Primordial Standard Clocks
as
Direct Probes of the Scenario of the Primordial Universe

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Status of Primordial Universe Model Building

- Inflation solves the horizon and flatness problem of the Big Bang Model, and explains the origin of the density fluctuations

- Several alternative-to-inflation scenarios were also proposed:
  they suffer more theoretical problems and are more incomplete;
  fixes and improvement are ongoing research activities

- However, 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 are alternatives to inflation that should be explored and tested

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

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

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

$\lvert p \rvert > 1$	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)

Two (related) challenges in primordial universe cosmology:

1) How to observationally distinguish inflation and alternative scenarios model-independently

2) There are criticisms that the inflation scenario is unfalsifiable against alternatives as a whole scenario due to too many model variations and eternal inflation. Can we find observables that address this criticism?

But, why do these questions arise?
-- after all, different scenarios are defined by drastically different $a(t)$.

Reason: Conventional observables do not directly measure $a(t)$

As a consequence:

1) Observables become degenerate in different $a(t)$

2) Observables can be very model-dependent, given the same $a(t)$

For Example: Primordial Gravitational Waves

(Grishchuk, 74; Staronbinsky, 79, …)

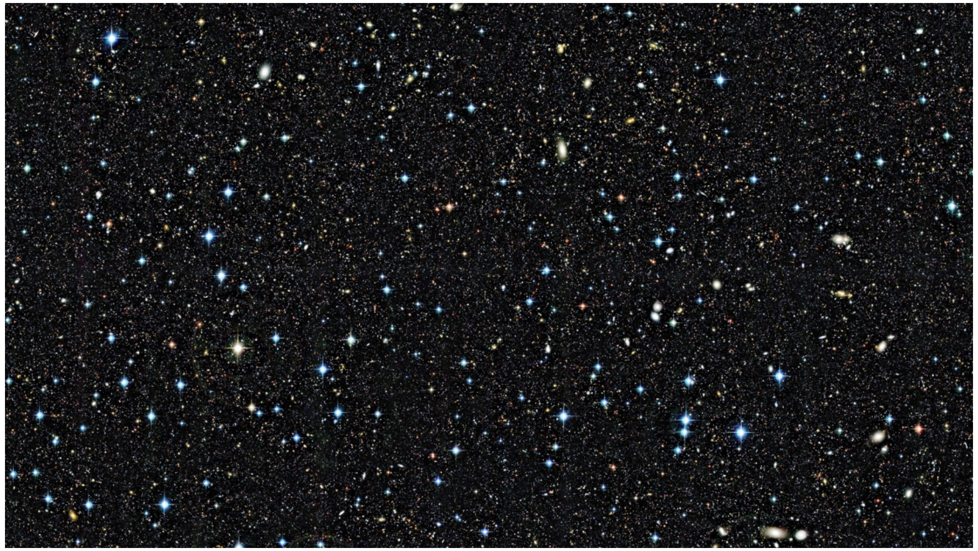
Measuring an approximately scale-invariant tensor spectrum
would rule out the Ekpyrotic Scenario – a type of slowly contracting scenario

BUT

- Measuring such a tensor spectrum would not rule out all alternatives to inflation.
  E.g. Matter Contraction Scenario -- a type of fast contracting scenario.
  This is an example of the $a(t)$-degeneracy problem.

- Not measuring such a tensor spectrum would not rule out Inflation Scenario.
  tree-level: $r \sim \mathcal{O}(10^{-1}) - \mathcal{O}(10^{-55})$
  This is an example of the unfasifiability criticism.

What do We Miss? -- A Historical Analogy



The images of stars we directly observe is 2D.

100 years ago, it was a great challenge to figure out the distances of these stars from us.

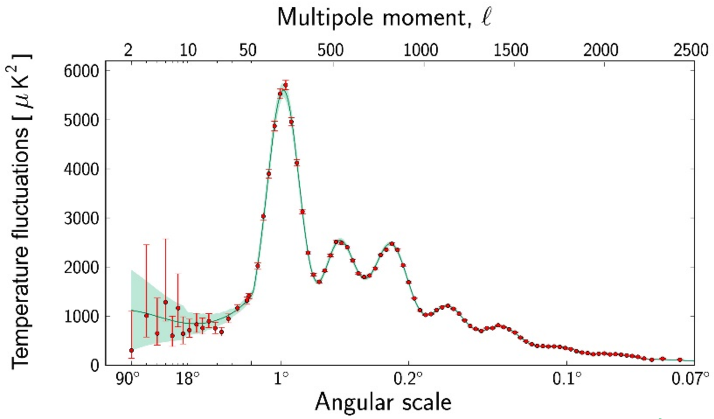
This led to debates on issues such as:

Is the sun at the center of the Galaxy?
Are there stars beyond the Milky Way?

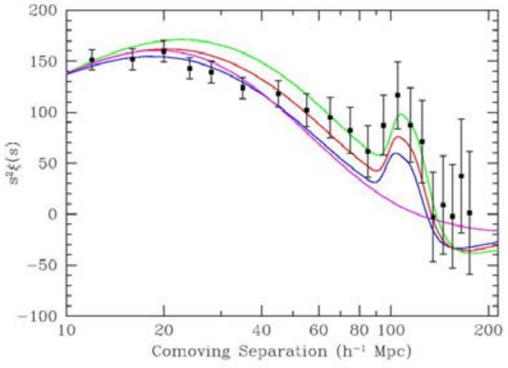
These issues were settled with the discovery of Standard Candles, such as Cepheid and Type Ia supernova

turning 2D images to 3D images

Current Situation for Primordial Universe Cosmology



(Planck)



(SDSS)

To learn about the primordial universe, we decompose 2D/3D information into "Fourier" modes.

Different modes are generated at different time when they exit the horizon during the primordial universe.

Each mode is a snapshot of the primordial universe

Analogy: A roll of film frames, each frame is a snapshot

But, we do not know:
time coordinates for these snapshots

No instruction on how the movie should be played

This leads to debates on issues such as:
Was the primordial universe inflating or contracting?
Was it slowly contracting or fast contracting?

We need to find Standard Clocks that put time stamps on each frame
and
turn a roll of film frames to a film

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

Yes. Such observables exist.

--- Massive Fields as Primordial Standard Clocks

(XC, 1104.1323, 1106.1635; XC, Namjoo, Wang, 1411.2349, 1509.03930; XC, Loeb, Xianyu, 1809.02603)

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

1) exist in any realistic models
2) oscillate in a standard way in any background

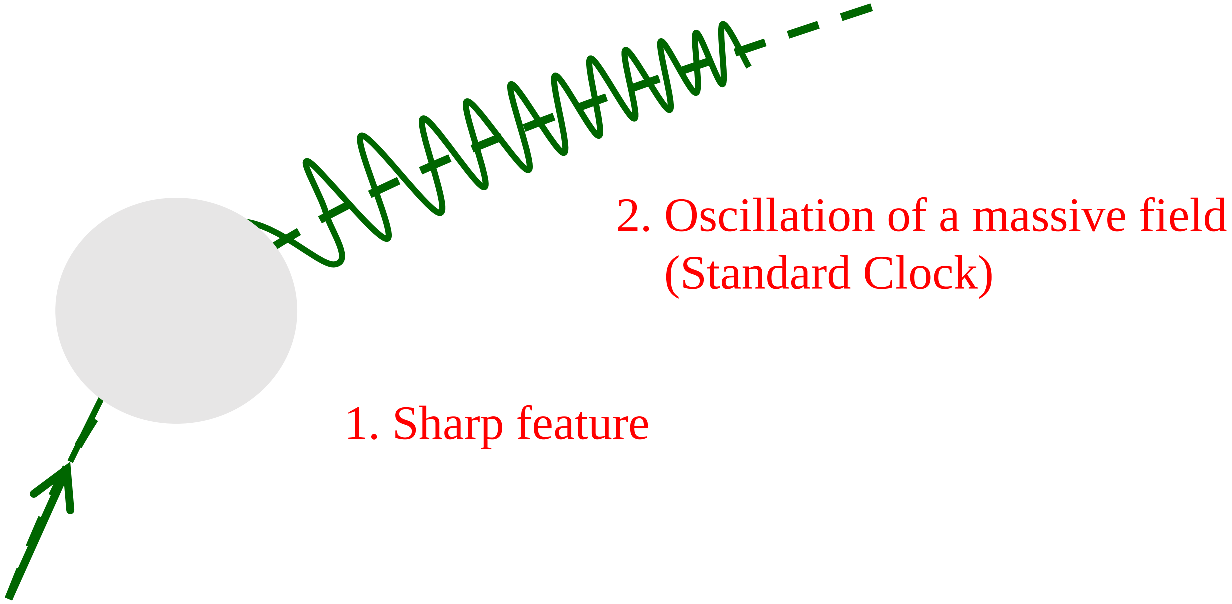
Oscillations provide ticks for the time coordinate t

Induce patterns of ticks in density perturbations – "**Clock Signals**"

Two types of primordial standard clocks
depending on how the oscillations of massive fields are generated

- **Classical primordial standard clocks**
- **Quantum primordial standard clocks**

Classical Primordial Standard Clocks (XC, 11, XC, Namjoo, Wang, 14)

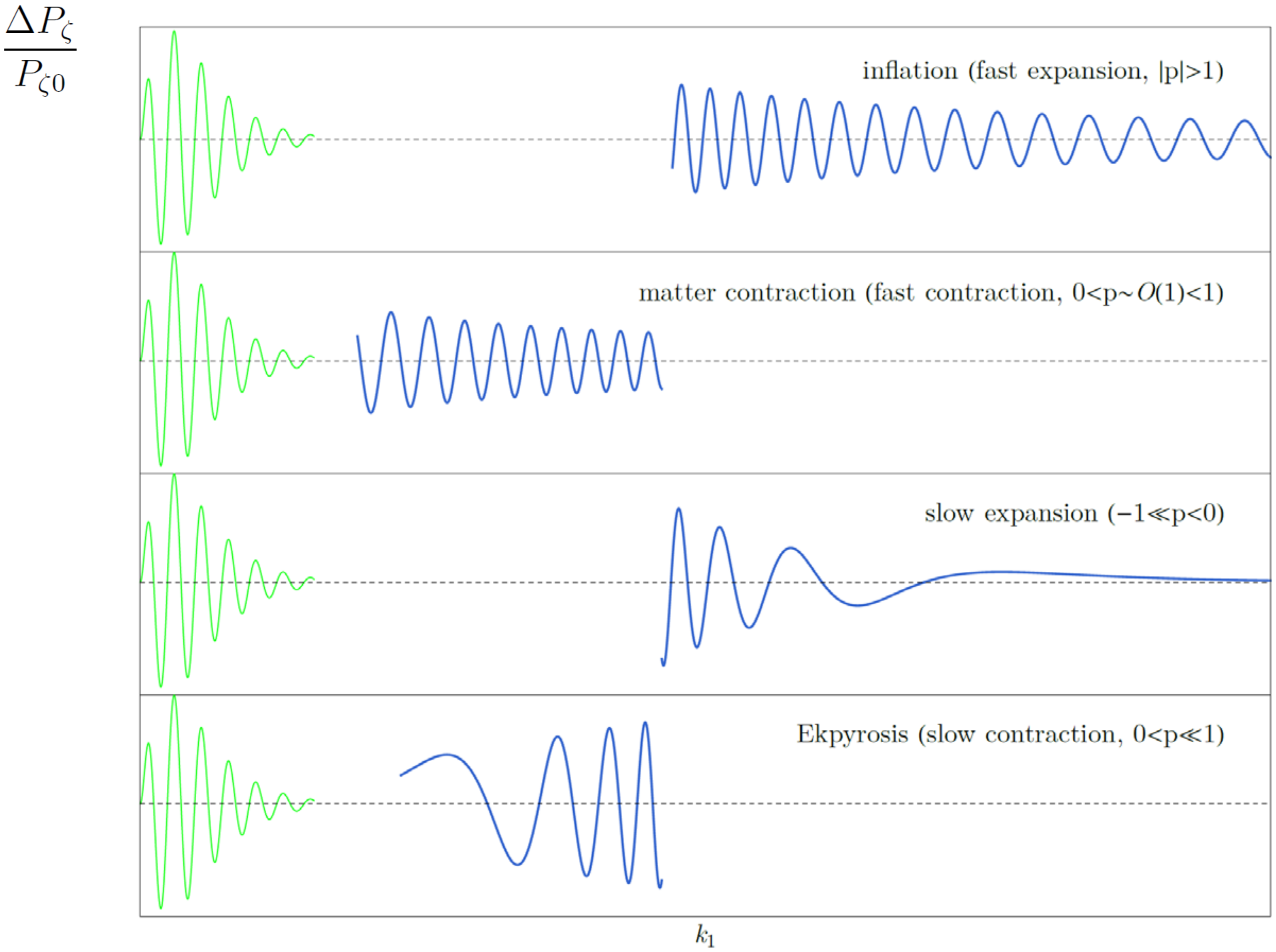


Massive field starts to oscillate classically due to some kind of kick (sharp feature)

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

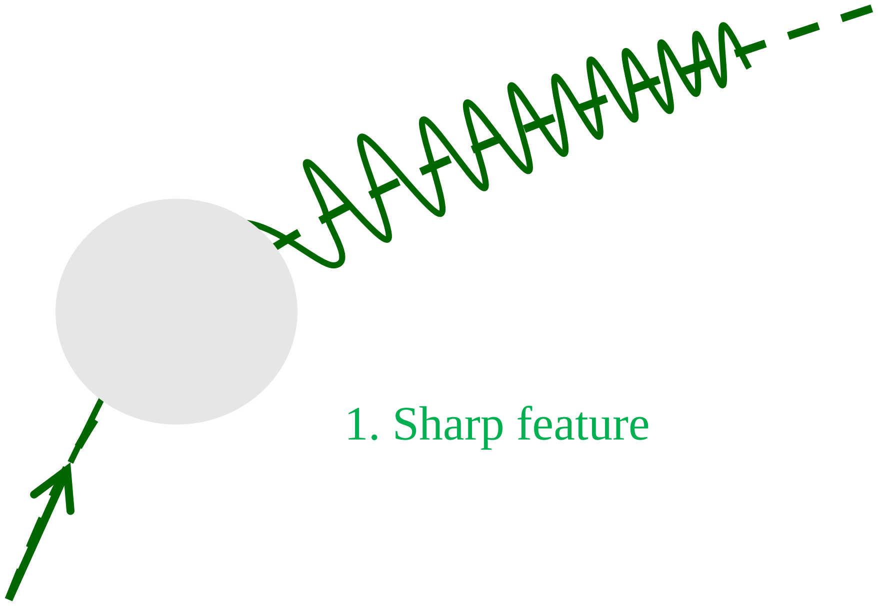
Fingerprints of Different Scenarios

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



Classical Primordial Standard Clocks

Sharp feature excites classical oscillation of massive field



Sharp Feature Signal

$$\frac{\Delta P_\zeta}{P_{\zeta 0}} \propto 1 - \cos(2k_1\tau_0)$$ with model-dependent envelop/phase

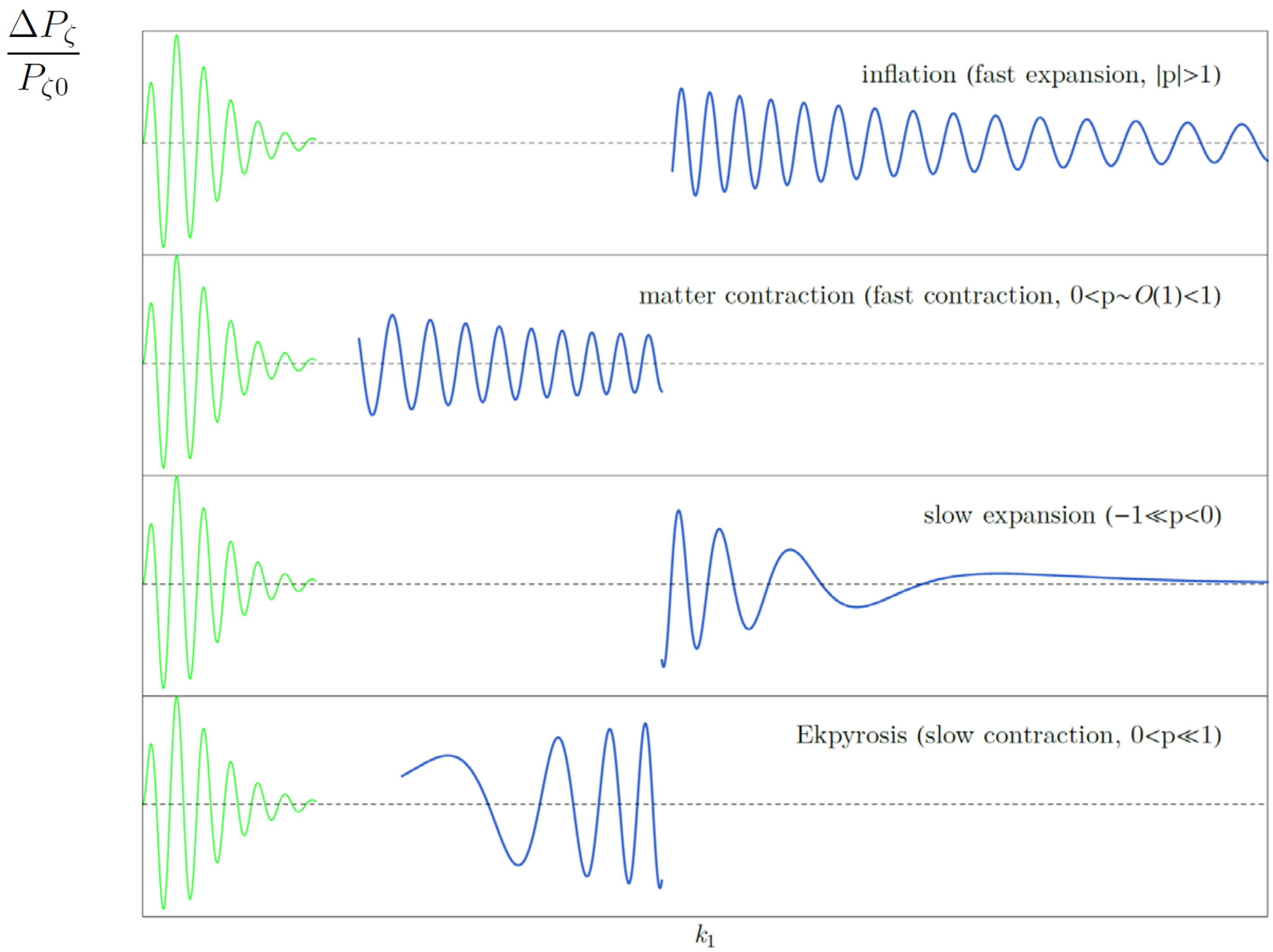
Sinusoidal running is a signature of "sharp feature";
but not a signature of massive field, **nor** does it record $a(t)$.

Universal for different scenarios, i.e. independent of p

Nonetheless, an important component of full classical PSC signal.

Fingerprints of Different Scenarios

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



Classical Primordial Standard Clocks

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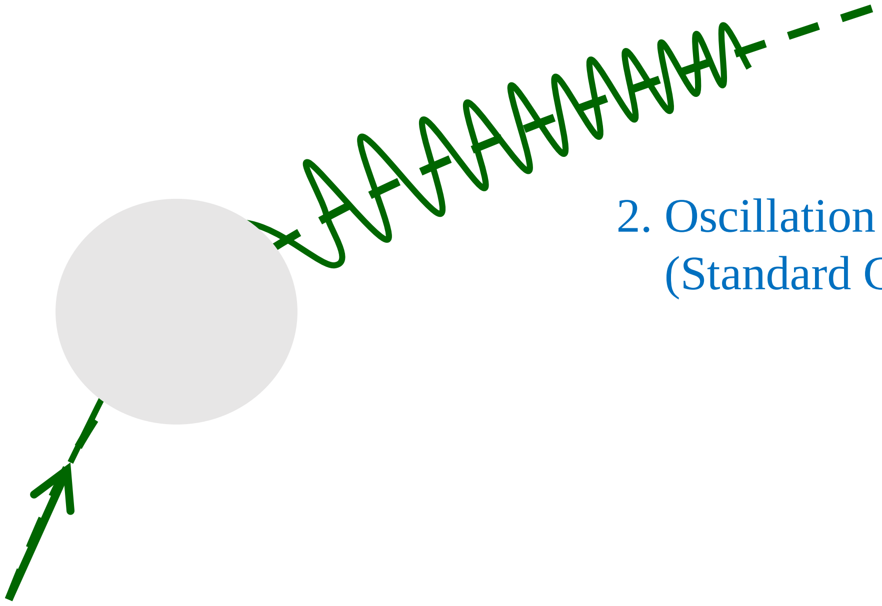


2. Oscillation of massive fields
(Standard Clocks)

Mechanism 1 of Primordial Standard Clocks

(XC, 11; XC, Namjoo, Wang, 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: $\frac{d}{dt}(mt - 2k\tau) = 0$

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

$$\boxed{\begin{array}{c} \langle \zeta_{\mathbf{k}}^2 \rangle \supset \exp\left[im\ t(2k/m) - 2ik\ \tau(2k/m)\right] \\ \\ t(2k/m) \text{ and } \tau(2k/m) \text{ are inverse functions of the scale factor } a(t) \text{ and } a(\tau) \end{array}}$$

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

The Clock Signal in Classical PSC

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

The background oscillation resonates with curvature fluctuations mode by mode

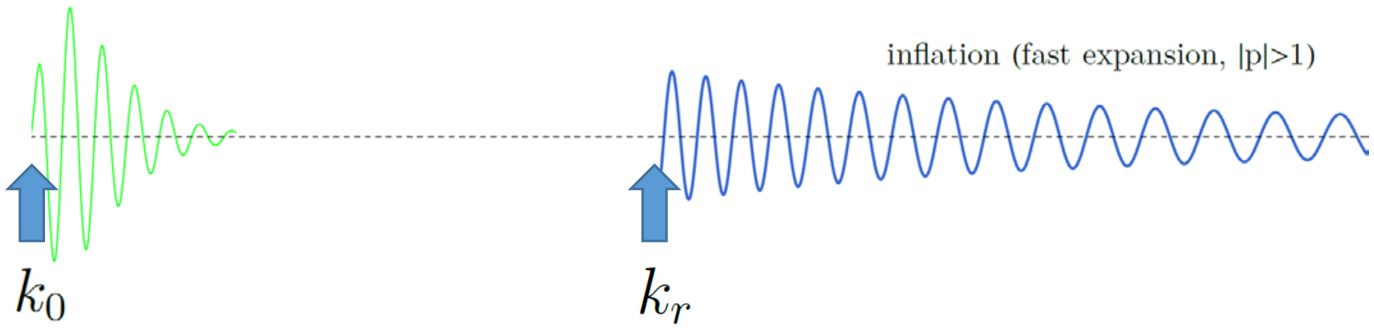
The clock signal: $\sim \sin\left[p\frac{m}{m_{\mathrm{h},0}}\left(\frac{K}{k_r}\right)^{1/p}+\varphi\right]$ $K \equiv k_1 + k_2 = 2k_1$ for power spectrum

horizon mass
at time of sharp feature

Inverse function of *a*(*t*)

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

A Consistency Relation between Clock Signal and Sharp Feature Signal



K-location of
first resonant mode

K-location of sharp feature

$$\frac{k_r}{k_0} = \frac{|p|}{|1-p|}\Omega = \frac{m}{m_h}$$

$$\frac{k_r}{k_0} = \frac{\text{Mass Scale of Clock Frequency}}{\text{Horizon Mass}}$$

Condition for Classical PSC:

Requires a sharp feature inducing classical oscillation of massive field

Theoretical Motivation

In particle physics, very massive field are hard to excite, and we integrate them out in low energy EFT

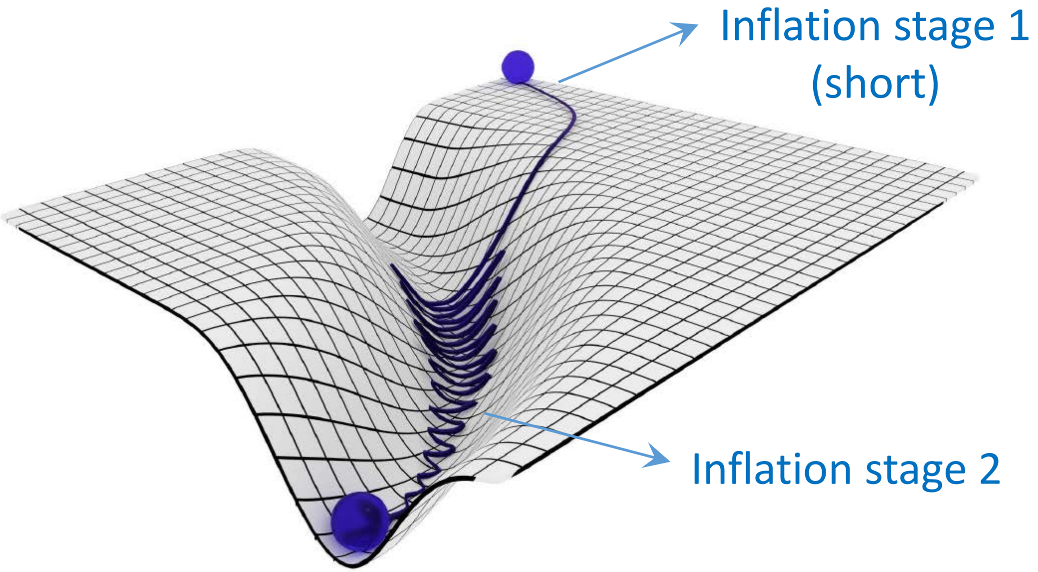
However, this intuition may **not** be true for primordial universe models:

Primordial universe was in an unstable state, unlike particle physics;
so a high energy state of one stage could be a low energy state of a previous stage.

For example
a tachyonic falling in a two-stage inflation model

This happens naturally when the inflaton was looking for a flat direction at early stage of inflation

A very massive field easily excited

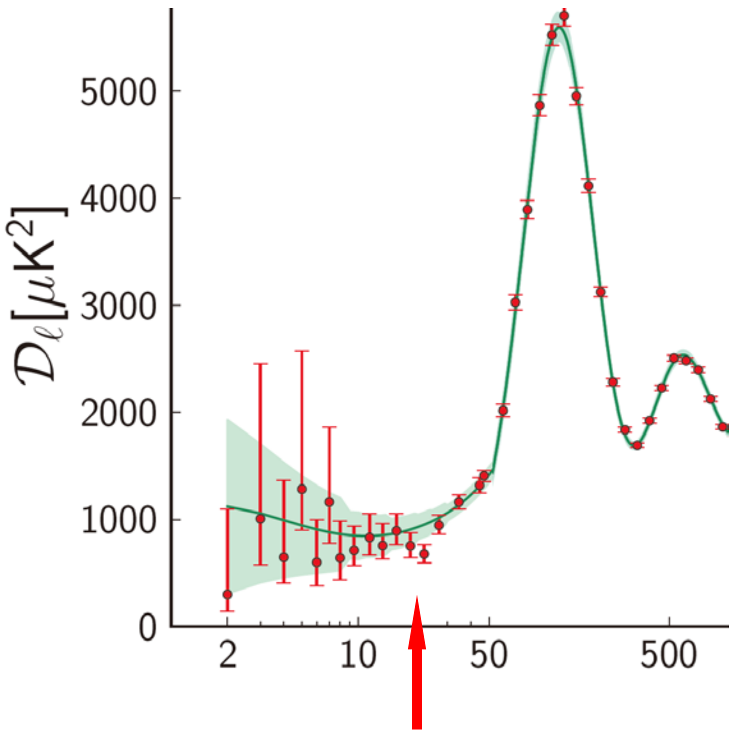


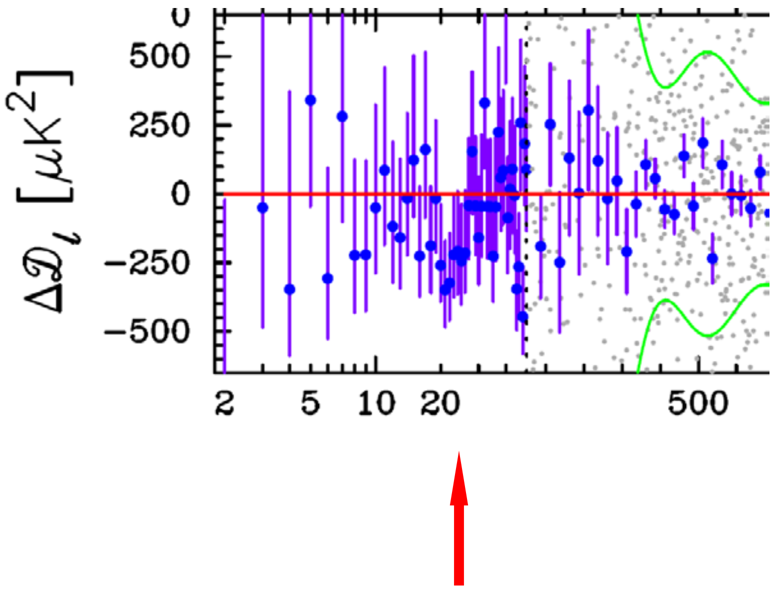
Experimental Motivation

Let us look at the data:

One of the most important anomalies in CMB data is a candidate of a sharp feature model

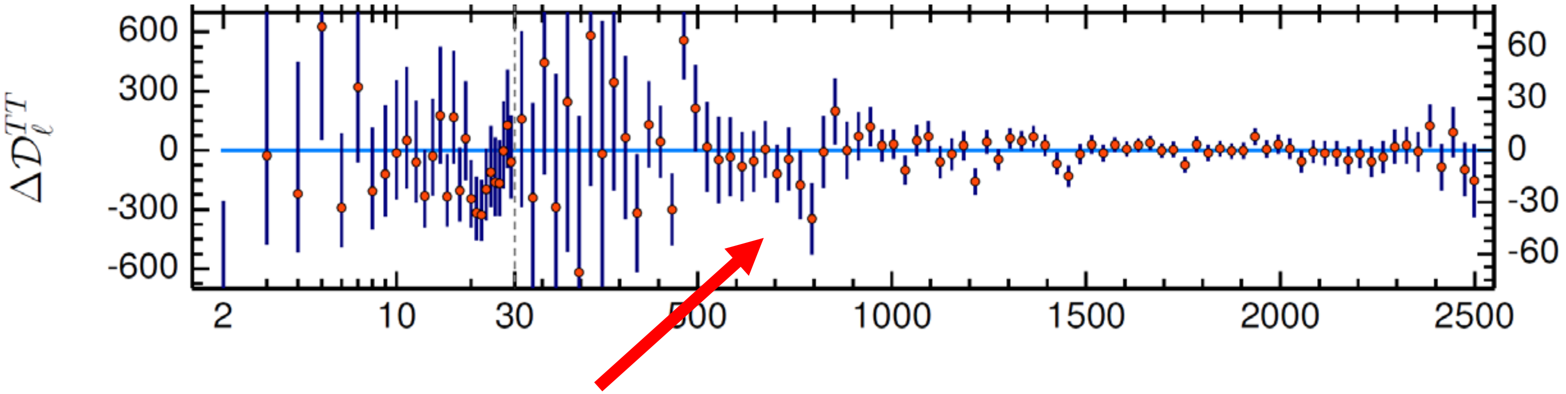
(WMAP, Planck)





If it was indeed a sharp feature, it may well have excited some massive fields.

Experimental Motivation (continued)

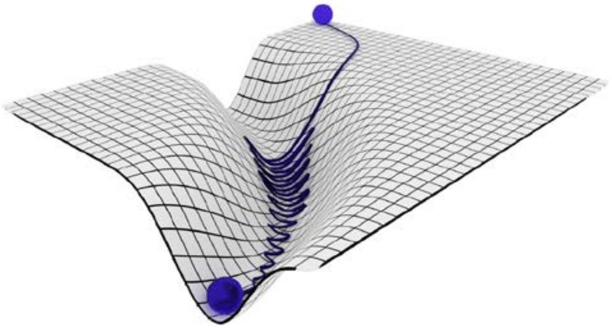


There is another feature candidate at large ℓ
that may be a candidate for the clock signal

Experimental Motivation (continued)

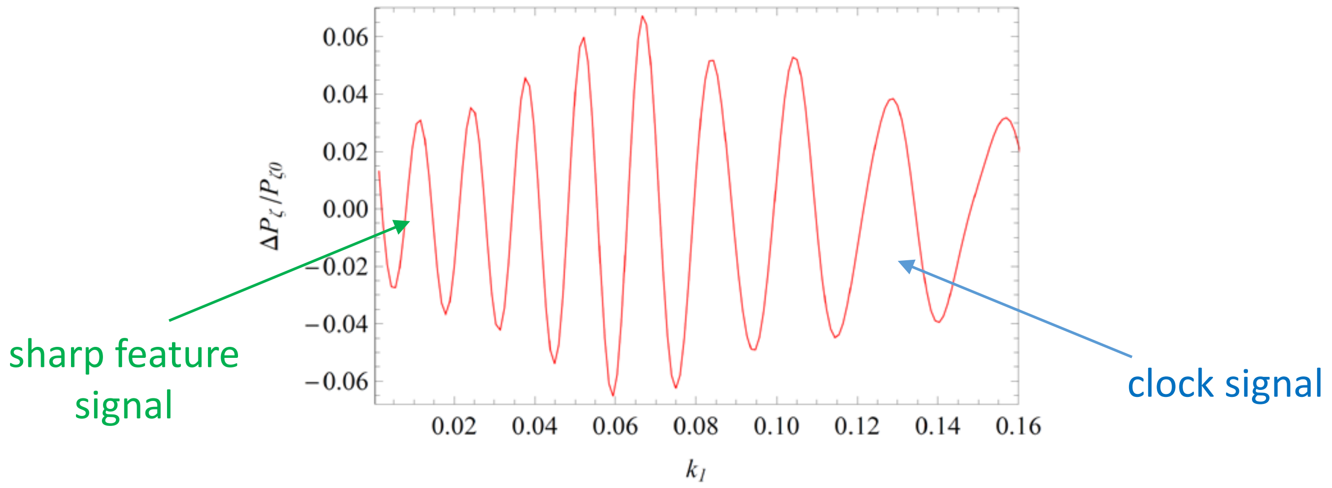
A fit of a PSC model to CMB:

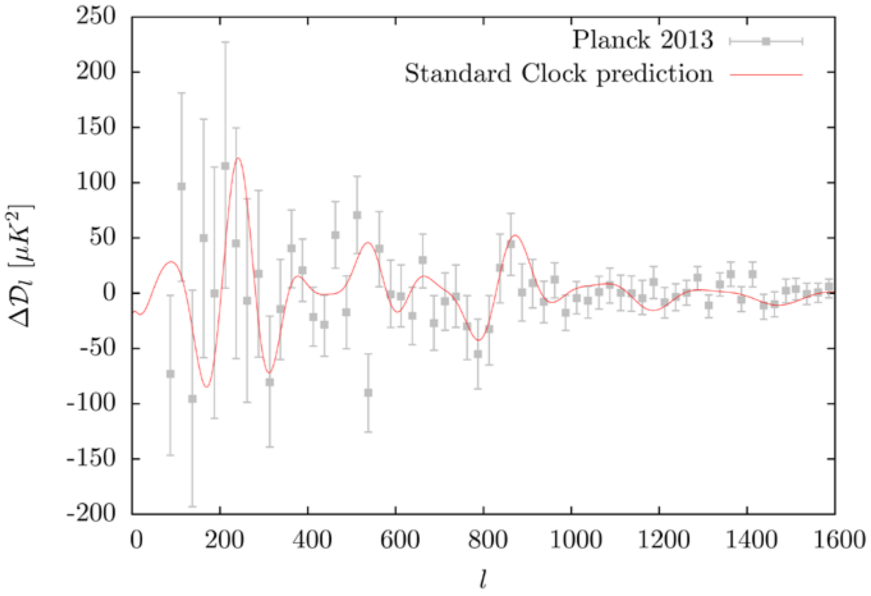
a two-stage inflation model



$$\mathcal{L} = -\frac{1}{2}(\tilde{R}+\sigma)^2 g^{\mu\nu}\partial_\mu\theta\partial_\nu\theta - V_{\rm sr}(\theta) - \frac{1}{2}g^{\mu\nu}\partial_\mu\sigma\partial_\nu\sigma - V_\sigma(\sigma)$$

$$V_\sigma = V_{\sigma 0}\left[1-\exp(-\sigma^2/\sigma_f^2)\right]$$





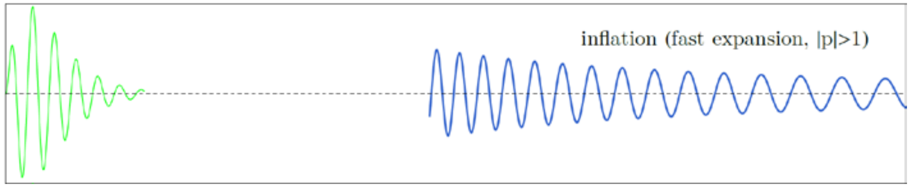
This PSC candidate so far only has marginal statistical significance; it nonetheless serves as an interesting example.

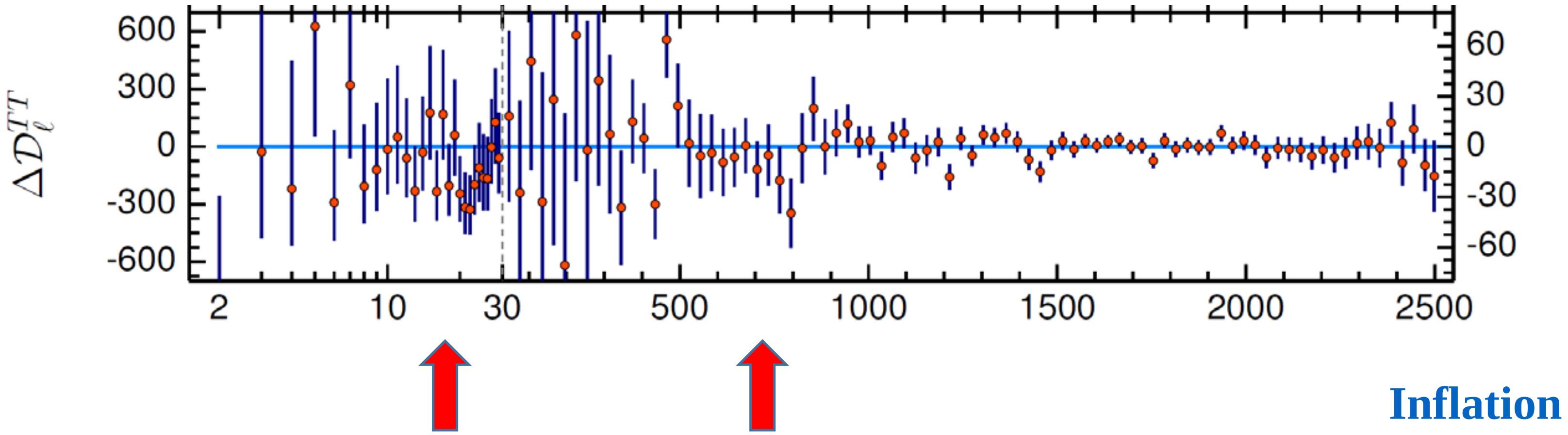
(XC, Namjoo, 14;
XC, Namjoo, Wang, 14)

Future LSS data will tell.

(XC, Dvorkin, Huang, Namjoo, Verde, 16)

A Candidate Standard Clock Signal in CMB, Containing Fingerprint of Inflation





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

Note that, these two features may also be explained by a single sharp feature signal; the 2nd feature may also be explained by resonant features.
Future data will test or distinguish these 3 possibilities.

(XC, Wang, Namjoo, 14)

Quantum Primordial Standard Clocks

(XC, Namjoo, Wang, 15; XC, Loeb, Xianyu 18)

What happens if there is no sharp feature?

Massive fields can oscillate without sharp features quantum-mechanically in any time-dependent background

Quantum fluctuations of massive fields can also be used as standard clocks

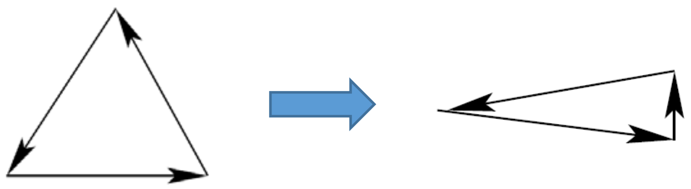
Quantum Primordial Standard Clocks in Inflation Scenario

Quantum fluctuations do not have preferred scales, where do we find the oscillatory signals?

- scale-dependence:

Scale invariance → No clock signal in leading order power spectrum (2pt)

- shape-dependence:



Clock signal as a function of shape of non-Gaussianities

Quantum PSC in Arbitrary Scenarios

classical regime:

- Find a massive field heavier than horizon scale: $m > m_{\rm h}$
- Look at the epoch when it is homogeneous over the Compton scale: $m > k/a$

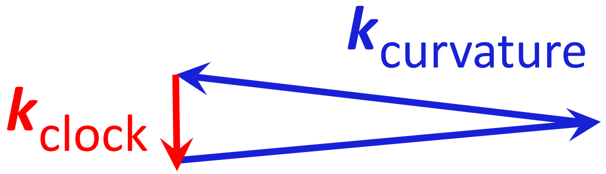
Mode function of the massive scalar field:

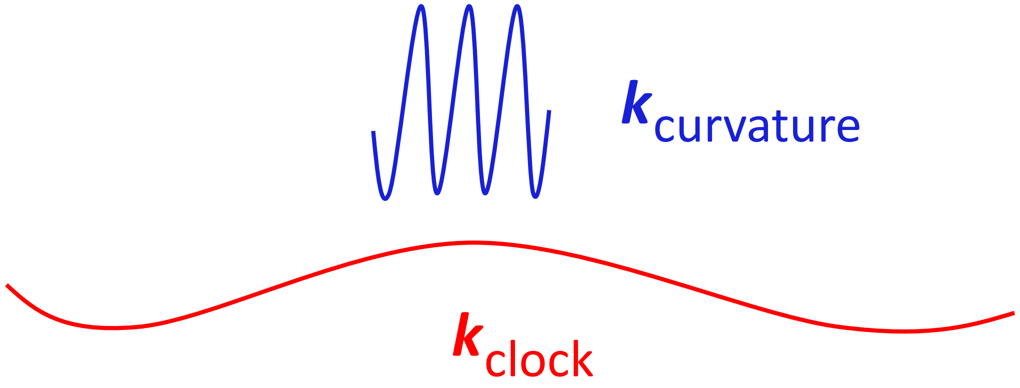
$$\Rightarrow \quad v_k \to \left(\frac{t}{t_k}\right)^{-3p/2} \left(c_+ e^{-imt} + c_- e^{imt}\right)$$

The quantum oscillation of massive is classical-like in the classical regime

Quantum PSC in Arbitrary Scenarios

Quantum fluctuations of massive fields at the classical regime can serve as Standard Clocks





Longer wavelength quantum fluctuations of massive field
serve as background clock fields for shorter wavelength curvature mode

⇒ physics then becomes similar to the classical PSC case

Shape-Dependent Clock Signals in Quantum PSC

(XC, Namjoo, Wang, 15)

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

Inverse function of *a*(*t*)

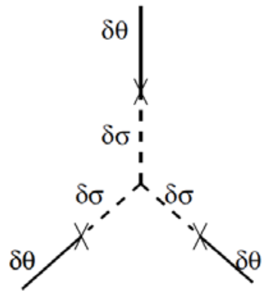
k_3 : long mode $\qquad$ k_1 : short mode

Shape-dependent oscillatory signal

Amplitudes of QPSC are Highly Model-Dependent

For example, for inflation models:

- Gravitational coupling $f_{NL} < 0.01$
- Direct coupling $f_{NL} < 1$
- Massive fields self-coupling $f_{NL} < 100$
- Boltzmann suppression $\sim \exp(-\pi m/H)$



Quantum primordial standard clocks may also appear in power spectrum for alternative to inflation scenarios

(XC, Loeb, Xianyu 18)

--- because alternative-to-inflation models are not shift symmetric,
e.g. the horizon energy scale changes with time

Signals of quantum clocks can appear in a non-scale-invariant way.

Basic Ideas of Primordial Standard Clocks II (XC, Loeb, Xianyu, 2018)

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

start with

$$v_k \propto \exp\left(\pm imt\right)$$

$\xrightarrow{\text{contraction scenario}}$

after entering k-dominated phase

$$v_k \propto \exp\left[i\ t(k)\right] \exp(\pm ik\tau)$$

start with

$$v_k \propto \exp(\pm ik\tau)$$

$\xrightarrow{\text{expansion scenario}}$

after entering m-dominated phase

$$v_k \propto \exp\left[i\ t(k)\right] \exp(\pm imt)$$

$t(k)$ is inverse function of $a(t)$

Clock Signal in Density Perturbations

(a) (b)

For alternative scenarios, main contribution comes from the horizon dominated regime.

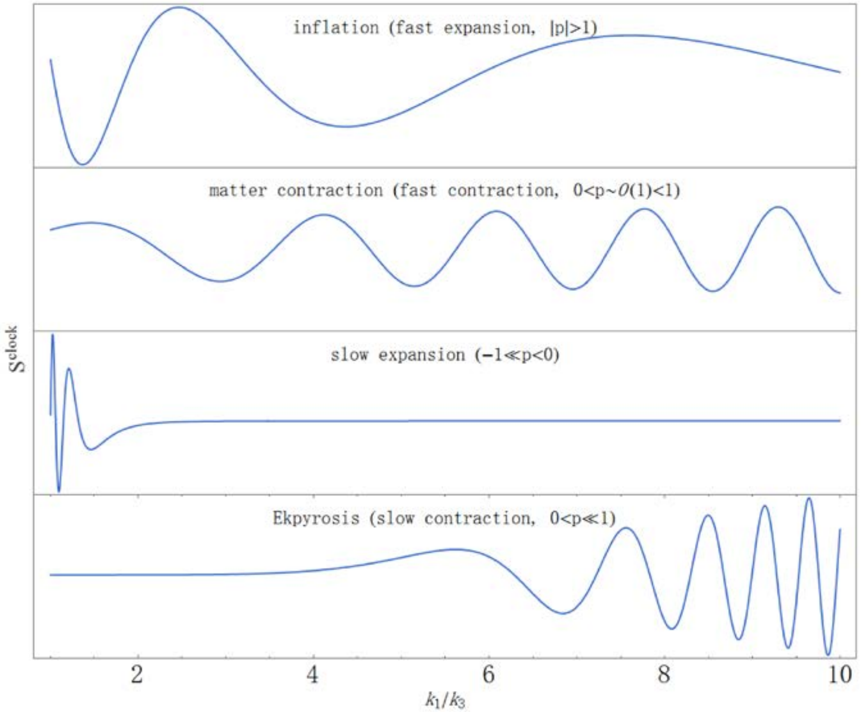
$$v_k \sim c_+ e^{-imt} + c_- e^{imt} \quad \Longrightarrow \quad v_k \propto \exp\left(\pm i\beta\tilde{k}^{1/p}\right)\exp\left(\pm ik\tau\right)$$

time-independent clock signal phase factor

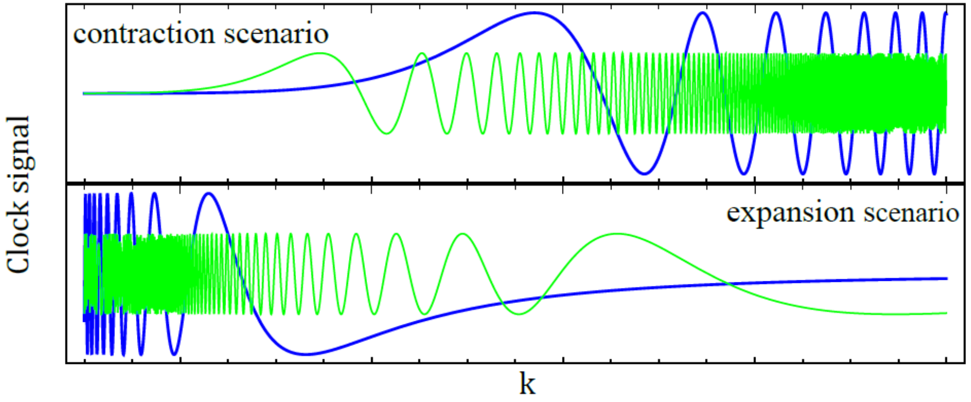
$$\Delta\langle\zeta^2\rangle' = |c_+c_-^*|\sin\left(2\beta\tilde{k}^{1/p}+\phi\right)f(k)+\ldots$$

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

A Summary of Quantum PSC



Non-Gaussianity



Power Spectrum

- Massive fields exist in any UV-completed models
- They quantum fluctuate in any time-dependent background
- They couple to any other field at least through gravity

Quantum primordial standard clock signal exists in any inflation models, and may be present in many alternative-to-inflation models too. Amplitude is highly model-dependent.

Some key properties that make these (both classical and quantum) primordial clocks “standard”:

- Massive fields (with mass larger than horizon scale) oscillate like harmonic oscillators in any time-dependent background

- The clock signals are created when the quantum fluctuations of the curvature field is at sub-horizon scales.

Sub-horizon behavior is standard --- Minkowski limit behavior;
C.f. the super-horizon behavior of scalar field is very model-dependent.

Assumptions: mass of the clock is approximately constant.

- How to mimic the signal with time-dependent mass/frequency (non-Standard Clocks), and how to distinguish them? (XC, 11; Huang, Pi, 16; Domenech, Rubio, Wons, 18)

An interesting connection
between Primordial Standard Clocks and Quasi-Single Field Inflation
through Quantum PSC

Quasi-Single Field Inflation and Cosmological Collider Physics

(XC, Wang, 09; Baumann, Green, 11; Noumi, Yamaguchi, Yokoyama, 12)
(Arkani-Hamed, Maldacena, 15)

What are the observational signatures for all the particles present during **INFLATION**?

The particle mass and spin spectra are encoded in various soft limits of non-Gaussianities:

E.g. **Squeezed limit bispectrum**

$$S \xrightarrow[\text{limit}]{\text{squeezed}} \underbrace{e^{-\pi\mu}}_{\text{Boltzmann suppression}} \left(\frac{k_{\rm long}}{k_{\rm short}}\right)^{\overbrace{\frac{1}{2}\pm i\mu}^{\text{mass}}} \underbrace{P_s}_{\text{spin}}(\cos\theta)$$

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

The Connection between Cosmological Collider Physics and QPSC

For *m>3H/2*, these signals directly encode the inflationary *a(t)*

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

$\Downarrow$

Inverse function of exp

$\Downarrow$

Background is exponential inflation

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

Quasi-Single Field Inflation and Cosmological Collider Physics:

Probing light and heavy particle spectra in inflation scenario, quantum mechanically

Primordial Standard Clocks:

Probing the background $a(t)$ using heavy field, classically or quantum mechanically, in arbitrary primordial universe models

A more general program:

Density perturbations as probes of both particle spectra and the background $a(t)$ in arbitrary primordial universe models classically or quantum mechanically

A Comparison between Inflation and Alternative Scenarios in this Program

Inflation works like a particle collider with fixed energy –
particle spectrum hiding in shapes of non-Gaussianities.

Alternative scenarios work like particle scanners –
scan over a tower of massive states one by one and display each of them as a pulse of signals at different length scales in the density perturbations.

Besides particle spectra, clock signals from both types of particle detectors also carry direct information about $a(t)$
--- can be used to falsify competing scenarios in a model-independent fashion.

Prospects for Future Observations

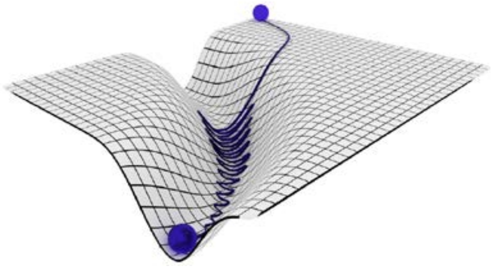
For scale-dependent primordial standard clocks , we look for correlated scale-dependent signals in :

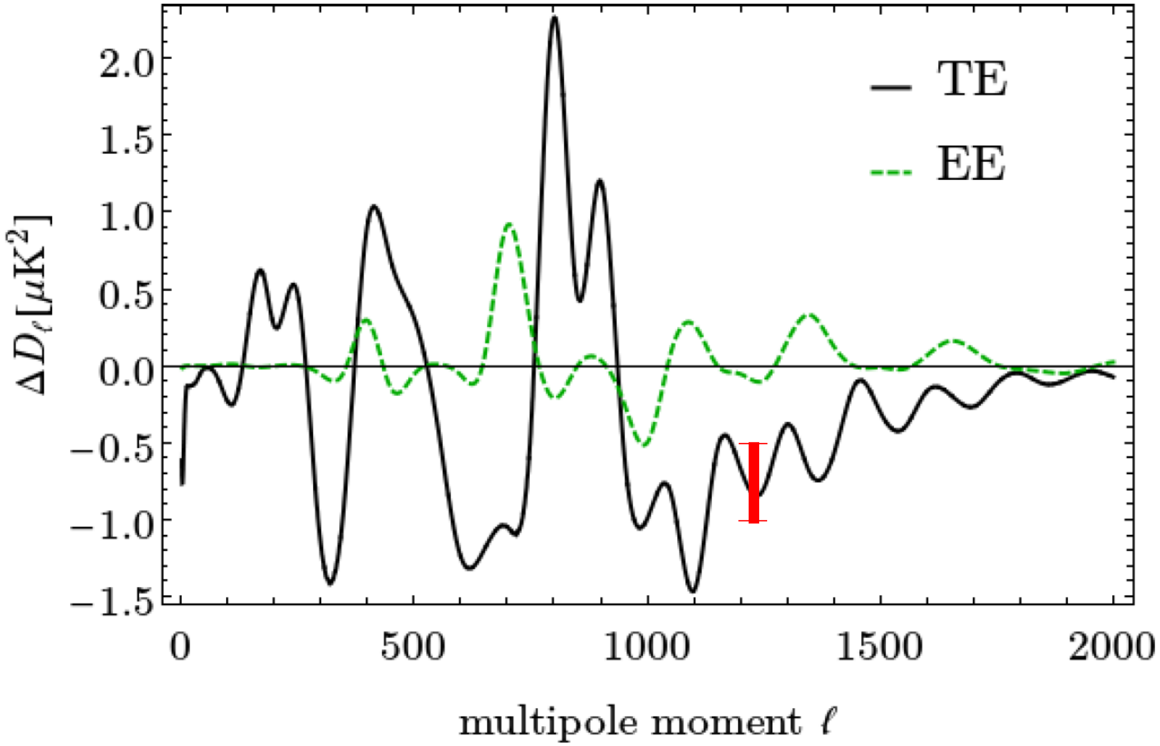
- All correlation functions:
  power spectrum and non-Gaussianities

- All manifestation of density fluctuations:
  CMB Temperature and Polarization, LSS, 21cm

Standard Clock models have strictly correlated signals in CMB polarization data

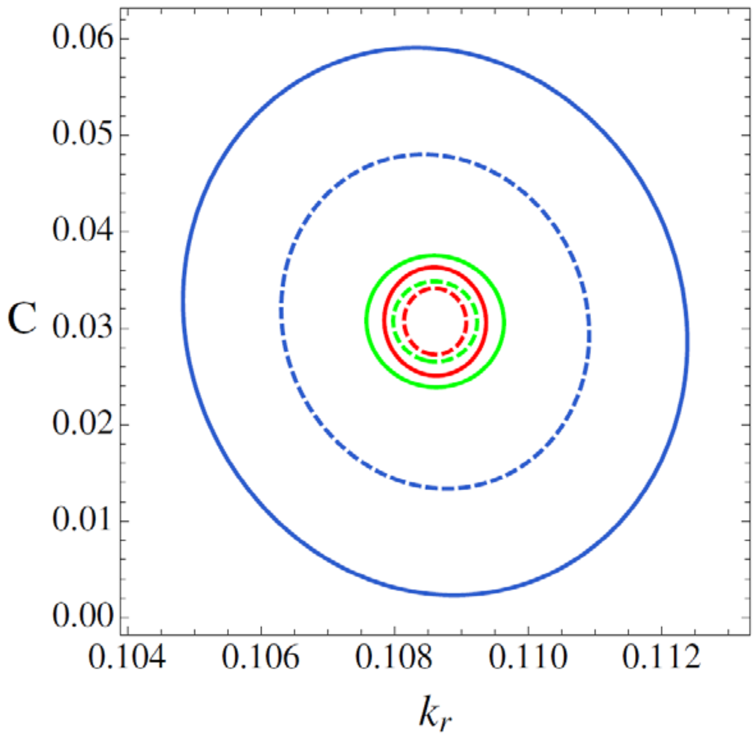
The same classical PSC example:

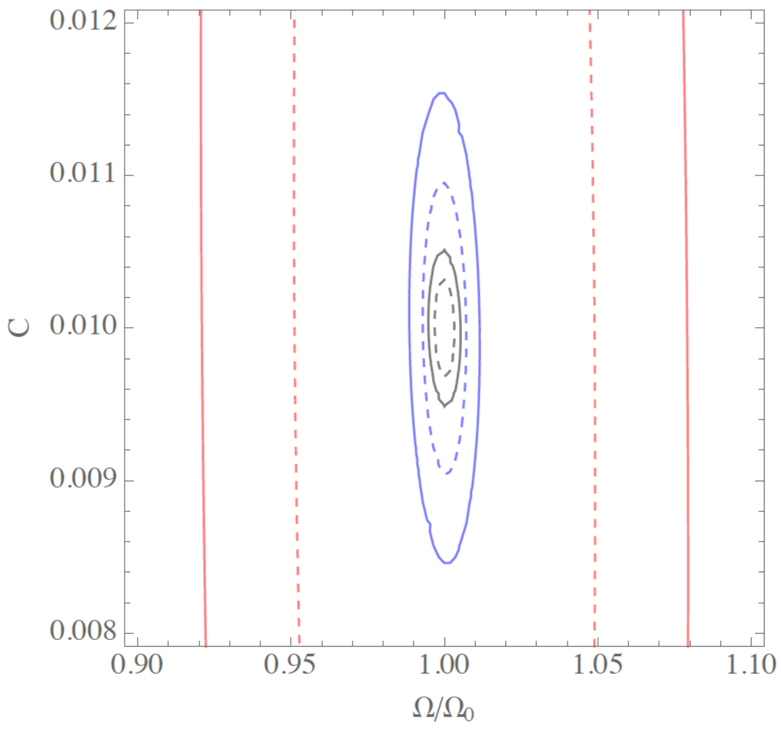




For TE, $\sigma(D_\ell) \approx 0.25\mu K^2$ with bin size $\Delta\ell = 30$

Correlated Signals in Large Scale Structure and 21cm Tomography





Planck Planck+LSST Planck+Euclid

A factor of 5 improvement on error

(XC, Dvorkin, Huang, Namjoo, Verde, 16)

21 cm experiment

may discover new features at much shorter scales

(*kr* = 0.01, 0.1, 1 /Mpc)

(XC, Meerburg, Munchmeyer, 16)

For shape-dependent primordial standard clocks, we look for correlated shape-dependent signals in non-Gaussian correlation functions

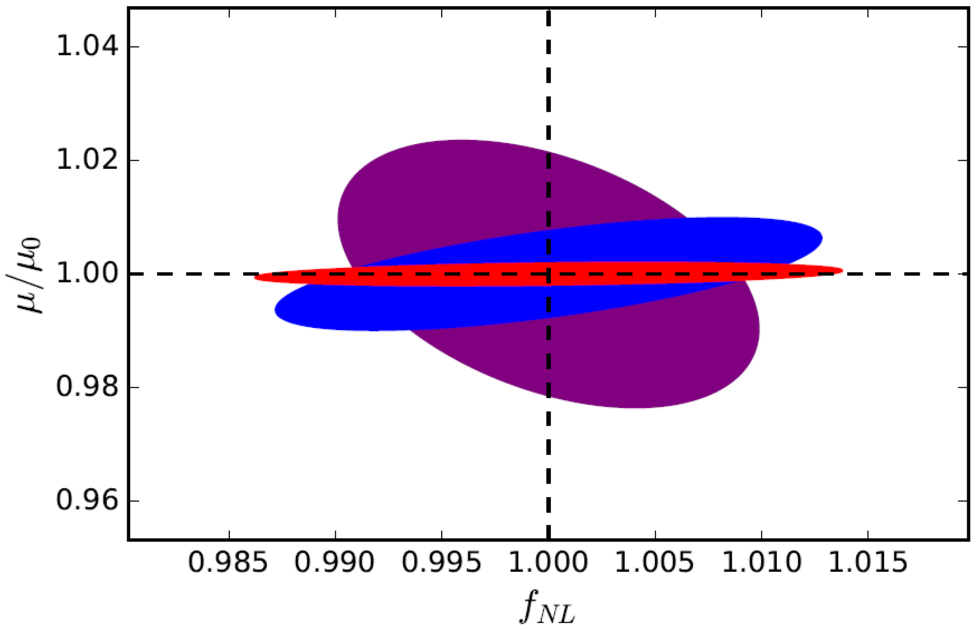
LSS: Galaxy Bispectrum

EUCLID	$k_{\max}(z=0) = 0.15\,h\ \mathrm{Mpc}^{-1}$	
	$\sigma(f_{\rm NL})$	$\sigma(\tilde{\nu})$
loc.	0.38	–
eq.	2.3	–
qsf ($\tilde{\nu}_{\rm fid} = 1$)	2.2	1.3
$\nu_{\rm fid} = 3$	$\sigma(f_{\rm NL})$	$\sigma(\nu)$
$s = 2$	0.66	0.35
$s = 3$	1.5	3.3
$s = 4$	0.68	0.098
$\nu_{\rm fid} = 6$	$\sigma(f_{\rm NL})$	$\sigma(\nu)$
$s = 2$	0.71	370
$s = 3$	1.5	250
$s = 4$	0.52	0.23

(Dizgah, Lee, Munoz, Dvorkin, 18)

21 cm: E.g. Cosmic Variance Limited 21cm Experiment with 30<z<100 and 100km baseline

Futuristic



μ = 0.7, 1.0, 3.0

$$\mu = \sqrt{(m/H)^2 - 9/4}$$

(Meerburg, Munchmeyer, Munoz, XC, 16)

Potential is great, how to realize such experiments is challenging

Thank You !