Primordial Features and Non-Gaussianities as Evidence for Inflation

Xingang Chen

Center for Theoretical Cosmology,
DAMTP, Cambridge University

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Distinguishing Inflation Paradigm and Its Alternatives

Looking for properties in density perturbations that are:

- Shared by all general models in one paradigm, not just a subset
- Distinctive for different paradigms

So far one candidate: Primordial tensor perturbations

Tensor 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 general distinguisher between different paradigms

Directly Observing the Scale Factor

Repeat features $\Longleftrightarrow$ Beats $\Longleftrightarrow$ Clock t

$\Updownarrow$

Comoving momenta: k $\Longleftrightarrow$ Physical momemta $\Longleftrightarrow$ Scale factor: a

Therefore, $a(t)$ $\Longleftrightarrow$ k (features)

What we observe is: features (k)

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

Looking for Standard Clocks

- **Identifiable from observable patterns**

- **As general as possible**

→ **Oscillation of massive modes**

Arbitrary Time-dependent Background

- Consider general power-law backgrounds

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

- Require quantum fluctuations exit event-horizon

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

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

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

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

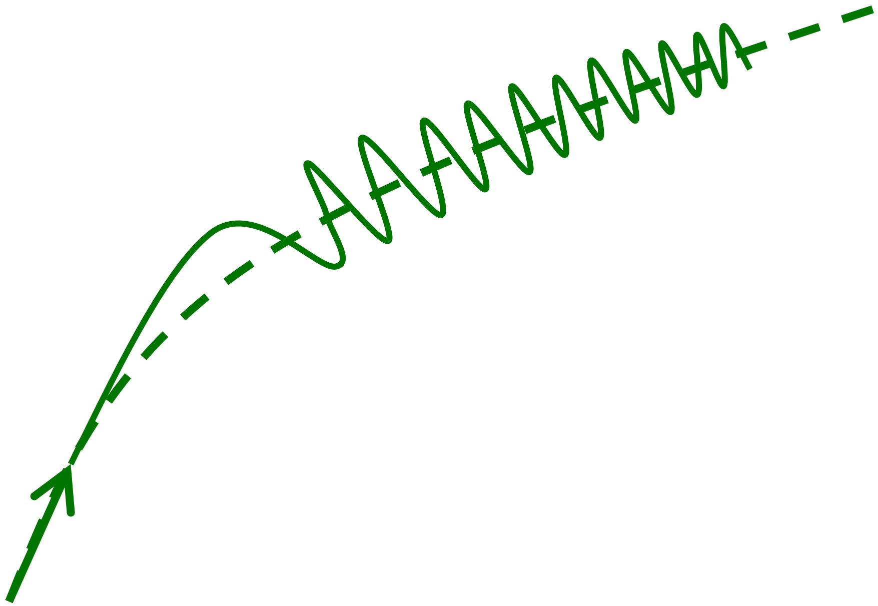
$$3M_{\rm P}^2 H^2 = \frac{1}{2}\dot{\sigma}^2 + \frac{1}{2} m^2 \sigma^2 + \text{other fields}$$

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

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

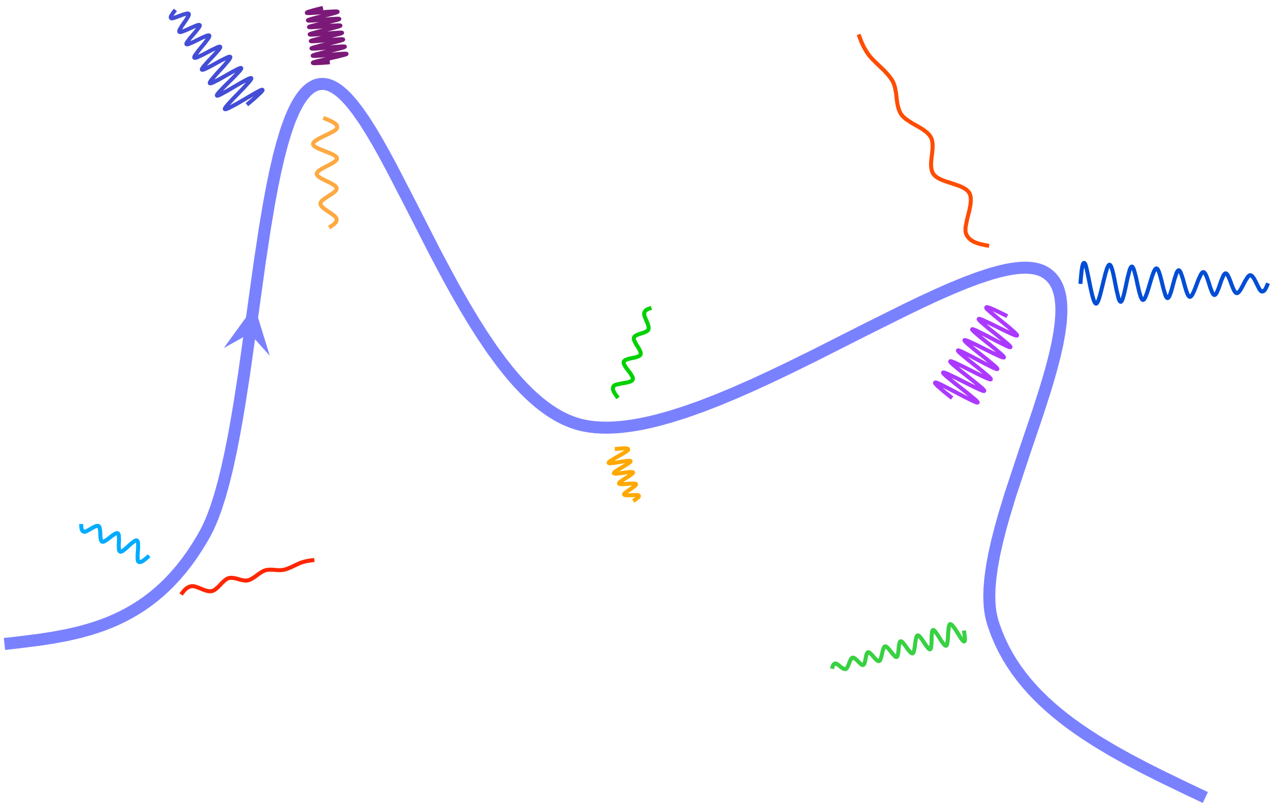
How to Excite Massive Modes

E.g. turning trajectory:



More generally, turning trajectory, sharp feature, particle creations, etc.

Excited Massive Modes are Generic



The question is how sensitive the observables are to these oscillations

Bunch-Davies Vacuum and Resonance Mechanism

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, $k > 1/|\tau|$

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

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.

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

- Probing the BD vacuum

Small oscillating background

⬇

High energy probe with wavelength smaller than horizon size

⬇

Resonant with BD modes one by one

$$\int d\tau B(t) e^{-iK\tau} + \text{c.c.} \qquad B(t) \sim e^{i\omega t}$$

Inflation background $\Longrightarrow$ $\sin\left[\frac{\omega}{H}\ln\frac{K}{k_r} + \text{phase}\right]$

(X.C, Easther, Lim, 08; Flauger, Pajer, 10, X.C., 10; Leblond, Pajer, 10)

Massive-Modes-Induced Resonance Phenomena in Arbitrary Time-Dependent Background

- Resonant running (how scale factor is encoded)
- Size of amplitude (how large is the effect)
- Running of amplitude

Measuring the Scale Factor

Massive-modes-induced resonant forms on
power spectrum (as correction) and bispectrum (as leading contribution)

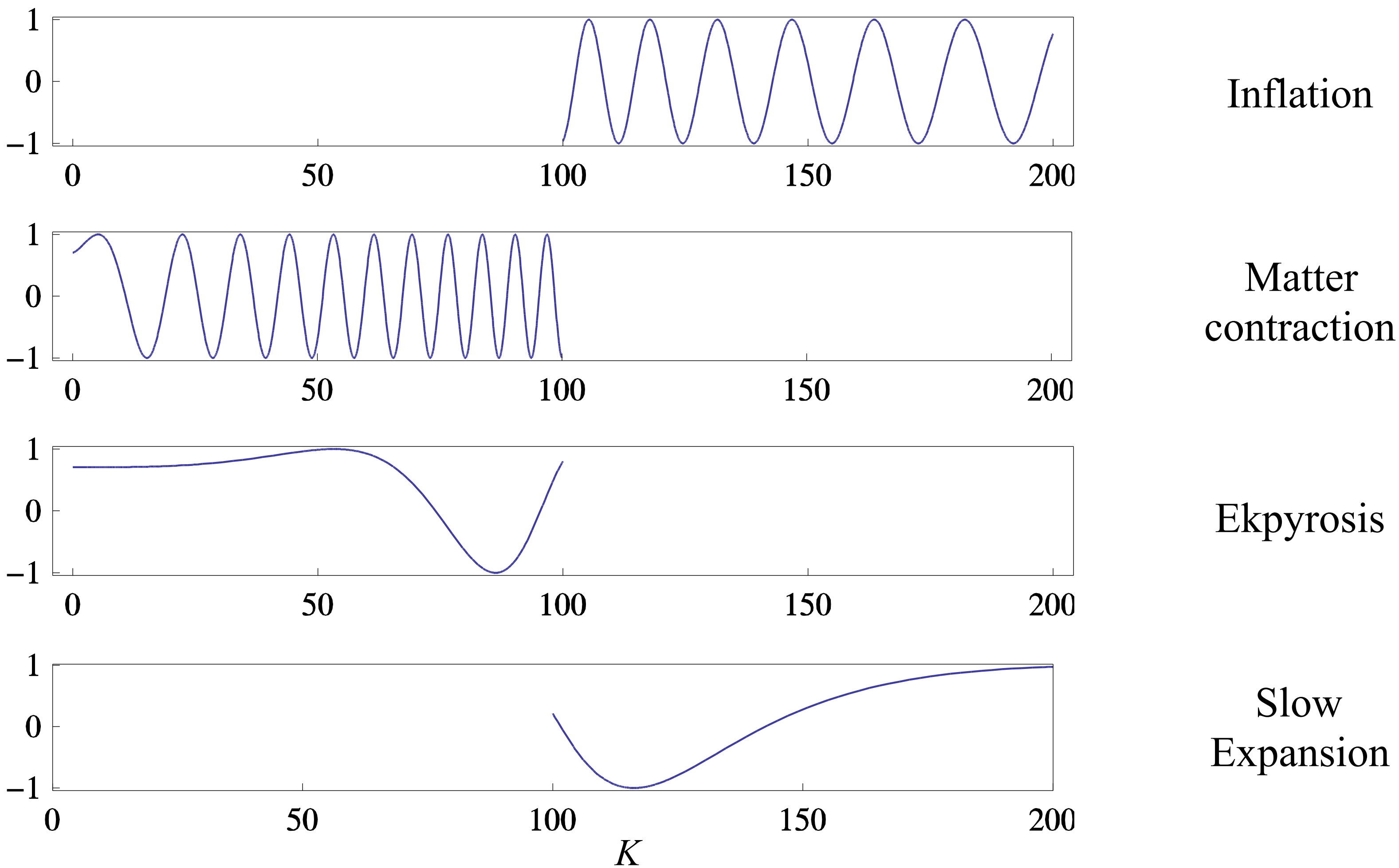
Resonance forms: $\sim \left(\frac{K}{k_r}\right)^{-3+\frac{7}{2p}} \sin\left[\frac{p^2}{1-p}\frac{2m_\sigma}{H_0}\left(\frac{K}{k_r}\right)^{1/p} + \text{phase}\right]$

Feature (K) $\sim$ Inverse function of $a(t)$

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

Inflation

Resonant Running for Different Paradigms



Distinguishable within a couple of efolds

Large Amplitudes

- Consider, for example, a massive mode coupled to inflaton only through gravity (after being excited)

$$\left(\frac{\Delta P_\zeta}{P_{\zeta 0}}\right)_A \sim \beta \left(\frac{m_\sigma}{H}\right)^{1/2}$$

$$f_{NL} \sim \beta \left(\frac{m_\sigma}{H}\right)^{5/2}$$

β: fraction of slow-roll kinetic energy convert to massive mode

E.g. $\beta \sim 10^{-2}$ $m_\sigma / H \sim 10^2$

$\Longrightarrow$ $\Delta P_\zeta / P_{\zeta 0} \sim 0.1$ $f_{NL} \sim 10^3$

Tiny oscillations induce large effects

Minimum requirements: 1) BD vacuum; 2) Gravity mediation.

Advantages, Caveats and Solutions

- Resonant runnings will not be modified in multifield evolution

  - ➢ Effects that change faster than horizon time-scale

    ⟶ Additional resonant forms superimposed onto each other

  - ➢ Effects that vary slower than horizon time-scale

    ⟶ Can only change overall amplitude or modulate envelop

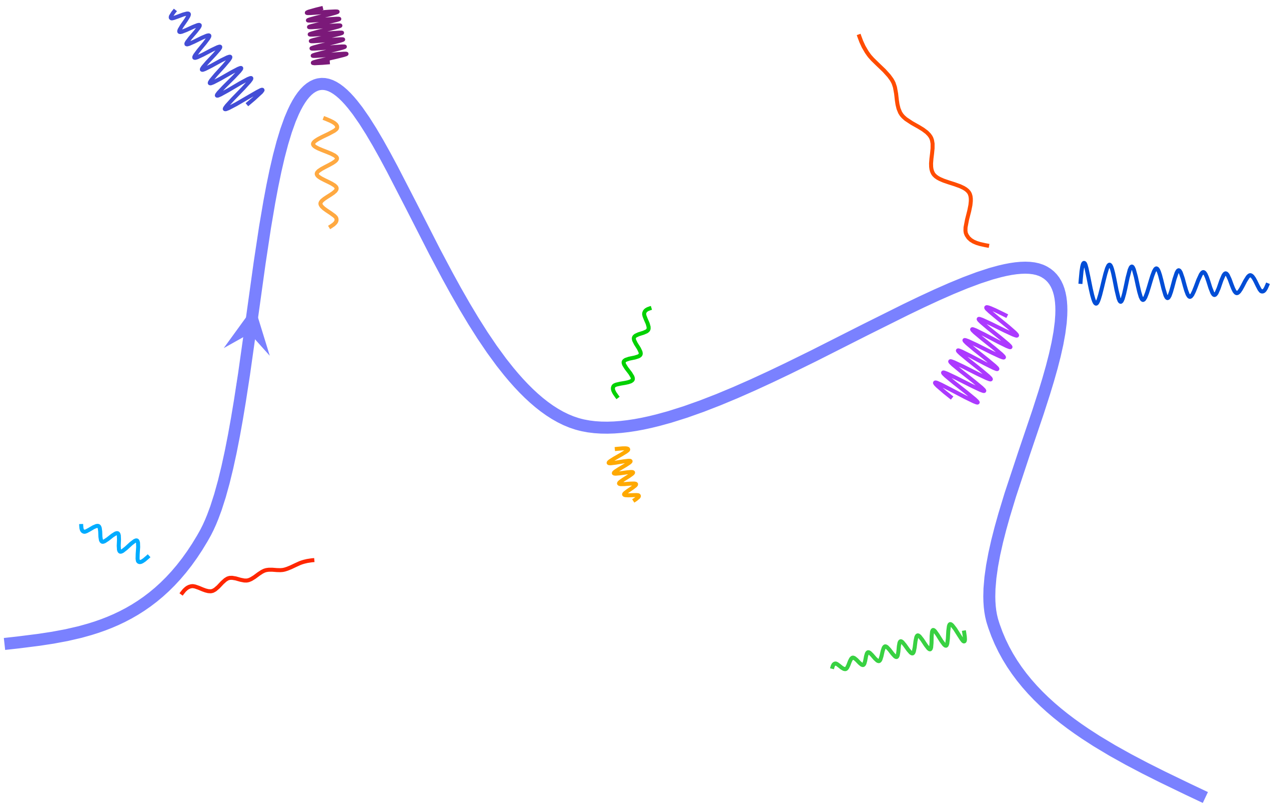
- Caveats: Engineering non-periodic features

$$B(t) \sim e^{ig\ln(t/t_0)} \Longrightarrow \sin\left[\frac{g}{p-1}\ln\frac{K}{k_r} + \text{phase}\right]$$ but not inflation

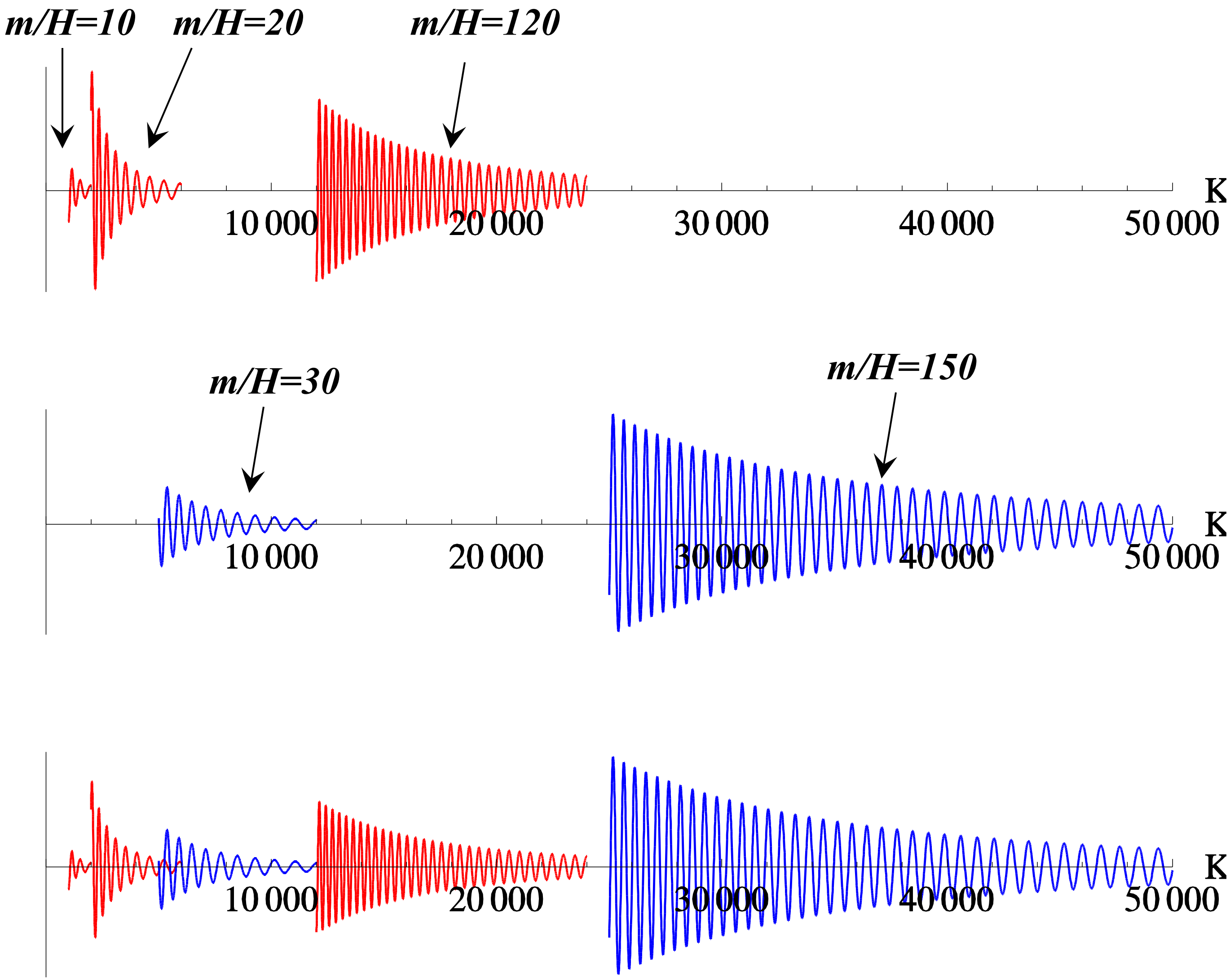
- Possible solutions:

  - ➢ Multiple characteristic signals:
    several massive modes, running amplitudes.

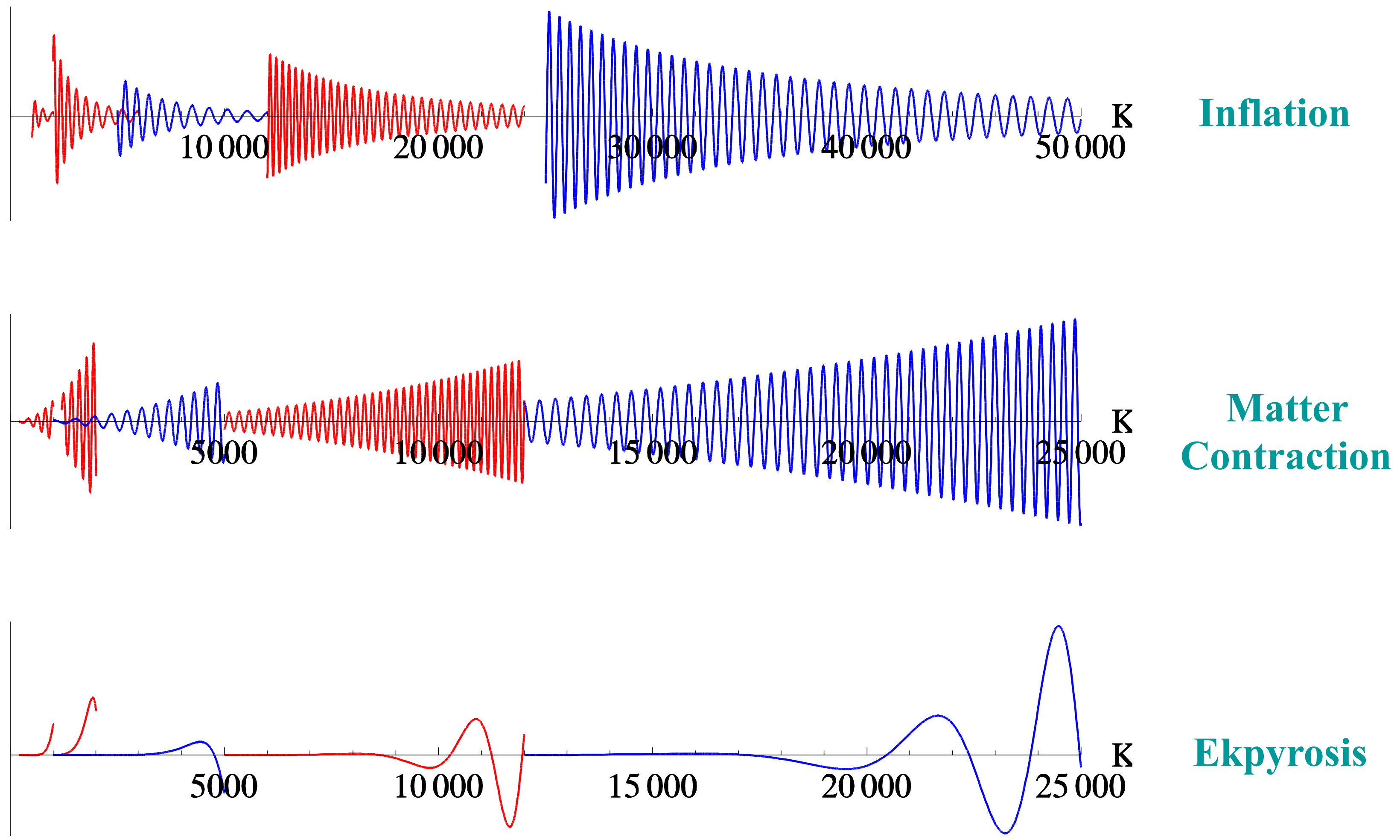
  - ➢ In conjunction with sharp feature that excites the massive modes



Inflation



Fingerprints for Different Paradigms



Experiments and Data Analyses

• Oscillation wavelength $\Delta\ell \ll \ell$ (small binning)

⟹ High precision experiments on large multipoles
(Planck, a few thousands; ACT, SPT, ten thousands)

• The resonance forms are orthogonal to most other signals,
in particular, astrophysical, nonlinear gravity, systematic effects

⟹ New assessment and analyses are necessary
for forecast and constraint/detection

• Variety of non-separable functional forms

⟹ Mode decomposition method (Fergusson, Shellard, Liguori, Regan, 06-11)

• Effects on Galaxy formation?