Primordial Density Perturbations as Probes of High Energy 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.

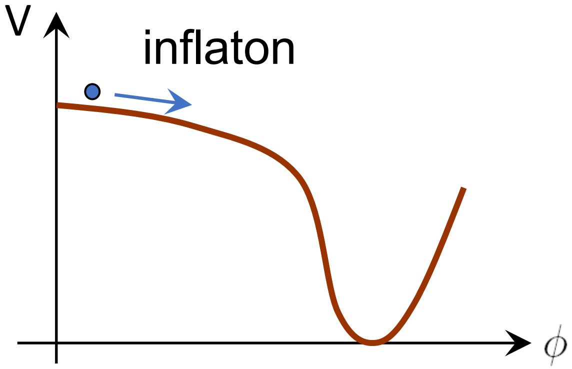
- These information includes the particle mass and spin spectra, and the scale factor evolutionary history $a(t)$ of the primordial universe. The latter would provide a direct evidence for the inflation or an alternative scenario.

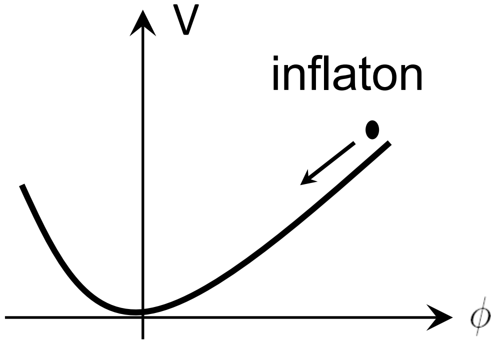
- As an example, we present an inflationary primordial feature model that can explain both the large and small-scale feature anomalies in the currently measured CMB anisotropy spectra, revealing a clip of adventurous history of the Universe during its primordial epoch and realizing some of the properties 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, …)

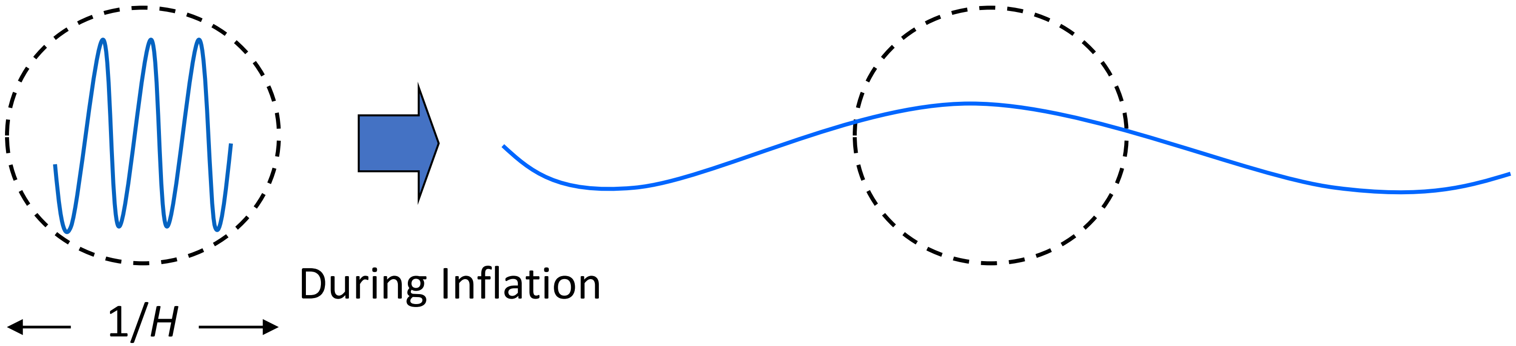




Scale Factor:

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

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?

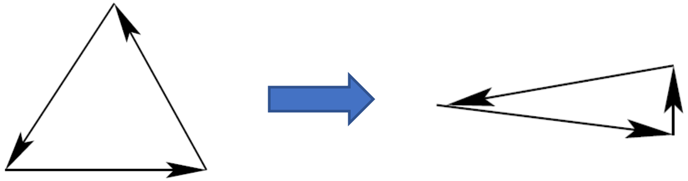
Tools:

Study correlation functions of density perturbation maps:

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

- scale-dependence:

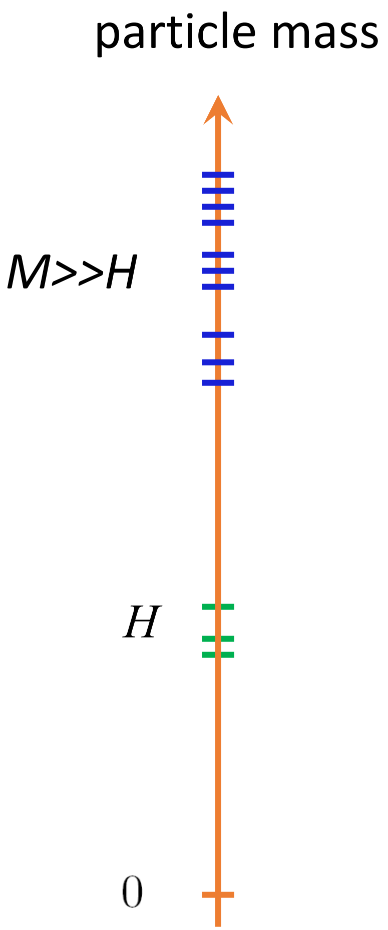
- shape-dependence:



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 $m \ll H$, tuning is necessary generically

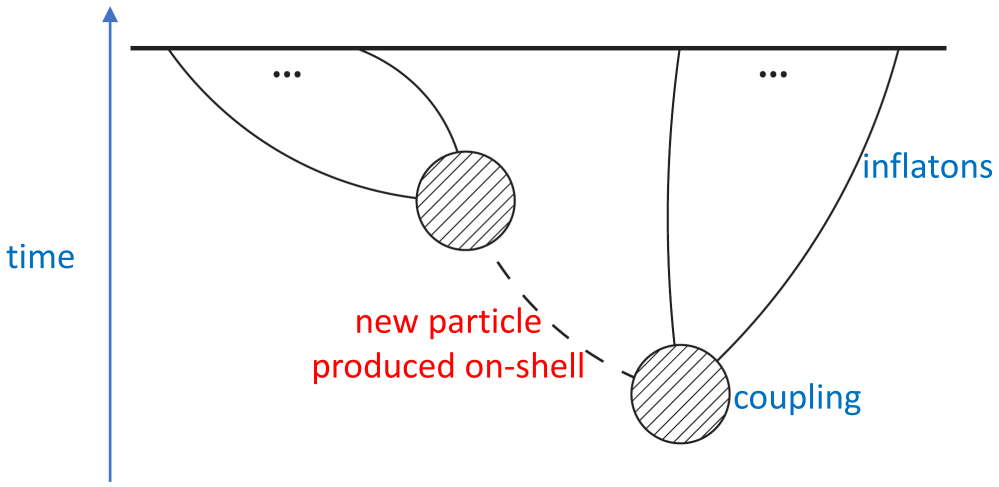
$$m^2 \sim H^2 \xrightarrow{\text{tune}} m^2 \lesssim \mathcal{O}(0.01) H^2$$

The η - problem

- Many others remain of order *H* or higher

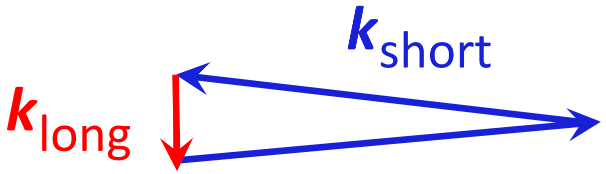
- These fields are not as important classically, but may be important quantum mechanically

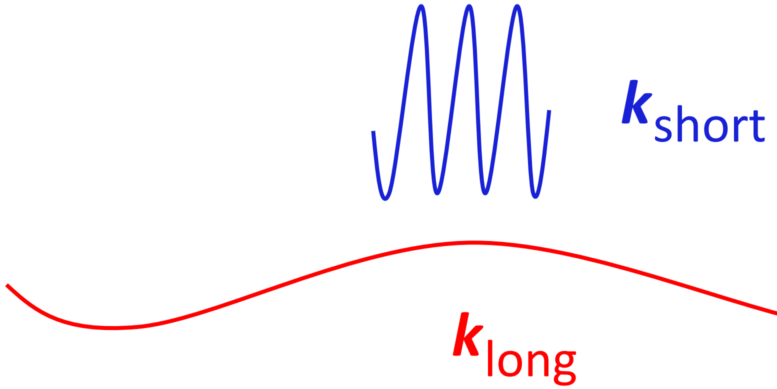
Quasi-Single-Field Inflation



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:

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

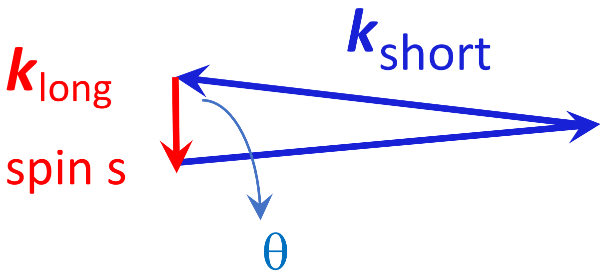
serve as background oscillating clock for shorter wavelength inflaton mode clock oscillation from massive field: $\sigma \propto e^{\pm imt}$

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)

- Applied to curvaton scenario (Lu, Wang, Xianyu, 19)
- … … …

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?**

(Model-independent: independent of models used to achieve inflation, or an alternative-to-inflation, background.)

- **Evolutionary history of cosmic inflation.**

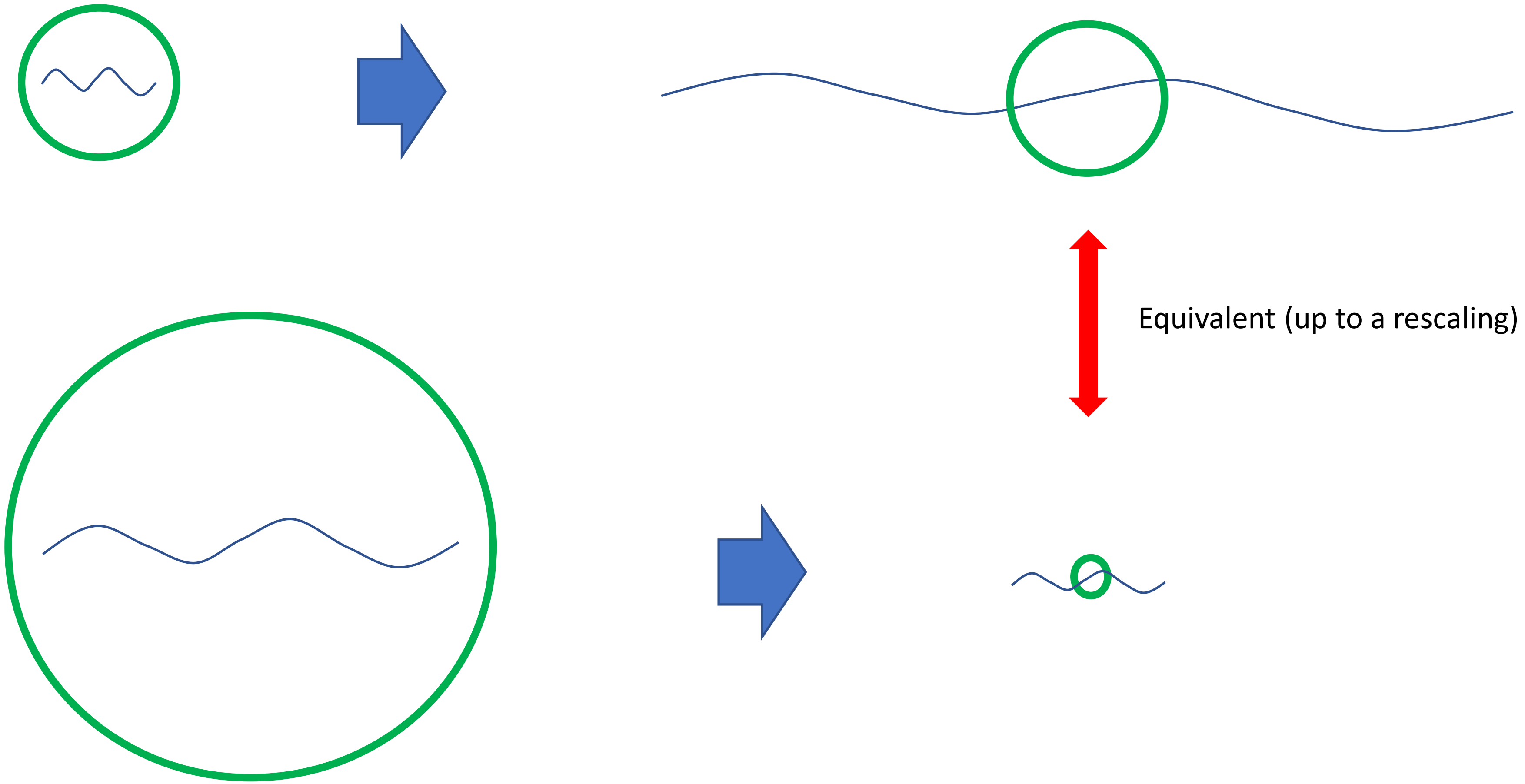
Is the primordial universe inflationary?

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

Inflation:

Contraction:

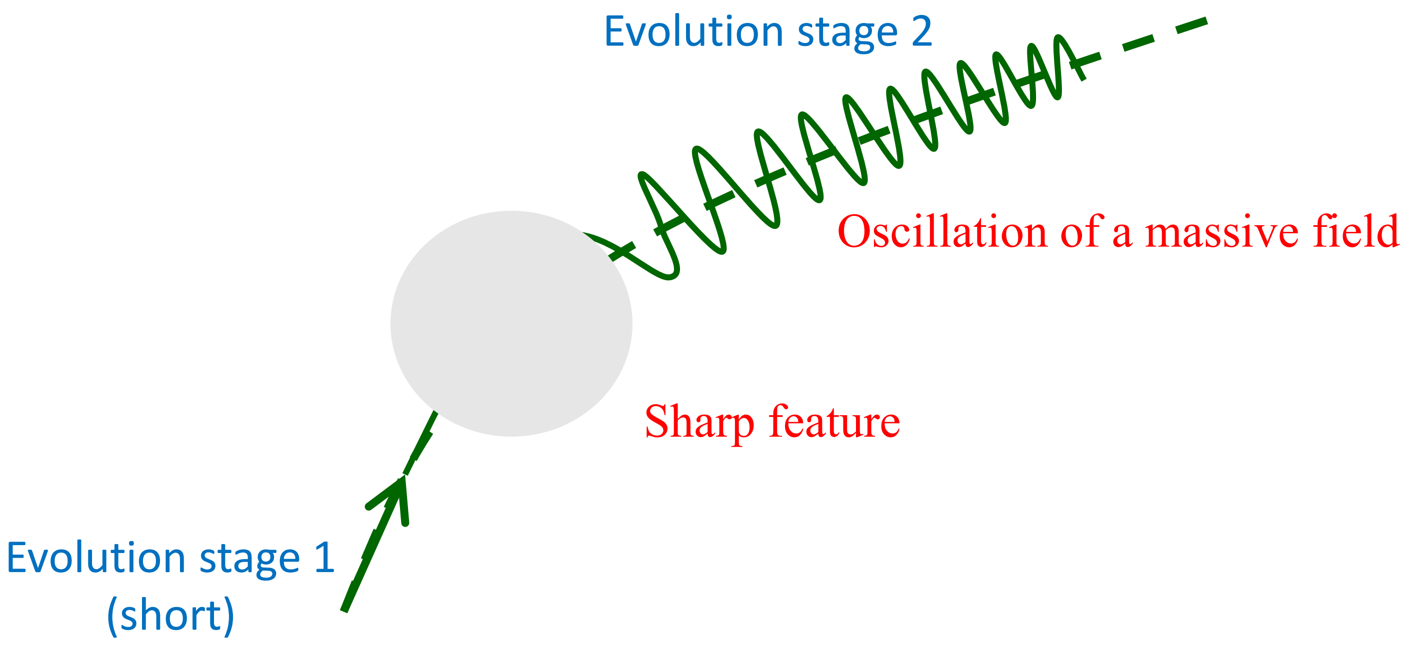


Are there any observables that can directly measure $a(t)$?

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: $\frac{d}{dt}(mt - 2k\tau) = 0$

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

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

$t(2k/m)$ 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*

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

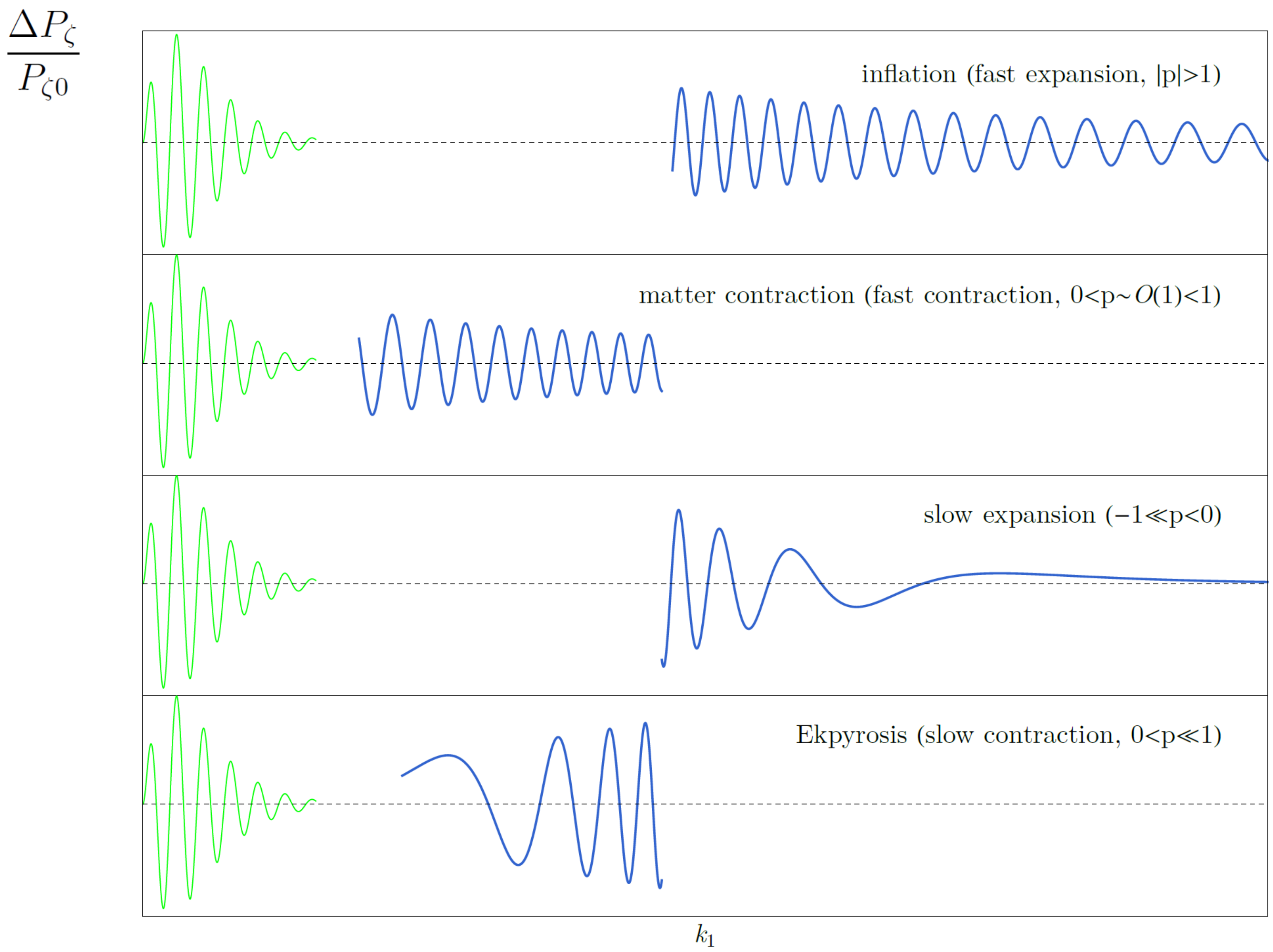
Inverse function of *a*(*t*)

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

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

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

↓

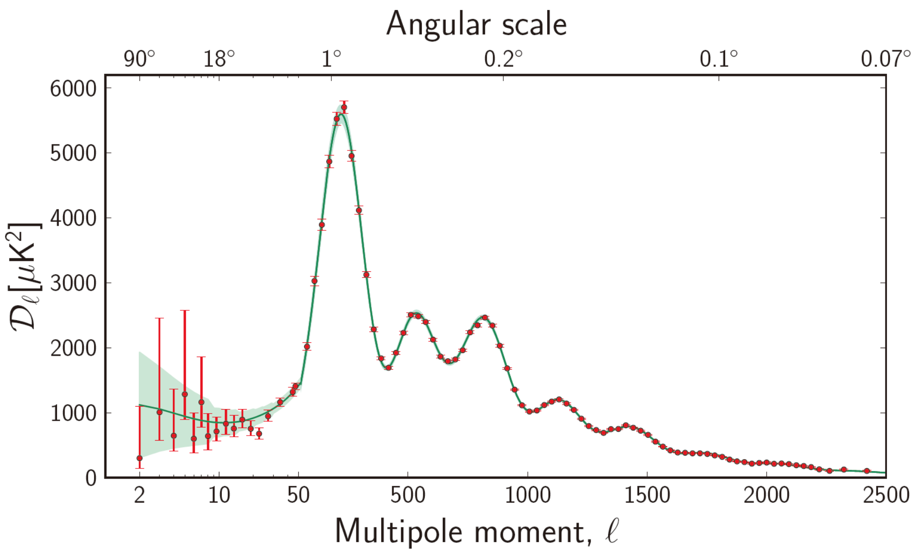
Background is exponential inflation

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

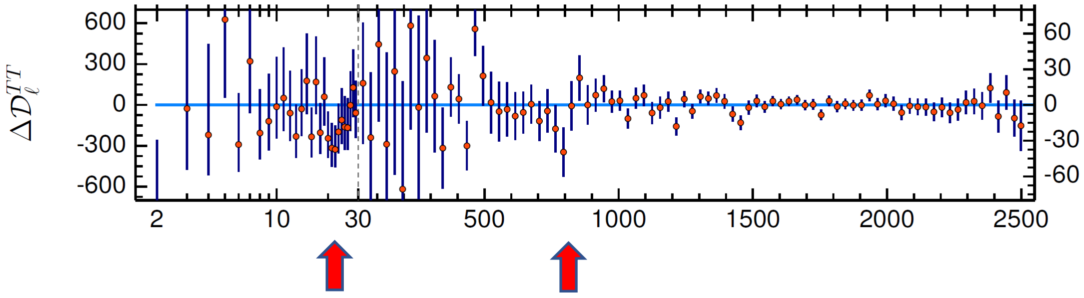
Classical primordial standard clock model building
and
data comparison

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)

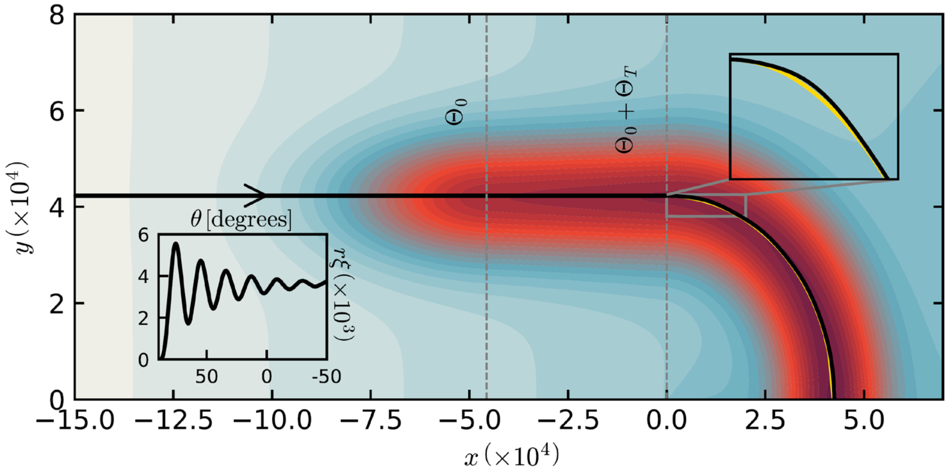


Two well-separated features in CMB may be connected by the Standard Clock effect

(Planck, 13, 18)

A Classical Primordial Standard Clock Model

(Braglia, XC, Hazra, 21)



Birdseye view of the potential

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

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

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

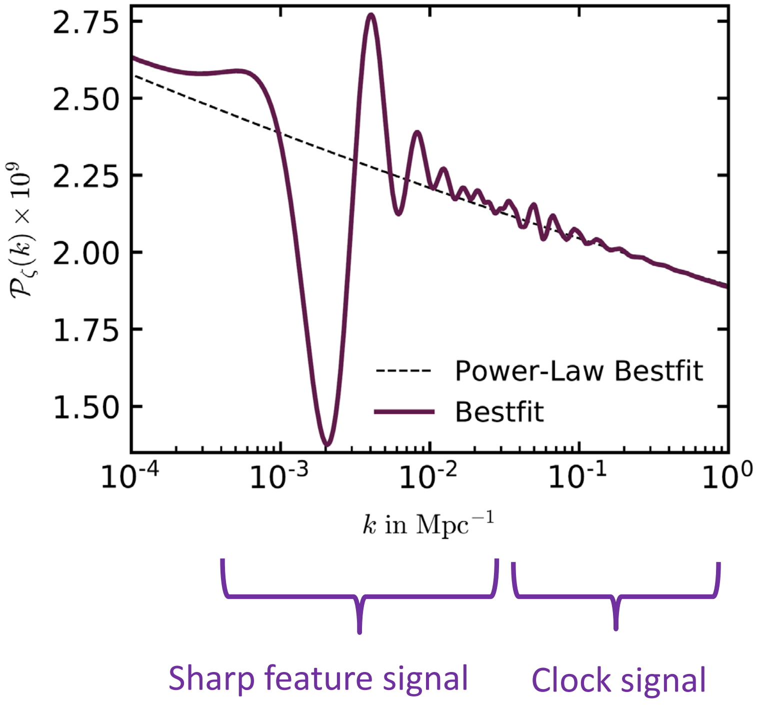
1st stage inflation ➞ Rolling off a cliff ➞ Fast-roll, entering a curved path of valley

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

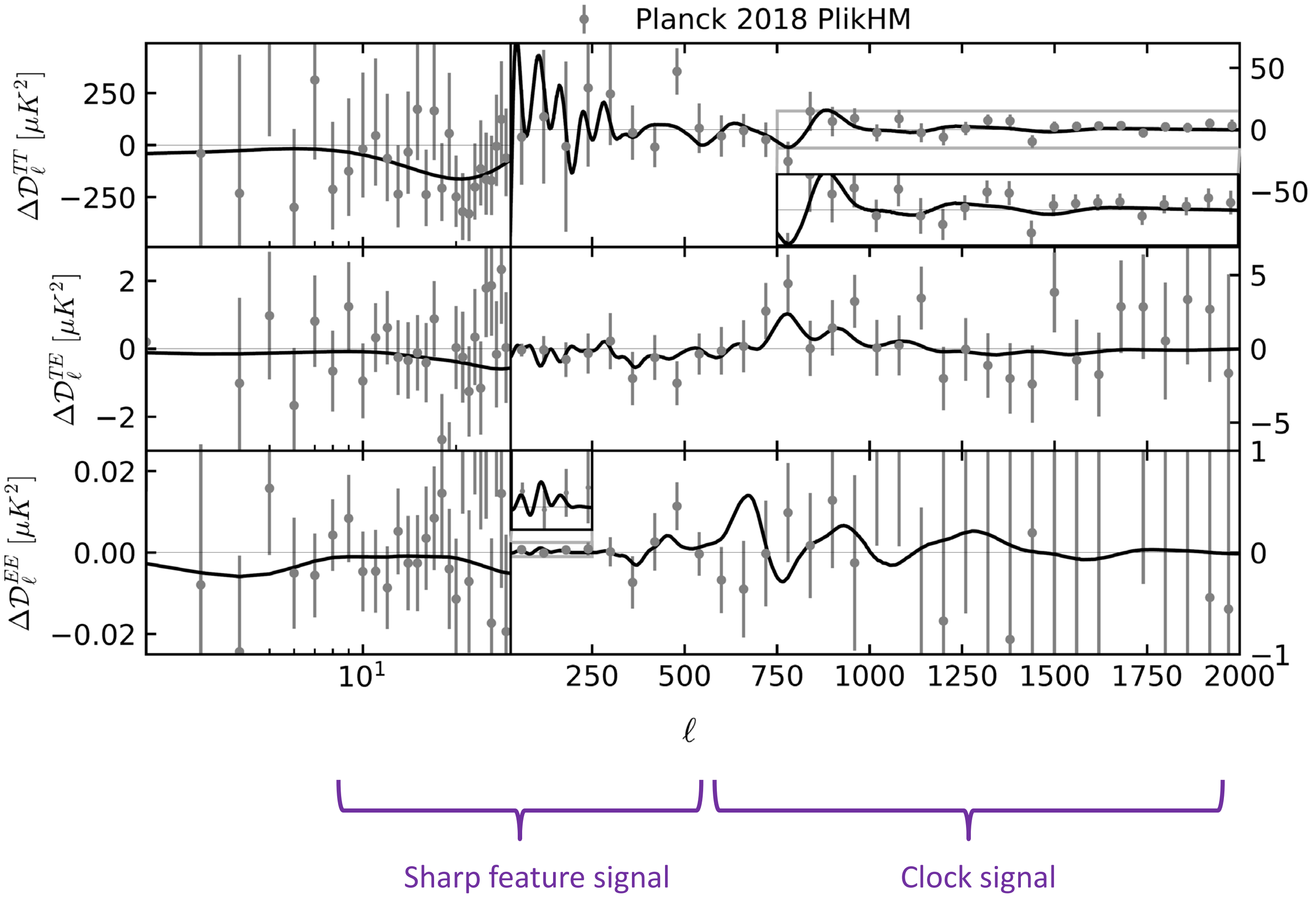
➞ Oscillation decays, settles down to 2nd stage inflation, (very model-independent)

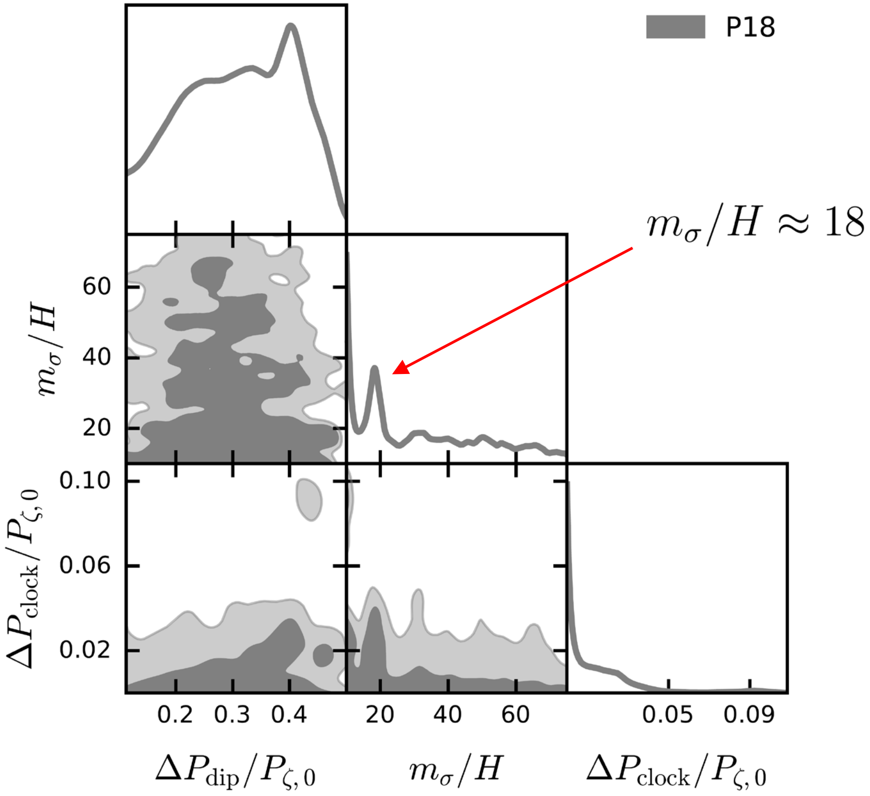
Sharp feature signal part of the model predictions sensitively depend on background evolution

Power spectrum



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





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

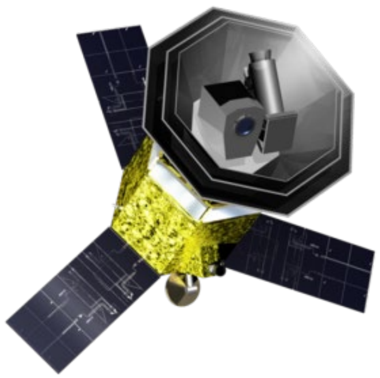
Bayes factor:

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

This feature model is indistinguishable from Standard Model

Some future experiments measuring CMB polarizations

LiteBIRD



Satellite, full sky 70%

Large-scale polarization

Launch ~2028

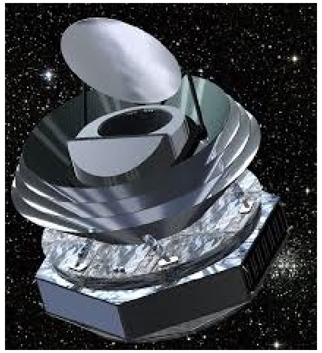
Simons Observatory

Ground-based, 40% sky
Finer resolution (<3')

Small-scale polarization

Taking data ~2020

PICO



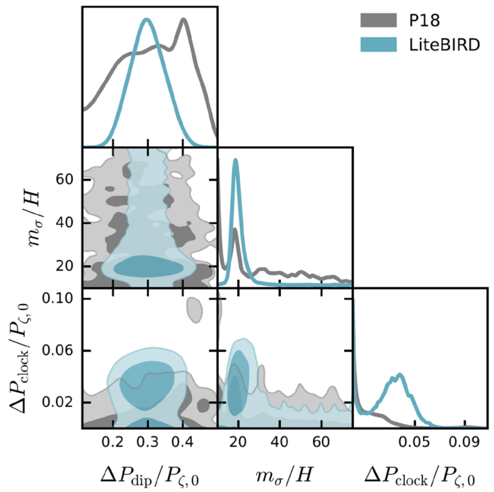
Satellite, full sky,
excellent resolution
and very low noise

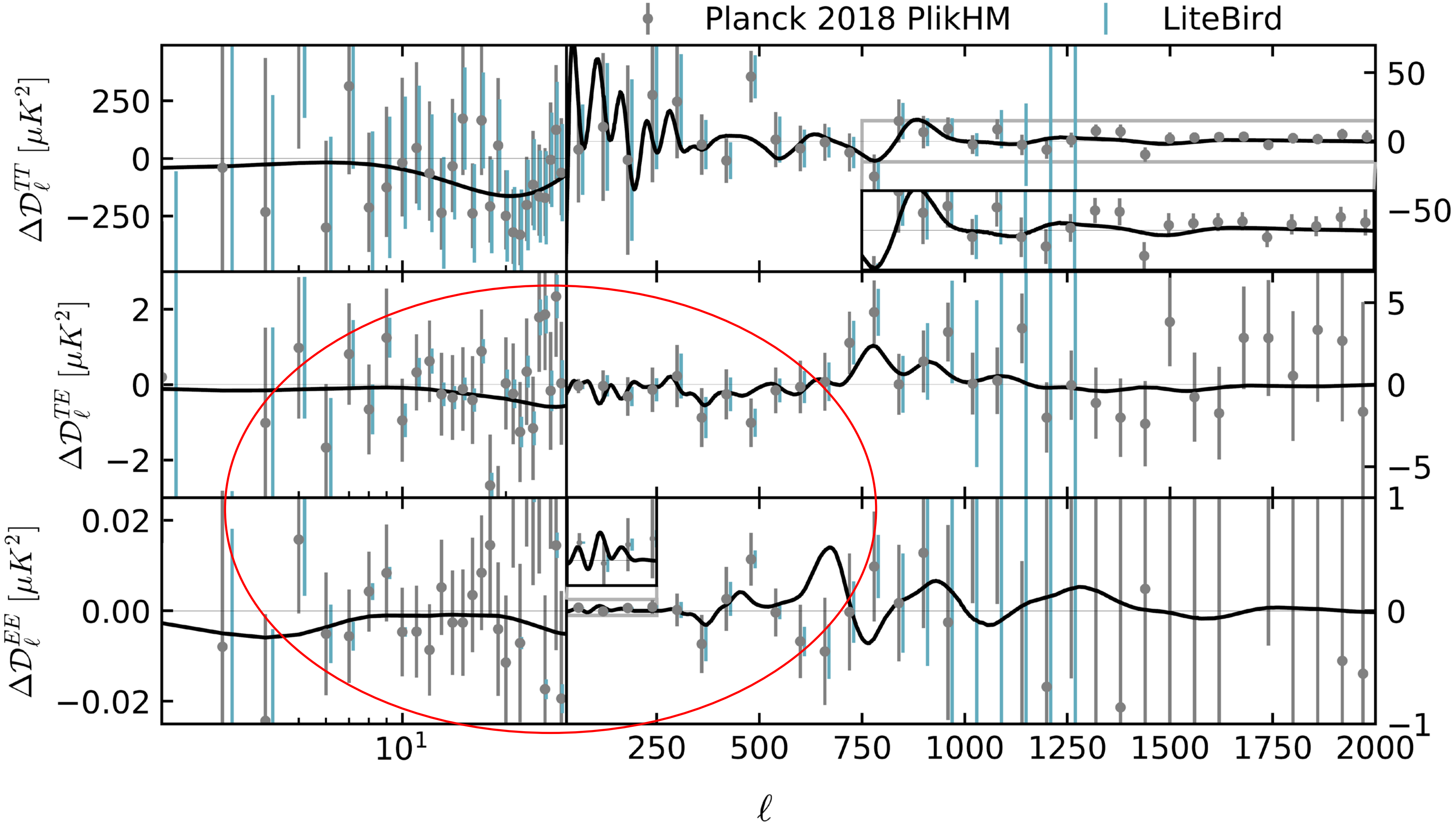
All-scale polarization

NASA funded mission study
If fully funded, ~2030

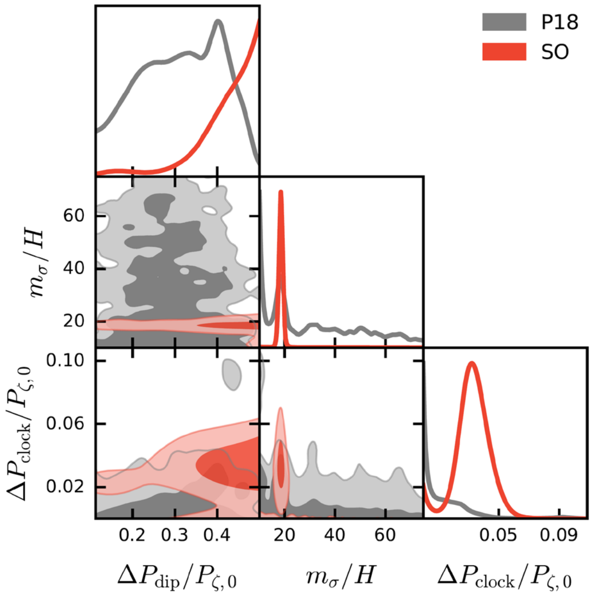
We will use their E-mode data

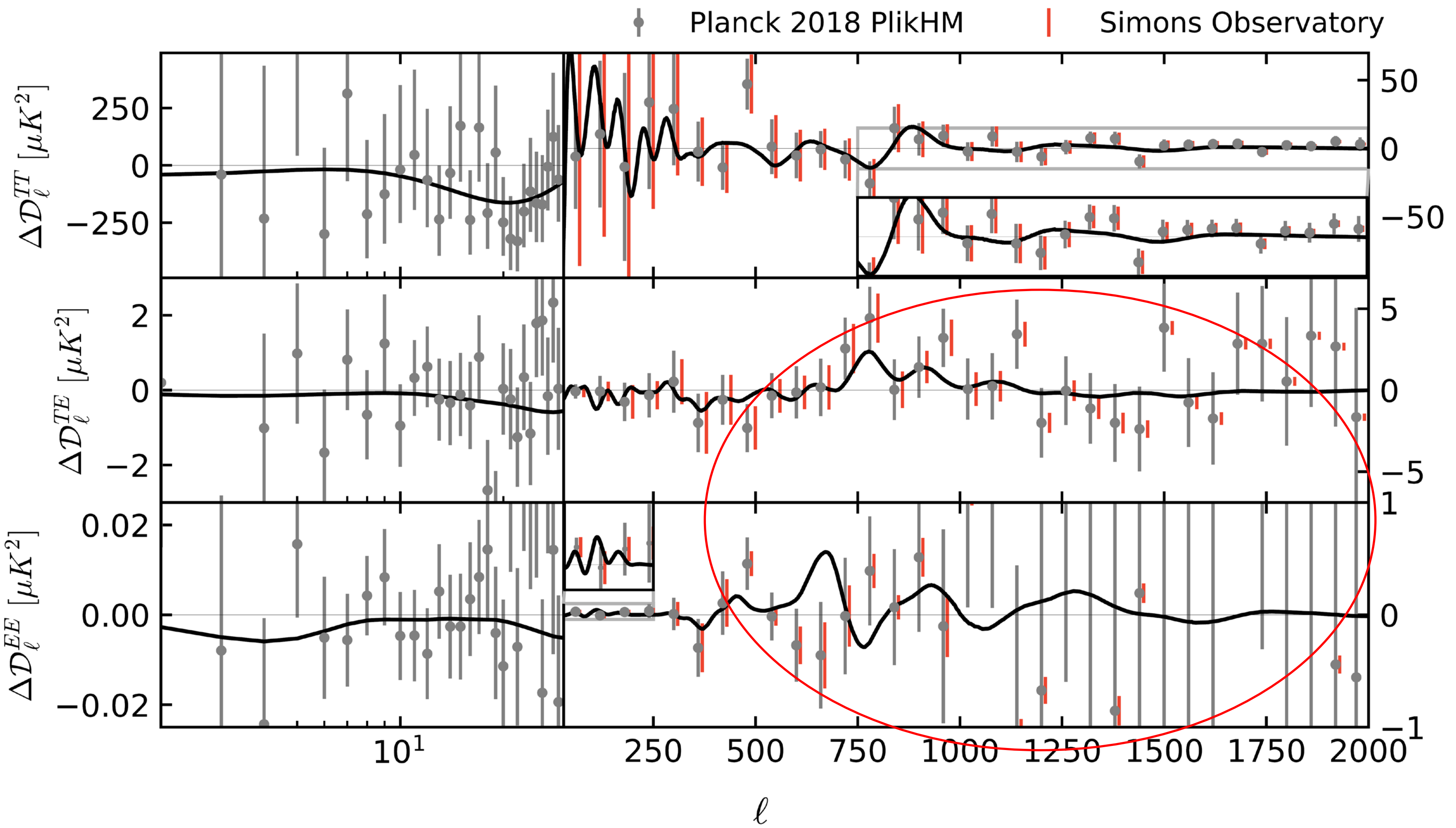
Forecast with the best-fit model: LiteBIRD





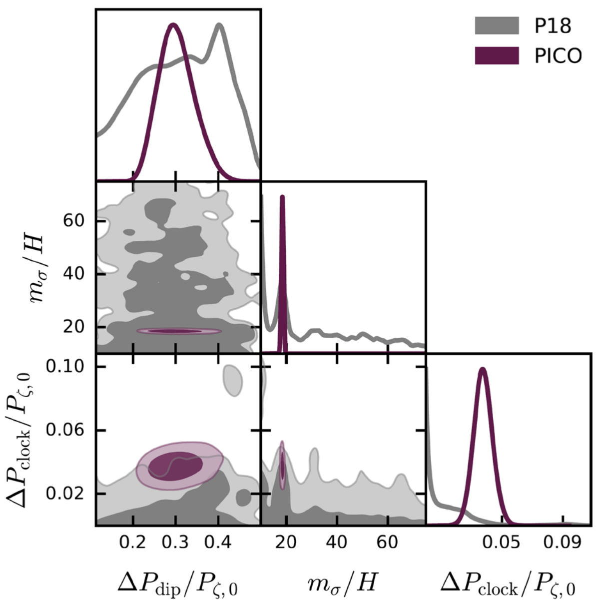
Forecast with the best-fit model: Simons Observatory

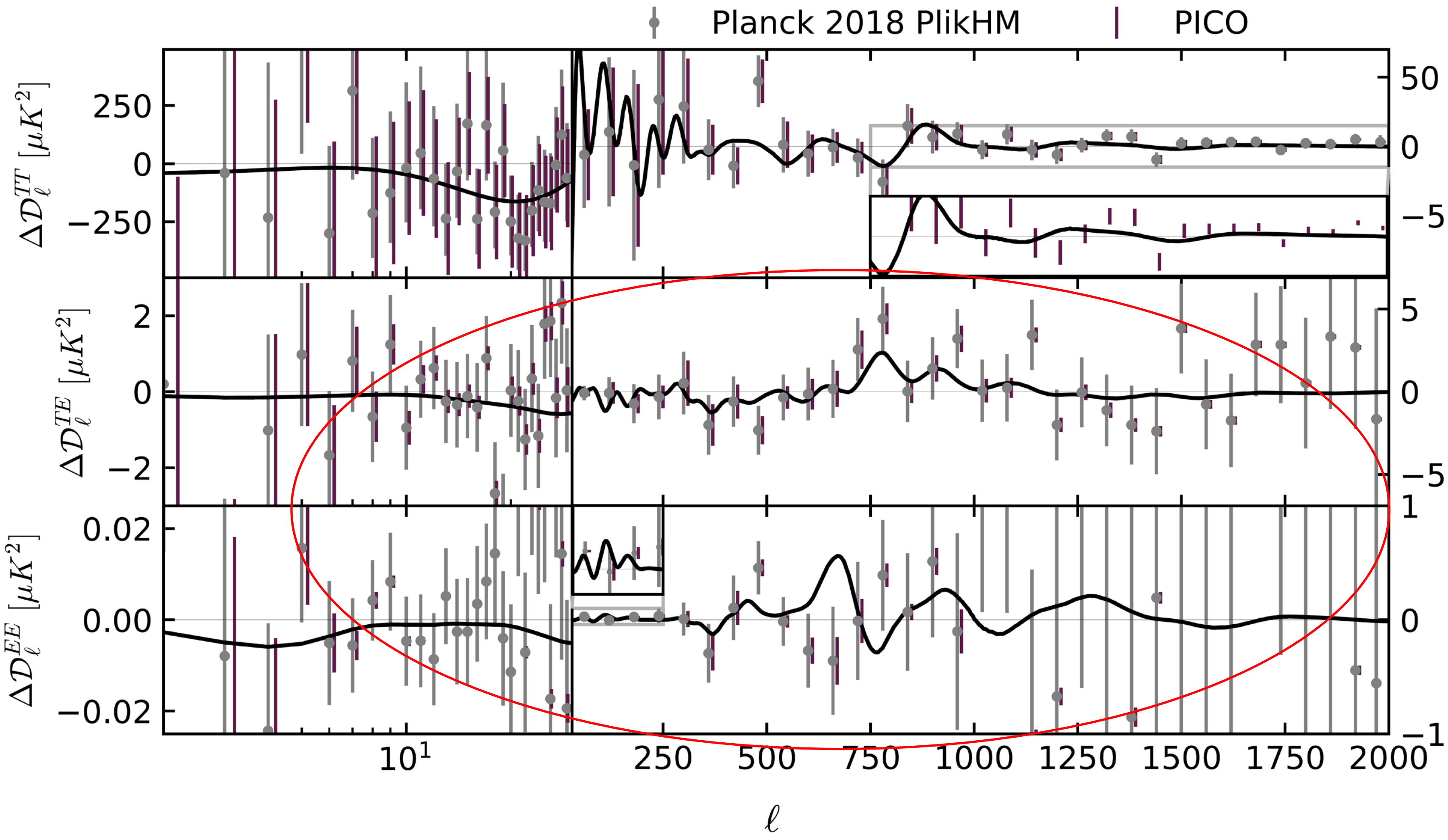




The clock signal carries information of a(t), which can be used to distinguish the inflation and alternatives in a model-independent fashion.

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;)

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.
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Thank You !