Cosmology

A short introduction

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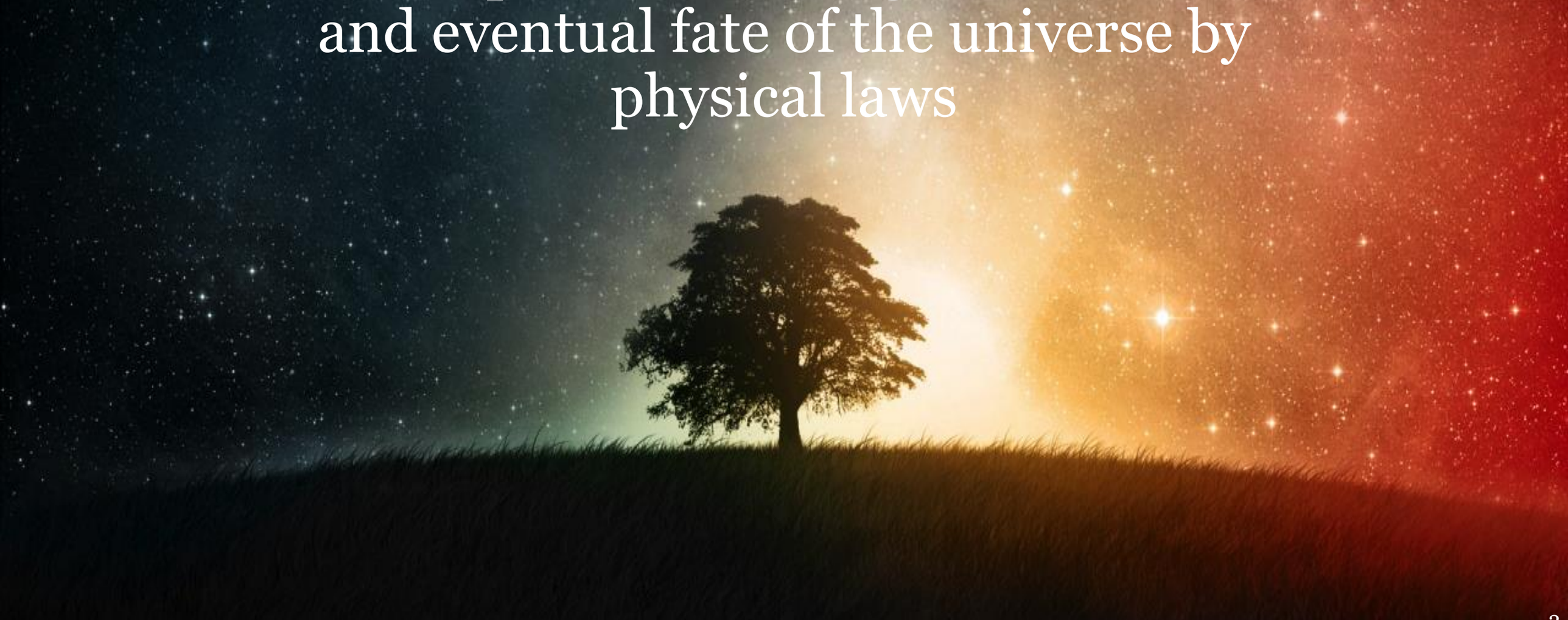
CERN

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

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Outline

Dimensions of our universe

Dynamics of the universe

A journey through time

Mysteries of the universe

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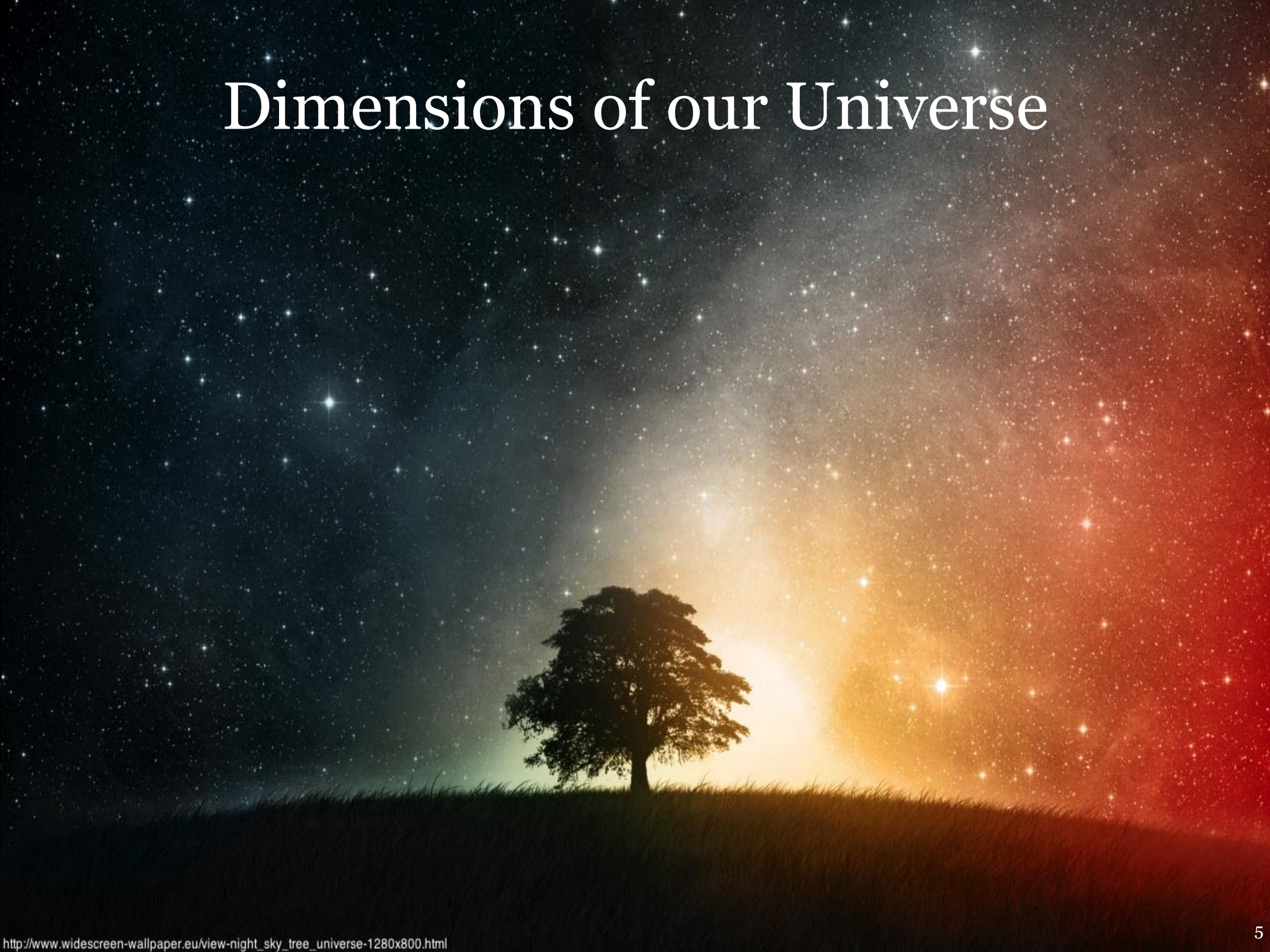
Dimensions of our Universe



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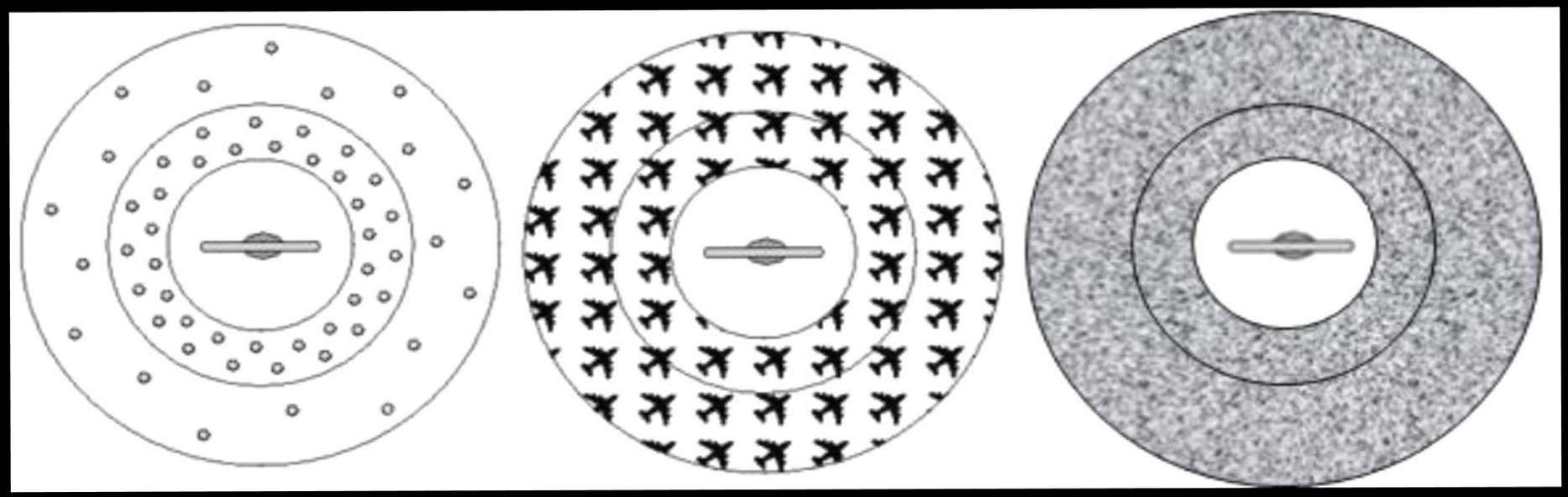
The Cosmological Principle

"On large scales the Universe is homogeneous and isotropic"

We don't find ourselves in a special place.



Credit: http://www.astronomynotes.com

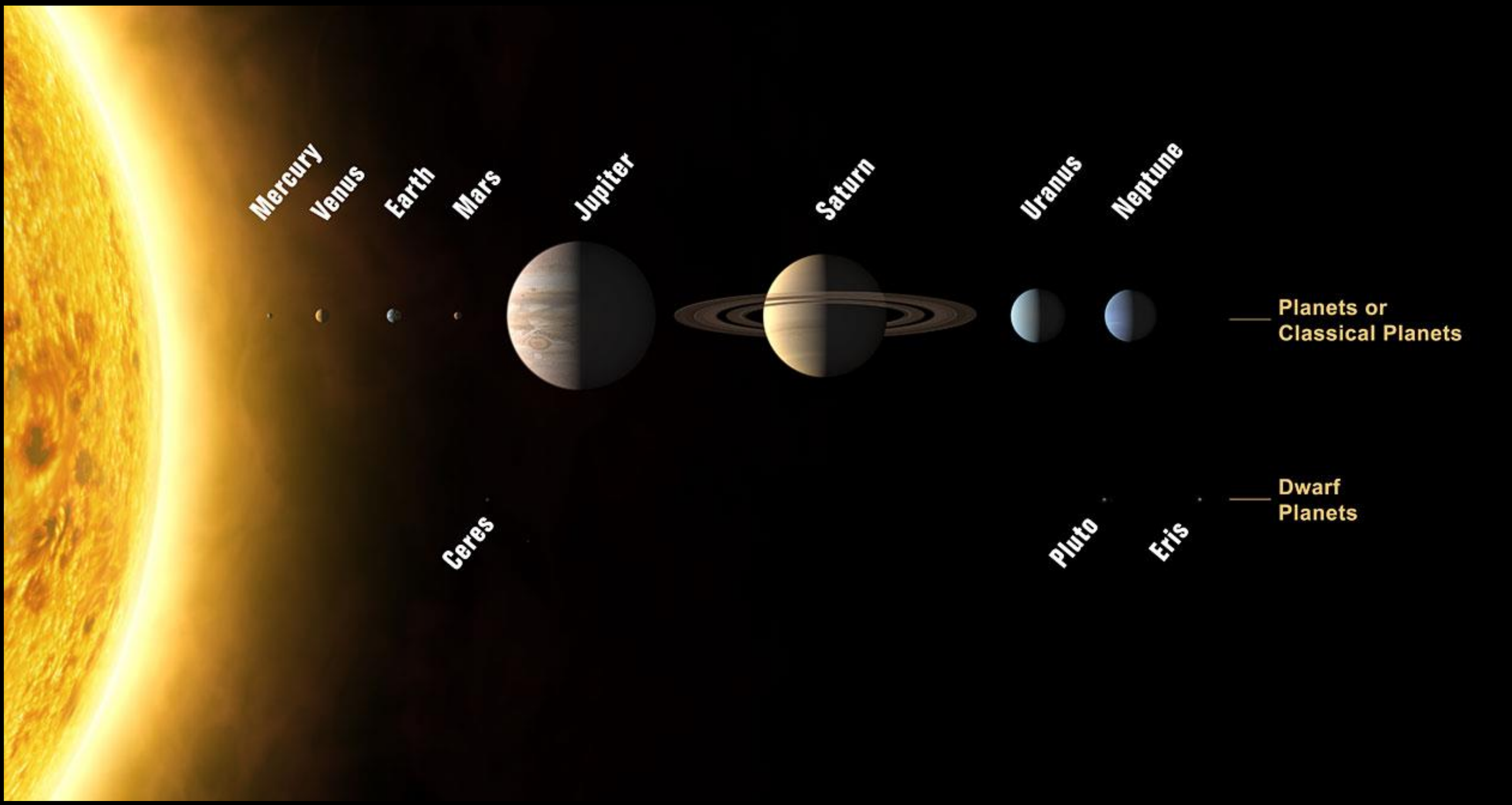
isotropic, but not homogeneous

homogeneous, but not isotropic

homogeneous and isotropic

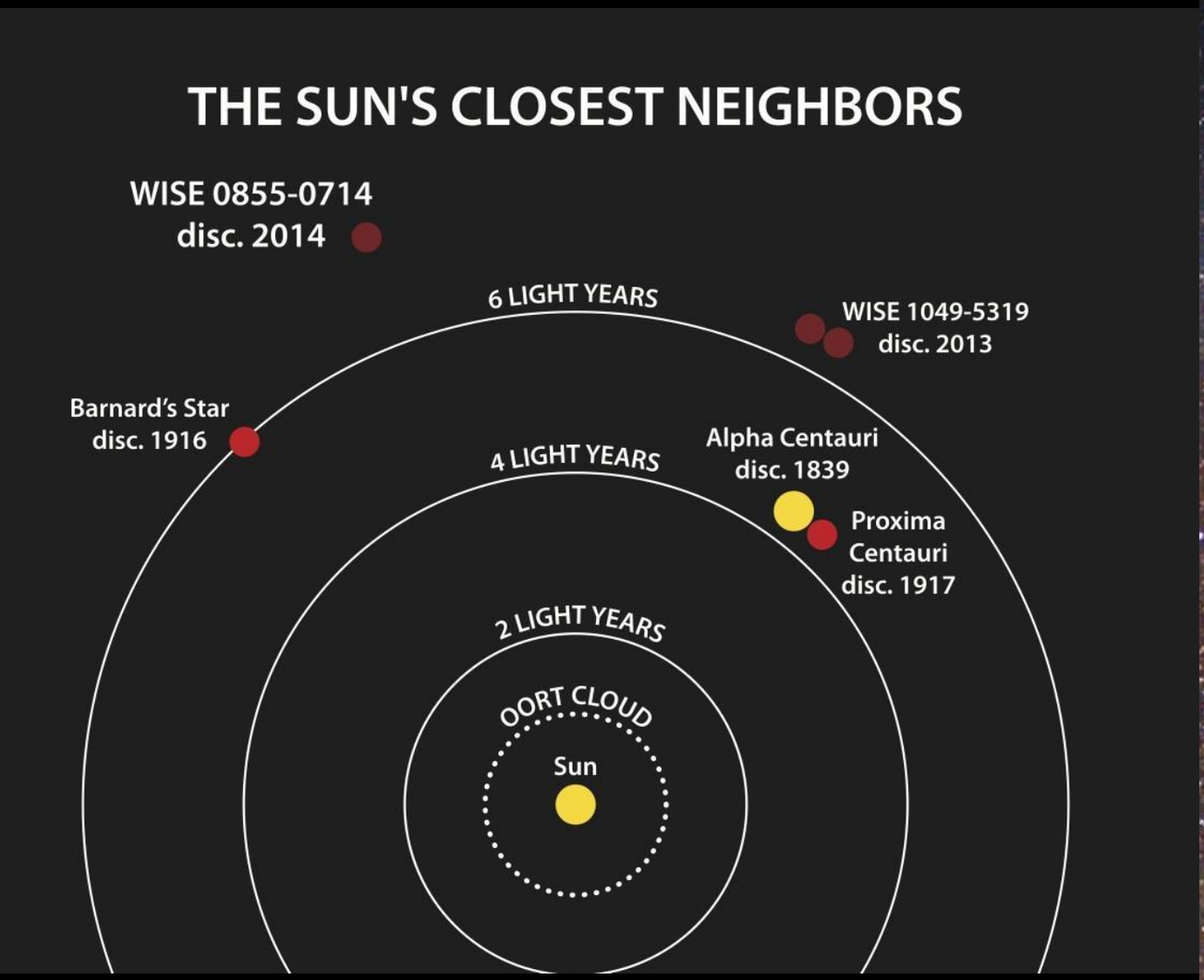
The Earth: ≈13000 km in diameter

The Solar System:
≈10 billion km in diameter



Credit: The International Astronomical Union/Martin Kornmesser

Proxima Centauri:
40×10^{12} km = 4,24 light years distance



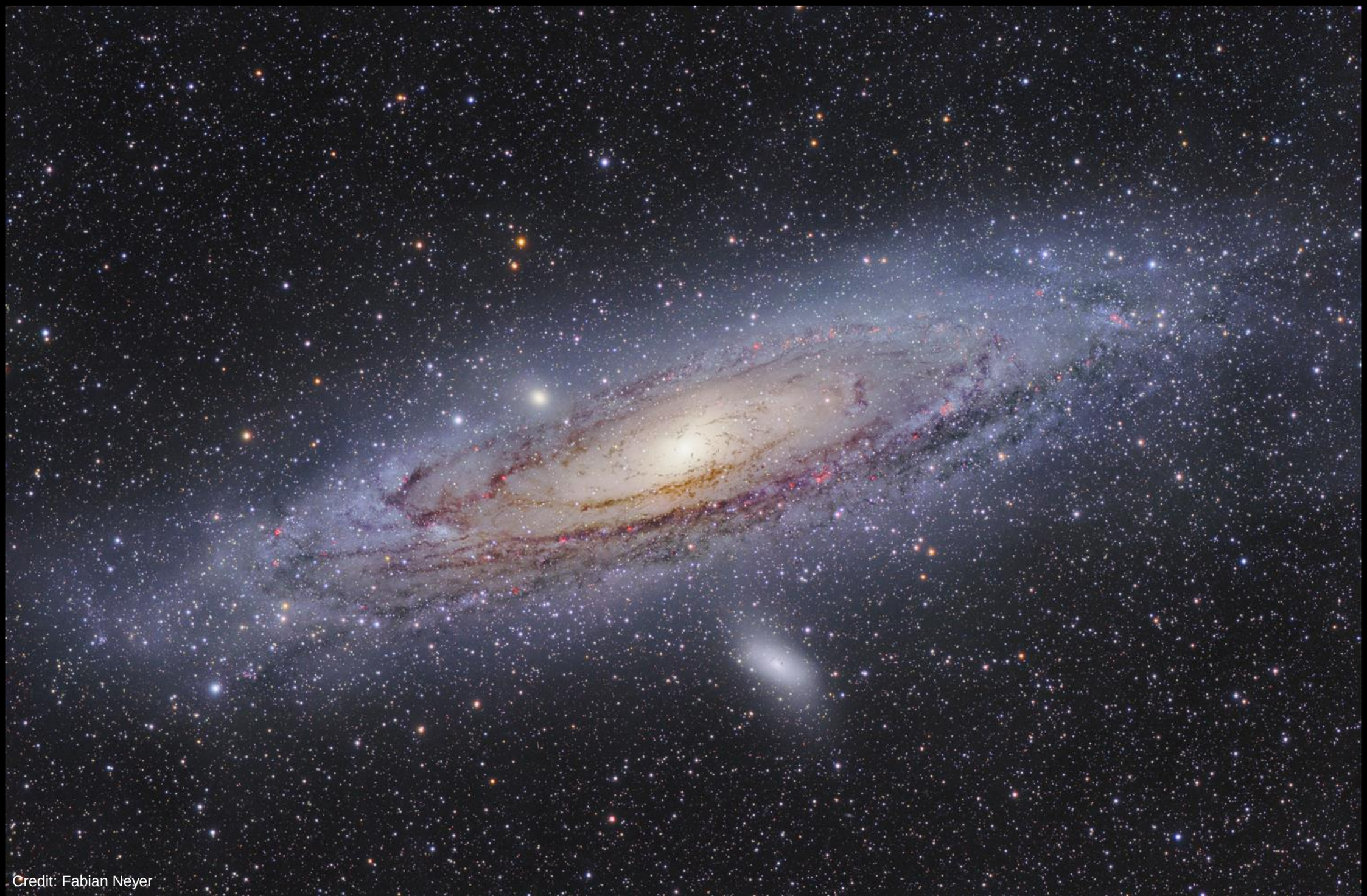
Credit: NASA/Penn State University

Credit: Wikimedia Commons user Skatebiker

Our Milky Way:
9.5×10^{17} km = 100000 light years in diameter

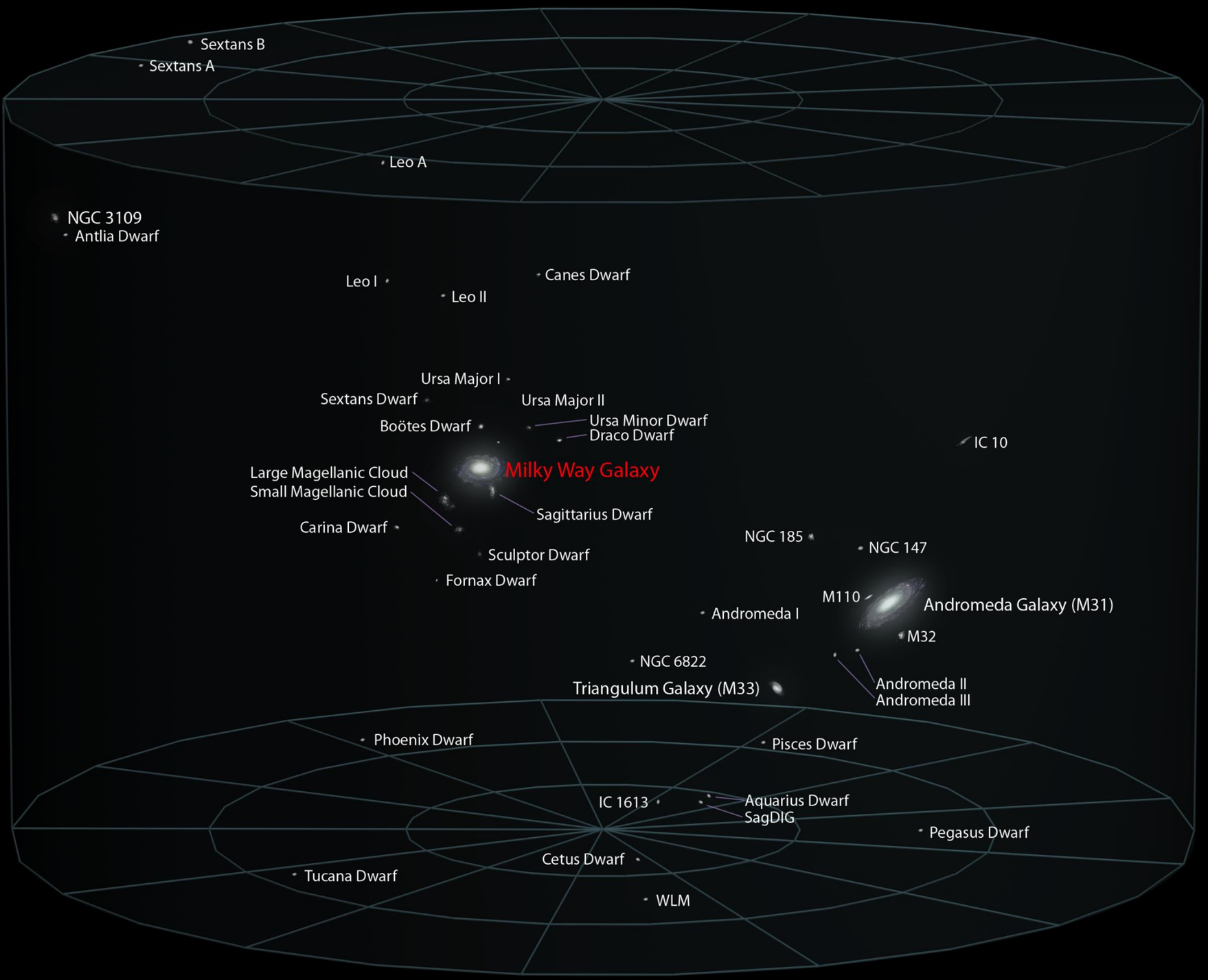
Credit: Alan Dyer/Stocktrek Imagesr

Andromeda Galaxy:
2.5 million light years distance



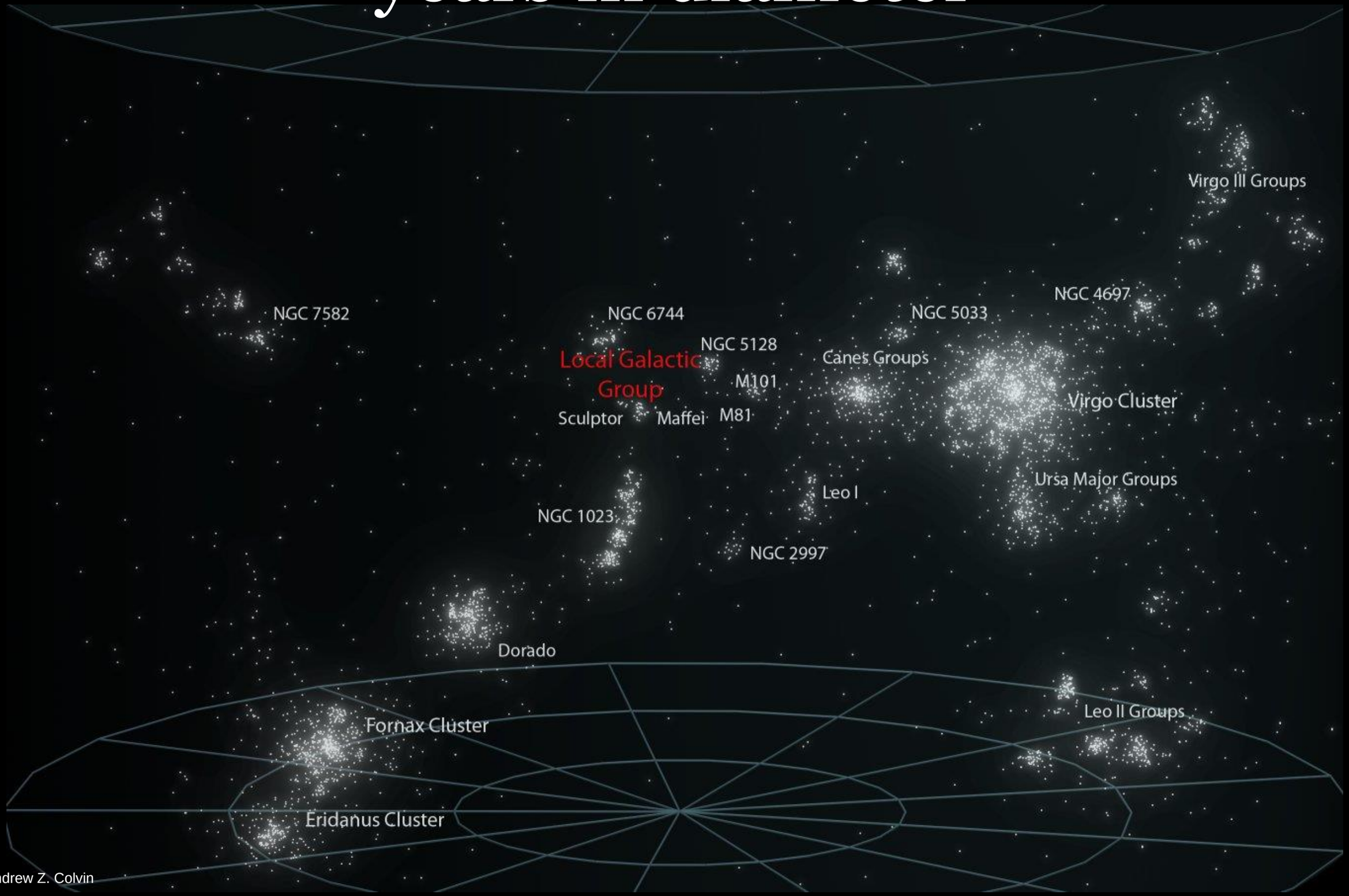
Credit: Fabian Neyer

Local Group:
8 million light years in diameter



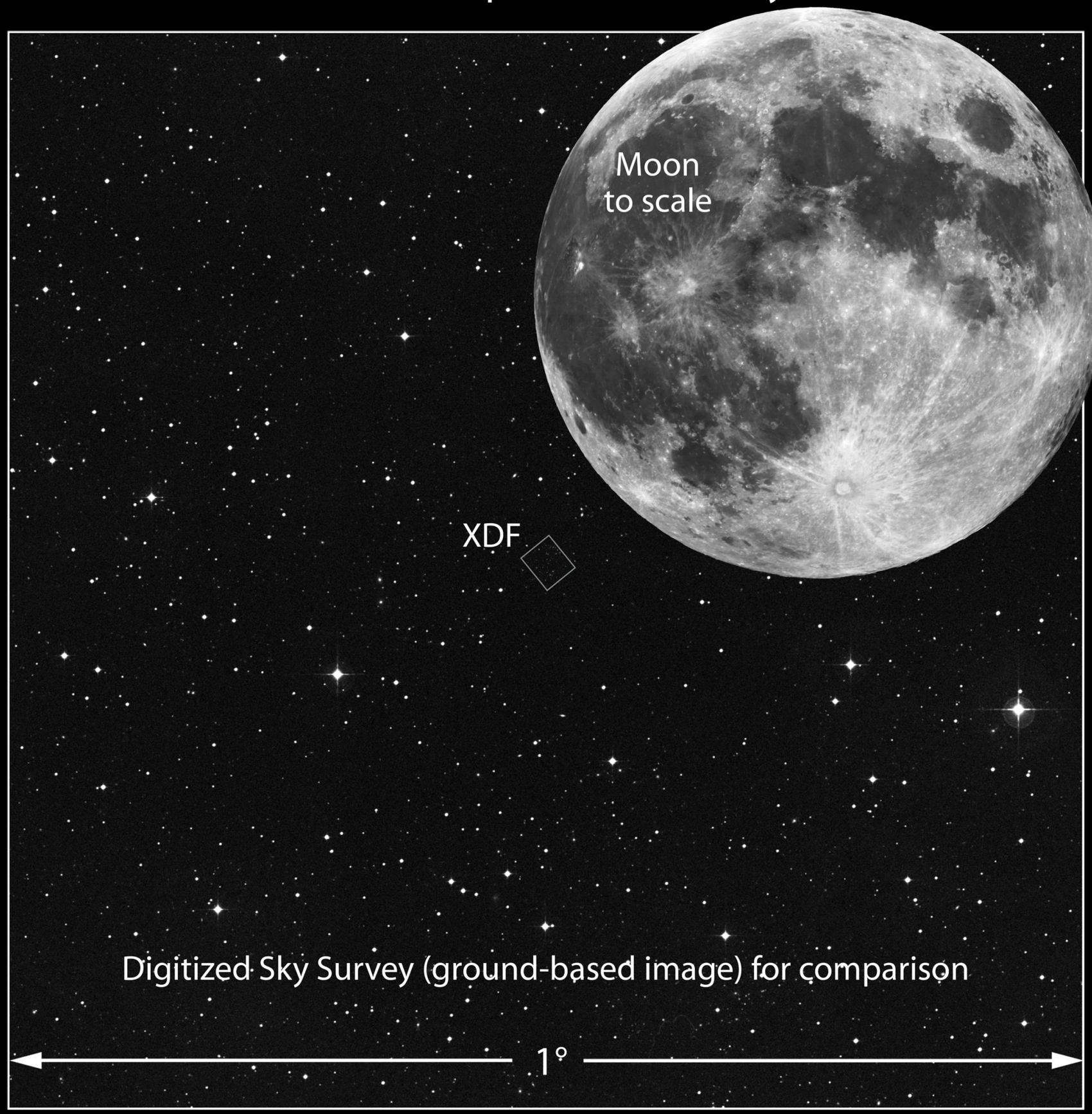
Credit: Andrew Z. Colvin

Virgo Supercluster: ≈130 million light years in diameter



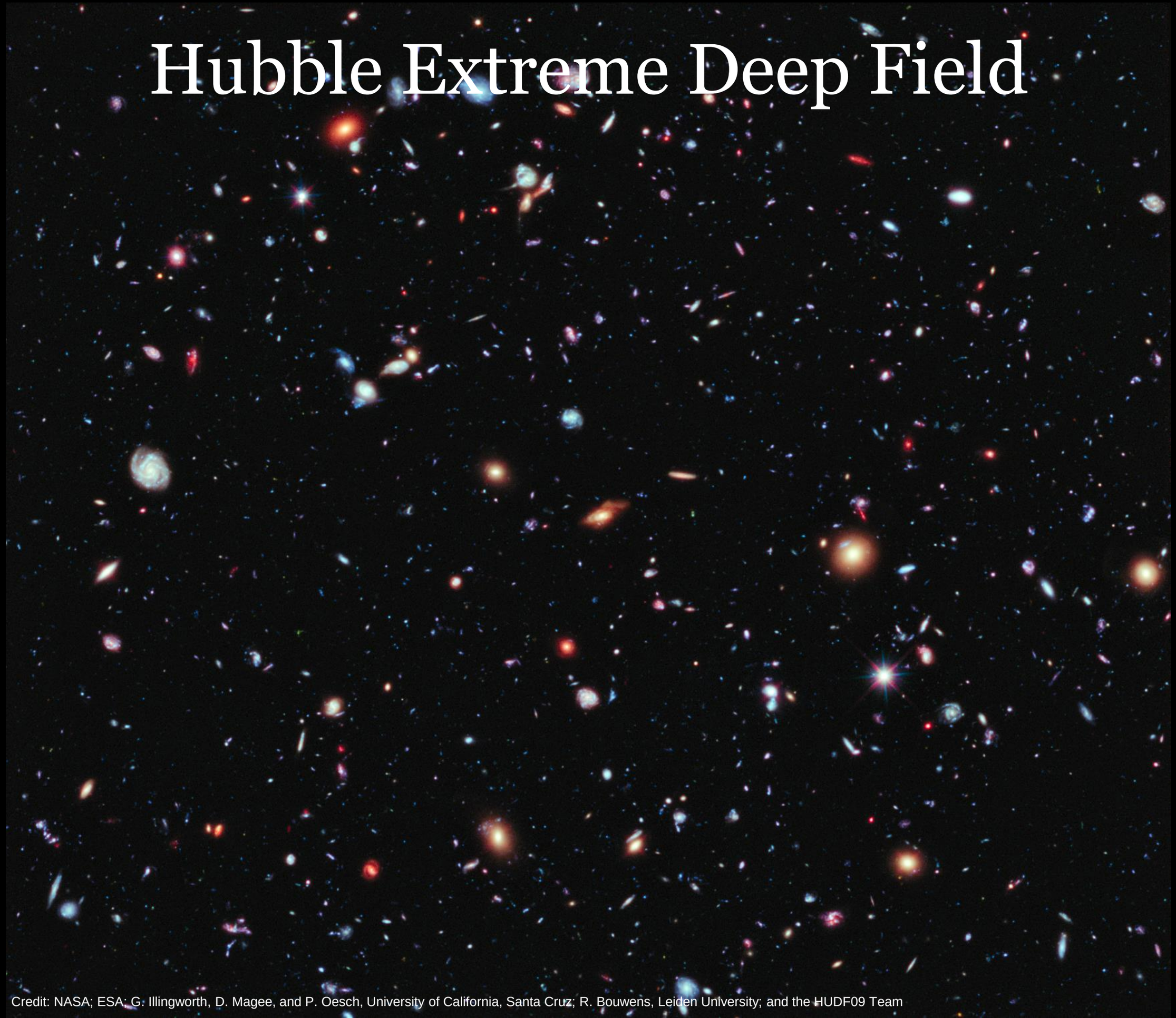
Credit: Andrew Z. Colvin

Size of Hubble eXtreme Deep Field on the Sky



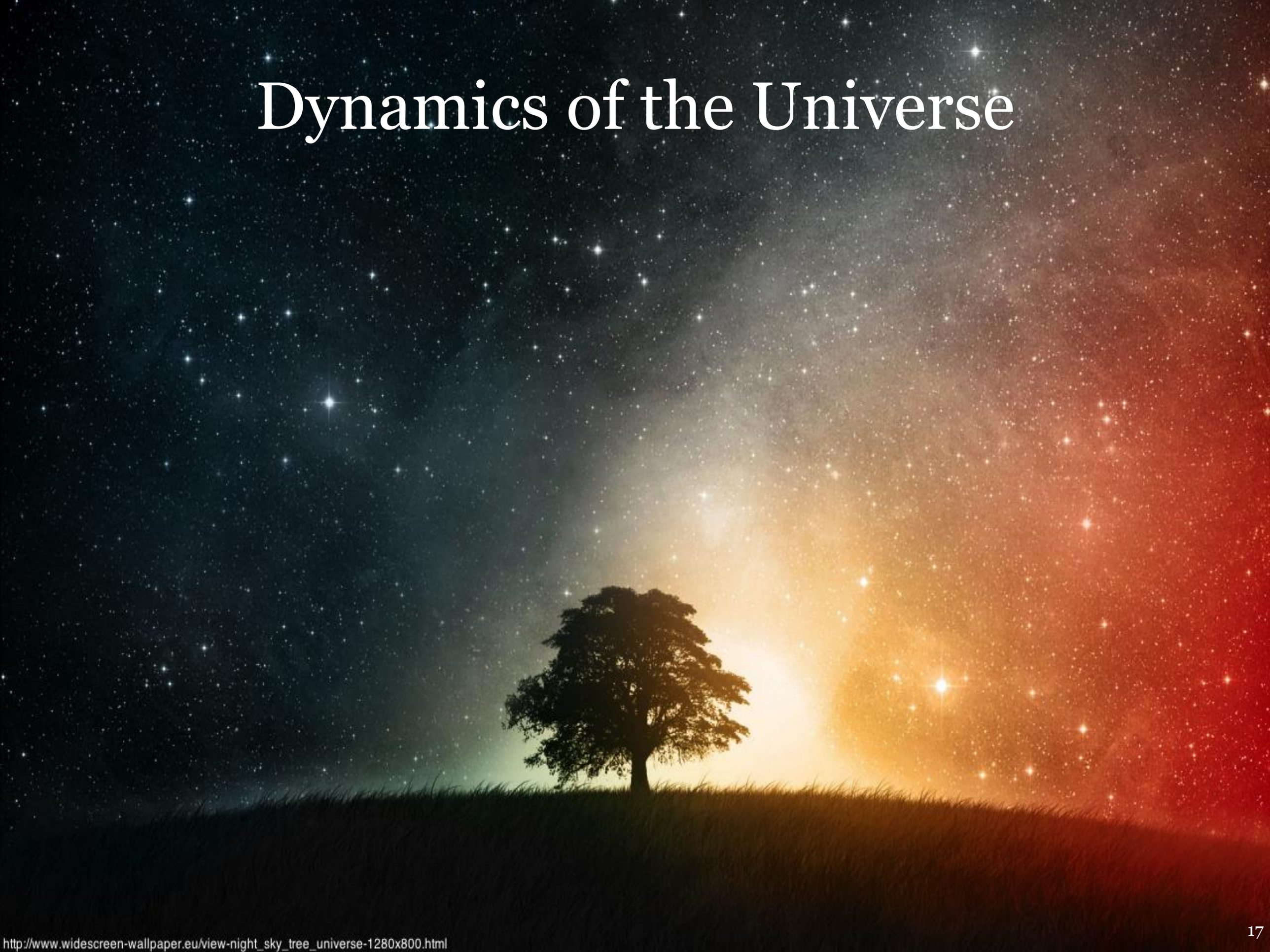
Credit: Illustration: NASA, ESA, and Z. Levay (STScI); Image: T. Rector, I. Dell'Antonio/NOAO/AURA/NSF, Digitized Sky Survey (DSS), STScI/AURA , Palomar/Caltech, and UKSTU/AAO

Hubble Extreme Deep Field



Credit: NASA; ESA; G. Illingworth, D. Magee, and P. Oesch, University of California, Santa Cruz; R. Bouwens, Leiden University; and the HUDF09 Team

Dynamics of the Universe



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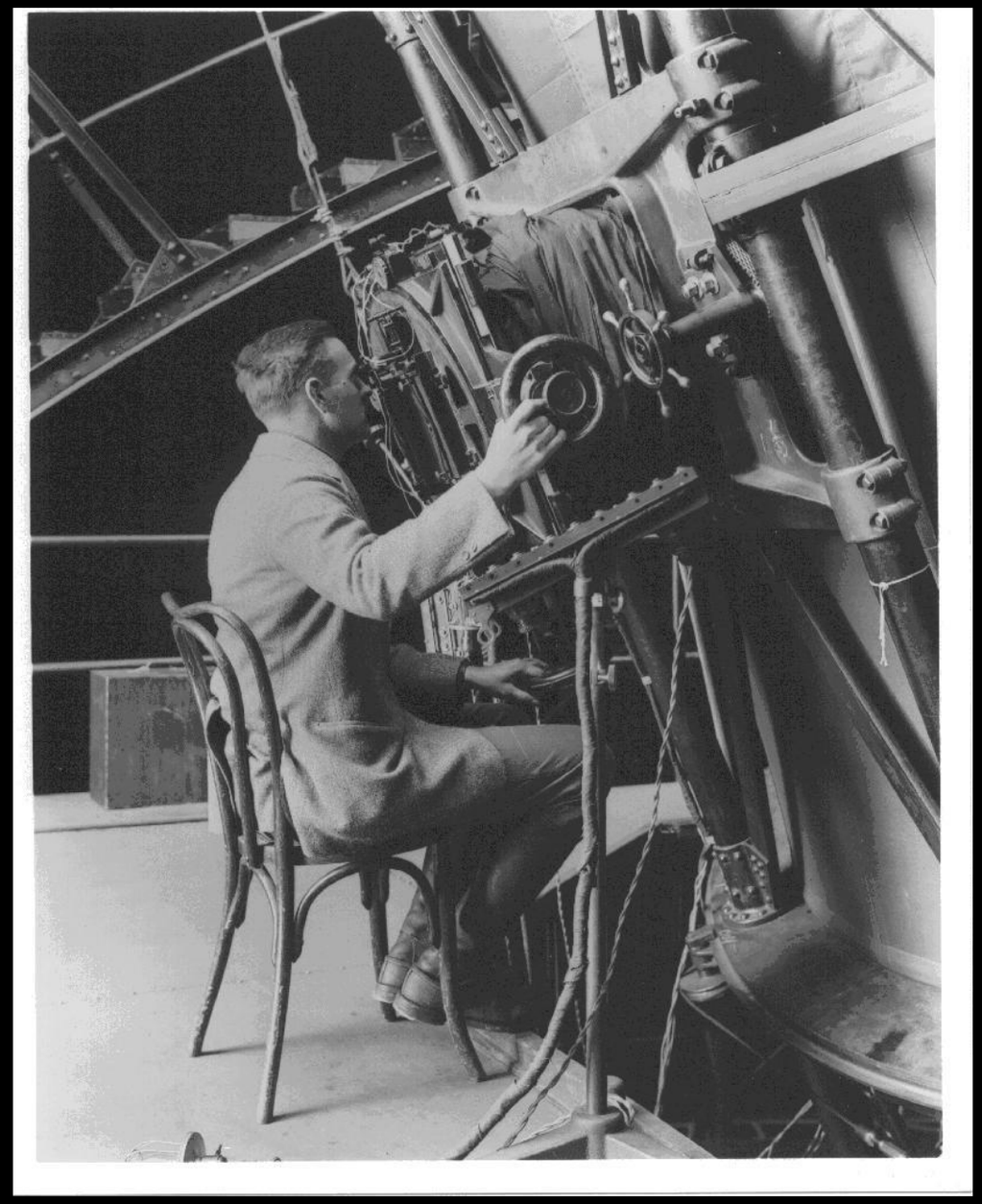
The Universe is bigger than we thought!

Credit: Bettmann / Contributor

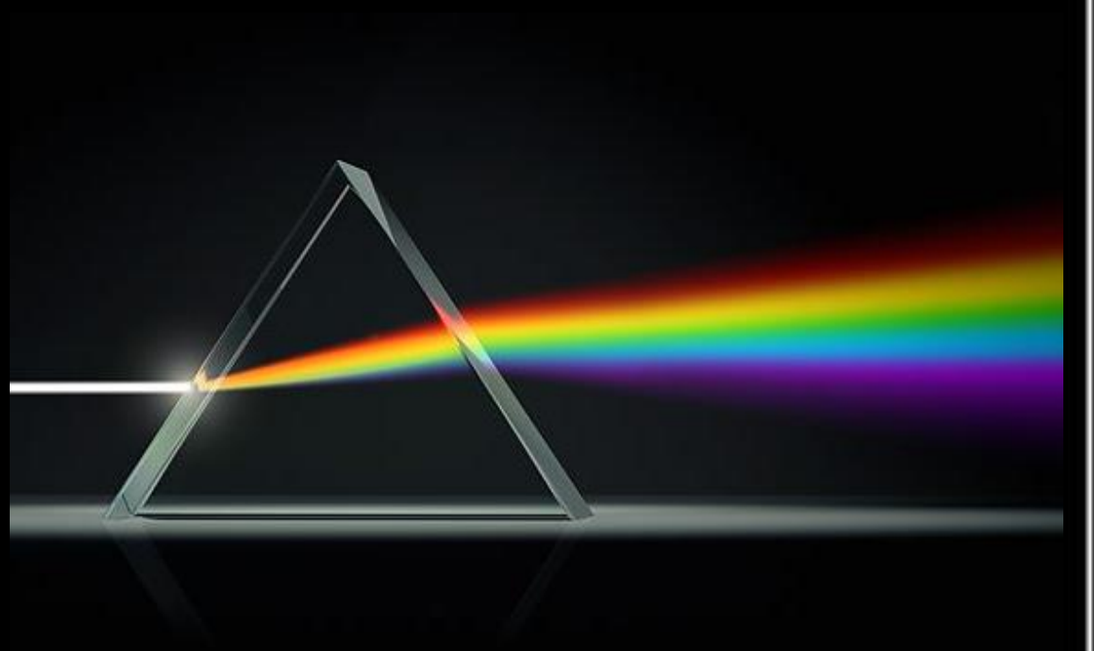
Edwin Hubble (1924)
Mt. Palomar telescope

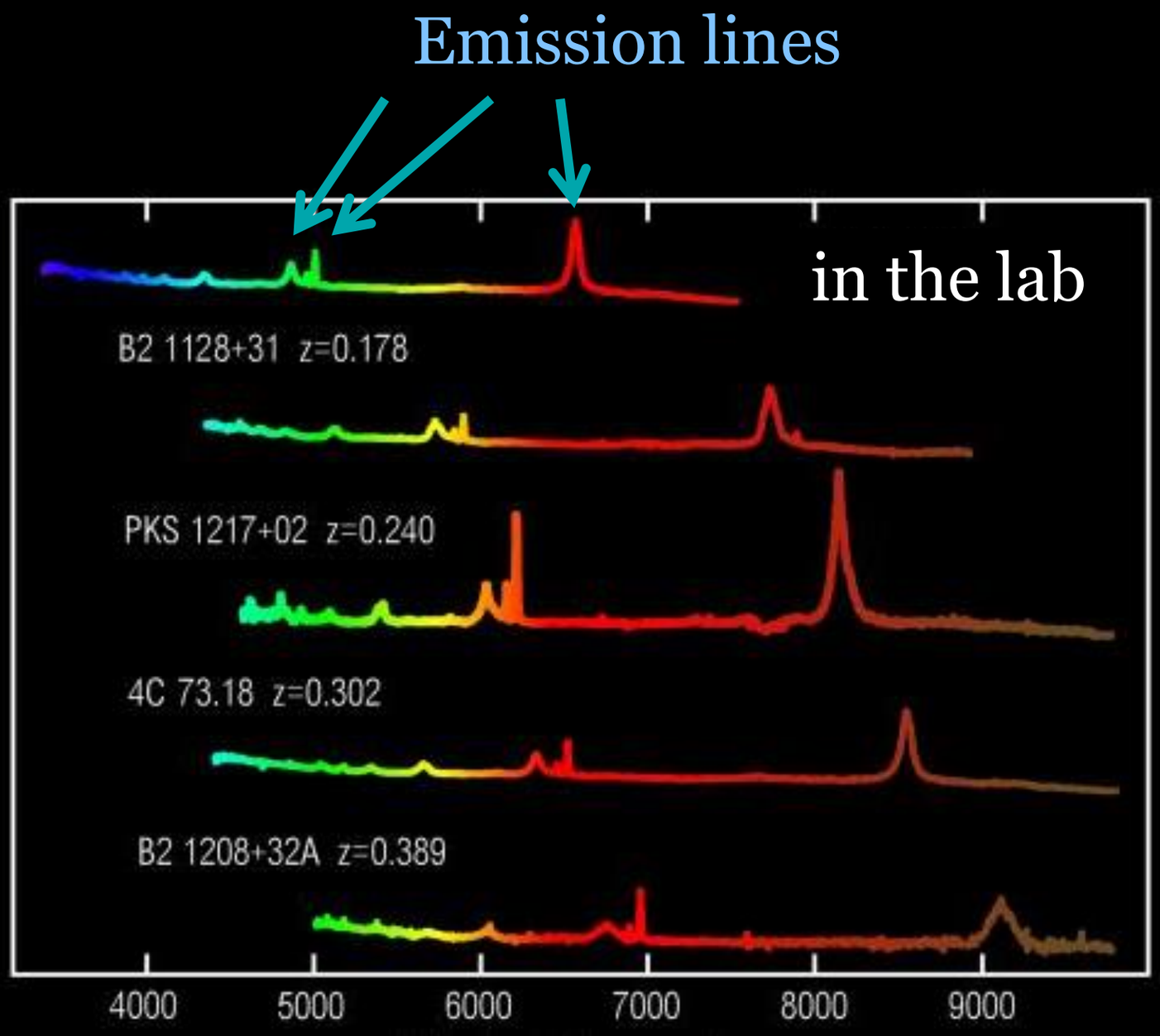


Observation of „nebulas“
Proof of the existence of galaxies outside the Milky Way

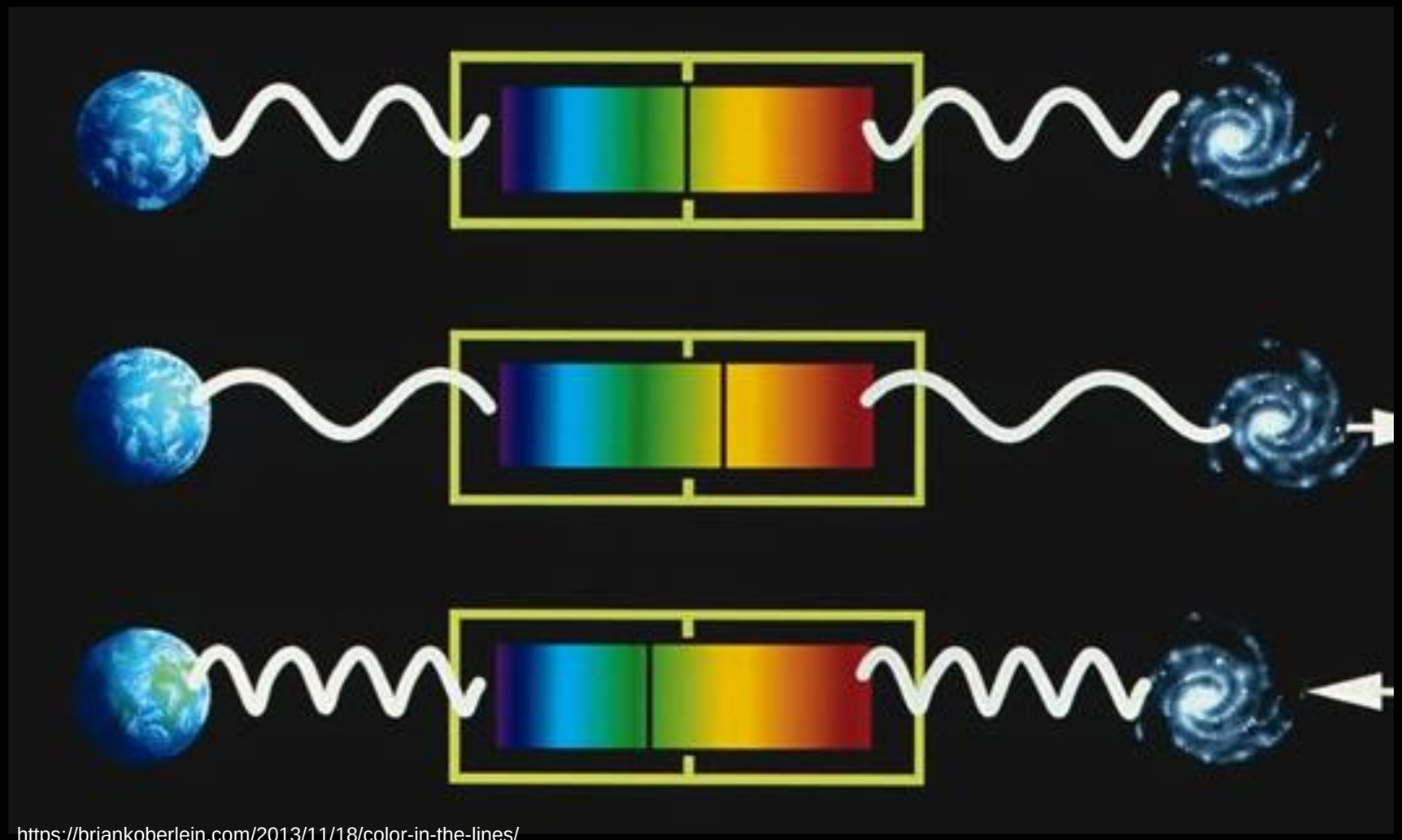
Measuring the Redshift

Spectroscopy





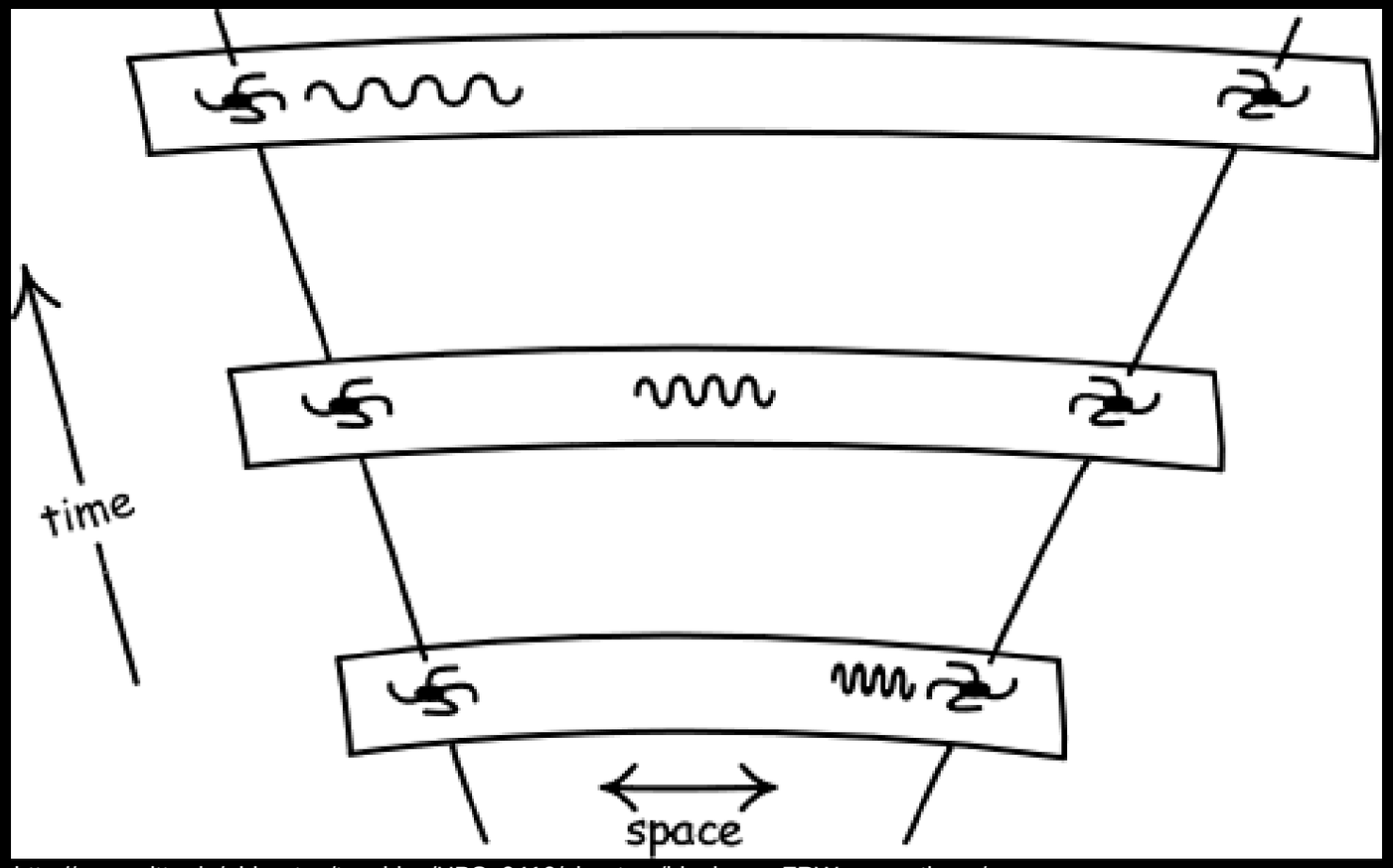
Cosmological Redshift vs. Doppler Effect



https://briankoberlein.com/2013/11/18/color-in-the-lines/

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

Cosmological Redshift

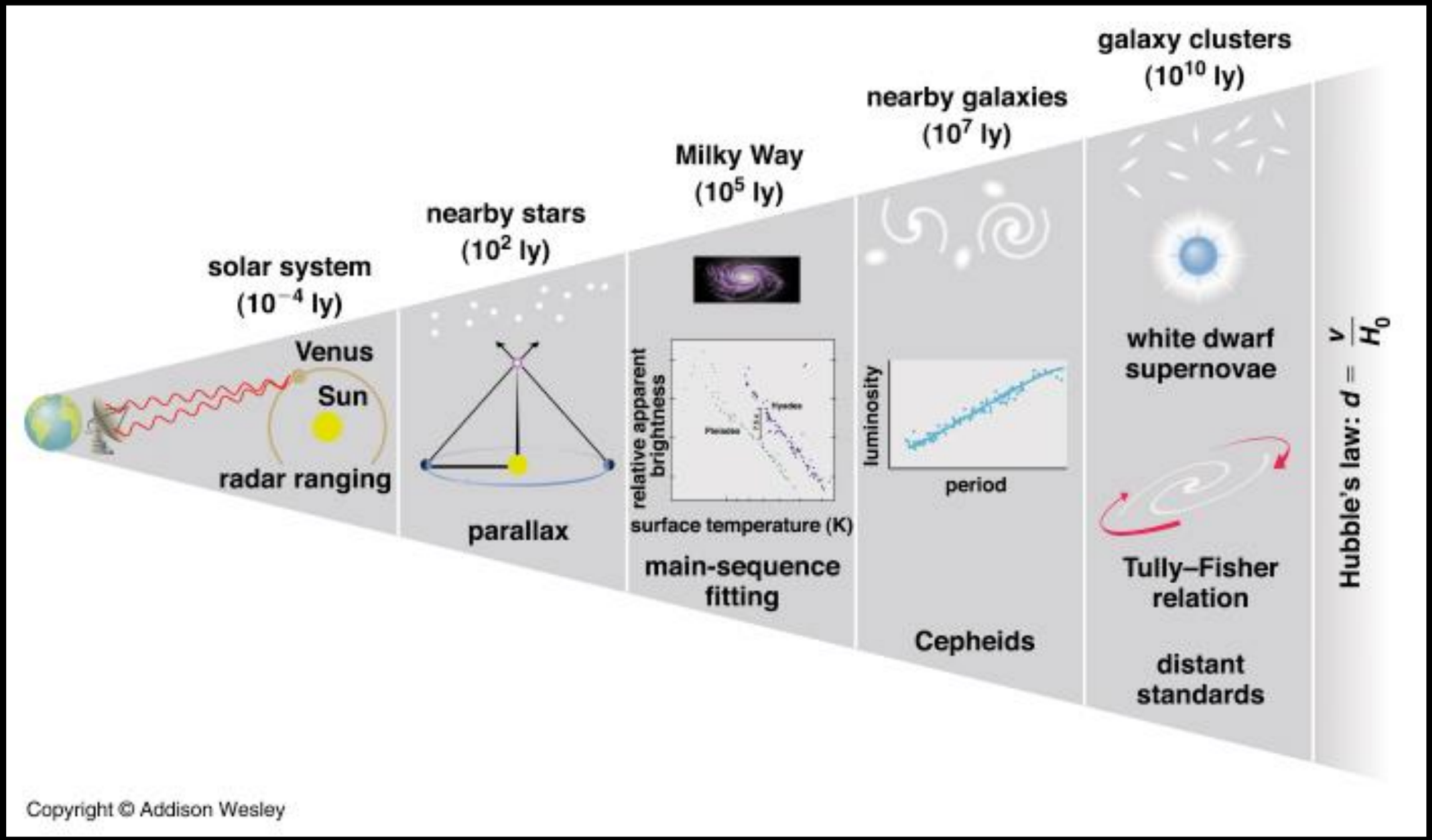


http://www.pitt.edu/~jdnorton/teaching/HPS_0410/chapters/big_bang_FRW_spacetimes/

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

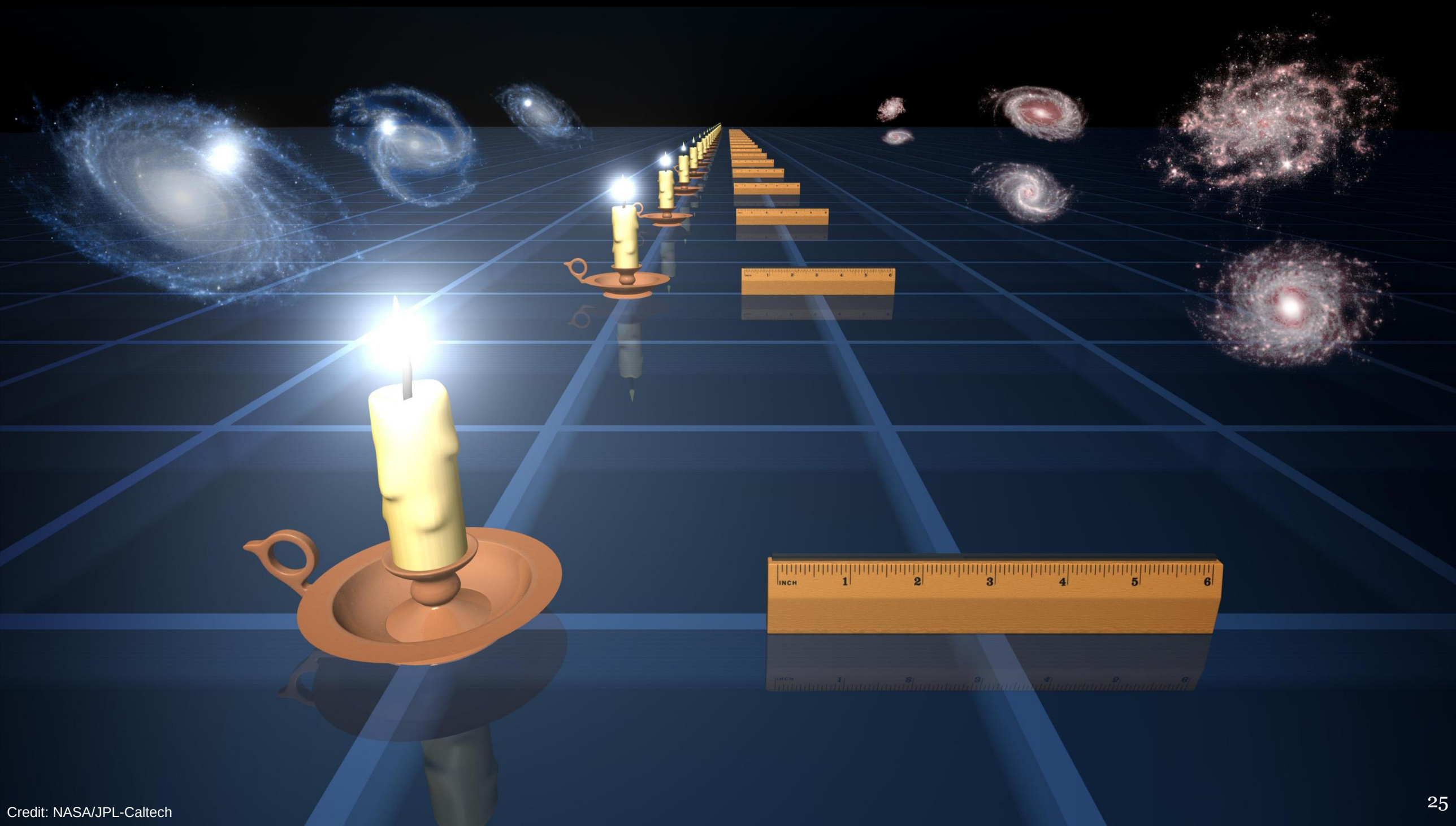
Cosmological Redshift

Distance Ladder



Type Ia Supernova

Standard Candles and Brightness



Credit: NASA/JPL-Caltech

Example of a Supernova from 1994

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

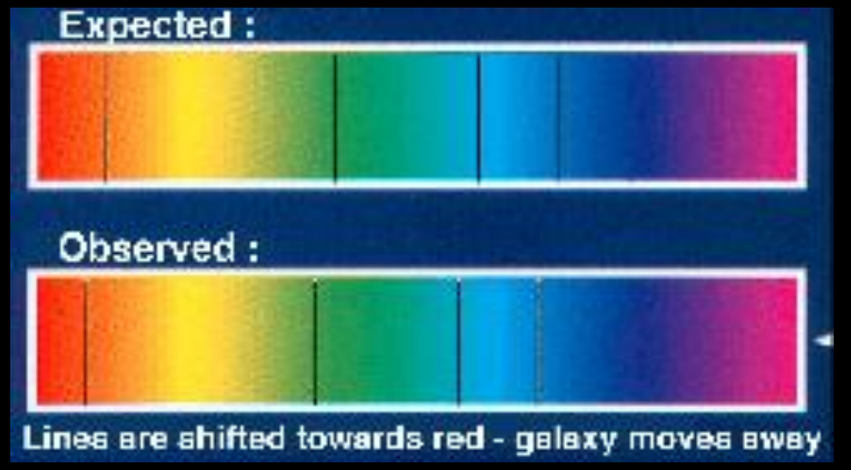
The Universe is expanding

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



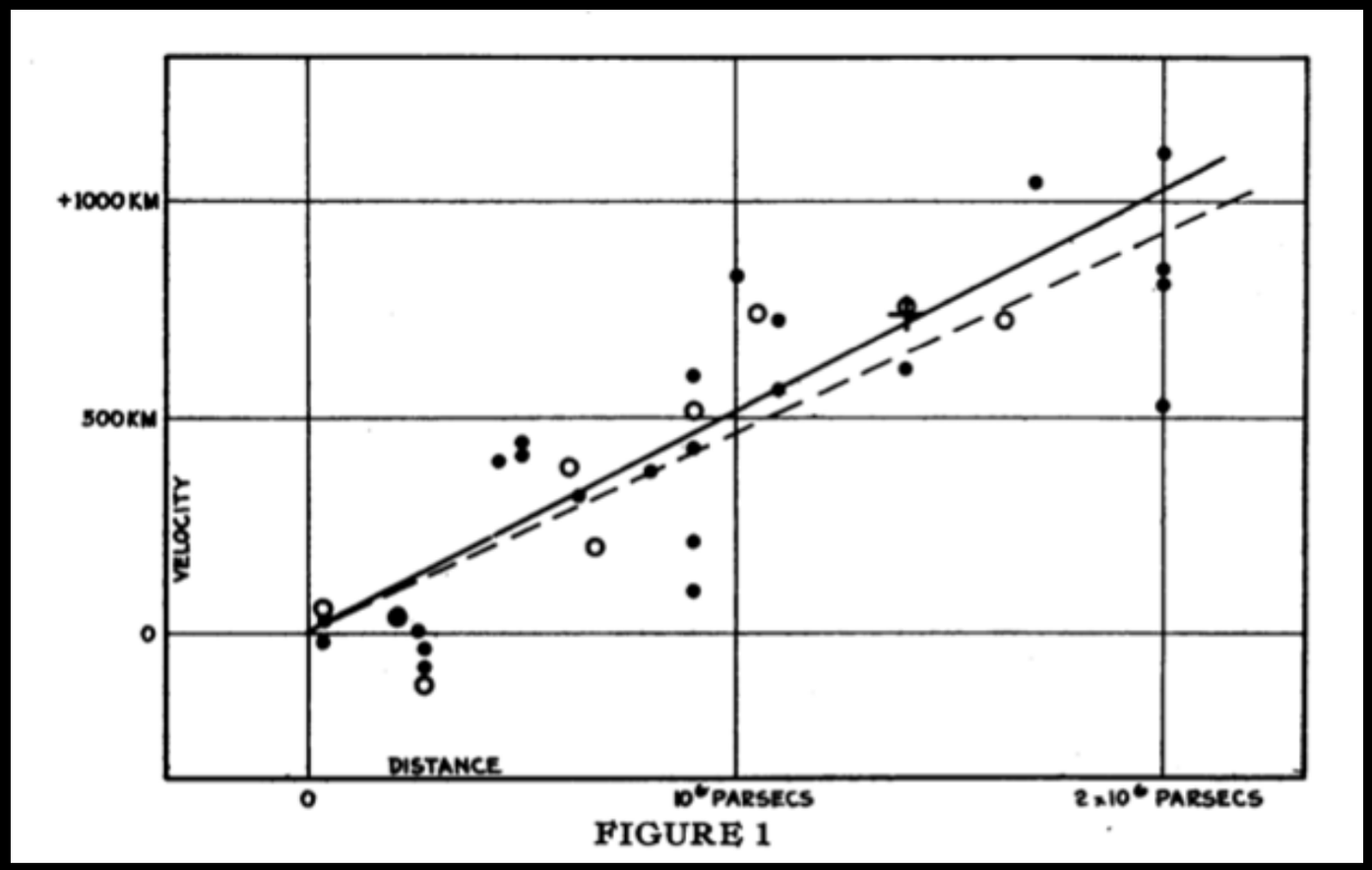


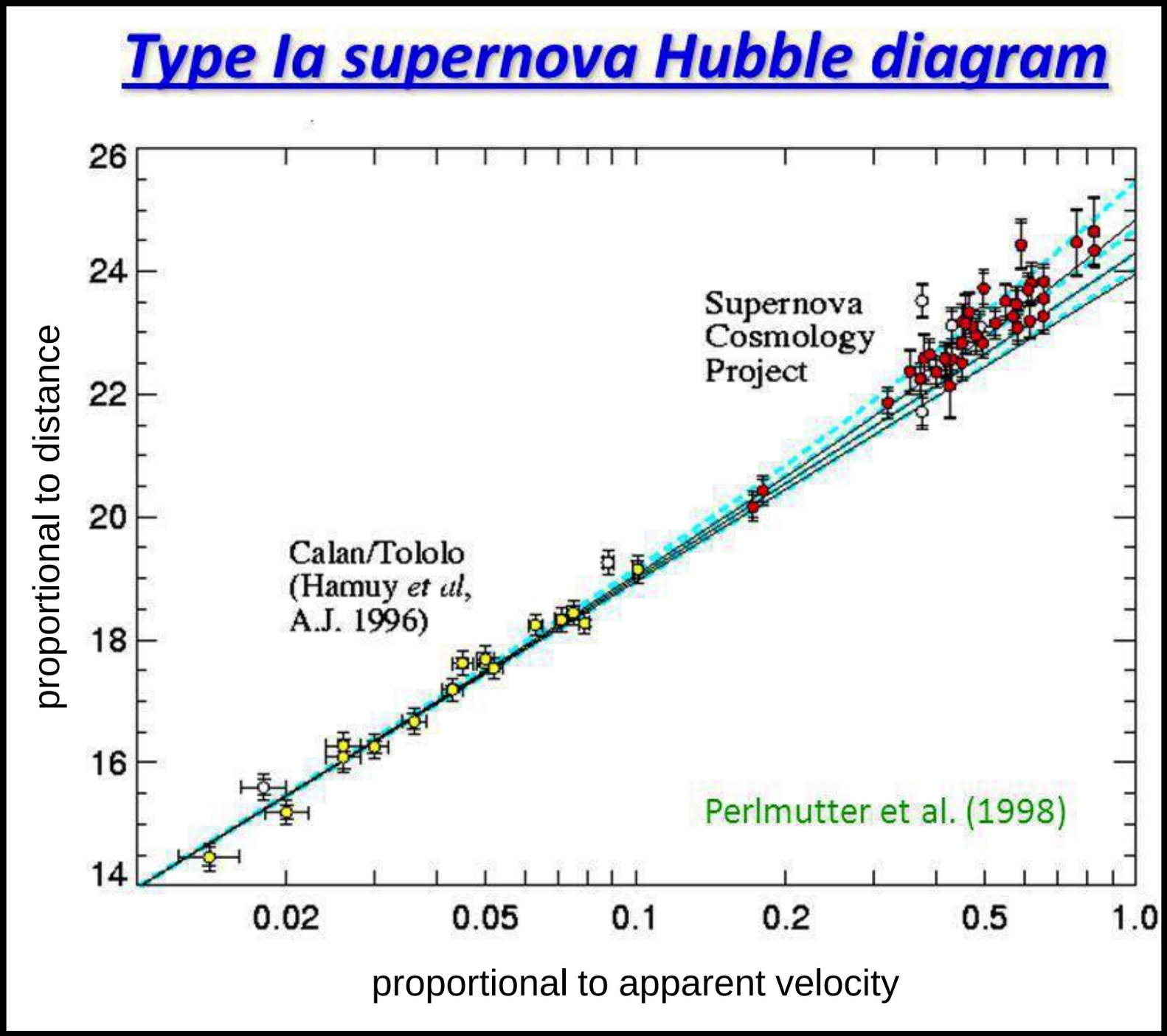
FIGURE 1

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

Hubble‘s law: $v = H_0 d$

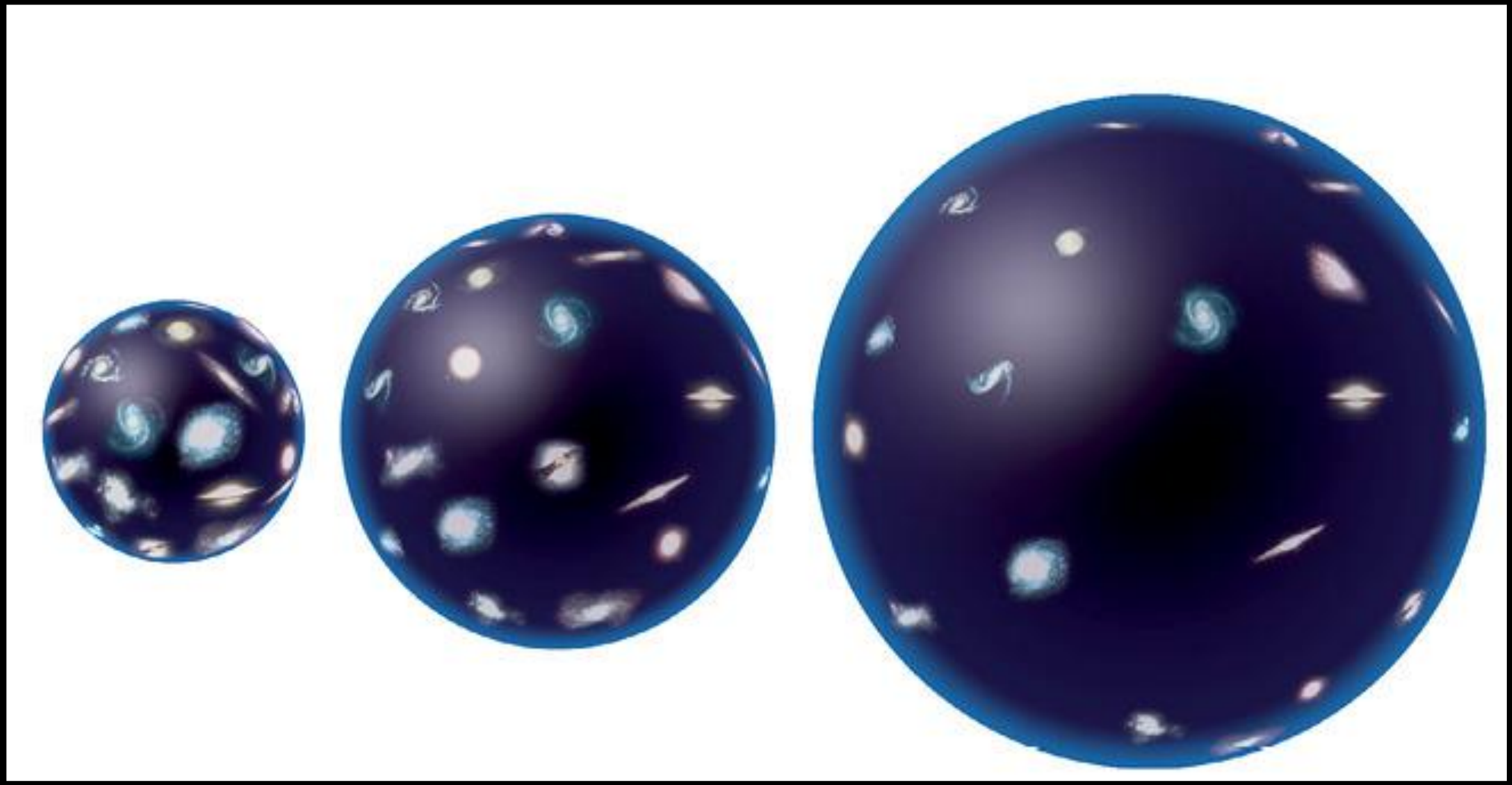
$H_0 = 530$ km/s / Mpc !!

The present value of the Hubble ”constant”



Today: $H = 67{,}3 \pm 1{,}2$ 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

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$t = 13.8 \times 10^{9}$ y
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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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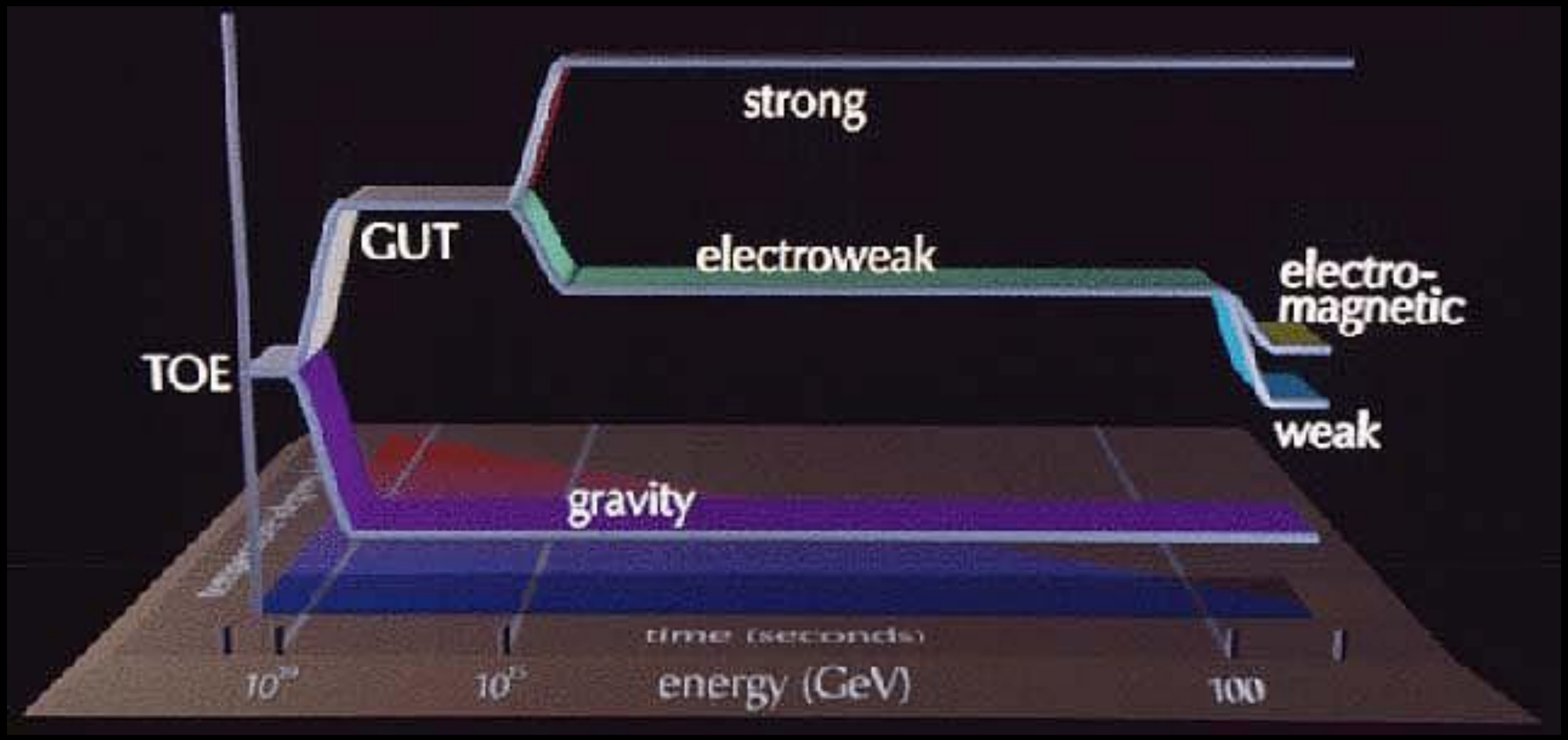
Unification of the Forces

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



http://crestroyertheory.com/2013/11/09/grand-unification/

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quark, gluon, electron, muon, tau

neutrino, bosons, meson, baryon

ion, atom, photon

star, galaxy, black hole

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HISTORY OF THE UNIVERSE

destruction battle

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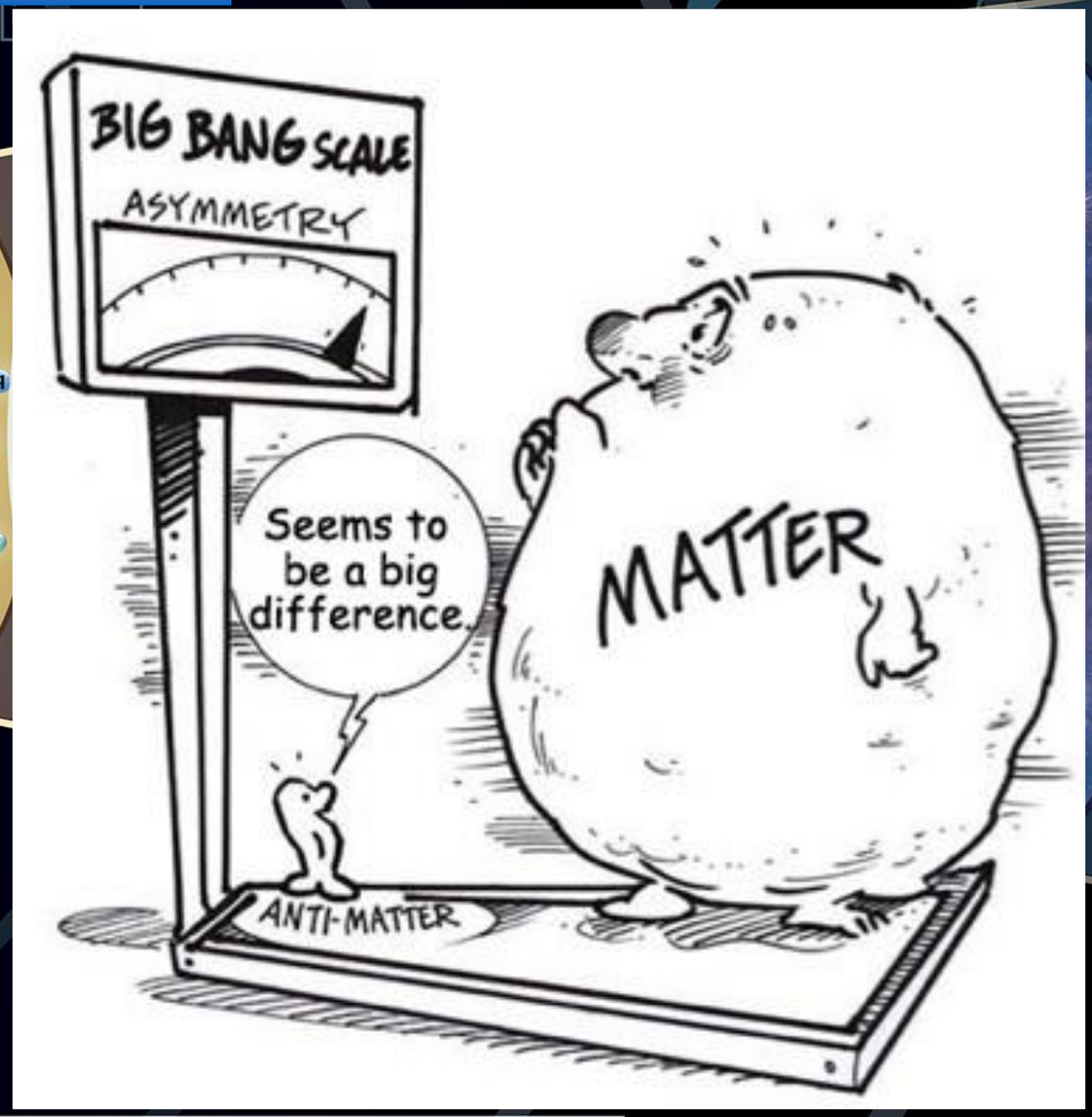

TODAY

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HISTORY OF THE UNIVERSE

nucleosynthesis

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wave Background radiation is visible

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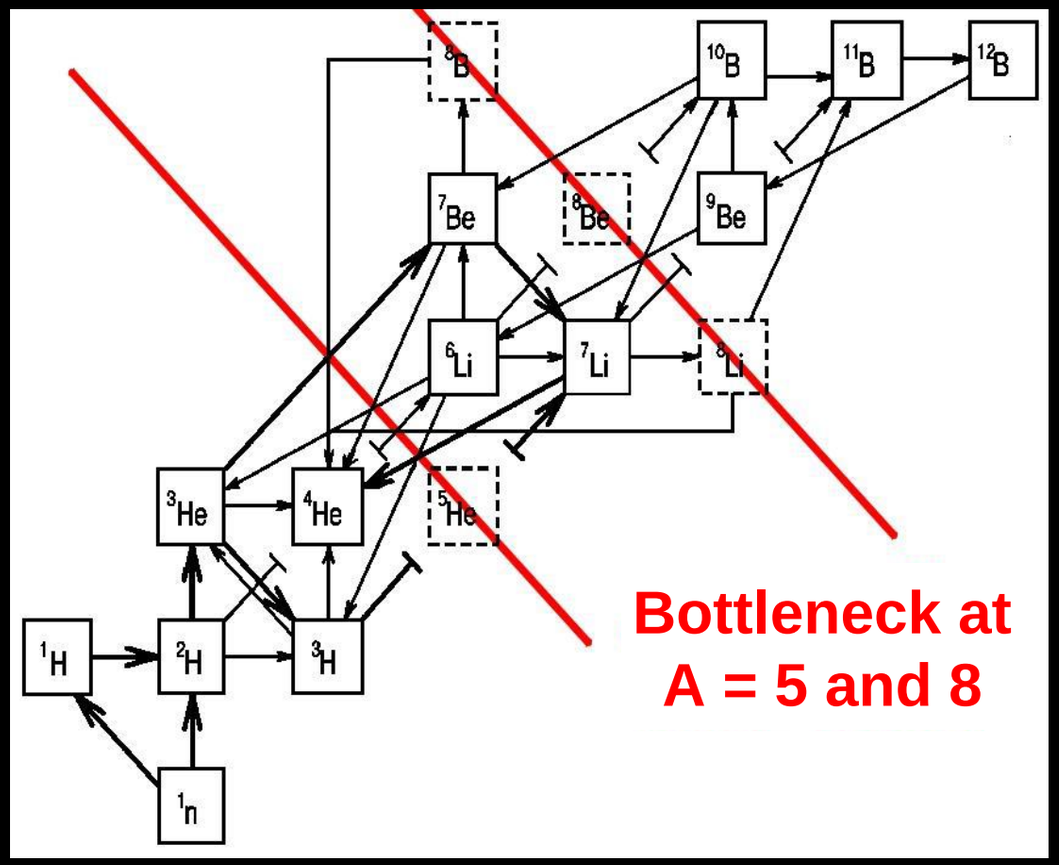
Supported by DOE

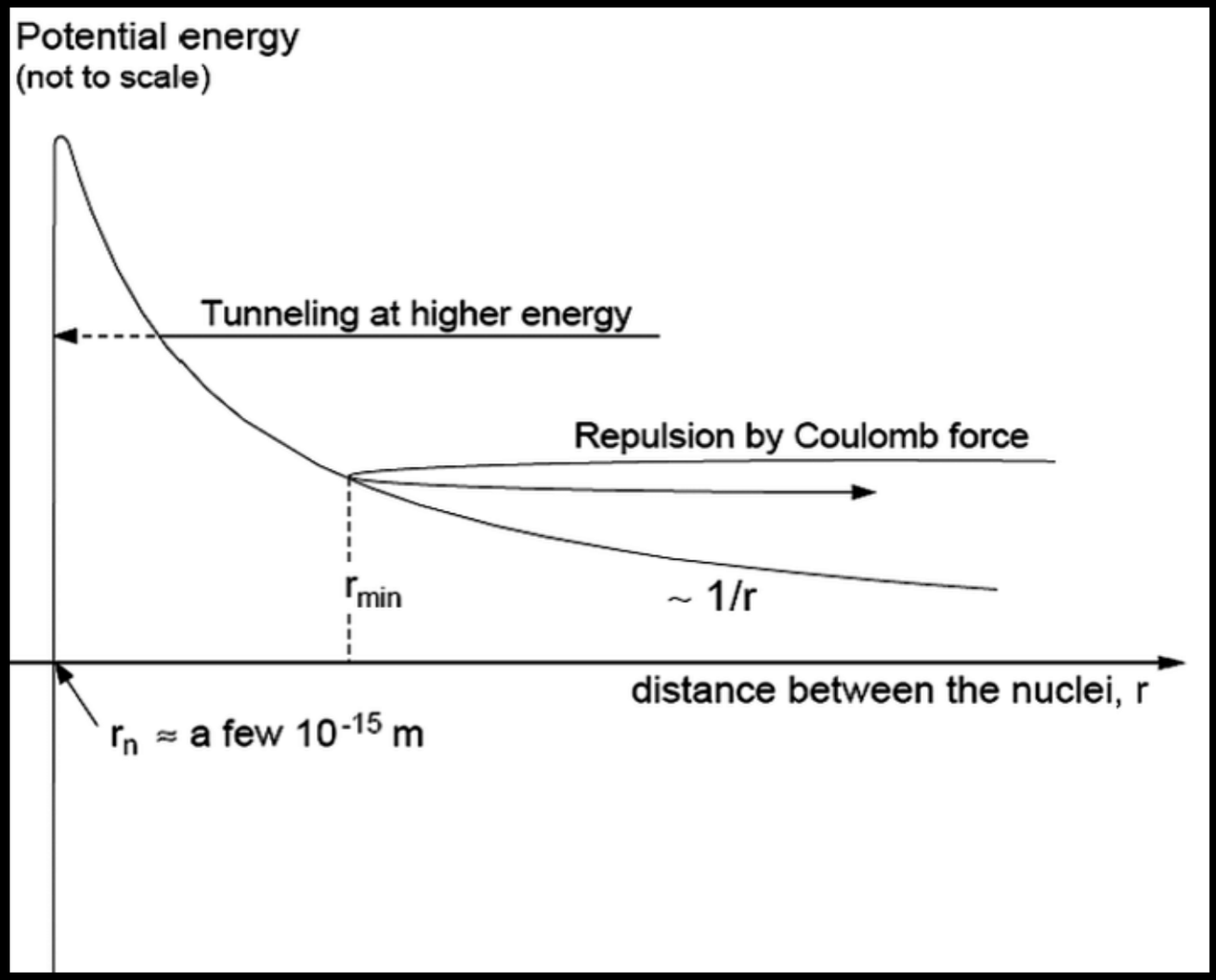
Nuclear Fusion

fusion in particle collisions

fusion needs high temperatures and high particle densities



Credit: Ohio State University



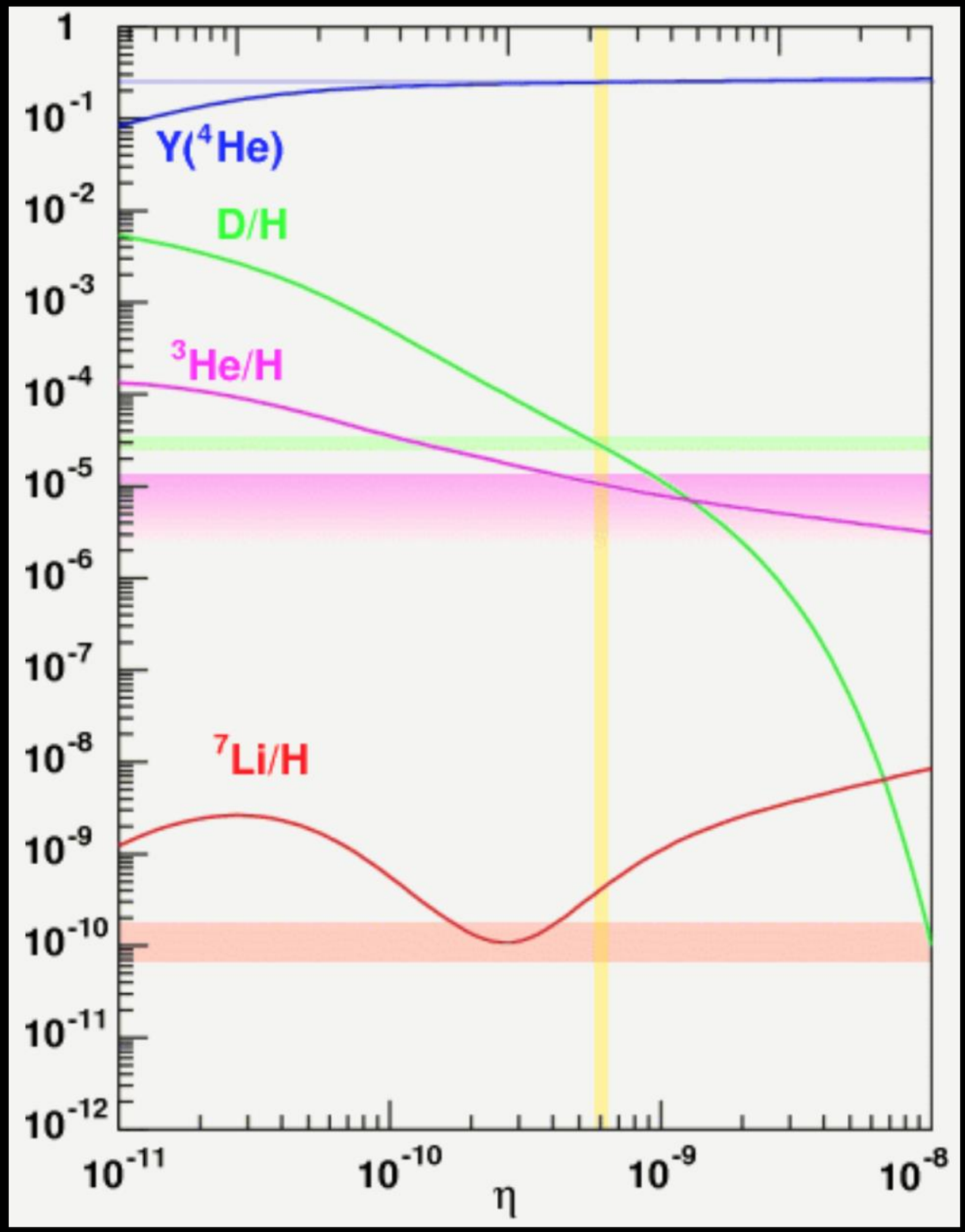
Ongena, J. (2015). Fusion: A true challenge for an enormous reward. EPJ Web of Conferences 98, 05004

Primordial Nucleosynthesis

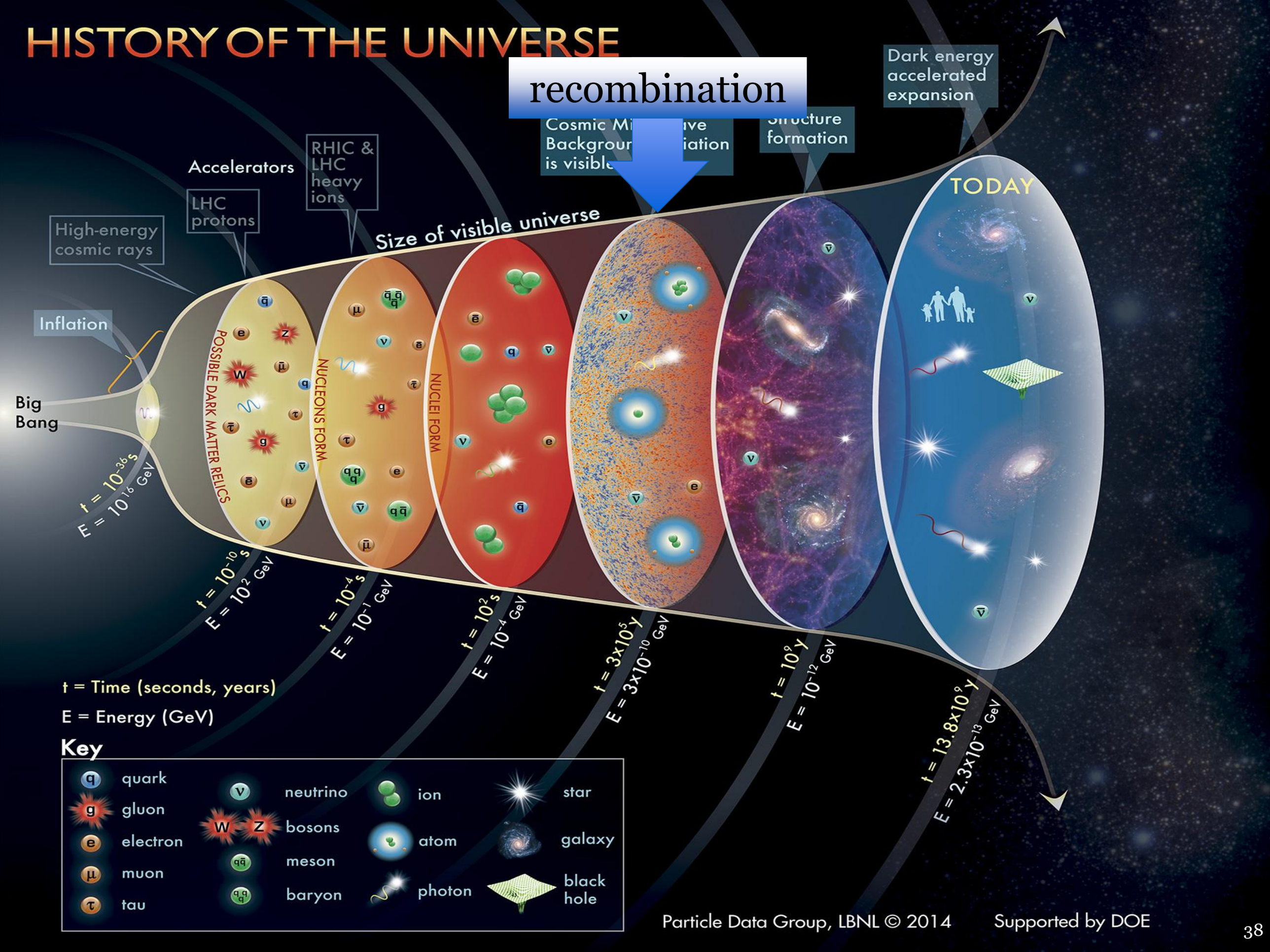
Comparison of theory
(curves) and observation
(horizontal lines)

abundances
of light elements:

74 % hydrogen
25 % helium
1 % rest



Heffernan, M. J. and Walker-Loud, A. (2016). Quantifying the sensitivity of Big Bang Nucleosynthesis to isospin breaking


HISTORY OF THE UNIVERSE
recombination
Dark energy accelerated expansion
Cosmic Microwave Background is visible
Structure formation
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LHC protons
High-energy cosmic rays
Size of visible universe
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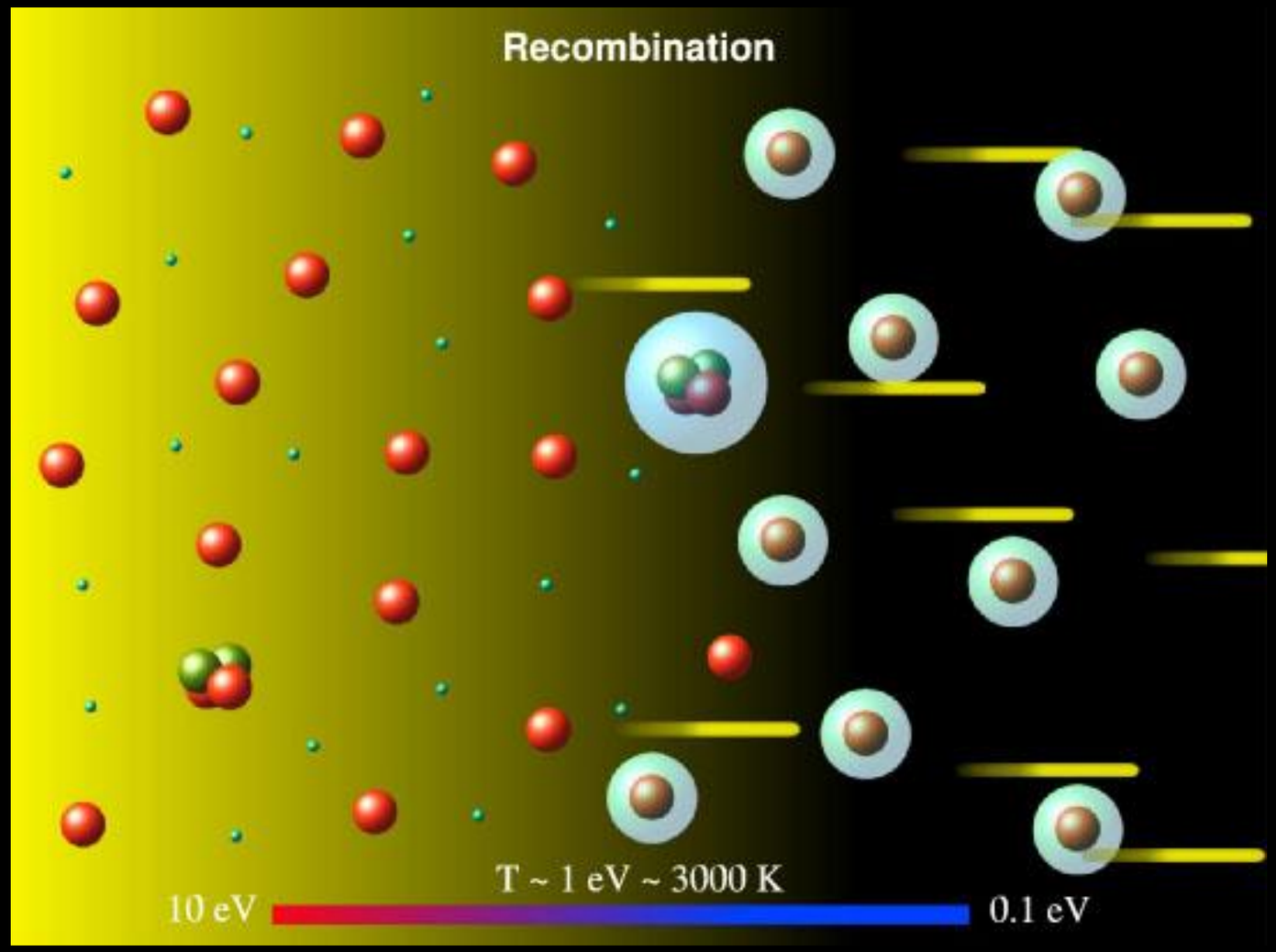
galaxy
black hole
Particle Data Group, LBNL © 2014
Supported by DOE

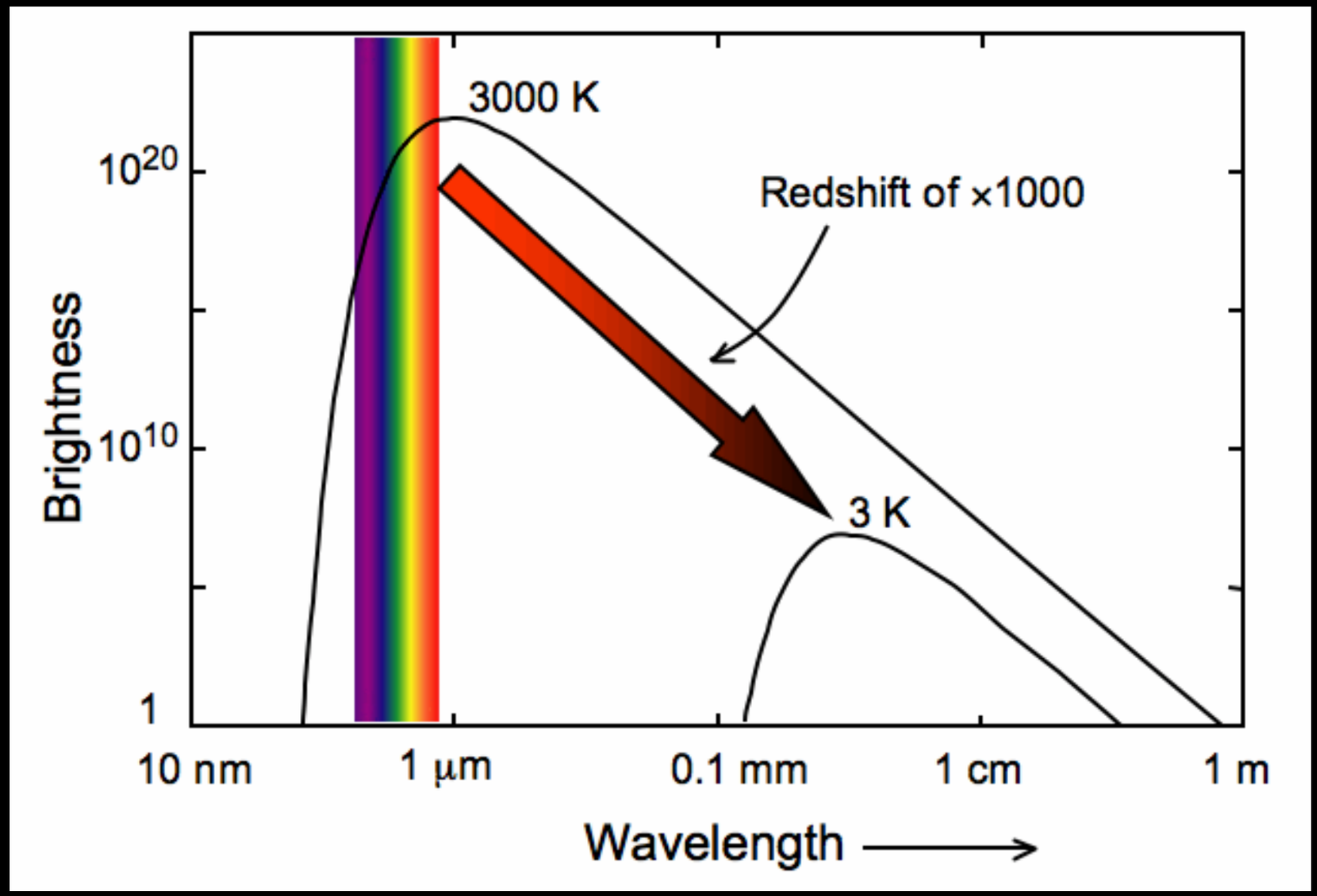
Recombination



Credit: W. H. Kinney, arXiv:astro-ph/0301448v2

- 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!

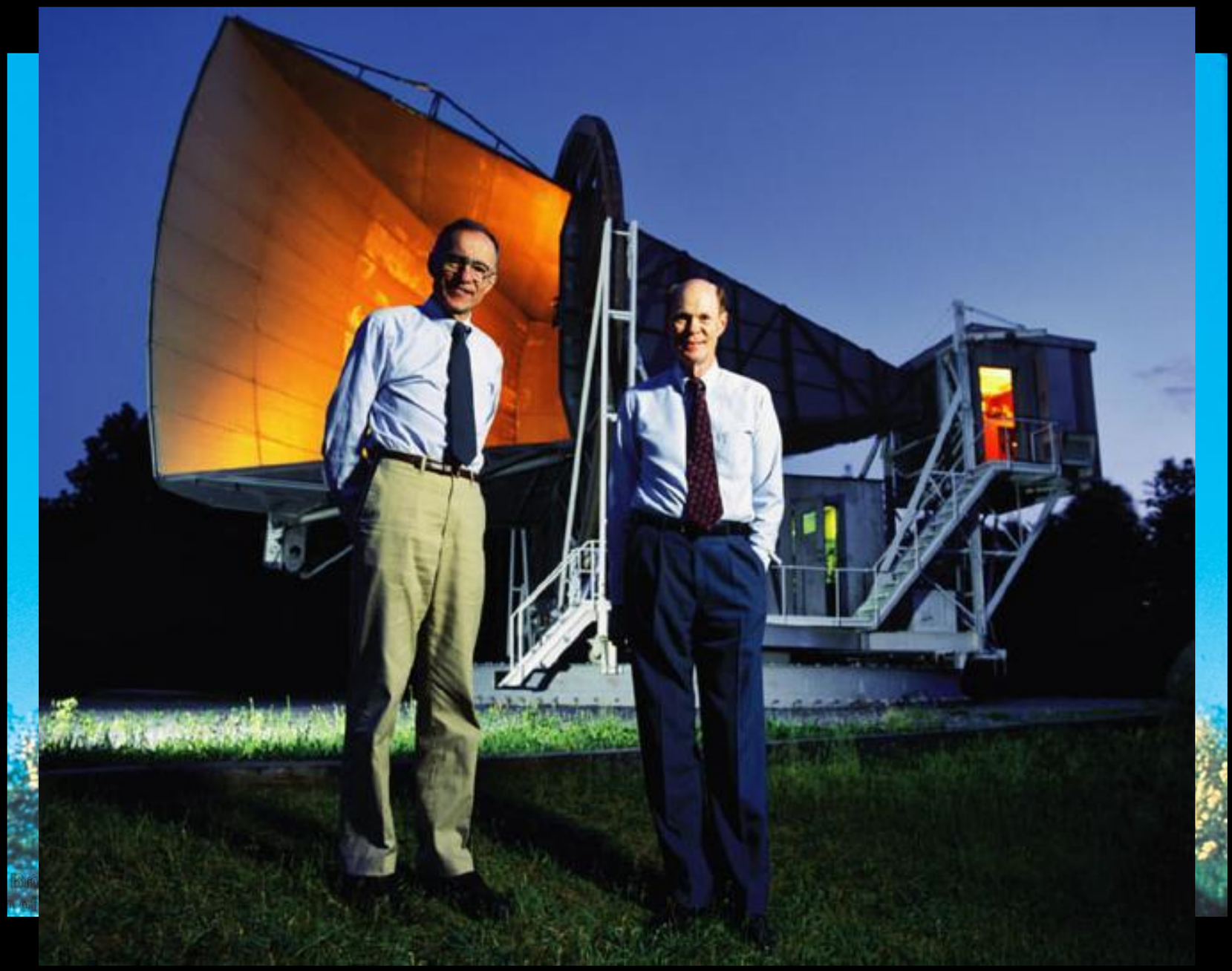
The Cosmic Microwave Background (CMB)



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



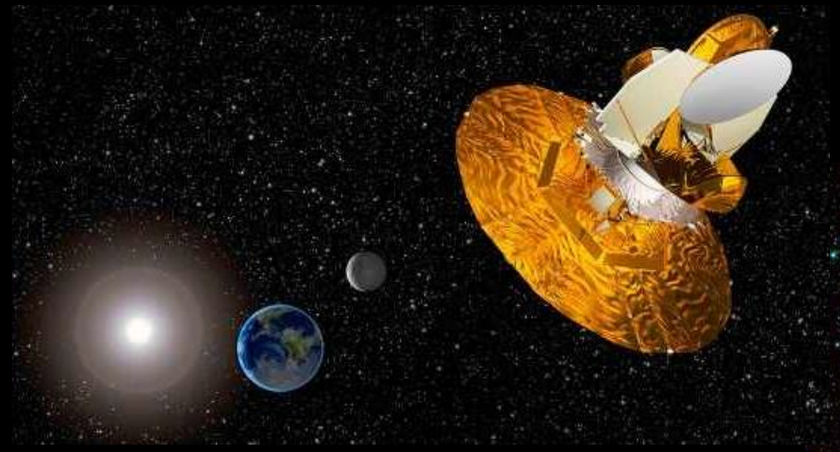
1964 Penzias und Wilson discovered a noise, which they couldn’t explain

 (1978)

Satellites for the investigation of the CMB

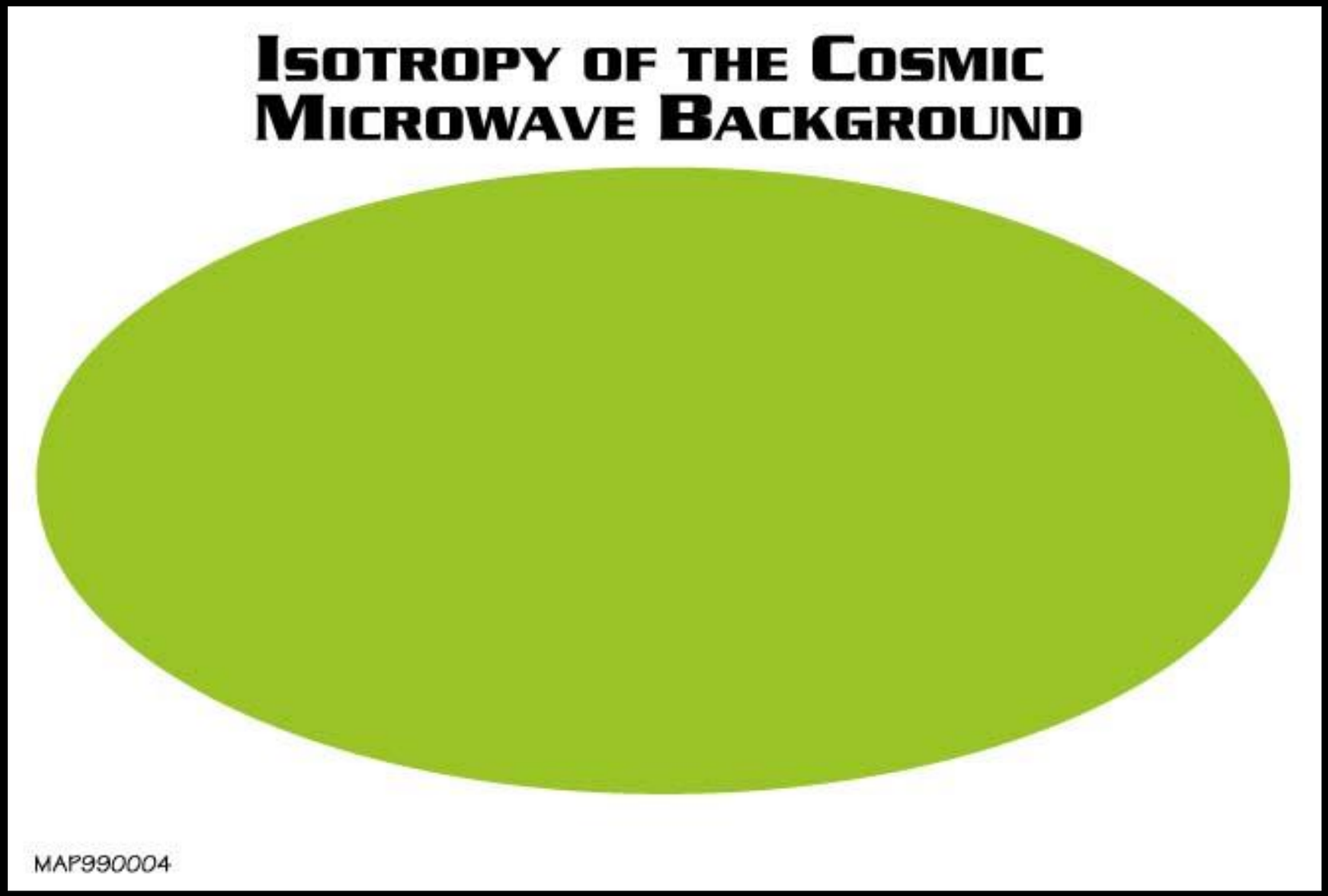
- COBE
  Cosmic Background Explorer
  1989-1993
  Nobel Prize 2006
  (Smoot & Mather)

- WMAP
  Wilkinson Microwave
  Anisotropy Probe
  2001-2010



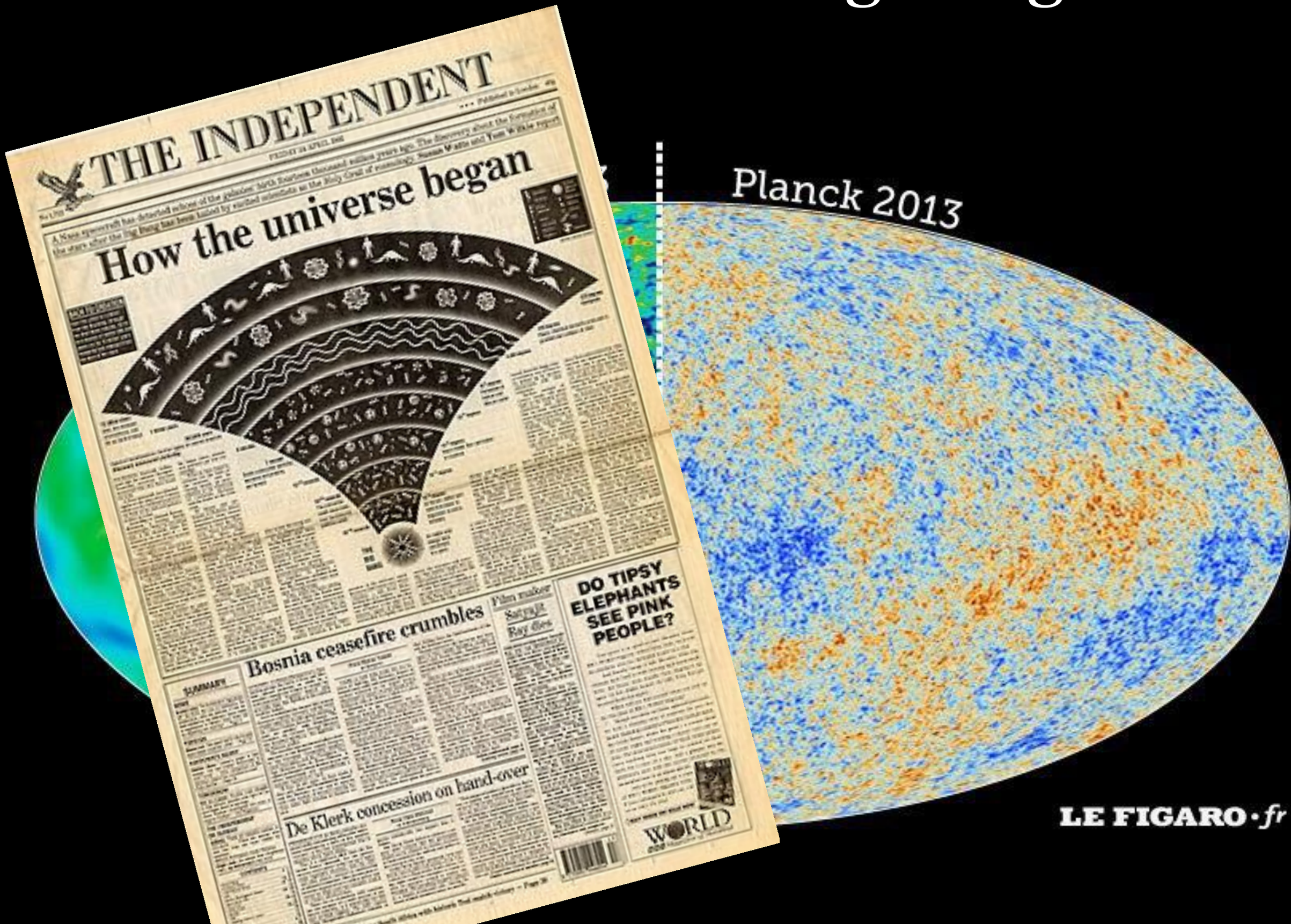
- Planck
  2009-2013

Next problem for the Big Bang theory



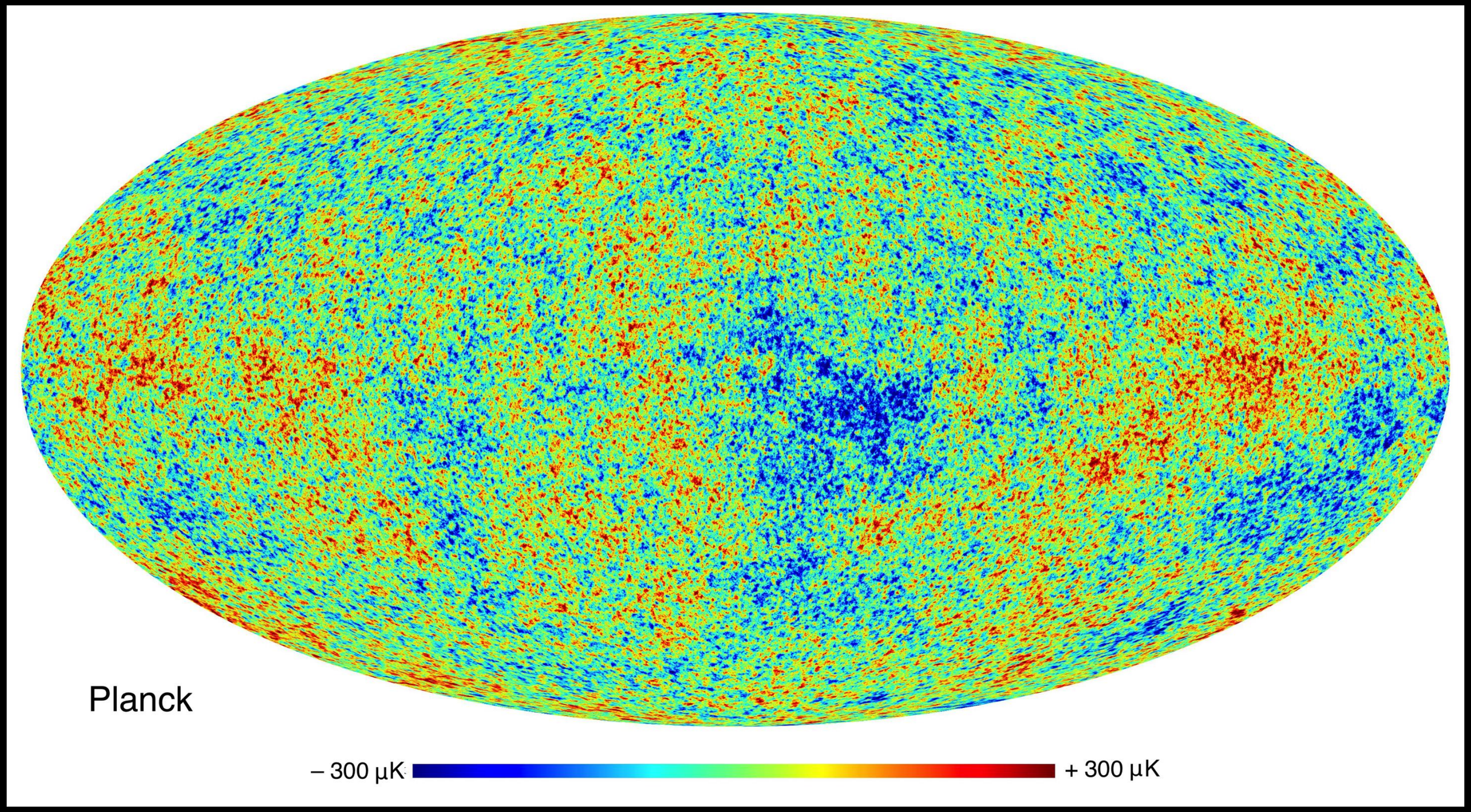
The second analysis revealed no sign of any variation at a level of 1 part in 10.000!
Where are the galaxies coming from, if not from density fluctuations?

The Echo of the Big Bang

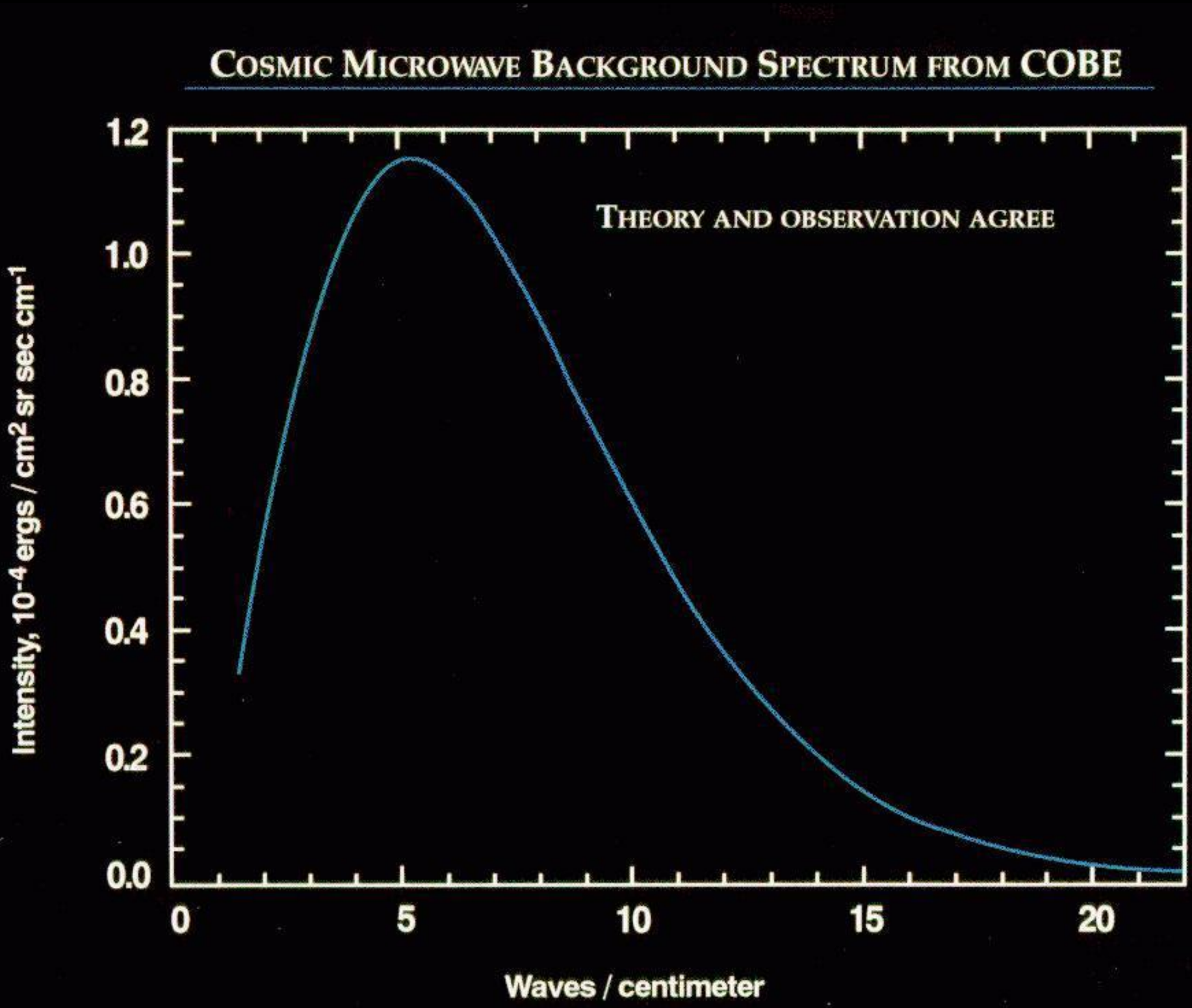


The Echo of the Big Bang

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



The spectrum of the CMB



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structure building

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

t = Time (seconds, years)

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Key

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

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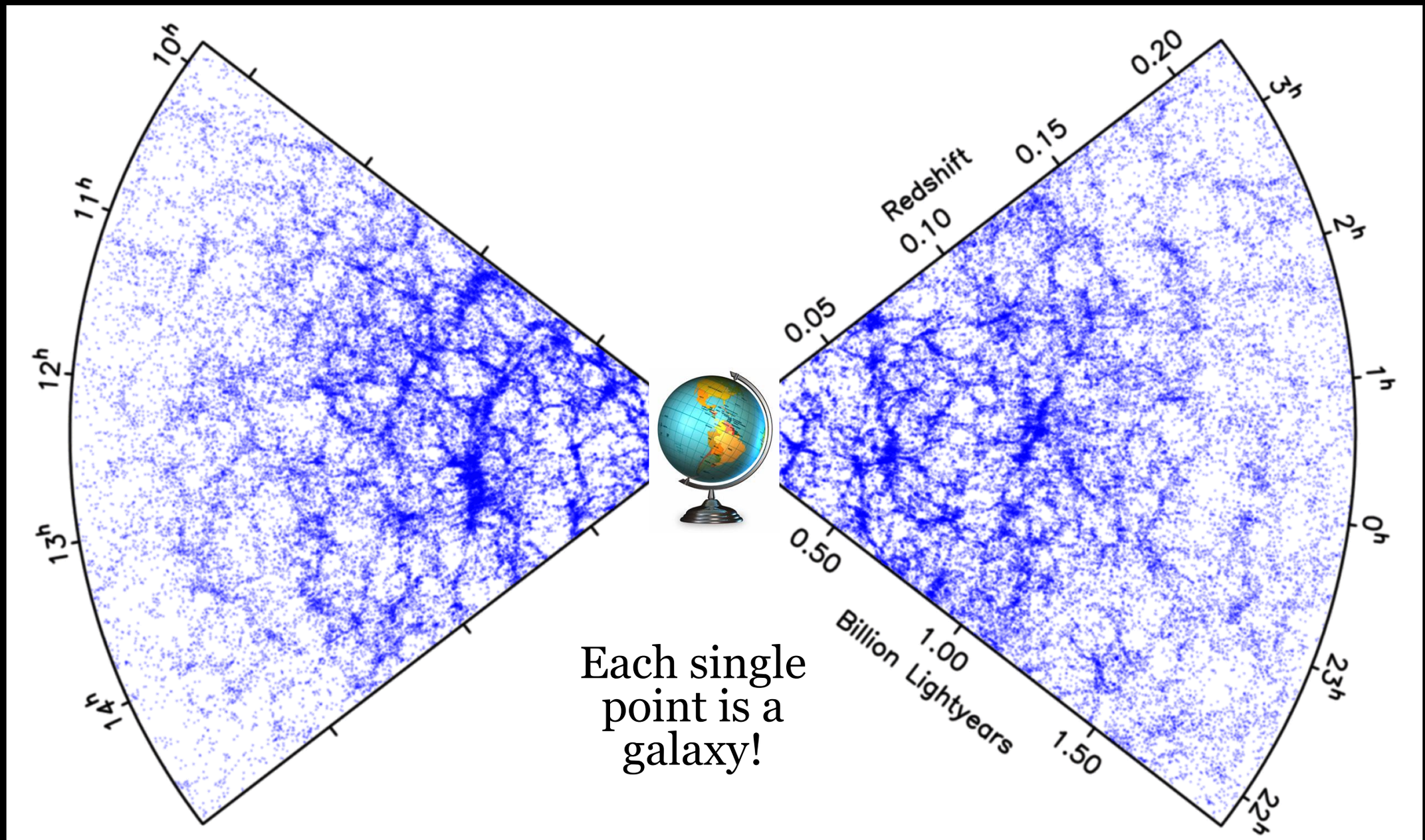
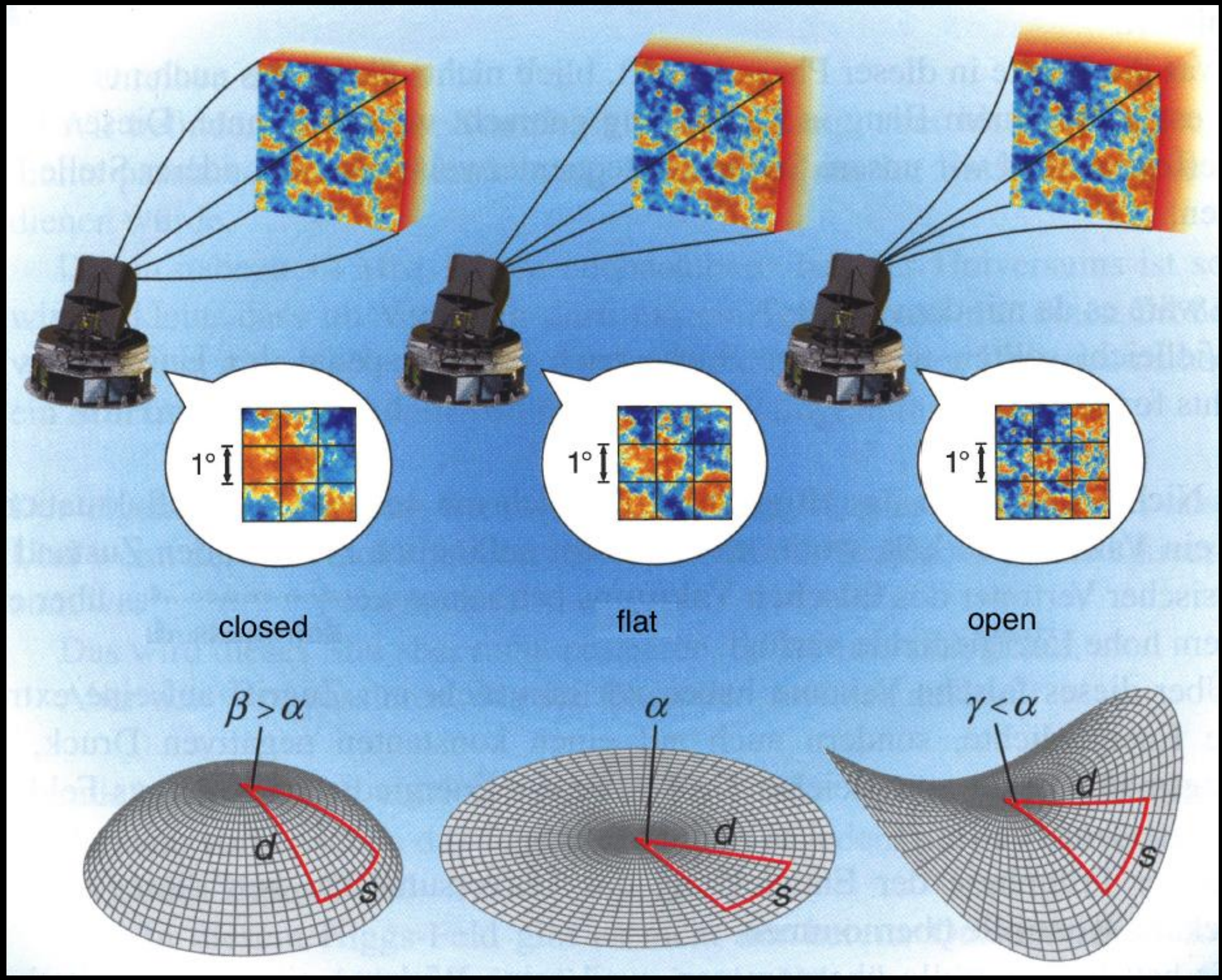
Galaxy Distribution

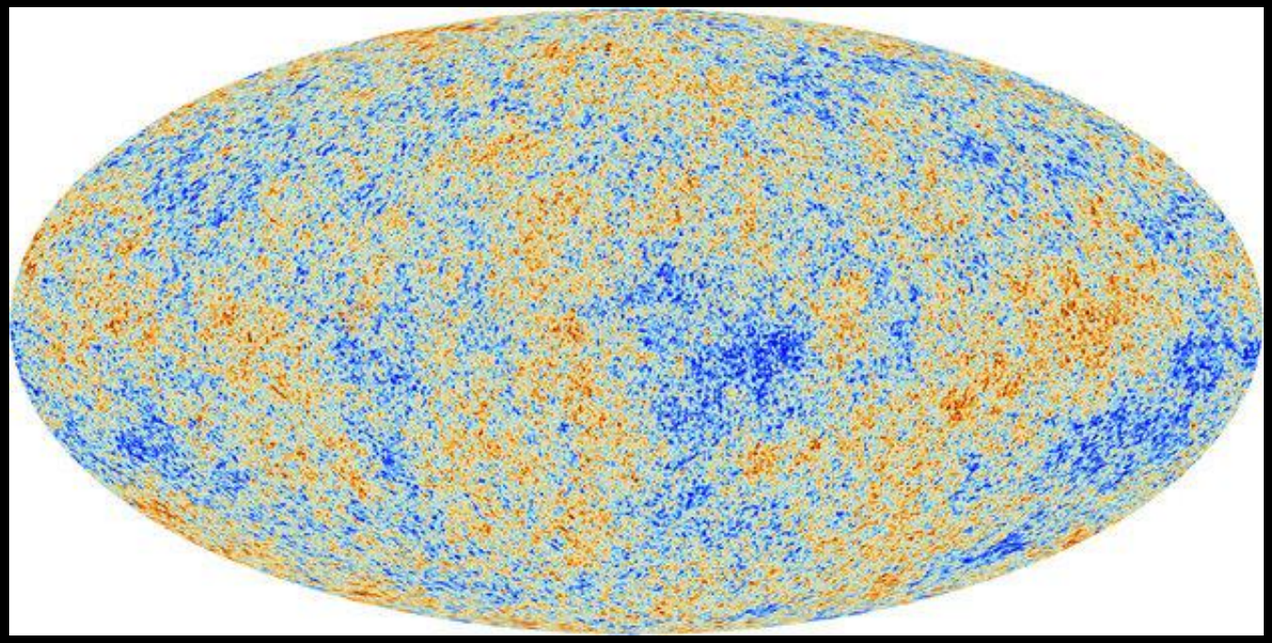
In the past the universe was much more homogeneous than today

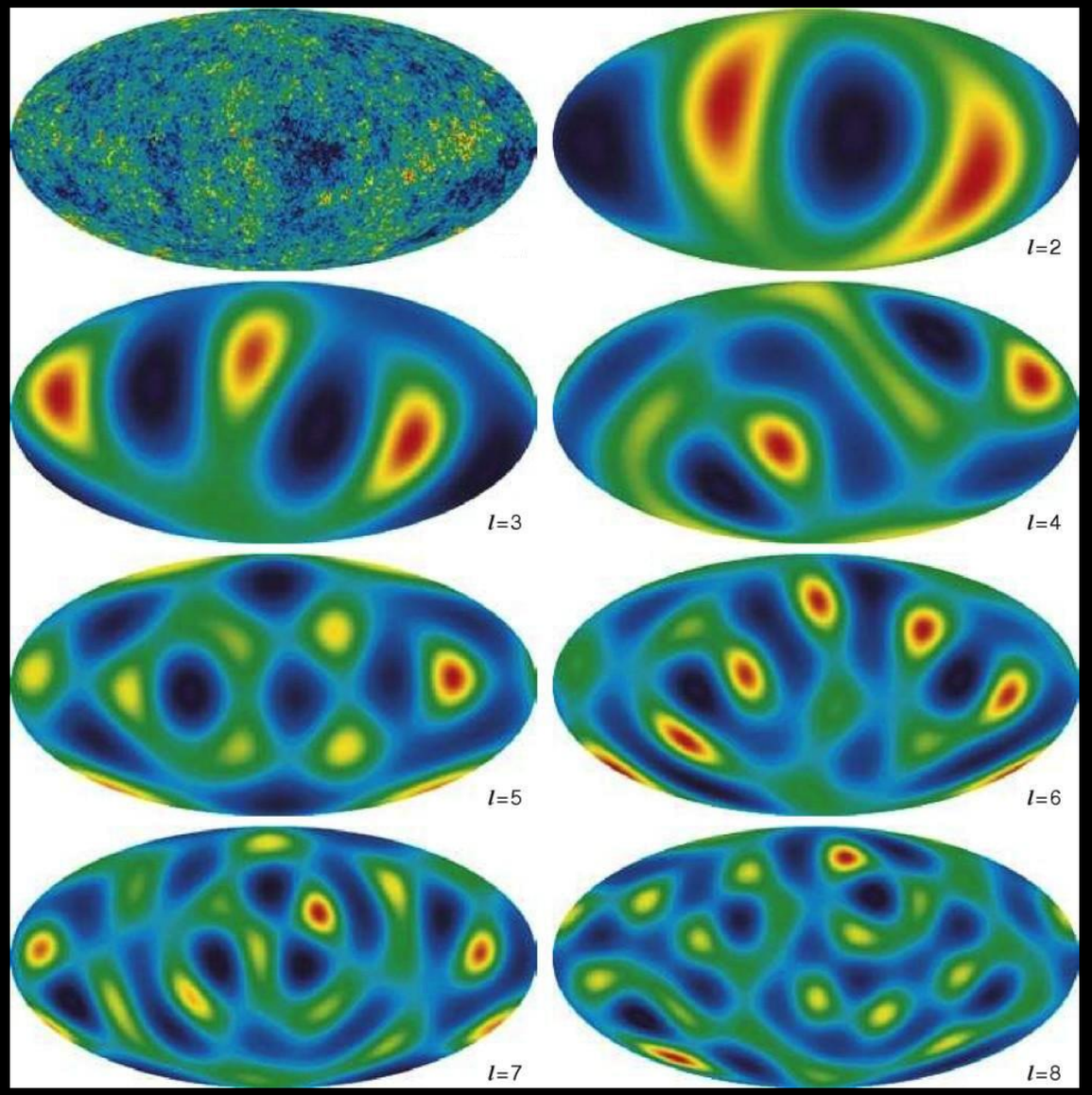


Geometry of the universe



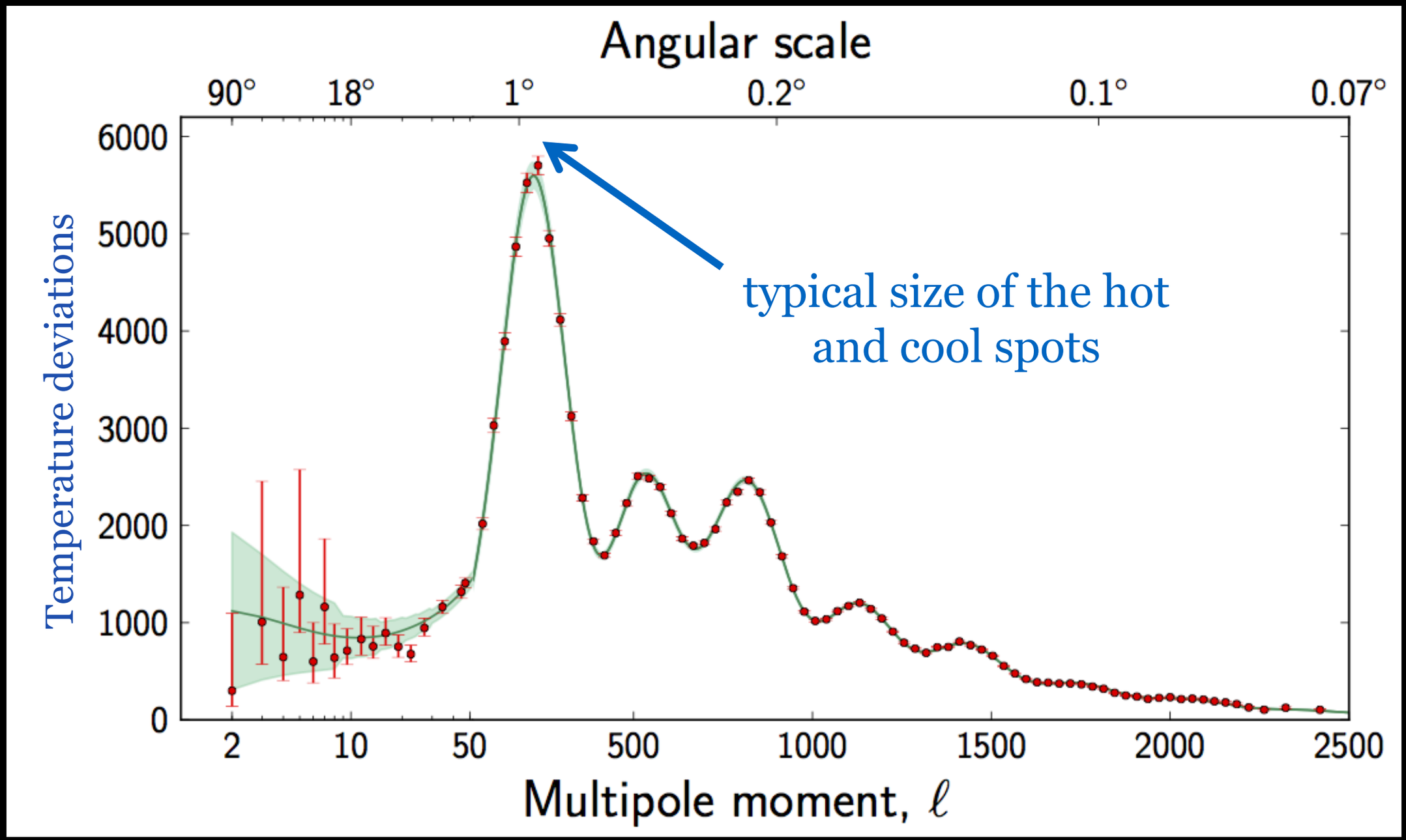
From the map to the spectrum…



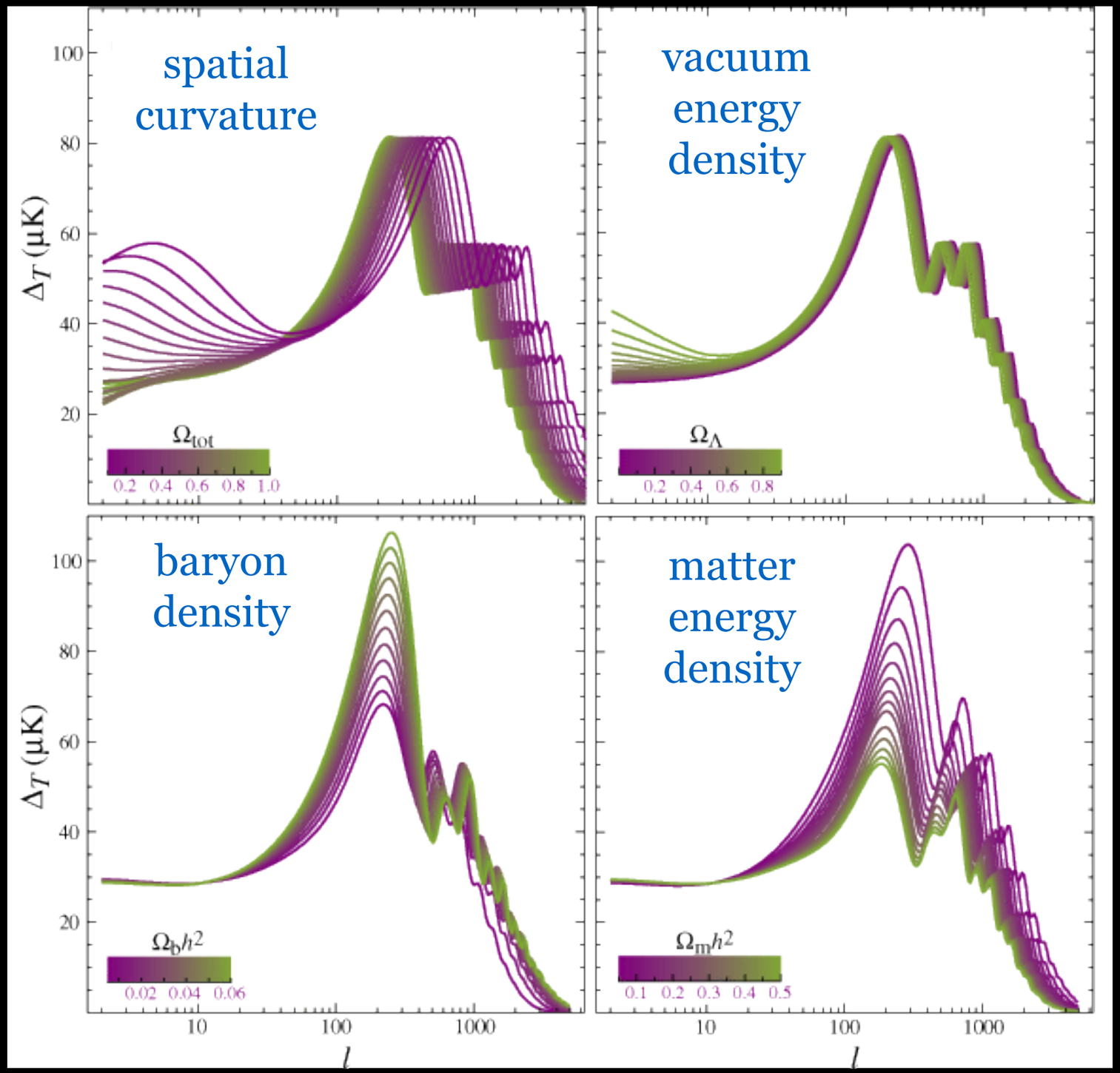


- theory is not able to predict the exact position of individual hot or cool spots
- instead: prediction of statistical properties of the temperature map (for example mean value, variance, correlations,…)

The Angular Power Spectrum of the CMB



Theoretical Predictions of the CMB Spectrum

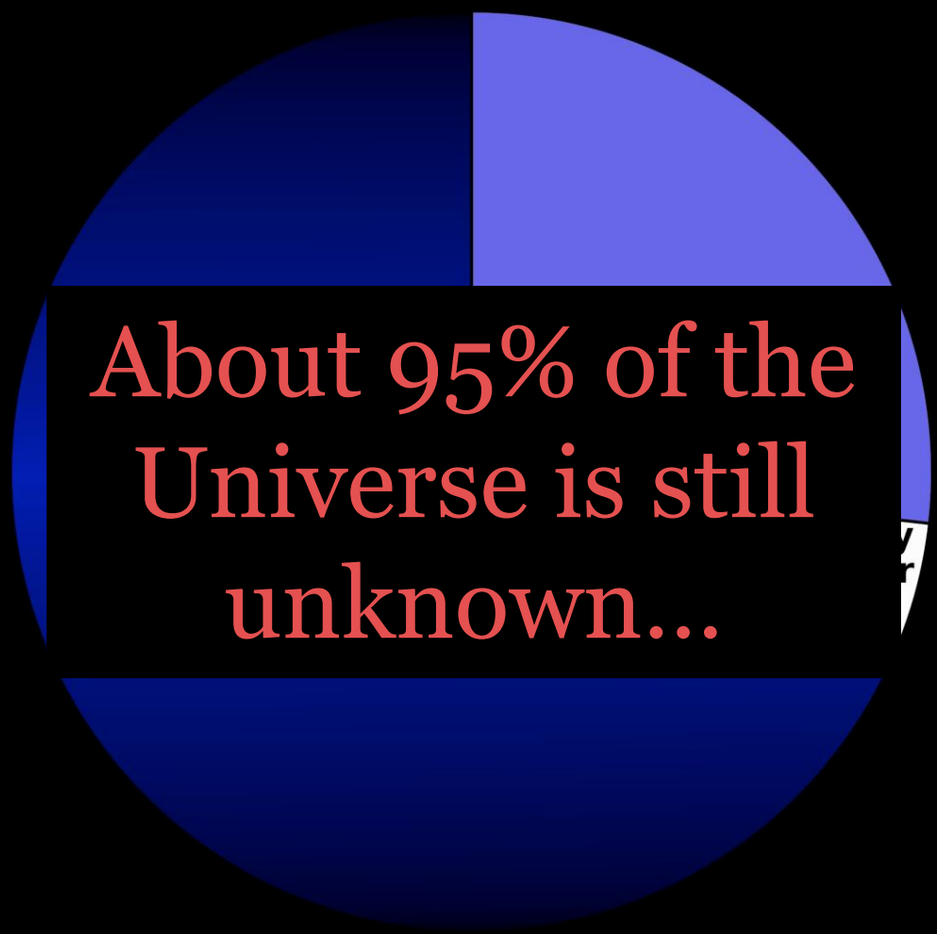


- The theoretical CMB spectrum is depending on values of certain cosmological parameters

- 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!)



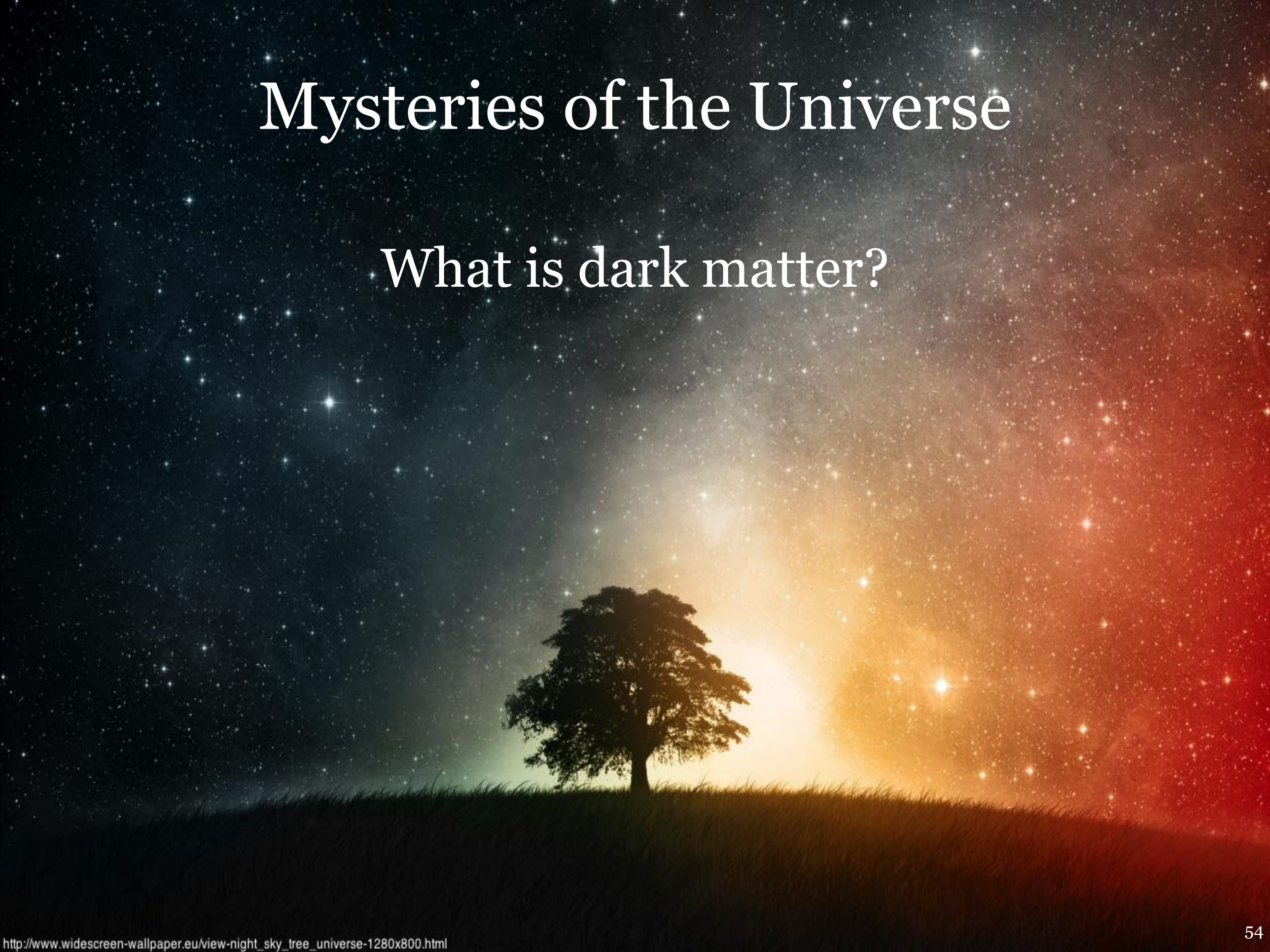
dark energy?!?!
(vacuum energy)

dark matter?!

"normal" matter

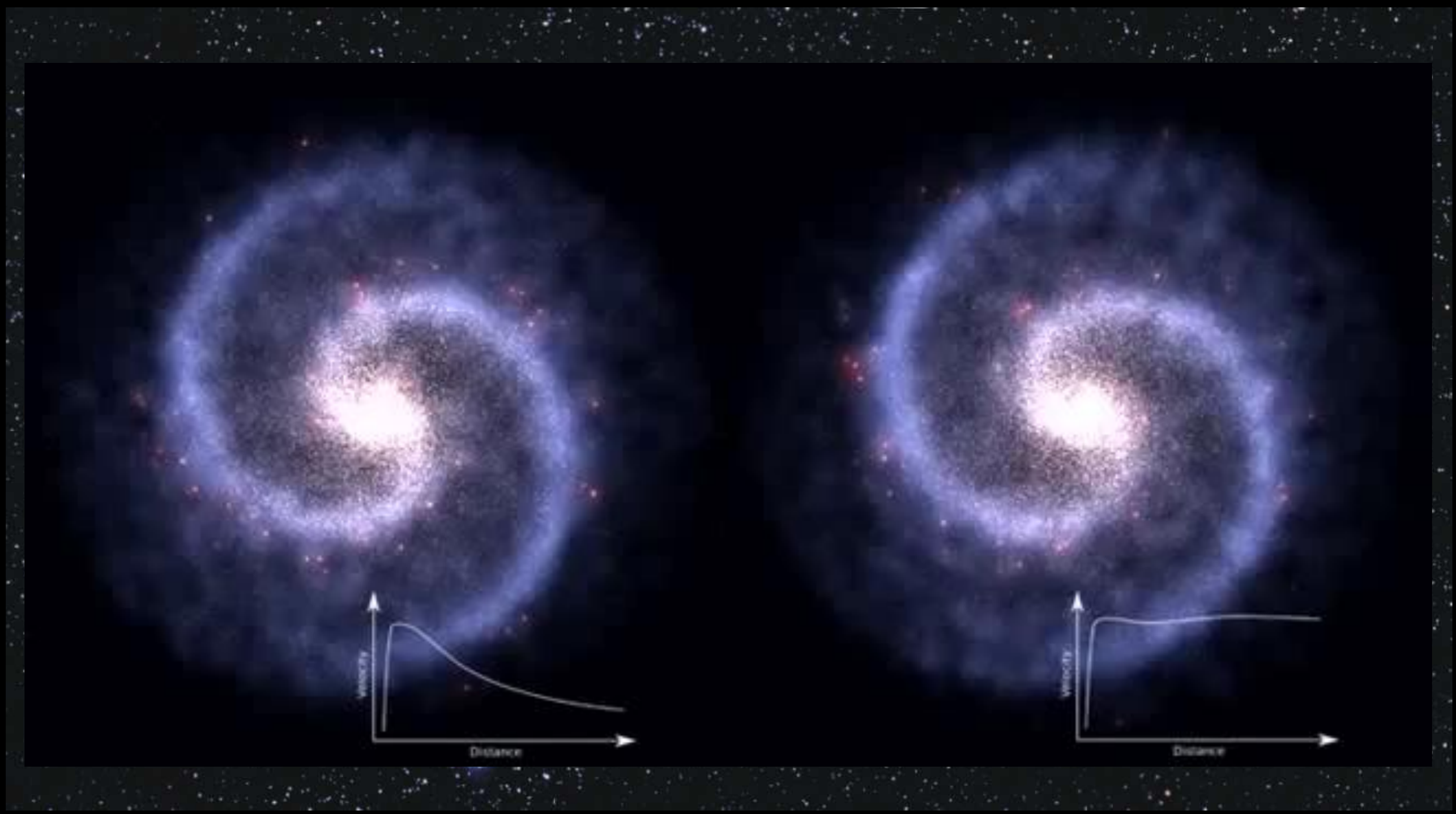
Mysteries of the Universe

What is dark matter?

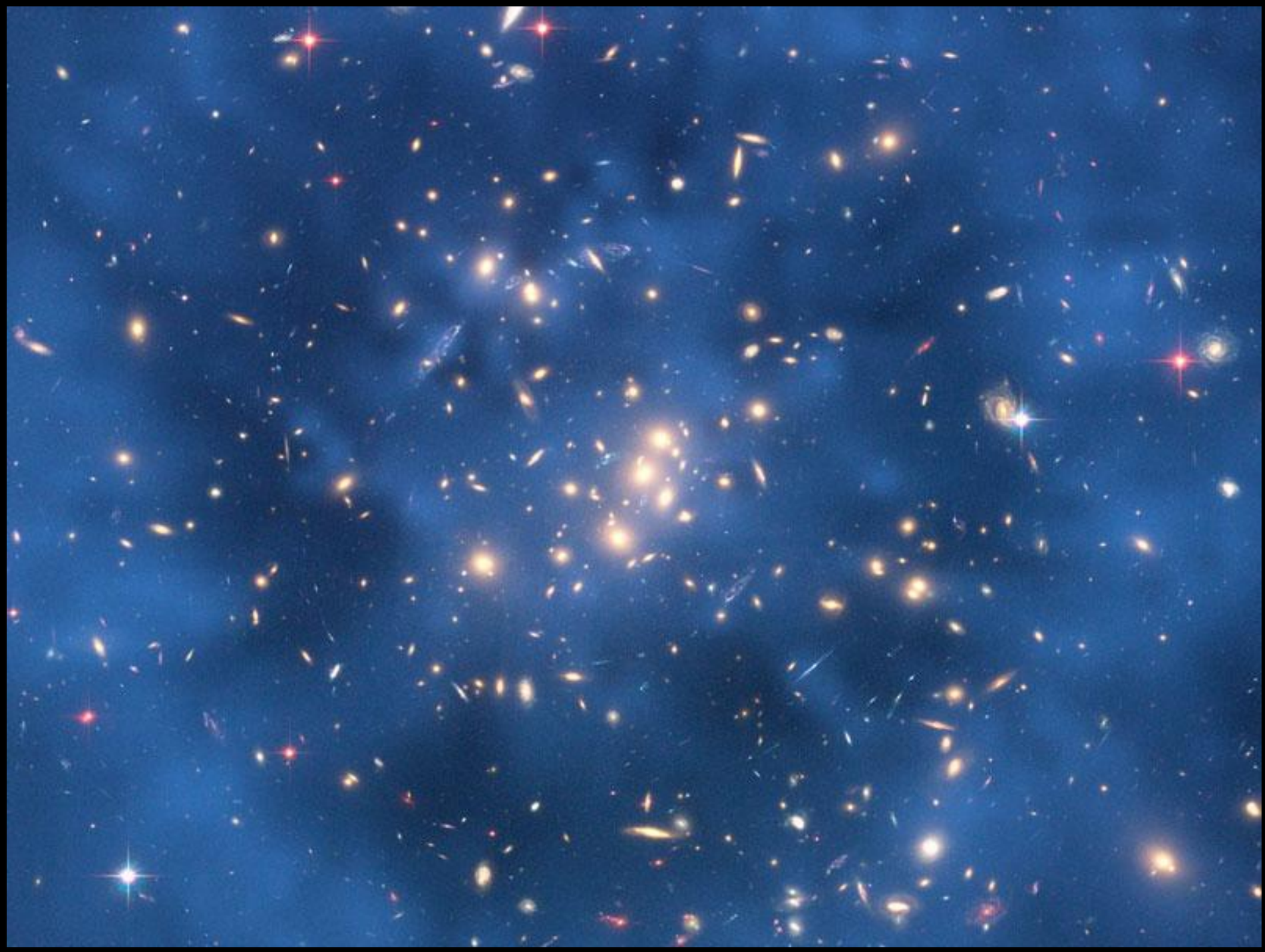


http://www.widescreen-wallpaper.eu/view-night_sky_tree_universe-1280x800.html

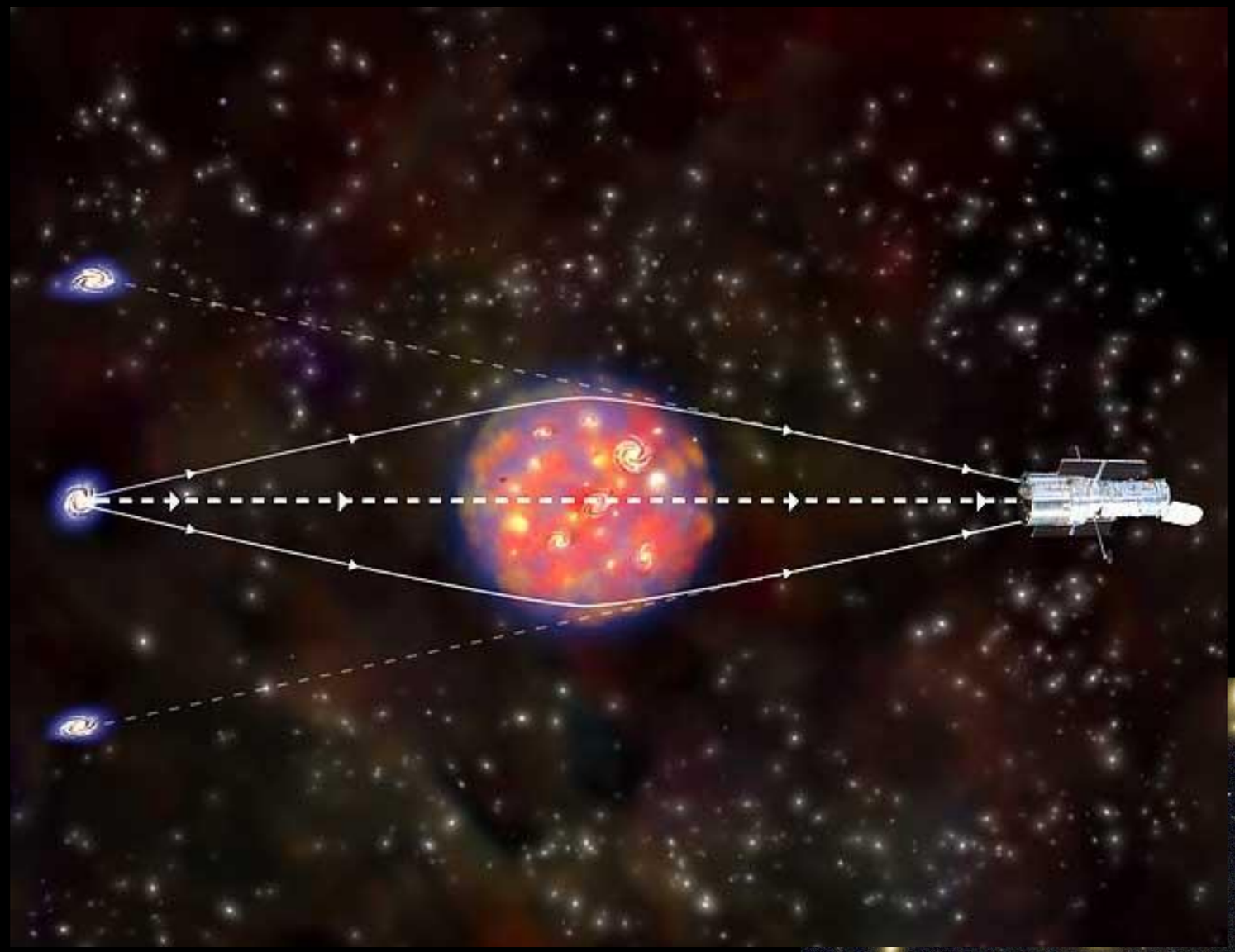
Rotation Curves of Galaxies



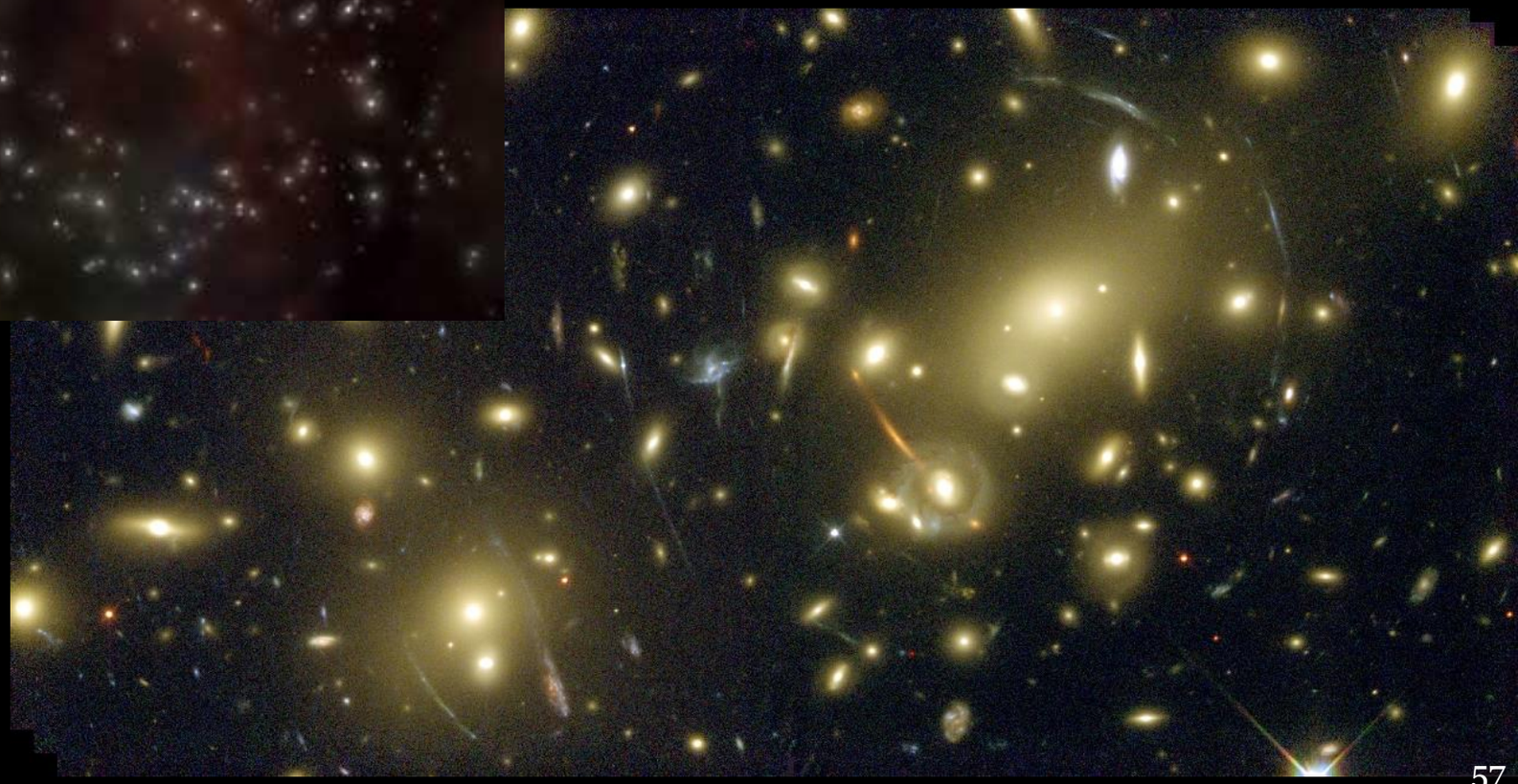
Galaxy Cluster CL0024+17



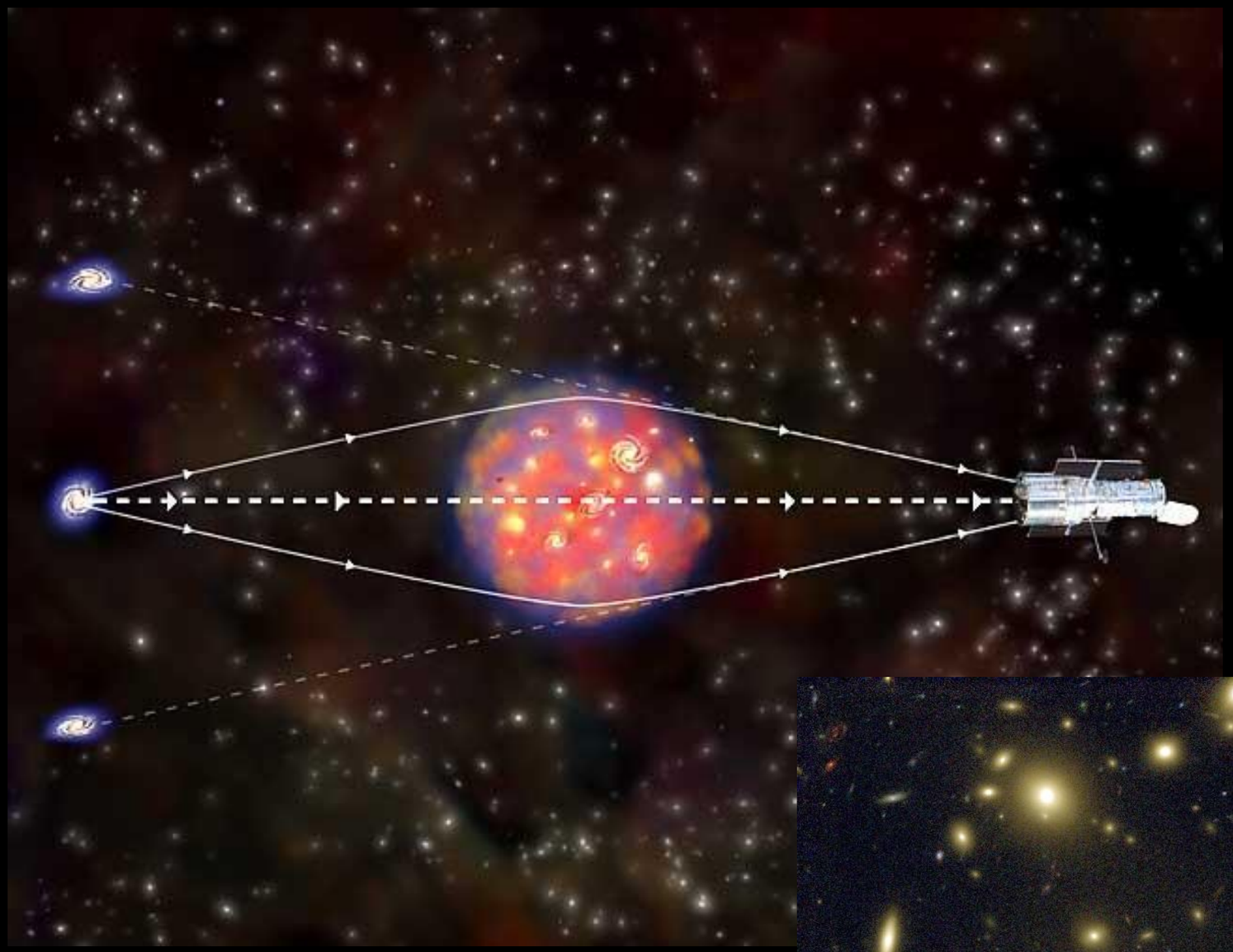
Gravitational Lenses



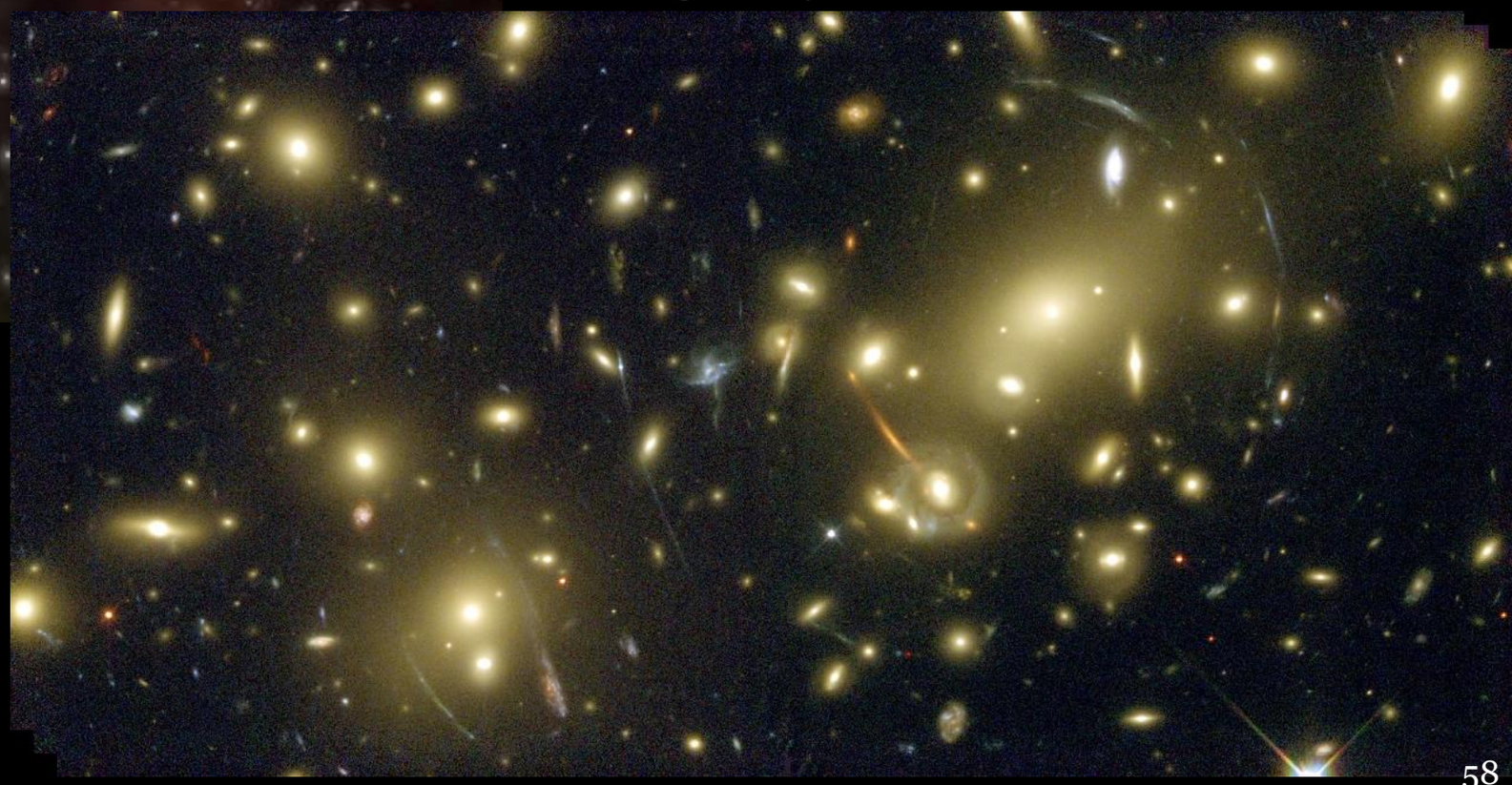
Massive objects curve space-time and therefore distort the light of the objects behind.



Gravitational Lenses

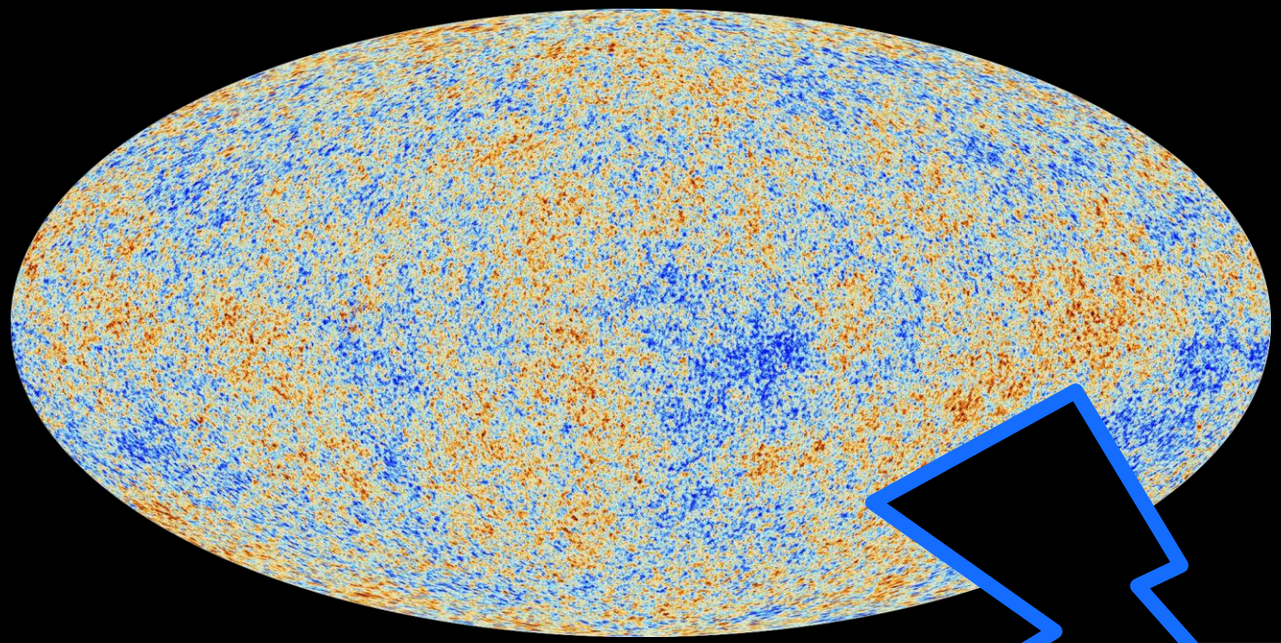


galaxy cluster Abell 2218



Thereby light arcs of the objects behind are visible.

Structure building in the early universe



HISTORY OF THE UNIVERSE

era of 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

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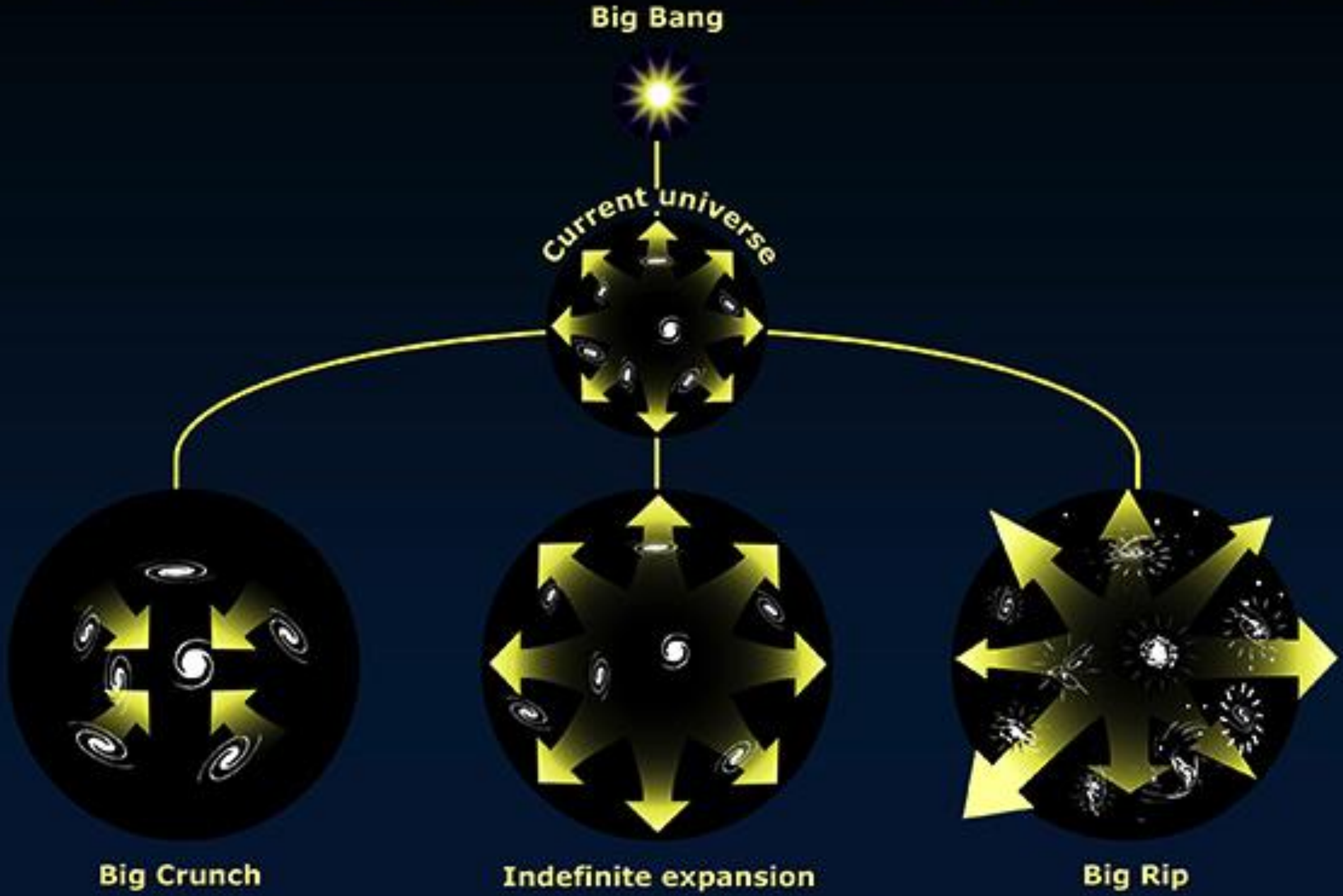
Future fates of the dark-energy universe



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…**

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.

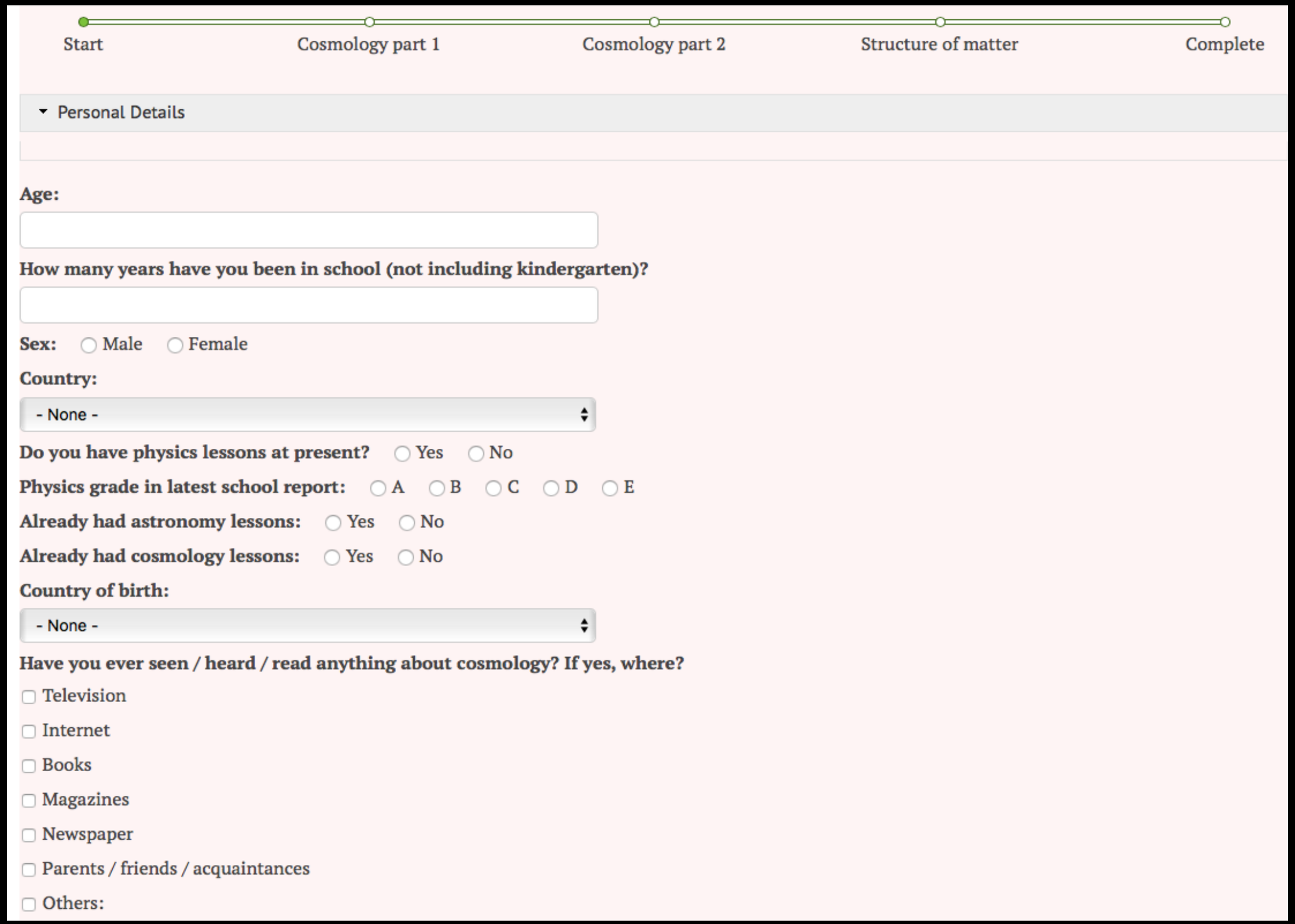
Information about participation in this project

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



Many thanks for your attention!

Are there any questions?