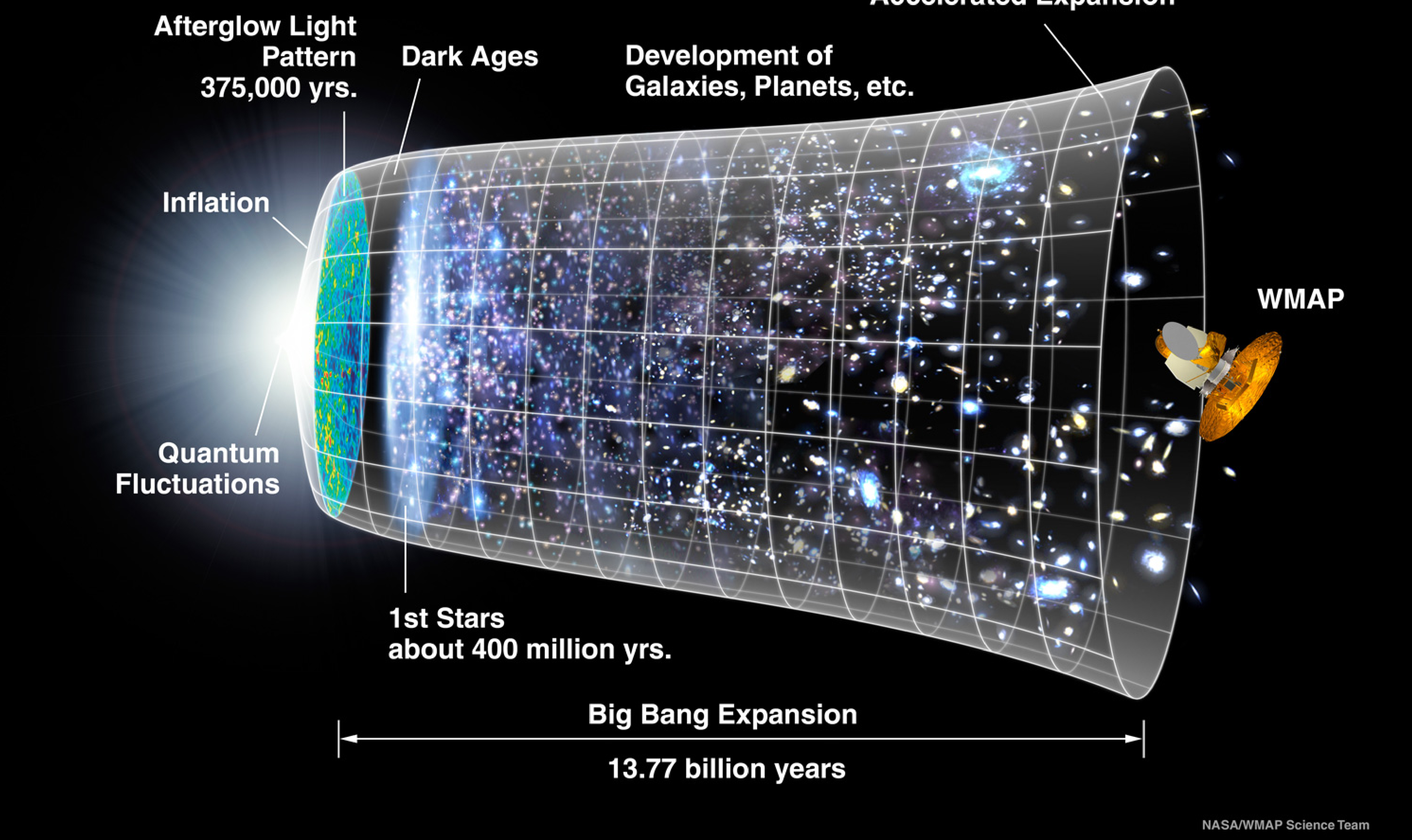
Big Bang (model)



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What can be seen / measured?

- basically only light (and a few particles: $e^{\pm}$, p, $\bar{p}$, ν_x)
  - in different wave lengths: microwave to γ-rays
  - in different intensities (measured in magnitudes)
  - with variations in time
  - from different directions

→ classification of the astronomical objects

- ★ stars: all the different types . . .
- ★ galaxies, nebulae
- ★ novae / supernovae
- ★ quasars, etc . . .
- ★ background radiation

Cosmological Principle

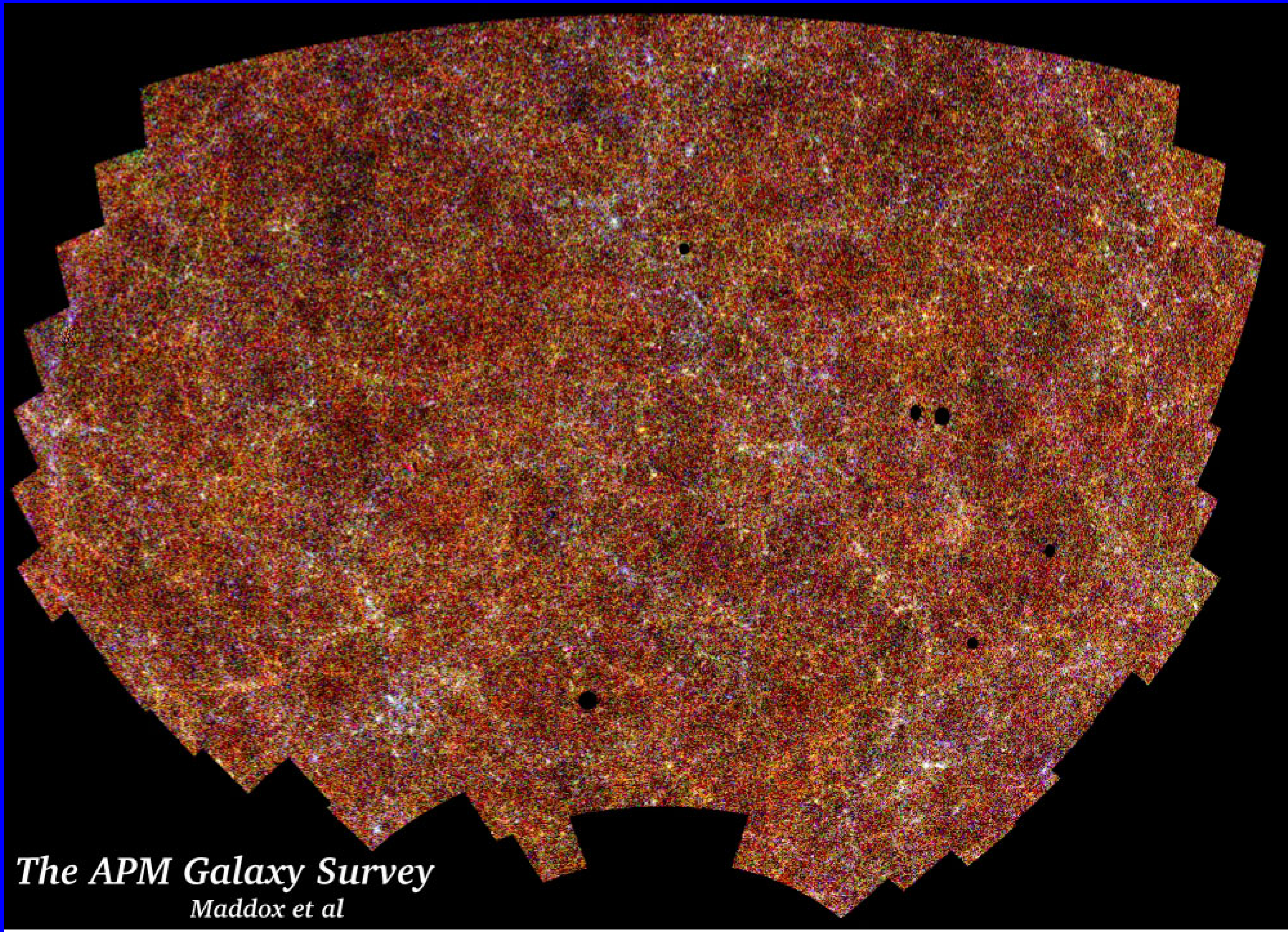
looking at galaxies

- homogeneous: similar everywhere
- isotropic: the same in every direction

➡ the stress-energy tensor has only 2 parameters:

★ density ρ

★ pressure p



Over 2 million galaxies are depicted above in a region 100 degrees across centered toward our Milky Way Galaxy's south pole. Bright regions indicate more galaxies, while bluer colors denote larger average galaxies. Dark ellipses have been cut away where bright local stars dominate the sky.

Olbers' paradoxon

IF the universe is

- homogeneous
- isotropic
- and infinite

➡ the sky should be infinitely bright !

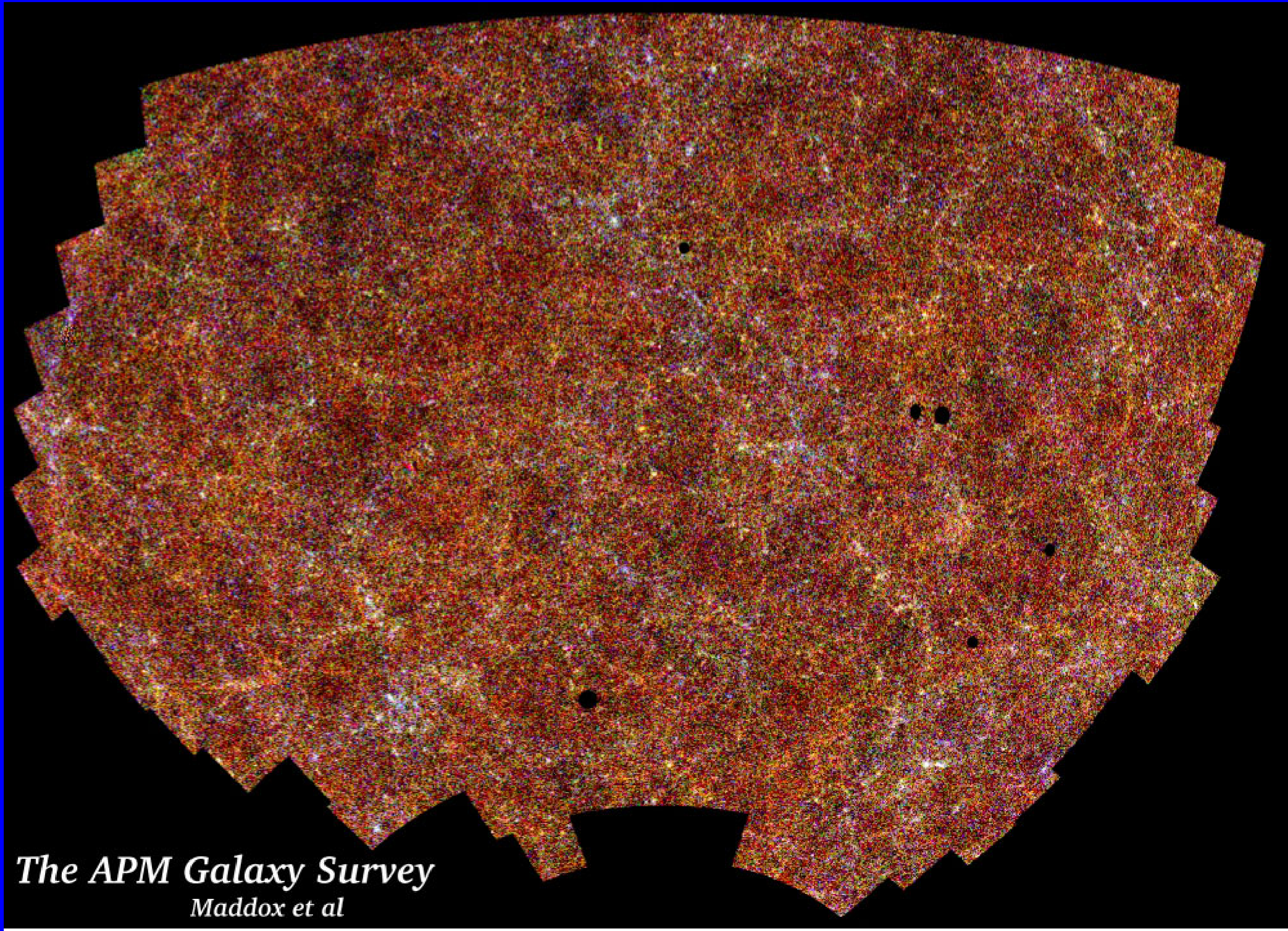
- it is not

➡ the universe is finite in time

➡ it had a start

⬇

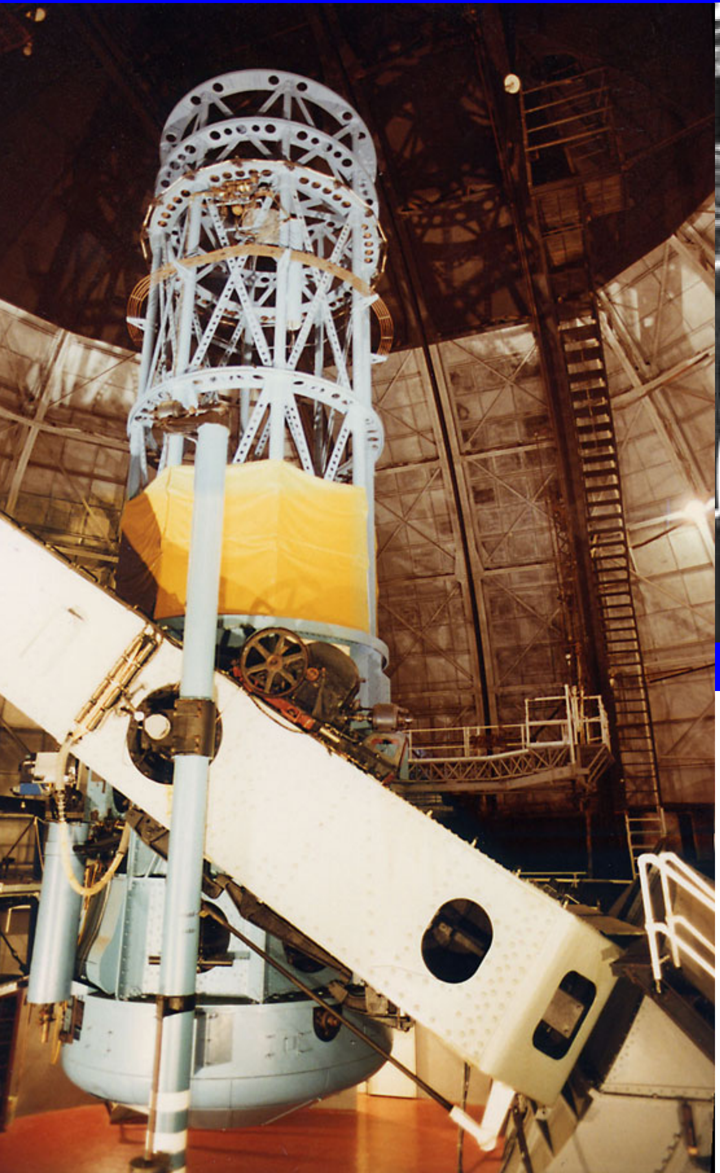
Big Bang

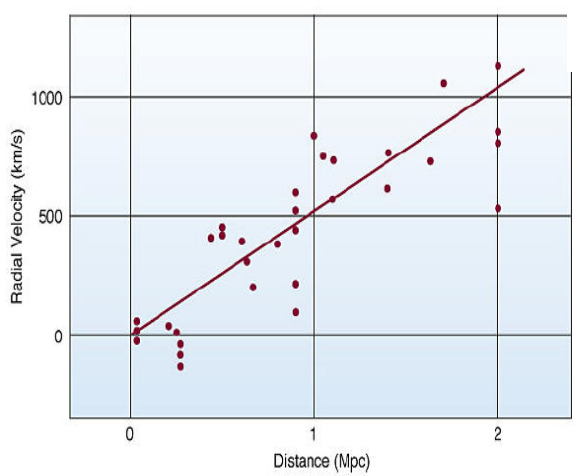


Over 2 million galaxies are depicted above in a region 100 degrees across centered toward our Milky Way Galaxy's south pole. Bright regions indicate more galaxies, while bluer colors denote larger average galaxies. Dark ellipses have been cut away where bright local stars dominate the sky.

Hubble parameter

- measured by Edwin Hubble 1929





galaxies outside of our Milky Way are moving away from us with a speed that is proportional to their distance from us:

$$H_0 = 67.80 \pm 0.77 \frac{\mathrm{km/s}}{\mathrm{Mpc}}$$

Planck+WMAP+highL+BAO: 68% limits

➡ indication for a homogeneous expanding universe !

theoretical foundations

- Cosmological Principle
  - homogeneous
  - isotropic
- Robertson-Walker (RW) metric

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega\right] \quad \text{with} \quad k = -1, 0, 1$$

- General Relativity: Einstein equations

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

↑ stress-energy tensor

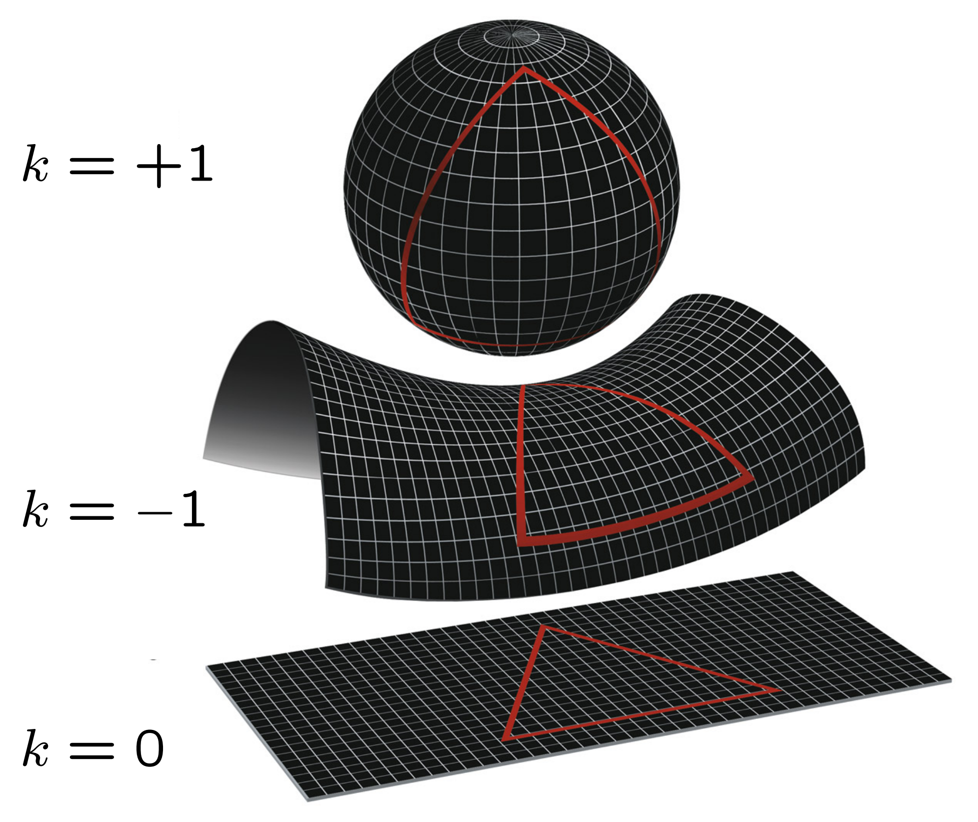
Friedman-Lemaître models

- are solutions to the Einstein equations
  - using the RW-metric
  - type of curvature is determined by k:
  - scale factor $a(t)$
  - Hubble parameter

$$H = \frac{\dot{a}}{a}$$

  - deceleration parameter

$$q = -\frac{a\,\ddot{a}}{\dot{a}^2}$$



Friedman-Lemaître models

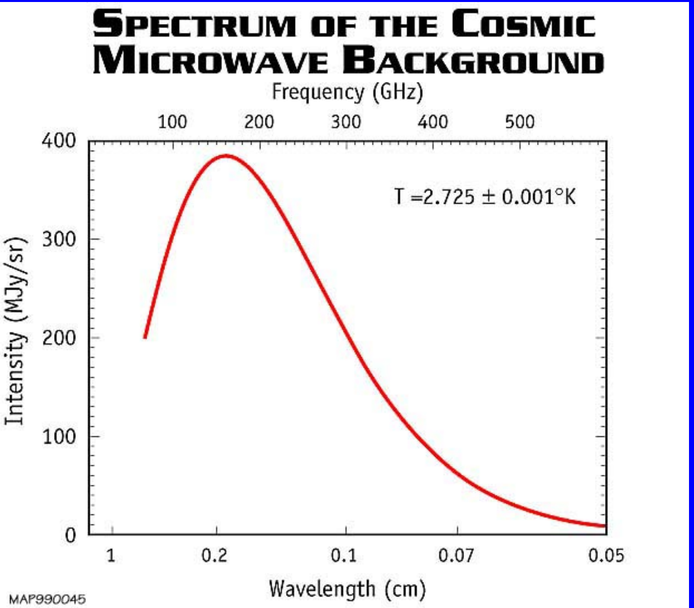
- **they are models!**
  - all observations have to be interpreted consistently within the model
  - they consider the whole universe
  - the Hubble parameter H describes the expansion rate of the spatial part of the universe
  - the scale factor $a(t)$ describes the length scale at the time t
- $a(t \to 0) \to 0$ describes the "Big Bang"
- **that does not mean, the universe was small!**
  - it means, all what we can see today was very close together

Extrapolating backwards

- using the assumptions
  (General Relativity,
  Cosmological Principle, . . .)

→ prediction of

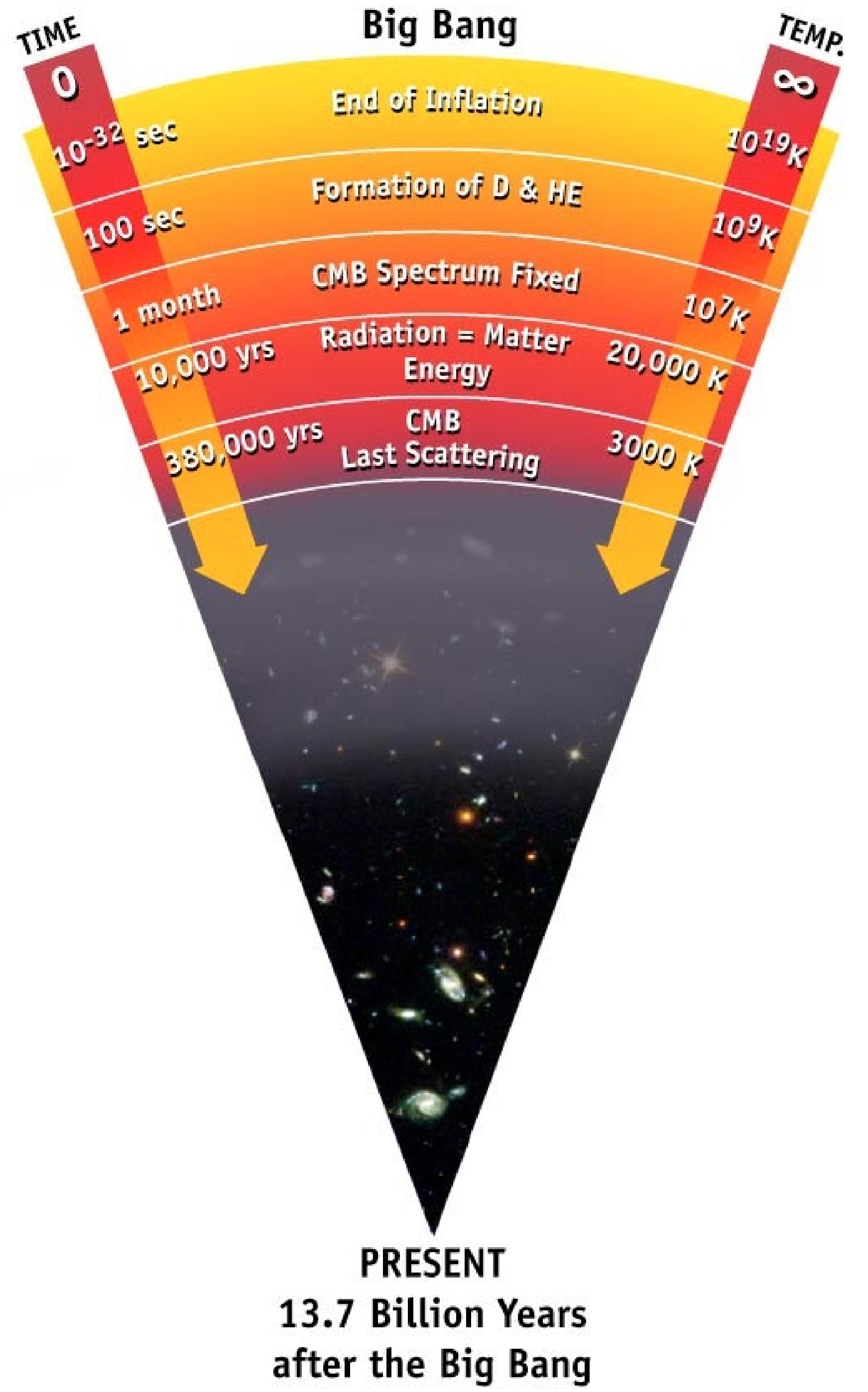
- Big Bang Nucleo-synthesis (BBN)
- Cosmic Microwave Background (CMB)



★ temperature (black body)

★ spatial distribution

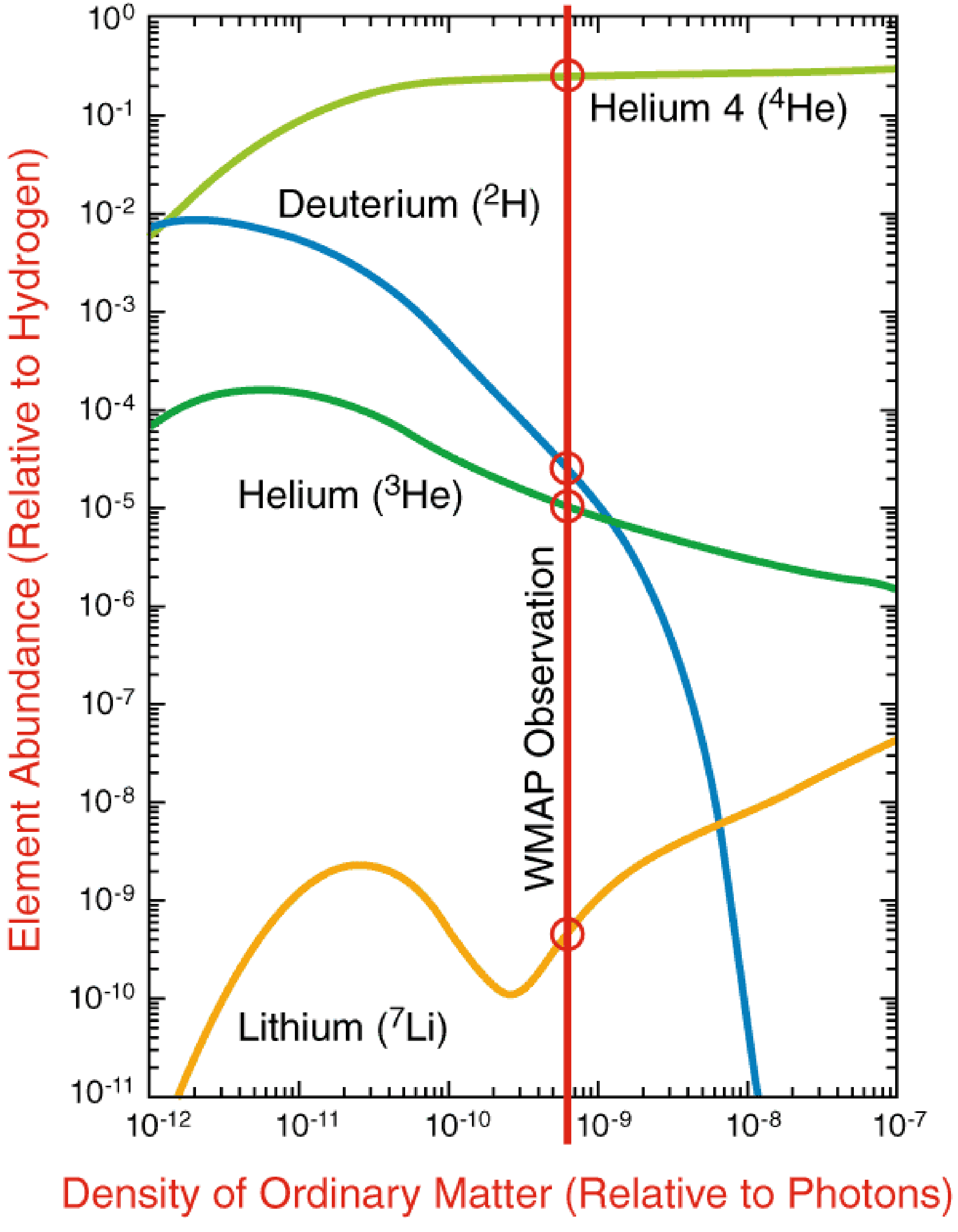
★ fluctuations



Big Bang Nucleosynthesis (BBN)

- uses the **known** cross sections for the scattering of ^{1}H, ^{2}H, ^{3}He, ^{4}He, and ^{7}Li !

➡ comparison to measurement



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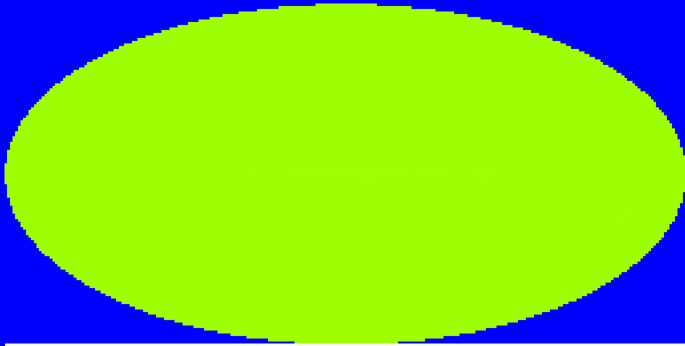
WMAP101087

Element Abundance graphs: Steigman, Encyclopedia of Astronomy and Astrophysics (Institute of Physics) December, 2000

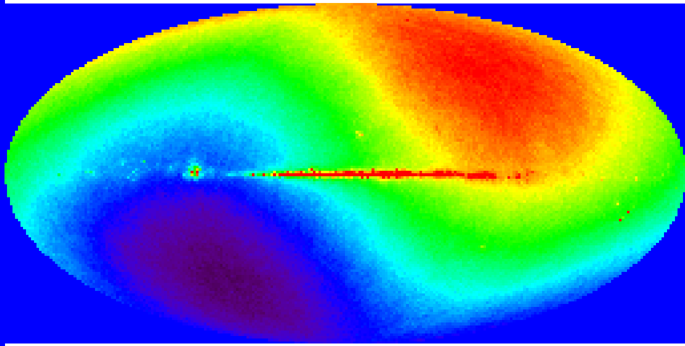
Cosmic Microwave Background (CMB)

- in the hot early universe radiation and matter are in equilibrium
- the universe expands and cools down:
  - radiation and matter decouple
- Friedman equations:
  - density of matter goes like $\rho = a^{-3}$
  - density of radiation goes like $\rho = a^{-4}$
- matter dominates in a large universe – just as we see it !

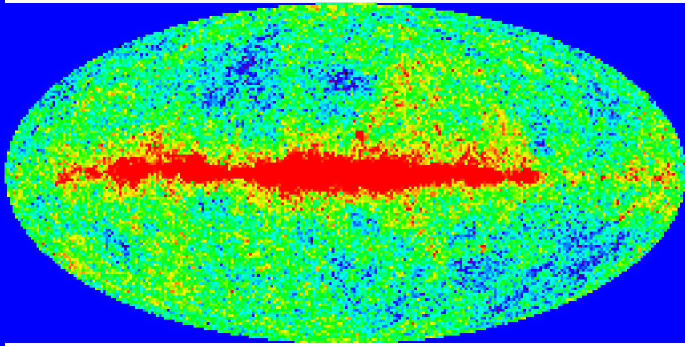


0 K . . . to . . . 4 K

motion of the sun relative to the CMB



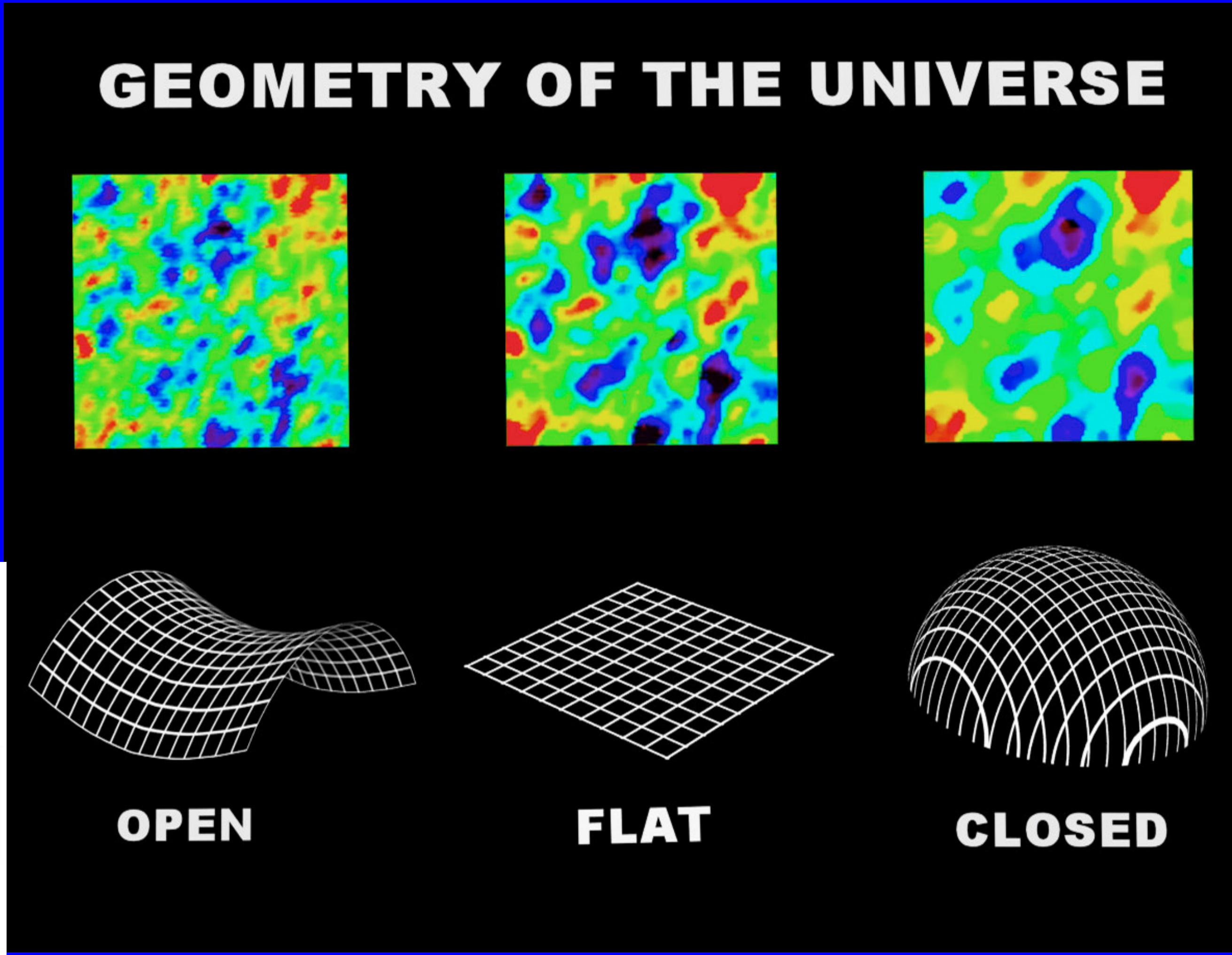
2.721 K – 2.729 K

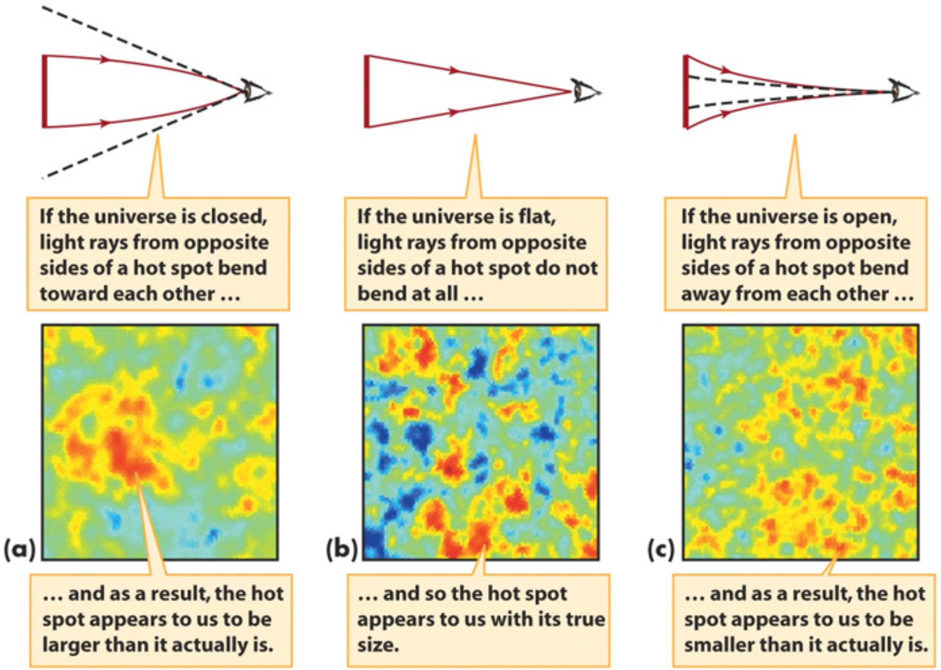


2.7249 K – 2.7251 K

Cosmic Microwave Background (CMB)

- fluctuations in the early universe expand
  - depending on the geometry
- the geometry depends on the energy density





If the universe is closed, light rays from opposite sides of a hot spot bend toward each other …

… and as a result, the hot spot appears to us to be larger than it actually is.

If the universe is flat, light rays from opposite sides of a hot spot do not bend at all …

… and so the hot spot appears to us with its true size.

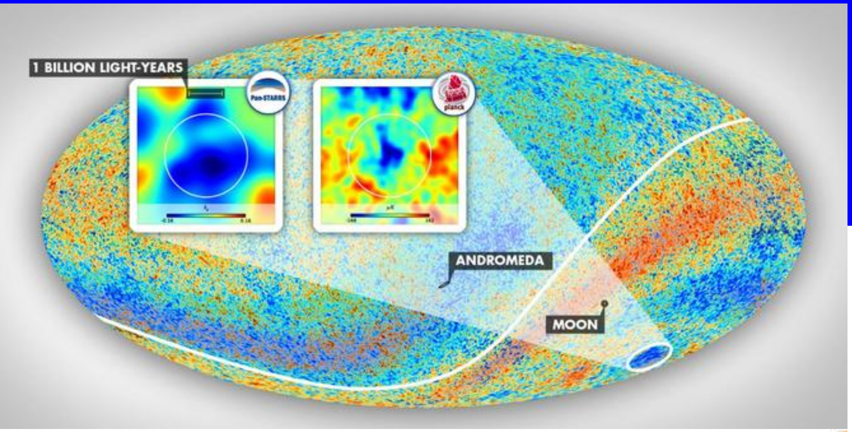
If the universe is open, light rays from opposite sides of a hot spot bend away from each other …

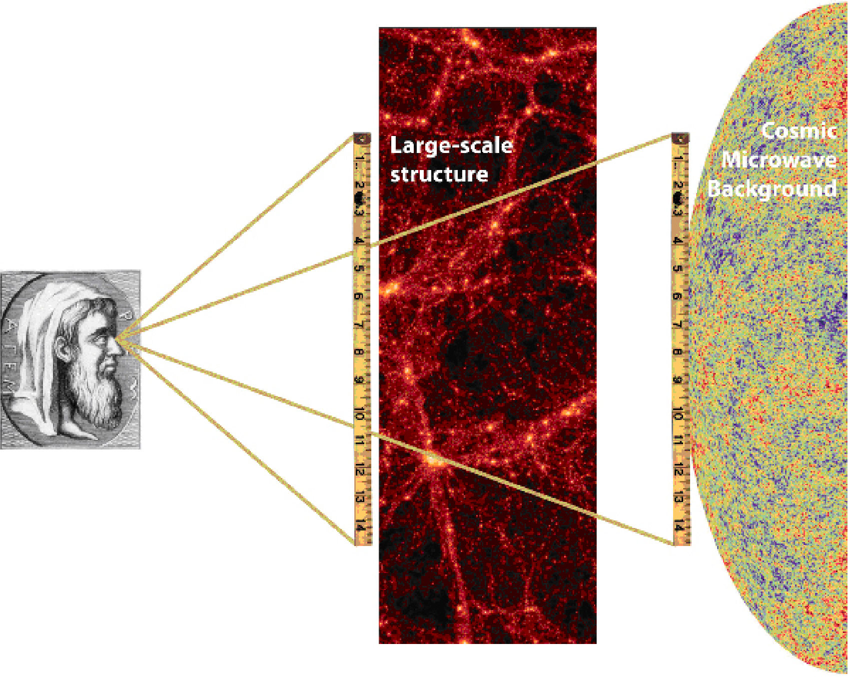
… and as a result, the hot spot appears to us to be smaller than it actually is.

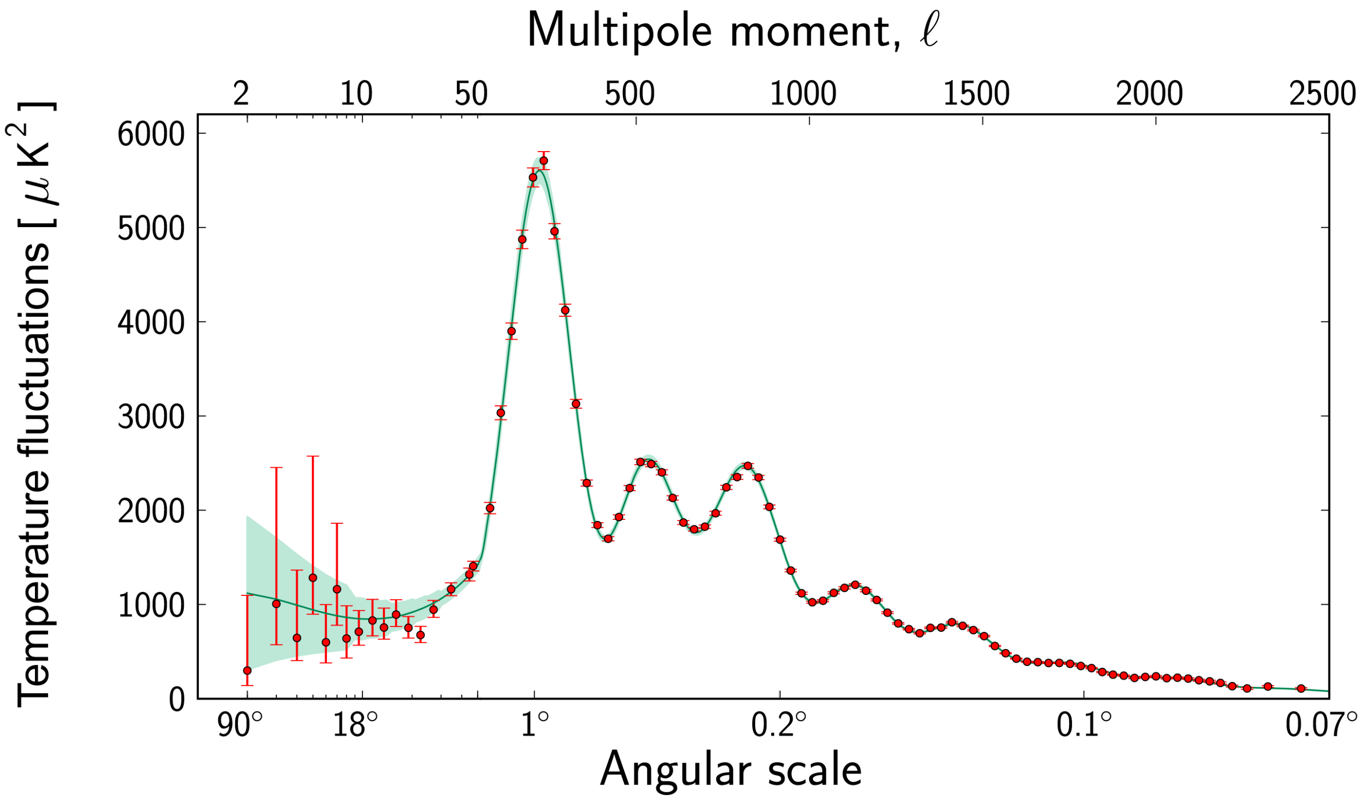
- measuring the size of the fluctuations tells about the energy density!

Cosmic Microwave Background (CMB)

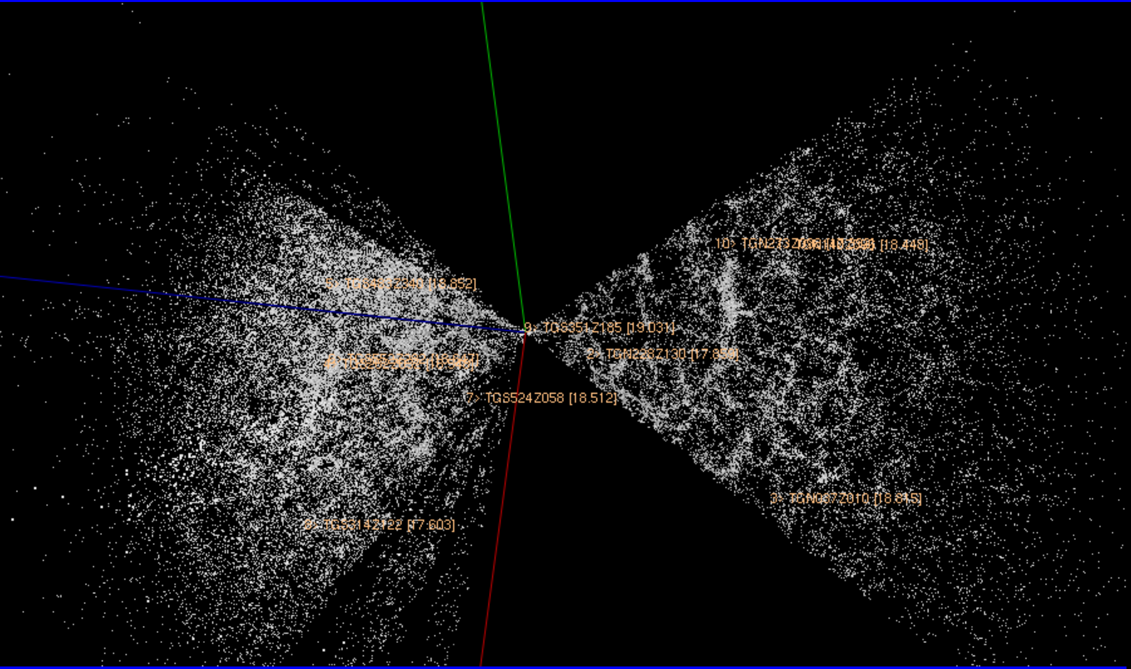
- sonic waves in the early universe are recorded by the freeze out of the CMB
  - more information about relative densities of different parts of the matter content!

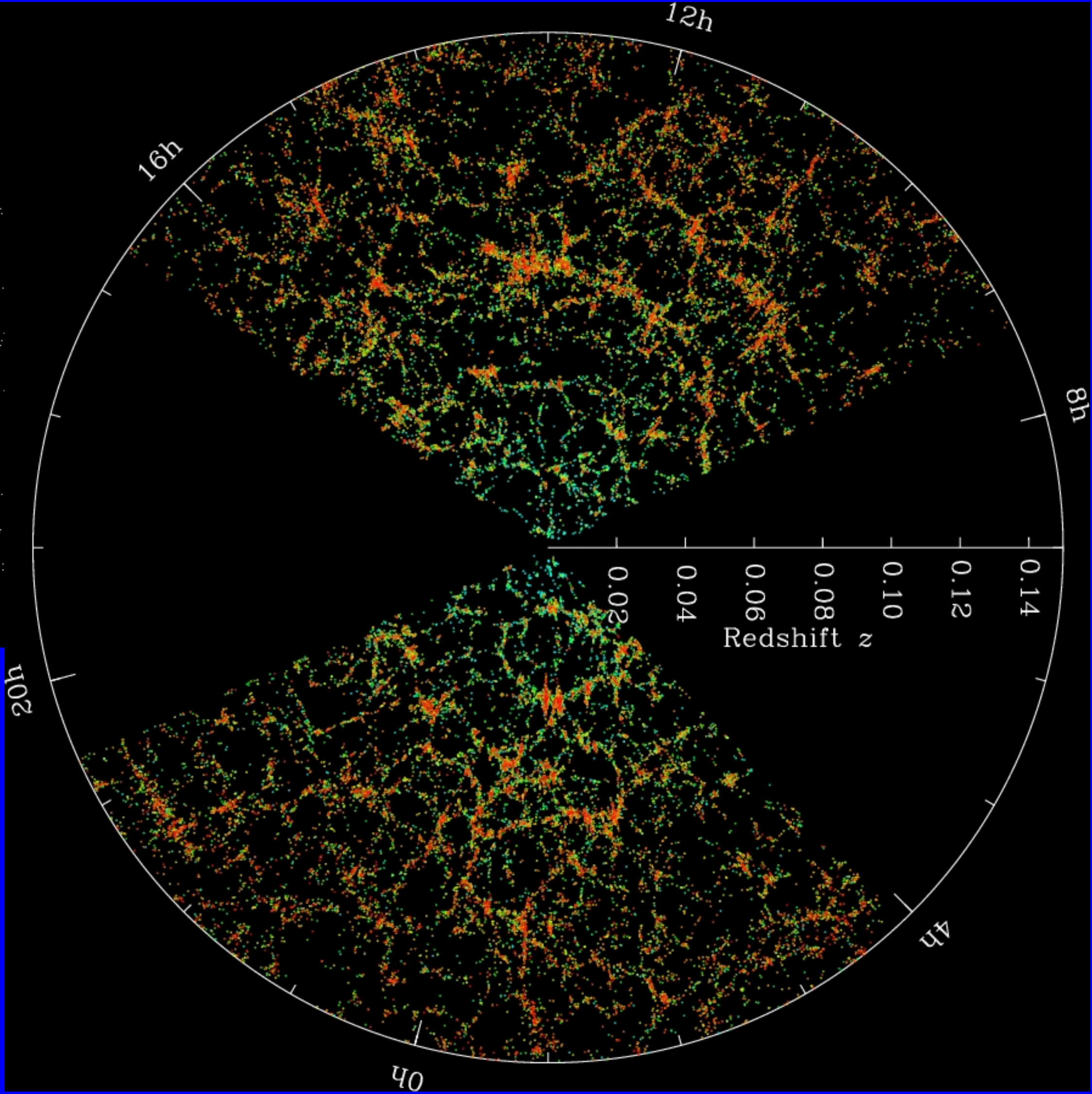






Galaxy redshift surveys





map the sky

- investigate the large scale structures in the visible universe
- model structure formation
- see weak gravitational lensing

CMB + large scale structure + Supernovae

on the experimental side

General Relativity + Cosmological Principle

on the theory side

⇓

Lambda-Cold Dark Matter (ΛCDM)

or concordance model

explains most observations

- BBN
- CMB + fluctuations
- large scale structure
- rotational curves

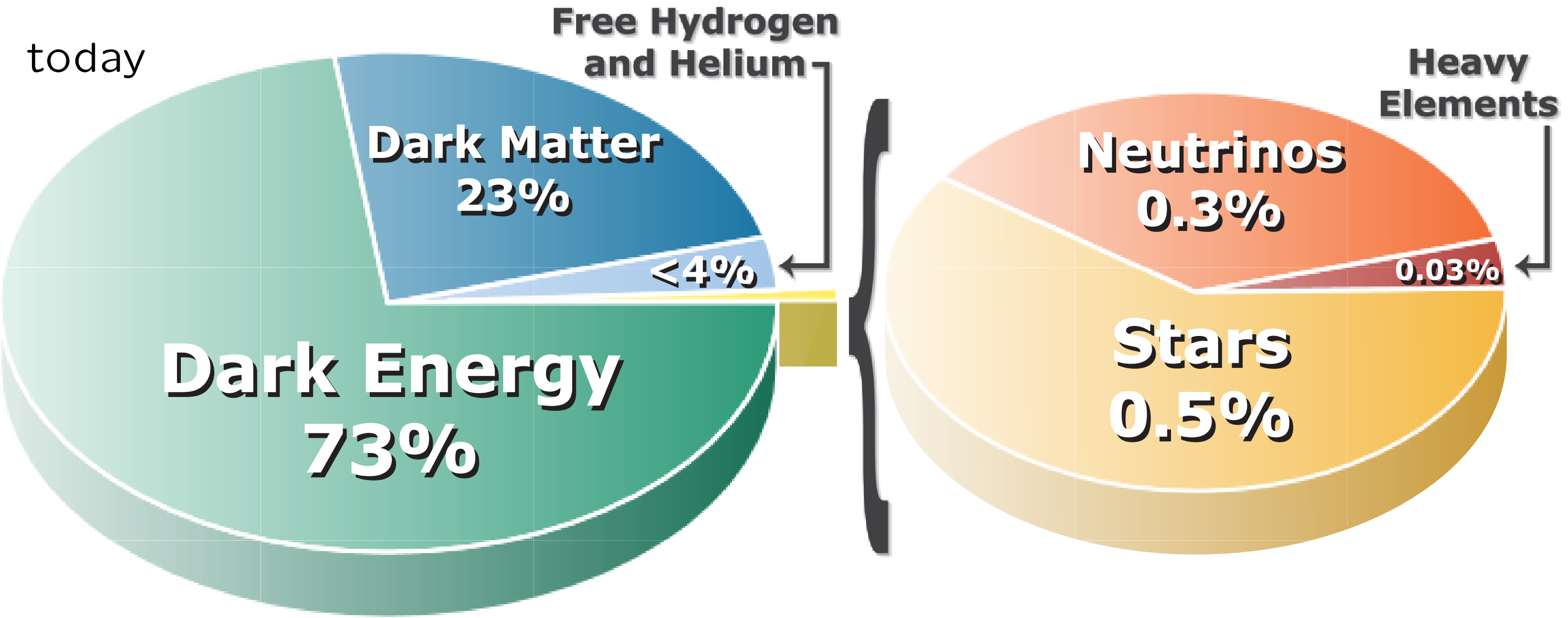
needs inflation

to explain

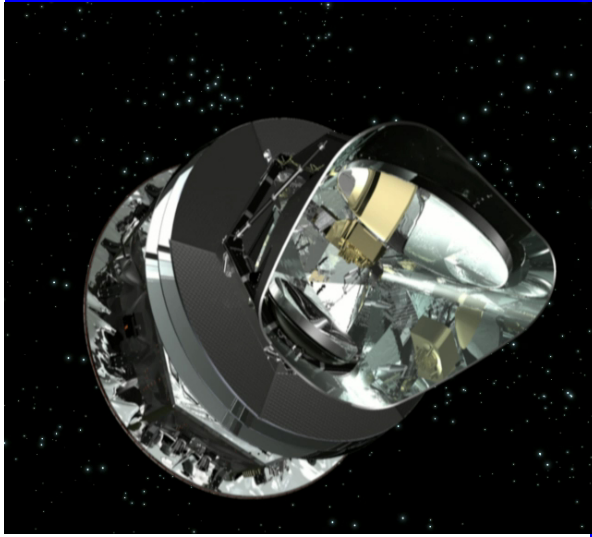
- why the density of the universe is nearly the critical density, that gives a flat universe

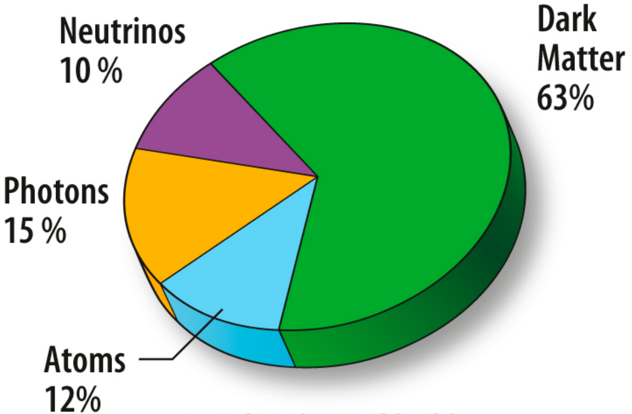
Lambda-Cold Dark Matter (ΛCDM) or concordance model

today



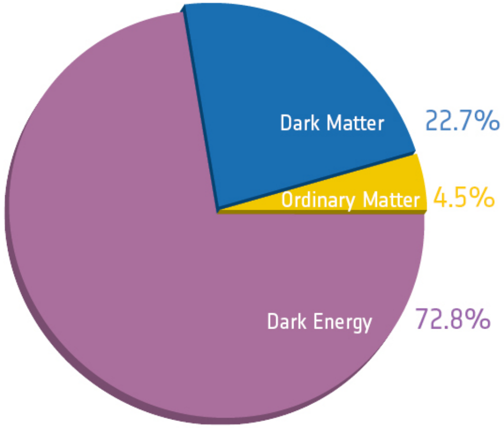
Planck in space



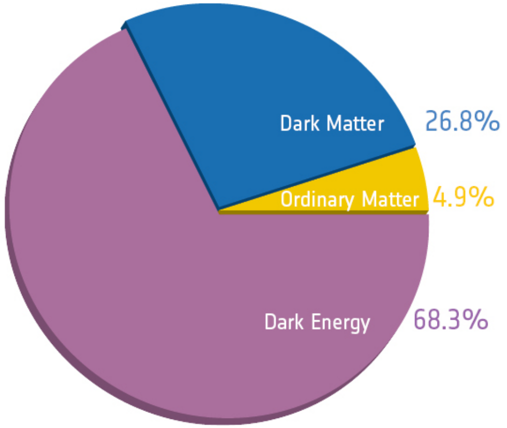


13.7 BILLION YEARS AGO
(Universe 380,000 years old)

before Planck



after Planck



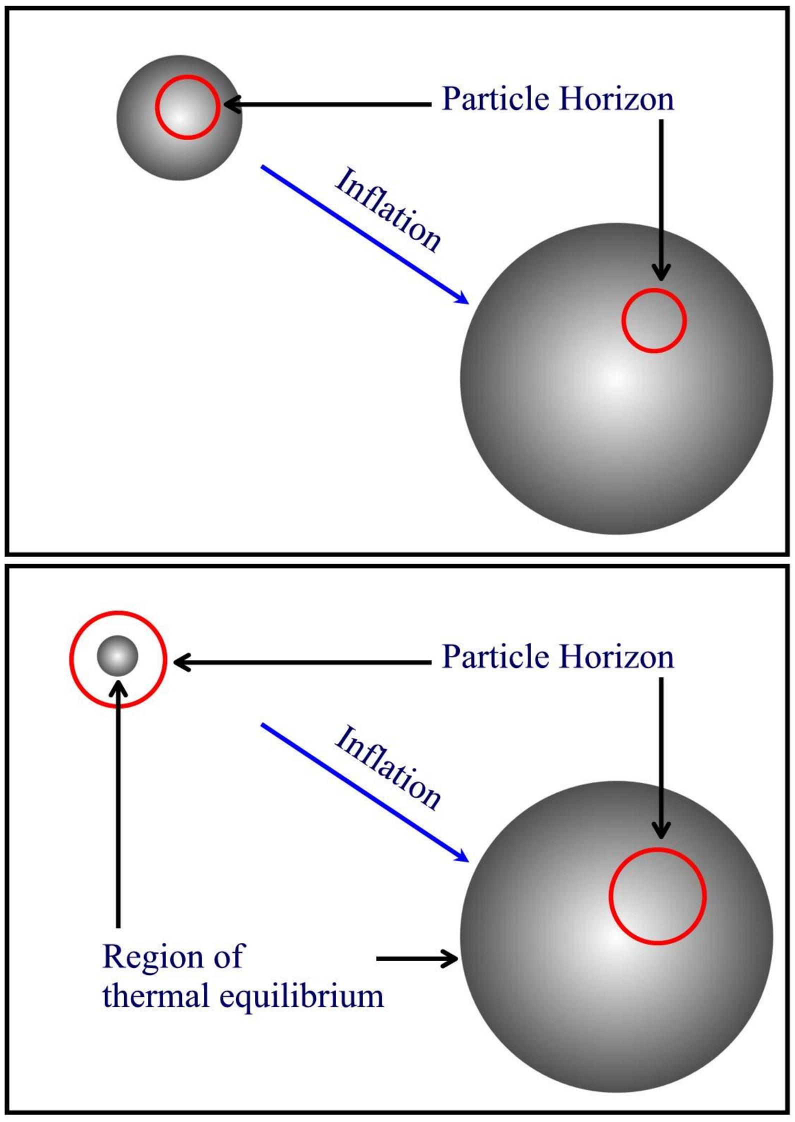
cosmological inflation

is the name for the rapid growth of the universe during a very short and early period

- a small ball has a small radius and hence a large curvature
- an inflated ball has a large radius and hence a small curvature
- the scale factor $a(t)$ increased by a factor of 10^{+26} in 10^{-32} s

→ the universe becomes flat, homogenous and isotropic

- without inflation there would be no way to have thermal equilibrium between different visible regions
- quantum fluctuations are extended to cosmic sizes



cosmological inflation

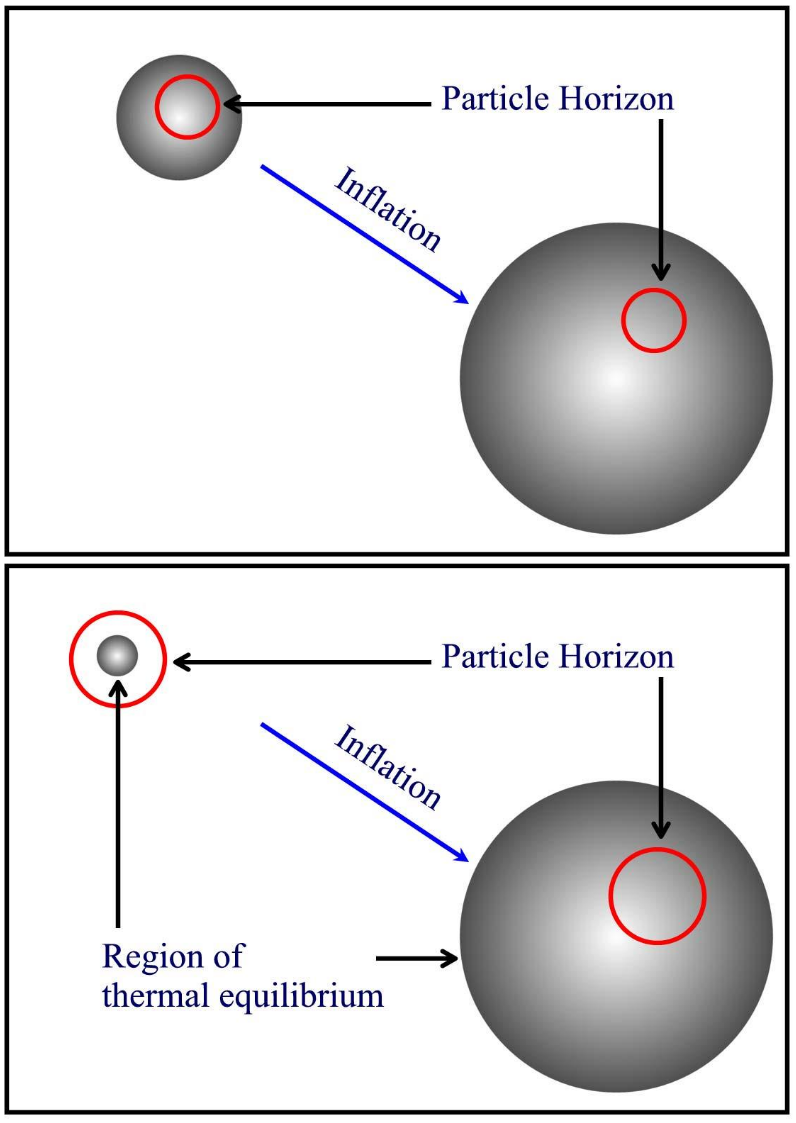
- temperature goes down when a volume expands

➡ freezing out of quantum fluctuations

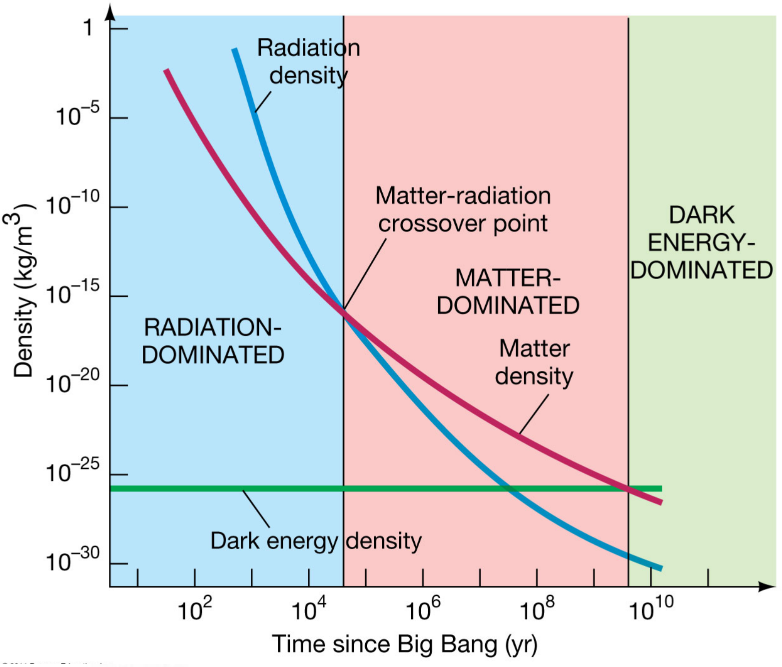
- a scalar field can trigger inflation
  - this scalar field (inflaton) decays at the end of inflation

➡ reheating of the universe:
  - depending on the energy scale of the scalar field, we get the production of all particles from the decay
  - similar to the experimental collisions in the accelerators

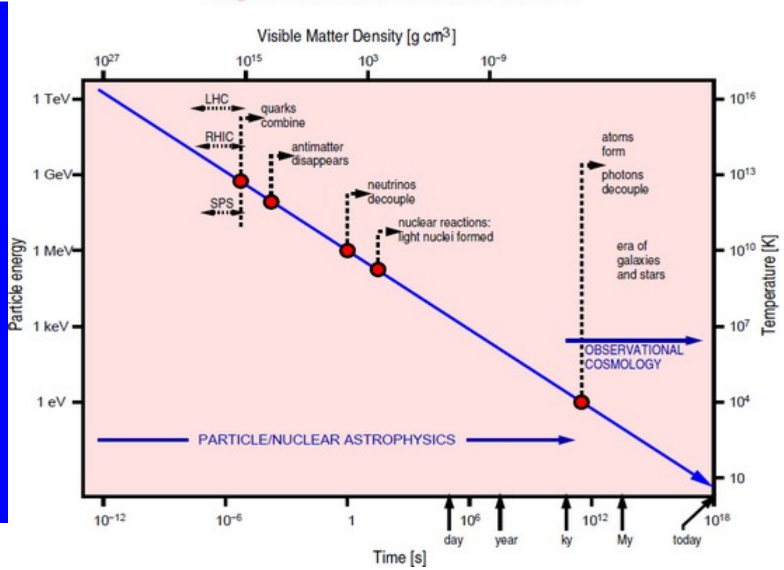
➡ Cosmology meets Particle Physics



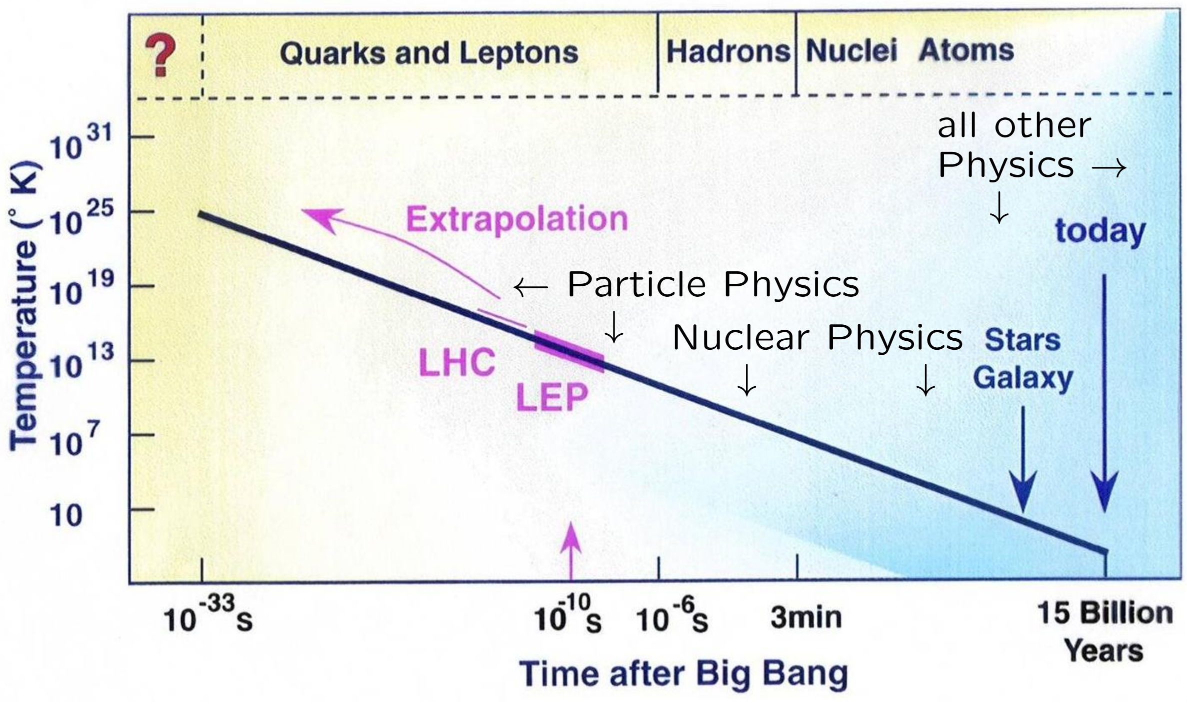
Scales in Cosmology



Stages in the evolution of the Universe



Creation of the Universe

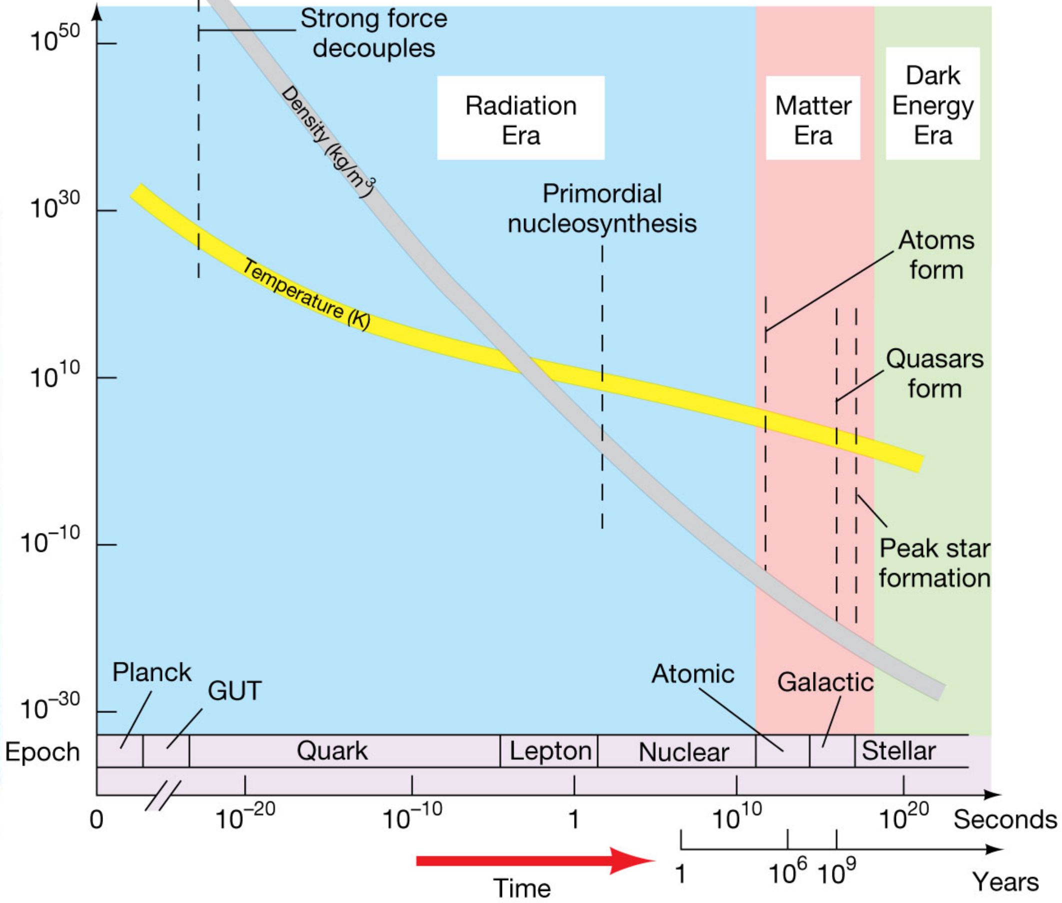


all other Physics →
↓

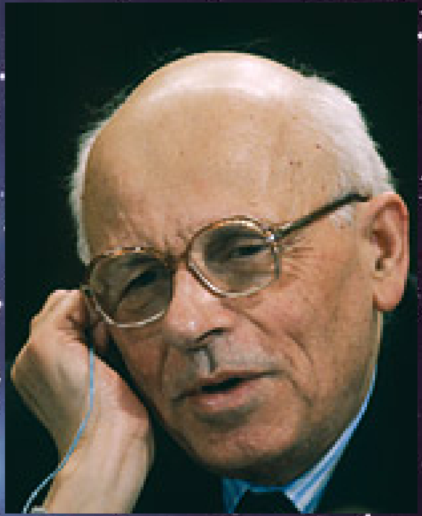
← Particle Physics
↓

Nuclear Physics
↓

↓



★ implications of CP-violation in Cosmology



why CP-violation is important for our existence:

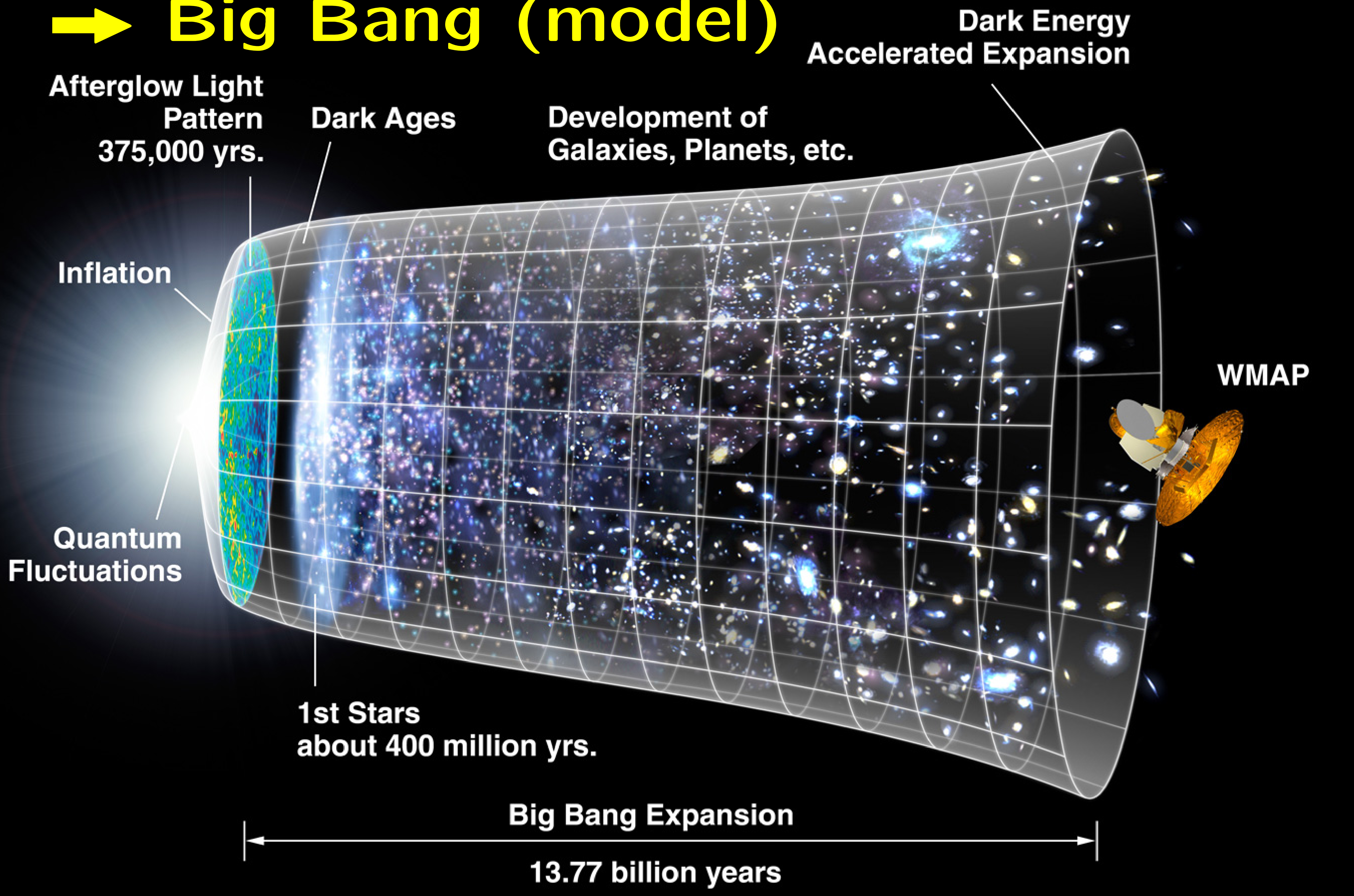
- our universe consists – as far as we know – almost completely of matter
- but where is the anti-matter?
- and why haven‘t matter and anti-matter just annihilated?

possible explanation:

- at the big bang, there were large amounts of matter and anti-matter
- almost all of them annihilated
- but smallest asymmetries in the laws of nature for matter and anti-matter left a tiny excess of matter: the matter of our universe
- 1967, Andrej Sacharow gave a list of conditions for this explanation
  - ▶ one of it is CP-violation

Without CP-violation, our universe would not be the one we know!

→ Big Bang (model)



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