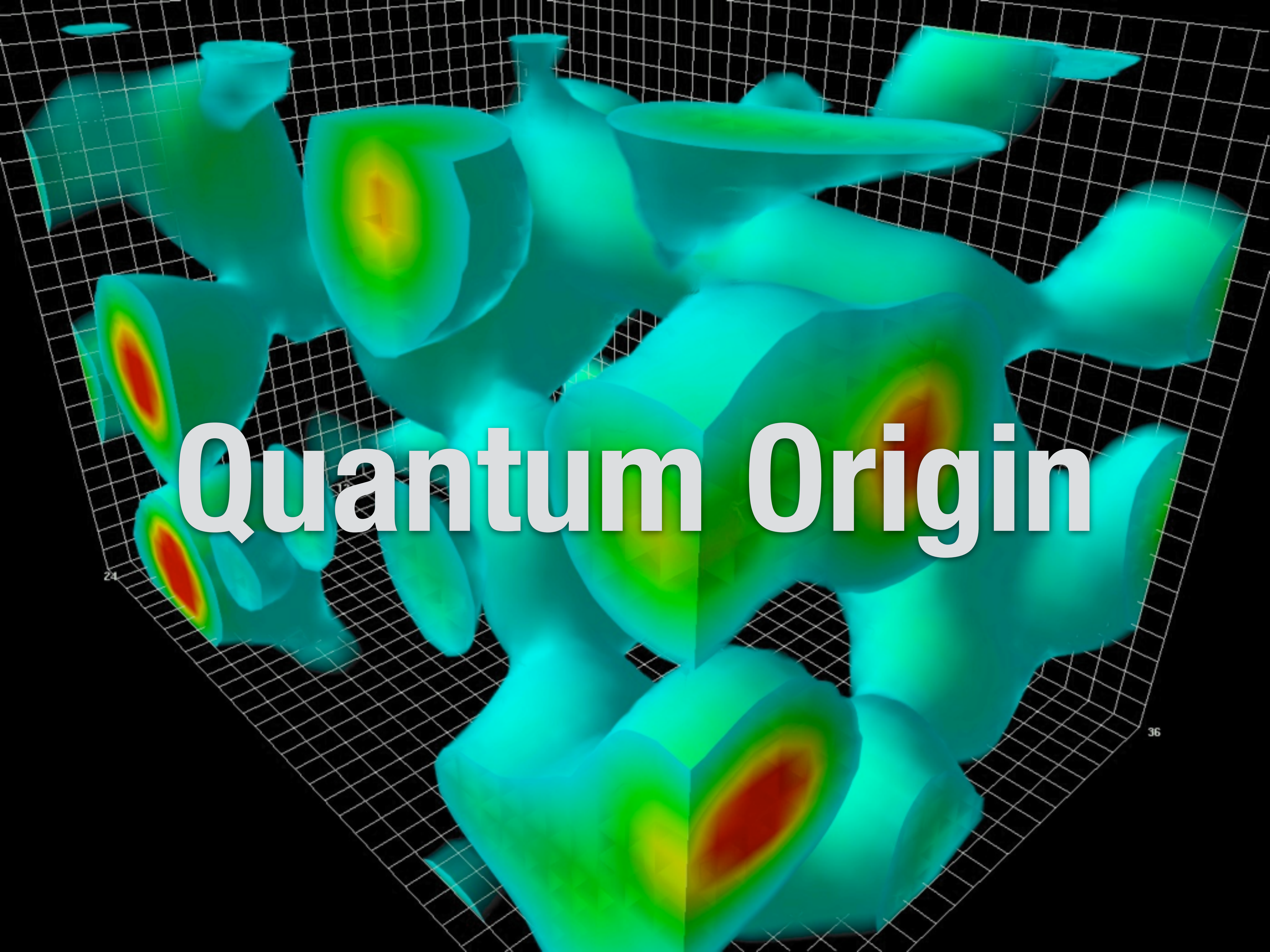
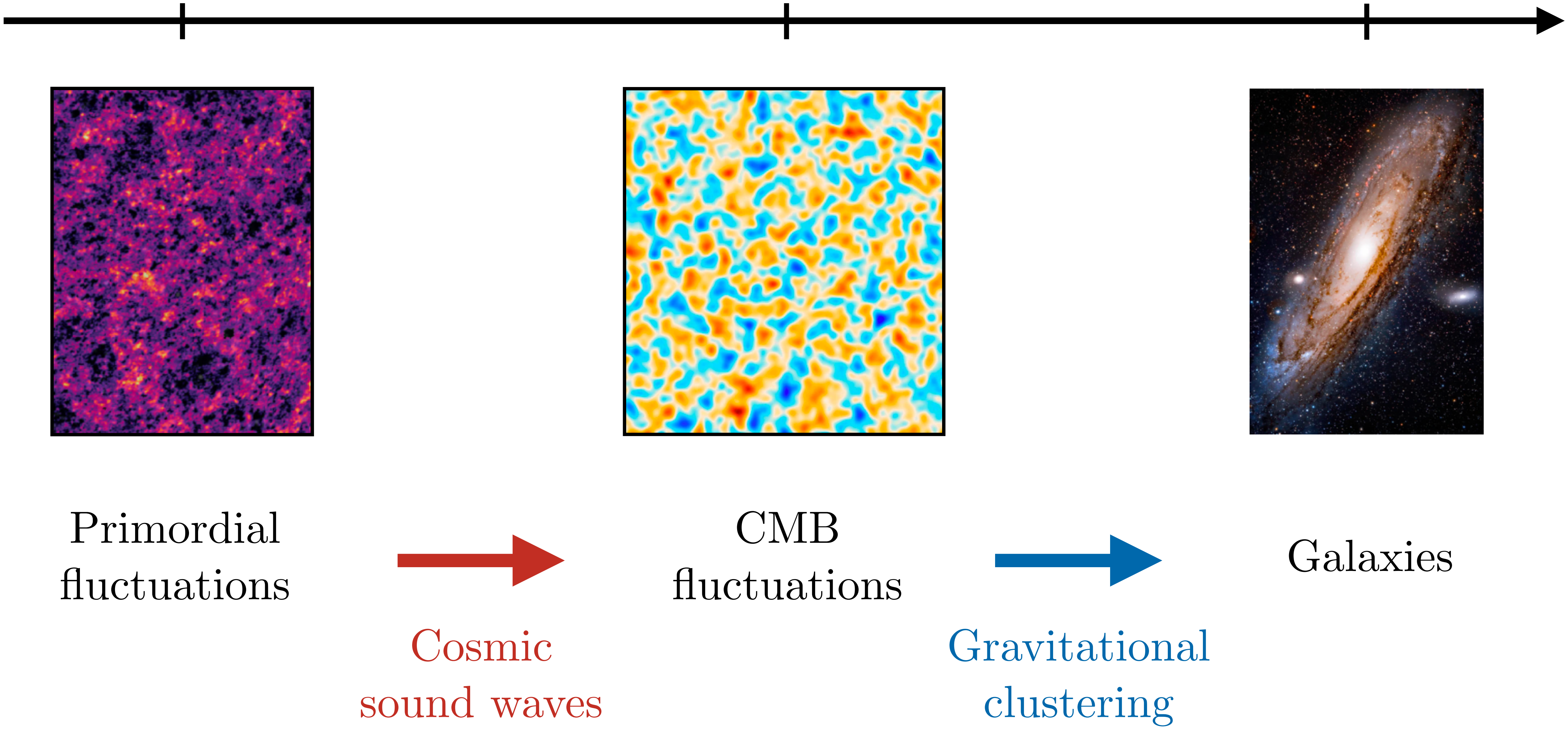
Quantum Origin



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:



Primordial fluctuations

Cosmic sound waves

CMB fluctuations

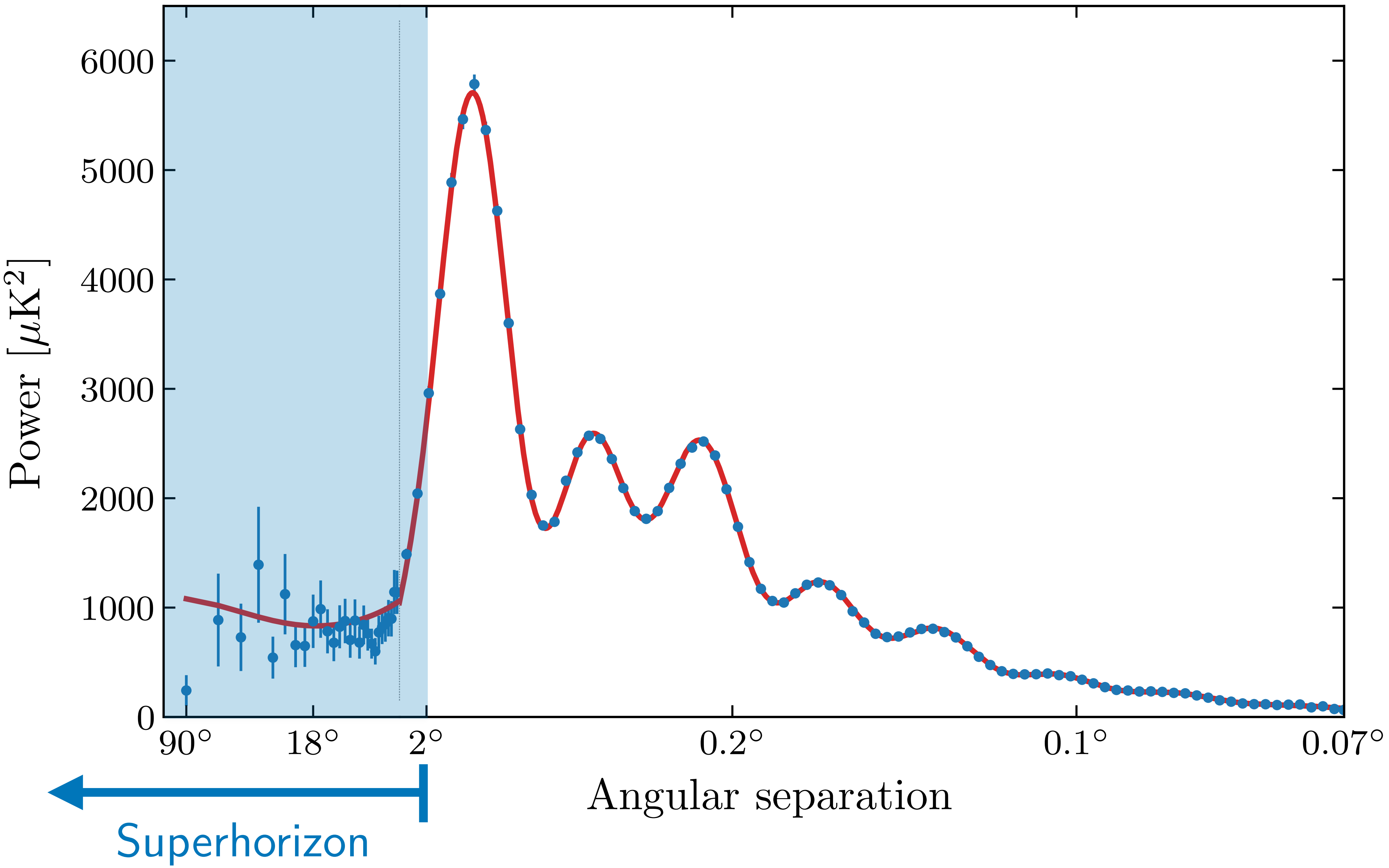
Gravitational clustering

Galaxies

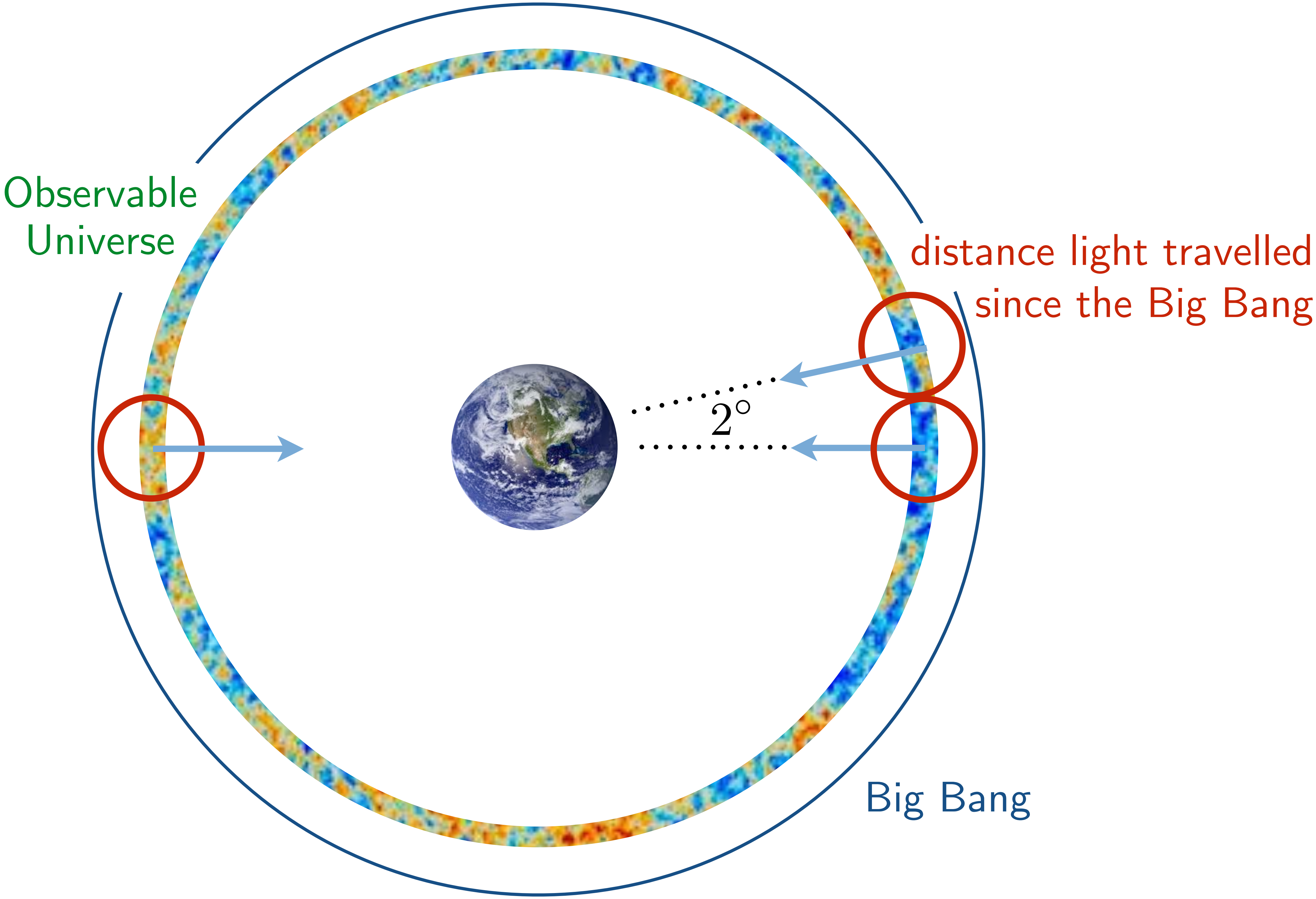
We now want to ask:

What created the primordial fluctuations?

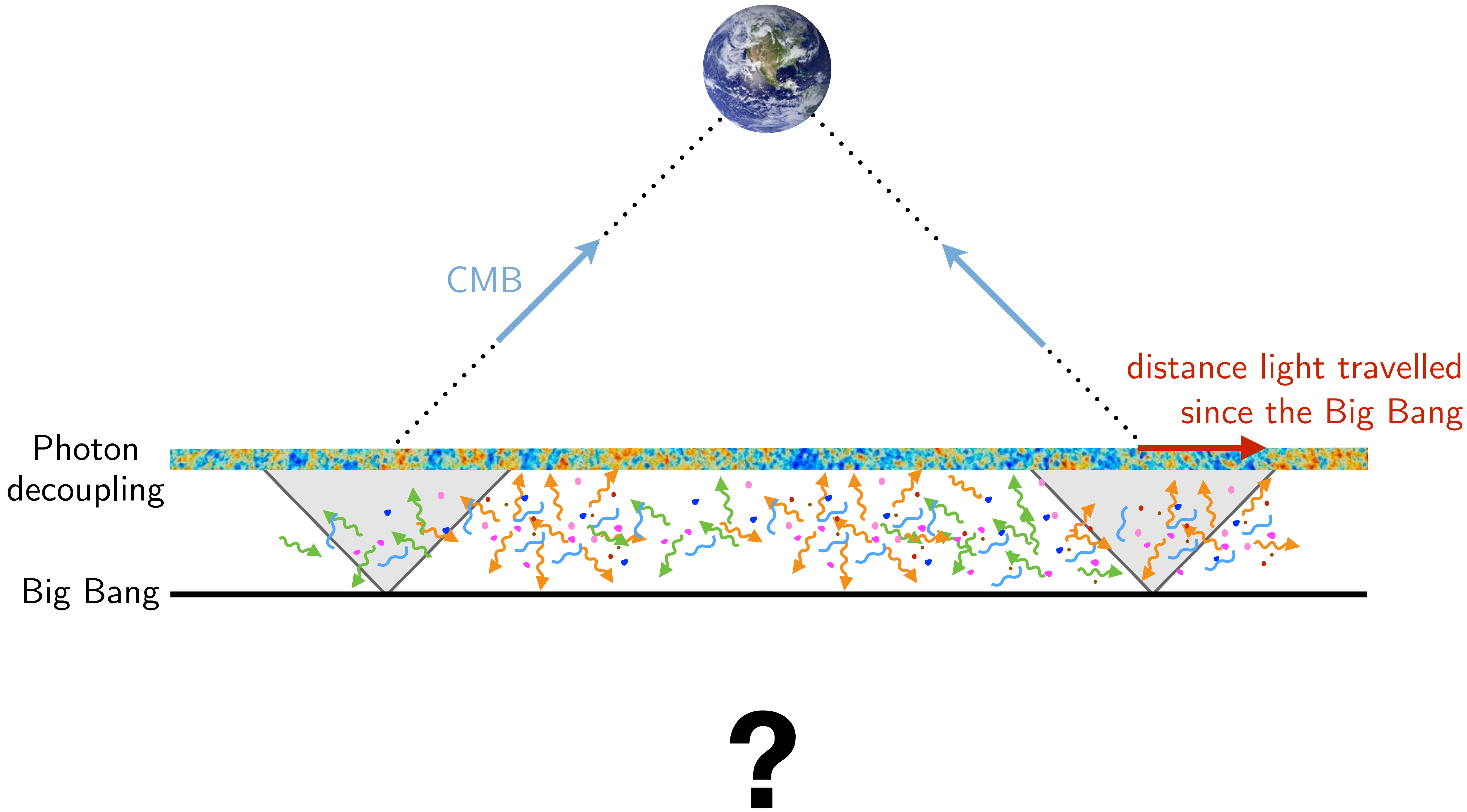
An important clue is the fact that the CMB fluctuations are **correlated over the whole sky**:



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

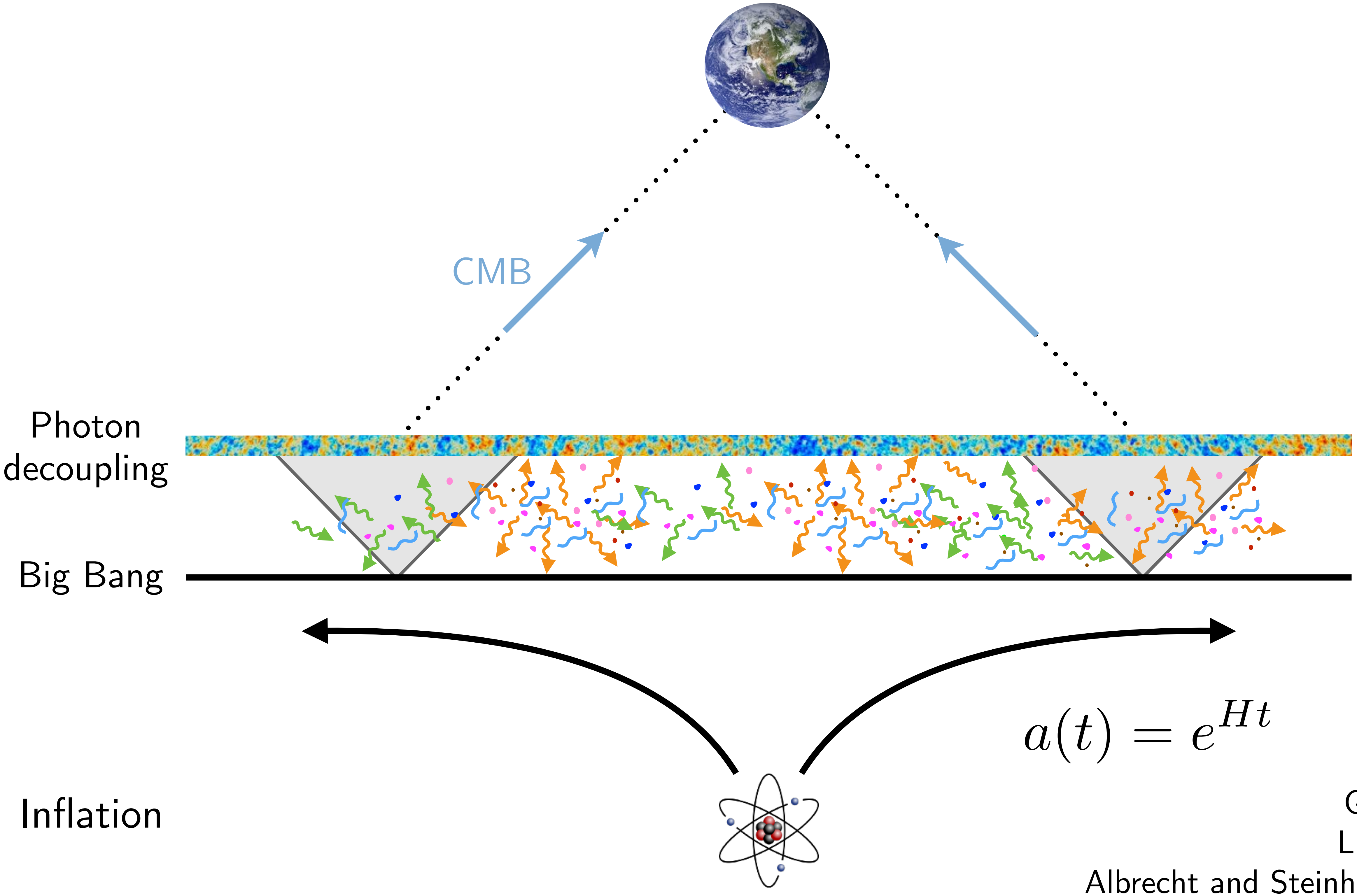


The correlations must have been created **before the hot Big Bang**:



Inflation

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

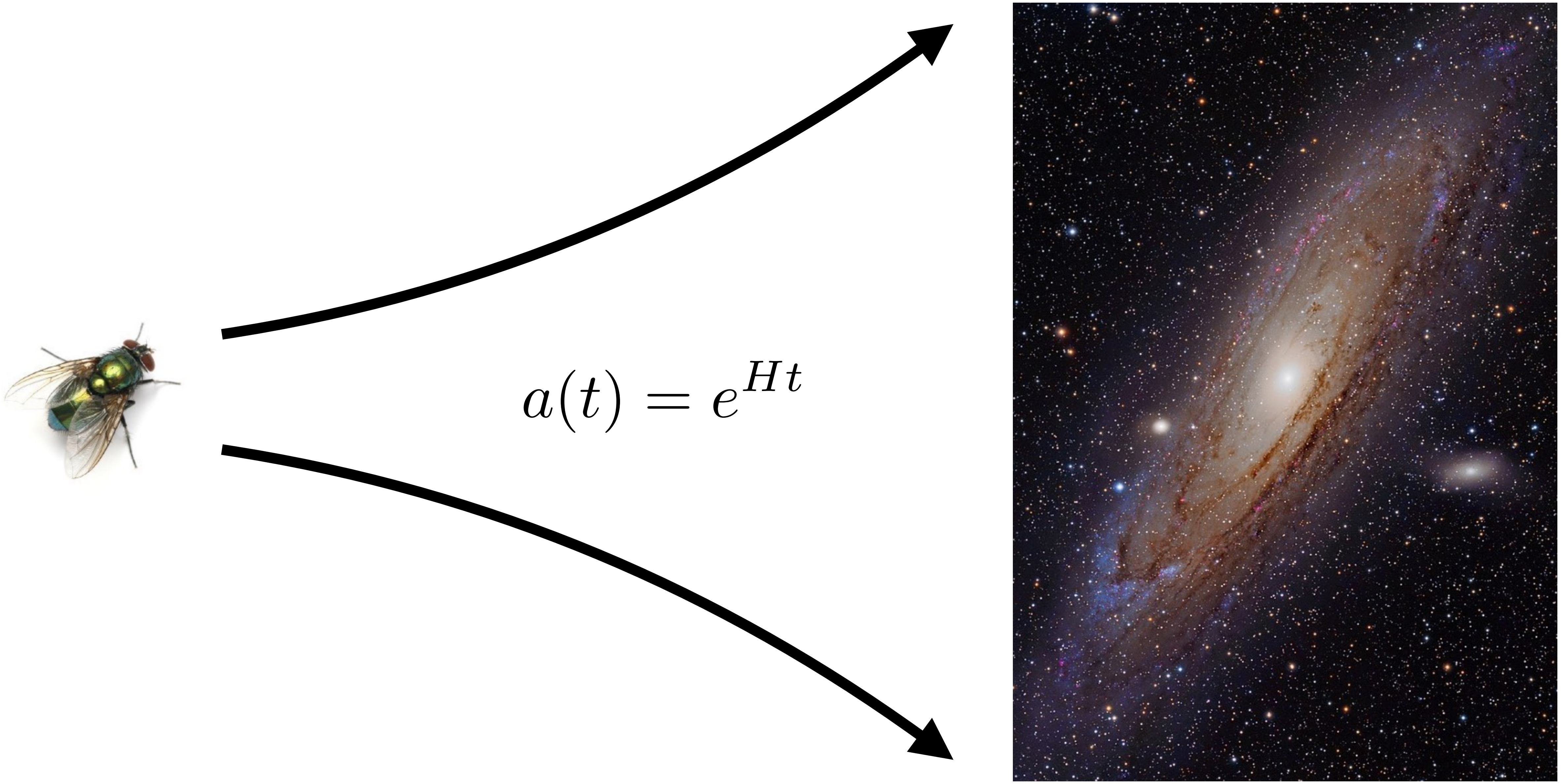


$$a(t) = e^{Ht}$$

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

Inflation

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

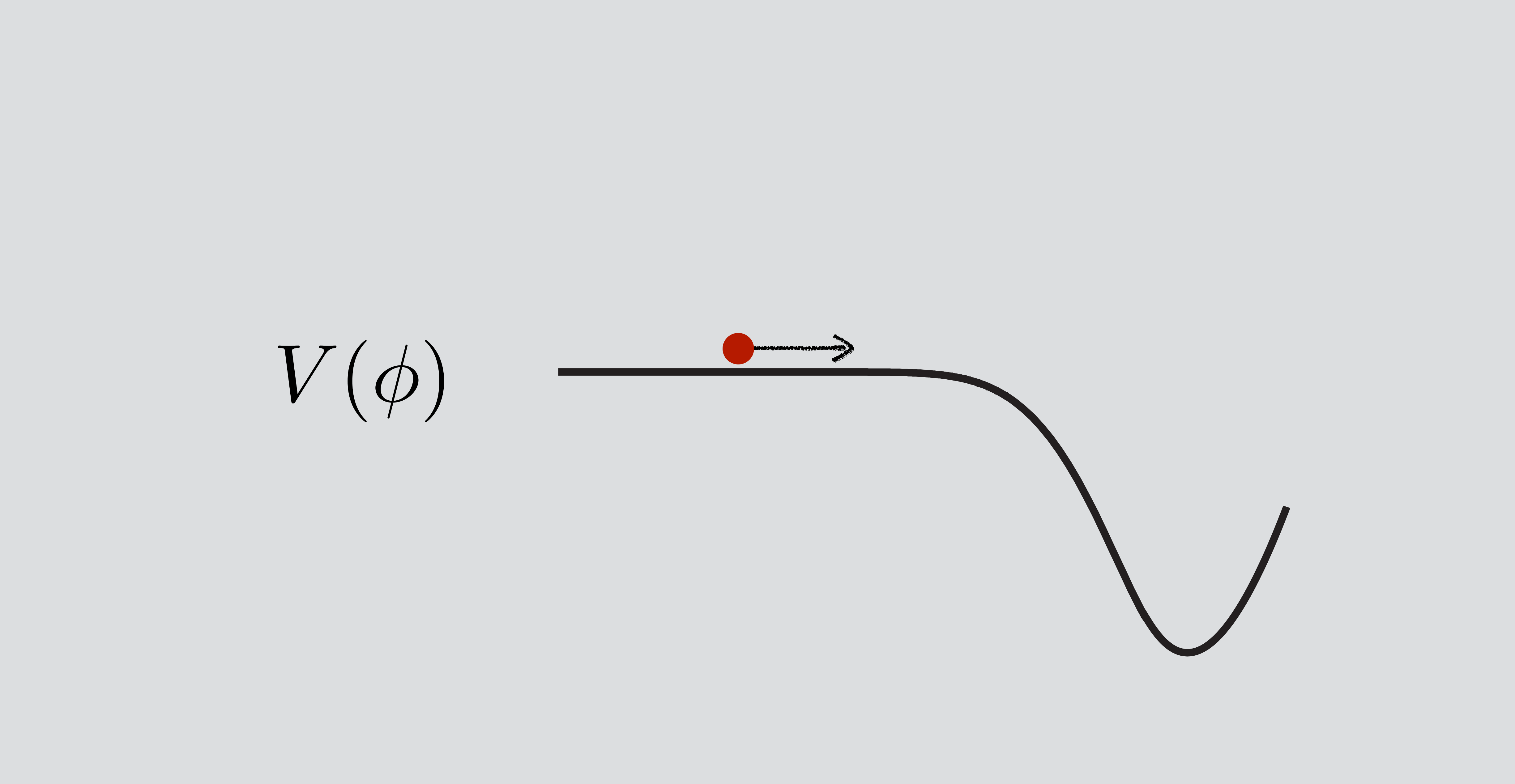


$$a(t) = e^{Ht}$$

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

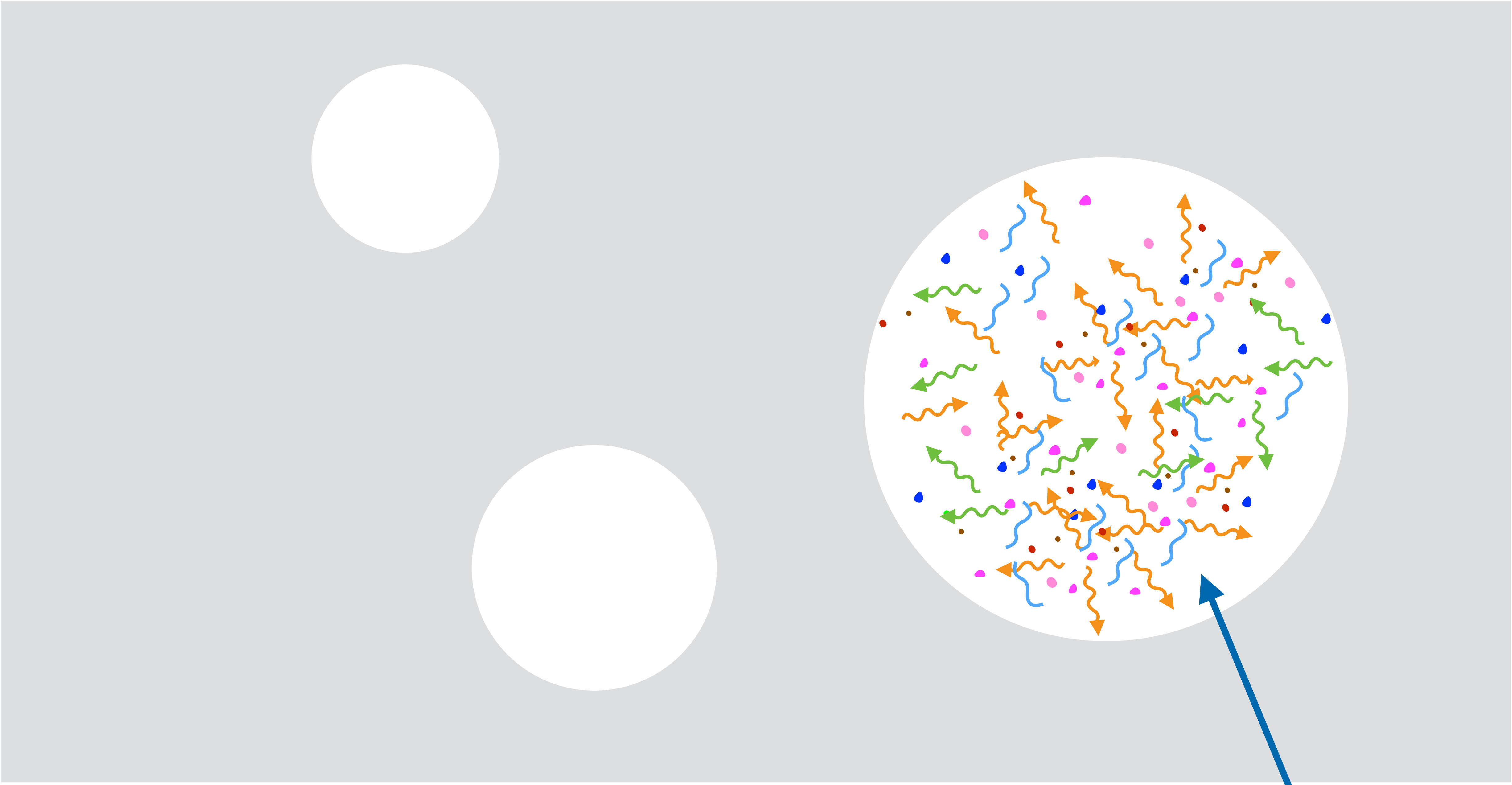
Inflation

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



Inflation

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

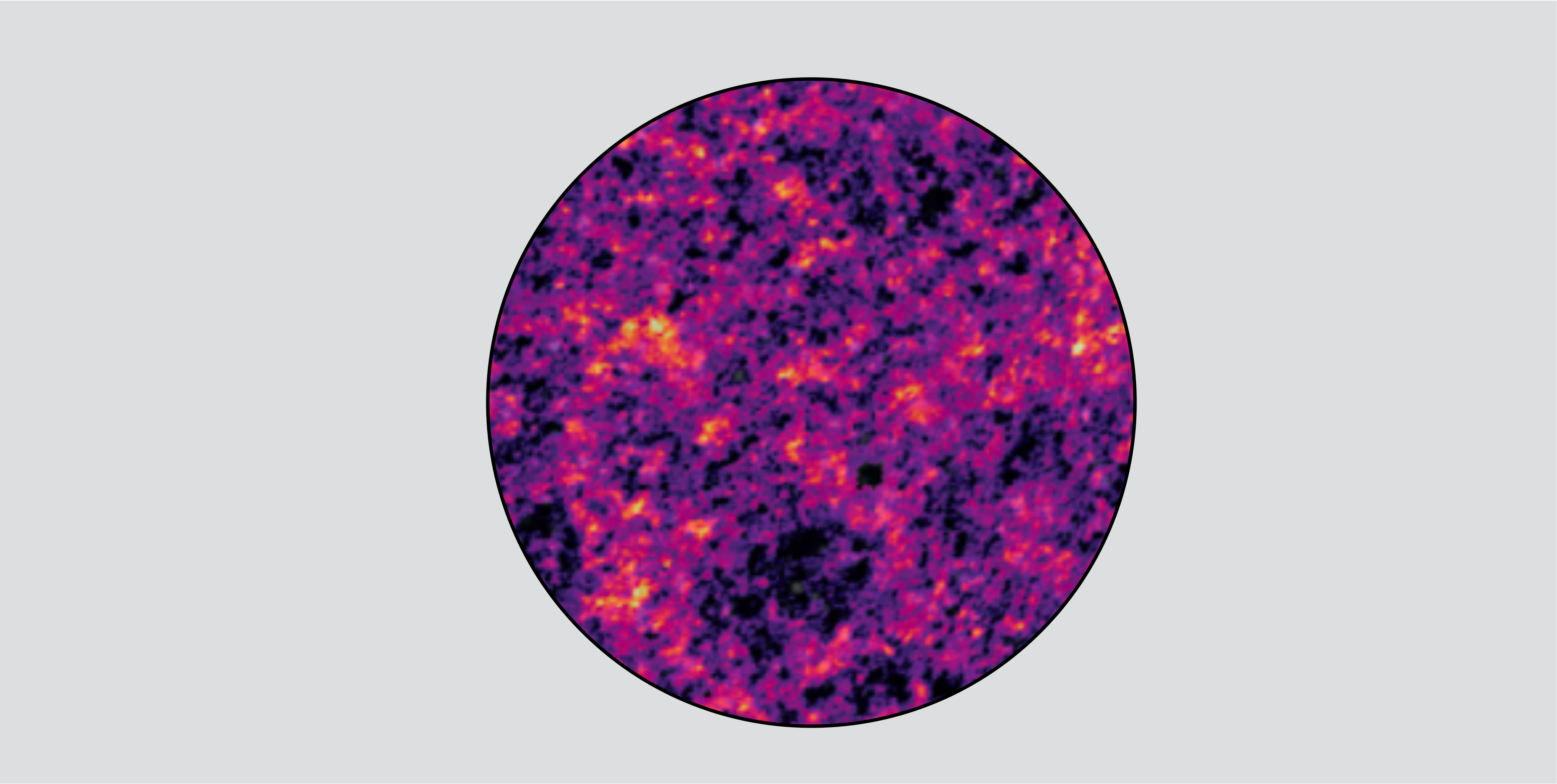


The product of this decay is the **hot Big Bang**.

One of these bubbles
is our Universe.

Inflation

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

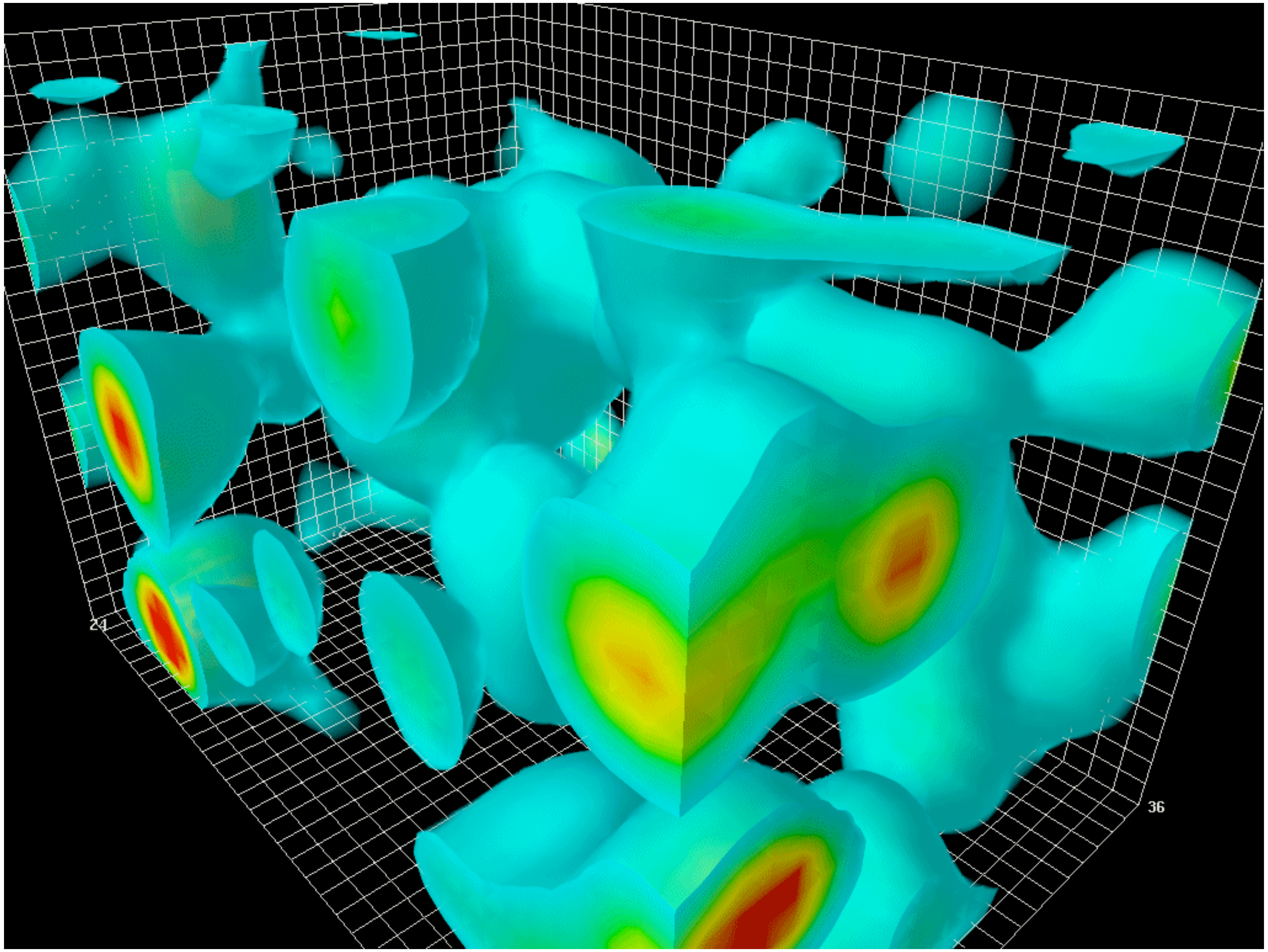


This creates the **primordial density fluctuations**.

Quantum Fluctuations

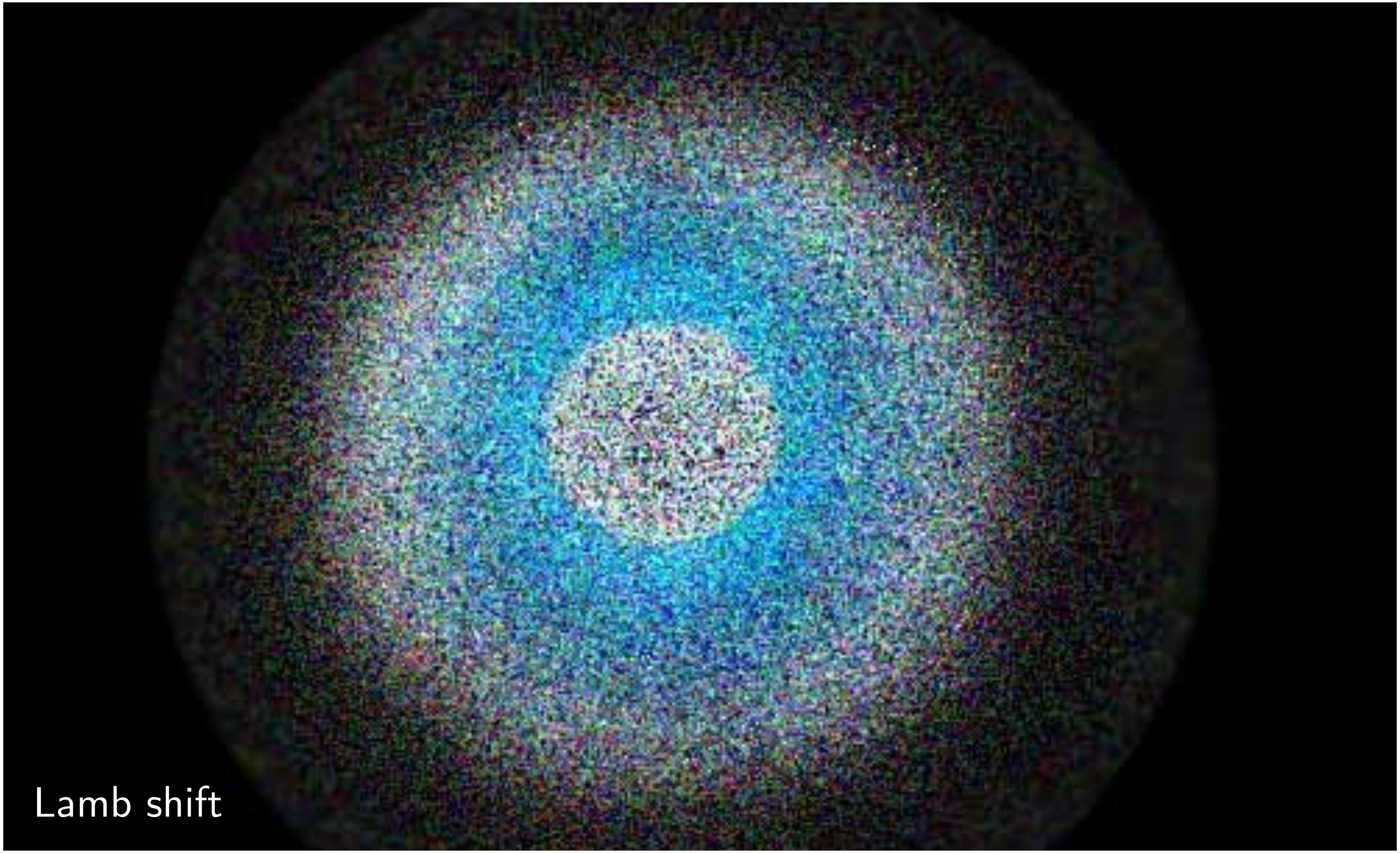
In quantum mechanics, empty space is full of violent fluctuations:

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



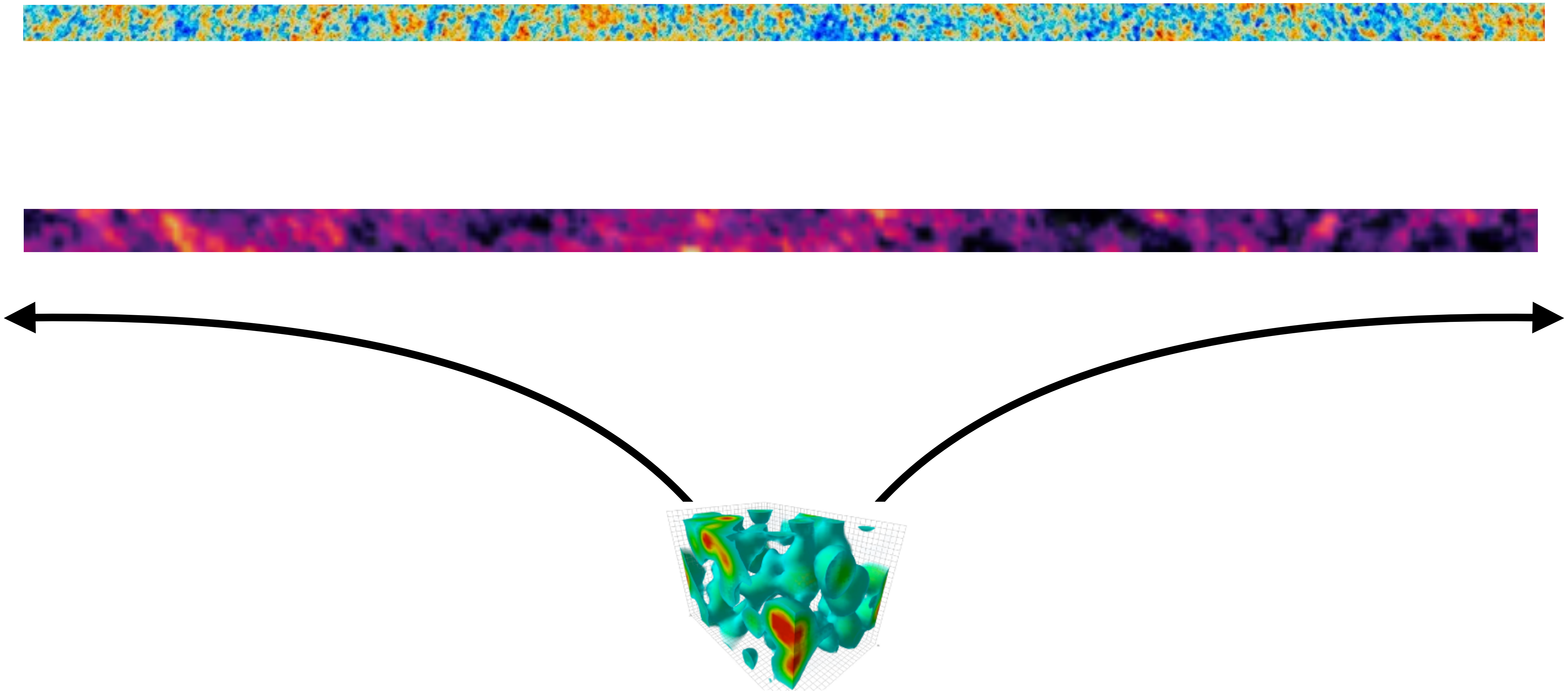
Quantum Fluctuations

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



Quantum Fluctuations

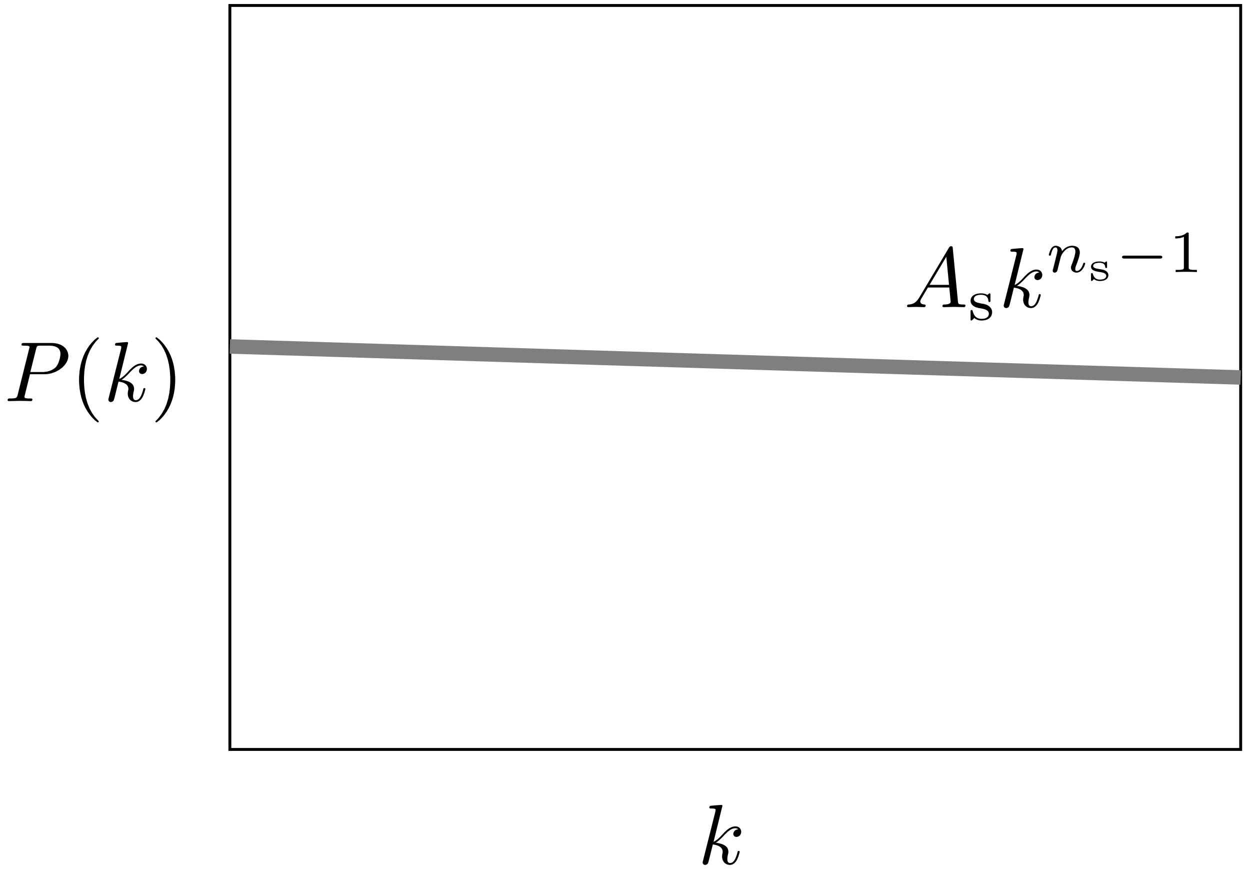
During inflation, these quantum fluctuations get amplified and stretched:

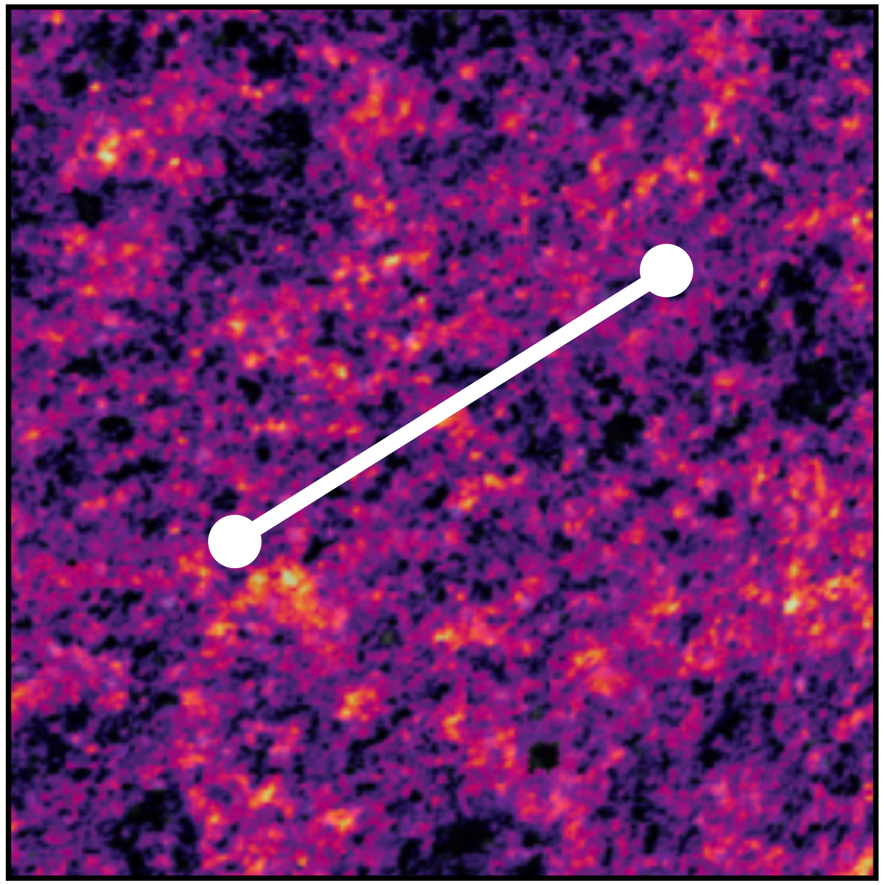


After inflation, these fluctuations become the large-scale density fluctuations.

Primordial Correlations

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

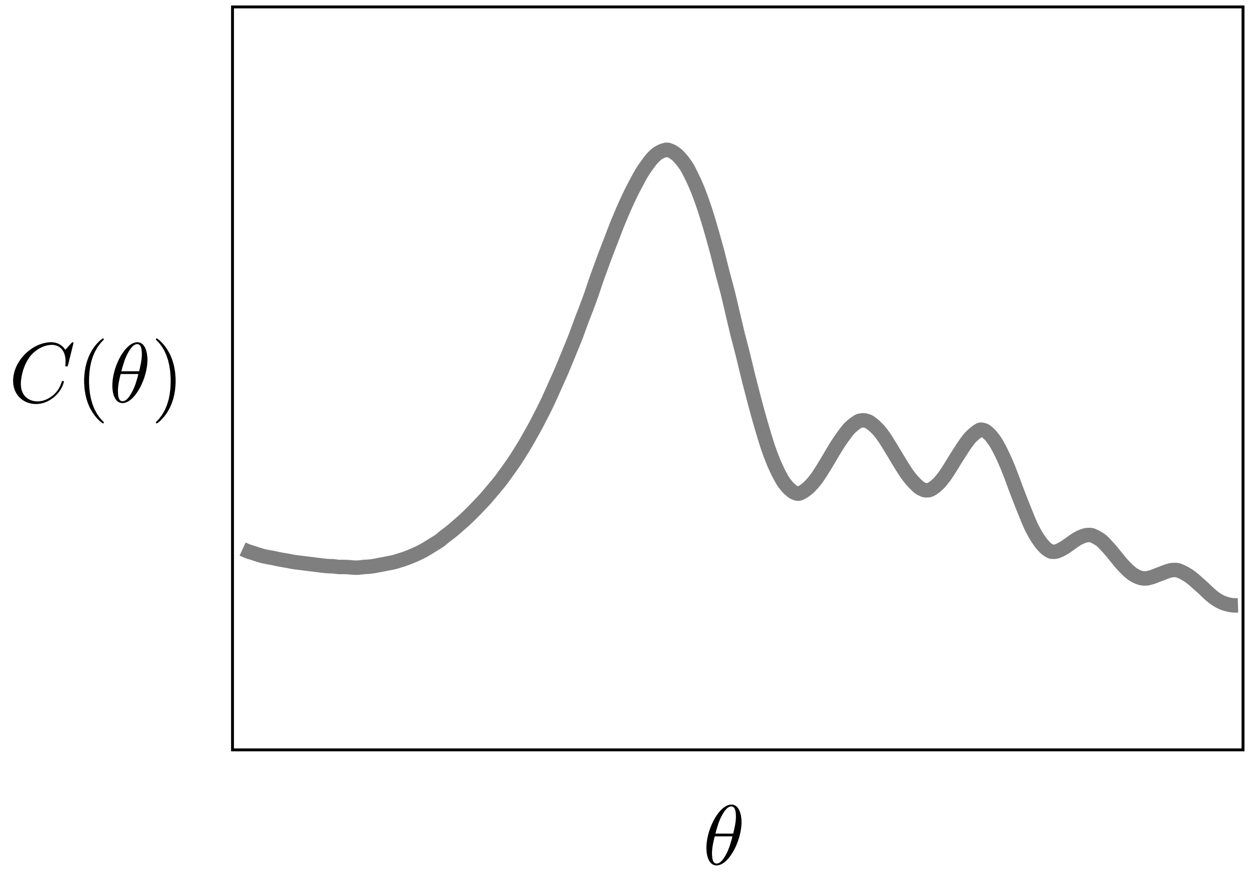


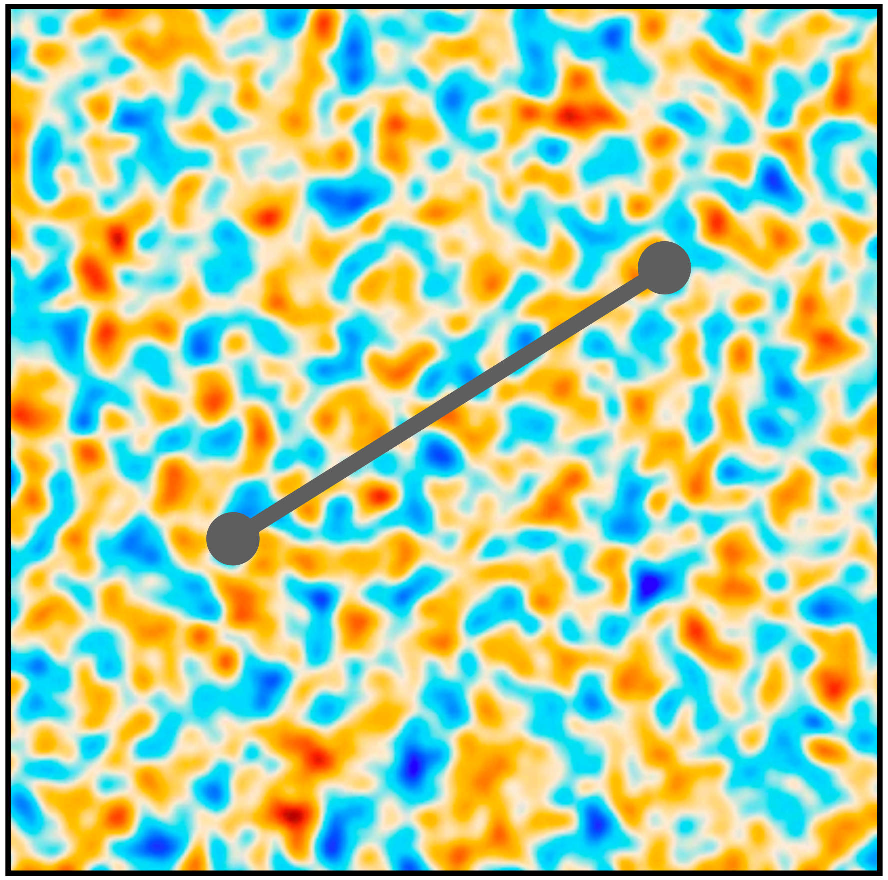


The slow decay of the inflationary energy predicts slightly more power on large scales: $n_{\mathrm{s}} < 1$

CMB Anisotropies

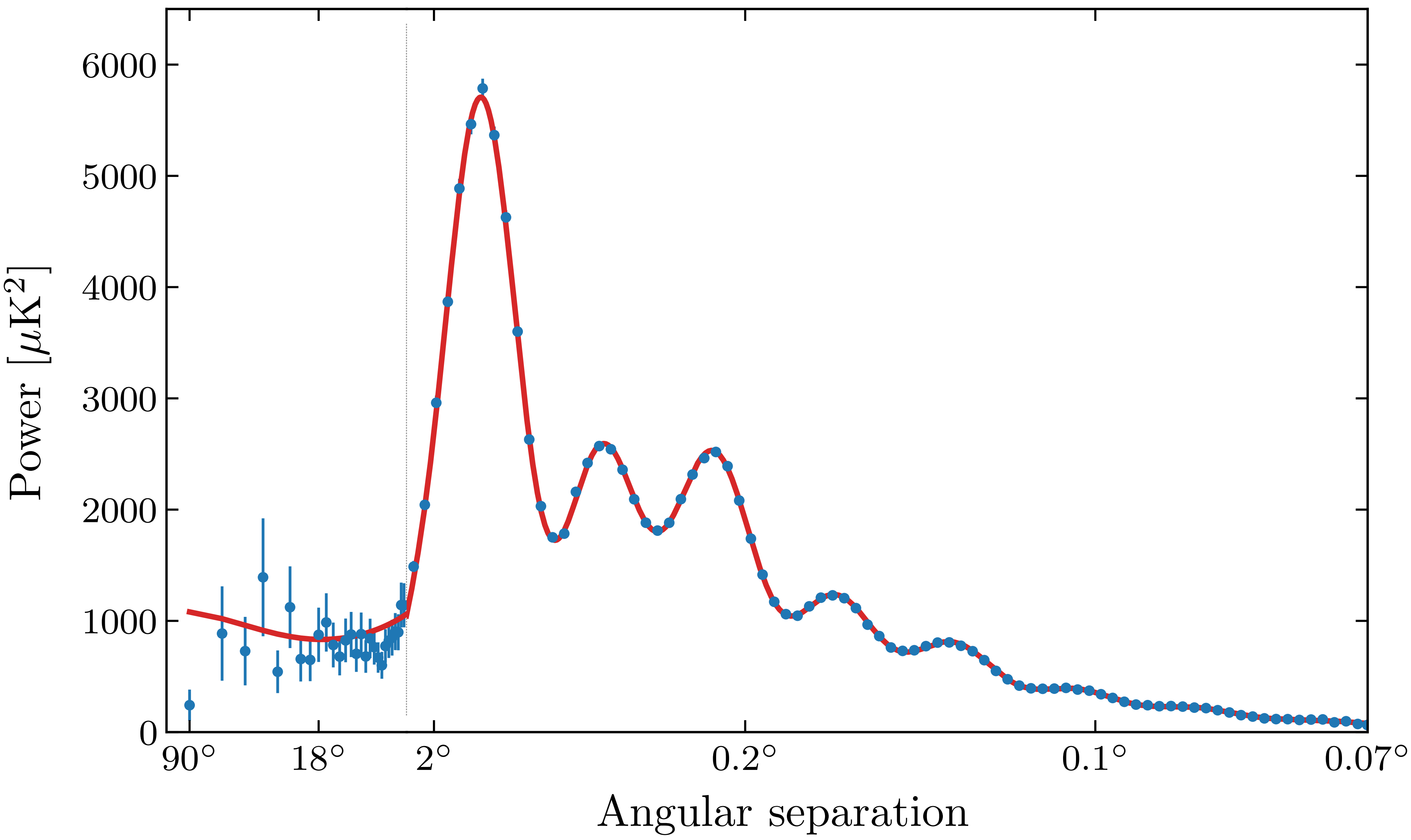
The well-understood physics of the photon-baryon fluid turns these primordial correlations into correlations of the CMB anisotropies:





CMB Anisotropies

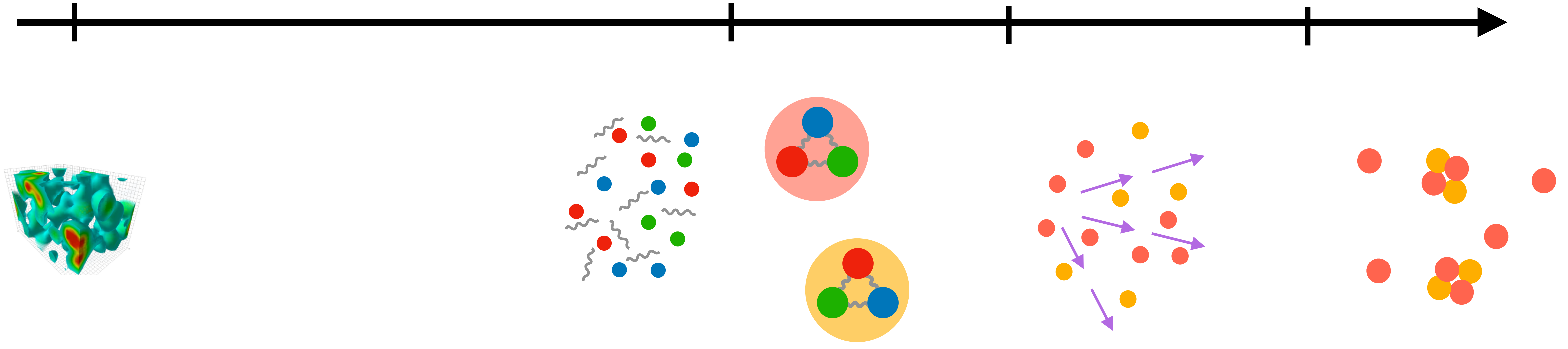
The predicted correlations are in remarkable agreement with the data:



“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?



10^{-32} s

10 μs

1 s

3 min

Inflation?

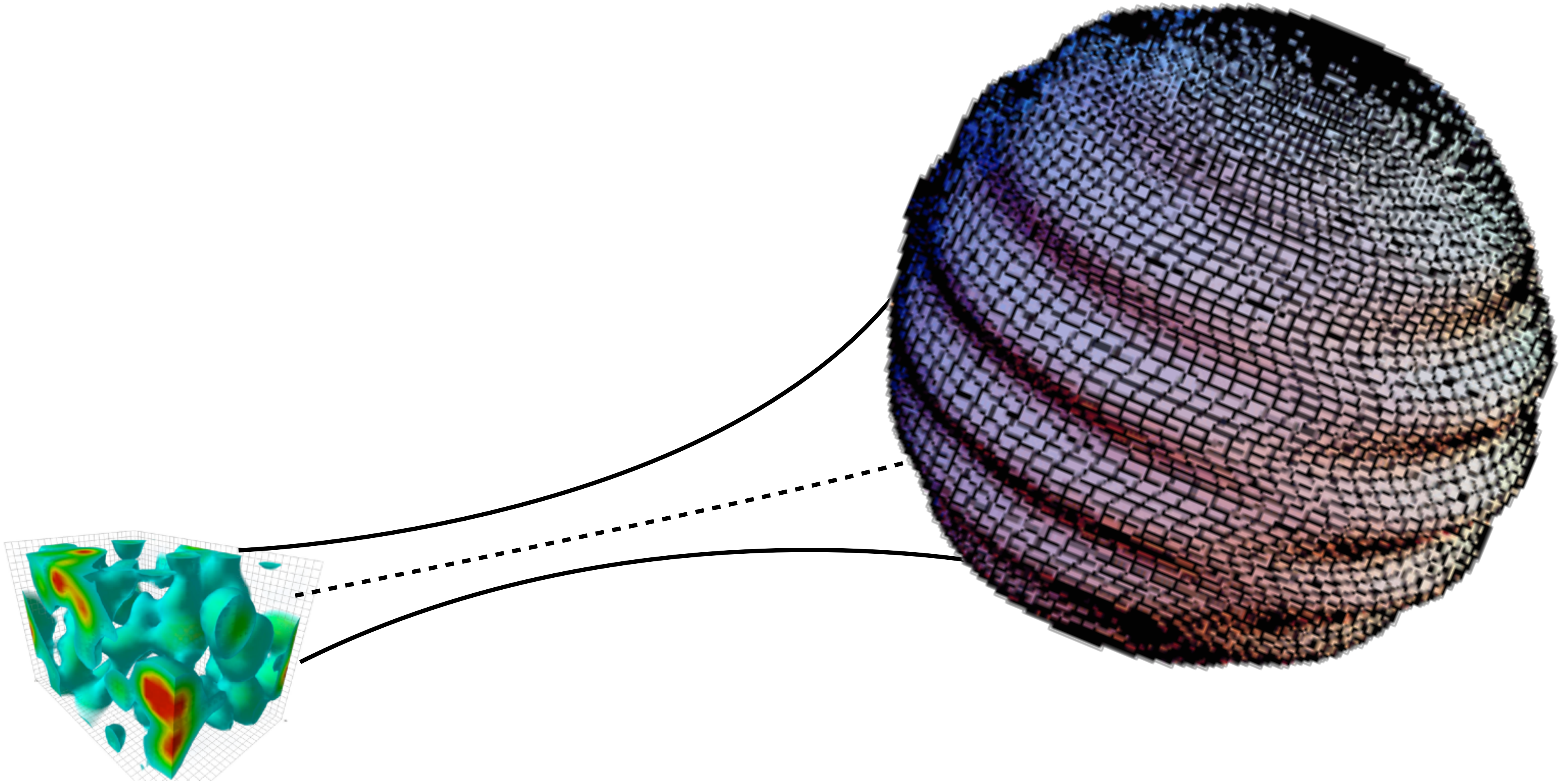
QCD phase transition

Neutrino decoupling

BBN

Primordial Gravitational Waves

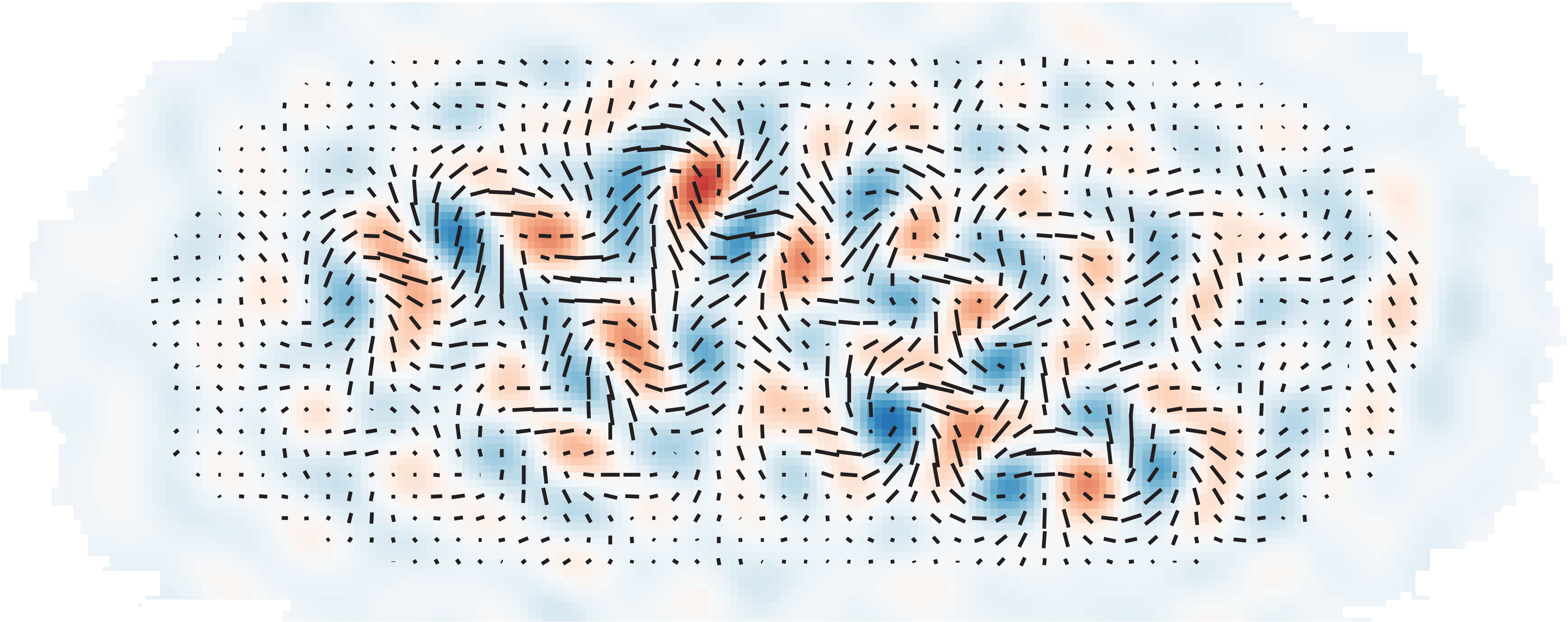
Besides density fluctuations, inflation predicts **gravitational waves**:



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

B-modes

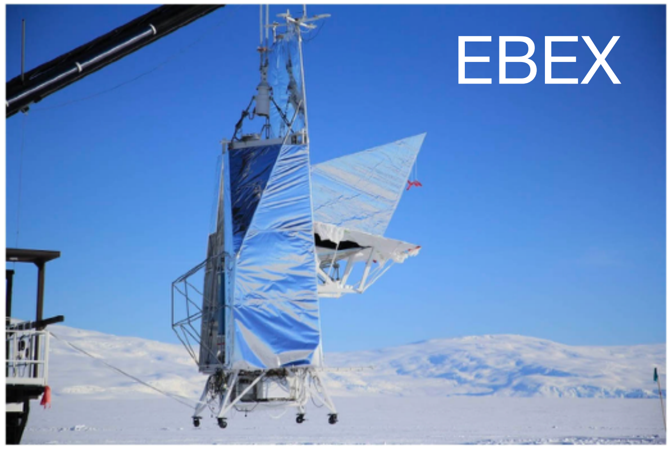
These gravitational waves would produce a characteristic swirl pattern (called **B-modes**) in the polarization of the CMB:



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

Ongoing Experiments

CMB Stage III



Planned Experiments

SIMONS
OBSERVATORY

CMB Stage III.5

(2023-2030)

Planned Experiments

CMB Stage IV

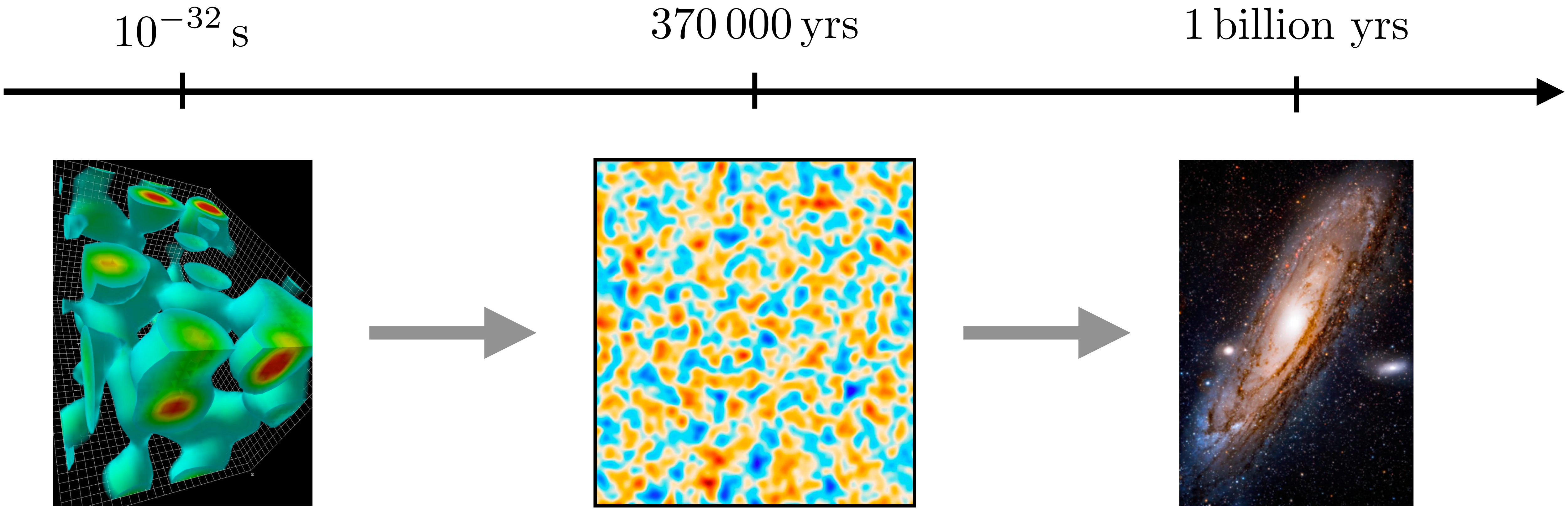
(2028-2035)

Planned Experiments

LiteBIRD

(2028-2032)

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

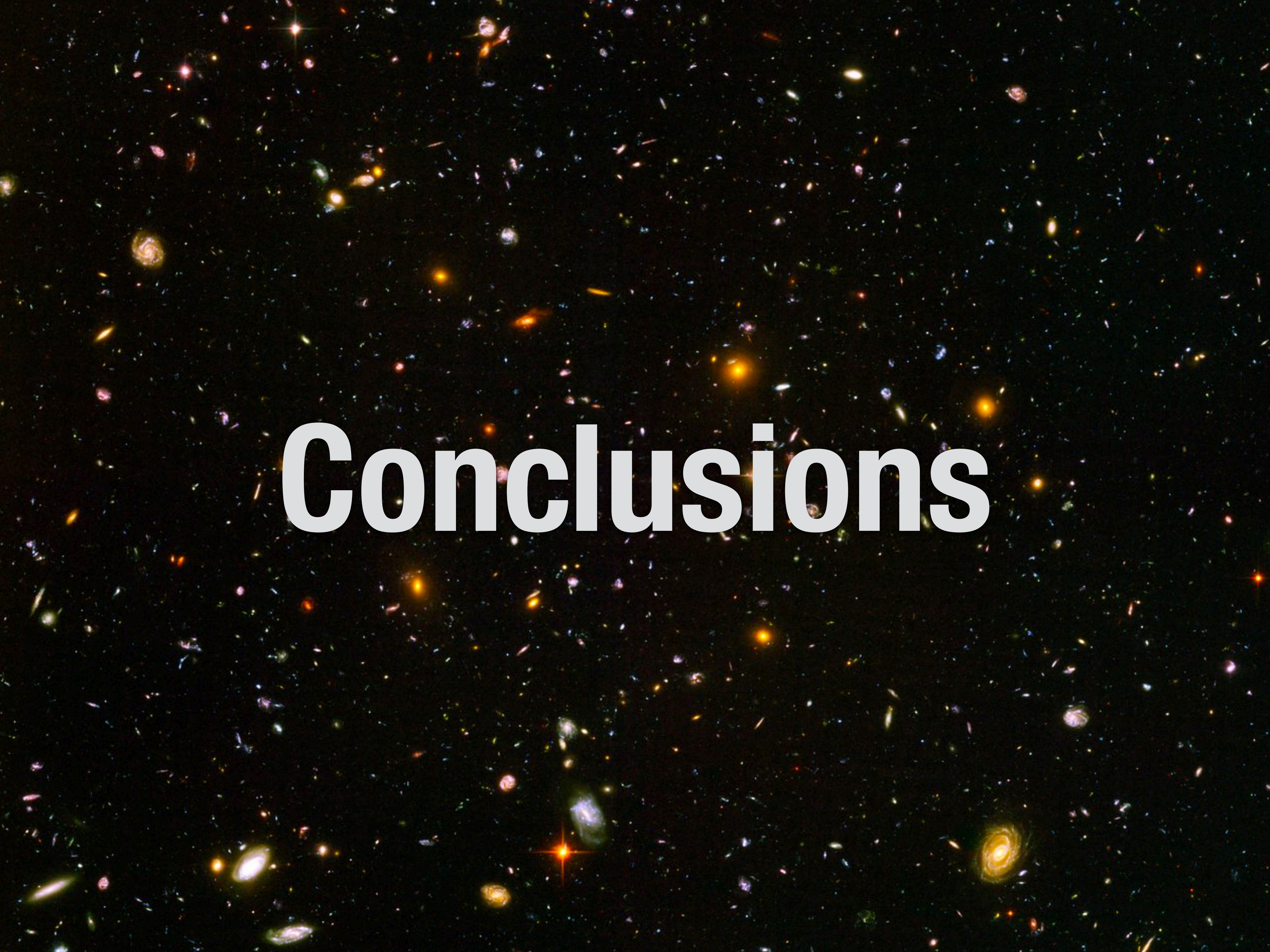


10^{-32} s

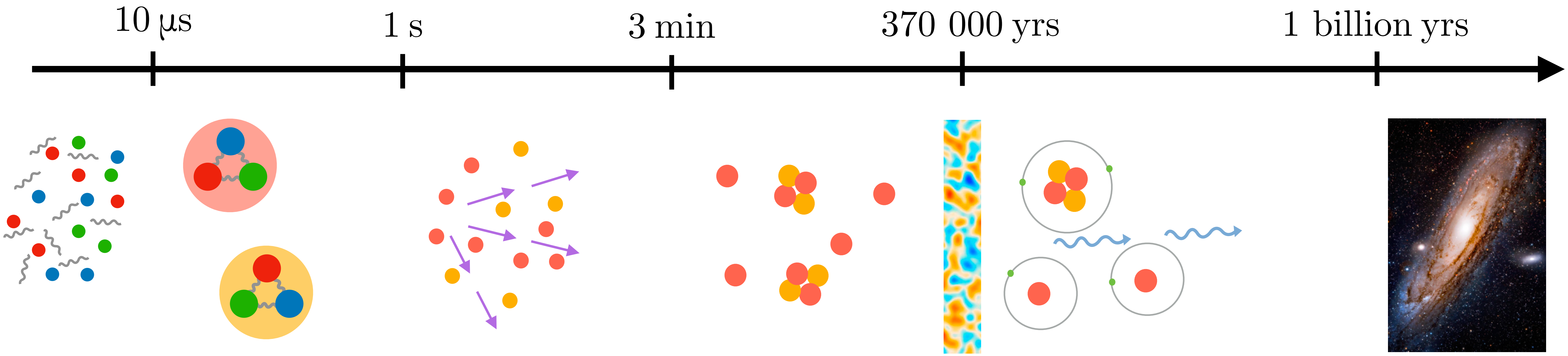
370 000 yrs

1 billion yrs

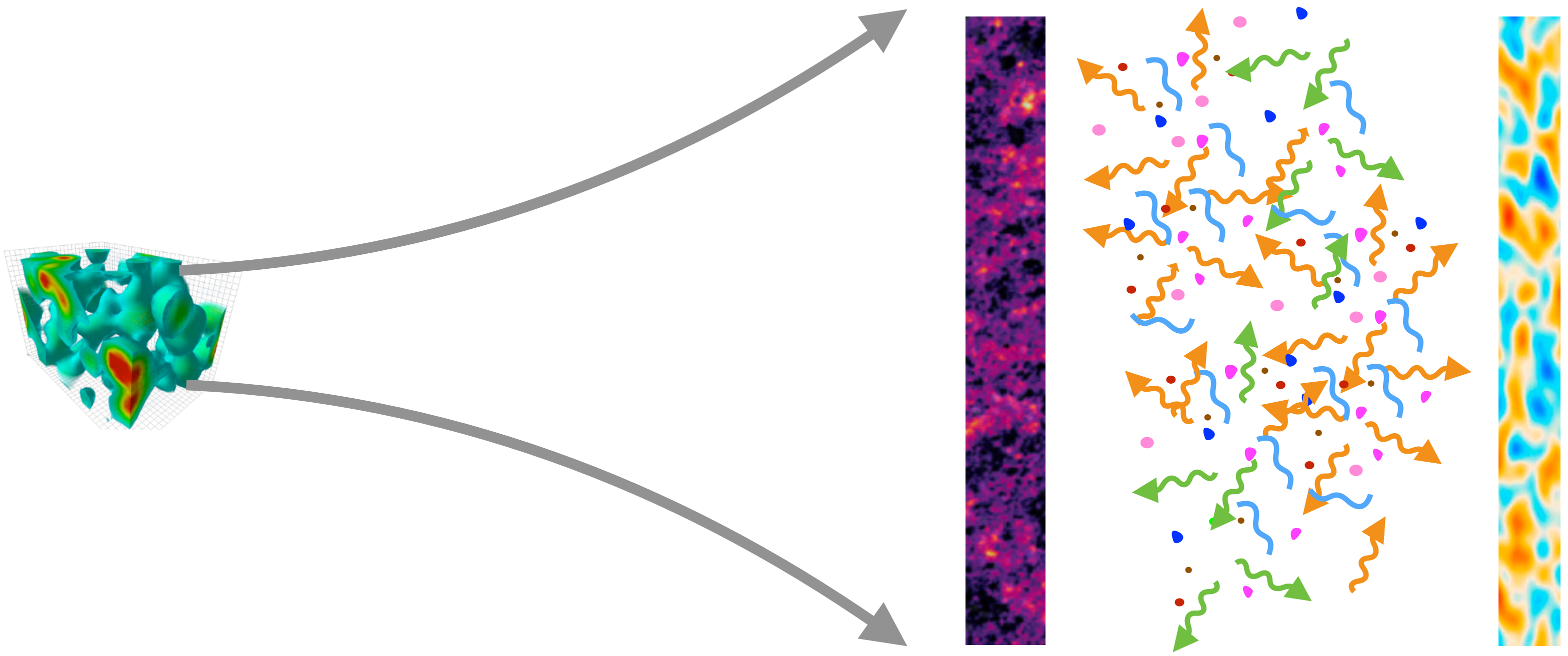
Conclusions



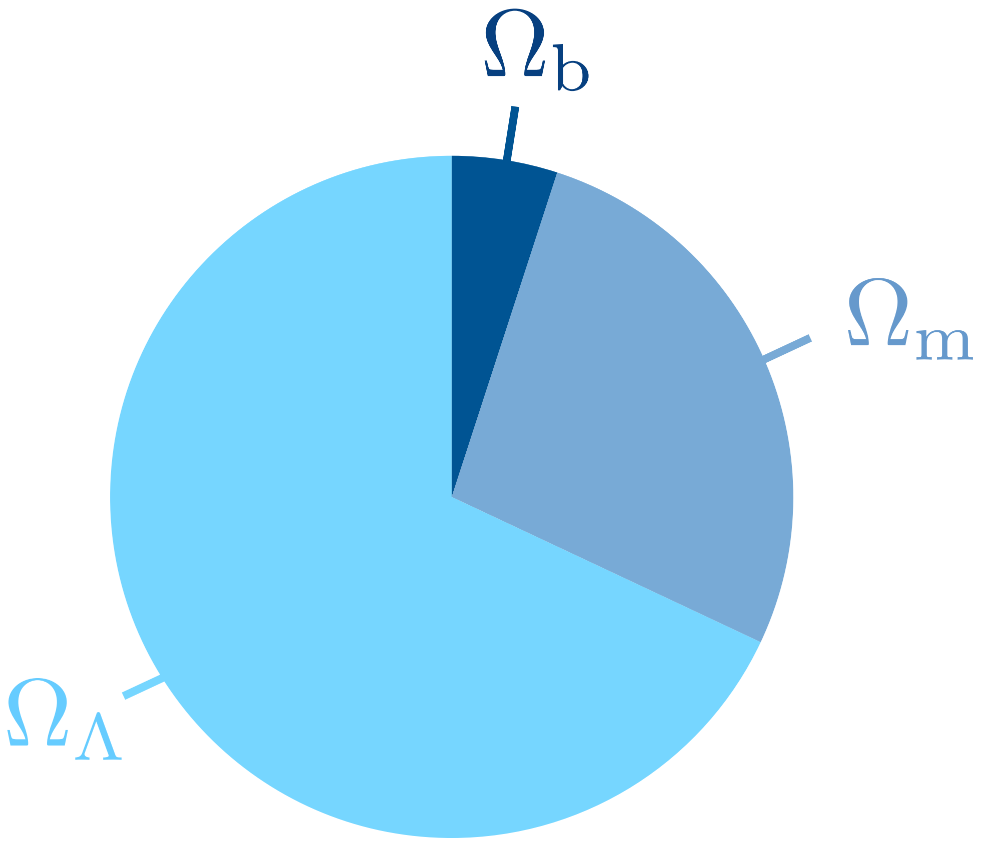
We have a remarkably consistent picture of the history of the Universe from fractions of a second after the Big Bang until today:

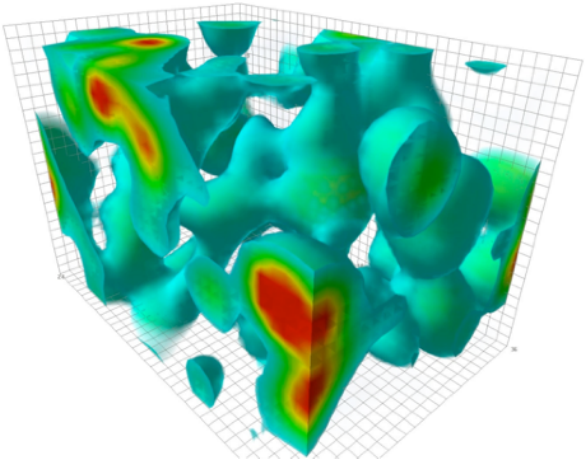


We also have tantalizing evidence that the primordial seed fluctuations for the formation of structure were created during a period of inflation:



Observations of the CMB have revolutionized cosmology:





A_s , n_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.

Thank you for your attention!

Appendix

Fluctuations during Inflation

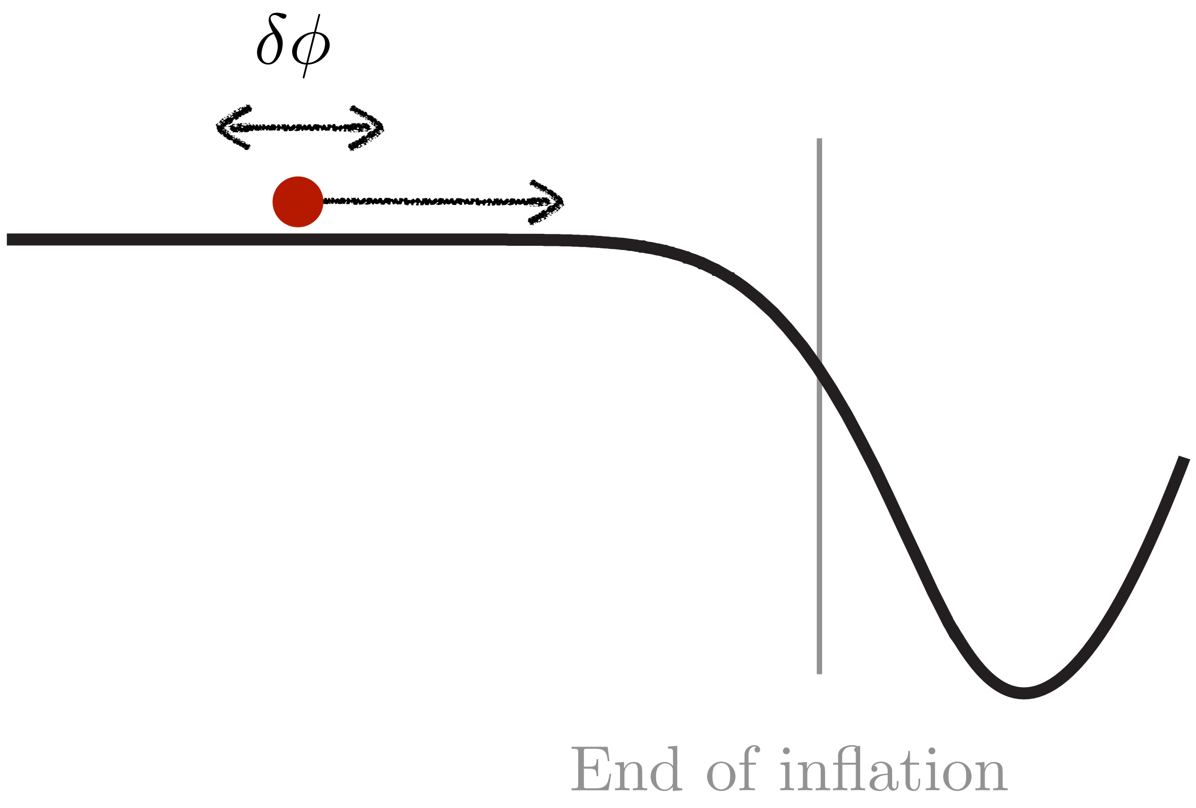
Each Fourier mode of the inflaton fluctuations satisfies:

$$\boxed{\ddot{\delta\phi} + 3H\dot{\delta\phi} + \omega_k^2(t)\delta\phi = 0}$$

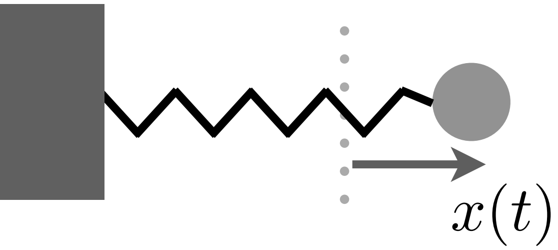
Hubble friction

$k^2/a^2(t)$

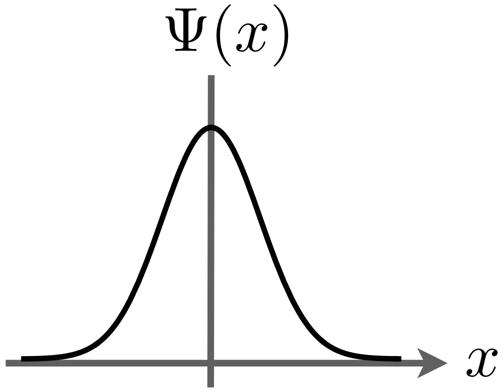
This is the equation of a time-dependent harmonic oscillator.



Quantum Harmonic Oscillators



$$\ddot{x} + \omega^2 x = 0$$



$$\langle x^2 \rangle = \frac{\hbar}{2\omega}$$

Zero-point fluctuations

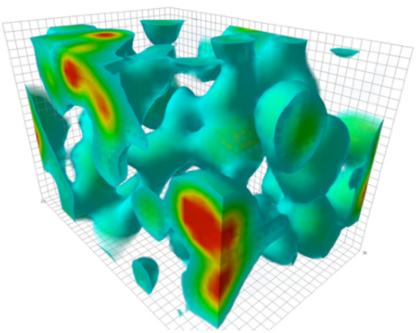
$$\boxed{\delta\ddot{\phi} + 3H\delta\dot{\phi} + \omega_k^2(t)\delta\phi = 0}$$

$$\Big\downarrow \; \delta\phi_c \equiv a^{3/2}\delta\phi$$

$$\boxed{\delta\ddot{\phi}_c + \omega_k^2(t)\delta\phi_c = 0}$$

$$\Big\downarrow$$

$$\boxed{\langle (\delta\phi)_c^2 \rangle = \frac{1}{2\,\omega_k(t)}}$$



$$\Big\downarrow$$

$$\boxed{\langle (\delta\phi)^2 \rangle = \frac{1}{2}\,\frac{1}{a^3(t)}\,\frac{1}{k/a(t)}}$$

Hollands and Wald (2002)

Quantum Fluctuations during Inflation

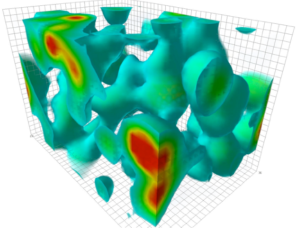
This holds as long as the mode evolves adiabatically (inside the horizon):

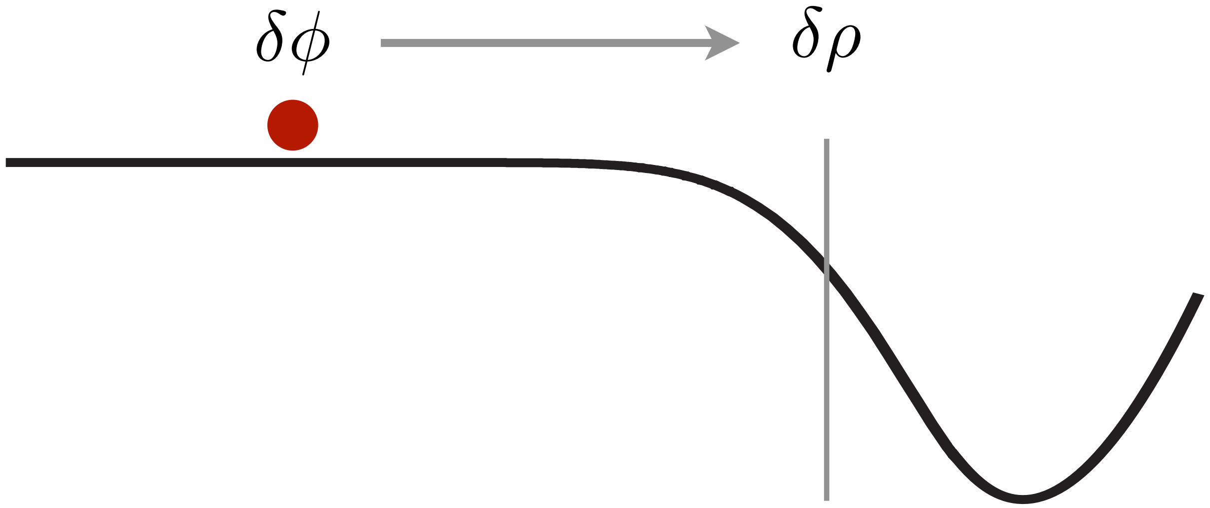
$$\boxed{\langle(\delta\phi)^2\rangle = \frac{1}{2}\frac{1}{k^3}\left(\frac{k}{a(t)}\right)^2}$$

At horizon crossing, $k/a(t_*) = H(t_*)$, the fluctuations freeze and we get

$$\boxed{P_{\delta\phi}(k) \equiv \frac{k^3}{2\pi^2}\langle(\delta\phi)^2\rangle_* = \left(\frac{H}{2\pi}\right)^2} \approx \text{const}$$

After inflation, these become nearly scale-invariant density fluctuations.





Summary