Constraints on Axion Dark Matter Isocurvature from CMB

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Axion Dark Matter Cosmology

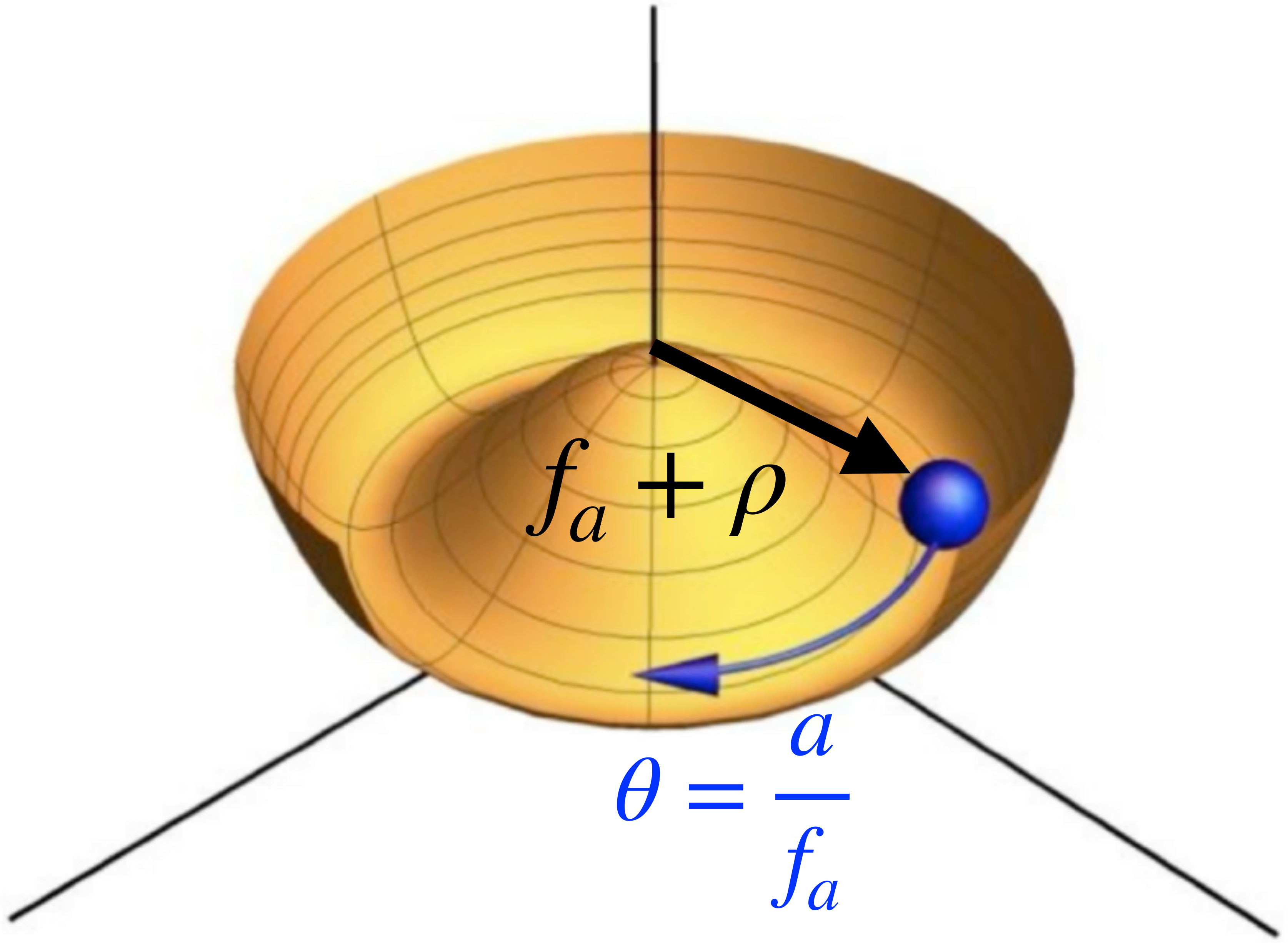
South Pole Telescope

QCD Axion Field

- Peccei Quin (PQ) symmetry broken at energy scale, f_a
- Axion field, a is the goldstone mode of the broken $U(1)_{PQ}$ symmetry.
- Non-perturbative effects "switch-on" at energy scale, $\Lambda_{QCD} << f_a$
- Induces mass for the axion, m_a

PQ field, $\chi = \frac{f_a + \rho}{\sqrt{2}} e^{ia/f_a} = \frac{f_a + \rho}{\sqrt{2}} e^{i\theta}$

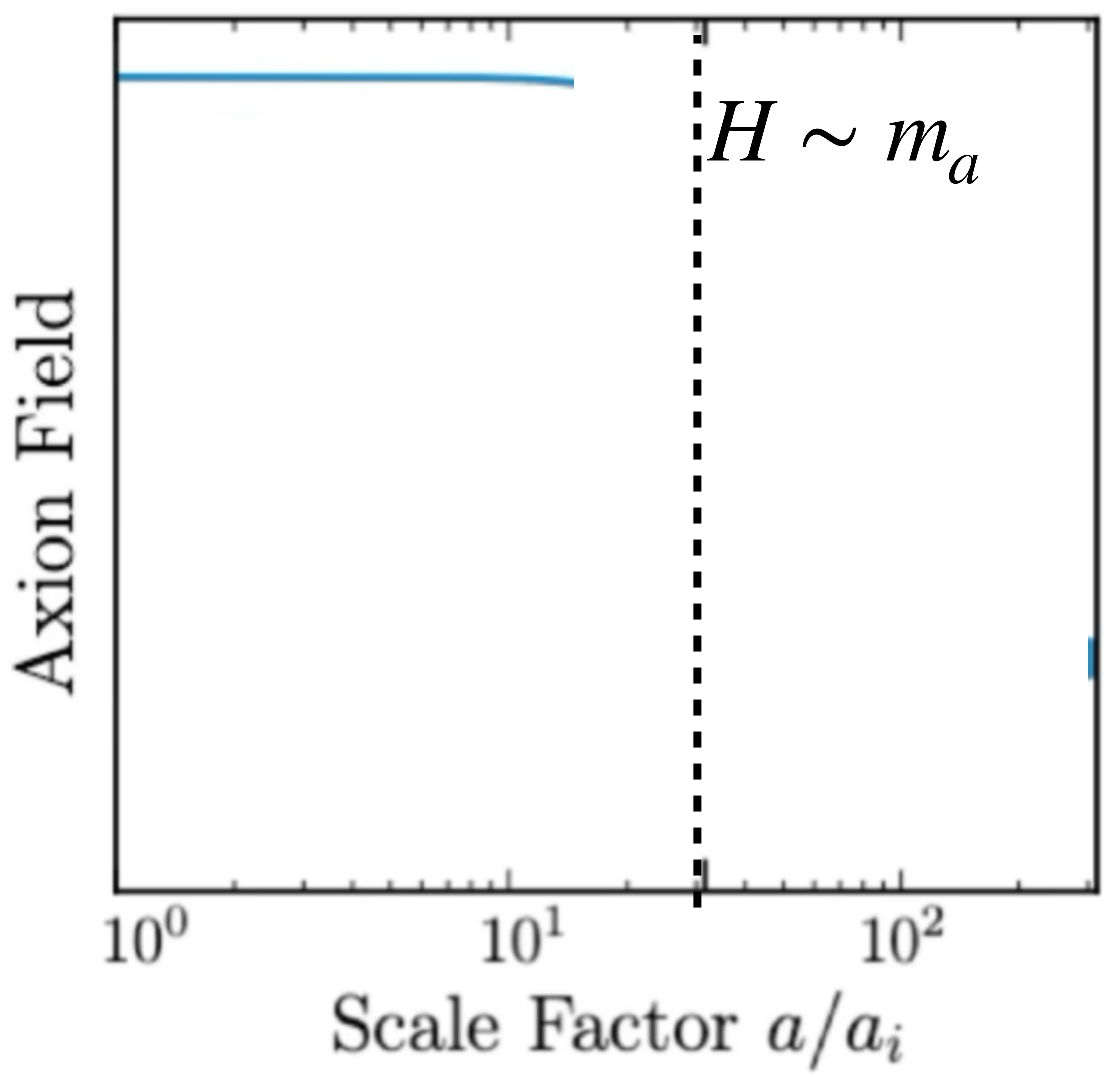
VEV, $< \chi > = \frac{f_a}{\sqrt{2}}$ 4D axion model

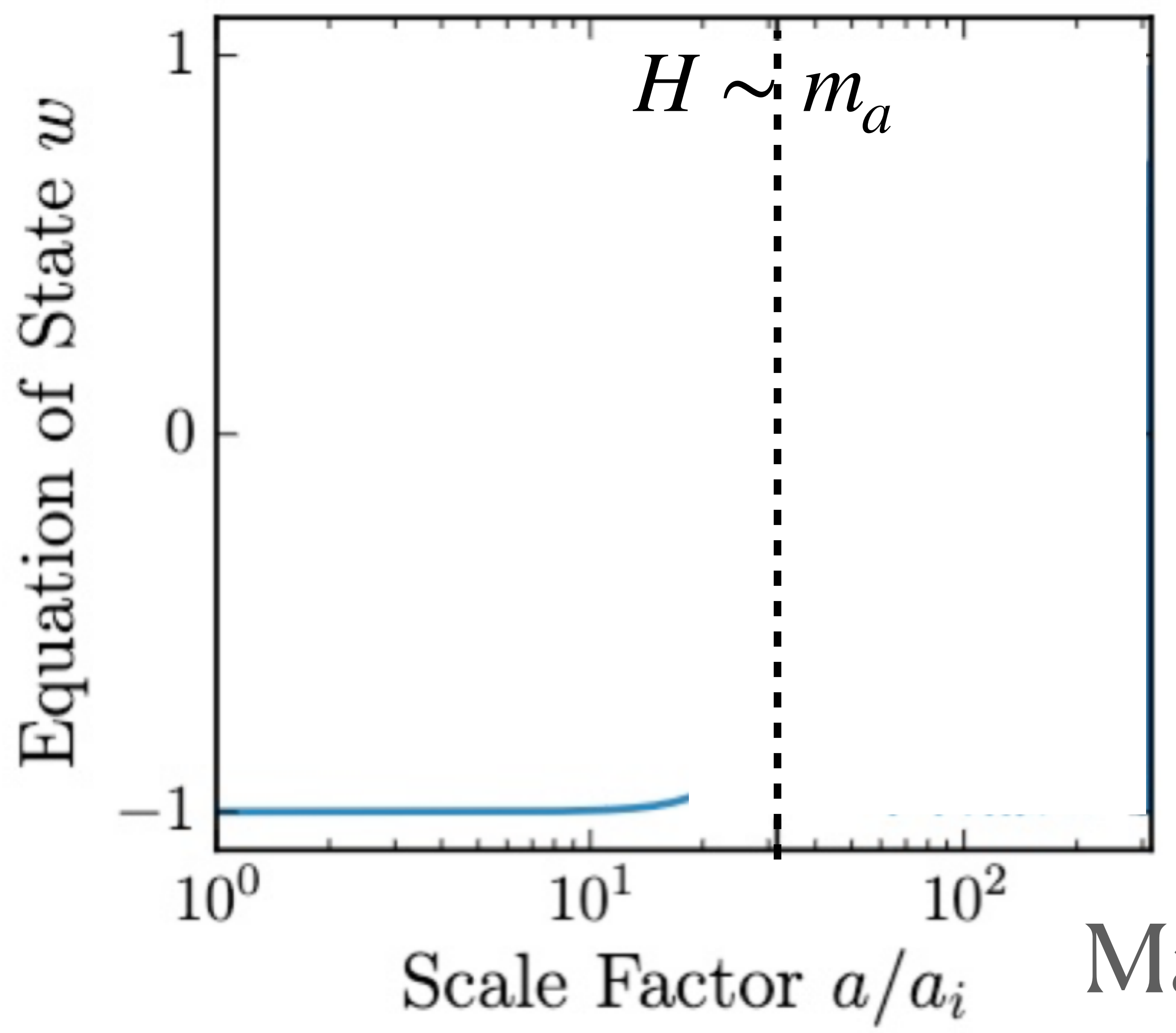


QCD Axion DM

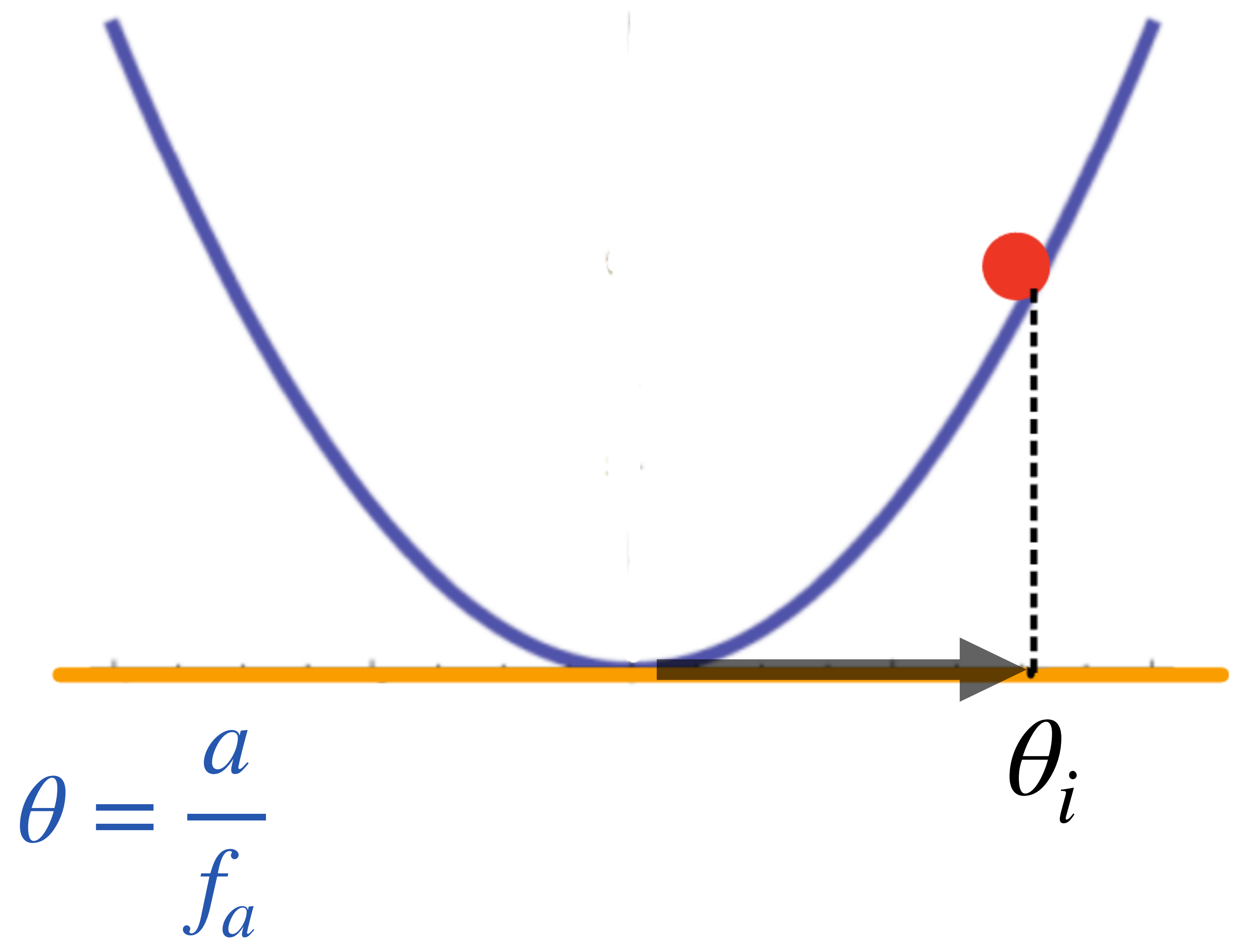
- Pre-inflationary axion: $f_a > H_I/2\pi$
- Initial misalignment angle takes a random value, $\theta_i \in [-\pi, \pi]$

$H_I \longrightarrow$ Hubble scale during inflation





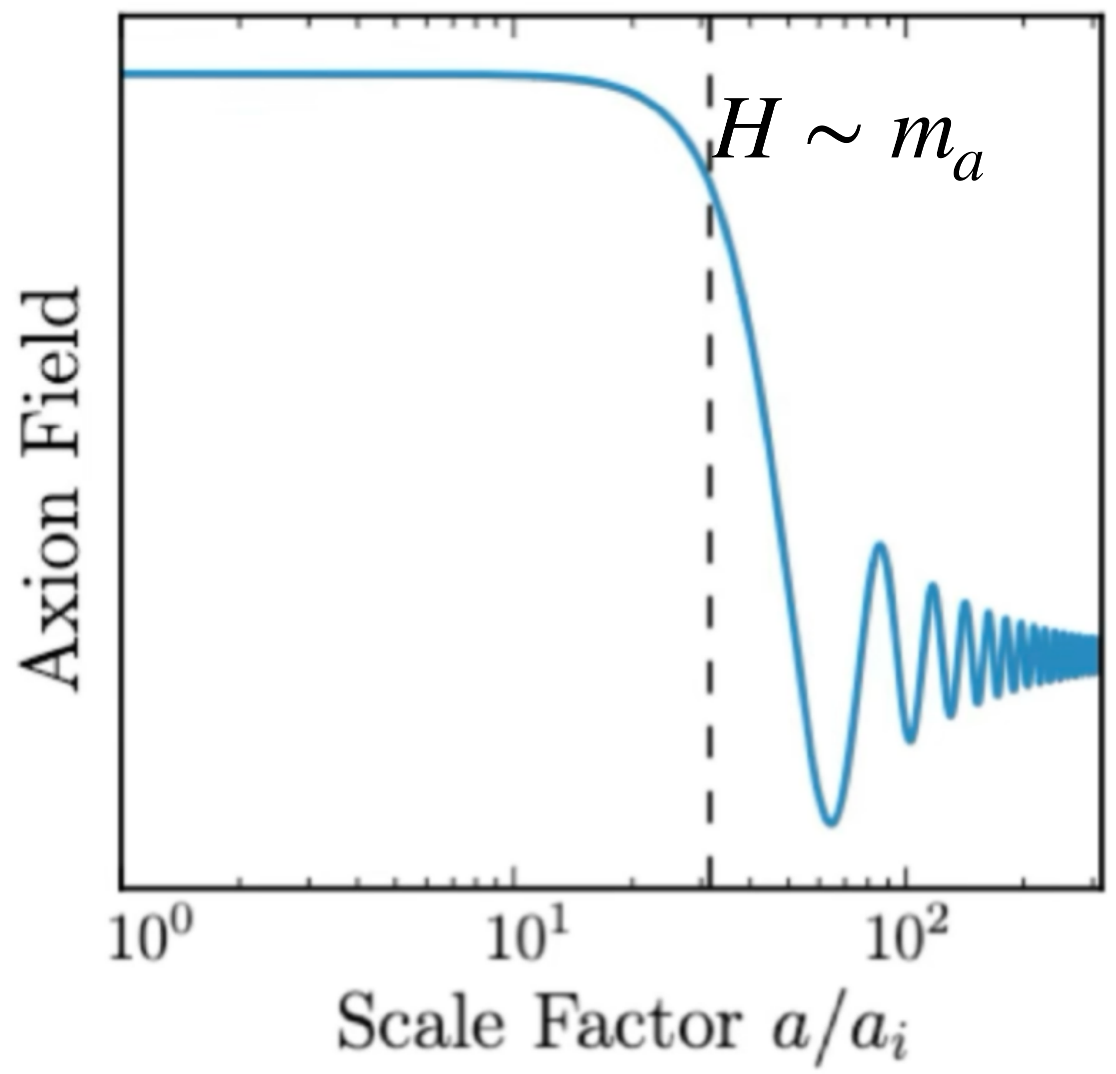
Marsh 2015

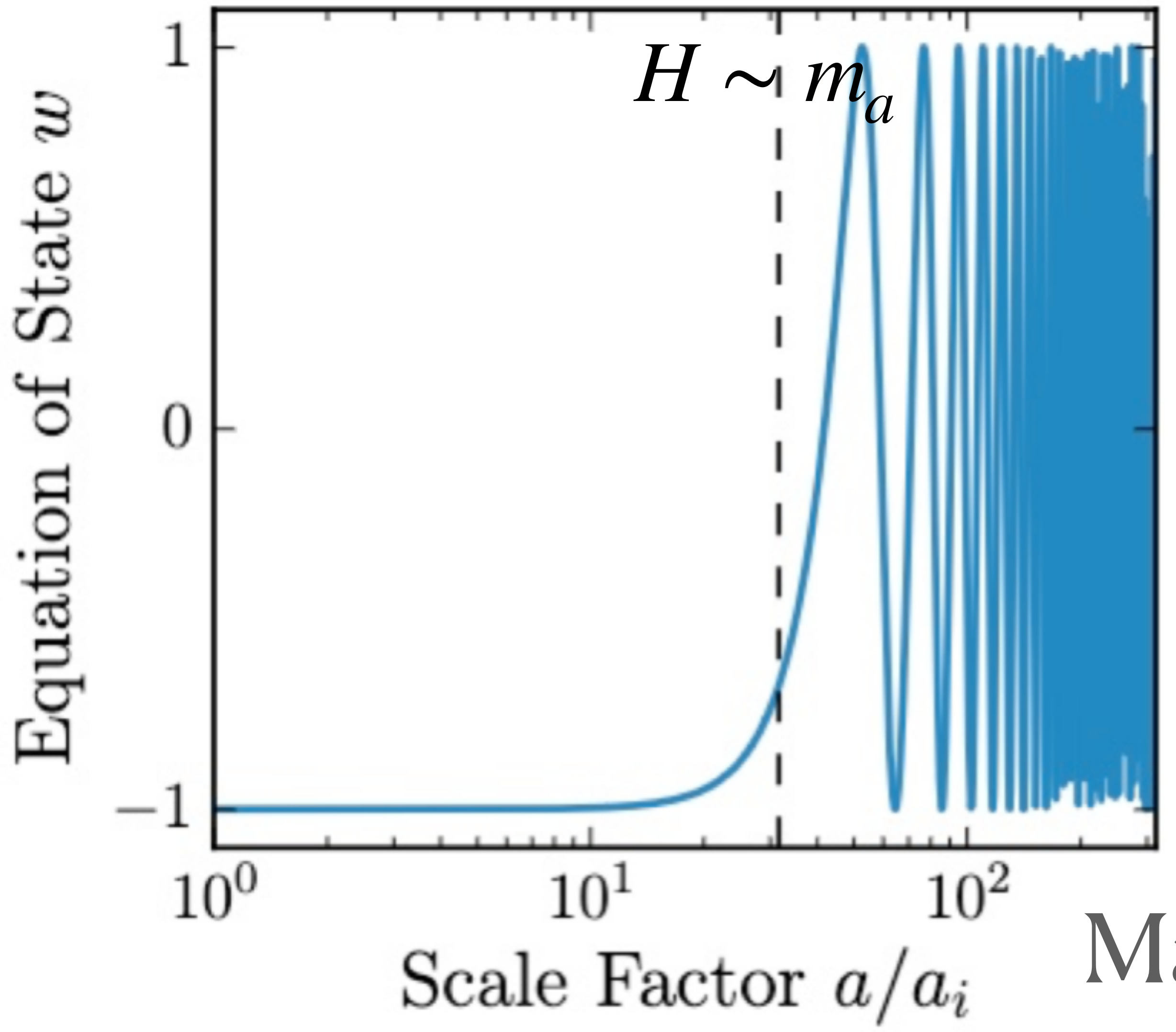


QCD Axion DM

- Pre-inflationary axion: $f_a > H_I/2\pi$
- Initial misalignment angle takes a random value, $\theta_i \in [-\pi, \pi]$
- Axion becomes dynamical at $H \sim m_a$
- For $H << m_a$, axion contributes to DM energy density

$H_I \longrightarrow$ Hubble scale during inflation





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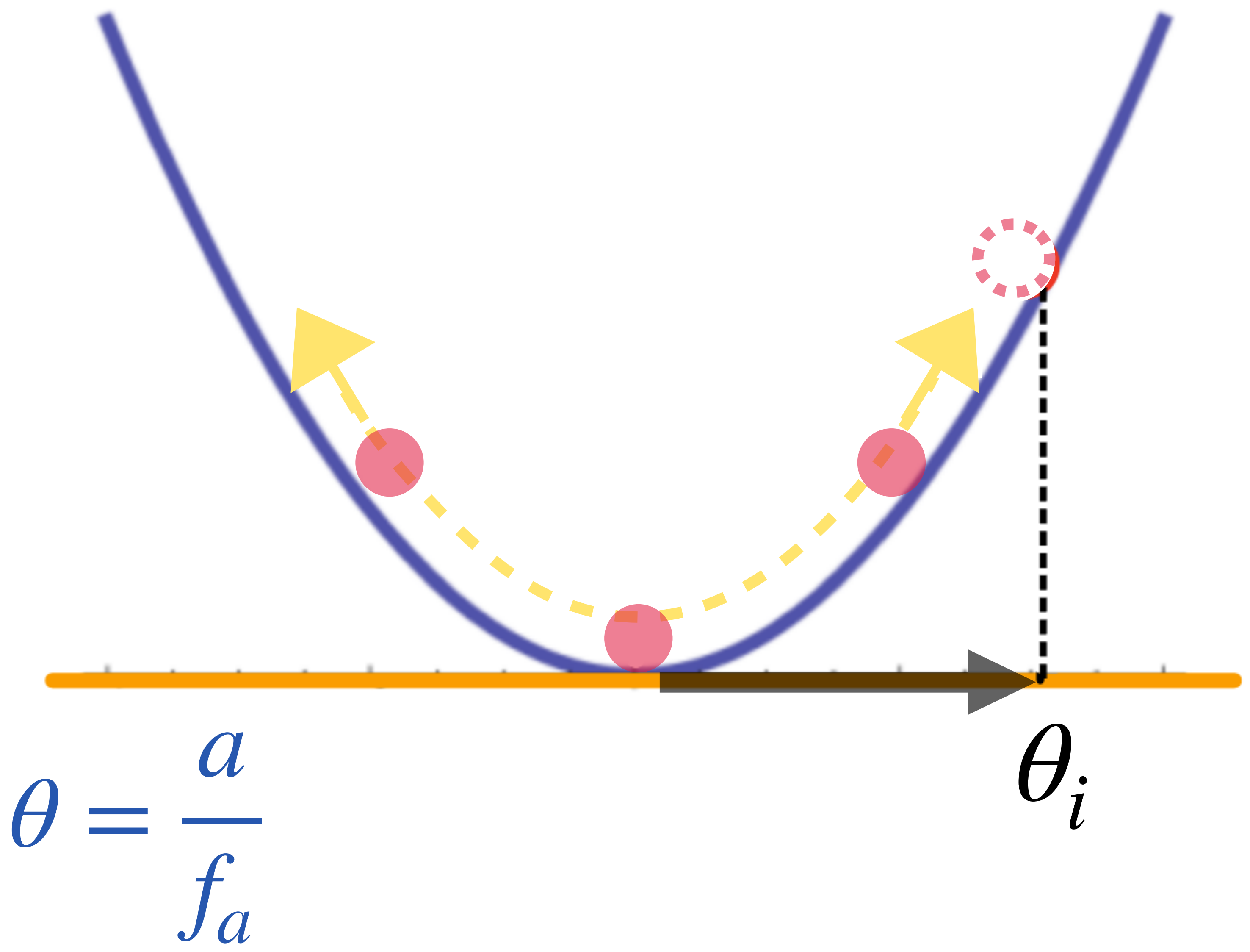

misalignment mechanism

Axion Perturbations

- Axion is light scalar during inflation
- $\delta\theta(\vec{x}, t)$ undergo quantum fluctuations
- At superhorizon co-moving scale, $k << aH$:

$$|\delta\theta_k| \sim \frac{H_I}{f_a\sqrt{2k^3}}$$

- θ is a spectator field during inflation
- $\delta\theta(\bar{x}, t)$ are independent of inflaton perturbation

$$\theta(\vec{x}, t) = \underbrace{\bar{\theta}(t)}_{\text{background field}} + \underbrace{\delta\theta(\vec{x}, t)}_{\text{axion perturbation}}$$

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background field

axion perturbation

- θ is a spectator field during inflation
- $\delta\theta(\bar{x}, t)$ are independent of inflaton perturbation → Isocurvature fluctuations

Axion Isocurvature Perturbations

- Axions contribute to DM later $\Longrightarrow$ $\delta\theta$ sources cold DM isocurvature (CDI)
- CDI primordial power spectrum could be parameterized as:

$$P_{II}(k) = \underbrace{A_I}_{\text{amplitude}} \left(\frac{k}{k_*} \right)^{n_{II}-1}$$

spectral index

characteristic wavenumber

- For minimal QCD axion DM $\rightarrow$ $\underbrace{n_{II} = 1}_{\text{scale-invariant}}$, $A_I = \left(\frac{\gamma H_I}{2\pi f_a} \frac{\partial \ln \Omega_a}{\partial \theta_i} \right)^2$

$$\gamma = \frac{\Omega_a}{\Omega_d}$$

fraction of axion contribution to DM density

- $\partial \ln \Omega_a / \partial \theta_i$ factor due to anharmonic effects (Allali et al 2025, Kobayashi et al 2013)

Data and Methods

South Pole Telescope

Primordial Spectrum Parameterization

$$P_{XX}(k) = \exp\left[\left(\frac{\ln(k) - \ln(k_2)}{\ln(k_1) - \ln(k_2)}\right)\ln\left(P_{XX}^{(1)}\right) + \left(\frac{\ln(k) - \ln(k_1)}{\ln(k_2) - \ln(k_1)}\right)\ln\left(P_{XX}^{(2)}\right)\right]$$

power spectrum at scale k_1

power spectrum at scale k_2

$$P_{XX}(k) = A_X\left(\frac{k}{k_*}\right)^{n_{XX}-1}$$

$X = \{R, I\}$

$R =$ curvature perturbation

$I =$ isocurvature perturbation

reference scales:

$k_1 = 0.002\ \mathrm{Mpc}^{-1} \implies \ell \sim 28$

$k_2 = 0.1\ \mathrm{Mpc}^{-1} \implies \ell \sim 1400$

$k_* = 0.05\ \mathrm{Mpc}^{-1} \implies \sim \ell \sim 700$

CDI Templates

- Free CDI amplitude and spectral index, $\{n_{II}, A_I\} \iff \{P_{II}^{(1)}, P_{II}^{(2)}\}$ free

- Free CDI amplitude, fixed-spectral index $\iff P_{II}^{(1)}$ free
  - Red-tilted spectrum, $n_{II} = 0$
  - Flat spectrum, $n_{II} = 1 \longrightarrow$ minimal QCD axion DM
  - Blue-tilted spectrum, $n_{II} = \{2,\ 3\} \longrightarrow$ supersymmetric PQ model with a Hubble induced mass term

Spectral tilt depends on the dynamics of the PQ field during inflation

(Kasuya et al 2009)

f_a gets promoted to a field, starts with a high value and then decays to settle into a constant value

CMB Dataset

- *Planck*

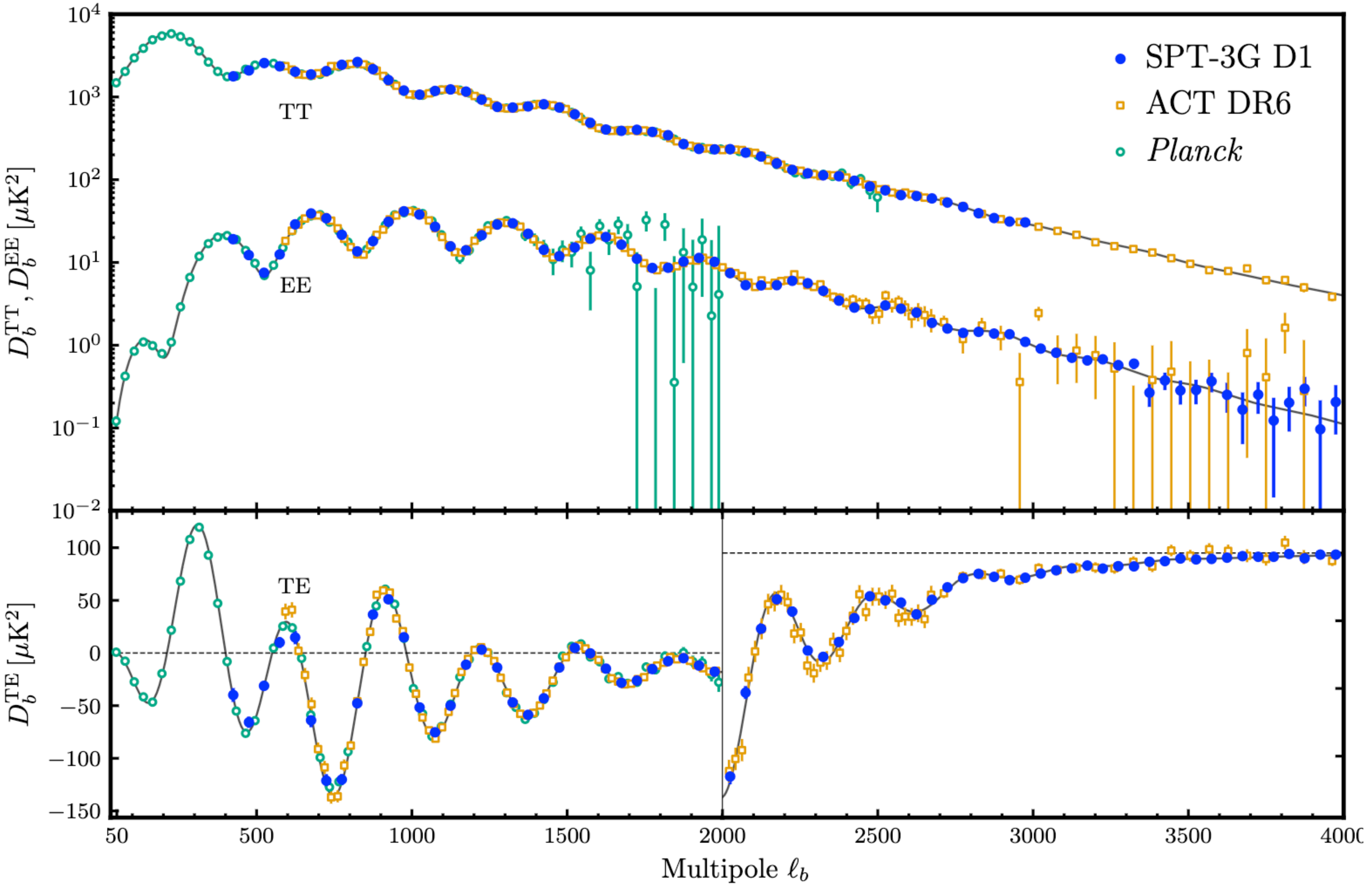
  TT $\rightarrow \ell < 2500$
  TE/EE $\rightarrow \ell < 2000$

- South Pole Telescope (SPT-3G D1)

  TT $\rightarrow \ell \in [400, 3000]$
  TE/EE $\rightarrow \ell \in [400, 4000]$

- Atacama Cosmology Telescope (ACT DR6)

  TT/TE/EE $\rightarrow \ell \in [600, 8500]$



Camphuis et al (SPT-3G Collaboration) 2025

Data Combinations

- *Planck*

$$\text{TT} \rightarrow \ell < 2500$$
$$\text{TE/EE} \rightarrow \ell < 2000$$

- P-ACT = *Planck* + ACT

	Planck	ACT
TT	$\ell < 1000$	$600 < \ell < 8500$
TE/EE	$\ell < 600$	$600 < \ell < 8500$

- P-SPT = *Planck* + SPT

	Planck	SPT
TT	$\ell < 2000$	$1200 < \ell < 4000$
TE/EE	$\ell < 1200$	$1200 < \ell < 3000$

Data Combinations

- *Planck*

$$\text{TT} \rightarrow \ell < 2500$$
$$\text{TE/EE} \rightarrow \ell < 2000$$

- P-ACT = *Planck* + ACT

	Planck	ACT
TT	$\boxed{\ell < 1000}$	$\boxed{600 < \ell < 8500}$
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- P-SPT = *Planck* + SPT

	Planck	SPT
TT	$\boxed{\ell < 2000}$	$\boxed{1200 < \ell < 4000}$
TE/EE	$\ell < 1200$	$1200 < \ell < 3000$

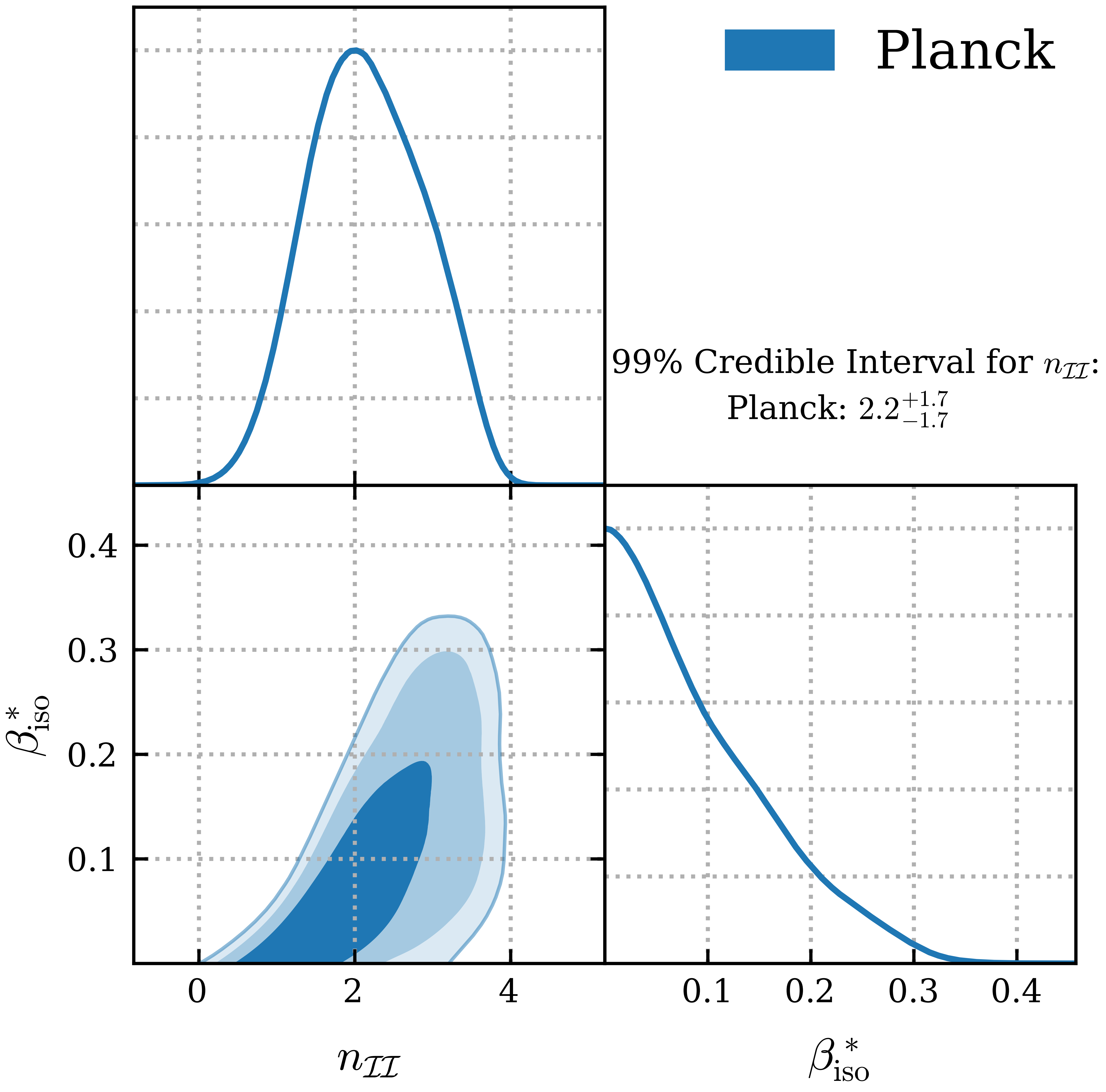
Results: Constraints on CDI Spectra

South Pole Telescope

Results : Free n_{II}

$$\beta^{*}_{\rm iso} = \left.\frac{\mathcal{P}_{\mathcal{II}}}{\mathcal{P}_{\mathcal{II}}+\mathcal{P}_{\mathcal{RR}}}\right|_{k=k_*}$$

- *Planck:* larger ℓ unconstrained region leads to blue-tilted spectrum



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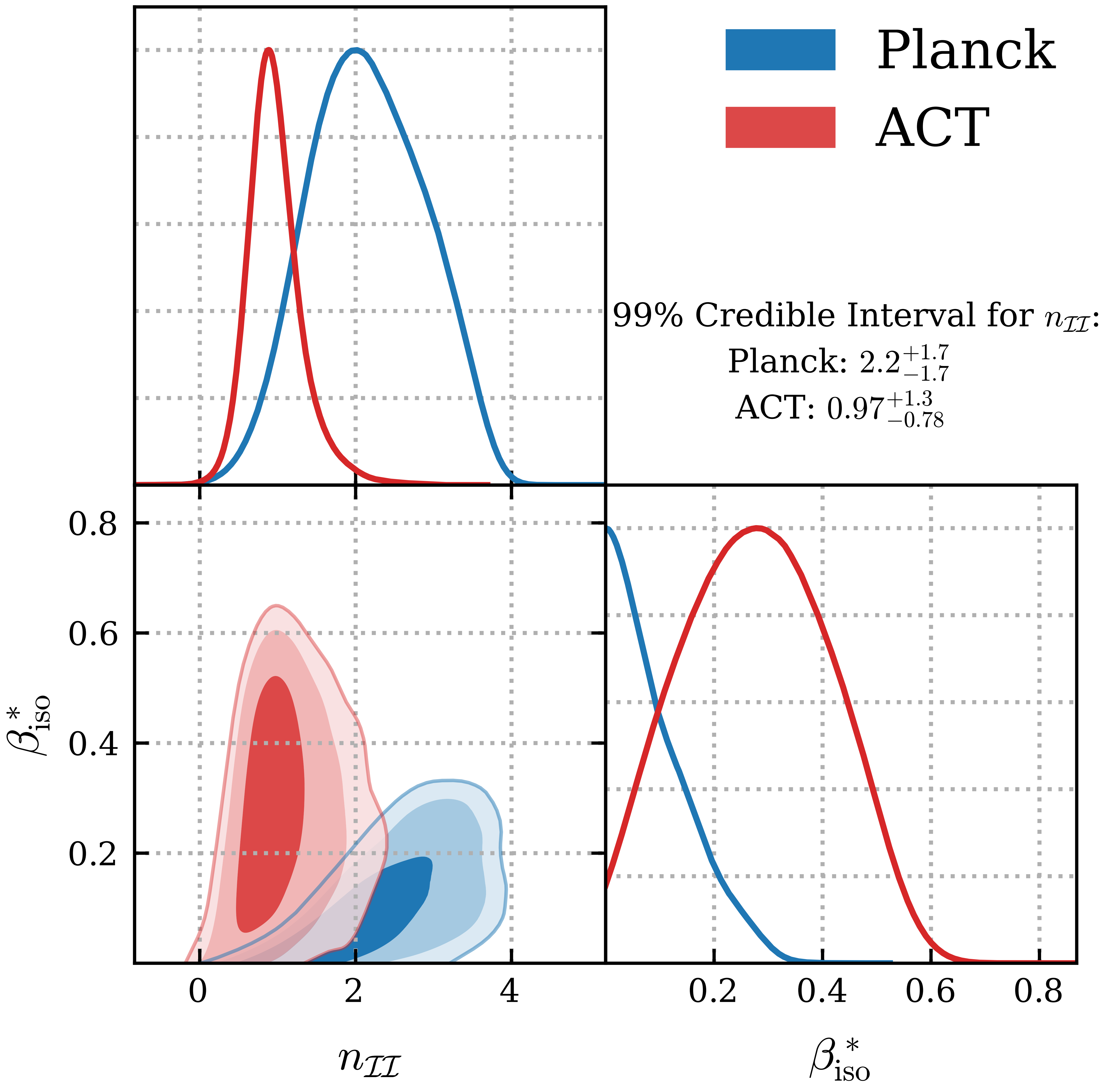
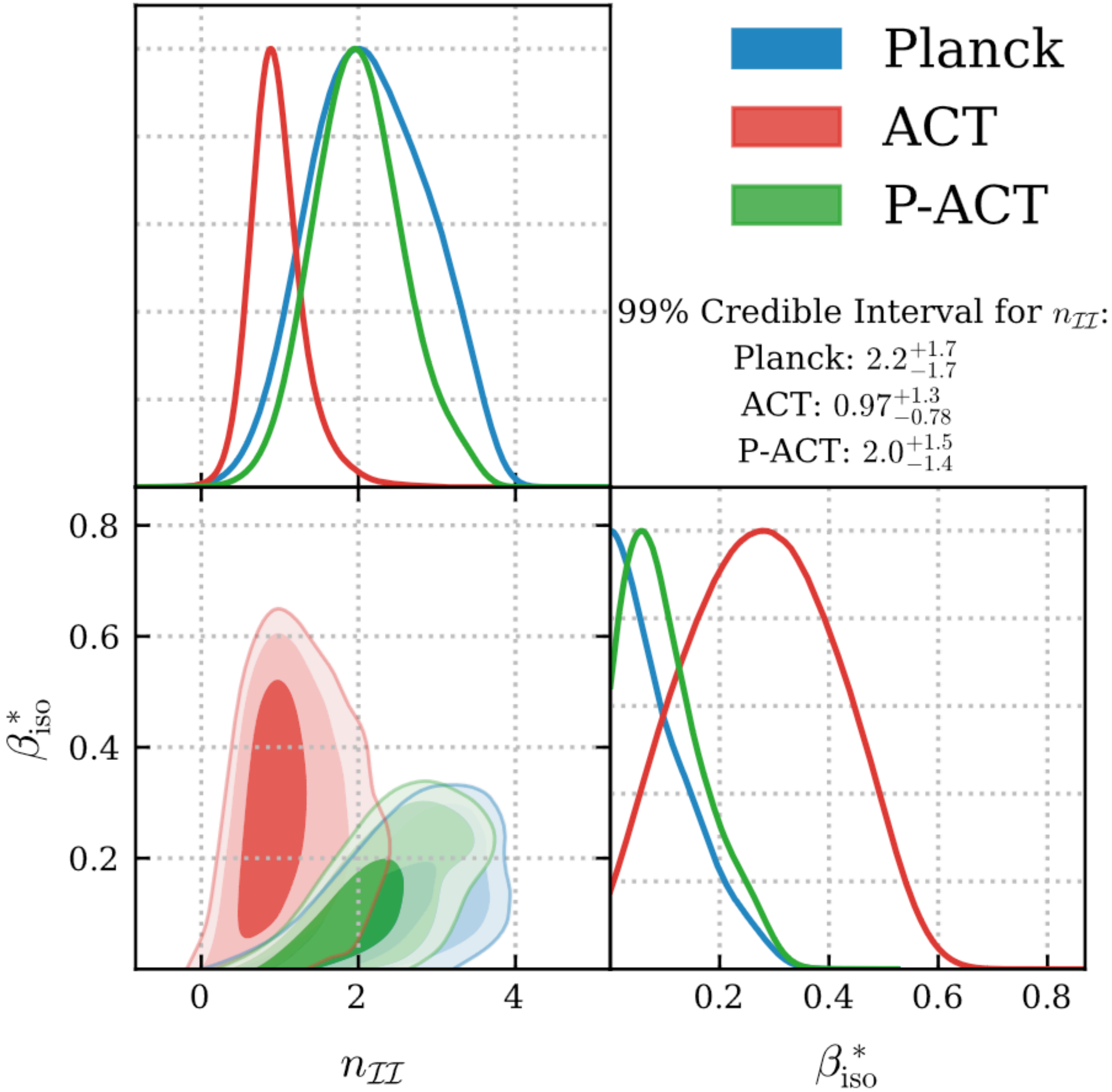
- ACT: smaller ℓ unconstrained region leads to red-tilted spectrum



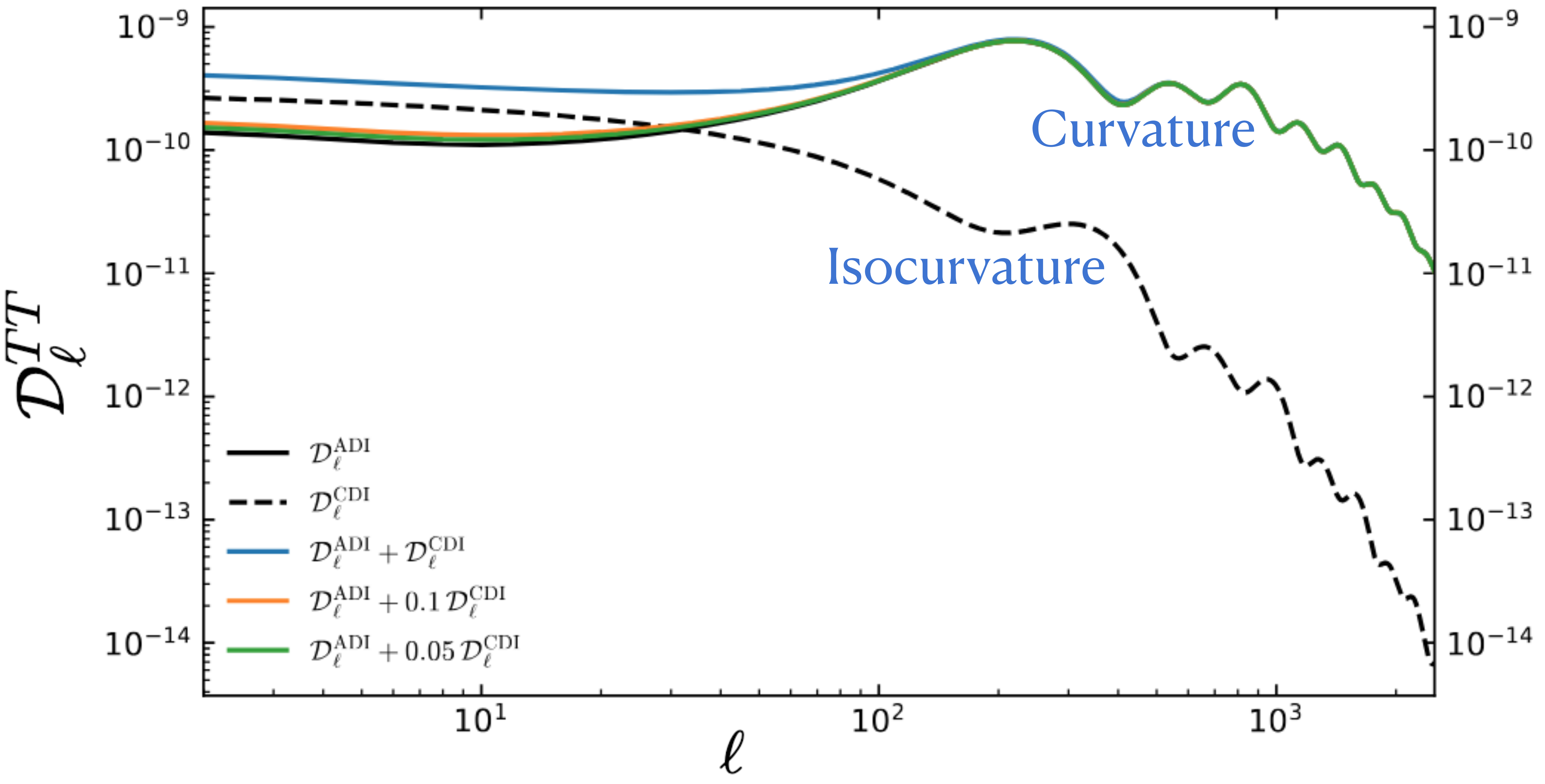
Results : Free n_{II}

$$\beta^*_{\rm iso} = \left.\frac{\mathcal{P}_{\mathcal{II}}}{\mathcal{P}_{\mathcal{II}}+\mathcal{P}_{\mathcal{RR}}}\right|_{k=k_*}$$

- *Planck:* larger ℓ unconstrained region leads to blue-tilted spectrum
- ACT: smaller ℓ unconstrained region leads to red-tilted spectrum
- P-ACT:
  1) Moderate improvement in the constraint on the spectral index, n_{II}
  2) Tilt is closer to *Planck*



CDI Imprint on the CMB



- CDI decays rapidly for smaller scales
- Lower ℓ has more constraining power than higher ℓ for CDI

Theoretical Implications

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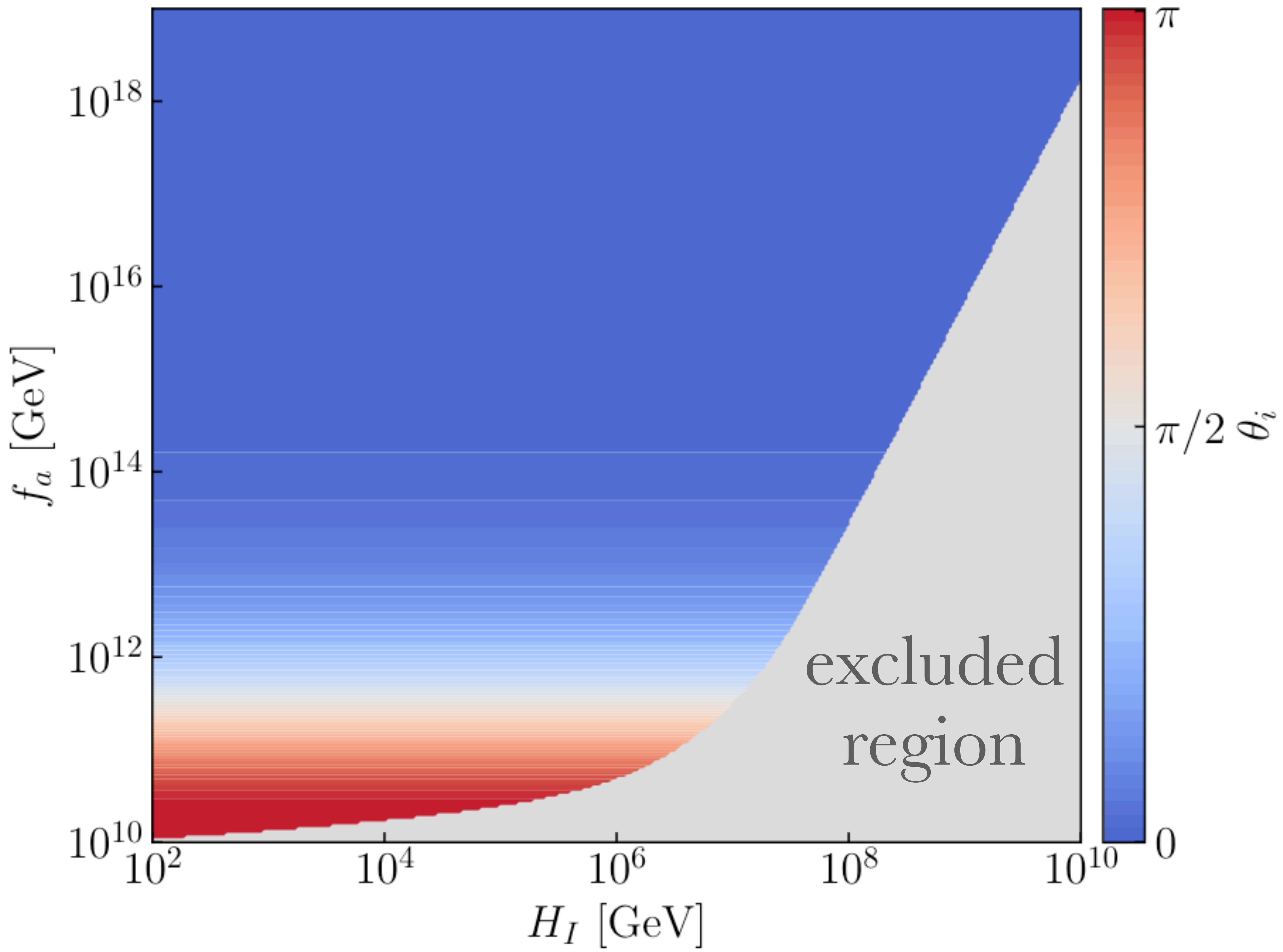
QCD Axion DM

- Assuming DM entirely consists of QCD axion
- For natural $\theta_i \sim 1, H_I \lesssim 10^7$ GeV
- H_I bounds even stronger for higher θ_i



QCD Axion DM

- Assuming DM entirely consists of QCD DM
- For natural $\theta_i \sim 1, H_I \lesssim 10^7$ GeV
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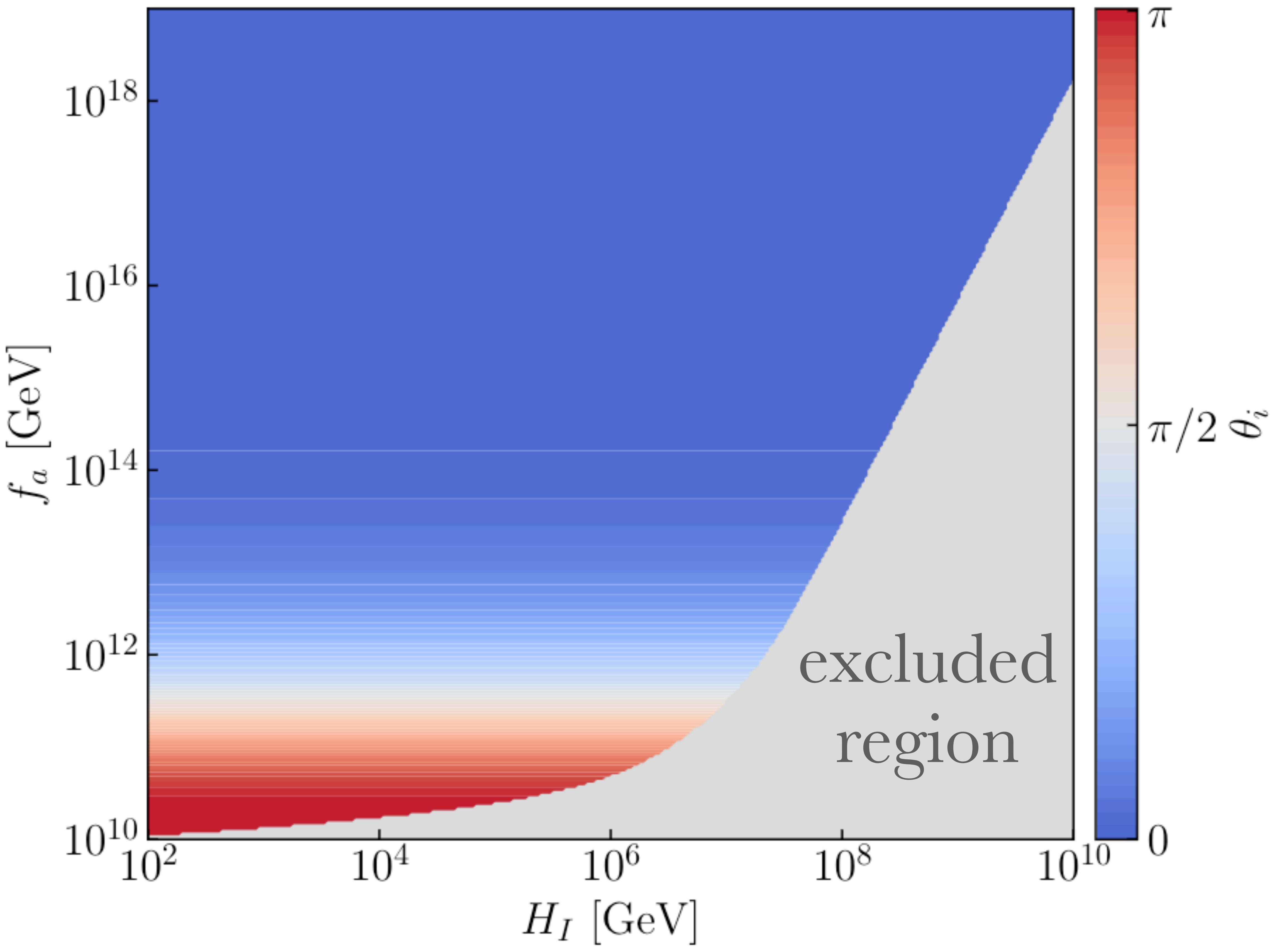
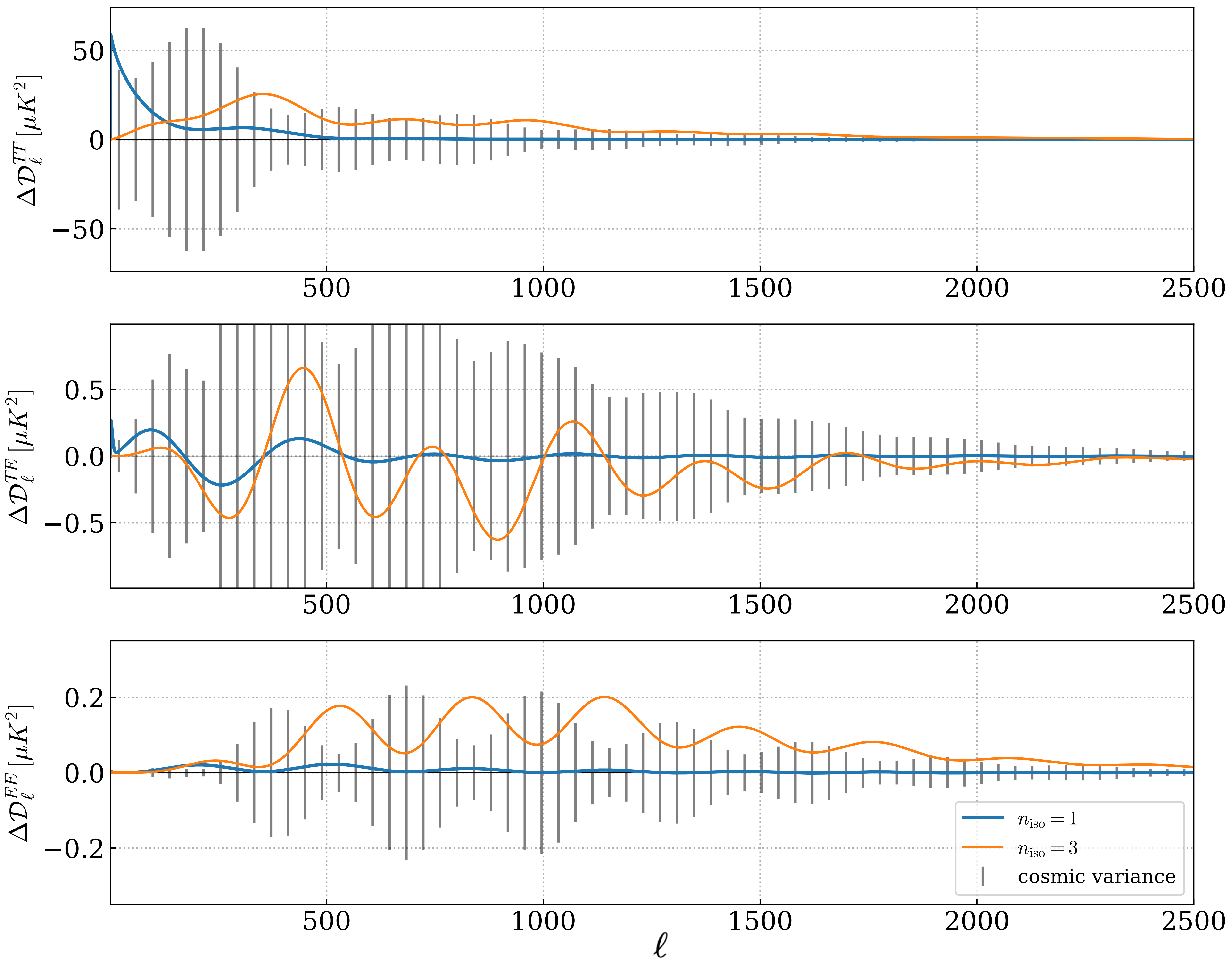
QCD axion DM isocurvature problem

- Work out parameter space for axion DM models with blue-tilted CDI



Future Improvements



- Smaller uncertainties of future CMB measurements (i.e. polarization) can potentially improve constrains for blue-tilted CDI models.

Summary

- Quantum fluctuations in axion perturbations sources CDI initial conditions.
- Constrain CDI using CMB dataset from *Planck*, ACT and SPT.
- Moderate improvement in the CDI spectral index constraint.
- Studied theoretical implications of axion DM models.

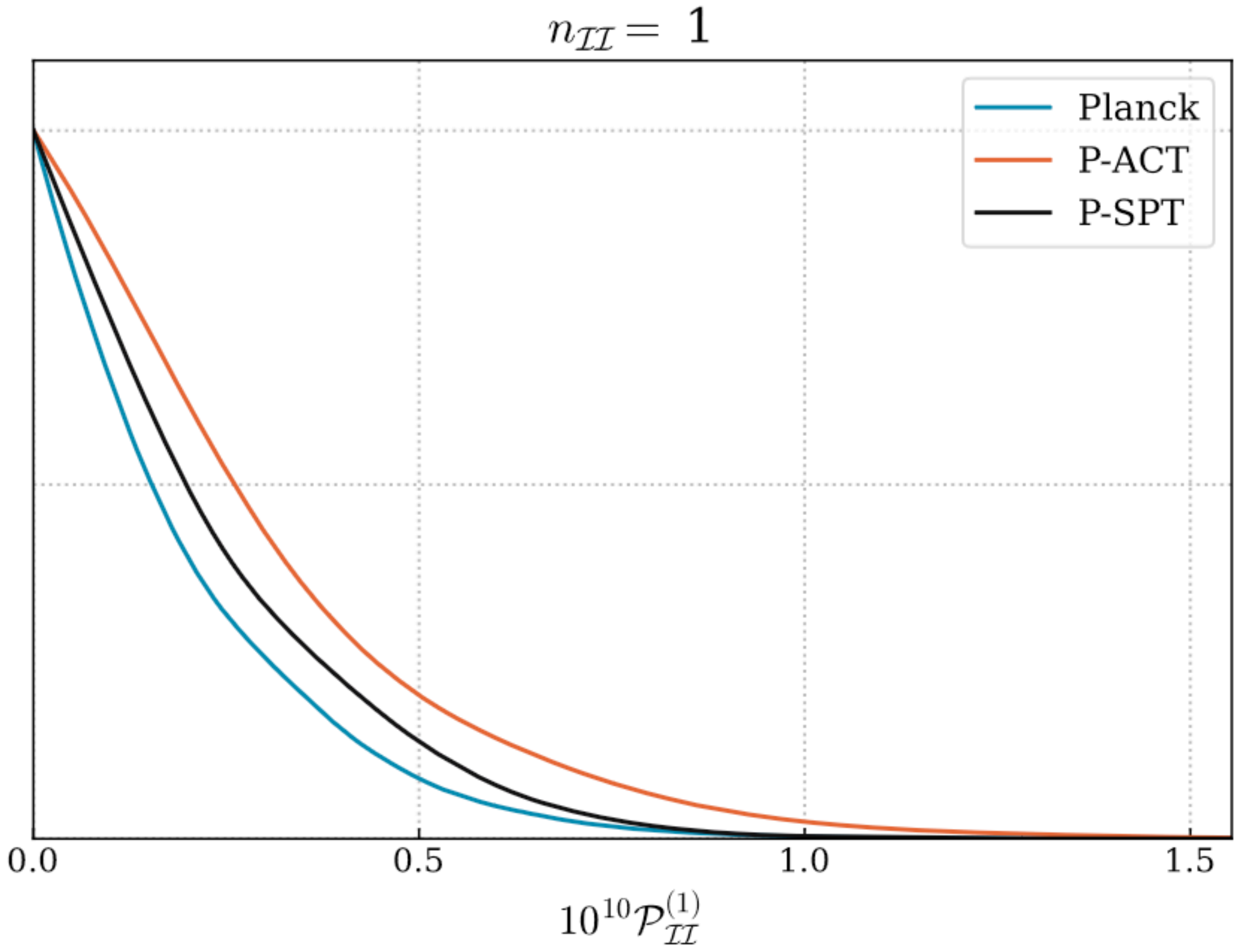
Thank You!
Questions?

South Pole Telescope

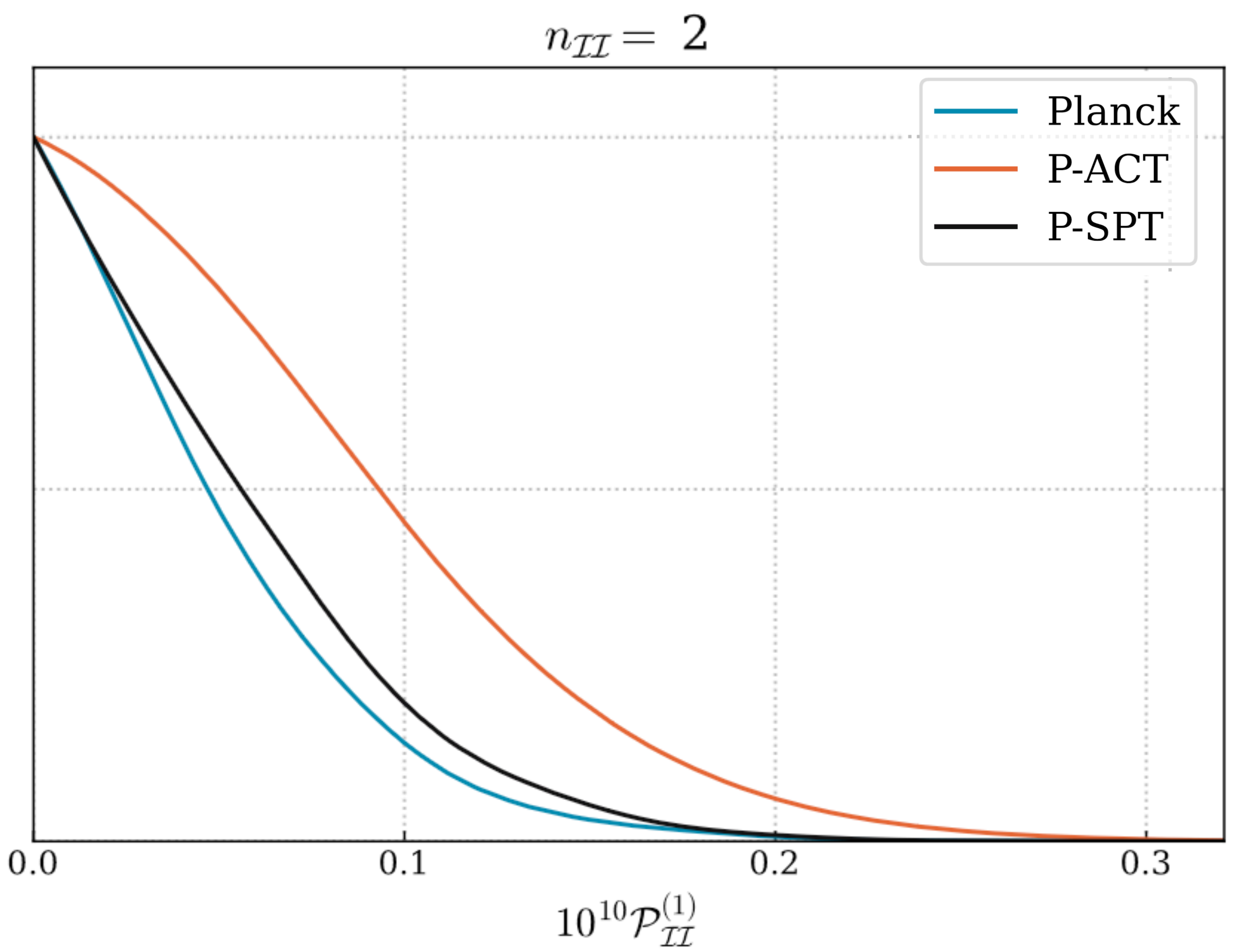
Backup Slides

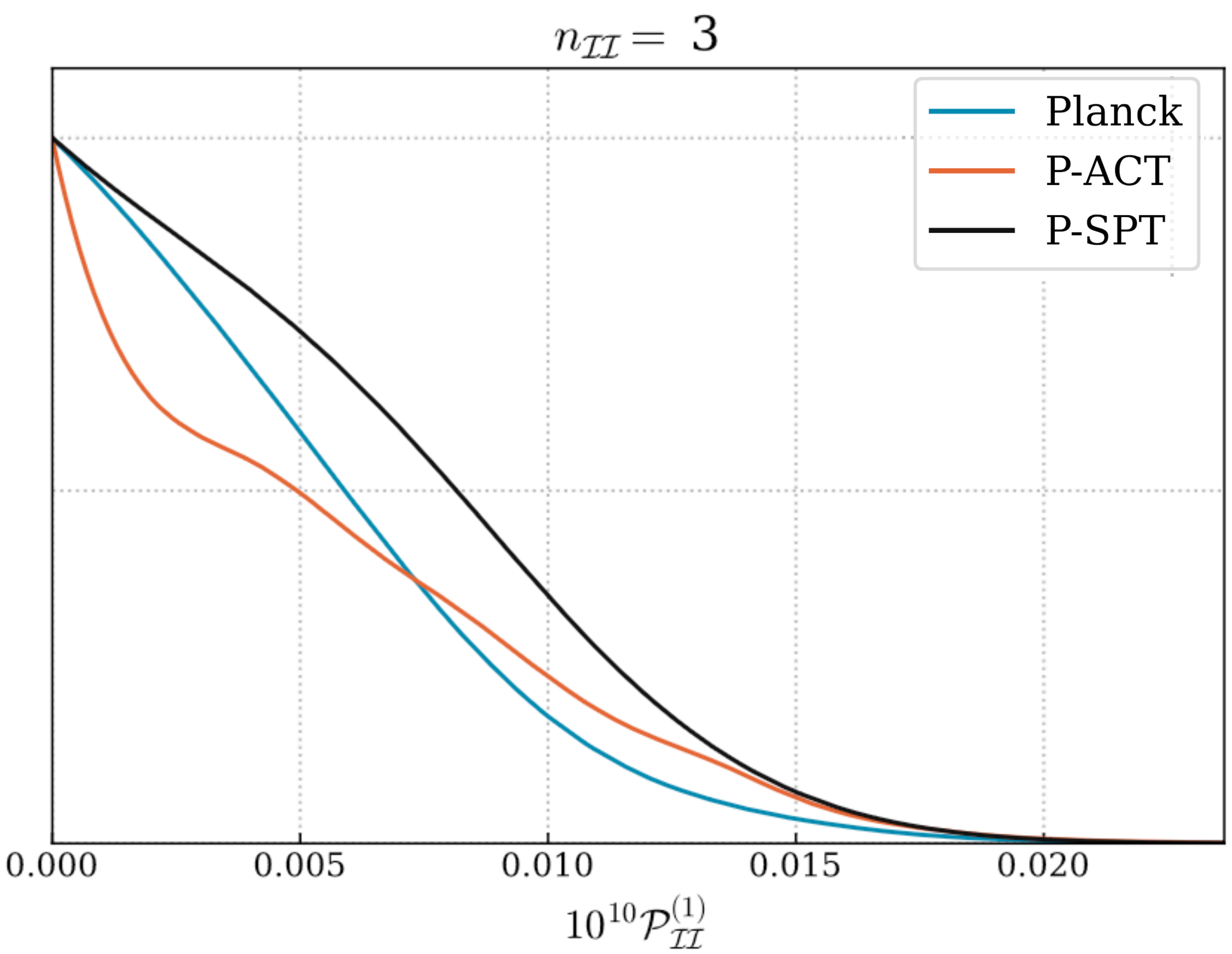
South Pole Telescope

Results: Flat CDI Spectrum



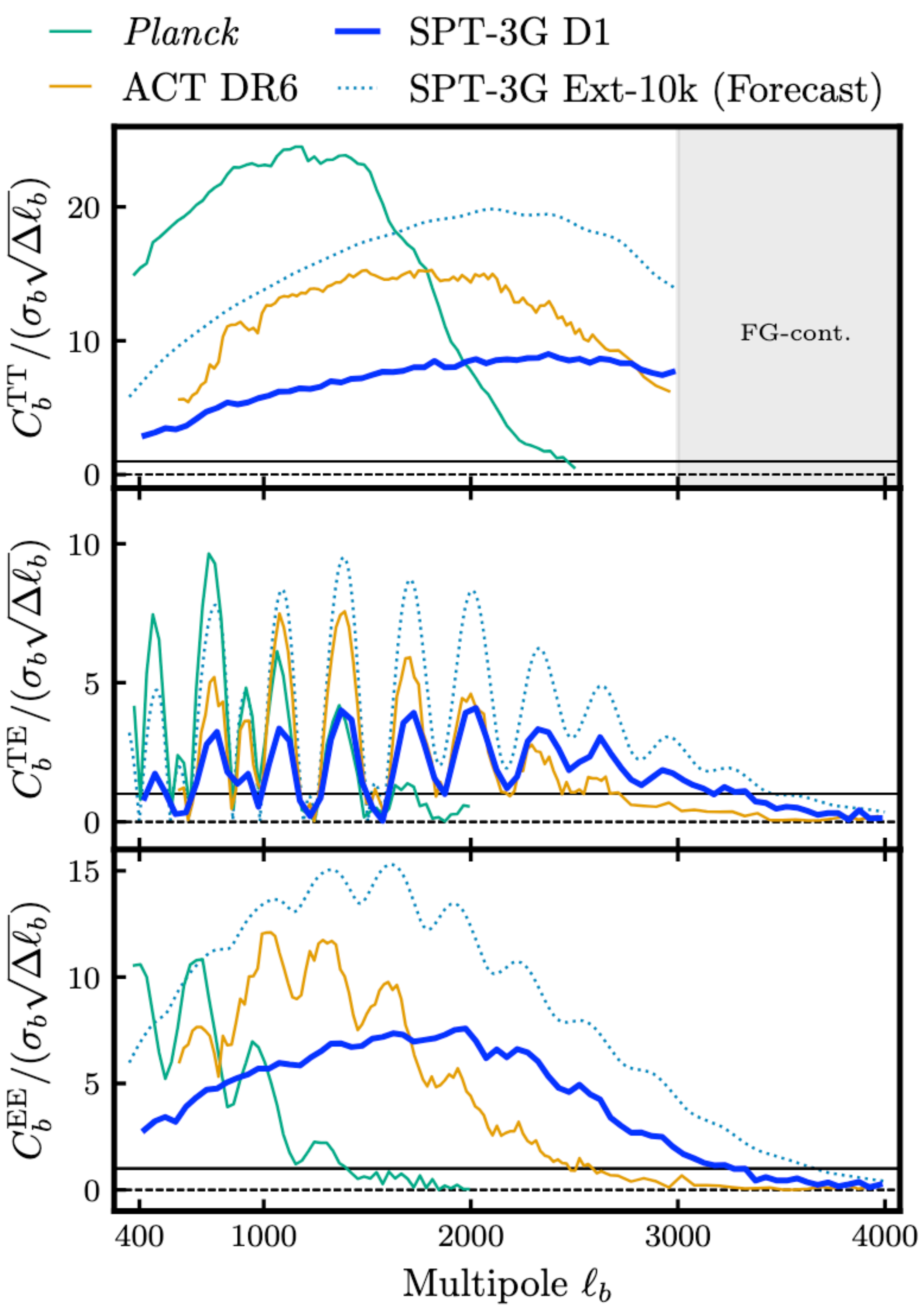
Results: Blue-tilted CDI Spectrum





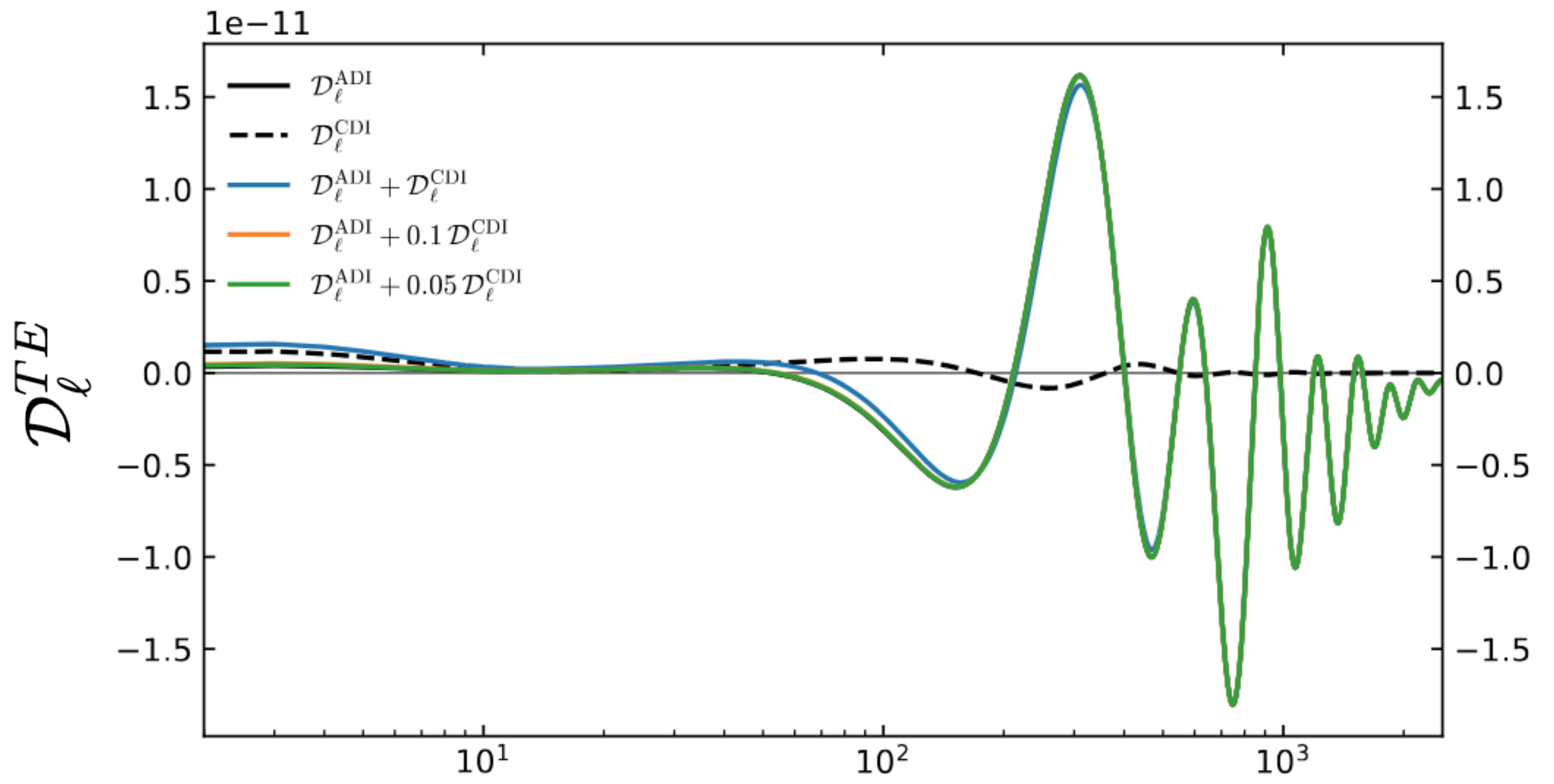
- $n_s \uparrow$ for P-ACT/ P-SPT, higher power in larger ℓ's
- More room for isocurvature power in lower $\ell's$

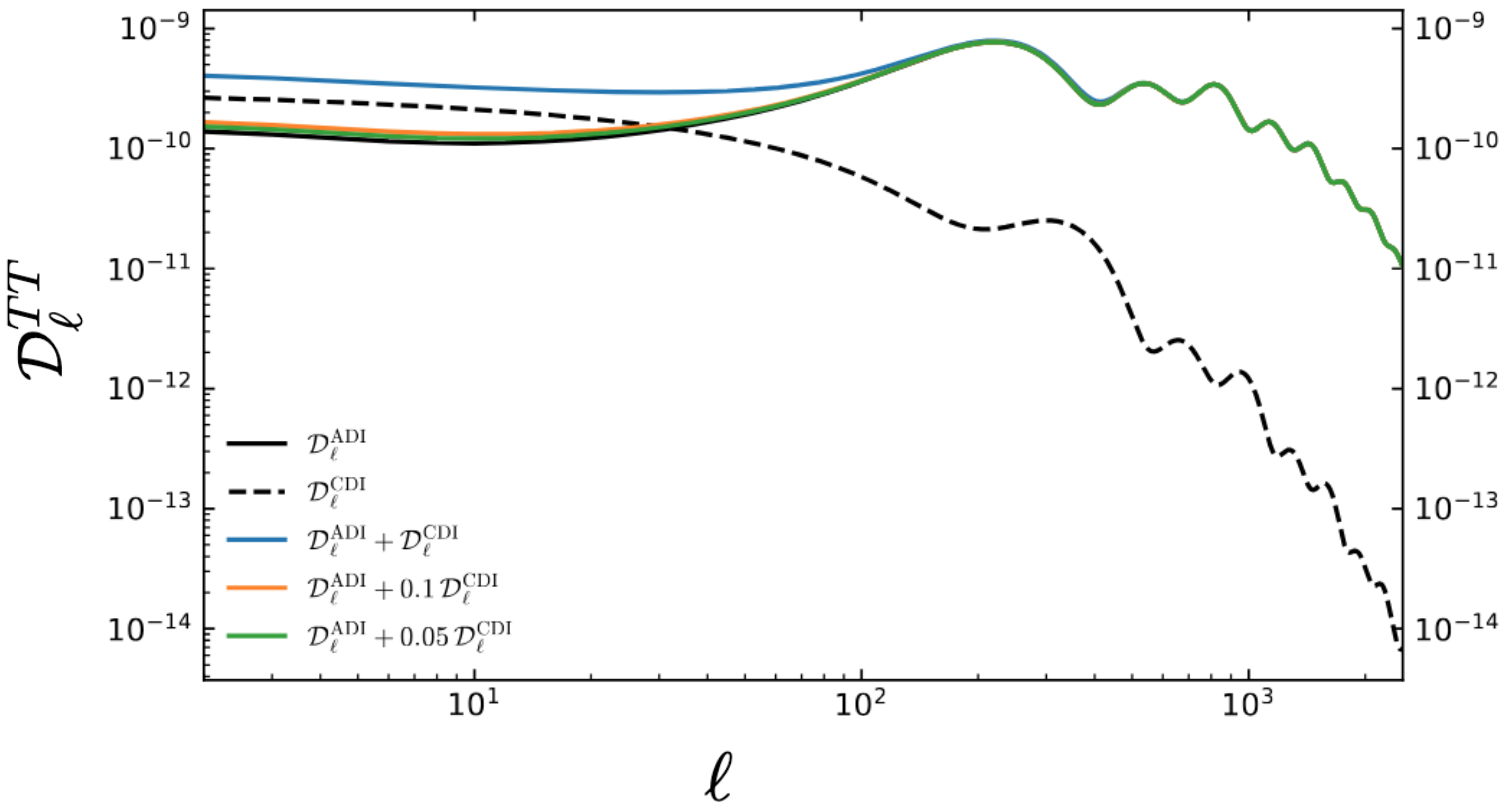
Signal to Noise Ratio

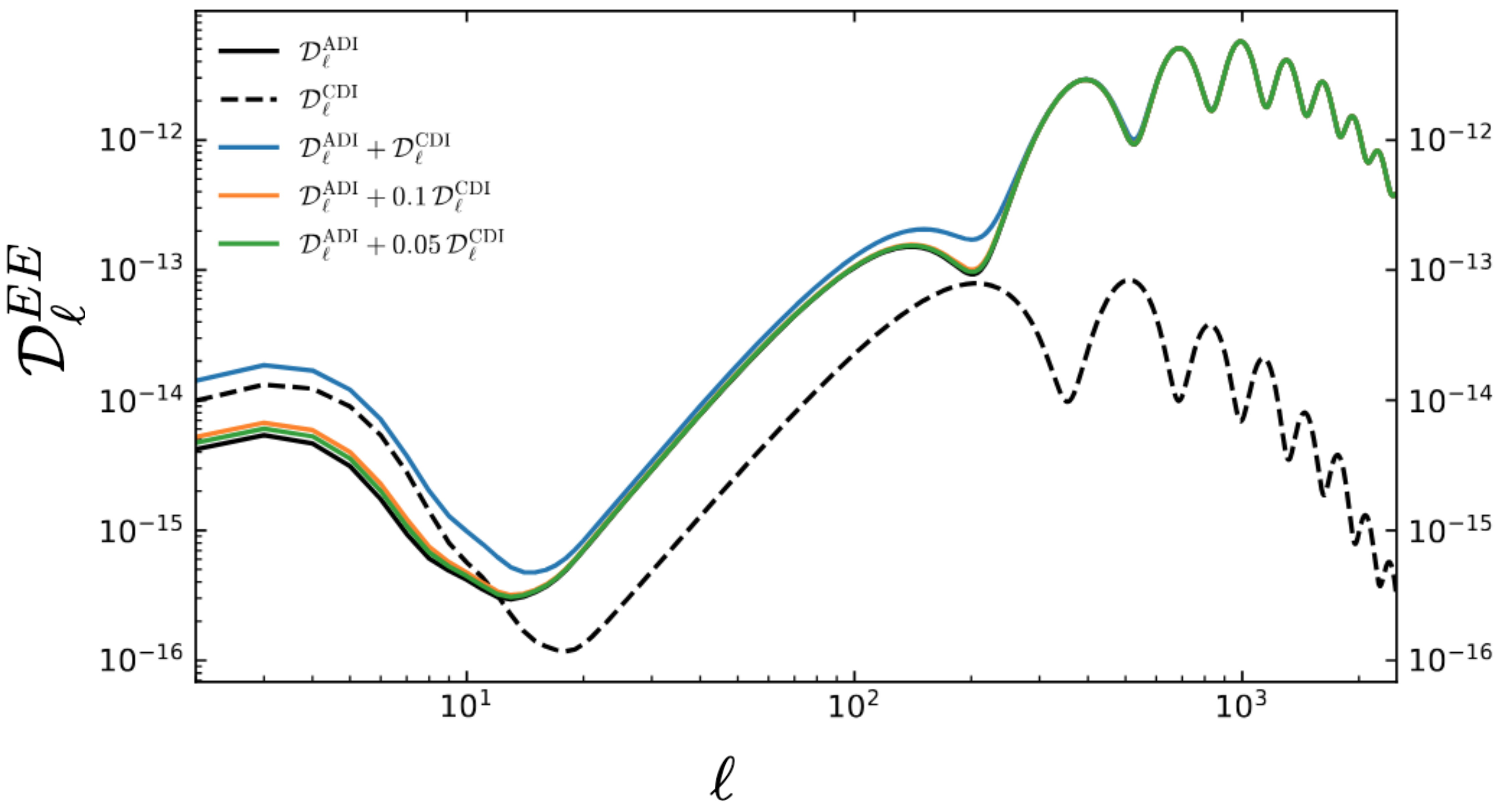


CDI Imprint on the CMB

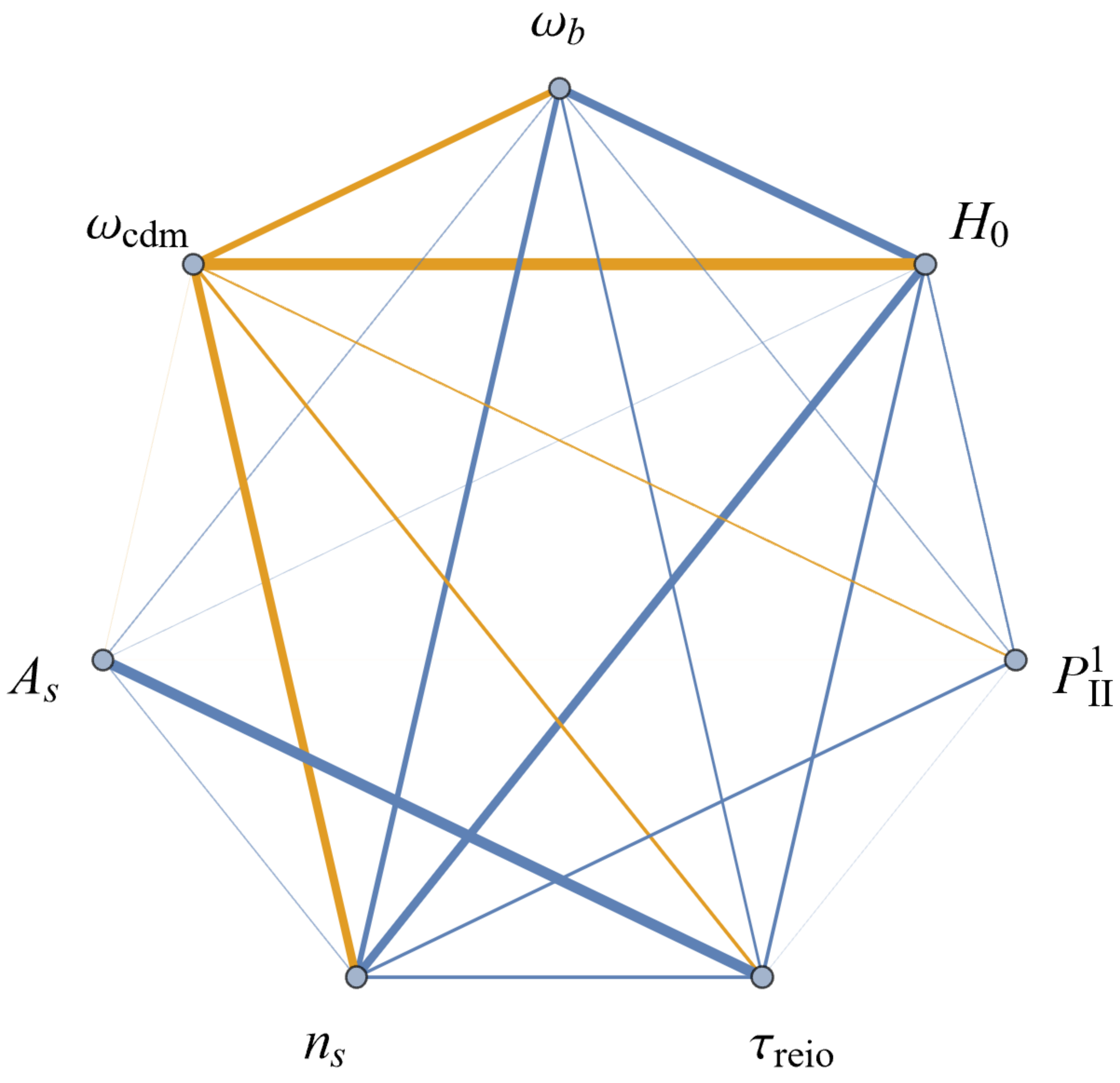
Angular spectra of CMB anisotropies for uncorrelated adiabatic (ADI) and CDI initial conditions, assuming a near scale invariant power spectrum with the same tilt and amplitude.



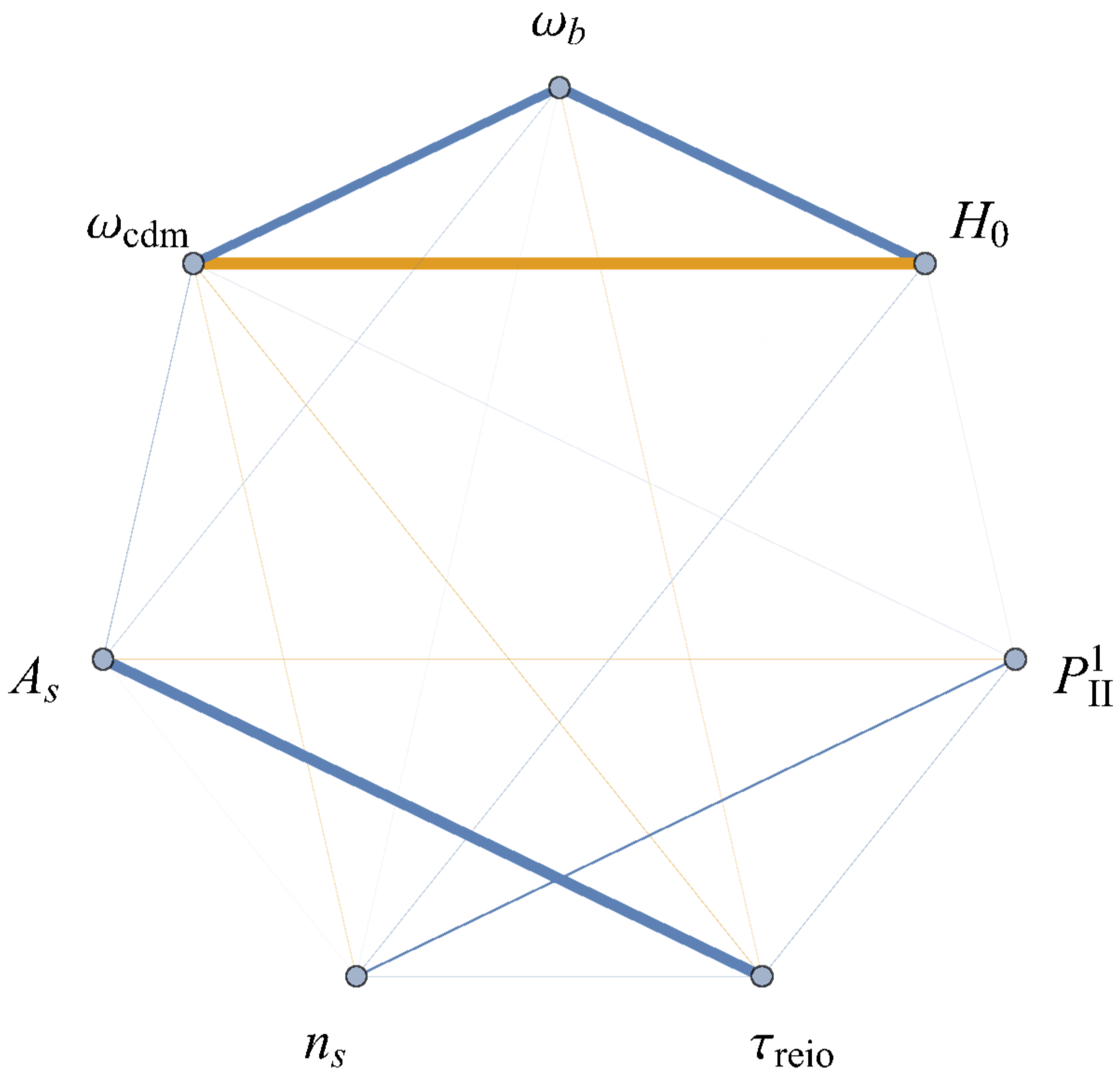




Correlations: $n_{II} = 2$, P-ACT



Pearson Correlation



Partial Correlation

QCD Axion DM

- Assuming QCD axion makes up a fraction of the DM