# SEARCHING FOR PRIMORDIAL FEATURES IN THE COSMIC MICROWAVE BACKGROUND


## Matteo Braglia

Marie Skłodowska-Curie Fellow — CERN Theory Department


*This talk draws on work with many collaborators*

Yacine Ali-Haimoud · Sebastián Céspedes · Xingang Chen · Fabio Finelli · Dhiraj Kumar Hazra · Nanoom Lee · Sonia Paban · Catherine Petretti · Lucas Pinol · Wenzer Qin · Tracy Slatyer · L. Sriramkumar

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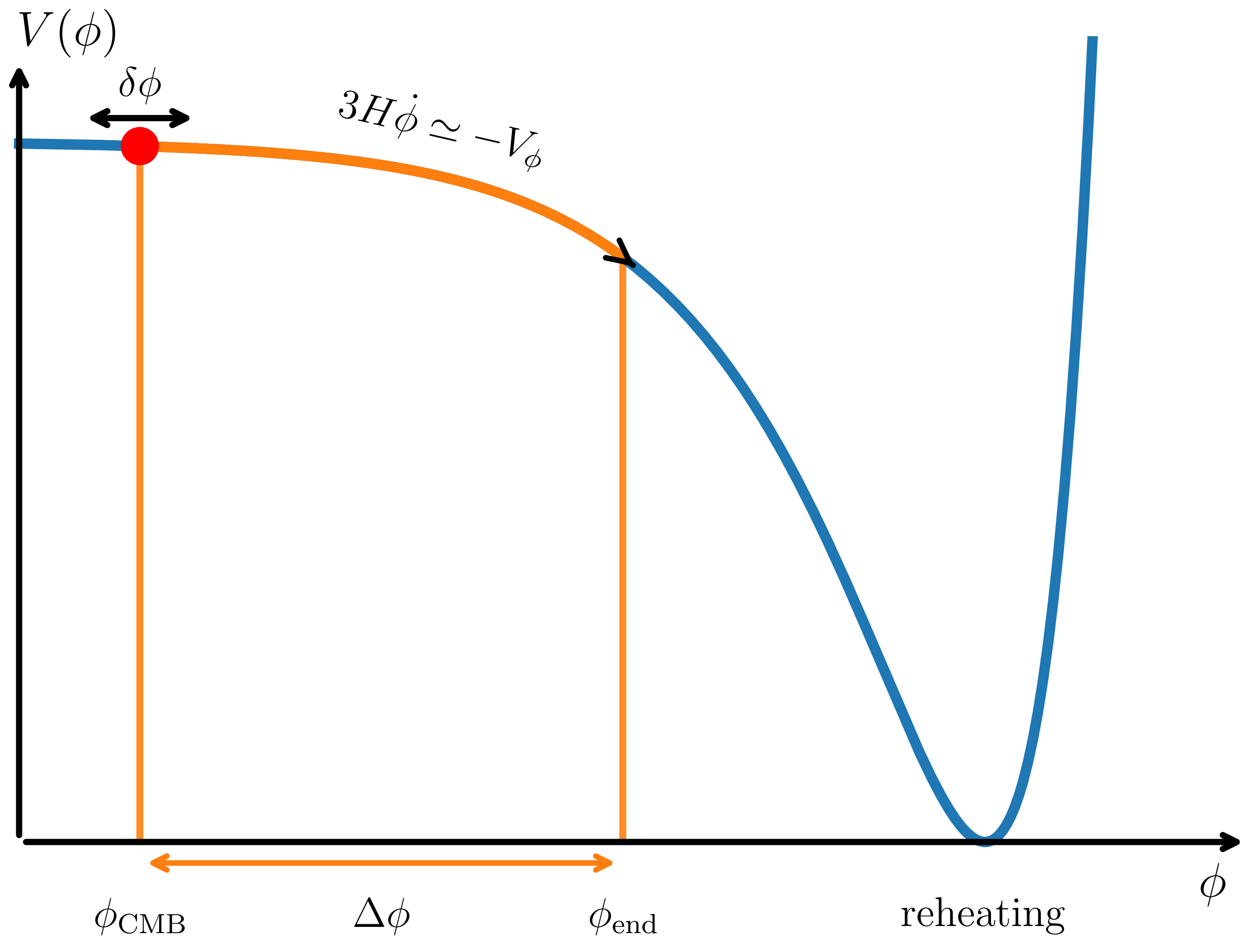
# Single Field Slow-Roll

**SR conditions** ensure a long lasting inflationary stage

$$\epsilon = -\dot{H}/H^2 \ll 1,\ |\eta| = |\dot{\epsilon}/H\epsilon| \ll 1,\ |\eta_2| = |\dot{\eta}/H\eta| \ll 1,\ \cdots$$

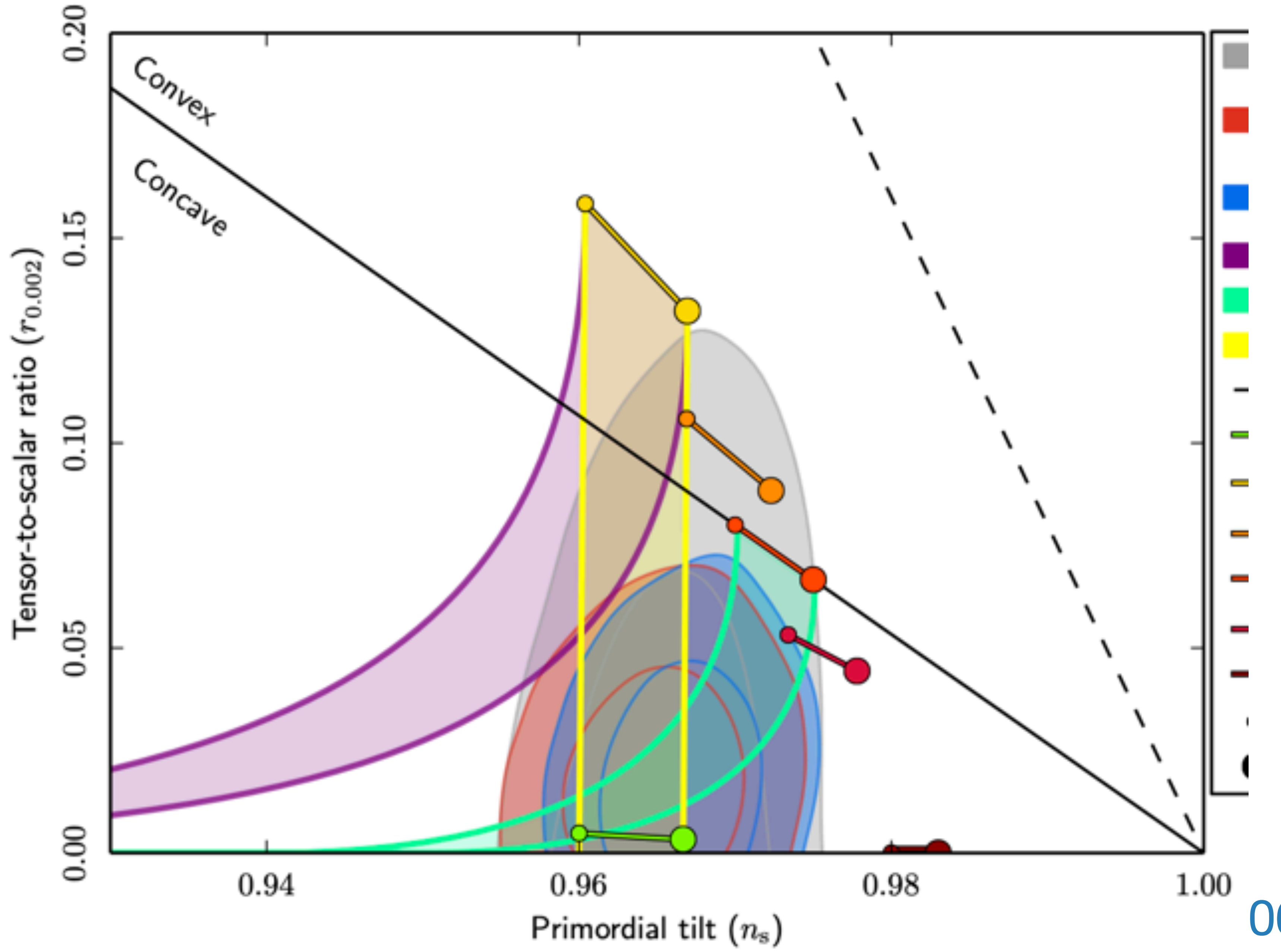



**SR predicts:**

1. Near scale-invariant spectra $\mathscr{P}_\zeta = A_s \left(\frac{k}{k_*}\right)^{n_s-1}$ $\mathscr{P}_T = r \times A_s \left(\frac{k}{k_*}\right)^{n_t}$

2. Adiabatic and Gaussian initial spectra

3. Still no smoking gun



# Primordial features

SR for $60$ $e$folds

SR for **a few** $e$folds

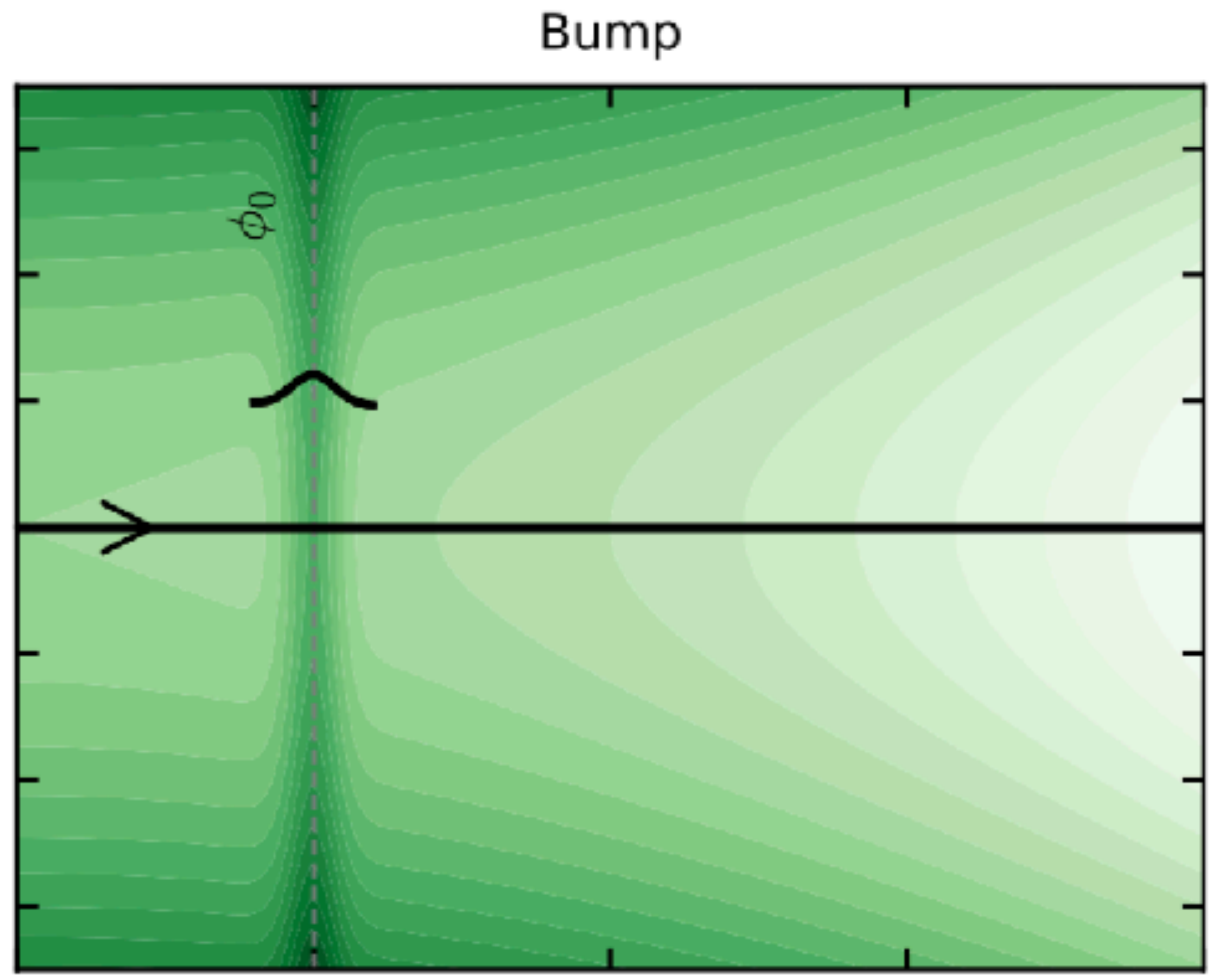
UV-complete embeddings of inflation predict the presence of additional fields. In this landscape, **SF-SR** inflation **is** a **tuned** realization.

The trajectory may undergo transient departures from SR, which can excite **oscillations** of massive degrees of freedom and leave small oscillations in the primordial spectra.

Chen 1002.1416, Achucarro et al 2203.08128

CMB data constrain these deviations to be small. We can use tiny departures as a test of inflation.

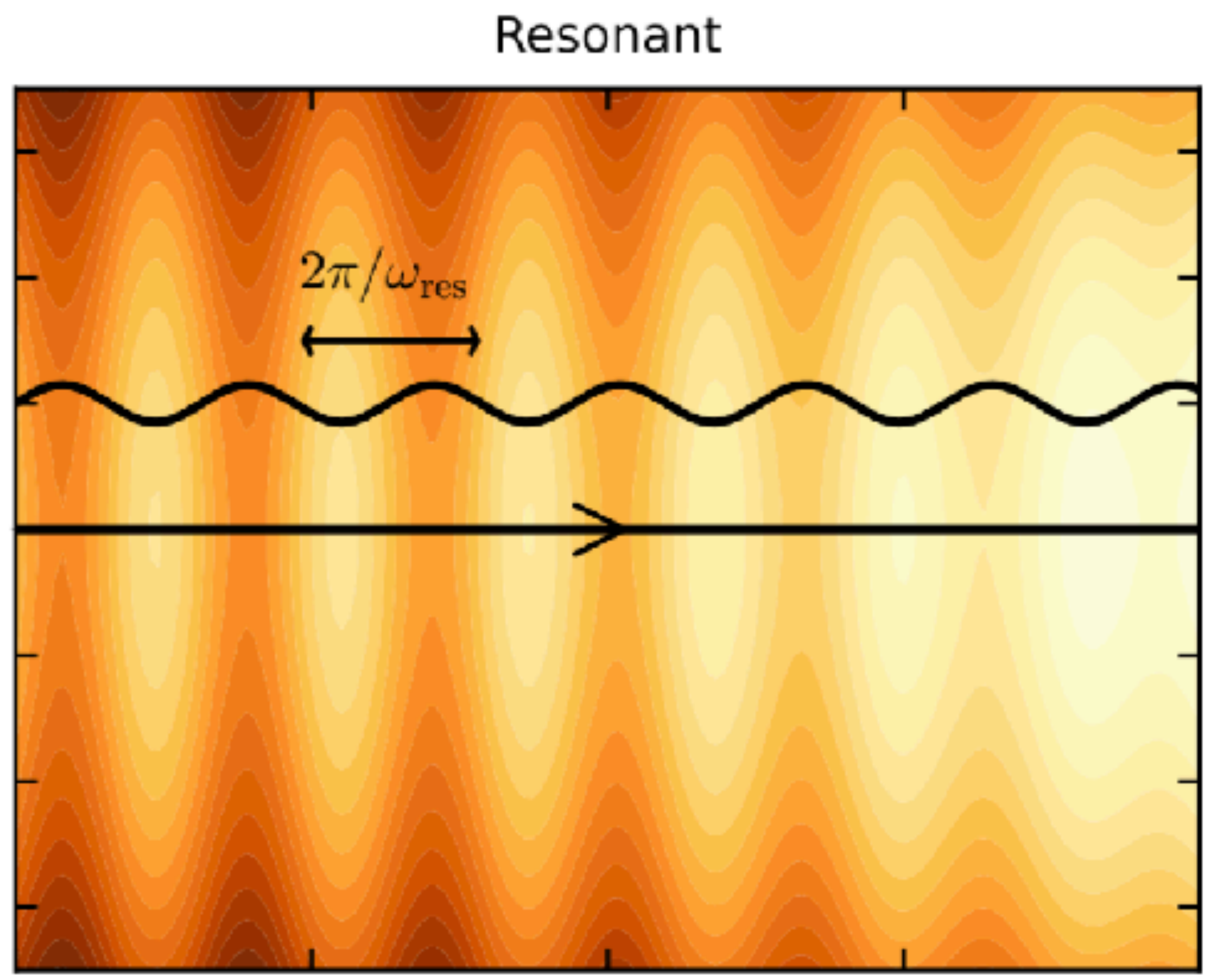
# Models of primordial features




## Bump-step

Localized departures

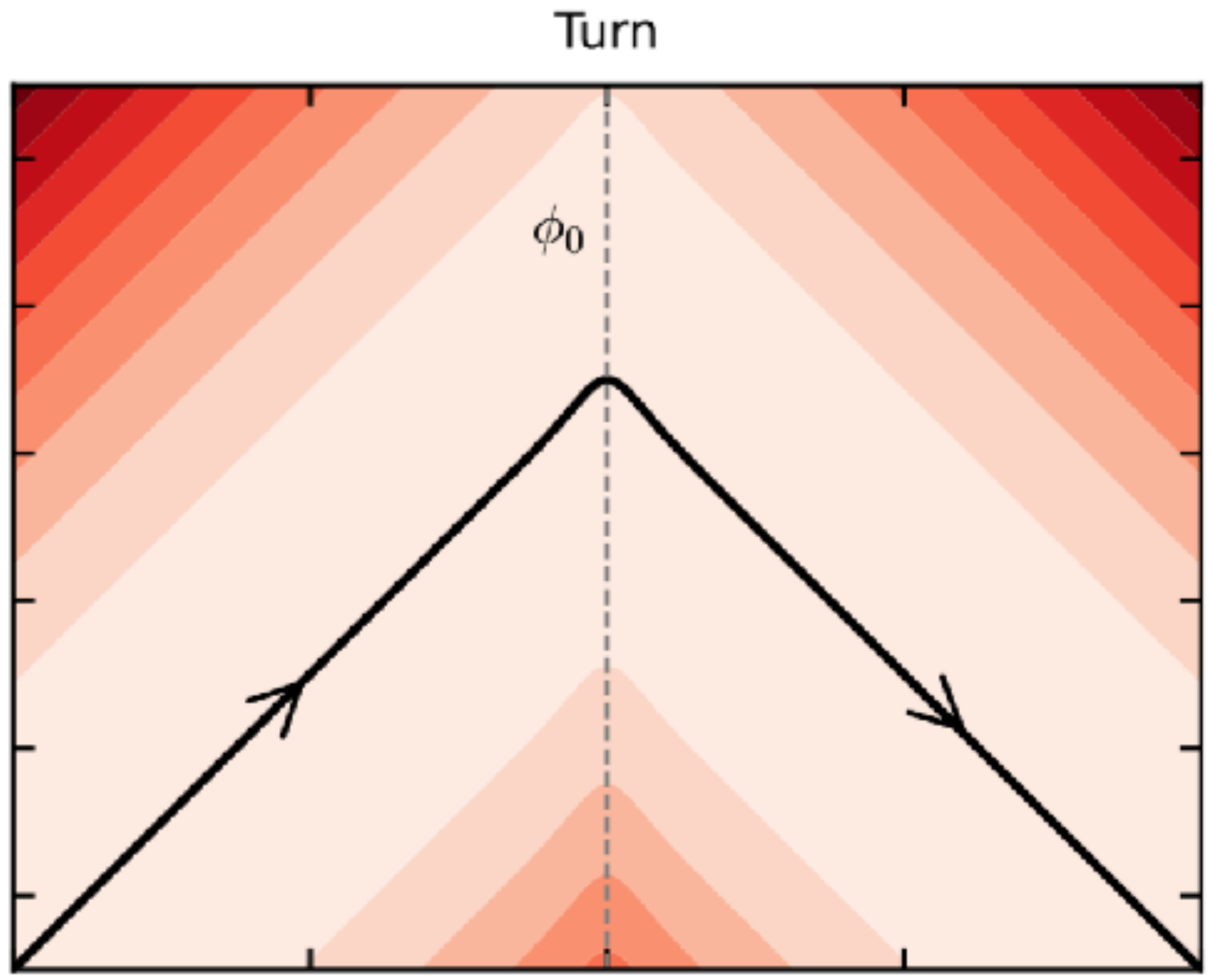
→ sharp feature




## Axion Monodromy

Periodic modulation

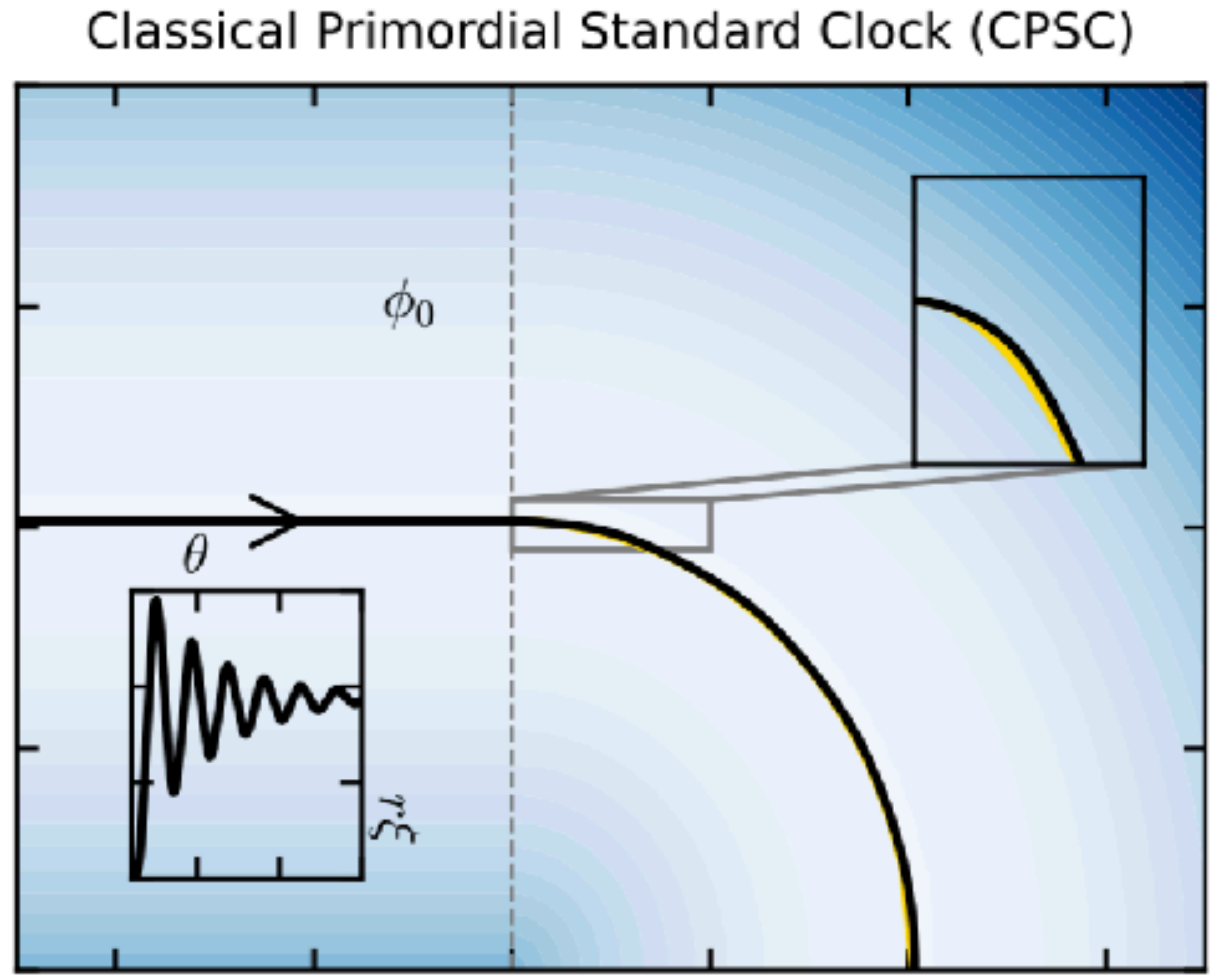
→ resonant feature




## Field-space turn

Transient multifield dynamics

→ sharp feature




## Standard clocks

Oscillating massive degree of freedom

→ standard clock feature

# Primordial features as inflationary spectroscopy

Small corrections to primordial spectra: $$\mathcal{P}_\zeta(k) = A_s \left(\frac{k}{k_*}\right)^{n_s-1} \left(1+\delta(k)\right)$$

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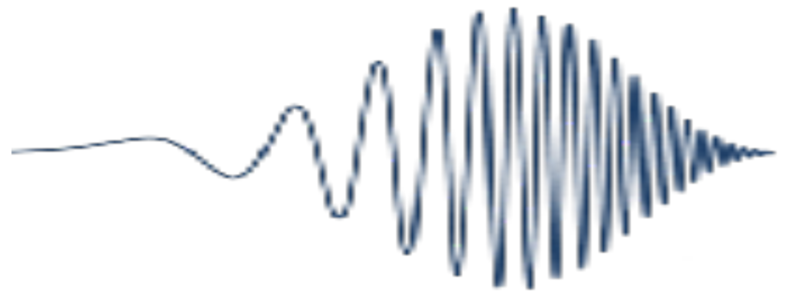

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**At what time does inflation deviate from SR?**

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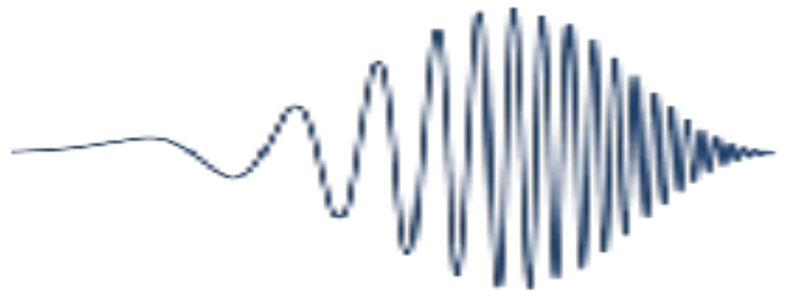

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**Resonant**

$$\delta(k) = A\sin\left(\omega\ln\frac{k}{k_*}+\varphi\right)$$

**Is there a periodic background oscillation?**

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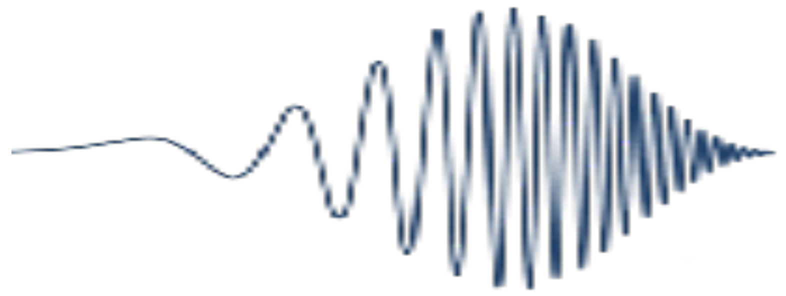

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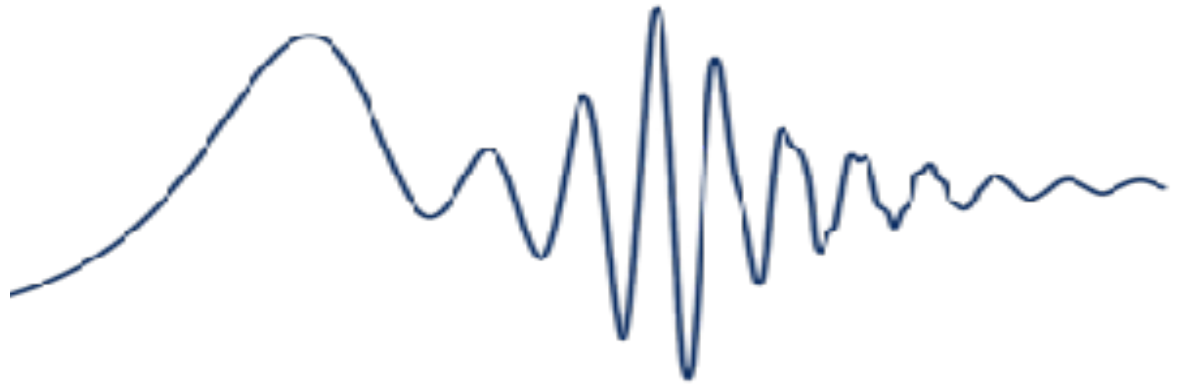

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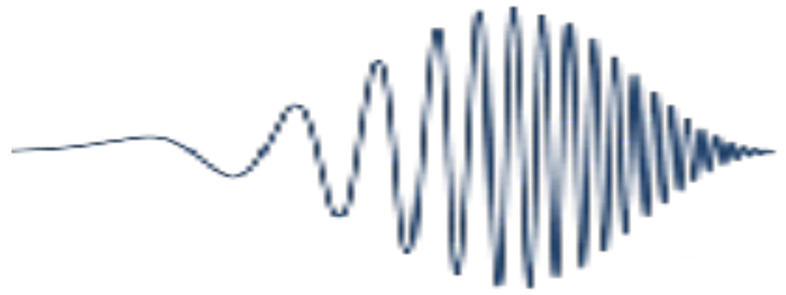

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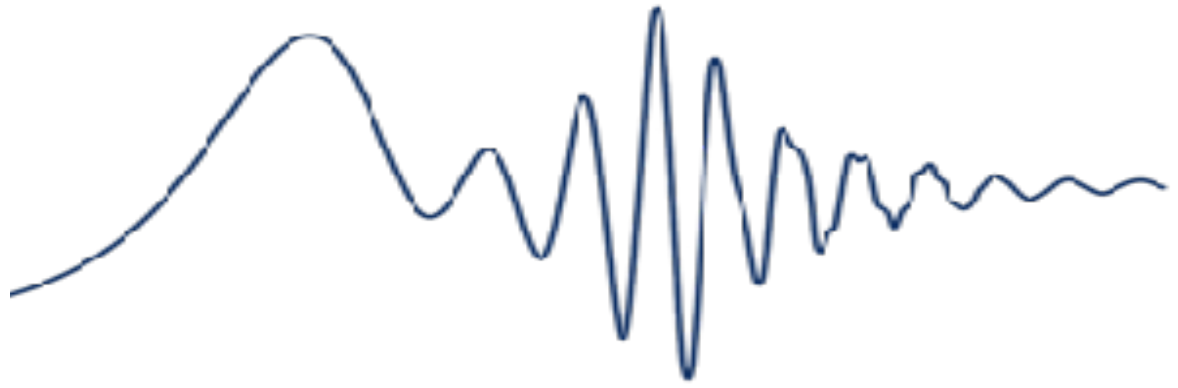

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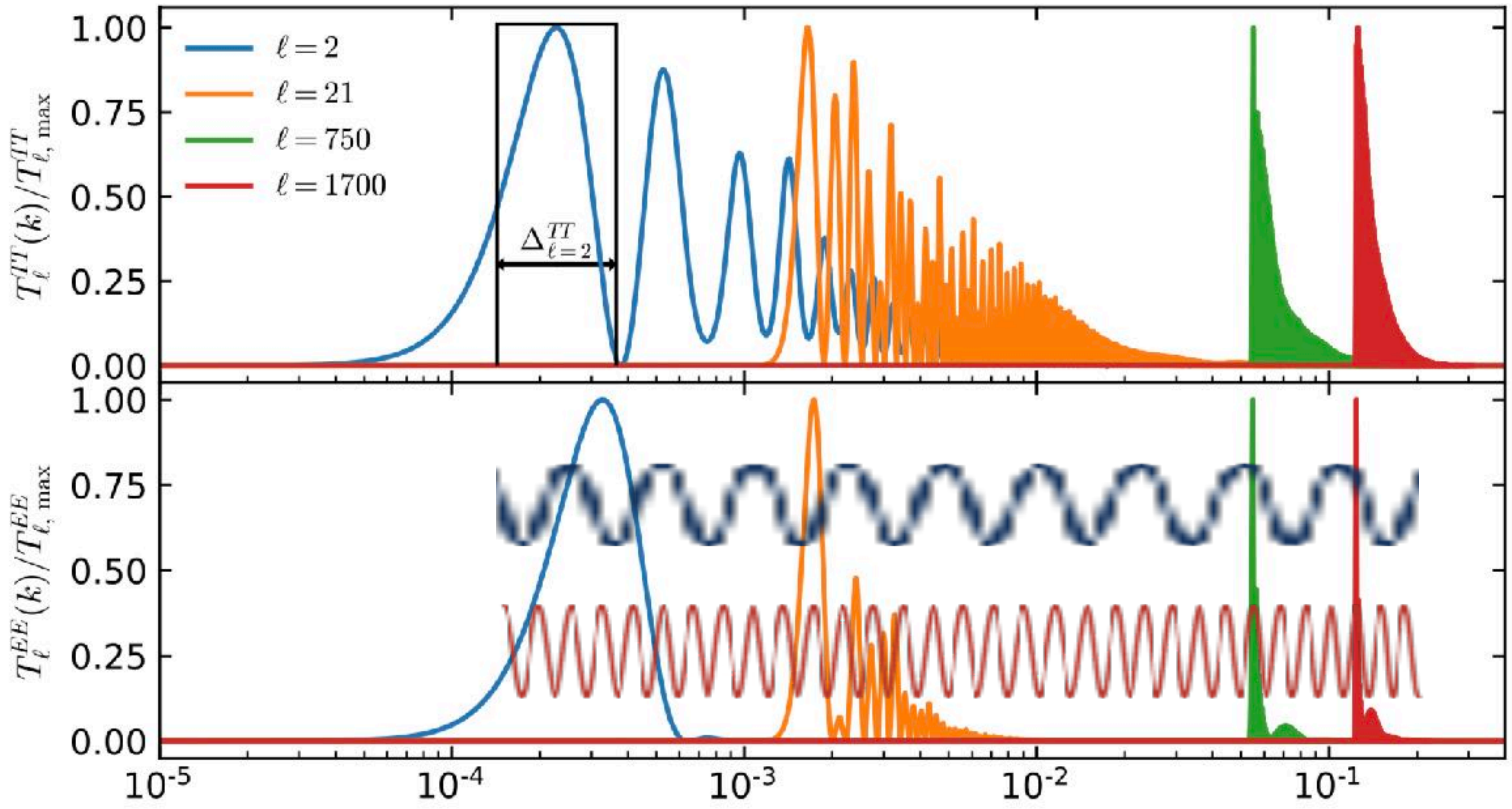
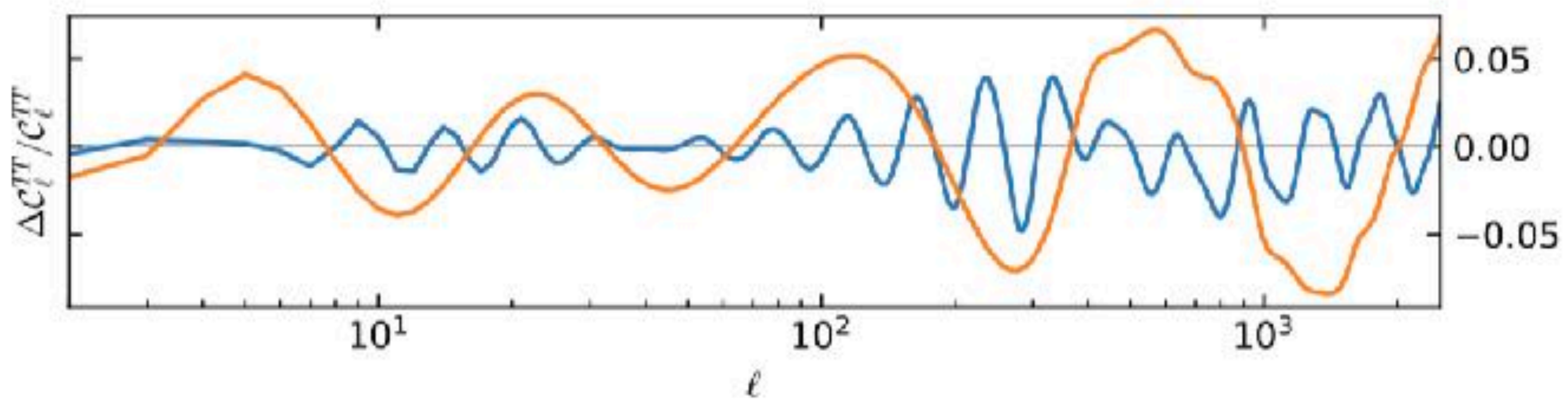
**Was a massive field excited?**

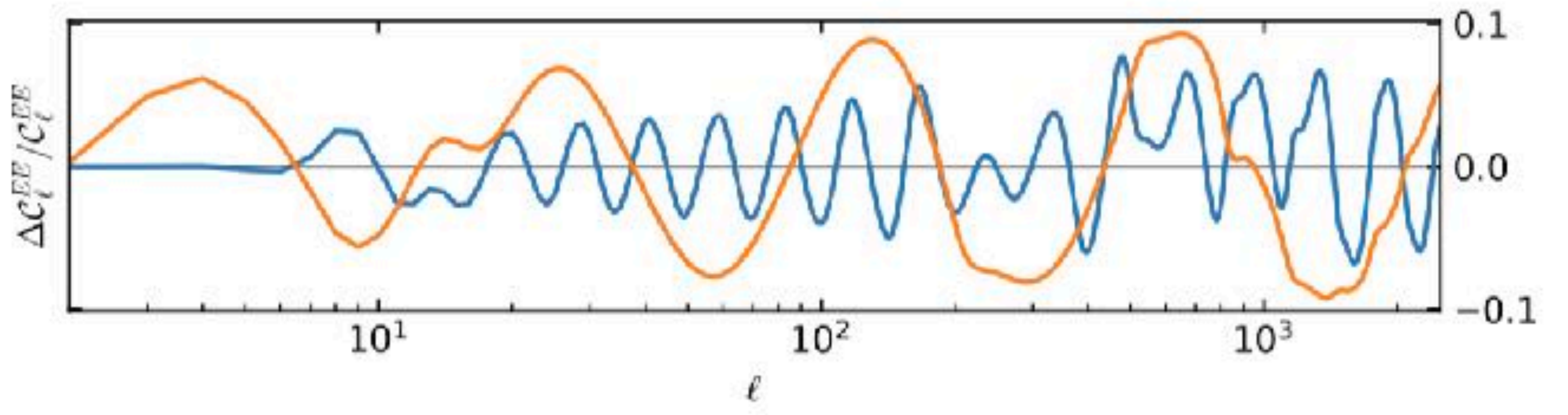
Measuring the running, the frequency, and the phase we can learn about new energy scales and degrees of freedom during inflation.

# Imprints on CMB spectra

The observable is the CMB anisotropy spectra: $C_\ell = \int \mathrm{d}\ln k \underbrace{\mathscr{P}(k)}_{\text{primordial}} \underbrace{T_\ell(k)}_{\text{Late-time physics}}$



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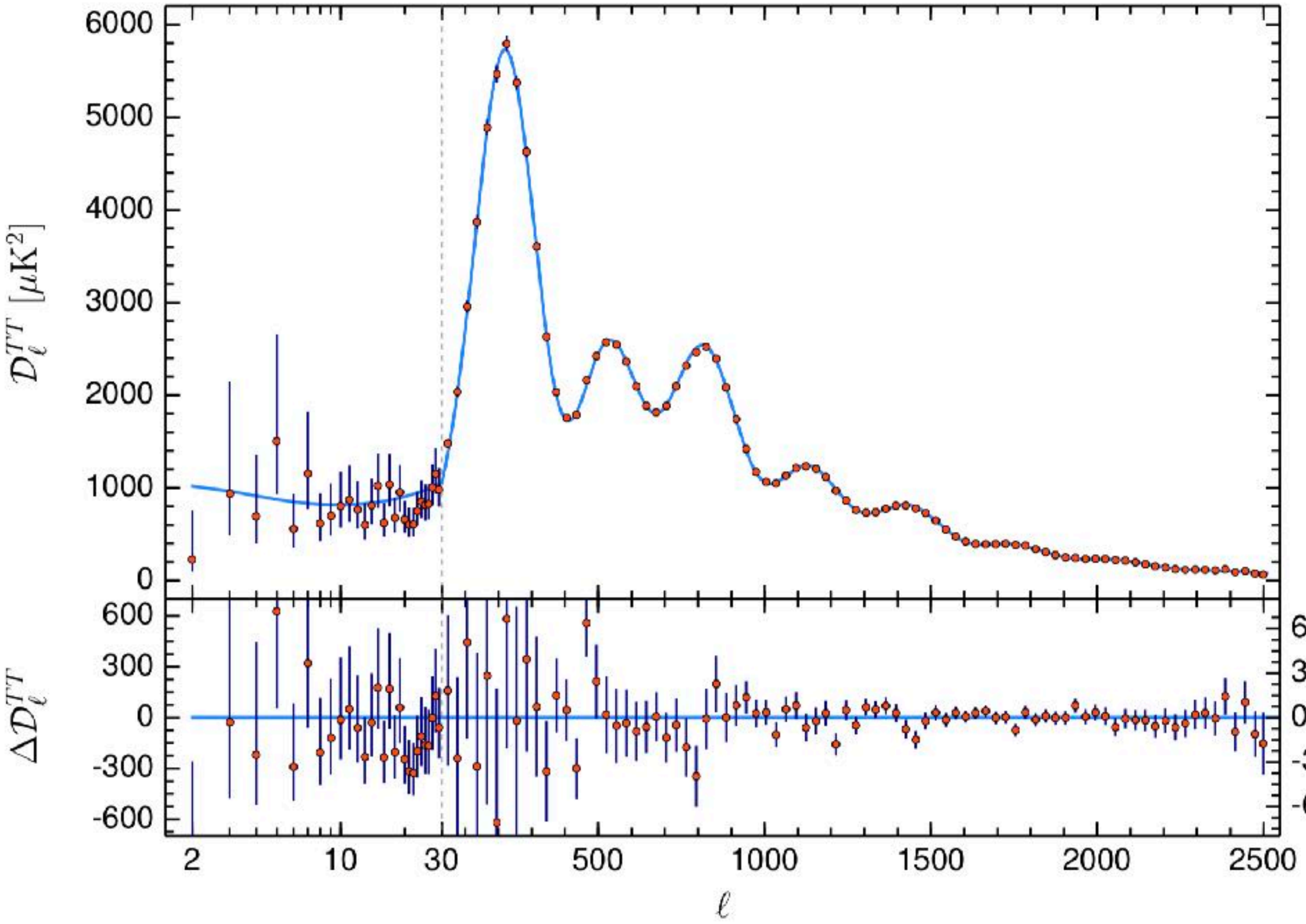


Planck Collaboration 1807.06209

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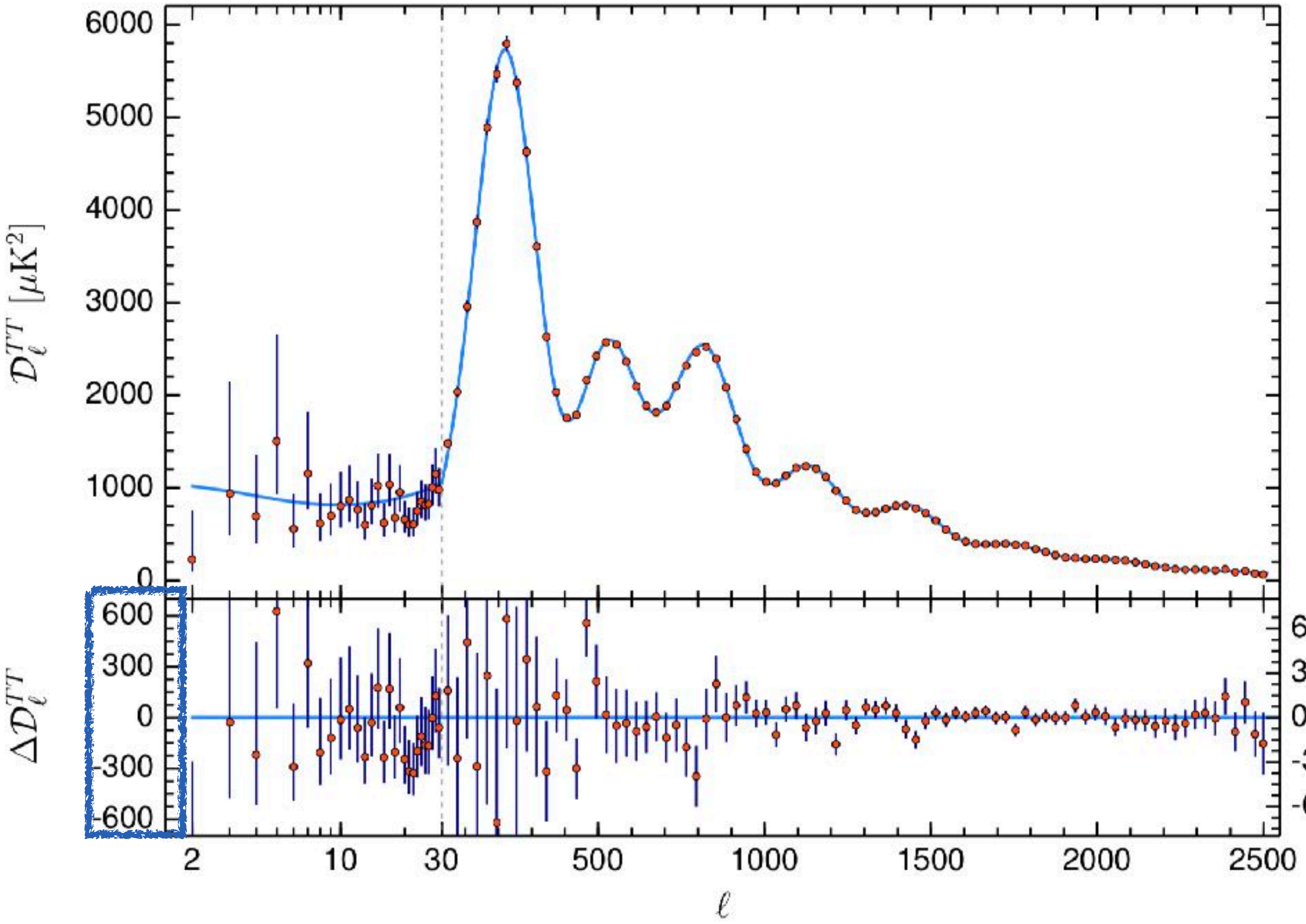


Planck Collaboration 1807.06209

*Low $\ell$:* large amplitude of residuals.

Also observed by WMAP

Plagued by cosmic variance

Need very localized primordial features

Petretti, **MB**, Chen, Hazra, Paban 2411.03459

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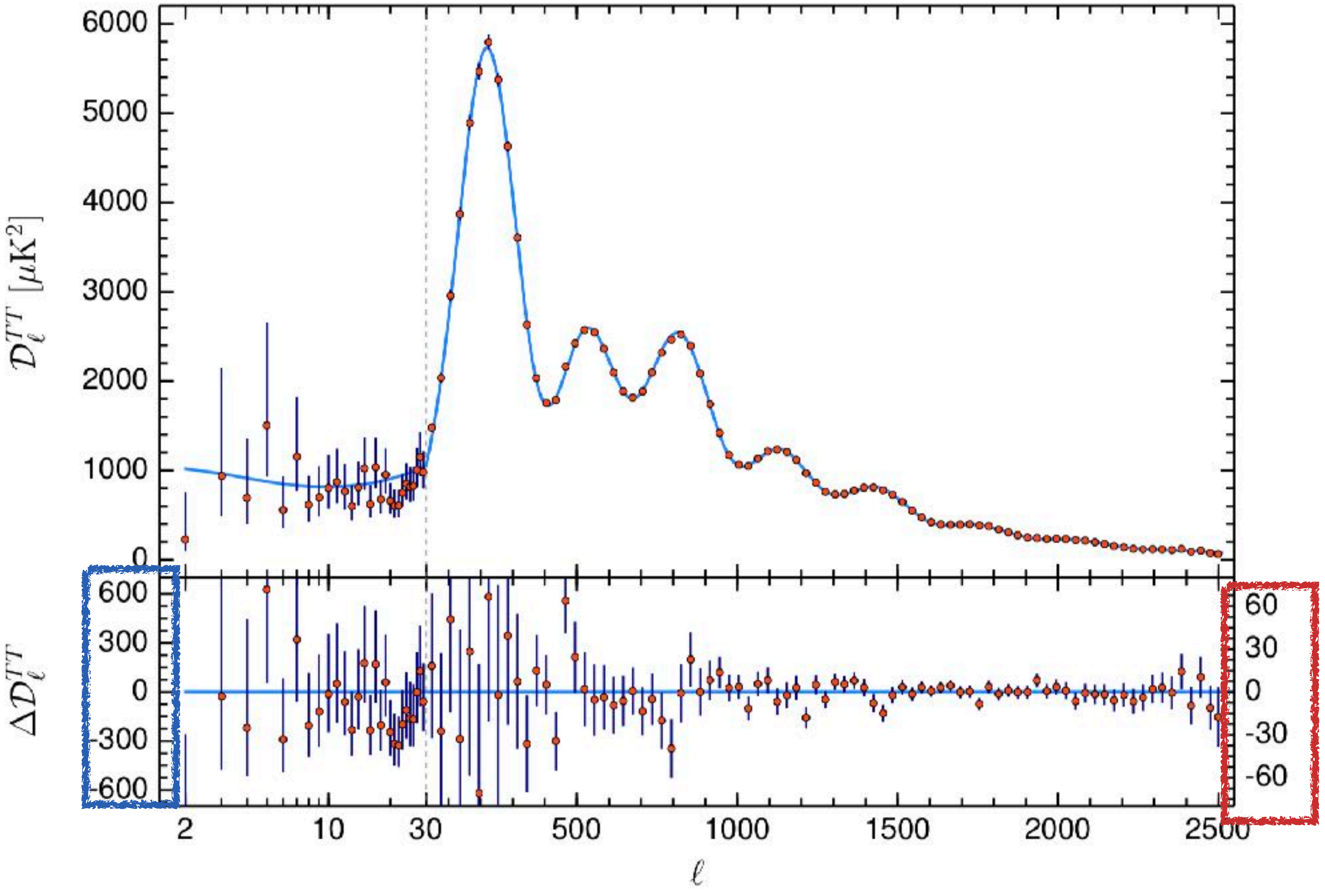


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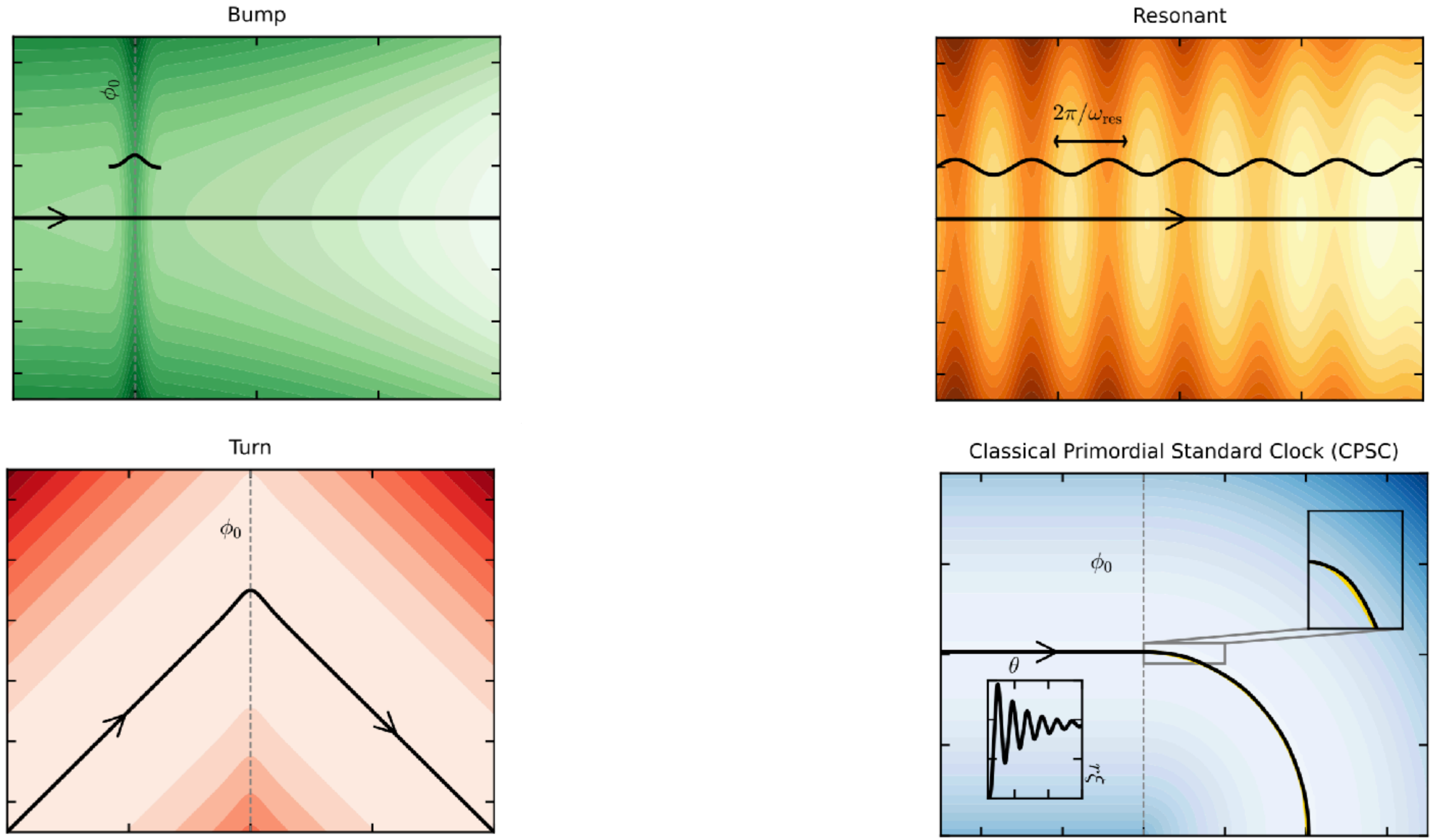
*High $\ell$:* ~10 times smaller residuals

Potentially higher SNR

Also detectable in other observables

Can also be fit by persistent features

# Hints for primordial features




**MB**, Chen, Hazra, Pinol 2210.07028

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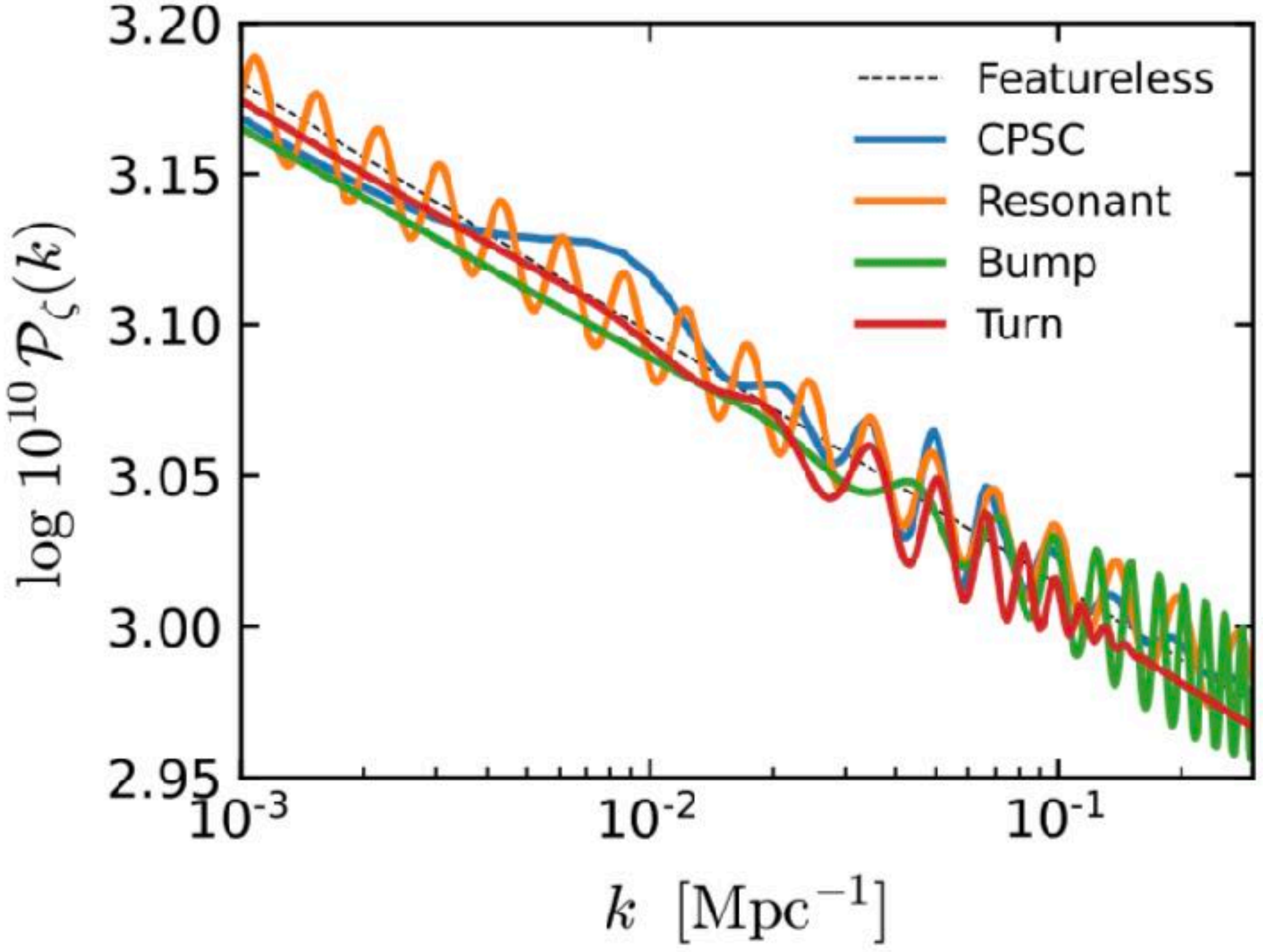


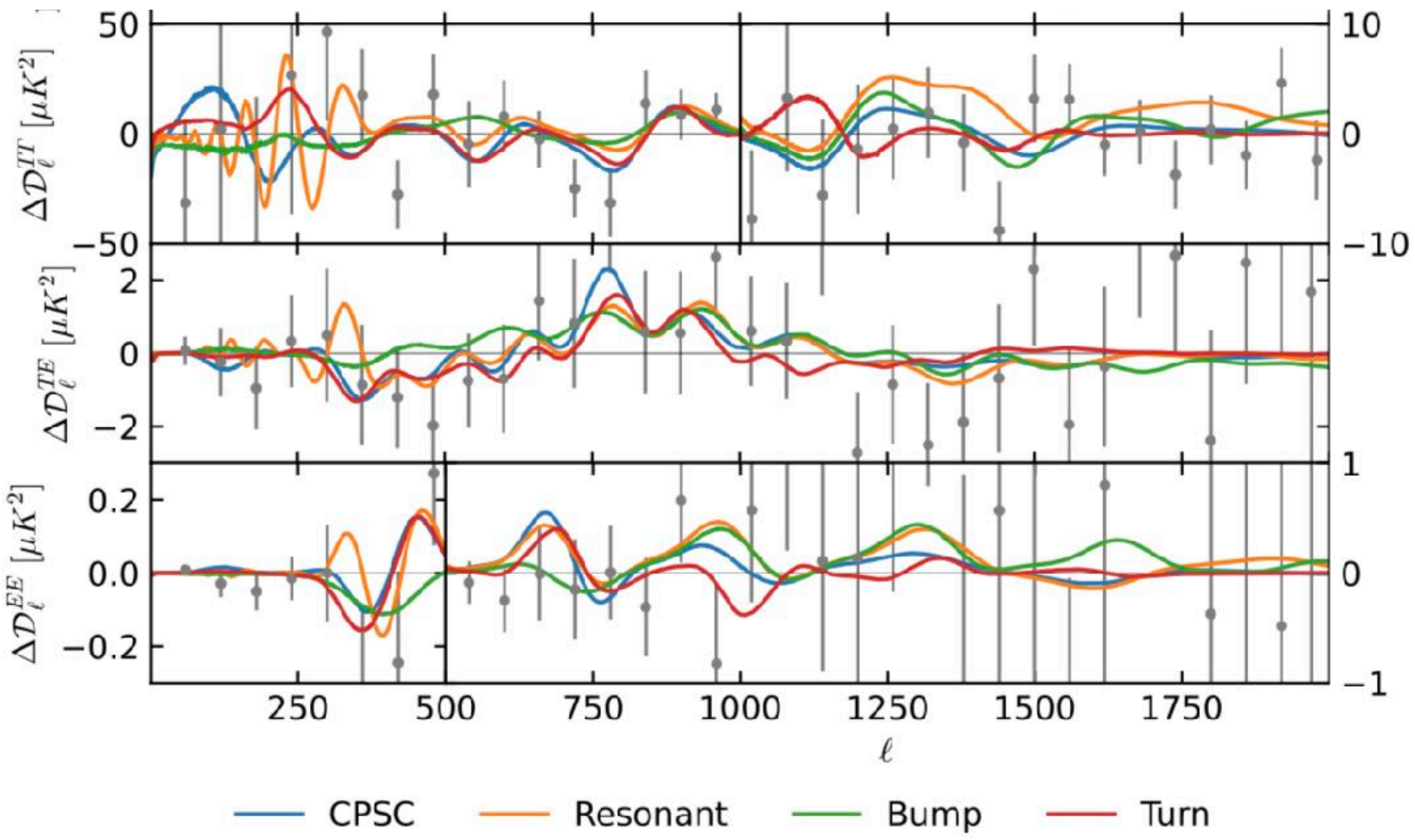


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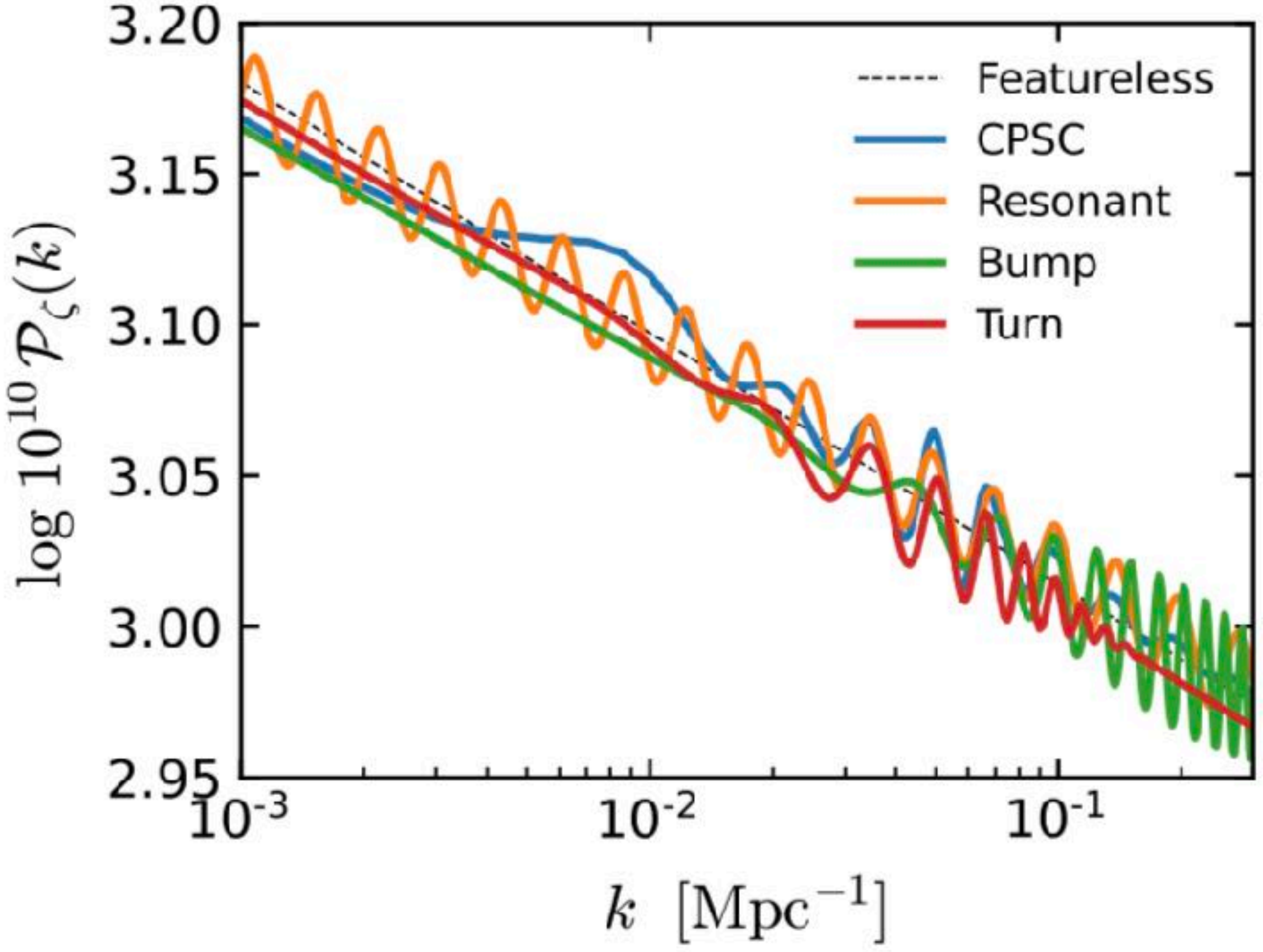


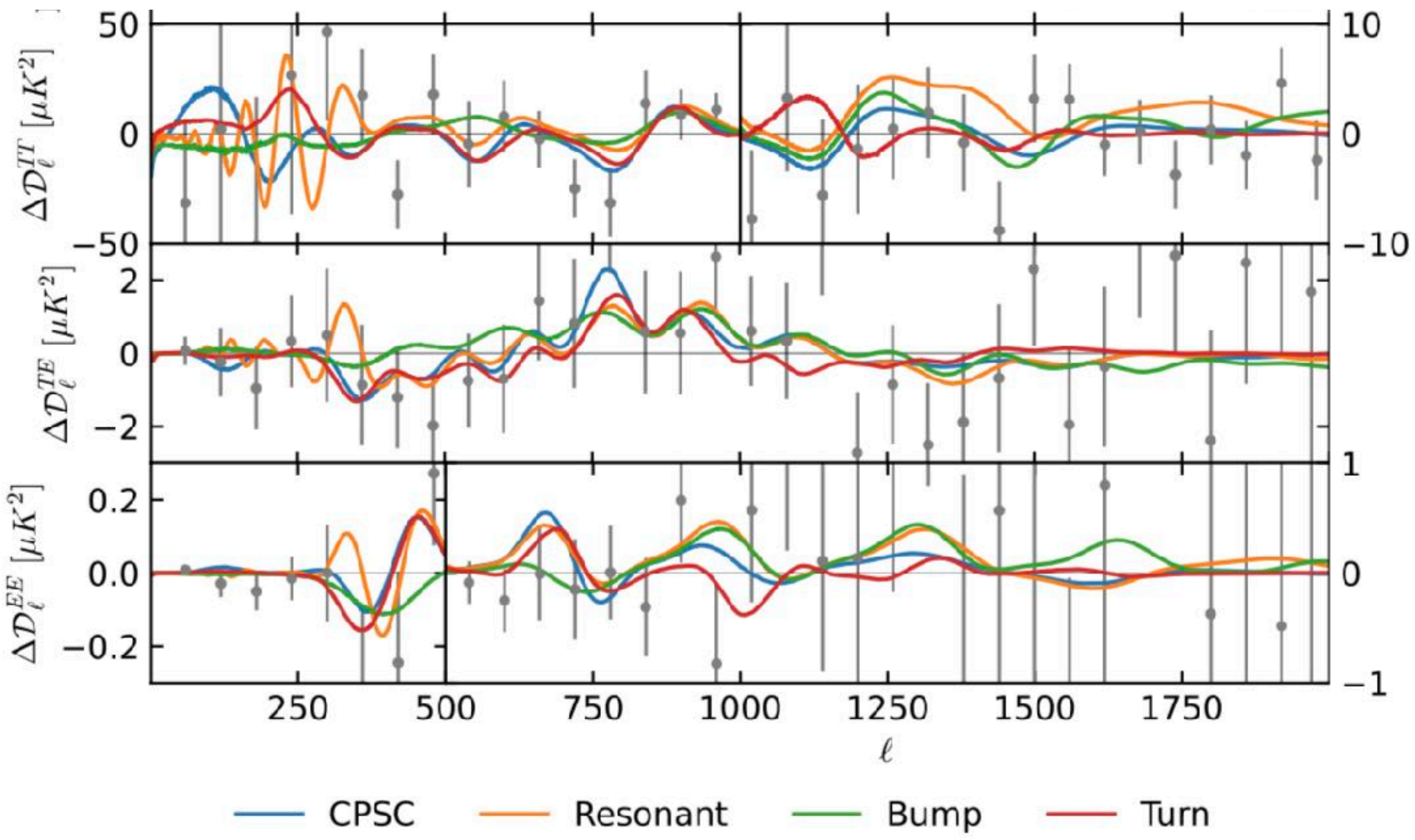


No statistical evidence, *only hints*, but this time the improvement to the fit is substantial.

| | CPSC | Resonant | Bump | Turn |
|---|---|---|---|---|
| $\ln B$ | $-1.2 \pm 0.36$ | $-2.24 \pm 0.38$ | $-1.44 \pm 0.36$ | $-2.31 \pm 0.36$ |
| $\Delta\chi^2$ | 13.4 | 10.9 | 8.9 | 8.6 |

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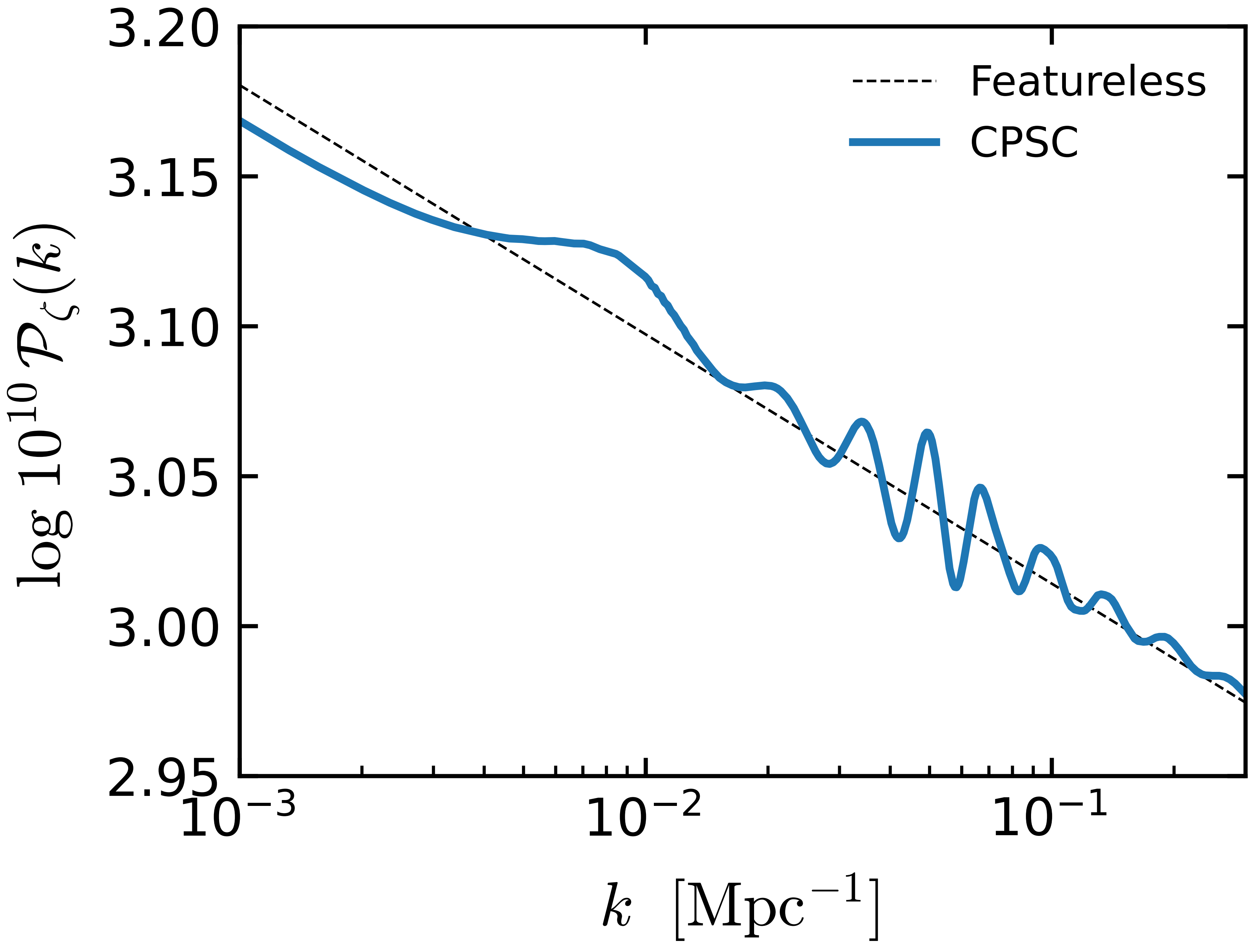


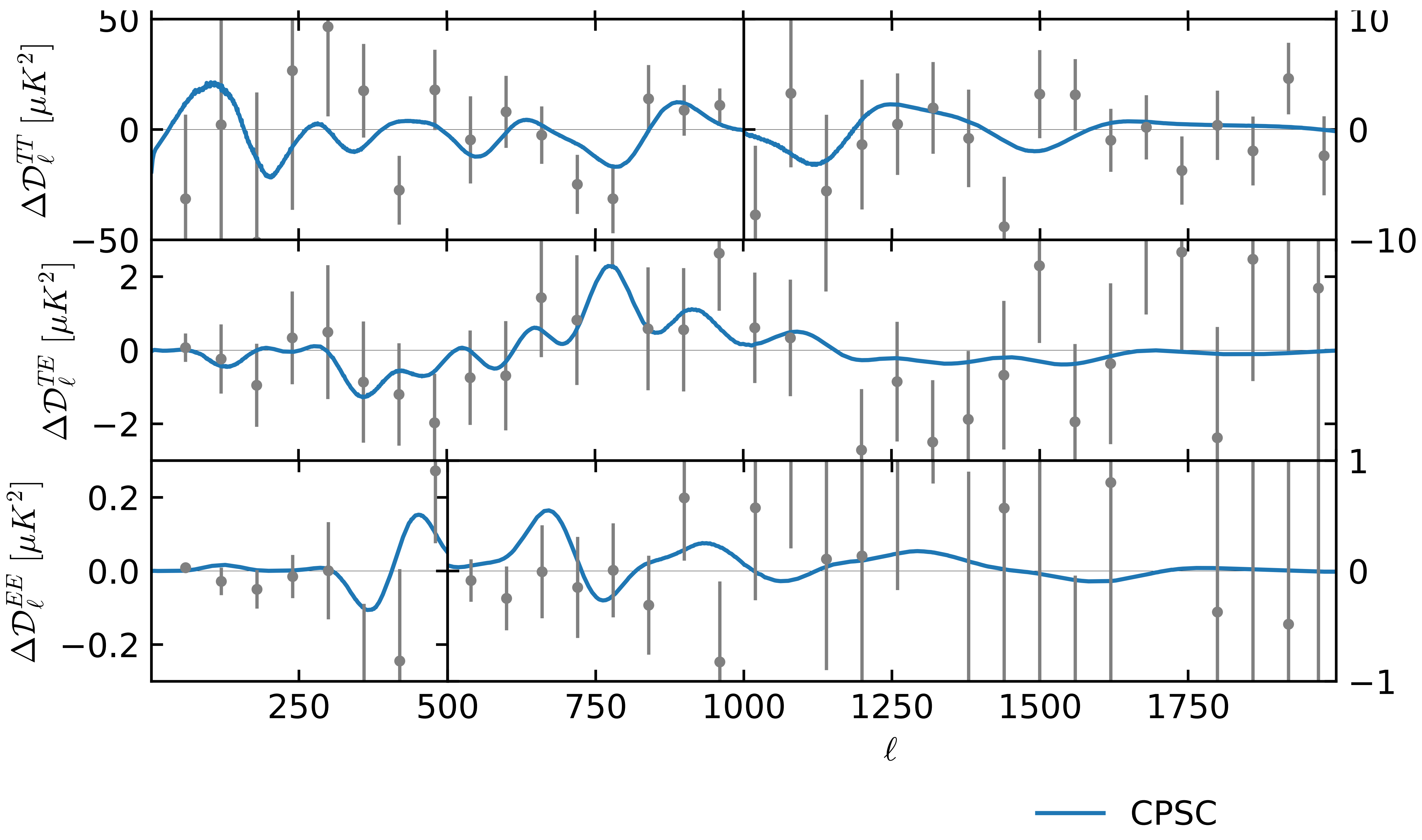


The *CPSC model* is the best fit. Planck data hint at a heavy field oscillating with mass $m_\sigma/H \approx 18$.

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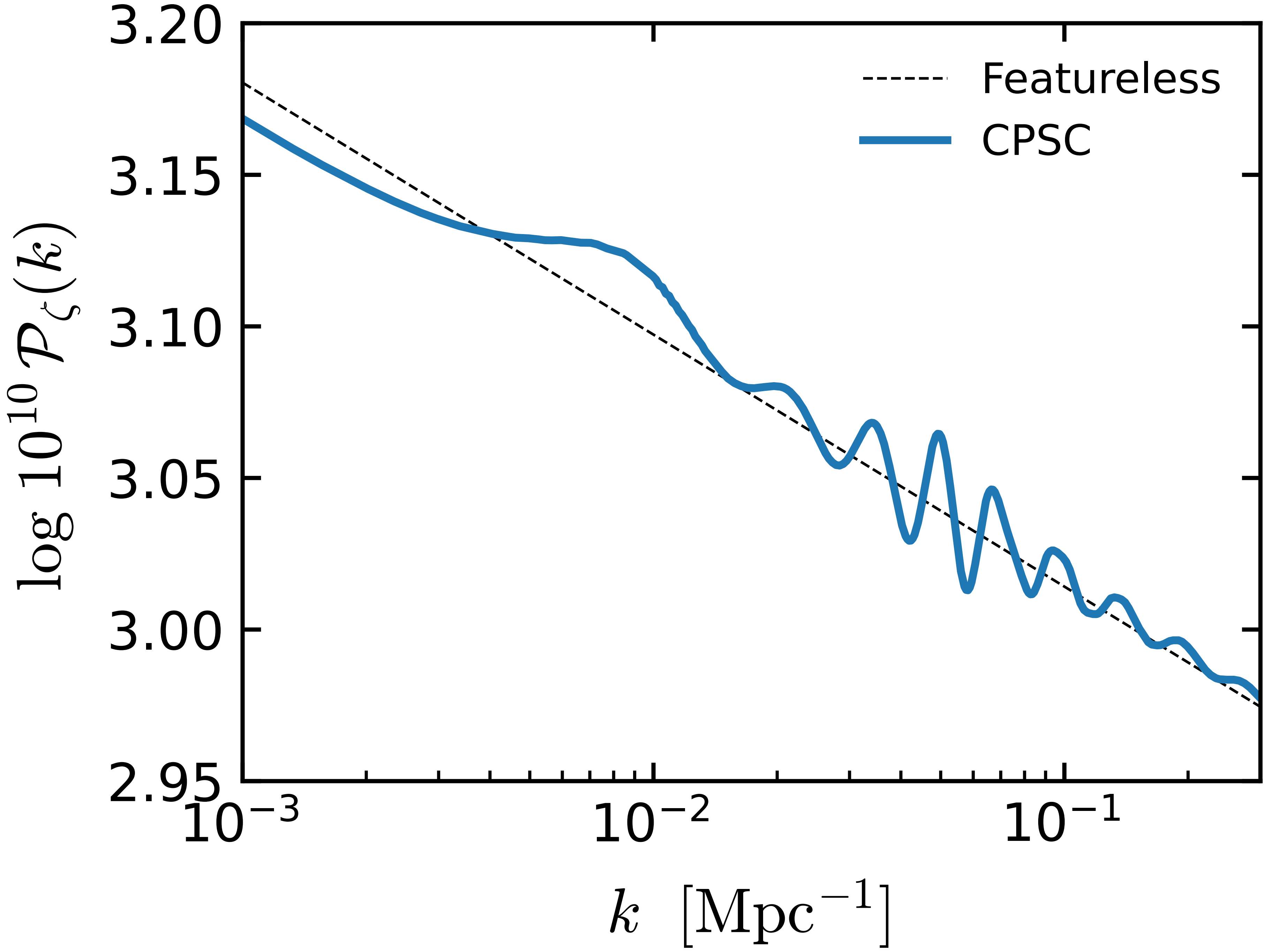
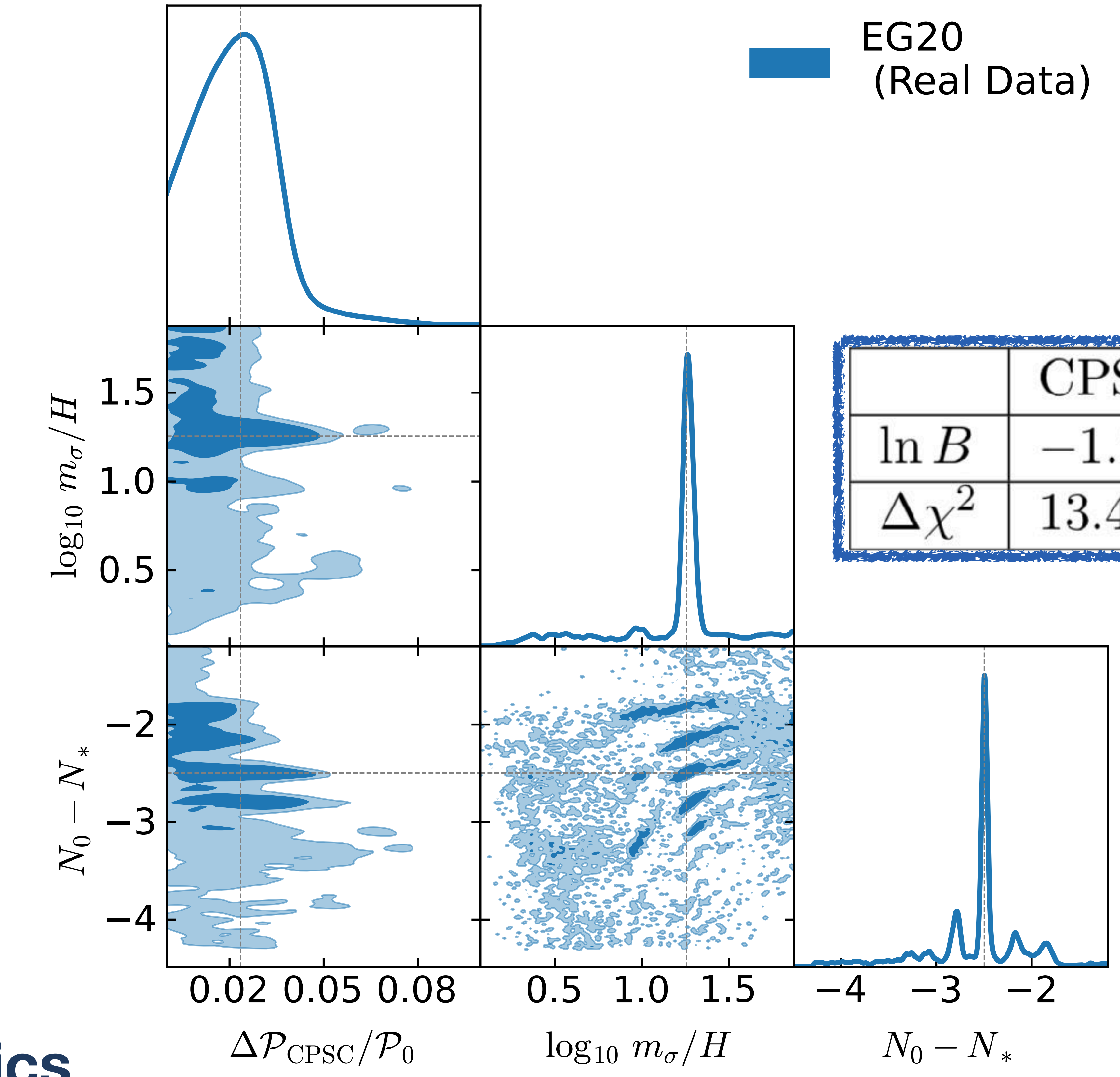
# Hints, not evidence

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Several feature models improve the fit, and hint at **interesting physics**, but Bayesian model comparison penalizes extra parameters, and **no candidate is a compelling detection**.

The right question is: **Can future data detect or rule out these signals?**

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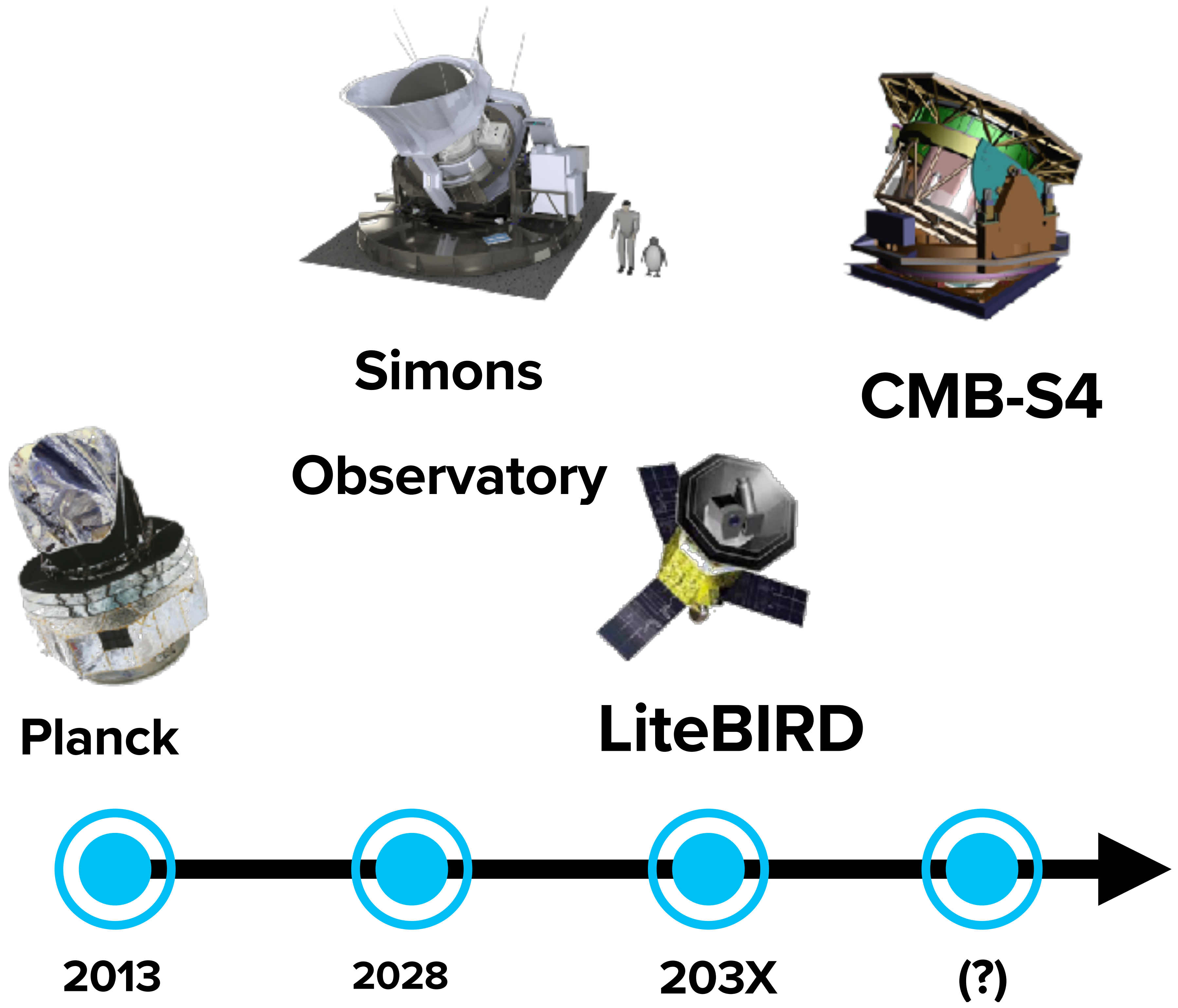
# Polarization as a detector for primordial features

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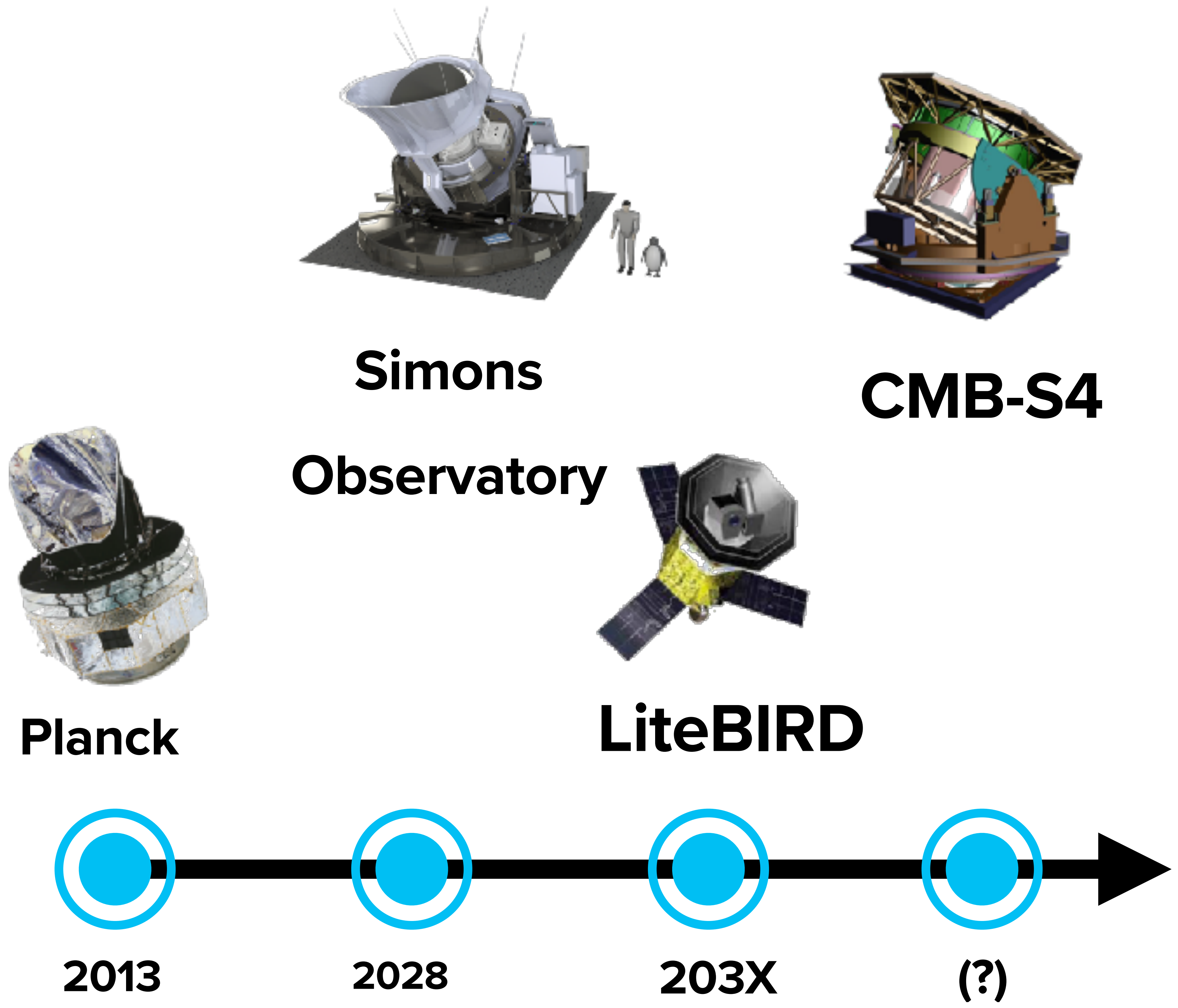


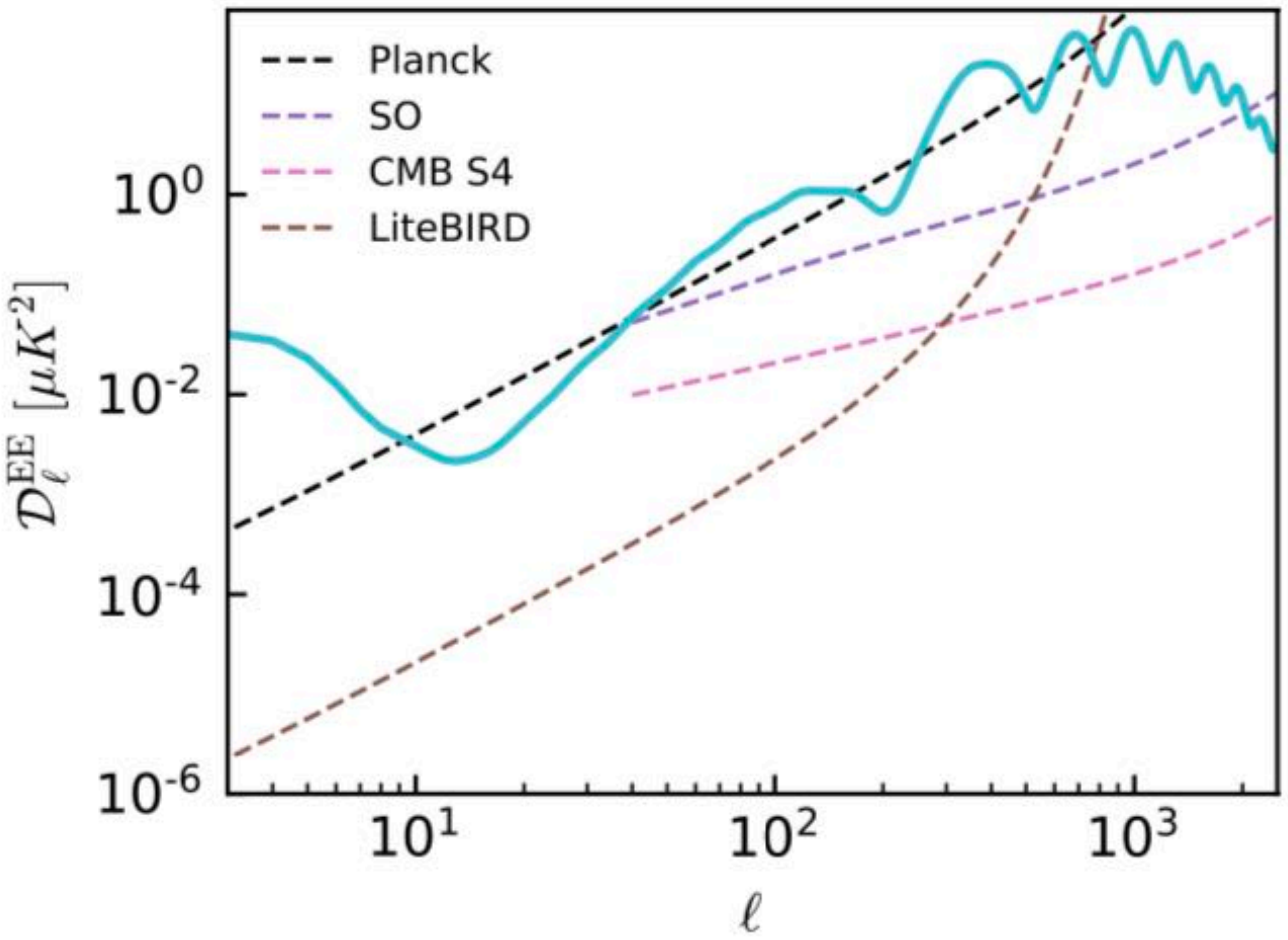


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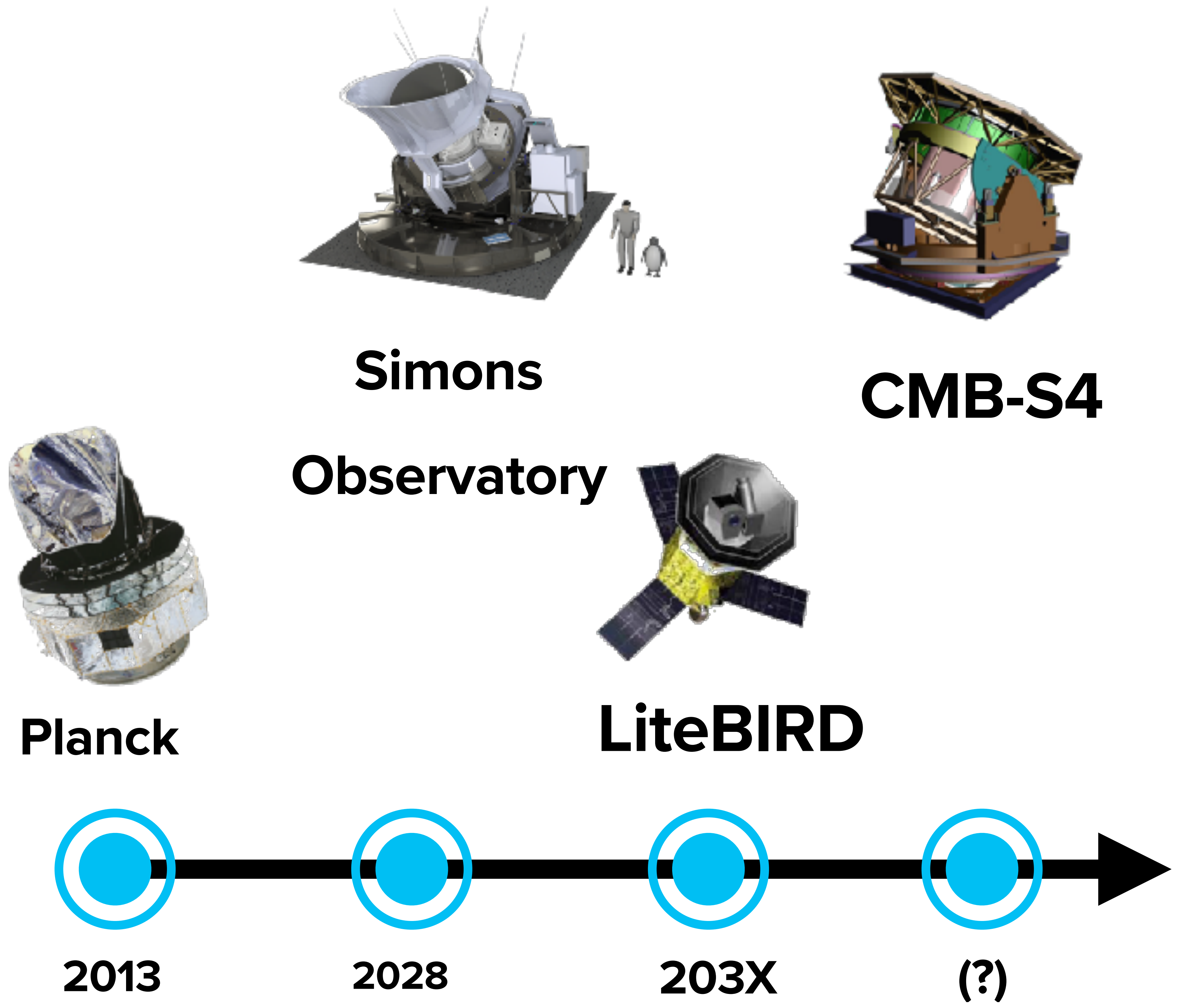


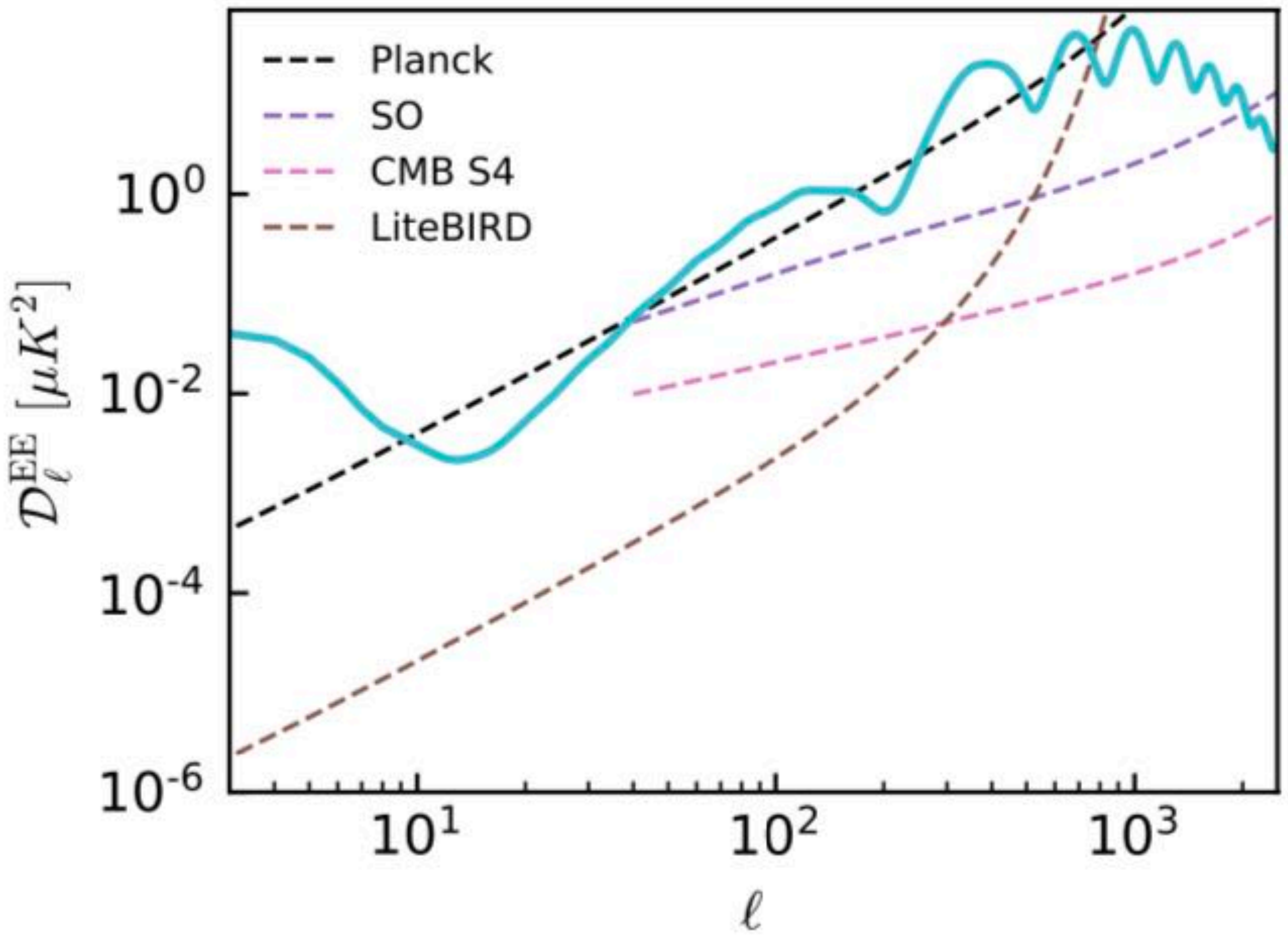


Future CMB experiments will increase the sensitivity to CMB polarization. E-modes are a better detector for primordial features due to sharper transfer functions than T-modes.

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# Polarization as a detector for primordial features

If the best-fit is **real**

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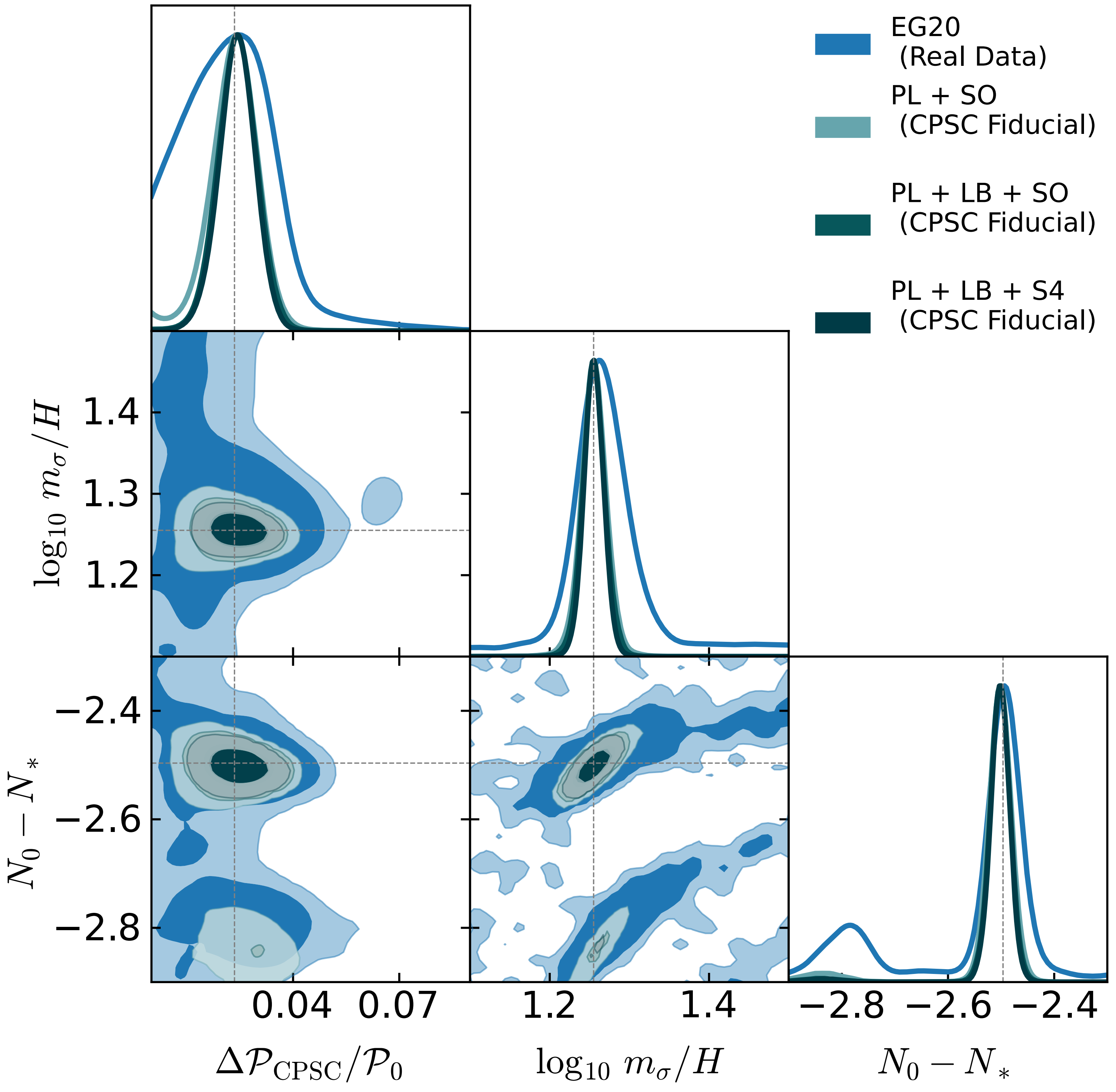


The best-fit can be **detected at** $\sim 5\sigma$ with an experiment like CMB-S4. This would imply a massive field oscillating with

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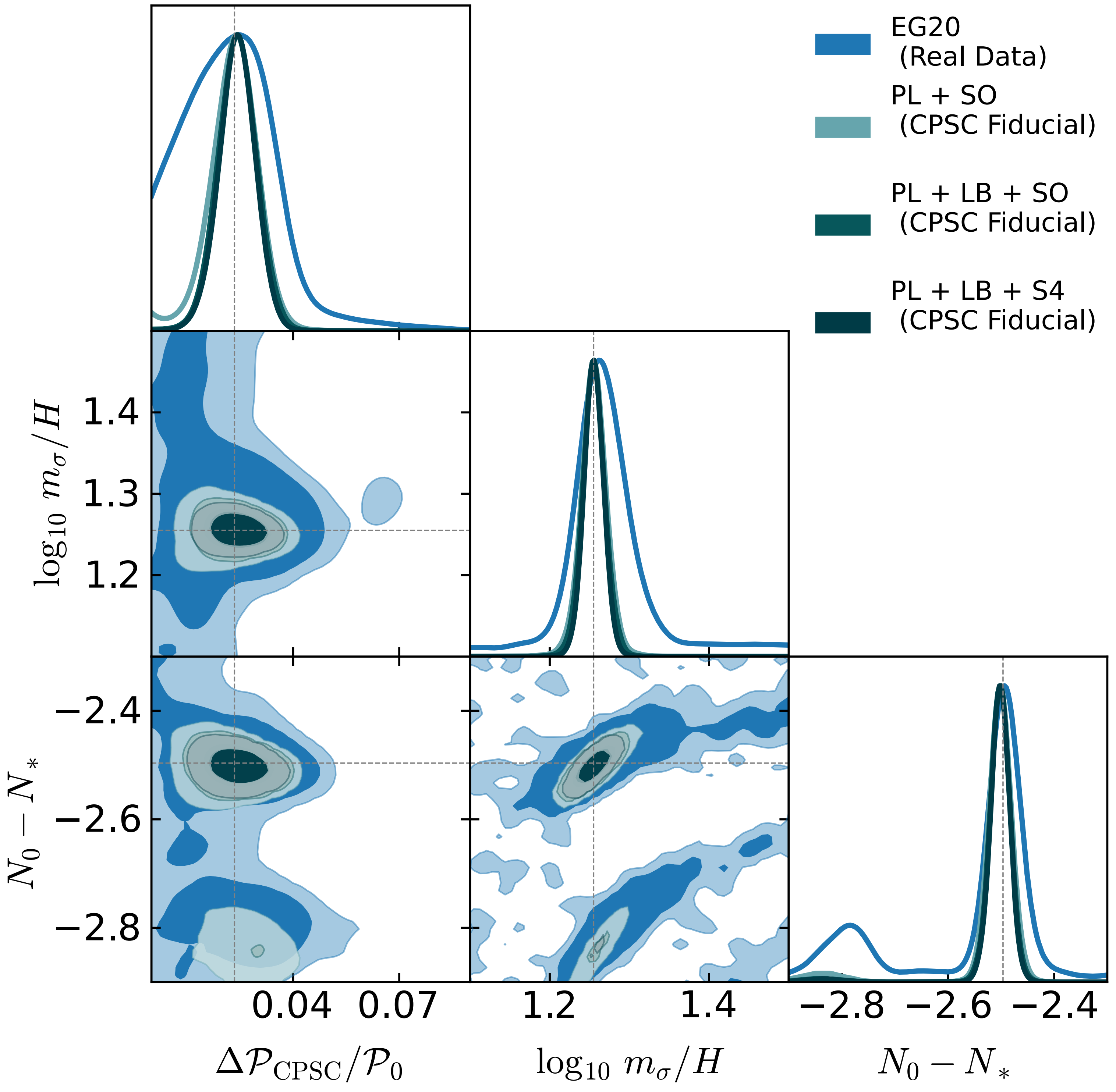


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If it is a **statistical fluke**

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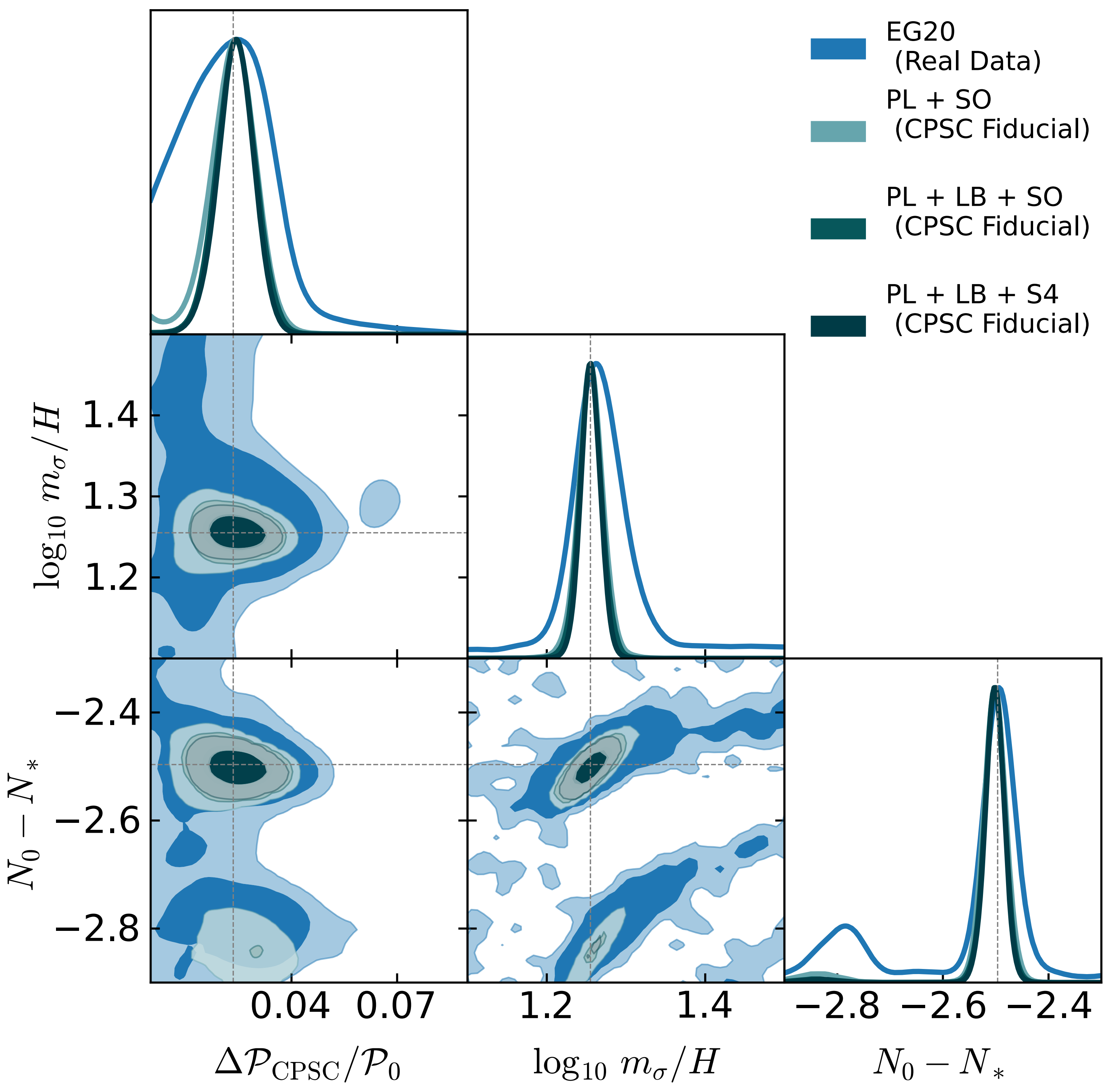


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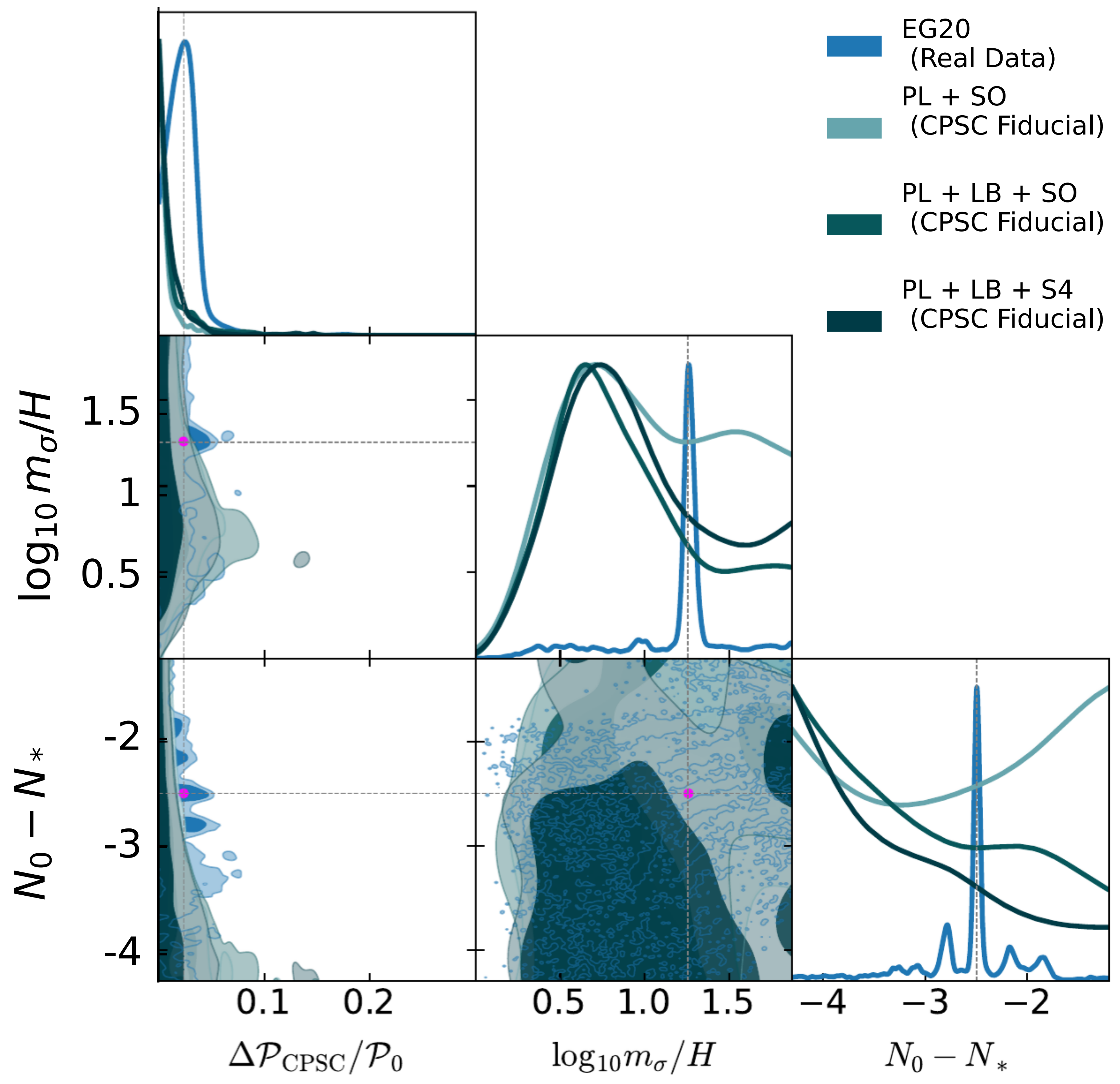


The best-fit can be **ruled out**, though with a less strong statistical significance.

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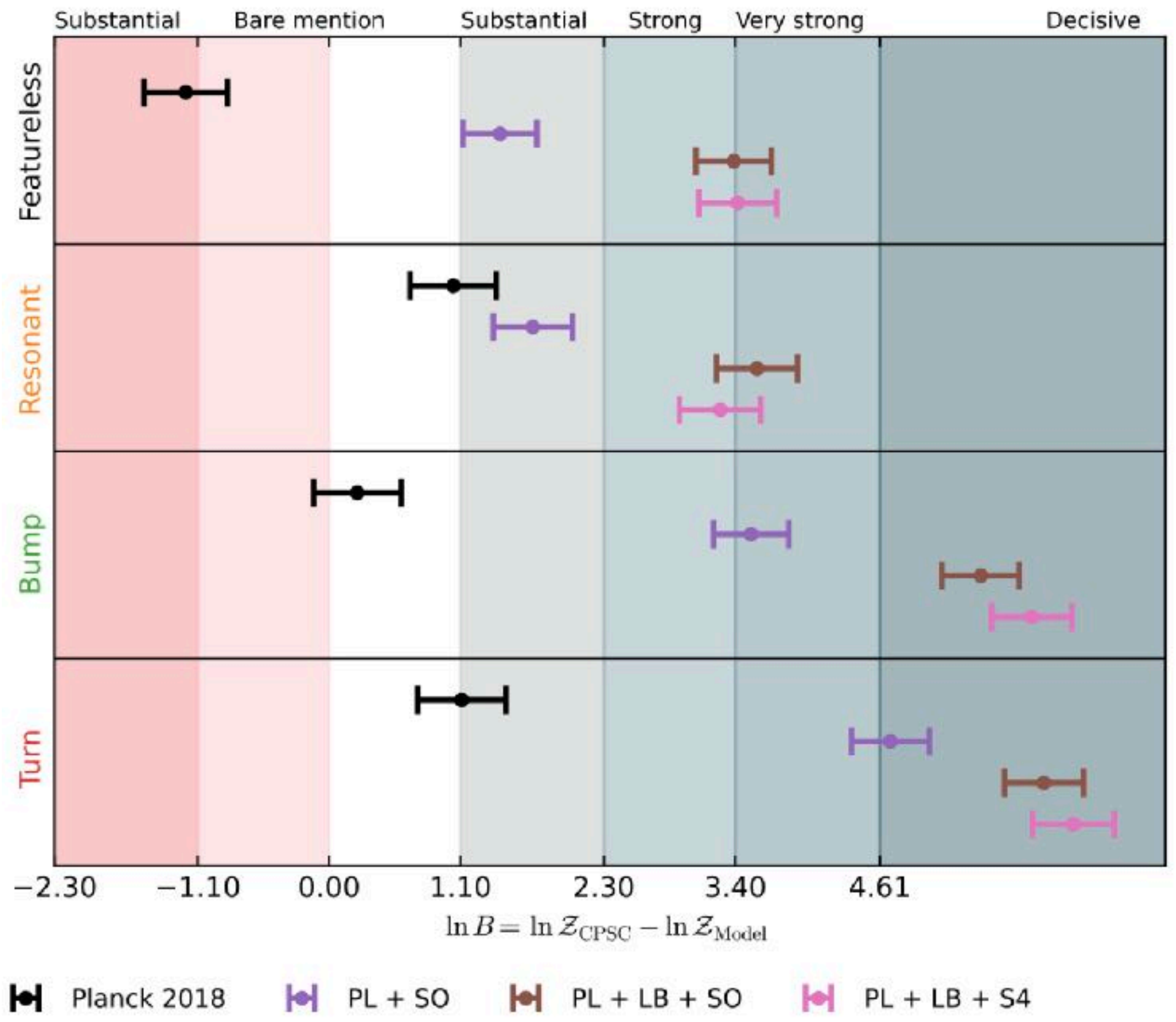
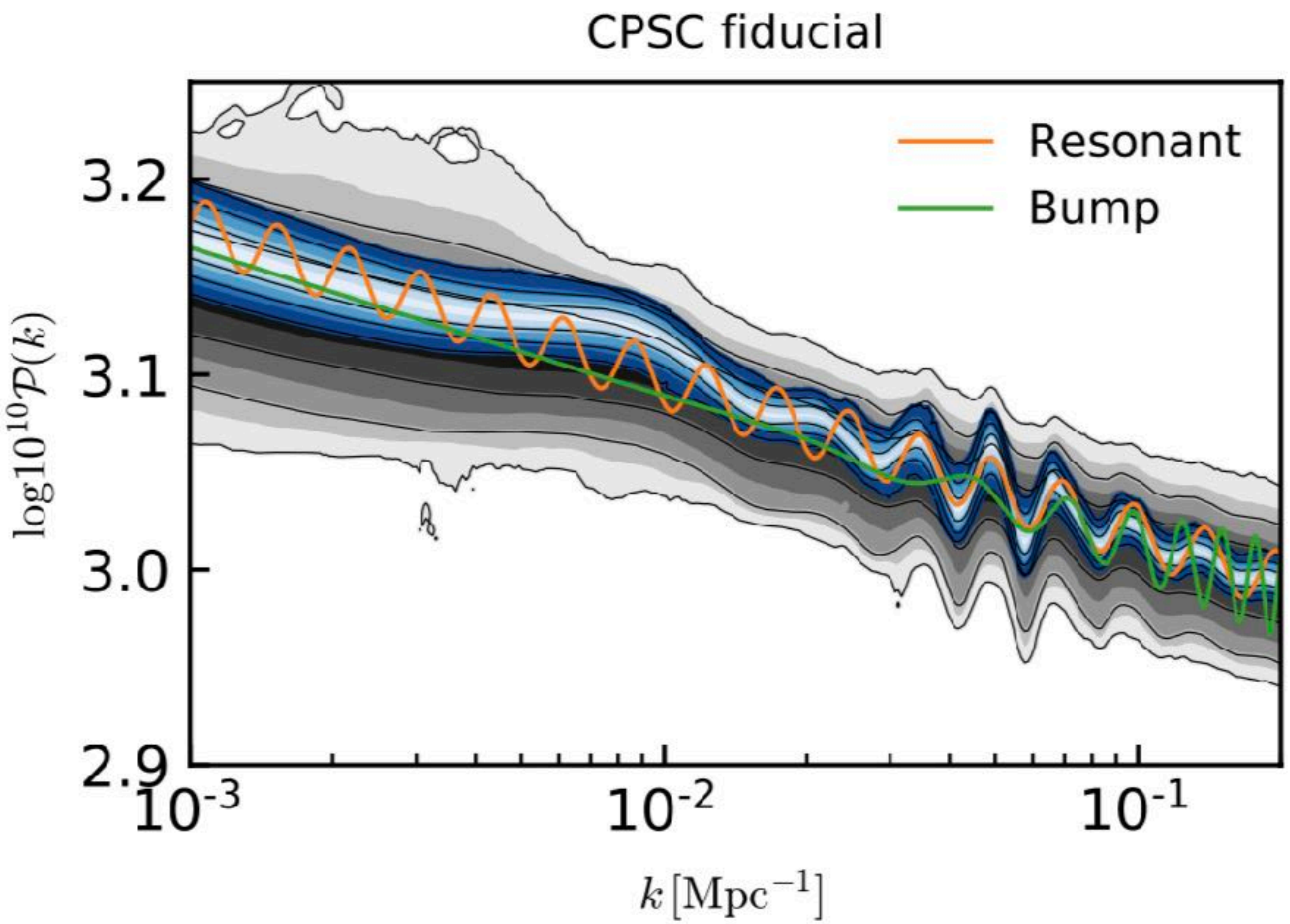
# Not just detection, model selection




If the CPSC is the true model of the Universe, other feature models—as well as single-field slow-roll—will be ruled out with very strong to decisive statistical significance.

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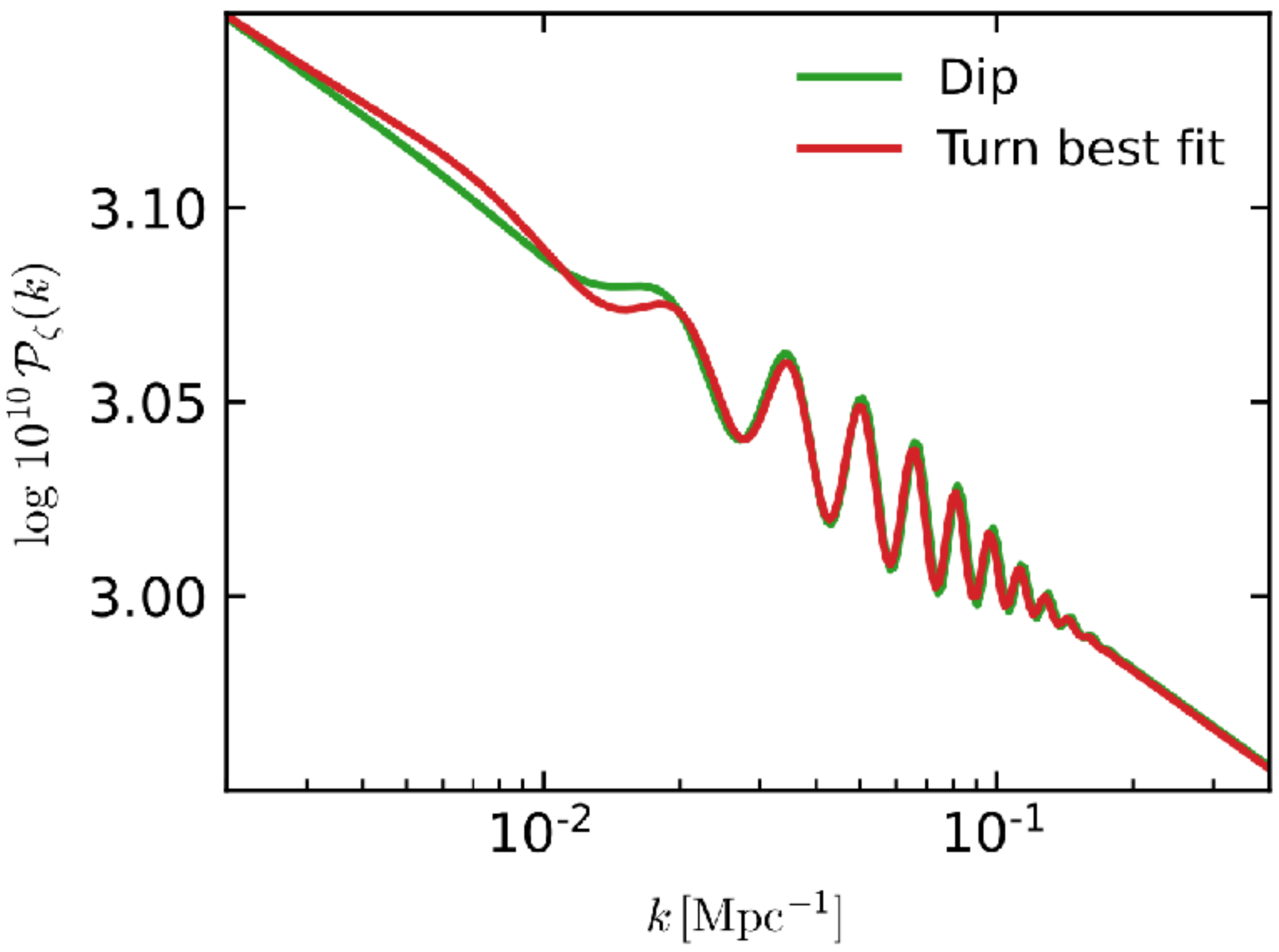
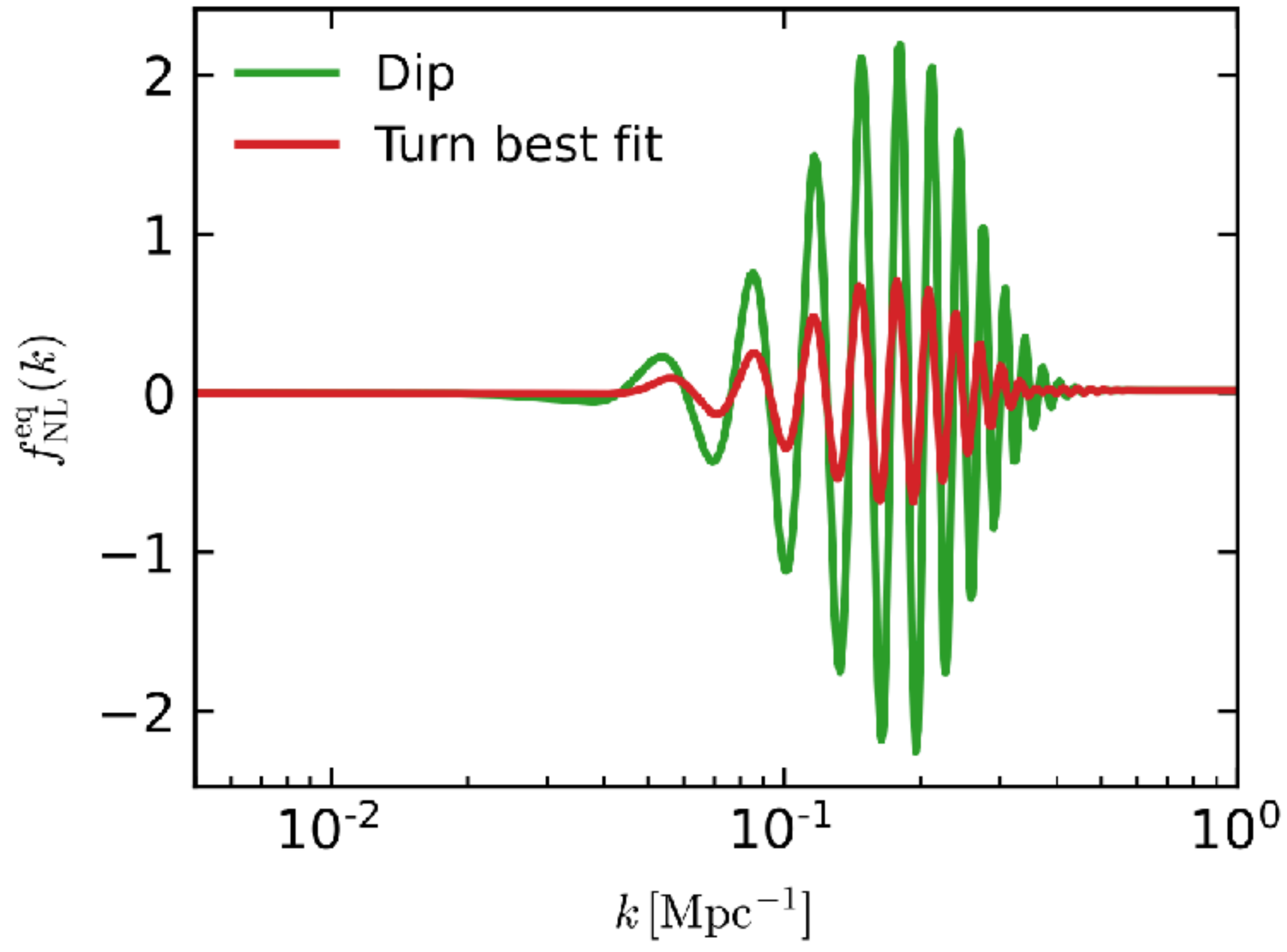
# Breaking degeneracies with PNGs




Some models can predict similar features in the power spectrum. In that case PNGs could break degeneracies.

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# Can we fake primordial features?

$$\underset{\text{late time}}{\delta C_\ell} = \int \mathrm{d}\ln k \;\; \mathscr{P}(k) \;\; \underset{\text{late time}}{\delta T_\ell(k)}$$

$$\underset{\text{primordial}}{\delta C_\ell} = \int \mathrm{d}\ln k \;\; \underset{\text{primordial}}{\delta \mathscr{P}(k)} \;\; T_\ell(k)$$

Can these two produce the same CMB signal?

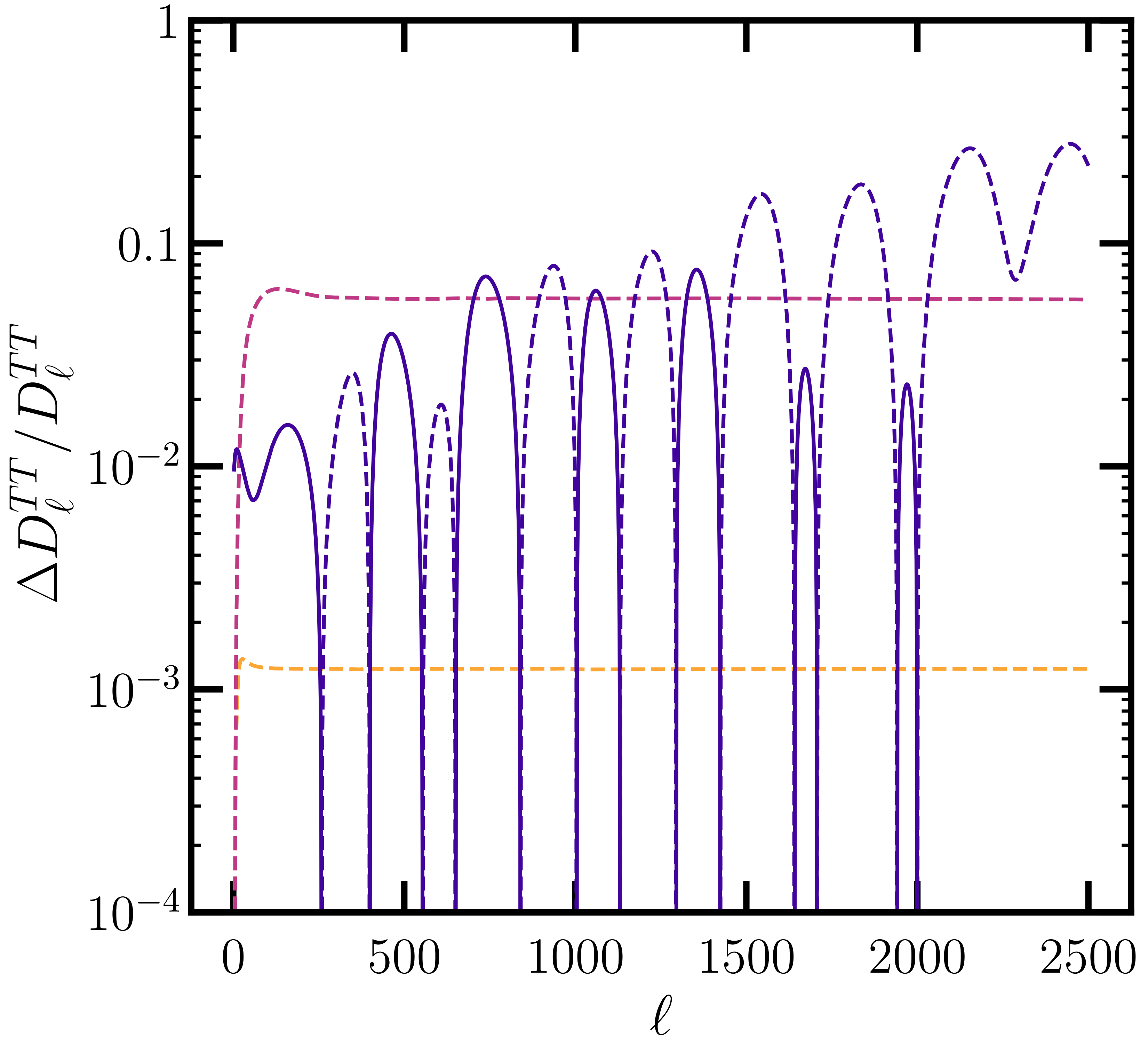
Within $\Lambda$CDM there is essentially no degeneracy, what about **exotic** physics?

Qin, **MB**, Chen, Slatyer in preparation

# Can we fake primordial features?
# Case 1: thermal and ionization history

$$\left(\frac{dE}{dVdt}\right)^{\mathrm{inj}}_{\mathrm{dec}} = \frac{\Gamma_{22}}{s} c^2 \Omega_{\mathrm{DM}} \rho_c (1+z)^3 \delta(z - z_{\mathrm{inj}})$$

Different $z_{\mathrm{inj}}$ distort the acoustic pattern differently.

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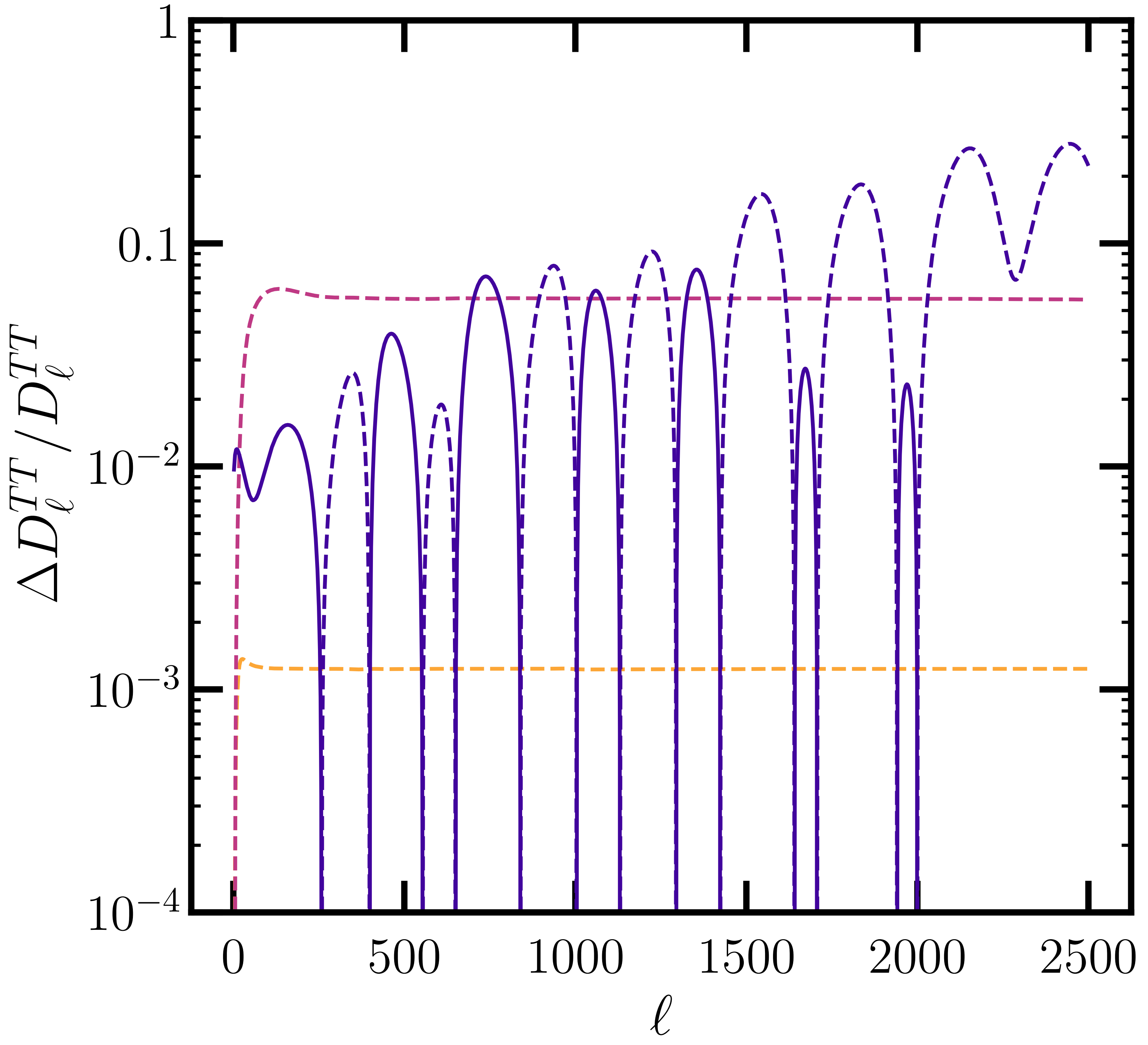
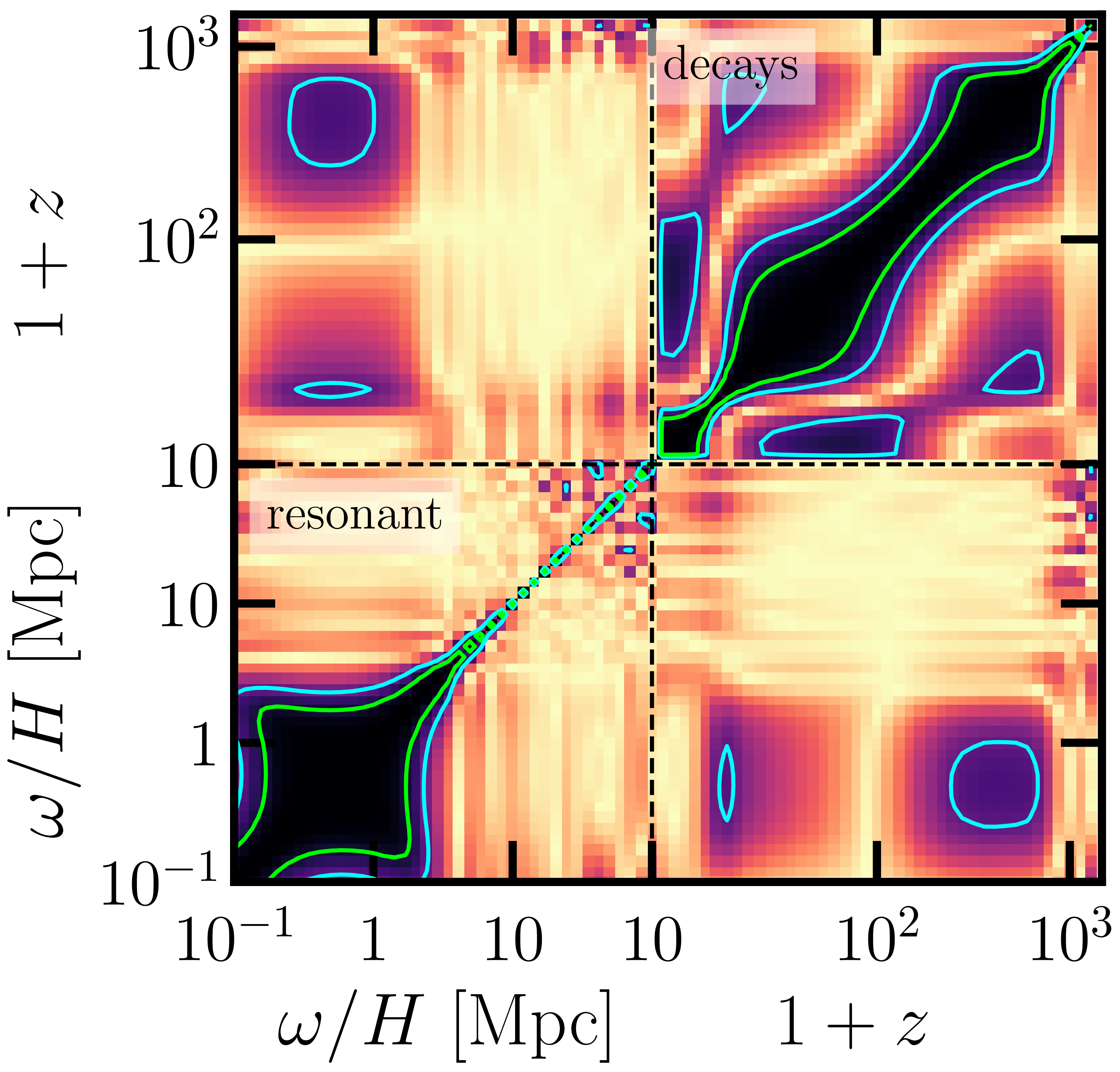



PCA: no correlation with primordial features

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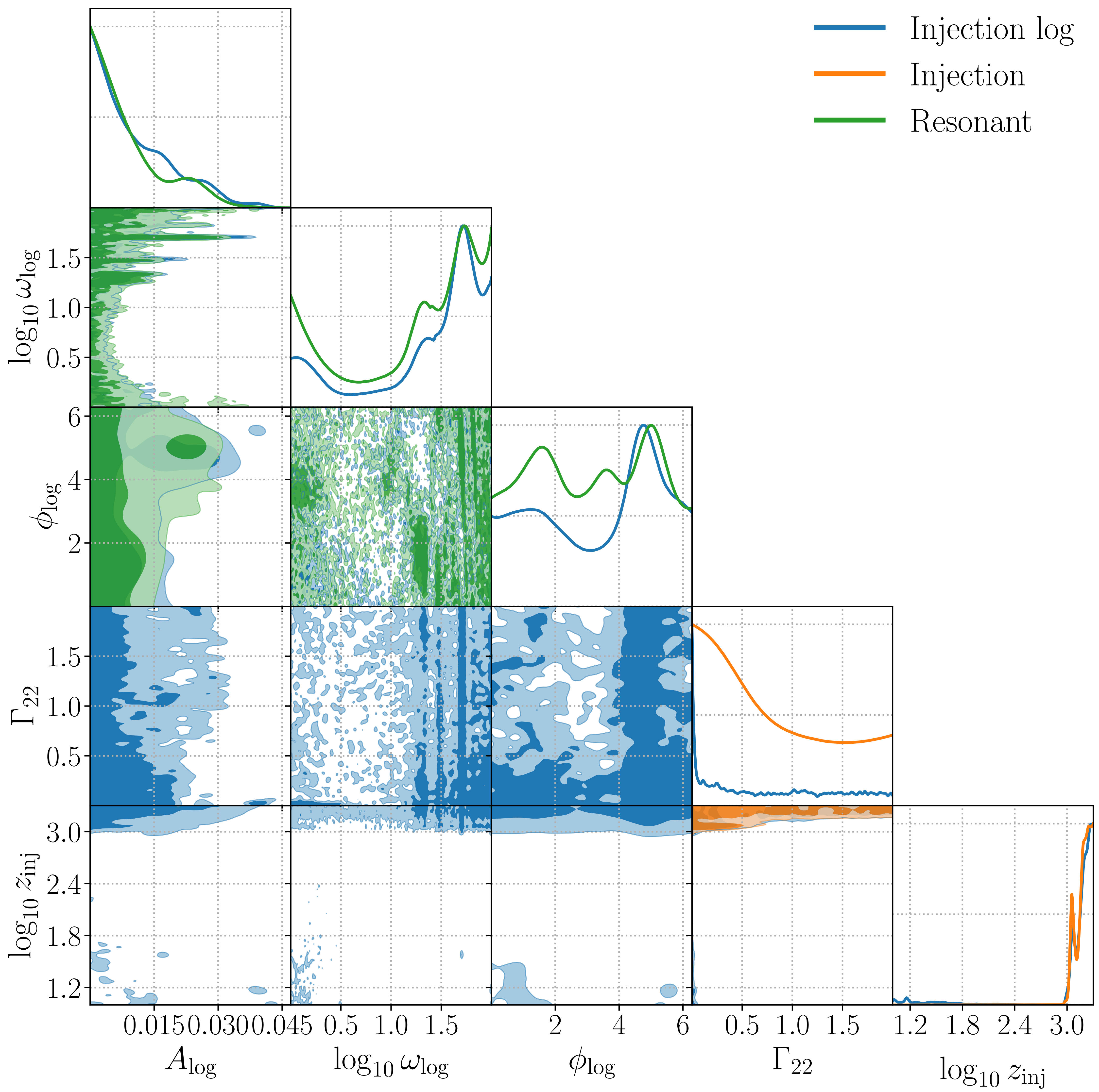
The analysis of Planck data confirms the simplified PCA. Constraints of each model's parameters are insensitive to whether the models are jointly compared to data.

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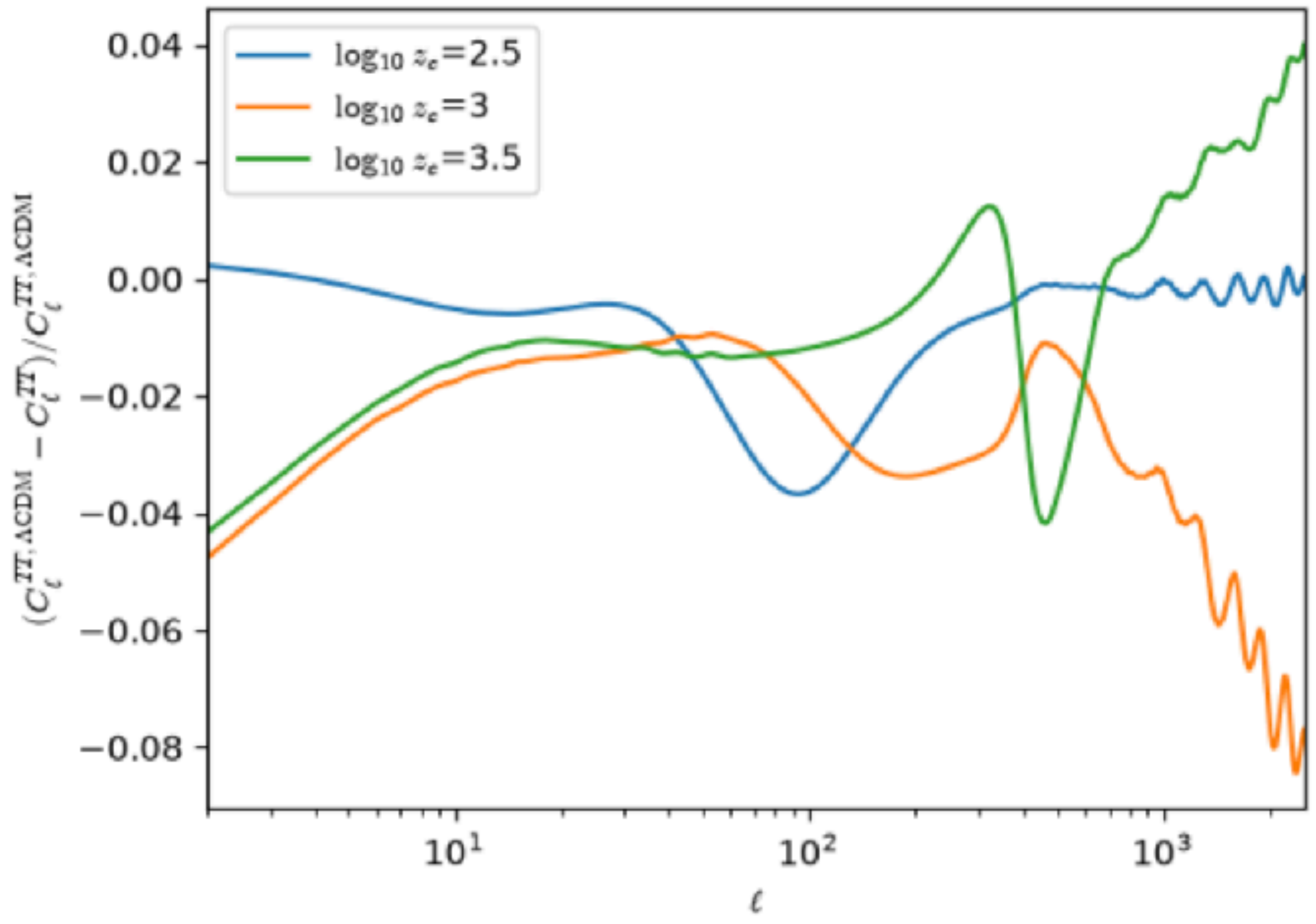
# Can we fake primordial features?
# Case 2: modified expansion history

$$w_{\rm DF}(z) = -1 + \frac{1+w_f}{2}\left[1 - \tanh\left(\frac{\ln z - \ln z_{\rm inj}}{\sigma}\right)\right]$$

Even when the expansion history produces oscillatory CMB residuals, the primordial-feature parameters remain essentially unchanged.

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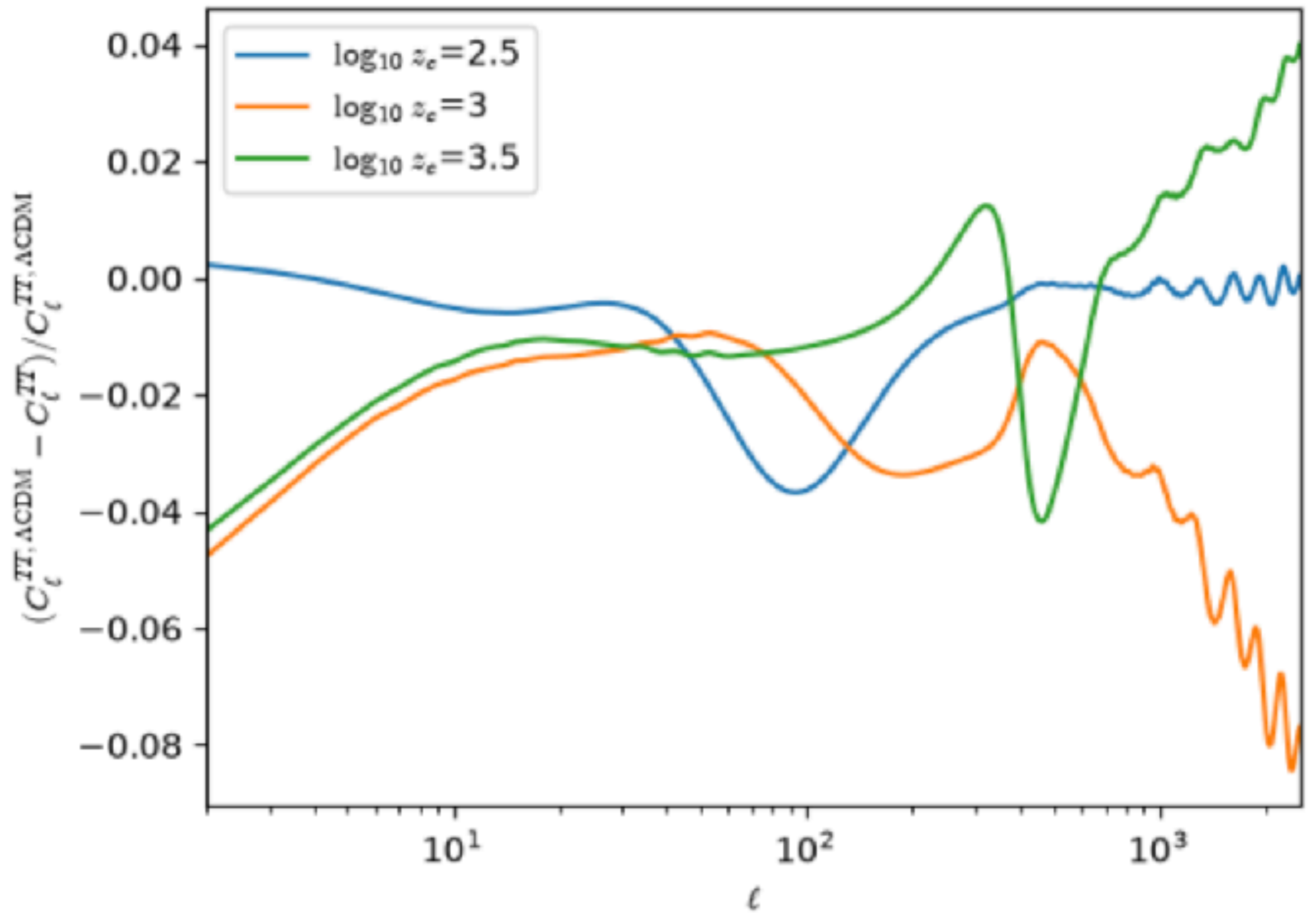


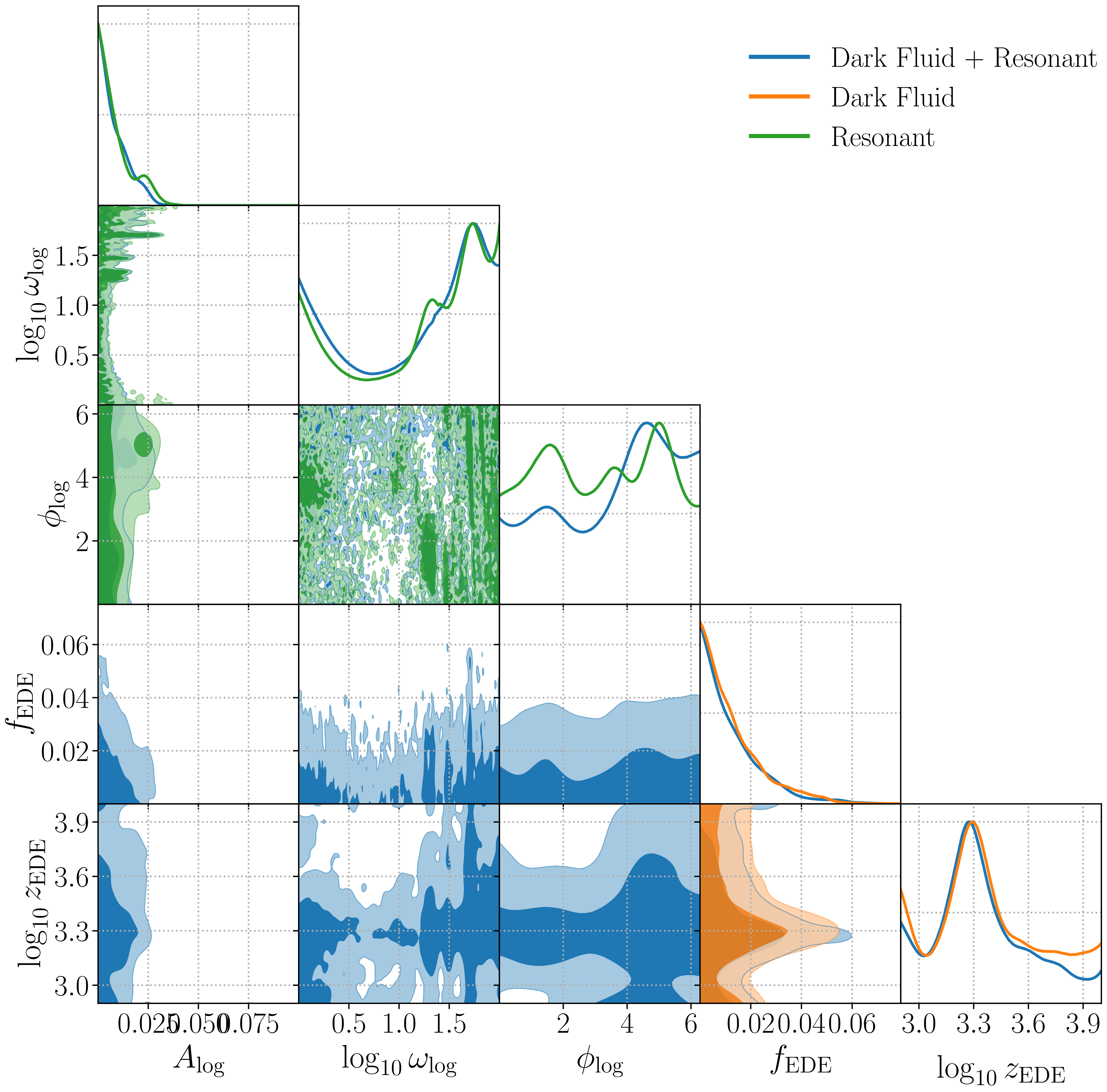


Qin, **MB**, Chen, Slatyer in preparation

# Can we fake primordial features?

$$\underset{\text{late time}}{\delta C_\ell} = \int \mathrm{d}\ln k \;\; \mathscr{P}(k) \;\; \underset{\text{late time}}{\delta T_\ell(k)}$$

$$\underset{\text{primordial}}{\delta C_\ell} = \int \mathrm{d}\ln k \;\; \underset{\text{primordial}}{\delta \mathscr{P}(k)} \;\; T_\ell(k)$$

Can these two produce the same CMB signal?

Different physics is processed through the CMB transfer functions in different ways.

Primordial features remain remarkably distinctive in the CMB.

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# Take-home messages

Primordial features provide a clean test of inflation and carry directly interpretable information.

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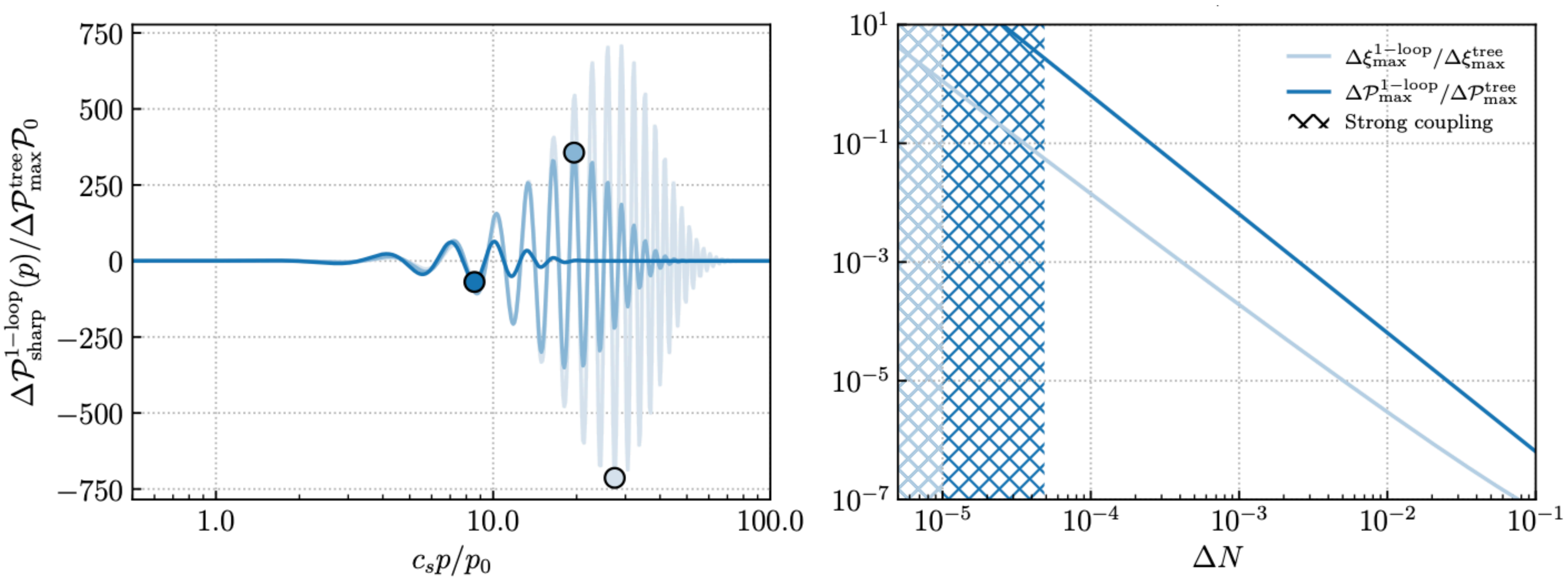
Extremely precise predictions: linear theory is very accurate, loops under control.

See **MB**, Cespedes & Pinol 2603.12216 and **Lucas' talk tomorrow**



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Hints in CMB data—many extended models widely studied without such observational support.

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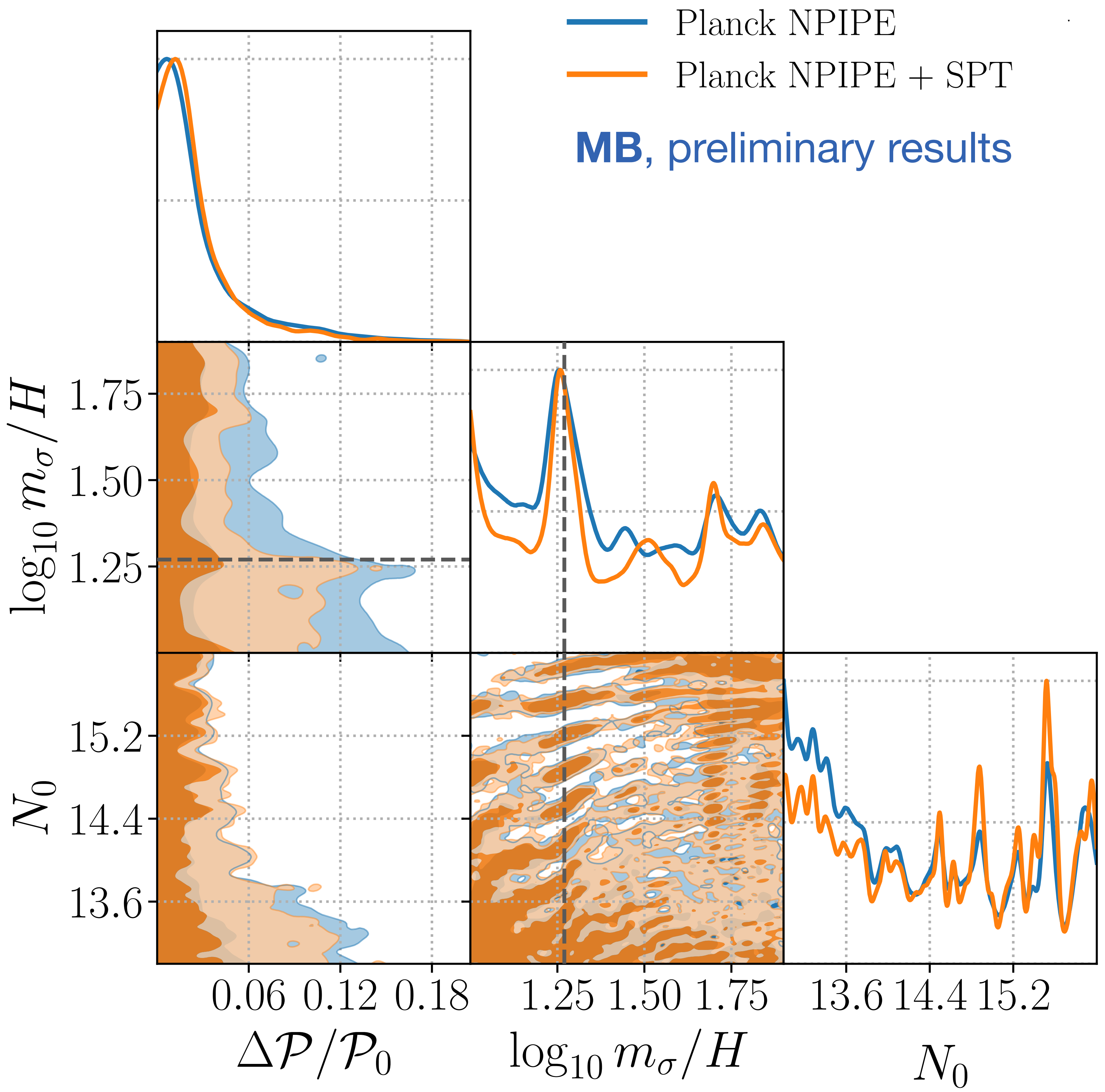

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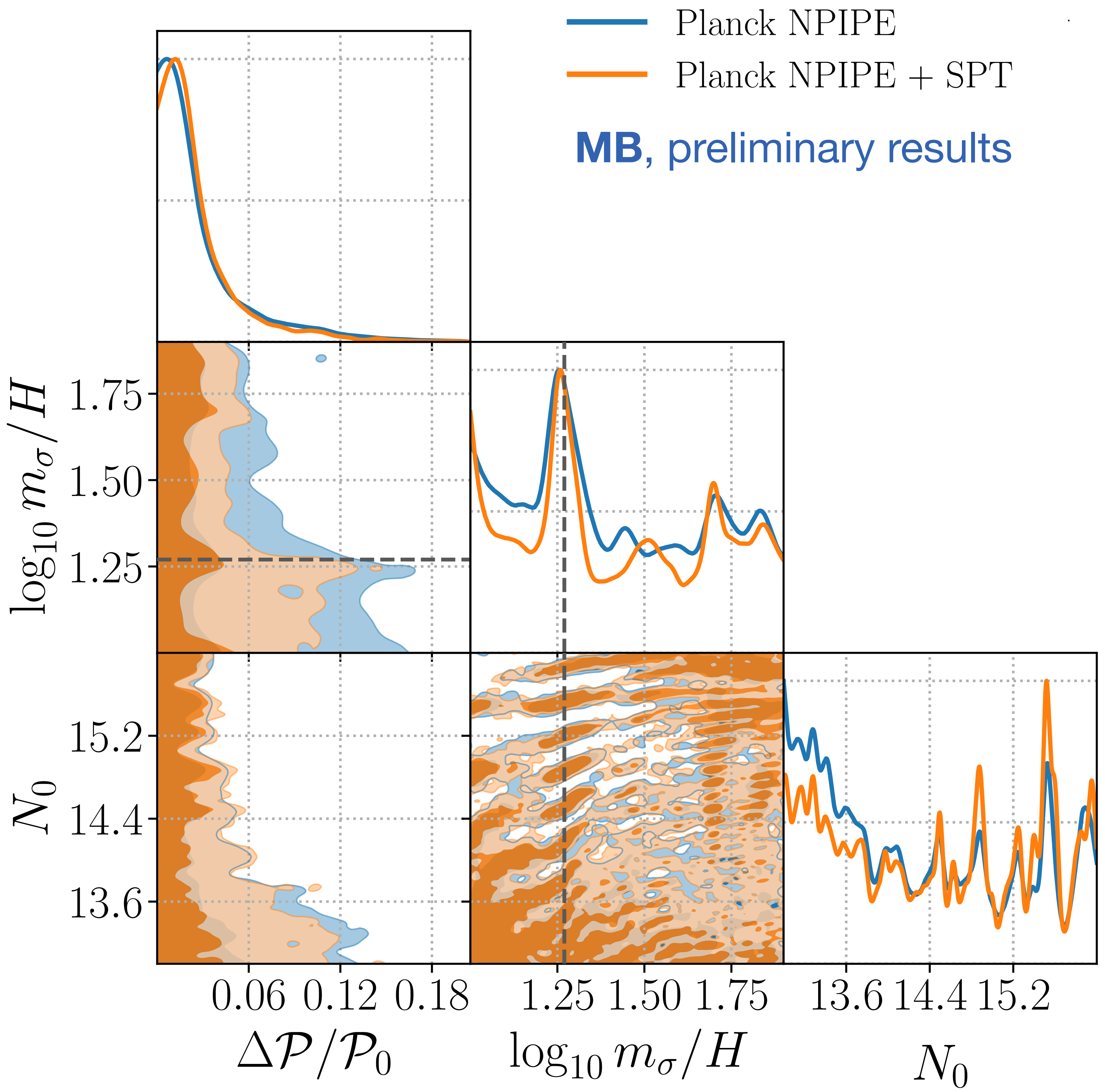

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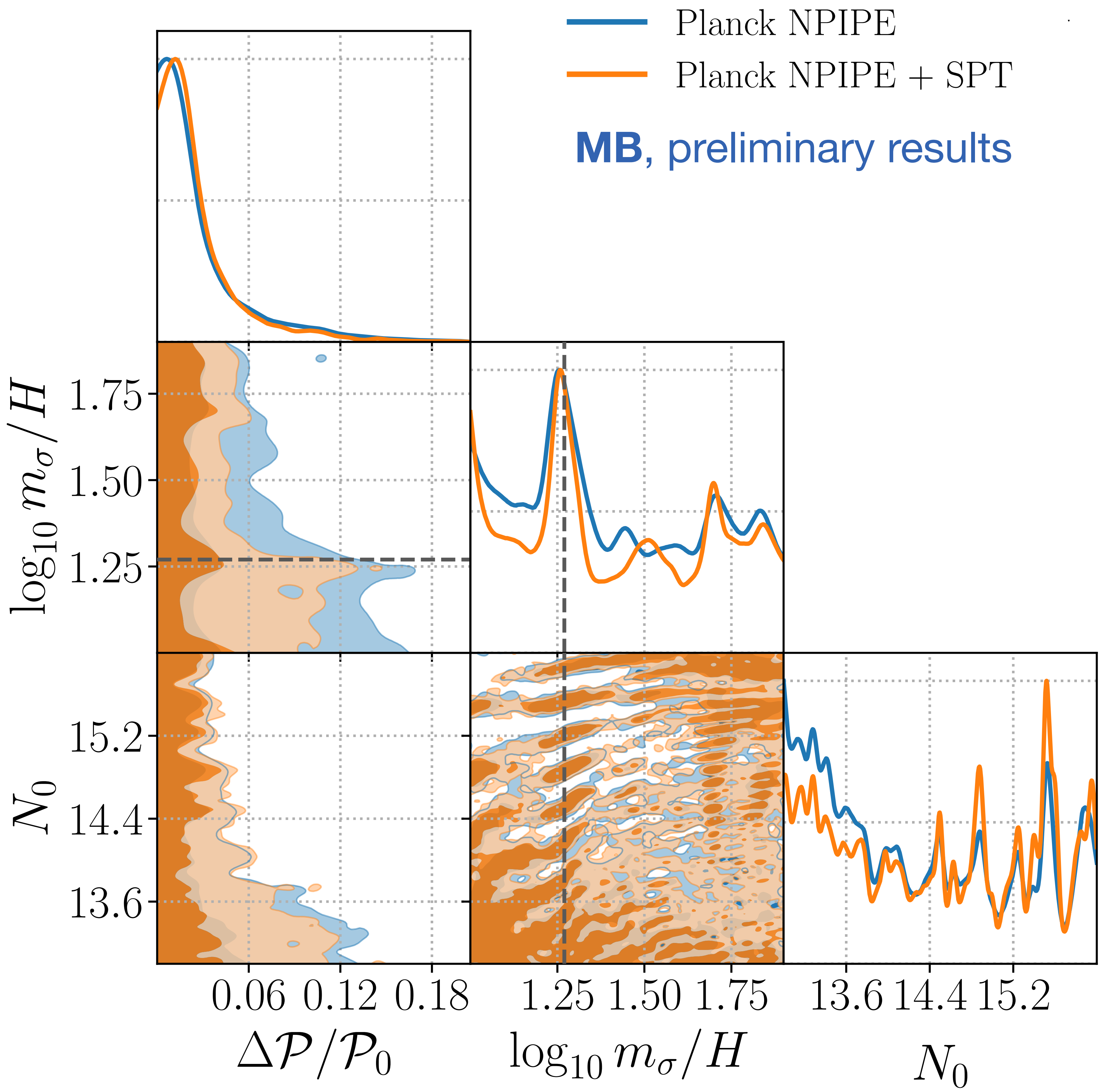

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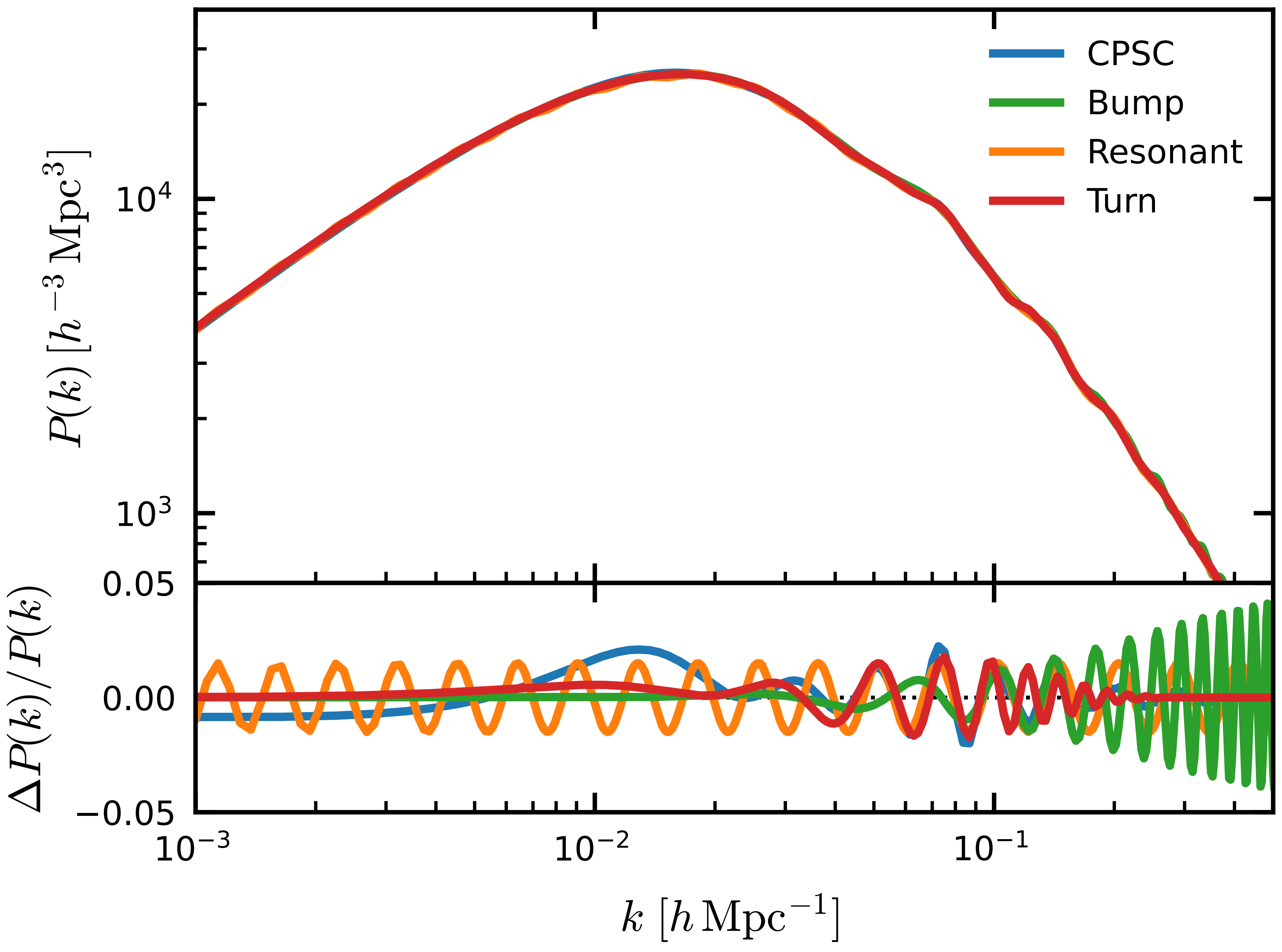

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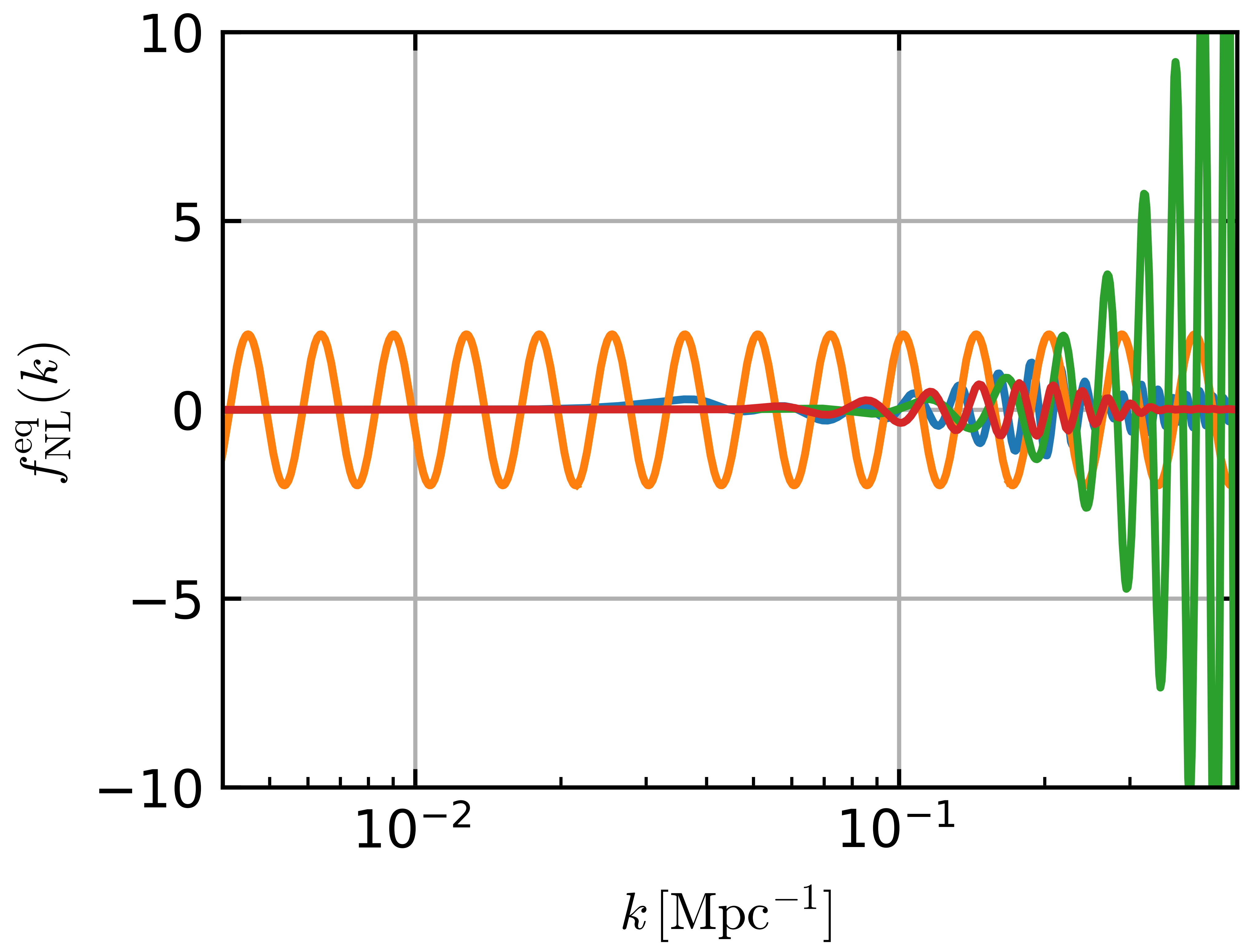
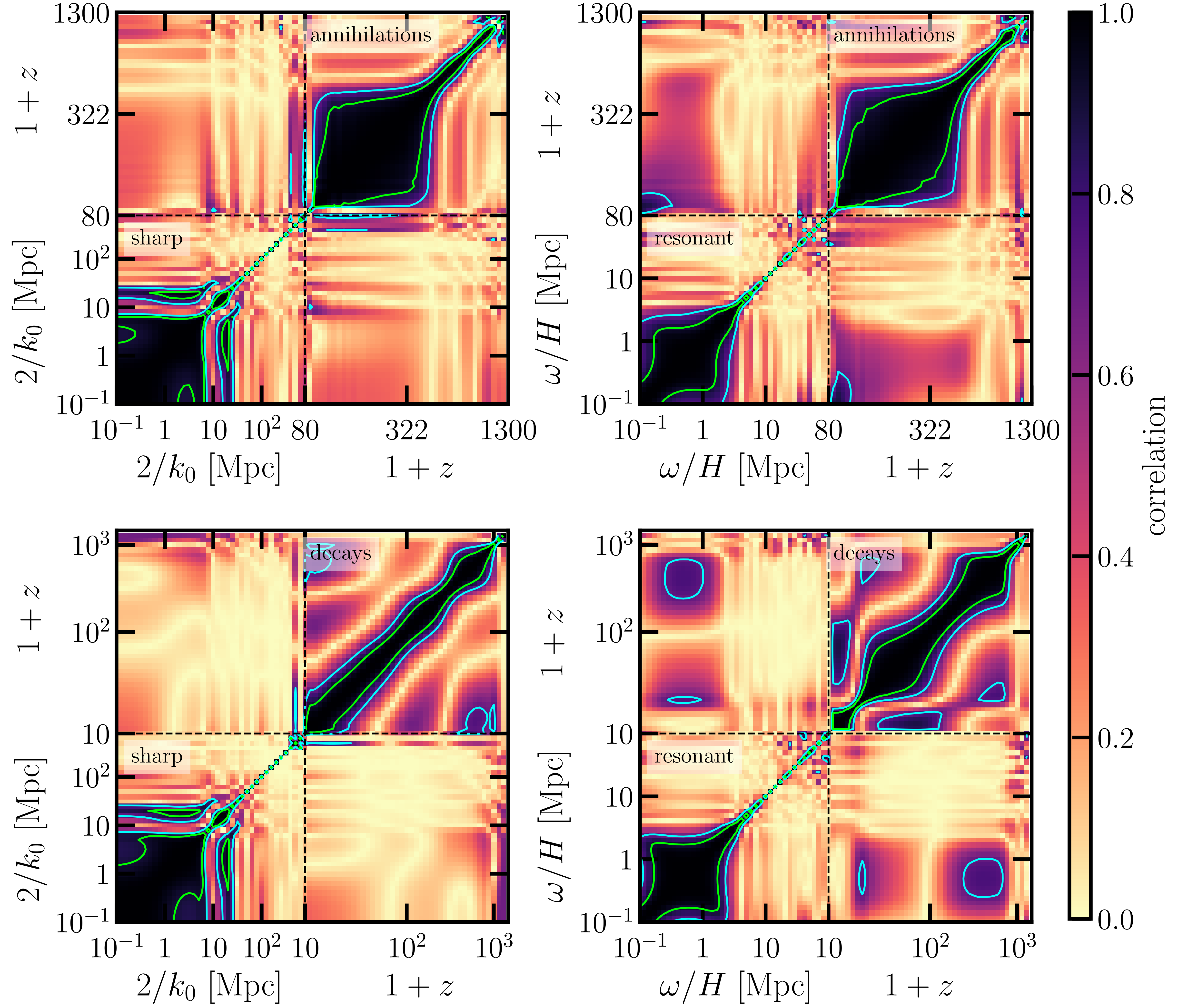
Correlated predictions in LSS…and in PNGs



# THANK YOU!

# BACKUP SLIDES

# Can we fake primordial features?
# Case 1: exotic energy injection

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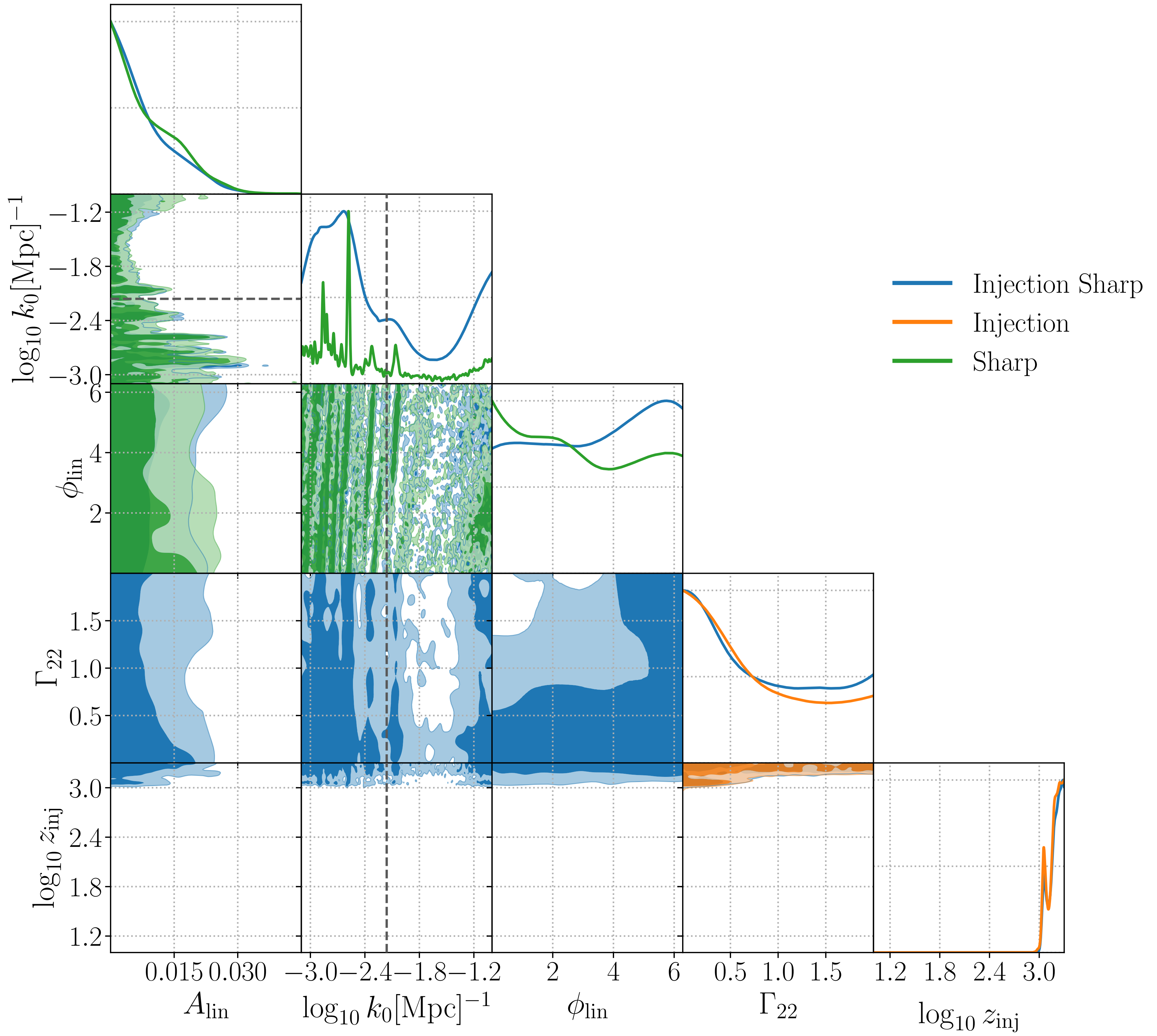
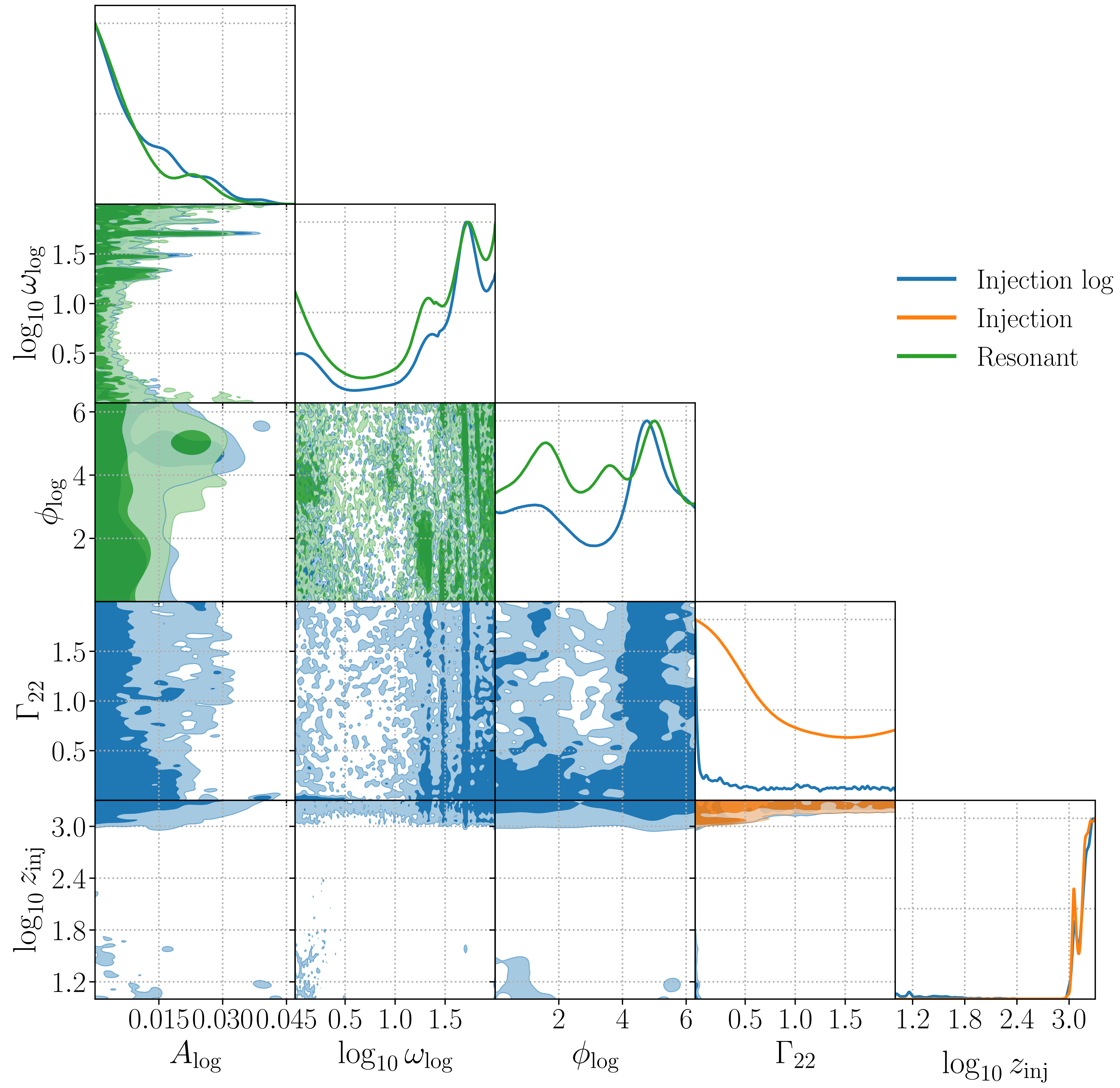
# Can we fake primordial features?
# Case 1: exotic energy injection

The expectation is confirmed by the analysis of real Planck data. The constraints of primordial and late-time models do not change when analyzing the two models together.

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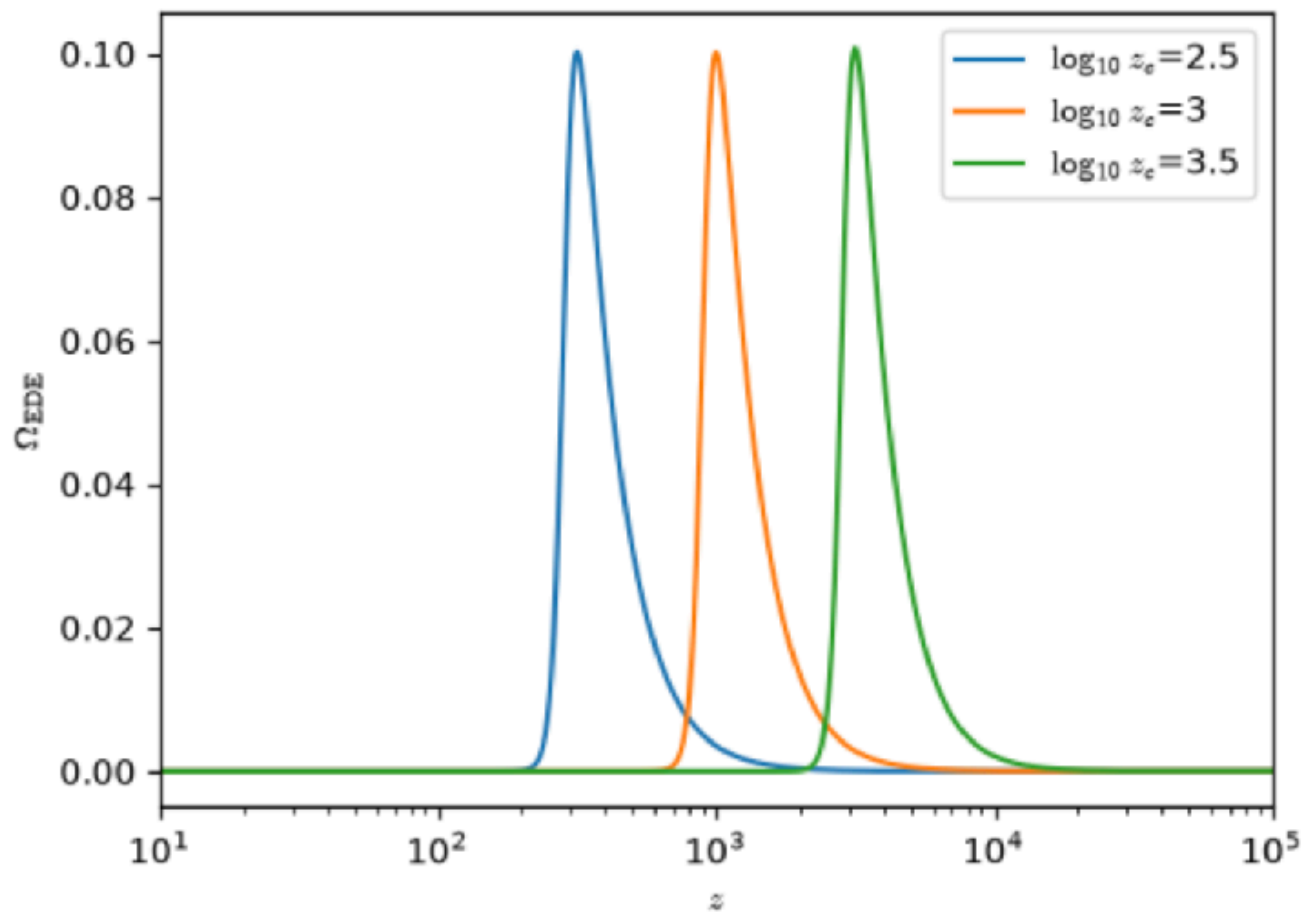
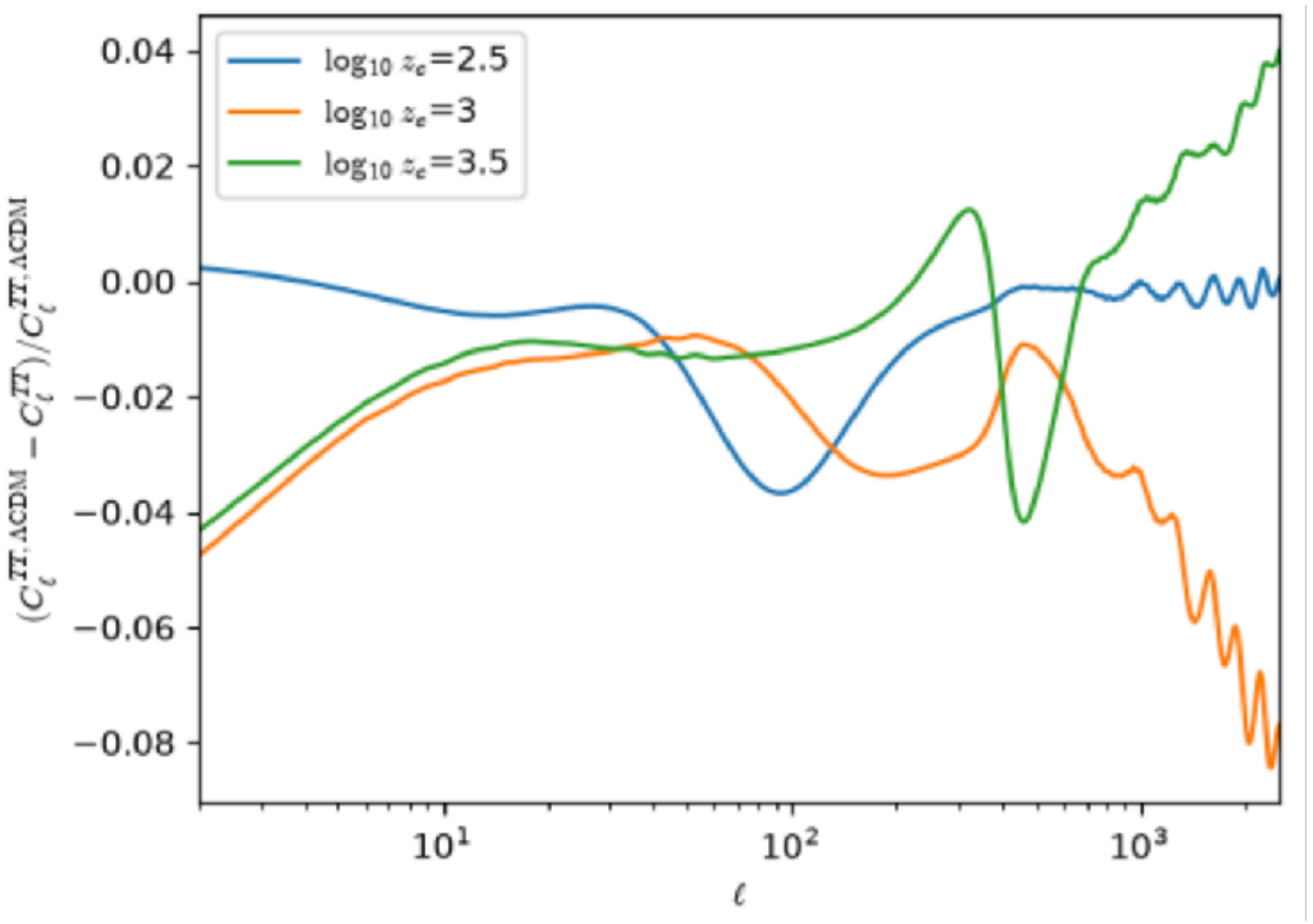
# Can we fake primordial features?
# Case 2: injection in $H(z)$

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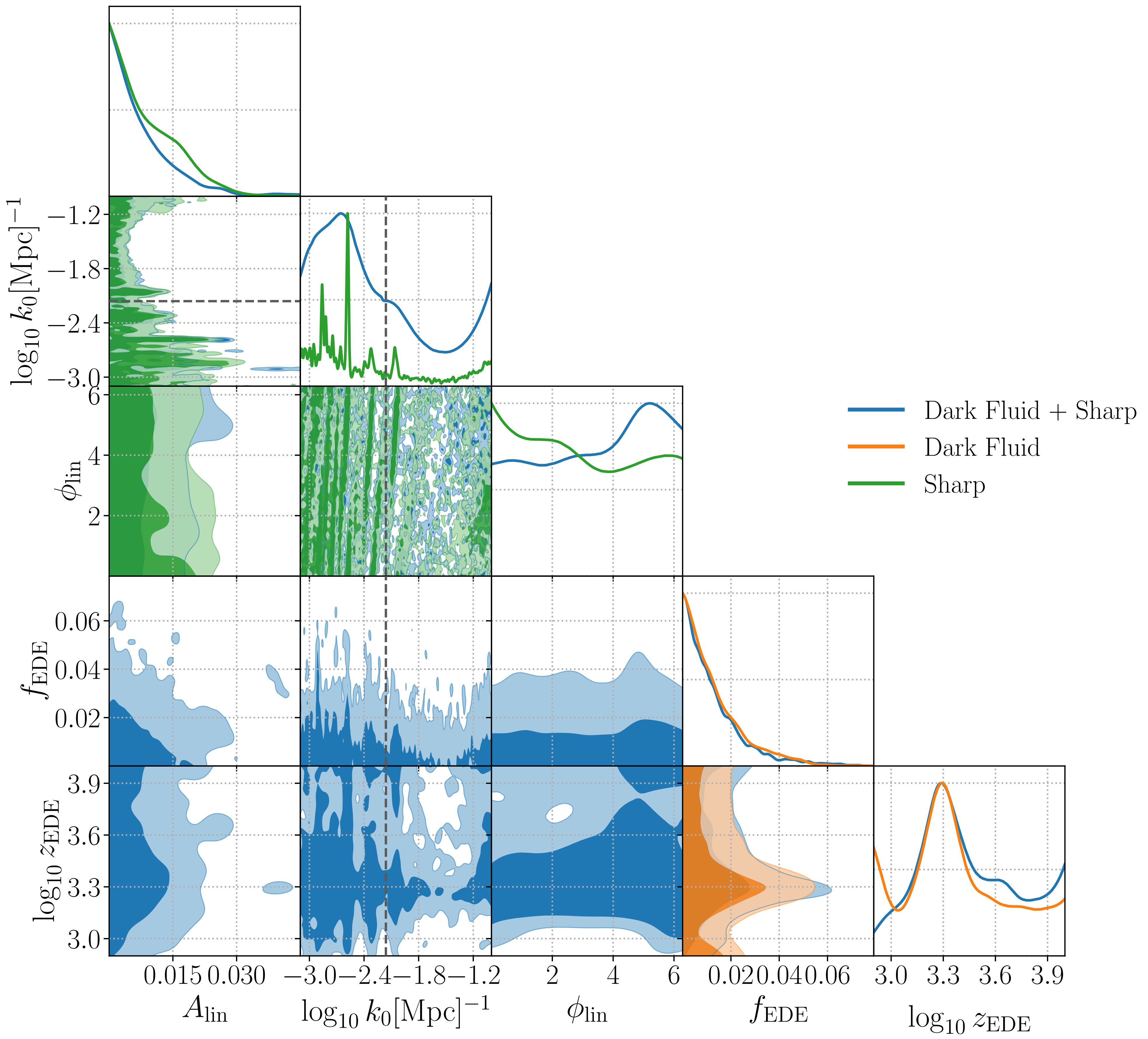
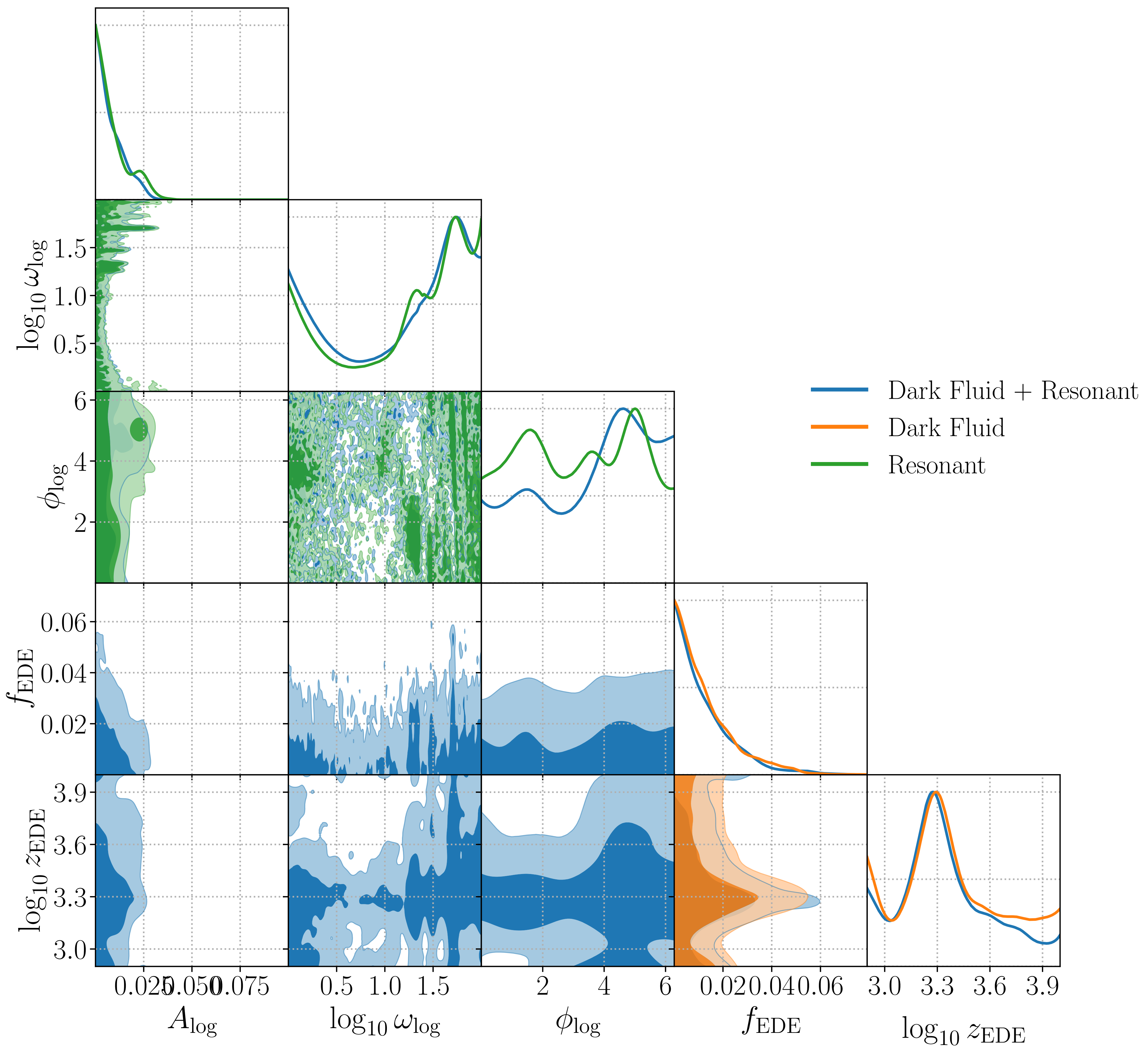
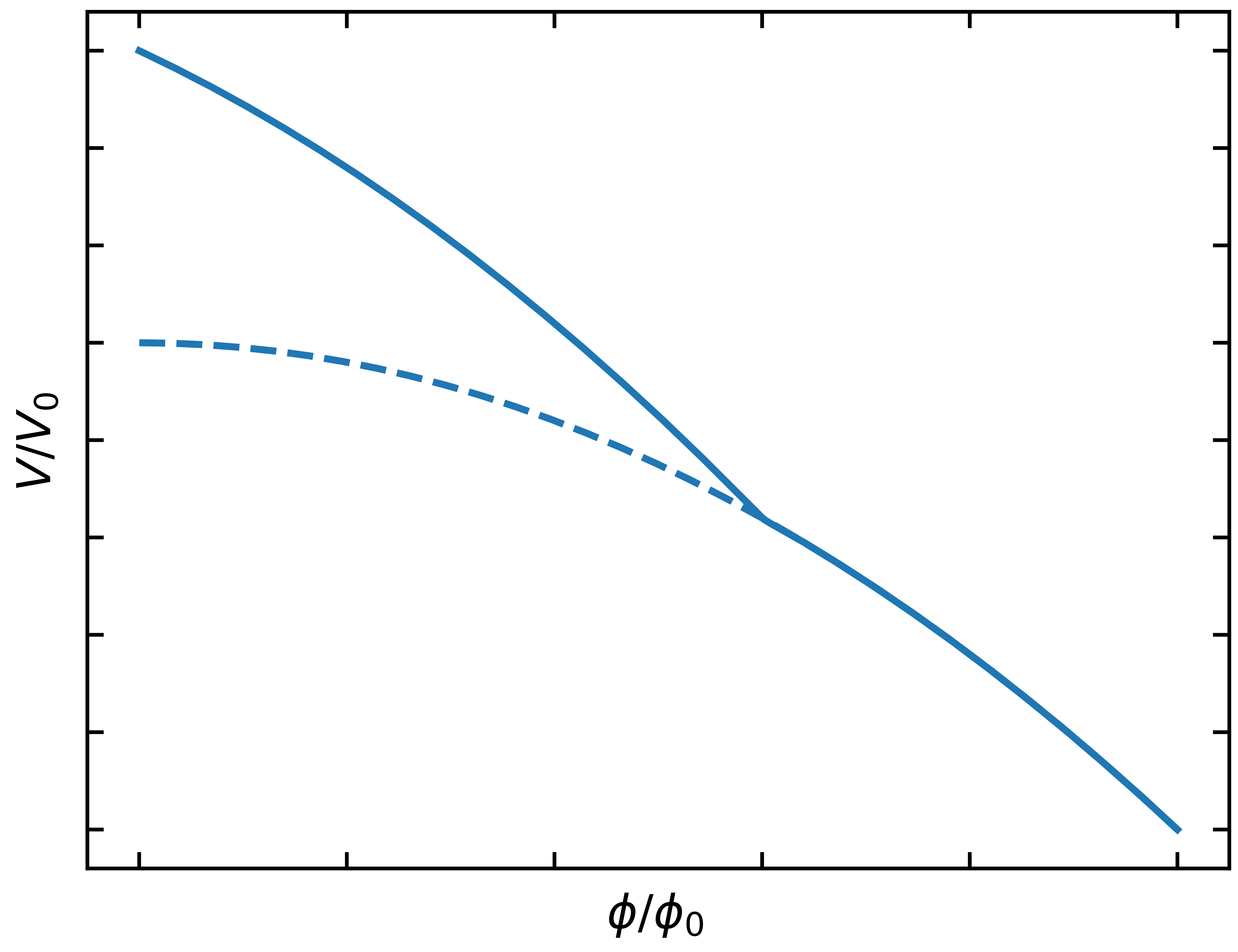



Qin, **MB**, Chen, Slatyer in preparation

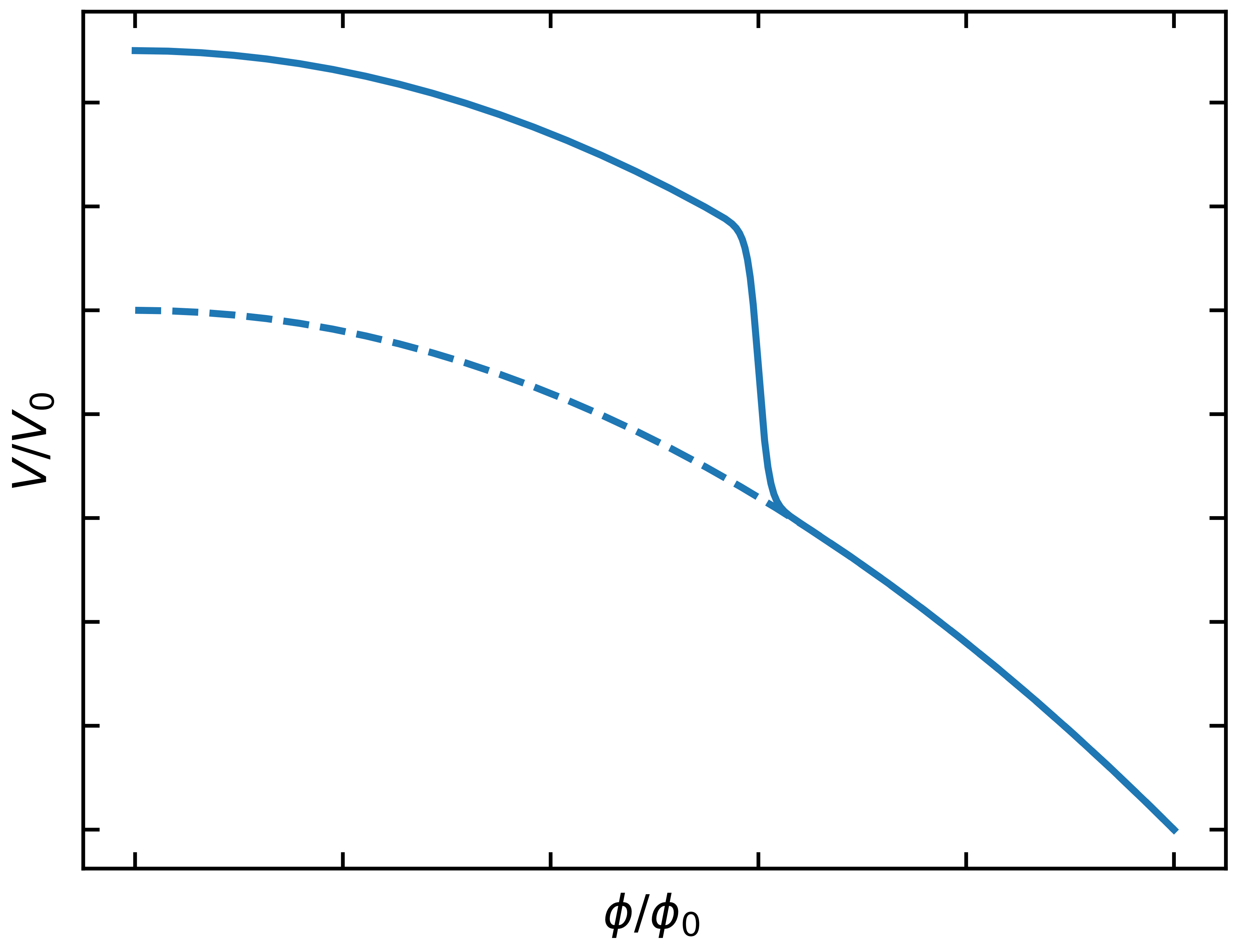
# (Less significant) hints at low $\ell$

**Kink** in the inflaton potential



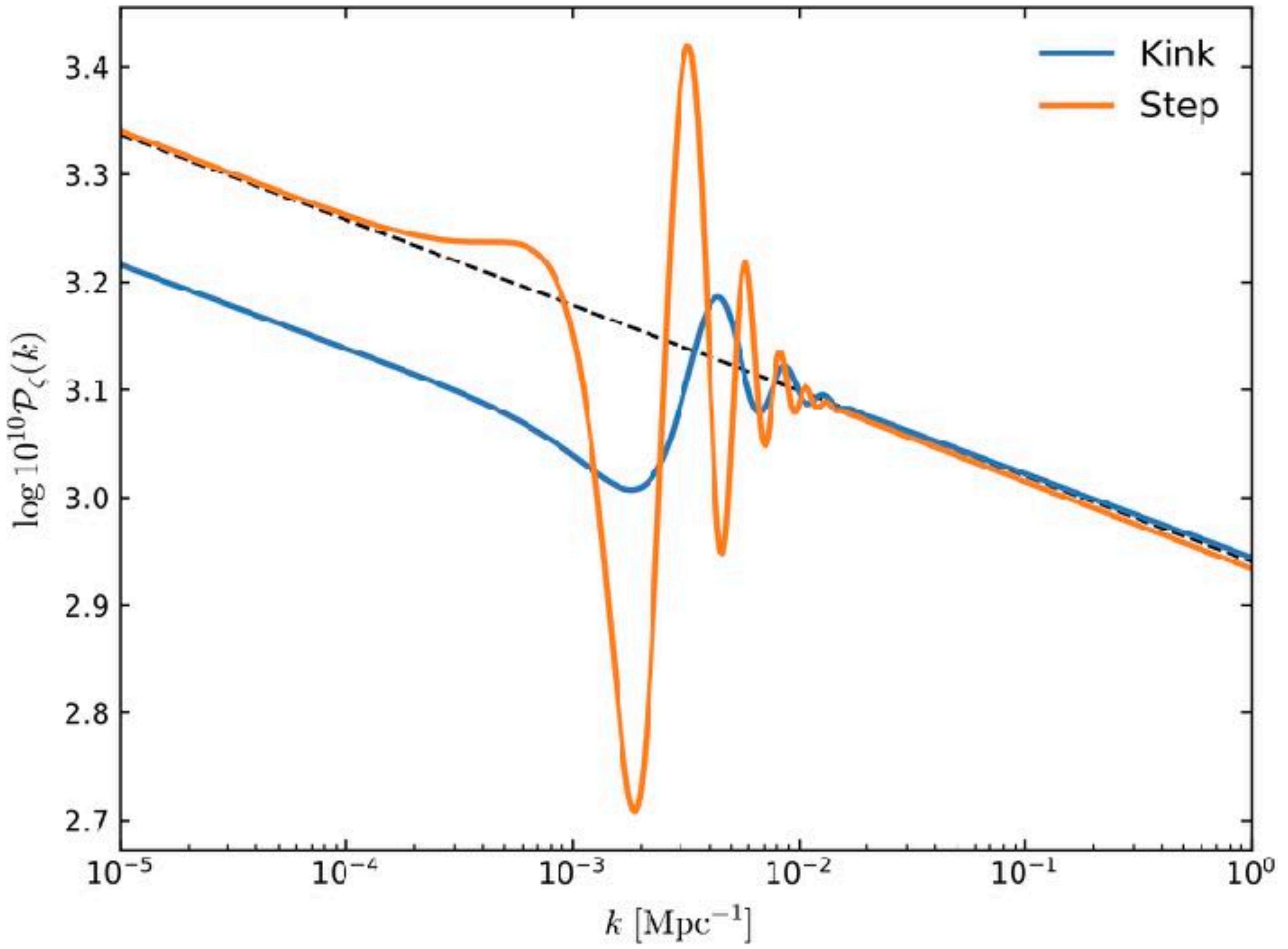

Starobinsky JETP Lett. 55 (1992)
Jain et al 0809.3915, 0904.2518

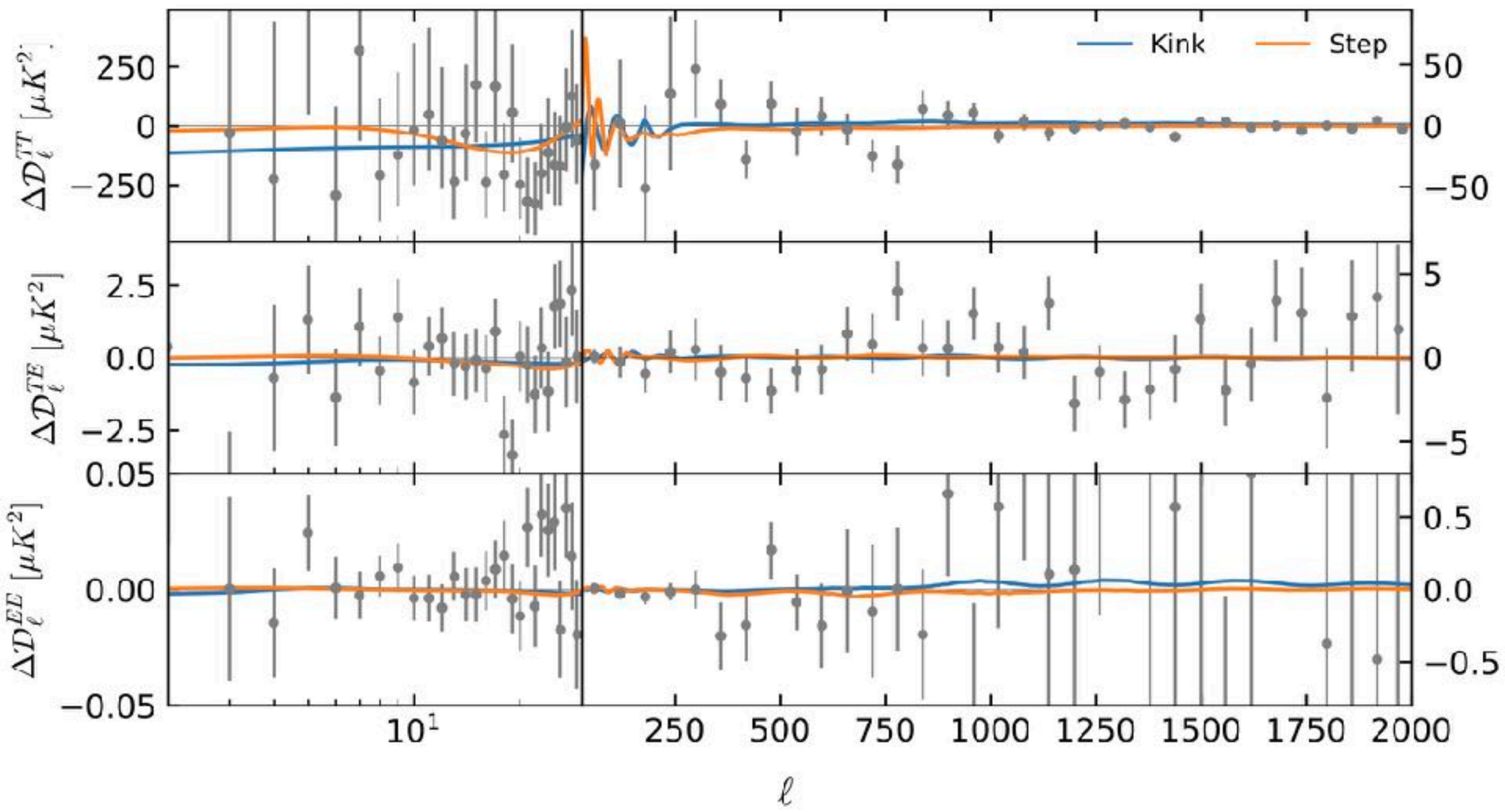
**Step** in the inflaton potential




Adams, Cresswell, Easther astro-ph/0102236
Hazra, Jain, Sriramkumar, Souradeep1005.2175
**MB**, Chen Hazra 2108.10110
Tiwari, Bhaumik, Jain 2206.13320, etc

# (Less significant) hints at low $\ell$




Modest improvement to the fit, the signals *die off* at *smaller scales* the inflaton potential

| | Kink | Step |
|---|---|---|
| $\ln B$ | $-2.5 \pm 0.36$ | $-1.3 \pm 0.38$ |
| $\Delta\chi^2$ | $3.8$ | $5.3$ |

Petretti, **MB**, Chen, Hazra, Paban 2411.03459

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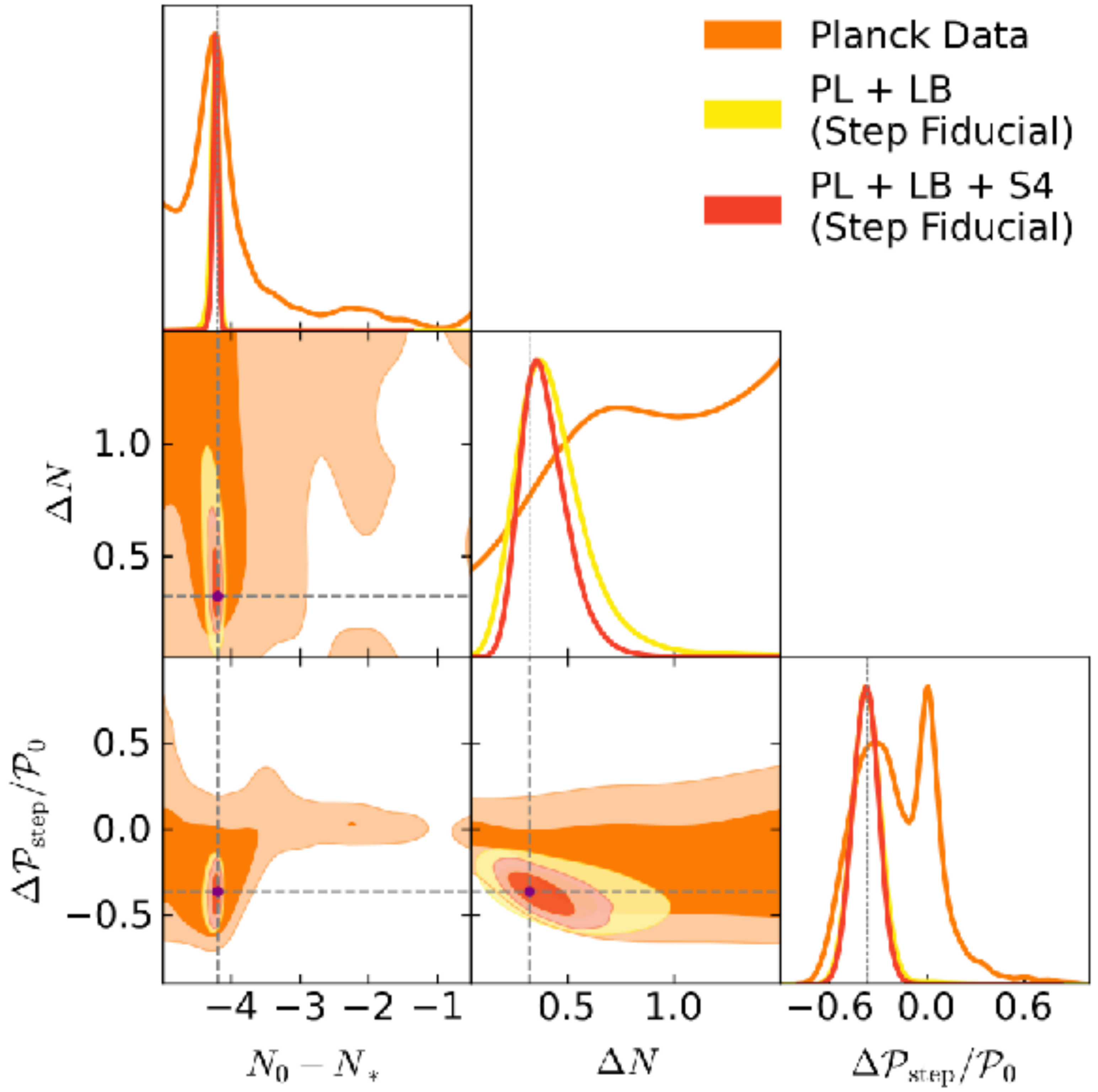
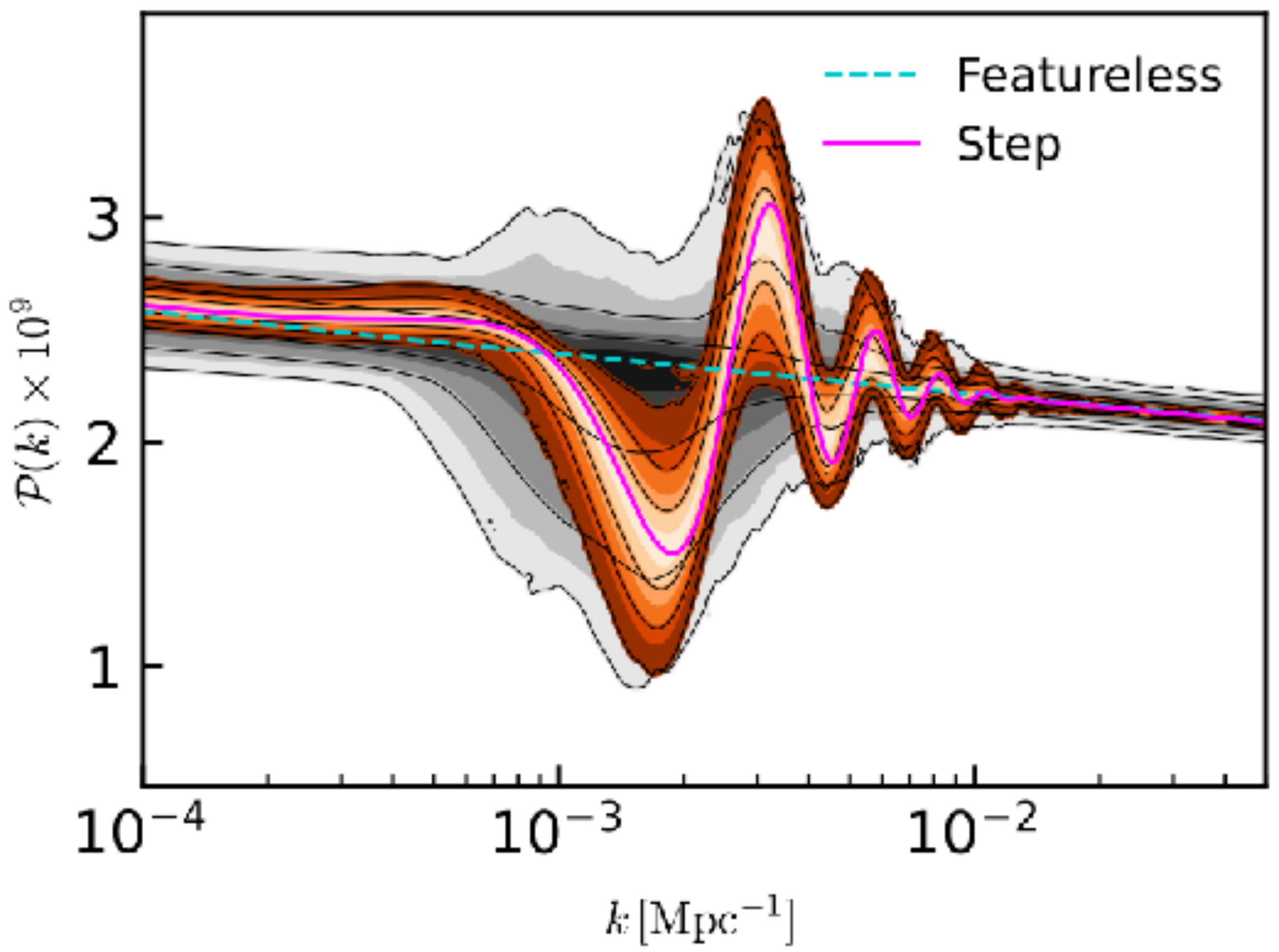
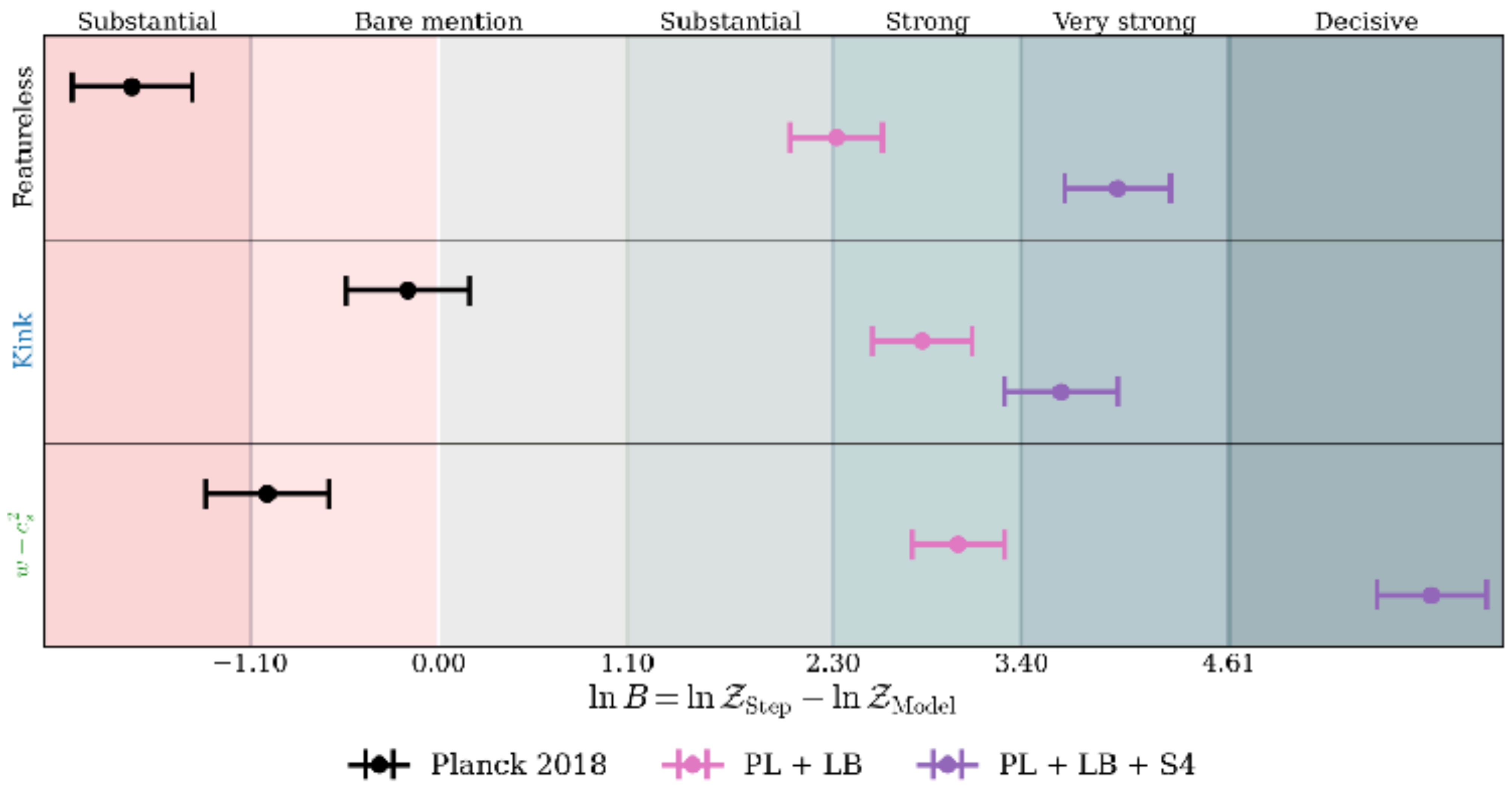
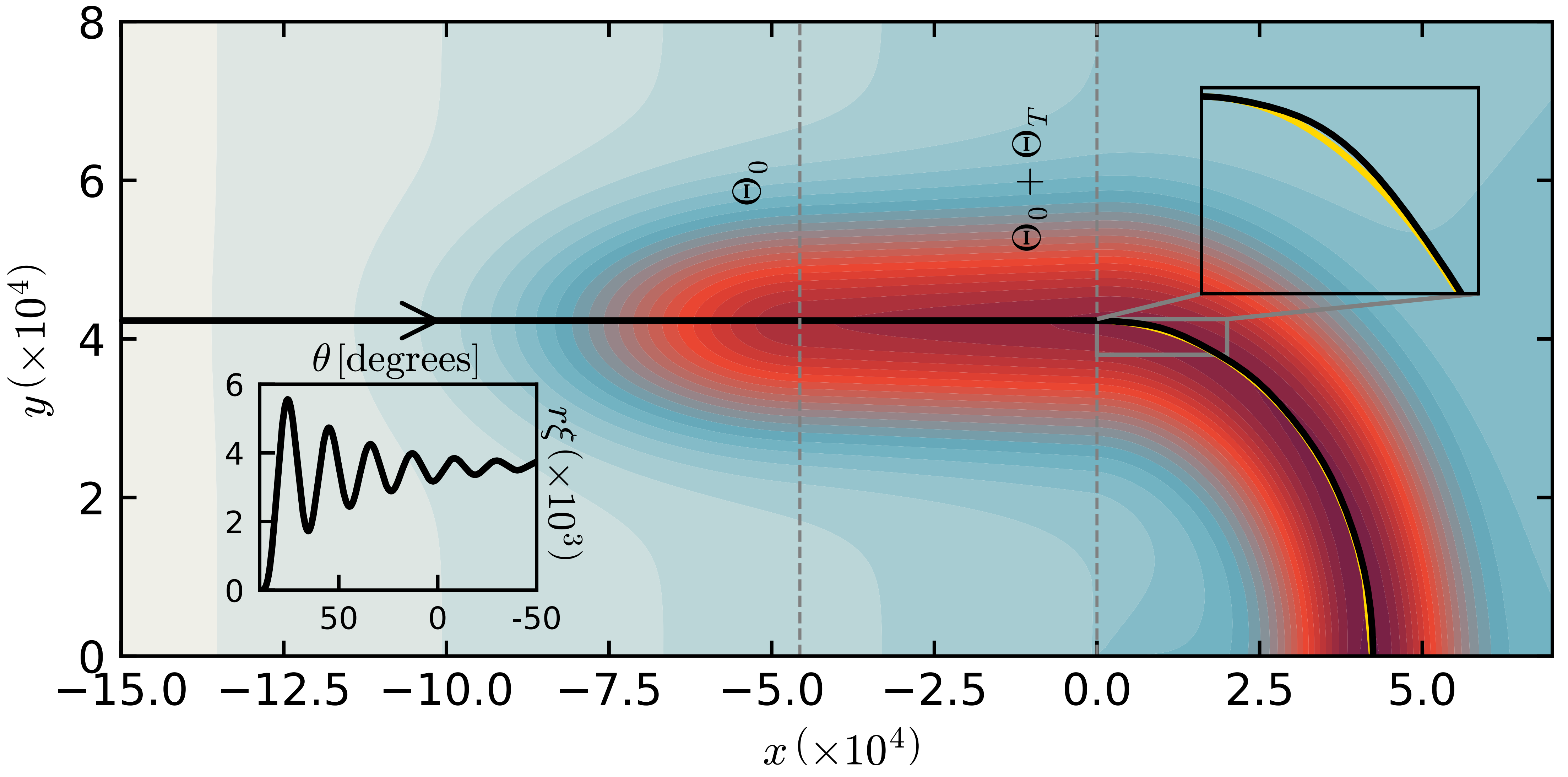


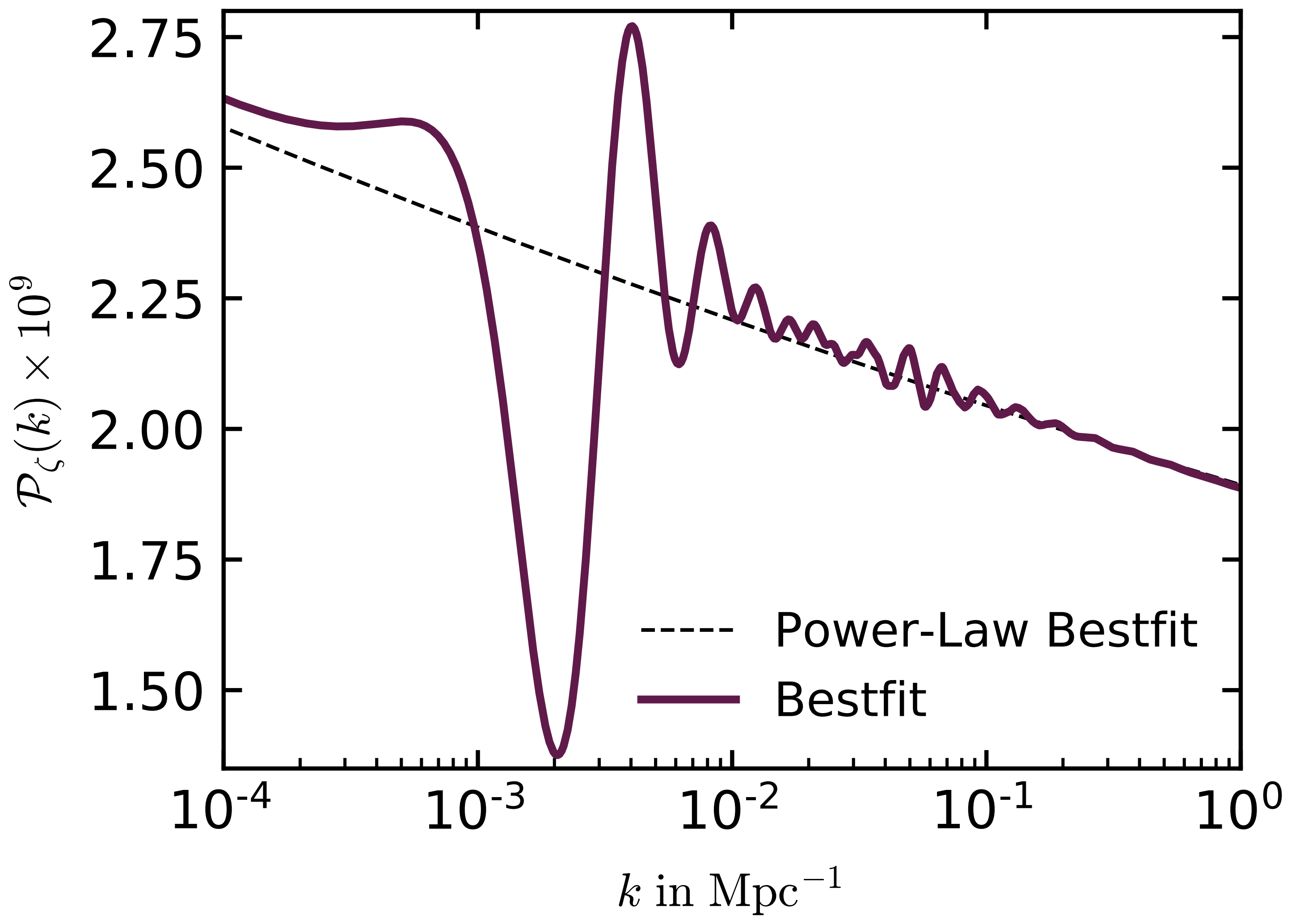



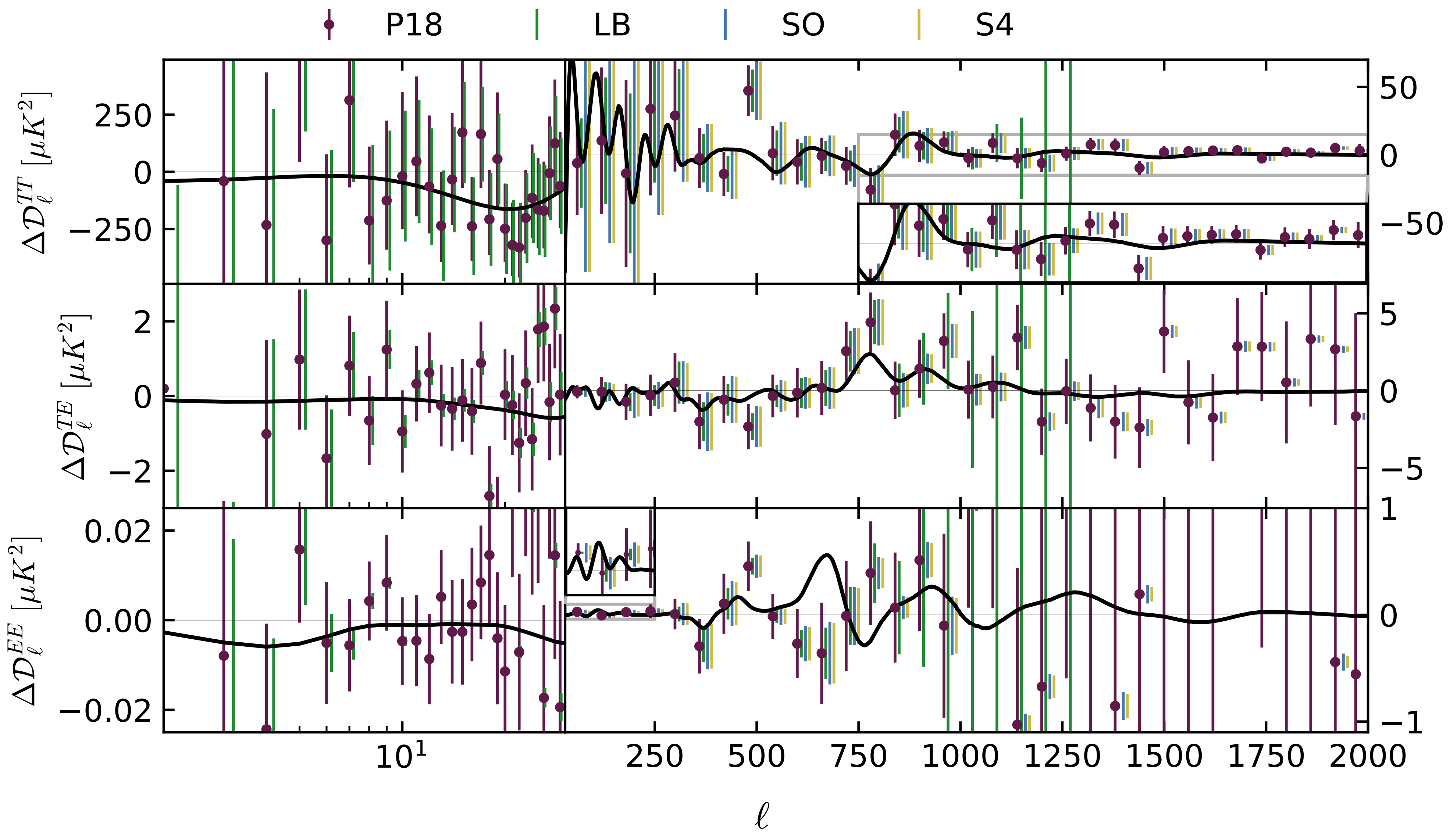




Petretti, **MB**, Chen, Hazra, Paban 2411.03459

# Model building to fit both high and low $\ell$




**MB**, Chen, Hazra 2106.07546, 2108.10110