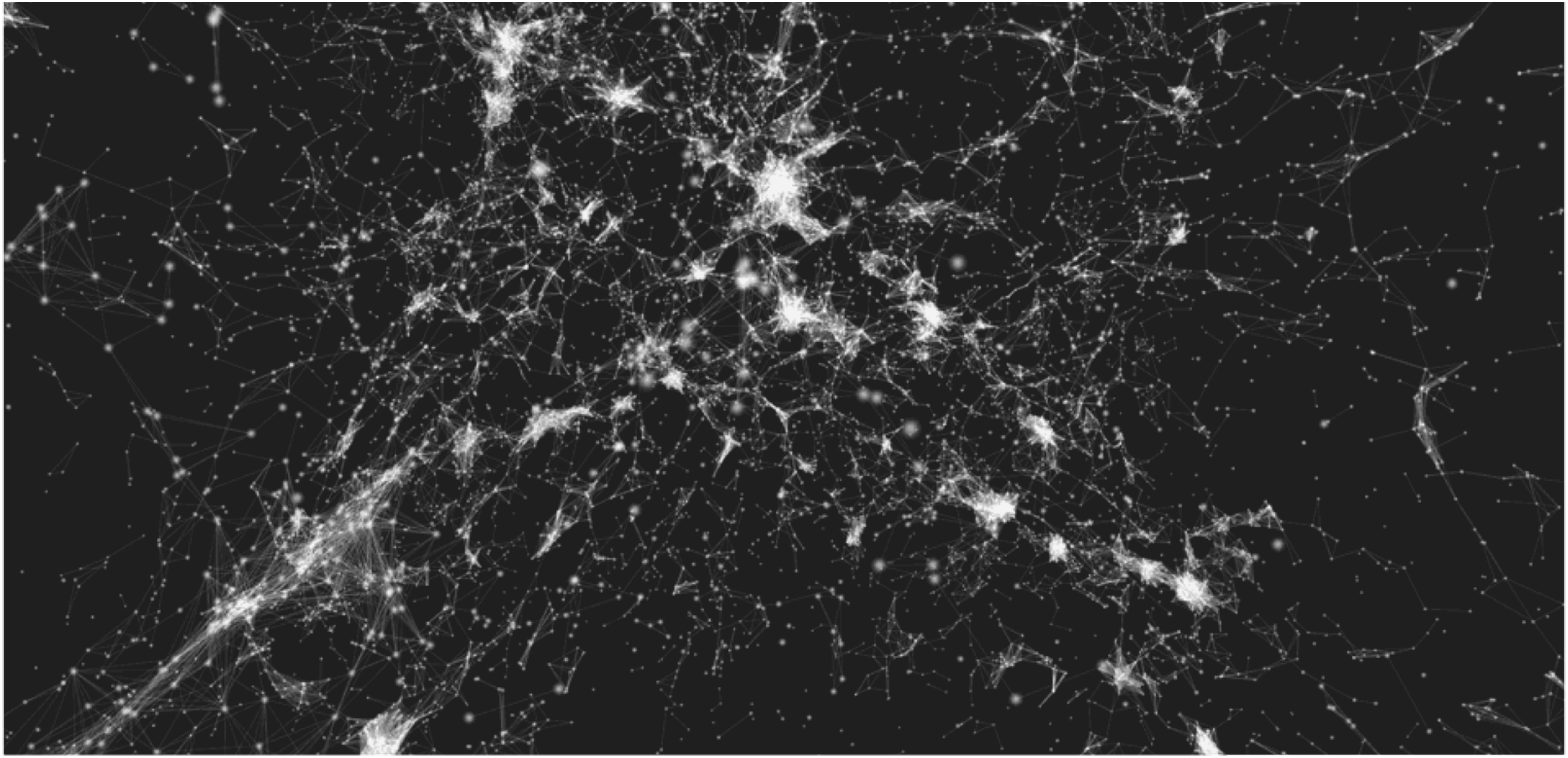
The Early Universe



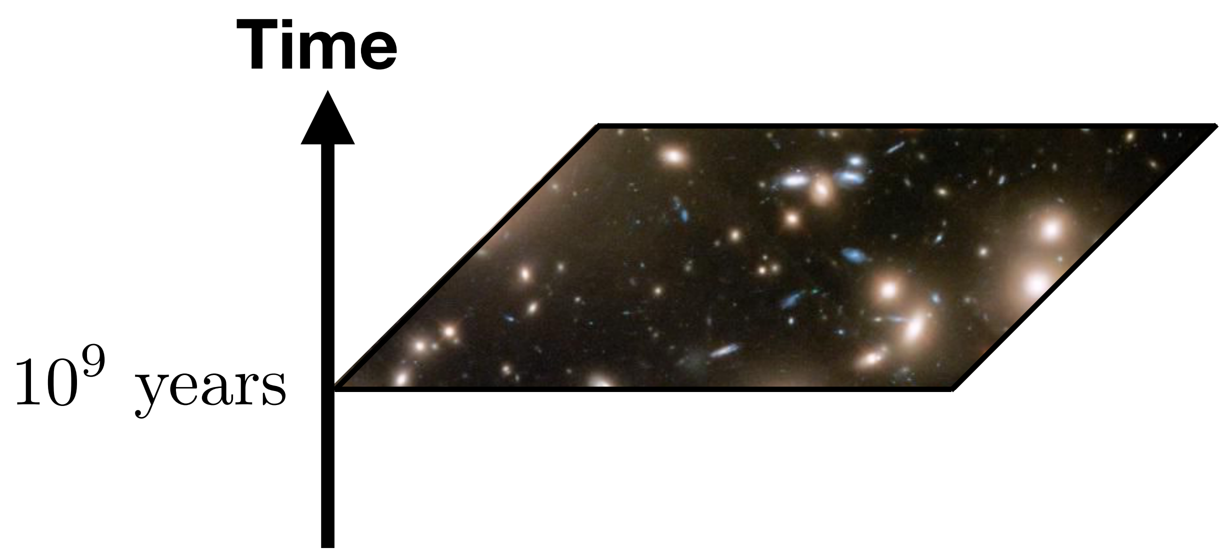
Austin Joyce
Kavli Institute for
Cosmological Physics
University of Chicago

Snowmass 2021, Seattle

THE UNIVERSITY OF CHICAGO

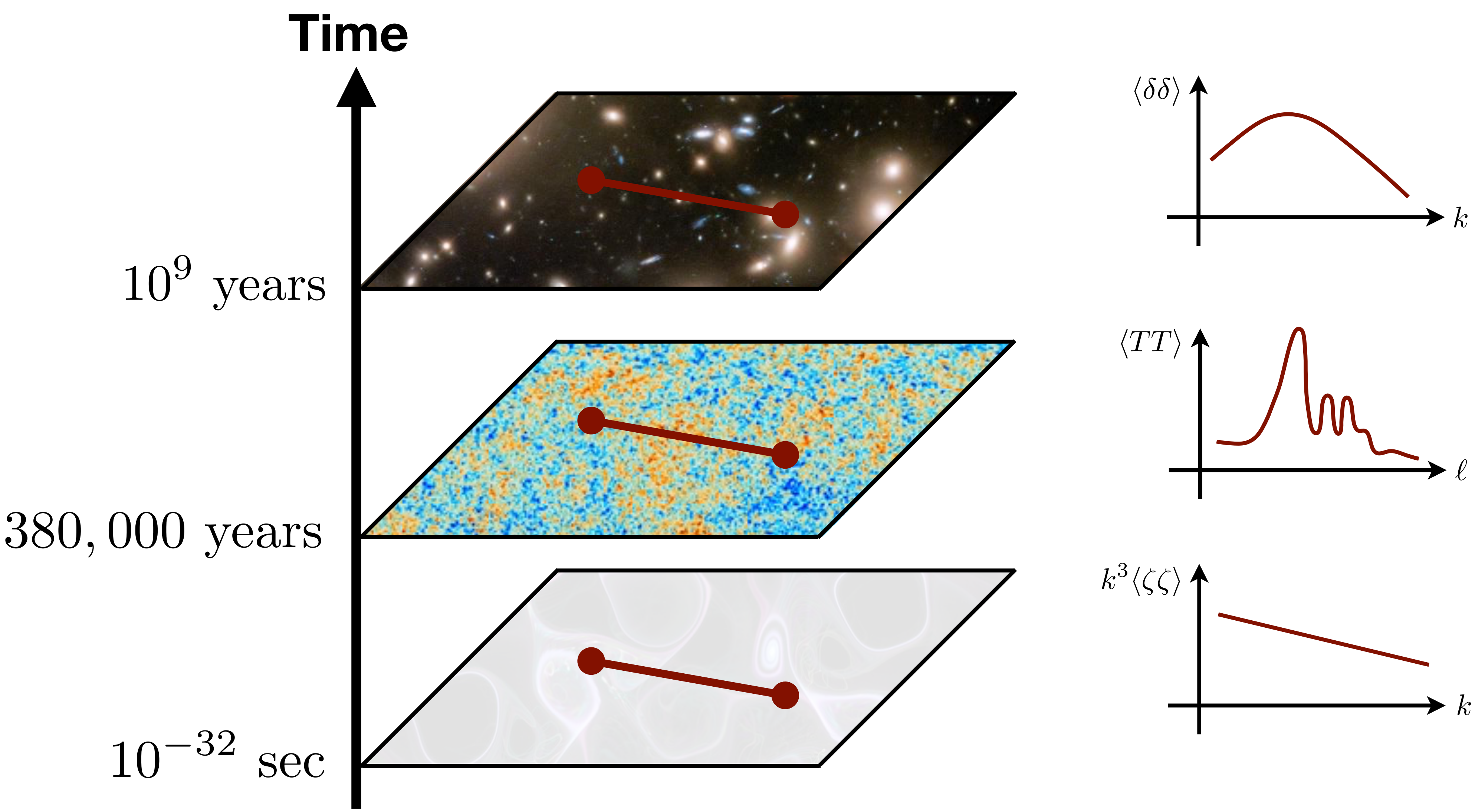
KICP

Cosmology is a study of correlations



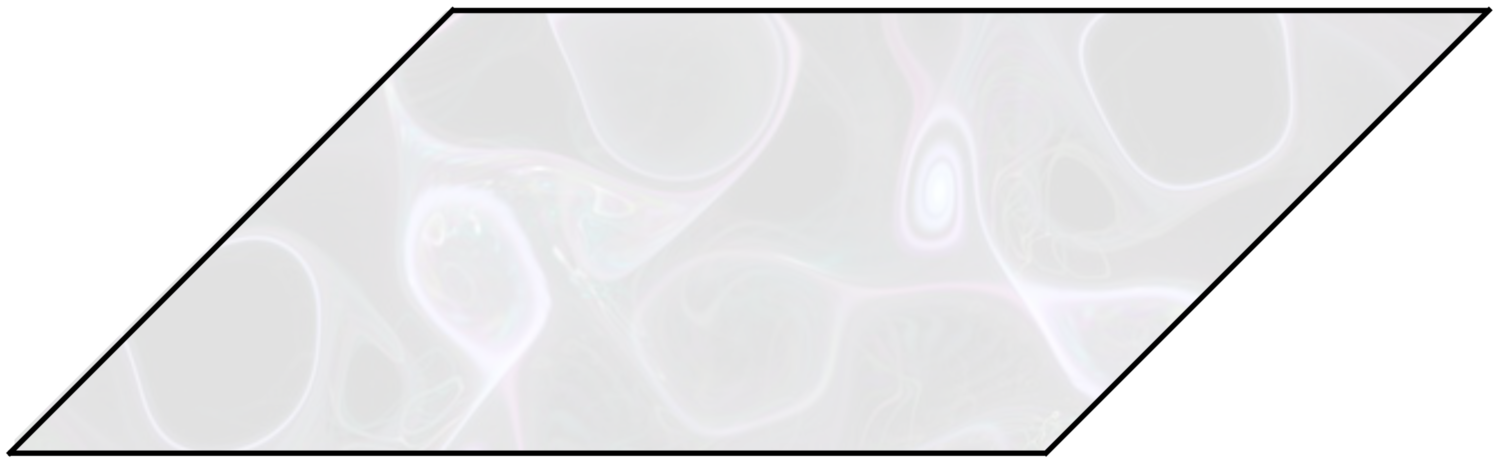
Cosmology is a study of correlations

Distribution of objects is not random

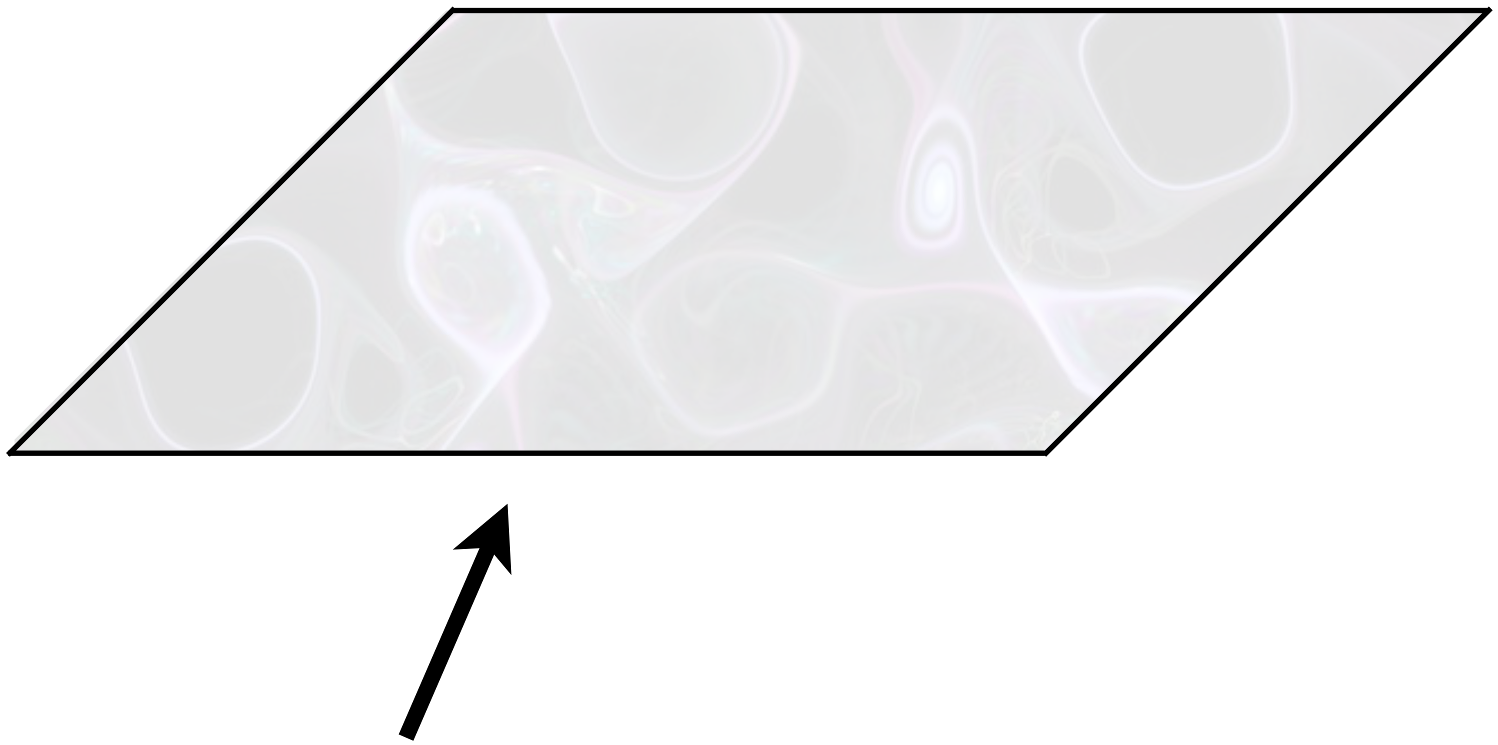


Tracing these correlations across cosmic time we infer dynamics and contents

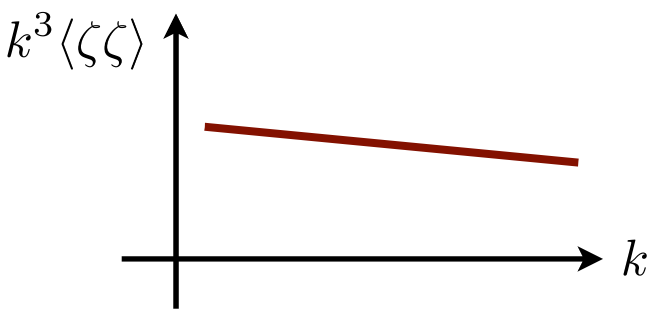
Inspirational fact: we can only look so far back in time



Inspirational fact: we can only look so far back in time



fluctuations on this surface look acausal



Superhorizon correlations

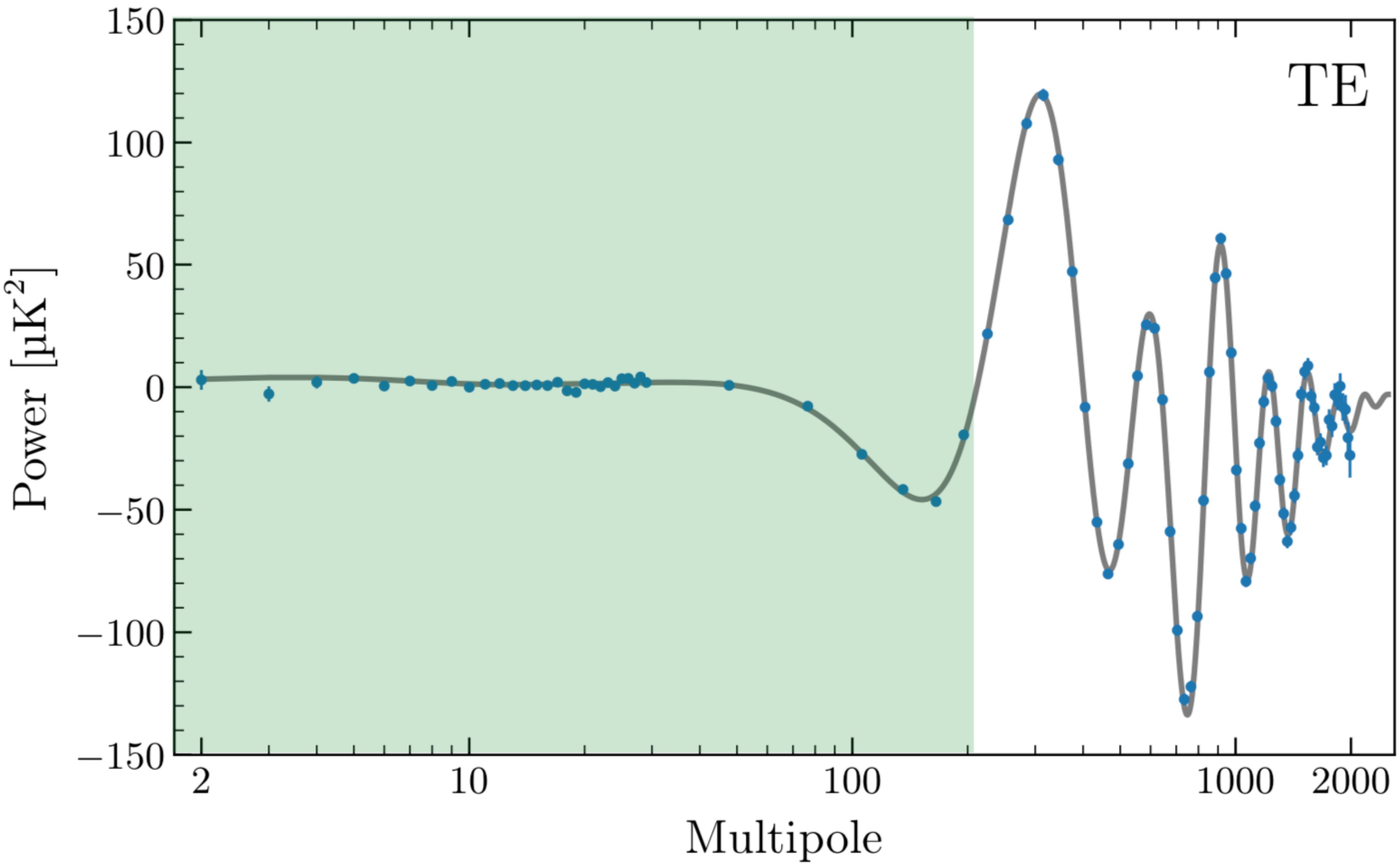
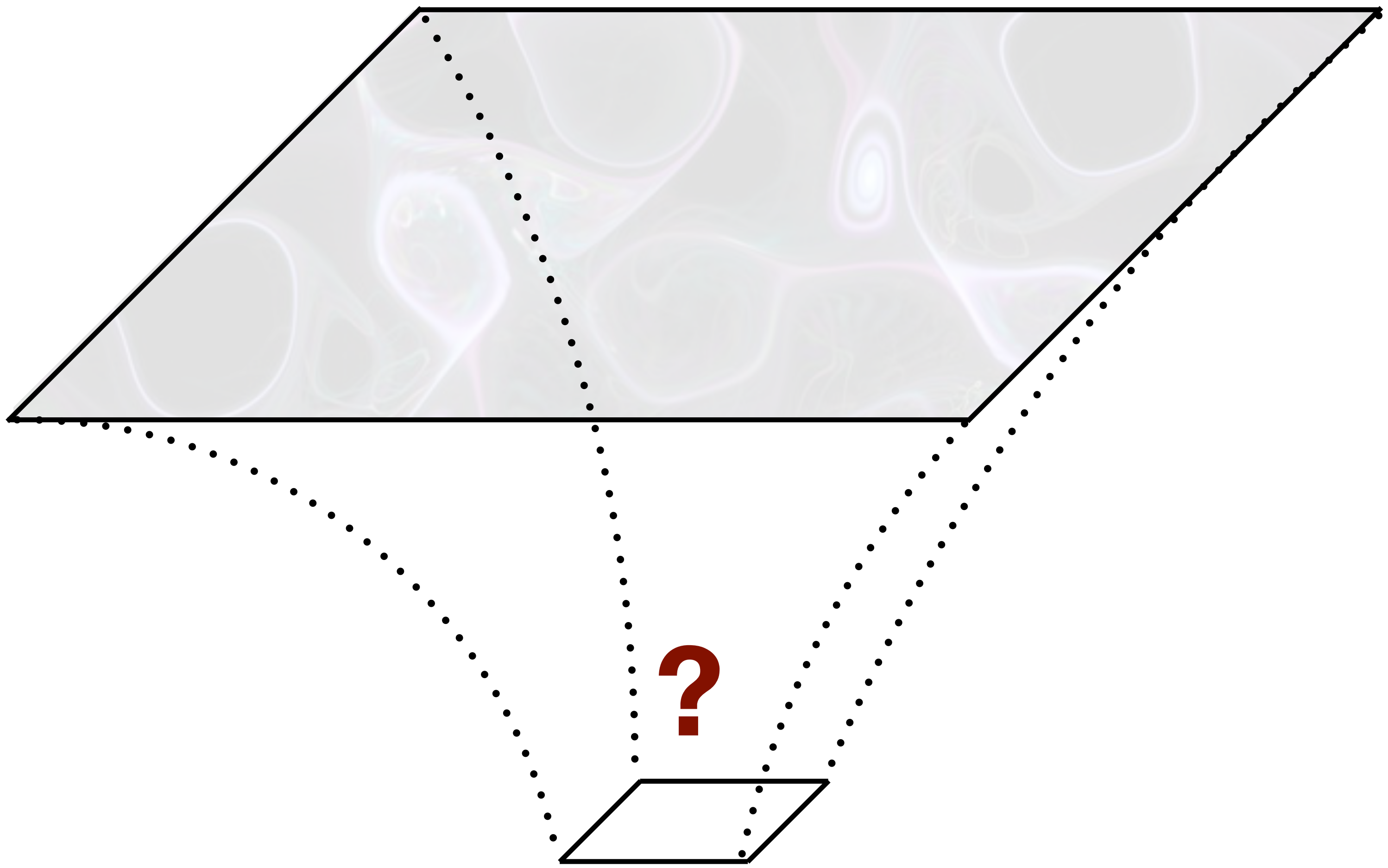


Figure from Daniel Baumann

The hot big bang cannot be the beginning of time



All we can do is infer the properties of earlier phase

Inflation

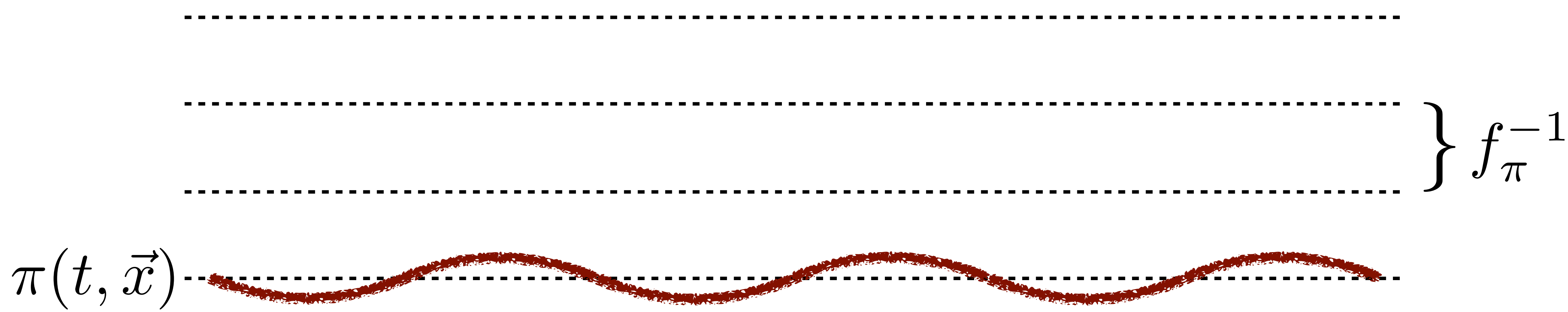
Inflation explains how these perturbations could have arisen causally

Understanding the physics of this phase is one of the key challenges of cosmology

Inflation White Paper: 2203.08128

What is Inflation?

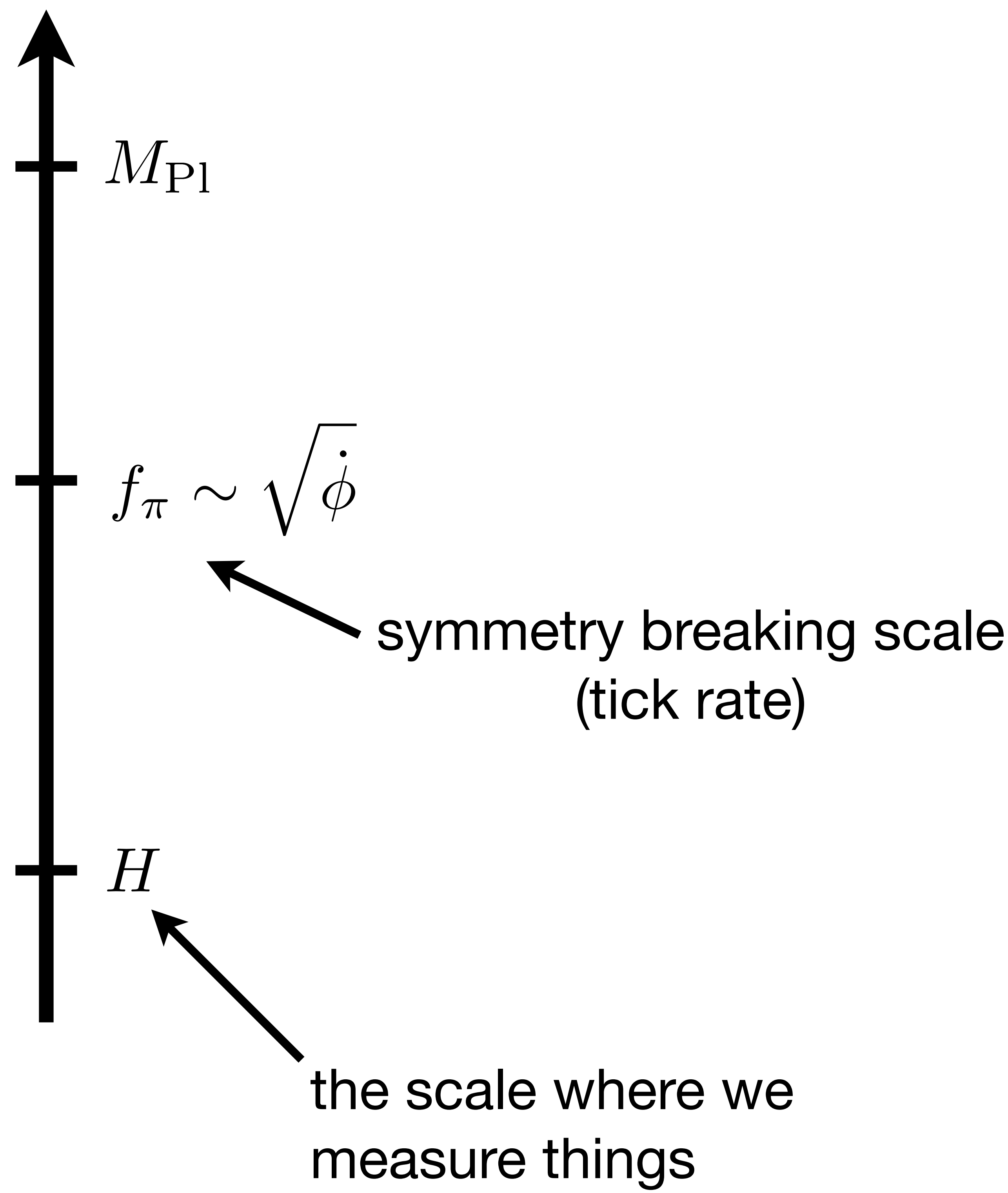
A **clock** coupled to gravity



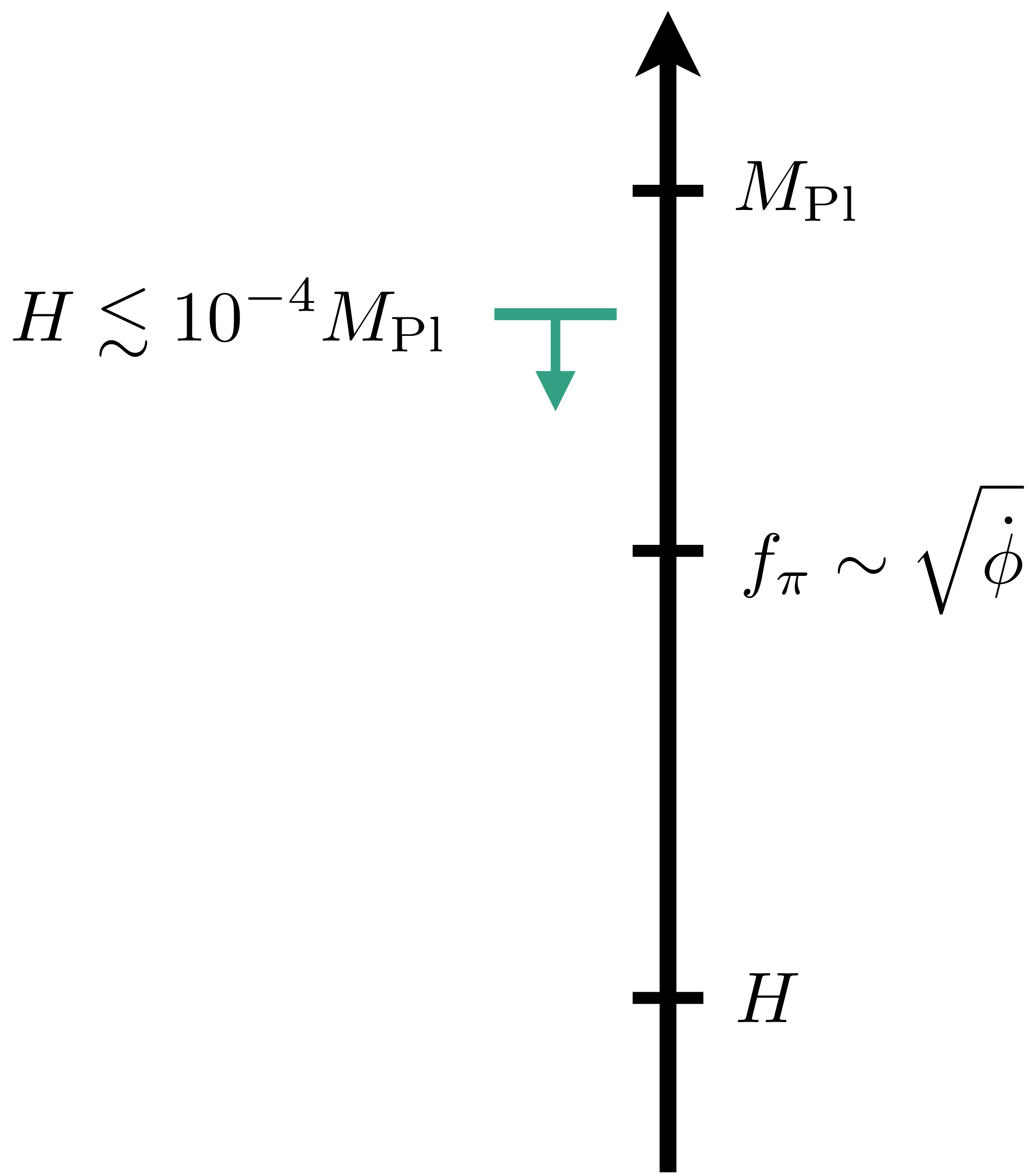
Heisenberg: no clock is perfect, fluctuations are **Nambu-Goldstone** mode

Inflation is **symmetry breaking**

Energy scales



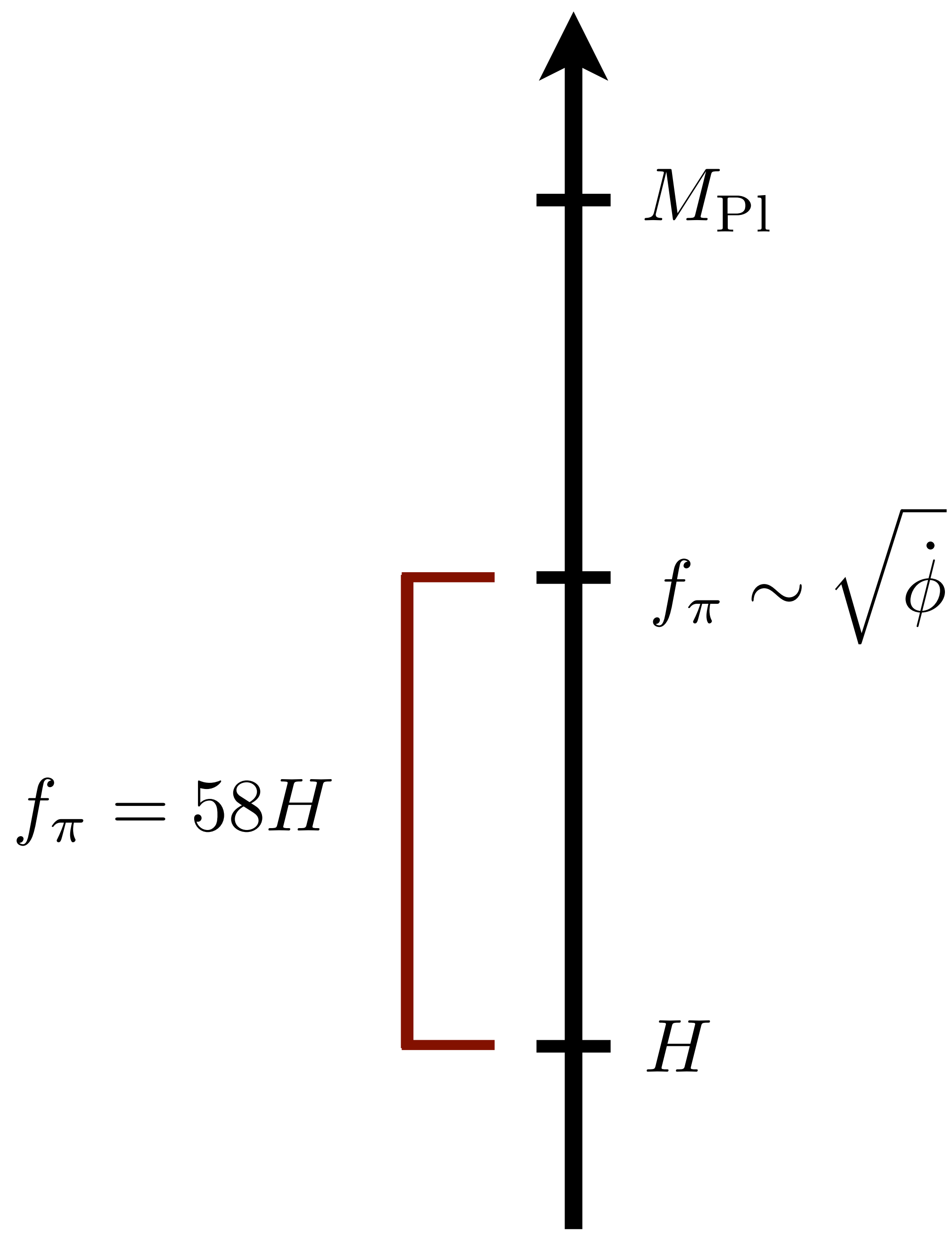
What is the energy scale of inflation?



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

Tensor power spectrum is a direct probe of the energy scale

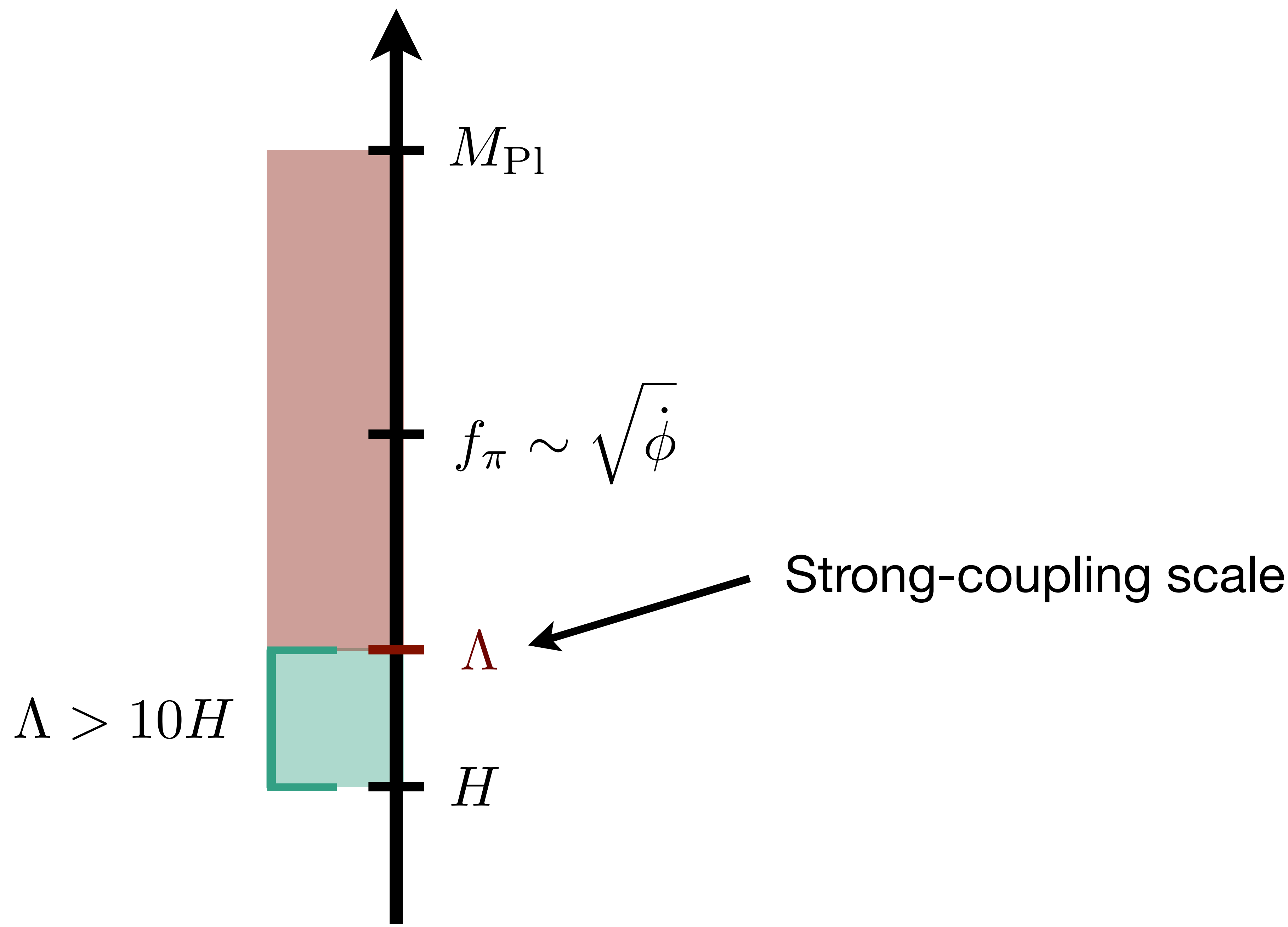
Symmetry-breaking scale



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

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

Strong-coupling scale

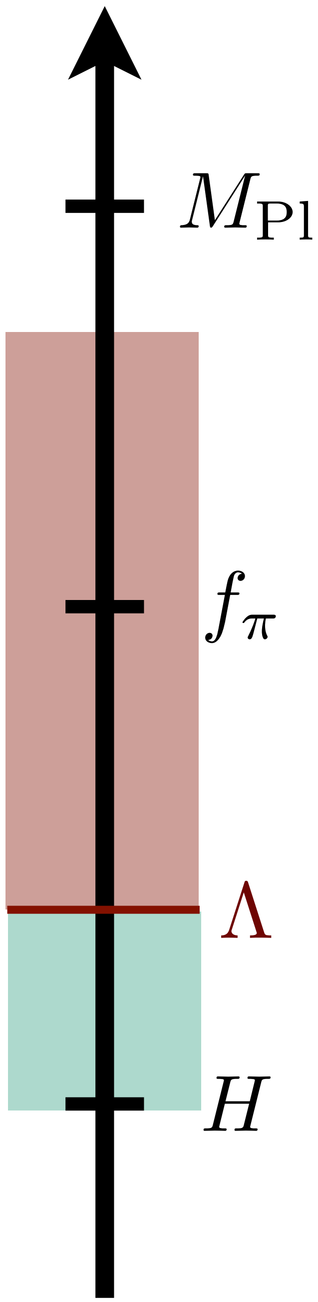


Non-Gaussianity non-detections already put some constraints on strong-coupling scale

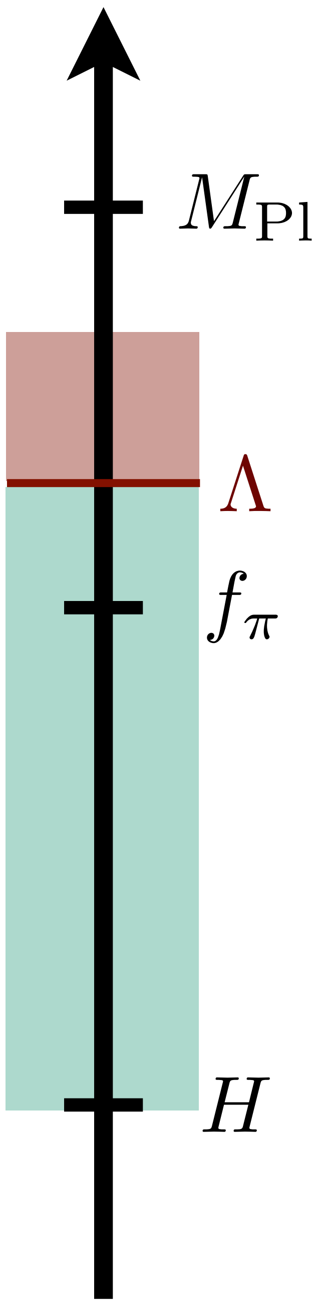
$$f_{\rm NL}^{\rm eq.} \sim 10^4 \left(\frac{H}{\Lambda}\right)^2$$

Baumann, Green 1102.5343

Is inflation UV completed at weak coupling?



vs.

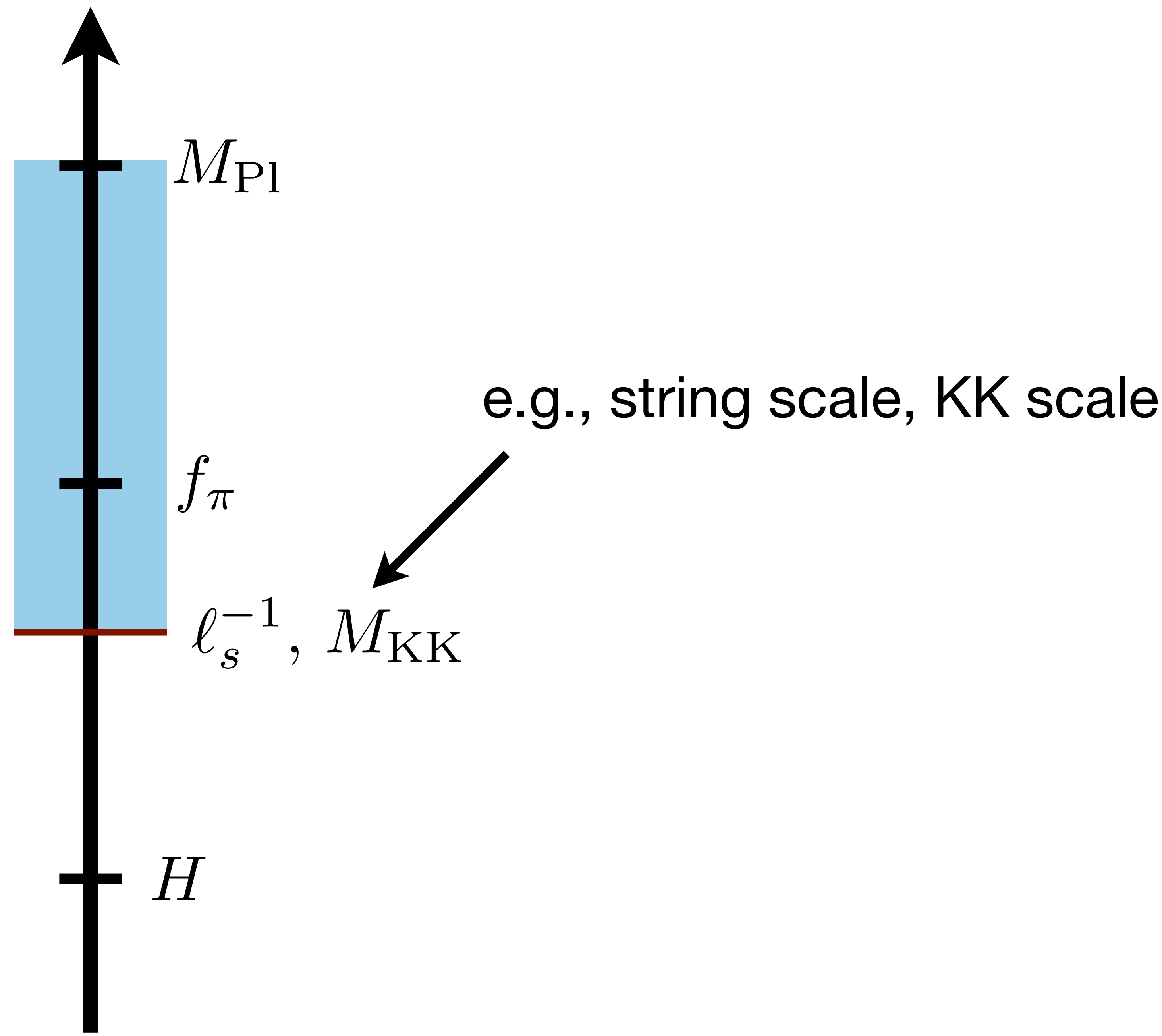


Threshold around $f_{\rm NL}^{\rm eq.} \sim 1$

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

Is the inflaton alone?

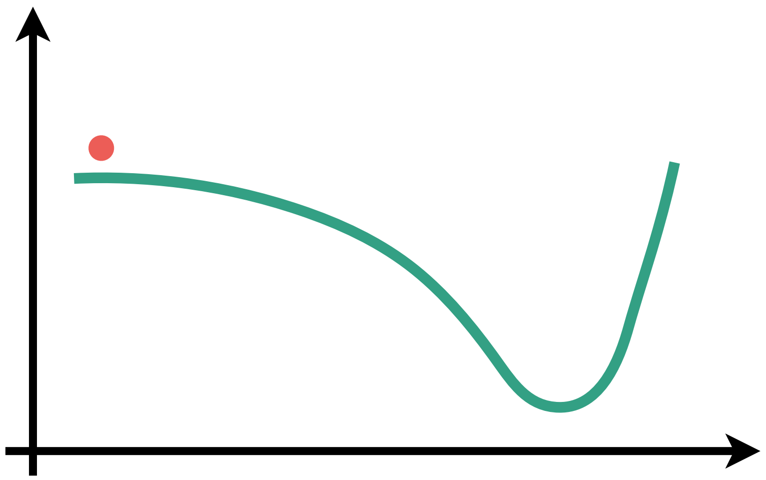
The UV completion of inflation could involve new states near the Hubble scale



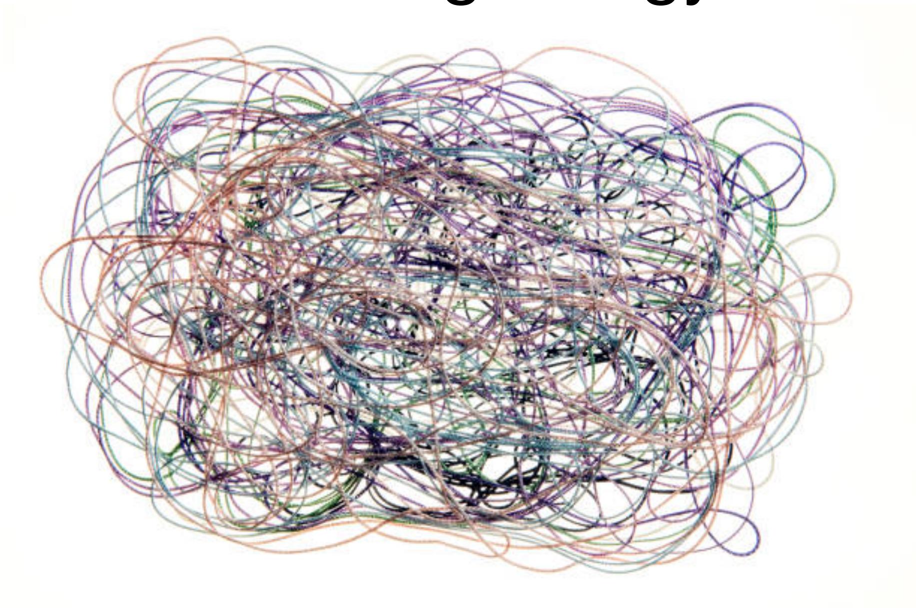
Benchmark $f_{\rm NL}^{\rm loc.} \sim 1$

What is the nature of inflation?

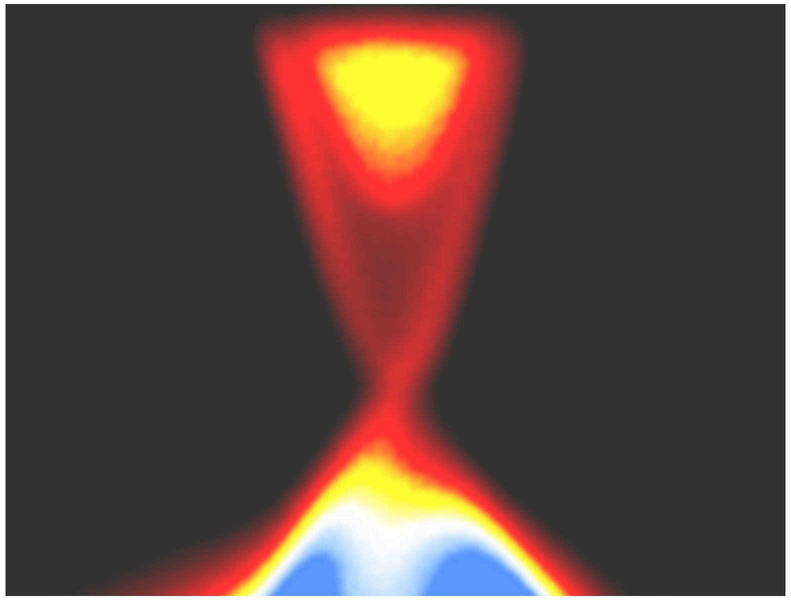
Field(s) rolling in a potential?



Something stringy?



An exotic phase of matter?

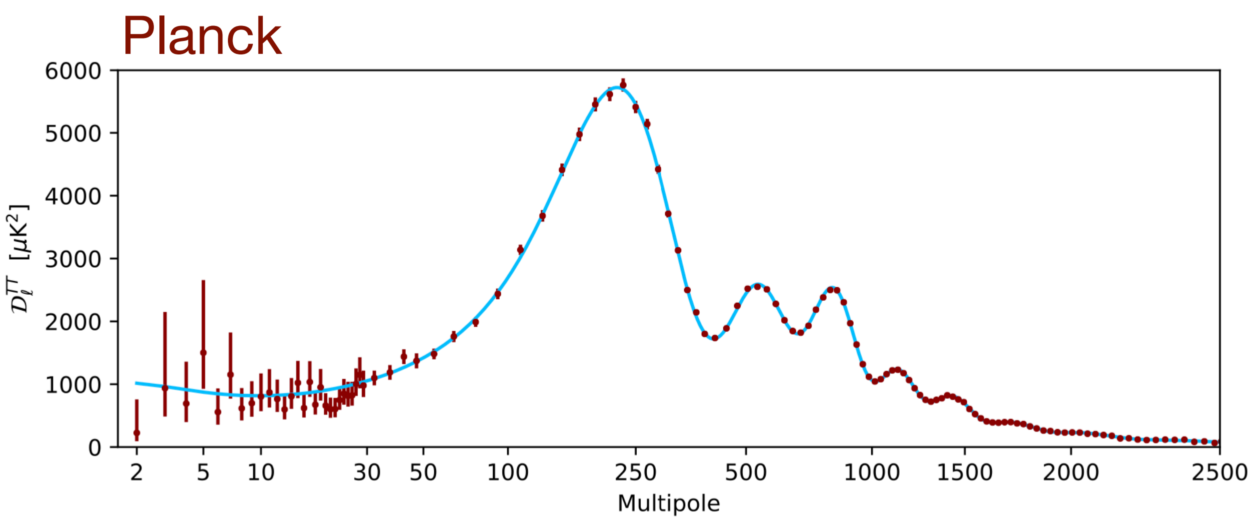


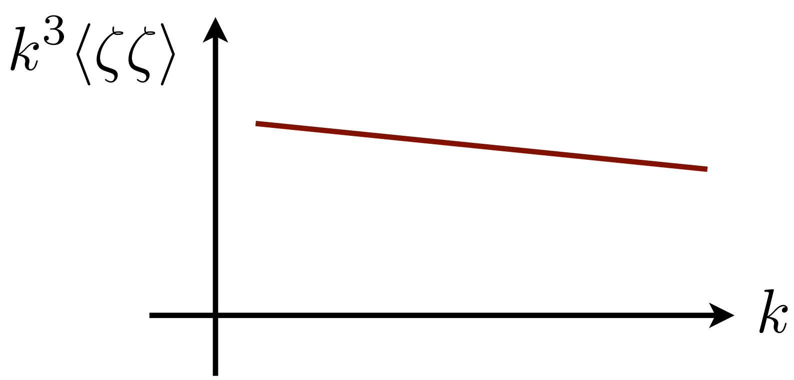
Unique probe of ultraviolet physics.

White Paper: Flauger, Gorbenko, AJ, McAllister, Shiu, Silverstein 2203.07629

Microphysics

The information we currently have about inflation is **kinematic**, follows from **symmetry**

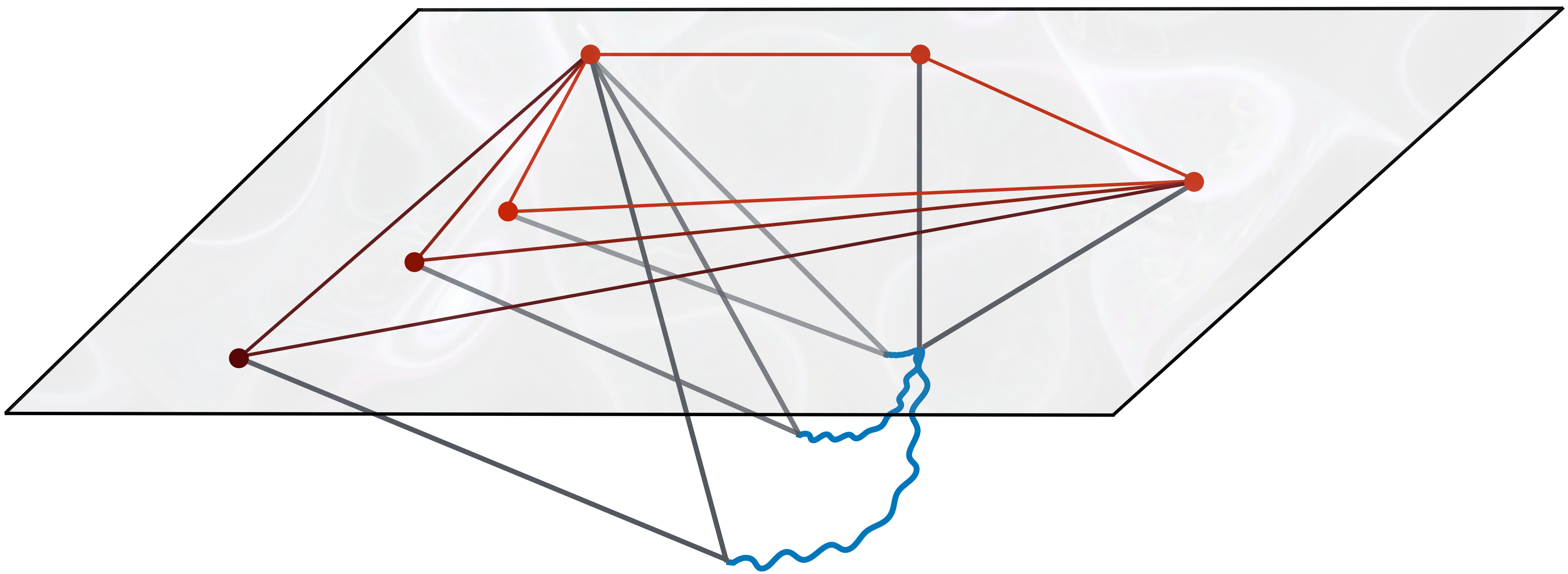




Understanding microphysics requires probing **interactions**

Back to the Future

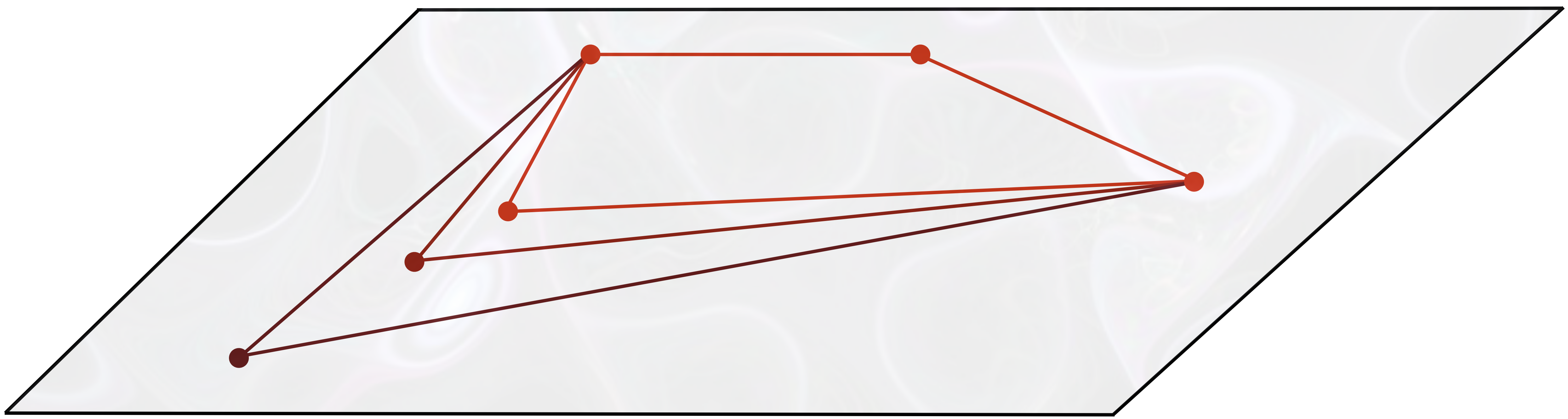
Signatures of interactions are encoded at the **end** of inflation as correlations on the future boundary (reheating surface)



Serve as the initial conditions for the evolution of the universe, retain a memory of the physics **during** inflation

Cosmological Bootstrap

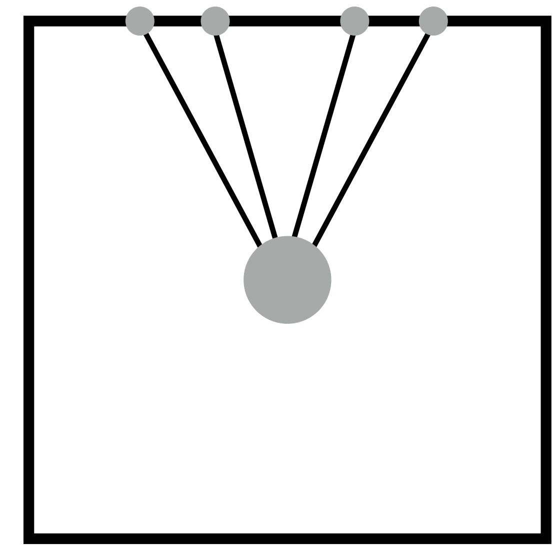
Since we only **infer** the inflationary epoch, can we directly reconstruct the observable outputs?



Properties of inflationary physics (locality, unitarity, symmetries, particle content) are **encoded** in a nontrival way

White Paper: Baumann, Green, AJ, Pajer, Pimentel, Sleight, Taronna 2203.08121

Motivations



Calculational:

- Simplifies many calculations, emphasizes different aspects of the physics — complementary to lagrangians

- Useful to suggest observational signatures or analysis strategies?

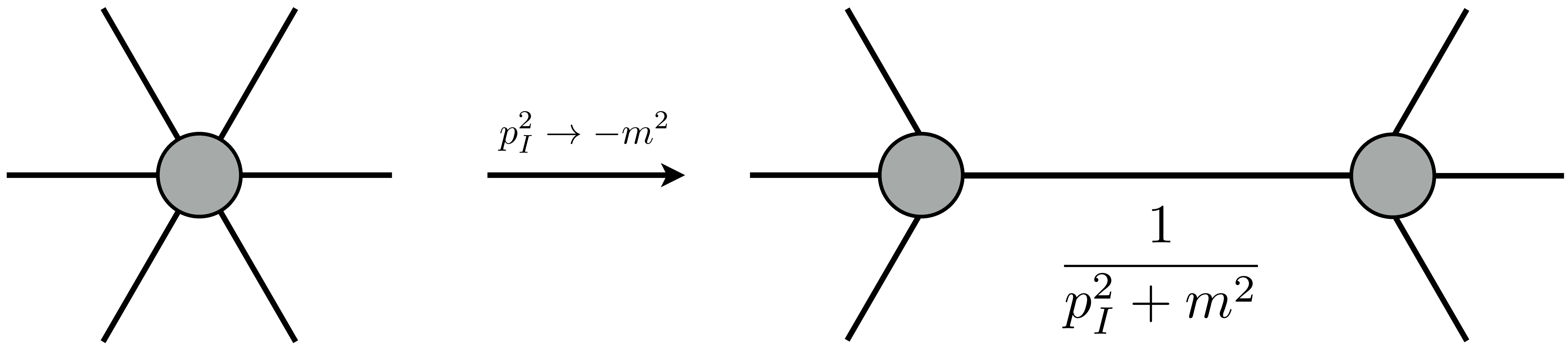
Conceptual:

- Reveals features that are not so obvious in usual approach, e.g., importance of singularities, commonalities of different processes

- Gives us a different language to talk about inflationary models outside the standard paradigms

An S-matrix Lesson

Much of the physics of scattering is controlled by **singularities**



Amplitudes factorize when intermediate particles go on-shell

Consistent factorization very constraining for massless spinning particles, in some cases fix amplitudes completely

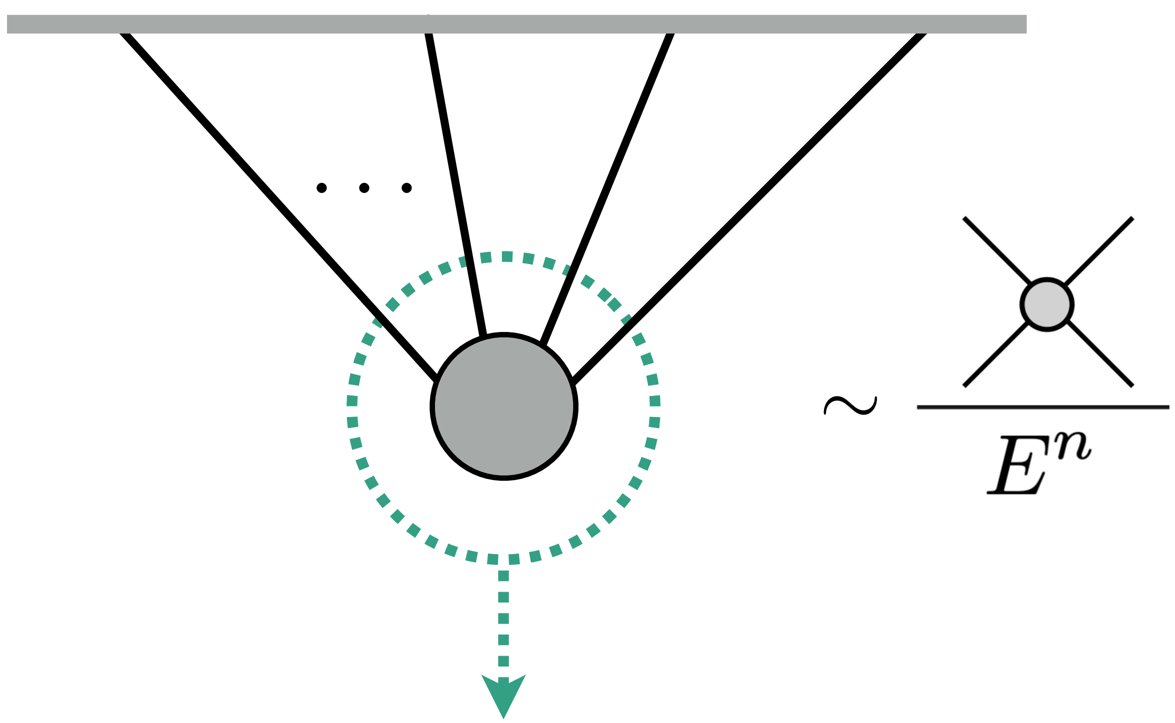
- What are the singularities of cosmological correlations?

Maldacena, Pimentel 1104.2846
Raju 1201.6449
Arkani-Hamed, Benincasa, Postnikov 1709.02813
Baumann, Duaso Pueyo, AJ, Lee, Pimentel 2005.04234

Singularities

Energy is not conserved in cosmology, instead correlators are singular when energy flowing into a vertex is conserved

- Singularity when **total energy** of a process is conserved



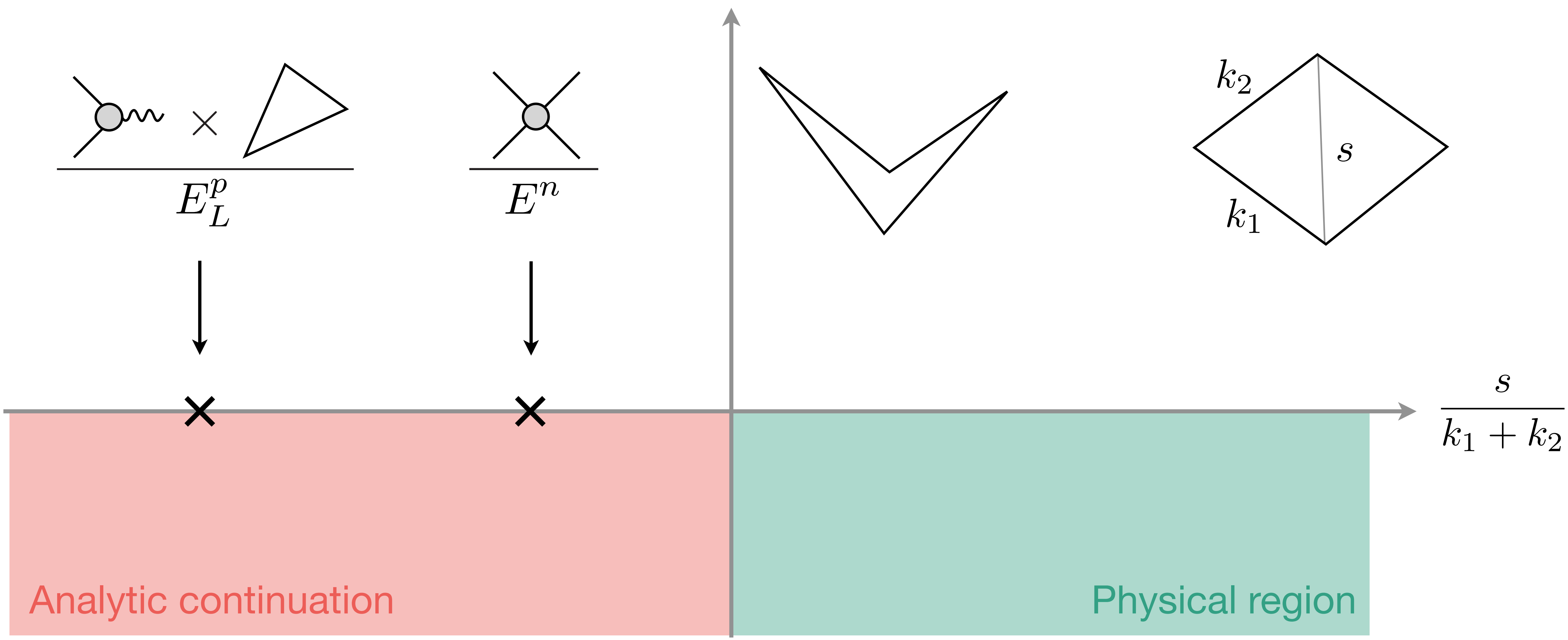
$$\sim \frac{}{E^n}$$

(Almost) all correlators have this singularity—coefficient is (high energy limit of the) scattering amplitude for same process

beautifully connects amplitudes and cosmological correlators

Linking Singularities

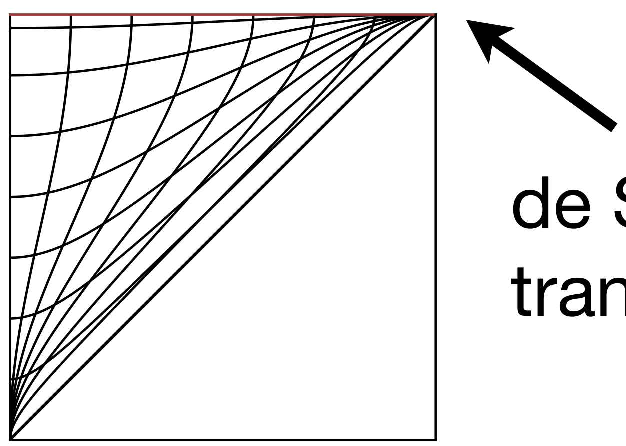
These singularities lie at unphysical configurations, we are interested in the correlator for real kinematics



Challenge is to extend away from singular configurations: time $\longrightarrow$ shape

Linking Singularities

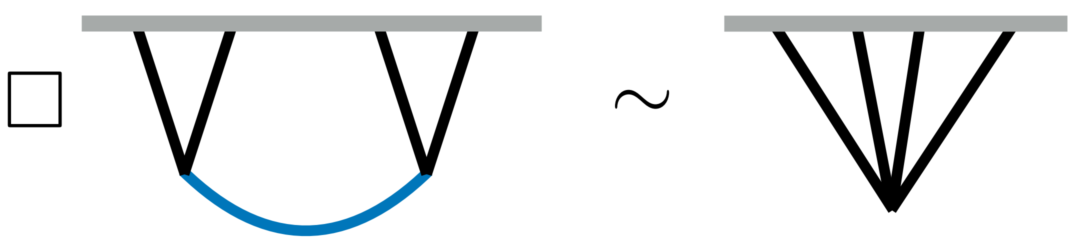
Symmetries Connects the study of de Sitter space and CFT



de Sitter isometries act as conformal transformations on the future boundary

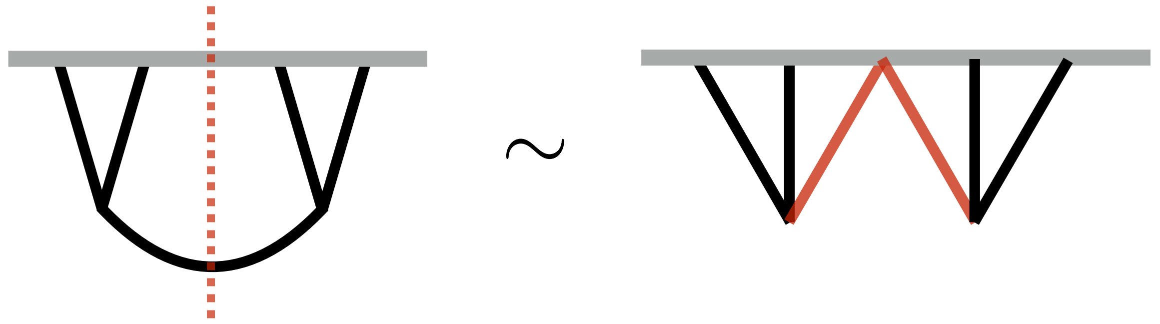
Differential equations

Signature of locality



Unitarity

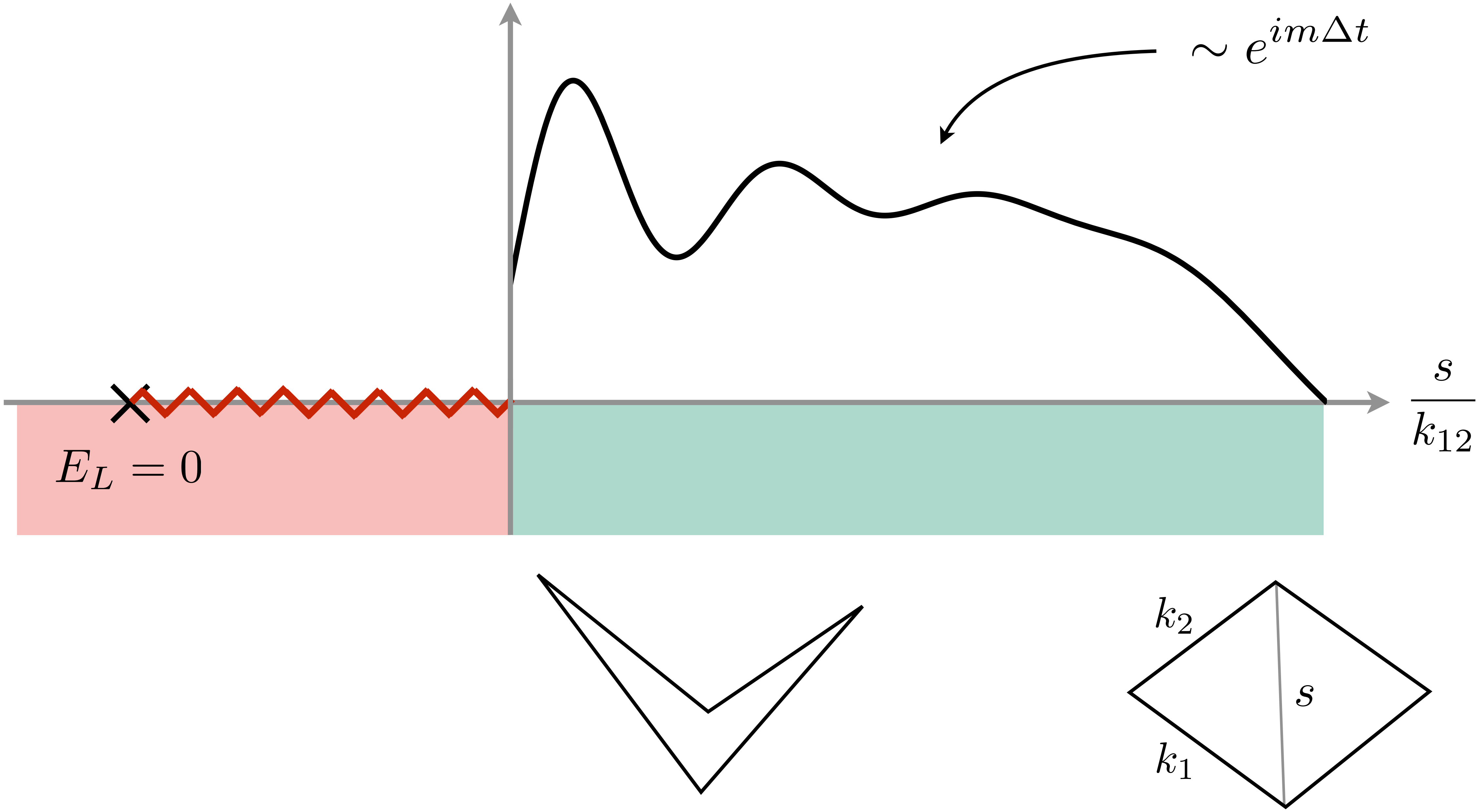
Goodhew, Jazayeri, Pajer 2009.02898
Cespedes, Davis, Melville 2009.07874



Arkani-Hamed, Maldacena 1503.08043
Arkani-Hamed, Baumann, Lee, Pimentel 1811.00024

Particle Production

If exchange involves a **massive particle**, the correlator is forced to have an oscillatory feature in the physical region:



Would be an **opportunity** to probe very high energy physics — **requires** theoretical modeling of templates

Outlook

Sleight, Taronna 2007.09993
Hogervorst, Penedones, Vaziri 2107.13871
Di Pietro, Gorbenko, Komatsu 2108.01695

Non-perturbative Bootstrapping

Unitarity in dS implies positivity of certain spectral densities

$$\langle O(\vec{x}_1)O(\vec{x}_2)O(\vec{x}_3)O(\vec{x}_4)\rangle = \mathbf{1}_s + \sum_J \int_{\frac{d}{2}-i\infty}^{\frac{d}{2}+i\infty} \mathrm{d}\Delta\, \rho_J(\Delta)\, \Psi^{(s)}_{\Delta,J}(\vec{x}_1,\vec{x}_2,\vec{x}_3,\vec{x}_4)$$

Still conceptual difficulties to overcome, but very interesting questions:

- Can the inflaton be parametrically lighter than heavy states in UV complete models? (Is single-field inflation allowed?)
- Can we learn something about initial singularity?

From IR to UV

One of the goals of cosmology is to use low-energy measurements to infer information about early universe microphysics

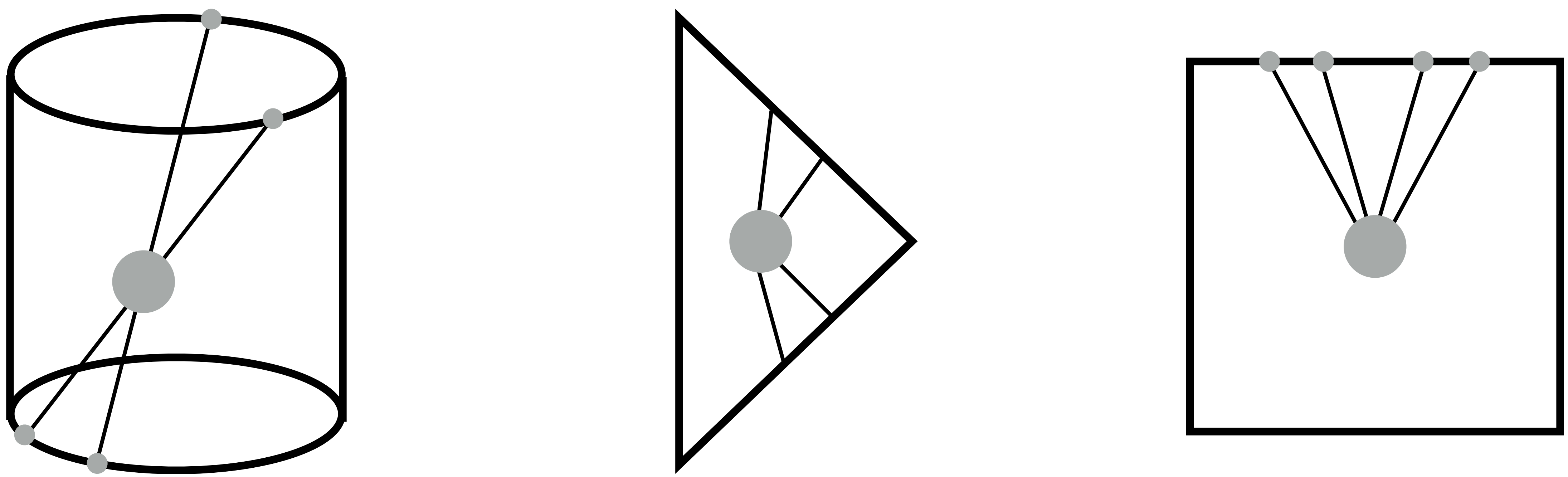
Precise manifestation of this is UV-IR relations like dispersion relations/ positivity bounds

- Requires more refined understanding of both analytic structure and unitarity in cosmology

Cosmological Holography

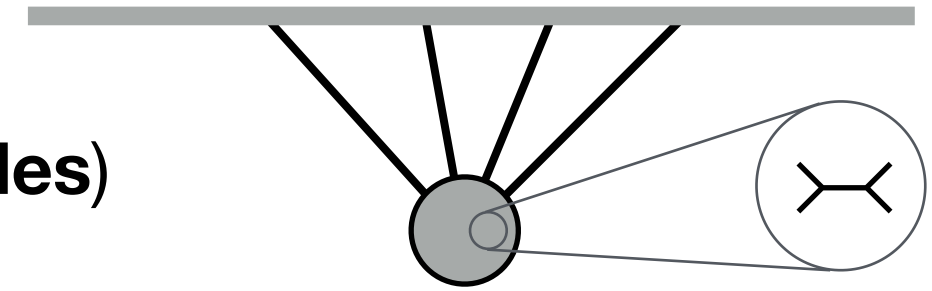
Is there a truly holographic description of dS/cosmology?

Realism



Understanding

Targets/Questions



- What is the energy scale of inflation? (**B-modes**)
- What is the strong coupling scale of inflation? (**equil. nG**)
- Are other degrees of freedom besides the inflaton important during inflation? (**squeezed limit nG**)
- Are there qualitatively new implementations of inflation? Can they shed light on conceptual puzzles of inflation?
- Can we understand the physics of cosmological singularities?
- We are just starting to make connections between amplitudes/CFT and cosmological observables, there is clearly much to be learned