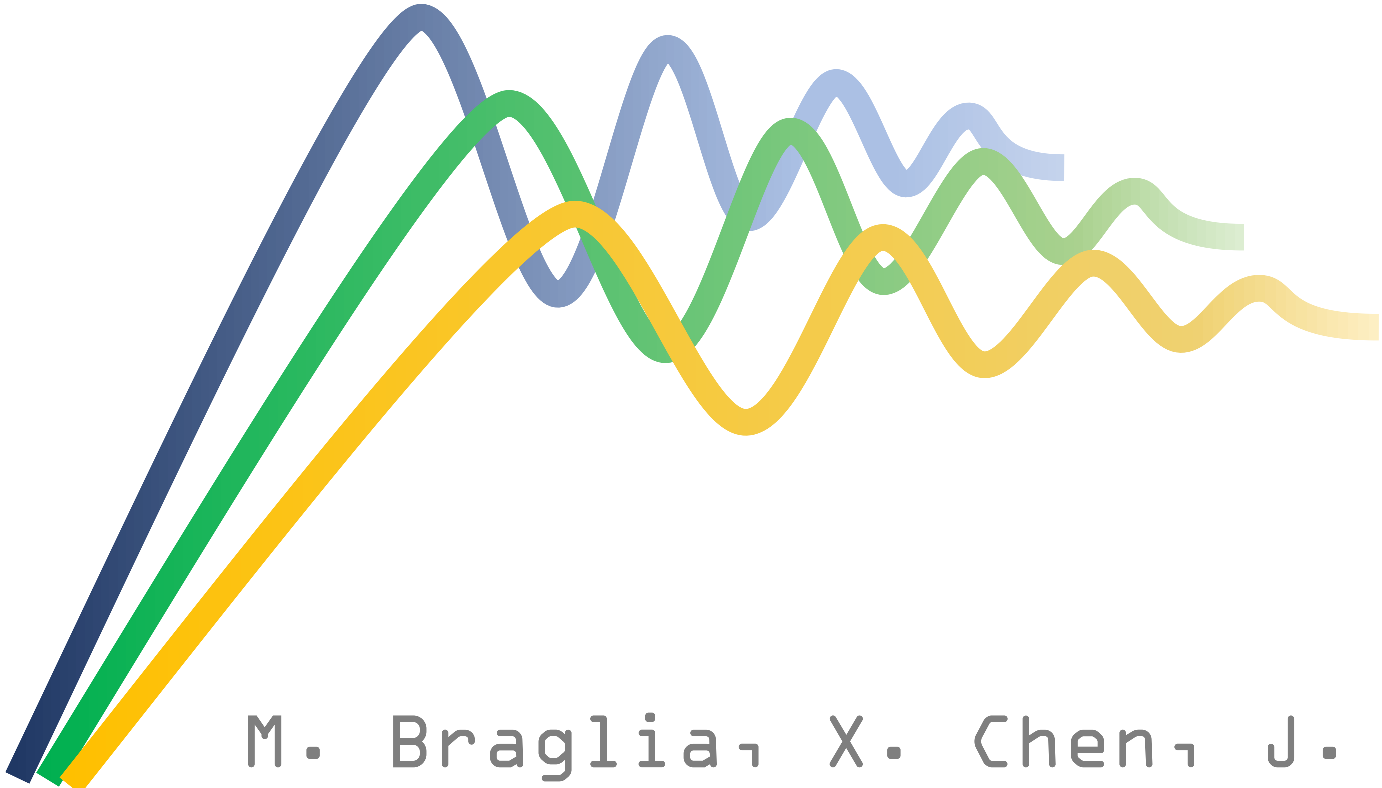
NEW ISOCURVATURE CONSTRAINTS & ITS AXIONIC INTERPRETATIONS



Lingfeng Li

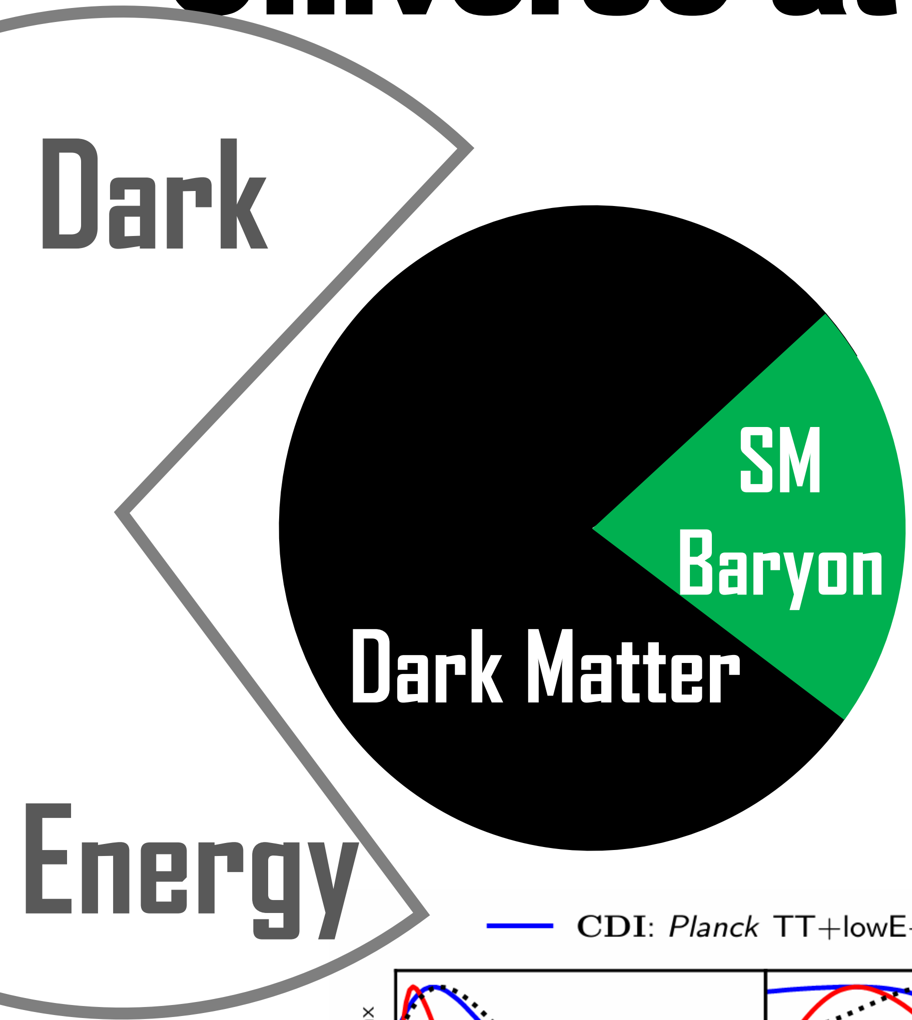
李凌风

Aug. 11, 2026

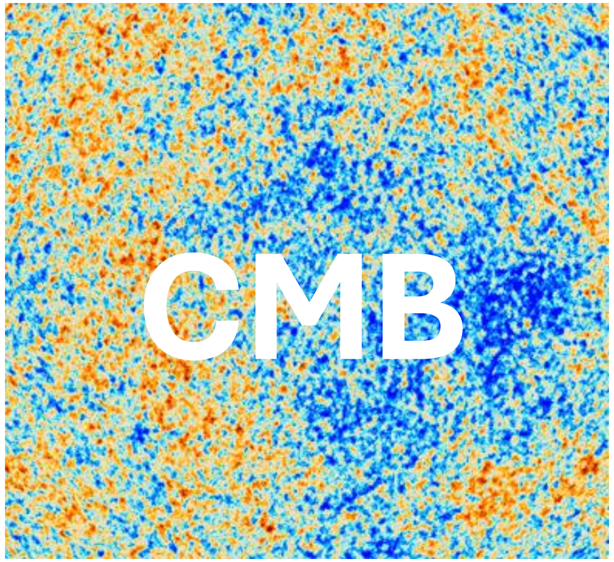
M. Braglia, X. Chen, J. Fan, LFL, C. Petretti, P. Singh, 2606.11312

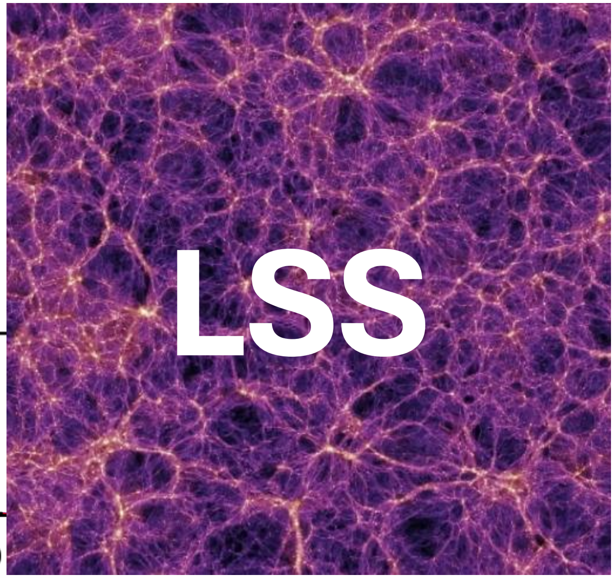
The 5th International Conference on Axion Physics and Experiment (Axion 2026)

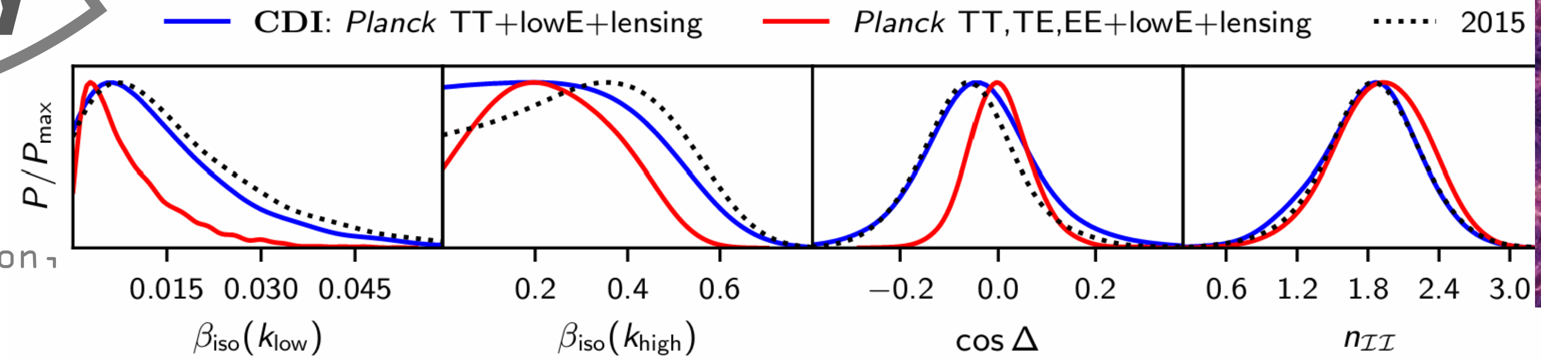
Universe at Large Scales



- ❑ The spacetime is almost flat
- ❑ DM >> Baryon
- ❑ The curvature power index ~ 1 indicates an inflationary stage in the early universe
- ❑ Dominated by scalar curvature perturbations at this scale







Planck Collaboration, 1807.06211

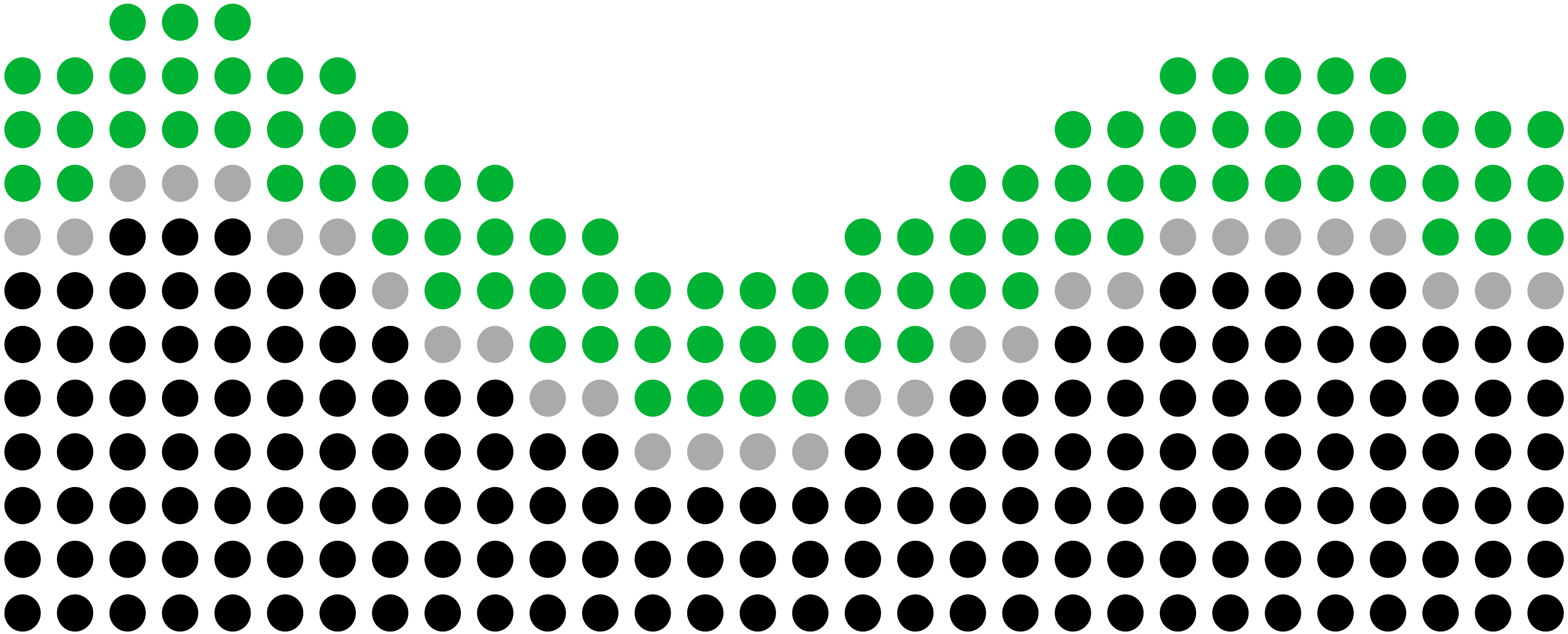
Disclaimer: the Wavelength

The smallest scale involved in this talk will be of O(100) kpc and not directly coming from the axion mass or other fundamental parameters.

The constraint is put on the background mode of axion/ALP CDM.

Curvature vs. Isocurvature

- Curvature or adiabatic: all species fluctuate together. The dominant mode observed today

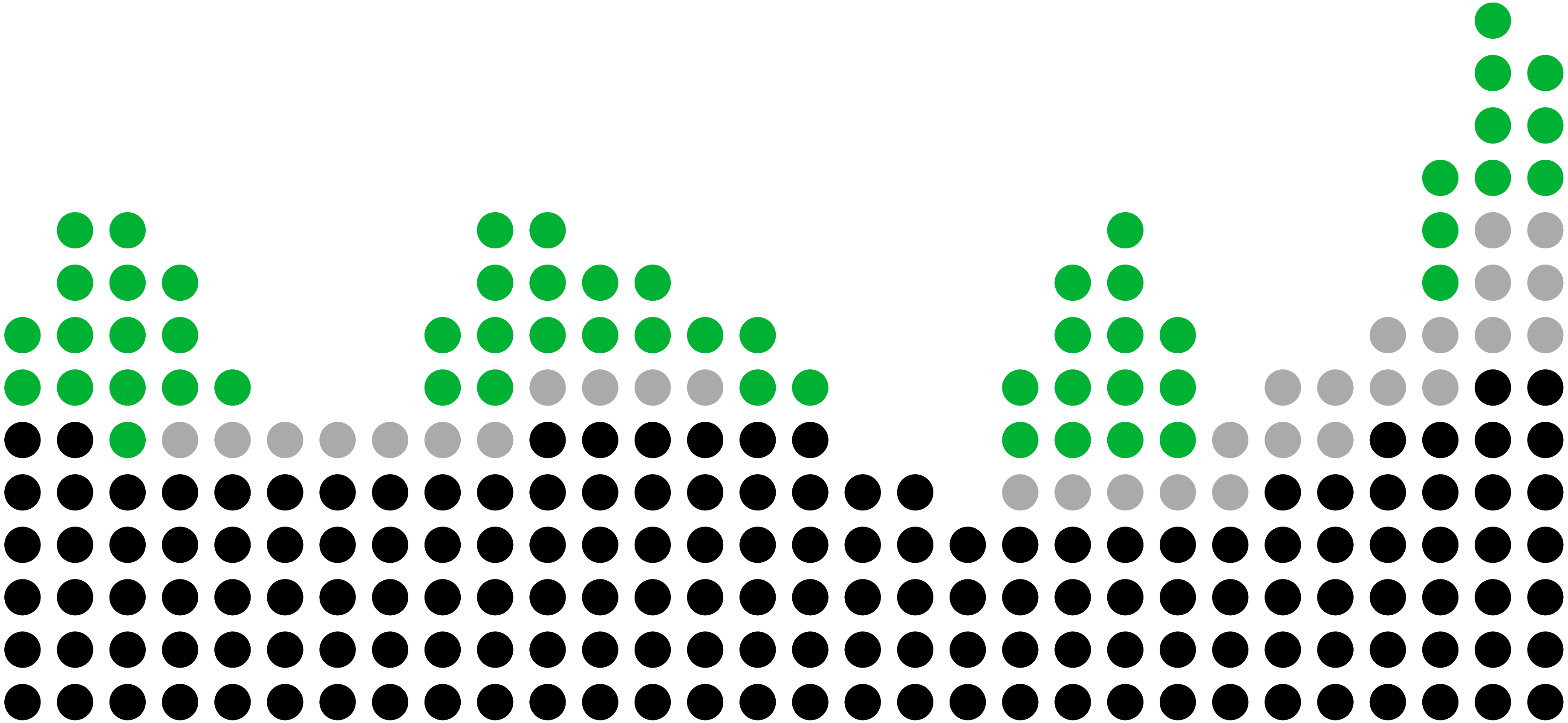


Curvature vs. Isocurvature

- Isocurvature: relative composition fluctuates differently (to their dilution rates)

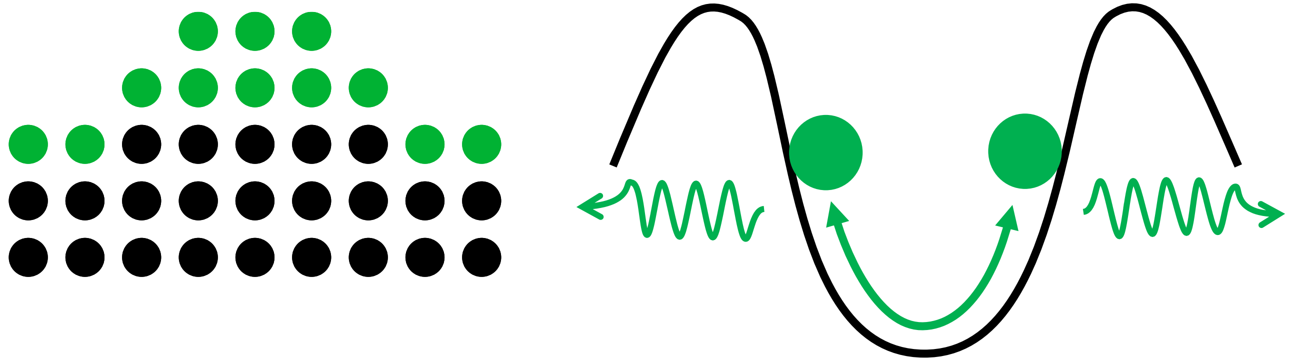
$$\zeta_i \equiv -\Phi - H\frac{\delta\rho_i}{\dot{\rho}_i}$$

$$S_{ij} \equiv 3\left[\zeta_i - \zeta_j\right]$$



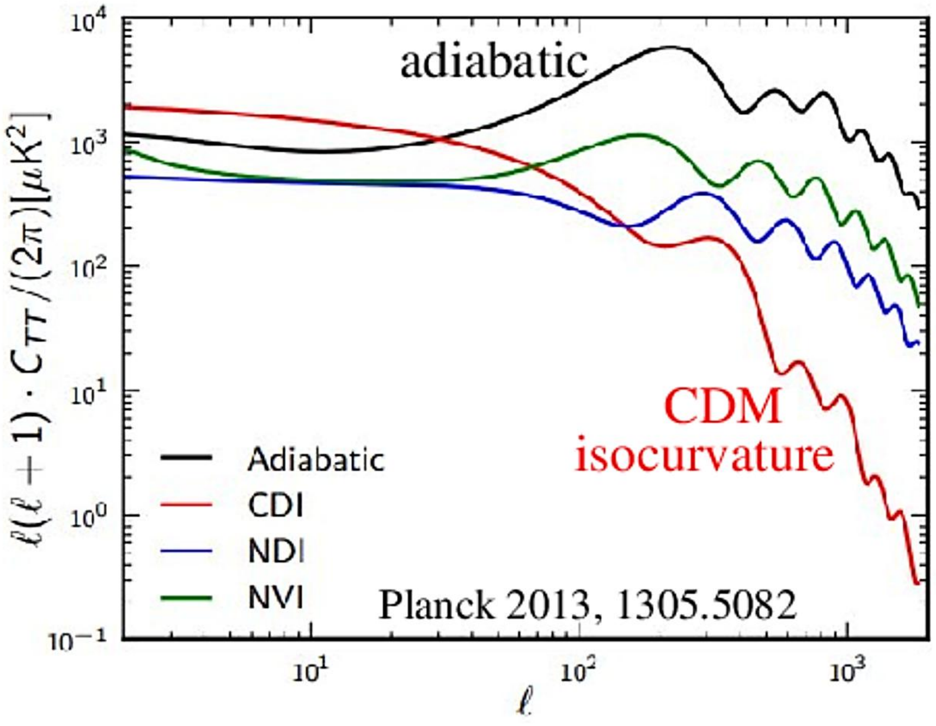
Here we can consider CDM induced (e.g. from axion) isocurvature perturbation

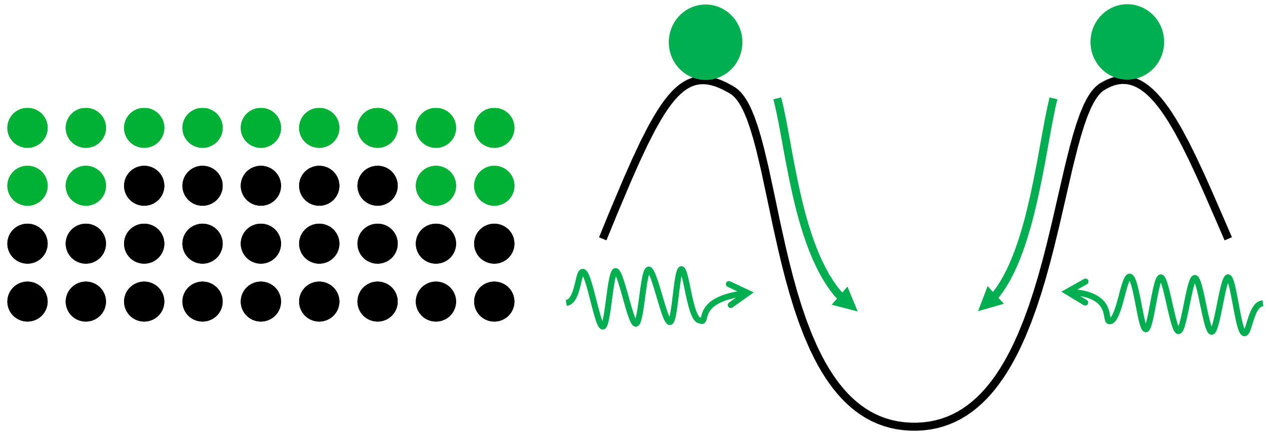
S. Weinberg, 0302326; I. Allali, P. Chakraborty, J.Fan, M. Reece, 2510.07371……



Pure curvature: photon released at the most compression

See also: W. Hu, 9511130

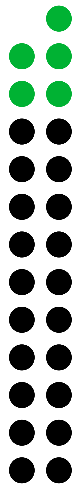




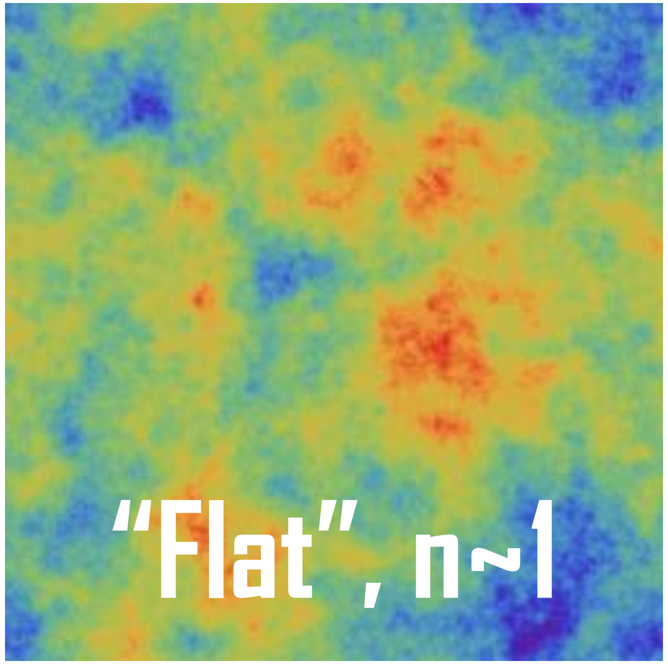
Pure isocurvature: alternative conditions

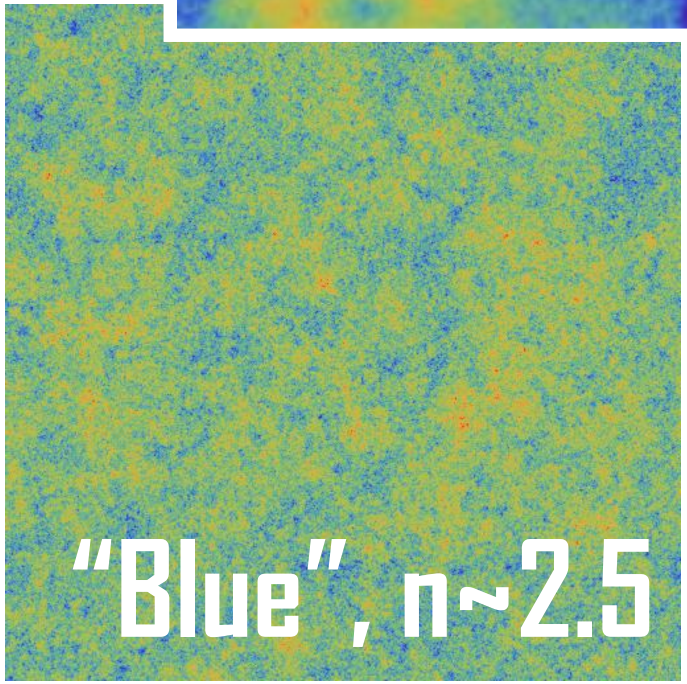
- ❑ The transfer function drops much faster than curvature/adiabatic terms
- ❑ Challenging even sensitive to smaller angular scales

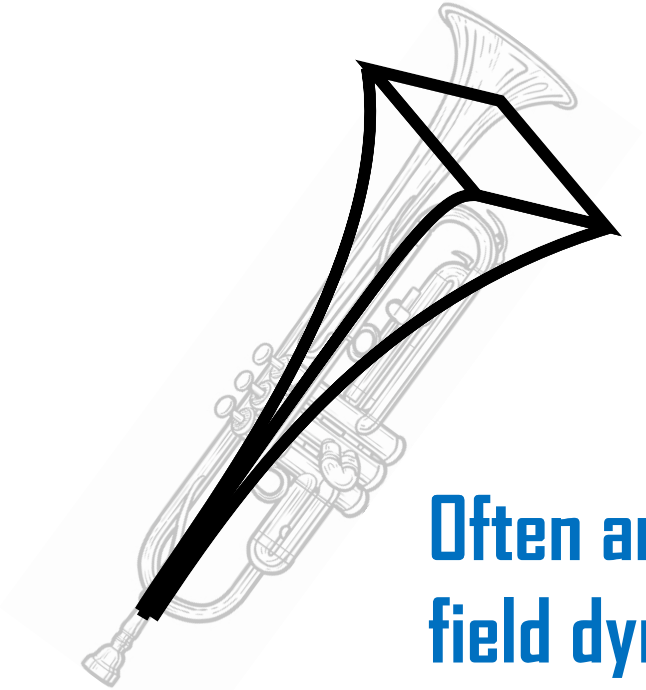
For compensated isocurvature, see e.g.
D. Grin, O. Dore, M. Kaminowski, 1107.5047



The Cosmic Blues







$$u_k(\eta) \equiv c_\theta(-k\eta)^{3/2} H^{(1)}_{\nu_\theta}(-k\eta)$$

$$P_\theta(k,\eta) = \frac{k^3}{2\pi^2}\frac{H_I^2}{R_{\rm min}^2}|u_k(\eta)|^2$$

$$P_\theta(k,\eta_{\rm end}) \propto \left(\frac{k}{k_{\rm end}}\right)^{3-2\nu_\theta}$$

Often arise from semi-heavy (≈H) field dynamics during inflation

- Constraint on extremely blue case (n ≳ 4) from CMB spectral distortion

N. Schoneberg, M. Lucca and D. C. Hooper, 2010.07814; B. Cyr, T. Kite, J. Chluba, J. C. Hill, D. Jeong, S. K. Acharya et al., 2309.02366; M. Tagliazucchi, M. Braglia, F. Finelli and M. Pieroni, 2310. 08527

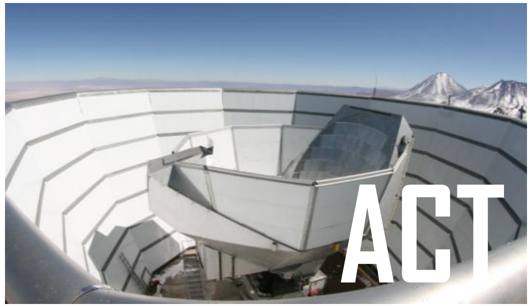
A. Bodas, R. T. Co, A. Ghalsasi, K. Harigaya, L.T. Wang, 2503.04888; M. Redi, A. Tesi, 2211.06421; S. Kalia, 2510.11803…

- Stochastic limit (n=4) case, post-inflationary axion cases

Y. Bao, J. Fan, LFL, 2209.09908

Data Input Structure

- ❑ACT and SPT sensitive to smaller angular scales, constraining blue spectra better



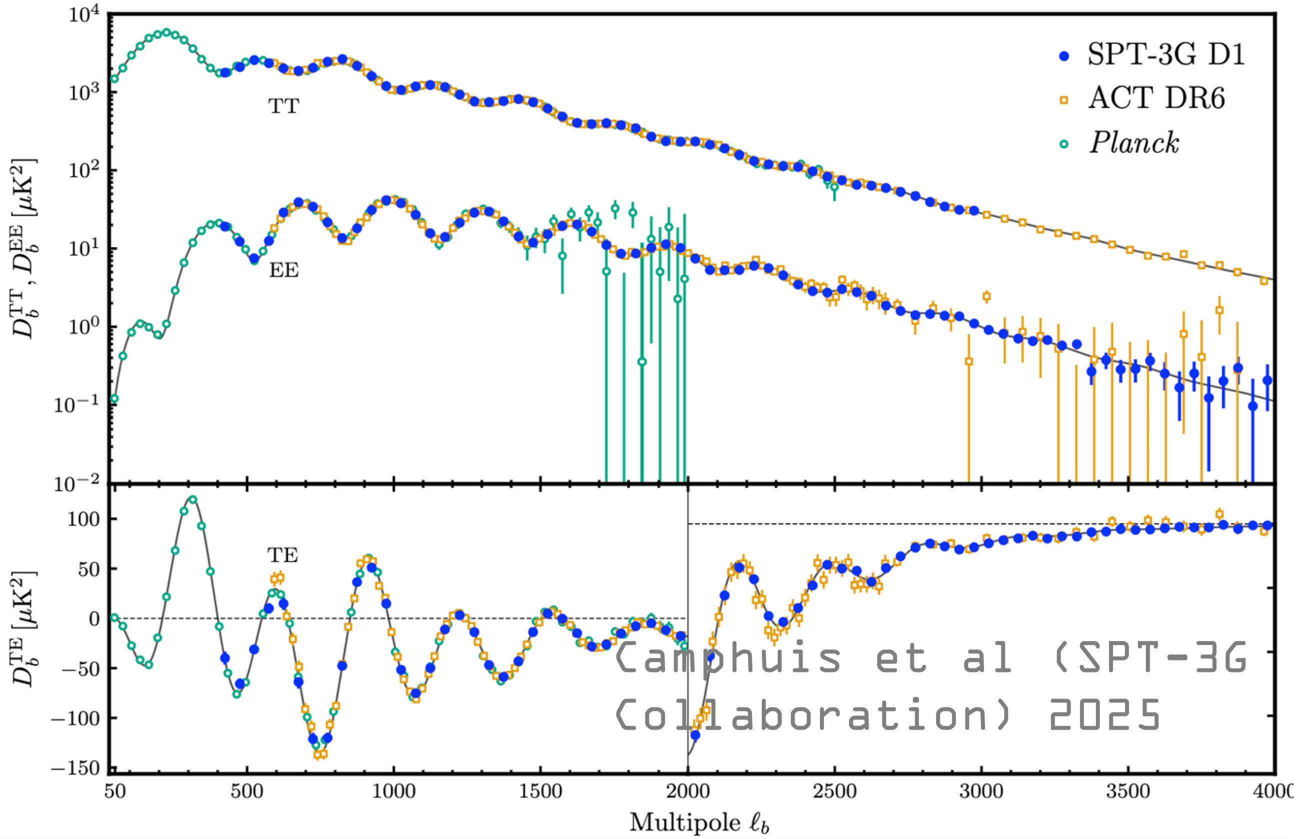
Planck-only

TT : $\ell<2500$

TE/EE: $\ell<2000$

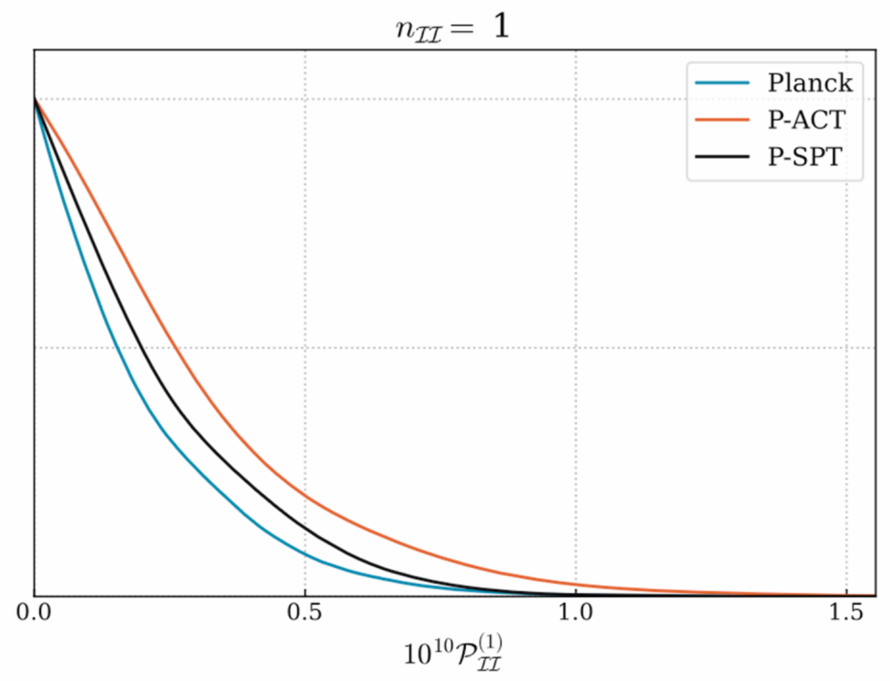
P-ACT(DR6)	ACT/SPT
TT: $\ell<1000$	$600 < \ell < 8500$
TE/EE: $\ell<600$	$600 < \ell < 8500$

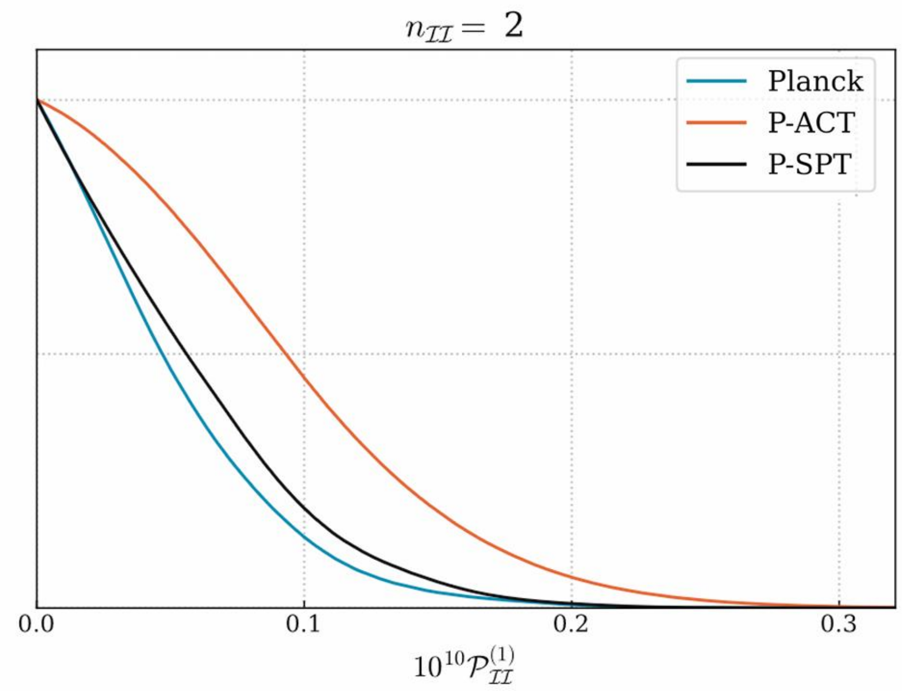
P-SPT(-3G D1)	
TT: $\ell<2000$	$1200 < \ell < 4000$
TE/EE: $\ell<1200$	$1200 < \ell < 3000$

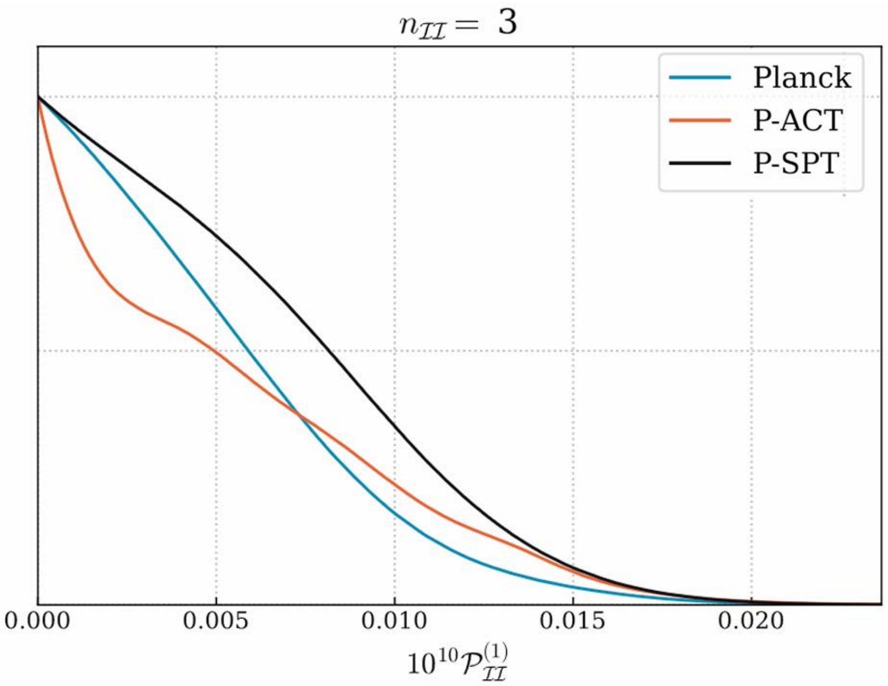


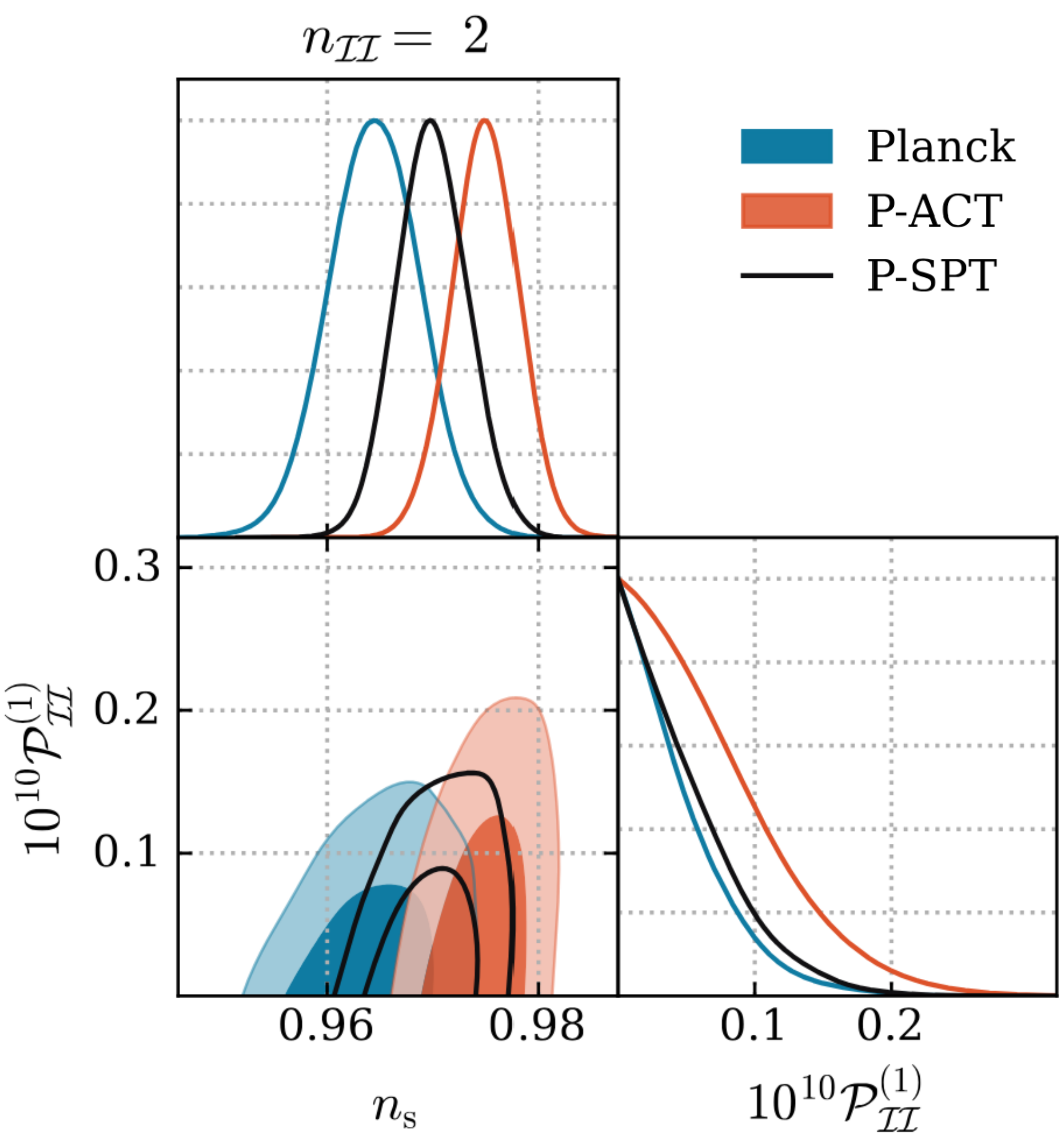
Results: Fixed Spectrum Index

The constraints are relaxed when new data are combined

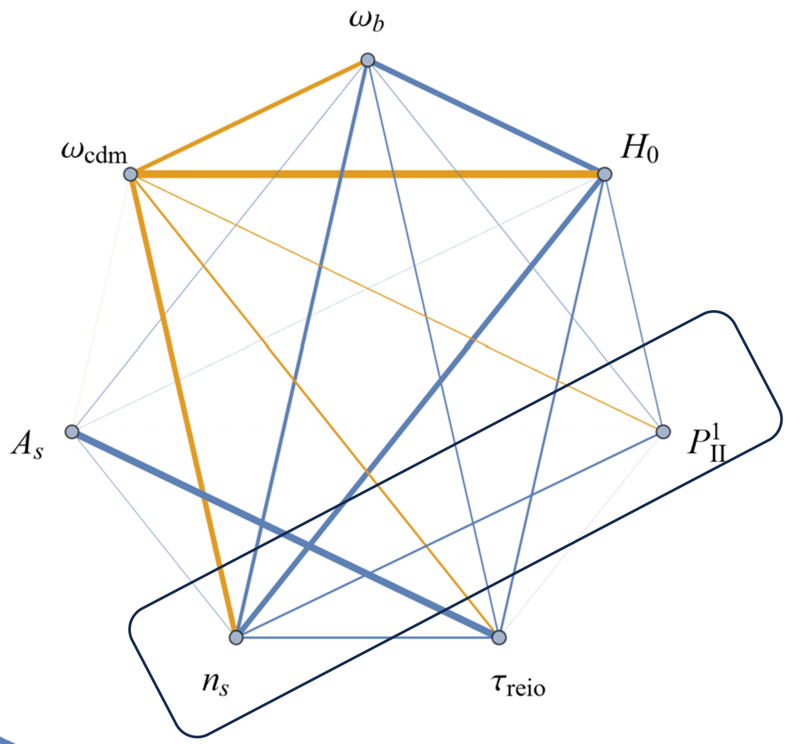


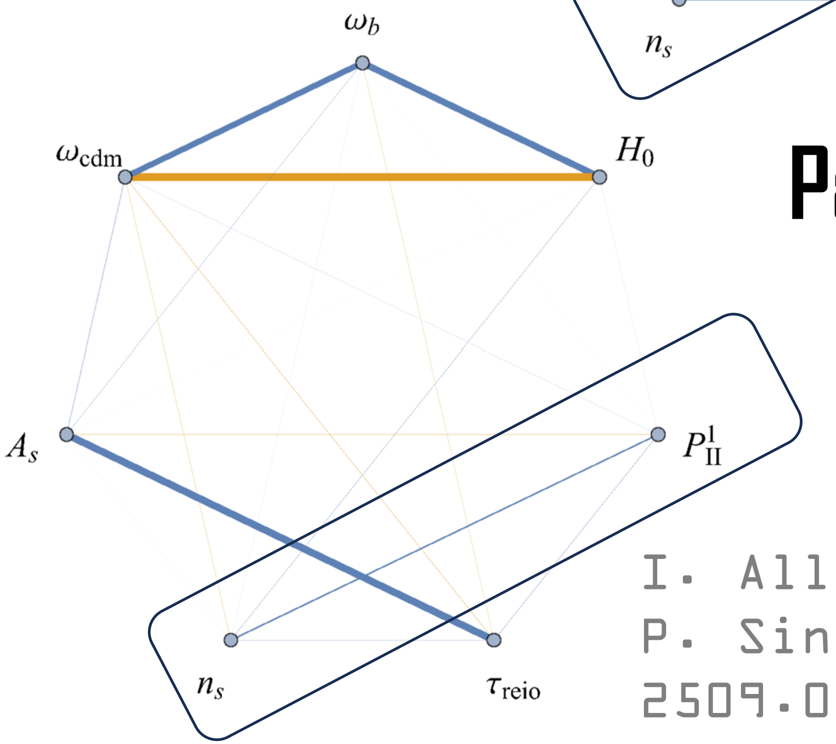






Pearson Correlation





Partial Corr.

I. Allali, LFL,
P. Singh, J. Fan,
2509.09678

Results: Free Spectrum Index

❑ Planck:

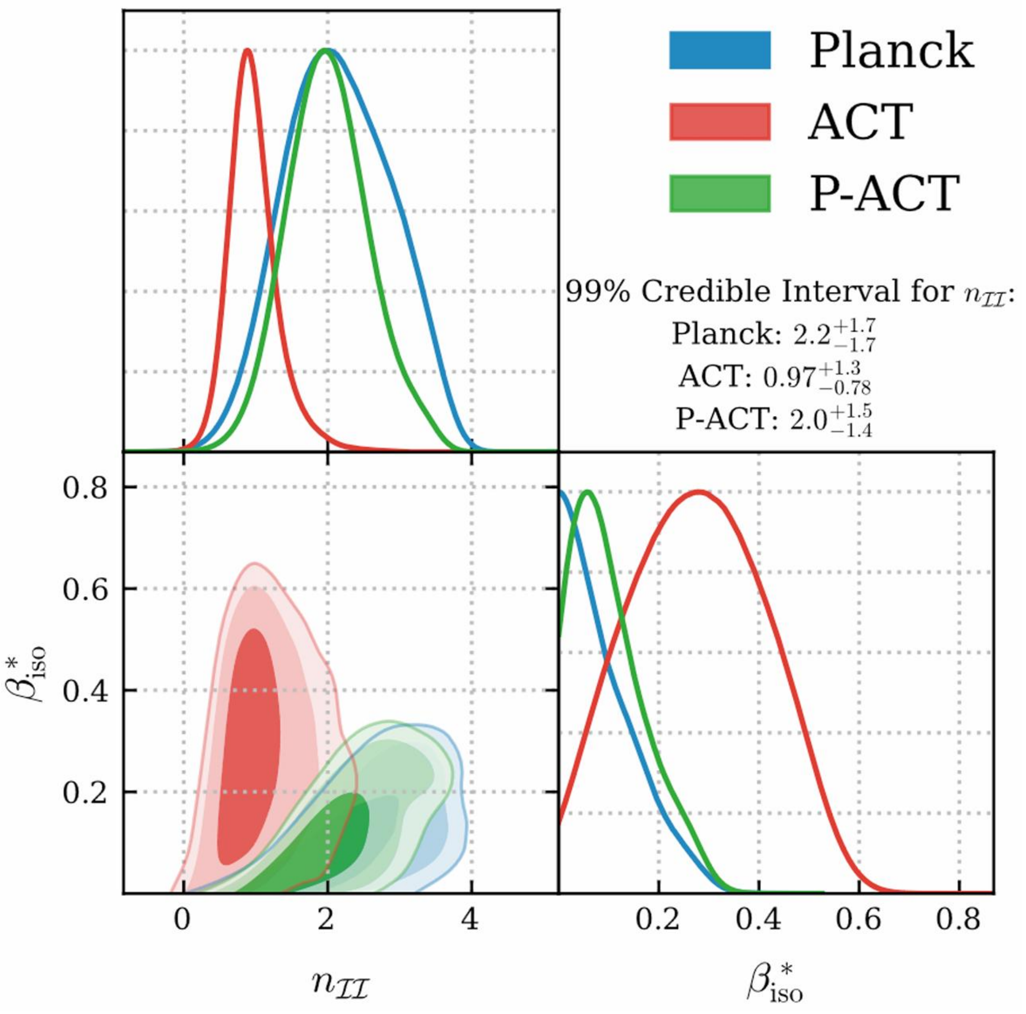
Larger ℓ unconstrained region prefers a blue-tilted spectrum

❑ ACT:

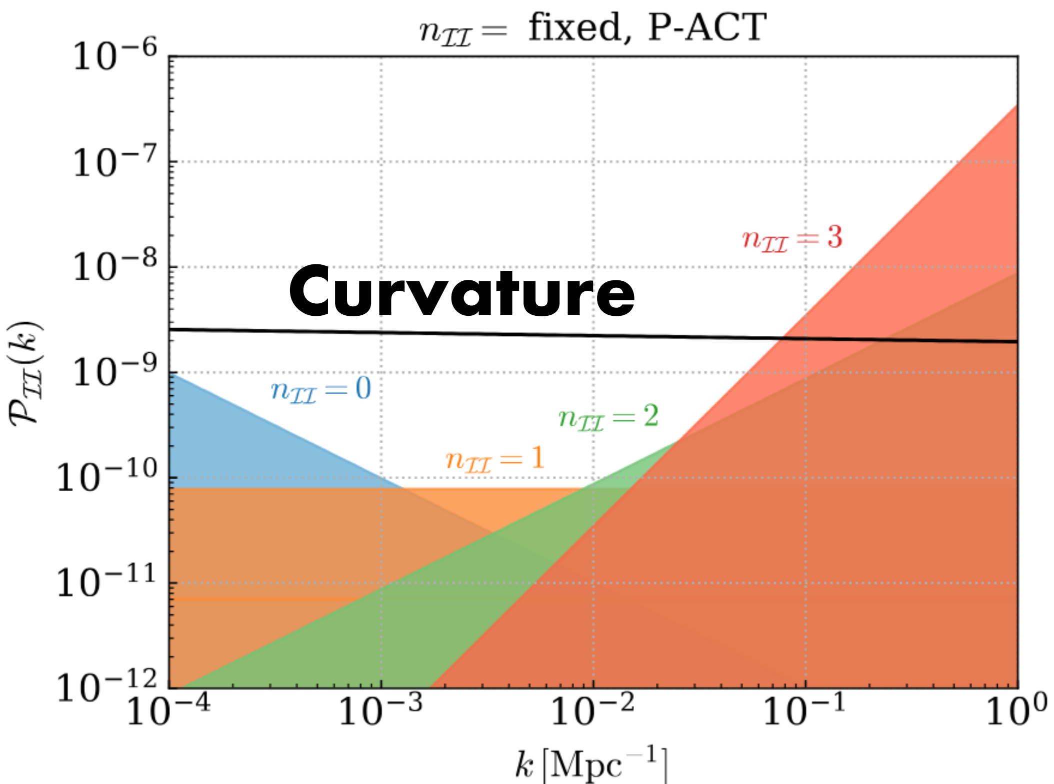
Smaller unconstrained region leads to red-tilted spectrum

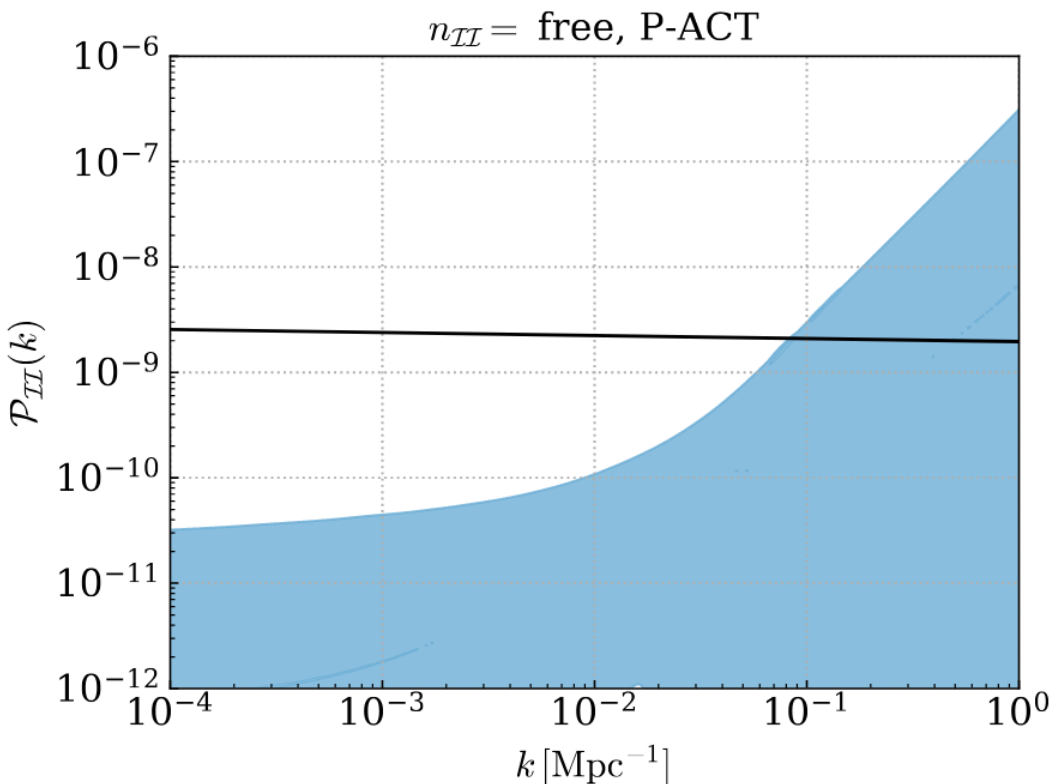
❑ P-ACT:

1) Moderate improvement in the constraint on the spectral index,
2) Tilt is closer to Planck



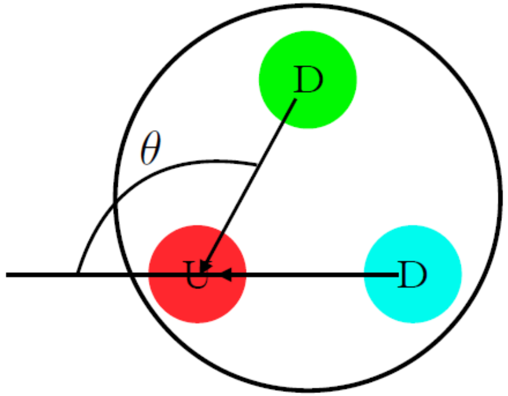
Model & Data	$\mathcal{P}_{\mathcal{II}}^{(1)}$	$\mathcal{P}_{\mathcal{II}}^{(2)}$	$100\ \beta_{\rm iso}^{(1)}$	$100\ \beta_{\rm iso}^{*}$	$100\ \beta_{\rm iso}^{(2)}$	$n_{\mathcal{II}}$
$n_{\mathcal{II}} = 2$						
Planck	$< 1.18 \times 10^{-11}$	$< 5.88 \times 10^{-10}$	< 0.500	< 12.2	< 22.2	...
P-ACT	$< 1.68 \times 10^{-11}$	$< 8.38 \times 10^{-10}$	< 0.716	< 16.3	< 28.3	...
P-SPT	$< 1.27 \times 10^{-11}$	$< 6.34 \times 10^{-10}$	< 0.540	< 13.0	< 23.3	...
$n_{\mathcal{II}} = 3$						
Planck	$< 1.14 \times 10^{-12}$	$< 2.86 \times 10^{-9}$	< 0.0491	< 25.4	< 58.3	...
P-ACT	$< 1.33 \times 10^{-12}$	$< 3.34 \times 10^{-9}$	< 0.0575	< 28.0	< 61.3	...
P-SPT	$< 1.28 \times 10^{-12}$	$< 3.19 \times 10^{-9}$	< 0.0549	< 27.4	< 60.6	...





You Know Everything Already...

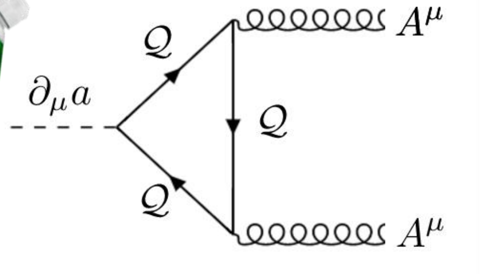
The extreme fine-tuning indicates the strong CP problem



$$\mathcal{L} \supset \theta \frac{g^2}{32\pi^2} G\tilde{G}$$

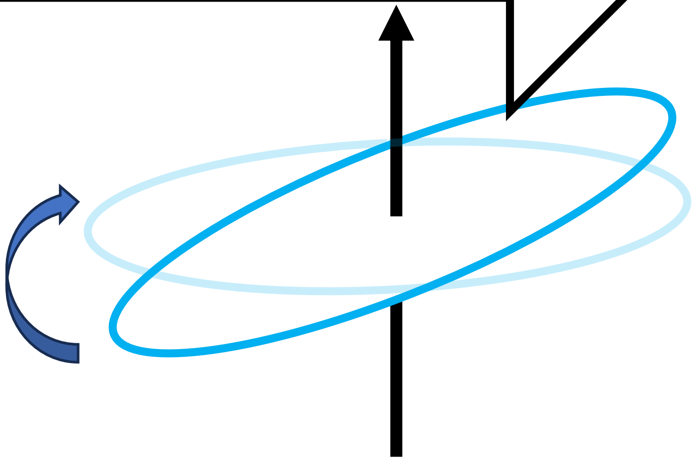
Experimental hints: neutron EDM
Experimental result $\lesssim 10^{-26}$ e cm,
$\theta \lesssim 10^{-10}$

QCD axion: A pseudo Nambu-Goldstone Boson (pNGB) of a the Peccei-Quinn symmetry



$$\mathcal{L} \supset \left(\frac{a}{\boxed{f_a}} + \theta\right) \frac{1}{32\pi^2} G\tilde{G}$$

Greater than ~10^9 GeV from data
Suppressed interaction with SM



The strong CP θ angle are set to zero at the minima during the current universe

Peccei, Quinn; Weinberg; Wilczek; Kim; Shifman, Vainshtein, Zakharov; Zhitnitsky; Dine, Fischler, Srednicki, 1977-1981

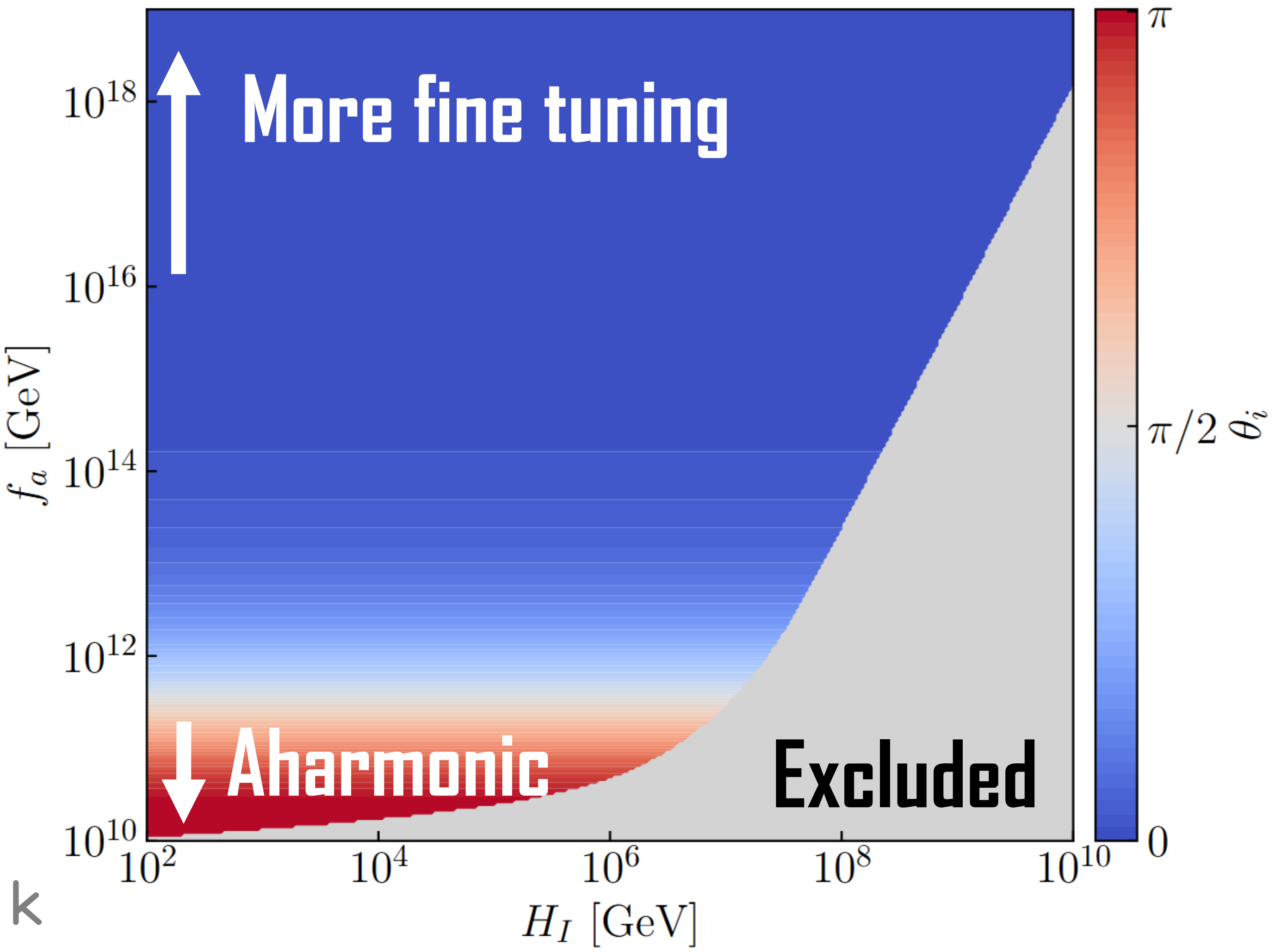
(QCD) Axionic Interpretation Standard Misalignment (n_{iso} = 1)

$$\Omega_a \simeq 0.27 \times \tilde{\theta}_i^2 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{\frac{7}{6}},$$

$$\tilde{\theta}_i^2 = \theta_i^2 \log\left[\frac{e}{1-(\theta_i^2/\pi^2)}\right]^{\frac{7}{6}},$$

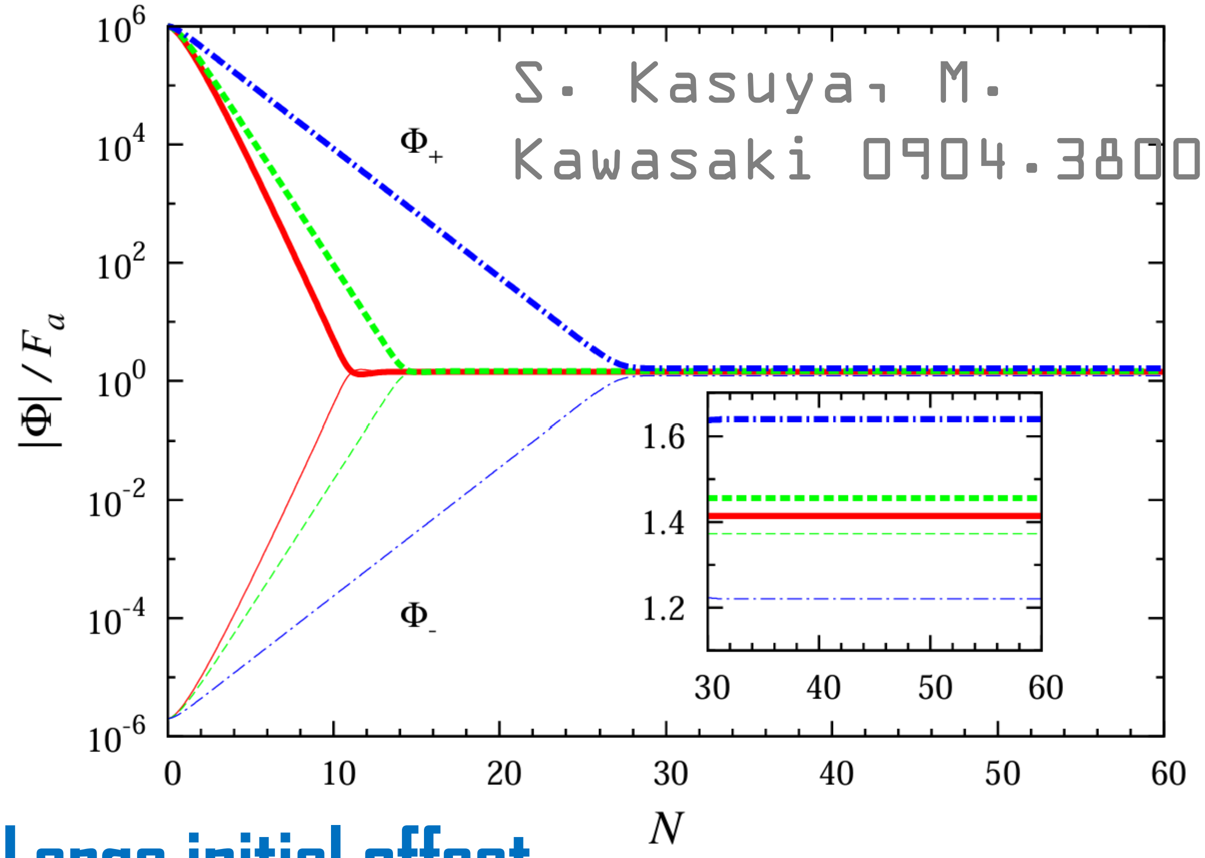
$$A_{\mathcal{I}} = \left(\gamma\sigma_\theta \frac{\partial \ln \Omega_a}{\partial \theta_i}\right)^2 = \left(\frac{\gamma H_I}{2\pi f_I}\frac{\partial \ln \Omega_a}{\partial \theta_i}\right)^2$$

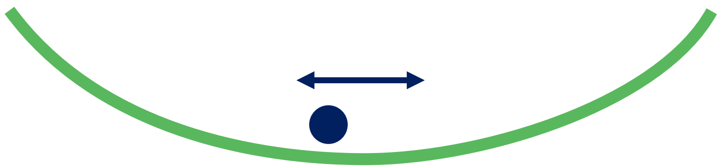
Assuming the "standard" QCD axion DM



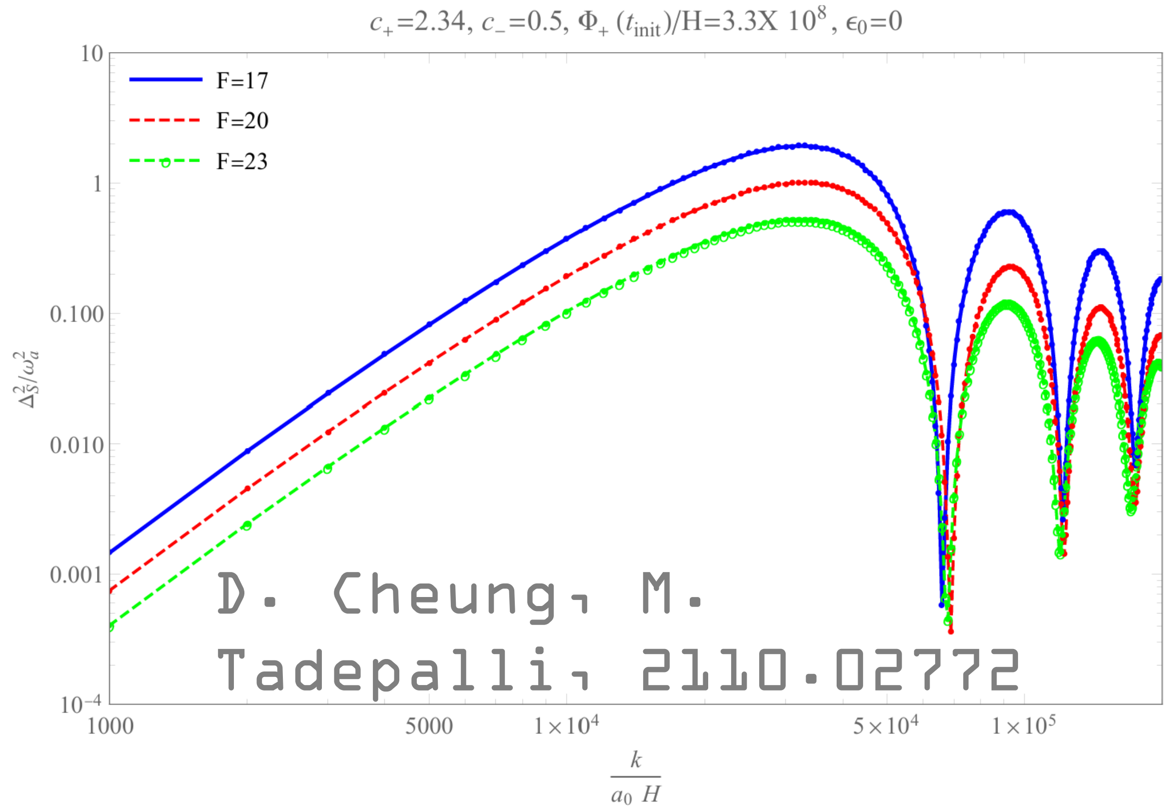
See also: Qiaoli Yang's talk

(QCD) Axionic Interpretation of Inflationary Dynamics ($n_{iso} > 1$)

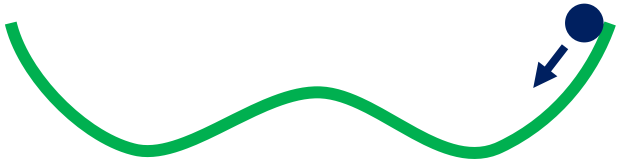




Potential Large Features around the Cutoff

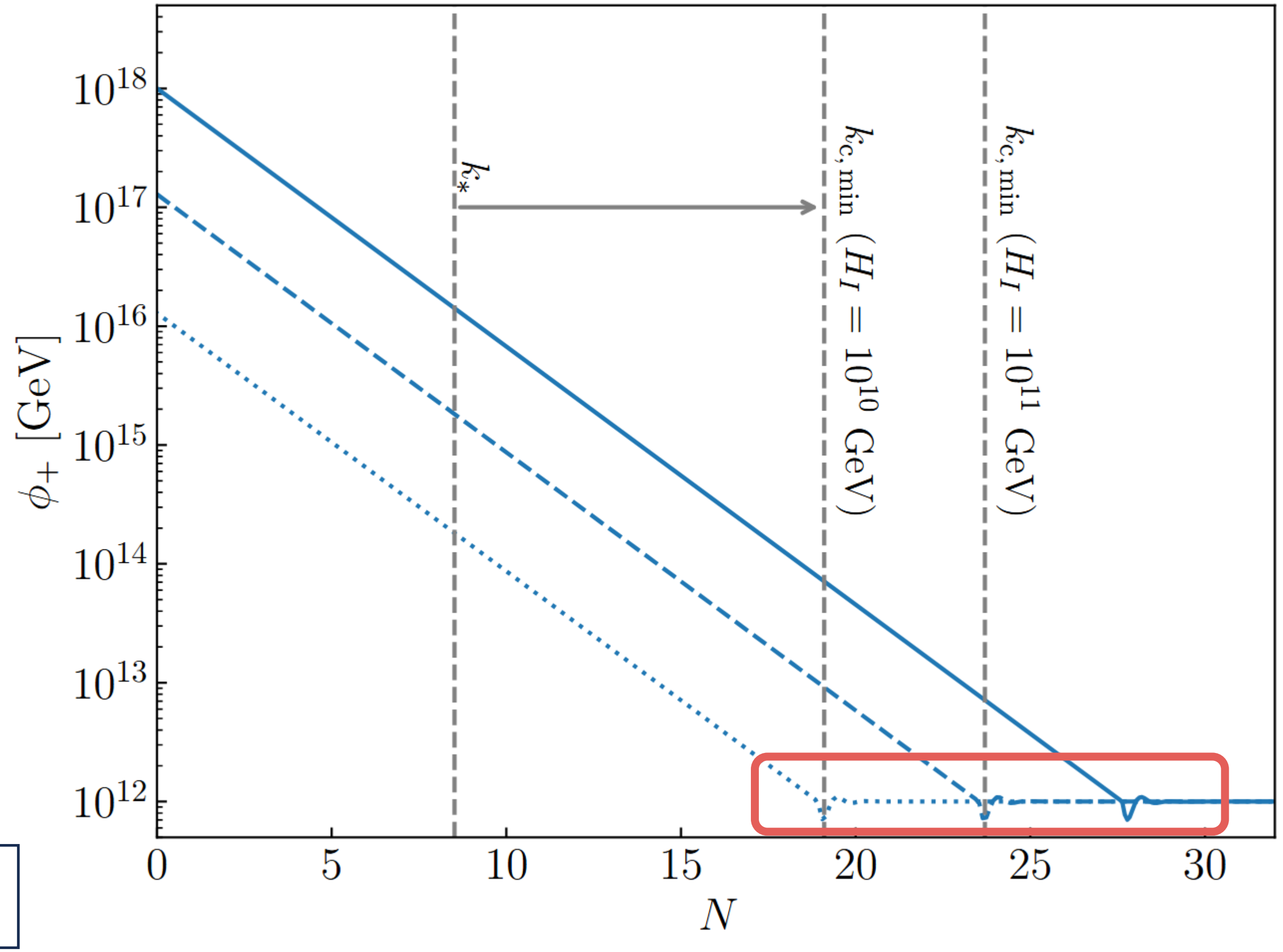


Large initial offset during inflation and sliding dynamics



Axionic Interpretation
Inflationary Dynamics

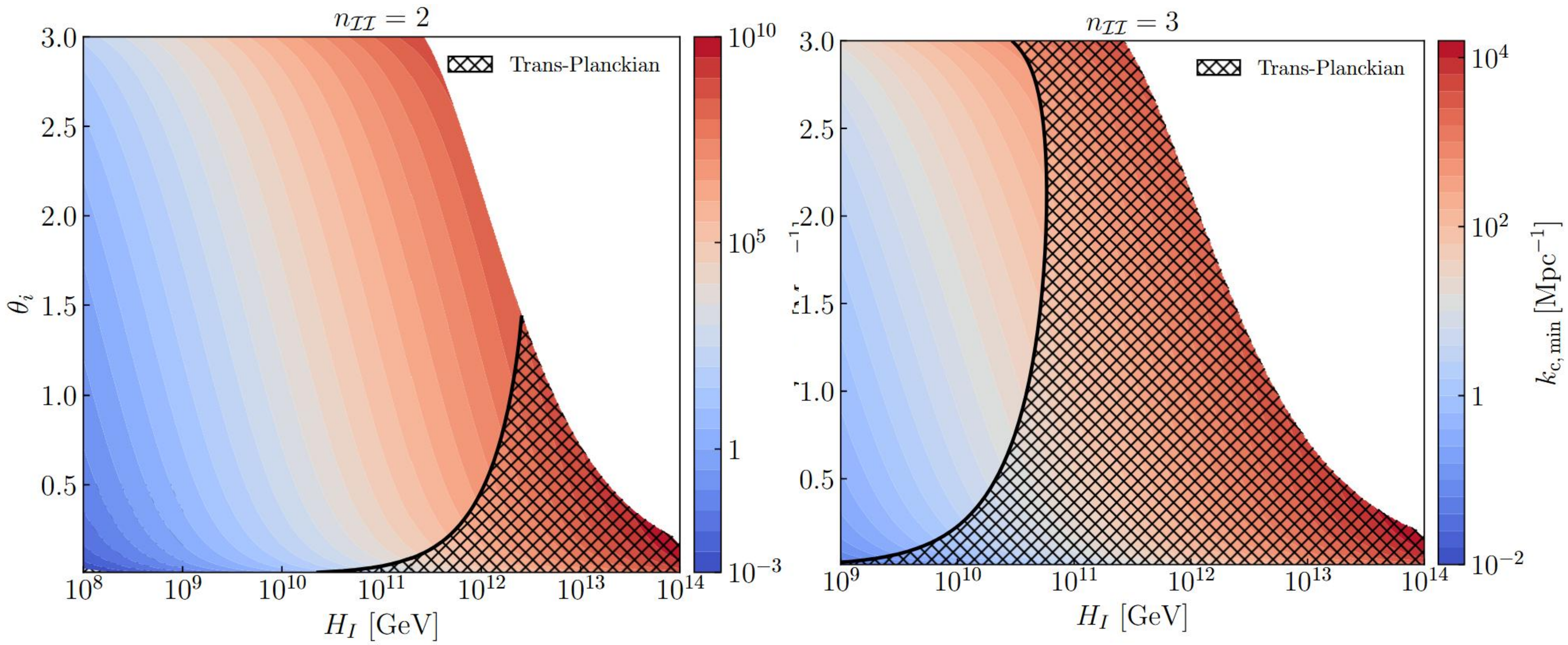
Small field values, large isocurvature violating current constraints



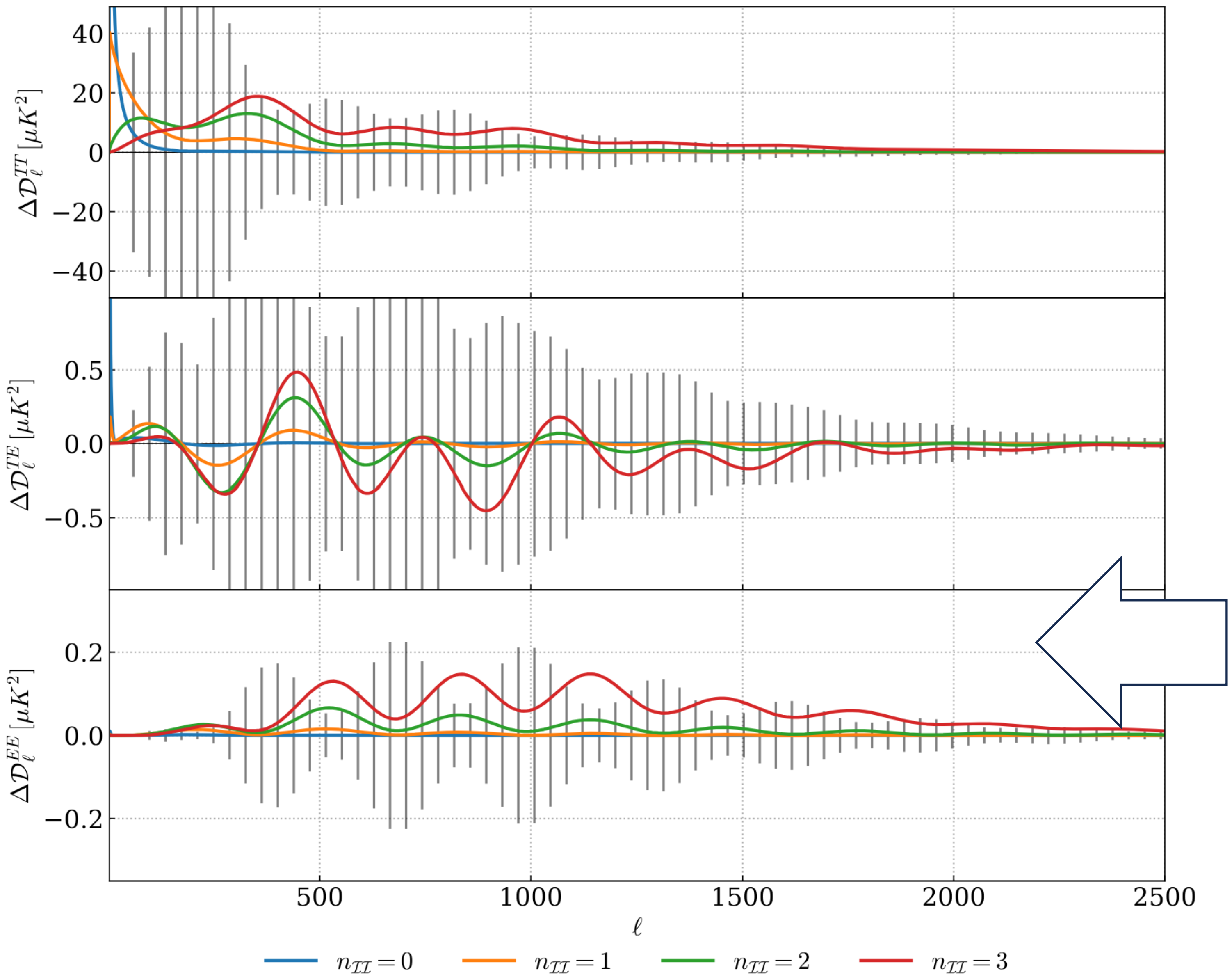
Transplanckian initial condition (at a scale of 10^{-5} Mpc^{-1})

Transition and potential kinetic features detectable

The Largest Scale for Possible Kinetic Phenomena



Future CMB Perspective



Cosmic variance only, "statistical" limit

- ❑ Current best fit points, both TT and EE could contribute

Summary

- Constrain on blue (and red) tilted CDI using CMB dataset from Planck, ACT and SPT, with Planck contributing the most.
- Moderate improvement in the isocurvature spectral index.
- Moderate upshift shift in the isocurvature magnitude, might come from the correlation with n_s.
- Future High precision CMB projects will be necessary at large scales given the decay of isocurvature transfer function.
- The impact of a feature on halo mass distributions is on the way.