Cosmology

A short introduction

Sarah Aretz
CERN

http://www.widescreen-wallpaper.eu/view-night_sky_tree_universe-1280x800.html

What is cosmology all about?

Κοσμολογία = study of the world

description of the origin, evolution and eventual fate of the Universe by physical laws

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Cosmological Questions:

- What is the Universe made of?
- How does it's structure look like?
- What is it's origin?
- Can we reconstruct the history of the Universe?

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Contents

- Dimensions of our Universe
- Dynamics of the Universe
- A Journey through Time
- Mysteries of the Universe

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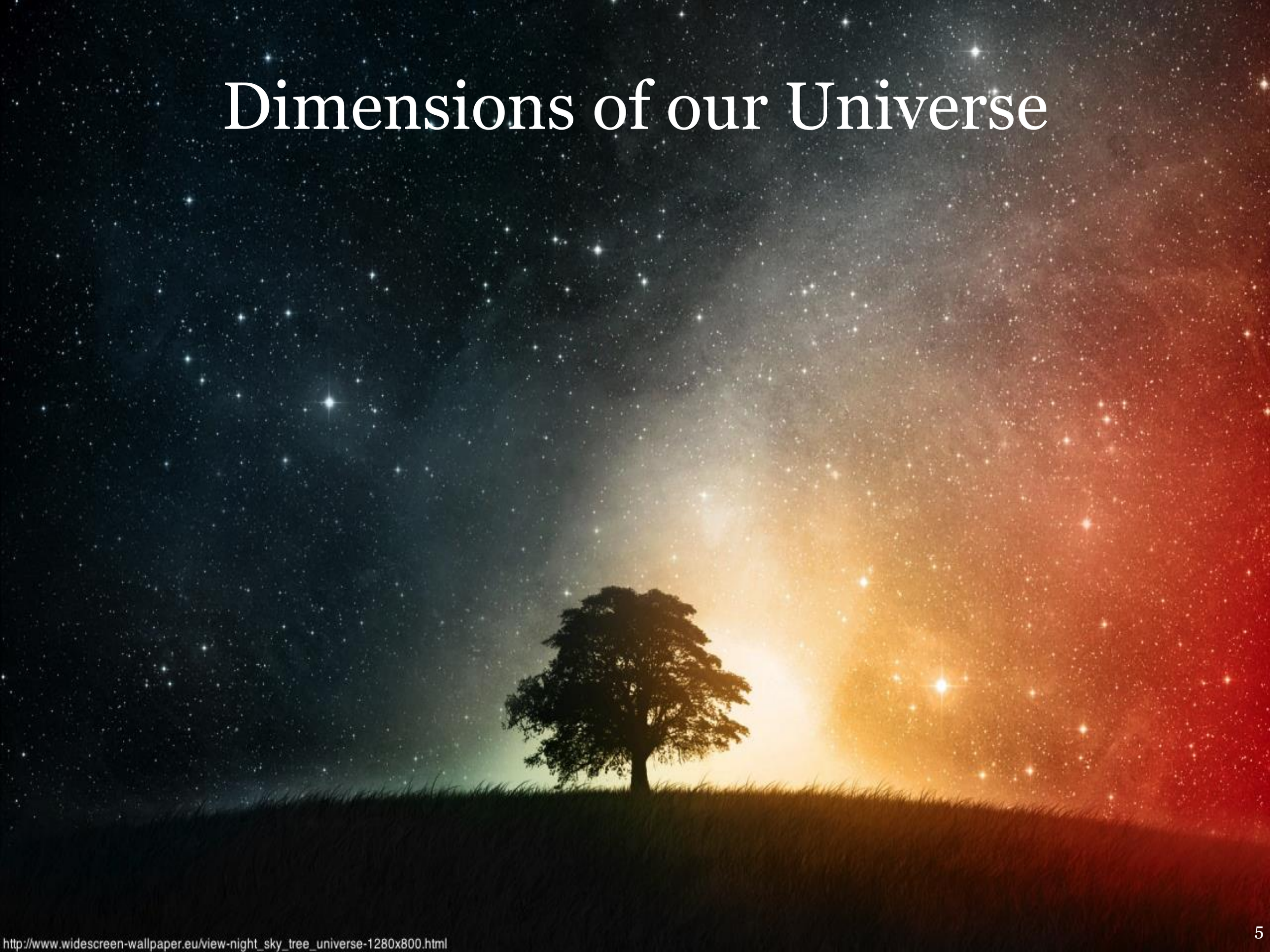
Dimensions of our Universe



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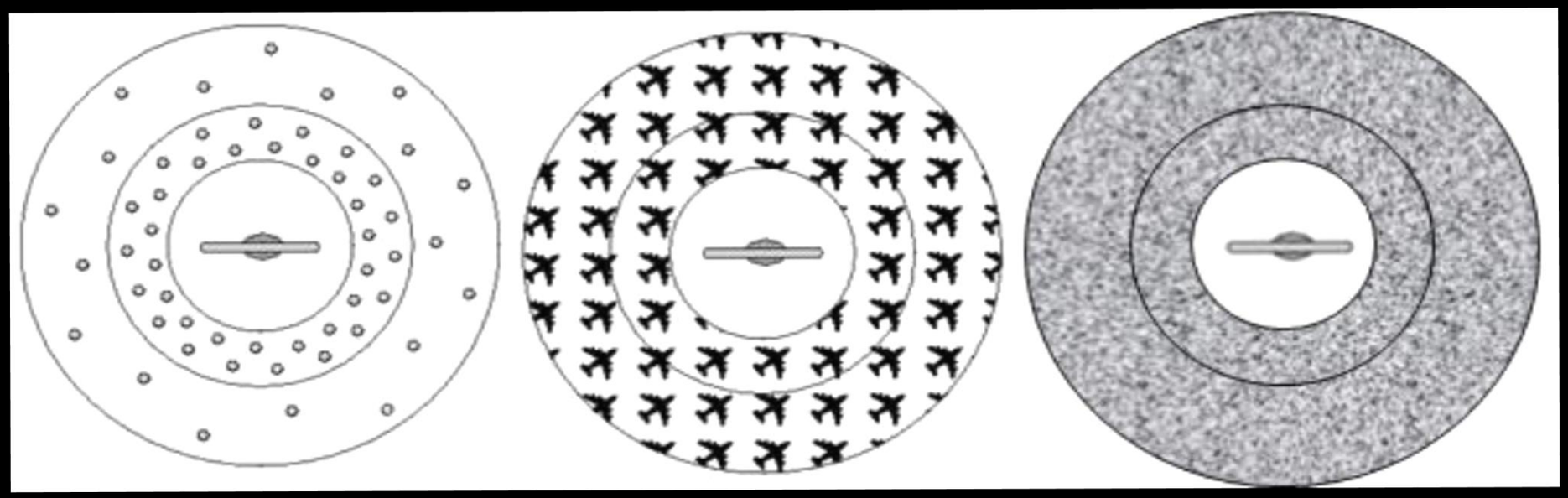
The Cosmological Principle

"On large scales the Universe is homogeneous and isotropic"

We don't find ourselves in a special place.



isotropic, but not homogeneous

homogeneous, but not isotropic

Homogeneous and isotropic

The Universe

Before the 20th century the Universe seemed to be a quiet place.
It was not very busy.

Most of the physicists believed the Universe being infinite in space and time.

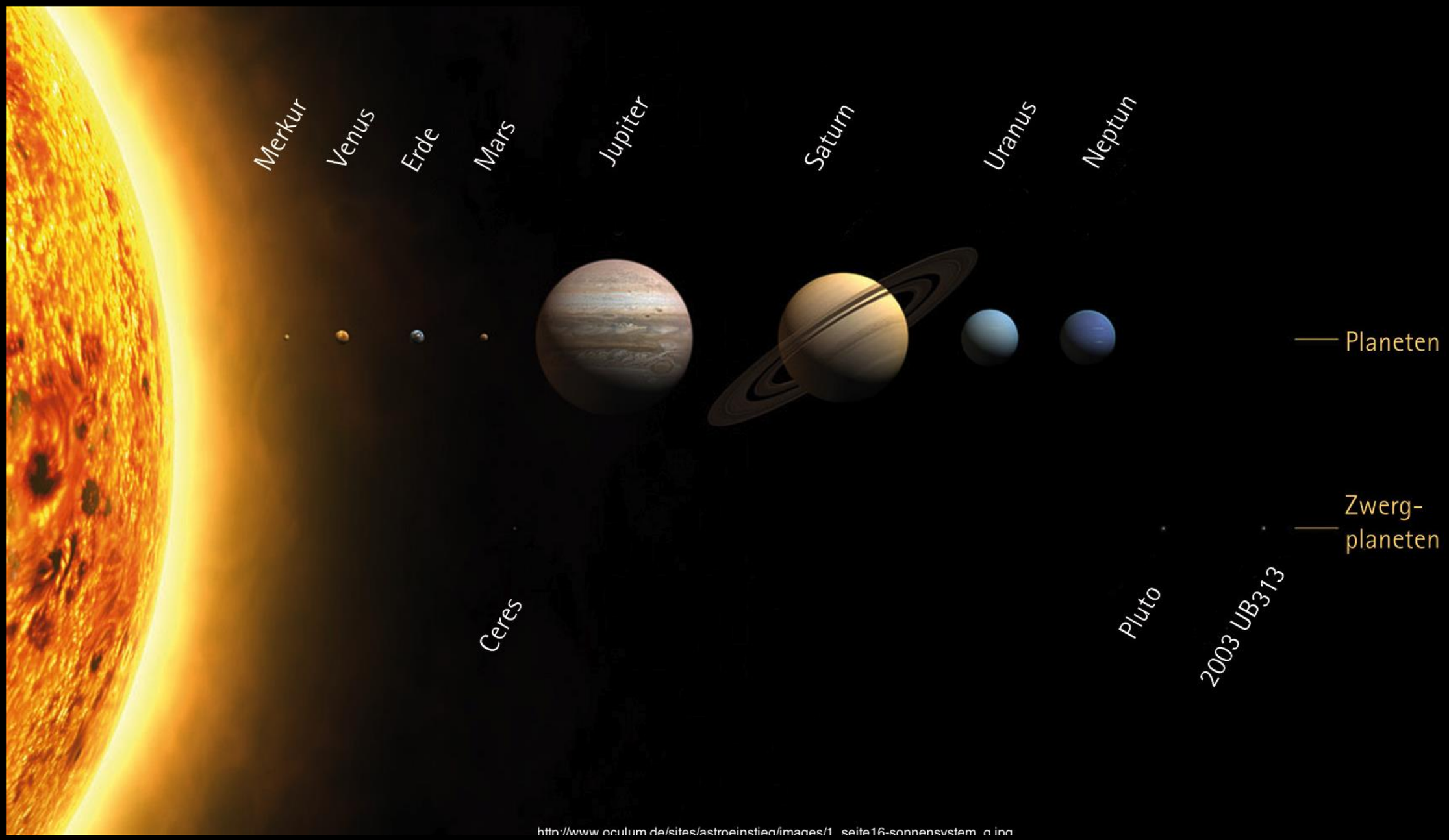
But there was a strange observation:

At night it is dark

This couldn‘t be explained with an infinitely large and old Universe.

The Earth: ≈13000 km in diameter

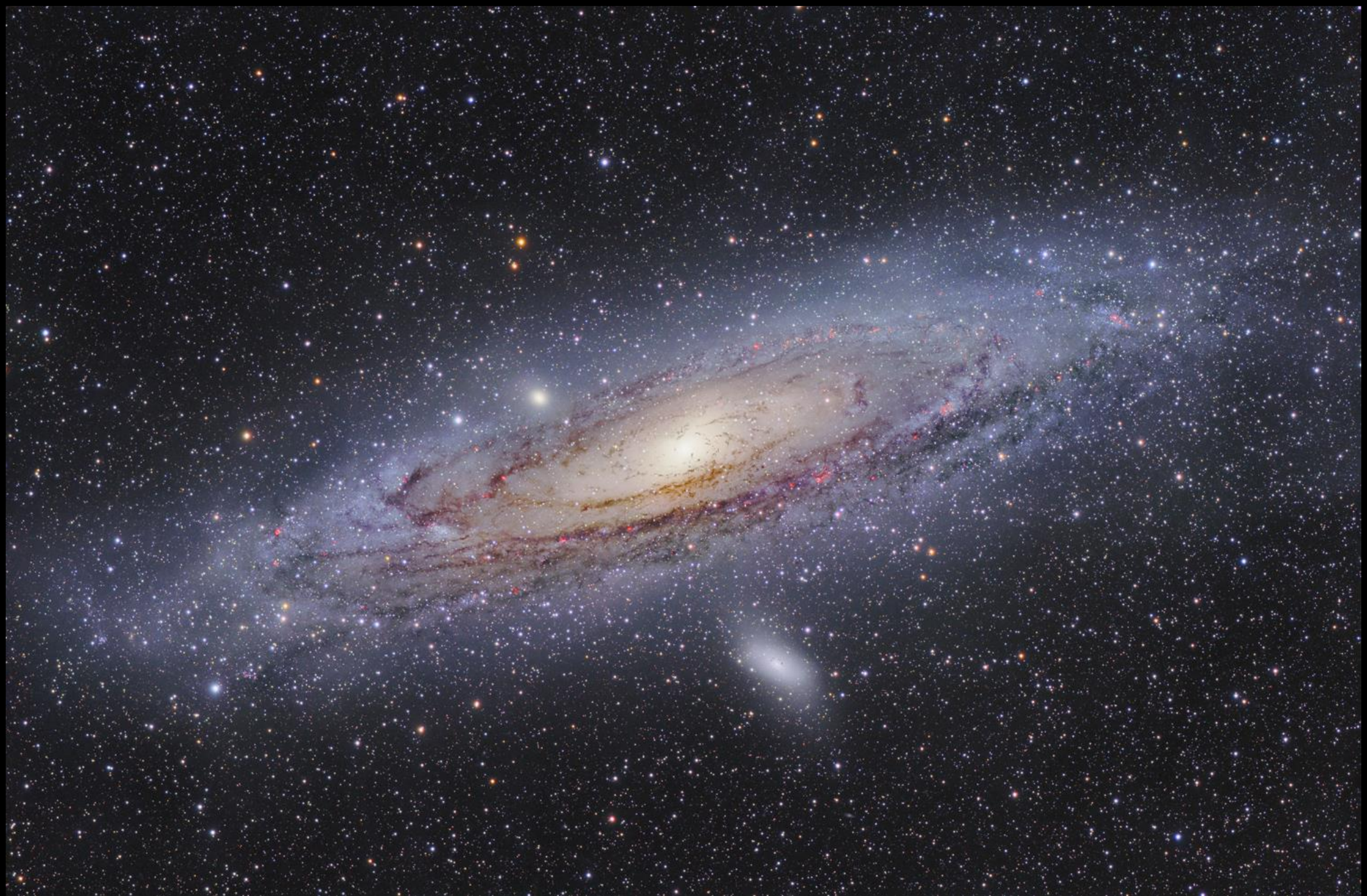
The Solar System:
≈10 billion km in diameter



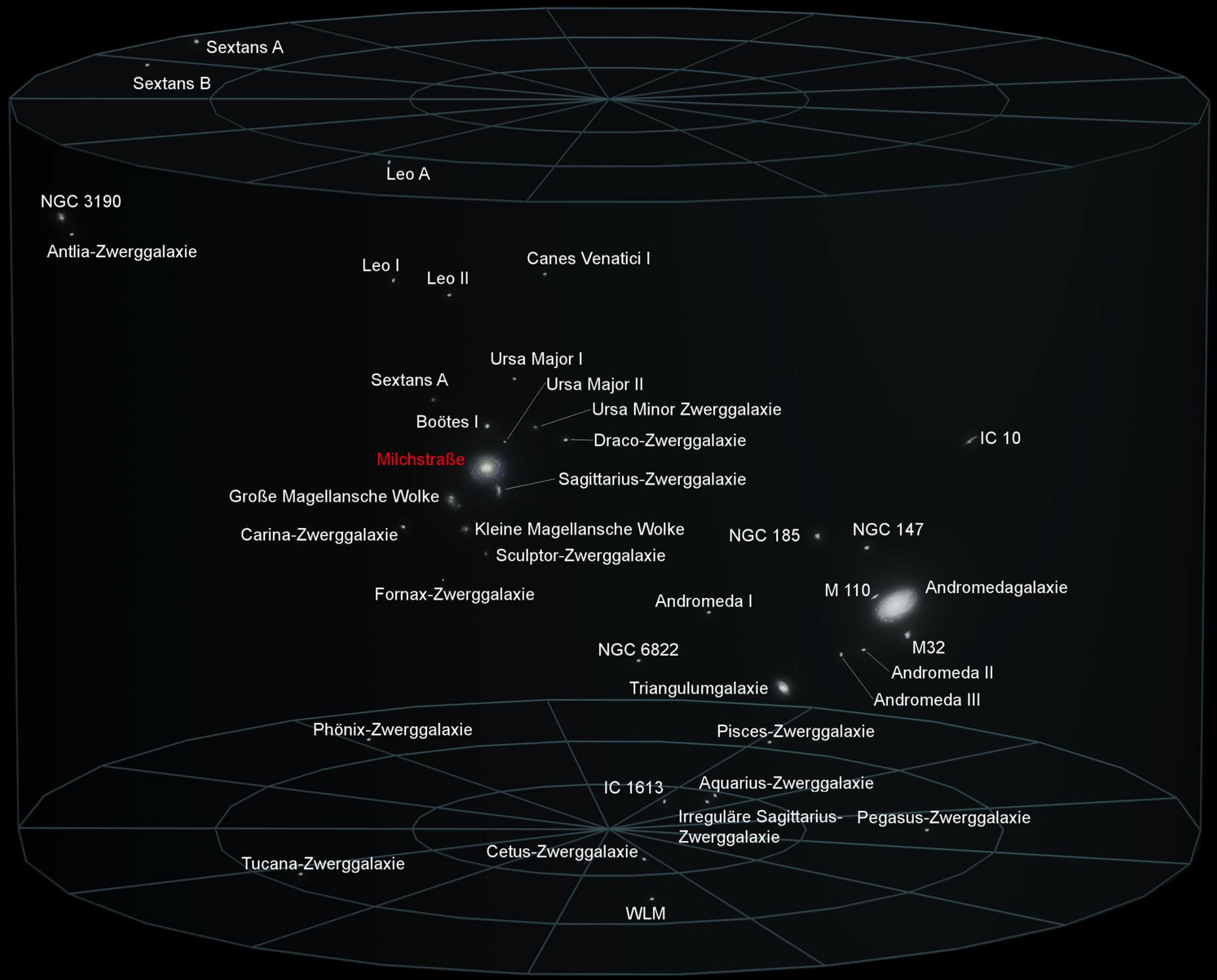
http://www.oculum.de/sites/astroeinstieg/images/1_seite16-sonnensystem_g.jpg

Our Milky Way:
10^{18} km = 100000 light years in diameter

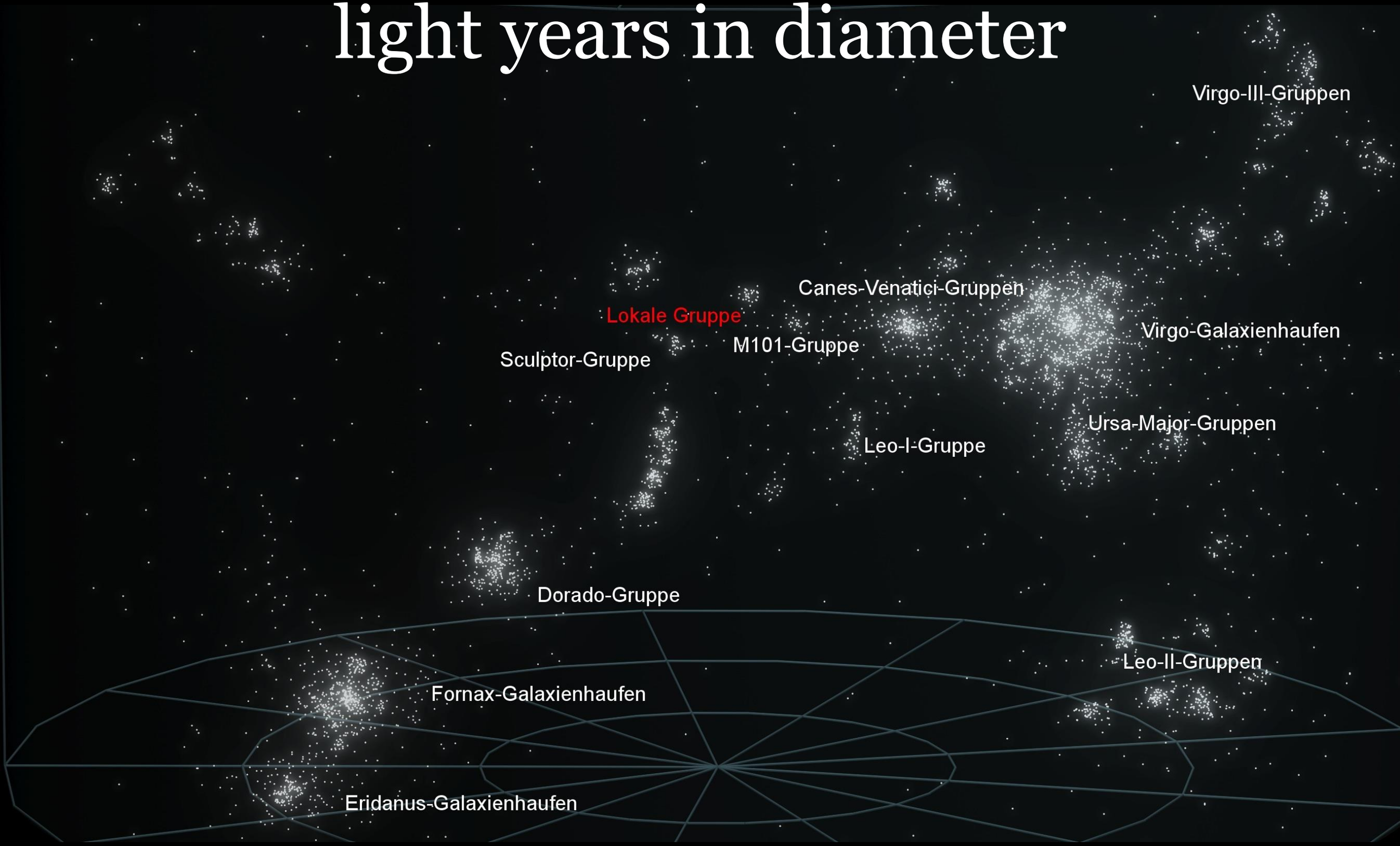
Andromeda Galaxy:
2.5 million light years distance



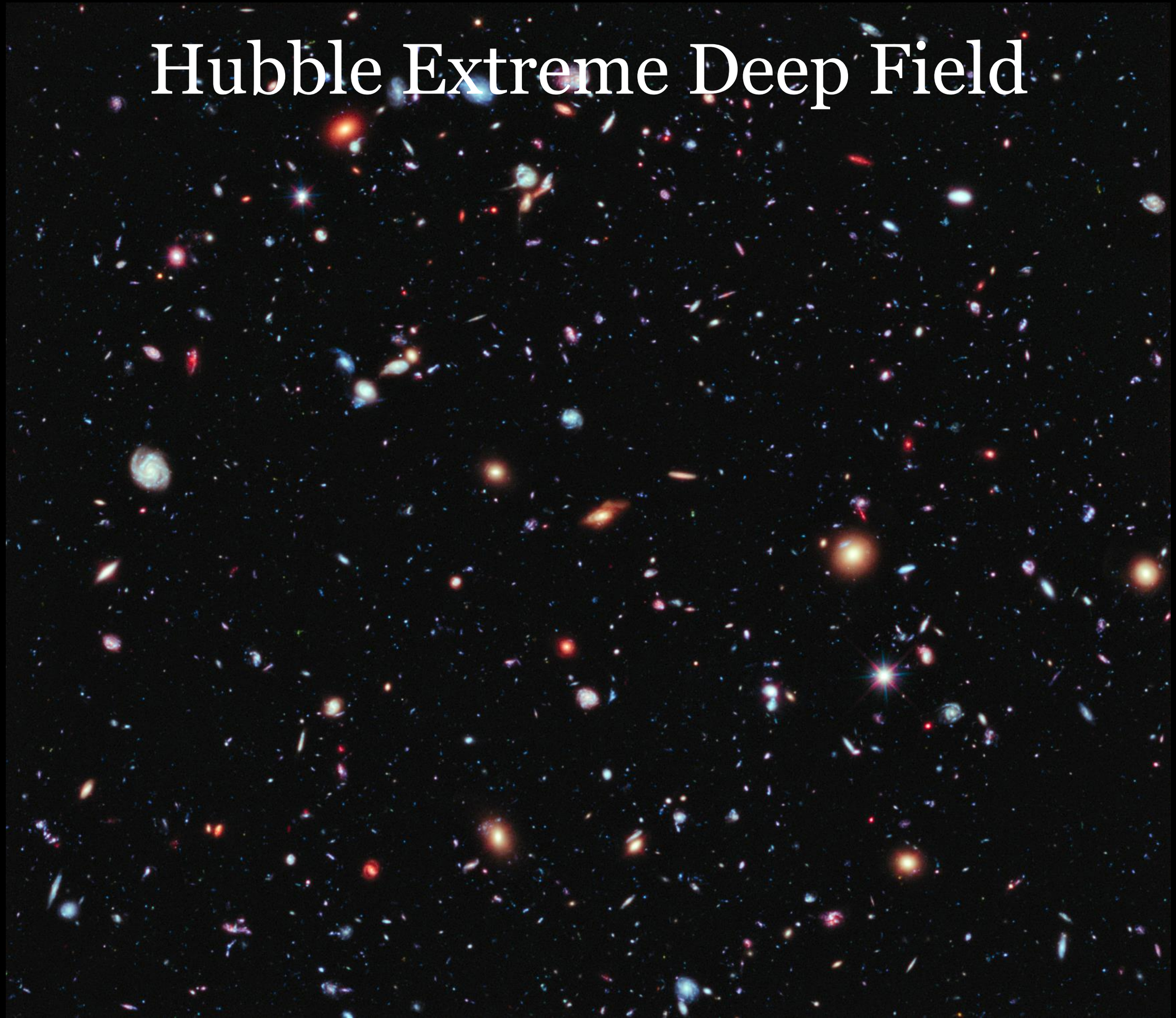
Local Group:
8 million light years in diameter



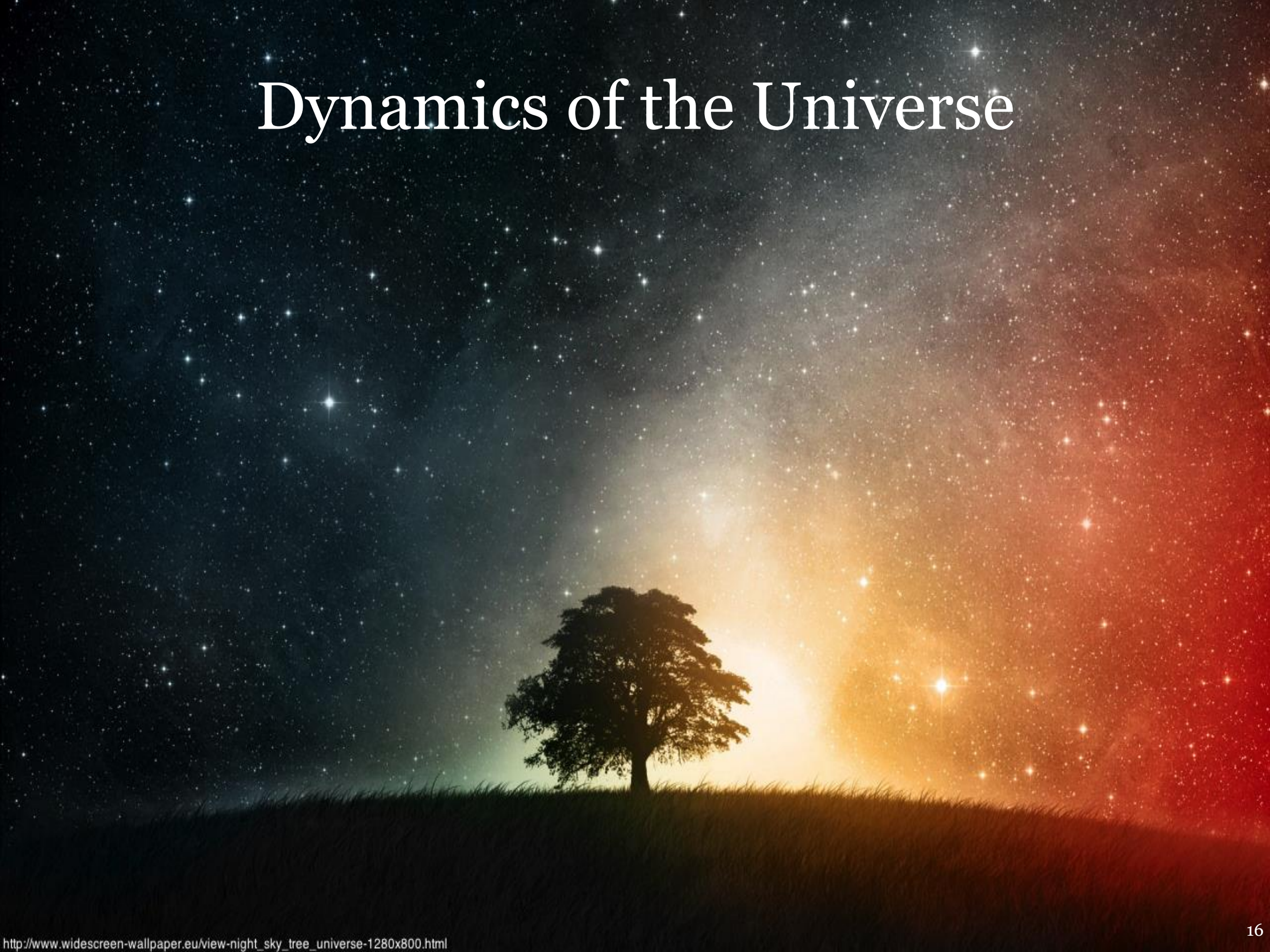
Virgo Supercluster: 100-200 million light years in diameter



Hubble Extreme Deep Field



Dynamics of the Universe



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The Universe is bigger than we thought!

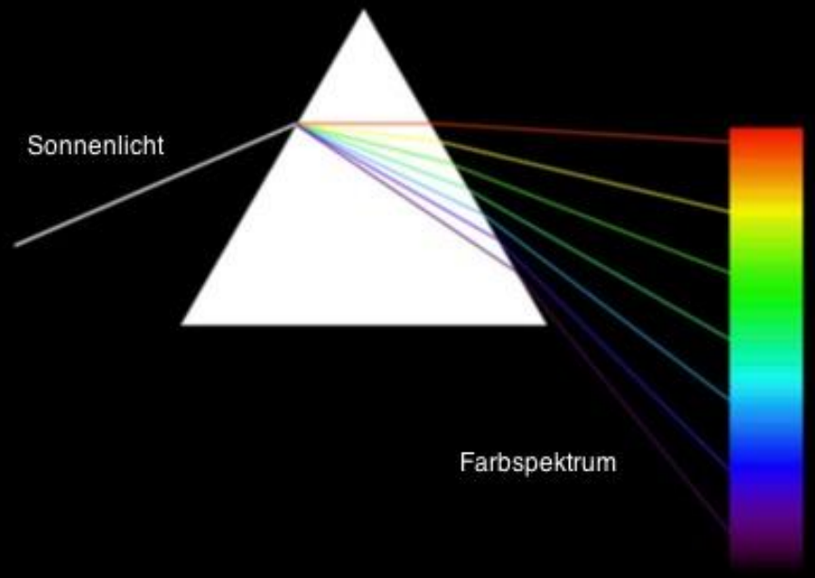
1924

Edwin Hubble
Mt. Palomar telescope

Observation of „nebulas“
Proof of the existence of galaxies outside the Milky Way

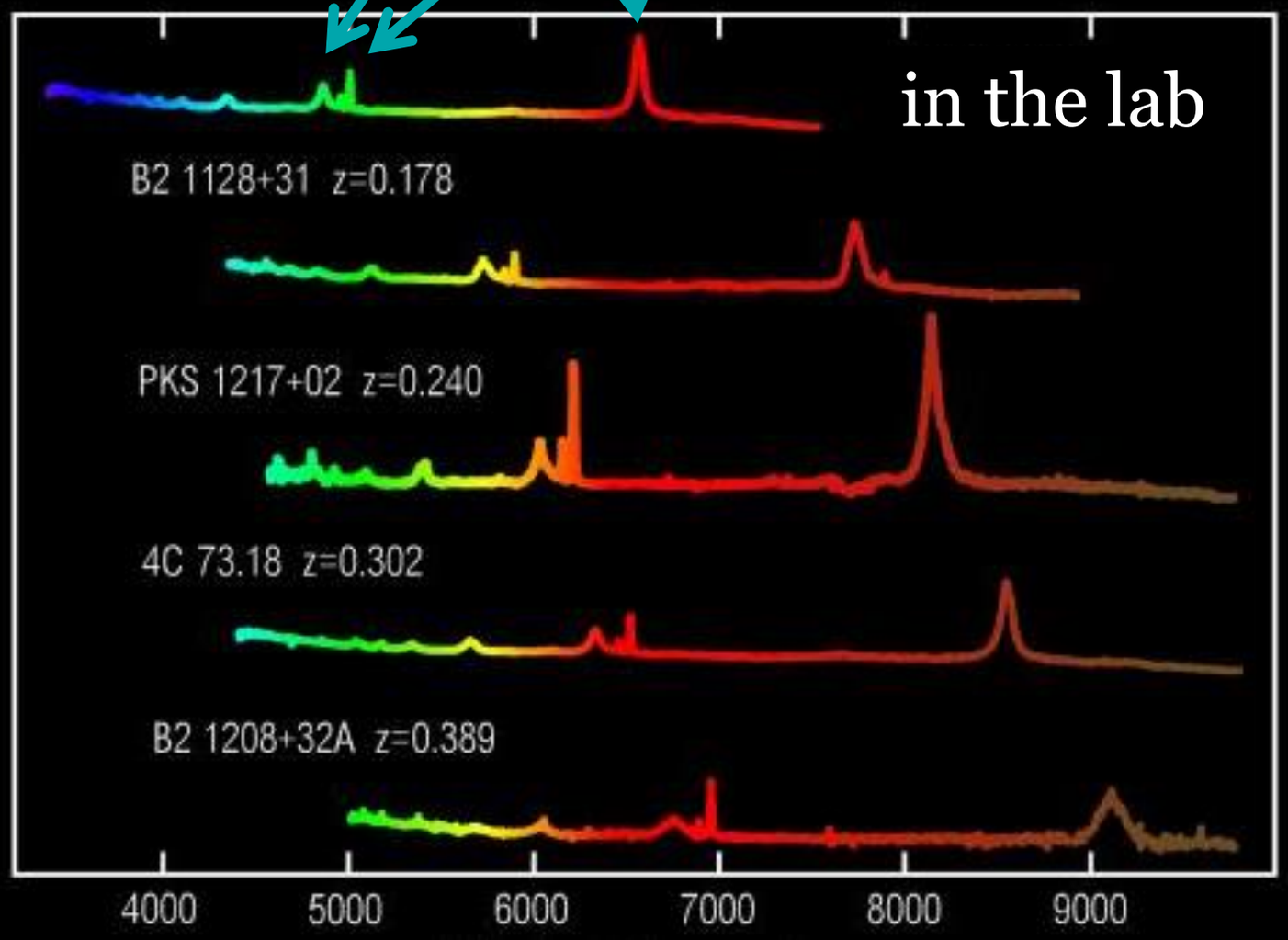
Measuring of the Redshift

Spectroscopy



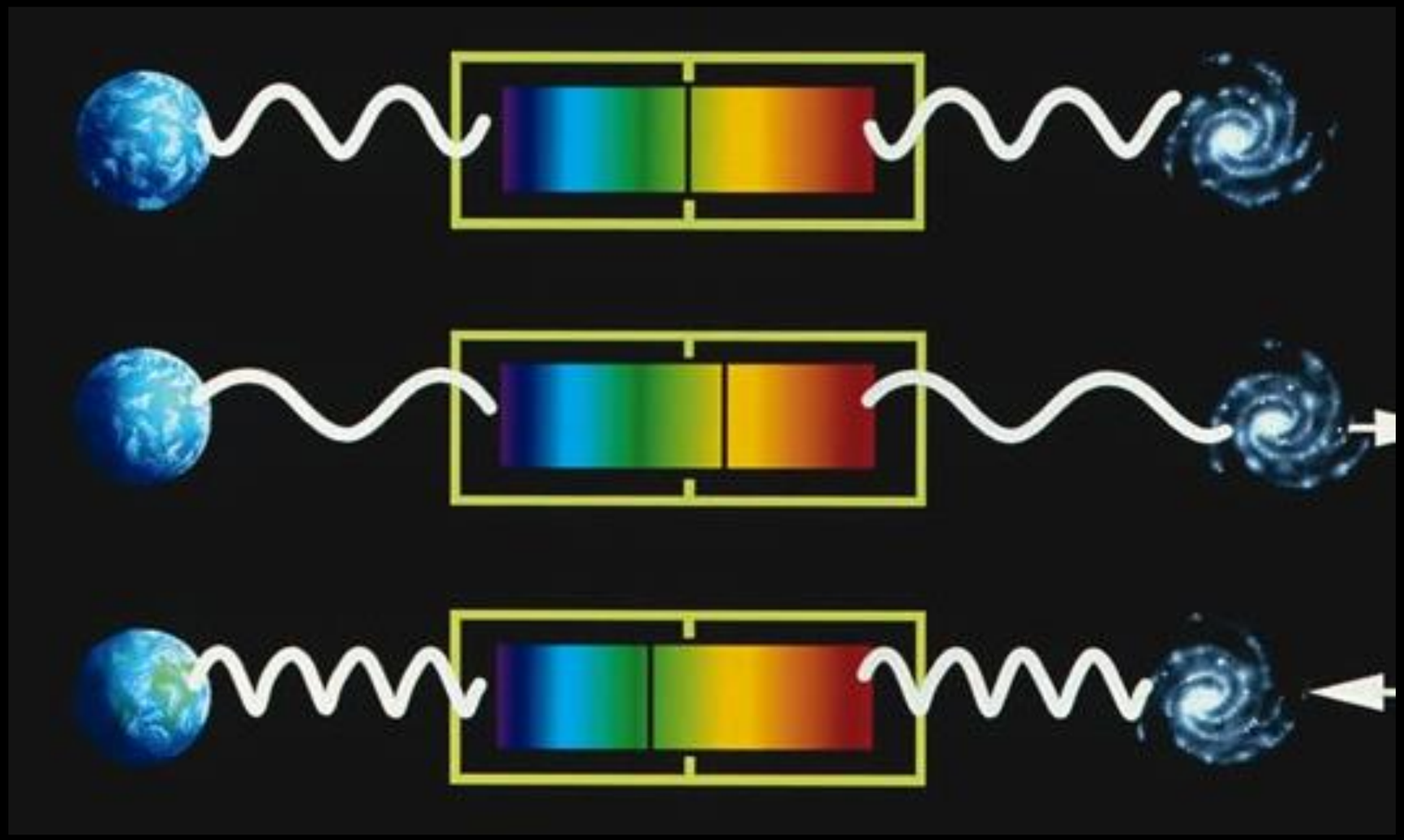
Emission lines

in the lab



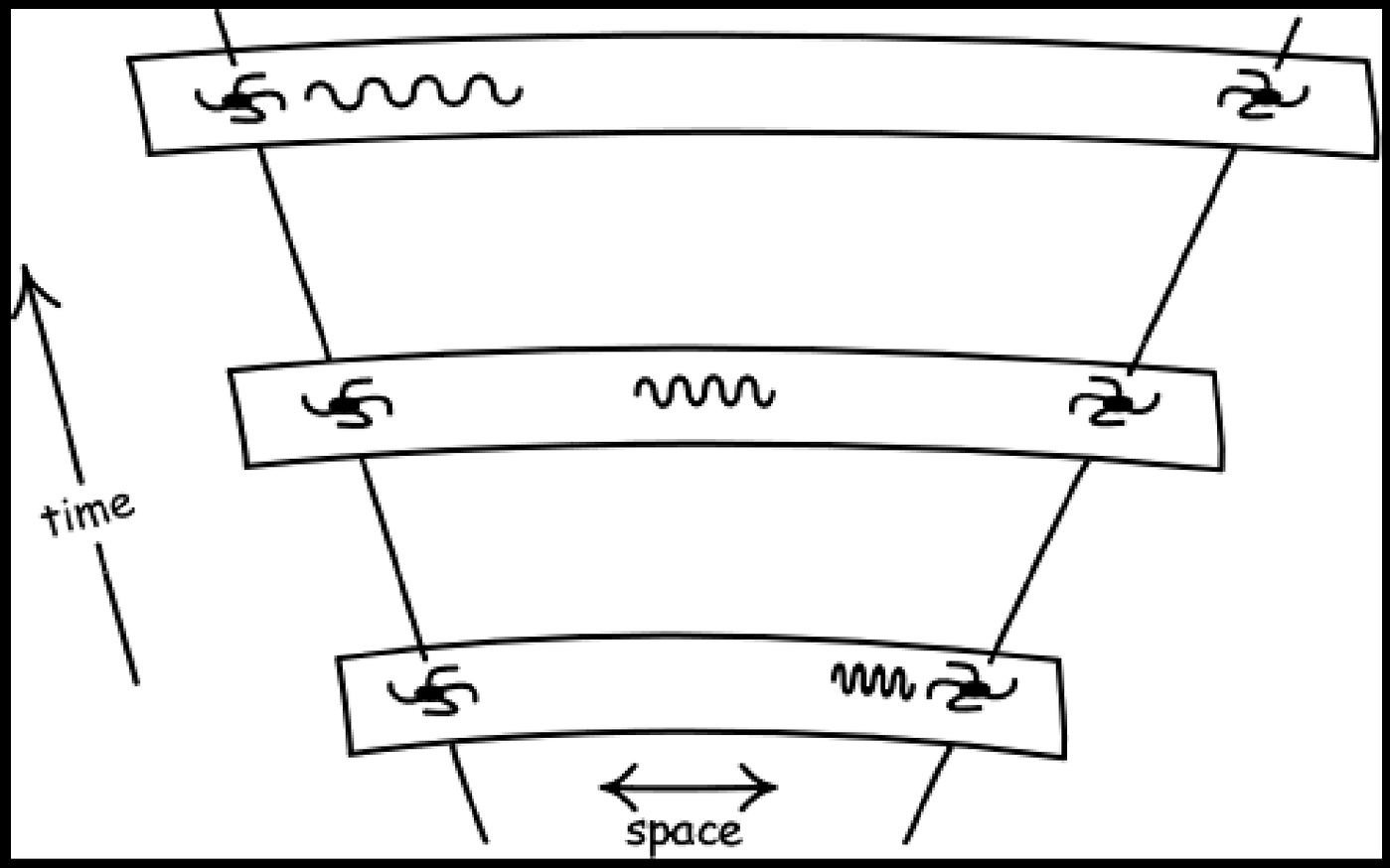
Wavelength [Å]

Cosmological Redshift vs. Doppler Effect



The cosmological redshift is comparable with a redshift caused by a relative movement of source and observer

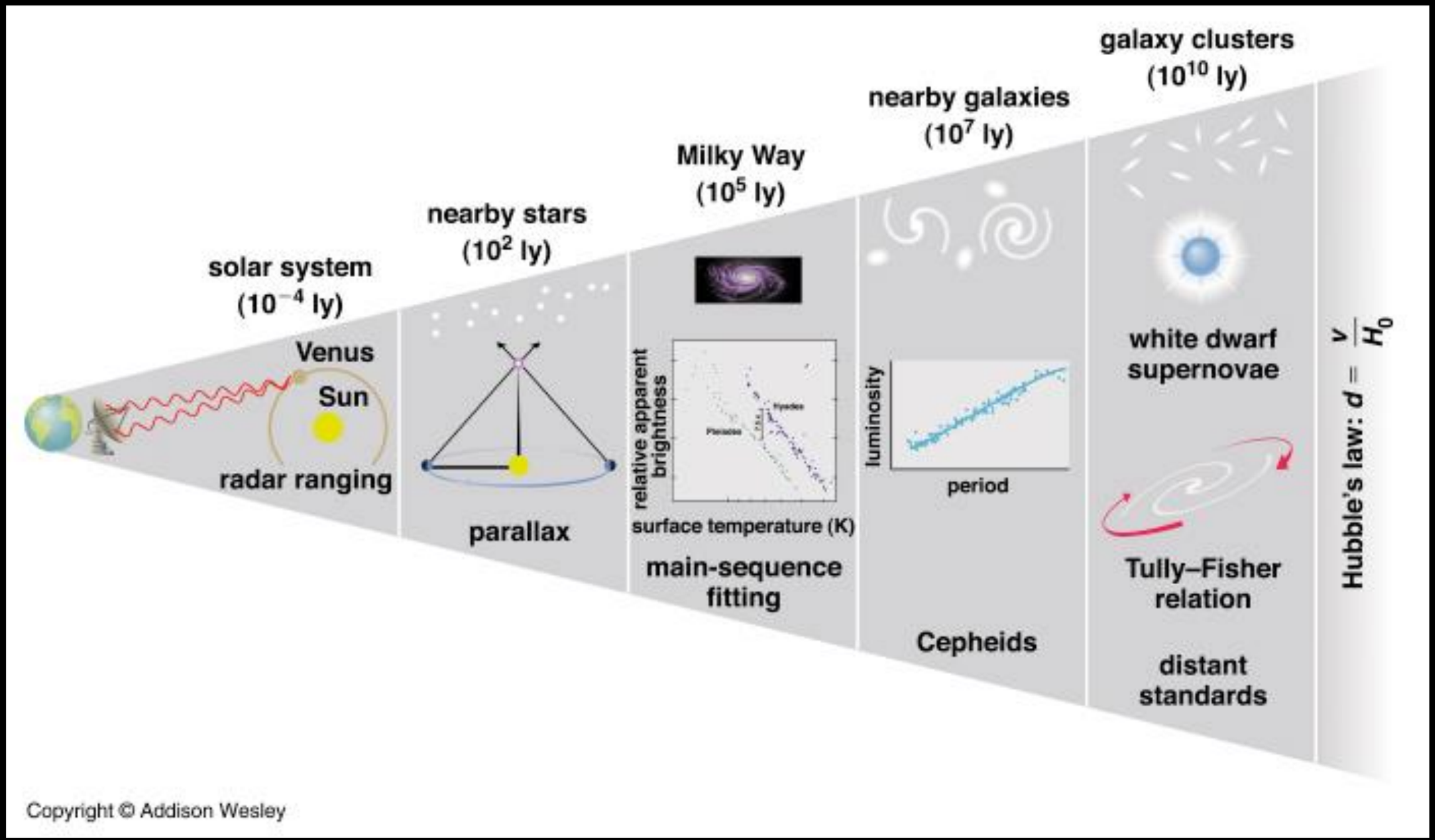
Cosmological Redshift



Space itself expands and “stretches” the wavelength of the photons.

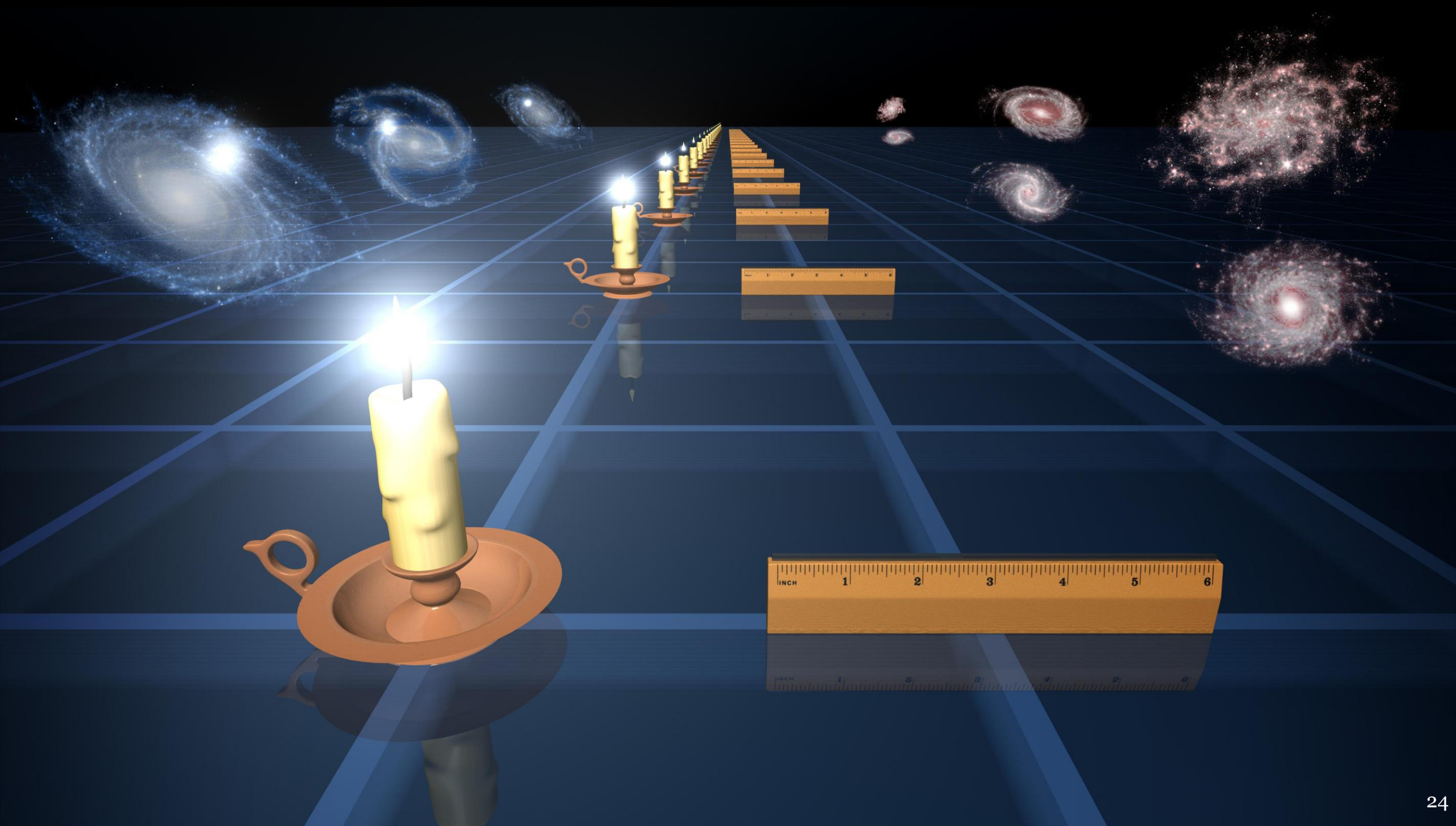
Cosmological Redshift

Distance Ladder



Type Ia Supernova

Standard Candles and Brightness



Example of a Supernova from 2011

Supernovae can temporarily release as much energy as a whole galaxy!

The Universe is expanding

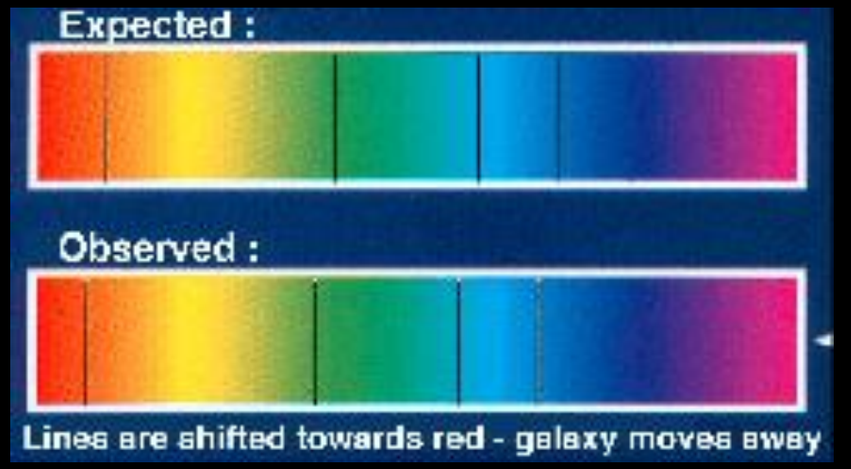
1929

A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY AMONG EXTRA-GALACTIC NEBULAE

By Edwin Hubble

Mount Wilson Observatory, Carnegie Institution of Washington

Communicated January 17, 1929



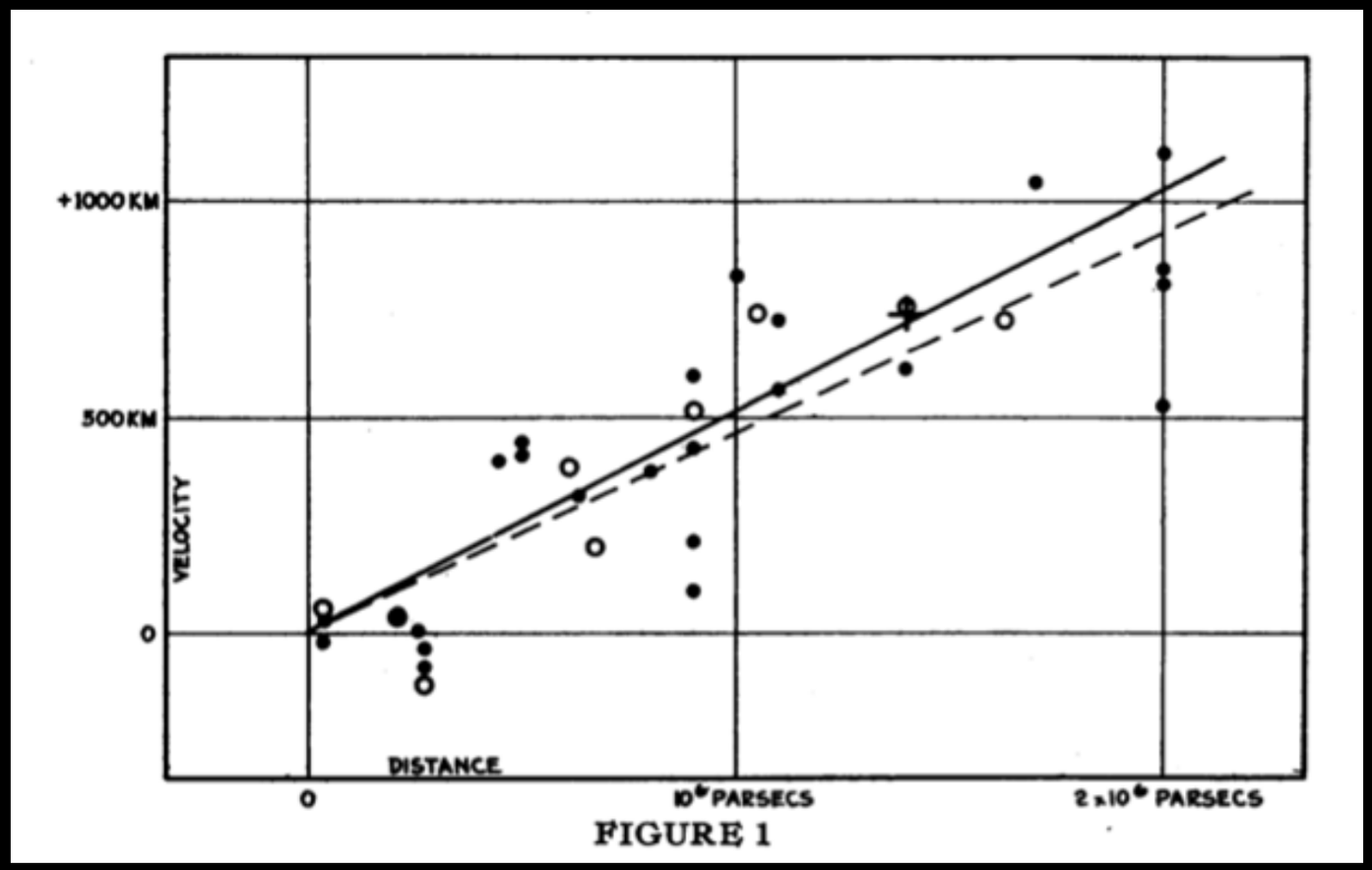


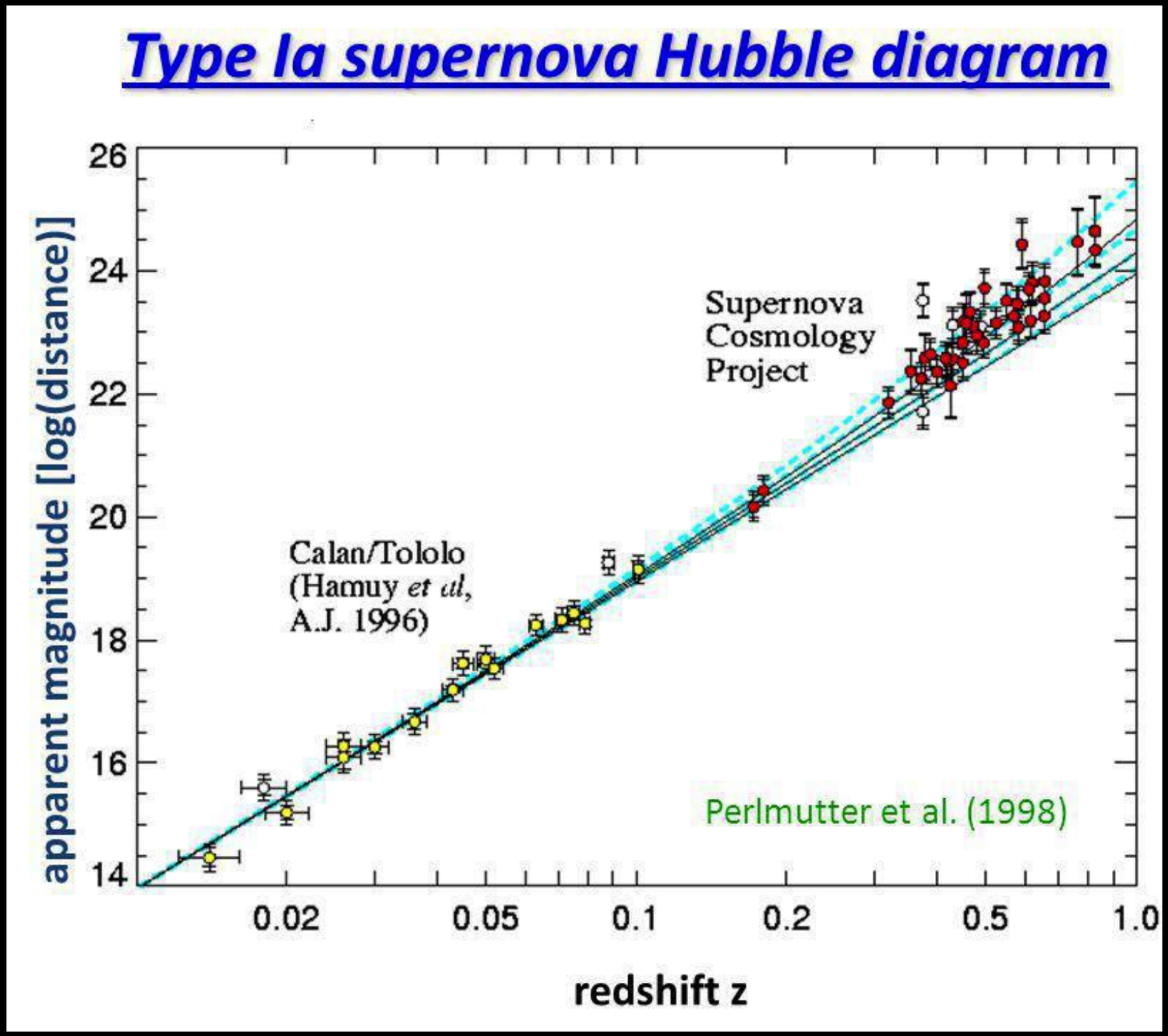
FIGURE 1

redshift is proportional to the distance of the galaxies (galaxy escape)

Hubble‘s law: $v = H_0 \, d$

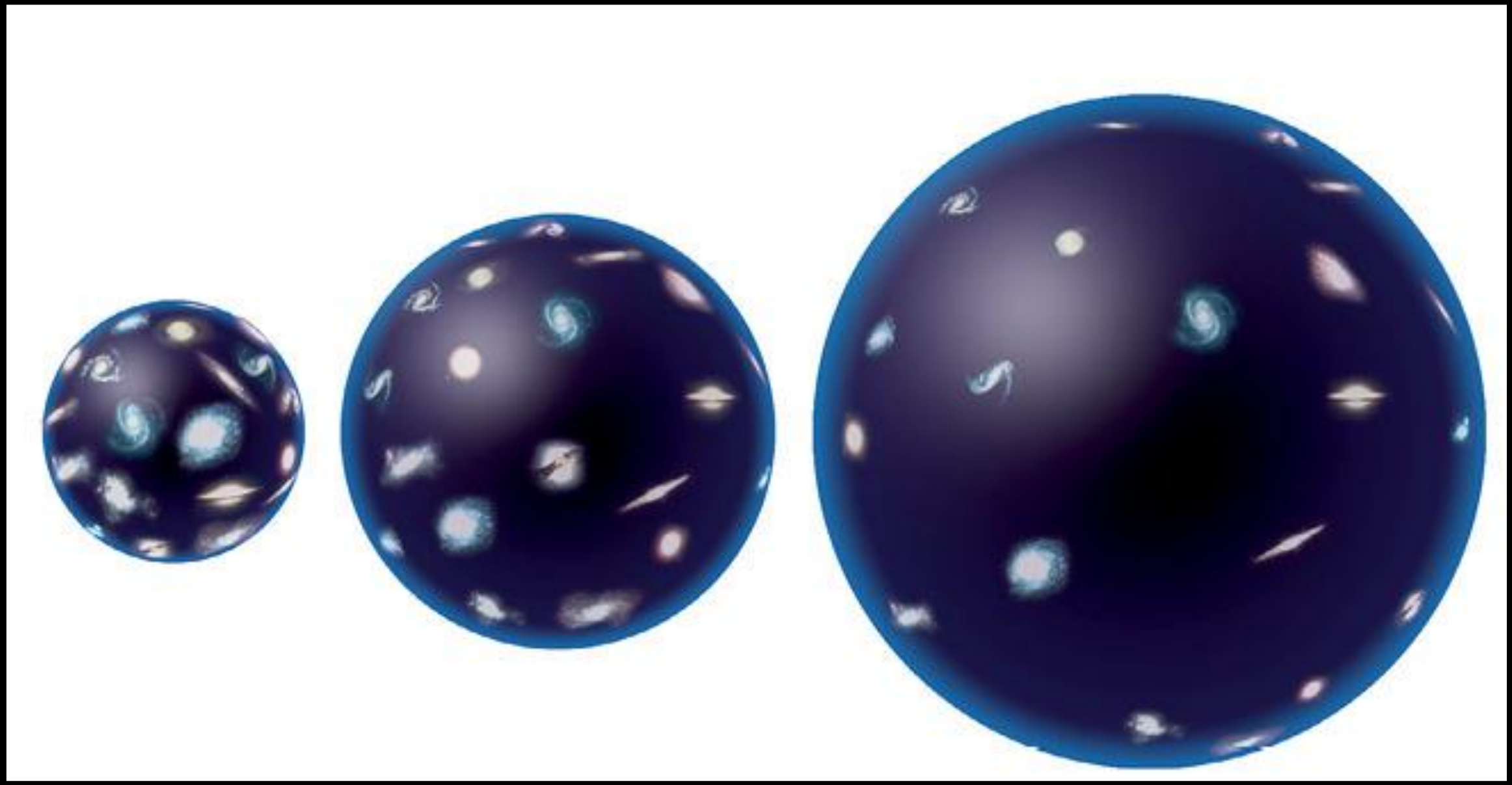
$H_0 = 530$ km/s / Mpc !!

The present value of the Hubble ”constant”



Today: $H = 67{,}3 \pm 1{,}2$ km s^{-1} Mpc^{-1}

Consequences of the Cosmological Expansion



The further we look back into the past, the smaller was the Universe.

→ conclusion about the Big Bang

A Journey through Time

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HISTORY OF THE UNIVERSE

Dark energy accelerated expansion

Structure formation

Cosmic Microwave Background radiation is visible

Accelerators

RHIC & LHC heavy ions

LHC protons

High-energy cosmic rays

Size of visible universe

TODAY

Inflation

Big Bang

POSSIBLE DARK MATTER RELICS

NUCLEONS FORM

NUCLEI FORM

$t = 10^{-36}$ s
$E = 10^{16}$ GeV

$t = 10^{-10}$ s
$E = 10^{2}$ GeV

$t = 10^{-4}$ s
$E = 10^{-1}$ GeV

$t = 10^{2}$ s
$E = 10^{-4}$ GeV

$t = 3 \times 10^{5}$ y
$E = 3 \times 10^{-10}$ GeV

$t = 10^{9}$ y
$E = 10^{-12}$ GeV

$t = 13.8 \times 10^{9}$ y
$E = 2.3 \times 10^{-13}$ GeV

t = Time (seconds, years)

E = Energy (GeV)

Key

- quark
- gluon
- electron
- muon
- tau
- neutrino
- bosons
- meson
- baryon
- ion
- atom
- photon
- star
- galaxy
- black hole

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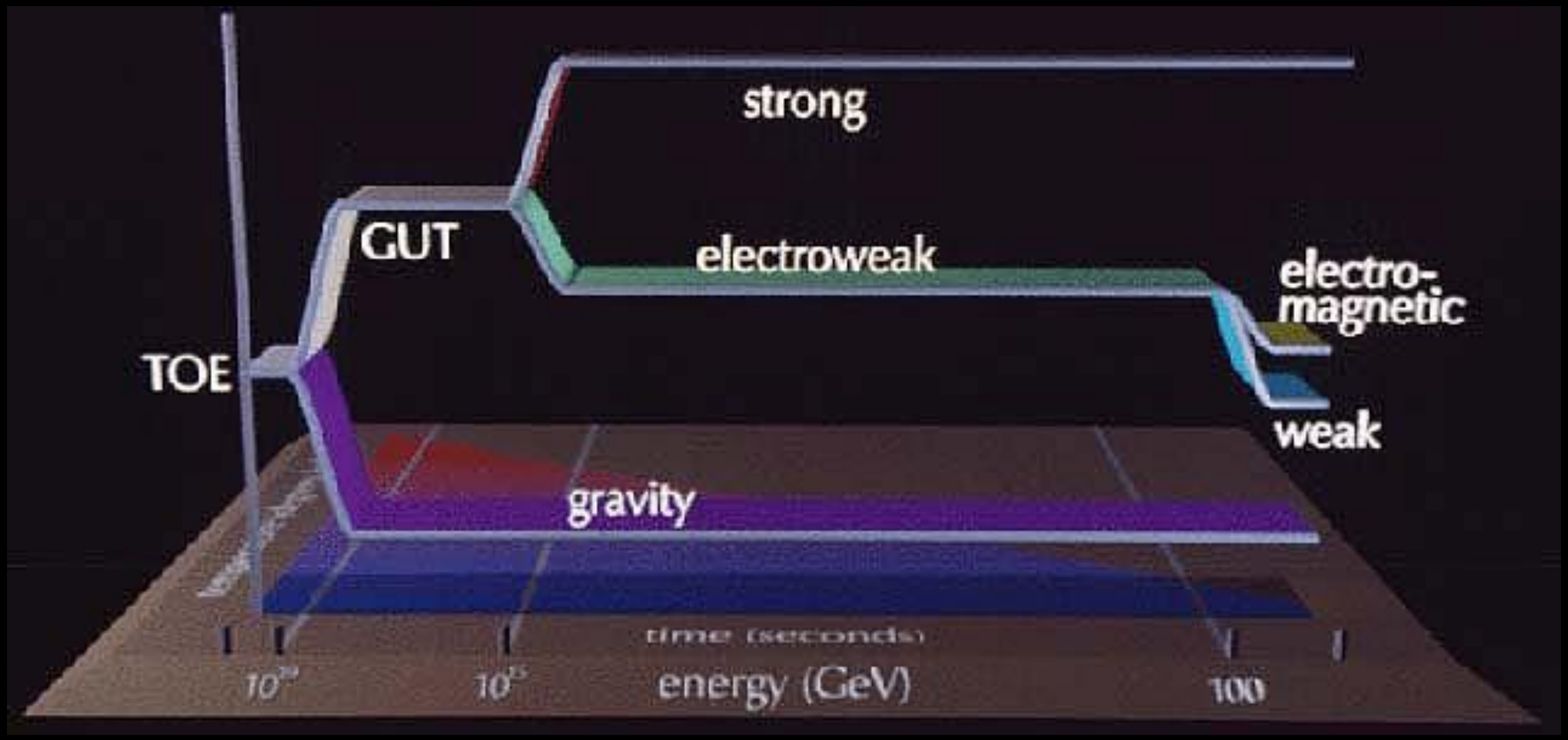
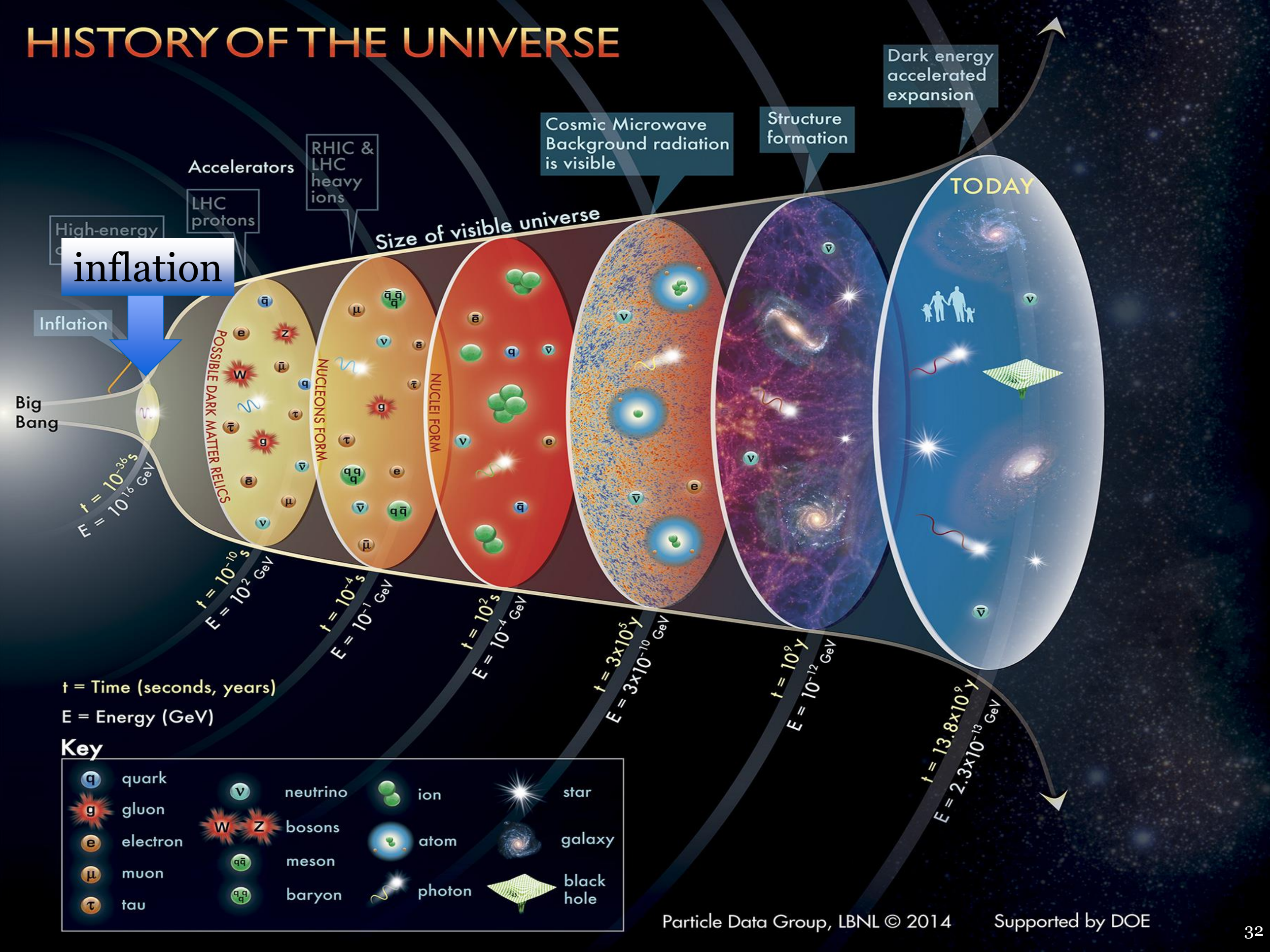
Unification of the Forces

age 10^{-36} s: strong and electroweak force get separated

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HISTORY OF THE UNIVERSE

destruction battle

Dark energy accelerated expansion

Cosmic Microwave Background radiation is visible

Structure formation

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LHC proton

ions

High-energy cosmic rays

Size of visible universe

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star, galaxy, black hole

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HISTORY OF THE UNIVERSE

nucleosynthesis

Dark energy accelerated expansion

Structure formation

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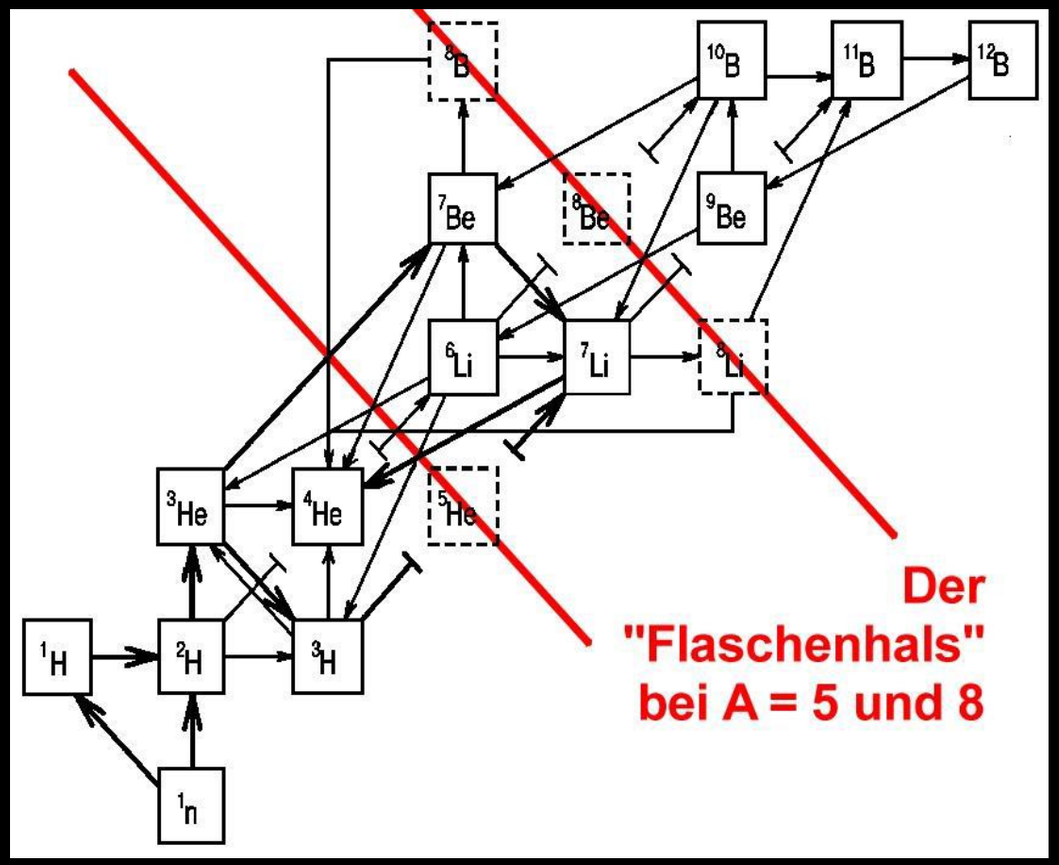
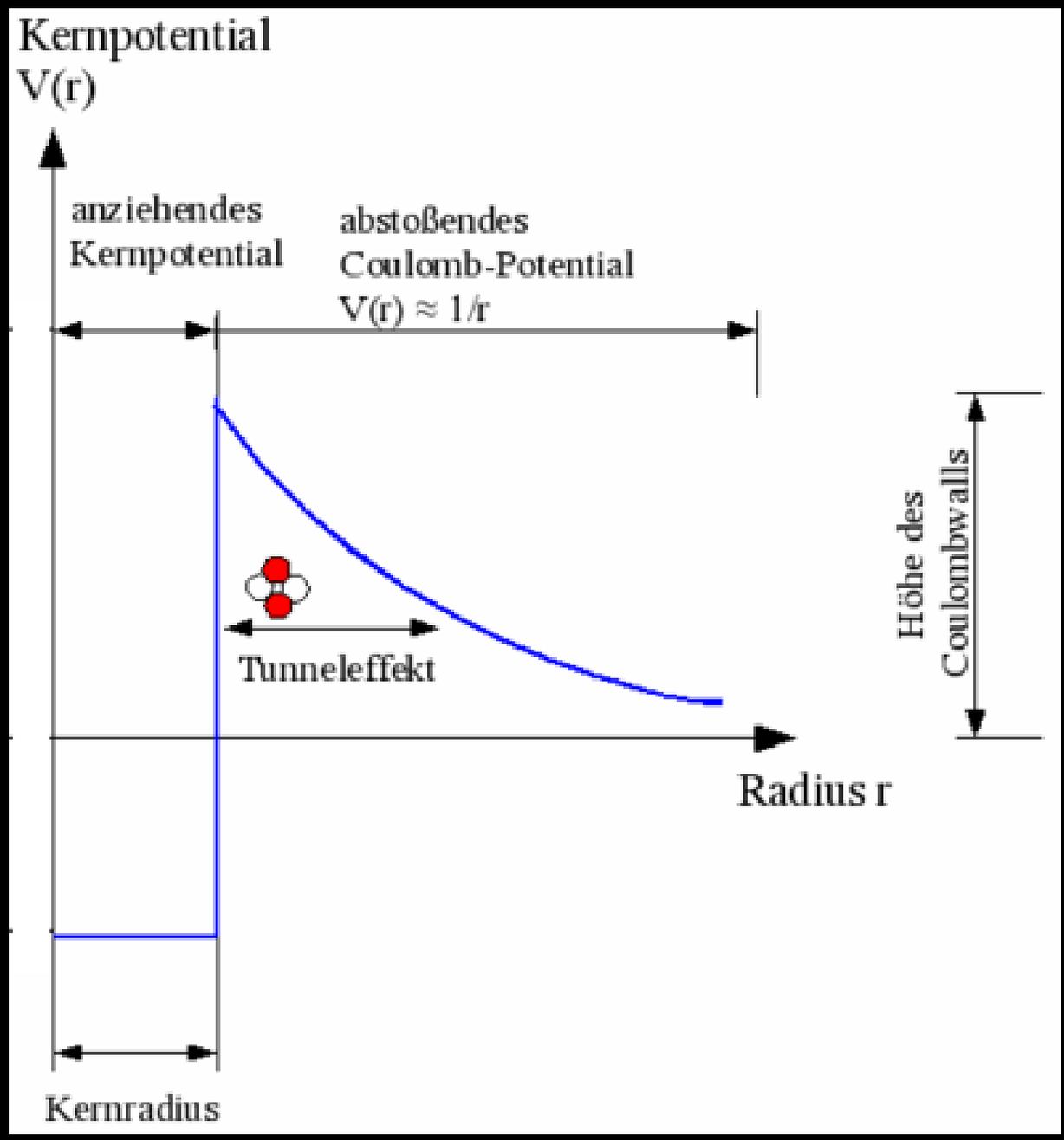
Nuclear Fusion

fusion in particle collisions

fusion needs high temperatures
and high particle densities





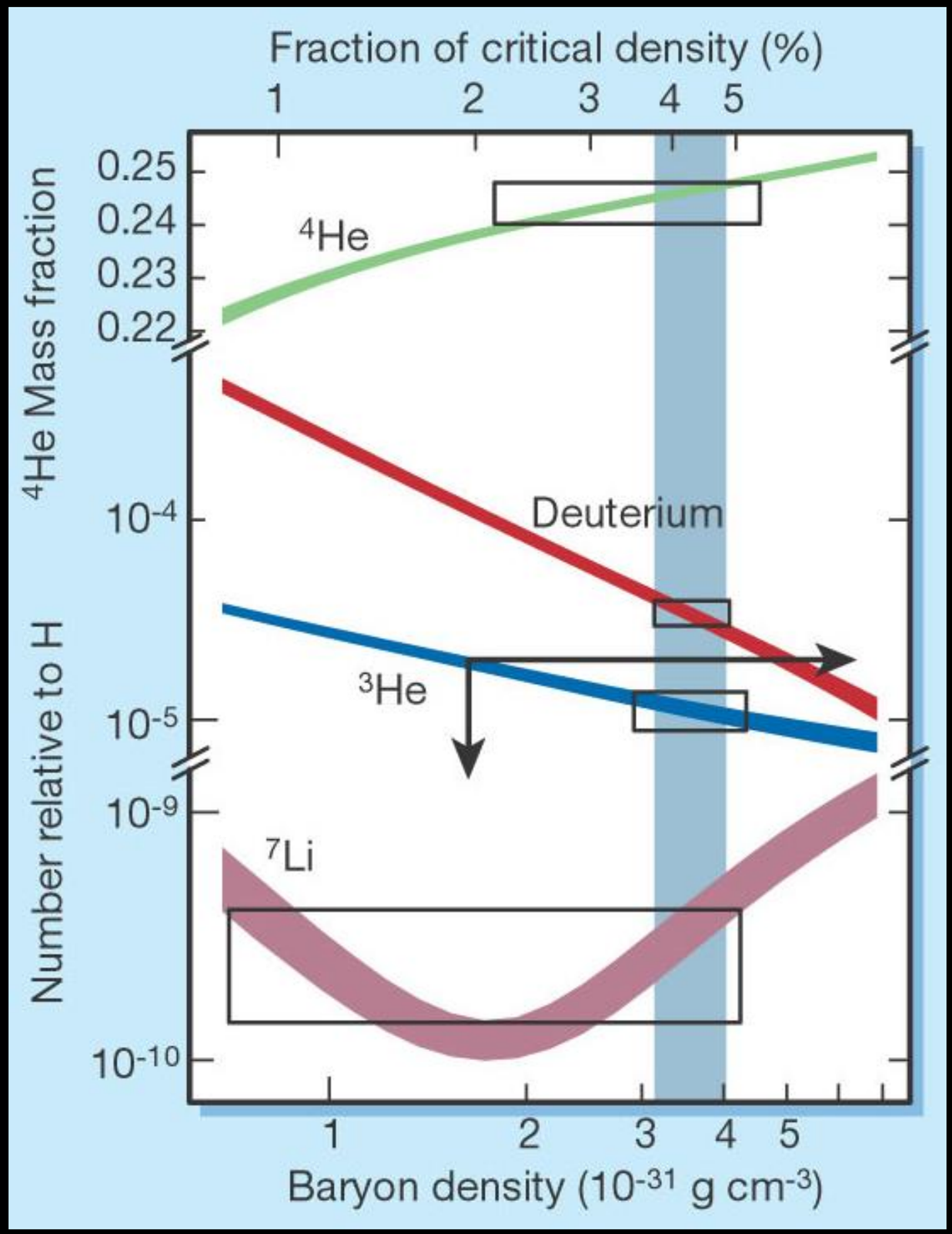
Primordial Nucleosynthesis

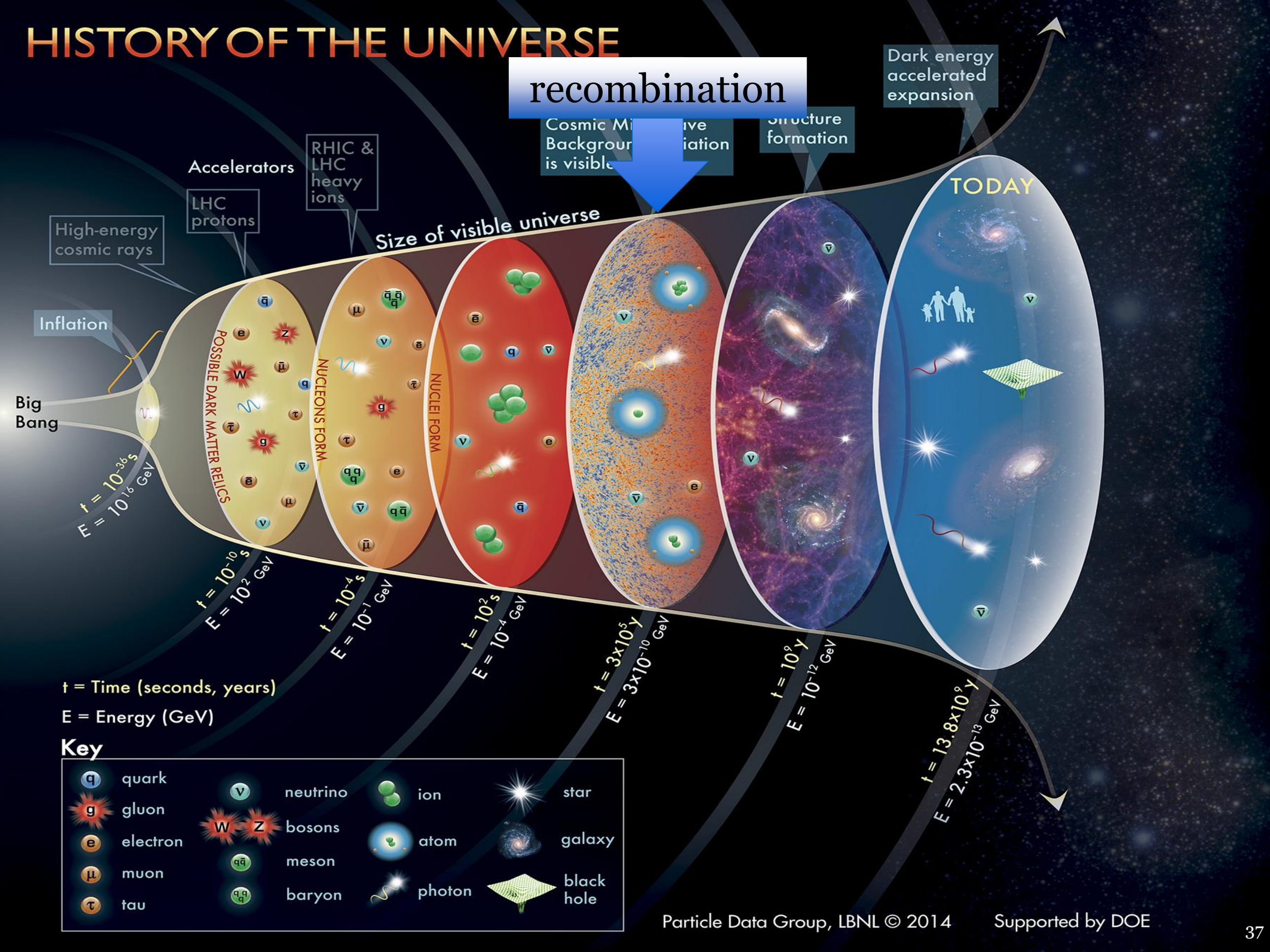
explains the abundances of light elements

- 74 % hydrogen
- 25 % helium
- 1 % rest

baryon density about
3,5 10^{-31} g/cm^3 or
0,2 hydrogen atoms/m^3

baryons contribute about
4-5% to the critical density

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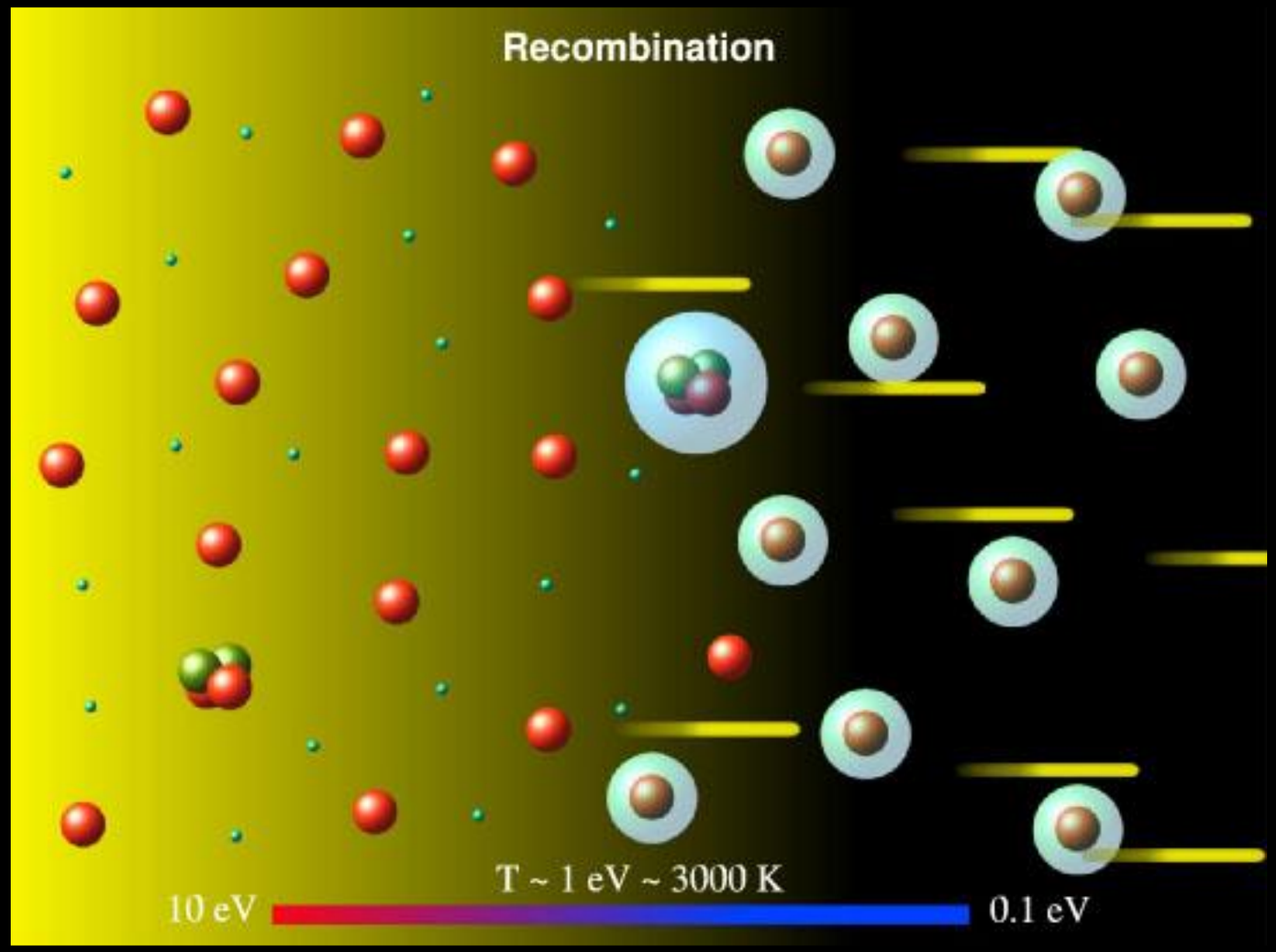
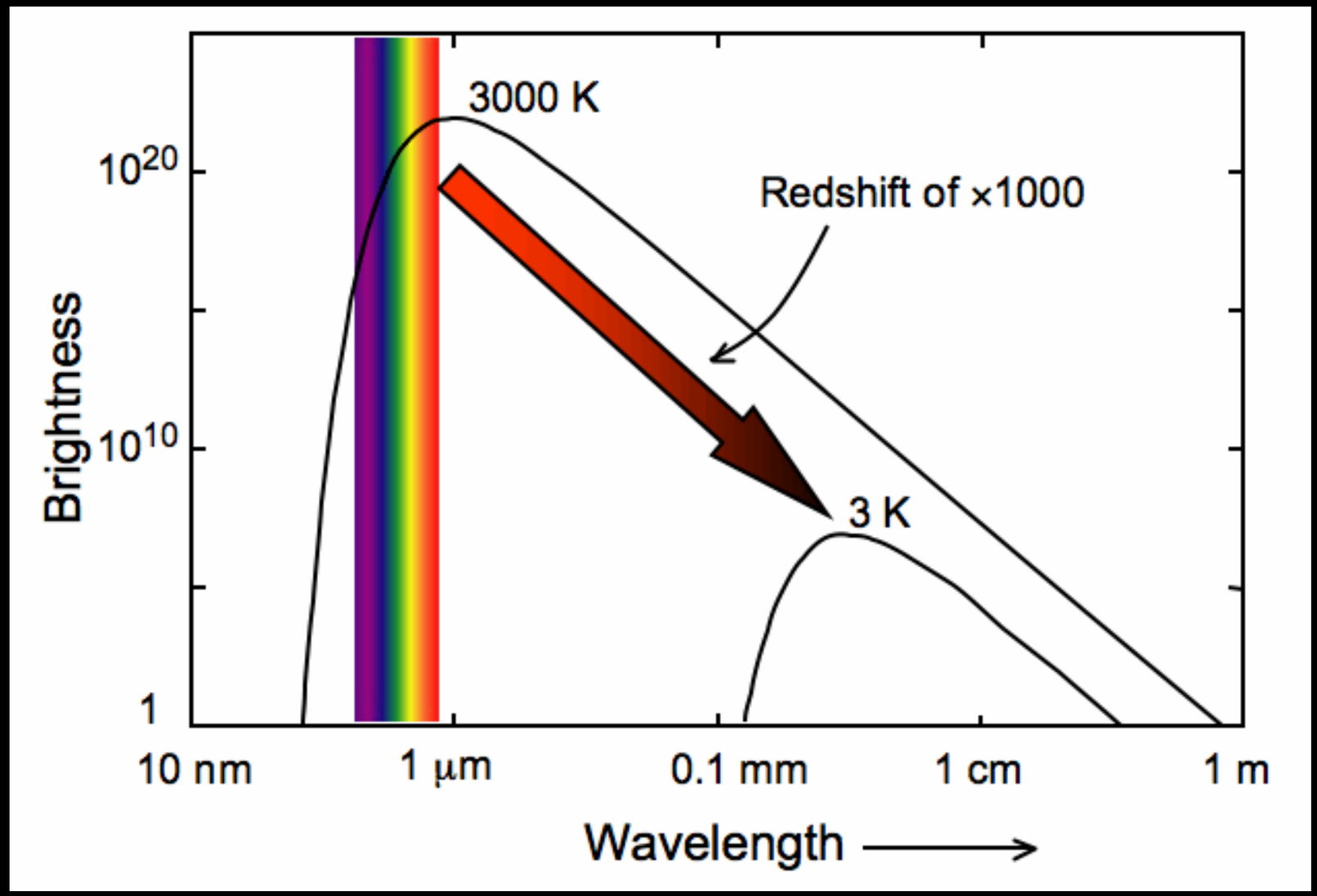
Recombination



- below T = 3000 K (t = 380000 a) neutral atoms can form
- afterwards photons don't scatter any more on free electrons
  ⟹ The Universe becomes transparent!

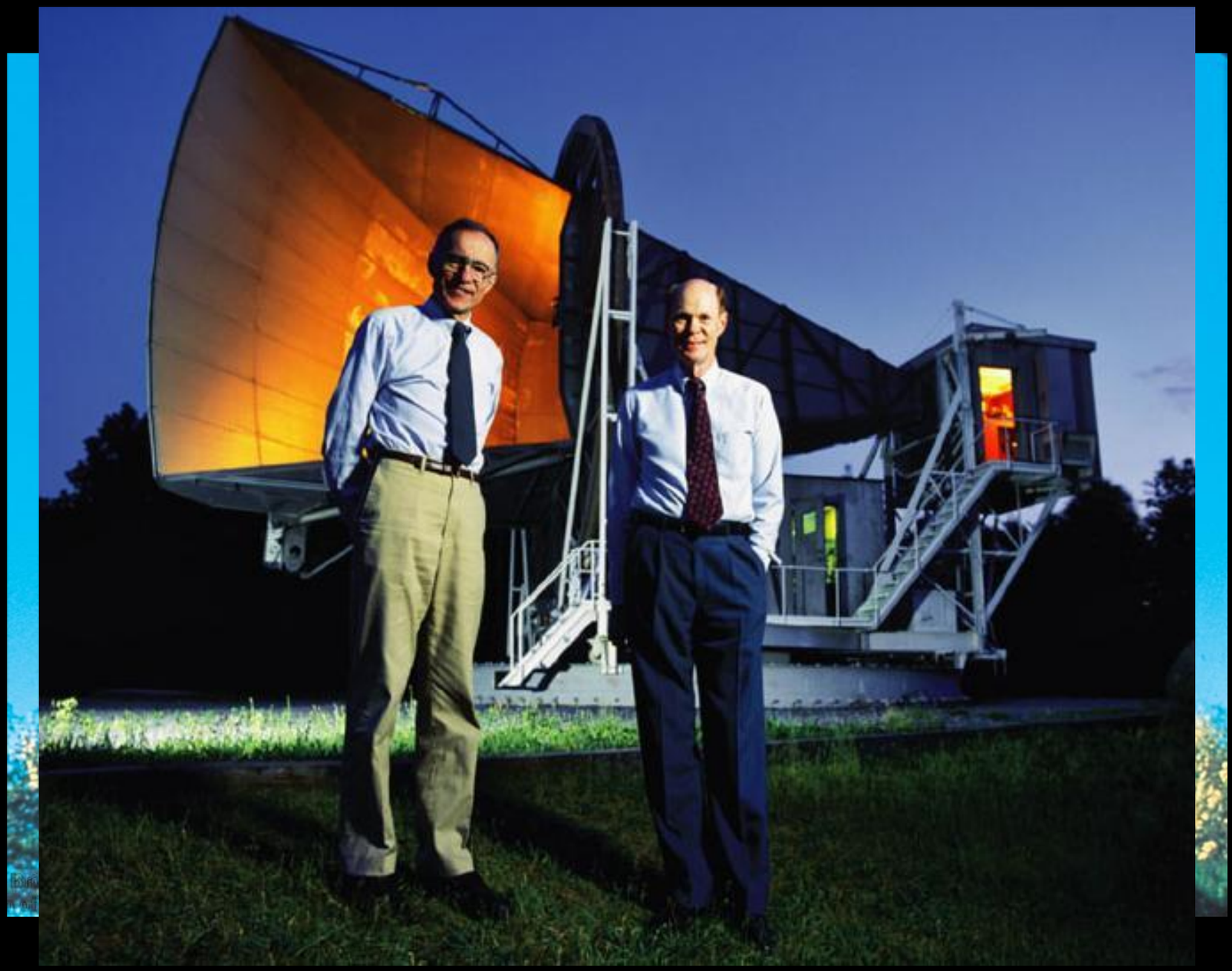
The Cosmic Microwave Background (CMB)



During recombination the photons are in thermic equilibrium with the electrons and atomic nuclei.

Their energy spectrum is the one of a black body ("Planck spectrum")

Discovery of the CMB



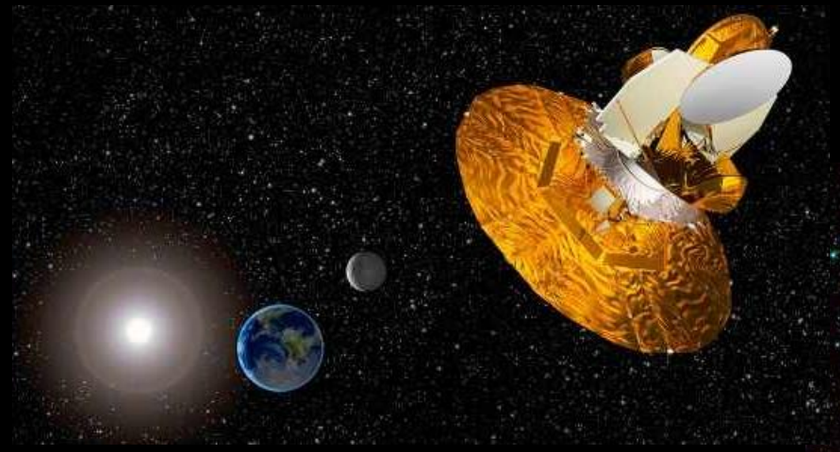
1964 Penzias und Wilson discovered a noise, which they couldn’t explain

 (1978)

Satellites for the investigation of the CMB

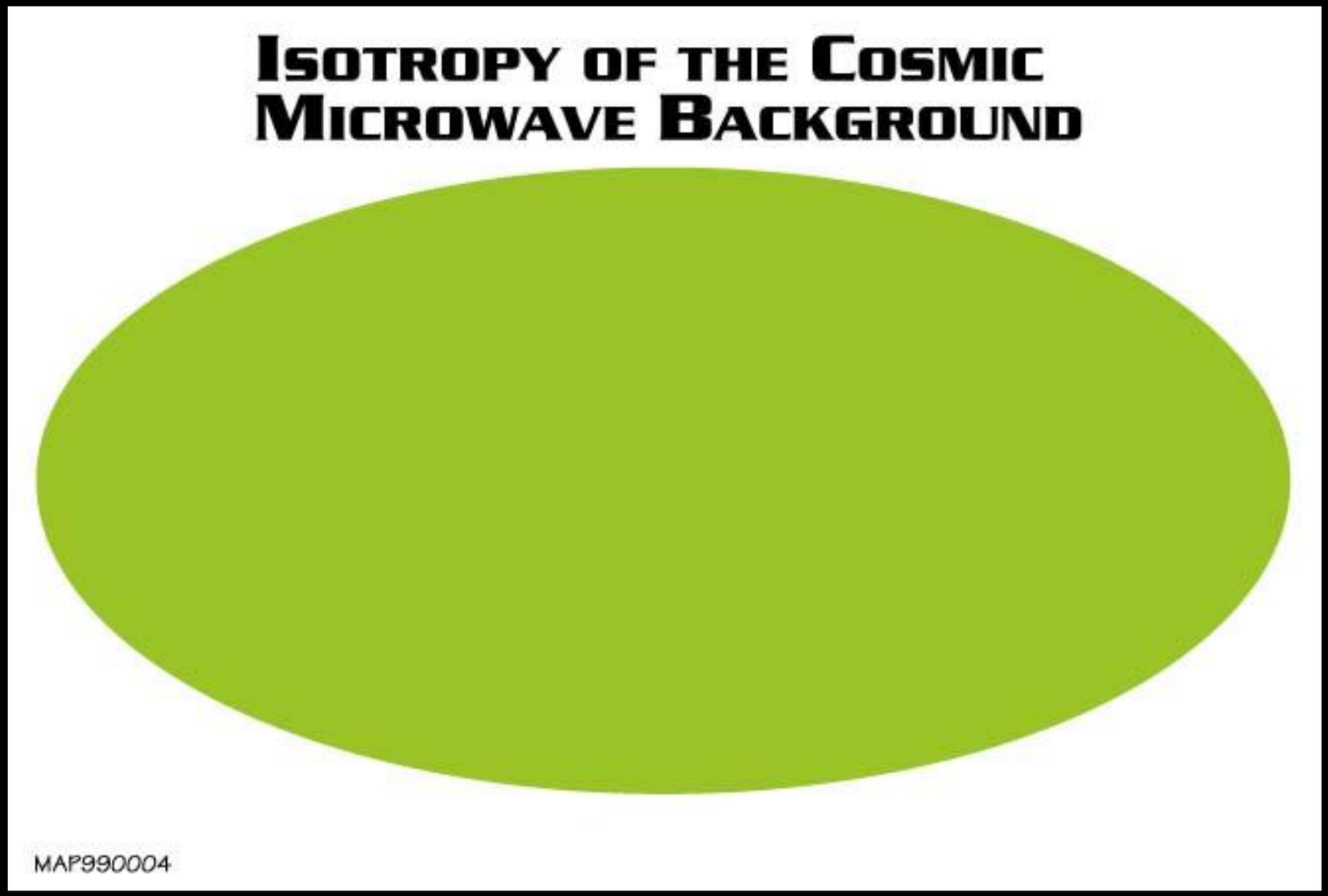
- COBE
  Cosmic Background Explorer
  1989-1993
  Nobel Prize 2006
  (Smoot & Mather)

- WMAP
  Wilkinson Microwave
  Anisotropy Probe
  2001-2010



- Planck
  2009-2013

Next problem for the Big Bang theory

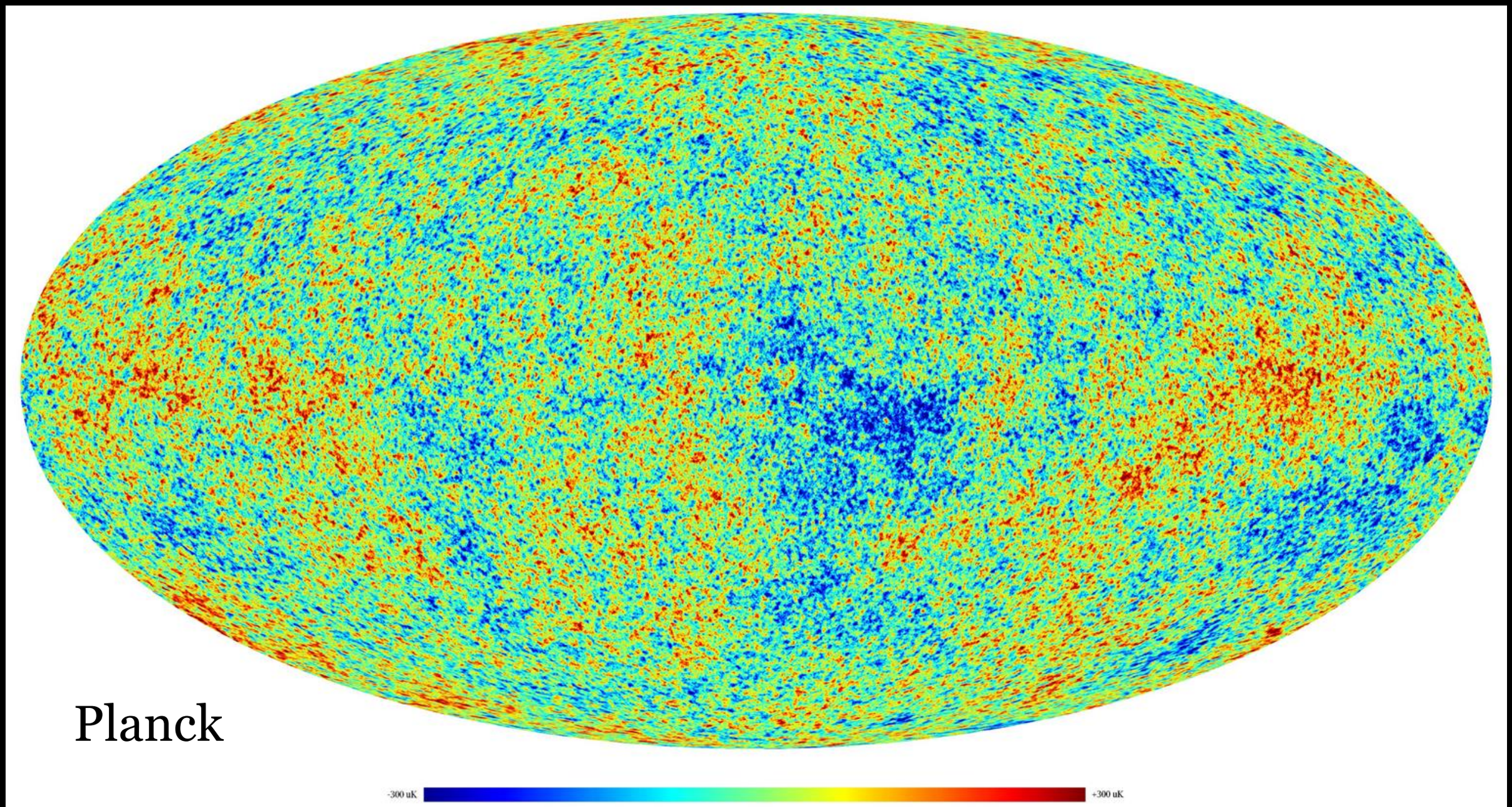


The second analysis revealed no sign of any variation at a level of 1 part in 10.000!
Where are the galaxies coming from, if not from density fluctuations?

The Echo of the Big Bang

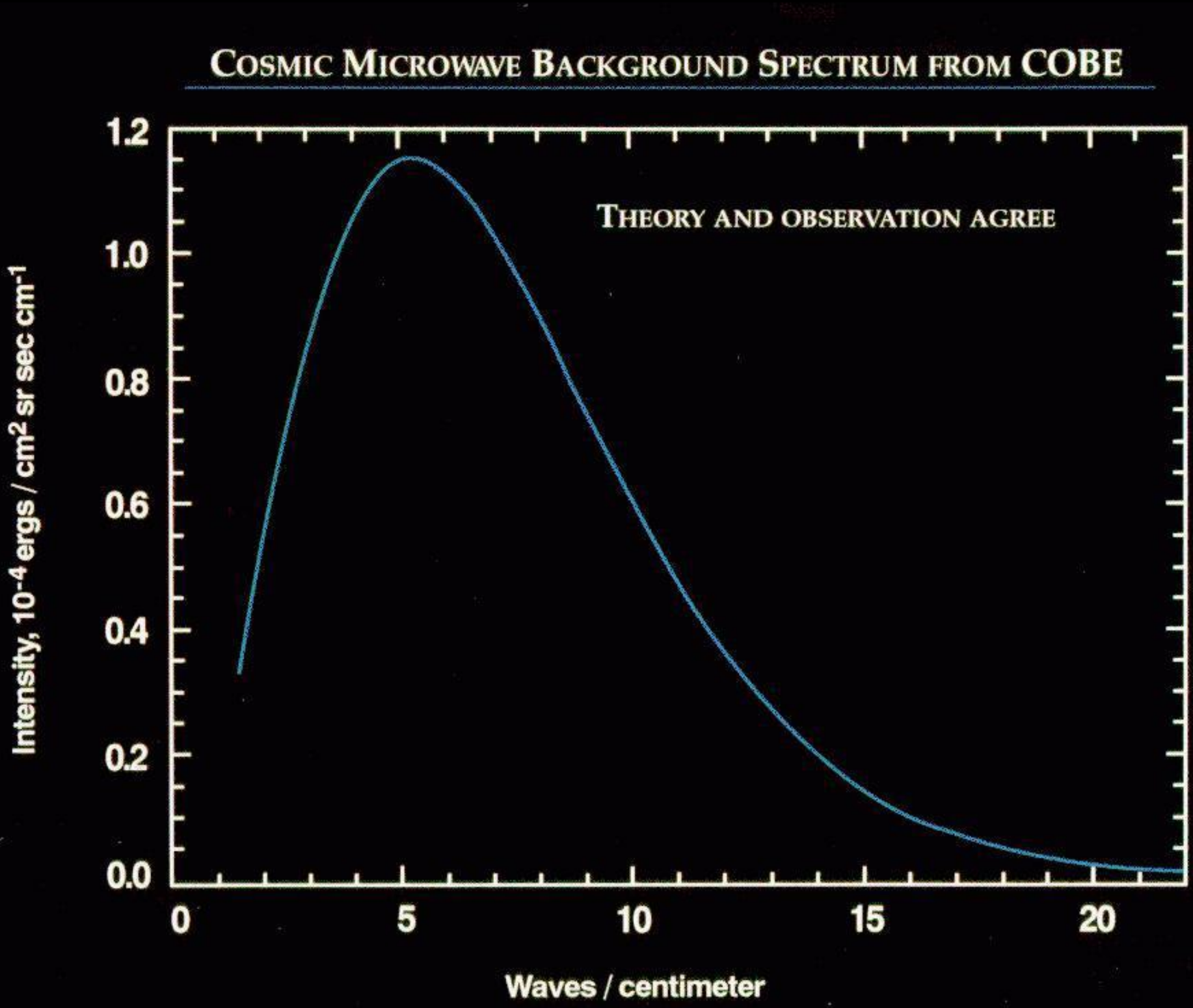
The Echo of the Big Bang

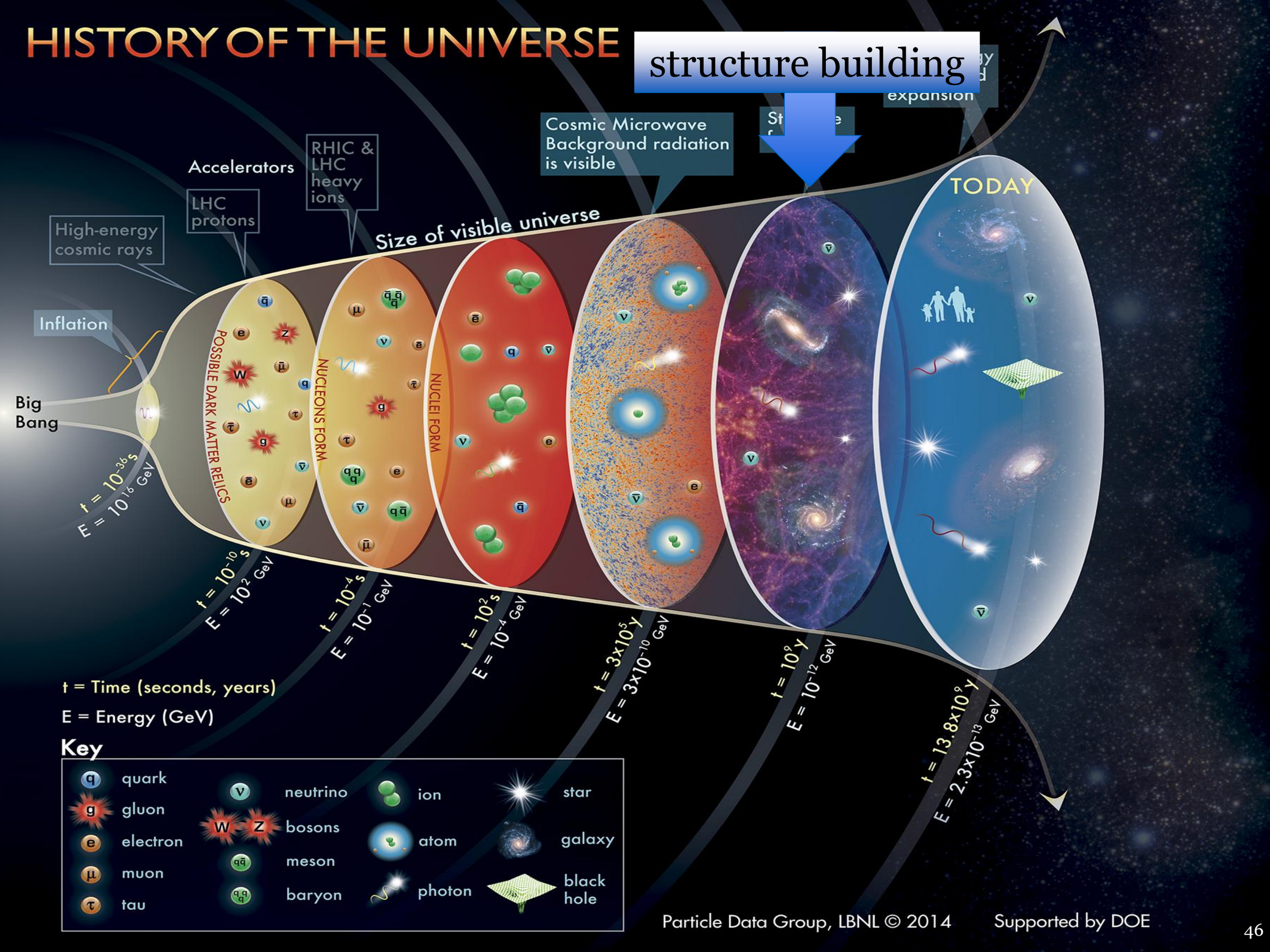
The CMB is extremely isotropic with a temperature of T_{CMB} = 2,725 K.
The temperature differences are in the range of microkelvin!



Planck

The spectrum of the CMB

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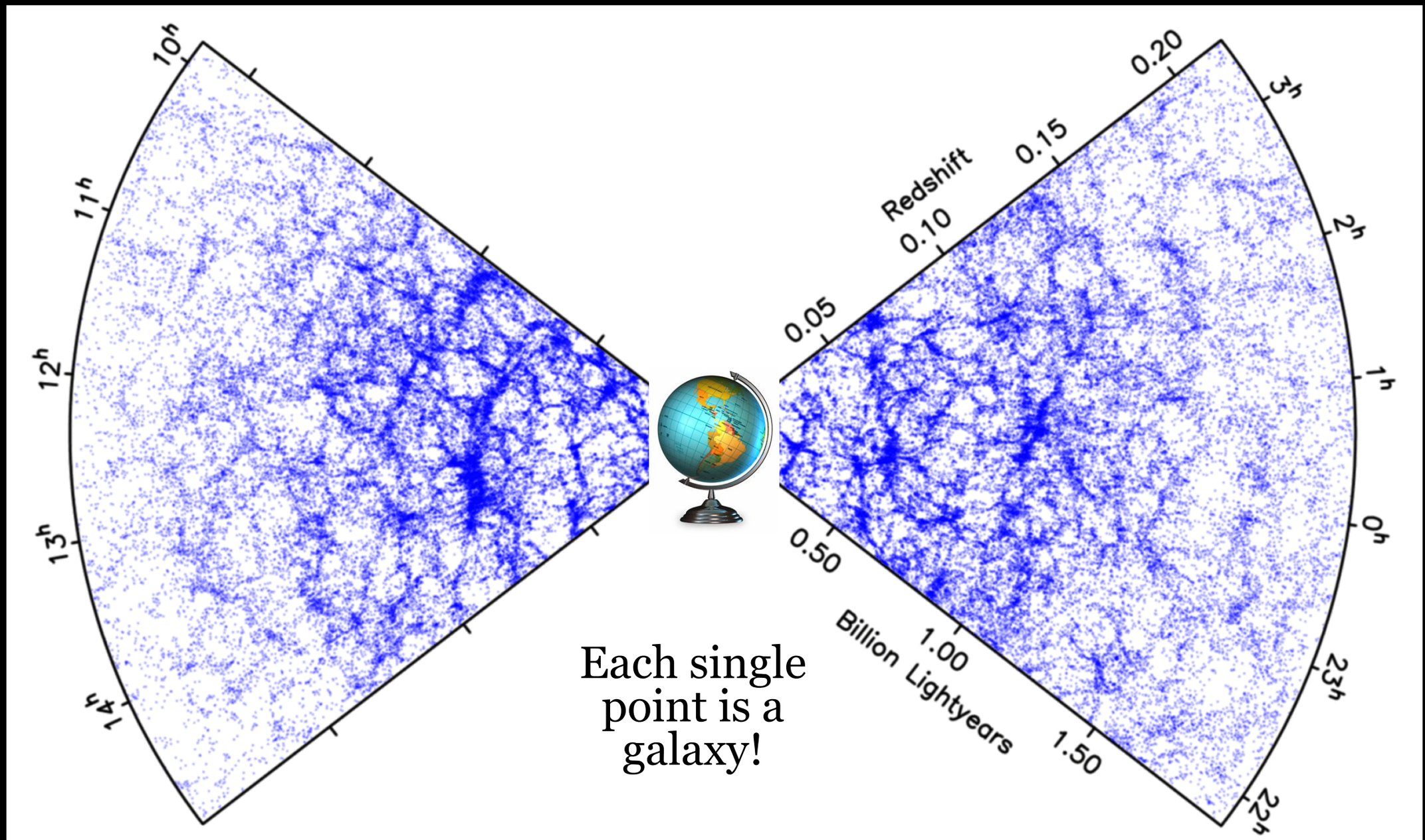
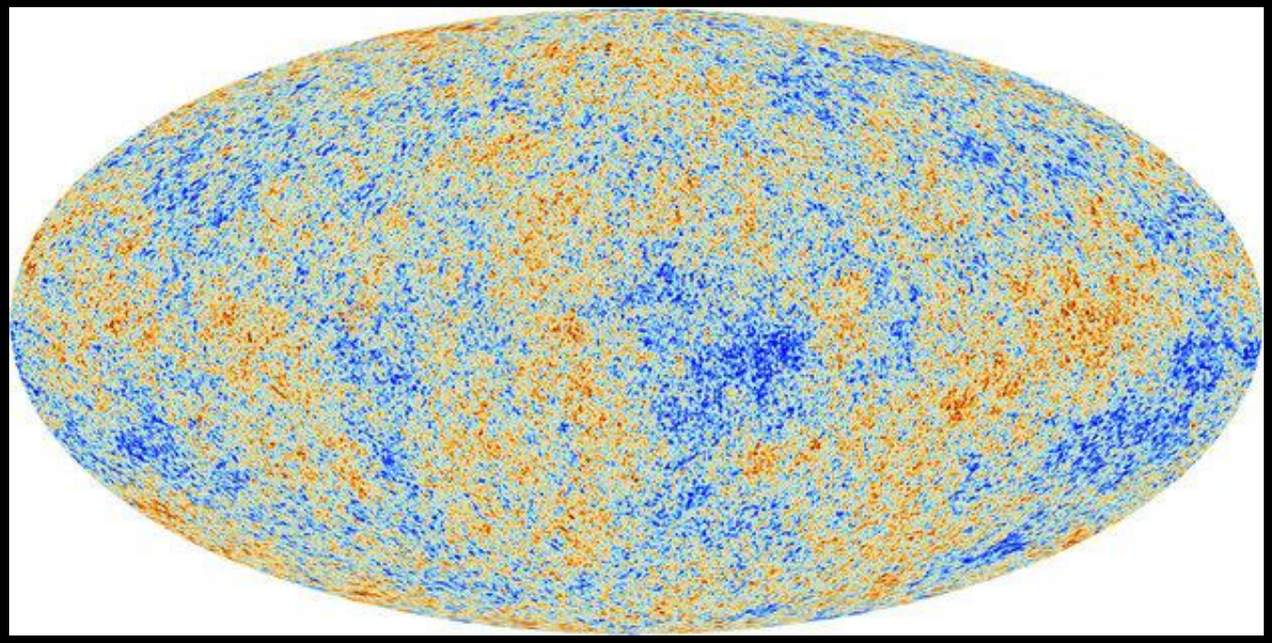
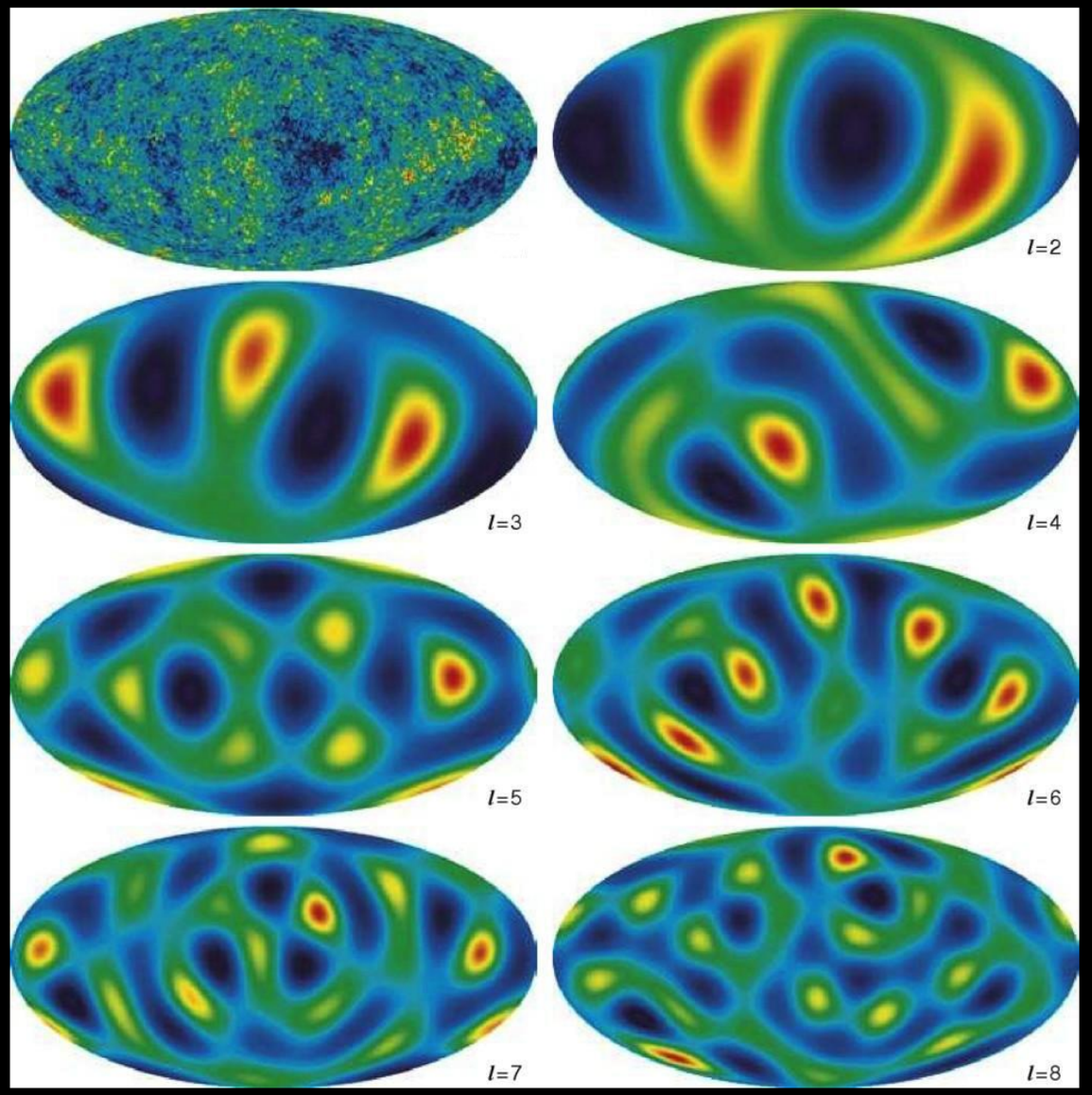
Galaxy Distribution

In the past the Universe was much more homogeneous than today:



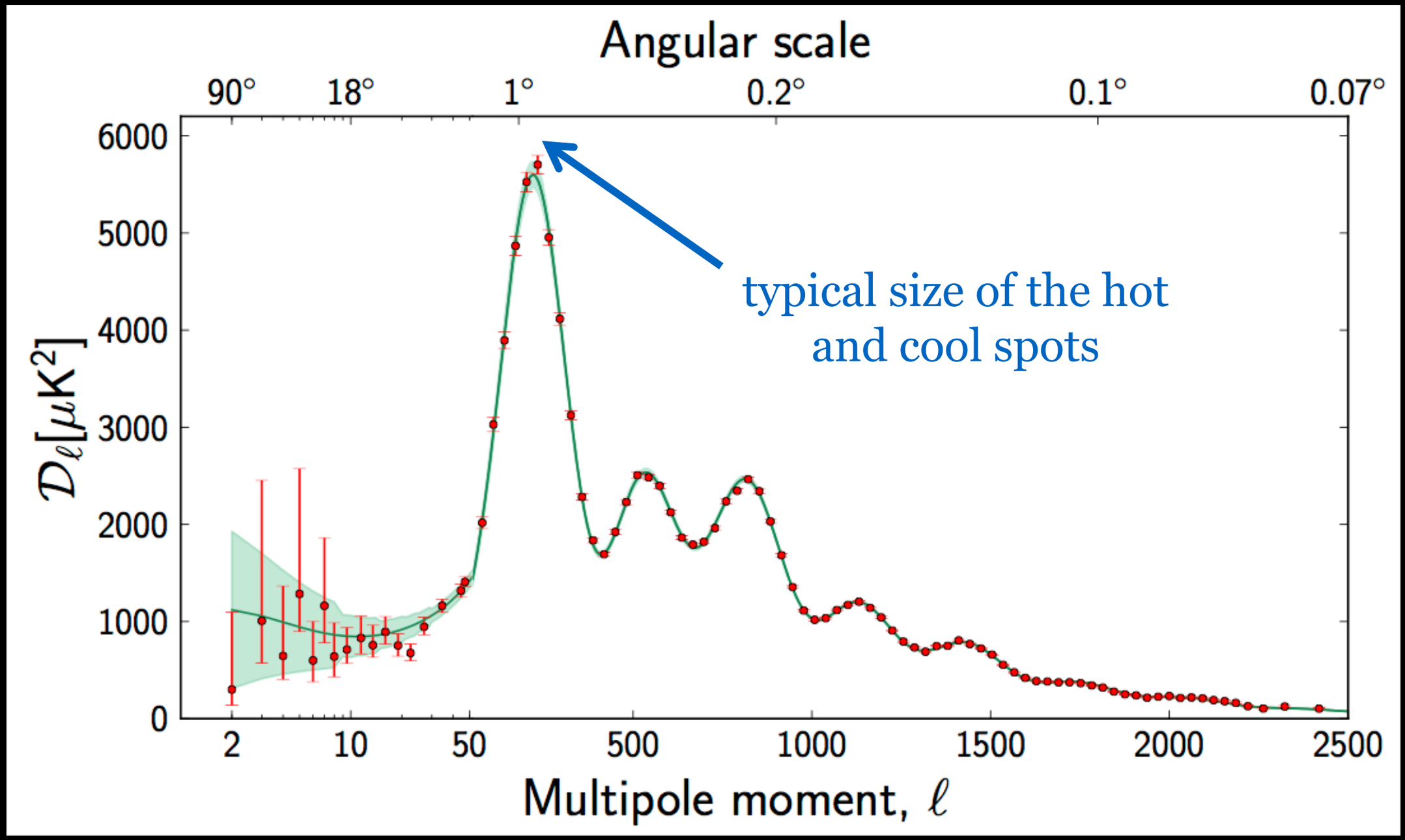
From the map to the spectrum…



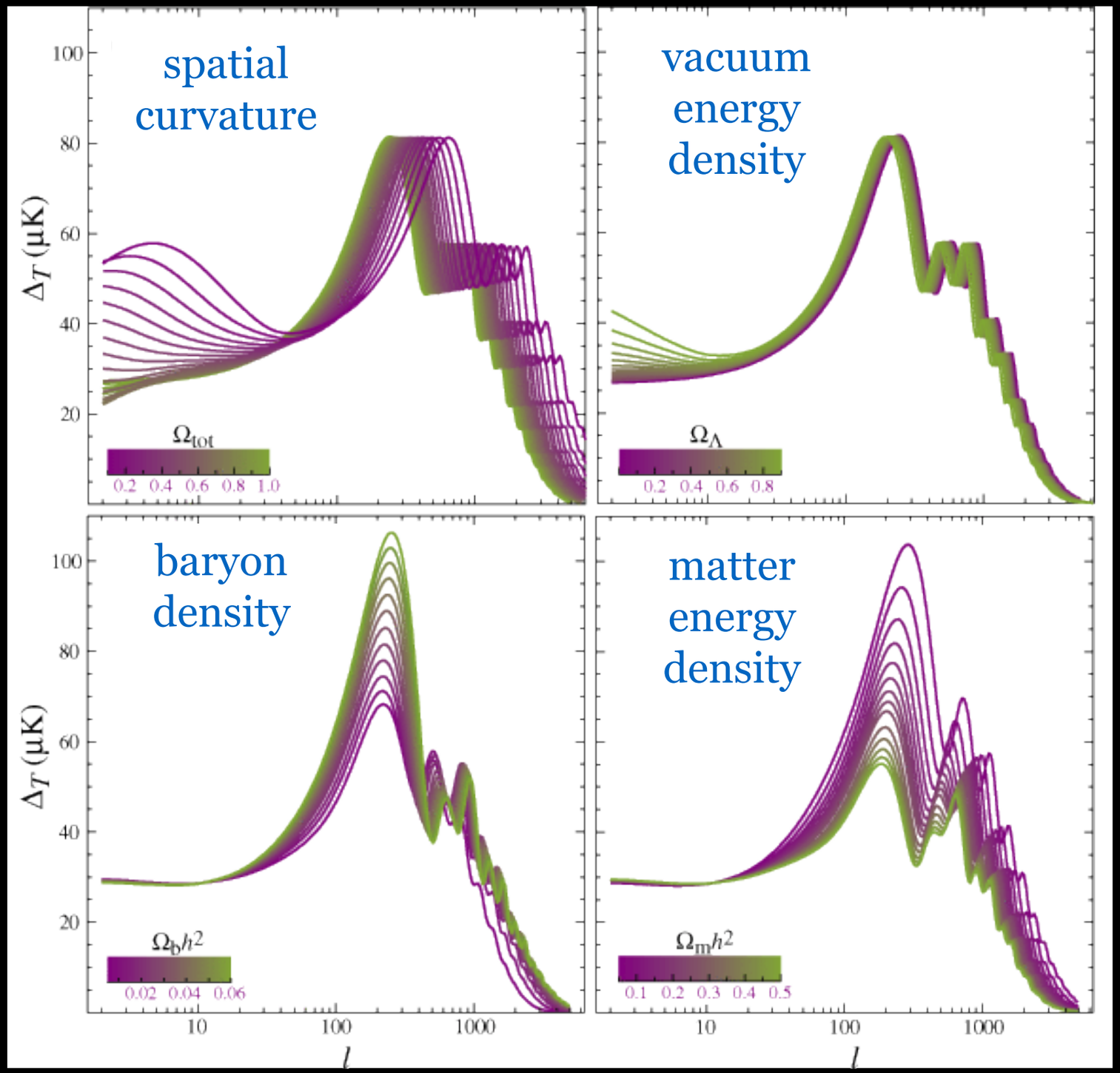


- theory is not able to predict the exact position of individual hot or cool spots
- instead: prediction of statistical properties of the temperature map (for example mean value, variance, correlations,…)

The Angular Power Spectrum of the CMB



Theoretical Predictions of the CMB Spectrum



- The theoretical CMB spectrum is depending on values of certain cosmological parameters

- Comparison with the measured spectrum allows to distinguish between the models and to determine the values of the unknown parameters

The Standard Cosmological Model

The simplest model, with which the data can be explained (Ockham's Razor!)

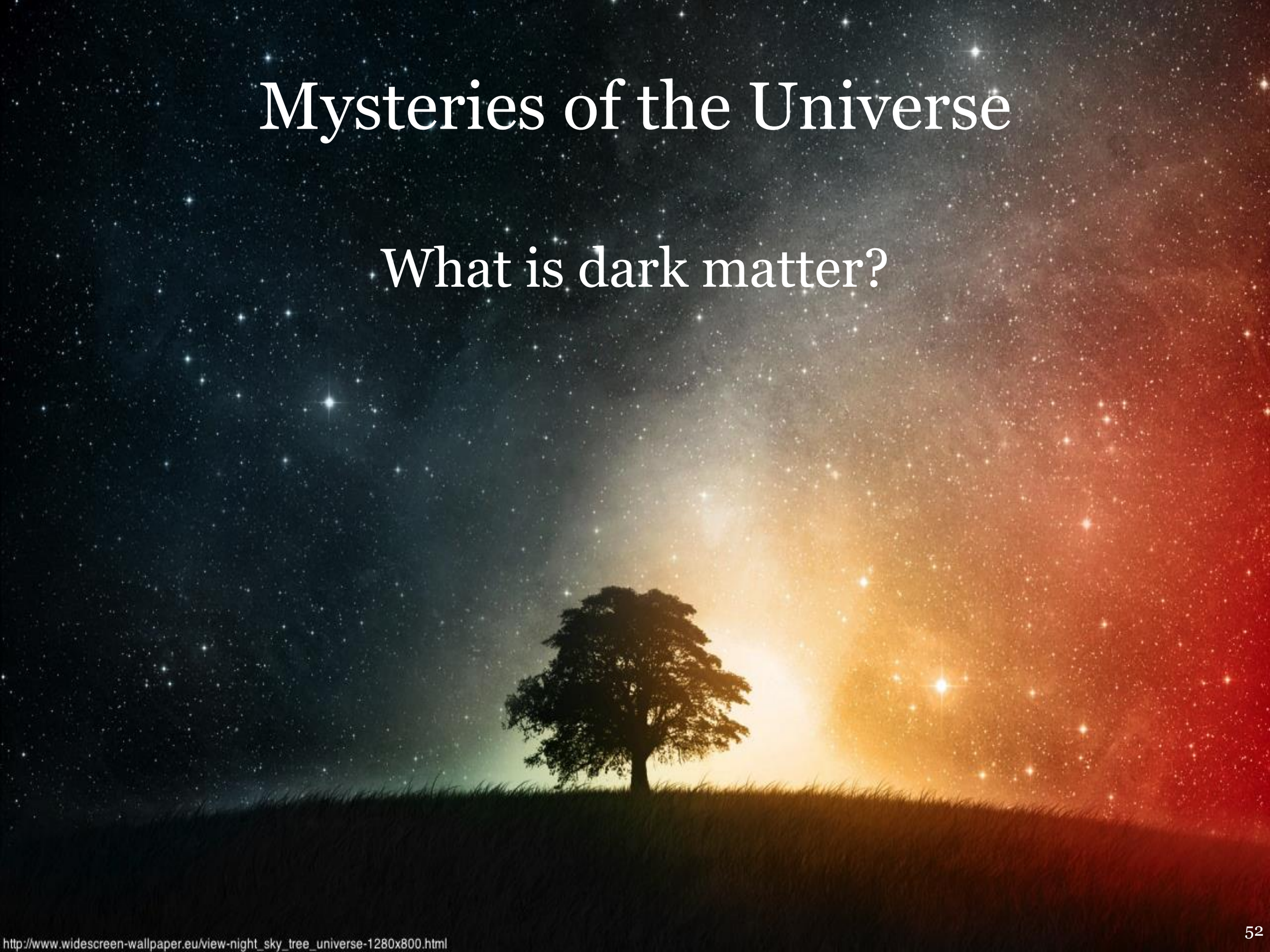
dark energy?!?!
(vacuum energy)

dark matter?!

"normal" matter

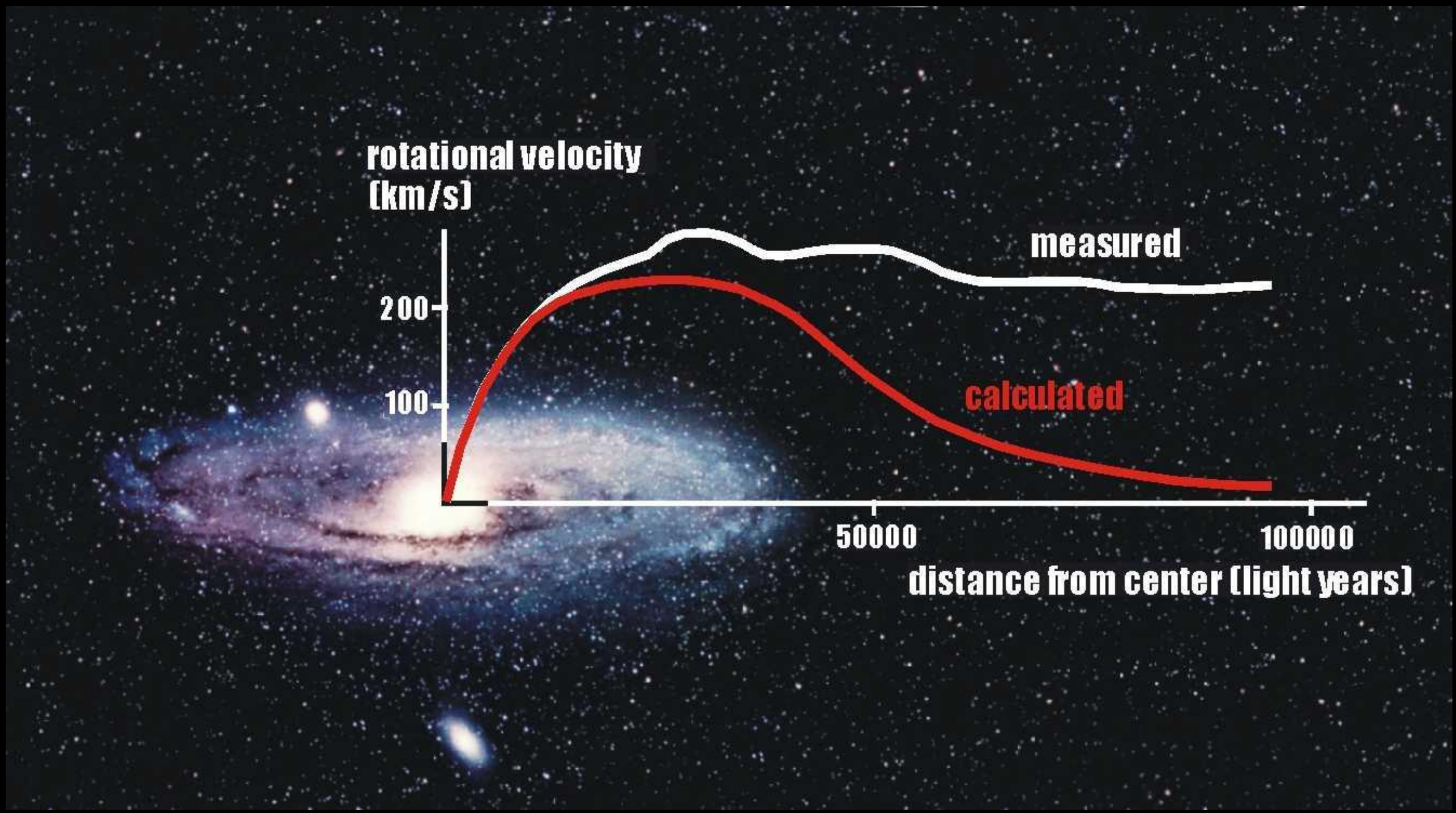
Mysteries of the Universe

What is dark matter?

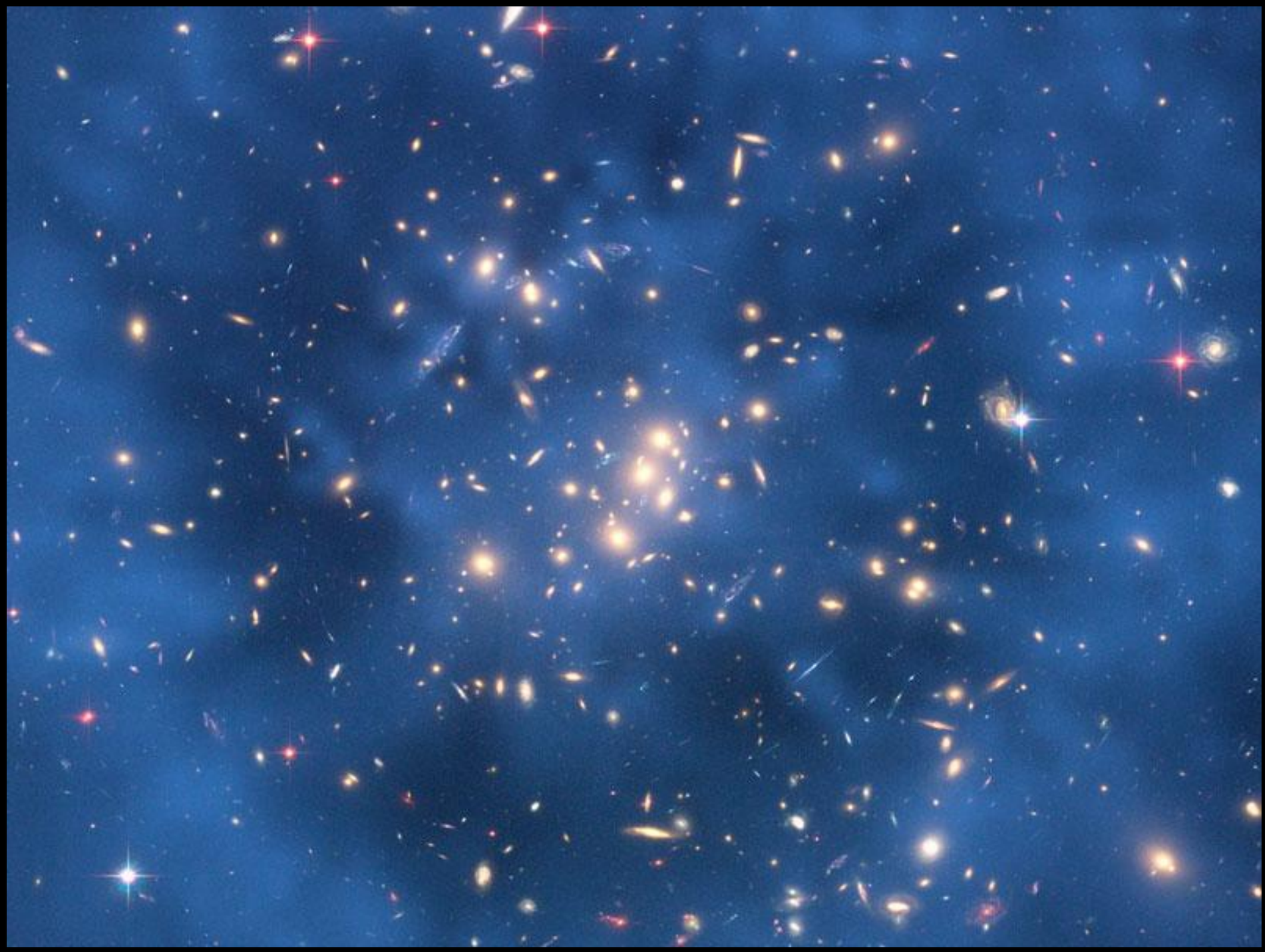


http://www.widescreen-wallpaper.eu/view-night_sky_tree_universe-1280x800.html

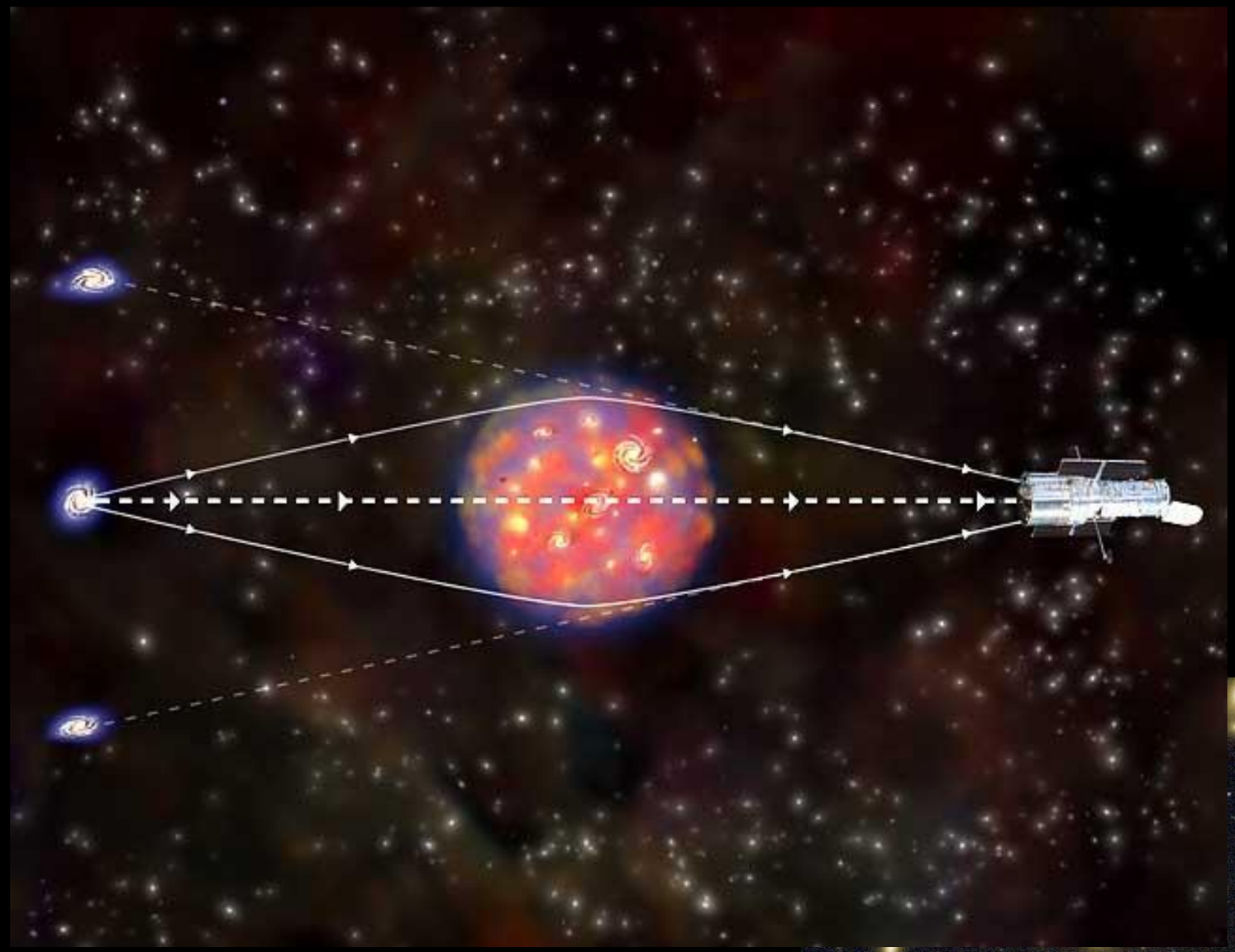
Rotation Curves of Galaxies



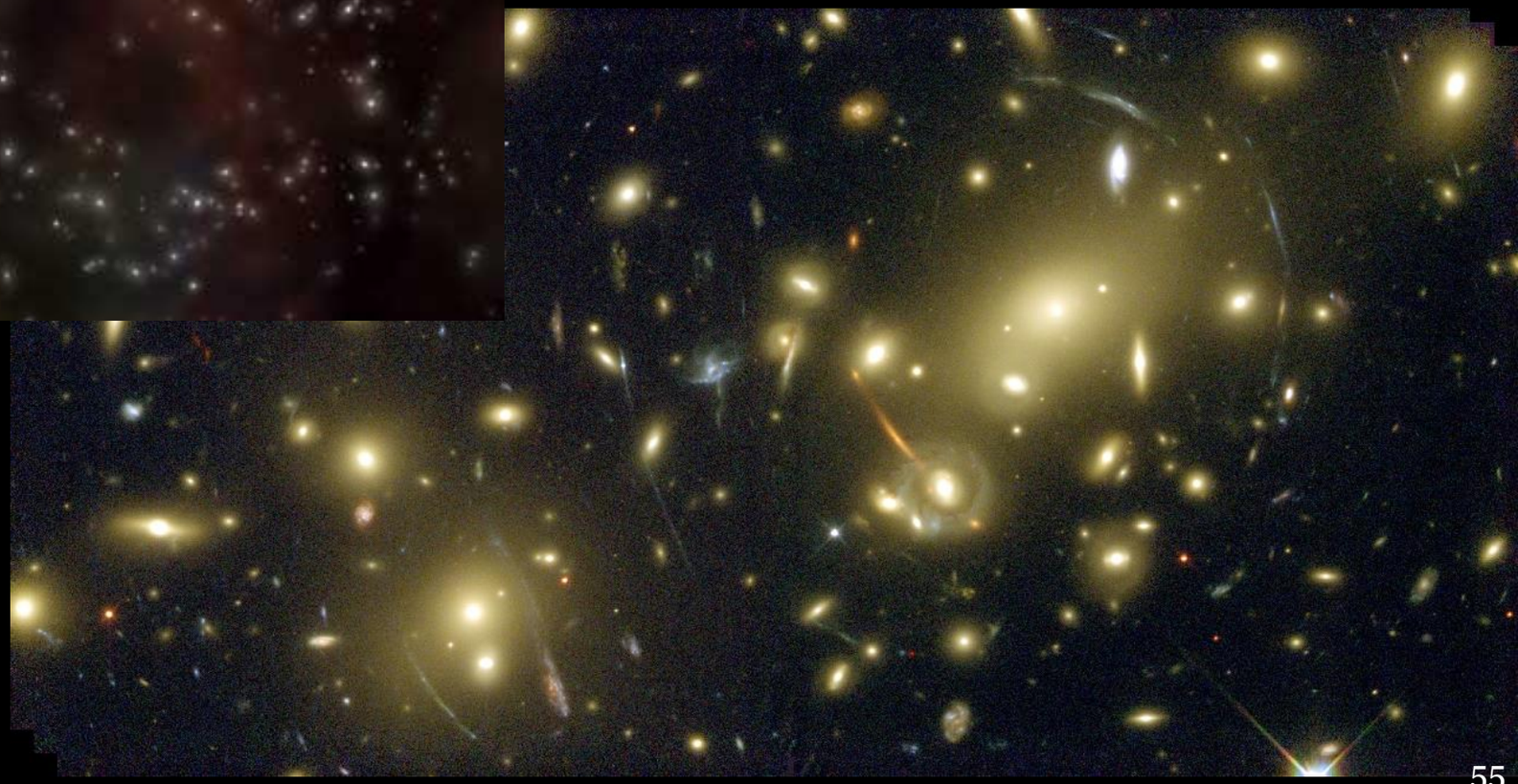
Galaxy Cluster CL0024+17



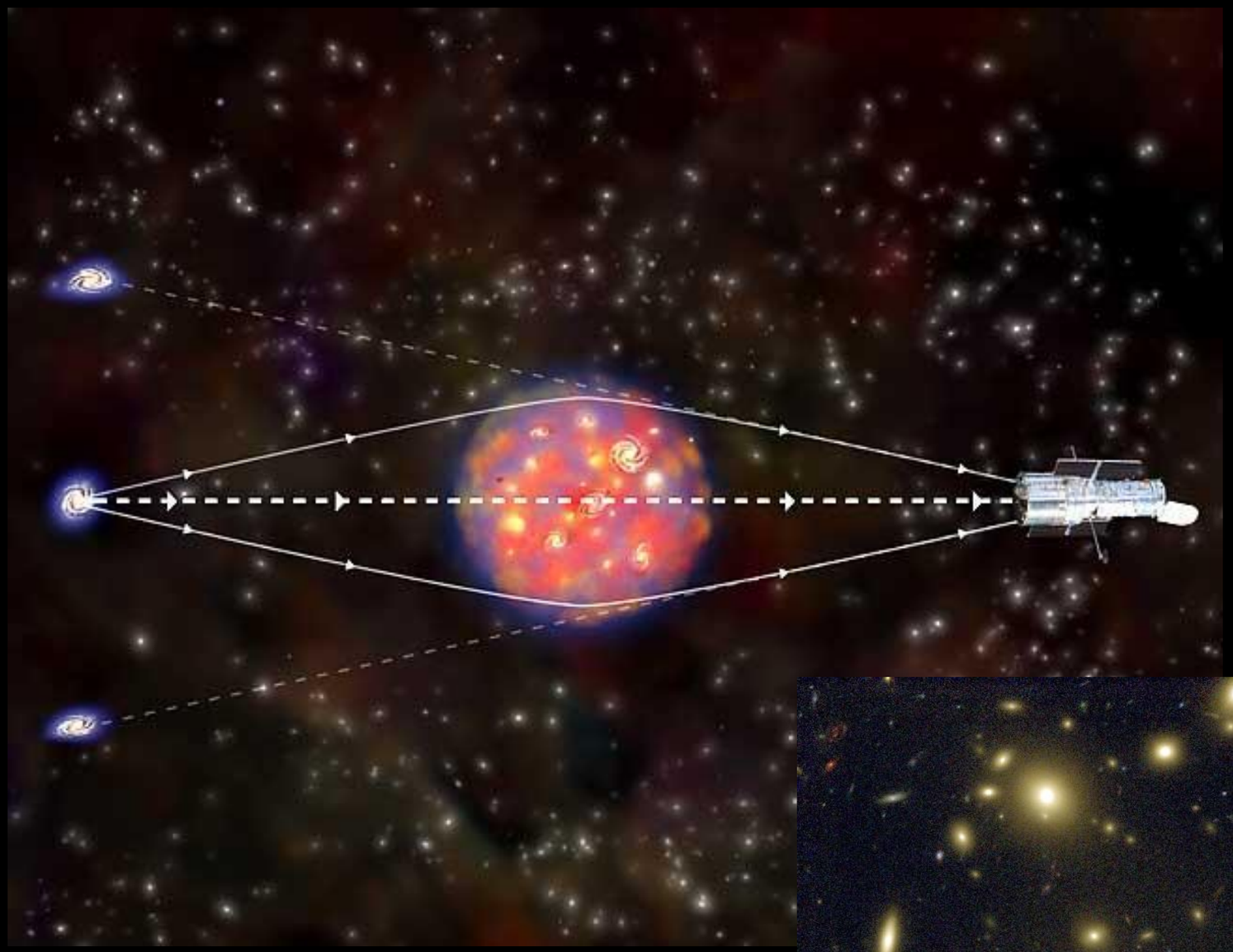
Gravitational Lenses



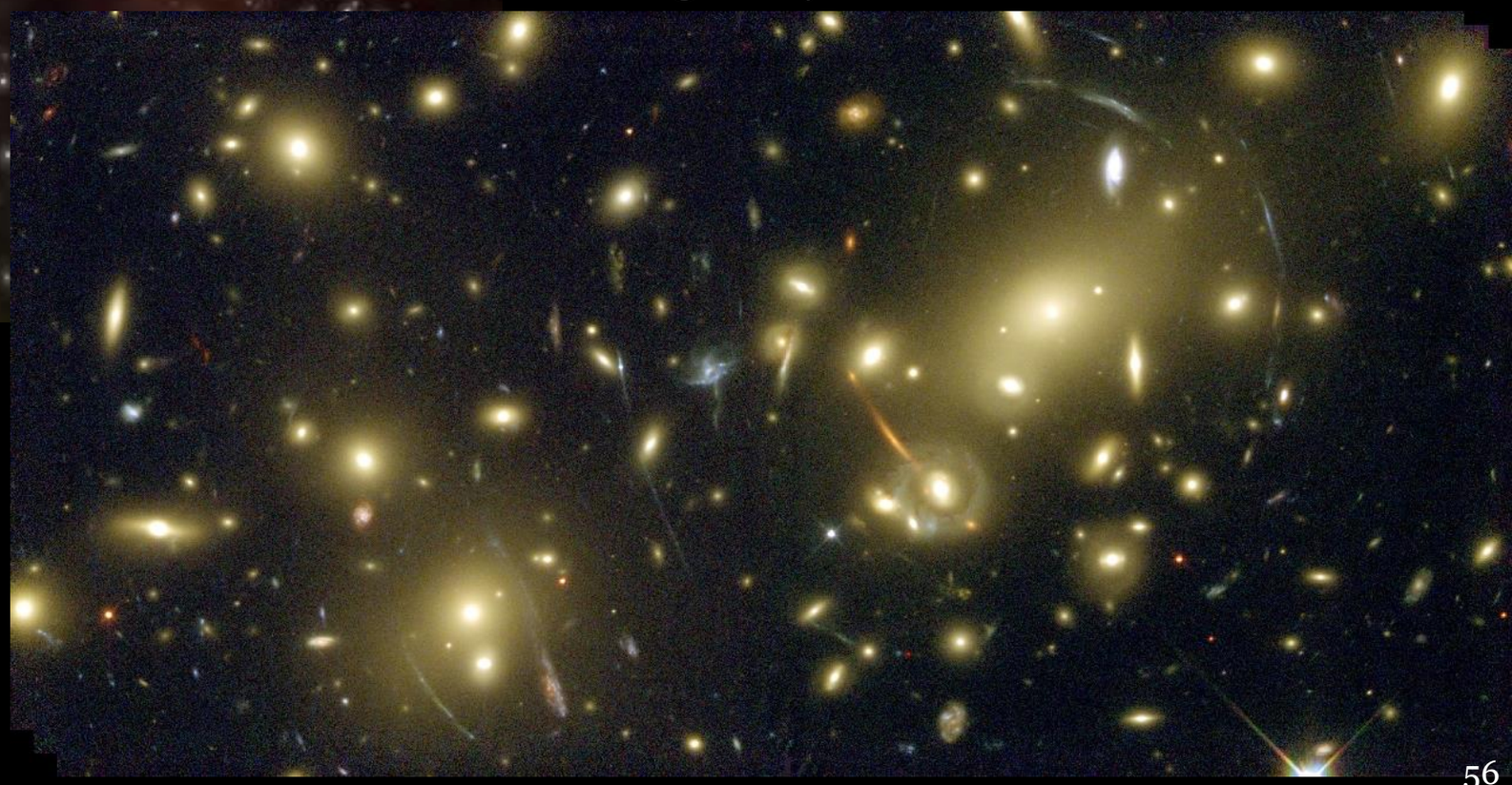
Massive objects curve space-time and therefore distort the light of the objects behind.



Gravitational Lenses



galaxy cluster Abell 2218



Thereby light arcs of the objects behind are visible.

HISTORY OF THE UNIVERSE

era of the dark energy

accelerat
expansio

Cosmic Microwave Background radiation is visible

Structure formation

TODAY

Accelerators

RHIC & LHC heavy ions

LHC protons

High-energy cosmic rays

Size of visible universe

Inflation

Big Bang

POSSIBLE DARK MATTER RELICS

NUCLEONS FORM

NUCLEI FORM

$t = 10^{-36}$ s
$E = 10^{16}$ GeV

$t = 10^{-10}$ s
$E = 10^{2}$ GeV

$t = 10^{-4}$ s
$E = 10^{-1}$ GeV

$t = 10^{2}$ s
$E = 10^{-4}$ GeV

$t = 3 \times 10^{5}$ y
$E = 3 \times 10^{-10}$ GeV

$t = 10^{9}$ y
$E = 10^{-12}$ GeV

$t = 13.8 \times 10^{9}$ y
$E = 2.3 \times 10^{-13}$ GeV

t = Time (seconds, years)

E = Energy (GeV)

Key

quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole

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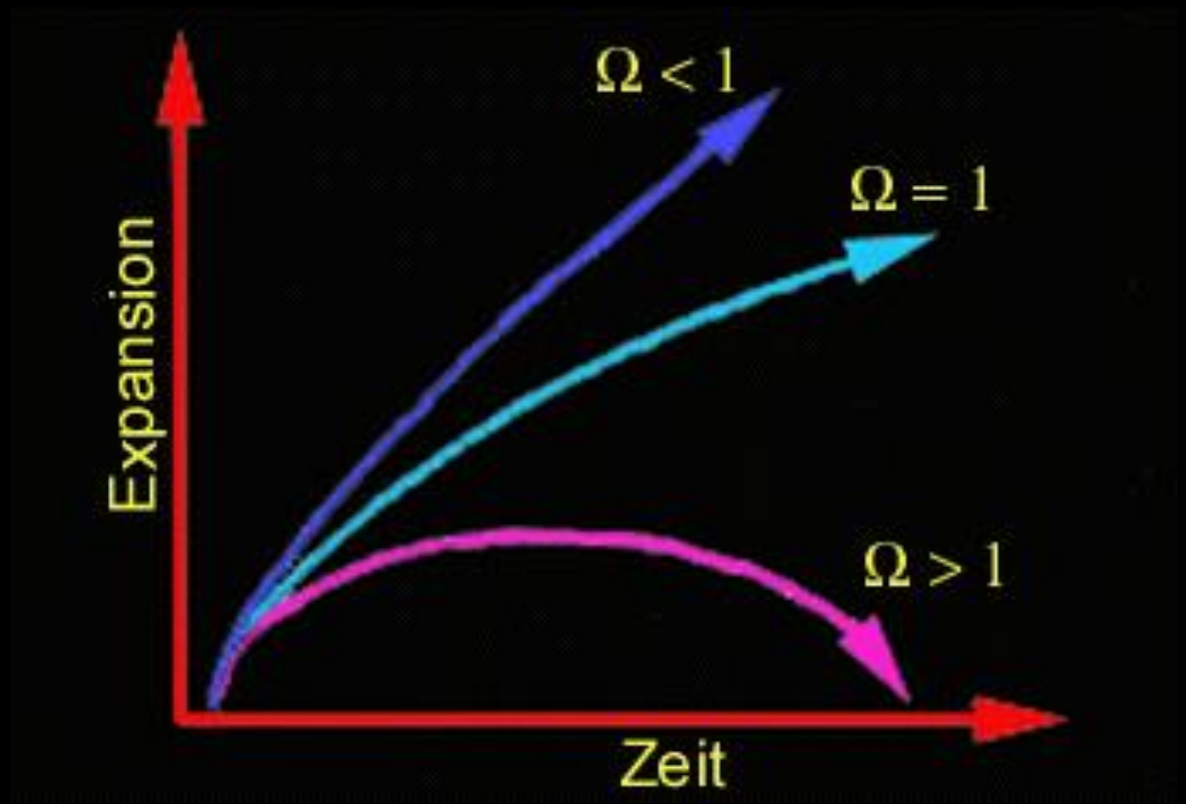
The Fate of the Universe...

... depends on the balance between contraction and expansion

$$\Omega = \rho/\rho_{krit}$$

ρ_{krit} is the critical density, which is necessary to stop the expansion:

$$P_{krit} = 10^{-29} g/cm^3 = 5 \text{ protons}/m^3$$



- $\Omega > 1$
  gravitation wins, the Universe collapses
- $\Omega = 1$
  expansion reaches “saturation” and ultimately stops
- $\Omega < 1$
  expansion wins, the Universe will expand forever

Cosmology of the 21st century

- **Dark Matter**
  What is it made of, what are its properties?
  Or another model (e.g. MOND)?

- **Dark Energy**
  What kind of energy is it? How does it influence the expansion of the Universe?

- **Inflation**
  Can we find experimental confirmation? If yes, what caused it?

- **Matter-Antimatter Asymmetry**
  Where is the tiny surplus of matter coming from, from which everything around us is made of?

- **The Moment of the Big Bang**
  Will we find a unified theory, which describes the beginning of the Universe?

- **The Fate of the Universe…**

Many thanks for your attention!

Are there any questions?