Primordial Features as Probes of Inflation Models and High Energy Physics

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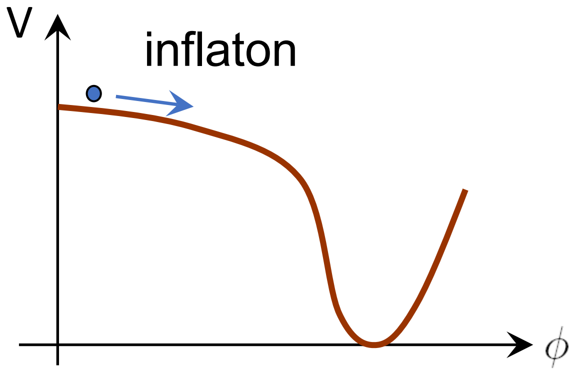
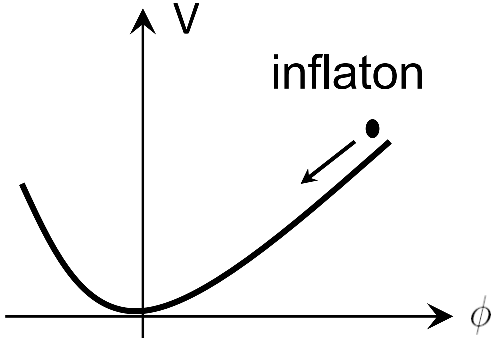
CfA Harvard

2106.07546, 2108.10110, with Braglia, Hazra;
2205.01107, with Ebadi, Kumar;
2210.07028, with Braglia, Hazra, Pinol;
2303.03406, with Fan, Li.

Simplest Single Field Inflation Models





Primordial Features

Motivations:

- Fine-tuning problem of potential
- Inflationary landscape

Low energy trajectory may not be smooth, i.e., sharp features, periodic features

Orthogonal directions are lifted by potentials and represented by massive fields

Small (or large) components that significantly depart from scale-invariance, in power spectrum or non-Gaussianities, Induced by scale-dependent physics

However, no known model-independent lower bound on the amplitudes

- Sharp feature: Temporary deviation from attractor, due to a sharp feature

E.g., step, bump, kink, interactions, … …

(Starobinsky, 92, …)

$$\frac{\Delta P_\zeta}{P_{\zeta 0}} \propto 1 - \cos(2k/k_f)$$

With a highly model-dependent envelop

- Resonance feature: (Semi)-periodic background oscillations with frequency larger than Hubble

(XC, Easther, Lim, 06; Flauger et al, 09, …)

Inflation example:

Background oscillation with fixed frequency

Inflaton oscillation with time-dependent (decrease) frequency

⇒ Resonate mode by mode

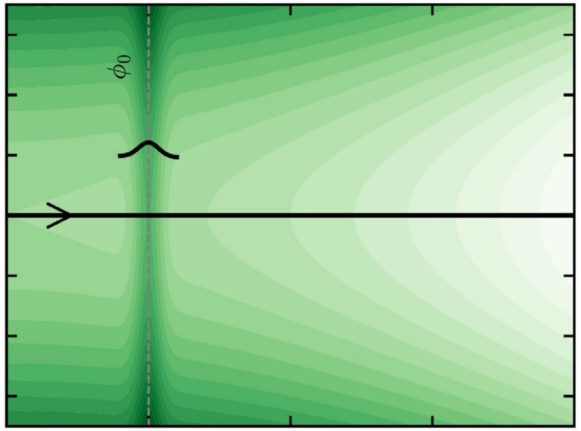
$$\frac{\Delta P_\zeta}{P_{\zeta 0}} \propto \sin(\Omega \log(2k) + \phi)$$

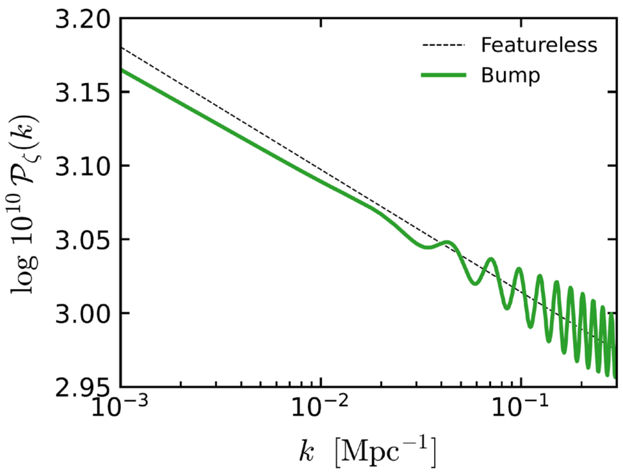
With a model-dependent envelop

Feature Model Examples

Sharp feature in potential
e.g. step, bump, dip, … …

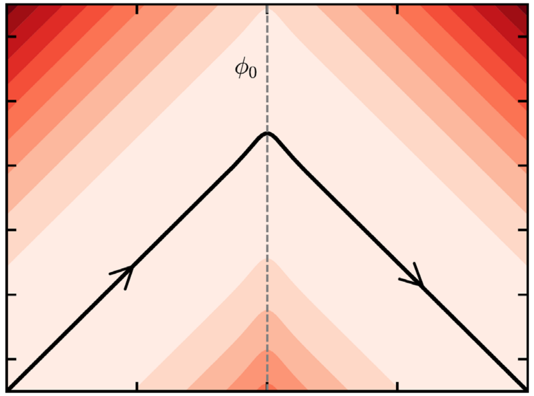
(Starobinsky, 92; Adam, Cresswell, Easther, 01, …)

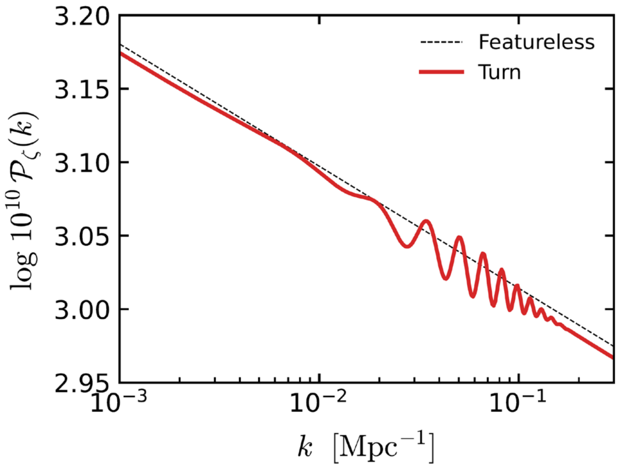




Multifield sharp-turn

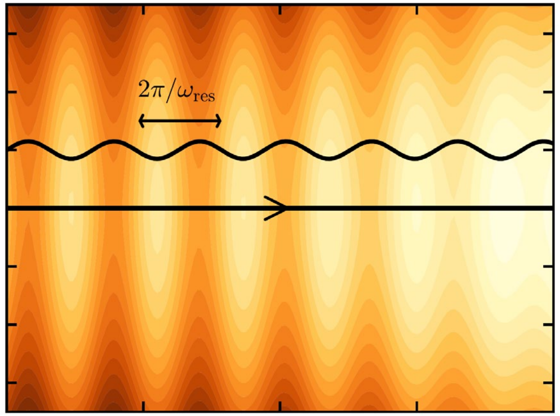
(Achucarro et al, 10)

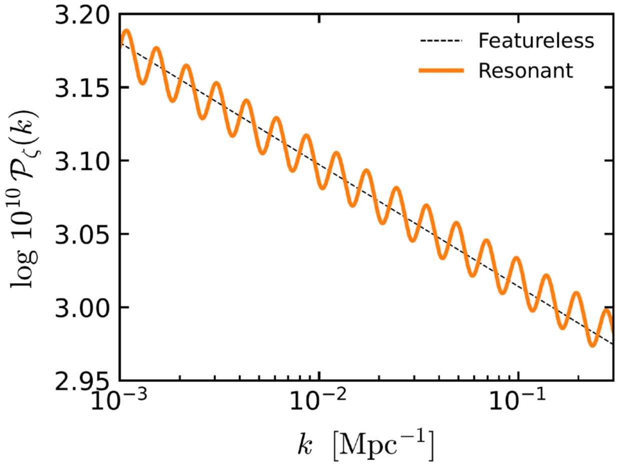




Period features in potential

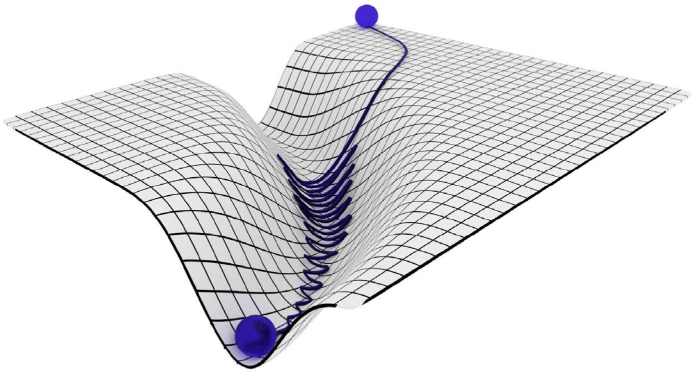
(XC, Easther, Lim, 06; Flauger et al, 09, …)



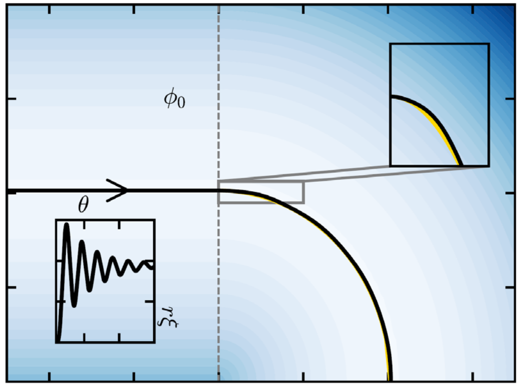


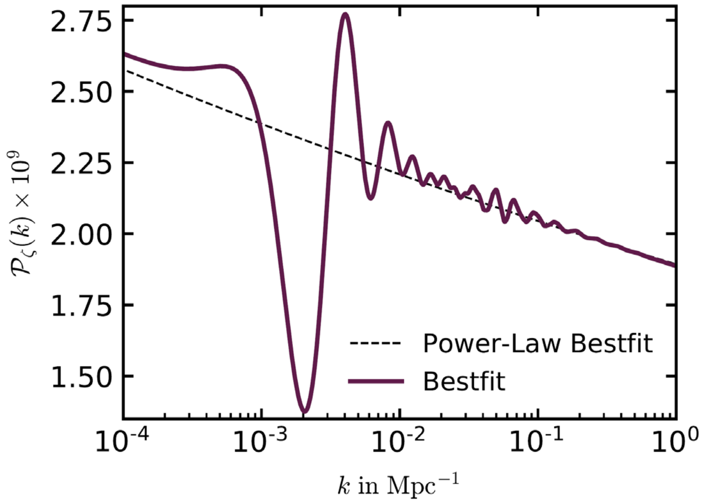
Feature Model Examples

Tachyonic falling inducing massive field oscillation



Bending trajectory inducing massive field oscillation





Sophisticated combination
of sharp and resonance features

(XC, 11; XC, Namjoo, Wang, 14; Braglia, XC, Hazra, 21)

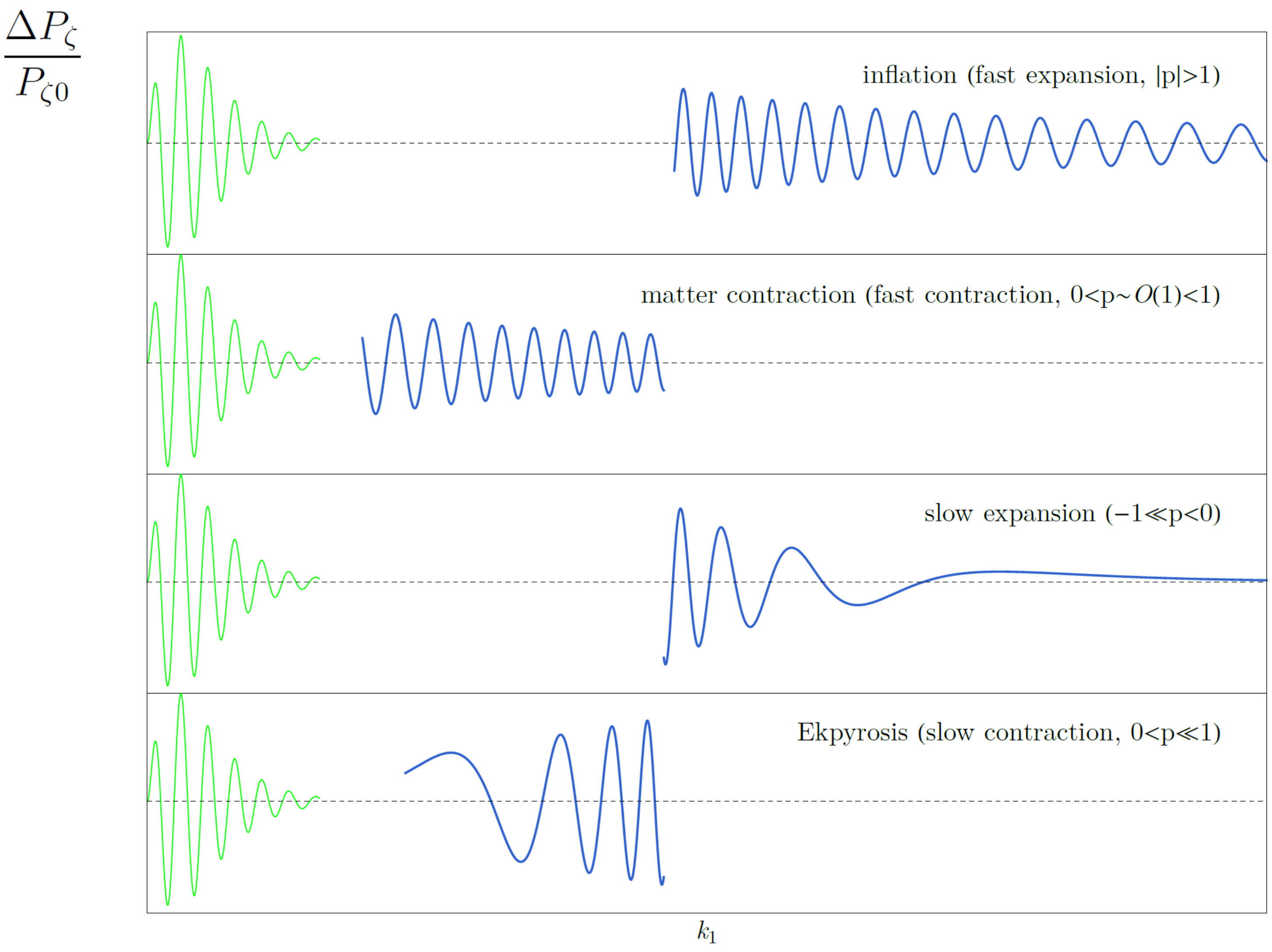
(Classical) Primordial Standard Clocks

Measuring $a(t)$ of Different Scenarios

(XC, 11, XC, Namjoo, Wang, 14)

In both power spectra (as corrections) and non-Gaussianities

Qualitative sketch



$$a(t) = a_0 \left(\frac{t}{t_0}\right)^p$$

The Clock Signal in Classical PSC

The background oscillation resonates with curvature fluctuations mode by mode

The clock signal: $\sim \sin\left[p\frac{m}{m_{\mathrm{h},0}}\left(\frac{K}{k_r}\right)^{1/p}+\varphi\right]$ $K \equiv k_1 + k_2 = 2k_1$ for power spectrum

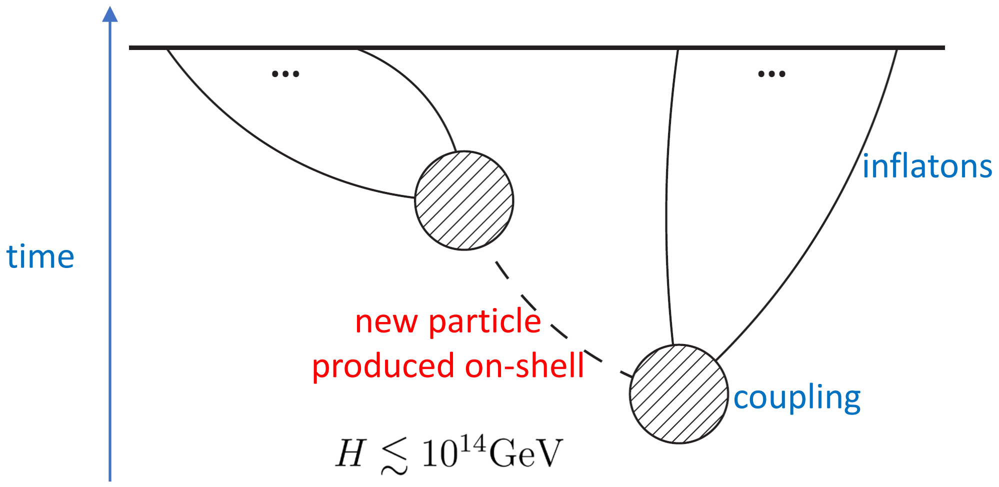
horizon mass at time of sharp feature

Inverse function of *a*(*t*)

This phase pattern is a direct measure of *a*(*t*)

Cosmological Collider Physics

Quantum production of massive particles



New particles, with mass up to O(H), are produced on-shell due to quantum fluctuations,
They couple to inflatons, and leave imprints in inflaton correlation functions

What are the observational signatures of these particle states?

Mass and spin spectra of intermediate state are encoded in soft limits of non-Gaussianities:

E.g. **Squeezed limit bispectrum**

$$S \xrightarrow[\text{limit}]{\text{squeezed}} e^{-\pi\mu} \left(\frac{k_{\text{long}}}{k_{\text{short}}} \right)^{\frac{1}{2} \pm i\mu} P_s(\cos\theta)$$

$e^{-\pi\mu}$ → Boltzmann suppression

$\left(\frac{k_{\text{long}}}{k_{\text{short}}} \right)^{\frac{1}{2} \pm i\mu}$ → mass

$P_s(\cos\theta)$ → spin

$$\mu = \sqrt{\frac{m^2}{H^2} - \frac{9}{4}}$$

Cosmological Collider Physics

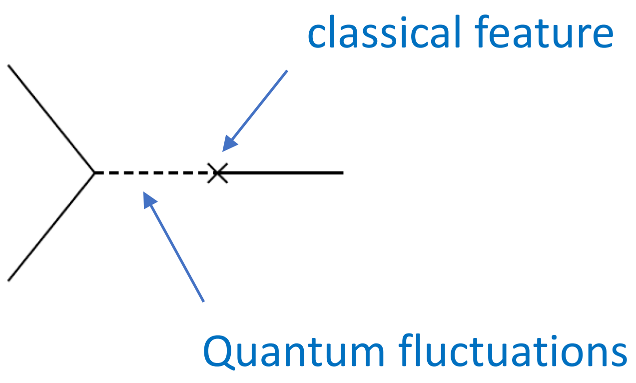
(XC, Wang, 09
Arkani-Hamed, Maldacena, 15)

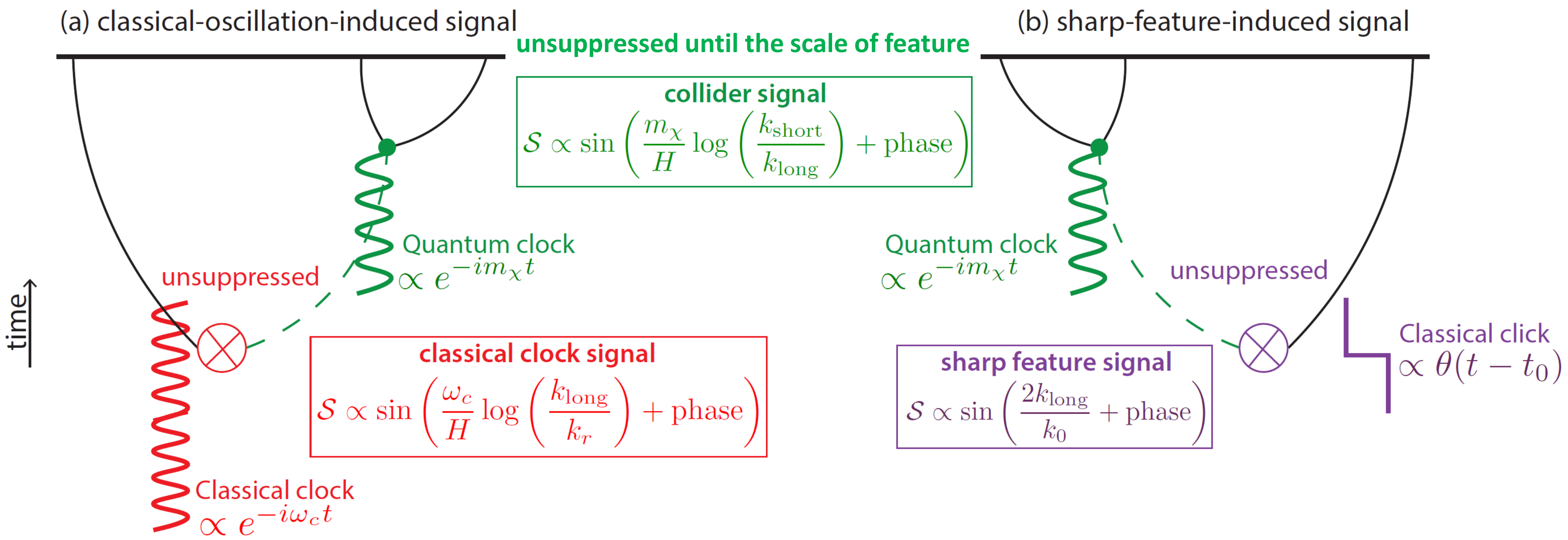
- Amplitude of non-G is very model-dependent, open for predictions from model building

Classical Cosmological Collider Physics

(XC, 11; XC, Ebadi, Kumar, 22)

Primordial features inject extra energy to inflation models
and
boost the energy of the cosmological collider by orders of magnitude




(a) classical-oscillation-induced signal
unsuppressed until the scale of feature
(b) sharp-feature-induced signal
collider signal
$\mathcal{S} \propto \sin\left(\frac{m_\chi}{H}\log\left(\frac{k_{\rm short}}{k_{\rm long}}\right)+\text{phase}\right)$
Quantum clock
$\propto e^{-im_\chi t}$
unsuppressed
time
classical clock signal
$\mathcal{S} \propto \sin\left(\frac{\omega_c}{H}\log\left(\frac{k_{\rm long}}{k_r}\right)+\text{phase}\right)$
Classical clock
$\propto e^{-i\omega_c t}$
Quantum clock
$\propto e^{-im_\chi t}$
unsuppressed
Classical click
$\propto \theta(t-t_0)$
sharp feature signal
$\mathcal{S} \propto \sin\left(\frac{2k_{\rm long}}{k_0}+\text{phase}\right)$

An Example of Particle Dark Matter Model

Axion Model as Example of Massive Field

(XC, Fan, Li, 23)

$$\mathcal{L} = -\frac{(\partial_\mu \phi)^2}{2} - |\partial_\mu \chi|^2 - V_\phi(\phi) - V_\chi(\chi)$$

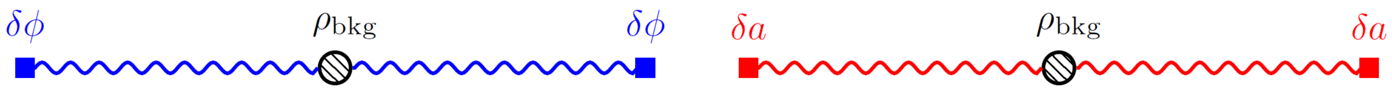
$$V_\chi(\chi) = \frac{\lambda}{2}\left(|\chi|^2 - \frac{f_a^2}{2}\right)^2$$

Add a coupling: $-\frac{c}{\Lambda^2}(\partial\phi)^2|\chi|^2$

A sharp feature in inflaton potential can induce oscillation of radial mode

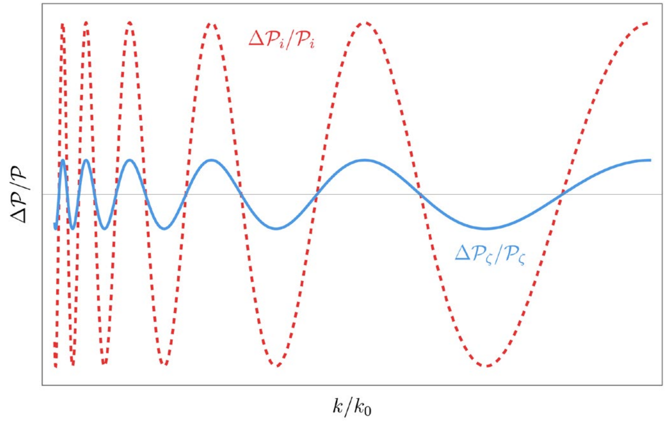
Imprint in both inflaton and axion fields

Correlated clock signals in both curvature and dark matter isocurvature perturbations



- A signature of Peccei-Quinn field during inflation

- Feature signal dominates in DM isocurvature perturbation



$$\left|\frac{\Delta P_\zeta}{P_\zeta}\right|_{\text{clock;amp}} \approx 0.019 \left(\frac{q}{0.02}\right)^2 \left(\frac{bV_{\phi 0}}{0.3\dot{\phi}_0^2}\right) \left(\frac{\dot{\phi}_0}{(60H)^2}\right)^2 \left(\frac{40H}{f_I}\right)^{7/2} \left(\frac{1}{\lambda}\right)^{3/4}$$

$$\left|\frac{\Delta P_i}{P_i}\right|_{\text{clock;amp}} \approx 0.96 \left(\frac{q}{0.02}\right) \left(\frac{bV_{\phi 0}}{0.3\dot{\phi}_0^2}\right) \left(\frac{\dot{\phi}_0}{(60H)^2}\right)^2 \left(\frac{40H}{f_I}\right)^{7/2} \left(\frac{1}{\lambda}\right)^{3/4}$$

- Break the degeneracy in measurement of f_I and H

Dark matter physics
(amplitude of axion isocurvaure): $\beta \propto \theta_i^2 H^2 f_I^{1/3}$

Cosmological collider physics $\mu_\rho = \sqrt{\lambda}(f_I/H)$

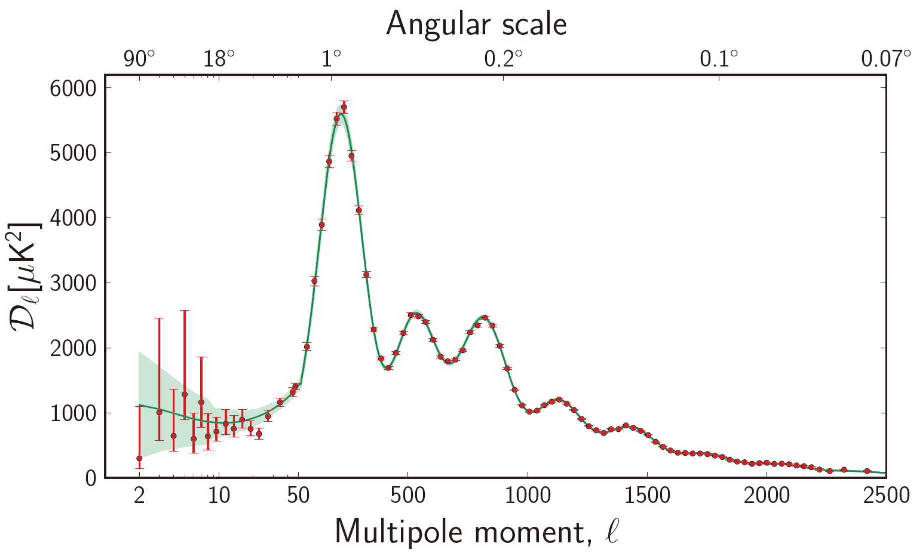
Degeneracy directions in f_I-H plane
are quite orthogonal to each other

Summary: What may we learn from signals of primordial features?

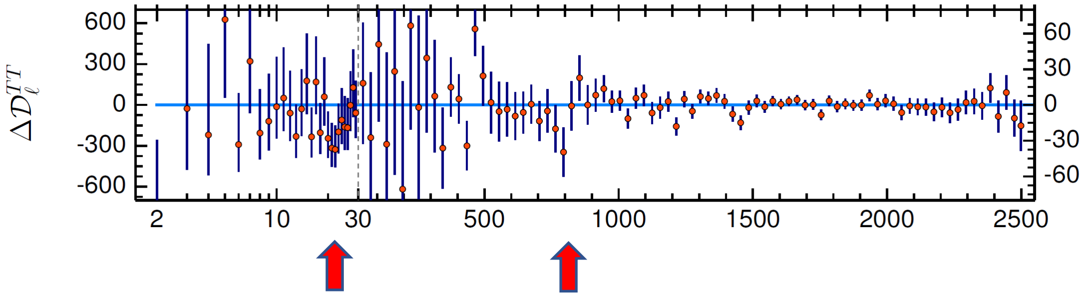
- Inflation or not inflation
- Details of (non-) inflationary potential or internal space
- High energy physics at super-Hubble energy scales

CMB Power Spectra Residuals

There are some interesting, statistically marginal, anomalies in CMB residual data



CMB TT residuals (also has counterparts in TE and EE)

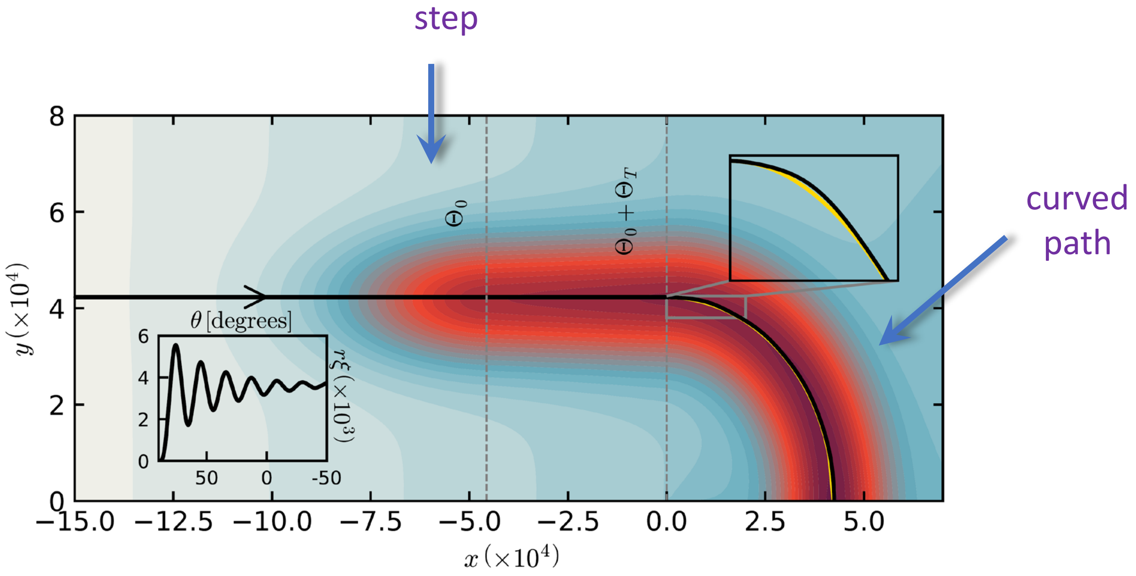


(Planck, 13, 18)

The two well-separated features in CMB may be connected by the Standard Clock effect; or explained by other feature models.

A Classical Primordial Standard Clock Model

(Braglia, XC, Hazra, 21)



Birdseye view of the potential

$$\mathcal{L} = -\frac{1}{2}\left[1+\Xi(\Theta)\sigma\right]^2(\partial\Theta)^2 - \frac{1}{2}(\partial\sigma)^2 - V(\Theta,\sigma)$$

$$\Xi(\Theta) = \xi \ \mathrm{Heav}(\Theta - \Theta_0 - \Theta_T)$$

$$V(\Theta,\sigma) = V_{\rm inf}\left\{1 - \frac{1}{2}C_\Theta\Theta^2 + C_\sigma\left[1 - \exp\left(-\frac{(\Theta-\Theta_0)^2}{\Theta_f^2}\mathrm{Heav}(\Theta-\Theta_0) - \frac{\sigma^2}{\sigma_f^2}\right)\right]\right\}$$

(6 more parameters than standard model)

1st stage inflation ➡ Rolling off a cliff ➡ Fast-roll, entering a curved path of valley

➡ Overshoots bottom of valley and climbs on cliff ➡ Excites classical oscillation of a massive field

➡ Oscillation decays, settles down to 2nd stage inflation

Use effective parameters and nested sampling.

To compare models, we use **Bayes Factor:**

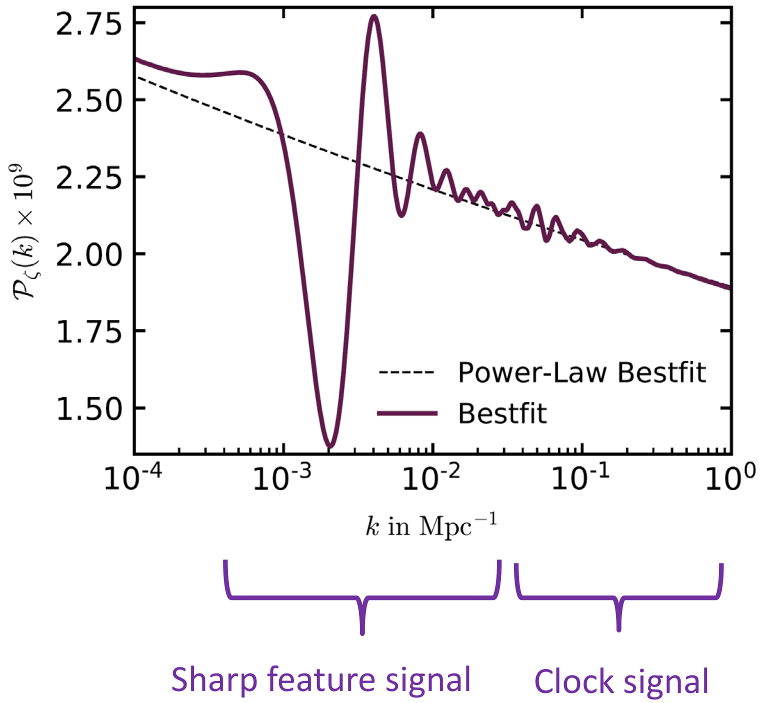
$$B_{12} \equiv \frac{Z_1}{Z_2} = \frac{\int d\boldsymbol{\theta}_1 \, \pi(\boldsymbol{\theta}_1|\mathcal{M}_1)\mathcal{L}(\mathbf{x}|\boldsymbol{\theta}_1, \mathcal{M}_1)}{\int d\boldsymbol{\theta}_2 \, \pi(\boldsymbol{\theta}_2|\mathcal{M}_2)\mathcal{L}(\mathbf{x}|\boldsymbol{\theta}_2, \mathcal{M}_2)}$$

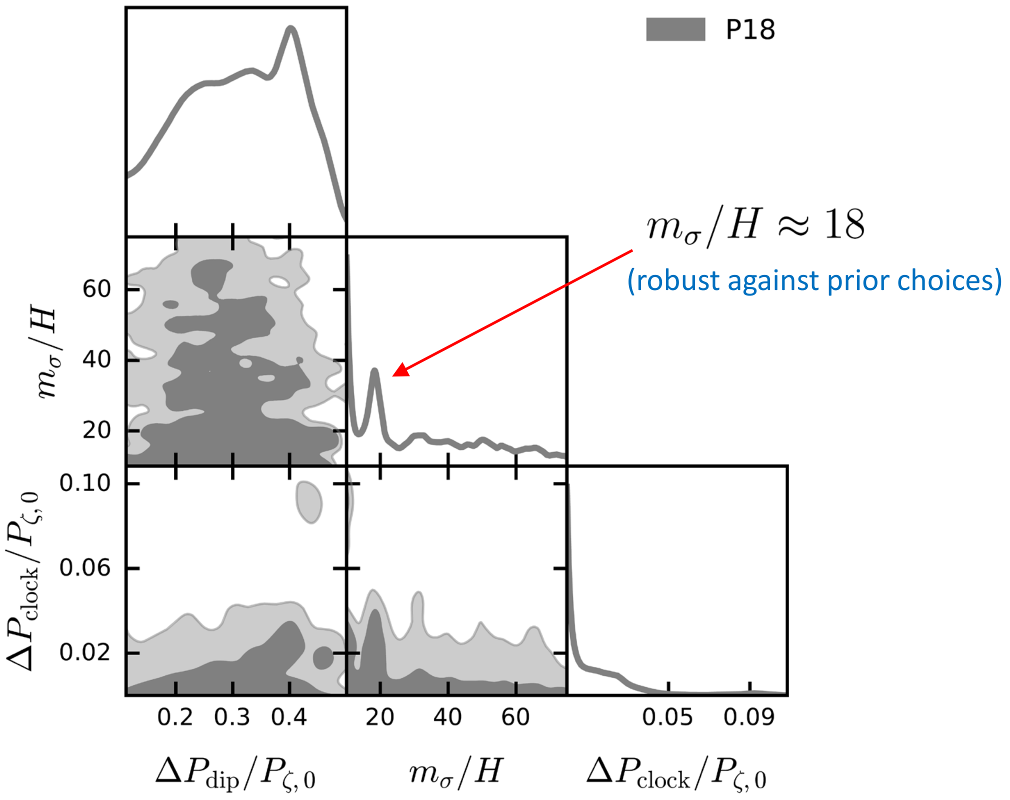
Z’s are marginalized likelihoods for different models:
probability of data given the model

Evidence Categories for Bayes Factor given by Jeffreys (1961)

BF_{ij}	$\ln(BF_{ij})$	Interpretation
>100	>4.61	Decisive evidence for H_i
30–100	3.40 to .61	Very strong evidence for H_i
10–30	2.30 to 3.40	Strong evidence for H_i
3–10	1.10 to 2.30	Substantial evidence for H_i
1–3	0 to 1.10	Not worth more than a bare mention
1/3–1	−1.10 to 0	Not worth more than a bare mention
1/10–1/3	−2.30 to −1.10	Substantial evidence for H_j
1/30–1/10	−3.40 to −2.30	Strong evidence for H_j
1/100–1/30	−4.61 to −3.40	Very strong evidence for H_j
<1/100	<−4.61	Decisive evidence for H_j

Best-fit, Posteriors, and Bayes Evidence



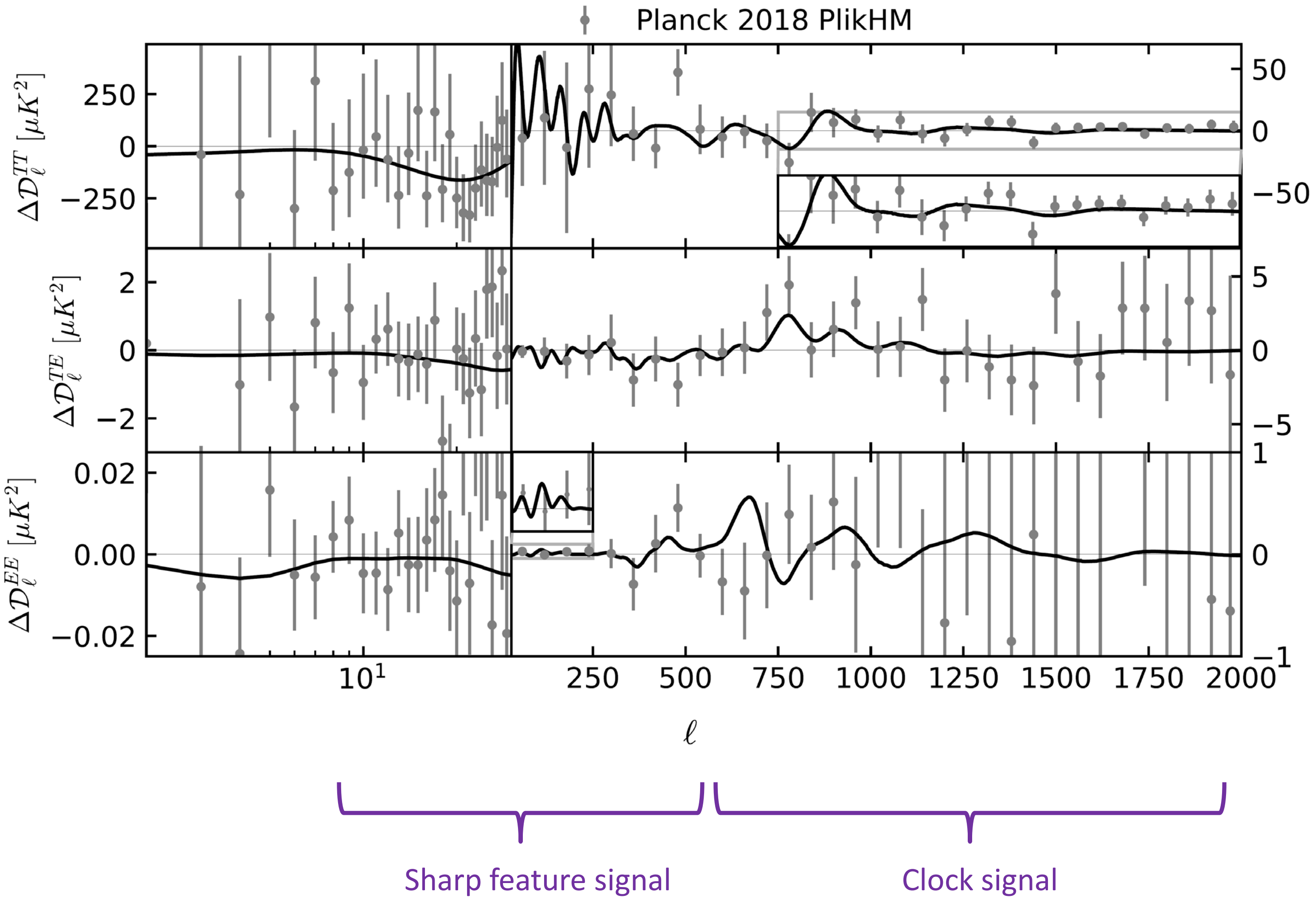


Best-fit: $\Delta\chi^2 = 19.8$ (with 6 extra parameters)

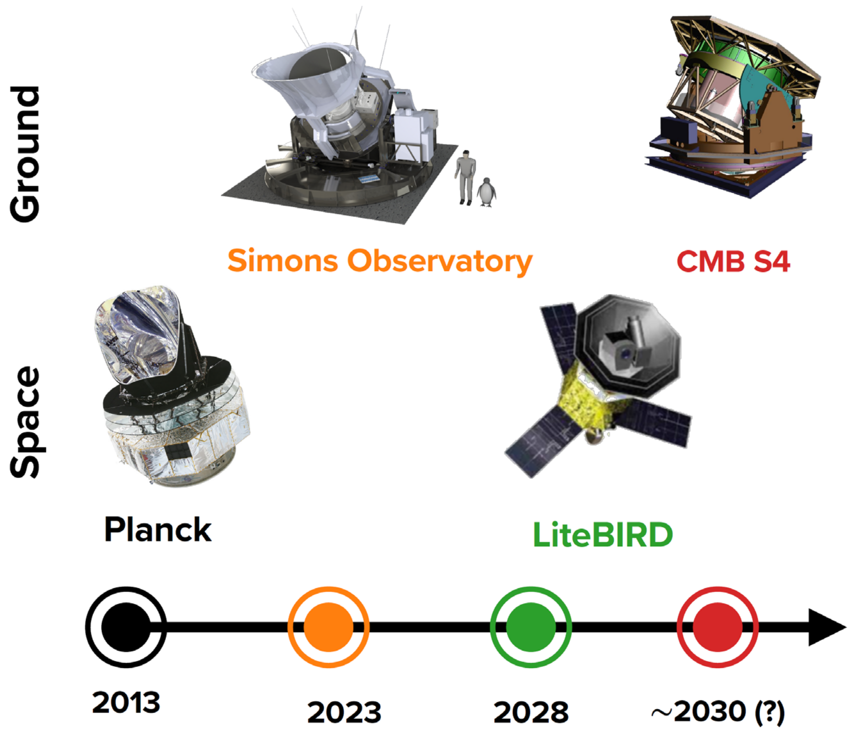
Bayes factor: $\ln B \equiv \ln Z_{\rm feature} - \ln Z_{\rm featureless} = -0.13 \pm 0.38$

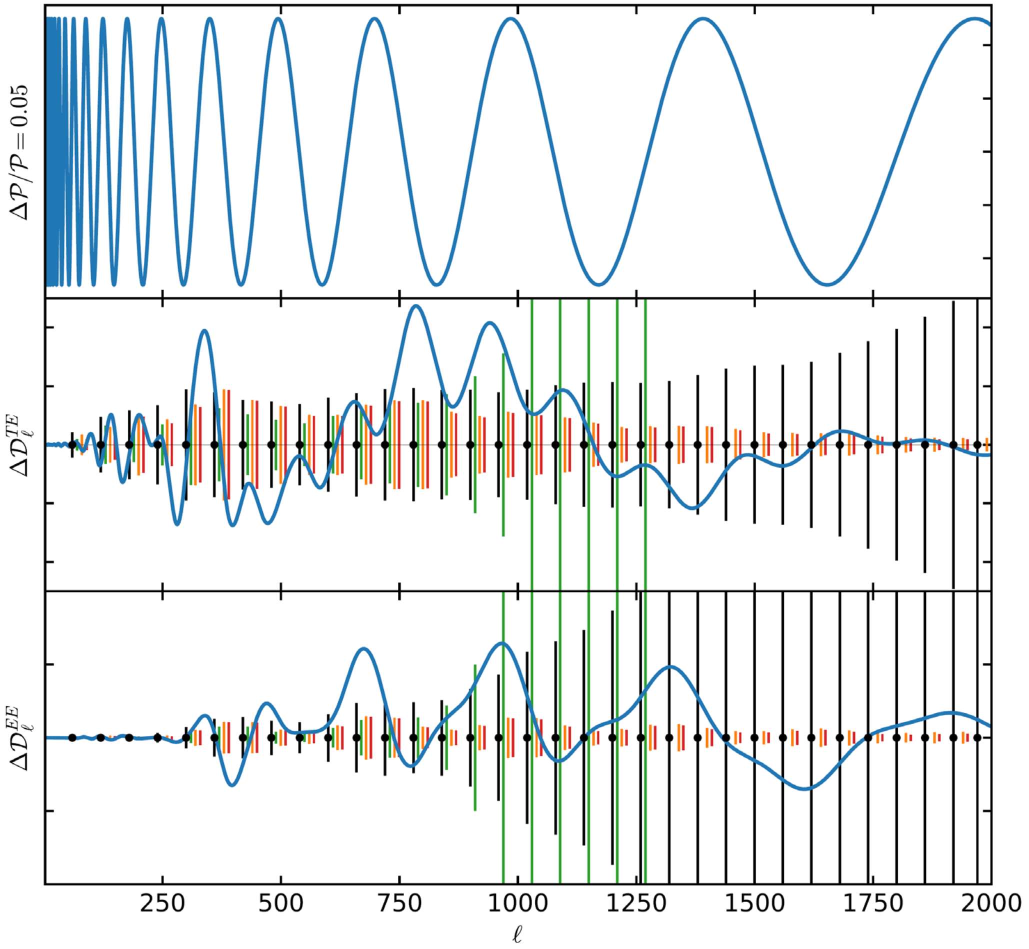
This feature model is currently indistinguishable from Standard Model

Best-fit v.s. binned residuals (Planck 18)



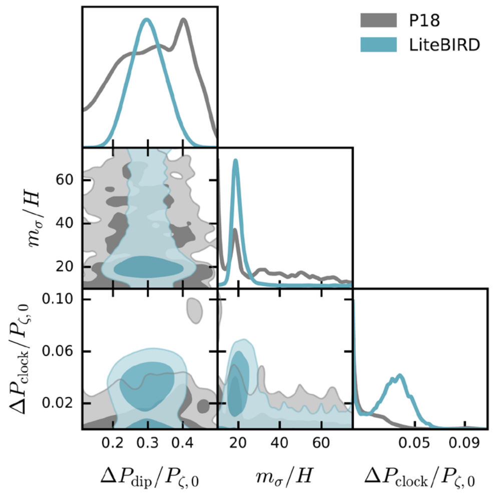
Future CMB Polarization Experiments

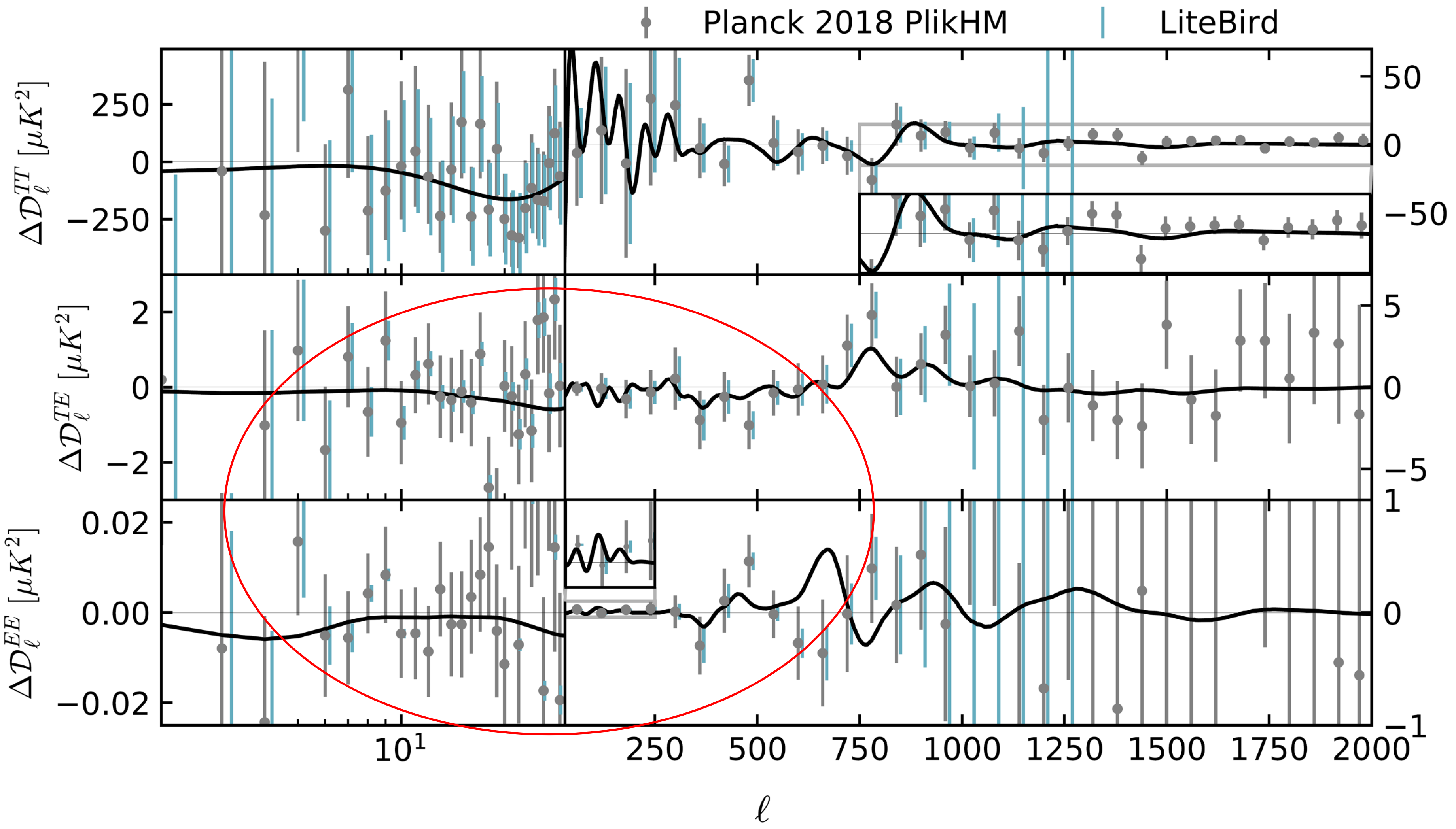




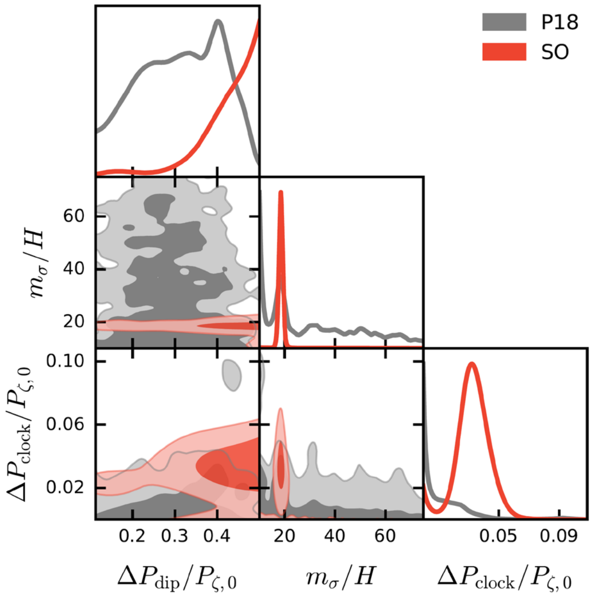
Error bar sizes in the example of resonance model

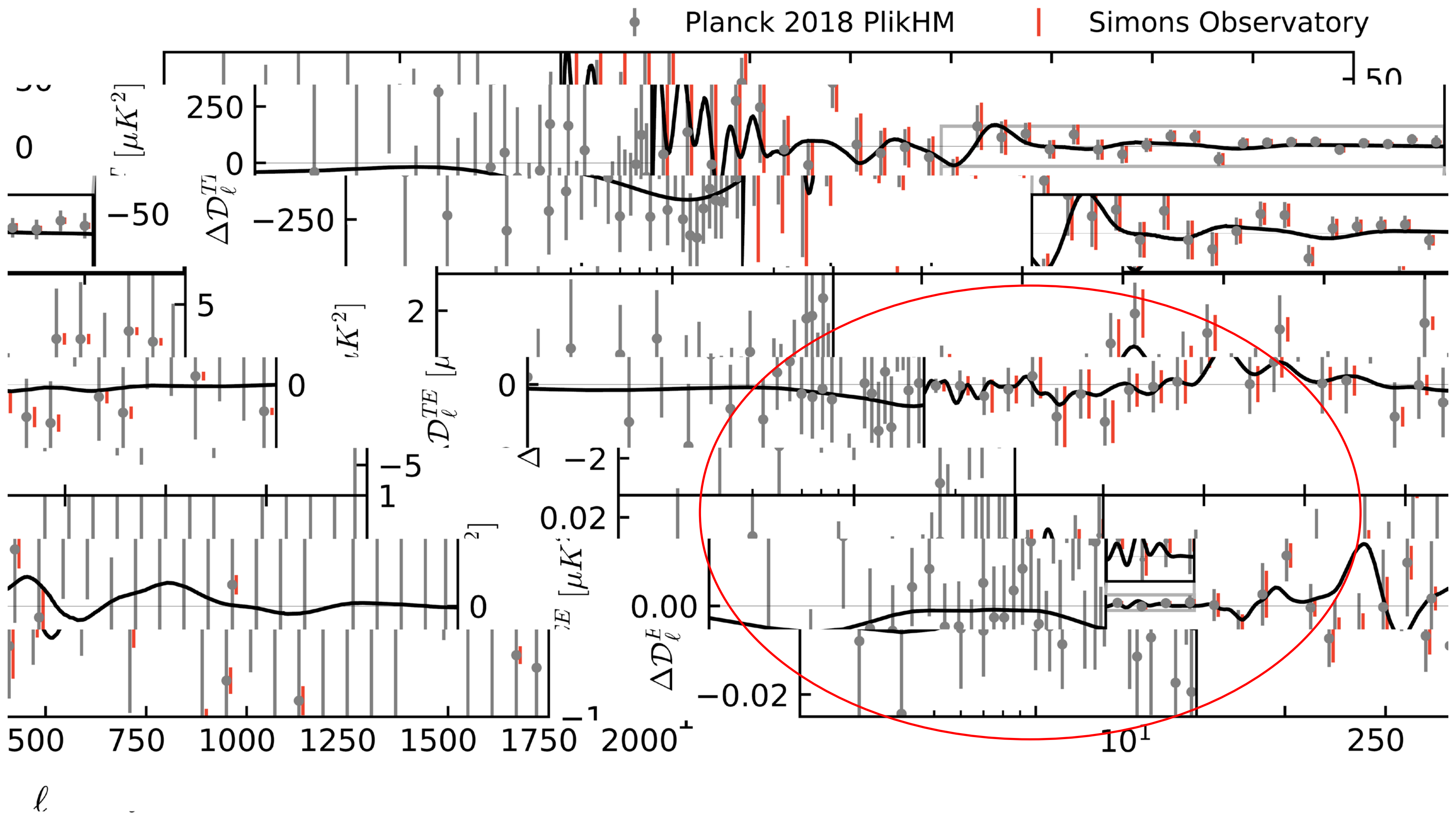
Forecast with the best-fit model: LiteBIRD





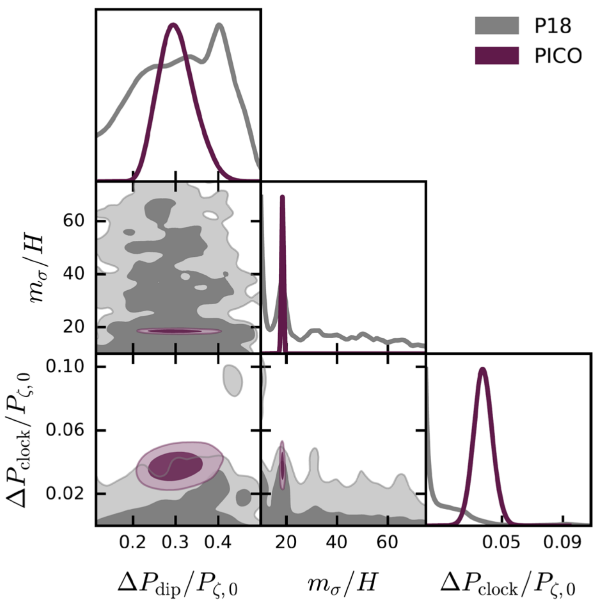
Forecast with the best-fit model: Simons Observatory

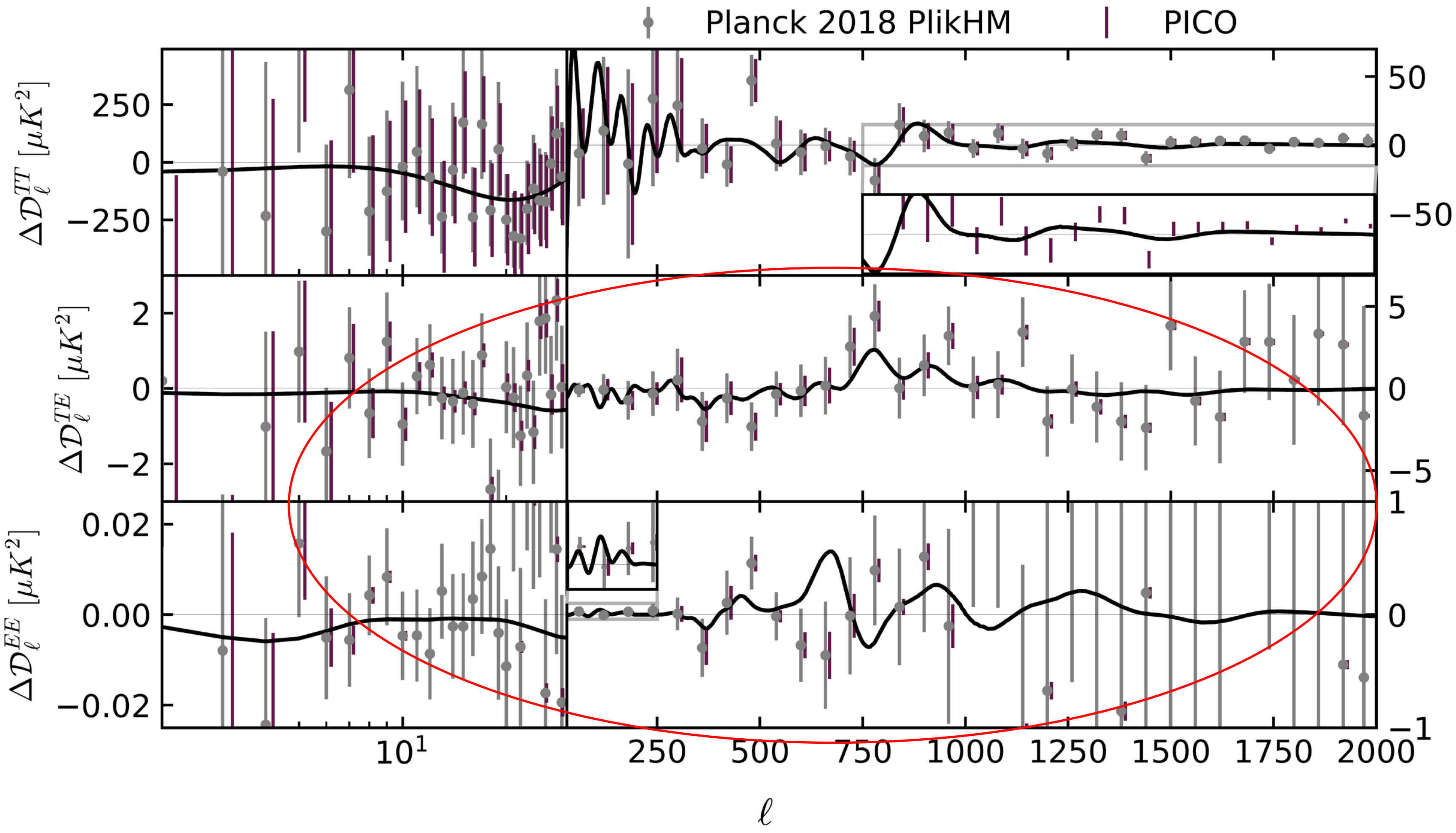




The clock signal carries information of a(t), which can be used to distinguish the inflation and alternatives in a model-independent fashion.

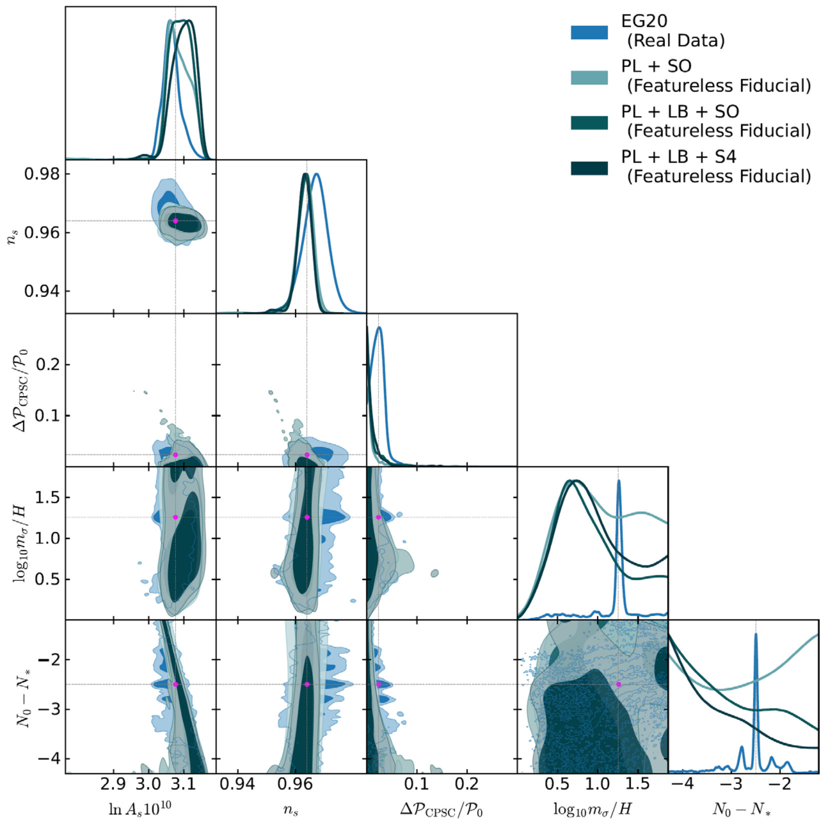
Forecast with the best-fit model: PICO



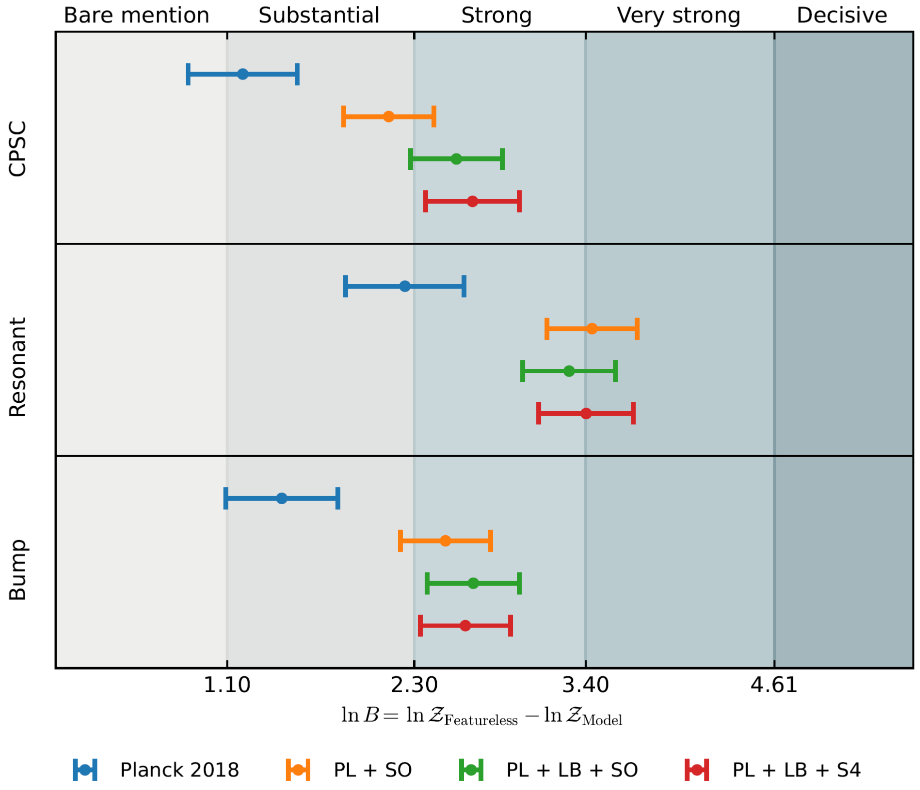


Constraints on feature model using featureless as fiducial

Example: a CPSC model



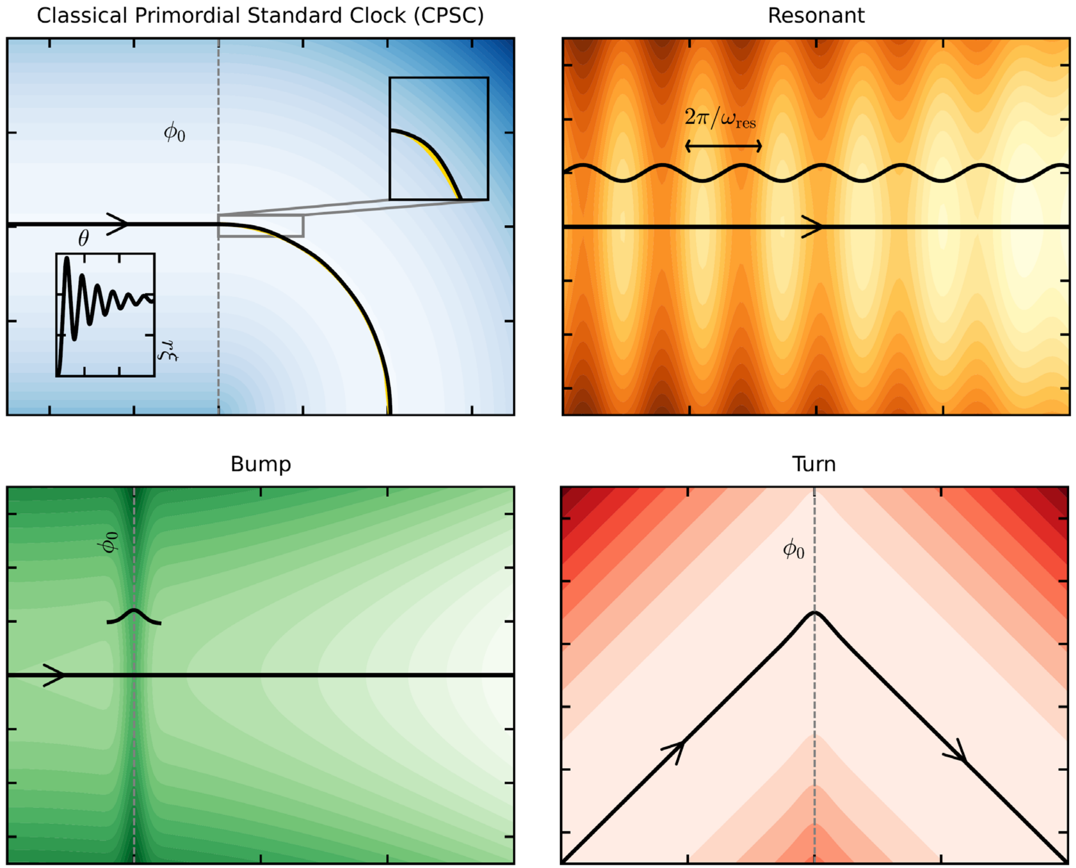
Summary for all example models:
in terms of Bayes factors

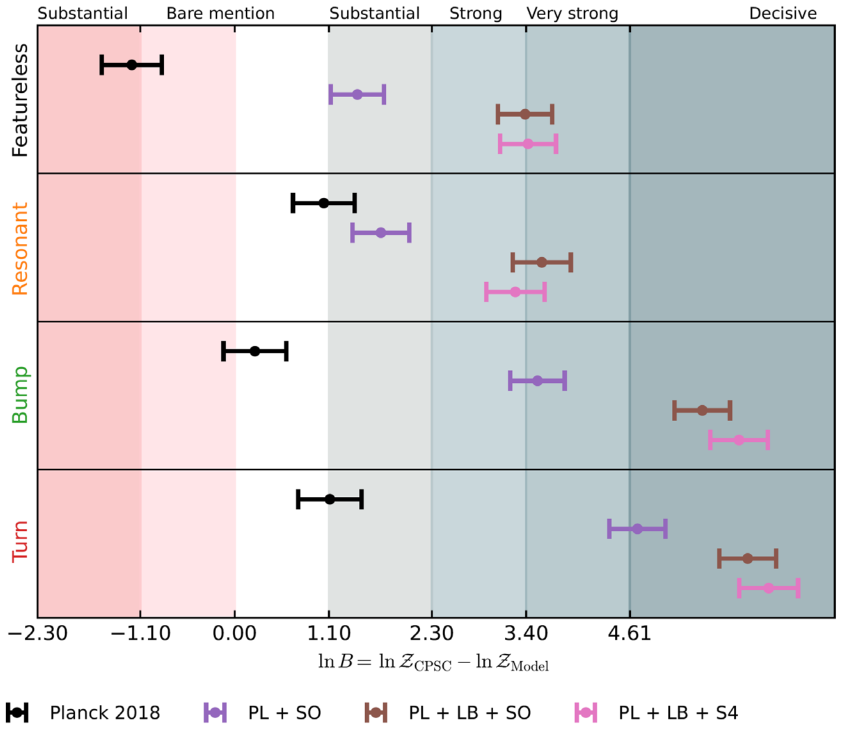


Evidences are generally strong, but not decisive -- feature amplitudes can be zero

Even if a primordial feature signal were discovered, at initial stages it will likely have multiple possible explanations.

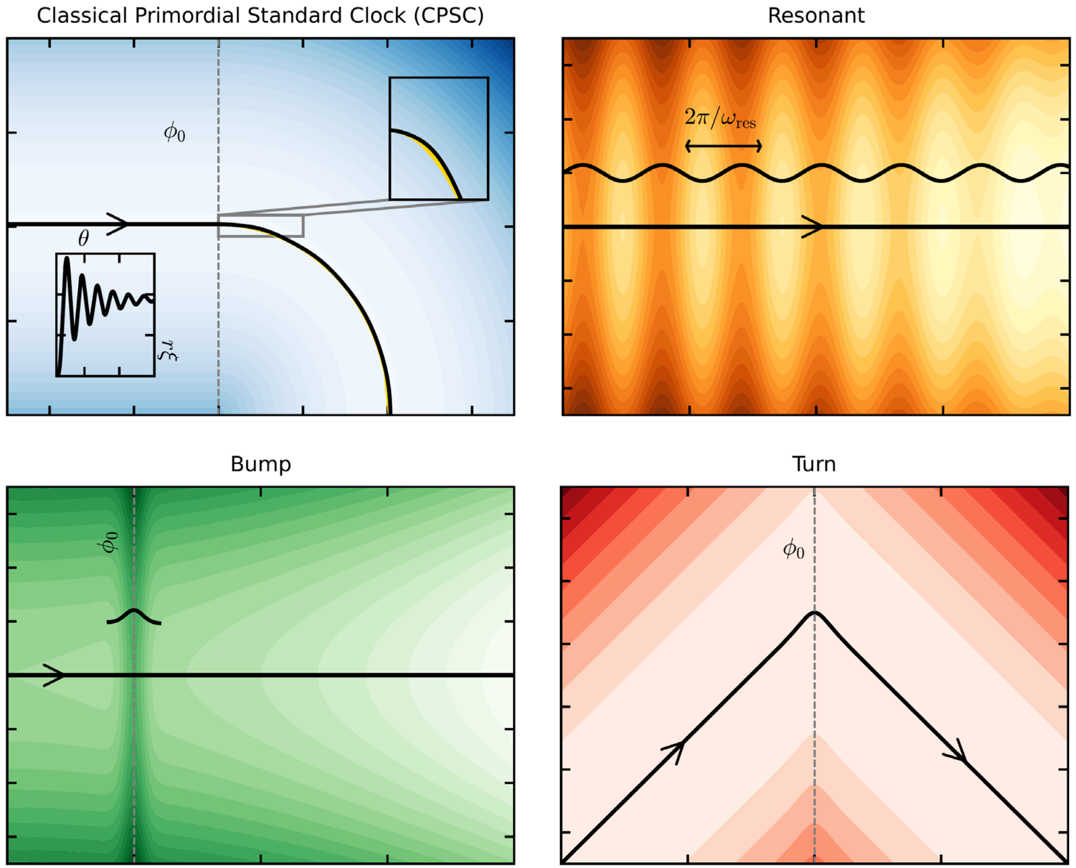
1) How confident can we detect the feature if the Universe has such a feature?



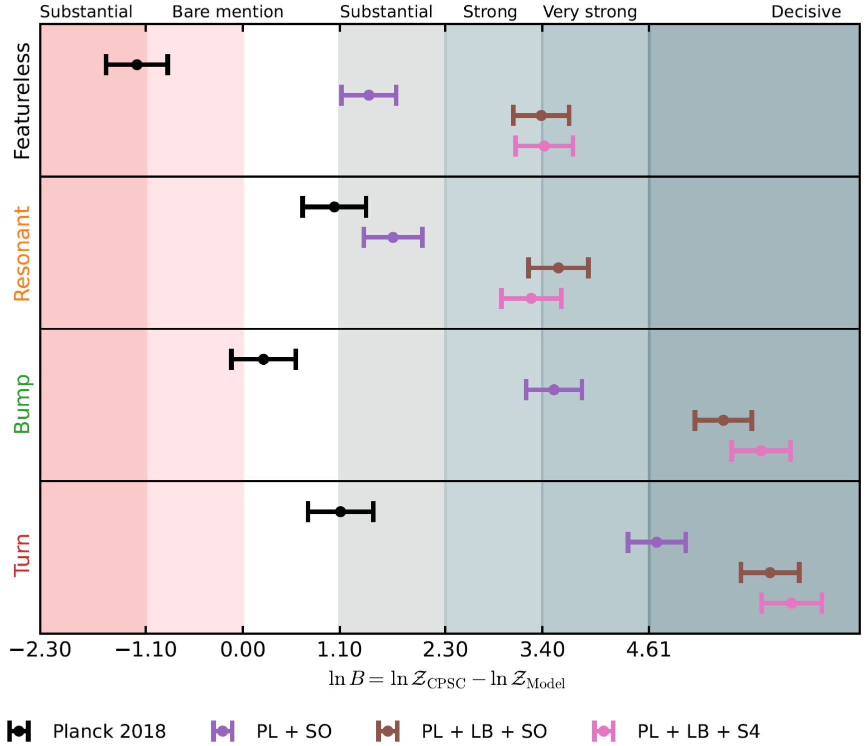


Even if a primordial feature signal were discovered, at initial stages it will likely have multiple possible explanations.

2) To what extent can we distinguish different feature models if the Universe has a feature?



E.g. using the CPSC bestfit as fiducial

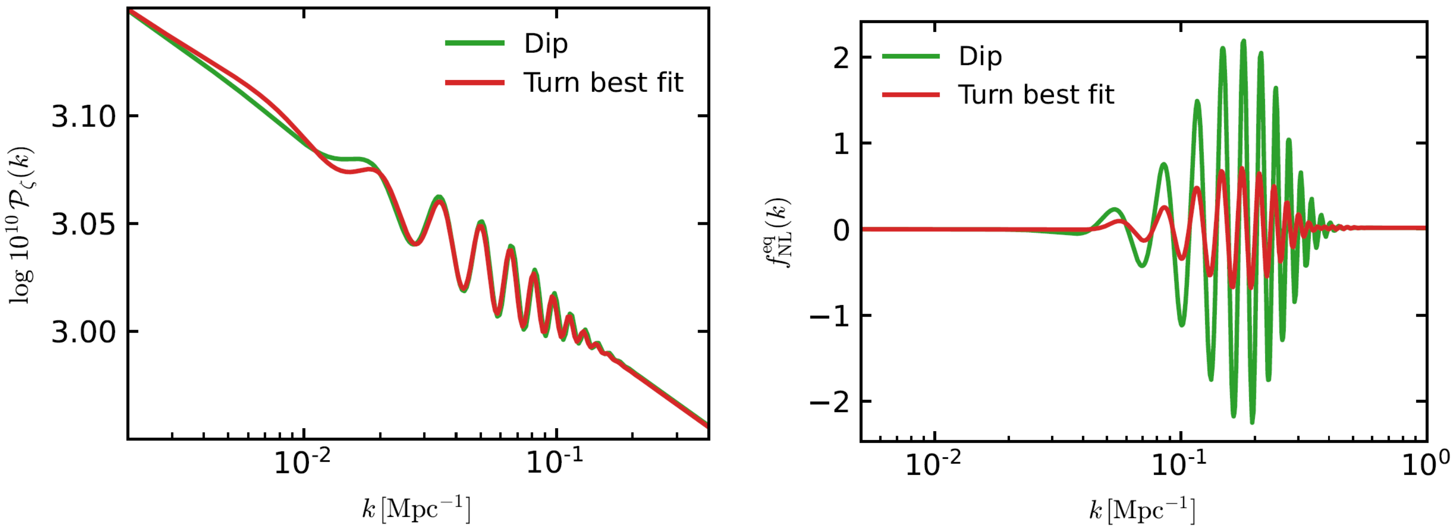


Strong to decisive evidences

(Braglia, XC, Hazra, 22)

In some special cases, the two feature models have very similar 2pt.

We may need higher order correlation functions.



Correlated feature signals should also appear in other observables

- Galaxy surveys

(Huang,Verde,Vernizzi,12; XC, Dvorkin,Huang,Namjoo,Verde,16; Ballardini,Finelli,Fedeli,Moscardini,16; Palma,Sapone,Sypsas,17; L'Huilier,Shafieloo,Hazra,Smoot,Starobinsky,17; Beutler,Biagett,Green,Slosar,Wallisch,19, …….)

- 21 cm from atomic hydrogen

(XC,Meerburg,Munchmeyer,16; Xu,Hamann,Chen,16)

- Stochastic gravitational wave background

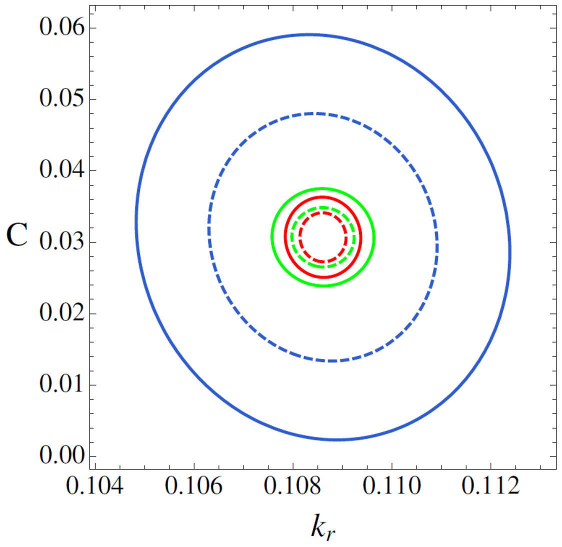
(Fumagalli, Renaux-Patel, 20; Braglia, XC, Hazra, 20; Bodas, Sundrum, 22)

- Non-Gaussianities

(Fergussion, Shellard, Liguori, 14, …)

- Isocurvature perturbations

(XC, Fan, Lin, 23)



Planck Planck+LSST Planck+Euclid

Thank You !