High Energy Physics in Primordial Density Perturbations

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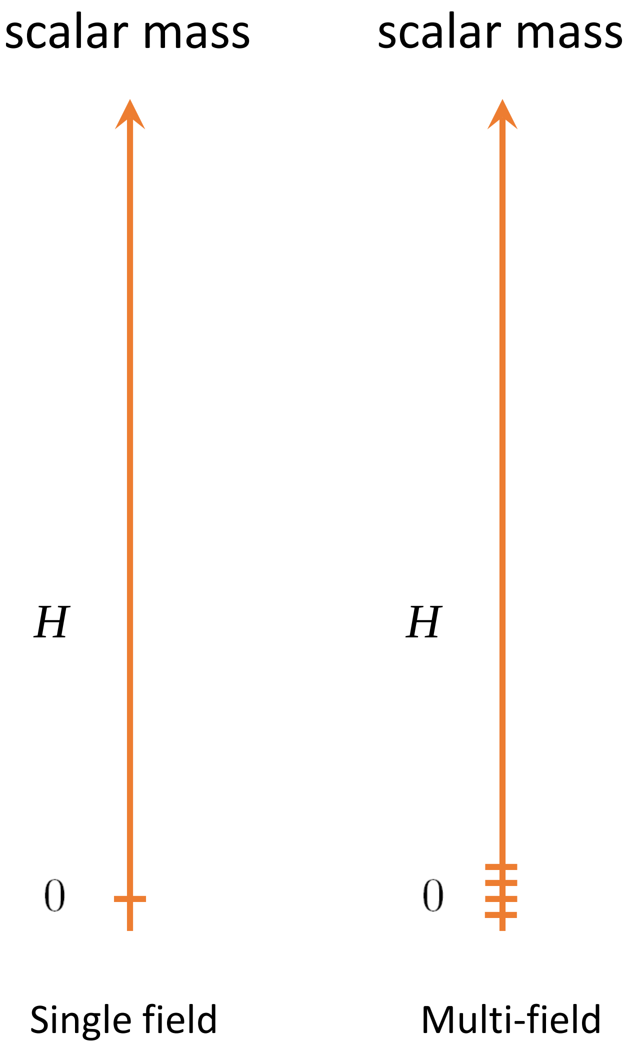
arXiv: 1104.1323, 1106.1635, 1205.6085,
1404.1536, 1411.2349;
0909.0496; 0911.3380;
with Y. Wang. M.H. Namjoo, C. Ringeval.

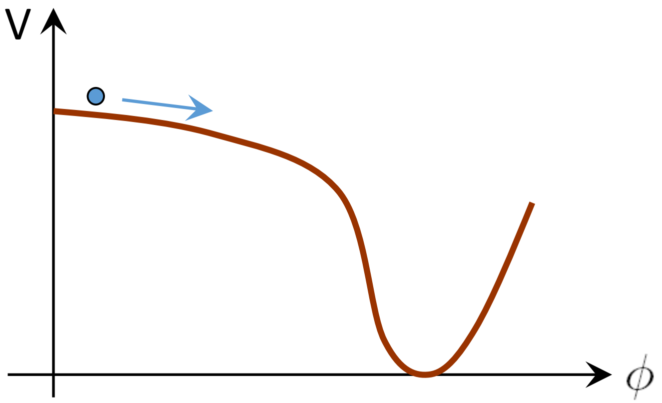
Open Questions in Early Universe Cosmology

- Are there possibly alternative scenarios to inflation?
- For inflation, what kind of fundamental physics can we probe?

→ Searching for beyond-Standard-Model (6 parameter ΛCDM) signals.

Particle Spectrum in Inflation Models





Slow-roll conditions:

$$\epsilon_V \equiv \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2 \ll \mathcal{O}(1)$$

$$\eta_V \equiv M_P^2 \frac{V''}{V} \ll \mathcal{O}(1)$$

The 2nd condition is more restrictive.

It requires: $m^2 \lesssim \mathcal{O}(0.01) H^2$ ⟵ Inflaton

⟹ One or more light fields: $m << H$

Fine-Tuning Problem in Inflation Model Building:

In the inflationary background, fine-tuning (or symmetry) is needed to obtain a scalar mass $m \ll H$

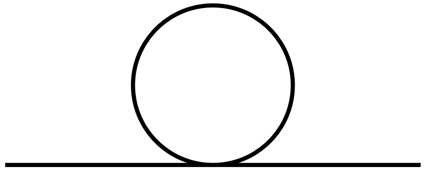
Scalar Mass in Inflationary Background: Tree Level

Coupling between scalar and spacetime curvature

$$\sim \; R\phi^2$$

$$R \sim H^2 \quad \longrightarrow \quad m^2 \sim H^2$$

Loop Corrections



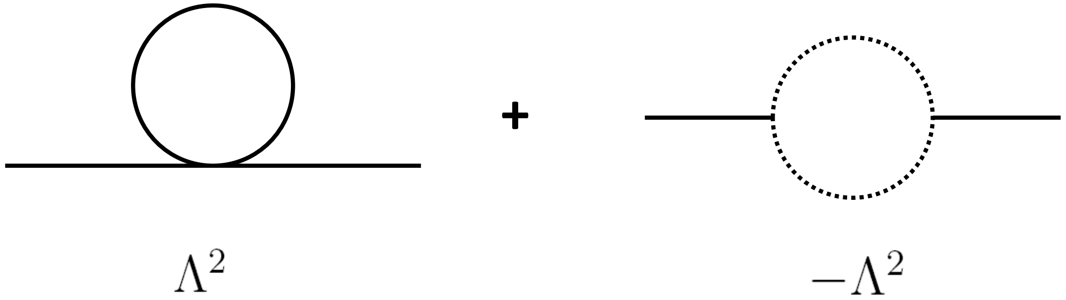
$$\Lambda^2$$

$$m^2 \sim g\Lambda^2$$

Scalar mass is generally very large, due to loop corrections

Needs extreme fine-tuning to get $m^2 \lesssim \mathcal{O}(0.01)H^2$

Supersymmetry Protects Small Mass



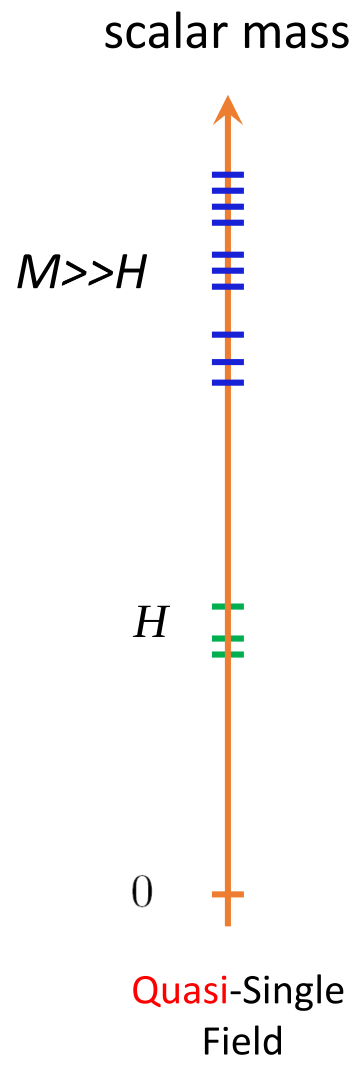
Light mass protected by supersymmetry

Supersymmetry is broken at Hubble scale *H*

Many light scalars with mass: $m^2 \sim H^2$

(Copeland, Liddle, Lyth, Stewart, Wands, 94; Baumann, Green, 11)

Mass Spectrum in Inflation Models



- One of them has to be tuned to be << *H*

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

The η - problem

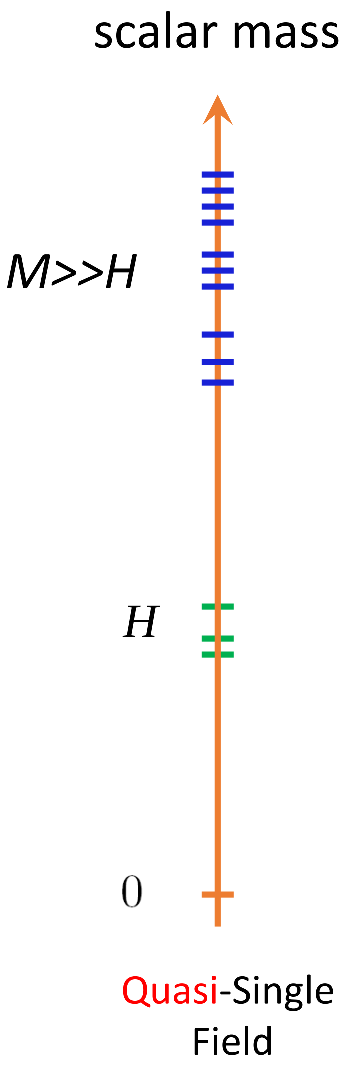
- Many others remain of order *H*

- We of course always have many states with *M>>H*

Quasi-Single Field Inflation

(X.C., Wang, 09)

Quasi-Single Field Inflation Models



- dS space has a Gibbon-Hawking temperature *H*

  ⟹ Quantum-mechanically, states of mass of order H are important

- In low energy effective theory,
  contribution from heavier fields are suppressed by $\sim \frac{H^2}{M^2}$

  But, in the primordial universe,
  the universe was not even in a meta-stable state.

  ⟹ Massive states with *M>>H* may be easily excited

Phenomenology of these higher energy states
and
fundamental physics they probe

Fields with mass >> H

A direct measurement of a(t),
hence a direct and independent evidence for inflation (or an alternative scenario)

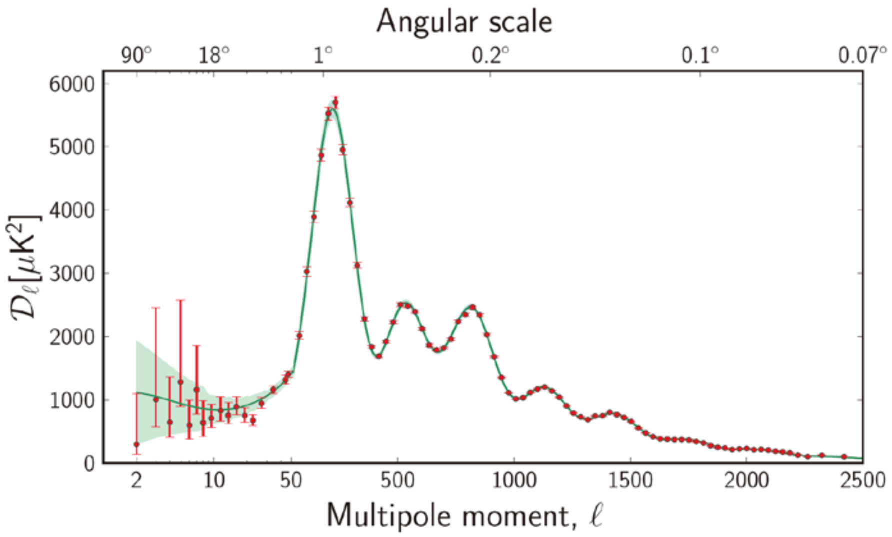
Can we distinguish Inflation and possible alternatives experimentally?

Minimal (non-zero) predictions from inflation:

- Acoustic Peaks

- Approximate scale invariance

Described by two parameters
in the six-parameter Standard Model of cosmology



Is This Prediction Uniquely from Inflation?

Possibilities besides inflation: Matter contraction; Ekpyrosis; Slow-expansion; etc … …, although none as successful so far.

(Wands, 98; Khoury, Ovrut, Steinhardt, Turok, 01; Finelli, Brandenberger, 01; … … …)

As far as model building is concerned, inflation is already the winner for a long time.

Alternative models evolve with time, and can be “improved” and complicated.

It is equally crucial to look for additional experimental evidences.

Tensor Mode

(B-mode in CMB)

Four Different Kinds of Phenomenological Scenarios

Large r possible

?

Fast Expanding (Inflation) Scenarios

?

Fast Contracting Scenarios

~~Slowly Expanding Scenarios~~

~~Slowly Contracting (Ekpyrosis) Scenarios~~

Large r impossible

tensor-to-scalar ratio r: measures magnitude of Hubble parameter

If the tensor mode is large enough to be observable in the future:

- rules out all slowly-varying scenarios
- Fast-contracting scenarios are still phenomenologically possible

Can we directly measure *a*(*t*) for Primordial Universe?

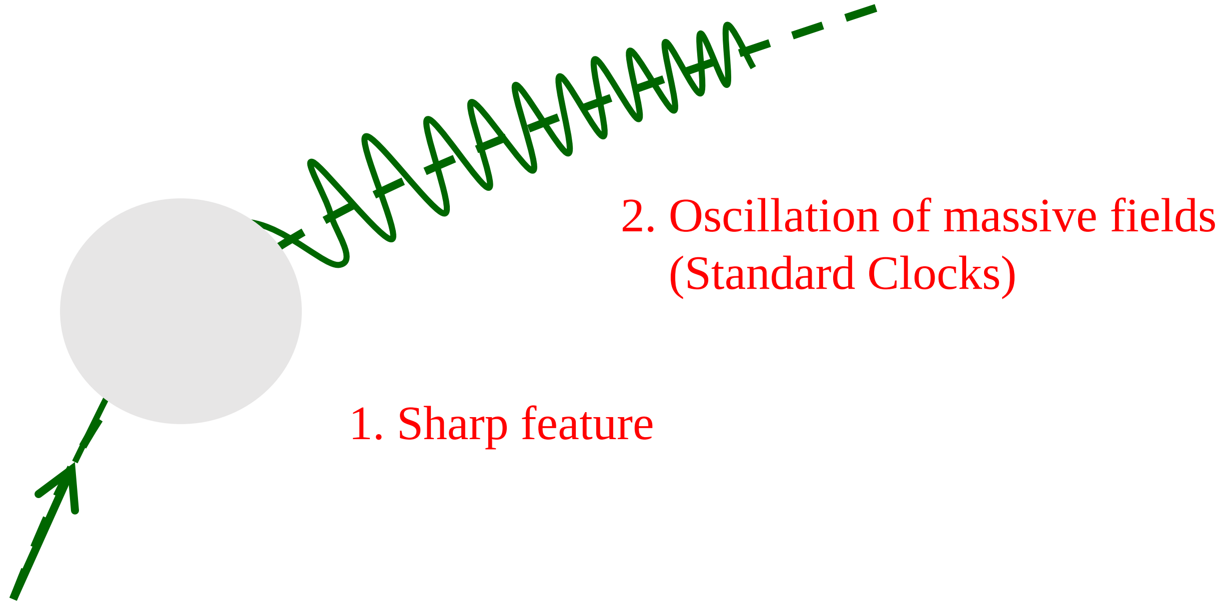
We can look for **"Standard Clocks"!**

Classical oscillation of massive fields in any t-dependent background is simple

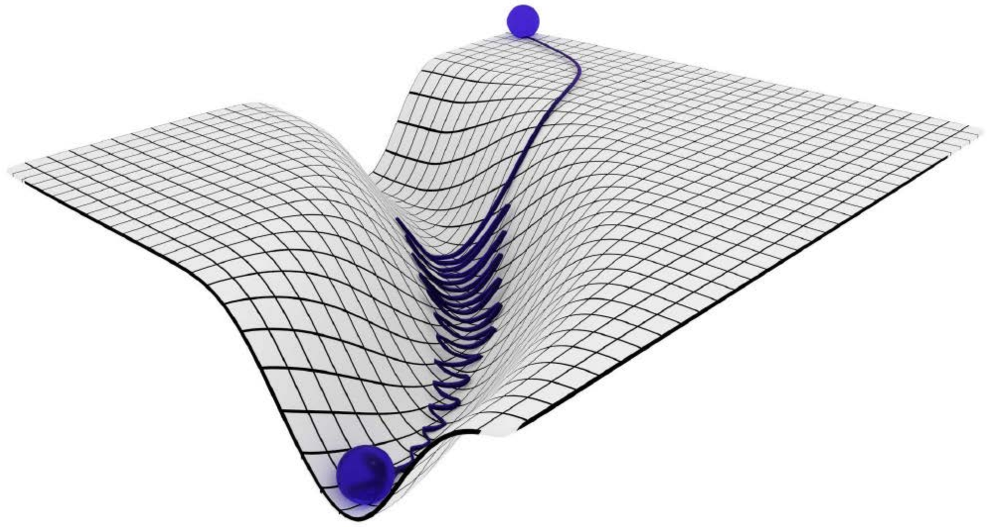
→ Clocks that generate standard ticks (X.C., 11)

Excitation of Massive Modes

A broad-brush picture:



An Example in Inflation



- Many fields rolling at the beginning of inflation
- Due to the η-problem, only very few can find flat potential and drive the entire 60-efolds of inflation
- Many of them roll to the bottom of valley after a few efolds, oscillating and settling down, leaving only one (necessary condition) inflaton direction.

These are the natural candidates for the clock fields

$$\mathcal{L} = -\frac{1}{2}(\tilde{R}+\sigma)^2 g^{\mu\nu}\partial_\mu\theta\partial_\nu\theta - V_{\rm sr}(\theta) - \frac{1}{2}g^{\mu\nu}\partial_\mu\sigma\partial_\nu\sigma - V_\sigma(\sigma) \ , \qquad V_\sigma = V_{\sigma 0}\left[1-\exp(-\sigma^2/\sigma_f^2)\right]$$

Arbitrary Time-Dependent Background

- Consider general power-law backgrounds

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

- Require quantum fluctuations exit event-horizon $|a\tau|$

$p > 1$	expansion	t: $\text{from } 0 \text{ to } +\infty$
$0 < p < 1$	contraction	t: $\text{from } -\infty \text{ to } 0$
$p < 0$	expansion	t: $\text{from } -\infty \text{ to } 0$

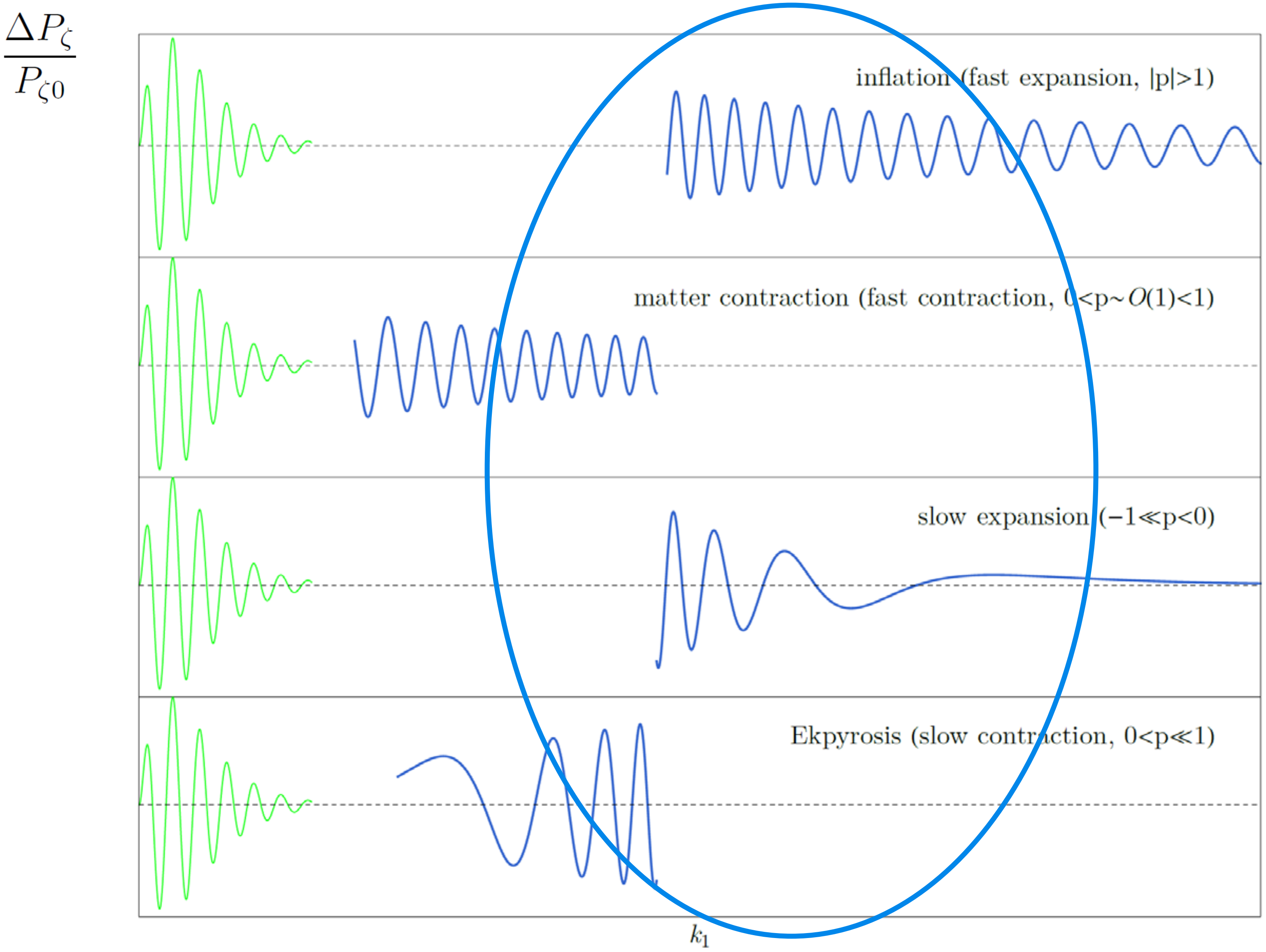
τ always runs from $-\infty$ to 0

E.g. $p > 1$ Inflation; $p = 2/3$ Matter contraction (Matter bounce);
(Wands, 98; Finelli, Branderberger, 01)

$p \ll 1$ Ekpyrosis; (Khoury, Ovrut, Steinhardt, Turok, 01)

Fingerprints of Different Scenarios (X.C., 11, X.C., Namjoo, Wang, 14)

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



The Clock Signal
– the Most Important Property of the Standard Clock Models

The running pattern:

$$\sim \sin\left[\frac{p^2}{1-p}\Omega\left(\frac{K}{k_r}\right)^{1/p} + \varphi\right]$$

$K \equiv k_1 + k_2 = 2k_1$ for power spectrum

⇓

Inverse function of $a(t)$

This pattern is a direct consequence of $a(t)$

Resonance Mechanism

(X.C., Easther, Lim, 08)

- Resonance

Background Oscillation

Oscillating quantum fluctuations in BD vacuum

} Resonant when frequencies match

- In terms of correlation functions

$\int$ couplings • mode-functions

couplings ⇩ oscillating with bkgd frequency

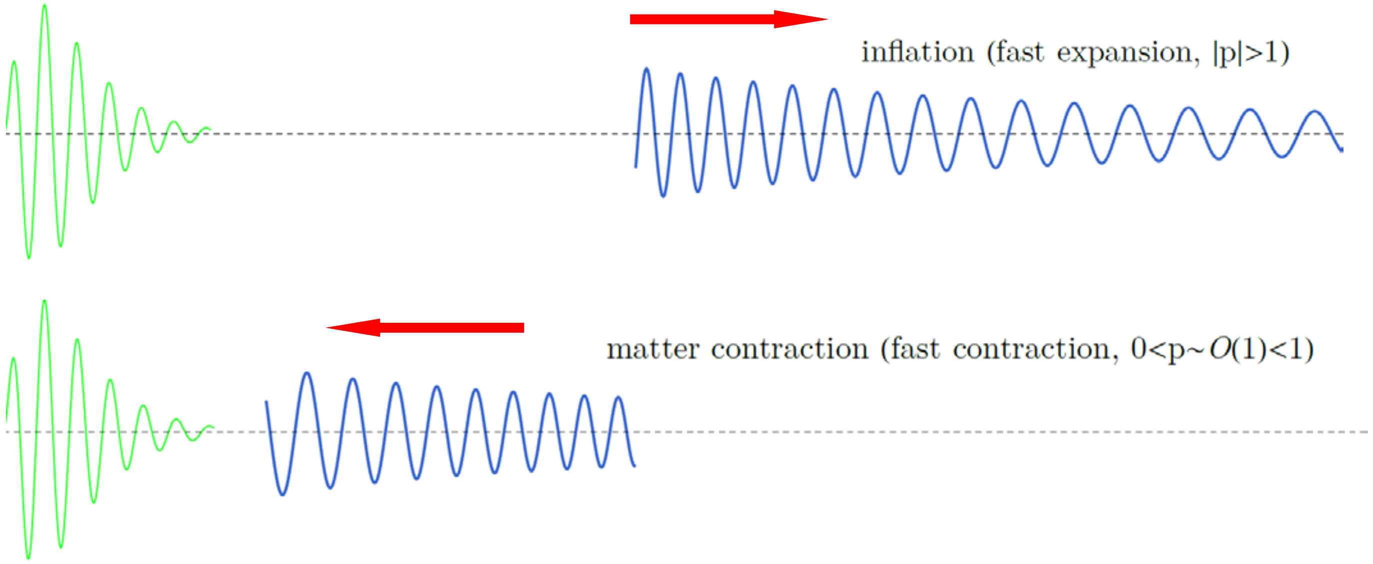
mode-functions ⇩ oscillating frequency scans

Resonate when two freq coincide

➢ Large amplitude: powers of ω

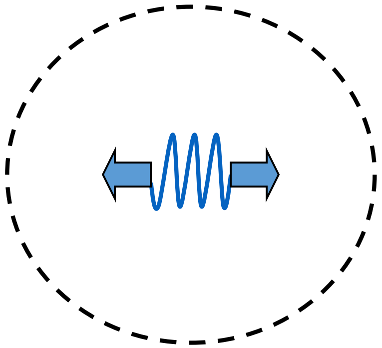
➢ Distinctive scale-dependence: characteristic oscillatory running

Example: Inflation versus Fast Contraction (Matter Contraction)



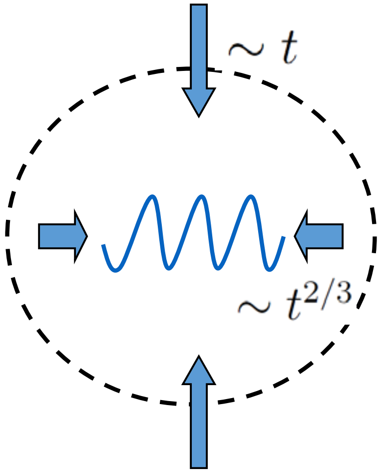
Resonance between
quantum fluctuations
and background oscillations

Inflation:



Longer modes
resonate first

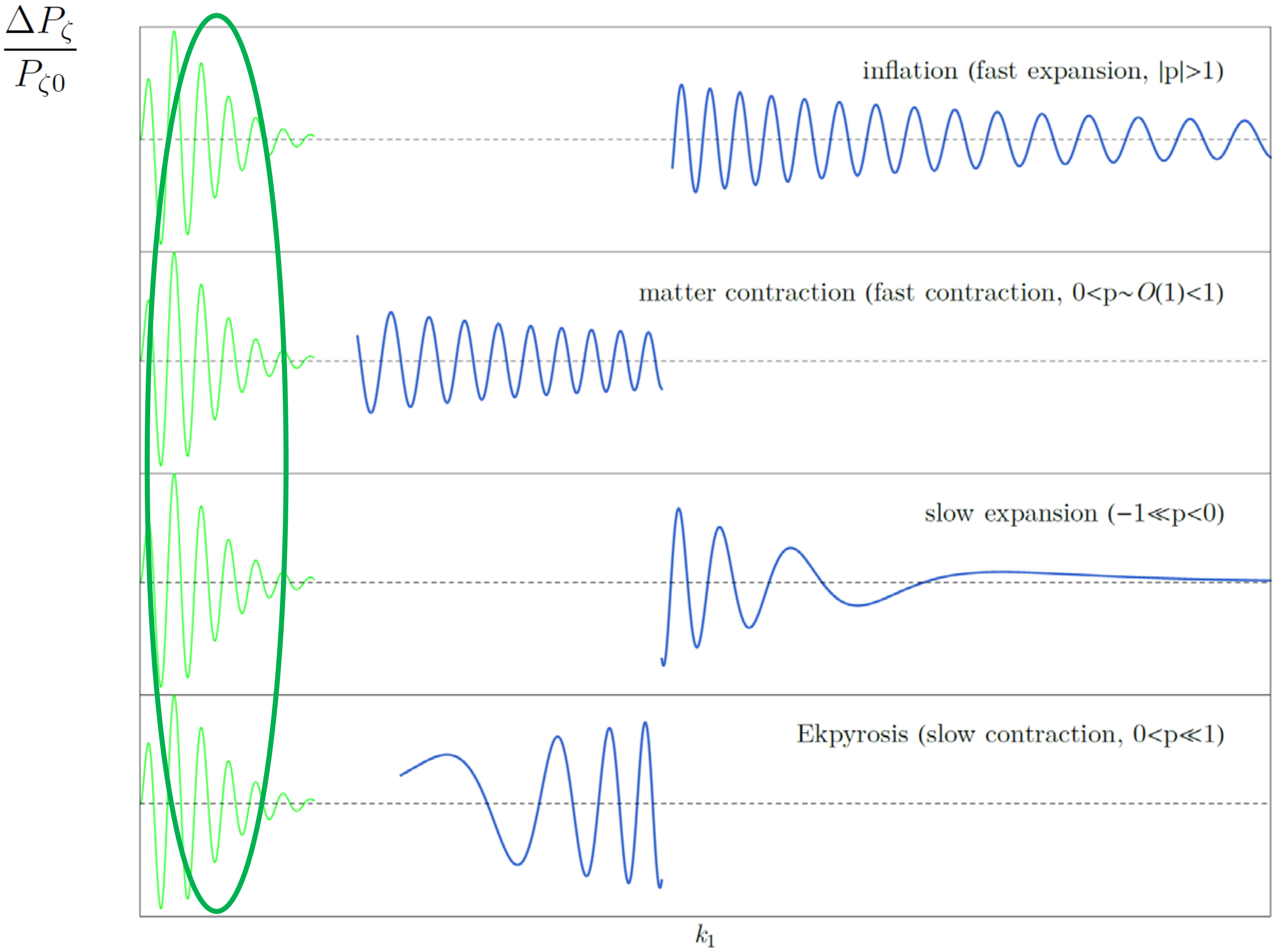
Matter Contraction



Shorter modes
resonate first

Fingerprints of Different Scenarios (X.C., 11, X.C., M.H.Namjoo, Y. Wang, 14)

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



Sharp Feature Signal

Sharp feature does not contain a "clock",
only one click.

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

Universal for different paradigms, i.e. independent of *p*

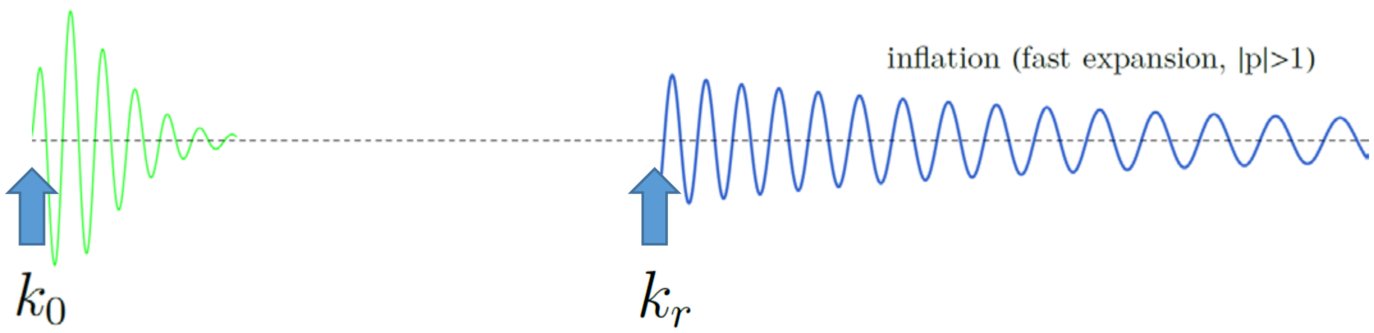
Sinusoidal running is a general property of "sharp features", not a signature of massive field

Relation between Clock Signal and Sharp Feature Signal

K-location of first resonant mode

K-location of sharp feature

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

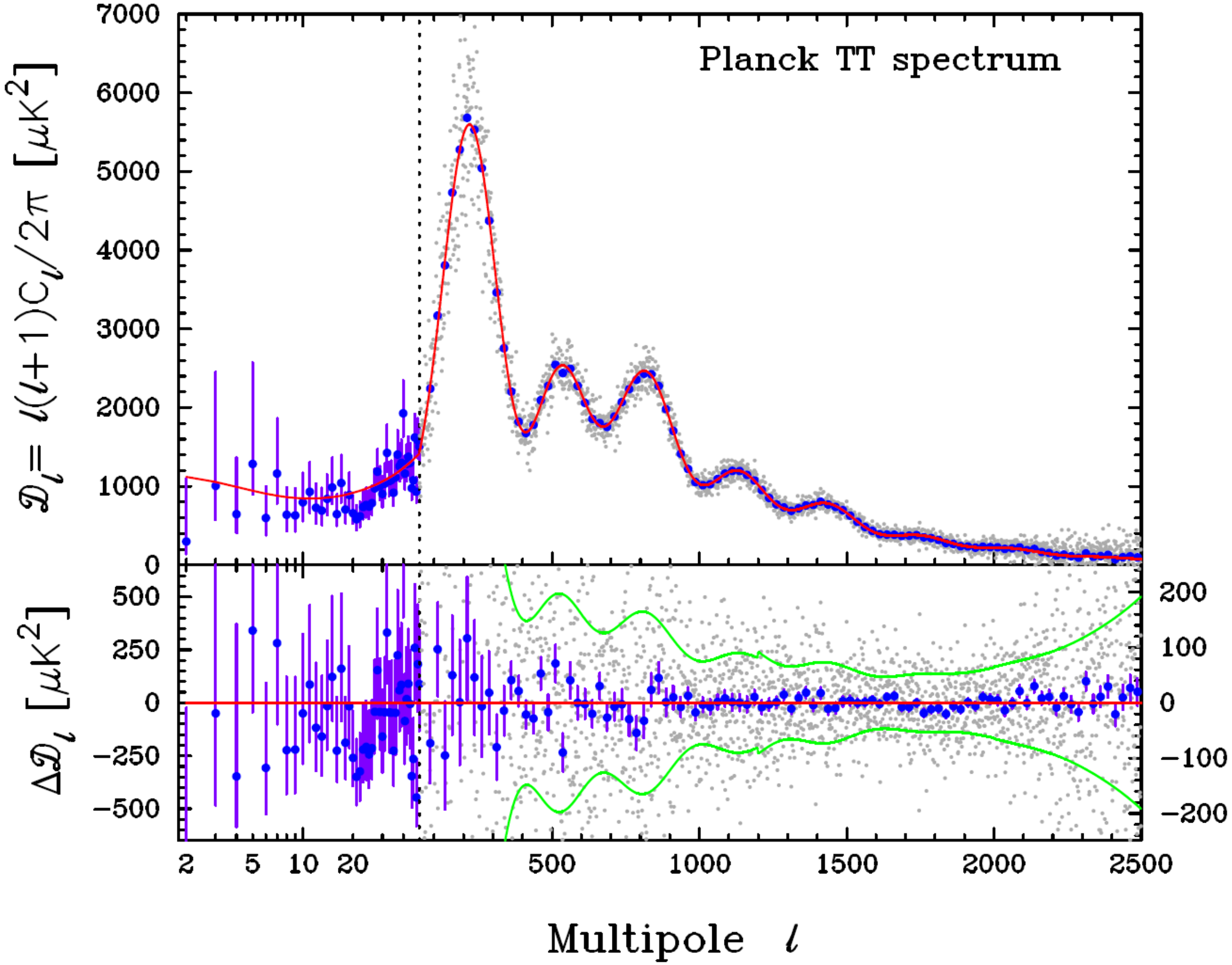


This is also a direct consequence of *a*(*t*)

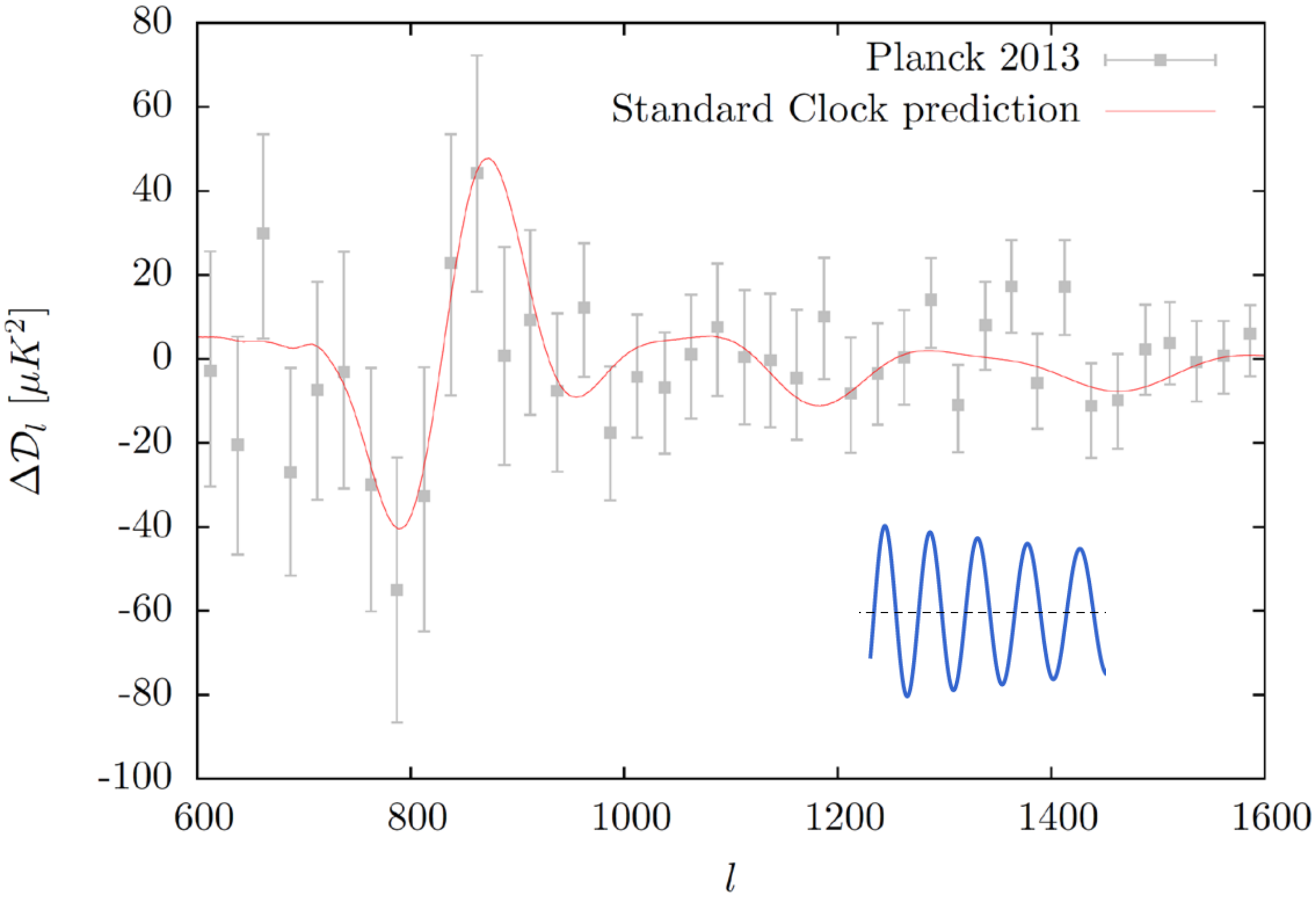
$$\frac{k_r}{k_0} = \frac{\text{Mass Scale of Clock Frequency}}{\text{Horizon Mass}}$$

Let us Look at the Data

Planck Power Spectrum (Planck, 13)



A Fit with the Clock Signal ONLY (X.C., Namjoo, 14)



$$\omega = 30,\ C = 0.075,\ k_r = 0.1015\ \mathrm{Mpc}^{-1},\ p = 100,\ \varphi = -0.263\pi$$

- Amplitude decays slowly in k-space; but much faster in *l*-space.
- p>>1 is preferred than other values; fits well with the special running pattern of inflation
- Marginal Improvement $2\Delta \ln \mathcal{L} \approx -10$
- Predicts a correlated sharp feature signal

Using the relation:

$$\frac{\ell_{\rm clock}}{\ell_{\rm sharp}} \sim \frac{k_r}{k_0} = \frac{|p|}{|1-p|}\omega$$

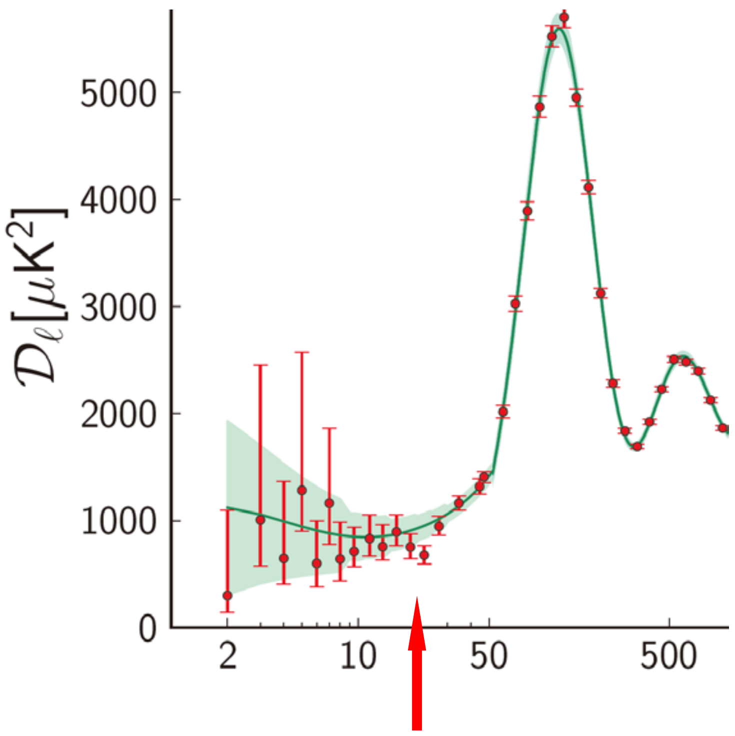
From the fit for the Clock Signal:

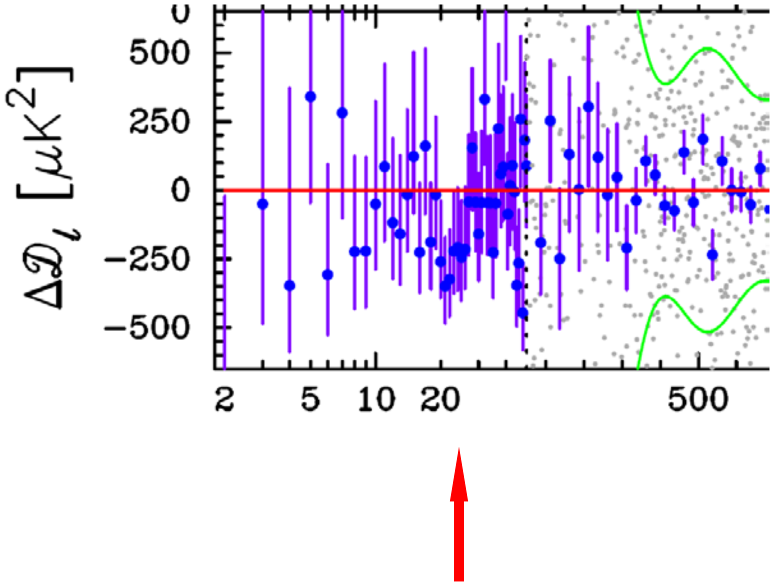
$k_{\rm clock} \approx 0.05/{\rm Mpc}$ $\qquad$ $\omega \approx 30$ $\qquad$ $|p| \gg 1$

$\ell_{\rm clock} \approx 685$

→ $\ell_{\rm sharp} \sim 23$!

Matches A Known Sharp Feature Candidate

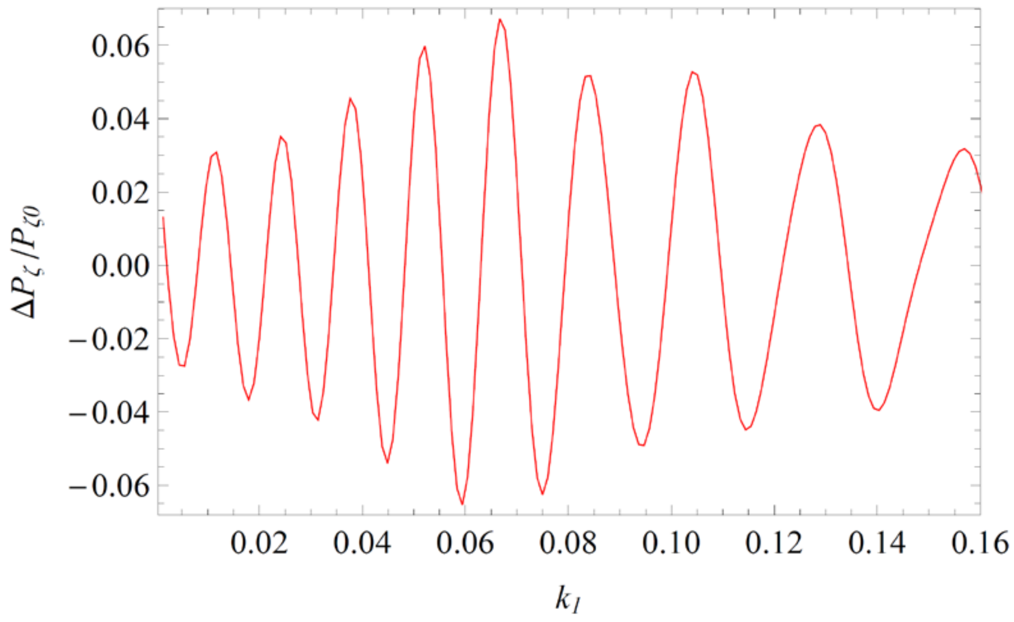


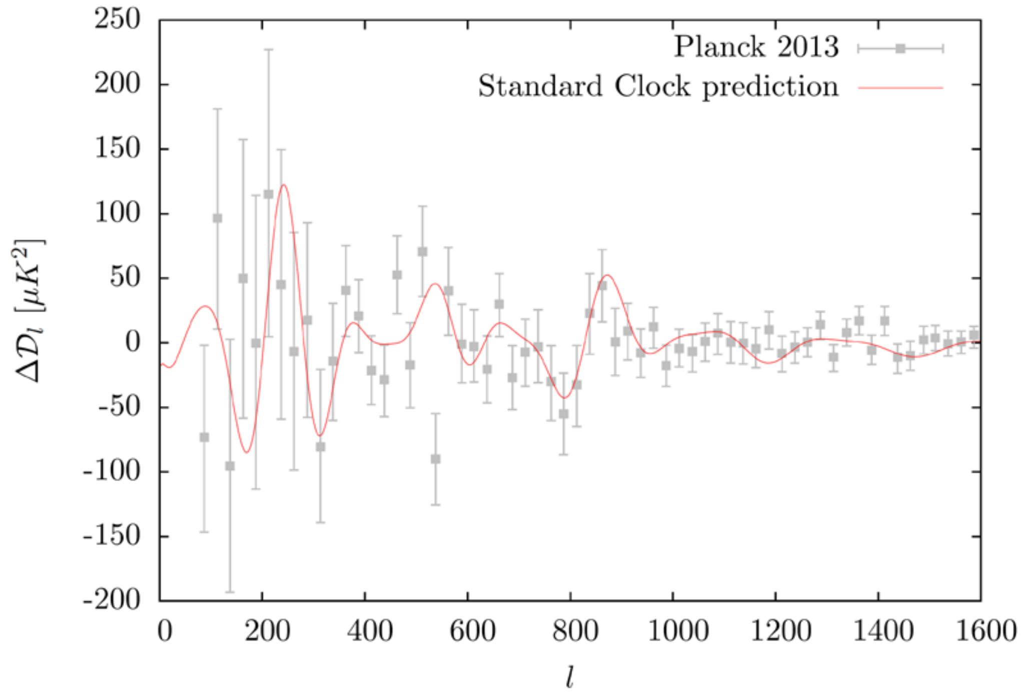


This sharp feature candidate is known since WMAP 2003, with marginal statistical significance.

A Full Model and its Comparison with Data

(X.C., Namjoo, Wang, 14)





Planck 2015 papers were just released last week.
This feature is still there, and the analysis is work in progress.

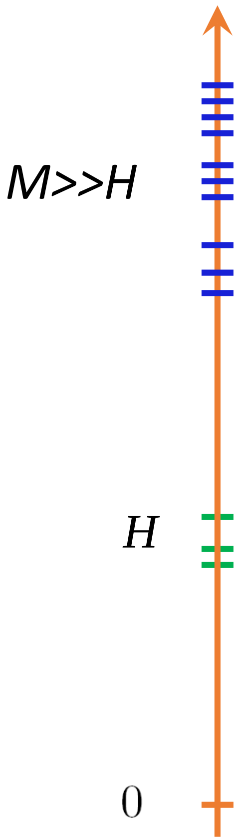
Fields with mass of order H

Probing the existence of supersymmetry in the primordial universe

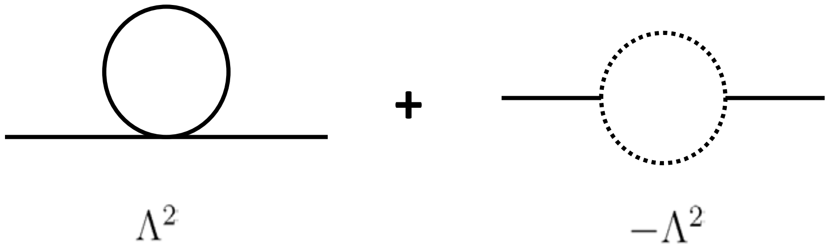
QSF inflation as an Indirect Evidence for Supersymmetry

(X.C., Wang, 09; Baumann, Green, 11; Craig, Green, 14)

scalar mass



Quasi-Single Field



- Scalar fields with mass of order H is a naturally consequence of inflation models in supergravity
- Other scenarios requires finetuning to get mass of order H

What are the Observable Signatures of the fields with mass of order H?

A special kind of large non-Gaussianities

(X.C., Wang, 09)

Higher-point correlation functions of density perturbation maps

↑

Non-linear correlation of quantum fluctuations

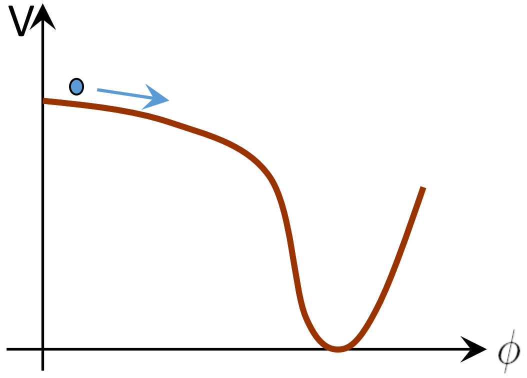
↑

Interaction terms in the inflation models

Poor men's collider – Non-Gaussianities in density perturbations

Large

In single field slow-roll inflation model:



Inflaton

$$V''_{sr} \sim \mathcal{O}(\epsilon) H^2$$

$$V'''_{sr} \sim \mathcal{O}(\epsilon^2) P_\zeta^{1/2} H$$
$$< 10^{-9} H$$

Slow-roll conditions

↓

Very flat potential

↓

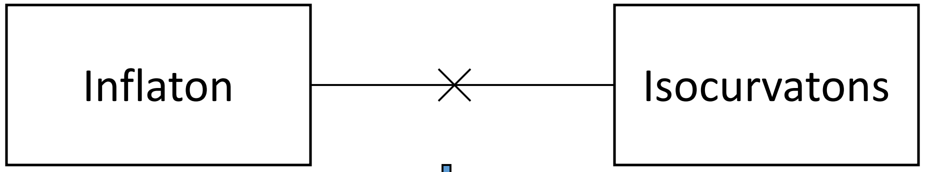
Very small nonlinearity

↓

Unobservablely small non-Gaussianities

(Maldacena, 02; Acquaviva, Bartolo, Matarrese, Riotto, 02)

However in QSF, we have a New Sector



$$V_{sr}'' \sim \mathcal{O}(\epsilon) H^2$$

$$V_{sr}''' \sim \mathcal{O}(\epsilon^2) P_\zeta^{1/2} H$$
$$< 10^{-9} H$$

$$V'' \sim H^2$$

V''' can be H

V'''' can be 1 , etc

Source of large non-G

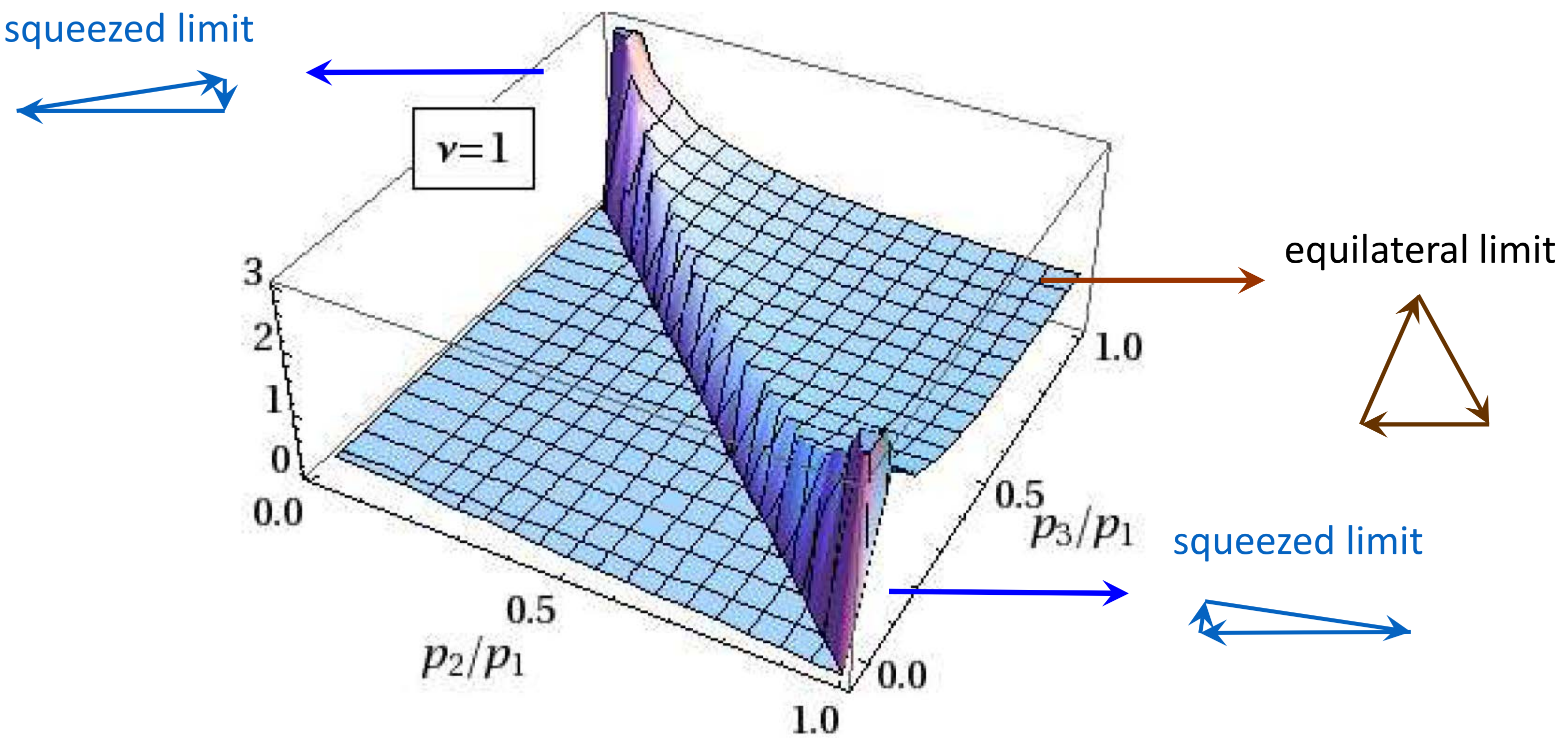
Introducing coupling without spoiling the slow-roll conditions

Special

Shapes of Bispectra

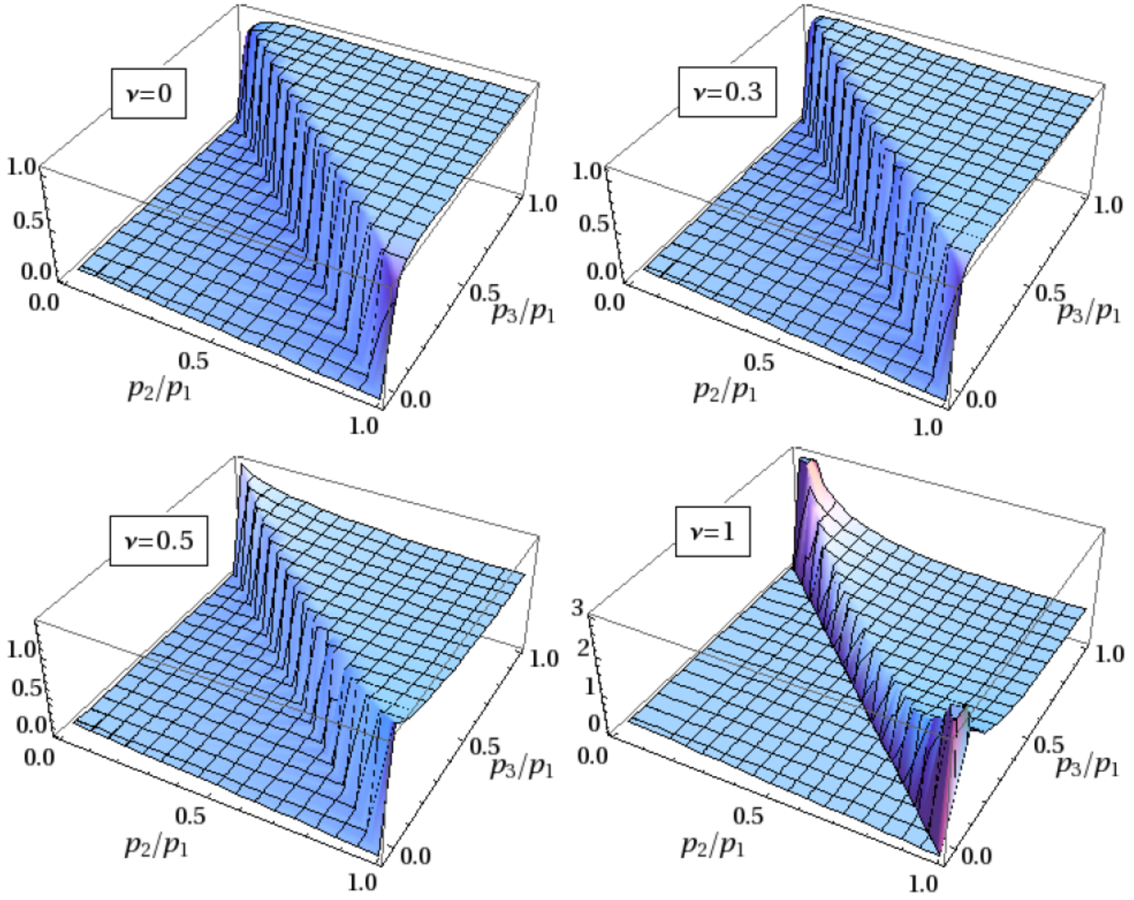
$$\langle \zeta^3 \rangle \equiv S(p_1, p_2, p_3) \frac{1}{(p_1 p_2 p_3)^2} \tilde{P}_\zeta^2 (2\pi)^7 \delta^3 (\sum_{i=1}^{3} \mathbf{p}_i)$$

$$S(p_1, p_2, p_3) \xrightarrow{\text{scale-invariance}} S(1, p_2/p_1, p_3/p_1)$$



Shapes of Bispectra in QSF inflation

(X.C., Wang, 09)

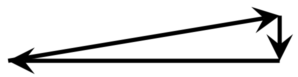


$$\nu \equiv \sqrt{\frac{9}{4} - \frac{m^2}{H^2}}$$

Shapes of bispectra (in squeezed limit) directly measure the mass

Soft Limit

Squeezed-limit: $p_3 \ll p_1 = p_2$



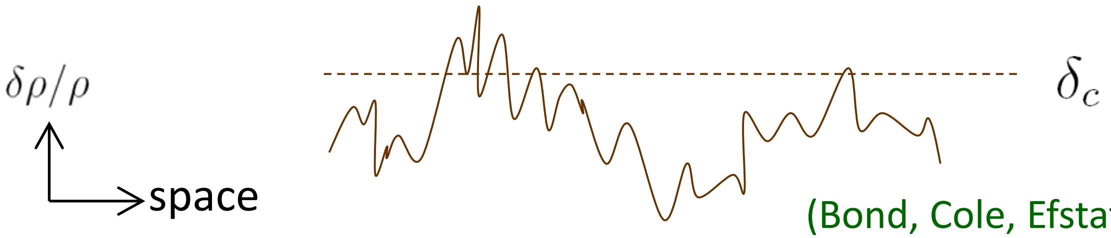
Shape: $$S \to f_{NL} \left(\frac{p_3}{p_1} \right)^{\alpha}$$

$$\alpha = \frac{1}{2} - \sqrt{\frac{9}{4} - \frac{m^2}{H^2}}$$ (X.C., Wang, 09)

$m: \ 0 \to 3H/2$ $$S: \left(\frac{p_3}{p_1} \right)^{-1} \to \left(\frac{p_3}{p_1} \right)^{1/2}$$

Local shape

Galactic Halo Bias



(Bond, Cole, Efstathiou, Kaiser, 91)

- Only density peaks above the threshold can form halo

Bias: $b = \dfrac{\text{halo overdensity}}{\text{matter overdensity}}$

- Density peaks affected by the long wavelength modulation over short wavelength

For local shape: $b \propto f_{NL}\ k^{-2}$ (Dalal, Dore, Huterer, Shirokov, 07)

squeezed-limit of 3pt

For QSFI: $b \propto f_{NL}\ k^{-1/2-\nu}$

(Scoccimarro, Manera, Hui, Chan, 11; Emiliano, Fergusson, X.C., Shellard, 12)

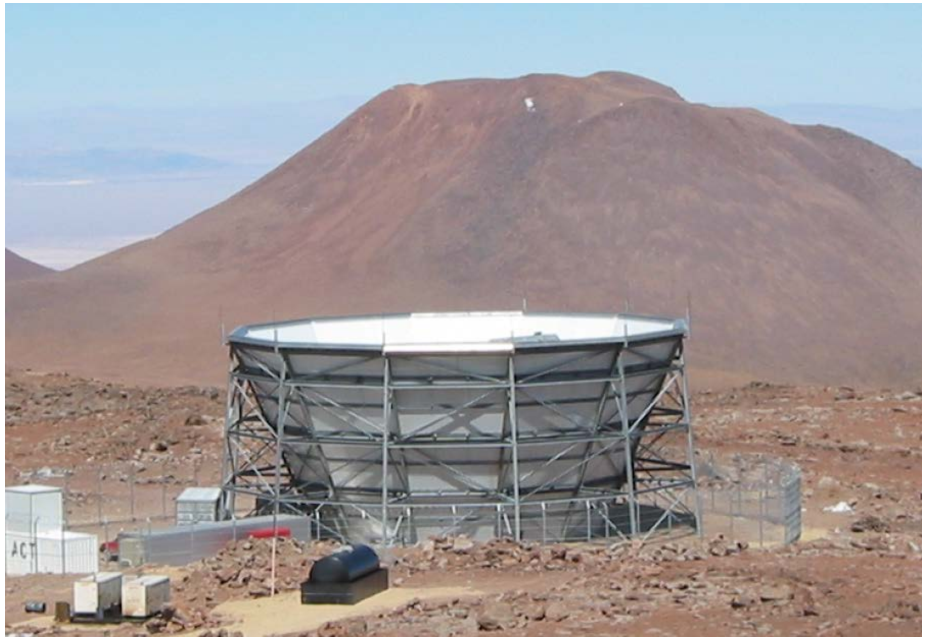
Future Directions

Many CMB polarization experiments:

BICEP/Keck, Simons Array, CLASS, PolarBear, LiteBird, COrE, CMBpol,

- Primordial B-mode in CMB polarization. (An opportunity)
- Fine structures in T and E mode. (Another opportunity)

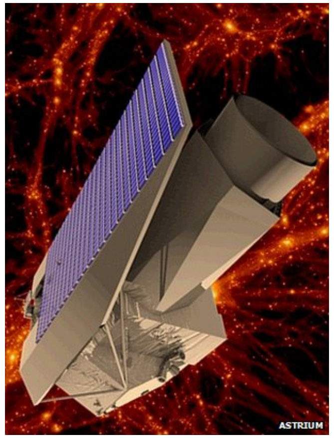
E.g. Ground-Based CMB Polarization Telescopes



Advanced ACTPol:
Atacama Cosmology Telescope

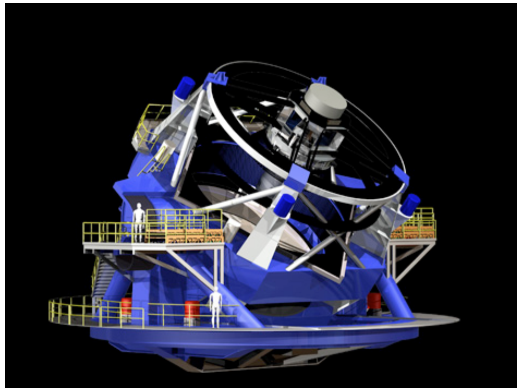
- 20,000 square degrees
- 5x better resolution and 5x better sensitivity than Planck
- Cosmic-variance-limited EE measurement out to ℓ=2000

Large Scale Structure Surveys



Euclid Satellite:

- 20,000 degree-squared
- 3D map, $0.4 < z < 2$



LSST telescope:

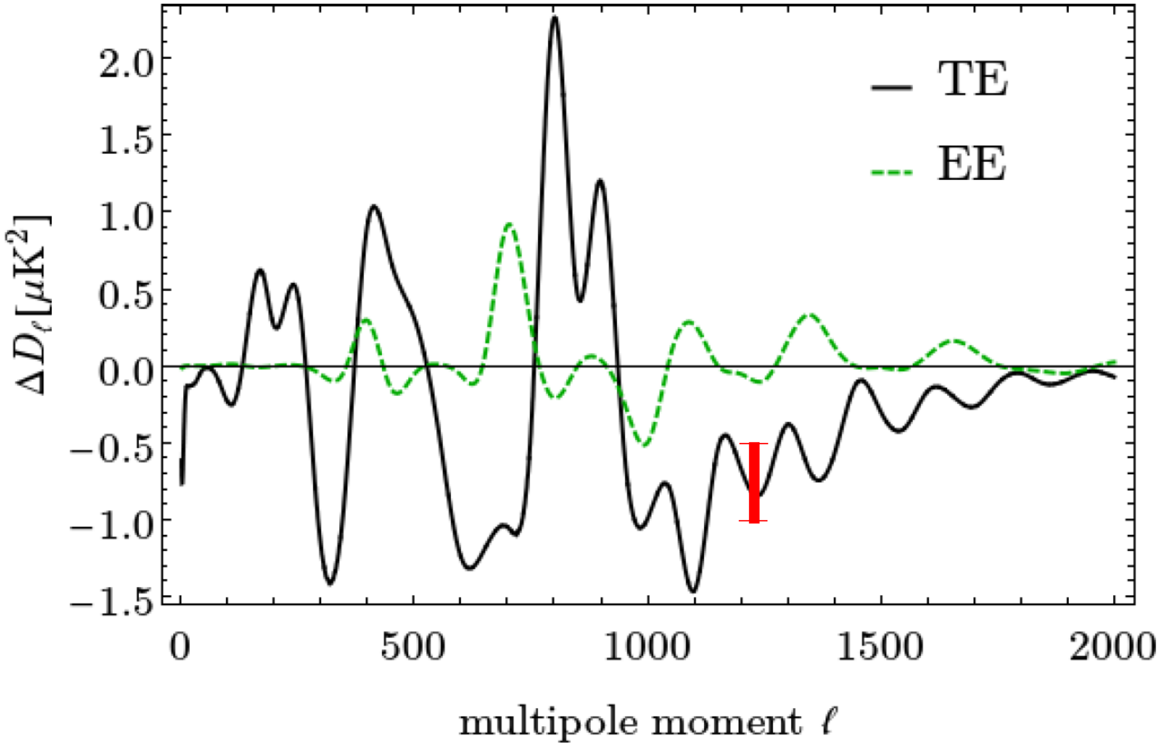
- 30,000 degree-squared
- 3D map, $0.3 < z < 3.8$

Standard Clock candidates identified in CMB TT data can be well tested in future experiments

Cross correlation between different observables:

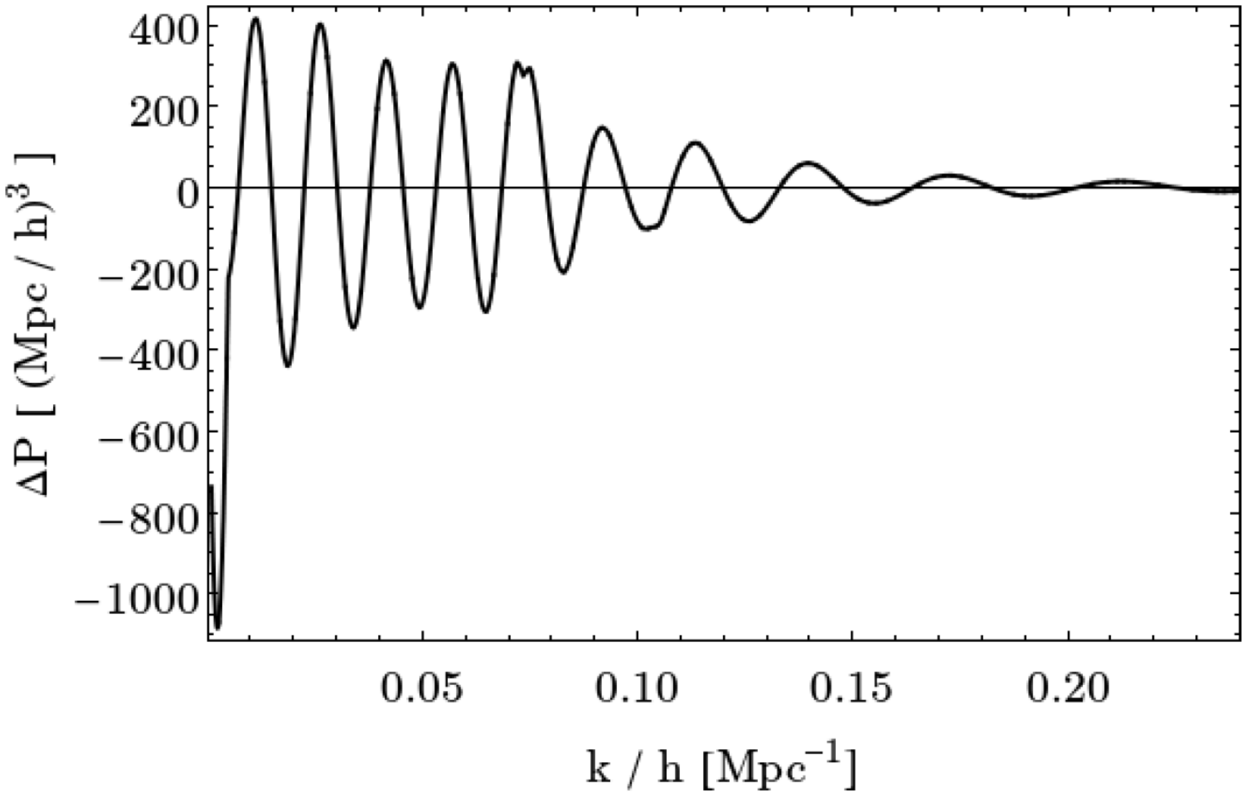
- CMB temperature
- CMB polarization
- Large scale structure
- CMB non-Gaussianities
- … …

Standard Clock models have strictly correlated signals in CMB polarization data



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

Correlated signal in the distribution of large scale structure



Forecast is work in progress.

Correlated Non-Gaussianities

- Due to the same resonance mechanism (X.C., Easther, Lim, 08)

clock part $\sim \sin\left[\frac{p^2}{1-p}\omega\left(\frac{K}{k_r}\right)^{1/p}+\varphi\right]$

$K \equiv k_1 + k_2 = 2k_1$ for power spectrum

$K \equiv k_1 + k_2 + k_3$ for bispectrum and so on

(X.C., 11)

Prediction of the full model is work in progress

- Interesting 3-sigma hints for resonance and sharp feature non-G in Planck 2015 data release

"…… It will remain a high priority to investigate resonance models for the final Planck data release ……"

"….. we note that oscillatory models will continue to be investigated thoroughly …. using the more reliable polarization data available in the final Planck data release."

Planck 2015 release, paper XVII

Thank You !