Primordial Standard Clocks
as A Direct Probe of the Scenario of the Primordial Universe

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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 as a whole scenario due to too many model variations and eternal inflation.

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, …)

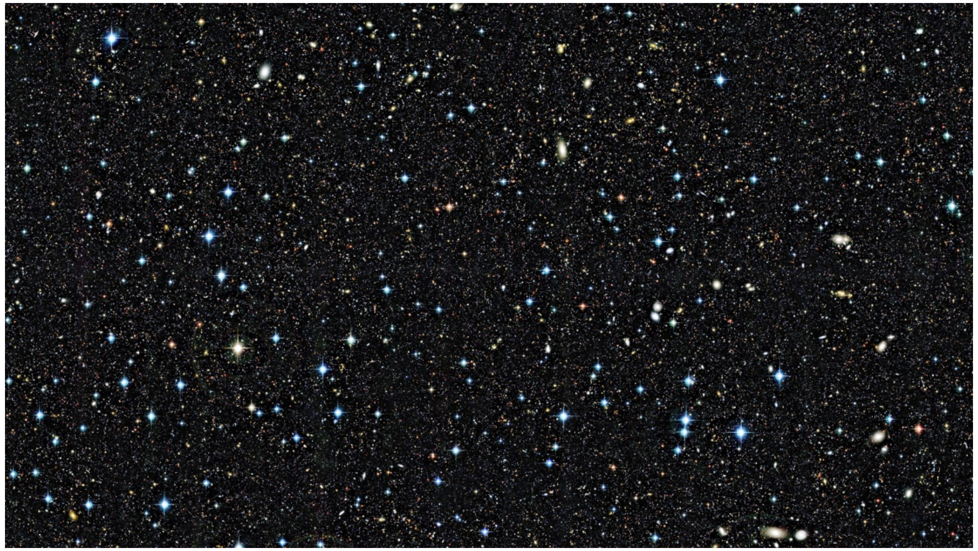
Measuring an approximately scale-invariant tensor spectrum
would rule out Ekpyrotic Scenario – a type of slowly contracting scenario

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.
  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.

↓

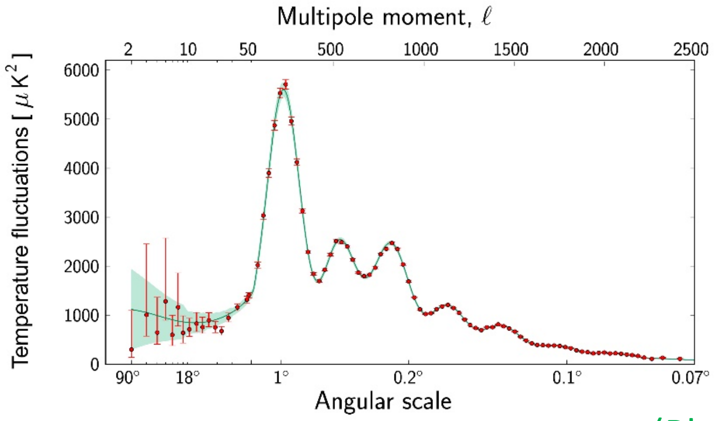
This led to debates on issues such as:

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

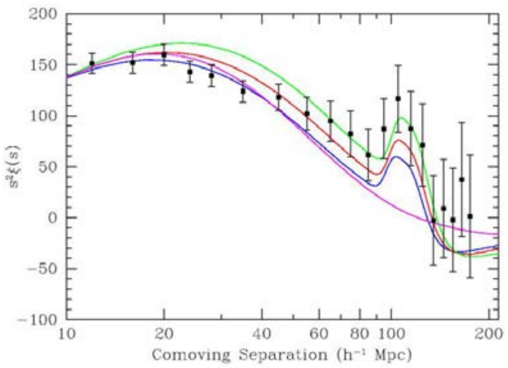
These issues were settled with the discovery of Standard Candles, such as Cepheid and Type Ia supernova.

2D map → 3D map

Current Situation for Primordial Universe Cosmology



(Planck)



(SDSS)

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

Evidences show that:
different modes are generated at different time during the primordial universe.

But, we do not know:
the time coordinates for these time slices

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: to turn 3D map to 3+1 D map (for primordial universe)

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

Yes. Such observables exist;

some type of them are even

present in every realistic inflation model,

and should exist generically in alternative-to-inflation models too.

--- Massive Fields as Primordial Standard Clocks

(XC: 1104.1323, 1106.1635; XC, Namjoo, Wang: 1411.2349, 1509.03930)

Massive: Mass larger than horizon scale of the epoch

Basic Ideas 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 function: $\langle \zeta_{\mathbf{k}}^2 \rangle \supset \int e^{i(mt - 2k\tau)} d\tau$

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*

Describe background of different scenarios by a simple power-law function

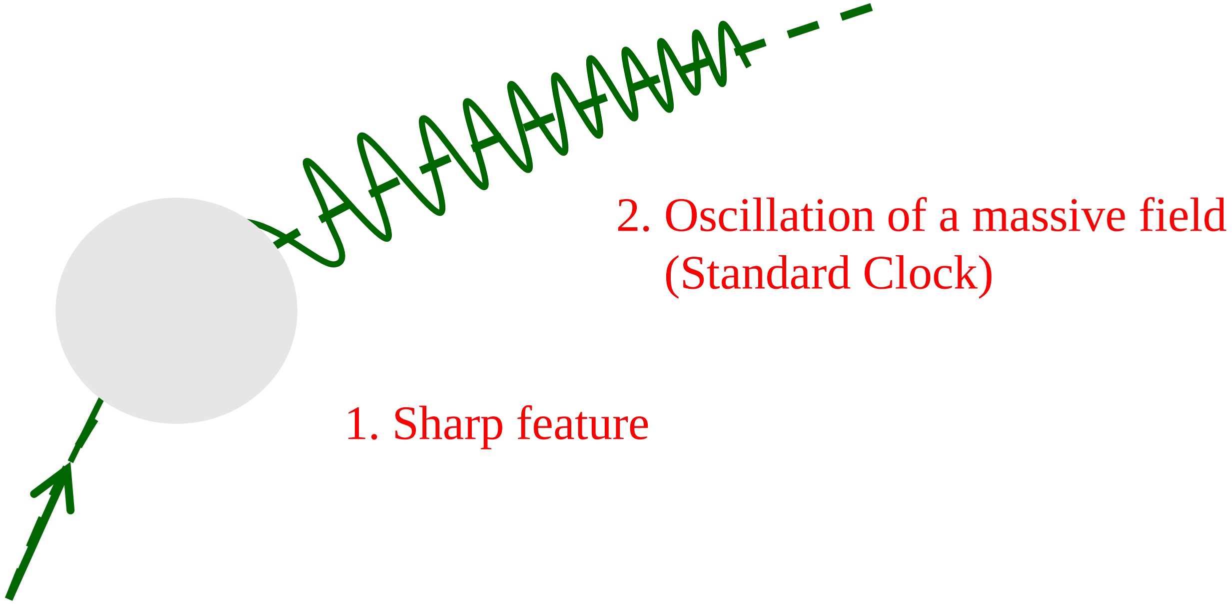
$$a(t) \sim t^p$$ arbitrary *p*

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

$\lvert p \rvert > 1$	t: from 0 to $+\infty$	Fast expansion (Inflation)
$0 < p \sim \mathcal{O}(1) < 1$	t: from $-\infty$ to 0	Fast contraction (e.g. Matter contraction) (Wands, 98; Finelli, Branderberger, 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 types of primordial standard clocks
depending on how the oscillations of massive fields are generated

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.

Sharp Feature Signal

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

besides 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.

The Clock Signal in Classical PSC

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

The background oscillation resonates with curvature fluctuations mode by mode

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

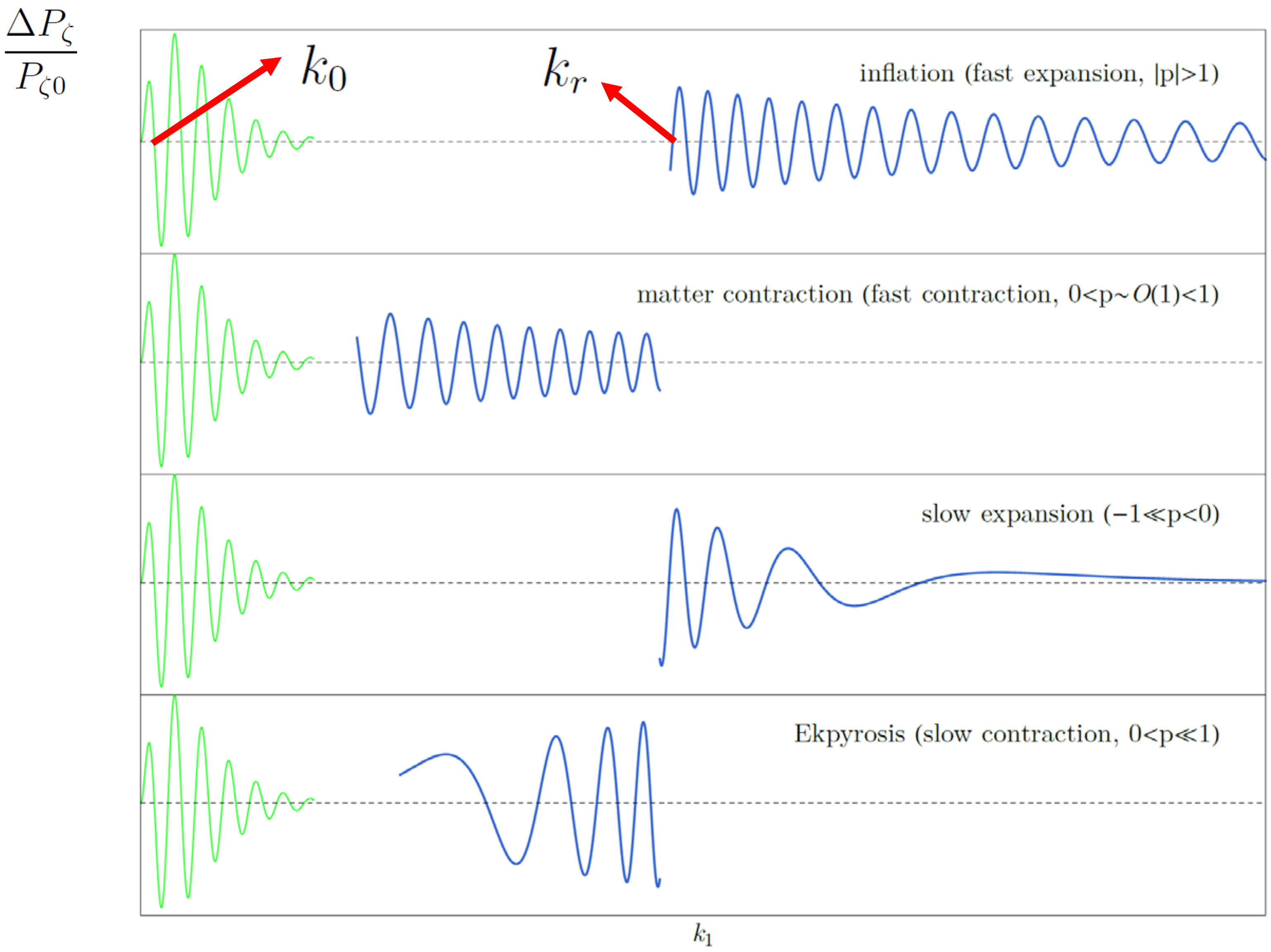
horizon mass
at time of sharp feature

Inverse function of *a*(*t*)

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

Sketch of Full Classical PSC Signals for Different Scenarios (X.C., 11, X.C., Namjoo, Wang, 14)

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



Location of sharp feature signal: k_0

Location of clock signal: k_r

A relation between them:

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

Limitation of Classical PSC:

Requiring a sharp feature inducing classical oscillation of massive field

Maybe you do not like sharp features and classical excitation of a heavy field,
because they do not exist in all models.

Nonetheless, let us have three comments on this point.

Comment 1

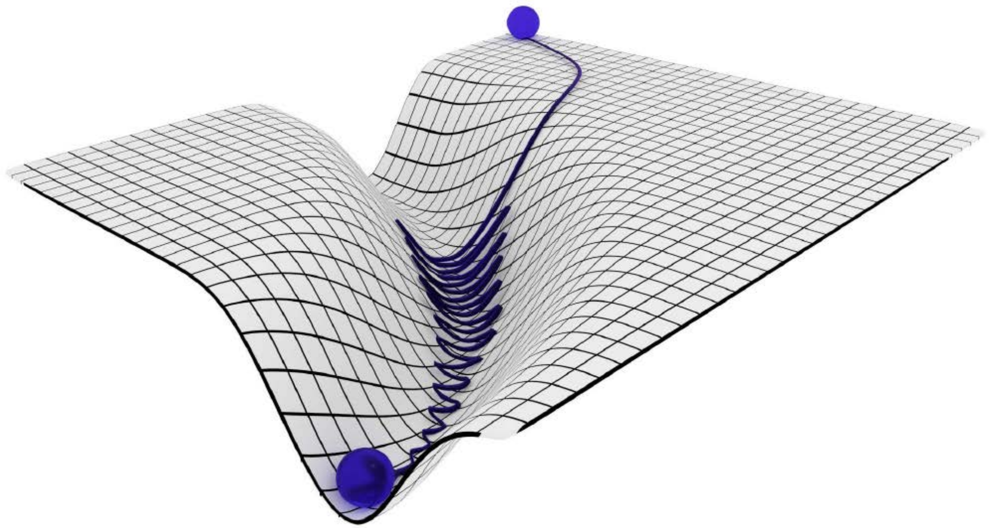
In particle physics, very massive field are hard to excite, and we integrate them out in low energy EFT

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



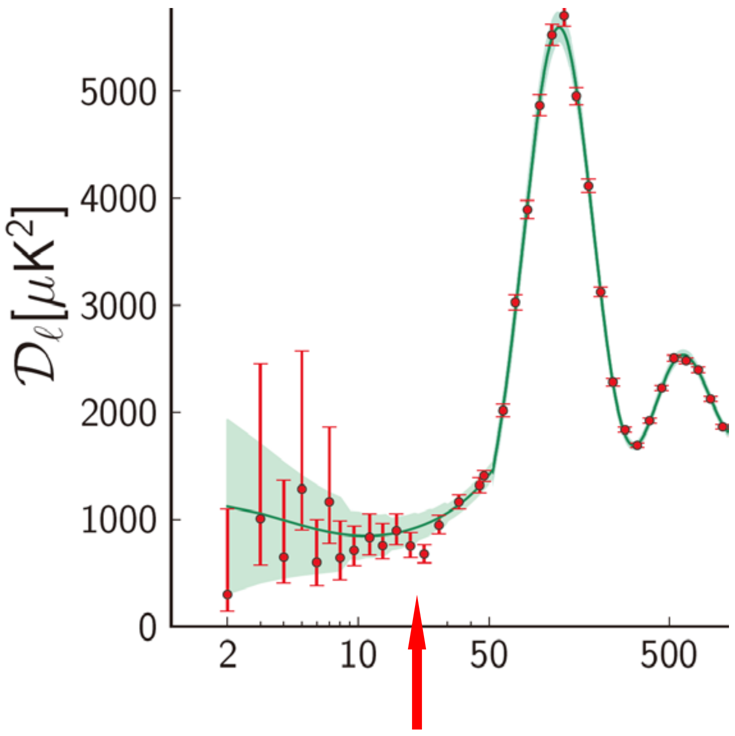
→ **A very massive field easily excited**

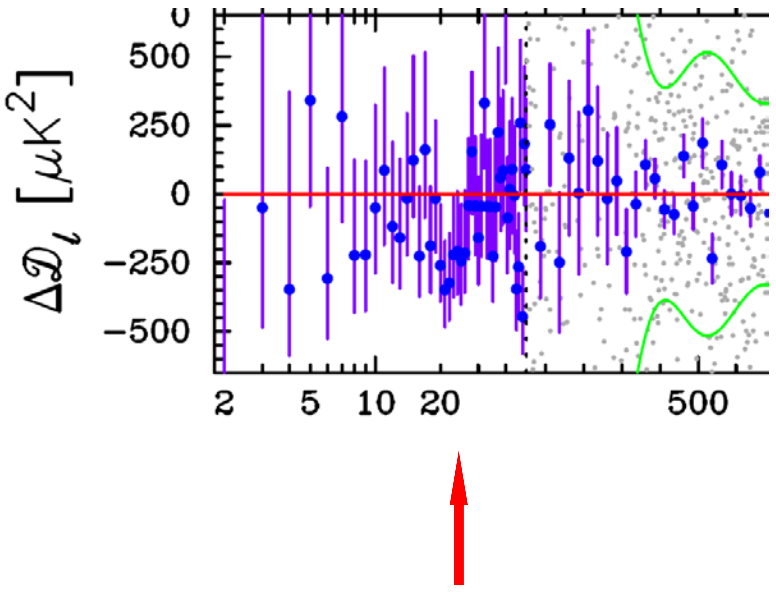
Comment 2

Let us look at the data:

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

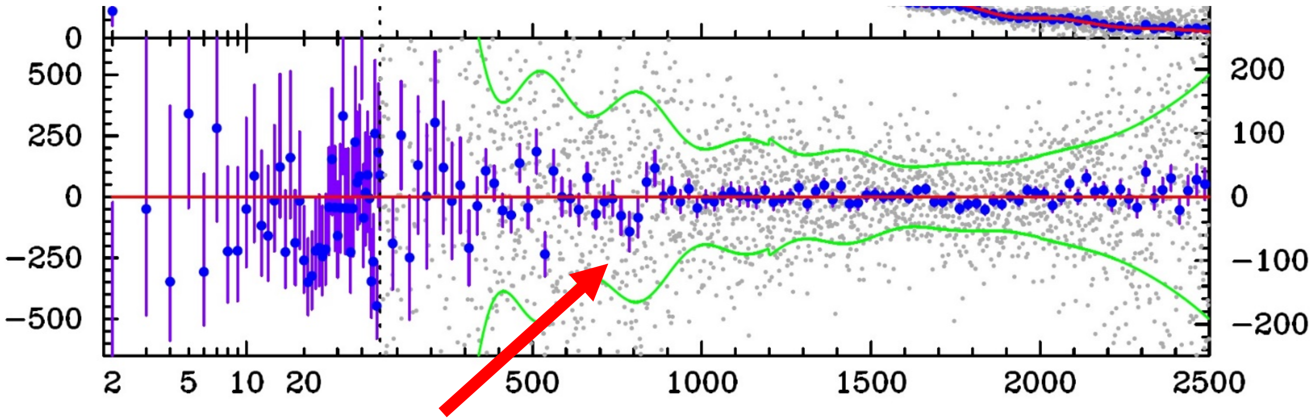
(WMAP, Planck)





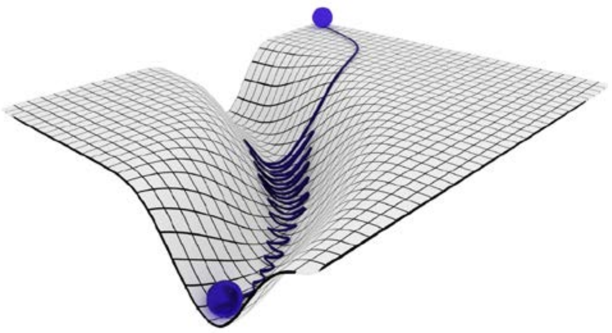
If it was indeed a sharp feature, it may well have excited some massive fields.

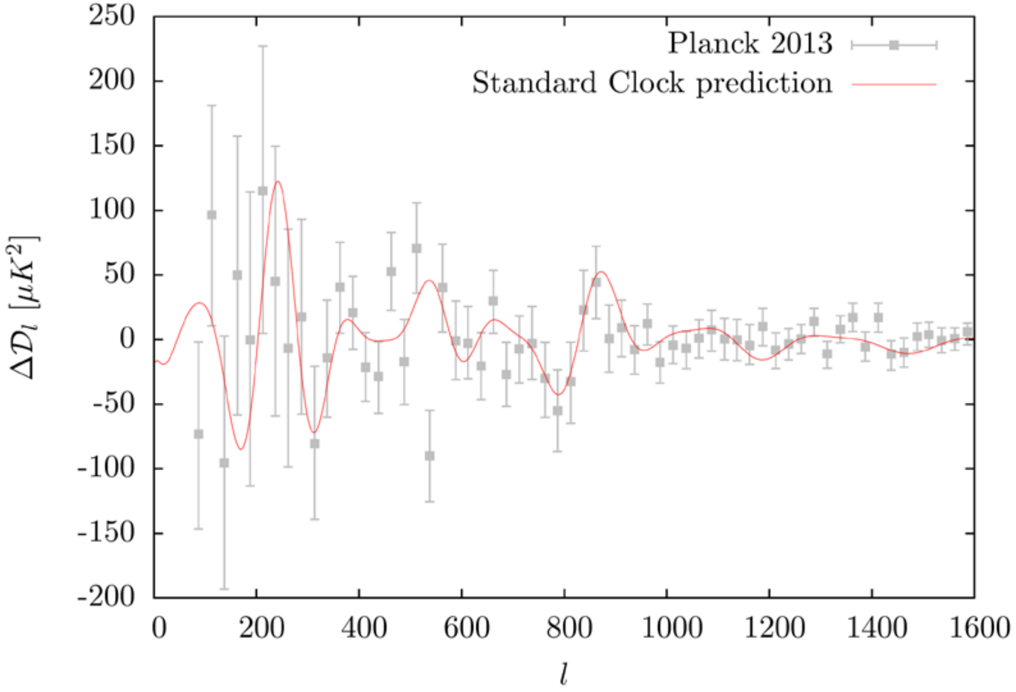
Comment 2 (continued)



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

A fit of a PSC model to CMB





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

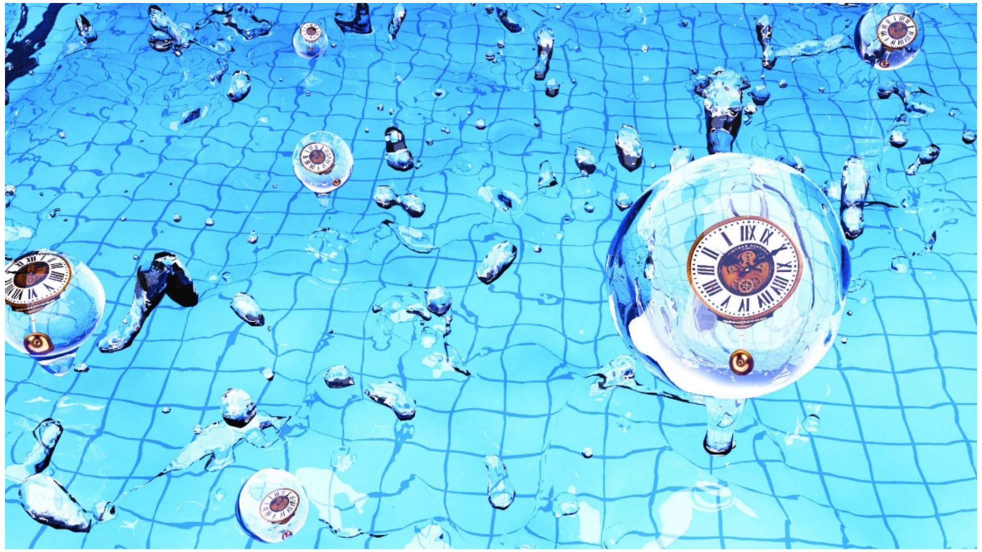
(XC, Namjoo, 14;
XC, Namjoo, Wang, 14)

Comment 3

What happens if there is no sharp feature?

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

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



Quantum Primordial Standard Clocks (XC, Namjoo, Wang, 15)

Quantum Primordial Standard Clocks in Inflation

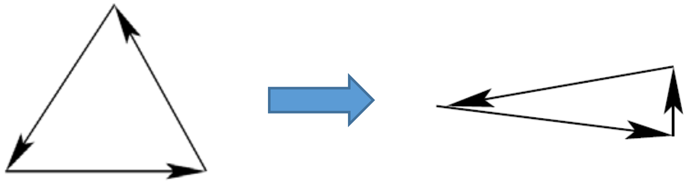
Quantum fluctuations do not have preferred scales, where do we find the oscillatory signals?

Look for them in non-Gaussianities.

- scale-dependence:

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

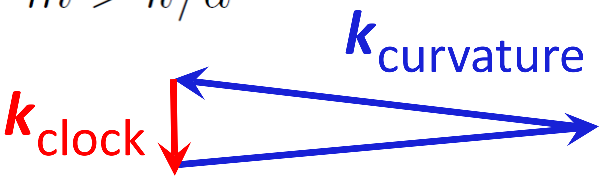
- shape-dependence:

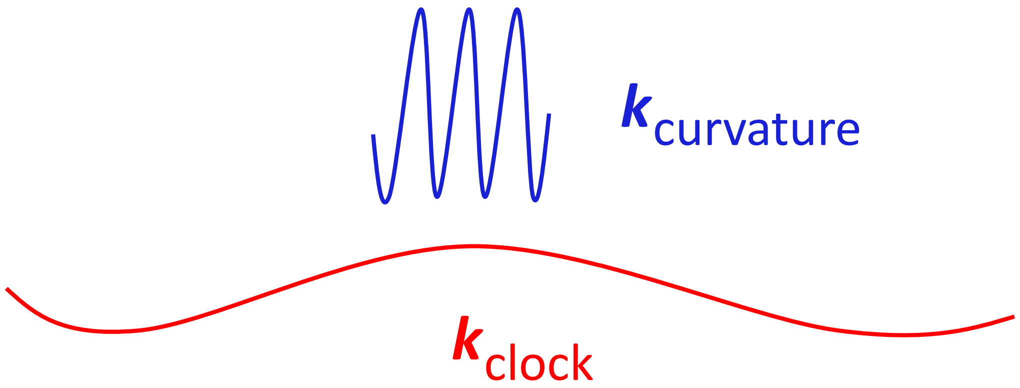


clock signal as a function of shape of non-Gaussianities

Quantum PSC in Arbitrary Scenarios

- Find a massive field heavier than horizon scale: $m > m_{\mathrm{h}}$
- Look at the epoch when it is homogeneous over the Compton scale: $m > k/a$
- Look at the squeezed configuration: $k_{\mathrm{clock}} < k_{\mathrm{curvature}}$





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

The Clock Signals in Quantum PSC

(XC, Namjoo, Wang, 15)

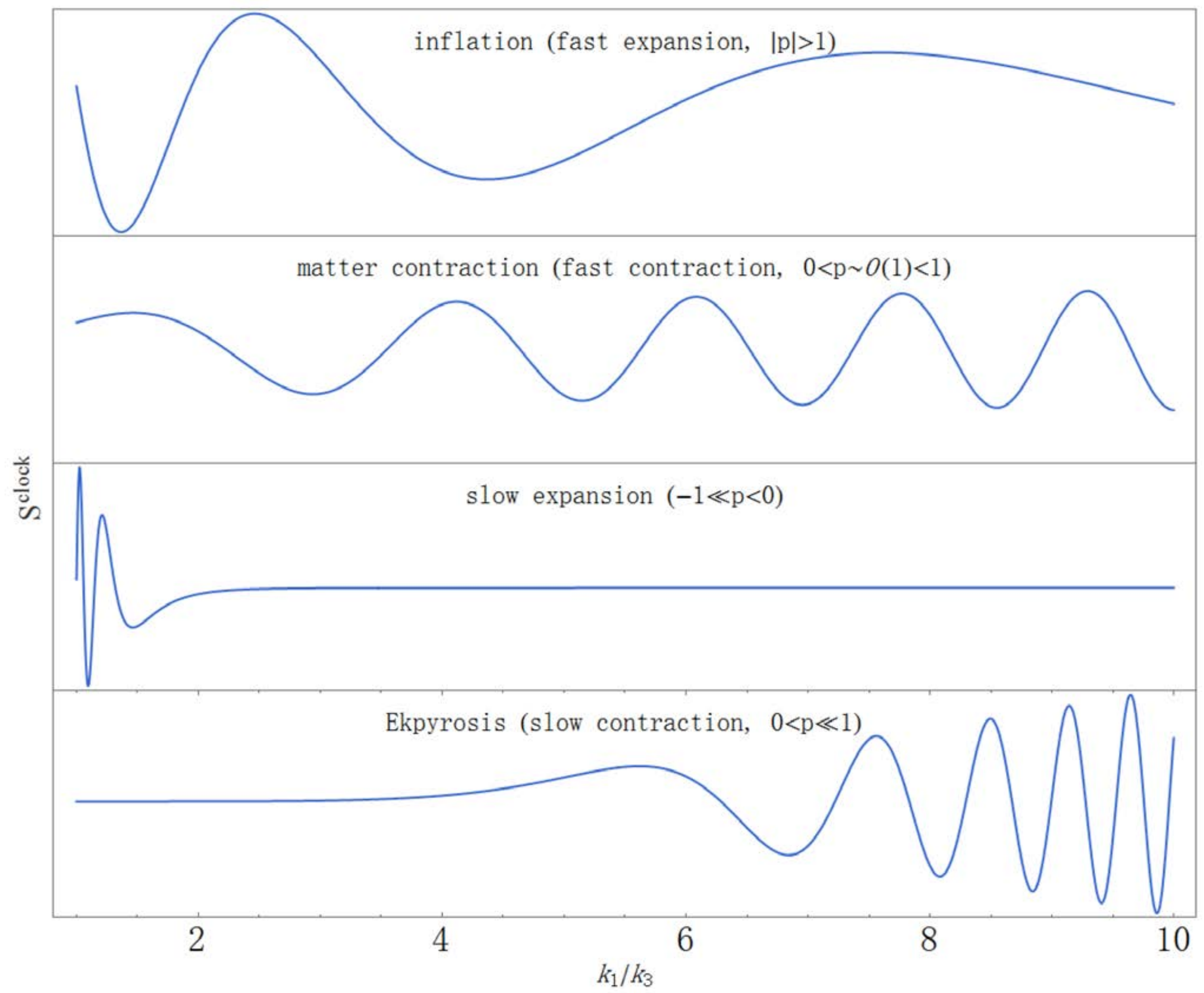
$$S^{\rm clock} \propto \left(\frac{2k_1}{k_3}\right)^{-\frac{1}{2}+\frac{1}{2p}} \sin\left[p\,\frac{m}{m_{{\rm h},k_3}}\left(\frac{2k_1}{k_3}\right)^{1/p} + \varphi(k_3)\right]$$

Inverse function of *a*(*t*)

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

Shape-dependent oscillatory signal

Sketch of Quantum PSC for Different Scenarios



- 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 should be generic for alternative-to-inflation models as well.

Amplitude is highly model-dependent.

Prospects for Future Observations

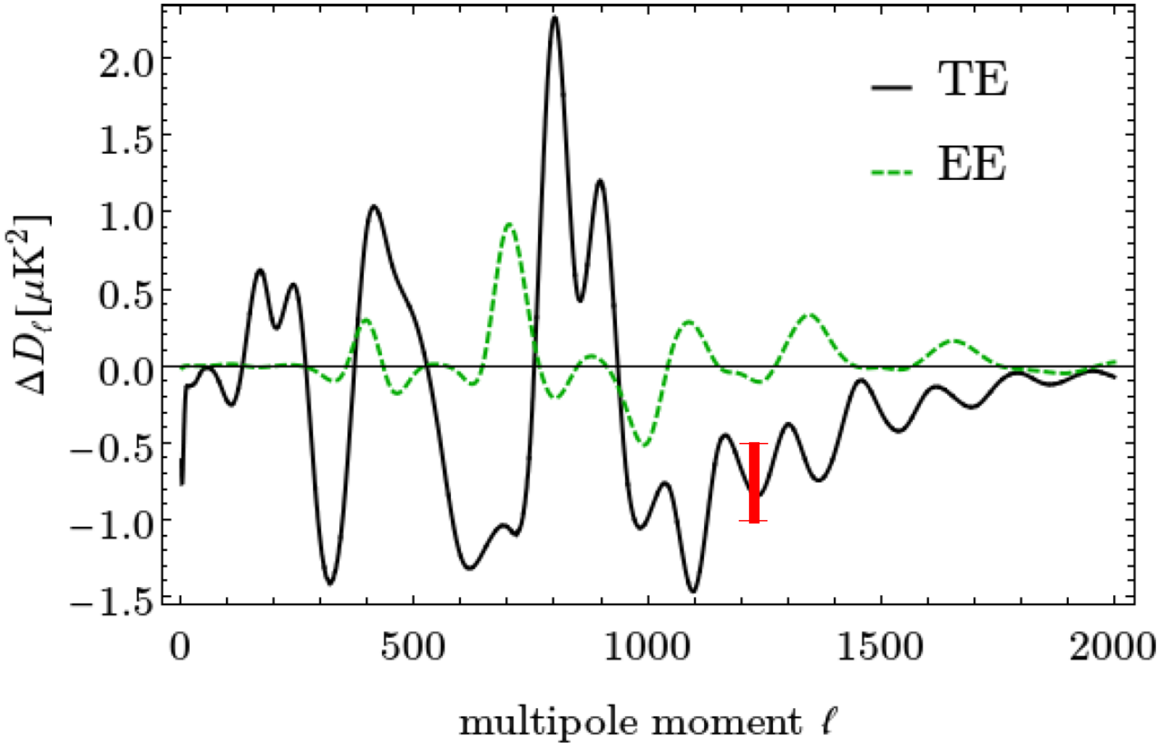
For **classical** primordial standard clocks, we look for correlated scale-dependent clock signals in :

- All correlation functions:
  power spectrum and non-Gaussianities

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

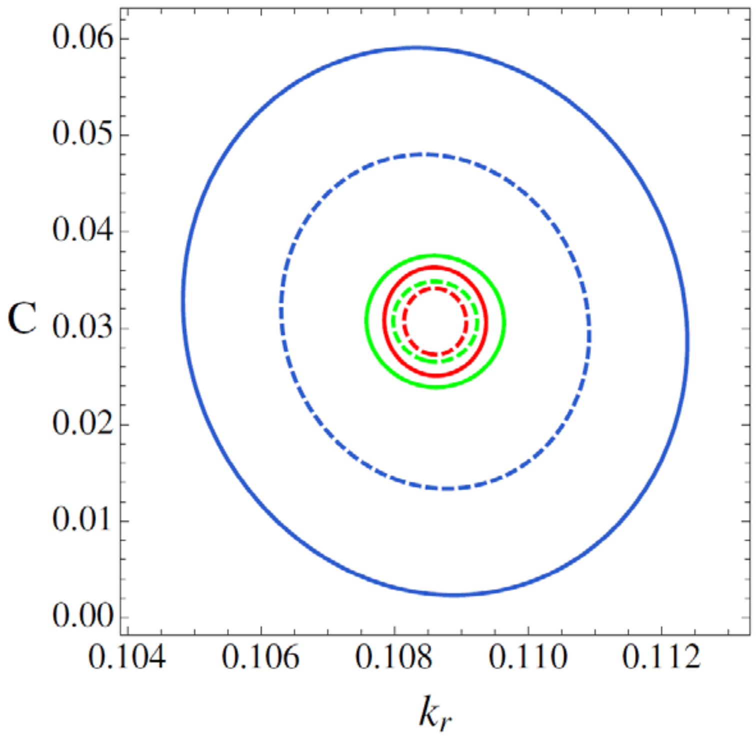
Standard Clock models have strictly correlated signals in CMB polarization data

The same classical PSC example:



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

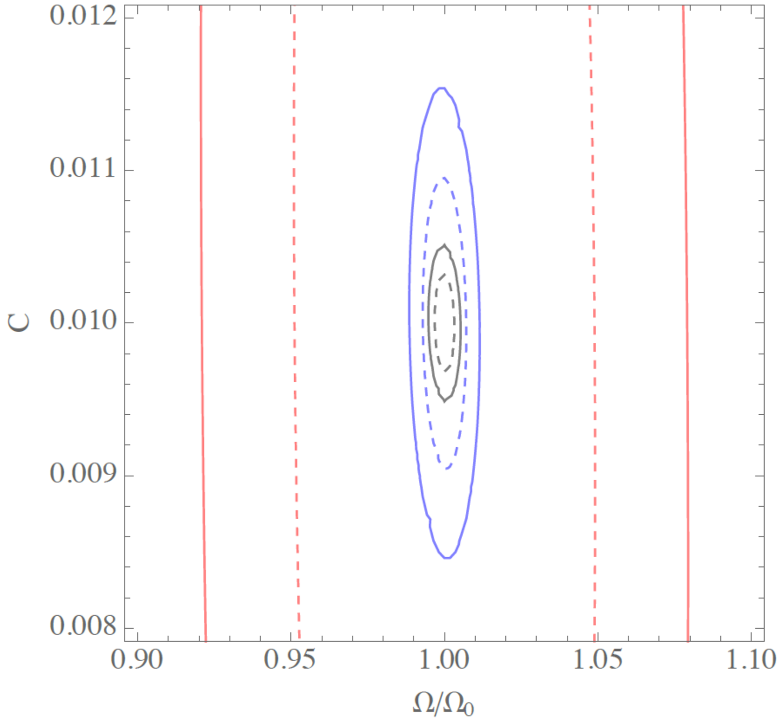
Correlated Signals in Large Scale Structure and 21cm Tomography



Planck Planck+LSST Planck+Euclid

A factor of 5 improvement on error

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



21 cm experiment

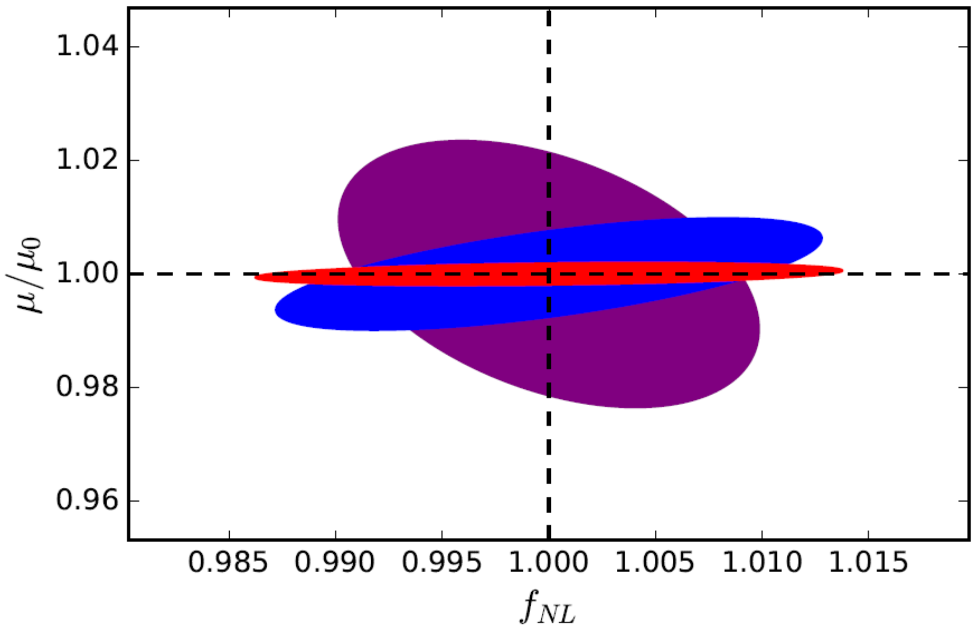
may discover new features at much shorter scales

(kr = 0.01, 0.1, 1 /Mpc)

(XC, Meerburg, Munchmeyer, 16)

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

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



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 !