BACK TO THE FEATURES

MATTEO BRAGLIA, THURSDAY JULY 14 2022

IIT Gravitation and Cosmology Seminar

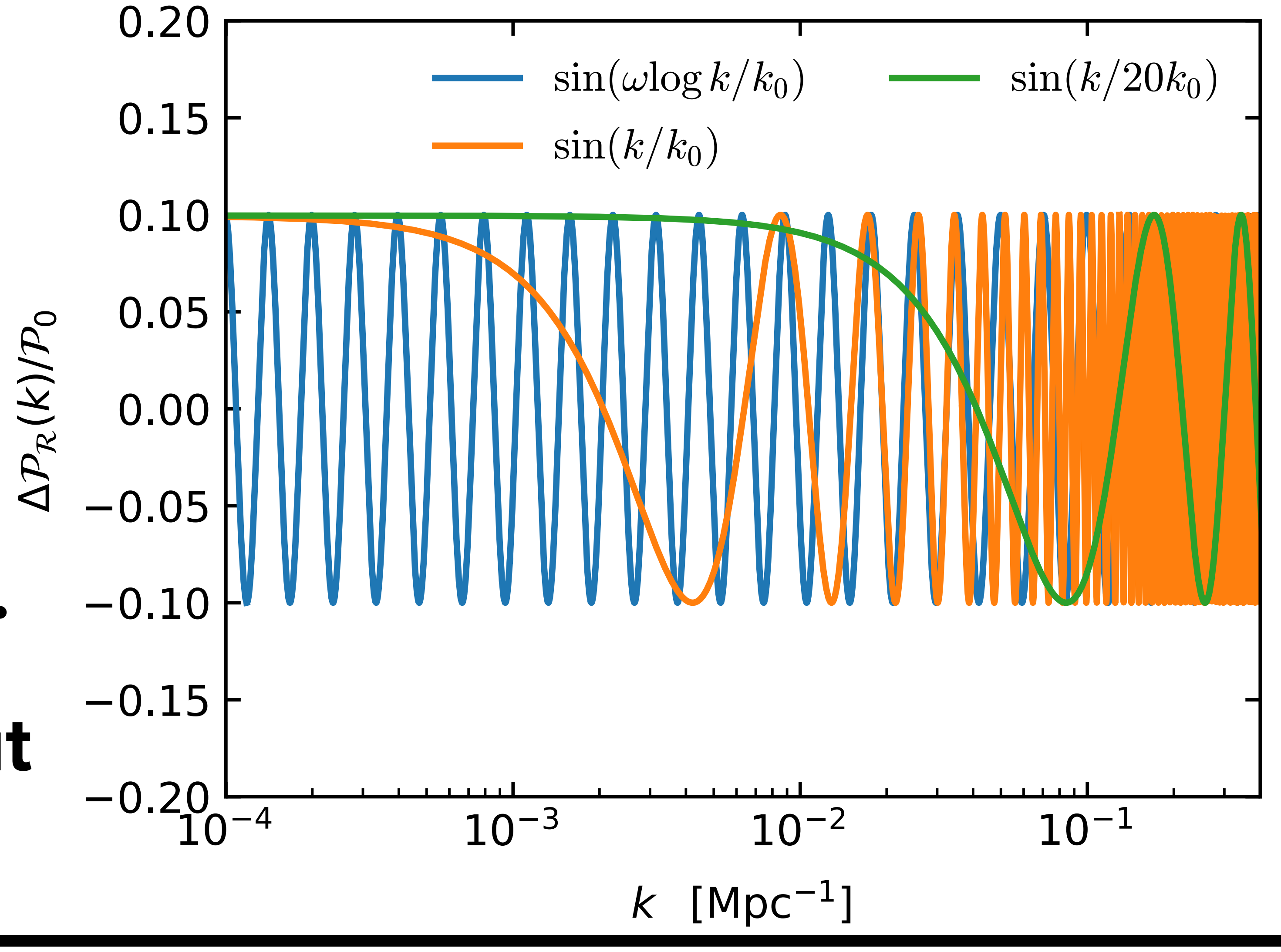
INAF
ISTITUTO NAZIONALE DI ASTROFISICA
NATIONAL INSTITUTE FOR ASTROPHYSICS

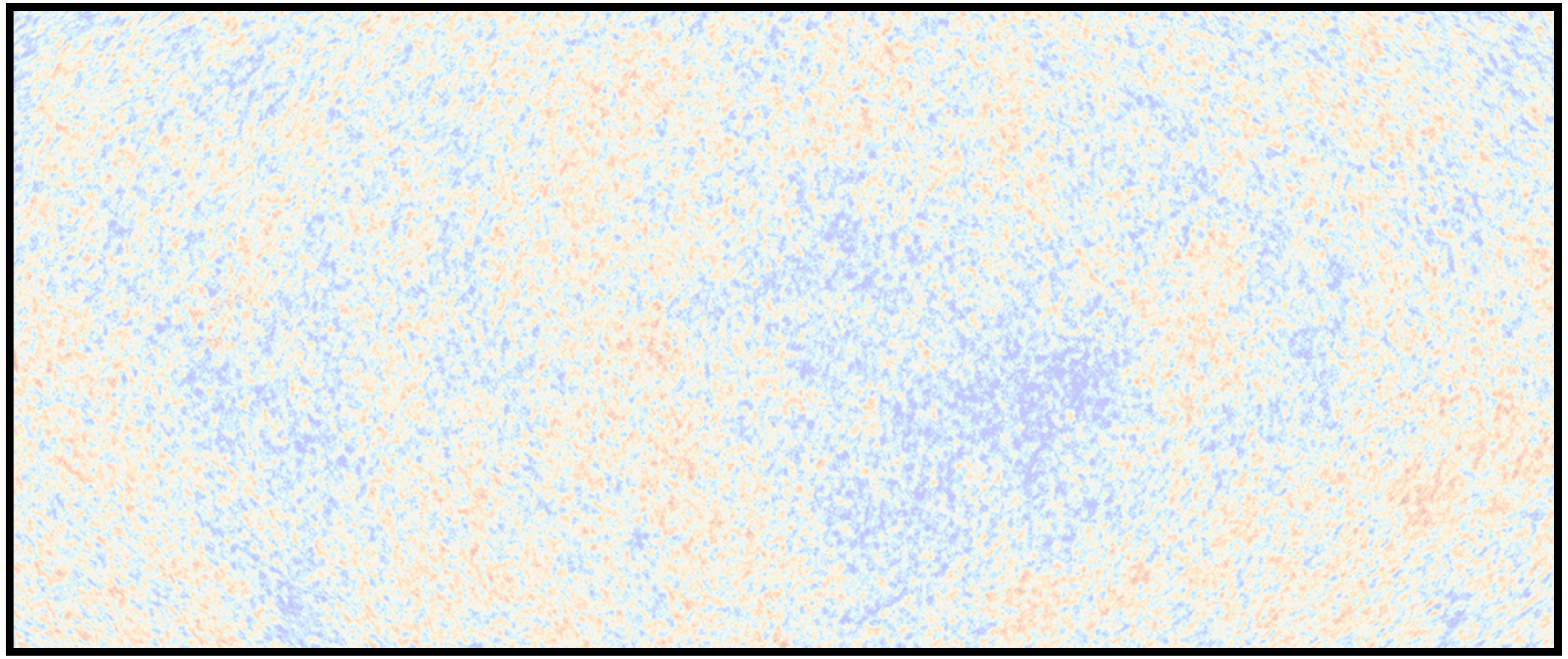
ift Instituto de Física Teórica UAM-CSIC

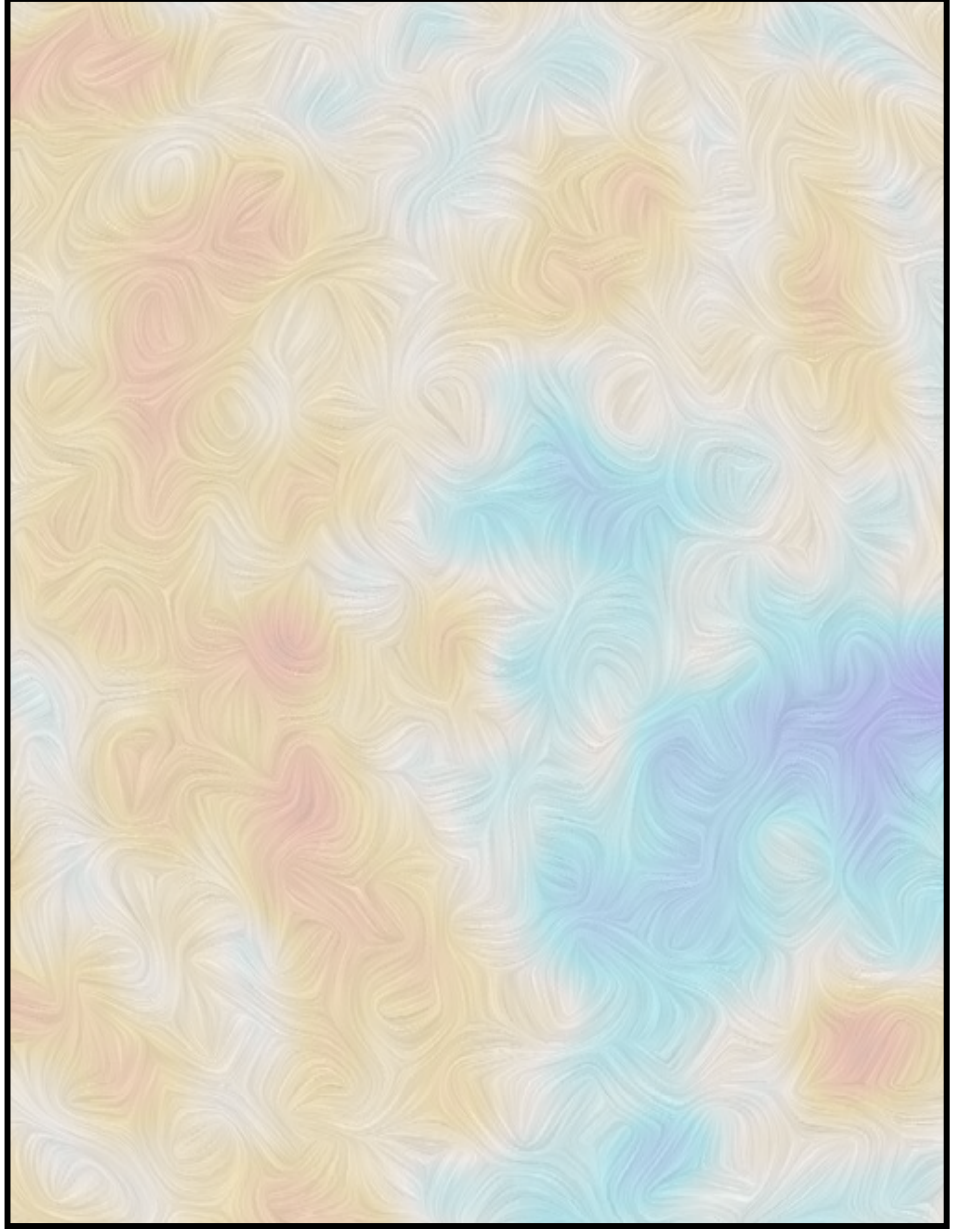
PRIMORDIAL FEATURES: WHAT THEY ARE AND HOW TO TEST THEM

Primordial features **are scale-dependent *deviations from near-scale invariant* primordial spectrum from inflation.**

***Observationally*, they improve the fit to CMB data. *Theoretically*, they encode invaluable information about Early Universe Physics.**







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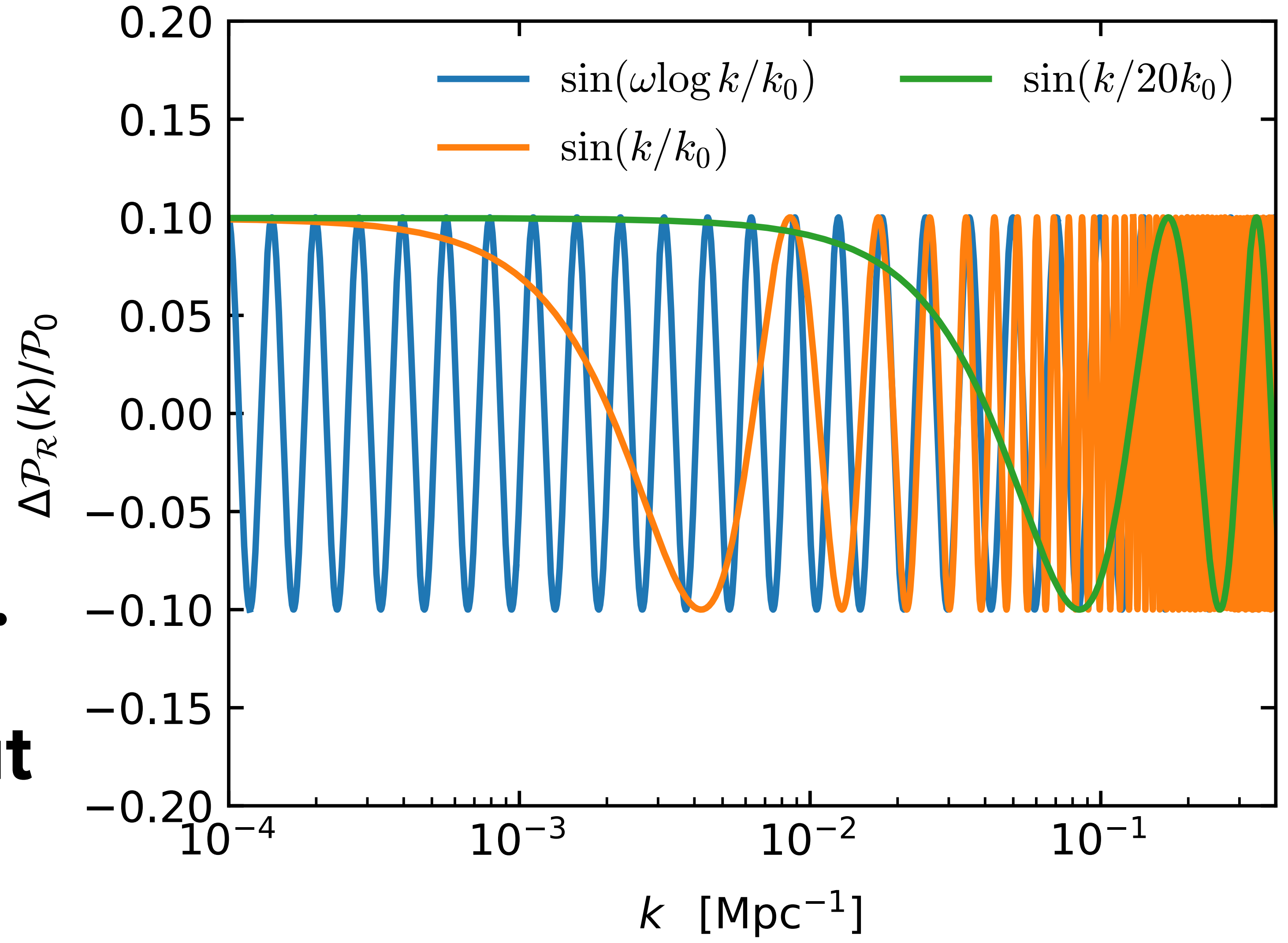

HINTS OF FEATURES IN CMB DATA FROM PLANCK

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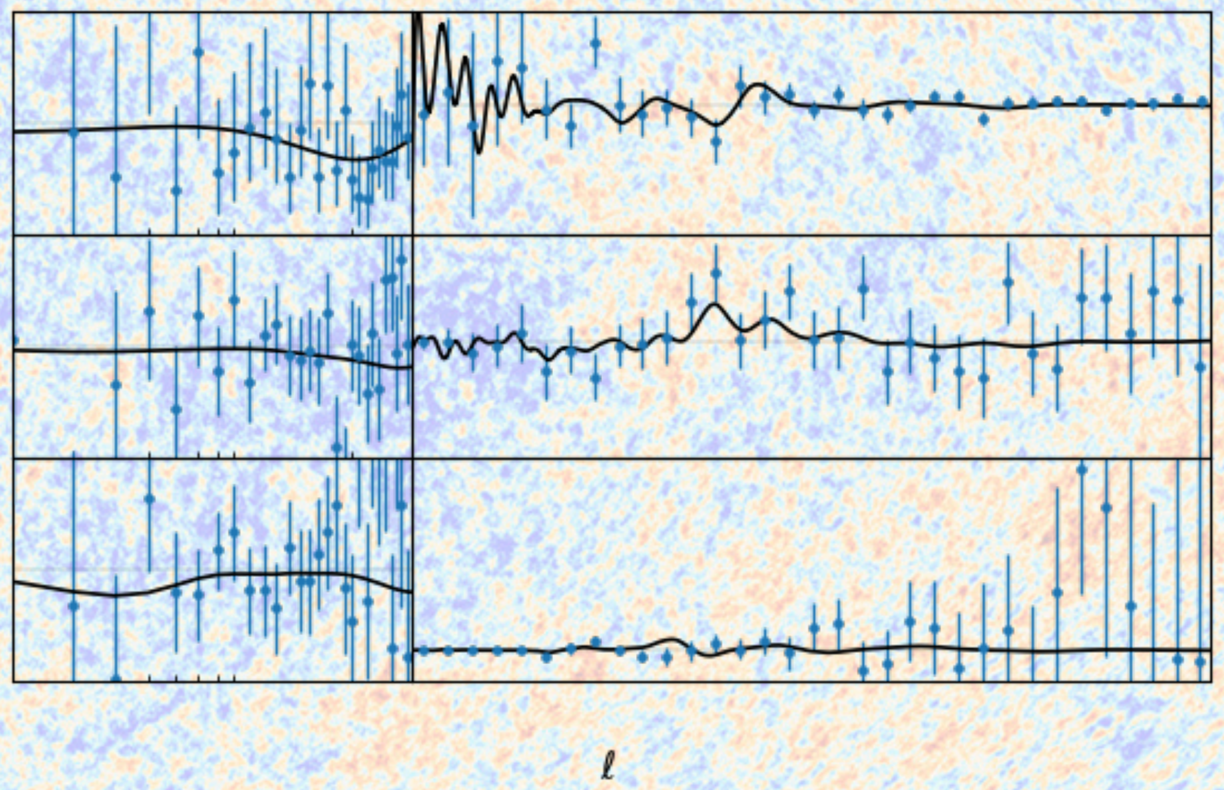
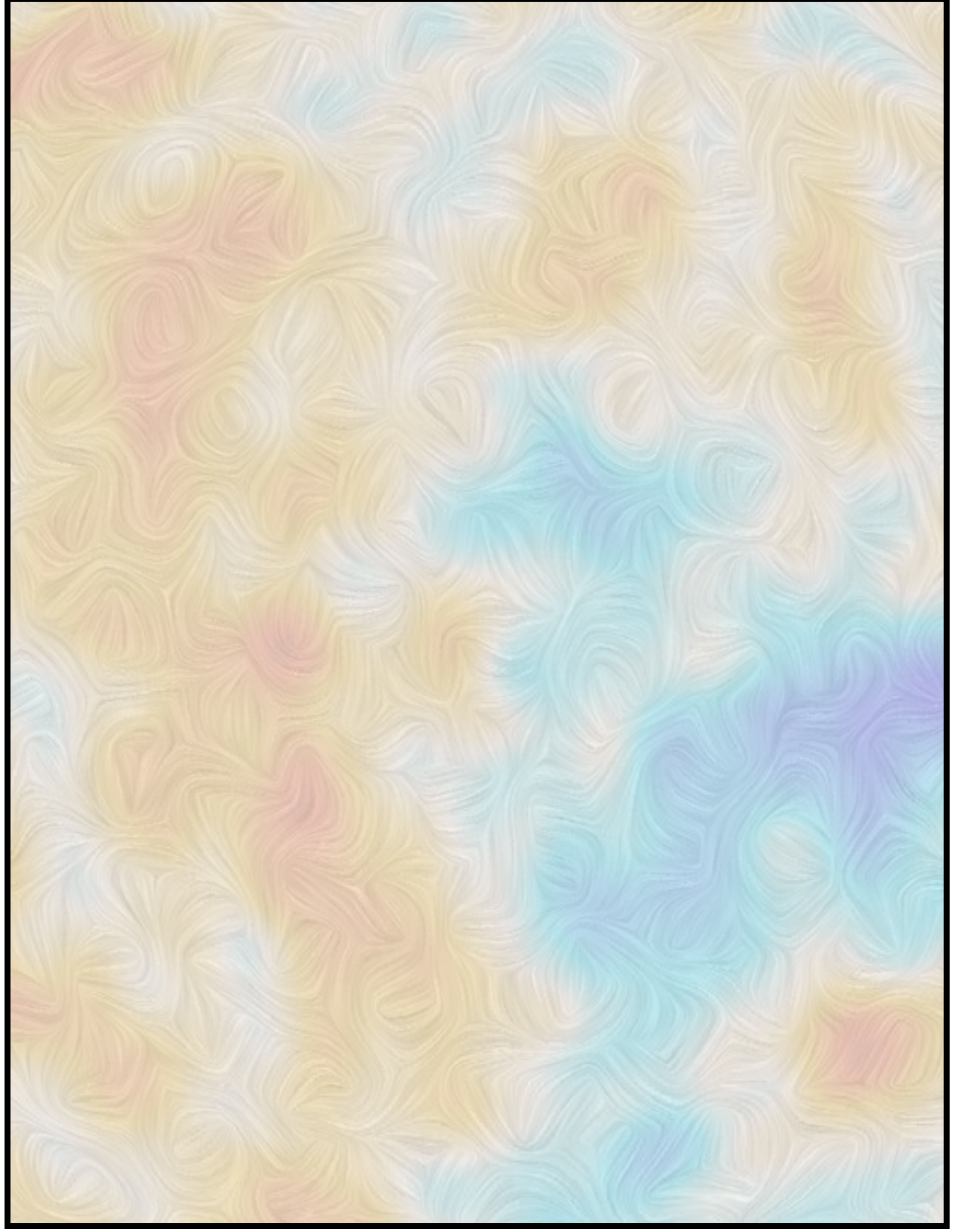
Using a recently developed model as an example, I illustrate the *challenges* for data comparison and the immense *reward* in case of a detection of primordial features.





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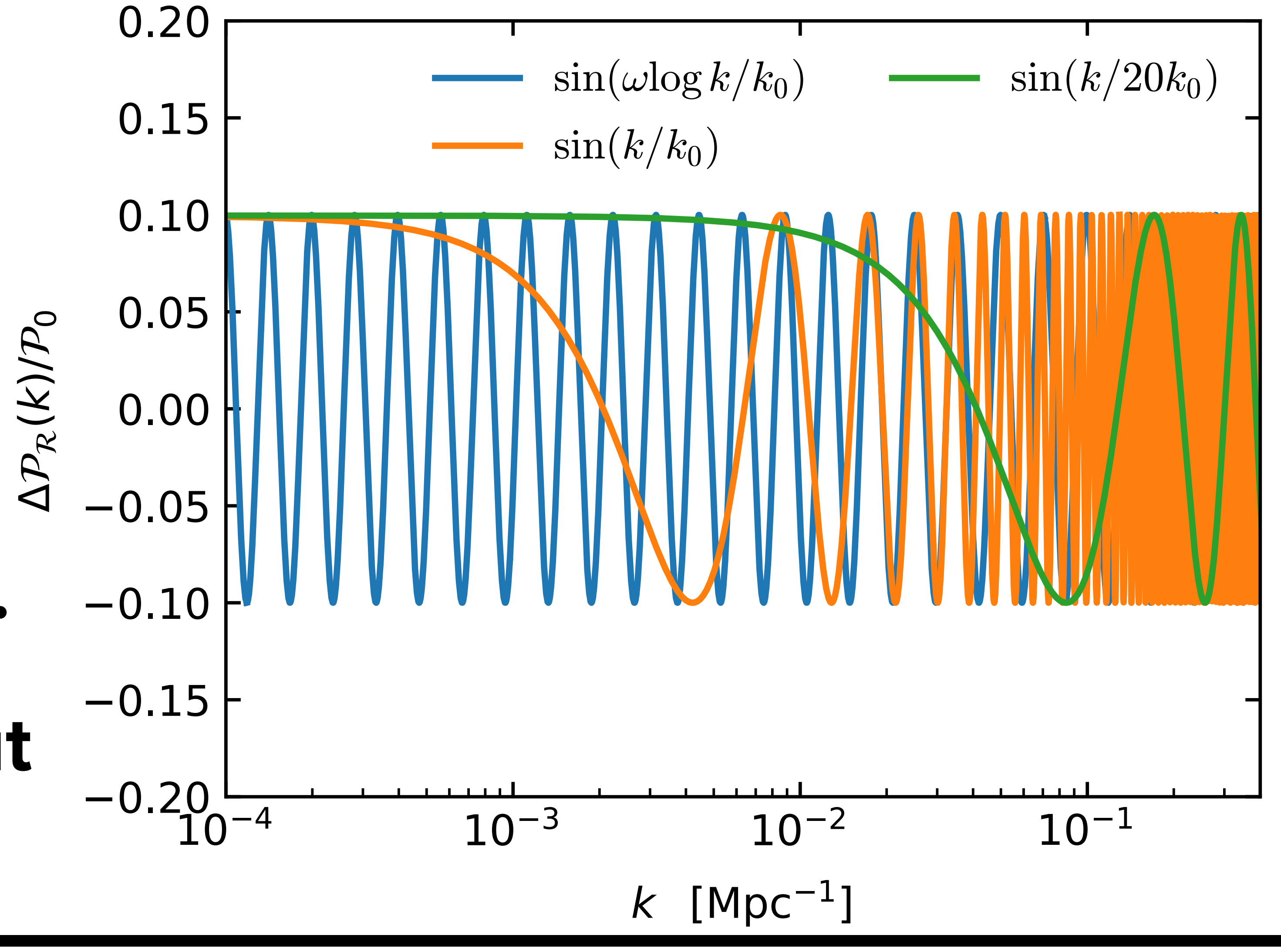

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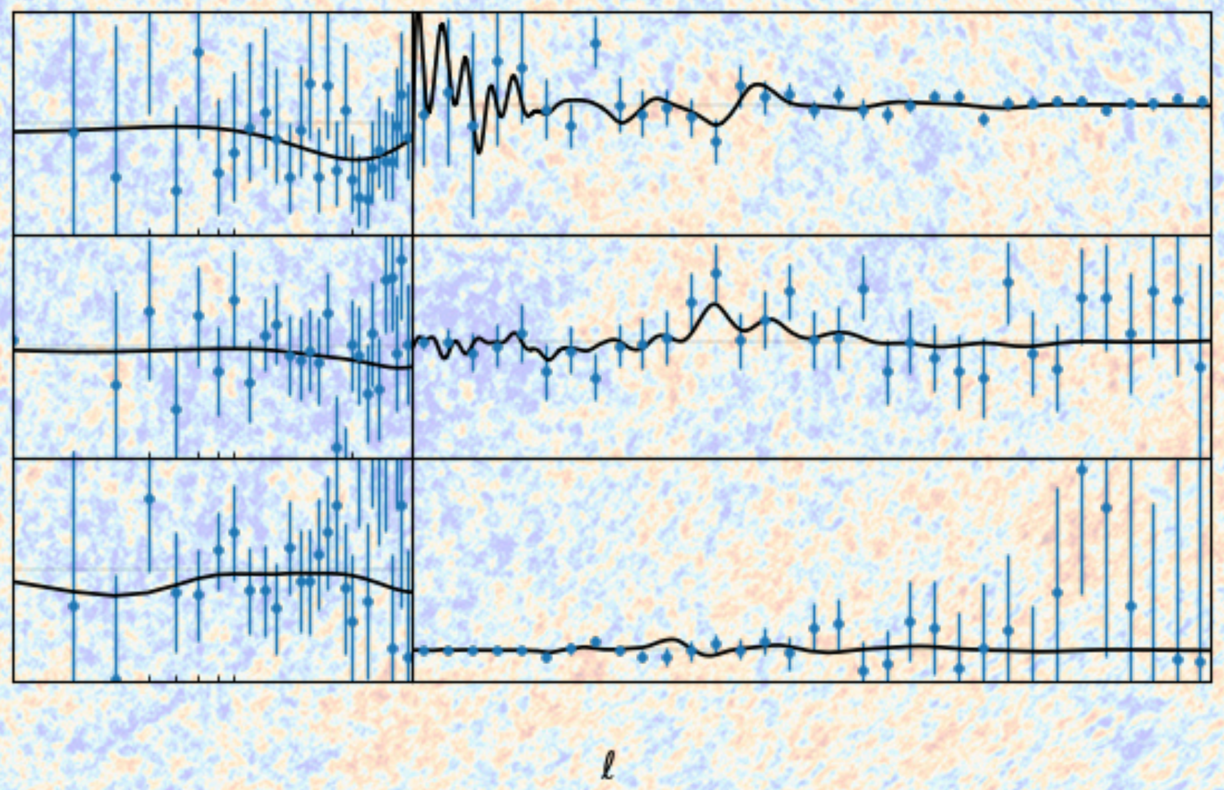
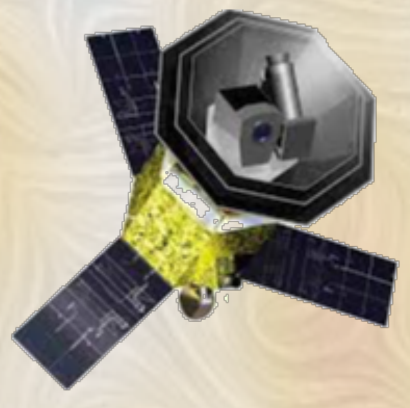
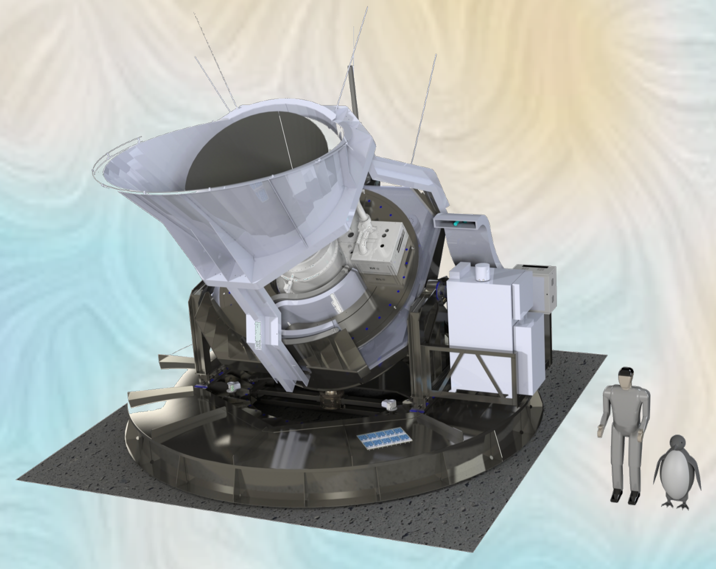


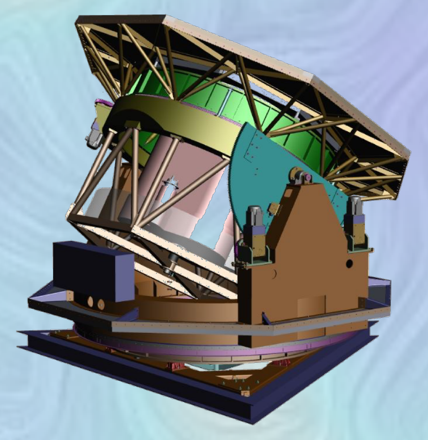
3

PROSPECTS FOR TESTING FEATURES WITH FUTURE CMB EXPERIMENTS

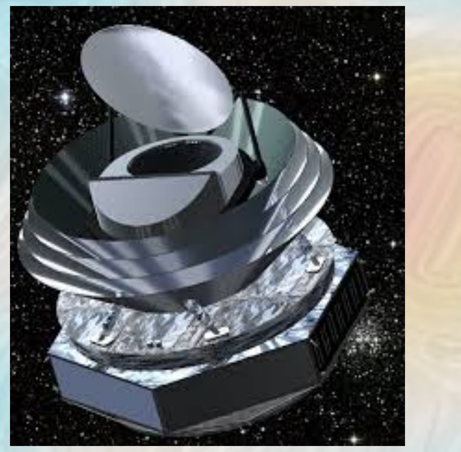




Future **experiments will map the *E-modes* of the CMB with a much *better* accuracy *than Planck* at all scales.**



This will greatly *enhance* (or reduce) the statistical *significance* of primordial *features*.



INFLATION & PRIMORDIAL FEATURES

NOTATIONS

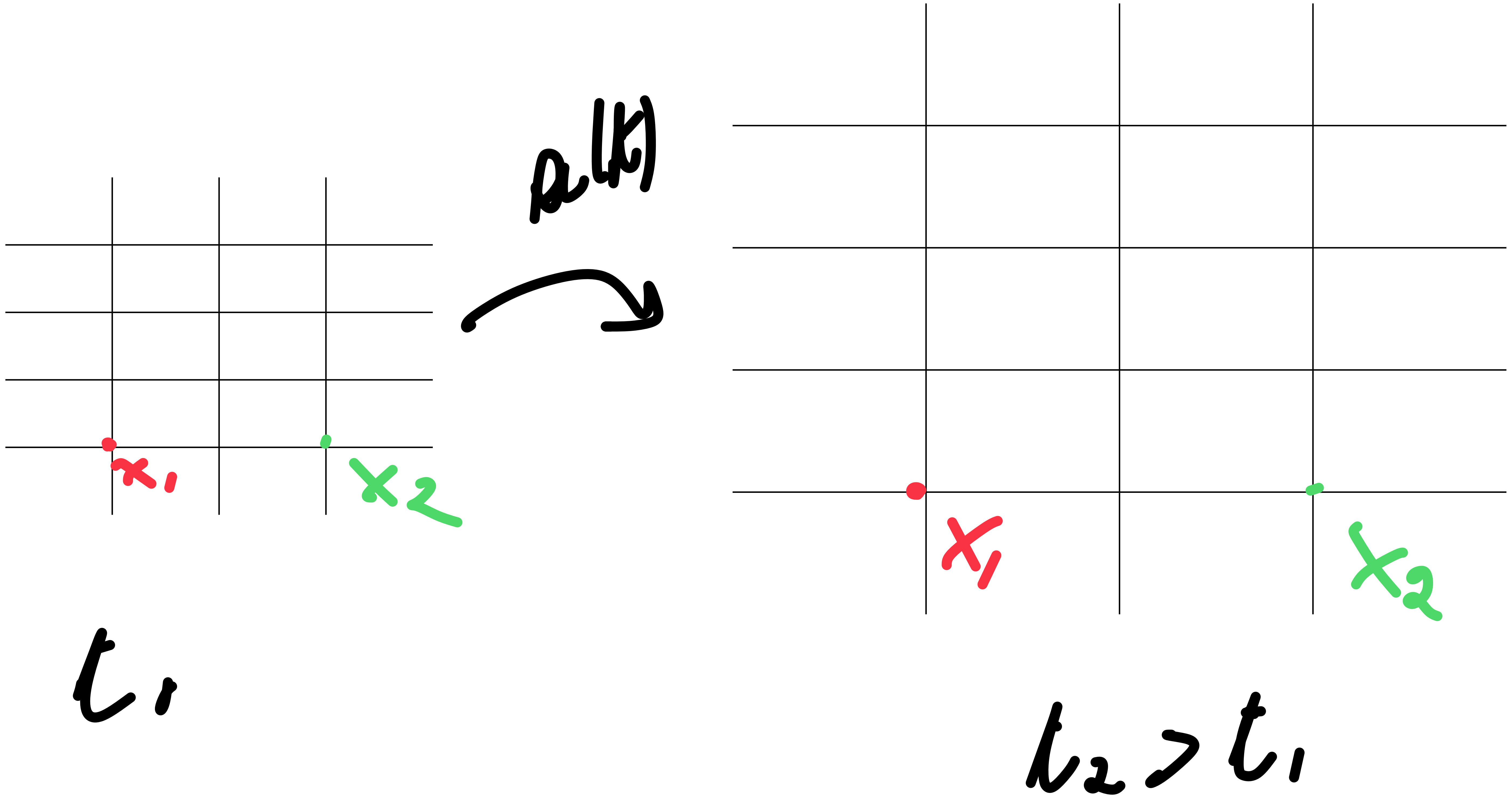
FLRW Metric $ds^2 = -dt^2 + a^2(t)dx^2 = -a^2(\tau)[d\tau^2 - dx^2]$

Scale factor $a(t)$

Comoving distance x

Physical distance $a(t)x$

Hubble parameter $H = d\ln a/dt$



SLOW-ROLL INFLATION AND NEAR SCALE-INVARIANCE

Action of a scalar field

$$S = \int d^4x \sqrt{-g} \left[-\frac{(\partial\phi)^2}{2} - V(\phi) \right]$$

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$$\ddot{\phi} + 3H\dot{\phi} + dV/d\phi = 0$$

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Conditions for inflation

$$\ddot{a}(t) > 0$$

$$-\frac{\dot{H}}{H^2} \ll 1$$

SLOW-ROLL INFLATION AND NEAR SCALE-INVARIANCE

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EINSTEIN EQUATIONS

$$\epsilon = \frac{\dot{\phi}^2}{2H^2} \ll 1$$

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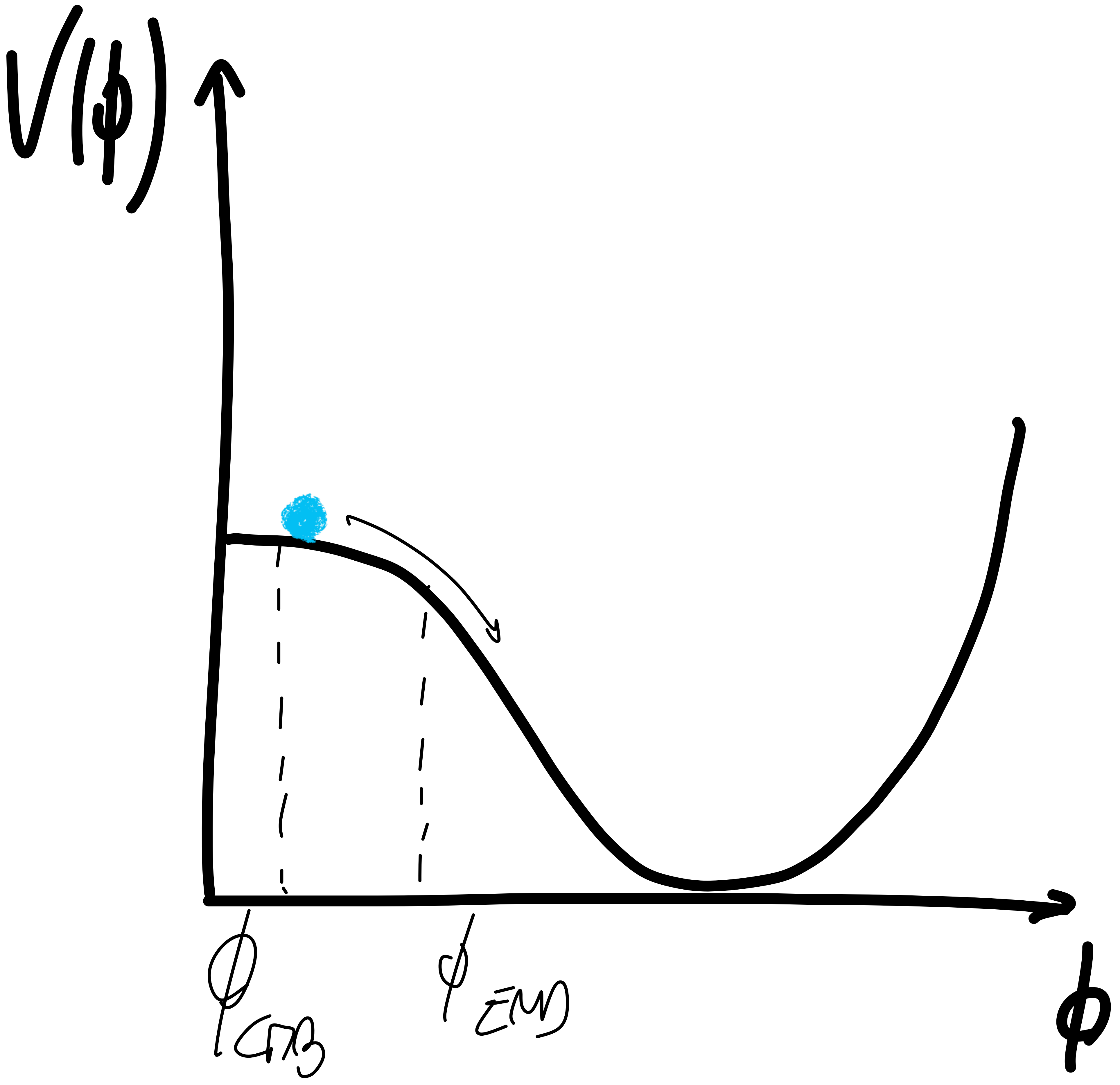
$$\epsilon = \frac{V_\phi^2}{2V^2} \ll 1$$



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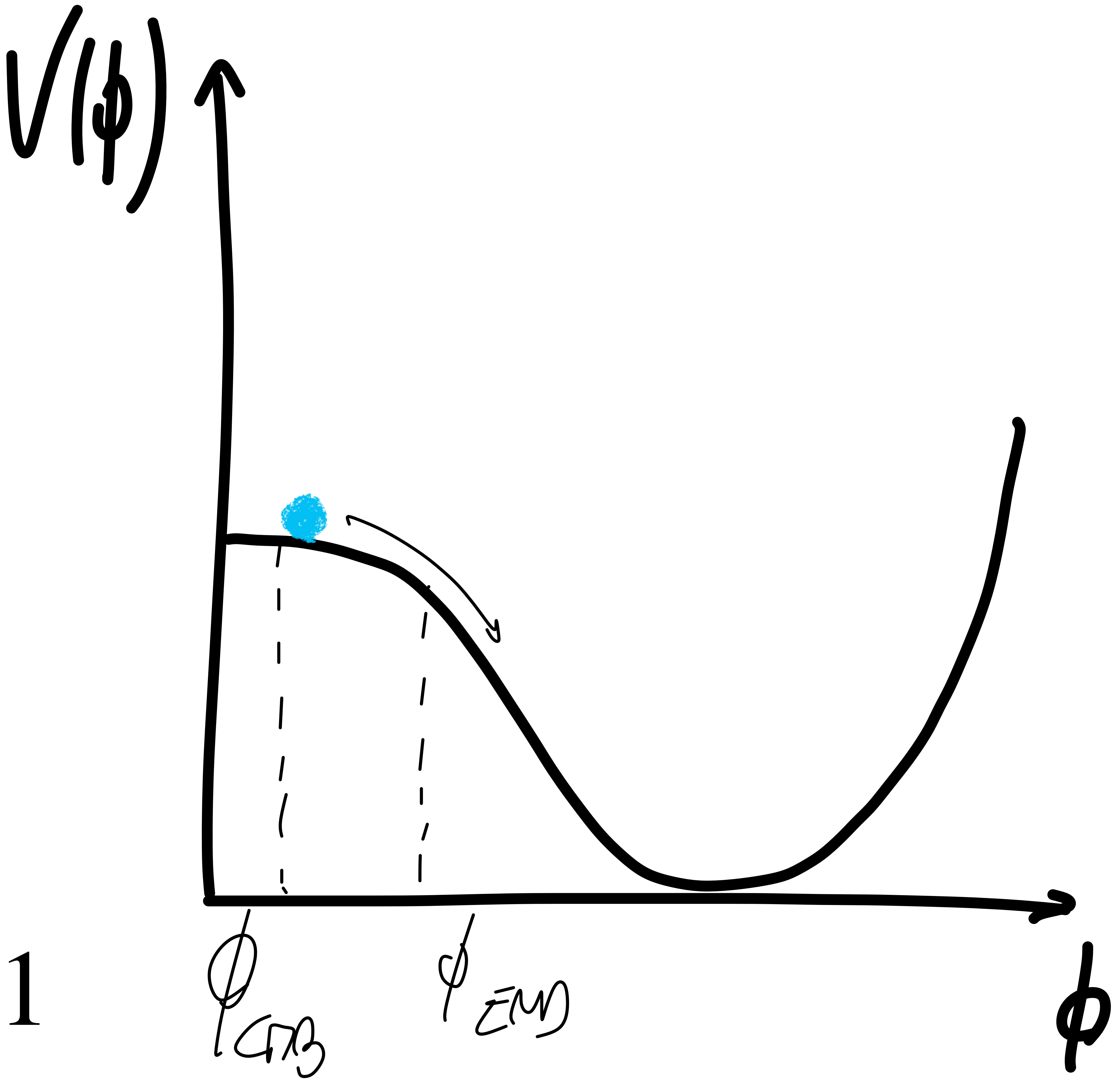
$$\epsilon = \frac{V_\phi^2}{2V^2} \ll 1$$

$$\eta = \dot{\epsilon}/H\epsilon \ll 1$$

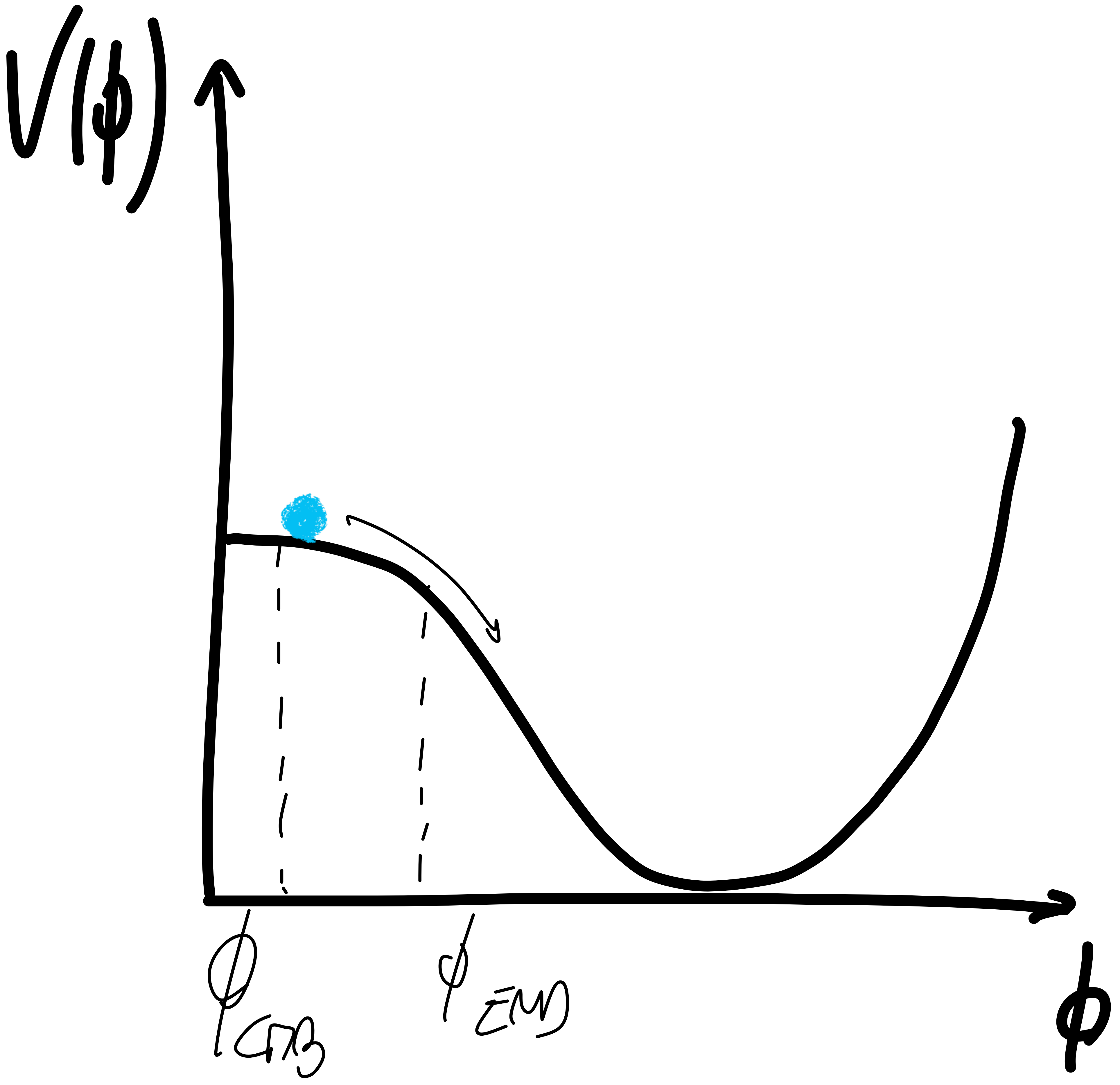


SLOW-ROLL INFLATION AND NEAR SCALE-INVARIANCE

Slow-roll conditions

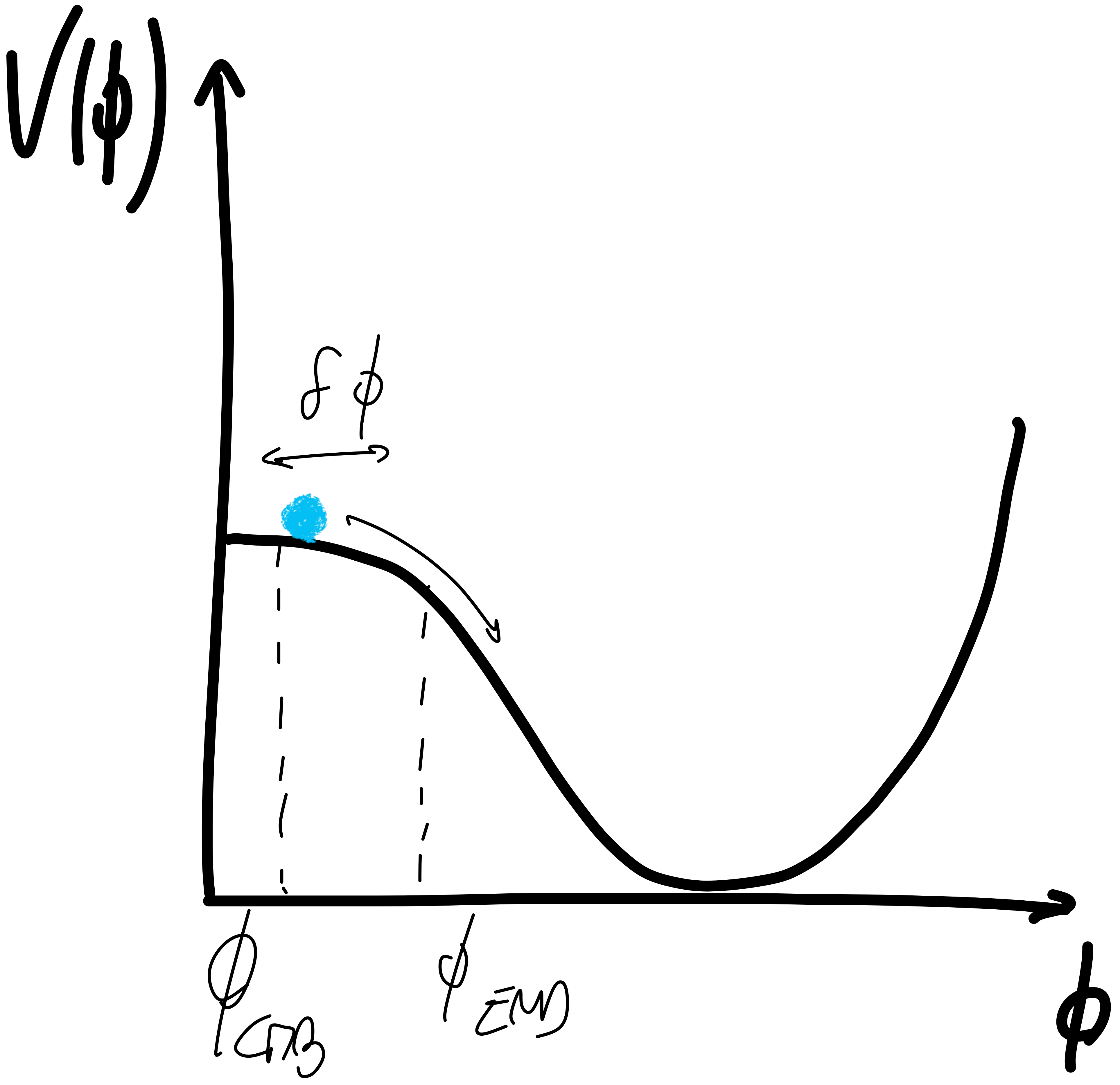
$$\epsilon = \frac{\dot{\phi}^2}{2H^2} \ll 1$$

$$\eta = \dot{\epsilon}/H\epsilon \ll 1$$



SLOW-ROLL INFLATION AND NEAR SCALE-INVARIANCE

Quantum fluctuations $\delta\phi(x, t)$



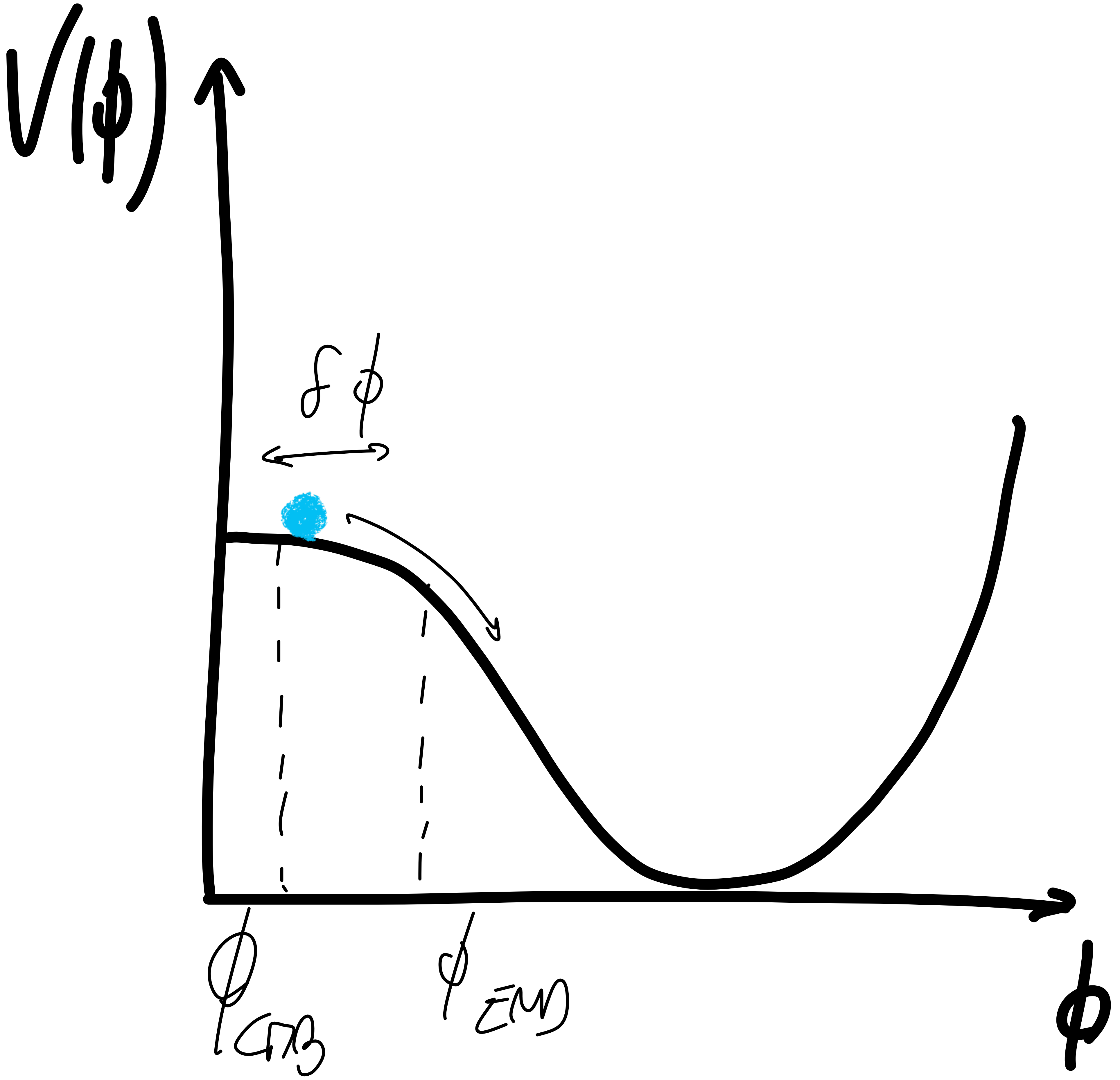
SLOW-ROLL INFLATION AND NEAR SCALE-INVARIANCE

Quantum fluctuations $\delta\phi(x,t)$

$$\delta\hat{\phi}(x,t) = \sum_k \left[\hat{b}_k \delta\phi_k(t) + \hat{b}_k^\dagger \delta\phi_k^*(t)\right]$$

Primordial power spectrum

$$\mathcal{P}(k) = \left(\frac{H}{\dot{\phi}}\right)^2 \mathcal{P}_{\delta\phi}(k) = \left(\frac{H}{\dot{\phi}}\right)^2 |\delta\phi_k|^2$$



SLOW-ROLL INFLATION AND NEAR SCALE-INVARIANCE

Slow-roll conditions

$\epsilon = \dot{\phi}^2/2M_{\rm pl}^2H^2 \ll 1$

$\eta = \dot{\epsilon}/H\epsilon \ll 1$

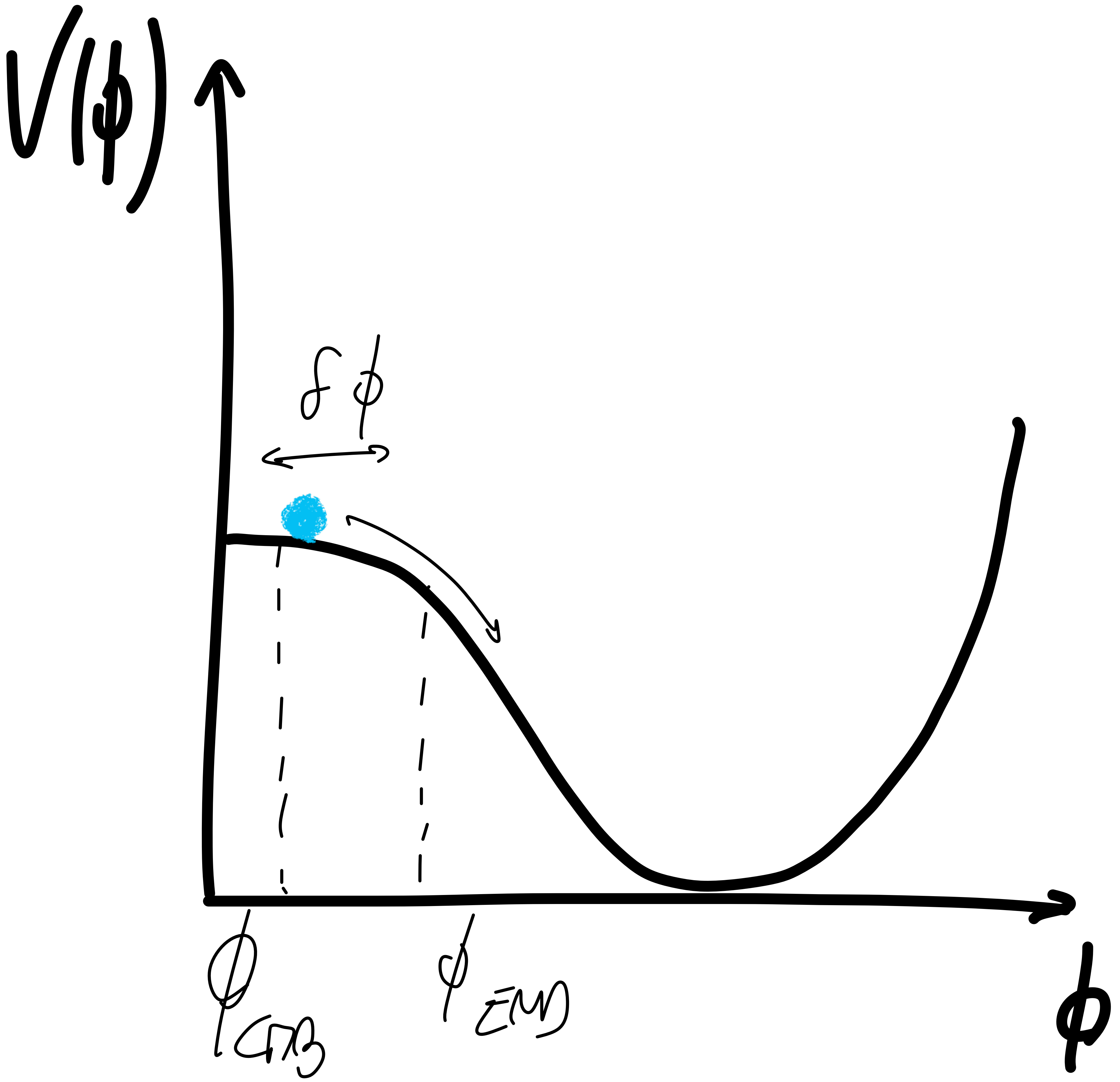
Predictions

$A_s = H^2/8\pi^2\epsilon M_{\rm pl}^2$

$n_s - 1 = -2\epsilon - \eta$

$$\mathscr{P}(k) = \left(\frac{H}{\dot{\phi}}\right)^2 \mathscr{P}_{\delta\phi}(k) \equiv A_s \left(\frac{k}{k_*}\right)^{n_s-1}$$

Slow-roll inflation predicts $n_s \simeq 1$



SEEDS FOR STRUCTURE FORMATION

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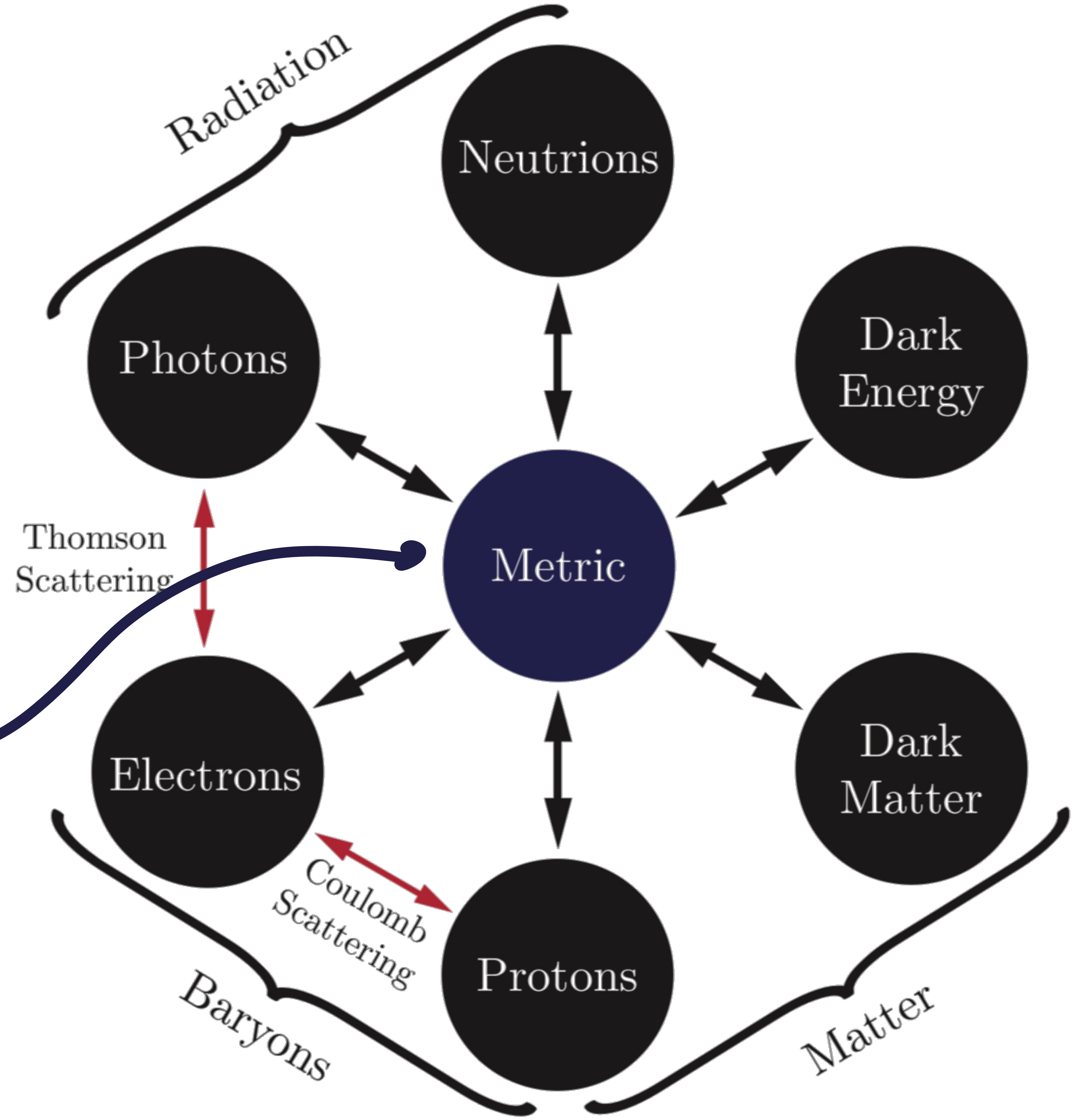

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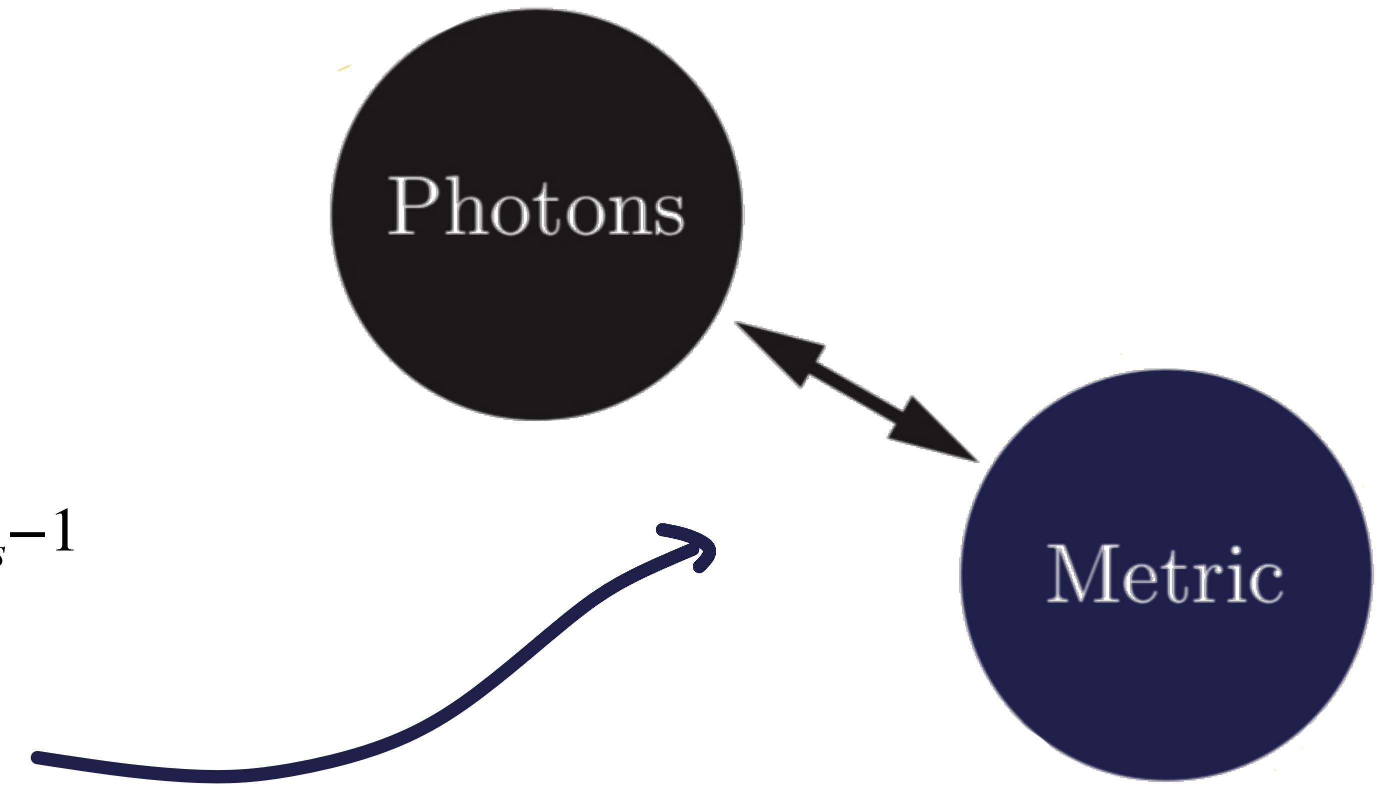
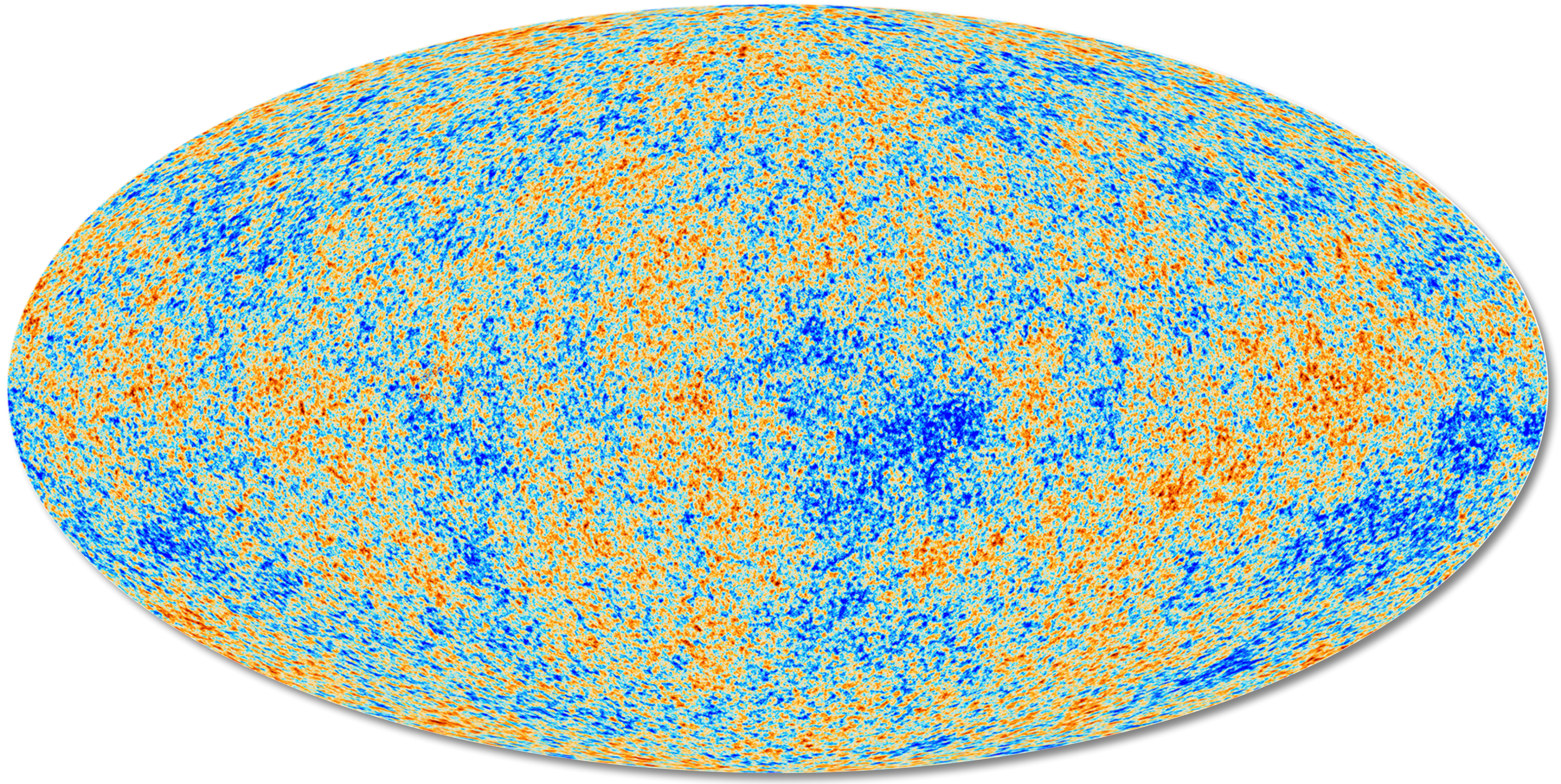


SEEDS FOR COSMIC MICROWAVE BACKGROUND ANISOTROPIES

Metric

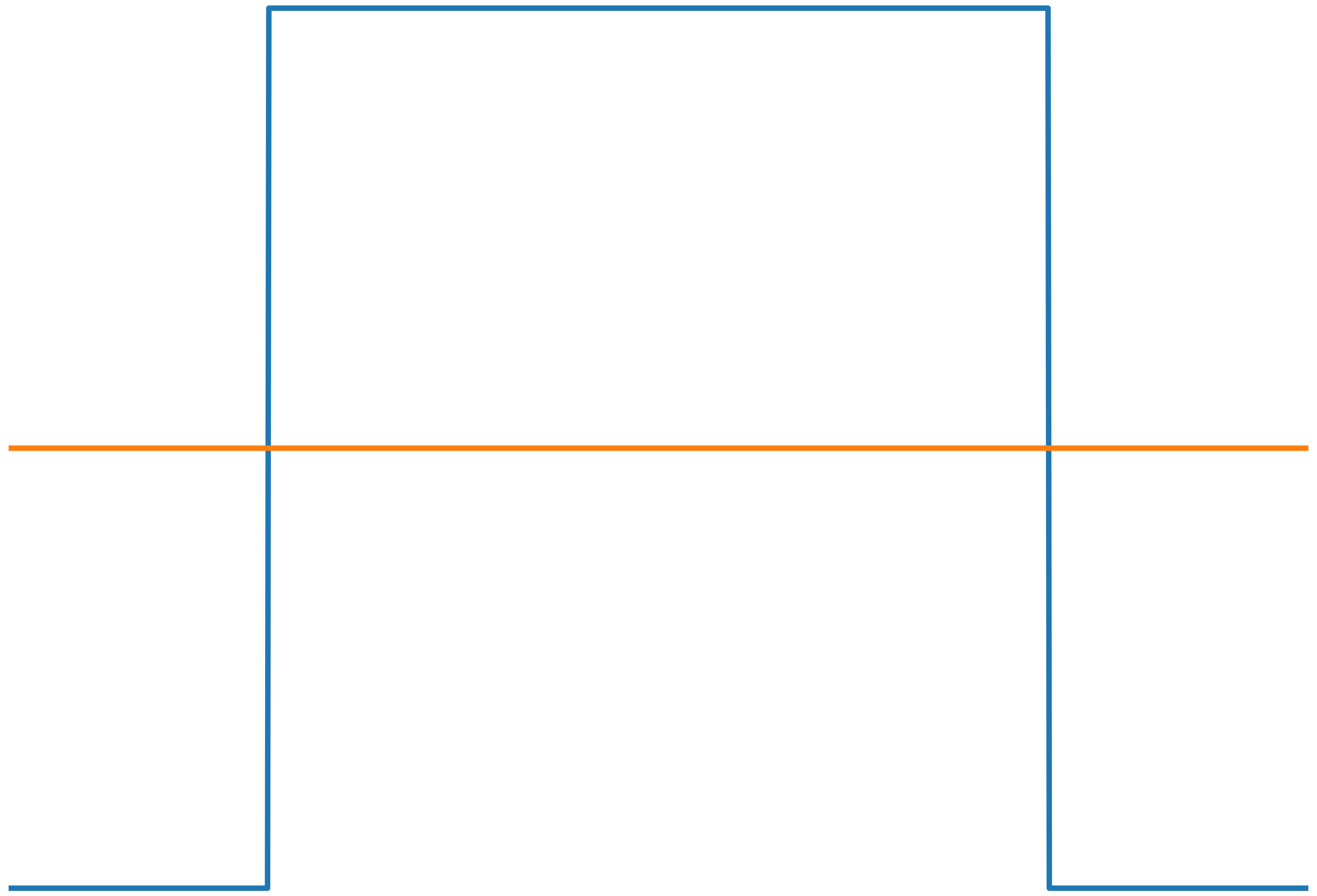
Photons

$$\mathscr{P}(k) = \left(\frac{H}{\dot{\phi}}\right)^2 \mathscr{P}_{\delta\phi}(k) \equiv A_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$

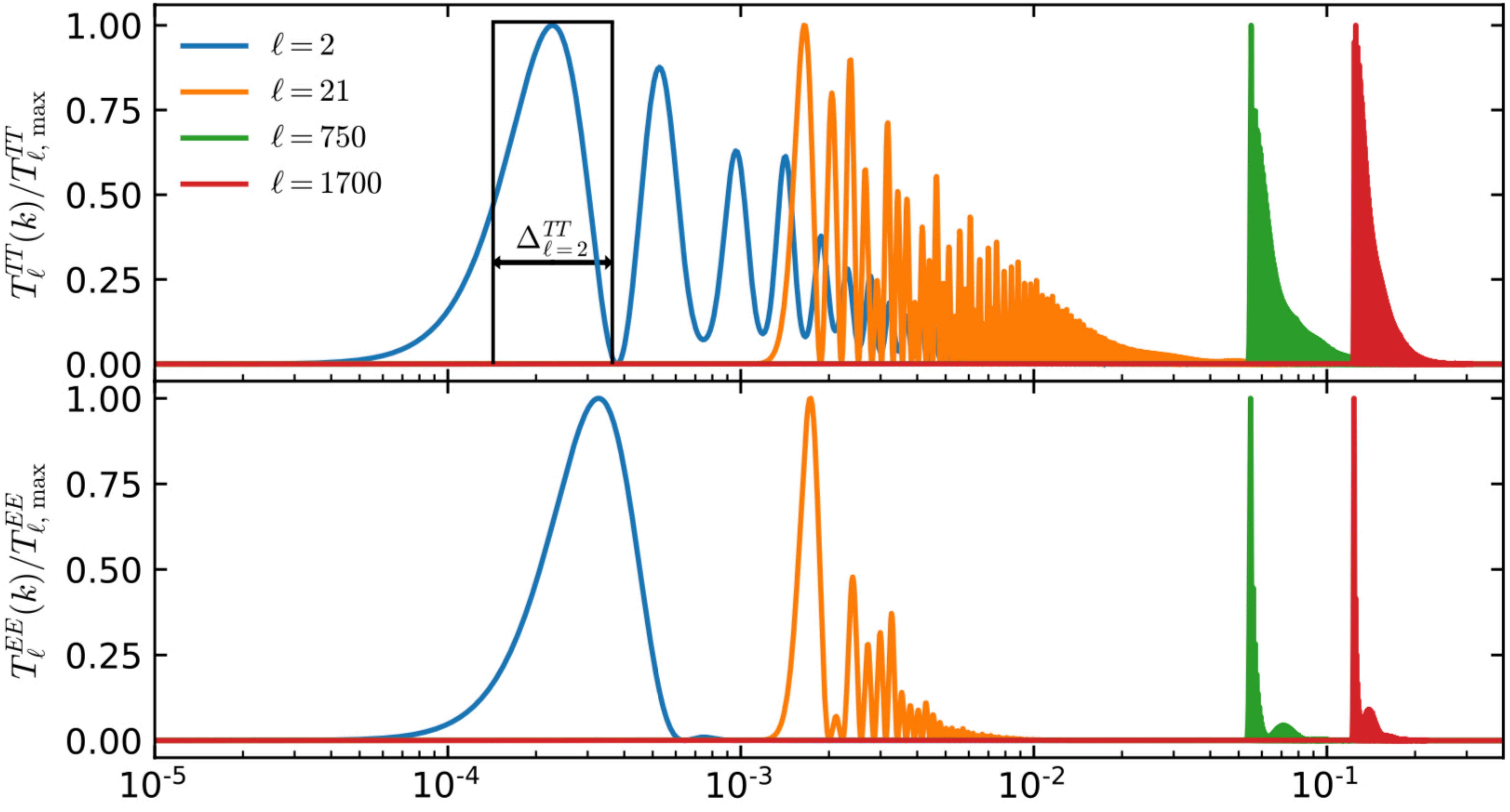


HOW TO CONSTRAIN THE PRIMORDIAL POWER SPECTRUM

$$C_\ell \propto \int d\ln k\, T(k)\, \mathscr{P}(k)$$



$$C_\ell \propto A_s \left(\frac{\ell}{\ell_*}\right)^{n_s-1} \int d\ln k\, T(k)$$



CMB transfer functions

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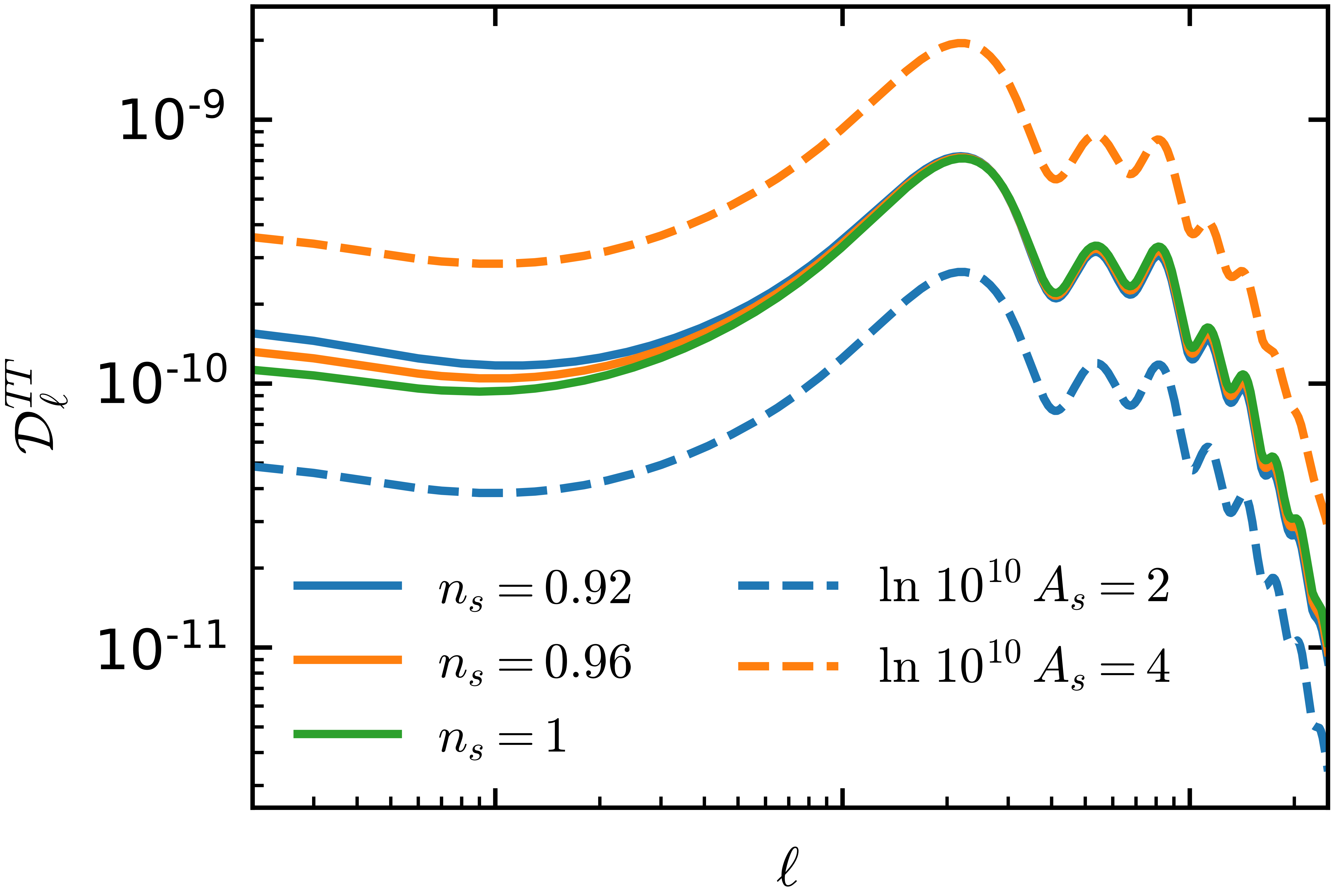

THE PRIMORDIAL SPECTRUM AND THE CMB

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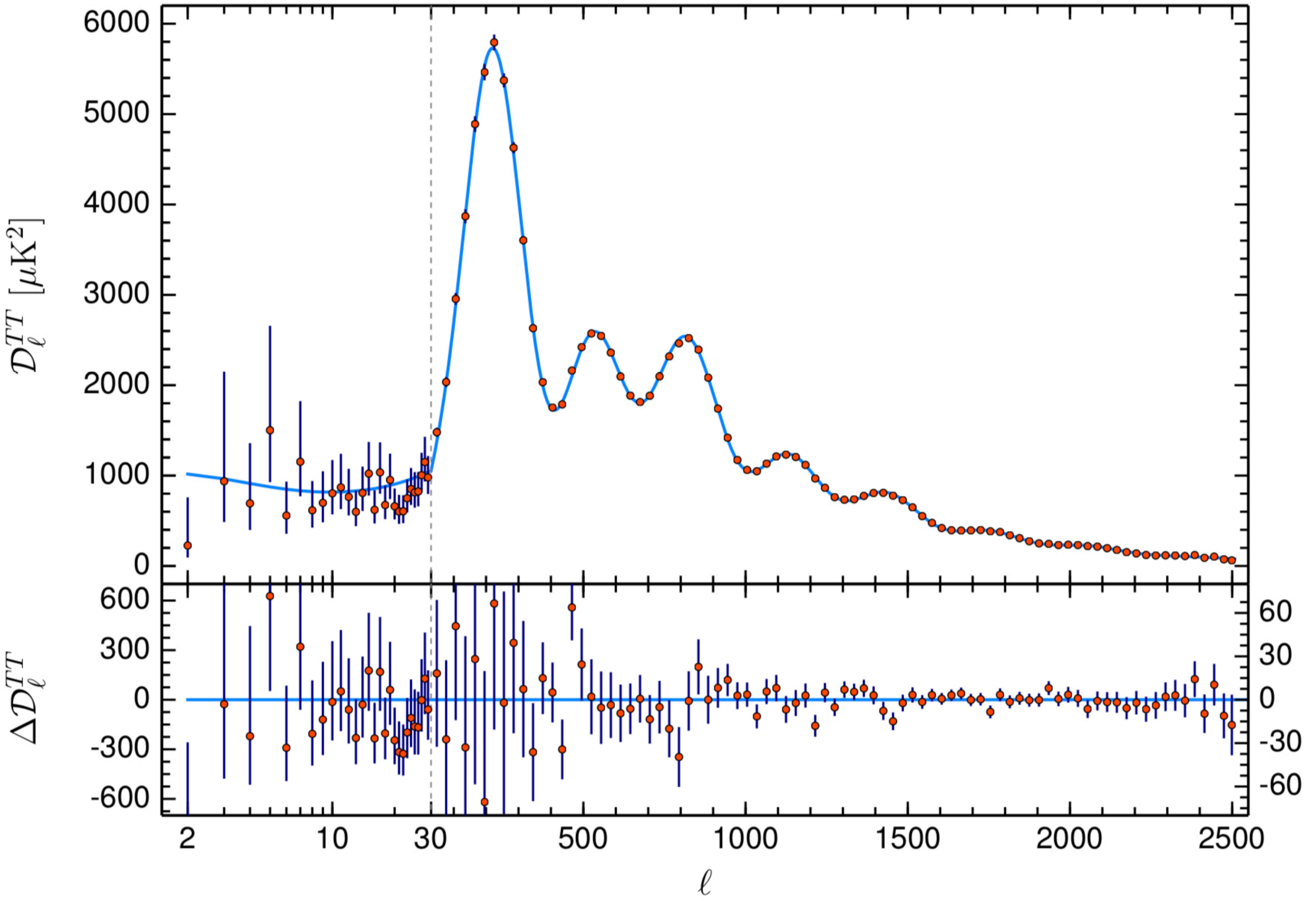


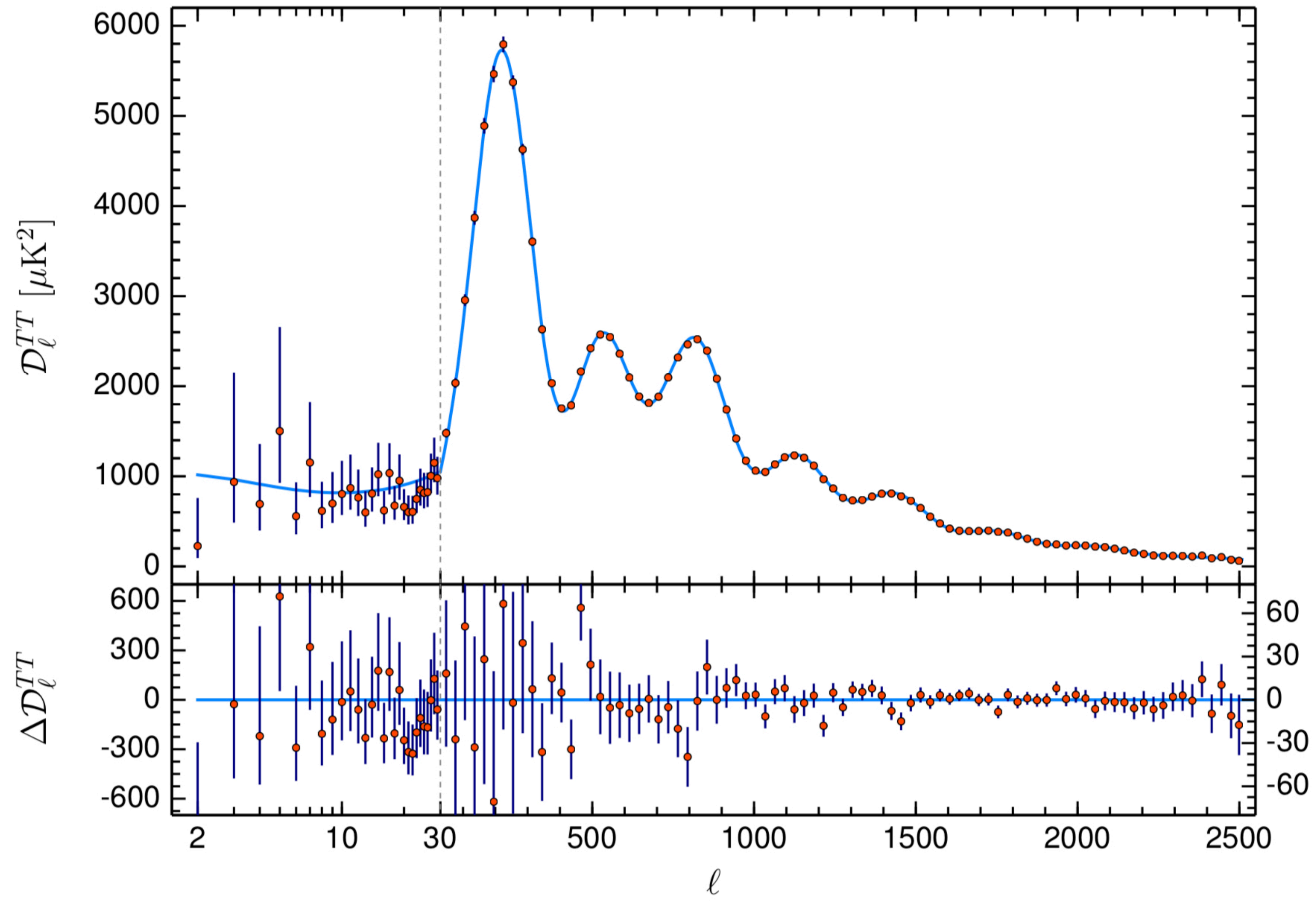
PLANCK 2018

THE PRIMORDIAL SPECTRUM AND THE CMB

$$\mathscr{P}(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1} \quad \longrightarrow \quad C_\ell \propto \int d\ln k \, T(k)\, \mathscr{P}(k)$$

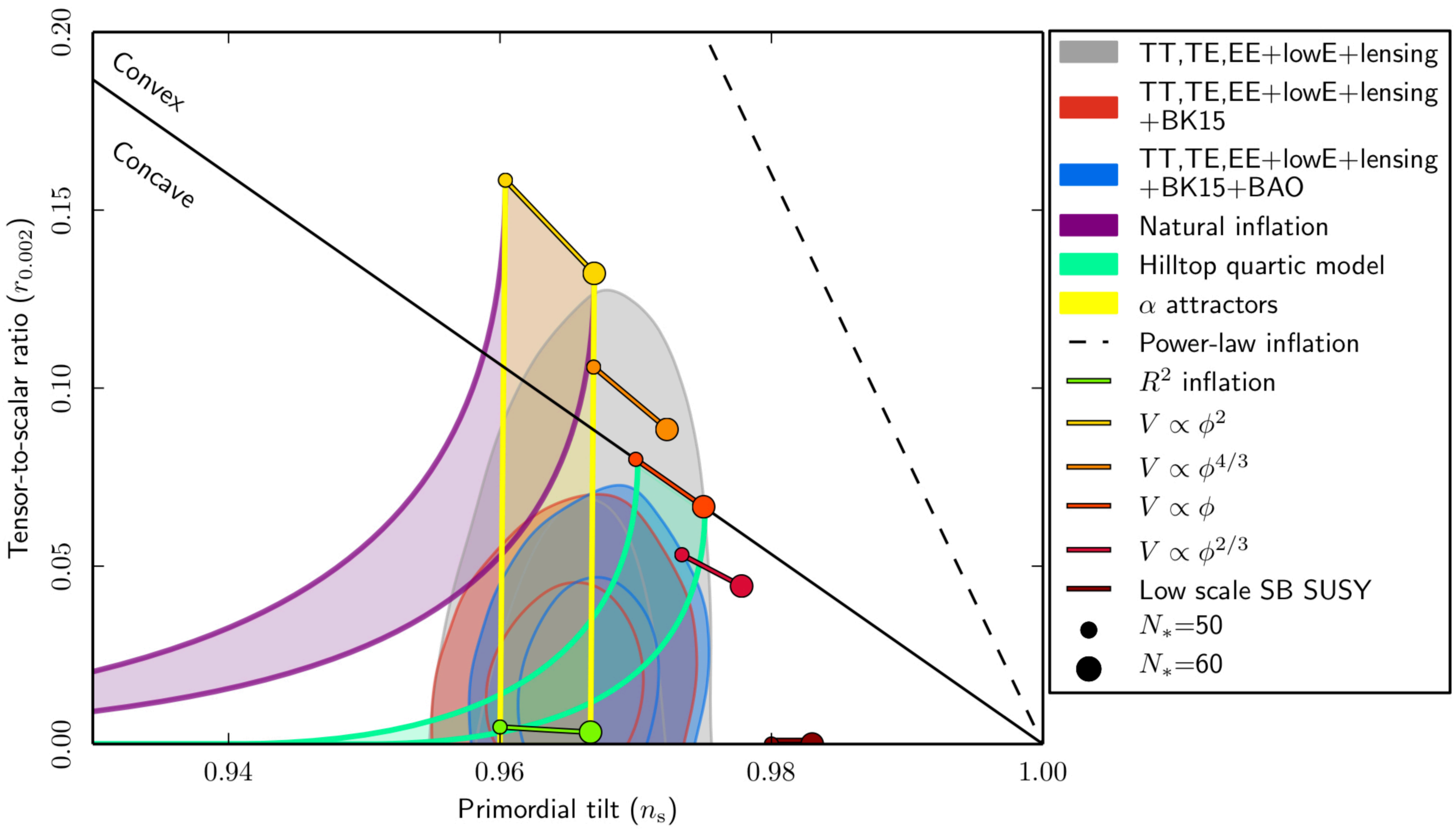
$$n_s = 0.9649 \pm 0.0042 \, (68\,\%\,\mathrm{CL})$$

Slow-roll inflation is consistent with data!



PLANCK 2018

SLOW-ROLL INFLATION AND NEAR SCALE-INVARIANCE



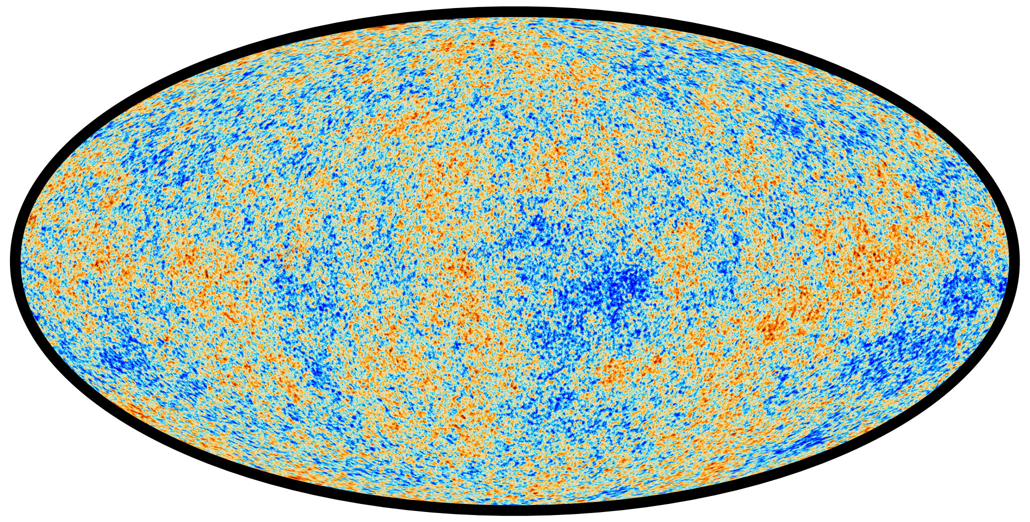
PLANCK 2018 INFLATION PAPER

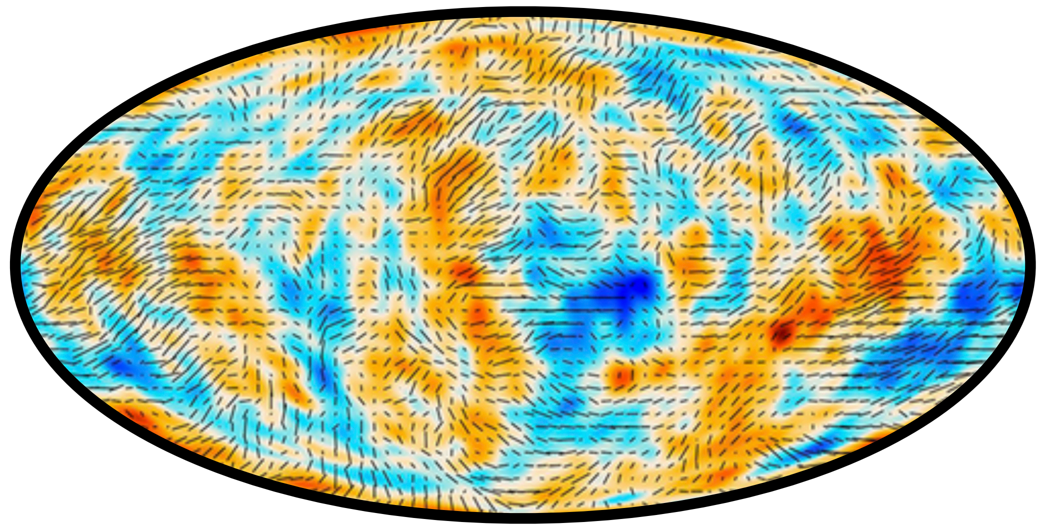
FEATURES IN THE PRIMORDIAL SPECTRUM (?)

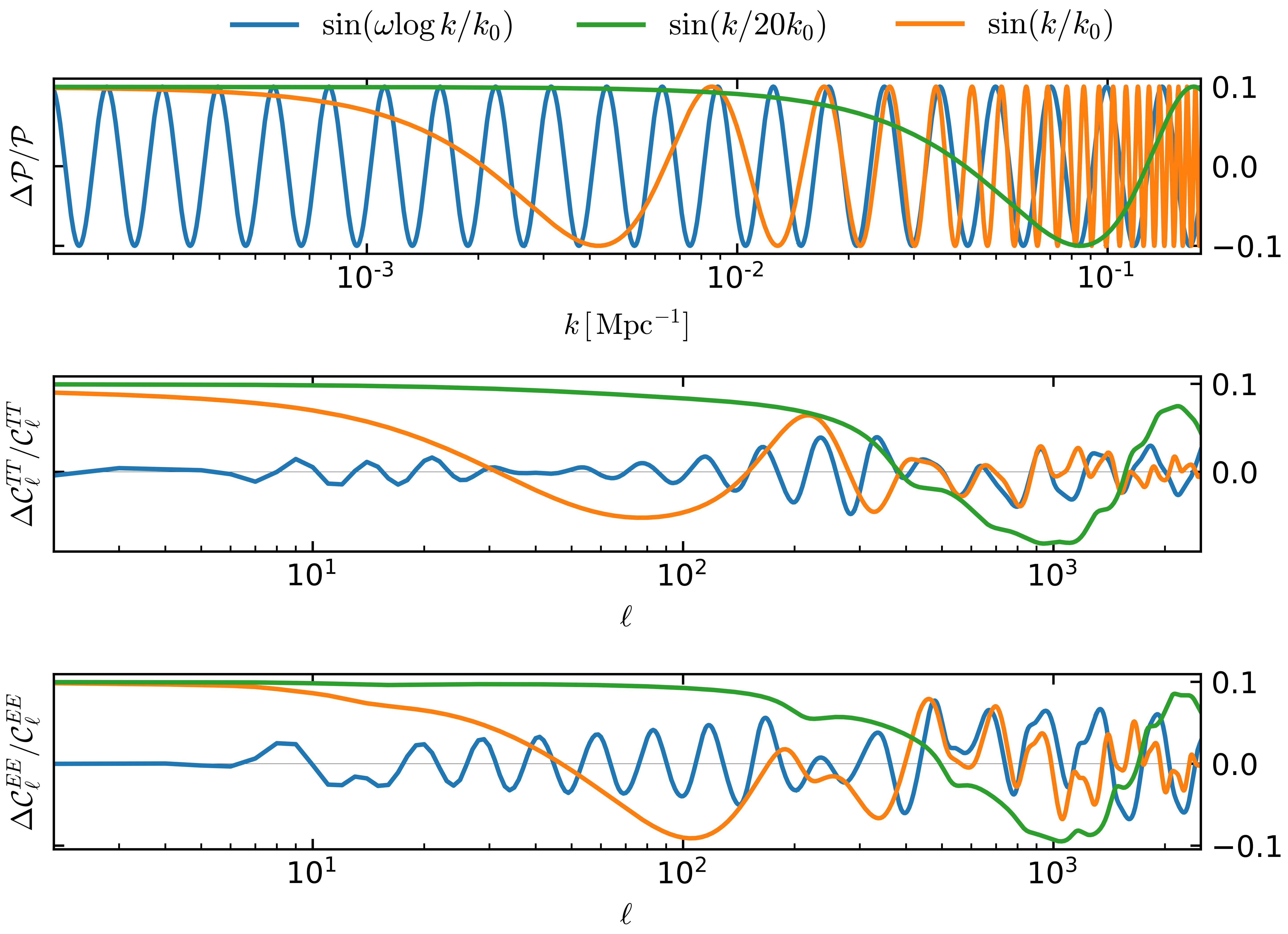
Features are small (oscillatory) corrections to the near scale invariant power spectrum

OBSERVABLE EFFECTS OF FEATURES

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







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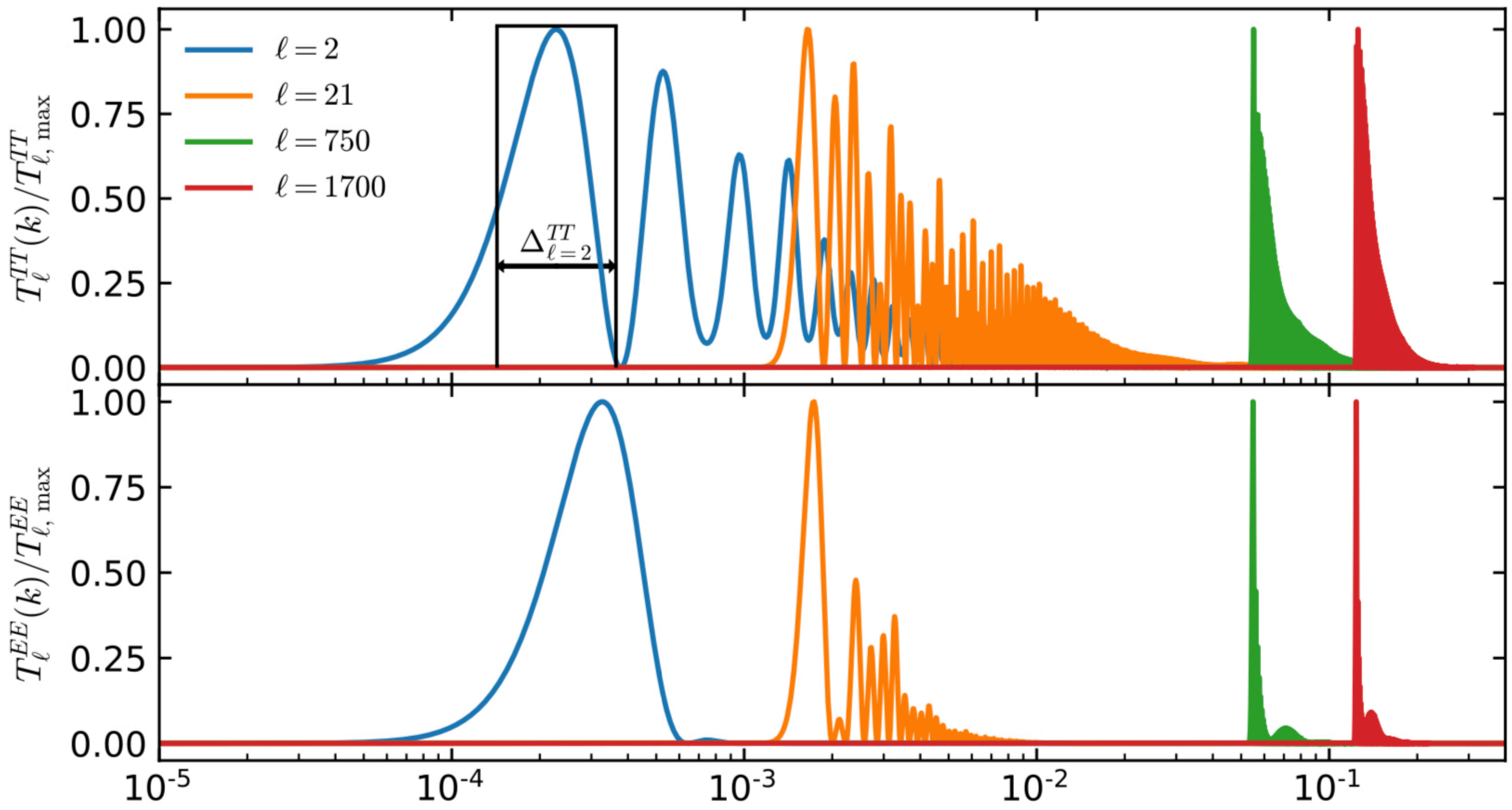

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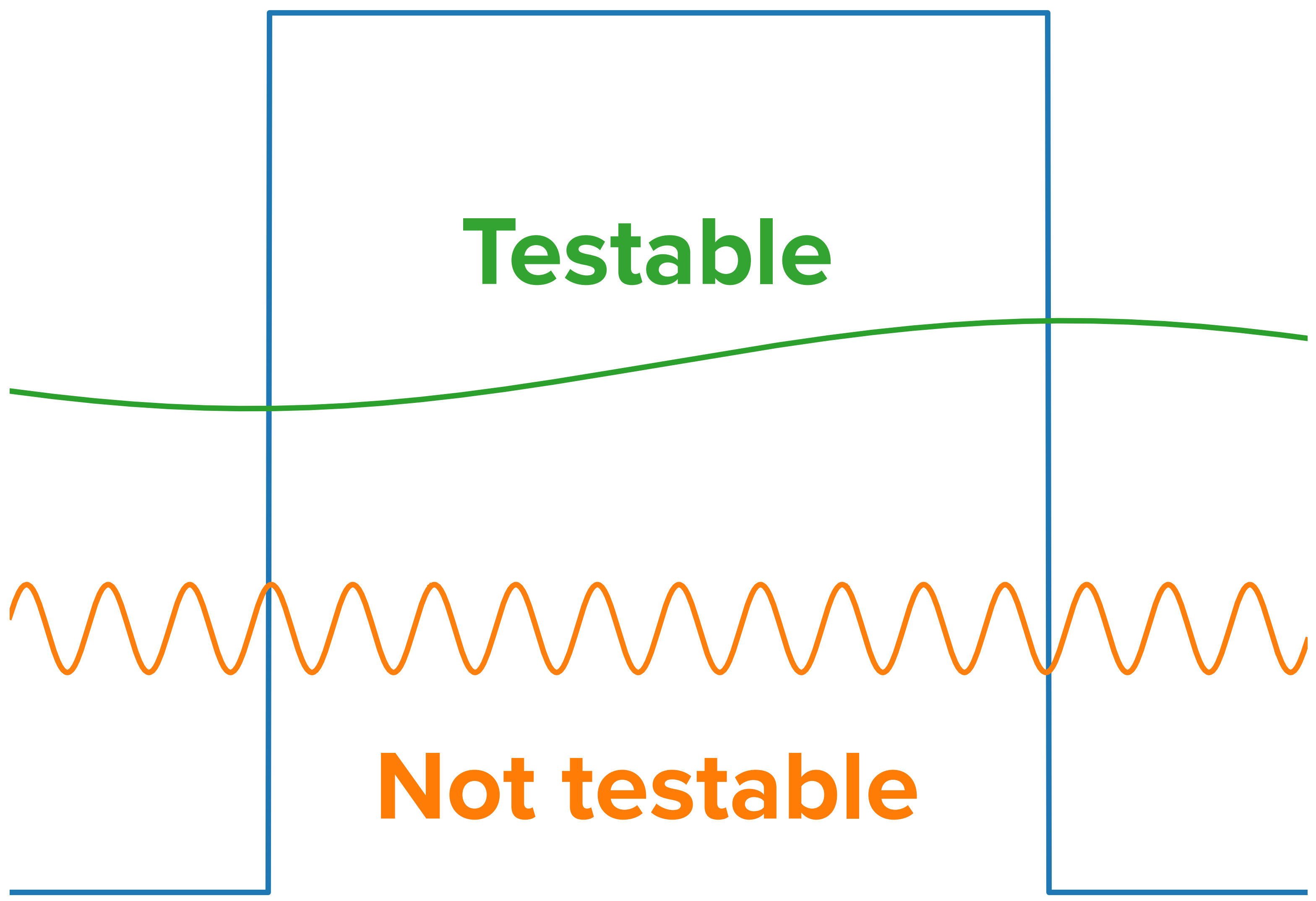
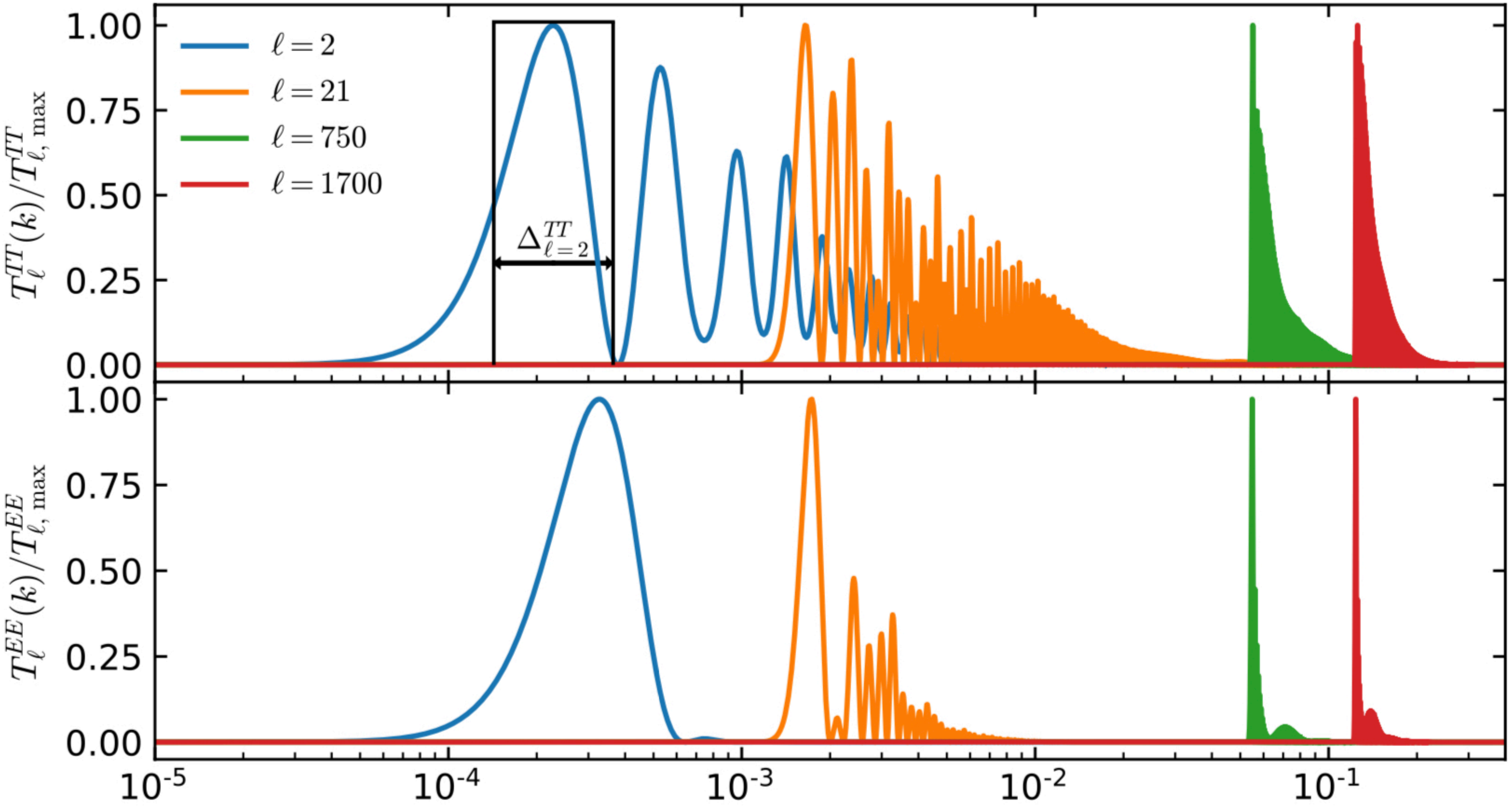
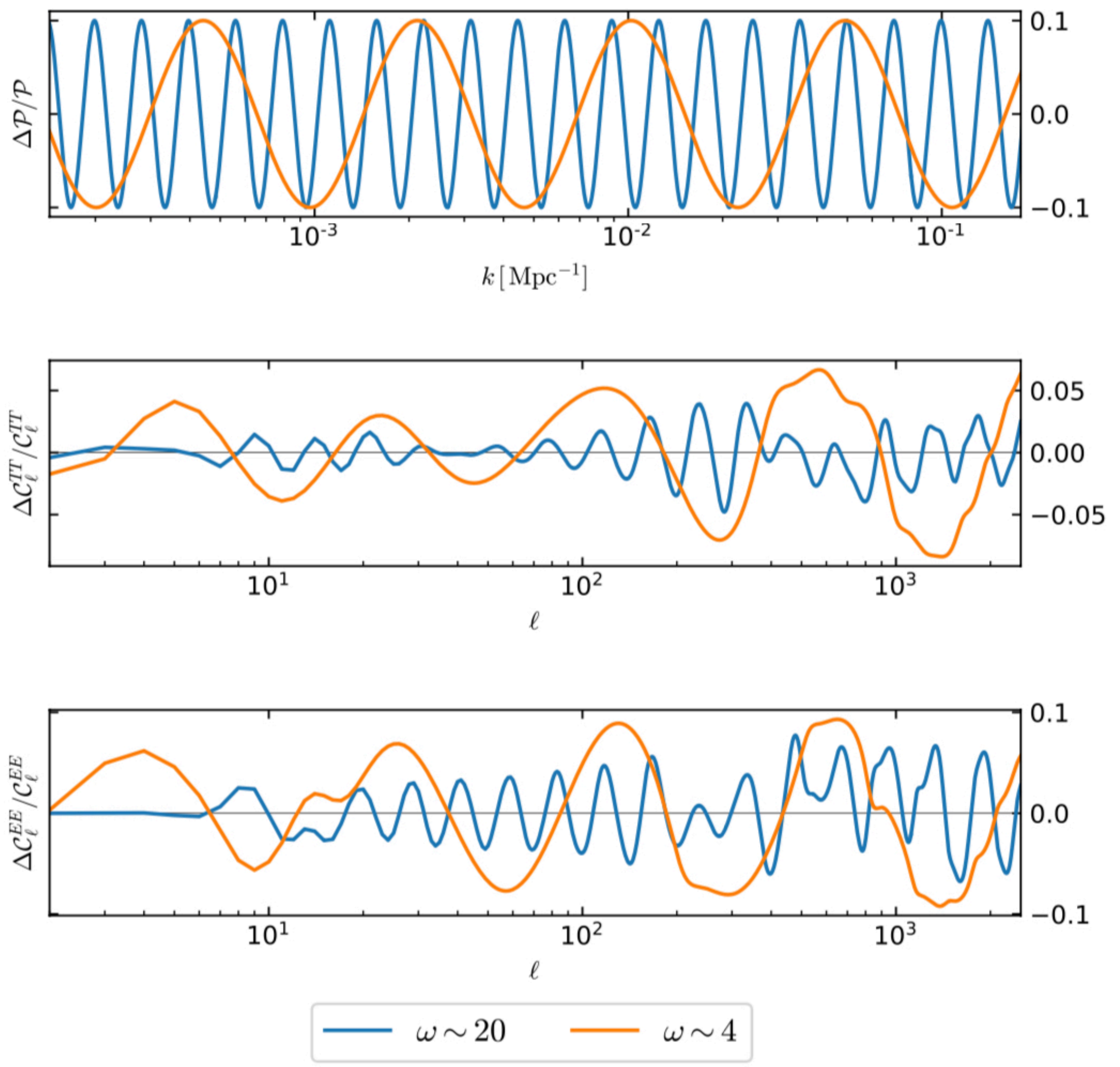




OBSERVABLE EFFECTS OF FEATURES

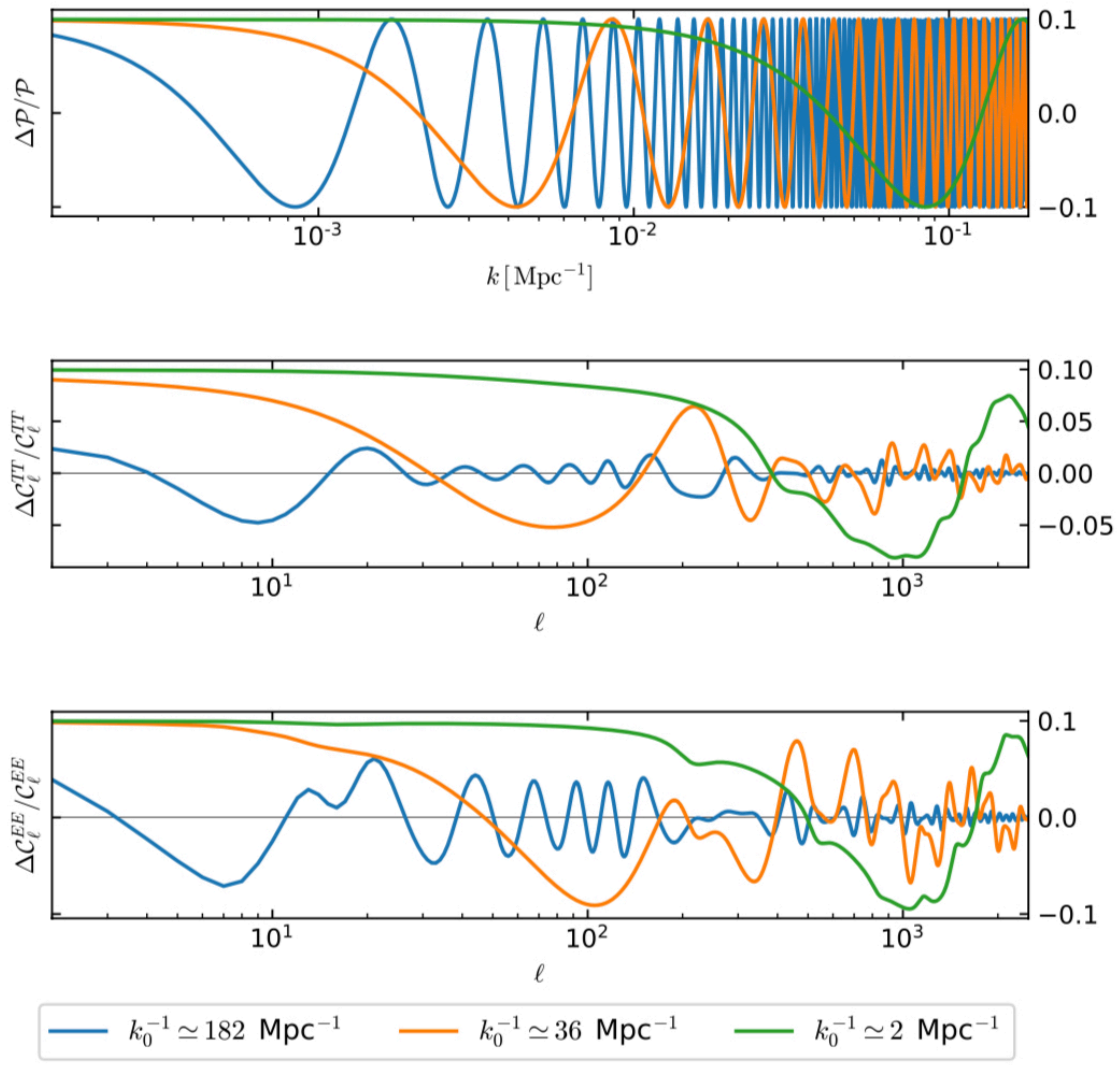
$$\delta_\ell \sim \frac{C}{\Delta_\ell^{\rm XY}} \int_{\log k_\ell - \Delta/2}^{\log k_\ell + \Delta/2} d\log k \, \sin(\omega \log k)$$

- increases with ℓ
- decreases with ω



$$\delta_\ell \sim \frac{C}{\Delta_\ell^{\rm XY}} \int_{\log k_\ell - \Delta/2}^{\log k_\ell + \Delta/2} d\log k \, \sin(k/k_0)$$

- decreases with ℓ
- decreases with ω

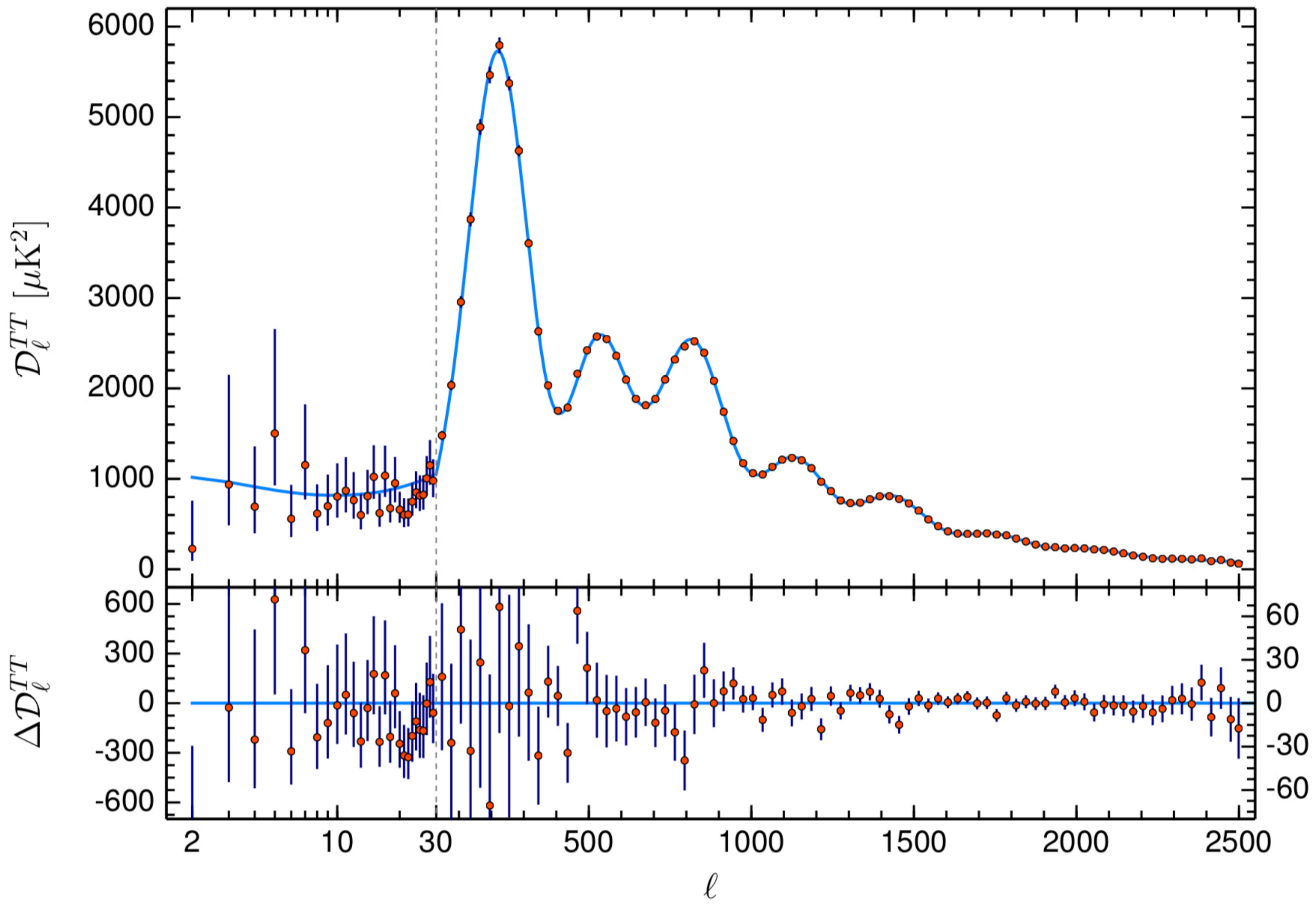


FEATURES & BEYOND SLOW-ROLL

DATA

THEORY

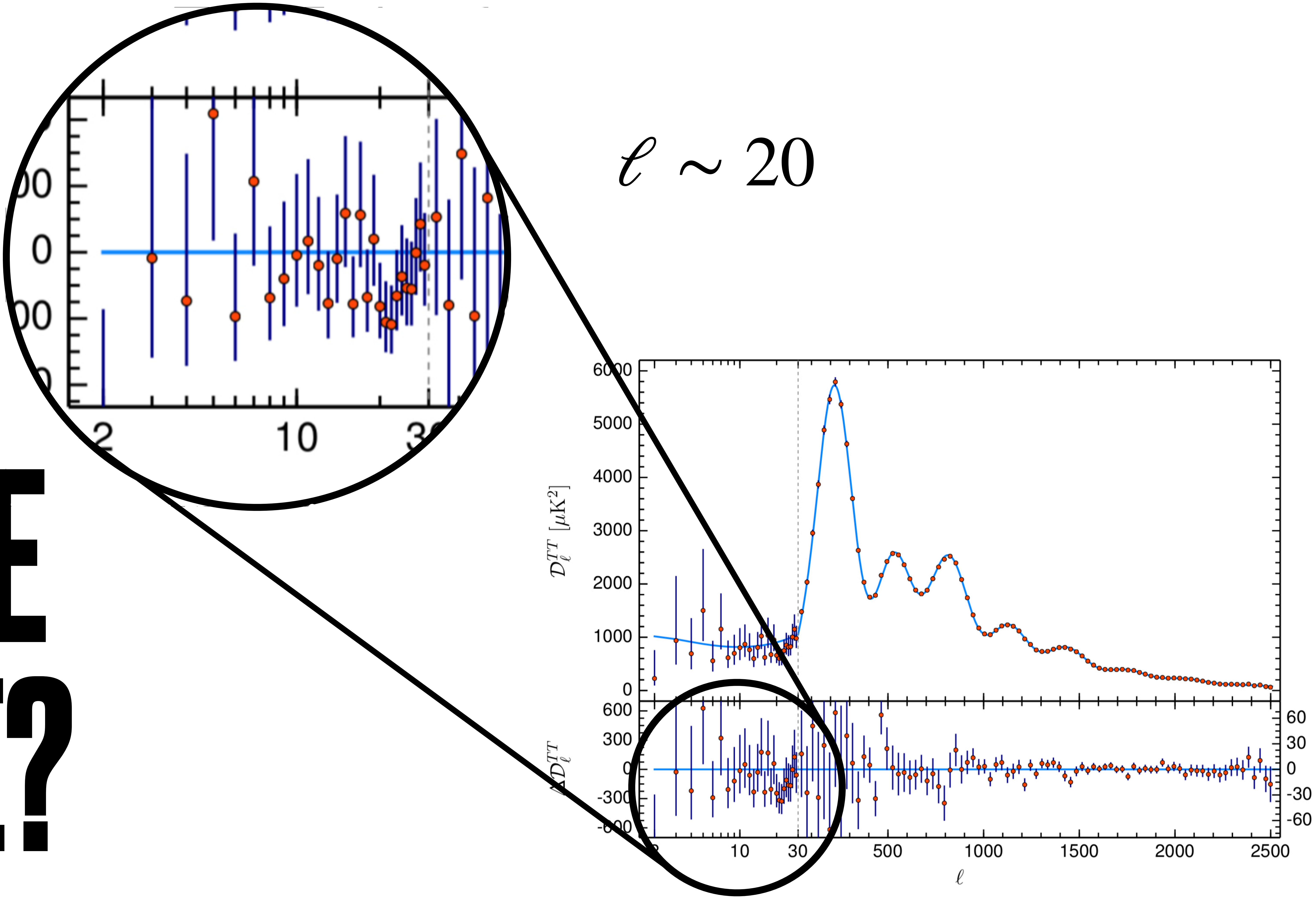
NEAR SCALE INVARIANCE?

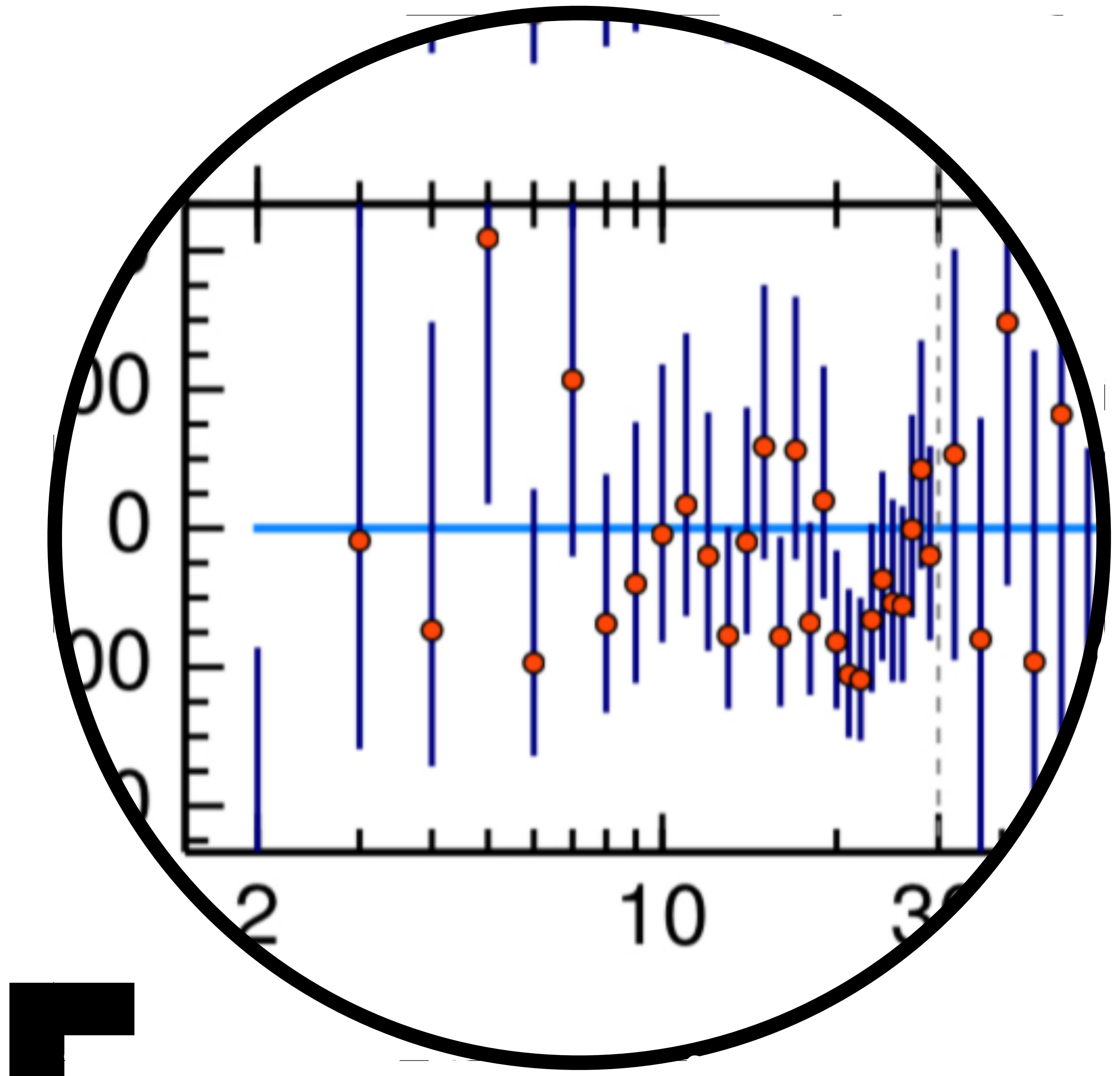


The standard cosmological model is completely specified by 6 parameters. Do we need deviations from scale invariance?

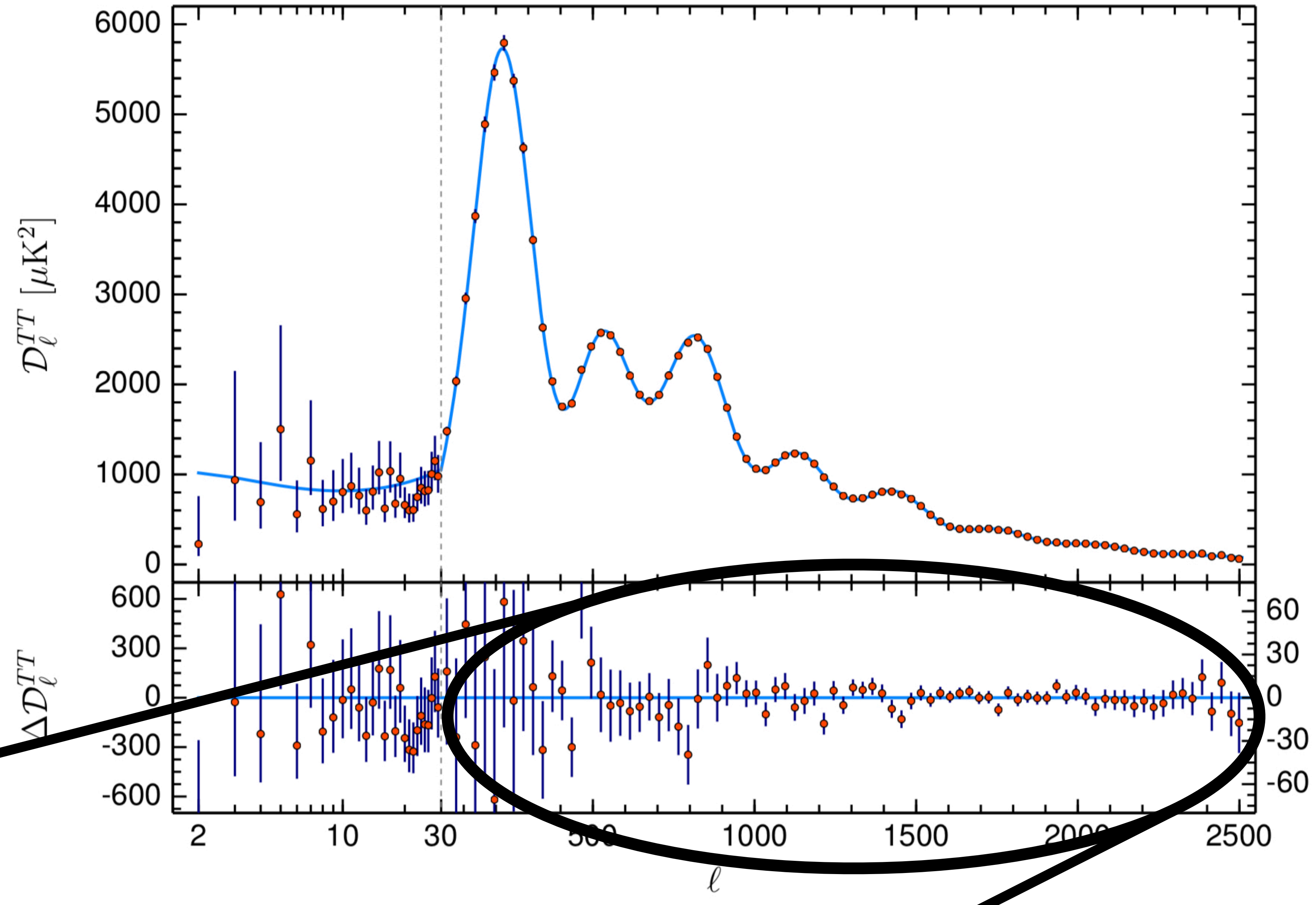
NEAR SCALE INVARIANCE?

$\ell \sim 20$



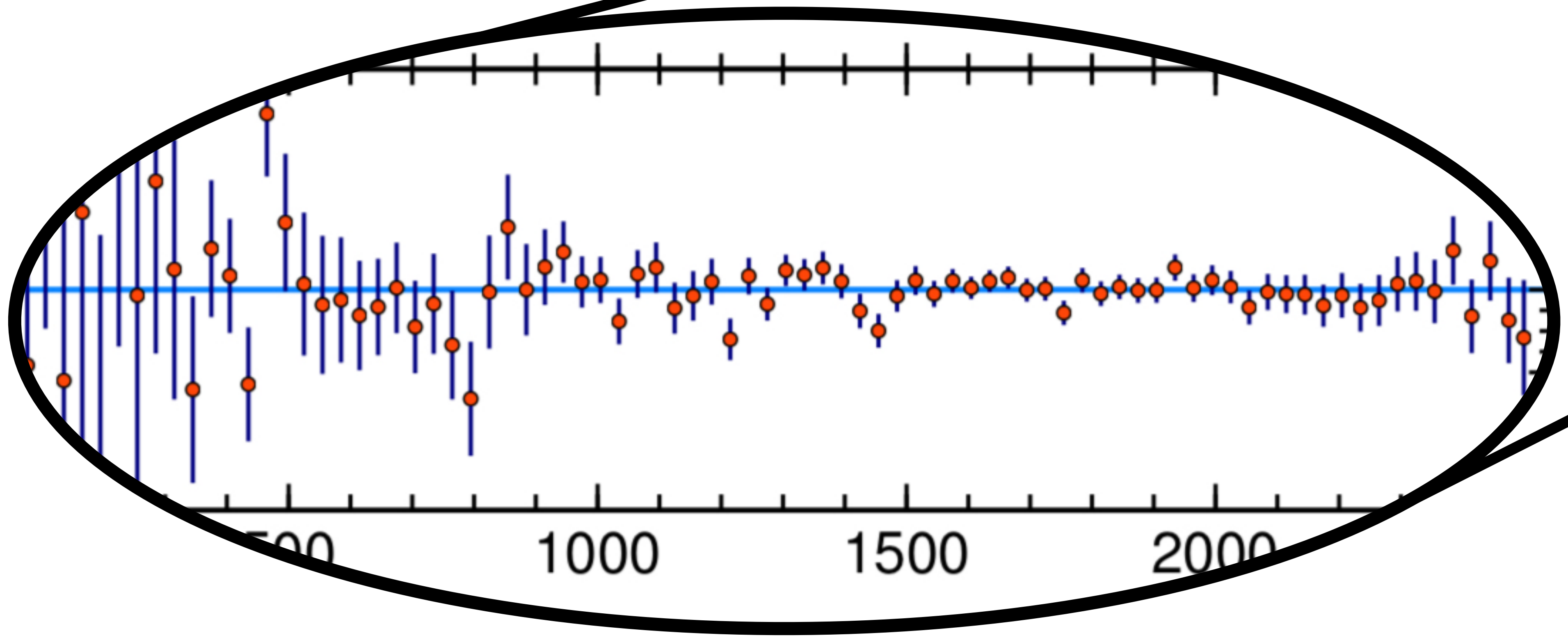


$\ell \sim 20$



NEAR SCALE INVARIANCE?

High ℓ



INFLATIONARY LANDSCAPES

INFLATIONARY LANDSCAPES

HOW TO TEST FEATURES: CHALLENGES

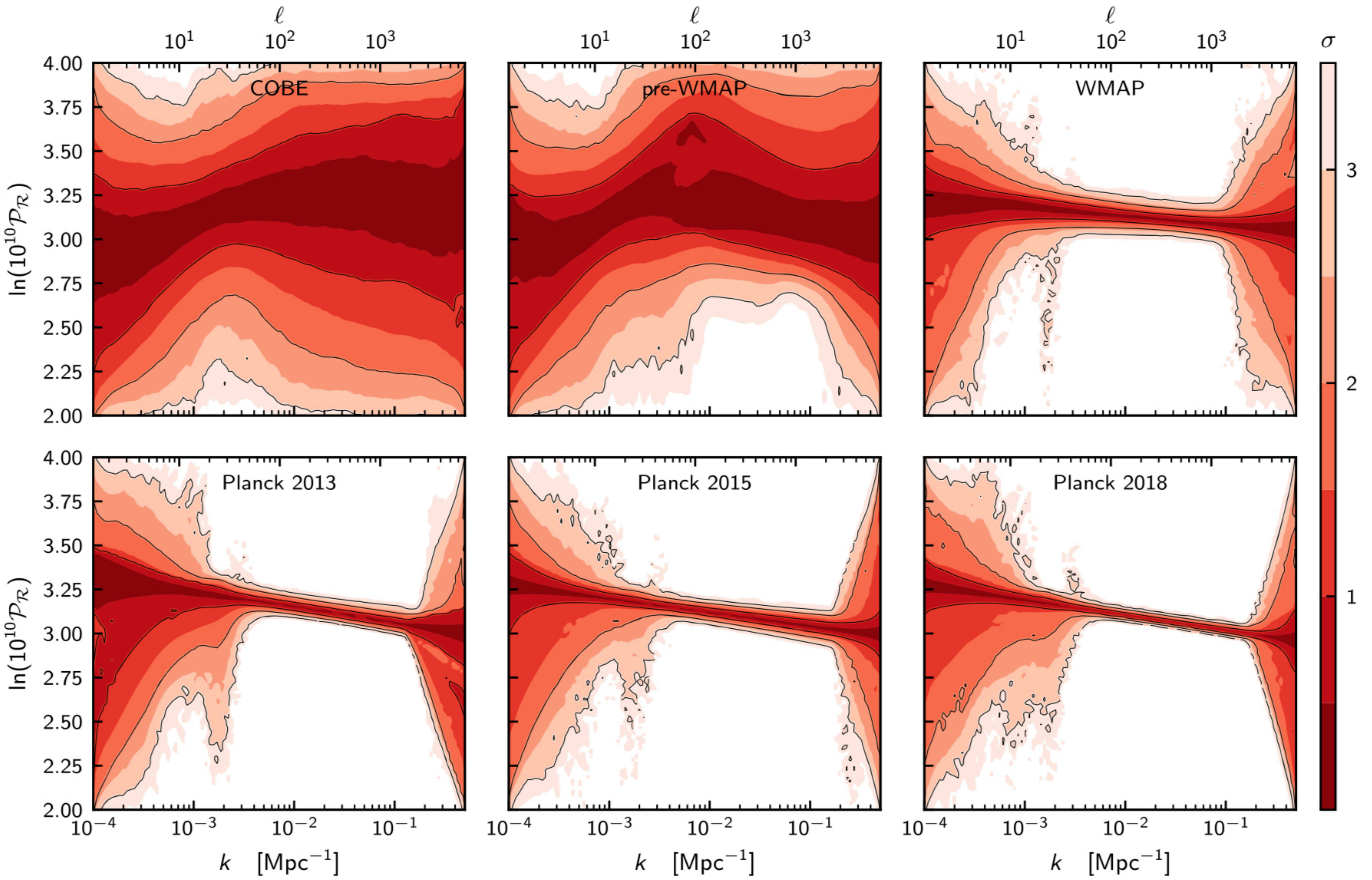
- Primordial features improve a lot the fit (i.e. the χ^2) to data, but the introduce extra parameters: penalized Bayesian evidence.
- Features in Planck data have a low SNR + larger prior volume: multimodal distributions.
- Highly oscillatory features: overfitting issues & need to increase accuracy of Einstein-Boltzmann solvers

HOW TO TEST FEATURES

BOTTOM-UP

TOP-DOWN

BOTTOM-UP APPROACH (Reconstruction of the primordial power spectrum)

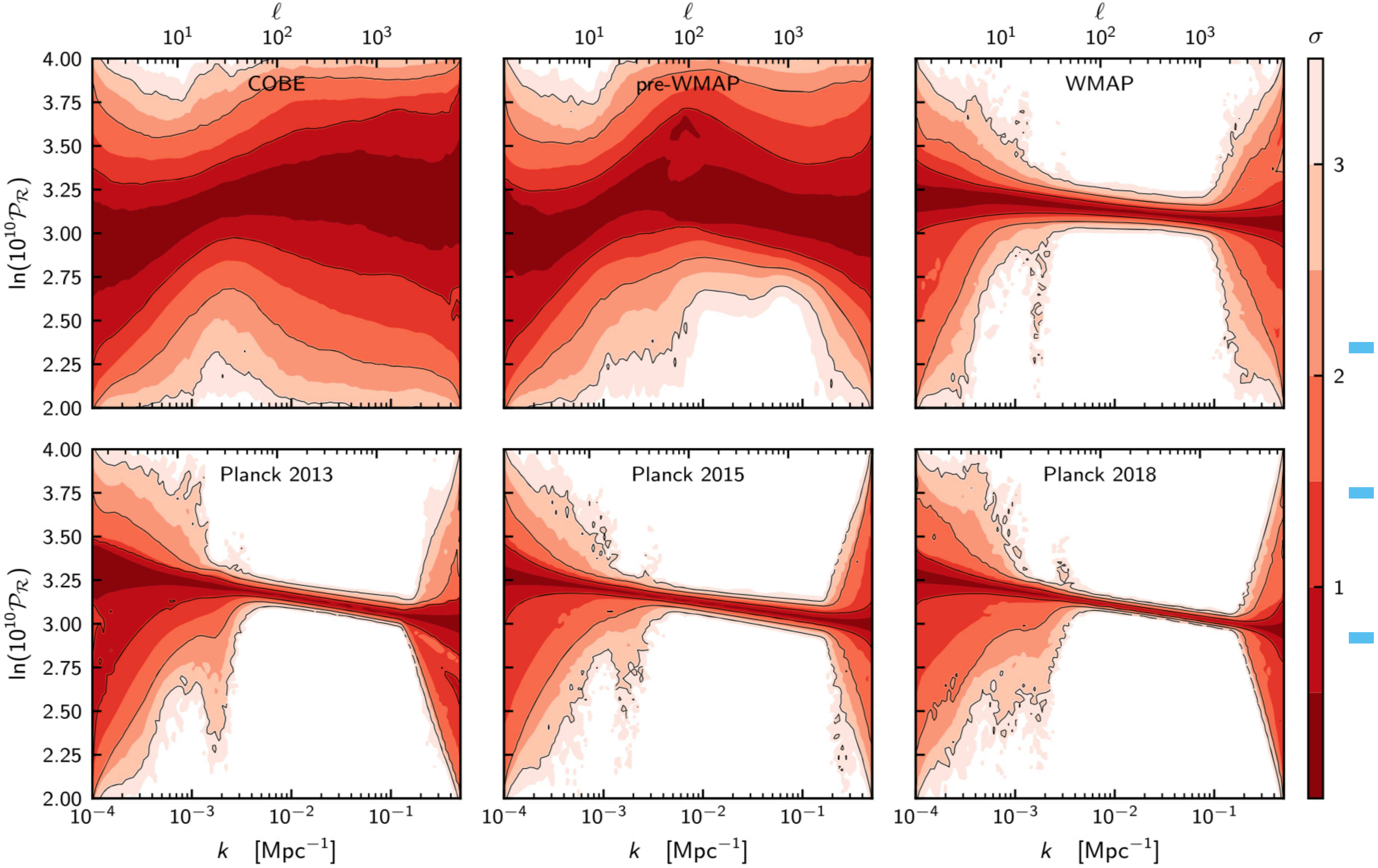


Handley et al 2019, but see also a lot of works by Dhiraj

BOTTOM-UP APPROACH (Reconstruction of the primordial power spectrum)

PROS

- Model independence



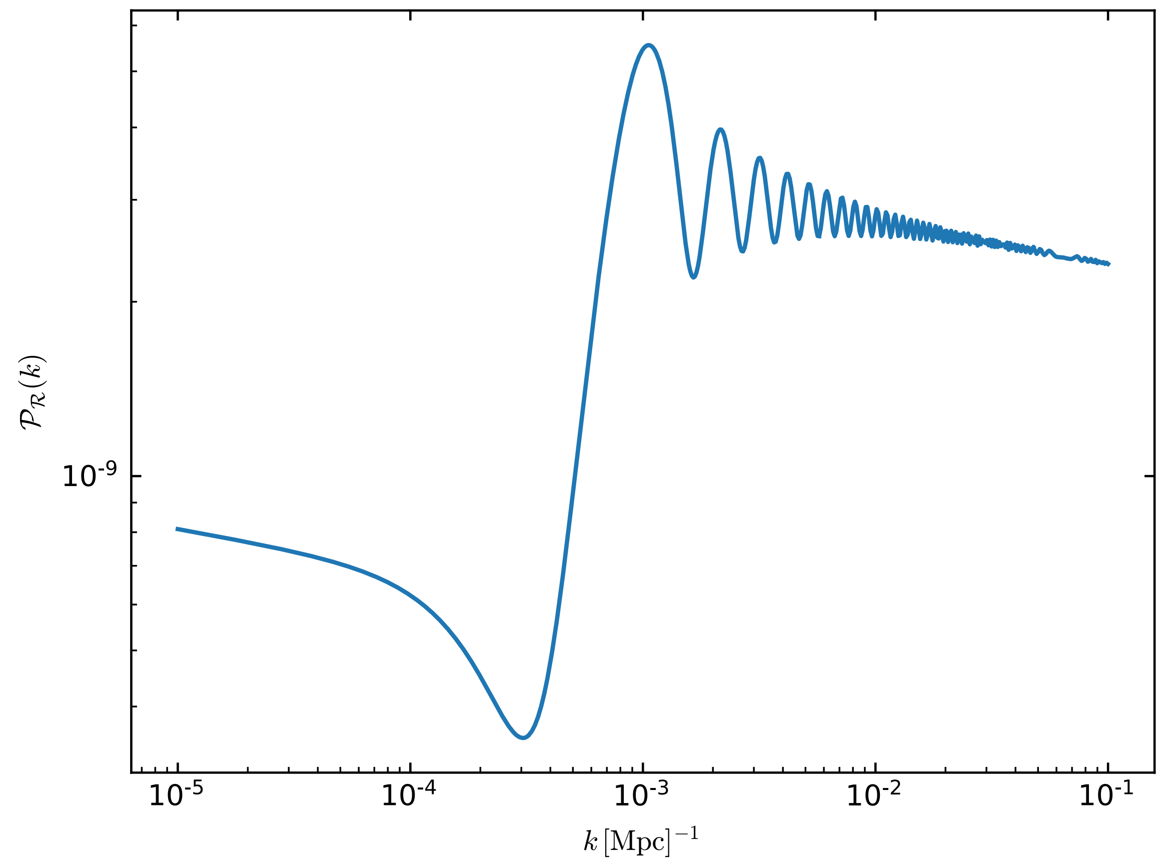
Handley et al 2019, but see also a lot of works by Dhiraj

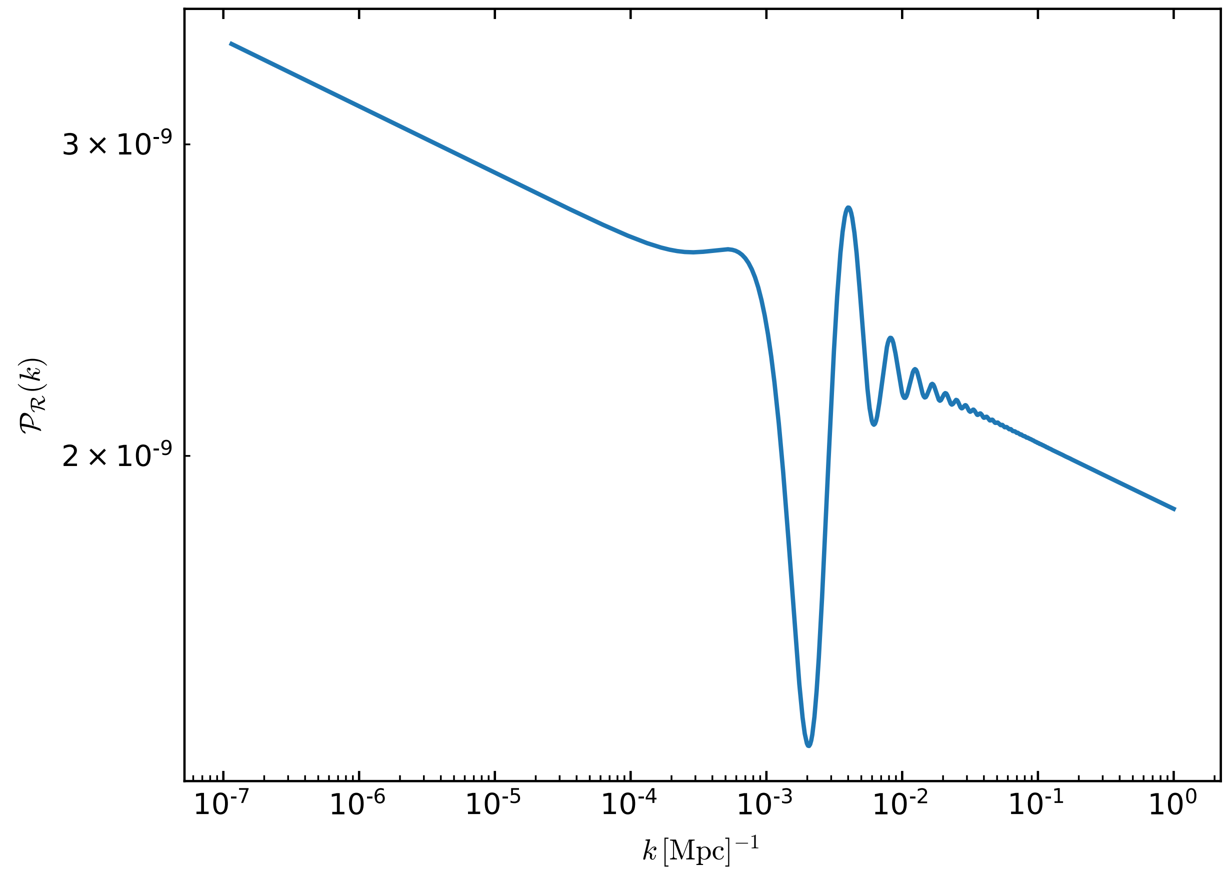
CONS

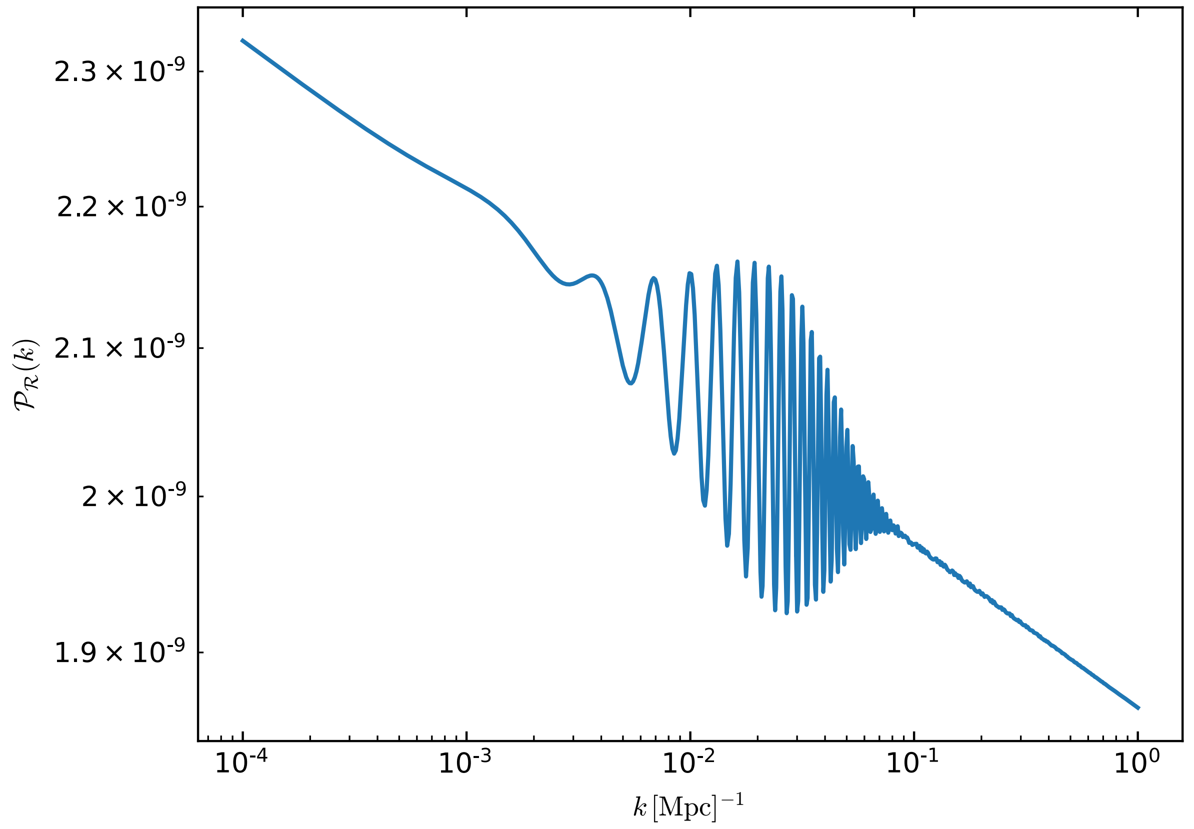
- The results are not necessarily physical
- Not sensitive to features finer than the binning
- Typically requires large number of parameters

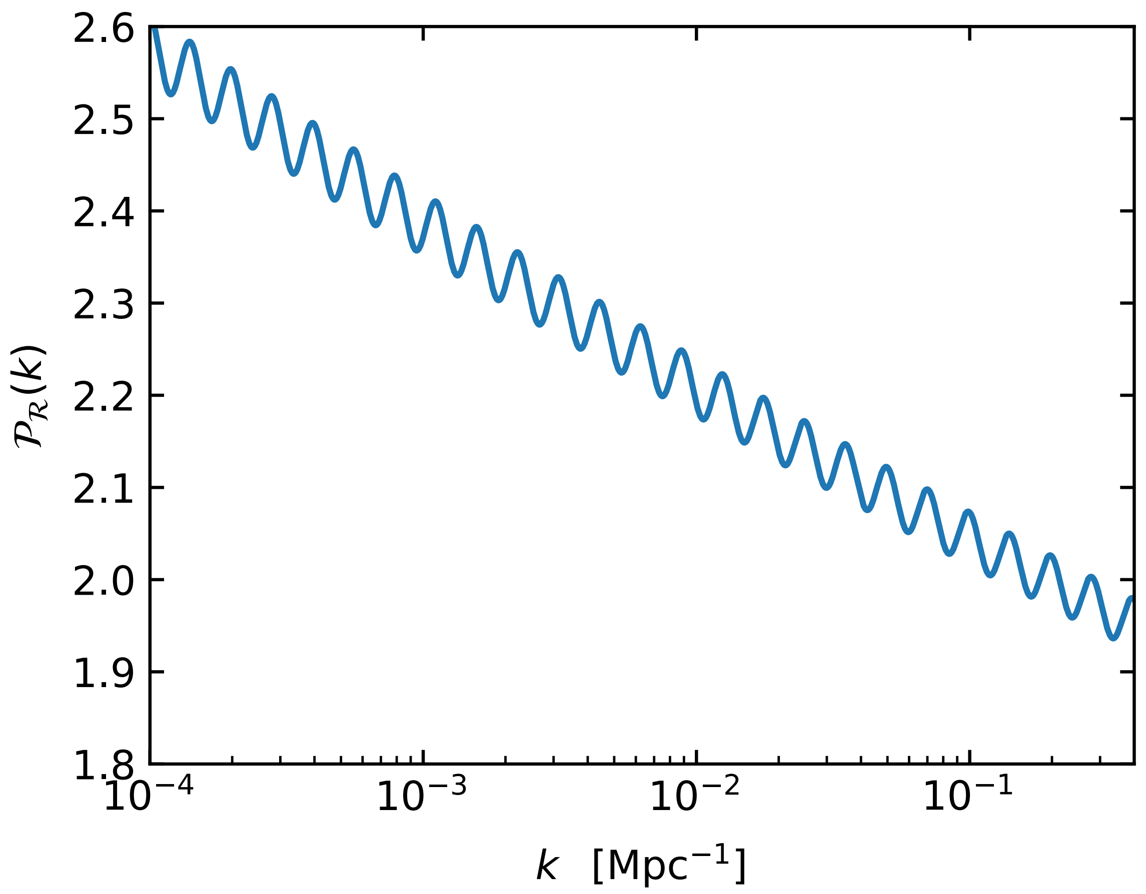
TOP-DOWN APPROACH

(Fitting models to data)







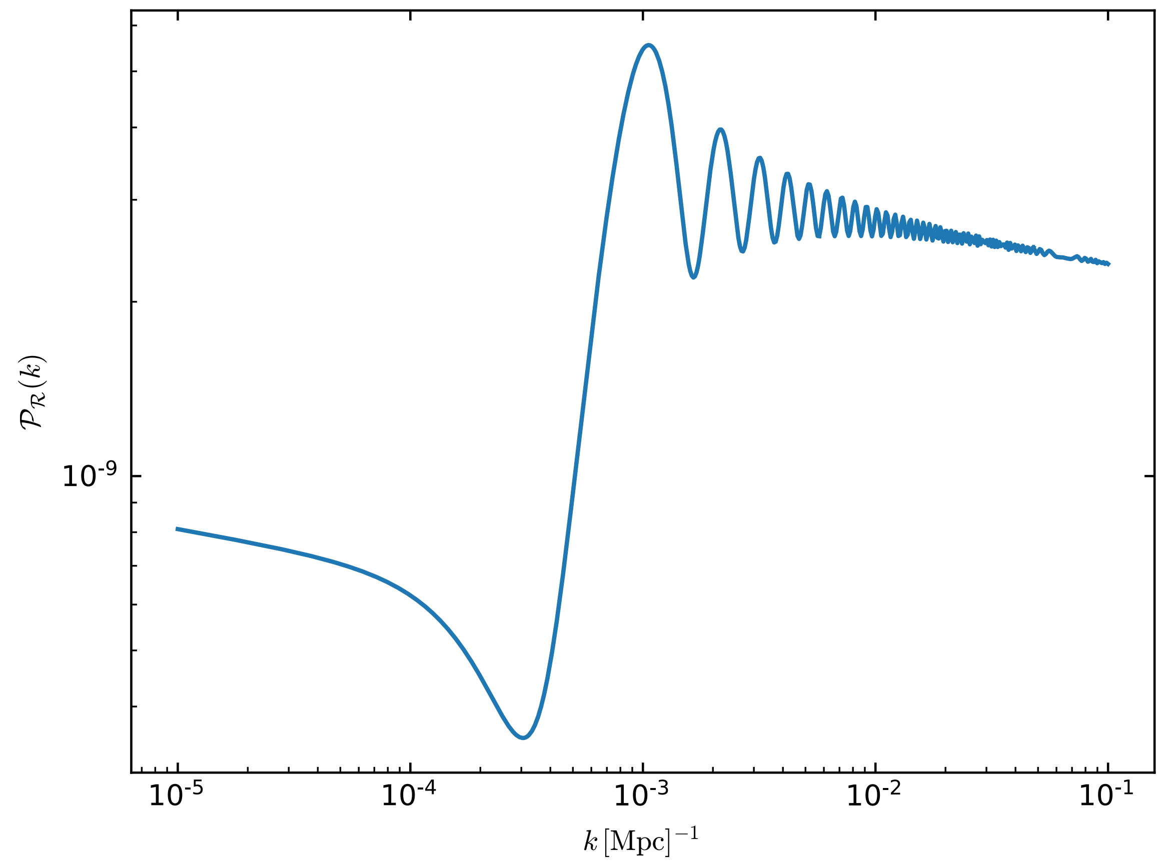


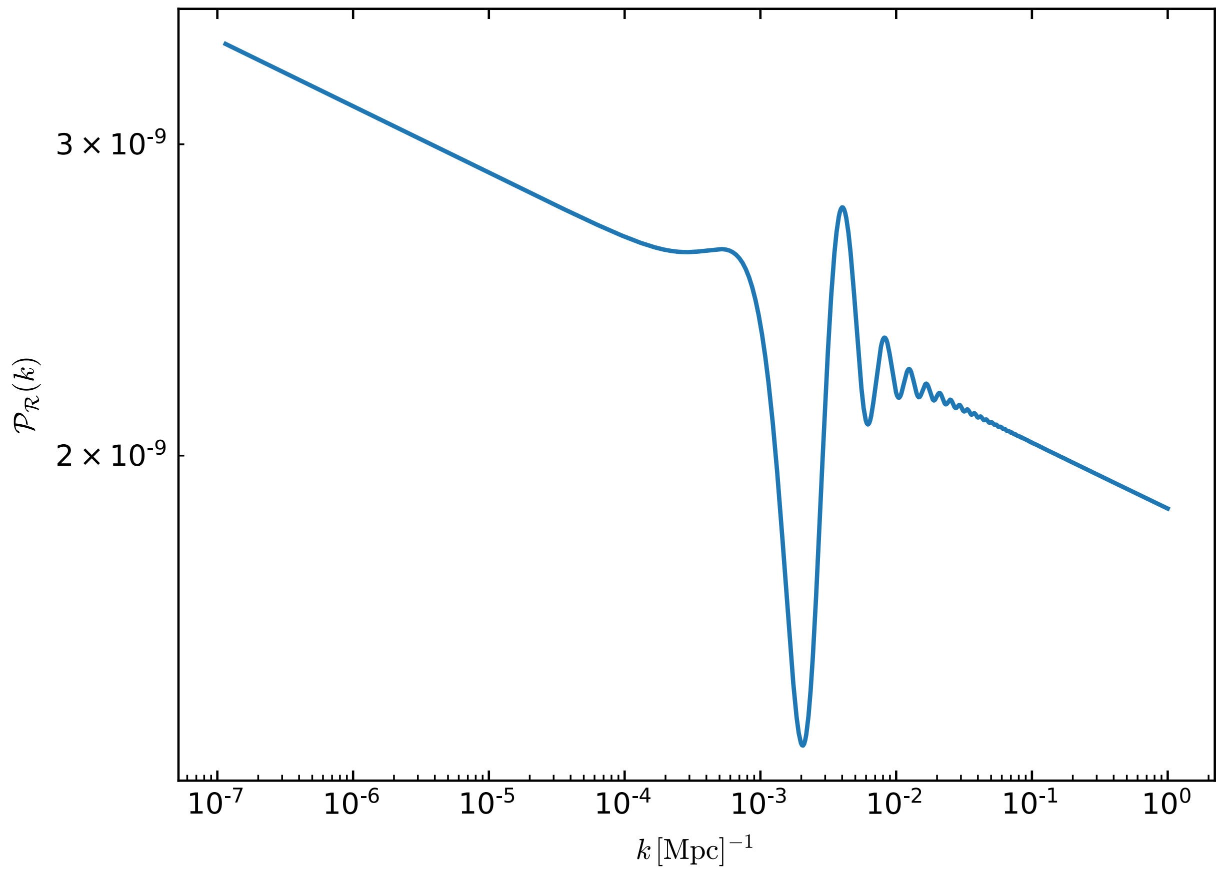
TOP-DOWN APPROACH

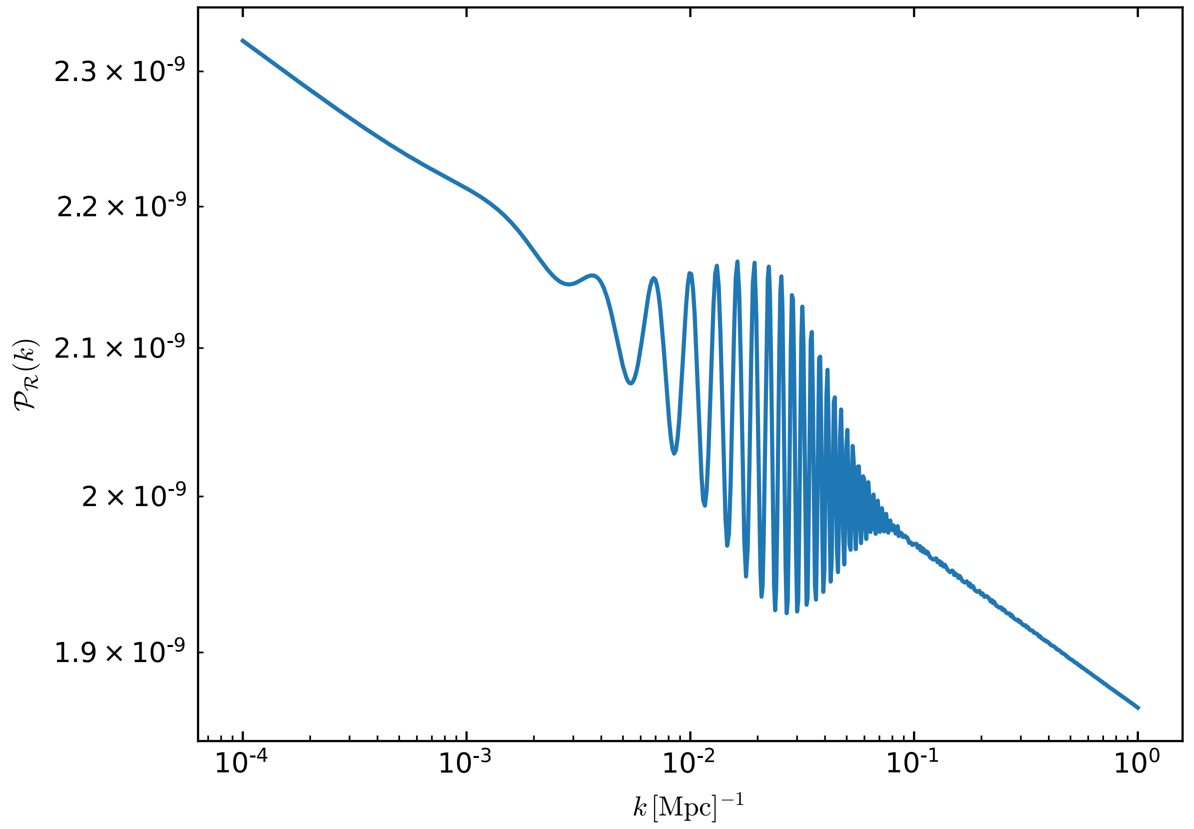
(Fitting models to data)

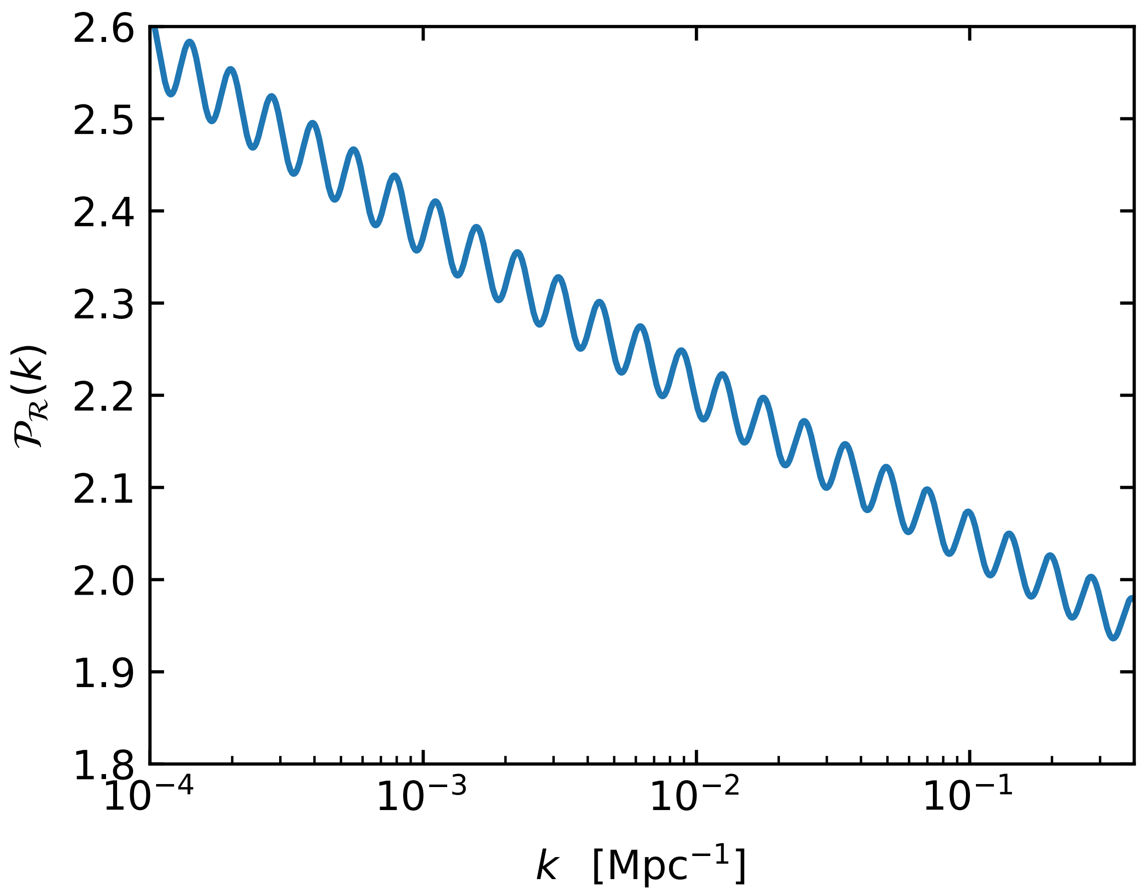
PROS

- Model dependence (extract clear info from data)
- Fewer extra parameters
- High predictivity
- Access to high frequency features









CONS

- Model dependence (more restricted scope)

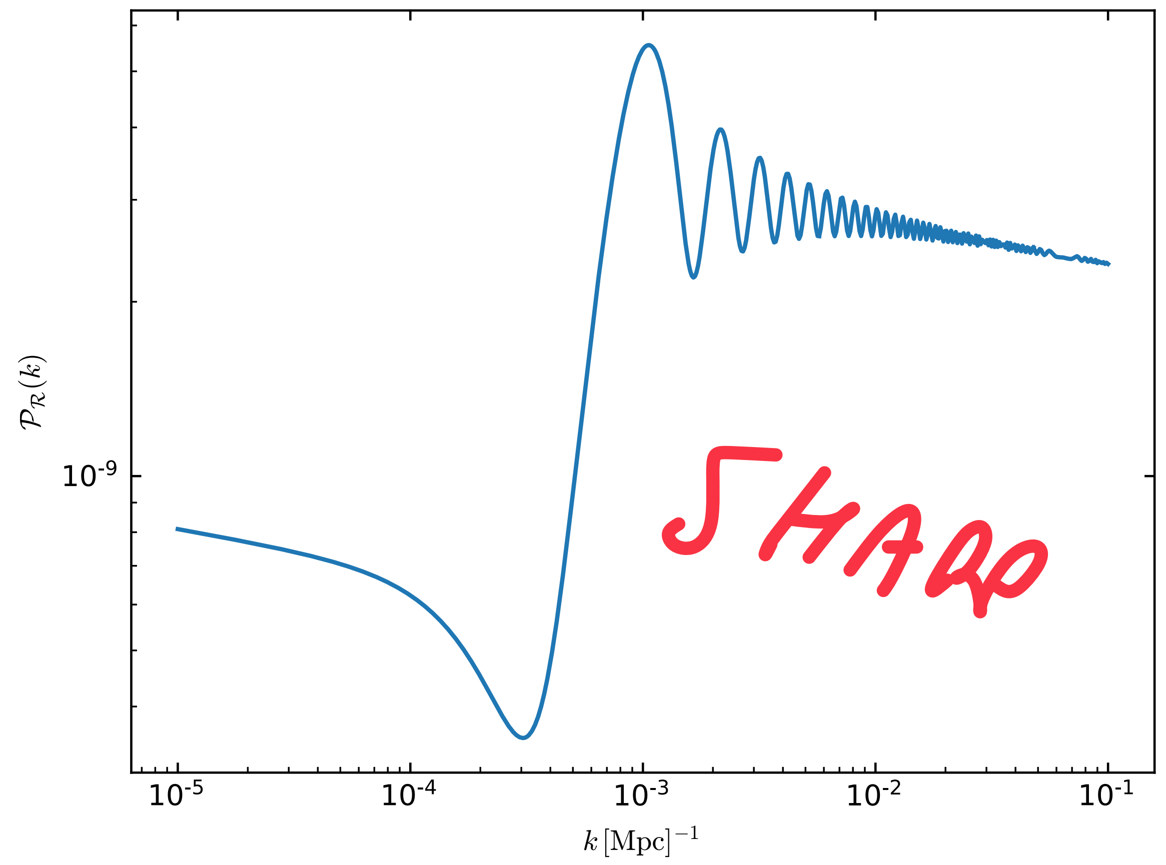
TOP-DOWN APPROACH

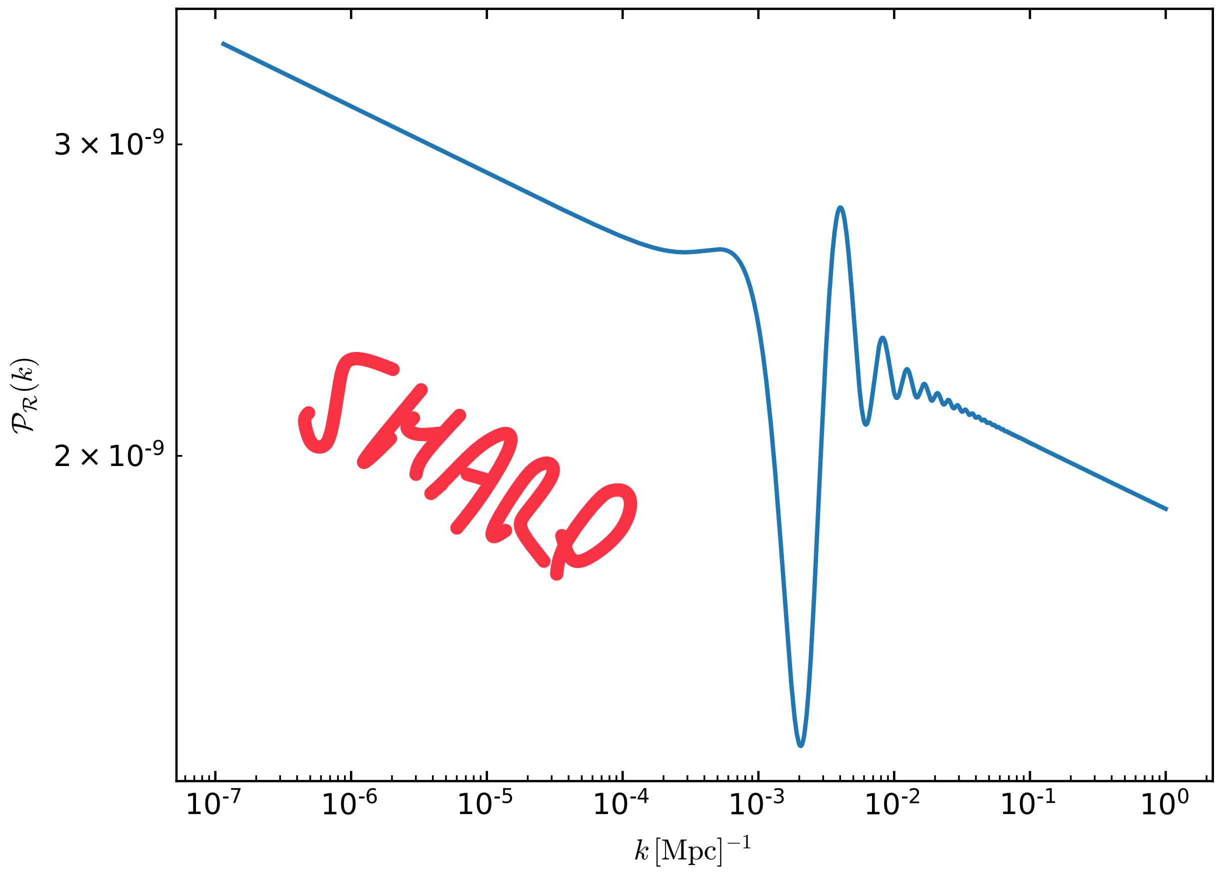
(Fitting models to data)

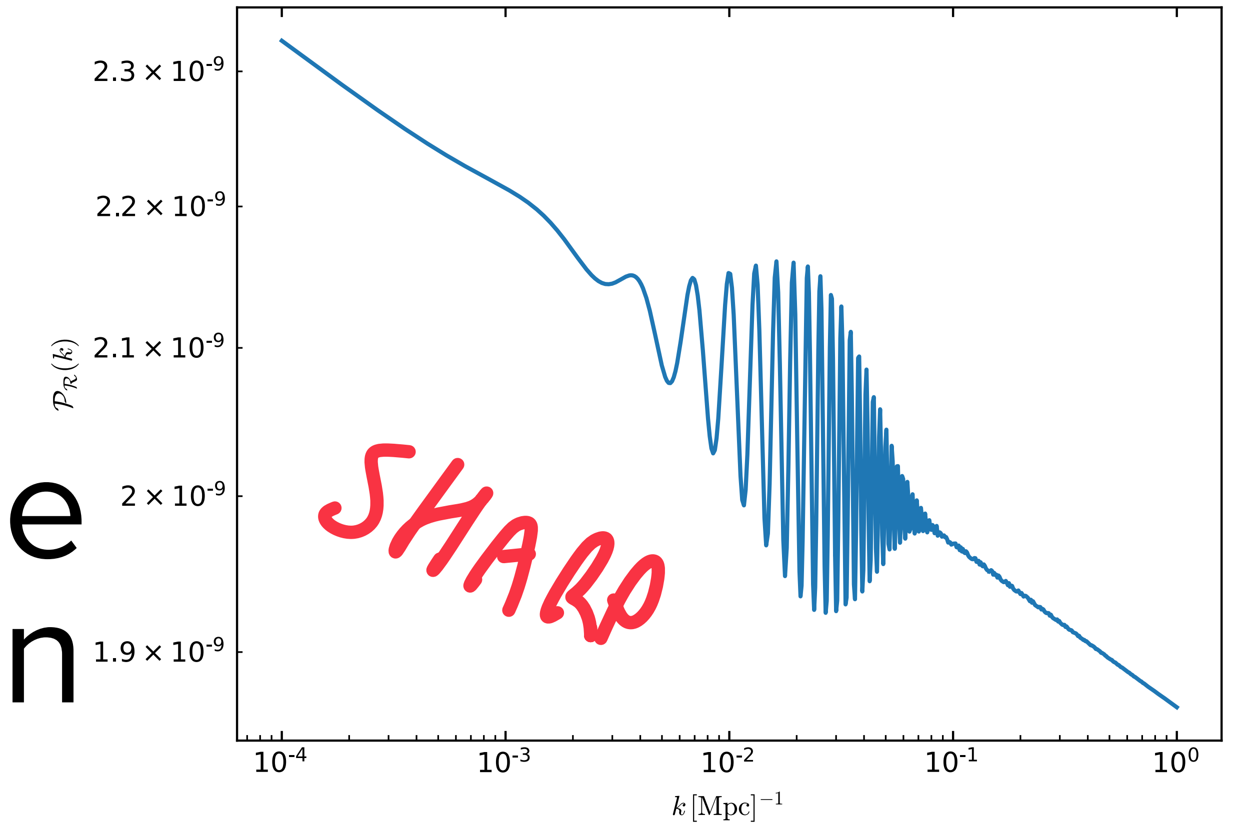
Sharp features

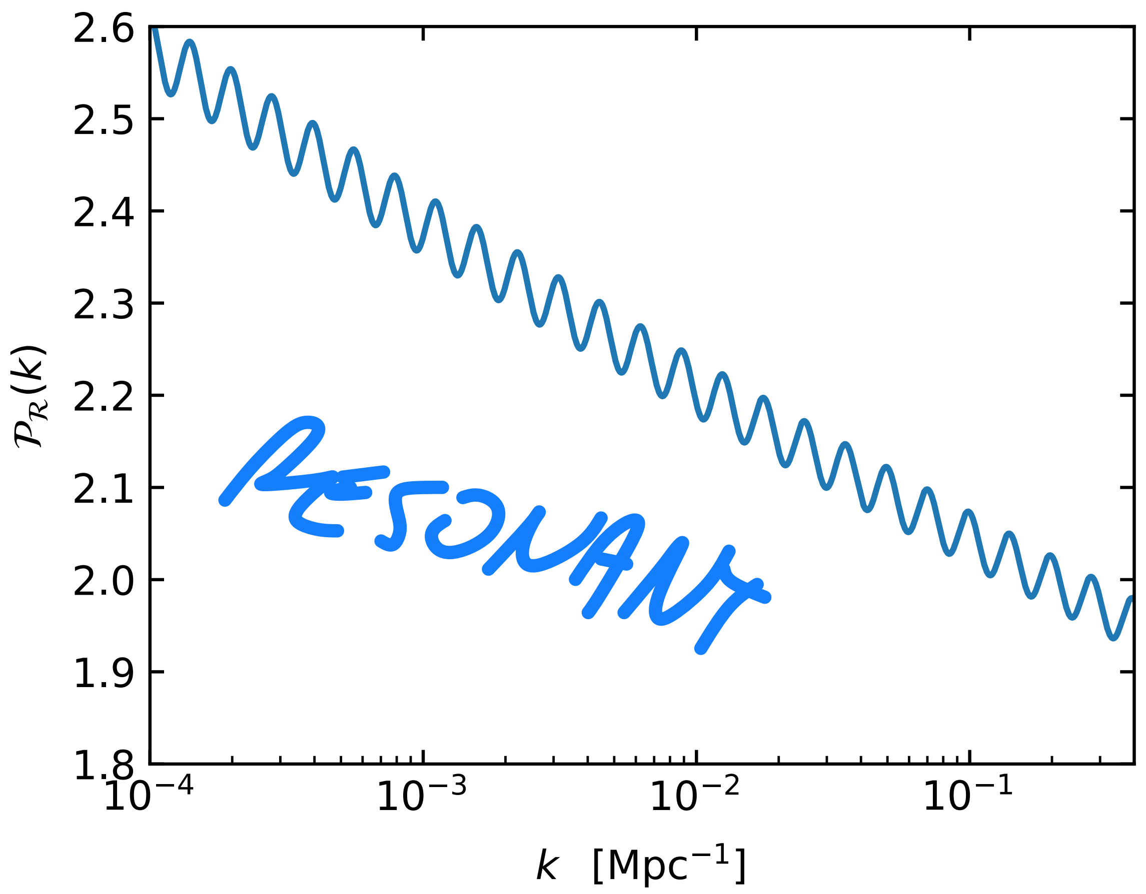
$$\sim \sin\left(2k/k_0\right)$$

Produced by momentary departure of a background quantity from the attractor solution $|\dot{B}/BH| \ll 1$









Resonant features

$$\sim \sin\left[\omega \log\left(2k/k_r\right)\right]$$

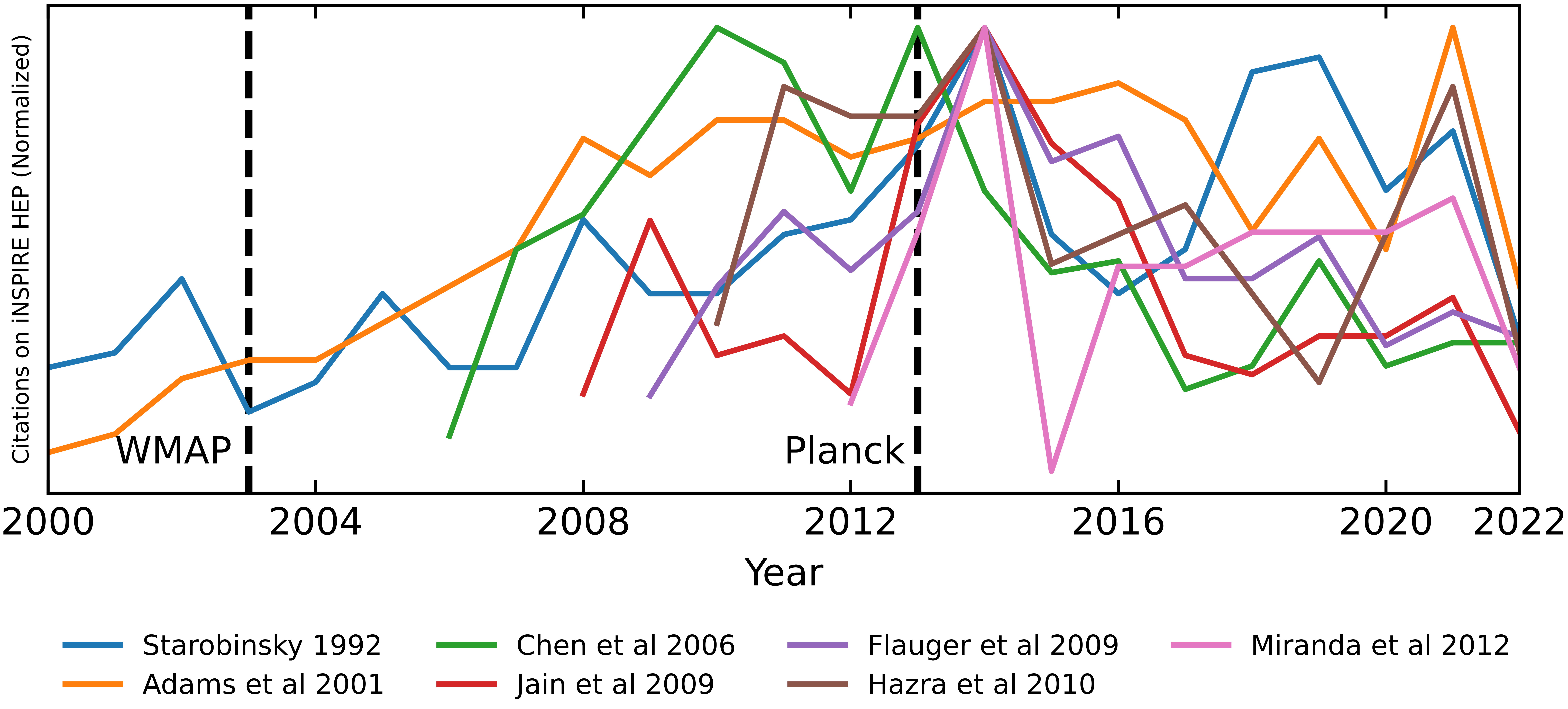
Produced by the periodic oscillation of a background quantity around the attractor

STATUS OF FEATURES 😢

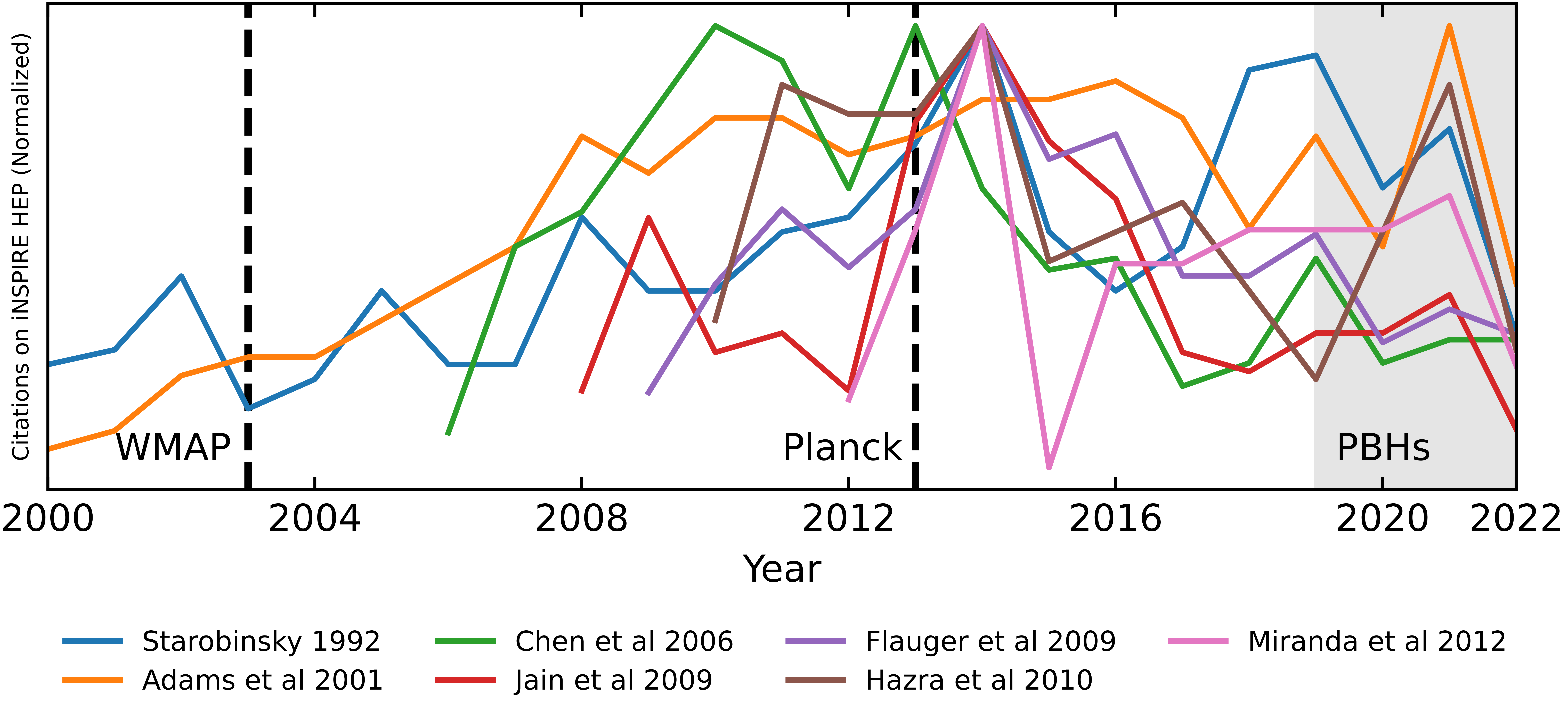
Consequently, the Bayesian evidence for all combinations of models and data lies between barely worth mentioning and substantial evidence against the feature model on the Jeffreys scale. This implies that, currently, the *Planck* data do not show a preference for the feature models considered here.

From Planck inflation paper 2018

STATUS OF FEATURES



STATUS OF FEATURES



EXAMPLE OF TOP-DOWN ANALYSIS: CLASSICAL PRIMORDIAL STANDARD CLOCKS

BRAGLIA, CHEN, HAZRA   ARXIV: 2103.03025, 2106.07546, 2108.10110

PRIMORDIAL STANDARD CLOCKS SIGNAL

CHEN 2011A, CHEN 2011B, CHEN & NAMJOO 2014, CHEN, NAMJOO, WANG 2014

Full clock signal (correction to the leading order near scale invariant spectrum)

$=$

Sharp feature signal

$$\frac{\Delta P}{P} \sim \sin\left(2k/k_0 + \text{phase}\right)$$

Depends on the mechanism exciting the oscillations

$+$

Resonant feature signal

$$\frac{\Delta P}{P} \sim \left(\frac{2k}{k_r}\right)^{\alpha} \sin\left[\frac{p^2}{1-p}\frac{m_\sigma}{H}\left(\frac{2k}{k_r}\right)^{1/p} + \varphi\right]$$

Produced by the sub horizon resonance with the

background oscillations of the curvature modes

PRIMORDIAL STANDARD CLOCKS SIGNAL

CHEN 2011A, CHEN 2011B, CHEN & NAMJOO 2014, CHEN, NAMJOO, WANG 2014

What can we learn if the signal is detected?

$k_0 = a_0 H_0$ is the scale of the sharp feature. It sets the frequency of the sin

$$\frac{\Delta P}{P} \sim \sin\left(2k/k_0 + \text{phase}\right)$$

p records the evolution of the scale factor (remember $a(t) \sim t^p$). It sets the running of the resonant signal

m_σ / H is the effective mass of the heavy field. It sets the frequency of the resonant signal

$$\frac{\Delta P}{P} \sim \left(\frac{2k}{k_r}\right)^{\alpha} \sin\left[\frac{p^2}{1-p}\frac{m_\sigma}{H}\left(\frac{2k}{k_r}\right)^{1/p} + \varphi\right]$$

PRIMORDIAL STANDARD CLOCKS SIGNAL

CHEN 2011A, CHEN 2011B, CHEN & NAMJOO 2014, CHEN, NAMJOO, WANG 2014

What can we learn if the signal is detected?

$$\frac{\Delta P}{P} = C(k) \sin\left(2k/k_0 + \text{phase}\right)$$

$k_0 = a_0 H_0$ is the scale of the sharp feature. It sets the frequency of the

p records the evolution of the scale factor (remember $a(t) \sim t^p$). It sets the

running of the resonant signal

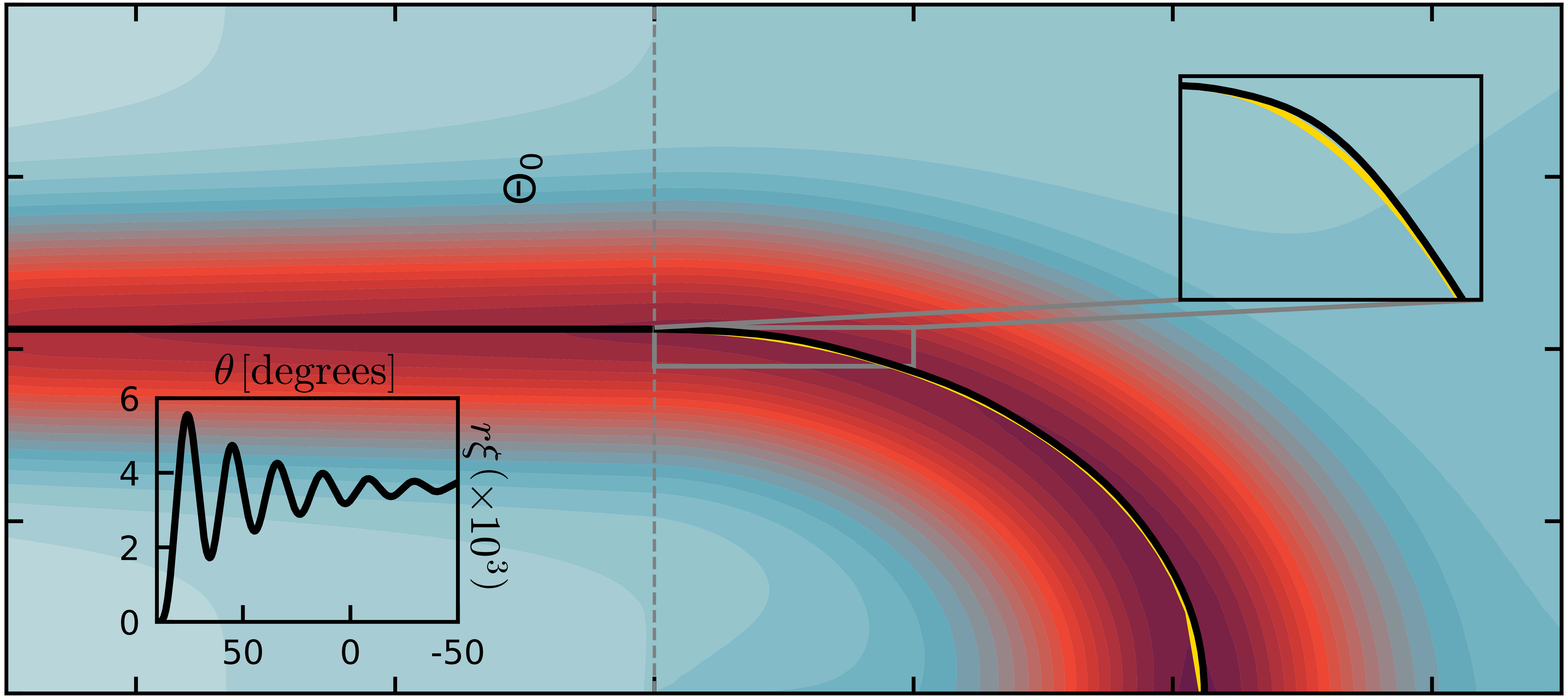
m_σ/H is the effective mass of the heavy field. It sets the frequency of the

resonant signal

$$\frac{\Delta P}{P} \sim \left(\frac{2k}{k_r}\right)^{\alpha} \sin\left[\frac{p^2}{1-p}\frac{m_\sigma}{H}\left(\frac{2k}{k_r}\right)^{1/p} + \varphi\right]$$

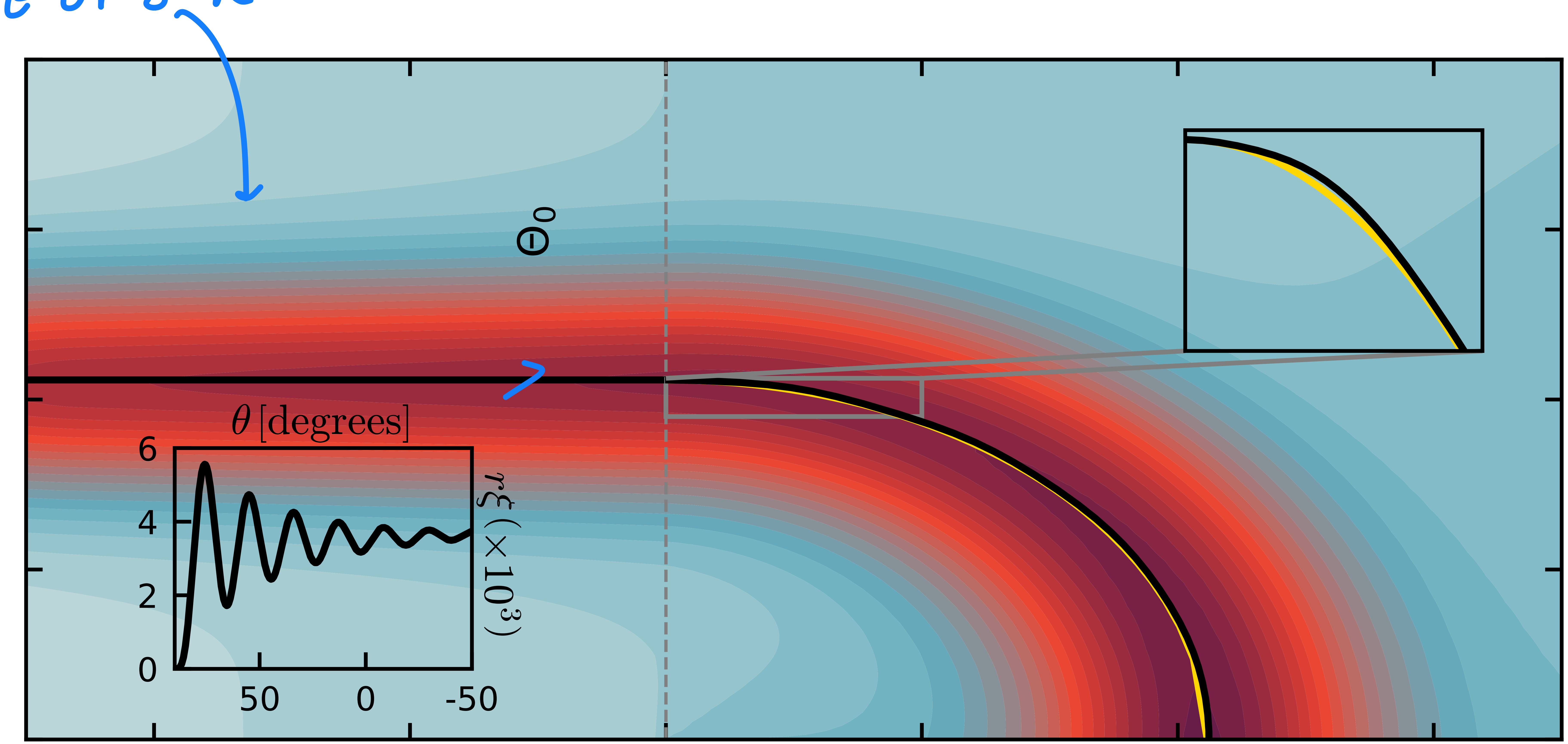
The envelope gives us information about which sharp feature mechanism excited the background oscillations.

MODEL BUILDING: INFLATIONARY TRAJECTORY



MODEL BUILDING: INFLATIONARY TRAJECTORY

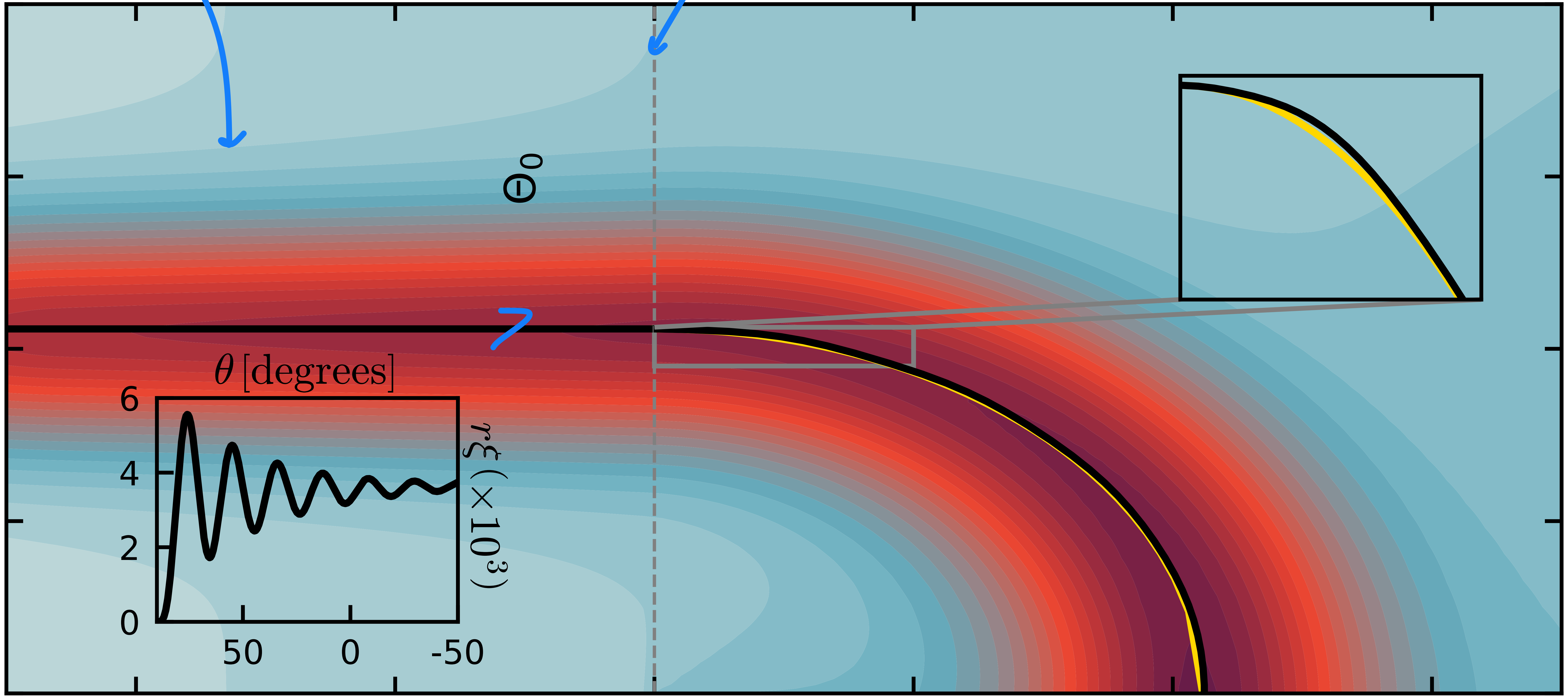
1ST STAGE OF S-R



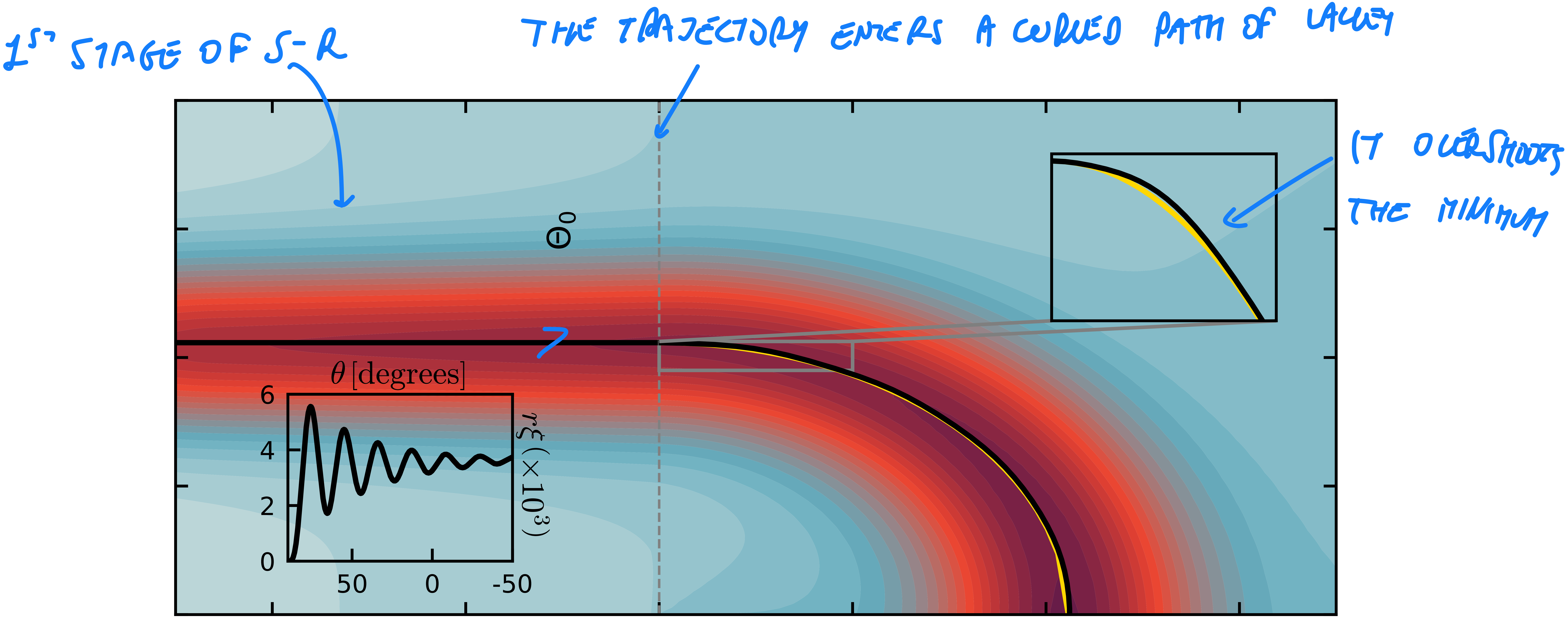
MODEL BUILDING: INFLATIONARY TRAJECTORY

1st STAGE OF S-R

THE TRAJECTORY ENTERS A CURVED PATH OF VALLEY



MODEL BUILDING: INFLATIONARY TRAJECTORY



MODEL BUILDING: INFLATIONARY TRAJECTORY

1st STAGE OF S-R

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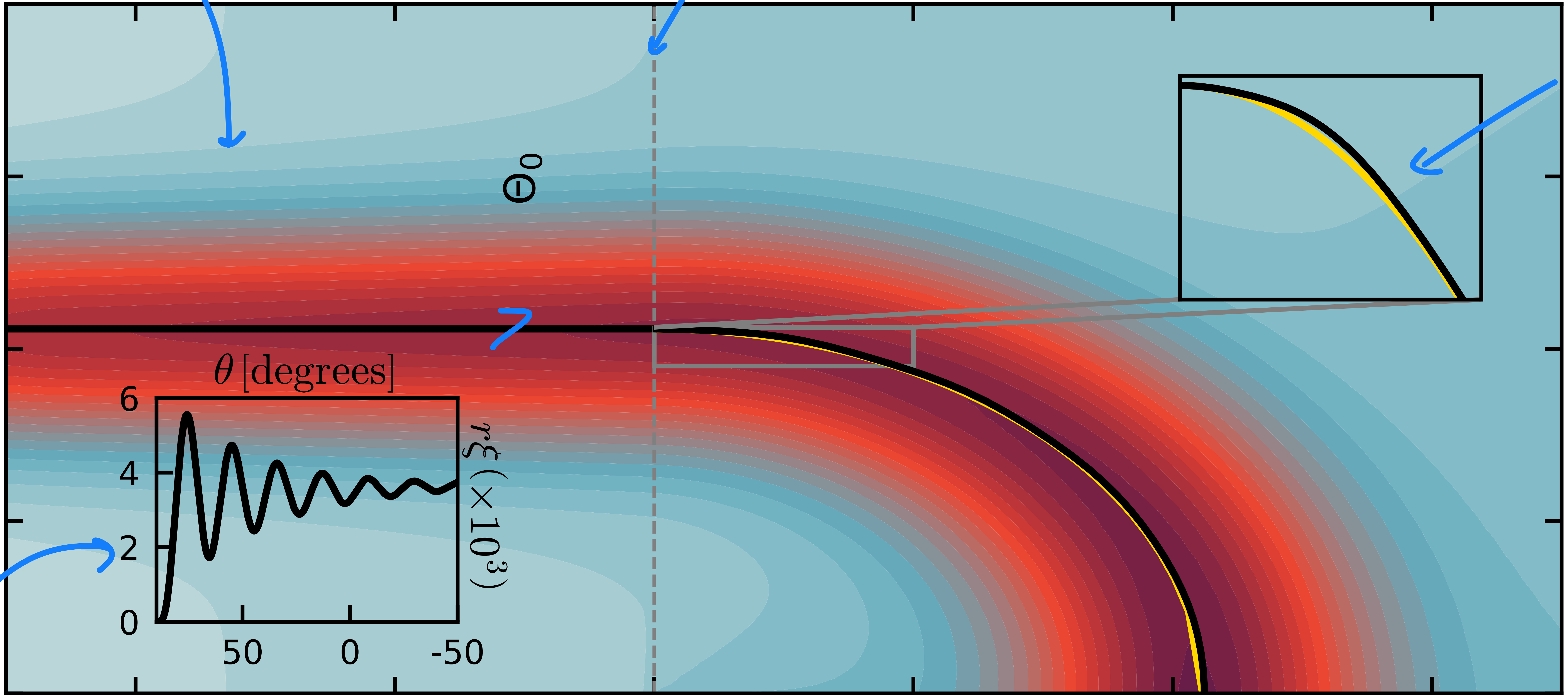
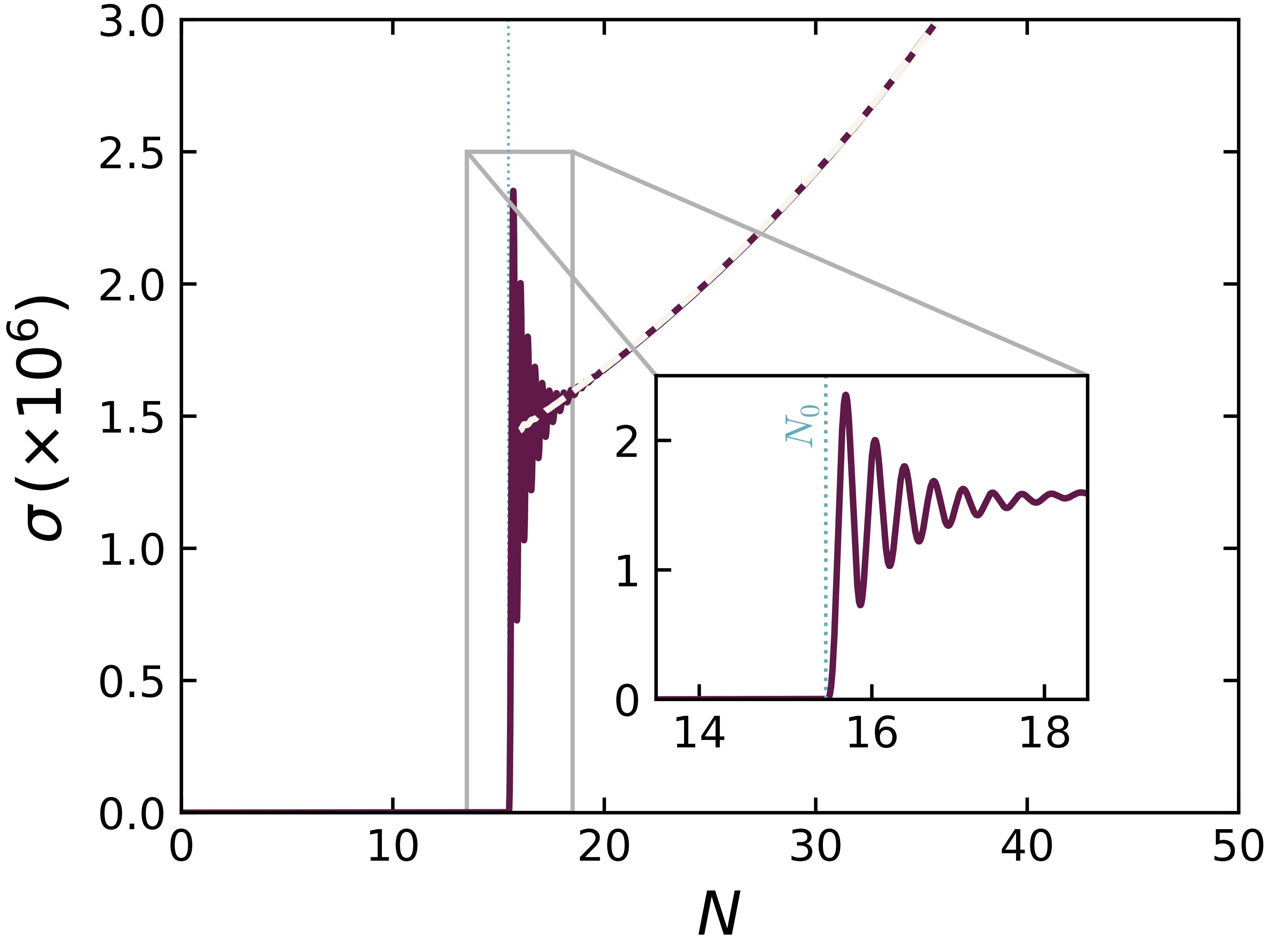


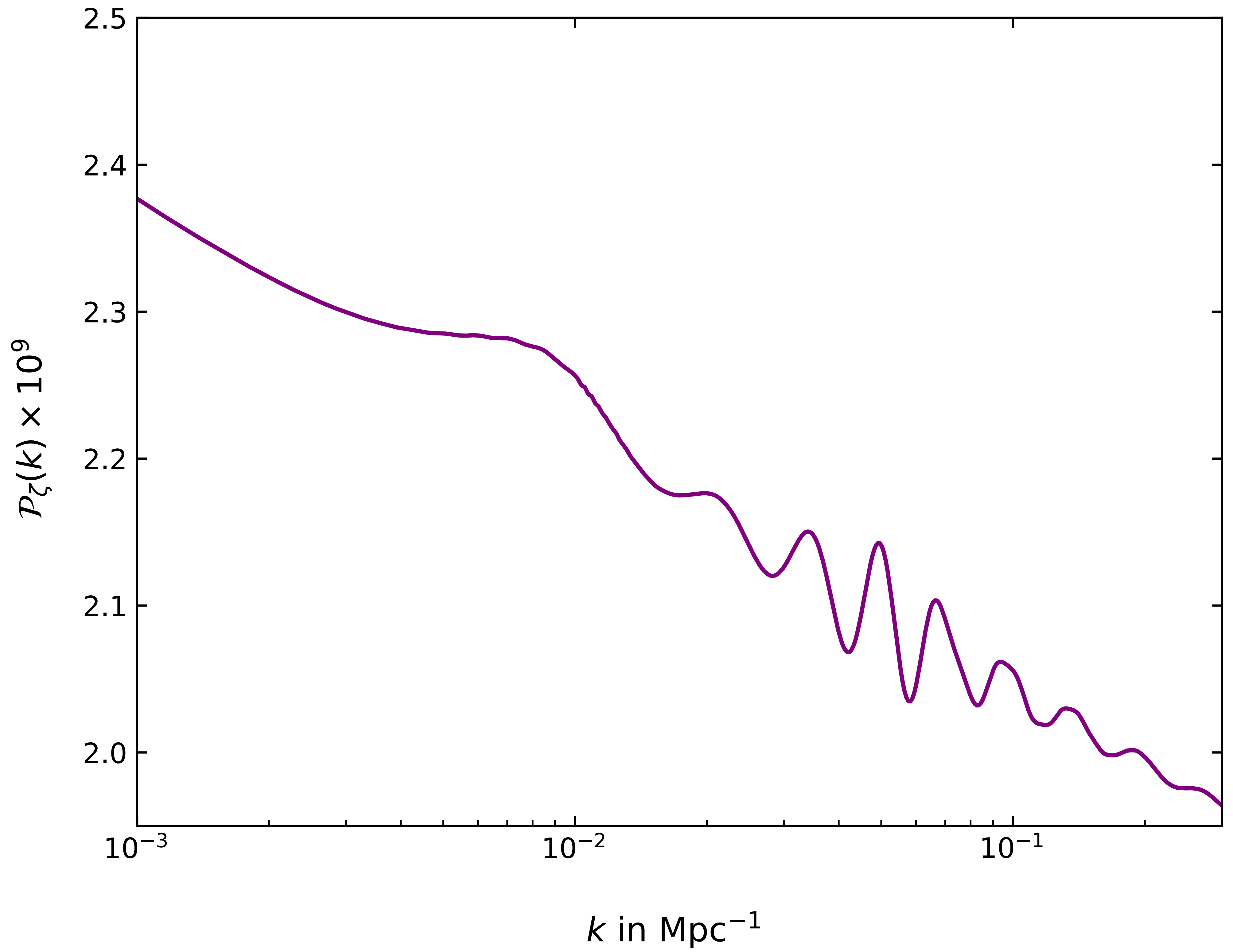
IT OVERSHOOTS THE MINIMUM

THE CLASSICAL OSCILLATIONS OF A MASSIVE FIELDS ARE EXCITED

MODEL BUILDING: EMBEDDING IN A 2 FIELD LAGRANGIAN

$$\mathscr{L} = -\frac{1}{2}\left[1 + \Xi\,\mathrm{Heav}(\Theta - \Theta_0)\sigma\right]^2(\partial\Theta)^2 + V_{\rm inf}\left\{\left(1 - \frac{C_\Theta}{2}\Theta^2\right)\right\} - \frac{(\partial\sigma)^2}{2} + \frac{m_\sigma^2}{2}\sigma^2$$





COMPARISON WITH PLANCK DATA

DATA ANALYSIS PIPELINE

Model Lagrangian

DATA ANALYSIS PIPELINE

Model Lagrangian

↓

Effective parameters describing distinct properties of the signal

DATA ANALYSIS PIPELINE

Model Lagrangian

↓

Effective parameters describing distinct properties of the signal

↓

Model parameters

DATA ANALYSIS PIPELINE

Model Lagrangian

↓

Effective parameters describing distinct properties of the signal

↓

Model parameters

↓

Numerical solution using BINGO

Braglia, Hazra, Sriramkumar, Finelli 2020

DATA ANALYSIS PIPELINE

Model Lagrangian

↓

Effective parameters describing distinct properties of the signal

↓

Model parameters

↓

Numerical solution using BINGO

↓

CMB spectra with CAMB

Lewis, Challinor, Lasenby 2000

DATA ANALYSIS PIPELINE

Model Lagrangian

↓

Effective parameters describing distinct properties of the signal

↓

Model parameters

↓

Numerical solution using BINGO

↓

CMB spectra with CAMB

↓

Nested sampling (POLYCHORD)

Handley, Hobson, Lasenby 2015

DATA ANALYSIS PIPELINE

Model Lagrangian

↓

Effective parameters describing distinct properties of the signal

↓

Model parameters

↓

Numerical solution using BINGO

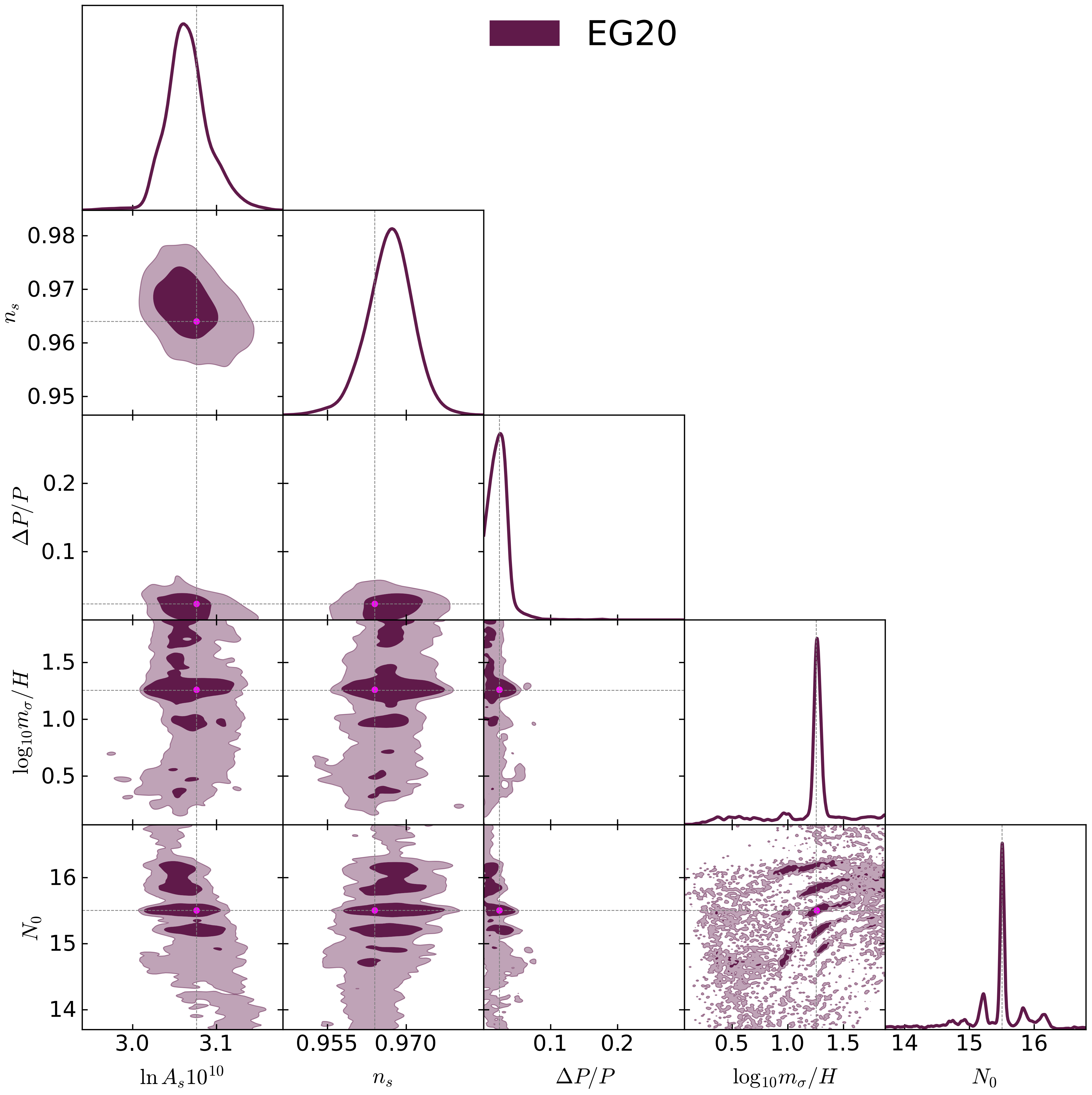
↓

CMB spectra with CAMB

↓

Nested sampling

ANALYSIS USING PLANCK 2018 TTTEEE DATA



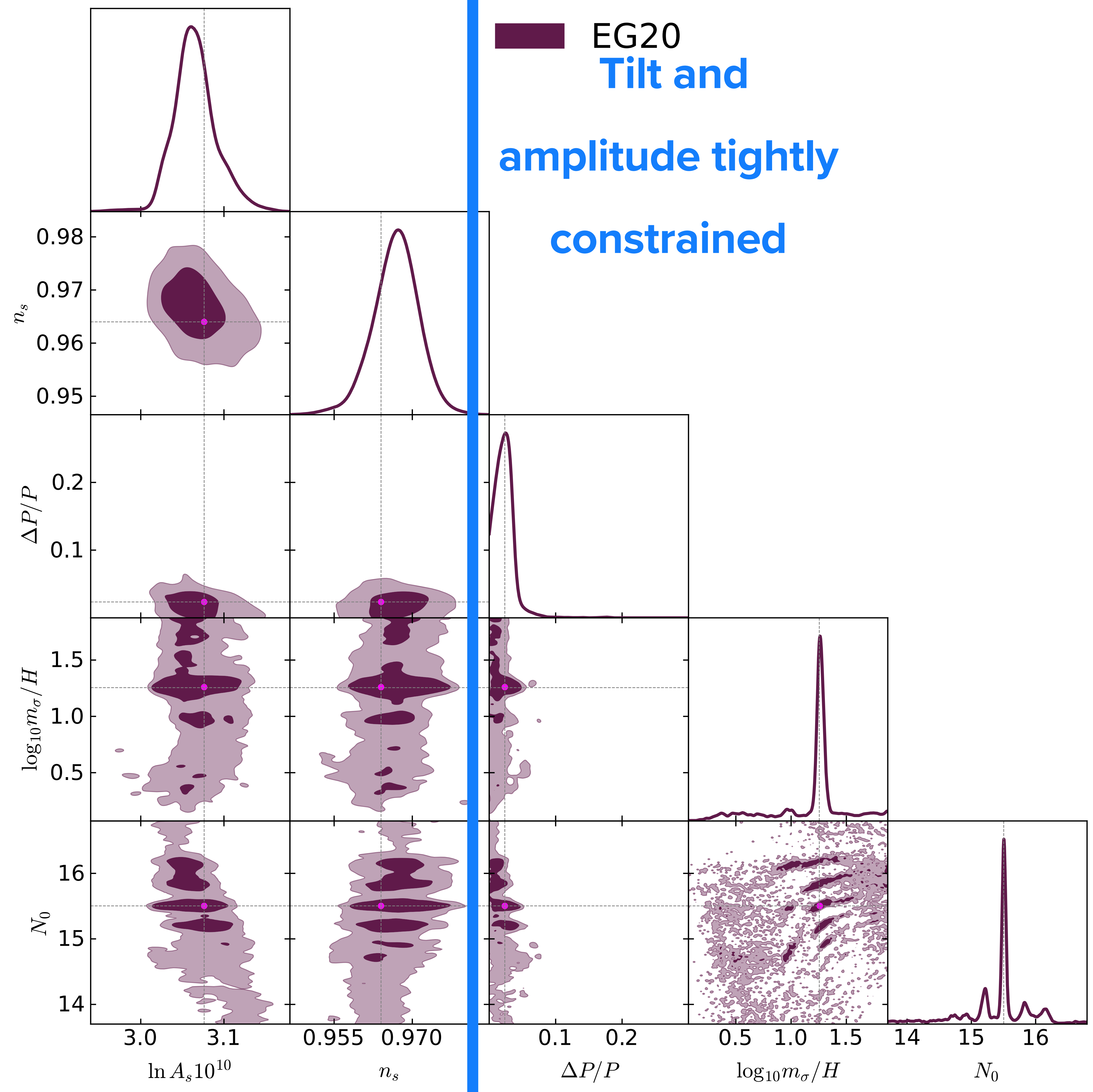
Multimodal posteriors

$$\ln B = -1.2 \pm 0.30$$

↓

The model is currently indistinguishable from the SM

ANALYSIS USING PLANCK 2018 TTTEEE DATA



Tilt and amplitude tightly constrained

Multimodal posteriors

$$\ln B = -1.2 \pm 0.30$$

↓

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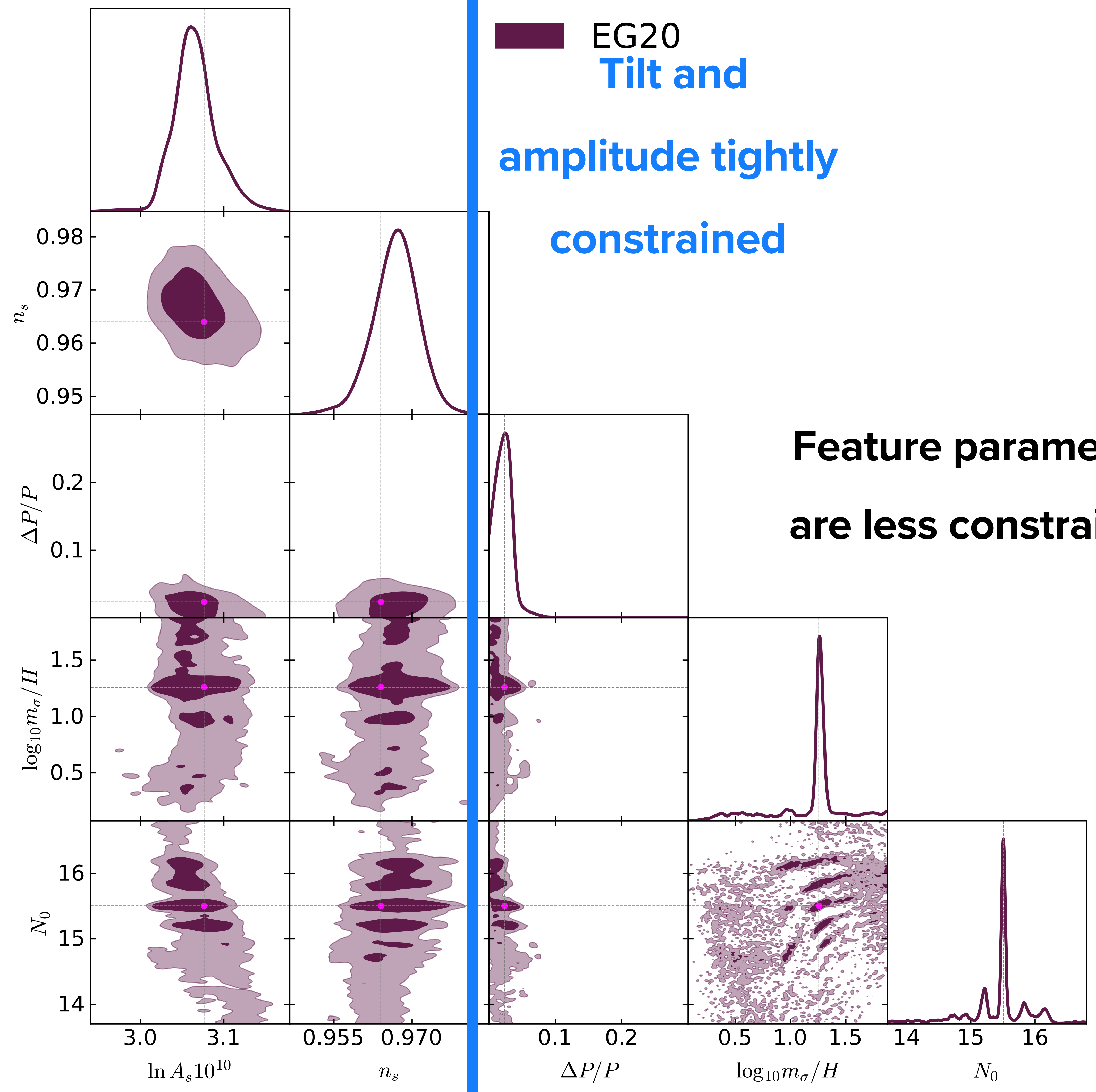
ANALYSIS USING PLANCK 2018 TTTEEE DATA



Tilt and amplitude tightly constrained

Feature parameters are less constrained

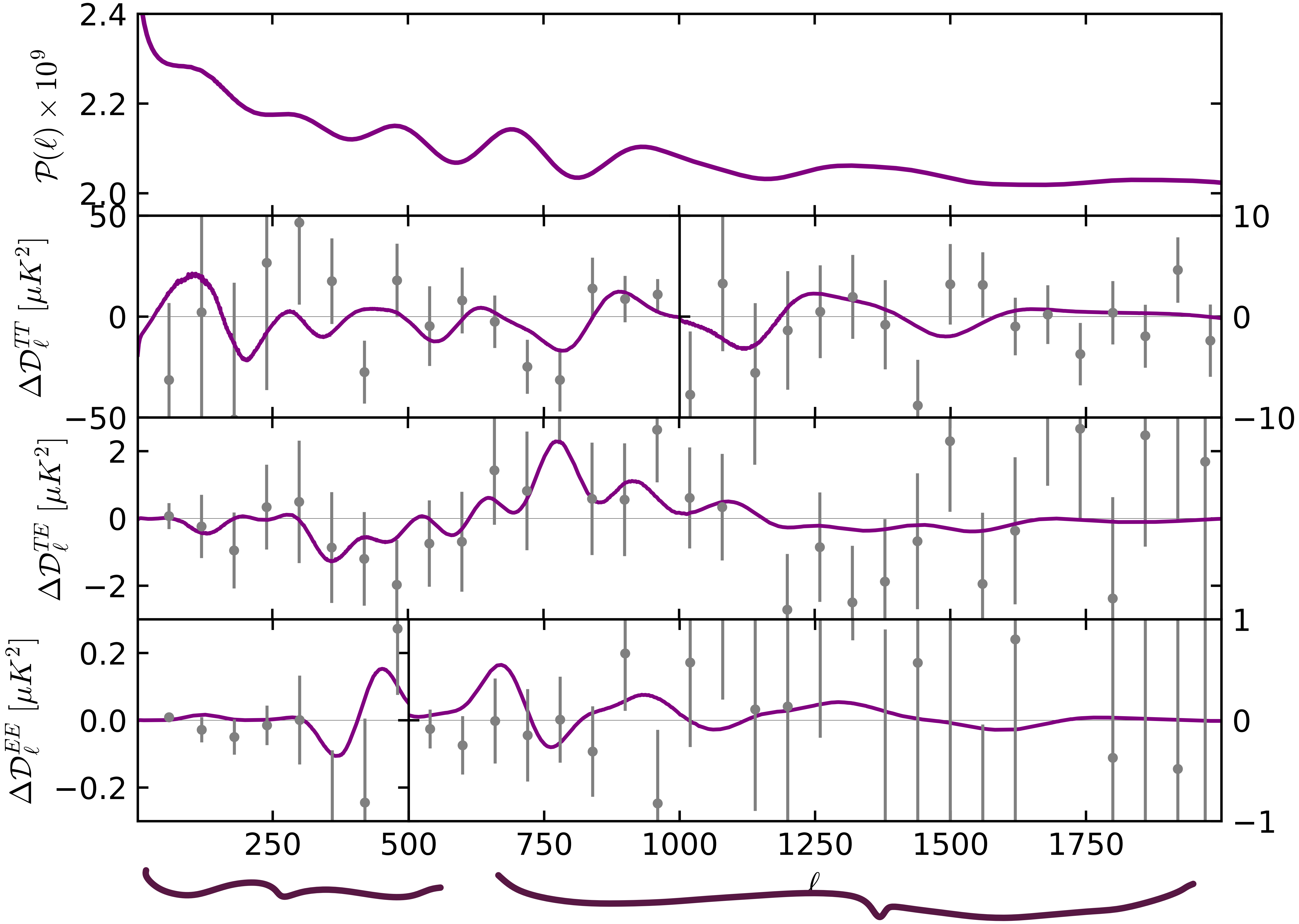
Multimodal posteriors

$$\ln B = -1.2 \pm 0.30$$

↓

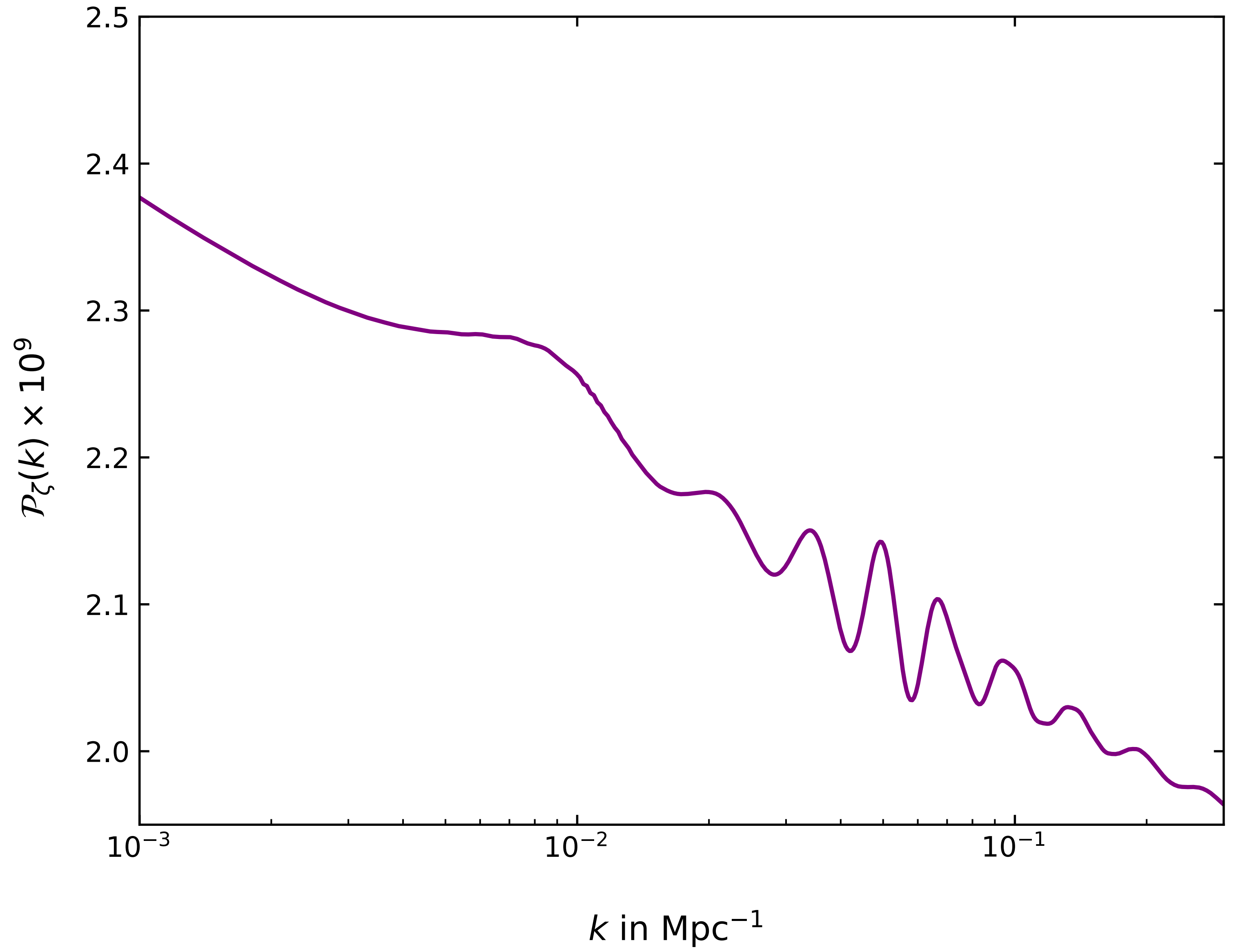
The model is currently indistinguishable from the SM

PLANCK 2018 BESTFIT



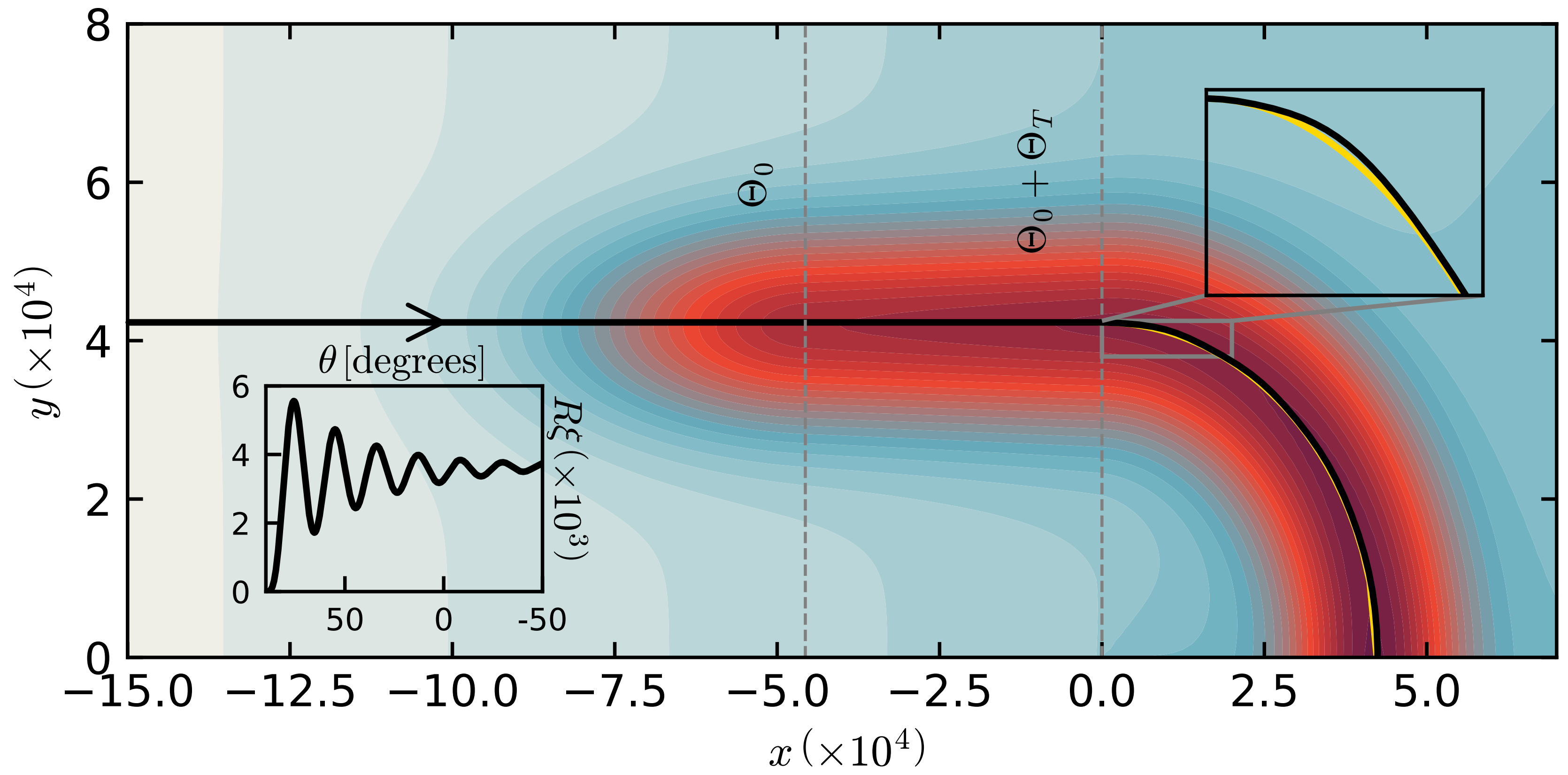
Sharp feature

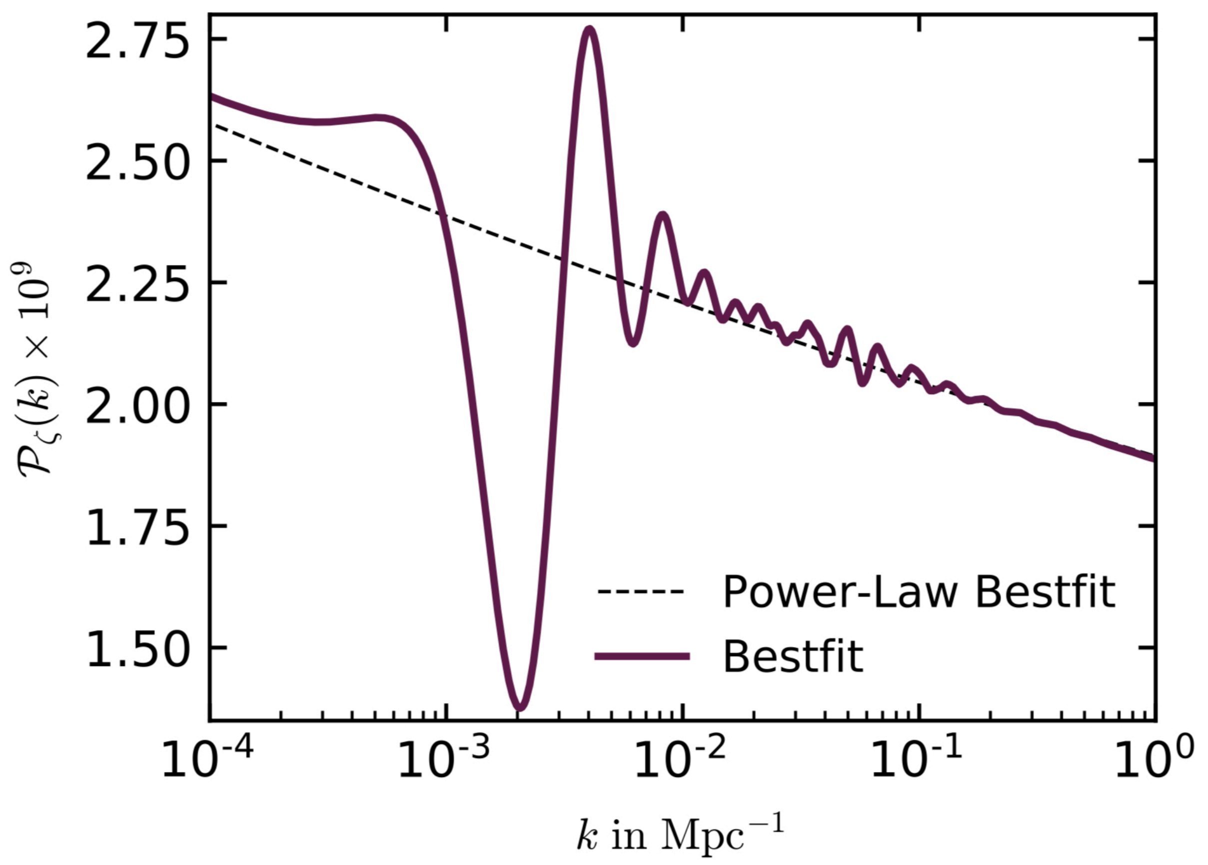
Clock signal

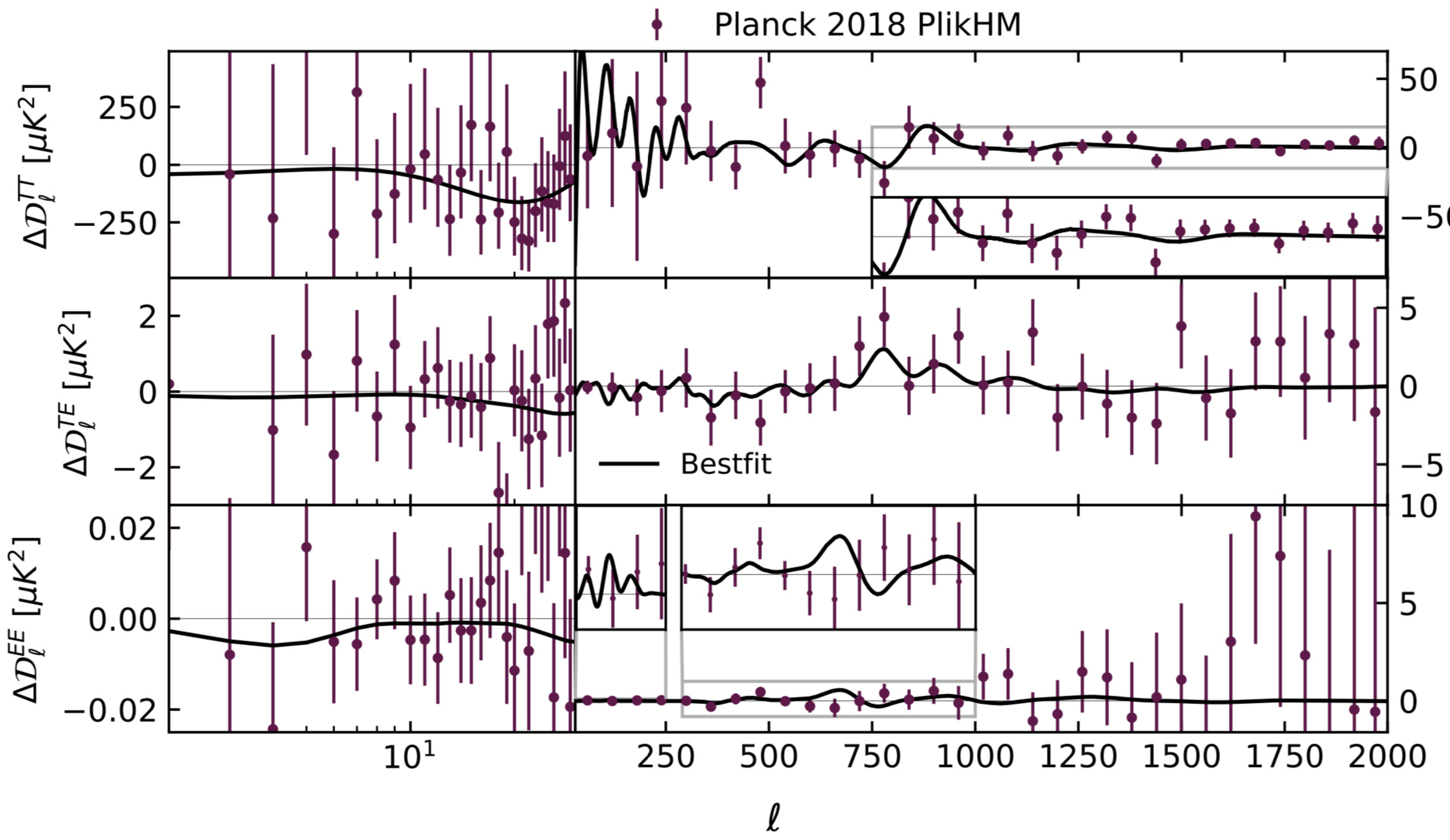


	$\Delta\chi^2_{\mathrm{TOT}}$	$\Delta\chi^2_{\mathrm{prior}}$	$\Delta\chi^2_{\mathrm{high}-\ell}$	$\Delta\chi^2_{\mathrm{low\text{-}T}}$	$\Delta\chi^2_{\mathrm{low\text{-}E}}$
CPSC	13.4	−0.11	13.28	0.30	−0.03

ADDRESSING LARGE AND SMALL SCALES ANOMALIES
ADDING A STEP







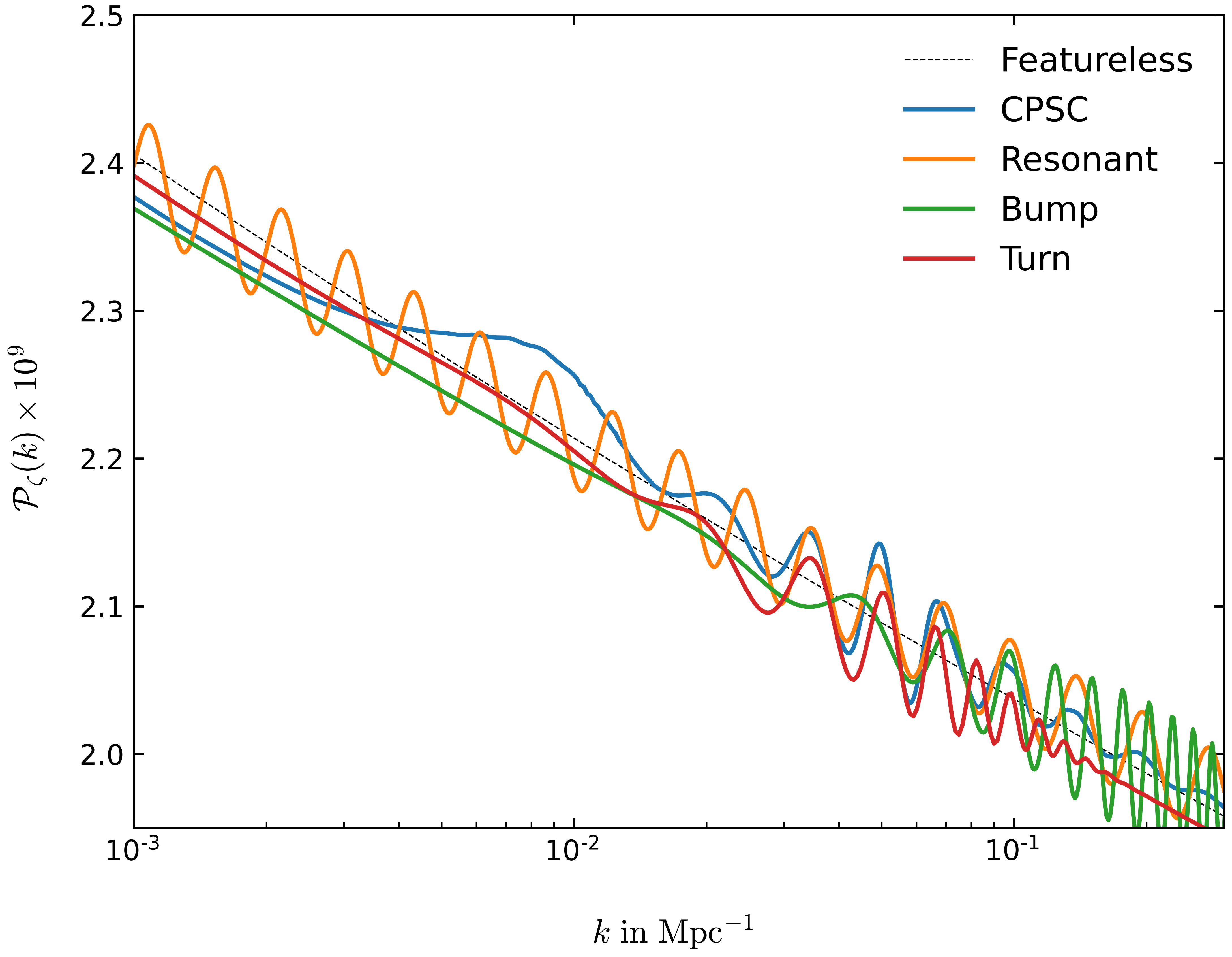
$\Delta\chi^2_{\mathrm{tot}}$	19.8
$\Delta\chi^2_{\mathrm{prior}}$	0.01
$\Delta\chi^2_{\mathrm{high}-\ell}$	13.31
$\Delta\chi^2_{\mathrm{lowT}}$	5.34
$\Delta\chi^2_{\mathrm{lowE}}$	1.11

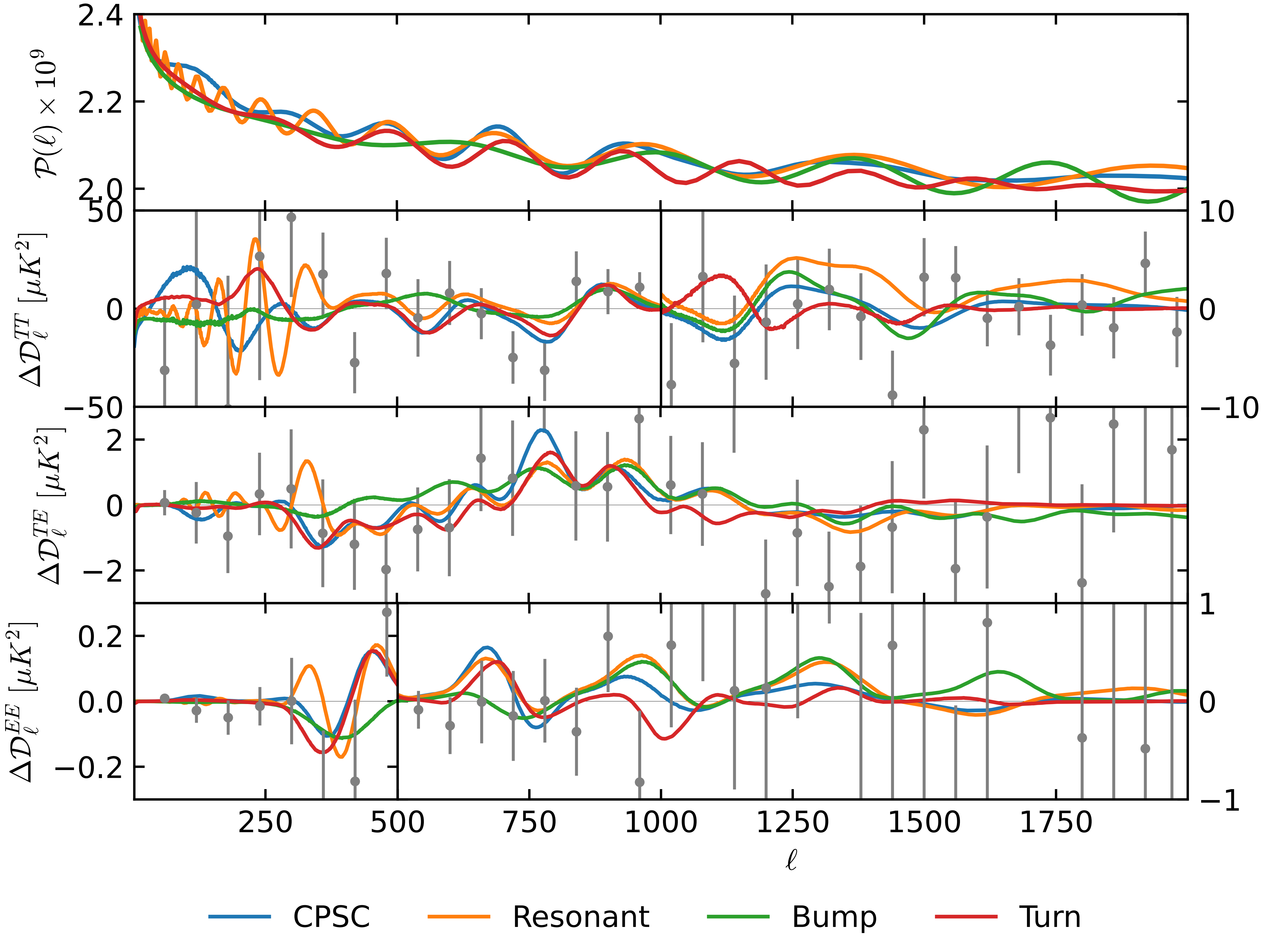
IS THERE A FUTURE FOR FEATURES?

BRAGLIA, CHEN, HAZRA ARXIV: 2106.07546, 2108.10110
BRAGLIA, CHEN, HAZRA PINOL ARXIV: 220X.XXXXX

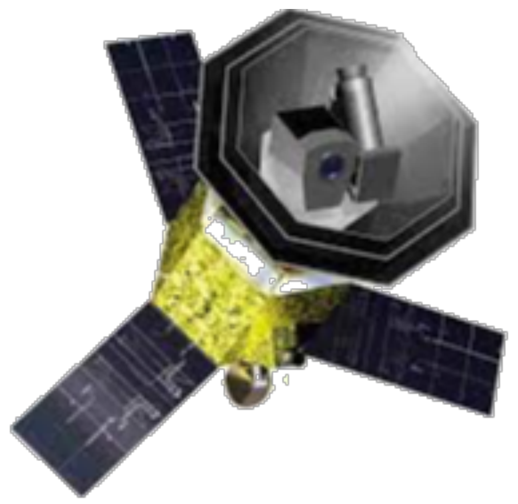
FEATURE MODELS

Other feature models provide a similar fit to Planck

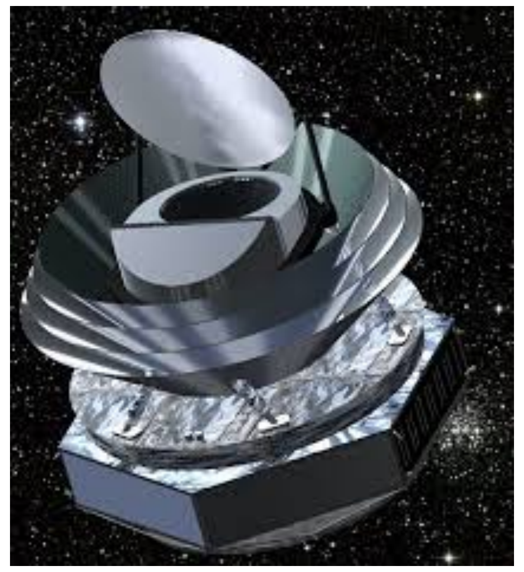




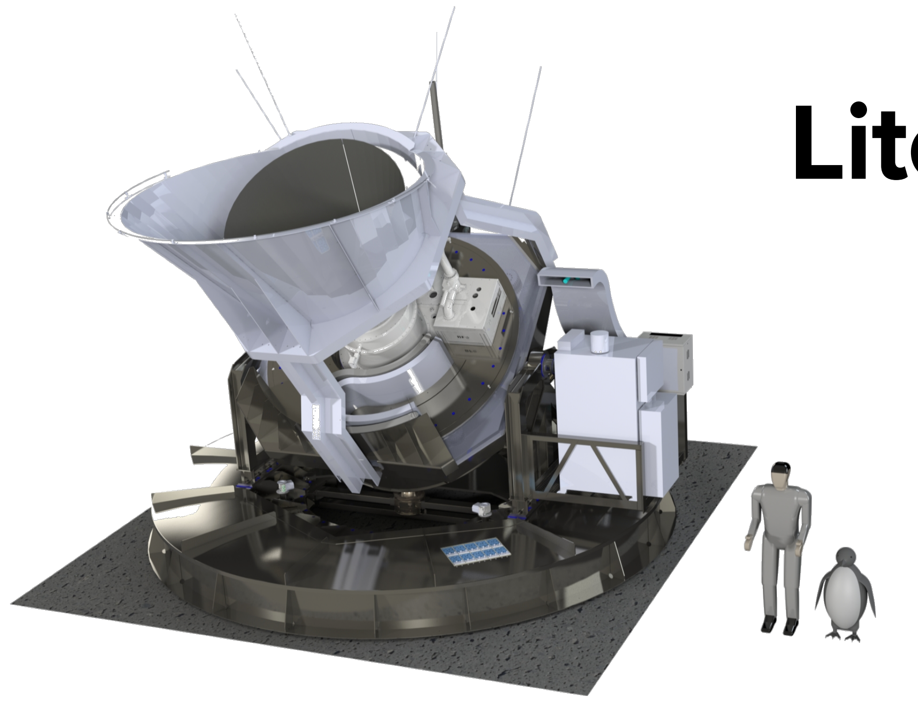
FORECASTS FOR FUTURE CMB EXPERIMENTS



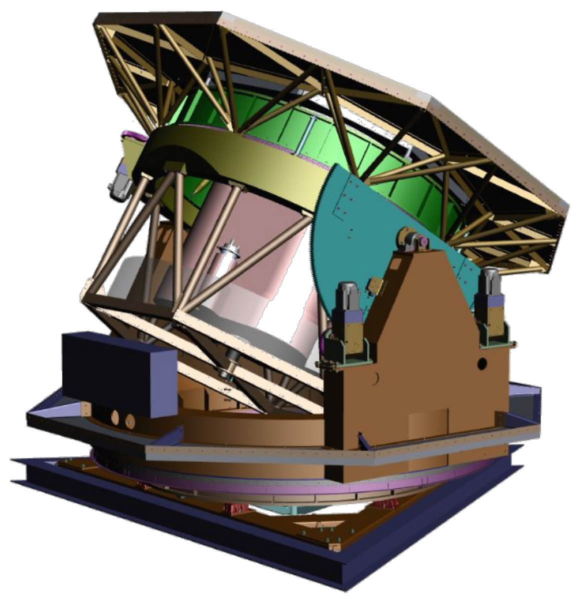
LiteBIRD



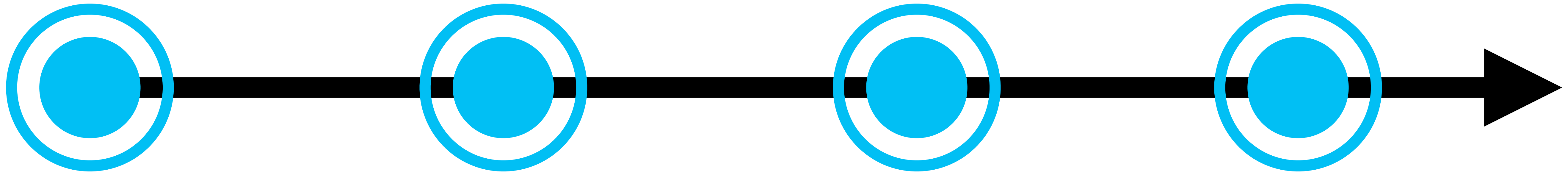
PICO



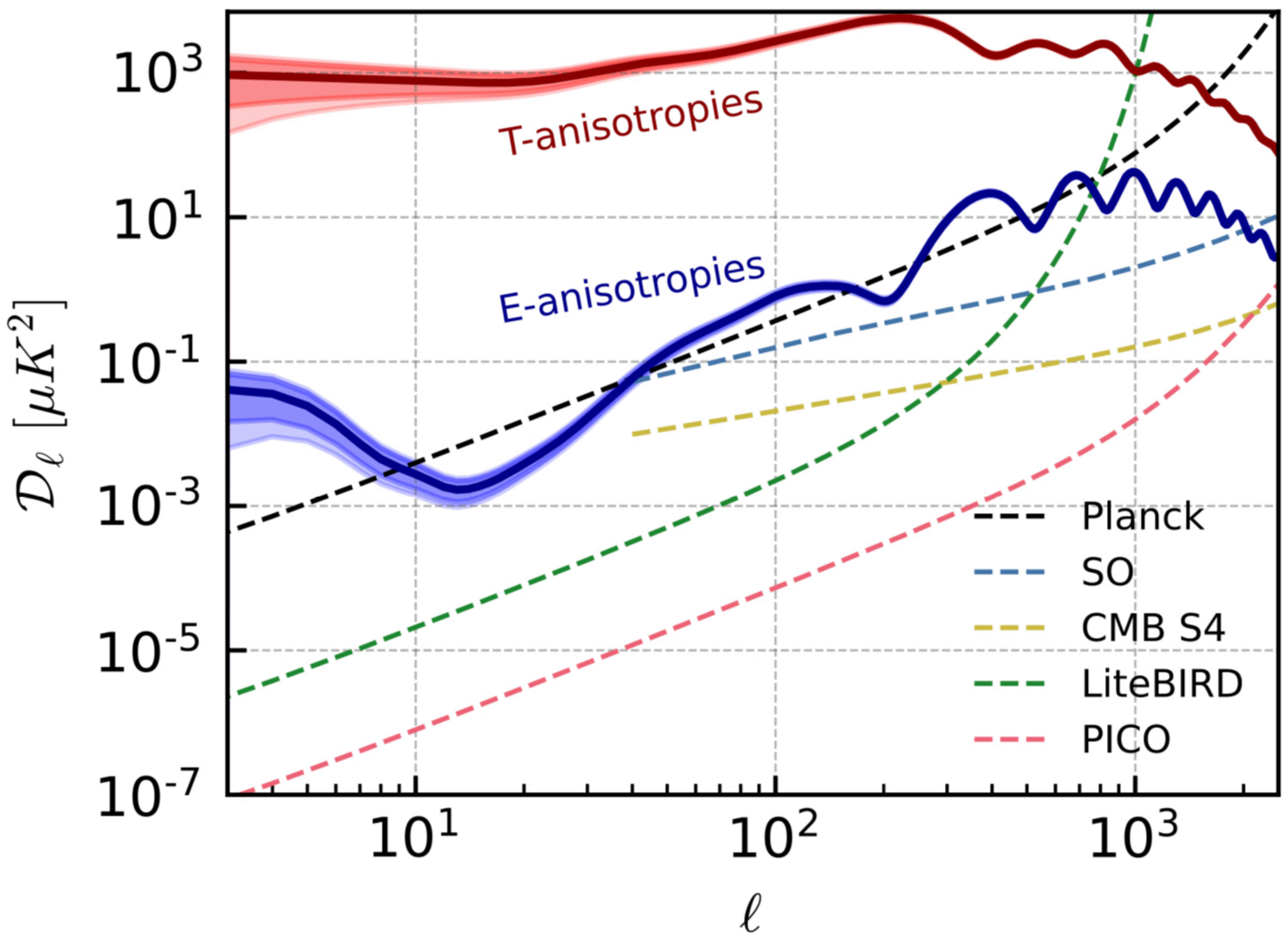
SO



CMB S4

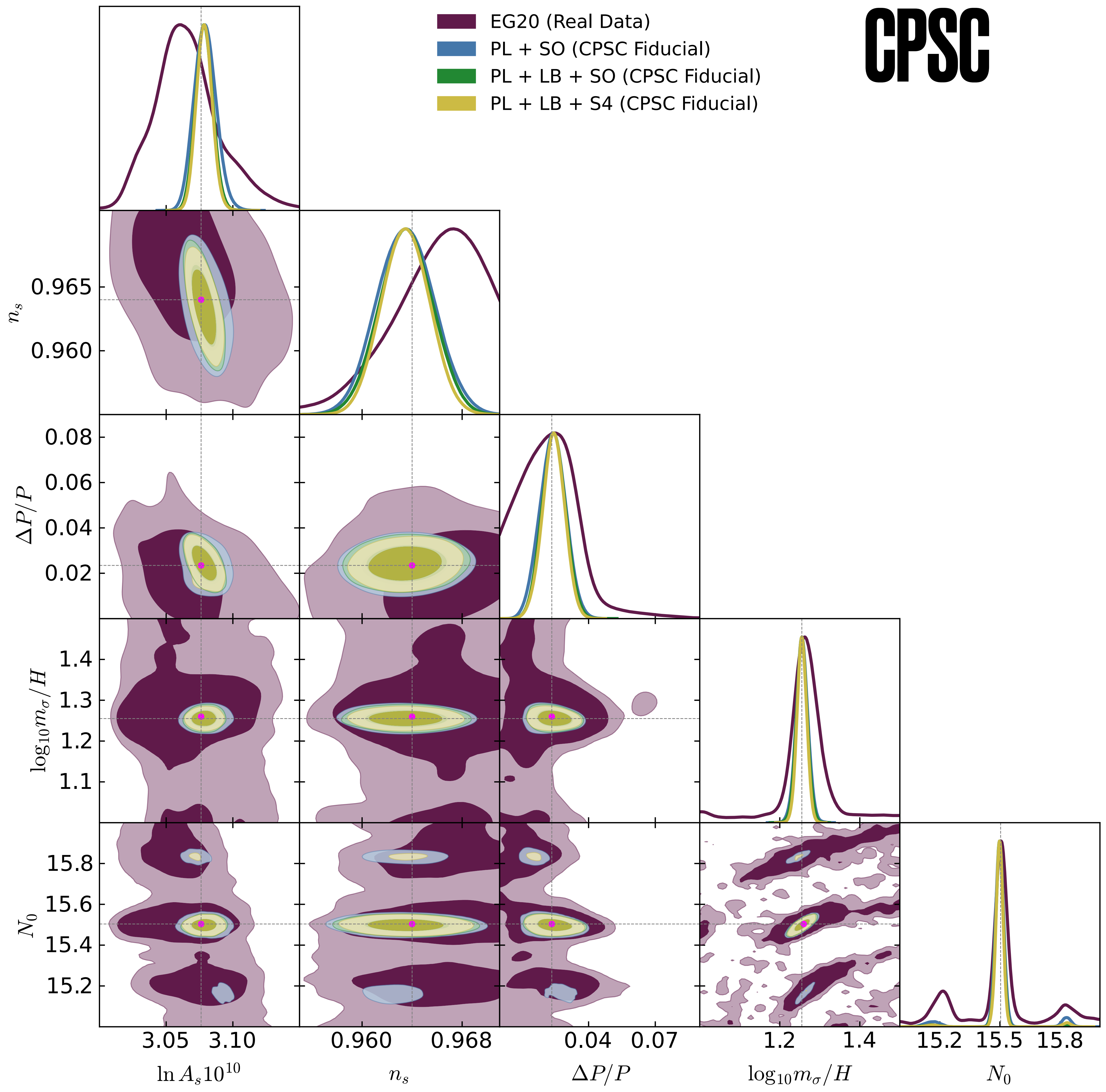


2023 2028 ~2030 (?) NASA concept



CPSC FIDUCIAL

We assume the CPSC bestfit is the true model of the Universe



CPSC

WHAT WILL WE LEARN?

- 4σ to 6σ **detection of the feature amplitude: detection of a massive particle**
- **The mass of the particle will be tightly constrained to** $m_\sigma/H = 18.16 \pm 0.83$ **by S4**
- **Evidence for inflation**

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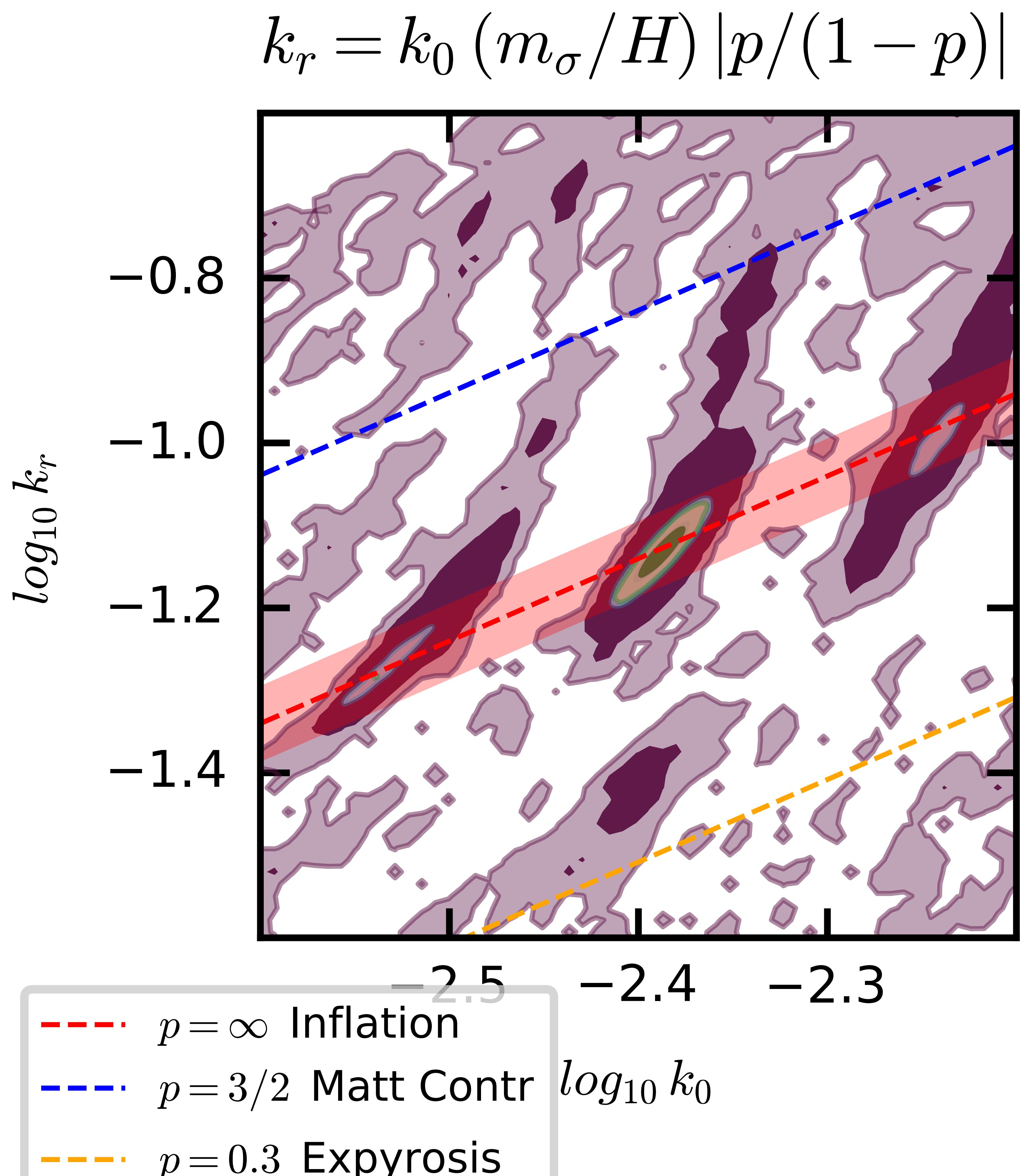
CPSC



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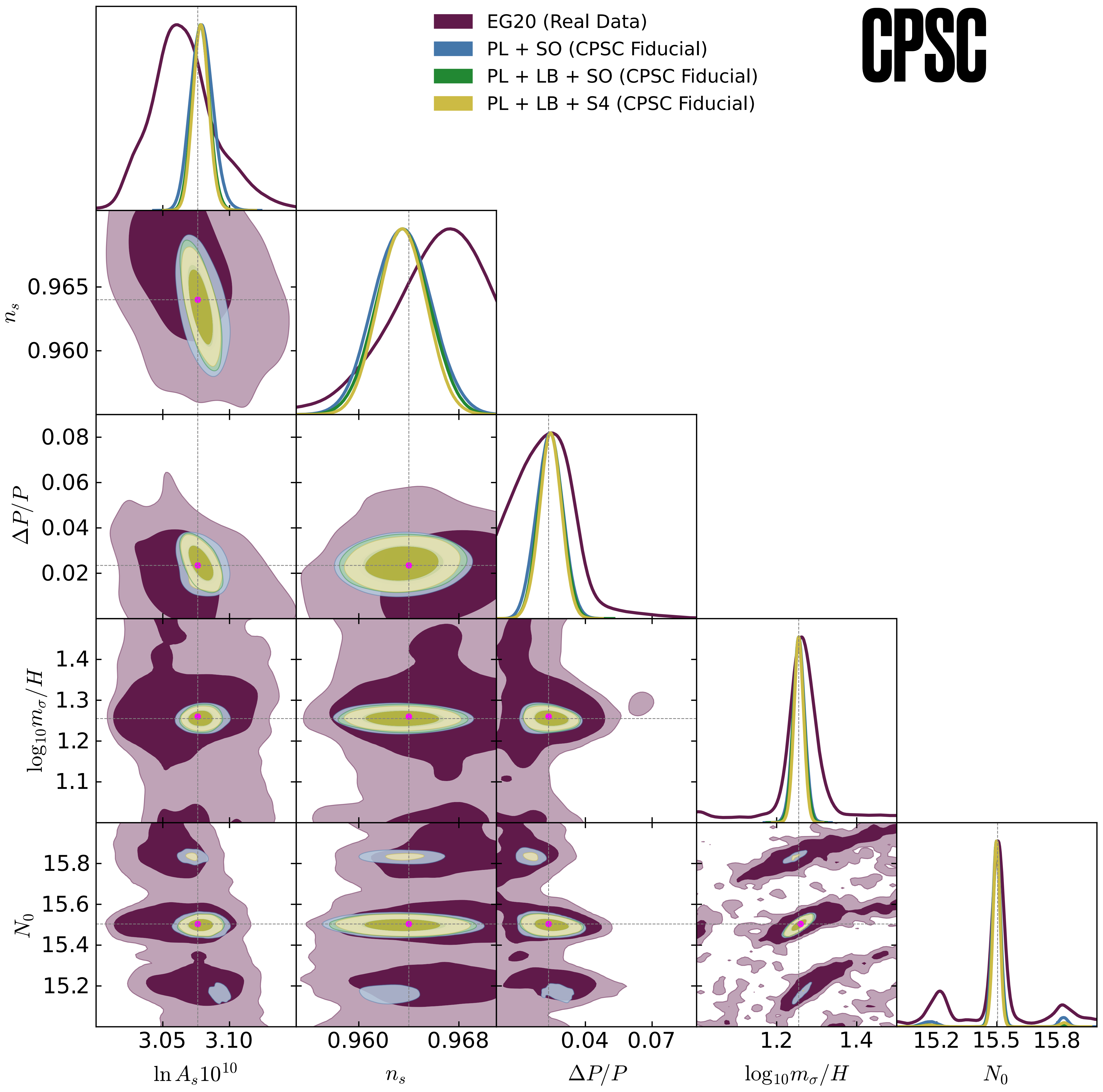

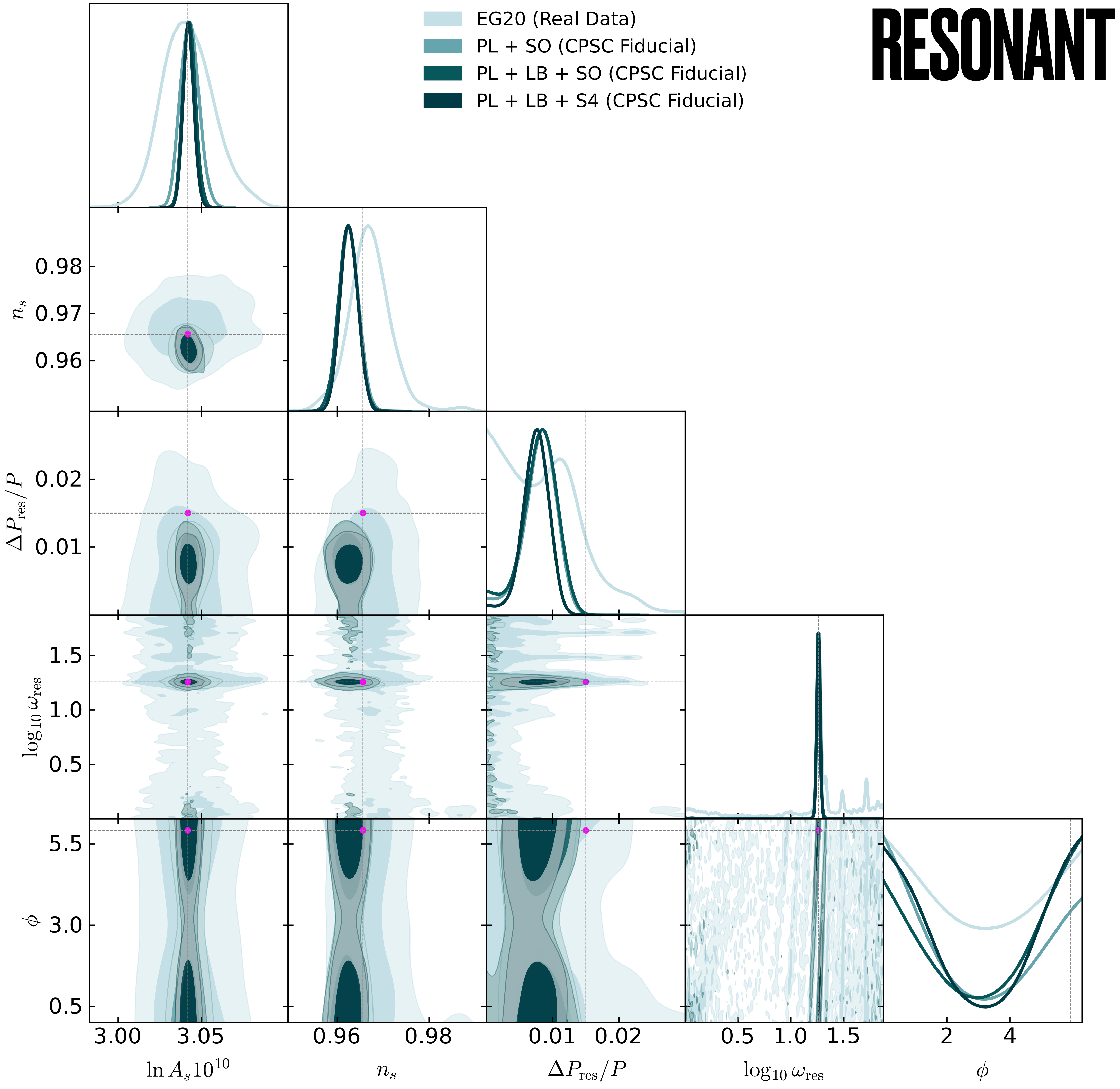

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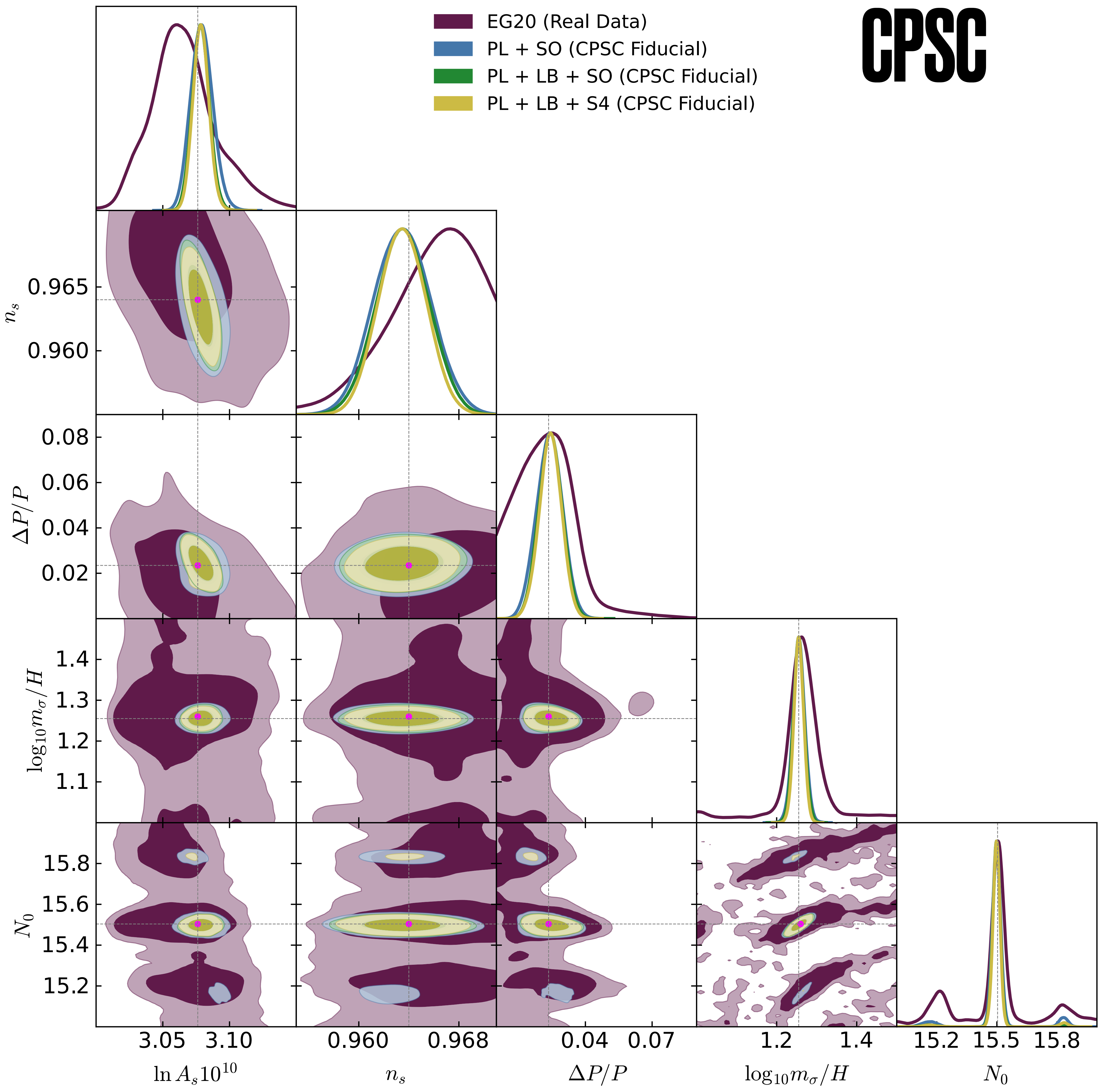

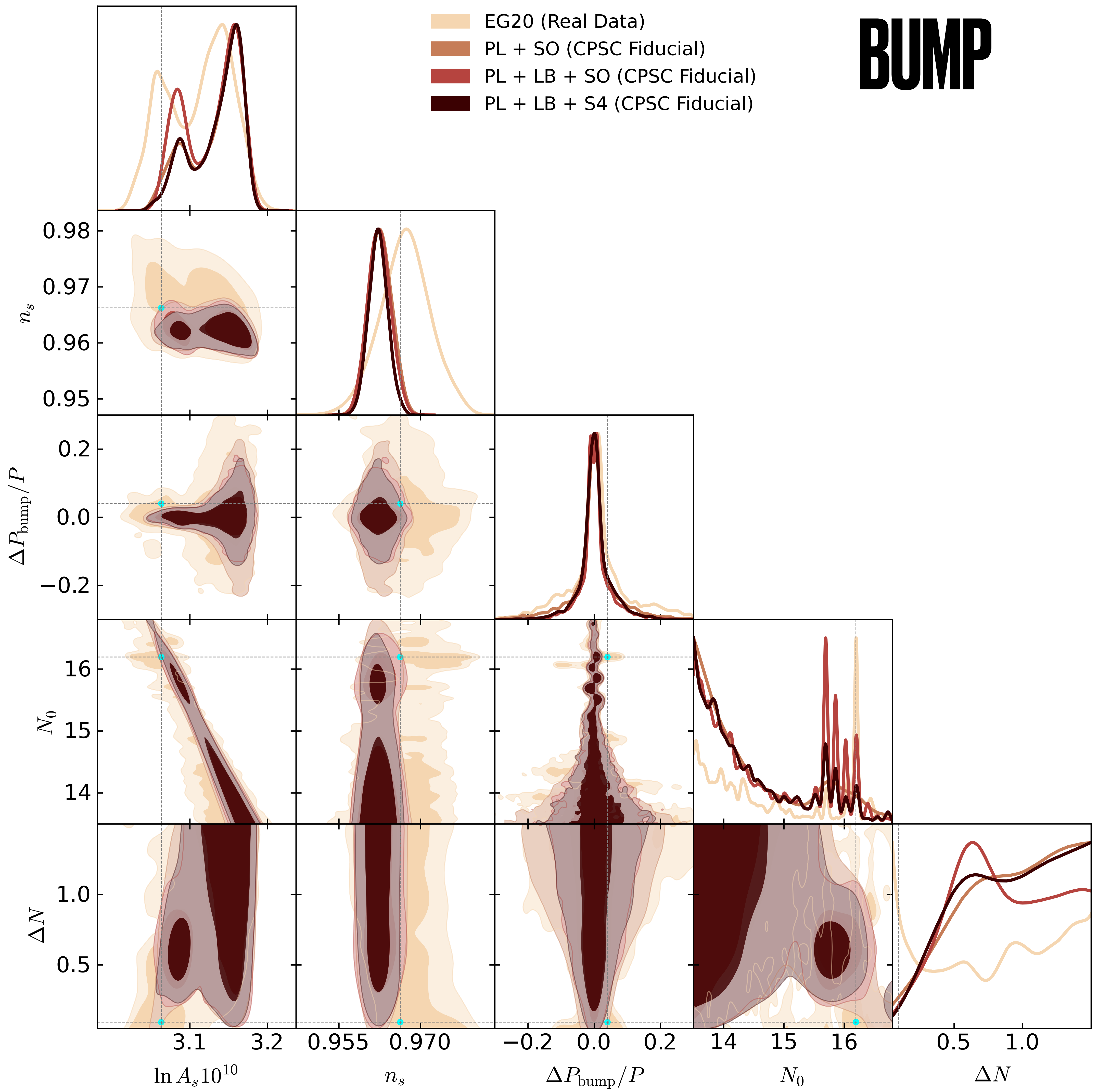

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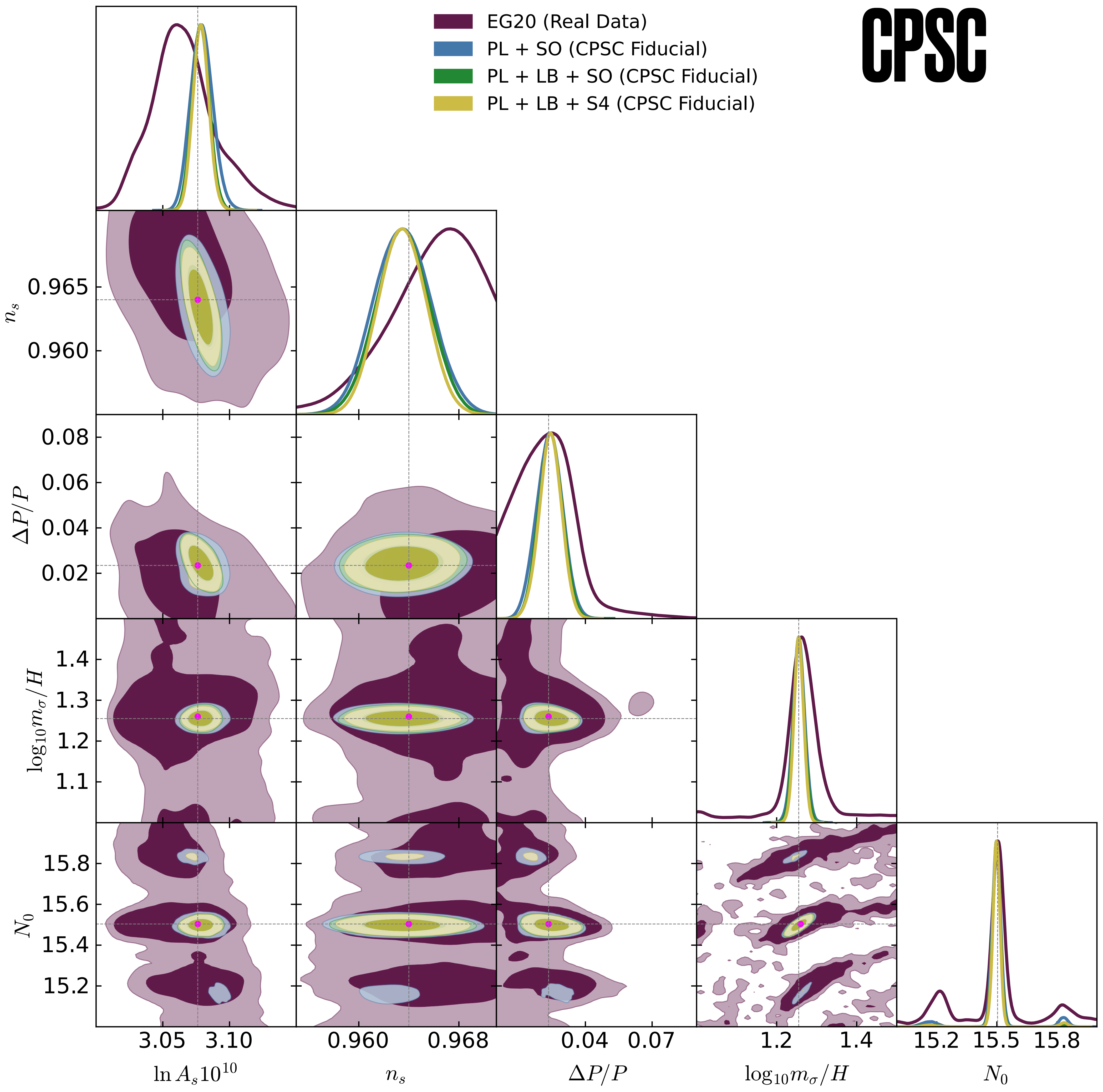

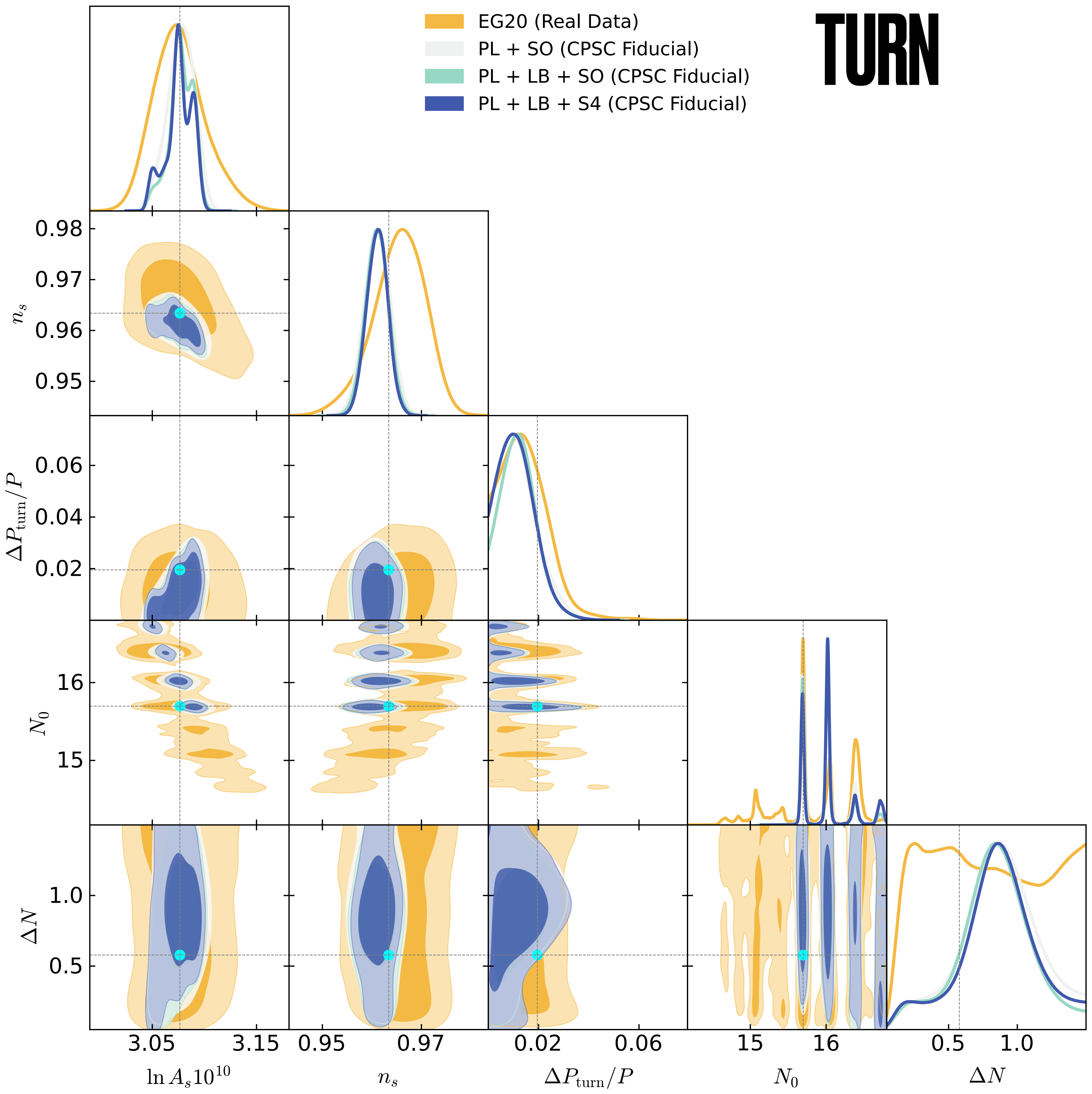

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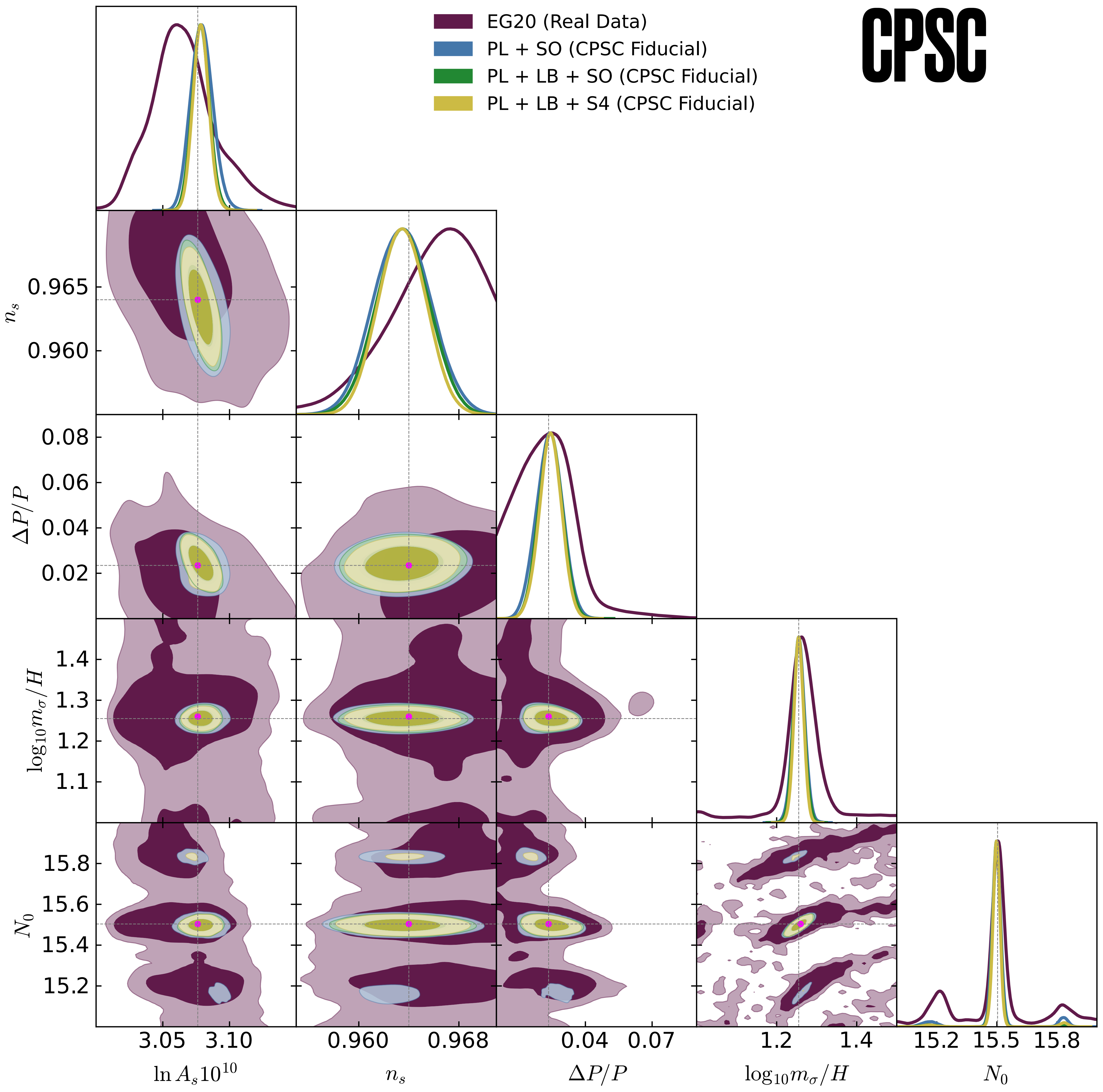
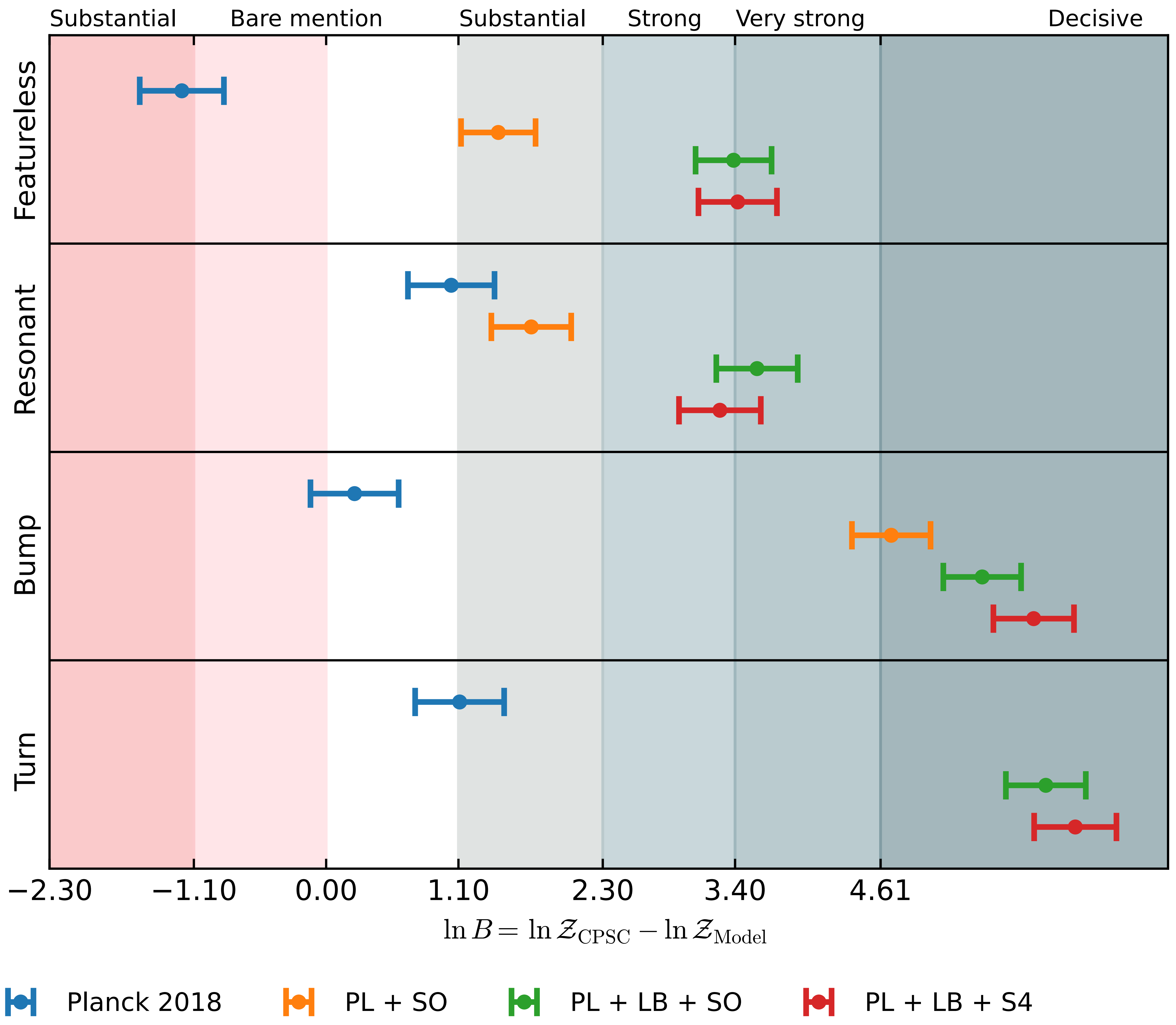
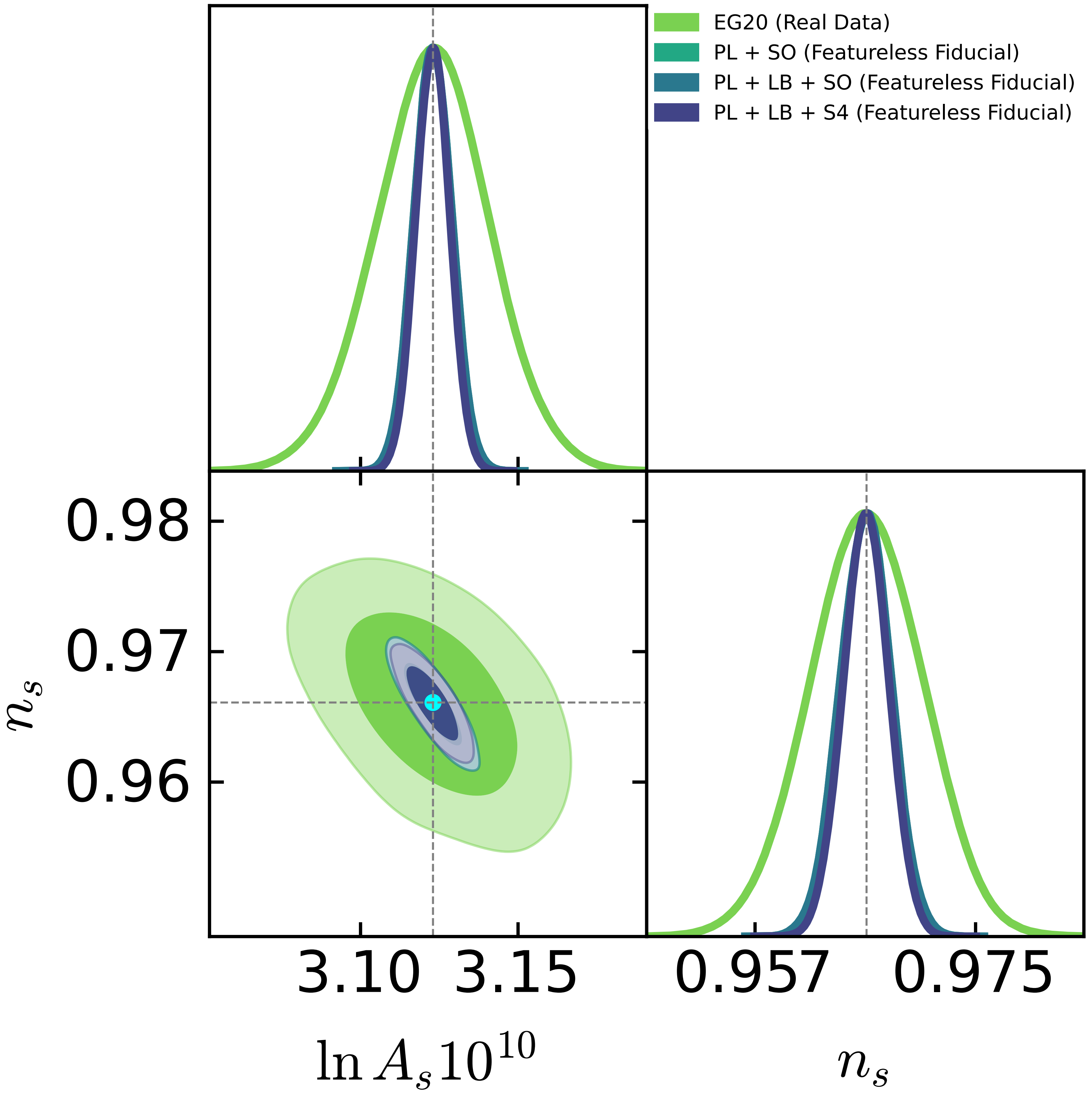


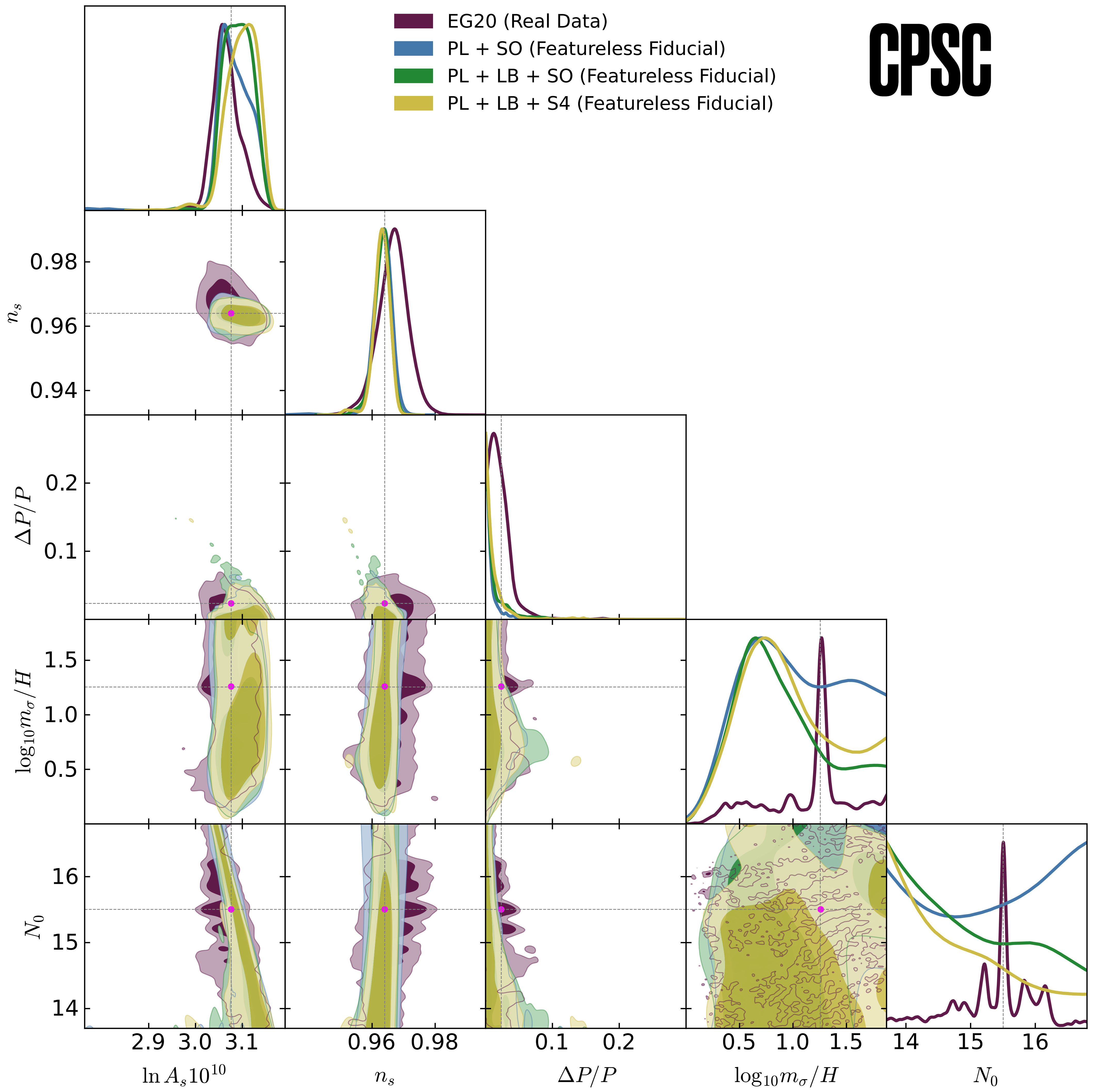


FEATURELESS FIDUCIAL

We assume the featureless bestfit is the true model of the Universe

$$A_s - n_s$$





CPSC

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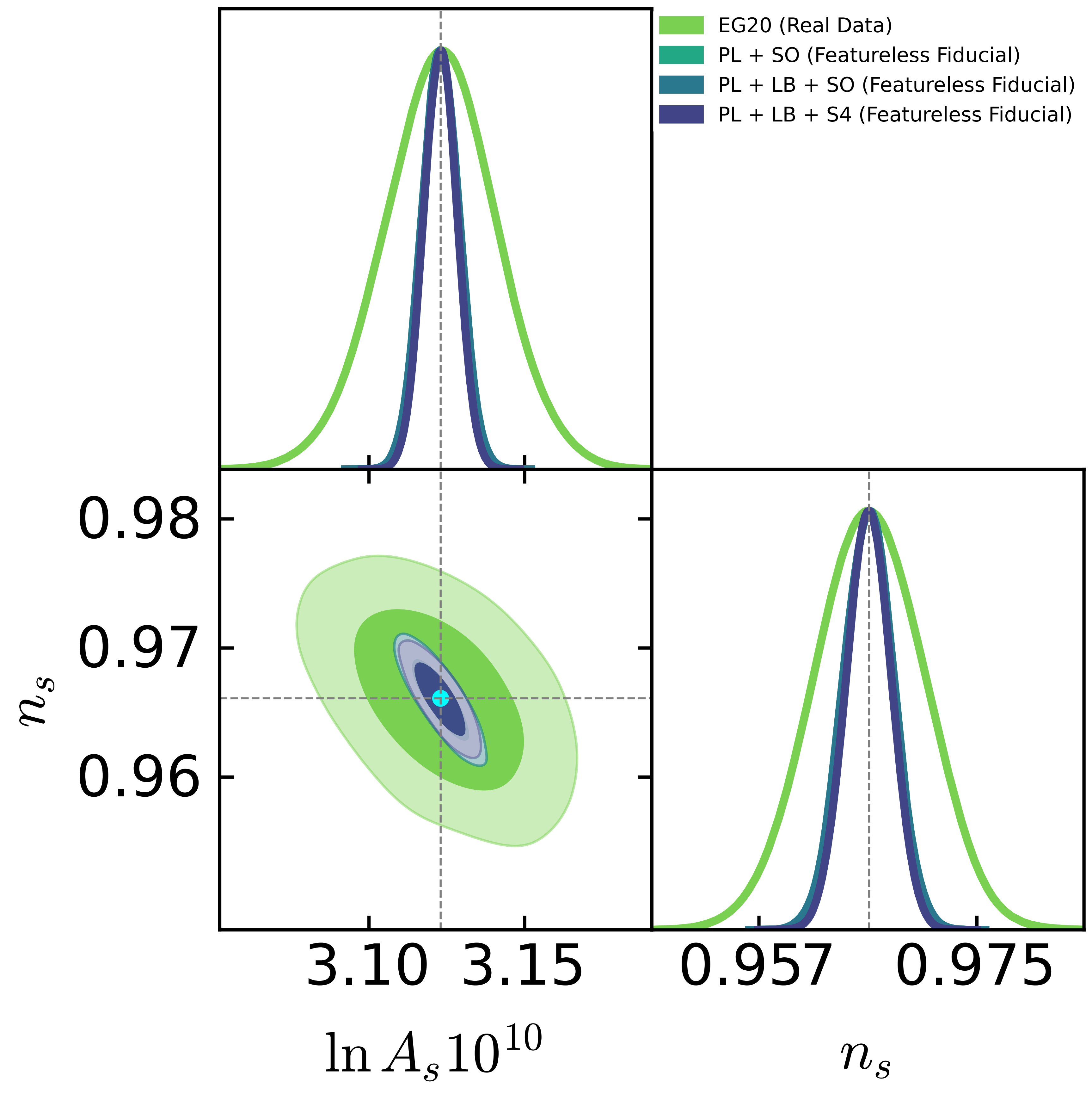
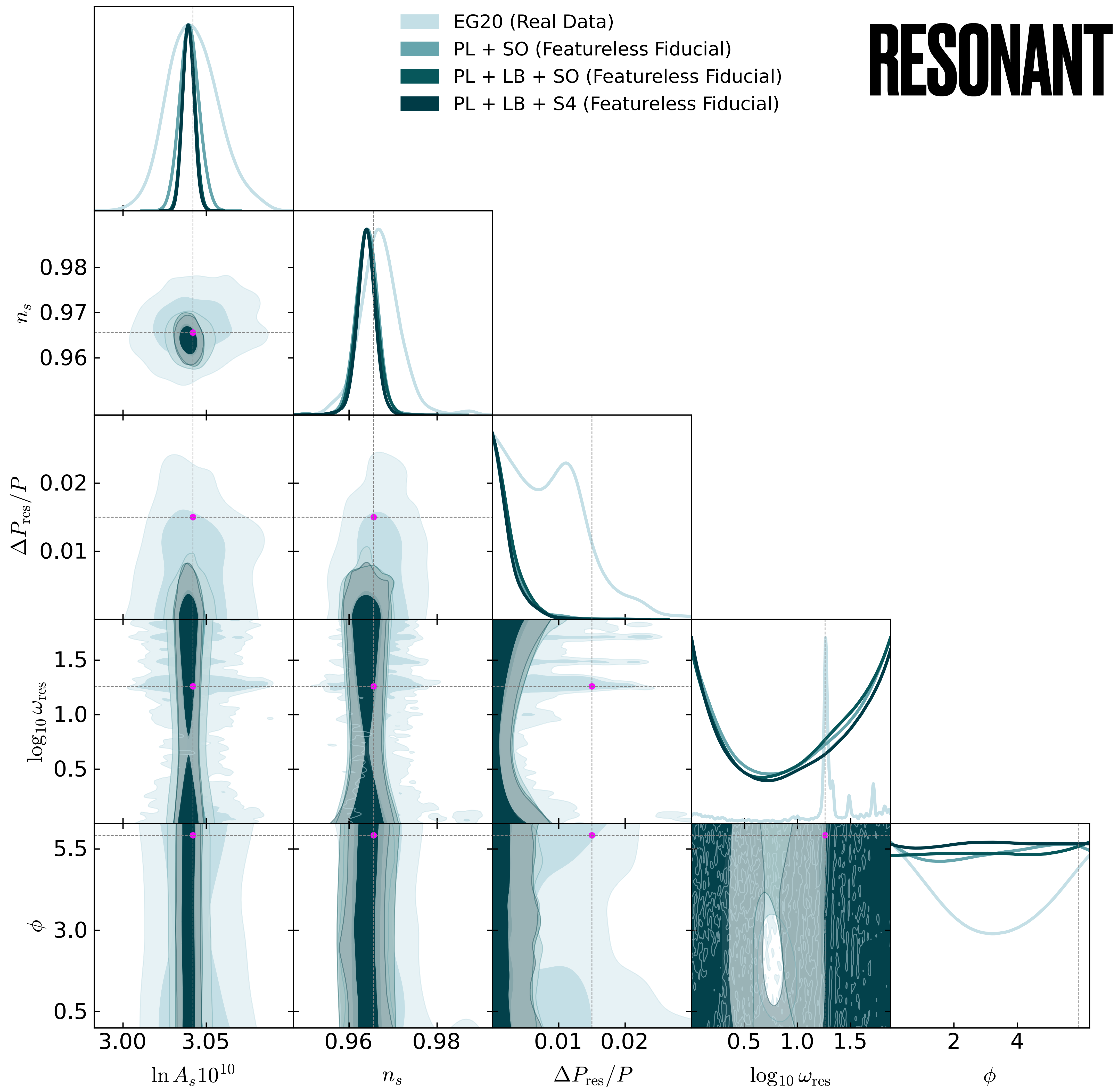


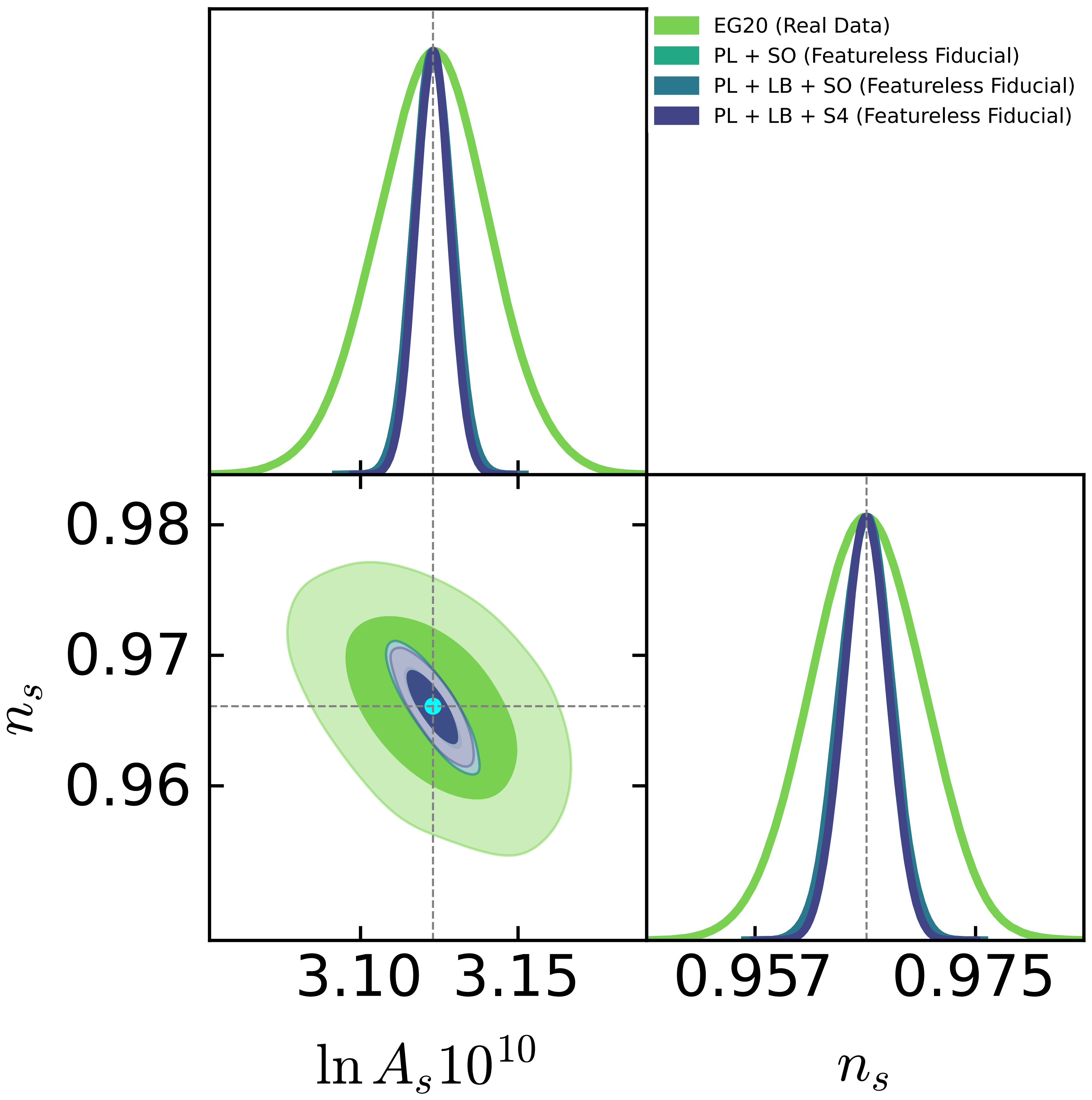
RESONANT

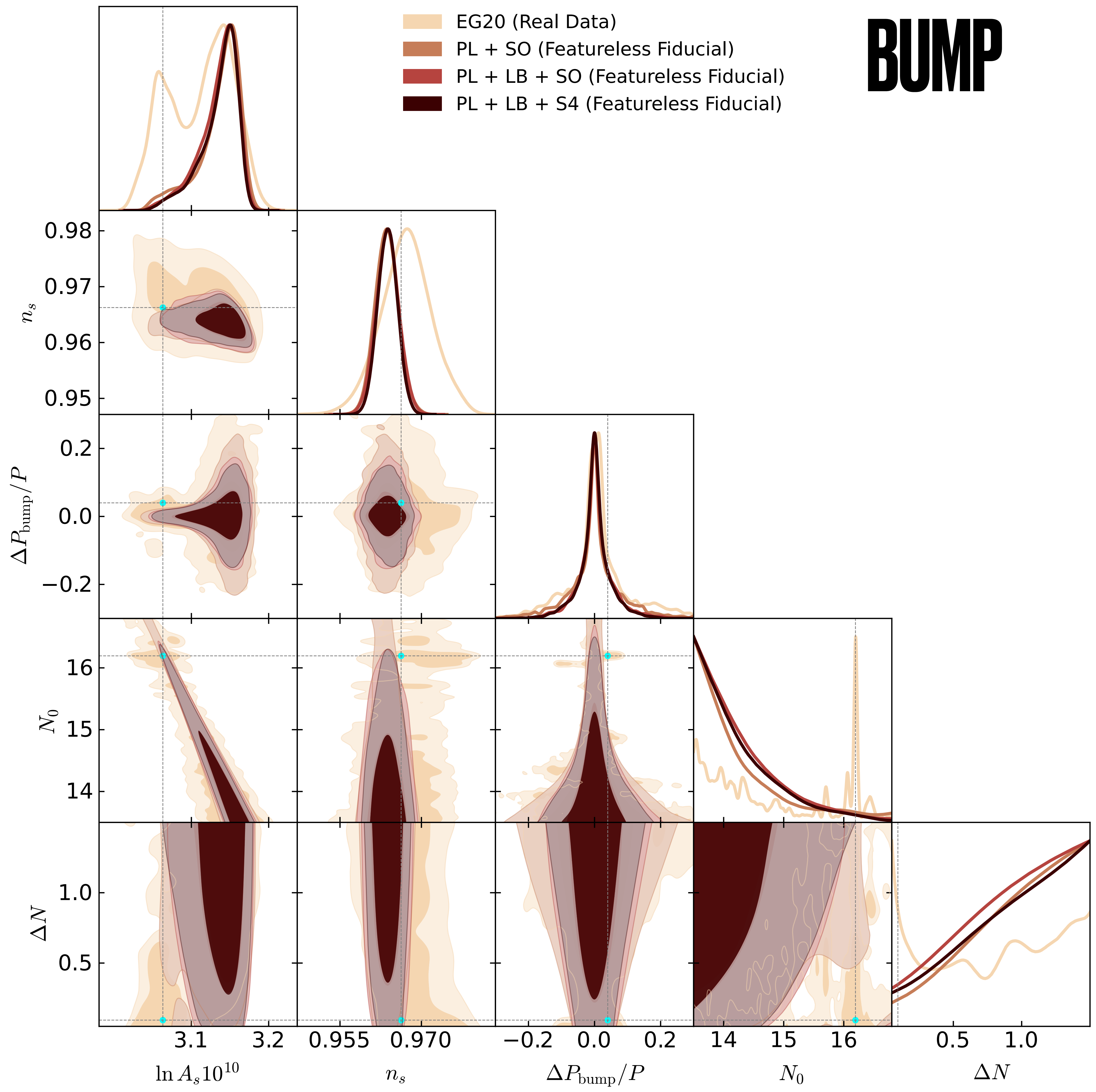


FEATURELESS FIDUCIAL

We assume the featureless bestfit is the true model of the Universe

$$A_s - n_s$$





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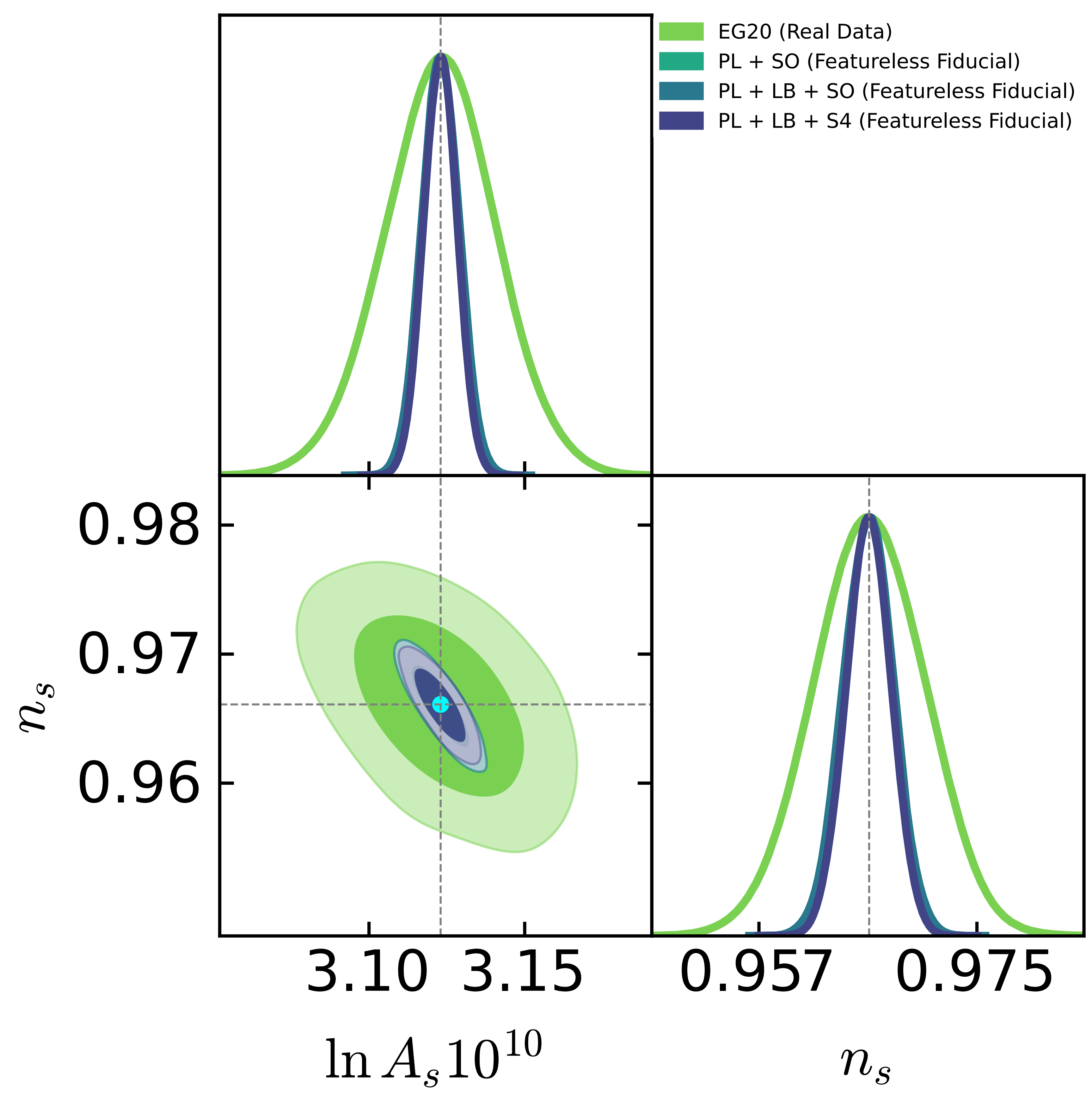
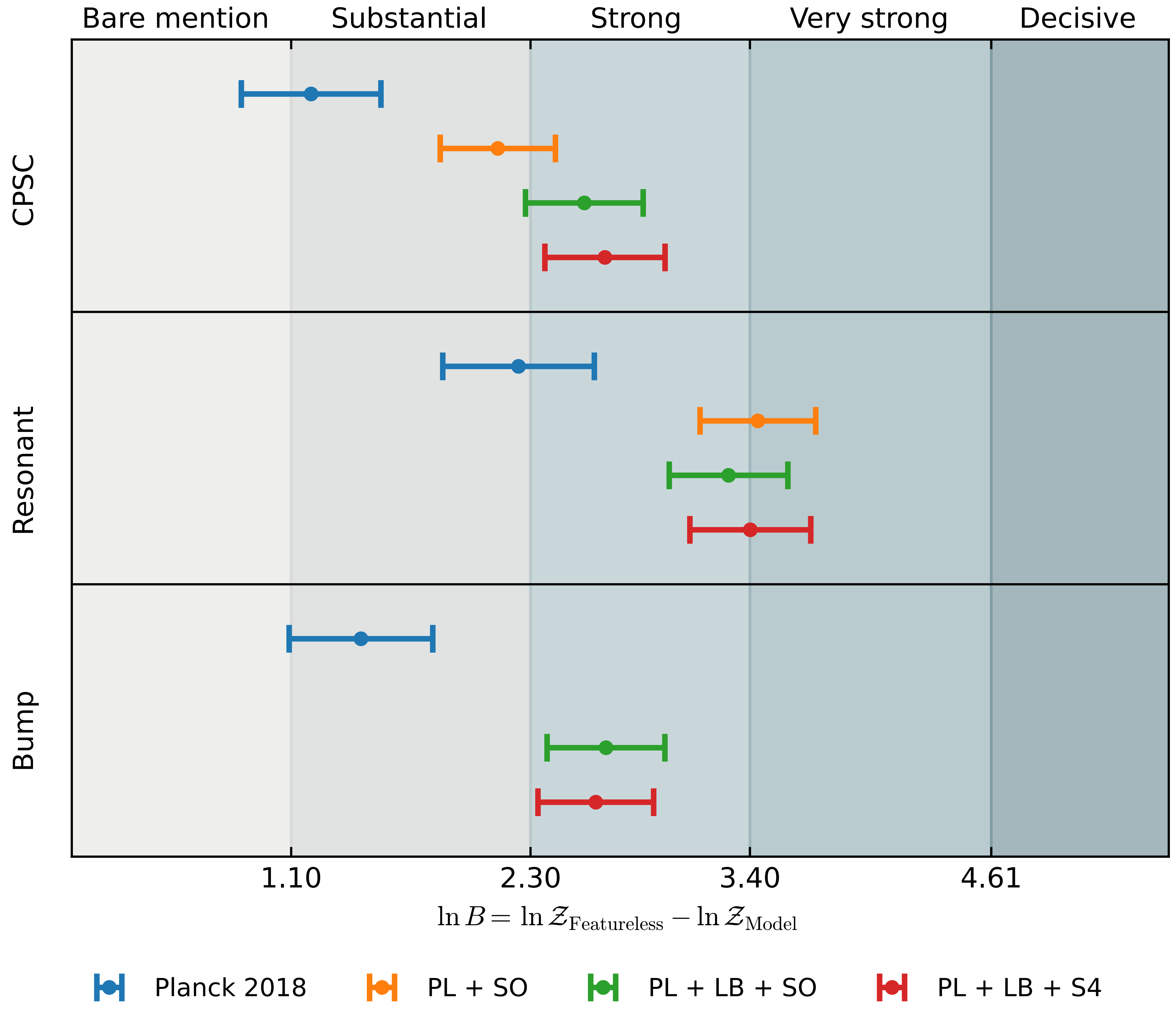
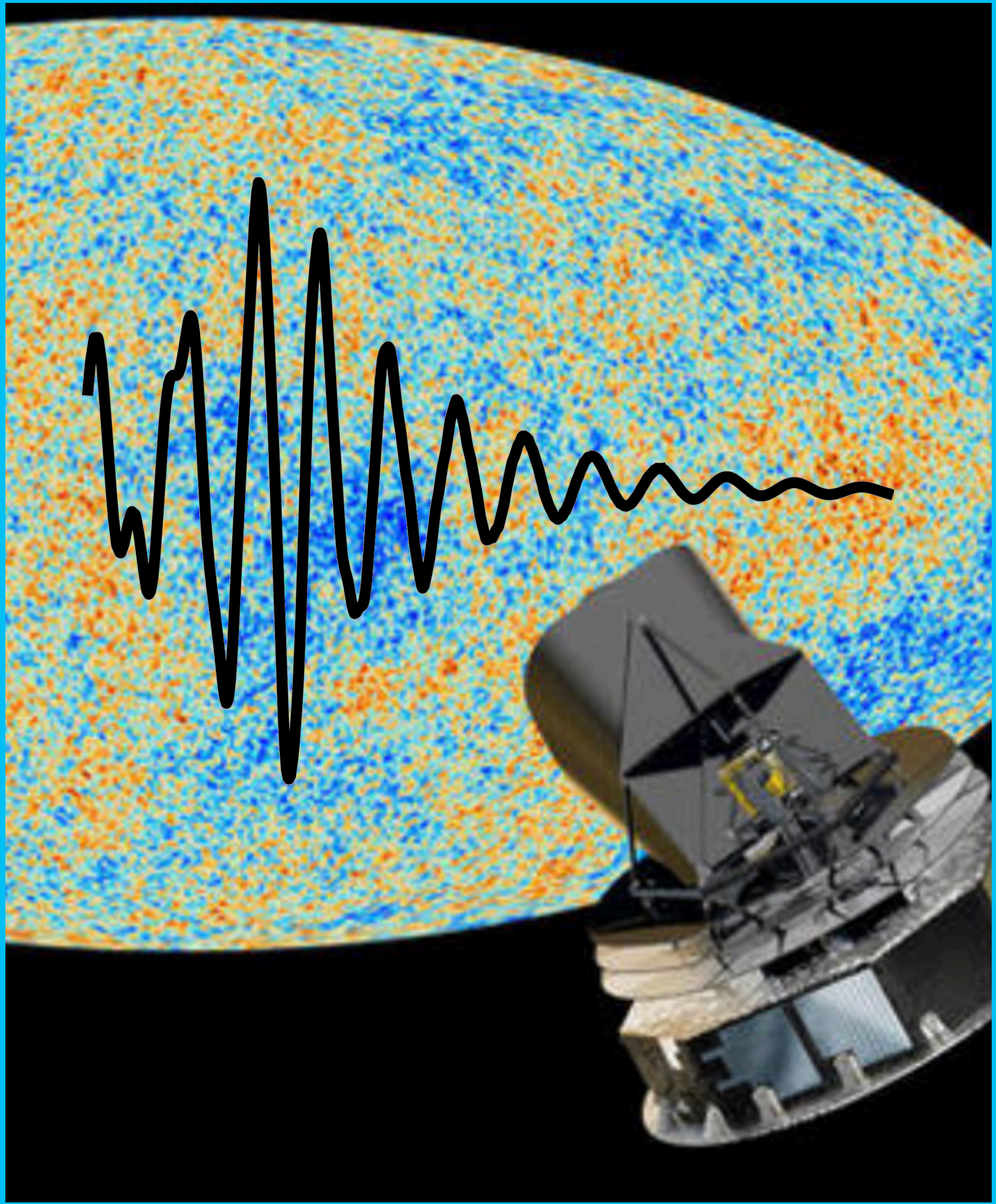
$$A_s - n_s$$





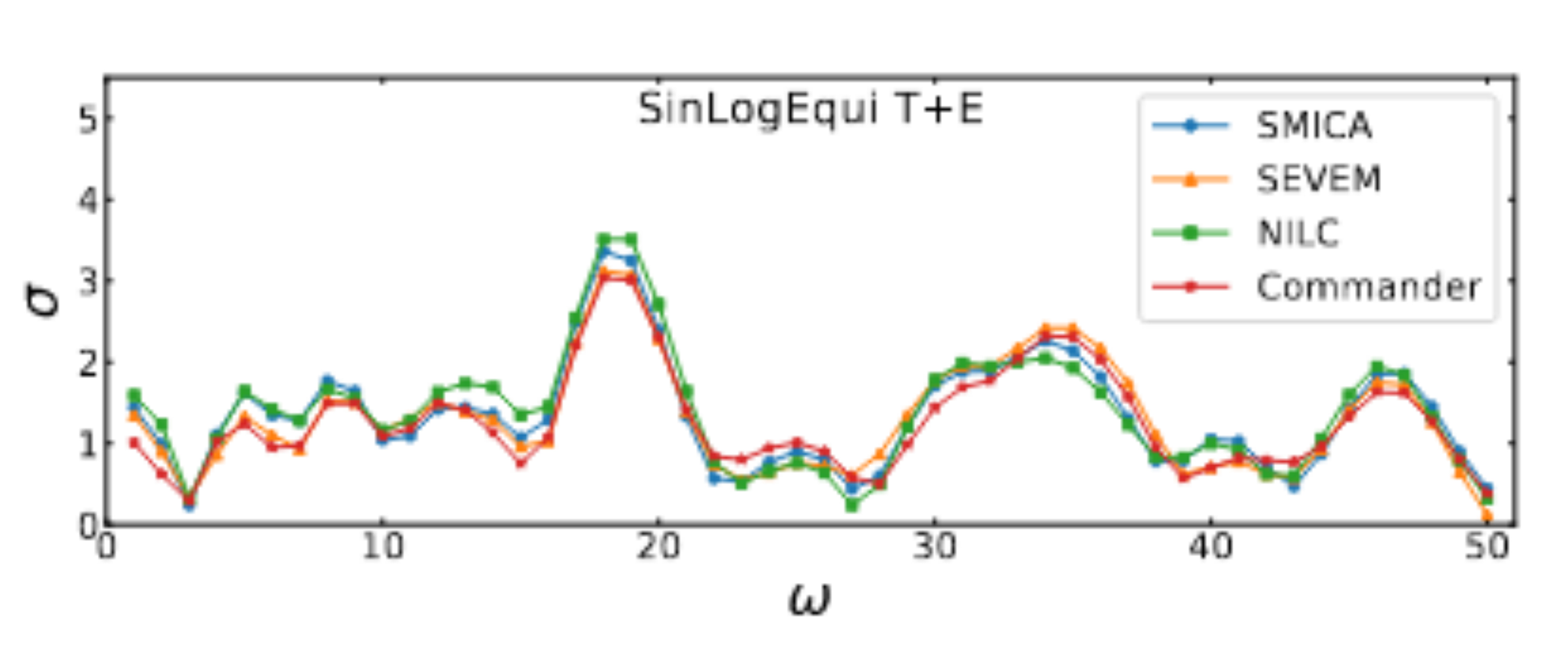
CONCLUSIONS

- Features carry invaluable information about the dynamics of the Early Universe
- They are not statistical significant, but we found some very interesting bestfit candidates
- Future experiments will put stringent constraints on them making it possible to inspect exotic Early Universe Physics



PROSPECTS

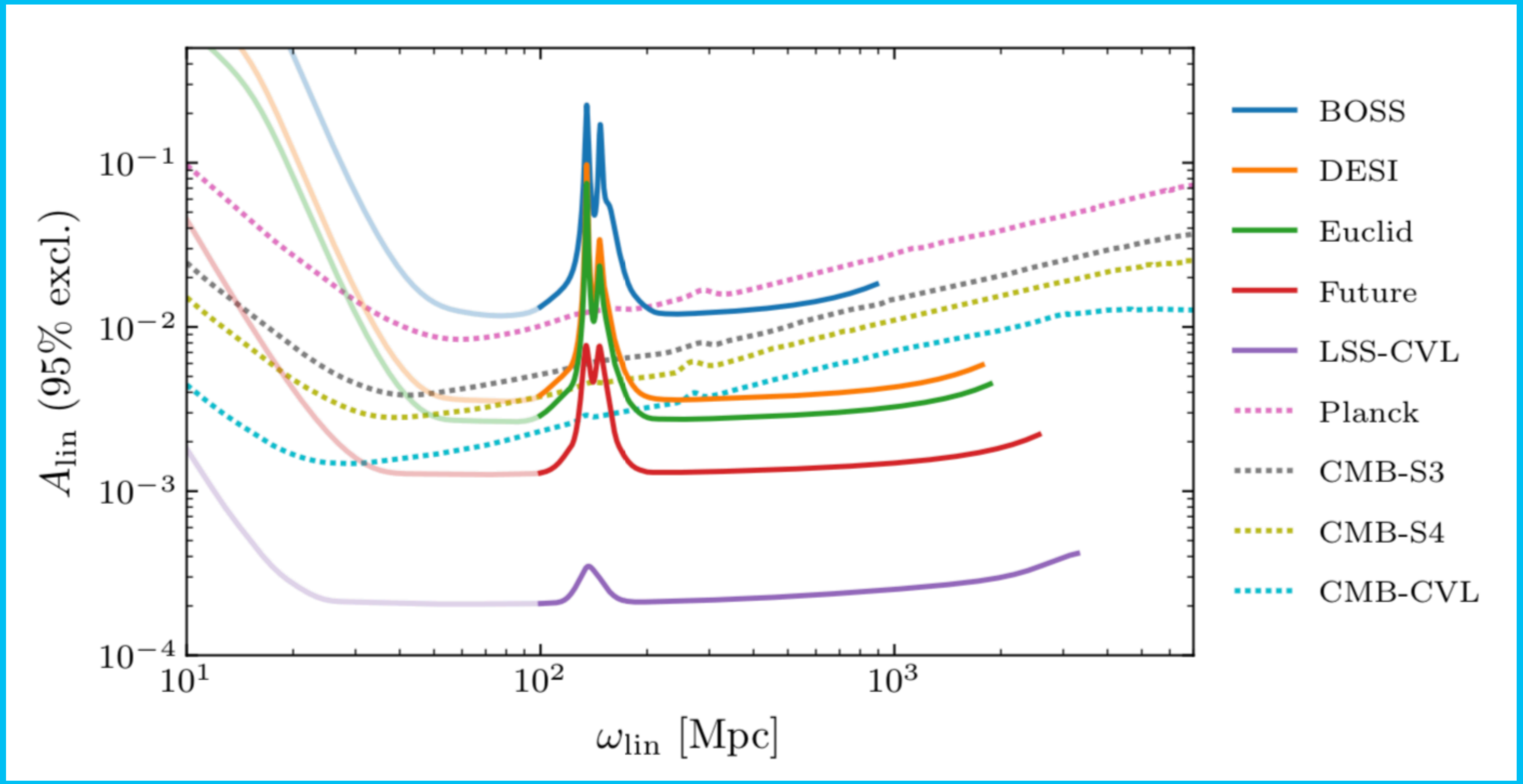
- **Primordial non-Gaussianities**



PLANCK 2018 PRIMORDIAL NON-GAUSSIANITY

PROSPECTS

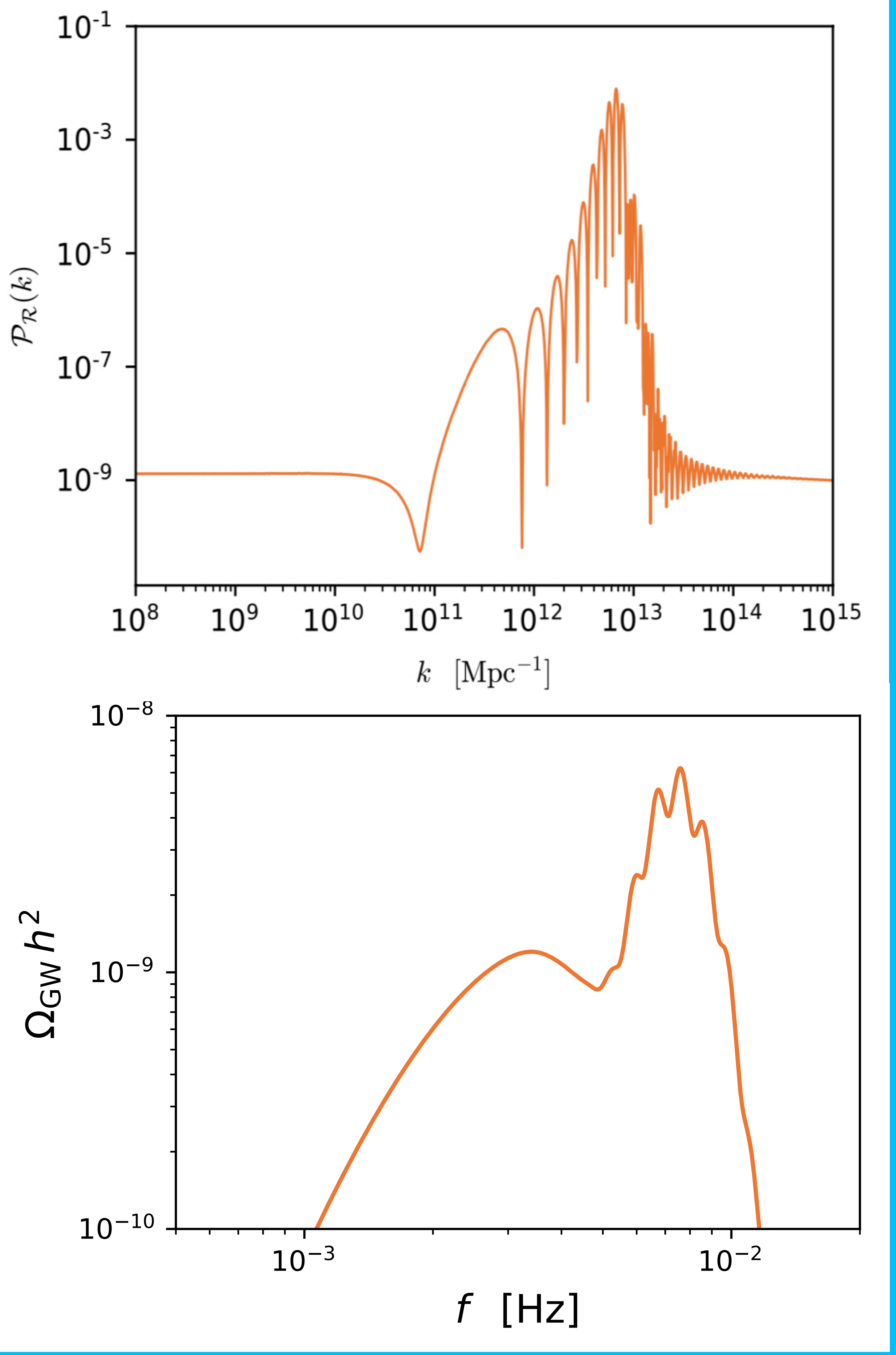
- Primordial non-Gaussianities
- Test feature signals with LSS data



BUTLER ET AL 2018

PROSPECTS

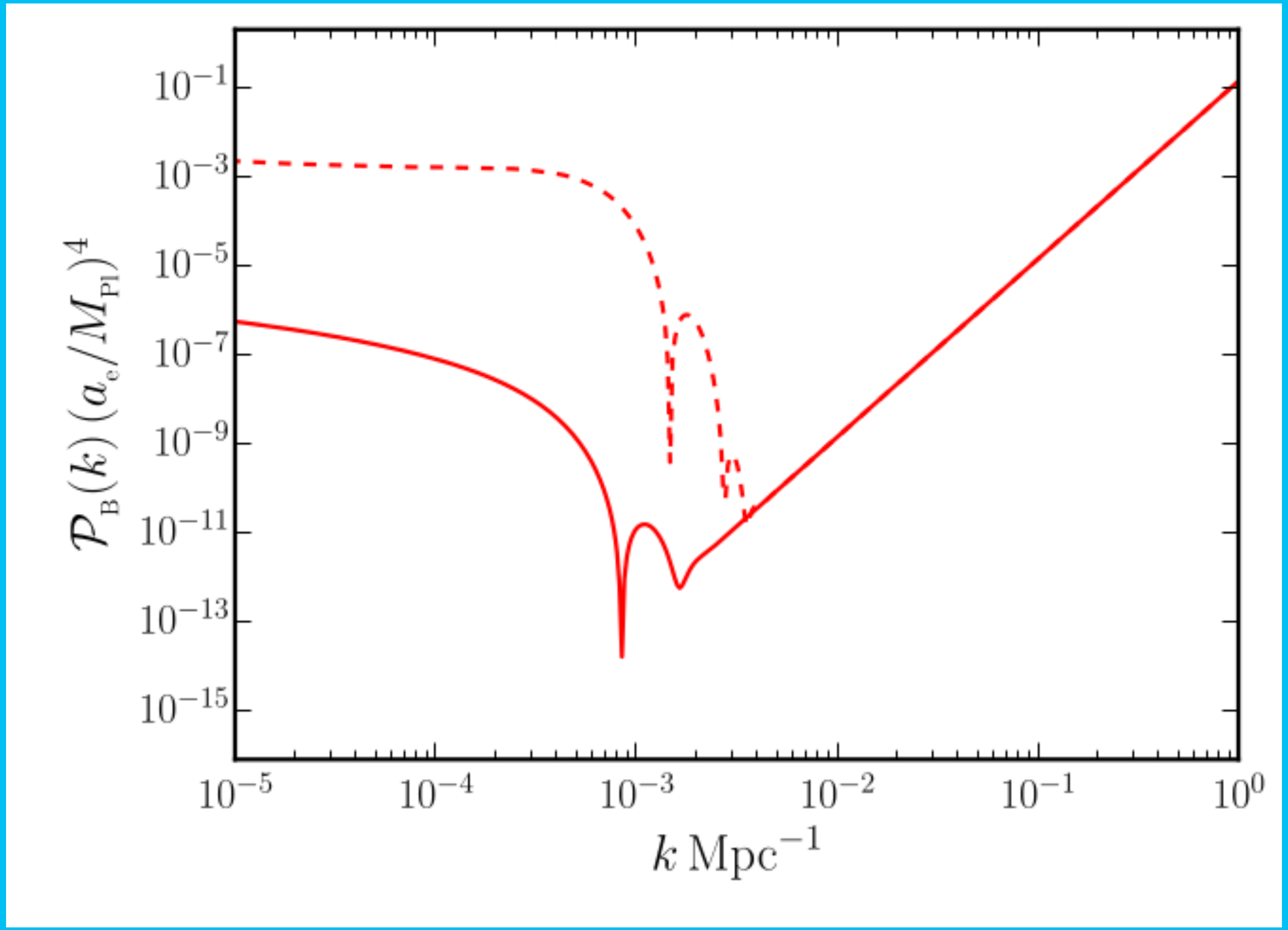
- Primordial non-Gaussianities
- Test feature signals with LSS data
- Test features with GW interferometers?



BRAGLIA, CHEN, HAZRA, ARXIV: 2012:05821

PROSPECTS

- Primordial non-Gaussianities
- Test the feature signals with LSS data
- Test features clocks GW interferometers?
- Or with other Physics?



TRIPATHY ET AL, ARXIV: 2111.01478

PROSPECTS

- Primordial non-Gaussianities
- Test the feature signals with LSS data
- Test features clocks GW interferometers?
- Or with other Physics?

THANK YOU!