Cosmology

A short introduction

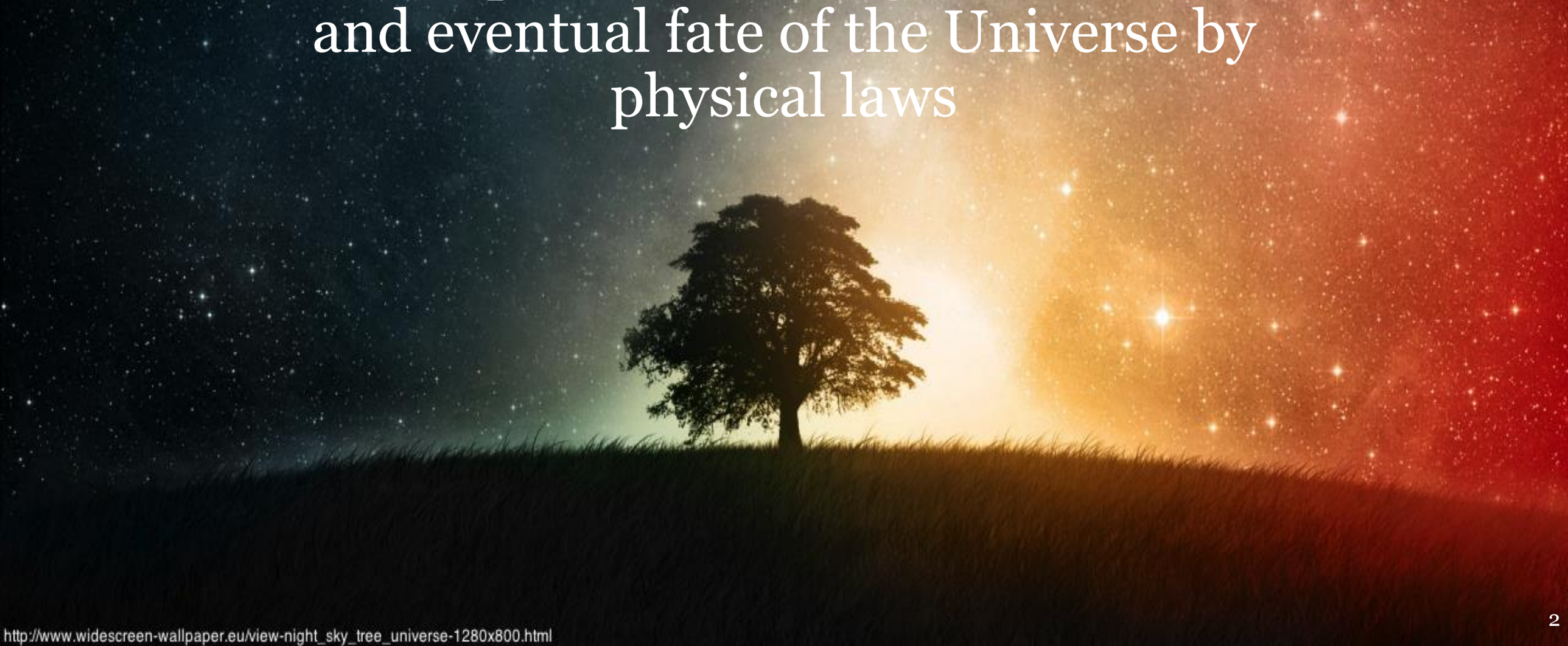
Sarah Aretz
CERN

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?
- Where is the journey taking us?

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Contents

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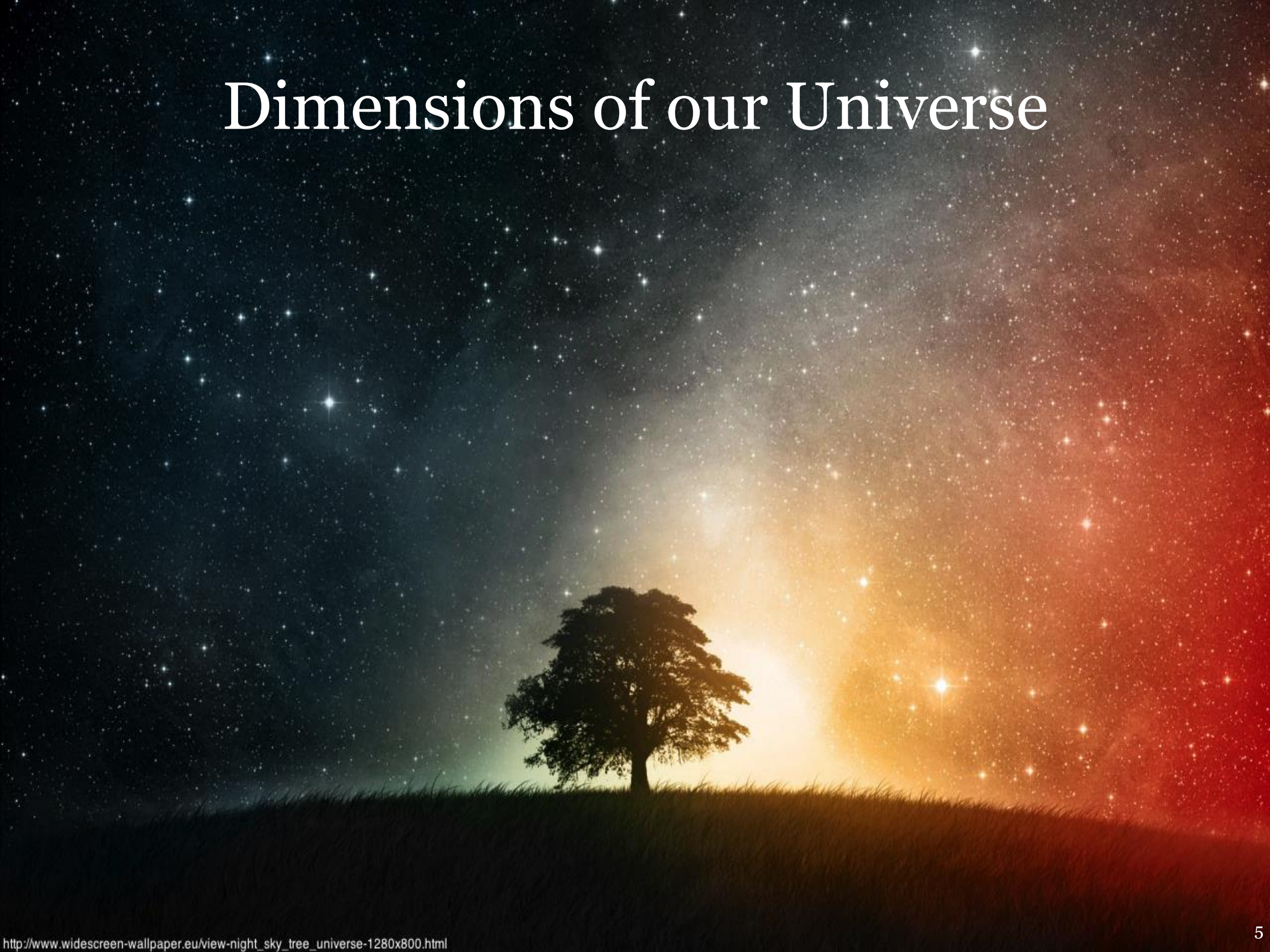
Dimensions of our Universe



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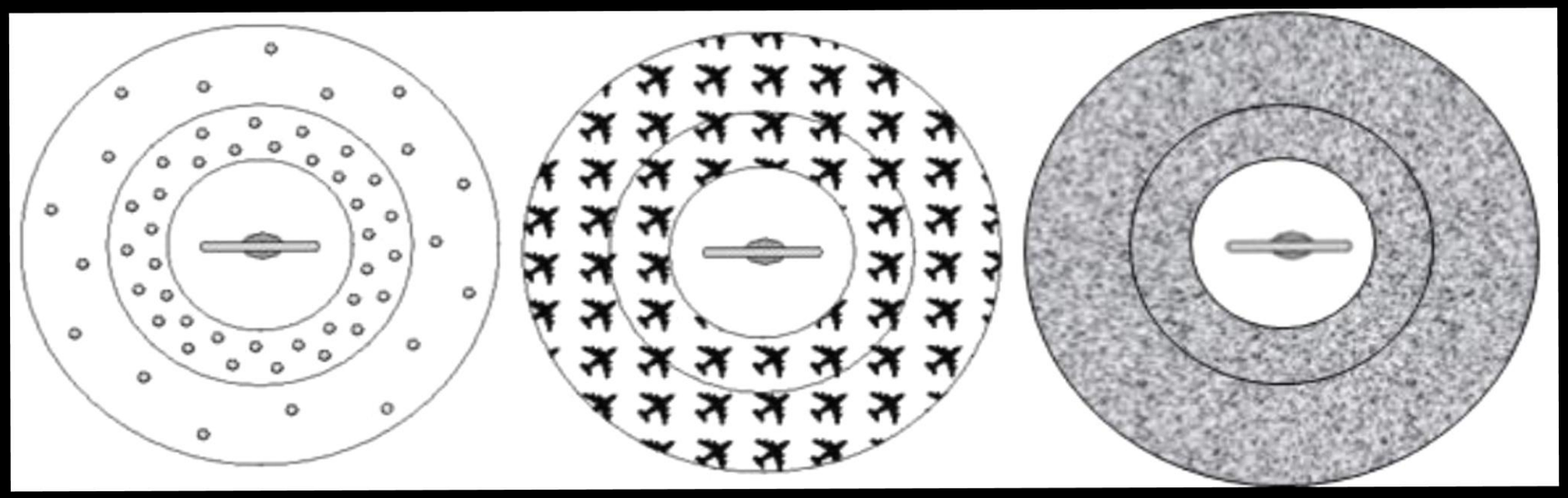
The Cosmological Principle

"On large scales the Universe is homogeneous and isotropic"

We don't find ourselves in a special place.



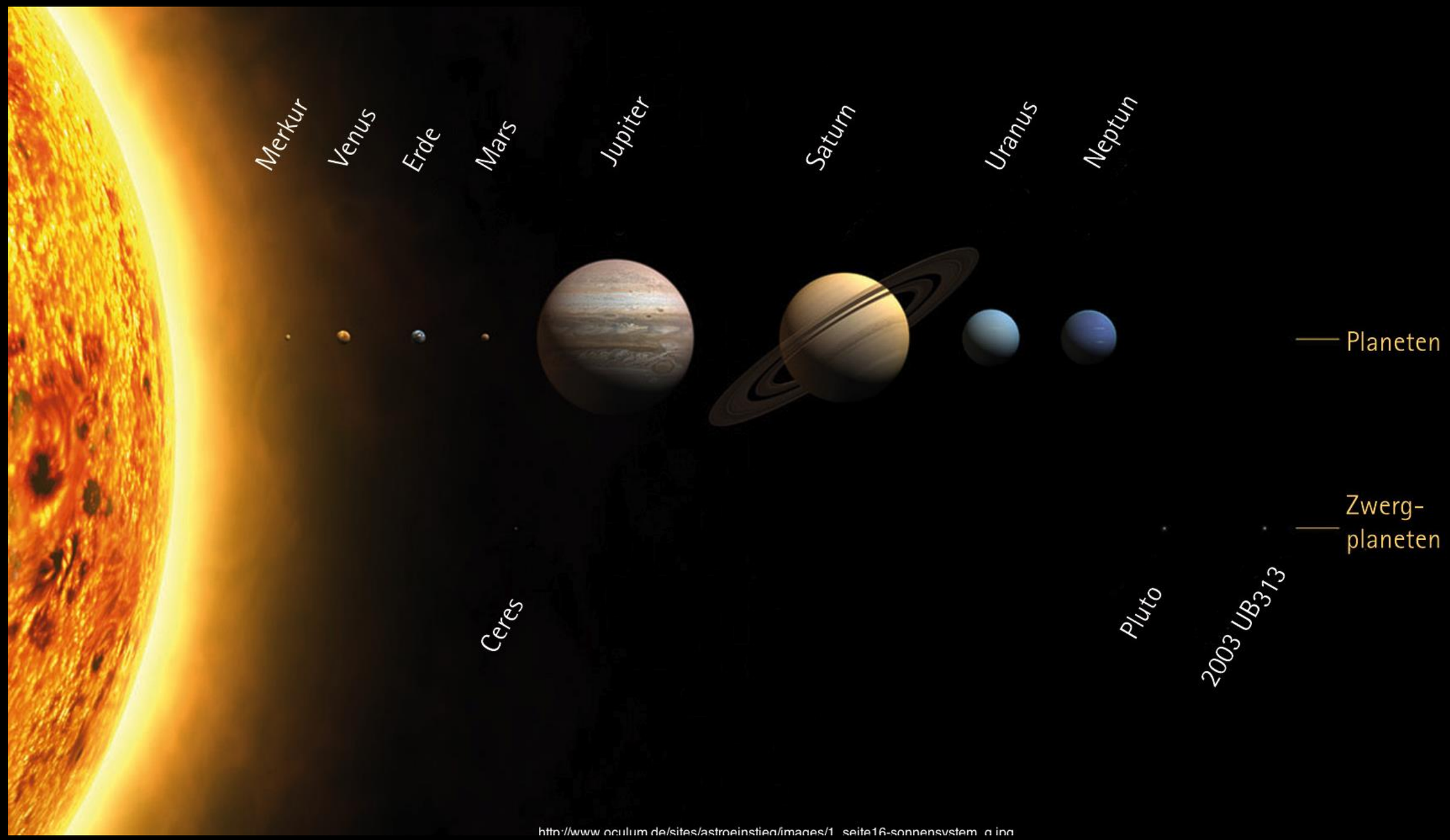
isotropic, but not homogeneous

homogeneous, but not isotropic

homogeneous and isotropic

The Earth: ≈13000 km in diameter

The Solar System:
≈10 billion km in diameter

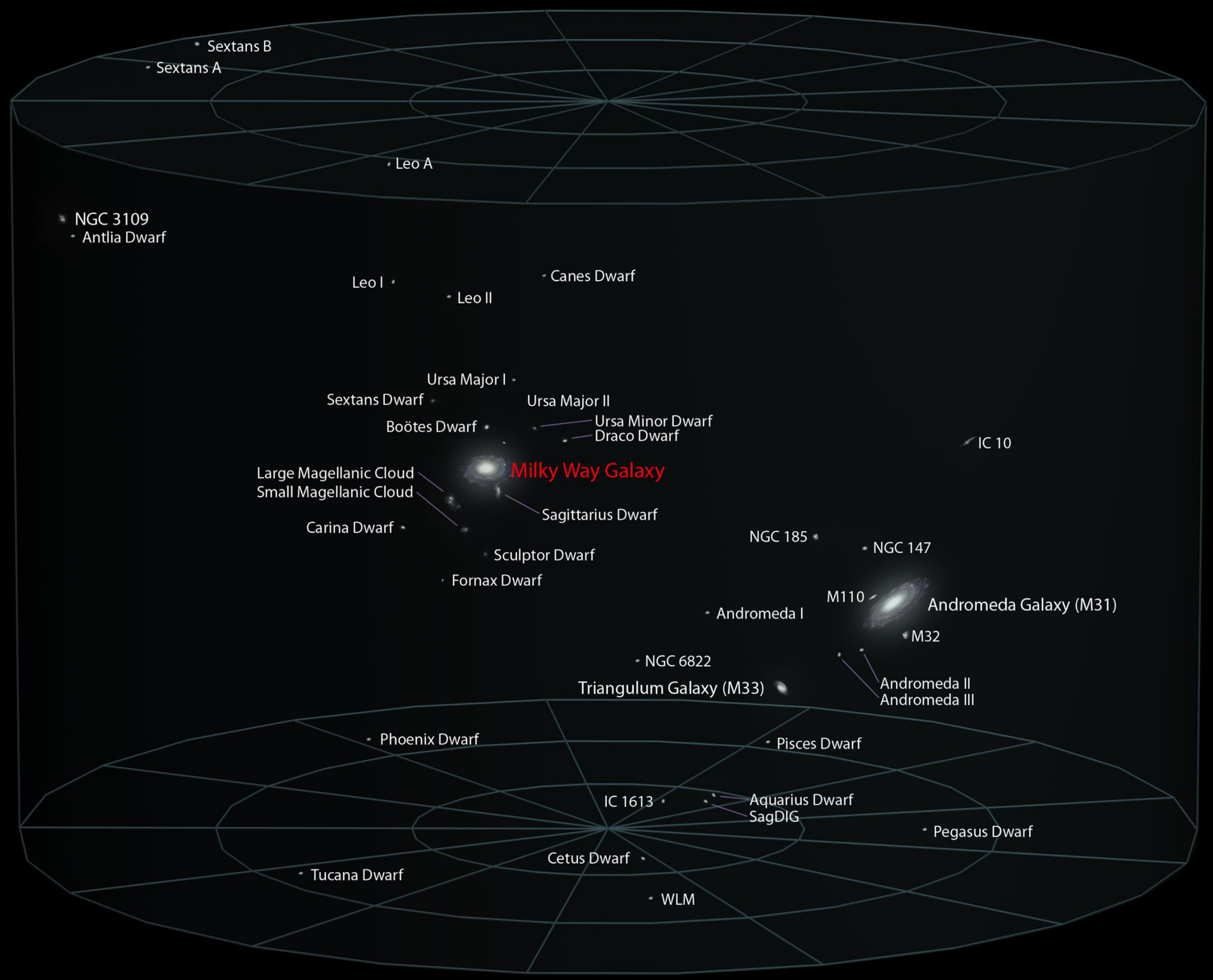


http://www.oculum.de/sites/astroeinstieg/images/1_seite16-sonnensystem_g.jpg

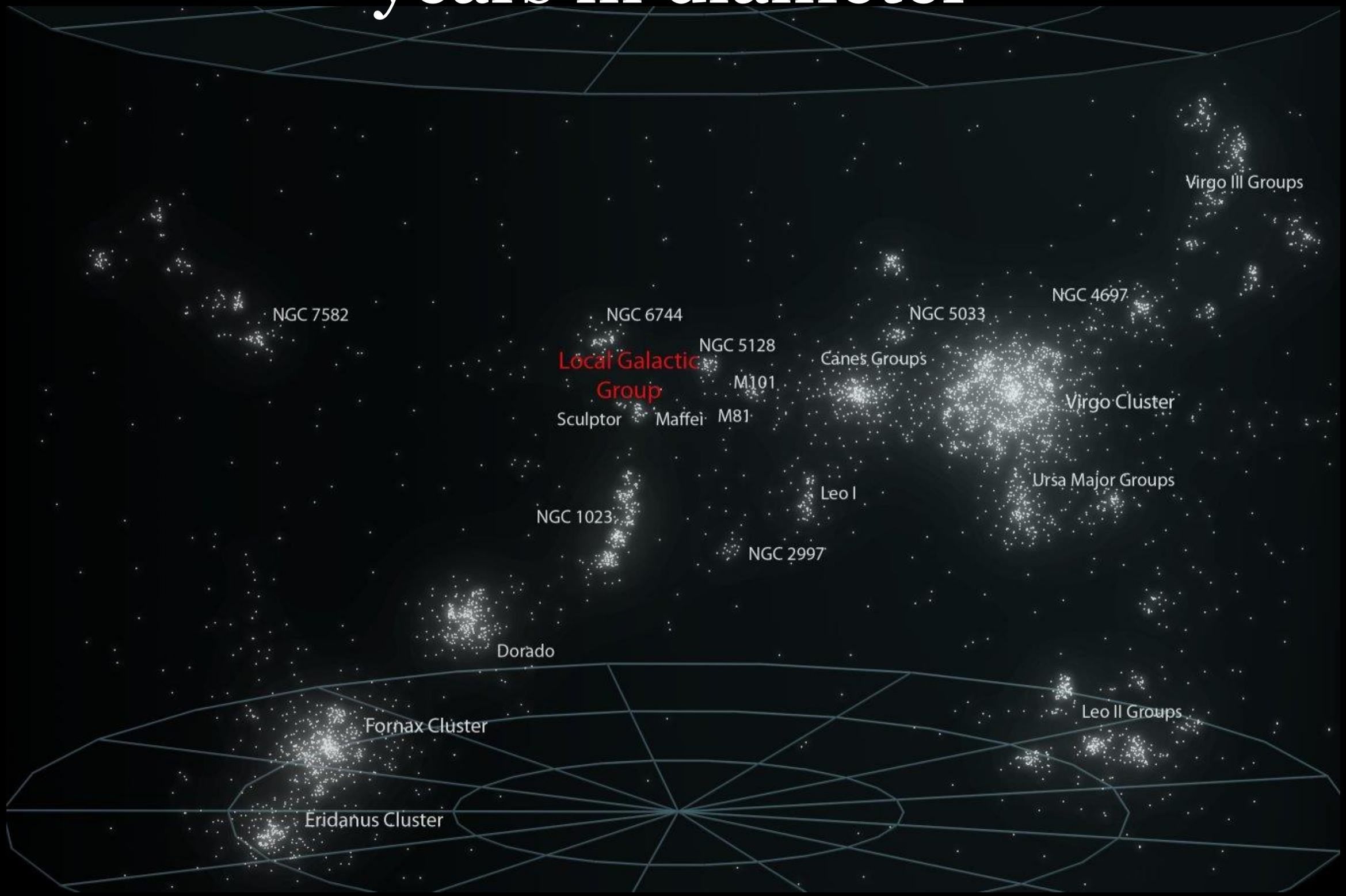
Our Milky Way:
$1{,}4 \times 10^{18}$ km = 150000 light years in diameter

Andromeda Galaxy:
2.5 million light years distance

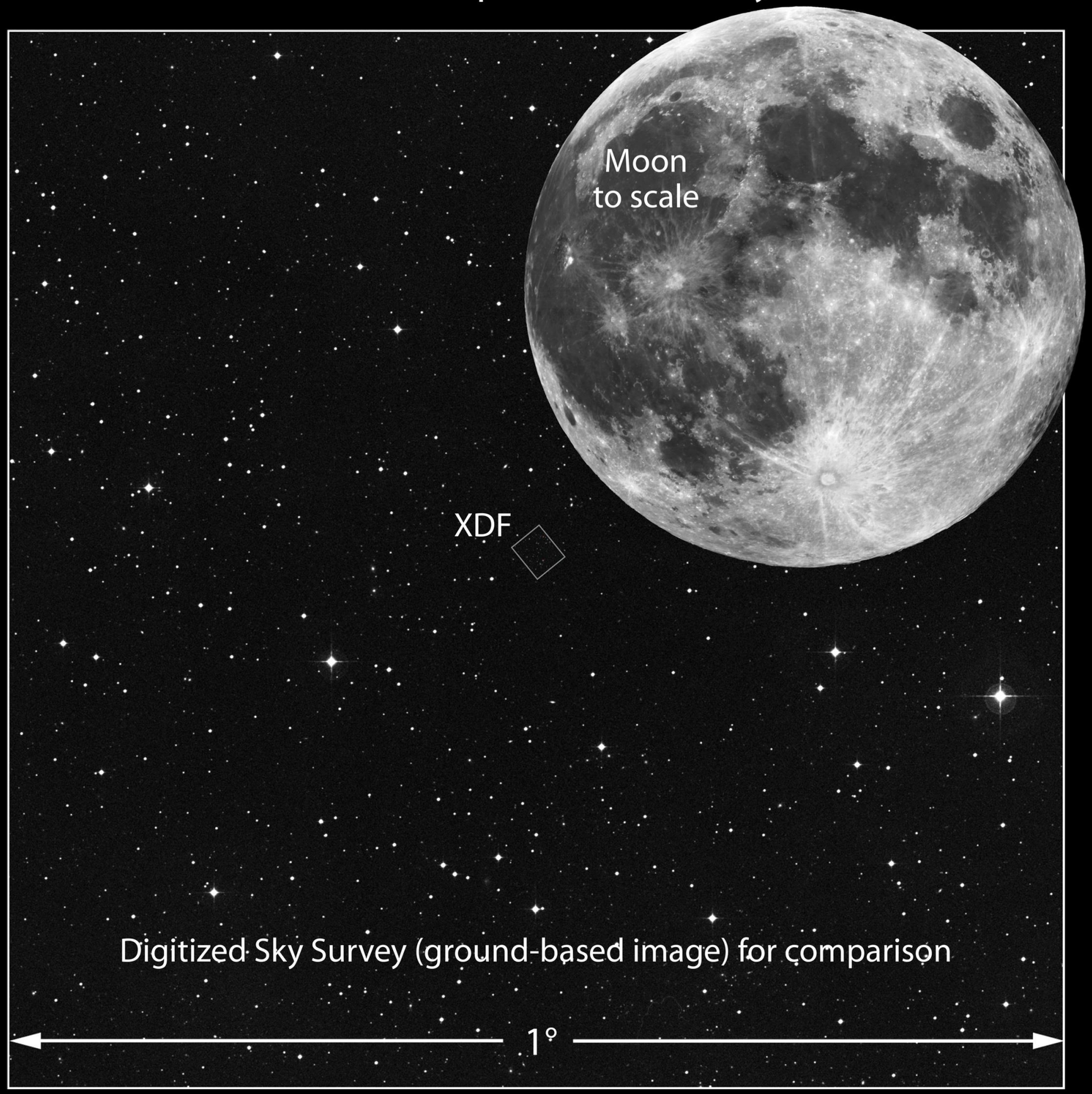
Local Group:
8 million light years in diameter



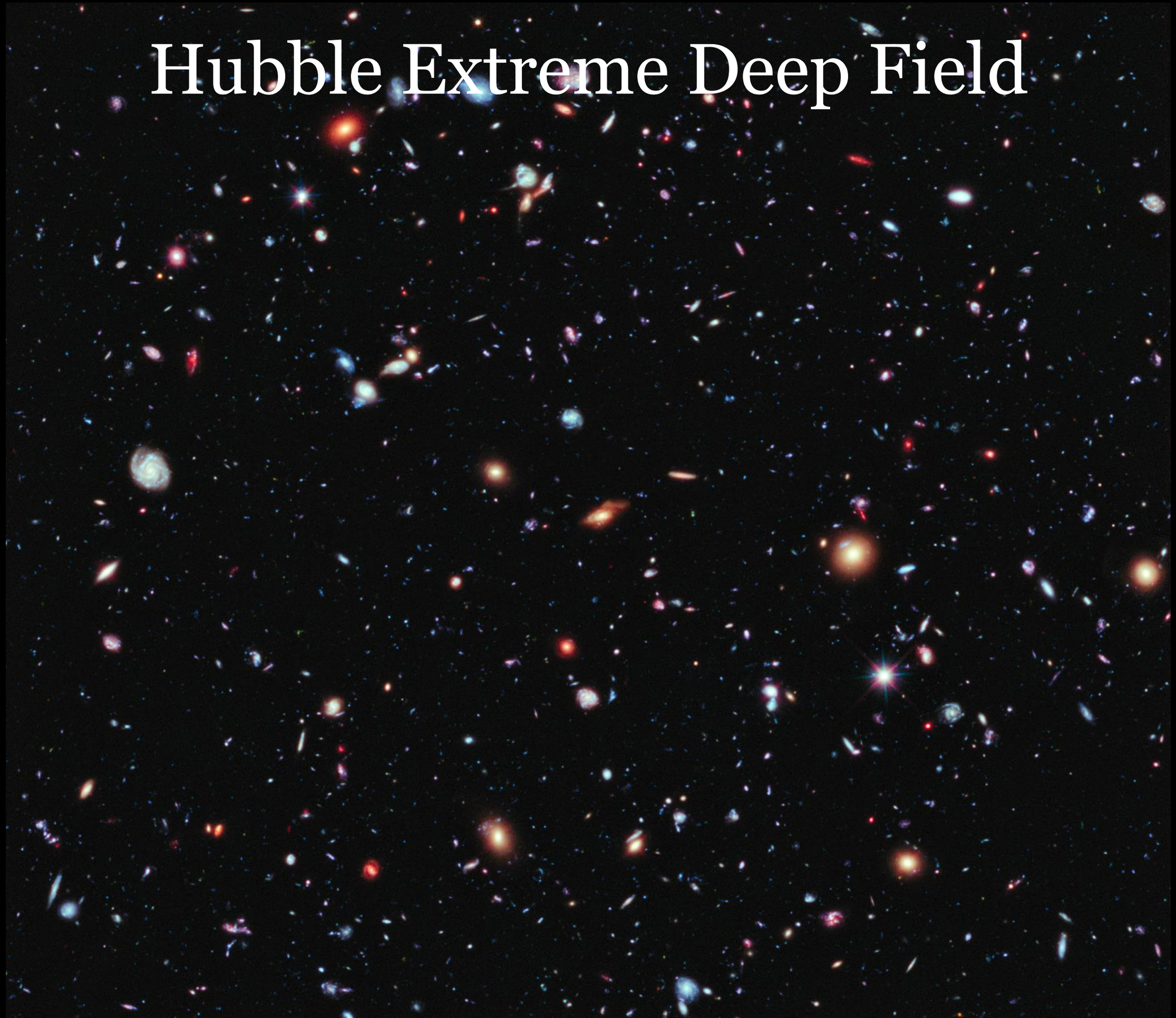
Virgo Supercluster: ≈130 million light years in diameter



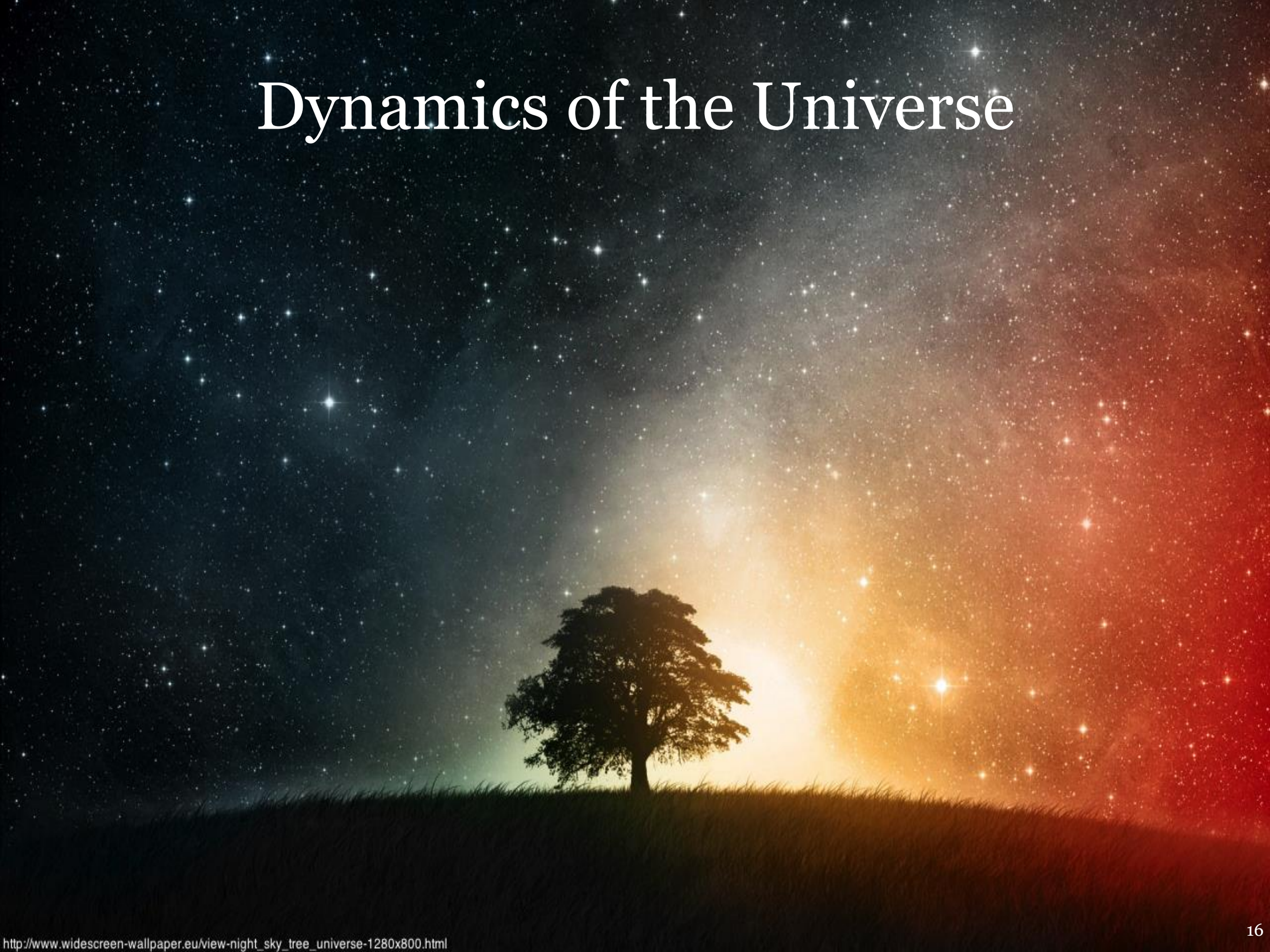
Size of Hubble eXtreme Deep Field on the Sky



Hubble Extreme Deep Field



Dynamics of the Universe



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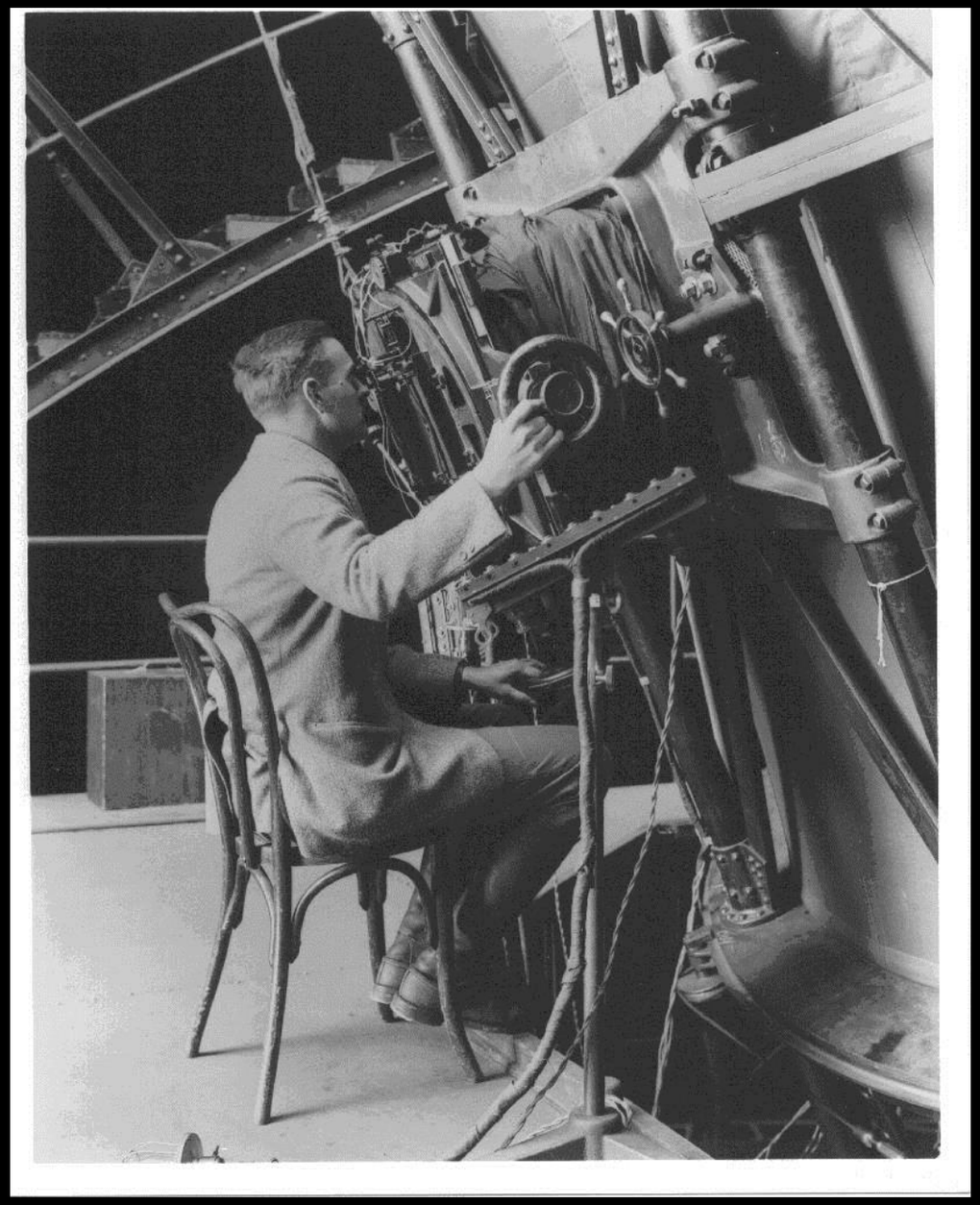
The Universe is bigger than we thought!

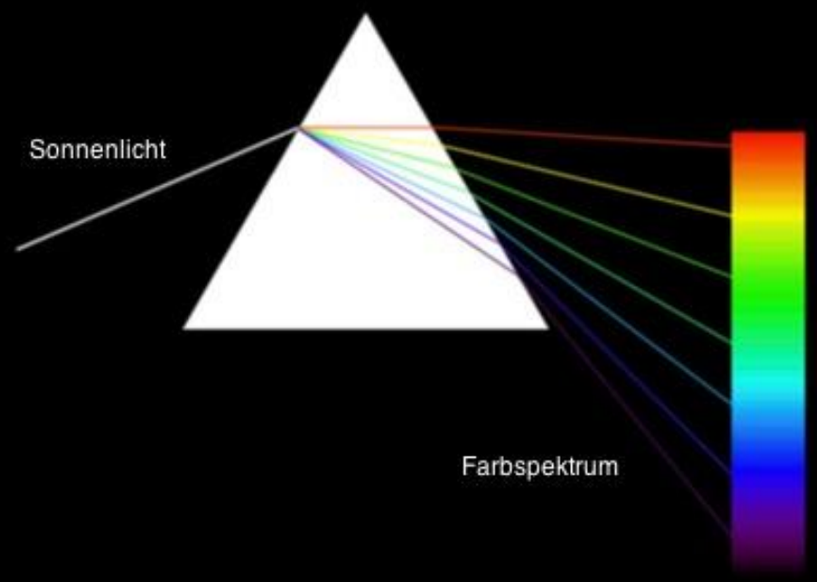
Edwin Hubble (1924)
Mt. Palomar telescope



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

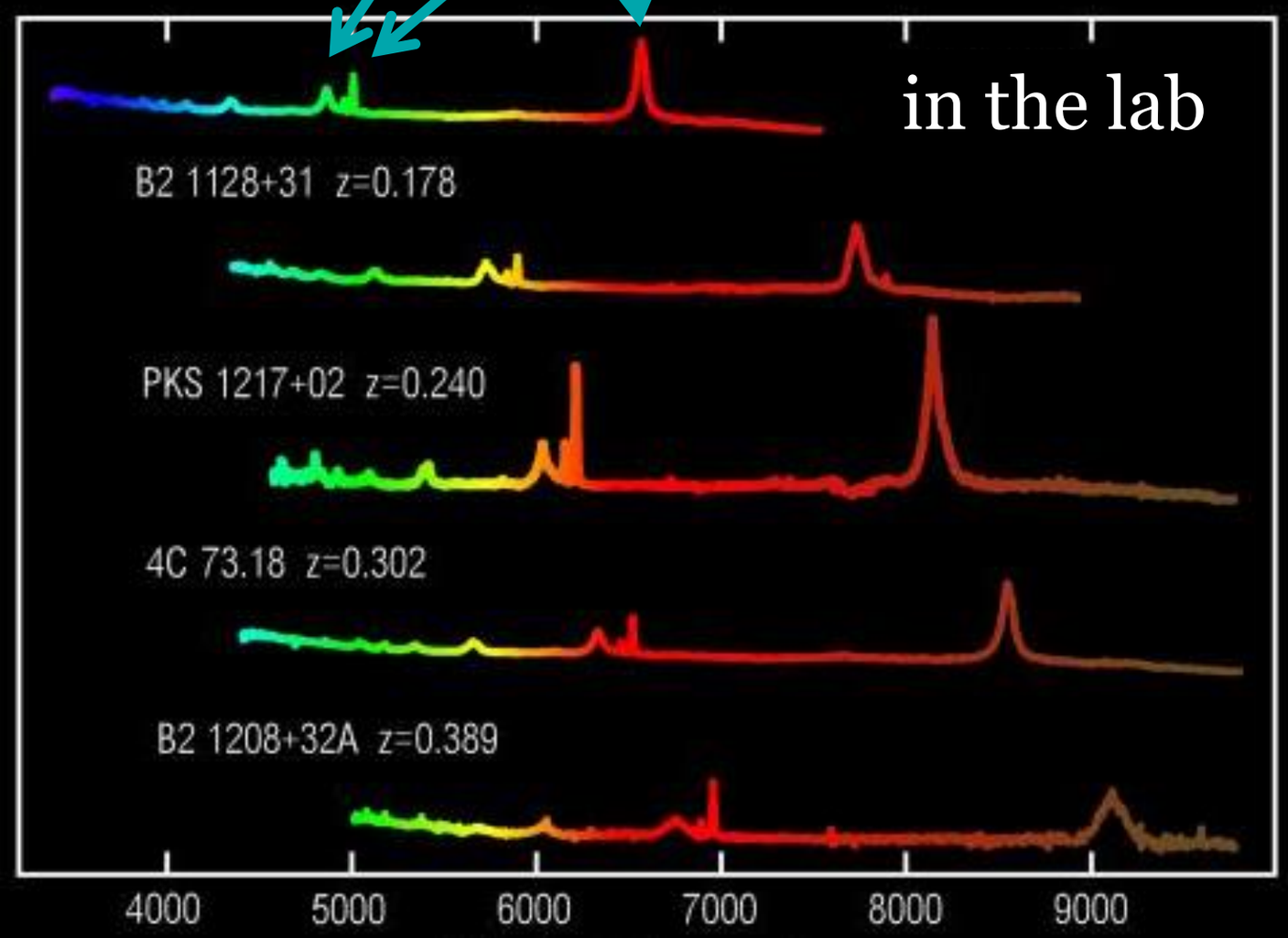
Measuring of the Redshift

Spectroscopy



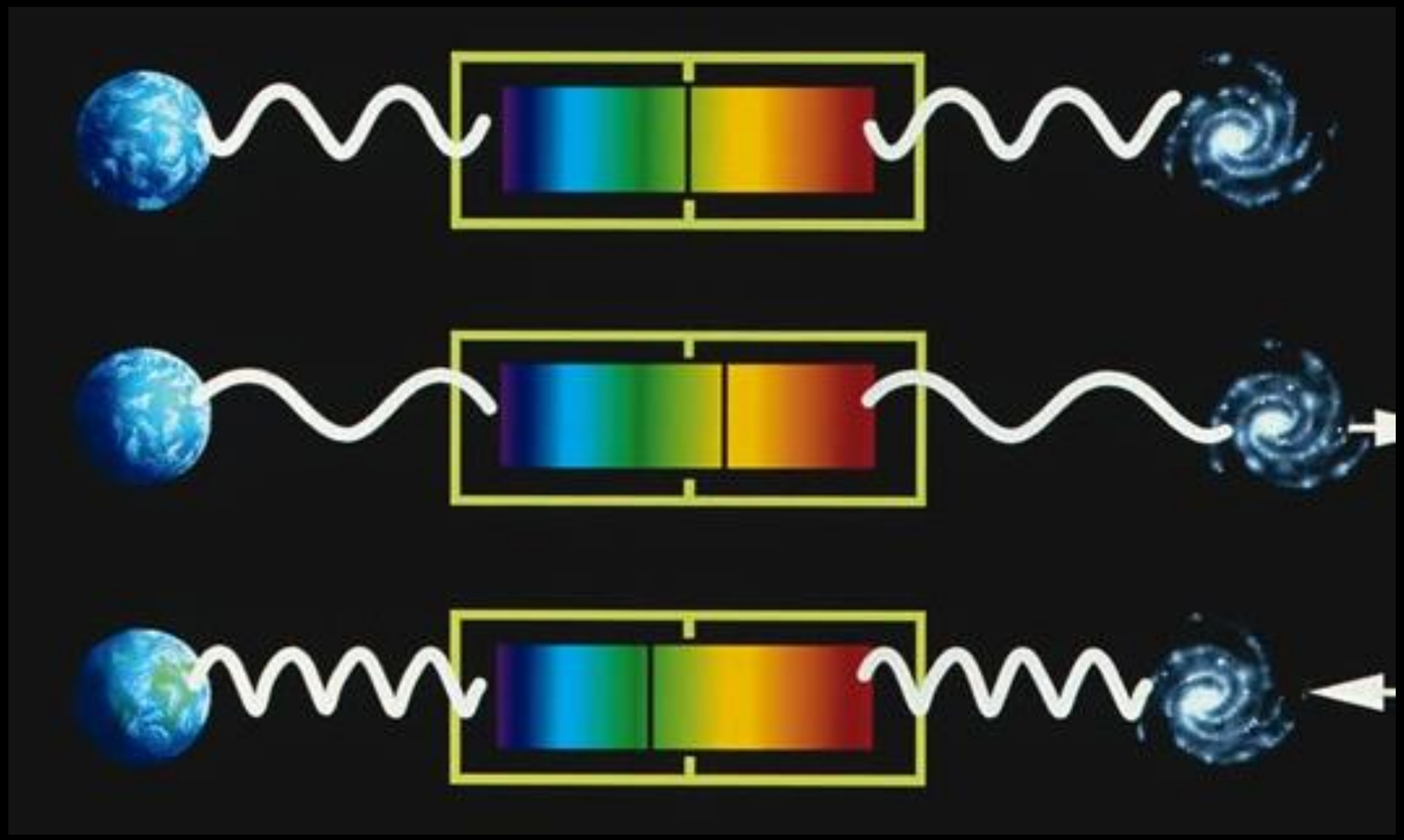
Emission lines

in the lab



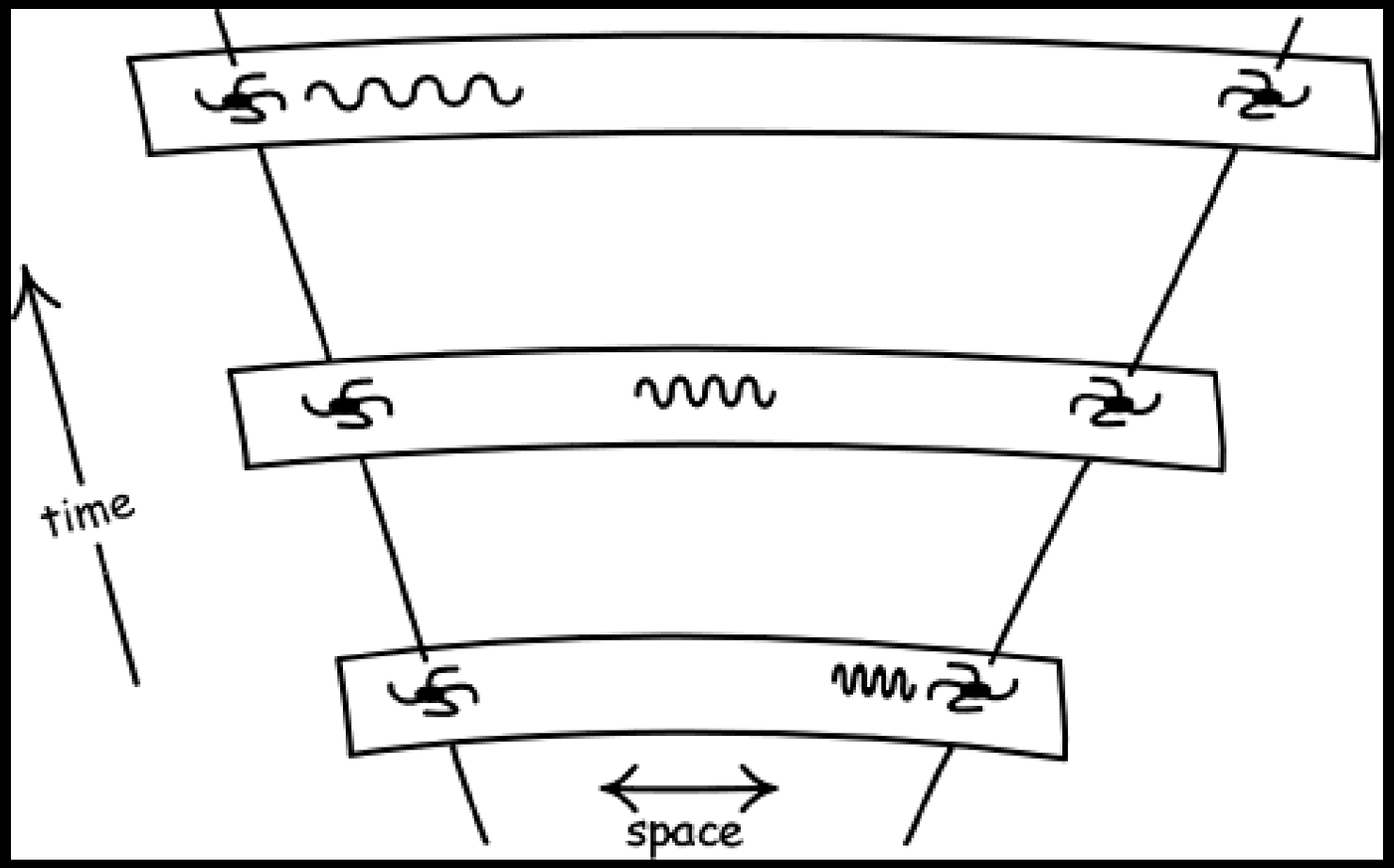
Wavelength [Å]

Cosmological Redshift vs. Doppler Effect



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

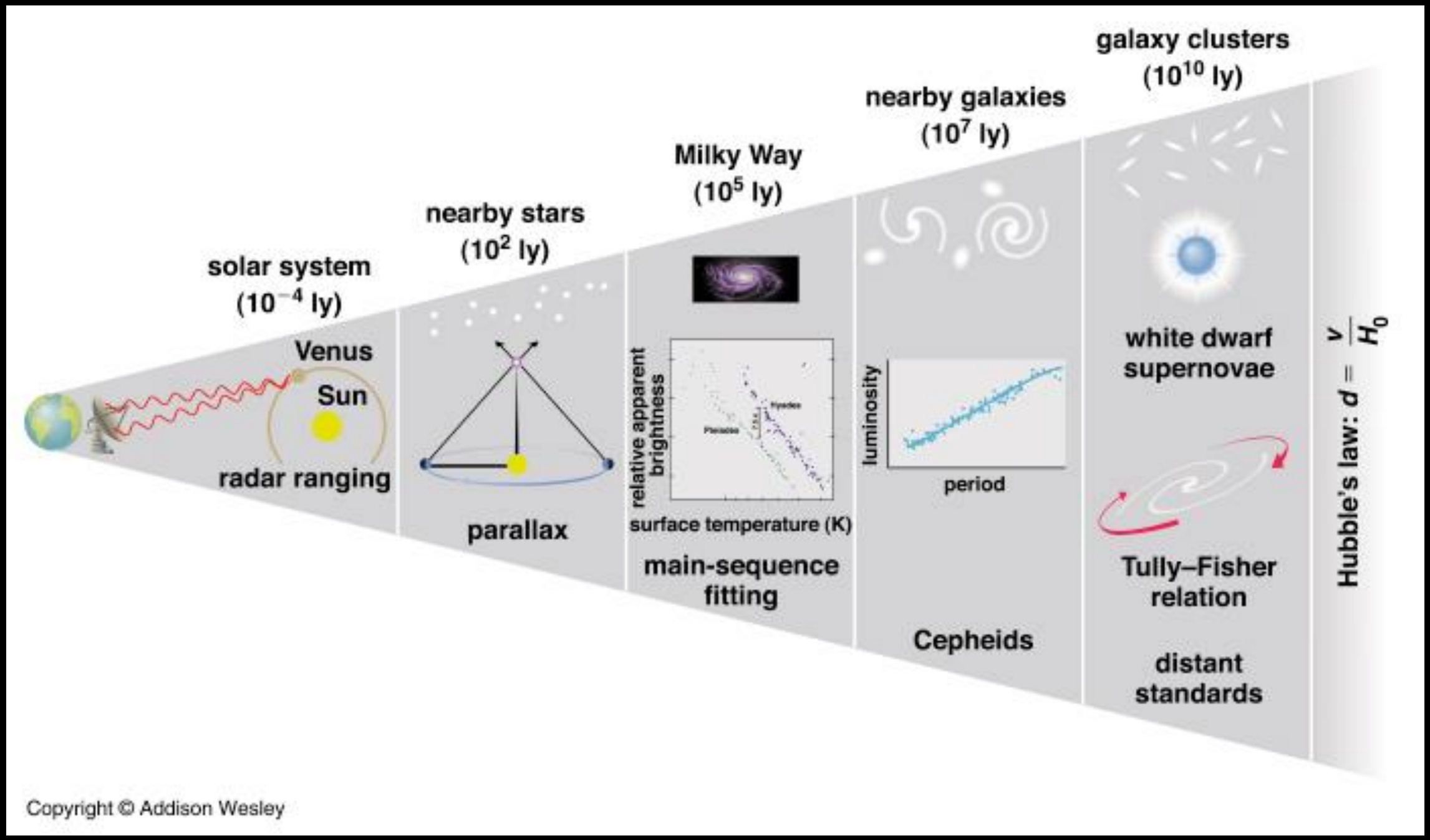
Cosmological Redshift



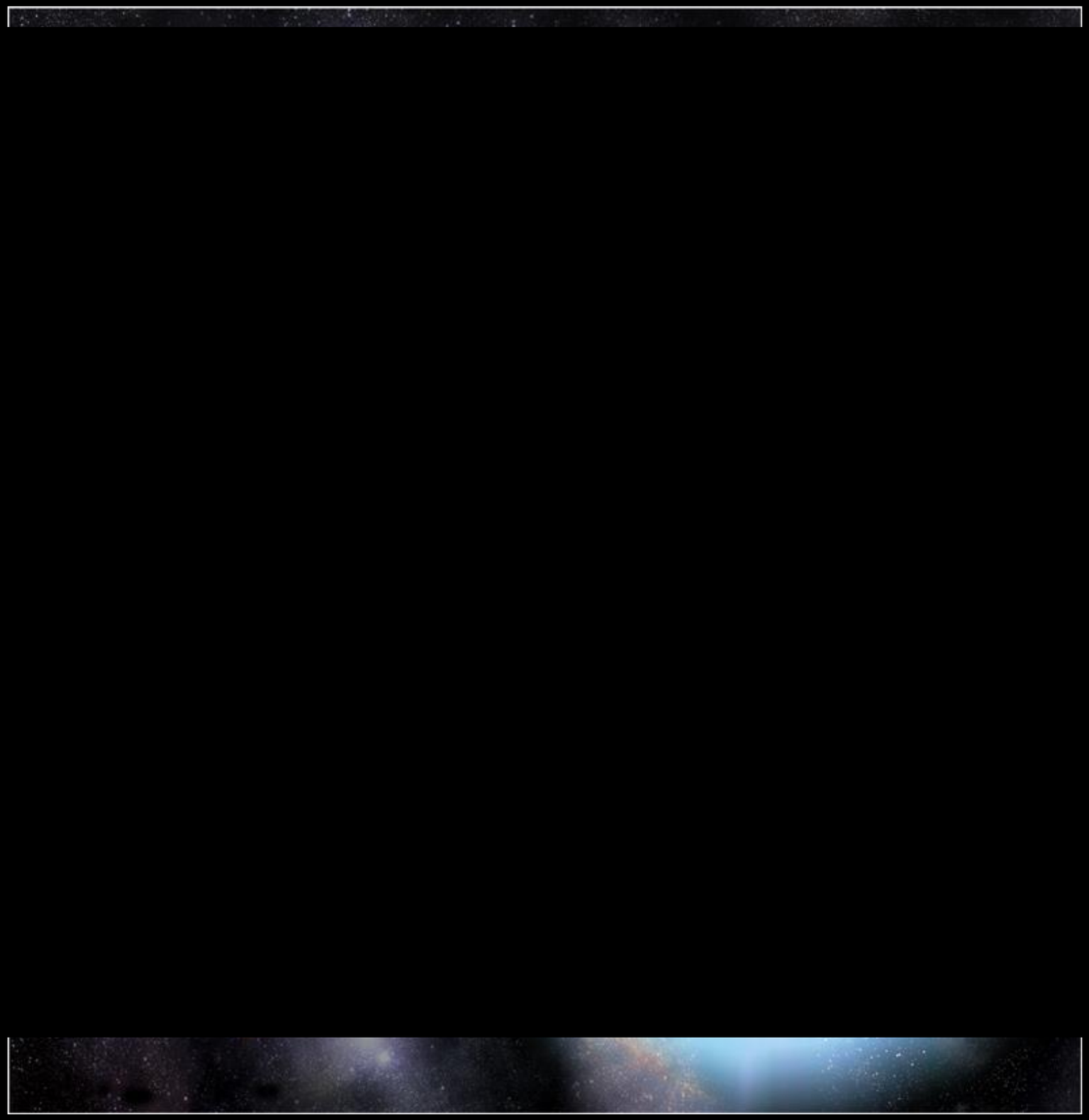
Space itself expands and “stretches” the wavelength of the photons.

Cosmological Redshift

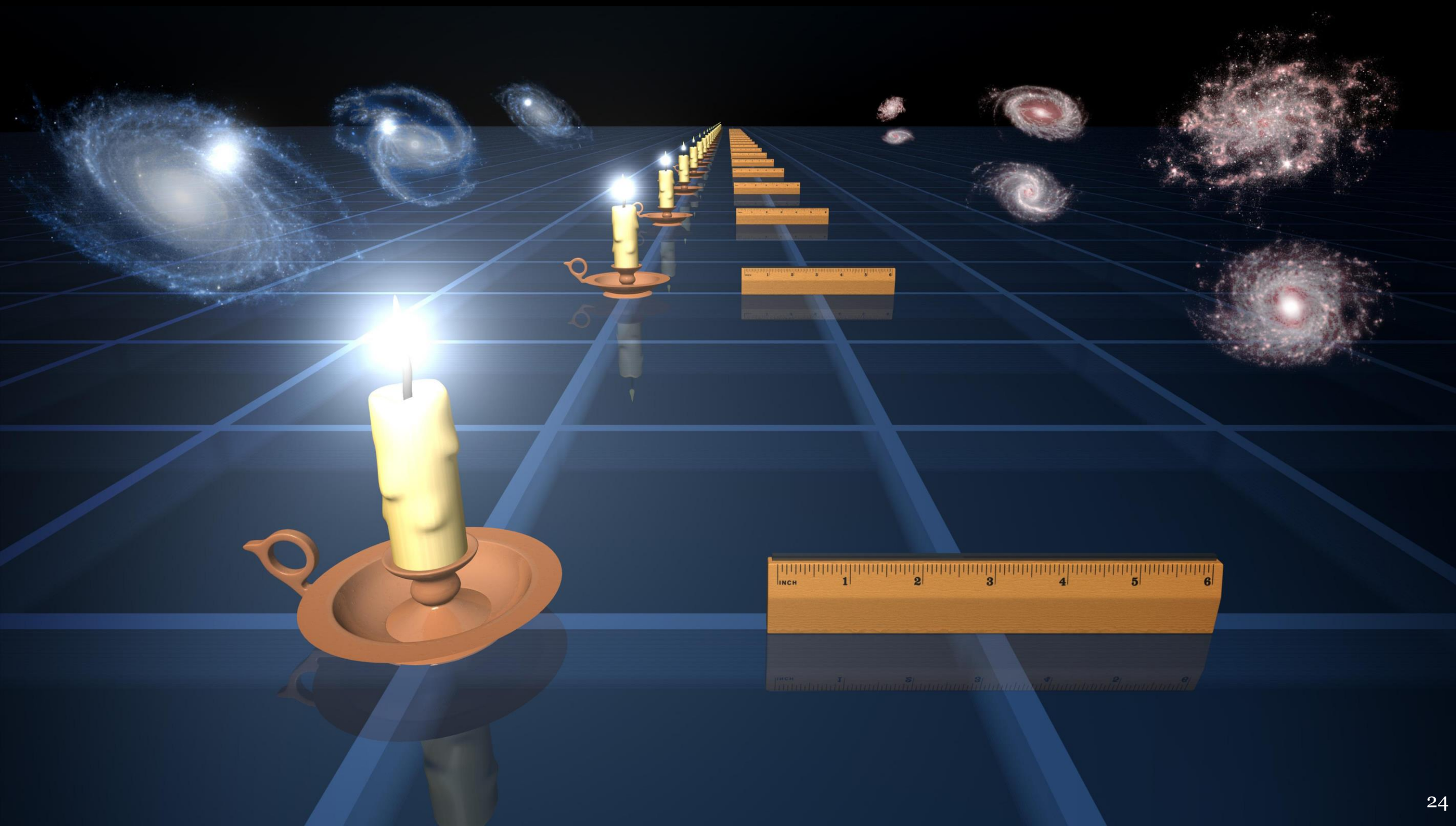
Distance Ladder



Type Ia Supernova



Standard Candles and Brightness



Example of a Supernova from 1994

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

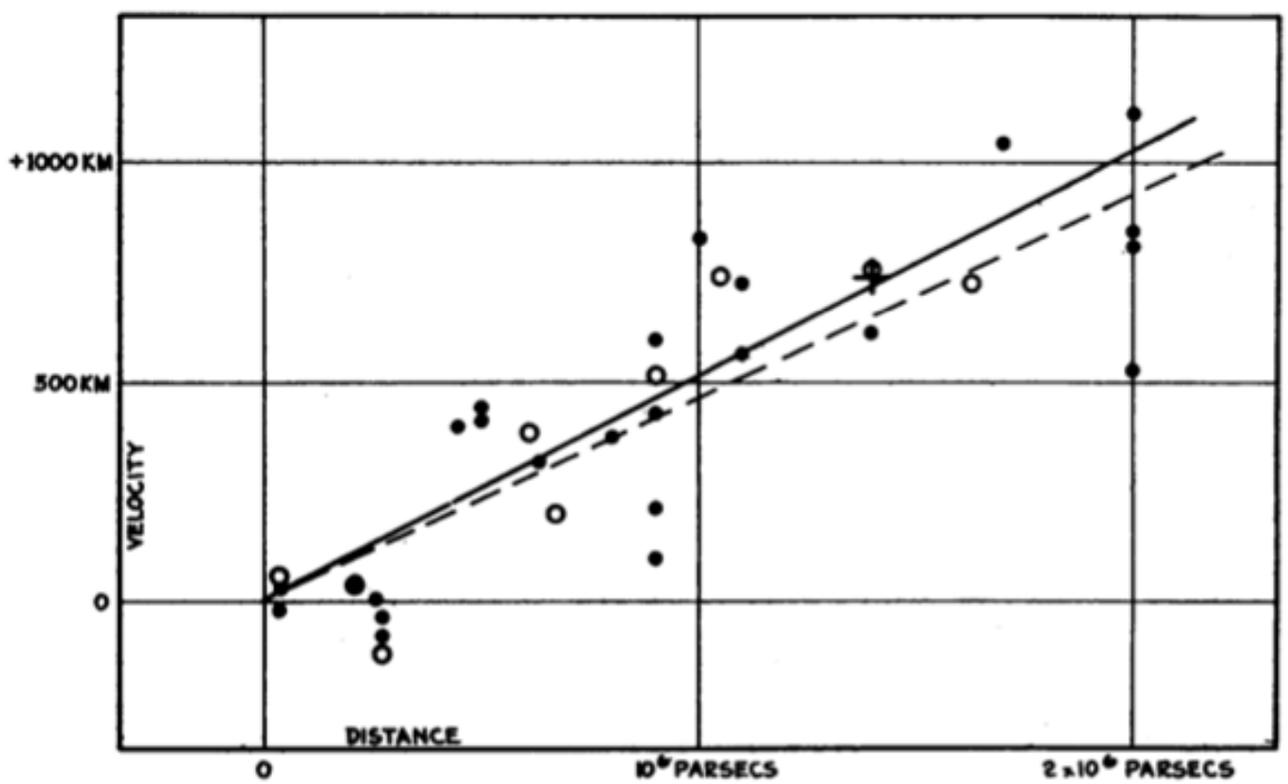


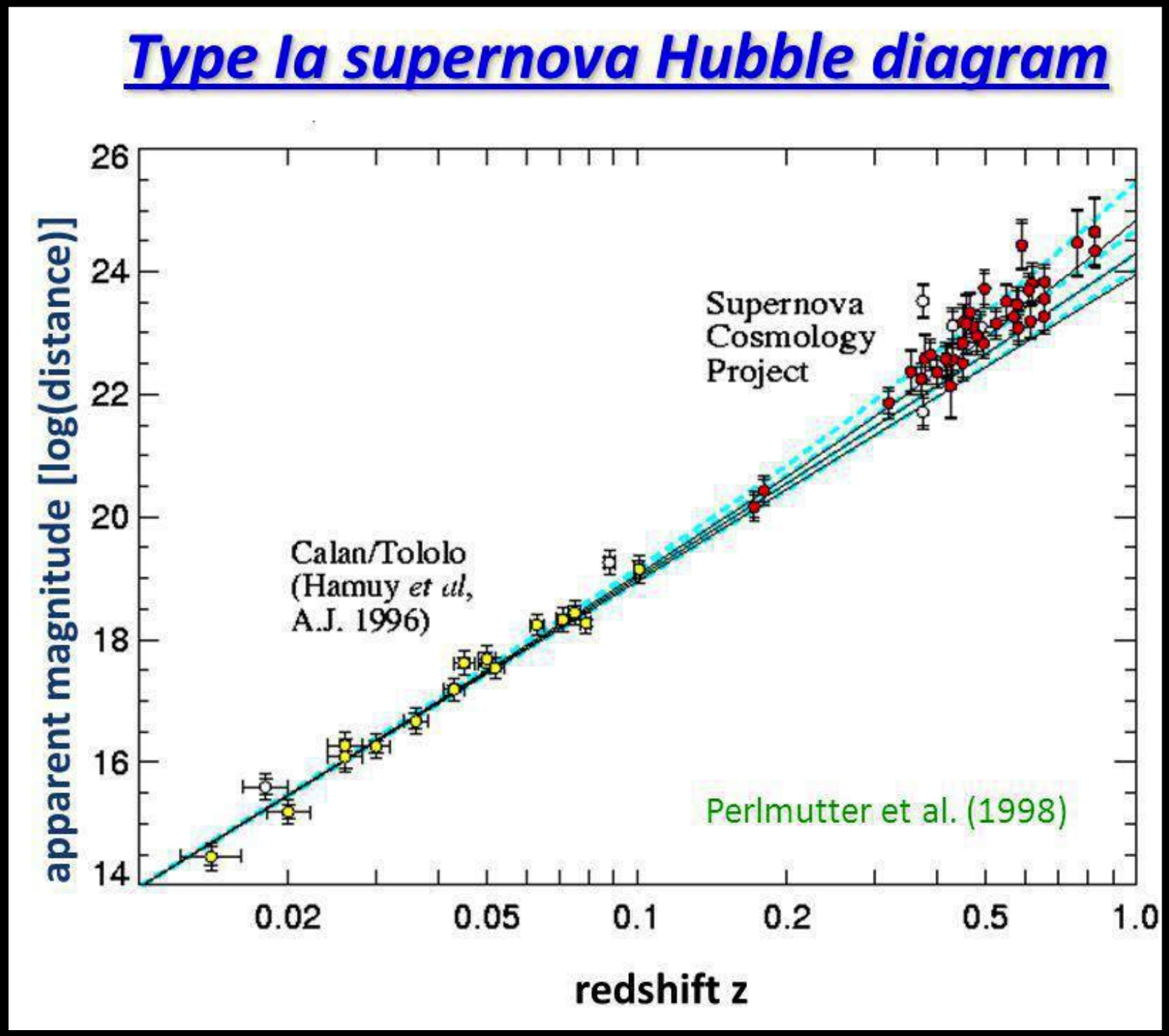
FIGURE 1

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

Hubble's law: $v = H_0 d$

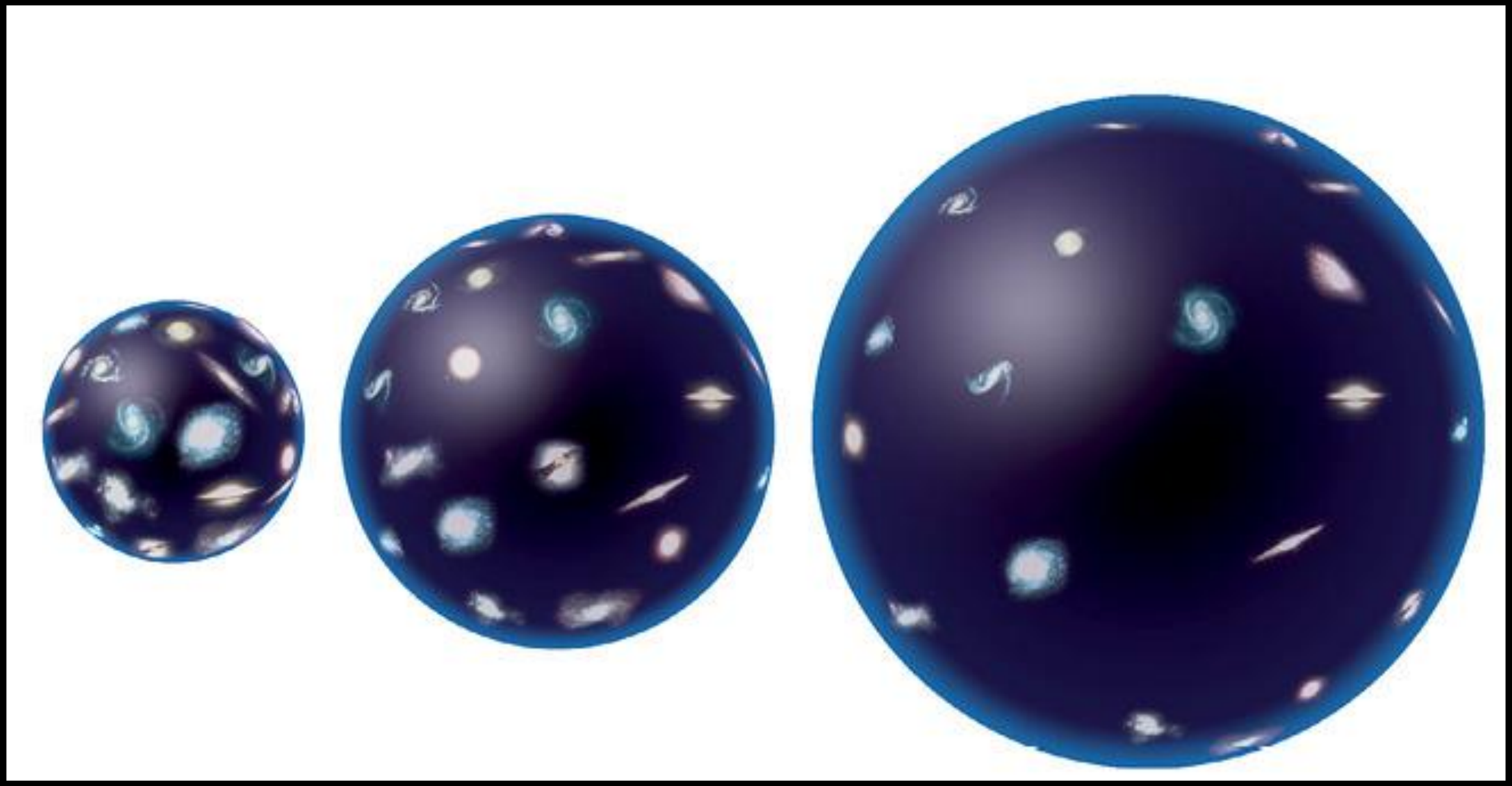
$H_0 = 530$ km/s / Mpc !!

The present value of the Hubble ”constant”



Today: H = 67,3±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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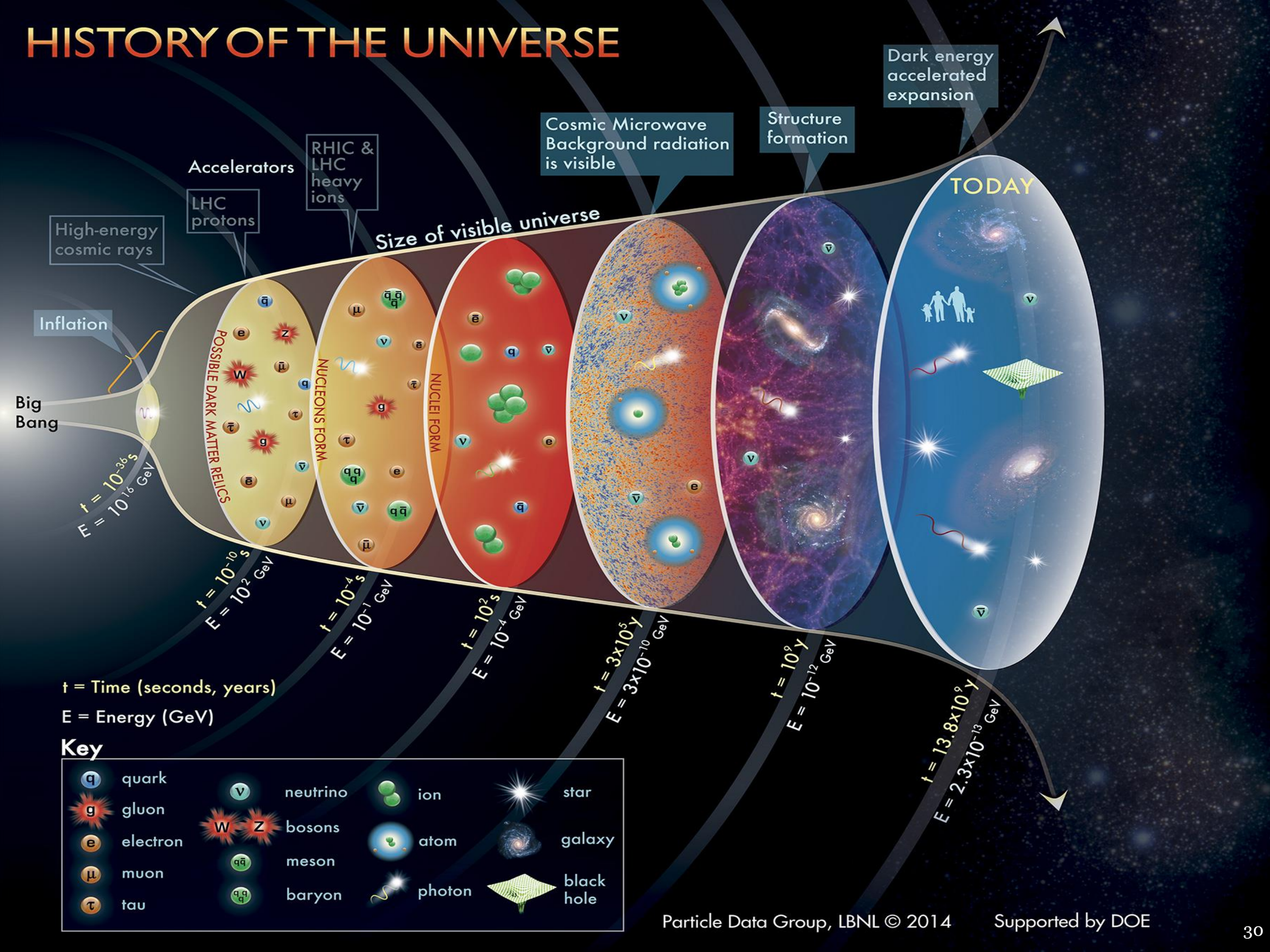
HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
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galaxy
black hole
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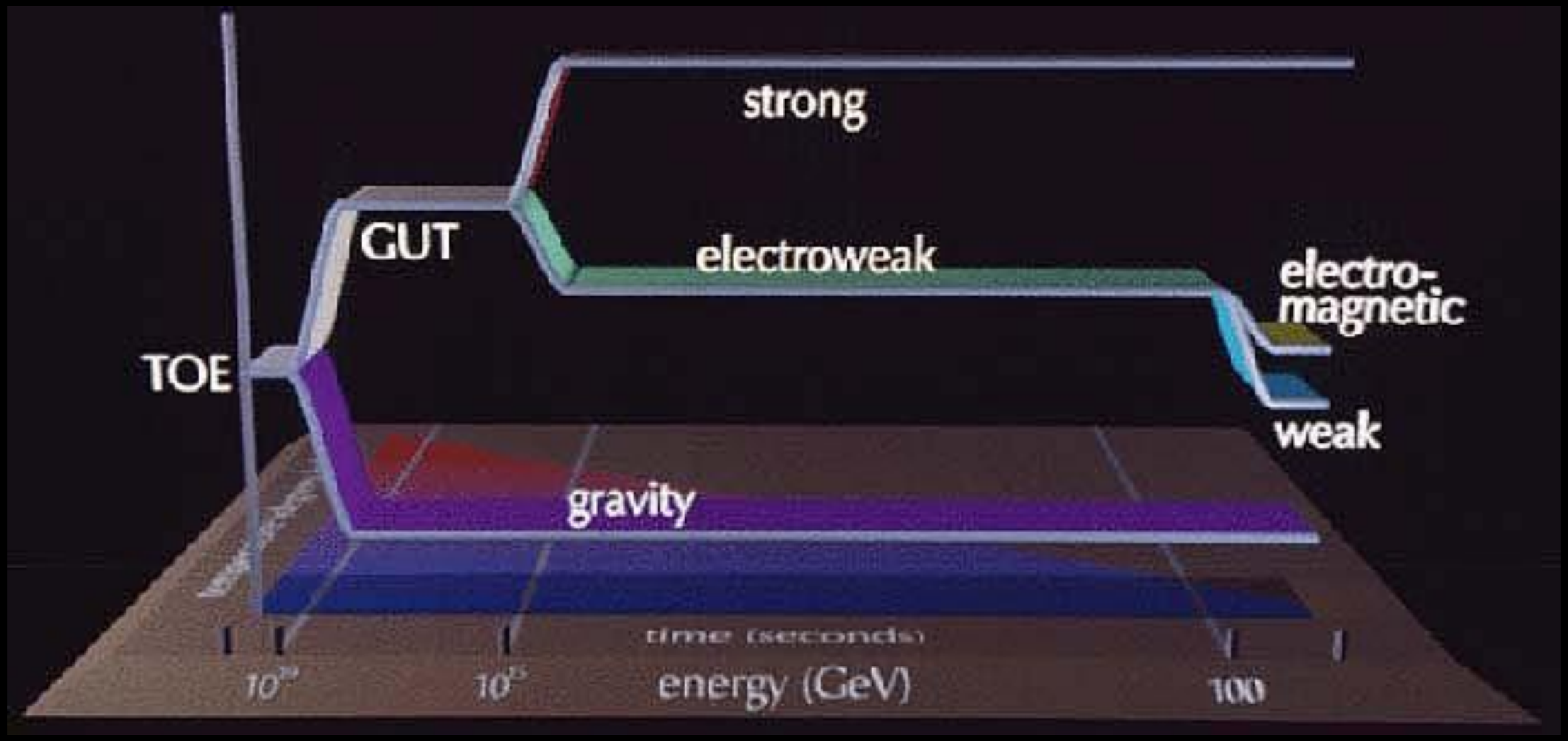
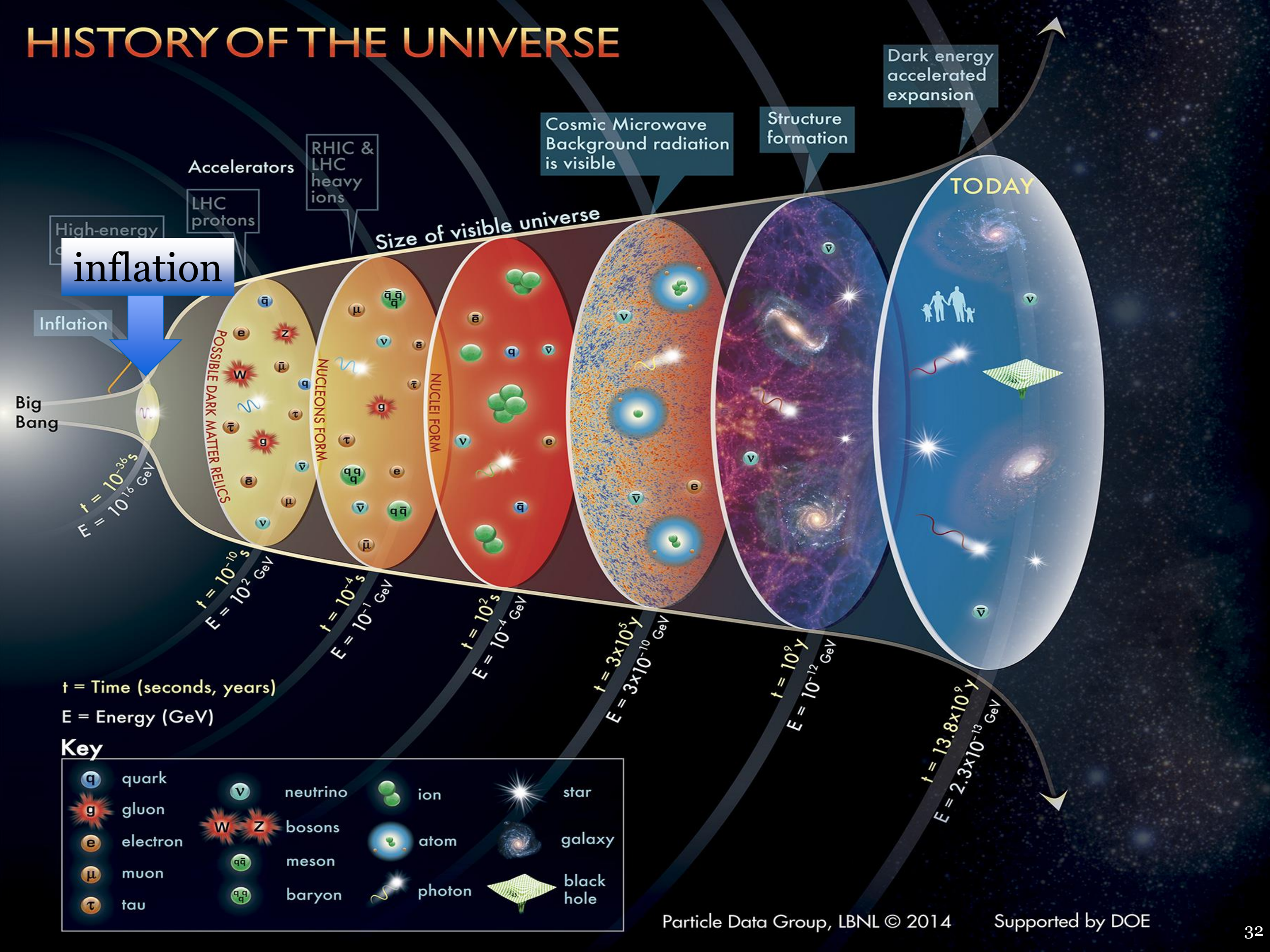
Unification of the Forces

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




HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy
inflation
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
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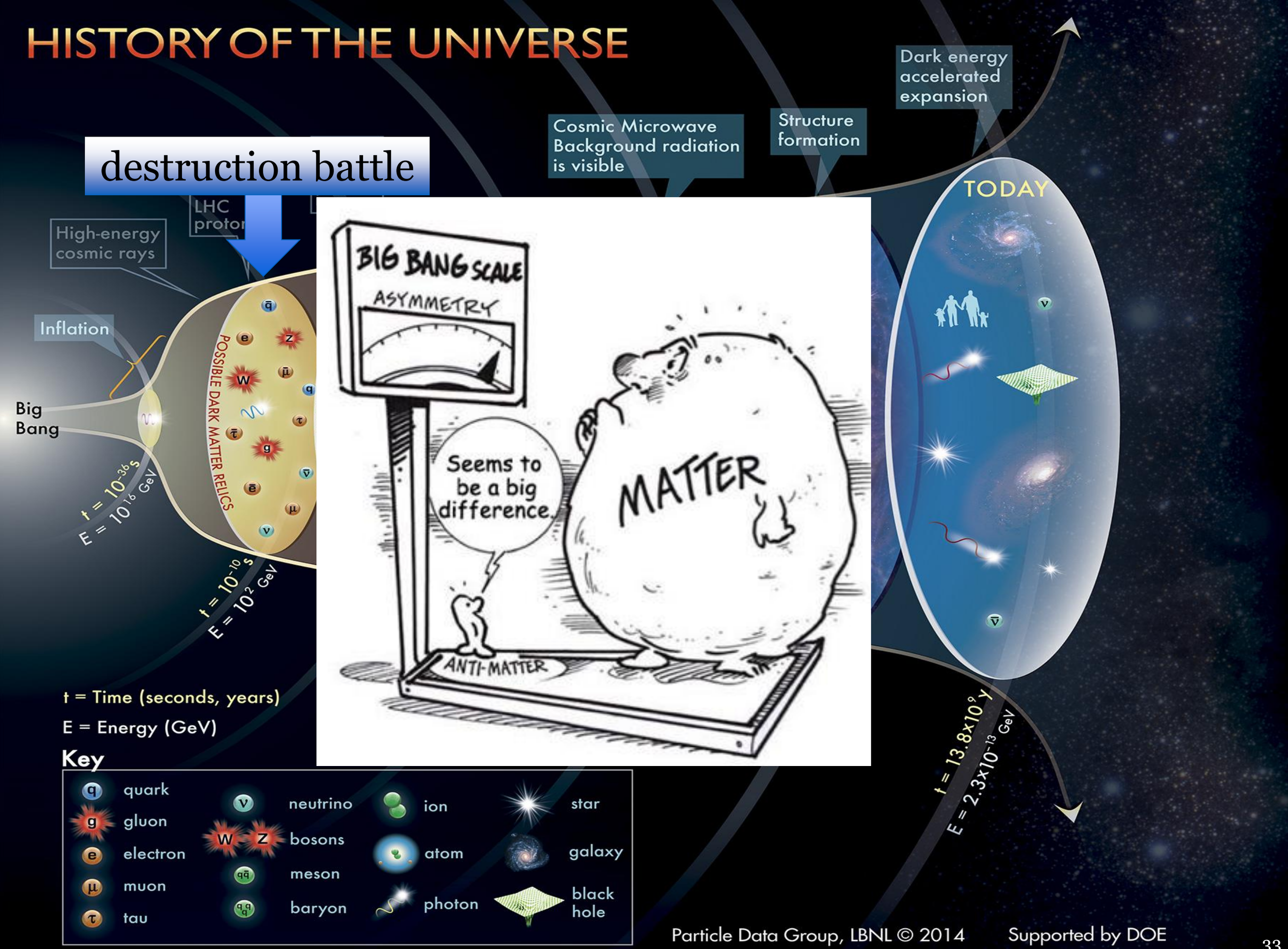
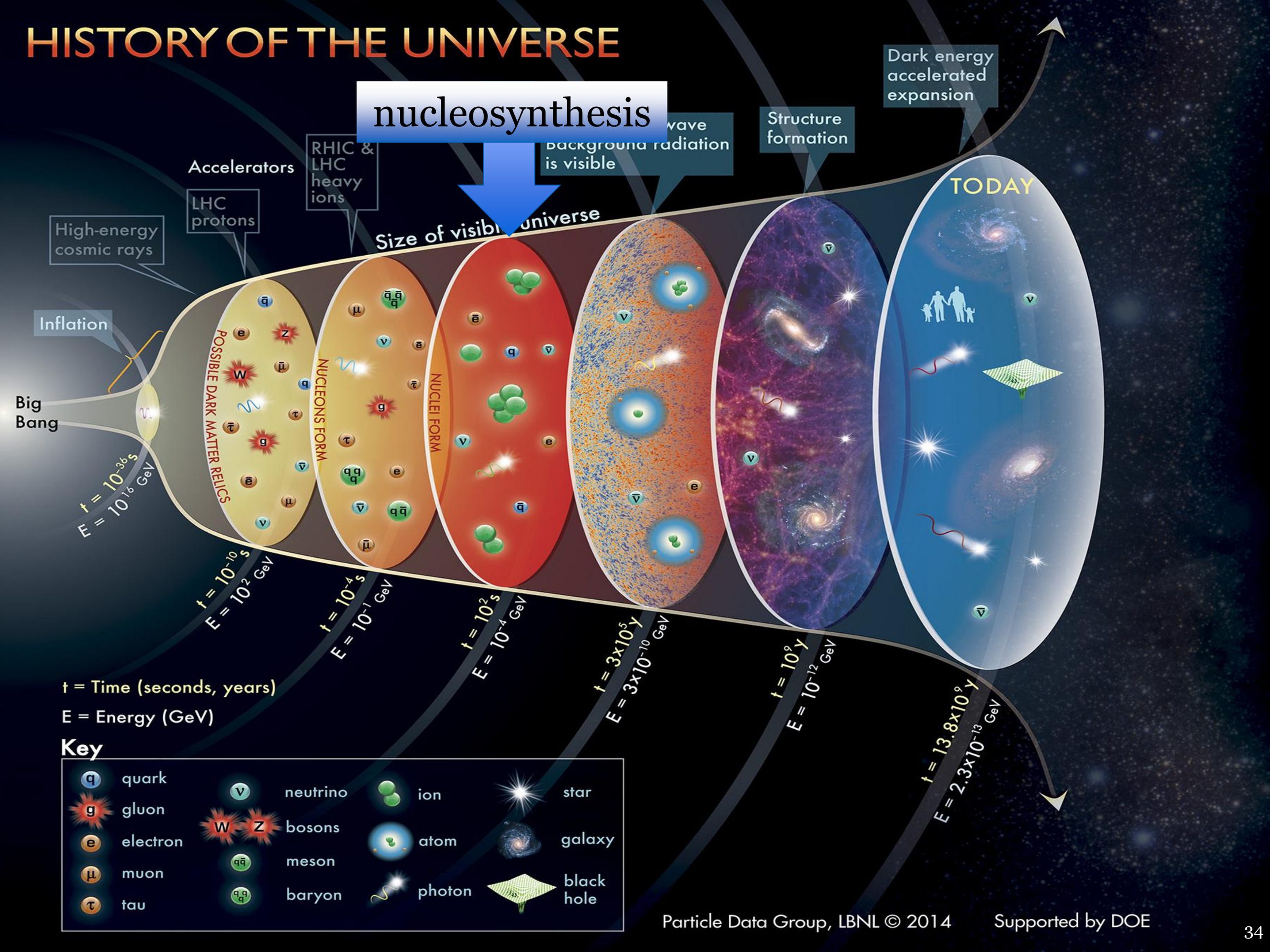
HISTORY OF THE UNIVERSE

destruction battle




HISTORY OF THE UNIVERSE
nucleosynthesis
Dark energy accelerated expansion
Structure formation
wave 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
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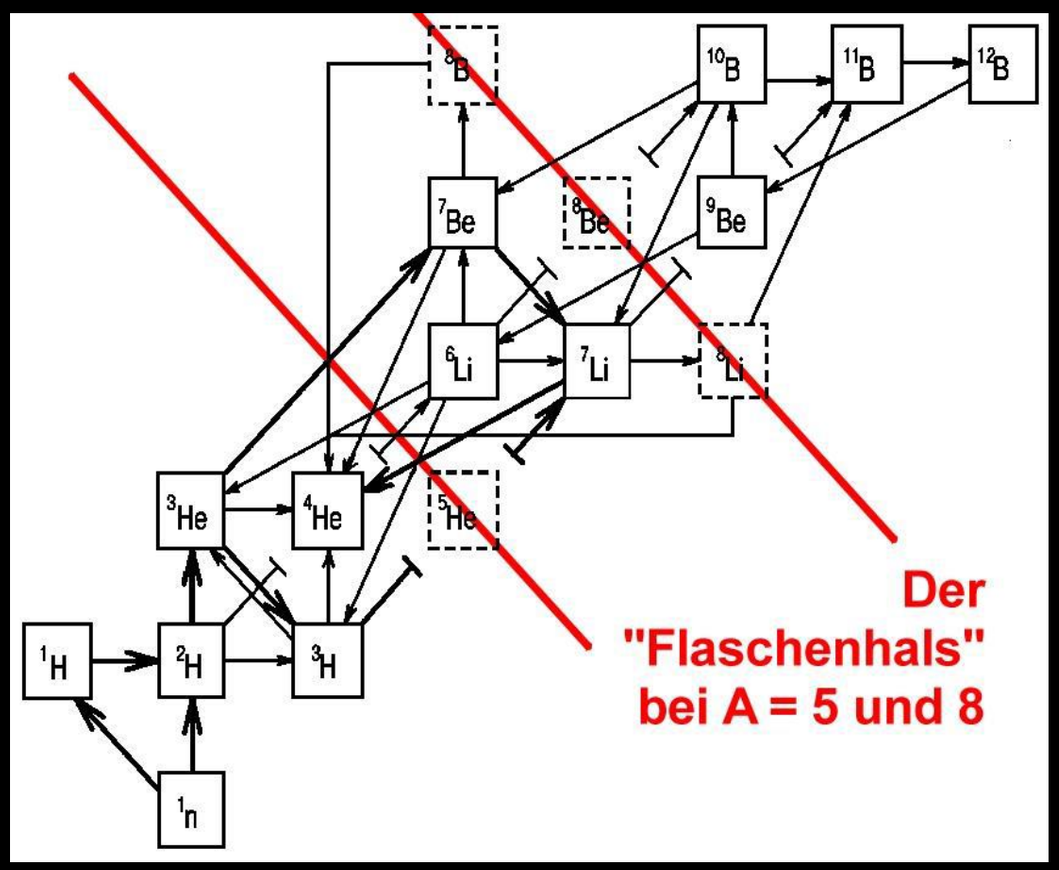
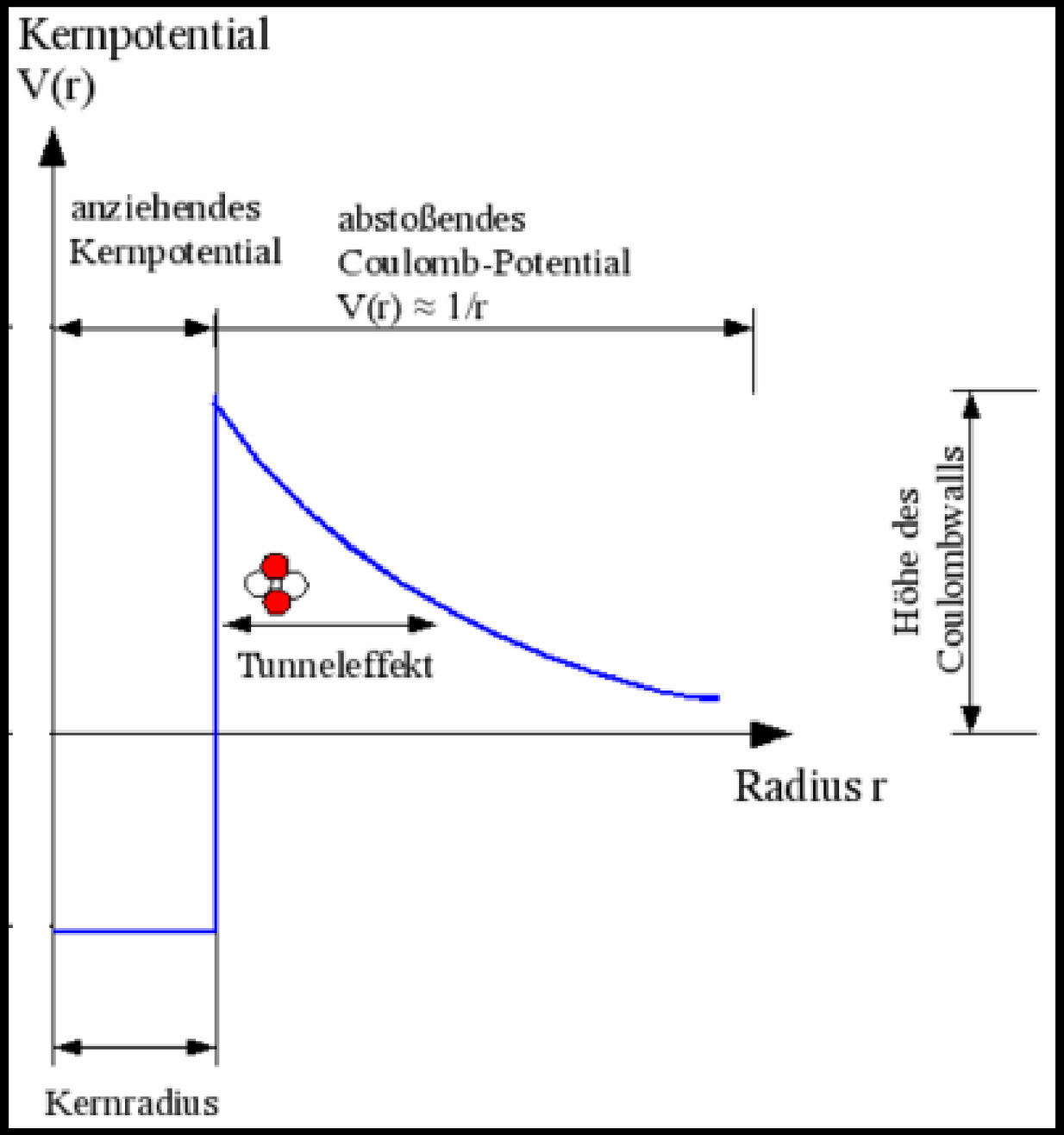
Nuclear Fusion

fusion in particle collisions

fusion needs high temperatures
and high particle densities



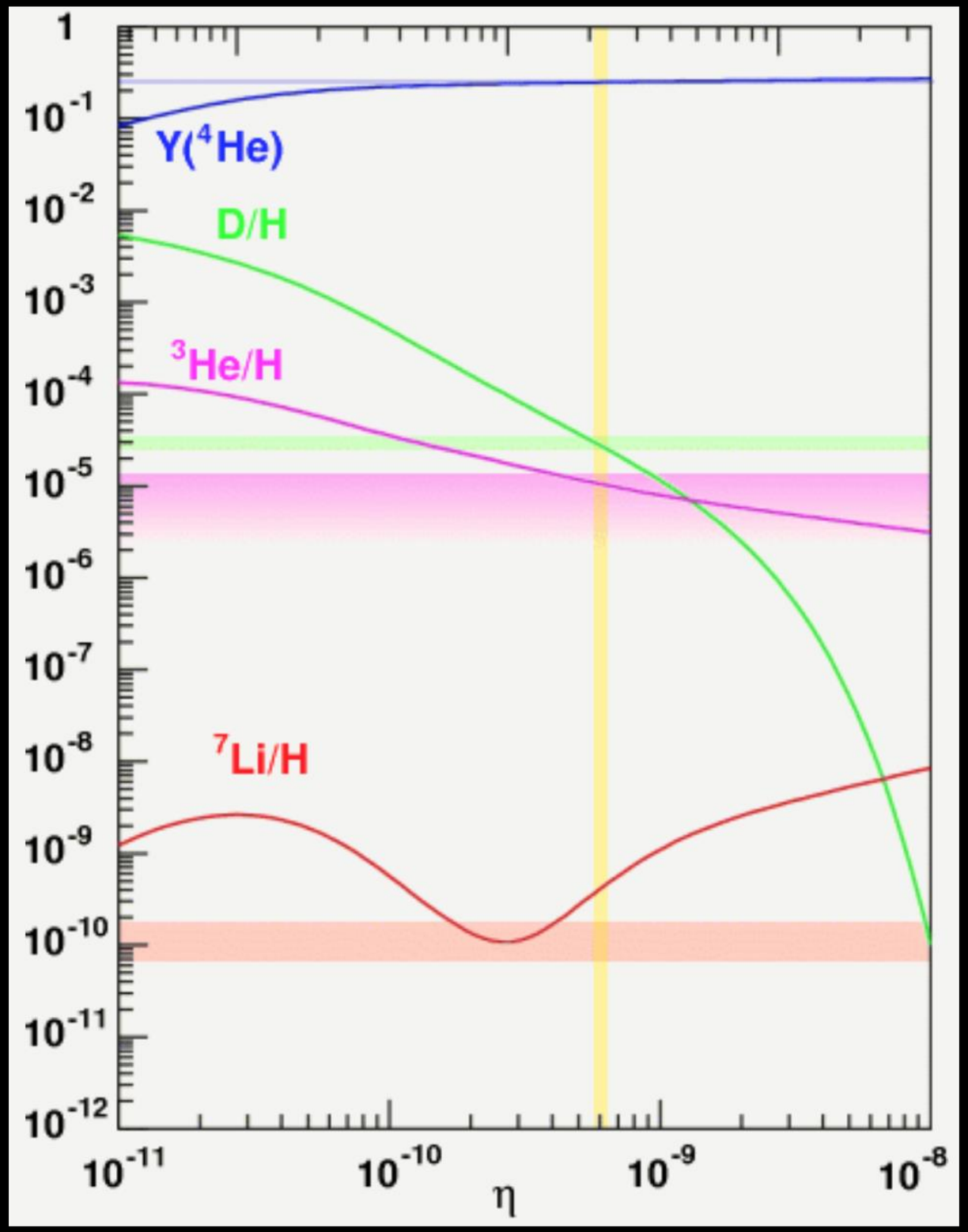


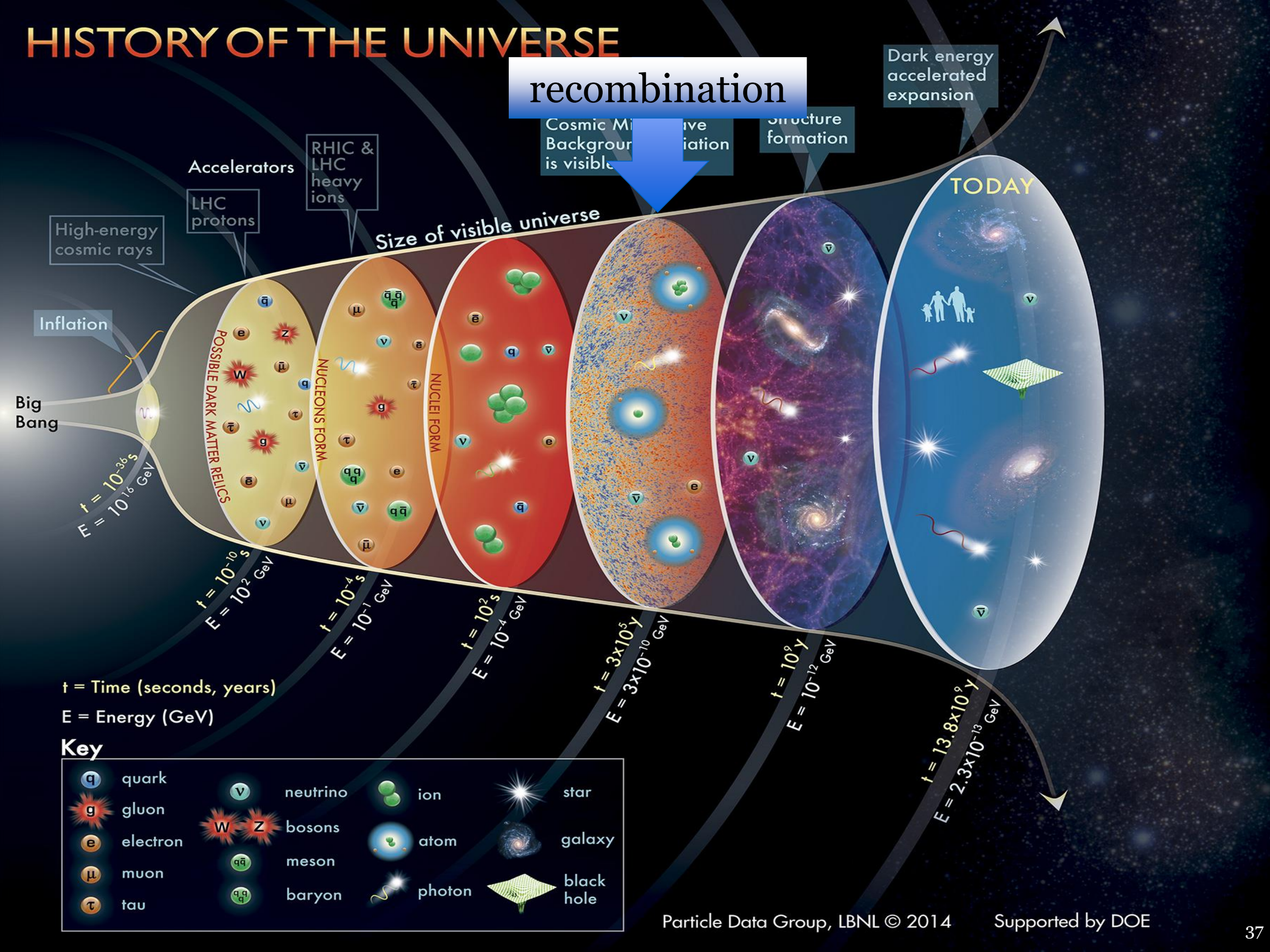
Primordial Nucleosynthesis

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

abundances
of light elements:

74 % hydrogen
25 % helium
1 % rest




HISTORY OF THE UNIVERSE
recombination
Dark energy accelerated expansion
Cosmic Mi ave Backgrou iation is visible
Structure formation
Accelerators
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LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
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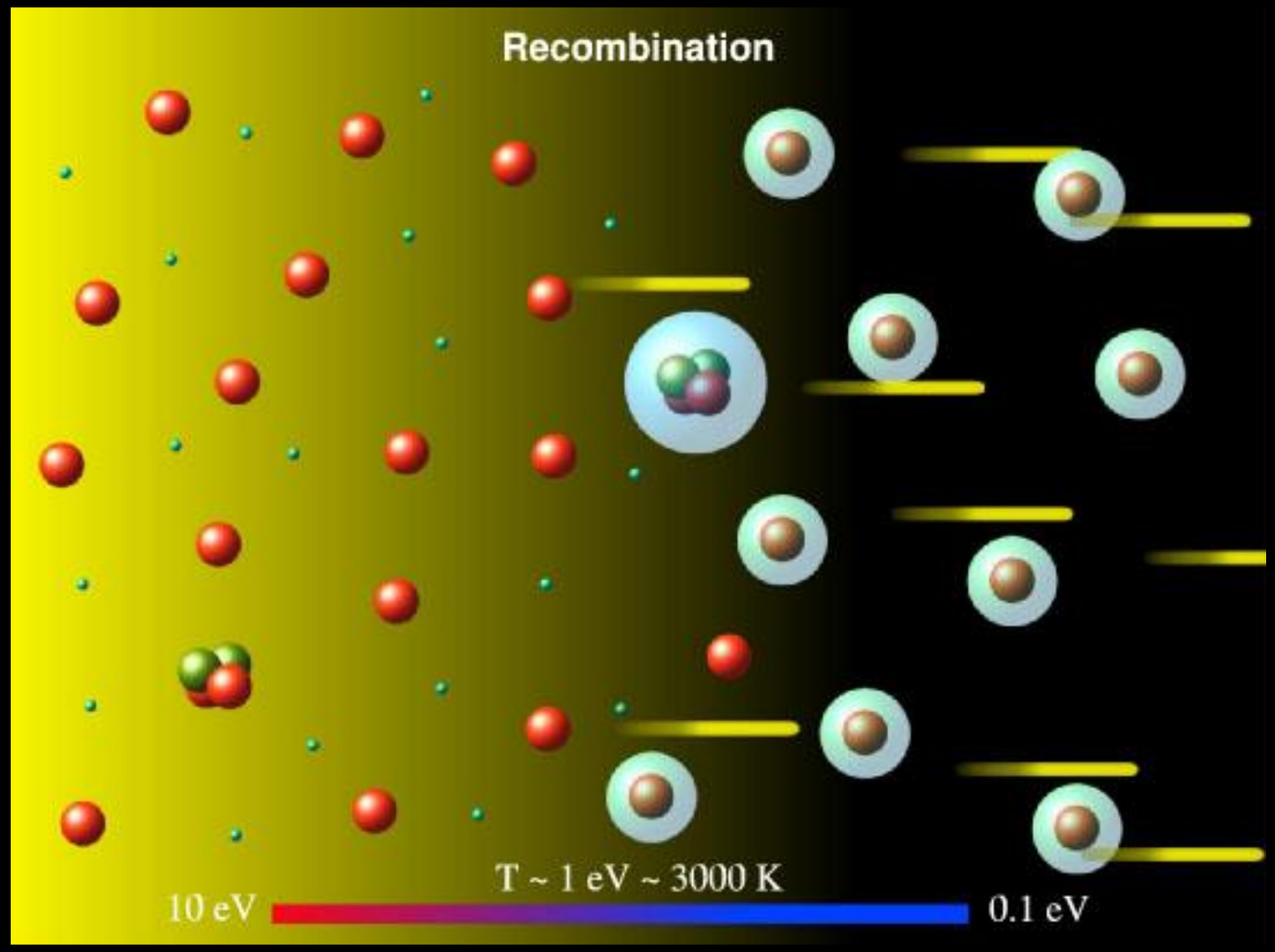
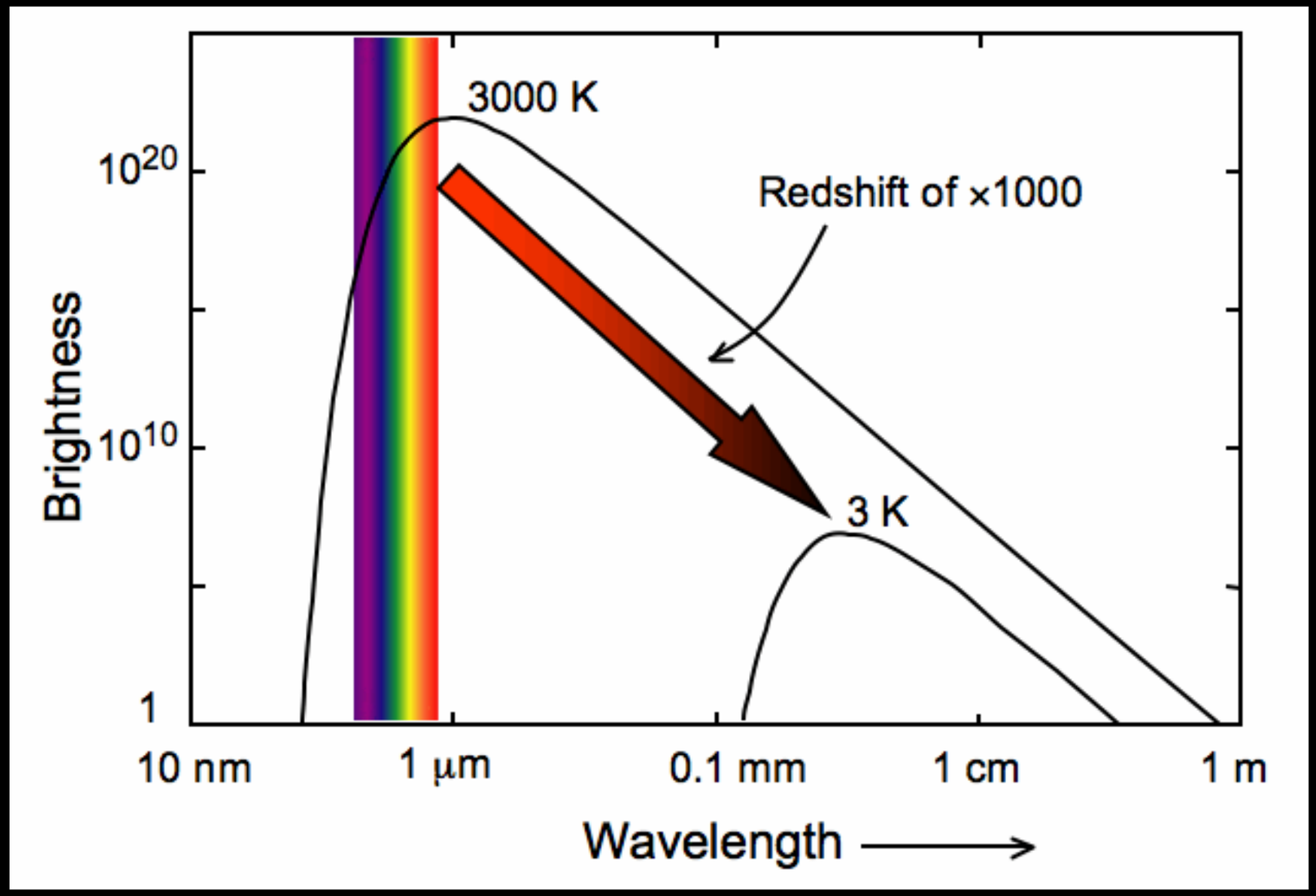
Recombination



- 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!

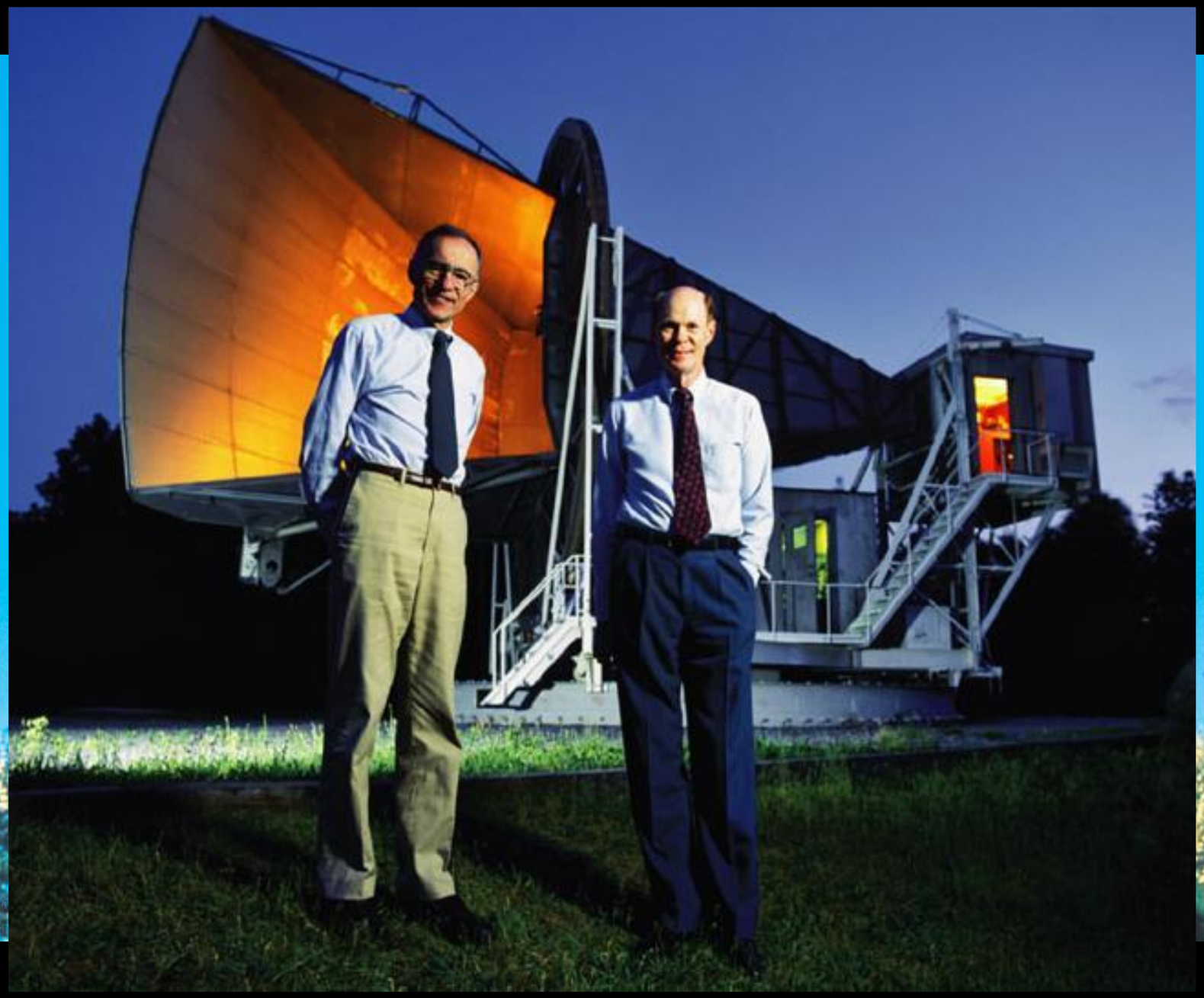
The Cosmic Microwave Background (CMB)



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



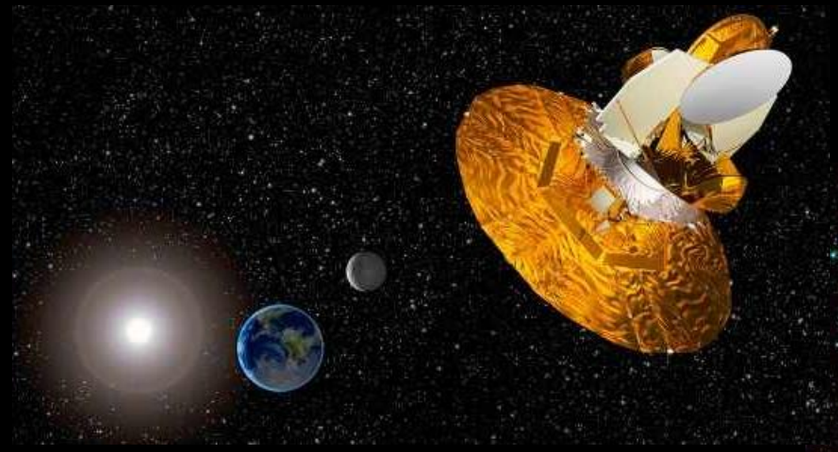
1964 Penzias und Wilson discovered a noise, which they couldn’t explain

(1978)

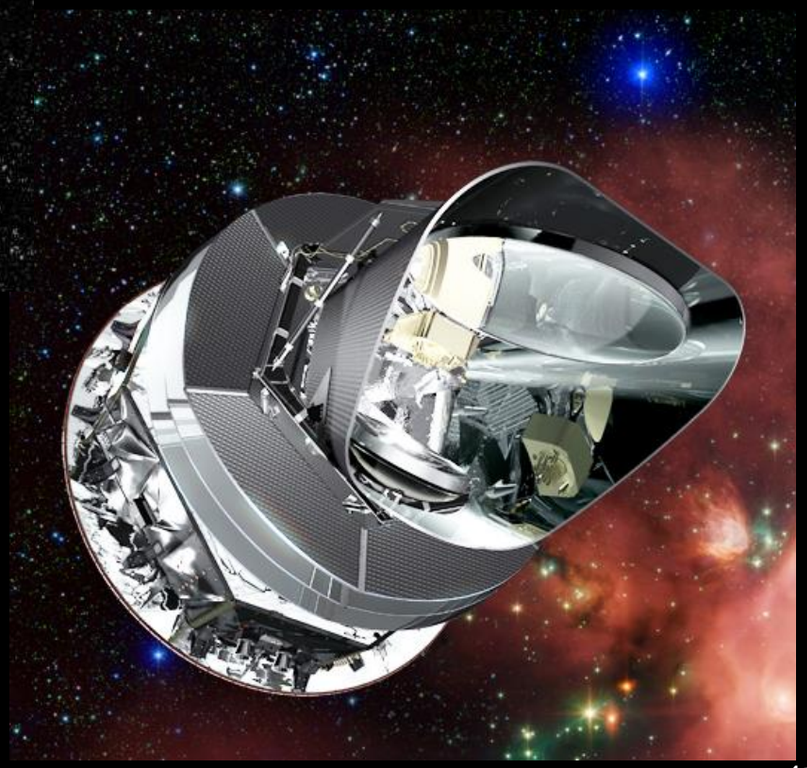
Satellites for the investigation of the CMB

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

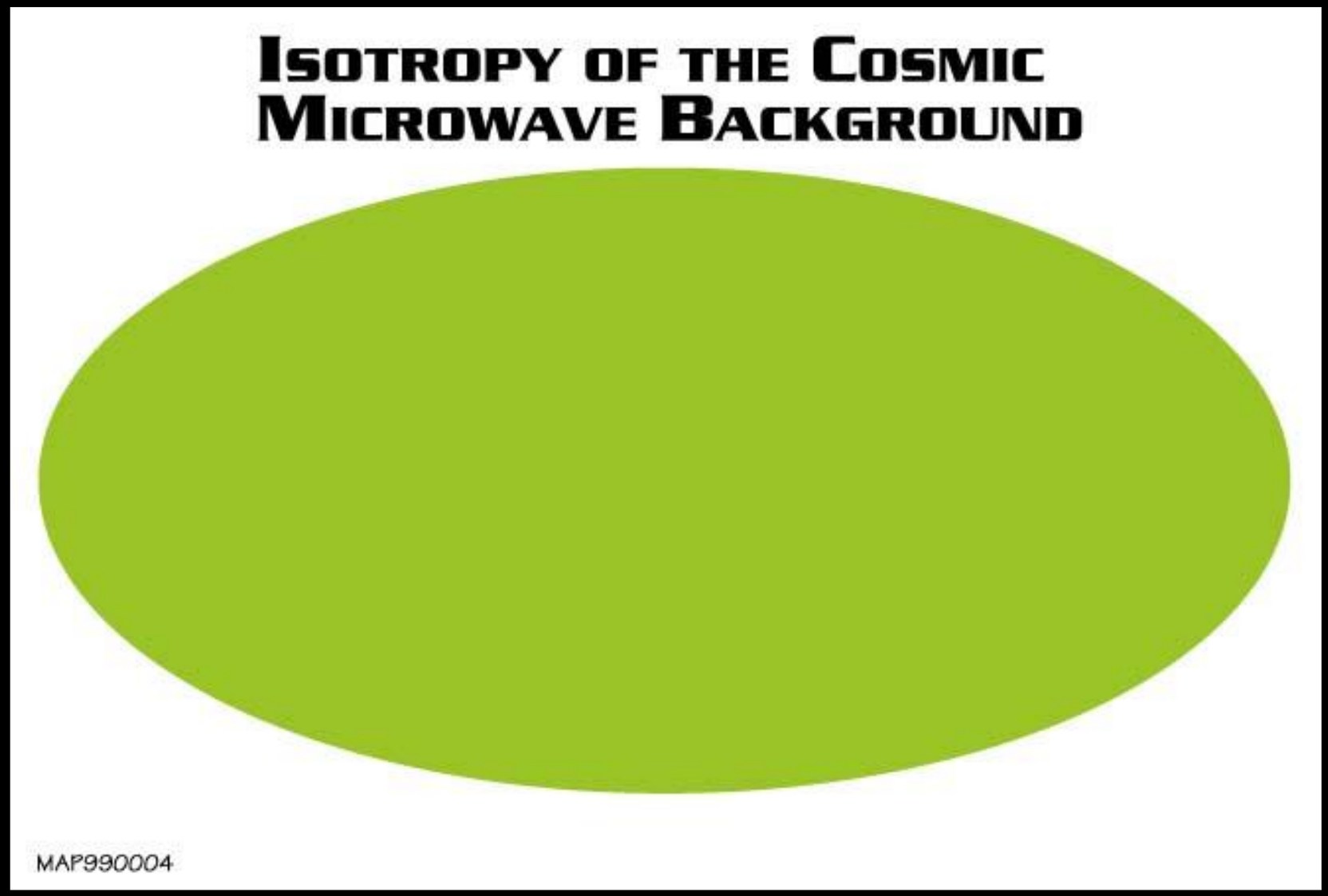
- WMAP
  Wilkinson Microwave
  Anisotropy Probe
  2001-2010



- Planck
  2009-2013



Next problem for the Big Bang theory



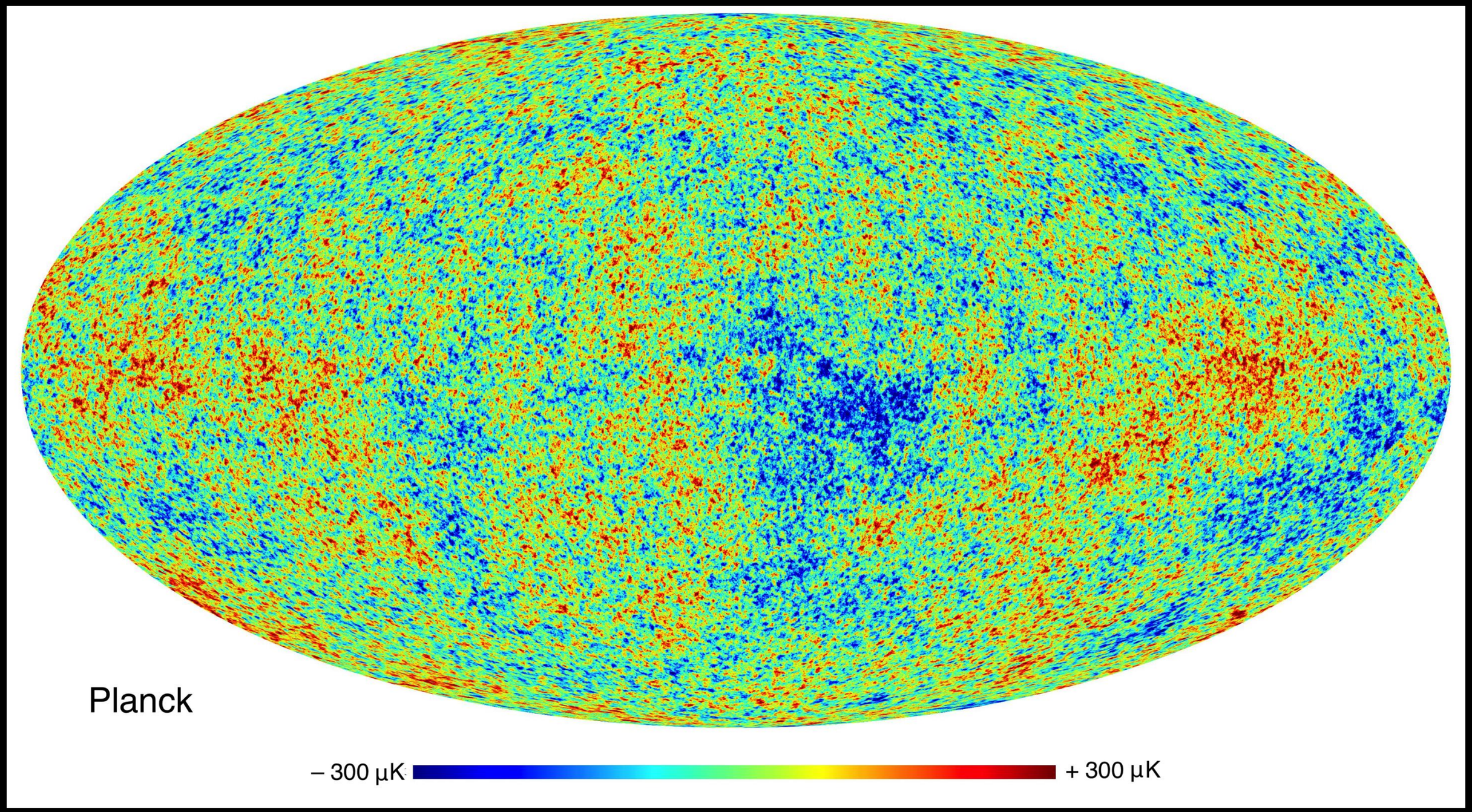
The second analysis revealed no sign of any variation at a level of 1 part in 10.000!
Where are the galaxies coming from, if not from density fluctuations?

The Echo of the Big Bang

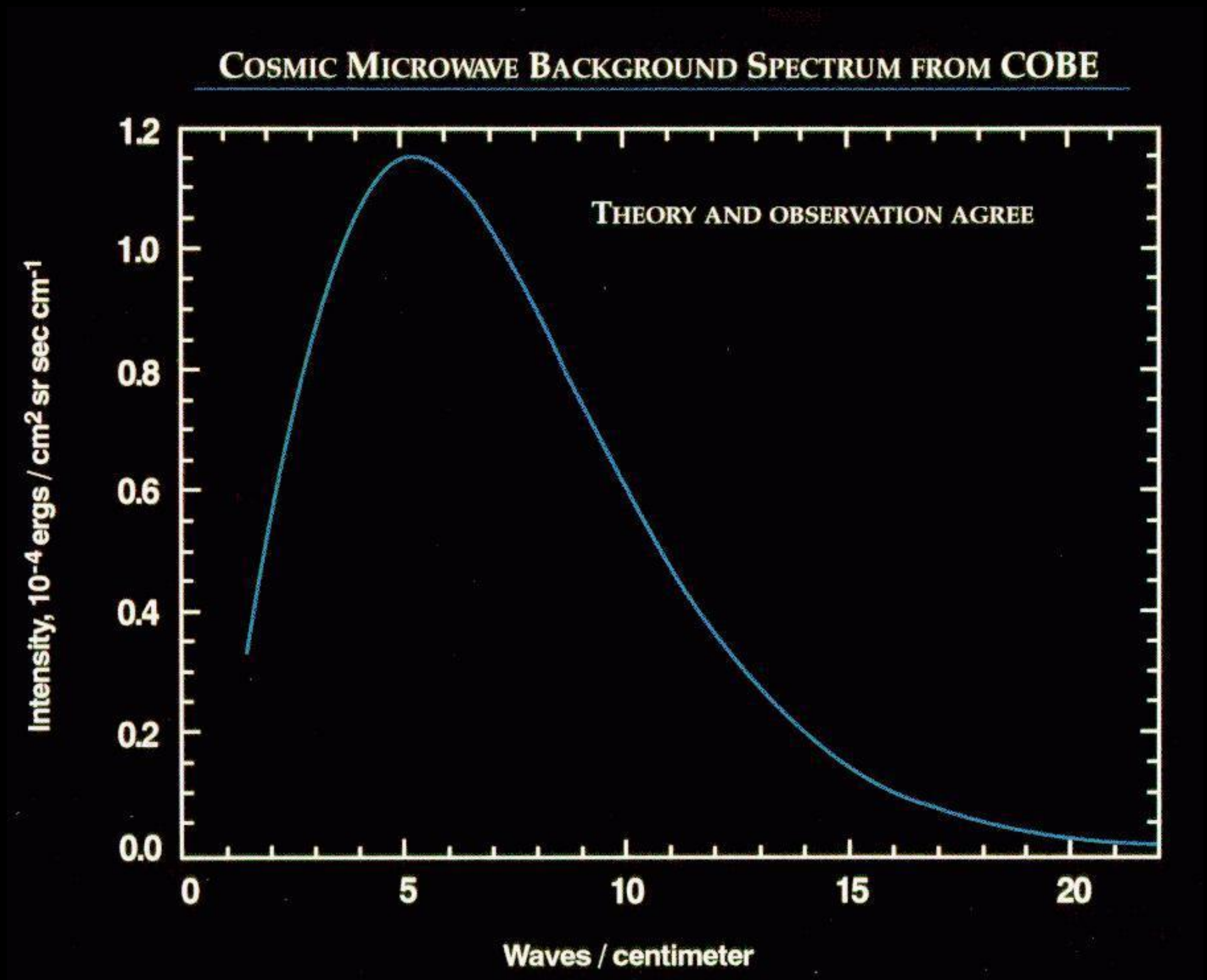
LE FIGARO·fr

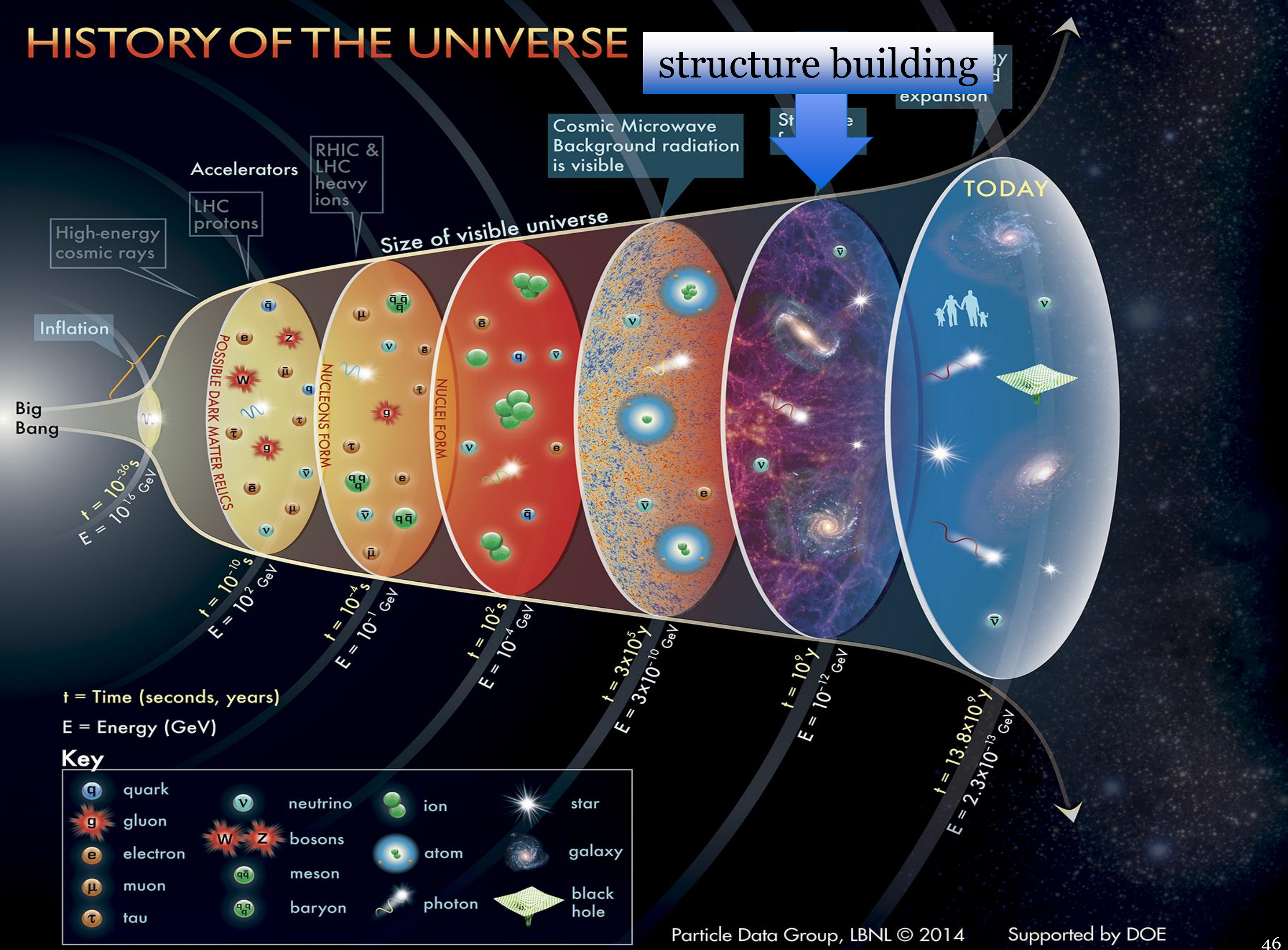
The Echo of the Big Bang

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



The spectrum of the CMB

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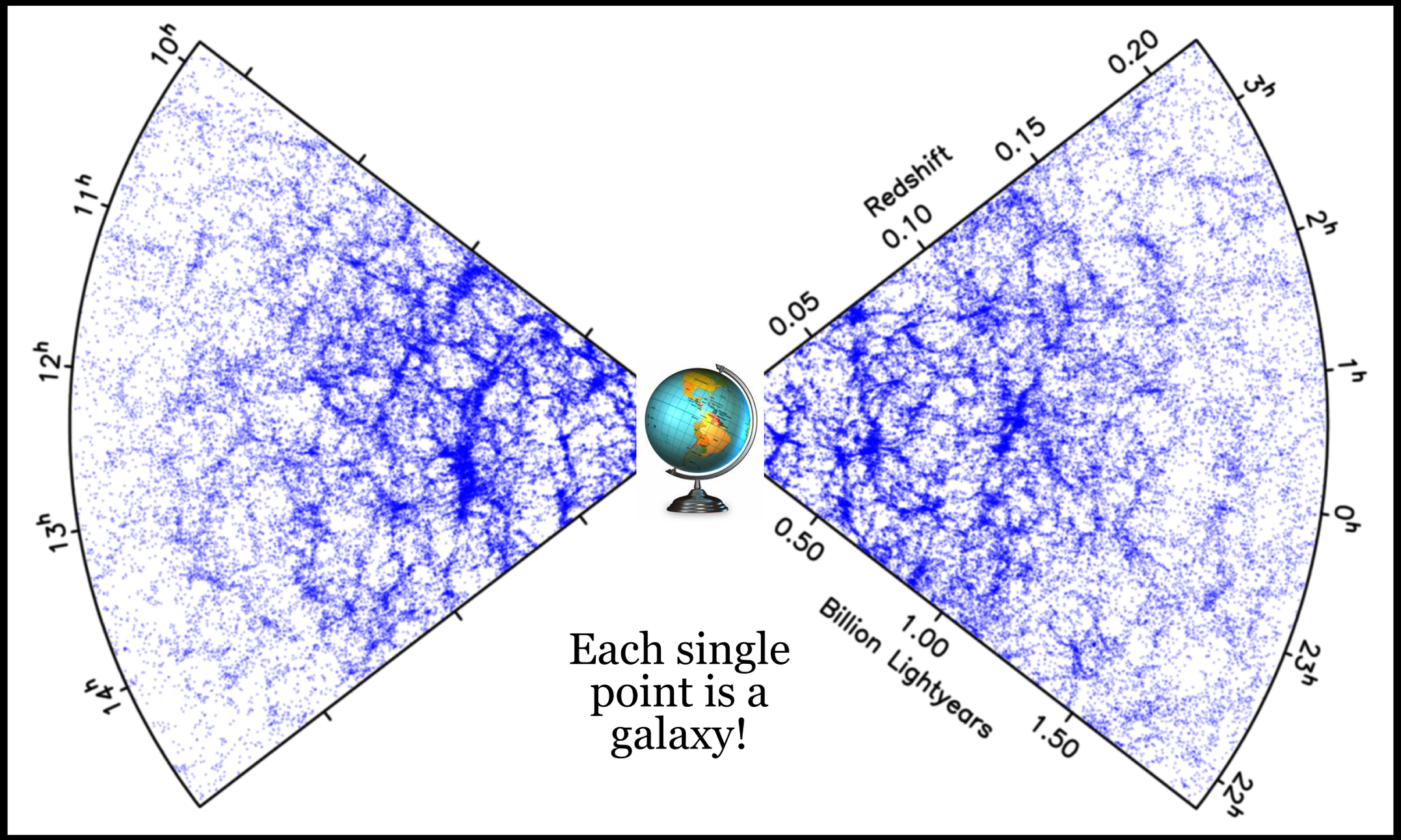
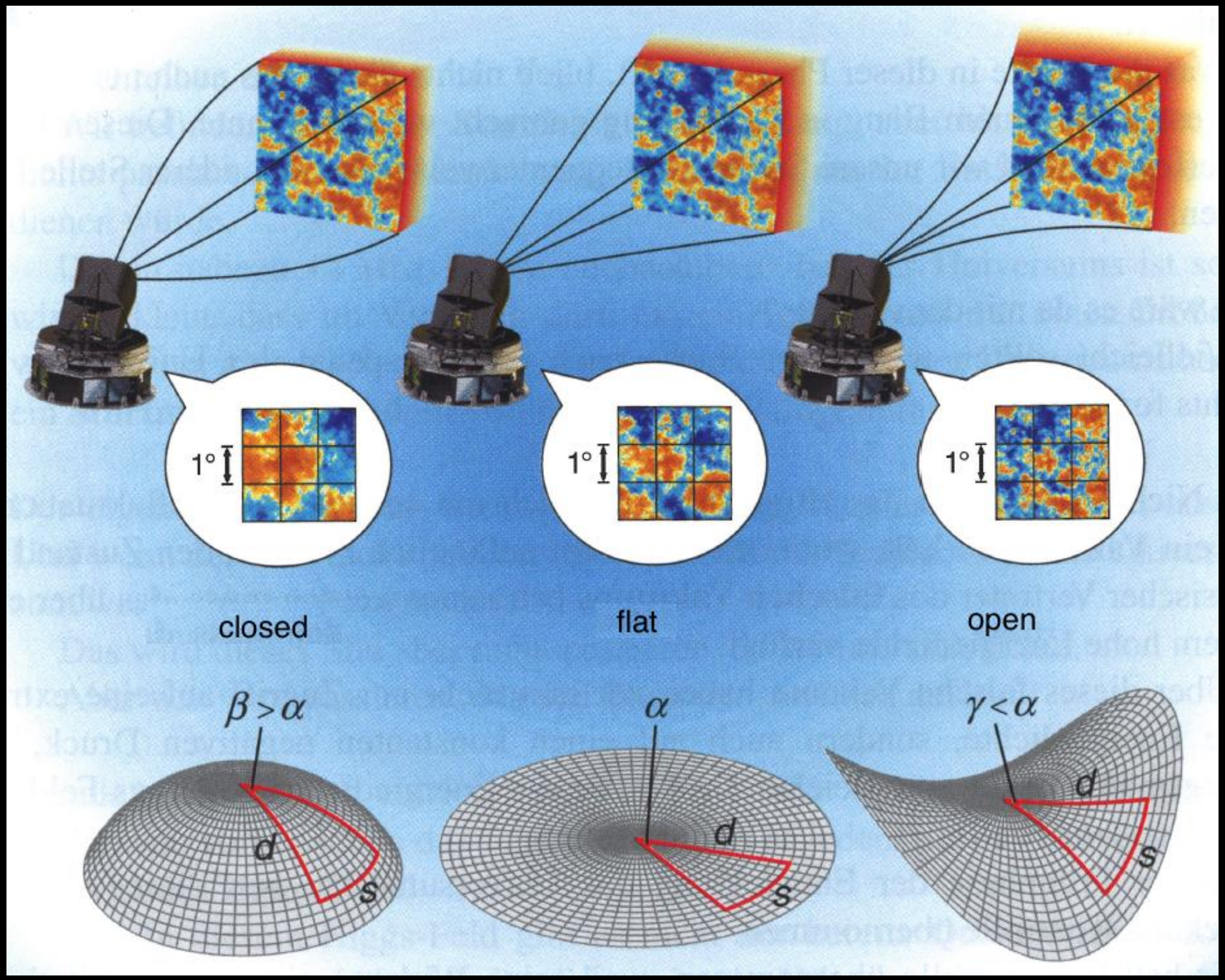
Galaxy Distribution

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

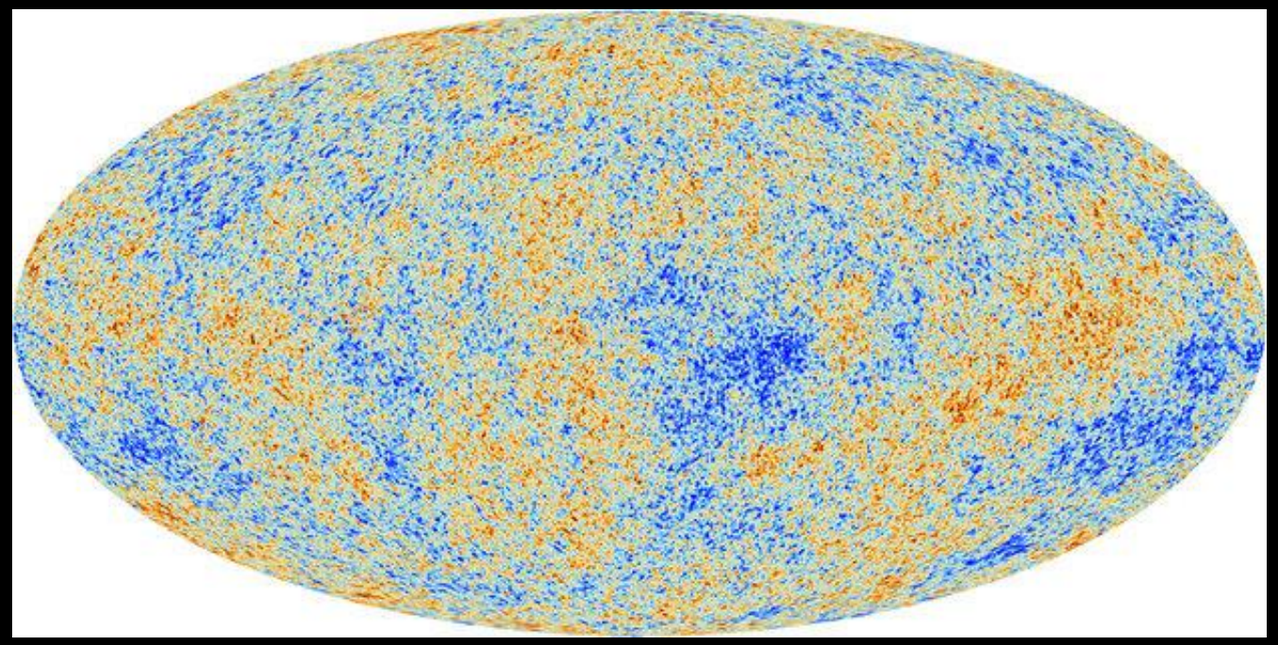


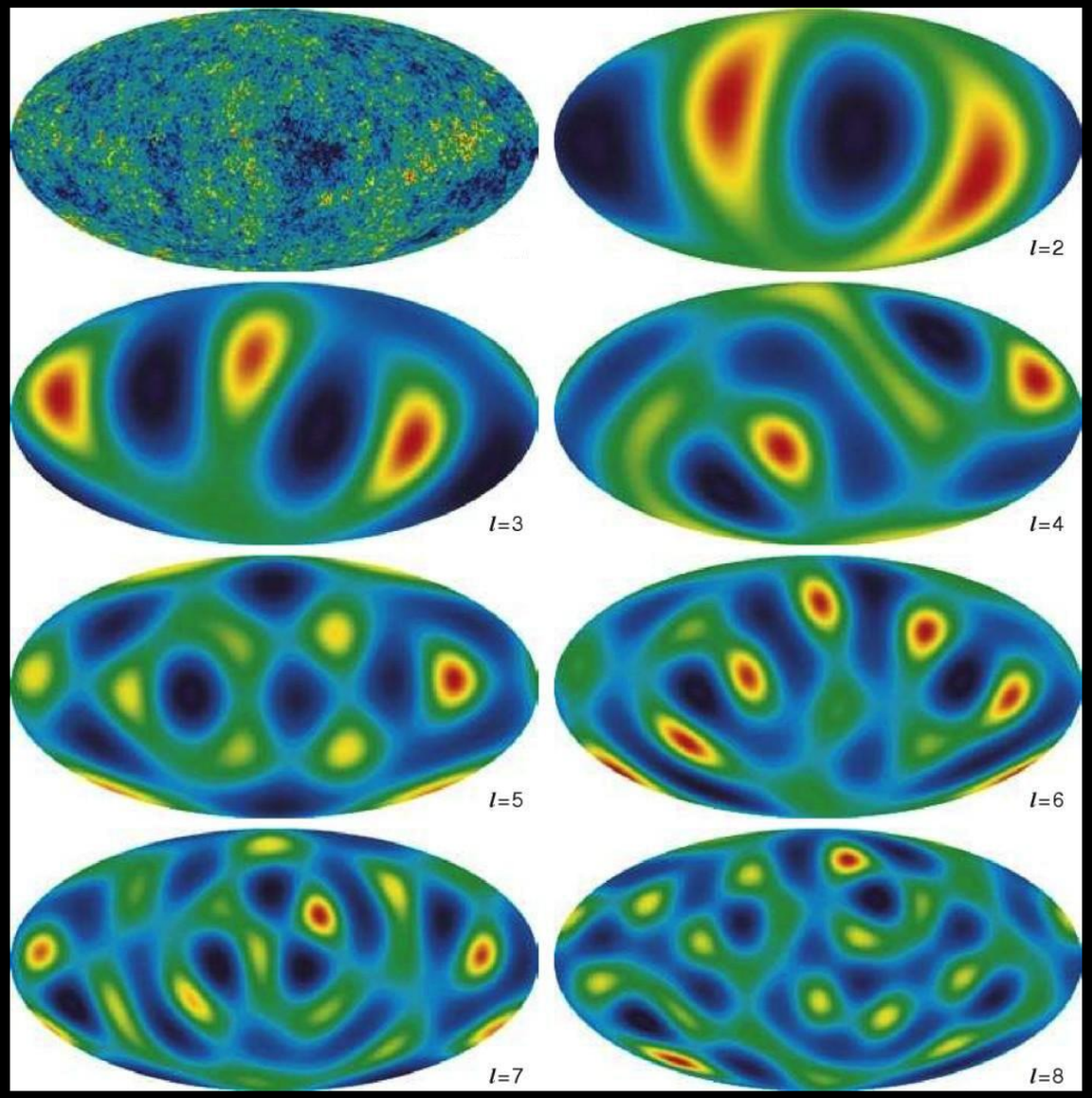
Each single point is a galaxy!

Geometry of the universe



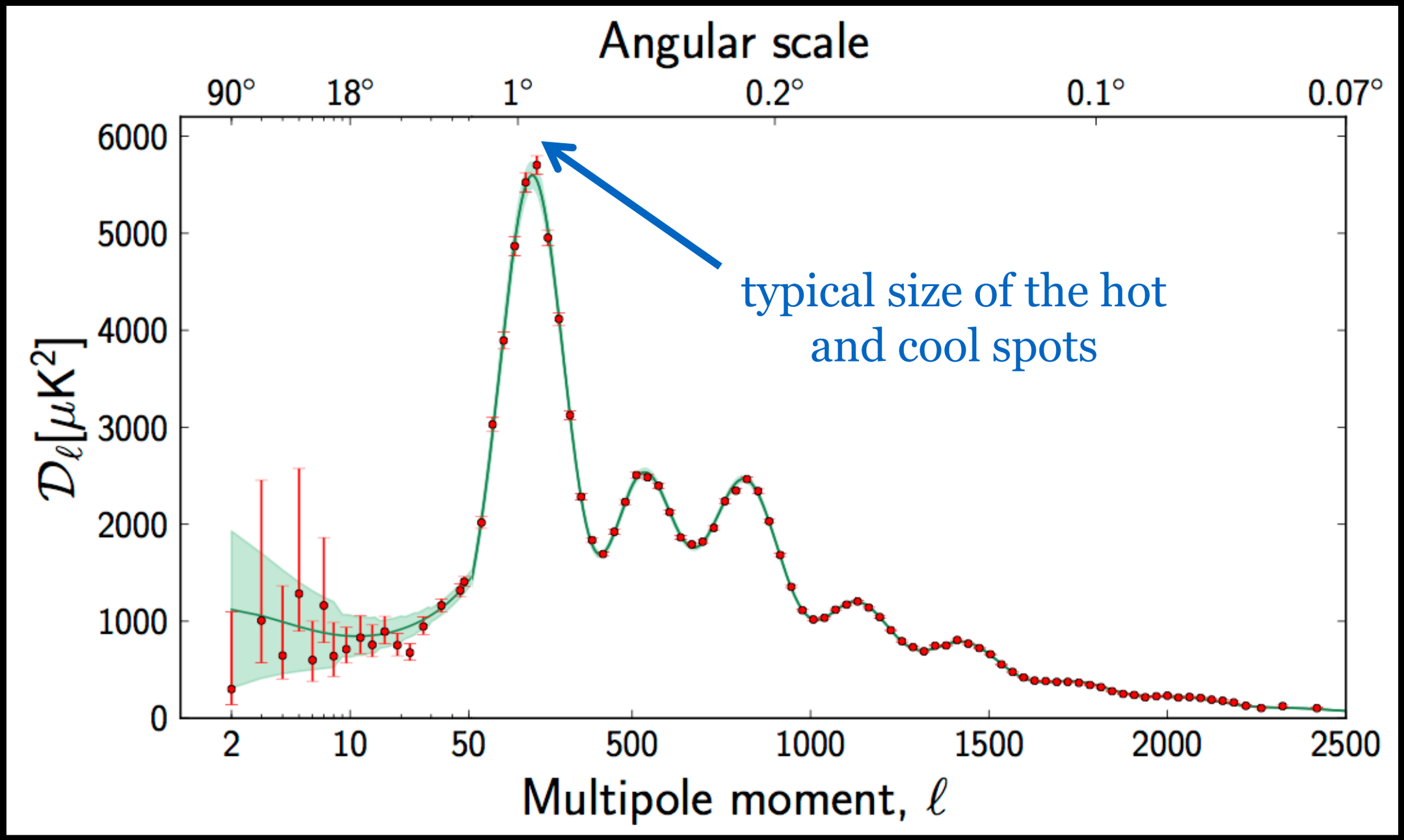
From the map to the spectrum...



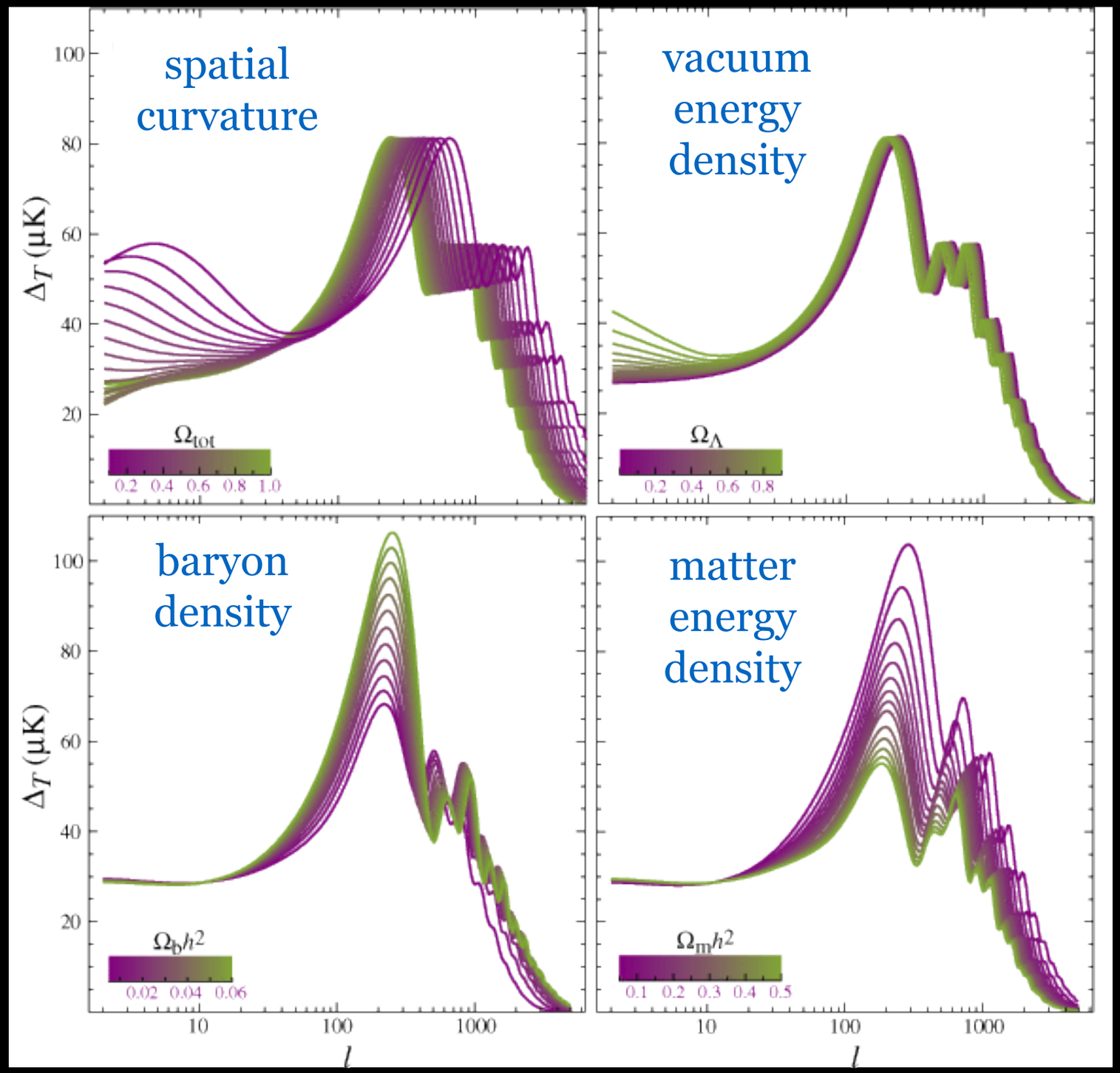


- theory is not able to predict the exact position of individual hot or cool spots
- instead: prediction of statistical properties of the temperature map (for example mean value, variance, correlations,...)

The Angular Power Spectrum of the CMB



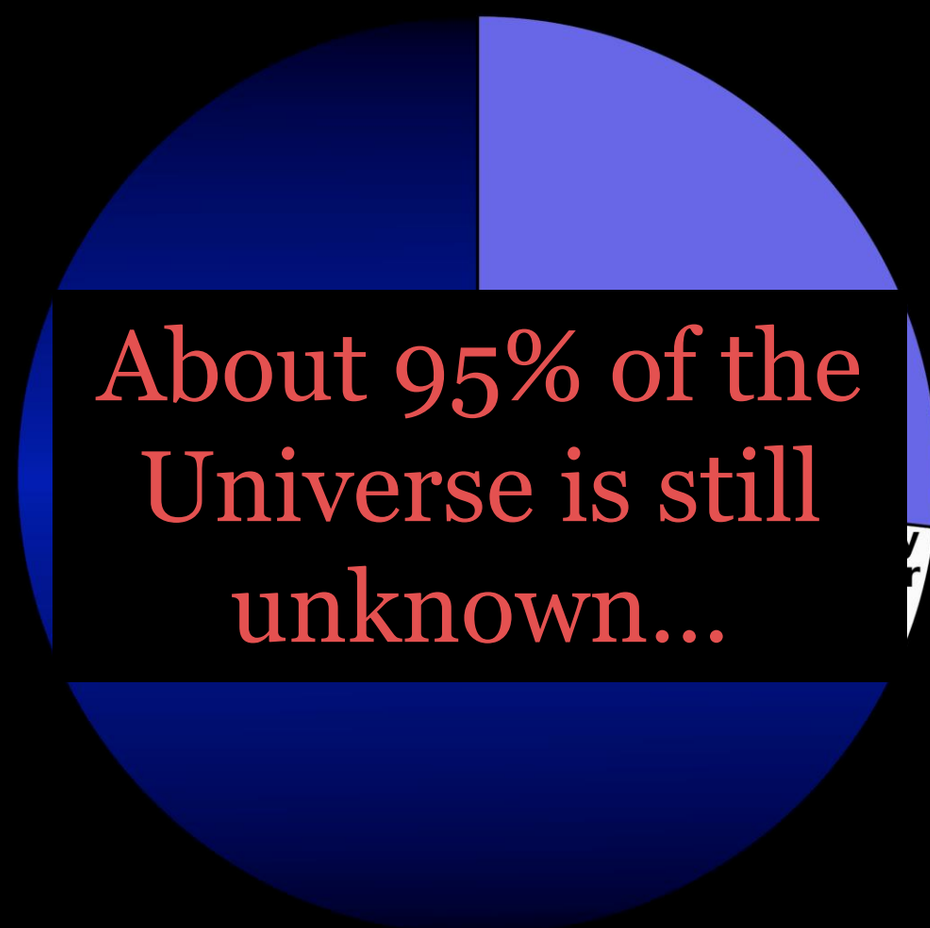
Theoretical Predictions of the CMB Spectrum



- 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!)



dark energy?!?!
(vacuum energy)

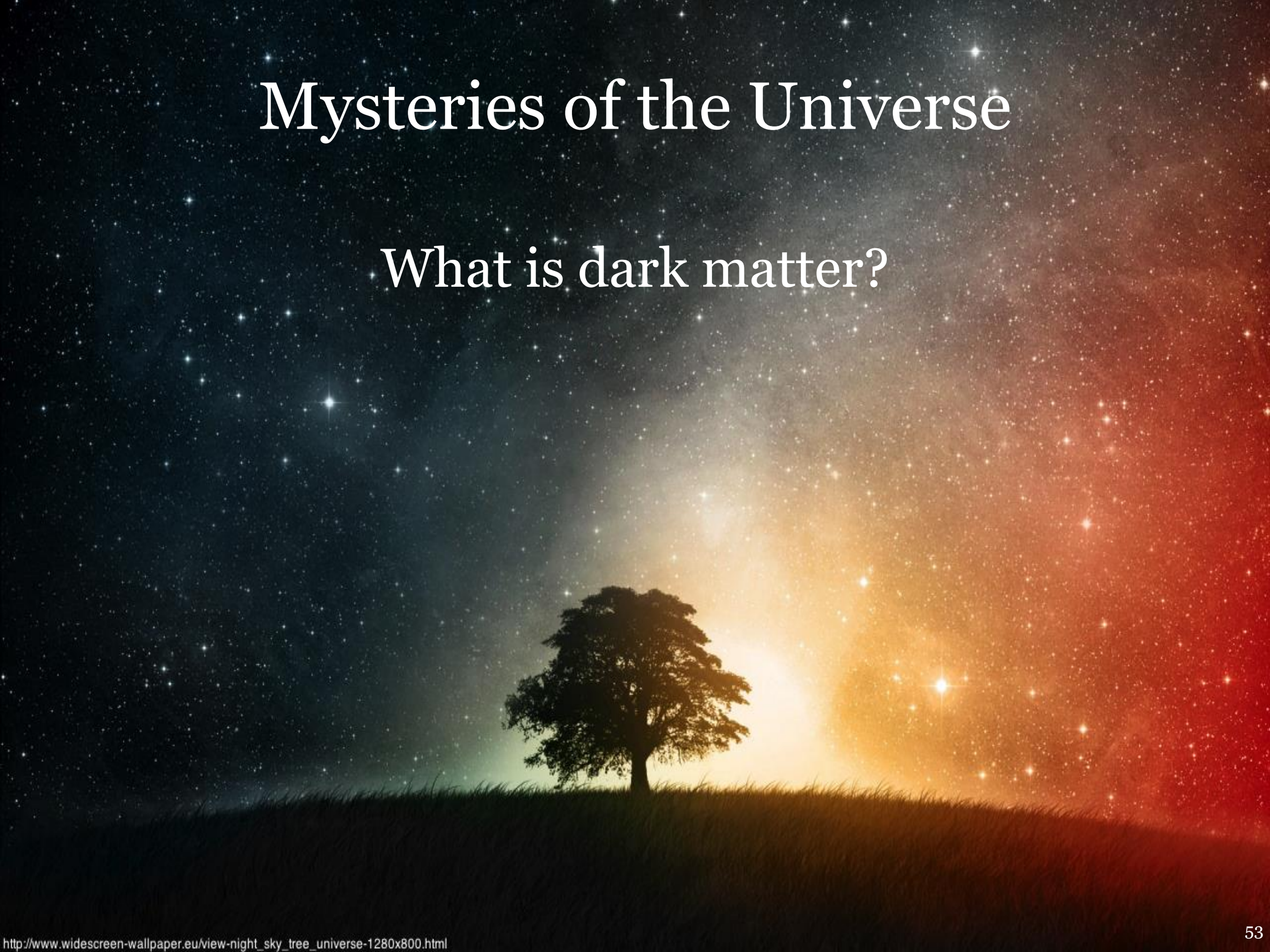
dark
matter?!

"normal"
matter

About 95% of the Universe is still unknown...

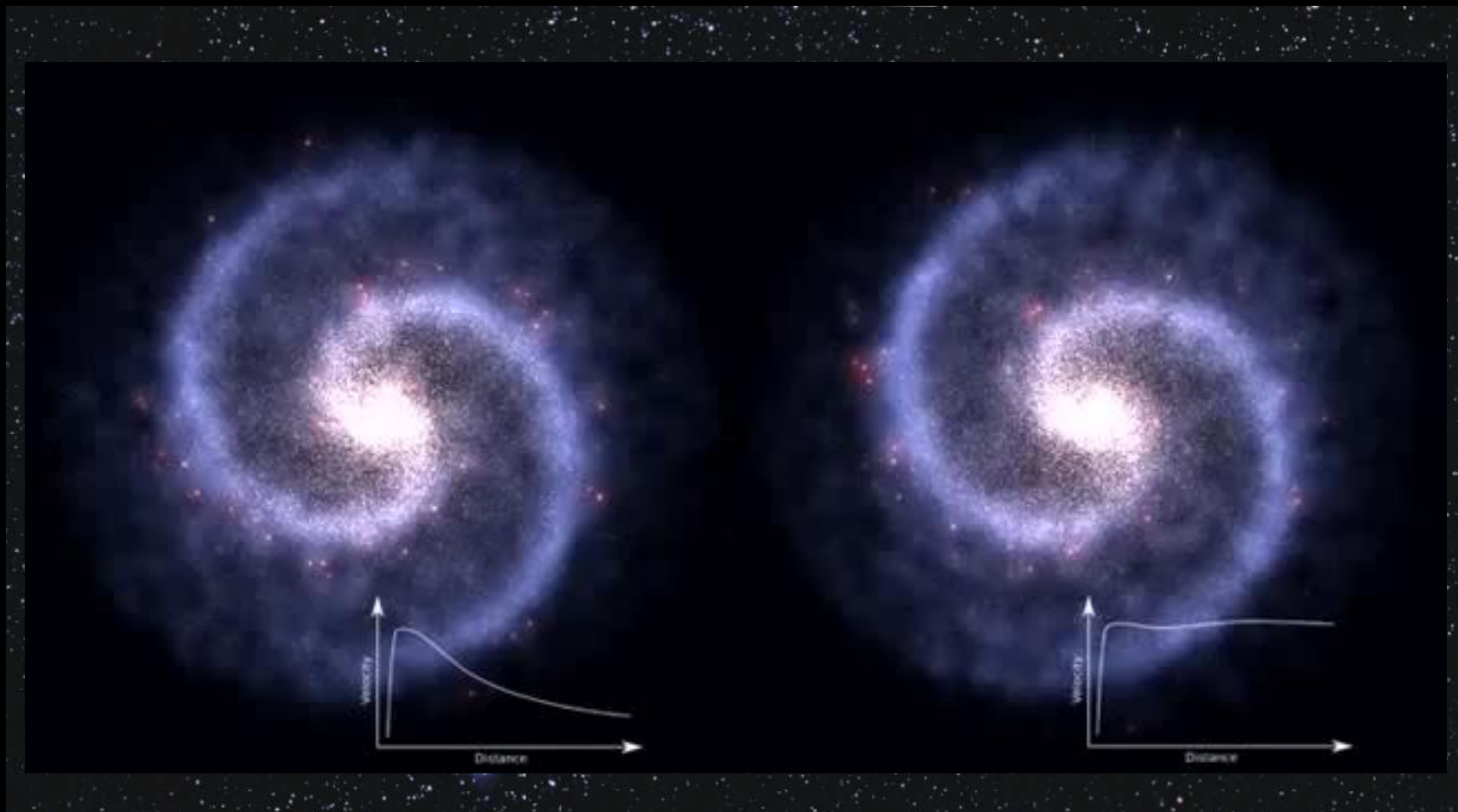
Mysteries of the Universe

What is dark matter?

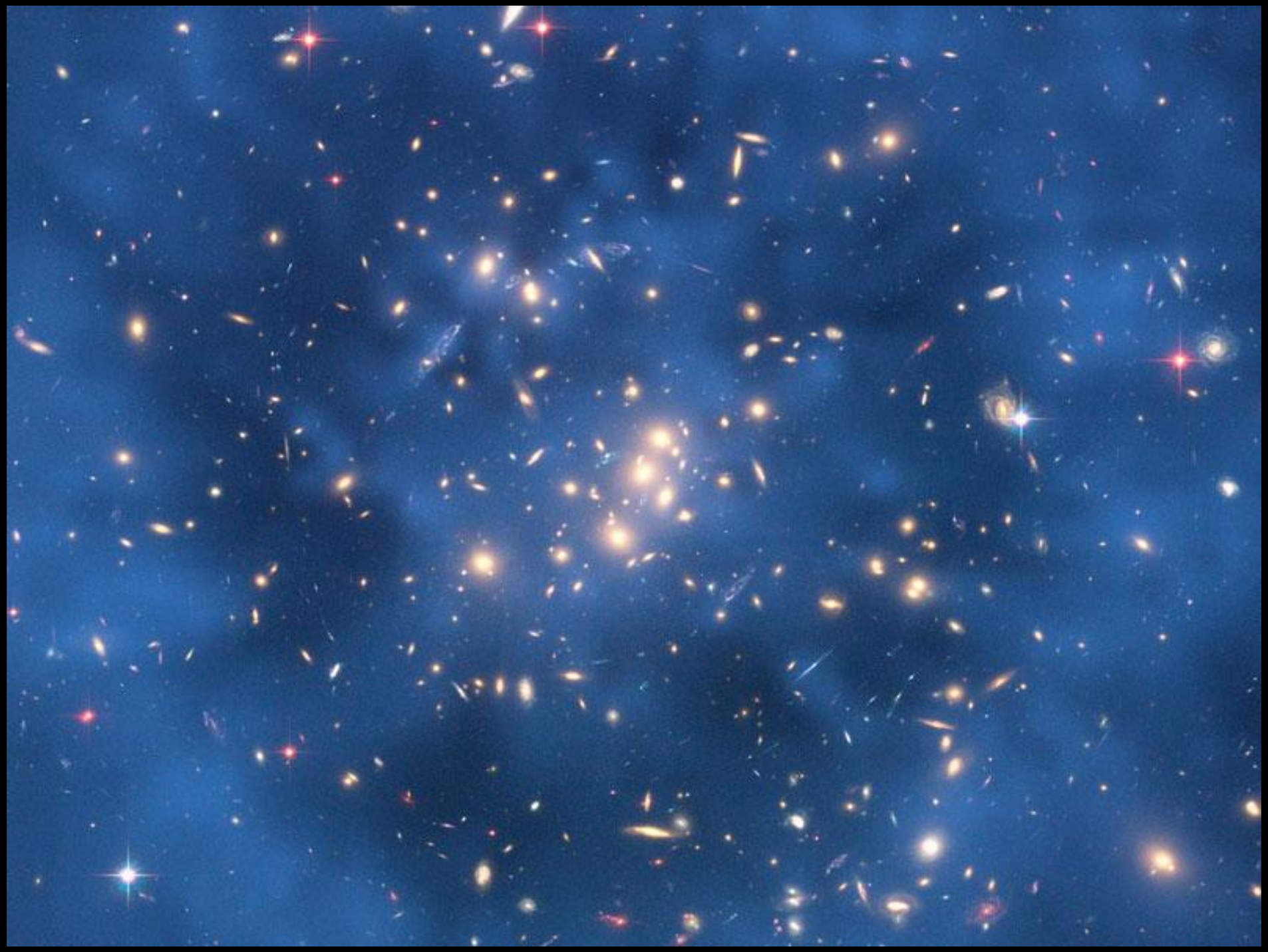


http://www.widescreen-wallpaper.eu/view-night_sky_tree_universe-1280x800.html

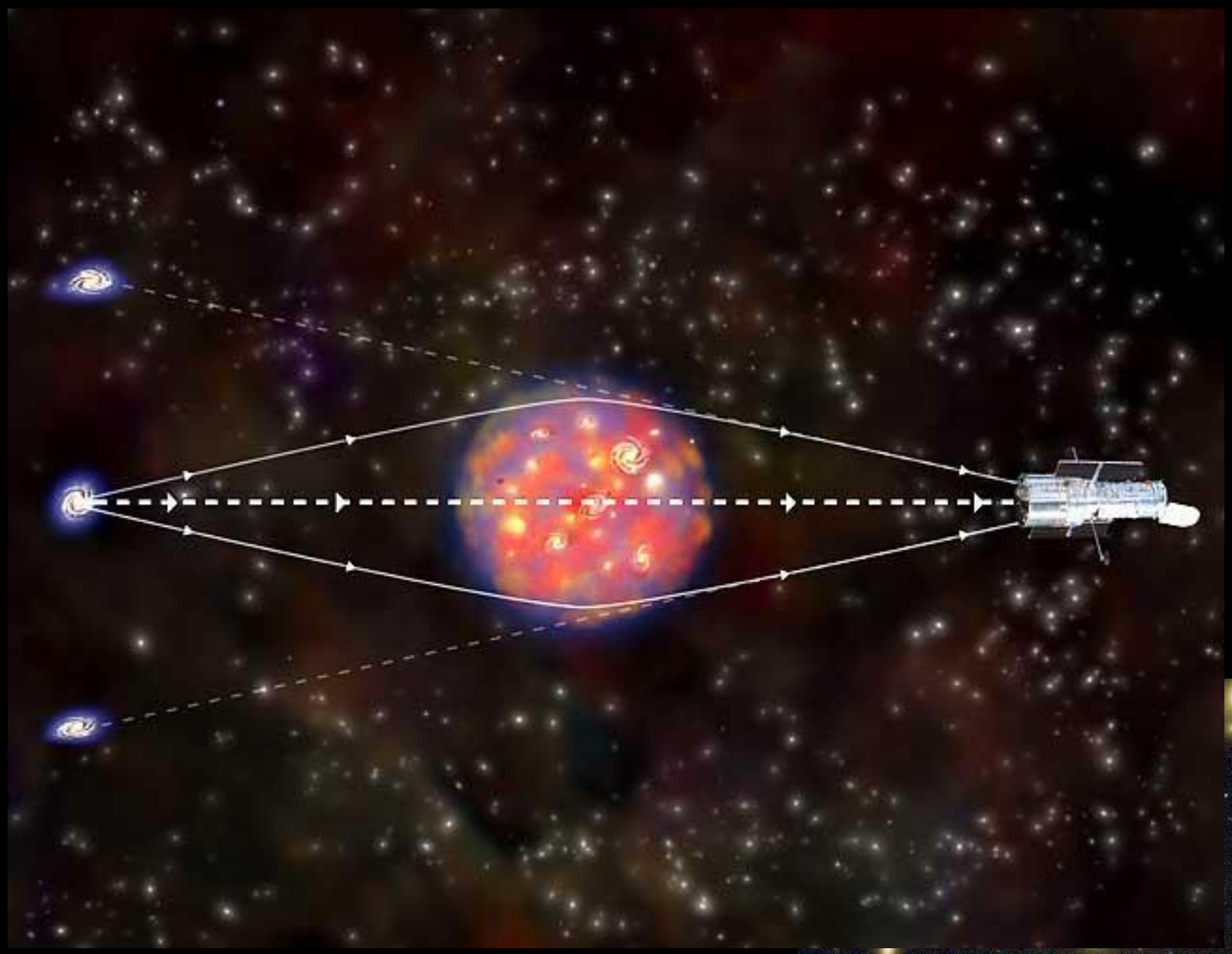
Rotation Curves of Galaxies



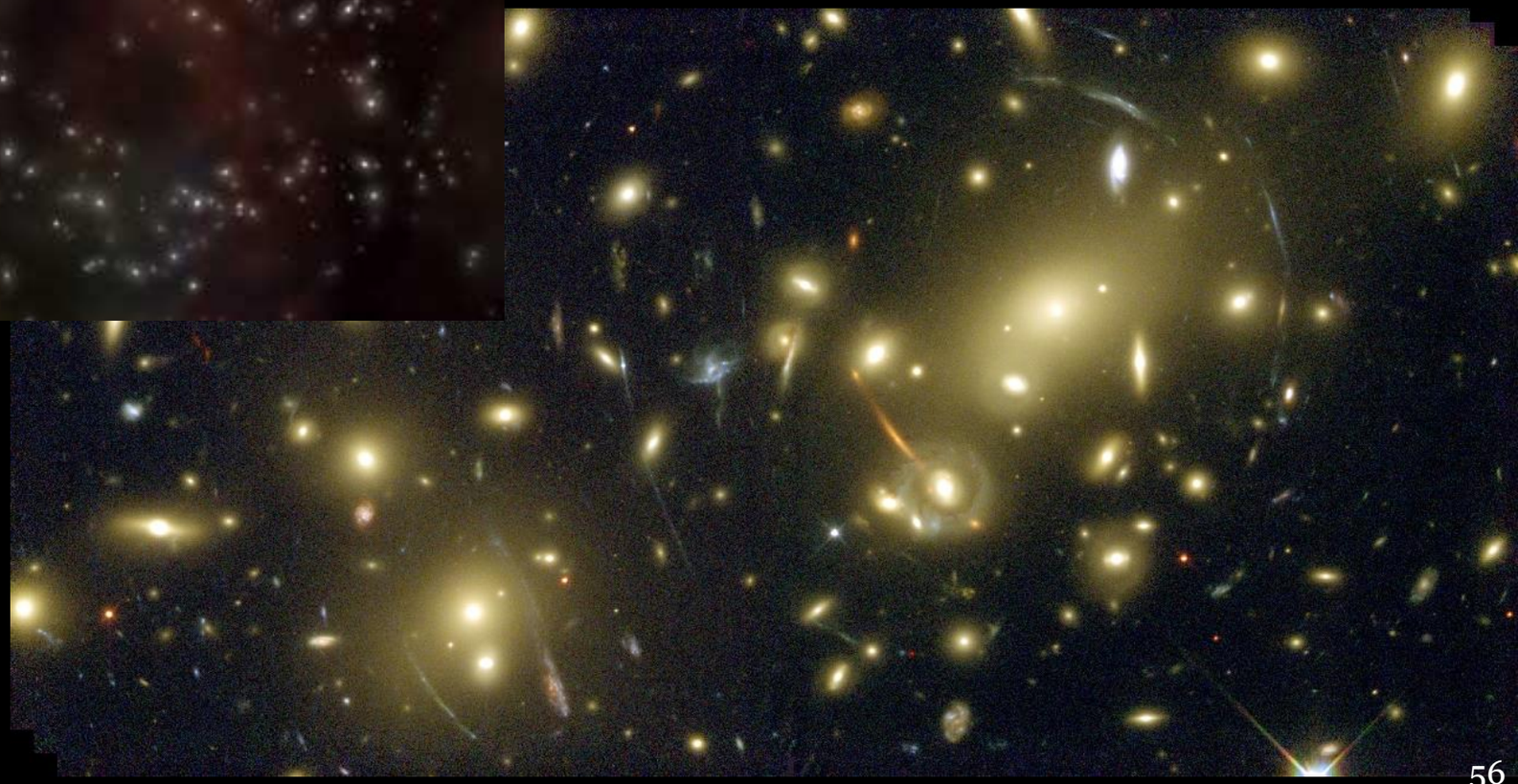
Galaxy Cluster CL0024+17



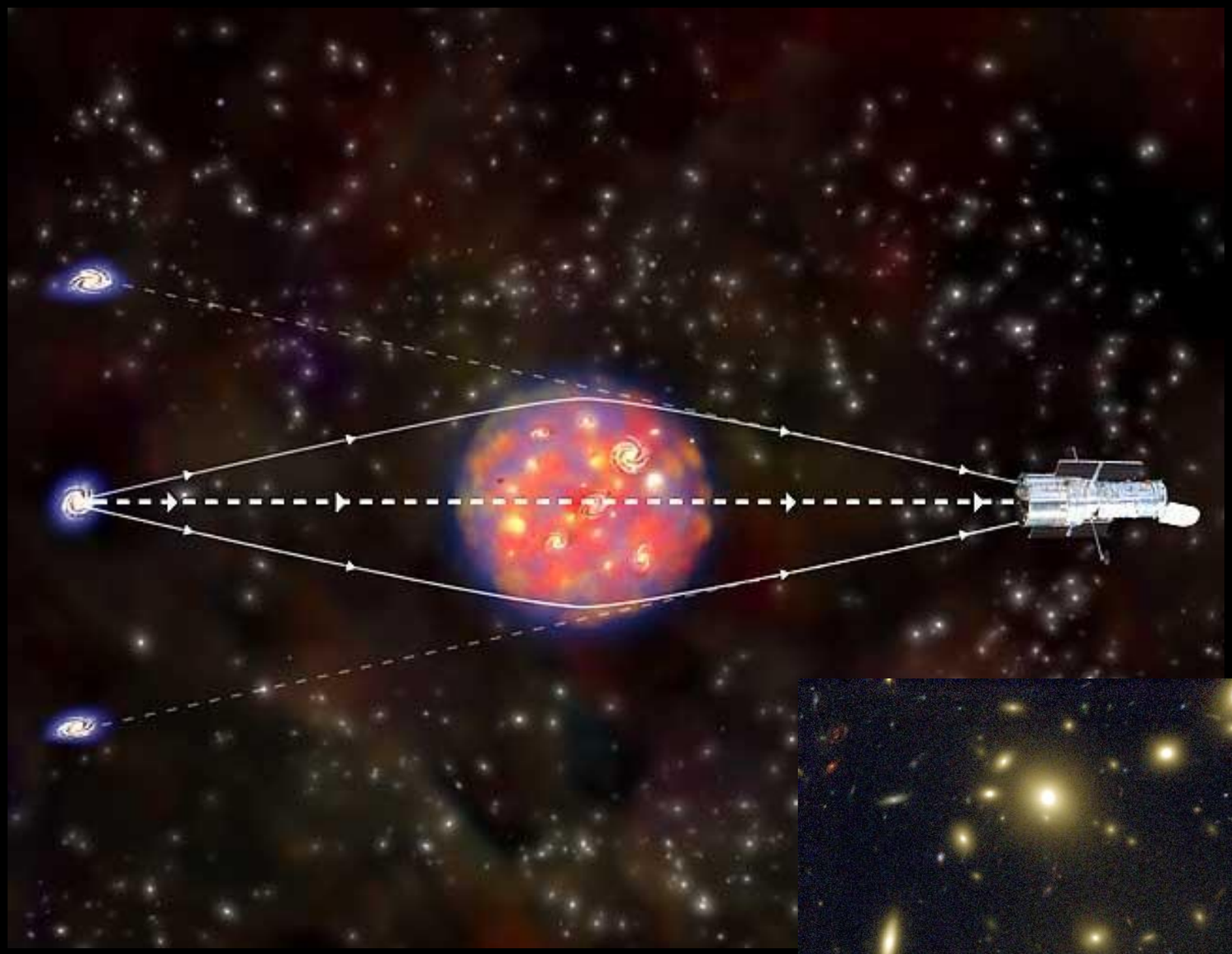
Gravitational Lenses



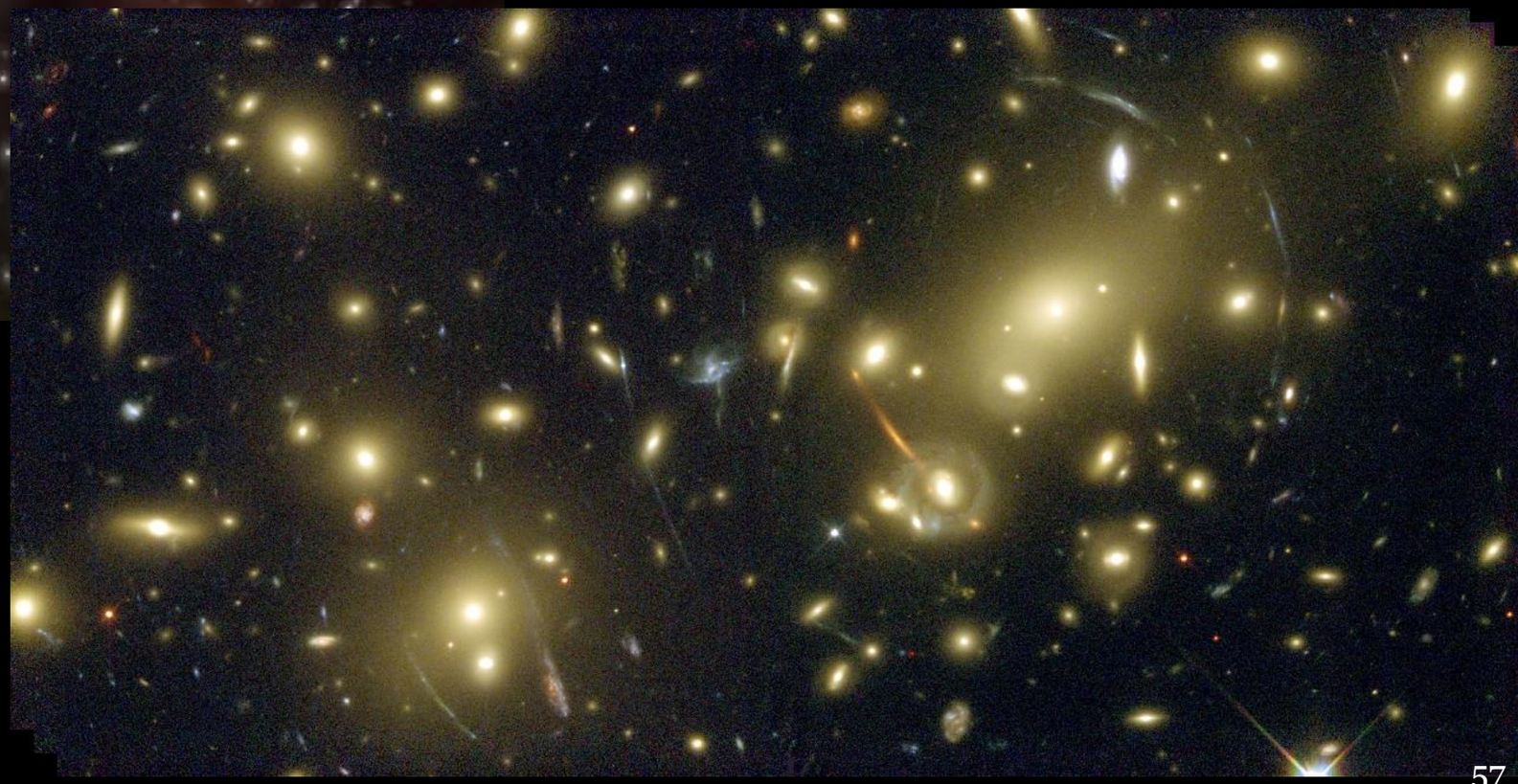
Massive objects curve space-time and therefore distort the light of the objects behind.



Gravitational Lenses

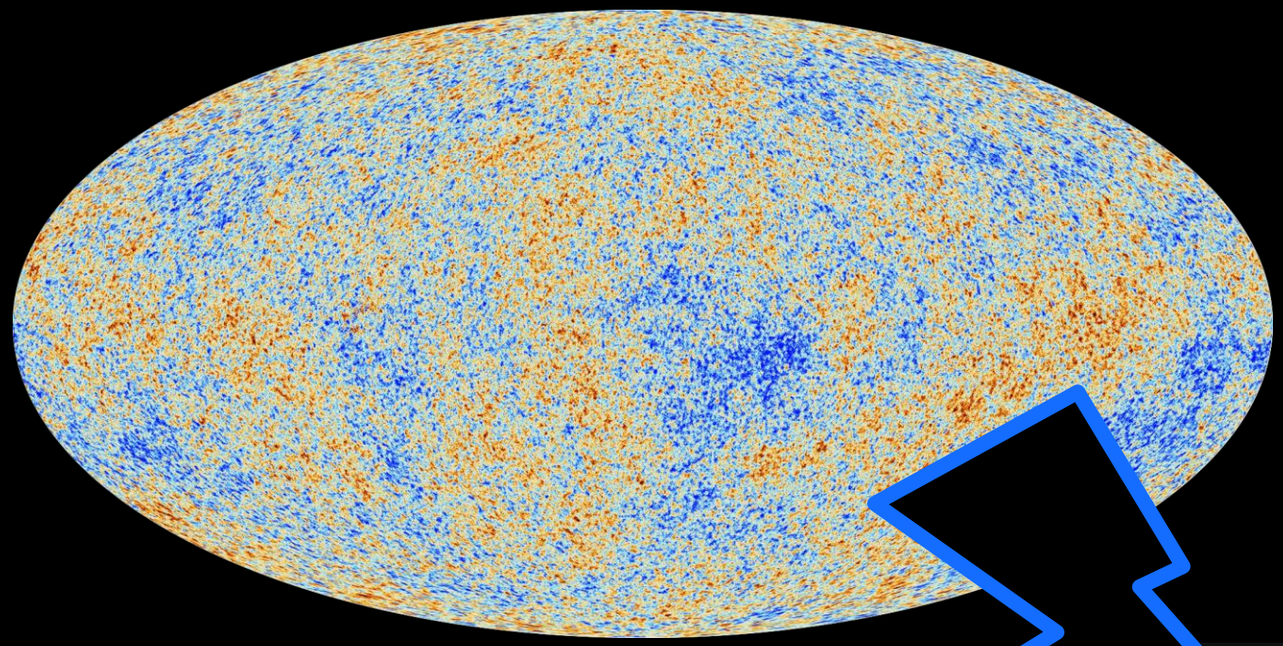


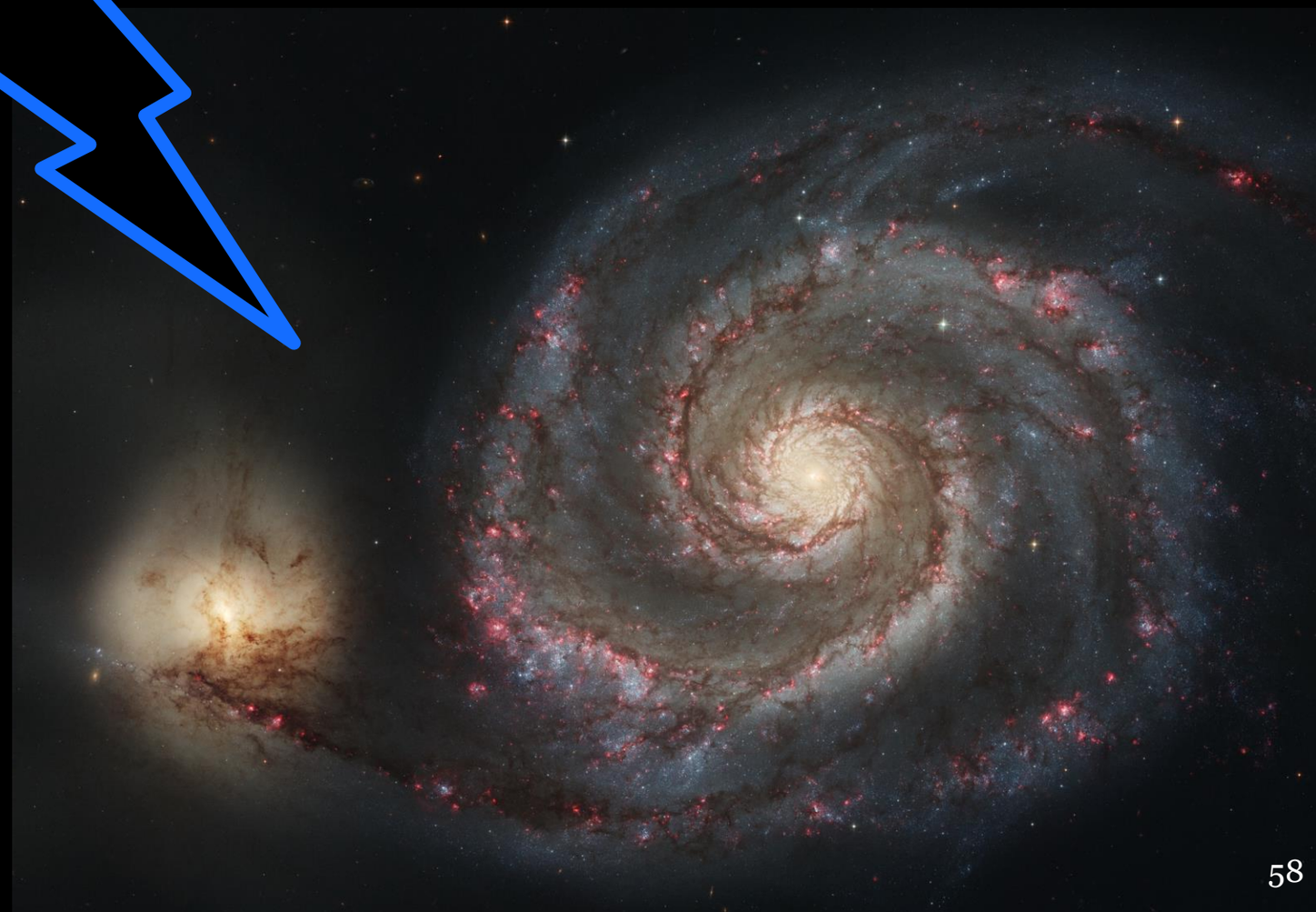
galaxy cluster Abell 2218

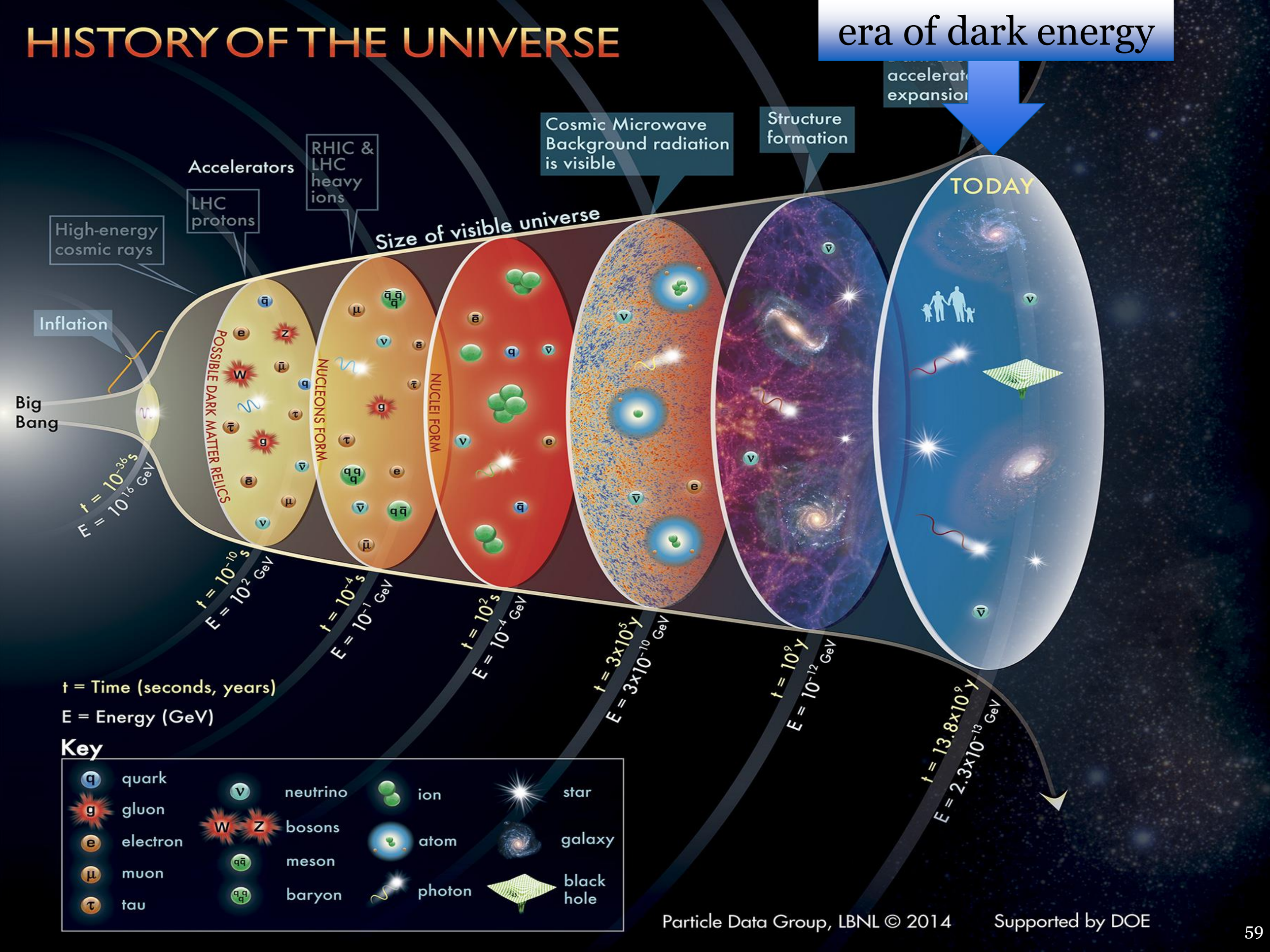


Thereby light arcs of the objects behind are visible.

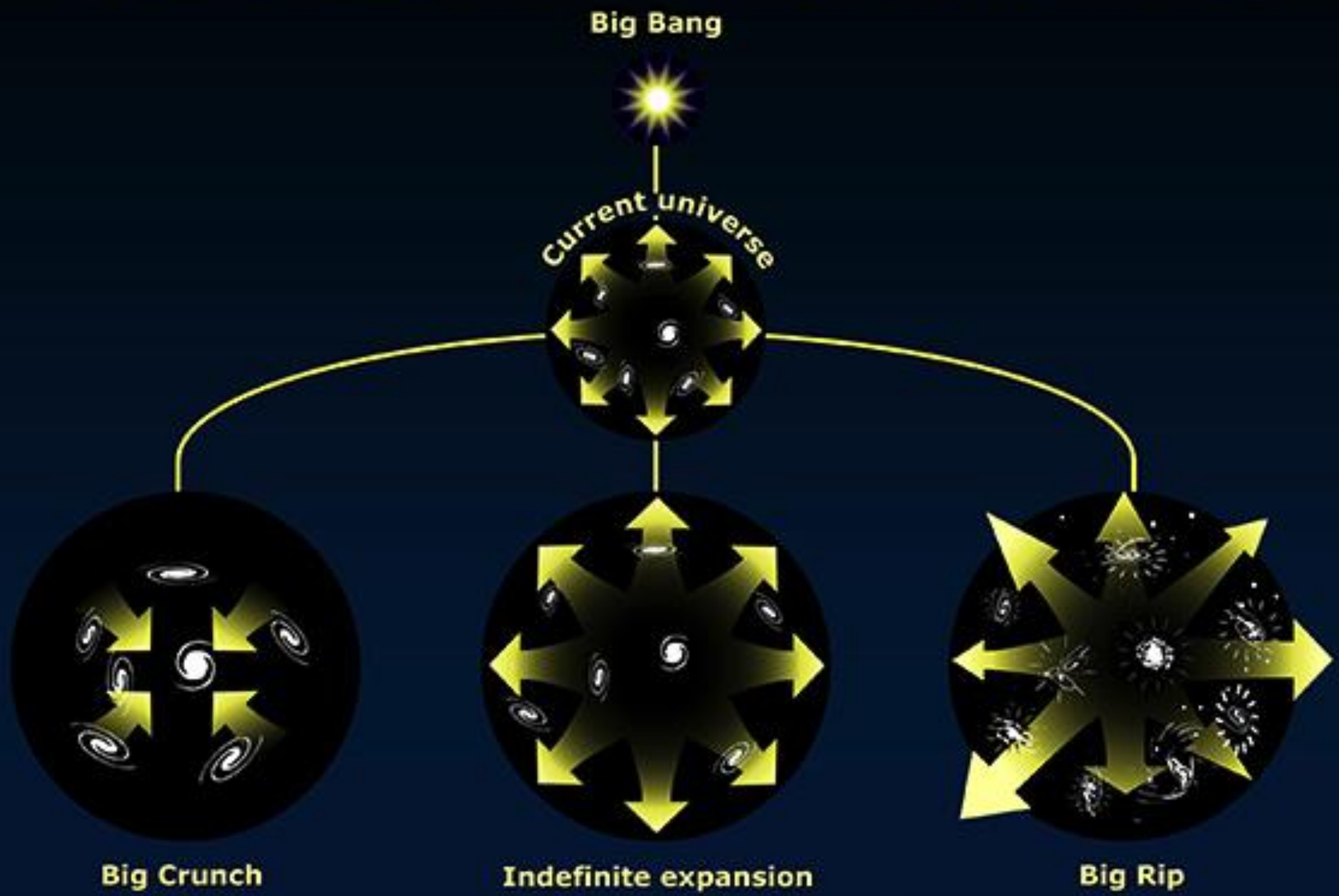
Structure building in the early universe






HISTORY OF THE UNIVERSE
era of dark energy
accelerat
expansion
Cosmic Microwave Background radiation is visible
Structure formation
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 = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-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
Particle Data Group, LBNL © 2014
Supported by DOE

Future fates of the dark-energy universe



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…**

Students' conceptions about Cosmology

About

There are more stars in the Universe than there are grains of sand on earth — and it seems to be equally with students' conceptions.

About this project

Cosmology deals with the origin, development and possible fates of our universe. The insights we have obtained so far have formed the modern scientific worldview. Transferring this to students through science teaching is a frequent request in science literacy discussion.

However, it is not yet clear in science education if students' conceptions about cosmology vary by nationality, and therefore, if it is possible to apply the same teaching modules to students from different countries, who may have diverse social and cultural backgrounds and different curricula.

Information about participation in this project

About the target group:
Our target group are high school students in the age range of about 15-20 years. They shouldn't have had any instruction in cosmology yet. We would like to include students who have currently physics lessons as well as students who do not. Therefore, you are welcome to ask also your colleagues from your own or other schools to take part.

About the questionnaire:
It consists of 20 questions about cosmology and 10 questions about the

cosmology.web.cern.ch

Students' conceptions about cosmology – The questionnaire

Start | Cosmology part 1 | Cosmology part 2 | Structure of matter | Complete

Personal Details

Age:

How many years have you been in school (not including kindergarten)?

Sex: ◯ Male ◯ Female

Country:

- None -

Do you have physics lessons at present? ◯ Yes ◯ No

Physics grade in latest school report: ◯ A ◯ B ◯ C ◯ D ◯ E

Already had astronomy lessons: ◯ Yes ◯ No

Already had cosmology lessons: ◯ Yes ◯ No

Country of birth:

- None -

Have you ever seen / heard / read anything about cosmology? If yes, where?

- ☐ Television
- ☐ Internet
- ☐ Books
- ☐ Magazines
- ☐ Newspaper
- ☐ Parents / friends / acquaintances
- ☐ Others:

Many thanks for your attention!

Are there any questions?