

Cosmology

A short introduction

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CERN

What is cosmology all about?

Κοσμολογία = study of the world

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

Cosmological Questions

- What is the universe made of?
- How does its structure look like?
- What is its origin?
- Can we reconstruct the history of the universe?
- Where is the journey taking us?

Outline

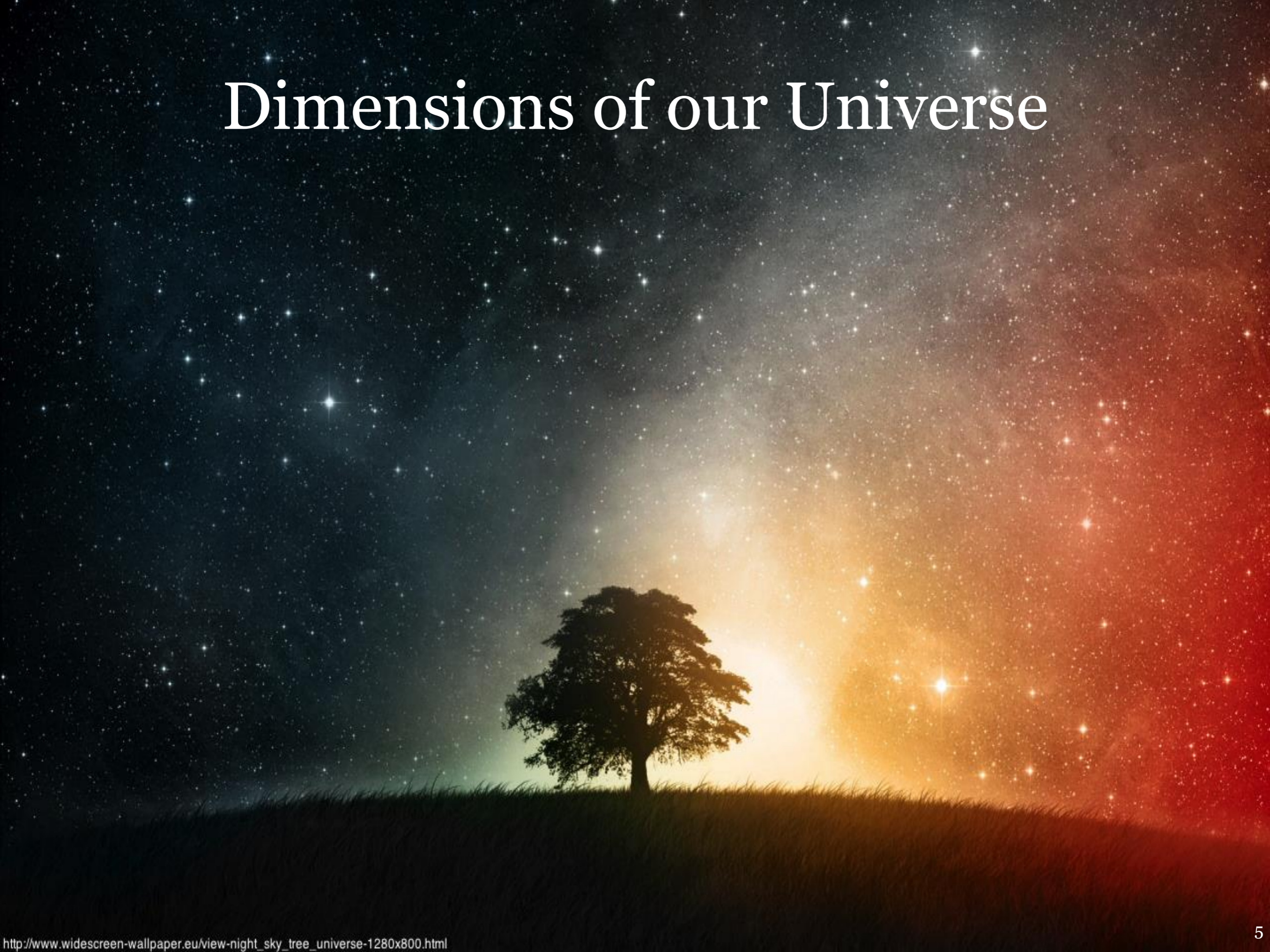
Dimensions of our universe

Dynamics of the universe

A journey through time

Mysteries of the universe

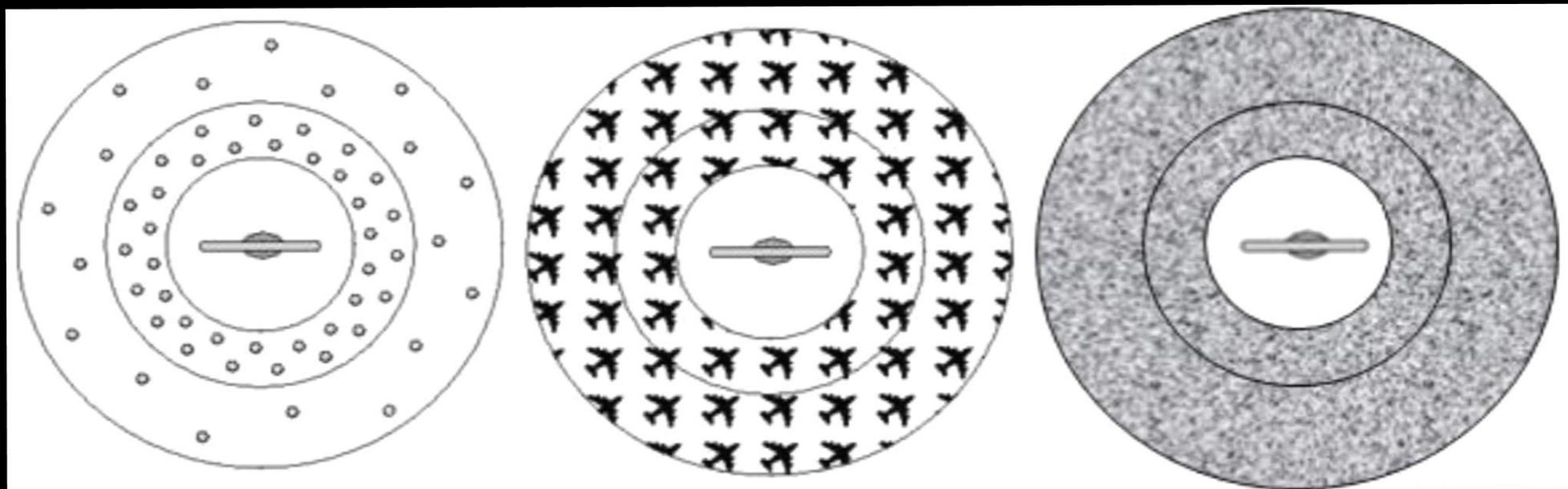
Dimensions of our Universe



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

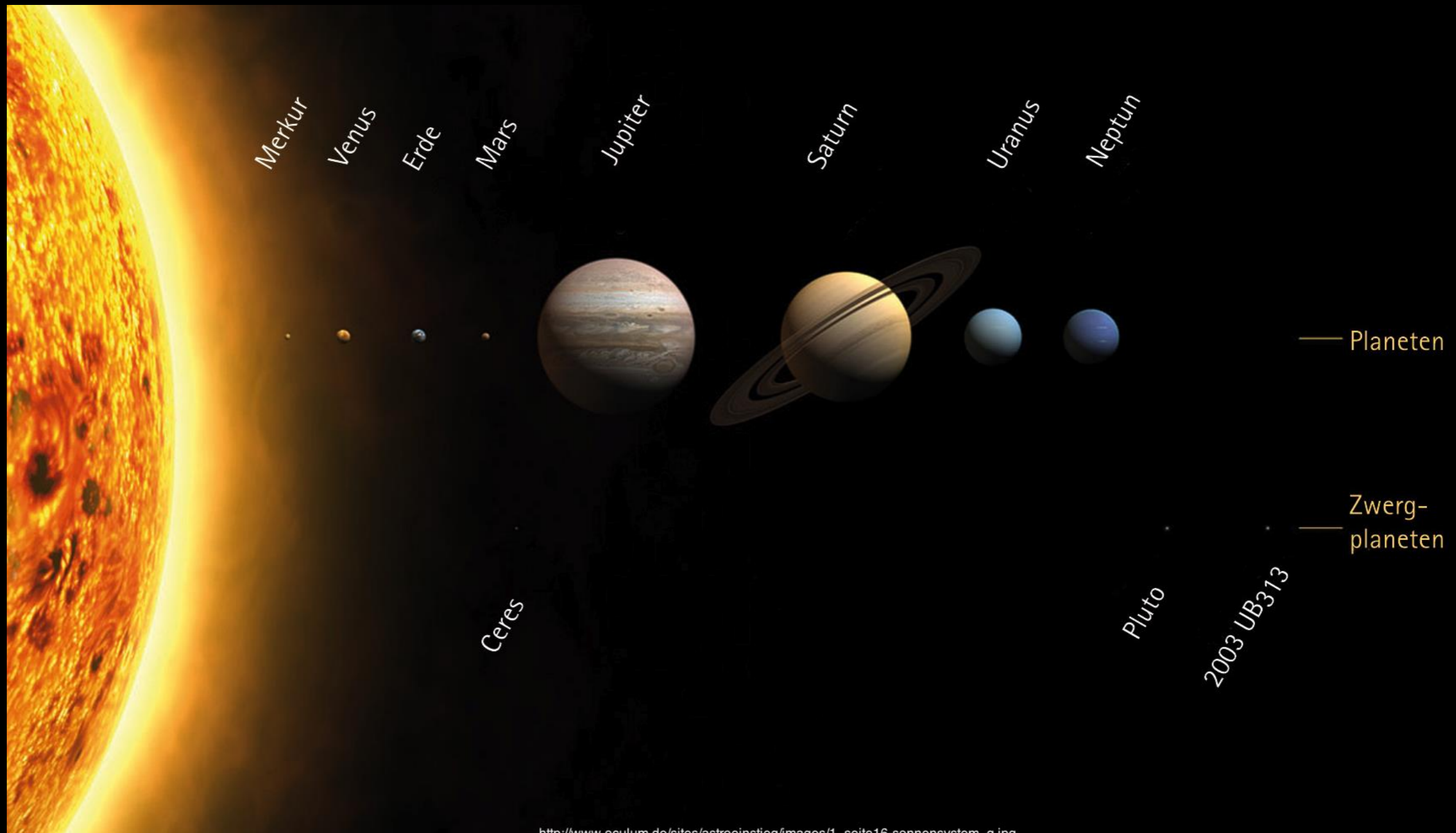
homogeneous,
but not isotropic

homogeneous
and isotropic

The Earth: ≈ 13000 km in diameter



The Solar System: ≈ 10 billion km in diameter



http://www.oculum.de/sites/astroeinstien/images/1_seite16-sonnensystem_a.jpg

Our Milky Way:

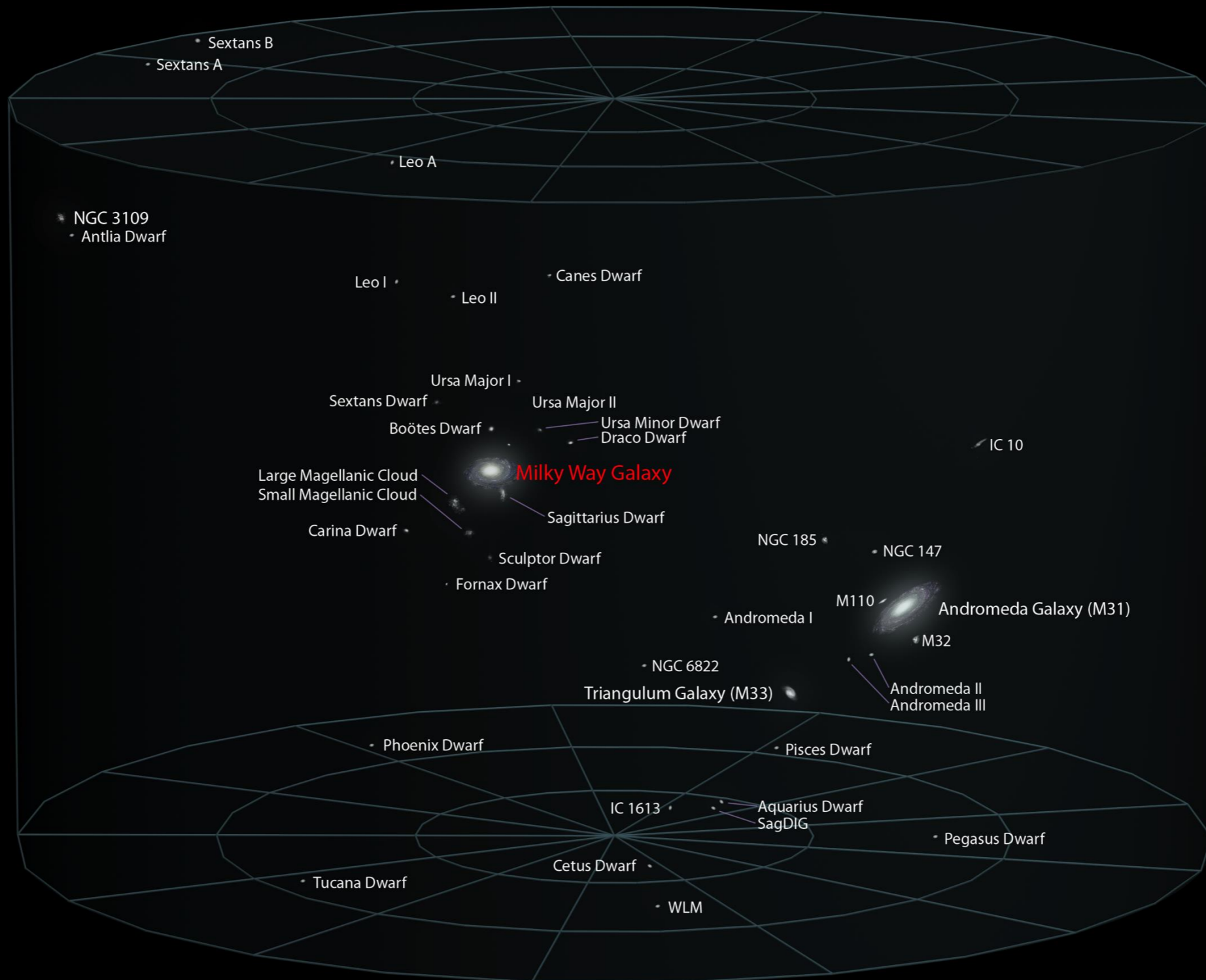
$1,4 \times 10^{18}$ km = 150000 light years in diameter



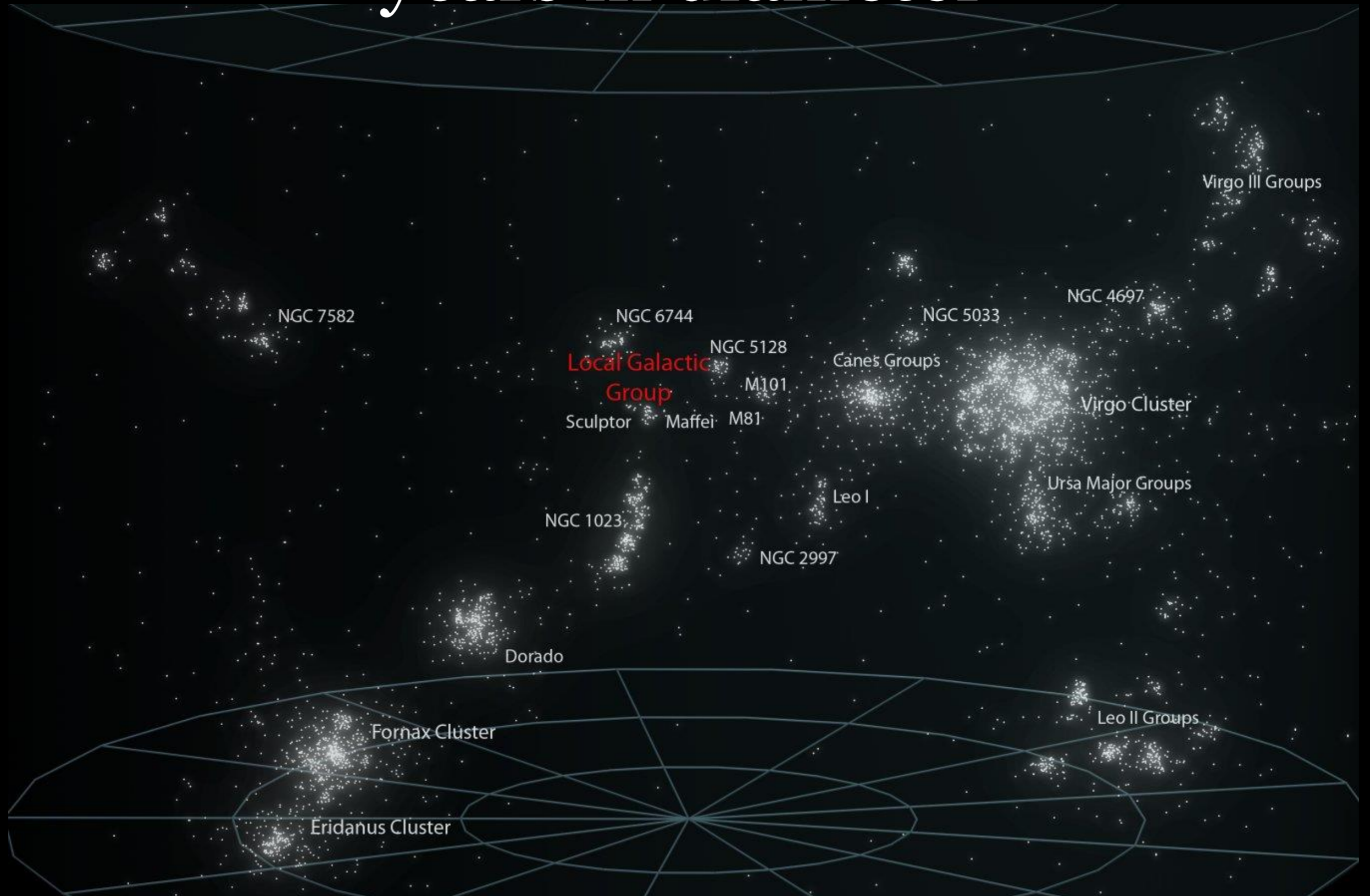
Andromeda Galaxy: 2.5 million light years distance



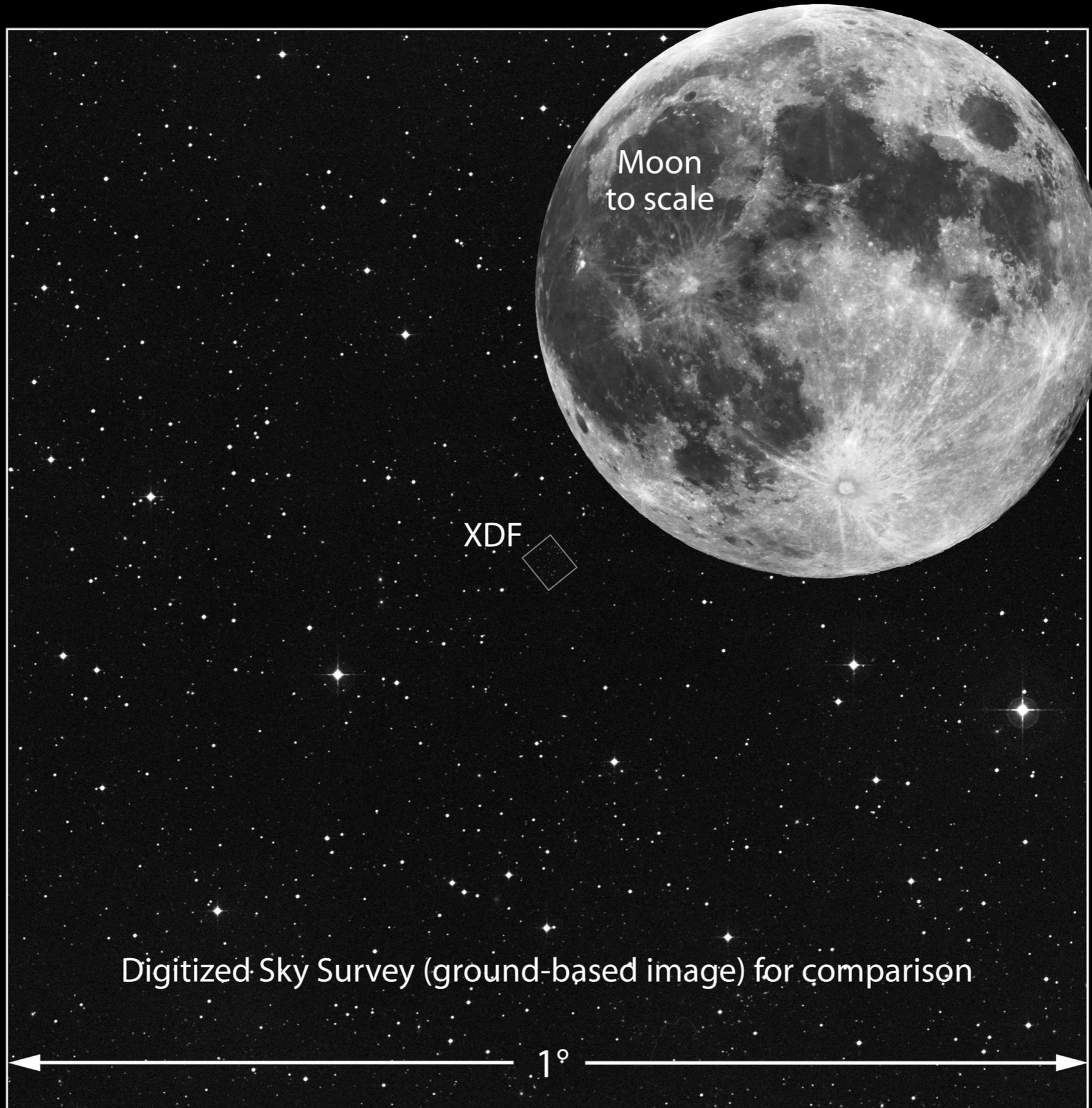
Local Group: 8 million light years in diameter



Virgo Supercluster: ≈ 130 million light years in diameter



Size of Hubble eXtreme Deep Field on the Sky



Hubble Extreme Deep Field



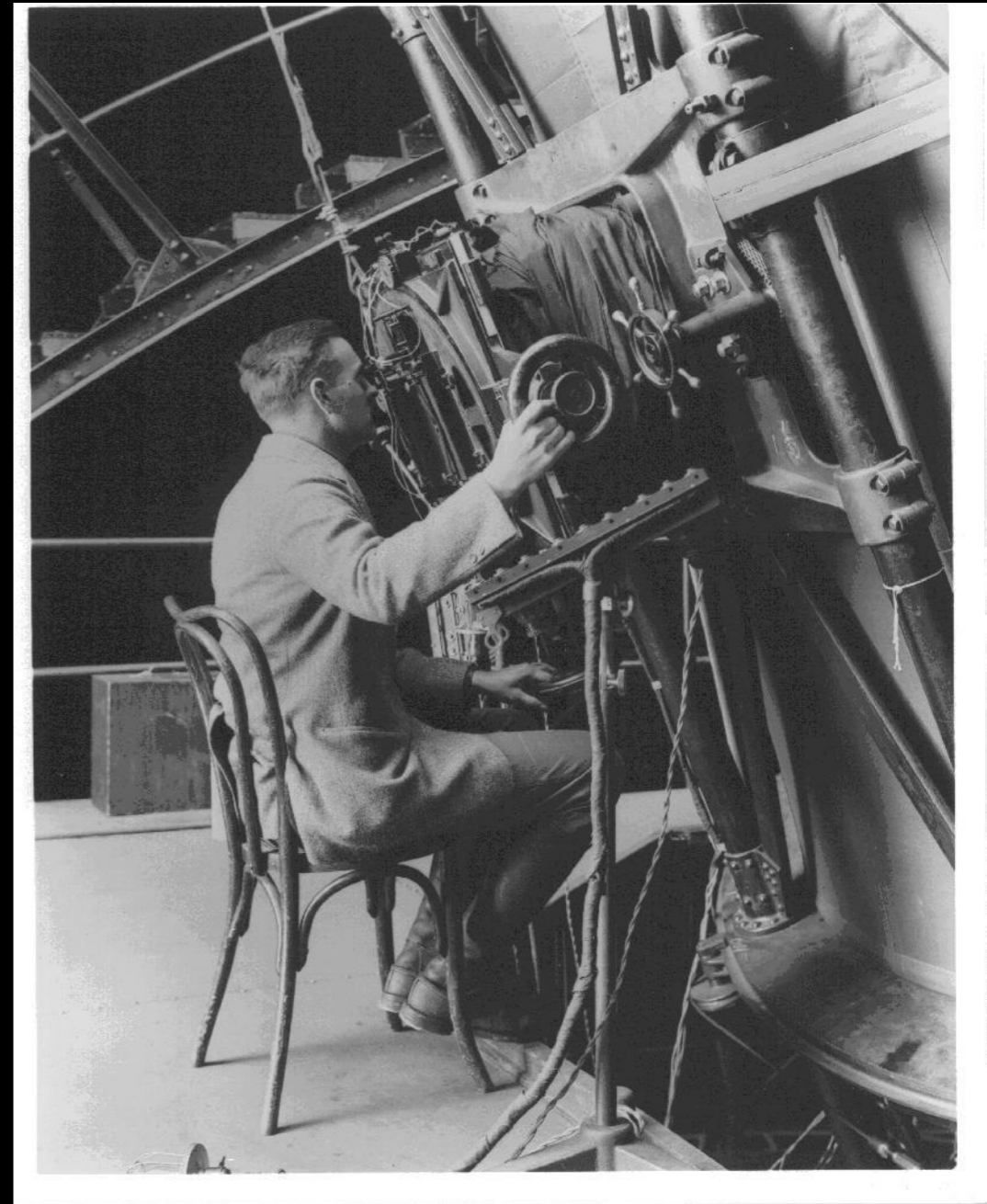
Dynamics of the Universe

The image is a composite background. The top half is a starry night sky with a color gradient from dark blue on the left to bright red on the right. The bottom half shows a silhouette of a tree on a grassy hill. A bright yellow sun or star is visible in the background, partially obscured by the tree's silhouette.

The Universe is bigger than we thought!

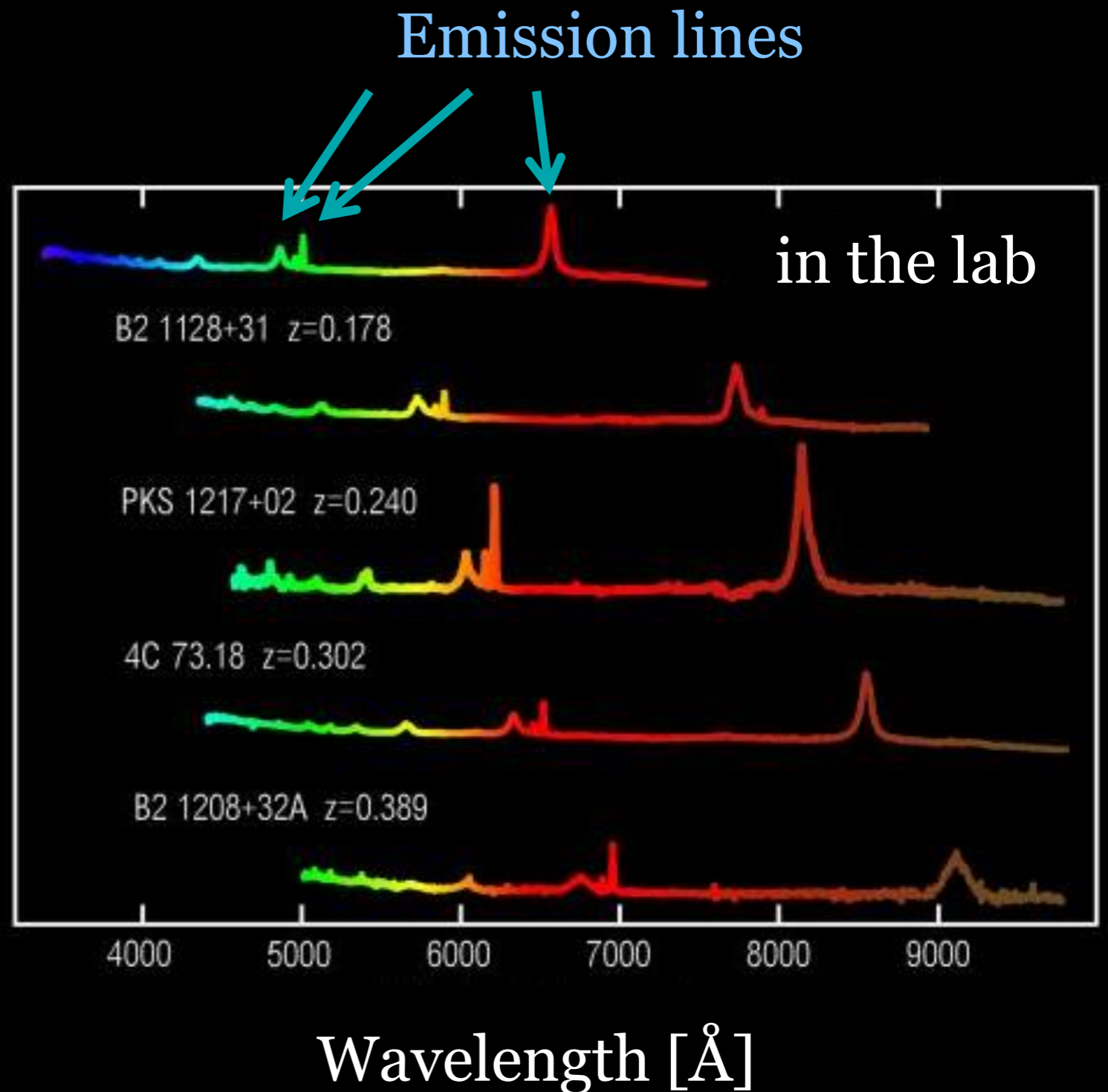
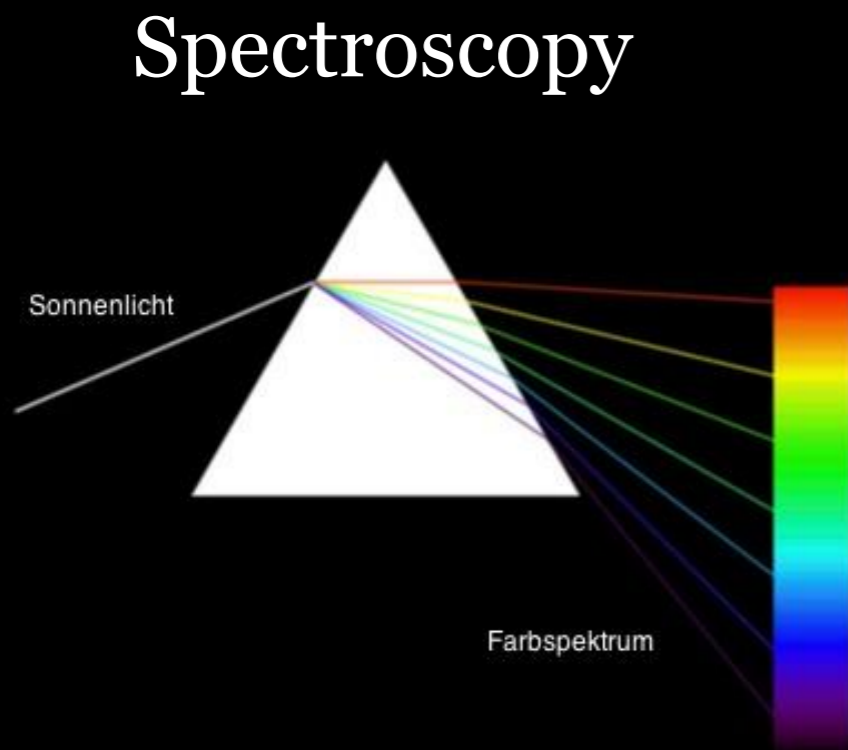


Edwin Hubble (1924)
Mt. Palomar telescope

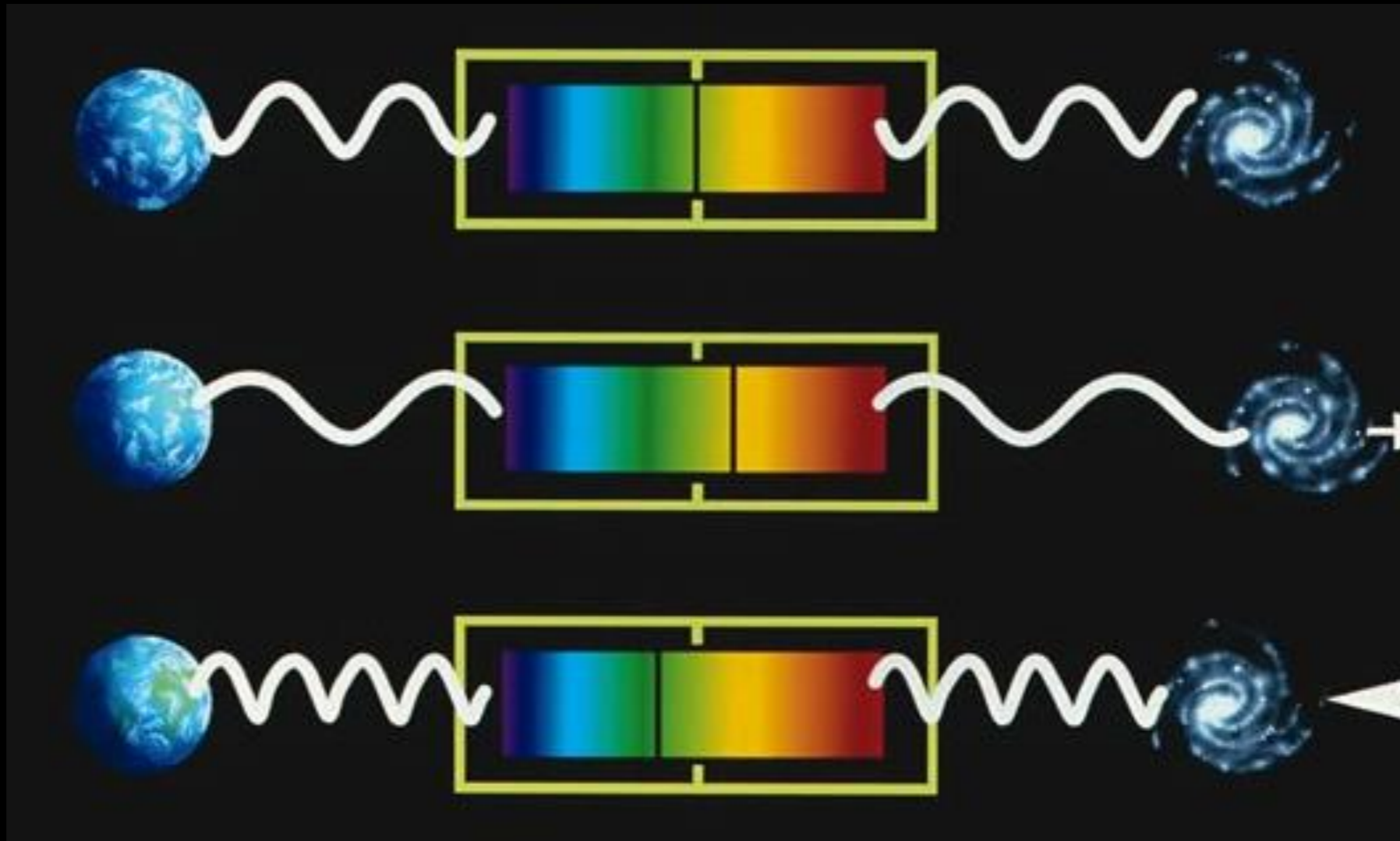


Observation of „nebulas“
Proof of the existence of galaxies outside the
Milky Way

Measuring the Redshift

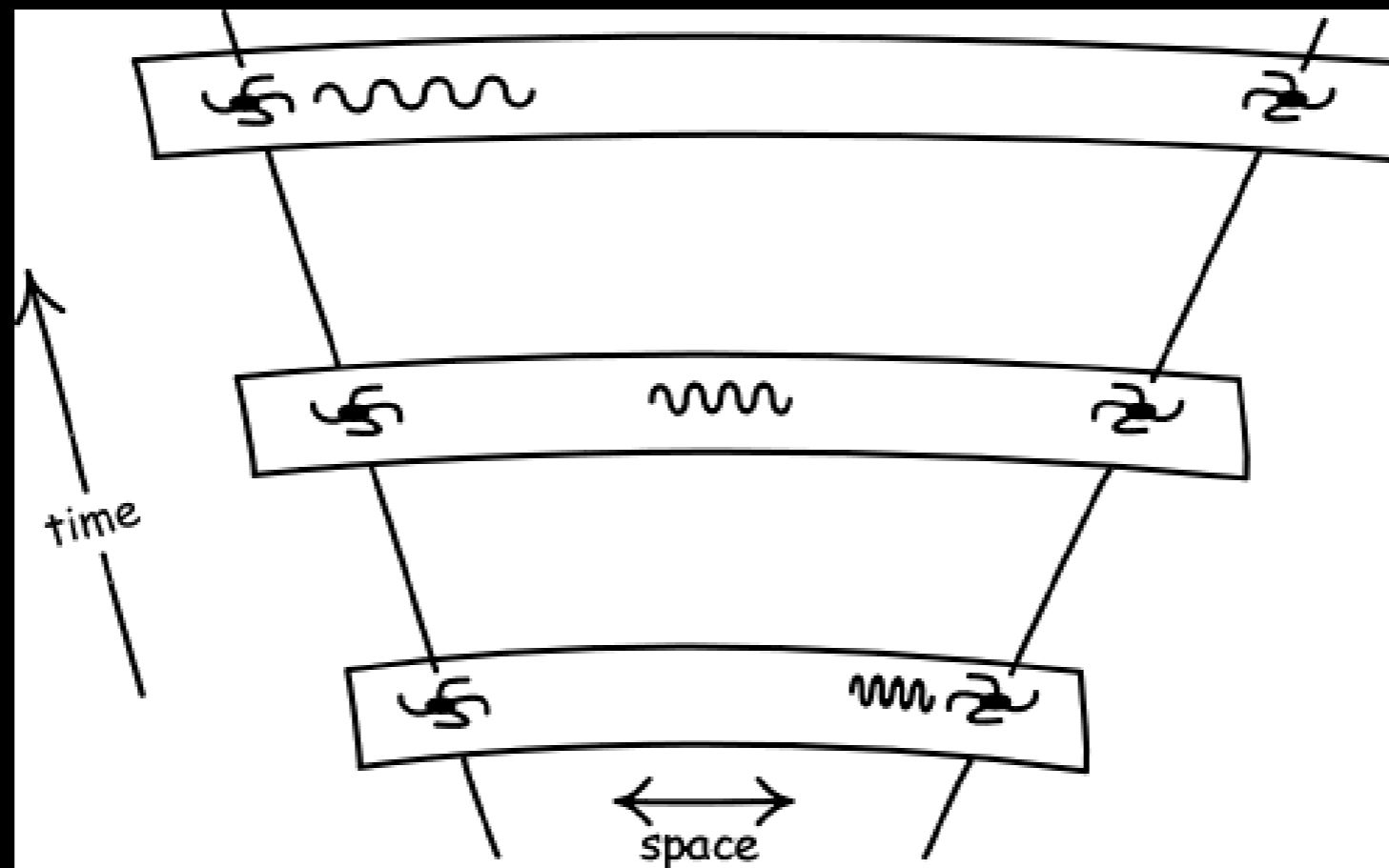


Cosmological Redshift vs. Doppler Effect



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

Cosmological Redshift

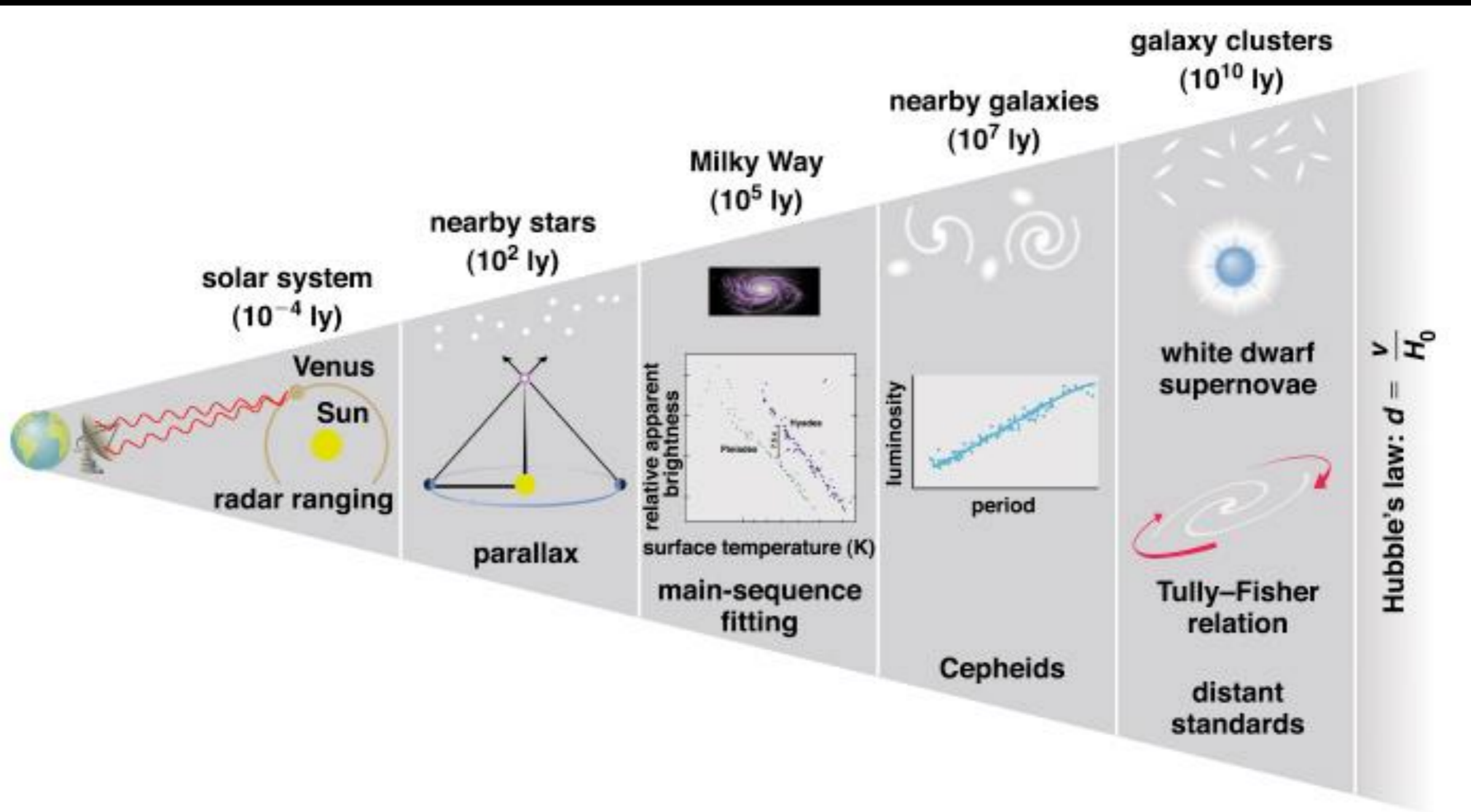


Space itself expands and “stretches” the wavelength of the photons.

Cosmological Redshift



Distance Ladder

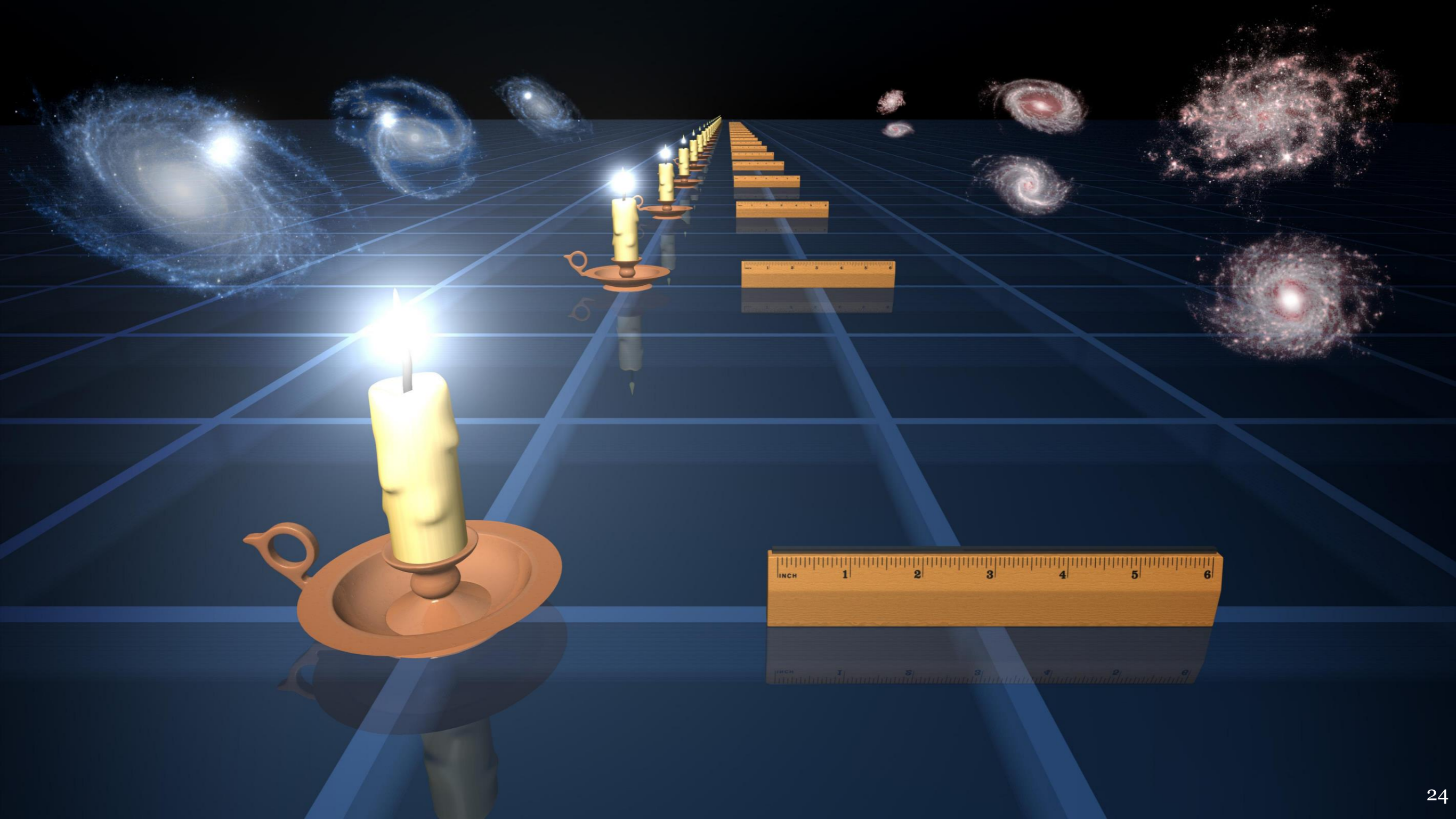


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Type Ia Supernova



Standard Candles and Brightness



Example of a Supernova from 1994



Credit: High-Z Supernova Search Team, HST, NASA

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

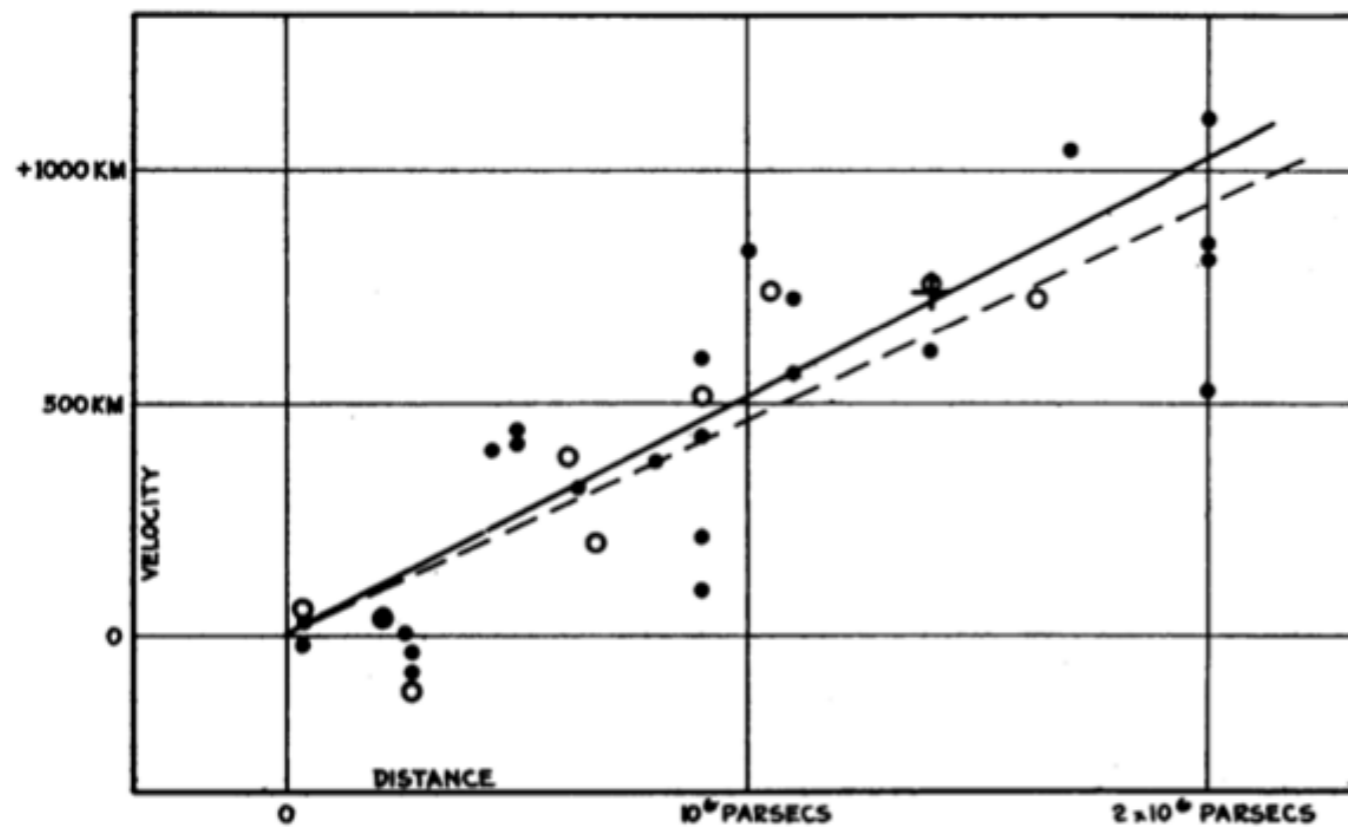
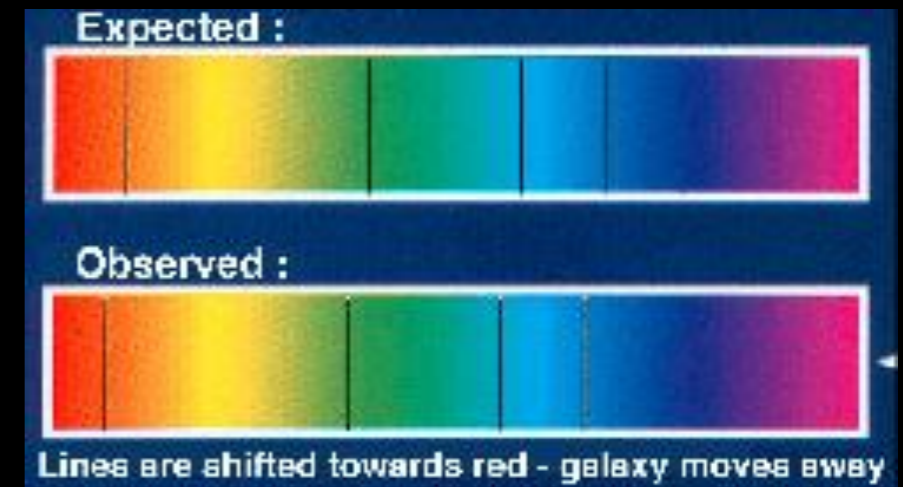
The Universe is expanding

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

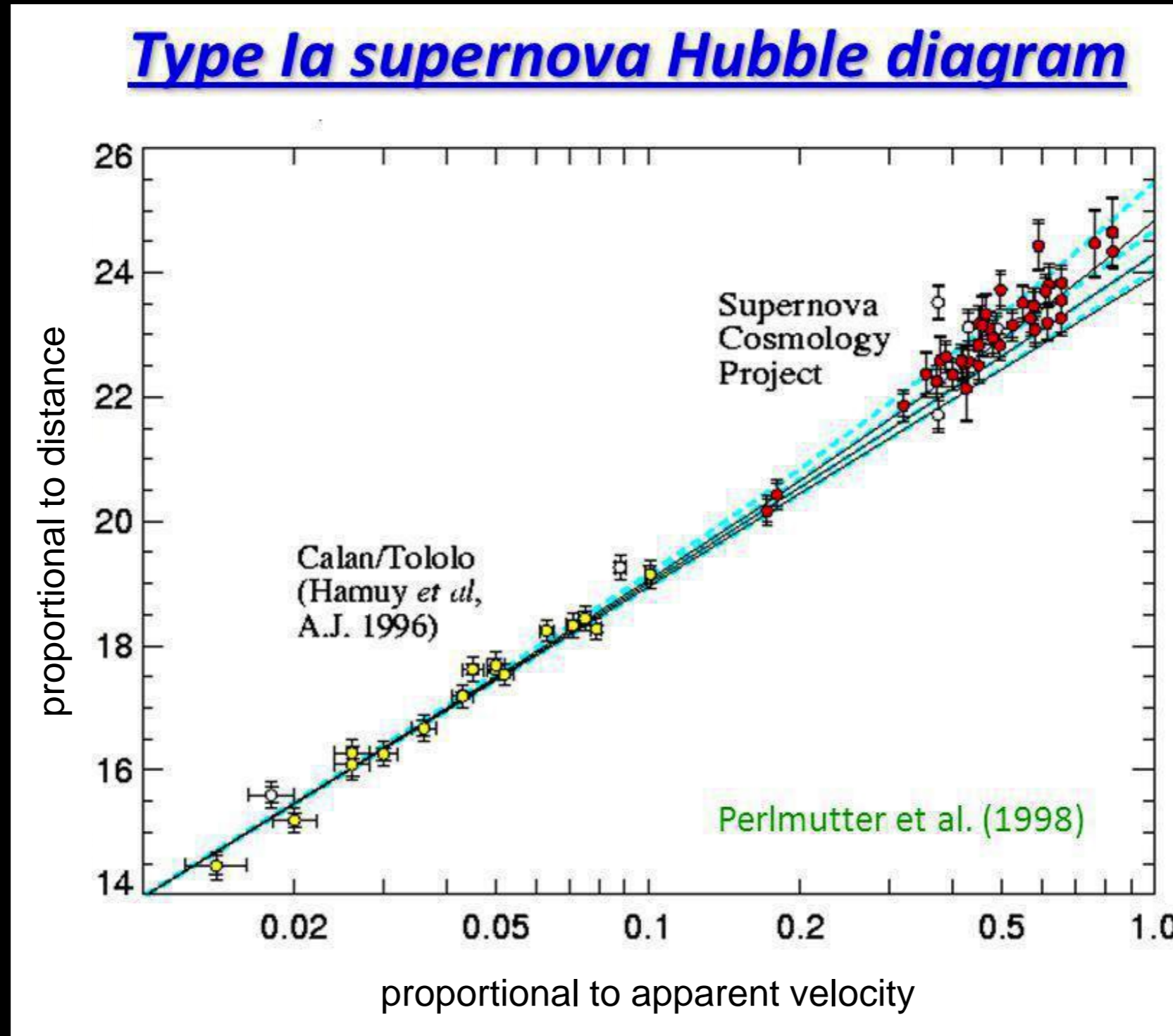


redshift is proportional to the distance of the galaxies (galaxy escape)

Hubble's law: $v = H_0 d$

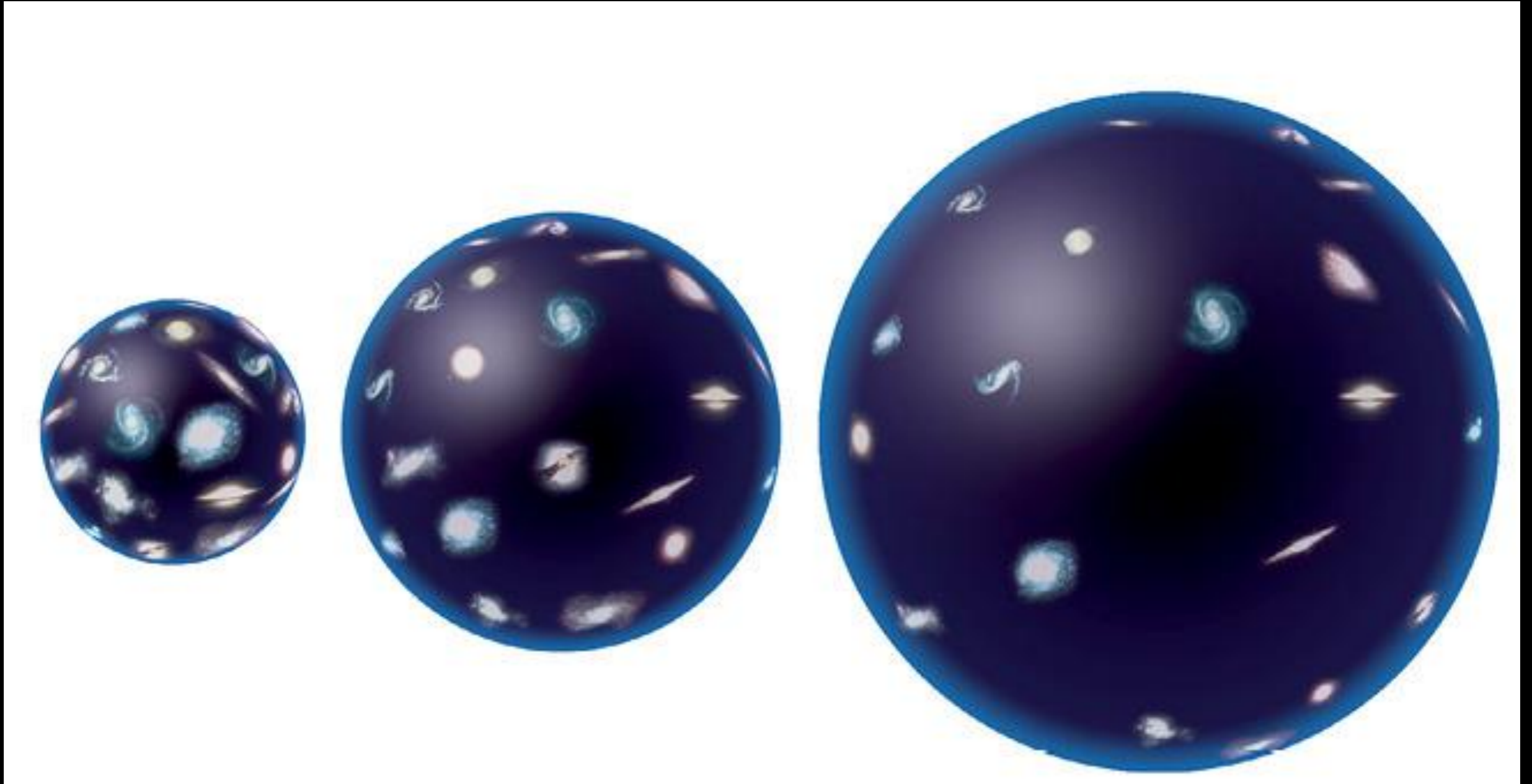
$H_0 = 530 \text{ km/s / Mpc !!}$

The present value of the Hubble "constant"



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

Consequences of the Cosmological Expansion

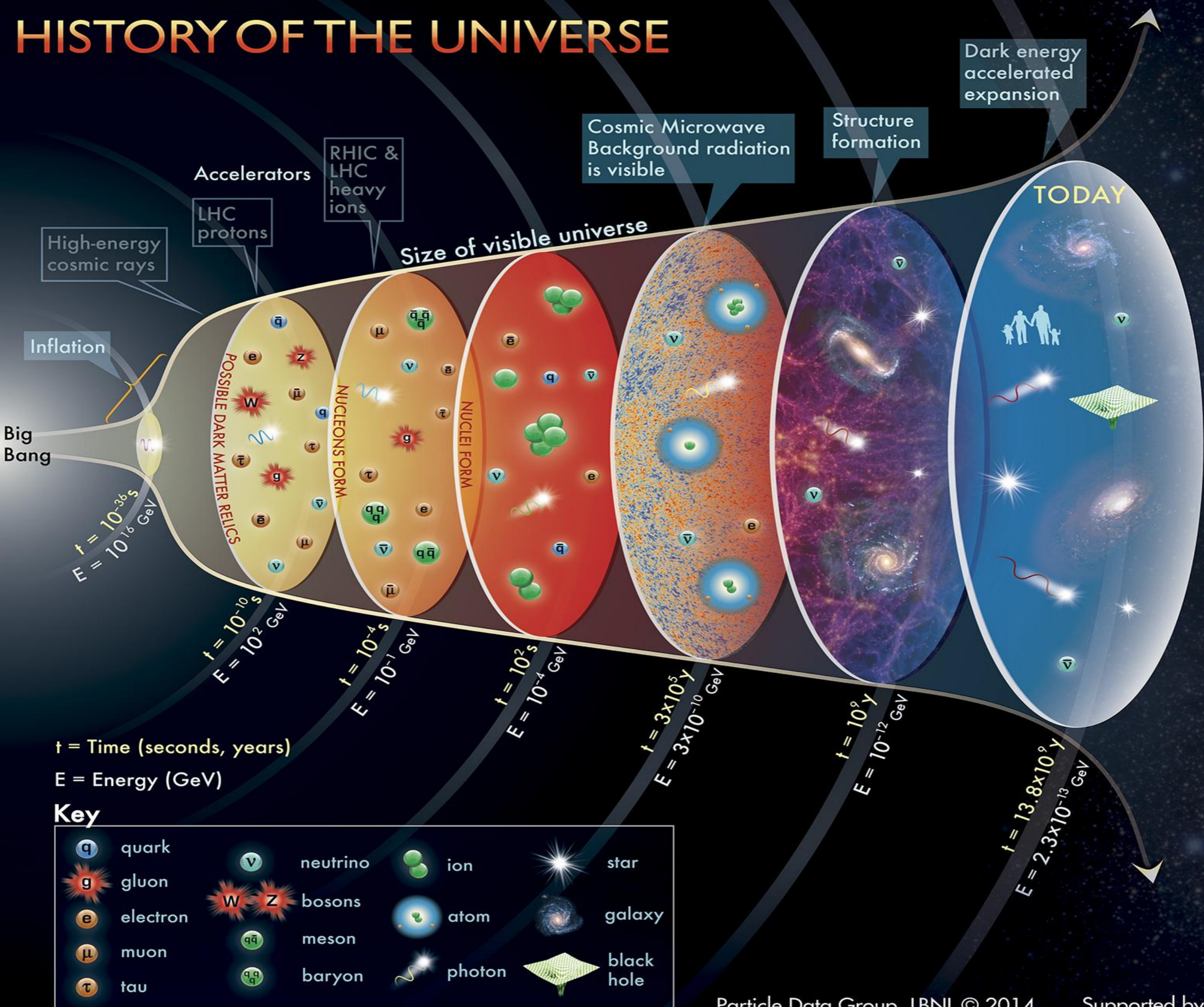


The further we look back into the past, the smaller was the Universe.
➡ conclusion about the Big Bang

A Journey through Time

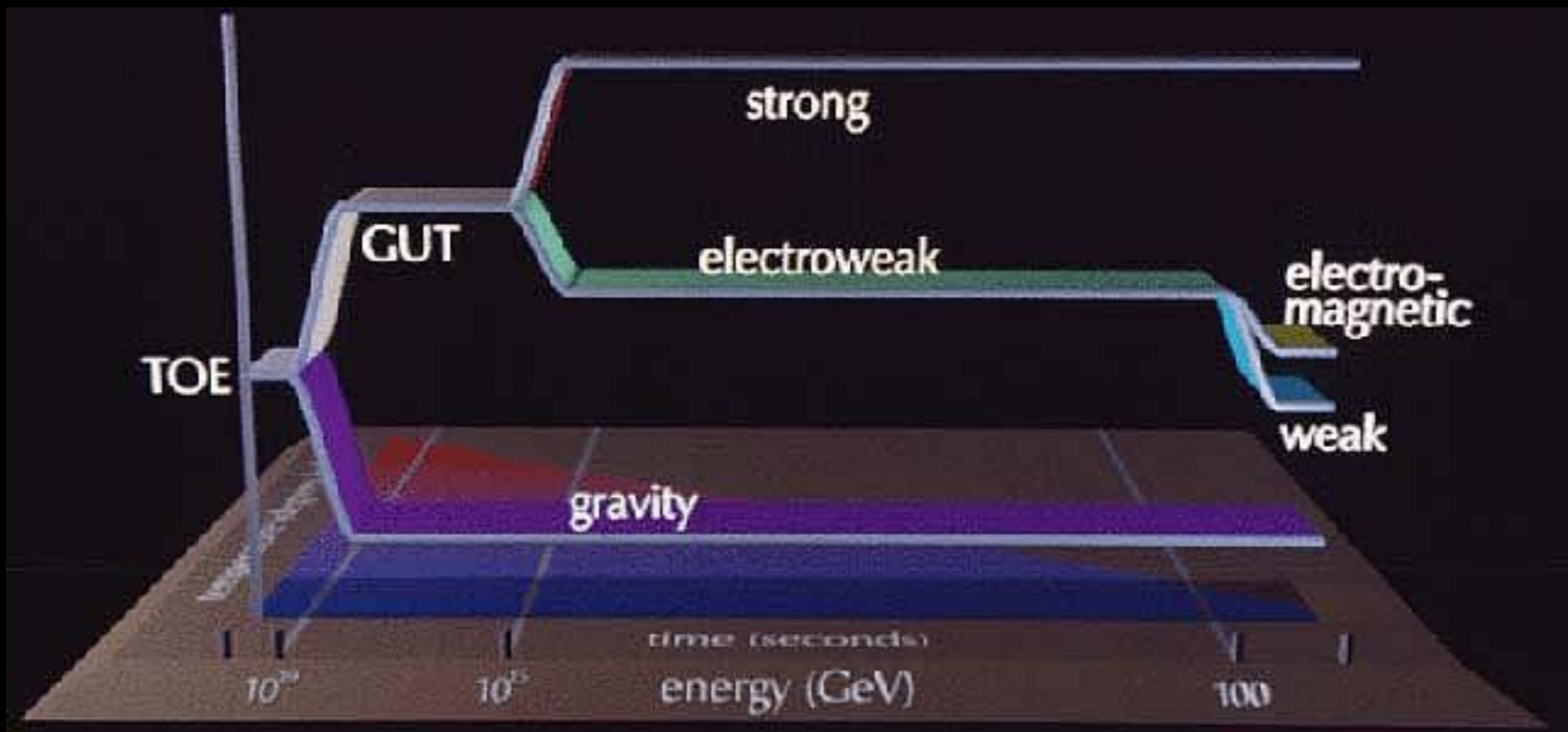


HISTORY OF THE UNIVERSE

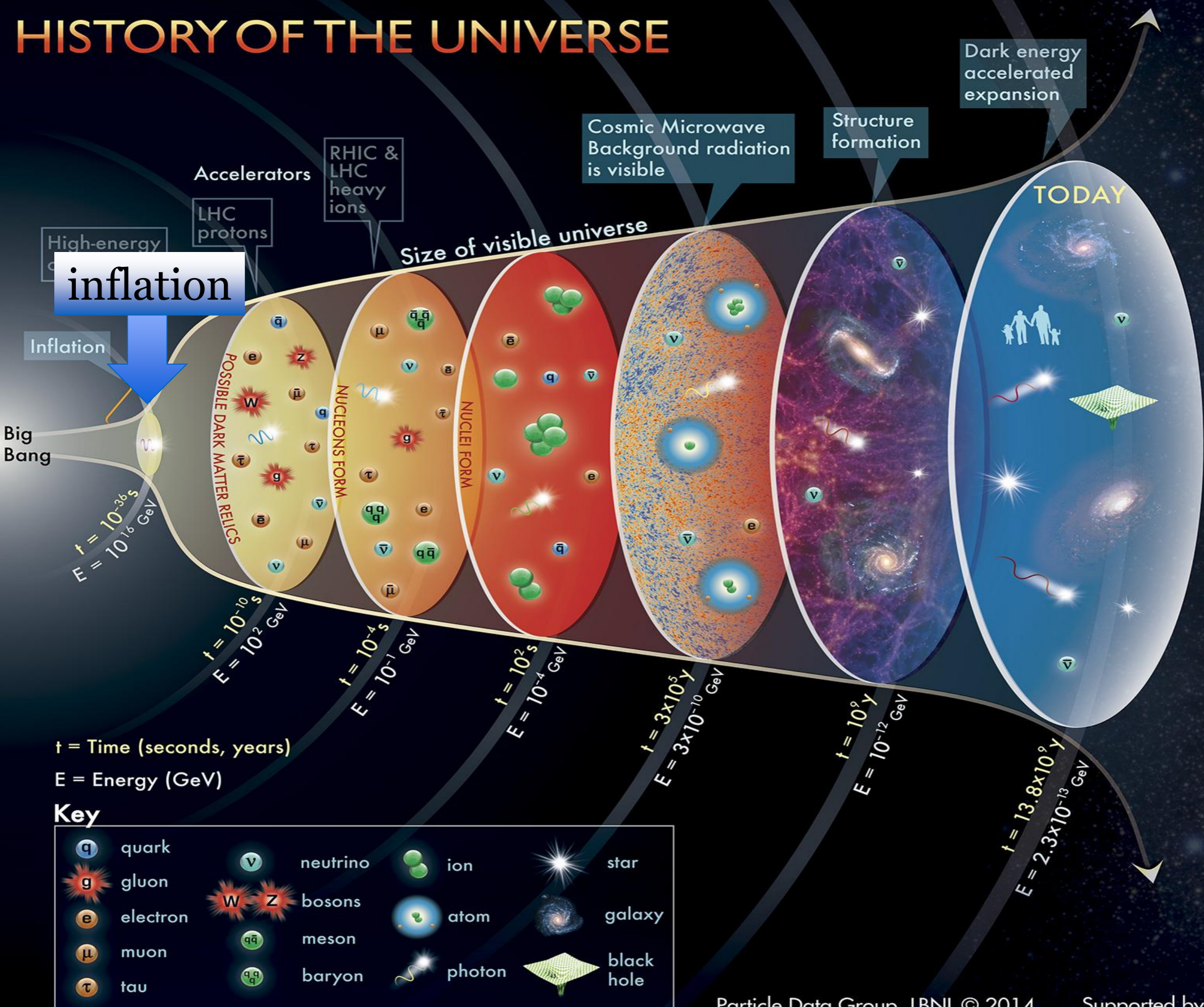


Unification of the Forces

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

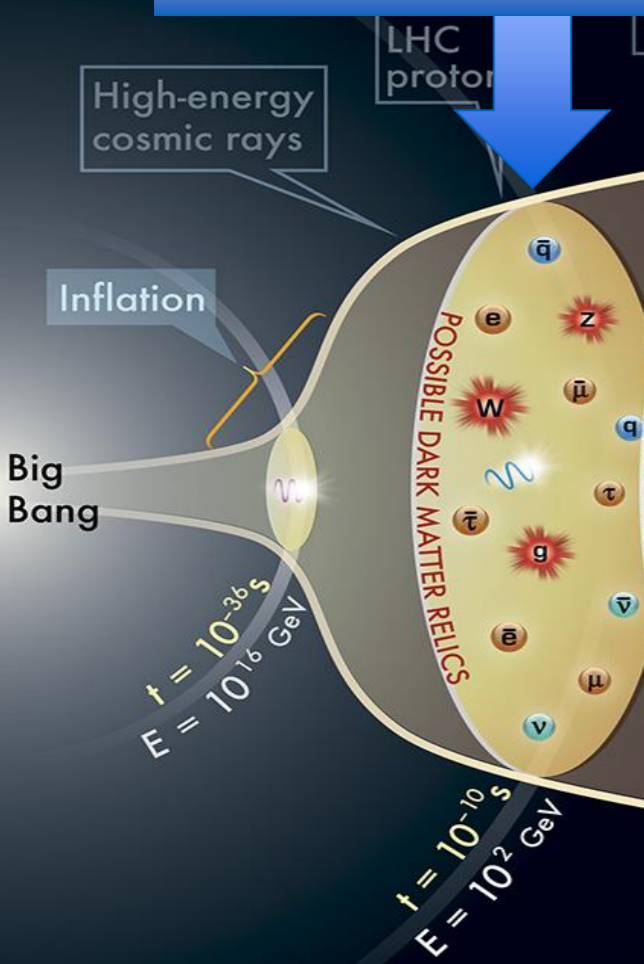


HISTORY OF THE UNIVERSE



HISTORY OF THE UNIVERSE

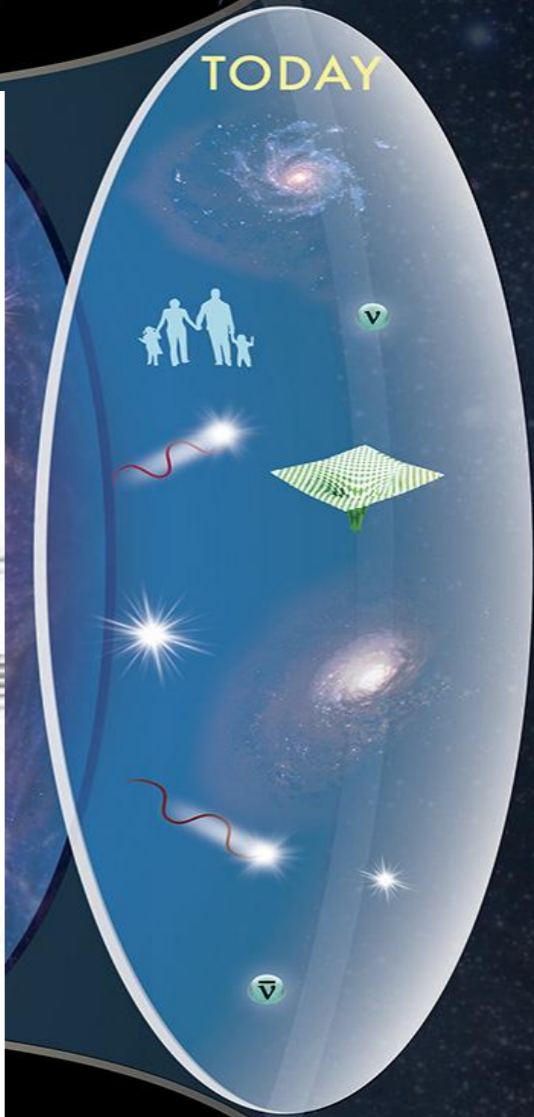
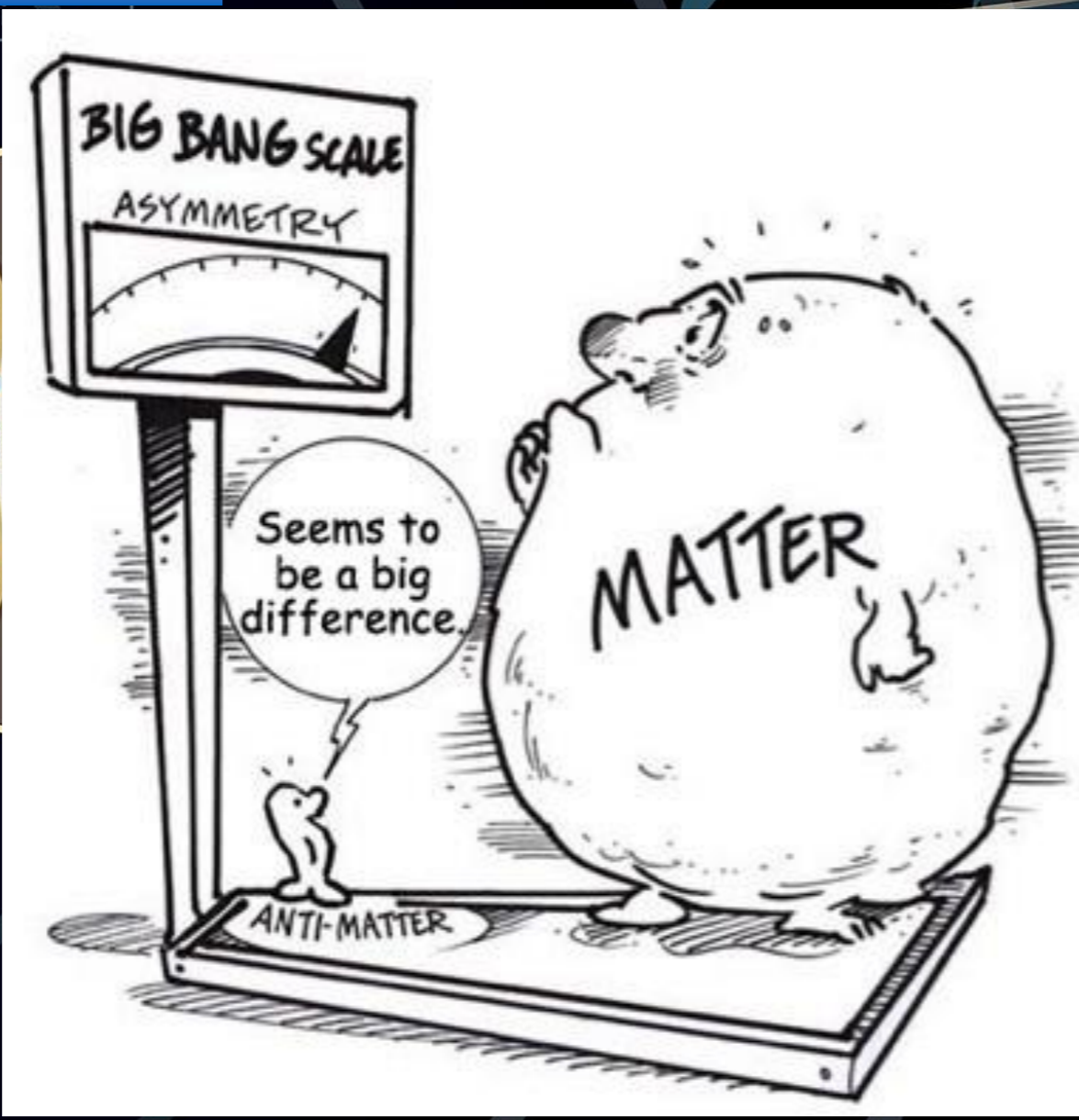
destruction battle



Cosmic Microwave Background radiation is visible

Structure formation

Dark energy accelerated expansion



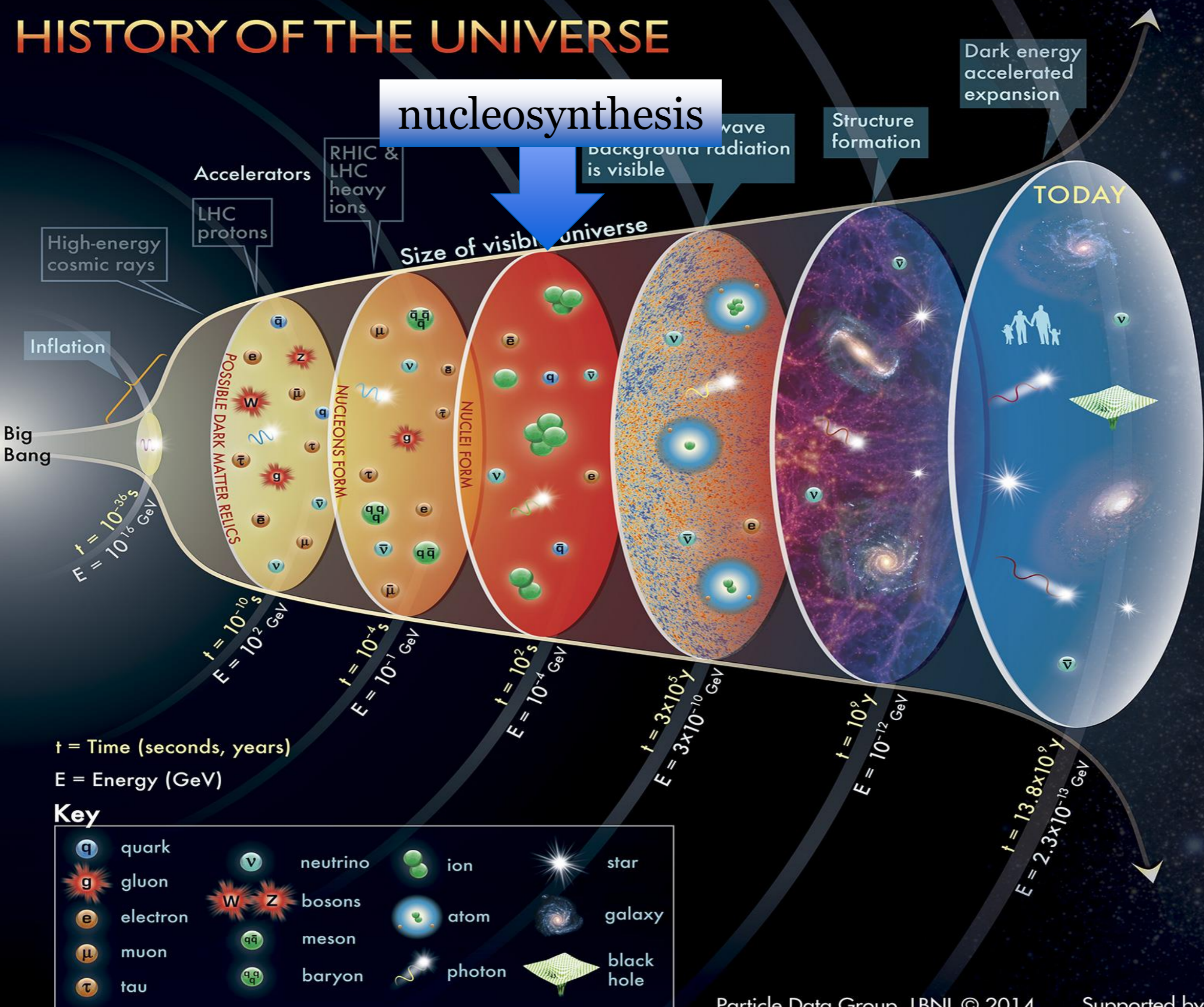
t = Time (seconds, years)
E = Energy (GeV)

Key

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

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

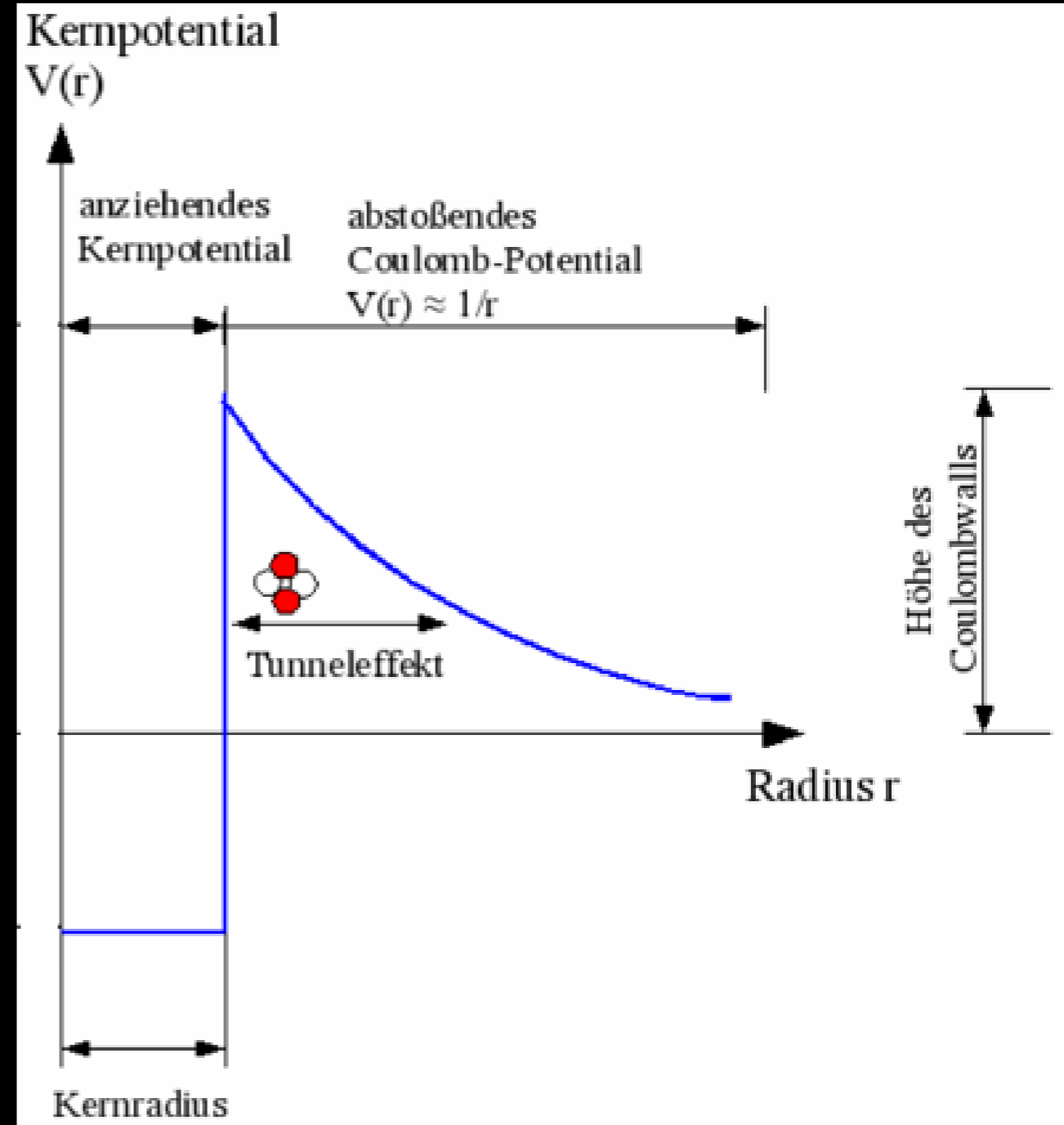
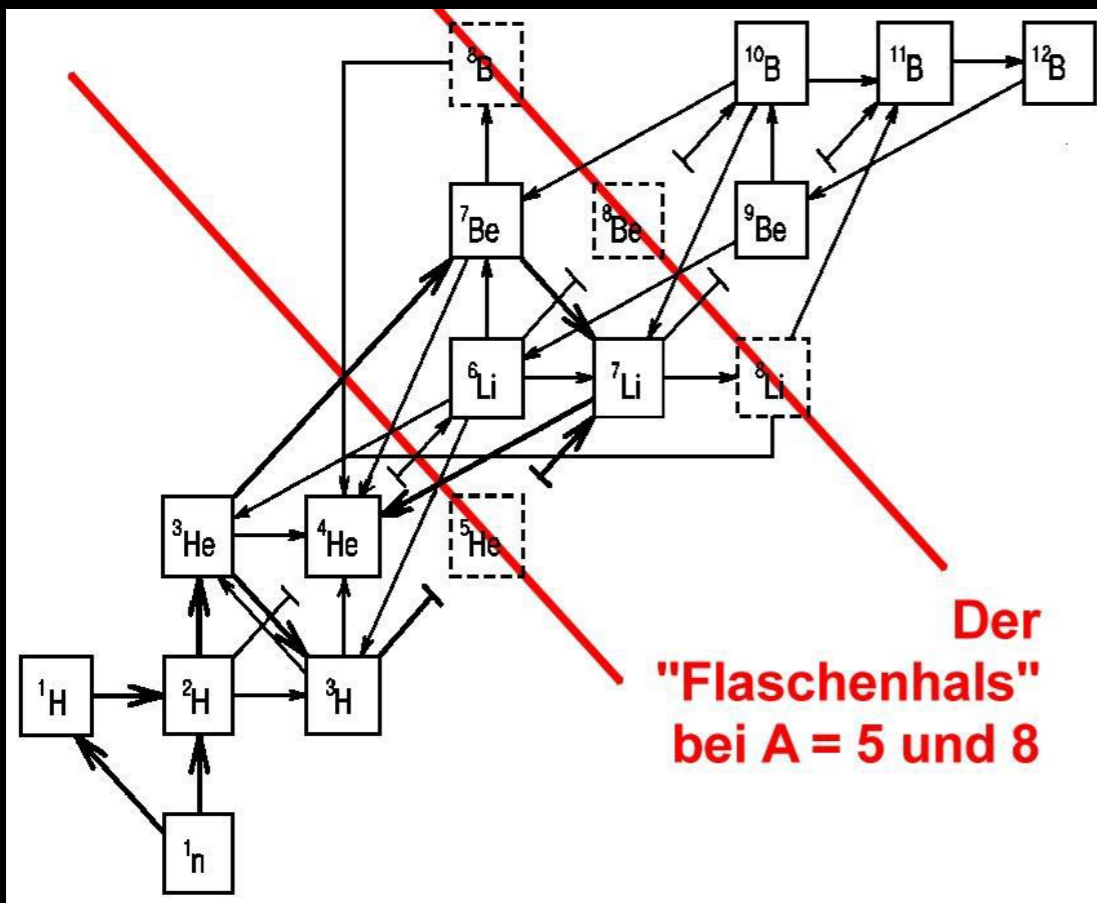
HISTORY OF THE UNIVERSE



Nuclear Fusion

fusion in particle collisions

fusion needs high temperatures
and high particle densities

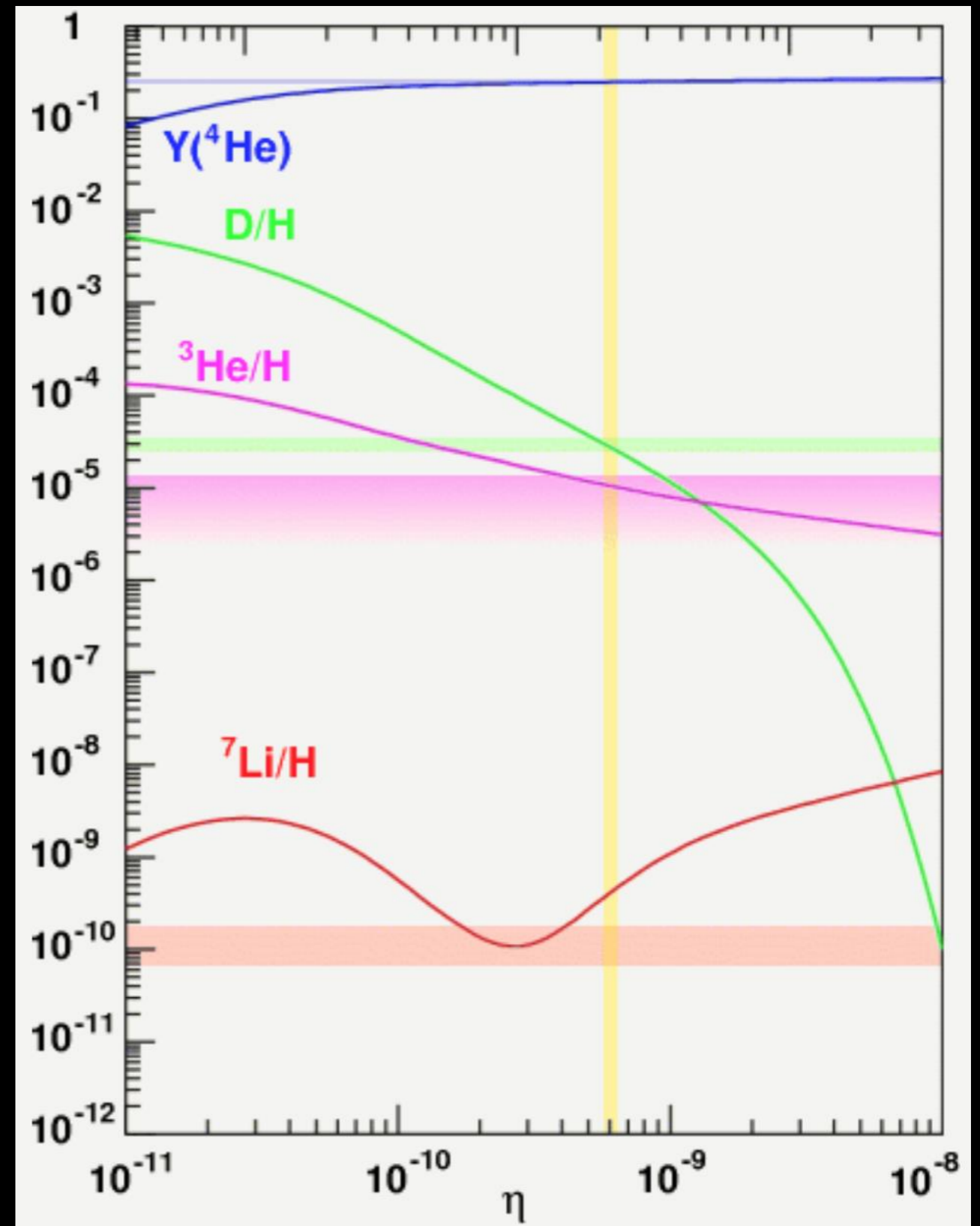


Primordial Nucleosynthesis

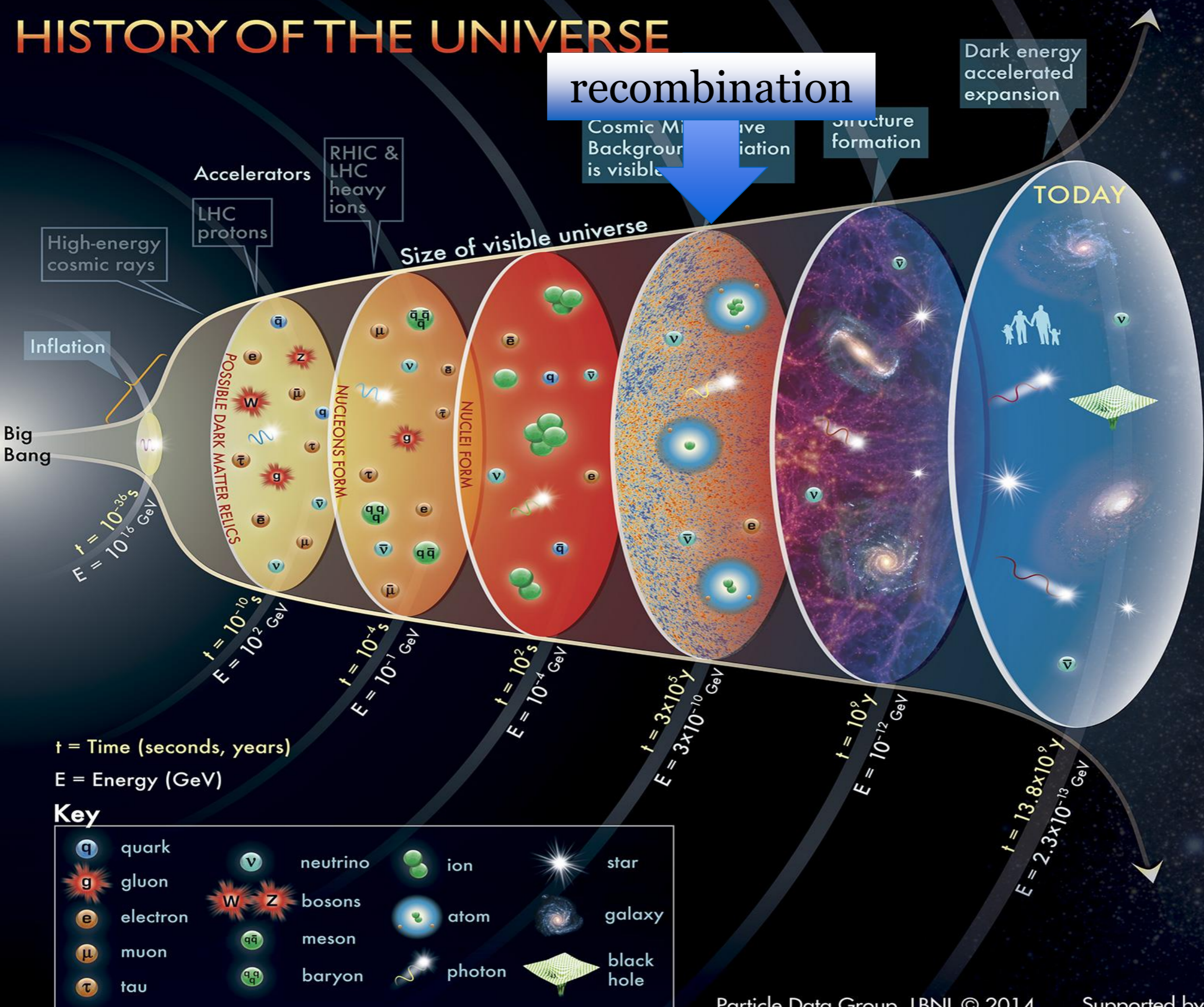
Comparison of theory
(curves) and observation
(horizontal lines)

abundances
of light elements:

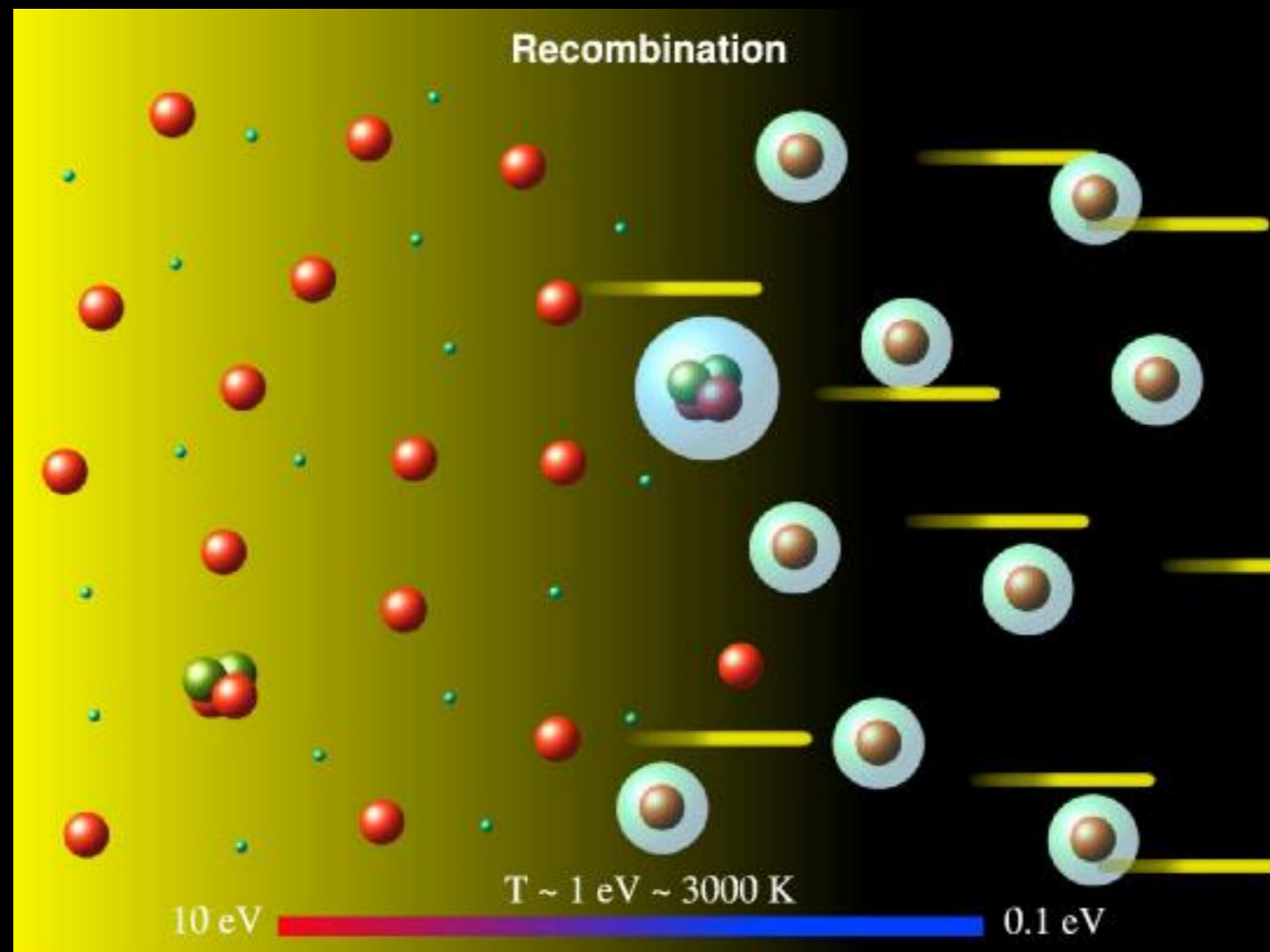
74 % hydrogen
25 % helium
1 % rest



HISTORY OF THE UNIVERSE

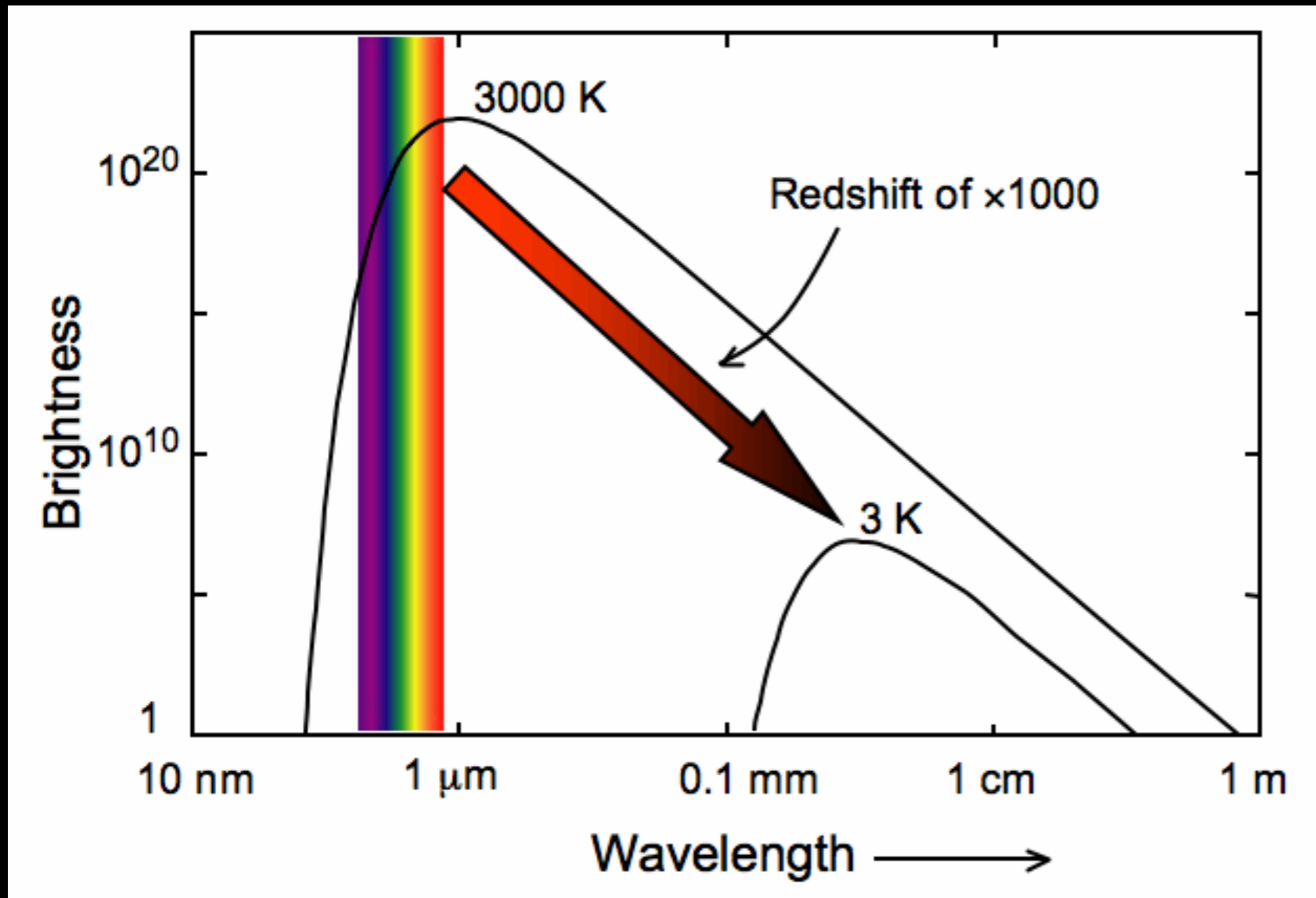


Recombination

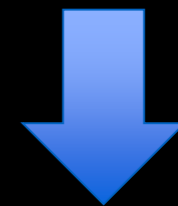


- below $T = 3000 \text{ K}$ ($t = 380000 \text{ a}$) neutral atoms can form
- afterwards photons don't scatter any more on free electrons
➔ The Universe becomes transparent!

The Cosmic Microwave Background (CMB)

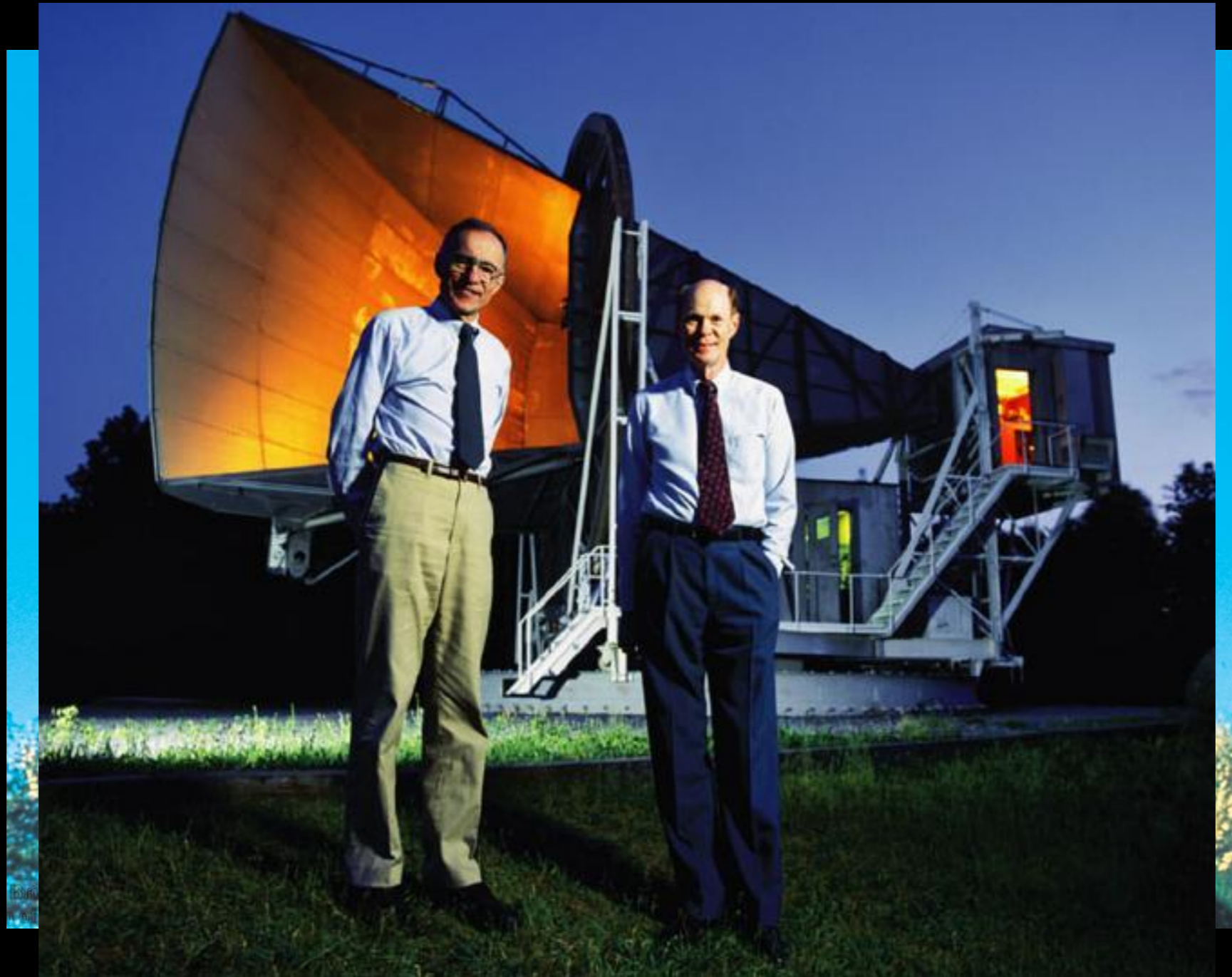


During recombination the photons are in thermic equilibrium with the electrons and atomic nuclei.



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

Discovery of the CMB



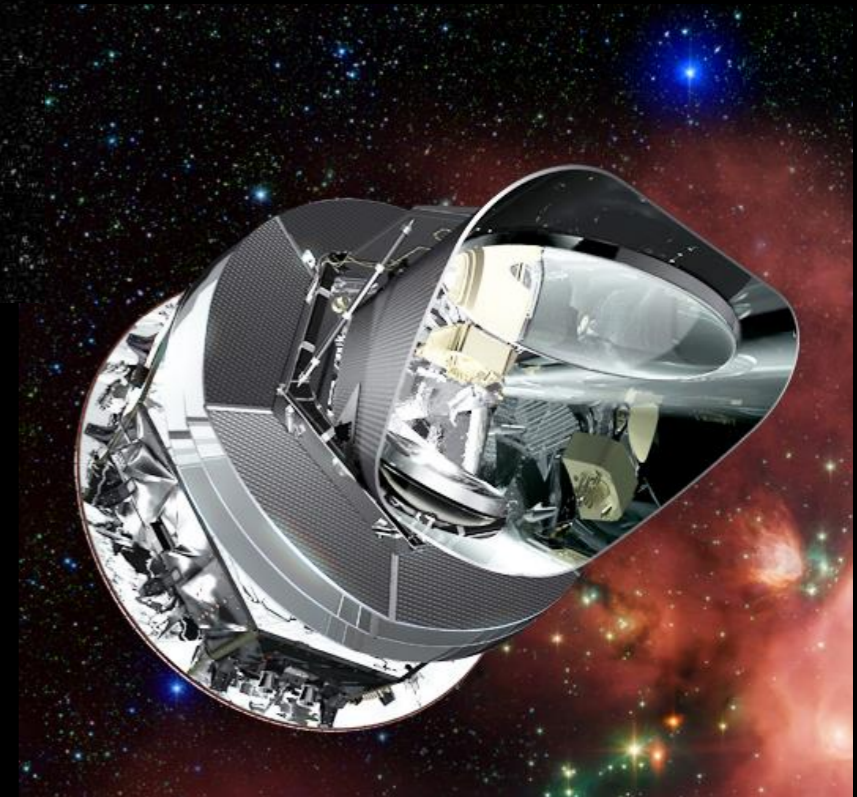
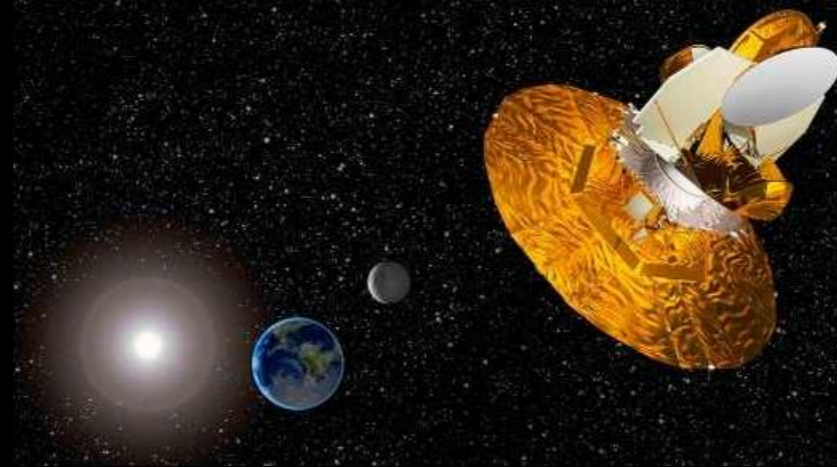
1964 Penzias und Wilson discovered a noise, which they couldn't explain



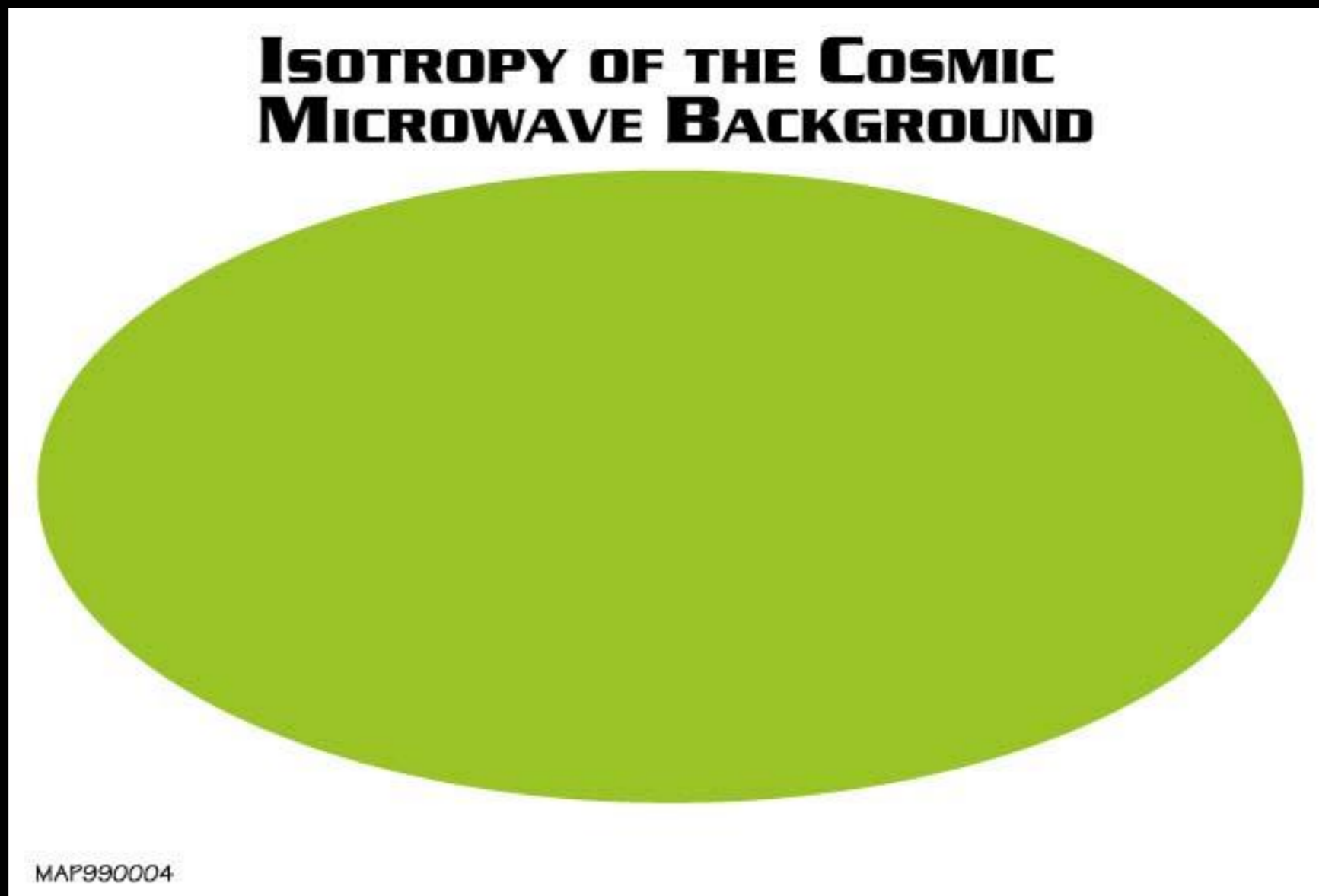
(1978)

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

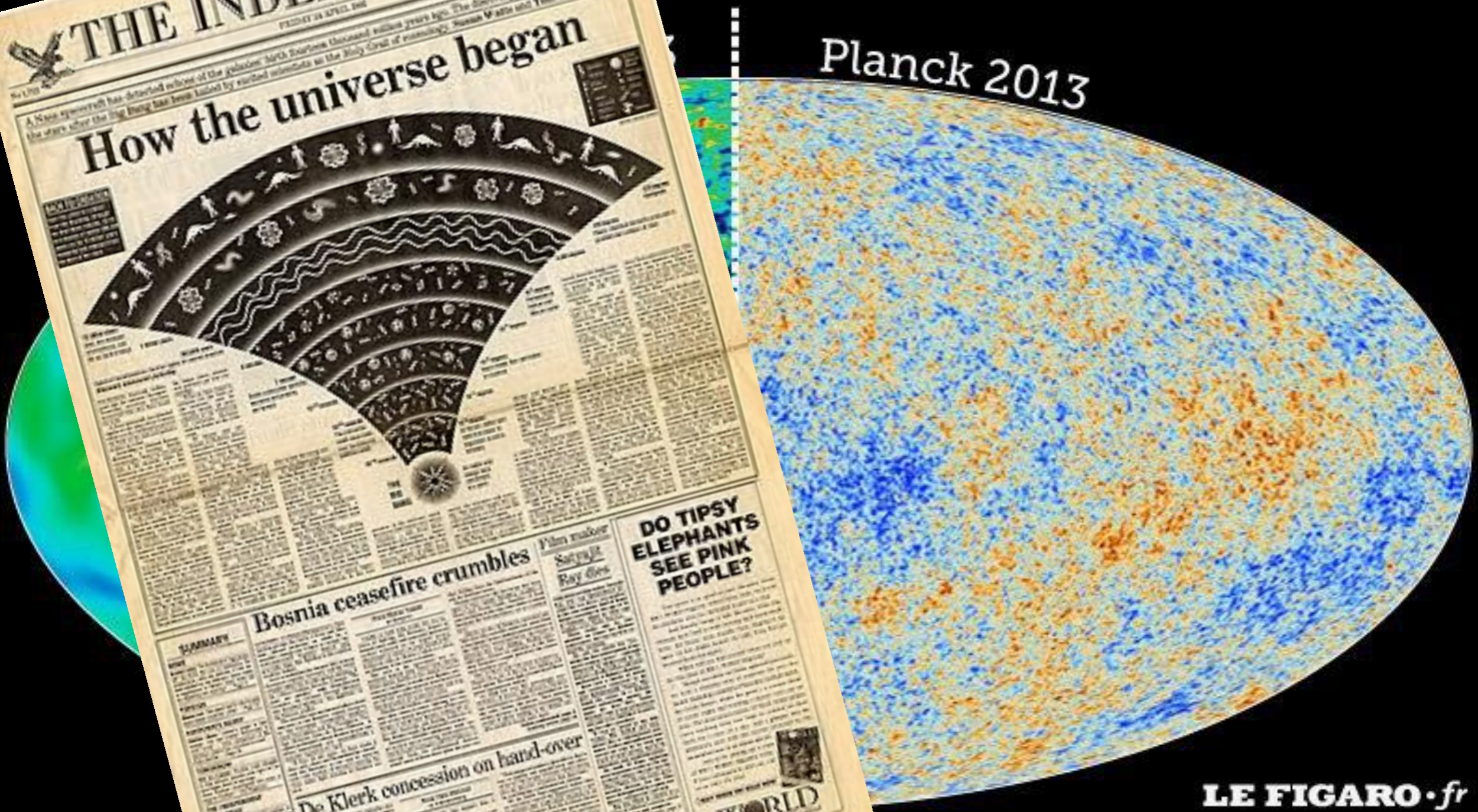


Next problem for the Big Bang theory



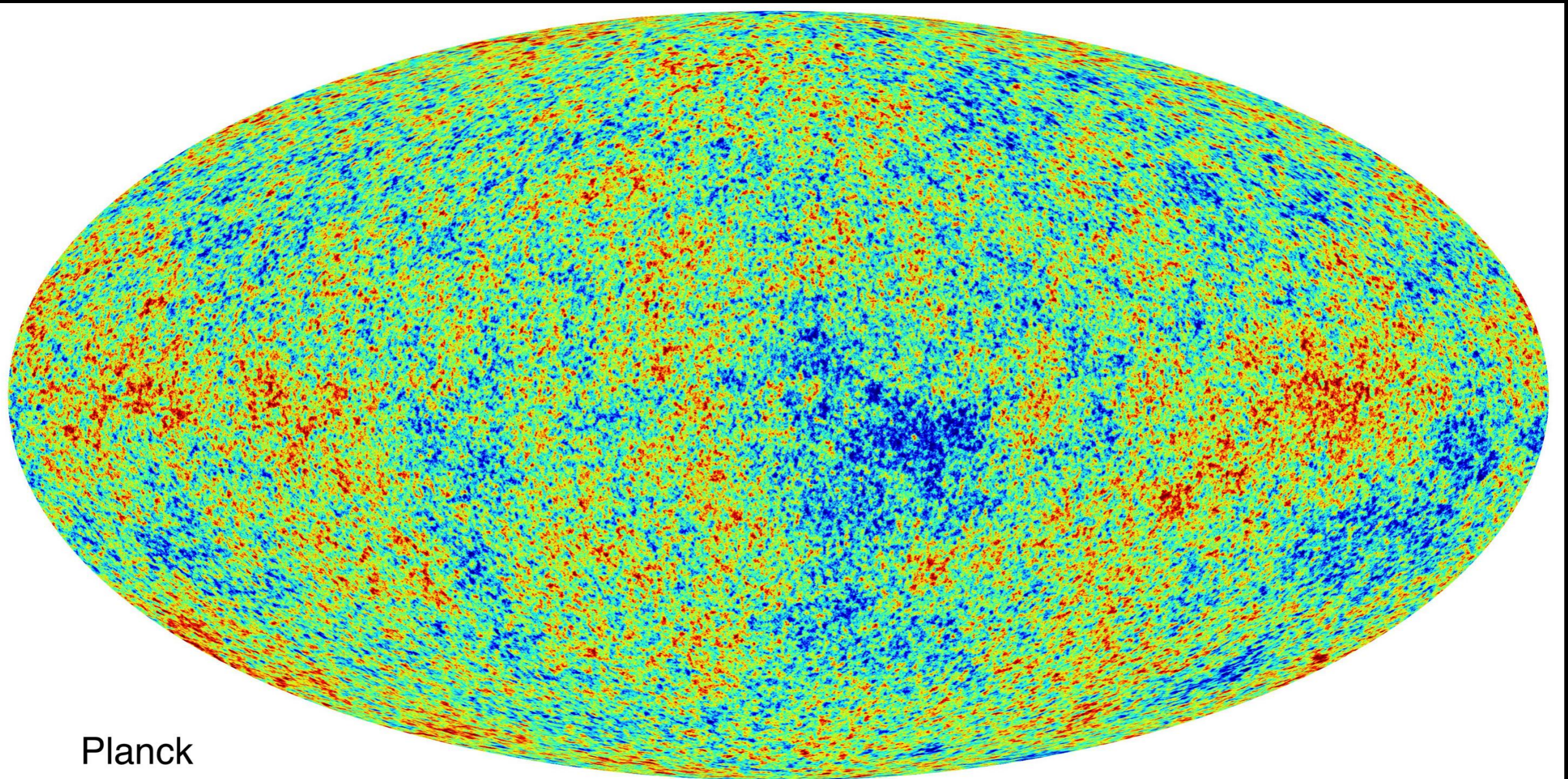
The second analysis revealed no sign of any variation at a level of 1 part in 10.000!
Where are the galaxies coming from, if not from density fluctuations?

The Echo of the Big Bang



The Echo of the Big Bang

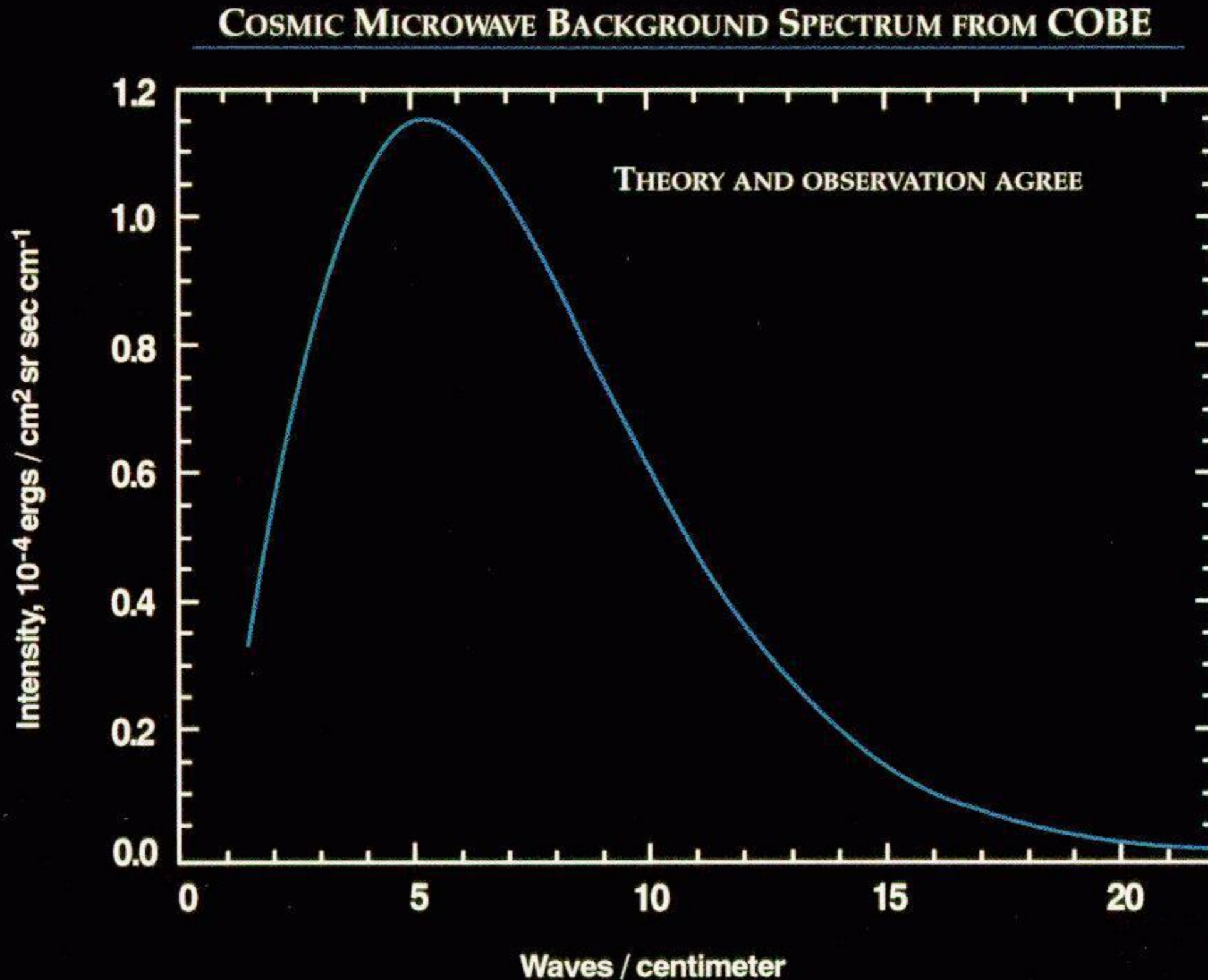
The CMB is extremely isotropic with a temperature of $T_{\text{CMB}} = 2,725 \text{ K}$.
The temperature differences are in the range of microkelvin!



Planck

- 300 μK  + 300 μK

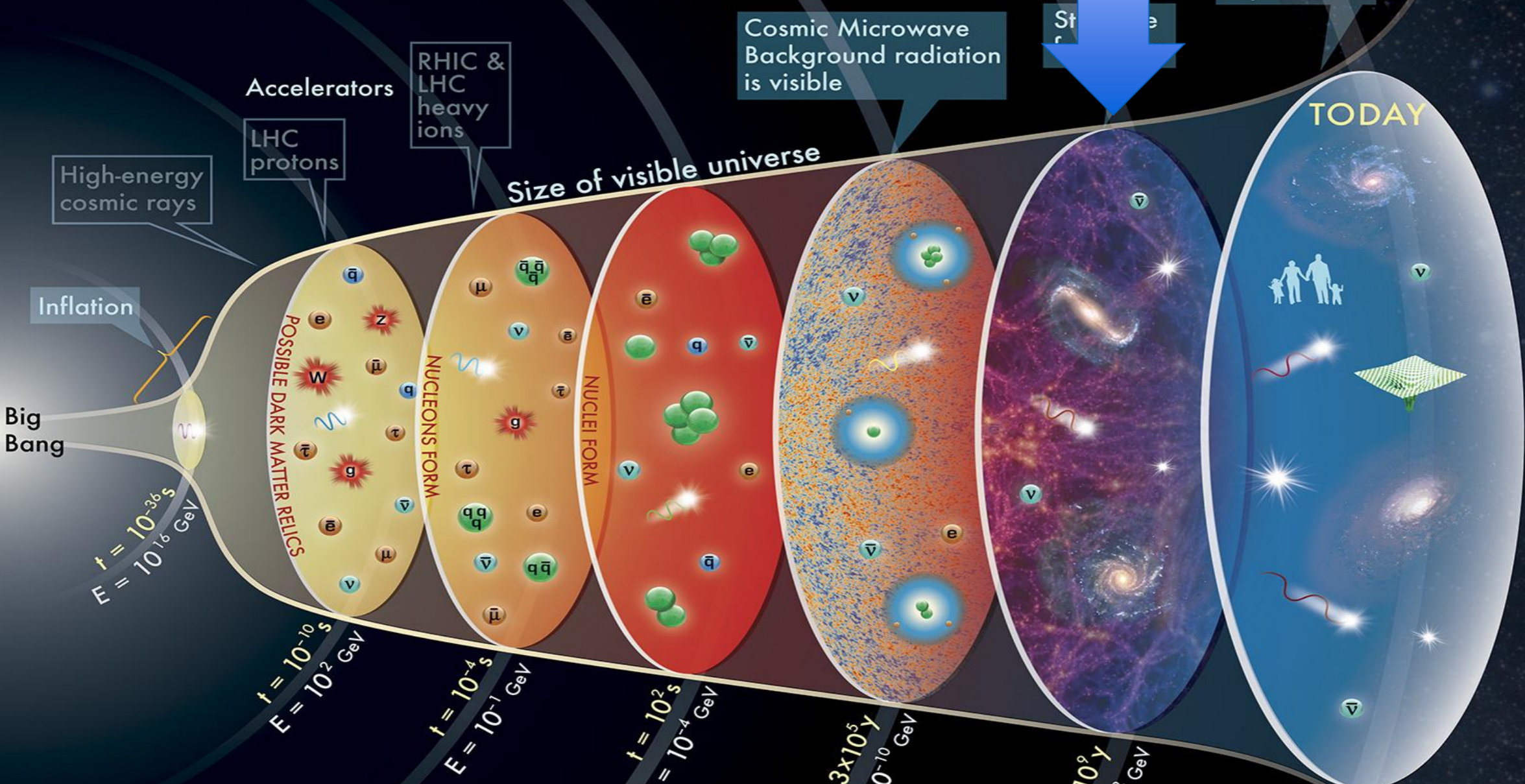
The spectrum of the CMB



HISTORY OF THE UNIVERSE

structure building

expansion



t = Time (seconds, years)

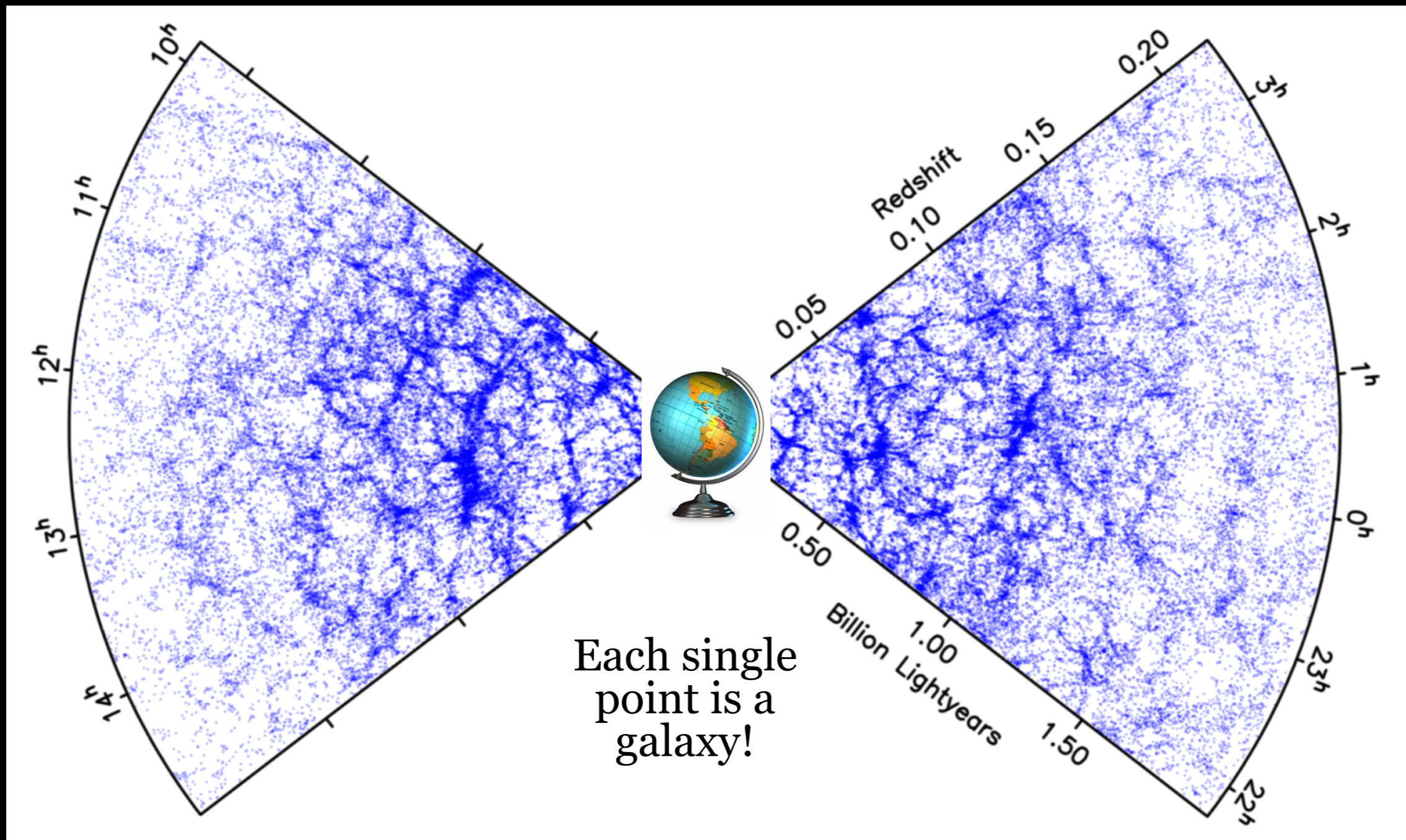
E = Energy (GeV)

Key

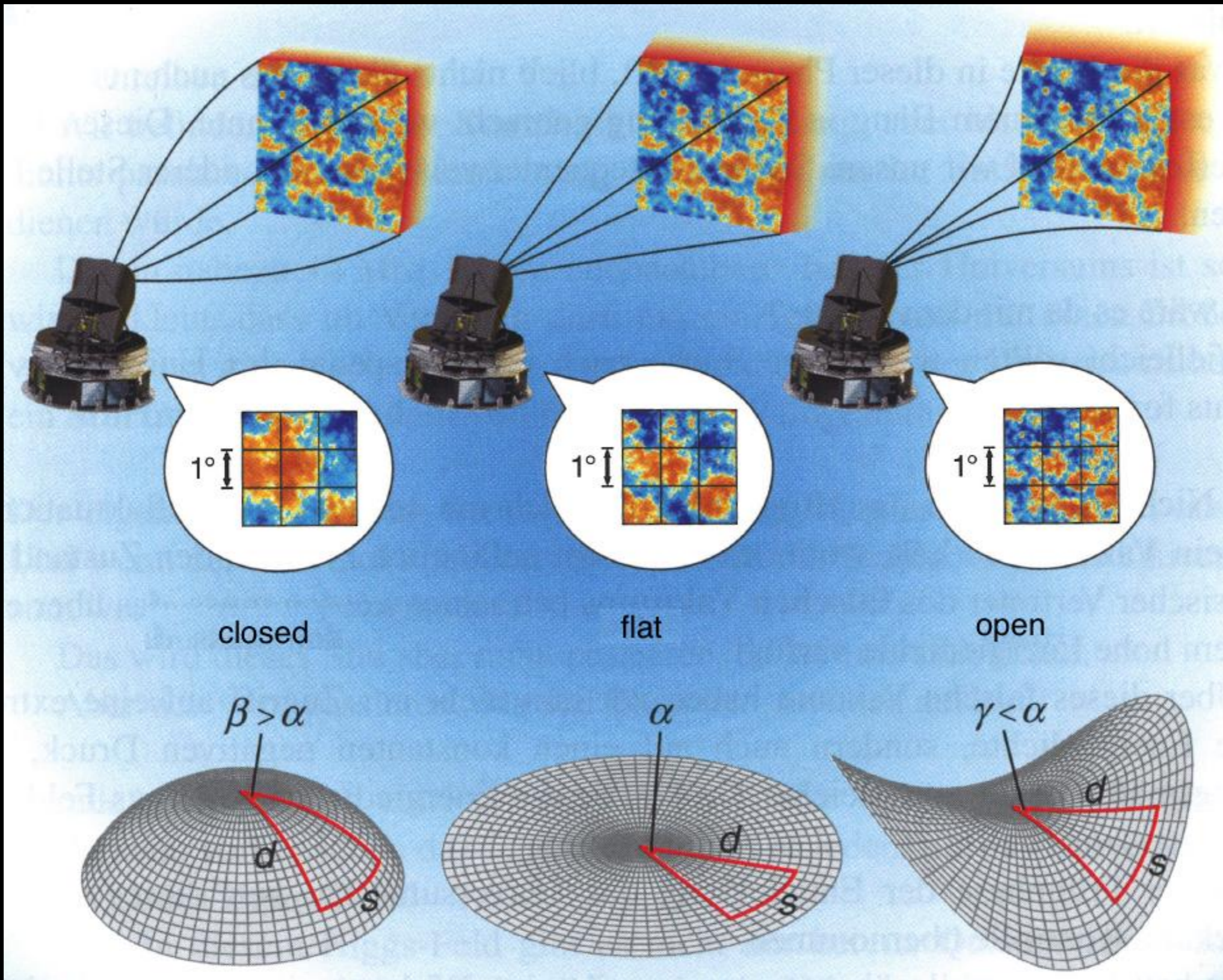
quark	neutrino	ion	star
gluon	bosons	atom	galaxy
electron	meson	photon	black hole
muon	baryon		
tau			

Galaxy Distribution

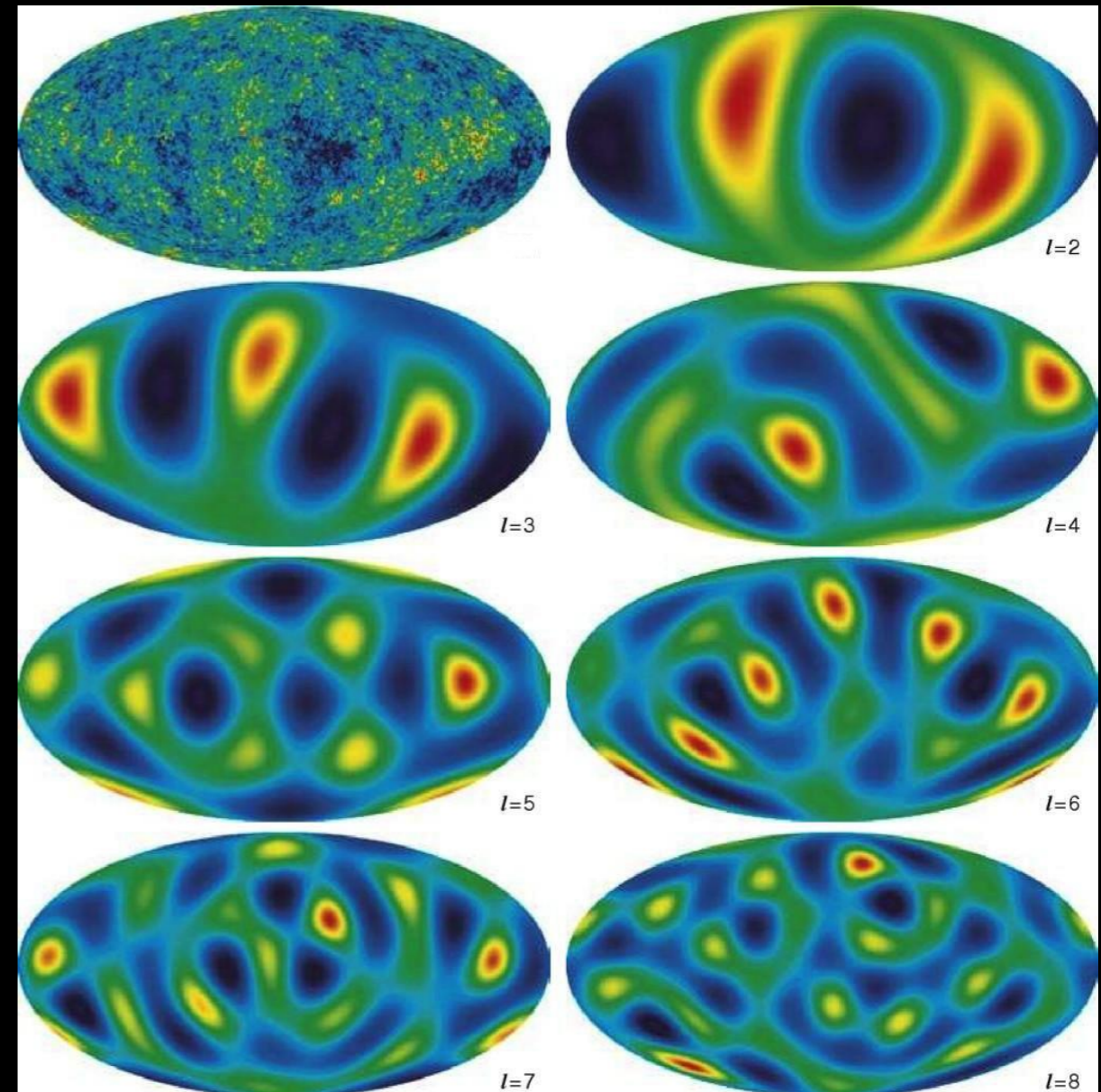
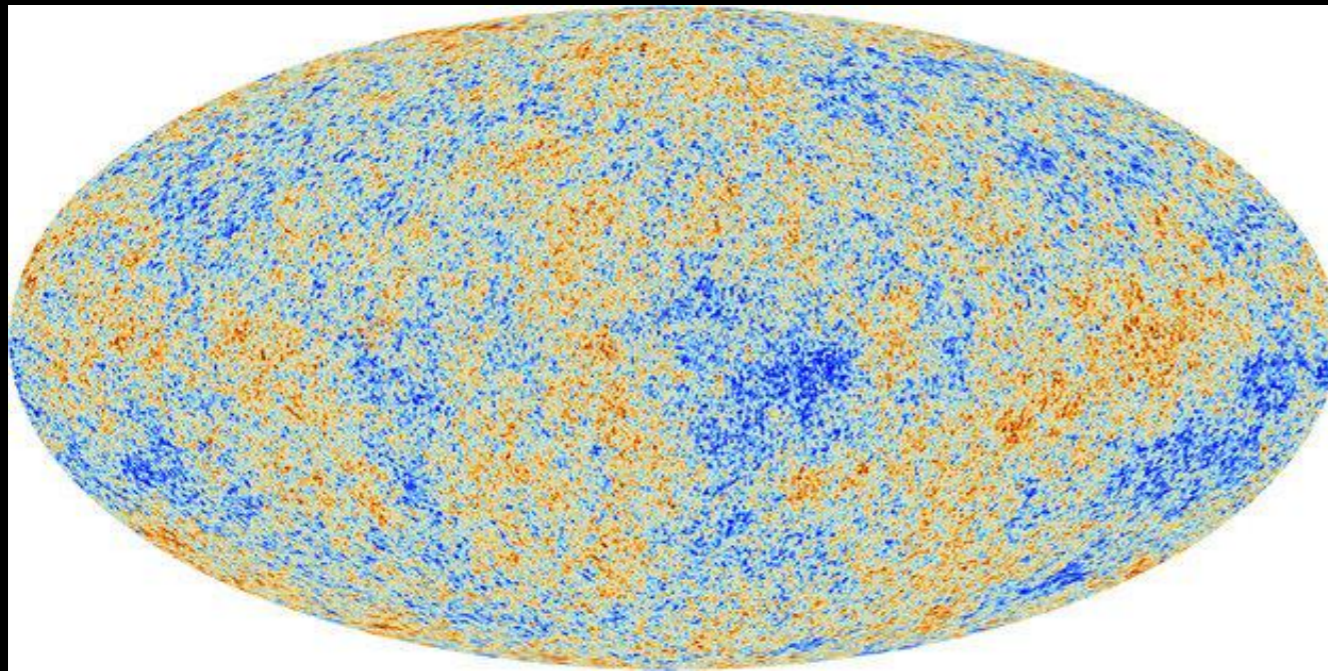
In the past the universe was much more homogeneous than today



Geometry of the universe

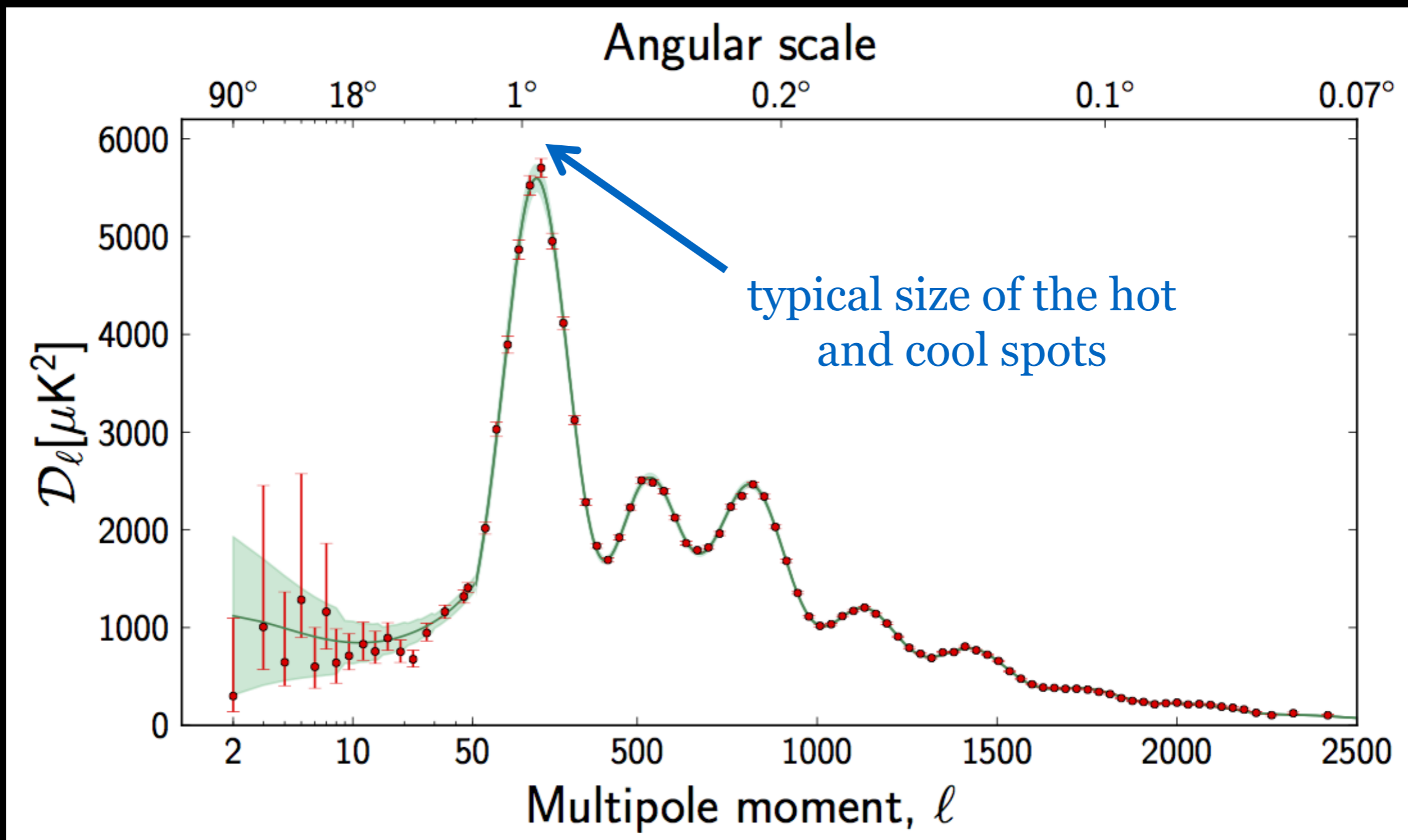


From the map to the spectrum...

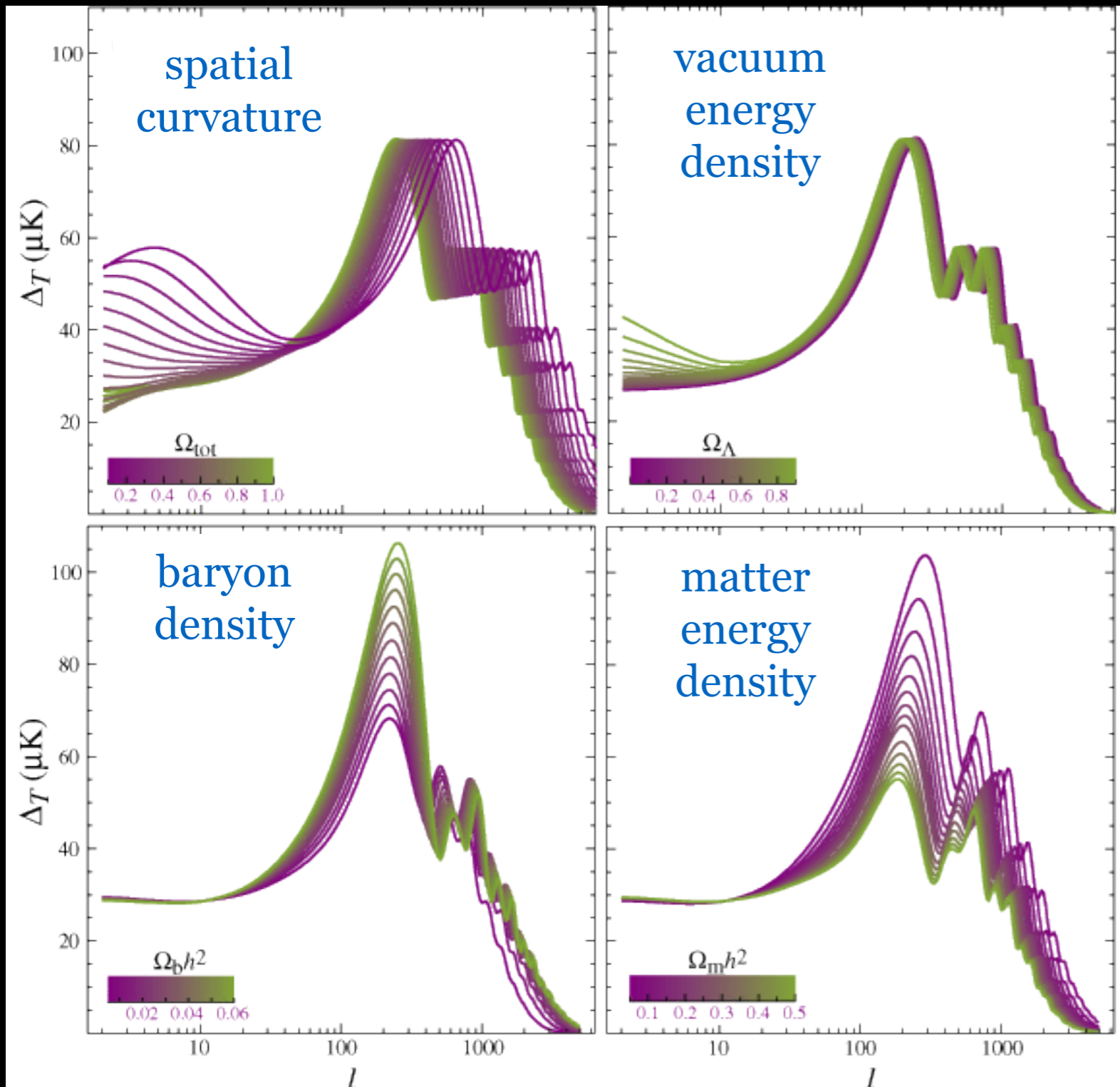


- theory is not able to predict the exact position of individual hot or cool spots
- instead: prediction of statistical properties of the temperature map (for example mean value, variance, correlations,...)

The Angular Power Spectrum of the CMB



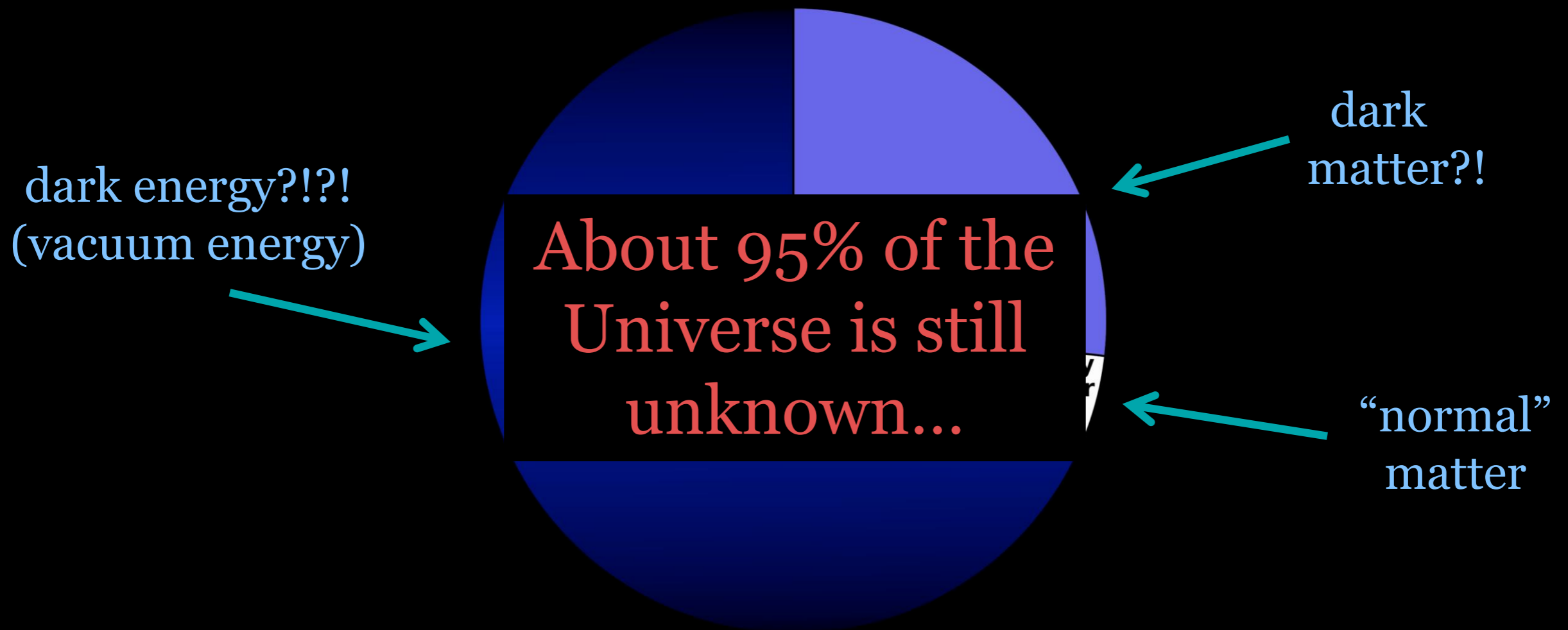
Theoretical Predictions of the CMB Spectrum



- 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!)



Mysteries of the Universe

What is dark matter?

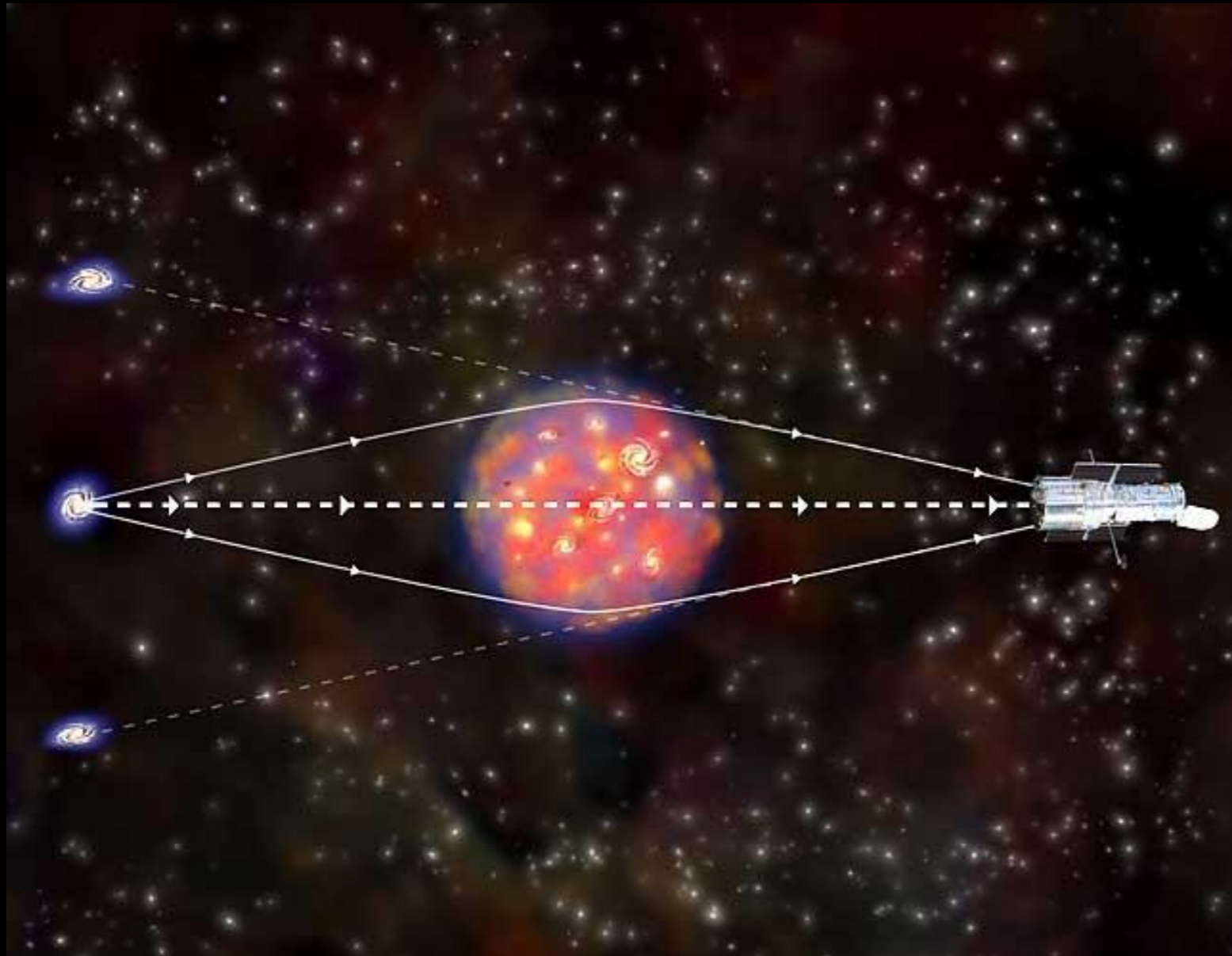
Rotation Curves of Galaxies



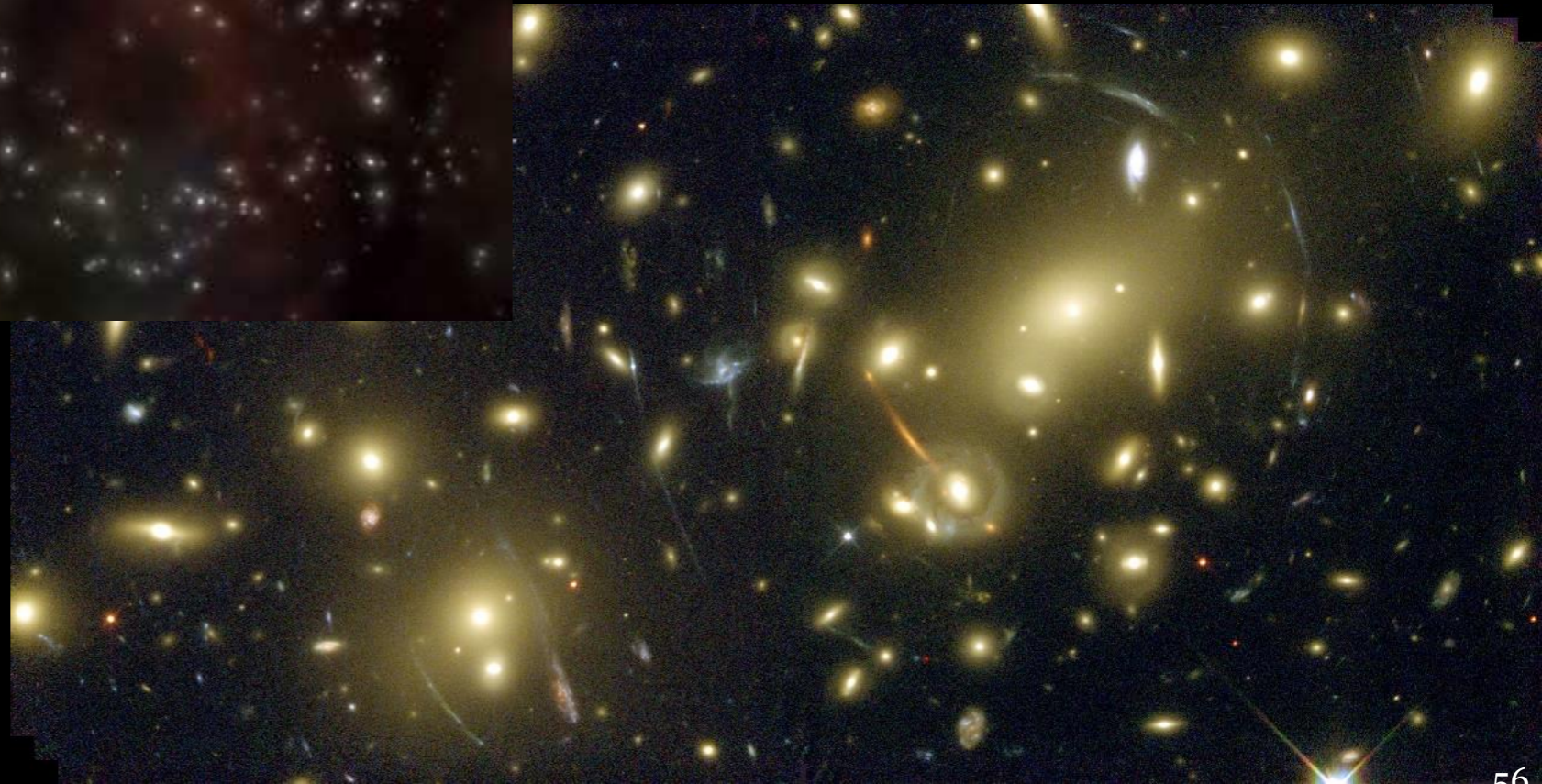
Galaxy Cluster CL0024+17



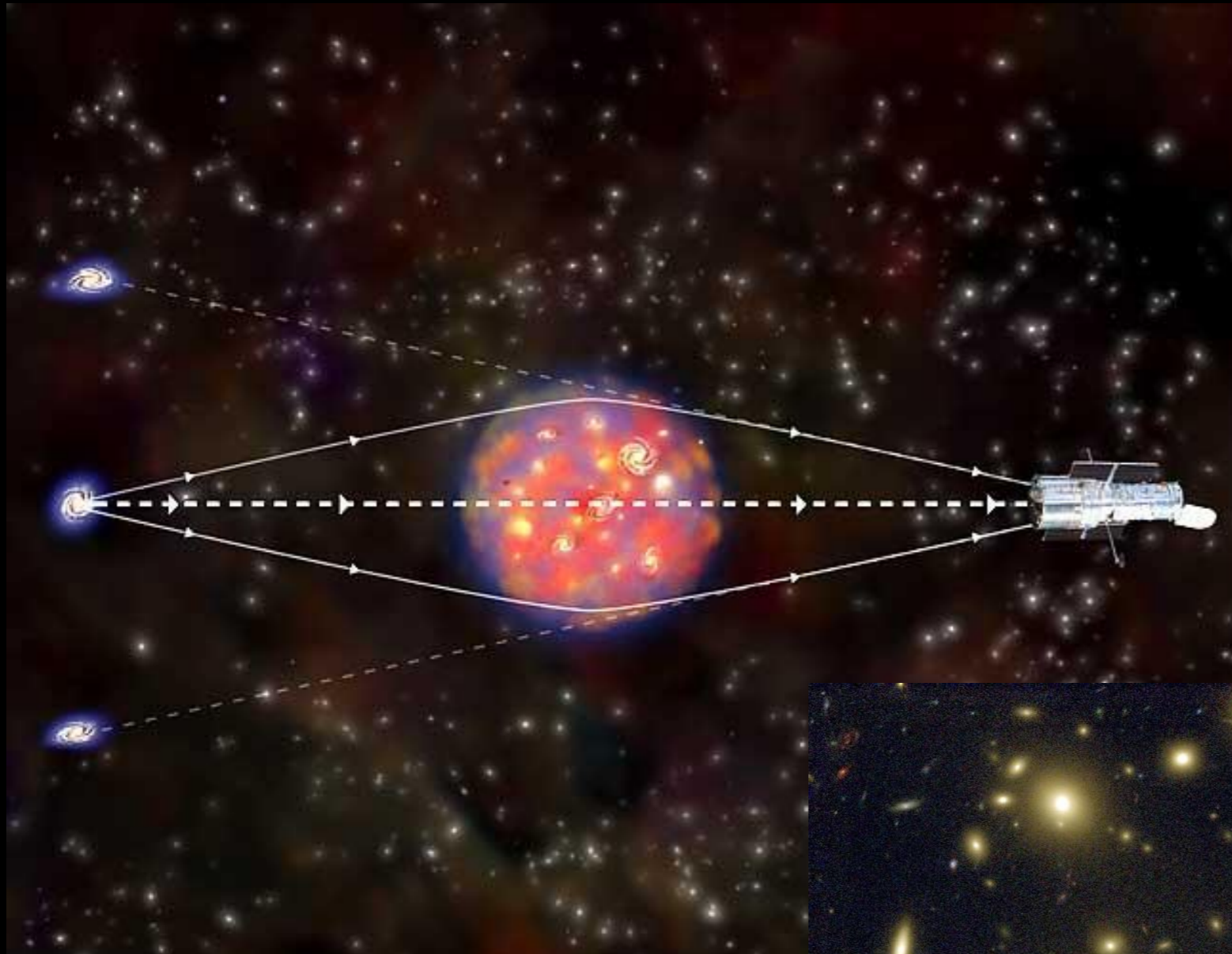
Gravitational Lenses



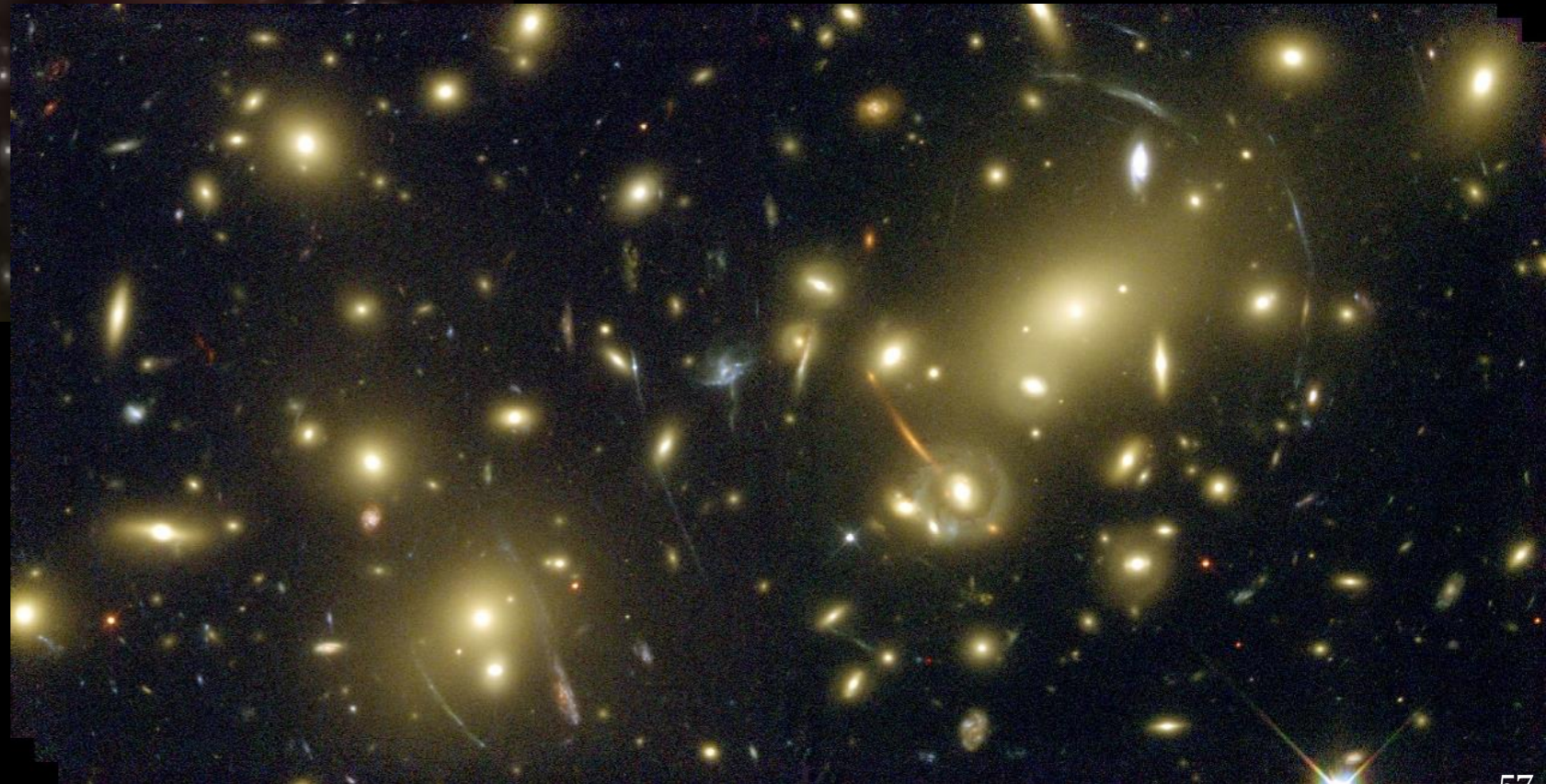
Massive objects curve space-time and therefore distort the light of the objects behind.



Gravitational Lenses

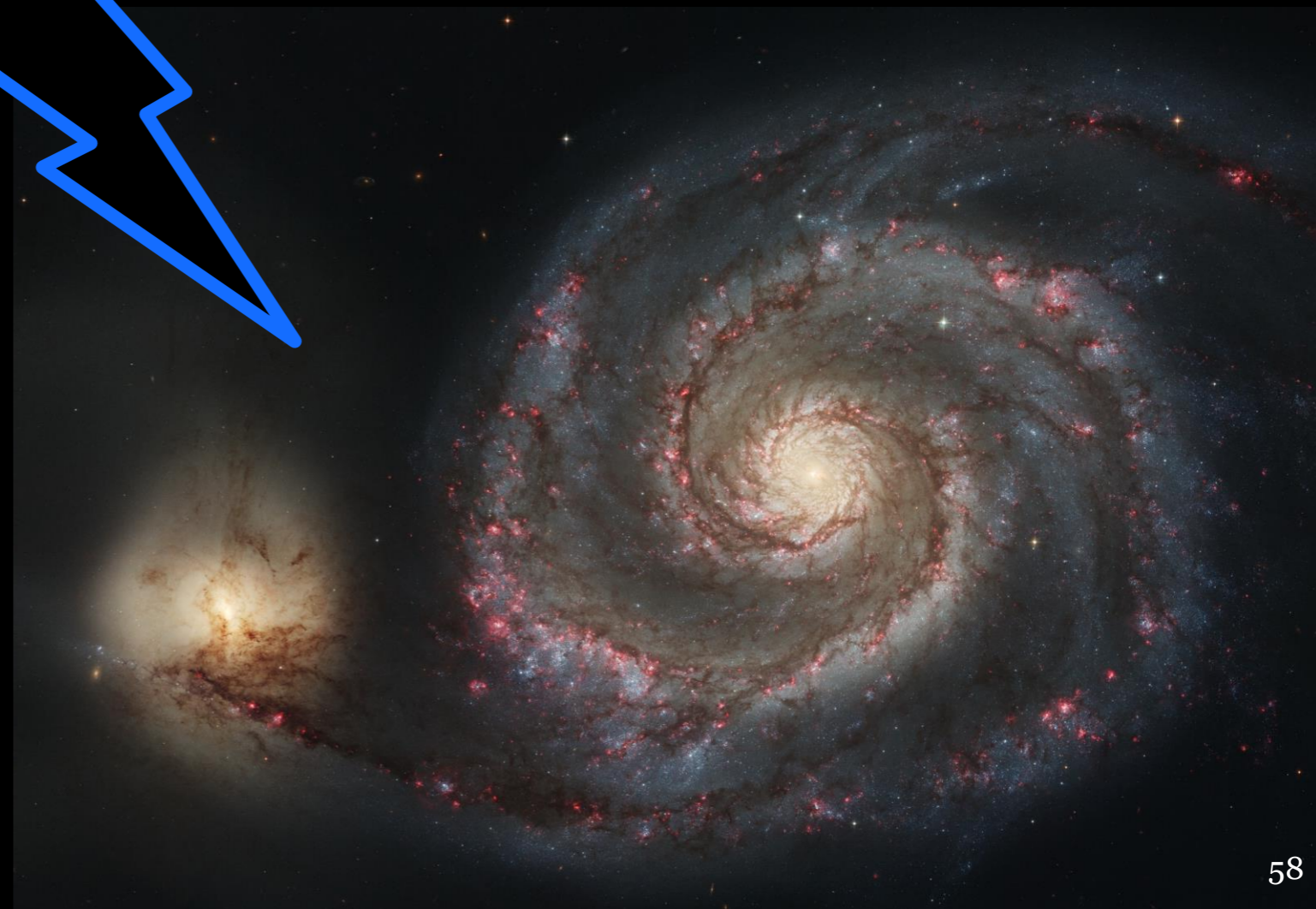
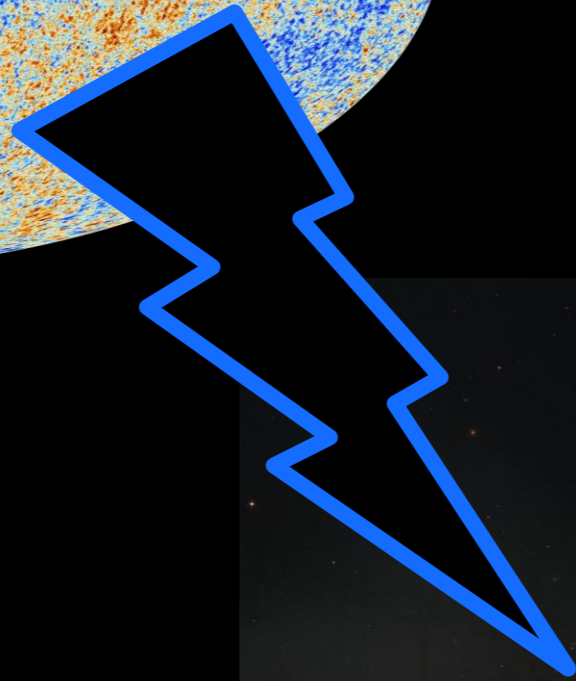
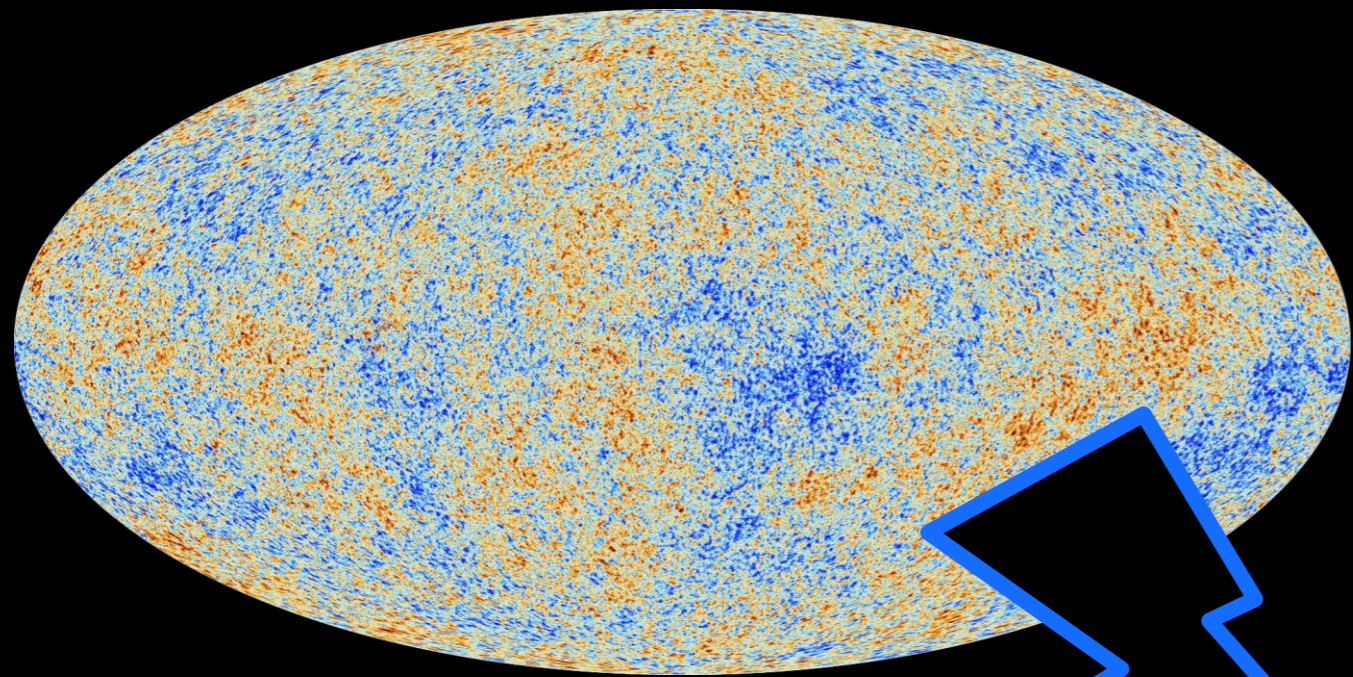


galaxy cluster Abell 2218



Thereby light arcs of the objects behind are visible.

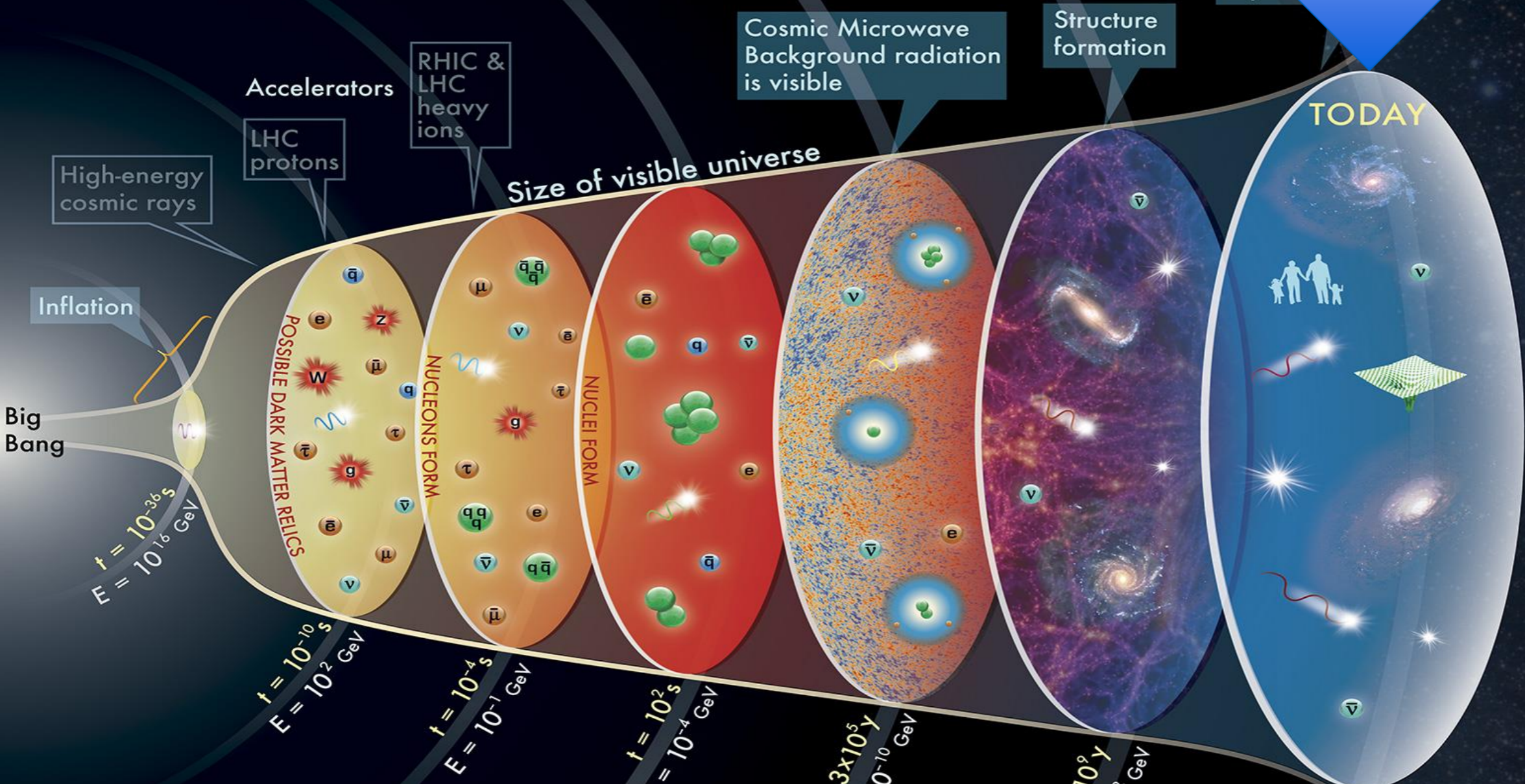
Structure building in the early universe



HISTORY OF THE UNIVERSE

era of dark energy

accelerated expansion



Big Bang

Inflation

Accelerators

LHC protons

RHIC & LHC heavy ions

Cosmic Microwave Background radiation is visible

Structure formation

TODAY

Size of visible universe

POSSIBLE DARK MATTER RELICS

NUCLEONS FORM

NUCLEI FORM

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

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

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

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

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

$t = 10^8 y$
 $E = 10^{-12} GeV$

$t = 13.8 \times 10^8 y$
 $E = 2.3 \times 10^{-13} GeV$

t = Time (seconds, years)

E = Energy (GeV)

Key

quark	neutrino	ion	star
gluon	bosons	atom	galaxy
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muon	baryon		
tau			

Future fates of the dark-energy universe

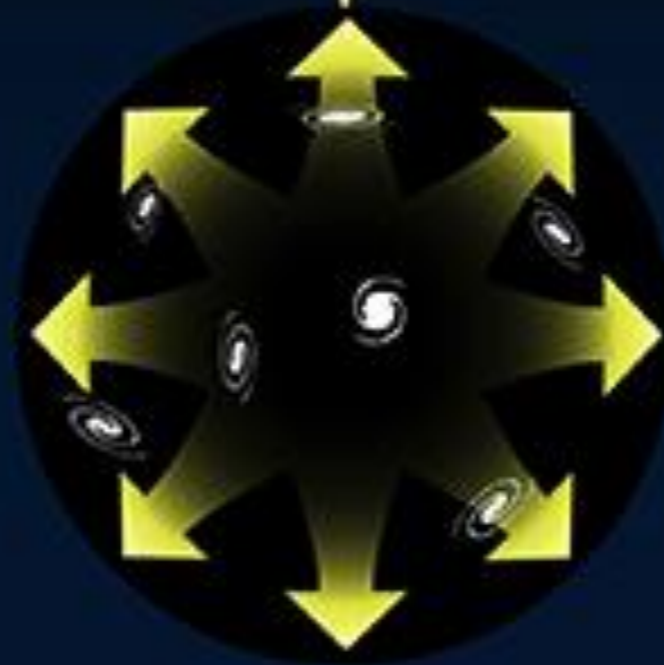
Big Bang



Current universe



Big Crunch



Indefinite expansion



Big Rip

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?

