Standard Clocks Signals in Primordial Density Perturbations

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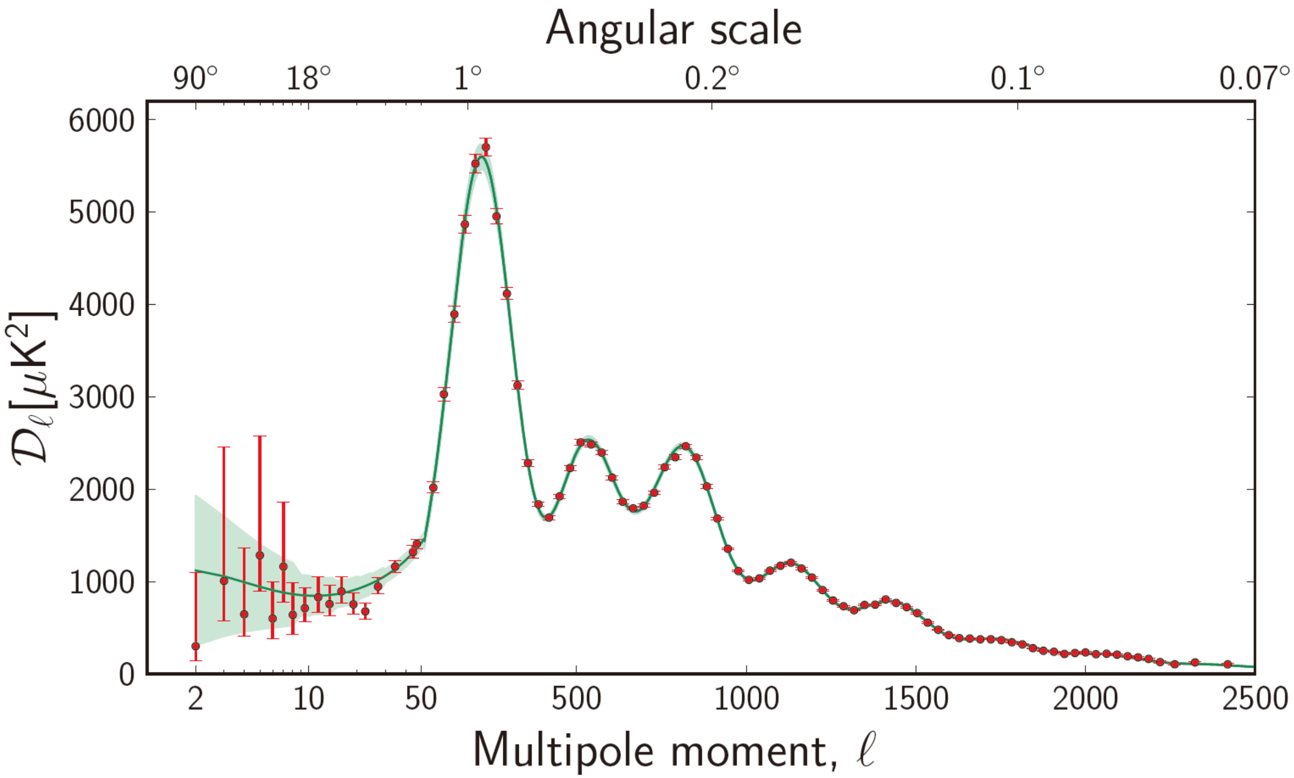
arXiv:1104.1323, 1106.1635
arXiv:1205.6085 with Ringeval
and work in progress with Namjoo, Ringeval, Langlois, …

CMB Power Spectrum (Planck,13)



- ➢ Superhorizon
- ➢ Approximately Gaussian
- ➢ Approximately scale-invariant
- ➢ Adiabatic

Is This Prediction Uniquely from Inflation?

Minimal predictions from inflation:

- Acoustic Peaks
- Approximately scale invariance

Equations Behind the Theoretical Predictions

- Curvature mode ζ

$$v_k'' + k^2 v_k - \frac{z''}{z} v_k = 0 \qquad v \equiv z\zeta \qquad z \equiv a\sqrt{2\epsilon} \qquad \epsilon \equiv -\dot{H}/H^2 \qquad H \equiv \dot{a}/a$$

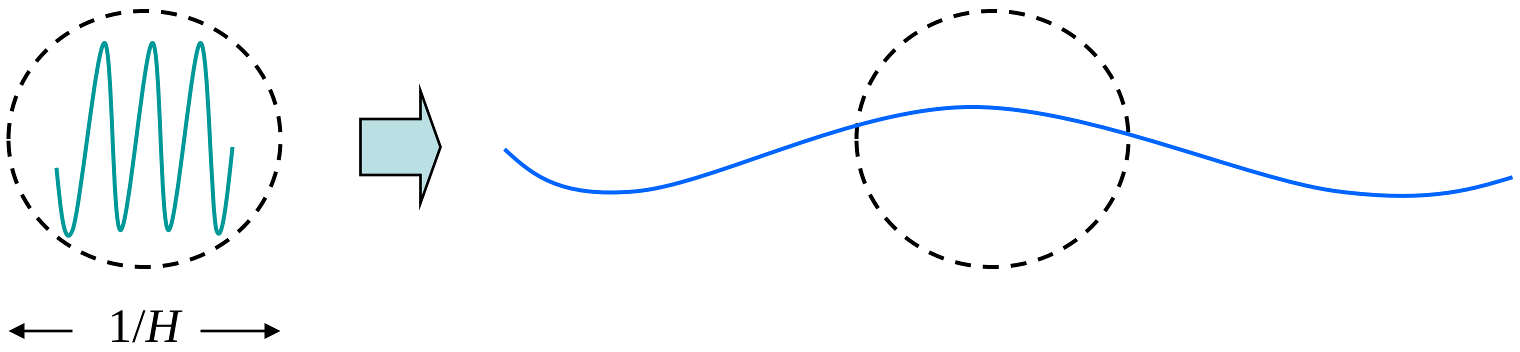
- Isocurvature mode $\delta\phi$

$$v_k'' + k^2 v_k - \left(\frac{a''}{a} - a^2 V_{\phi\phi}\right) v_k = 0 \qquad v \equiv a\delta\phi$$

⇨ Scale-invariance requires: $\frac{z''}{z} = \frac{2}{\tau^2}$ or $\frac{a''}{a} - a^2 V_{\phi\phi} = \frac{2}{\tau^2}$

Indirect and Degenerate!

Other Paradigms Besides Inflation?



For inflation: • horizon size is constant • superhorizon modes are frozen

What if in other backgrounds **?**

• Time dependent horizon • Evolving superhorizon modes • Multiple fields (isocurvatons)

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

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

Models involve with time, and can be “improved” and complicated

It is crucial to look for additional experimental evidences

Tennsor Modes

- Shared by all general models in one paradigm, not just a subset

✓ Inflation has generic prediction: Scale-invariant with red-tilt

? Caveat: Not always observable: $r \sim \mathcal{O}(10^{-1}) - \mathcal{O}(10^{-55})$

Experimental sensitivity: $\Delta r \sim \mathcal{O}(10^{-3})$

- Distinctive for different paradigms

✓ Cyclic model: unobservable tensor modes

String gas cosmology: blue tilt

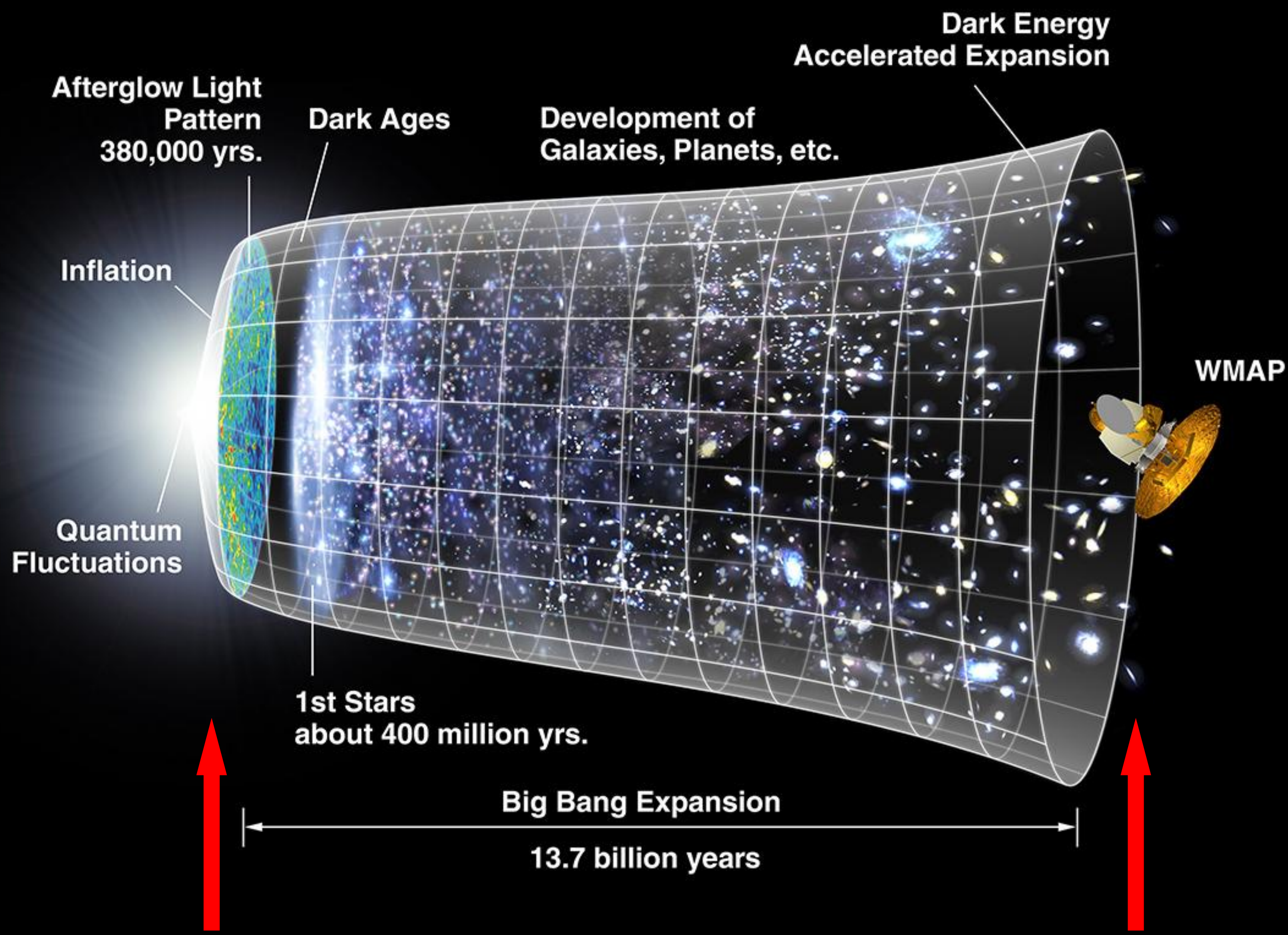
✗ Caveat: Other alternatives may have the same prediction as inflation

E.g. Matter contraction

Look for complimentary information as model-independent distinguisher between different paradigms

Can we directly observe the scale factor $a(t)$ in the primordial universe?

Inflation ?!



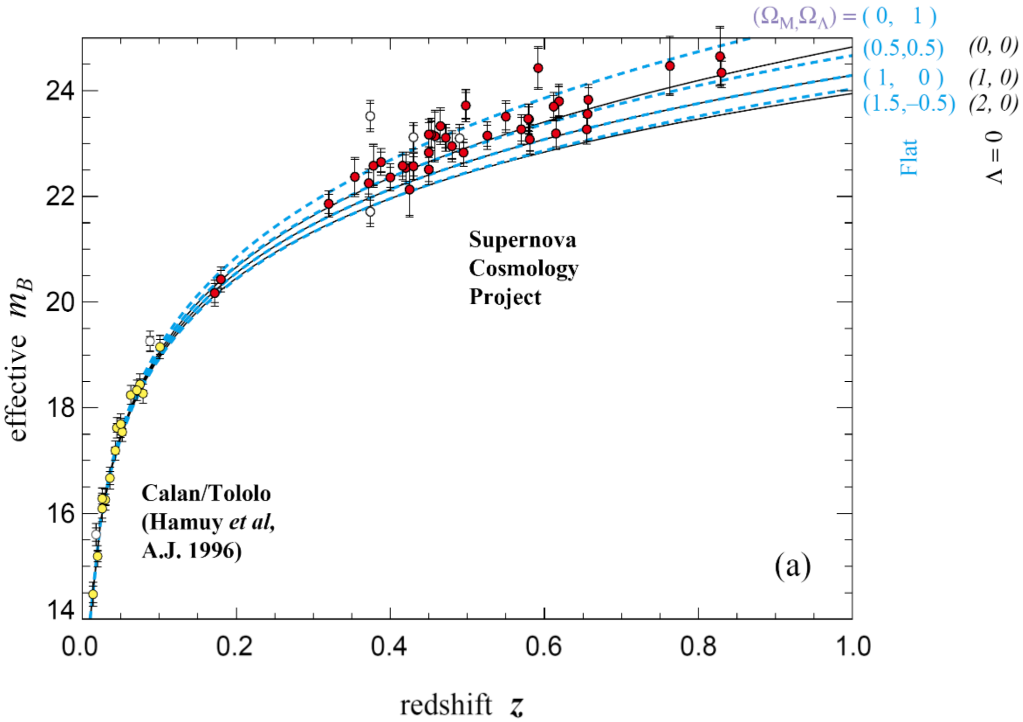
Inflation?!

Inflation!!

Late-Time Inflation: Standard Candle

(Riess, et al, 98; Perlmutter, et al, 98)

A Direct Measurement of $a(t)$



Standard candle: Supernovae Ia

Magnitude ⟹ Time: t

Redshift ⟹ Scale factor: a

Directly measure $a(t)$

Can we directly measure $a(t)$ for Primordial Inflation?

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

(X.C., 11)

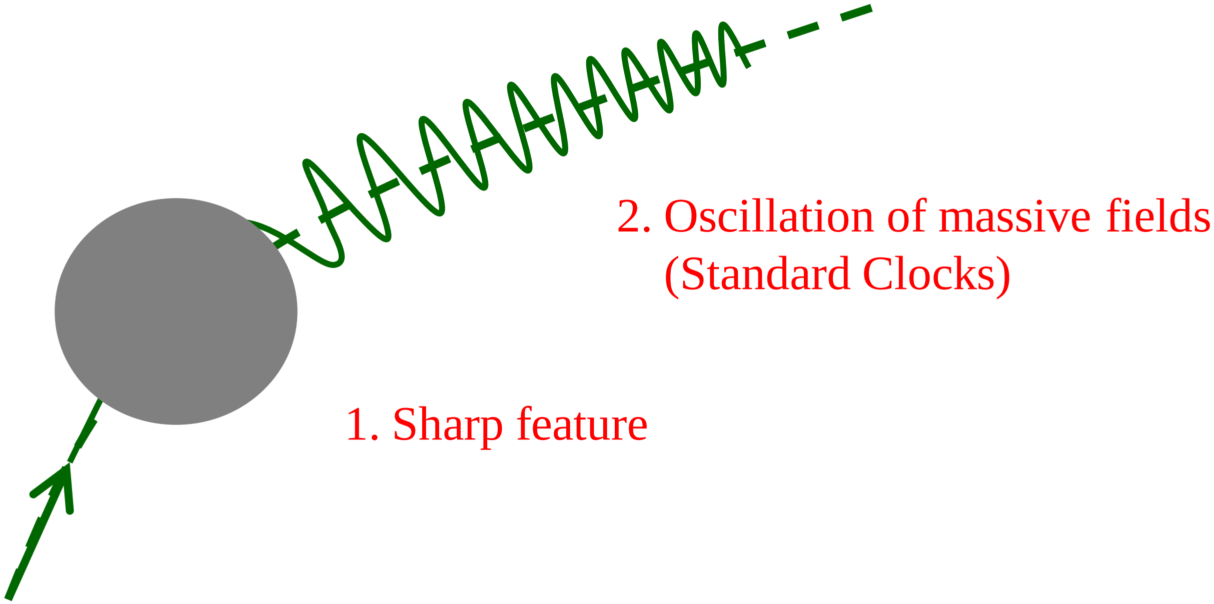
- **Identifiable with observable patterns**
- **As general as possible**

⟹ **Classical oscillation of massive fields**

(m >> horizon-mass-scale)

Excitation of Massive Modes

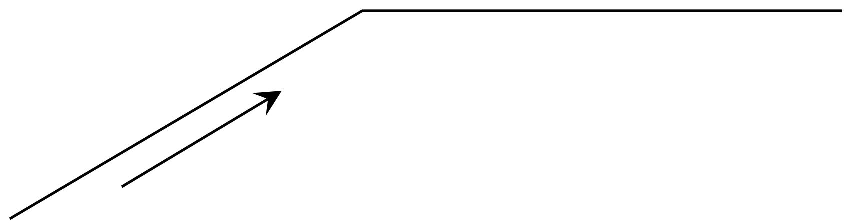
E.g. turning trajectory (broad-brush picture) :



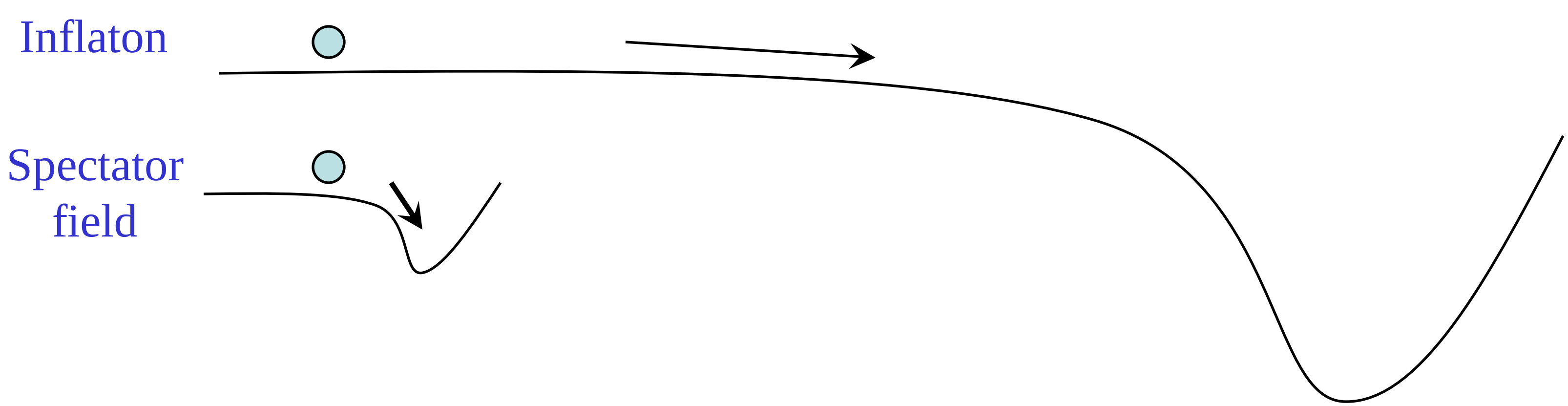
Averaged out for most purposes, but important here.

Examples of Turning Trajectories

- Sharp Bending



- Tachyonic Falling



- ……

Standard Clock: Directly Observing *a*(*t*)

Oscillating massive fields ⟷ Ticks ⟷ Clock *t*

⇕

Comoving momenta: *k* ⟷ Physical momemta ⟷ Scale factor: *a*

Therefore, $a(t)$ ⟷ k (features)

What we observe is: features (k)

which can tell us: inverse function of $a(t)$

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;
(Wands, 98; Finelli, Branderberger, 01)

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

Three Universal Properties Realizing the Standard Clocks

1) Massive Spectator Modes as Standard Clocks

- Oscillating massive modes in time-dependent background

$$\ddot{\sigma} + 3H\dot{\sigma} + m_\sigma^2 \sigma = 0$$

$$\sigma \approx \sigma_A \left(\frac{t}{t_0}\right)^{-3p/2} \left[\sin(m_\sigma t + \alpha) + \frac{-6p + 9p^2}{8 m_\sigma t} \cos(m_\sigma t + \alpha)\right]$$

- Inducing oscillating components to background parameters

$$3M_{\rm P}^2 H^2 = \frac{1}{2}\dot{\sigma}^2 + \frac{1}{2} m^2 \sigma^2 + \text{other fields}$$

$$H_{\rm osci} = -\frac{\sigma_A^2 m_\sigma}{8M_{\rm P}^2} \left(\frac{t}{t_0}\right)^{-3p} \sin(2m_\sigma t + 2\alpha)$$

Induce oscillating components to $\epsilon \equiv -\dot{H}/H^2 \quad \eta \equiv \dot{\epsilon}/(H\epsilon)$

Generating ticks in cosmological parameters

2) Bunch-Davies Vacuum

• Quantum fluctuations originate from BD vaccum

$$L = \int d^3x \left[\frac{a^3}{2}(\dot{\delta\phi})^2 - \frac{a}{2}(\partial_i\delta\phi)^2\right]$$

$$a^3\delta\phi\dot{\delta\phi}^* - \text{c.c.} = i$$

For modes within event-horizon, $k > 1/|\tau|$

$$\delta\phi \to \frac{1}{a\sqrt{2k}}e^{-ik\tau}$$ mostly BD

Minkowski spacetime, time-dependence incorporated adiabatically

Applies to inflationary and non-inflationary scenarios,
expansion and contraction universes,
attractor and non-attractor evolution,
single field and multifield models,
curvatons and isocurvatons.

3) 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

↓ oscillating with bkgd frequency

↓ oscillating frequency scans

Resonate when two freq coincide

- ➢ Large amplitude: powers of ω
- ➢ Distinctive scale-dependence: characteristic oscillatory running

Three Universal Properties Nicely Fit into Each Other

- Classical oscillation of massive fields

  ⟹ Standard clock

- They affect density perturbation through BD-vacuum, instead of model-dependent horizon/superhorizon evolution

  ⟹ General analyses possible

- Subhorizon scale is where the strong resonant effect takes place

  ⟹ Enhance effects in density perturbations

Running Patterns (X.C., 11)

- Power spectrum (as corrections to leading 2pt)

Leading scale-invariant 2pt is provided by whatever mechanisms from different paradigms (not our concern here)

$$\frac{\Delta P_\zeta}{P_{\zeta 0}} \propto \left(\frac{2k_1}{k_r}\right)^{-3+\frac{5}{2p}} \sin\left[\frac{p^2}{1-p}\frac{2m_\sigma}{H_0}\left(\frac{2k_1}{k_r}\right)^{1/p} + \text{phase}\right]$$

- Leading bispectrum (as leading 3pt)

$$S \propto \left(\frac{K}{k_r}\right)^{-3+\frac{7}{2p}} \sin\left[\frac{p^2}{1-p}\frac{2m_\sigma}{H_0}\left(\frac{K}{k_r}\right)^{1/p} + \text{phase}\right]$$

Feature (K) ~ Inverse function of $a(t)$

Exp inflation limit $p \gg 1$ ~ $\left(\frac{K}{k_r}\right)^{-3} \sin\left[\frac{2m_\sigma}{H}\ln K + \hat{\alpha}\right]$

Exponential inflation

- In both cases, also note the running of the amplitudes.

A Comparison with Sharp feature Signals

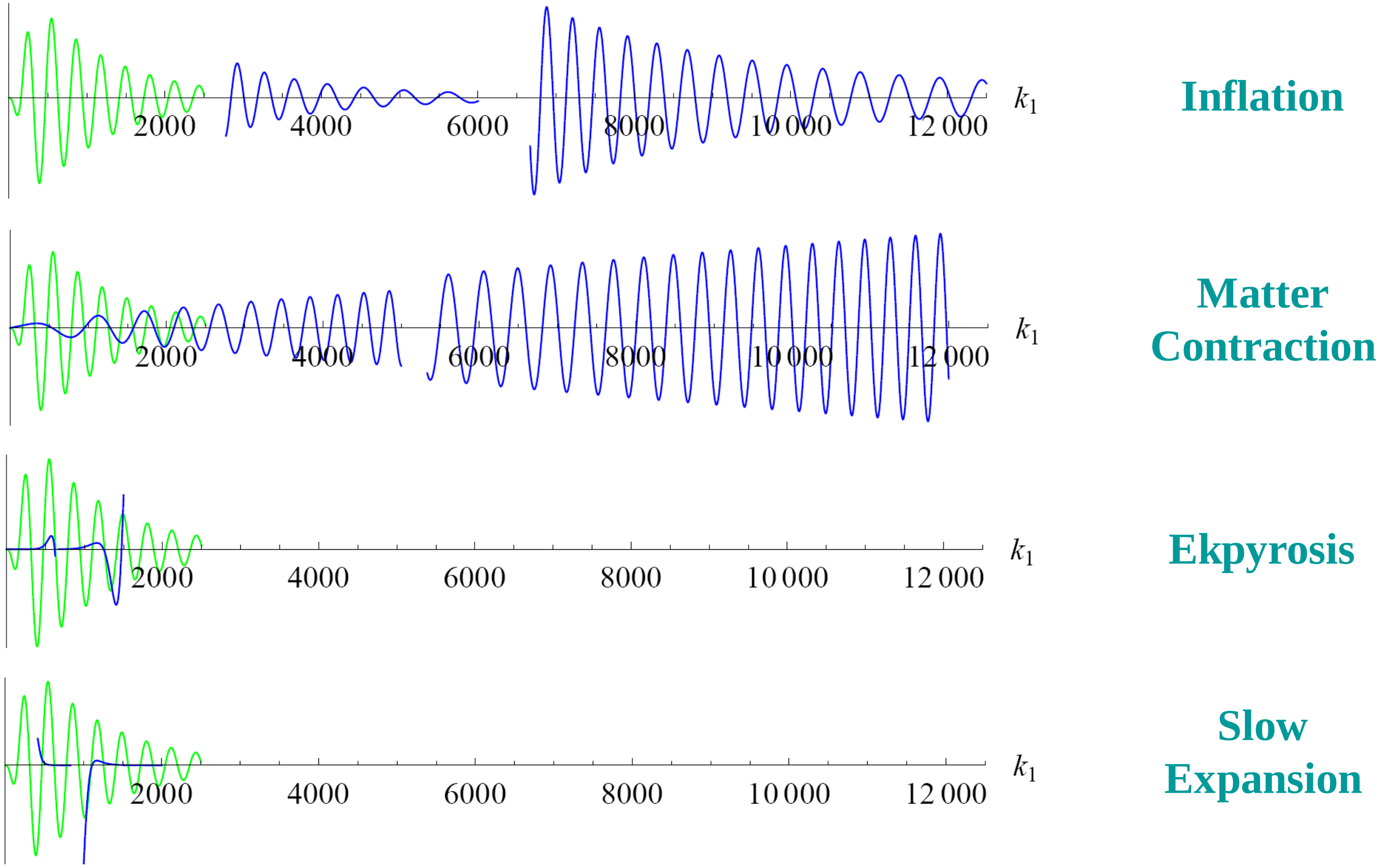
Sharp feature does not contain a "clock",
only one click.

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

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

Fingerprints of Different Paradigms (X.C., 11)

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



Key Features of these Fingerprints are all Direct Consequences of $a(t)$.

1) Resonant Running Patterns

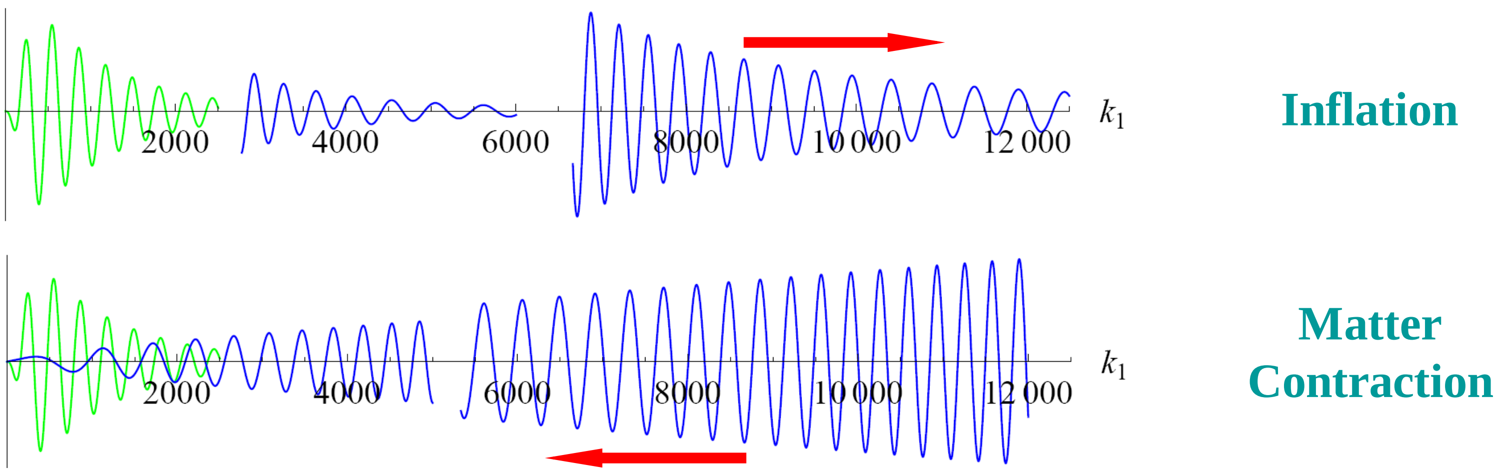
$$\sim \sin\left[\frac{p^2}{1-p}\frac{2m_\sigma}{H_*}\left(\frac{2k}{k_{\rm r}}\right)^{1/p}+\varphi\right]$$

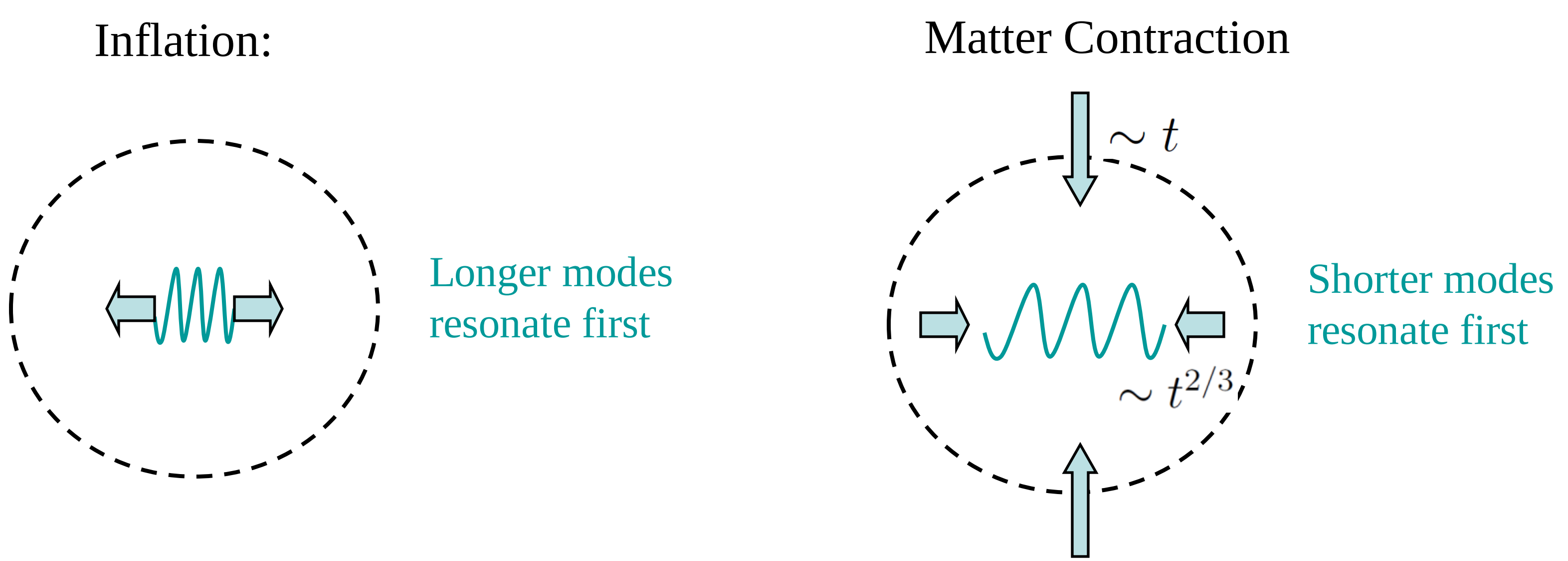
⇩

Inverse function of $a(t)$

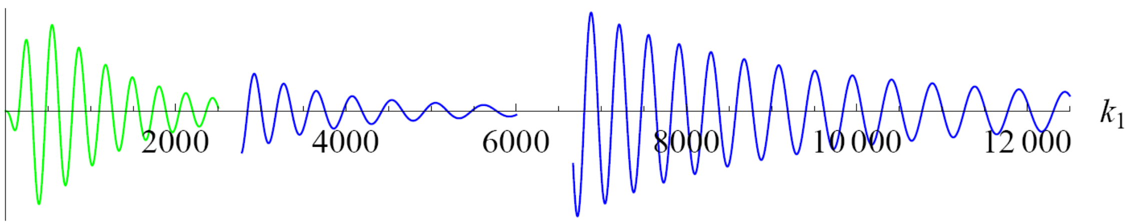
Different patterns can also be explained qualitatively from $a(t)$

Example: Inflation versus Fast Contraction (Matter Contraction)

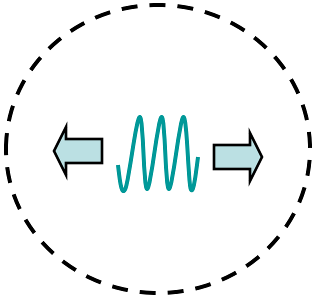




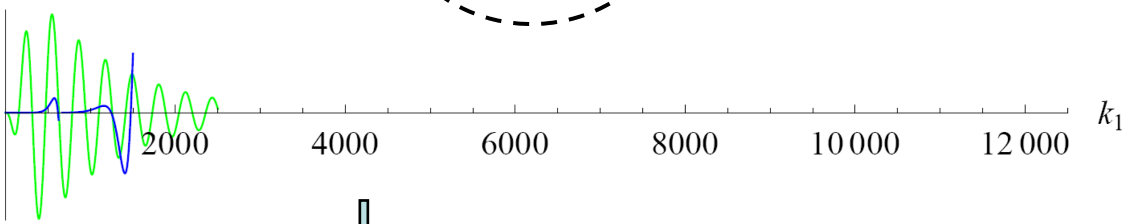
Example: Inflation versus Slow Contraction (Ekpyrosis)



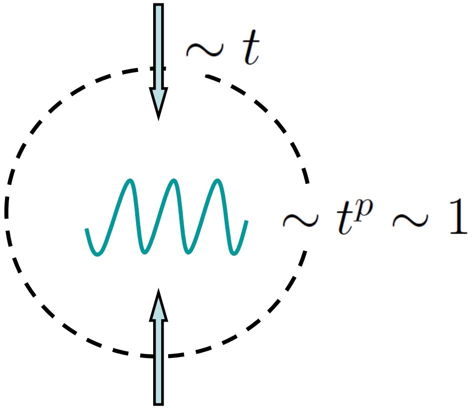
Inflation



Horizon size fixed;
All modes resonate



Ekpyrosis



Scalar factor changes very slowly;
Horizon shrinks fast;
Few modes can resonate

2) Relation between Locations of Two Type of Features

K-location of first resonant mode → k_r

K-location of sharp feature → k_0

$$\frac{k_r}{k_0} = \frac{|p|}{|1-p|} \frac{2m_\sigma}{H_0}$$

Determined by paradigm index *p* (↑ $\frac{|p|}{|1-p|}$)

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

$$\frac{k_r}{k_0} = \frac{2m_\sigma}{\text{Horizon Mass}} = \frac{H_0}{\text{Horizon Mass}} \frac{2m_\sigma}{H_0}$$

⇓

$$\frac{|p|}{|1-p|}$$

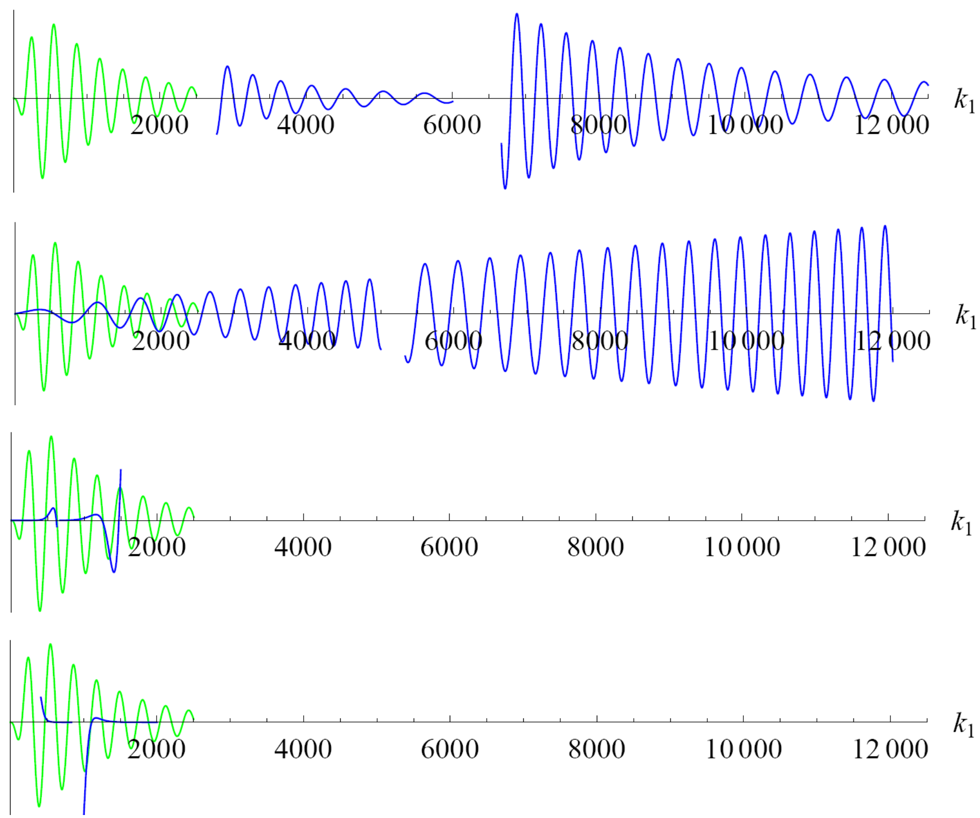
$$\frac{k_r}{k_0} = \frac{|p|}{|1-p|}\frac{2m_\sigma}{H_0}$$

$|p| \gg 1$ — **Inflation**

$p = 2/3 \sim 1$ — **Matter Contraction**

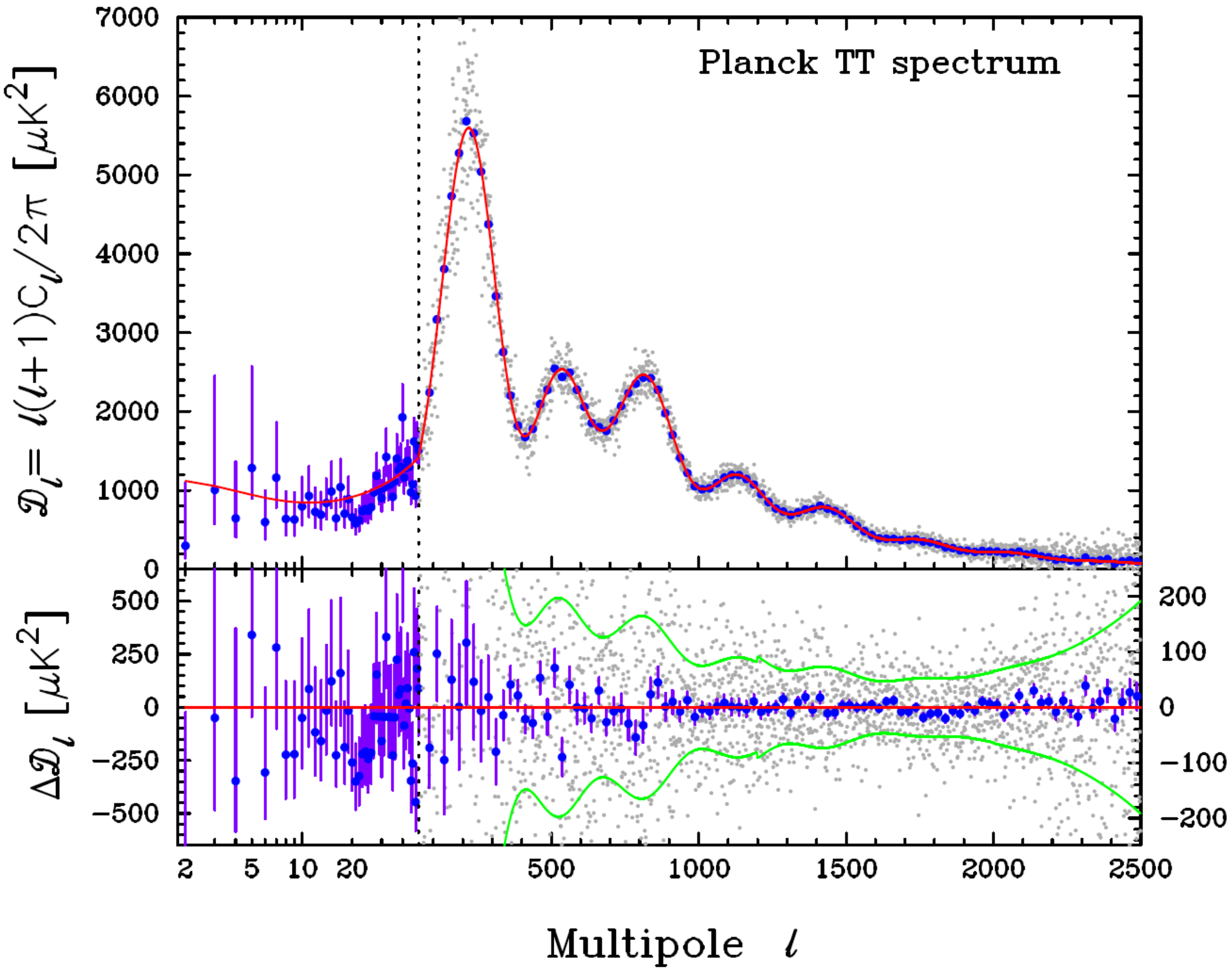
$0 < p \ll 1$ — **Ekpyrosis**

$-1 \ll p < 0$ — **Slow Expansion**

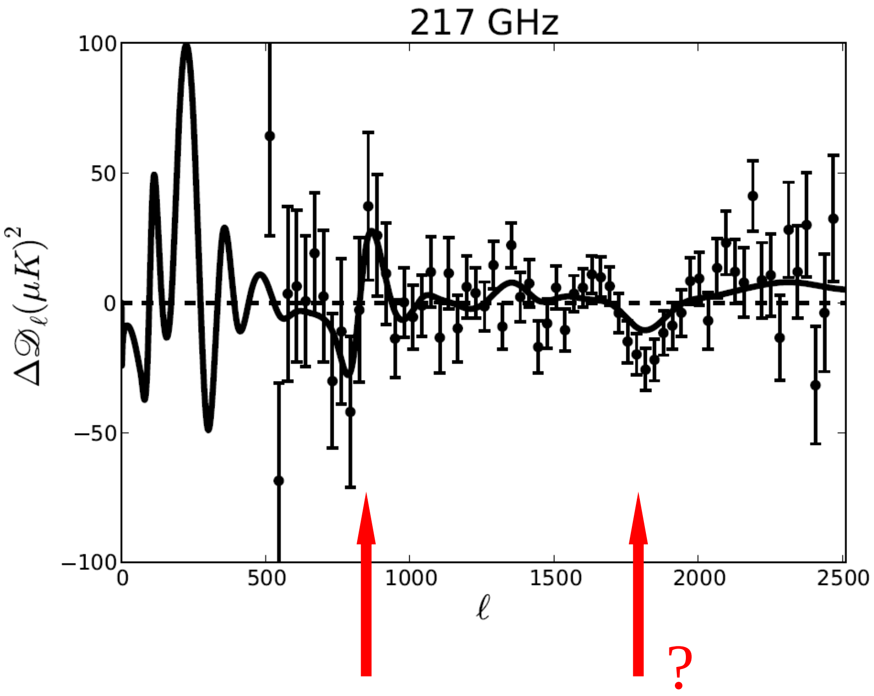


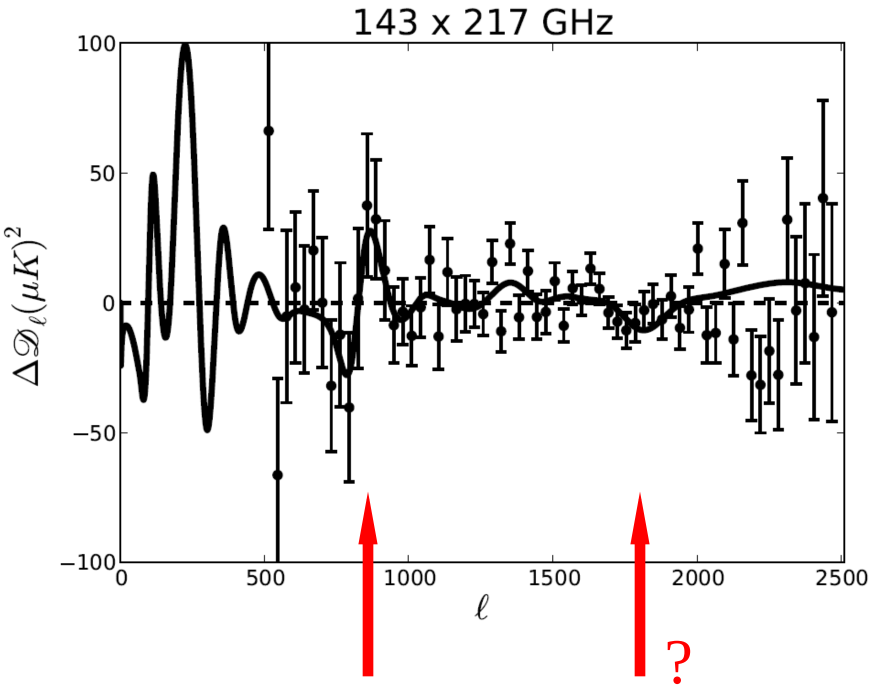
Let us Look at the Data

Planck Power Spectrum (Planck, 13)

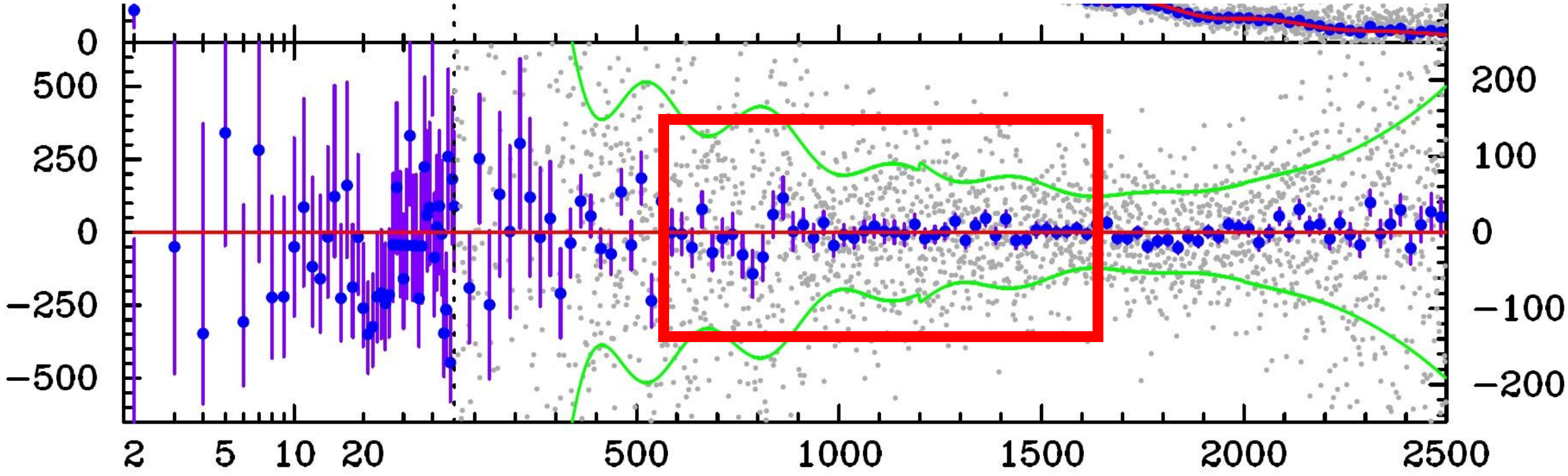


The Standard Clock Candidates

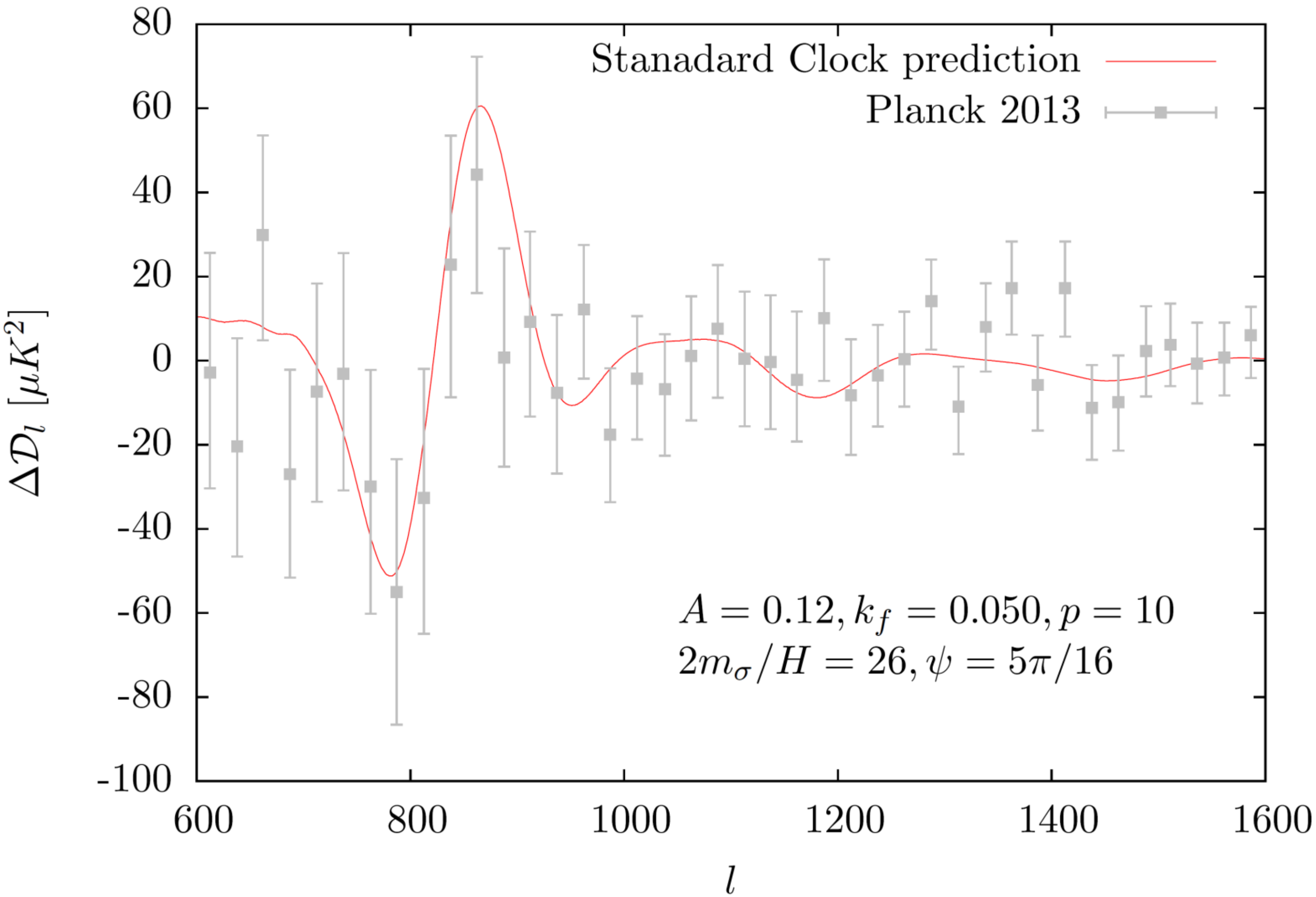




Planck Binned Power Spectrum Residues



A Fit for Standard Clock (X.C. 14, unpublished)



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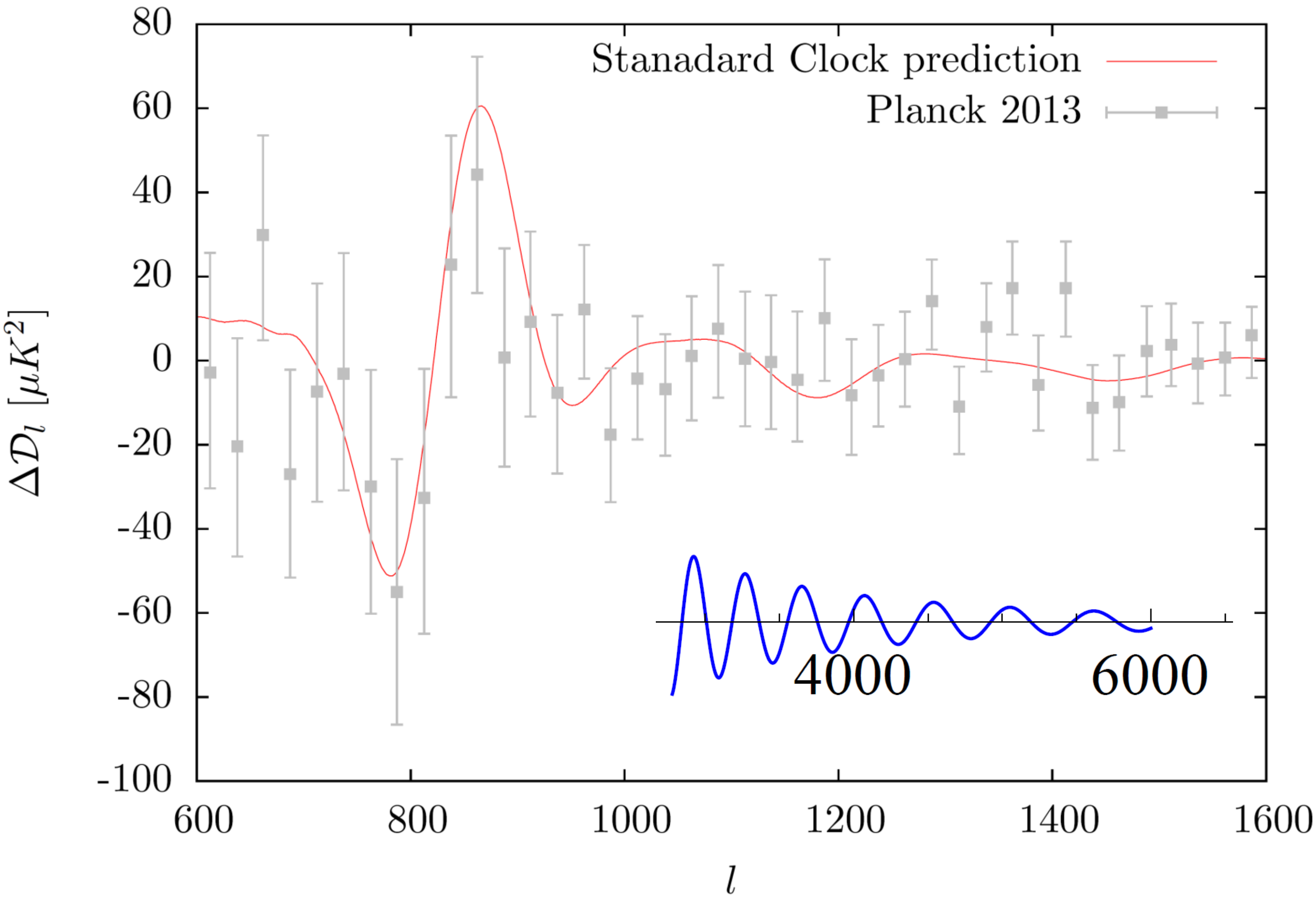


Fit only for $|p|>>1$ ➡ Inflation!

Let's look at this relation:

$$\frac{\ell_{\rm clock}}{\ell_{\rm sharp}} \sim \frac{k_r}{k_0} = \frac{|p|}{|1-p|} \frac{2m_\sigma}{H_0}$$

From the fit for Standard Clock

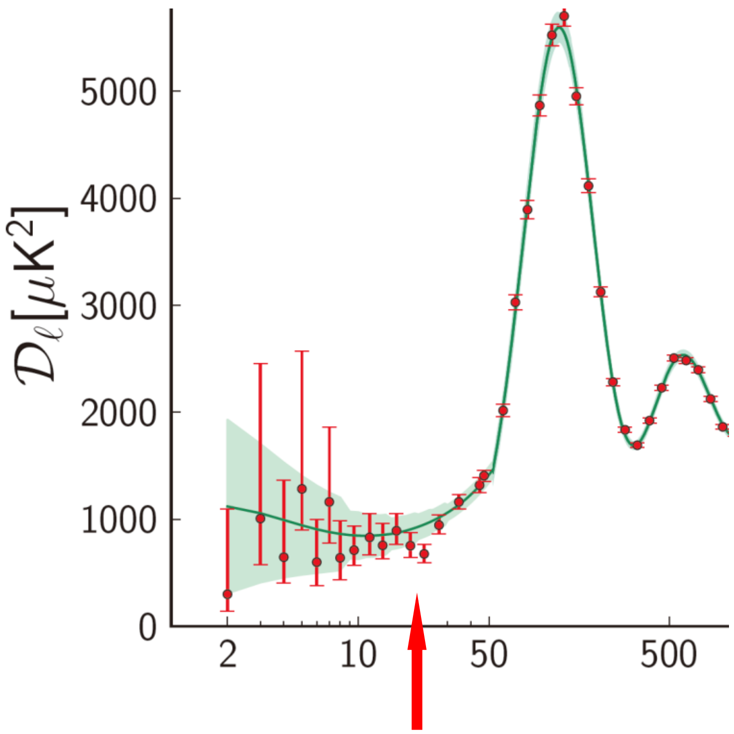
$k_{\rm clock} \approx 0.05/{\rm Mpc}$ $\qquad$ $2m_\sigma/H_0 \approx 26$ $\qquad$ $|p| \gg 1$

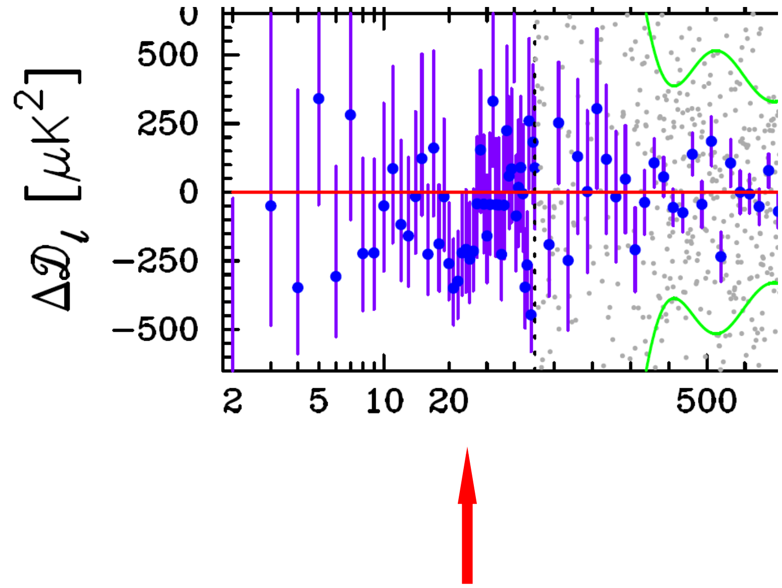
$\Updownarrow$

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

$\longrightarrow$ $\ell_{\rm sharp} \approx 26$!

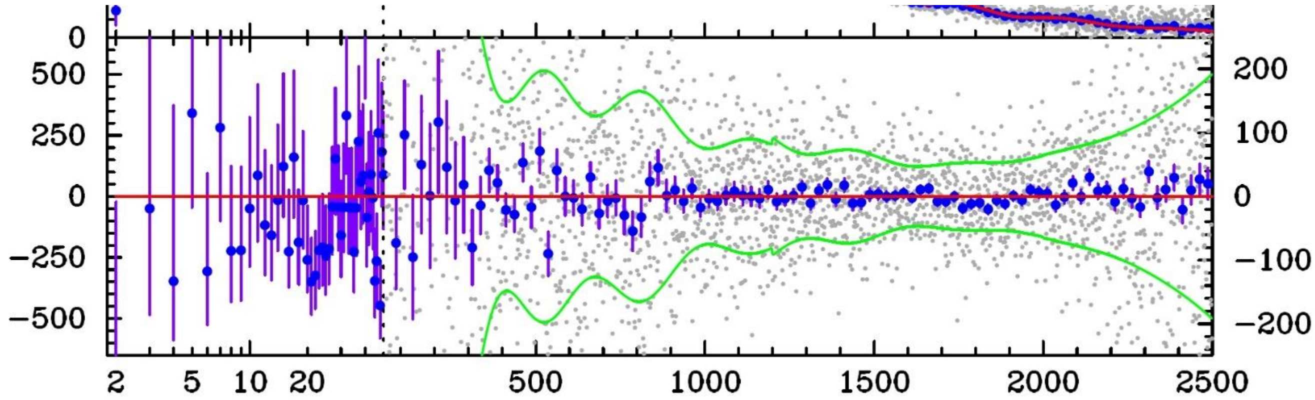
Matches the Known Sharp Feature Candidate

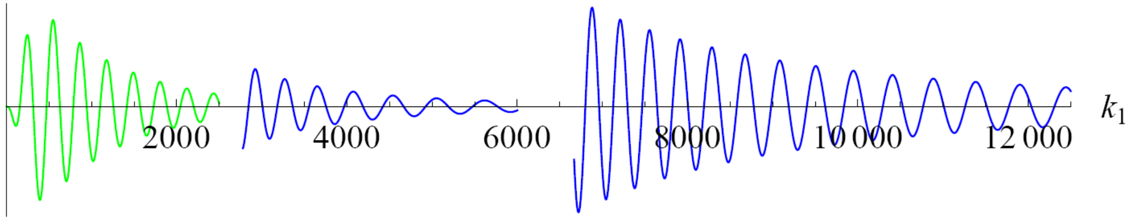




This relation holds only for $|p|>>1$ → Inflation!

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

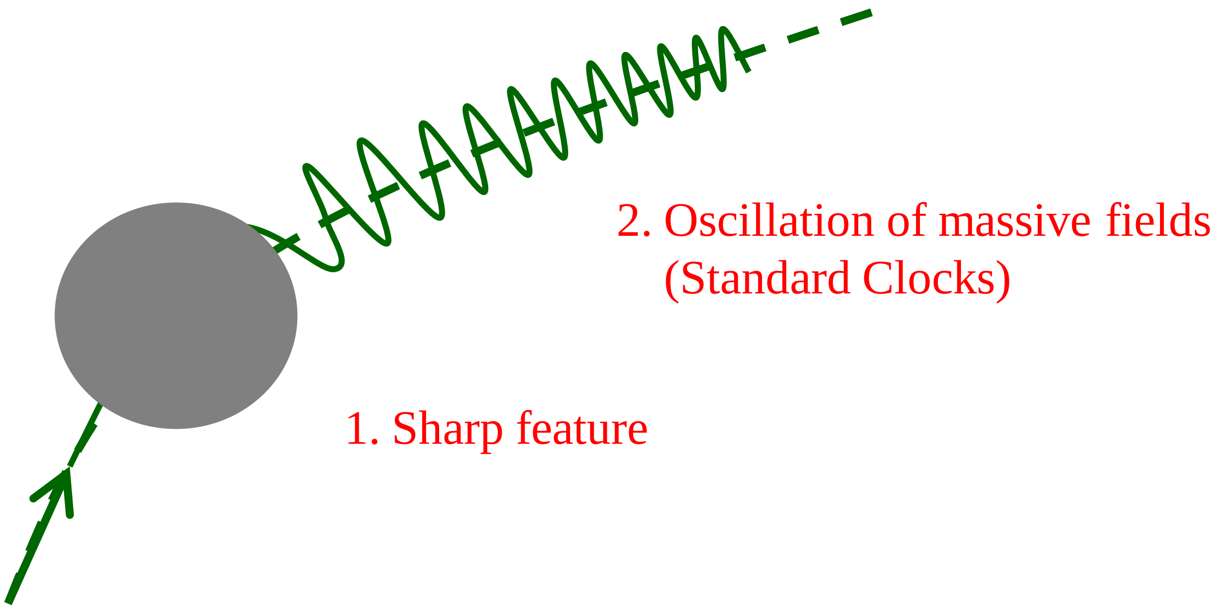




Improving Statistics

- Joint fitting with both types of features
- Correlated signals in E mode polarization
- Correlated signals in non-Gaussianities

Explicit Model Building



Gravitational Coupling Case (during resonance)

Minimal Effect, Most Natural in Model Building

$$H_{int} = \int d^4x\, a^3 \left[-\Delta\epsilon\, \dot{\zeta}^2 + \Delta\epsilon (\partial\zeta/a)^2 + \frac{\dot{\sigma}}{H}\dot{\delta\sigma}\dot{\zeta} + (3\dot{\sigma} + V'_\sigma/H)\delta\sigma\dot{\zeta} - \frac{\dot{\sigma}}{Ha^2}\partial\zeta\,\partial\delta\sigma \right]$$

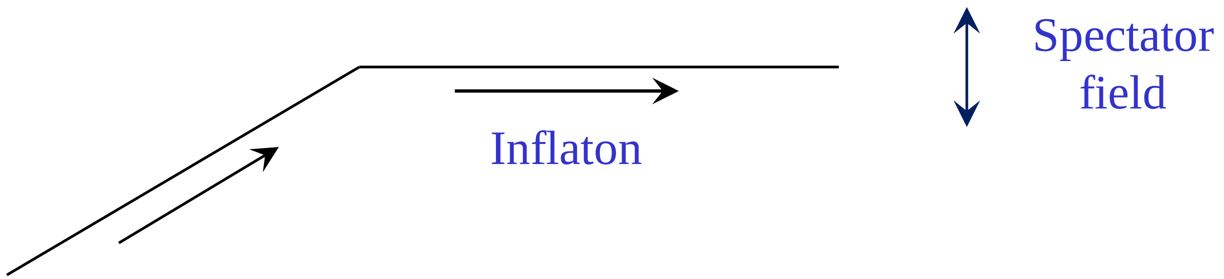
background resonance — Model Independent

conversion effect — Model Dependent

Depend on initial conditions for the modes; i.e. the cause of the oscillation of massive mode

- Similarly for non-Gaussianities

- Sharp Bending

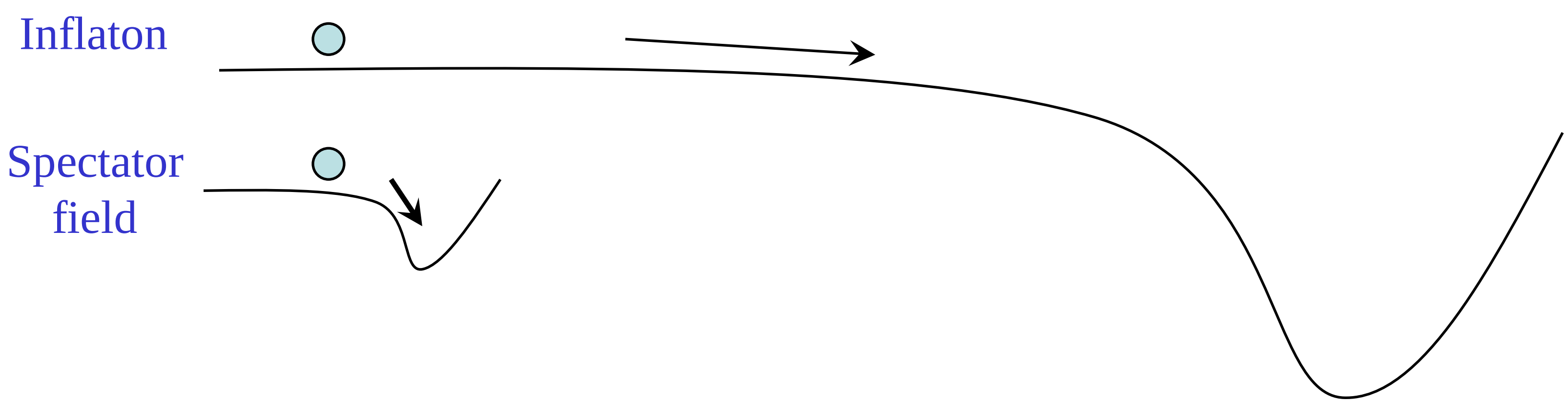


Background Resonance (model independent): Large resonance in both power spectrum and non-Gaussianities. (X.C., 11)

Conversion Effect (for bending case): Leading resonance in power spectrum cancelled (Noumi, Yamaguchi; Gao, Langlois, Mizuno, 13)

Leading resonance in non-Gaussianity remain (Noumi, Yamaguchi, 13)

- Tachyonic Falling (X.C., Namjoo, …., work in progress)



Model building: Naturally motivated from fine-tuning problem

Data fitting: Need smaller sharp feature signal, larger SC signals

Background Resonance (model independent): Same as before, X.C.,,11

Conversion Effect: (work in progress)

Summary

A bigger deal for finding features

Potentially we can look for “Standard Clock” signals

A direct measure of $a(t) \sim t^p$

Breaking the Leading Degeneracy

$\lvert p \rvert > 1$	inflation (fast expansion)
$p \sim 1$	fast contraction
$0 < p \ll 1$	slow contraction (Ekpyrotic)
$-1 \ll p < 0$	slow expansion

Not very good at distinguishing, say, p~8 from p~15, for inflation; but this is the subleading problem, which can be probed by conventional observables, like spectral index.

Thank You !