Cosmological Collider Physics using Primordial Clocks & Clicks

Reza Ebadi

University of Maryland – College Park

Based on [2205.01107] w/ Xingang Chen and Soubhik Kumar

PHENO 2022 | University of Pittsburg | 5.9.2022

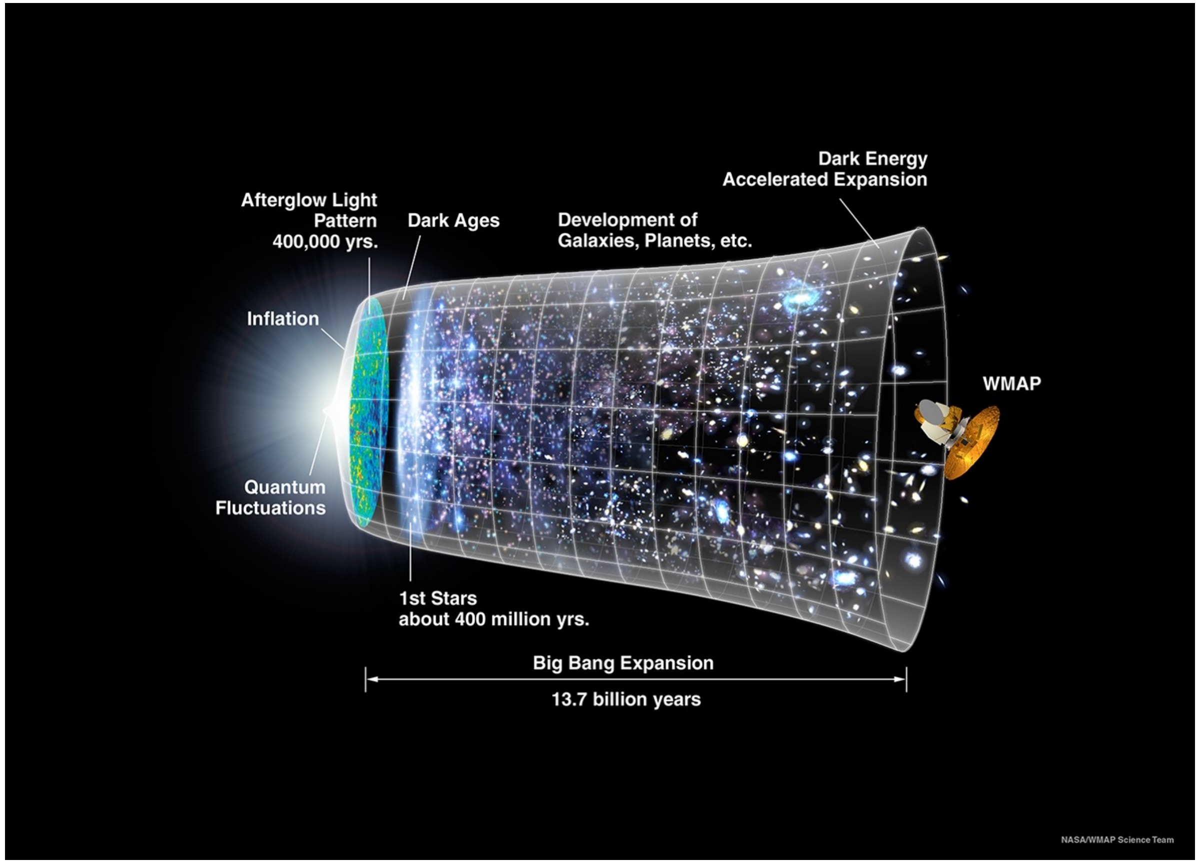
Standard Model of Cosmology

Precision Cosmology

- Cosmic Microwave Background
- Large Scale Structure
- Gravitational Lensing
- Lyα
- Type Ia Supernovae
- Quasars
- Local Galactic Surveys
- Hydrogen 21 cm Map
- Gravitational Waves
- ….

Connections with particle physics

- BBN
- Neutrinos
- Dark matter
- Baryogenesis
- ….



Reza Ebadi (ebadi@umd.edu)

Inflation

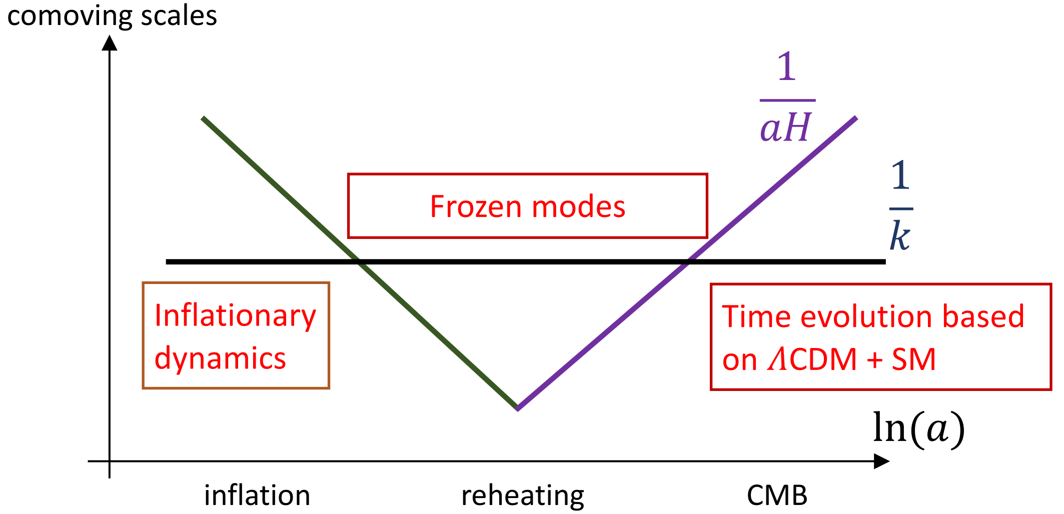
Leading paradigm for pre-Big Bang cosmology

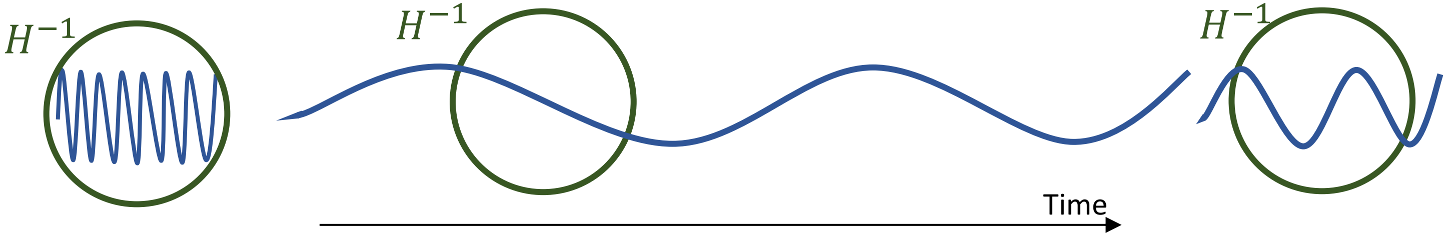
Background (early accelerated expansion era)

- Horizon problem
- Flatness problem
- (Monopole problem)

Perturbations (quantum fluctuation of the inflaton)

- Scale-Invariant
- Gaussian
- Adiabatic





Guth, Linde, Mukhanov, Starobinski, Albrecht, Steinhardt, …

Inflation

Leading paradigm for pre-Big Bang cosmology

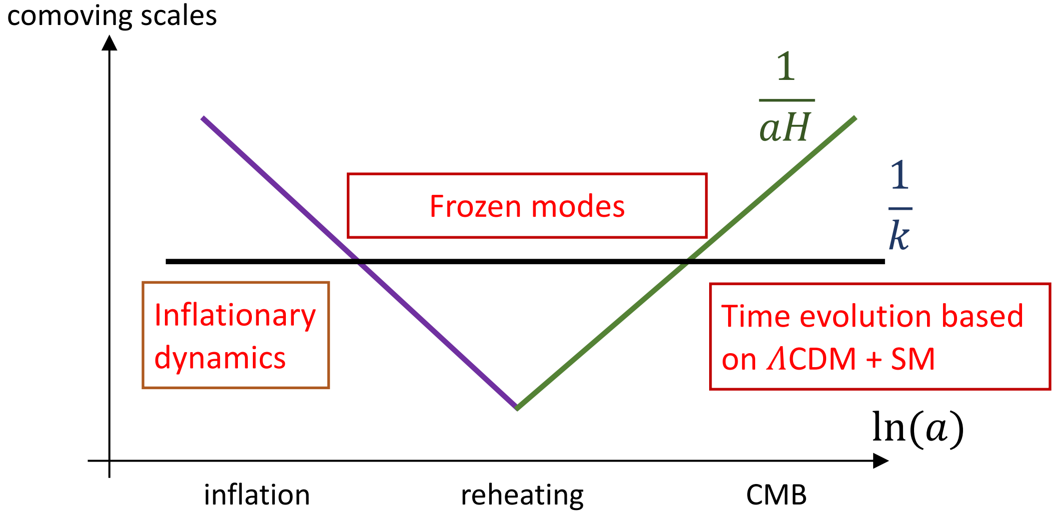
Background (early accelerated expansion era)

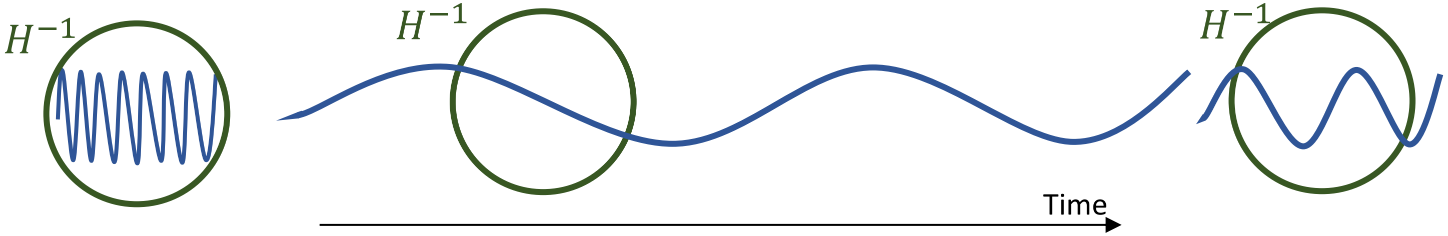
- Horizon problem
- Flatness problem
- (Monopole problem)

Perturbations (quantum fluctuation of the inflaton)

- Scale-Invariant
- Gaussian
- Adiabatic

Beyond “zeroth-order picture”?





Guth, Linde, Mukhanov, Starobinski, Albrecht, Steinhardt, …

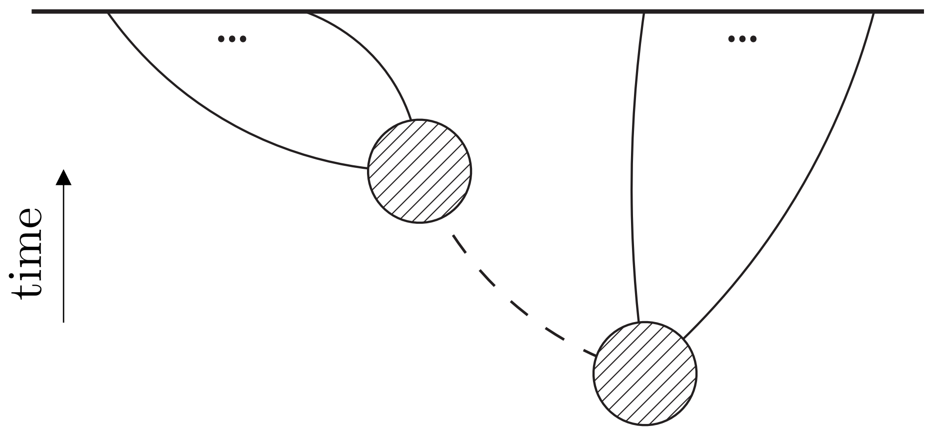
Outline

I. Cosmological Collider Physics

II. Primordial Features

III. “Classical Cosmological Collider”

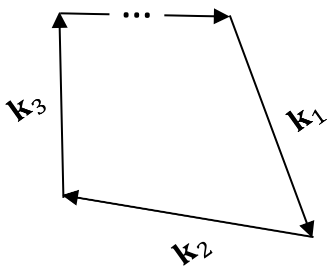
Cosmological correlation functions



In-in formalism:

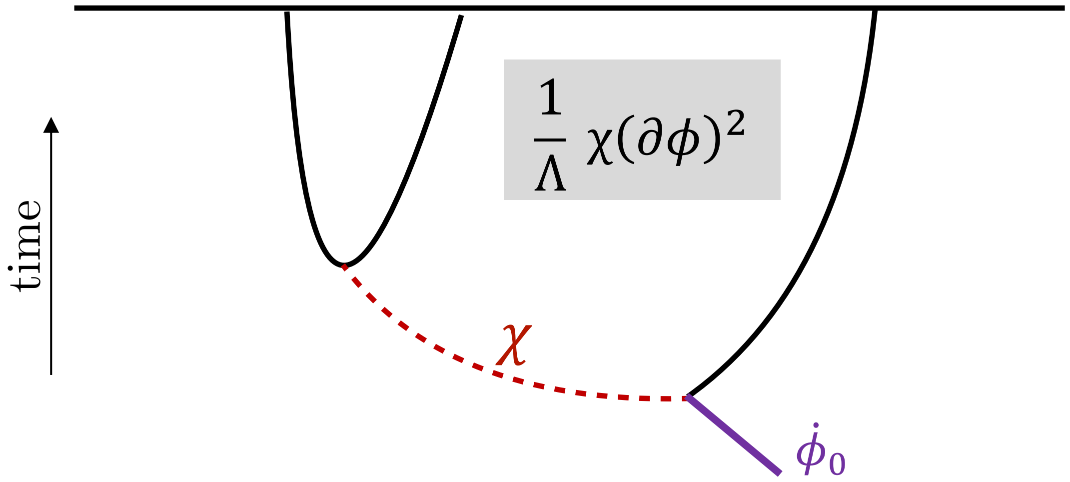
$$\langle Q \rangle = \langle 0 | \left[\bar{T} e^{i \int dt' H_{\rm I}(t')} \right] Q_{\rm I}(t_{\rm end}) \left[T e^{-i \int dt' H_{\rm I}(t')} \right] | 0 \rangle$$

Momentum conservation (due to statistical homogeneity of the universe):



Schwinger and Keldysh (see e.g. Weinberg ’05)

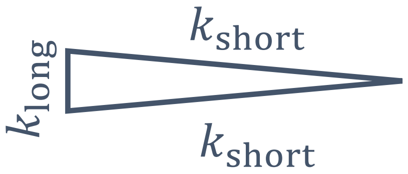
Cosmological collider physics



$$\mathcal{S} \propto e^{-\pi\mu}\left(\frac{k_{\text{short}}}{k_{\text{long}}}\right)^{-3/2-i\mu} f_s(\cos\theta)$$

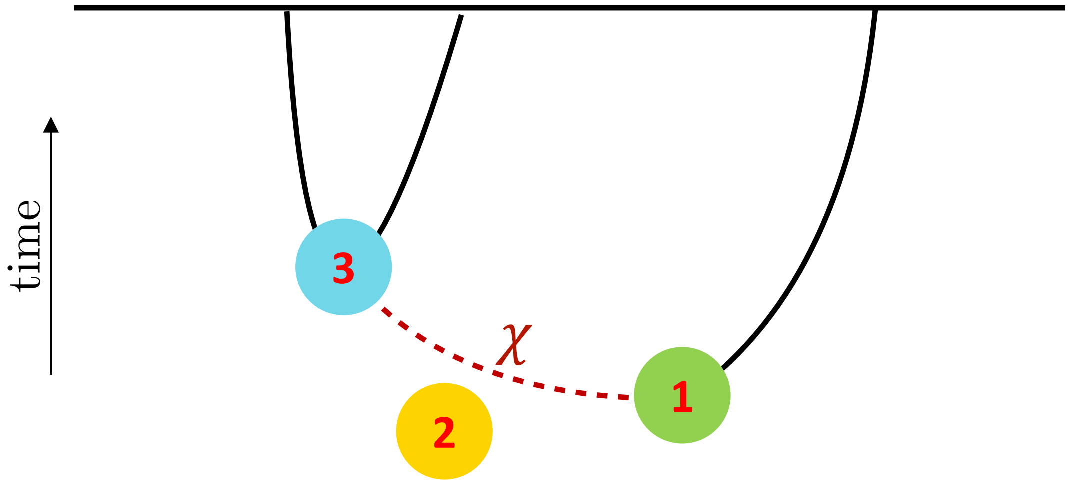
$$\mu = \sqrt{\frac{m_\chi^2}{H^2}-\frac{9}{4}} \qquad \theta = \hat{k}_{short}\cdot\hat{k}_{long}$$

Squeezed limit



Chen & Wang ‘09; Arkani-Hamed & Maldacena ‘15

Cosmological collider physics



1 Spontaneous particle production

2 Heavy field propagation

3 Resonant decay to inflaton particles at a later time

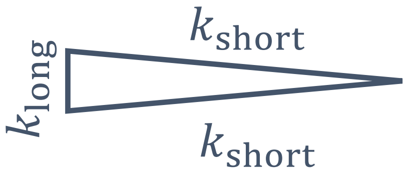
Boltzmann suppression

Oscillatory collider signal
for $m_\chi > 1.5\ H$

$$\mathcal{S} \propto e^{-\pi\mu}\left(\frac{k_{\text{short}}}{k_{\text{long}}}\right)^{-3/2-i\mu} f_s(\cos\theta)$$

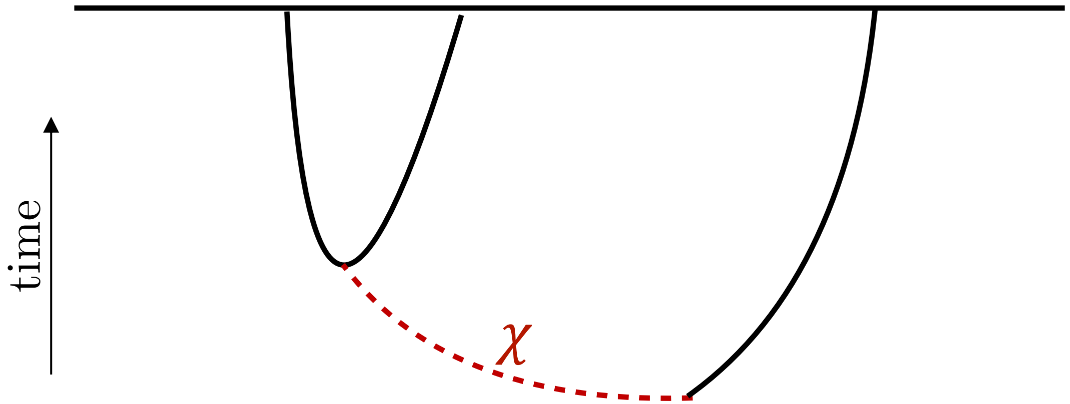
$$\mu = \sqrt{\frac{m_\chi^2}{H^2} - \frac{9}{4}} \qquad \theta = \hat{k}_{short} \cdot \hat{k}_{long}$$

Squeezed limit

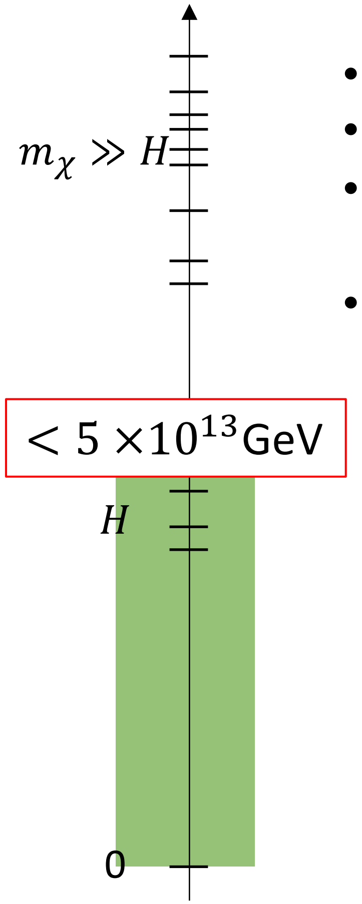


Chen & Wang ‘09; Arkani-Hamed & Maldacena ‘15

Cosmological collider physics



Boltzmann suppression
limits the reach of the cosmological collider.



- Grand Unification
- Wide particle spectrum (like the SM)
- UV completion of the low-energy effective theories of inflation
- ….

The upper limit can be extended:

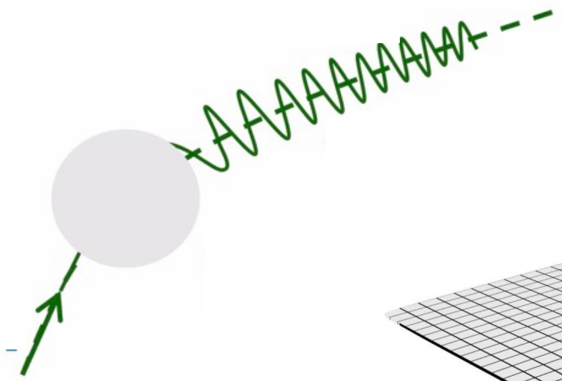
X. Chen, W. Z. Chua, Y. Guo, Y. Wang [1803.04412]
A. Hook, J. Huang, and D. Racco [1907.10624]
A. Hook, J. Huang, and D. Racco [1908.00019]
L.-T. Wang and Z.-Z. Xianyu [1910.12876]
L.-T. Wang and Z.-Z. Xianyu [2004.02887]
A. Bodas, S. Kumar, and R. Sundrum [2010.04727]
C. M. Sou, X. Tong, and Y. Wang [2104.08772]

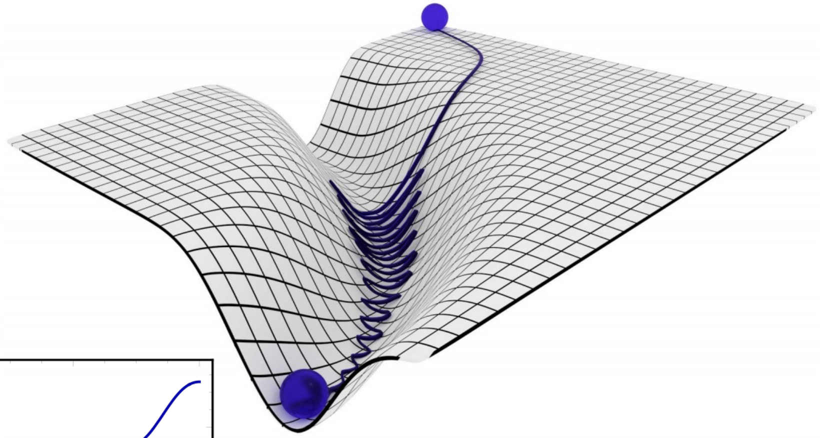
Chen & Wang '09; Arkani-Hamed & Maldacena '15

Primordial features

Inflaton as a valley in a vast landscape (the early universe field space)

Primordial features

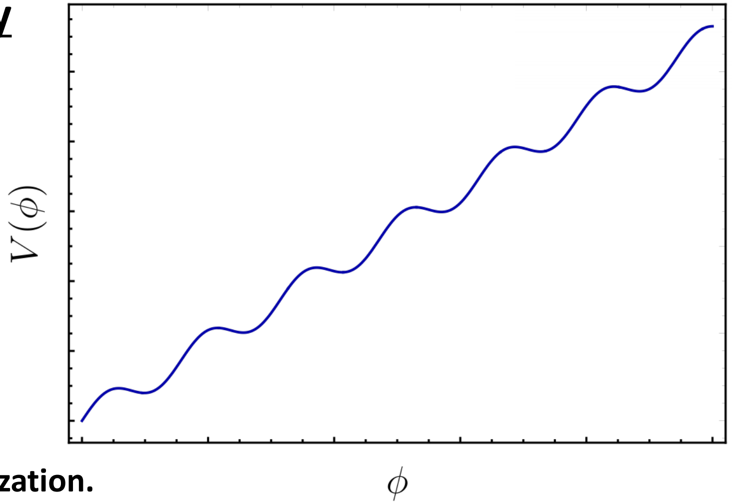




Inflaton as a valley in a vast landscape (the early universe field space)

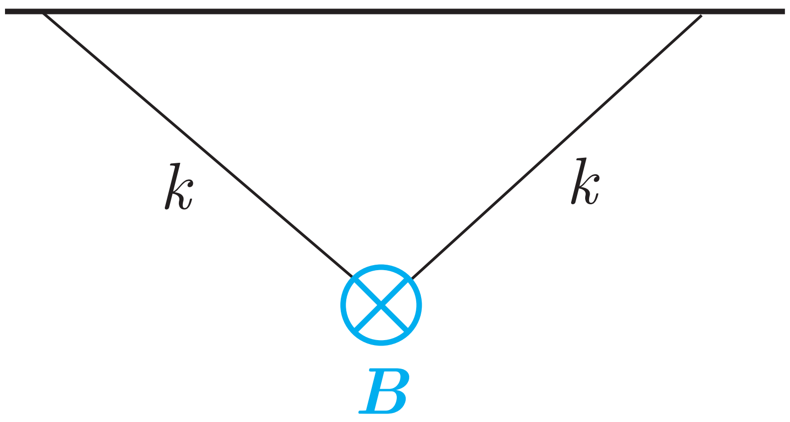
$$B_c(t) = B_0 a^{-n} \sin(\omega_c t + \alpha)$$

$$B_s(t) = B_0 \theta(t - t_0)$$



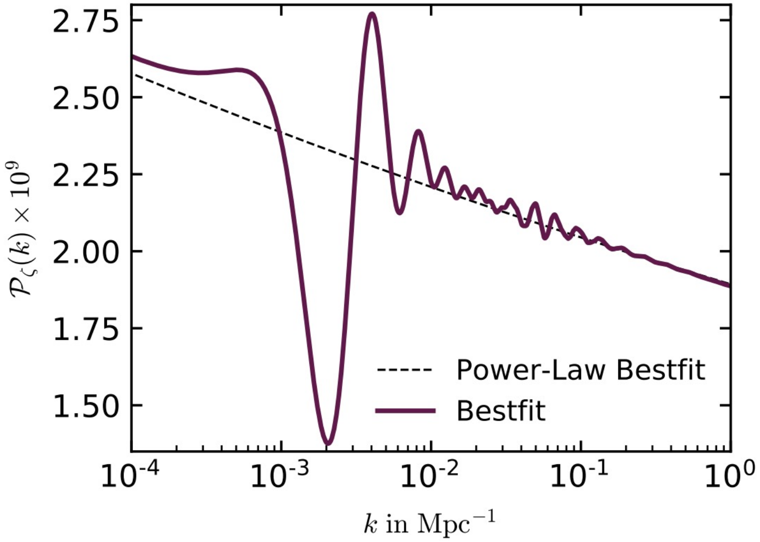
See the paper [2205.01107] for references and explicit model realization.

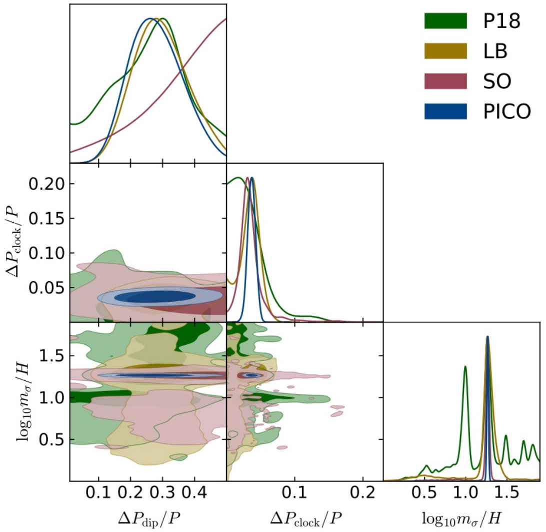
Primordial features



These features have been sought through the CMB power spectrum.

$$\frac{\Delta P_\zeta}{P_\zeta} \propto B_0 \left(\frac{2k}{k_r}\right)^{-n-i\mu_c} + \text{c.c.}$$



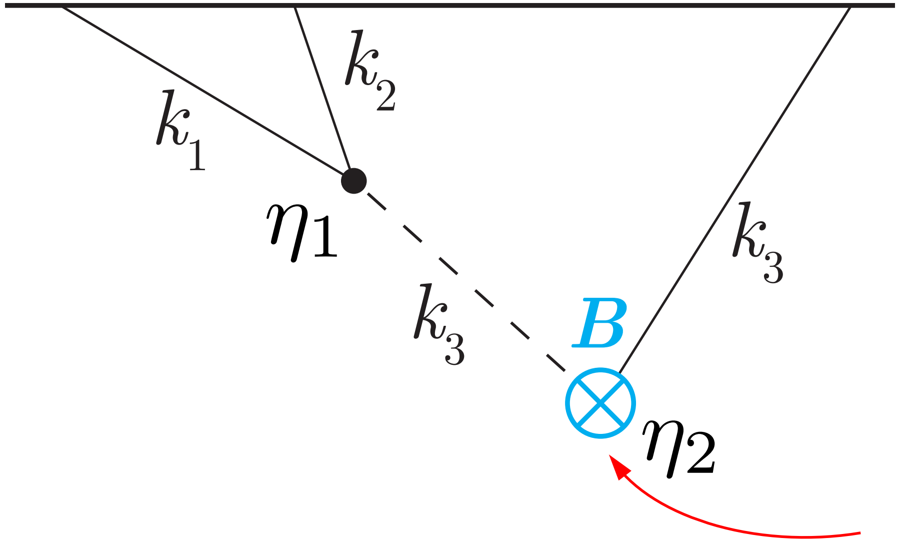


A low-statistics candidate at $\omega_c \sim 20$.

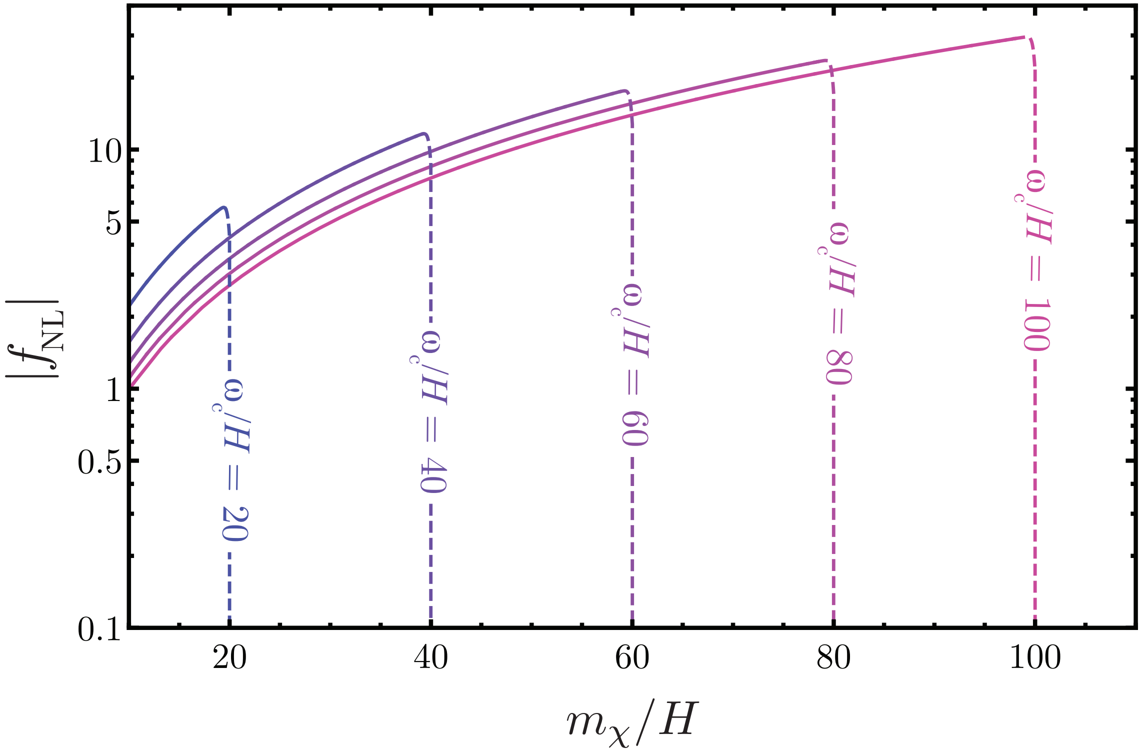
E.g., Braglia, Chen, and Hazra '21

"Classical cosmological collider"

$$L_{int} \supset \rho\, B_c(t)\, \delta\dot{\phi}\, \delta\chi$$

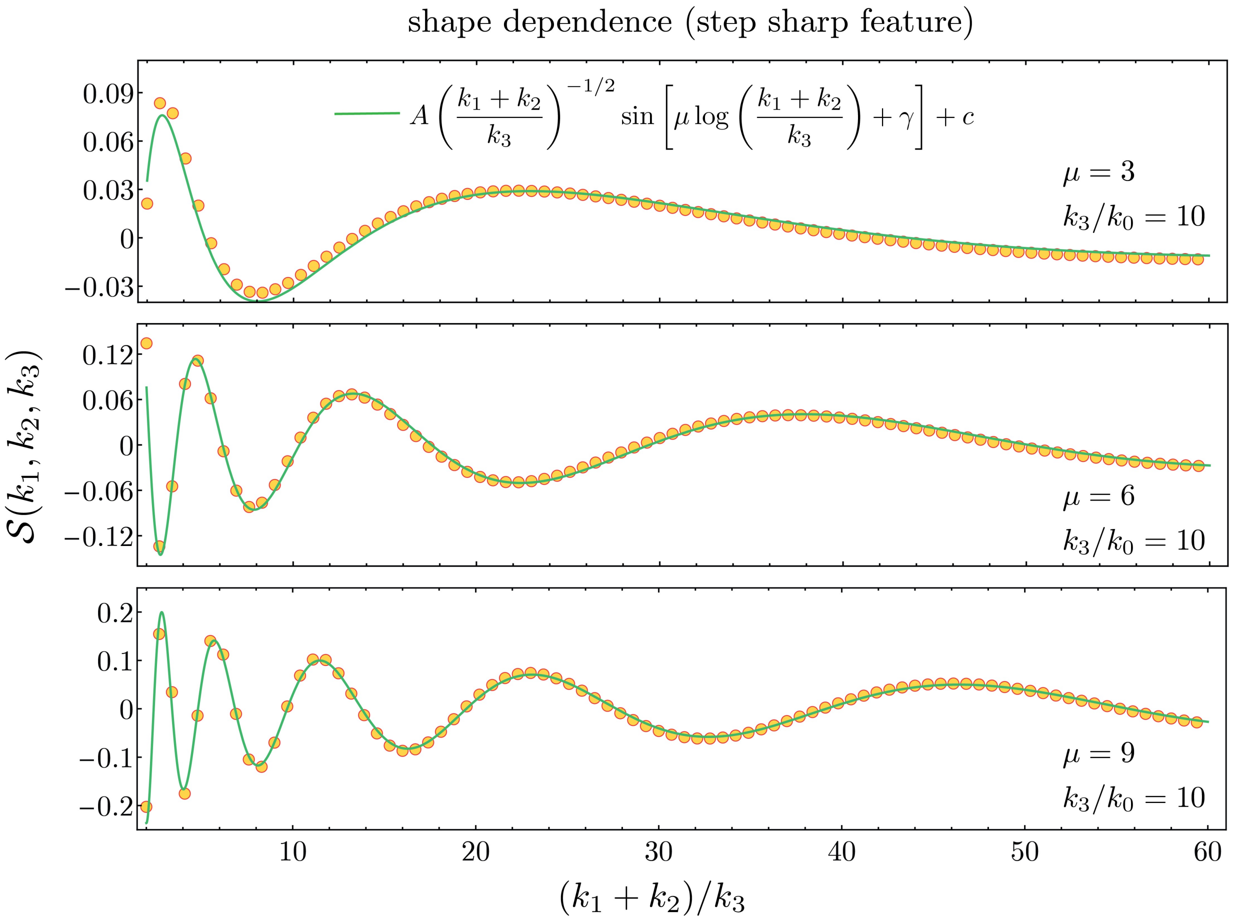


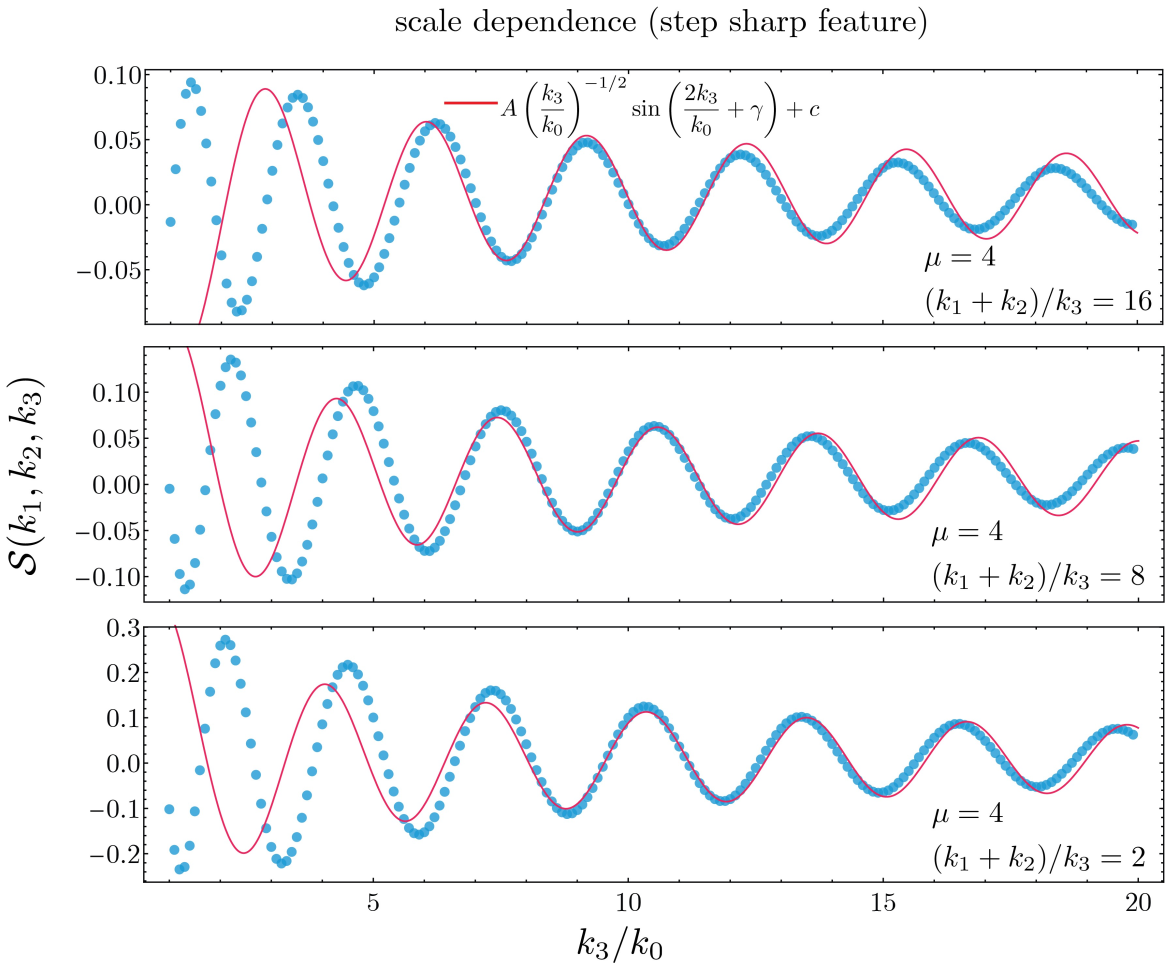
$$\mathcal{S}(k_1,k_2,k_3) = f_{\rm NL}\left(\frac{k_3}{k_r}\right)^{-n-i\mu_c}\left(\frac{k_1}{k_3}\right)^{-1/2-i\mu}$$



<u>High-frequency energy injection eliminates Boltzmann suppression</u>
(up to the associated energy scale)

"Classical cosmological collider"

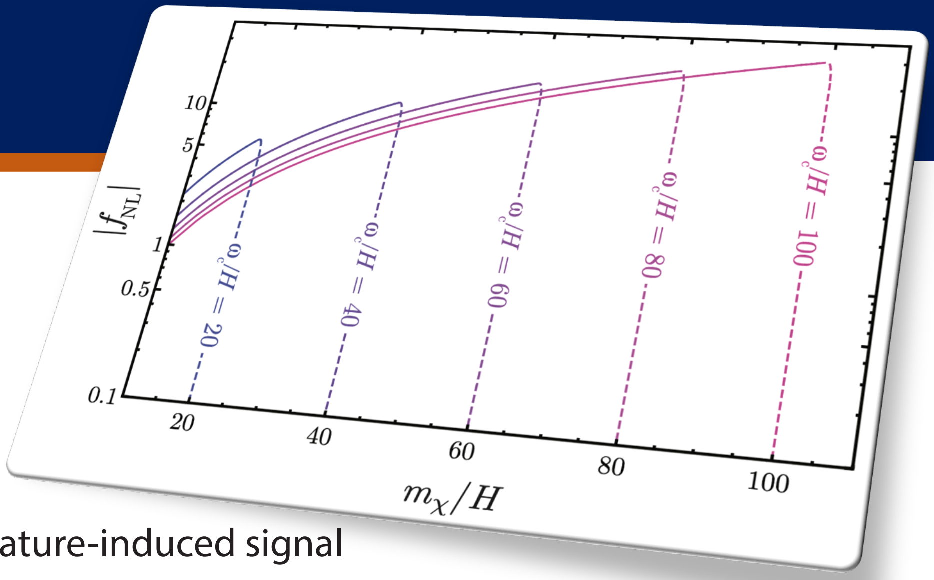




In addition to unsuppressed, non-Gaussian collider signals, the analyzed models also predict **scale dependence**.

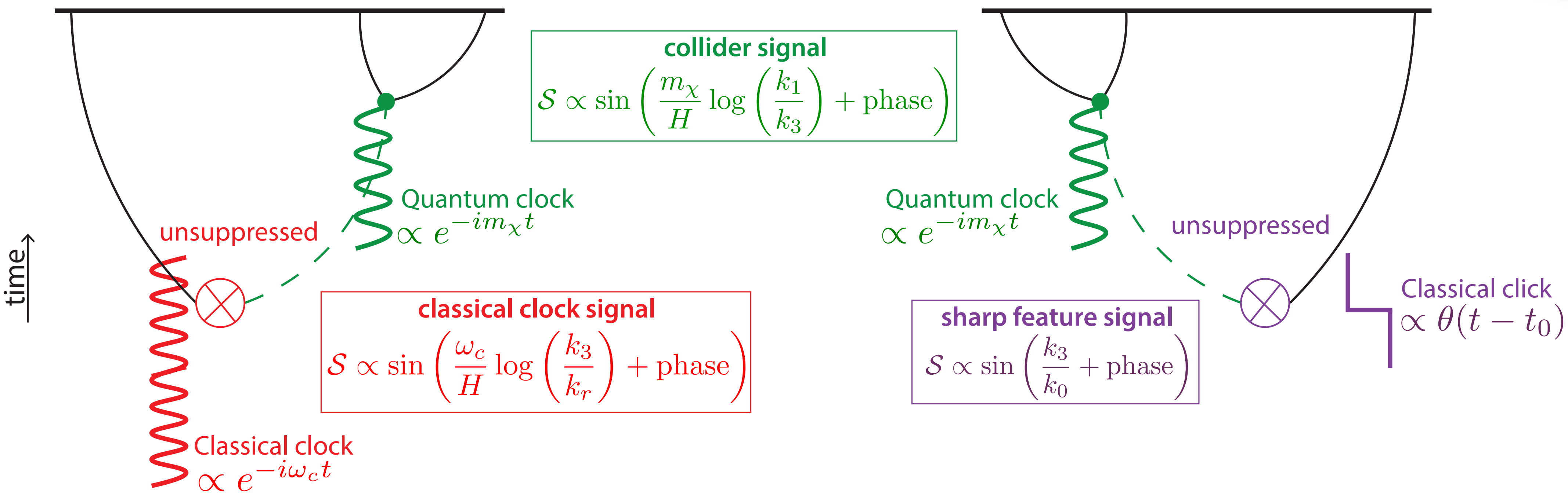
Summary

- ✓ **Primordial features extend the energy reach of the cosmological collider.**
- ✓ **New type of non-Gaussian signals are predicted (including non-trivial scale dependence).**
- ✓ **If features are detected in power spectrum, we will expect "classical cosmological collider" signals in bispectrum.**



(a) classical-oscillation-induced signal

(b) sharp-feature-induced signal



collider signal

$$\mathcal{S} \propto \sin\left(\frac{m_\chi}{H}\log\left(\frac{k_1}{k_3}\right) + \text{phase}\right)$$

classical clock signal

$$\mathcal{S} \propto \sin\left(\frac{\omega_c}{H}\log\left(\frac{k_3}{k_r}\right) + \text{phase}\right)$$

sharp feature signal

$$\mathcal{S} \propto \sin\left(\frac{k_3}{k_0} + \text{phase}\right)$$