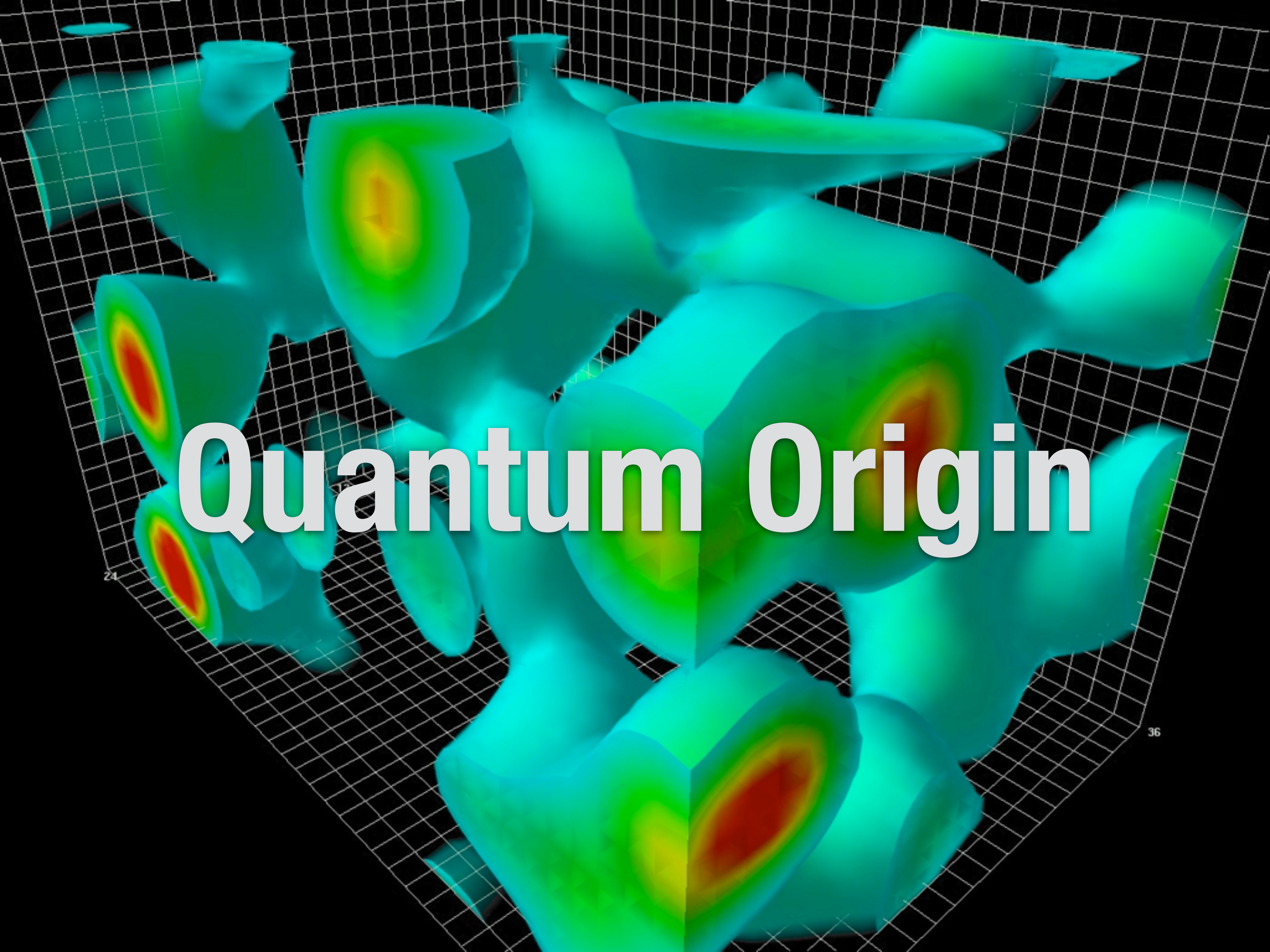
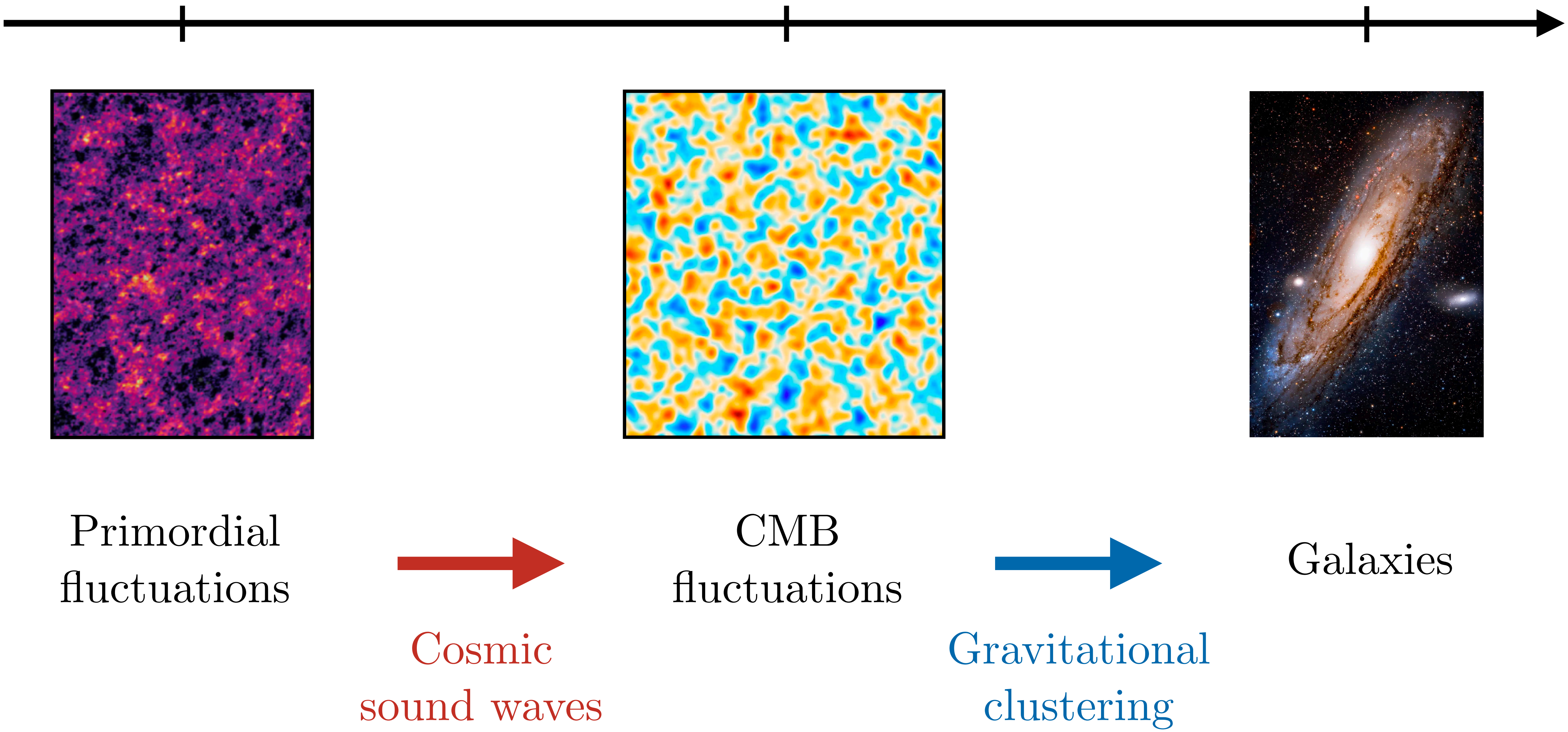

Quantum Origin
24
36

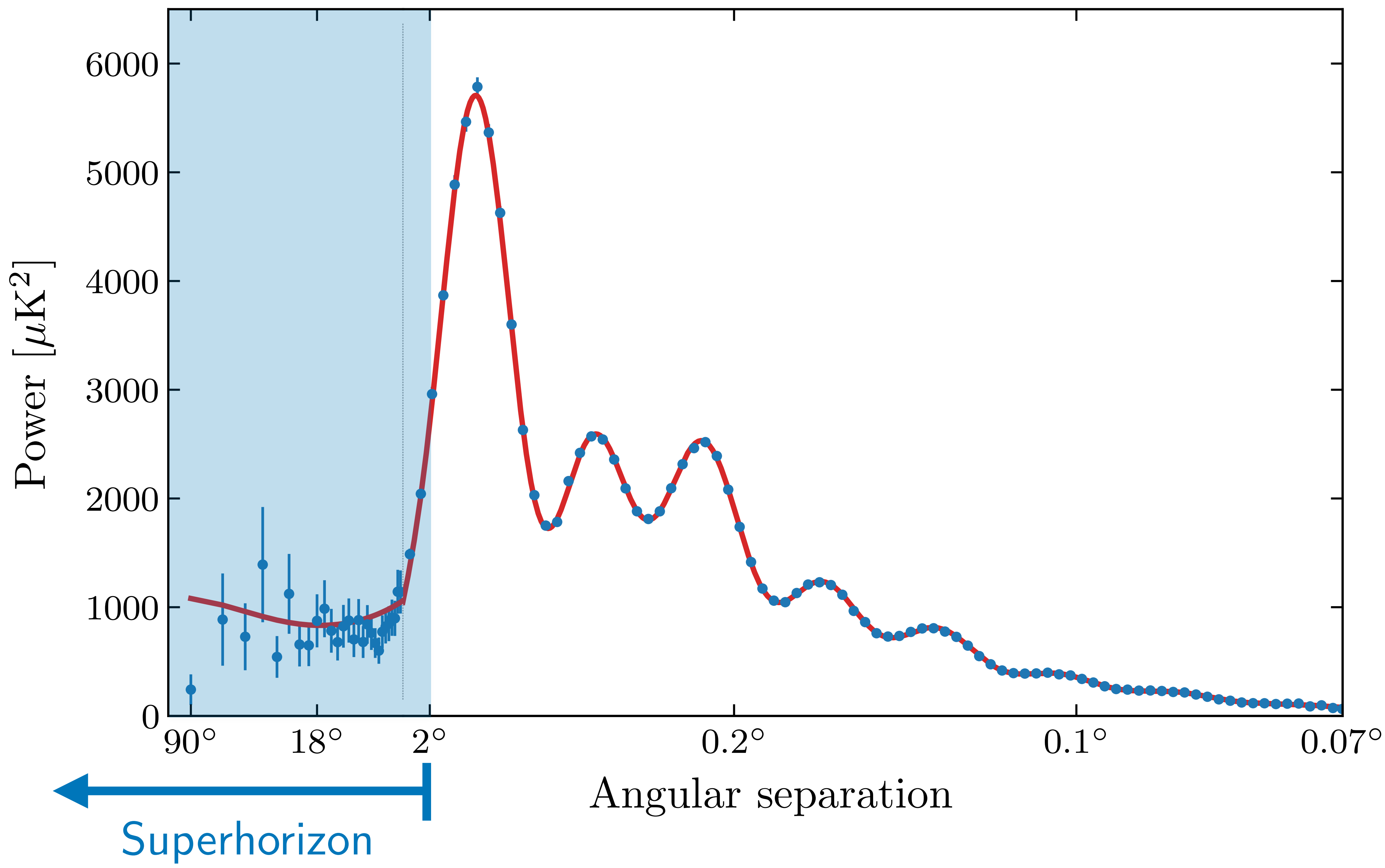
So far, we have described the evolution of fluctuations in the hot Big Bang and the formation of the large-scale structure of the Universe:



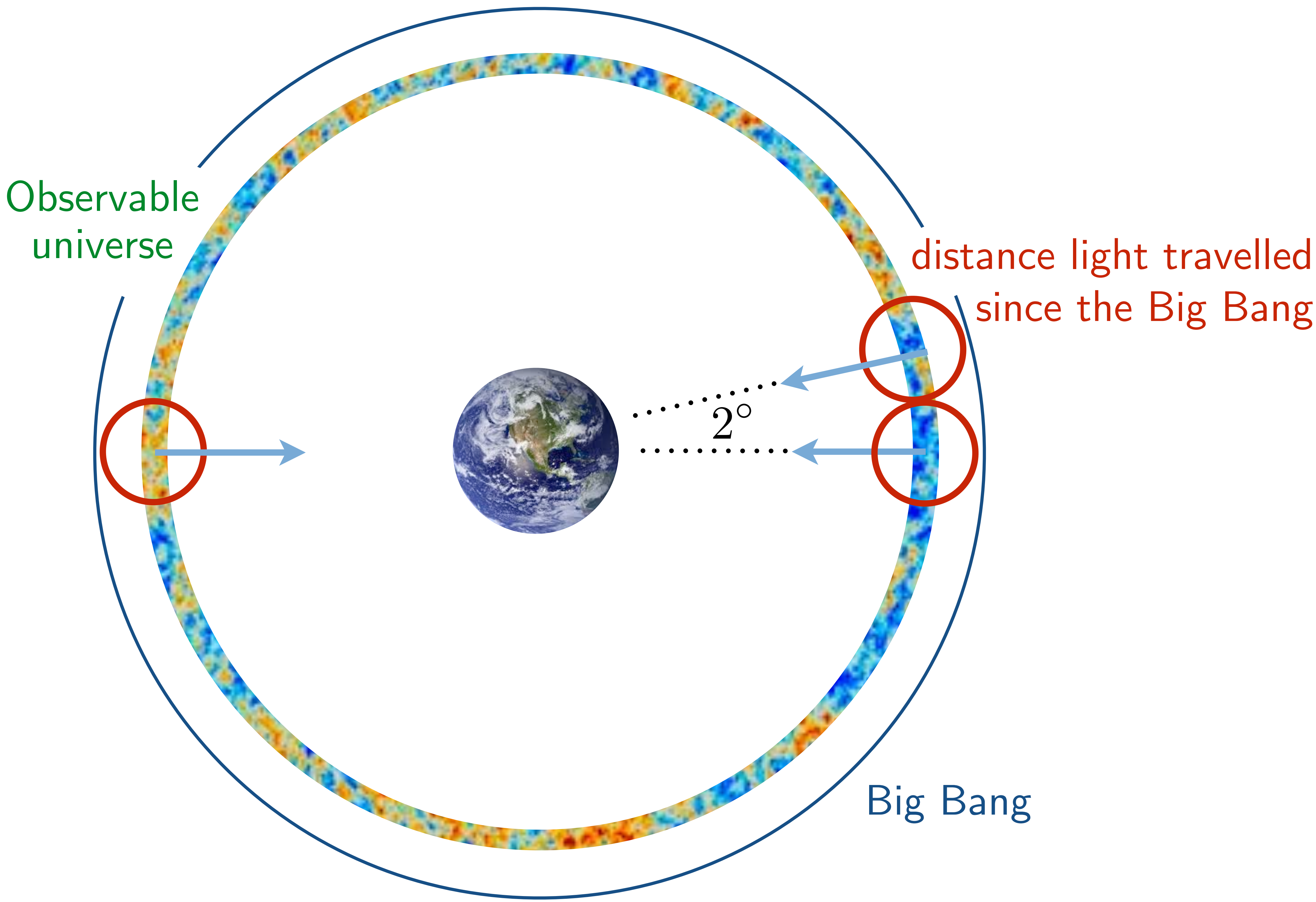
We now want to ask:

What created the primordial fluctuations?

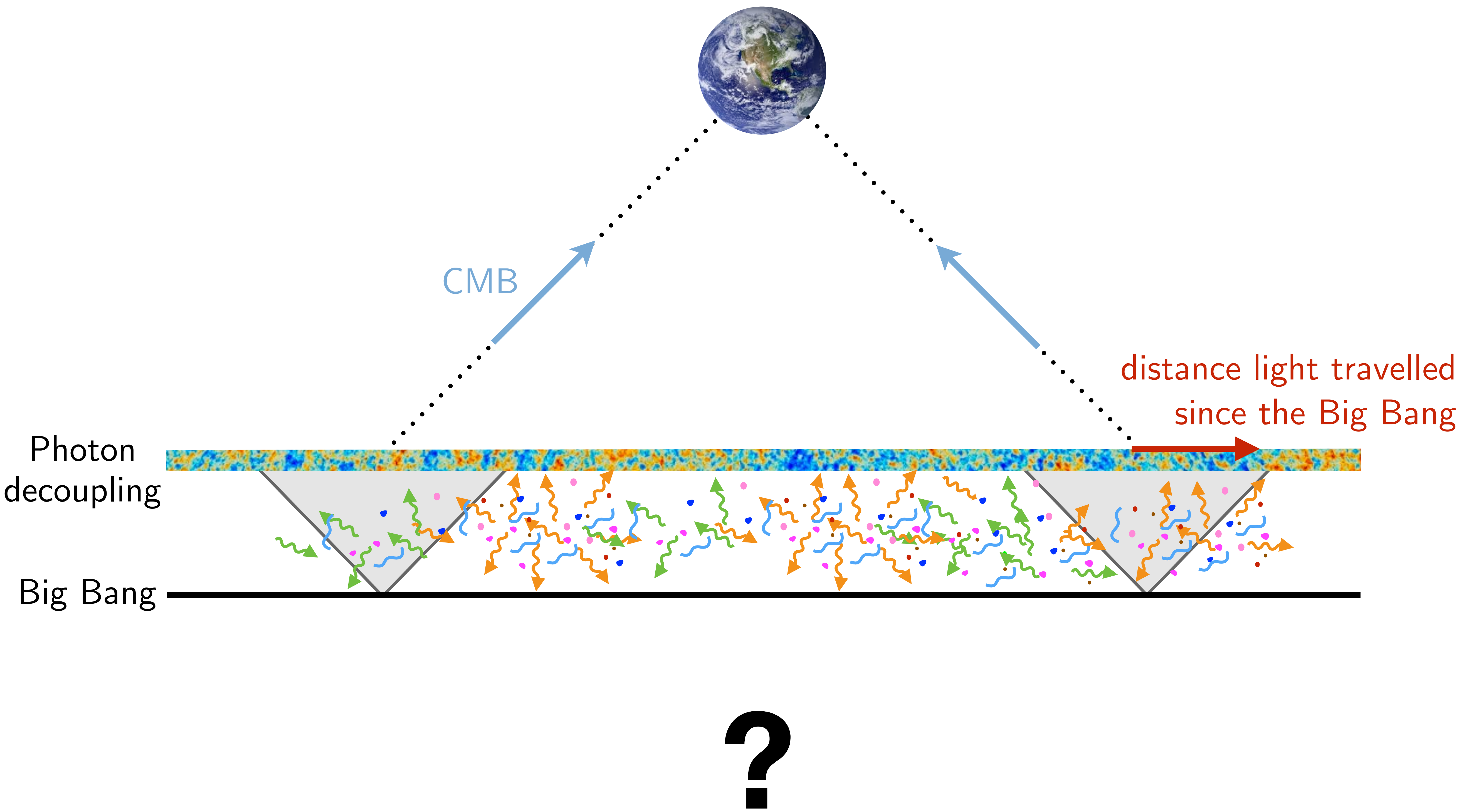
An important clue is the fact that the CMB fluctuations are **correlated over the whole sky**:



In the standard hot Big Bang theory, this is **impossible**:

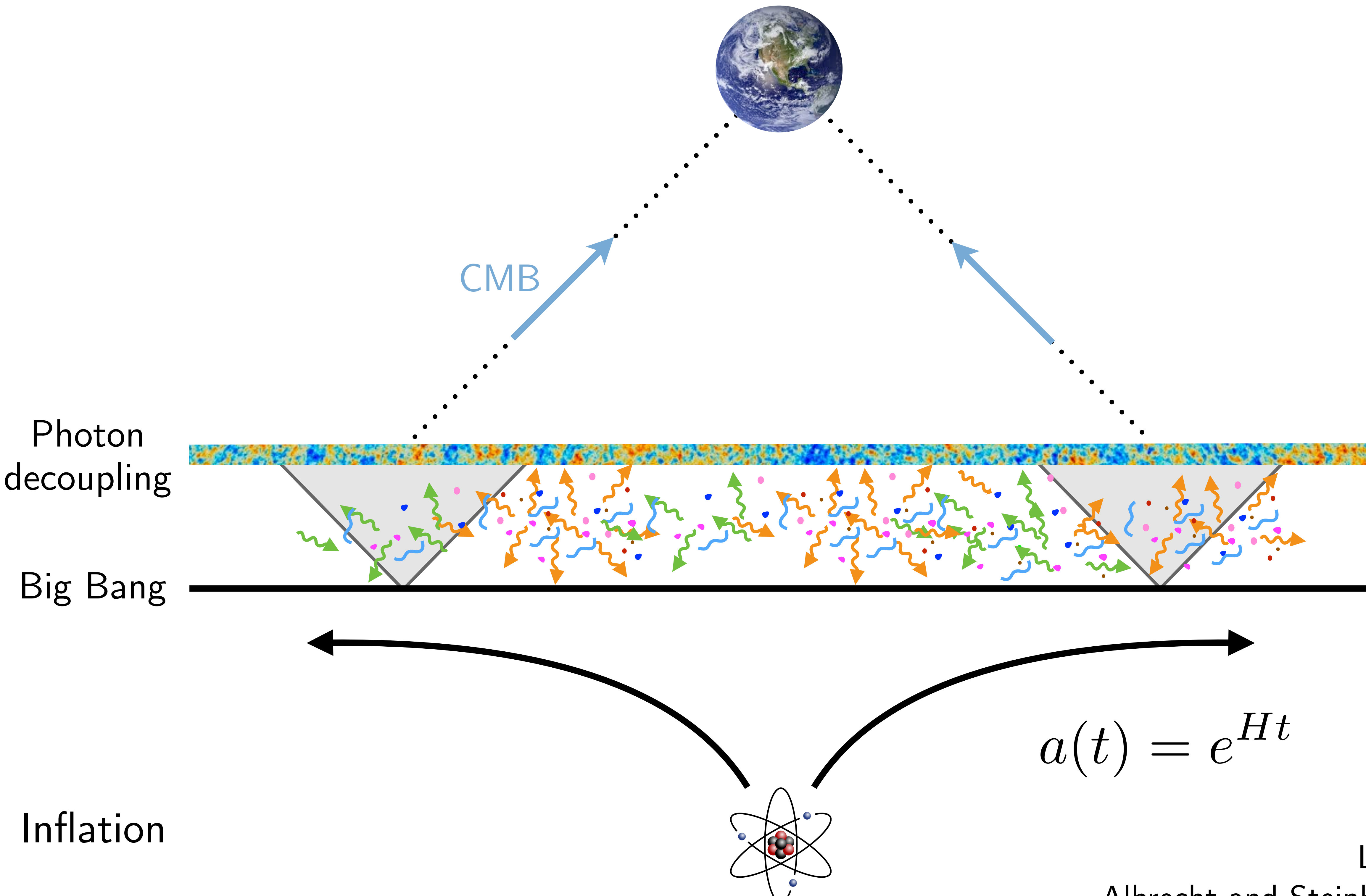


The correlations must have been created **before the hot Big Bang**:



Inflation

Inflation solves the problem by invoking a period of **superluminal expansion**:



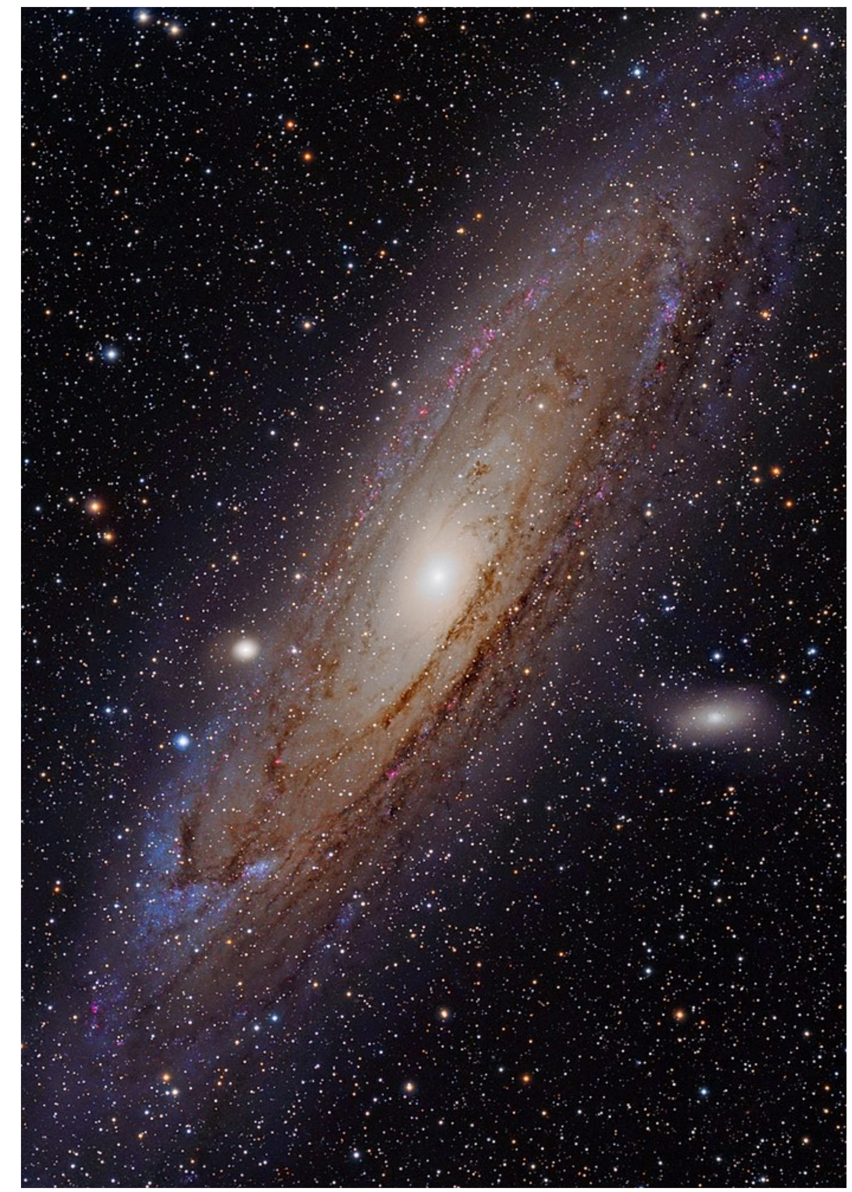
$$a(t) = e^{Ht}$$

Guth (1980)
Linde (1982)
Albrecht and Steinhardt (1982)

Inflation

In less than 10^{-32} seconds, the universe doubled in size at least 80 times:

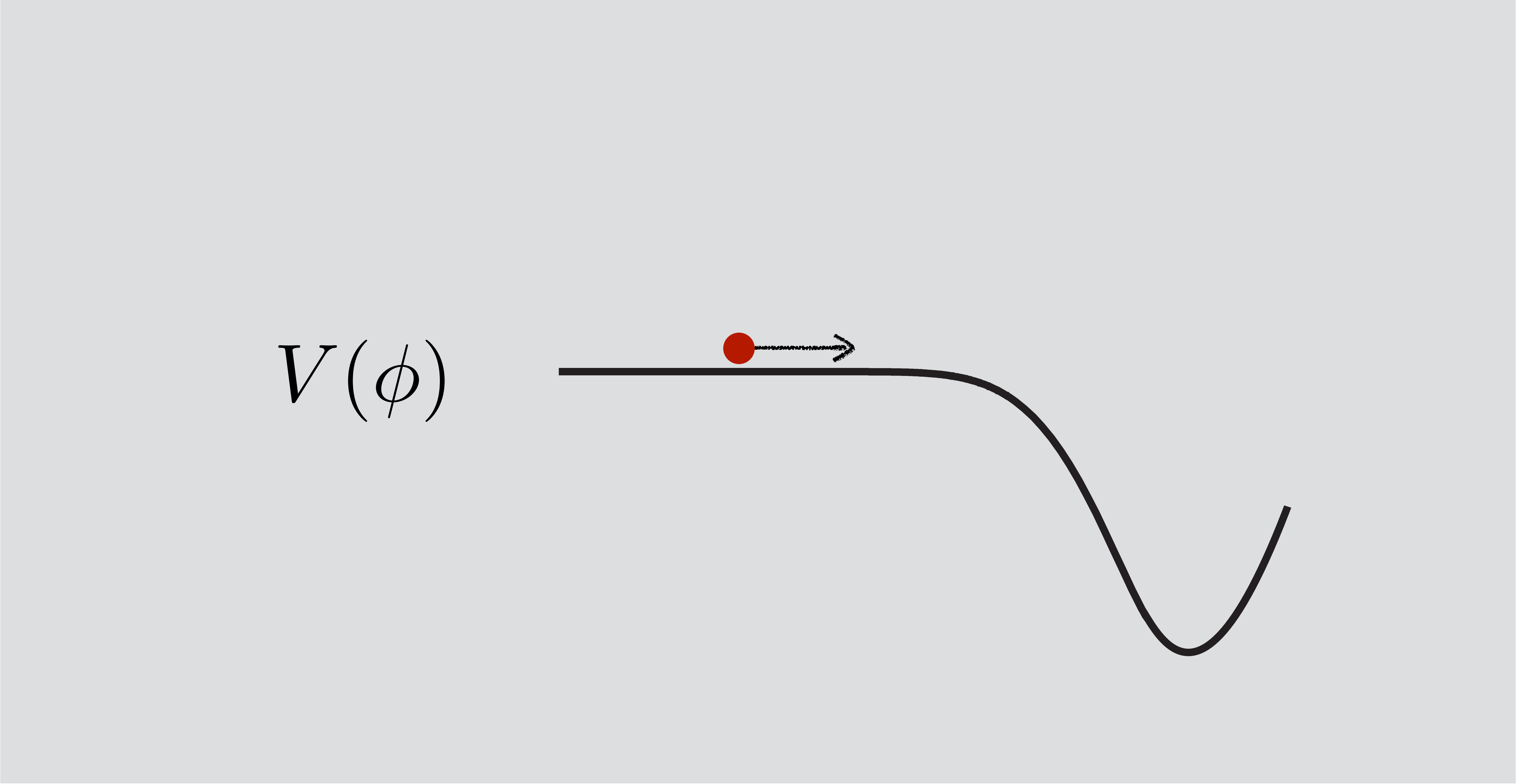
$$a(t) = e^{Ht}$$



The entire observable universe then originated from a microscopic, causally connected region of space.

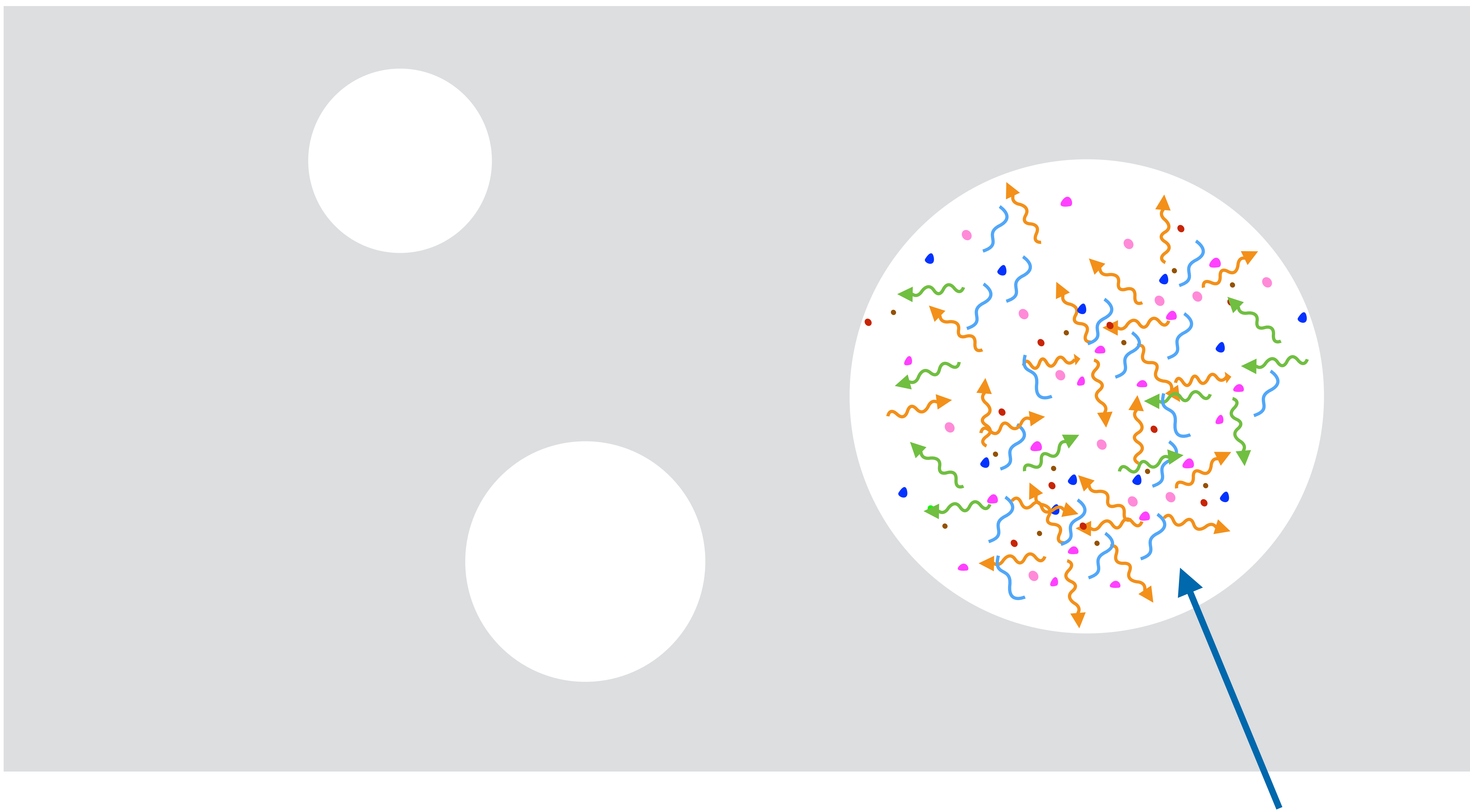
Inflation

To achieve inflation requires a substance with nearly **constant energy density** (like dark energy):



Inflation

To end inflation, this substance must **decay** (like a radioactive material):

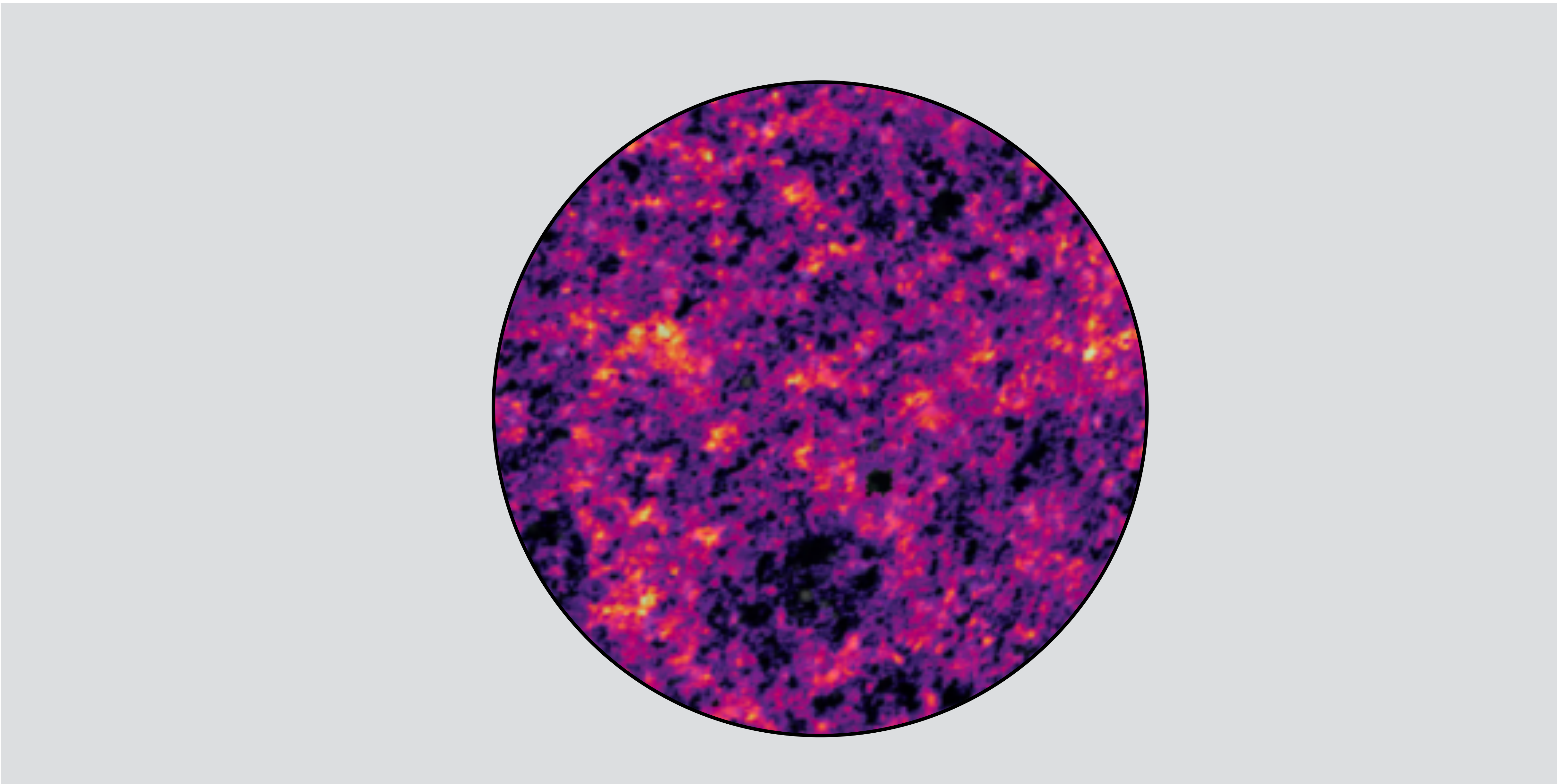


The product of this decay is the **hot Big Bang**.

One of these bubbles is our universe.

Inflation

In quantum mechanics, the end of inflation is **probabilistic** and varies throughout space:

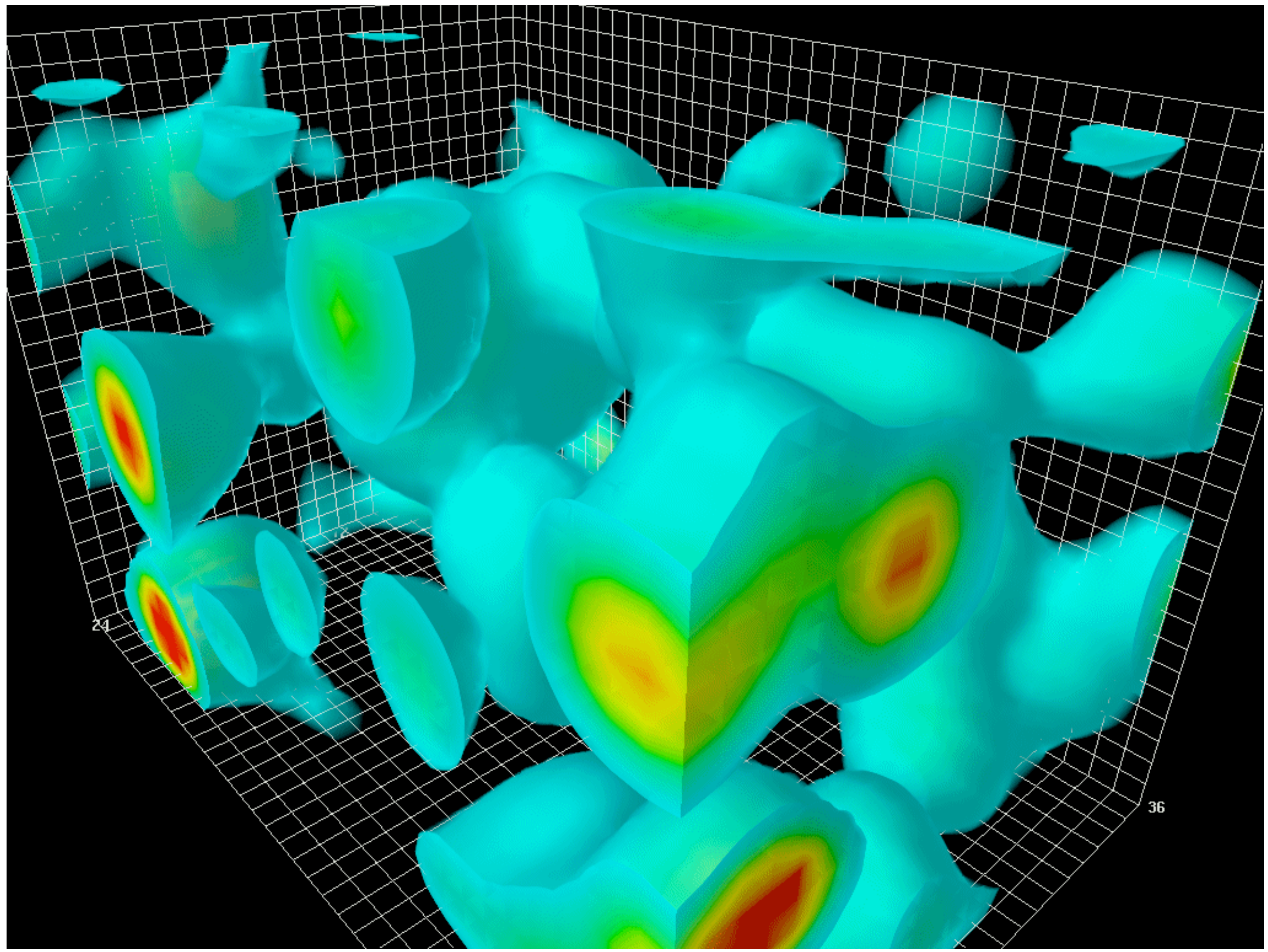


This creates the **primordial density fluctuations**.

Quantum Fluctuations

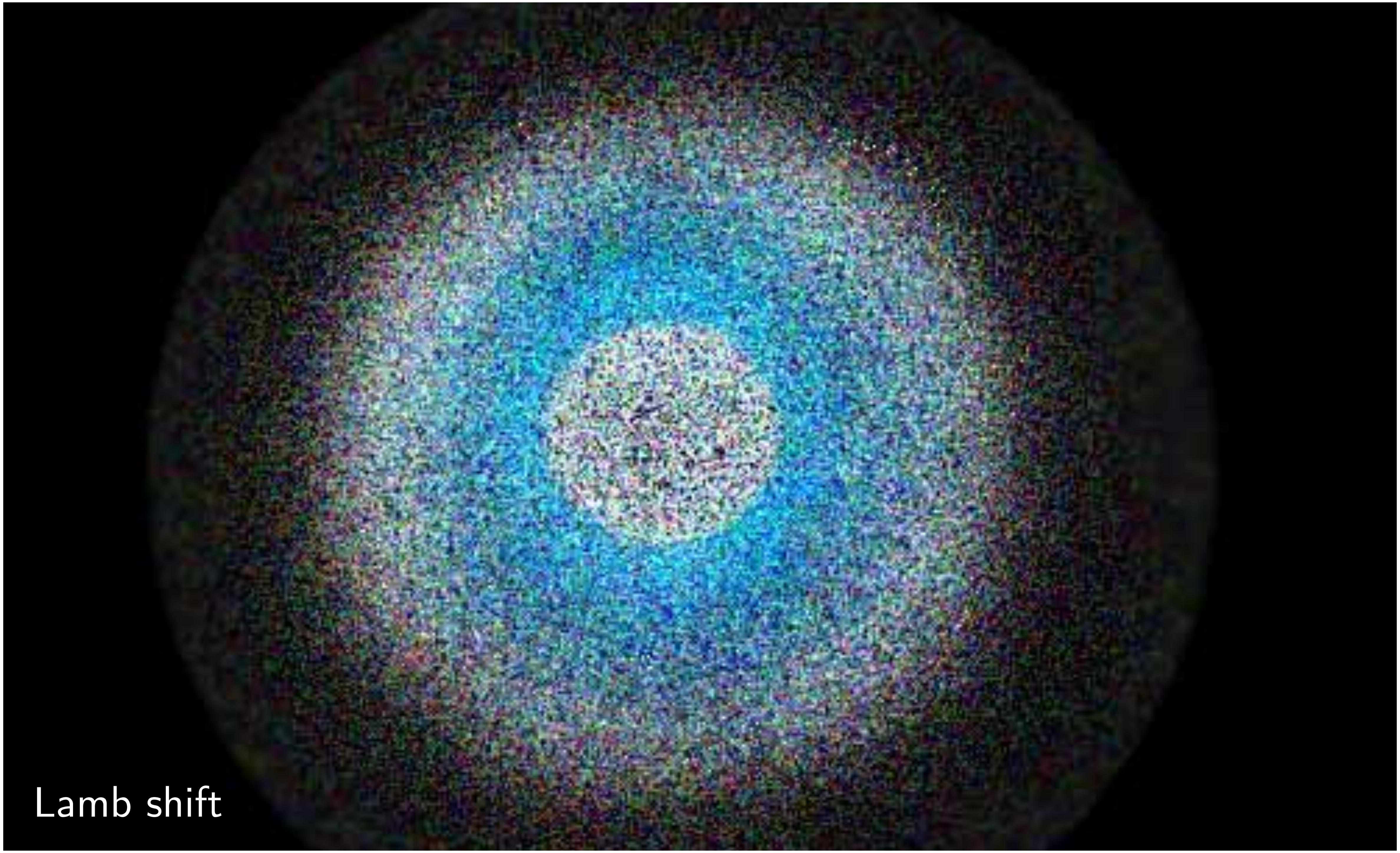
In quantum mechanics, empty space is full of violent fluctuations:

$$\Delta x \Delta p \geq \hbar$$



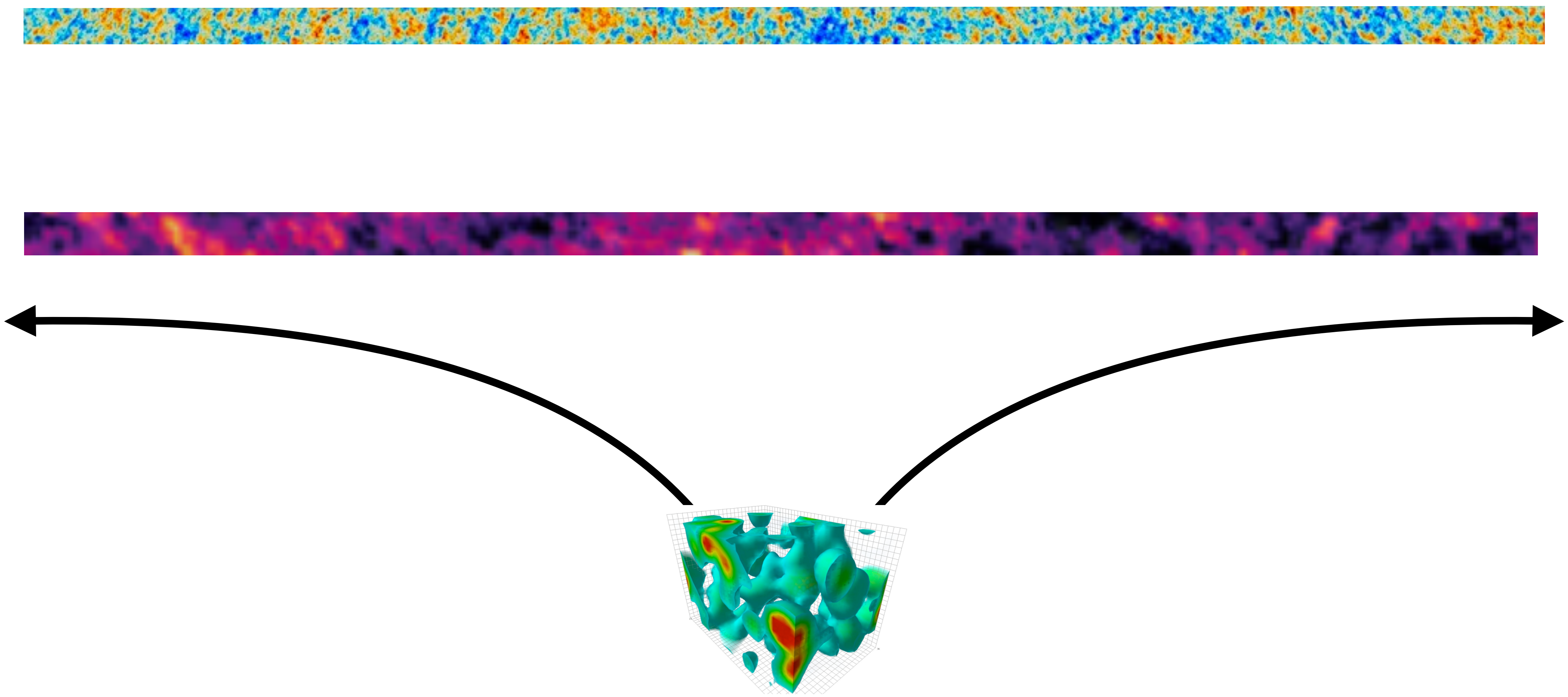
Quantum Fluctuations

These quantum fluctuations are real, but usually have small effects:



Quantum Fluctuations

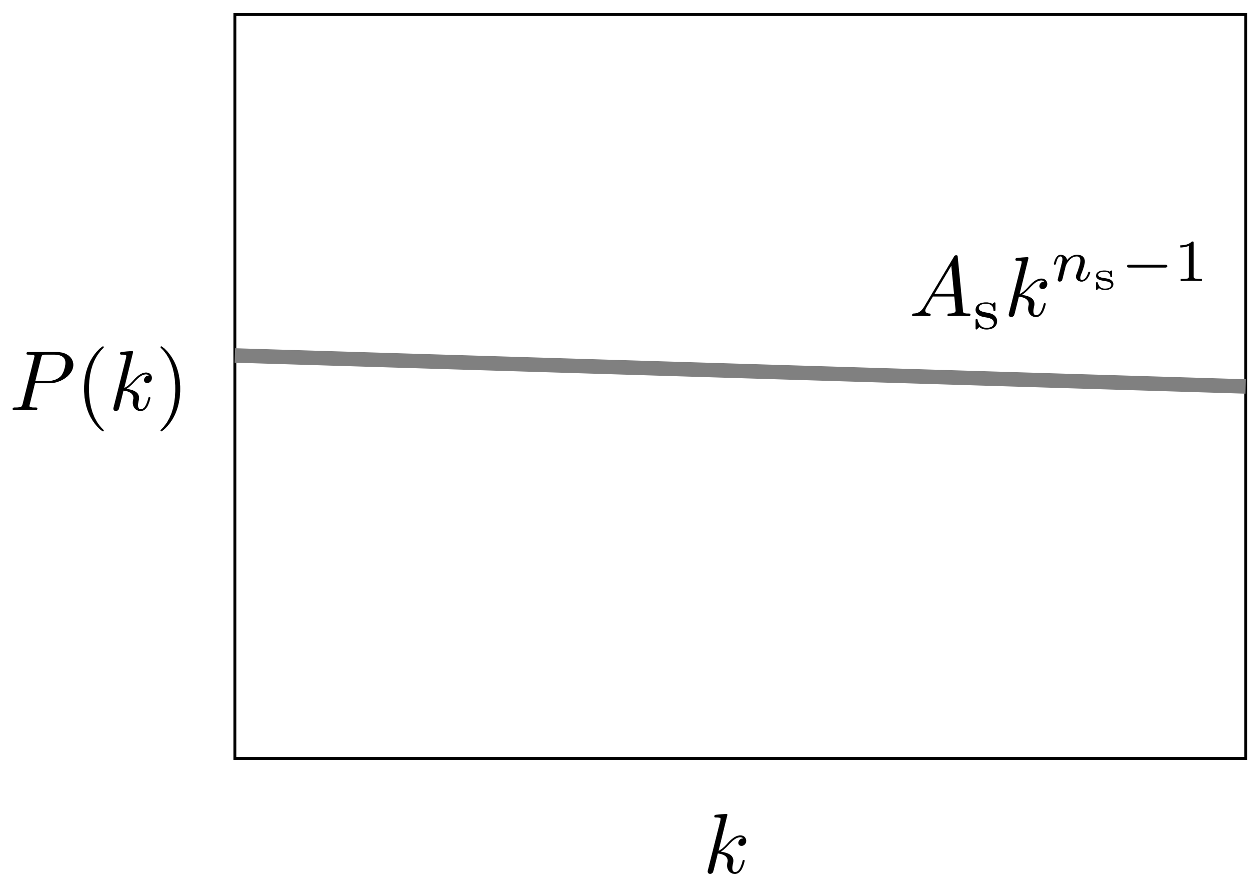
During inflation, these quantum fluctuations get amplified and stretched:

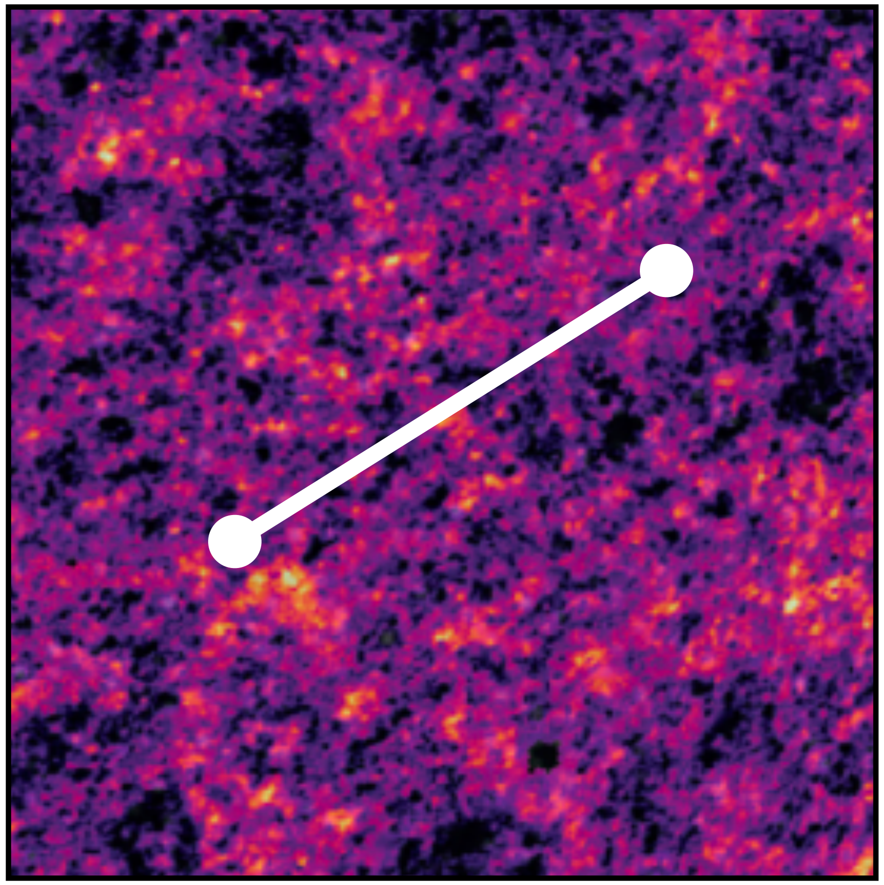


After inflation, these fluctuations become the large-scale density fluctuations.

Primordial Correlations

The nearly constant inflationary vacuum energy leads to an approximately **scale-invariant** power spectrum:

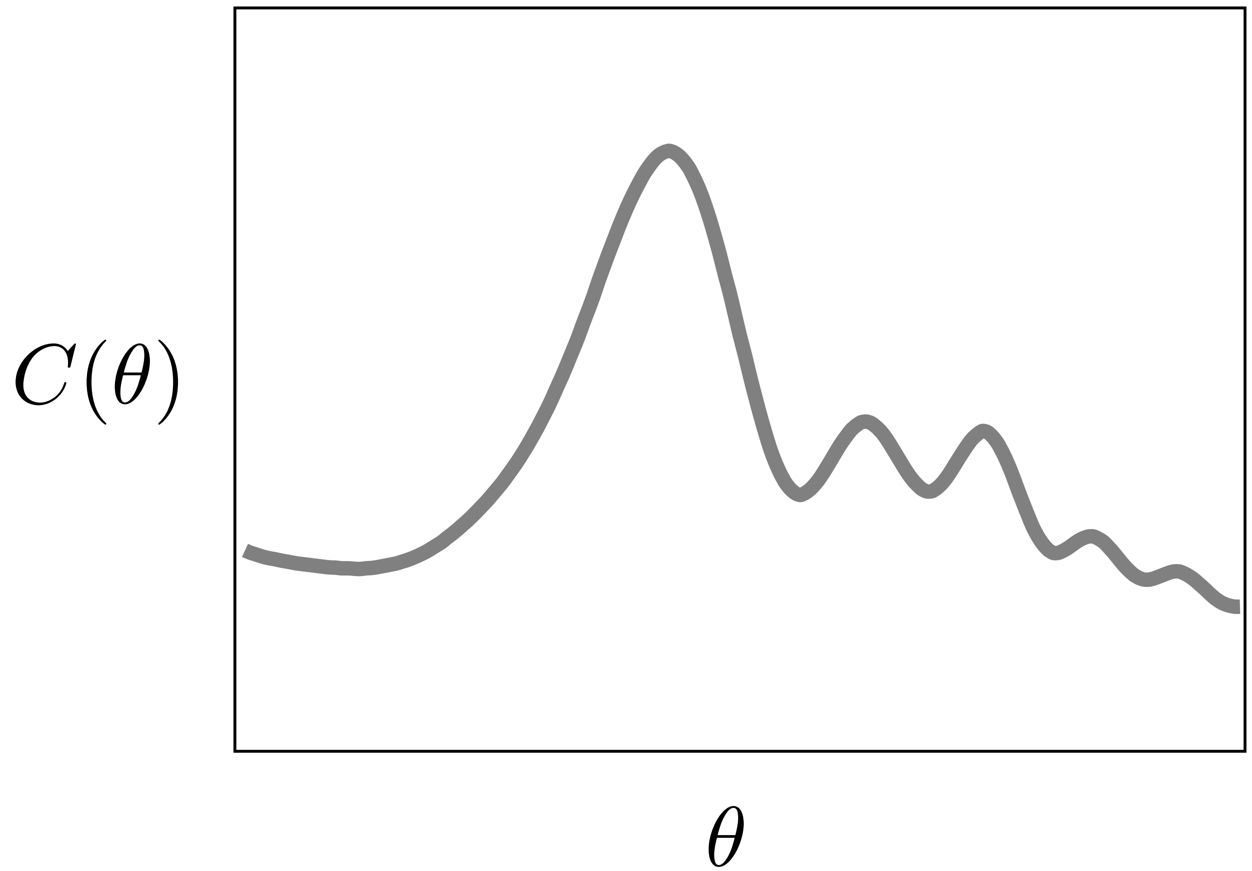


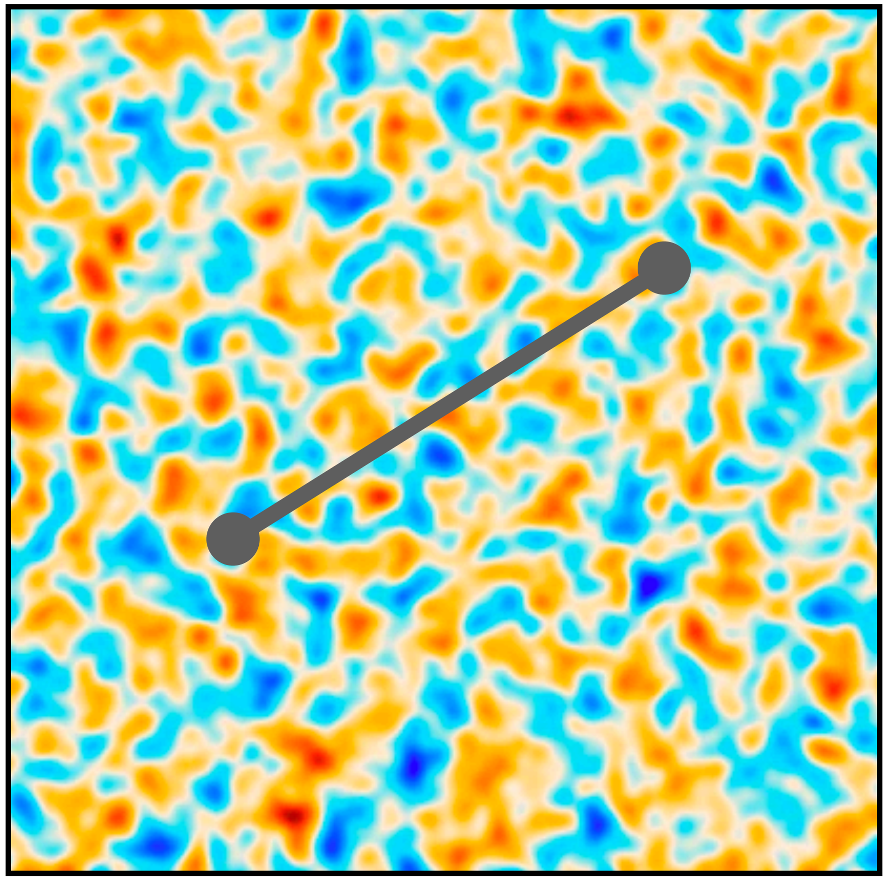


The slow decay of the inflationary energy predicts slightly more power on large scales: $n_\mathrm{s} < 1$

CMB Anisotropies

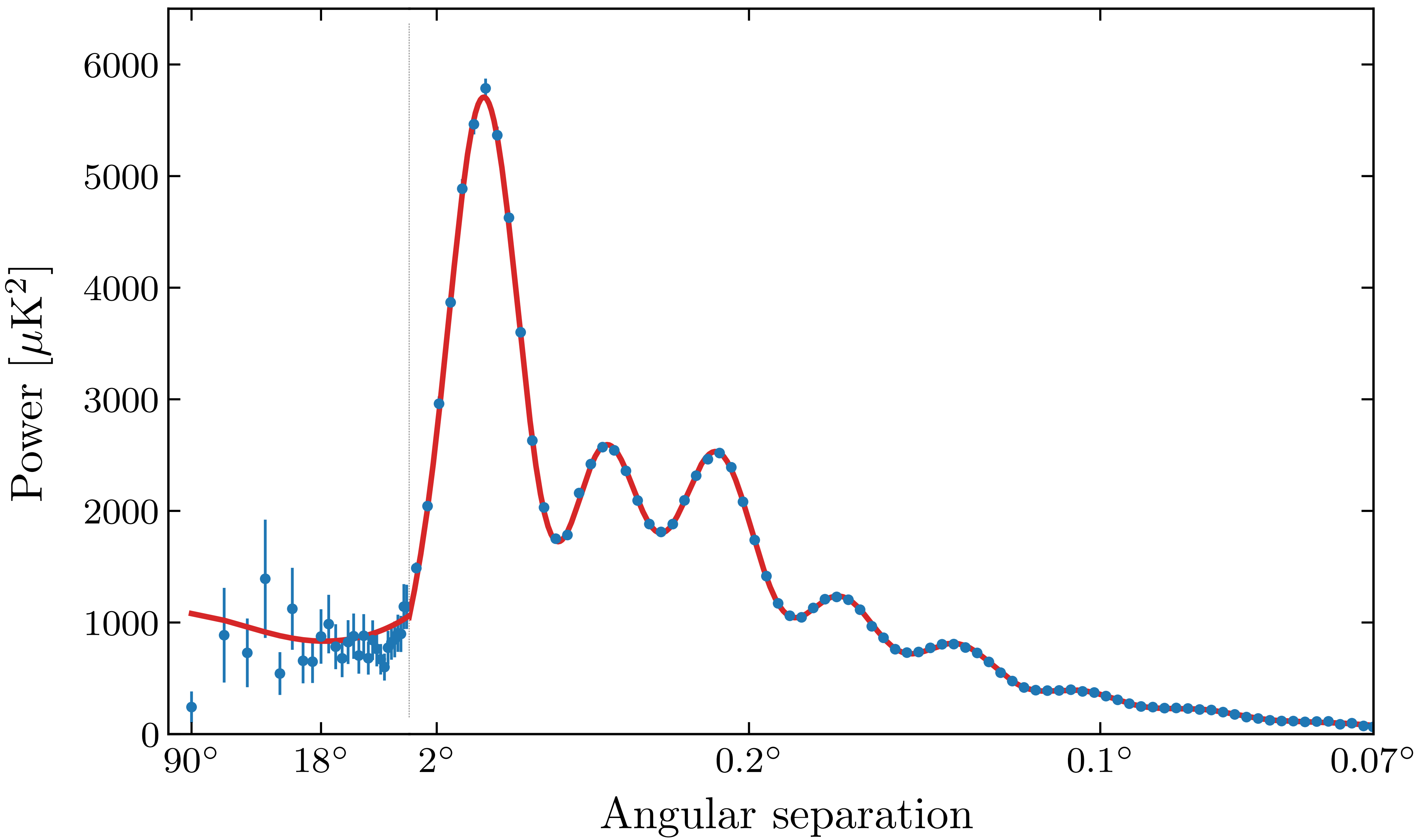
The well-understood physics of the photon-baryon fluid turns these primordial correlations into correlations of the CMB anisotropies:





CMB Anisotropies

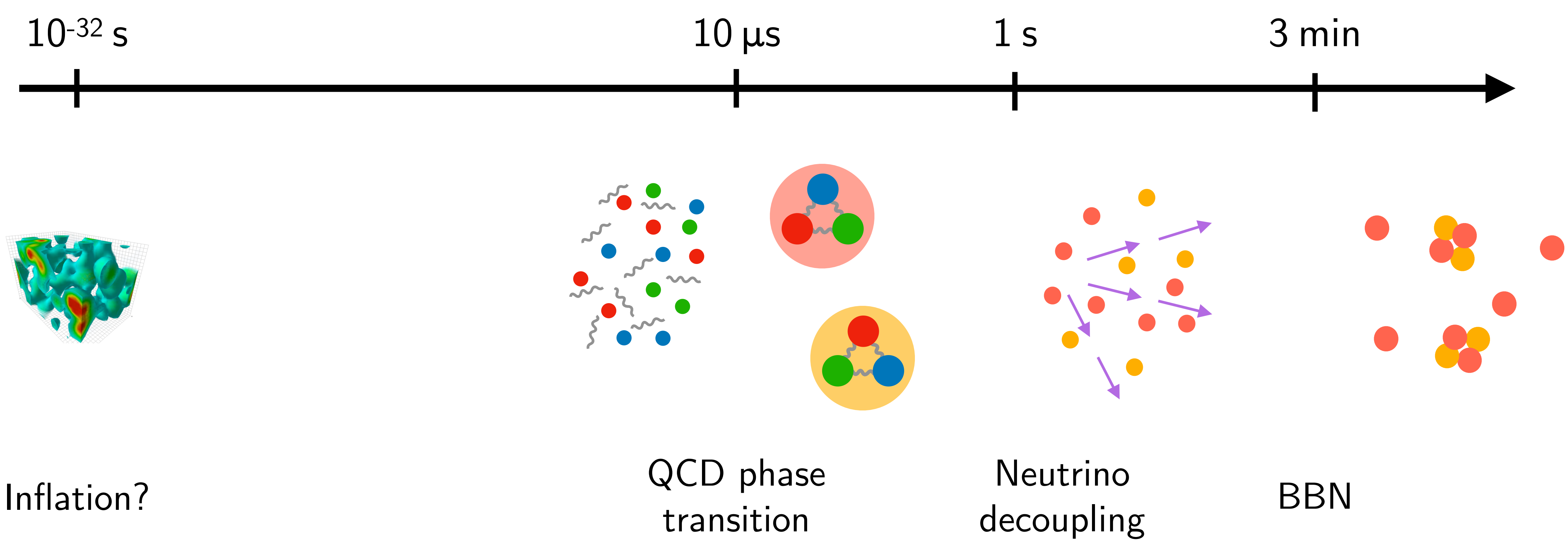
The predicted correlations are in remarkable agreement with the data:



“Extraordinary claims require extraordinary evidence”

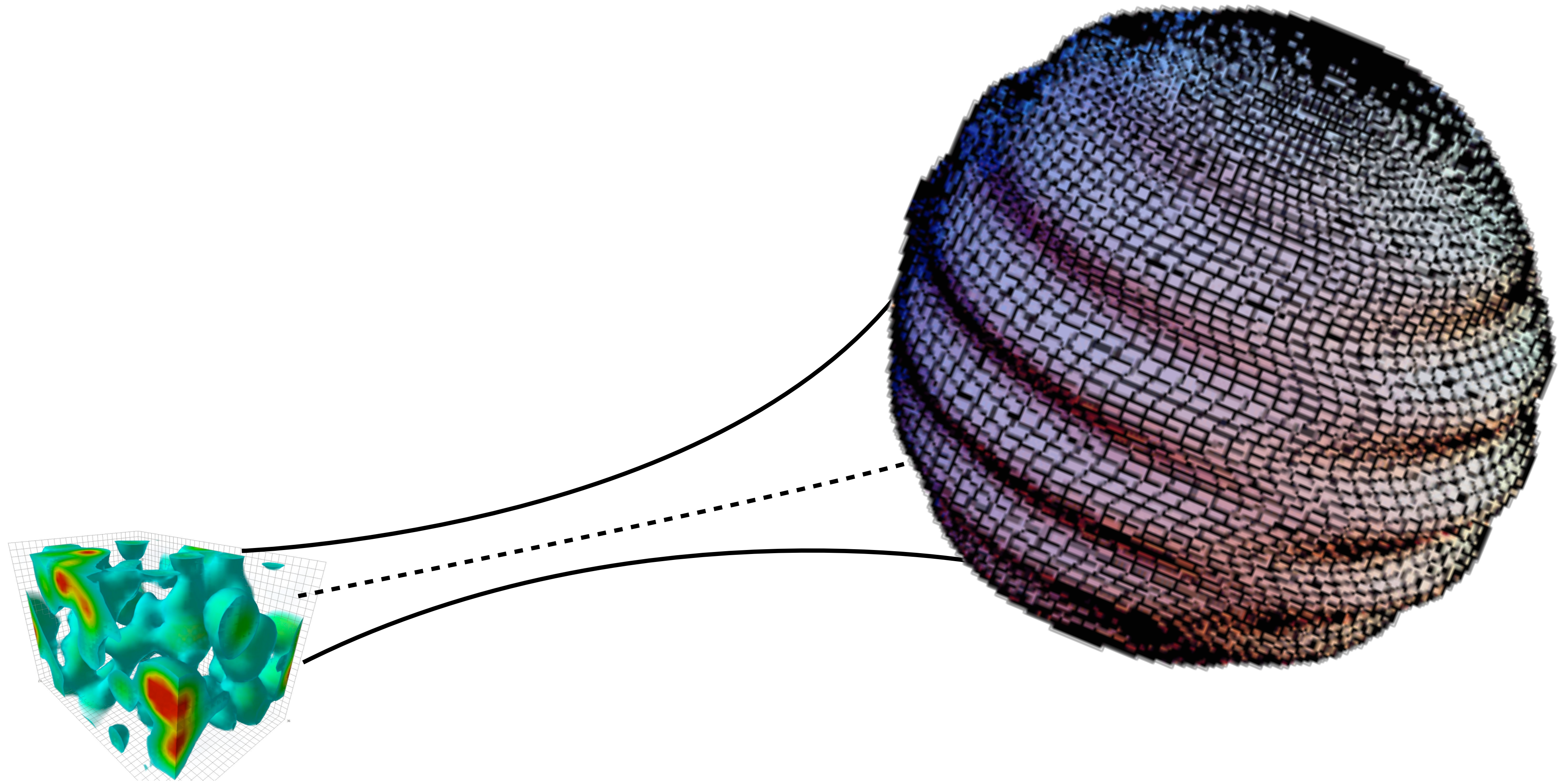
Carl Sagan

How can inflation become part of the standard history of the universe with the same level of confidence as BBN ?



Primordial Gravitational Waves

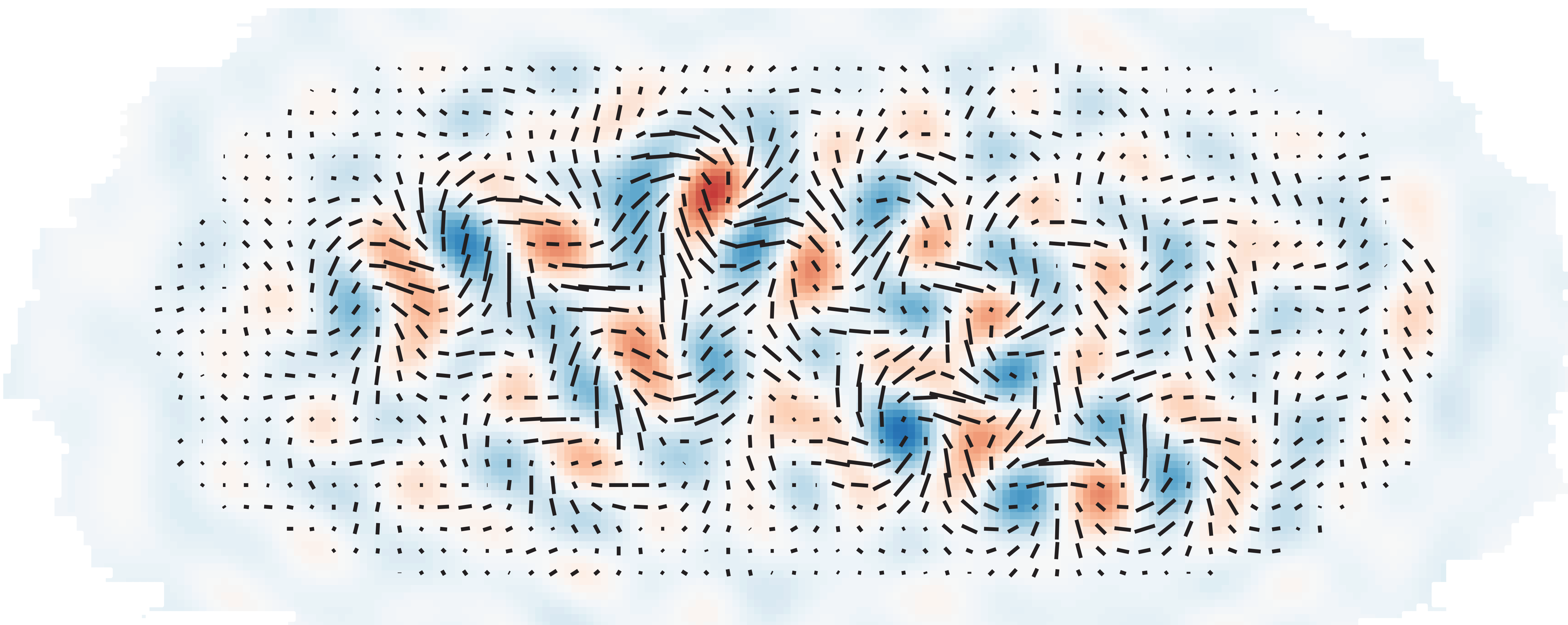
Besides density fluctuations, inflation predicts **gravitational waves**:



The strength of the signal depends on the energy scale of inflation, which may be as high as 10^{16} GeV.

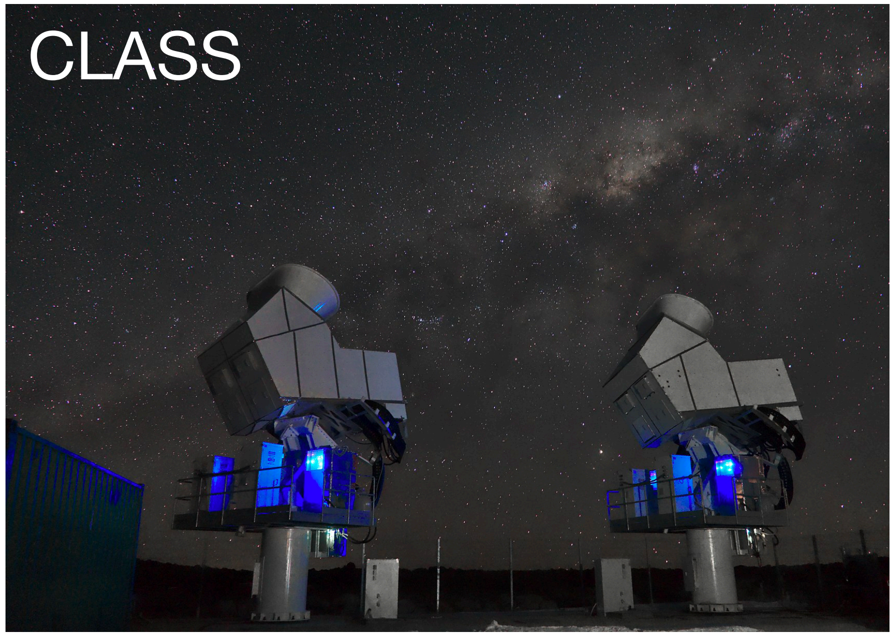
B-modes

These gravitational waves would produce a characteristic swirl pattern (called **B-modes**) in the polarization of the CMB:



Detecting these B-modes is a central goal of observational cosmology.

Ongoing Experiments



CMB Stage III

Planned Experiments

SIMONS
OBSERVATORY

CMB Stage III.5

(2021-2028)

Planned Experiments

CMB Stage IV

(2028-2035)

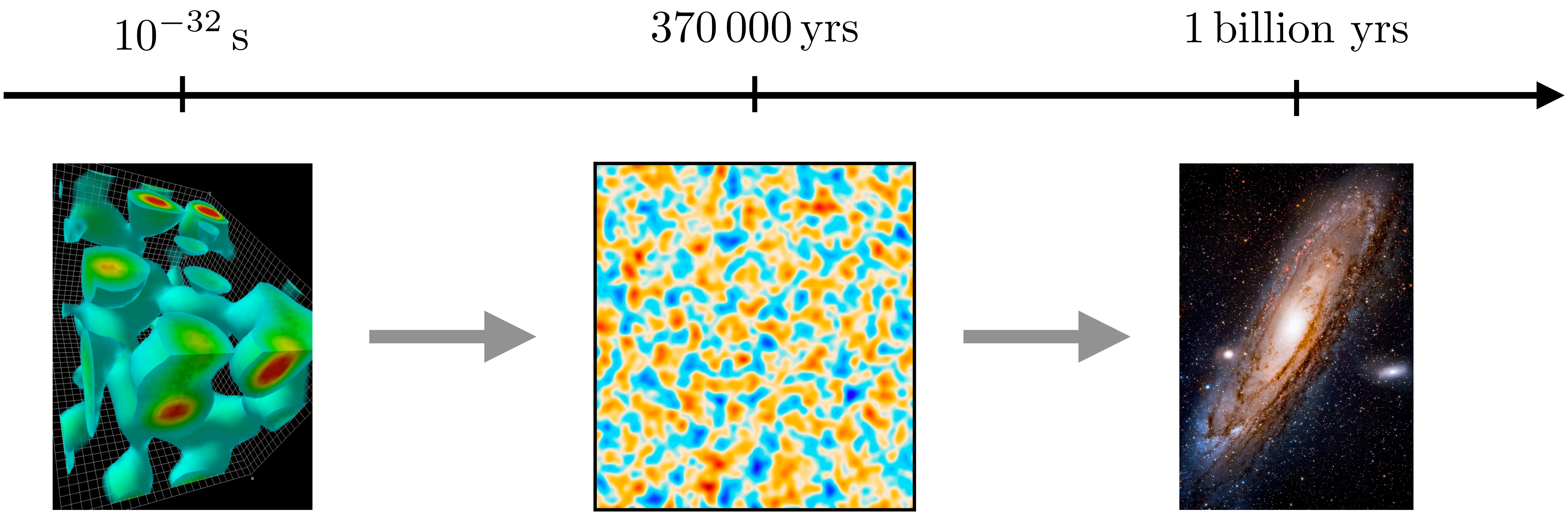
Planned Experiments

LiteBIRD

Selected by JAXA in 2019

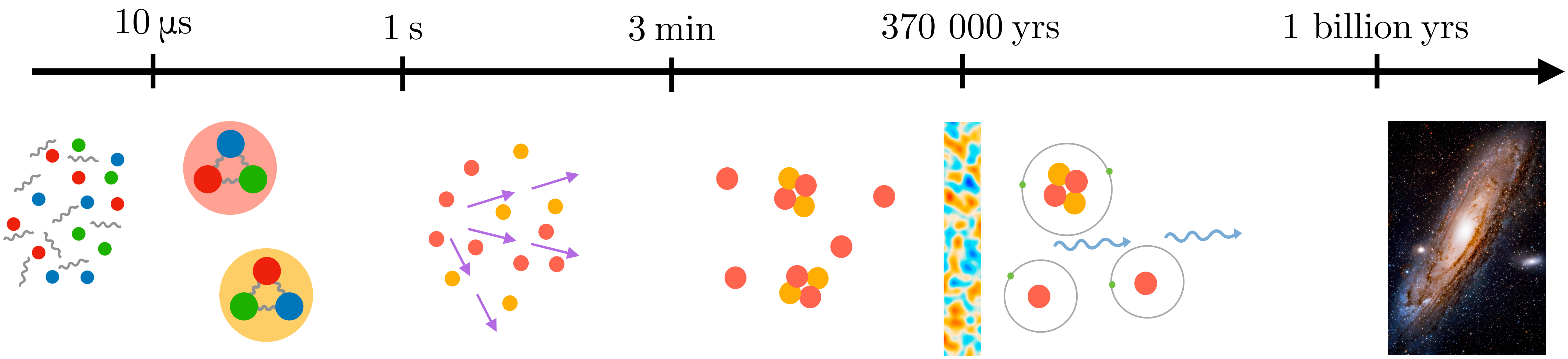
Launch in 2028

A B-mode detection would be a milestone towards a complete understanding of the origin of all structure in the universe

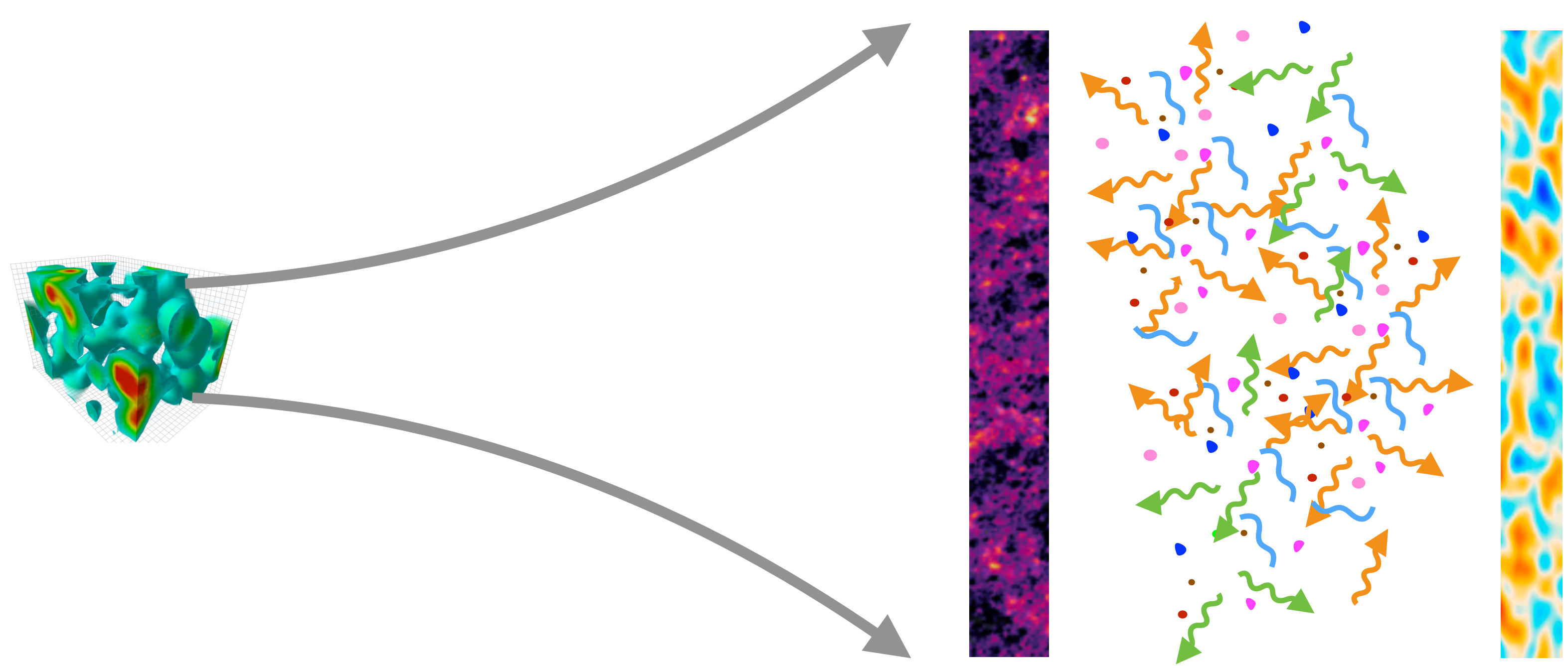


Conclusions

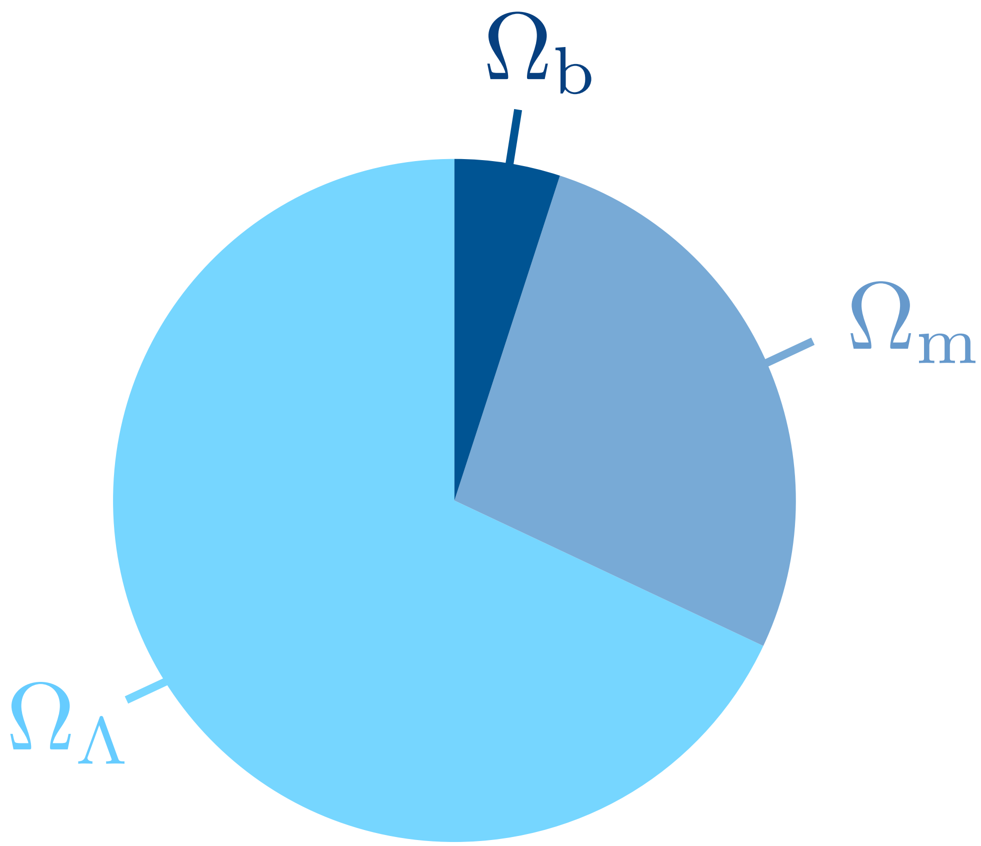
We have a remarkably consistent picture of the history of the Universe from fractions of a second after the Big Bang until today:

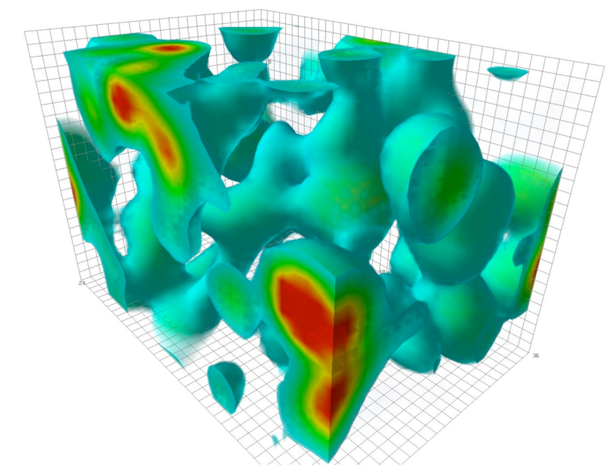


We also have tantalizing evidence that the primordial seed fluctuations for the formation of structure were created during a period of inflation:



Observations of the CMB have revolutionized cosmology:





$A_{\rm s}$, $n_{\rm s}$

Yet, many fundamental questions remain:

- What is dark matter and dark energy?
- Did inflation really occur? And what was driving it?
- What is the origin of the matter-antimatter asymmetry?
- ...

We hope that future observations will shed light on these questions.