Probing primordial features due to particle production during inflation in the CMB data

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Based on **JCAP07(2022)016** [arXiv:2202.05862] by **Suvedha Suresh Naik, Kazuyuki Furuuchi (MCNS) & Pravabati Chingangbam (IIA)**

Plan of the talk

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- The Models
- Methodology
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  - Selection of priors
- Results
  - Single burst of particle production
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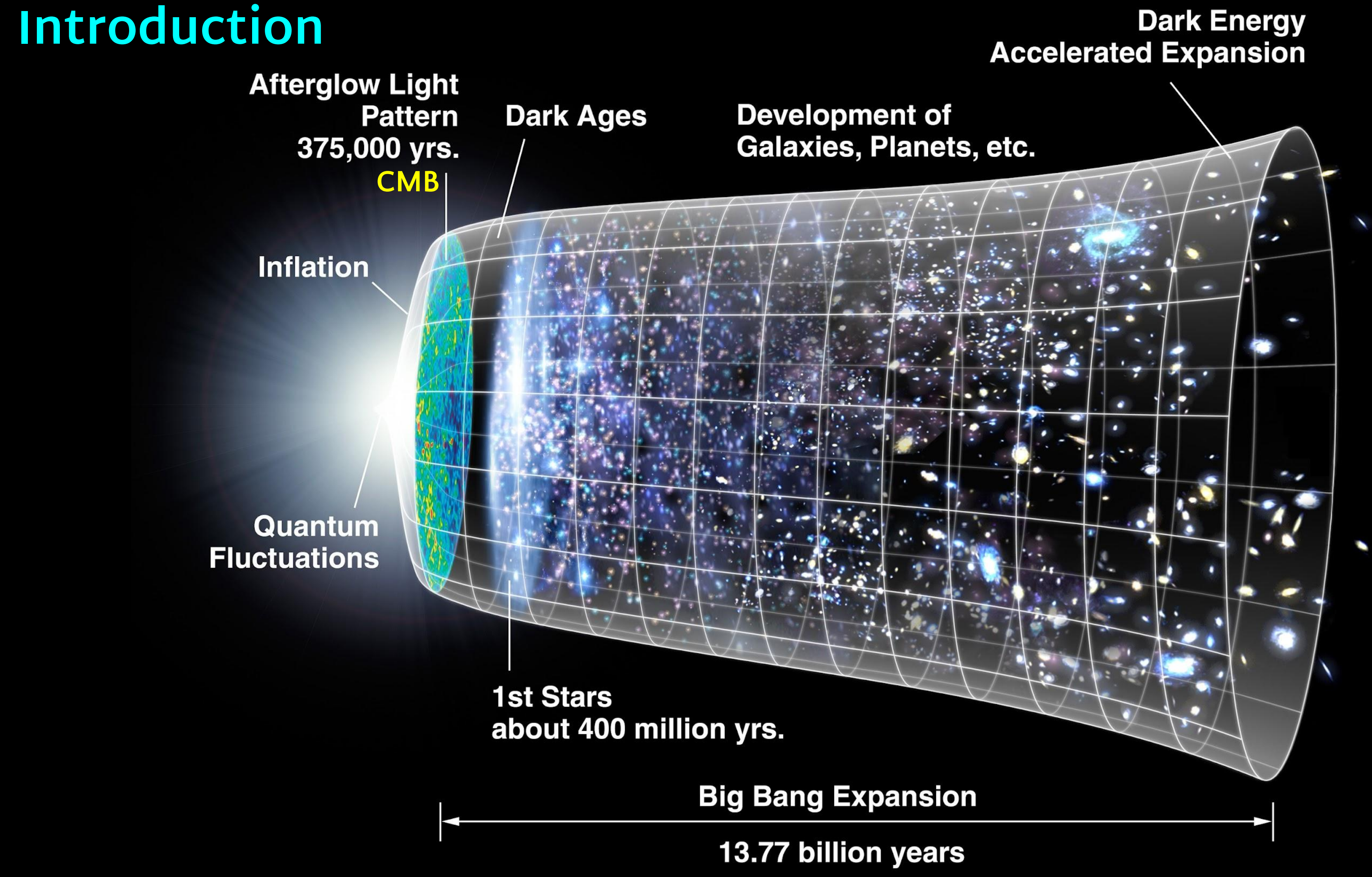
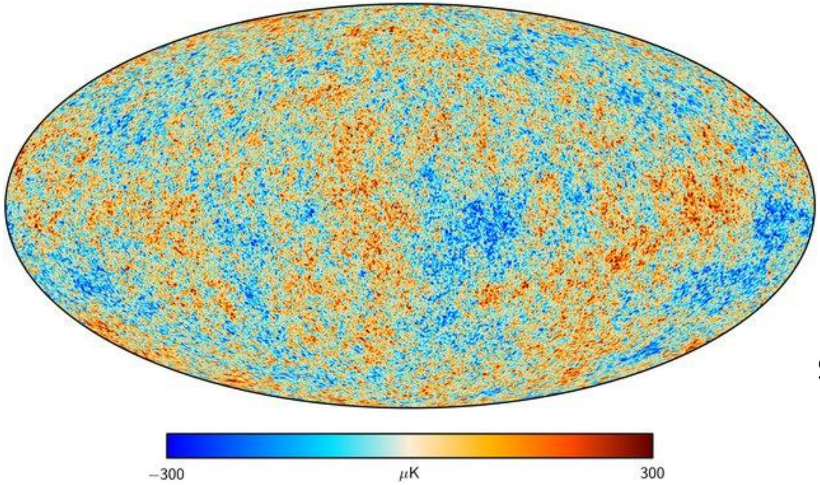
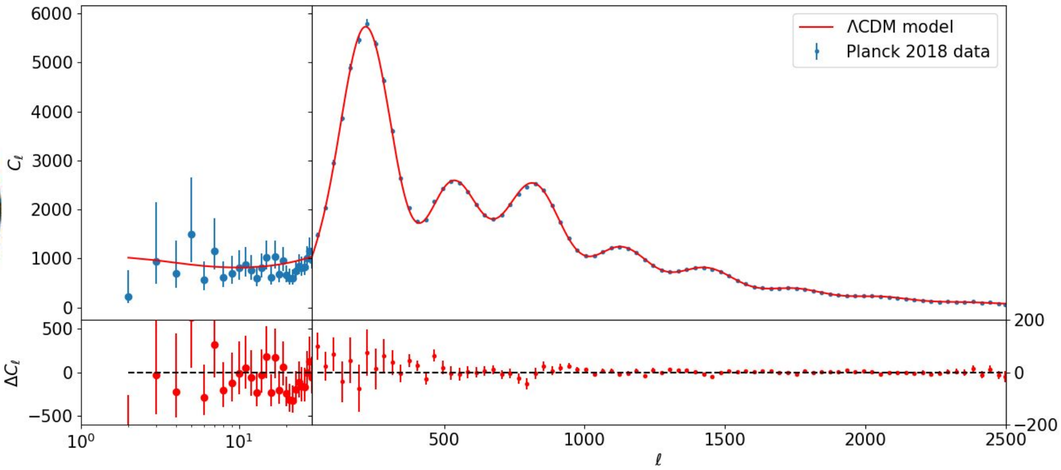
Introduction



Cosmic Microwave Background (CMB) Observations





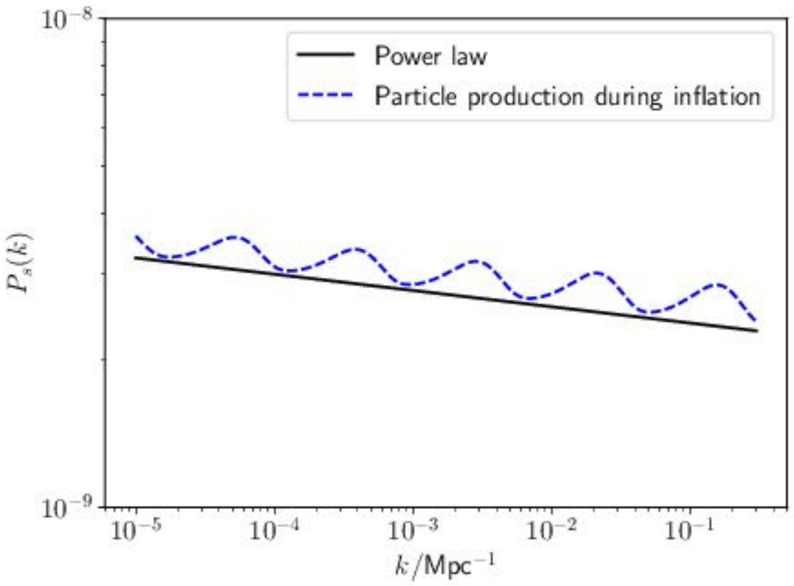
The Models

- **Interaction term**: $g^2 (\phi - \phi_0)^2 \chi^2$

  *g*² - dimensionless coupling constant, model parameter

- **Particle production**: When the inflaton field value crosses $\phi = \phi_0$ during inflation → Field χ becomes massless → Burst of particle productions*

  → **Bump-like features in primordial power spectrum**



* Chung et al. (2000), Barnaby et al. (2009), Barnaby & Huang (2009), Barnaby (2010), Chluba et al. (2015), Pearce et al. (2017), Furuuchi (2016), Furuuchi et al. (2020a), Furuuchi et al. (2020b)

The Models

Inflation models based on gauge theory in higher dimension

$$S = \int d^4x \left[\frac{1}{2}\partial_\mu \phi(x)\partial^\mu \phi(x) - V(\phi) + \sum_{n=-\infty}^{\infty} \left\{ D_\mu \chi_n^\dagger(x) D^\mu \chi_n(x) + \chi_n^\dagger(x) g^2 \left(\phi(x) - 2\pi f n\right)^2 \chi_n(x) \right\} \right]$$

ϕ - extra-dimensional component of the gauge field
f - symmetry breaking scale
n - integer values

V (ϕ) - potential for inflaton field
χ - complex scalar fields
D_μ - gauge covariant derivative
g - 4D gauge coupling constant

[Furuuchi (2016), Furuuchi et al. (2020a), Furuuchi et al. (2020b)]

Primordial Power Spectrum

The fiducial model: $P_s(k) = A_s \left(\frac{k}{k_*}\right)^{n_s-1}$

PLANCK collaboration

$k_* = 0.05\text{Mpc}^{-1}$

$n_s = 0.9649 \pm 0.0042$

Models with primordial features due to particle production during inflation:

Barnaby & Huang (2009) - Power spectrum template by fitting numerical results

Pearce et al. (2017) - analytical expression

$$P_s(k) = A_s \left(\frac{k}{k_*}\right)^{n_s-1} + A_{\rm I} \sum_i \left(\frac{f_1(x_i)}{f_1^{\rm max}}\right) + A_{\rm II} \sum_i \left(\frac{f_2(x_i)}{f_2^{\rm max}}\right)$$

$$A_{\rm I} \simeq 6.6 \times 10^{-7} g^{7/2}$$

$$A_{\rm II} \simeq 1.1 \times 10^{-10} g^{5/2} \ln\left(\frac{g}{0.0003}\right)^2$$

$$f_1^{\rm max} \simeq 0.11 \quad f_2^{\rm max} \simeq 0.85$$

$$f_1(x_i) \equiv \frac{[\sin(x_i) - \text{SinIntegral}(x_i)]^2}{x_i^3}$$

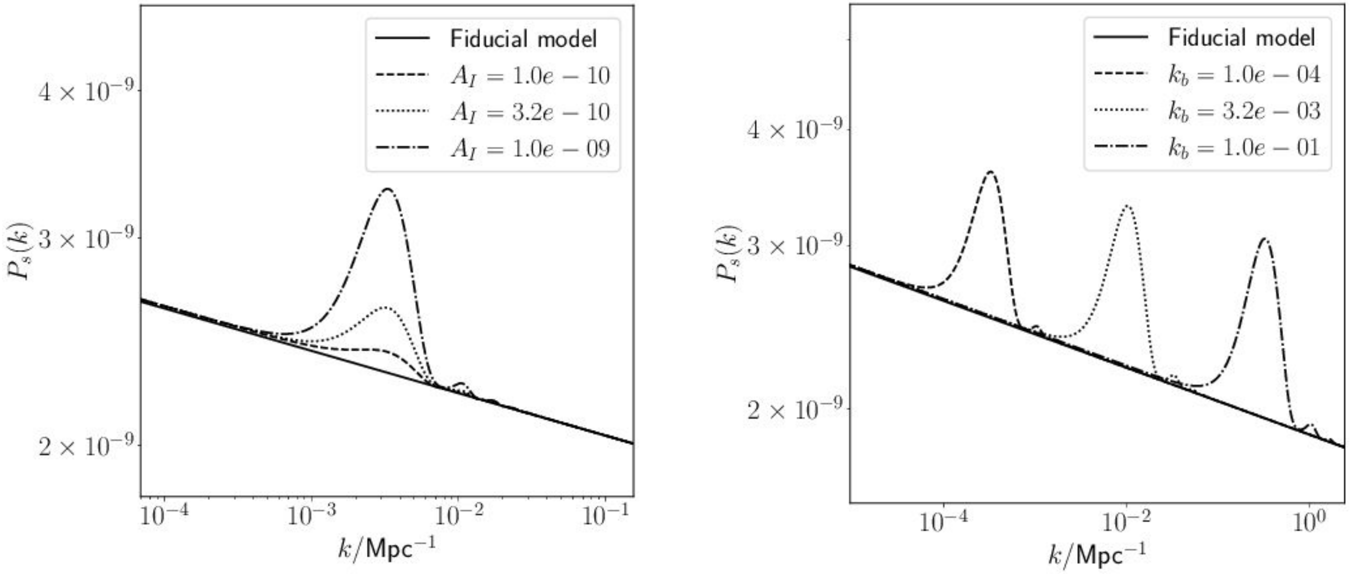
$$f_2(x_i) \equiv \frac{-2x_i \cos(2x_i) + (1 - x_i^2)\sin(2x_i)}{x_i^3}$$

$$x_i \equiv \frac{k}{k_i} \qquad \text{SinIntegral}(x) = \int_0^x \frac{\sin z}{z} dz$$

Primordial Power Spectrum

Models with primordial features due to particle production during inflation:

$$P_s(k) = A_s\left(\frac{k}{k_*}\right)^{n_s-1} + A_{\rm I}\left(\frac{f_1(k/k_b)}{f_1^{\max}}\right) + A_{\rm II}\left(\frac{f_2(k/k_b)}{f_2^{\max}}\right)$$



Methodology: Model Selection

- **Effective $\Delta\chi^2$**

$$\Delta\chi^2_{\rm eff} := \chi^2_{M_1} - \chi^2_{M_0}$$

Planck collaborations 2013, 2015, 2018

- **Bayes Theorem**

$$\text{Posterior probability distribution } p(\theta|\text{data}) = \frac{\text{Likelihood } p(d|\theta) \times \text{Prior } p(\theta)}{\text{Evidence } Z,\ p(d)}$$

- **Bayes factor $B_{01} = Z_{M1}/Z_{M0}$**

$\lvert \ln B_{01} \rvert$	Odds	Probability	Strength of evidence
< 1.0	$\lesssim 3:1$	< 0.750	Inconclusive
1.0	$\sim 3:1$	0.750	Weak evidence
2.5	$\sim 12:1$	0.923	Moderate evidence
5.0	$\sim 150:1$	0.993	Strong evidence

Jeffrey's scale for Bayesian model comparison (Jeffreys, 1939); interpretations modified by (Trotta, 2007).

Methodology: Data and Codes

Data: Planck 2018 temperature and polarization

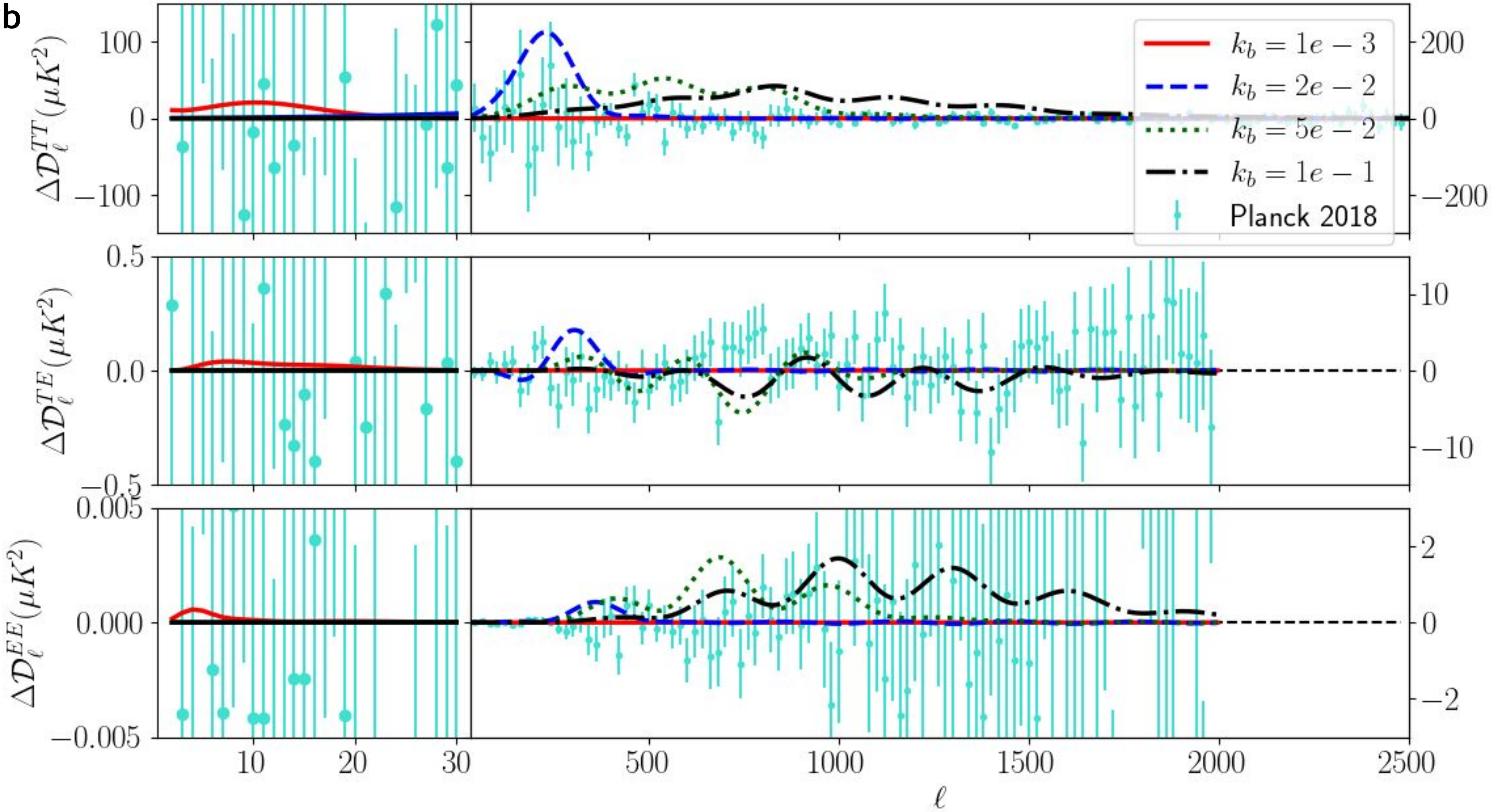
Codes:

- **CLASS** (The Cosmic Linear Anisotropy Solving System) to calculate the angular power spectrum of the CMB anisotropies for a given cosmological model.
- **MontePython**, a publicly available parameter sampling package in Python, to sample a model's parameter space.
- **MultiNest** - nested sampling approach developed is a Monte Carlo method aimed to efficiently calculate the evidence, producing posterior inferences

https://github.com/lesgourg/class_public
https://github.com/brinckmann/montepython_public

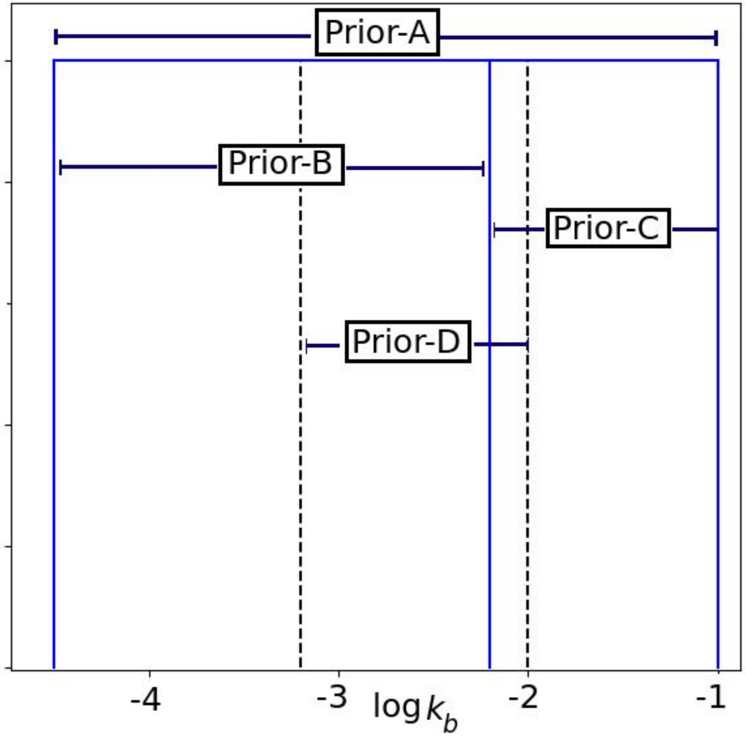
Methodology: Selection of priors

- $\log A_l = [-13, -8]$
- $\log k_b$



Methodology: Selection of priors

- log k_b



Single bump models	Prior-A	$\log A_I$ $\log k_b$	$[-13, -8]$ $[-4.5, -1.0]$
	Prior-B	$\log A_I$ $\log k_b$	$[-13, -8]$ $[-4.5, -2.2]$
	Prior-C	$\log A_I$ $\log k_b$	$[-13, -8]$ $[-2.2, -1.0]$
	Prior-D	$\log A_I$ $\log k_b$	$[-13, -8]$ $[-3.2, -2]$

Results: Single burst of particle production

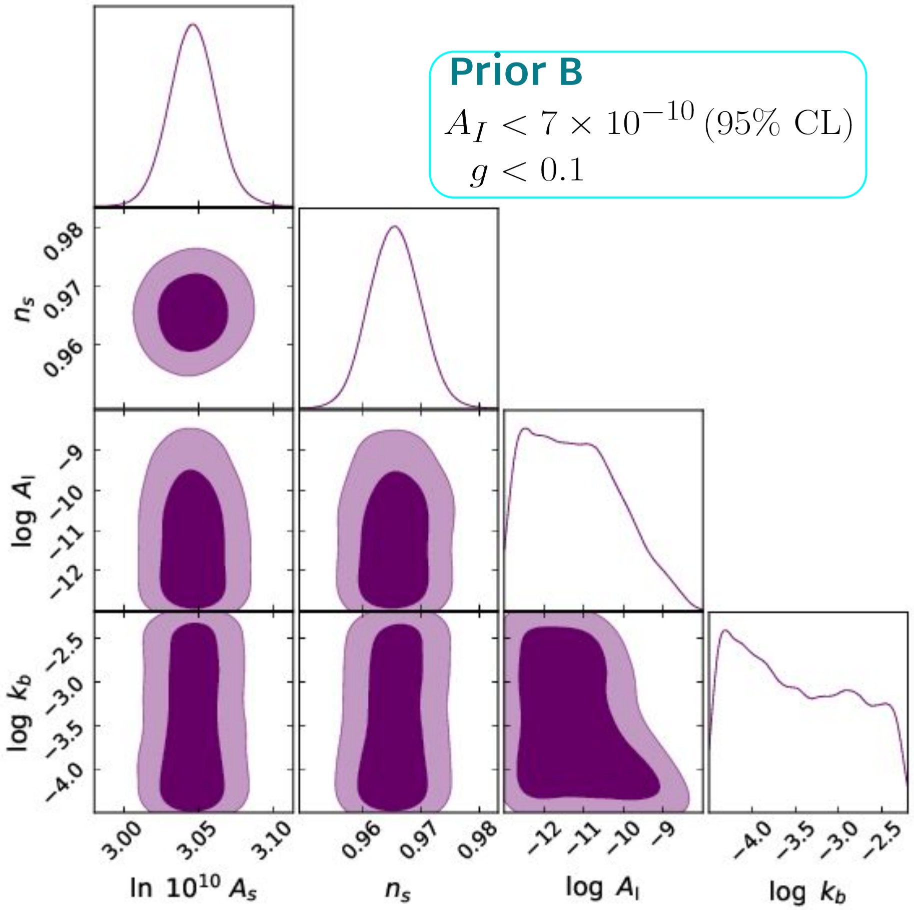
Parameters	Fiducial model	Single-bump model with different priors			
		Prior-A	Prior-B	Prior-C	Prior-D
$100\ \Omega_b$	2.237	2.239	2.235	2.231	2.233
Ω_{cdm}	0.1206	0.1204	0.1202	0.1211	0.1213
h	0.6716	0.6724	0.6731	0.6692	0.6688
τ_{reio}	0.05357	0.05127	0.05438	0.05287	0.05265
$\ln 10^{10} A_s$	3.044	3.039	3.046	3.043	3.048
n_s	0.9641	0.9678	0.9650	0.9678	0.9669
$A_{\rm I}$	–	1.85×10^{-11}	9.17×10^{-12}	1.83×10^{-11}	2.7×10^{-11}
$k_b/{\rm Mpc}^{-1}$	–	0.0086	0.0042	0.0086	0.0091
$\Delta\chi^2_{\rm eff}$	–	-0.3	-0.1	-1.0	-1.1
$\ln \mathcal{B}$	–	0.4	0.3	0.2	0.4

Results: Single burst of particle production

Prior B

$A_I < 7 \times 10^{-10}$ (95% CL)

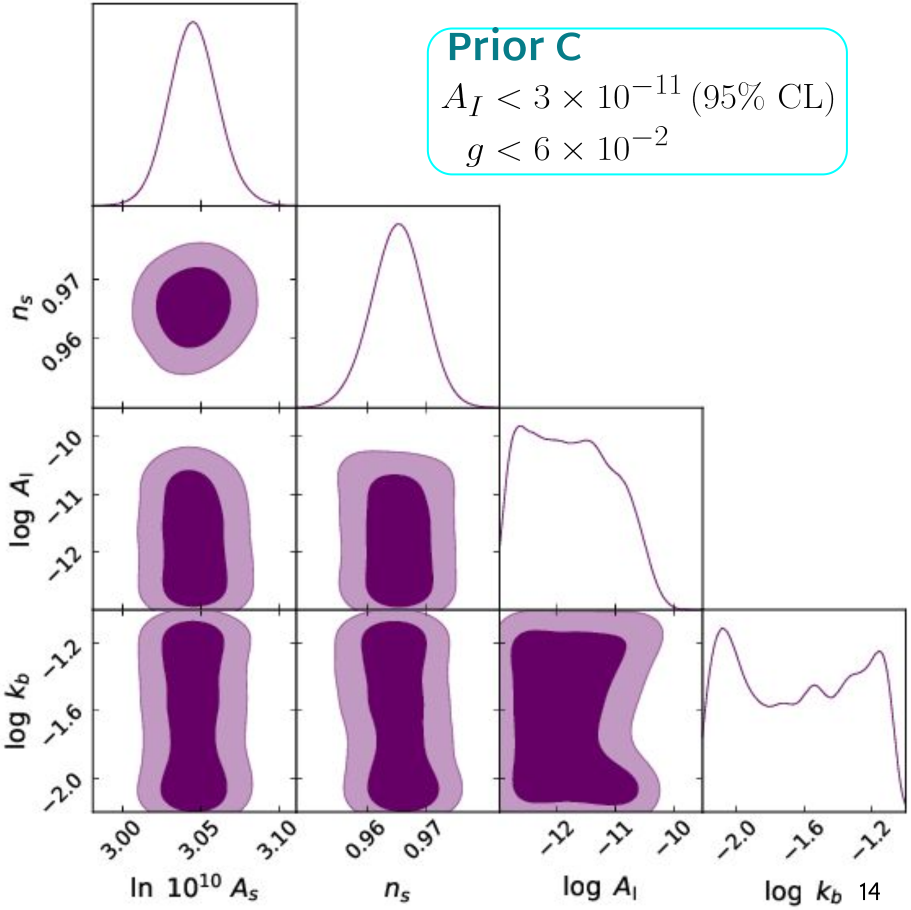
$g < 0.1$



Prior C

$A_I < 3 \times 10^{-11}$ (95% CL)

$g < 6 \times 10^{-2}$



Results: Multiple burst of particle productions

Multiple Bump Models:

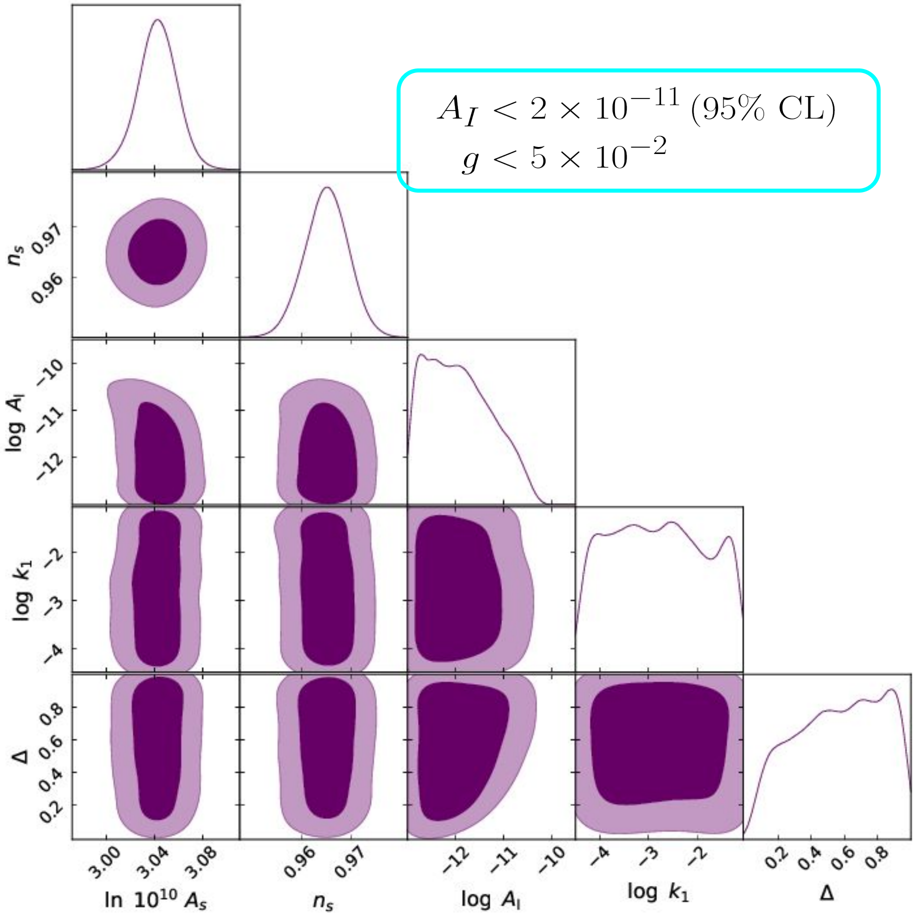
Location of i^th bump $k_i = e^{(i-1)\Delta} k_1$

Δ - separation between the bumps
k_1 - location of the first bump

Prior: 0 < Δ < 1

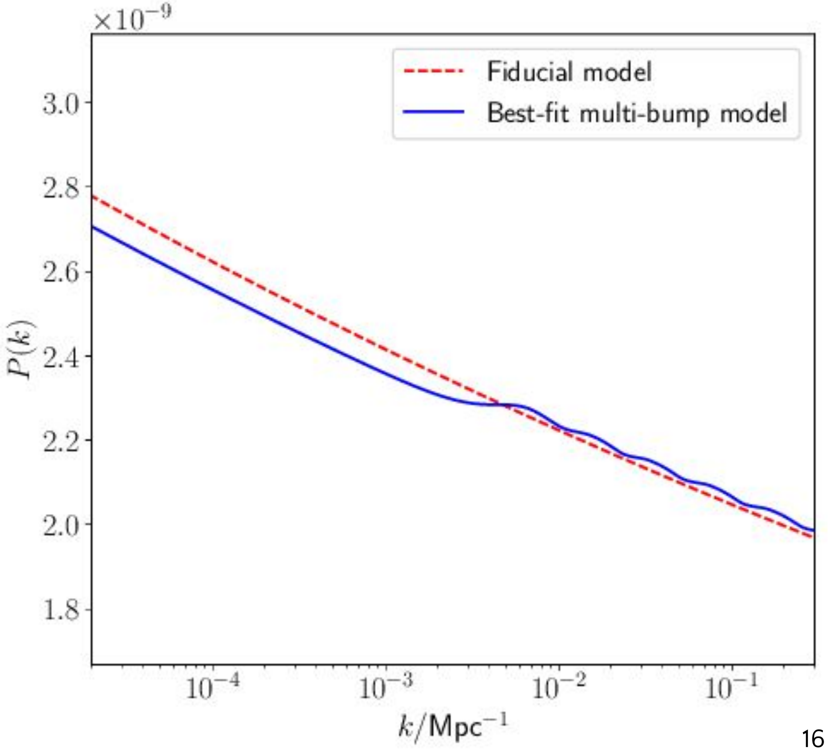
Parameters	Multi-bump model
$100\Omega_b$	2.235
$\Omega_{\rm cdm}$	0.121
h	0.6704
$\tau_{\rm reio}$	0.05751
$\ln 10^{10} A_s$	3.015
n_s	0.9644
$A_{\rm I}$	5.317×10^{-11}
$k_1/{\rm Mpc}^{-1}$	1.806×10^{-3}
Δ	0.799
$\Delta\chi^2_{\rm eff}$	-3.0
$\ln \mathcal{B}$	0.8

Results: Multiple burst of particle productions

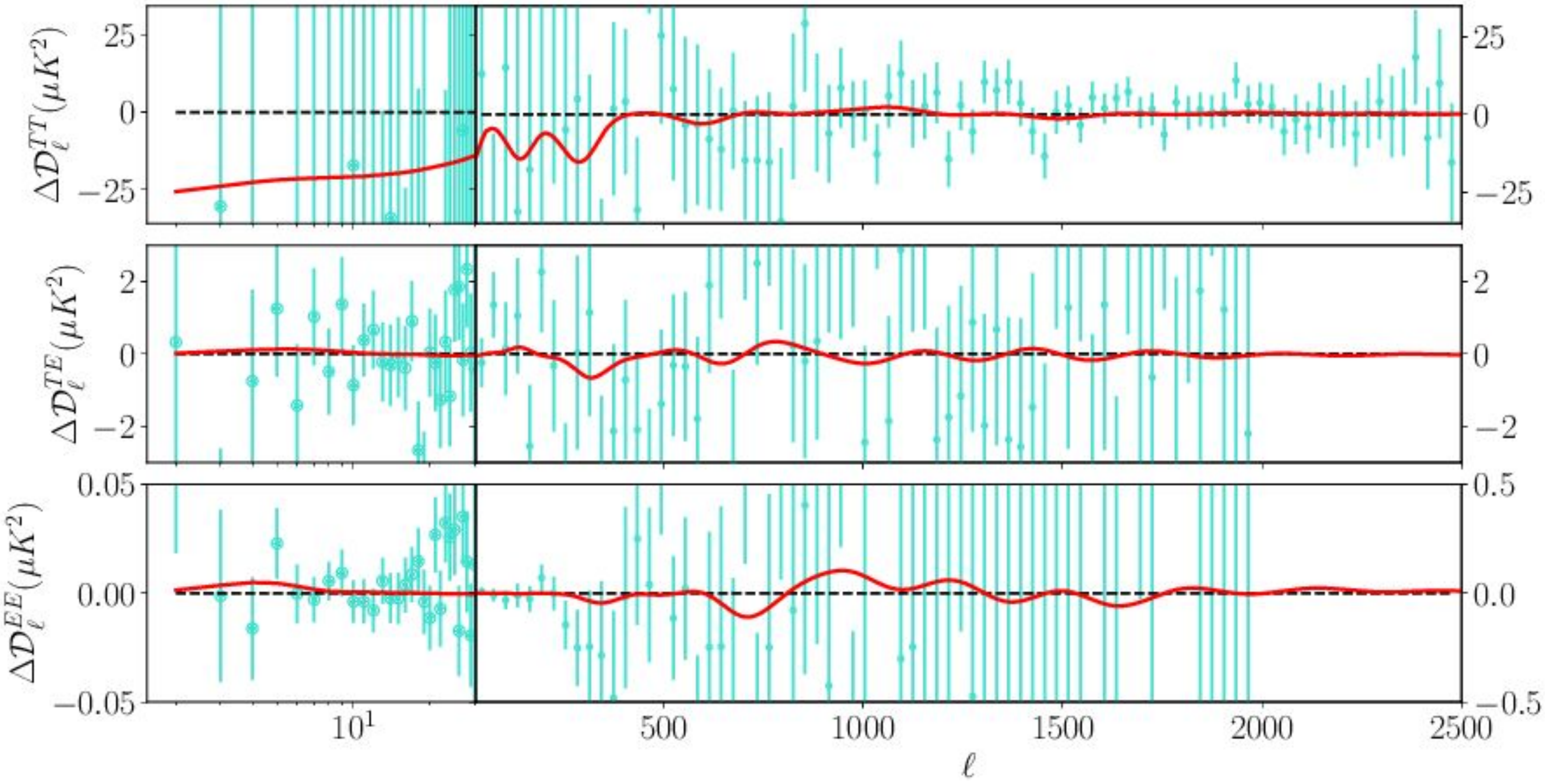


$$A_I < 2 \times 10^{-11} \; (95\% \text{ CL})$$
$$g < 5 \times 10^{-2}$$

Best-fit power spectrum



Results: Multiple burst of particle productions



The residuals in CMB power spectra of best-fit multi-bump model

Summary

- Investigated a class of models involving particle production during inflation using latest CMB data from Planck
- We parametrize the primordial power spectrum with bump-like features using the analytical expression (dominant + subdominant)
- We found 95% CL upper limits on amplitude of features at different scales and model parameter *g*
- Bayes factor for all the single bump models are positive yet within the inconclusive range as per Jeffreys' scale

Single burst of particle production (A_I, k_b)	
Features in the large-scale (low-ℓ) CMB data - Prior B	• Minor change in χ^2 value • $g < 0.1$ • For $\ell < 500$, $A_I < 35\%\ A_s$ (95% CL)
Features in the small-scale (high-ℓ) CMB data - Prior C	• Change in χ^2 value is ~1 • $g < 0.06$ • For $\ell > 500$, $A_I < 1.5\%\ A_s$ (95% CL)
Features in the intermediate scale CMB data - Prior D	• Minor change in χ^2 value • $g < 0.08$ • $A_I < 4\%\ A_s$ (95% CL)
Multiple bursts of particle productions (A_I, k_1, Δ) Prior: $0 \leq \Delta \leq 1$	• Change in χ^2 value is -3, Bayes factor 0.8 • $g < 0.05$ • $A_I < 1\%\ A_s$ (95% CL)

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Thank You