The Early Universe
Cosmology is a study of correlations.
Cosmology is a study of **correlations**

Distribution of objects is not random

- Time
- $10^9$ years
Tracing these correlations across cosmic time we infer dynamics and contents.
Inspirational fact: we can only look so far back in time
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fluctuations on this surface look acausal
Superhorizon correlations
The hot big bang cannot be the beginning of time

All we can do is infer the properties of earlier phase
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

\[ \pi(t, \bar{x}) \]

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

Inflation is symmetry breaking
Energy scales

\[ M_{Pl} \]

\[ f_\pi \sim \sqrt{\dot{\phi}} \]

symmetry breaking scale (tick rate)

\[ H \]

the scale where we measure things
What is the energy scale of inflation?

\[ H \lesssim 10^{-4} M_{Pl} \]

\[ f_\pi \sim \sqrt{\dot{\phi}} \]

\[ \Delta_\gamma = \frac{H}{M_{Pl}} = ? \]

Tensor power spectrum is a direct probe of the energy scale.
Symmetry-breaking scale

\[ f_\pi \sim \sqrt{\dot{\phi}} \quad \Delta_\zeta = \left( \frac{H}{f_\pi} \right)^2 \approx 10^{-4} \]

\[ f_\pi = 58H \]

Spectrum of scalar perturbations fixes ratio between Hubble and symmetry-breaking scale
Non-Gaussianity non-detections already put some constraints on strong-coupling scale

\[ f_{\text{NL}}^{\text{eq.}} \sim 10^4 \left( \frac{H}{\Lambda} \right)^2 \]
Is inflation UV completed at weak coupling?

Threshold around $f_{\text{eq.}}^\Lambda \sim 1$

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 \( f_{\text{NL}}^{\text{loc.}} \sim 1 \)
What is the nature of inflation?

Field(s) rolling in a potential?  Something stringy?

An exotic phase of matter?

Unique probe of ultraviolet physics.

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 nontrivial way.

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?
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

\[ \sim E^n \]

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

beautifully connects amplitudes and cosmological correlators
These singularities lie at unphysical configurations, we are interested in the correlator for real kinematics.

Challenge is to extend away from singular configurations: time $\rightarrow$ 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
If exchange involves a **massive particle**, the correlator is forced to have an oscillatory feature in the physical region:

\[ e^{im\Delta t} \]

Would be an **opportunity** to probe very high energy physics — **requires** theoretical modeling of templates.
Outlook
Non-perturbative Bootstrapping

Unitarity in dS implies positivity of certain spectral densities

\[ \langle O(\bar{x}_1)O(\bar{x}_2)O(\bar{x}_3)O(\bar{x}_4) \rangle = 1_s + \sum_J \int_{\frac{d}{2} - i\infty}^{\frac{d}{2} + i\infty} d\Delta \rho_J(\Delta) \Psi_{\Delta,J}^{(s)}(\bar{x}_1, \bar{x}_2, \bar{x}_3, \bar{x}_4) \]

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?
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