Updated constraints on infrared cutoff models and implications for CMB-BAO tension

Based on arXiv: 2602.16659 (Published in JCAP)

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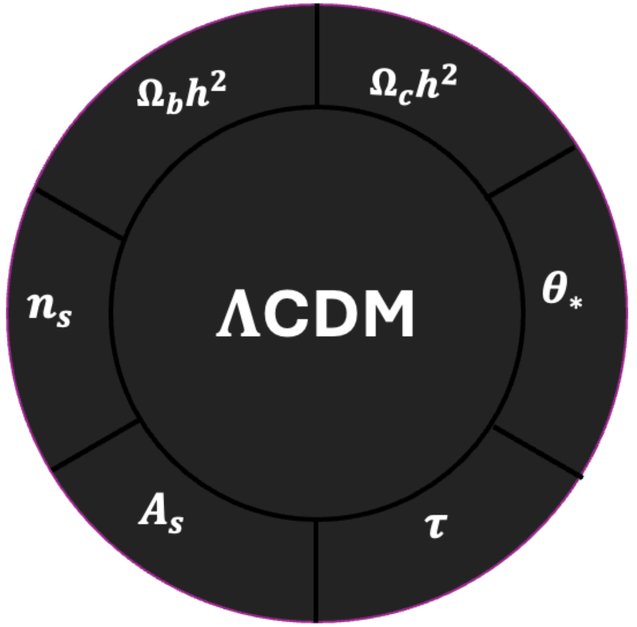
Outline

- ✦ The Standard Model of Cosmology
- ✦ Motivation for IR Cutoff Models of Primordial Power
- ✦ Renewed Interests IR Cutoff Models after DESI DR2
- ✦ Our work: Updated Constraints with Planck, ACT, SPT, ...
- ✦ Our work: Implications for CMB-BAO Tension
- ✦ Summary

The Standard Model of Cosmology: ΛCDM model

- $\Omega_b h^2$: Ordinary matter density
- $\Omega_c h^2$: Cold dark matter density
- θ_* : Angular scale of sound horizon
- τ : Optical depth up to EoR

- A_s : Amplitude of primordial power spectrum
- n_s : Tilt in primordial power spectrum



(Planck 2018:arXiv: 1807.06209)

Parameter	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02242 ± 0.00014
$\Omega_c h^2$	0.11933 ± 0.00091
$100\theta_{MC}$	1.04101 ± 0.00029
τ	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.047 ± 0.014
n_s	0.9665 ± 0.0038

$$P_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$

Dark Matter

Dark Energy

Inflation

Primordial Power Spectrum (PPS)

- Sets initial conditions for cosmological perturbations.
- Encodes information about **early-universe physics.**
- For the standard ΛCDM model, the power spectrum for curvature perturbations takes a nearly scale-invariant form:

$$\mathscr{P}_{\mathscr{R}}(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$

(Planck 2018:arXiv: 1807.06209)

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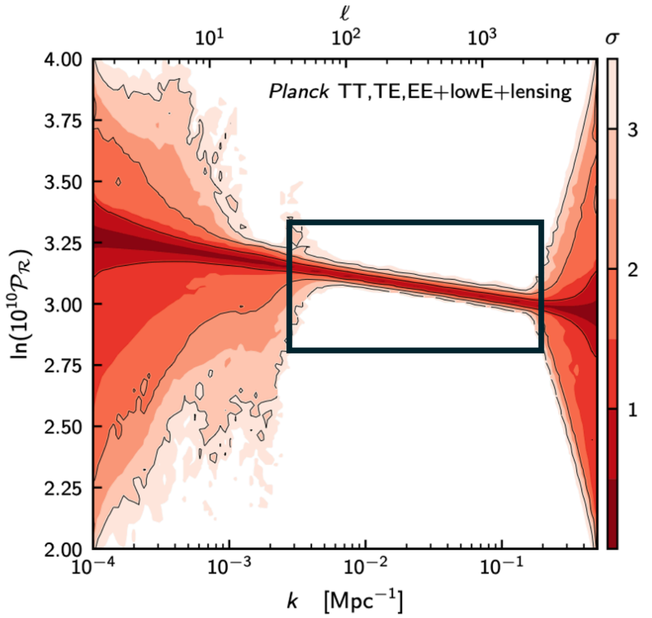
- **Not a direct observable:** acquire physical significance through their imprint on observable quantities as the Universe evolves within a given cosmological model.

$$C_\ell^{XY} \sim \int \frac{dk}{k} \mathscr{P}_{\mathscr{R}(k)} T_\ell^X(k) T_\ell^Y(k)$$

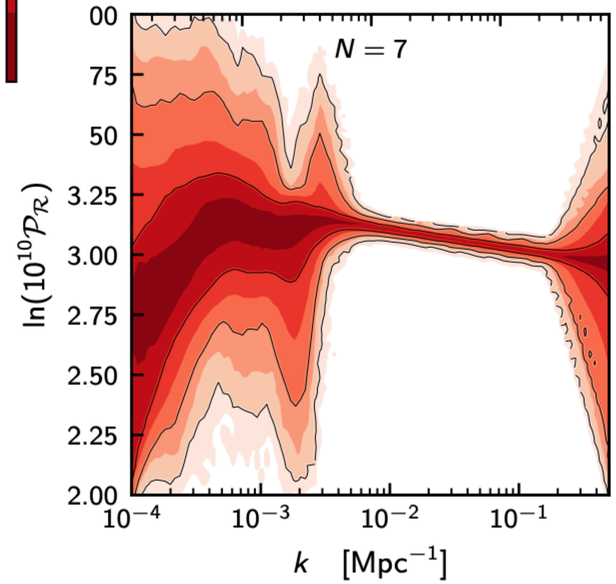
Constraints on PPS from Observations

What information can we extract about PPS from CMB data ?

- Parametric approaches (baseline + extensions models)
- Bayesian Reconstruction
- Non-parametric forms
- Deconvolution (Richardson Lucy algorithm)
- Feature based reconstructions



(arXiv: 1807.06211)



- **The CMB observations probe a small range:** $10^{-3} < k < 0.1\,\mathrm{Mpc}^{-1}$
- **Weak constraints on large scales (cosmic variance):** PPS reconstructions show broad freedom for $k < 10^{-3}\,\mathrm{Mpc}^{-1}$, allowing long-wavelength deviations.

Anomalies in CMB Power Spectrum

Features in power spectrum

Large scales:

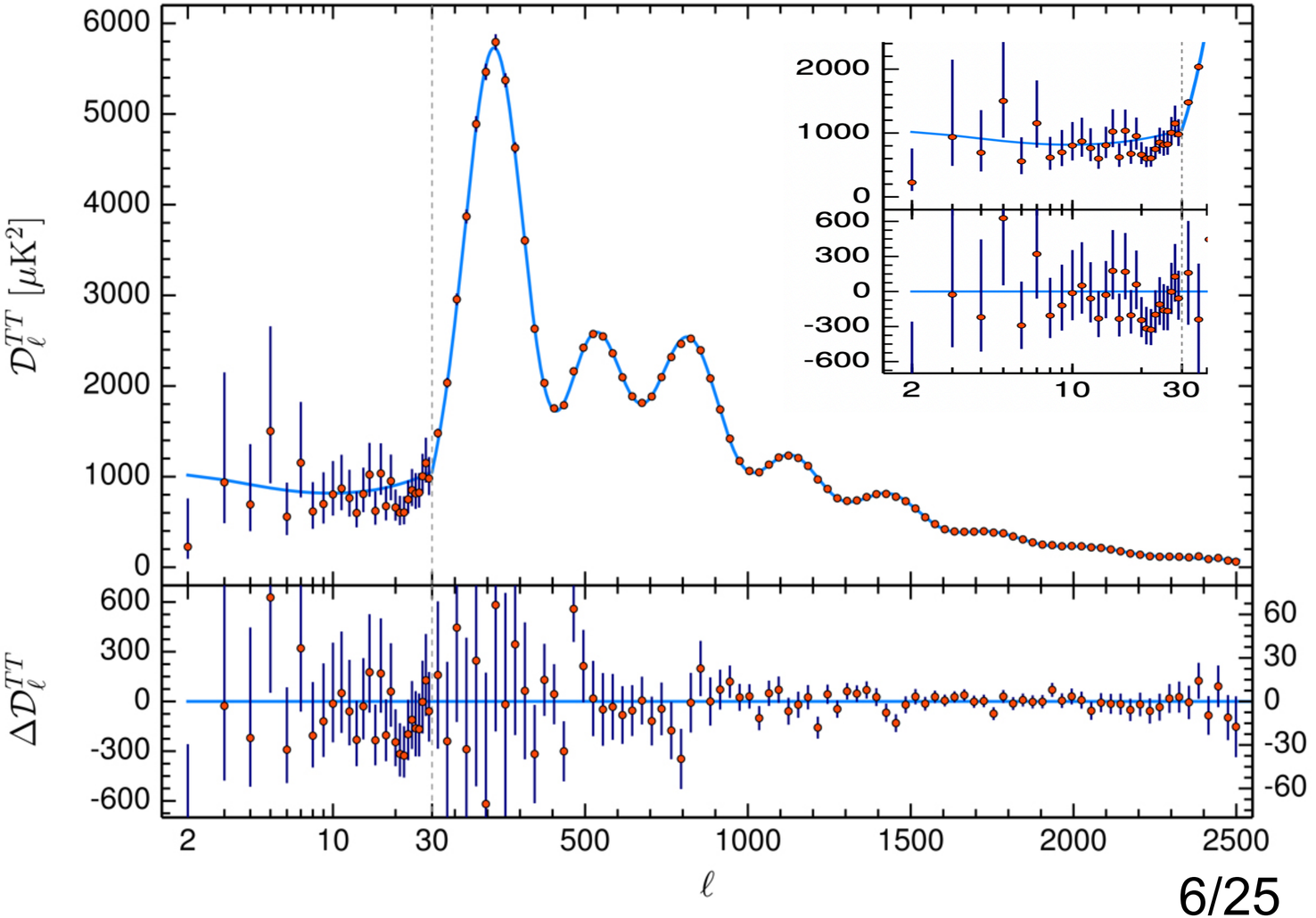
- Low quadrupole $\ell \sim 2$
- Localised dip around $\ell \sim 20 - 30$
- Odd-even power asymmetry at $\ell < 30$

Could have origin during inflation or before that?

Small-scale features:

- Oscillatory features around $\ell \sim 750$
- Lensing anomaly ? (almost settled !)

(arXiv: 1807.06209)



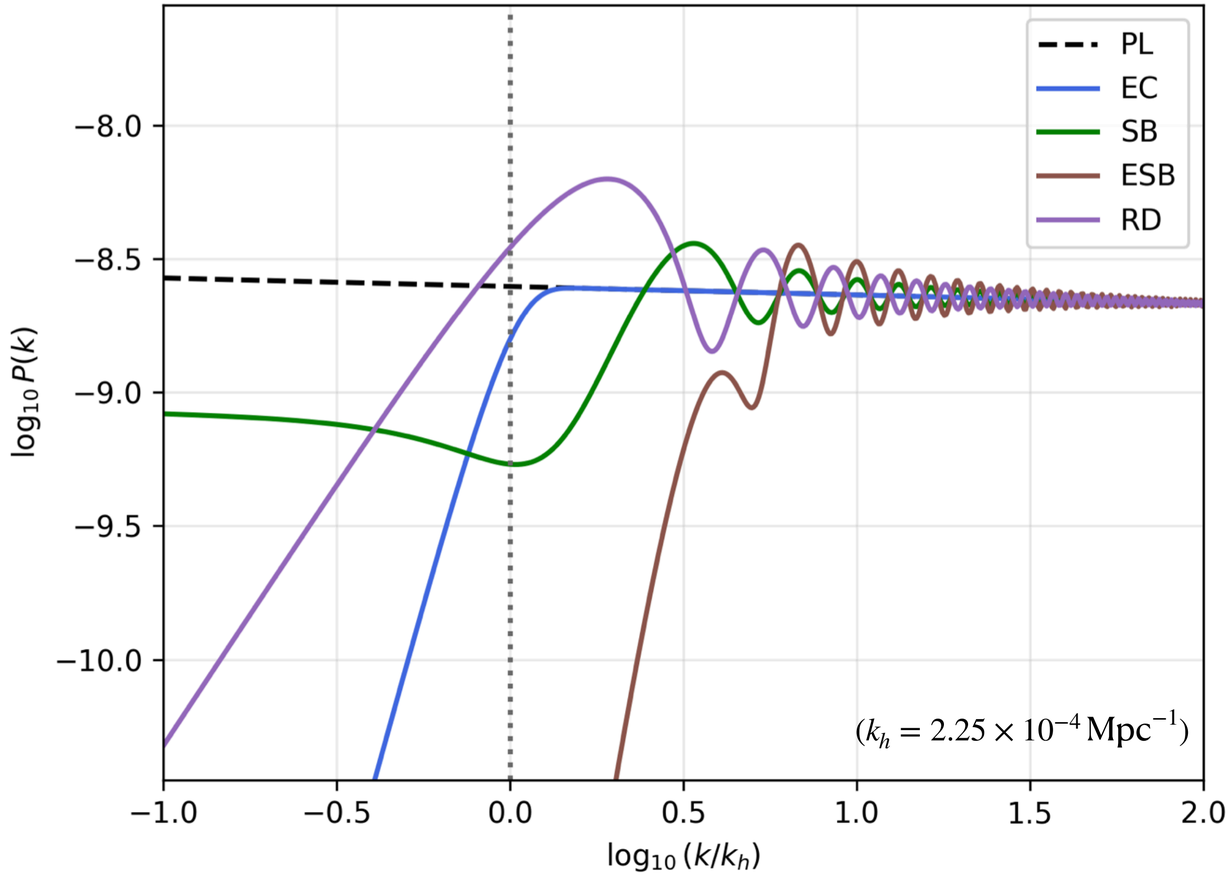
Primordial Power Spectrum with Infrared Cutoff

Observational Motivation:

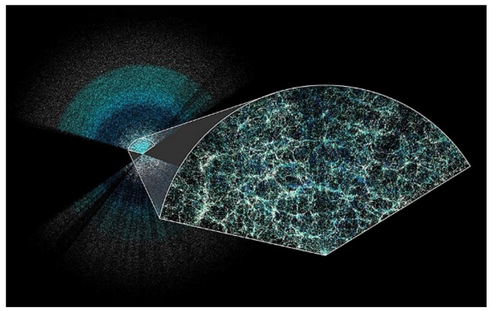
- Suppressed power on largest scales.
- Can address low quadrupole power ?
  (Though cosmic variance dominated !)
- Link to other low-ℓ CMB anomalies ?

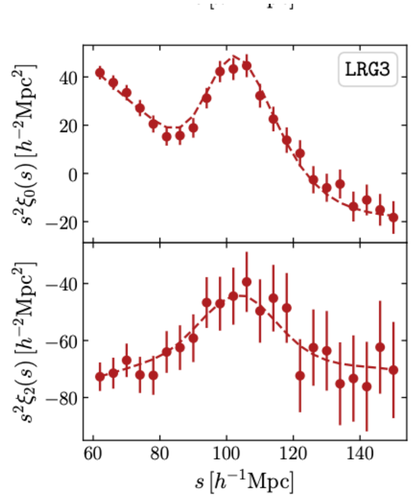
Deeper Motivation:

- Finite duration of inflation: we need 60 e-folds of inflation, which leaves room for non-trivial pre-inflationary physics.
- These non-trivial pre-inflationary physics can leave imprint on CMB.
- One of the imprint is large-scale power suppression.



CMB-BAO discrepancy after DESI DR2





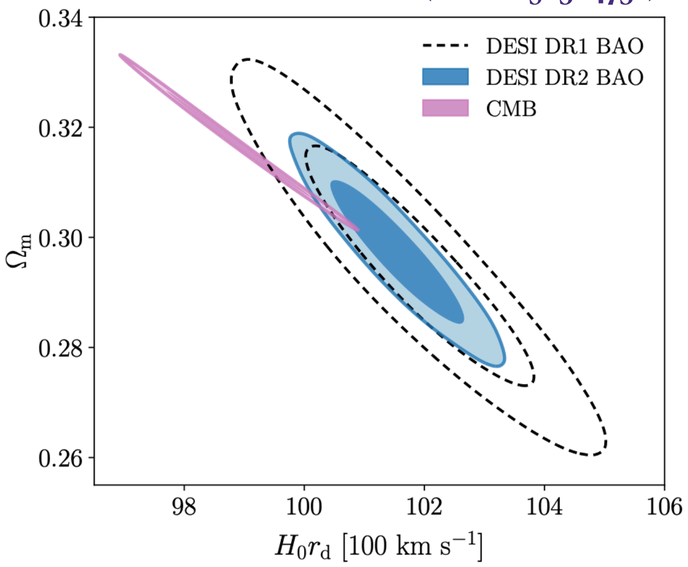


$$r_d = \int_{z_*}^{\inf} \frac{c_s(z')dz'}{H(z')}$$ Size of sound horizon (early-physics)

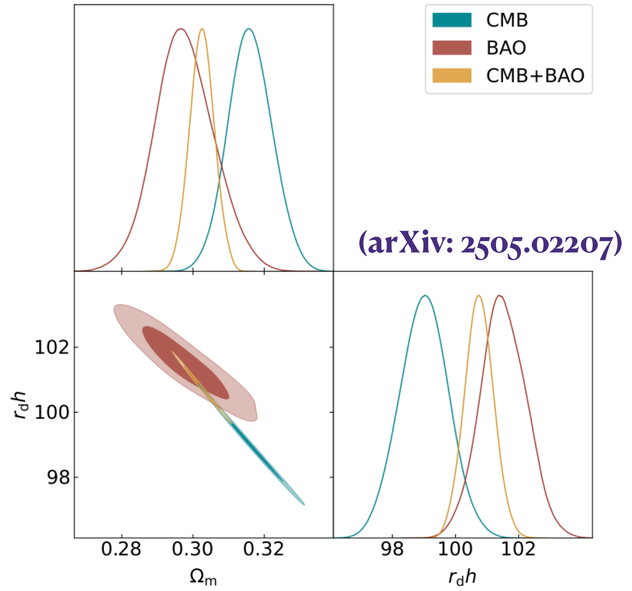
$$D_M(z) = \int_0^z \frac{dz'}{H(z')} \quad \text{and} \quad D_H(z) = \frac{c}{H(z)}$$

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + 1 - \Omega_m}$$ (ΛCDM model)

(arXiv: 2503.14738)



(arXiv: 2505.02207)

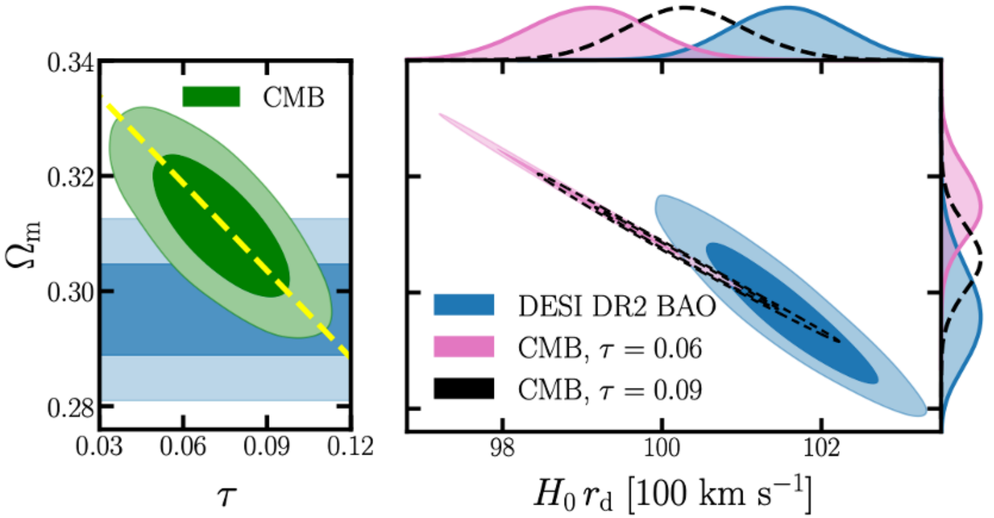


- Discrepancy in $\Omega_m - hr_d$ plane between CMB and BAO within ΛCDM.
- Particularly $> 2\sigma$ inconsistency in the parameter Ω_m.
- Resolved in extended scenarios like $w_0 w_a$CDM cosmology.

Link to inflationary features?

The optical depth resolution to the discrepancy !

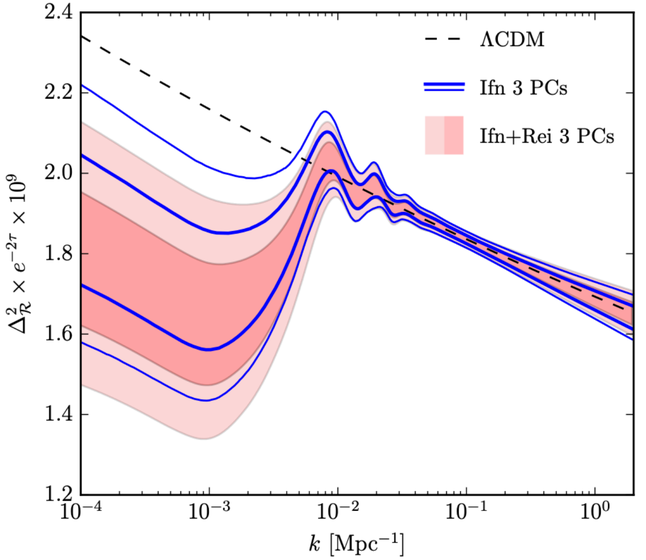
(arXiv: 2504.21813, arXiv: 2504.16932)



- **Increased optical depth** resolves discrepancy within ΛCDM.
- τ is also degenerate with inflationary parameters.

Large optical depth ⟷ Primordial power spectrum (IR cutoff)

- CMB temperature power spectrum constrains the combination $A_s e^{-2\tau}$
- Large τ leads to suppression of power by $e^{-2\tau}$
- Degenerate with effects of primordial power spectrum



(arXiv: 1803.01858)

This Work

Updated Constraints on Infrared Cutoff Models and Implications for Large-Scale CMB Anomalies

arXiv: 2602.16659 (Published in JCAP)

Authors: **Ujjwal Upadhyay**, Yashi Tiwari and Tarun Souradeep





IR Cutoff models

We work with a class of IR cutoff models of PPS using parametrised functional forms.

1. Updated constraints on model parameters : using latest CMB data sets (Planck, ACT, SPT)

2. Can IR cutoff features bias the inference of optical depth and help resolve CMB-BAO discrepancy, as pointed out in recent studies ? (No!)

3. CMB anomalies: A Bayesian view of large-scale anomaly statistics.

1. Updated Constraints on IR Cutoff Models

IR Cutoff models

Power Law (PL): $\mathscr{P}_{\mathscr{R}}(k) = \mathscr{P}_0(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1}$

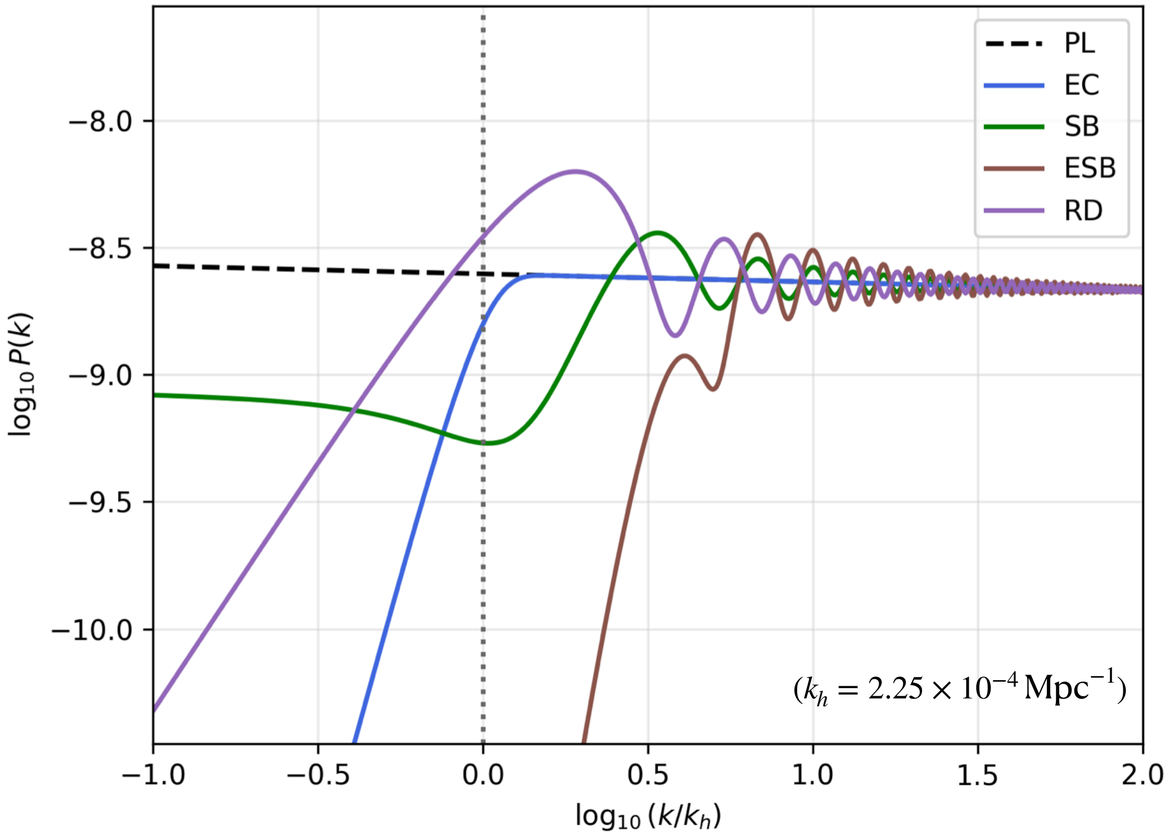
- Nearly scale-invariant spectrum with no preferred scale or features

Exponential Cutoff (EC): $\mathscr{P}_{\mathscr{R}}(k) = \mathscr{P}_0(k)\left[1 - e^{-(k/k_c)^{\alpha}}\right]$

- Can arise from finite-duration inflation or pre-inflationary modifications.
- Produces smooth suppression of power at very low k.

Starobinsky Break (SB): $\mathscr{P}_{\mathscr{R}}(k) = \mathscr{P}_0(k)\,\mathscr{D}^2(y, R_*),\ \ y = k/k_c$

- Generated by a sharp change in slope of the inflaton potential.
- Leads to large-scale suppression followed by damped oscillatory features



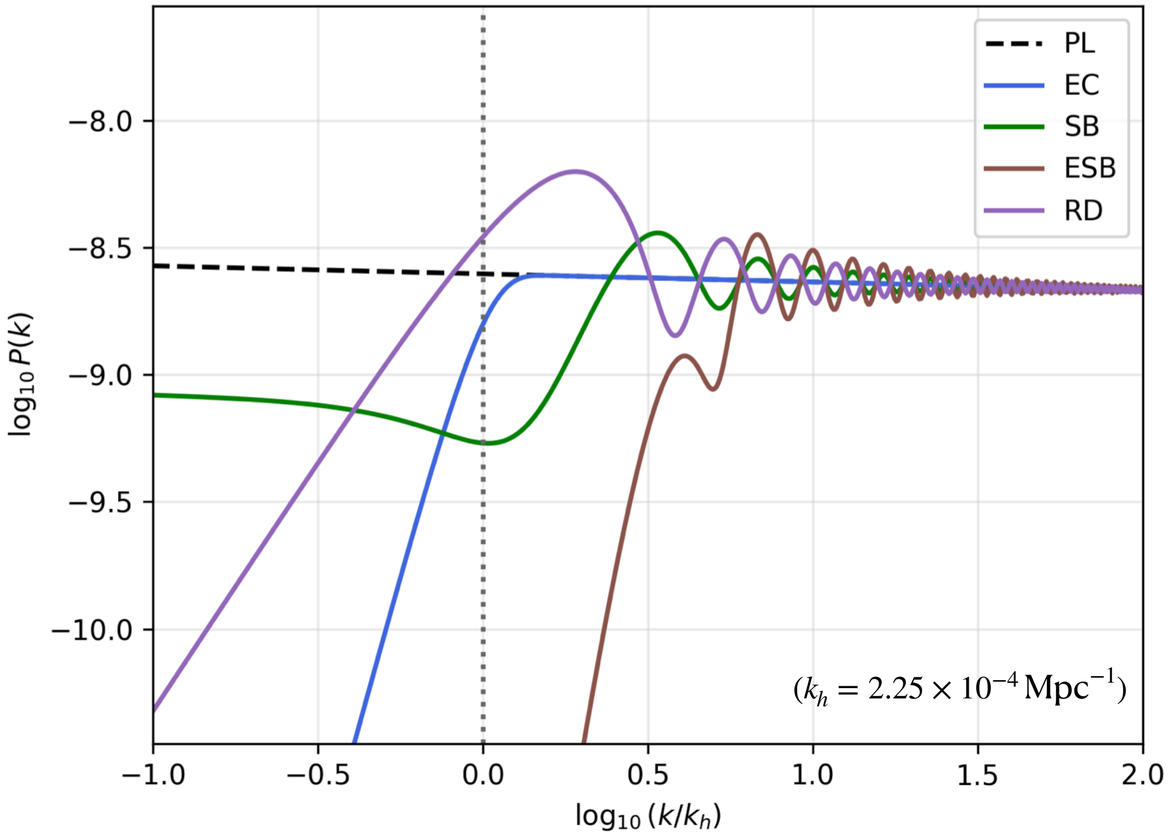
$$\mathscr{D}^2(y, R_*) = 1 - 3(R_* - 1)\frac{1}{y}\left(\left(1 - \frac{1}{y^2}\right)\sin(2y) + \frac{2}{y}\cos(2y)\right) + \frac{9}{2}(R_* - 1)^2\frac{1}{y^2}\left(1 + \frac{1}{y^2}\right)\left(1 + \frac{1}{y^2} + \left(1 - \frac{1}{y^2}\right)\cos(2y) - \frac{2}{y}\sin(2y)\right)$$

IR Cutoff models

Exponential-Starobinsky Model (ESB):

$$\mathscr{P}_{\mathscr{R}}(k) = \mathscr{P}_0(k)\left[1 - \exp\left(-\left(\frac{\epsilon k}{k_c}\right)^{\alpha}\right)\right] \mathscr{D}^2(y, R_*),$$

- Combines horizon-scale cutoff with a localized inflationary feature.
- Low- k suppression followed followed by a localized enhancement **(bump)** at intermediate scales.



Pre-inflationary Radiation Domination Model (RD):

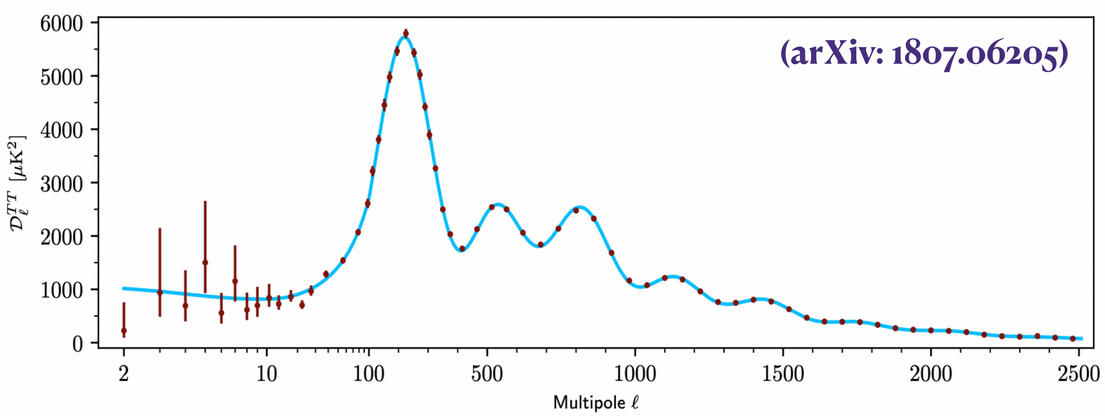
$$\mathscr{P}_{\mathscr{R}}(k) = \mathscr{P}_0(k)\frac{1}{4y^4}\left|e^{-2iy}(1+2iy) - 1 - 2y^2\right|^2$$

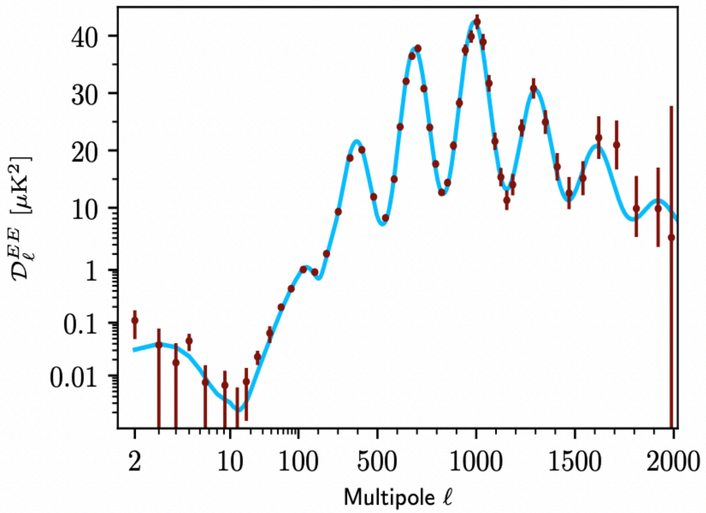
- Inflation preceded by a radiation-dominated era
- Similar dynamics can arise with an initial fast-roll (kinetic-dominated) phase preceding the onset of slow-roll inflation
- large-scale suppression followed by damped oscillatory features.

Features: IR Cutoff models

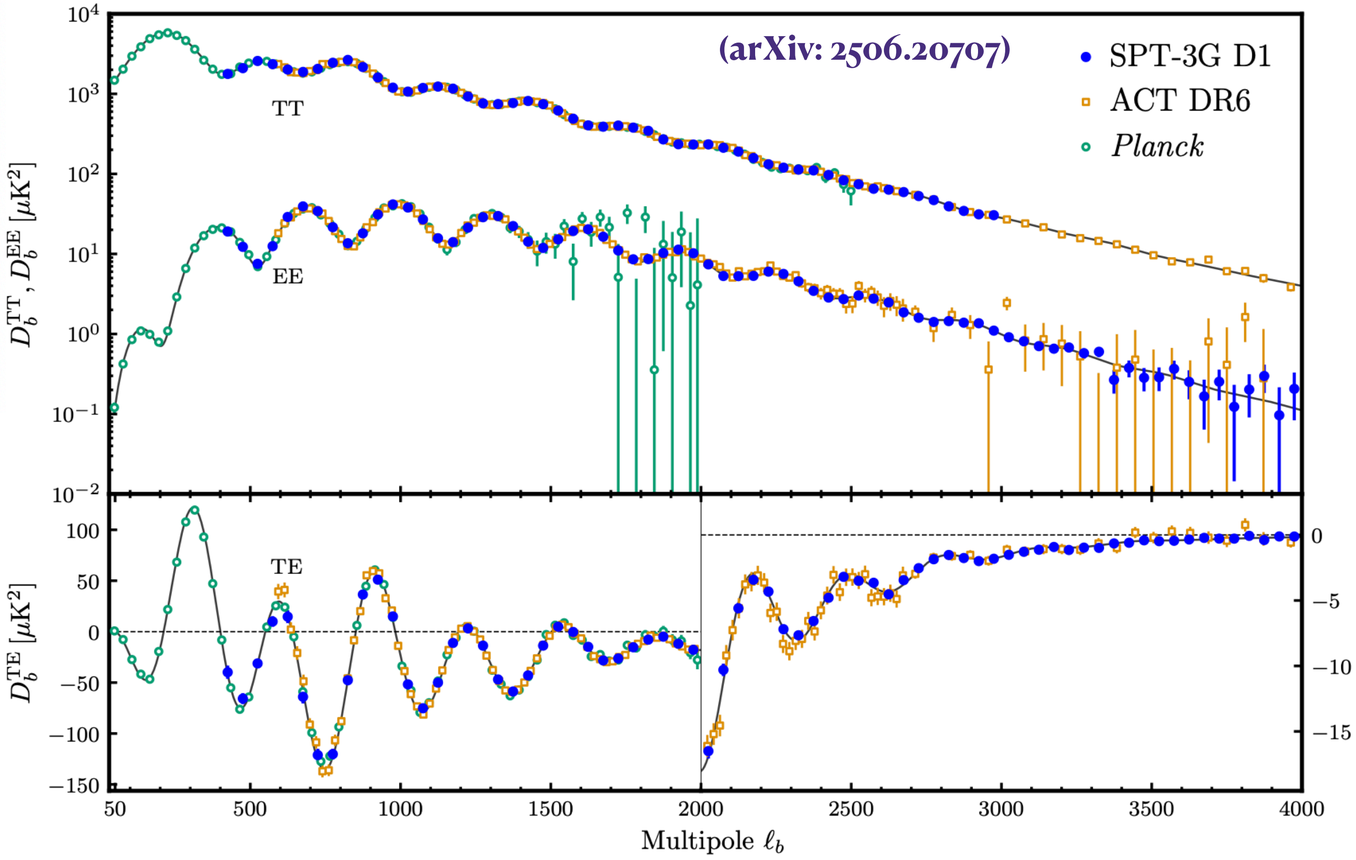
- **Cutoff Scale (k_c) :**
  - Large-scale power suppression.
  - Shows up in low-ℓ CMB power spectrum. (can improve fit at low multipoles?)
  - Can it perform better than standard case in model comparison ?
- **Oscillations on intermediate scales:**
  - most of these phenomenological models naturally give rise to oscillations spreading to smaller scales.
  - Oscillations in power spectrum are natural for any localised change, non-smooth transition (jump, step) etc in background.
  - Sensitivity to recent CMB observations like ACT, SPT: a complementary probe of such inflationary features?
- **Association with optical depth to reionisation:**

CMB Observations: Planck, ACT, SPT





- At low multipoles (large scales), the constraints are mainly from Planck 2018.
- Large error bars on low-multipoles due to cosmic variance, systematic uncertainties, limited sky coverage.

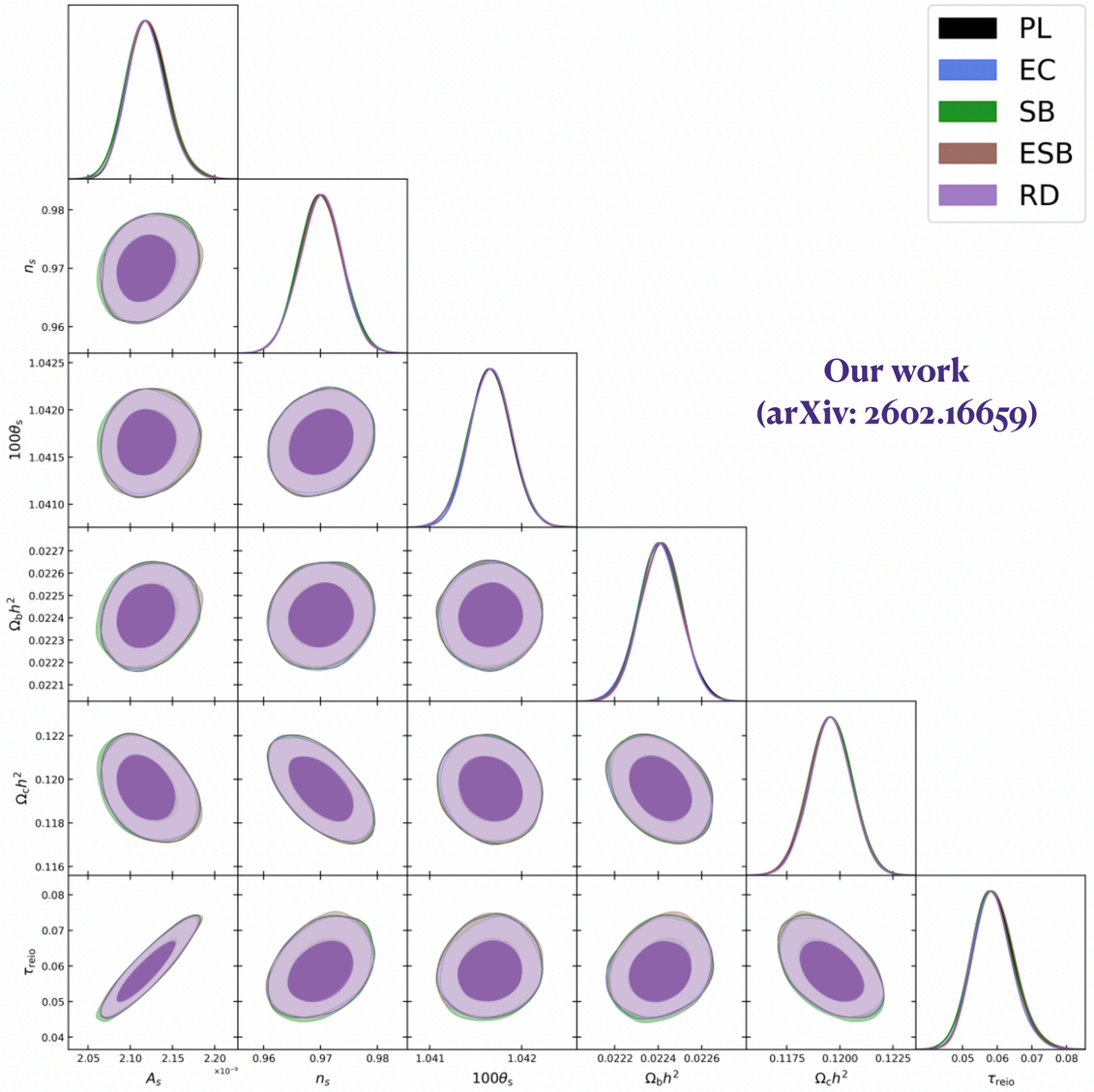


- ACT DR6 and SPT-3G D1 extends observations to large multipoles (smaller scales).
- sensitivity for small scale features.

IR Features: Constraints from CMB Observations

Description	Parameter	Prior
Physical baryon density	$\Omega_b h^2$	$\mathcal{U}(0.005, 0.1)$
Physical cold dark matter density	$\Omega_c h^2$	$\mathcal{U}(0.001, 0.99)$
Optical depth to reionization	τ_{reio}	$\mathcal{U}(0.01, 0.8)$
Angular scale of sound horizon	$100\theta_s$	$\mathcal{U}(0.5, 10)$
Amplitude of primordial power spectrum	$\ln(10^{10} A_s)$	$\mathcal{U}(1.6, 3.9)$
Scalar spectral index	n_s	$\mathcal{U}(0.8, 1.2)$
Infrared cutoff scale	$\ln k_c$	$\mathcal{U}(-12.0, -7.0)$
Sharpness of the cutoff	α	$\mathcal{U}(0.1, 10.0)$
Starobinsky parameter	R_*	$\mathcal{U}(0.01, 1.0)$

- Parameters remain largely unchanged and consistent with power-law case.
- Large-scale features mostly affect: A_s, n_s, τ (but no significant shift)



Our work
(arXiv: 2602.16659)

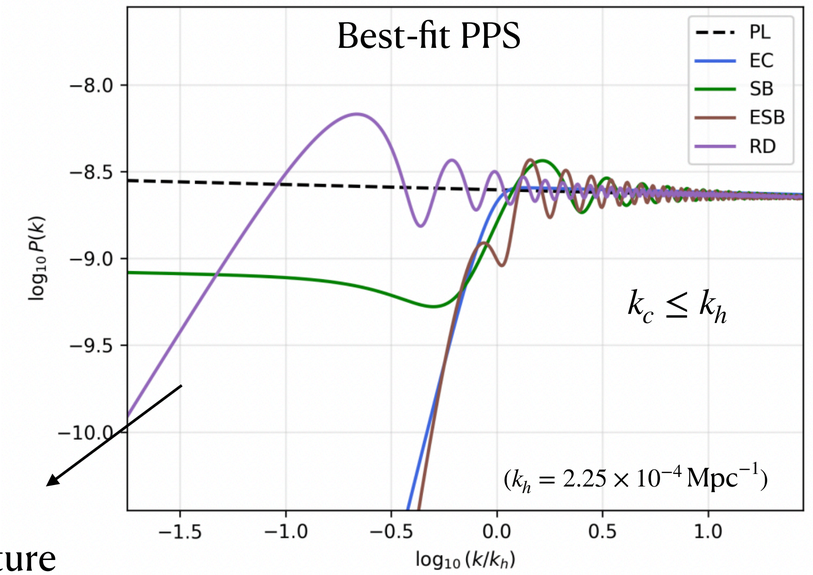
IR Features: Constraints from CMB Observations

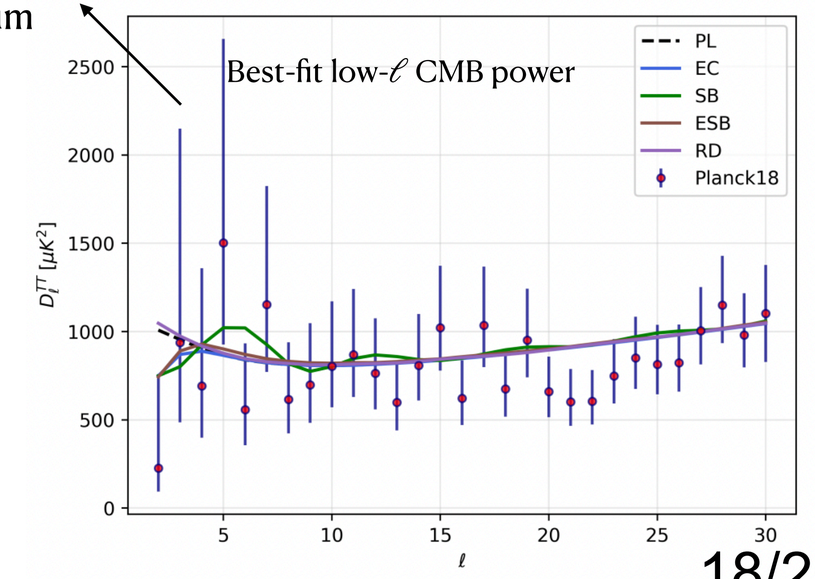
Parameter	PL	EC	SB	ESB	RD
$10^9 A_s$	2.1079	2.1257	2.1013	2.1228	2.11
n_s	0.9696	0.9714	0.9669	0.9726	0.9684
τ_{reio}	0.0564	0.0598	0.0525	0.0604	0.0579
$\Omega_b h^2$	0.0224	0.0224	0.0224	0.0223	0.0224
$\Omega_c h^2$	0.1198	0.1192	0.1197	0.1184	0.1199
H_0 [km s^{-1} Mpc^{-1}]	67.4042	67.6197	67.4864	67.8463	67.3878
$10^4 k_c$ [Mpc^{-1}]	-	2.1580	1.4056	0.4770	0.2561
α	-	4.7596	-	4.8963	-
R_*	-	-	0.5586	0.0422	-
$\chi^2_{\text{low}-\ell\ \text{TT}}$	22.5389	21.2241	21.7607	20.9235	22.4575
$\chi^2_{\text{low}-\ell\ \text{EE}}$	390.051	390.774	390.243	390.925	390.229
$\chi^2_{\text{PlanckACT}_{\text{cut}}}$	221.198	221.0	218.637	219.208	221.368
χ^2_{ACT}	158.732	158.675	159.399	160.836	158.533
χ^2_{SPT}	160.967	161.612	161.681	161.662	160.802
$\chi^2_{\text{PR4 lensing}}$	8.7412	8.8353	8.5527	8.3760	8.7810
χ^2_{total}	962.228	962.12	960.274	961.93	962.171
$\Delta\chi^2$	0	−0.108	−1.954	−0.298	−0.057
ΔAIC	0	+3.892	+2.046	+5.702	+1.943

Our work
(arXiv: 2602.16659)

- Cutoff scale is strongly constrained to very large scales (small k_c), leaving no significant suppression in temperature anisotropy power spectrum

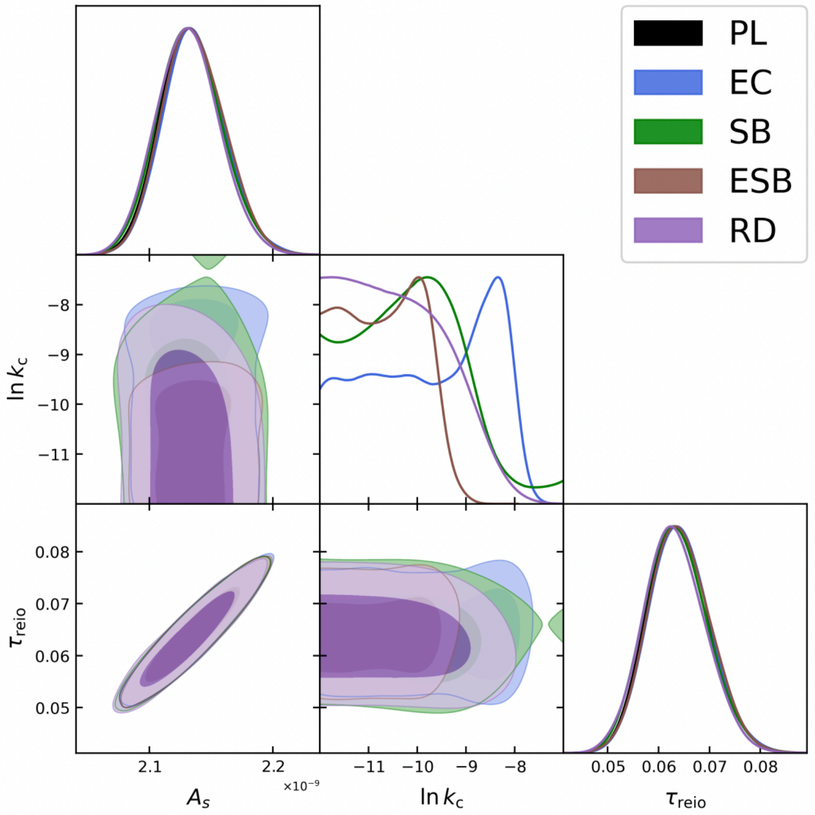
small improvement in low-ℓ χ^2





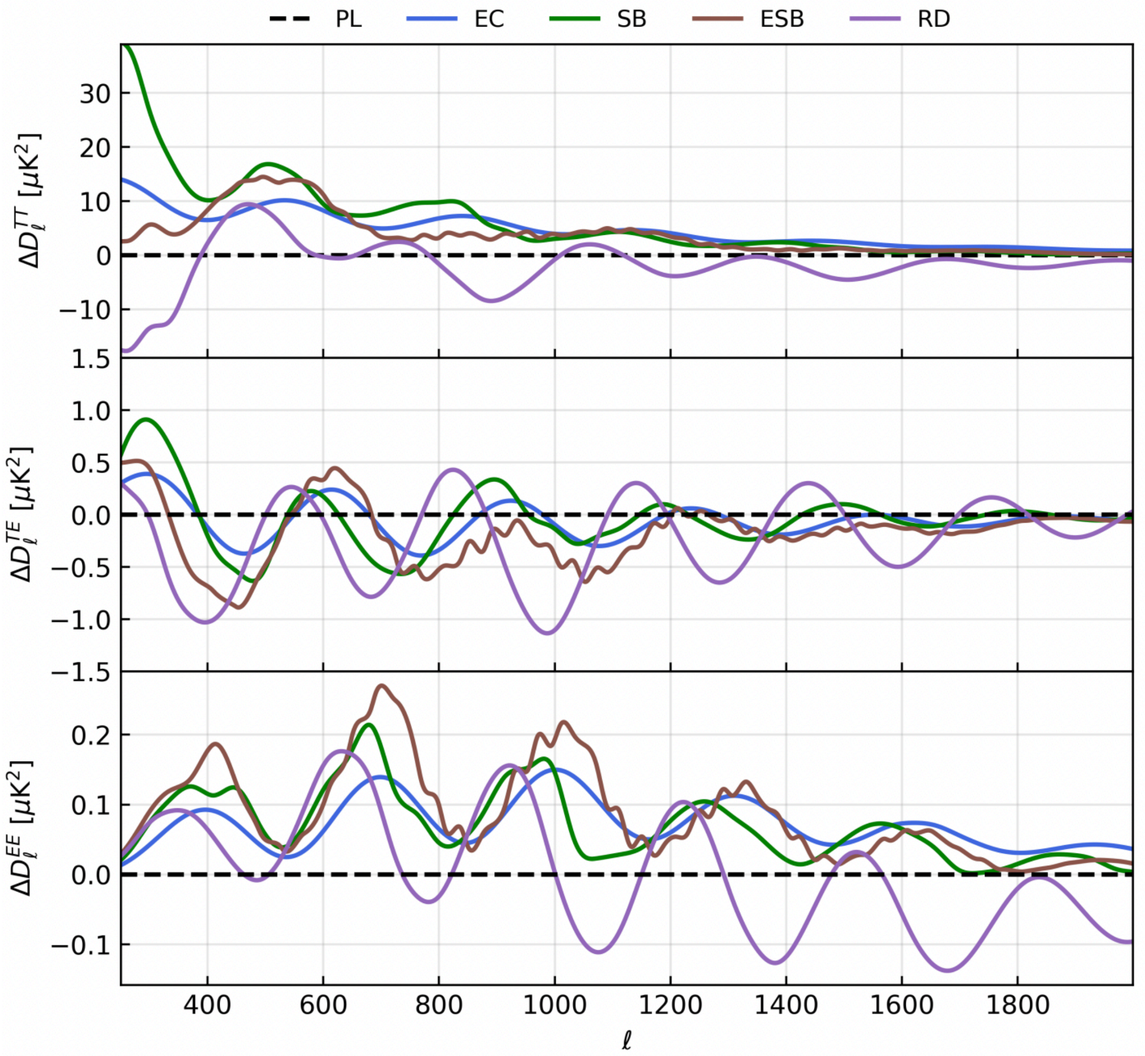
IR cutoff models do not out perform power-law due to statistical penalty of additional parameters. **(No strong evidence !)**

IR Features: Constraints from CMB Observations



Our work
(arXiv: 2602.16659)

- The oscillatory features on small scales in PPS, affects the power on large multipoles.
- That is why, cutoff scale is shifted towards scales when all data is combined.



Best-fit CMB residual power spectrum on large multipoles

- Upper bound on k_c ($\leq k_h$) in all cases.

RD model behaves relatively different on intermediate scales:
effects on the parameters like Ω_b, Ω_{cdm}, θ_*

IR cutoff Features : Do we have a verdict?

No strong preference from current data:

- But also not ruled out! (ICs indecisive)
- The tightest constraints on suppression features come from very low-ℓ C_ℓ^{TT}
- But Planck has almost reached cosmic variance limit in TT on very low multipoles !
  (**So no improvement expected from temperature anisotropy in future)**

What else: Future observations ?

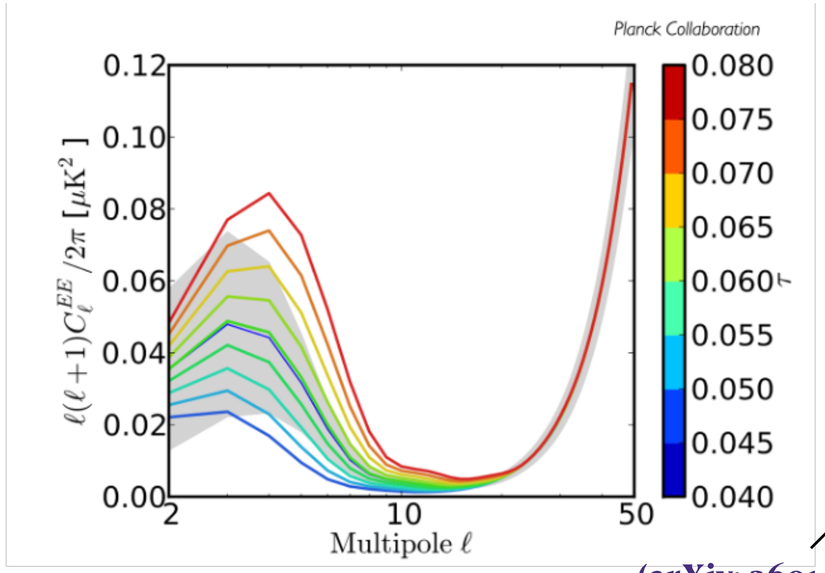
- Large Scale E-mode polarisation: LiteBird will reduce error bars by an order of magnitude on $\ell < 30$
- Cross-correlation between CMB and LSS? LiteBird, DESI, Euclid, SKA ?
  (Future LSS can constrain matter power on $k \sim 10^{-3}\,\mathrm{Mpc}^{-1}$ corresponding to $\ell \sim 10 - 30$)

2. Implication for the CMB-BAO Tension

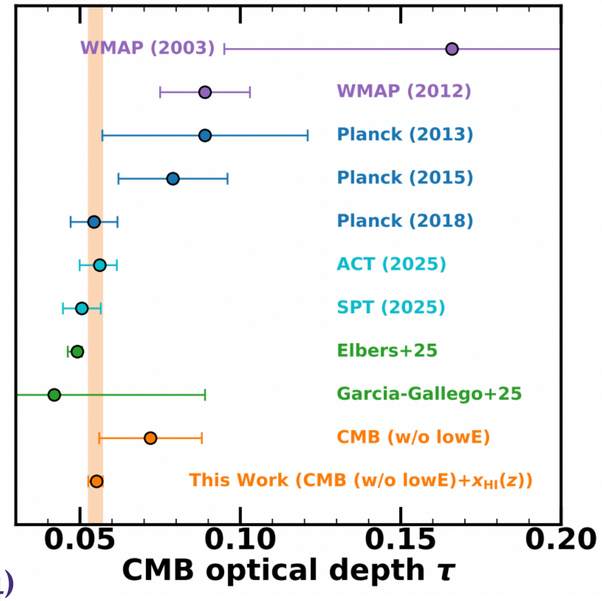
Optical Depth Resolution to CMB-BAO discrepancy ?

Optical depth to reionisation (τ):

- τ quantifies the integrated Thomson scattering probability of CMB photons after reionisation.
- Scattering suppresses CMB temperature anisotropies, particularly: $C_\ell^{TT} \to e^{-2\tau} C_\ell^{TT}$
- Moreover, low-ℓ C_ℓ^{TT} constrains $A_s\, e^{-2\tau}$ (inflation-reionsation degeneracy)
- **Scattering generates large-scale polarisation (at low multipoles): reionisation bump in C_ℓ^{EE}** ⟶ **Constrains τ independently**

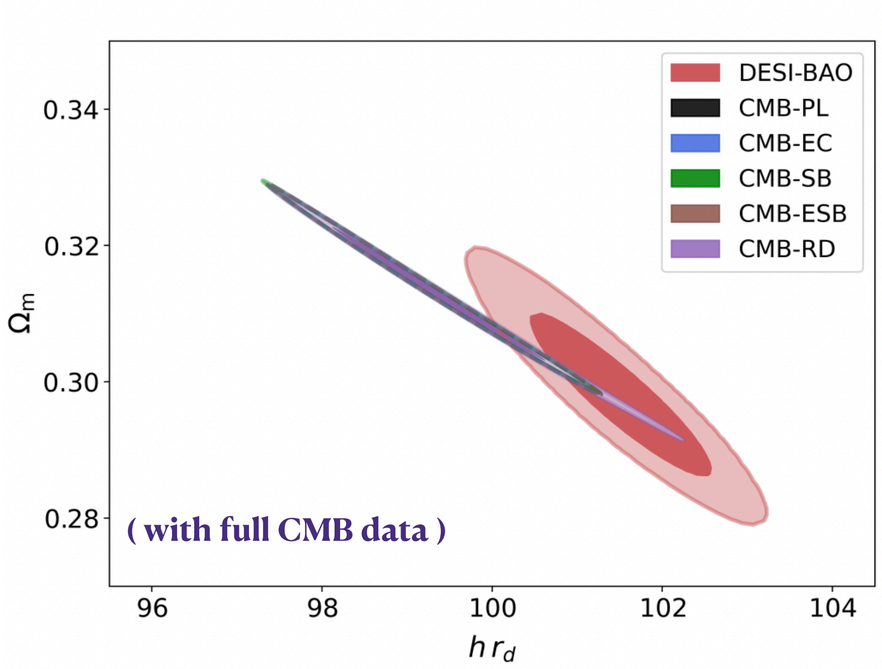


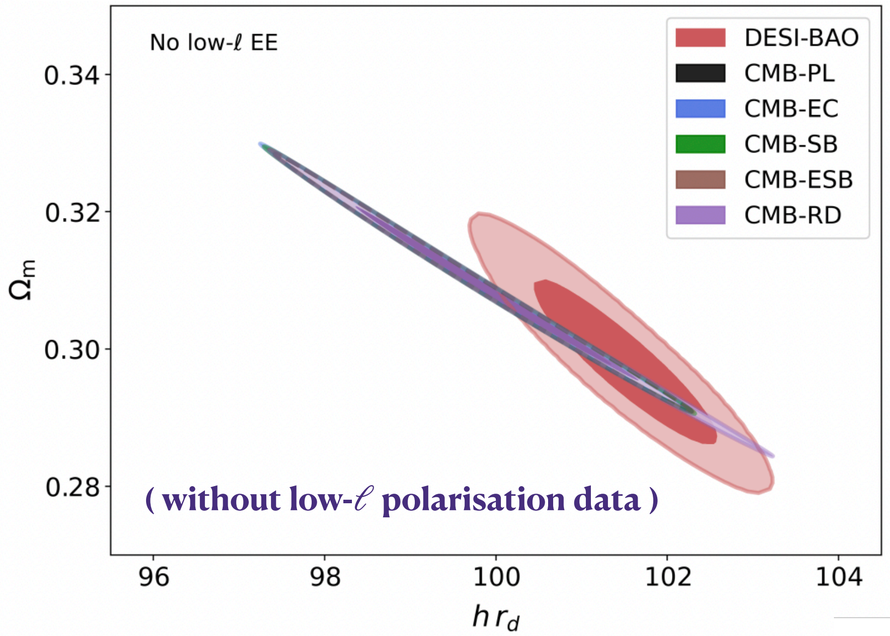
(arXiv: 2601.09644)



- Best constraint on τ from Planck low-ℓ polarisation.
  $$\tau = 0.059 \pm 0.007$$
- Large $\tau \sim 0.09$: relaxes CMB-BAO discrepancy.
- **Larger τ ??** Relaxing polarisation constraint? can IR cutoff features bias inference of τ ?

IR Cutoff Models and CMB-BAO Discrepancy

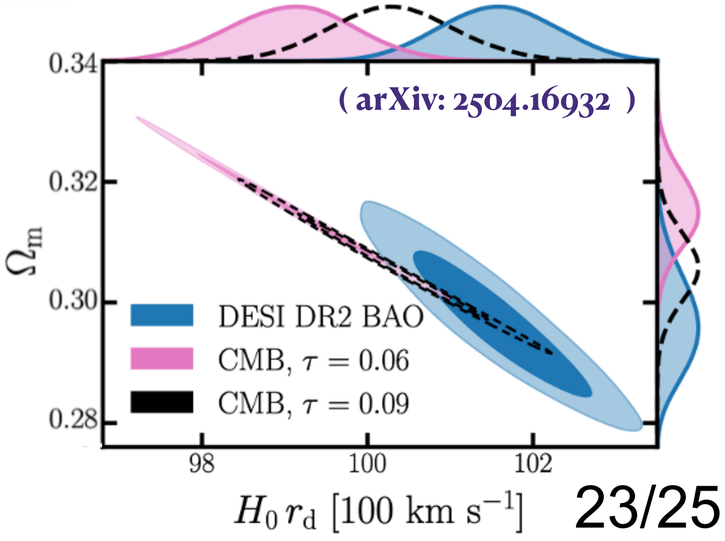




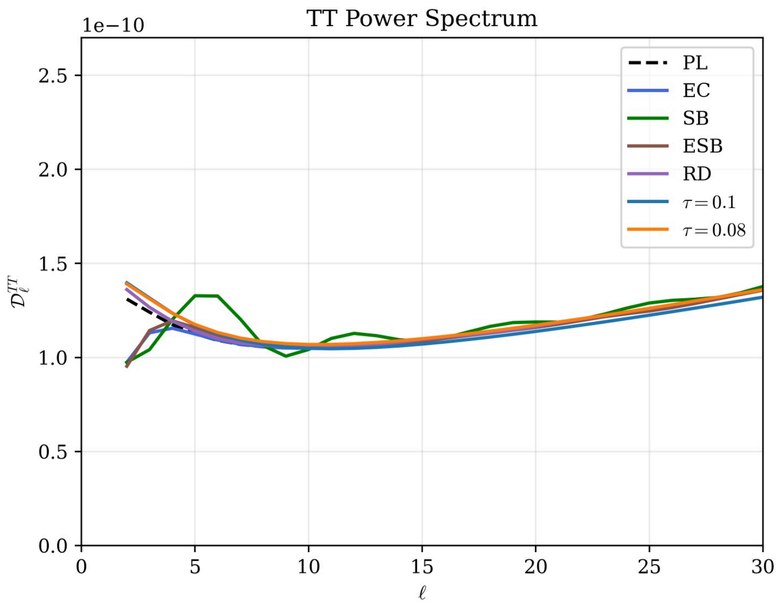
RD-model: shows improved consistency, which arises from asymmetric error bars in $\Omega_b, \Omega_{cdm}, \theta_*$ due to peculiar oscillations on intermediate scales. Not because of power suppression at large scales!

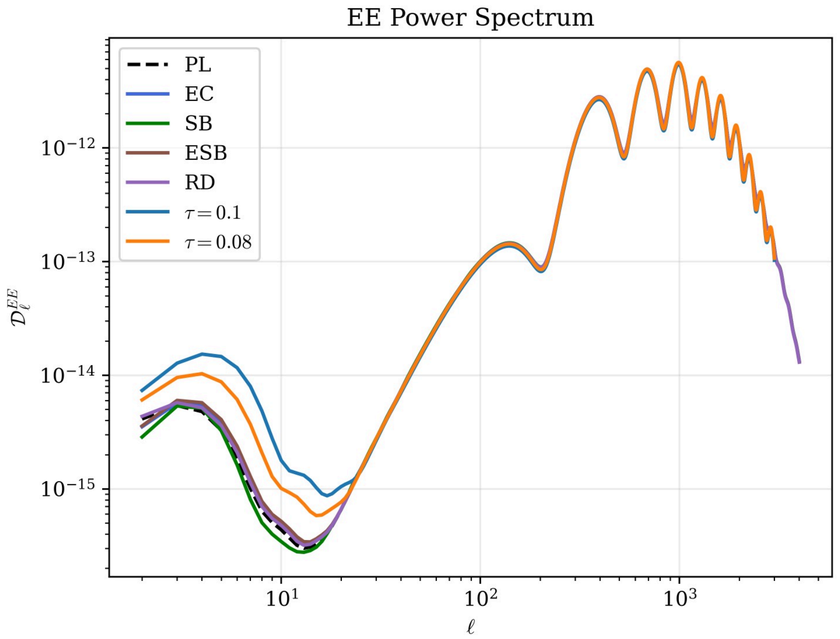
- All IR cutoff scenarios give similar constraints like power-law case (no-significant resolution of discrepancy in $\Omega_m - hr_d$ plane.
- **Only if we remove the polarisation constraints from low-ℓ polarisation (which relaxes constraints on τ.**
- **IR cutoff do not add much freedom to increase τ.**

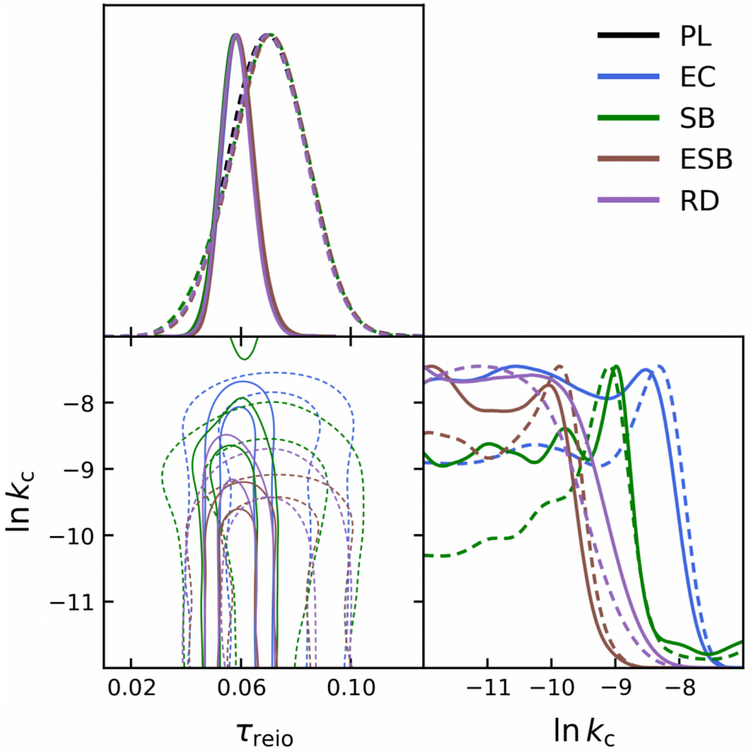
Our work
(arXiv: 2602.16659)



IR Cutoff Models and CMB-BAO Discrepancy







- Cutoff scale is tightly **constrained primarily by the CMB temperature power spectrum**: no significant features survive.
- This has a negligible impact on low-ℓ C_ℓ^{EE} (not enough to raise τ to sufficiently large values.)
- Even if polarisation data is removed, the cutoff constraints (k_c) do not change significantly.

Our work
(arXiv: 2602.16659)

Summary

IR cutoff models of PPS:

- No significant evidence for IR cutoff features from present CMB observations.
- These suppression features cannot help increase the inference of τ: hence cannot resolve CMB-BAO discrepancy by modifying PPS

About optical depth resolution to the tensions:

- Can increasing τ really resolve several cosmological discrepancies ?
- But at present we have best constraints on τ from CMB data which prefer low values !
- Independent measurement of τ from other observations (JWST, SKA) ?
- What physics can explain an increased τ ?

Thank You !