The Universe before the hot Big Bang

Valery Rubakov

Institute for Nuclear Research
of the Russian Academy of Sciences,

Department of Particle Physics and Cosmology
Physics Faculty
Moscow State University

Basic properties of the present Universe:

- Visible Universe is large

  Size of the visible part of the Universe is
  15 Gigaparsec ≈ 45 billion light years

  1 Mpc $= 3 \cdot 10^6$ light yrs $= 3 \cdot 10^{24}$ cm

- The Universe is old

  Its lifetime is at least 13.8 billion years

- Visible Universe is homogeneous on large scales
  ($\gtrsim 200$ Mpc): different parts of the Universe look the same.

Deep surveys of galaxies and quasars $\Longrightarrow$
map of a good part of visible Universe

- The Universe expands

  Space stretches out. Distances between galaxies increase in time.

  Wavelength of a photon also increases.

  If emitted at time t with wavelength λ,
  it comes to us with longer wavelength

$$\lambda_0 = (1+z)\lambda$$

  z = z(t): redshift, directly measurable.

- 3d space is Euclidean (observational fact!)

  Sum of angles of a triangle = 180°, even for triangles as large as the size of the visible Universe.

  Qualification: curvature radius $> 4.4\times$ (radius of visible part)

- All above is encoded in space-time metric (Friedmann–Lemâitre–Robertson–Walker)

$$ds^2 = dt^2 - a^2(t)\mathbf{dx}^2$$

$\mathbf{x}$: comoving coordinates, label distant galaxies.

$a(t)dx$: physical distances.

$a(t)$: scale factor, grows in time.
Set its present value to 1, then $a < 1$ in the past

$$H(t) = \frac{\dot{a}}{a} :$$ Hubble parameter, expansion rate

- Present value

$$H_0 = (67.8 \pm 0.9)\ \frac{\text{km/s}}{\text{Mpc}} = (14 \cdot 10^9\ \text{yrs})^{-1}$$

- The Universe is warm. It is filled with Cosmis Microwave Background: photons that were thermally produced when the Universe was young and hot.

CMB temperature today

$$T_0 = 2.7255 \pm 0.0006 \text{ K}$$

Fig.

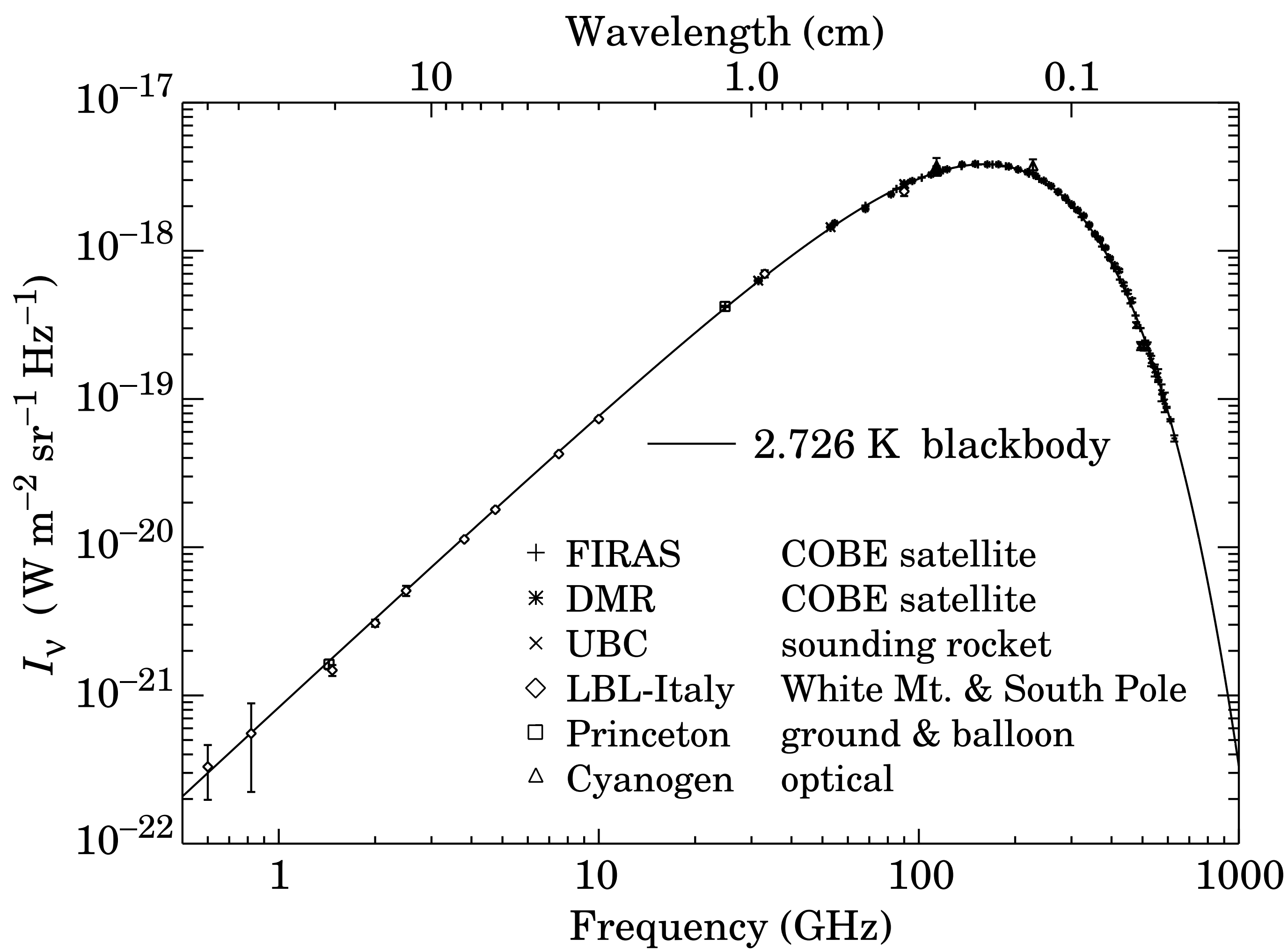
It was denser and warmer at early times.

It also expanded a lot faster at early times: according to General Relativity, expansion rate is determined by Friedmann equation

$$H^2 = \frac{8\pi}{3} G\rho$$

where ρ is energy density, G is Newton's gravity constant.

CMB spectrum



$T = 2.726$ K

Cornerstones of thermal history

- Recombination, transition from plasma to gas.

  $z = 1090$, $T = 3000$ K, $t = 380\,000$ years

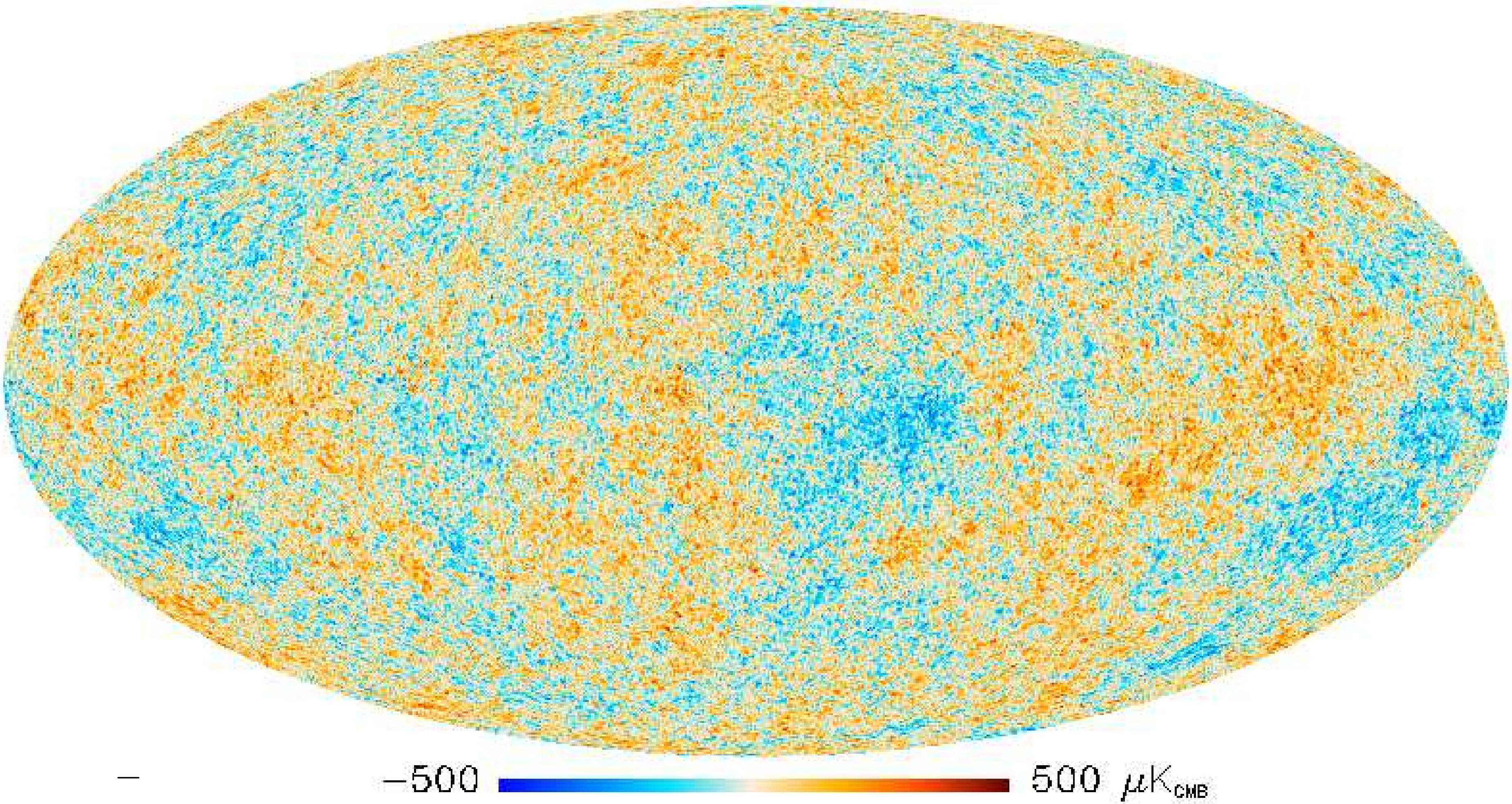
  Last scattering of CMB photons

  Photographic picture (literally!) of the Universe at that epoch Fig.

  The Universe was much more homogeneous: the inhomogeneities were at the level

$$\frac{\delta\rho}{\rho} \sim 10^{-4} - 10^{-5}$$

$$T = 2.726^{\circ}K, \quad \frac{\delta T}{T} \sim 10^{-4} - 10^{-5}$$



Planck

- Big Bang Nucleosynthesis, epoch of thermonuclear reactions

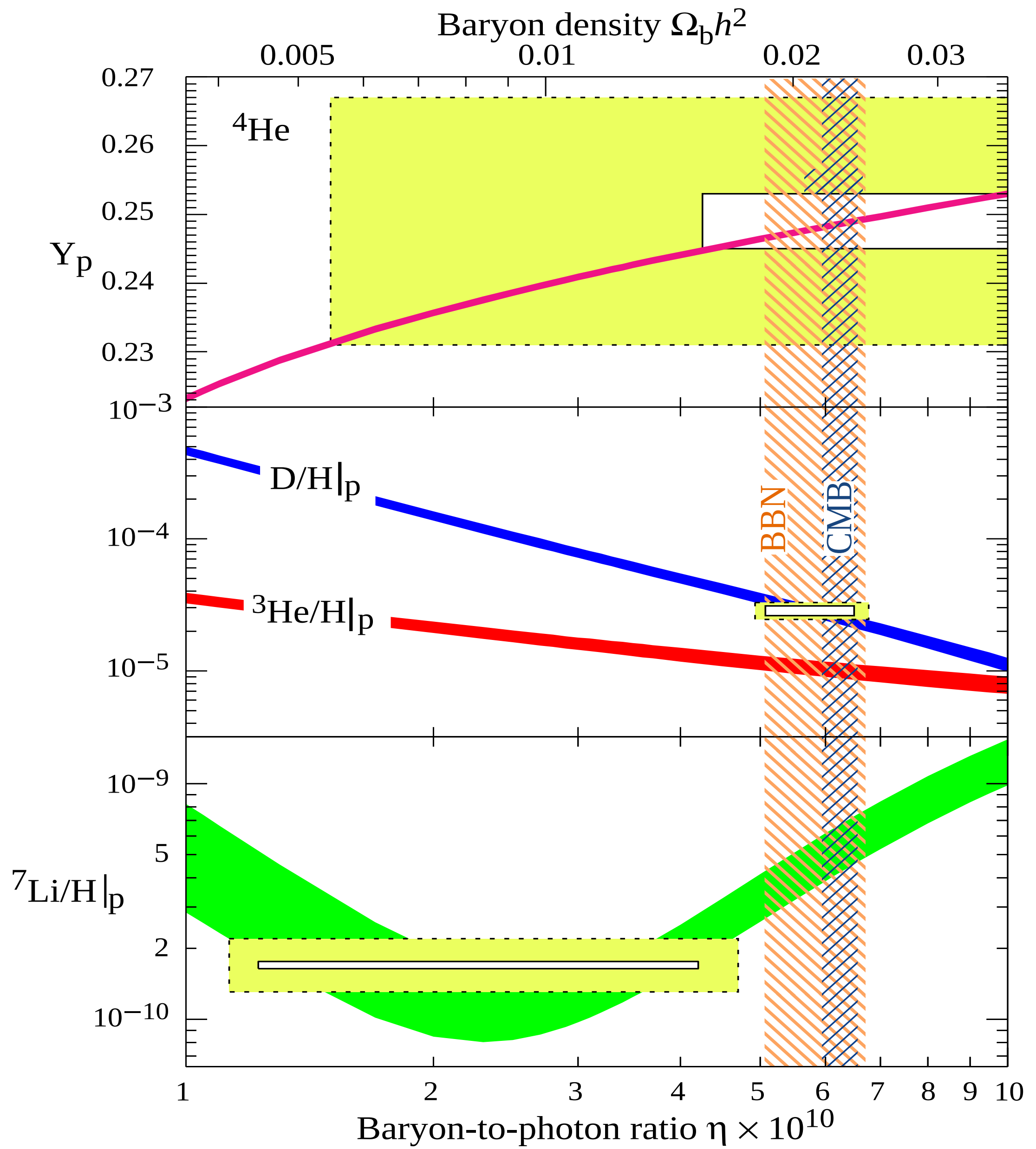
$$\begin{aligned} p+n &\to {}^2H \\ {}^2H+p &\to {}^3He \\ {}^3He+n &\to {}^4He \\ \text{up to} & \quad {}^7Li \end{aligned}$$

Abundances of light elements: measurements vs theory

$$T = 10^{10} \to 10^9 \text{ K}, \quad t = 1 \to 500 \text{ s}$$

Fig.

Agreement between independent determinations of baryon content: BBN vs CMB anisotropy

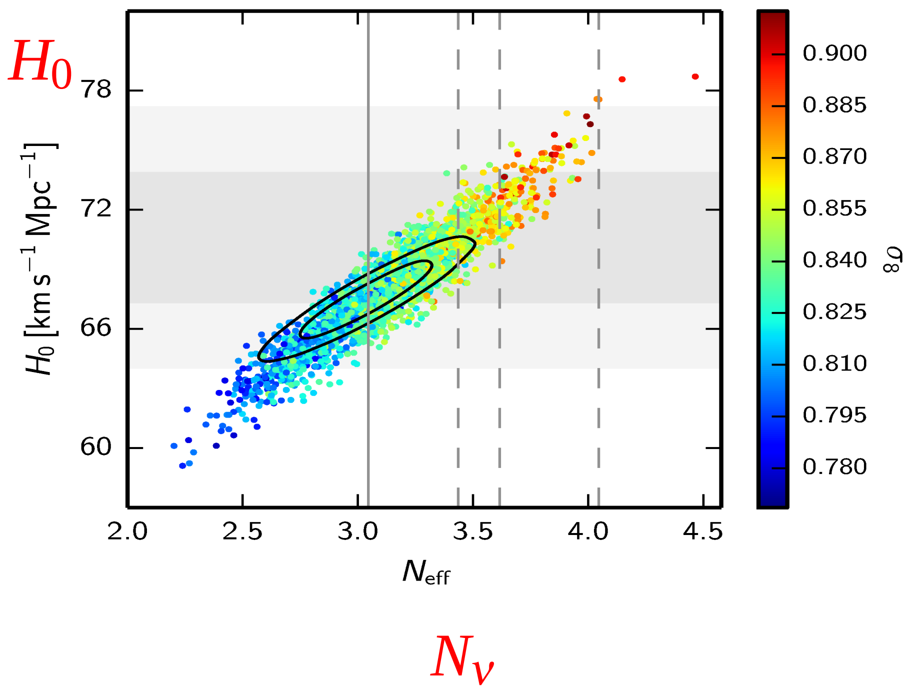


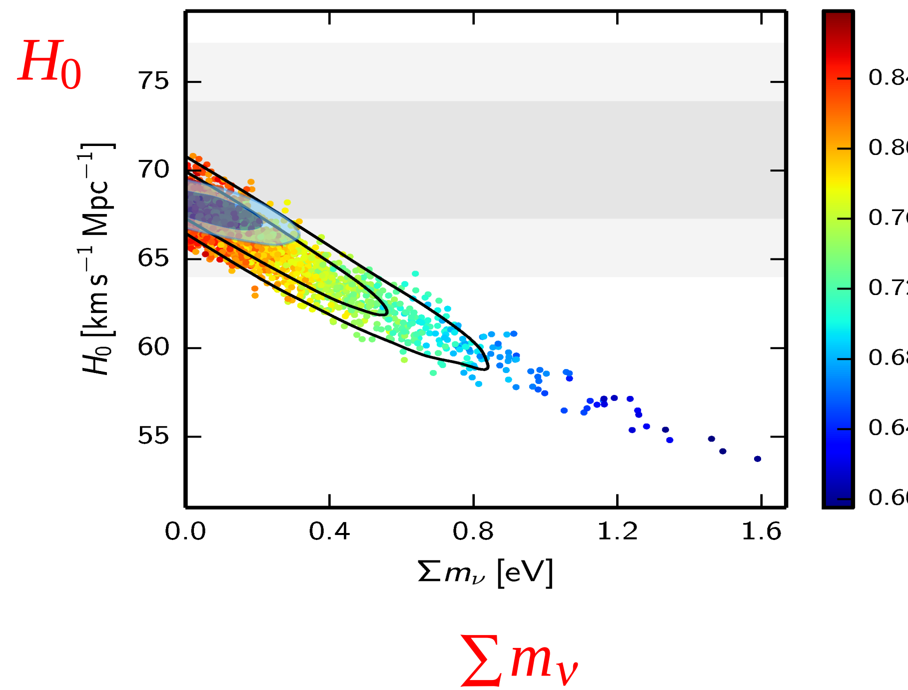
$\eta_{10} = \eta \cdot 10^{-10} =$ baryon-to-photon ratio. Consistent with CMB determination of η

Neutrino decoupling epoch

Temperature $2-3$ MeV, $t \sim 0.1$ s

Reactions like $\nu\bar{\nu} \longleftrightarrow e^+e^-$ switch off.
$\Longrightarrow$ There are 110 cm^{-3} neutrinos of every type today. They are "seen" in properties of CMB, structures.
$N_\nu \approx 3$ in agreement with particle physics. $\sum m_\nu \lesssim 0.3$ eV

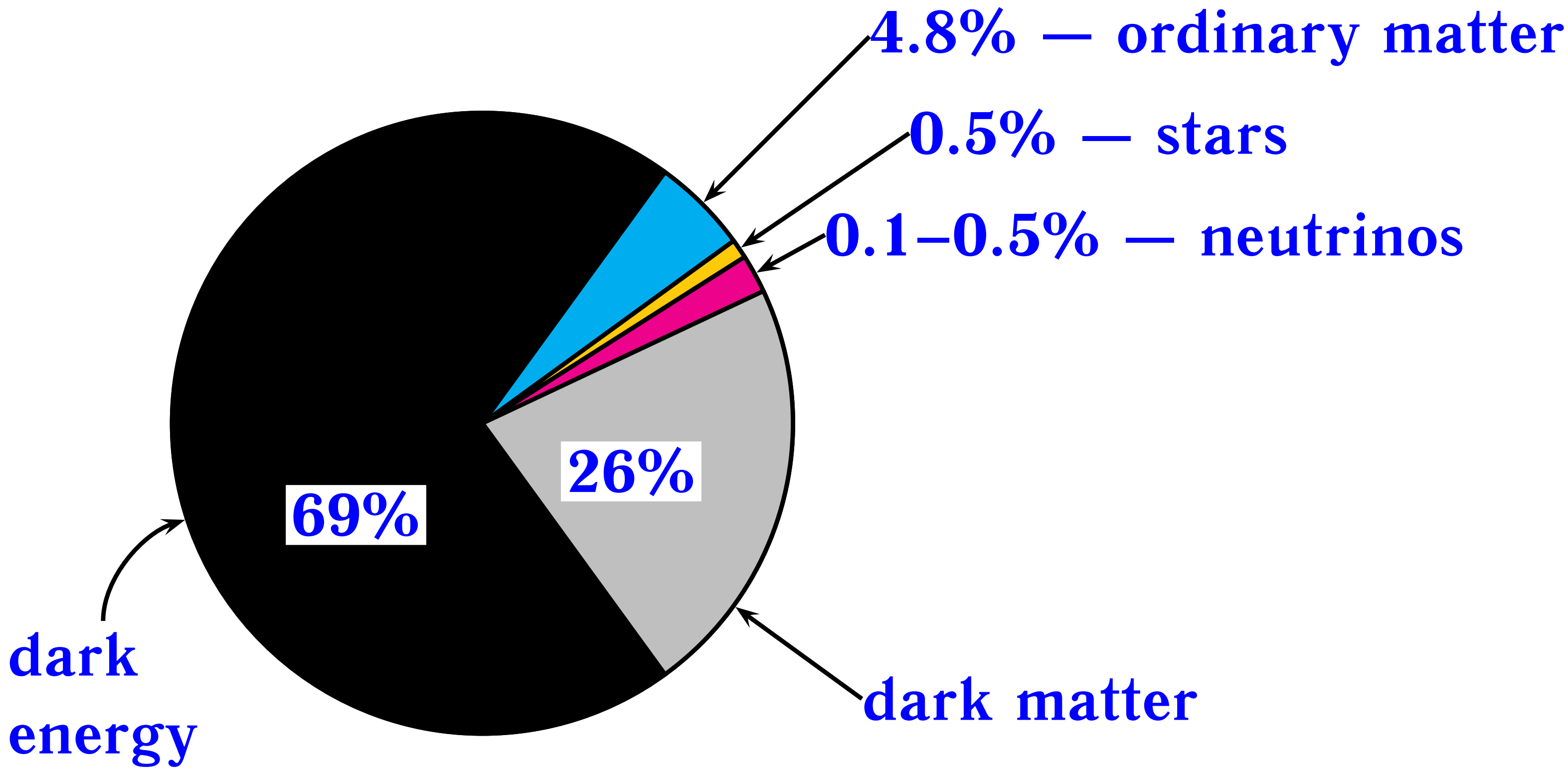


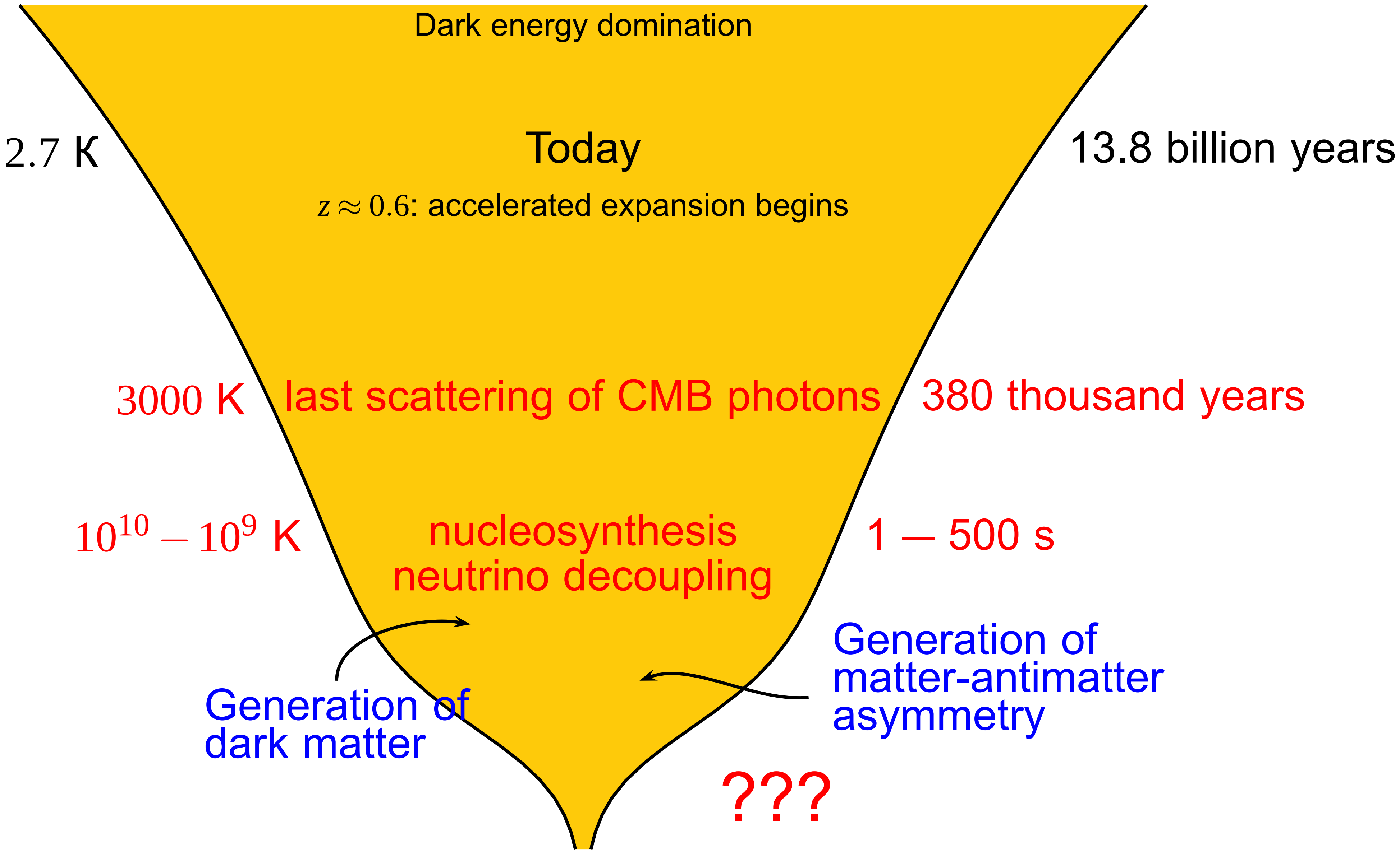


- We understand the Universe at age ~ 0.1 s, at temperature $\sim 2-3$ MeV.
  In particular, gravity was described by General Relativity at that time.

Yet unknown epochs:

- Generation of dark matter
- Generation of matter-antimatter asymmetry




Dark energy domination
2.7 K
Today
13.8 billion years
$z \approx 0.6$: accelerated expansion begins
3000 K
last scattering of CMB photons
380 thousand years
$10^{10} - 10^{9}$ K
nucleosynthesis
neutrino decoupling
1 — 500 s
Generation of
matter-antimatter
asymmetry
Generation of
dark matter
???

With Big Bang nucleosynthesis theory and observations
we are confident of the theory of the early Universe
at temperatures up to $T \simeq 3$ MeV, age $t \simeq 0.11$ second

With the Larege Hadron Collider, we hope to be able to go
up to temperatures $T \sim 100$ GeV, age $t \sim 10^{-10}$ second

Are we going to have a handle on even earlier epoch?

Key: cosmological perturbations

Our Universe is not exactly homogeneous.

Inhomogeneities: $\odot$ density perturbations and associated gravitational potentials (3d scalar), observed;

$\odot$ gravitational waves (3d tensor), not observed

Today: inhomogeneities strong and non-linear

In the past: amplitudes small,

$$\frac{\delta\rho}{\rho} = 10^{-4} - 10^{-5}$$

Linear analysis appropriate. Go to Fourier space.

Wealth of data

- Cosmic microwave background: photographic picture of the Universe at age 380 000 yrs, $T = 3000$ K
  - Temperature anisotropy
  - Polarization
- Deep surveys of galaxies and quasars
- Gravitational lensing, etc.

We have already learned a number of fundamental things

Extrapolation back in time with known laws of physics and known elementary particles and fields $\Longrightarrow$ hot Universe, starts from Big Bang singularity (infinite temperature, infinite expansion rate)

We now know that this is not the whole story.

Key point: causality

Friedmann–Lemaître–Robertson–Walker metric:

$$ds^2 = dt^2 - a^2(t) d\vec{x}^{\,2}$$

Expanding Universe:

$a(t) \propto t^{1/2}$ at "radiation domination epoch", before $T \simeq 1$ eV, $t \simeq 50$ thousand years

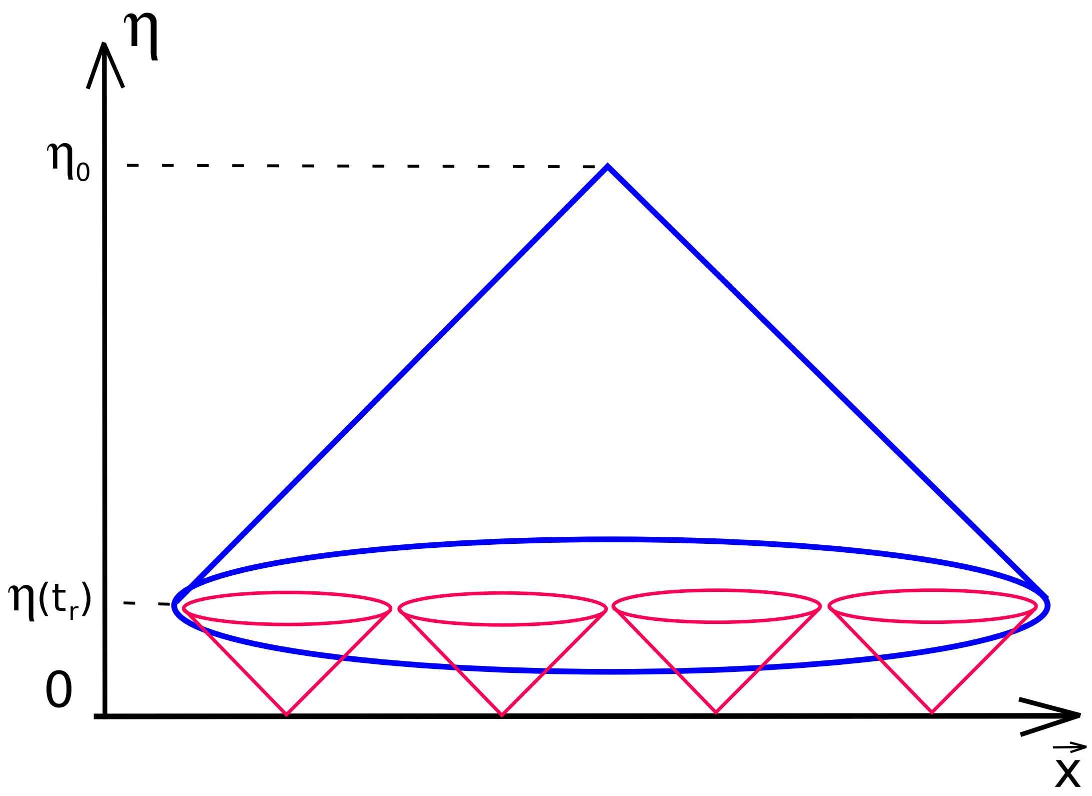
$a(t) \propto t^{2/3}$ later, until recently.

Cosmological horizon (assuming that nothing preceeded hot epoch): length that light travels from Big Bang moment,

$$l_H(t) = (2-3)ct$$

Causal structure of space-time in hot Big Bang theory (i.e., assuming that the Universe started right from the hot epoch)

$$\eta = \int \frac{dt}{a(t)}\,, \quad \text{conformal time}$$



Angular size of horizon at recombination $\approx 2^\circ$.

Horizon problem

Today our visible Universe consists of $50^3 \sim 10^5$ regions which were causally disconnected at recombination.

Why are they exacly the same?

May sound as a vague question.

But

Properties of perturbations make it sharp.

Major issue: origin of perturbations

Causality $\Longrightarrow$ perturbations can be generated only when their wavelengths are smaller than horizon size.

Off-hand possibilities:

- Perturbations were generated at the hot cosmological epoch by some causal mechanism.

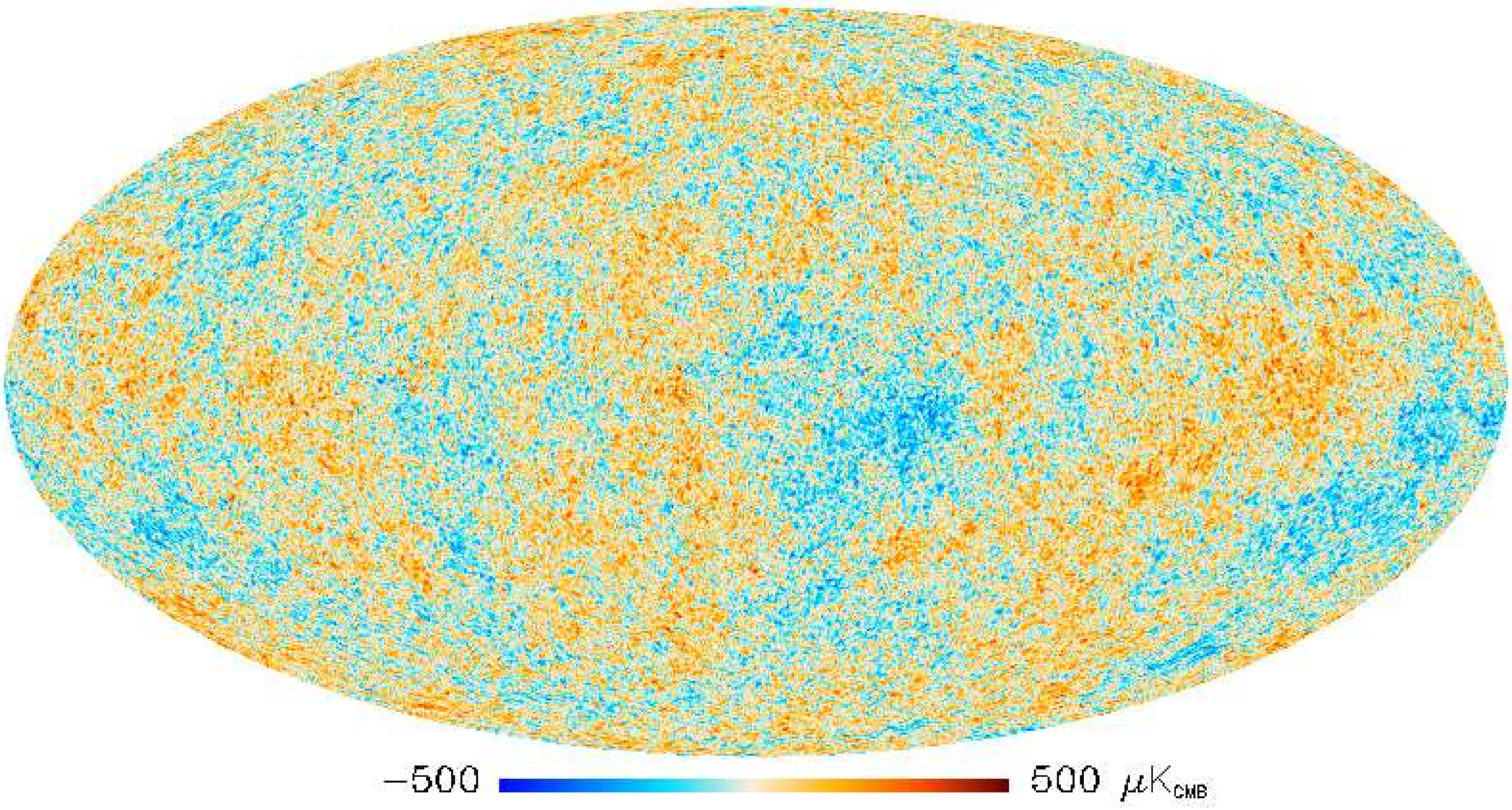
  E.g., seeded by topological defects (cosmic strings, etc.)

  N. Turok et.al.' 90s

  The only possibility, if expansion started from hot Big Bang.

  Not an option

- Hot epoch was preceeded by some other epoch. Perturbations were generated then.



—

There are perturbations which were superhorizon at the time of recombination, angular scale $\gtrsim 2^\circ$. Causality: they could not be generated at hot epoch!

In more detail

Wavelength of perturbation grows as $a(t)$.
E.g., at radiation domination

$$\lambda(t) \propto t^{1/2} \quad \text{while} \quad l_H \propto t$$

Today $\lambda < l_H$, subhorizon regime

Early on $\lambda(t) > l_H$, superhorizon regime.

NB: Horizon entry occured after Big Bang Nucleosynthesis for perturbations of all relevant wavelengths $\Longleftrightarrow$ no guesswork.

Shorter wavelengths: perturbations in baryon-photon plasma = sound waves.

If they were superhorizon, they started off with one and the same phase.

Reason: solutions to wave equation in superhorizon regime in expanding Universe

$$\frac{\delta\rho}{\rho} = \text{const} \qquad \text{and} \qquad \frac{\delta\rho}{\rho} = \frac{\text{const}}{t^{3/2}}$$

Assume that modes were superhorizon. Consistency of the picture: the Universe was not very inhomogeneous at early times, the initial condition is (up to amplitude),

$$\frac{\delta\rho}{\rho} = \text{const} \implies \frac{d}{dt}\frac{\delta\rho}{\rho} = 0$$

Acoustic oscillations start after entering the horizon at zero velocity of medium $\implies$ phase of oscillations well defined.

Perturbations develop different phases by the time of photon last scattering (= recombination), depending on wave vector:

$$\frac{\delta\rho}{\rho}(t_r) \propto \cos\left(\int_0^{t_r} dt\ v_s\ \frac{k}{a(t)}\right)$$

(v_s = sound speed in baryon-photon plasma)

cf. Sakharov oscillations’ 1965

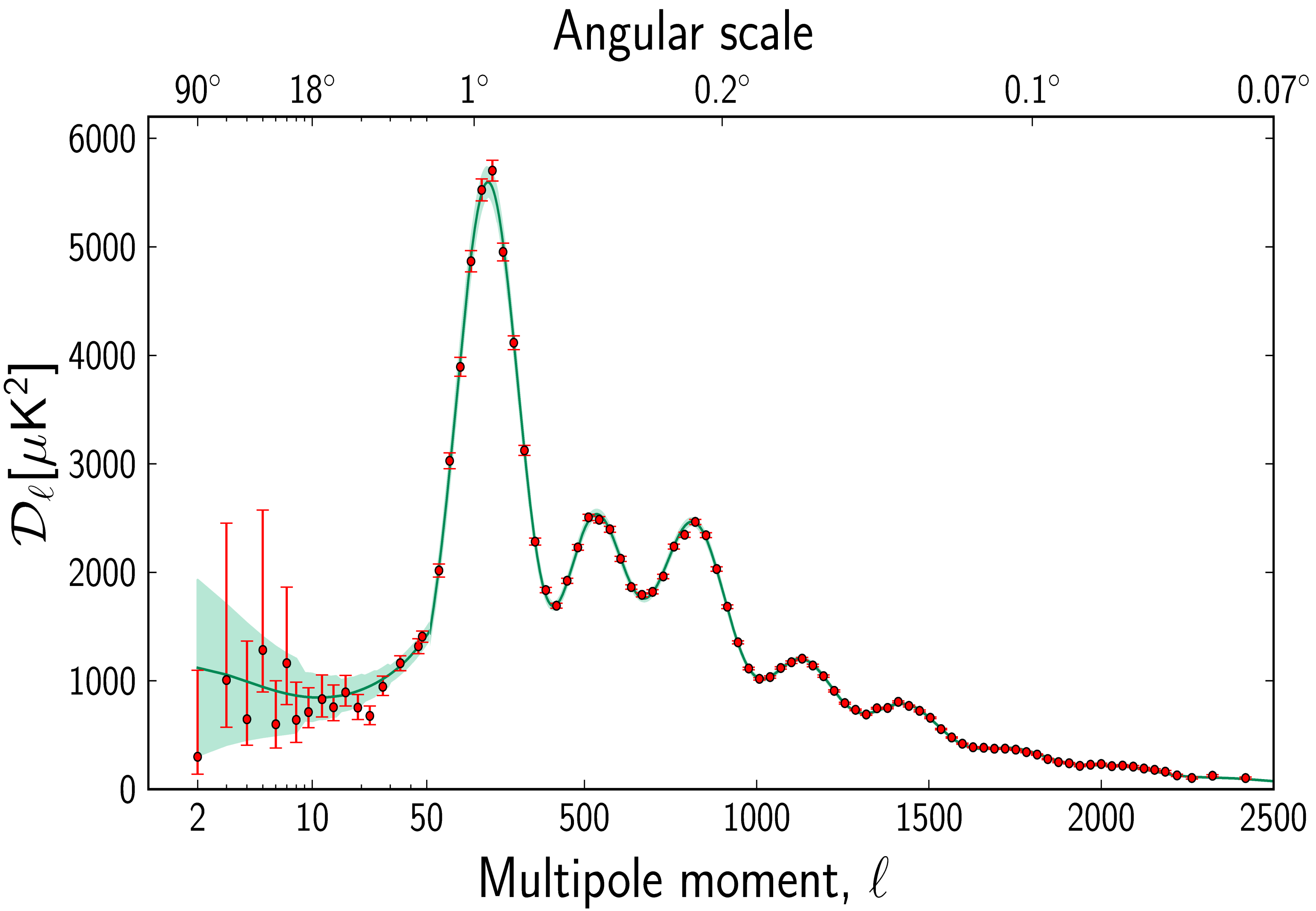
Oscillations in CMB temperature angular spectrum

Fourier decomposition of temperatue fluctuations over celestial sphere:

$$\delta T(\theta, \varphi) = \sum_{l,m} a_{lm} Y_{lm}(\theta, \varphi)$$

$\langle a^*_{lm} a_{lm} \rangle = C_l$, temperature angular spectrum;

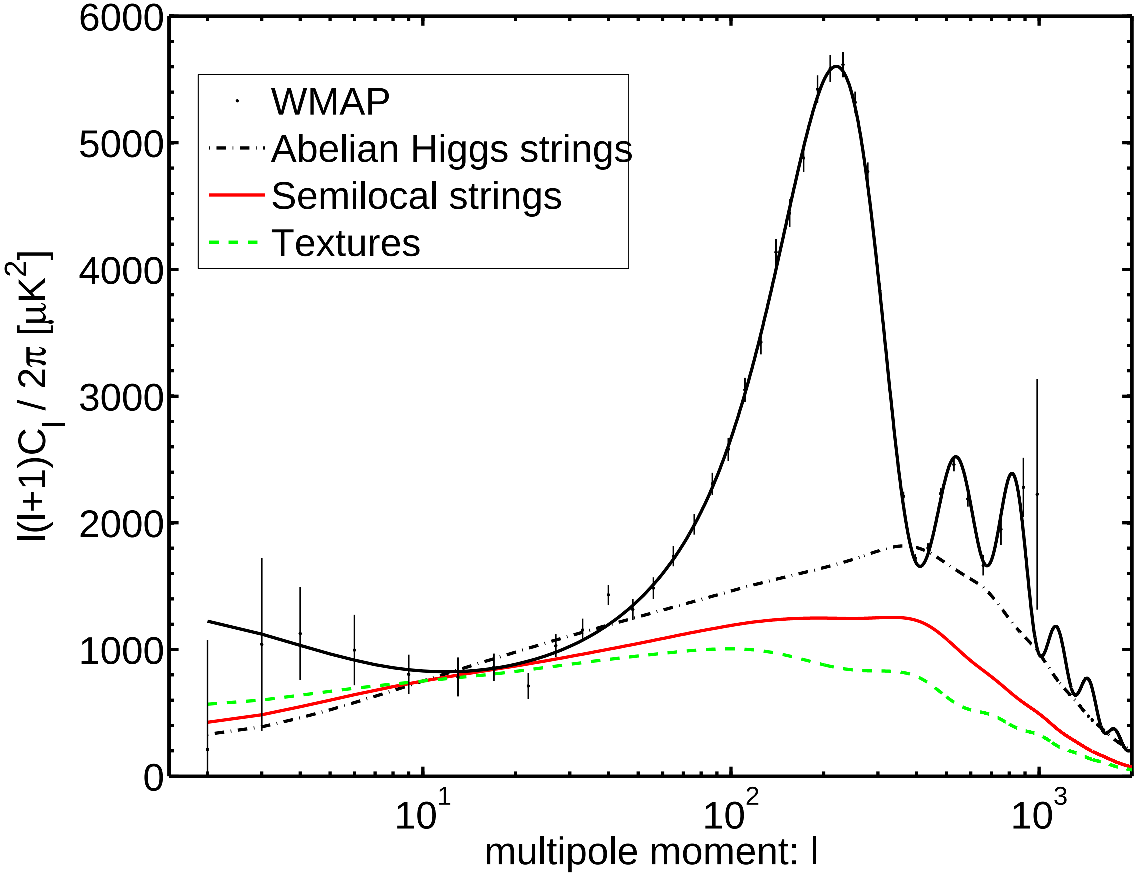
larger $l \Longleftrightarrow$ smaller angular scales, shorter wavelengths



Planck

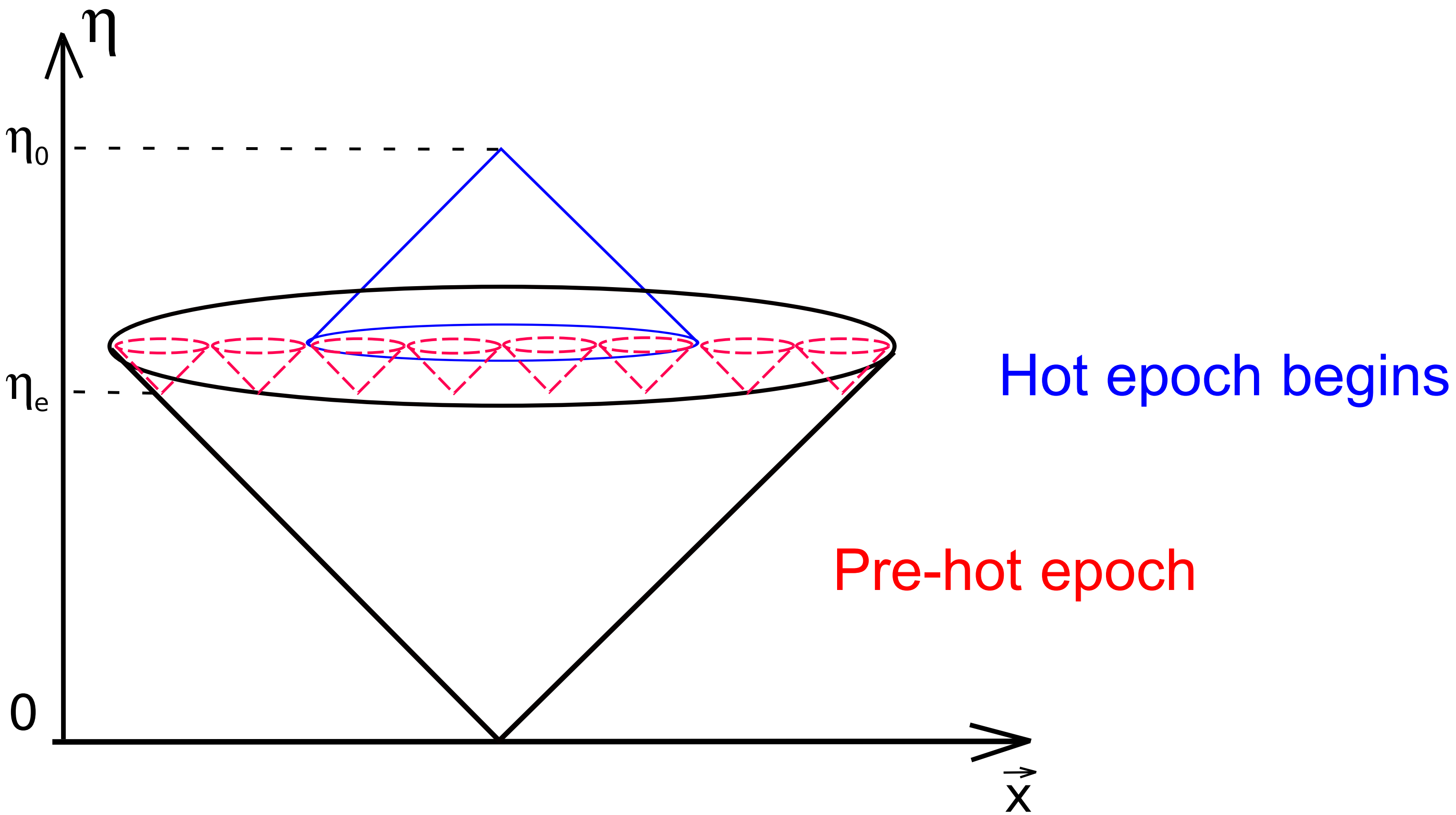
$$\mathscr{D}_l = \frac{l(l+1)}{2\pi} C_l$$

These properties would not be present if perturbations were generated at hot epoch in causal manner.



Primordial perturbations were generated at some yet unknown epoch before the hot expansion stage.

That epoch must have been long (in conformal time) and unusual: perturbations were subhorizon early at that epoch, our visible part of the Universe was in a causally connected region.



Excellent guess: inflation

Starobinsky'79; Guth'81; Linde'82; Albrecht and Steinhardt'82

Exponential expansion with almost constant Hubble rate,

$$a(t) = \mathrm{e}^{\int H dt}\,, \qquad H \approx \text{const}$$

- Initially Planck-size region expands to entire visible Universe in $t \sim 100\ H^{-1} \Longrightarrow$ for $t \gg 100\ H^{-1}$ the Universe is VERY large

- Perturbations subhorizon early at inflation:

$$\lambda(t) = 2\pi \frac{a(t)}{k} \ll H^{-1}$$

since $a(t) \propto \mathrm{e}^{Ht}$ and $H \approx$ const;
wavelengths gets redshifted, the Hubble parameter stays constant

NB: Typical time scale in inflationary models $H^{-1} \sim 10^{-37}$ s
energy scale $\rho^{1/4} \simeq \sqrt{M_{Pl} H} \sim 10^{16}$ GeV

Alternatives to inflation:

- Bouncing Universe: contraction — bounce — expansion
- “Genesis”: start up from static state

Creminelli et.al.’06; ’10

Difficult, but not impossible.

Other suggestive observational facts about density perturbations

(valid within certain error bars!)

- Primordial perturbations are Gaussian.

  This suggests the origin: enhanced vacuum fluctuations of weakly coupled quatum field(s)

  - Inflation does the job very well: vacuum fluctuations of all light fields get enhanced greatly due to fast expansion of the Universe.

    Including the field that dominates energy density (inflaton) $\Longrightarrow$ perturbations in energy density.

    Mukhanov, Chibisov'81; Hawking'82; Starobinsky'82;
    Guth, Pi'82; Bardeen et.al.'83

  - Enhancement of vacuum fluctuations is less automatic in alternative scenarios

Primordial power spectrum is almost flat: no length scale

Homogeneity and anisotropy of Gaussian random field:

$$\langle \frac{\delta\rho}{\rho}(\vec{k}) \frac{\delta\rho}{\rho}(\vec{k}') \rangle = \frac{1}{4\pi k^3} \mathscr{P}(k) \delta(\vec{k} + \vec{k}')$$

$\mathscr{P}(k) =$ power spectrum, gives fluctuation in logarithmic interval of momenta,

$$\langle \left(\frac{\delta\rho}{\rho}(\vec{x}) \right)^2 \rangle = \int_0^\infty \frac{dk}{k} \mathscr{P}(k)$$

Flat spectrum: $\mathscr{P}$ is independent of k

Harrison' 70; Zeldovich' 72, Peebles,Yu' 70

Parametrization

$$\mathscr{P}(k) = A \left(\frac{k}{k_*} \right)^{n_s - 1}$$

$A =$ amplitude, $(n_s - 1) =$ tilt, $k_* =$ fiducial momentum (matter of convention). Flat spectrum $\Longleftrightarrow n_s = 1$.
Experiment: $n_s = 0.97 \pm 0.01$ (WMAP, Planck)

There must be some symmetry behind flatness of spectrum

- Inflation: symmetry of de Sitter space-time $SO(4,1)$

$$ds^2 = dt^2 - \mathrm{e}^{2Ht} d\vec{x}^{\,2}$$

Relevant symmetry: spatial dilatations supplemented by time translations

$$\vec{x} \to \lambda \vec{x}\,, \quad t \to t - \frac{1}{2H} \log \lambda$$

- Alternative: conformal symmetry $SO(4,2)$

Conformal group includes dilatations, $x^\mu \to \lambda x^\mu$.
$\Longrightarrow$ No scale, good chance for flatness of spectrum

First mentioned by Antoniadis, Mazur, Mottola' 97
Concrete models: V.R.' 09;
Creminelli, Nicolis, Trincherini' 10.

NB: (Super)conformal symmetry has long been discussed in the context of Quantum Field Theory and particle physics.

Large and powerful symmetry behind, e.g., adS/CFT correspondence and a number of other QFT phenomena

It may well be that ultimate theory of Nature is (super)conformal

What if our Universe started off from or passed through an unstable (super)conformal state and then evolved to much less symmetric state we see today?

Exploratory stage: toy models + general arguments so far.

Can one tell?

More intricate properties of cosmological perturbations

Not detected yet.

- Primordial gravitational waves predicted by simplest (hence plausible) inflationary models, but not alternatives to inflation

  Huge wavelengths, from 100 Mpc to size of visible Universe

  Sizeable amplitudes, $h \sim 10^{-5} - 10^{-6}$
  (cf. $h \lesssim 10^{-22}$ for gravity waves of astrophysical origin)

  Almost flat power spectrum

  May make detectable imprint on CMB temperature anisotropy

  V.R., Sazhin, Veryaskin' 82; Fabbri, Pollock' 83; ...

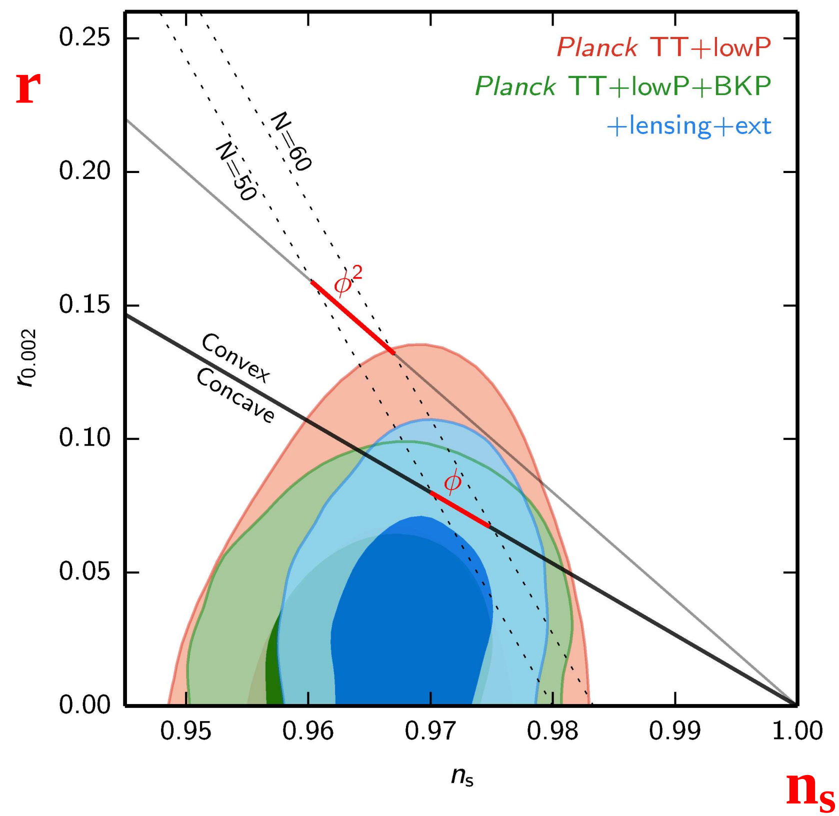
  and especially on CMB polarization

  Basko, Polnarev' 1980; Polnarev' 1985; Sazhin, Benitez' 1995
  Kamionkowski, Kosowsky, Stebbins' 96; Seljak, Zaldarriaga' 96; ...

Smoking gun for inflation

Present situation

Scalar spectral index vs gravity waves



$$r = \left(\frac{\text{amplitude of gravity waves}}{\text{amplitude of density perturbations}} \right)^2$$

BICEP-2 claim (March 2014): $r \approx 0.2$ not confirmed

- Non-Gaussianity: big issue
  - Very small in the simplest inflationary theories
  - Sizeable in more contrived inflationary models and in alternatives to inflation. Often begins with bispectrum

$$\langle \frac{\delta\rho}{\rho}(\mathbf{k_1})\frac{\delta\rho}{\rho}(\mathbf{k_2})\frac{\delta\rho}{\rho}(\mathbf{k_3})\rangle = \delta(\mathbf{k_1}+\mathbf{k_2}+\mathbf{k_3})G(k_i^2,\mathbf{k_1}\mathbf{k_2},\mathbf{k_1}\mathbf{k_3})$$

Shape of $G(k_i^2,\mathbf{k_1}\mathbf{k_2},\mathbf{k_1}\mathbf{k_3})$ different in different models $\Longrightarrow$ potential discriminator.

- Statistical anisotropy

$$\mathscr{P}(\mathbf{k}) = \mathscr{P}_0(k)\left(1 + w_{ij}(k)\frac{k_i k_j}{k^2} + \dots\right)$$

  - Anisotropy of the Universe at pre-hot stage
  - Possible in inflation with strong vector fields (rather contrived)

    Ackerman, Carroll, Wise' 07; Pullen, Kamionkowski' 07;
    Watanabe, Kanno, Soda' 09

  - Natural in conformal models

    Libanov, V.R.' 10; Libanov, Ramazanov, V.R.' 11

Entropy perturbations

- Adiabatic perturbations:

  Perturbations in energy densioty but not in composition

  $$\frac{\text{dark matter density}}{\text{entropy density}} = \text{const in space}$$

  Likewise for usual matter.

  The only option if dark matter and/or matter-antimatter asymmetry were generated at hot epoch.

- Entropy perturbations = perturbations in composition

  No admixture of entropy perturbations detected; strong limits from Planck.

To summarize:

- No doubt there was an epoch preceding the hot Big Bang. The question is what was that epoch?
- Inflation is consistent with all data. But there are competitors: the data may rather point towards (super)conformal beginning of the cosmological evolution.

More options:

Matter bounce, Finelli, Brandenberger' 01.

Negative exponential potential, Lehners et. al.' 07;
Buchbinder, Khouri, Ovrut' 07; Creminelli, Senatore' 07.

Lifshitz scalar, Mukohyama' 09

- Only very basic things are known for the time being.
- To tell, we need to discover

more intricate properties of cosmological perturbations

- Primordial tensor modes = gravitational waves

  Sizeable amplitude, (almost) flat power spectrum predicted by simplest (and hence most plausible) inflationary models
  but not alternatives to inflation

  - Together with scalar and tensor tilts $\Longrightarrow$ properties of inflation

- Non-trivial correlation properties of density perturbations (non-Gaussianity) $\Longrightarrow$ potential discriminator between scenarios. Very small in single field inflation.

  - Shape of non-Gaussianity: function of invariants $(\vec{k}_1 \cdot \vec{k}_2)$, etc.

- Statistical anisotropy $\Longrightarrow$ anisotropic pre-hot epoch.

  - Shape of statistical anisotropy $\Longrightarrow$ specific anisotropic model

- Admixture of entropy perturbations $\Longrightarrow$ generation of dark matter and/or matter-antimatter asymmetry before the hot epoch.

At the eve of new physics

LHC $\Longleftrightarrow$ Planck,
dedicated CMB polarization experiments,
data and theoretical understanding
of structure formation ...

chance to learn
what preceeded the hot Big Bang epoch

Barring the possibility that Nature is dull