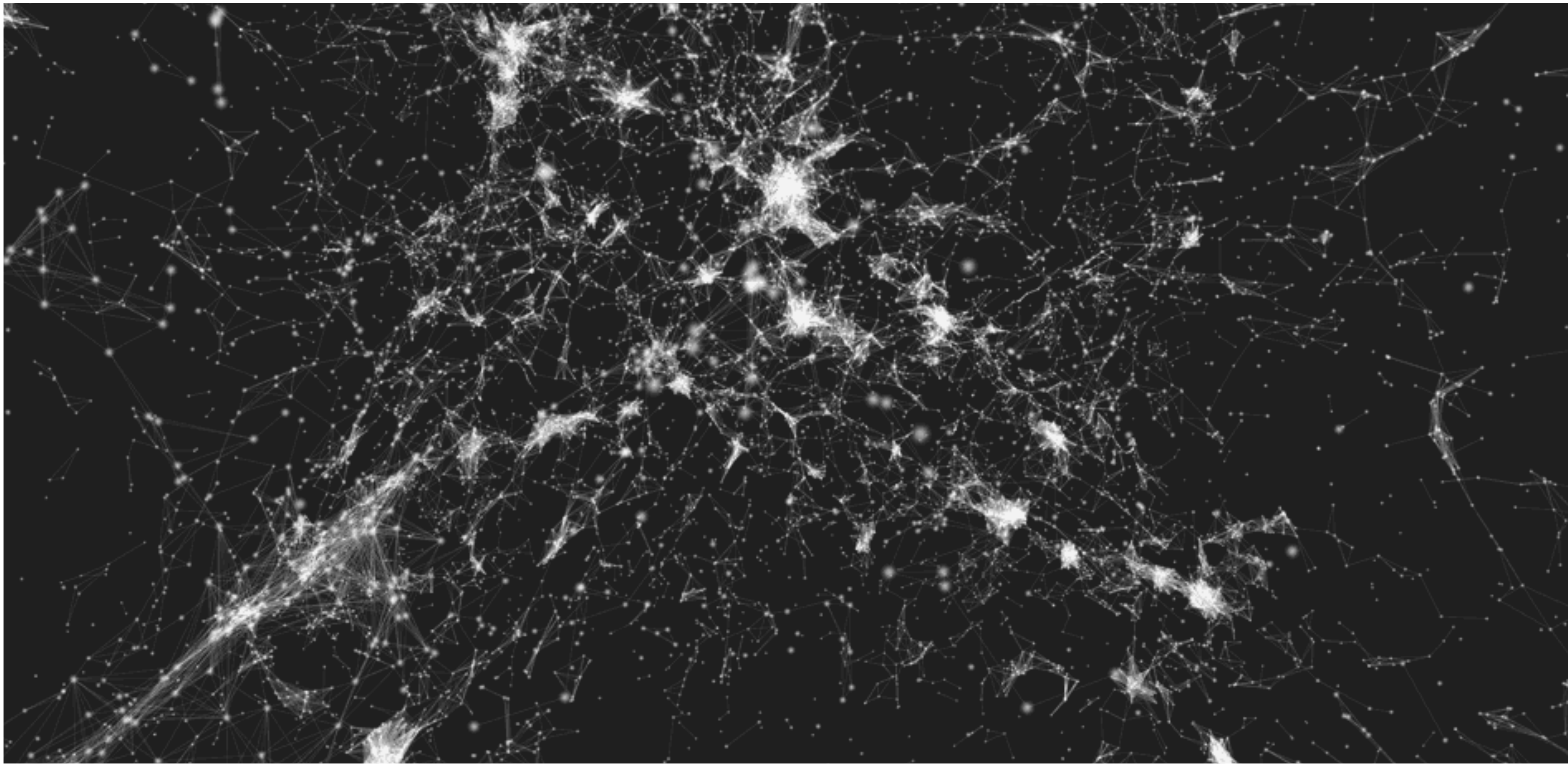
Primordial Non-Gaussianity

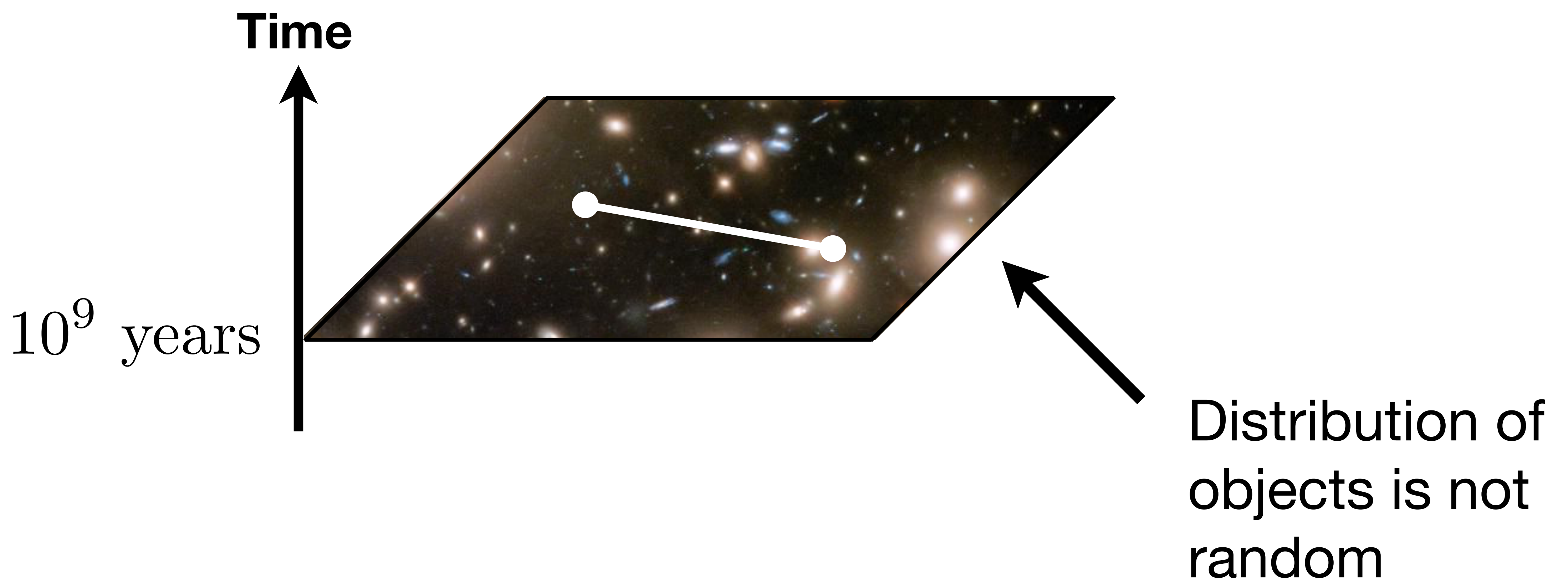


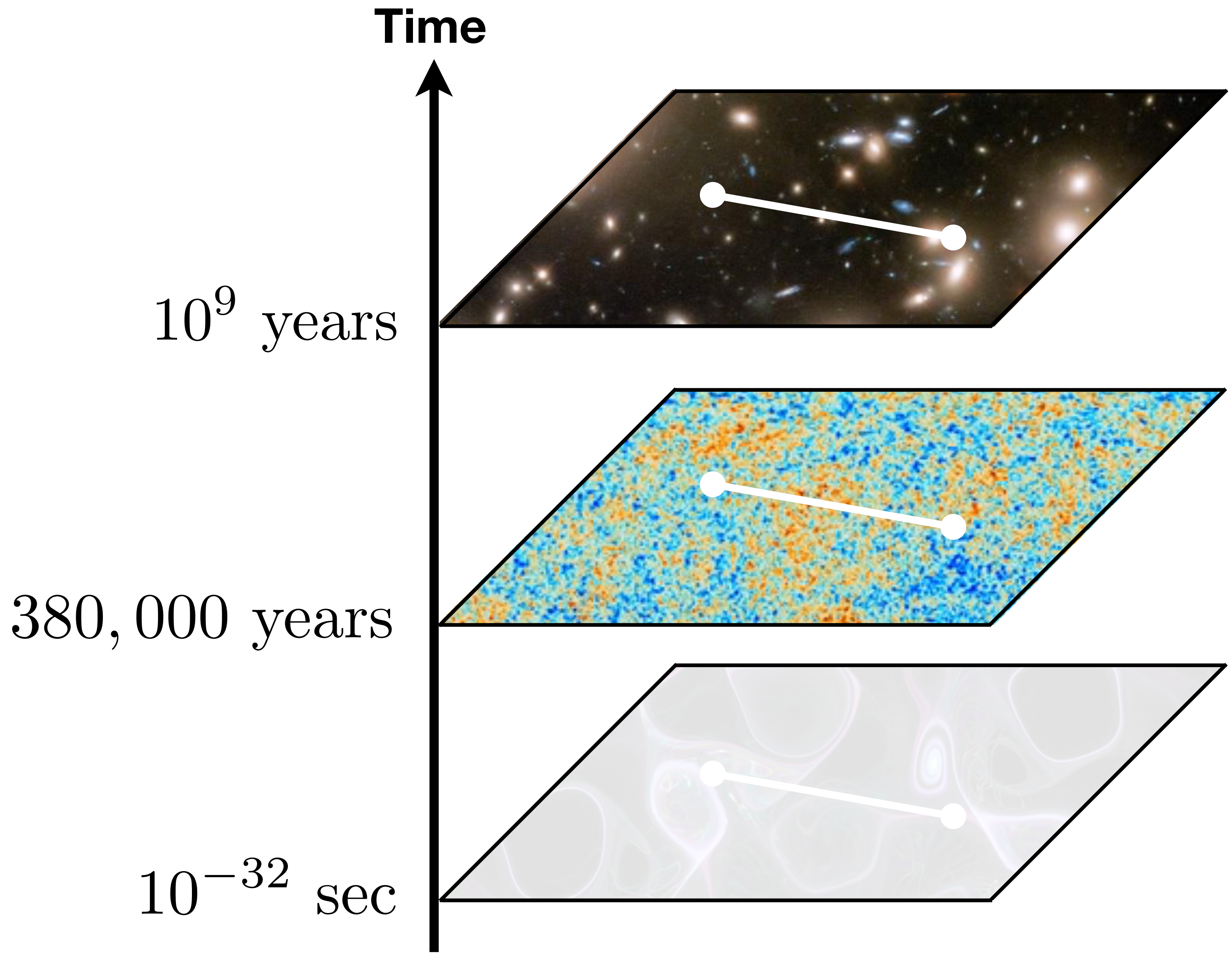
Austin Joyce
Kavli Institute for
Cosmological Physics
University of Chicago

Fundamental Physics From Future Spectroscopic Surveys, LBNL, May 2024

THE UNIVERSITY OF CHICAGO
KICP

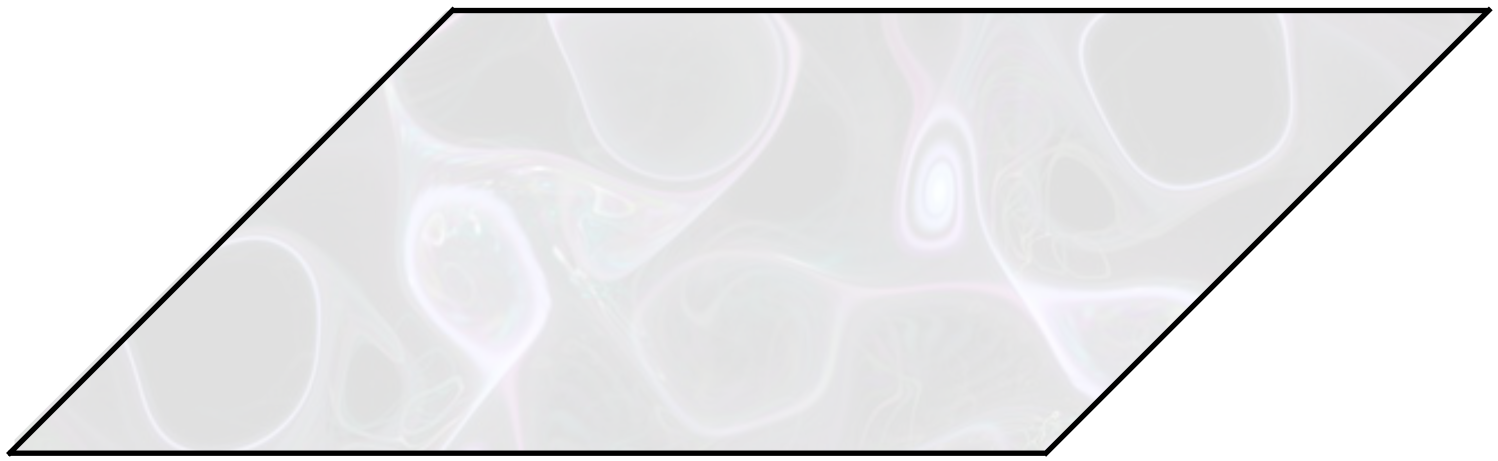
Cosmology is a study of **correlations**



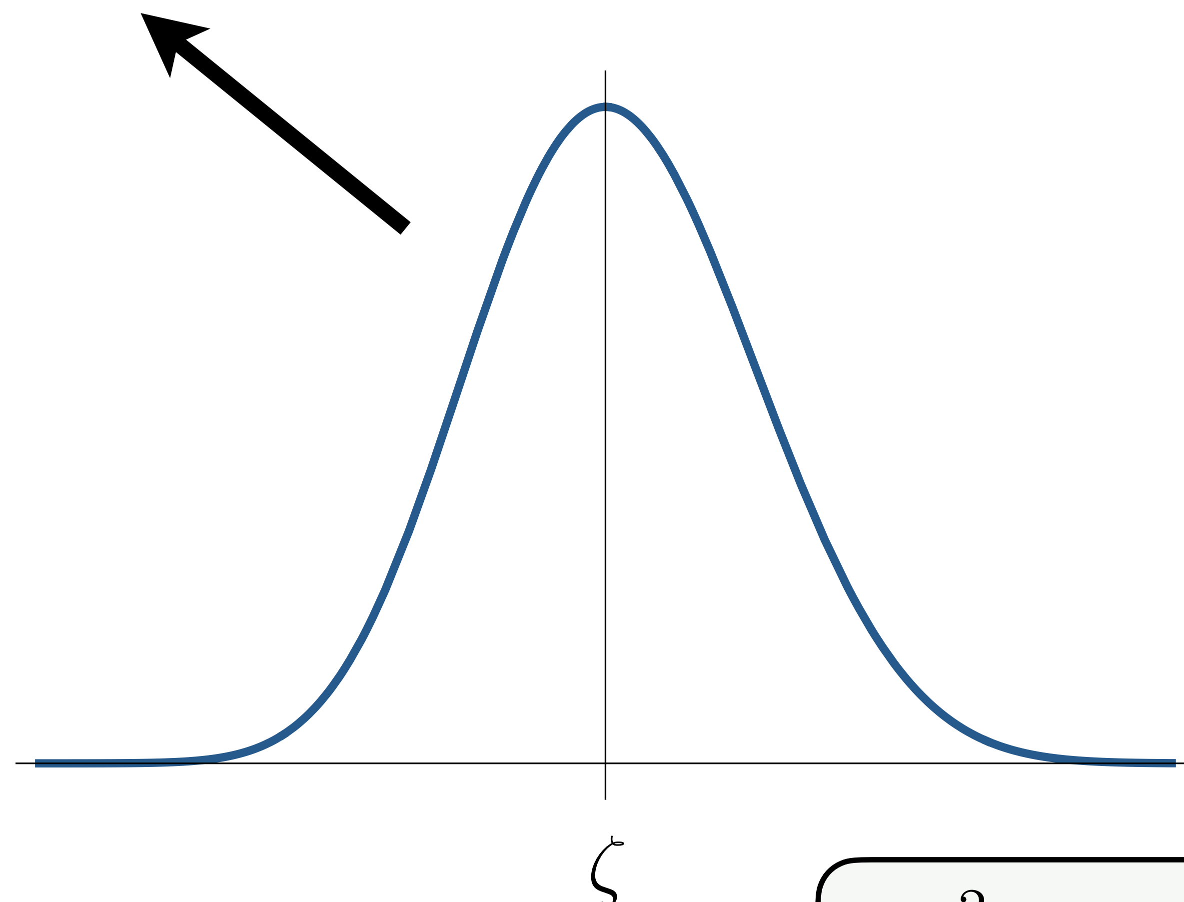


We learn about the universe by tracing these correlations through time

We can follow correlations all the way back to the reheating surface where the universe thermalized

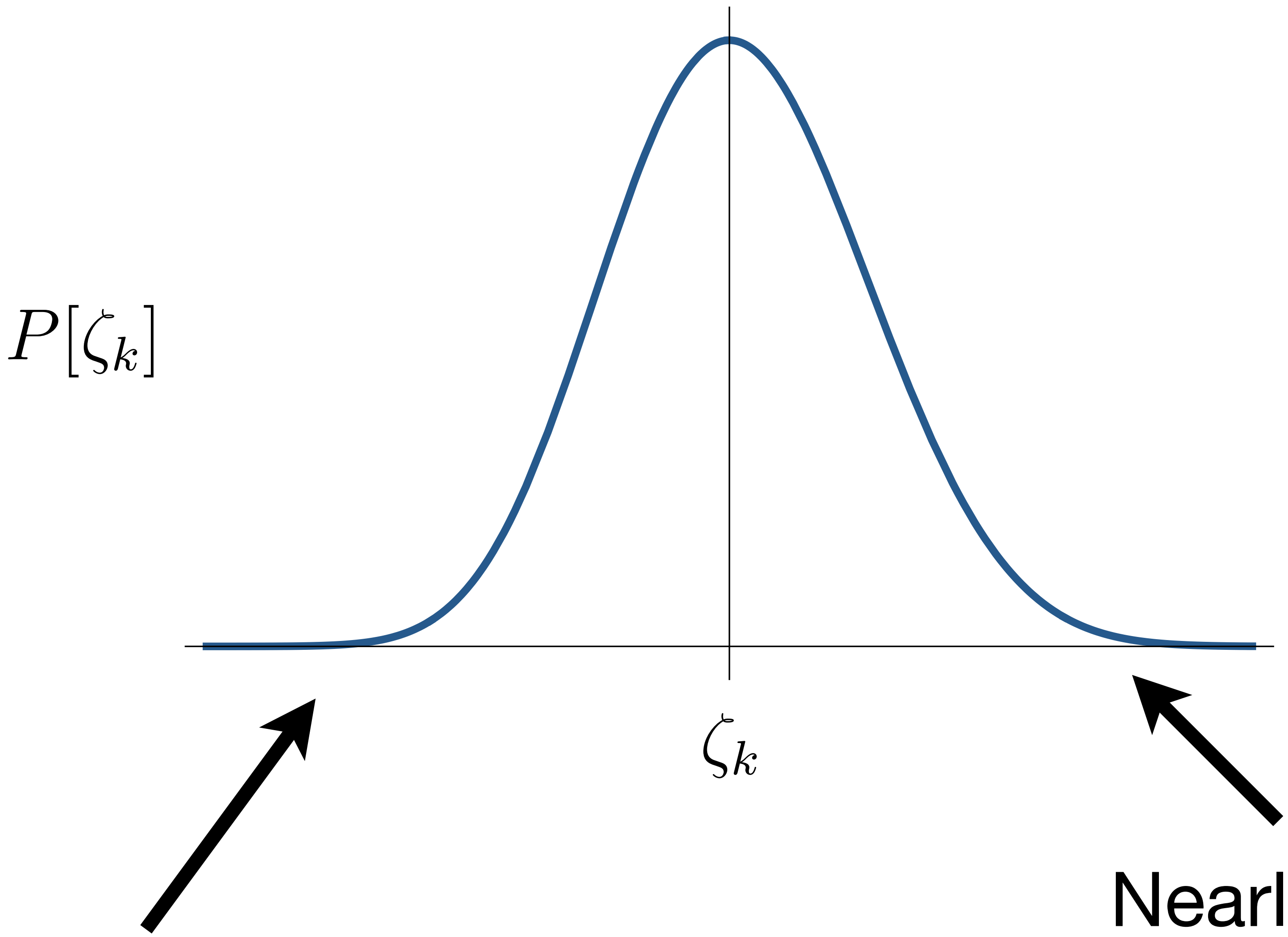


We infer the probability distribution for matter fluctuations at reheating $P[\zeta]$

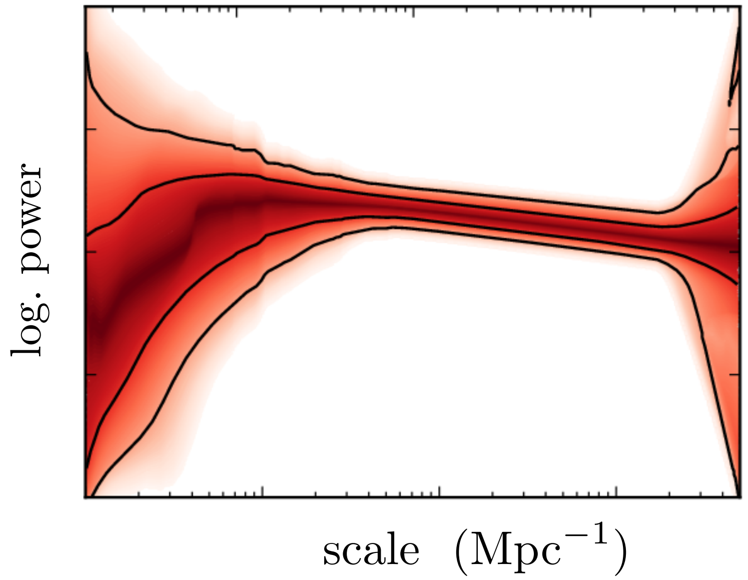


$$\nabla^2 \zeta \sim \delta$$

What do we know about $P[\zeta]$?



Nearly **scale-invariant**

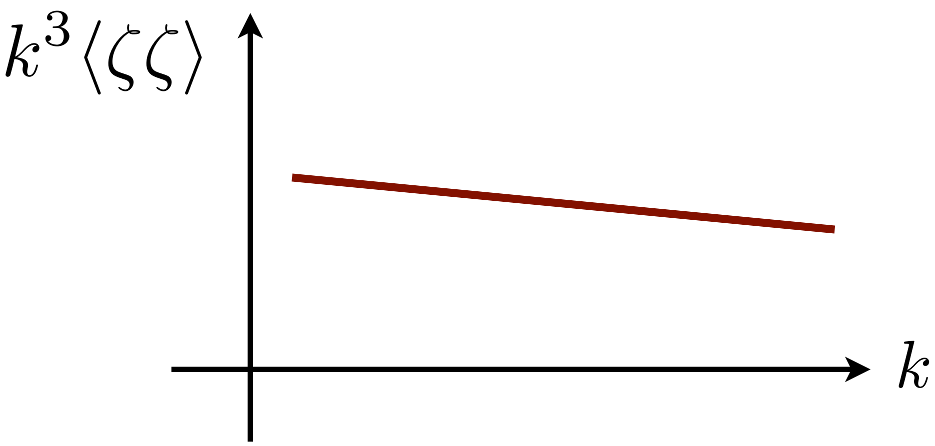


Close to **Gaussian**

$$\frac{\langle \zeta^3 \rangle}{\langle \zeta^2 \rangle^{3/2}} \ll 1$$

Interpretation

fluctuations on this surface look acausal



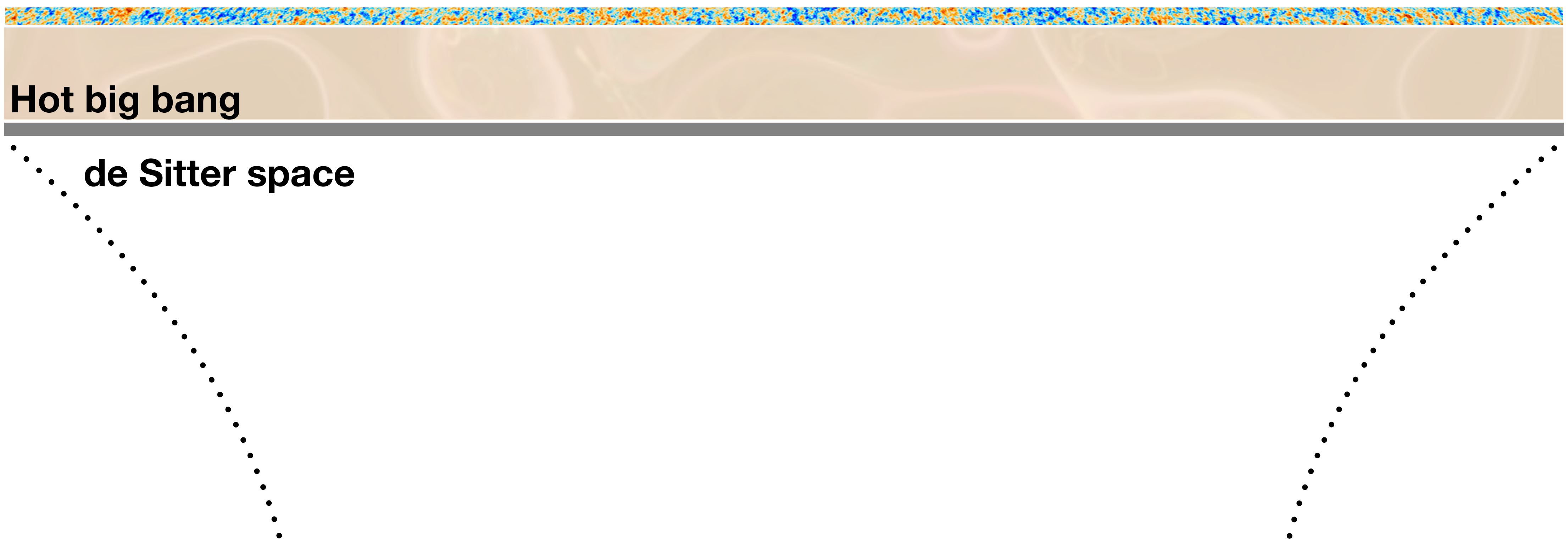
Snowmass 2203.08128

Inflation

The hot big bang cannot be the beginning of time

Inflation

The hot big bang cannot be the beginning of time



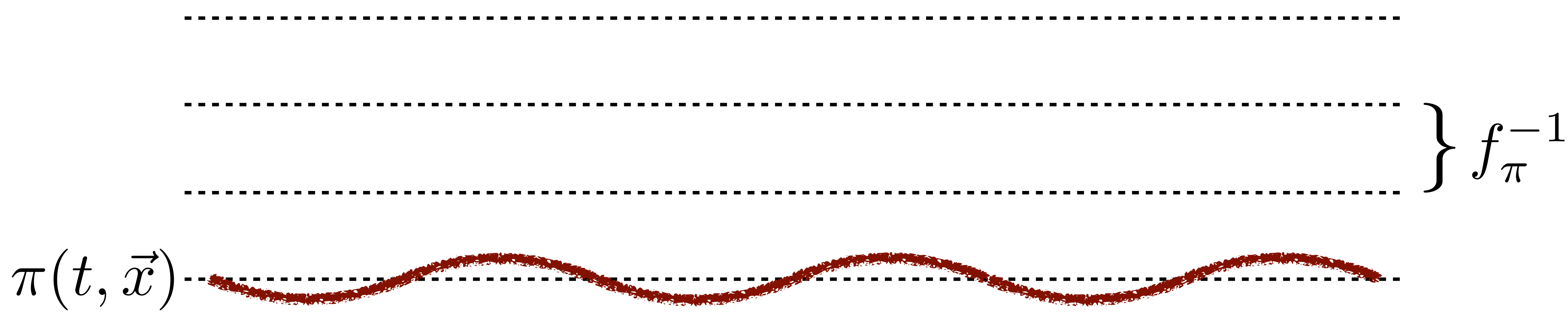
Inflation explains how these perturbations could have arisen *causally*

All we can do is infer the properties of this early phase

Creminelli, Luty, Nicolis, Senatore hep-th/0606090
Cheung, Creminelli, Kaplan, Senatore 0709.0293

What is Inflation?

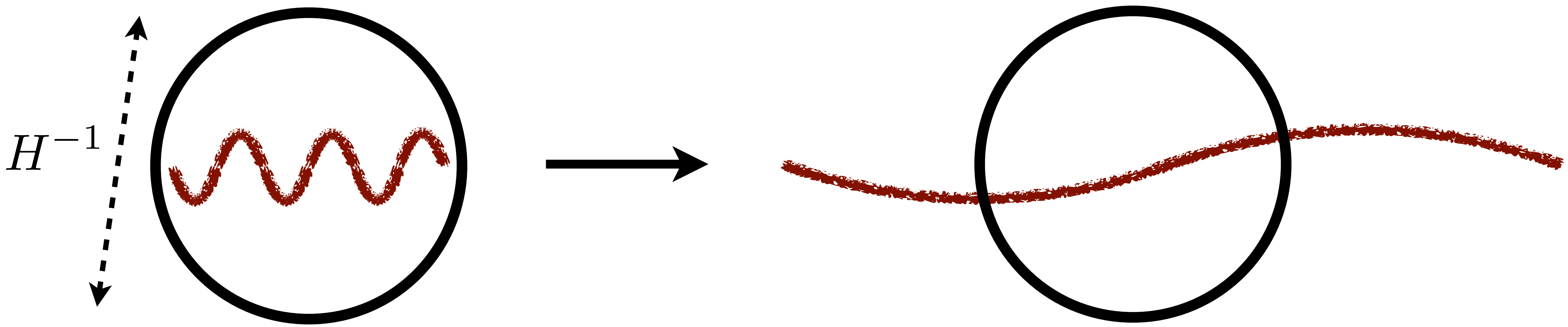
A (good) **clock** coupled to gravity



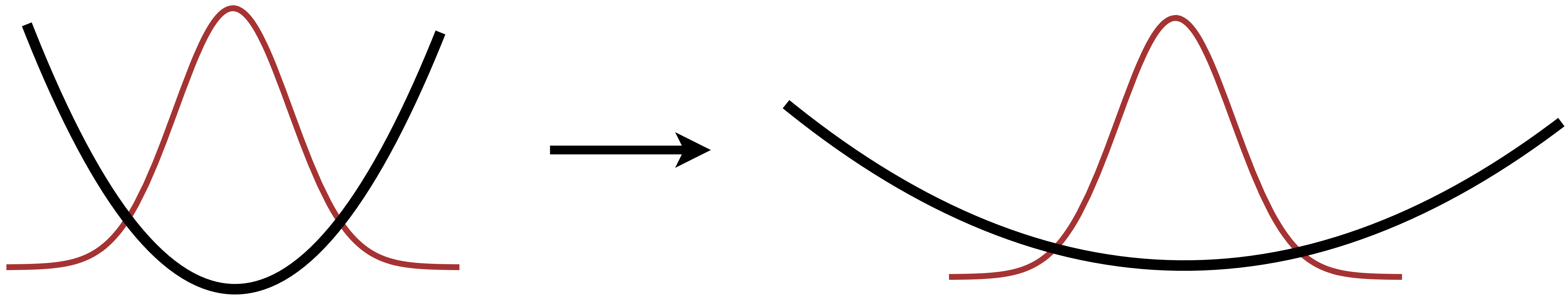
Heisenberg: no clock is perfect, fluctuations are a **Nambu-Goldstone** mode (symmetry breaking)

A Time-Dependent Oscillator

Small fluctuations get **stretched** by the expansion of space

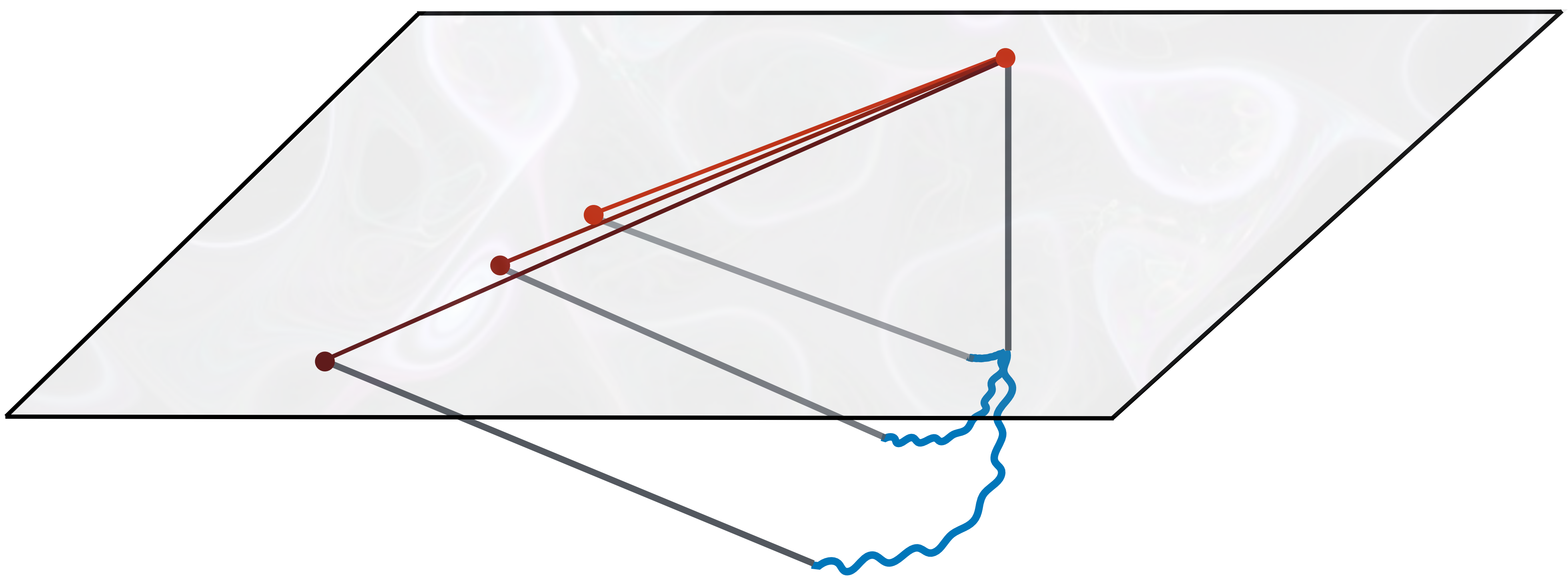


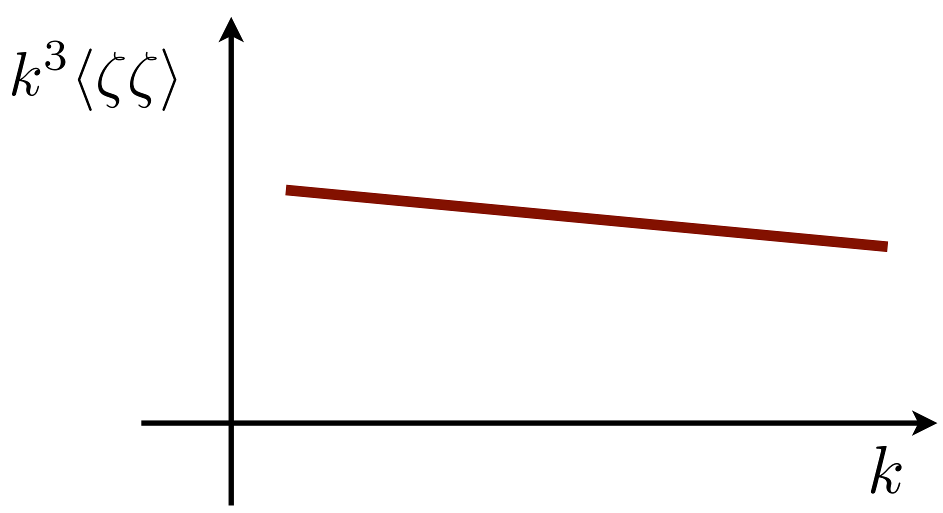
Eventually they **freeze** and get imprinted at the end of inflation



Time ⟶ Scale

Fluctuations on different **scales** freeze at different **times** during inflation

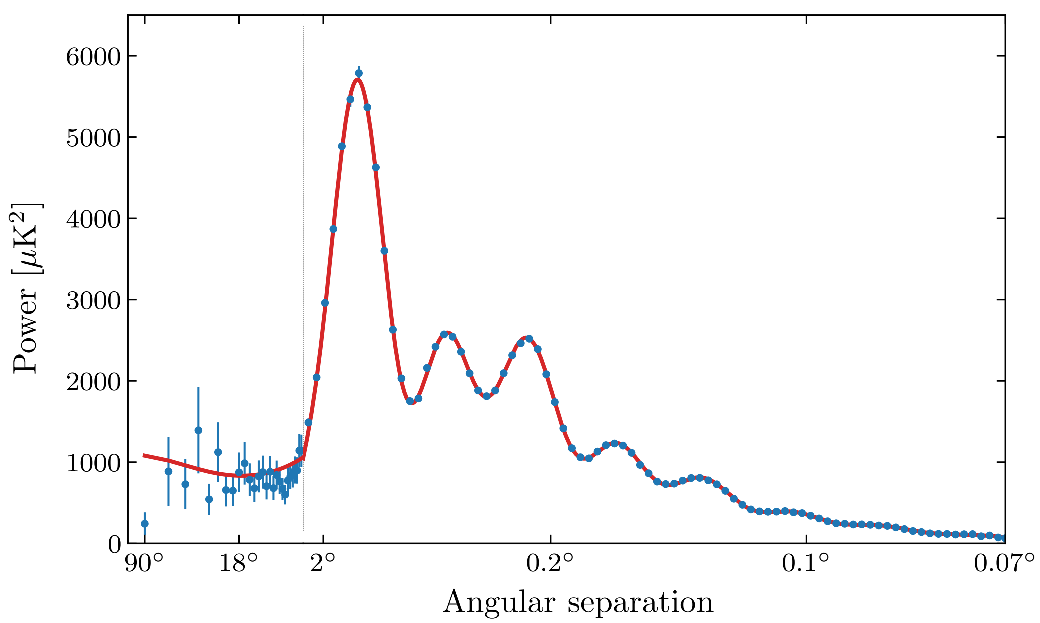


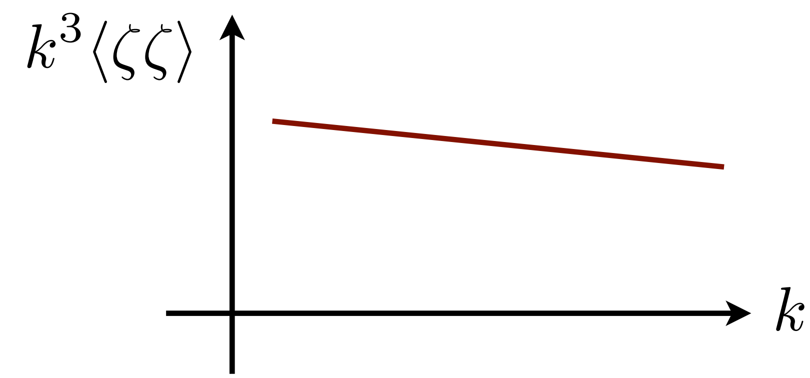


⟶ **Near** time-translation invariance

Microphysics

The information we currently have about inflation is **kinematic**, follows from **approximate symmetries** of inflation

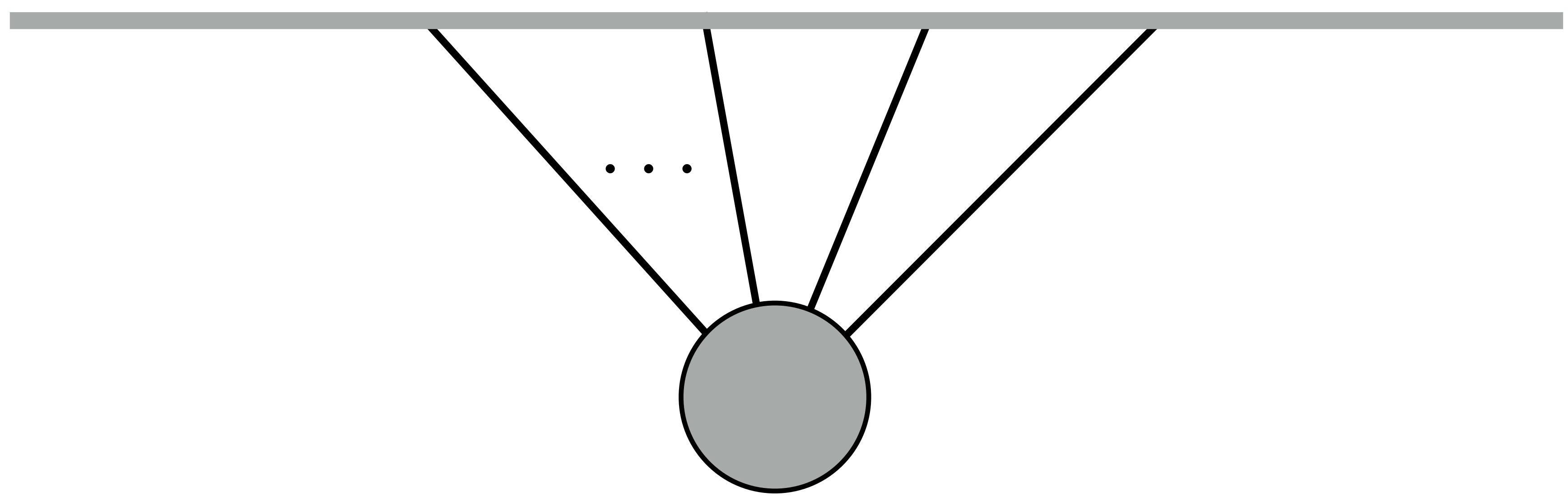




Understanding microphysics requires probing **interactions**

Microphysics

Interactions lead to higher-point correlations



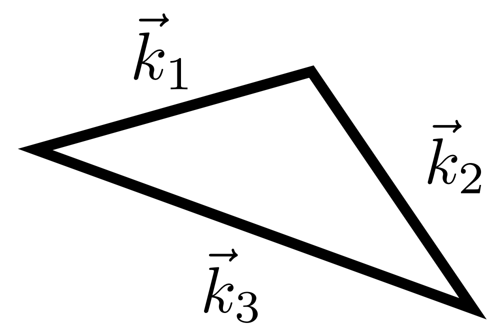
We can probe these higher-point correlations by measuring **non-Gaussianities**

Non-Gaussianity

Summarize information with **moments** of probability distribution

$$\langle \zeta(x)\zeta(y)\zeta(z)\rangle = \int \mathcal{D}\zeta\, \zeta(x)\zeta(y)\zeta(z)\, P[\zeta]$$

In Fourier space parameterize as



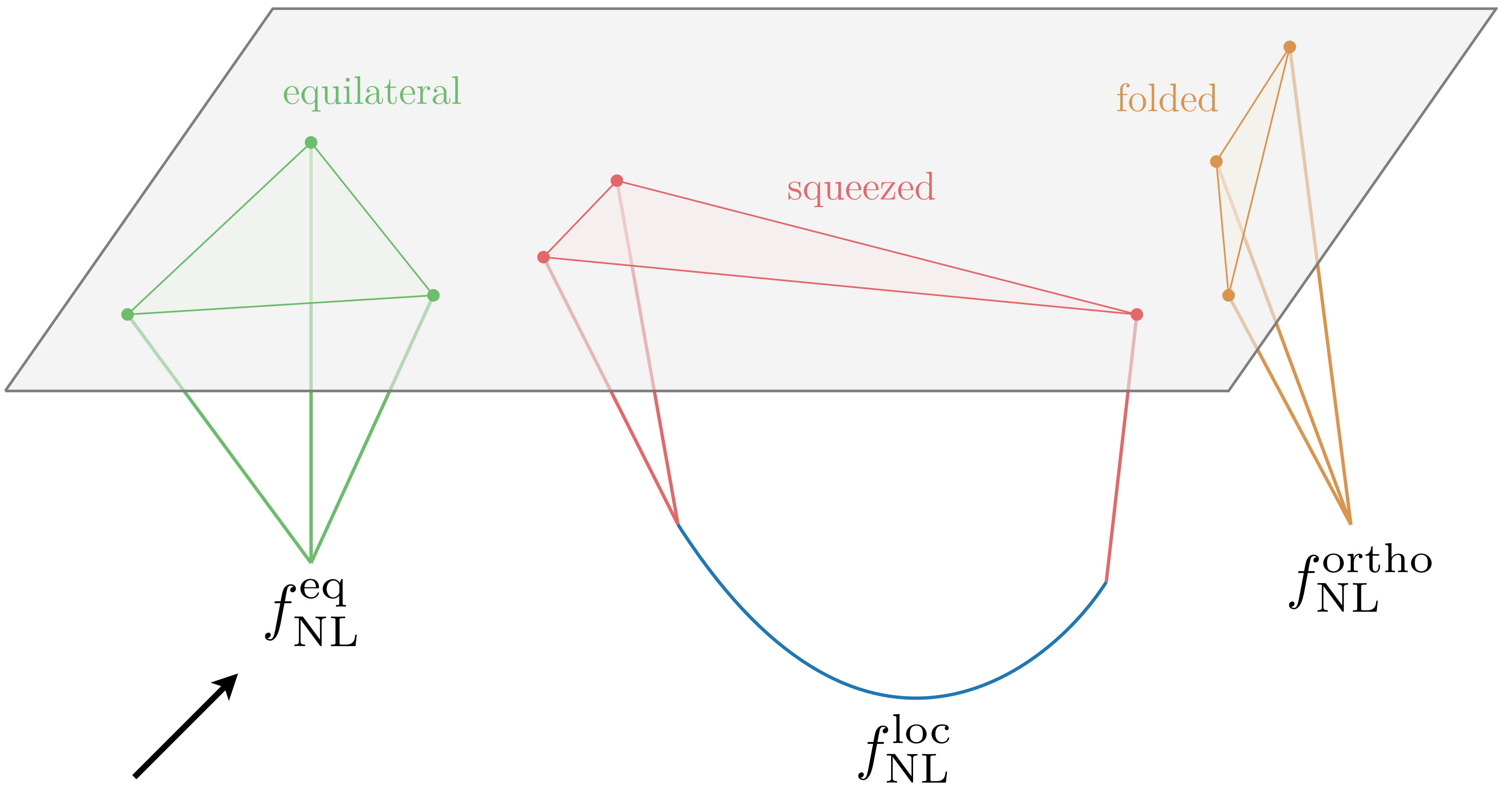
Shape

$$\langle \zeta_{\vec{k}_1}\zeta_{\vec{k}_2}\zeta_{\vec{k}_3}\rangle = (2\pi)^3\delta(\vec{k}_1+\vec{k}_2+\vec{k}_3)\,\frac{18}{5}\, f_{\rm NL} A_s^2\, \frac{\mathcal{S}(k_1,k_2,k_3)}{(k_1k_2k_3)^2}$$

Amplitude

Shapes of non-Gaussianity

Different kinds of interactions give rise to correlations that are strongest in particular configurations



Related to **sound speed** in simplest models (like a fluid)

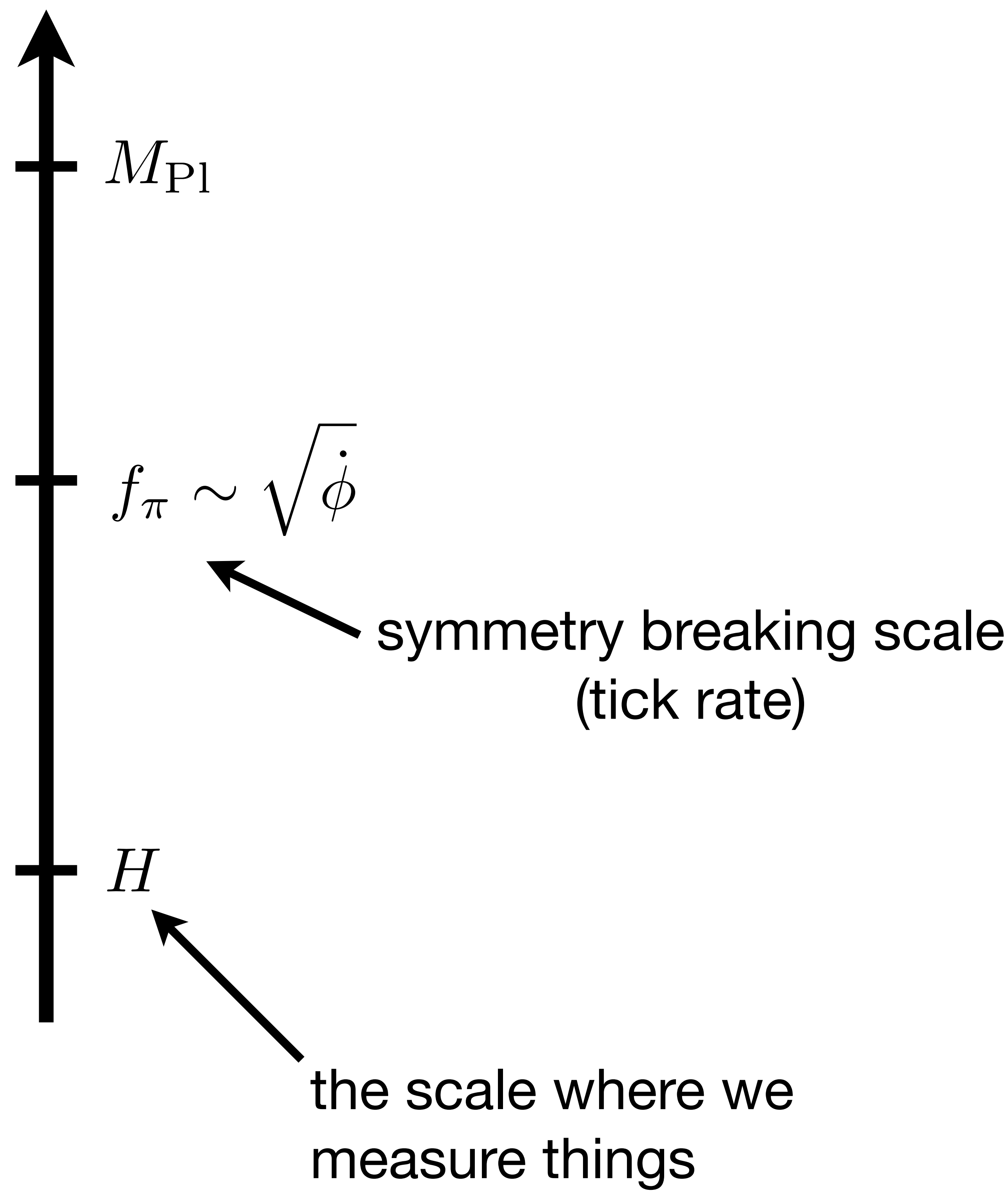
What is the nature of inflation?

Goal: Understand the underlying microphysics driving the inflationary universe

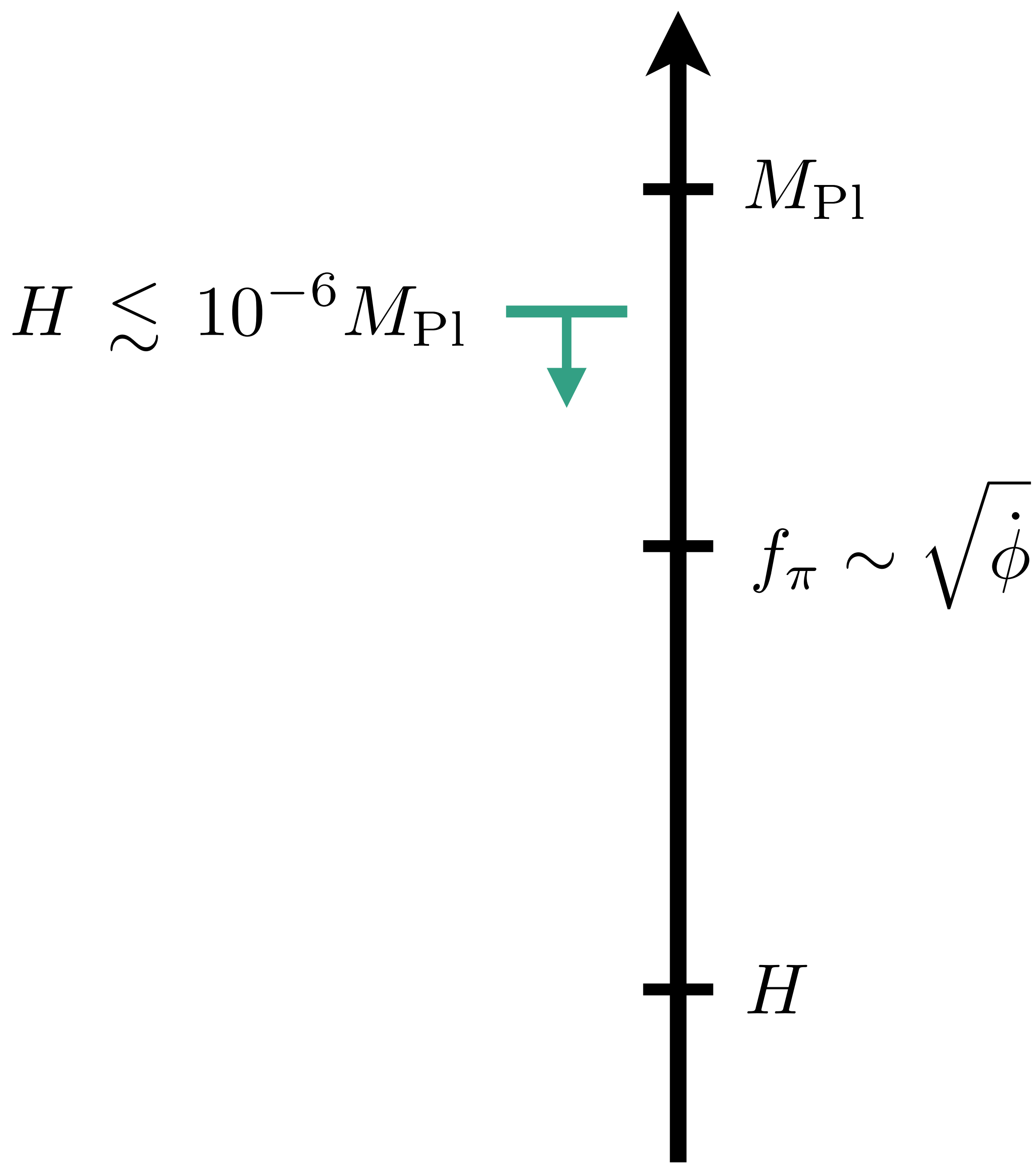
How do we organize our thinking about this question?

Focus on the **energy scales** in the problem

Energy scales



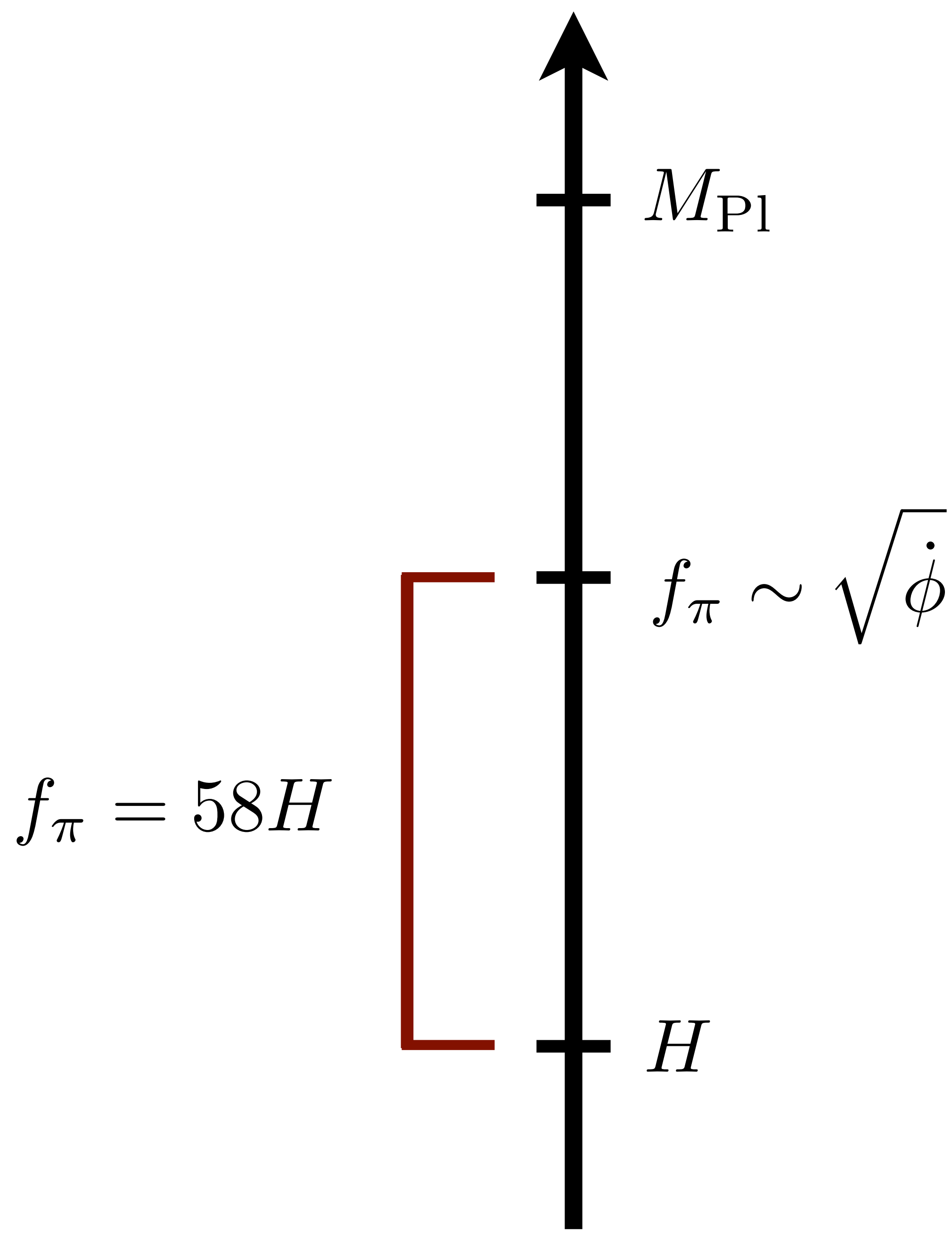
What is the energy scale of inflation?



$$\Delta_\gamma = \frac{H}{M_{\rm Pl}} = \ ?$$

Tensor power spectrum is a direct probe of the energy scale

Symmetry-breaking scale

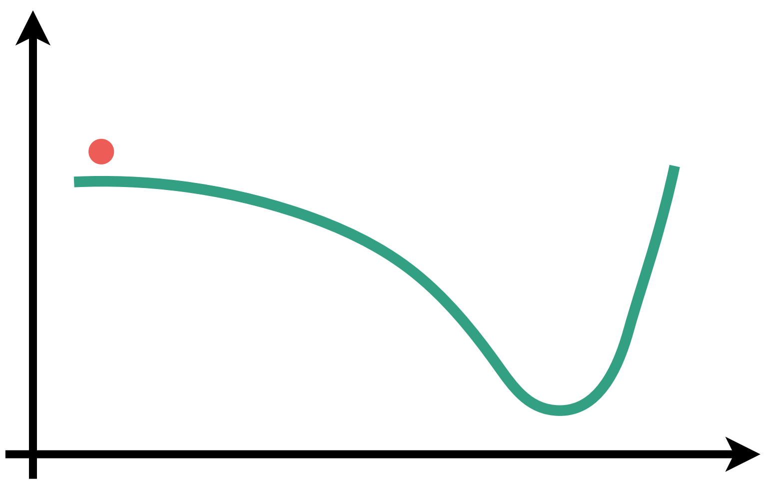


$$\Delta_\zeta = \left(\frac{H}{f_\pi}\right)^2 \simeq 10^{-4}$$

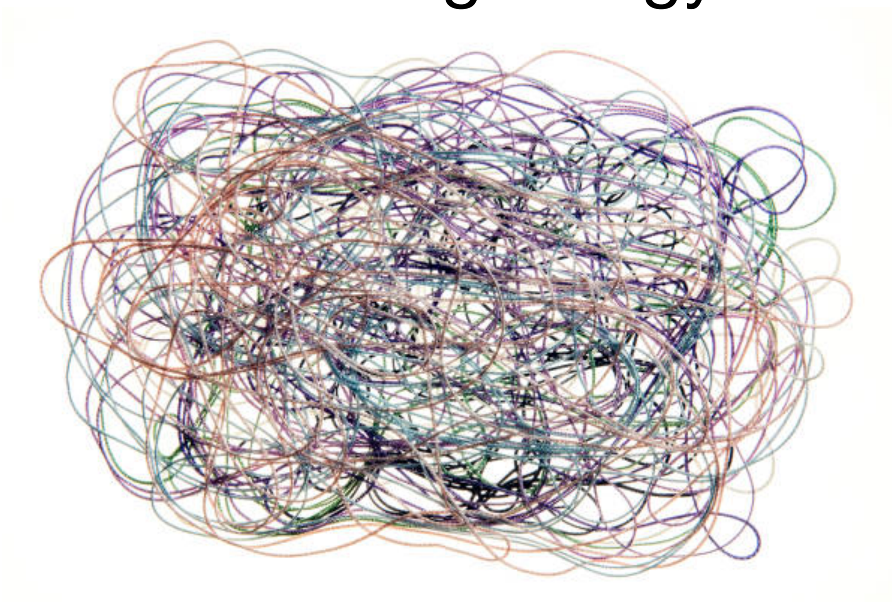
Spectrum of scalar perturbations fixes ratio between Hubble and symmetry-breaking scale

Microphysics of inflation?

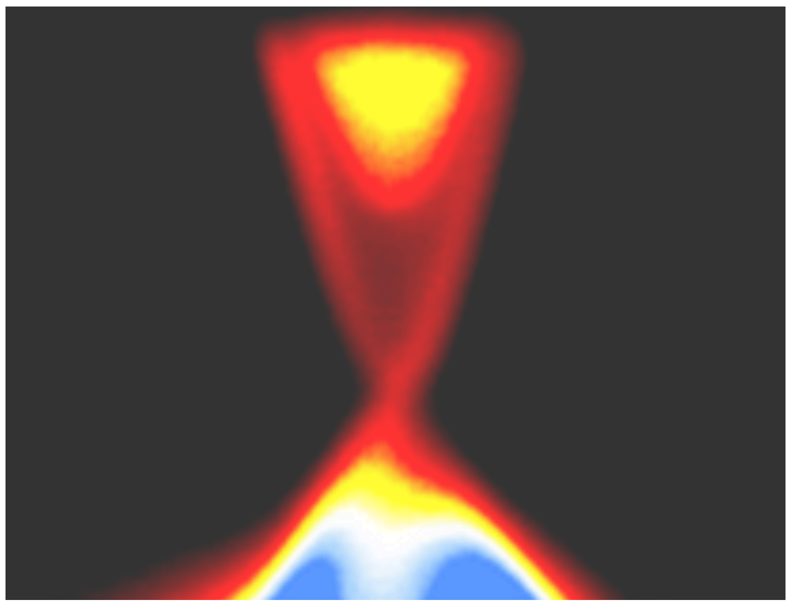
Field(s) rolling in a potential?



Something stringy?

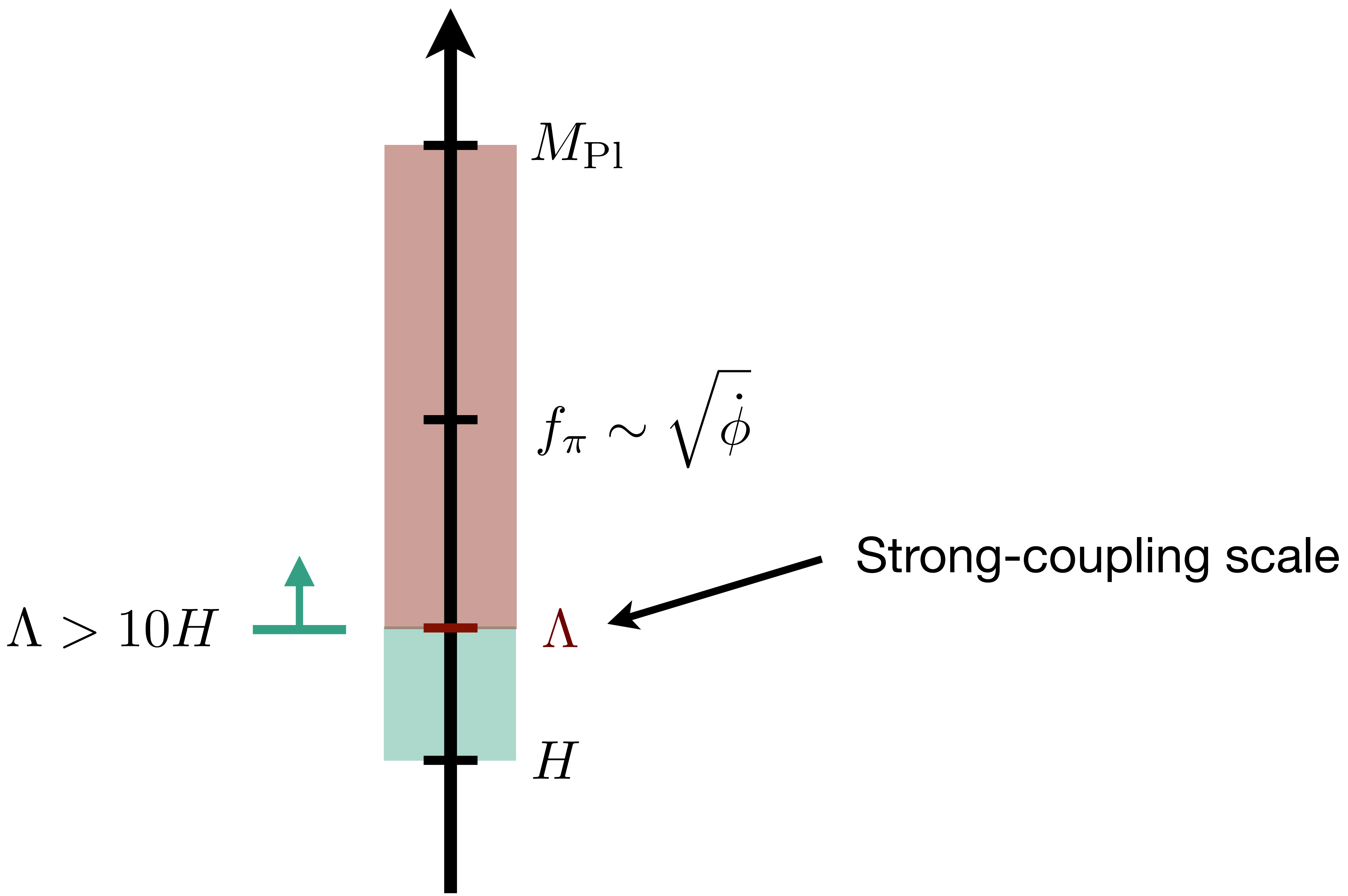


An exotic phase of matter?



Unique probe of ultraviolet physics Flauger, Gorbenko, AJ, McAllister, Shiu, Silverstein 2203.07629

Strong-coupling scale



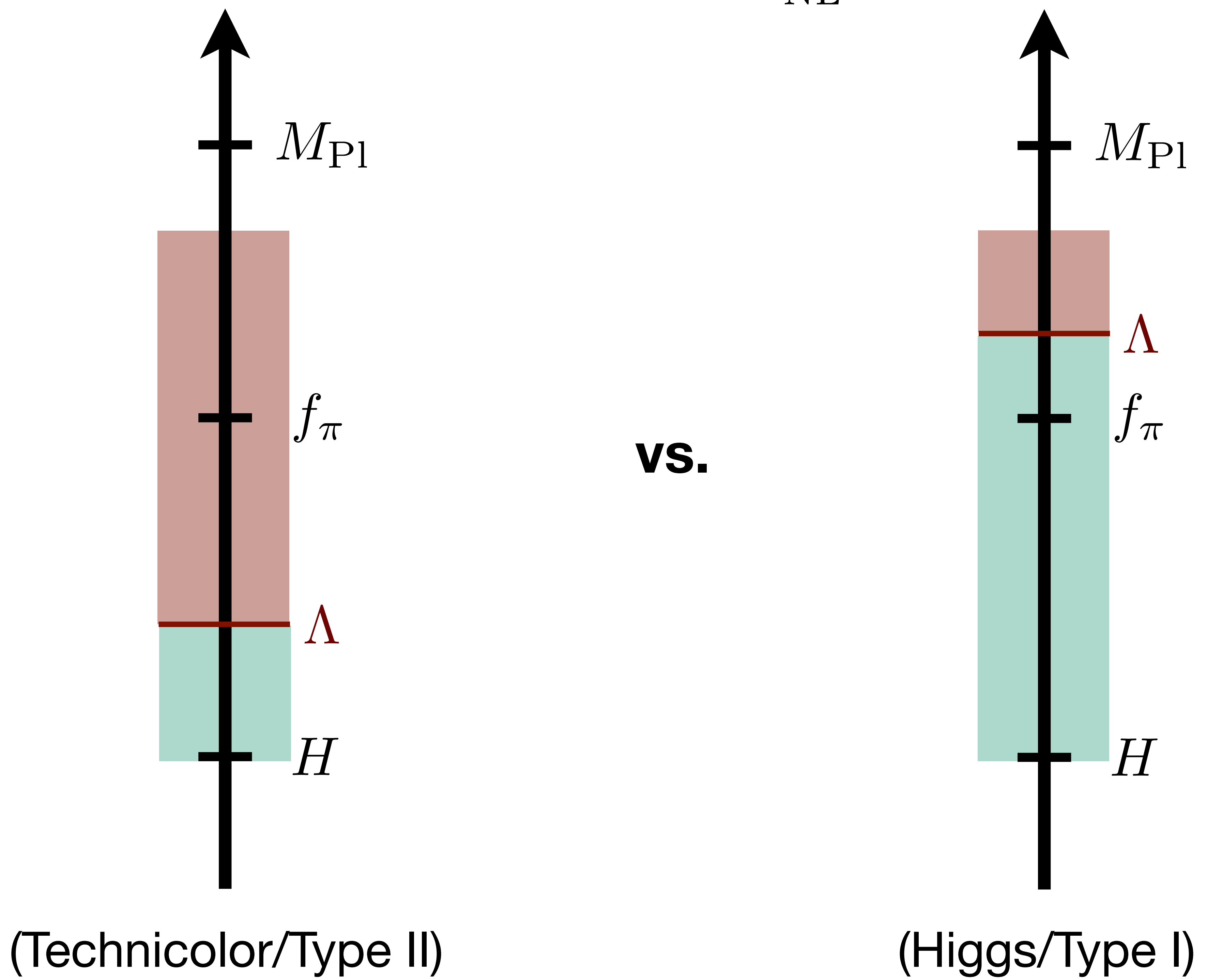
Non-Gaussianity non-detections already put some constraints on strong-coupling scale

$$f_{\mathrm{NL}}^{\mathrm{eq.}} \sim 10^4 \left(\frac{H}{\Lambda}\right)^2$$

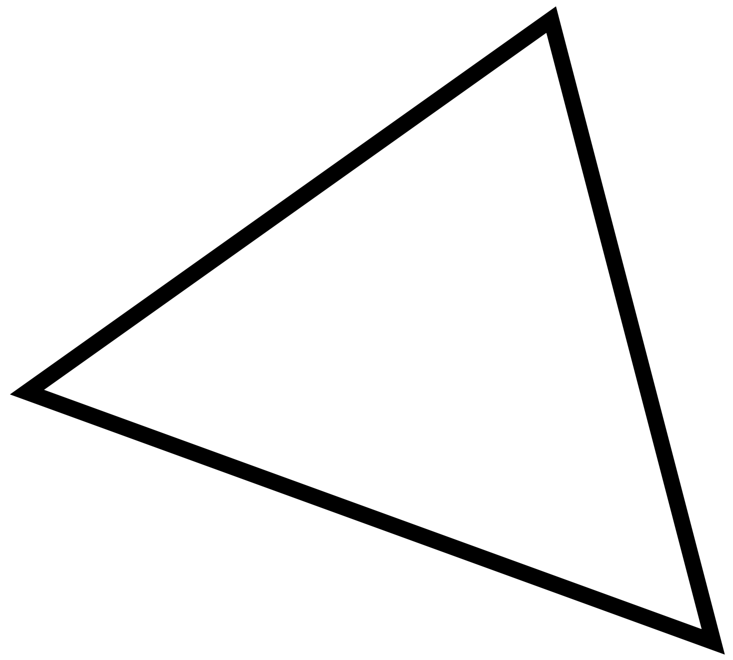
Creminelli astro-ph/0306122; Leblond Shandera 0802.2290
Baumann, Green 1102.5343

Is inflation UV completed at weak coupling?

Threshold around $f_{\rm NL}^{\rm eq.} \sim 1$



Extracting from data needs exquisite modeling/new ideas (**opportunity** for theory)

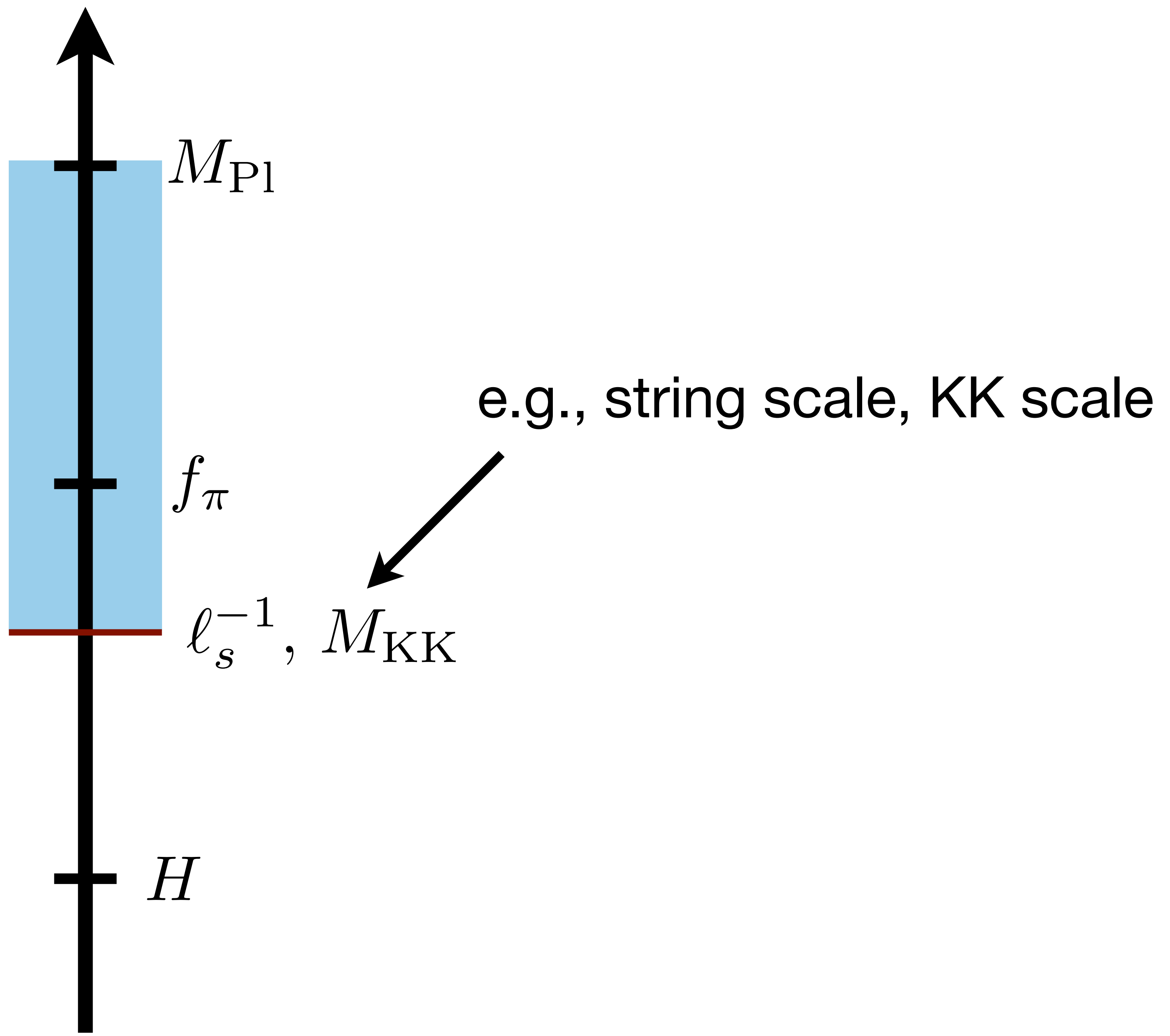


Equilateral non-Gaussianity is a probe of the self-coupling of the inflaton and its strong-coupling scale

Interesting threshold: $f_{\rm NL}^{\rm eq} \sim 1$

Is the inflaton alone?

The UV completion of inflation could involve **new states** near the Hubble scale

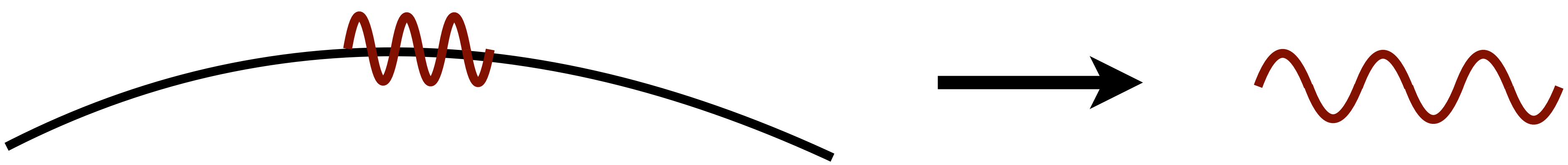


Benchmark $f_{\rm NL}^{\rm loc.} \sim 1$

Maldacena astro-ph/0210603
Creminelli, Zaldarriaga astro-ph/0407059

A soft theorem

In single-field inflation, non-Gaussianity vanishes in the squeezed limit



$$f_{\rm NL}^{\rm loc} \simeq 0^*$$

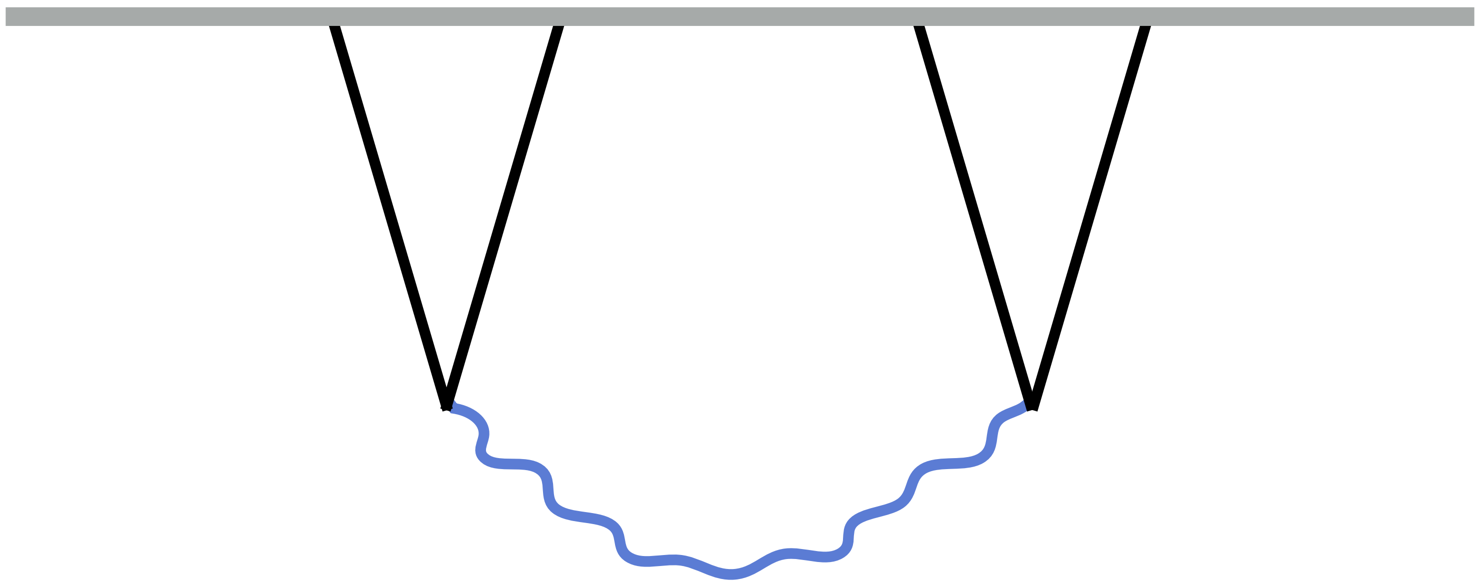
Detection is therefore suggestive of **additional particles** that contribute to density perturbations

*Of order $\sim (n_s - 1)k_L^2/k_S^2$ in the squeezed limit

Chen, Wang 0911.3380
Arkani-Hamed, Maldacena 1503.08043

A Cosmological Collider

Particles lighter than the inflationary expansion scale can be produced—an **opportunity** to probe high energies

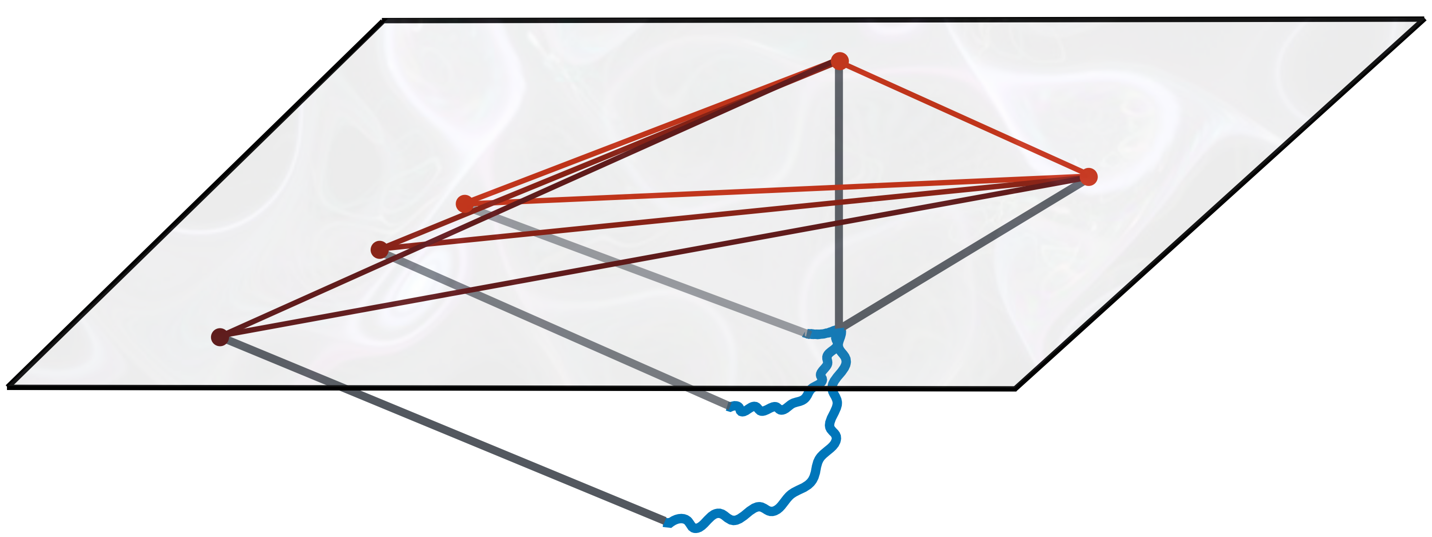


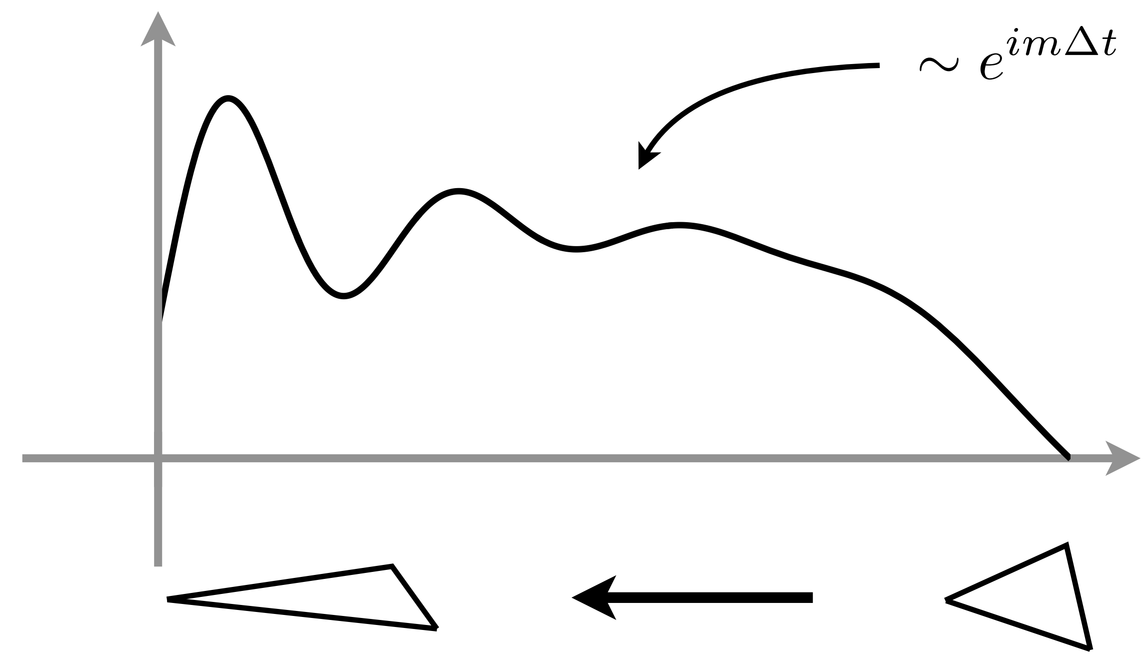
Leave imprints in the late-time correlations

Arkani-Hamed, Maldacena 1503.08043
Cosmological Bootstrap (AJ+) 2203.08121

Signatures of new particles

$f_{\rm NL}^{\rm loc}$ is a coarse measurement of additional particles, but there are more detailed signatures in shape

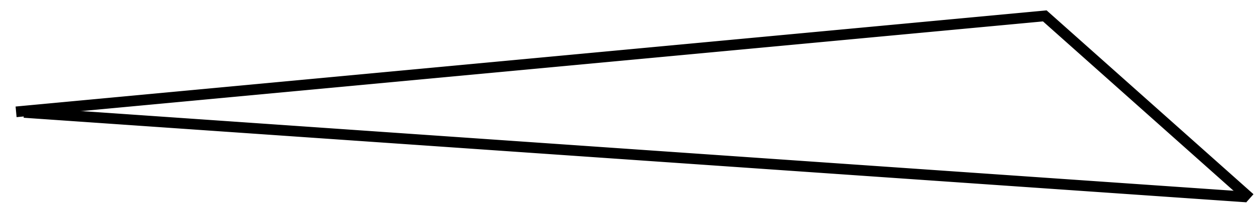




Oscillatory feature appears because of **massive particle** exchange, phase is related to mass, allows for **spectroscopy**

Cabass, Philcox, Ivanov, Akitsu, Chen, Zaldarriaga 2404.01894
Sohn, Wang, Fergusson, Shellard 2404.07203

Requires new calculations and theory development



Local non-Gaussianity is a probe of additional states beyond the inflaton

Rough benchmark: $f_{\rm NL}^{\rm loc} \sim 1$

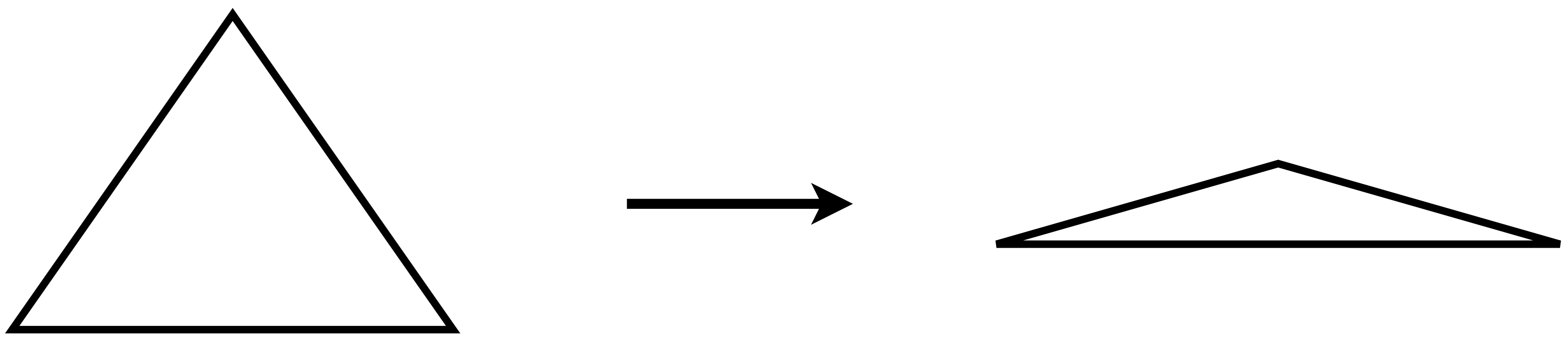
Possible fiducial target (curvaton): $f_{\rm NL}^{\rm loc} = -5/4$

Holman, Tolley 0710.1302; Meerburg, van der Schaar, Corasanti 0901.4044
Arkani-Hamed, Baumann, Lee, Pimentel 1811.00024
Green, Porto 2001.09149

Initial conditions

We believe inflationary perturbations are **quantum**

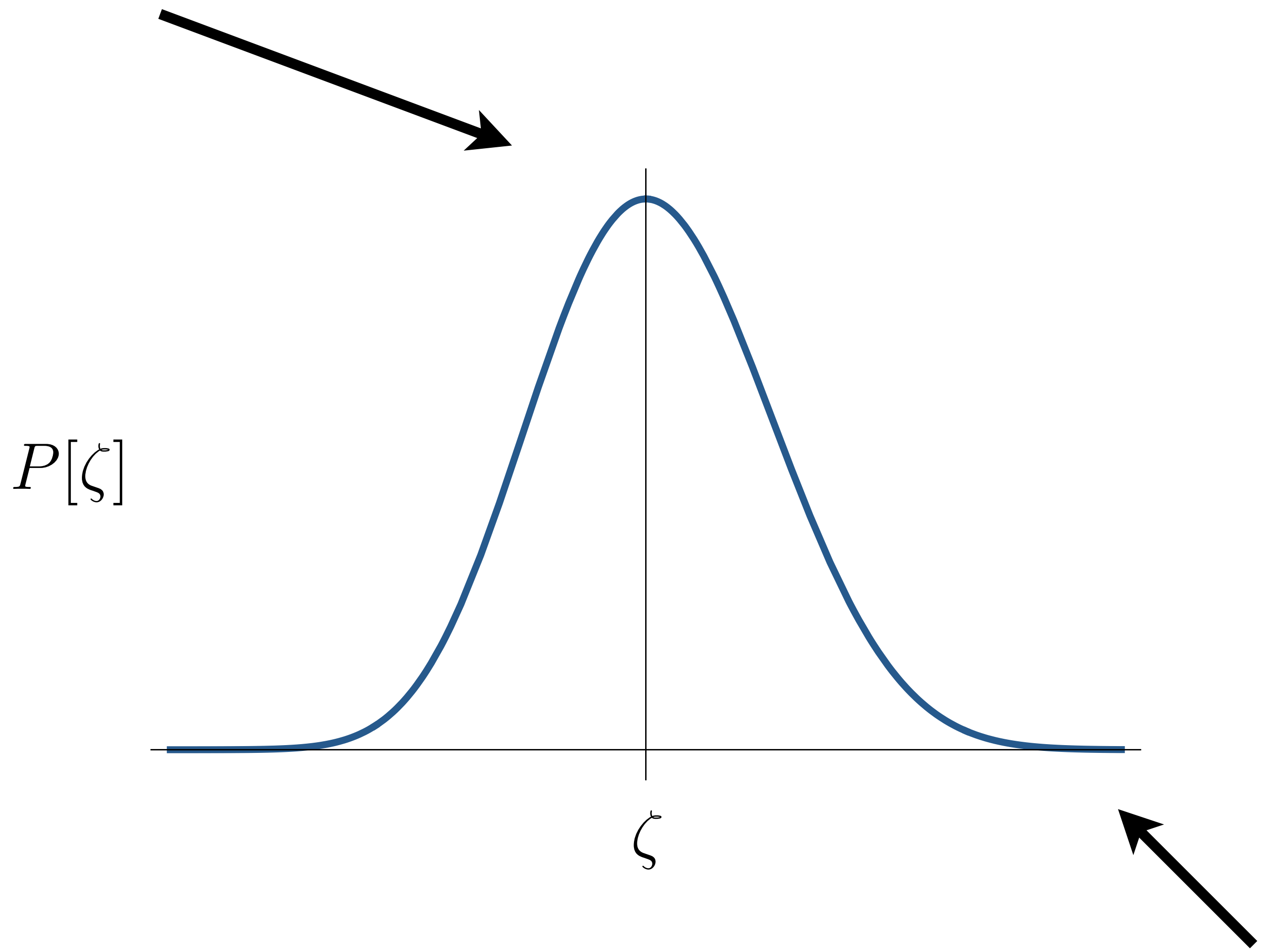
Minimal assumption: started in **adiabatic** vacuum,
regular in **folded limit**



Folded non-Gaussianity is therefore a probe of **initial conditions**

Beyond correlation functions

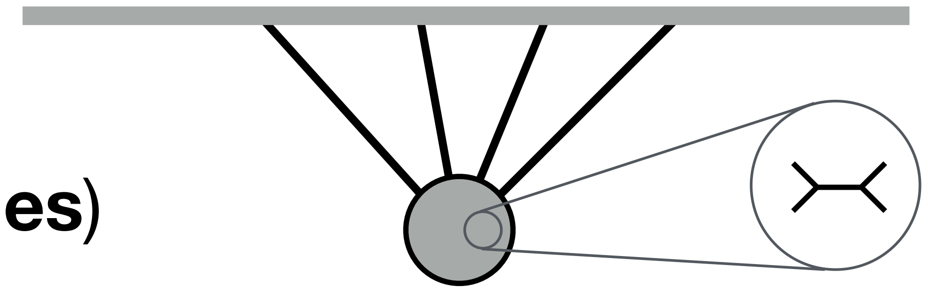
Correlation functions capture features of the distribution near the **peak** well



Moment expansion misses information in the **tails**

Challenge for both **theory** and **data**

Targets



- What is the energy scale of inflation? (**B-modes**)

- Are there other energy scales important during inflation? (**Features**)

- What is the strong coupling scale of inflation? (**equilateral nG**)

Threshold: $f_{\rm NL}^{\rm eq.} \sim 1$ (slow-roll/non-slow roll)

- Are other degrees of freedom besides the inflaton important during inflation? (**local nG**)

Benchmark: $f_{\rm NL}^{\rm loc.} \sim 1$ (single-field/multi-field)

- What are the **mass** and **spin** of new particles if present during inflation? (**particle nG templates**)