Primordial Features and Non-Gaussianities as Probes of Fundamental Physics

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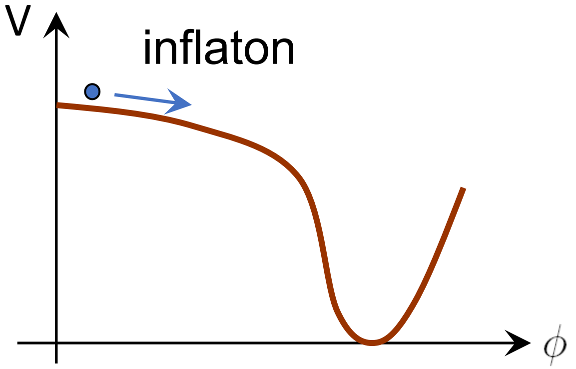
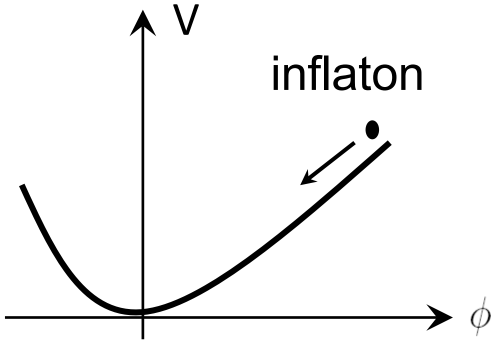
Outline

- During the primordial universe such as the inflationary epoch, all particles with mass up to the Hubble parameter or higher are excited quantum-mechanically or classically.
- These particles left their imprints in the primordial density perturbations, as primordial features and non-Gaussianities, which may be probed by astrophysical observations of the large-scale structure of the universe today.
- These information includes the particle mass and spin spectra, and the scale factor evolutionary history $a(t)$ of the primordial universe. The former resembles how particle colliders work. The latter would provide a direct evidence for the inflation or an alternative scenario.
- As an example, we present an inflationary primordial feature model that can explain both the large and small-scale feature anomalies in the currently measured CMB anisotropy spectra, revealing a clip of adventurous history of the Universe during its primordial epoch and realizing some of the properties outlined above.
- We show how to further test such models in future experiments.

Inflation scenario as the leading candidate for the Origin of the Big Bang

(Guth, Linde, Albrecht, Steinhardt, …)

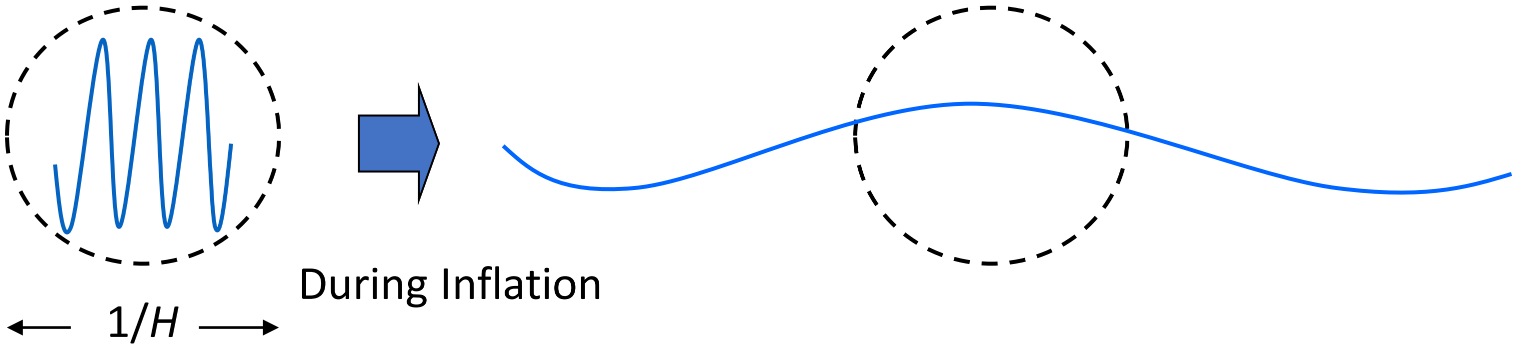




Scale Factor:

$$a(t) = a_0 e^{Ht}$$

quantum fluctuations
seeding
density perturbations



(Mukahanov, Chibisov, Hawking, Guth, Pi, Starobinsky …)

During inflation, the energy scale of the universe is given by the Hubble parameter:

$$H \lesssim 10^{14}\mathrm{GeV}$$

What can we learn about fundamental theory at this energy scale from density perturbations?

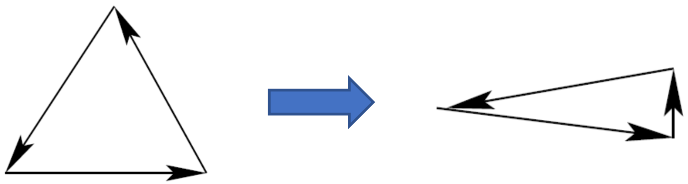
Tools:

Study correlation functions of density perturbation maps:

power spectra (2pt), non-Gaussianities (3pt/bispectra, 4pt/trispectra, ……)

- scale-dependence:

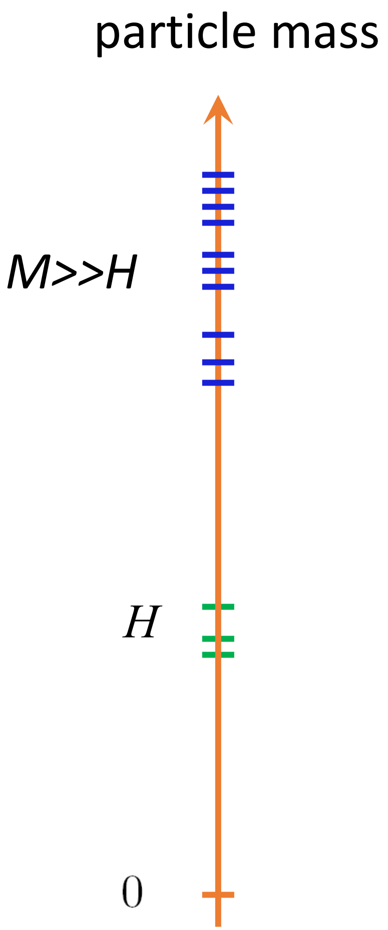
- shape-dependence:



Physics Questions

- What are the signatures of particles created on-shell at energies of order H?

- How to distinguish inflation from a possible alternative scenario in a model-independent fashion?



- To get *m* << *H*, tuning is necessary generically

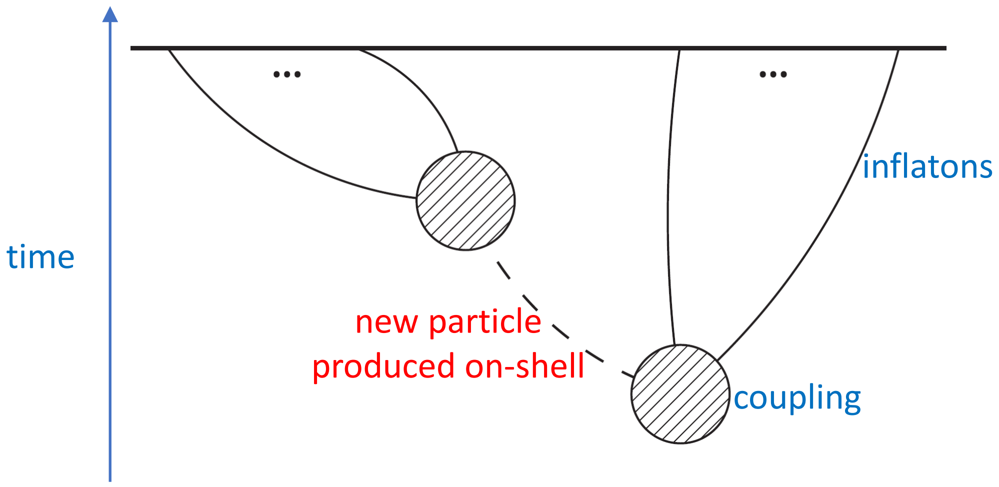
$$m^2 \sim H^2 \xrightarrow{\text{tune}} m^2 \lesssim \mathcal{O}(0.01)H^2$$

The η - problem

- Many others remain of order *H* or higher

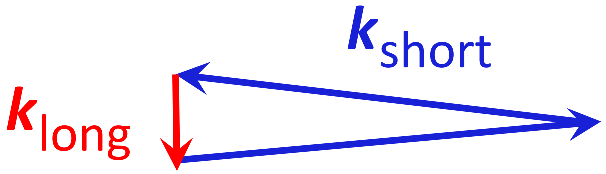
- These fields are not as important classically, but may be important quantum mechanically

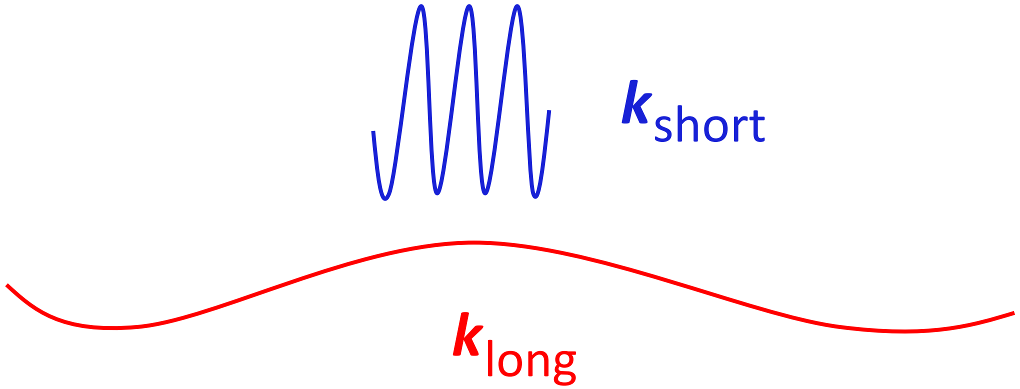
Quasi-Single-Field Inflation



New particles produced on-shell couple to inflatons, and leave imprints in inflaton correlation functions

Let us look at the limit in which wavelength of massive particle is long





Longer wavelength quantum fluctuations of massive field is classical-like:

$$v_k \sim a^{-3/2}\left(c_+ e^{-imt} + c_- e^{imt}\right)$$

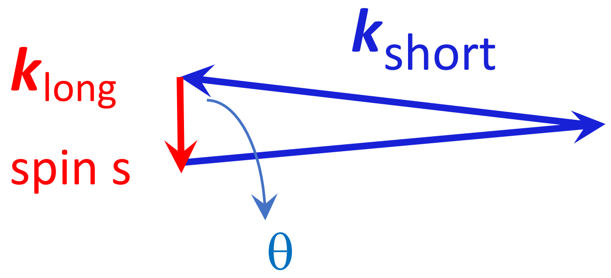
serve as background oscillating clock for shorter wavelength inflaton mode clock oscillation from massive field: $\sigma \propto e^{\pm imt}$

subhorizon inflaton field oscillation: $\zeta_{\mathbf{k}} \propto e^{-ik\tau}$

$$dt = e^{Ht} d\tau$$

resonance → scale-invariance

$$\left(\frac{k_{\rm long}}{k_{\rm short}}\right)^{\pm i \frac{m}{H}}$$



→ $P_s(\cos\theta)$

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

$\frac{1}{2}\pm i\mu$ → 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

- Signatures of Standard Model

  (Hook, Huang, Racco, 19; Kumar, Sundrum, 17; XC, Wang, Xianyu, 16, 17)

- Implication for SUSY finetuning problem (Baumann, Green, 11)

- Generalize to more general EFT (Noumi, Yamaguchi, Yokoyama, 12)

- Generalize to strong coupling (An, McAneny, Ridgway, Wise, 17)

- Signatures of sterile neutrino and gauge bosons (XC, Wang, Xianyu, 18; Wang, Xianyu, 20)

- Signatures of higher dimensional GUT (Kumar, Sundrum, 18, 19)

- Signatures of higher spin fields and bootstrap

  (Lee, Baumann, Pimentel, 16; Arkani-Hamed, Baumann, Lee, Pimentel, 18)

- Probing P and CP violation (Liu, Tong, Wang, Xianyu, 19)

- Applied to curvaton or preheating scenario (Lu, Wang, Xianyu, 19) (Fan, Xianyu, 20)

- … … …

Imprints of massive fields in scale-dependence of density perturbations

Primordial Feature Signals: strongly-scale-dependent deviations from otherwise scale-invariant spectra

There are many aspects that can be probed by primordial feature signals.
Here we focus on the following two questions:

- **Can we distinguish the inflation scenario and a possible alternative scenario in a model-independent fashion?**

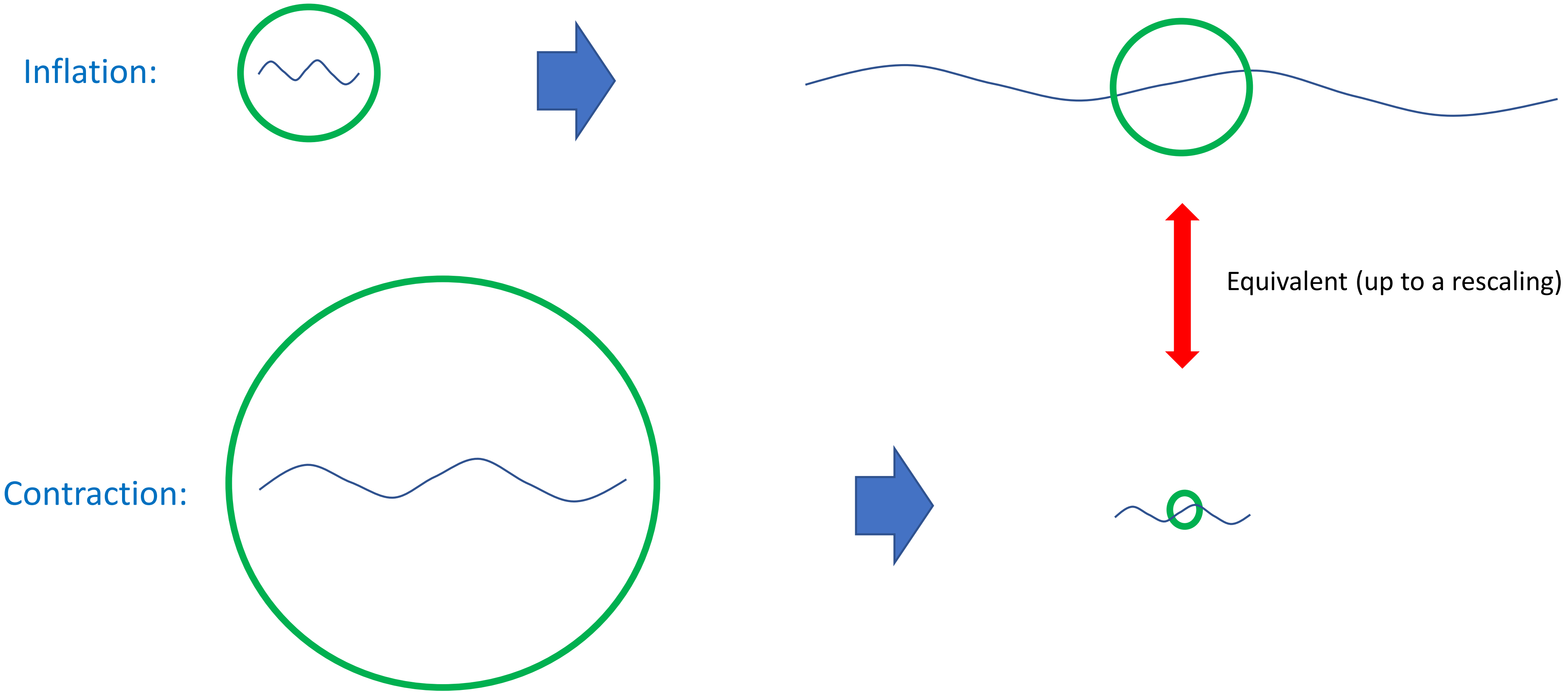
(N.B. Model-independent: independent of models used to achieve the inflation, or alternative-to-inflationary, background.)

- **Evolutionary history of cosmic inflation.**

Is the primordial universe inflationary?

Toy models of alternative-to-inflation act as a reminder that several key predictions of inflation may not be unique to the inflation scenario, and that there may be alternatives to inflation that should be explored and tested.

E.g. superhorizon perturbations



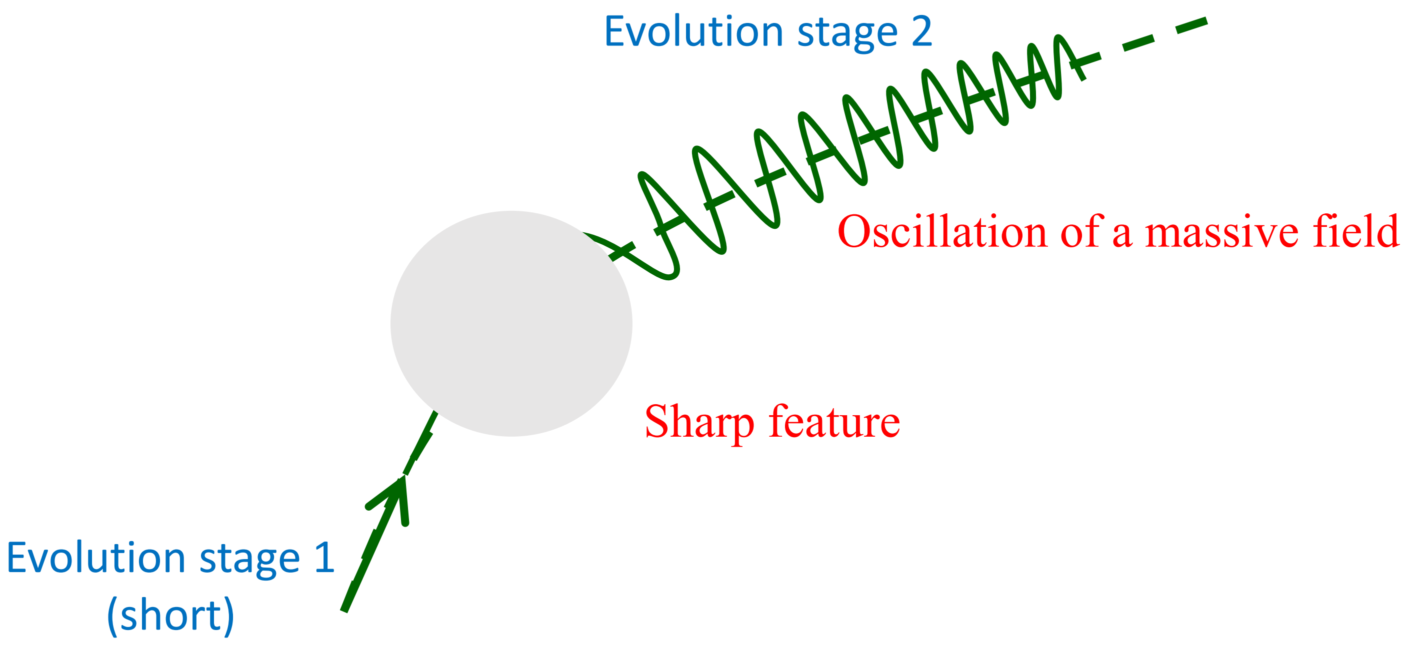
The degeneracy arises because different types of $a(t)$ predict the same value for an observable.

Are there any observables that can directly measure $a(t)$?

Landscape of Potential

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

Orthogonal directions are lifted by potentials, i.e., massive fields



Sharp features include: sharp turning, tachyonic falling, interactions, etc.

Massive field starts to oscillate classically due to some kind of kick (sharp feature)

Massive fields oscillate in a standard way (i.e. harmonic) in any background

(Massive: Mass larger than event-horizon scale of the primordial epoch)

Oscillations provide ticks for the time coordinate t

⇩

Induce patterns of ticks in density perturbations – “**Clock Signals**” – that encodes *a*(t)

Primordial Standard Clocks (XC, 11)

Generating Clock Signals

(XC, 11; XC, Namjoo, Wang, 14, 15)

Standard clock oscillation: $\sigma \propto e^{\pm imt}$

Subhorizon curvature field oscillation: $\zeta_{\mathbf{k}} \propto e^{-ik\tau}$

$dt = a d\tau$

Correlation functions, e.g.: $\langle \zeta_{\mathbf{k}}^2 \rangle \supset \int e^{i(mt - 2k\tau)} d\tau$

The correlation receives leading contribution at the resonance point: $\frac{d}{dt}(mt - 2k\tau) = 0$

⟹ $\langle \zeta_{\mathbf{k}}^2 \rangle \supset e^{i(mt_* - 2k\tau_*)}$ $a(t_*) = a(\tau_*) = 2k/m$

$$\langle \zeta_{\mathbf{k}}^2 \rangle \supset \exp\left[im\ t(2k/m) - 2ik\ \tau(2k/m)\right]$$

$t(2k/m)$ and $\tau(2k/m)$ are inverse functions of the scale factor $a(t)$ and $a(\tau)$

Scale factor as a function of time is directly encoded in the phase of the "clock signals" as a function of *k*

Phenomenological Approach to All Scenarios:
Describe background of different scenarios by a simple power-law function

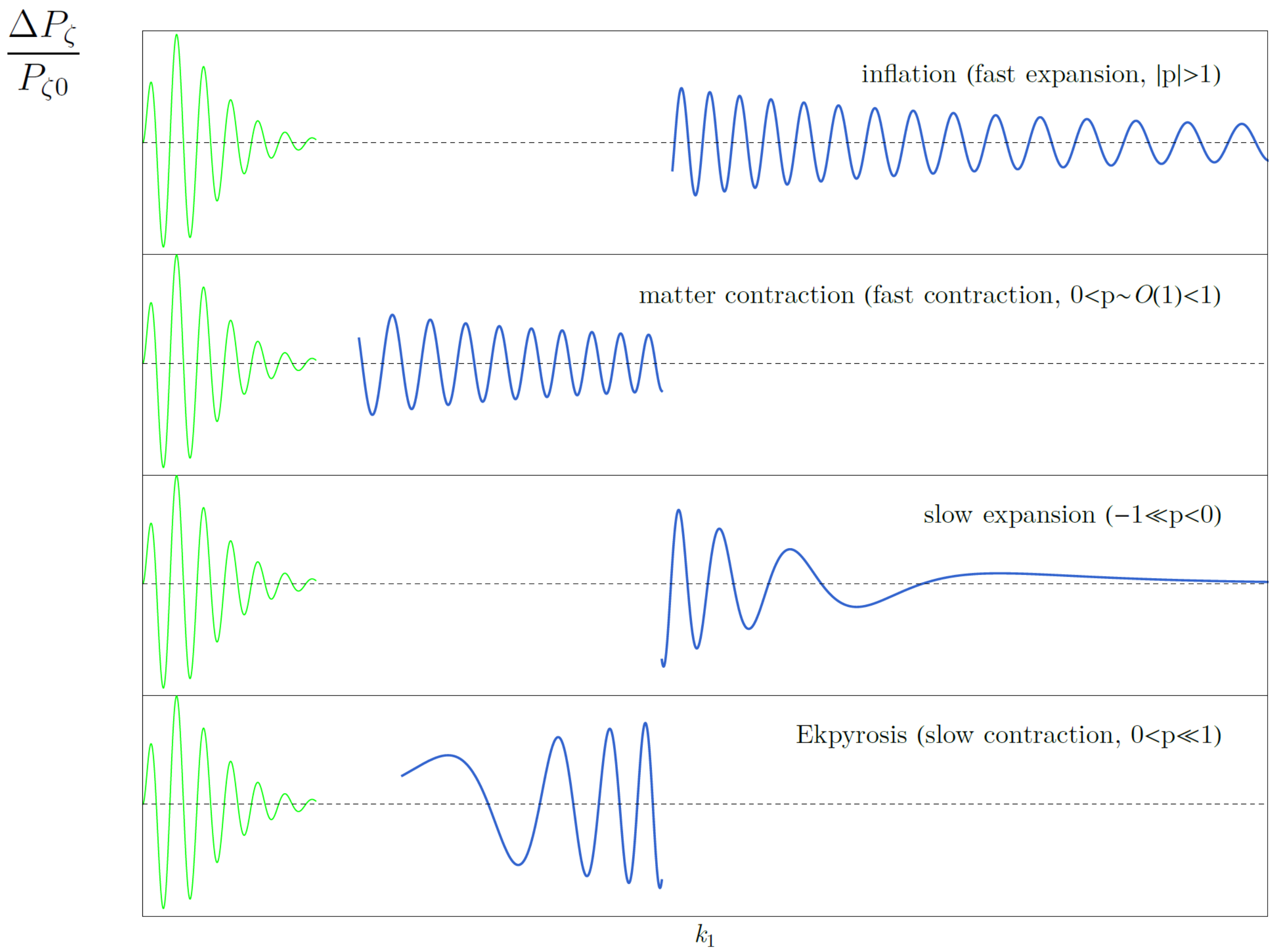
$$a(t) \sim t^p \qquad \text{arbitrary } p$$

Requiring quantum fluctuations exit horizon fixes the domain of *t* given *p*

$\|p\| > 1$	t: from 0 to $+\infty$	Fast expansion (Inflation) (Guth, 81, Linde, Albrecht, Steinhardt, 82)
$0 < p \sim \mathcal{O}(1) < 1$	t: from $-\infty$ to 0	Fast contraction (e.g. Matter contraction) (Wands, 98; Finelli, Brandenberger, 01)
$0 < p \ll 1$	t: from $-\infty$ to 0	Slow contraction (e.g. Ekpyrosis) (Khoury, Ovrut, Steinhardt, Turok, 01)
$-1 \ll p < 0$	t: from $-\infty$ to 0	Slow expansion (e.g. String gas cosmology) (Brandenberger, Vafa, 89)

Fingerprints of Different Scenarios

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



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

Sharp Feature Signal

$$\frac{\Delta P_\zeta}{P_{\zeta 0}} \propto 1 - \cos(2k_1\tau_0)$$

with model-dependent envelop/phase

Sinusoidal running is a signature of "sharp feature";
but not a signature of massive field, **nor** does it record $a(t)$.

Universal for different scenarios.

Nonetheless, an important component of full classical PSC signal.

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

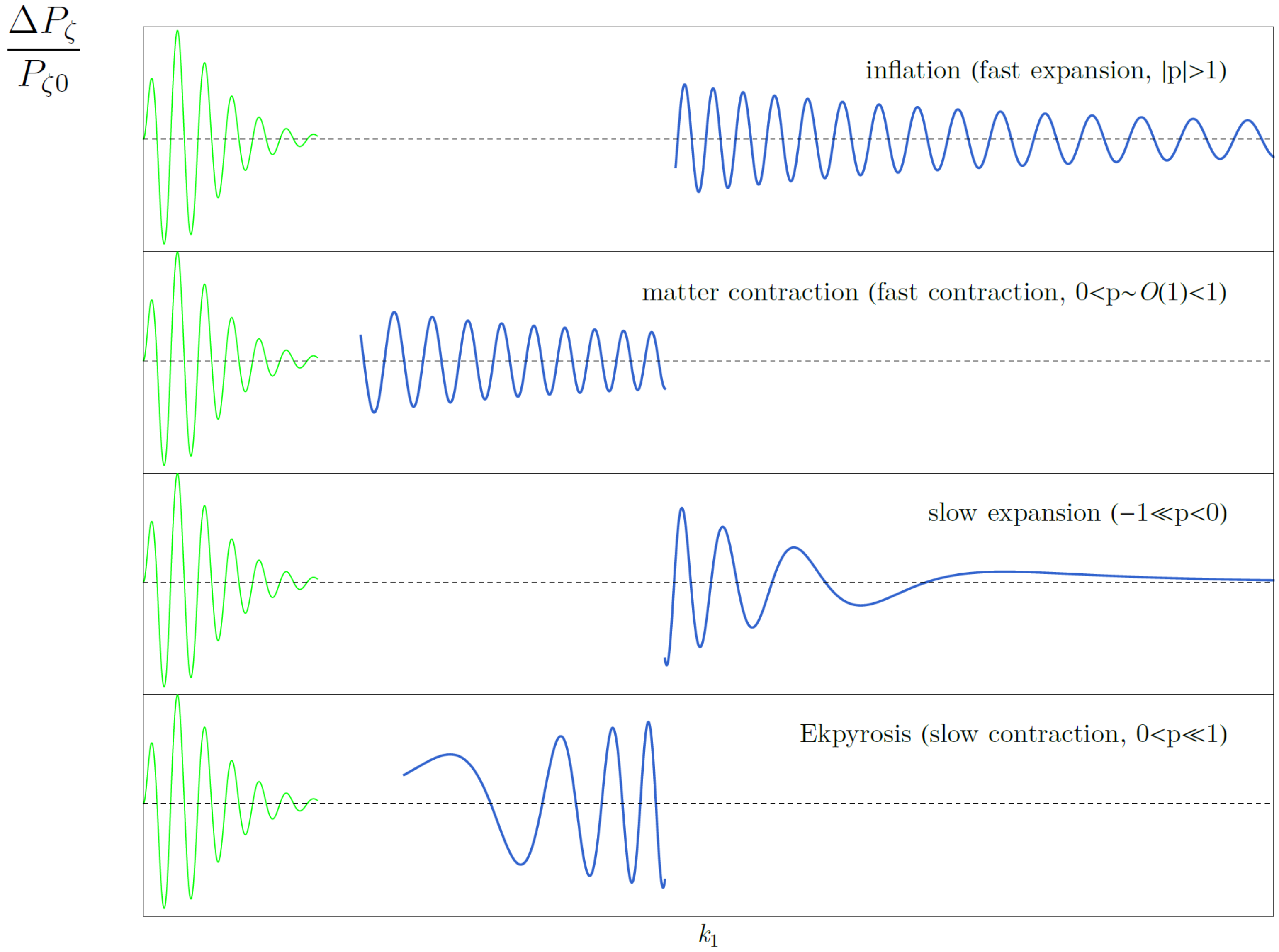
Inverse function of *a*(*t*)

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

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

Fingerprints of Different Scenarios

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



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

A Connection between Primordial Standard Clocks and Cosmological Collider Physics: Quantum Primordial Standard Clocks

(XC, Namjoo, Wang, 15)

For *m>3H/2*

$$S \propto \left(\frac{k_{\rm long}}{k_{\rm short}}\right)^{\frac{1}{2}\pm i\mu} \sim \left(\frac{k_{\rm long}}{k_{\rm short}}\right)^{\frac{1}{2}} \sin\left(\mu \ln \frac{k_{\rm long}}{k_{\rm short}} + {\rm phase}\right)$$

⇩

Inverse function of exp

⇩

Background is exponential inflation

So, cosmological collider is measuring not only the particle spectrum, but also the scale factor evolution of the inflationary background.

Shape-Dependent Clock Signals in Quantum PSC

$$S^{\rm clock} \propto \left(\frac{2k_1}{k_3}\right)^{-\frac{1}{2}+\frac{1}{2p}} \sin\left[p\,\frac{m}{m_{{\rm h},k_3}}\left(\frac{2k_1}{k_3}\right)^{1/p} + \varphi(k_3)\right]$$

Inverse function of *a*(*t*)

k_3 : long mode k_1 : short mode

Shape-dependent oscillatory signal

Scale-Dependent Clock Signals in Quantum PSC

(XC, Loeb, Xianyu, 18)

Quantum fluctuations of the massive field, at late time, develops a k-dependent phase that directly records *a*(*t*)

$$v_k \sim c_+ e^{-imt} + c_- e^{imt} \quad \Rightarrow \quad v_k \propto \exp\left(\pm i\beta\tilde{k}^{1/p}\right)\exp\left(\pm ik\tau\right)$$

time-independent clock signal phase factor

$$\Delta\langle\zeta^2\rangle' = |c_+c_-^*|\sin\left(2\beta\tilde{k}^{1/p}+\phi\right)f(k)+\ldots$$

clock signal: inverse function of *a*(*t*)

Non-Standard Primordial Clocks

Any repeated signals may be used as clocks – may cause confusion for standard clock signals

Non-standard clocks: (XC, 11)

$a(t) \sim t^p$ (arbitrary p)

engineer $B(t) \sim e^{ig\ln(t/t_0)}$ ⇒ $\sin\left[\frac{g}{p-1}\ln\frac{K}{k_r} + \text{phase}\right]$ mimic Inflation-like oscillatory pattern

Such as time-dependent mass or oscillatory potential

E.g.

Non-inflation mimics inflation: $\xi R\sigma^2$ ➡ $B(t) \sim e^{ig\ln(t/t_0)}$ (Wang, Wang, Zhu, 20)

Inflation mimics non-inflation: Field-dependent mass: $m^2(\phi)\chi^2$ (Huang, Pi, 16; Domenech, Rubio, Wons, 18)

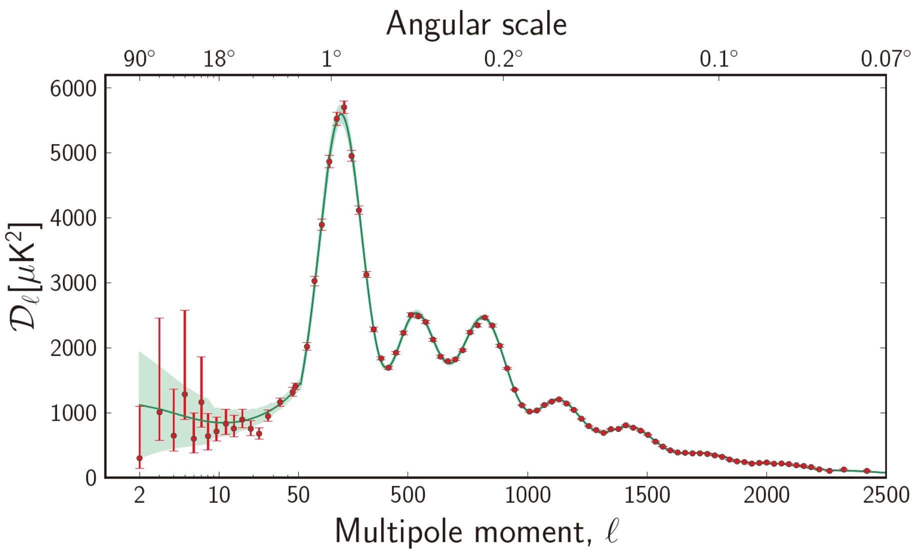
How to distinguish?

1) Running of the envelop of the clock signal, full signal; 2) Non-Gaussianities;
3) Constant mass case is general, and each scenario has its own general prediction.
Extra parameters are needed to just mimic.

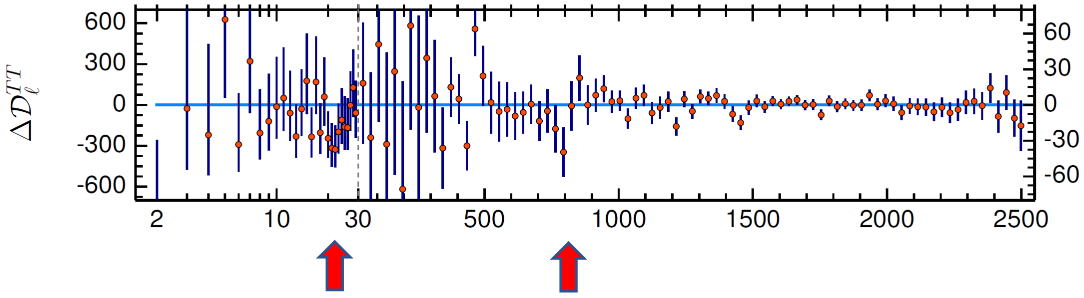
An explicit classical primordial standard clock model
and
data comparison

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)

Explicit models constructed in the past address either one of the anomalies, but not both.

The two well-separated features in CMB may be connected by the Standard Clock effect – pointed out but never explicitly constructed.

Basic model building requirements for CPSC

- Two observable inflationary stages joint by a sharp feature
- A massive field is excited classically by the sharp feature

Clock v.s. Sharp Feature signals

- Behavior (including running and envelop) of clock signal is quite general and robust, basically only depends on a(t)
- Running of sharp feature signal is robust; but its envelop behavior is highly model-dependent
- The relative amplitudes between clock and sharp feature signal is highly model-dependent

Both signals have their different physical significance:

- Use the robust clock signal to distinguish between inflation and alternative model-independently
- Use the model-dependent sharp feature signal to reveal the rather detailed history of inflation

Model building lessons

(Adams,Cresswell,Easther,01; Peiris et al, 03; XC,11; Gao,Langlois,Mizuno,12; Noumi,Yamaguchi,13; Saito,Nakashima,Takamizu,12; XC,Namjoo,Yi,14; Braglia,XC,Hazra,21, ……)

- A step sharp feature is desired for the large-scale dip (instead of e.g. bump or kink). The placement of the step in the multifield configuration is also important.
- Direct coupling between massive field and inflaton is desired to enhance amplitude of clock signal (such as a curved path)
- Bending of path cannot be too sharp to avoid a bump feature in large scales

There are many adjustable model details. Which ones should be described by free parameters?

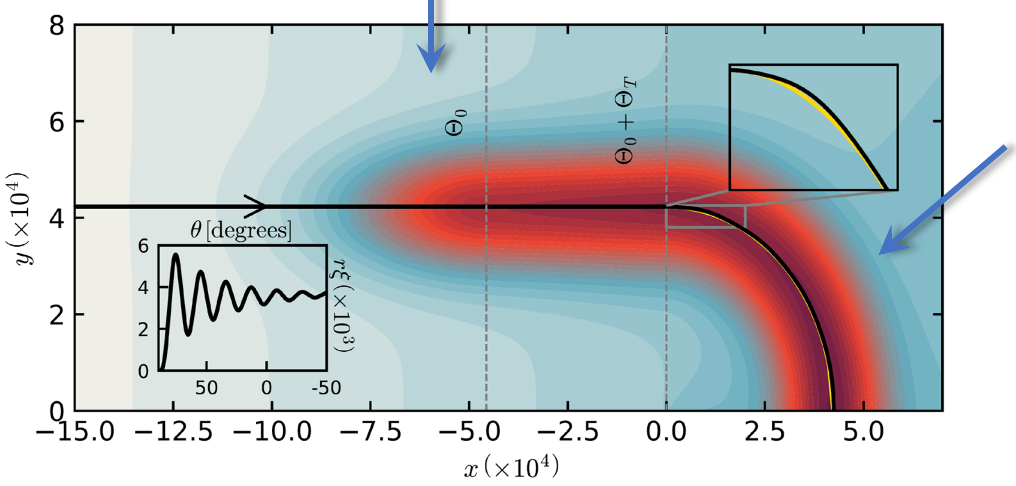
A guideline:

- If a property in data needs to be addressed by a parameter with finite value – parameterize it
- If a property can be addressed by a parameter satisfying an upper or lower bound – no need to parameterize

This guideline is supported by the way the parameters contribute to the Bayes Evidence.

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 c.f. standard model)

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

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

➡ Oscillation decays, settles down to 2nd stage inflation, (very model-independent)

Sharp feature signal part of the model predictions sensitively depend on background evolution

A efficient methodological pipeline to directly compare numerical results with Planck data for complicated feature models
(for method see Braglia, XC, Hazra, 21):

Model Lagrangian

↓

Effective parameters describing distinctive properties

e.g. $\frac{m_\sigma}{H} = \frac{V_{\sigma\sigma}(\sigma=0)}{H} \approx \frac{\sqrt{6C_\sigma}}{\sigma_f}$

$$\left.\frac{\Delta P_\zeta|_{\rm clock}}{P_{\zeta 0}}\right|_{\rm amp} \approx \frac{\sqrt{2\pi}}{3}\frac{\epsilon}{C_\sigma}(\sigma_f \xi)^2 \left(\frac{m_\sigma}{H}\right)^{1/2}$$

(more physical; easy prior choices; OK if approximate)

↓

Model parameters

↓

Numerical solution, using BINGO (Braglia,Hazra, Sriramkumar,Finelli,20)

↓

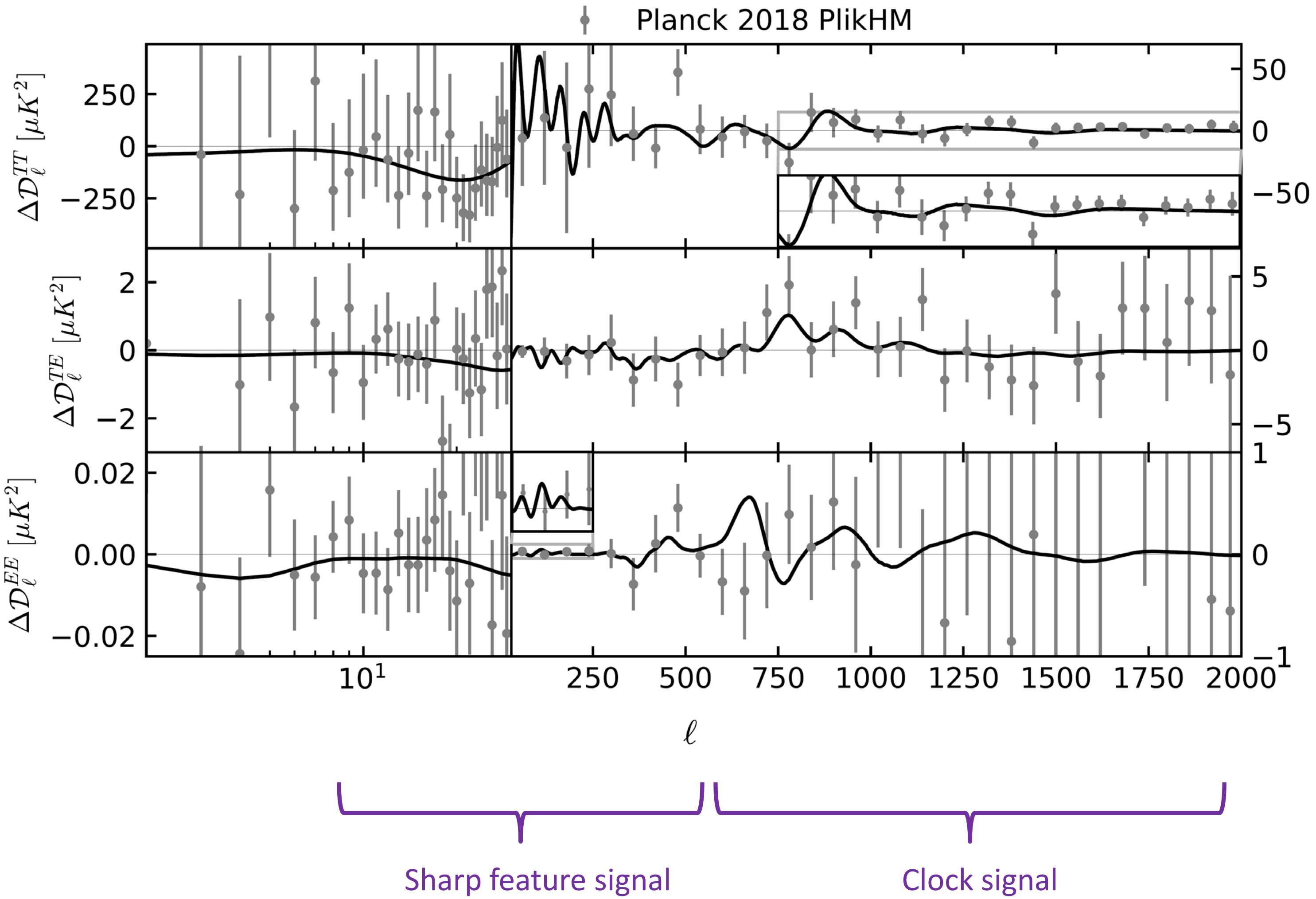
CAMB, get angular spectra

↓ **Planck likelihood + Priors**

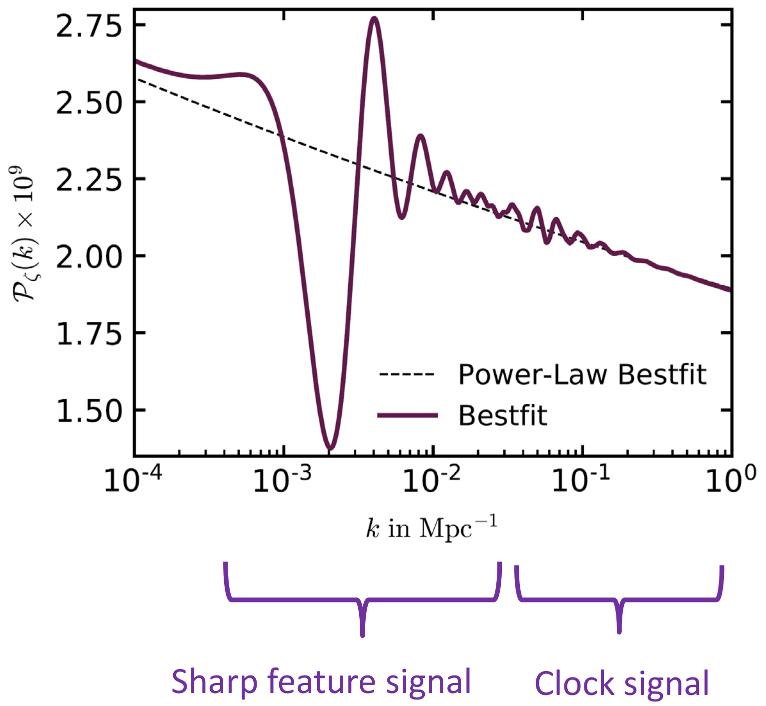
Nested sampling, using PolyChord (Skilling,06; Handley,Hobson,Lasenby,15)

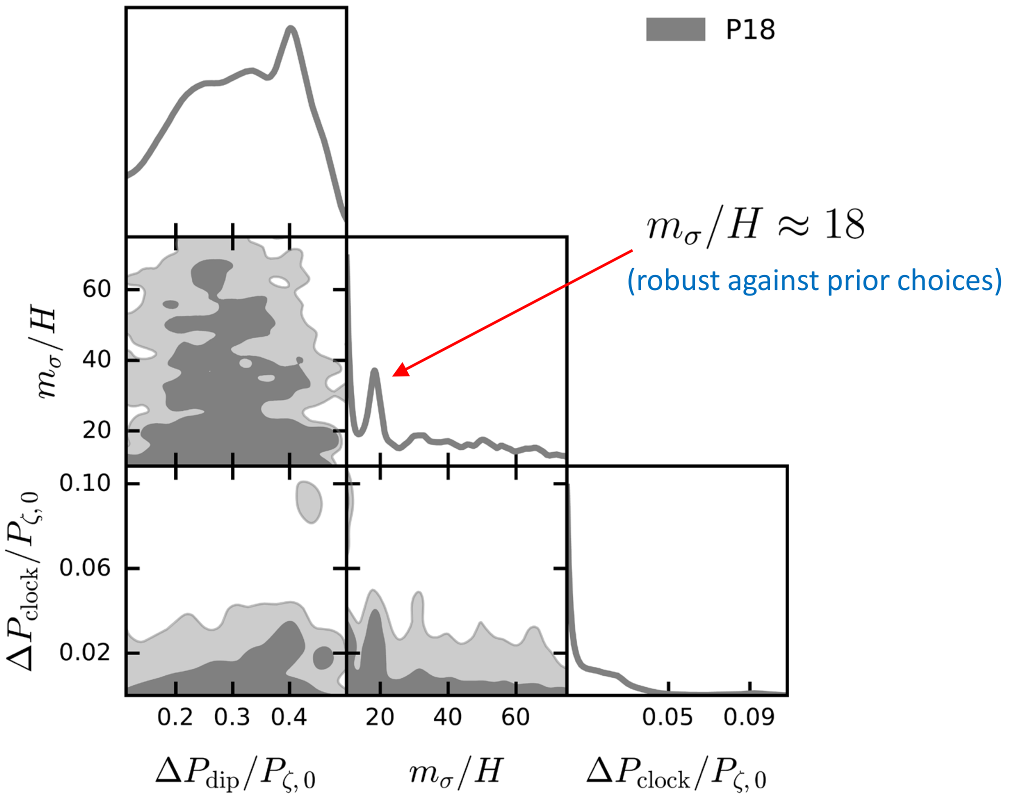
(multi-modality)

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



Best-fit, Posteriors, and Bayes Evidence



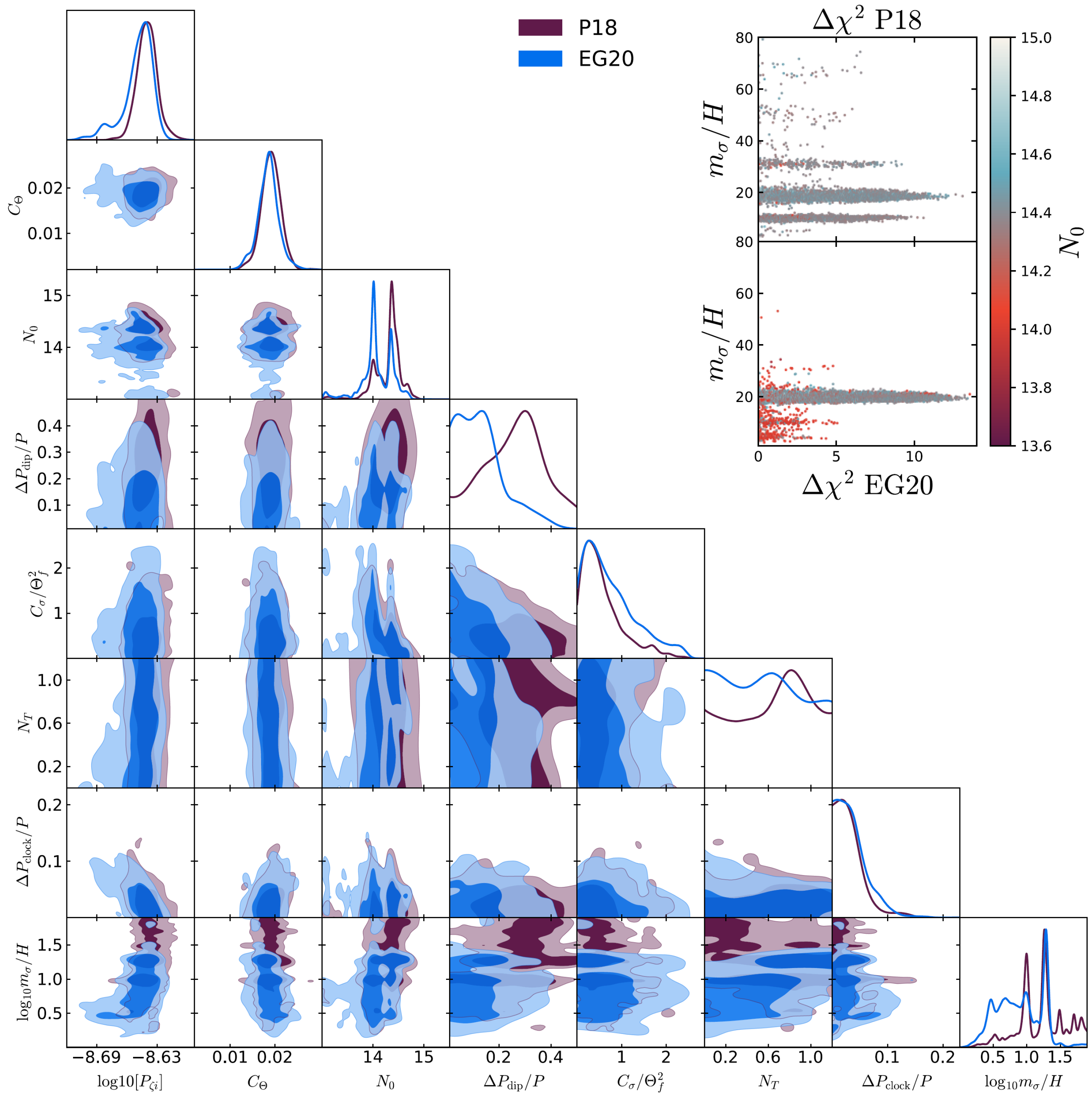


Best-fit: $\Delta\chi^2 = 19.8$ (with 6 extra parameters)

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

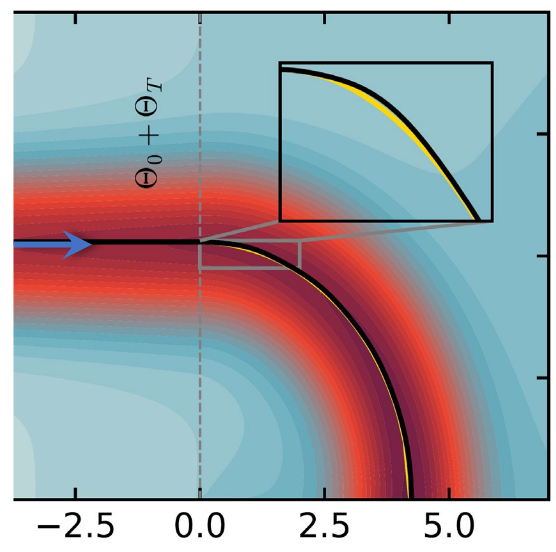
This feature model is currently indistinguishable from Standard Model

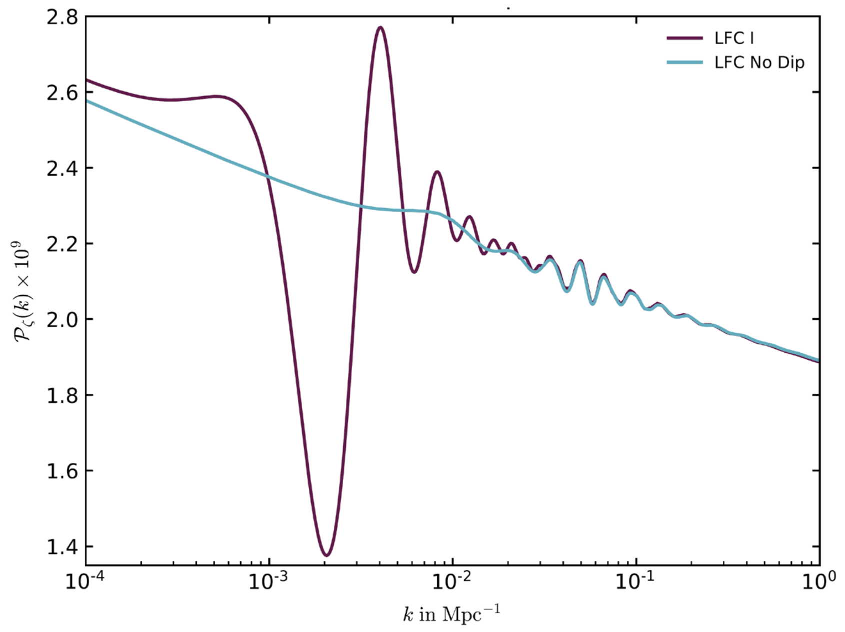
Tested with another more powerful Likelihood EG20: Efstathiou, Graton, 20



(Braglia,XC,Hazra, to appear)

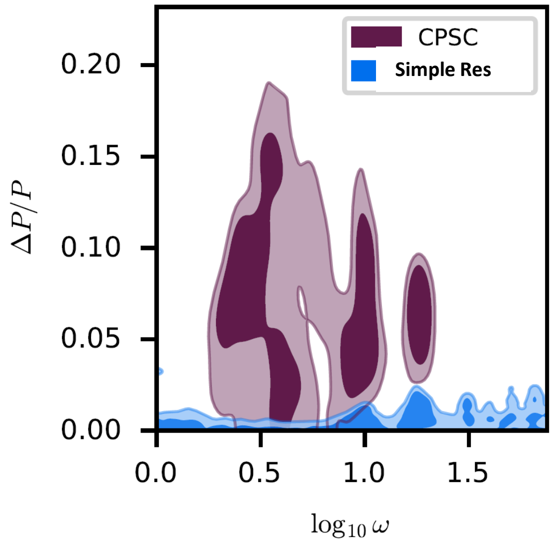
A restricted model without the step (3-parameter model), addressing small scale anomaly only





Best-fit:

$$\Delta\chi^2 = 12.9$$

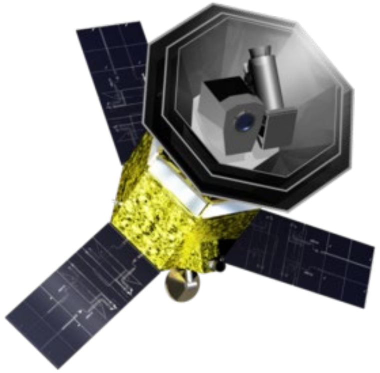
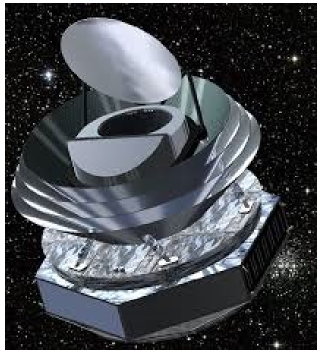


Restricted CPSC v.s. simple resonant model $\Delta P_\zeta / P_\zeta = C \sin(\omega \ln k + \text{phase})$

Both have 3 extra parameters

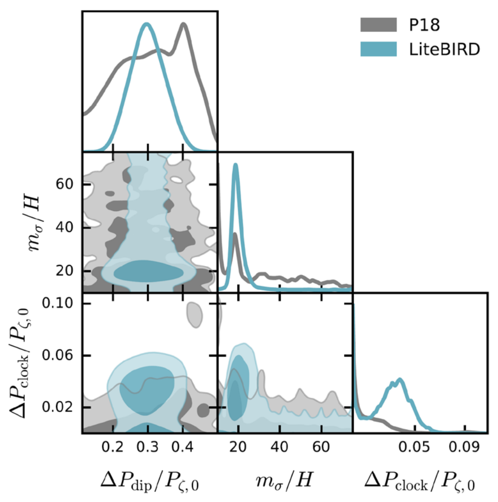
$\ln B = -0.38 \pm 0.38$ v.s. $\ln B = -2.29 \pm 0.38$

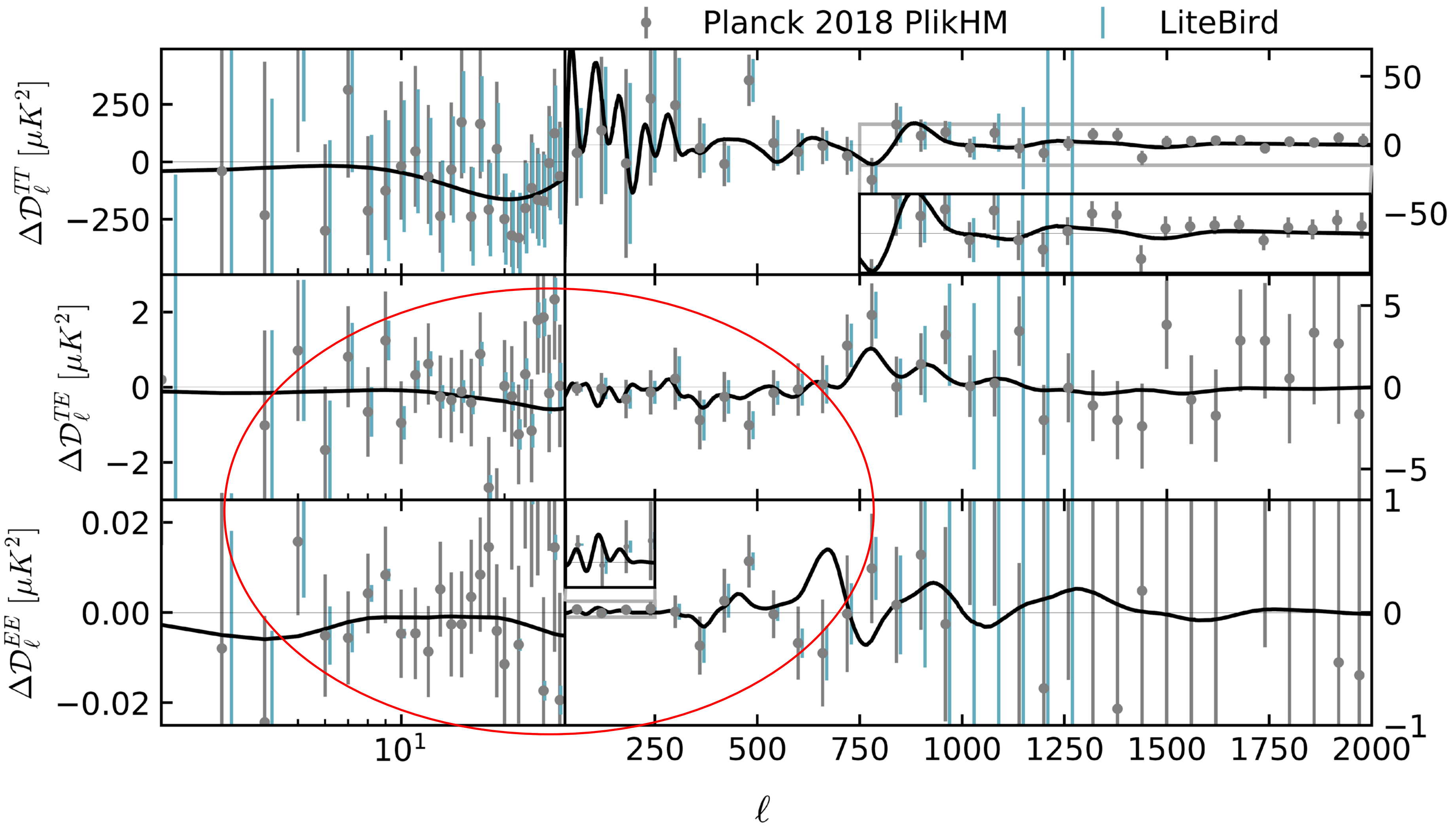
Some future experiments measuring CMB polarizations

LiteBIRD	Simons Observatory	PICO
		
Satellite, full sky 70%	Ground-based, 40% sky Finer resolution (<3’)	Satellite, full sky, excellent resolution and very low noise
Large-scale polarization	Small-scale polarization	All-scale polarization
Launch ~2028	Taking data ~2023	NASA funded mission study If fully funded, ~2030

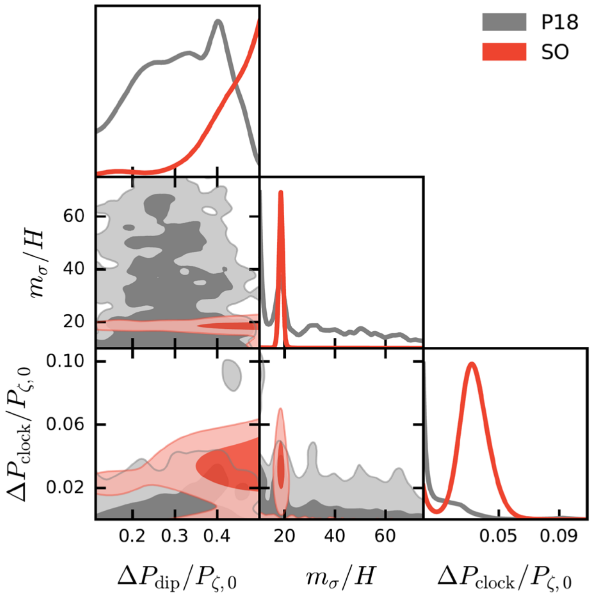
We will use their E-mode data

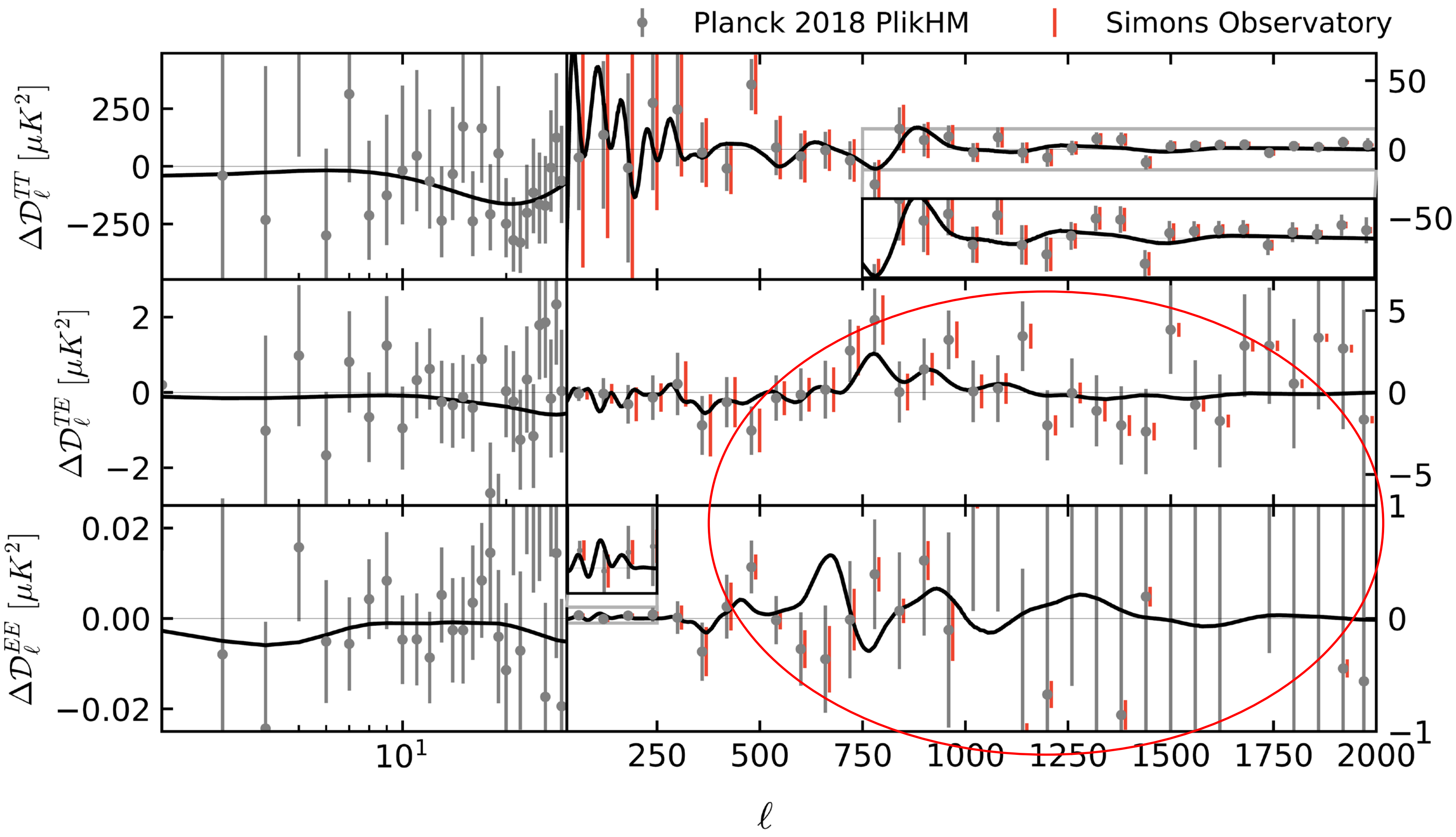
Forecast with the best-fit model: LiteBIRD





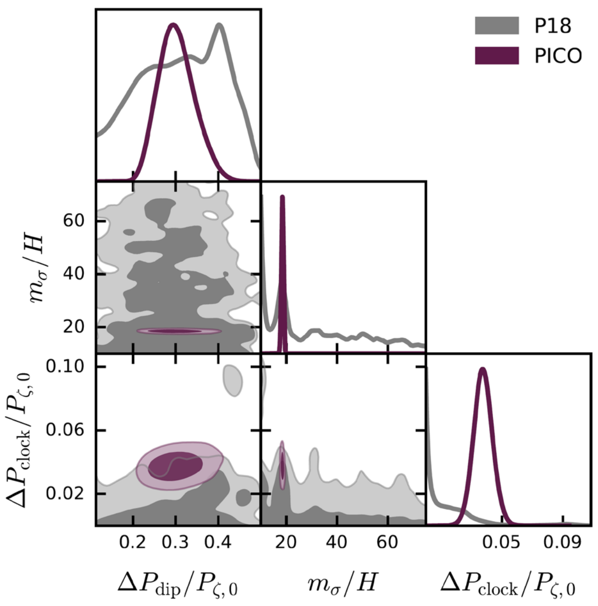
Forecast with the best-fit model: Simons Observatory

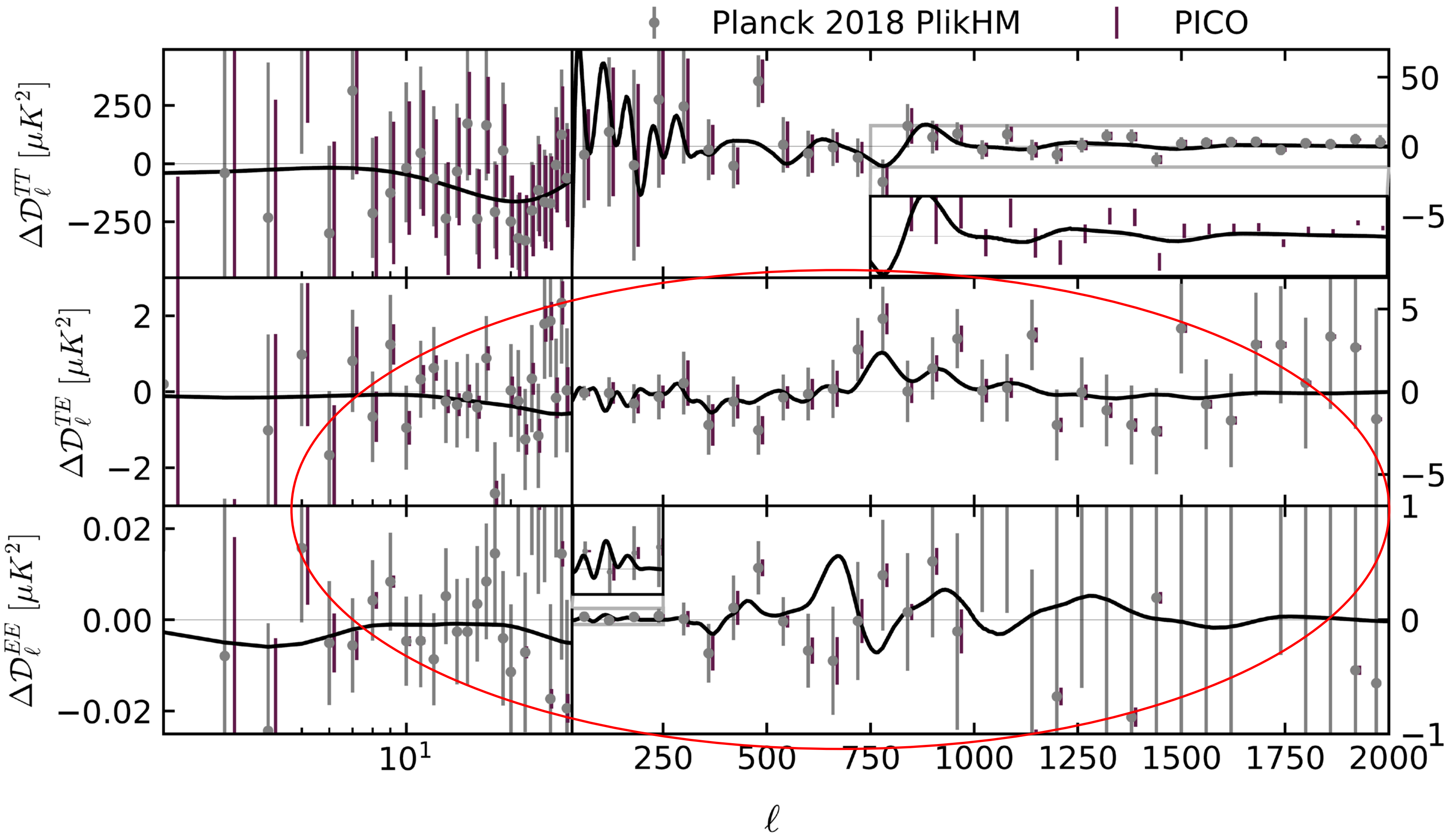




The clock signal carries information of a(t), which can be used to distinguish the inflation and alternatives in a model-independent fashion.

Forecast with the best-fit model: PICO





Correlated feature signals should also appear in:

- 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;)

The main message is the potential prospects of learning the evolutionary history of the primordial universe from future observations of primordial feature signals.

Conclusions

- During the primordial universe such as the inflationary epoch, all particles with mass up to the Hubble parameter or higher are excited quantum-mechanically or classically.
- These particles left their imprints in the primordial density perturbations, as primordial features and non-Gaussianities, which may be probed by astrophysical observations of the large-scale structure of the universe today.
- These information includes the particle mass and spin spectra, and the scale factor evolutionary history $a(t)$ of the primordial universe. The former resembles how particle colliders work. The latter would provide a direct evidence for the inflation or an alternative scenario.
- As an example, we present an inflationary primordial feature model that can explain both the large and small-scale feature anomalies in the currently measured CMB anisotropy spectra, revealing a clip of adventurous history of the Universe during its primordial epoch and realizing some of the properties outlined above.
- We show how to further test such models in future experiments.

Thank You !