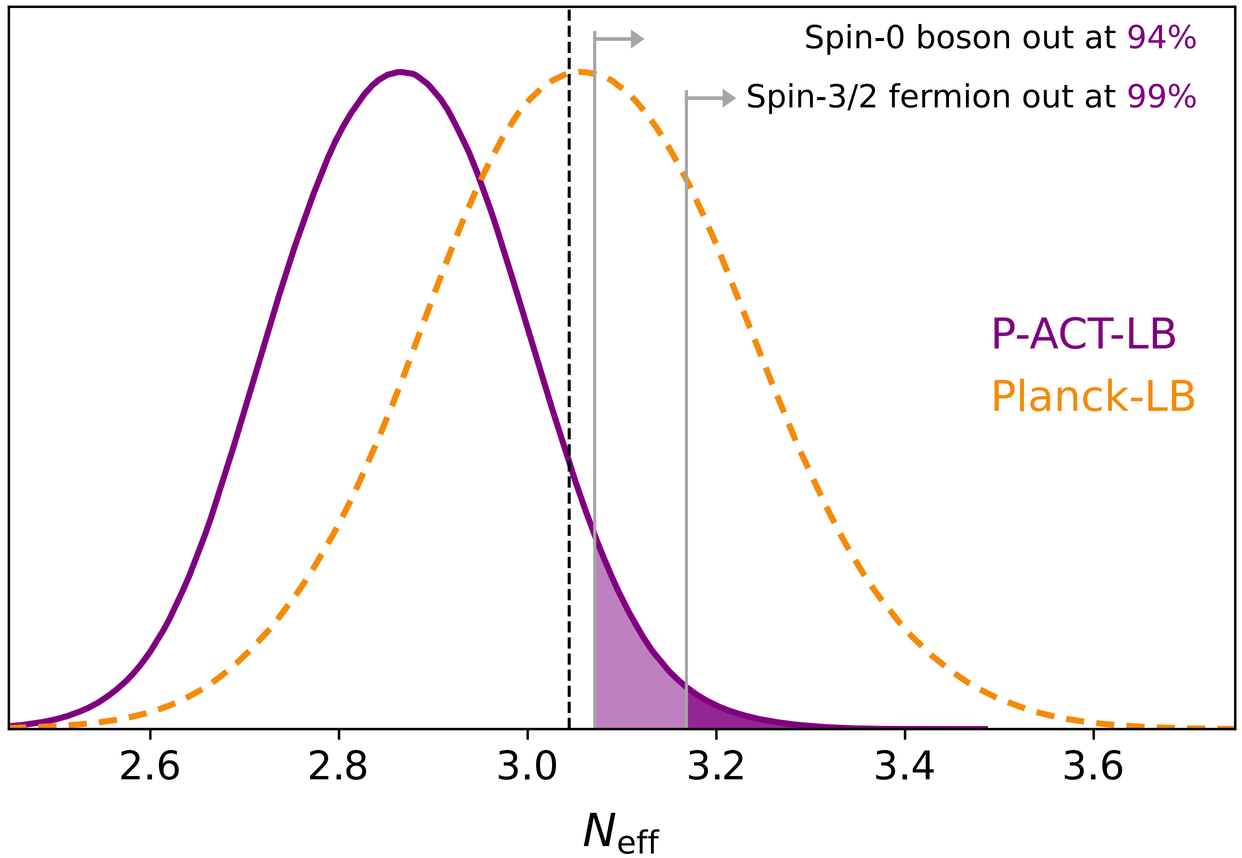
Free-streaming relativistic particles:

N_{eff} = 2.86 ± 0.13 (68%, P-ACT-LB)
N_{eff} = 2.89 ± 0.11 (68%, P-ACT-LB-BBN)
N_{eff} = 2.81 ± 0.12 (68%, CMB-SPA, Camphuis+)



~1.6x tighter than *Planck* limit

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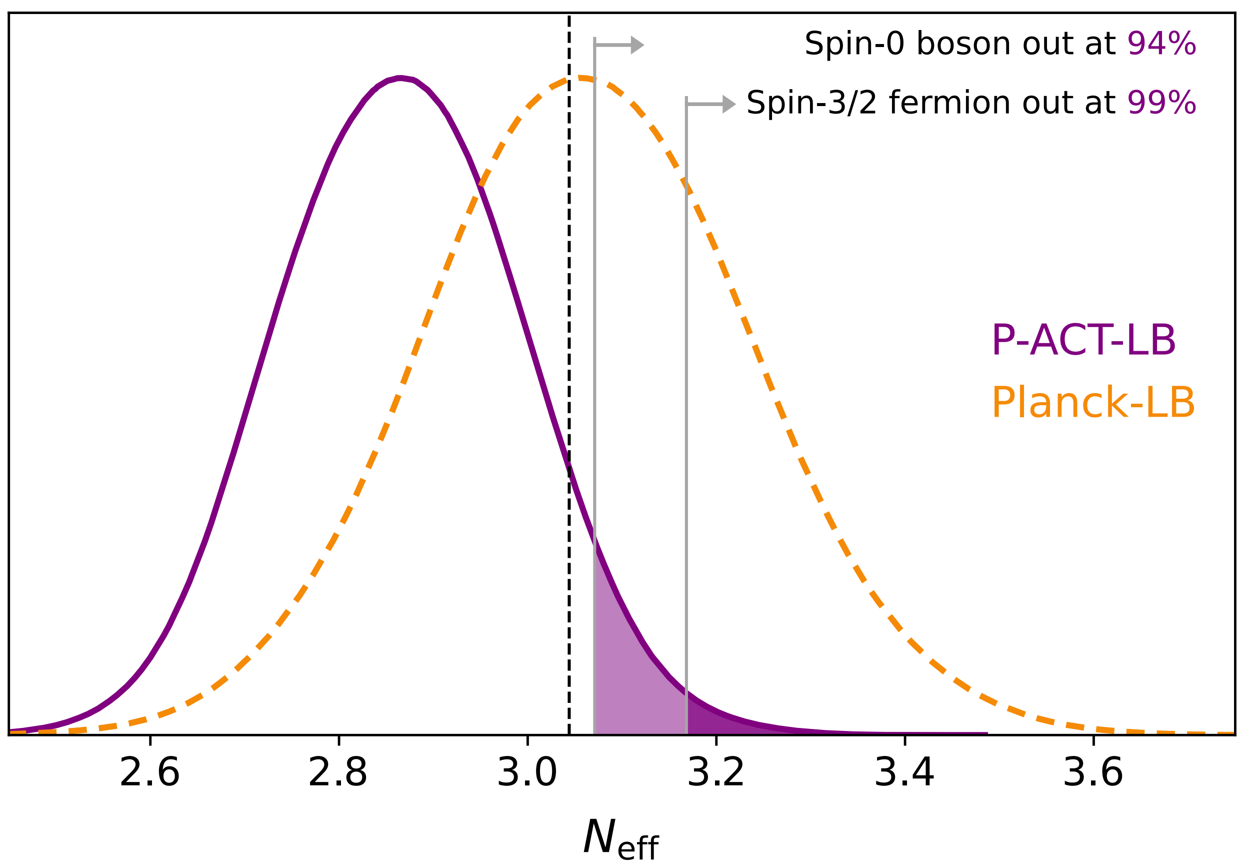

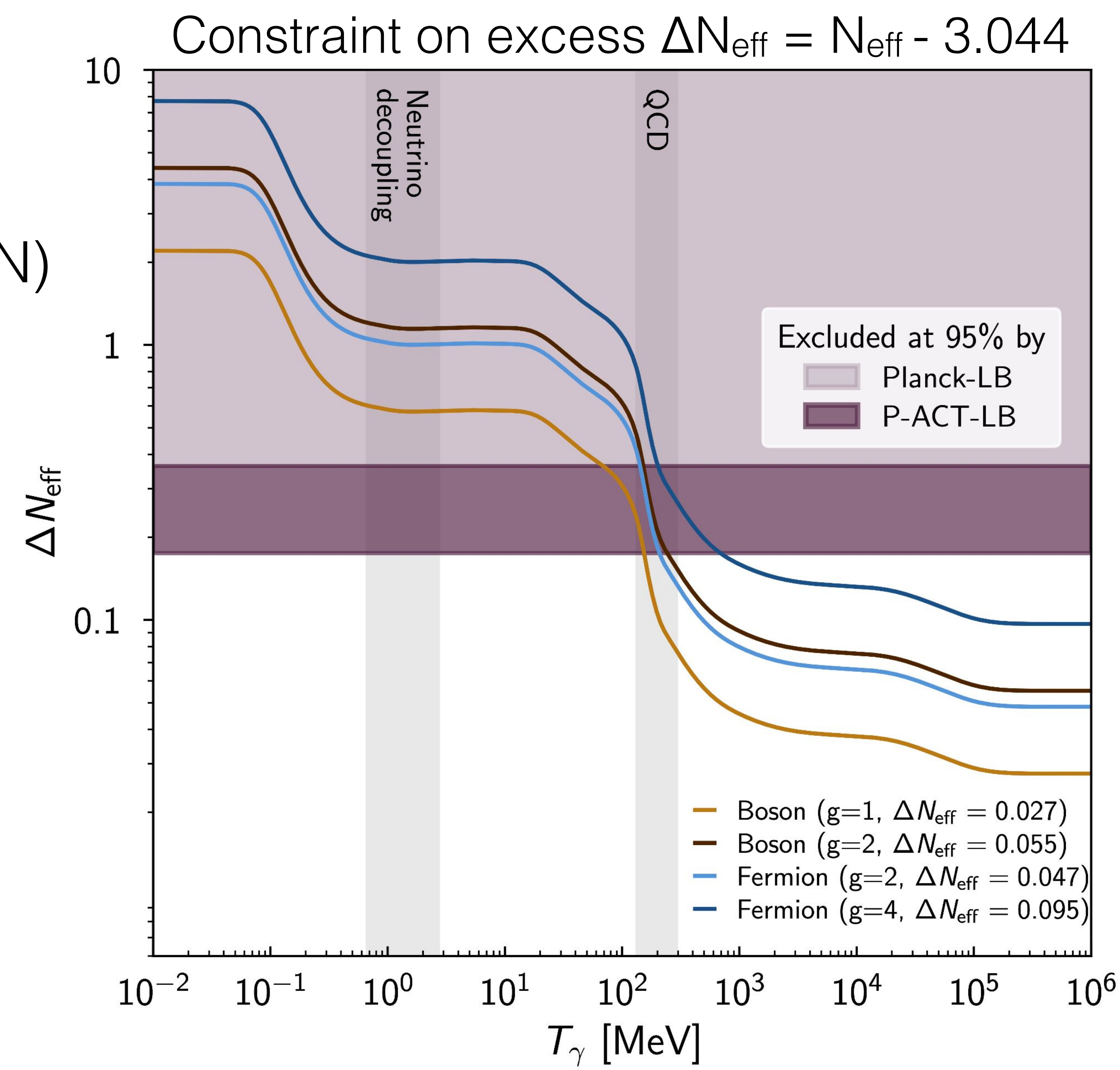

Any light, spin-3/2 particle must have decoupled from the plasma at T > 1 GeV

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New Light, Relativistic Particles

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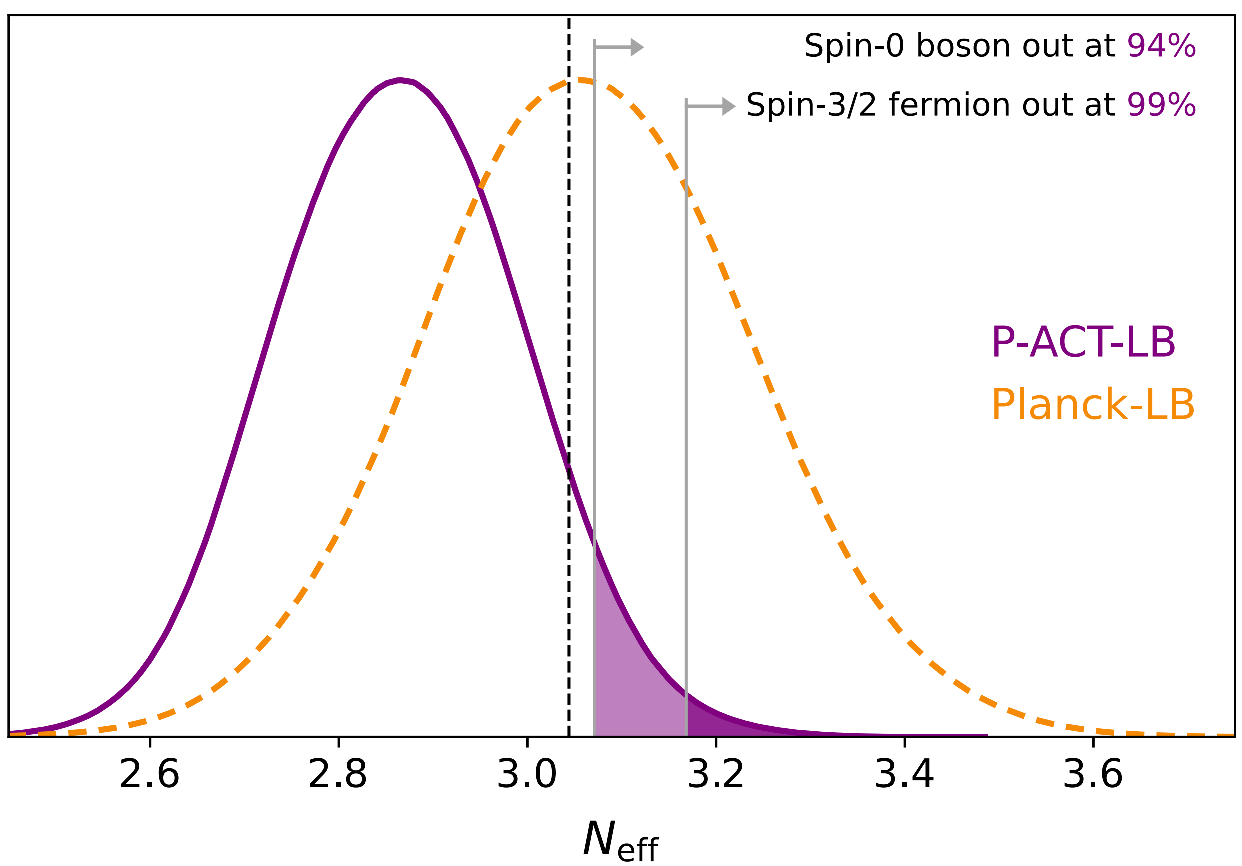
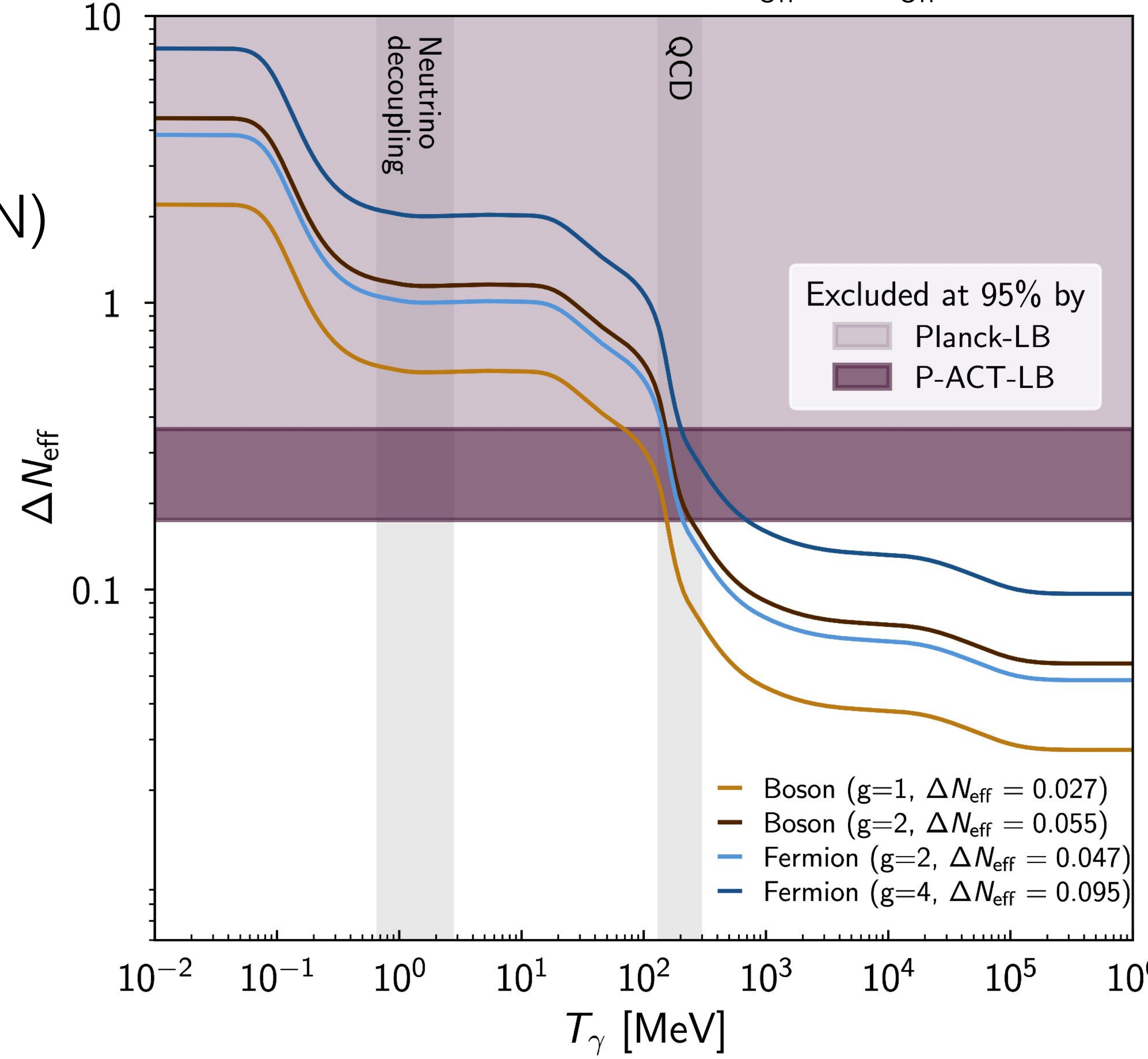
N_{eff} = 2.86 ± 0.13 (68%, P-ACT-LB)
N_{eff} = 2.89 ± 0.11 (68%, P-ACT-LB-BBN)



Constraint on excess $\Delta N_{eff} = N_{eff} - 3.044$



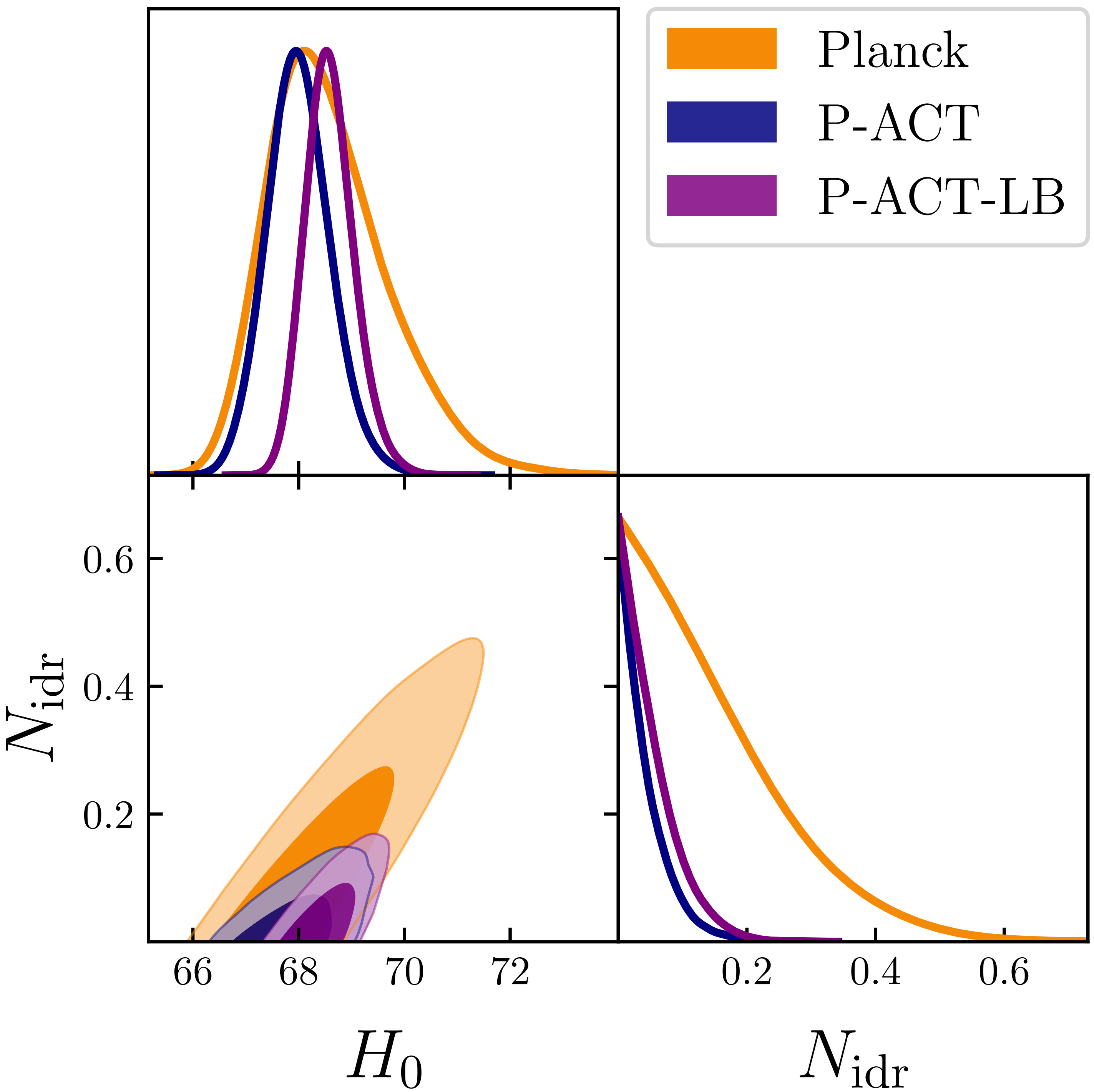
Also: no evidence for non-zero neutrino mass:
$\Sigma m_\nu < 0.082$ eV (95%, P-ACT-LB)

New Light, Relativistic Particles

Search for new light, relativistic particles that are strongly self-interacting

New Light, Relativistic Particles

Search for new light, relativistic particles that are strongly self-interacting



Self-interacting relativistic particles: N_{idr} < 0.134 (95%, P-ACT-LB)

~3x tighter than *Planck* limit

We exclude this scenario as a resolution of the H_0 tension

Also: no evidence of neutrino self-interactions or interactions between dark matter and dark radiation

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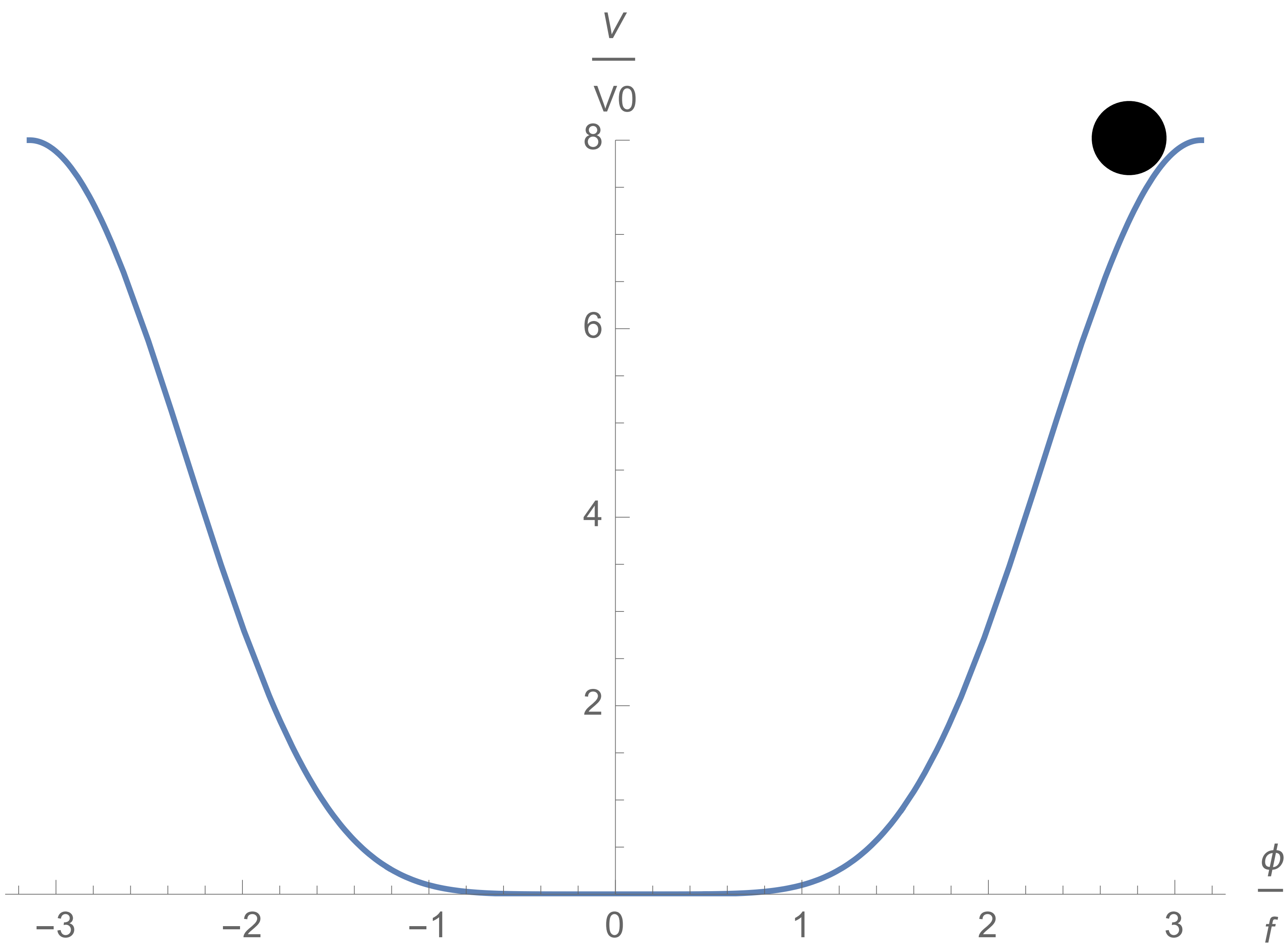
Early Dark Energy

New pseudo-scalar field that becomes dynamical around recombination

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



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

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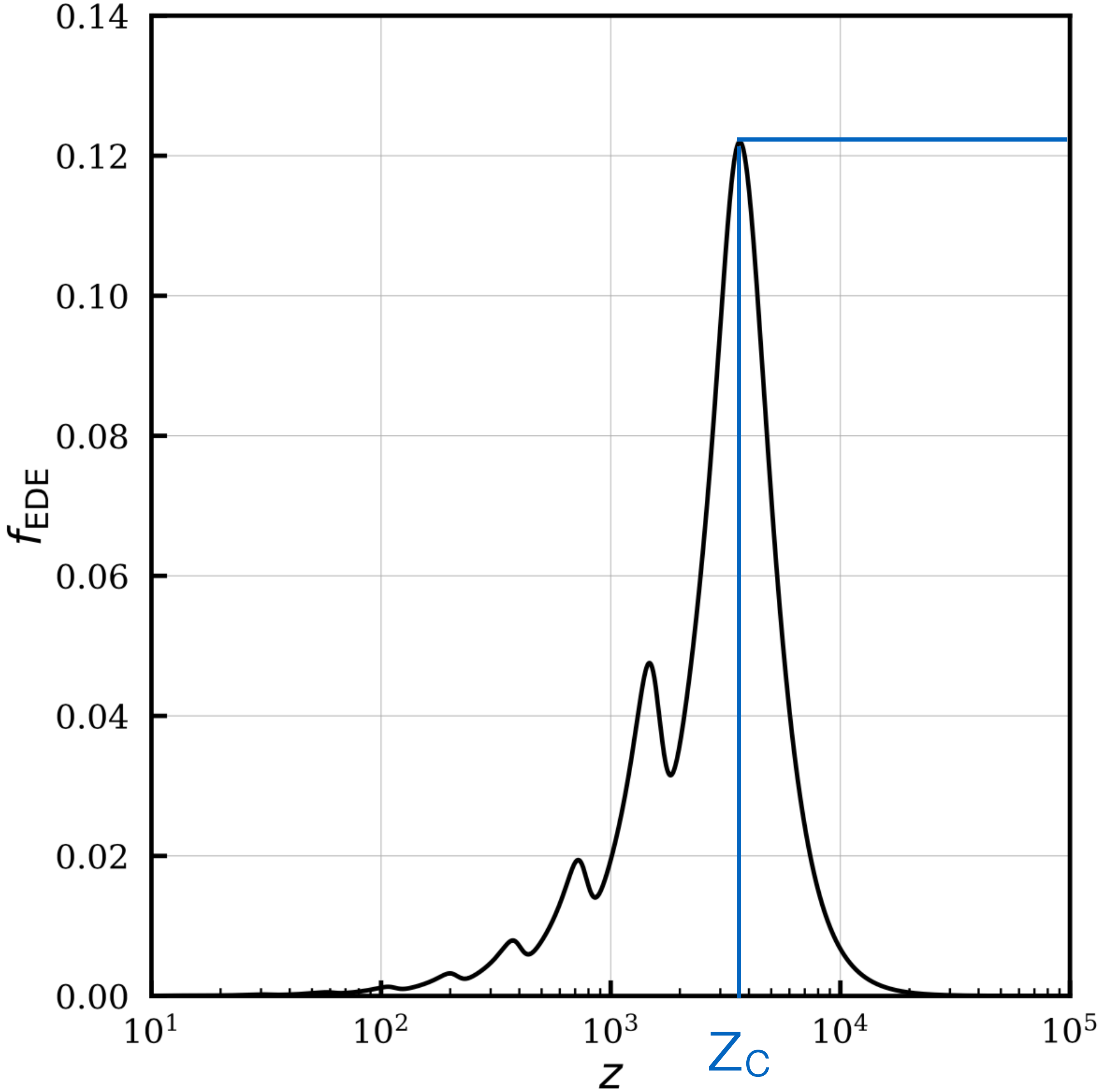
Early Dark Energy

New pseudo-scalar field that becomes dynamical around recombination

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)

→ $\{f_{EDE}, z_C, \theta_i\}$

3-parameter extension of ΛCDM

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

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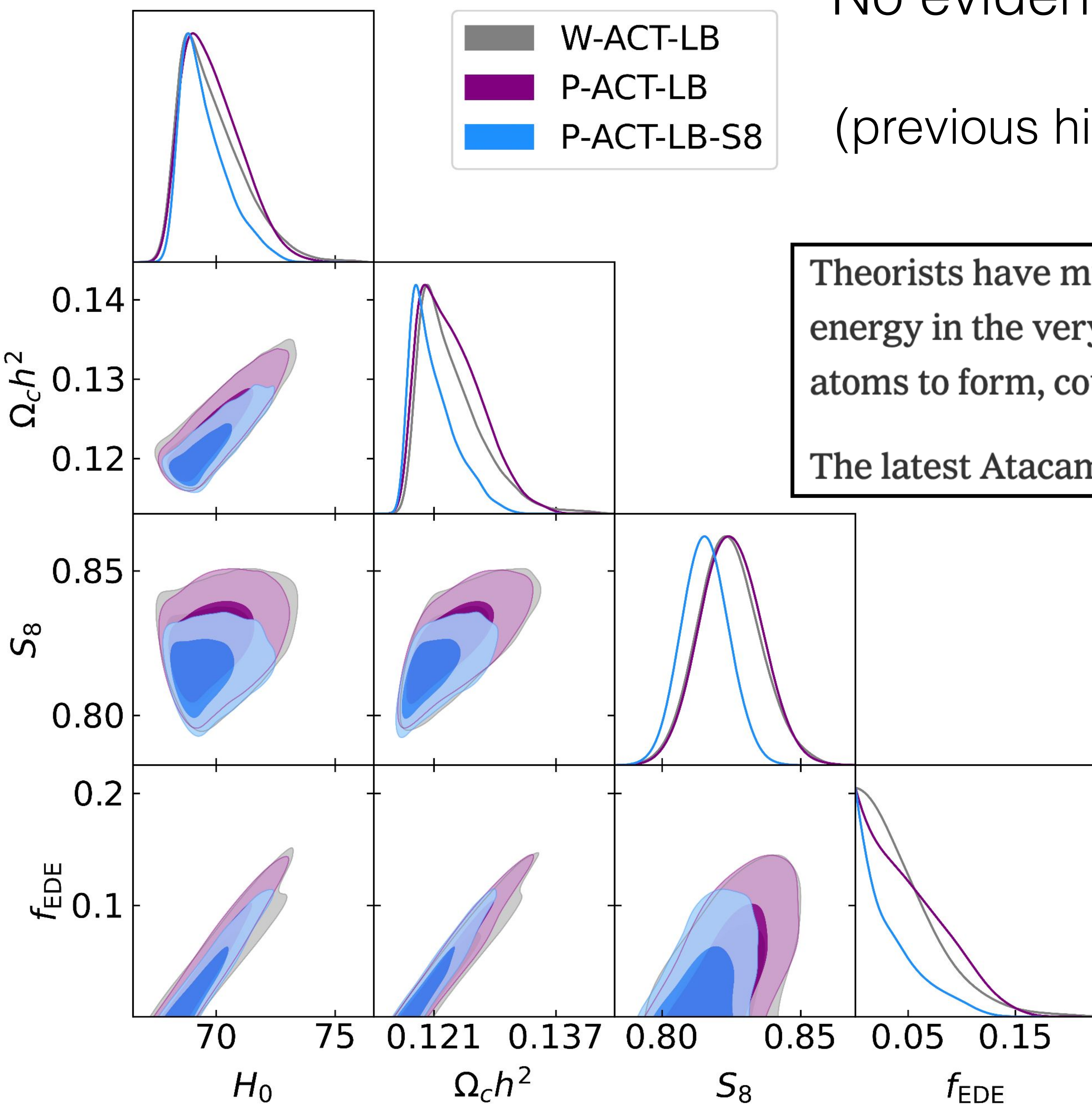
Early Dark Energy

New pseudo-scalar field that becomes dynamical around recombination



No evidence seen for EDE component in ACT DR6

(previous hint had been seen in ACT DR4 data [JCH+22])

> Theorists have mused that perhaps an additional spurt of dark energy in the very early universe, when conditions were too hot for atoms to form, could resolve this so-called Hubble tension.
>
> The latest Atacama results seem to rule out this idea.
>
> -NYT

Frequentist: max. preference:
$\Delta\chi^2 = 6.6$ (1.7σ)

Modified Recombination

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Ex.: primordial magnetic fields; variations of fundamental constants; change to CMB monopole temperature or distribution function

e.g., Jedamzik & Pogosian (2018); Sekiguchi & Takahashi (2020); JCH & Bolliet (2023); Lynch+ (2024)

Modified Recombination

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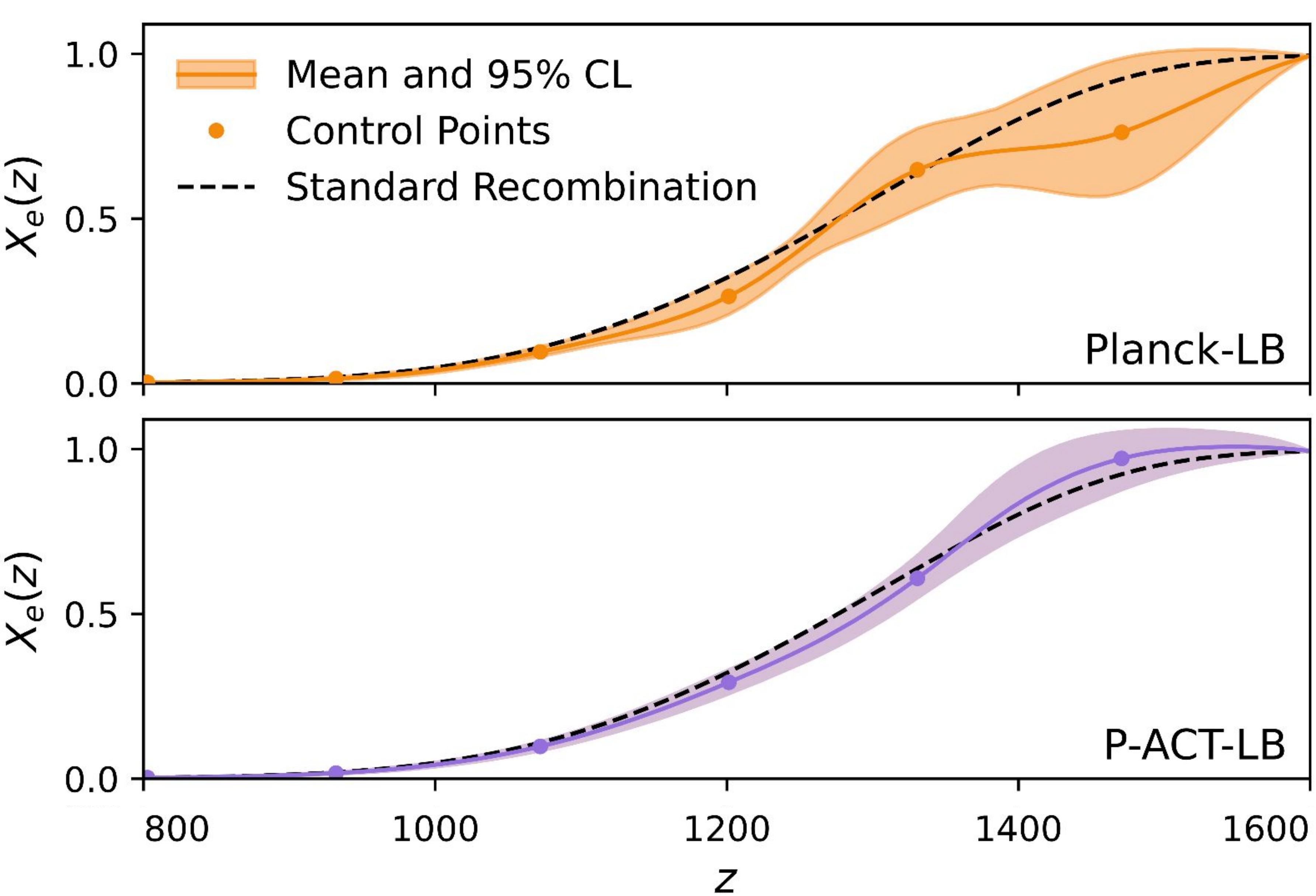
We perform a non-parametric reconstruction of the recombination history

We obtain the tightest limits to date and find no evidence of deviations from the standard history

ionization fraction



Planck

+ACT

redshift

Modified Recombination

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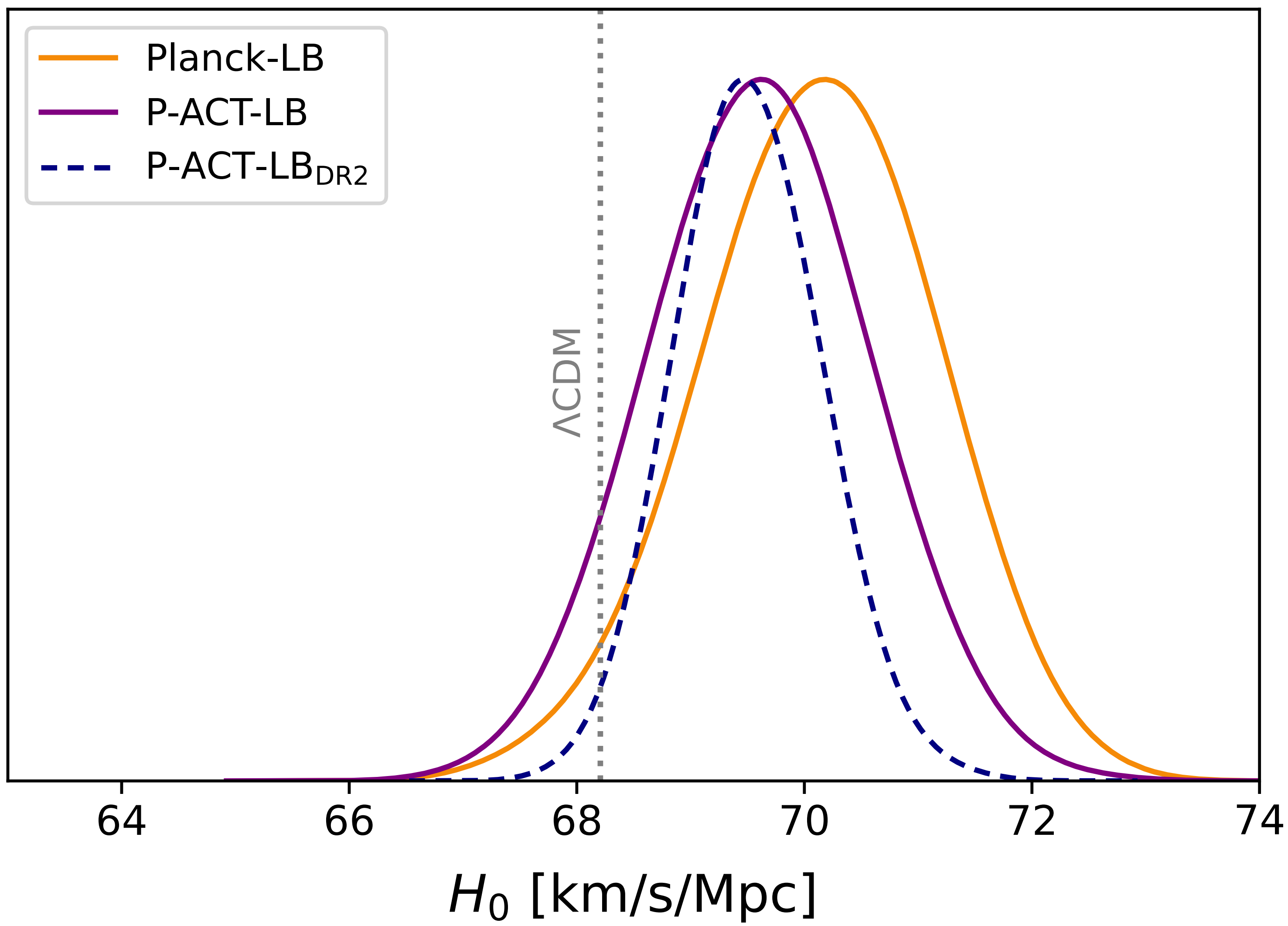
We perform a non-parametric reconstruction of the recombination history

We obtain the tightest limits to date and find no evidence of deviations from the standard history

This result restricts the ability of such scenarios to increase H_0



P-ACT-LB$_{DR2}$: H0 = 69.5 ± 0.7
CMB-SPA + DESI$_{DR2}$: H_0 = 69.5 ± 0.7

Cosmological Concordance

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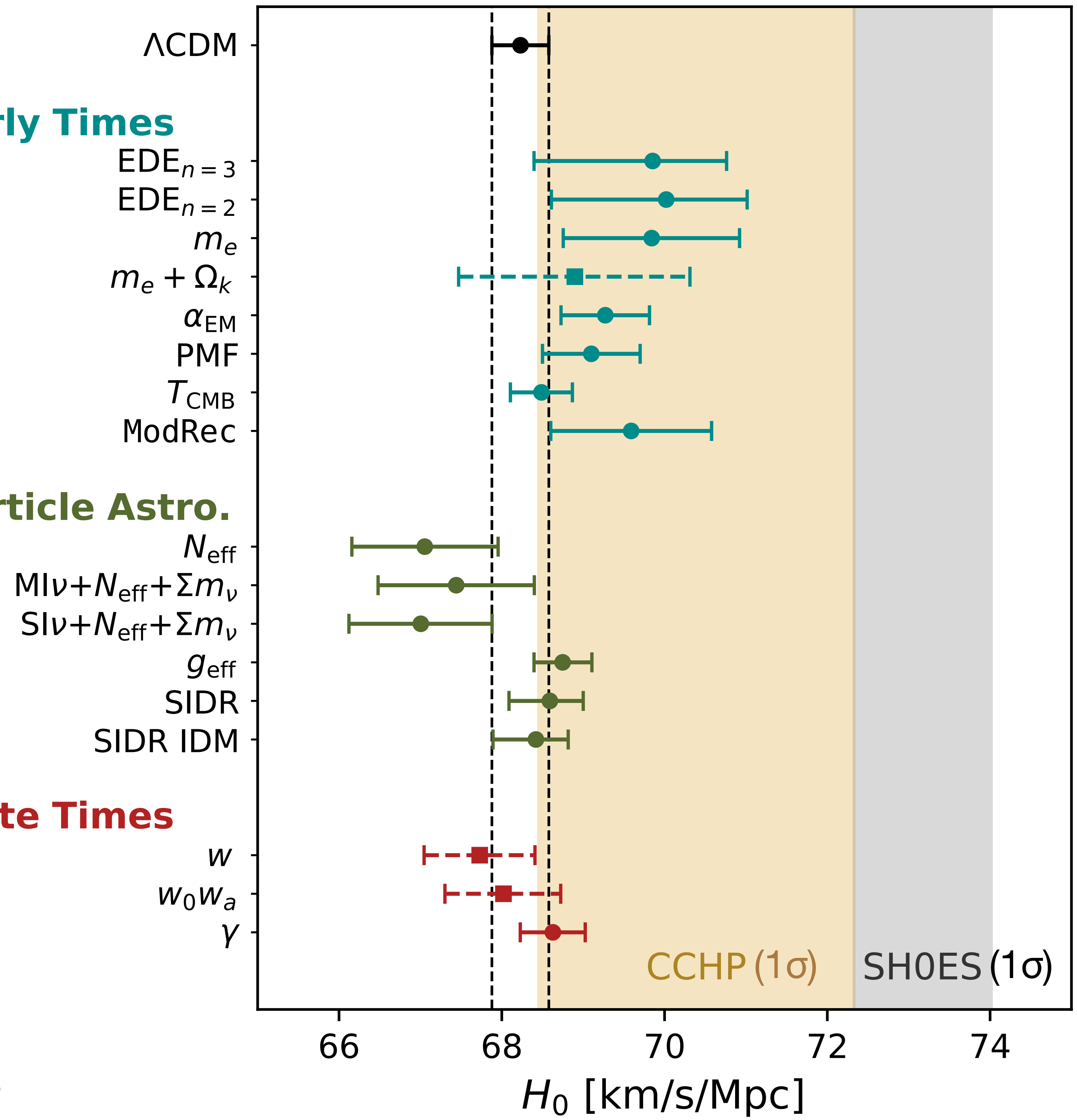
No evidence for new-physics models aiming to increase CMB-inferred H_0

Tightest limits to date on wide ranges of BSM scenarios

new-physics models



SH0ES H_0 remains discordant

Back to the theory drawing board…

solid = P-ACT-LB
dashed = P-ACT-LBS

Cosmological Concordance

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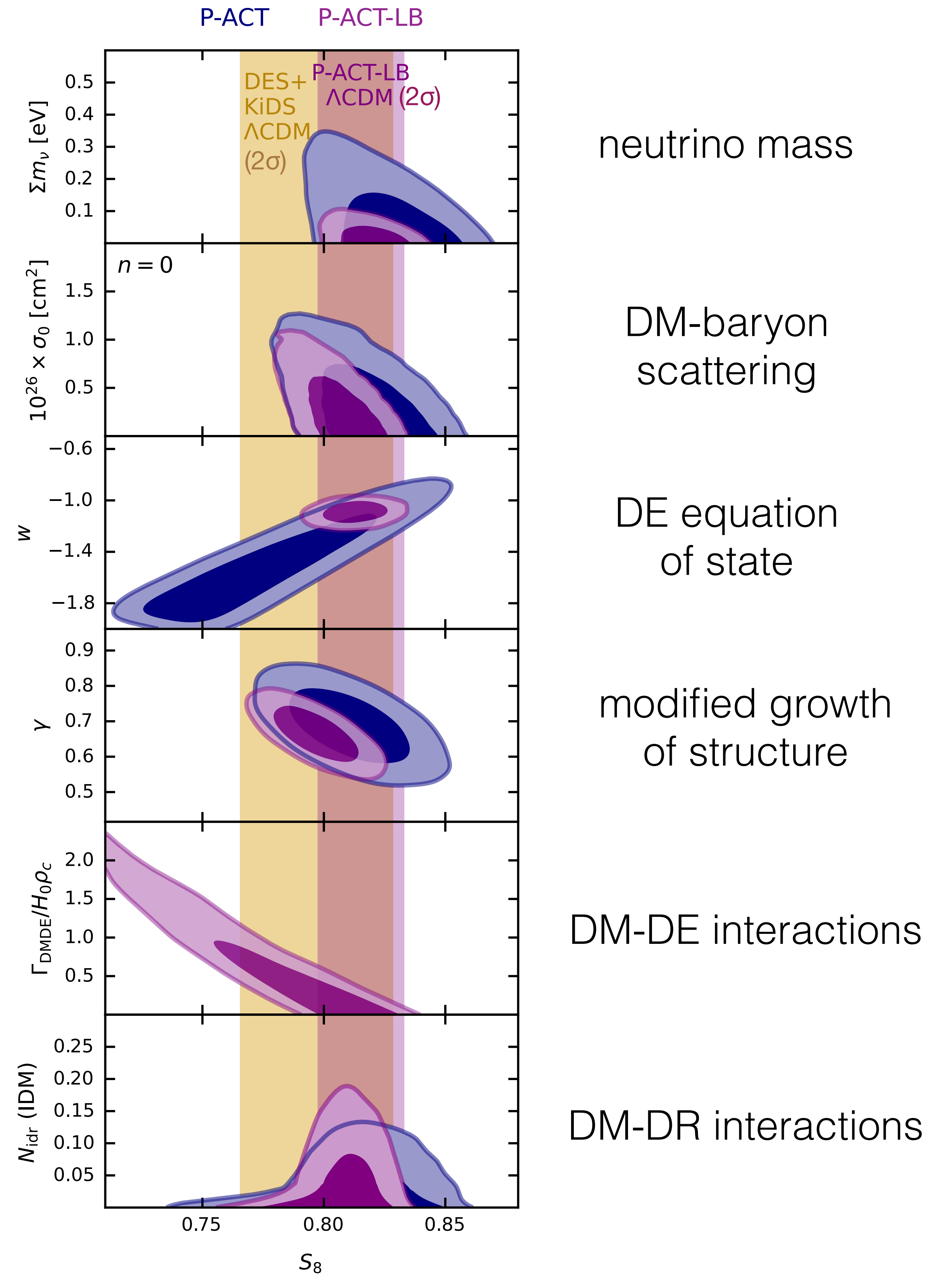
Also no evidence for models aiming to decrease S_8 (late-time fluctuation amplitude)

— but no significant tension is seen in ΛCDM for this parameter between our CMB-driven constraints and those from the DES+KiDS weak lensing surveys



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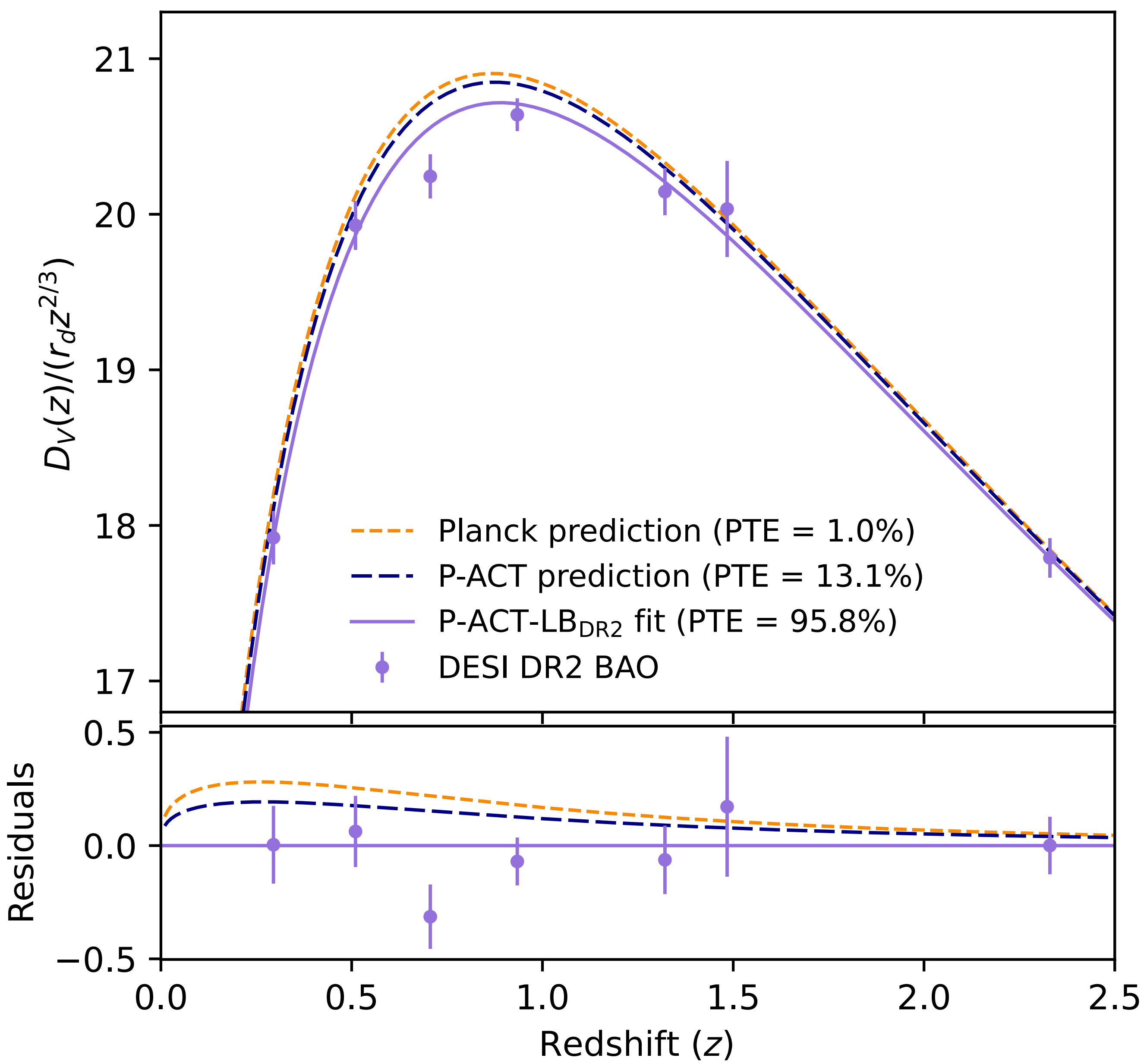
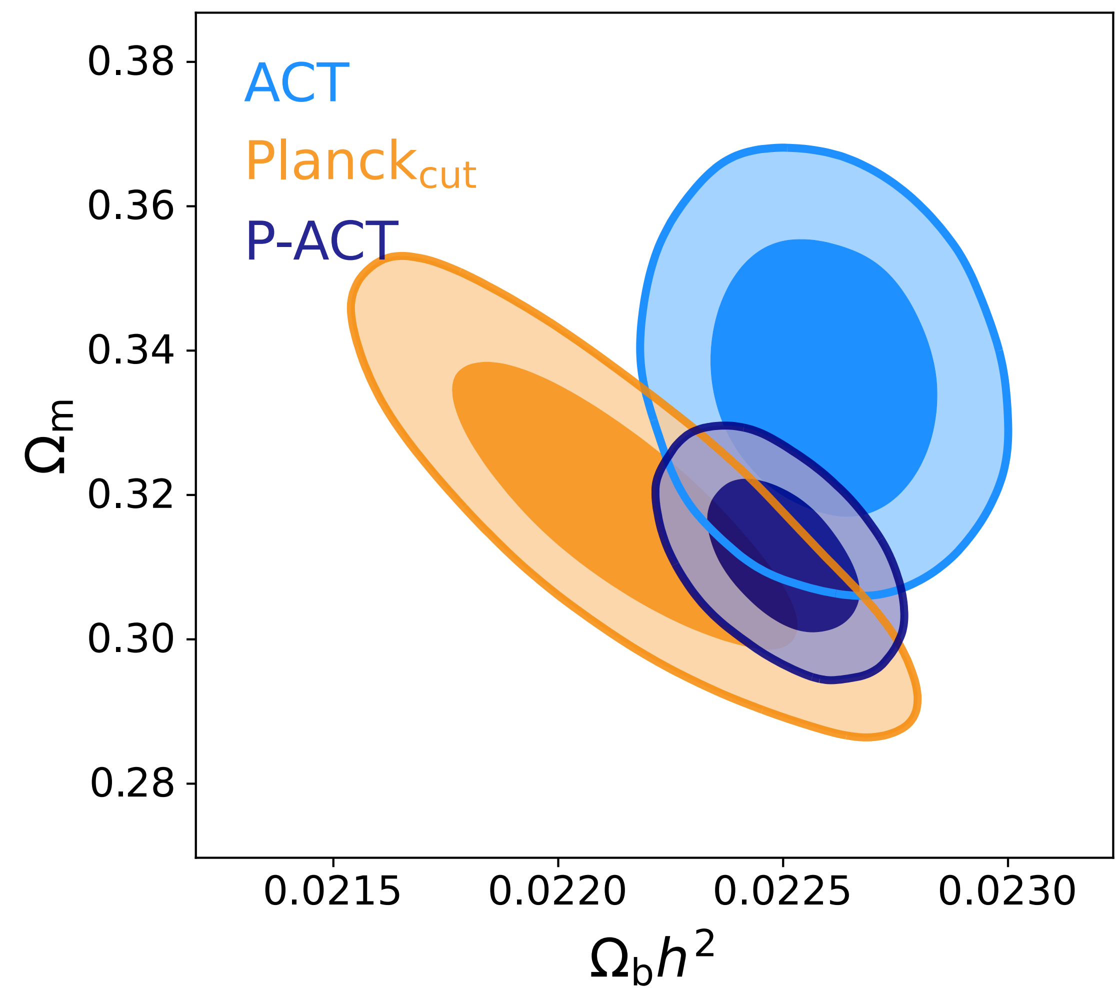
DESI and Dark Energy

P-ACT ΛCDM agrees well with DESI DR2



Why? P-ACT Ω_m slightly lower than Planck, hence in better agreement with DESI



Louis, La Posta, Atkins, Jense, et al. (2025)
Calabrese & JCH, Jense, La Posta, et al. (2025)
Garcia-Quintero et al. (2025)

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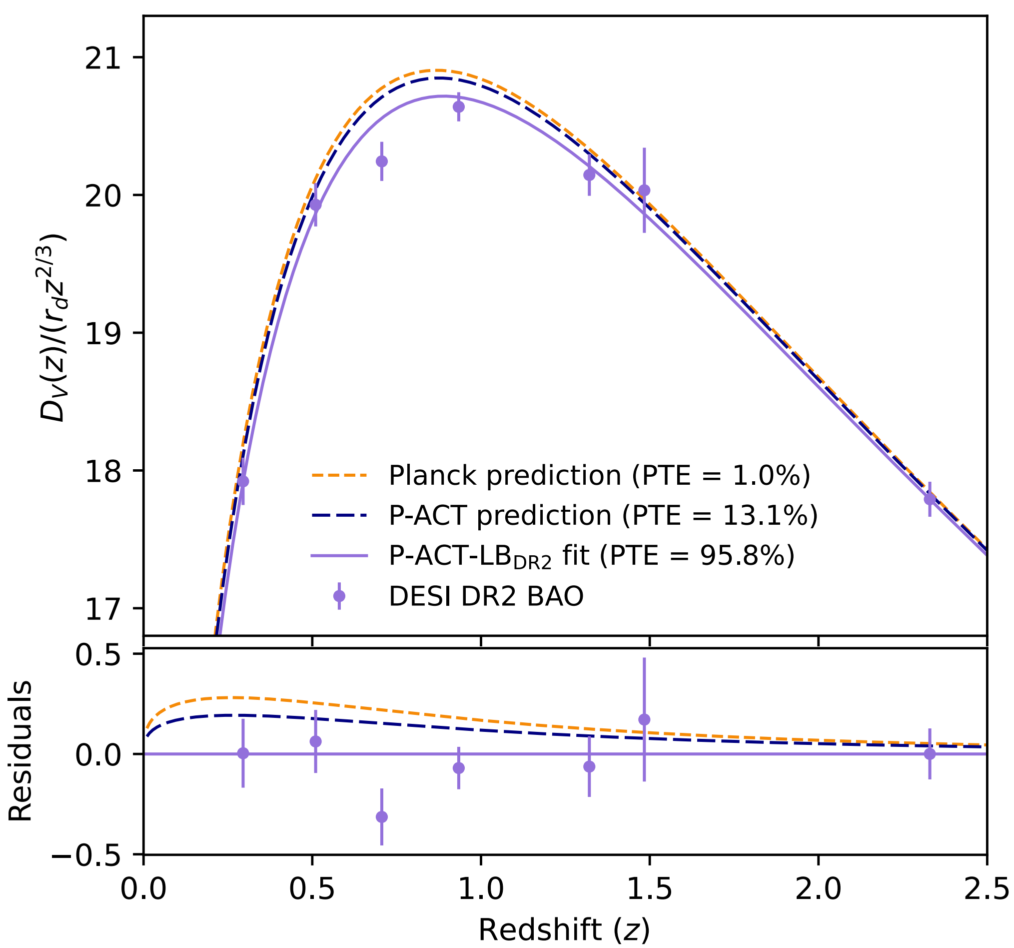
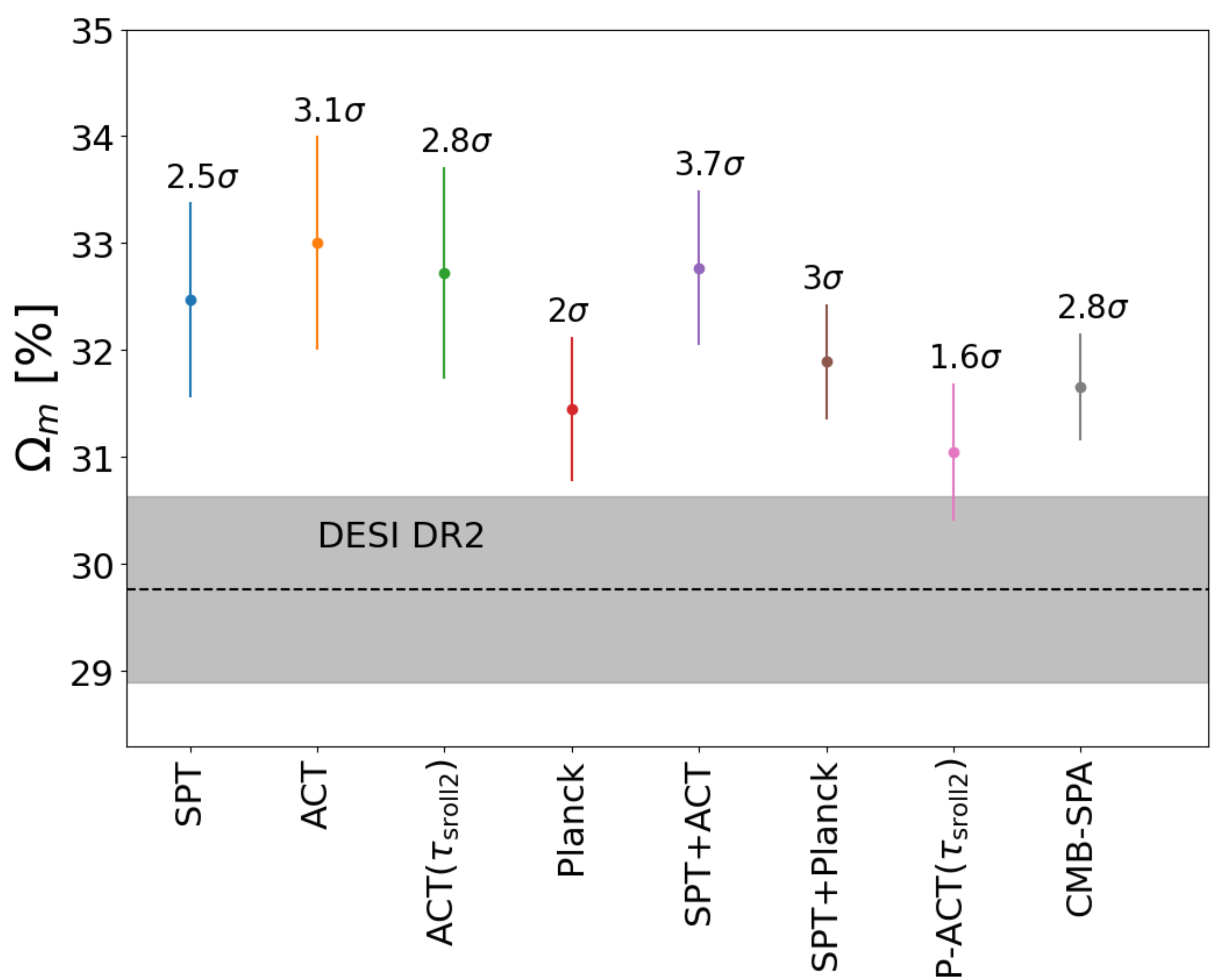
DESI and Dark Energy

… but CMB Ω_m predictions are consistently high
… and depend on the assumed τ

P-ACT ΛCDM agrees well with DESI DR2





All results here use τ_{PR4} unless labeled

$\tau_{sroll2} = 5.66 \pm 0.58$ [%]

$\tau_{PR4} = 5.1 \pm 0.6$ [%]

DESI and Dark Energy

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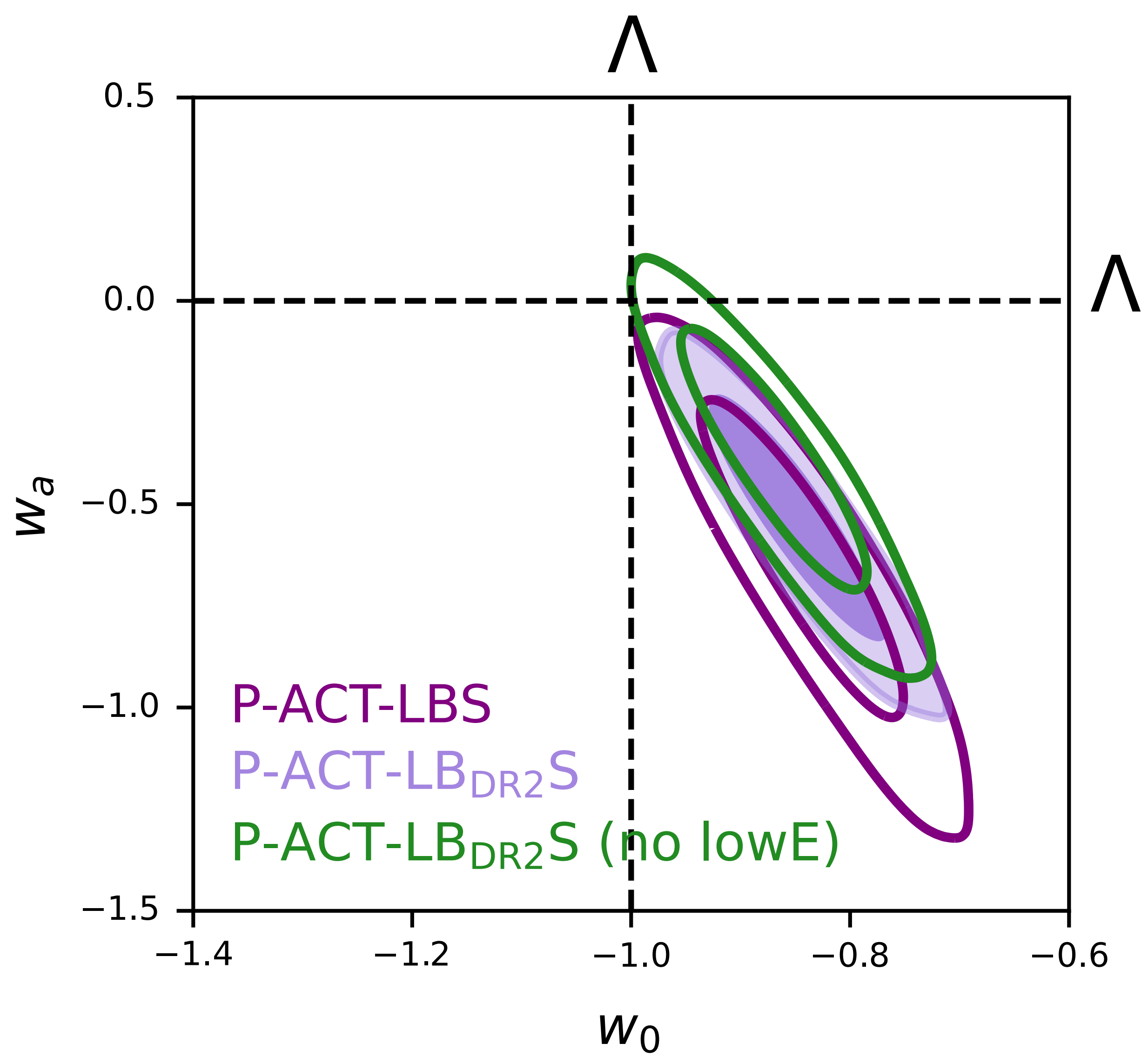
From P-ACT primary CMB data, we find no evidence for non-standard dark energy; hints of non-standard evolution are driven by low-redshift data

$$w(a) = w_0 + w_a(1 - a)$$



$$w_0 = -0.837 \pm 0.061$$
$$w_a = -0.66^{+0.27}_{-0.24}$$
(68%, P-ACT-LBS)

P-ACT-LBS consistent with Λ at 2.2σ
P-ACT-LB$_{DR2}$S consistent with Λ at 2.4σ

Discarding Sroll2 low-ell EE:
$\tau = 0.081 \pm 0.016$
consistent with Λ at ~2σ

Outlook

1) ACT DR6 provides a stringent new test of the cosmological model: ΛCDM continues to succeed
2) P-ACT yields the tightest constraints on a wide range of BSM scenarios in cosmology. Many previously-viable new-physics scenarios (e.g., those aiming to resolve the H_0 tension) are now severely constrained
3) The next decade will bring a torrent of incredible wide-area CMB data (SO ⟶ CMB-S4), with even higher sensitivity to new physics — stay tuned!

Photo: D. Kellner

Data at NASA LAMBDA and NERSC:
https://lambda.gsfc.nasa.gov/product/act/act_dr6.02/

Bonus

CMB: State of the Art

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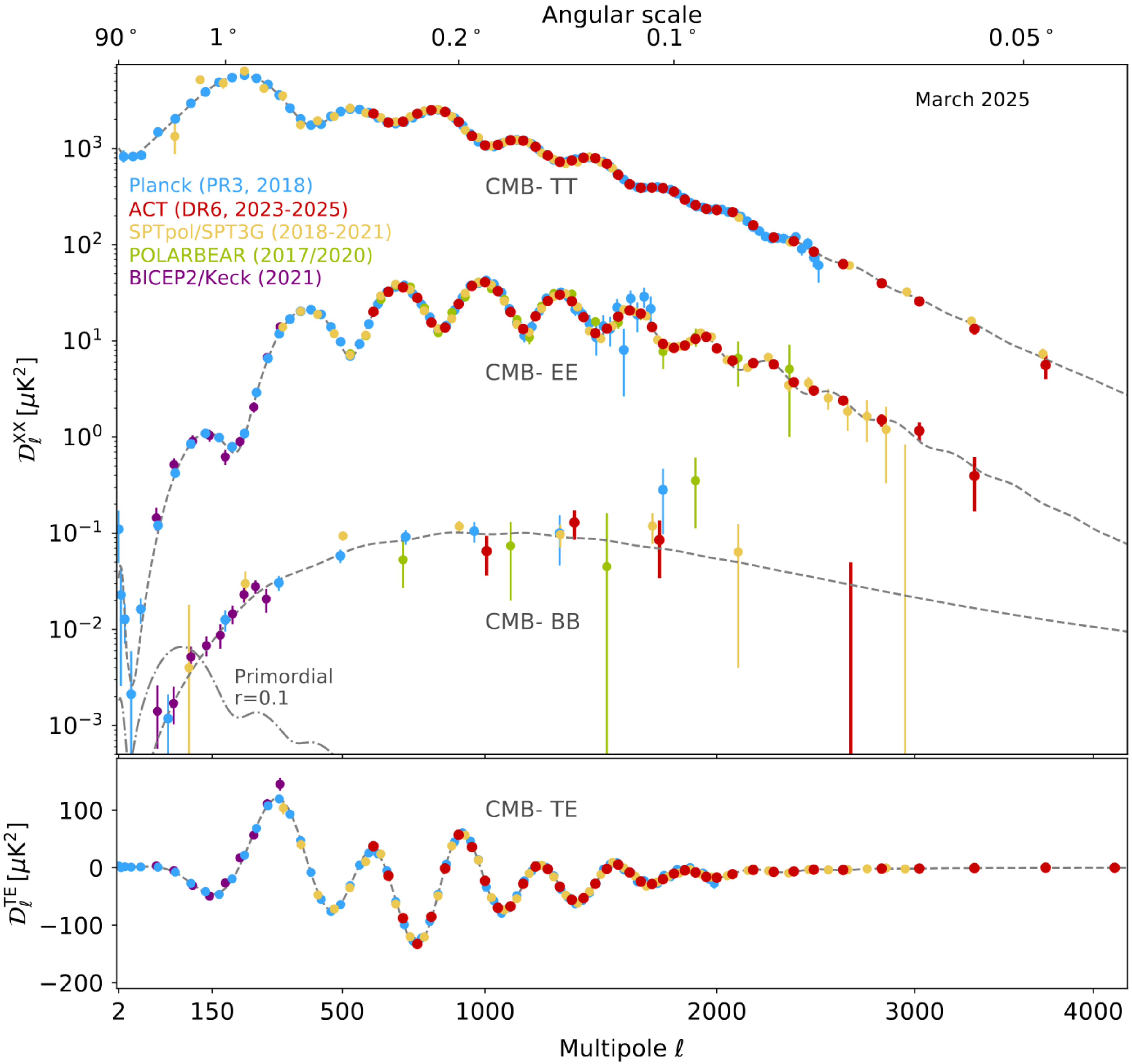

Louis, La Posta, Atkins, Jense, et al. (2025), 2503.14452

CMB: State of the Art

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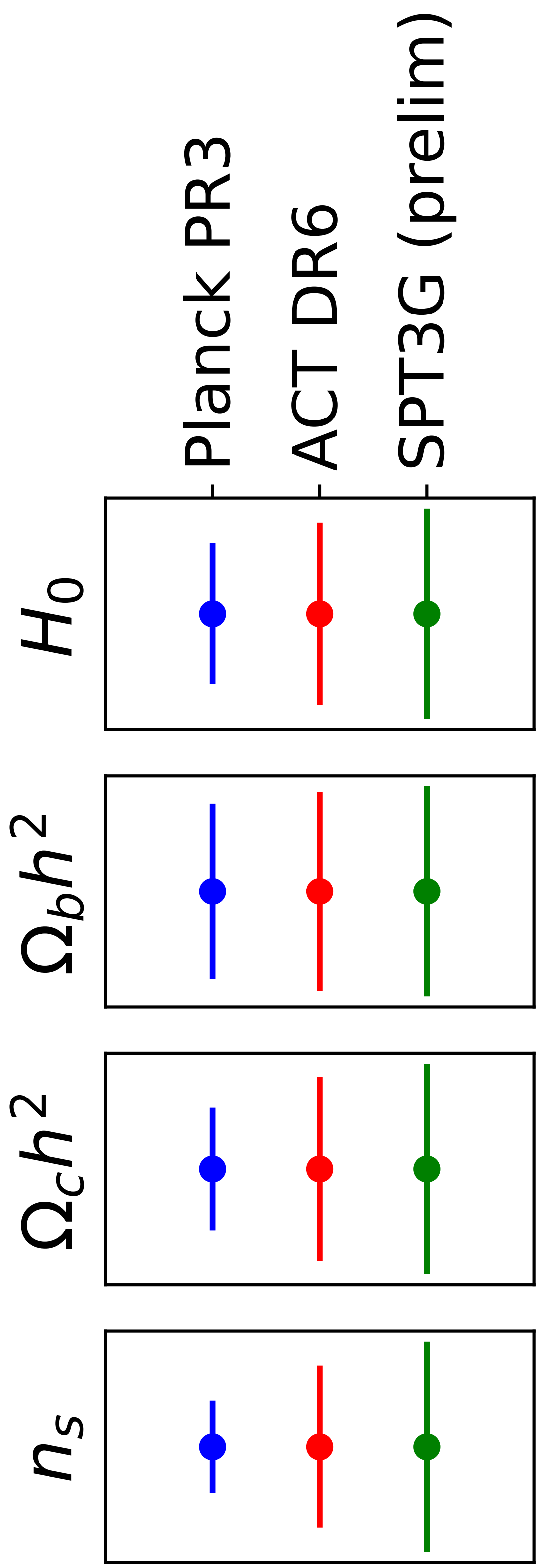
ΛCDM parameter error bars from Planck, ACT, SPT



Error bars computed from only primary CMB TT+TE+EE

SPT-3G not yet published; forecasts from talks shown by SPT Collaboration

P-ACT vs. ACT, Planck

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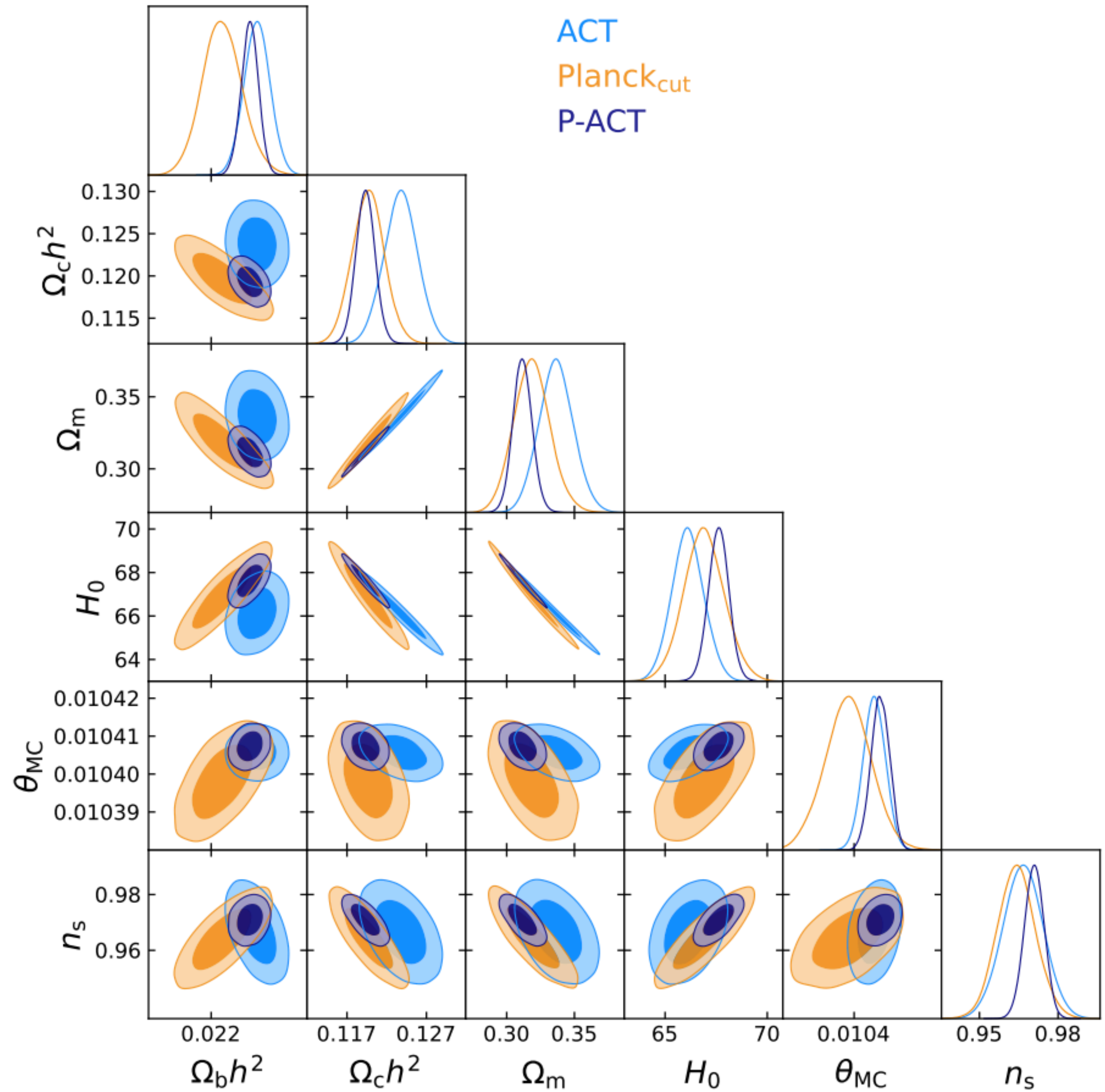

Cosmological Constraints

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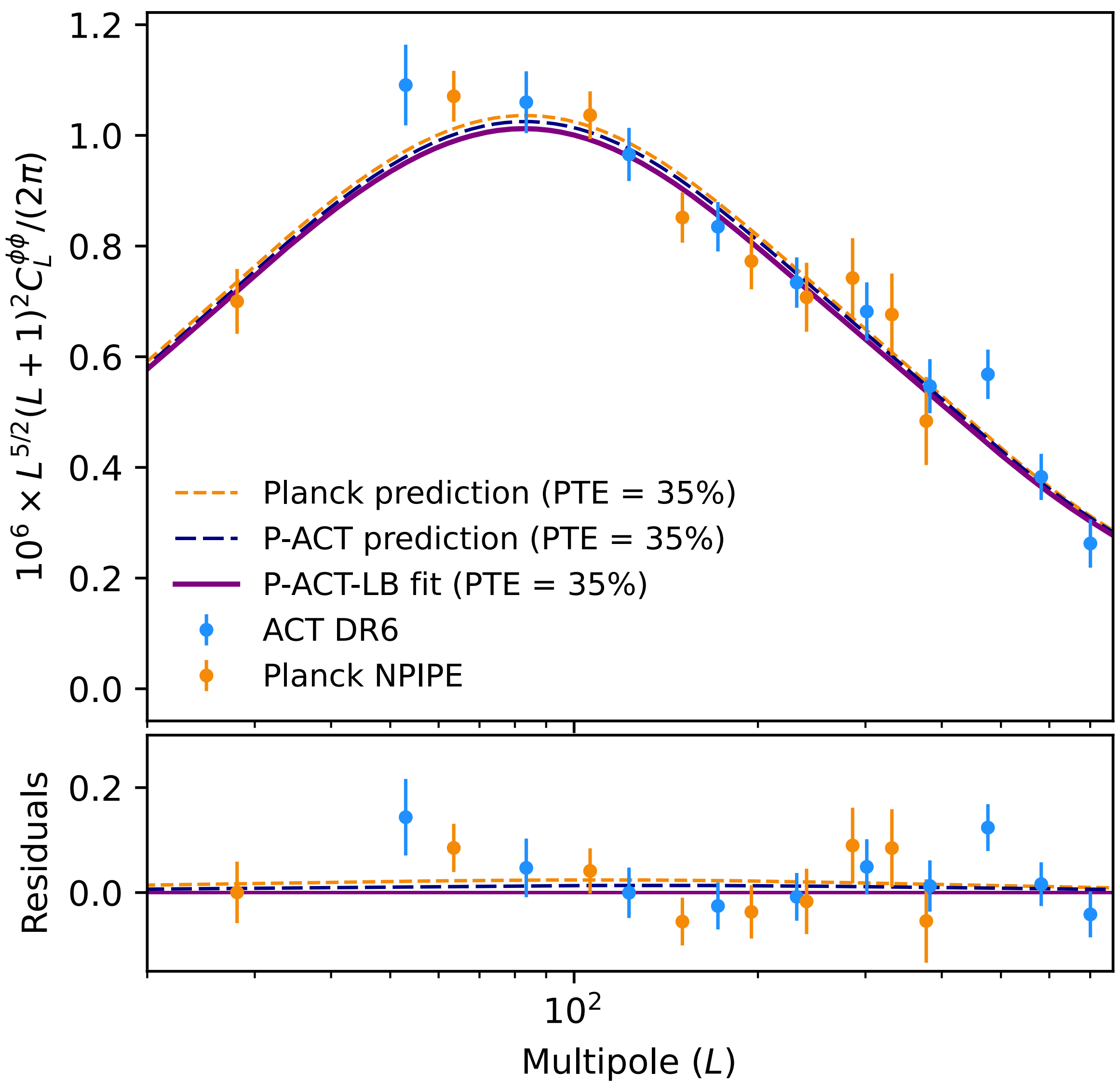
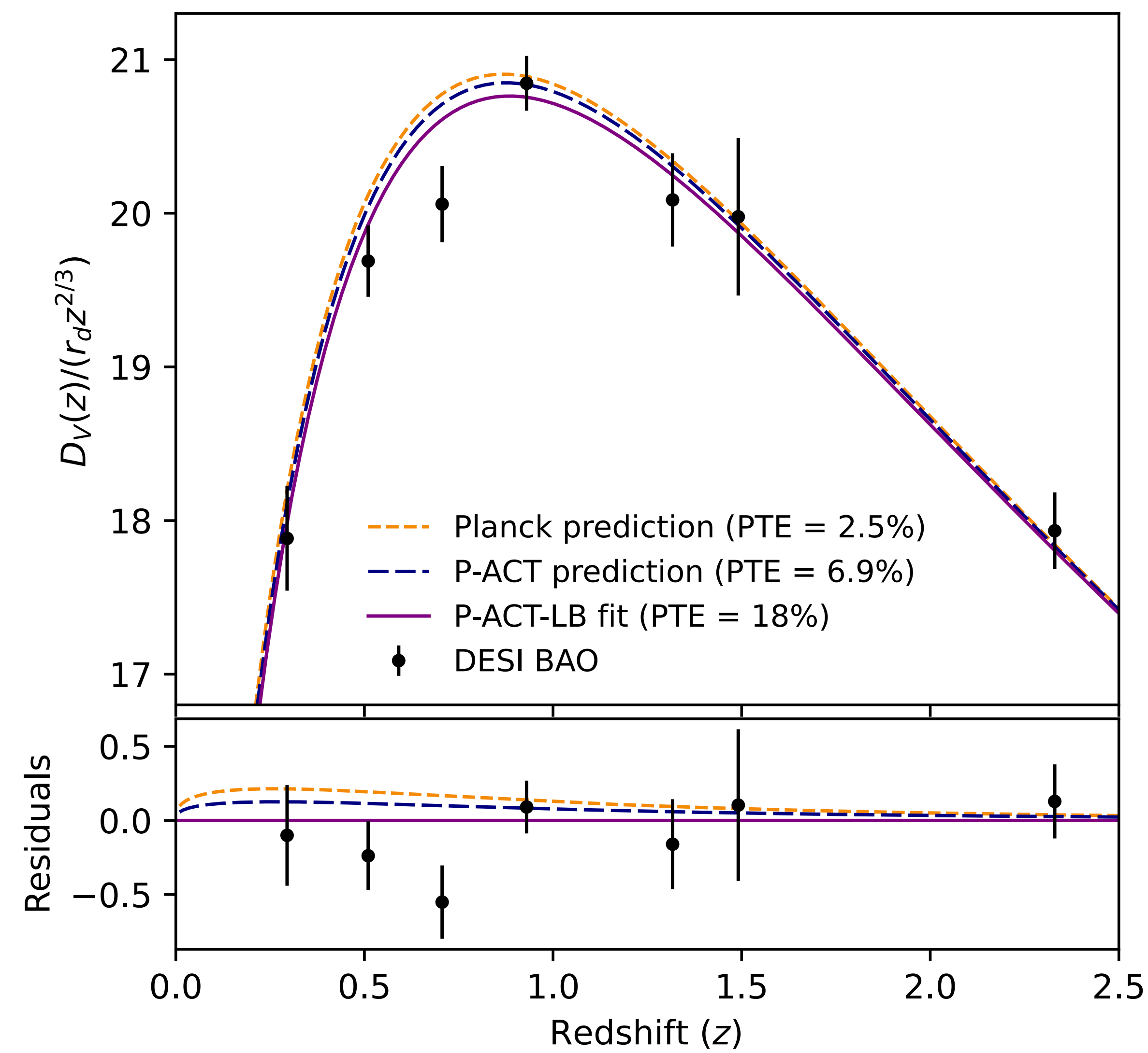
- Predictions of the best-fit P-ACT ΛCDM model agree well with direct low-redshift measurements
- ΛCDM gives an excellent joint fit to these datasets

CMB lensing power spectrum



BAO distance-redshift relation [DESI DR1]



Cosmological Constraints

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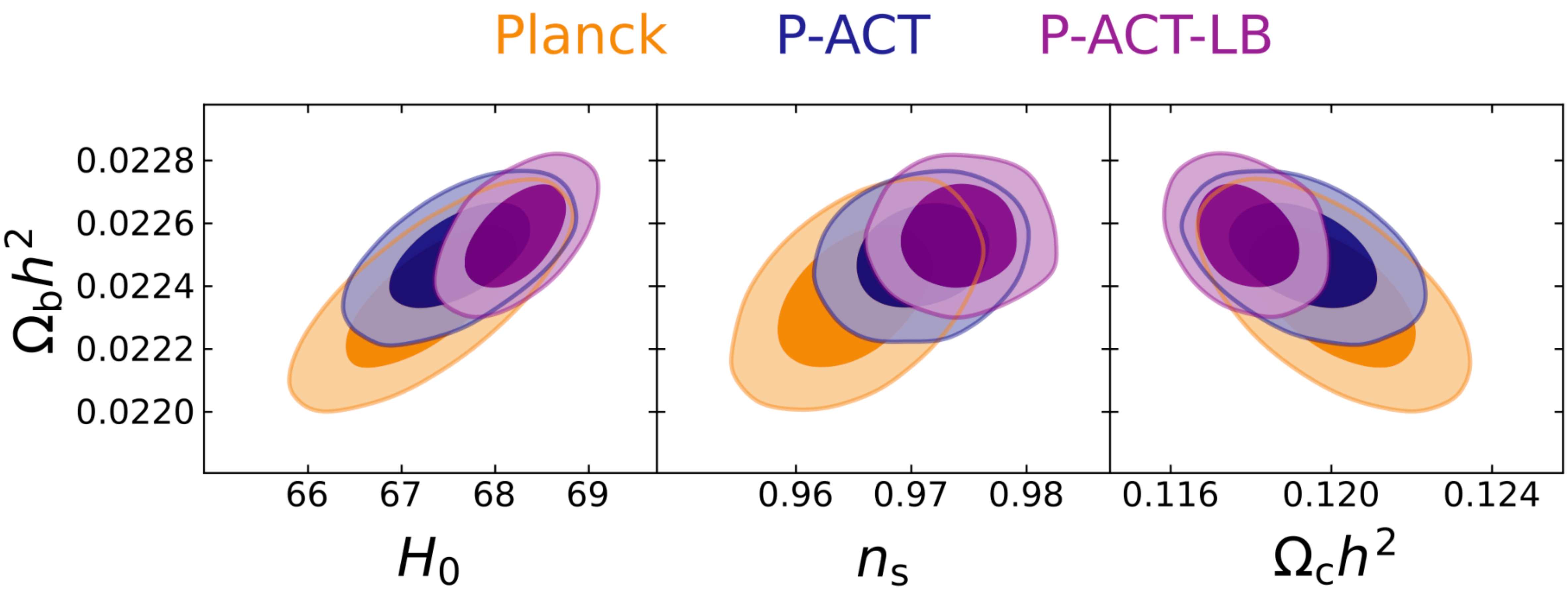
Combining ACT and Planck primary CMB data with CMB lensing ("L") and DESI-Y1 BAO ("B") data gives state-of-the art constraints on cosmological parameters



0.5% constraint on the (predicted) present-day expansion rate:
$H_0 = 68.22 \pm 0.36$ *km/s/Mpc*

>130σ detection of dark matter:
$\Omega_c h^2 = 0.1179 \pm 0.0009$

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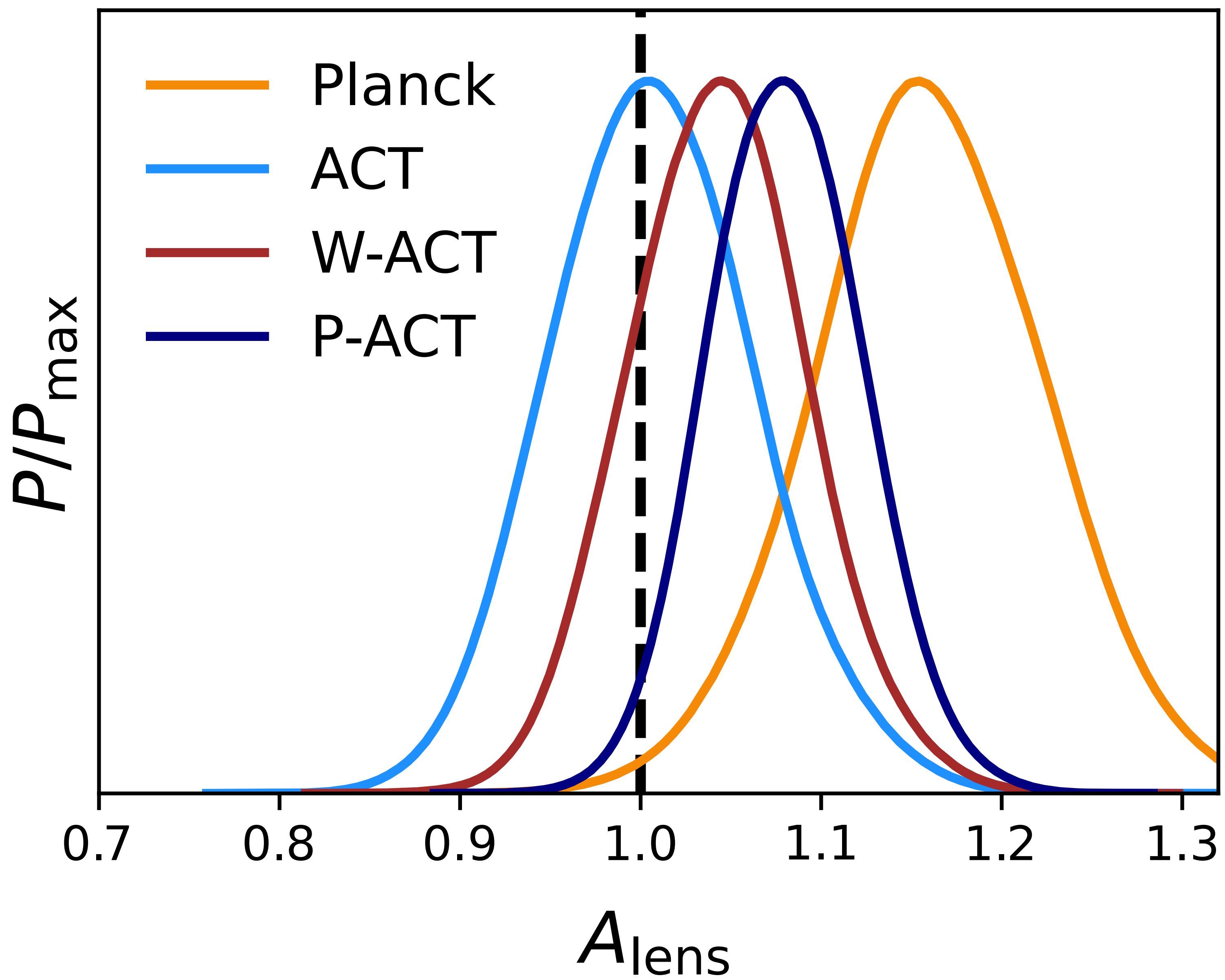
Lensing Amplitude

No evidence of excess “peak smearing” or “lensing anomaly” in ACT two-point power spectra



$$A_{\rm lens} = 1.007 \pm 0.057 \quad \text{(ACT)}$$
$$= 1.08^{+0.10}_{-0.12} \quad \text{(ACT-TT)}$$
$$= 1.24^{+0.18}_{-0.22} \quad \text{(ACT-TE)}$$
$$= 0.89^{+0.10}_{-0.23} \quad \text{(ACT-EE)}$$
$$A_{\rm lens} = 1.043 \pm 0.049 \quad \text{(W-ACT)},$$
$$A_{\rm lens} = 1.081 \pm 0.043 \quad \text{(P-ACT)}$$

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Curiosities / Hints?

“Do you feel lucky?”

If we looked at ~30 models, there should be at least one ~2.5σ hint…

Louis, La Posta, Atkins, Jense, et al. (2025), 2503.14452
Calabrese & JCH, Jense, La Posta, et al. (2025), 2503.14454

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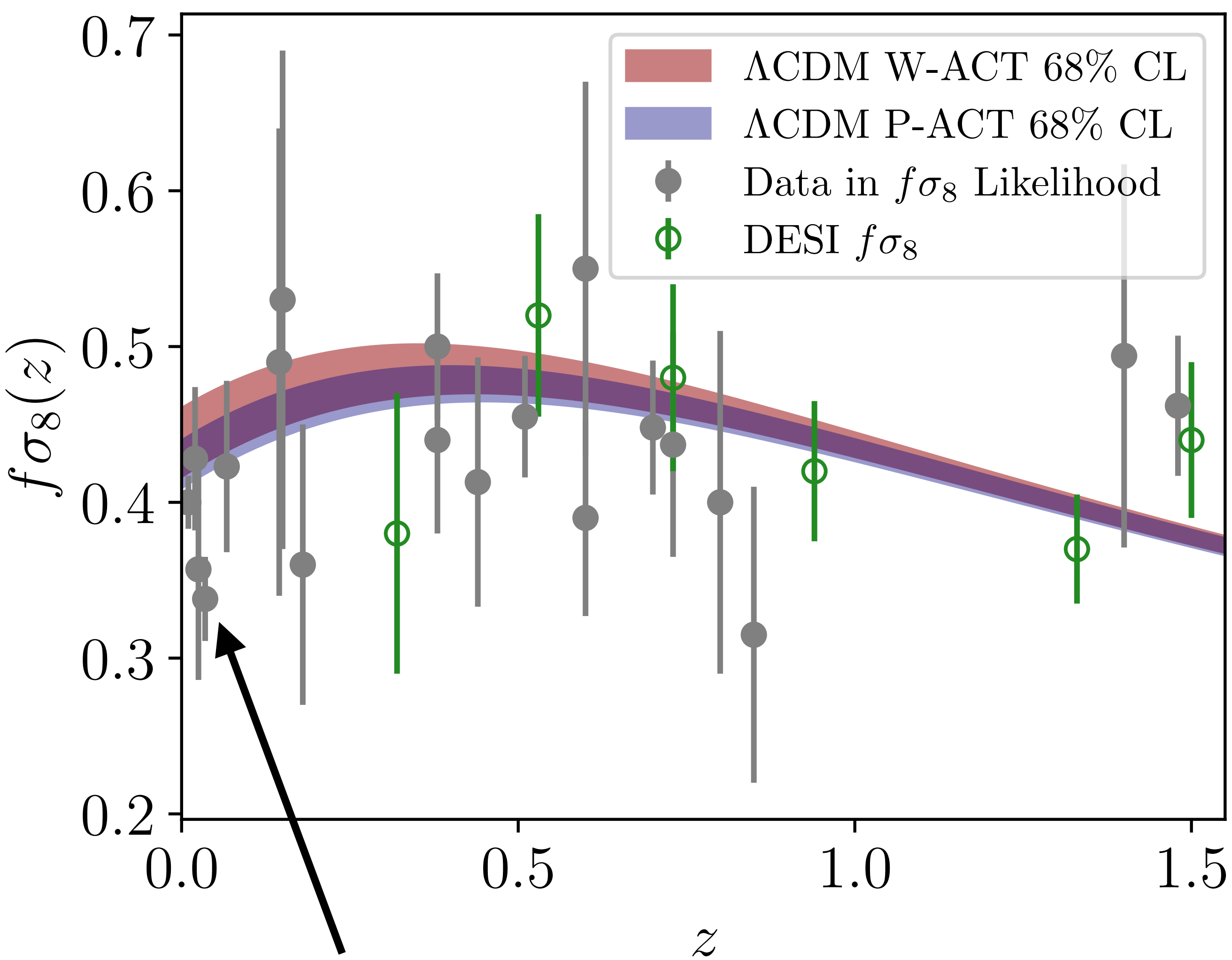
Modified Growth

f = dlnD/dlna

$$f(a) = \Omega_m^\gamma(a)$$

GR: γ = 0.55

fσ₈ from RSD and pec. vel.



two outlying points drive
3.5σ pref. for γ>0.55

$$\left.\begin{aligned} \gamma &= 0.630 \pm 0.023 \\ S_8 &= 0.8050 \pm 0.0081 \end{aligned}\right\} \text{(68\%, P-ACT-LB-f}\sigma_8\text{)}$$

cf. earlier work from Nguyen, Huterer, +

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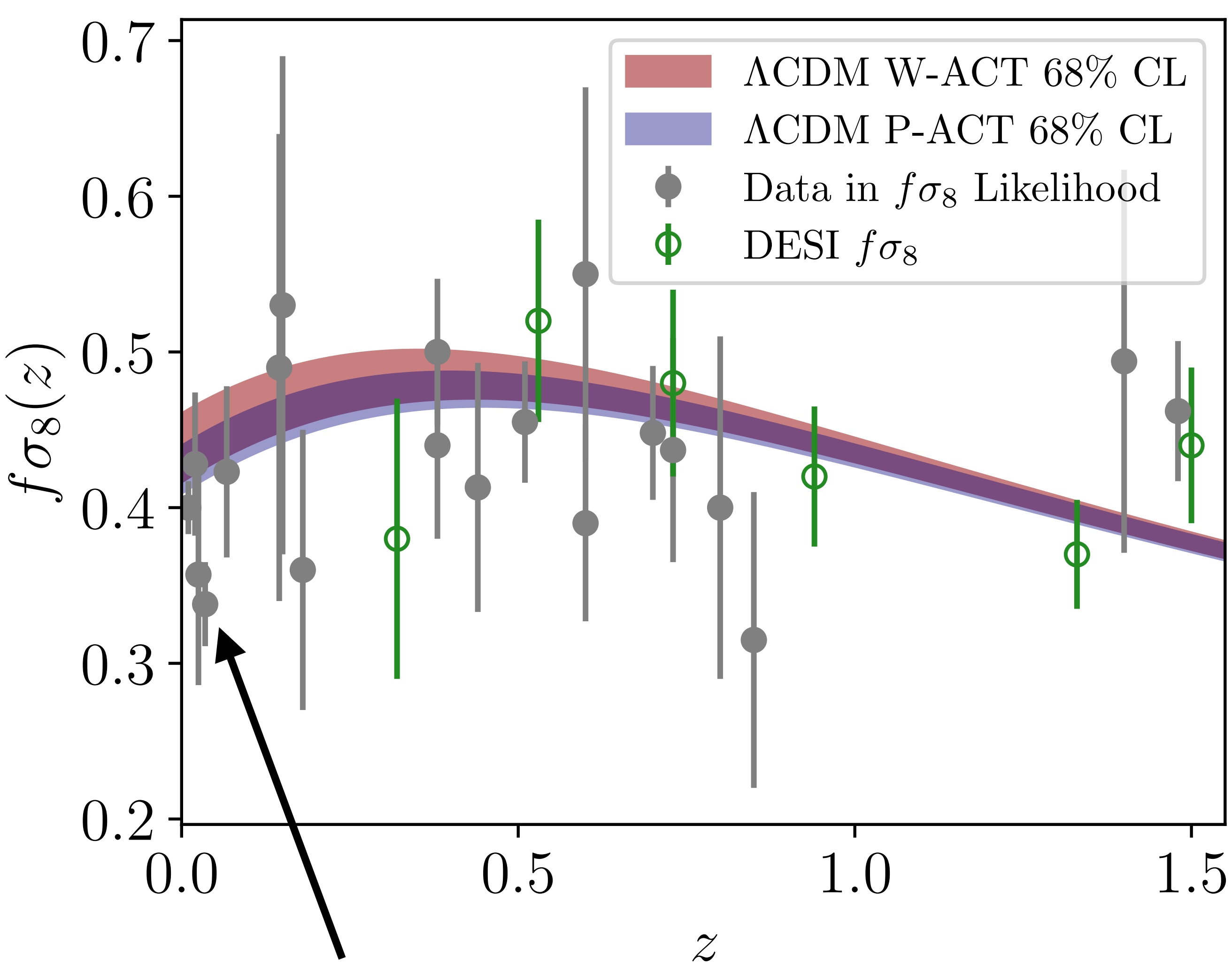
Modified Growth

f = dlnD/dlna $\quad f(a) = \Omega_m^\gamma(a) \quad$ GR: γ = 0.55

fσ8 from RSD and pec. vel.



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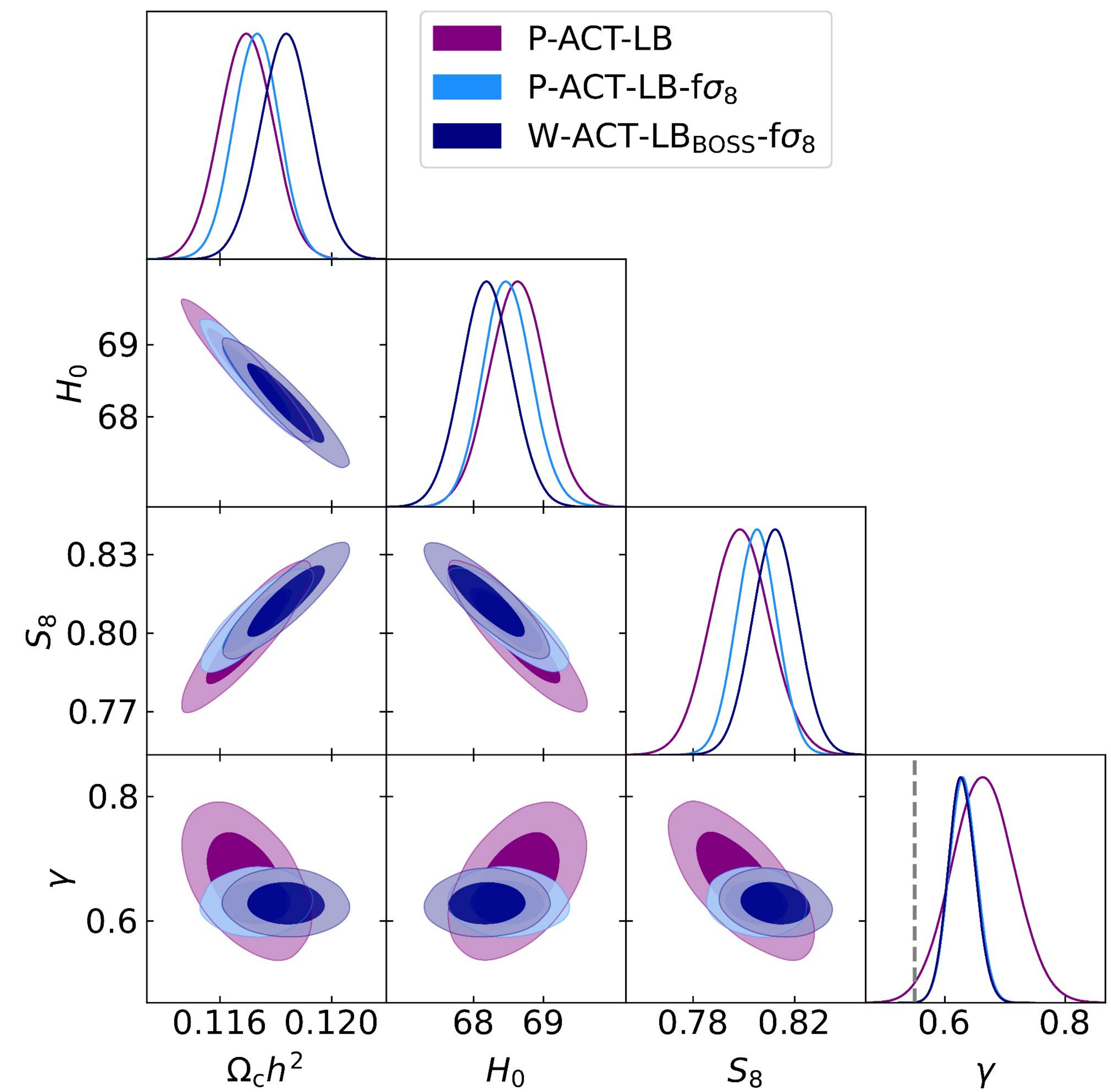

$$\left.\begin{aligned}\gamma &= 0.630 \pm 0.023 \\ S_8 &= 0.8050 \pm 0.0081\end{aligned}\right\} \text{(68\%, P-ACT-LB-}f\sigma_8\text{)}$$

$$\left.\begin{aligned}\gamma &= 0.663 \pm 0.052 \\ S_8 &= 0.799 \pm 0.012\end{aligned}\right\} \text{(68\%, P-ACT-LB)}$$

Modified Recombination

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Ex.: primordial magnetic fields; **variations of fundamental constants**; change to CMB monopole temperature or distribution function

Early-universe variation of fine-structure constant α_{EM}:

$$\alpha_{\rm EM}/\alpha_{\rm EM,0} = 1.0043 \pm 0.0017 \text{ (68\%, P-ACT-LB)}$$

$$H_0 = 69.27 \pm 0.54 \text{ km/s/Mpc}$$

~2.5σ fluctuation away from unity

But parameter degeneracies are far smaller than in varying electron mass scenario — thus no significant increase in H_0

Dominant physical effects:

$$\sigma_{\rm T} \propto \alpha_{\rm EM}^2 m_e^{-2} \qquad E \propto \alpha_{\rm EM}^2 m_e$$

$$m_e/m_{e,0} = 1.0063 \pm 0.0056$$

P-ACT-LBS

cf. earlier work from Hart & Chluba, Sekiguchi & Takahashi, ++

EB and TB Power Spectra

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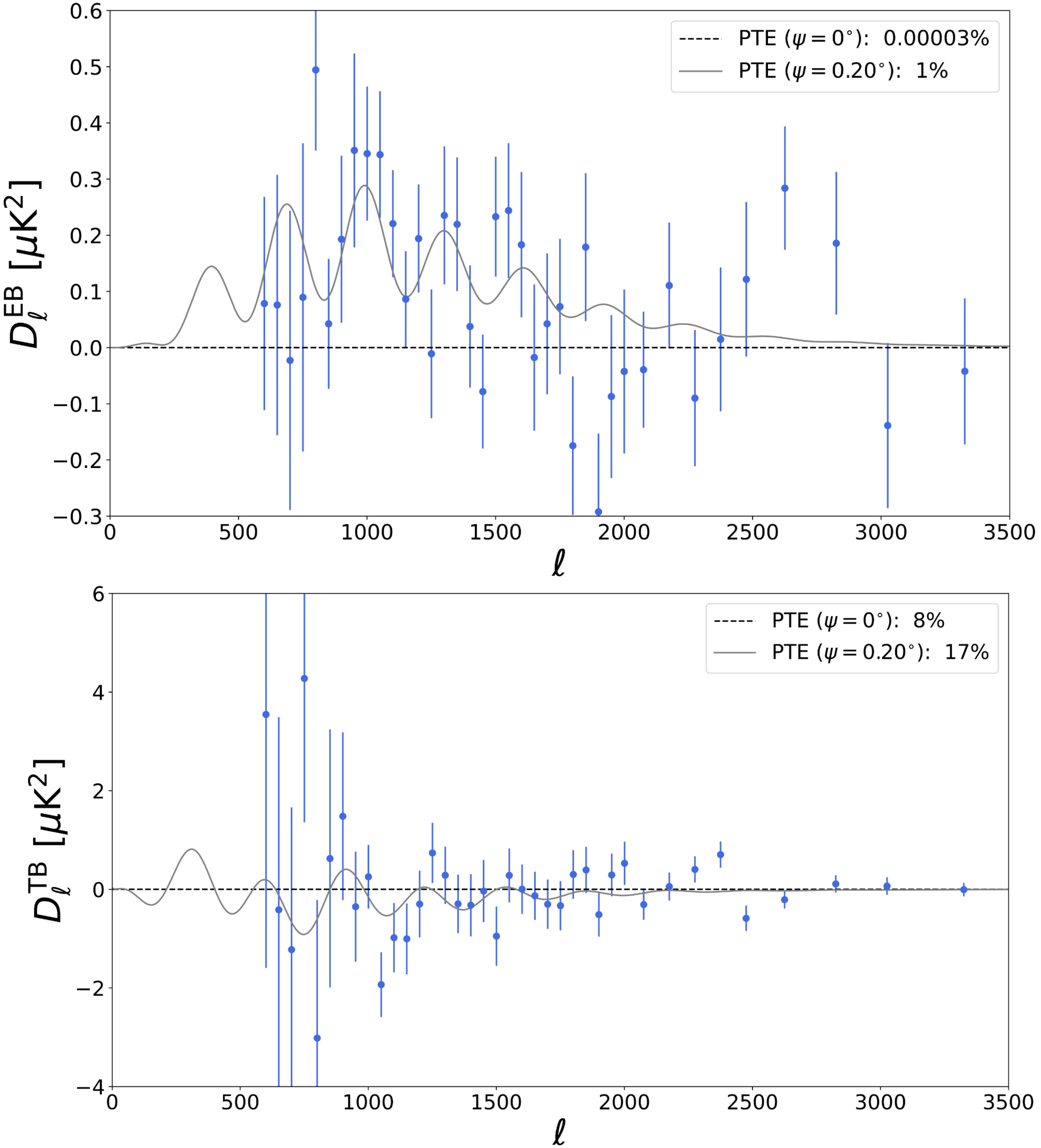

EB and TB Power Spectra

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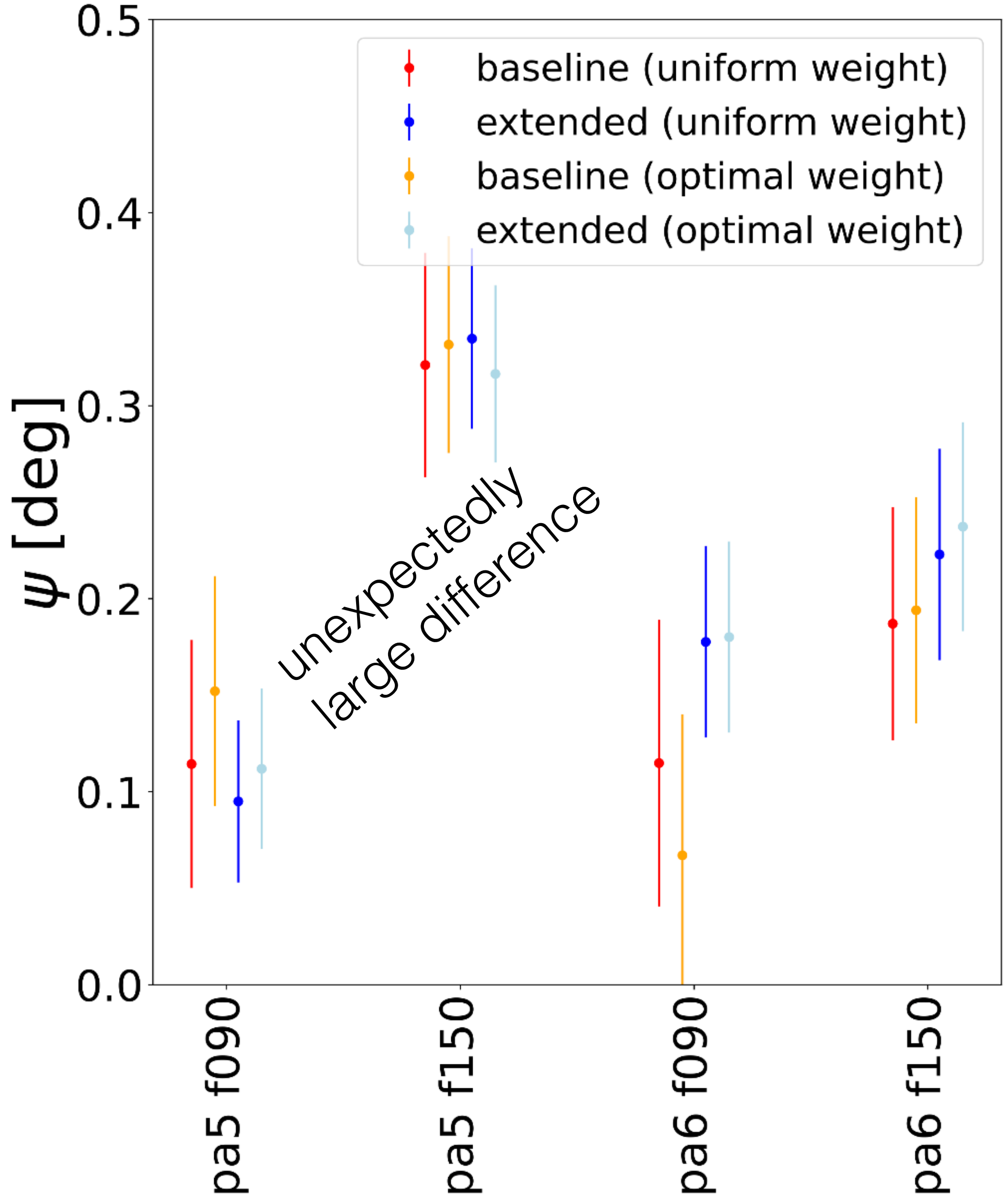
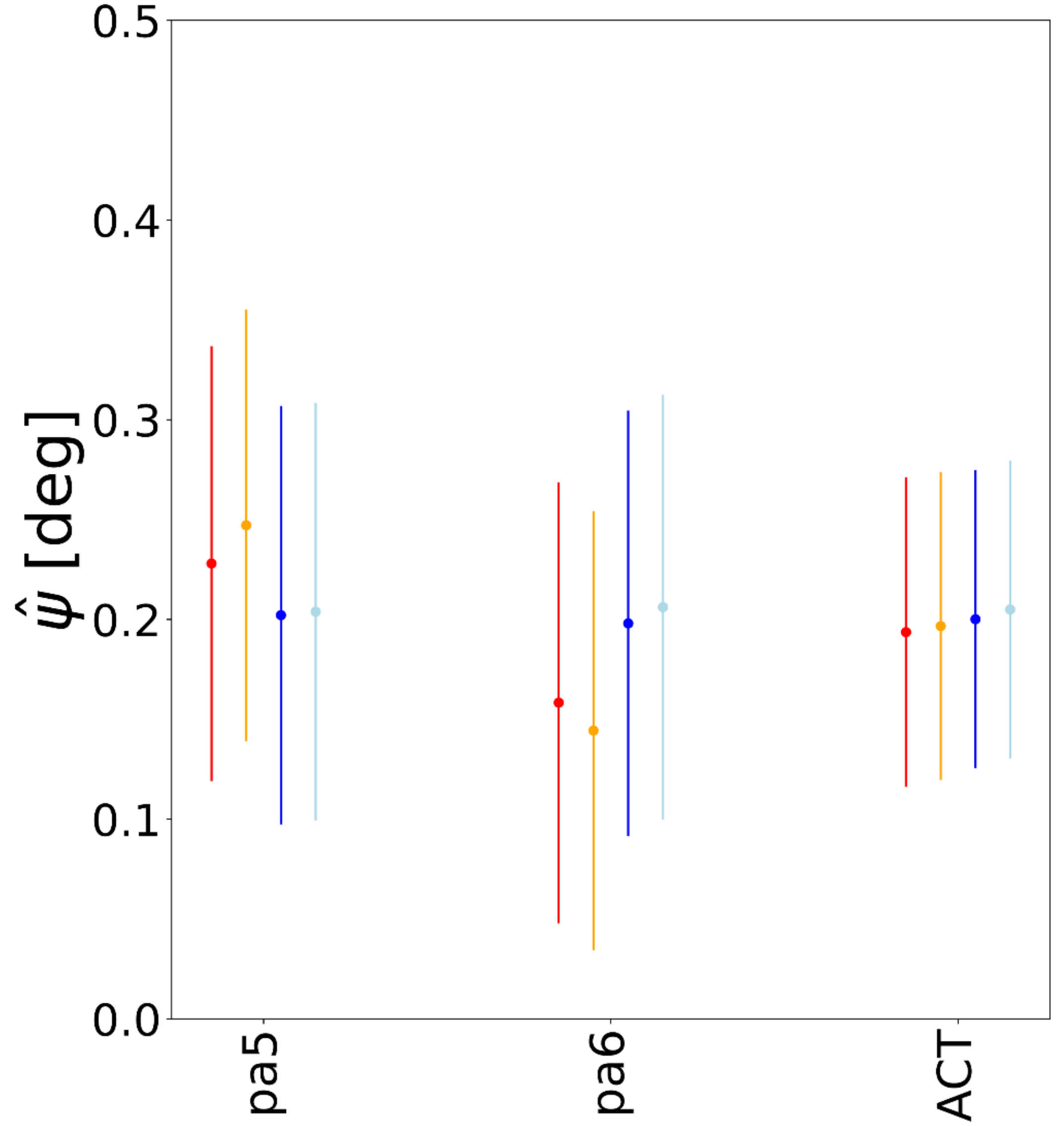
Combined best estimate of overall angle: 0.20° +/- 0.08°

Error bar dominated by systematic uncertainty from optics modeling

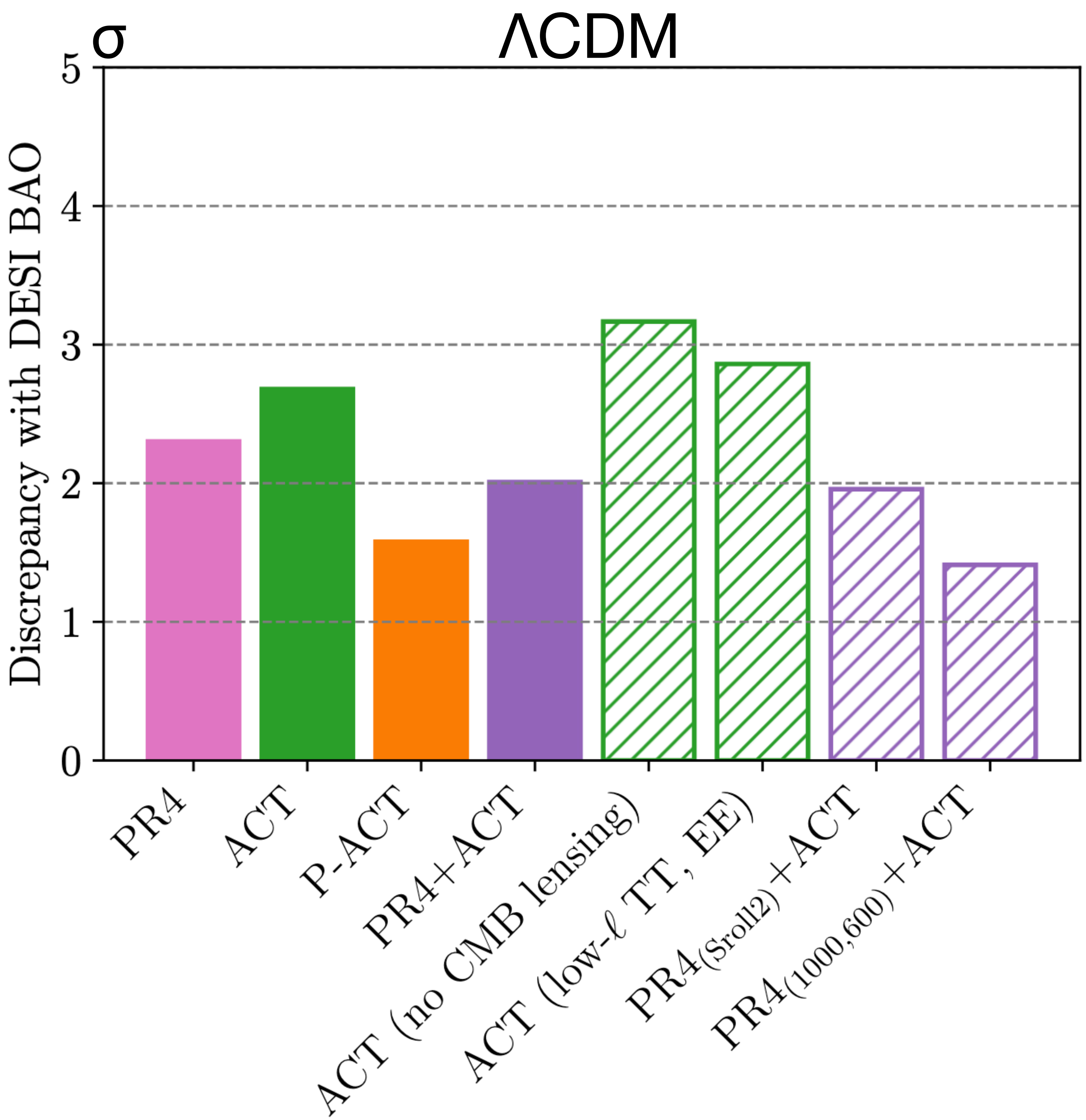




Planck (Eskilt & Komatsu 2022): 0.34° +/- 0.09°

Cosmological Concordance

Colin Hill
Columbia



DESI+P-ACT: only 2.4σ 'preference' for w_0w_aCDM over ΛCDM

DESI+$PR4_{(1000,600)}$+ACT: <2.4σ preference

DESI+PR4+ACT: 3σ preference

Garcia-Quintero+ (2504.18464)

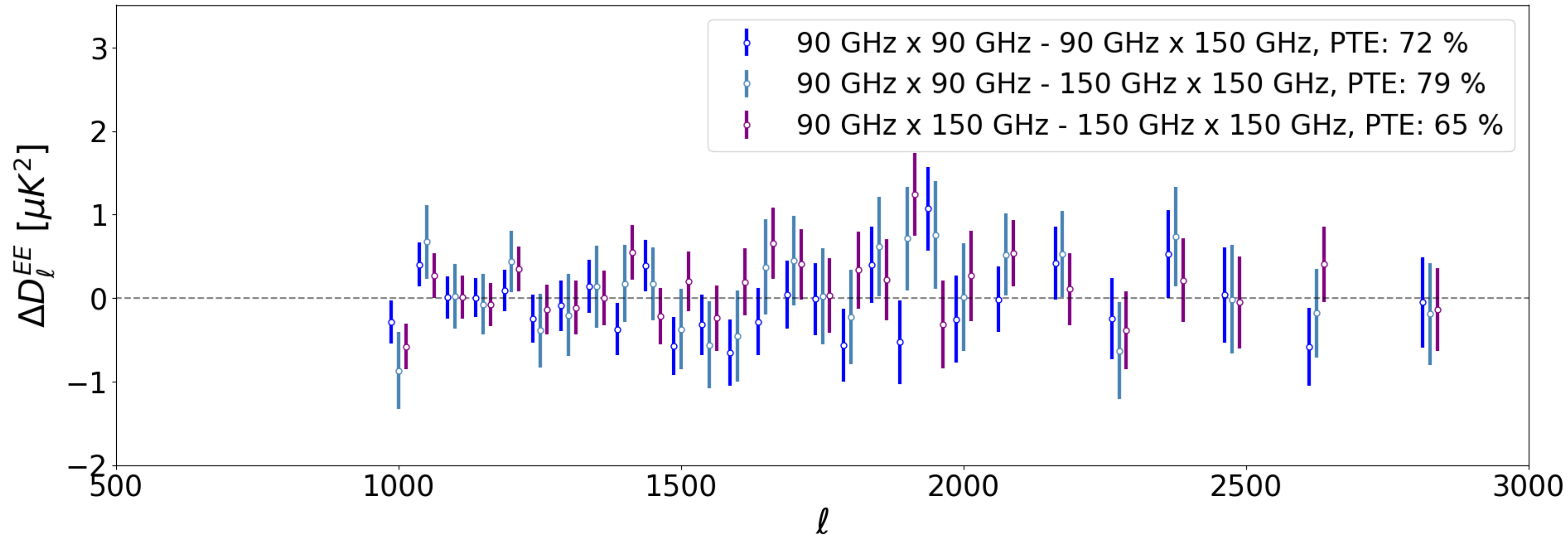
Opening the Box

Colin Hill
Columbia

- Our analysis was performed fully blind: we did not infer parameters or compare to Planck power spectra until ~2000 null tests had been passed and we had validated the full pipeline on realistic sky simulations

- These tests confirm that the measured power spectra are stable w.r.t.:
  - array bands (frequency)
  - weather conditions (precipitable water vapor in atmosphere)
  - scan elevation
  - sky location
  - time of observation
  - position of the detectors in the focal plane

Ex.: array-band null test for EE power spectrum

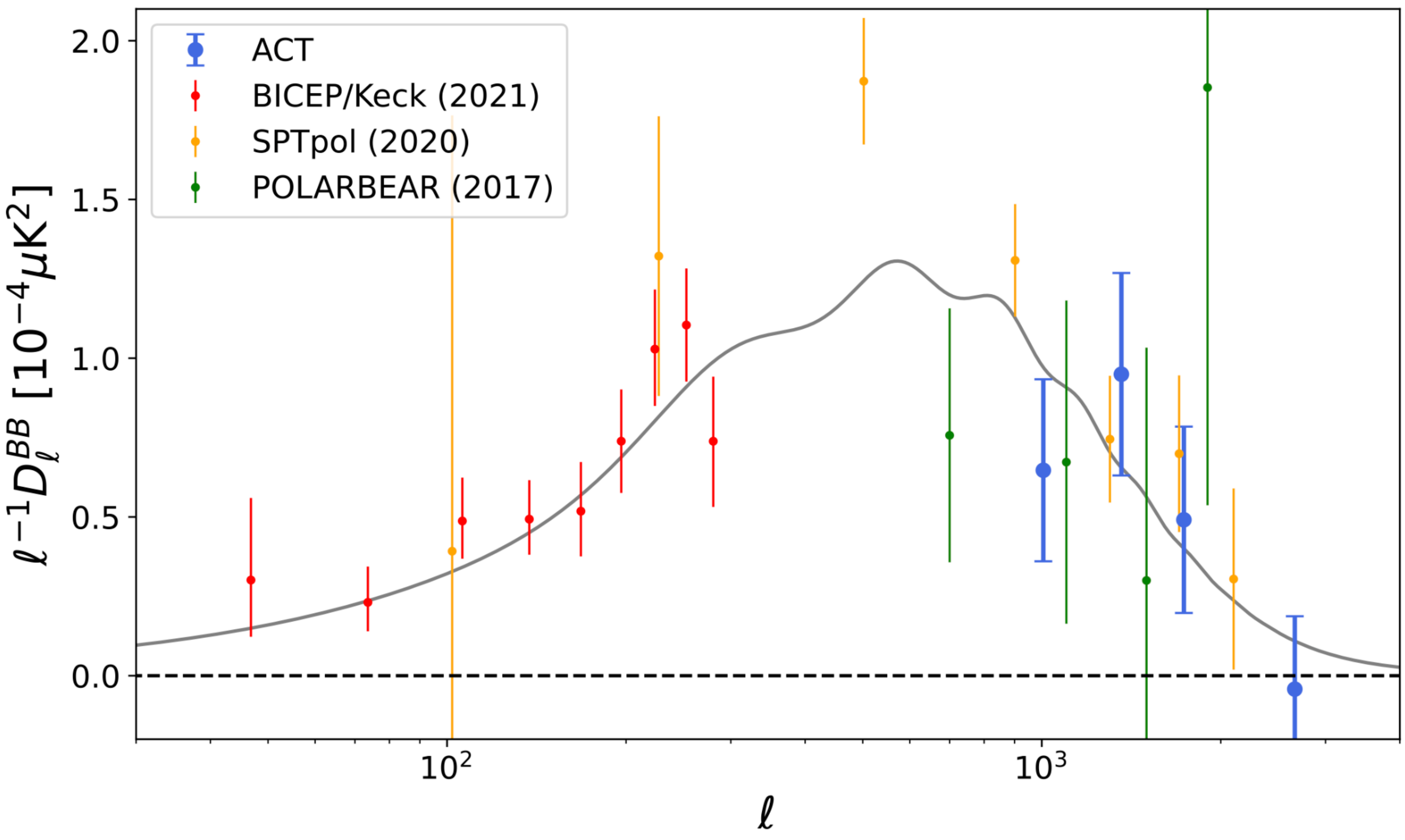


After passing all tests, we “opened the box” internally on April 18, 2024

B-Mode Power Spectrum

Colin Hill
Columbia

~4σ evidence for BB power sourced by gravitational lensing



Parameter Stability

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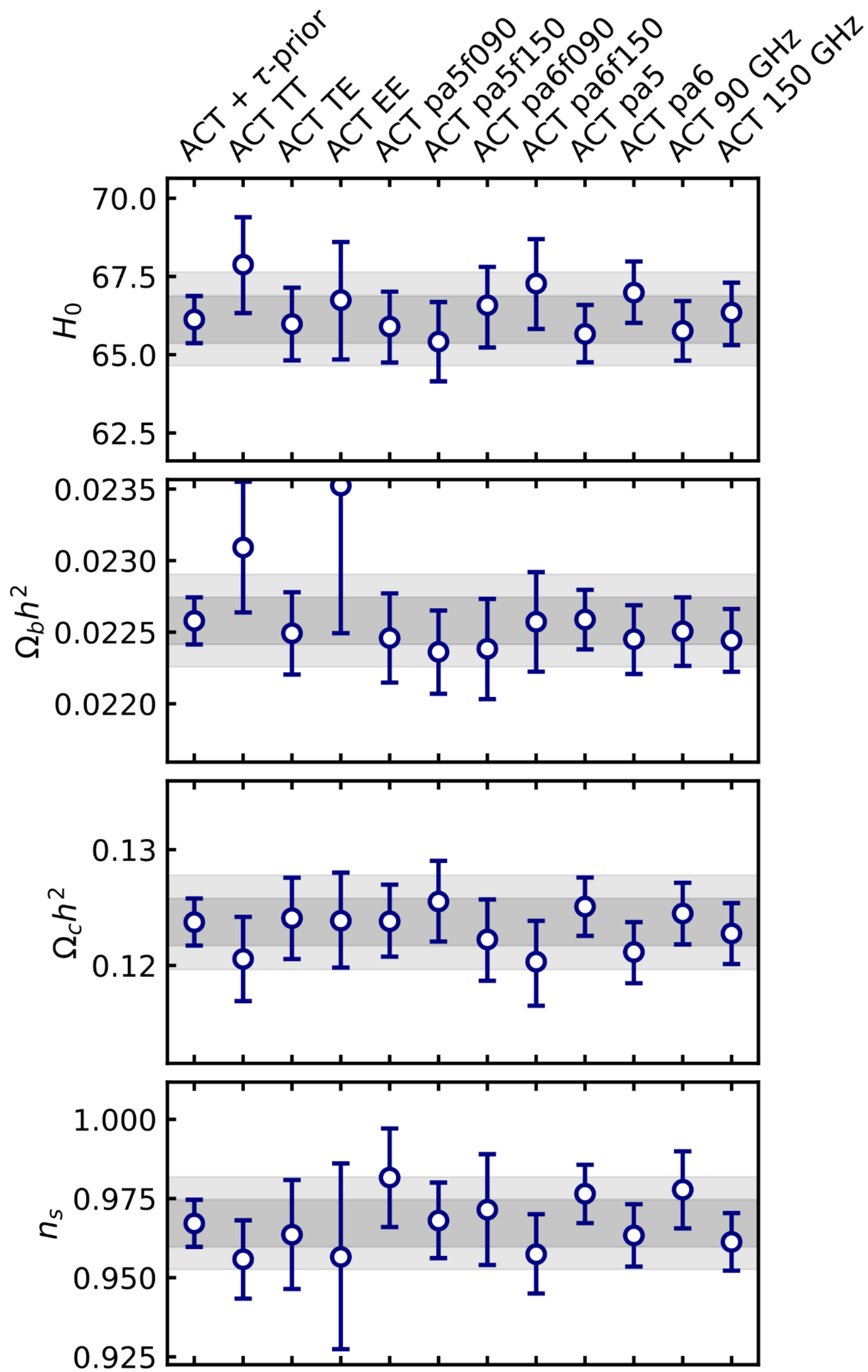

Breakdown of χ^2 for P-ACT fit in ΛCDM:

TT:
- ACT: 566.05/601
- Planck: 89.05/114

TE:
- ACT: 651.77/644
- Planck: 67.82/69

EE:
- ACT: 392.19/406
- Planck: 68.93/69

ACT and Planck on same patch of sky

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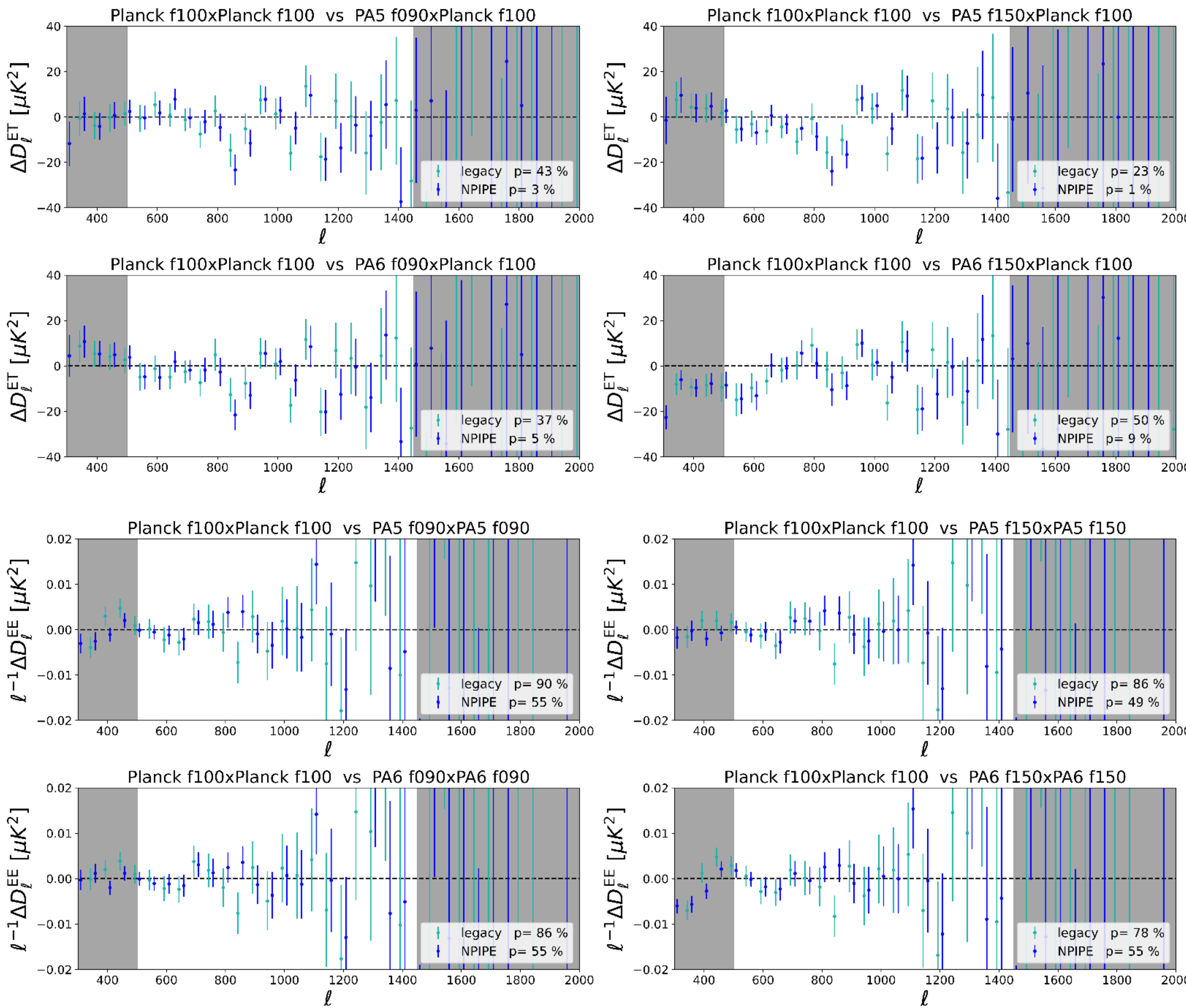

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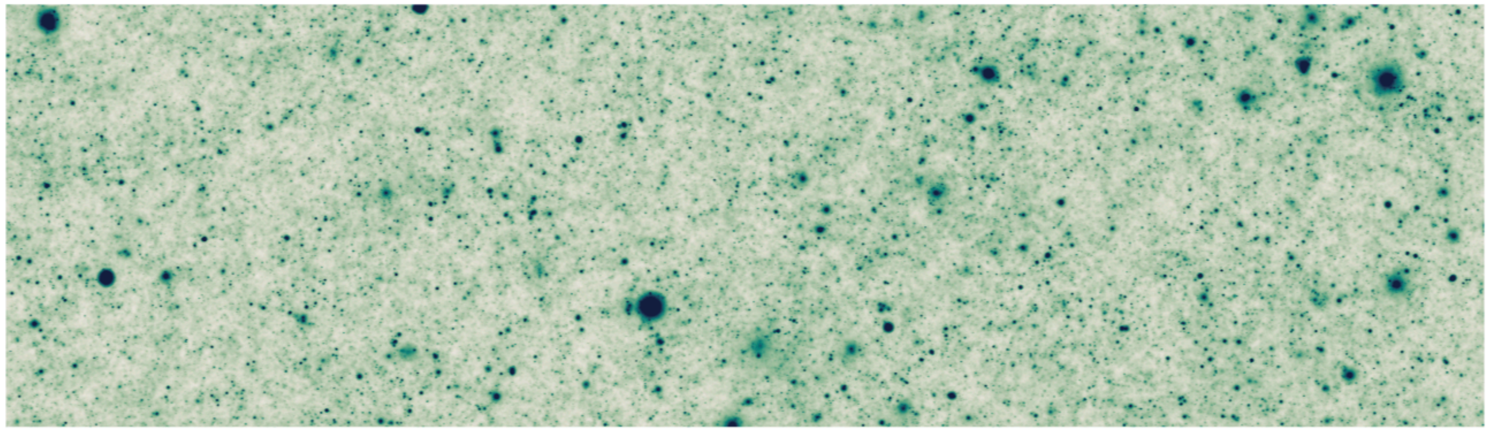
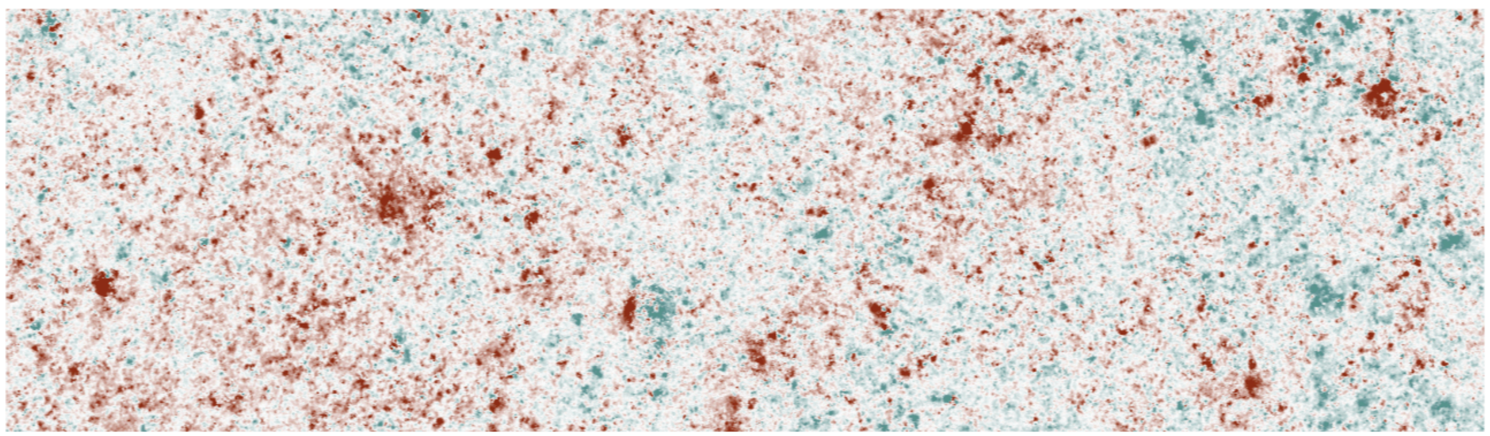
Foregrounds

Simulated sky maps from *Agora* [Omori 2022]

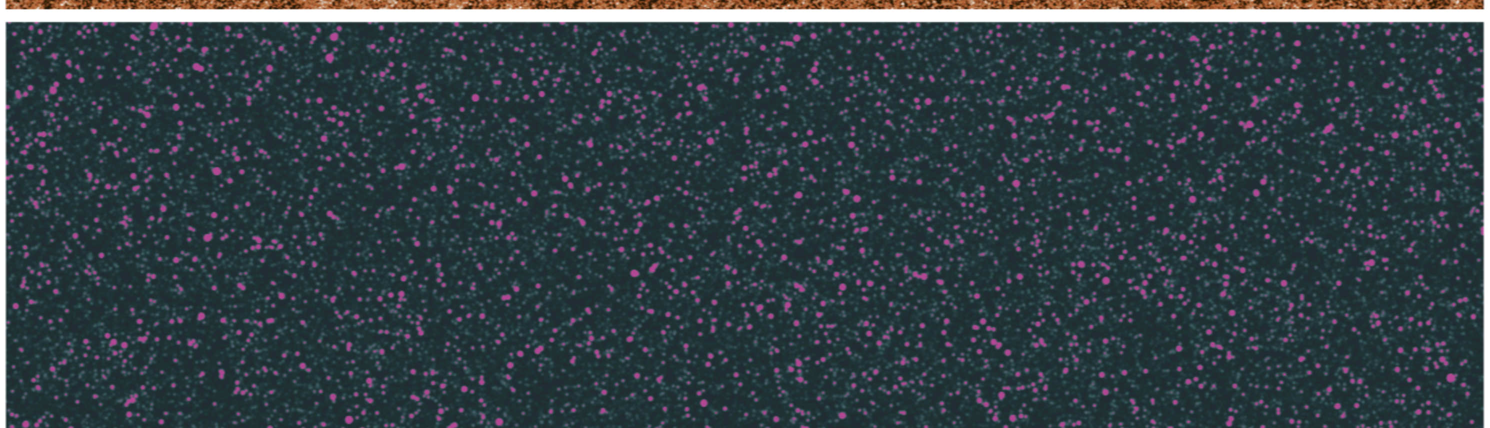


Thermal Sunyaev-Zel'dovich effect: inverse-Compton scattering of CMB photons off hot electrons



Kinematic Sunyaev-Zel'dovich effect: Doppler boosting of CMB photons due to Thomson scattering off moving electrons

Cosmic infrared background: thermal emission of warm dust grains in distant galaxies



Radio sources: synchrotron emission from active galactic nuclei (supermassive black holes)

Foregrounds

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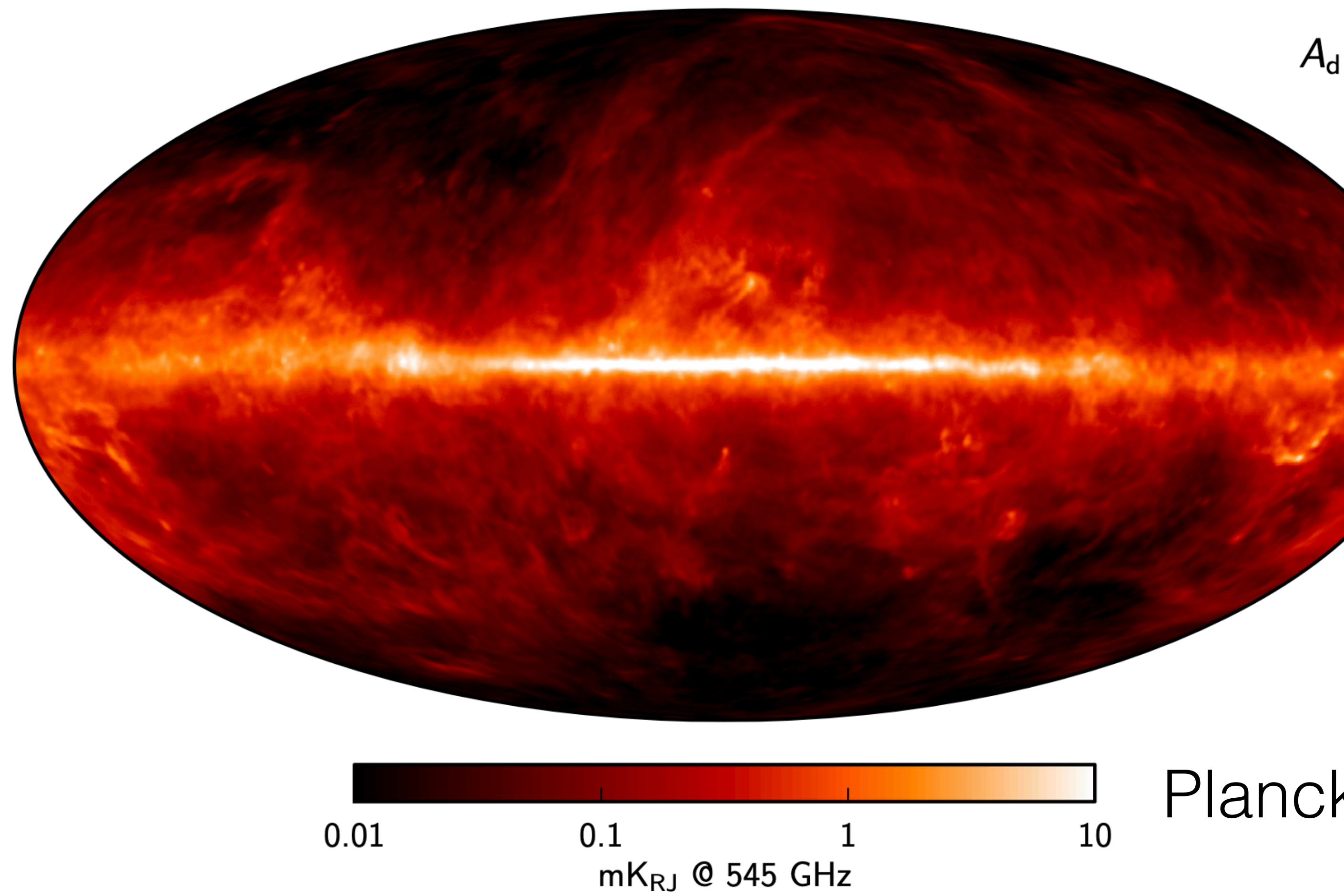
We also model the thermal emission from dust grains heated by starlight in the Milky Way



Planck 2015

Foregrounds

Colin Hill
Columbia

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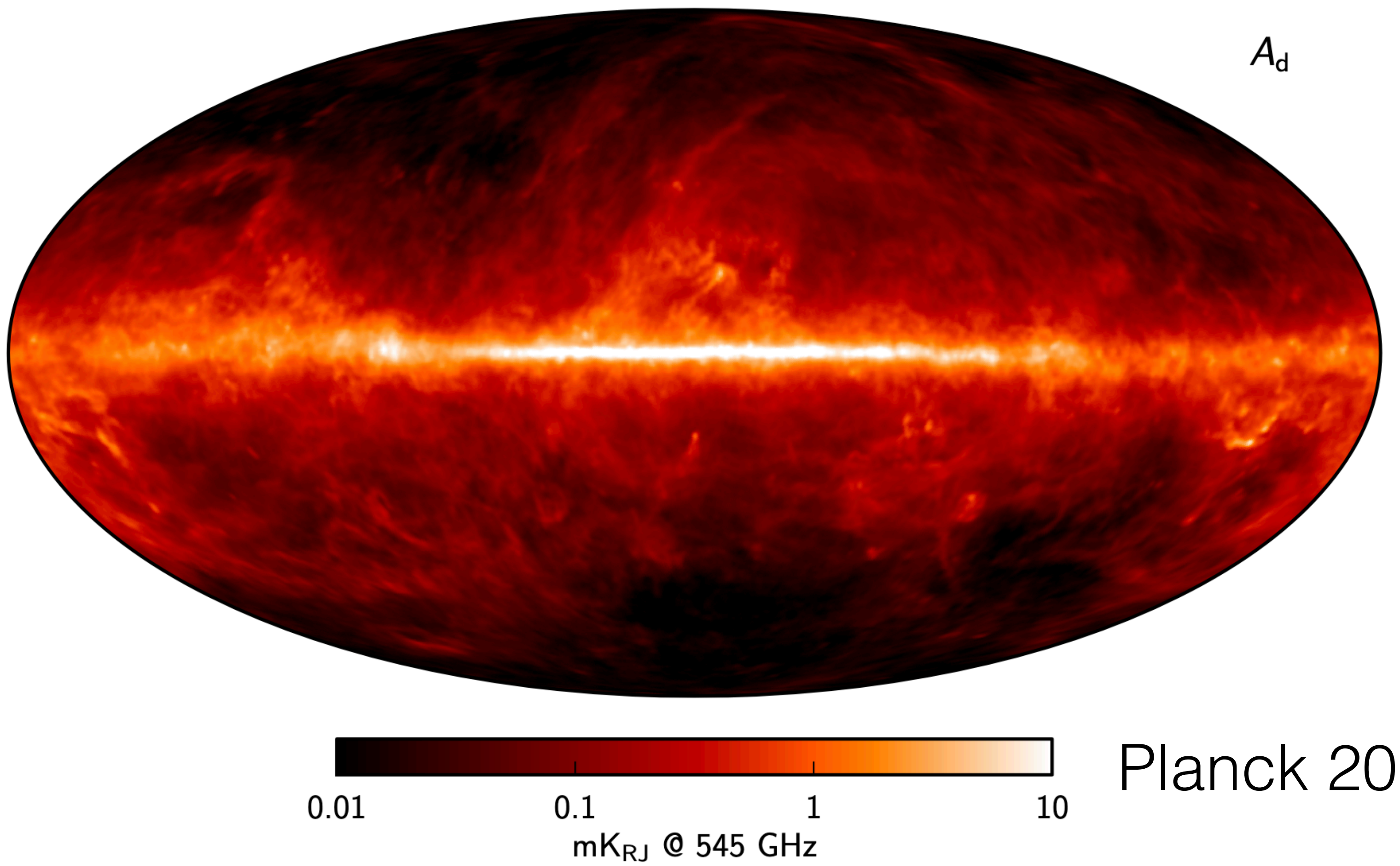

Planck 2015

We build analytic models for the power spectra of all foreground components and infer the parameters of these models simultaneously with the cosmological parameters inferred from the CMB component (via a Gaussian likelihood coupled to *Cobaya* MCMC sampler)

https://github.com/ACTCollaboration/act_dr6_mflike

Multifrequency Power Spectra

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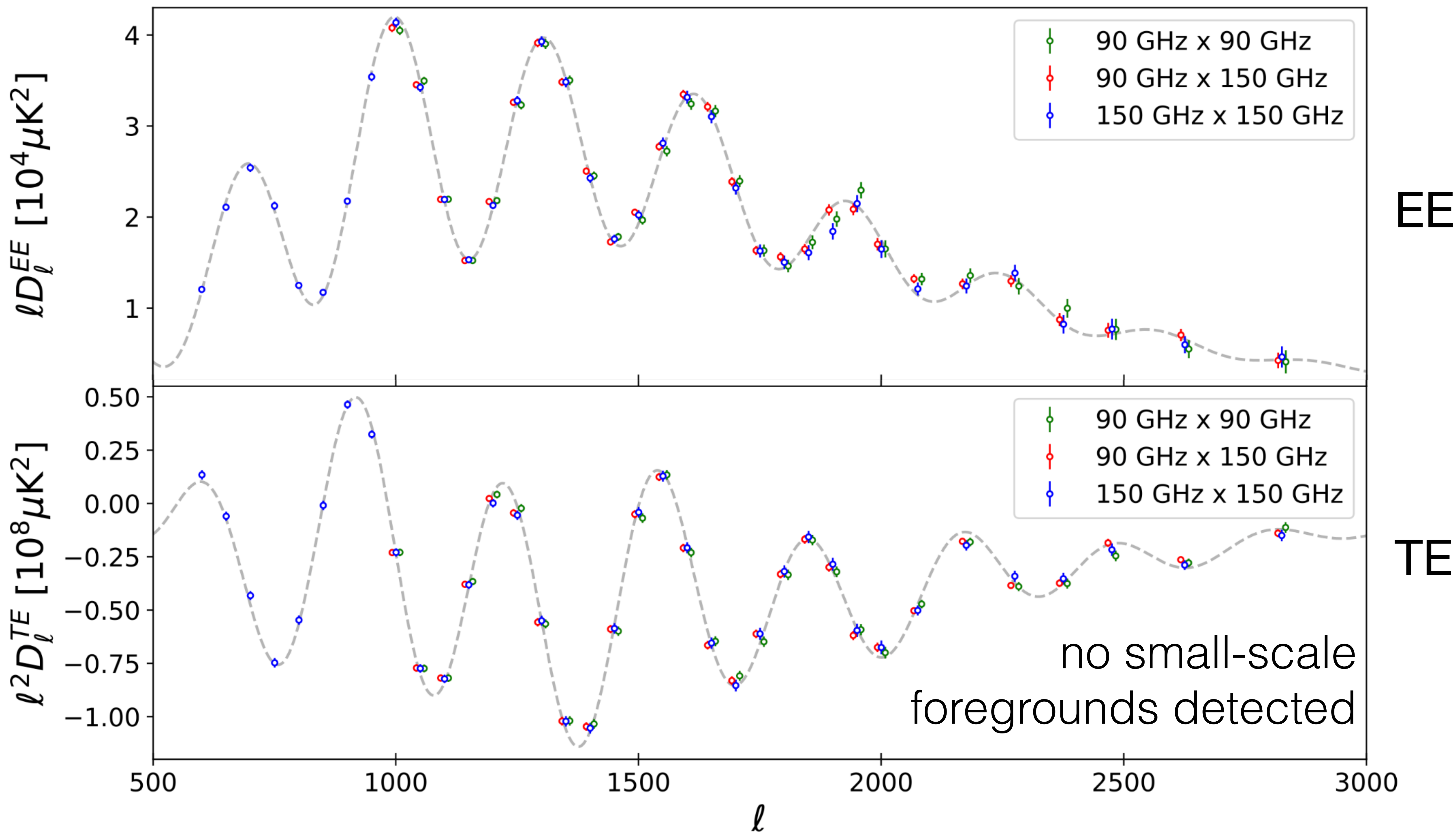
Foregrounds are significantly smaller in TE and EE power spectra



Multi-Component Model

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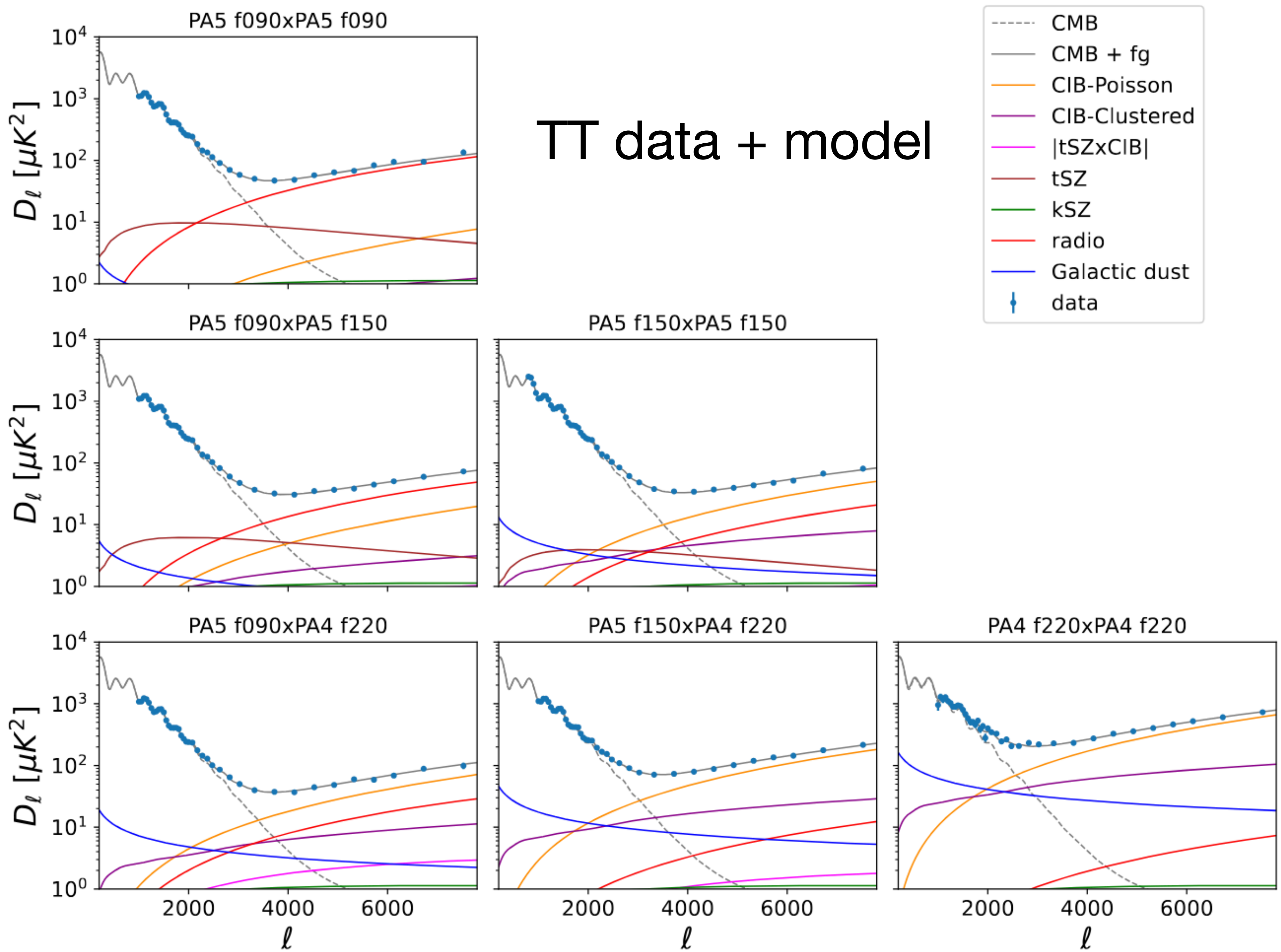
Columbia

We fit a multi-component sky model to the multi-frequency auto- and cross-power spectra



+ simpler models for TE and EE data

Foreground Model Robustness

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End-to-end validation from simulated sky maps to parameters

- Standard in previous CMB power spectrum analyses: simulate gaussian random fields and run analysis pipeline with the same sky model

- More stringent test in DR6: infer parameters from ~realistic, non-gaussian sky maps with realistic instrument systematics, using analysis pipeline that does not contain models designed to match these simulations

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Columbia

Foreground Model Robustness

End-to-end validation from simulated sky maps to parameters

- Standard in previous CMB power spectrum analyses: simulate gaussian random fields and run analysis pipeline with the same sky model

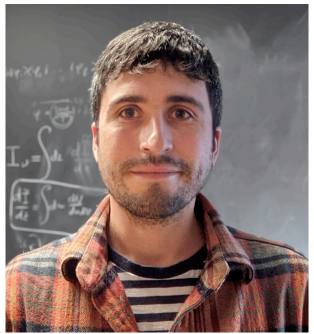
- More stringent test in DR6: infer parameters from ~realistic, non-gaussian sky maps with realistic instrument systematics, using analysis pipeline that does not contain models designed to match these simulations

- Extragalactic fields = *Agora* (Omori 2022): N-body simulation post-processed with detailed models for tSZ, kSZ, CIB, sources

- Galactic fields = *PySM3* (Thorne+2017, Zonca+2021)

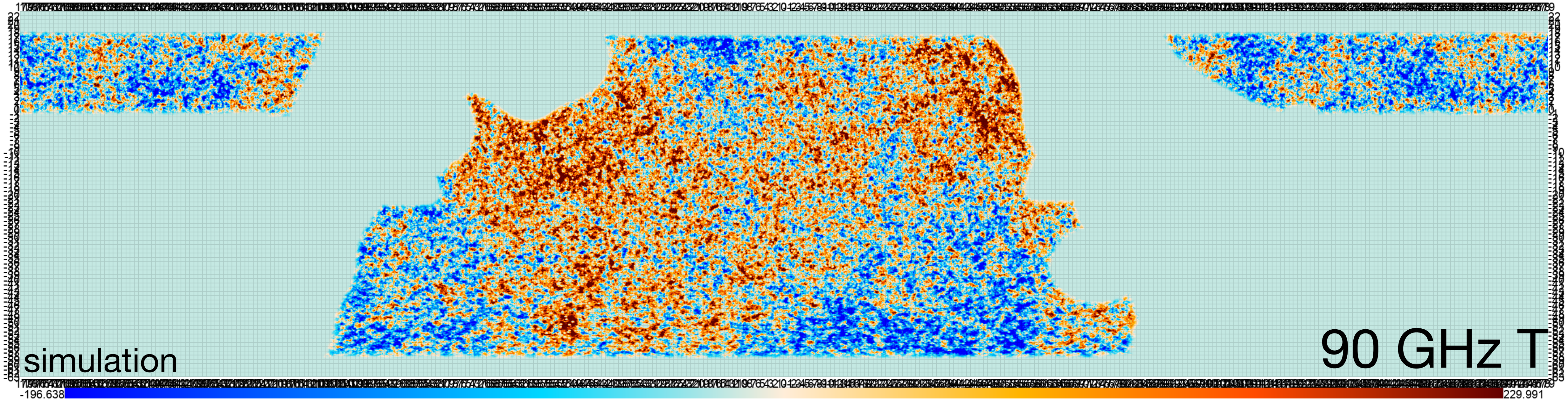
- Maps for each ACT detector array are generated and processed with beams, passbands, and noise model built from data (Atkins+ 2023)

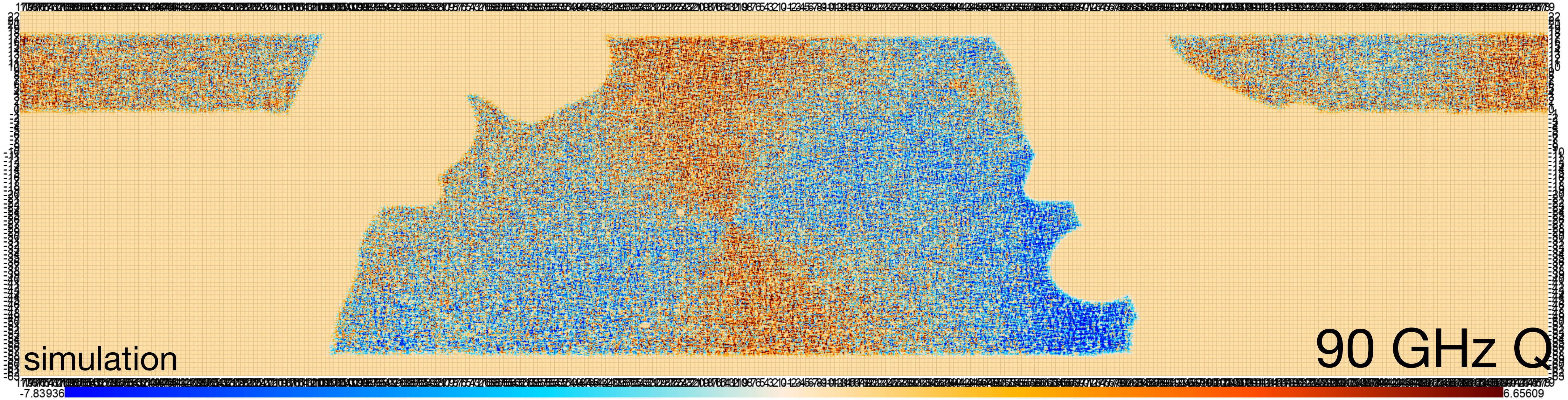
- Pipeline accelerated by >100x using neural-network-based Boltzmann code emulators (Bolliet, JCH,+ 2023)

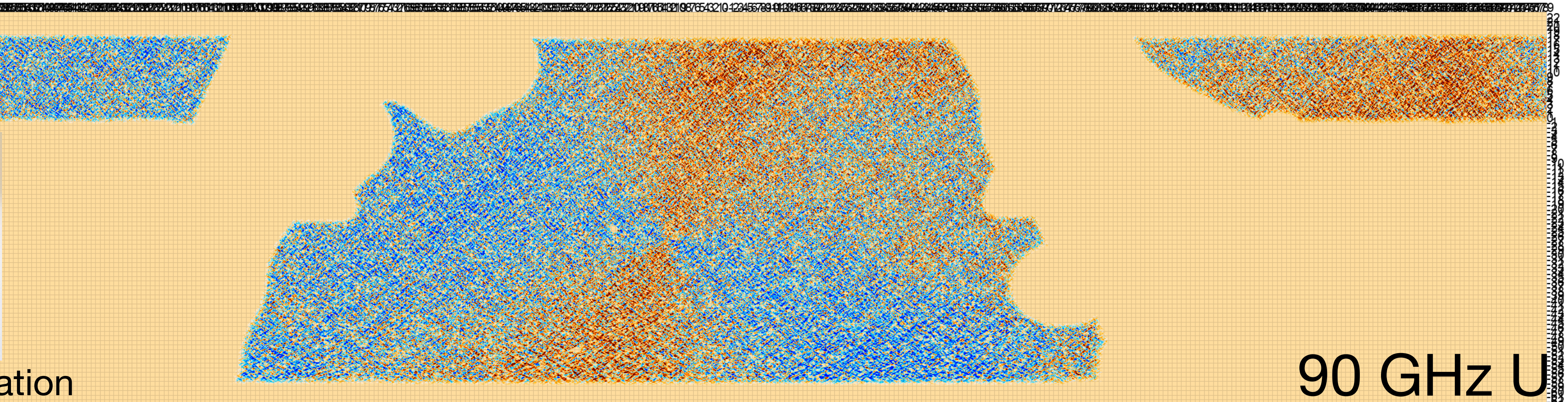


ACT DR6: Robustness

Colin Hill
Columbia







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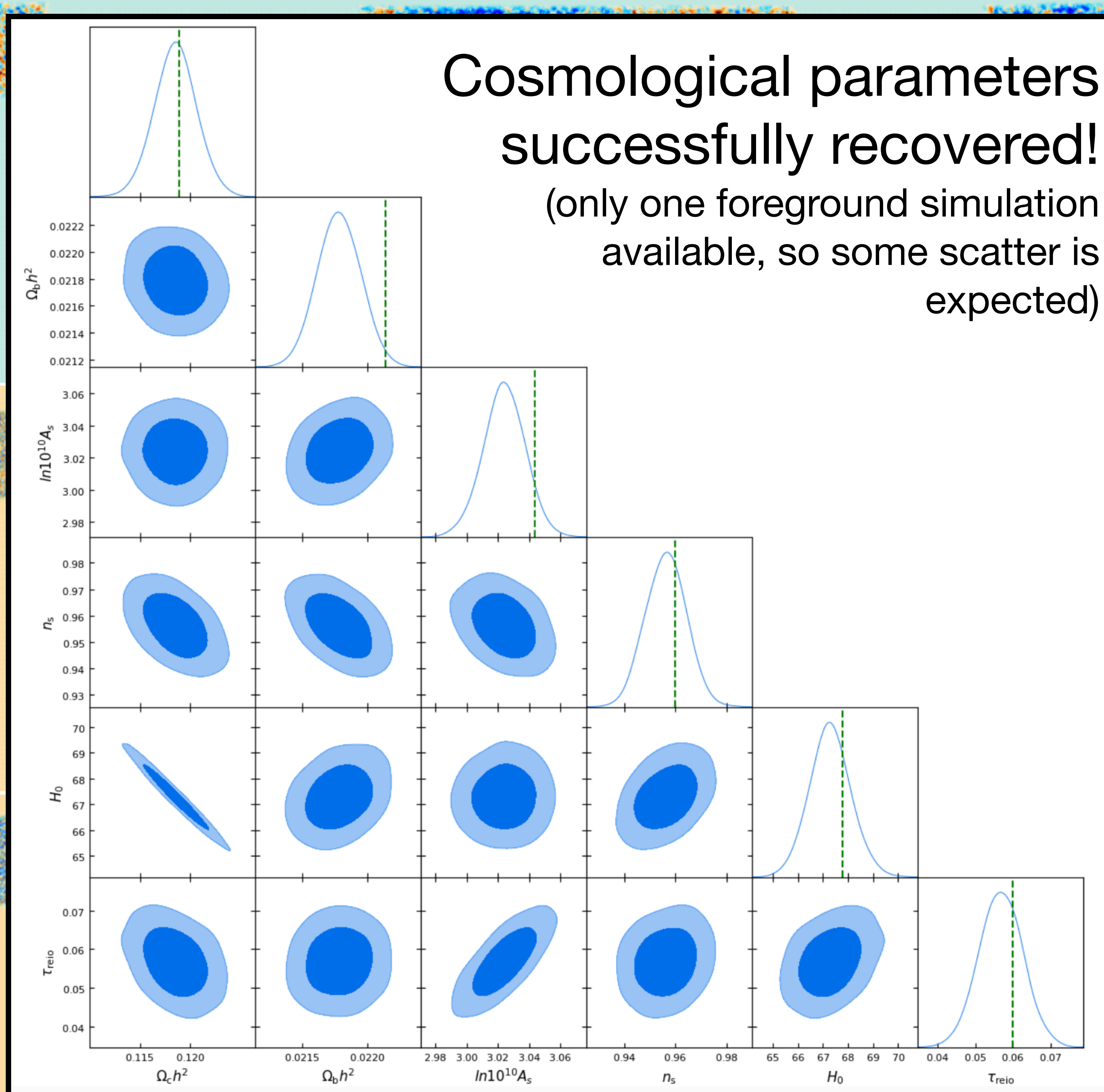
ACT DR6: Robustness

simulation
90 GHz T
simulation
90 GHz Q
90 GHz U

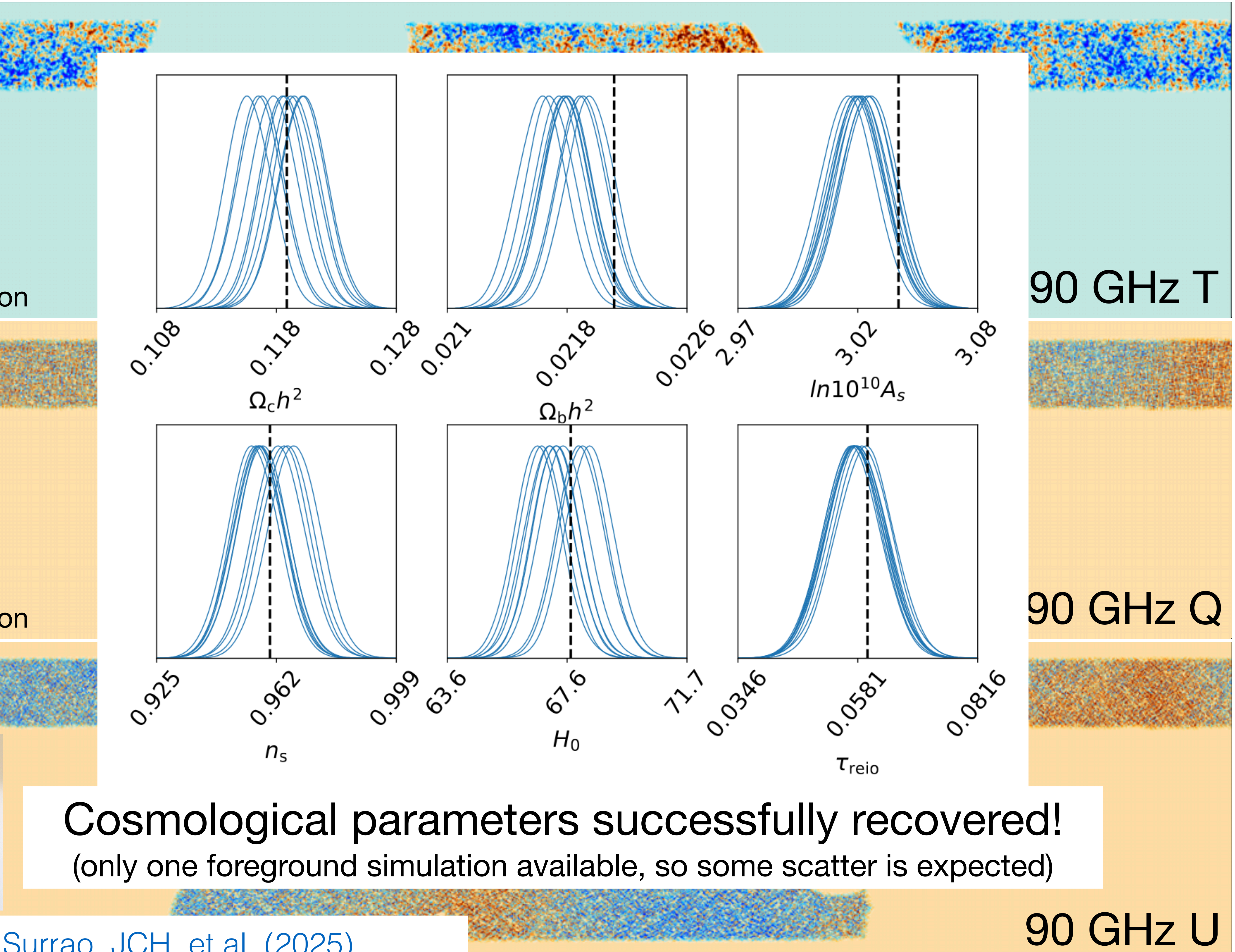


Cosmological parameters successfully recovered!
(only one foreground simulation available, so some scatter is expected)

Beringue, Surrao, JCH, et al. (2025)

ACT DR6: Robustness

Colin Hill
Columbia



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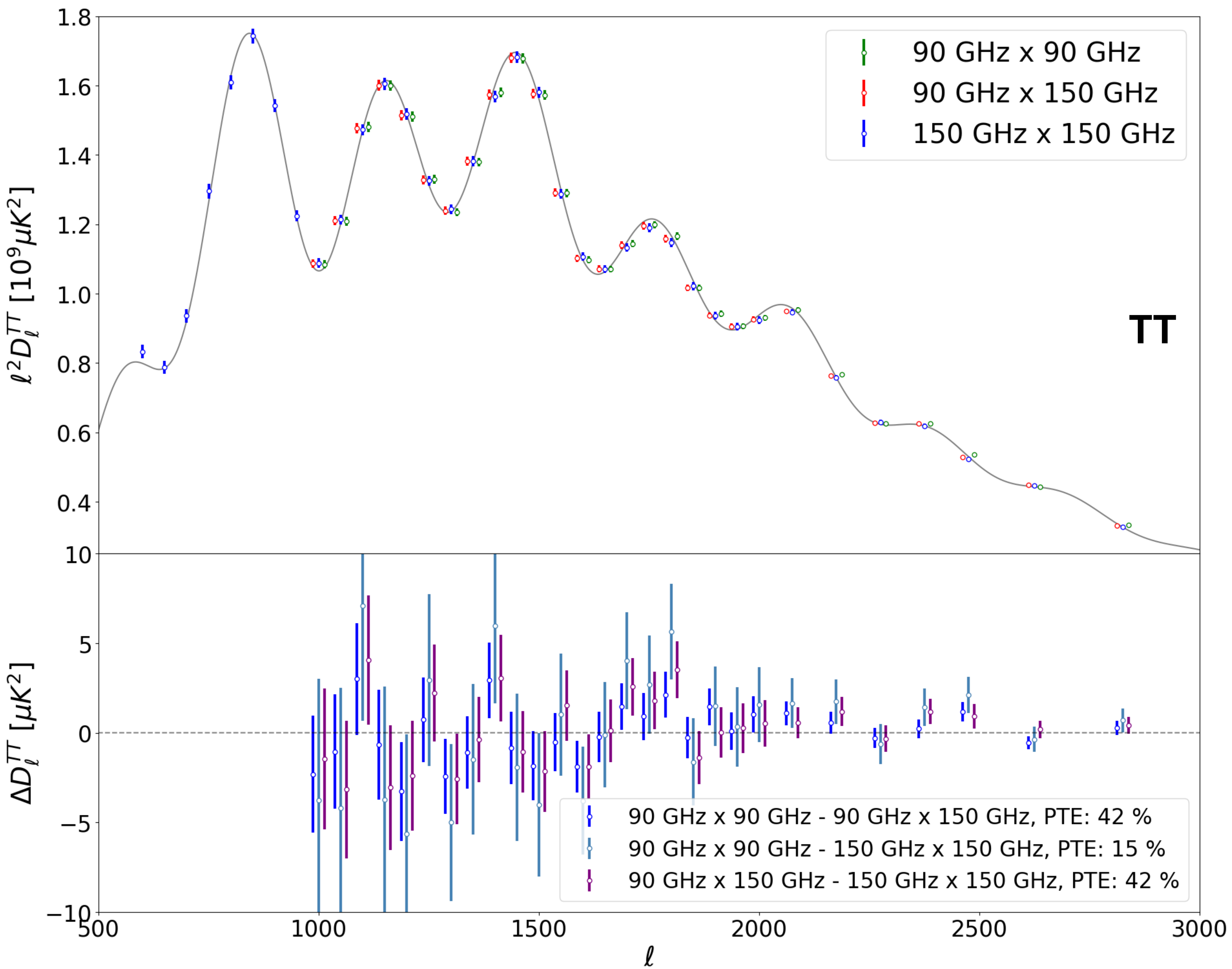
Foreground Model Robustness

Colin Hill
Columbia

Important null test: after subtracting the best-fit foreground model, do the different frequency auto- and cross-power spectra agree with one another? Yes



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Colin Hill
Columbia

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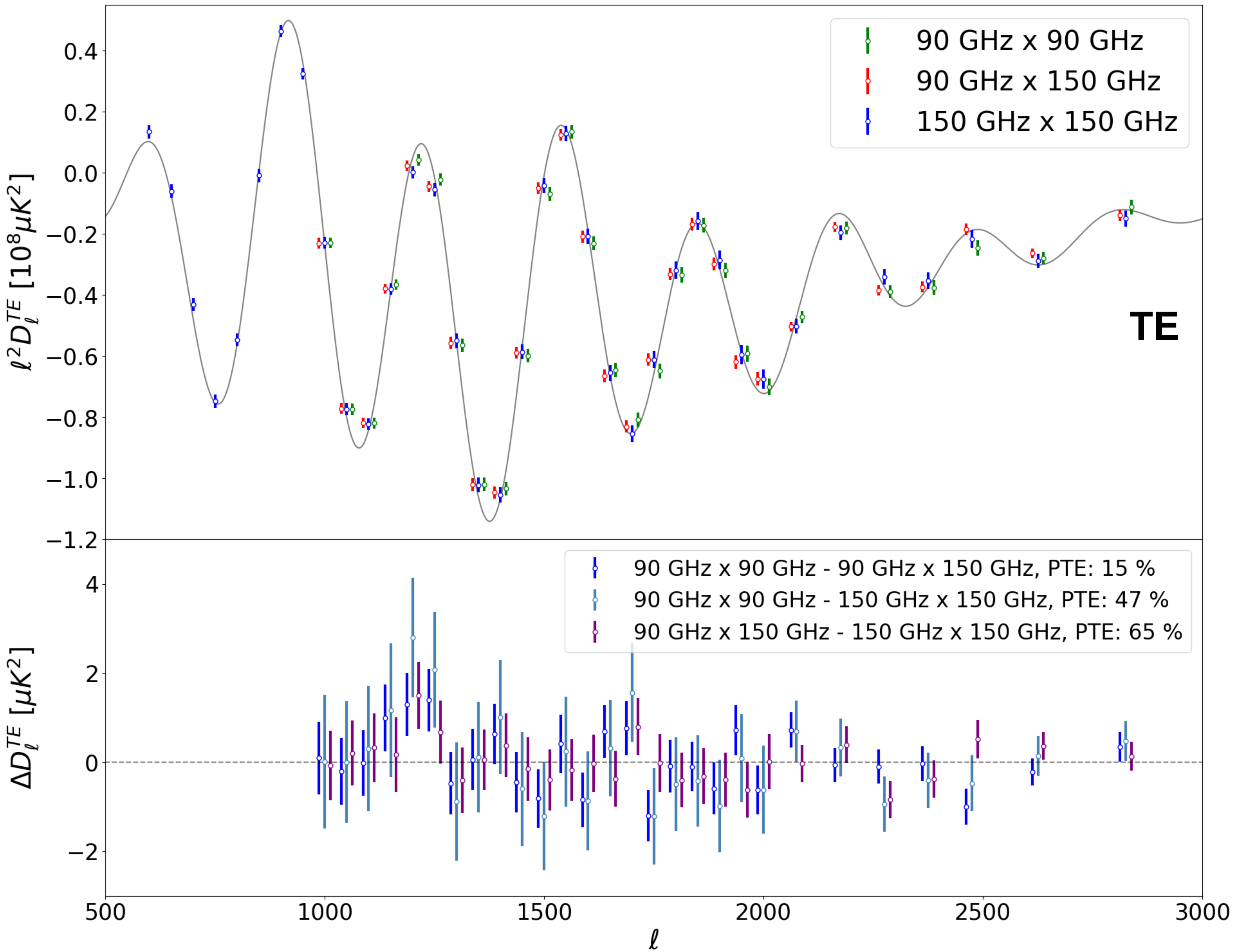

Foreground Model Robustness

Colin Hill
Columbia

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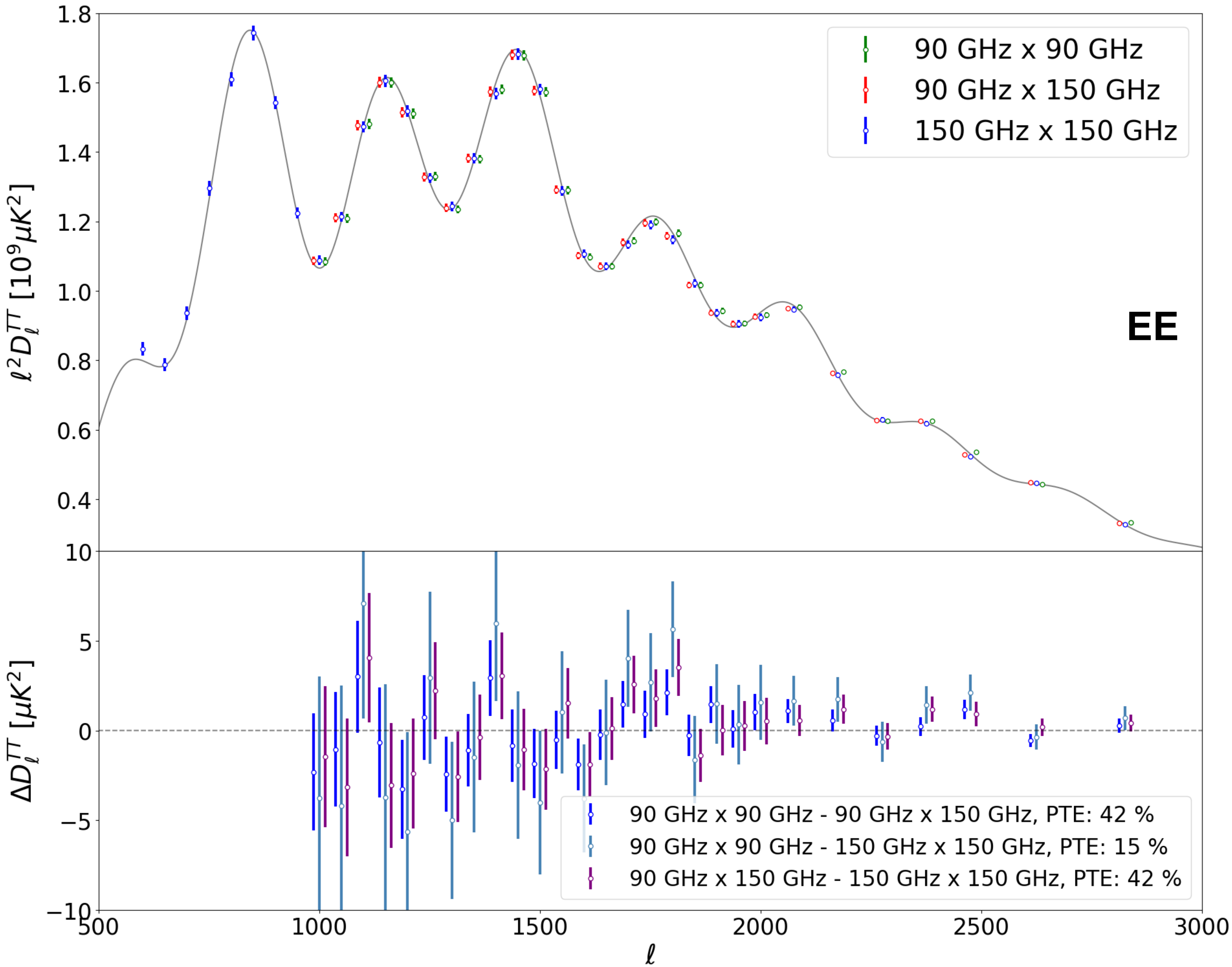

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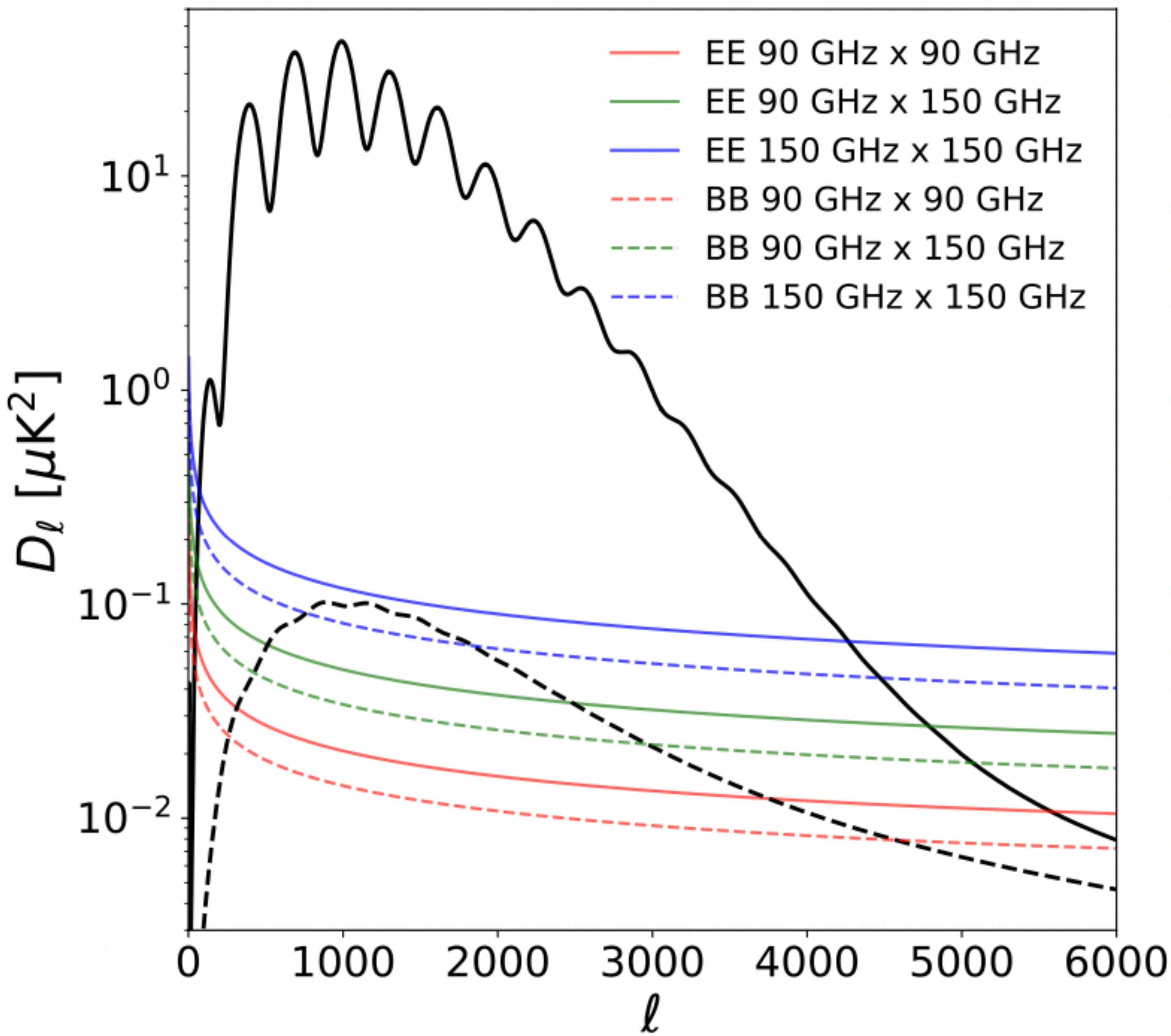
Galactic Dust on DR6 Footprint

Measured from Planck 353 GHz and extrapolated using modified blackbody SED



Foreground Model

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Baseline model

Extensions

	Description	Default Prior	Extension
$\boldsymbol{a_{\rm tSZ}}$	Thermal SZ amplitude at $\ell = 3000$ at 150 GHz	≥ 0	—
$\boldsymbol{\alpha_{\rm tSZ}}$	Thermal SZ template spectral index	$-5 \leq \alpha_{\rm tSZ} \leq 5$	—
$\boldsymbol{a_{\rm kSZ}}$	Kinematic SZ amplitude at $\ell = 3000$	≥ 0	
$\boldsymbol{a_c}$	Clustered CIB amplitude at $\ell = 3000$ at 150 GHz	≥ 0	—
$\boldsymbol{a_p}$	Poisson CIB amplitude at $\ell = 3000$ at 150 GHz	≥ 0	—
$\boldsymbol{\beta_c}$	Clustered CIB spectral index	$0 \leq \beta_c \leq 5$	—
$\boldsymbol{\xi_{yc}}$	tSZ–CIB correlation coefficient at $\ell = 3000$ at 150 GHz	$0 \leq \xi_{yc} \leq 0.2$	$0 \leq \xi_{yc} \leq 1$
$\boldsymbol{a_s^{\rm TT}}$	Poisson radio source amplitude in TT at $\ell = 3000$ at 150 GHz	≥ 0	—
$\boldsymbol{\beta_s}$	Radio source spectral index	$-3.5 \leq \beta_s \leq -1.5$	
$\boldsymbol{a_g^{\rm TT}}$	Galactic dust amplitude in TT at $\ell = 500$ at 150 GHz	$(7.95 \pm 0.32)\ \mu{\rm K}^2$	—
$\boldsymbol{a_s^{\rm TE}}$	Poisson radio source amplitude in TE at $\ell = 3000$ at 150 GHz	$-1 \leq a_s^{\rm TE} \leq 1$	—
$\boldsymbol{a_g^{\rm TE}}$	Galactic dust amplitude in TE at $\ell = 500$ at 150 GHz	$(0.42 \pm 0.03)\ \mu{\rm K}^2$	—
$\boldsymbol{a_s^{\rm EE}}$	Poisson radio source amplitude in EE at $\ell = 3000$ at 150 GHz	$0 \leq a_s^{\rm EE} \leq 1$	—
$\boldsymbol{a_g^{\rm EE}}$	Galactic dust amplitude in EE at $\ell = 500$ at 150 GHz	$(0.168 \pm 0.017)\ \mu{\rm K}^2$	—
$\boldsymbol{\alpha_g^{\rm TE/EE}}$	Galactic dust C_ℓ power-law index in TE/EE for $\ell > 500$	$\alpha_g^{\rm TE/EE} = -0.4$	$\alpha_g^{\rm TE/EE} \in [-2, 1]$
$\boldsymbol{\alpha_c}$	Clustered CIB C_ℓ power-law index for $\ell > 3000$	$\alpha_c = 0.8$	$\alpha_c = 0.6,\ \alpha_c = 1,\ \alpha_c \in [0.5, 1]$
$\boldsymbol{\beta_p}$	Poisson CIB spectral index	$\beta_p = \beta_c$	$0 \leq \beta_p \leq 5$
$\boldsymbol{\beta_s^E}$	Radio source spectral index in polarization	$\beta_s^E = \beta_s$	$-3.5 \leq \beta_s^E \leq -1.5$
$\boldsymbol{\xi_{ys}}$	tSZ–radio correlation coefficient at $\ell = 3000$ at 150 GHz	$\xi_{ys} = 0$	$0 \leq \xi_{ys} \leq 0.2$
$\boldsymbol{\xi_{cs}}$	CIB–radio correlation coefficient at $\ell = 3000$ at 150 GHz	$\xi_{cs} = 0$	$0 \leq \xi_{cs} \leq 0.2$
$\boldsymbol{r^{\rm CIB}_{\nu_i \times \nu_j}}$	CIB decorrelation between ν_i and ν_j	$r^{\rm CIB}_{\nu_i \times \nu_j} = 1$	$0.8 \leq r^{\rm CIB}_{\nu_i \times \nu_j} \leq 1.0$, (for $\nu_i \neq \nu_j$)
$\boldsymbol{r^{\rm radio}_{\nu_i \times \nu_j}}$	Radio decorrelation between ν_i and ν_j	$r^{\rm radio}_{\nu_i \times \nu_j} = 1$	$0.8 \leq r^{\rm radio}_{\nu_i \times \nu_j} \leq 1.0$, (for $\nu_i \neq \nu_j$)

Foreground Constraints

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	Nominal P-ACT	Nominal ACT	$\beta_c \neq \beta_p$ ACT
SZ			
a_{tSZ}	3.3 ± 0.4	3.4 ± 0.4	3.0 ± 0.4
α_{tSZ}	-0.6 ± 0.2	-0.5 ± 0.2	$-0.7^{+0.3}_{-0.2}$
a_{kSZ}	2.0 ± 0.9	$1.5^{+0.7}_{-1.1}$	$2.4^{+0.9}_{-0.8}$
CIB			
a_c	3.6 ± 0.5	3.7 ± 0.5	$2.4^{+0.4}_{-0.8}$
a_p	7.7 ± 0.3	7.7 ± 0.3	8.2 ± 0.4
β_p	1.9 ± 0.1	1.9 ± 0.1	1.8 ± 0.1
β_c			$2.6^{+0.4}_{-0.3}$
SZ-CIB			
ξ	$0.09^{+0.05}_{-0.07}$	$0.09^{+0.04}_{-0.08}$	< 0.15
Radio			
a_s^{TT}	2.8 ± 0.2	2.9 ± 0.2	2.7 ± 0.2
β_s	-2.8 ± 0.1	-2.8 ± 0.1	-2.8 ± 0.1
a_s^{TE}	-0.026 ± 0.012	-0.025 ± 0.012	-0.024 ± 0.012
a_s^{EE}	< 0.04	< 0.04	< 0.04

Foregrounds and Systematics

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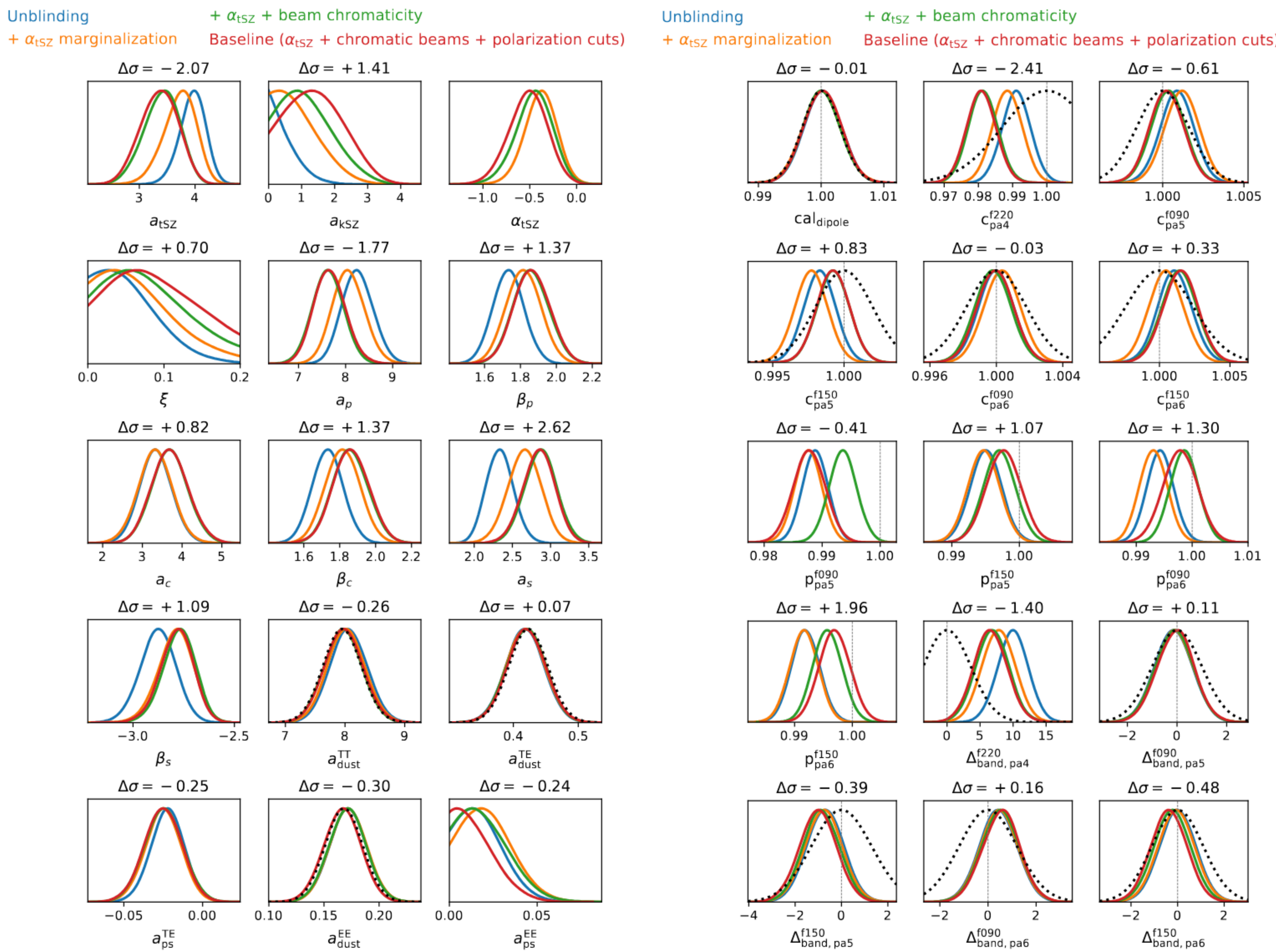

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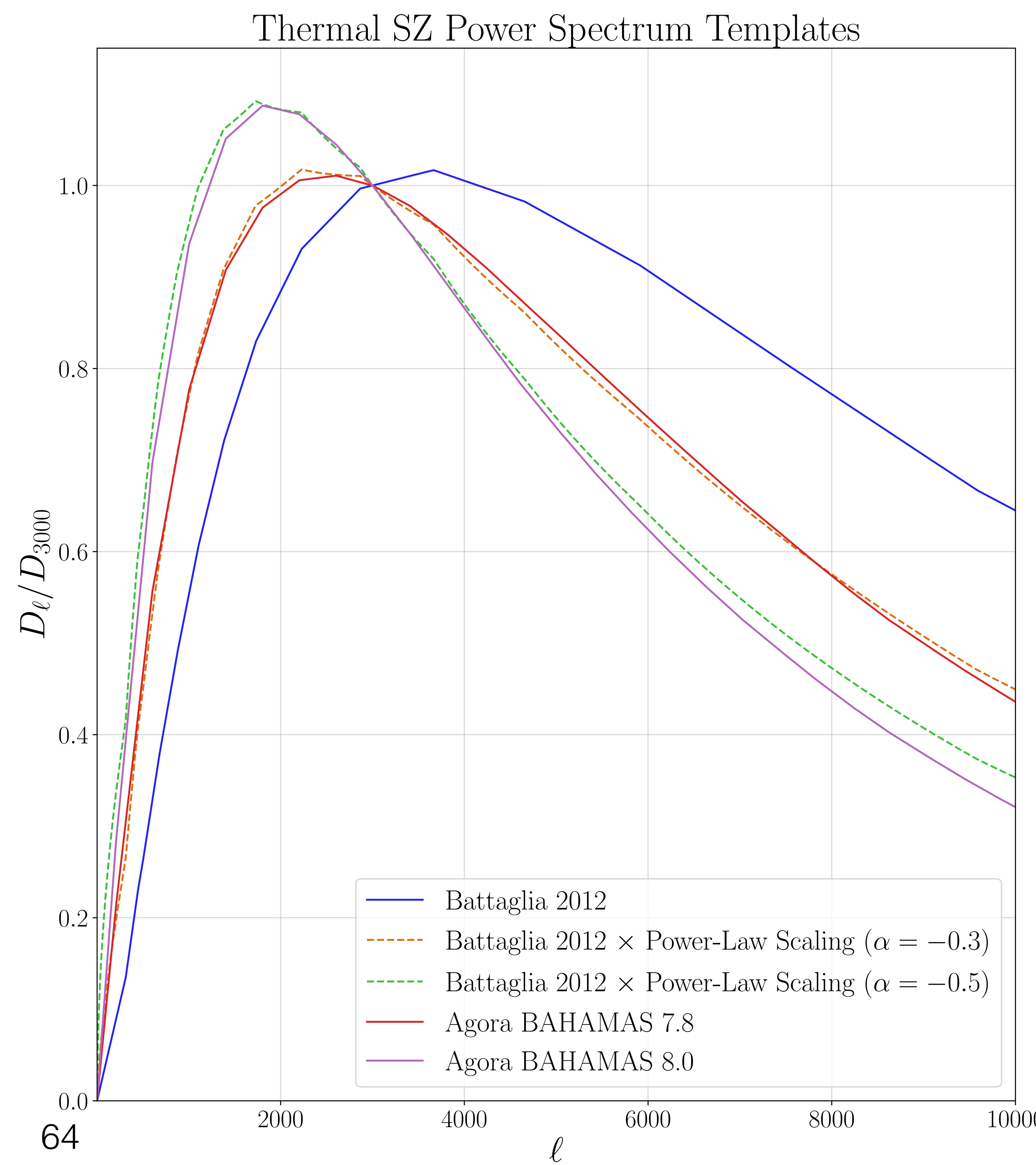
Foreground Robustness

New developments in foreground modeling

- Simulation-based tests indicated that DR6 parameter inference is now sensitive to the shape of the thermal SZ power spectrum template used in the TT modeling

- Efficiently captured by a single new free parameter: power-law index α_{SZ}

$$D_\ell^{\rm tSZ} = D_\ell^{\rm tSZ,Batt.} \left(\frac{\ell}{3000}\right)^\alpha$$



Thermal SZ

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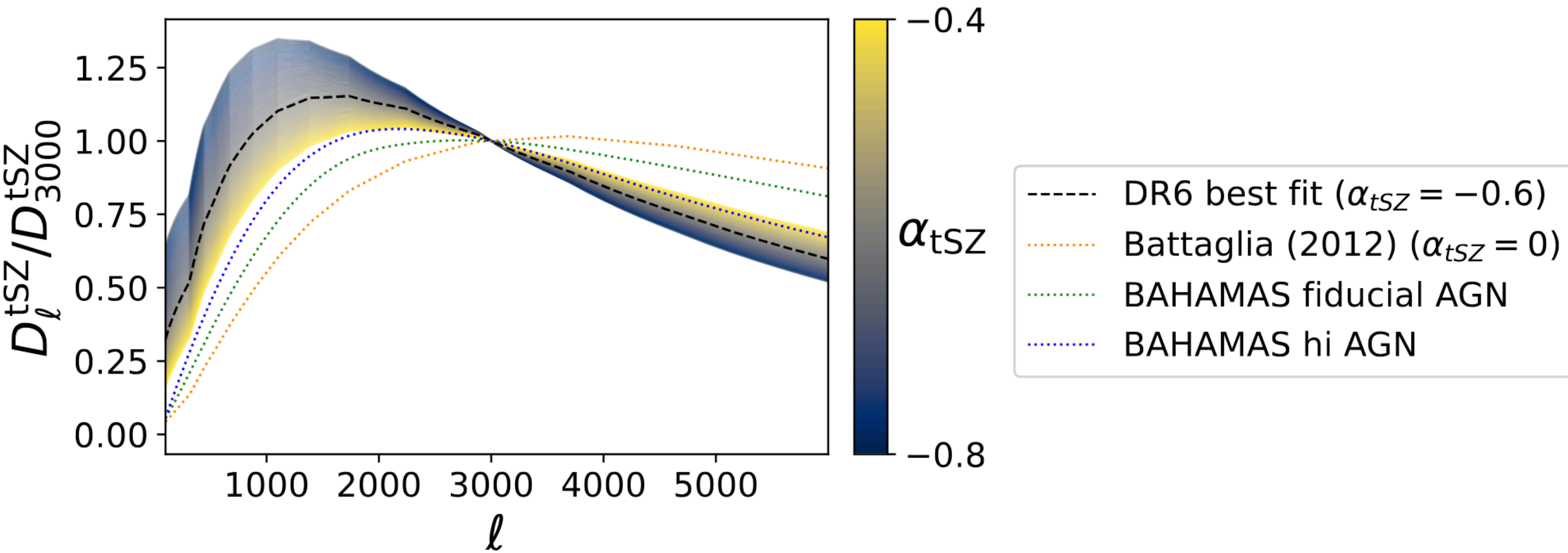
For the first time, our data are sufficiently sensitive to require the introduction of a new foreground parameter describing the scale dependence of the tSZ power spectrum

$$D_{\ell,\mathrm{tSZ}}^{T_iT_j} = a_{\mathrm{tSZ}} D_{\ell,\ell_0}^{\mathrm{tSZ}} \left[\frac{\ell}{\ell_0}\right]^{\alpha_{\mathrm{tSZ}}} \frac{f_{\mathrm{tSZ}}(\nu_i) f_{\mathrm{tSZ}}(\nu_j)}{f_{\mathrm{tSZ}}^2(\nu_0)}$$

We find ~3σ evidence for a steeper tSZ power spectrum than modeled in our fiducial template, consistent with hydro simulations invoking strong baryonic feedback



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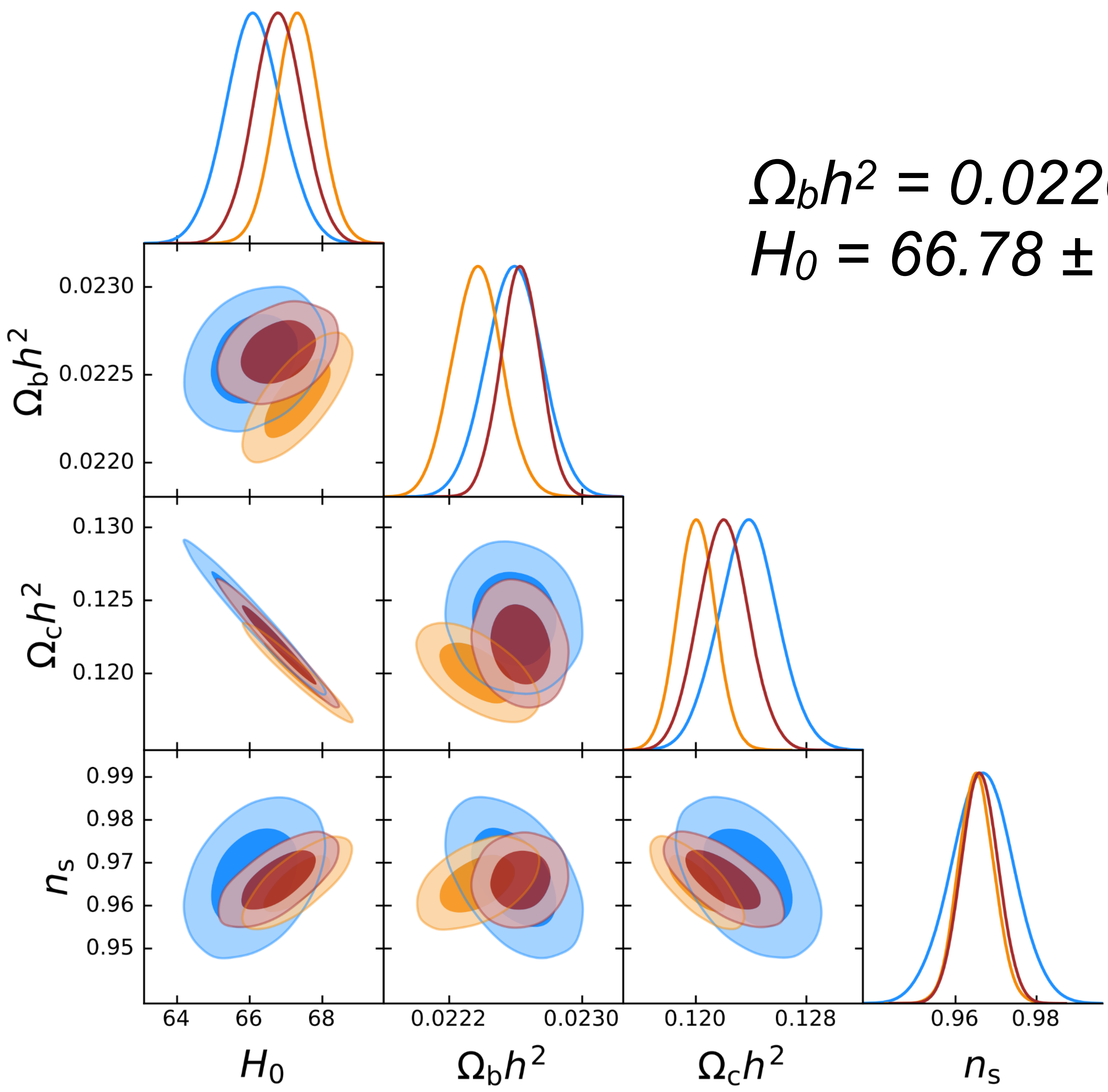
ACT+WMAP

Comparable constraining power to Planck; completely independent



$\Omega_b h^2 = 0.02263 \pm 0.00012$

$H_0 = 66.78 \pm 0.68$ km/s/Mpc

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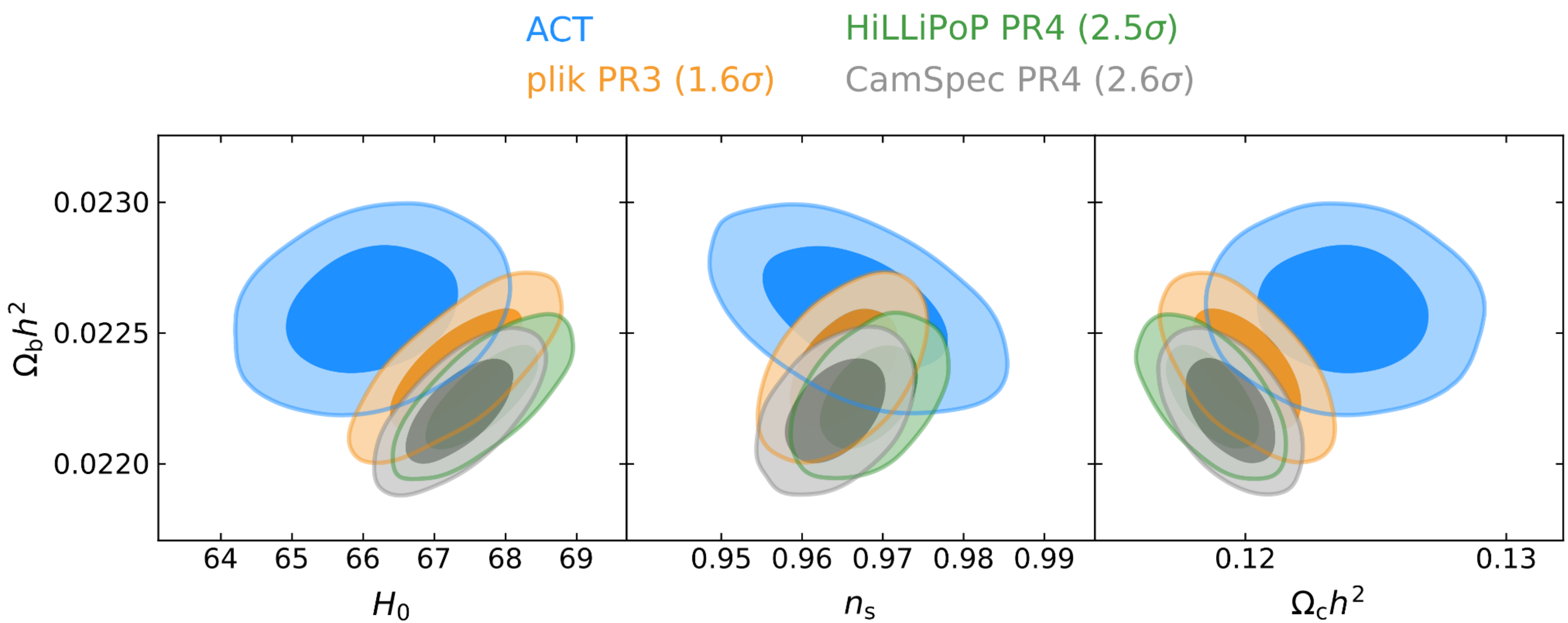
Comparison with Planck

ACT slightly more consistent with PR3 than PR4/NPIPE



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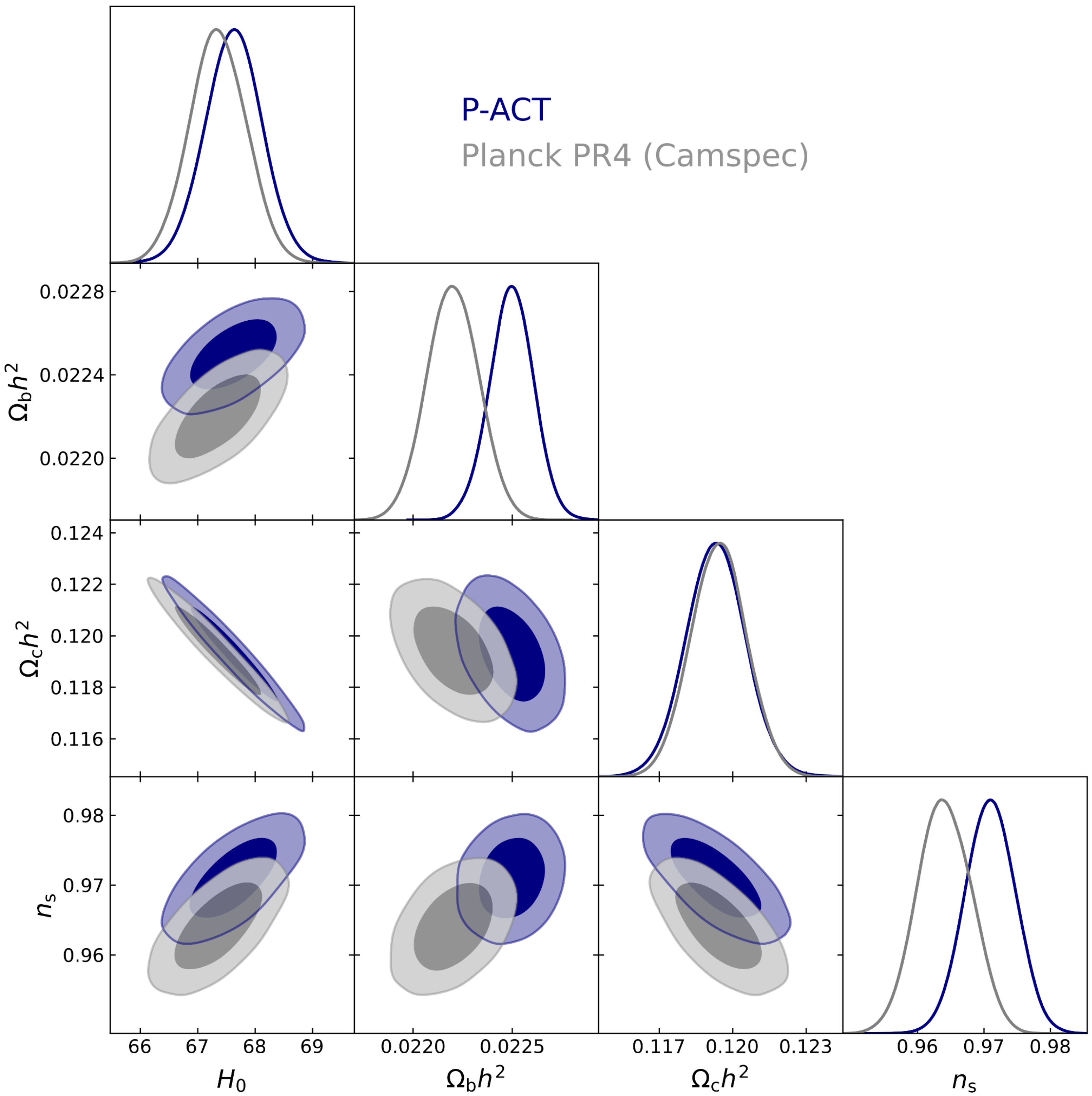
Comparison with Planck

Nevertheless, P-ACT is consistent with PR4/NPIPE



Comparison with BAO and H_0

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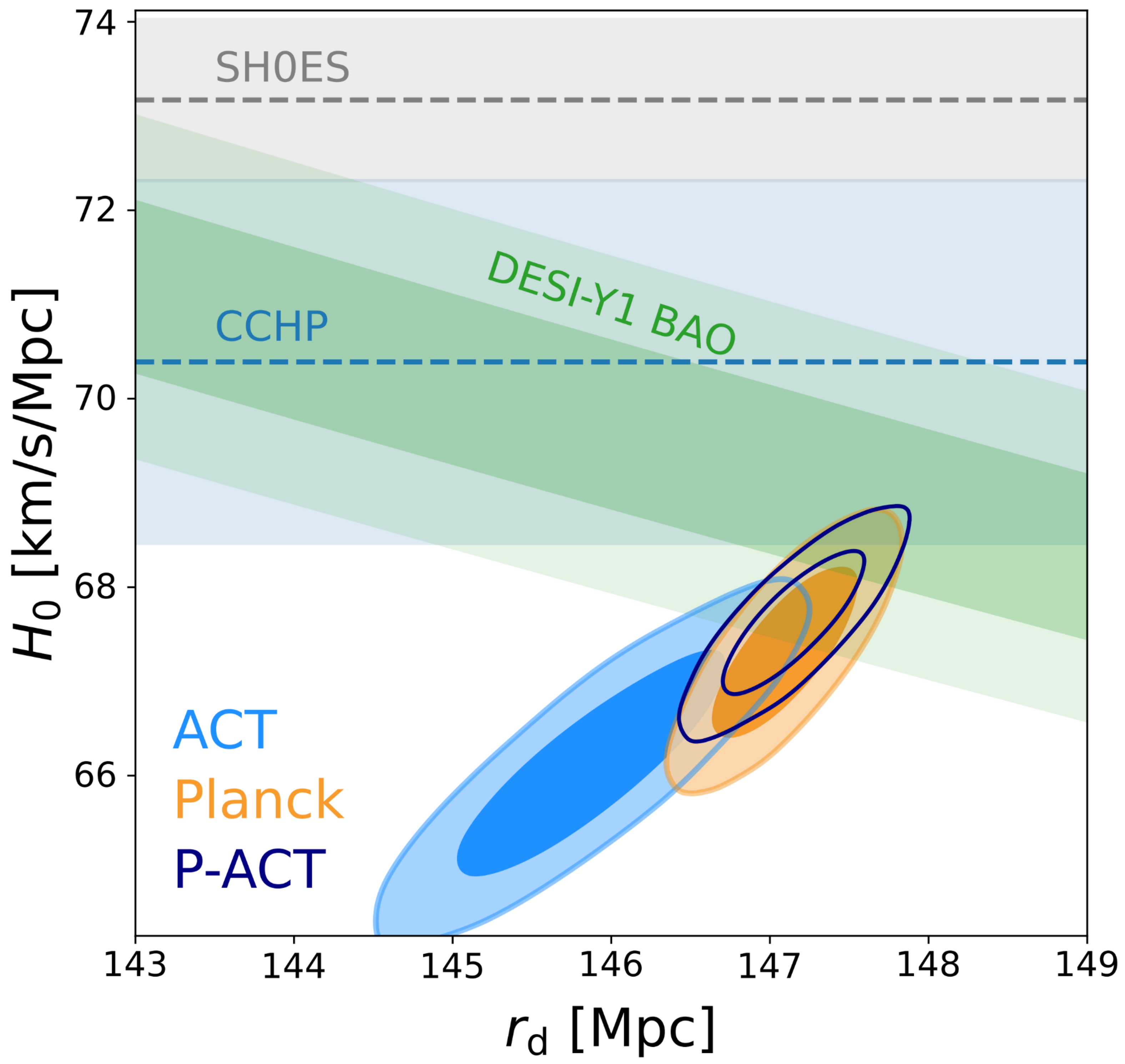


assuming
ΛCDM

SH0ES: *Breuval et al.* 2024, *Riess et al.* 2022
CCHP: *Freedman et al.* 2024

ACT DR6 vs. DR4

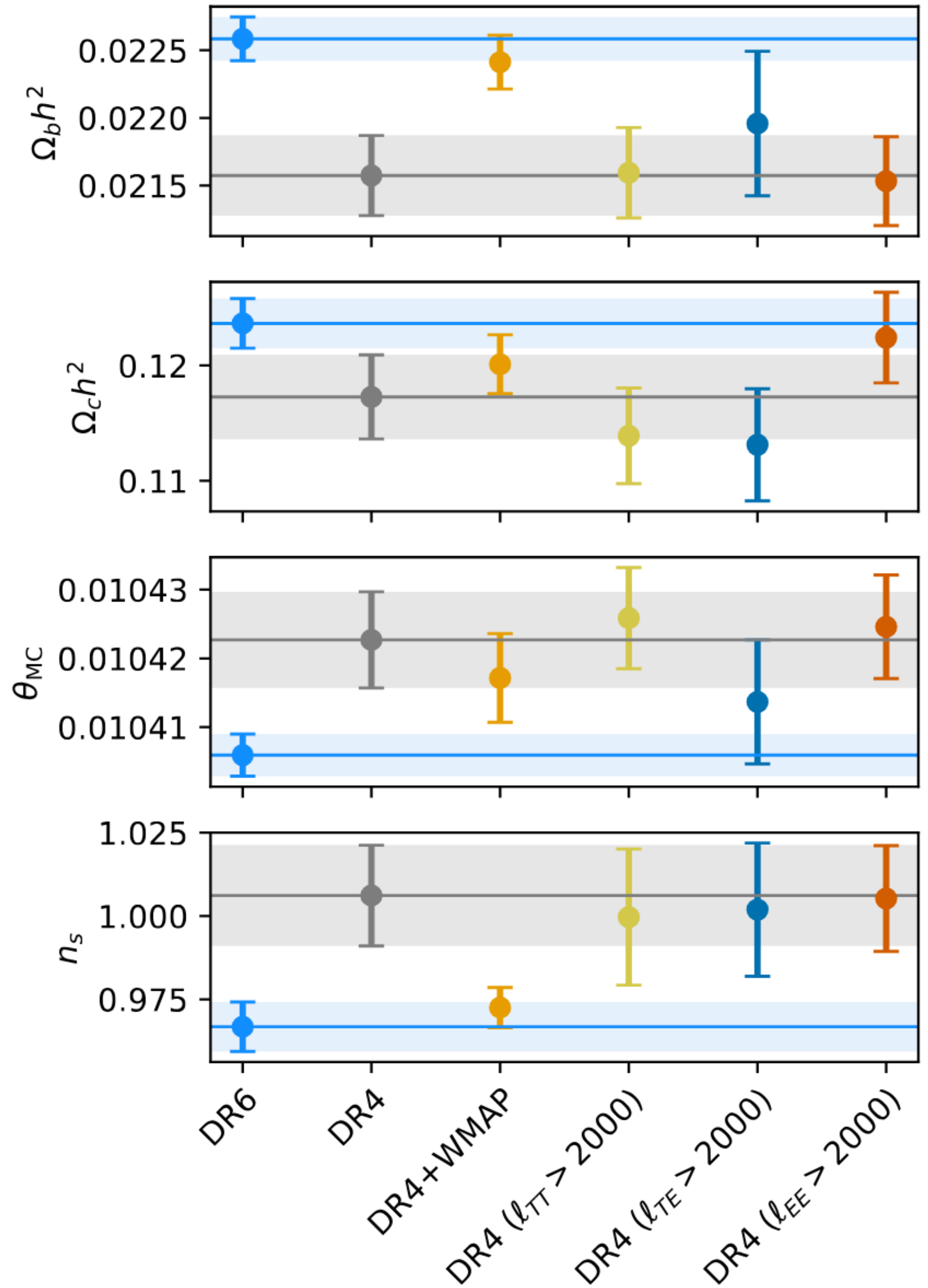
Colin Hill
Columbia

- Very good agreement between DR6 and DR4 baseline result obtained from ACT+WMAP

- Some differences between DR6 and DR4 ACT-alone cosmology

- Mainly driven by TE data at multipoles < 2000 (where residuals are mostly negative, disfavoring the DR6 ΛCDM cosmology)

- We speculate beam leakage modeling may be responsible (significantly improved in DR6)



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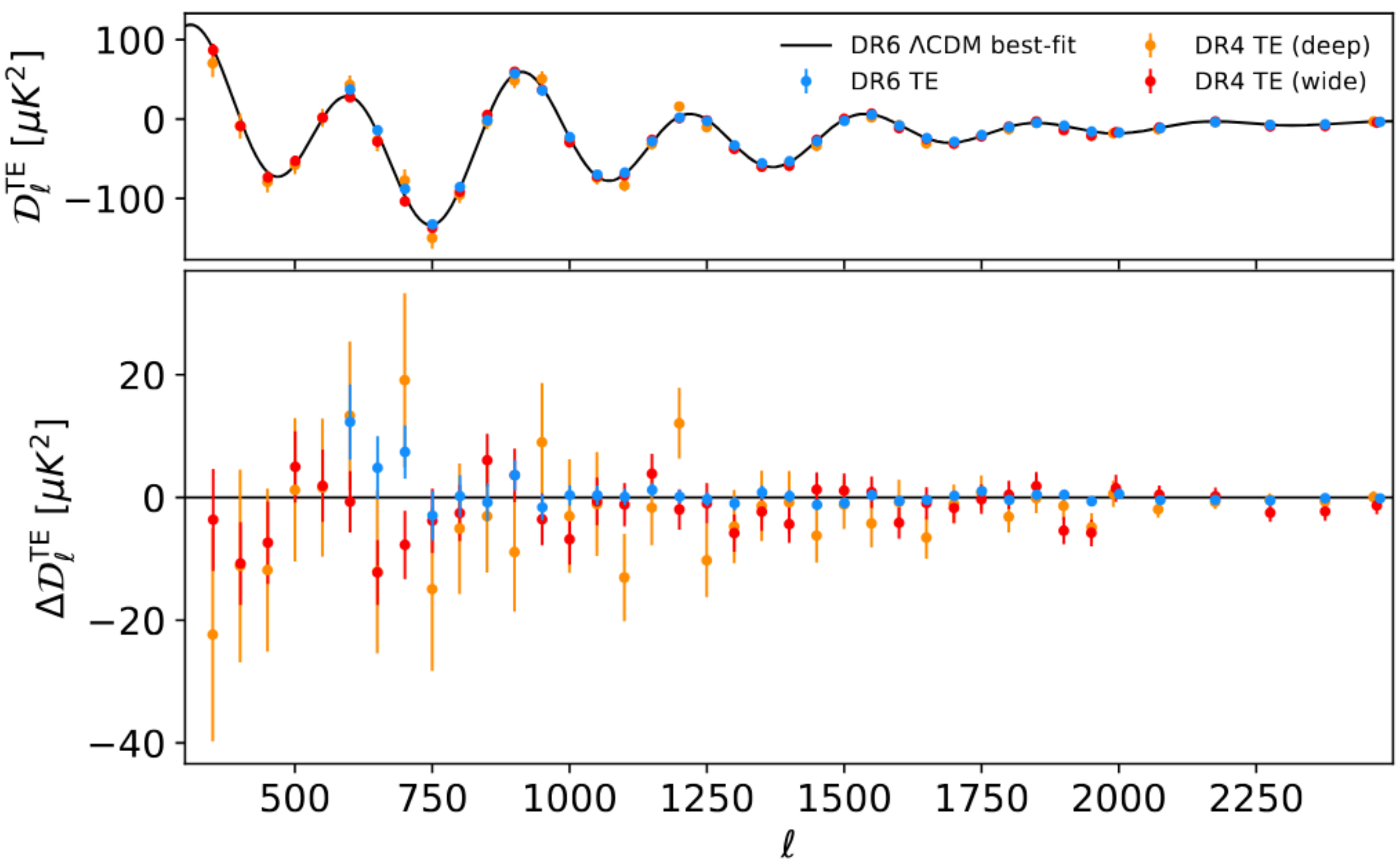

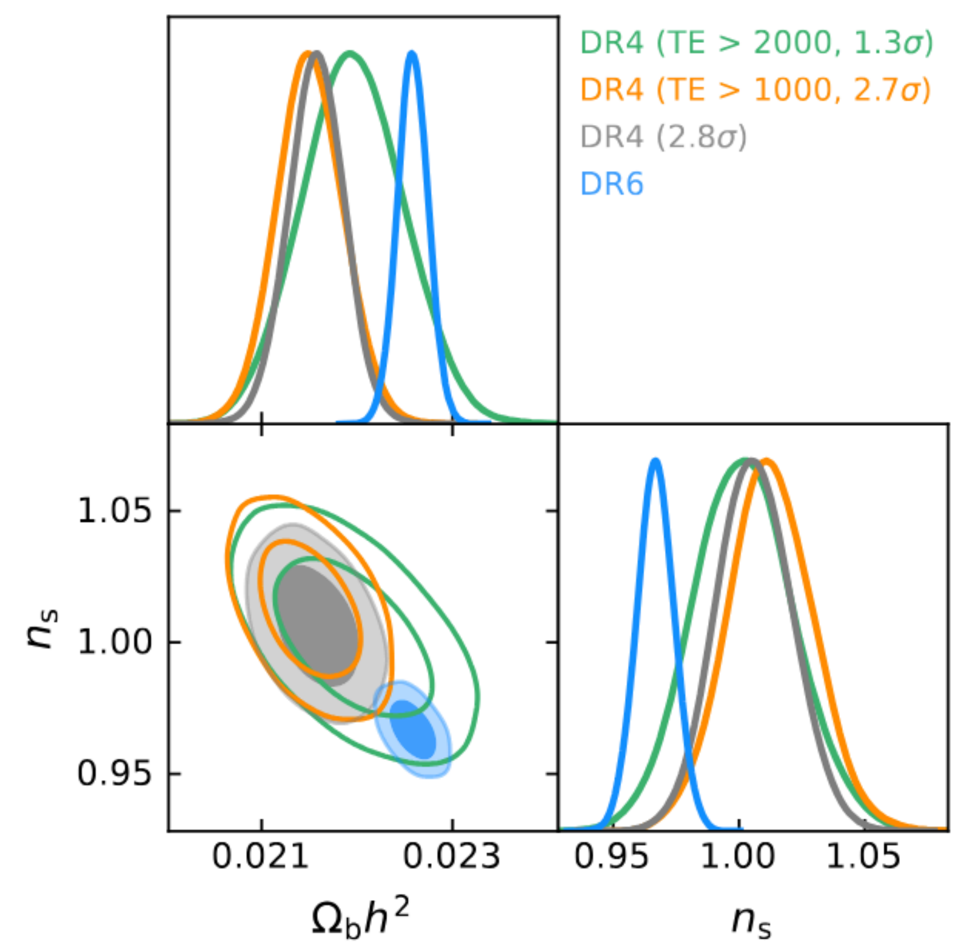

ACT DR6 vs. DR4

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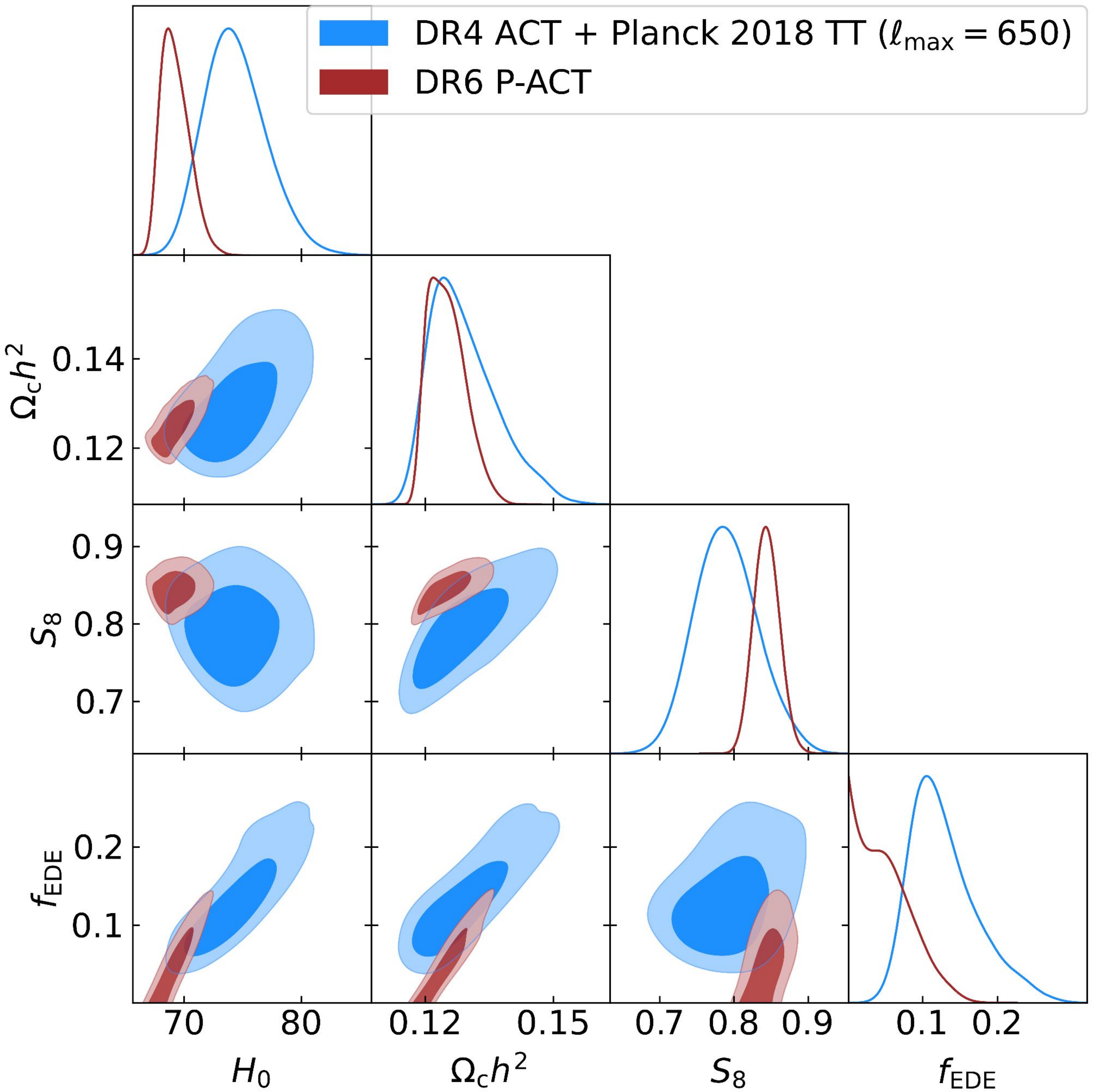
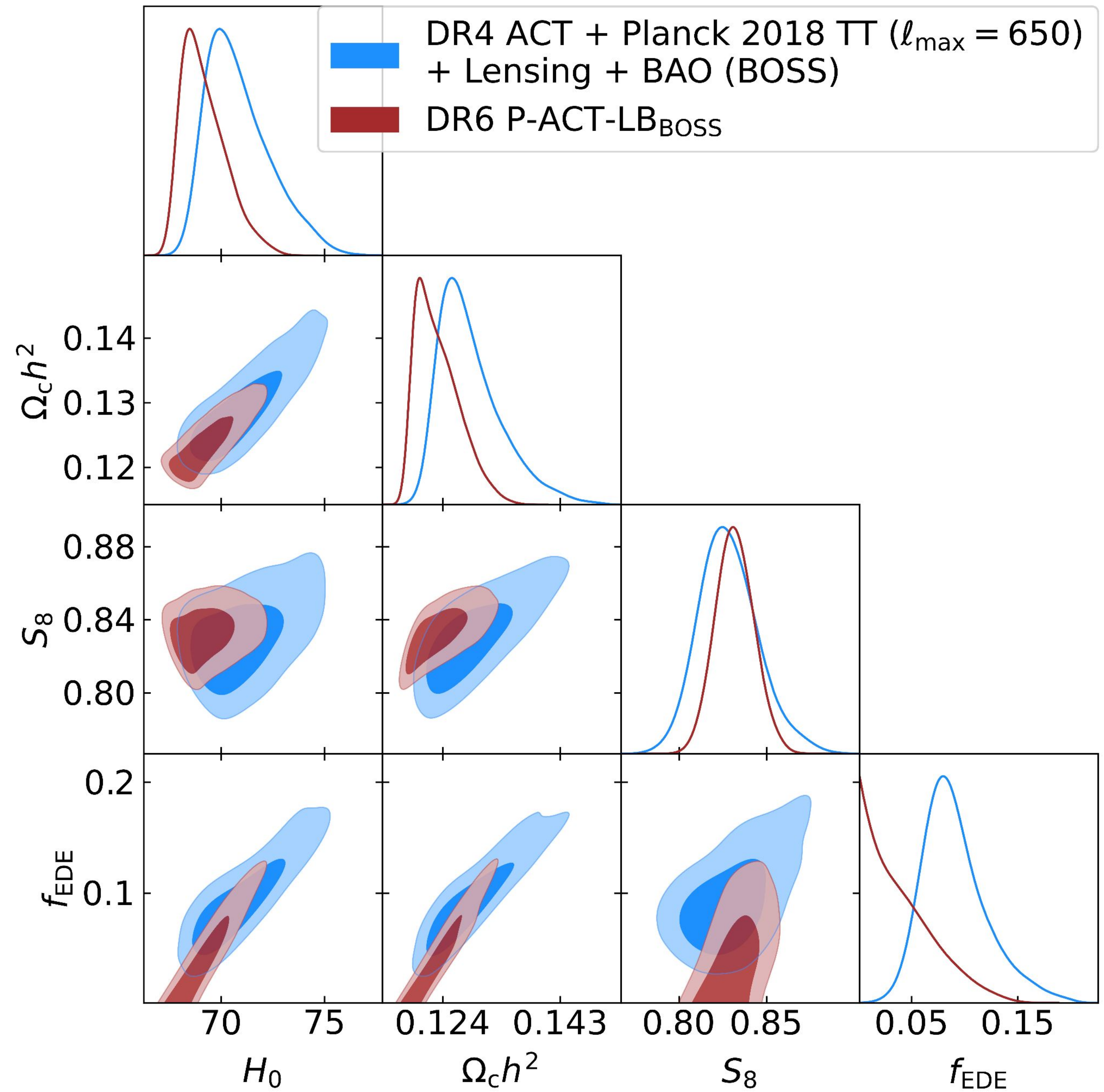
Comparison of early dark energy constraints

ACT+Planck



ACT+Planck+Lensing+BAO



DR4 constraints from JCH+ (2022)

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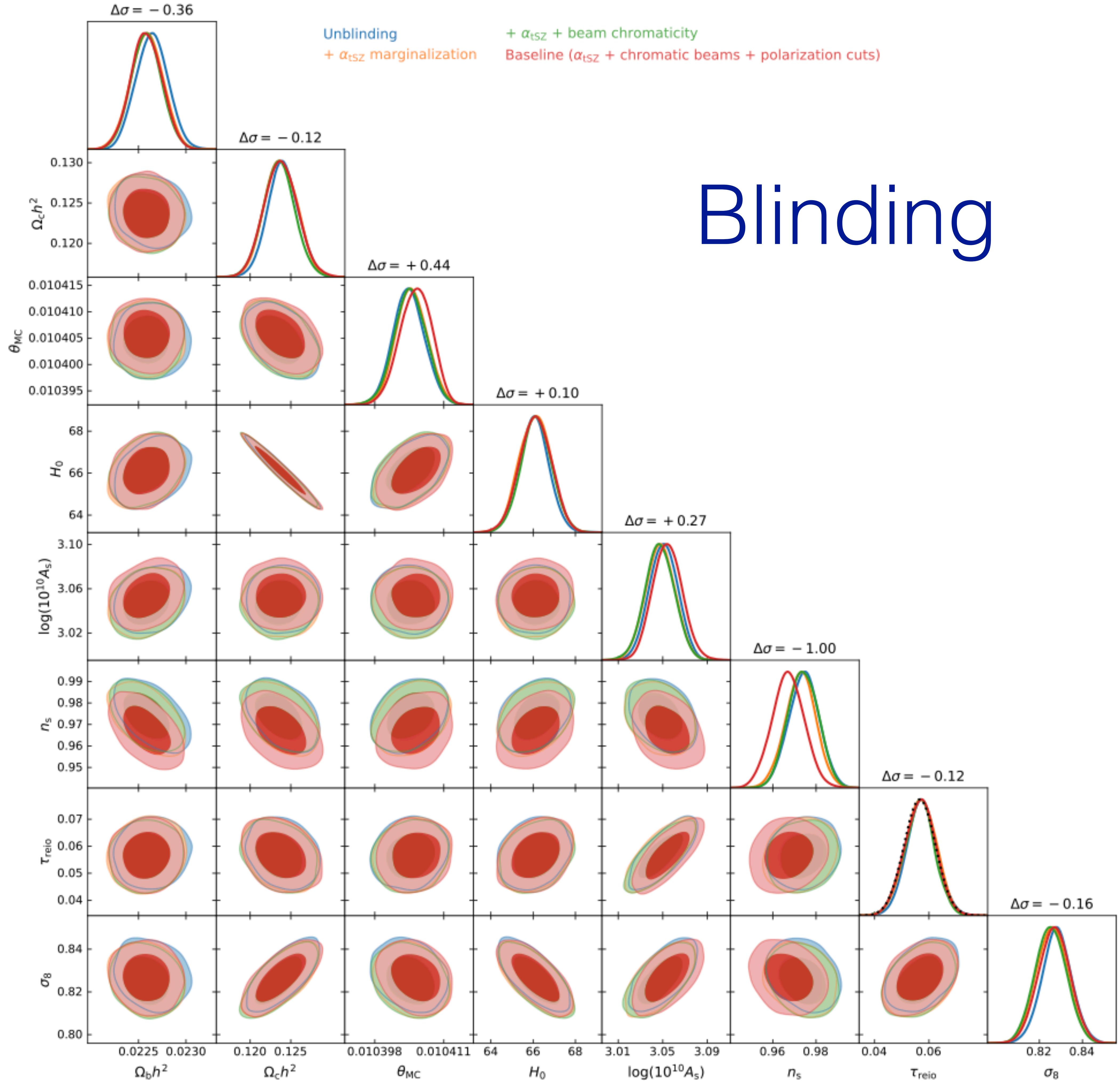
Blinding



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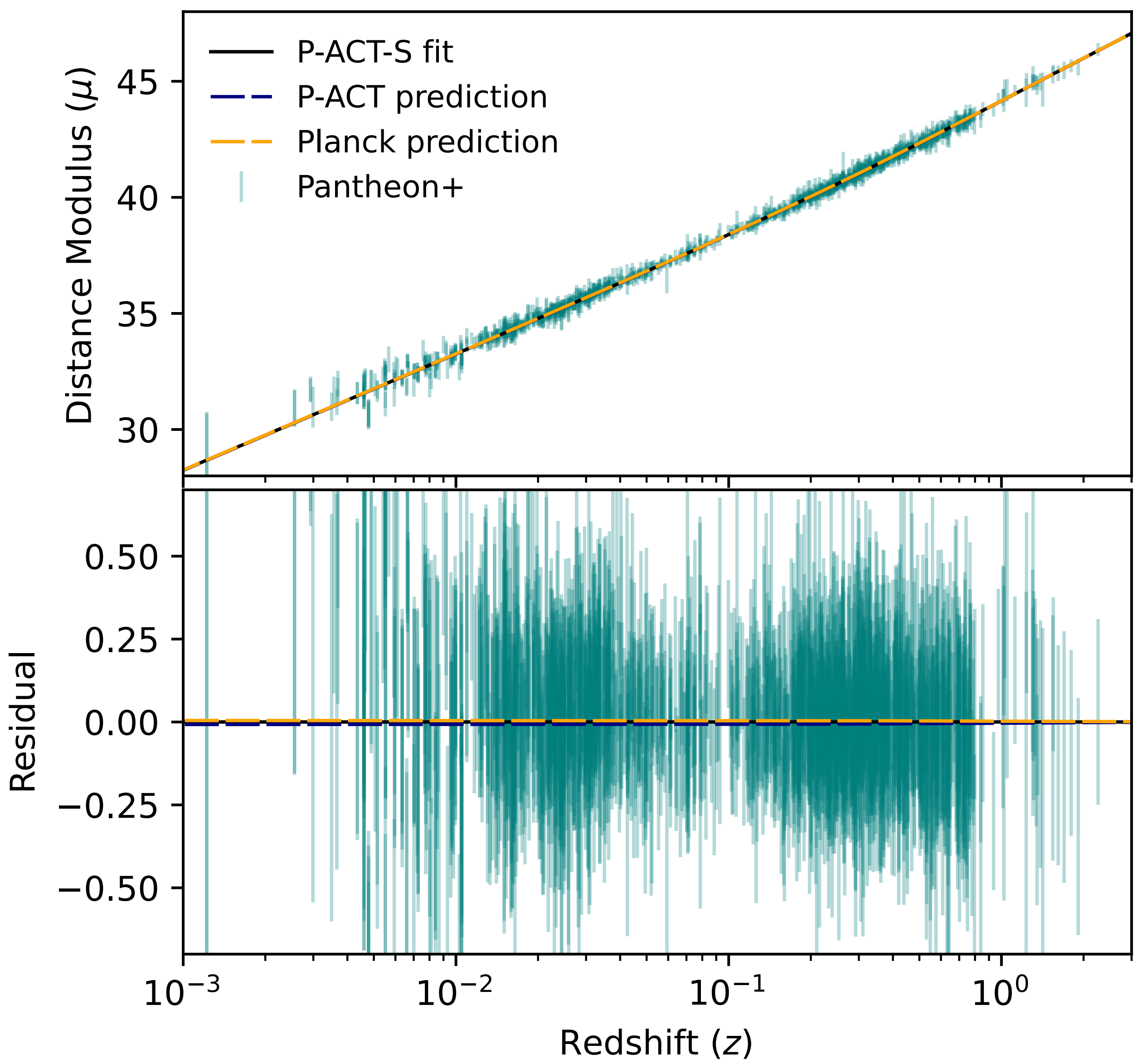
Cosmological Concordance

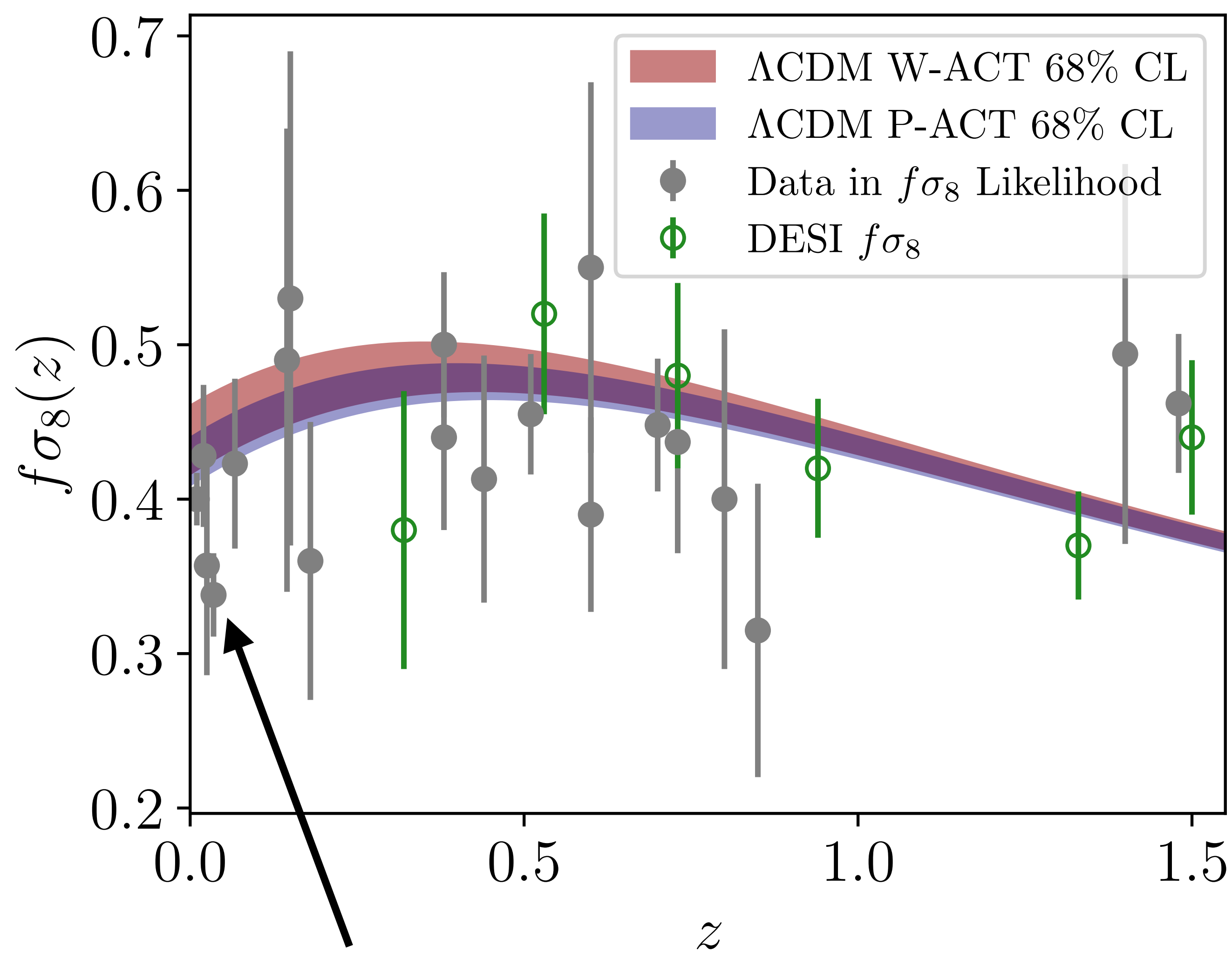
- Predictions of the best-fit P-ACT ΛCDM model agree well with direct low-redshift measurements
- ΛCDM gives an excellent joint fit to these datasets

f = dlnD/dlna

SNIa distance modulus



$f\sigma_8$ from RSD and pec. vel.



two outlying points drive
3.5σ pref. for γ>0.55

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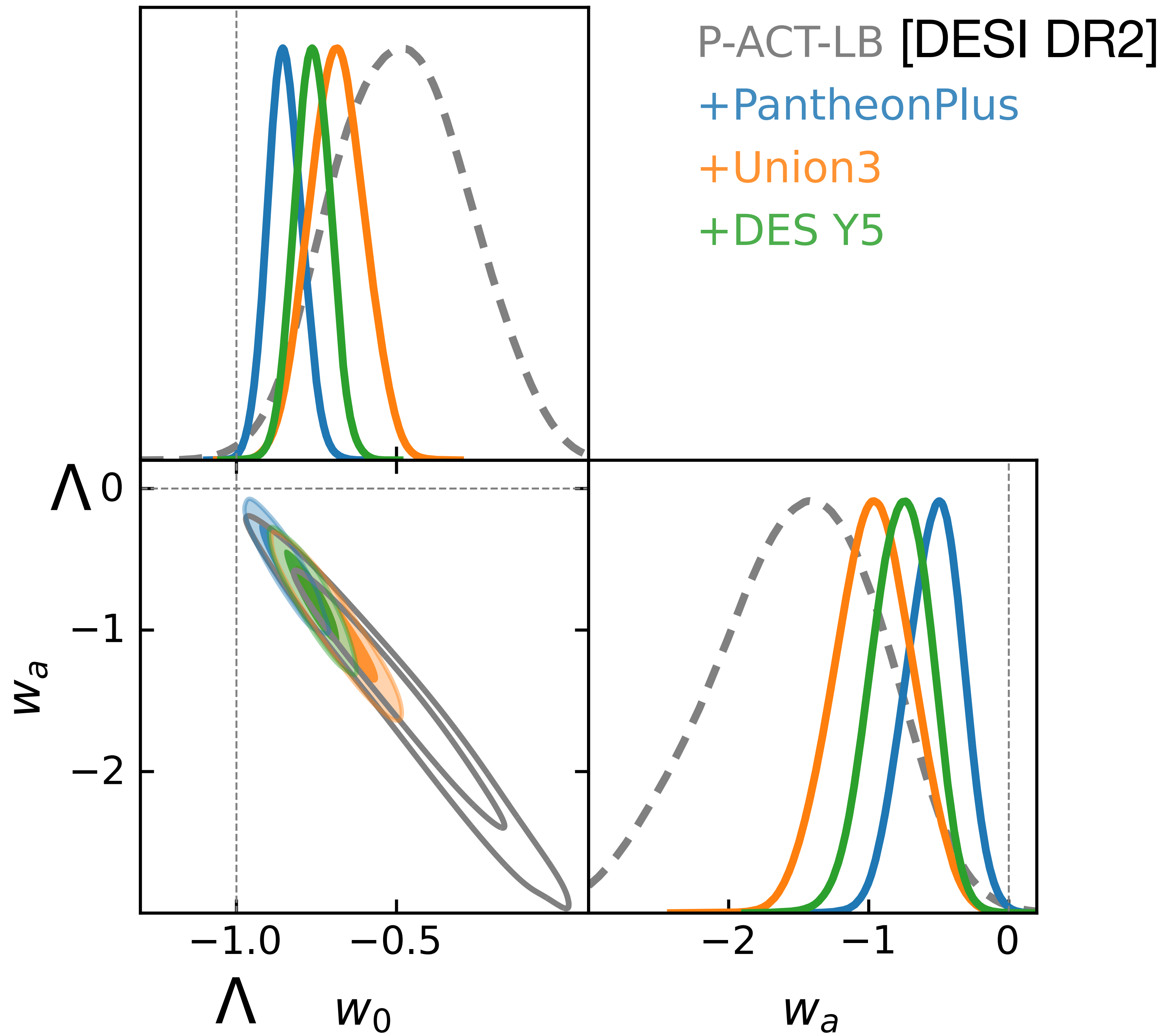
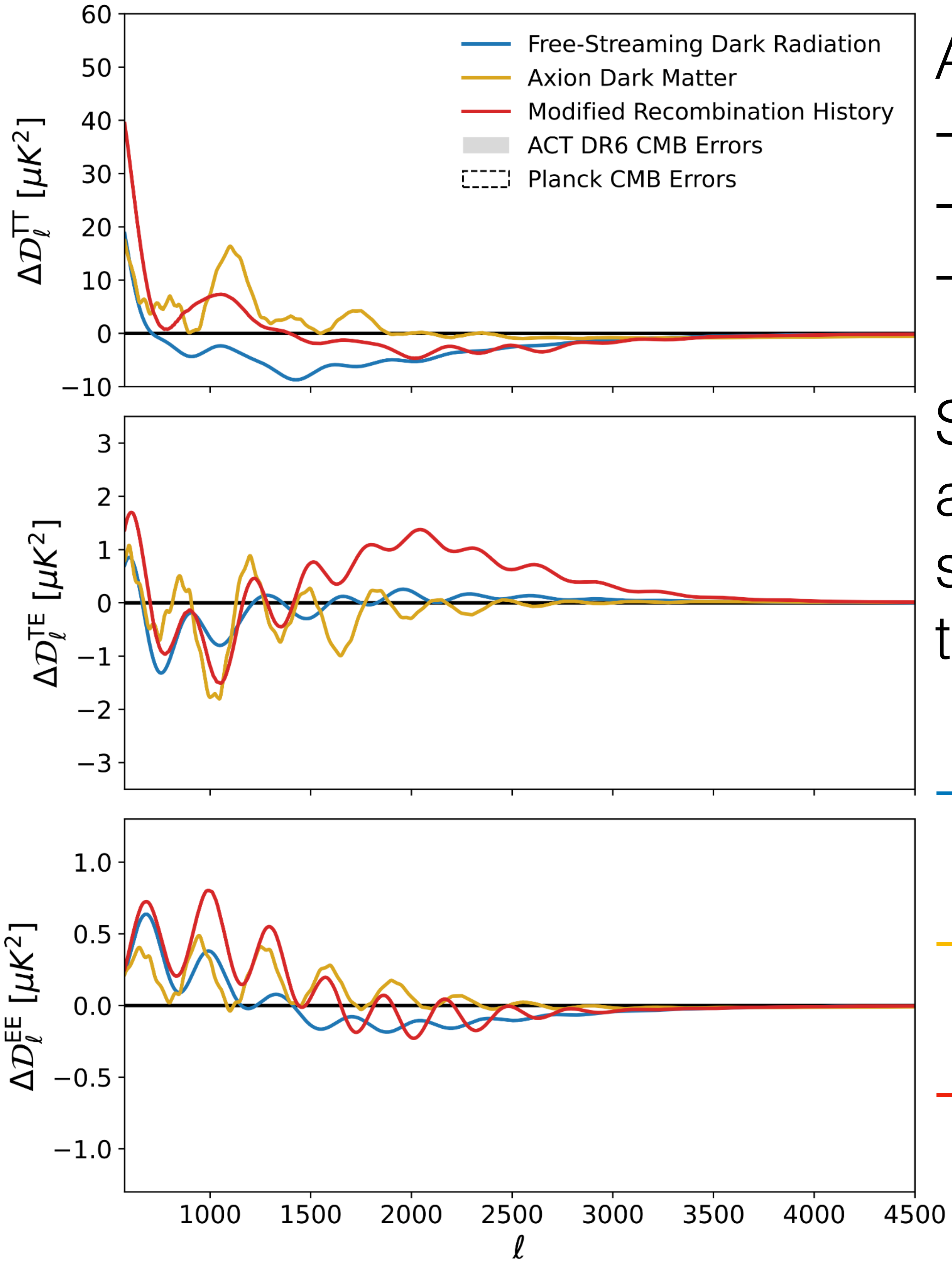
Dark Energy

Inclusion of ACT DR6 in joint fit with Planck + DESI-DR2 slightly moves best-fit point toward Λ (~0.2σ) — evidence for evolving DE from CMB+DESI drops below 3σ



ACT Constraining Power

Colin Hill
Columbia



ACT DR6 probes new information:

- in TT for multipoles > 1700,
- in TE for multipoles > 1000,
- in EE for multipoles > 600.

Select models that are well within allowed Planck bounds, but strongly excluded by the addition of the new ACT DR6 power spectra:

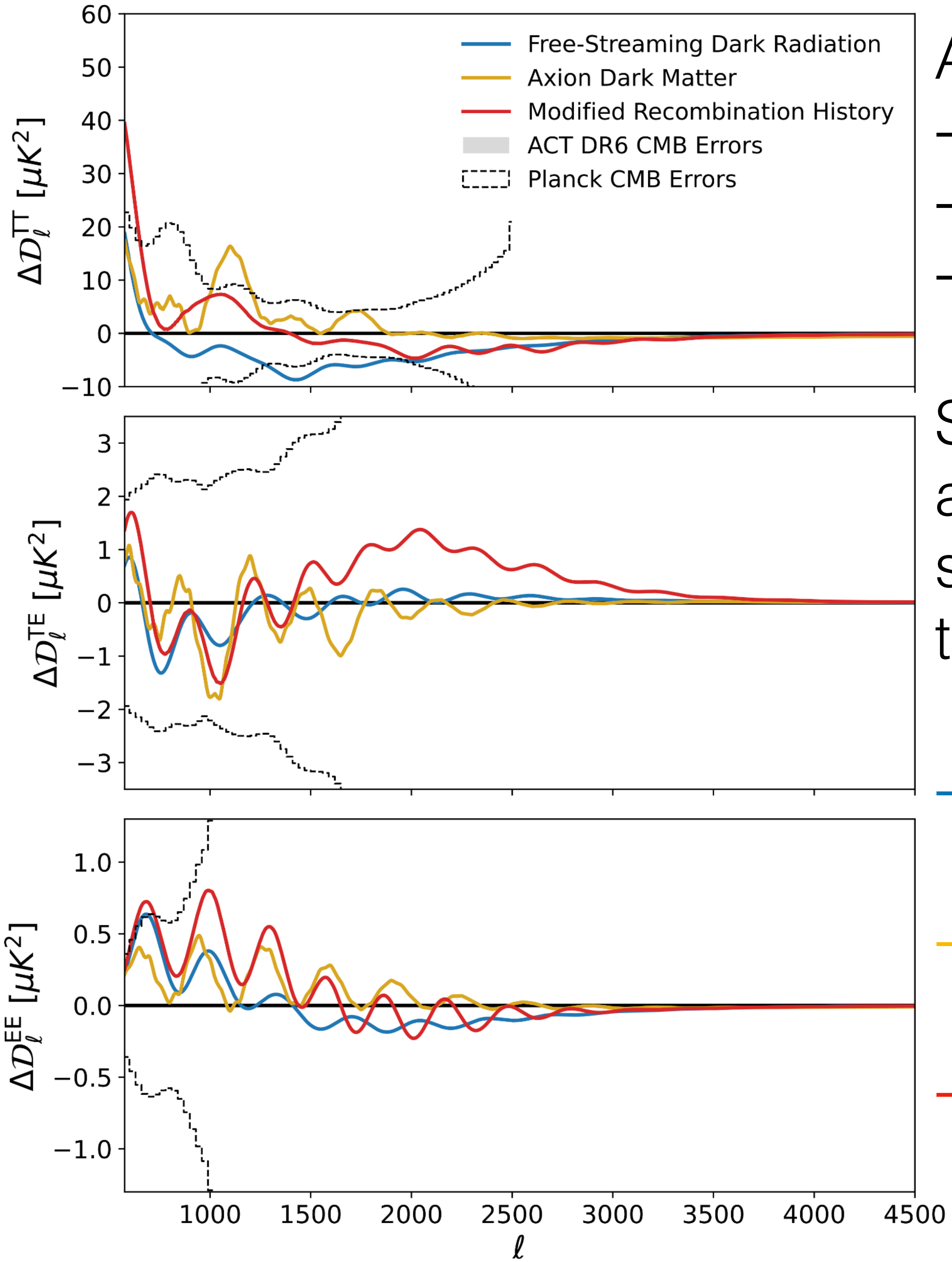
- Free-streaming dark radiation

- Axion-like DM sub-component

- Modified recombination history

ACT Constraining Power

Colin Hill
Columbia



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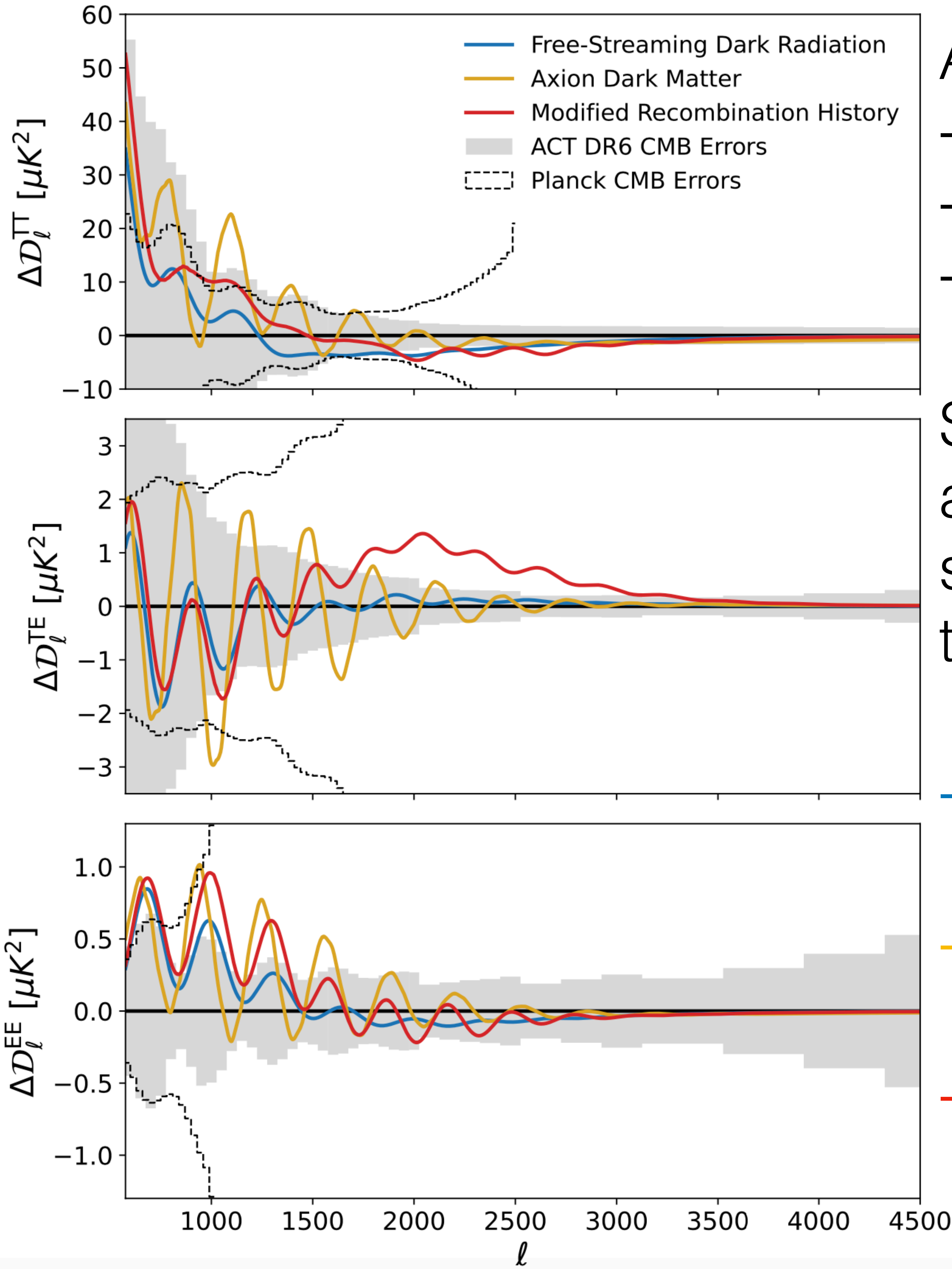
ACT Constraining Power

Colin Hill
Columbia



ACT DR6 probes new information:
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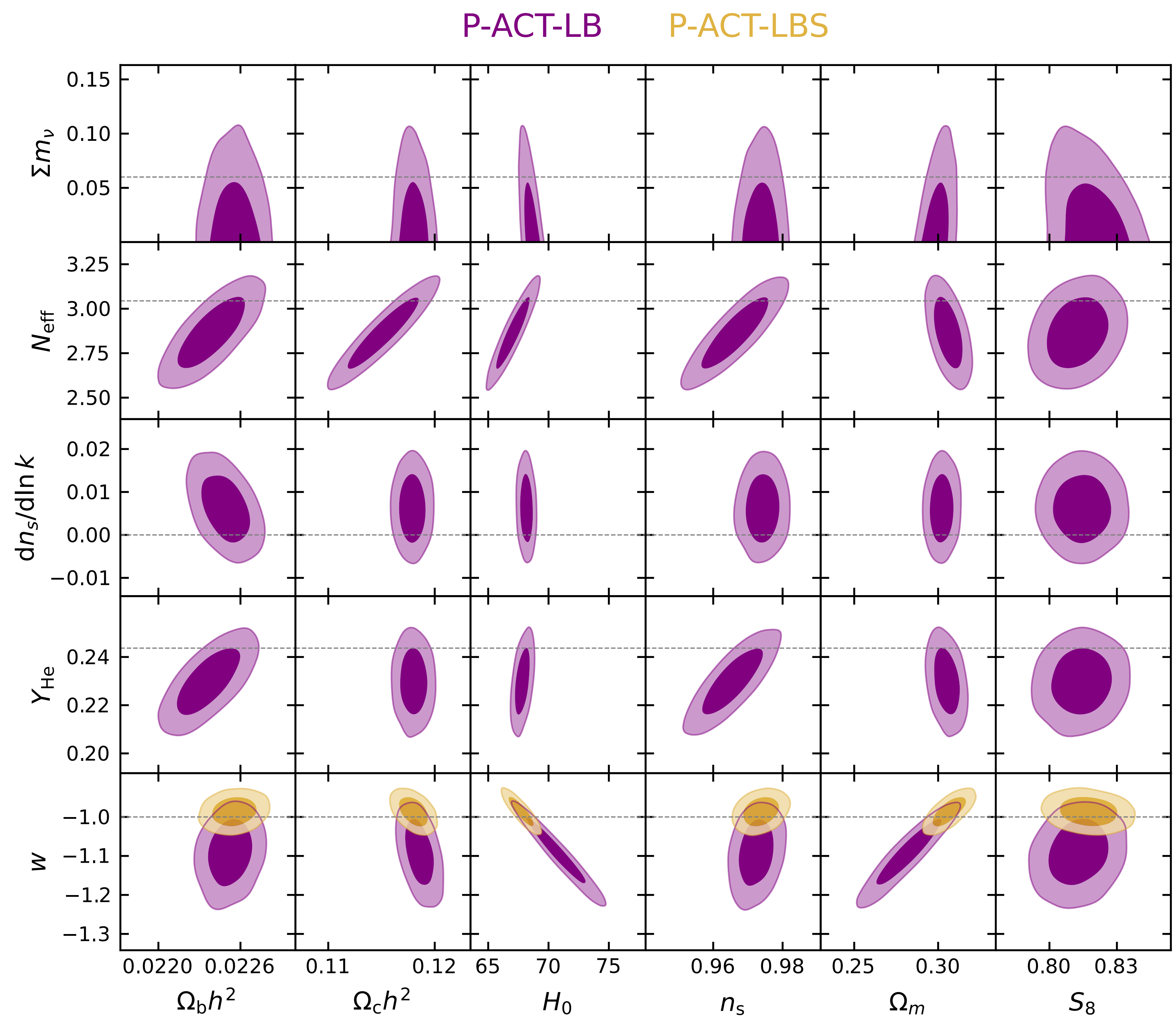
Cosmological Constraints

Colin Hill
Columbia

We investigated ~30 beyond-standard-model scenarios: no evidence of deviations from ΛCDM found



Model
Running of scalar spectral index
$P_{\mathcal{R}}(k)$
Isocurvature perturbations
Tensor modes
Early dark energy
Varying electron mass
Varying electron mass and curvature
Varying fine-structure constant
Varying fine-structure constant and curvature
Primordial magnetic fields
CMB temperature
Modified recombination history
Neutrino number, $N_{\rm eff}$
Neutrino mass, $\sum m_\nu$
$N_{\rm eff} + \sum m_\nu$
Neutrino self-interactions
Helium and deuterium
Axion-like particles
DM-baryon interactions
DM annihilation
Self-interacting DR
Interacting DR-DM
Spatial curvature
Dark energy equation of state, w
Dark energy equation of state, w_0/w_a
Interacting DE-DM
Modified gravity

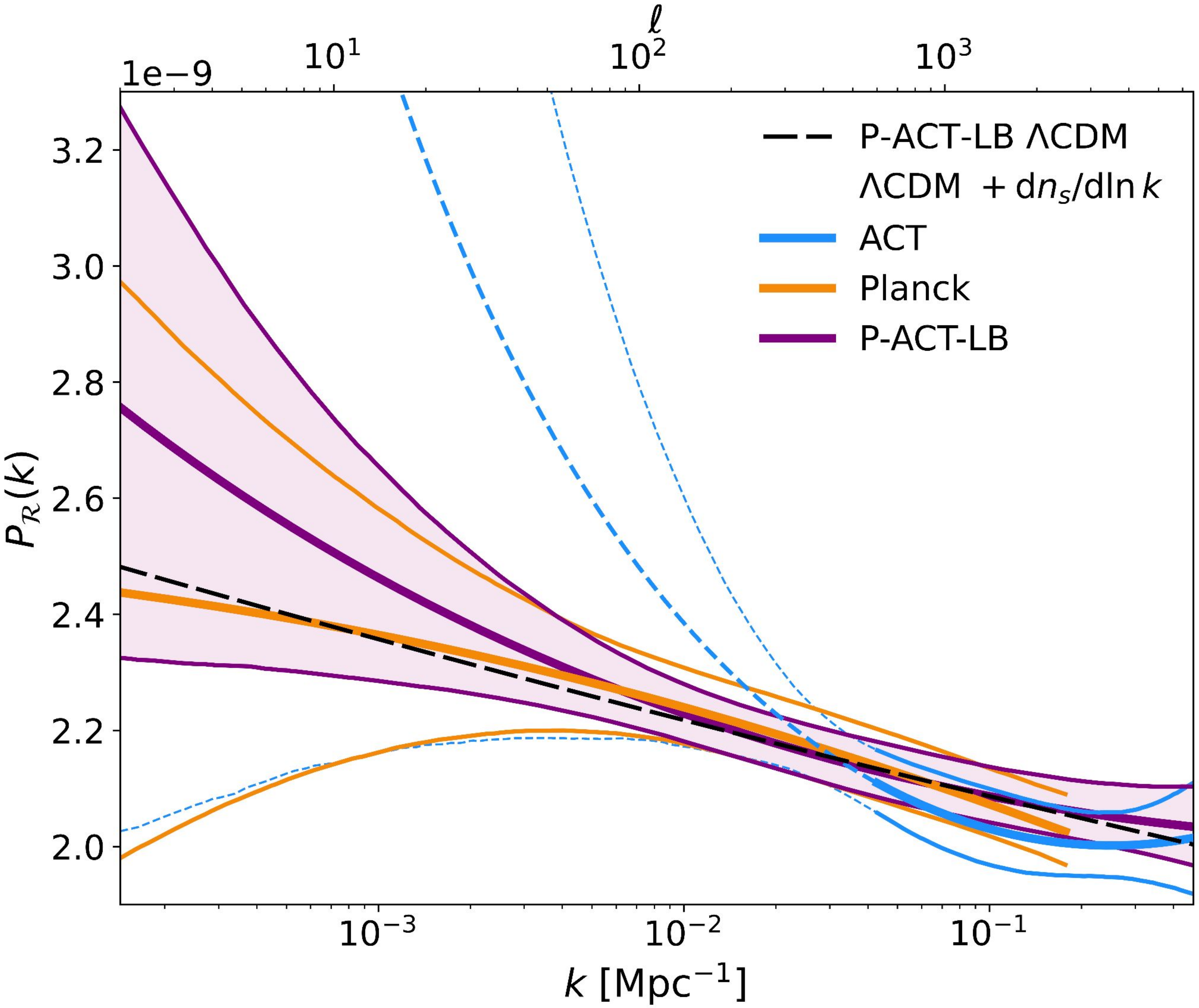
Primordial Power Spectrum

Colin Hill
Columbia

Constraints on scale dependence of primordial curvature perturbation power spectrum

$$\mathrm{d}n_s/\mathrm{d}\ln k = 0.0062 \pm 0.0052$$ (P-ACT-LB)

No evidence of departure from simple power-law



Primordial Power Spectrum

Colin Hill
Columbia

Constraints on scale dependence of primordial curvature perturbation power spectrum

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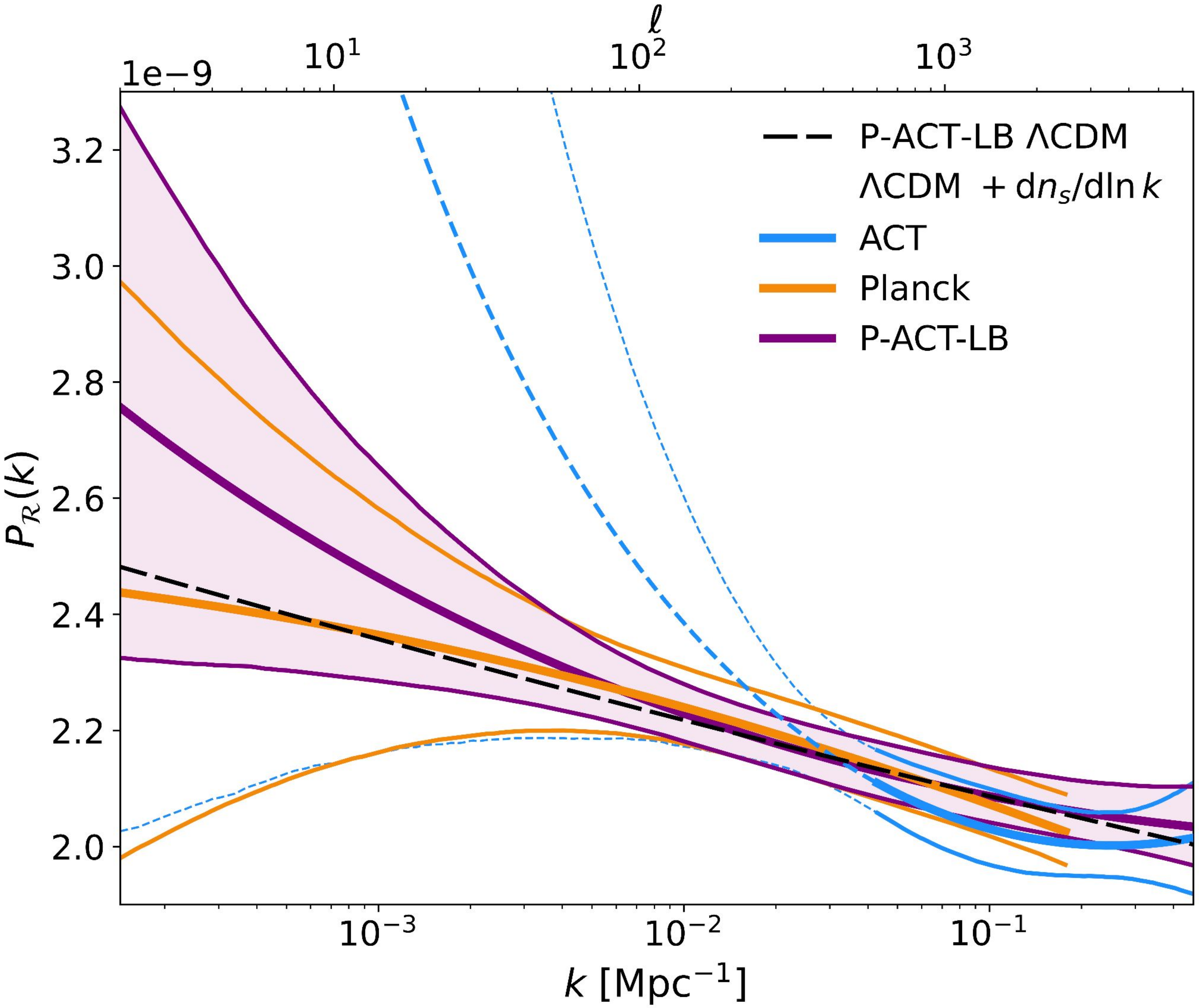


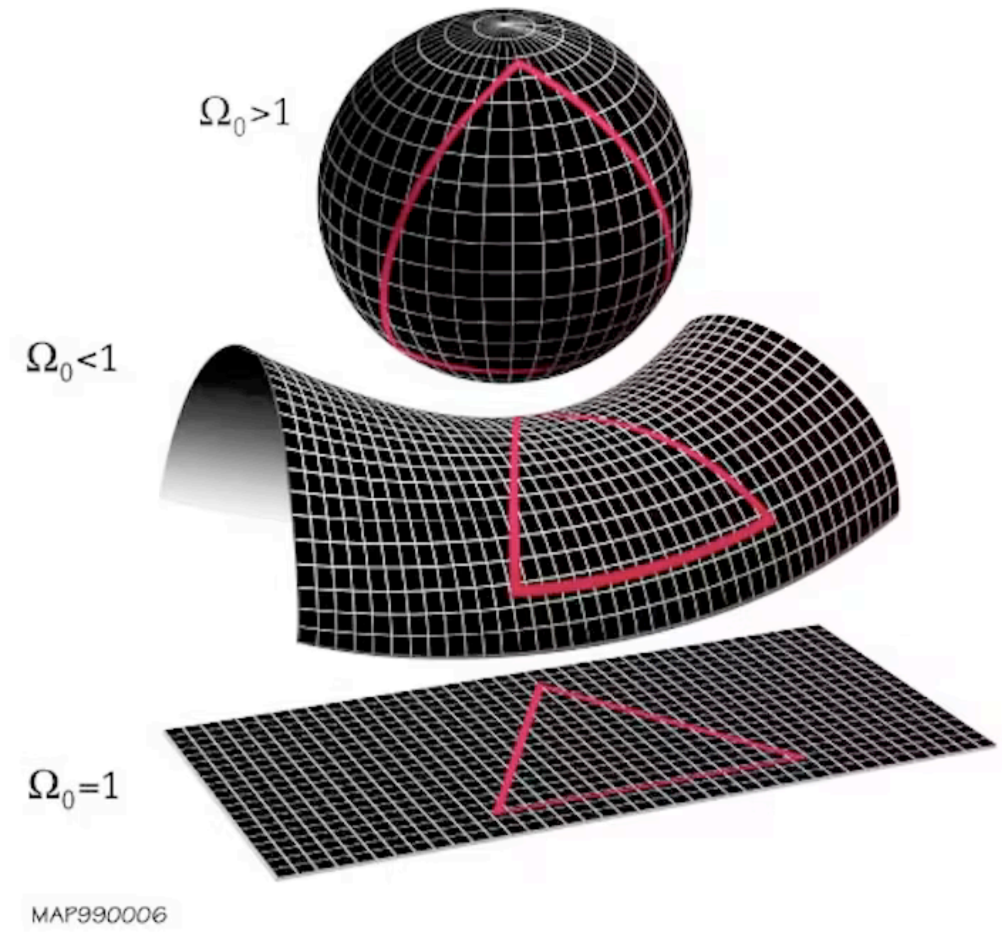
No evidence of departure from simple power-law

30% tighter than previous CMB+LSS constraints

+ tightened constraints on primordial isocurvature perturbations — no deviation from adiabaticity detected

Spatial Curvature

Colin Hill
Columbia



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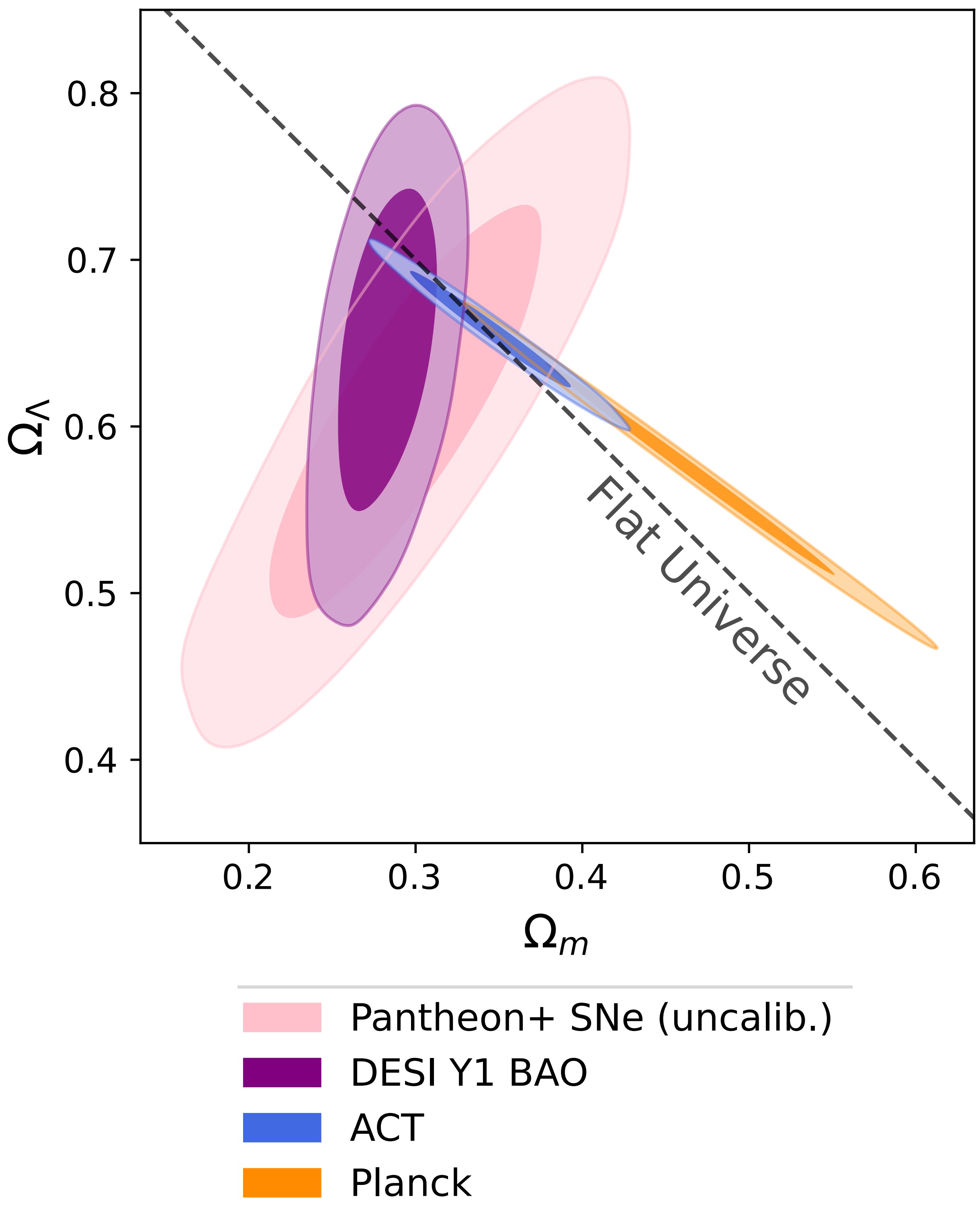
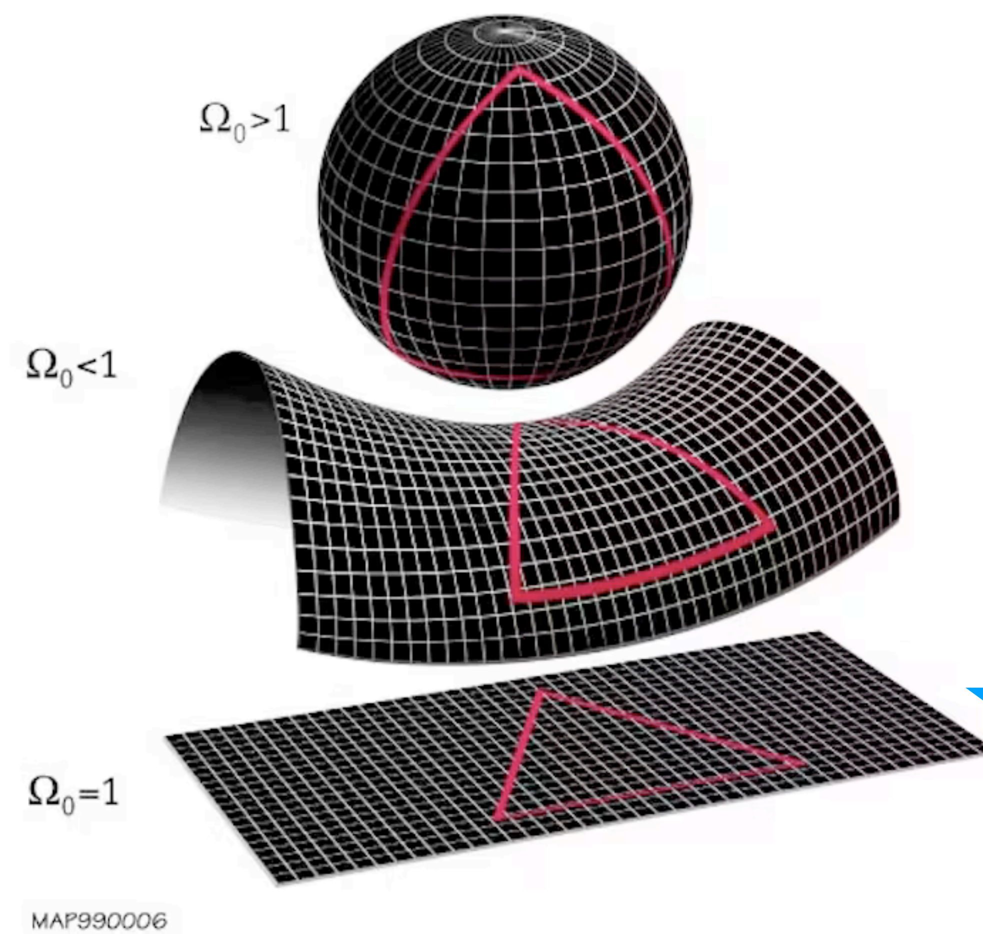
Spatial Curvature

No evidence of spatial curvature (3-geometry = Euclidean)





$$\Omega_k = 0.0019 \pm 0.0015 \quad (68\%, \text{P-ACT-LB})$$

Cosmological Constraints

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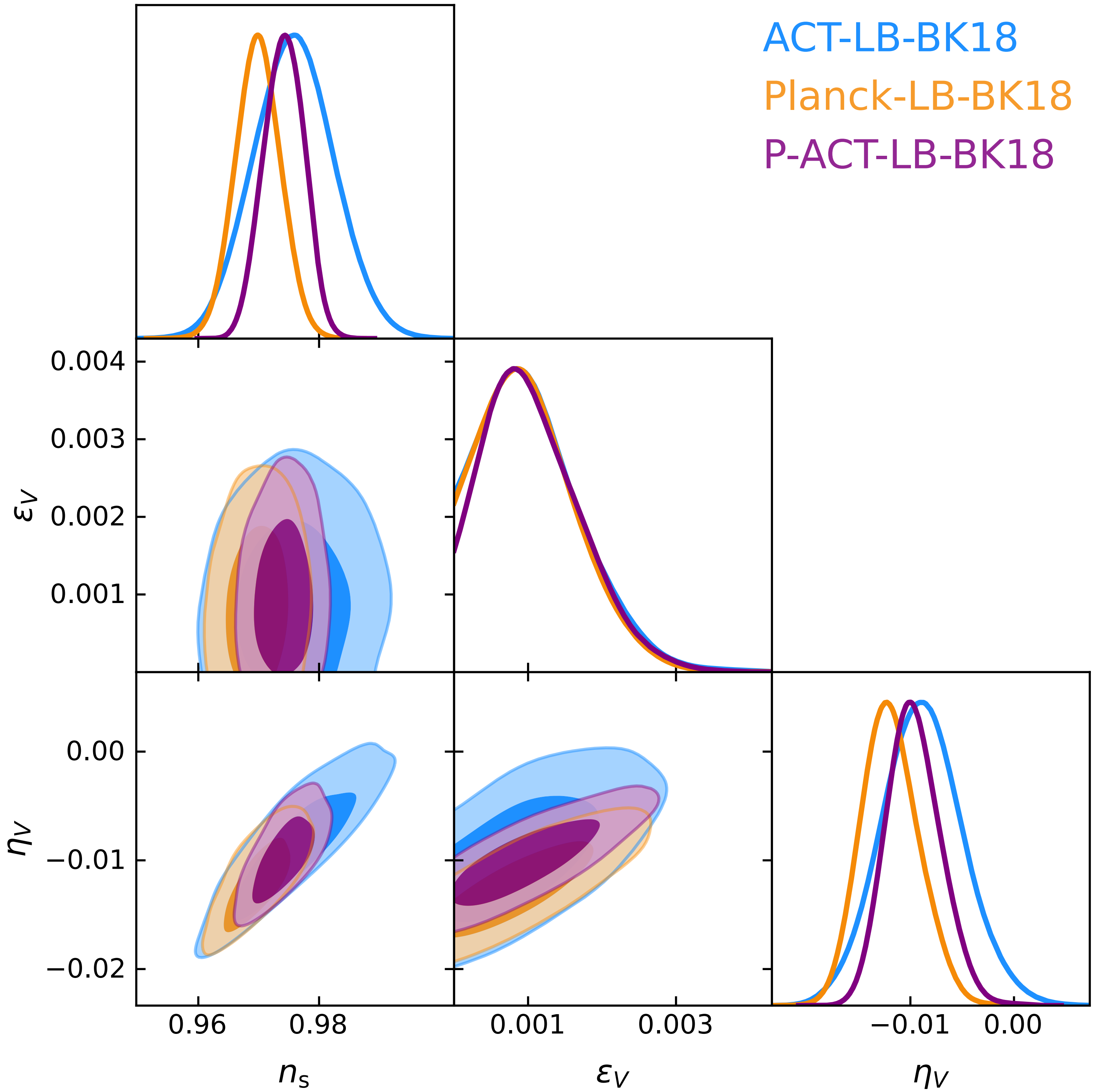
Constraints on potential slow-roll parameters (inflation)



$$\epsilon_V \equiv \frac{{M_{Pl}}^2}{2}\left(\frac{V_{,\phi}}{V}\right)^2$$

$$\eta_V \equiv {M_{Pl}}^2\left(\frac{V_{,\phi\phi}}{V}\right)$$

$$r = 16\epsilon_V,$$

$$n_s - 1 = 2\eta_V - 6\epsilon_V$$

Cosmological Constraints

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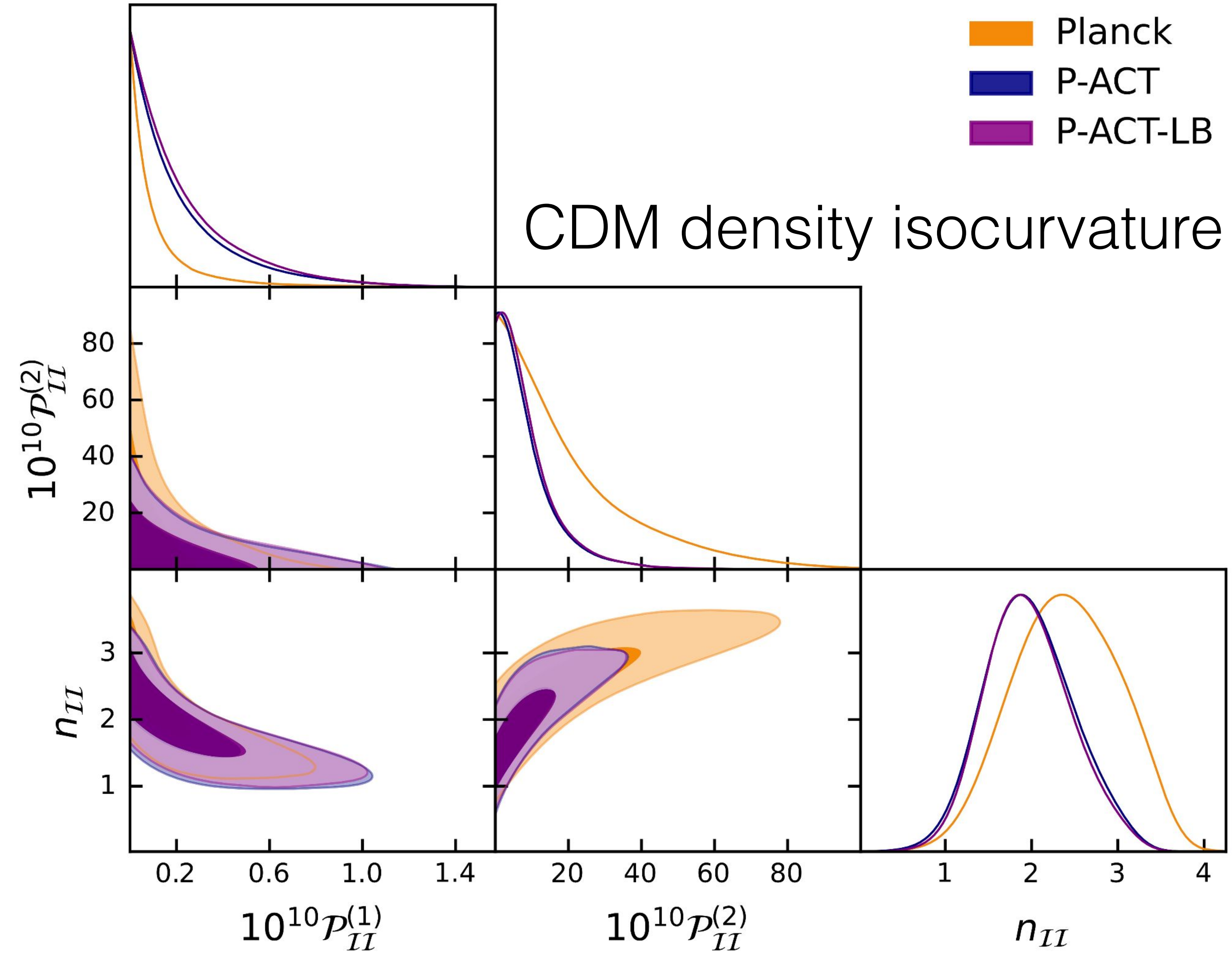
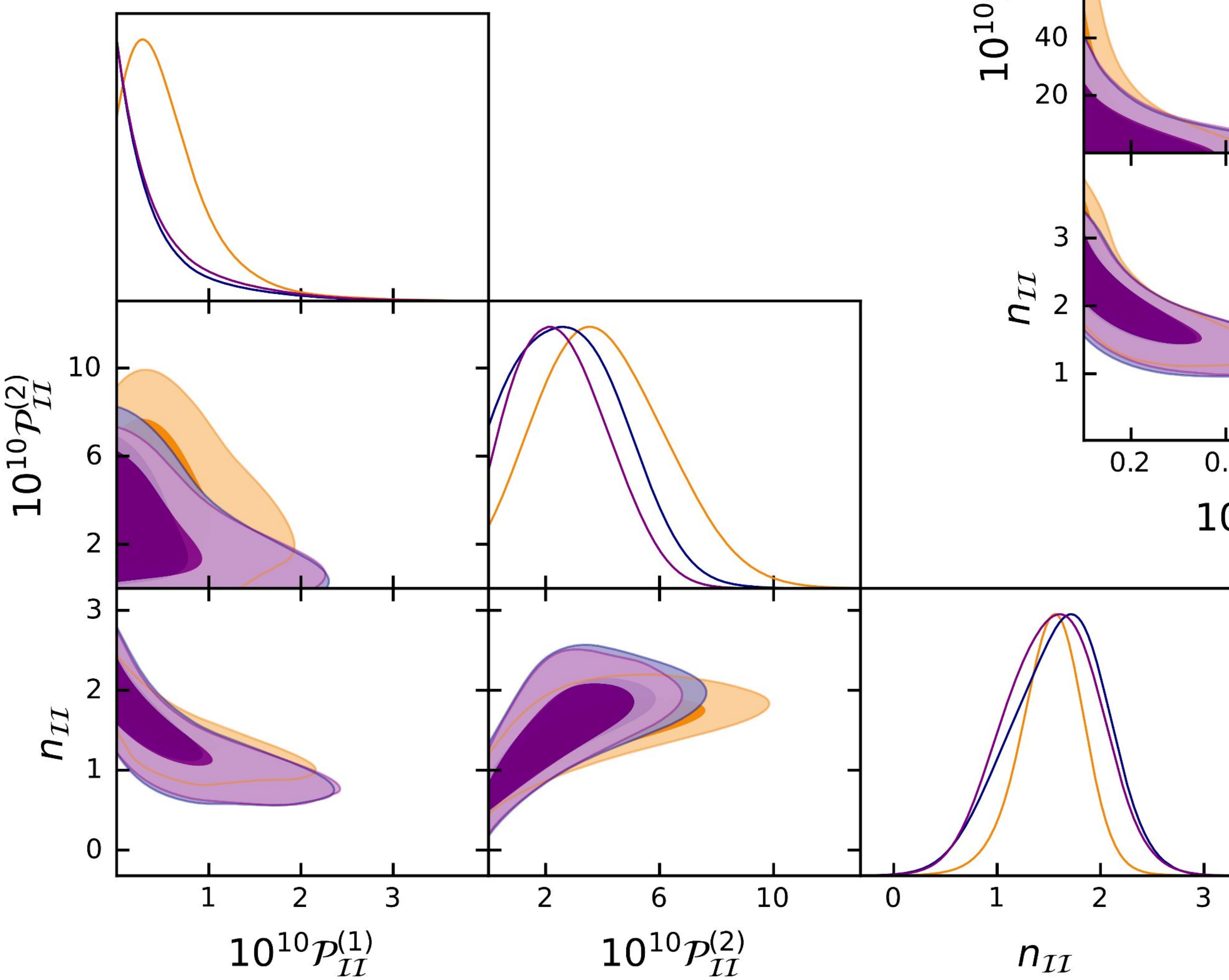
No evidence of primordial isocurvature perturbations



CDM density isocurvature

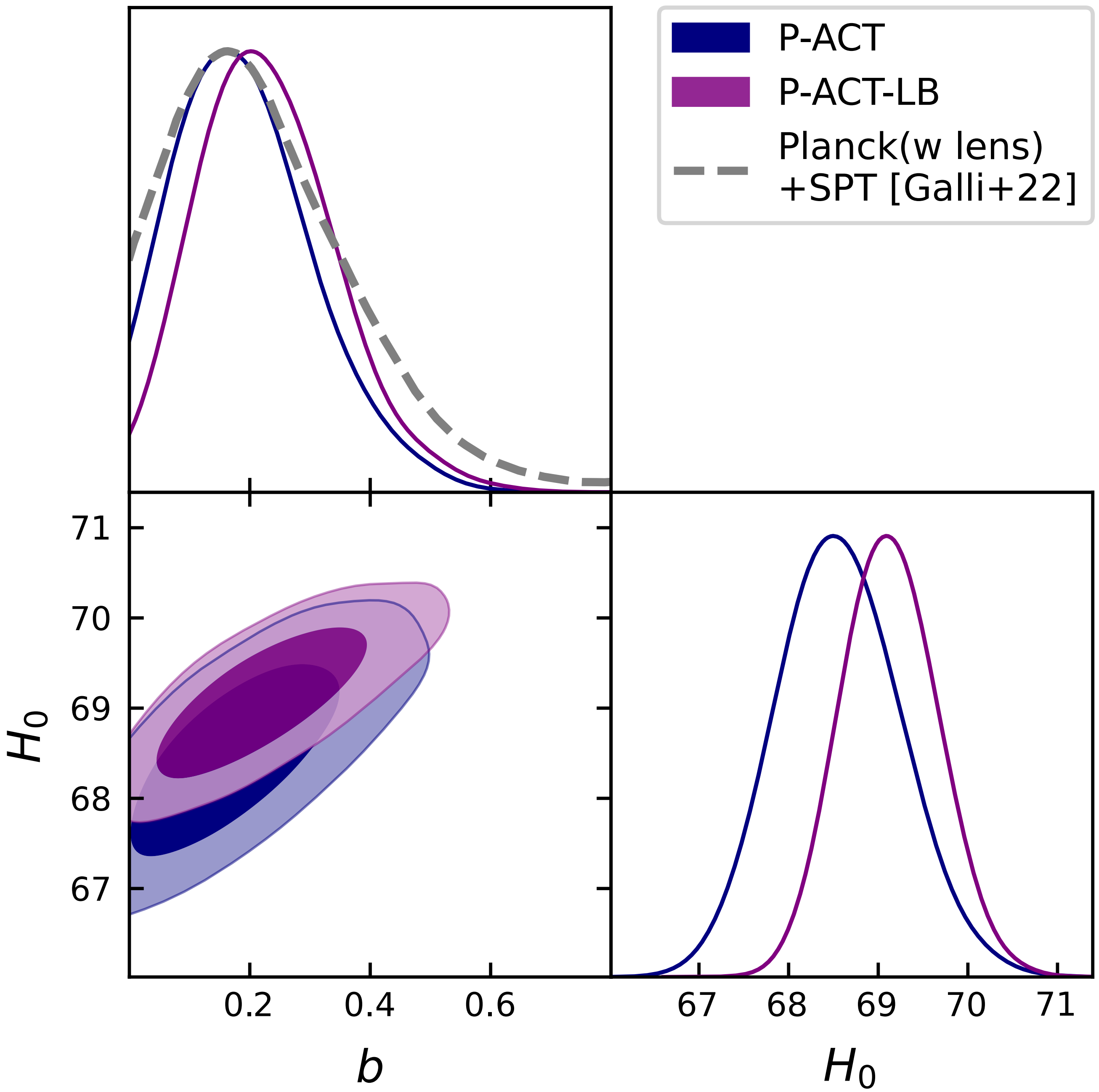


Neutrino density isocurvature

Modified Recombination

Colin Hill
Columbia

Ex.: **primordial magnetic fields/baryon clumping**; variations of fundamental constants; change to CMB monopole temperature or distribution function



variance of small-scale baryon density fluctuations:

$$1 + b \equiv \sum_i f_i \Delta_i^2$$

$$\Delta_i \equiv \rho_{b,i} / \langle \rho_b \rangle$$

volume fraction f_i

$$i = 1, 2, 3$$

$b < 0.41$ (95%, P-ACT),

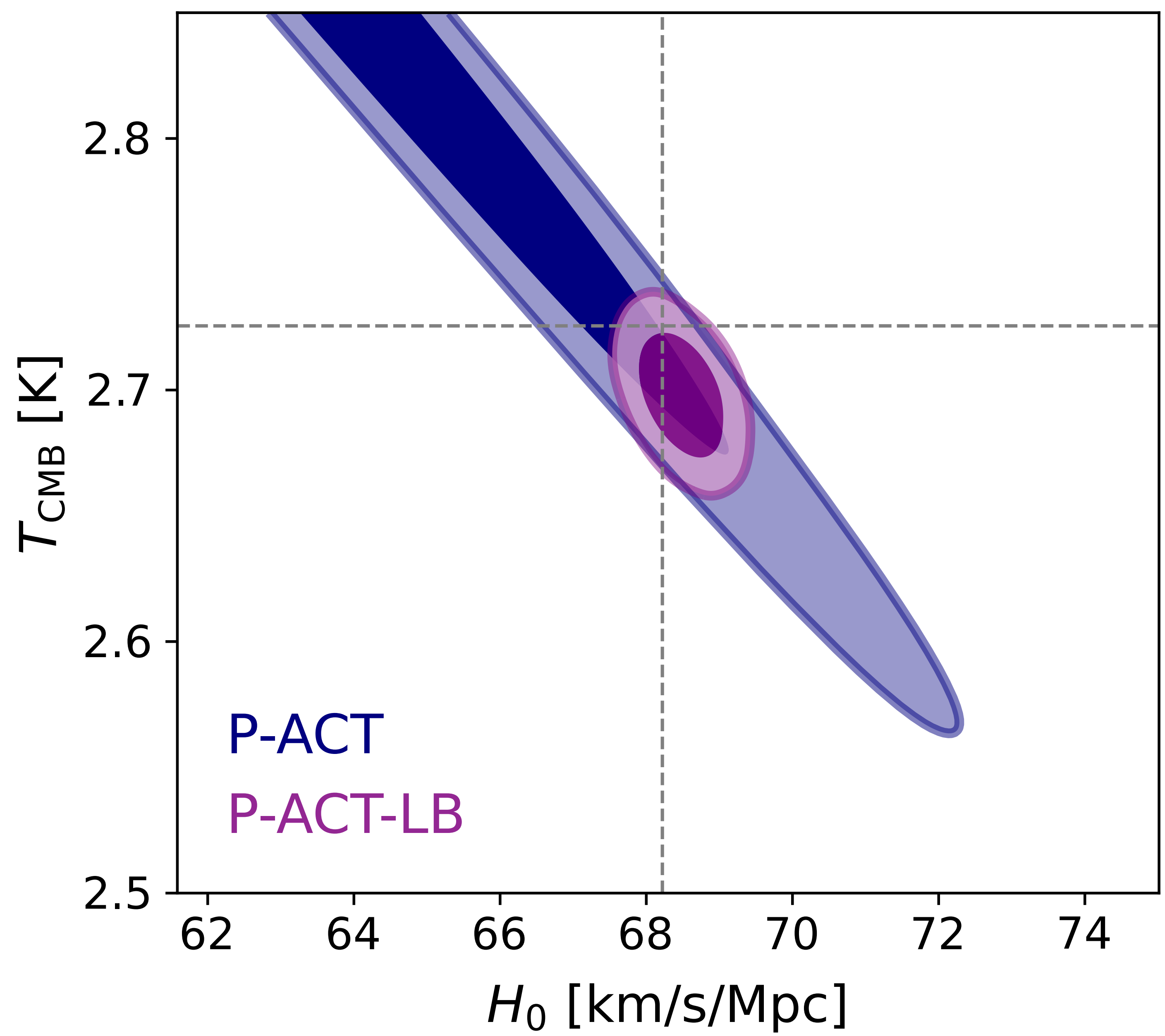
< 0.44 (95%, P-ACT-LB)

~30% improvement in sensitivity over Planck

Modified Recombination

Colin Hill
Columbia

Ex.: primordial magnetic fields; variations of fundamental constants; **change to CMB monopole temperature** or distribution function

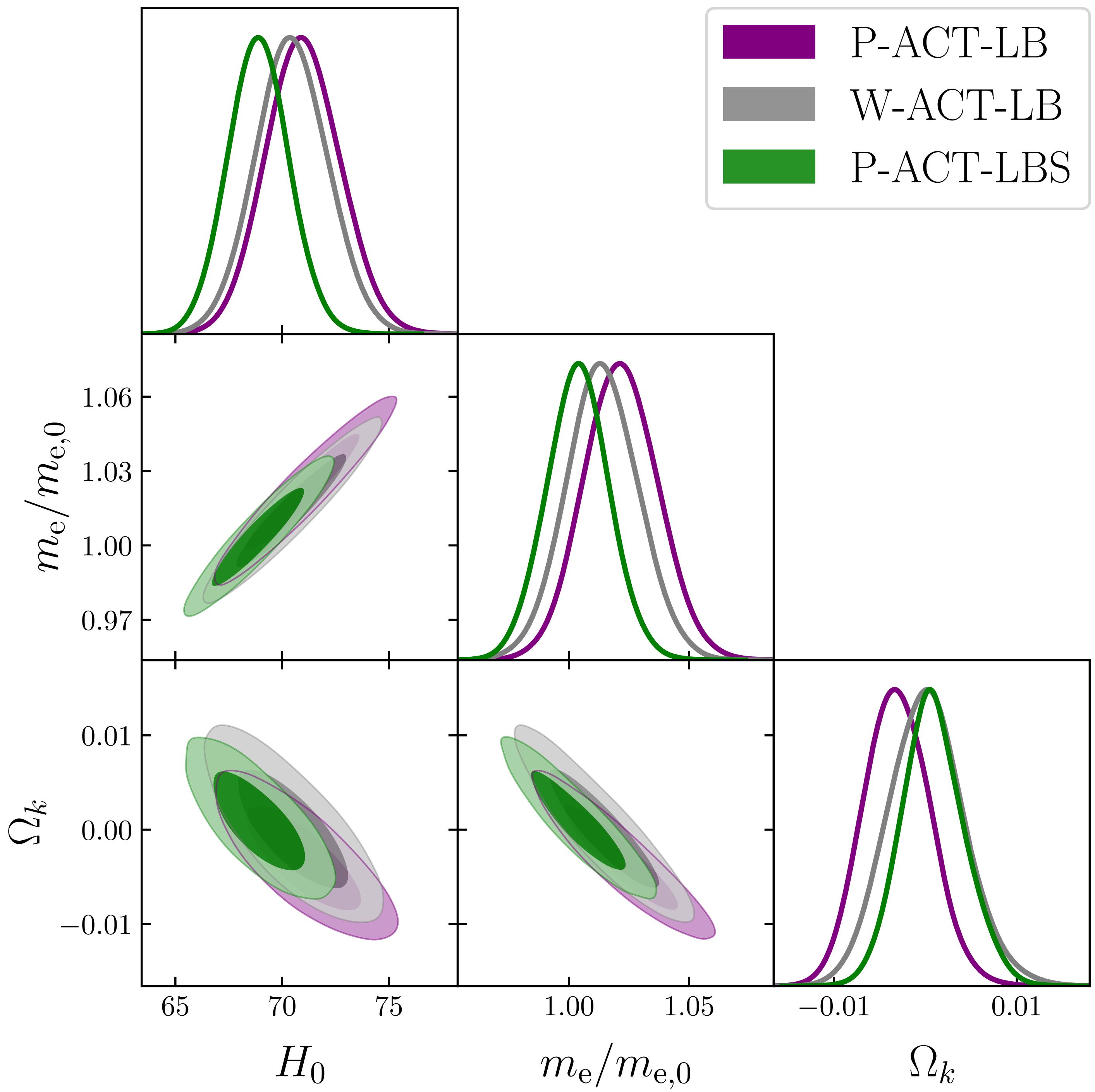


$$T_{\rm CMB} = 2.698 \pm 0.016\,{\rm K}\ \ (68\%, \text{P-ACT-LB})$$

Modified Recombination

Colin Hill
Columbia

Ex.: primordial magnetic fields; **variations of fundamental constants**; change to CMB monopole temperature or distribution function



Early-universe variation of m_e:

$$m_e/m_{e,0} = 1.0063 \pm 0.0056$$
$$H_0 = 69.1 \pm 1.0$$

P-ACT-LBS

+ varying spatial curvature:

$$m_e/m_{e,0} = 1.004 \pm 0.013$$
$$\Omega_k = 0.0008^{+0.0032}_{-0.0036}$$
$$H_0 = 68.9 \pm 1.4$$

P-ACT-LBS

Dominant physical effects:

$$\sigma_T \propto \alpha_{EM}^2 m_e^{-2} \qquad E \propto \alpha_{EM}^2 m_e$$

Self-Interacting Neutrinos

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Columbia

Delay ν free-streaming until z~z*

$$\mathcal{L}_{\rm eff} = G_{\rm eff}\bar{\nu}\nu\bar{\nu}\nu$$

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

Kreisch, Cyr-Racine, Dore, Sigurdson, ++

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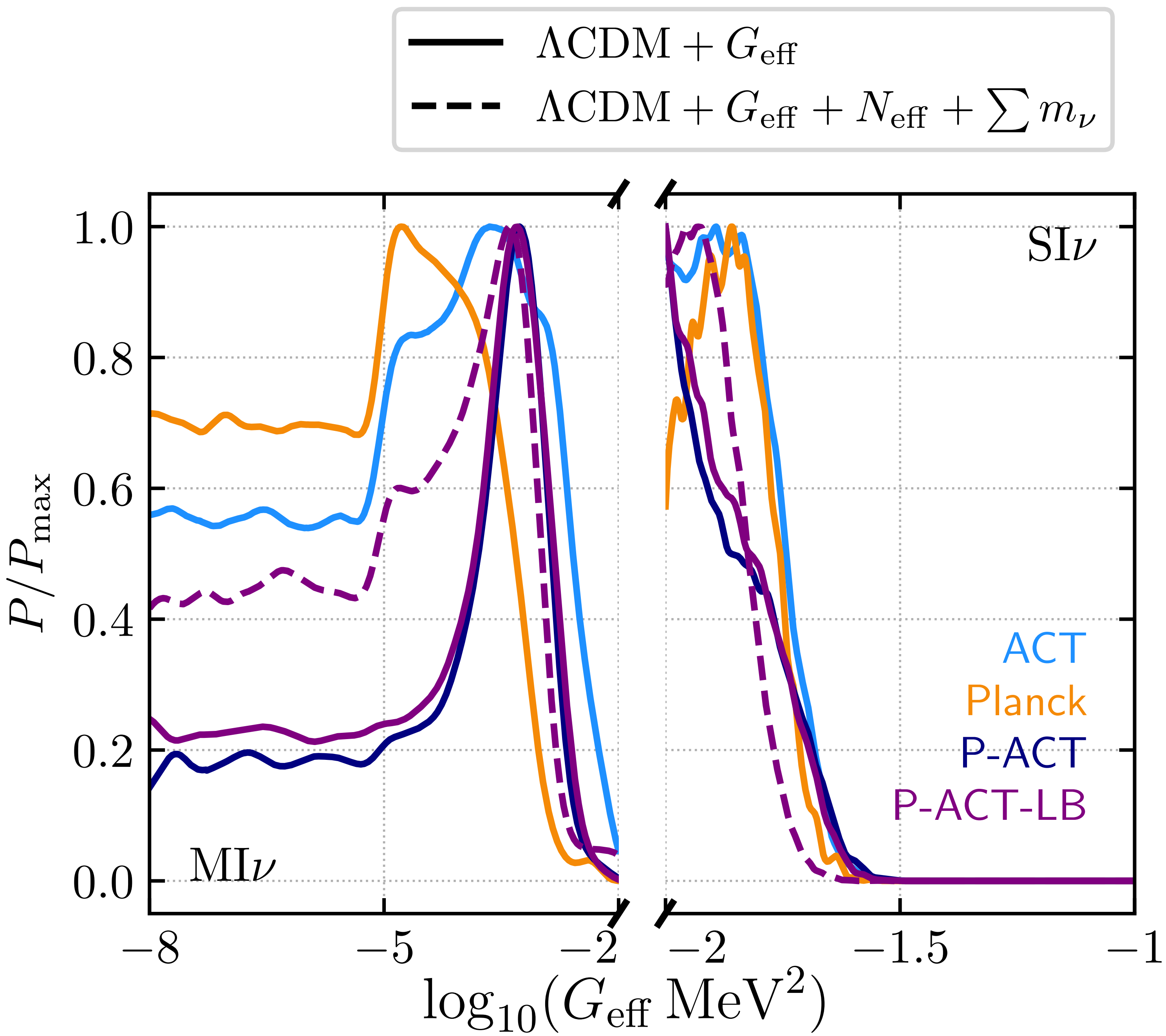
Self-Interacting Neutrinos

No evidence seen for self-interacting ν component in ACT DR6
(previous ~2.5σ hint had been seen in ACT DR4 data [Kreisch+24])



Frequentist: max. preference:
$\Delta\chi^2$ = 3.1 (1.8σ) for MIν
$\Delta\chi^2$ ~ 0 for SIν

MIν: H_0 = 68.2 ± 0.4 ($G_{\rm eff}$)
MIν: H_0 = 67.5 ± 1.0 ($G_{\rm eff}$+$N_{\rm eff}$+M_ν)

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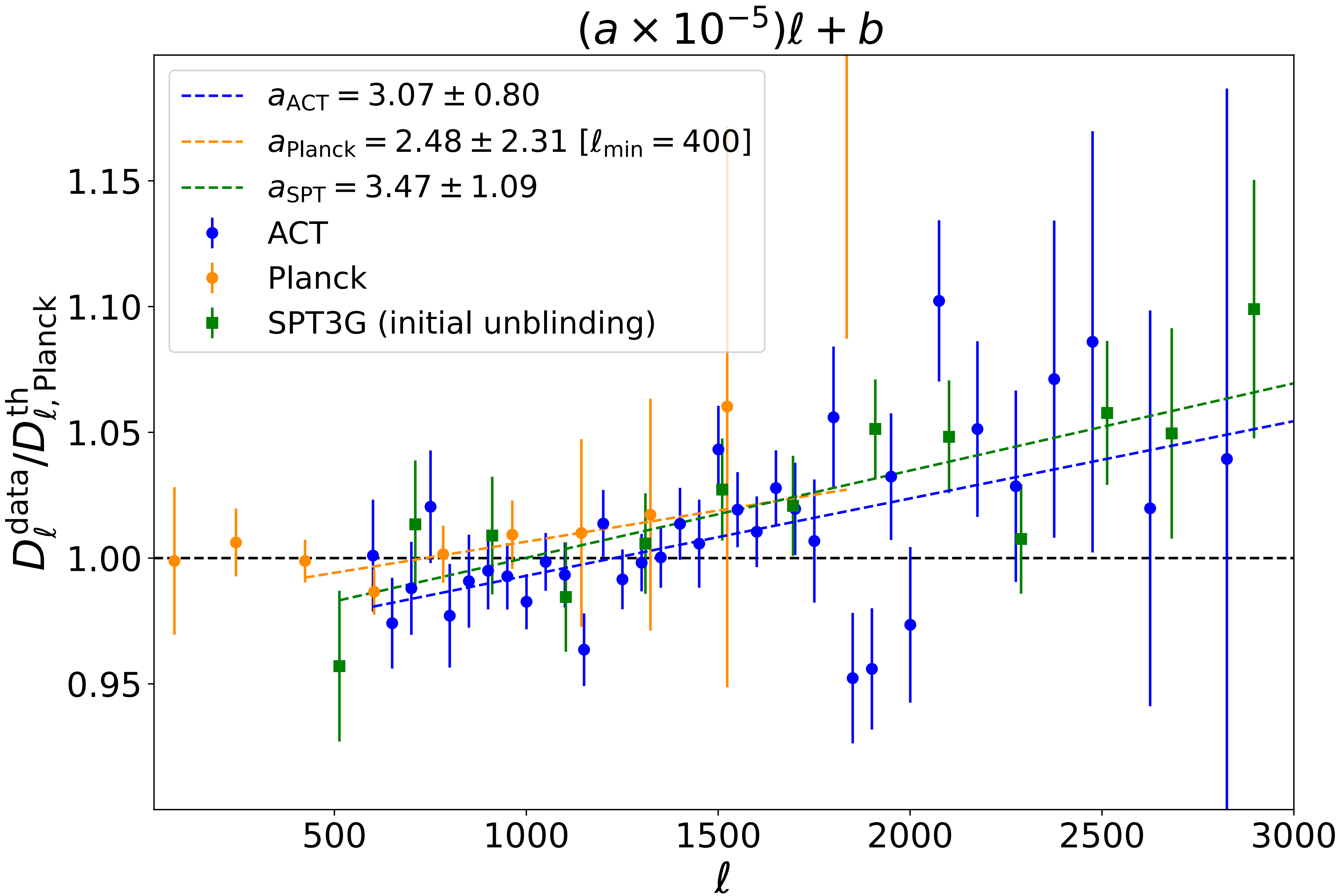
EE Slope at High Ell

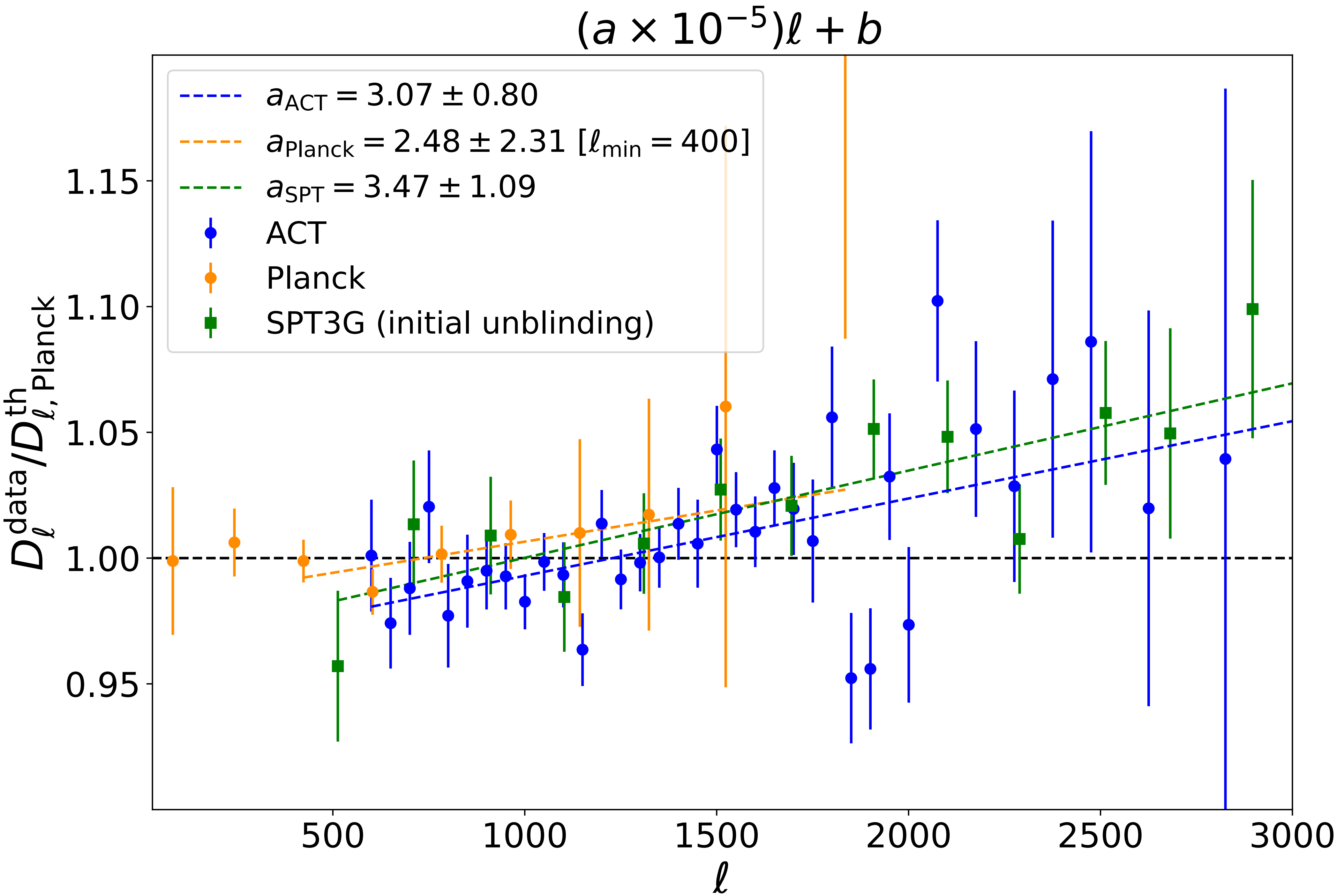
Ratio of EE data to *Planck* best-fit TT+TE+EE ΛCDM model



EE Slope at High Ell

Colin Hill
Columbia

Ratio of EE data to *Planck* best-fit TT+TE+EE ΛCDM model



Not significant enough to affect parameters: ACT EE-only ΛCDM matches *Planck* TT+TE+EE at 2.3σ

Noise Properties

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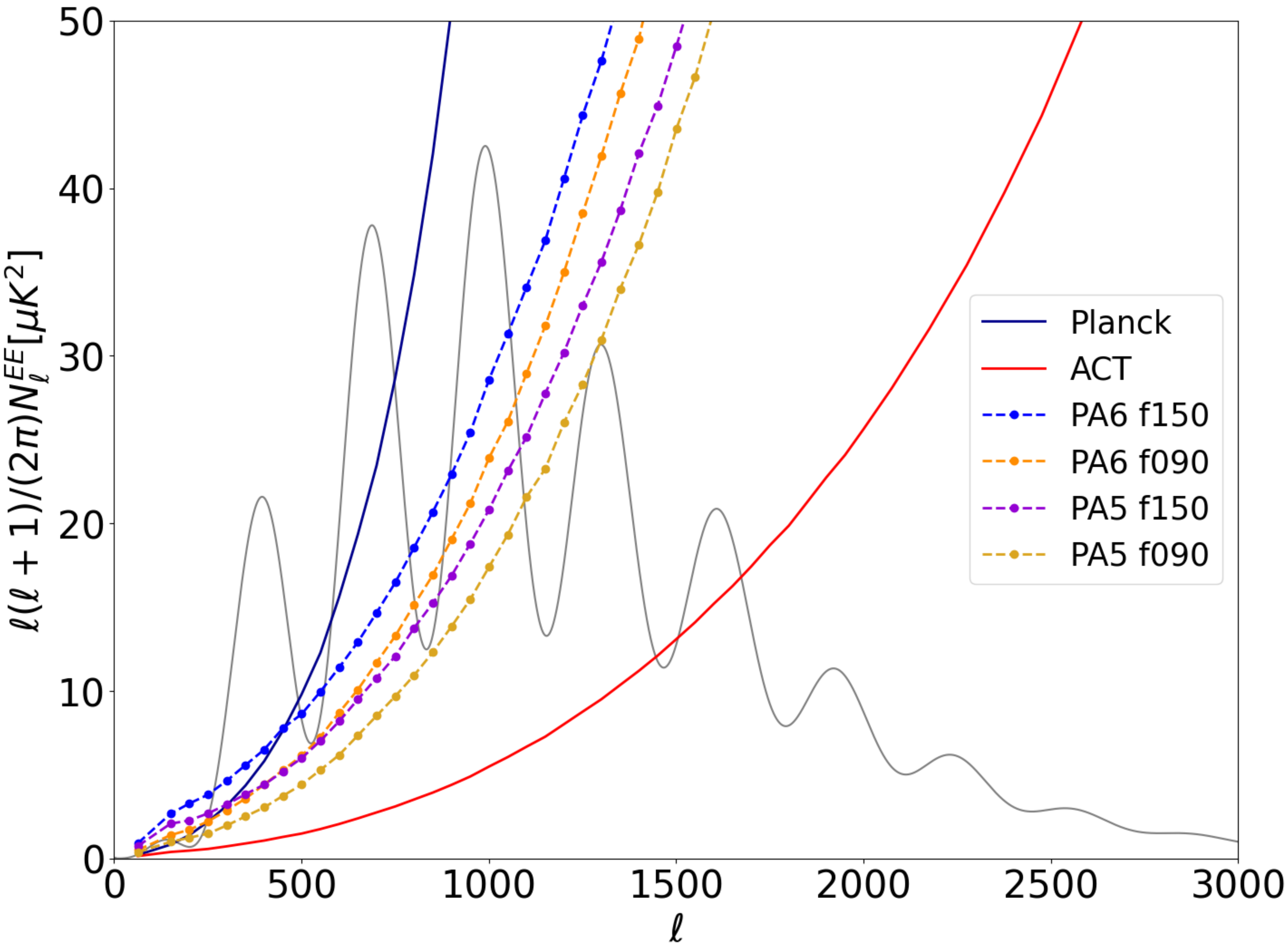
EE power spectrum is signal-dominated up to ell~1700 (θ~0.1 deg)
Comparable SNR from each array-band allows stringent null tests



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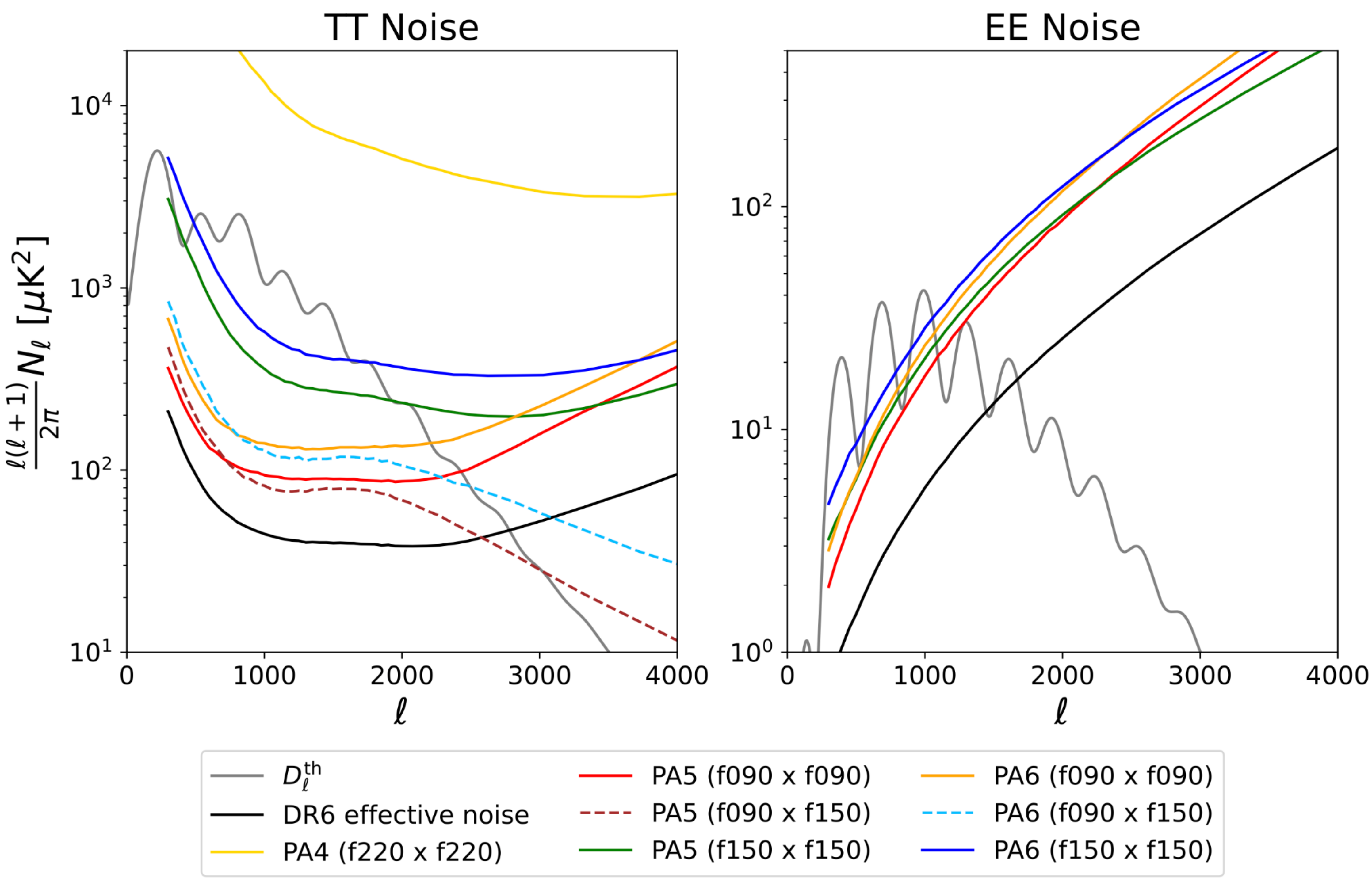
Noise Properties

Multifrequency noise power spectra



Noise Properties

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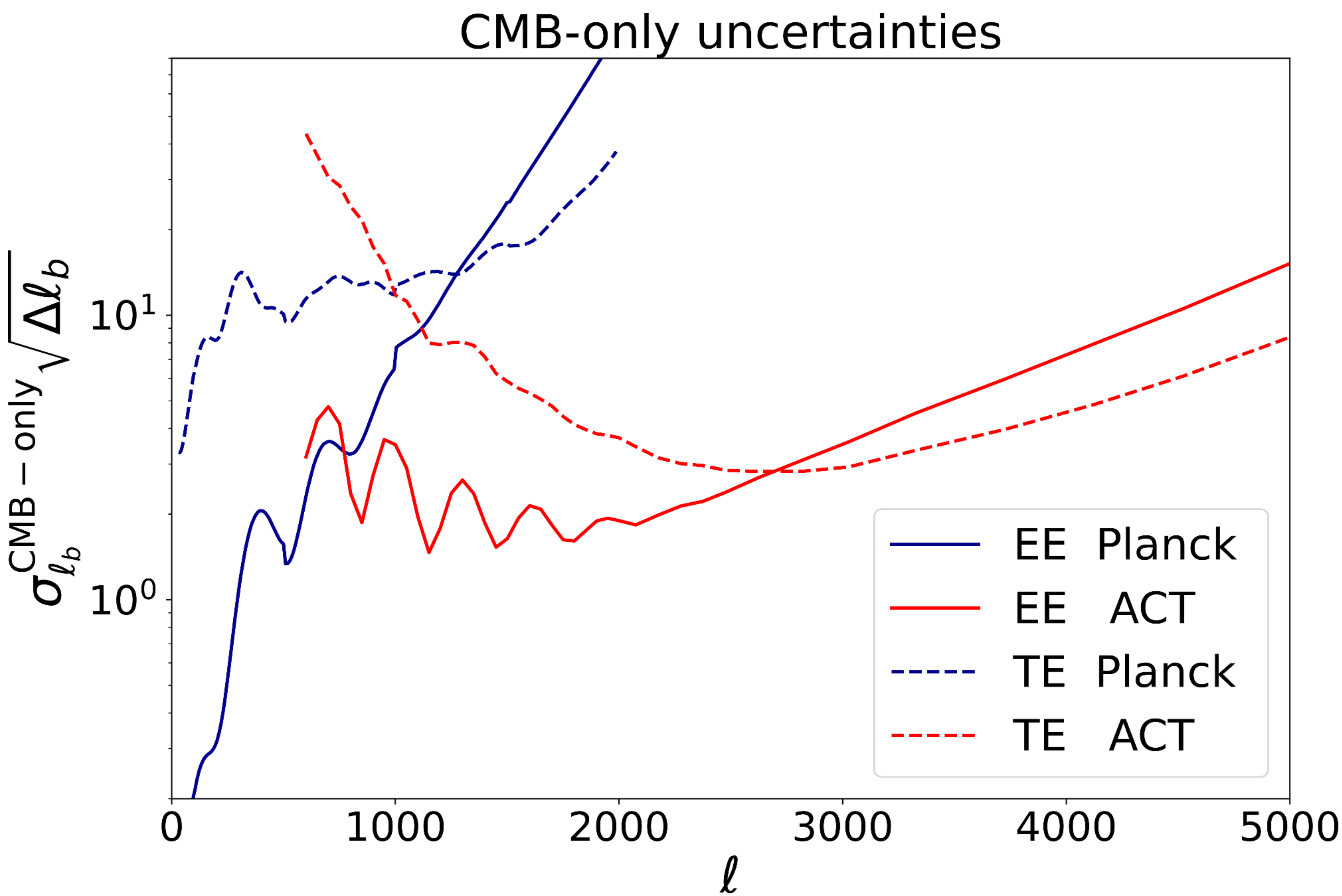
Foreground-marginalized ("CMB-only") bandpower error bars



Null Tests

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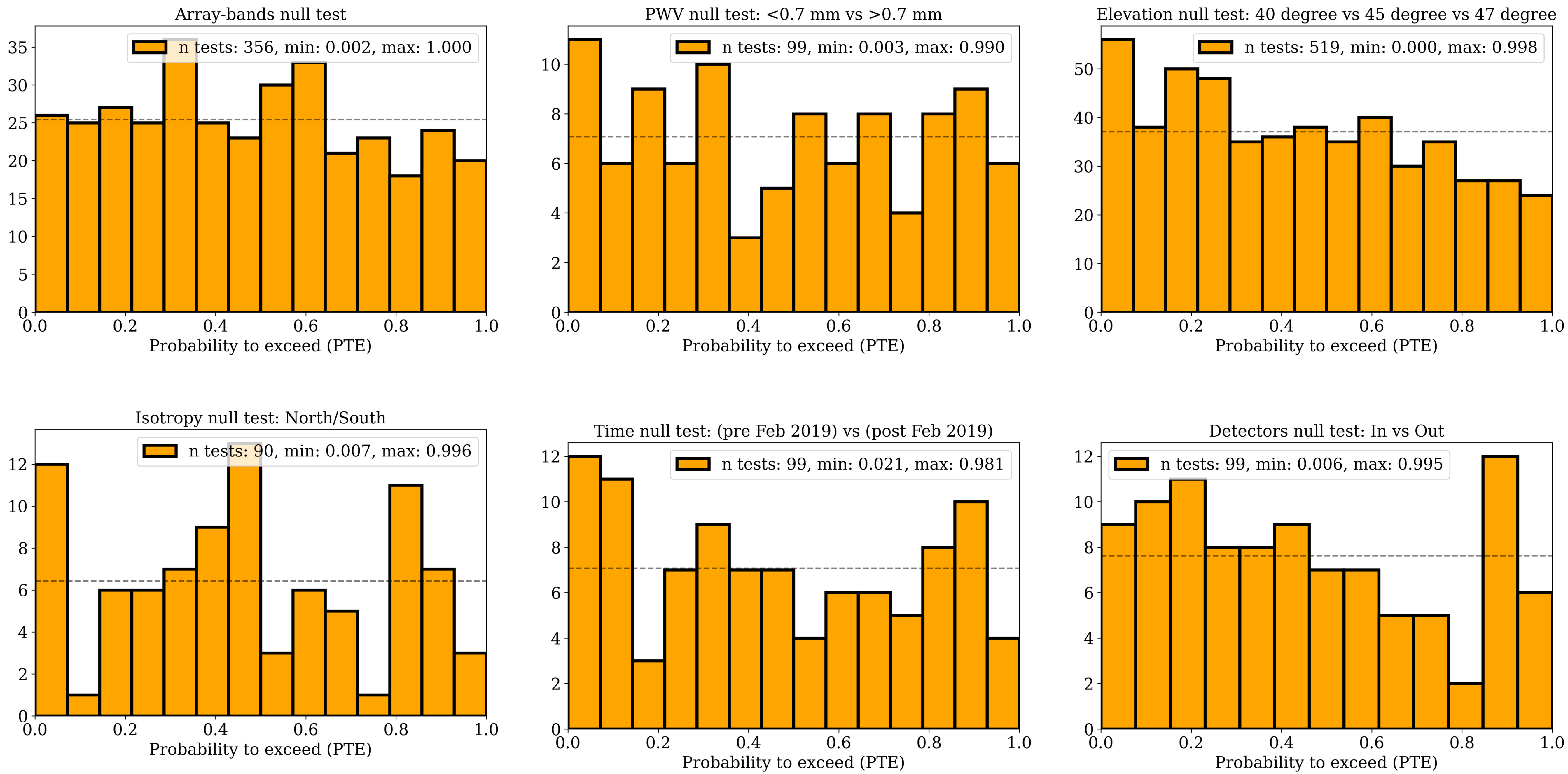
~2000 null tests passed before unblinding; PTE distributions are uniform



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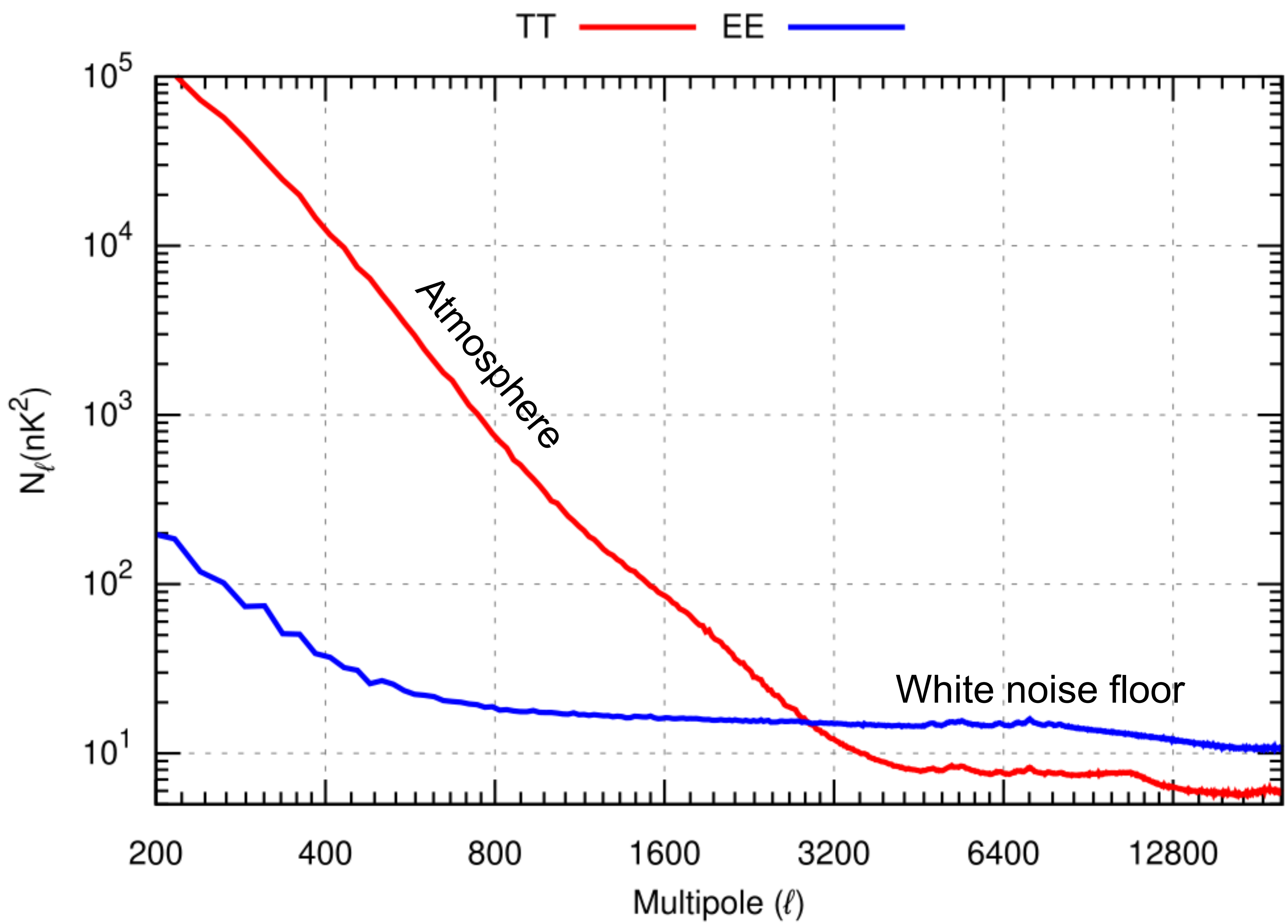
Complexities

Atmospheric Noise

Full sensitivity is only reached on small angular scales



Complexities

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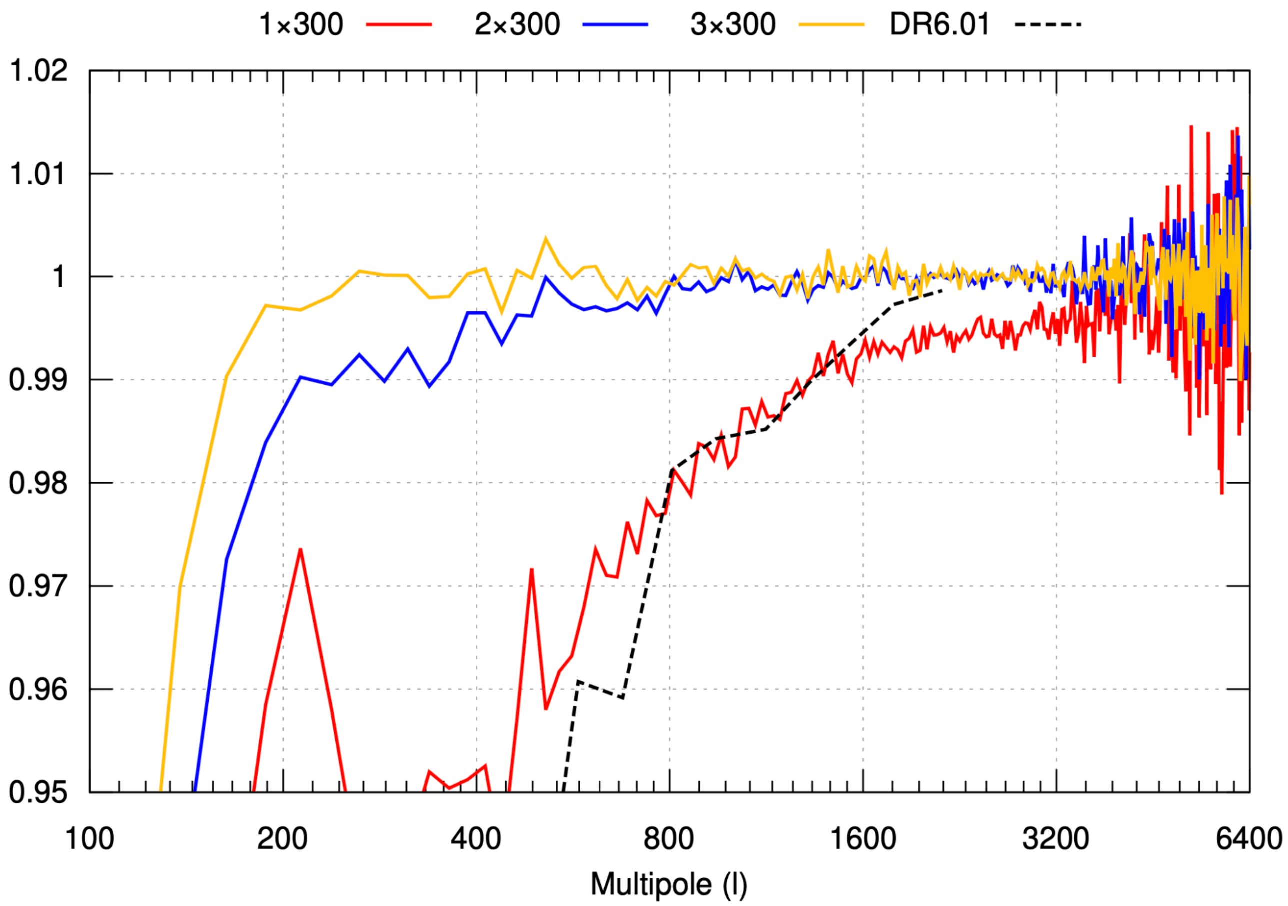
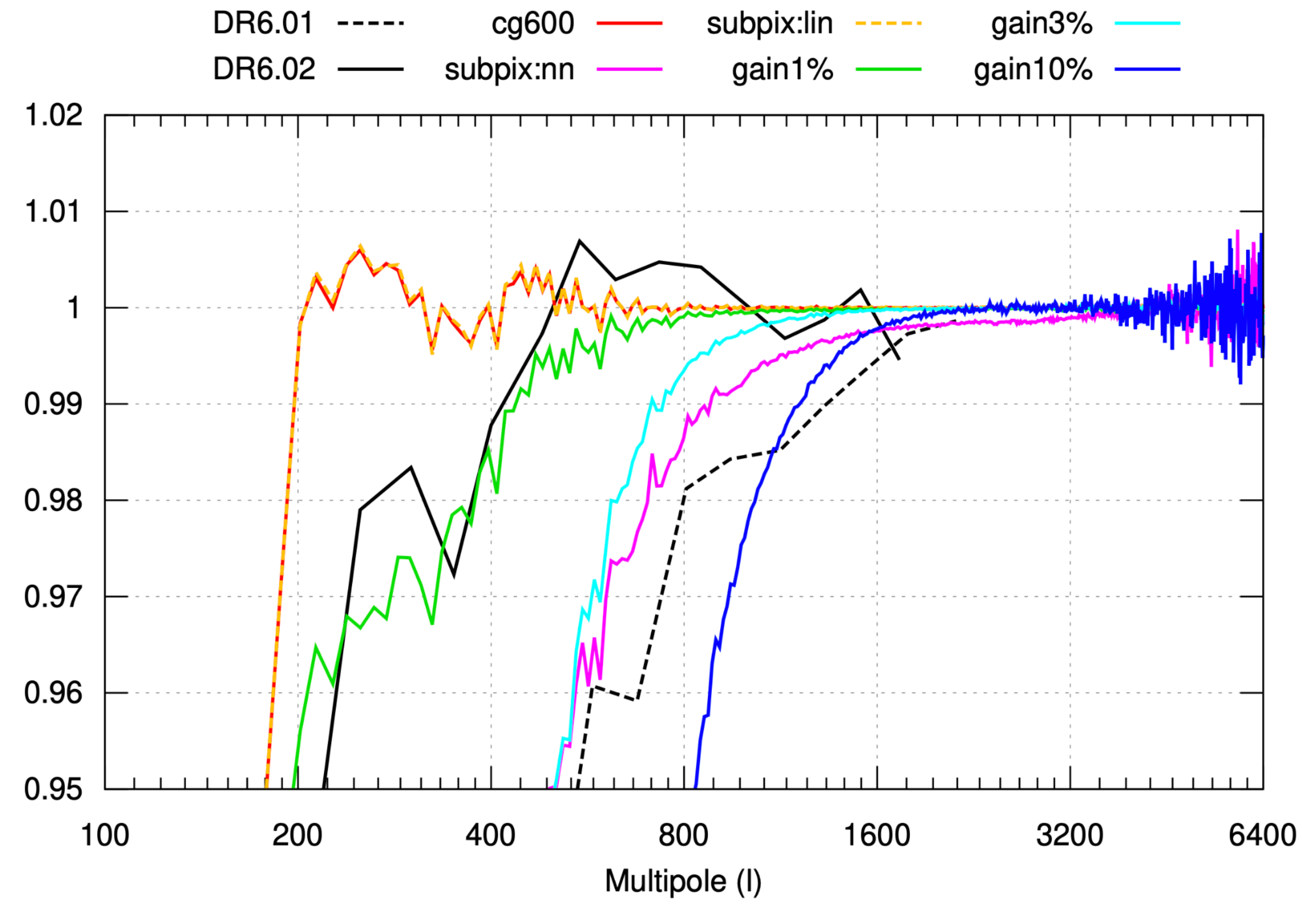
Transfer Function in Temperature Maps





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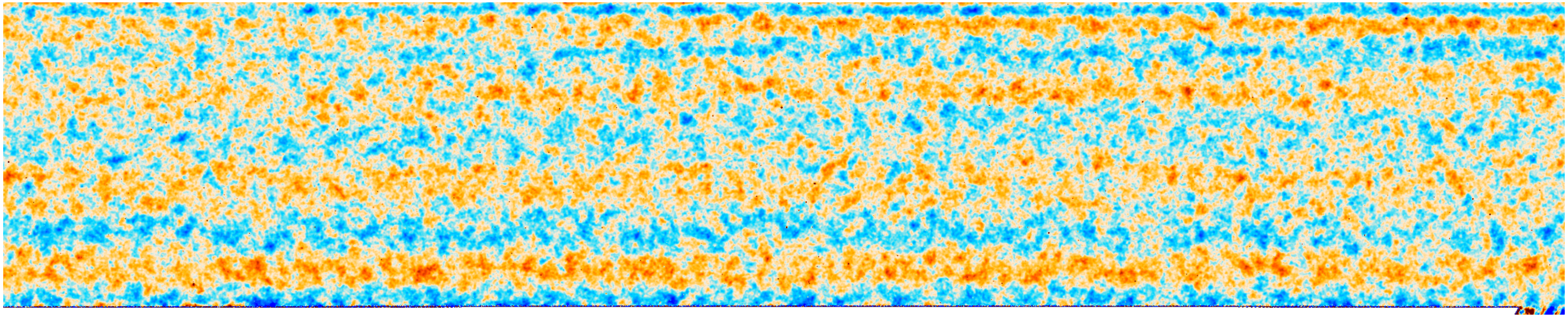
Complexities

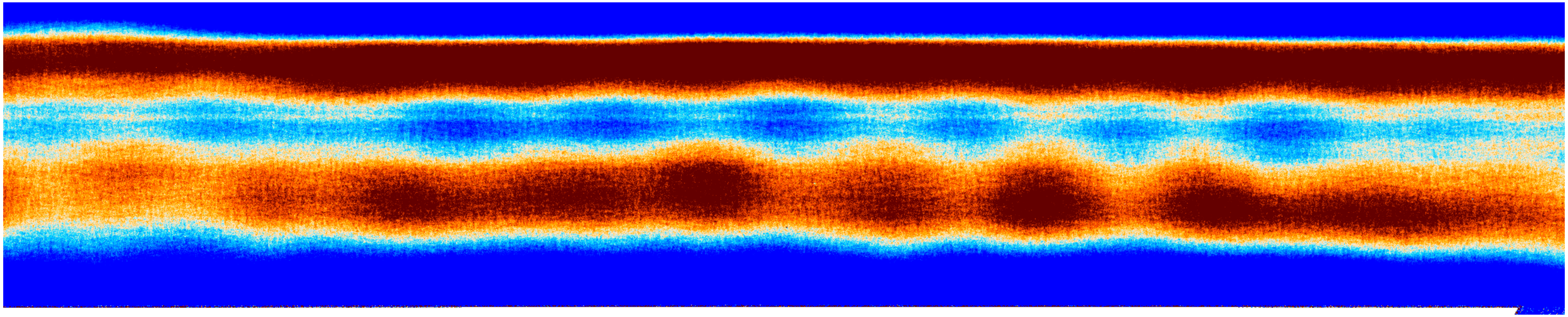
Scan-synchronous "pickup"

Manifests as horizontal stripes in maps

T



Q



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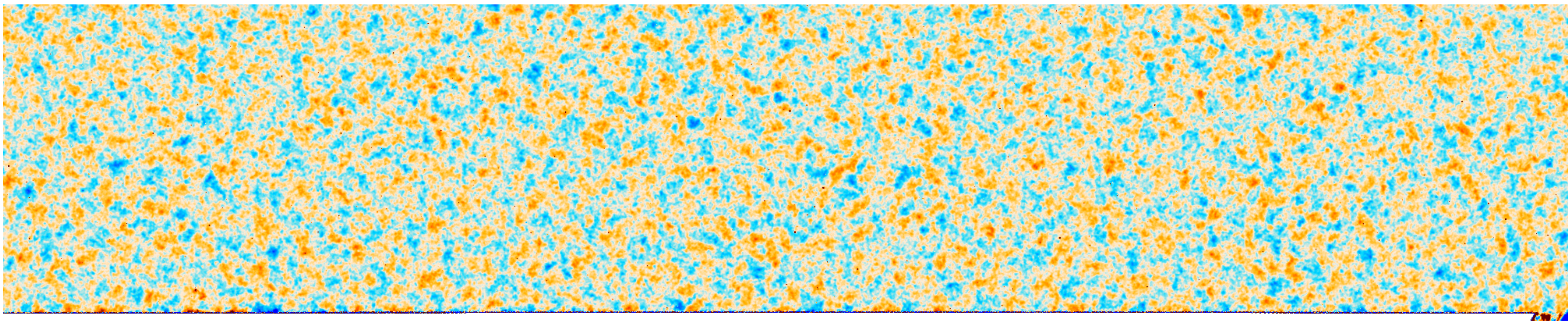
Complexities

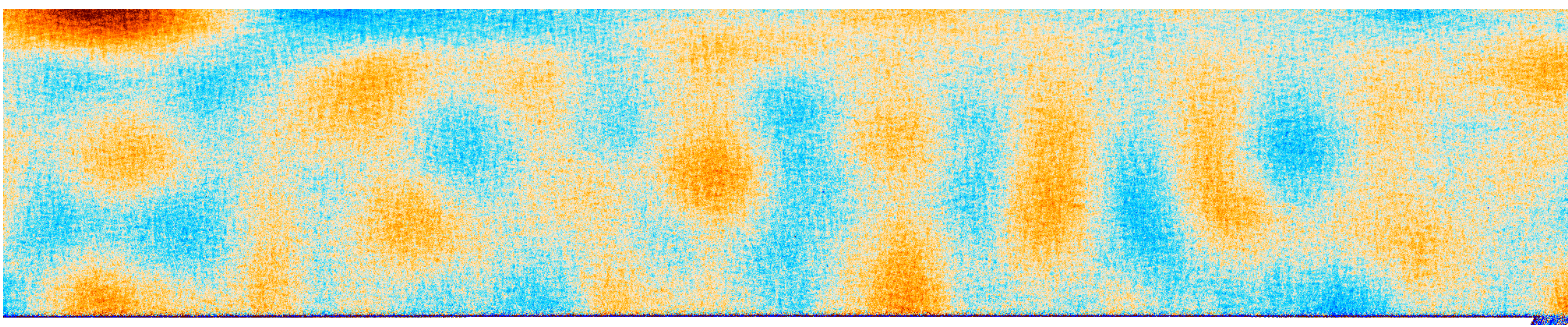
Scan-synchronous “pickup”

Heavily suppressed by removing |m| < 5 modes

T



Q



Remaining large-scale features in Q are correlated noise at ell<100

Beams

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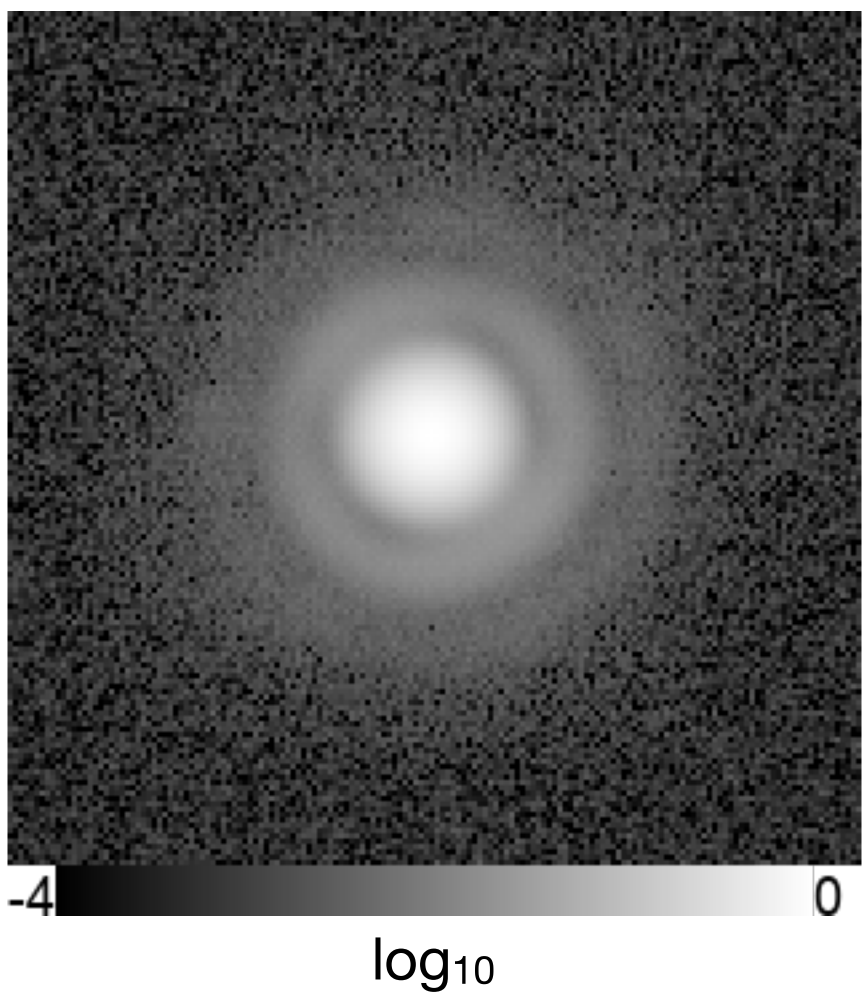
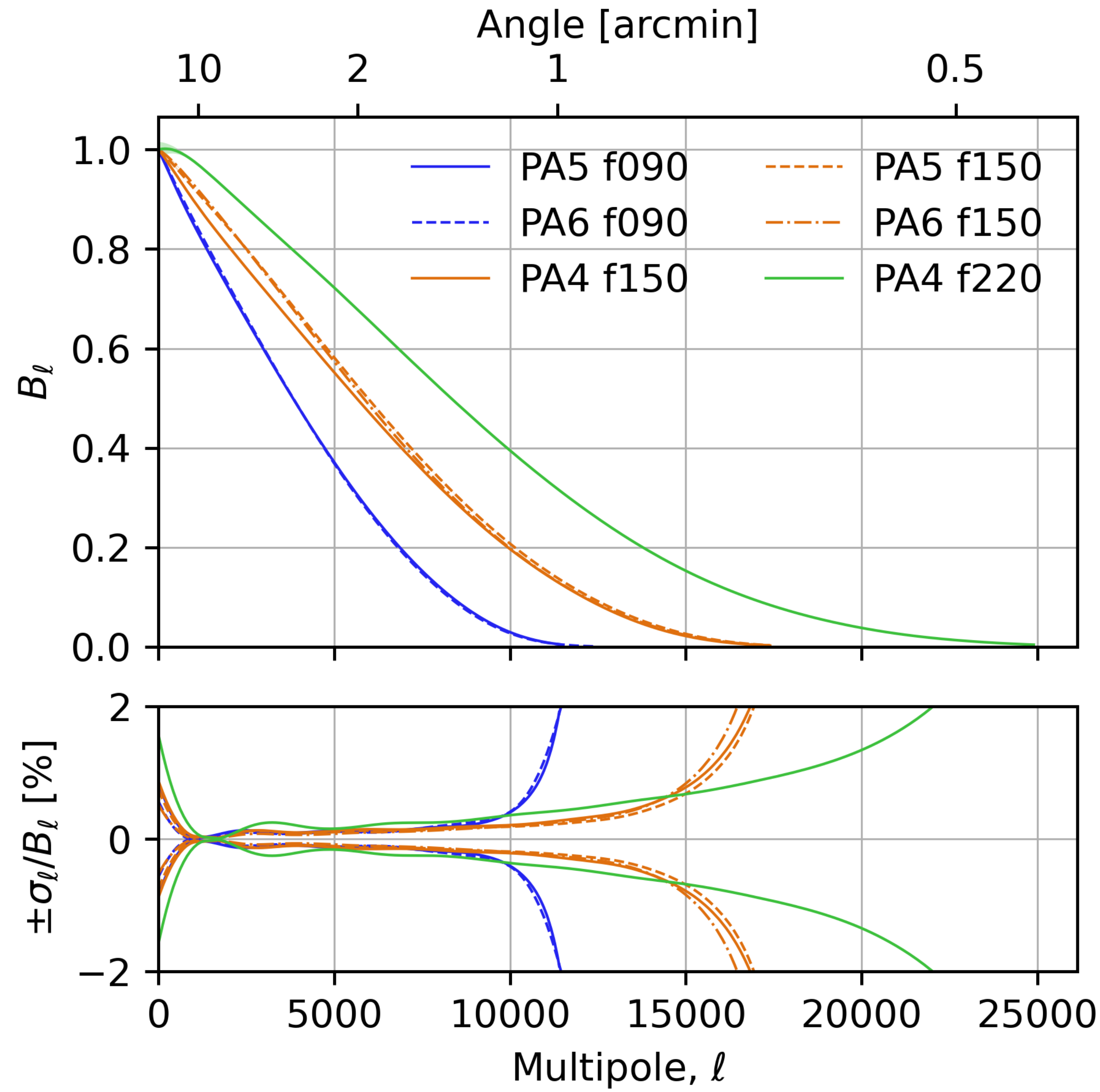
Beam (point spread function) calibration based on observations of Uranus, Saturn, and quasars

Effective resolution: 1-2 arcmin



Co-added Uranus obs. (PA5 f090, 2017-2022, 10’×10’, normalized)



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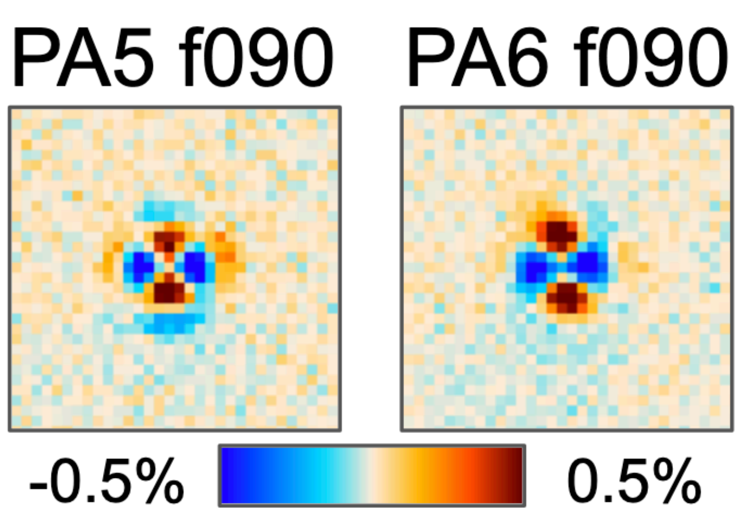
Temp.-to-Pol. Leakage

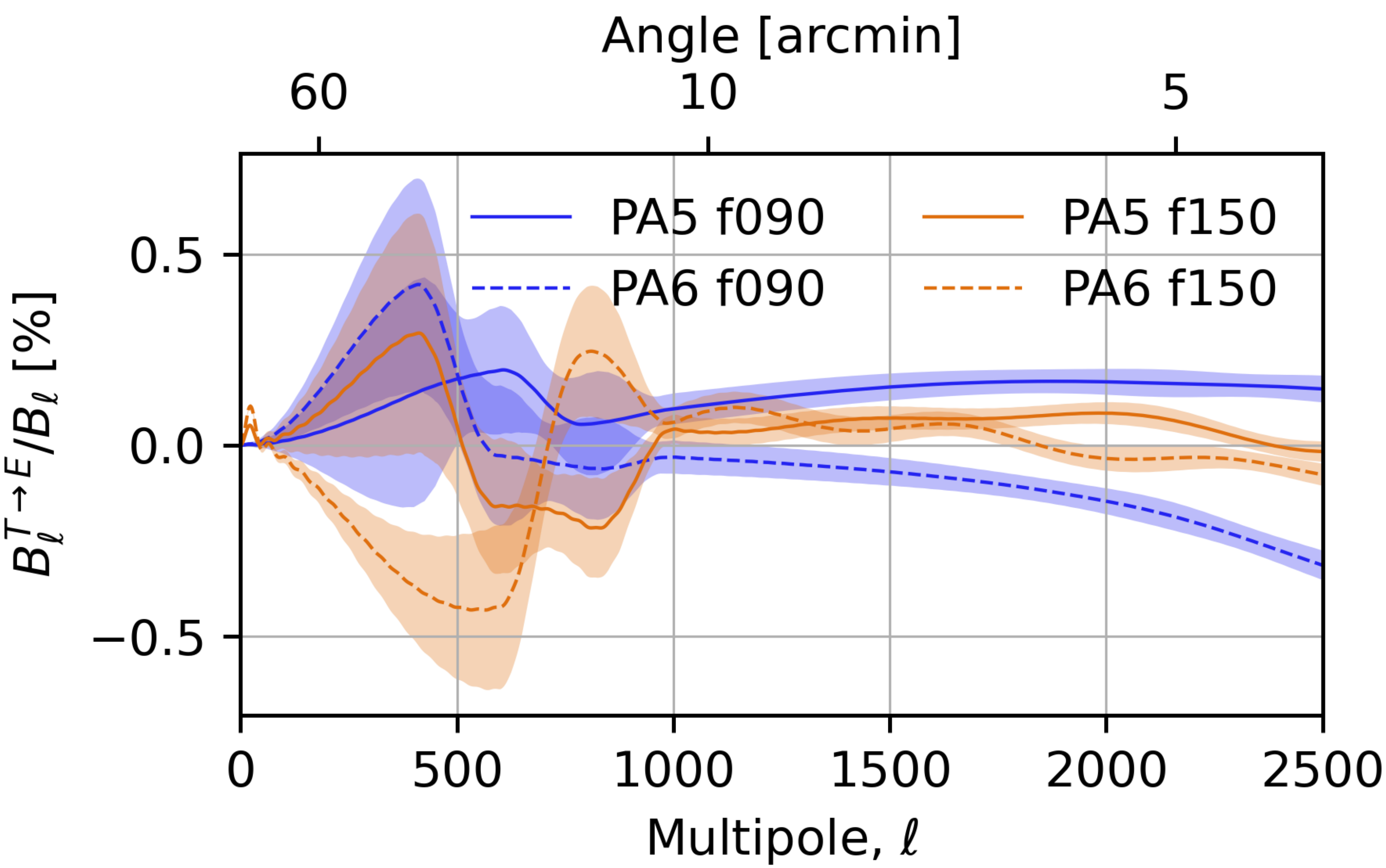
Spurious temperature-to-polarization seen in planet observations

Leakage corrections to the TE power spectra are clearly detectable in null tests

Redundancy from several arrays has been crucial for validation



Spurious polarization in co-added Uranus obs. (Stokes Q, 8’×8’)



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Beam Chromaticity

For the first time, the ACT power spectrum analysis properly takes into account the frequency dependence of the beam (previously considered in ACT DR4 component separation: Madhavacheril, JCH, et al. (2020))

~1 - 10% effect depending on angular scale

Very little impact on cosmological parameters

Significant impact on foreground parameters, such as the thermal Sunyaev-Zel'dovich effect

$$B_\ell^X \propto \int B_\ell(\nu) I^X(\nu) \tau(\nu) \mathrm{d}\nu$$

X : Sky components: CMB, planets, tSZ, etc.

$B_\ell(\nu)$: Beam as function of frequency

$I^X(\nu)$: Spectral energy distribution of sky signal

$\tau(\nu)$: Instrumental frequency passband

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Outlook: Simons Observatory

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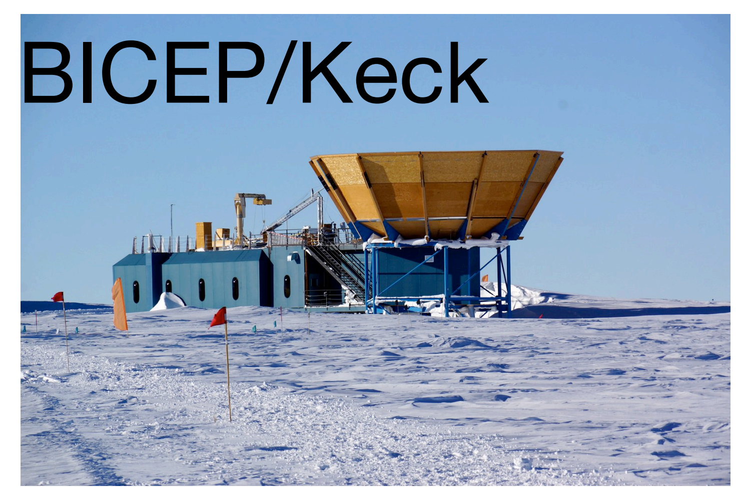
Columbia

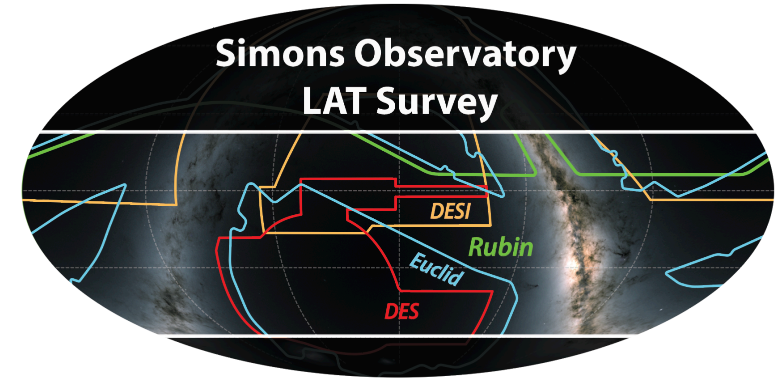
Landscape

Simons Observatory
Small Aperture
Telescopes



Astro2020: "To address the major science questions identified by the Panel on Cosmology, the cosmic microwave background ***(CMB) remains the single most important phenomenon that can be observed*** *… "*

Landscape

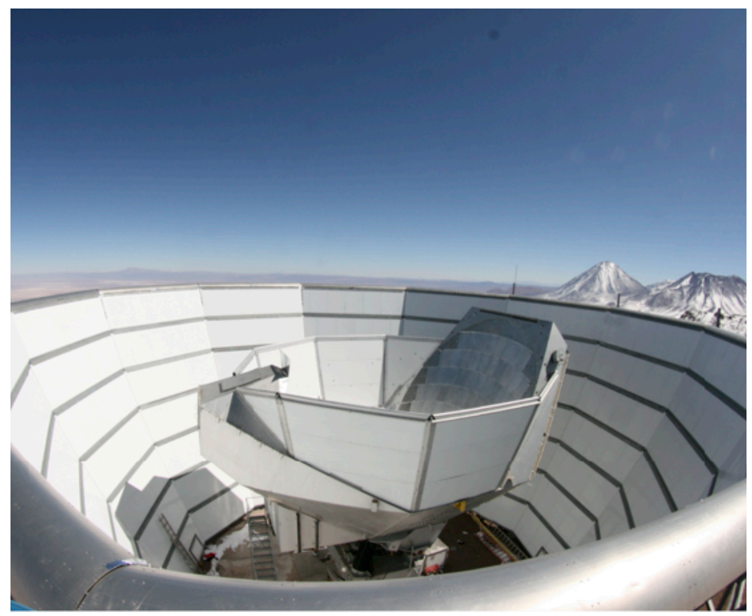


Planck →

Final data 2018/2020
100% sky

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

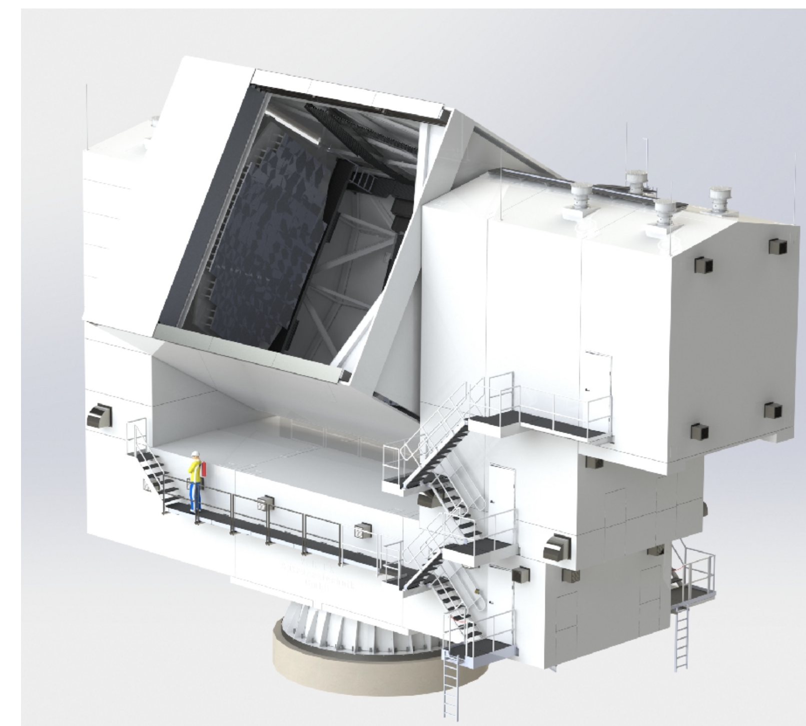
ACT →



Observations through 8/2022
40% sky
Noise ~3 times < Planck
1.4 — 10 mm (5 bands)
1 — 7' resolution

[South Pole Telescope - same timeframe]

SO Large Aperture Telescope



Observations 2024 - ~28
60% sky
Noise ~3 times < ACT
1 — 10 mm (6 bands)
1 — 7' resolution

+ ~6 low-resolution SATs

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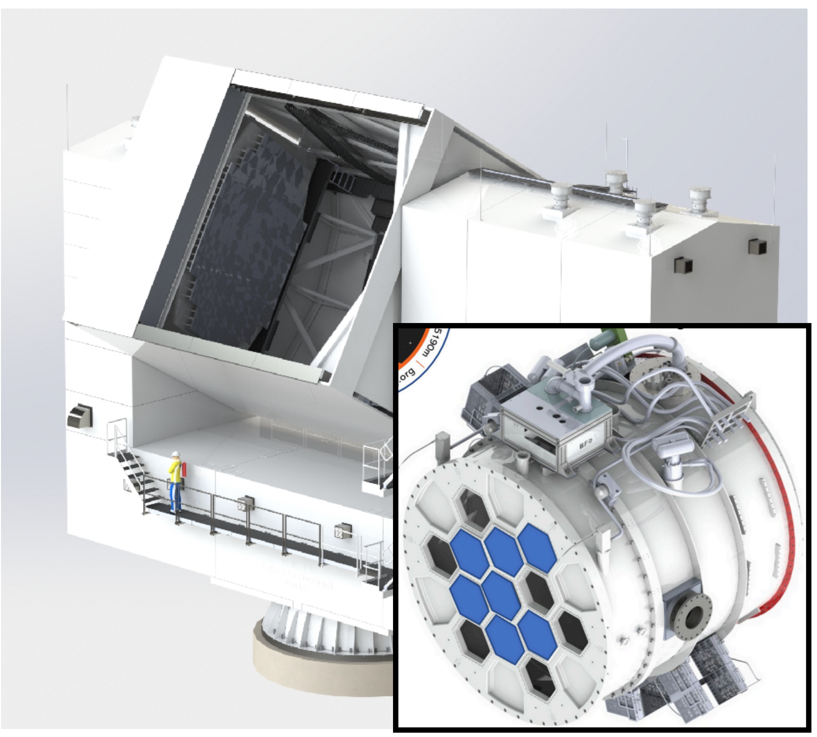
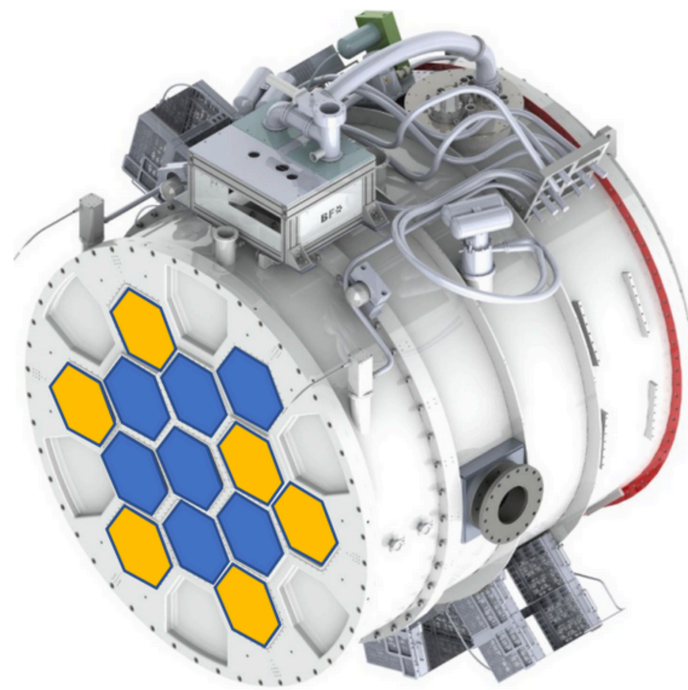
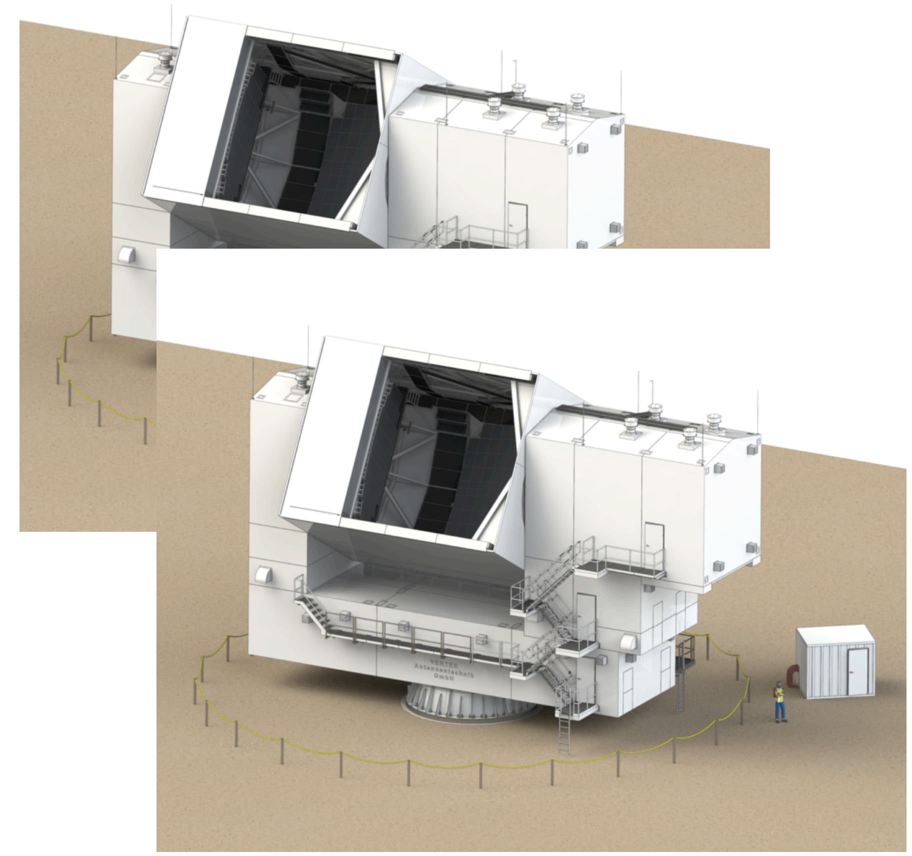
Landscape

SO → Advanced SO → CMB-S4 Large Aperture Telescopes







SO

Observations 2024 - ~28
60% sky
Noise ~3 times < ACT
1 — 10 mm (6 bands)
1 — 7' resolution

Advanced SO

Observations ~2028 - 2034
60% sky
Noise ~1.7 times < SO
1 — 10 mm (6 bands)
1 — 7' resolution

JCH: Co-Project Scientist

CMB-S4

Observations ~2033 - 2040 (TBD)
70% sky
Noise ~2.4 times < Adv. SO
1 — 10 mm (6 bands)
1 — 7' resolution

+ ~9 low-resolution SATs
with additional bands

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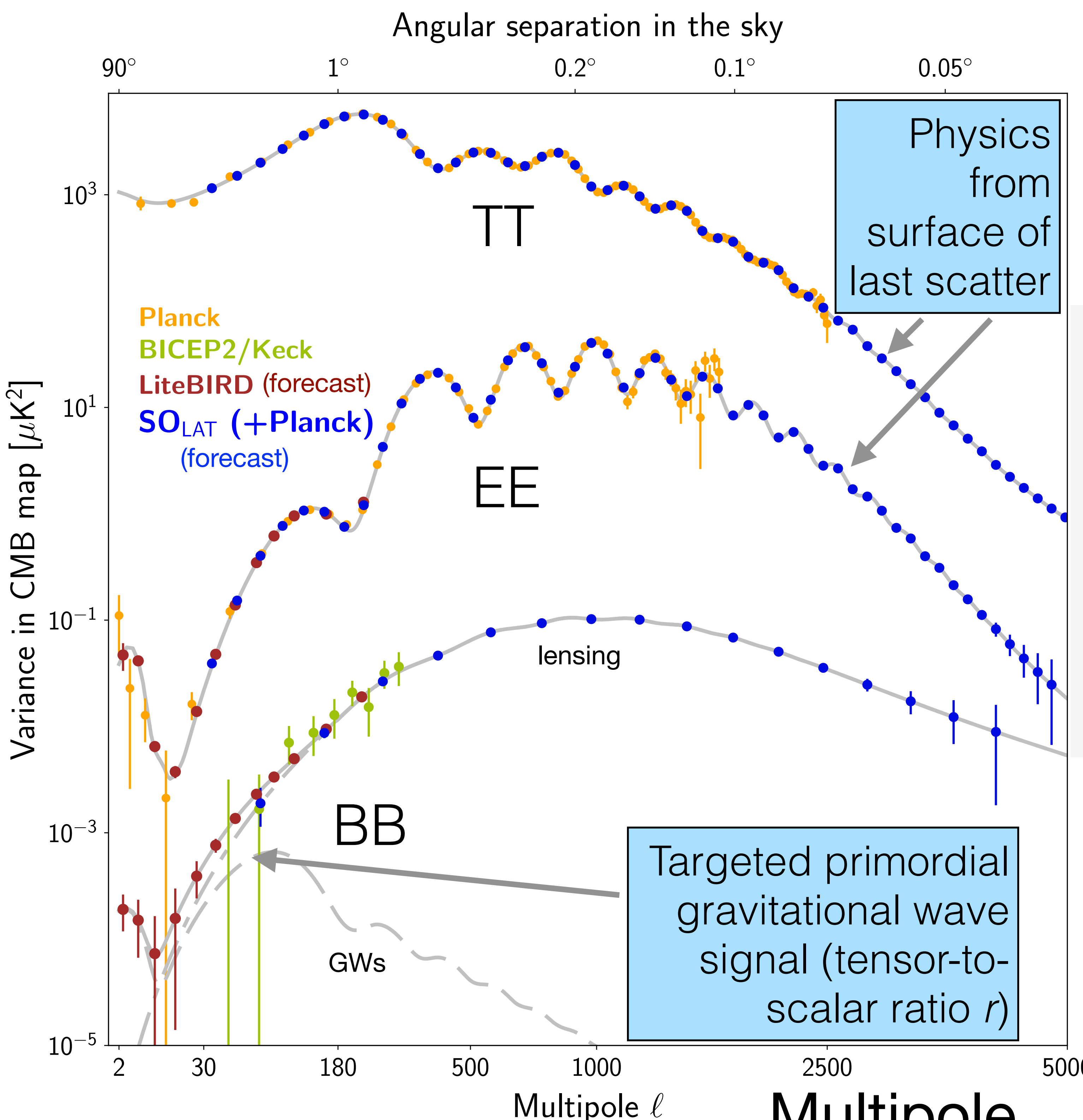
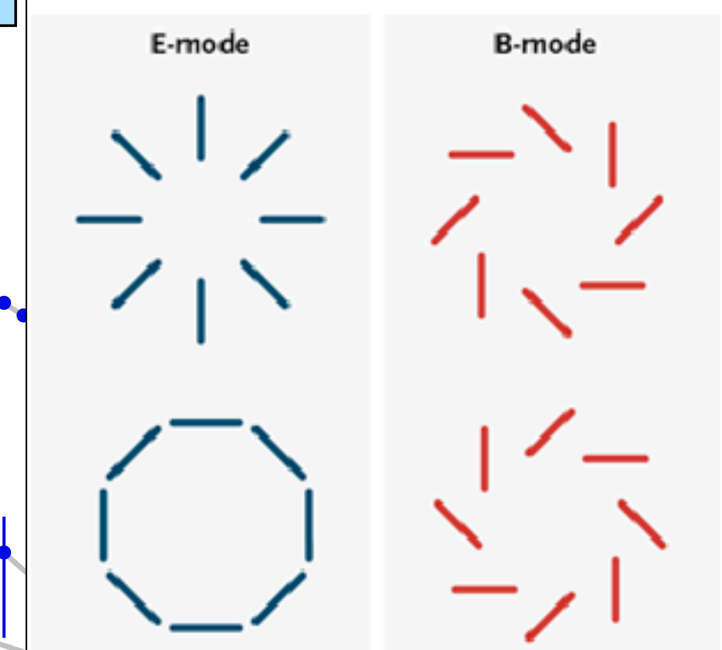
Columbia

Landscape

Angular Power Spectrum



Multipole



SO projection [2034]:
$\sigma(r) \sim 0.0012$

Simons Observatory Collaboration (2025, leads: JCH + Susan Clark)