Early Universe Cosmology

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Early Universe Cosmology

- Testing fundamental theories using limited and imperfect records of the past.
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What can we know?

One paradigm: Inflation

Extremes: Eternal Inflation
What can we know?

What we can know about the early Universe depends on what happens in the late Universe.
What can we know?

The best theoretical model for the late Universe:

\[ \Lambda \text{CDM} \]

\[ R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \]
What can we know?

Today

Cool and diffuse

Big Bang?

Hot and dense
What can we know?

We see only a small piece of the Universe.

Today

Big Bang?
What can we know?

- time
- space

Today

past light cone has finite size

Big Bang?
What can we know?

Time

Space

Today

$\infty$

Big Bang?

Big Bang?

Big Bang?

Size depends on ingredients
What can we know?

- We can’t directly see arbitrarily far into the past!

Today
CMB
Big Bang?
What can we know?

- We (almost) only measure what is on the light cone!
What can we know?

- In principle, we can infer what is inside the light cone.

Today

Big Bang?
What can we know?

- Today
- First Structure
- Big Bang?

linear fluctuations

nonlinear fluctuations
What can we know?

- **Today**
- **First Structure**
- **CMB**
- **Big Bang?**

Linear fluctuations

Nonlinear fluctuations
What can we know?

- Today
- First Structure
- Big Bang?

Initial conditions

- Time
- Space
What can we know?

- Today
- First Structure
- Big Bang?

simple evolution from initial conditions
What can we know?

Initial conditions

Simple evolution from initial conditions

Complex dynamics
N-body simulations necessary

Big Bang?

Today

First Structure

time

space
What can we know?

- Small scale modes are stretched into large scale modes.

\[ \lambda_{\text{ph}} = a(t) \lambda_{\text{com}} \]
What can we know?

- There is an upper limit on observable wavelengths:
What can we know?

- We are typically interested in statistics
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What can we know?

Ensemble of initial conditions

Today

CMB

Big Bang?

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(time)  

(space)
What can we know?

- We are typically interested in statistics

Ensemble of initial conditions

- Today
- CMB
- Big Bang?
What can we know?

- We are typically interested in statistics

We have only one realization -- Cosmic Variance
What can we know?

In practice restrictions:

- We are limited to a few snapshots on the light cone.
- We are limited by our ability to understand non-linear evolution.
What can we know?

- In practice restrictions:
  - We are limited to a few snapshots on the light cone.
  - We are limited by our ability to understand non-linear evolution.

- In principle restrictions:
  - Finite size past light cone.
  - Maximum wavelength.
  - Cosmic variance.
Strange Initial Conditions

- A first look at the CMB indicates that the initial conditions must be rather strange.
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!!Need a Theory of Initial Conditions!!
Inflation

- A non-diluting perfect fluid - Inflation!
- Grows the observable universe from a causally connected primordial patch.

\[
\Delta x \quad \text{time} \quad a \cdot \Delta x
\]

\[
a \propto \exp \left[ \sqrt{\frac{8\pi G_N}{3}} \rho \ t \right]
\]

\[
\rho \simeq 10^{85} \text{ kg/m}^3
\]

Perfect candidate: potential energy of a scalar field!
Inflationary Seeds of Density Perturbations

- An inflating Universe has thermodynamic properties:

\[ T = \frac{H}{2\pi} \quad \quad S = \frac{\text{Area}}{4G_N} = \frac{\pi}{H^2 G_N} \]
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- The Universe is a small/hot system, so fluctuations likely:

\[ H^{-1} \approx 10^{-28} \text{m} \quad T \approx 10^{12} \text{ GeV} \quad S \approx 10^{14} \]
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- All light fields fluctuate - gravitational waves!
Predictions from Models of Inflation

$$P_S(k) = A_S \ k^{n_S-1}$$

$$P_T(k) = A_T \ k^{n_T}$$
Discovery of Primordial Tensors?

BICEP2: E signal

\[ \text{1.7 \mu K} \]

BICEP2: B signal

\[ \text{0.3 \mu K} \]

Right ascension [deg.]

Declination [deg.]

\[ \chi^2 \]

PTE = 0.28

\[ \chi^2 \]

PTE = 0.30

\[ \chi^2 \]

PTE = 0.20

\[ \chi^2 \]

PTE = 0.04

\[ \chi^2 \]

PTE = 1.3 \times 10^{-7}
Discriminating Between Models

- Powerful discriminator for different models.
- Interesting tension with temperature power spectrum may hint at non-vanilla inflationary history.
- Can distinguish alternatives to inflation (Ekpyrotic Universe, string gas cosmology, etc.)
Inflationary Baggage

- Inflation has a lot of baggage:
  - Potential is sensitive to Quantum Gravity corrections.
  - Is the horizon problem really solved?
  - Still need to resolve the initial singularity.
  - Inflation can become future eternal.
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![Graphs showing the potential function $V(\phi)$ over $\phi$ with different behavior patterns.](Image)
Does the accelerated expansion ever end?

- In a static or decelerating universe:
Does the accelerated expansion ever end?

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No matter how slow, the phase transition always completes!
Does the accelerated expansion ever end?

- In an accelerating universe:
Does the accelerated expansion ever end?

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- In an accelerating universe:

Eternal Inflation  
Vilenkin, Linde, Guth

When the rate of pocket formation is lower than the rate of expansion, accelerated expansion doesn’t end everywhere!
Testing Eternal Inflation

- Do we live in an eternally inflating Universe?

  Our bubble does not evolve in isolation....

The collision of our bubble with others provides an observational test of eternal inflation.

Aguirre, MCJ, Shomer
Observational Tests of Eternal Inflation

**Predictions**

- Scalar field Lagrangian
- Eternal inflation
- Bubble collisions

**Constraints**

- Possible models?
- Motivation from theory?
- Constraints from observation?
- Probabilities and inferences?
- Relation to other versions of the multiverse?
- How are model parameters manifest?
- Predictions from specific models?
- Phenomenology?
- Perturbations inside the bubble?
- Detailed signature for temperature and polarization?
- Best data analysis strategies?
The data

WMAP7 W-Band data

Feeney, MCJ, McEwan, Mortlock, Peiris
Osbourne, Senatore, Smith

Posterior over the total number of observable collisions in a generic model
(Various assumptions in prior)

\[\text{cosmic variance}\]

\[\Lambda CDM\]
Closing Remarks

- In practice restrictions:
  - We are limited to a few snapshots on the light cone.
  - We are limited by our ability to understand non-linear evolution.

HUGE progress coming in the near future!!!!

CMB polarization, LSS surveys, lensing, 21 cm, N-body codes, analytic handles on non-linear evolution
Closing Remarks

• In principle restrictions:
  • Finite size past light cone.
  • Maximum wavelength.
  • Cosmic variance.

 Raises some thorny questions:

   If it can’t be observed in principle, is it real?

 How large is the fundamental degeneracy between models?

 Fundamental connection between early and late Universe?
Thank you!