

XIII^e édition des **Rencontres d'été de physique**
de **L'INFINIMENT GRAND** à l'infiniment petit

29 juin-3 juillet
2026

- Orsay
- Palaiseau
- Paris
- Saclay

Promotion Claudine HERMANN

de L'INFINIMENT
GRAND
à L'INFINIMENT
petit

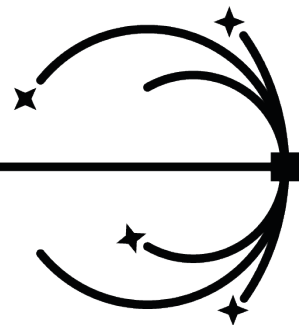
Rencontres

Niveau L3
ou équivalent



Observer l'infiniment grand

ASTROPARTICULE
& COSMOLOGIE

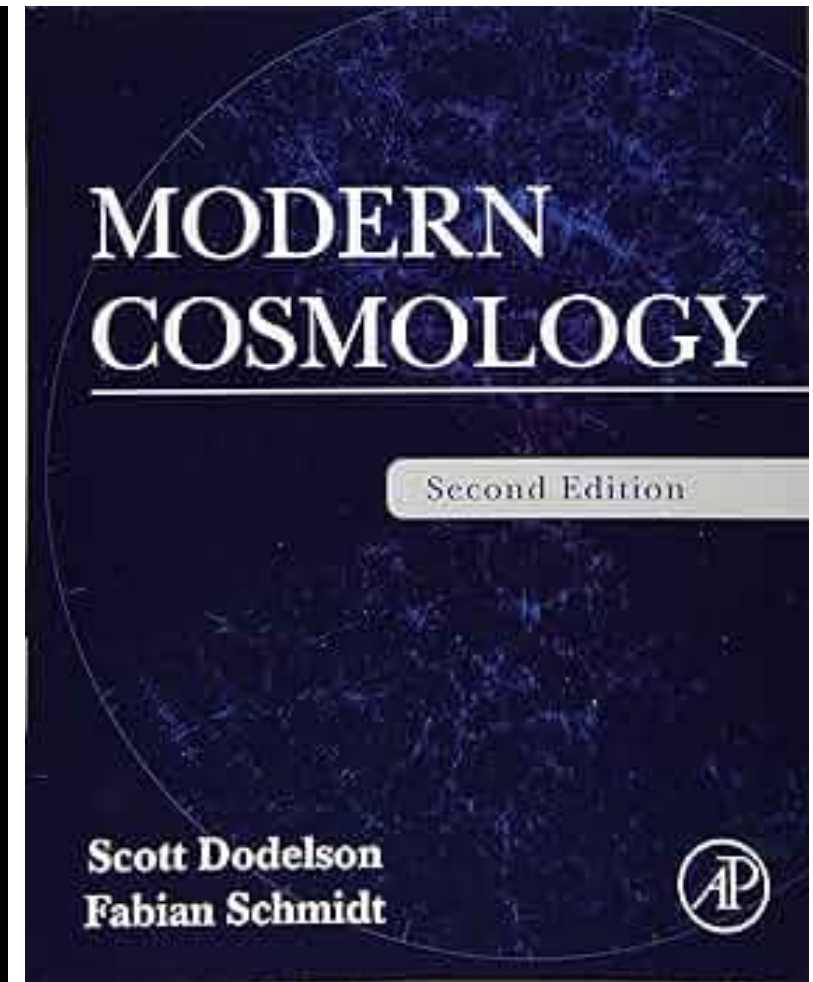
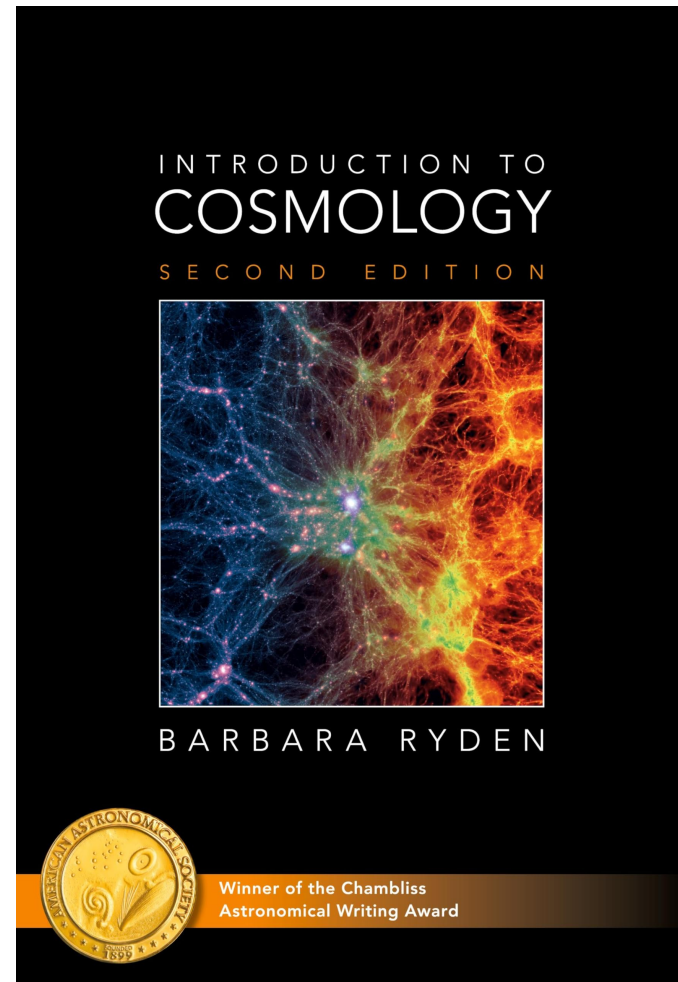
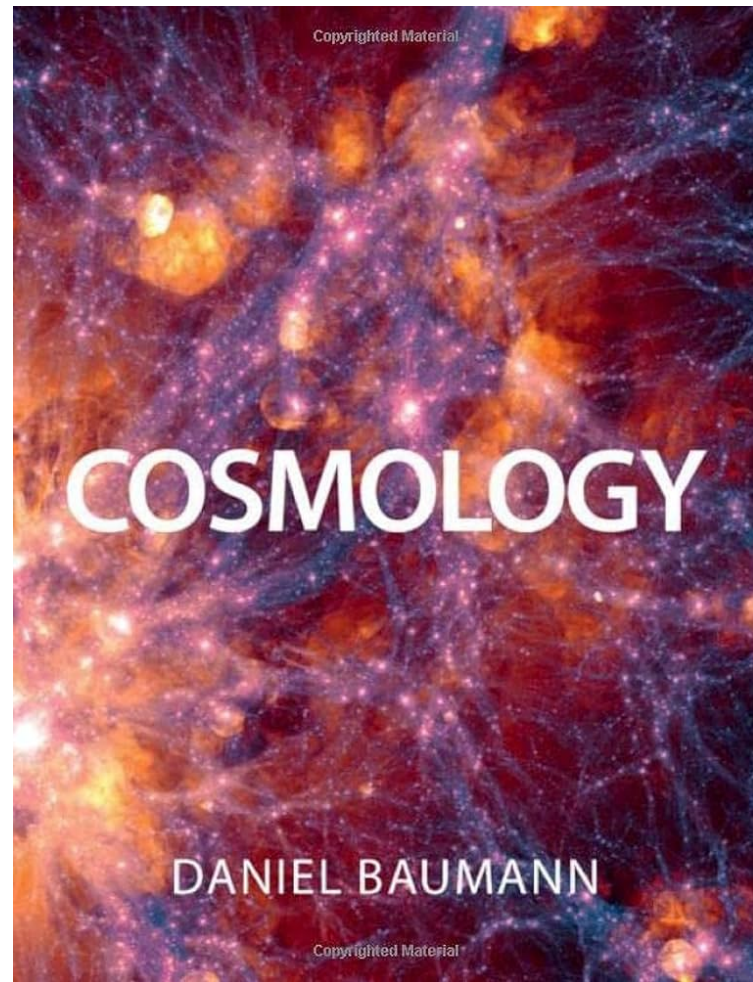


SciPo!



Josquin ERRARD, July 3rd, 2026

More can be found in:

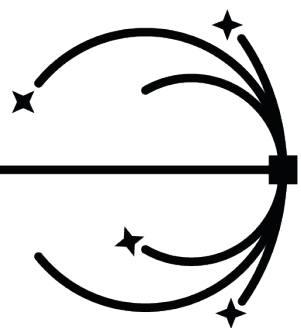


Observer l'infiniment grand

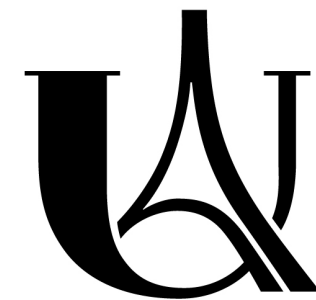


Josquin ERRARD, July 3rd, 2026

ASTROPARTICULE
& COSMOLOGIE



SciPo!



**Trous noirs,
Supernovae,**

...

**Galaxies,
CMB**

...

Rayons cosmiques

Rayons gamma

Neutrinos

Ondes

gravitationnelles

Photons

SVOM

KM3Net

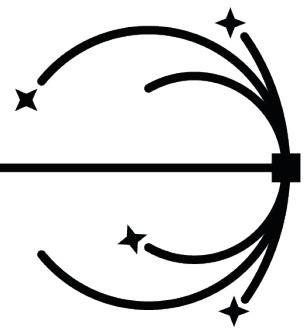
Virgo

Euclid

Simons
Observatory

LSST/Rubin

ASTROPARTICULE & COSMOLOGIE



SciPo!



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Josquin
Errard



Artem
Basyrov



Ève
Barlier



Wuhyun
Sohn



Amalia Villarrubia
Aguilar



Radek
Stompor



Binh
Nguyen



Pierre
Chanial



Ema Tsang
King Sang



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Bournaud



Maude
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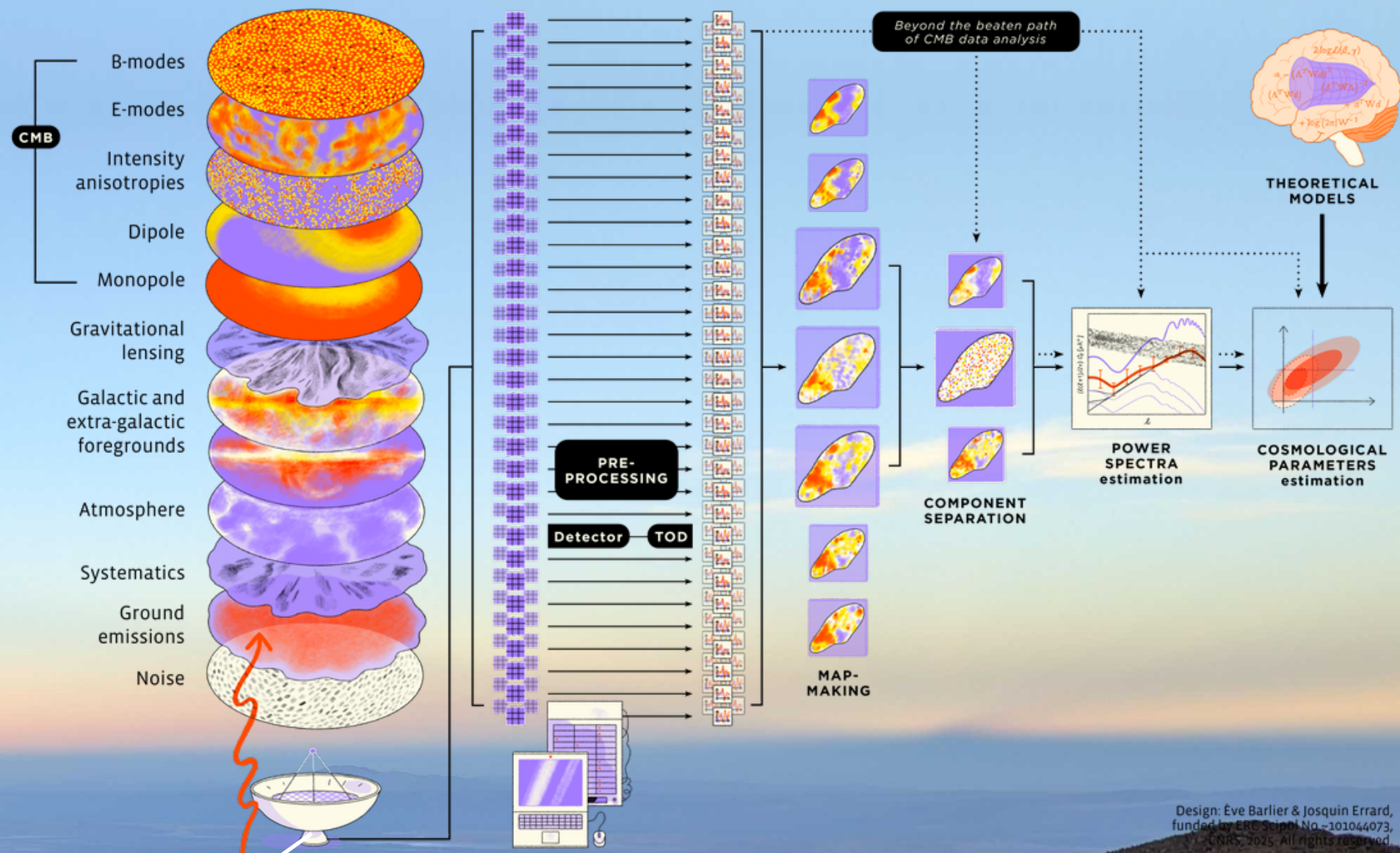
Simon
Biquard



European Research Council
Established by the European Commission



What do we work on?



Design: Eve Barlier & Josquin Errard,
funded by ERC Seipol No ~101044073,
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Recap of what you heard earlier this week

understanding/observing the
infinitely large = cosmology

We wish to derive, and then solve, the equation governing the evolution of the entire Universe.

This is possible because, on large scales, the Universe is homogeneous and isotropic, and therefore allows for a simple mathematical description.

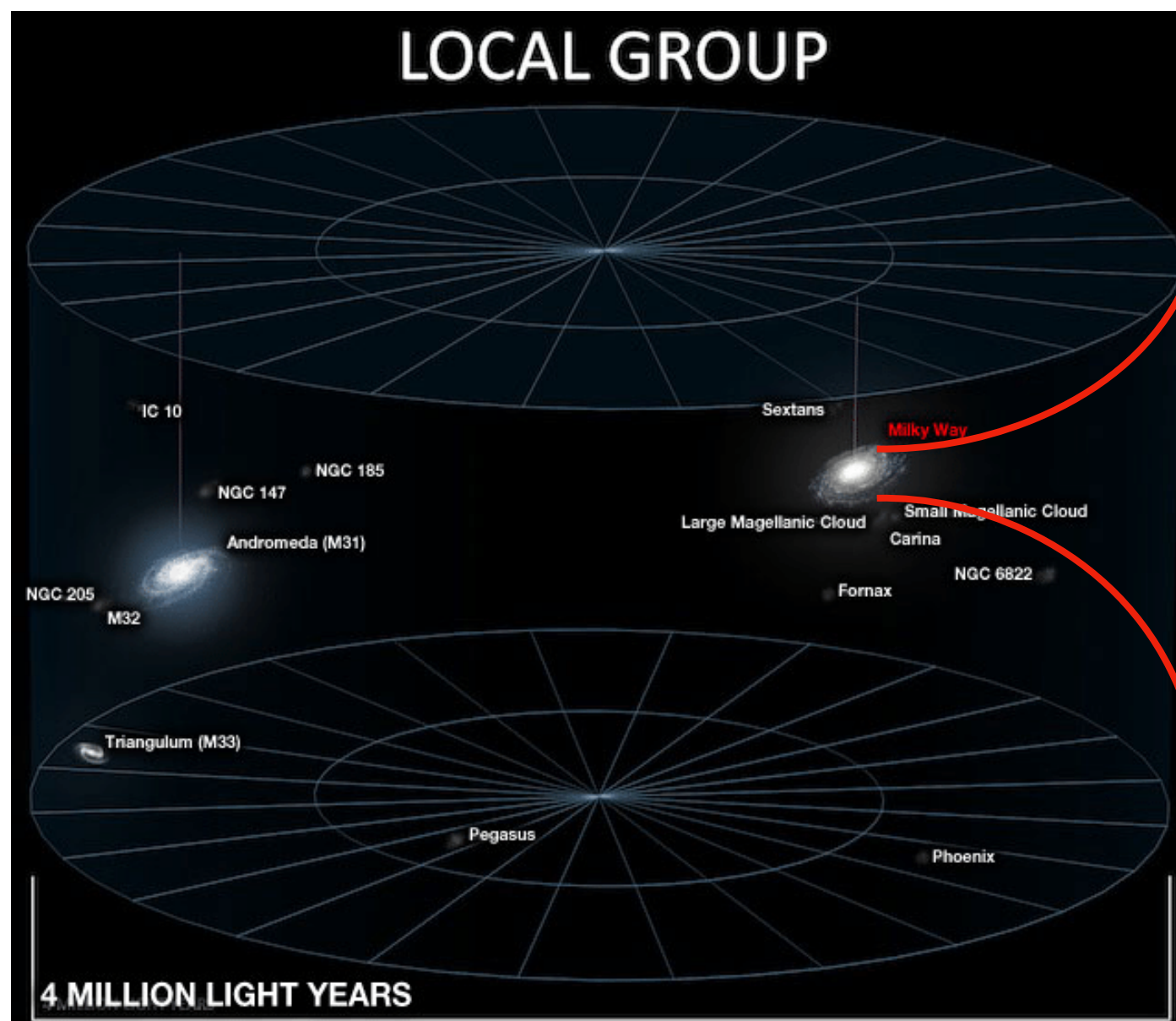


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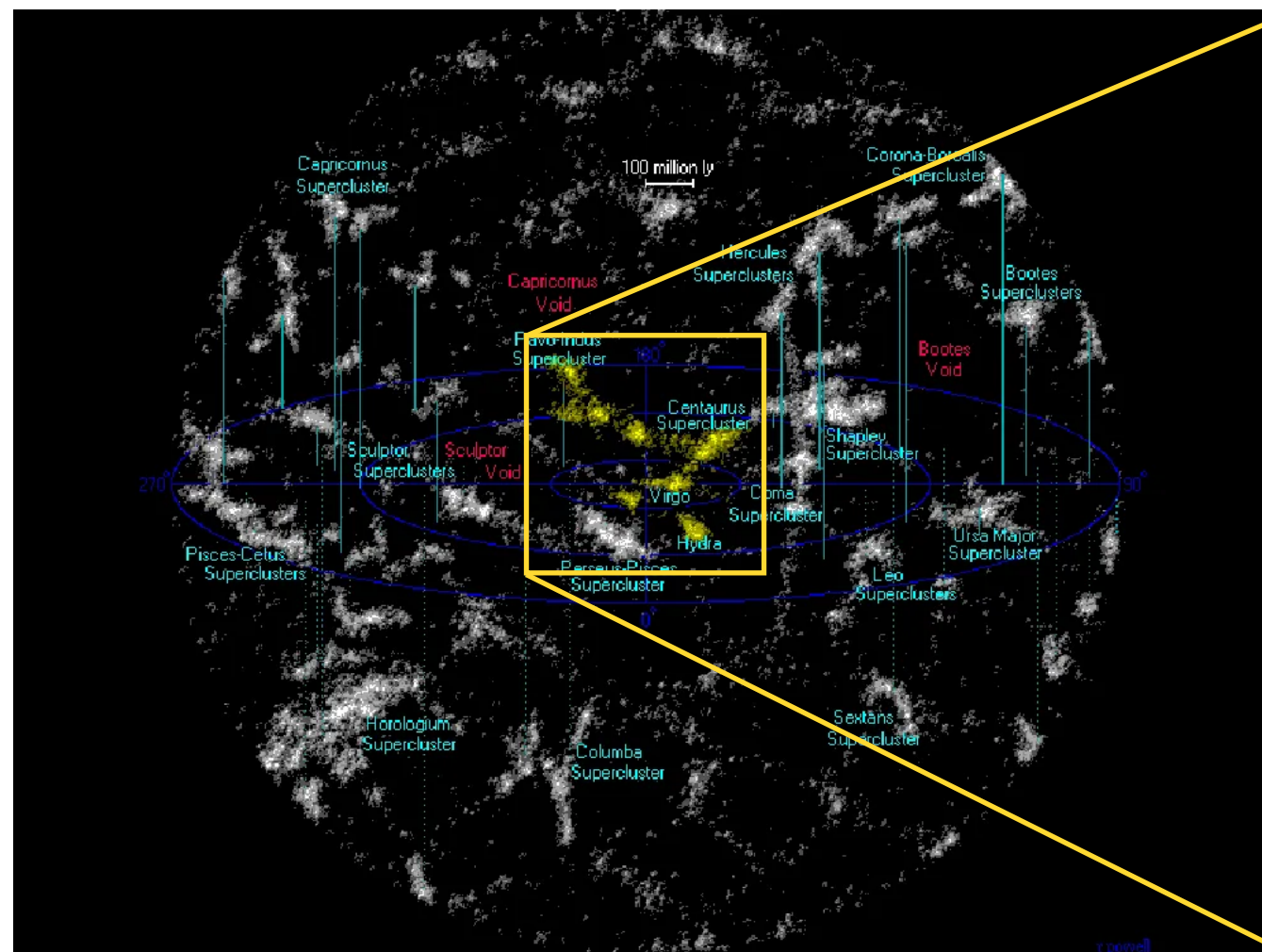


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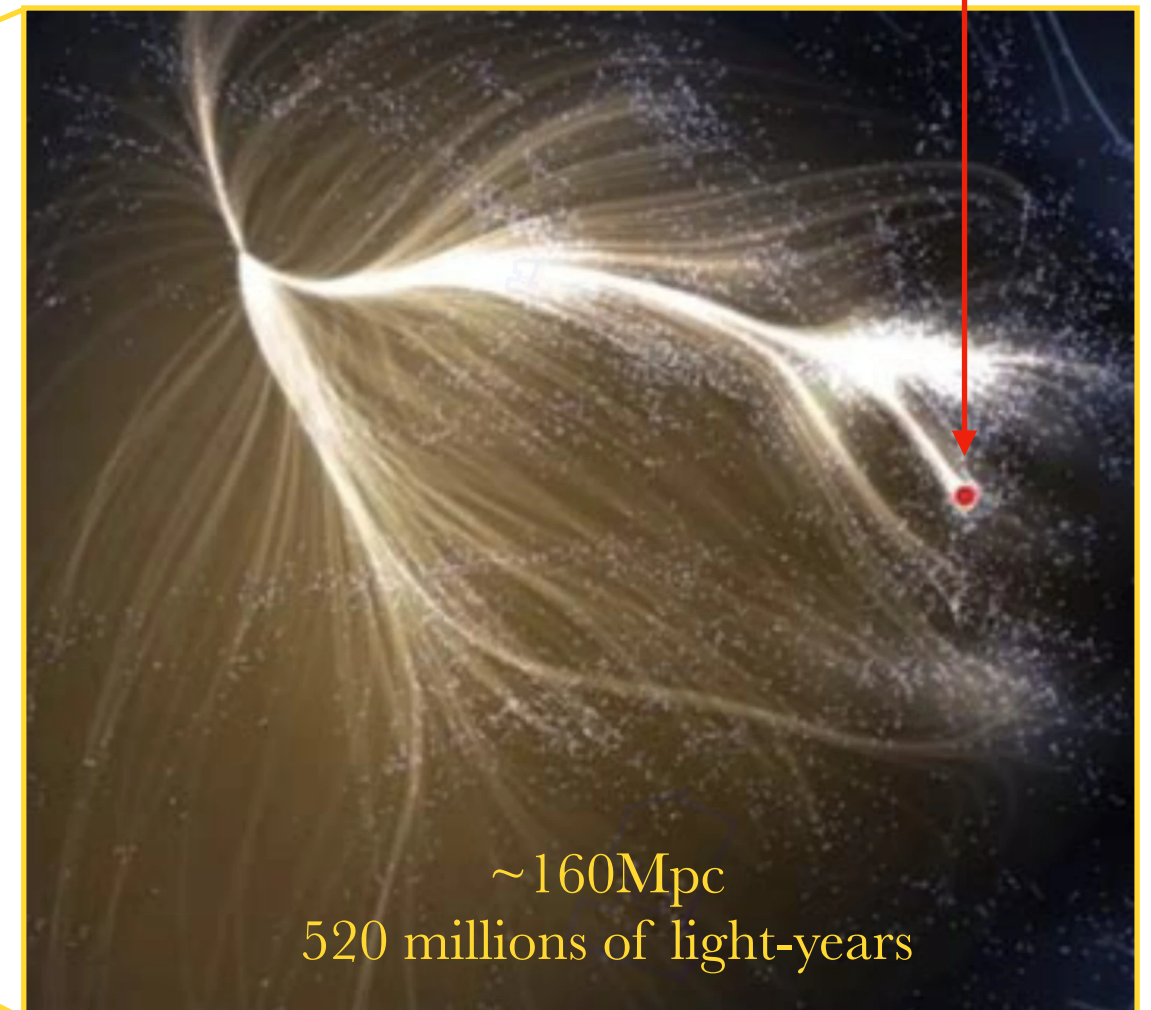
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Local Universe



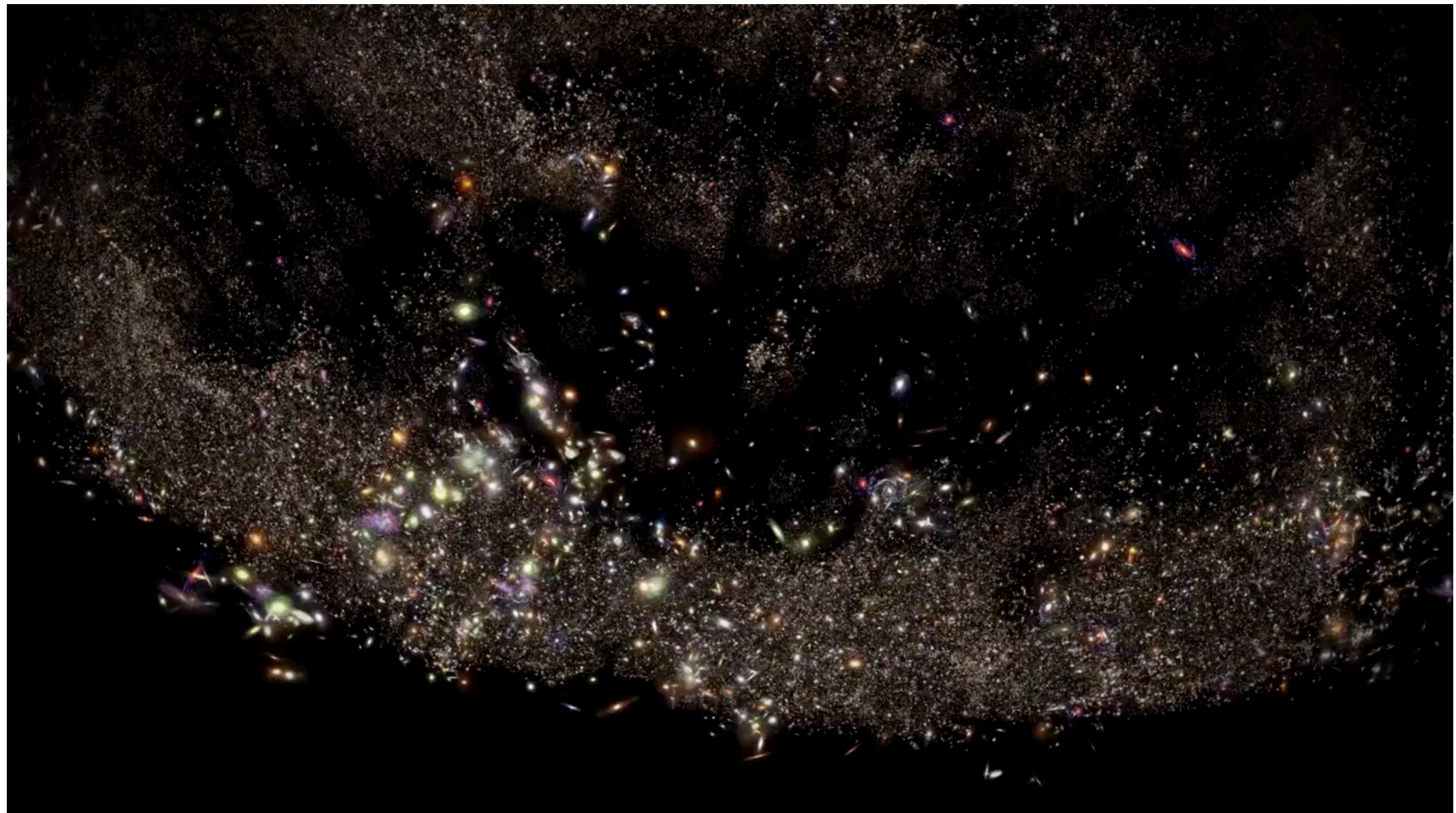
Laniakea

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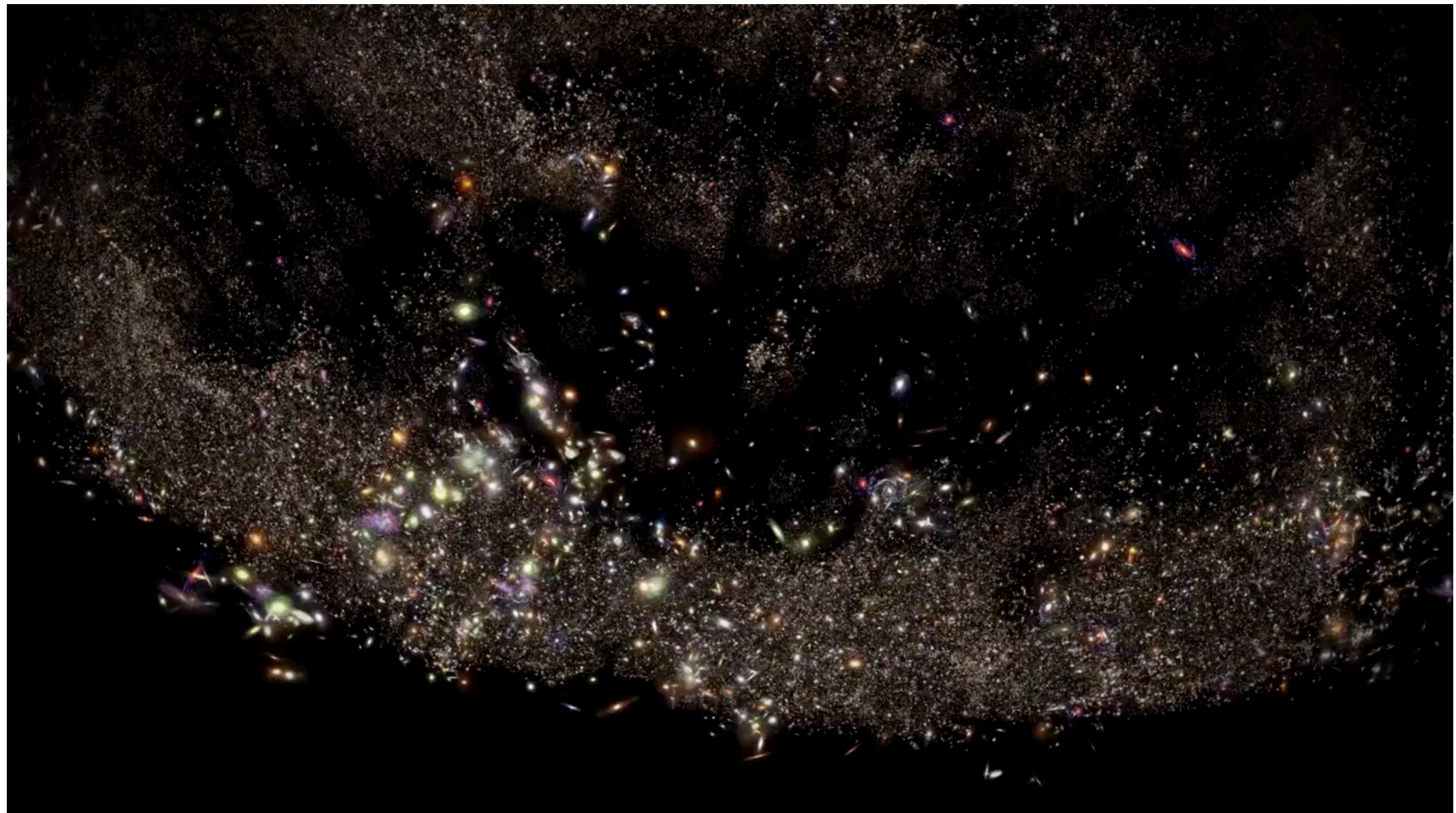
from DESI
~13 millions of galaxies

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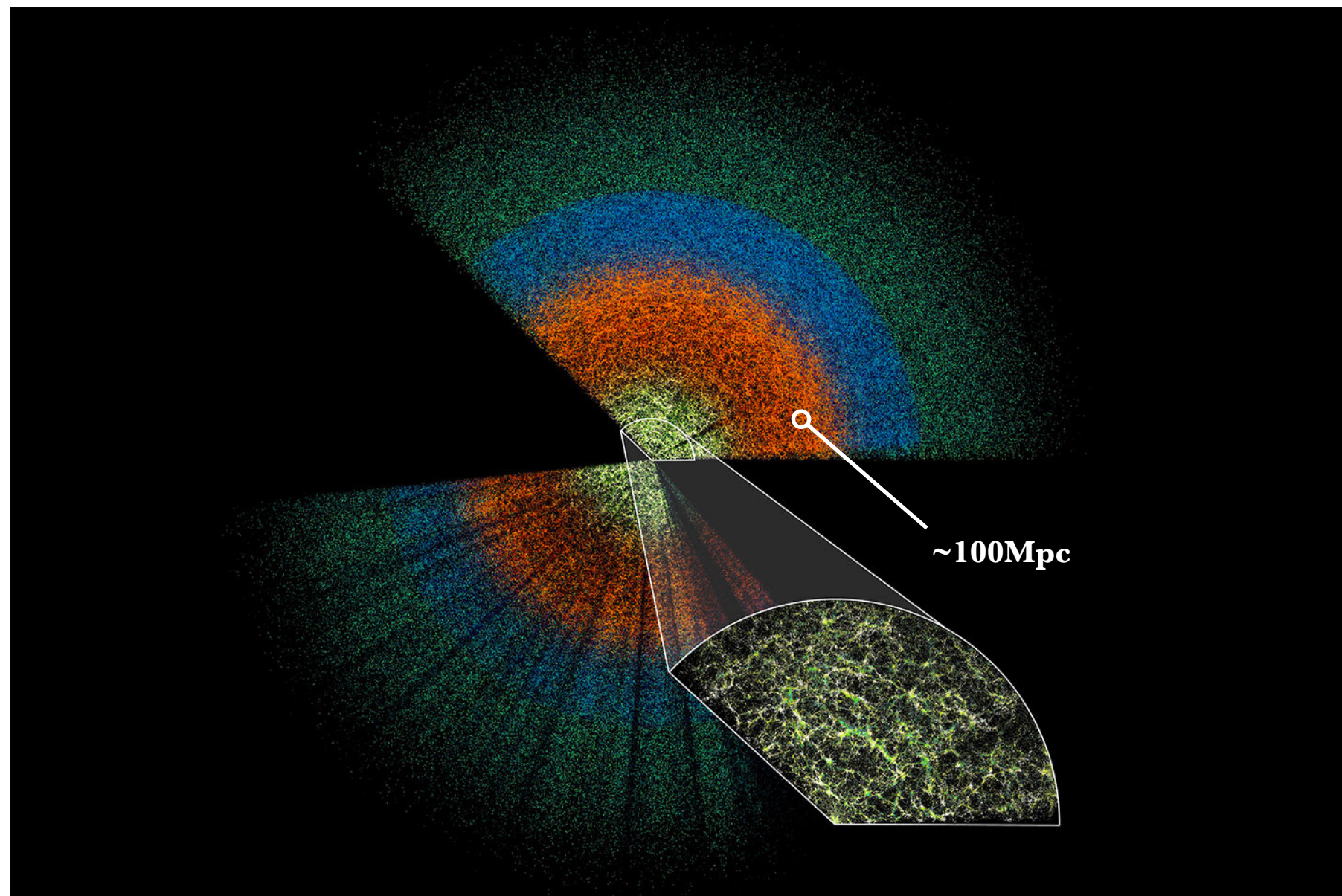
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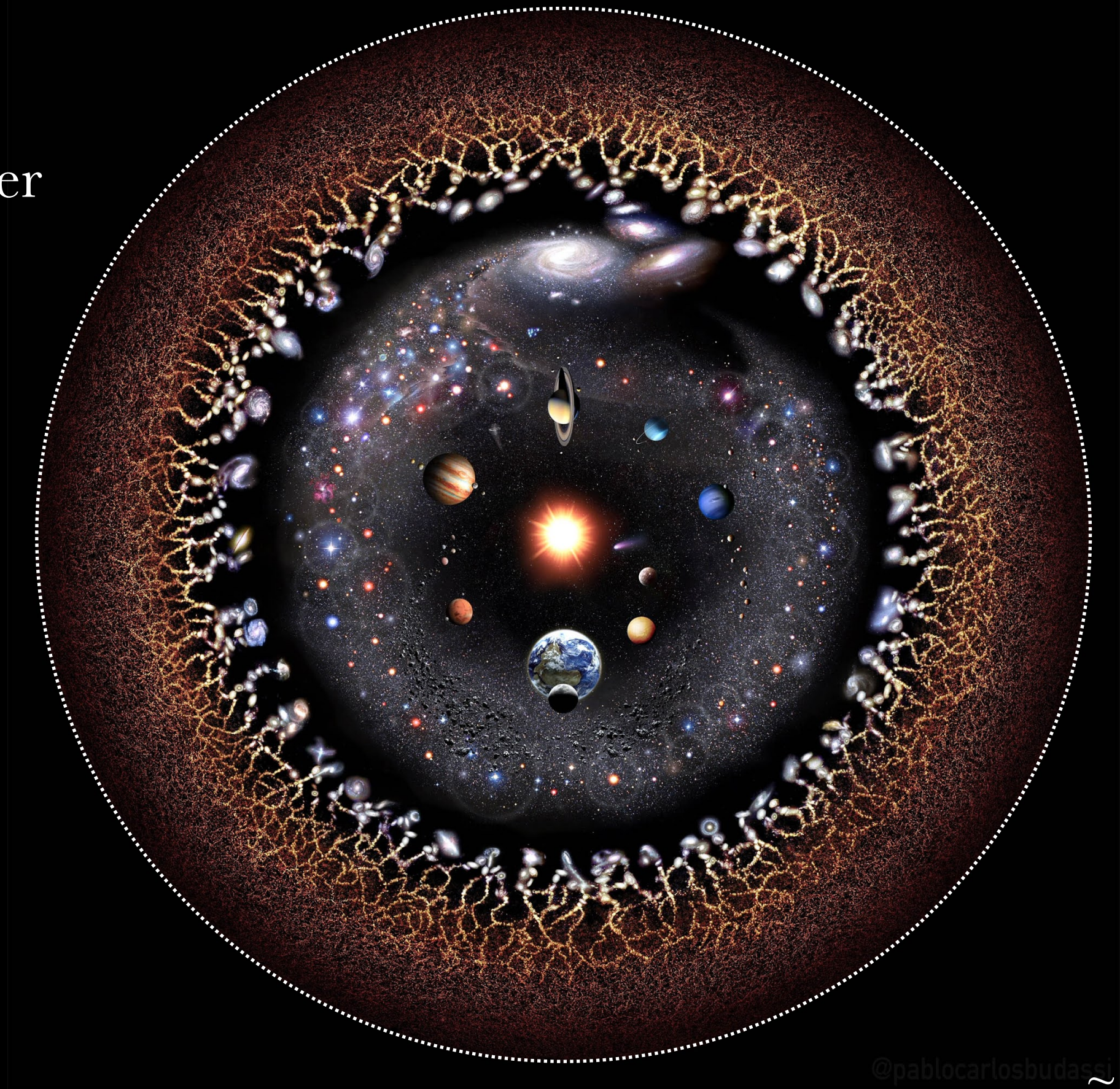
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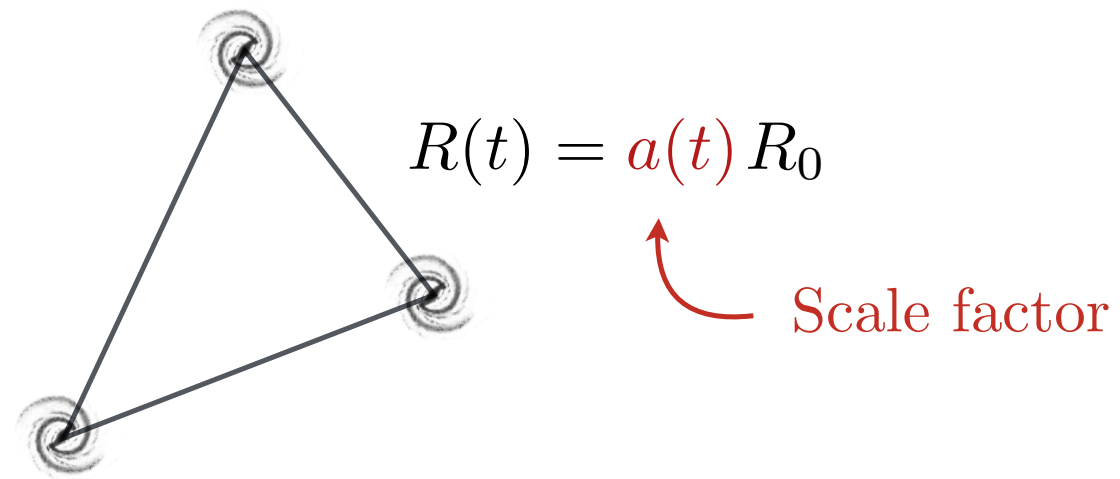


@pablocarlosbudassi

~ 93 Bly
 ~ 28.5 Gpc

Recap of what you heard earlier this week

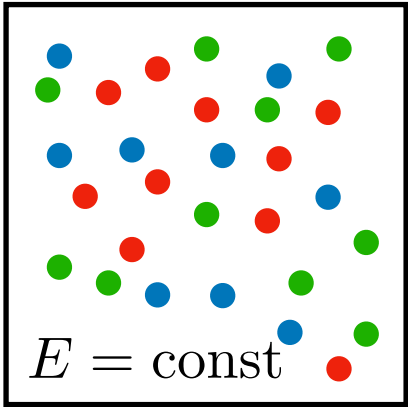
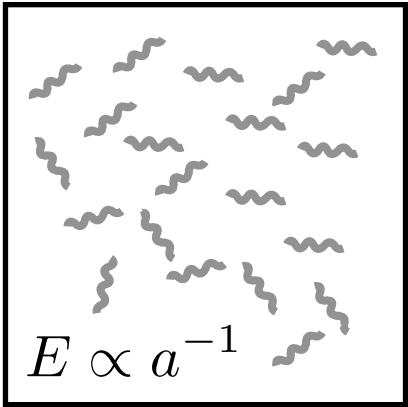
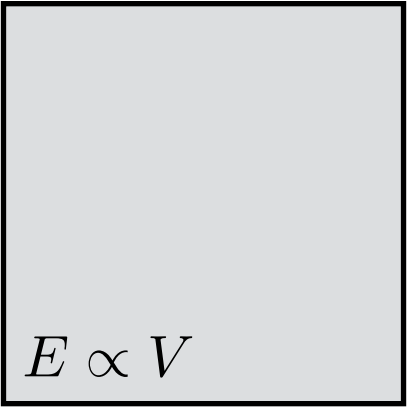
- The Universe is expanding:



- The rate of expansion is determined by the Friedmann equation:

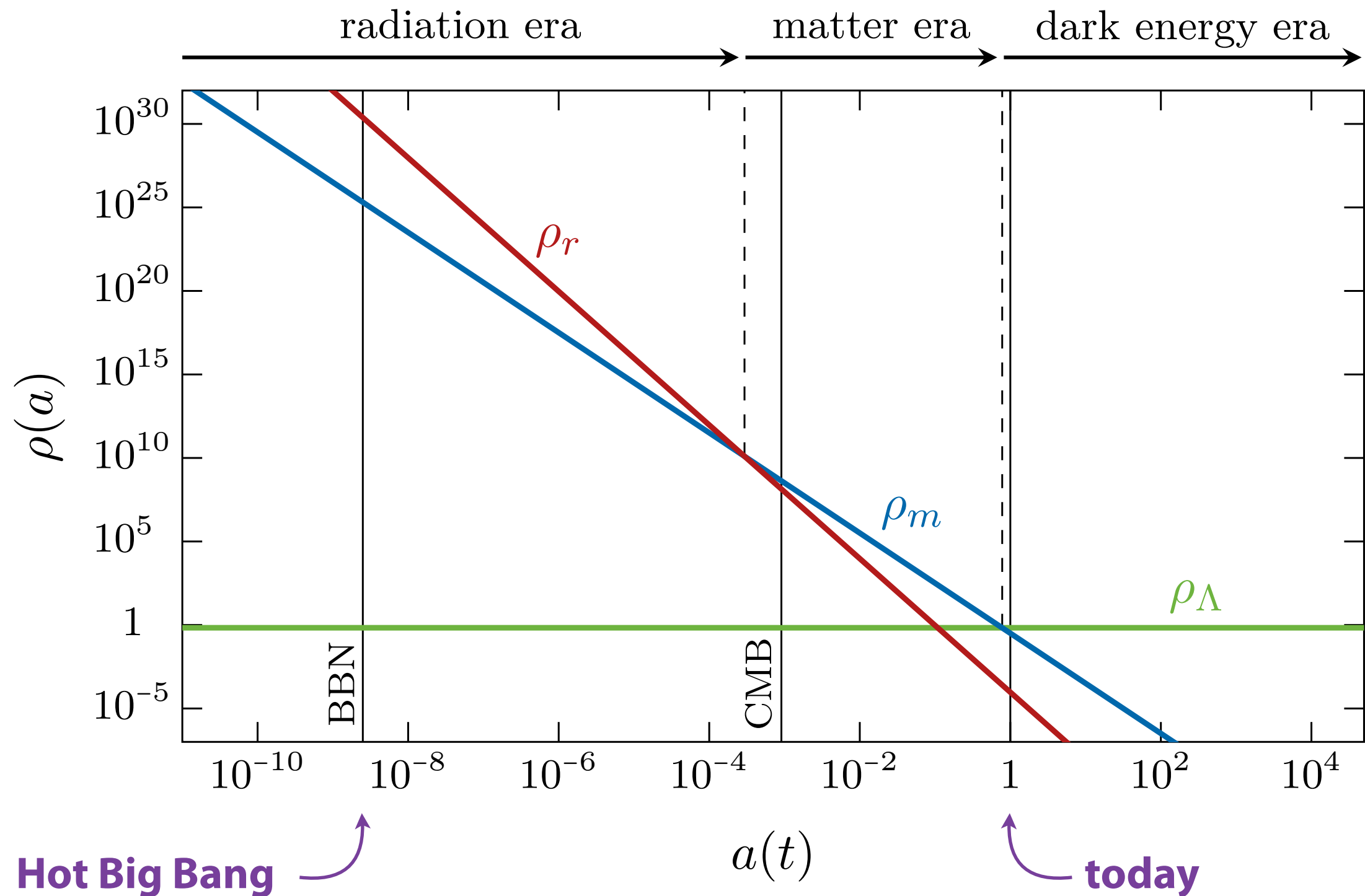
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

- The energy density of matter, radiation and dark energy dilutes as

$\rho_m \propto a^{-3}$	$\rho_r \propto a^{-4}$	$\rho_\Lambda \propto a^0$
		

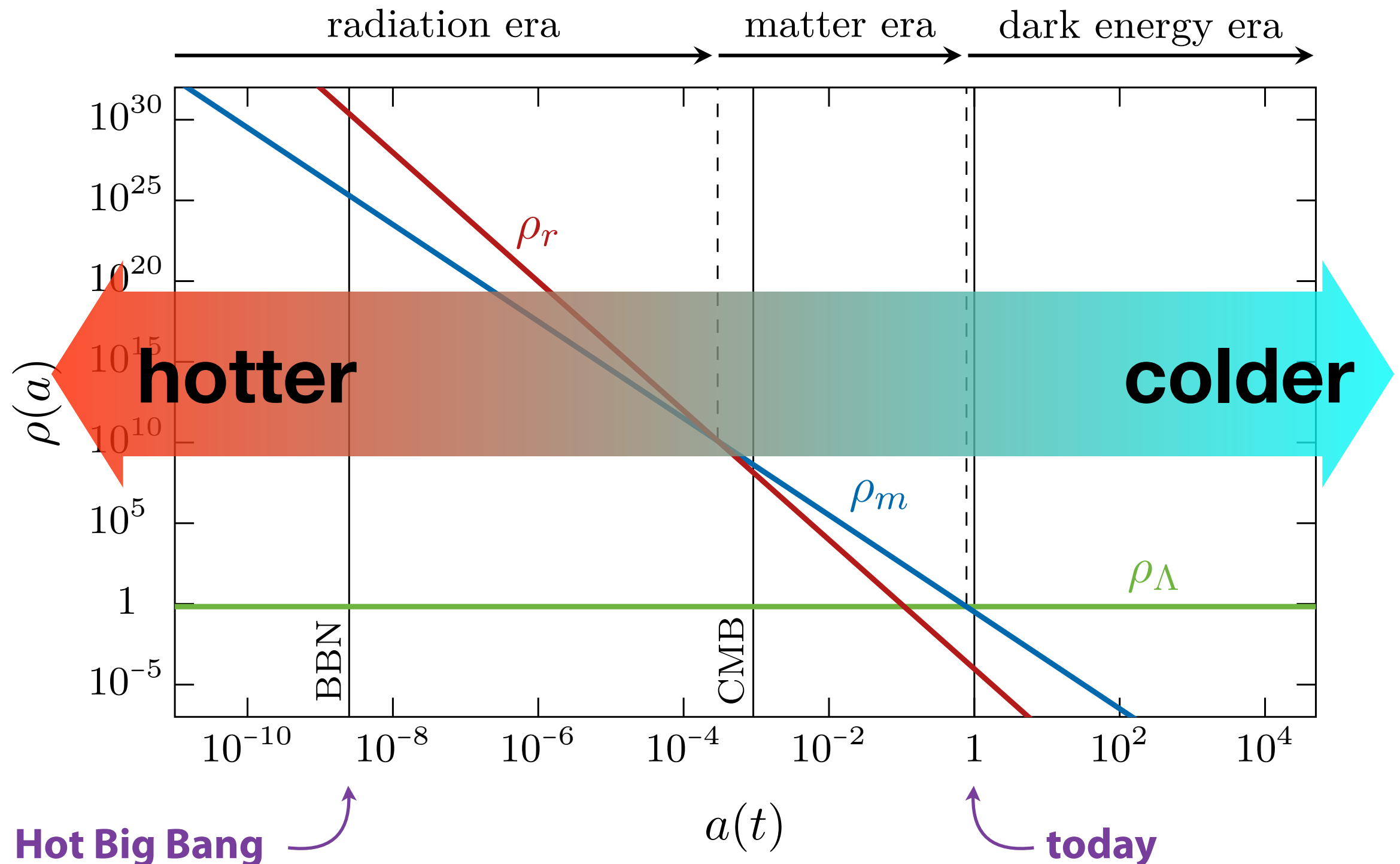
Recap of what you heard earlier this week

- The Universe started hot and dense, but then cooled and diluted:



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- The Universe started hot and dense, but then cooled and diluted:

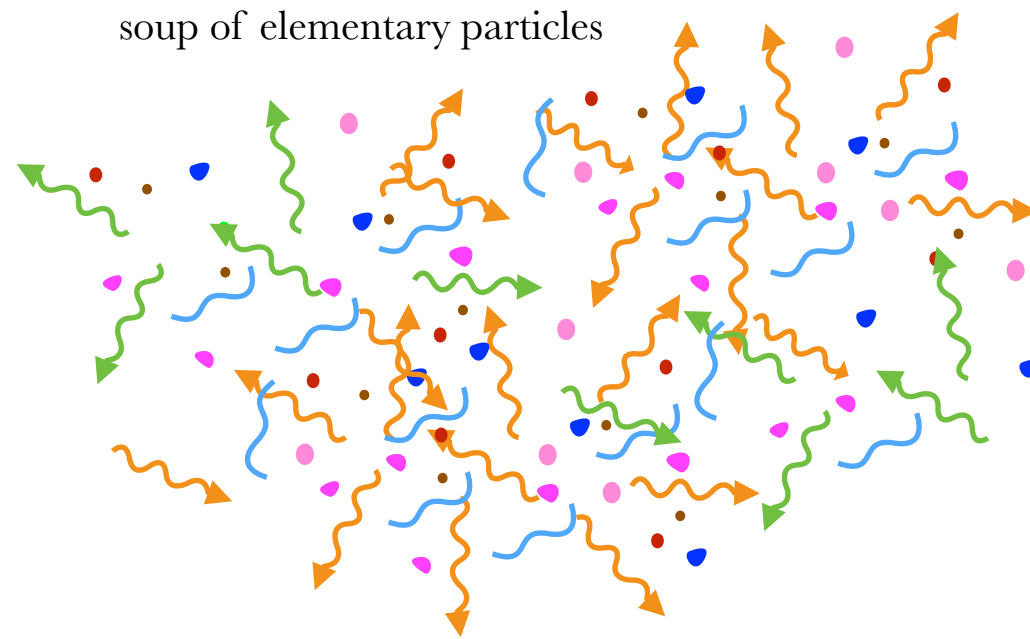


Today:

- Thermal history in the early universe, CMB
- Primordial perturbations, CMB anisotropies and structure formation
- Cosmic inflation and quantum fluctuations
- CMB polarization, B-modes and instrumentation

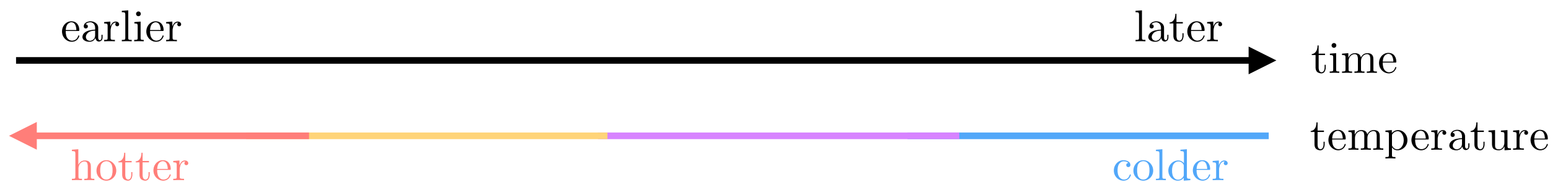
The Hot Big Bang

The Universe started in a hot and dense state:



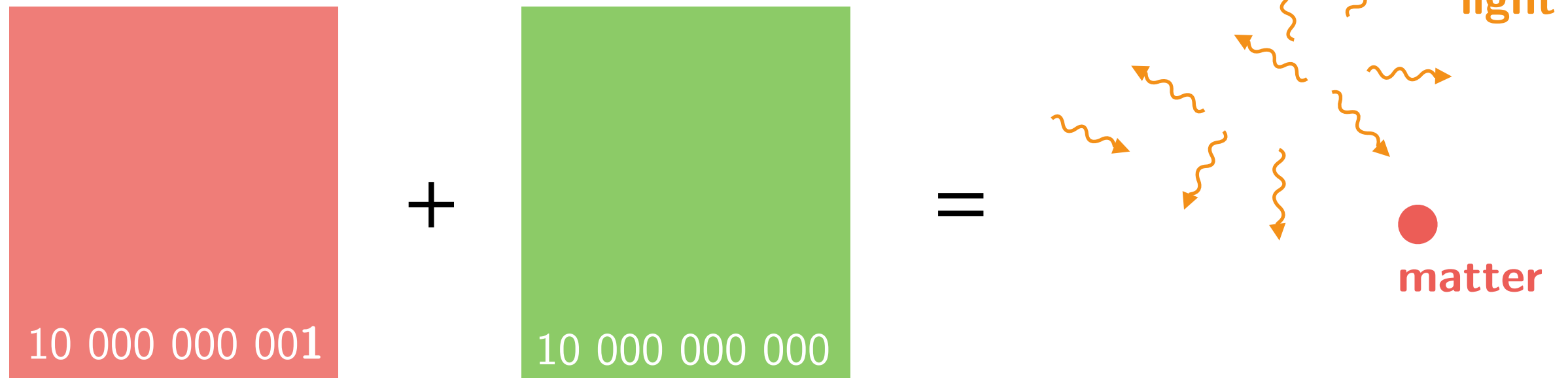
$$T(t) \propto a(t)^{-1}$$

As the Universe expands, it cools.
Many interesting things happened.



$$t = 10^{-19} \text{ s}$$

The Universe is filled with almost equal amounts of **matter** and **antimatter**



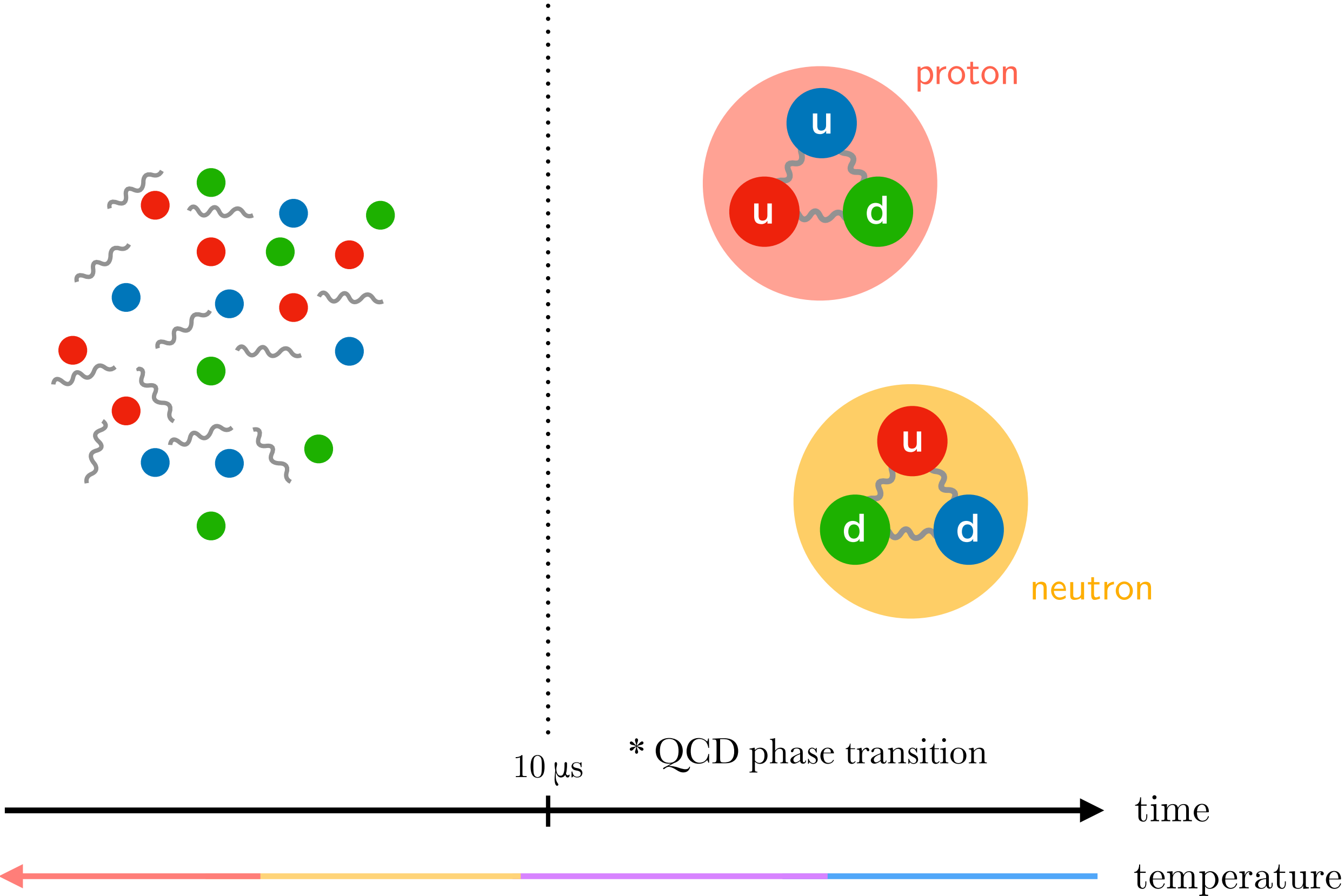
As the universe cools, matter and antimatter annihilate.

For some mysterious reason, there was initially a fraction more matter than antimatter. This matter survived the annihilation.

Without this **asymmetry** we wouldn't exist.

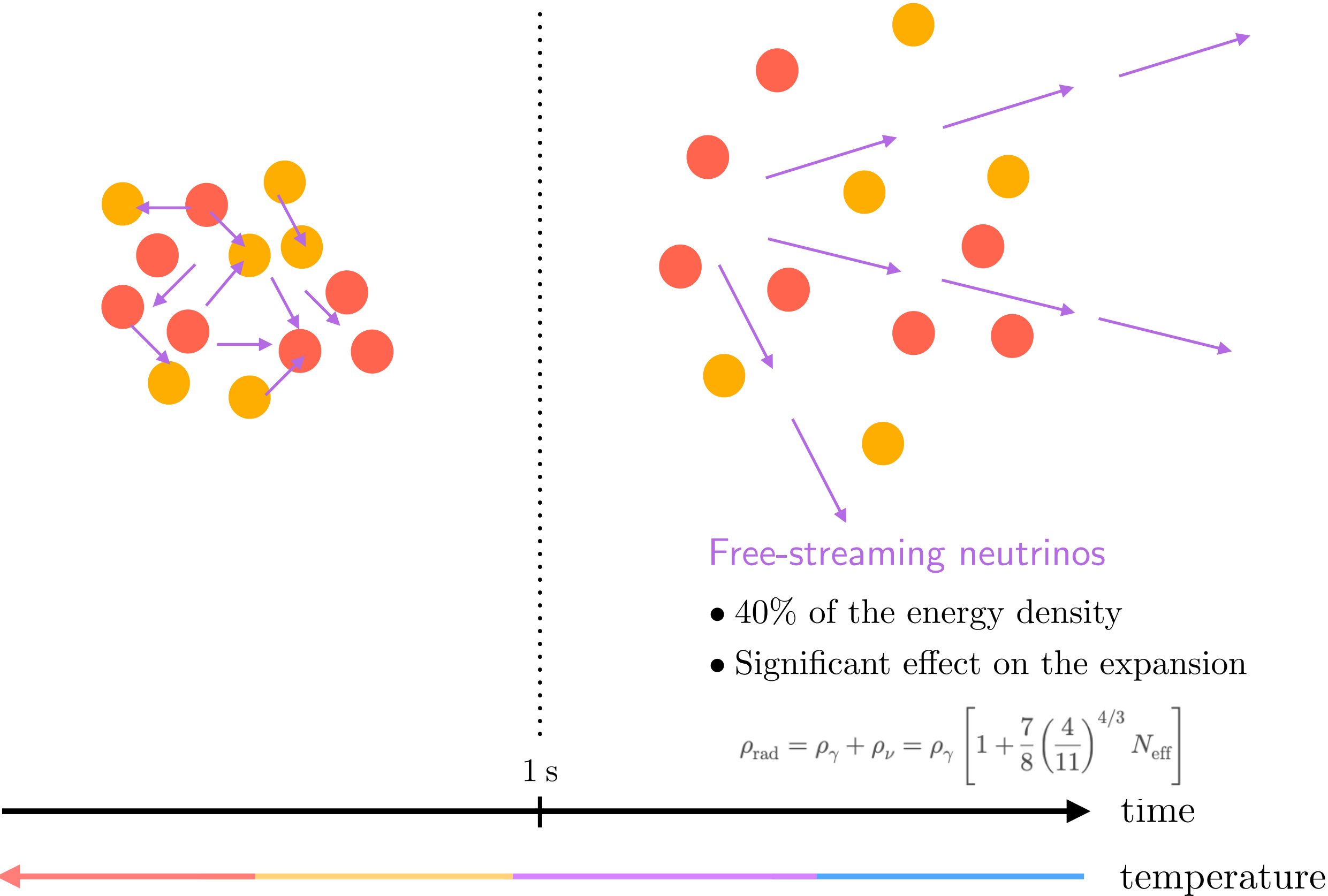
$t = 10^{-5} \text{ s}$

Quarks and gluons condense into nuclei:



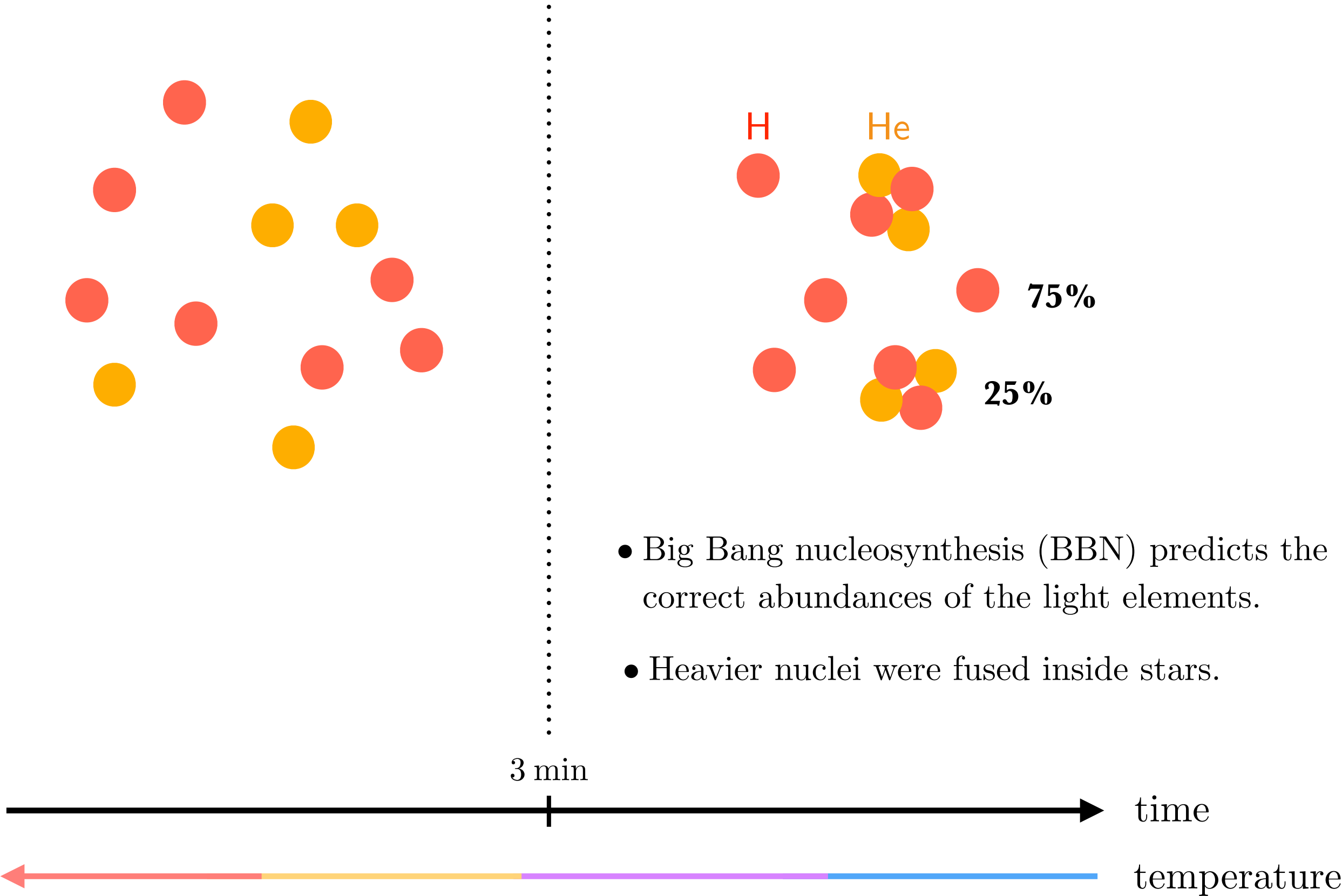
$t = 1\text{ s}$

Neutrinos decouple and neutrons freeze out:



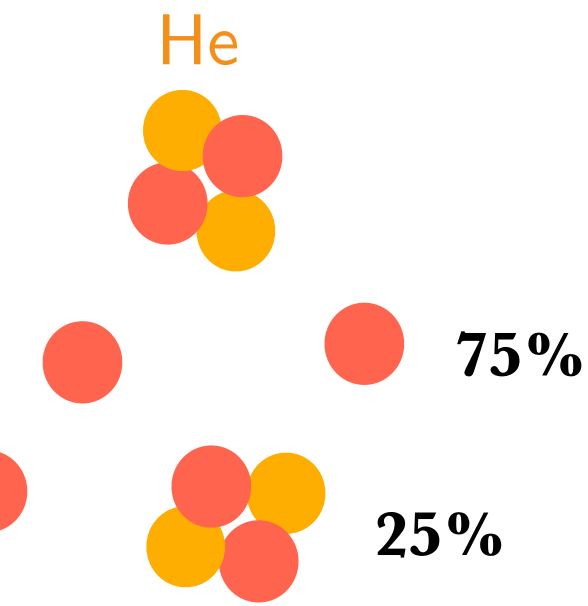
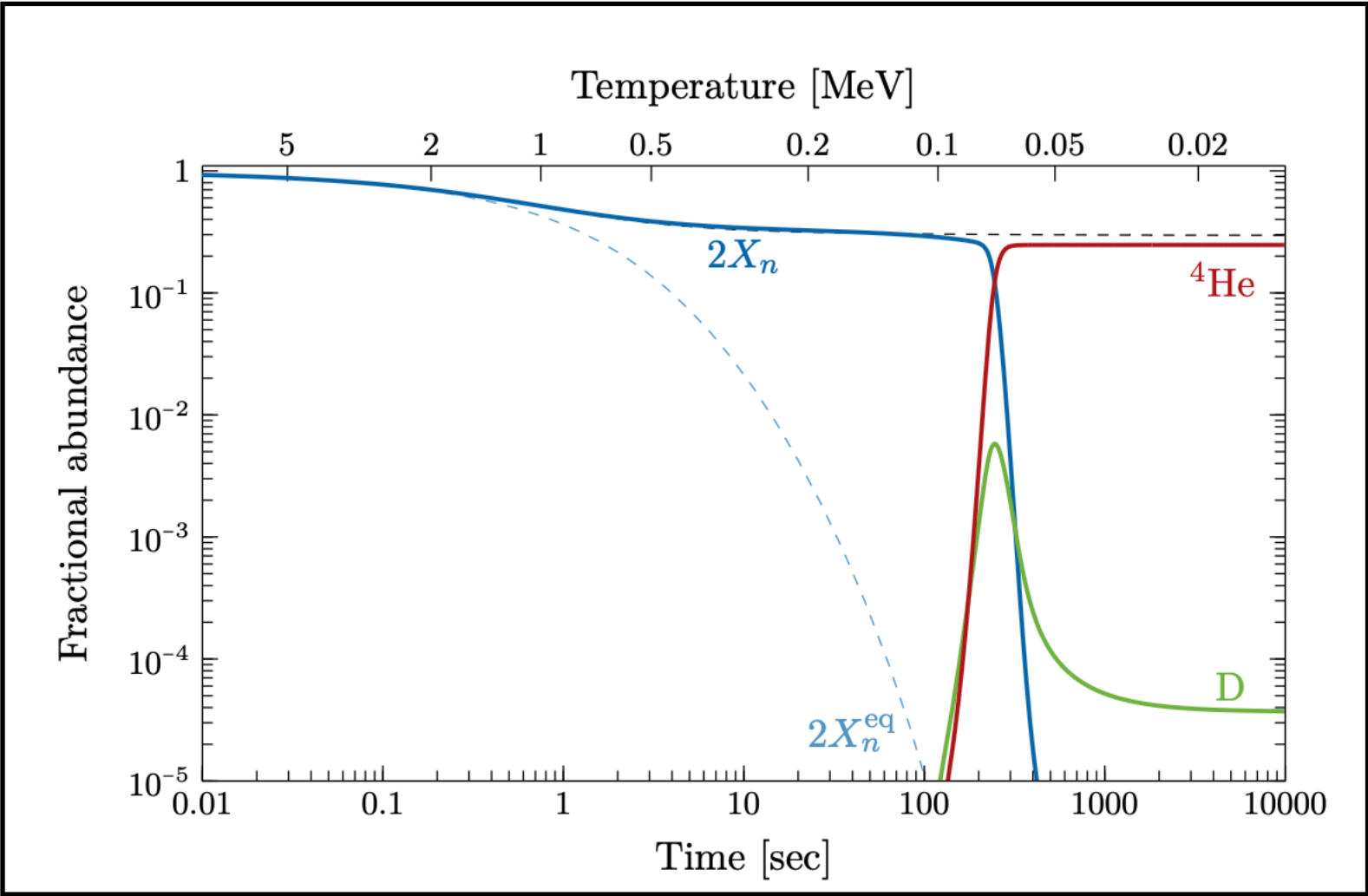
$t = 3 \text{ min}$

Light elements (H, He, and Li) form:

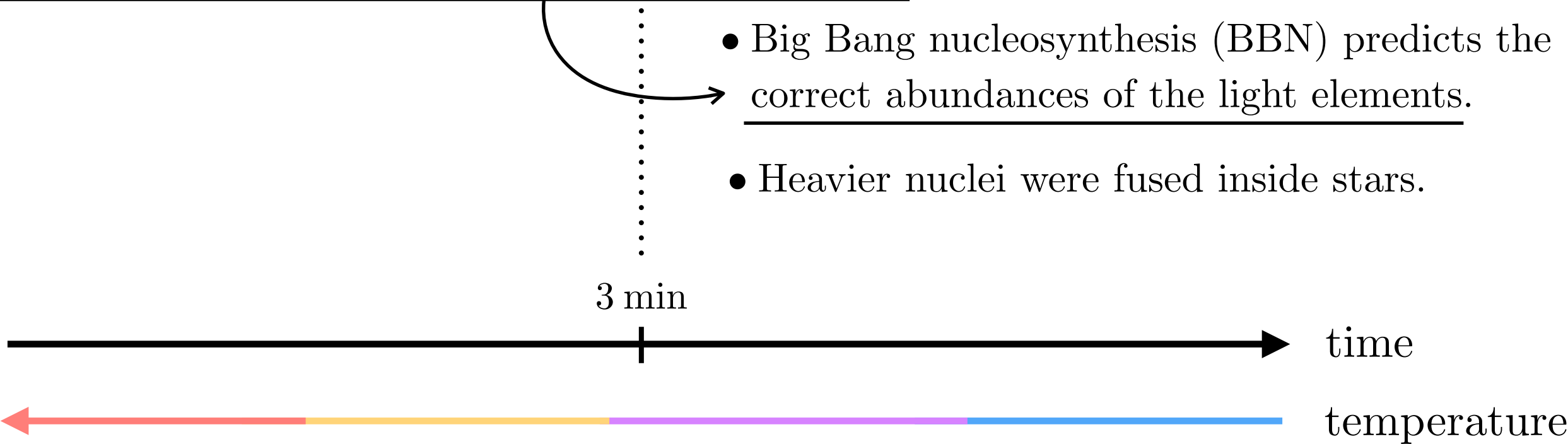


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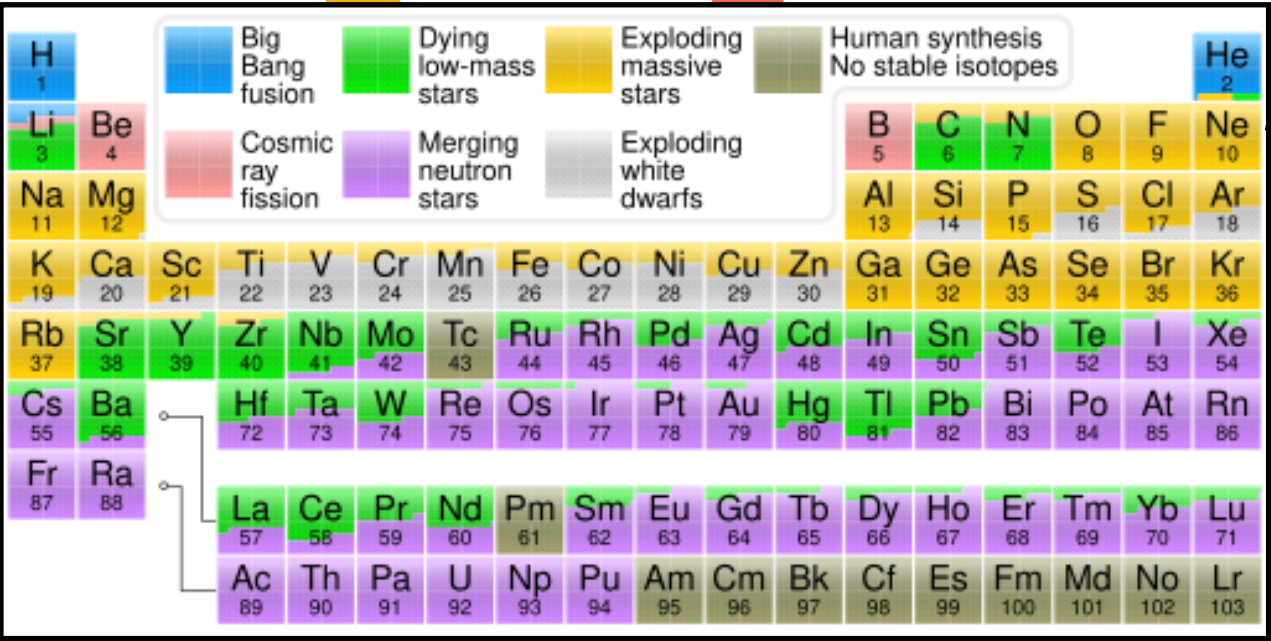
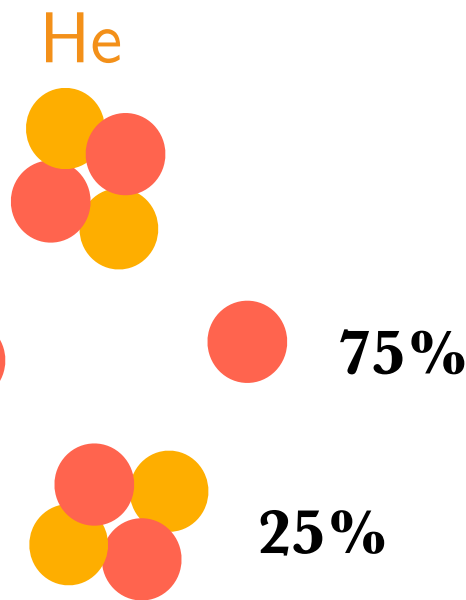
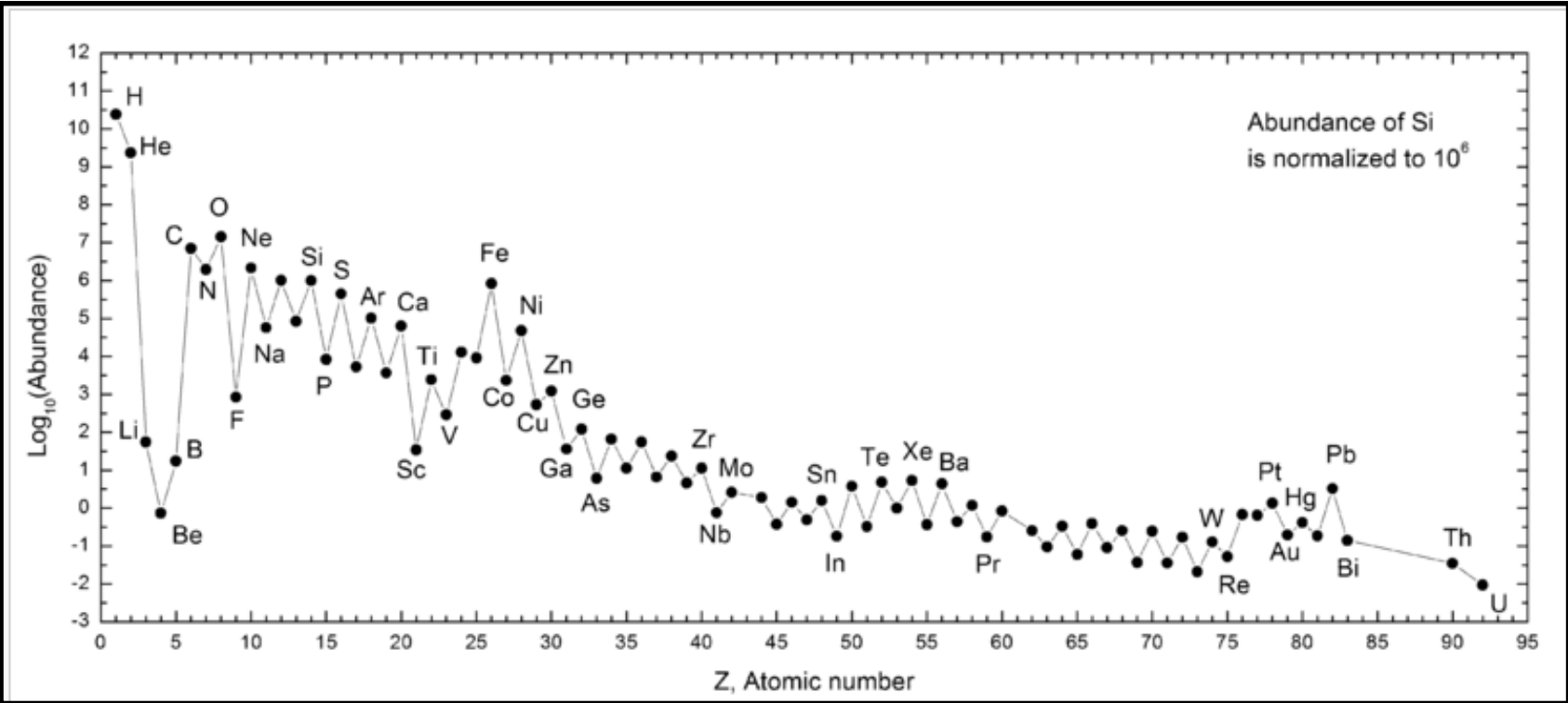


- Big Bang nucleosynthesis (BBN) predicts the correct abundances of the light elements.
- Heavier nuclei were fused inside stars.



$t = 3 \text{ min}$

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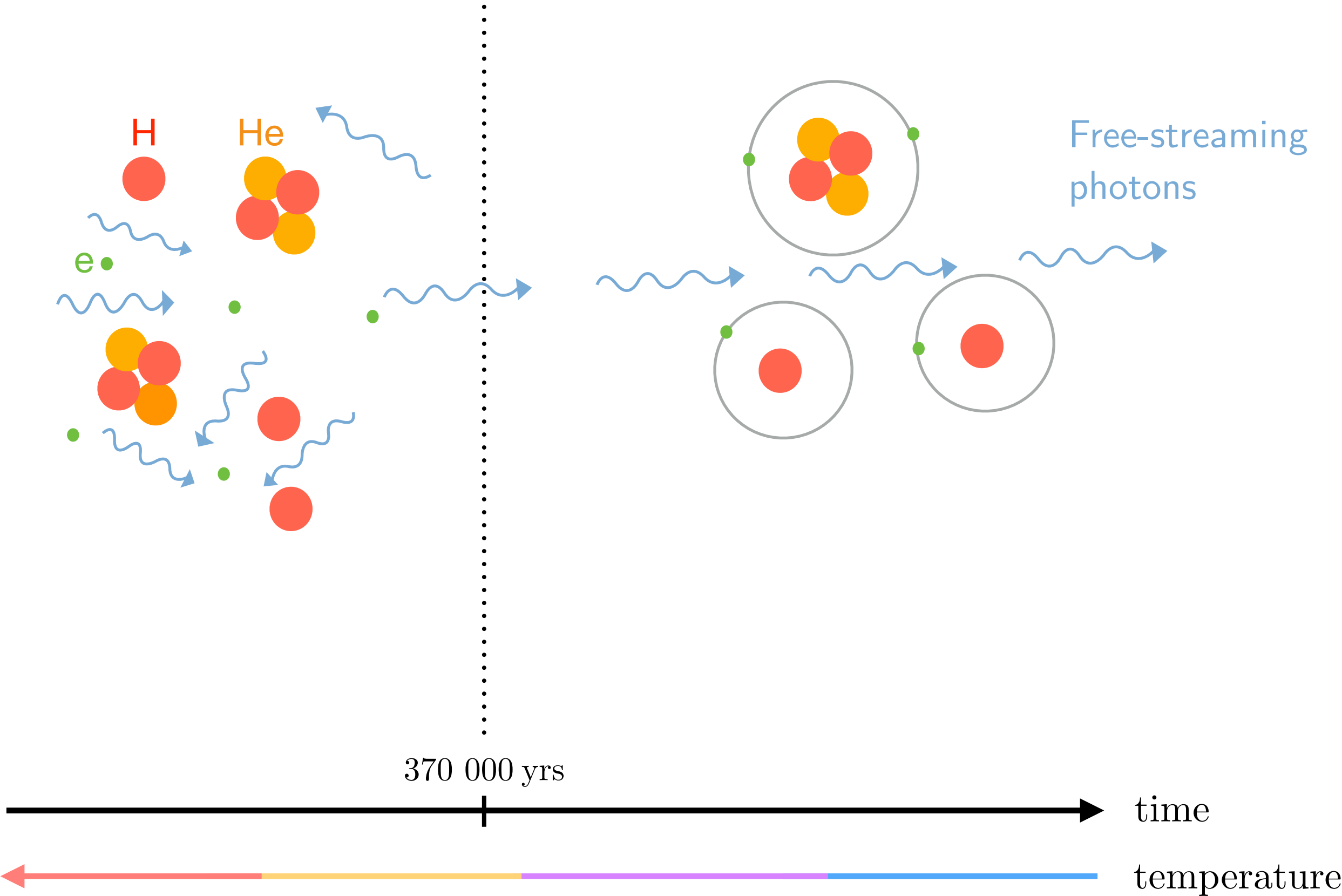


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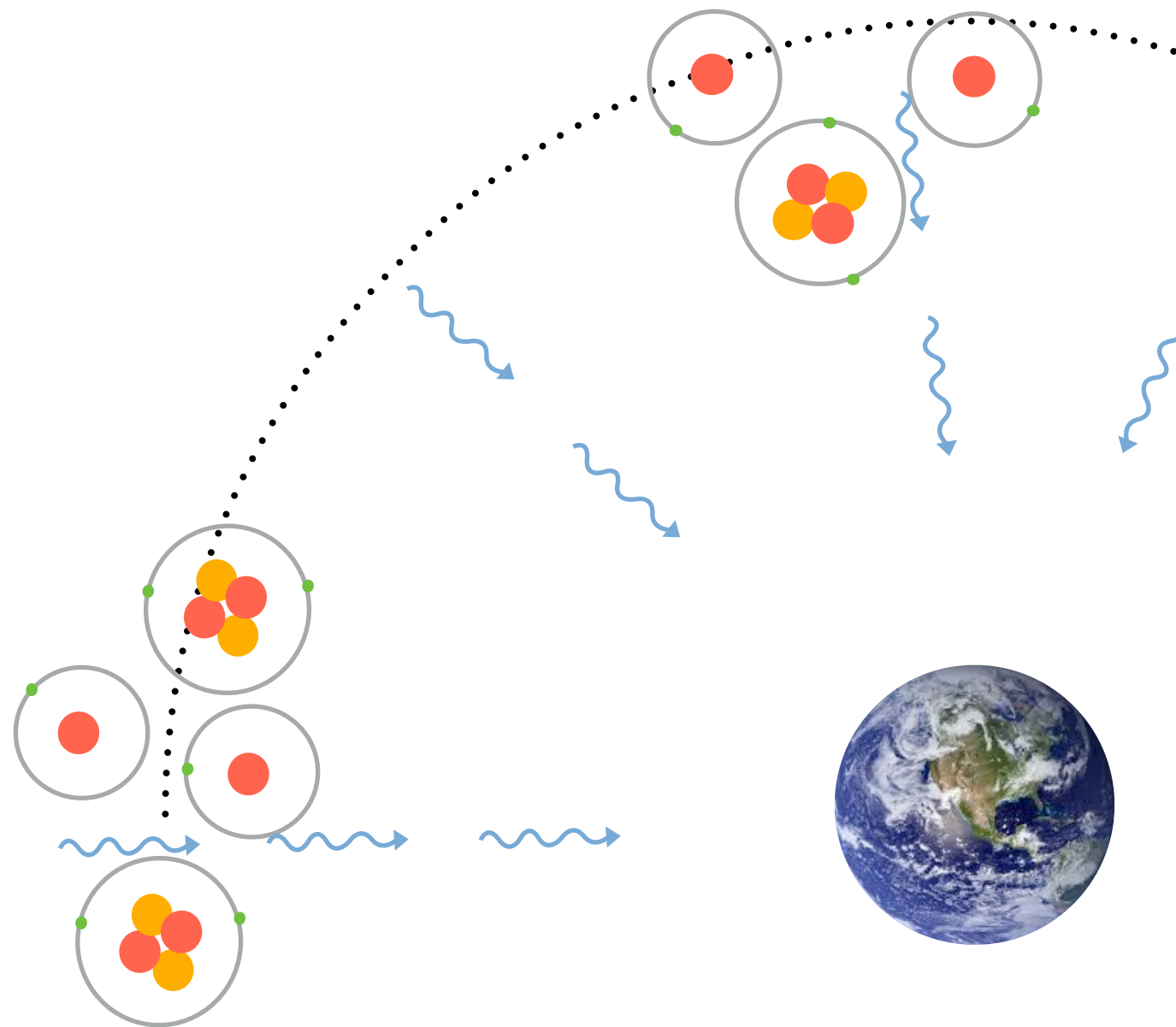


$t = 370\,000\text{ yrs}$

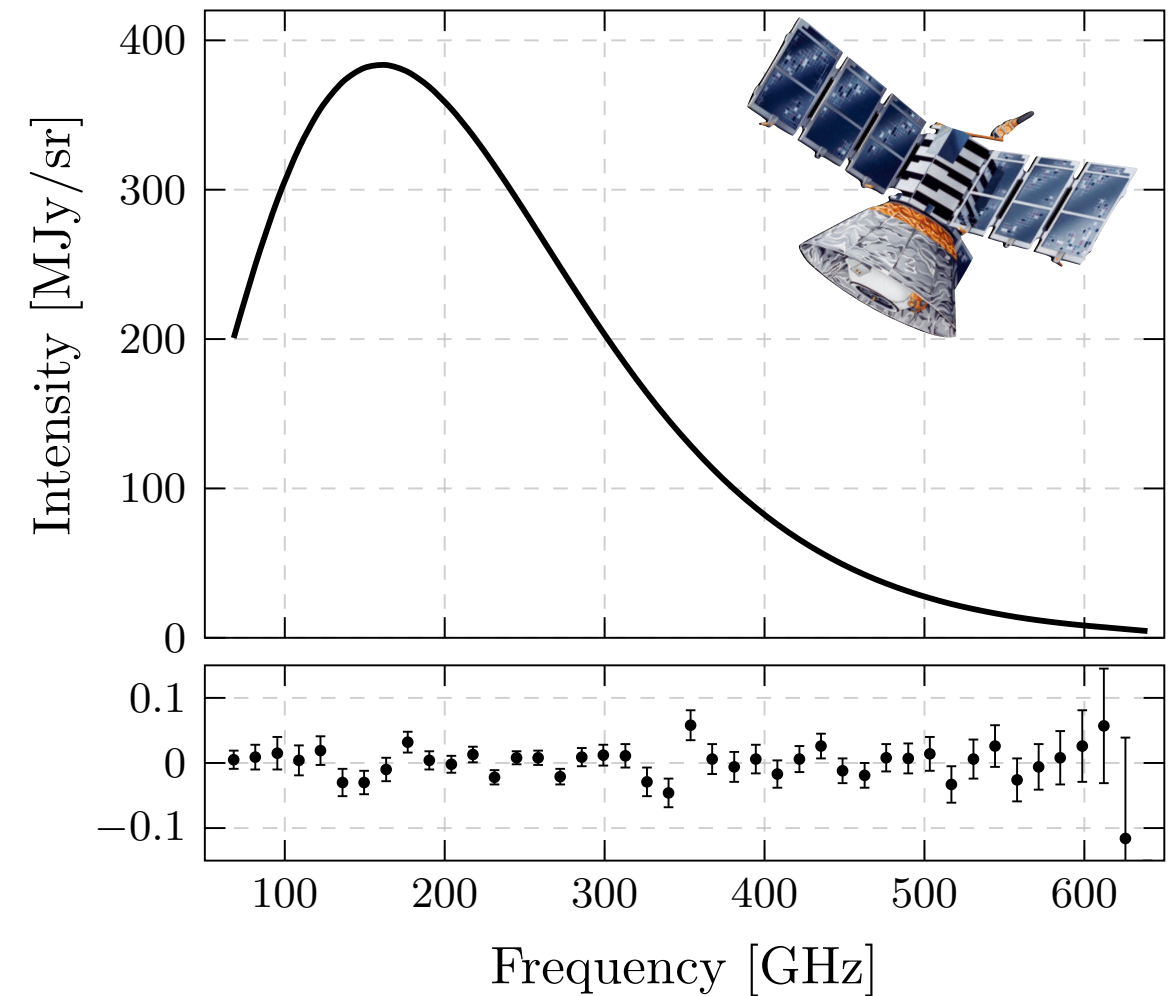
Atoms form and the first light is released:



This afterglow of the Big Bang is still seen today:



Cosmic Microwave Background

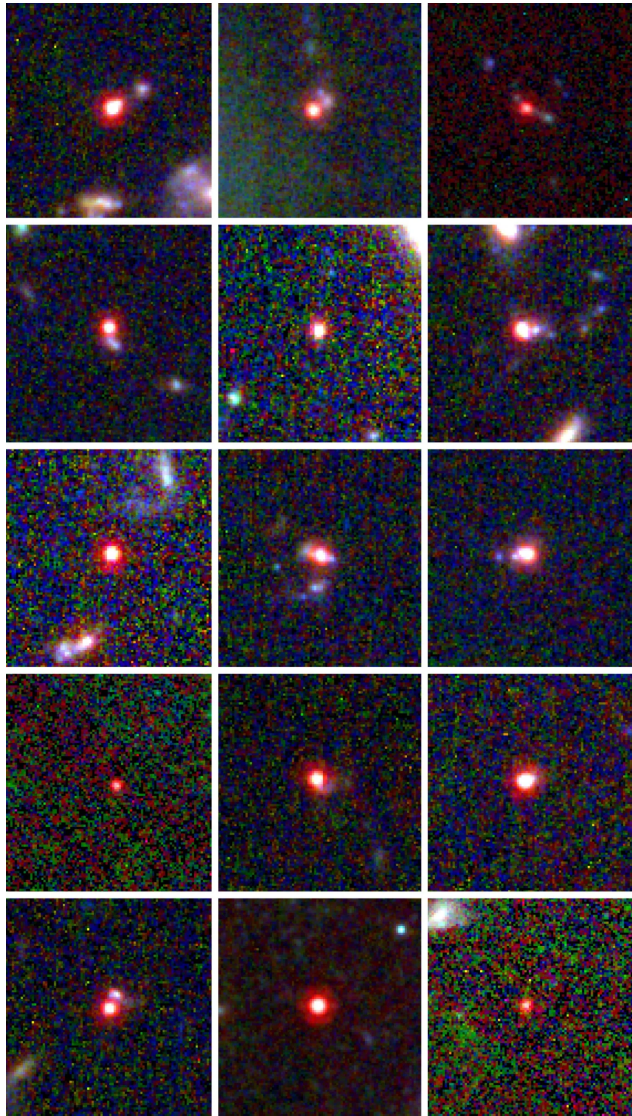
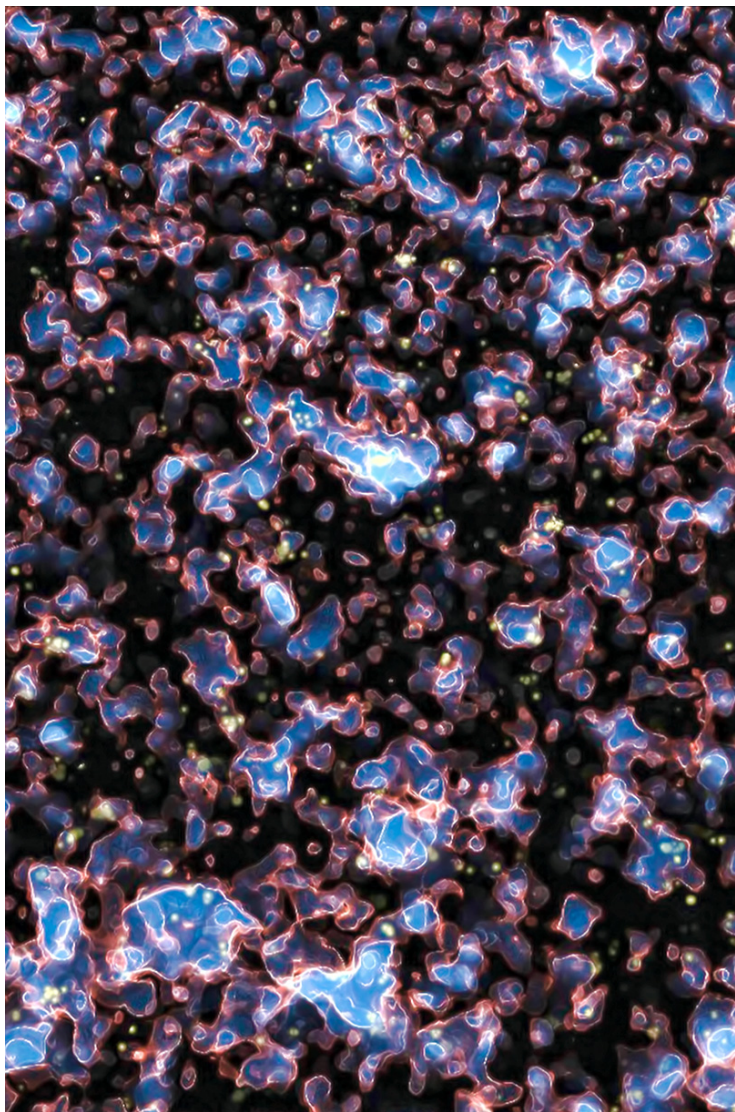


- 410 photons per cubic centimeter
- cooled by the expansion: 2.7 K
- faint microwave radiation: CMB

Measurement of the CMB blackbody spectrum by the COBE satellite. The error bars are too small to be seen in the top panel. In the bottom panel, we therefore also show the residuals relative to a blackbody spectrum with temperature $T_0 = 2.725$ K. Notice the change in scale between the two panels.

$t > 1$ billion yrs

Matter collapses into stars and galaxies:



1 billion years



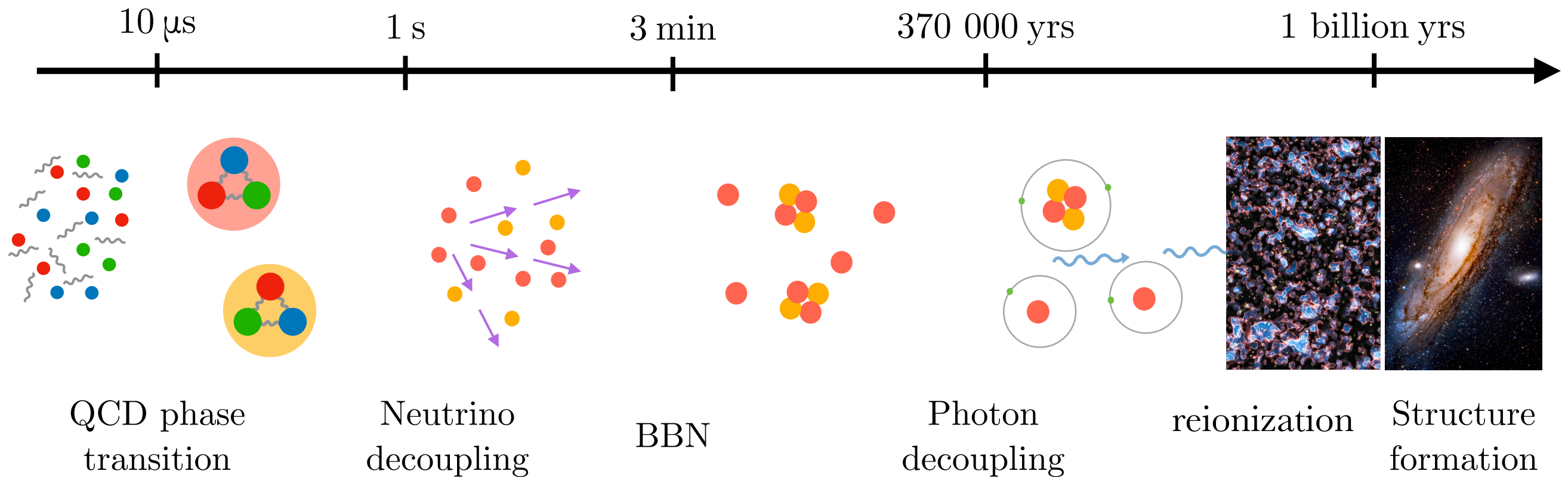
time



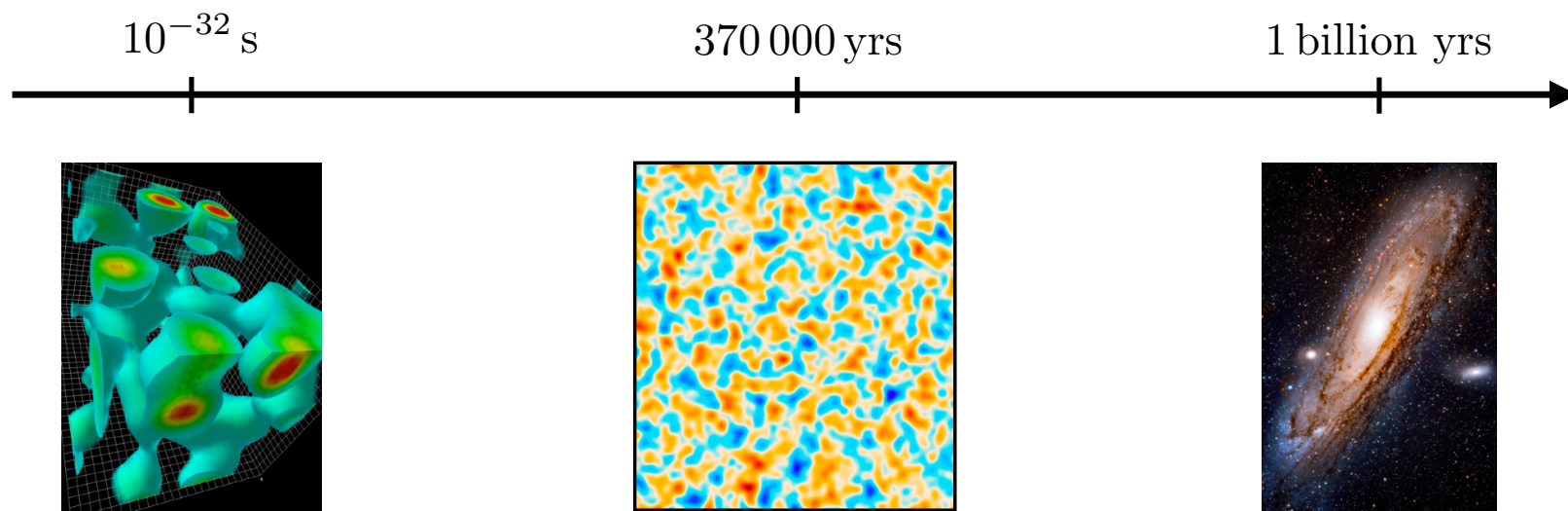
temperature

Recap

This history of the Universe is an observational fact:



- The basic picture has been confirmed by many independent observations.
- Many precise details are probed by measurements of the CMB.



Quantum
fluctuations



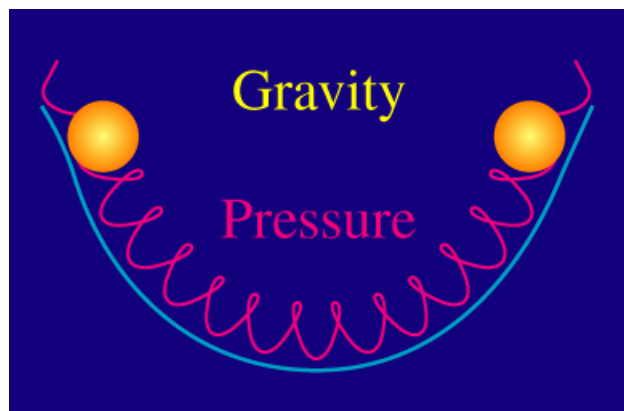
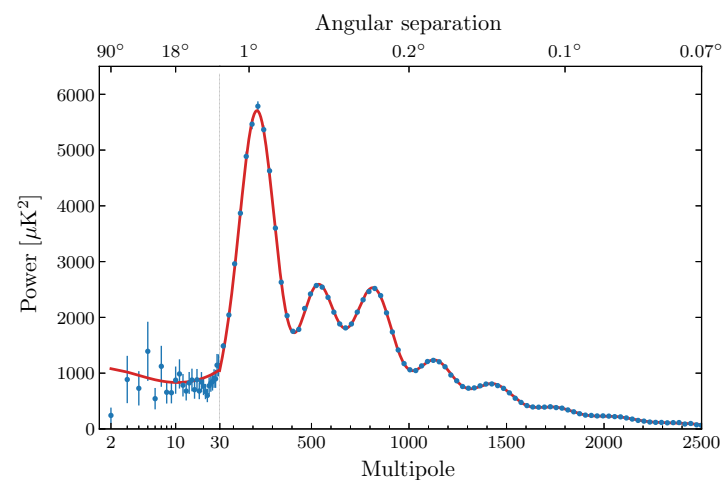
CMB
fluctuations



Galaxies

Cosmic
sound waves

Gravitational
clustering



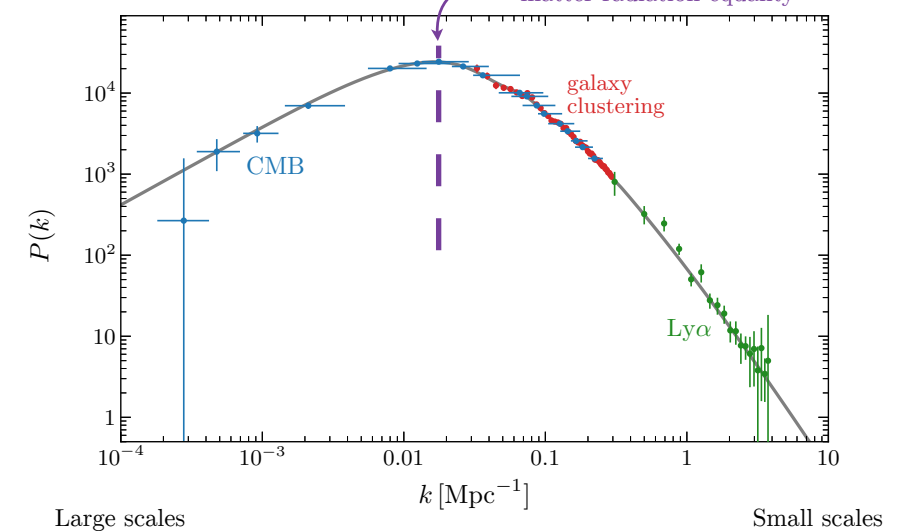
$$\ddot{\delta} + 2H\dot{\delta} = (4\pi G\bar{\rho})\delta$$

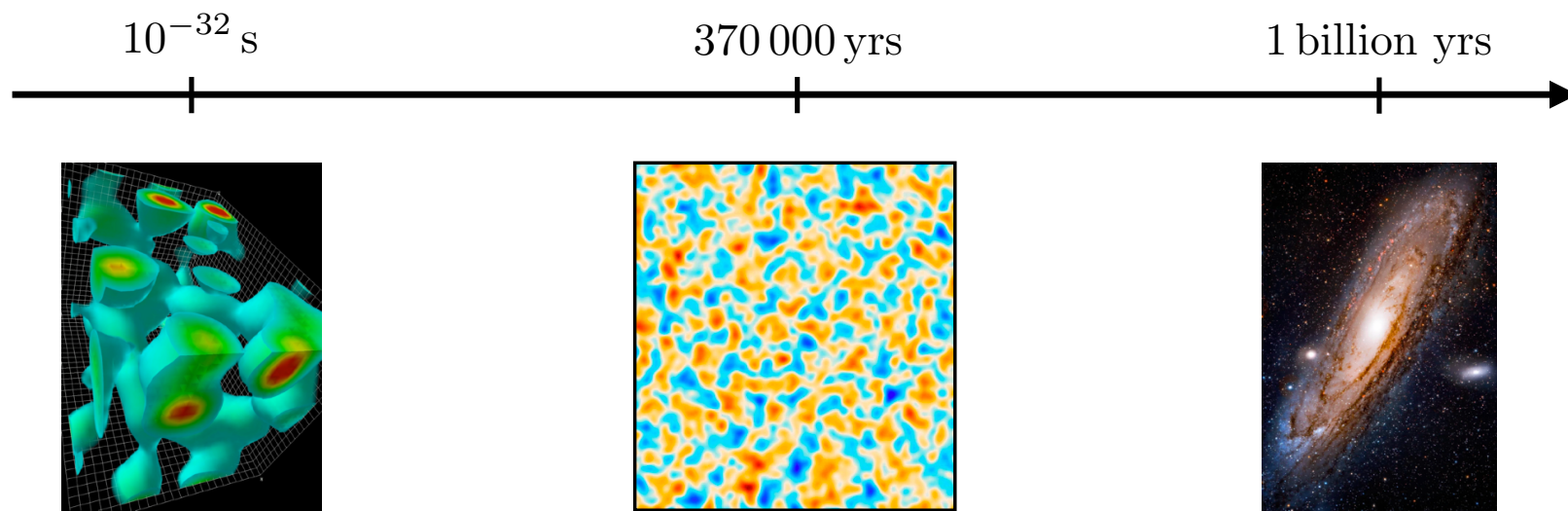
Gravitational force

Hubble friction

Power Spectrum

The observed **matter power spectrum** is





Quantum
fluctuations



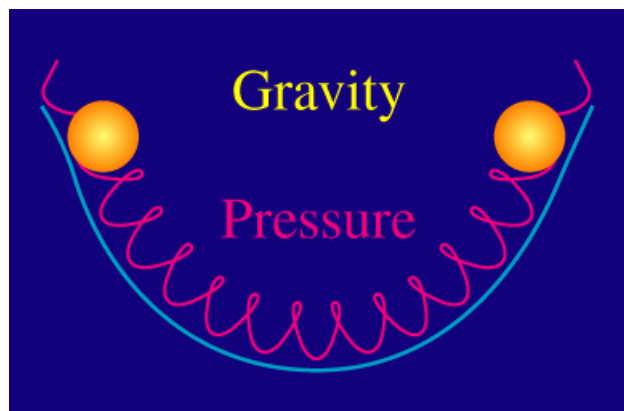
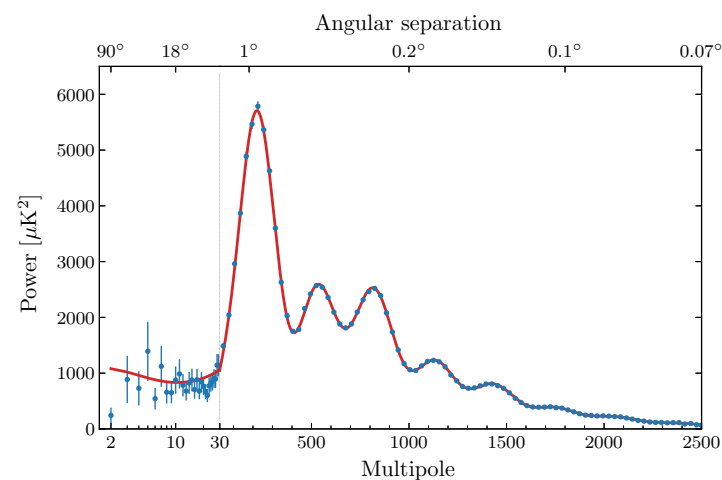
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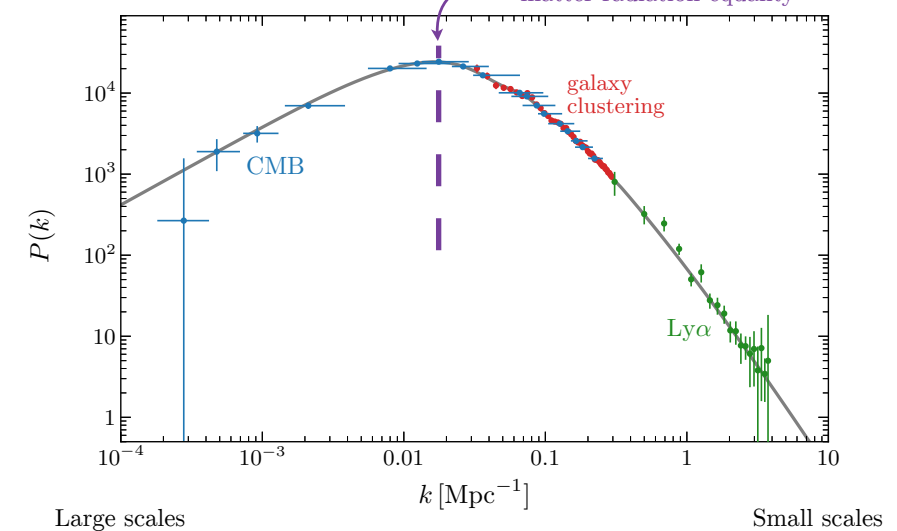
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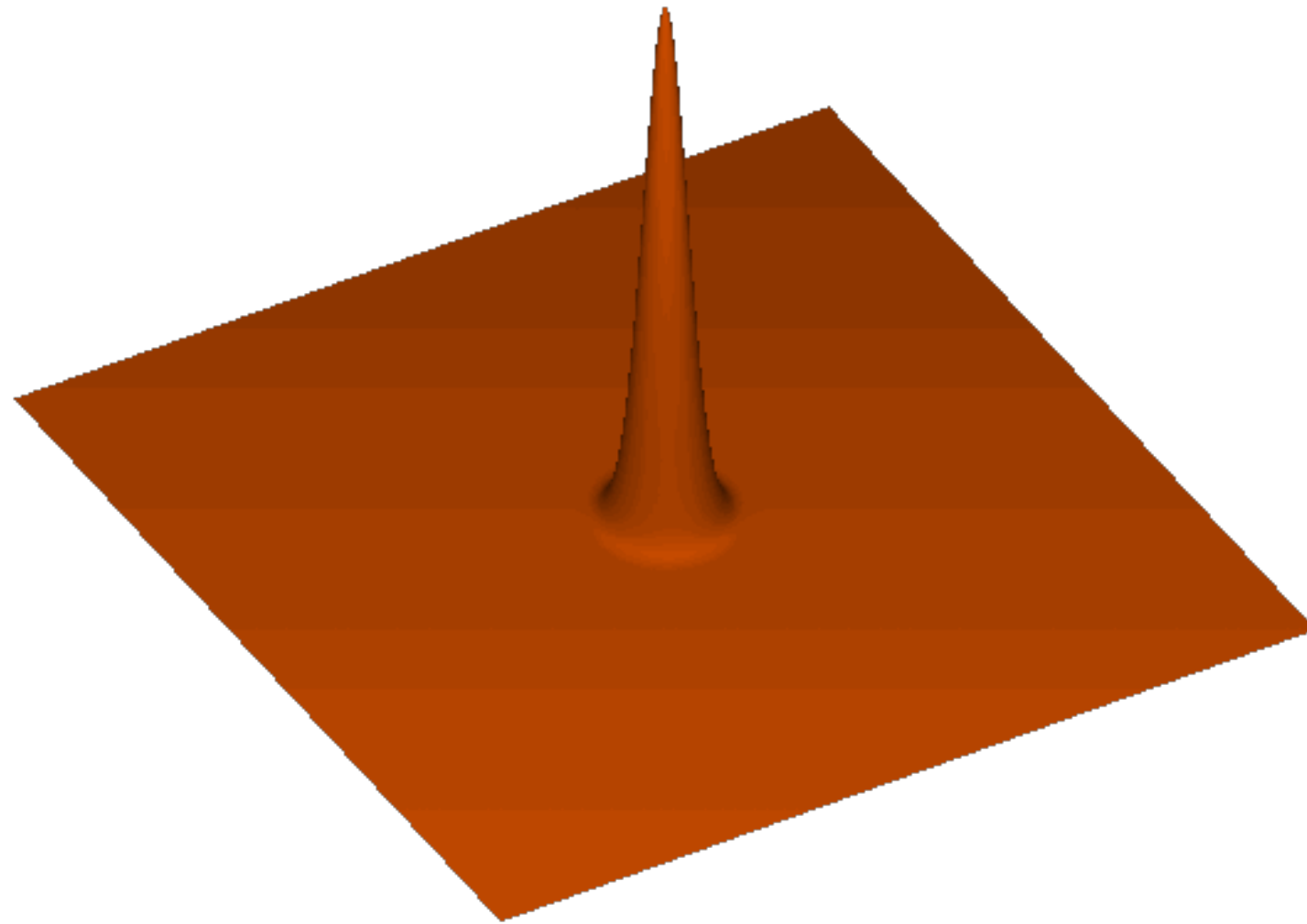
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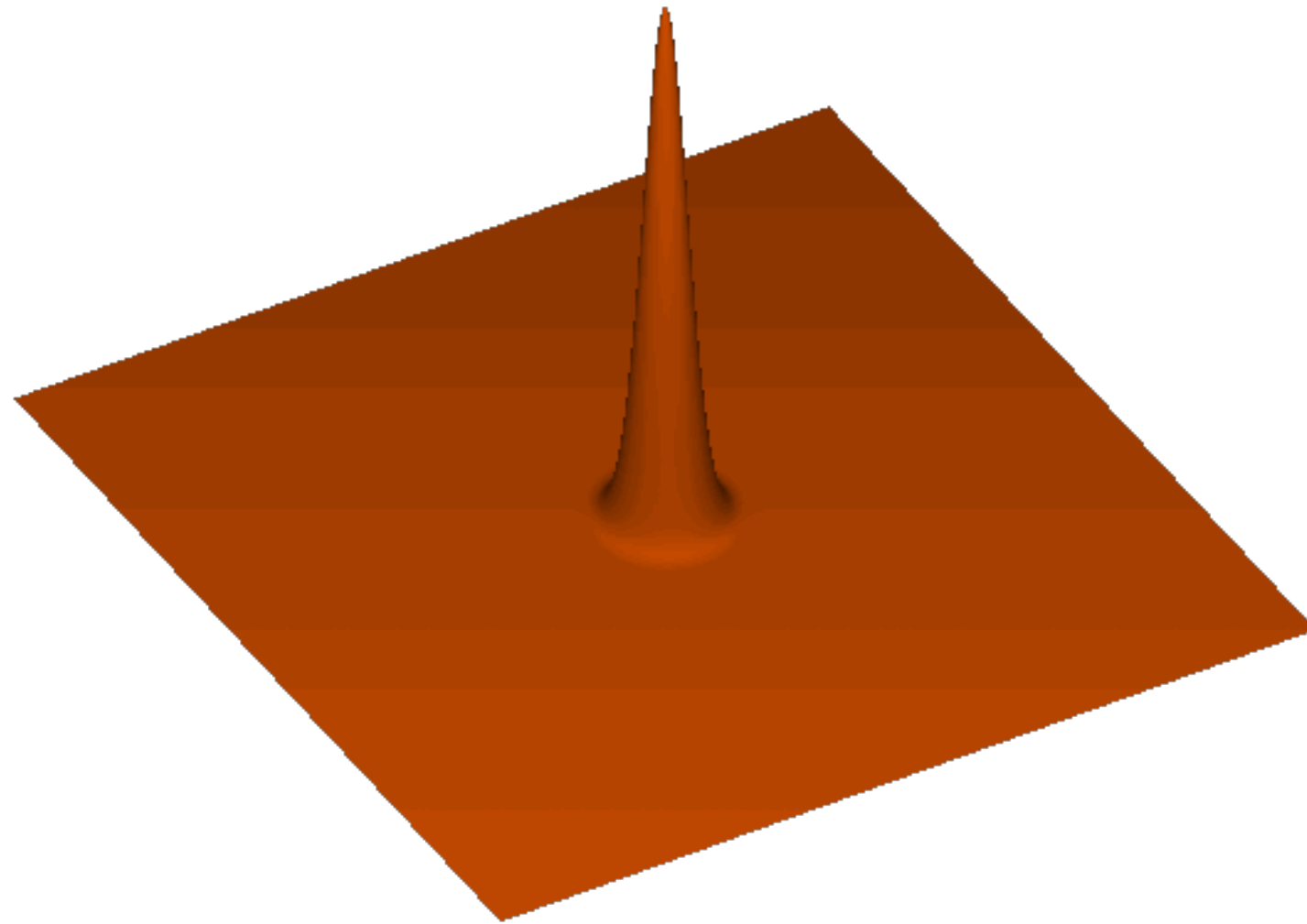
Cosmic Sound Waves

Consider the evolution of a single localized density fluctuation:



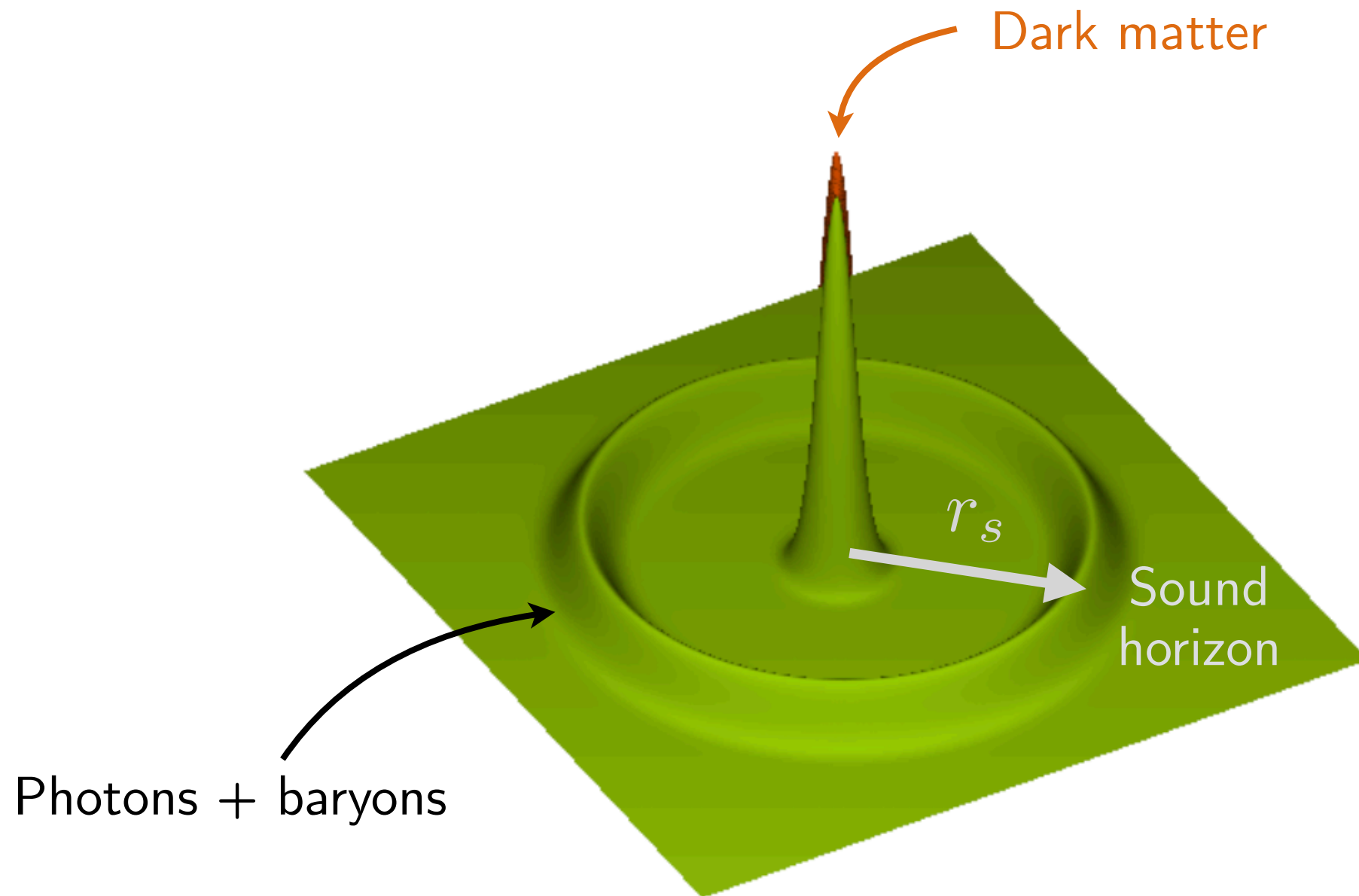
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Cosmic Sound Waves

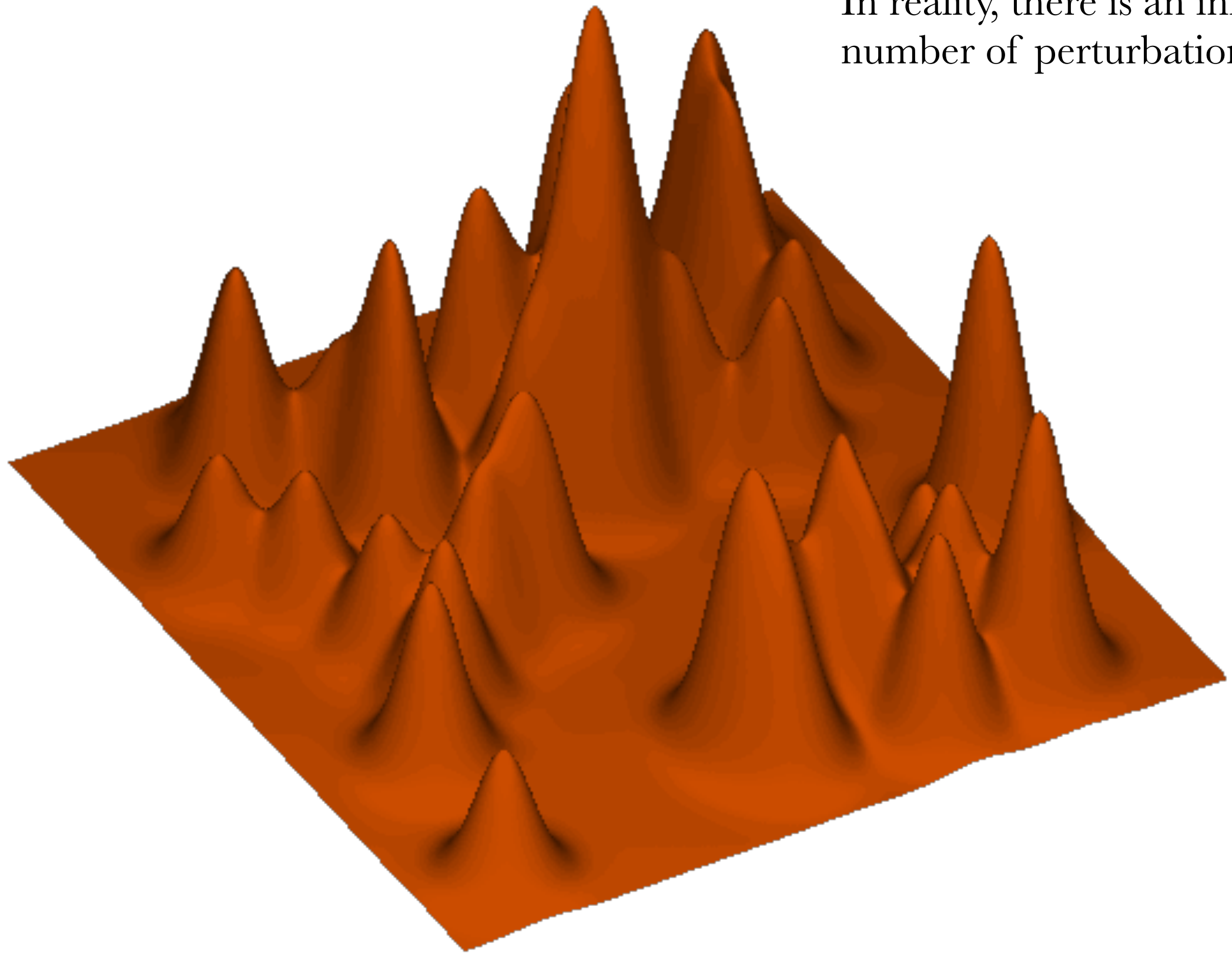
This creates a radial sound wave in the photon-baryon fluid:



The wave travels a distance of 50 000 light-years (called the **sound horizon**) before the Universe becomes transparent to light.

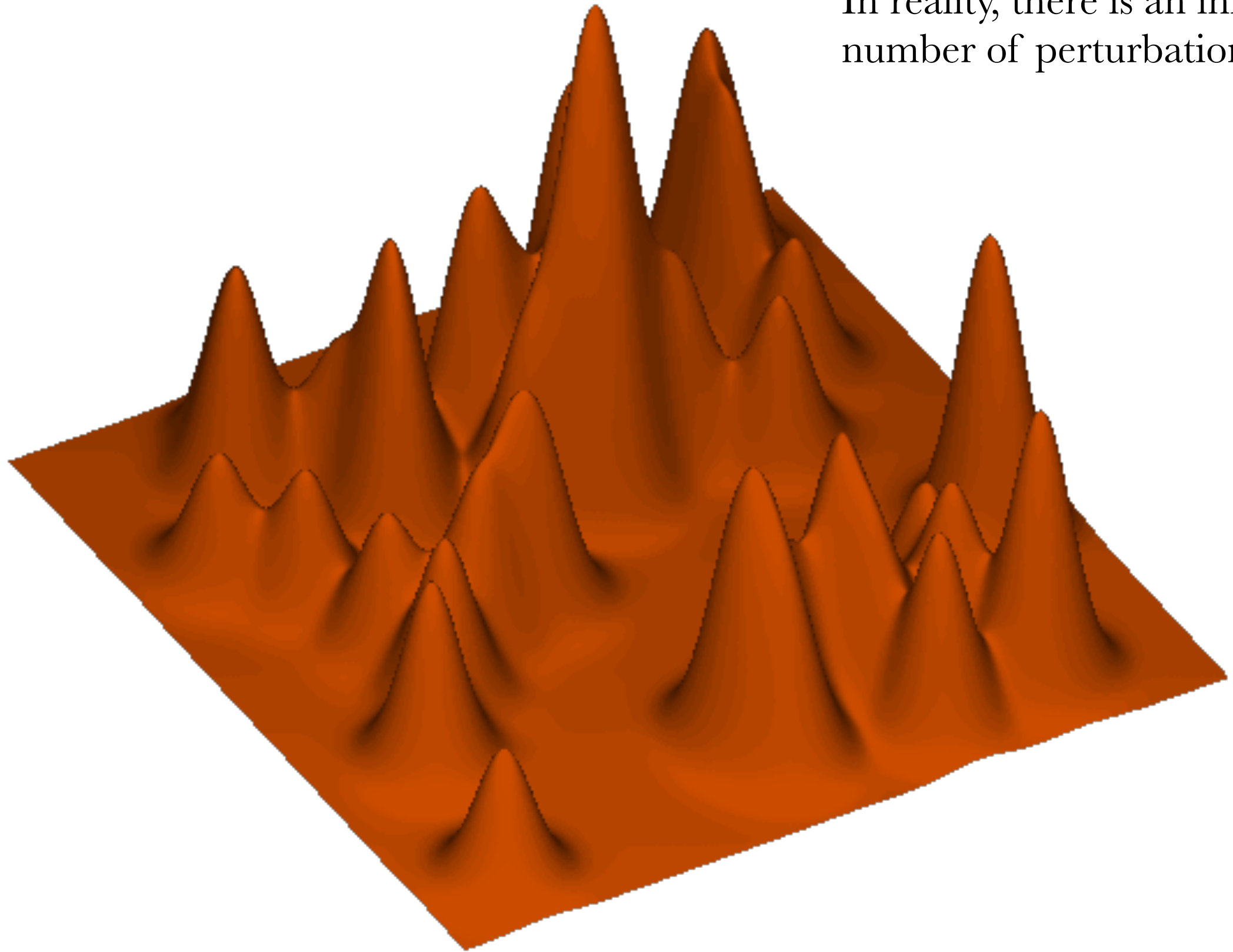
Cosmic Sound Waves

In reality, there is an infinite number of perturbations ...



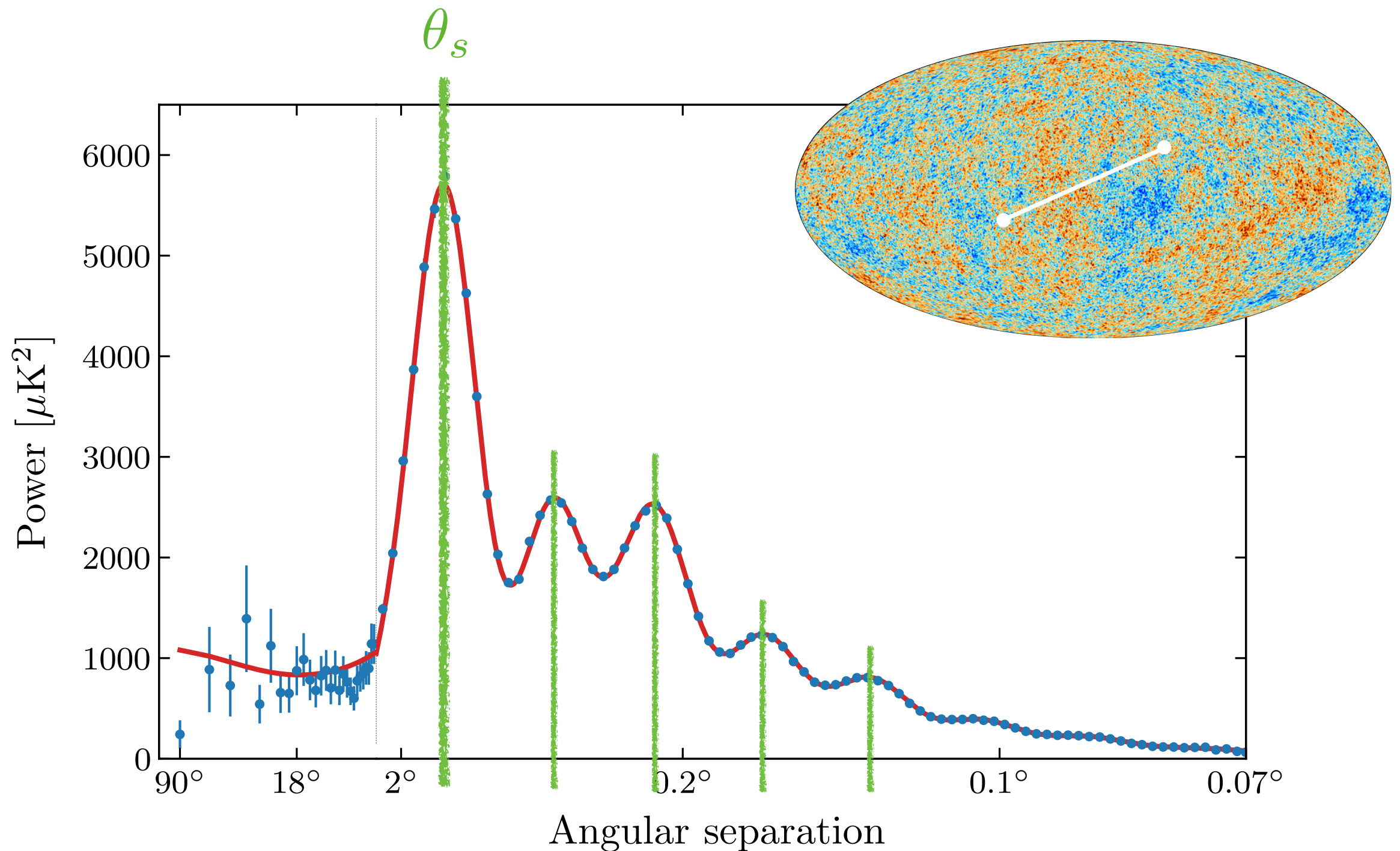
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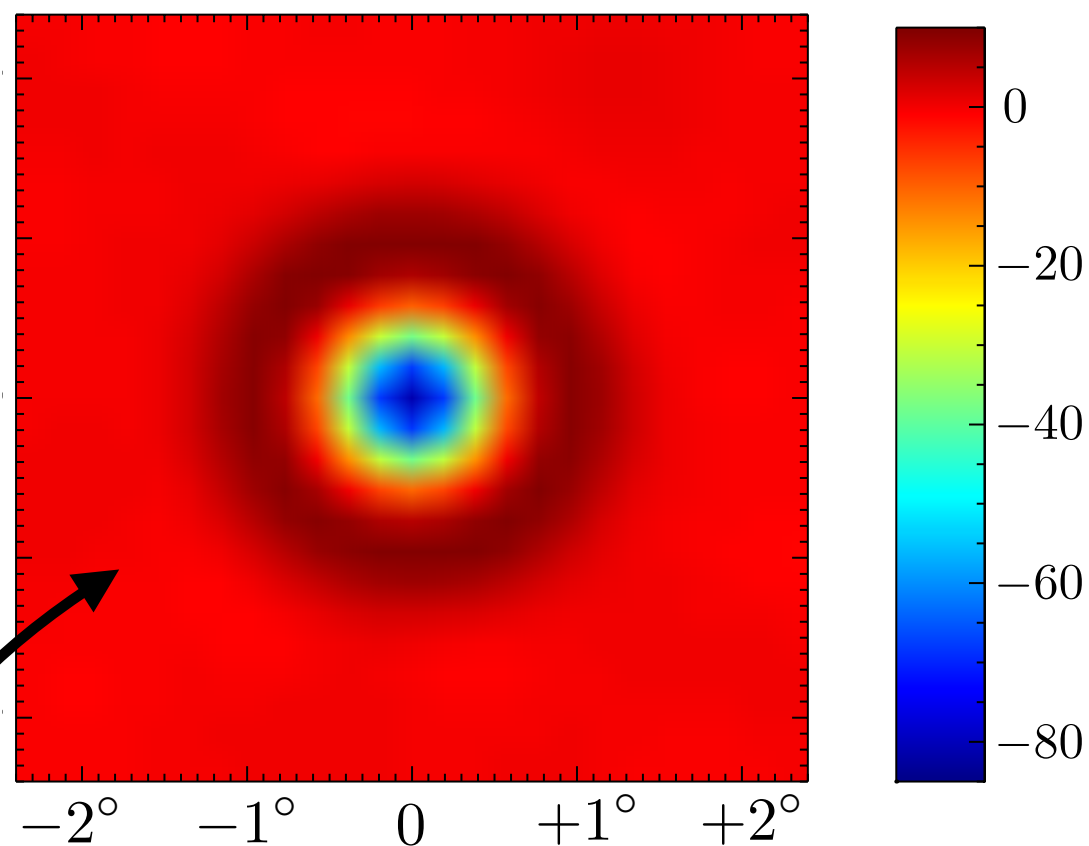


CMB Anisotropies

This sound horizon is imprinted in the pattern of CMB fluctuations:

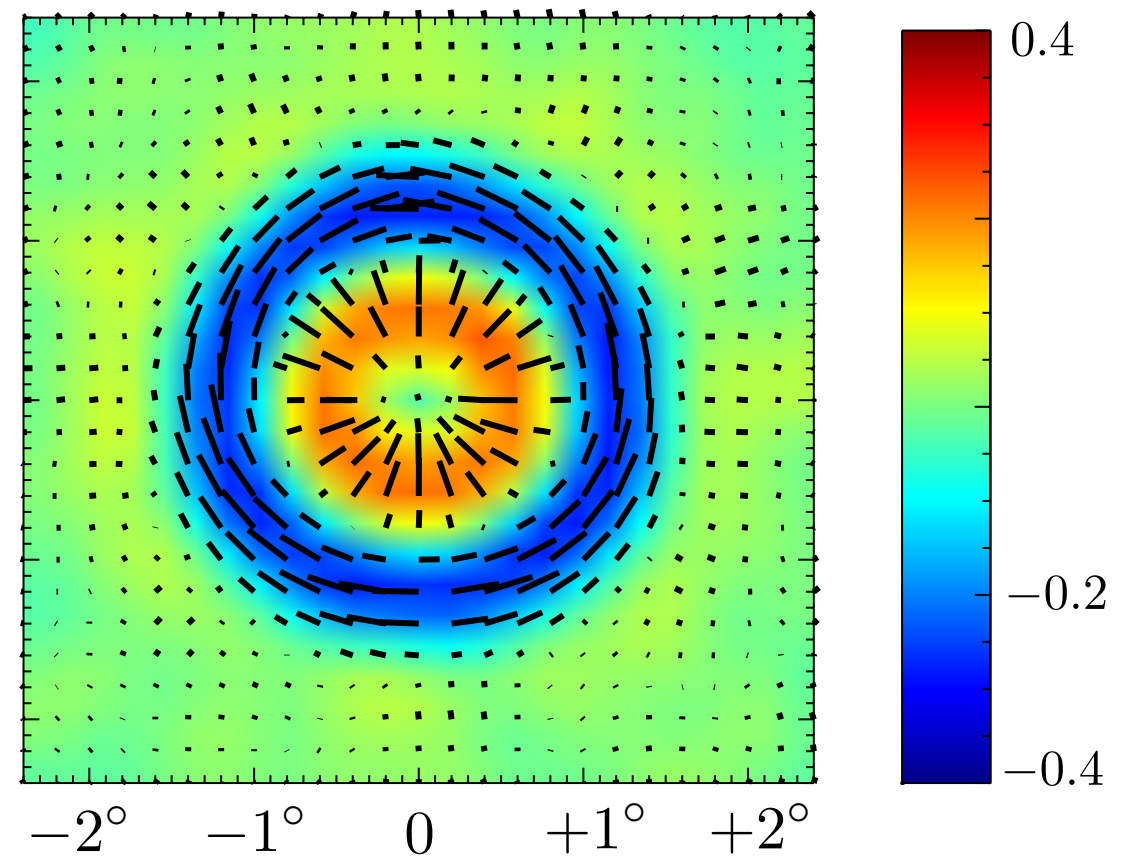


Temperature



intensity of 11396 cold spots

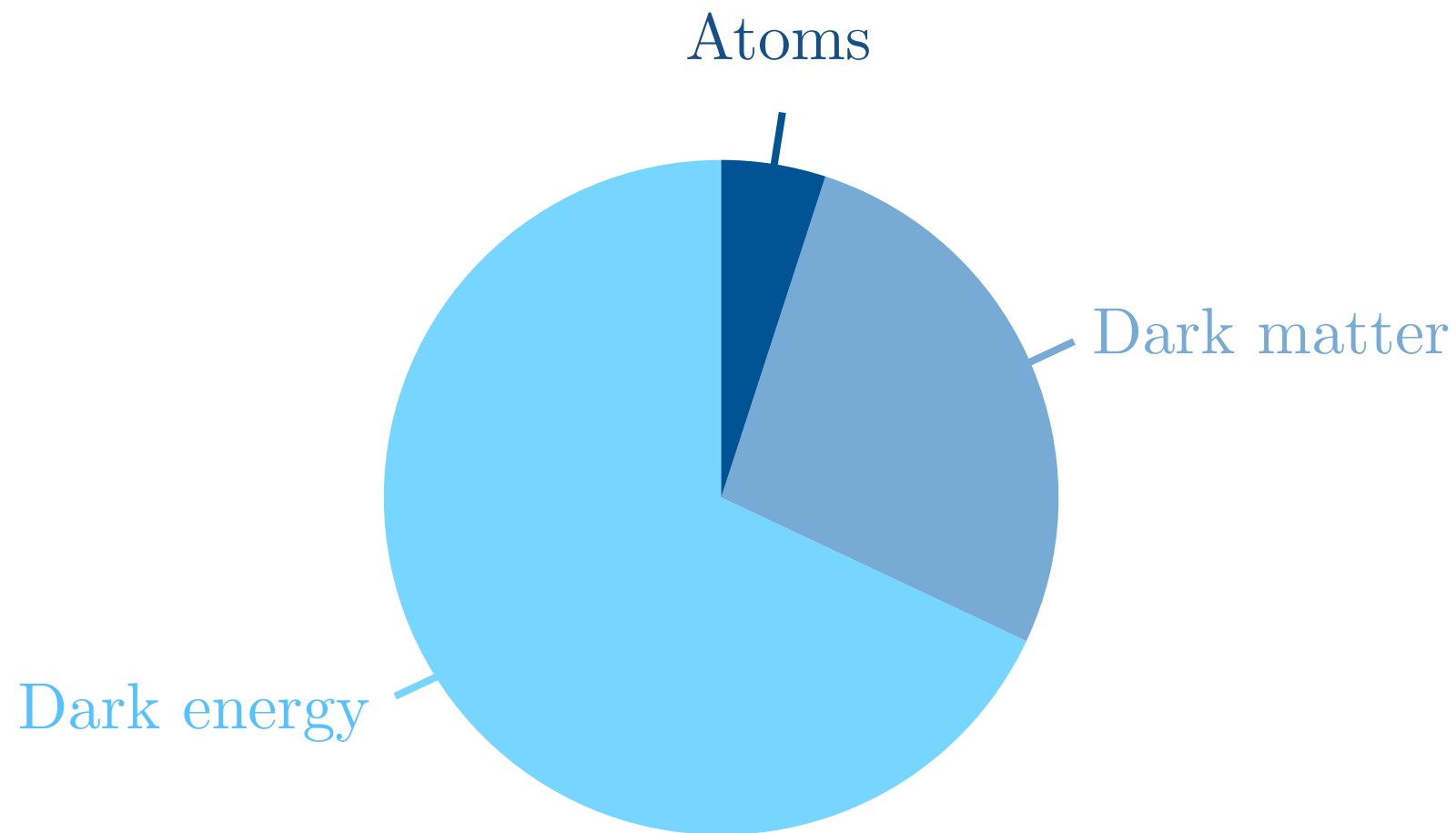
Polarization



Planck (2015)

CMB Anisotropies

The precise pattern of the CMB fluctuations depends on the composition of the Universe (and its initial conditions):

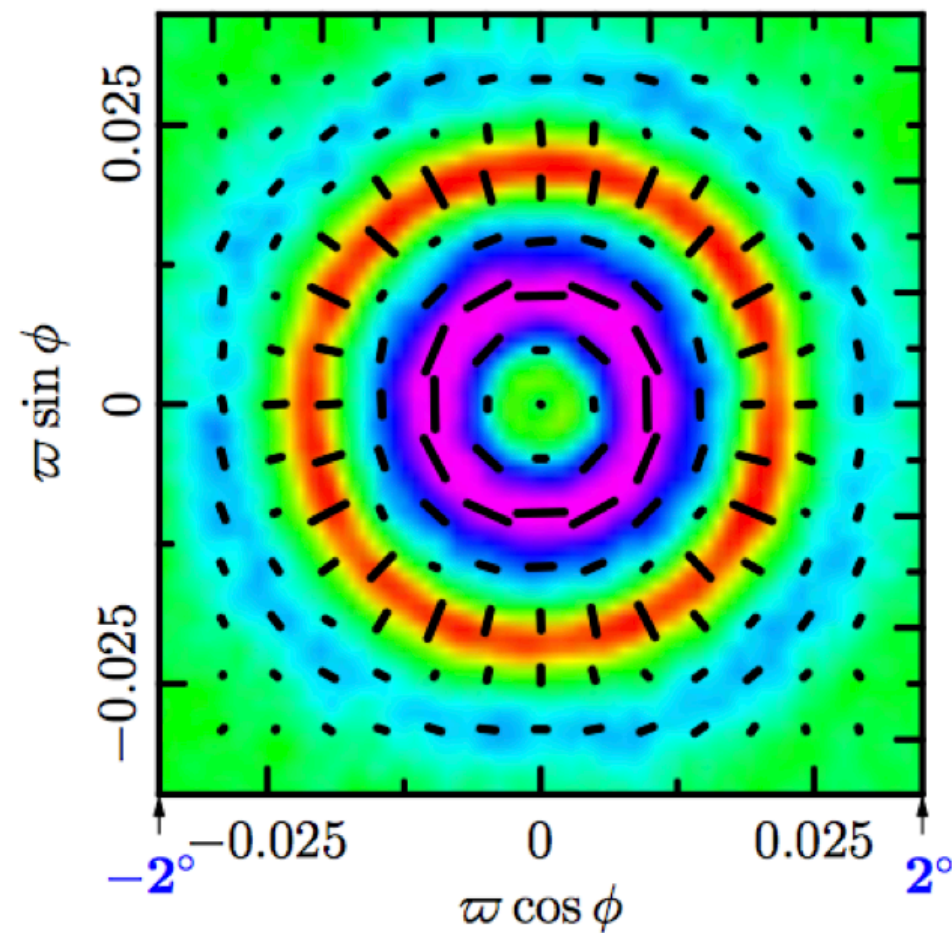


Observations of the CMB have therefore allowed us to determine the parameters of the cosmological standard model.

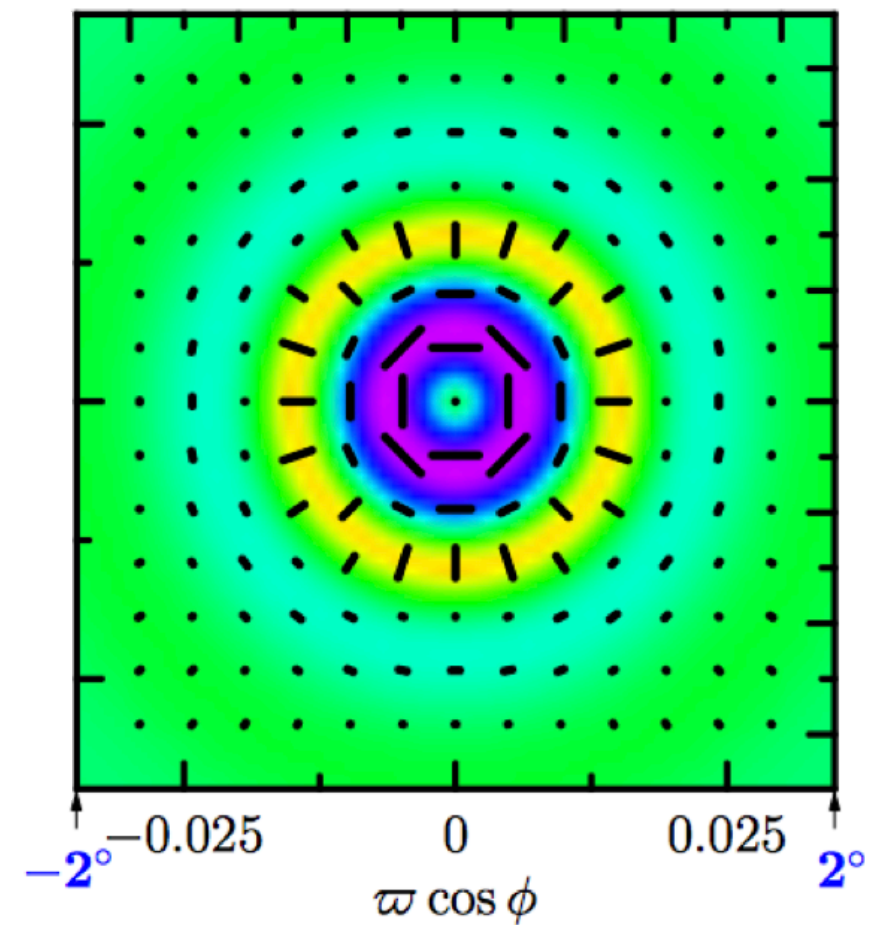
Dark Matter

Without dark matter, the data would look very different:

Data

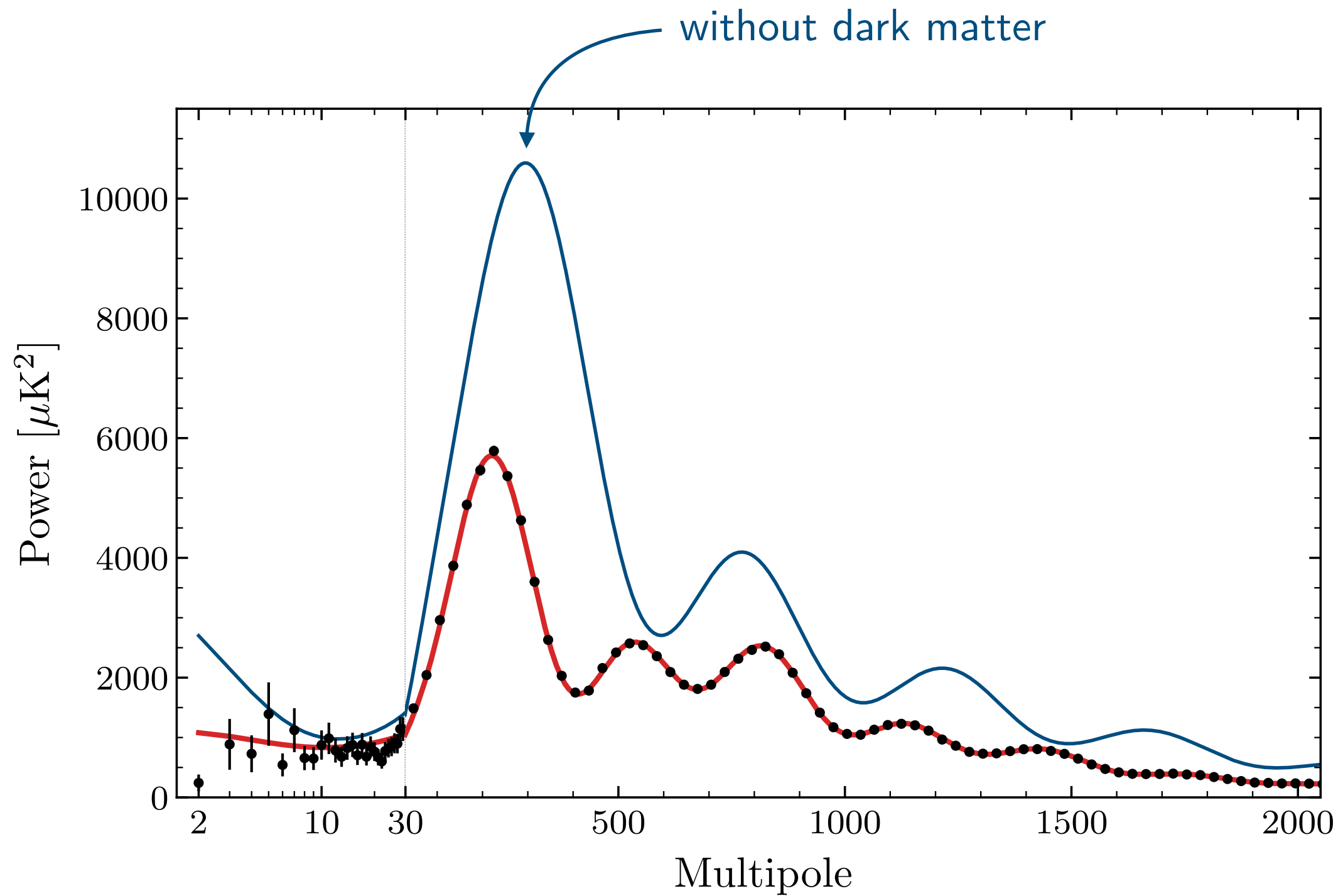


No Dark Matter



Figures courtesy of Zhiqi Huang and Dick Bond [ACT collaboration]

This can also be seen in the power spectrum: $\Omega_m = 0.32$

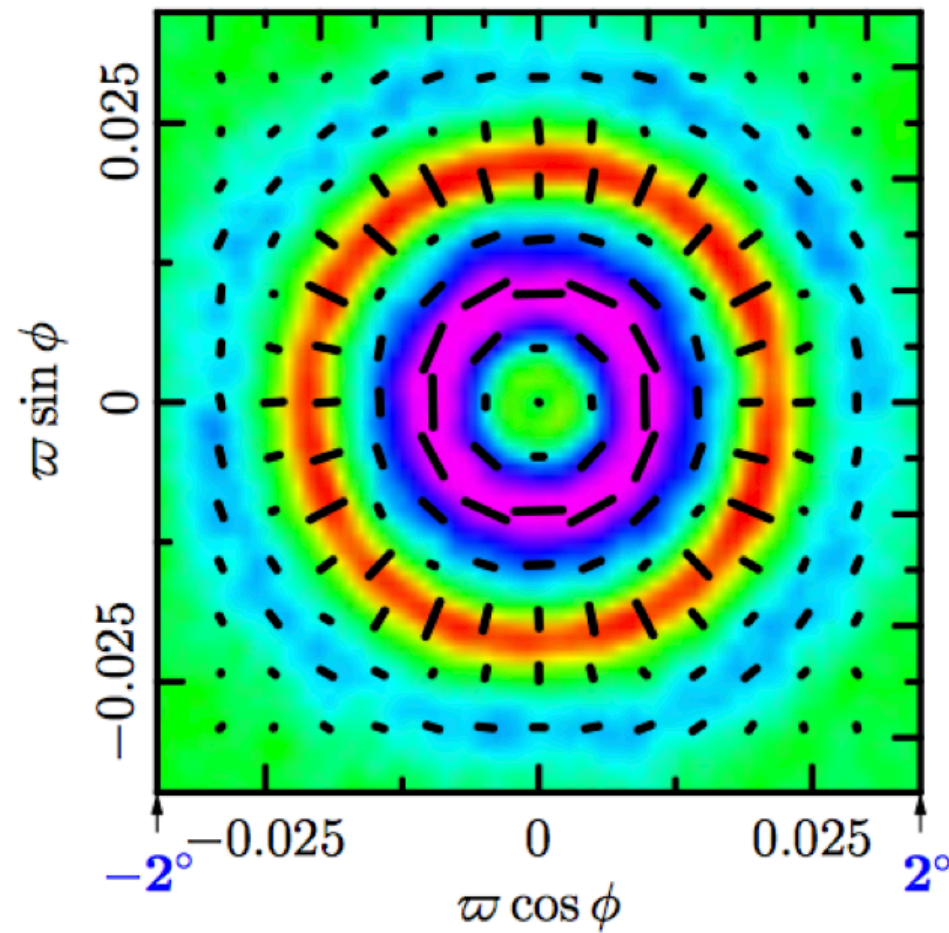


Planck (2018)

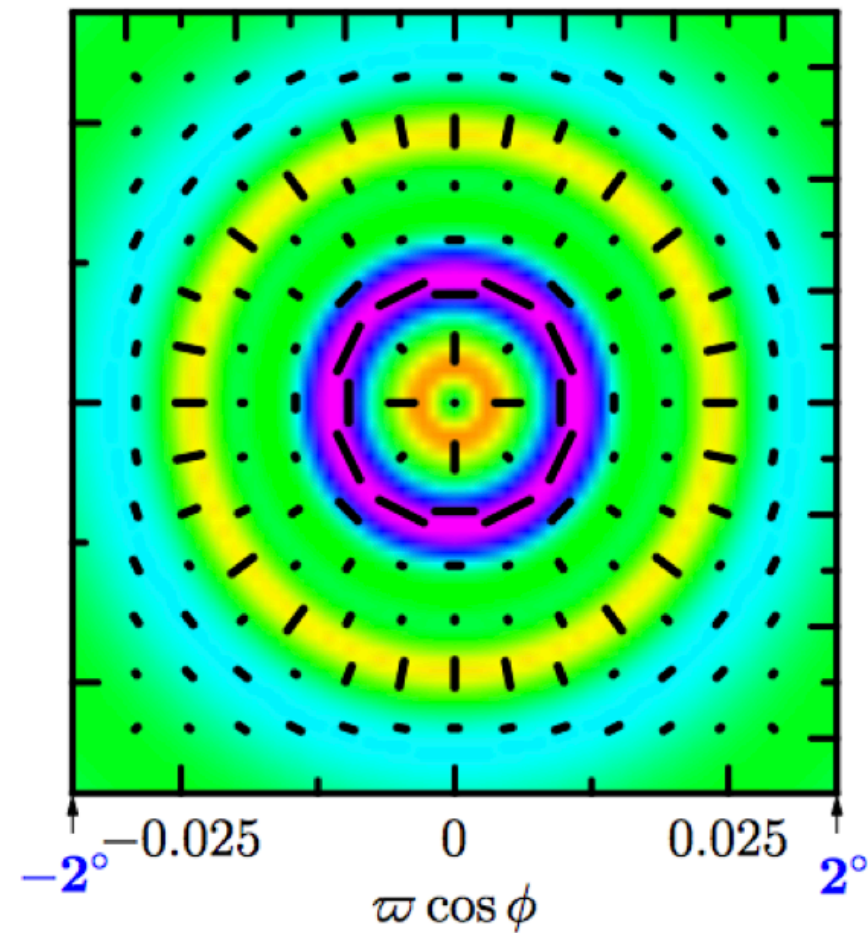
Dark Energy

Without dark energy, the data would look very different:

Data

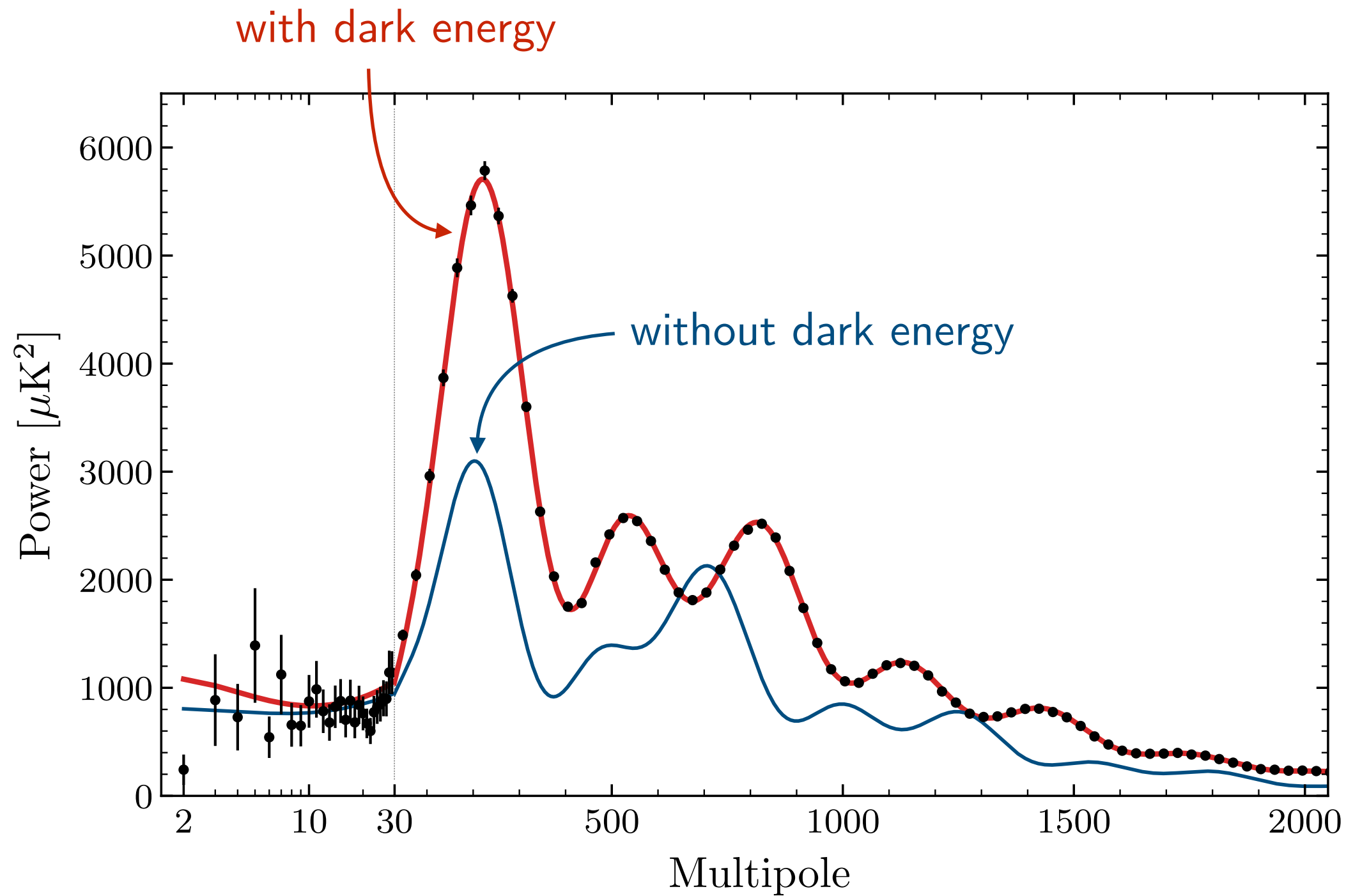


No Dark Energy



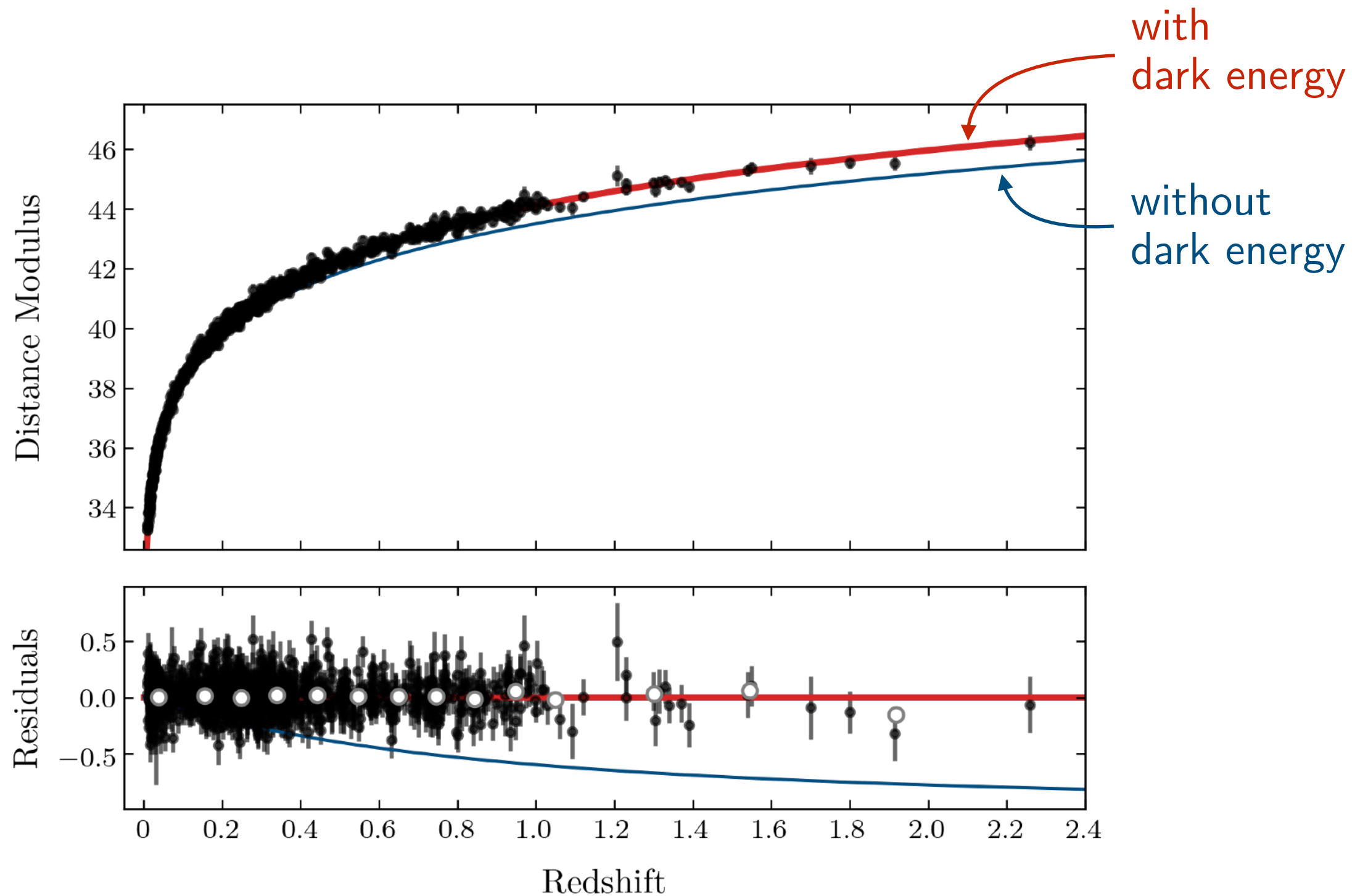
Figures courtesy of Zhiqi Huang and Dick Bond [ACT collaboration]

This can also be seen in the power spectrum: $\Omega_{\Lambda} = 0.68$



Planck (2018)

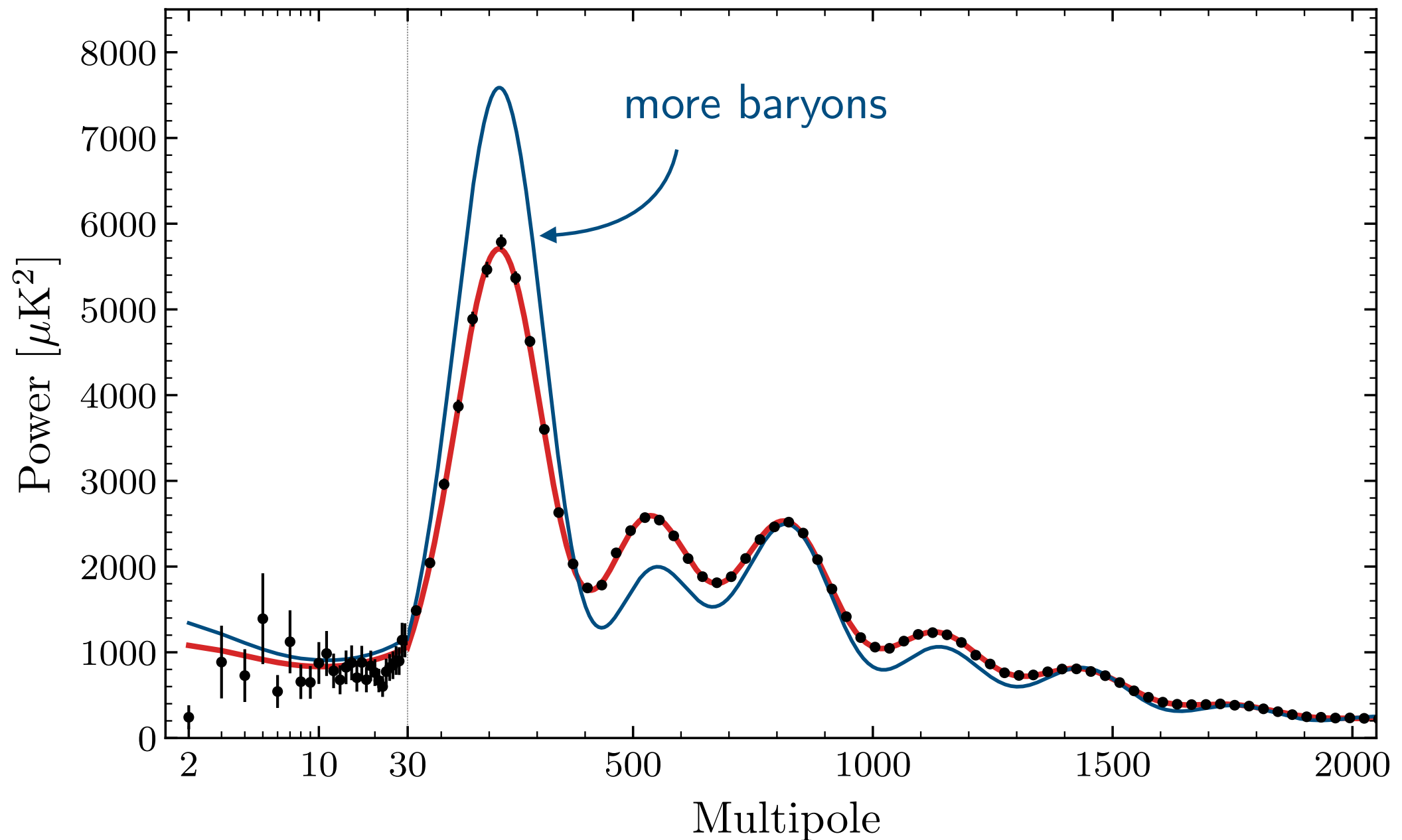
This is consistent with the direct observation of **dark energy** from supernova observations:



Riess et al (1998)
Perlmutter et al (1998)

Baryons

The peak heights depend on the baryon density: $\Omega_b = 0.04$

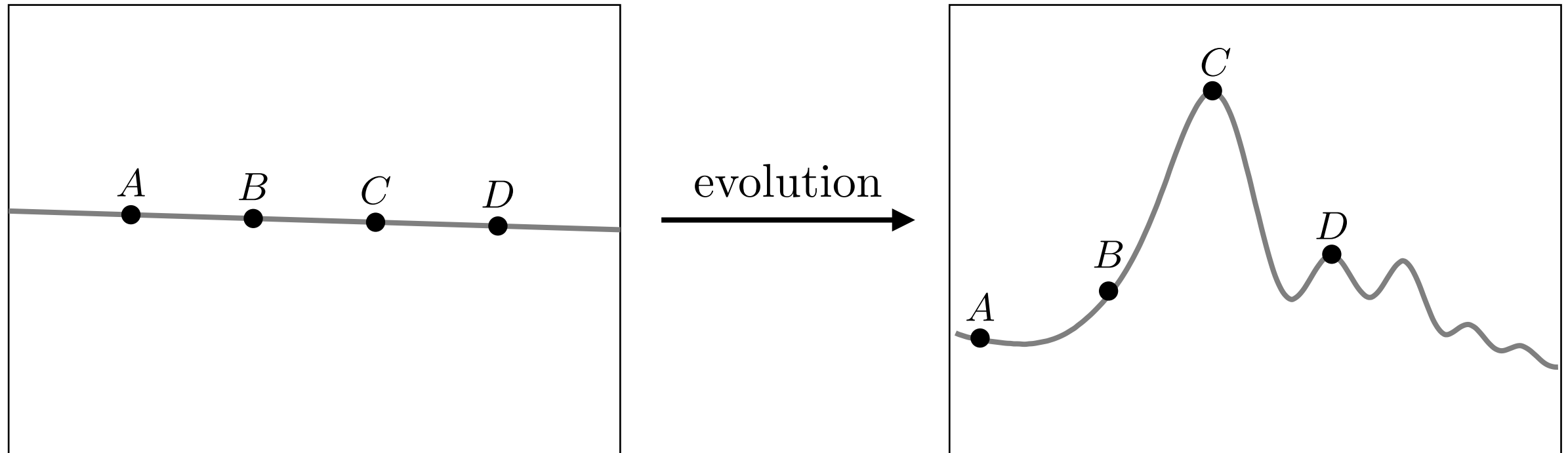


The measured baryon density is consistent with BBN.

Planck (2018)

Initial Conditions

The CMB power spectrum also probes the initial conditions:



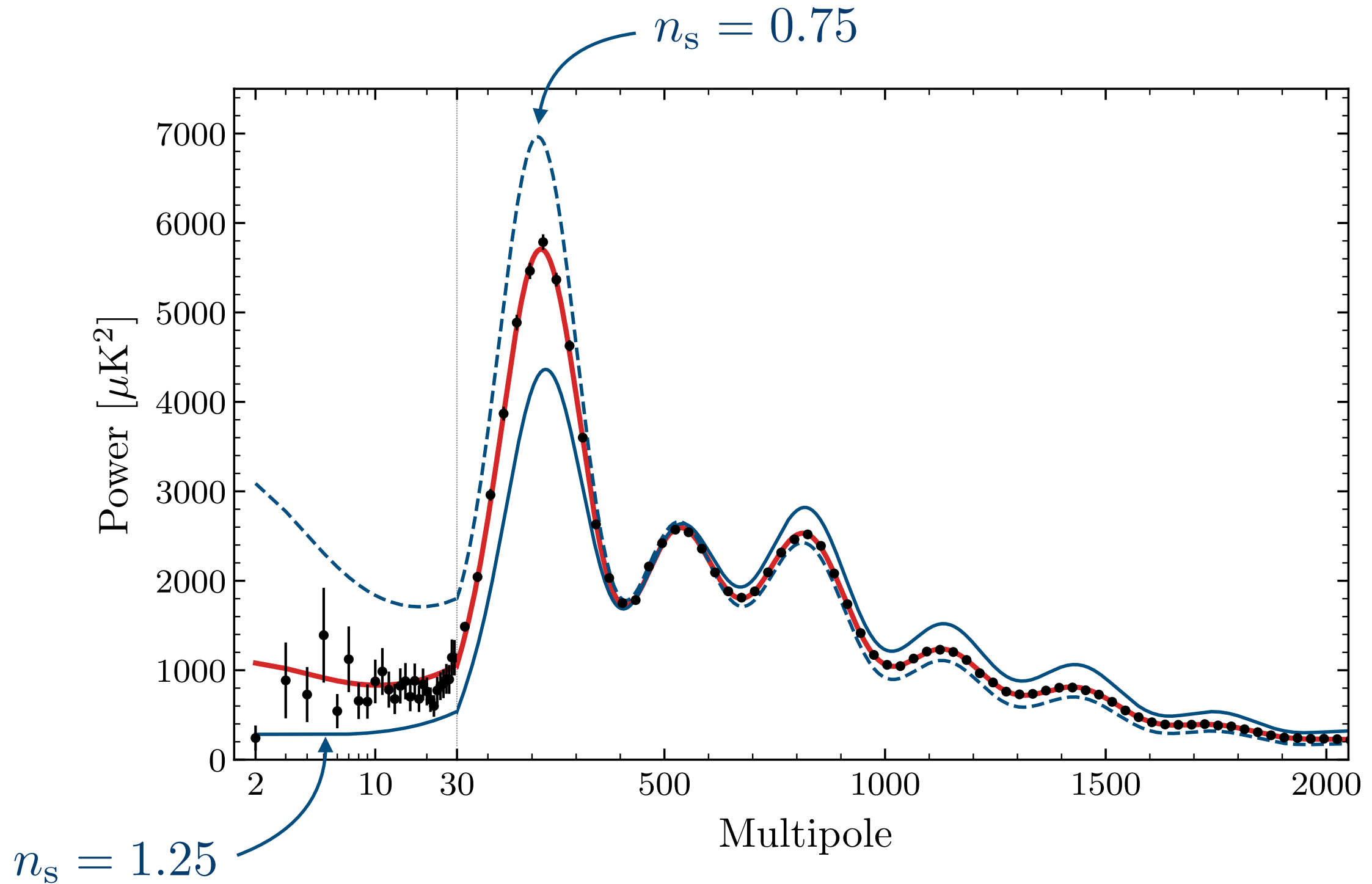
$$A_s \left(\frac{k}{k_0} \right)^{n_s - 1}$$

Amplitude

scale-dependence

$$A_s = 2.20 \times 10^{-9}$$

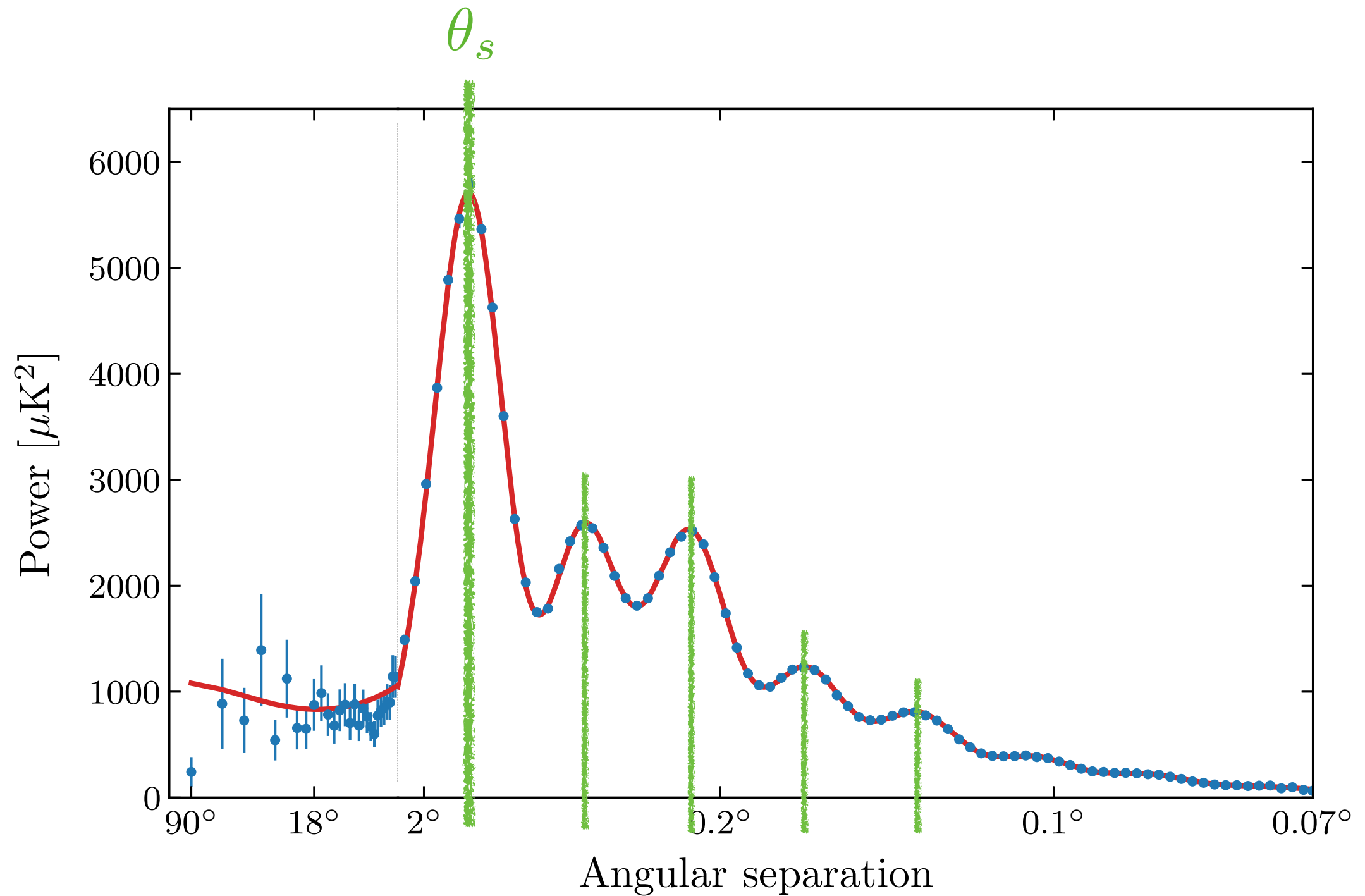
The primordial power spectrum is close to scale invariant: $n_s = 0.96$

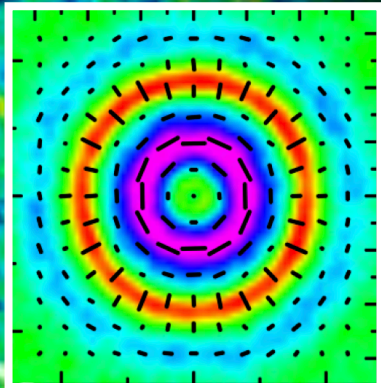


The observed deviation from scale invariance is significant.

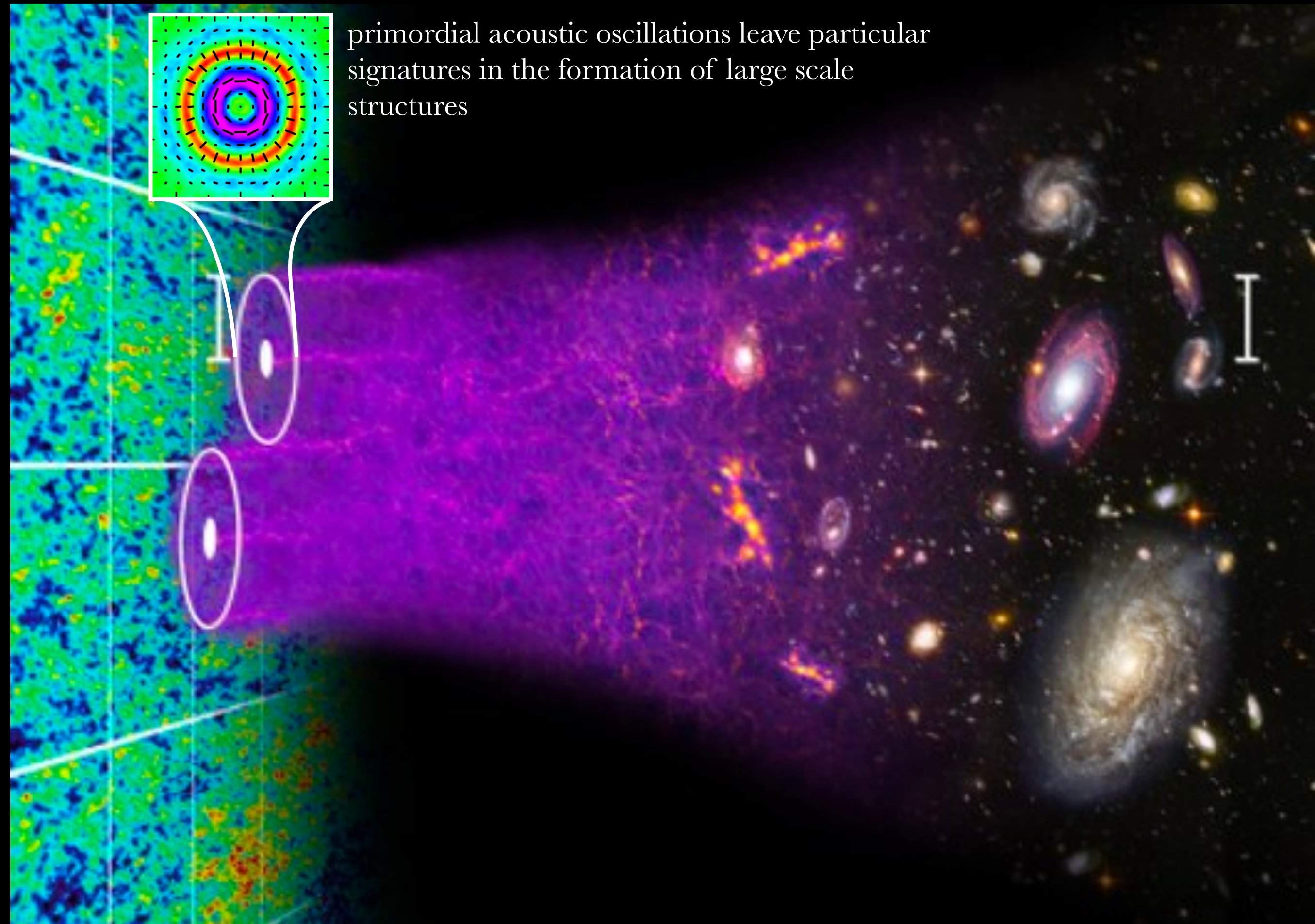
WMAP (2009)
Planck (2018)

primordial acoustic oscillations leave particular
signatures in the formation of large scale
structures

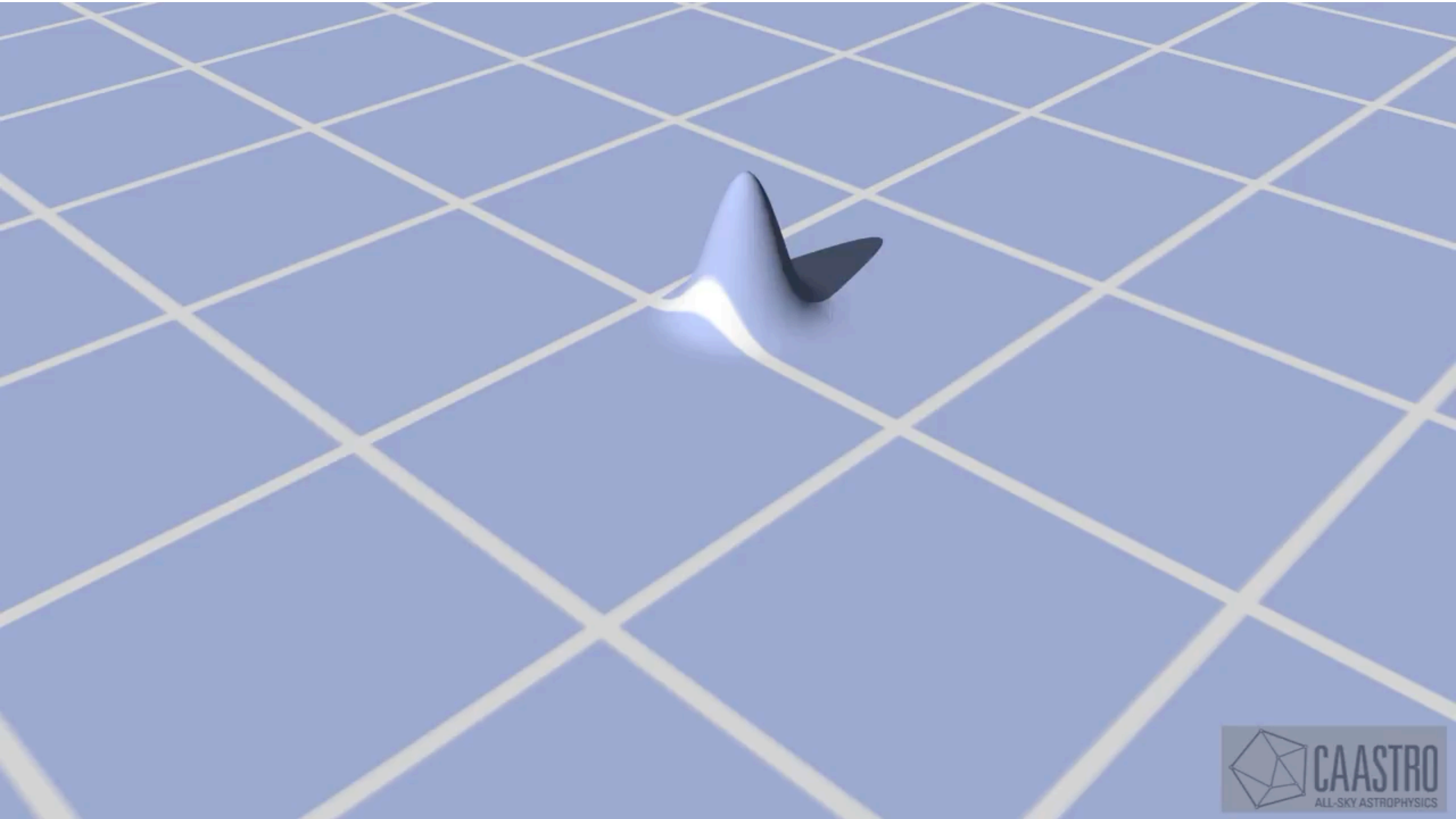




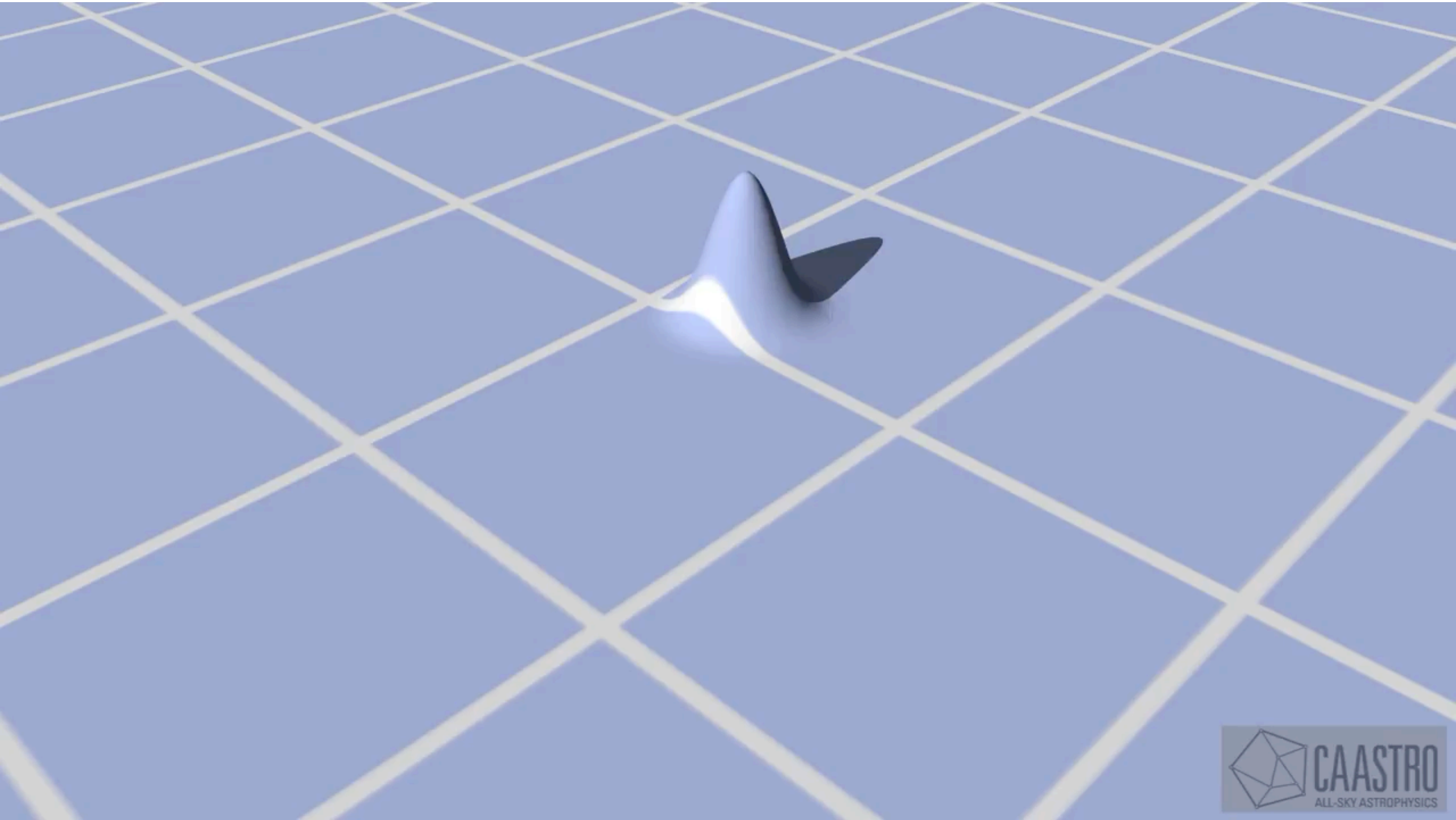
primordial acoustic oscillations leave particular signatures in the formation of large scale structures



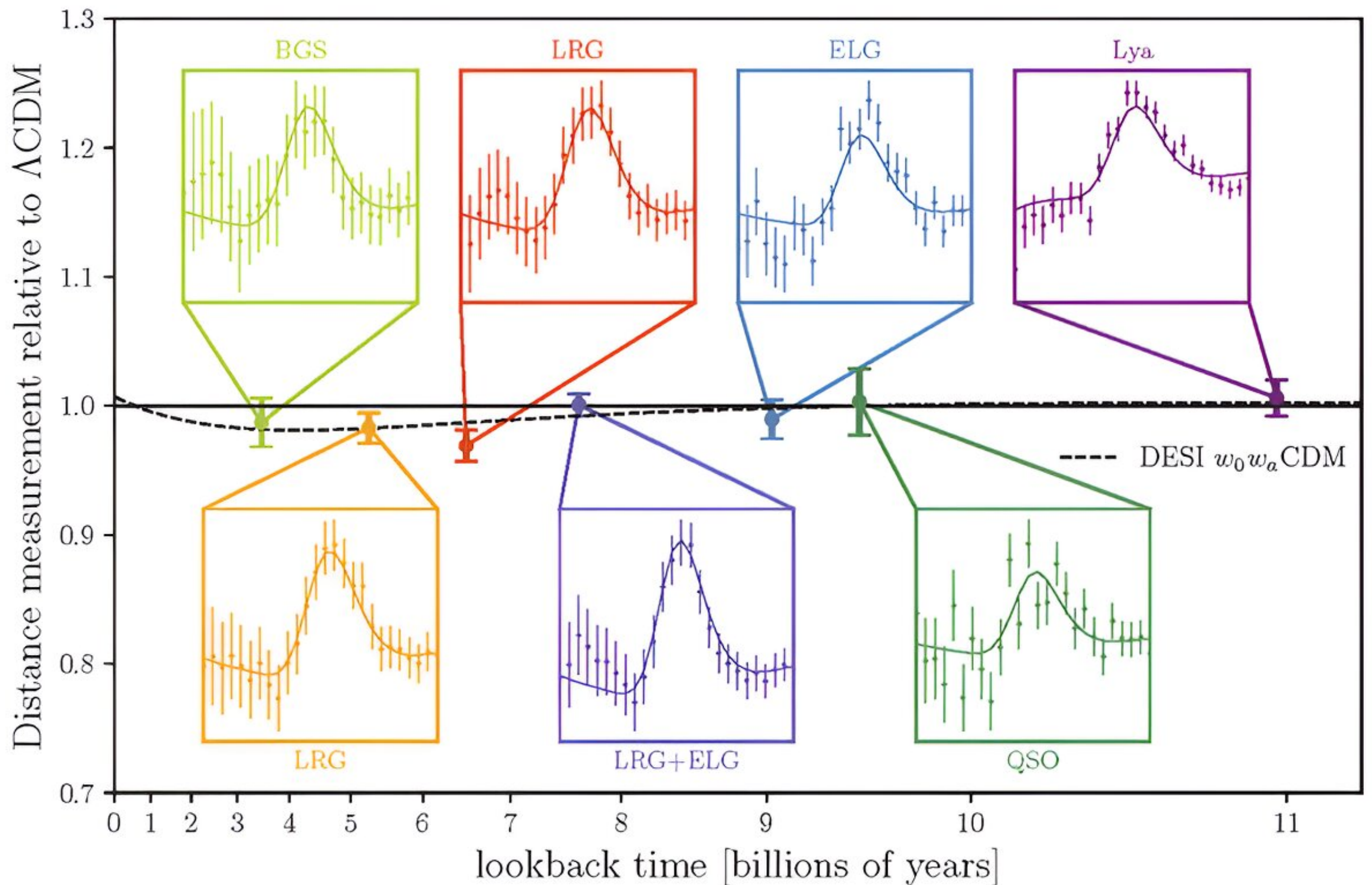
from primordial perturbations to the statistical study of galaxies' positions
[cf. C. Yèche's lecture]

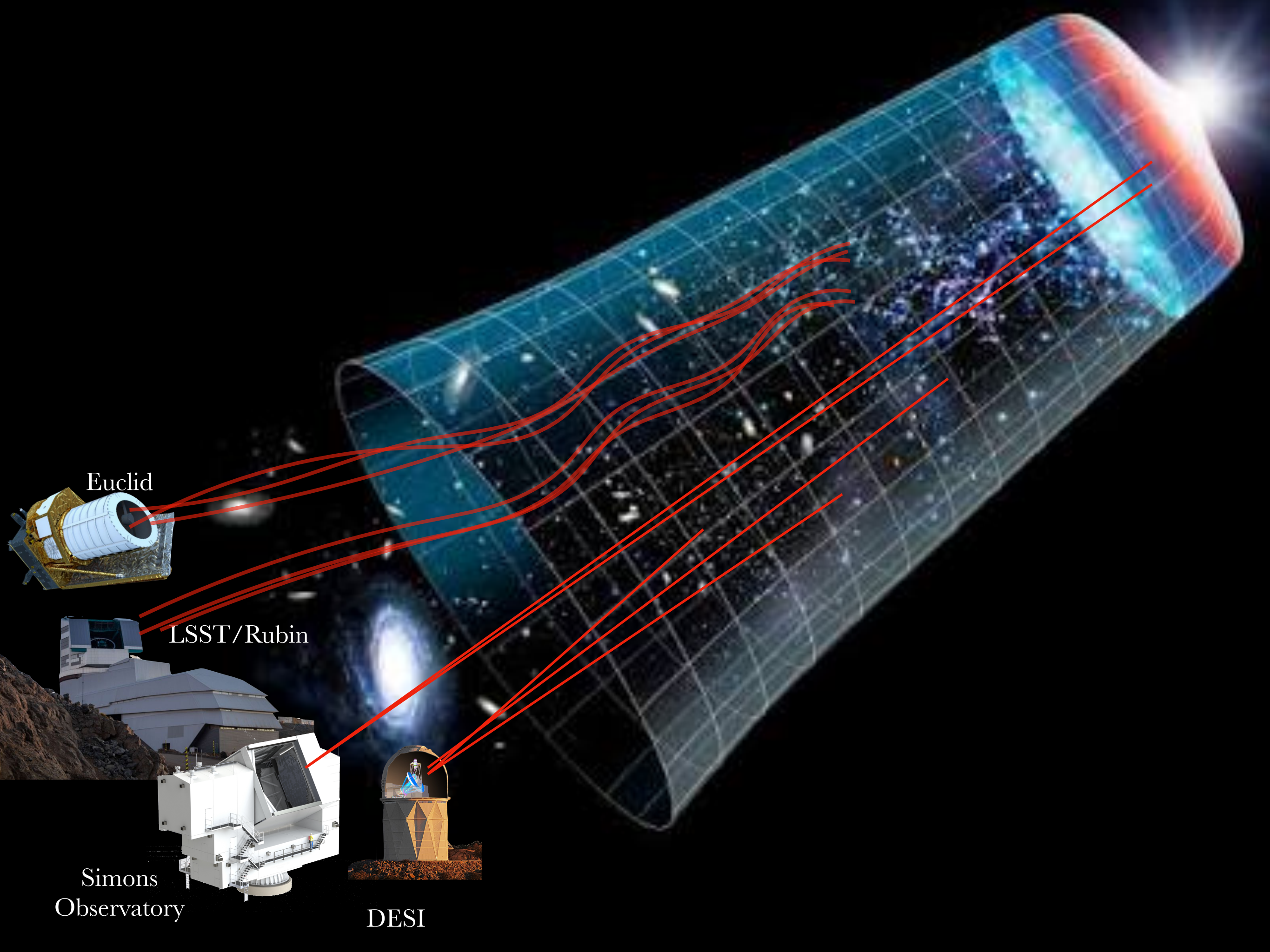


from primordial perturbations to the statistical study of galaxies' positions
[cf. C. Yèche's lecture]



from primordial perturbations to the statistical study of galaxies' positions
[cf. C. Yèche's lecture]





Euclid

LSST/Rubin

Simons
Observatory

DESI

A simple 5-parameter model fits all observations:

$$\Omega_b = 0.04 \quad \text{Amount of ordinary matter}$$

$$\Omega_m = 0.32 \quad \text{Amount of dark matter}$$

$$\Omega_\Lambda = 0.68 \quad \text{Amount of dark energy}$$

$$10^9 A_s = 2.20 \quad \text{Amplitude of density fluctuations}$$

$$n_s = 0.96 \quad \text{Scale dependence of the fluctuations}$$

A key challenge of modern cosmology is to explain these numbers:

$$\Omega_b = 0.04$$



Why is there more matter than antimatter?

$$\Omega_m = 0.32$$



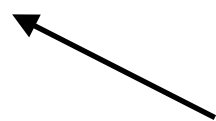
What is the dark matter?

$$\Omega_\Lambda = 0.68$$



What is the dark energy?

$$10^9 A_s = 2.20$$



What was the origin of the fluctuations?

$$n_s = 0.96$$



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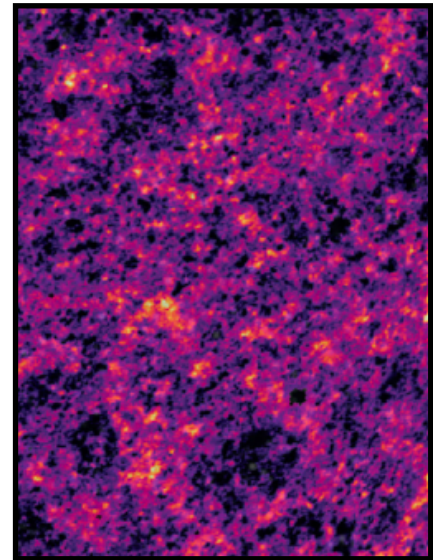


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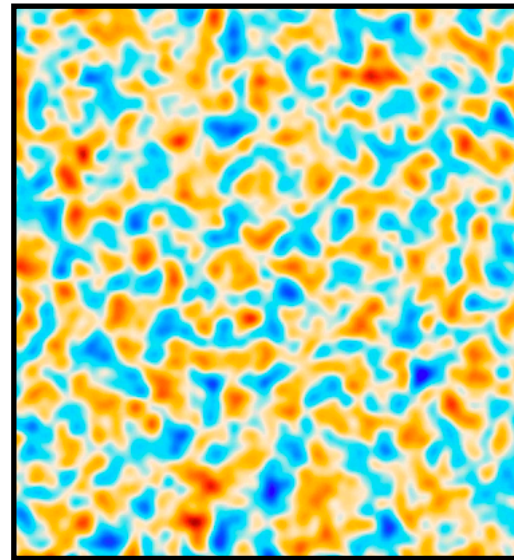
So far, we have described the evolution of fluctuations in the hot Big Bang and the formation of the large-scale structure of the Universe:



Primordial
fluctuations



Cosmic
sound waves



CMB
fluctuations



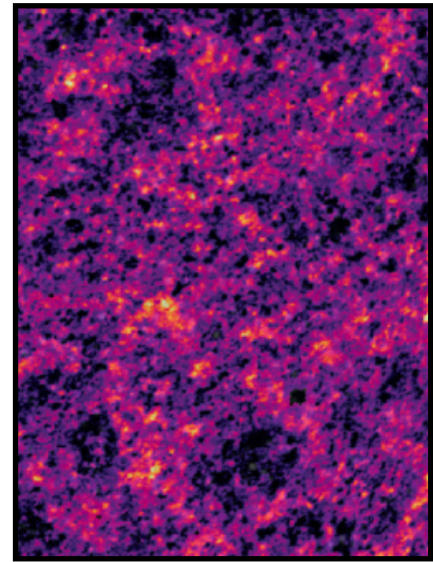
Gravitational
clustering



Galaxies

We now want to ask:

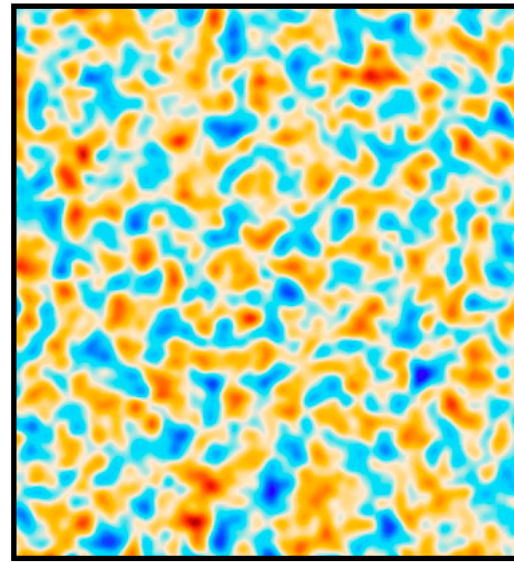
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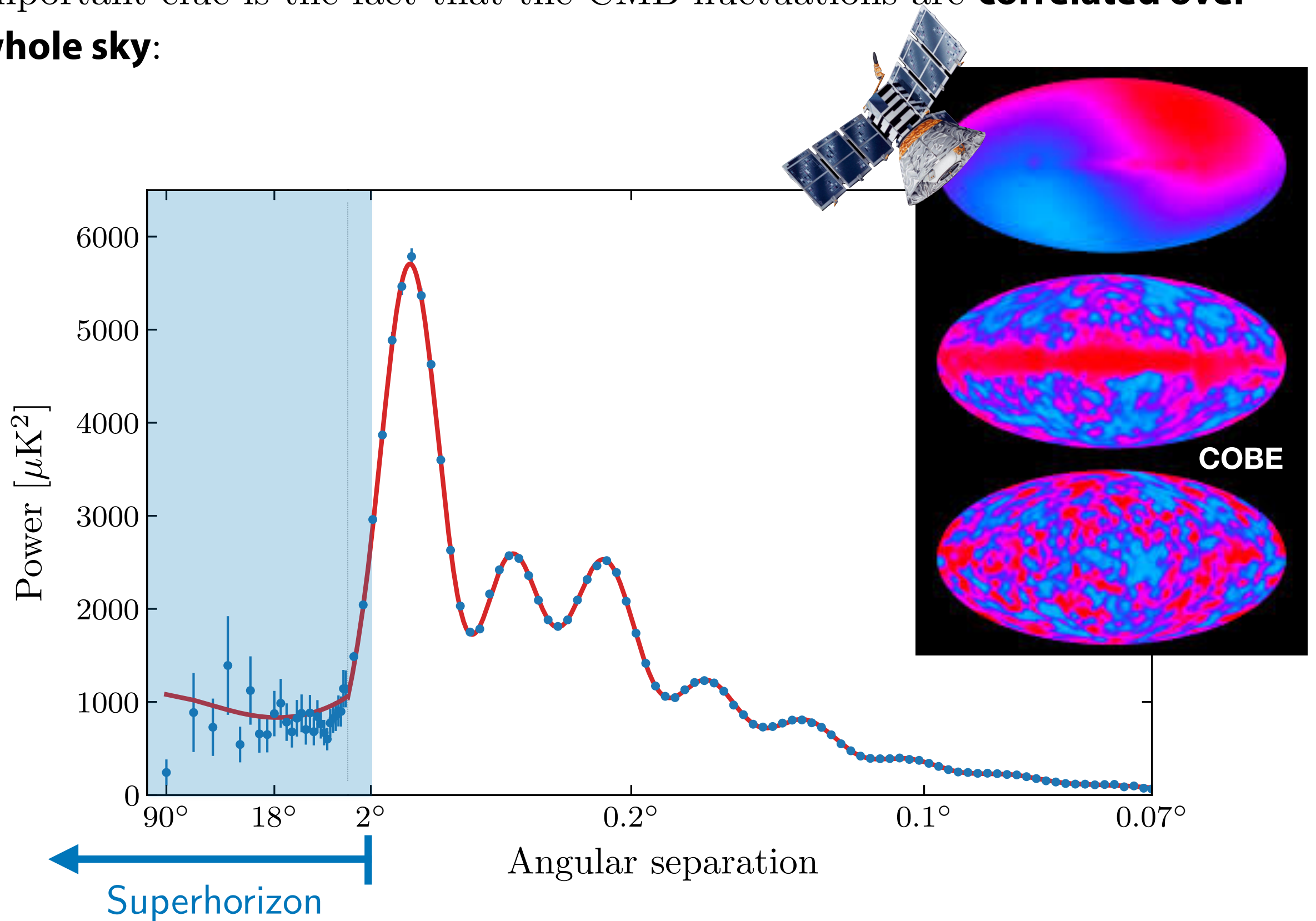


Galaxies

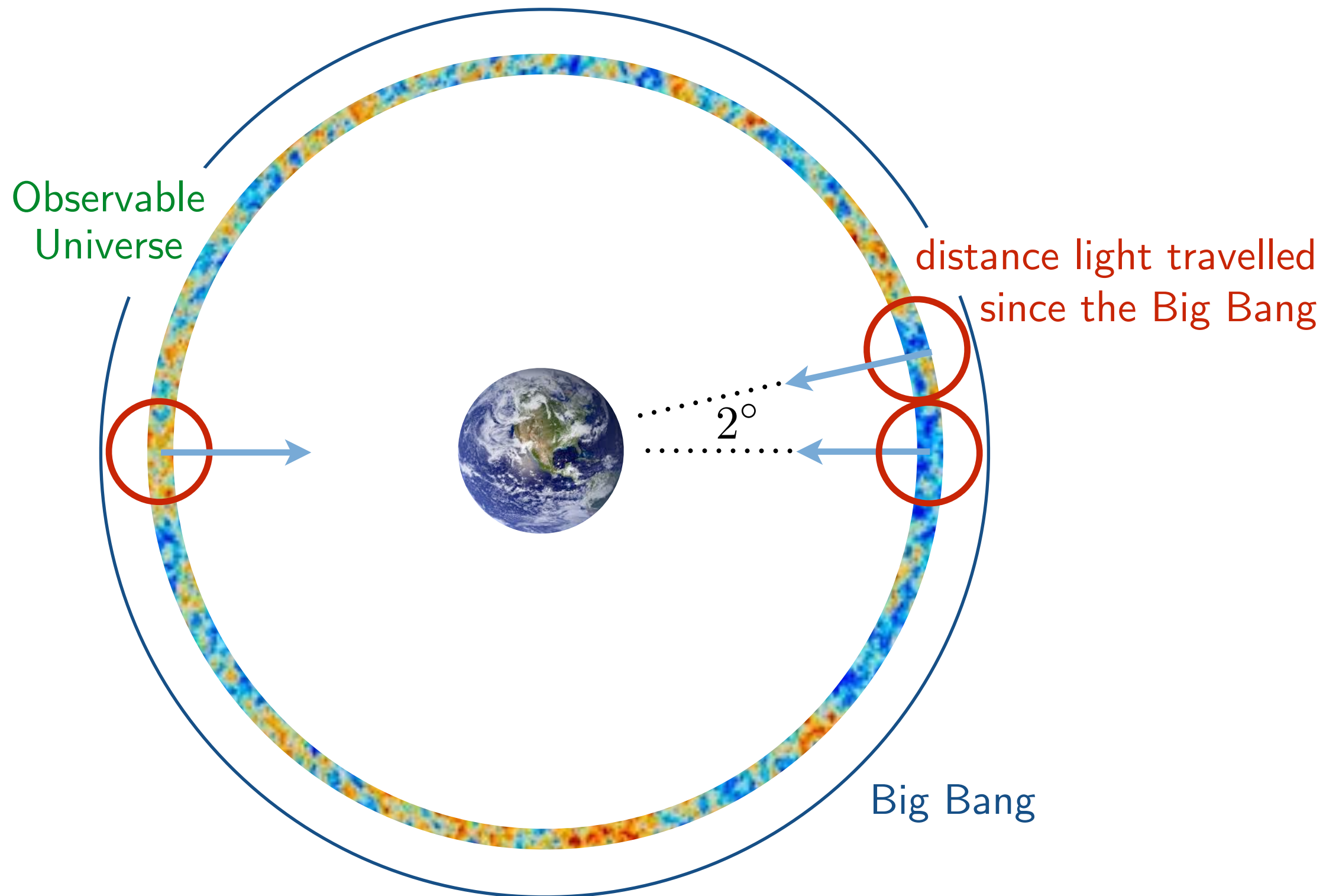
We now want to ask:

What created the primordial fluctuations?

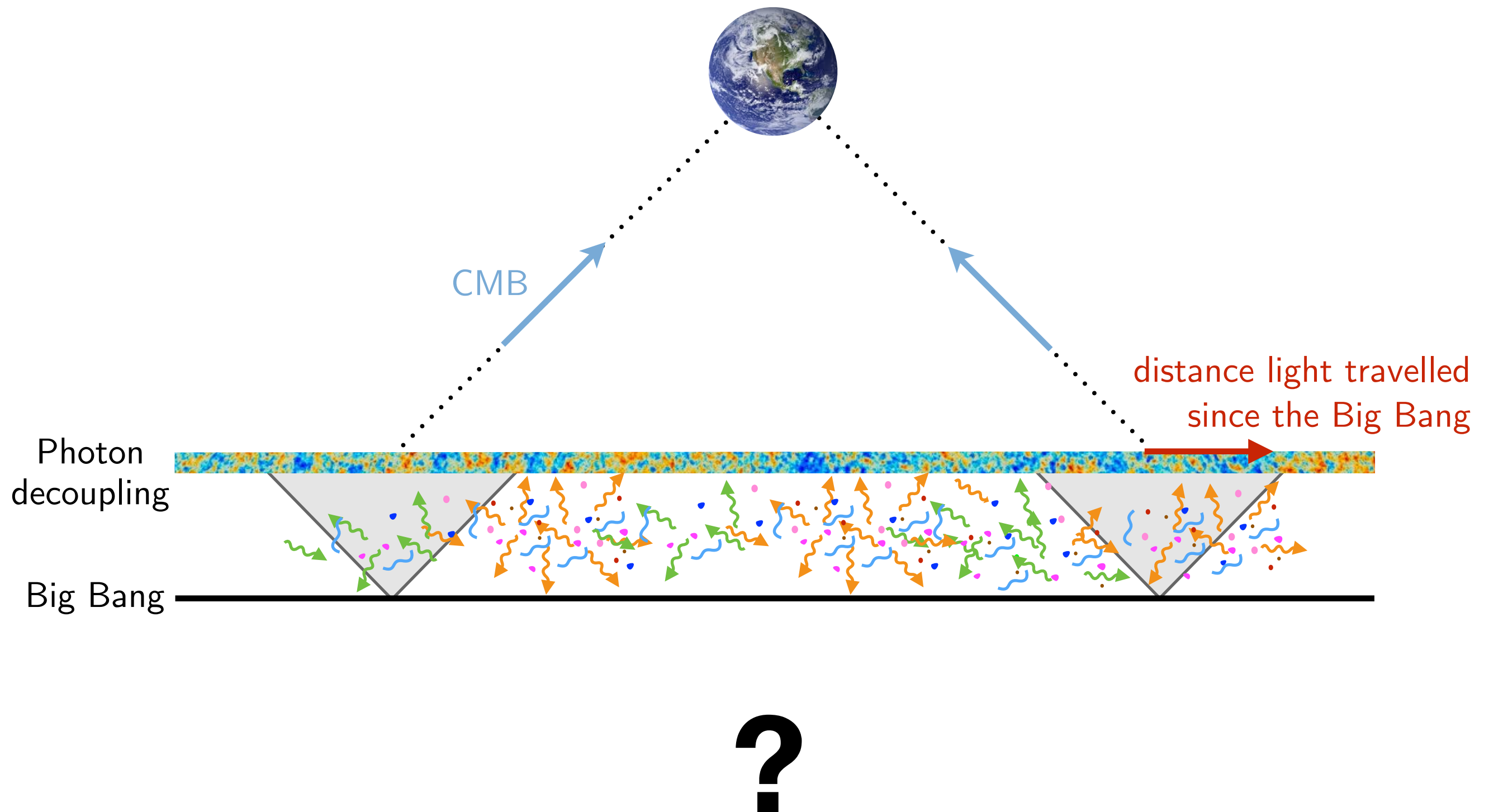
An important clue is the fact that the CMB fluctuations are **correlated over the whole sky**:



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

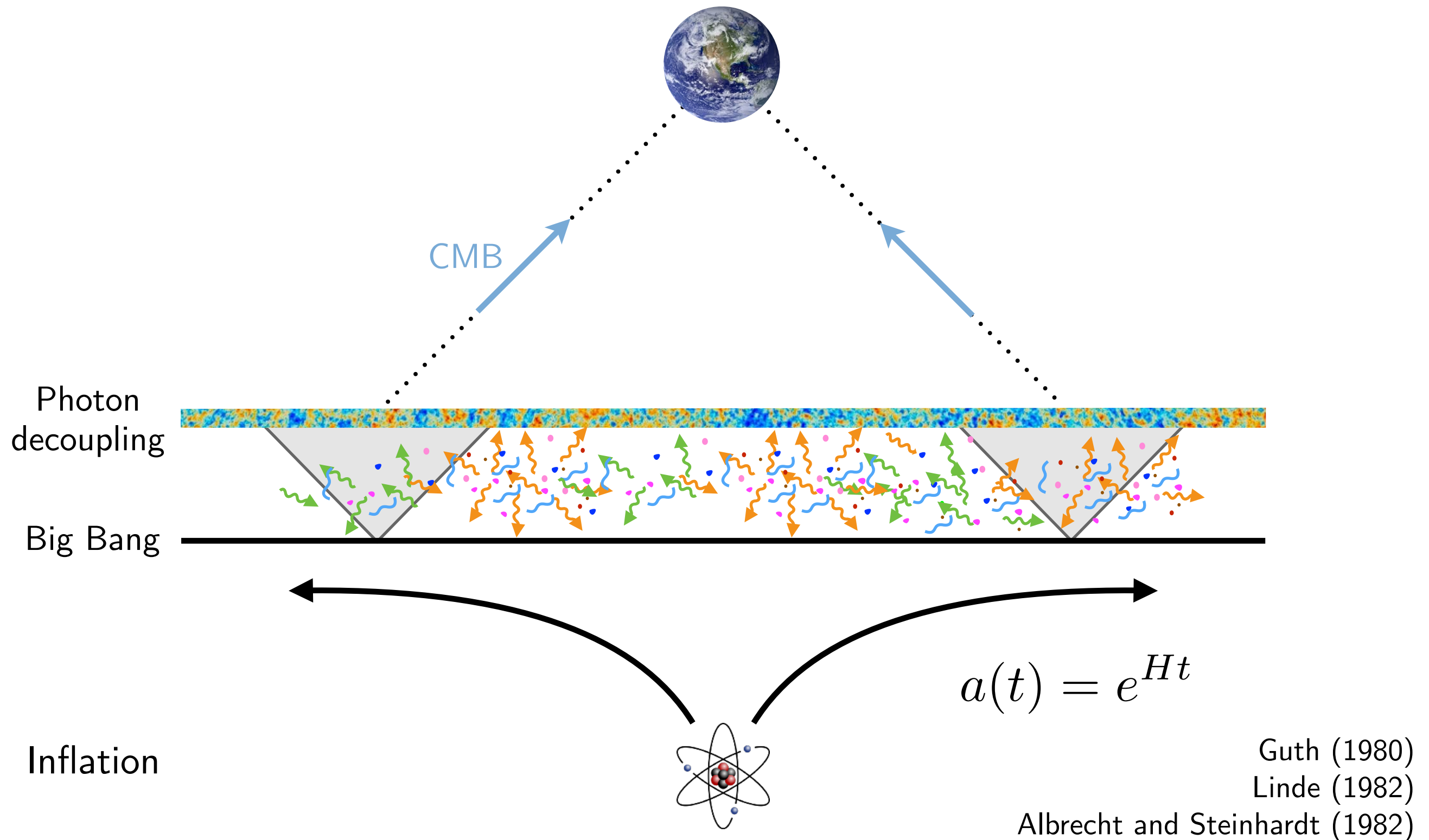


The correlations must have been created **before the hot Big Bang**:



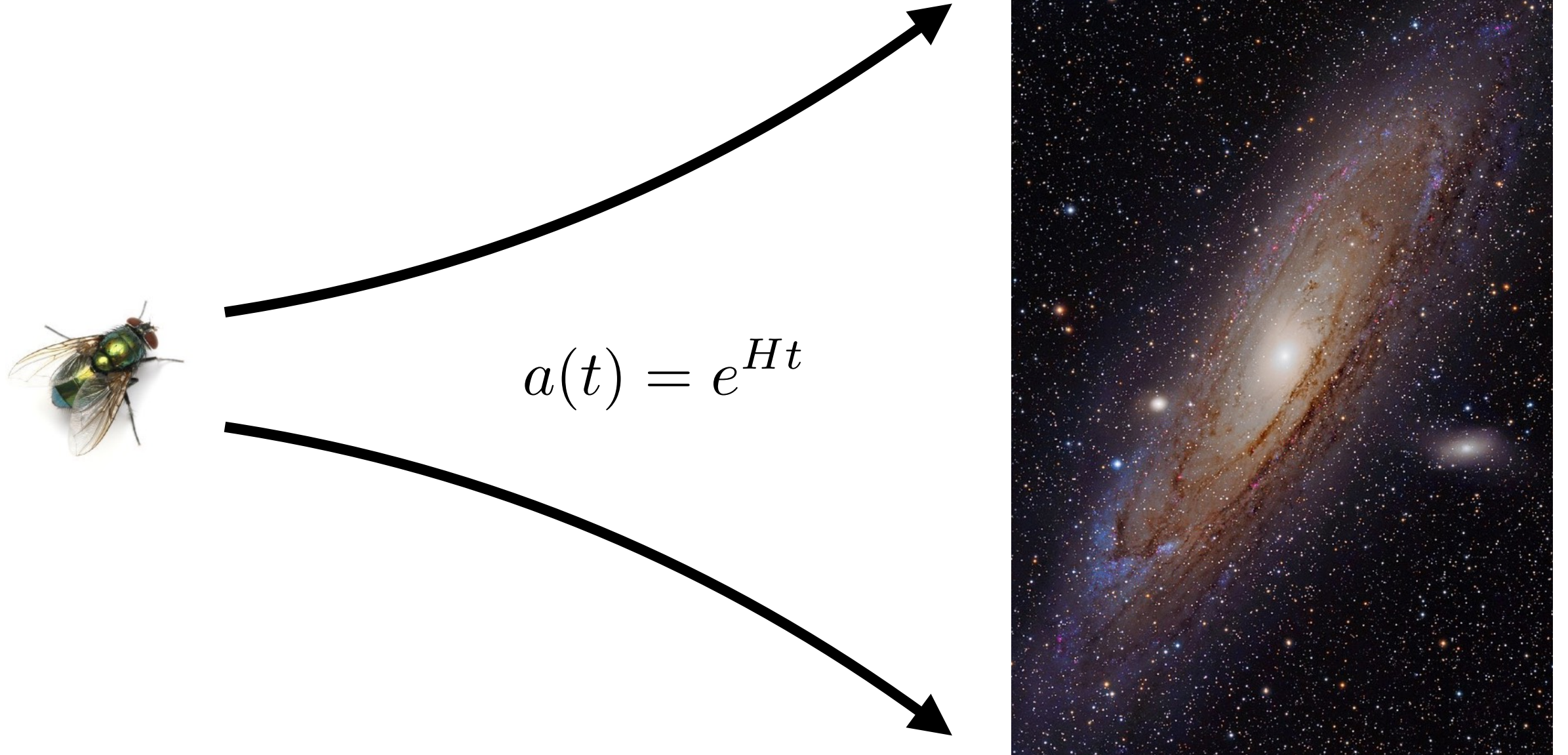
Inflation

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



Inflation

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



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**):

$$P > -\frac{1}{3}\rho$$

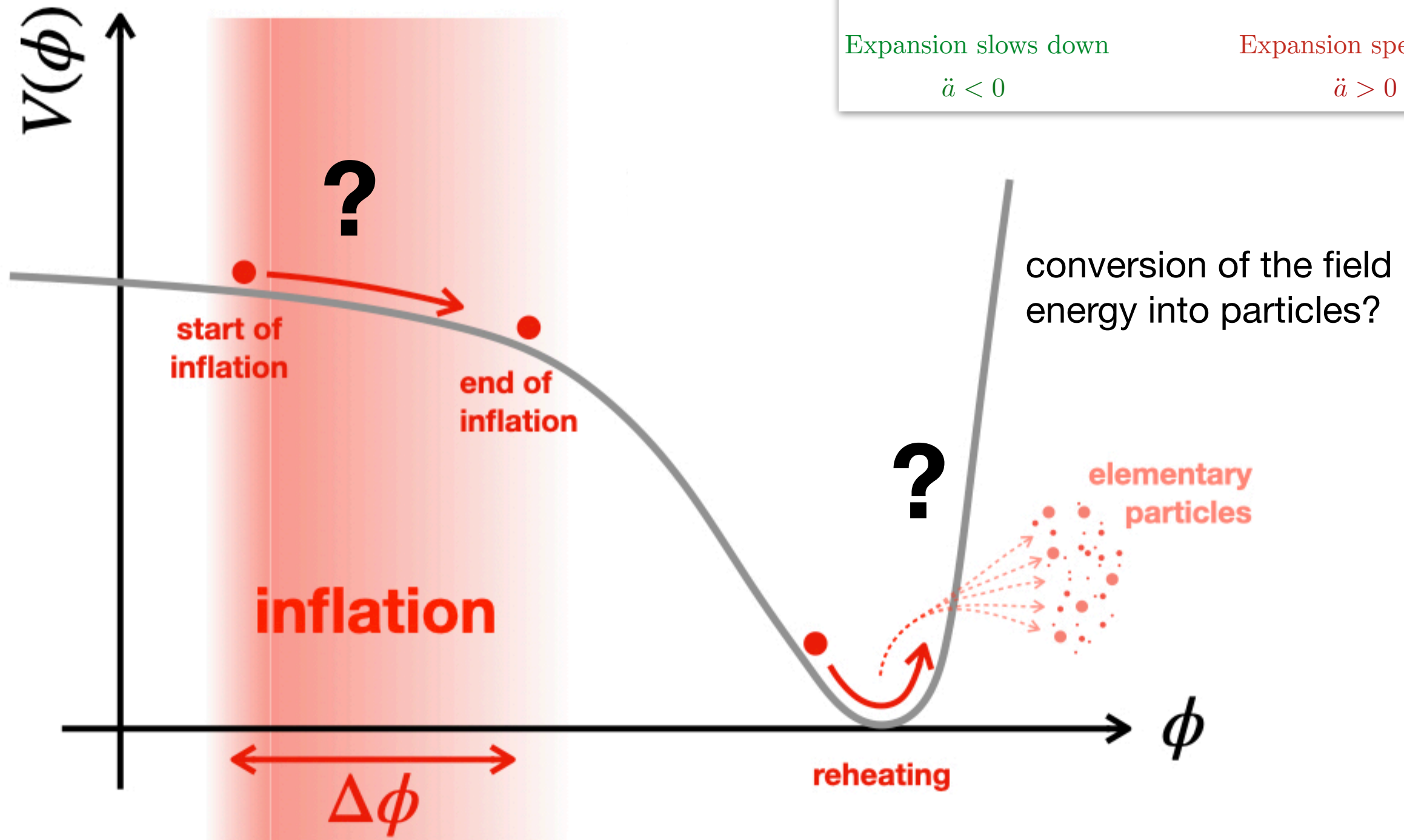
Expansion slows down

$$\ddot{a} < 0$$

$$P < -\frac{1}{3}\rho$$

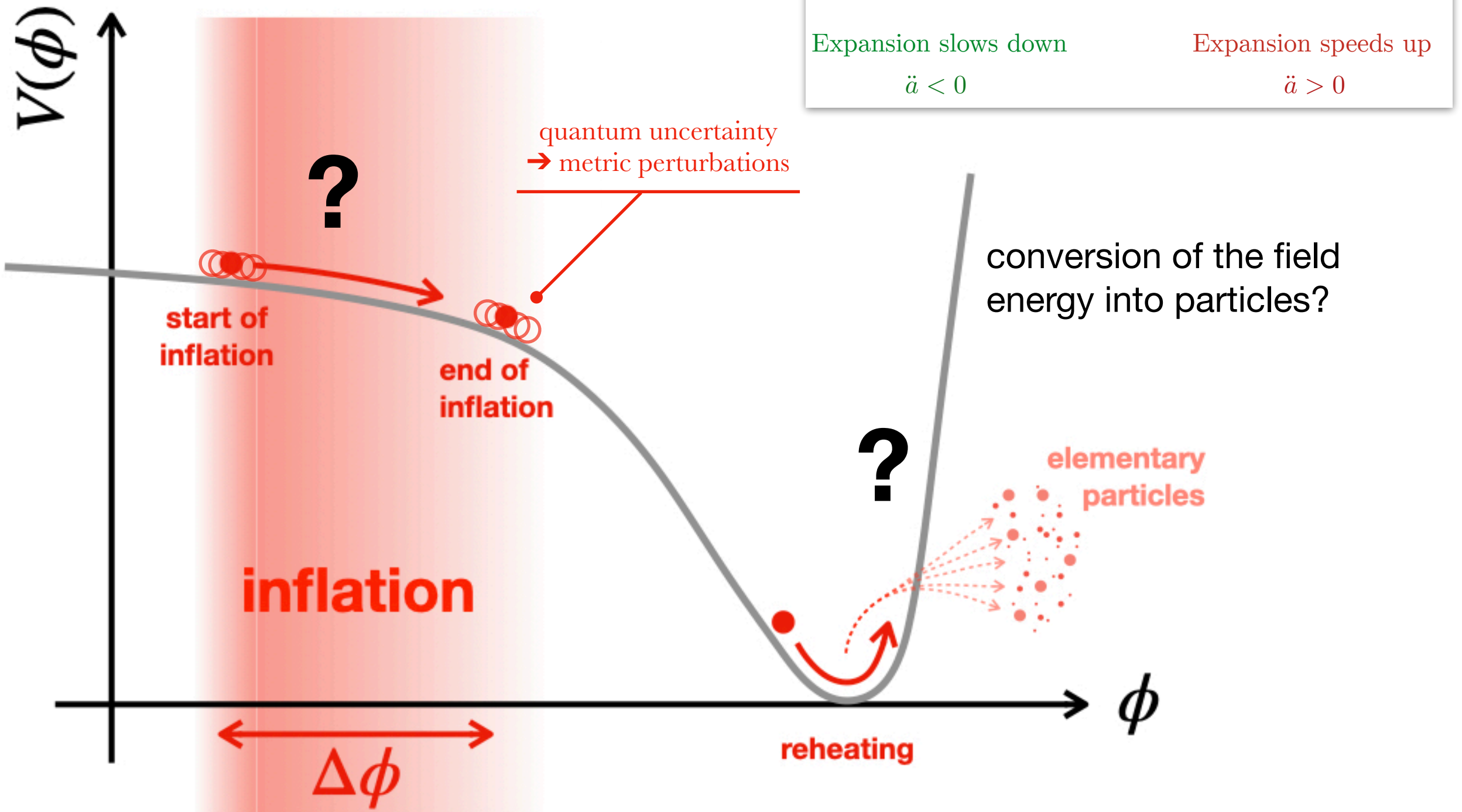
Expansion speeds up

$$\ddot{a} > 0$$



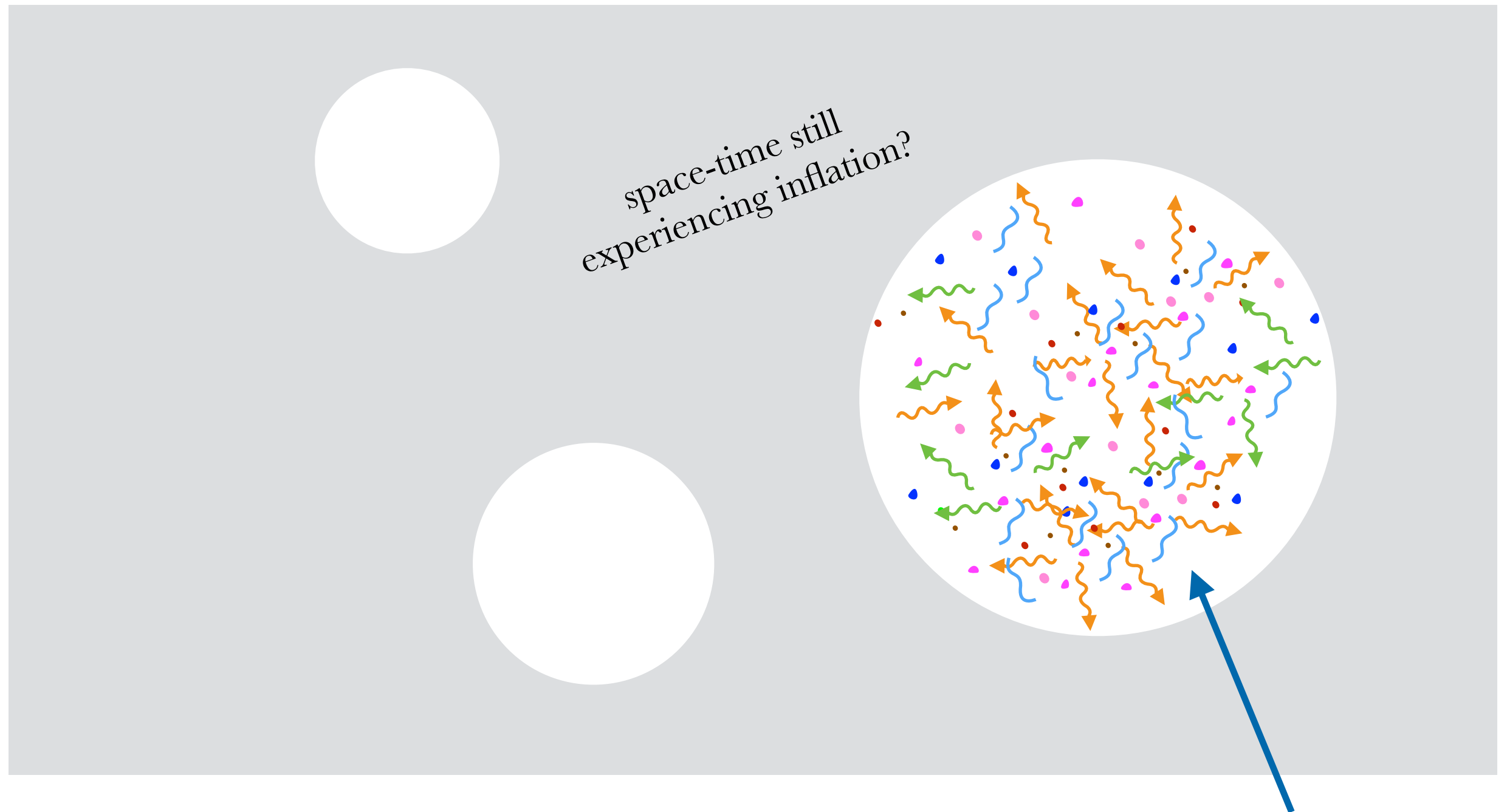
Inflation

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):

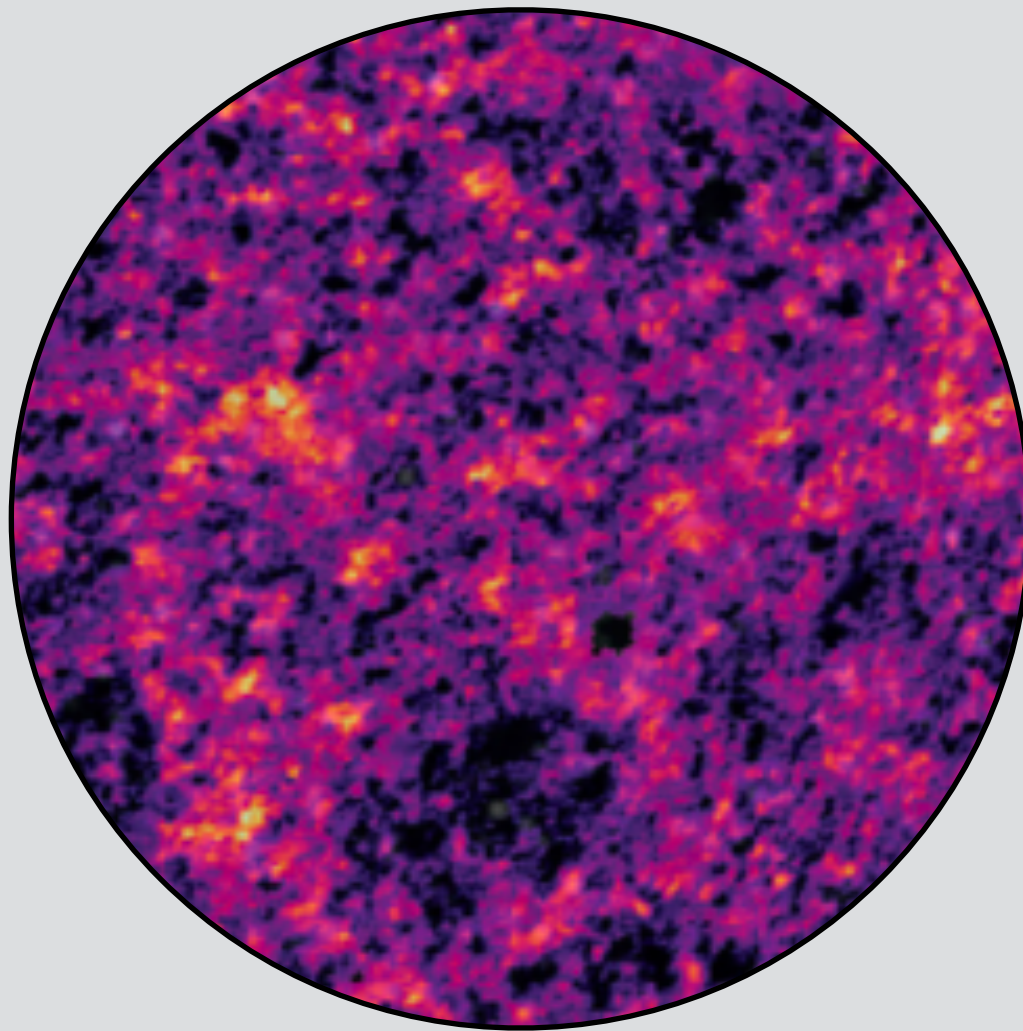


The product of this decay is the **hot Big Bang**.

One of these bubbles
is our Universe.

Inflation

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

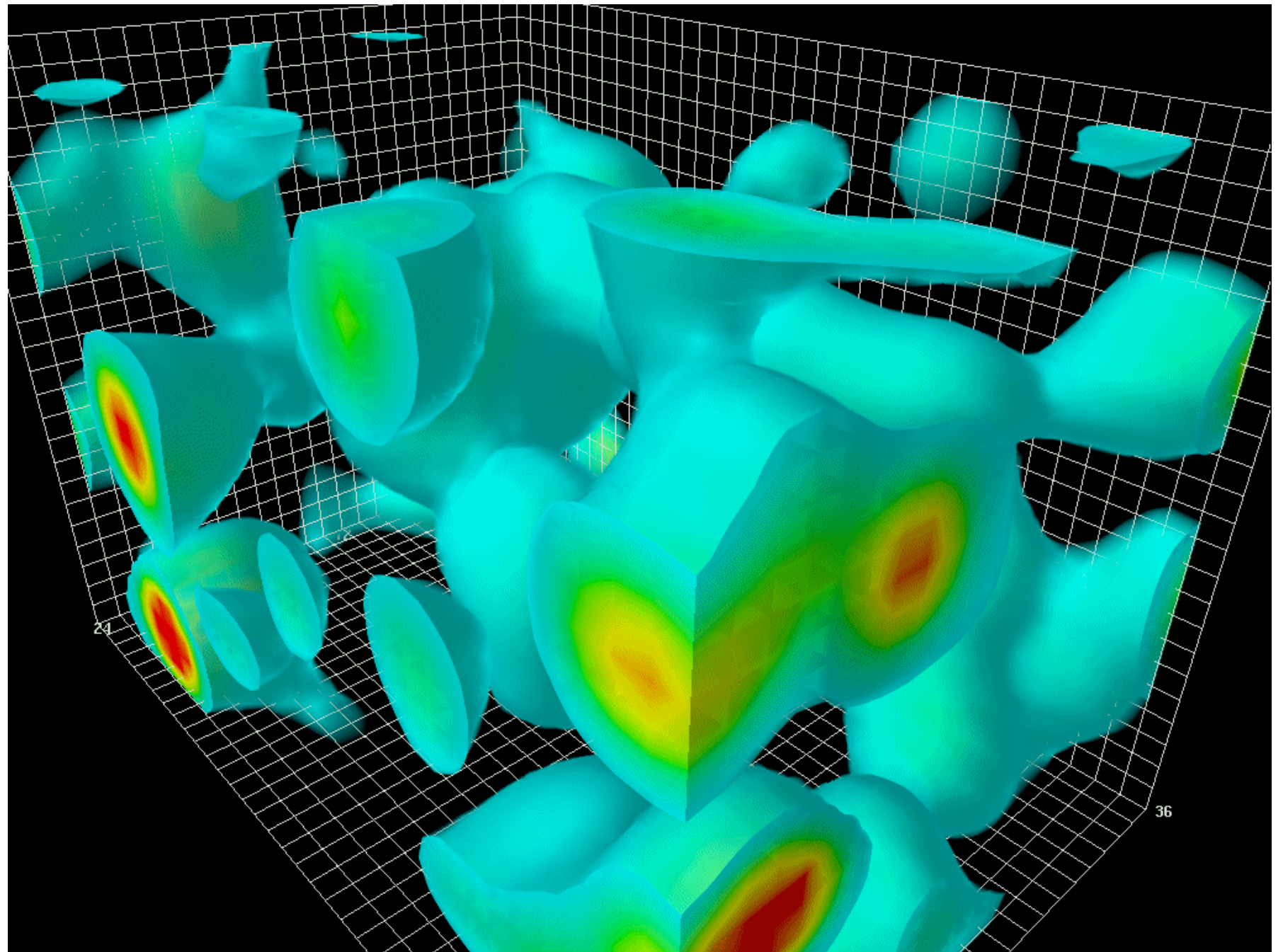


This creates the **primordial density fluctuations**.

Quantum Fluctuations

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

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

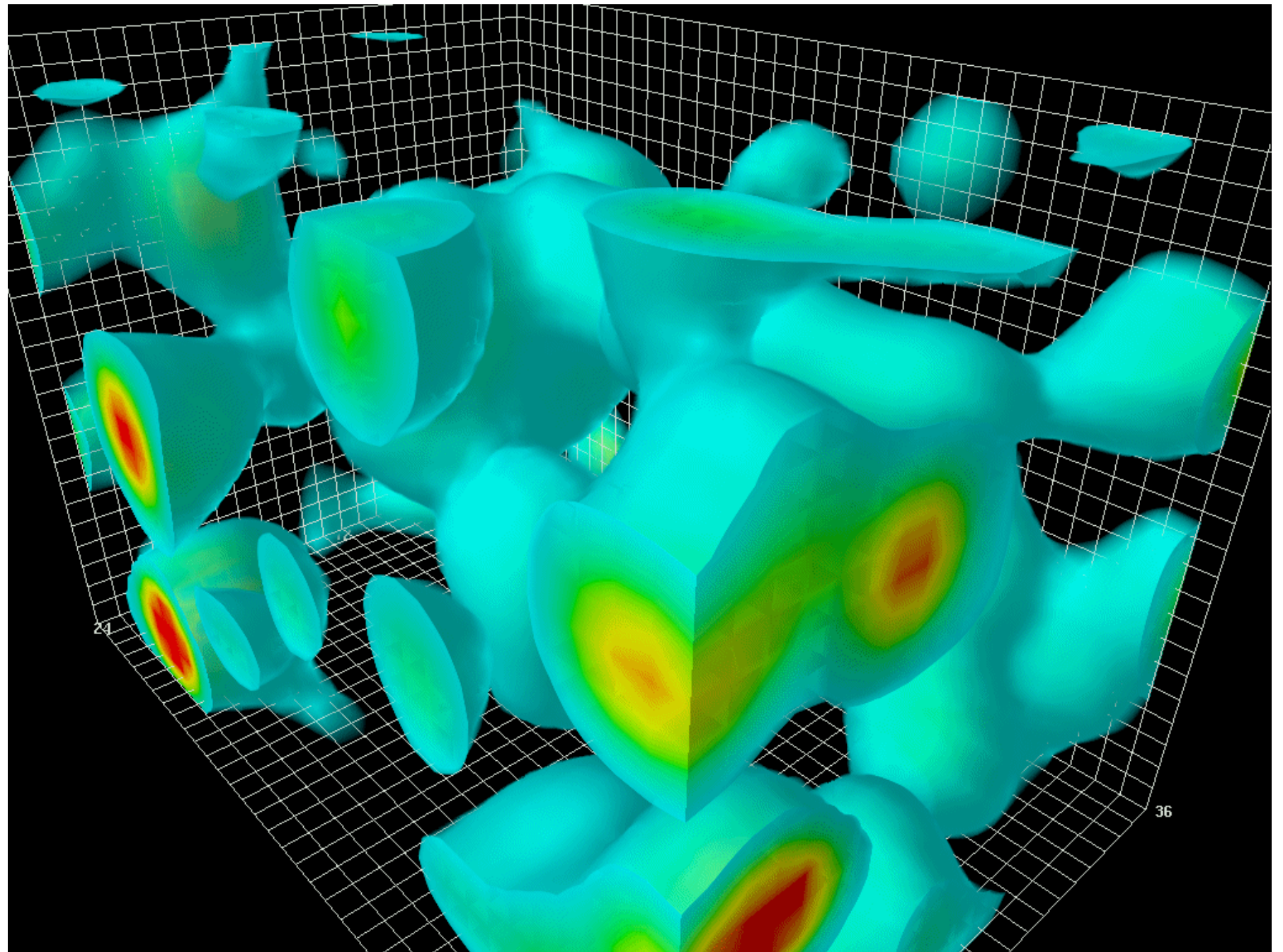


credits: Wikipedia. The animation illustrates the typical four-dimensional structure of gluon-field configurations averaged over in describing the vacuum properties of QCD. The volume of the box is 2.4 by 2.4 by 3.6 fm, big enough to hold a couple of protons. Contrary to the concept of an empty vacuum, QCD induces chromo-electric and chromo-magnetic fields throughout space-time in its lowest energy state. After a few sweeps of smoothing the gluon field (50 sweeps of APE smearing), a lumpy structure reminiscent of a lava lamp is revealed.

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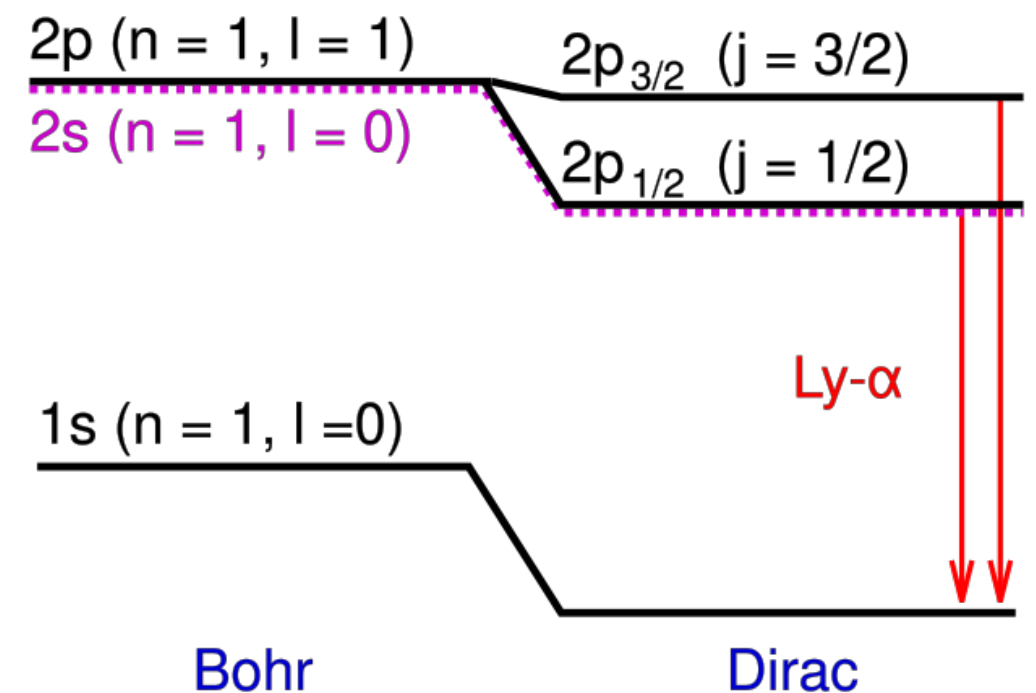
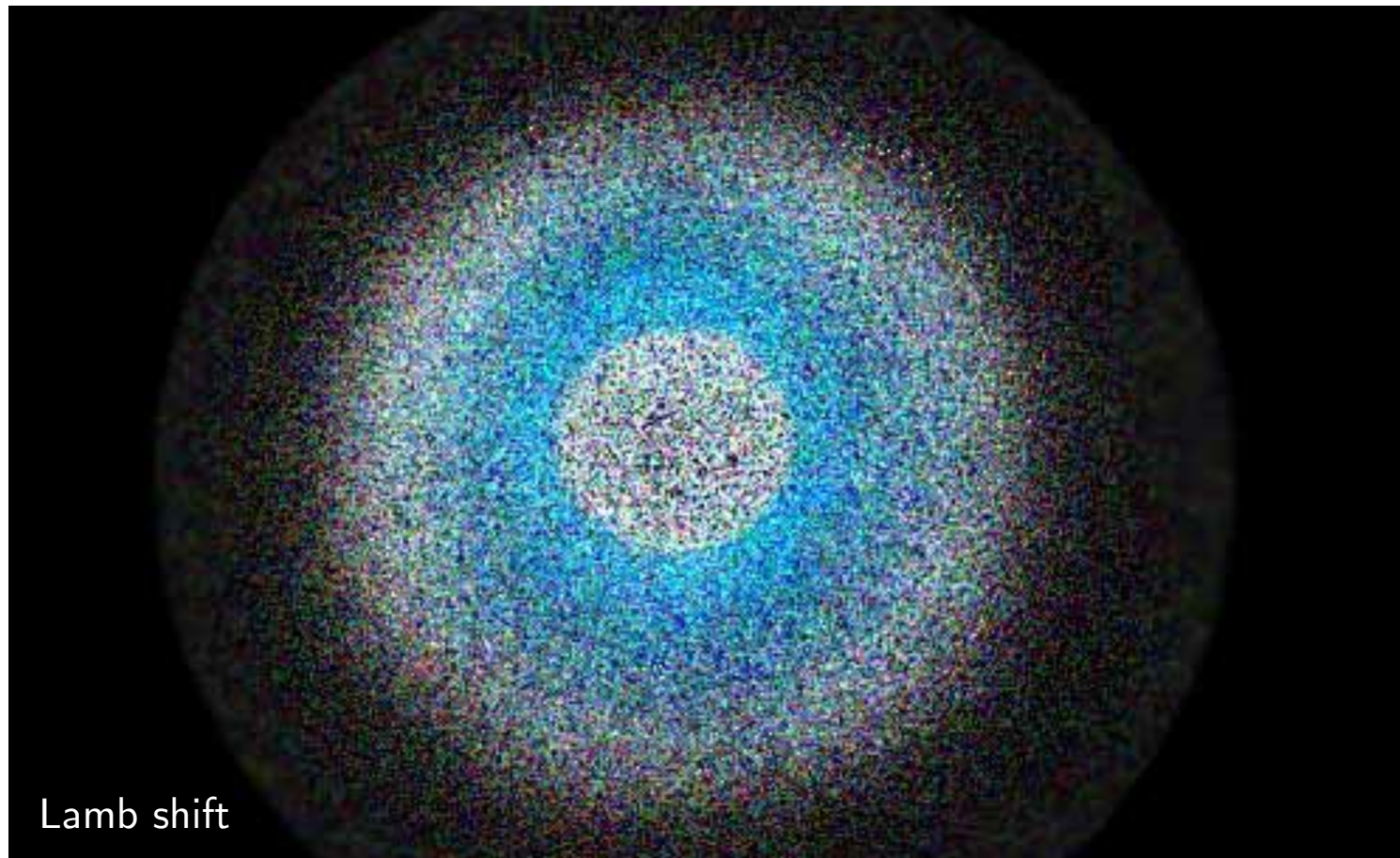
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Quantum Fluctuations

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



The electron interacts with the fluctuating quantum vacuum $\rightarrow$ its effective position “jitters” (Lamb called this the electron’s “self-field”).

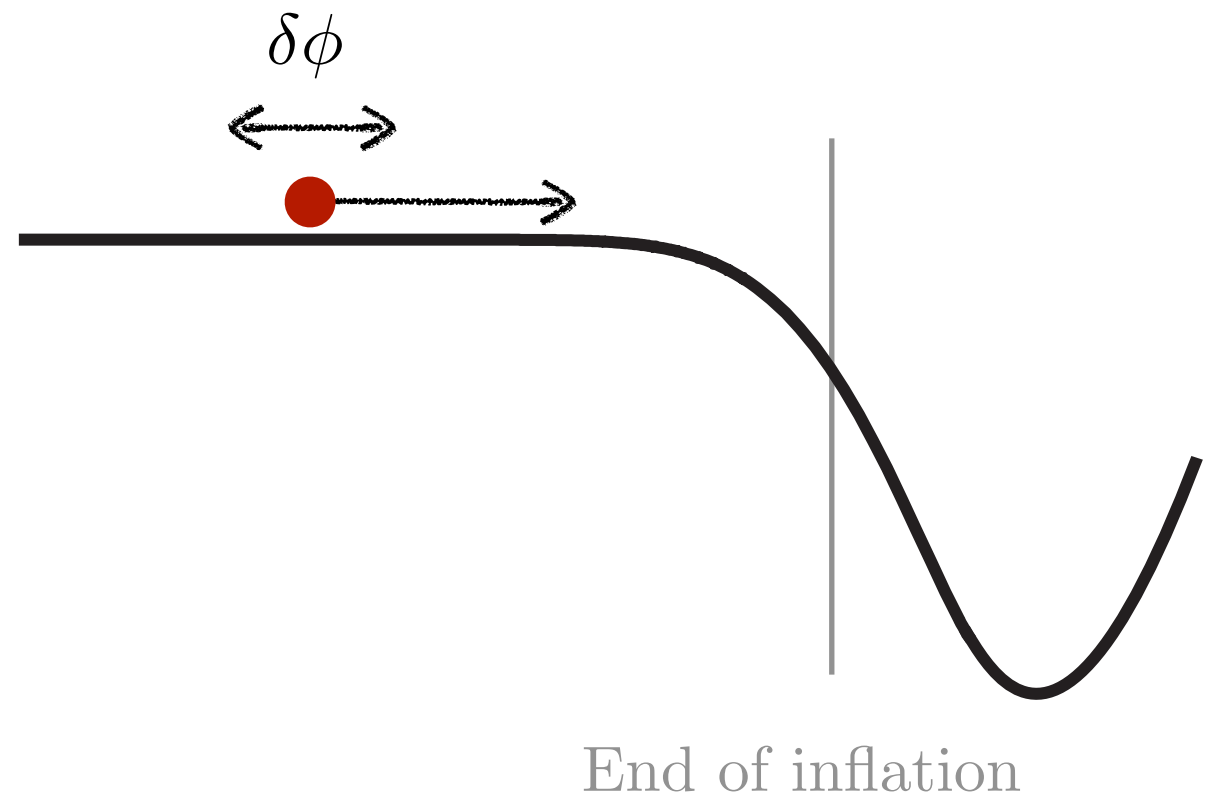
Fluctuations during Inflation

Each Fourier mode of the inflaton fluctuations satisfies:

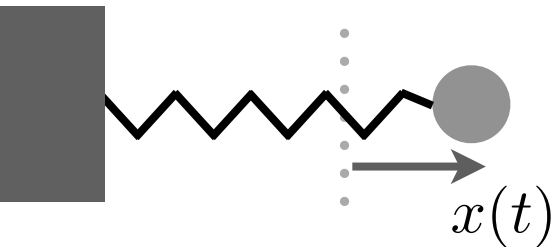
$$\ddot{\delta\phi} + 3H\dot{\delta\phi} + \omega_k^2(t)\delta\phi = 0$$

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

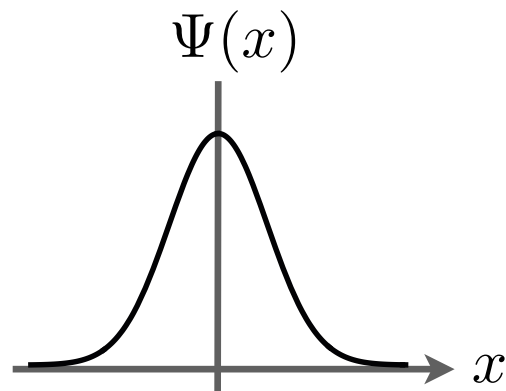
This is the equation of a time-dependent harmonic oscillator.



Quantum Harmonic Oscillators



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



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

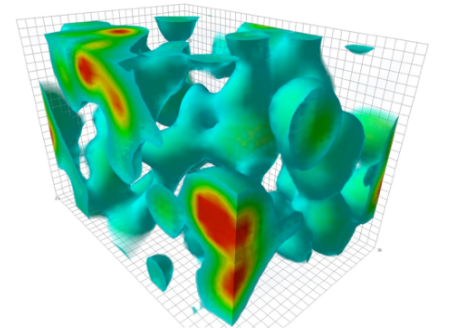
Zero-point fluctuations

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

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

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

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



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

Hollands and Wald (2002)

Quantum Fluctuations during Inflation

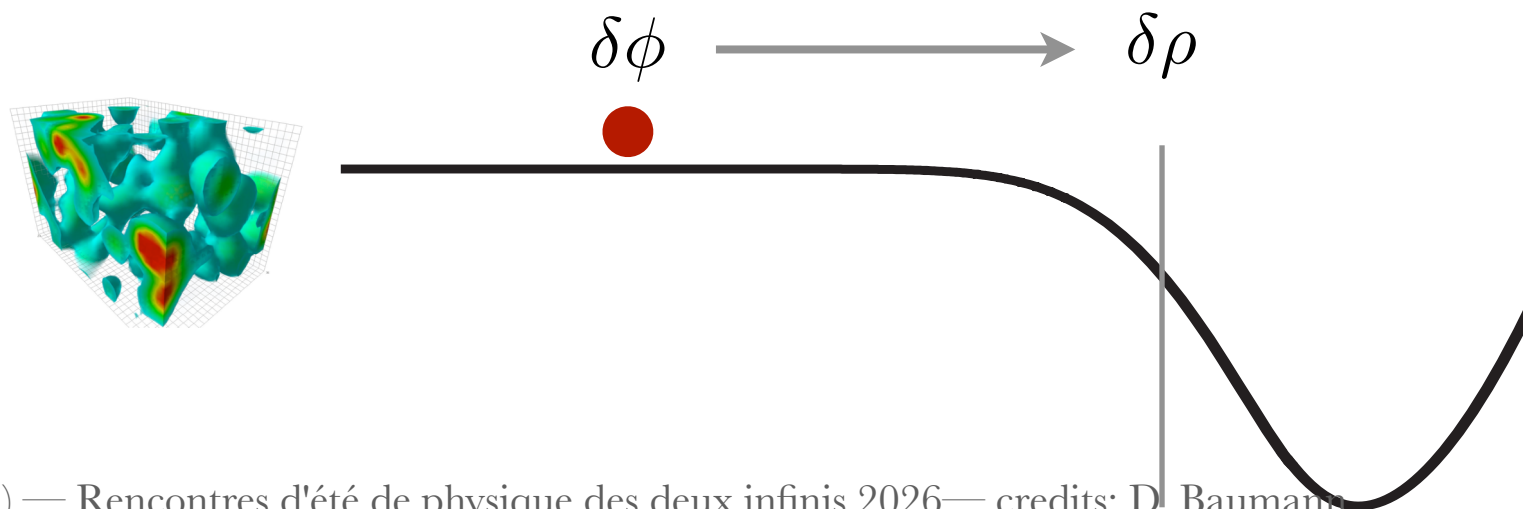
This holds as long as the mode evolves adiabatically (inside the horizon):

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

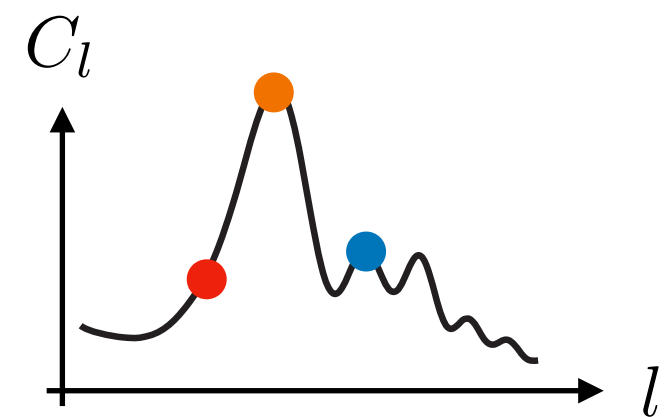
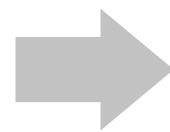
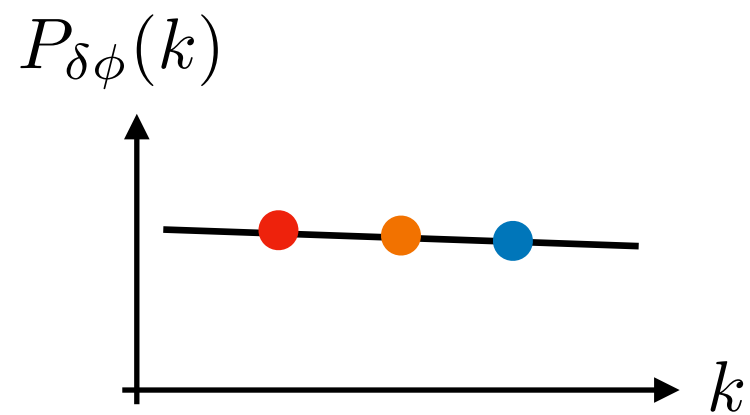
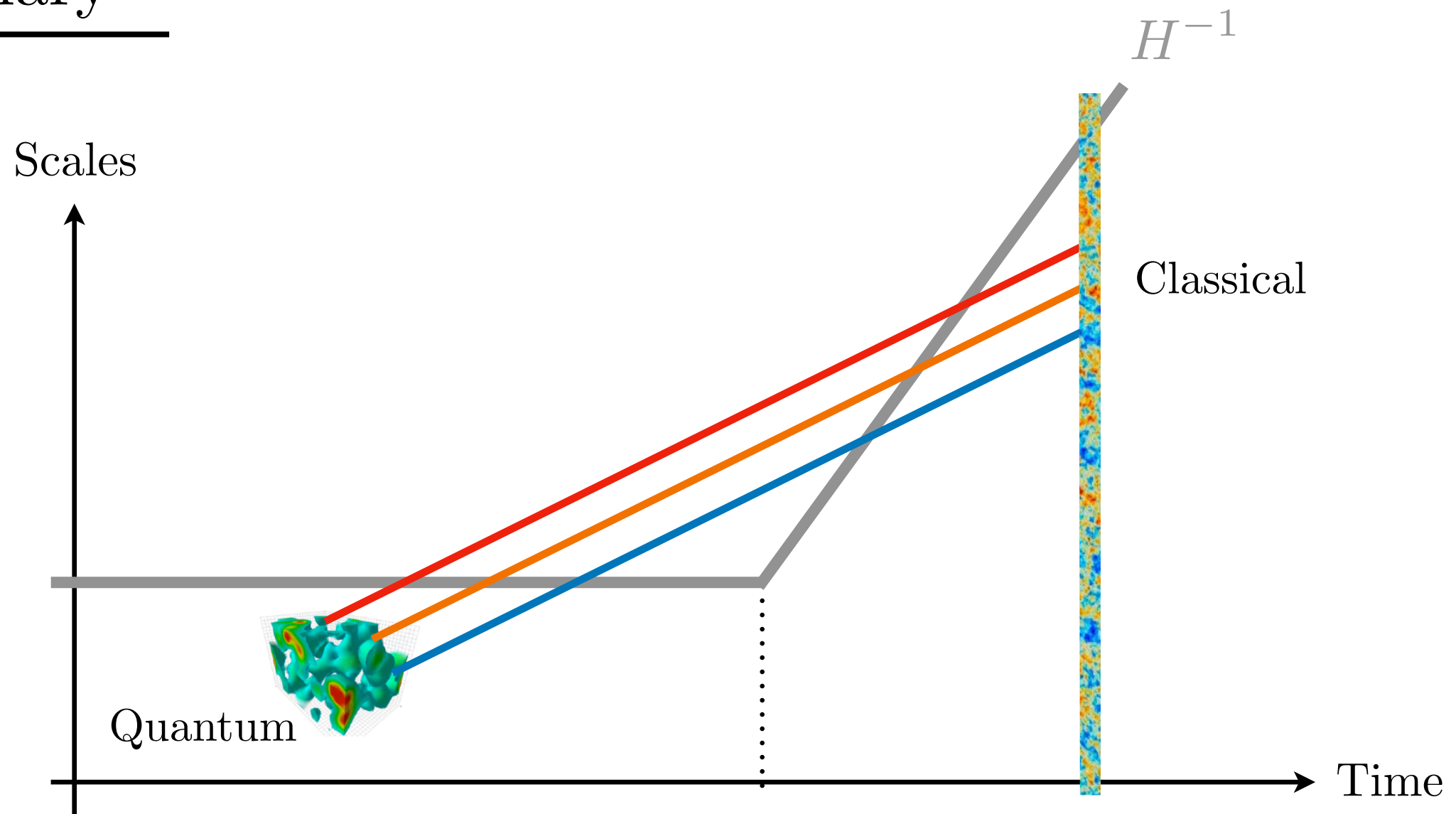
At horizon crossing, $k/a(t_*) = H(t_*)$, the fluctuations freeze and we get

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

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

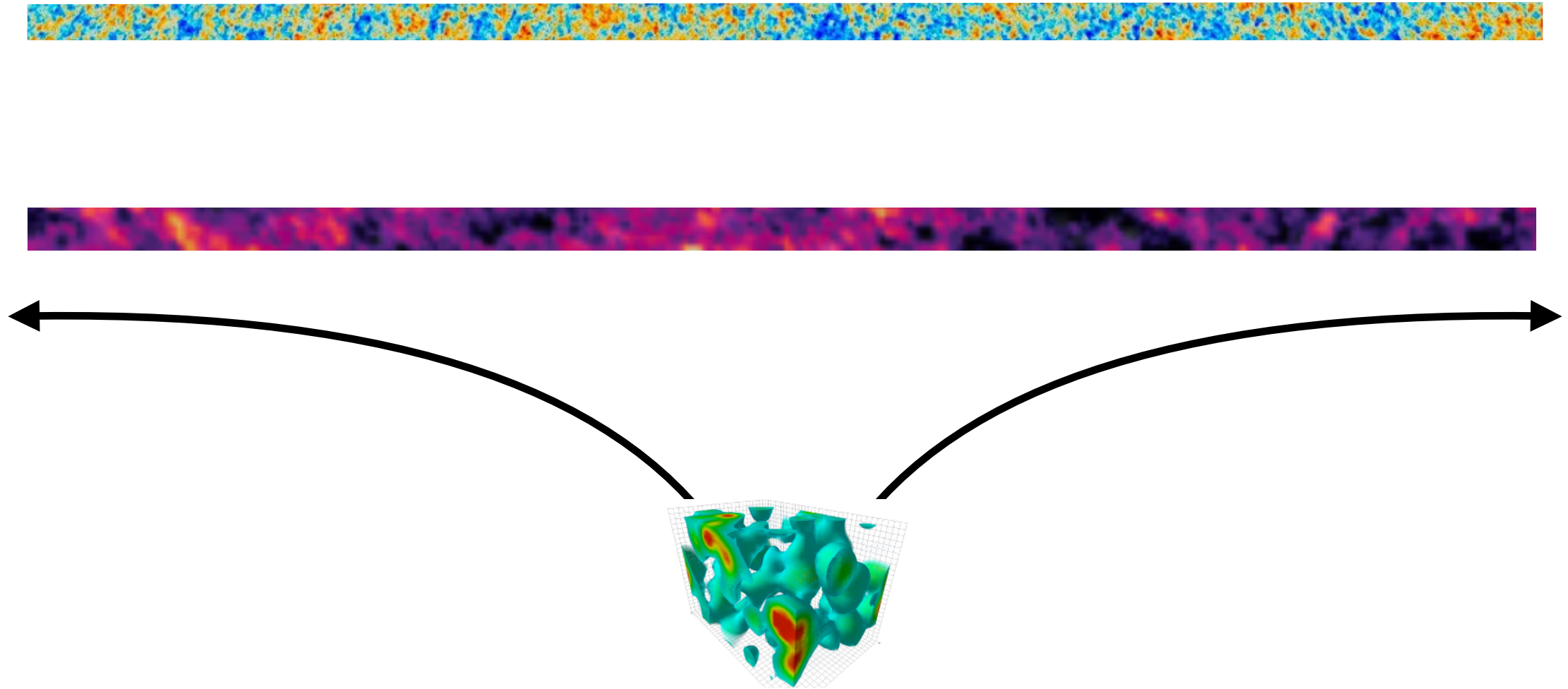


Summary



Quantum Fluctuations

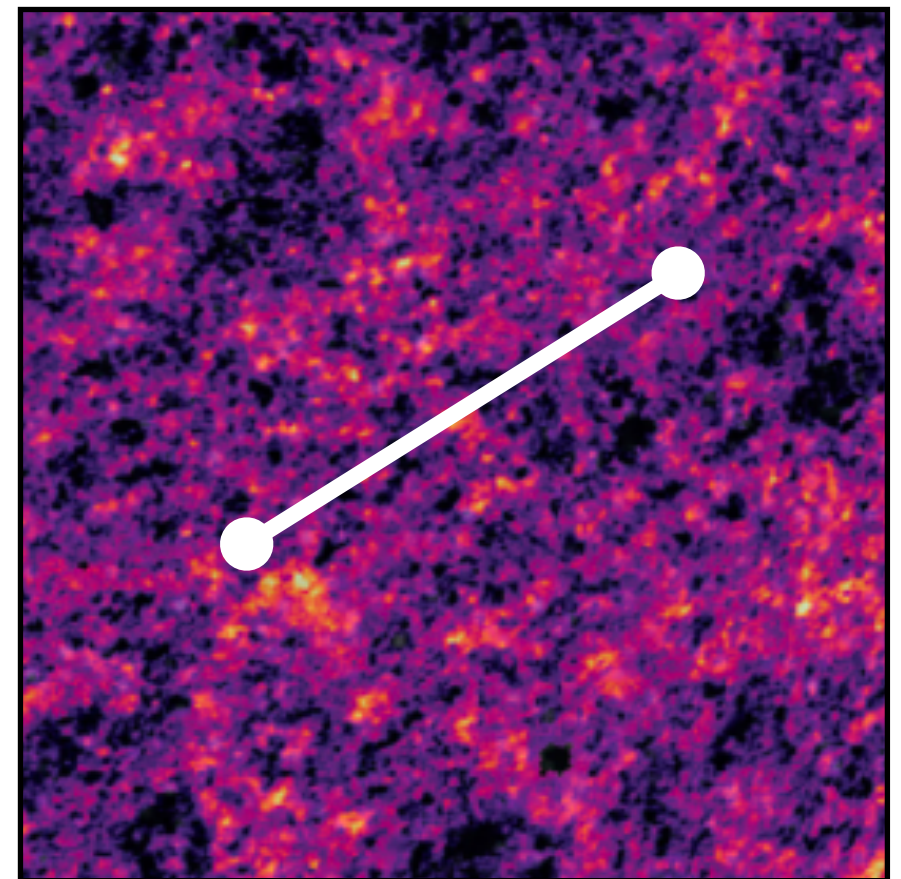
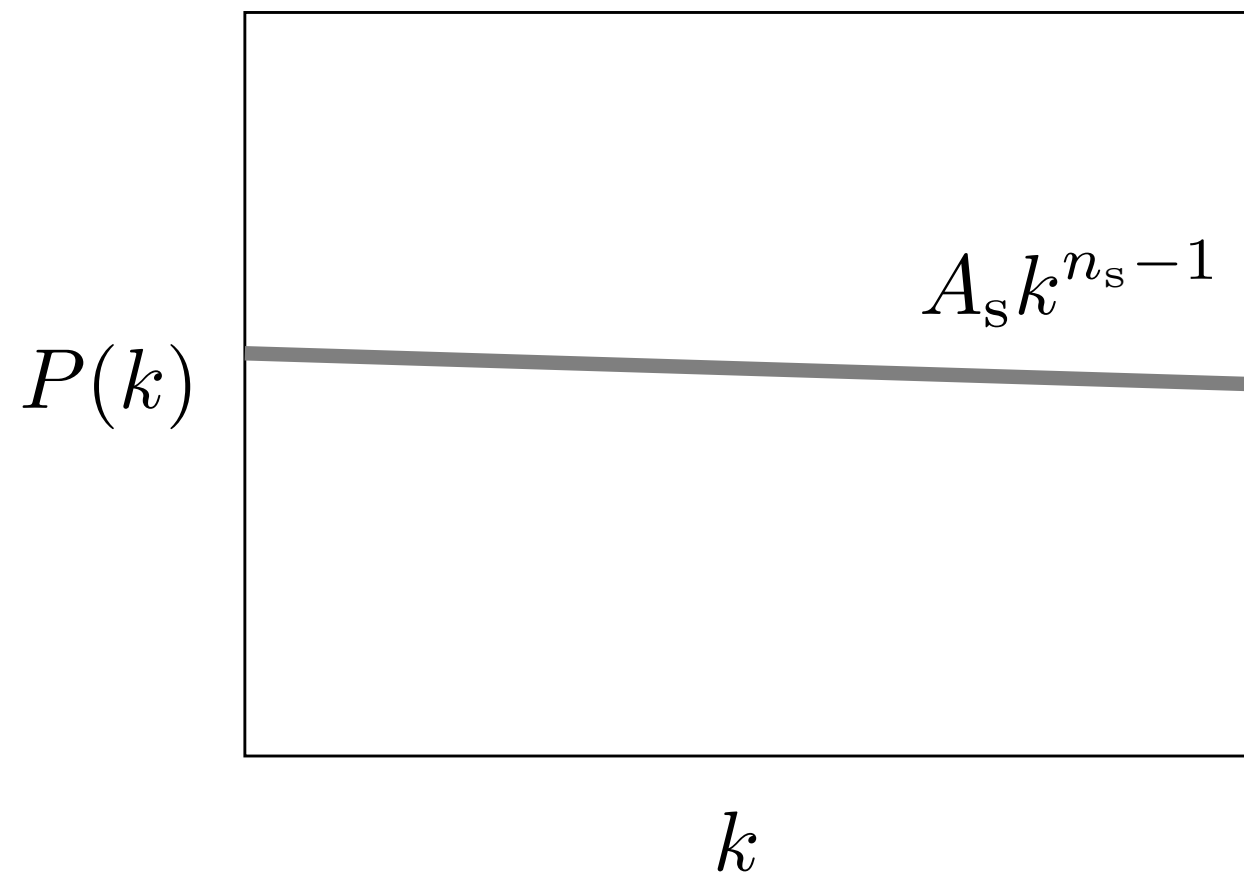
During inflation, these quantum fluctuations get amplified and stretched:



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

Primordial Correlations

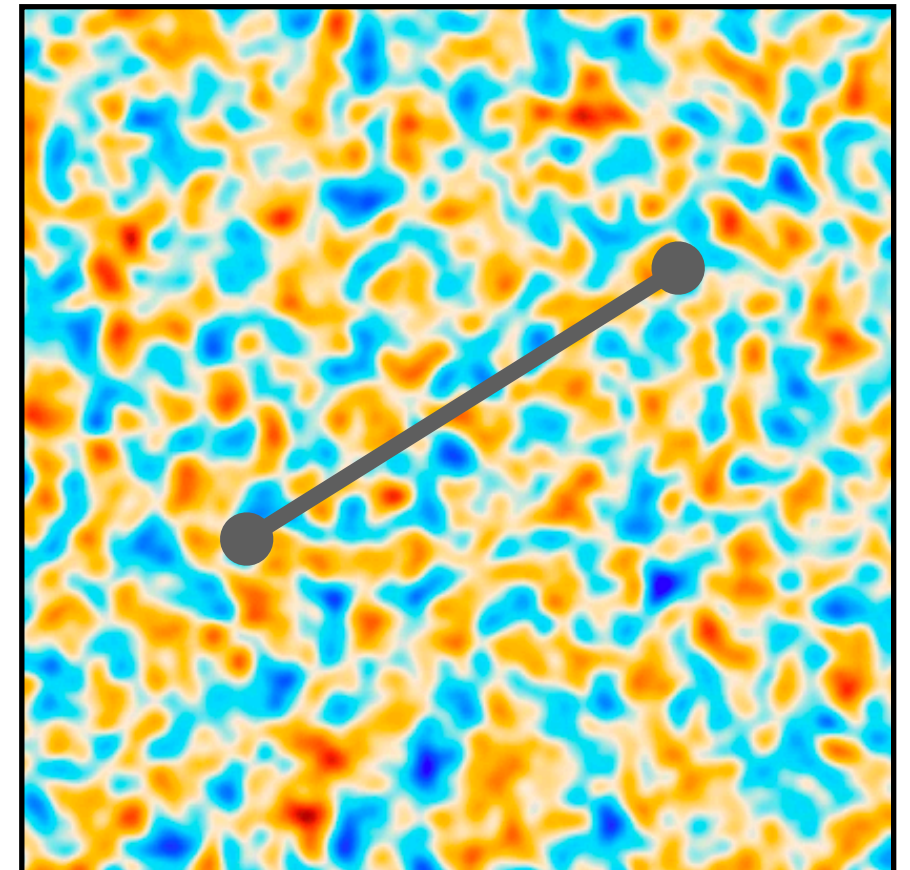
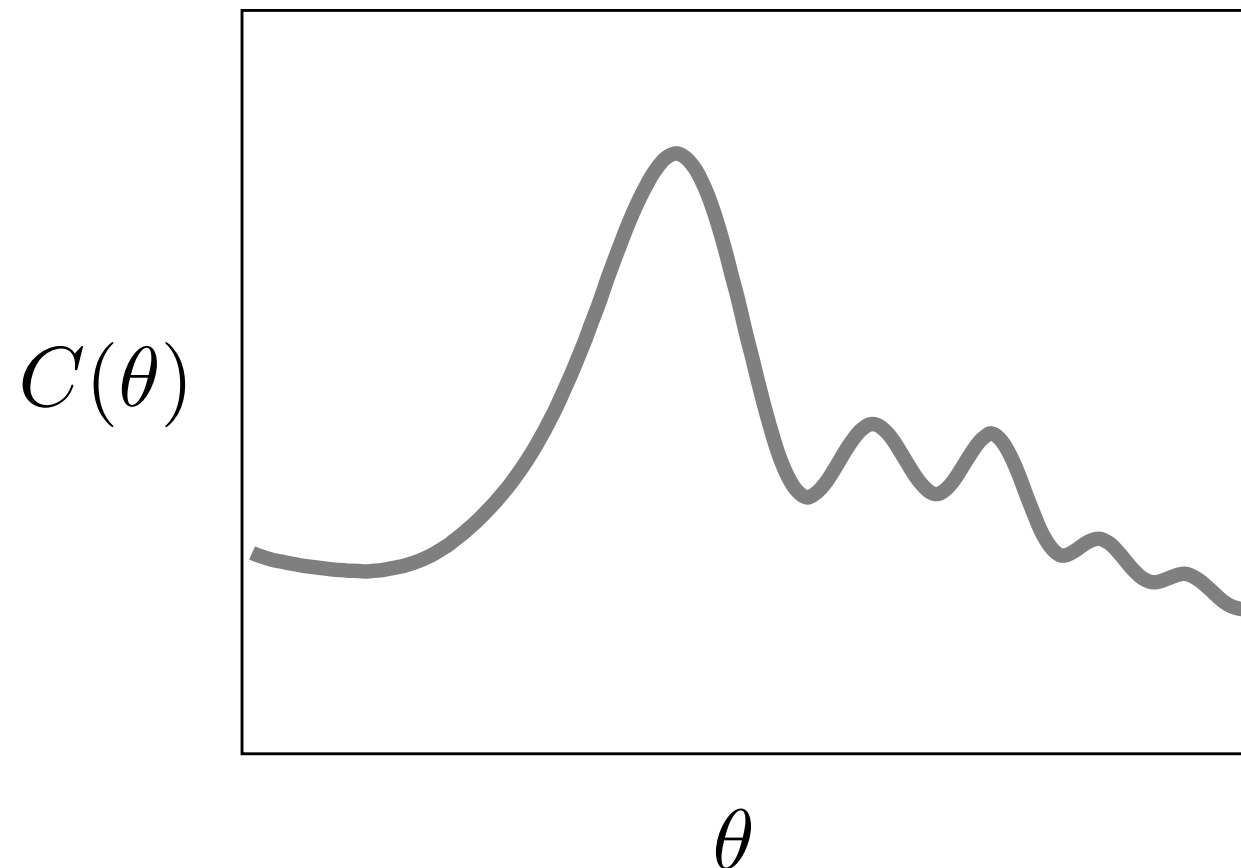
The nearly constant inflationary vacuum energy leads to an approximately **scale-invariant** power spectrum:



The slow decay of the inflationary energy predicts slightly more power on large scales: $n_s < 1$

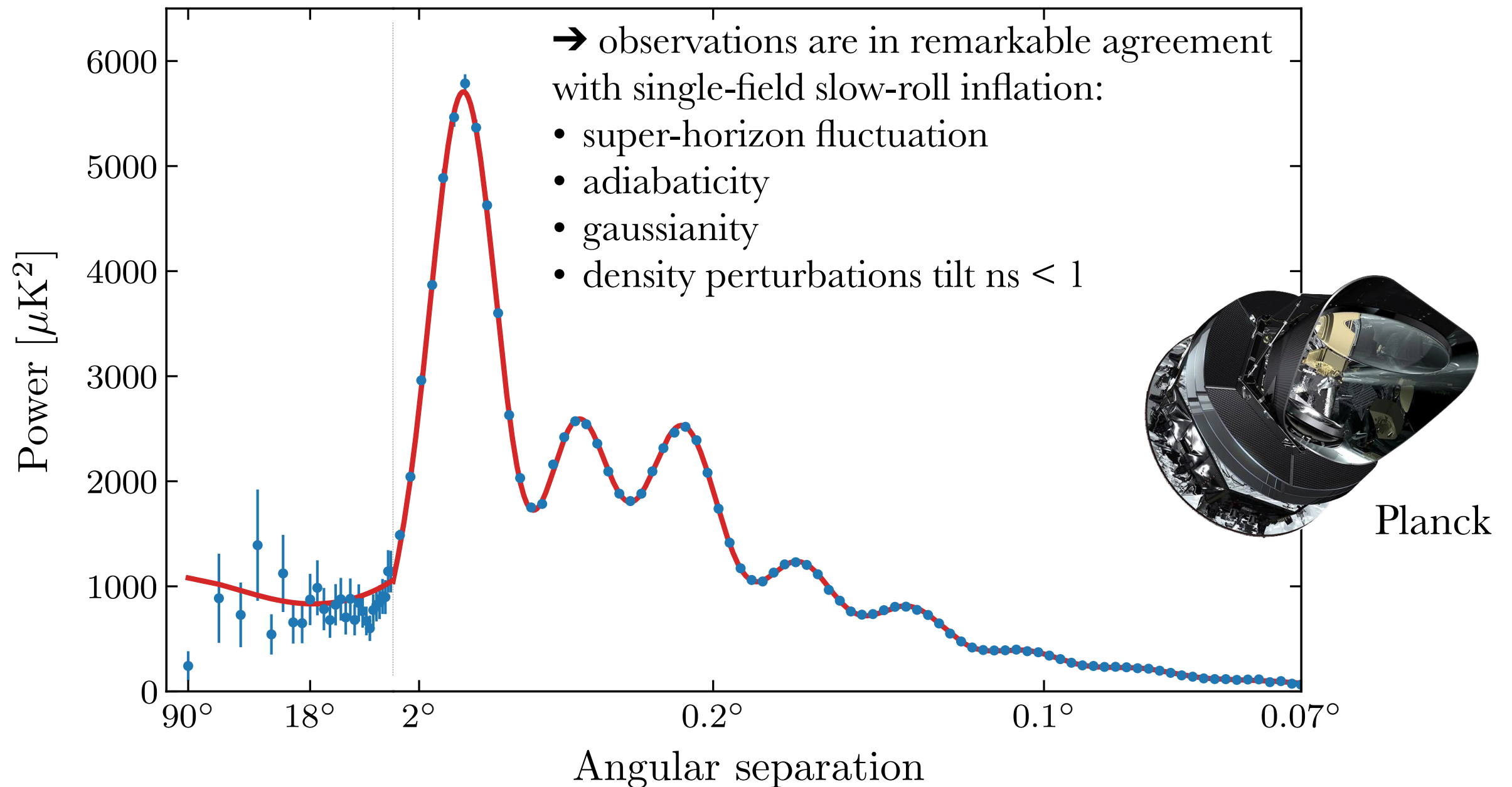
CMB Anisotropies

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:

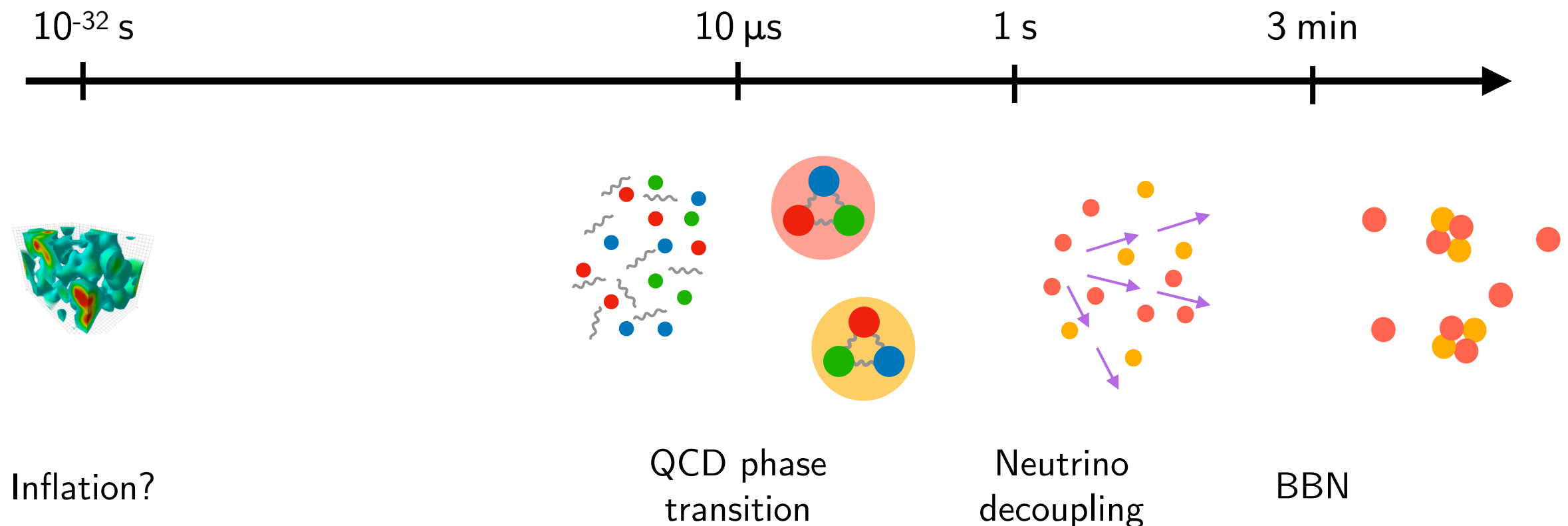


“Extraordinary claims require extraordinary evidence”

Carl Sagan

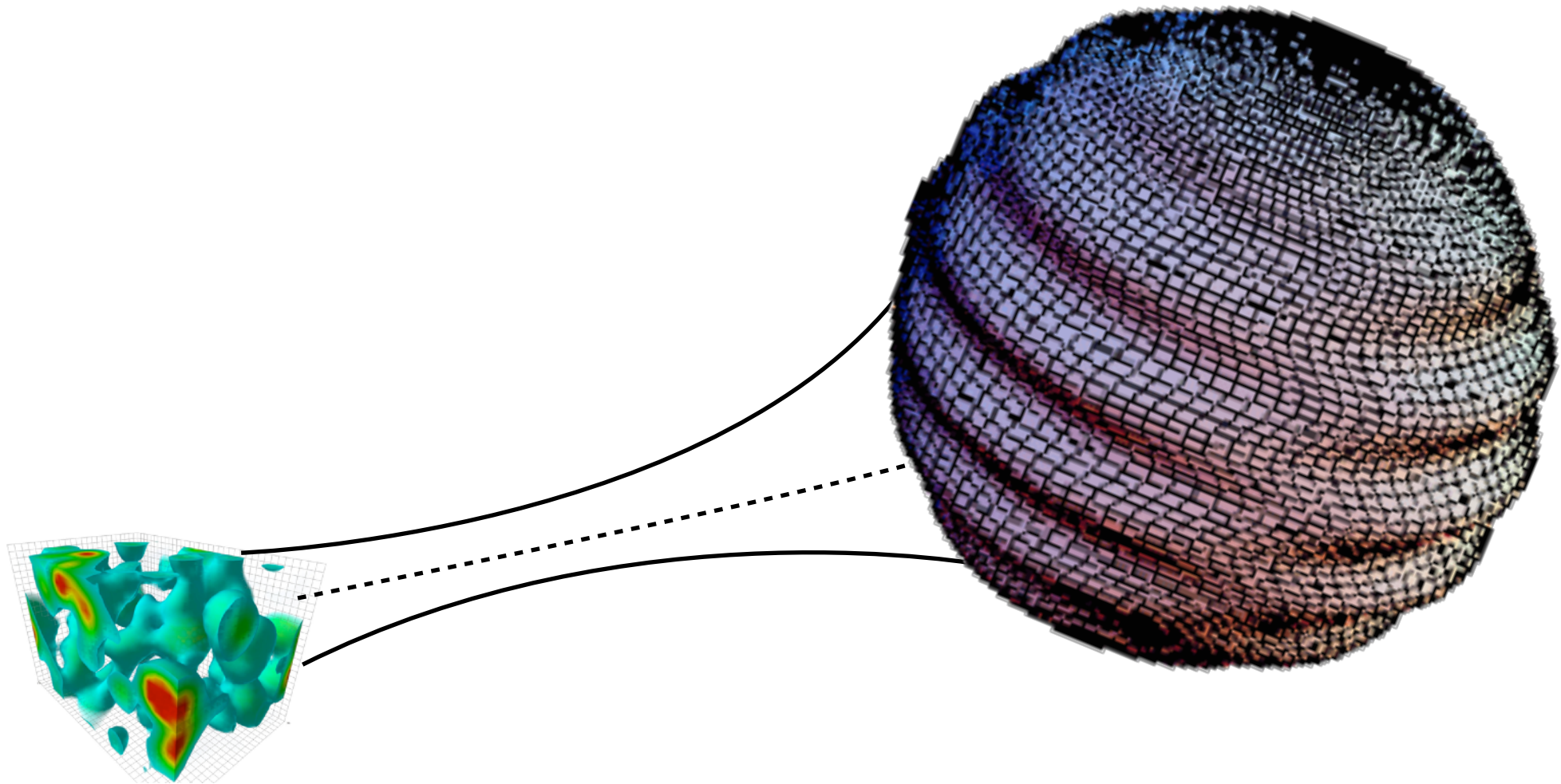


How can inflation become part of the standard history of the Universe with the same level of confidence as BBN?



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.

Inflation

- According to single field, slow-roll inflationary scenario, quantum vacuum fluctuations excite cosmological scalar and tensor perturbations

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0} \right)^{n_s - 1} \quad \text{scalar}$$

$$\mathcal{P}_{\mathcal{T}}(k) = A_t \left(\frac{k}{k_0} \right)^{n_t} \quad \text{tensor}$$

- With the definition of the tensor-to-scalar ratio “r” $r = A_t / A_s$ which characterizes the amplitude of GW and gives direct constraints on

- the shape of the potential $V^{1/4}(\phi) \simeq 10^{16} \text{ GeV} \left(\frac{r}{0.01} \right)^{1/4}$

- energy scale of inflation $\frac{\Delta\phi}{M_P} \simeq \mathcal{N}_* \left(\frac{r_*}{8} \right)^{1/2} \simeq \left(\frac{r}{0.001} \right)^{1/2}$

- inflaton field excursion $r = 8M_{\text{Pl}}^2 \left(\frac{V_\phi}{V} \right)^2$

- derivative of the potential $n_s - 1 \equiv \frac{d \ln \mathcal{P}_\zeta}{d \ln k} \simeq -3M_{\text{Pl}}^2 \left(\frac{V_\phi}{V} \right)^2 + 2M_{\text{Pl}}^2 \frac{V_{\phi\phi}}{V}$

CMB polarization and its description

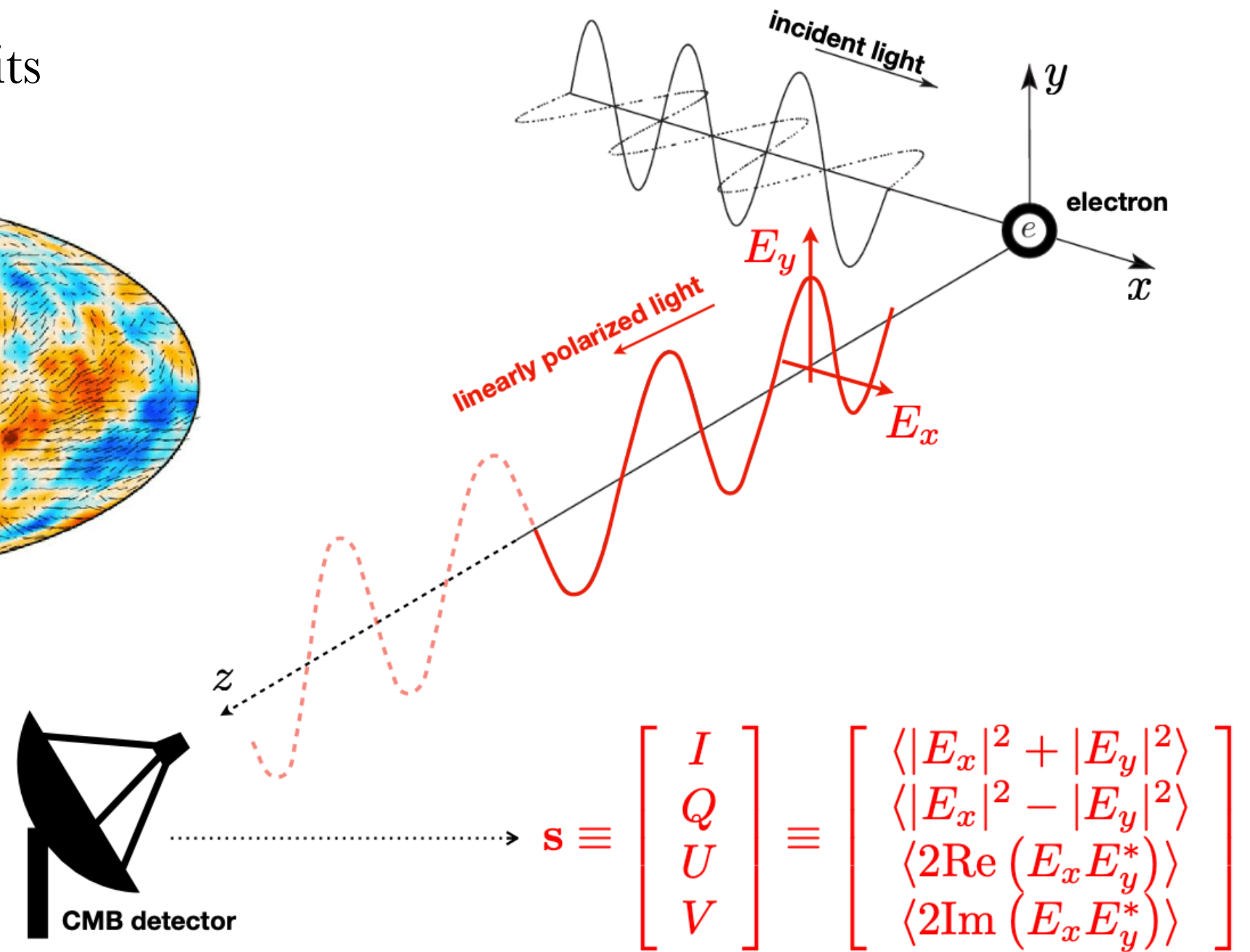
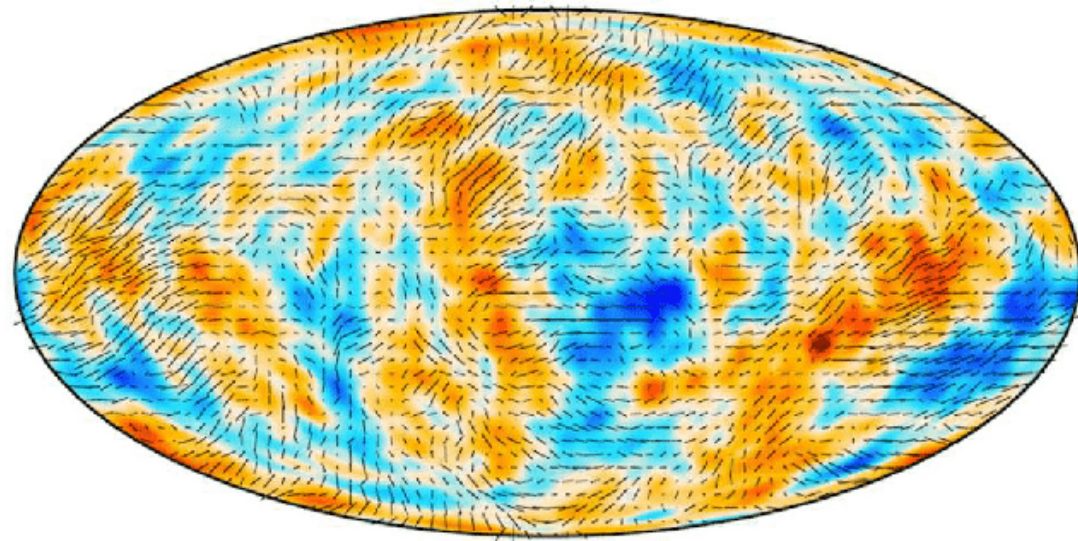
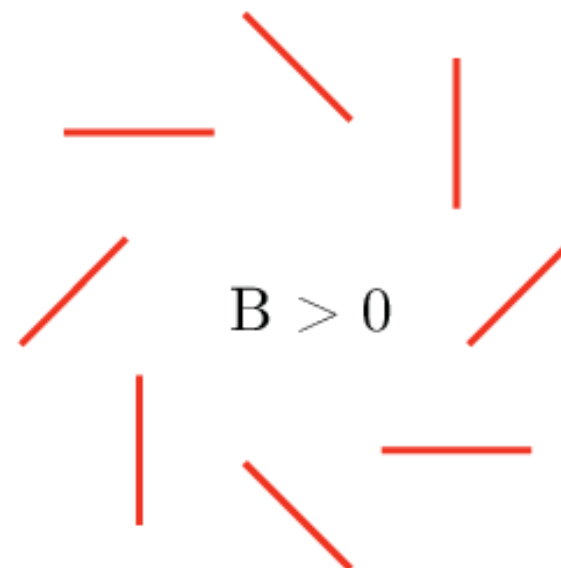
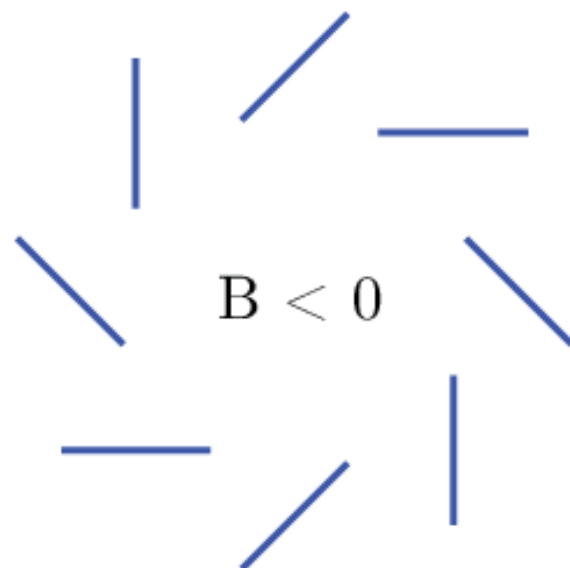
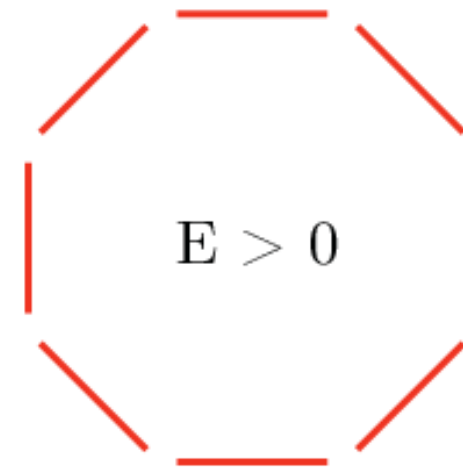
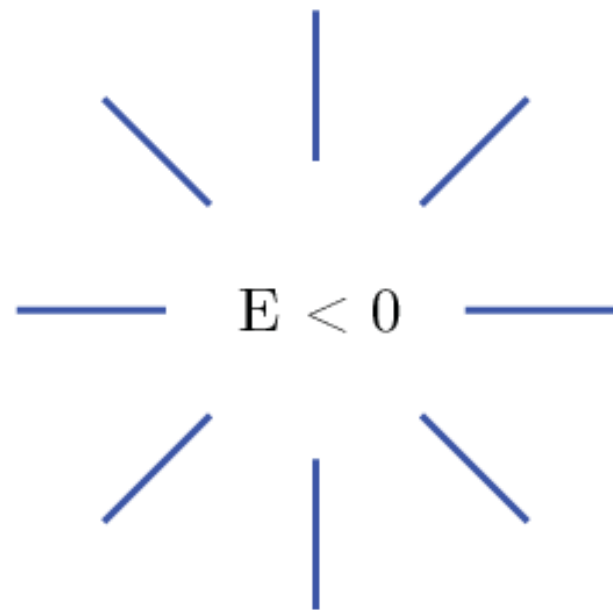
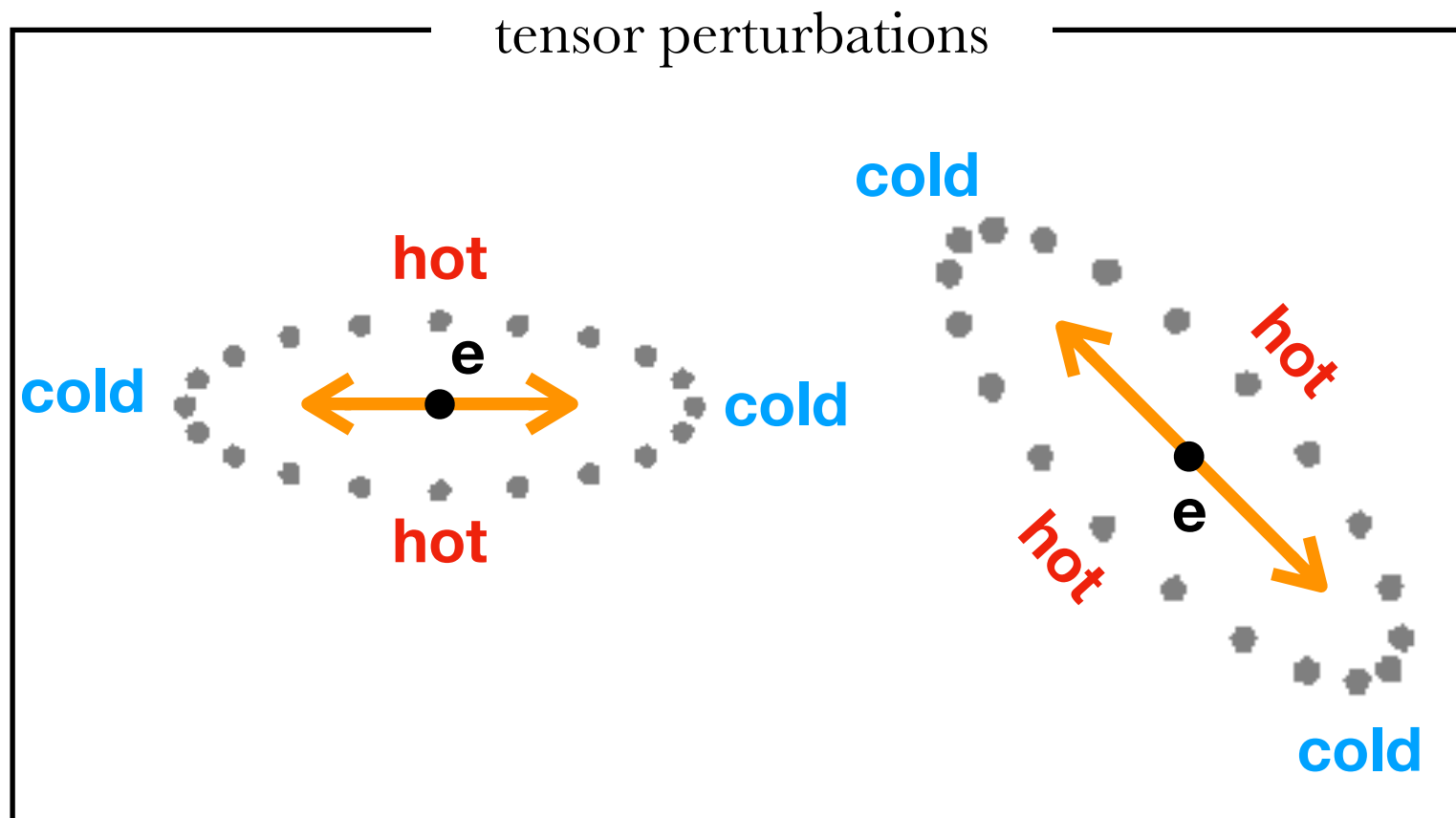
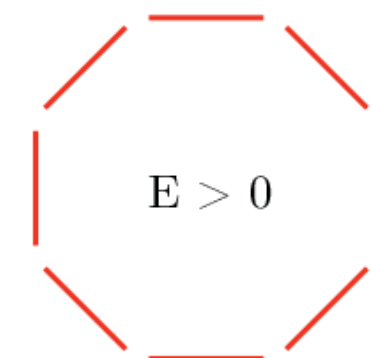
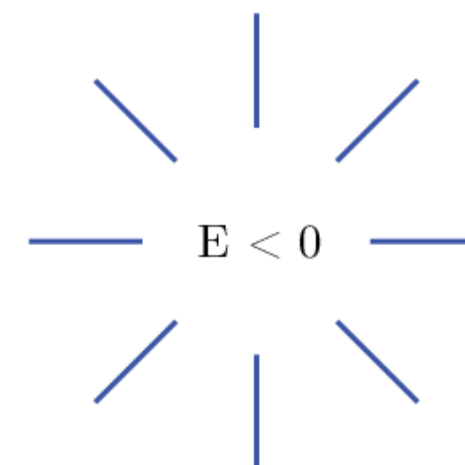
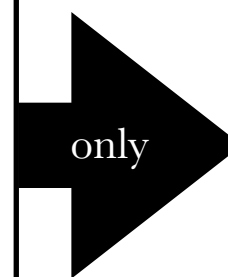
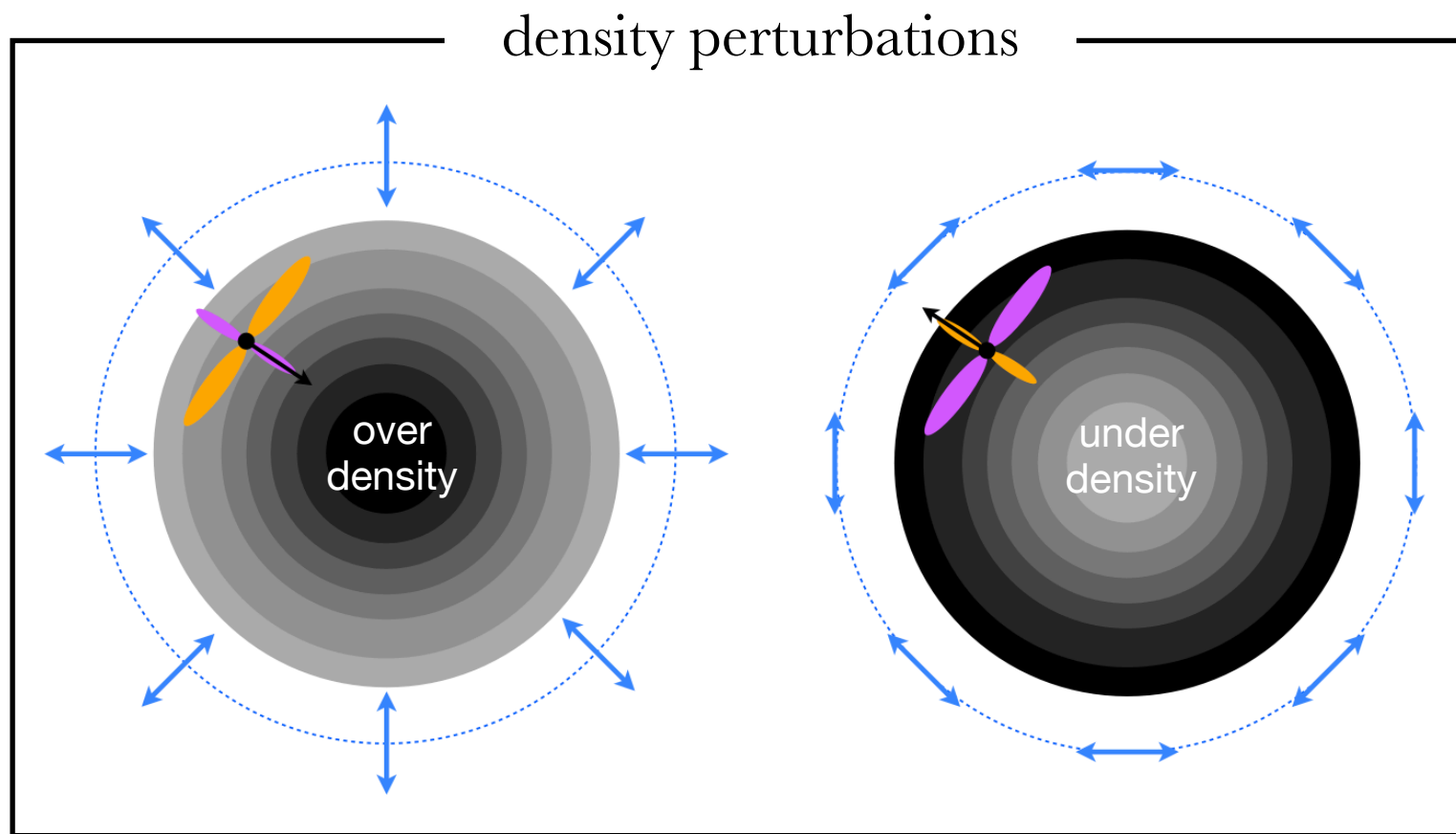


Figure 1.5: Thomson scattering, adapted from [186], and definition of the observed Stokes parameters. I corresponds to the total intensity of a given light beam, Q and U are the two Stokes parameters describing the linear polarization angle and amplitude, and V is for the circular polarization. In practice in this manuscript, the last dimension will be dropped as CMB light is, as far as it has been characterized, not circularly polarized (although atmospheric emission may be through the Zeeman splitting of O_2 molecules, e.g. [234]).

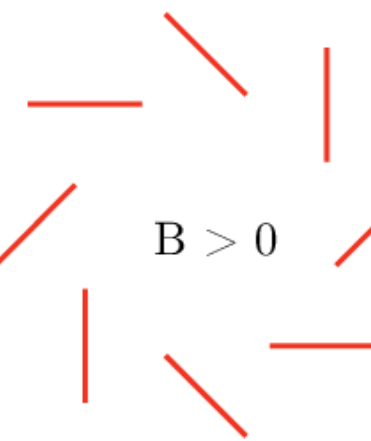
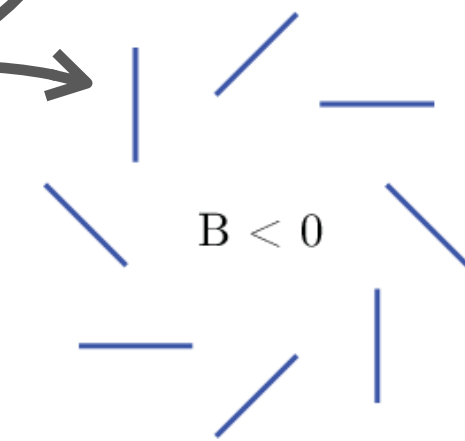
E-modes = Q in $\mathbf{k}$ coordinates

B-modes = U in $\mathbf{k}$ coordinates



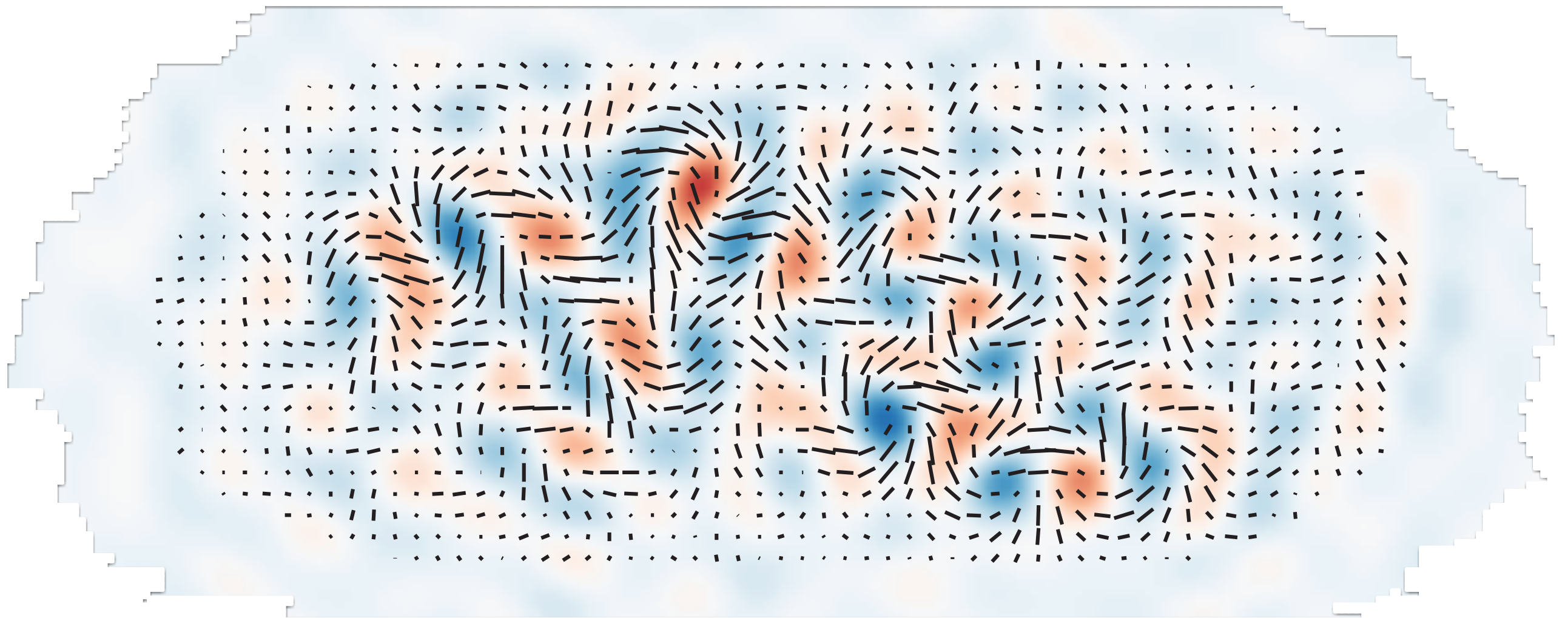


both



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.

Past and On-going experiments

CLASS



POLARBEAR



CMB Stage III

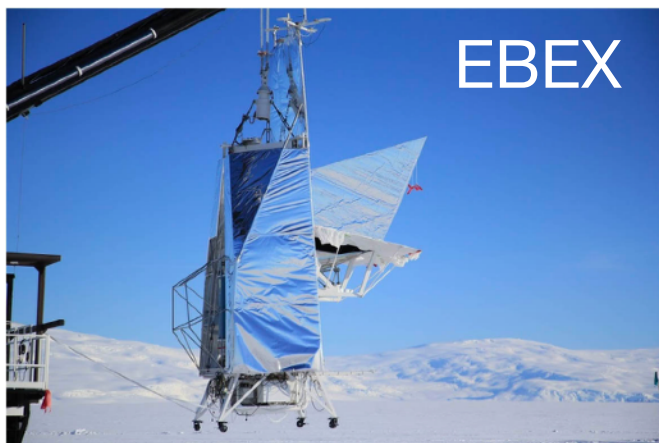
ACTPol



SPIDER



EBEX



ABS

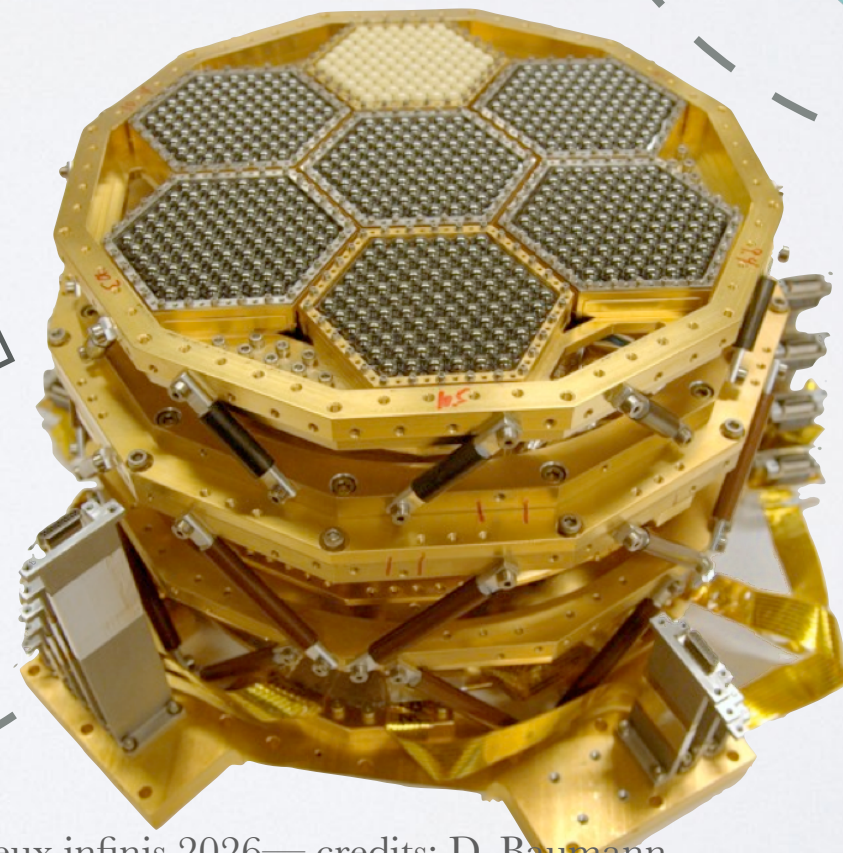
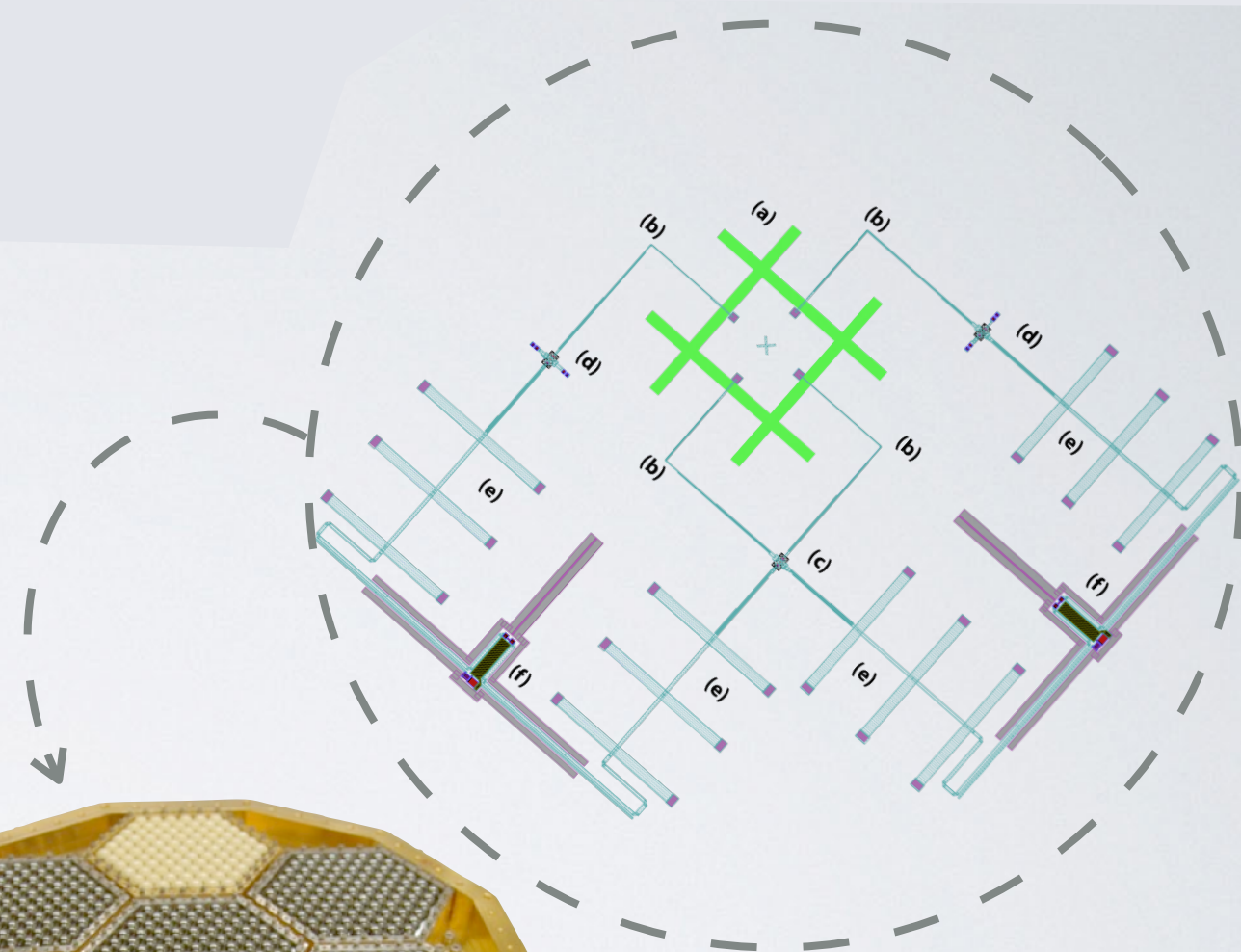
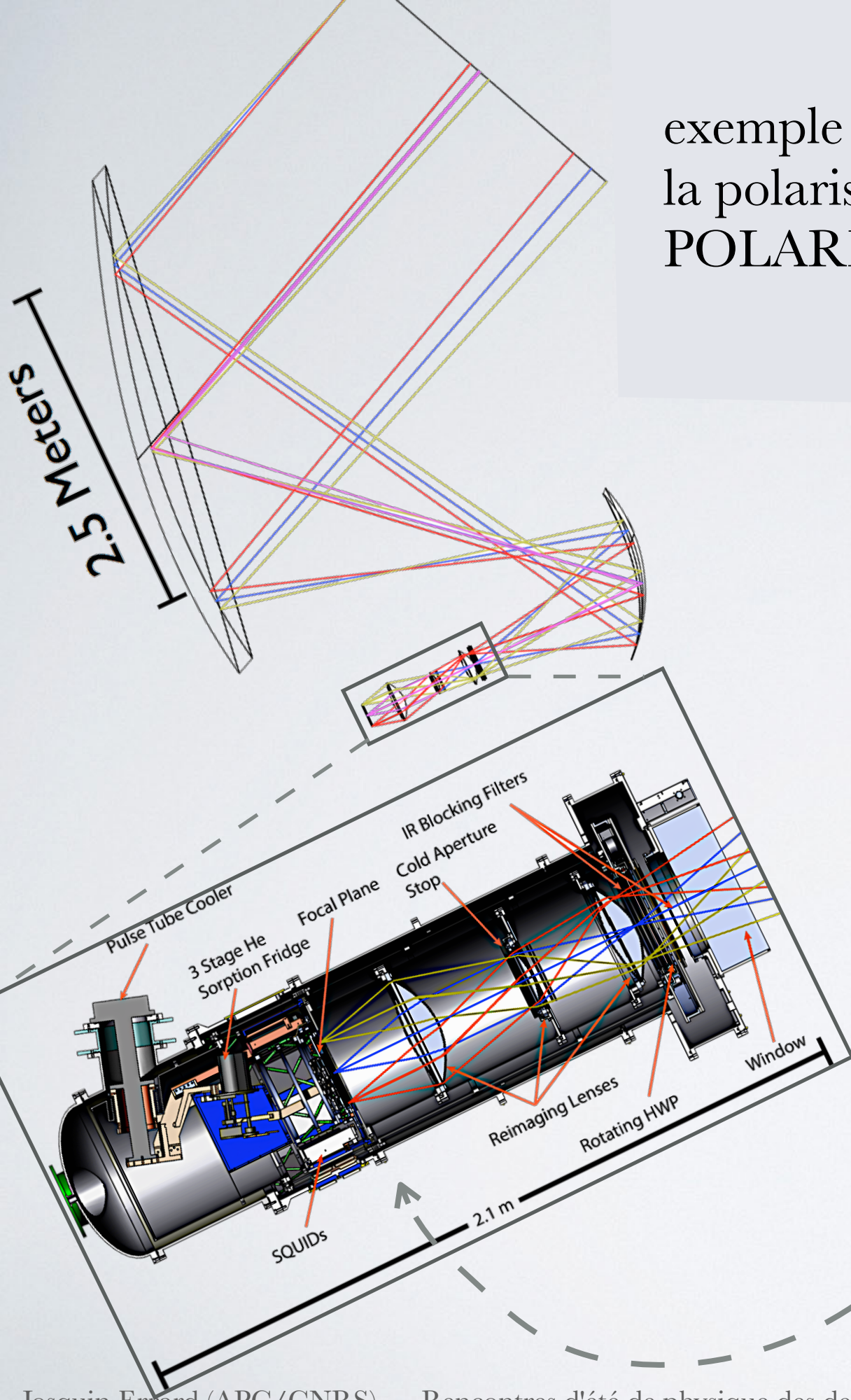


BICEP

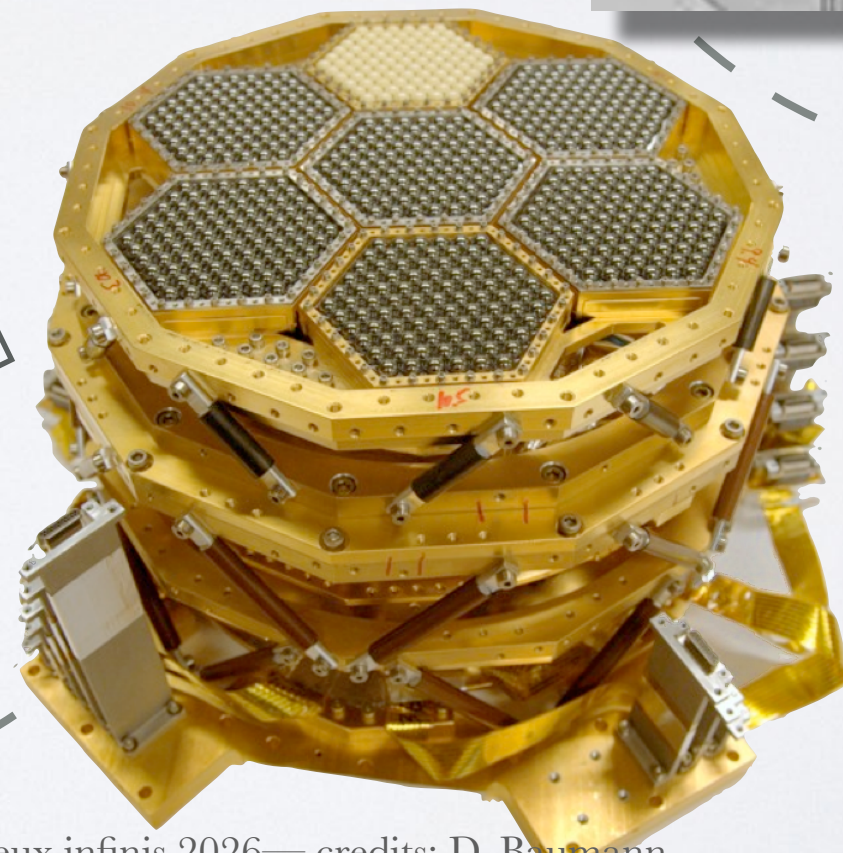
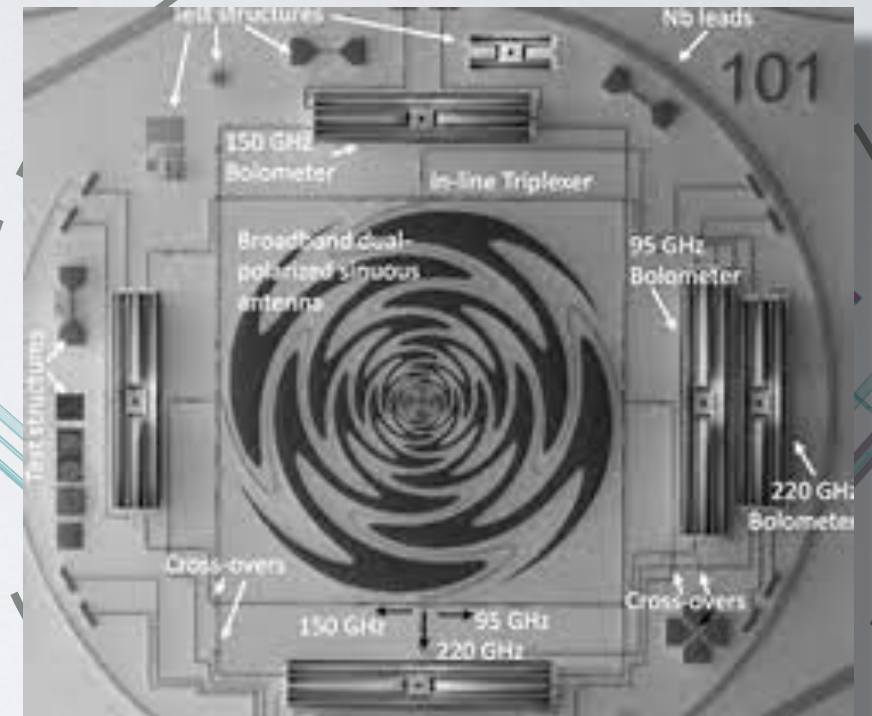
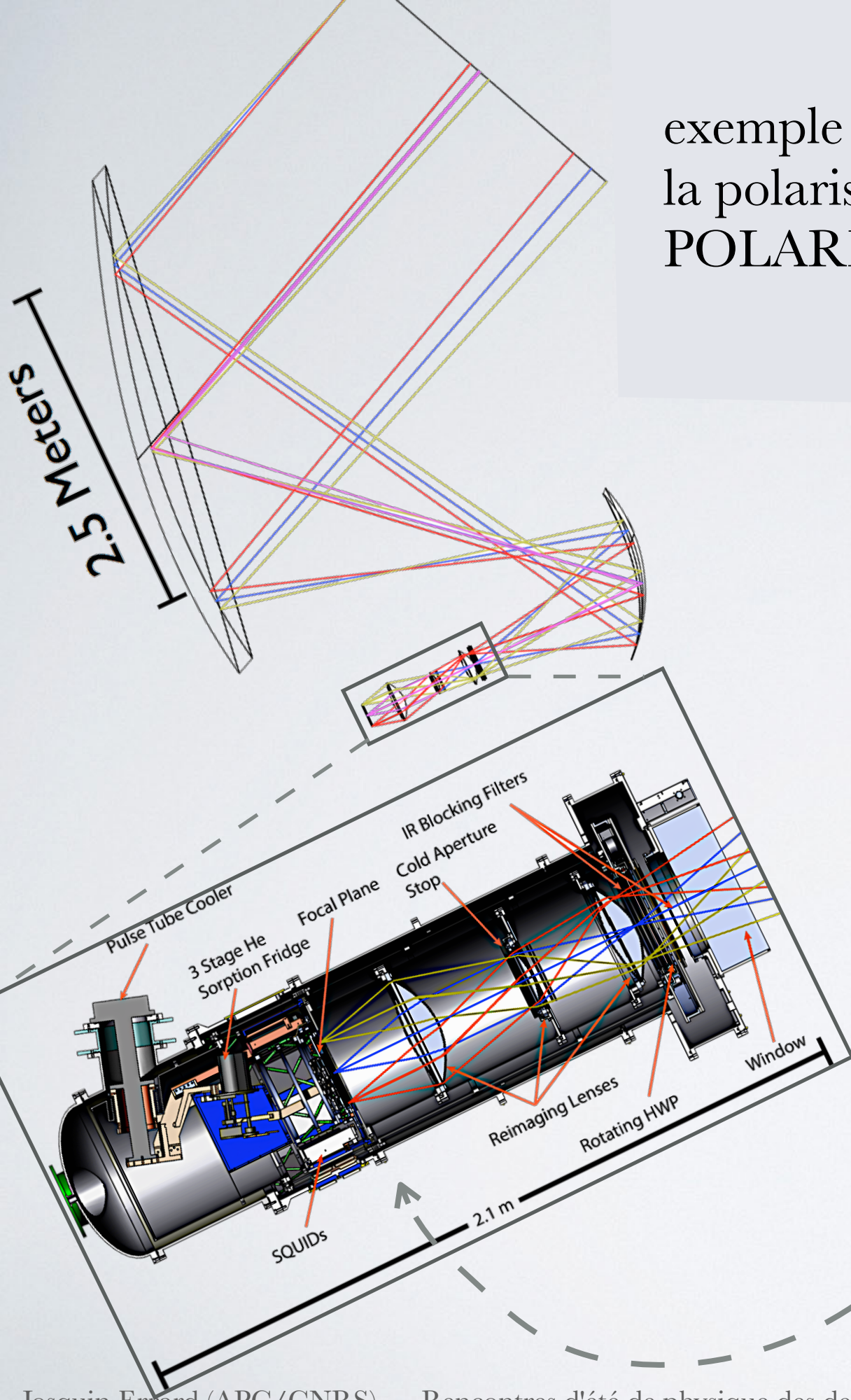


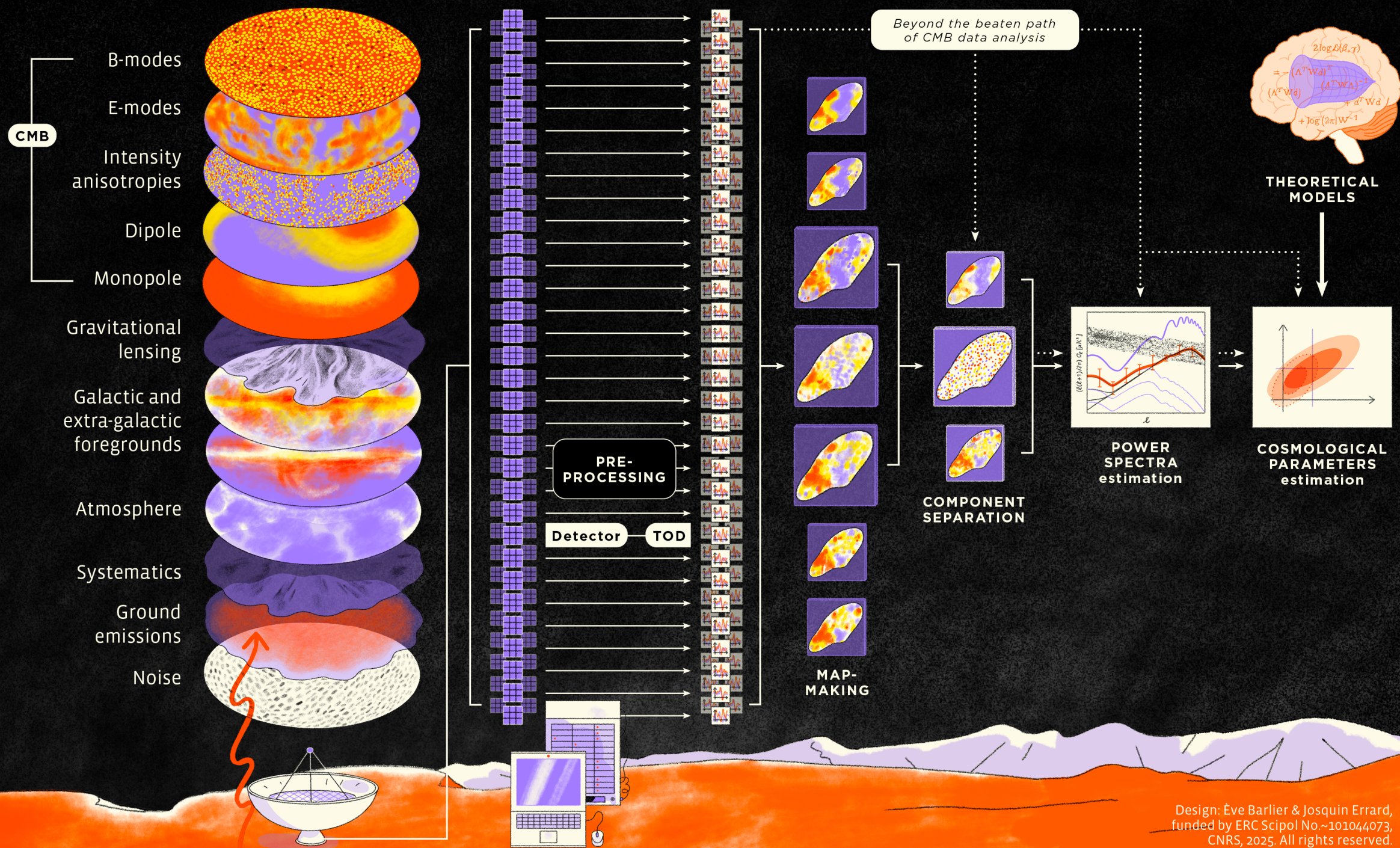
SPTPol

exemple d'observatoire de
la polarisation du CMB :
POLARBEAR

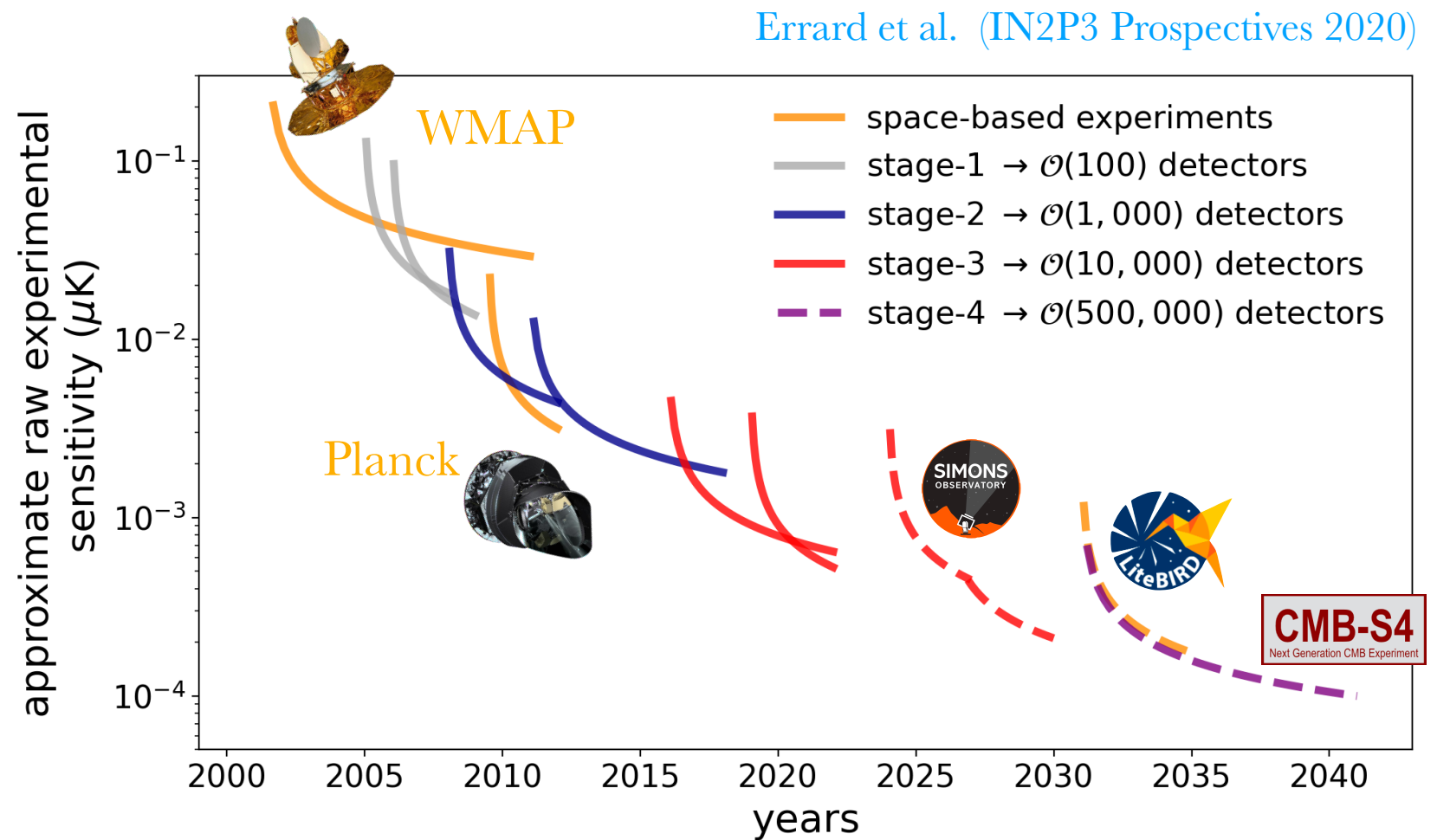


exemple d'observatoire de
la polarisation du CMB :
POLARBEAR

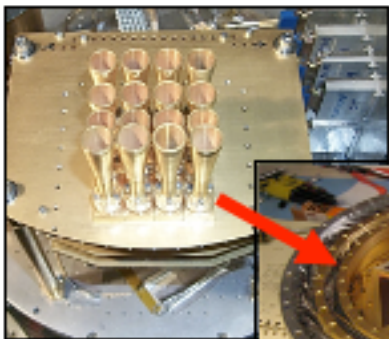




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funded by ERC Scipol No.~101044073,
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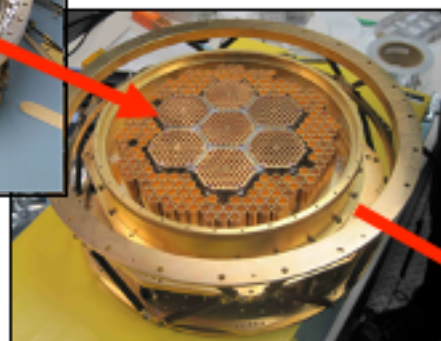
2001: ACBAR
16 detectors



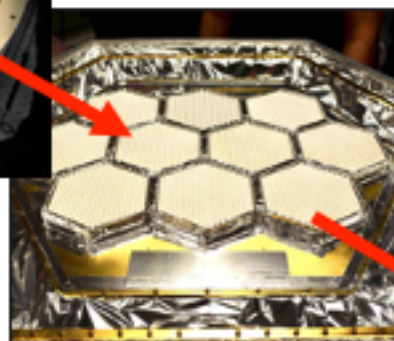
2007: SPT
960 detectors



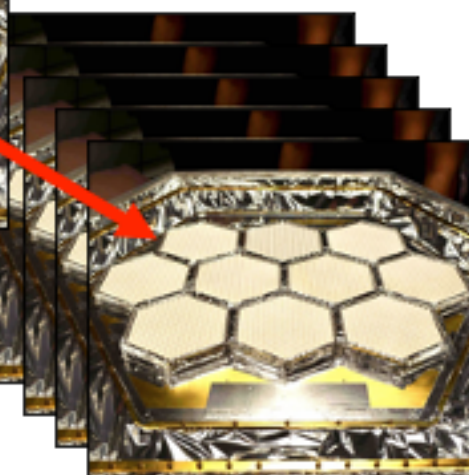
Stage-2
2012: SPTpol
~1600 detectors



Stage-3
2016: SPT-3G
~16,000 detectors



Stage-4
202: CMB-S4
500,000 detectors



Detector sensitivity has been limited by photon “shot” noise for last ~15 years; further improvements are made only by making more detectors!

credits: Nils Halverson

Zoom on an On-going experiment: the Simons Observatory



15+ Countries, 60+ Institutions, 375+ Researchers



F2F Chicago, July 2024



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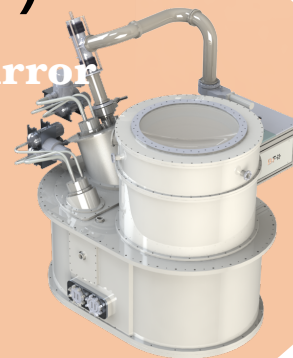
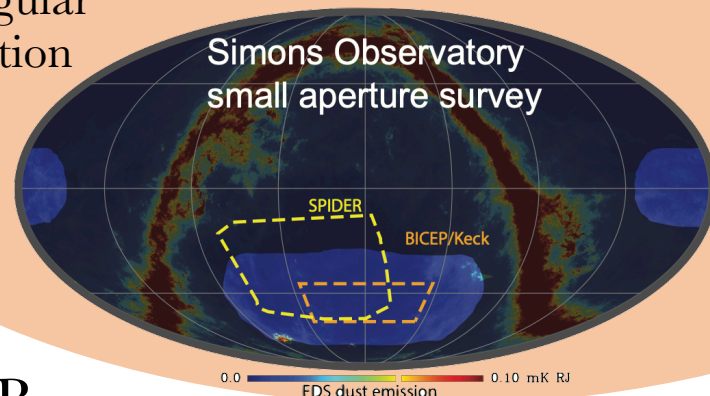


Two surveys are needed to measure large- and small-angular scales

Small aperture telescope (SAT)

Deep maps with low angular resolution

0.5m mirror



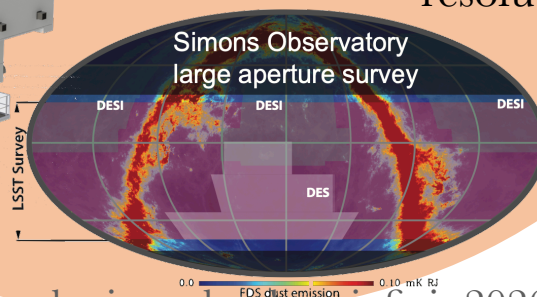
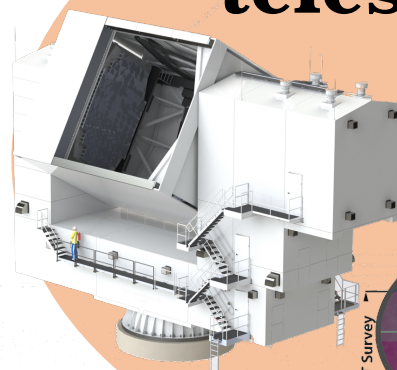
Excellent site for CMB observations:

- PWV ~ 1.2 mm (good but 3x South Pole)
- Low latitude (-23°) gives high fsky

Large aperture telescope (LAT)

6m mirror

Wide maps with high angular resolution



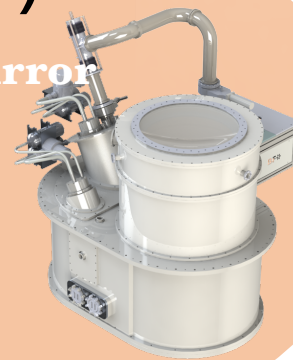
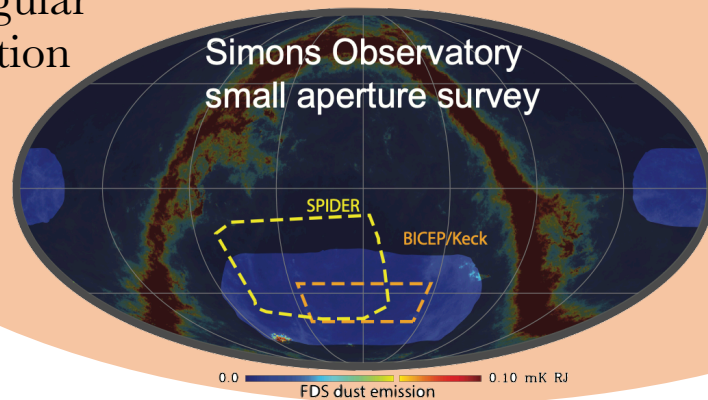
From: Gabriele Coppi, Rolando Dunner, Federico Nati, Matias Rojas



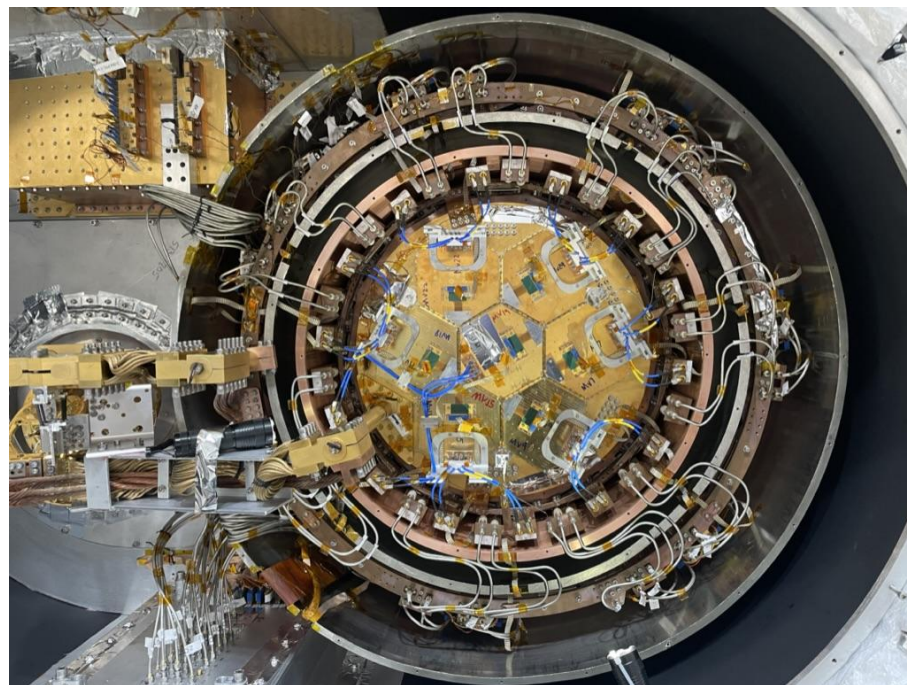
Small aperture telescope (SAT)

Deep maps with low angular resolution

0.5m mirror



3x SATs each with 12,000 detectors
Measuring large-scale correlations



SAT focal plane with 7 detector arrays

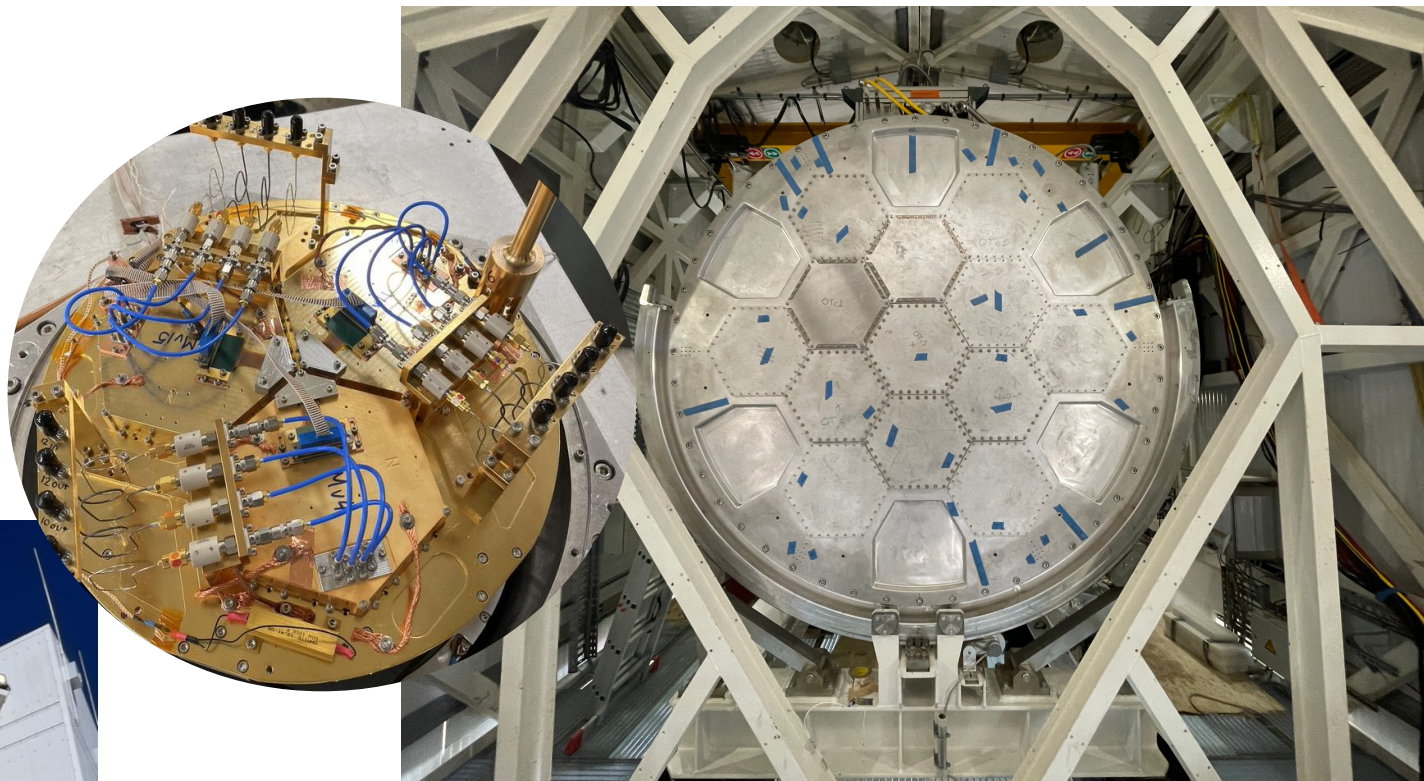


From: Gabriele Coppi, Rolando Dunner,
Federico Nati, Matias Rojas



Over 30,000 detectors
in six tubes
Targeting small scale
correlations

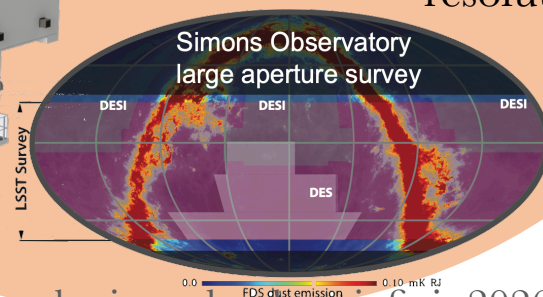
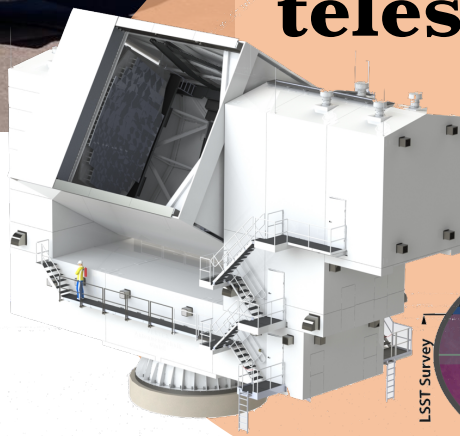
3x detector arrays per tube



**Large aperture
telescope (LAT)**

6m mirror

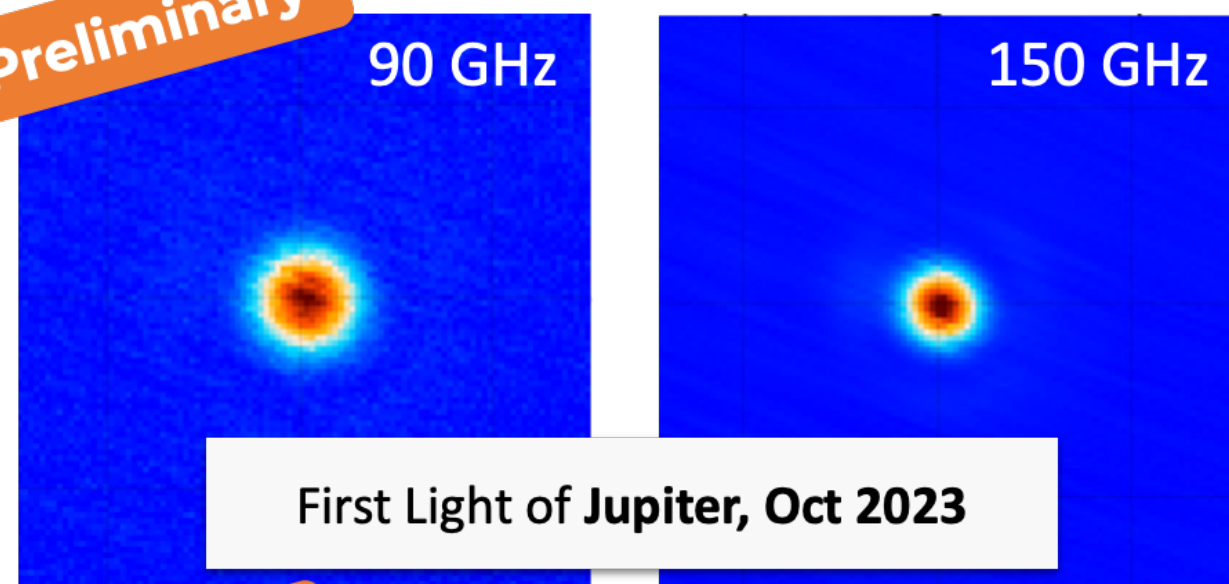
Wide maps with
high angular
resolution



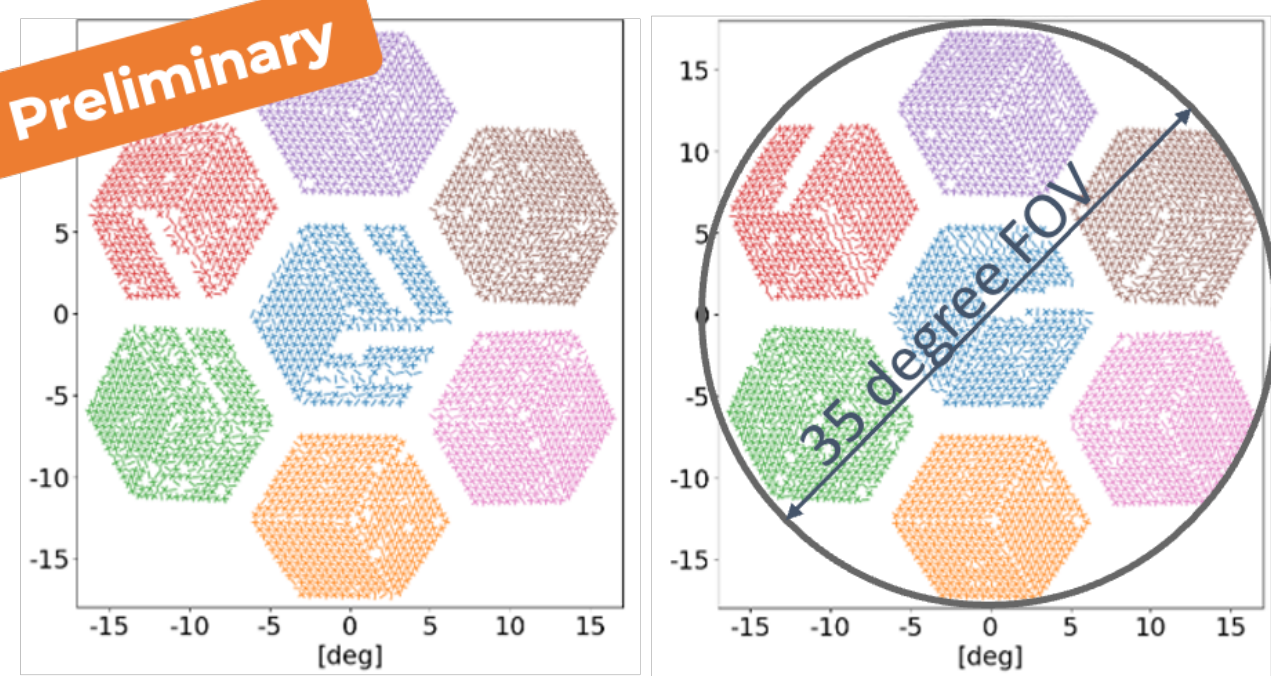
From: Gabriele Coppi, Rolando Dunner,
Federico Nati, Matias Rojas



Preliminary



Preliminary



First Light Maps from SATs

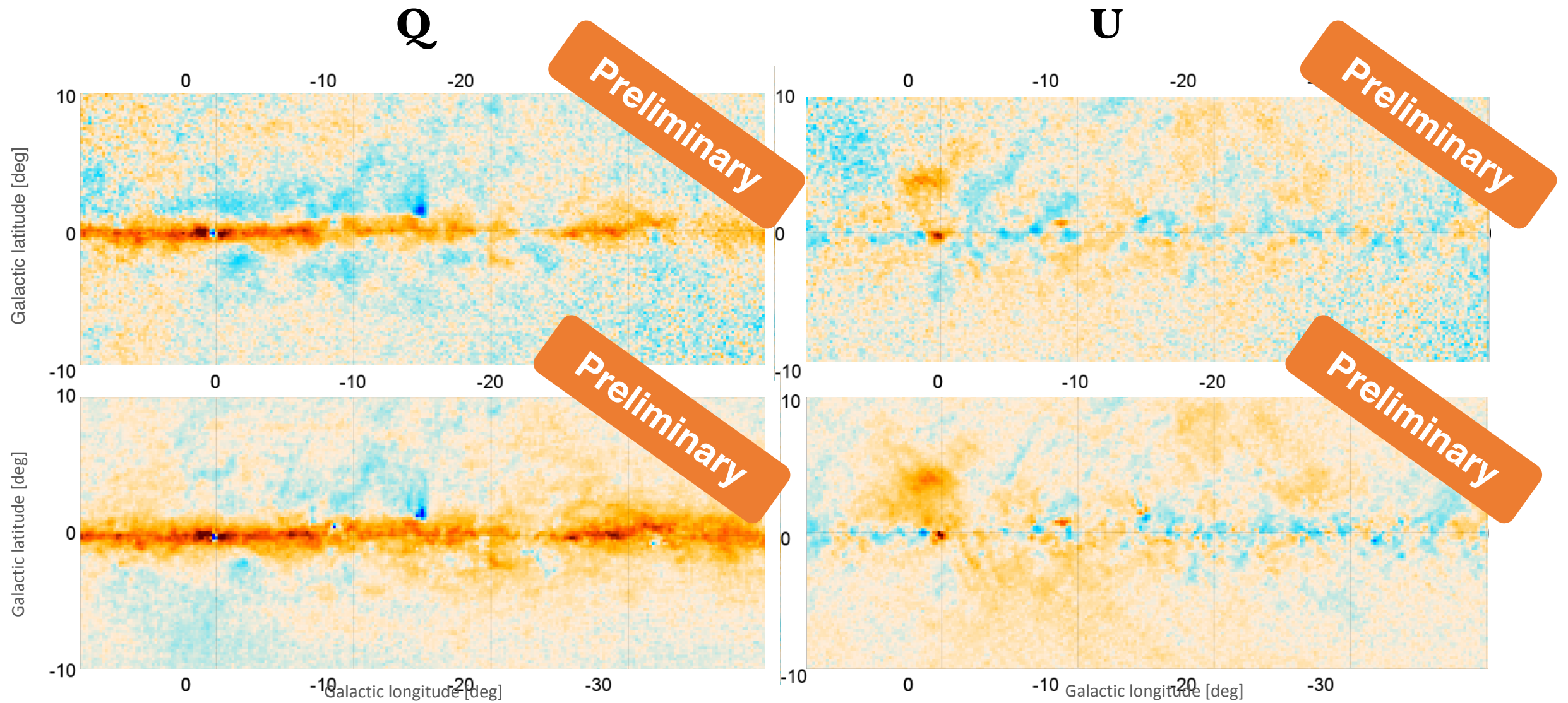




Galaxy maps

SO

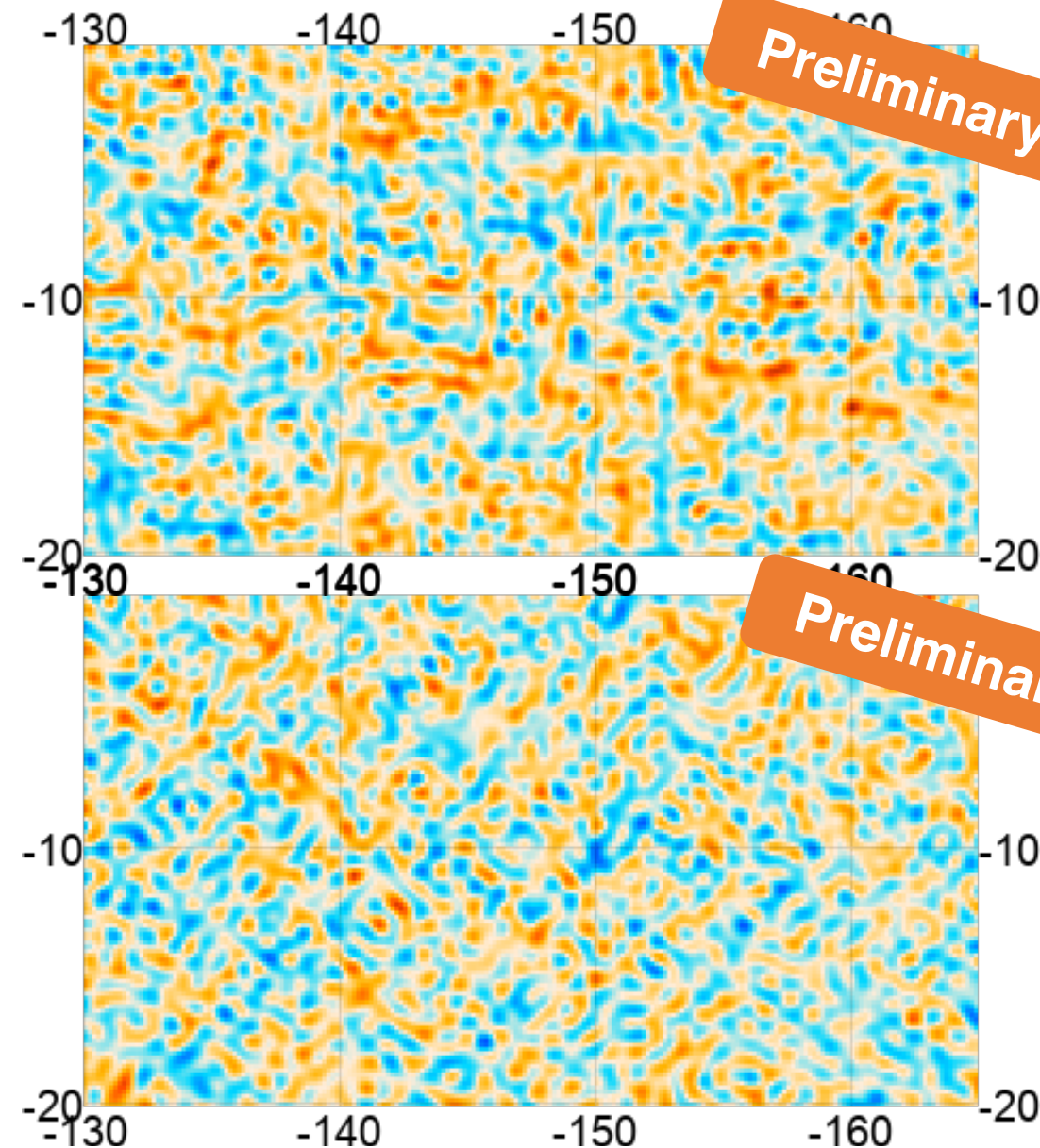
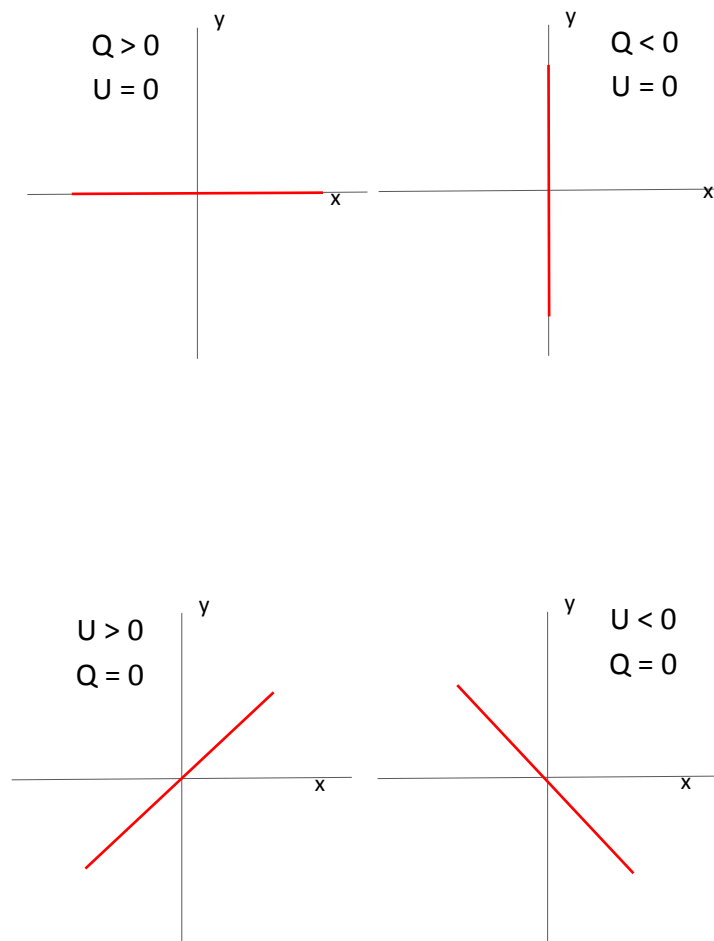
PLANCK



Galaxy center maps in comparison with Planck demonstrate instrument performance and larger scale recovery.



CMB maps



Started mapping the sky with two MF SATs.

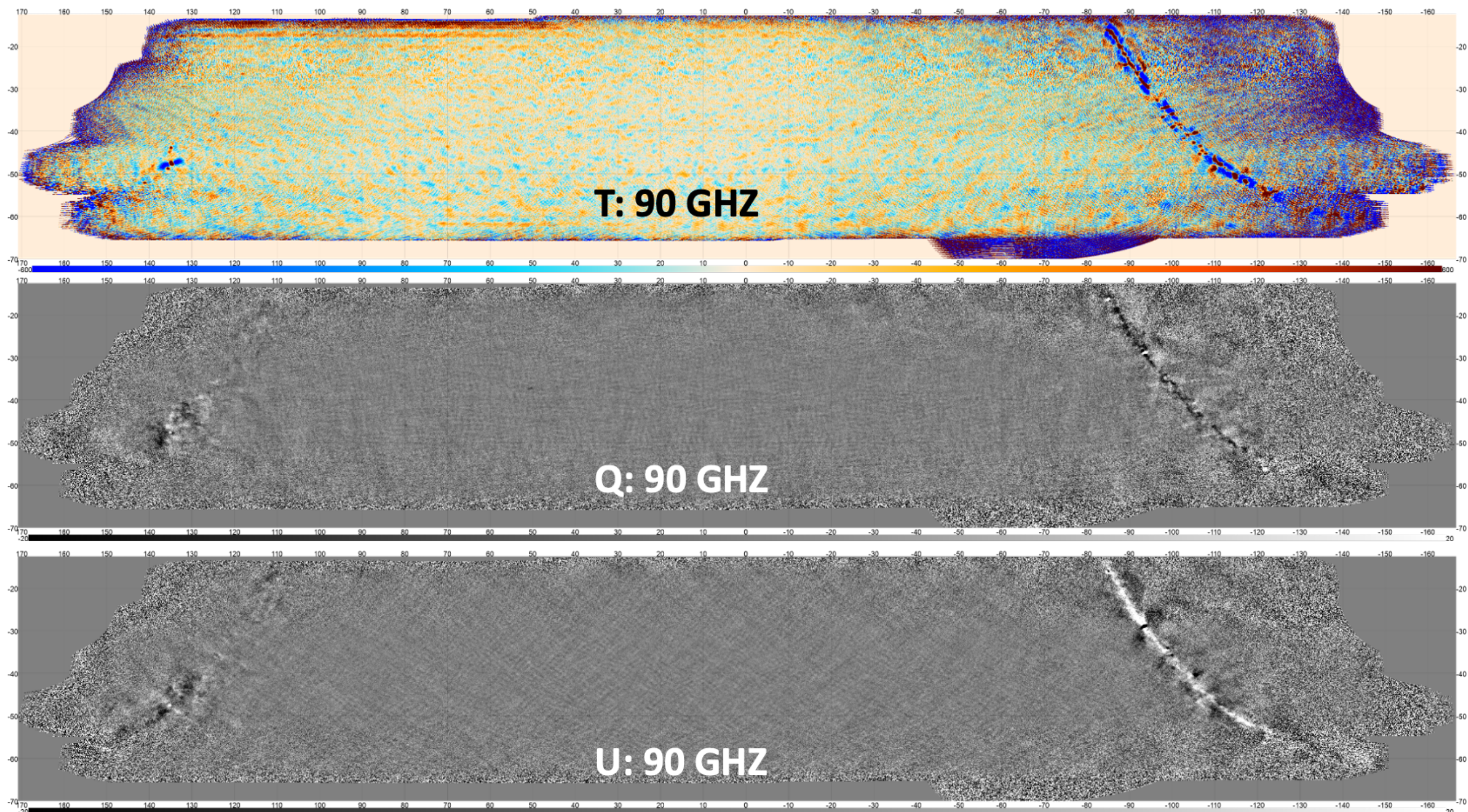
Applied low-pass filter to maps. → **Zoom-in**

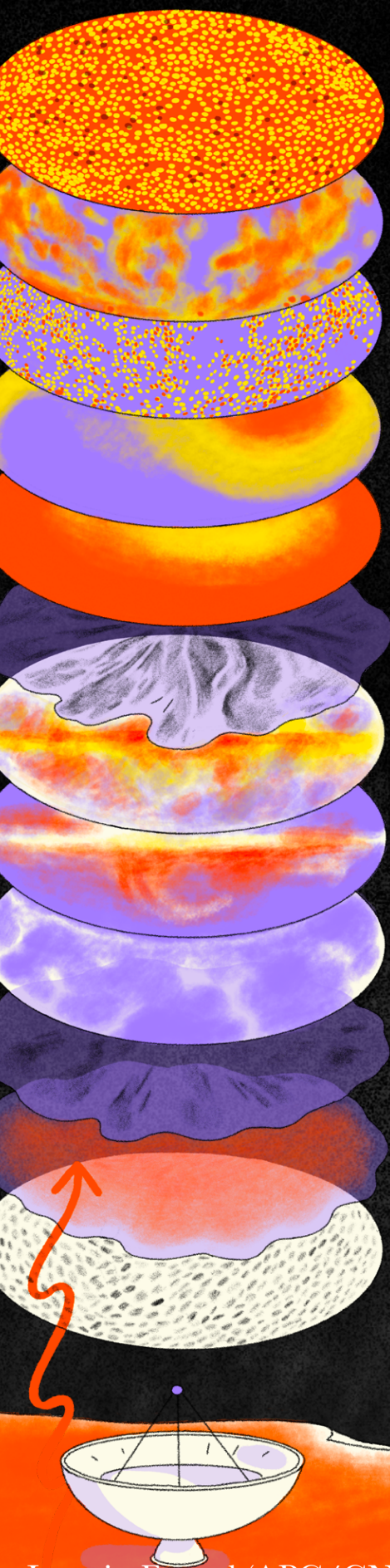
Q/U polarization patterns start being visible in the targeted SAT regions.



CMB maps

Preliminary SAT Maps: 90 GHz from One Telescope





B-modes

E-modes

Intensity
anisotropies

Dipole

Monopole

Gravitational
lensing

Galactic and
extra-galactic
foregrounds

Atmosphere

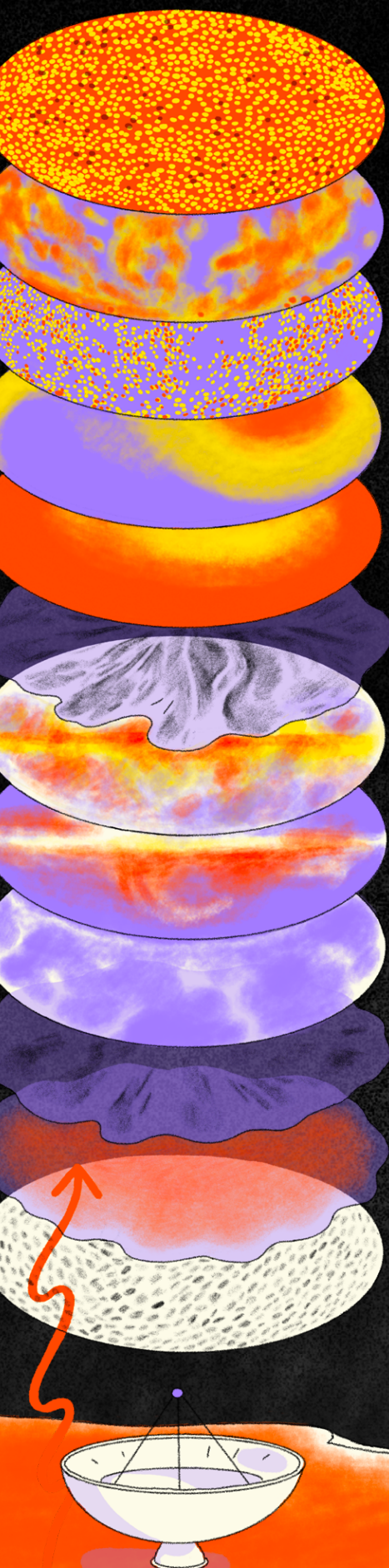
Systematics

Ground
emissions

Noise

CMB

Design: Ève Barlier & Josquin Errard,
funded by ERC Scipol No.~101044073,
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B-modes

E-modes

Intensity
anisotropies

Dipole

Monopole

Gravitational
lensing

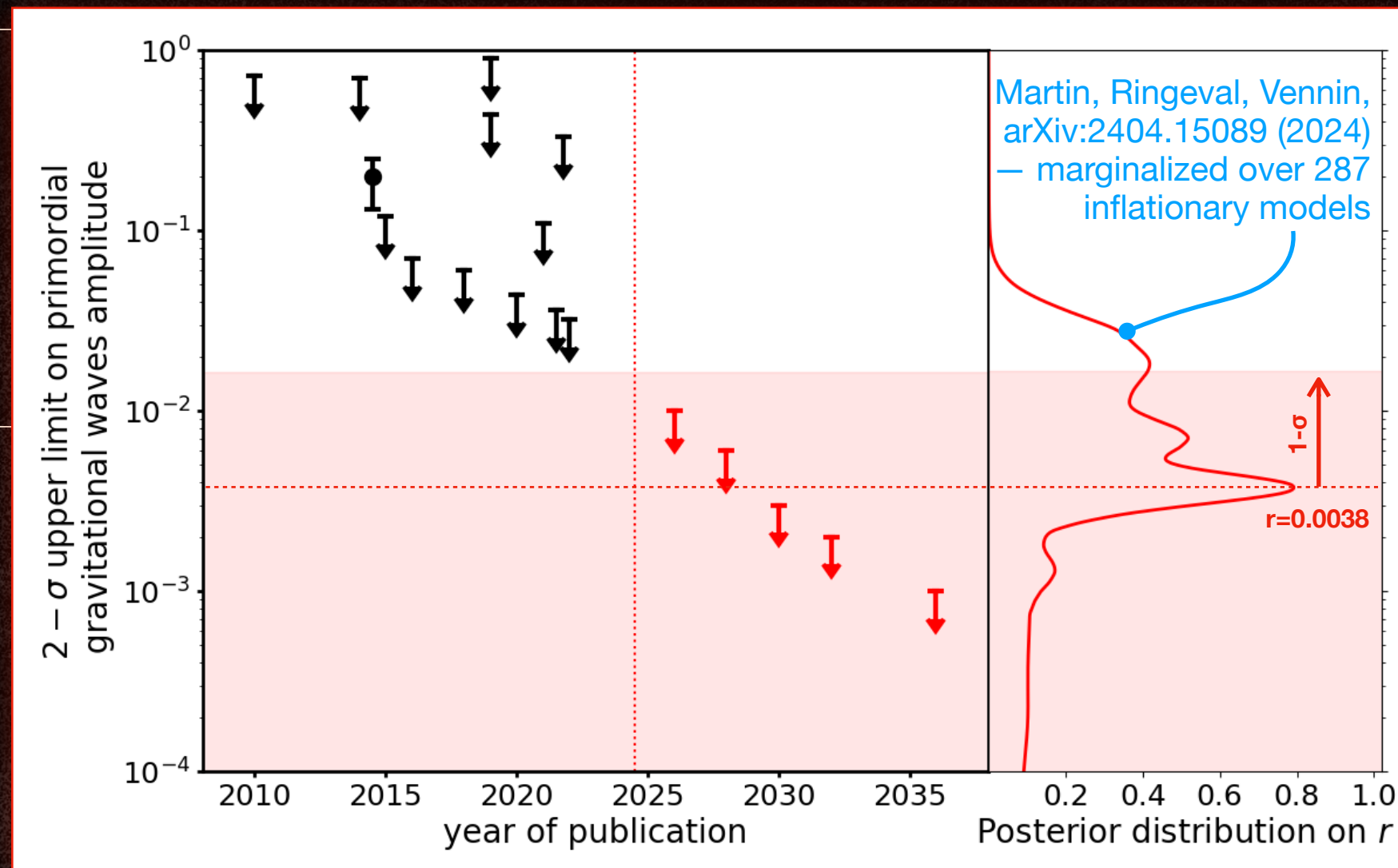
Galactic and
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LiteBIRD is the next-generation CMB satellite selected by JAXA as a Strategic Large Mission to be launched in 2029

4700 multichroic TES detectors

50x Planck sensitivity on large angular scales

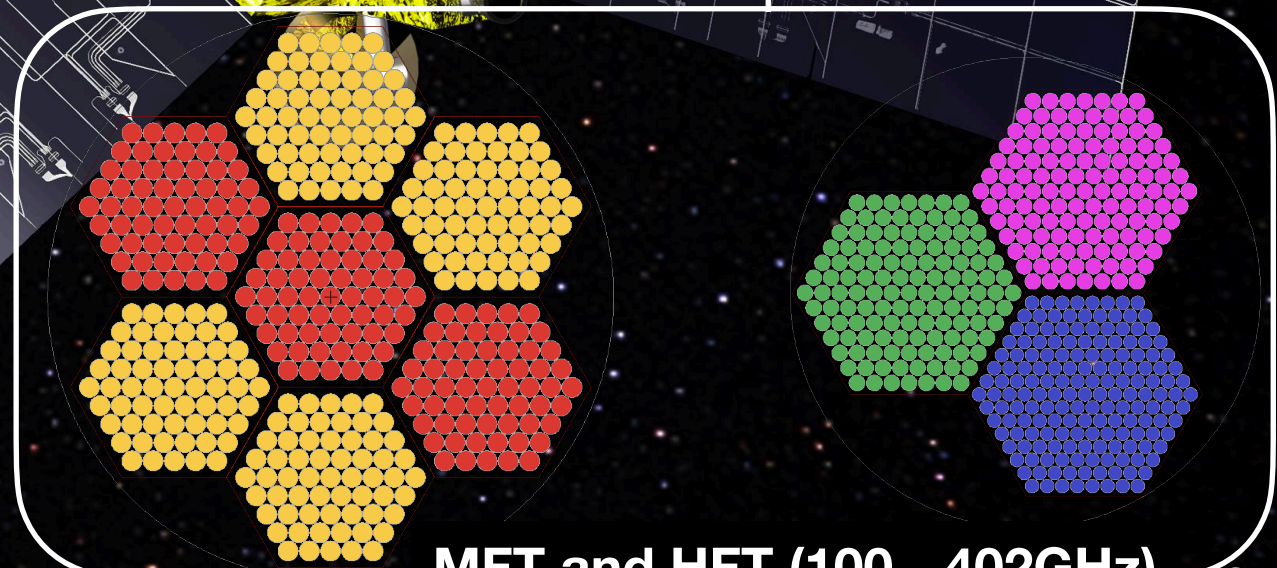
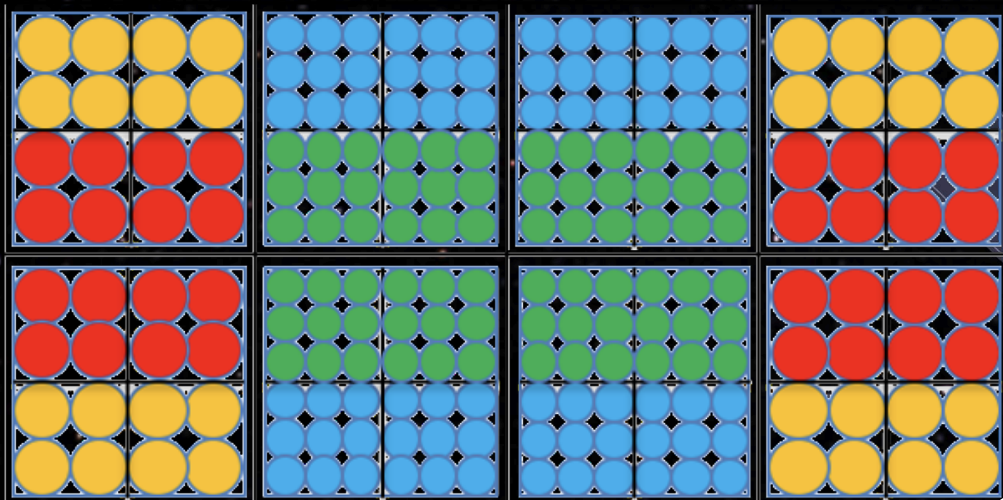
15 frequency bands

$40 \leq \nu \leq 402 \text{ GHz}$

3 telescopes + 3 instruments
rotating half-wave plates
year observation at L2

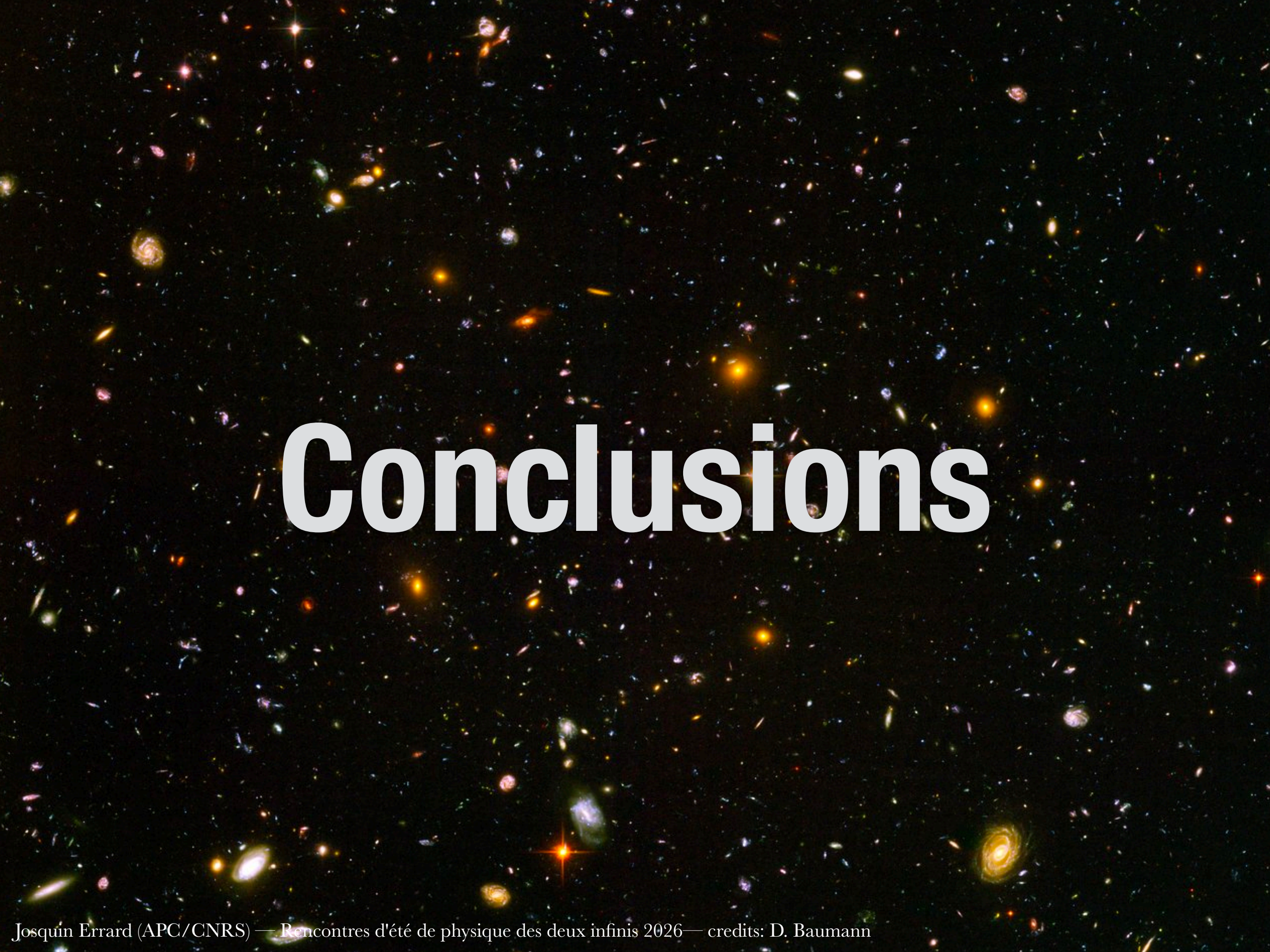
$$\sigma(r) \sim 5.7 \times 10^{-4}$$

LFT (40 - 140GHz)



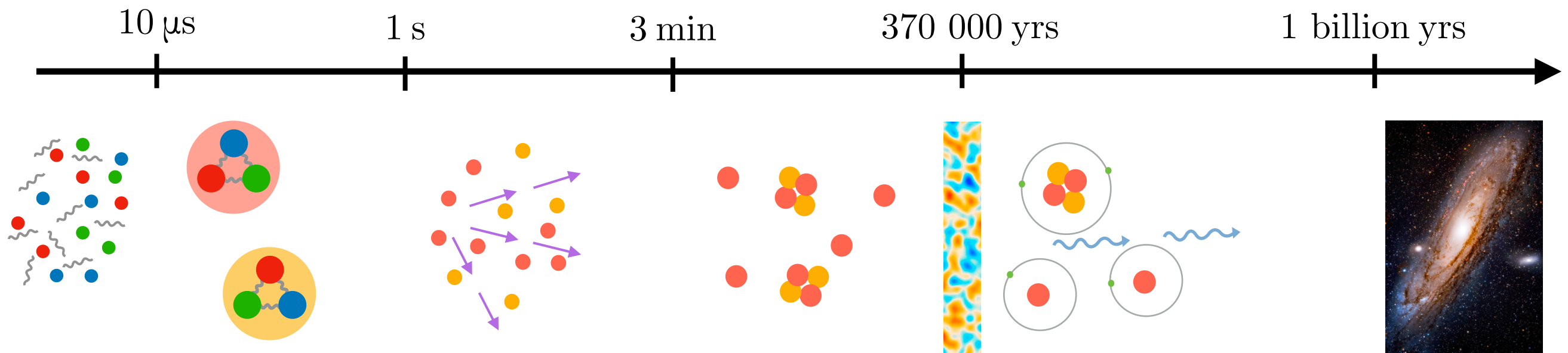
MFT and HFT (100 - 402GHz)



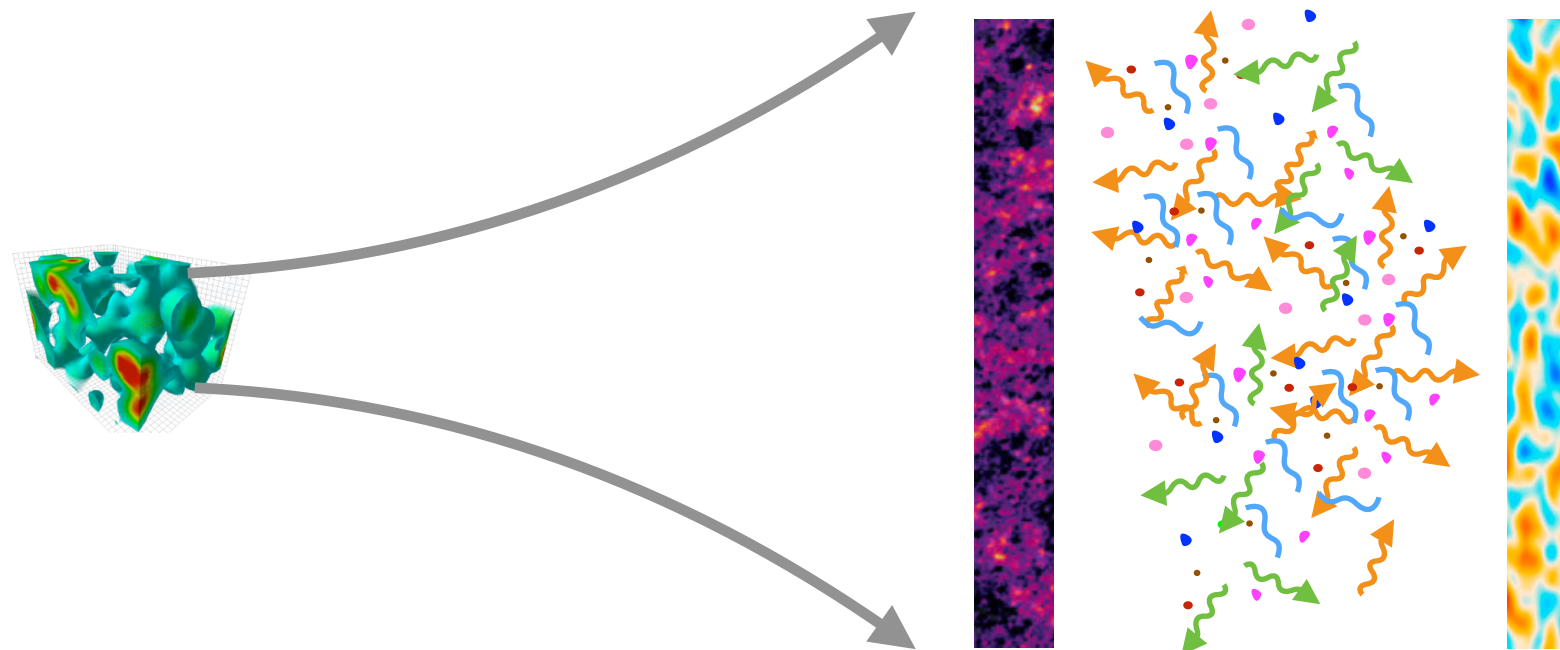


Conclusions

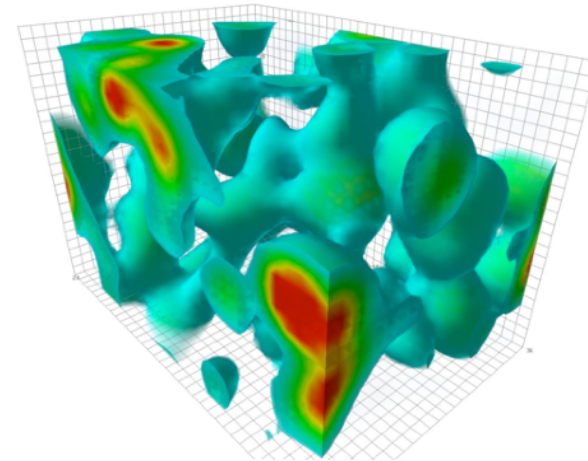
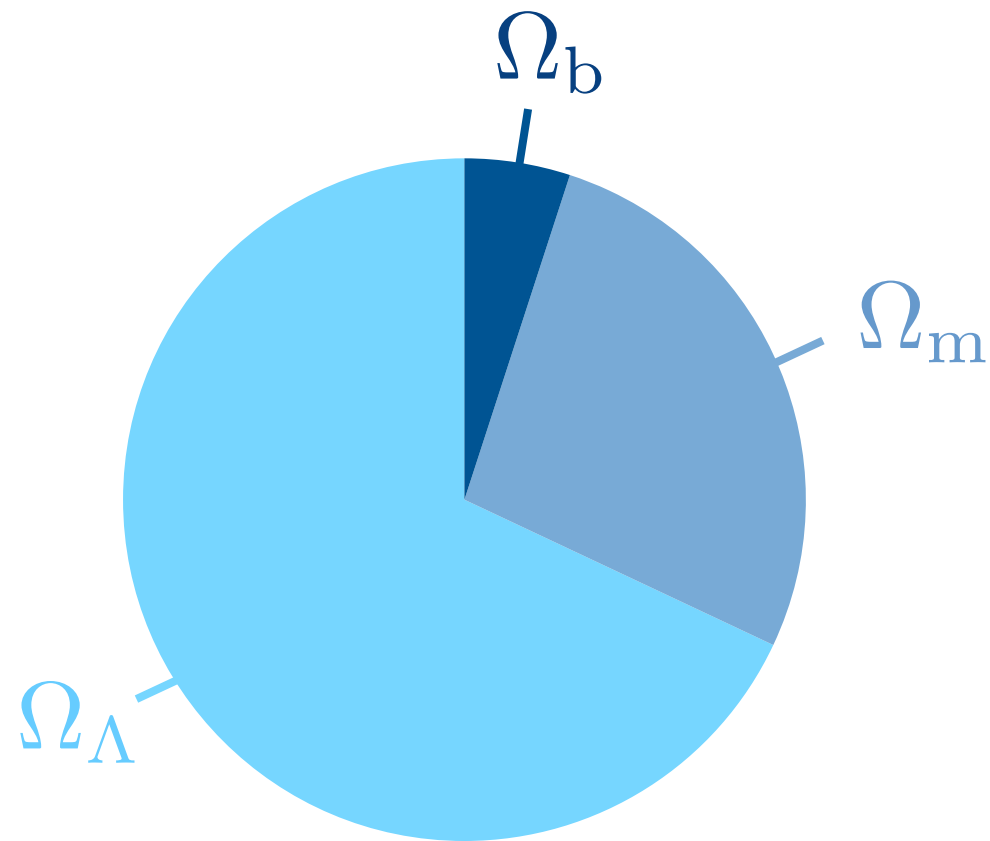
We have a remarkably consistent picture of the history of the Universe from fractions of a second after the Big Bang until today:



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.

