

# 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

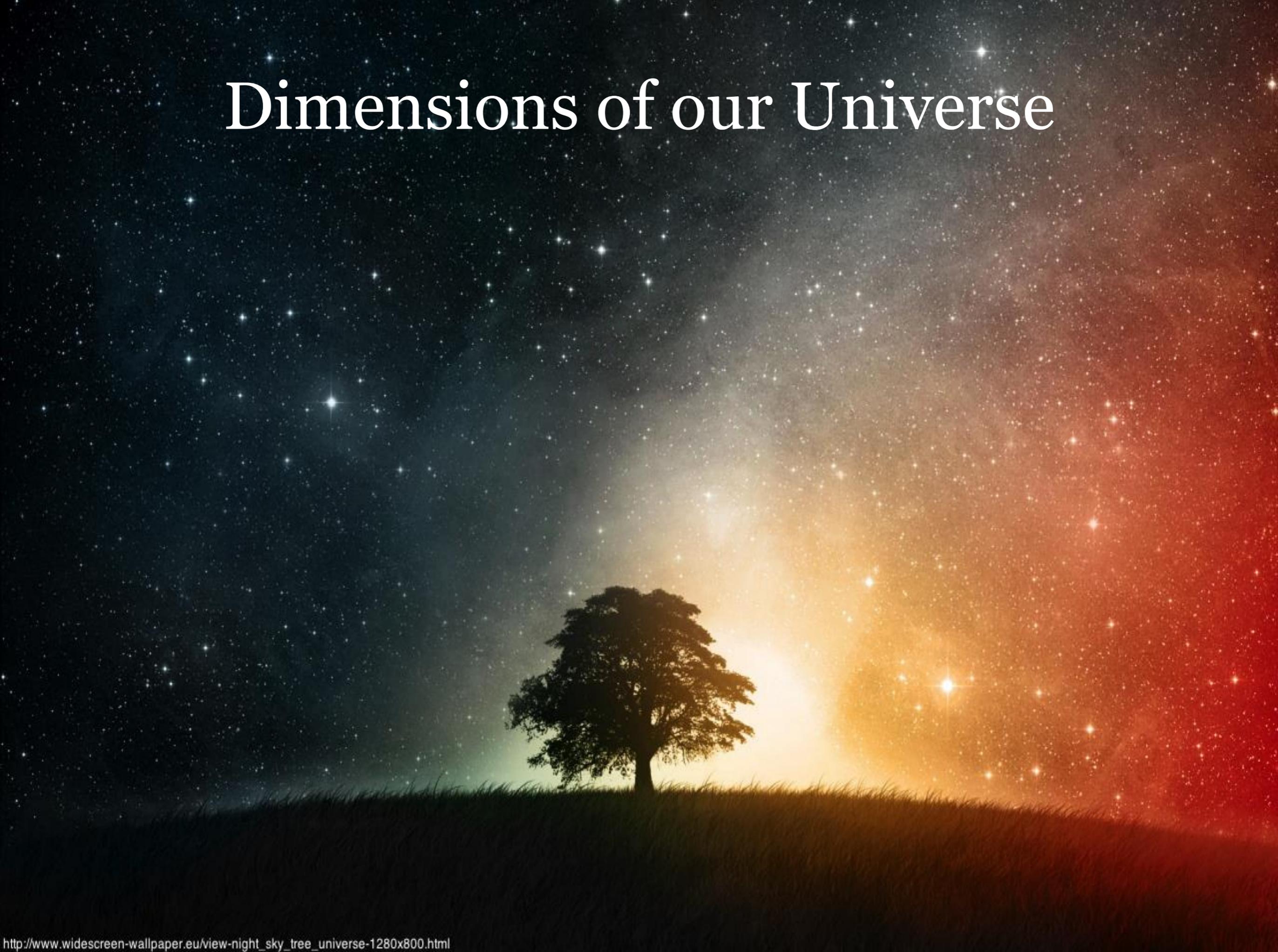
# Cosmological Questions:

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

# Contents

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

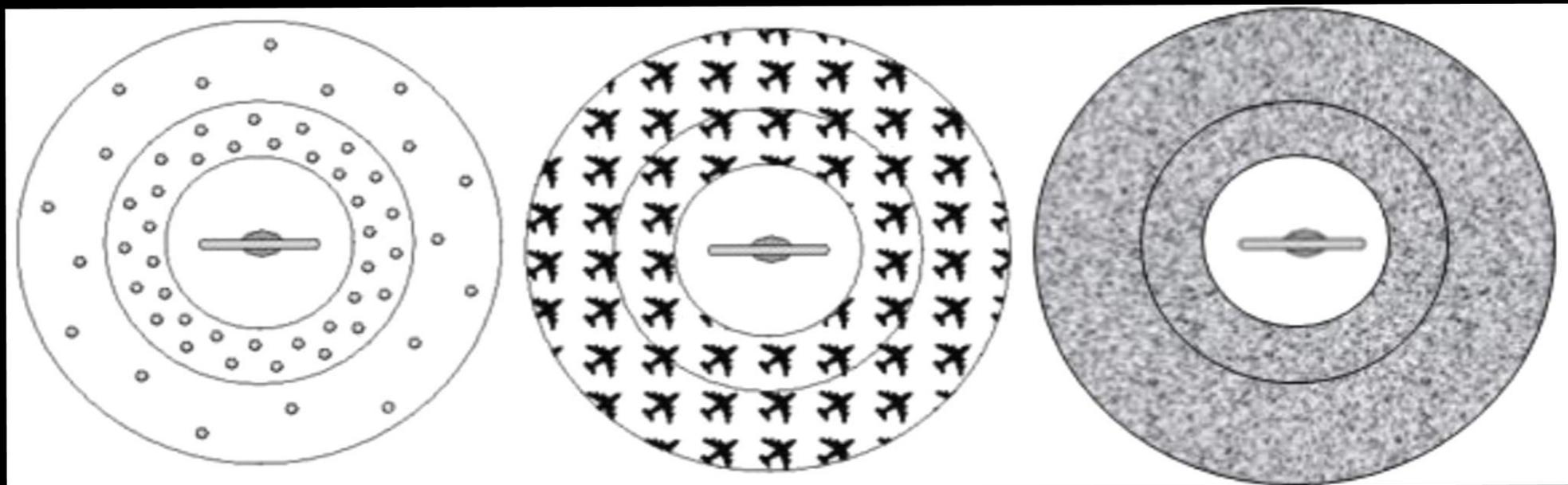
# Dimensions of our Universe



# 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 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:

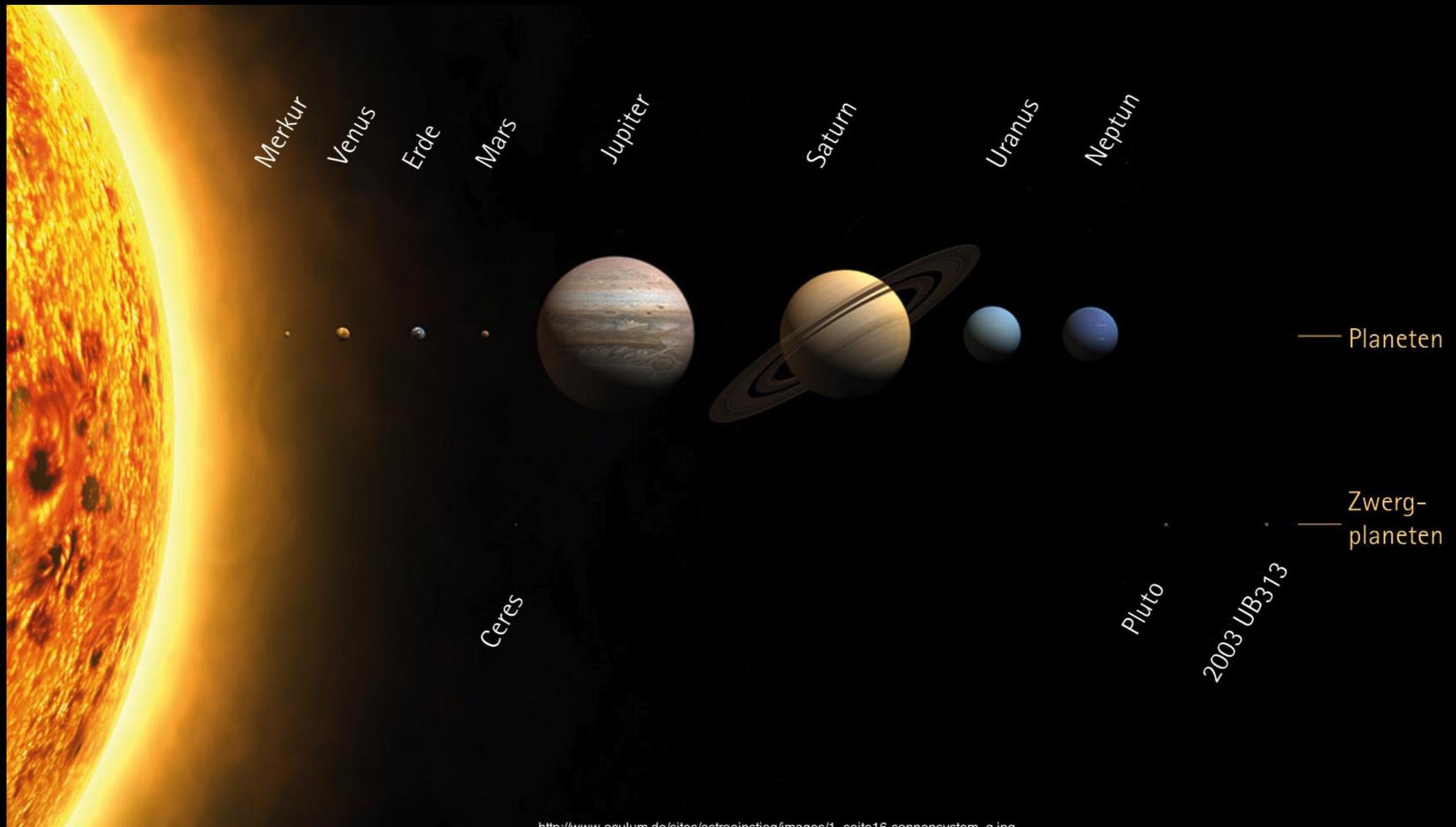
**At night it is dark**

This couldn't be explained with an infinitely large and old Universe.

The Earth:  $\approx 13000$  km in diameter



# The Solar System: ≈ 10 billion km in diameter

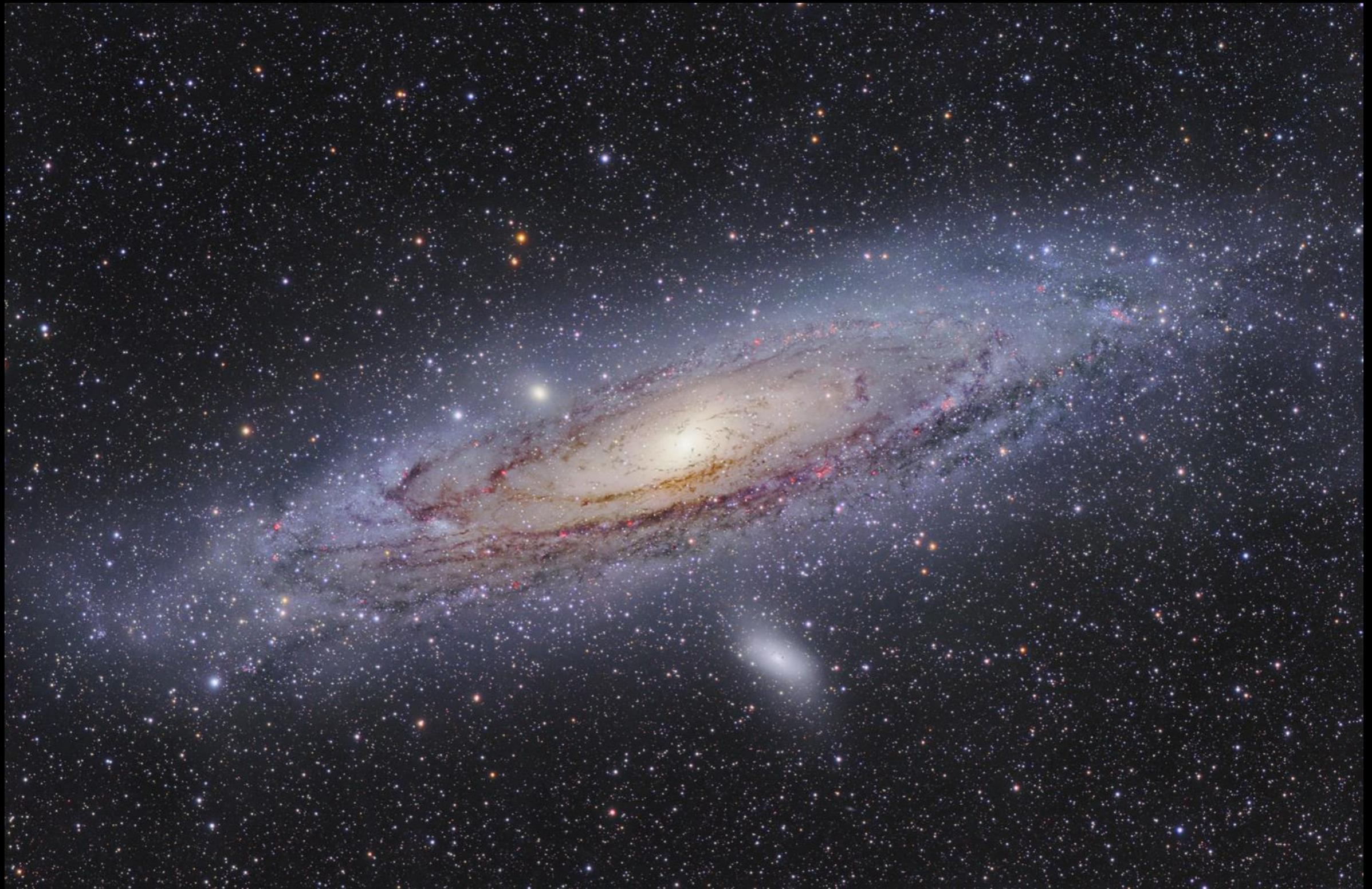


# Our Milky Way:

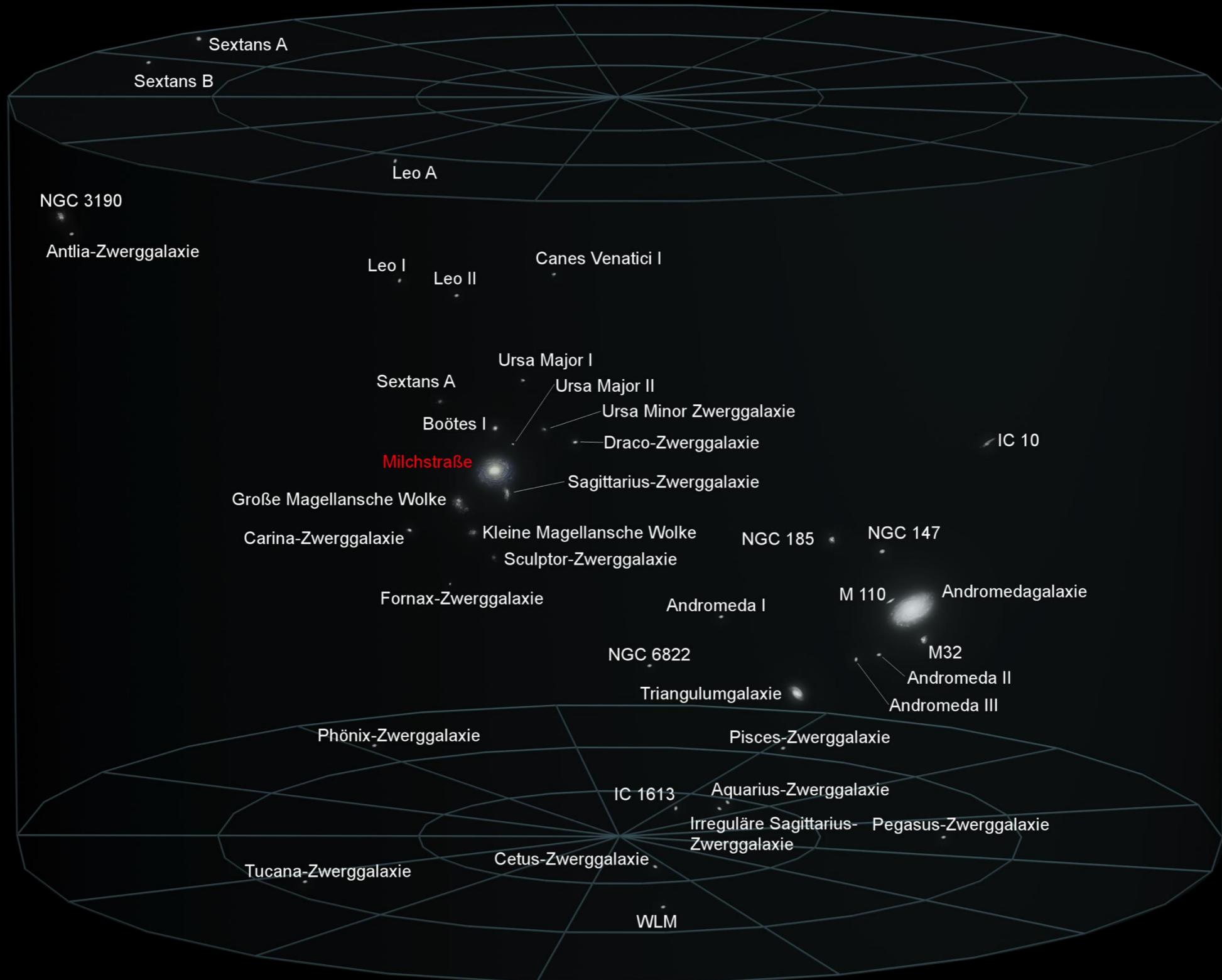
$10^{18}$  km = 100000 light years in diameter



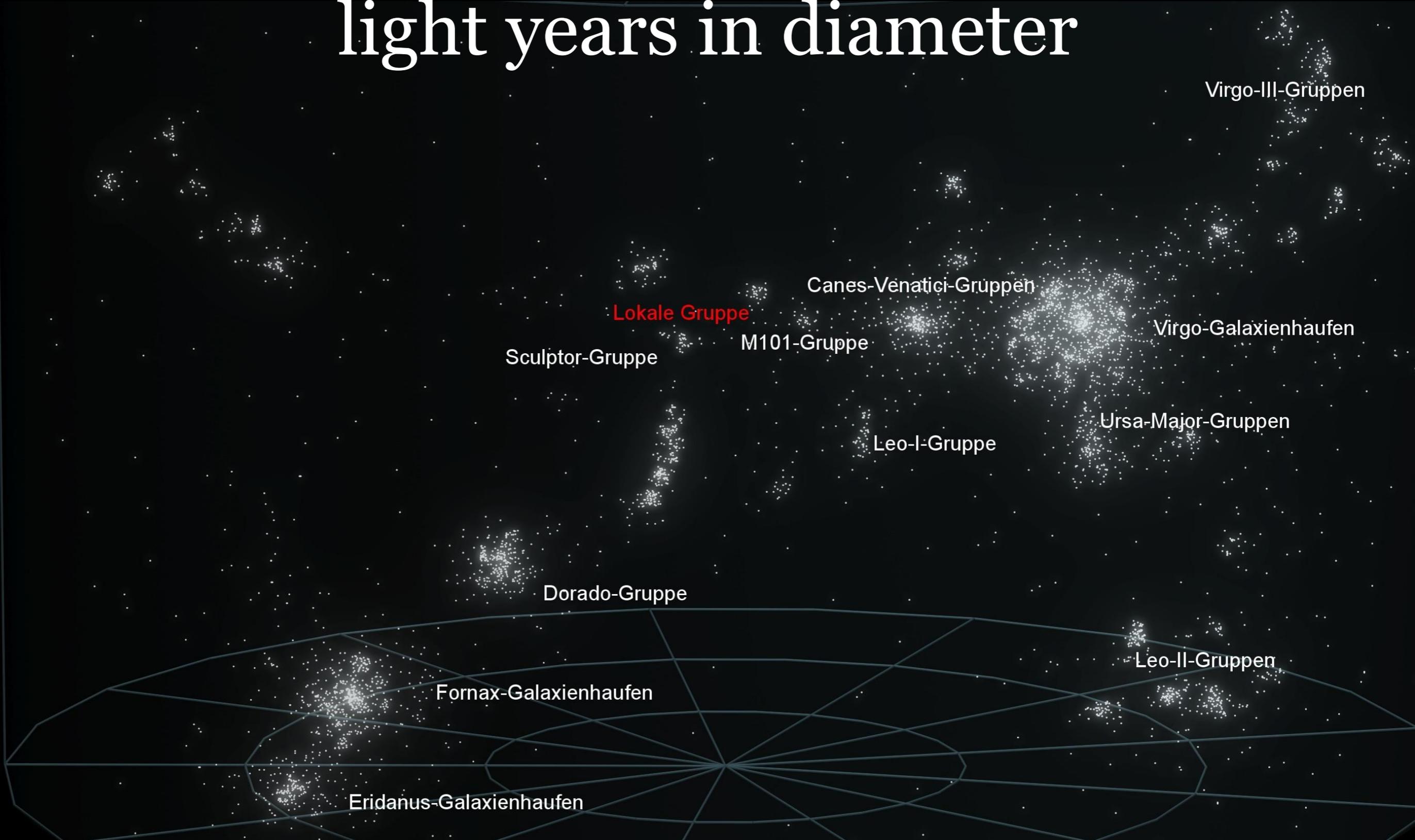
# Andromeda Galaxy: 2.5 million light years distance



# Local Group: 8 million light years in diameter



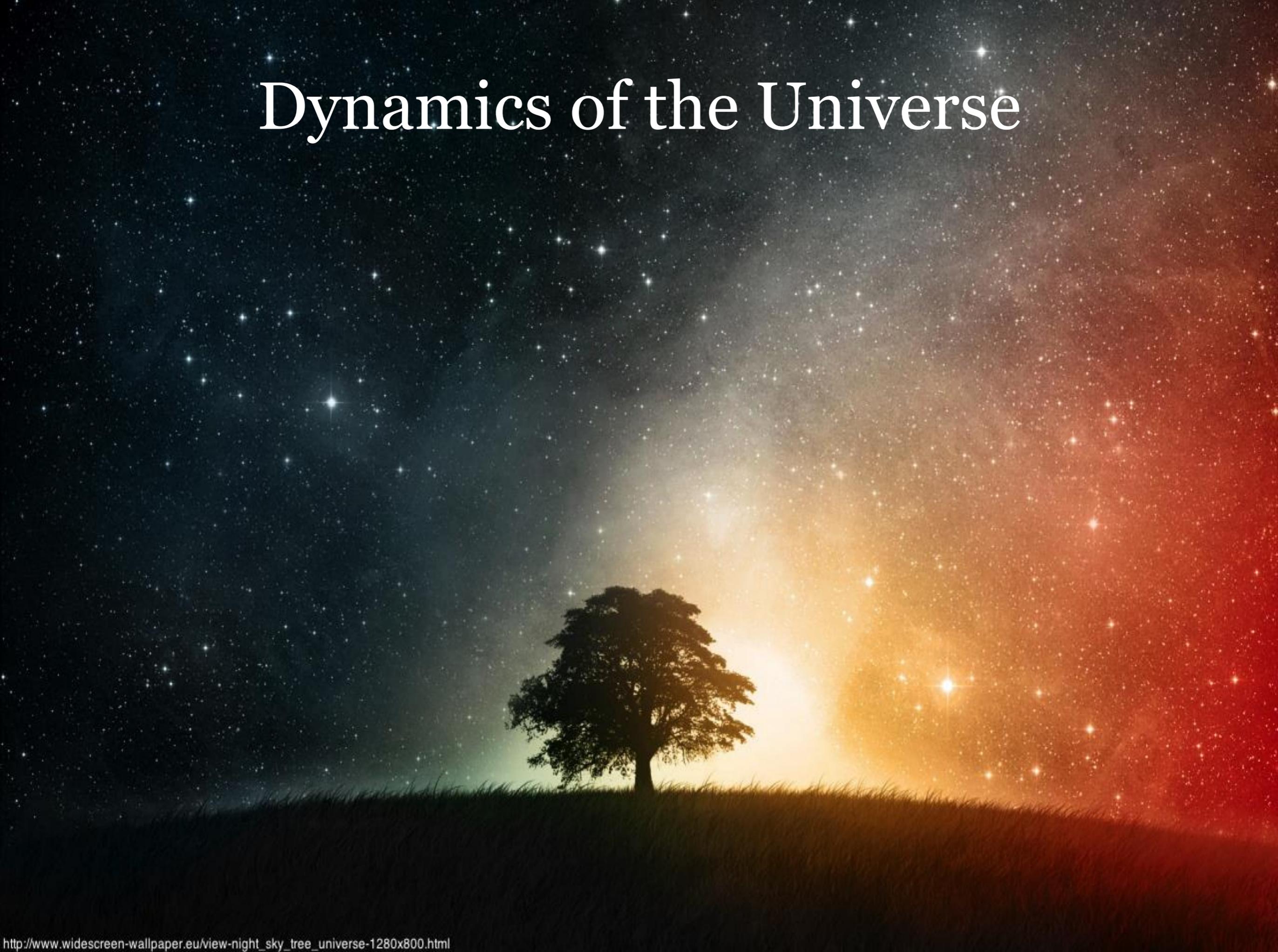
# Virgo Supercluster: 100-200 million light years in diameter



# Hubble Extreme Deep Field



# Dynamics of the Universe

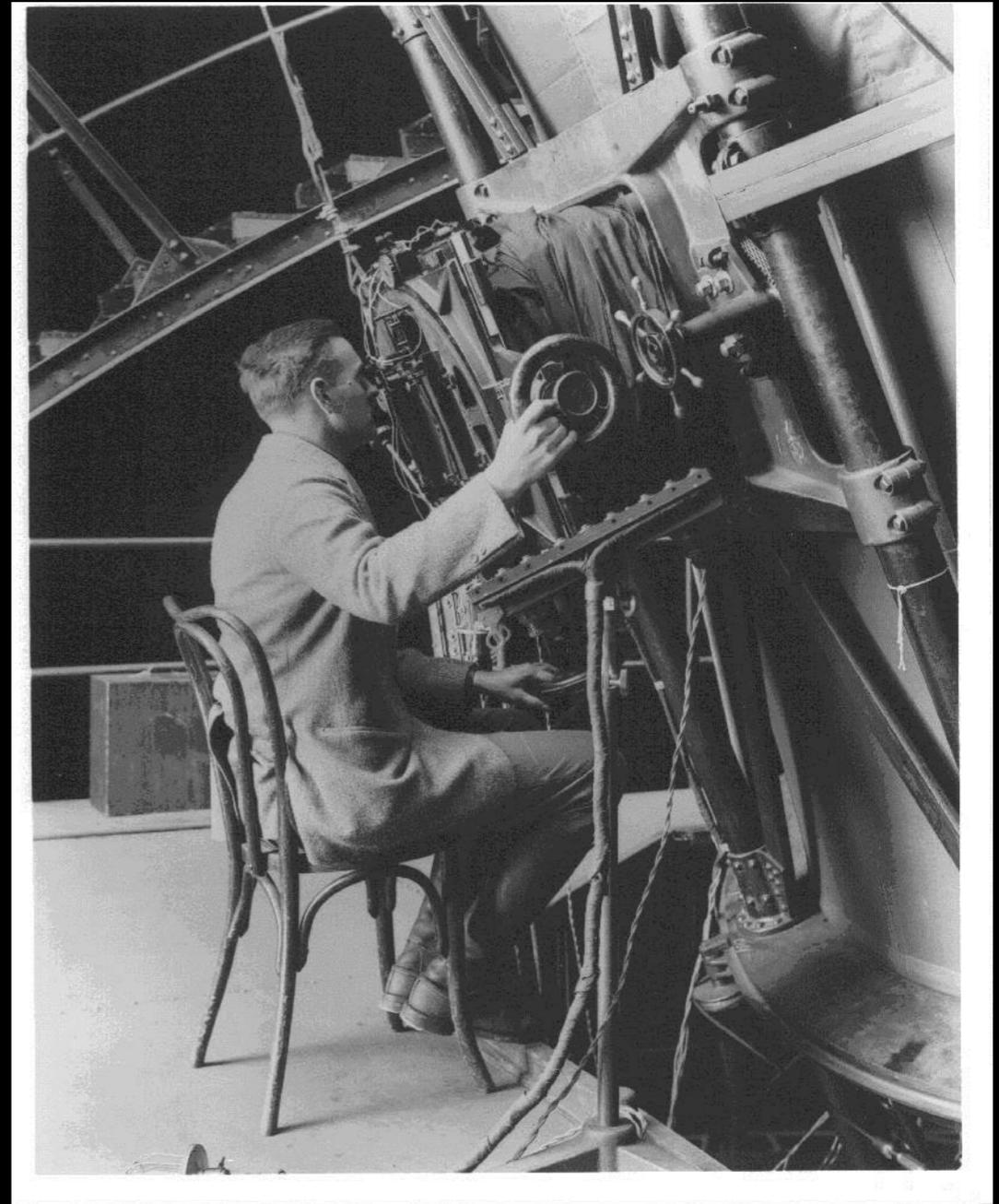


# The Universe is bigger than we thought!

1924

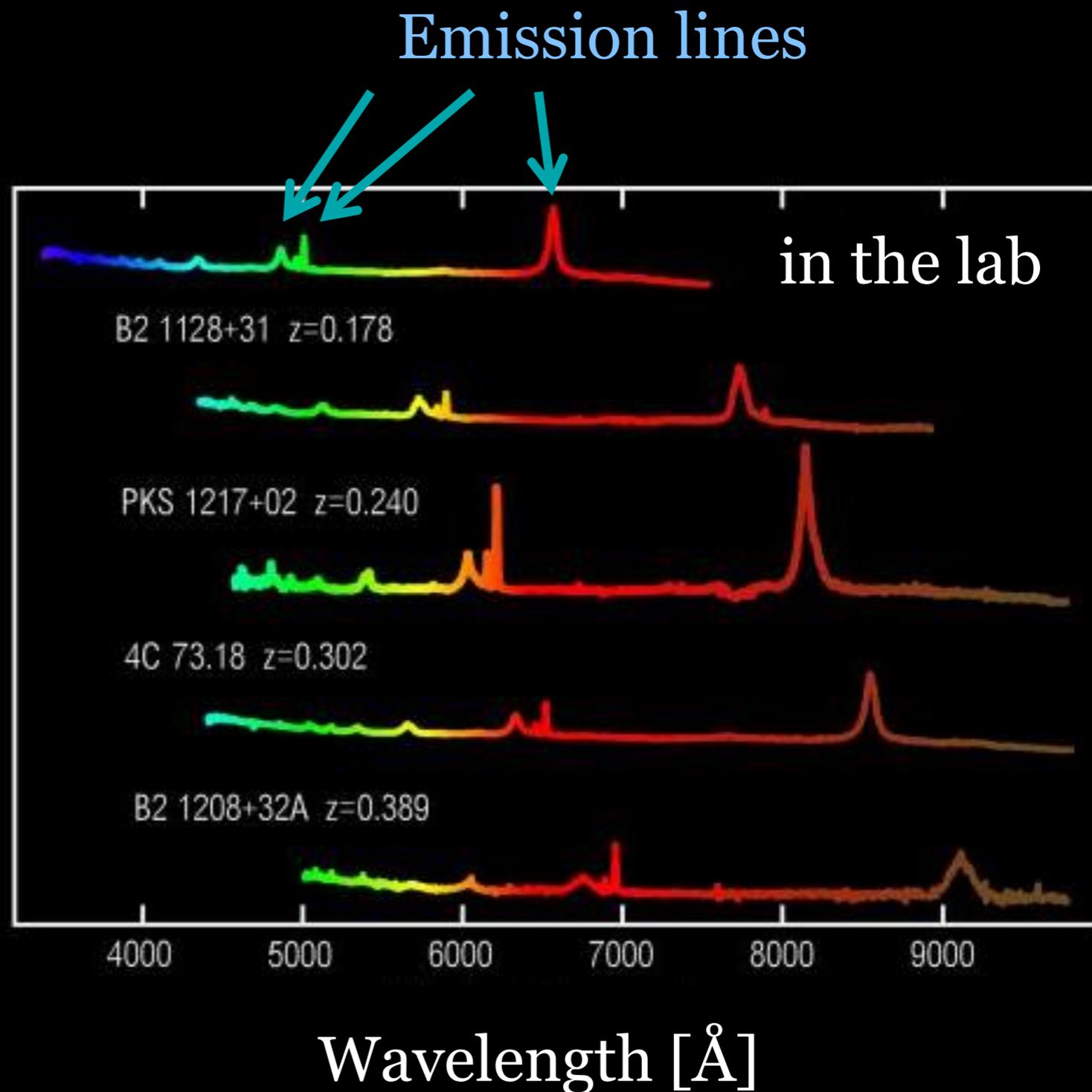
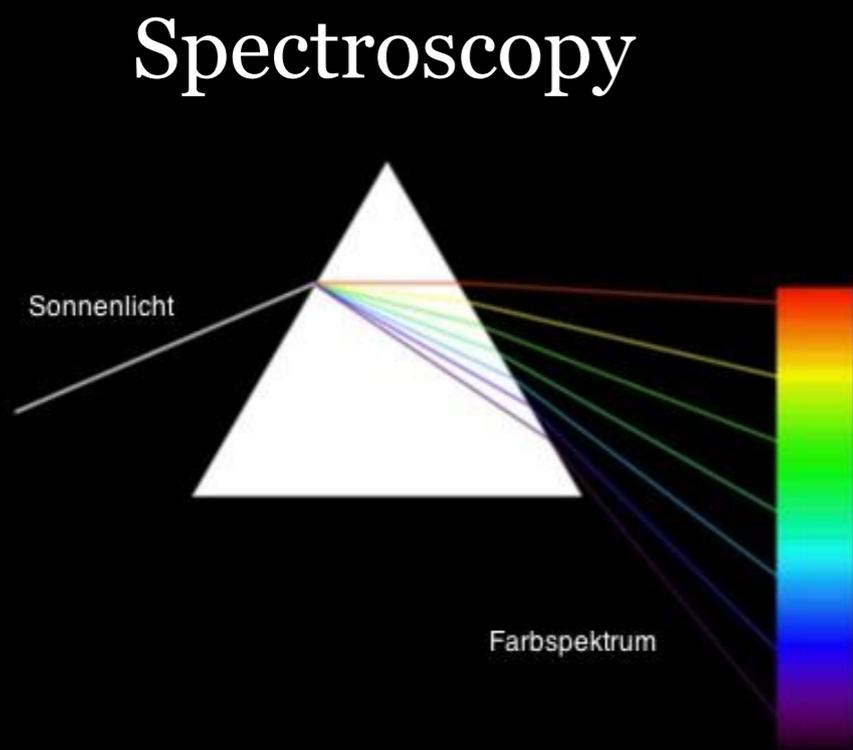


Edwin Hubble  
Mt. Palomar telescope

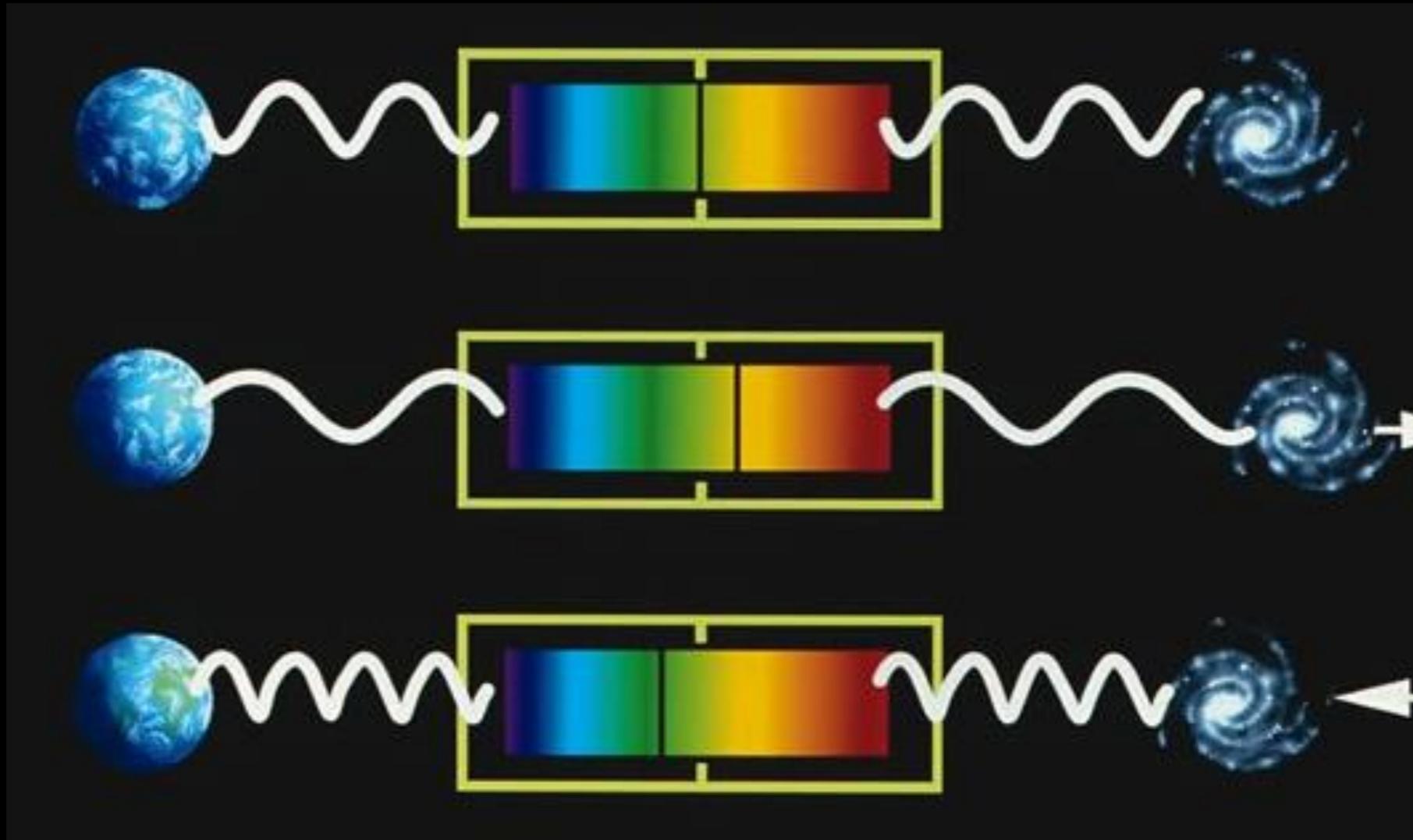


Observation of „nebulas“  
Proof of the existence of galaxies outside the  
Milky Way

# Measuring of the Redshift

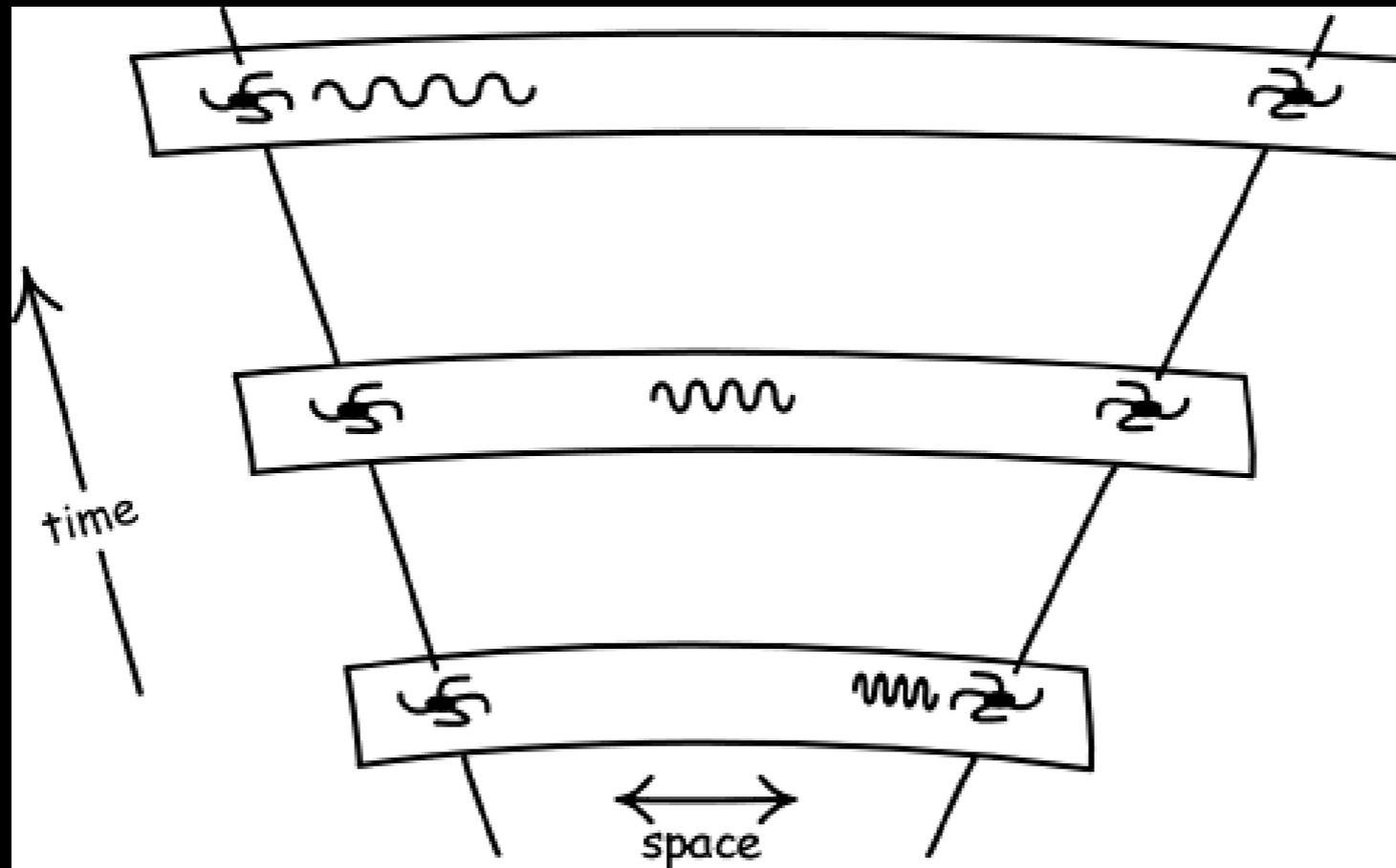


# Cosmological Redshift vs. Doppler Effect



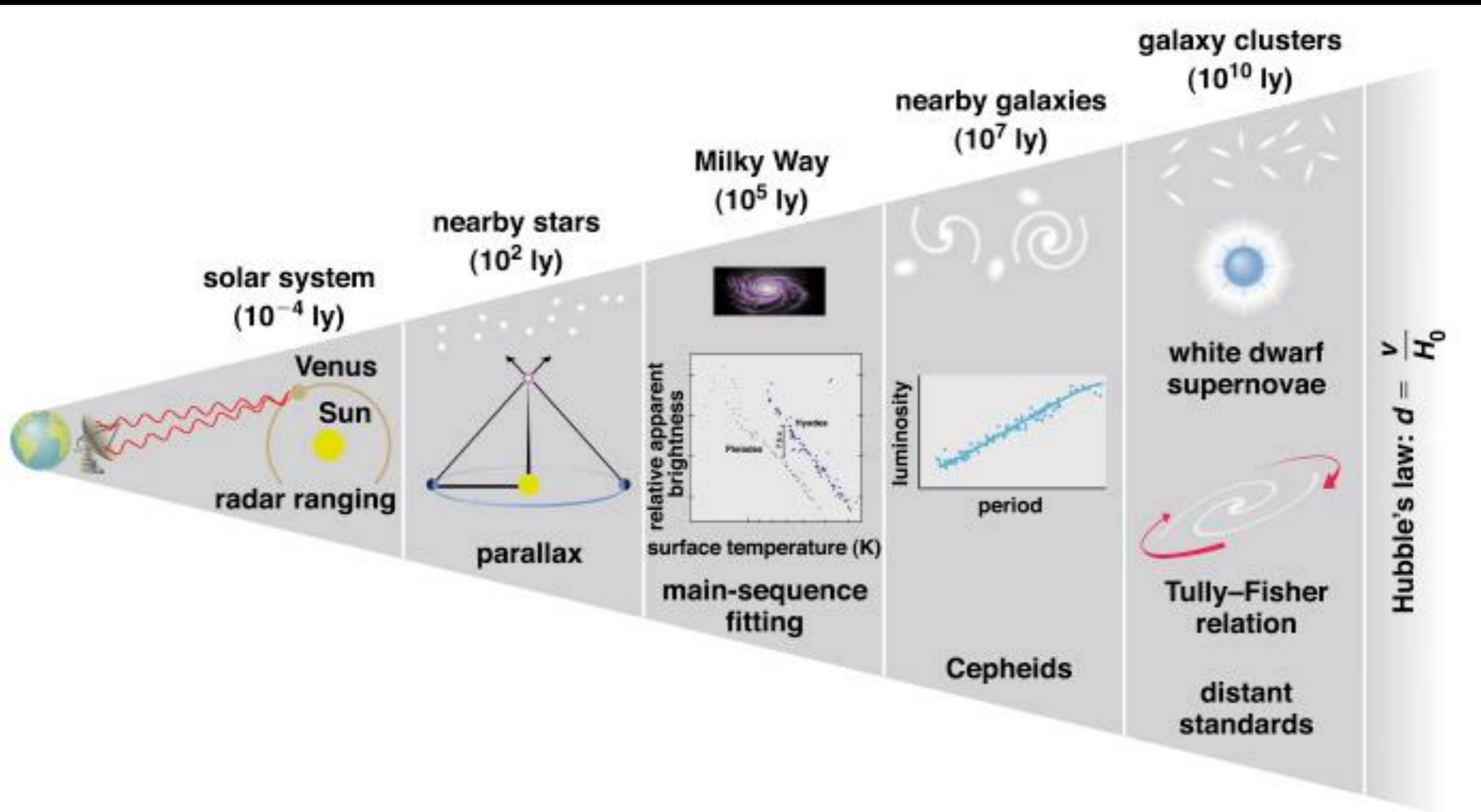
The cosmological redshift is comparable with a redshift caused by a relative movement of source and observer

# Cosmological Redshift

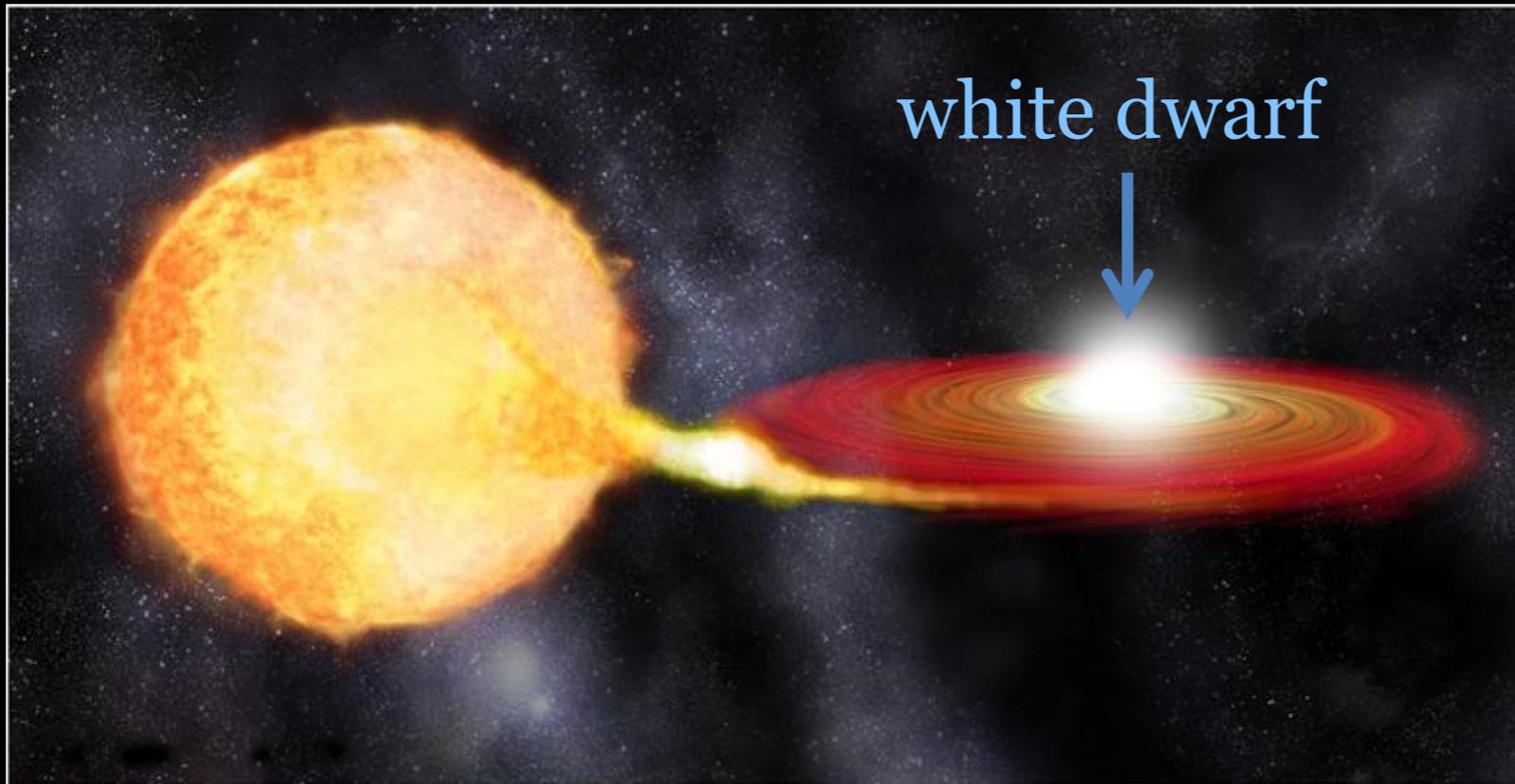


Space itself expands and “stretches” the wavelength of the photons.

# Distance Ladder

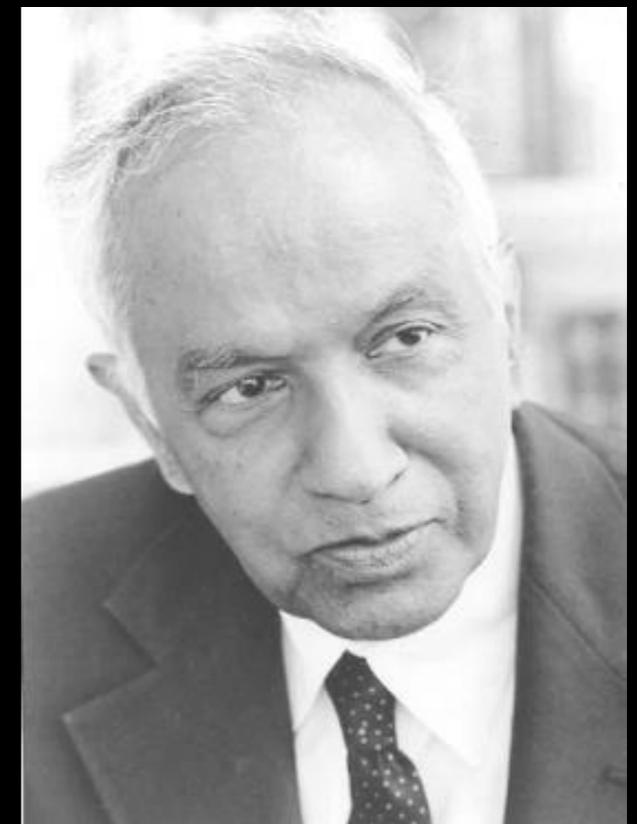
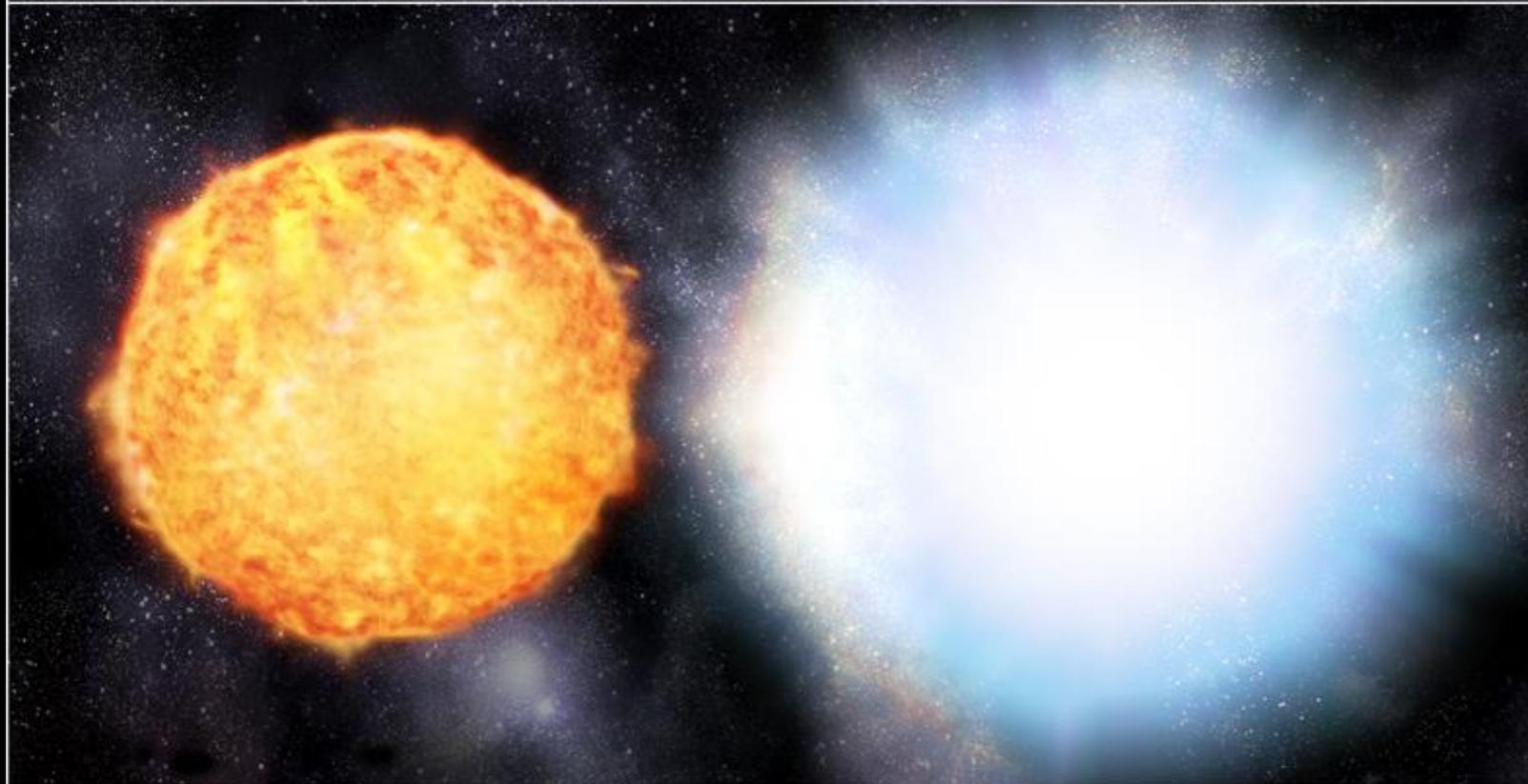


# Type Ia Supernova

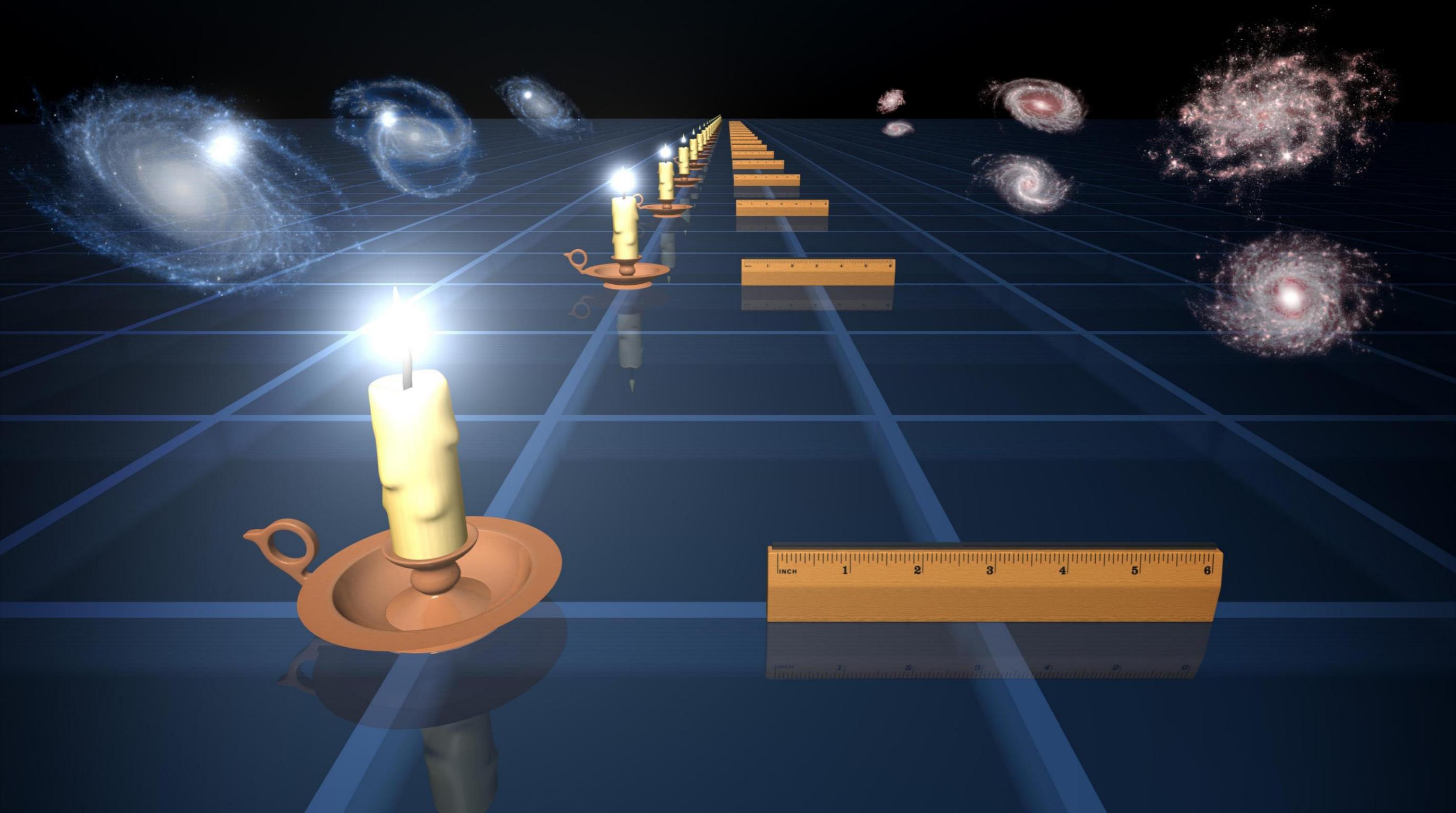


Chandrasekhar limit:

$$M \approx 1.4 M_{\text{sun}}$$



# 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

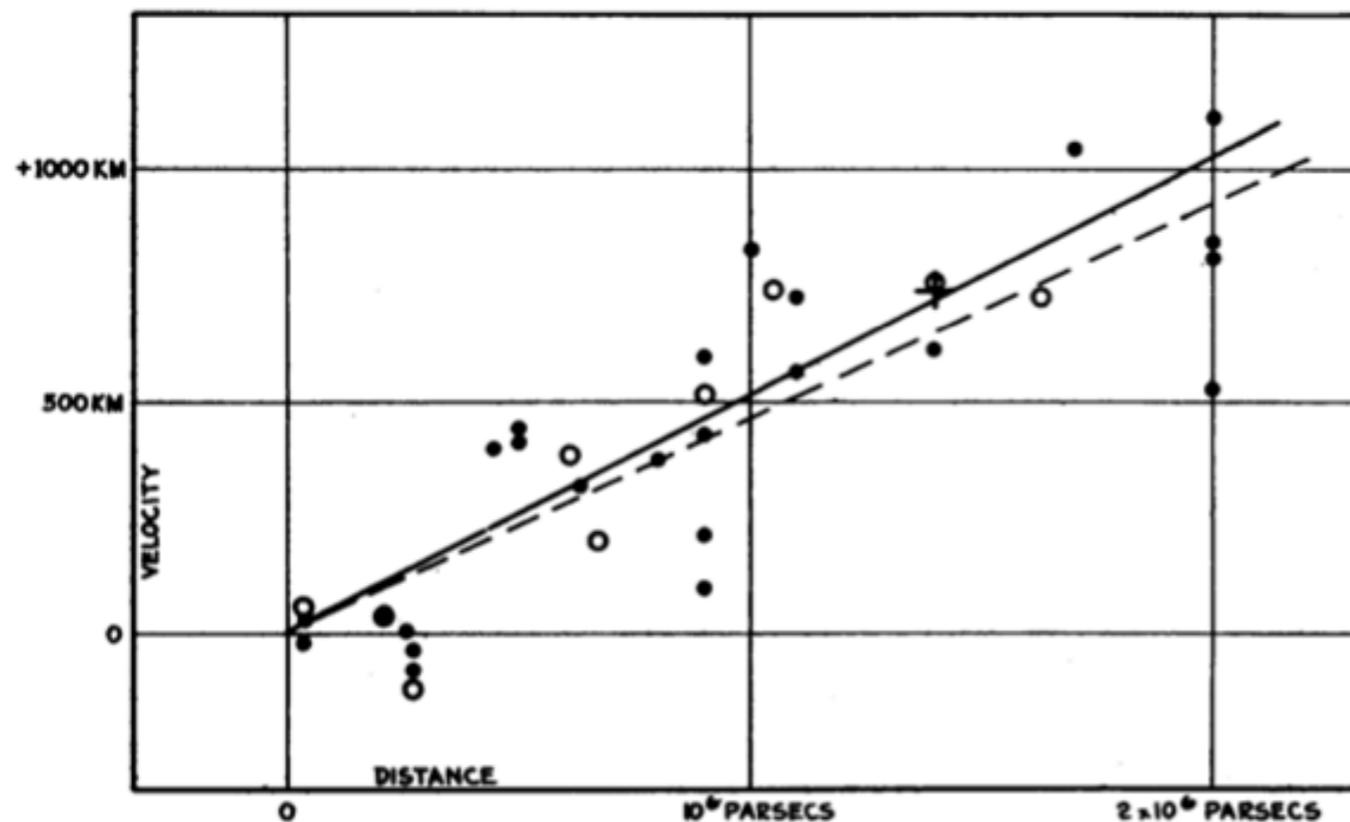


FIGURE 1

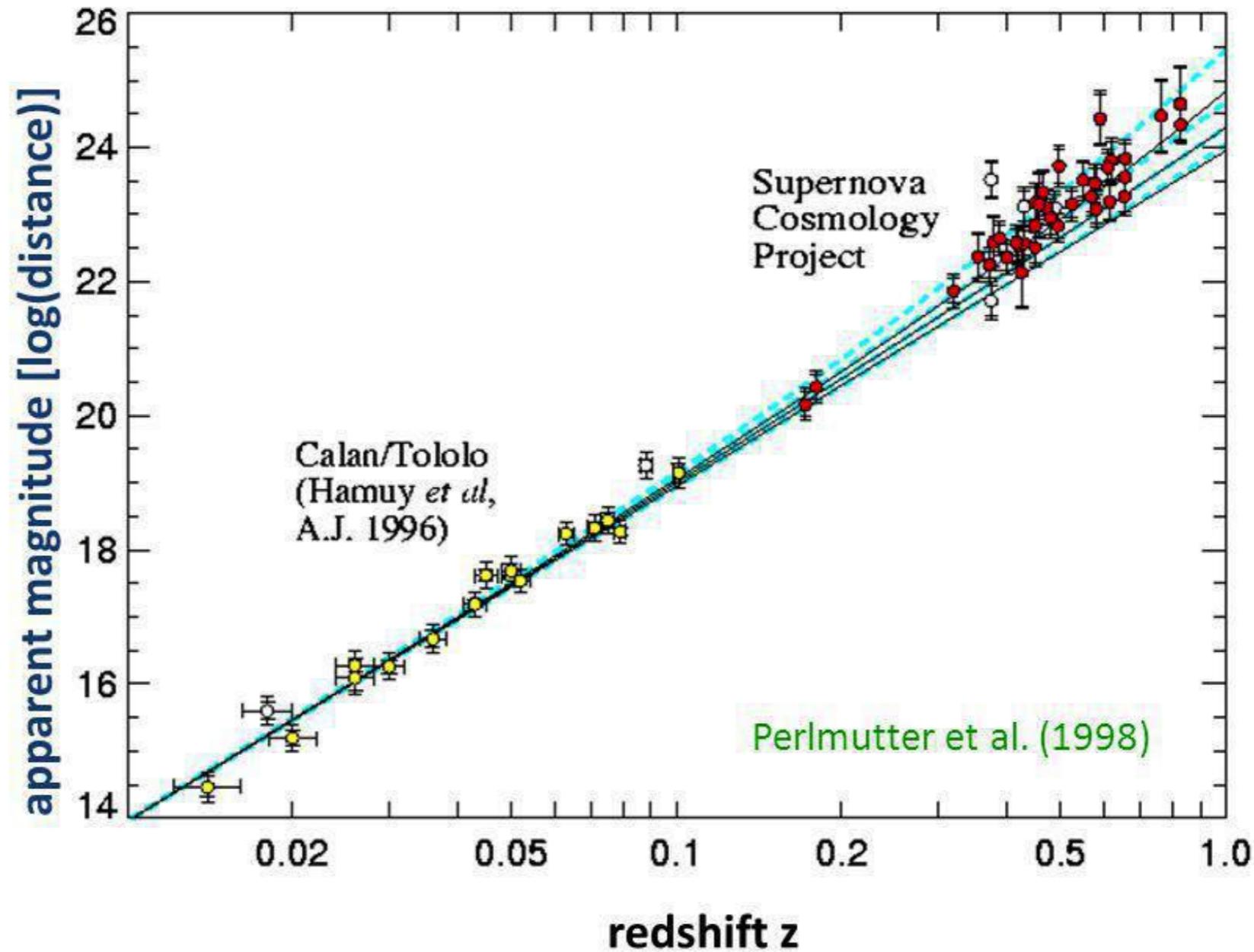
redshift is proportional to the distance of the galaxies (galaxy escape)

Hubble's law:  $v = H_0 d$

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

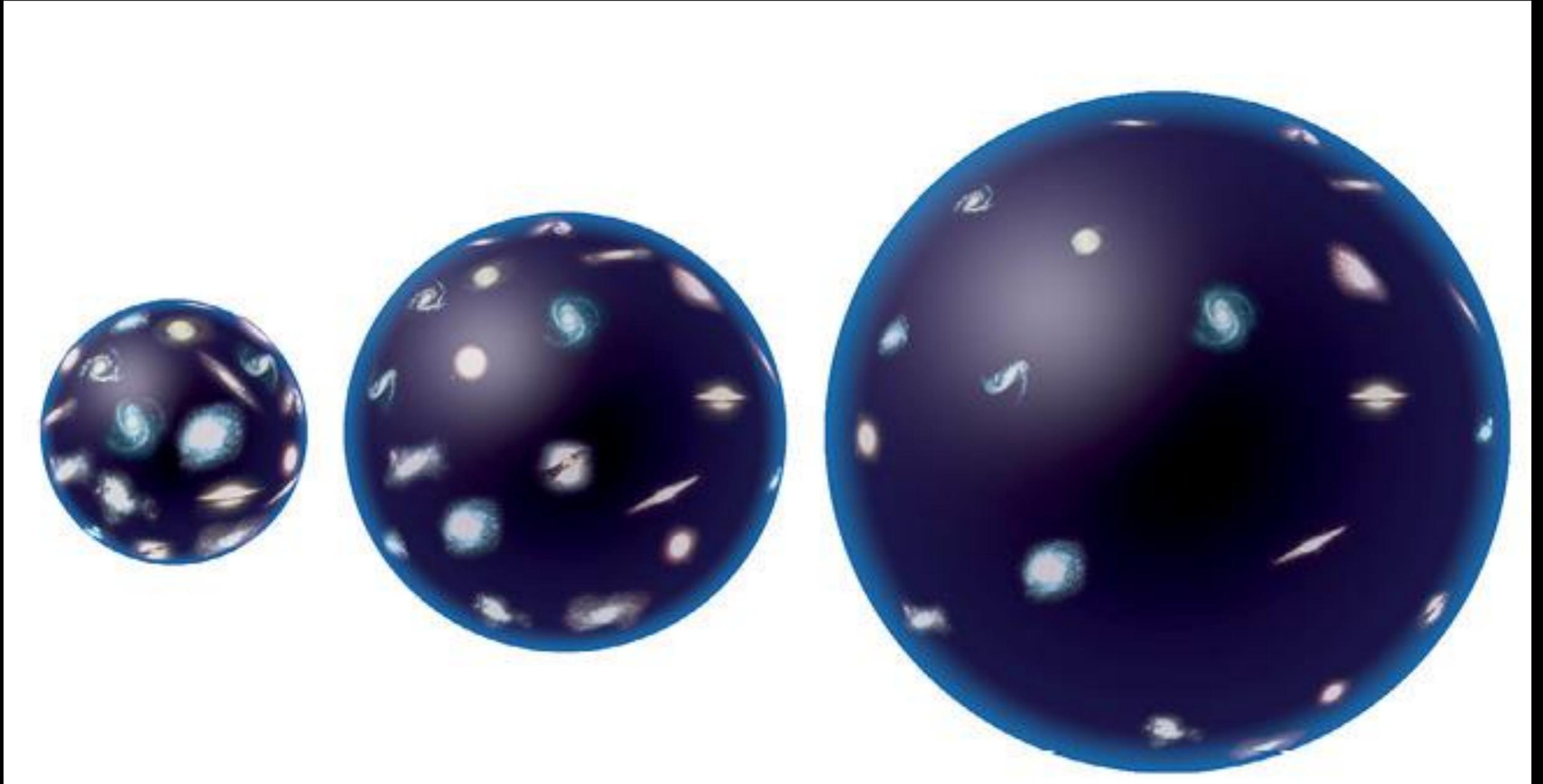
# The present value of the Hubble "constant"

## Type Ia supernova Hubble diagram



Today:  $H = 70 \pm 3 \text{ km s}^{-1} \text{ Mpc}^{-1}$

# Consequences of the Cosmological Expansion

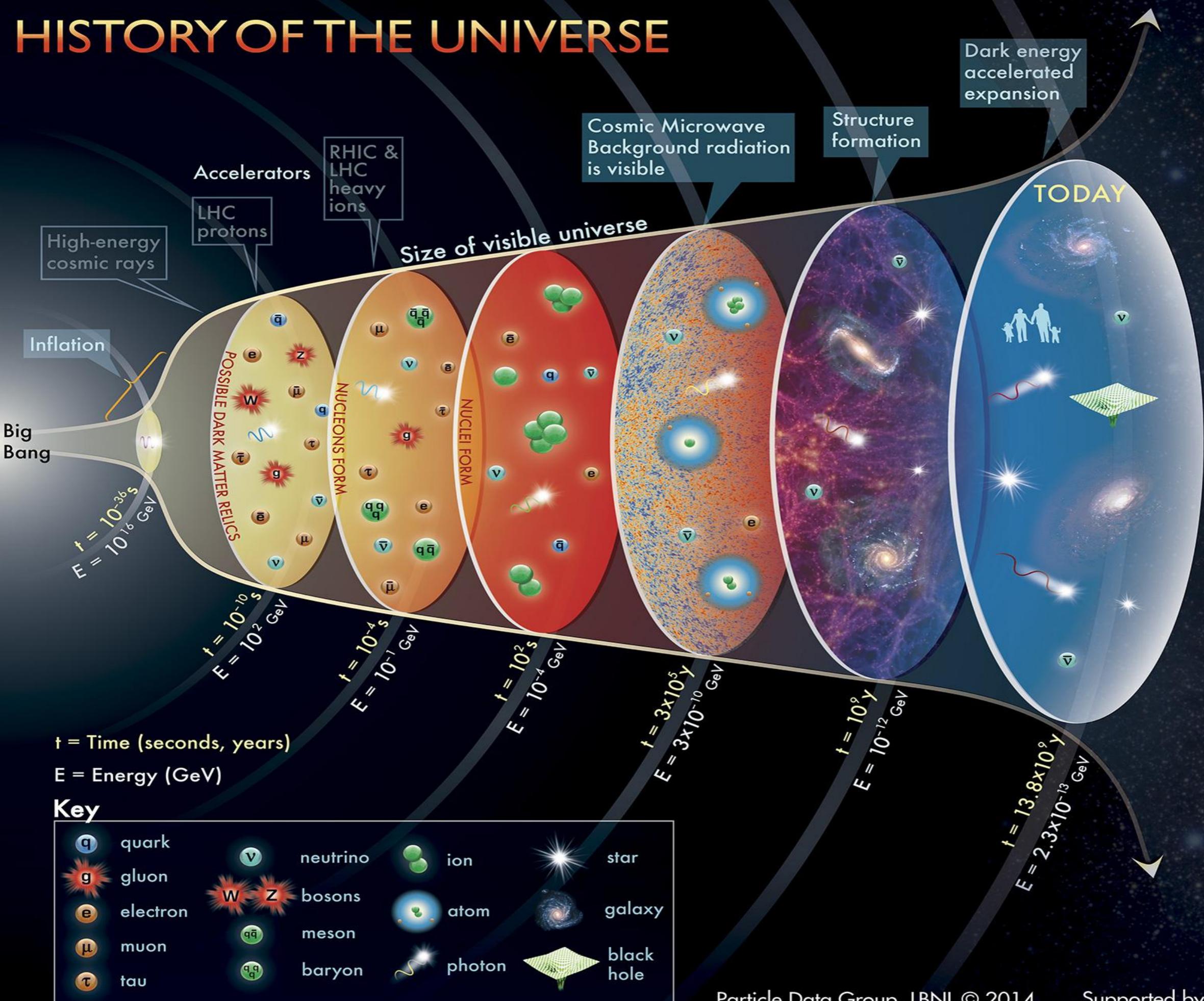


The further we look back into the past, the smaller was the Universe.  
➡ conclusion about the Big Bang

# A Journey through Time

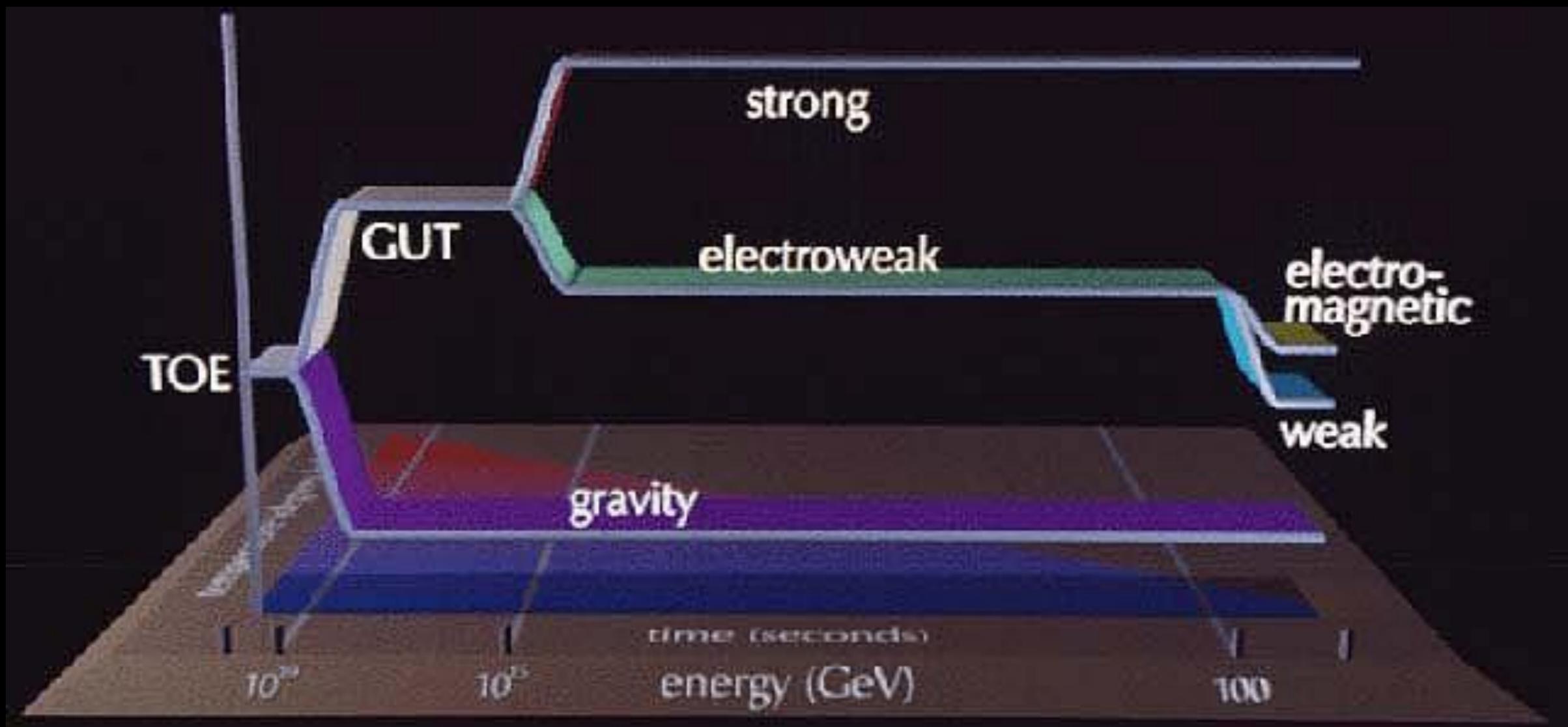


# HISTORY OF THE UNIVERSE

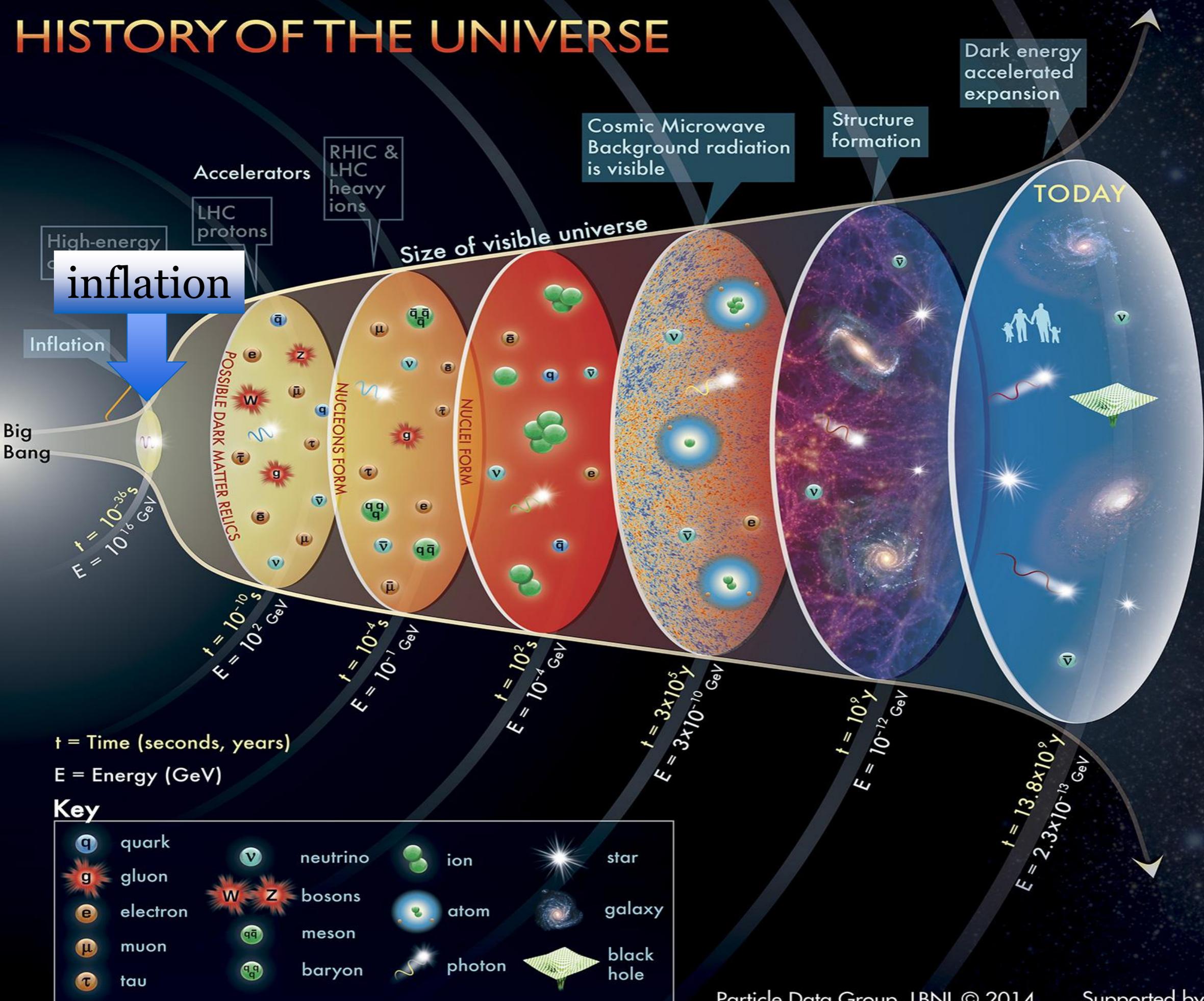


# Unification of the Forces

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



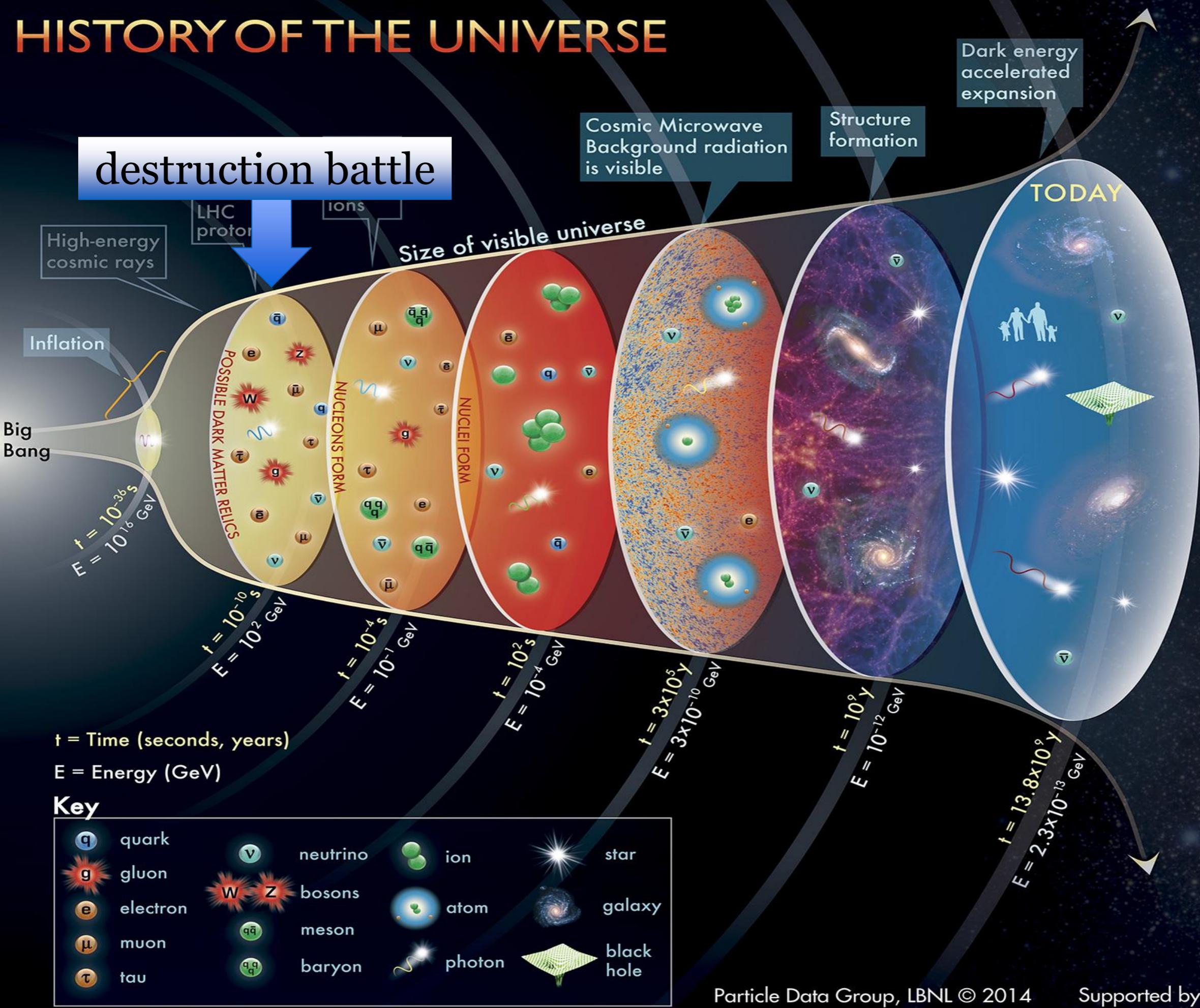
# HISTORY OF THE UNIVERSE



# HISTORY OF THE UNIVERSE

Dark energy accelerated expansion

destruction battle



Cosmic Microwave Background radiation is visible

Structure formation

TODAY

Size of visible universe

LHC proton ions

High-energy cosmic rays

Inflation

Big Bang

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

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

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

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

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

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

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

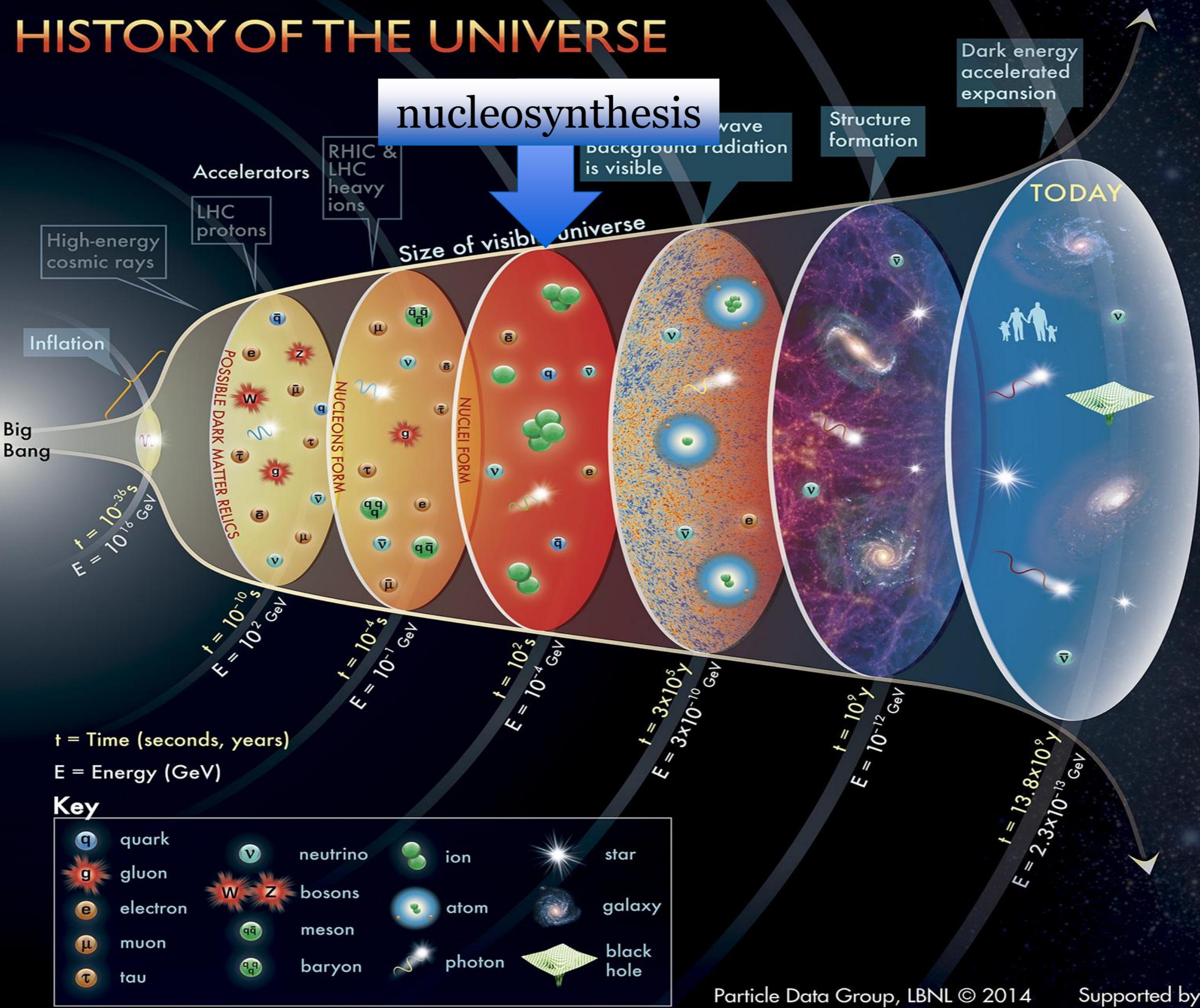
t = Time (seconds, years)  
E = Energy (GeV)

## Key

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

# HISTORY OF THE UNIVERSE

## nucleosynthesis



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

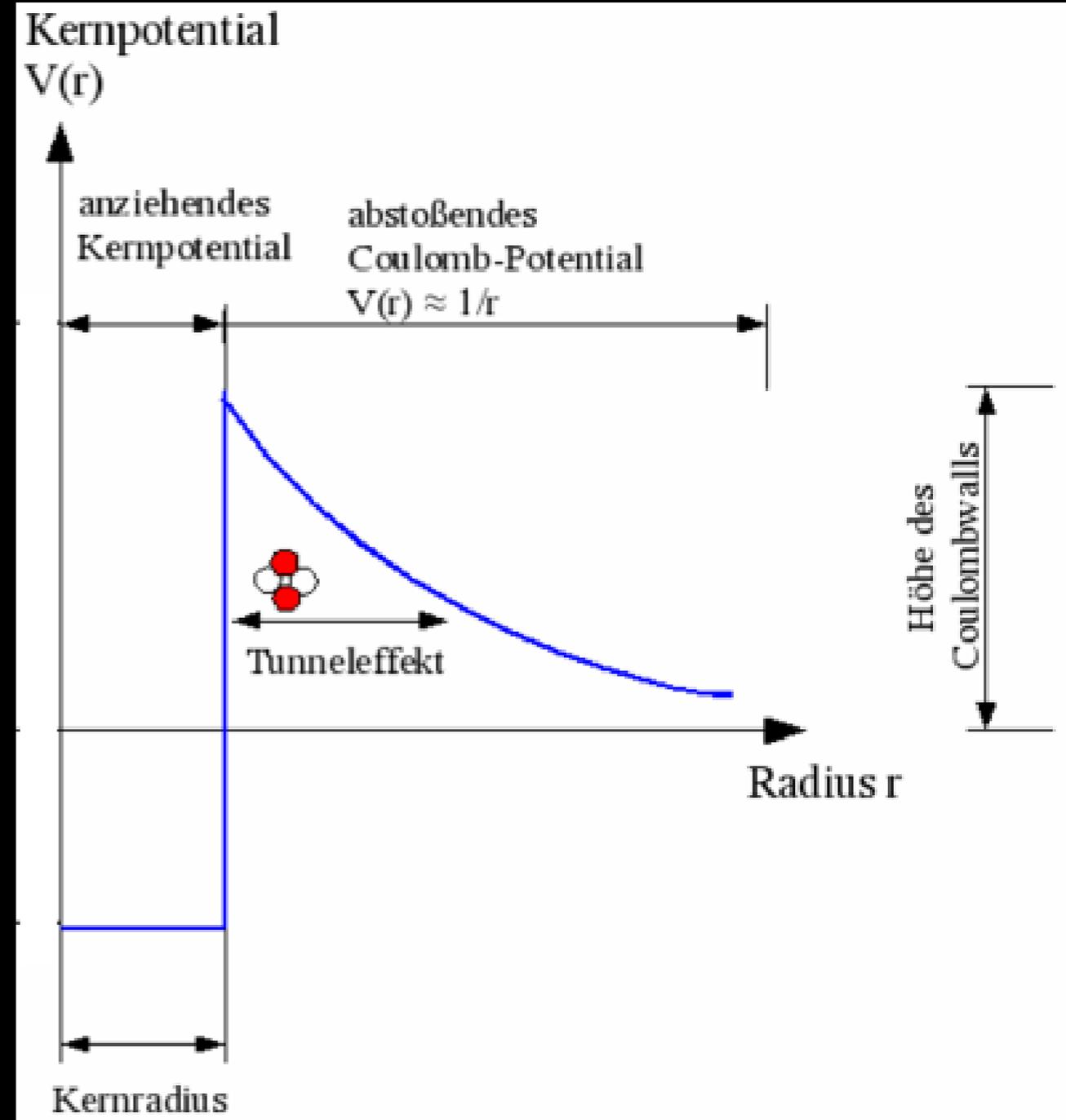
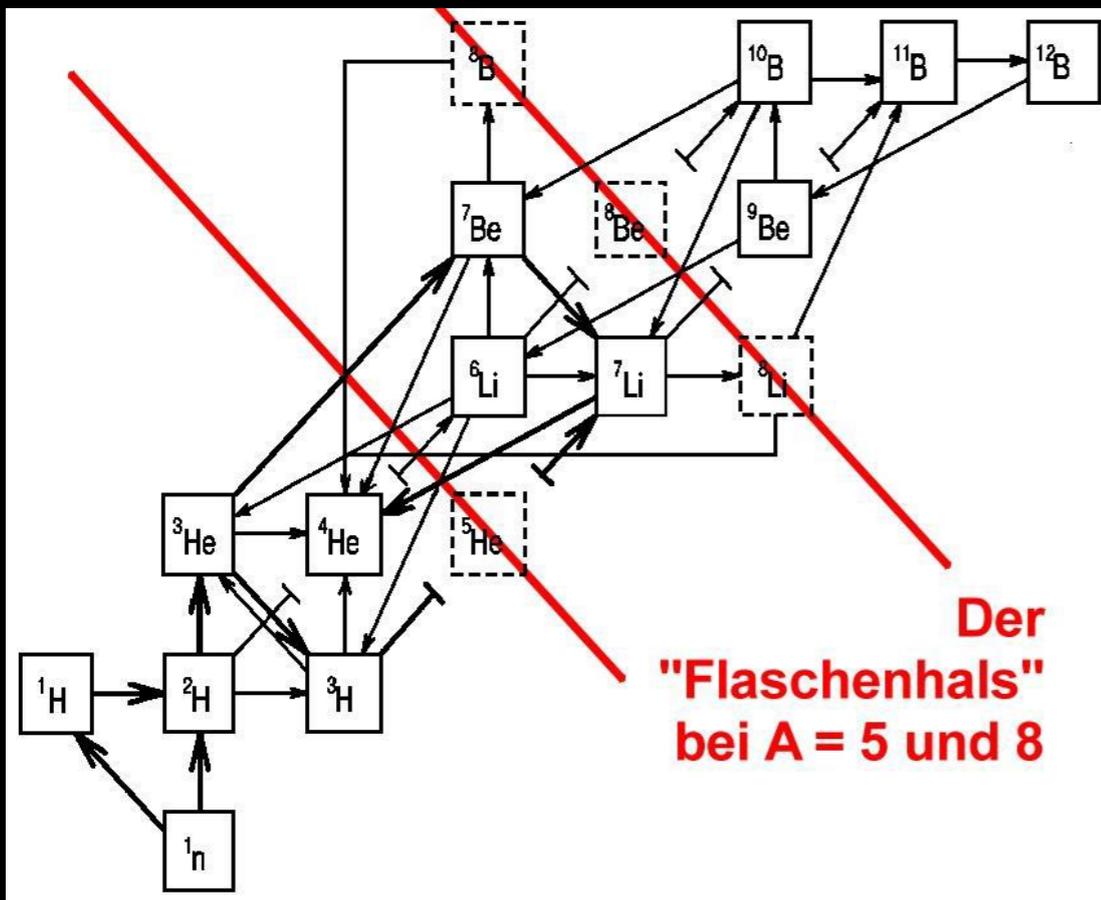
### Key

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# Nuclear Fusion

fusion in particle collisions

fusion needs high temperatures  
and high particle densities



# Primordial Nucleosynthesis

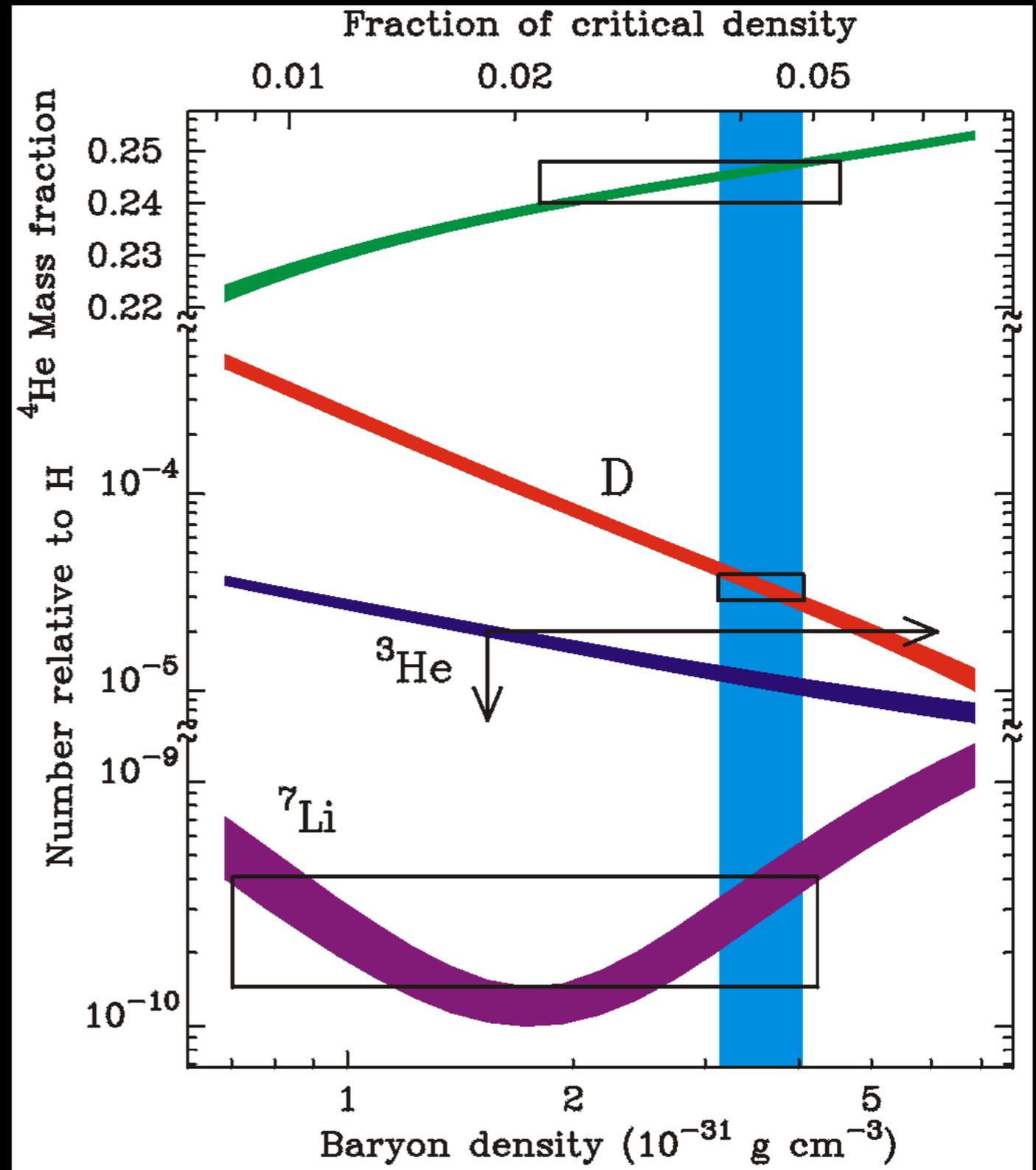
explains the abundances of light elements

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

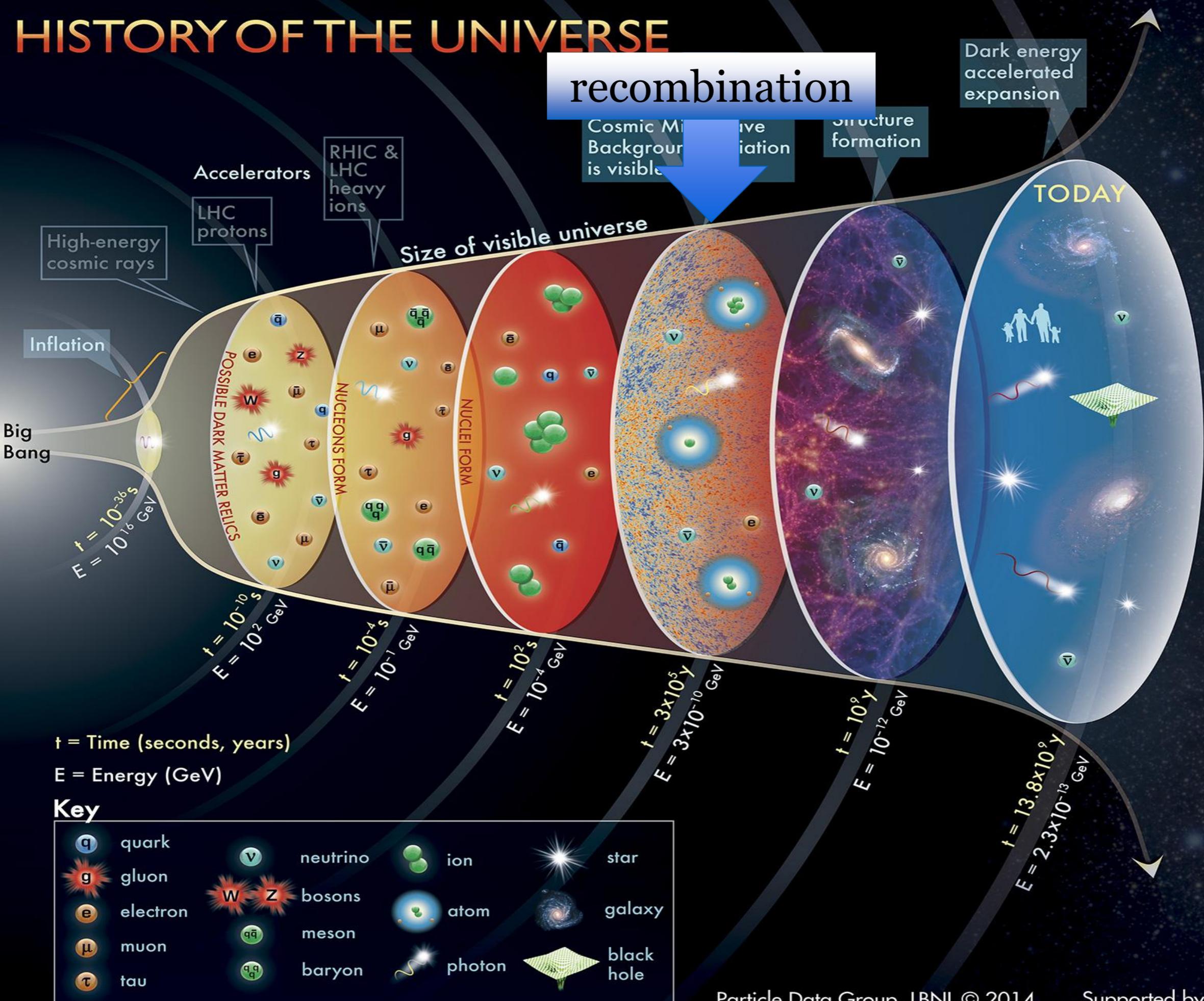
baryon density

$3,5 \cdot 10^{-31} \text{ g/cm}^3$  or  
0,2 hydrogen atoms/ $\text{m}^3$

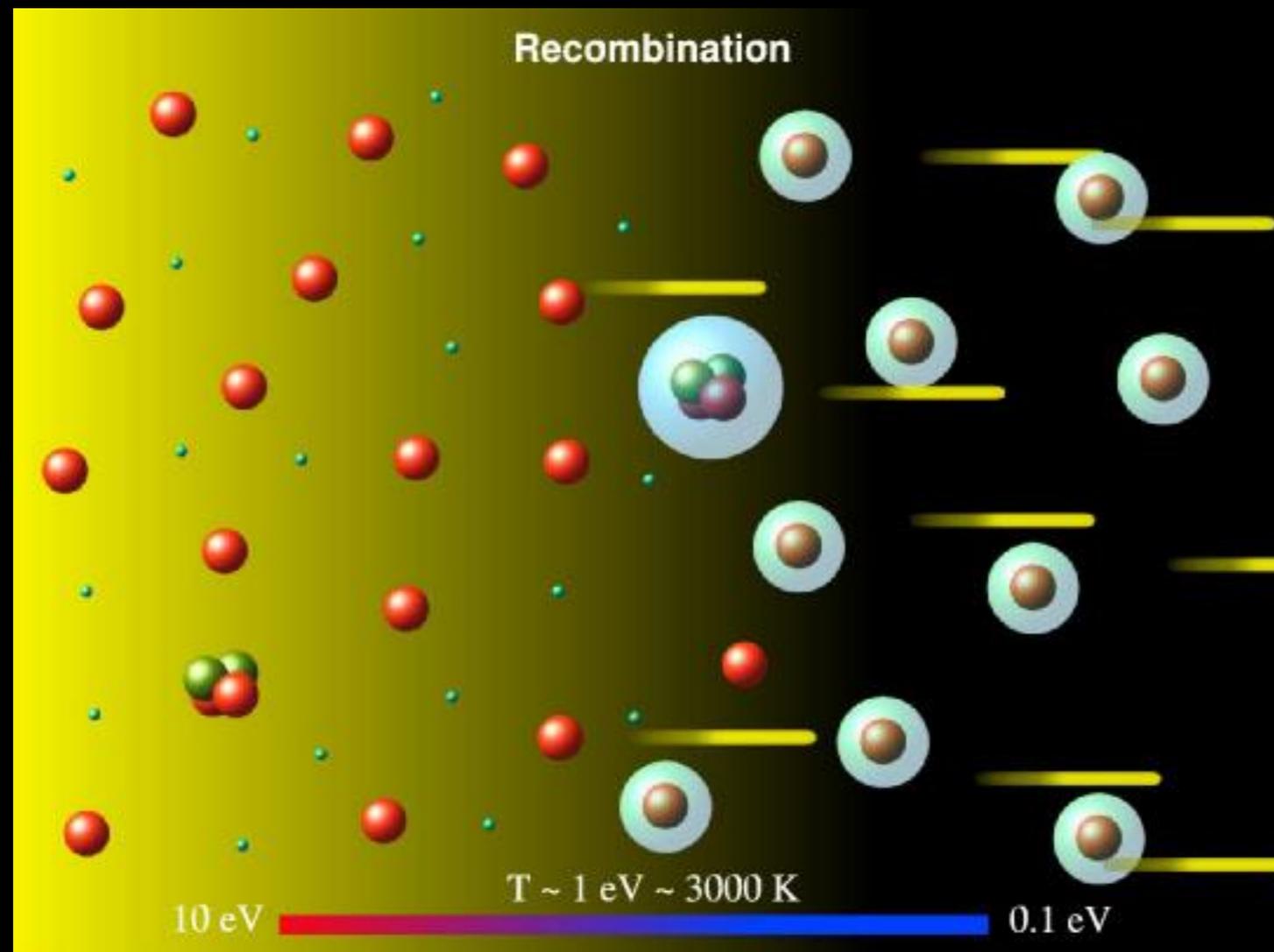
baryons contribute about  
4-5% to the critical density



# HISTORY OF THE UNIVERSE

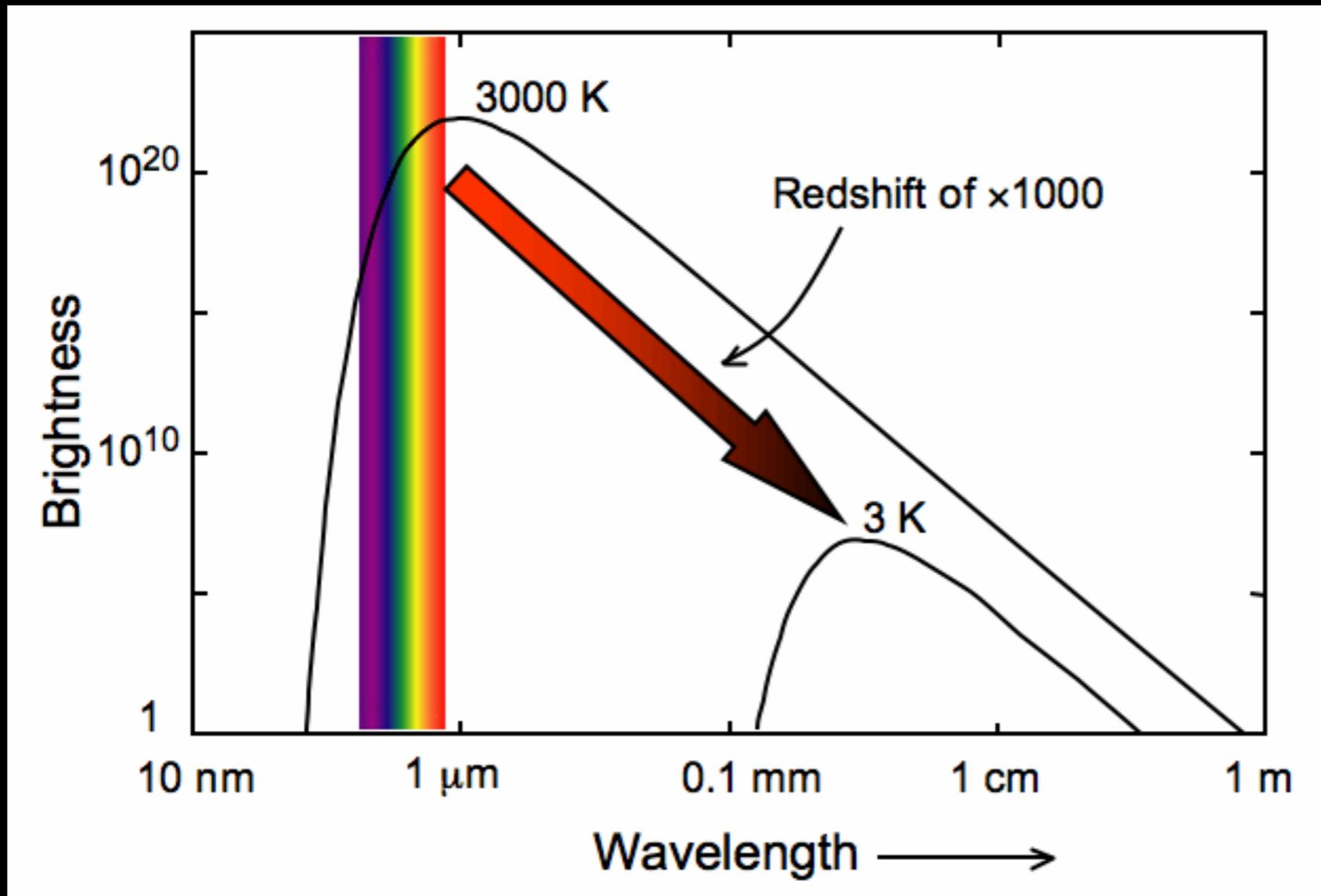


# Recombination



- 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)

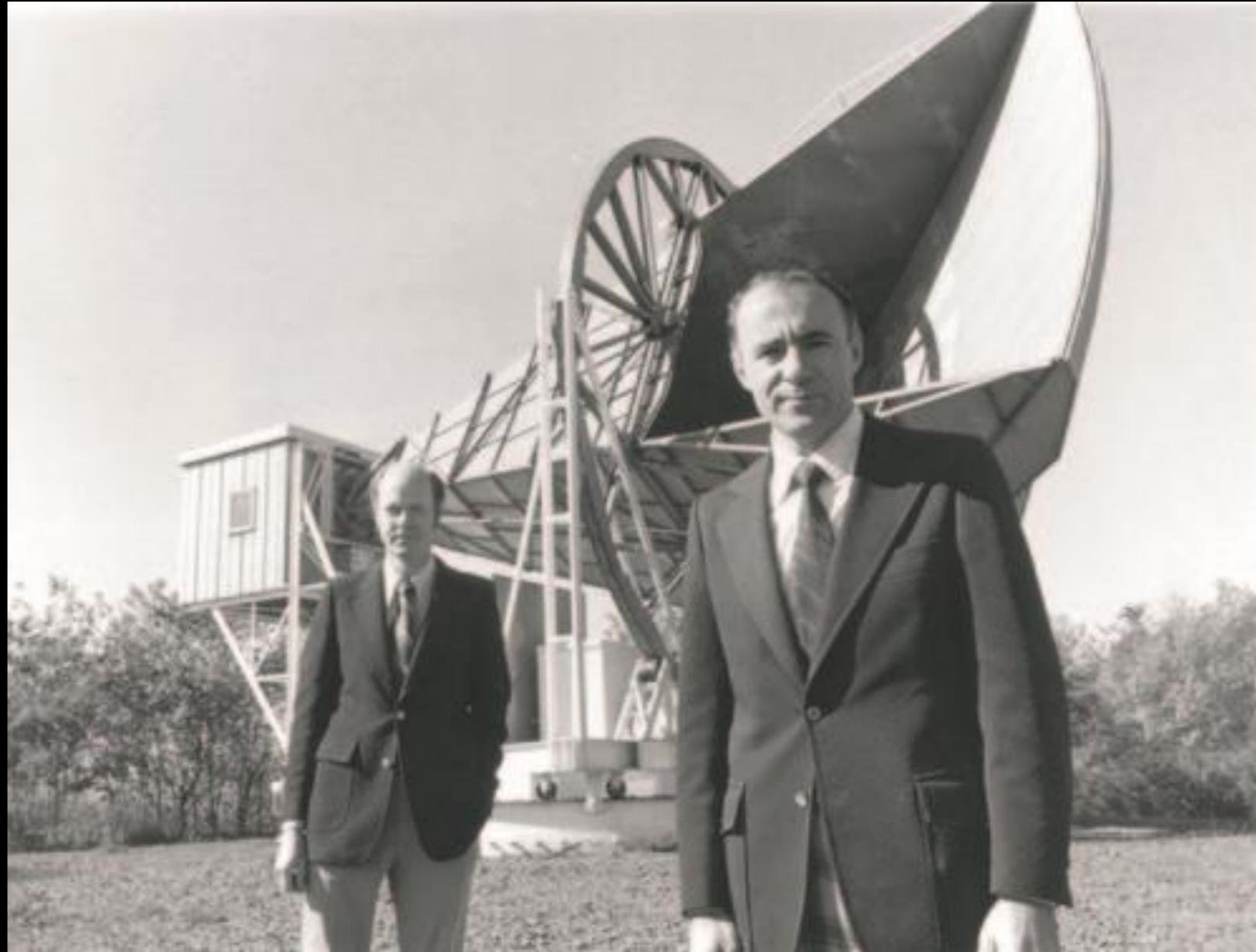


During recombination the photons are in thermic equilibrium with the electrons and atomic nuclei.



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

# Discovery of the CMB



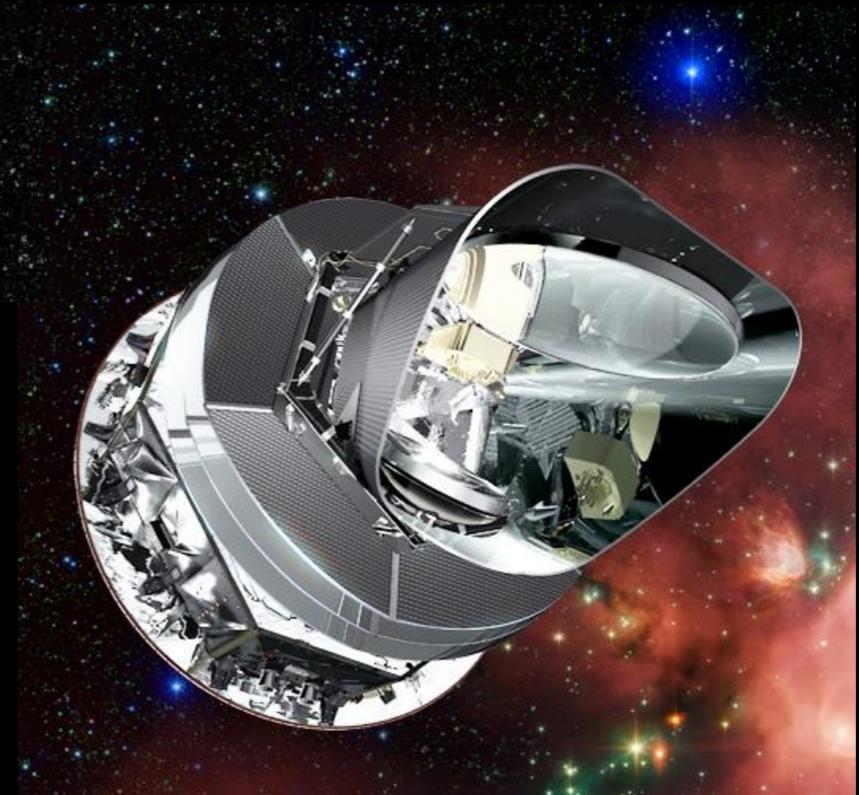
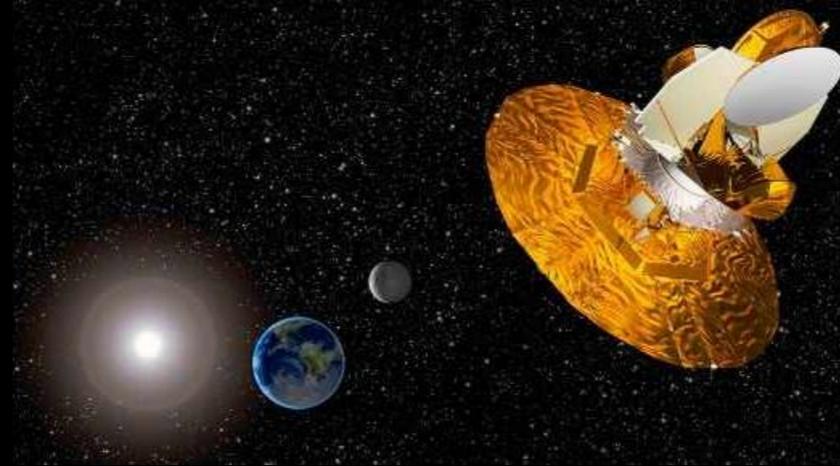
1964 Penzias und Wilson discovered a noise, which they couldn't explain



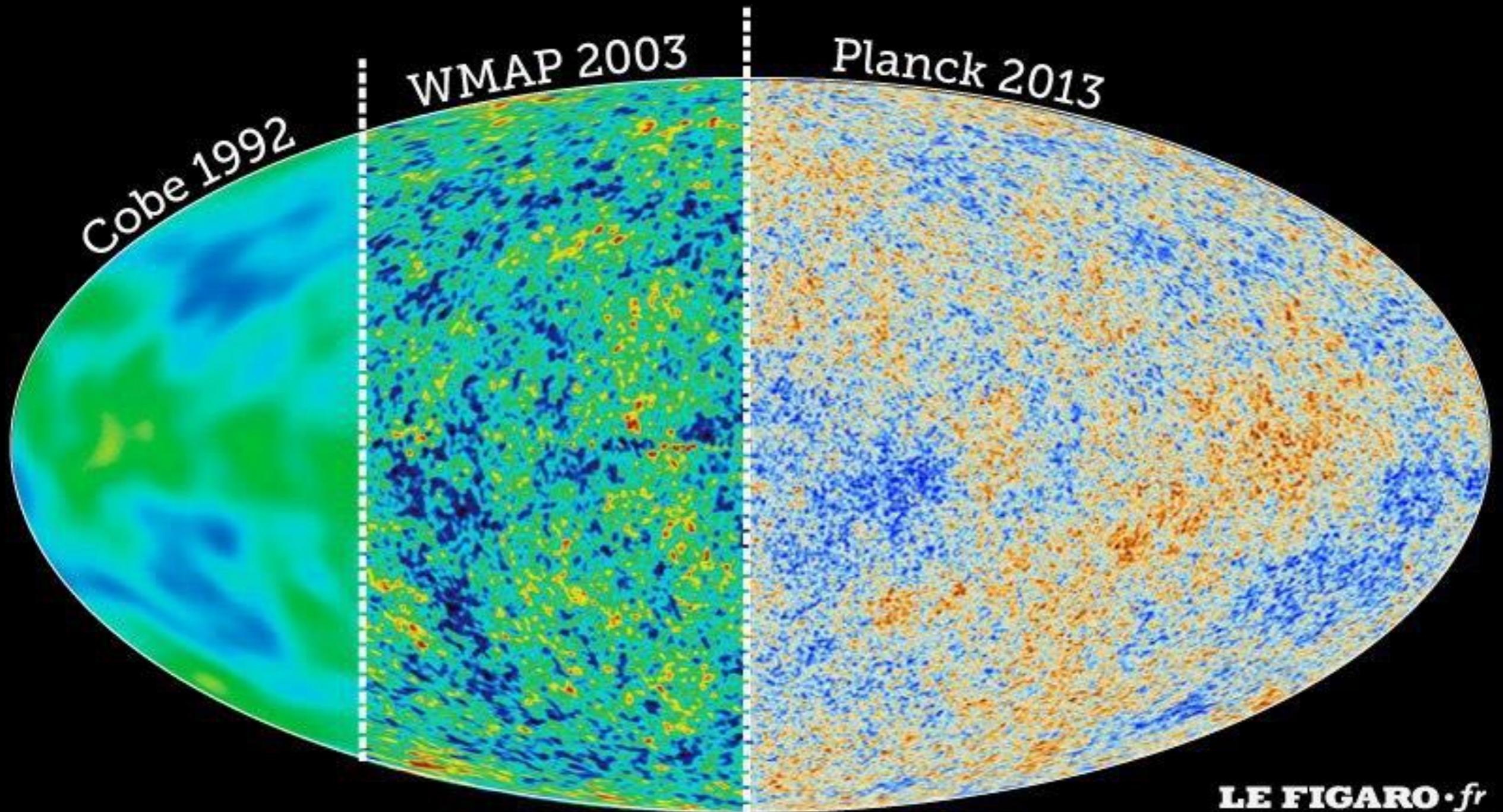
(1978)

# 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

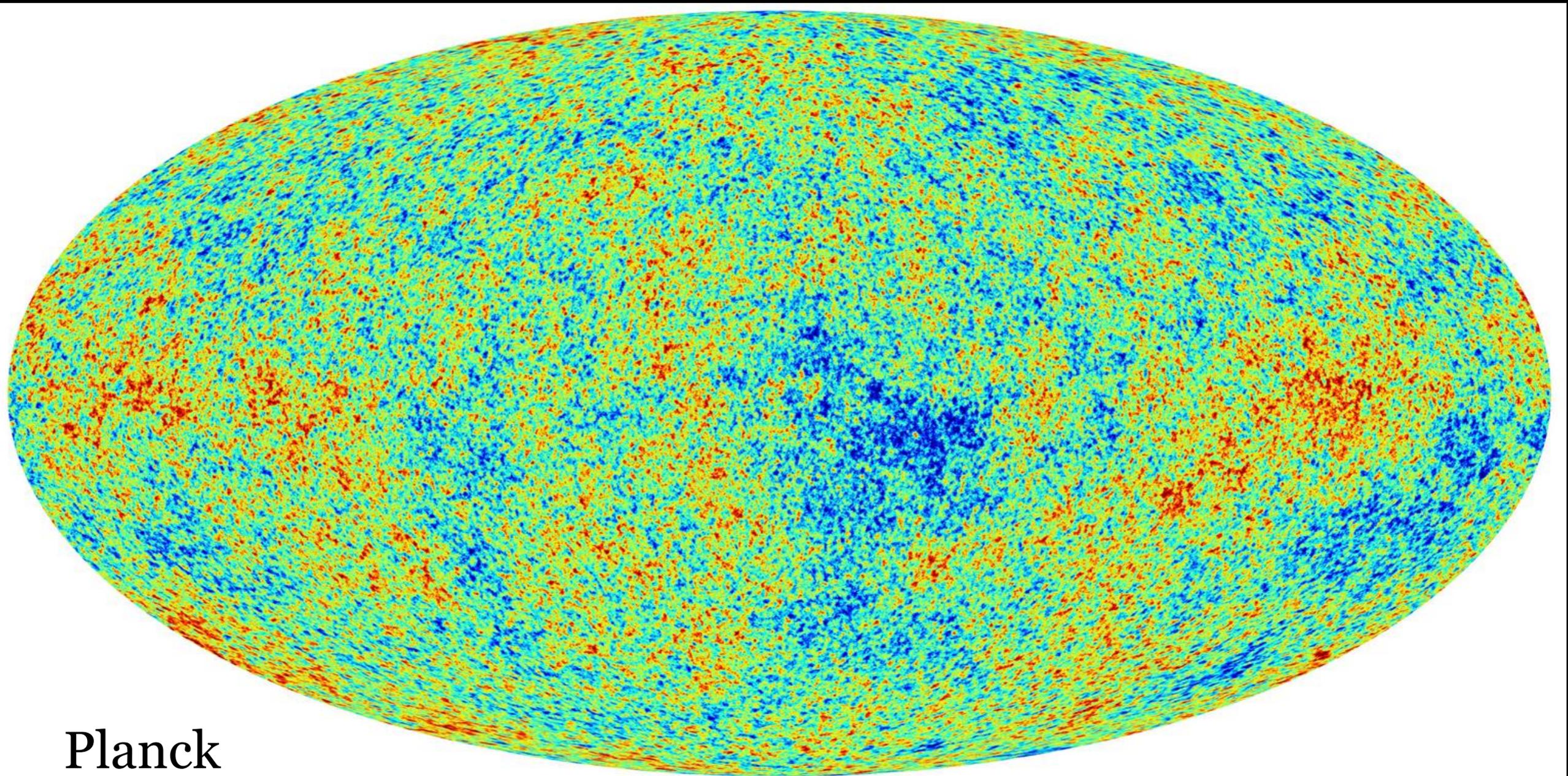


# The Echo of the Big Bang



# 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!

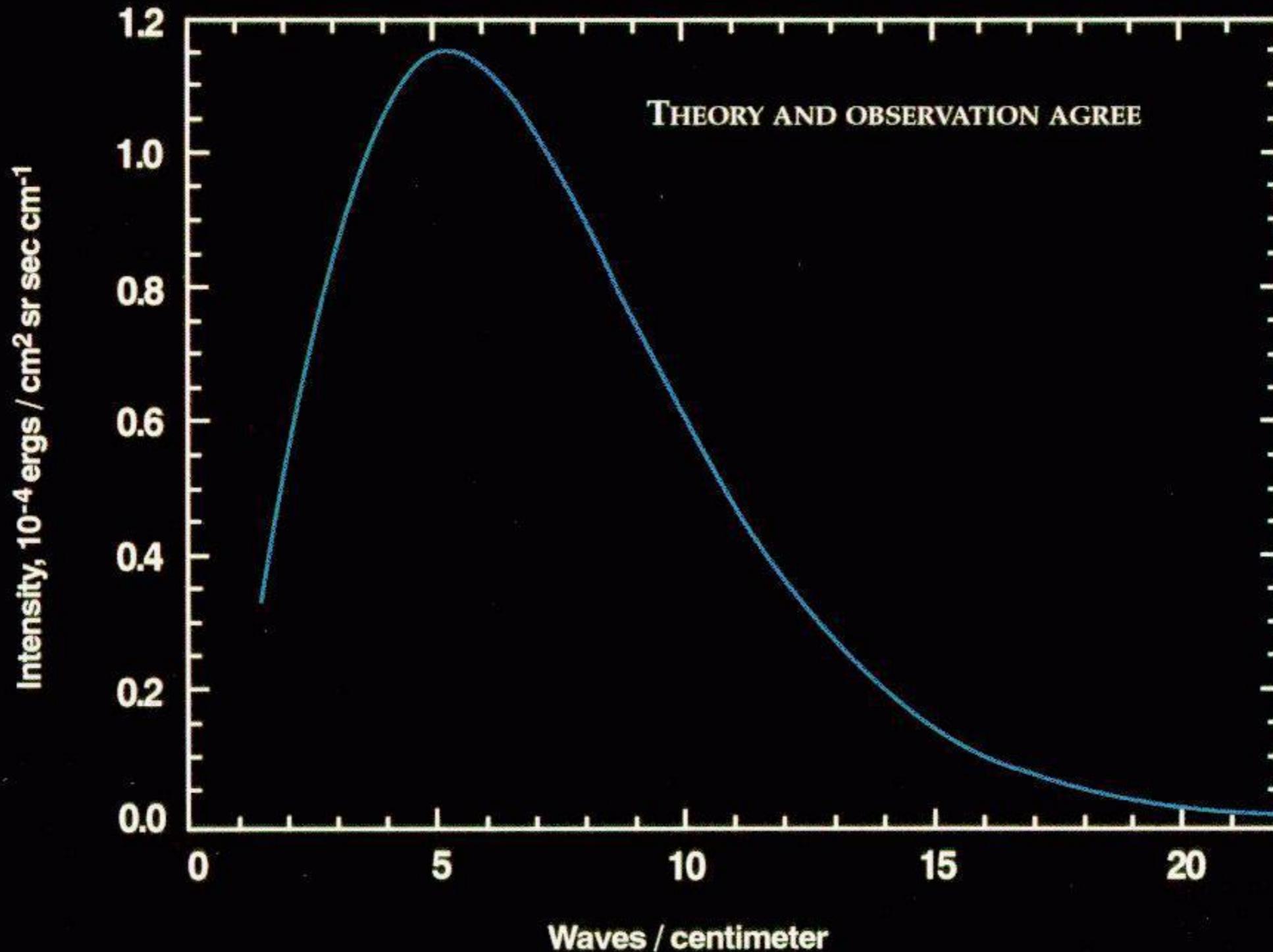


Planck

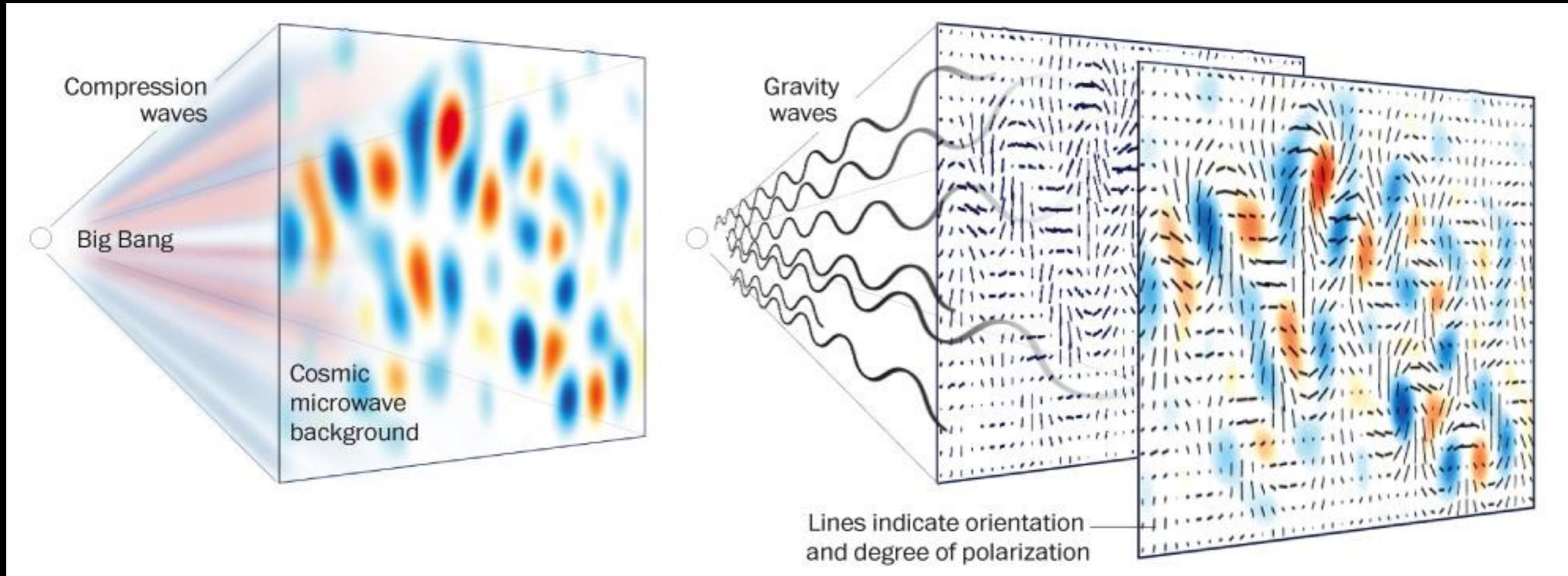


# The spectrum of the CMB

COSMIC MICROWAVE BACKGROUND SPECTRUM FROM COBE



# Gravitational Waves as a Proof of Inflation

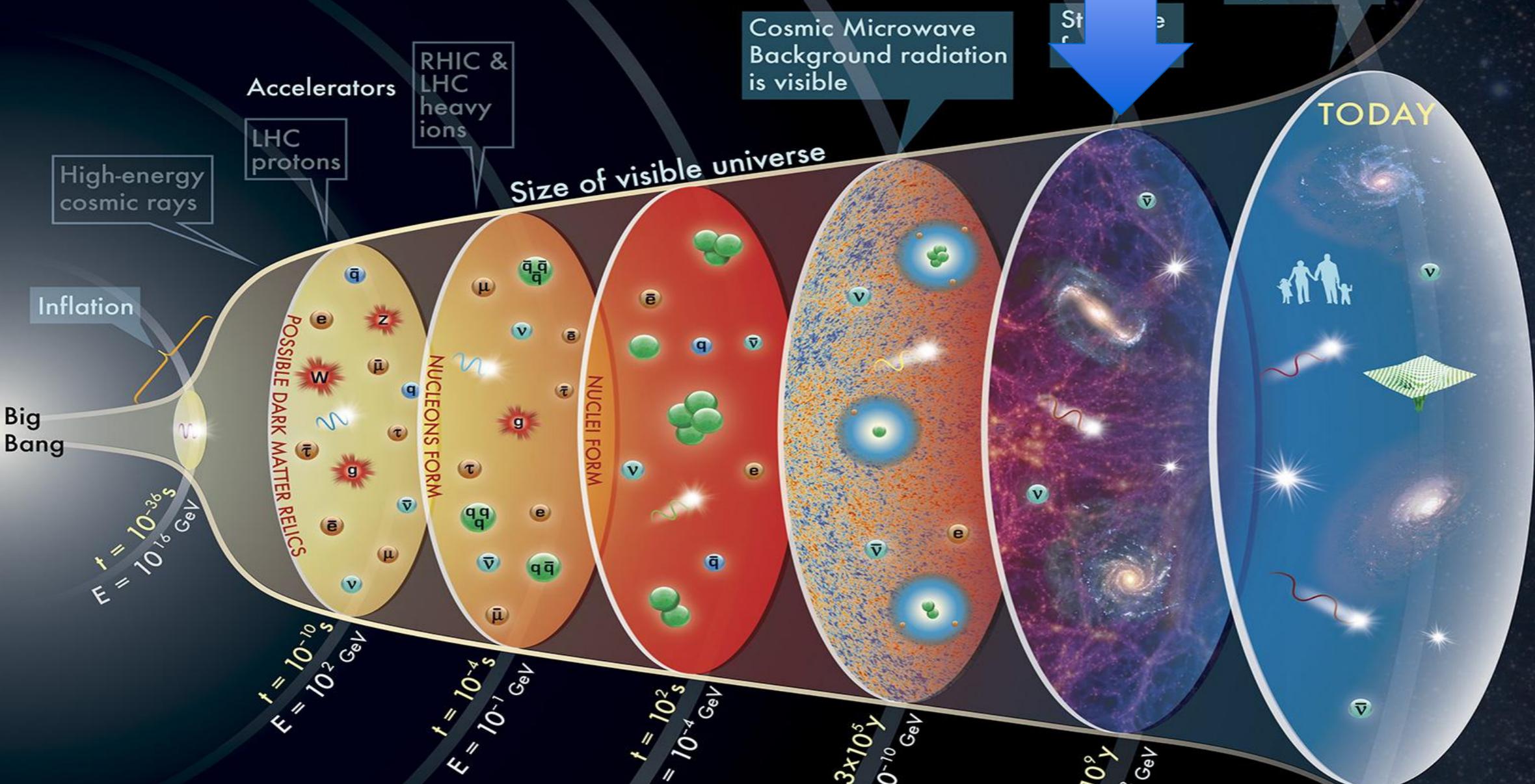


could be indirectly seen in the polarization of the CMB

# HISTORY OF THE UNIVERSE

structure building

expansion



Cosmic Microwave Background radiation is visible

Accelerators

LHC protons

RHIC & LHC heavy ions

High-energy cosmic rays

Inflation

Big Bang

Size of visible universe

TODAY

t = Time (seconds, years)

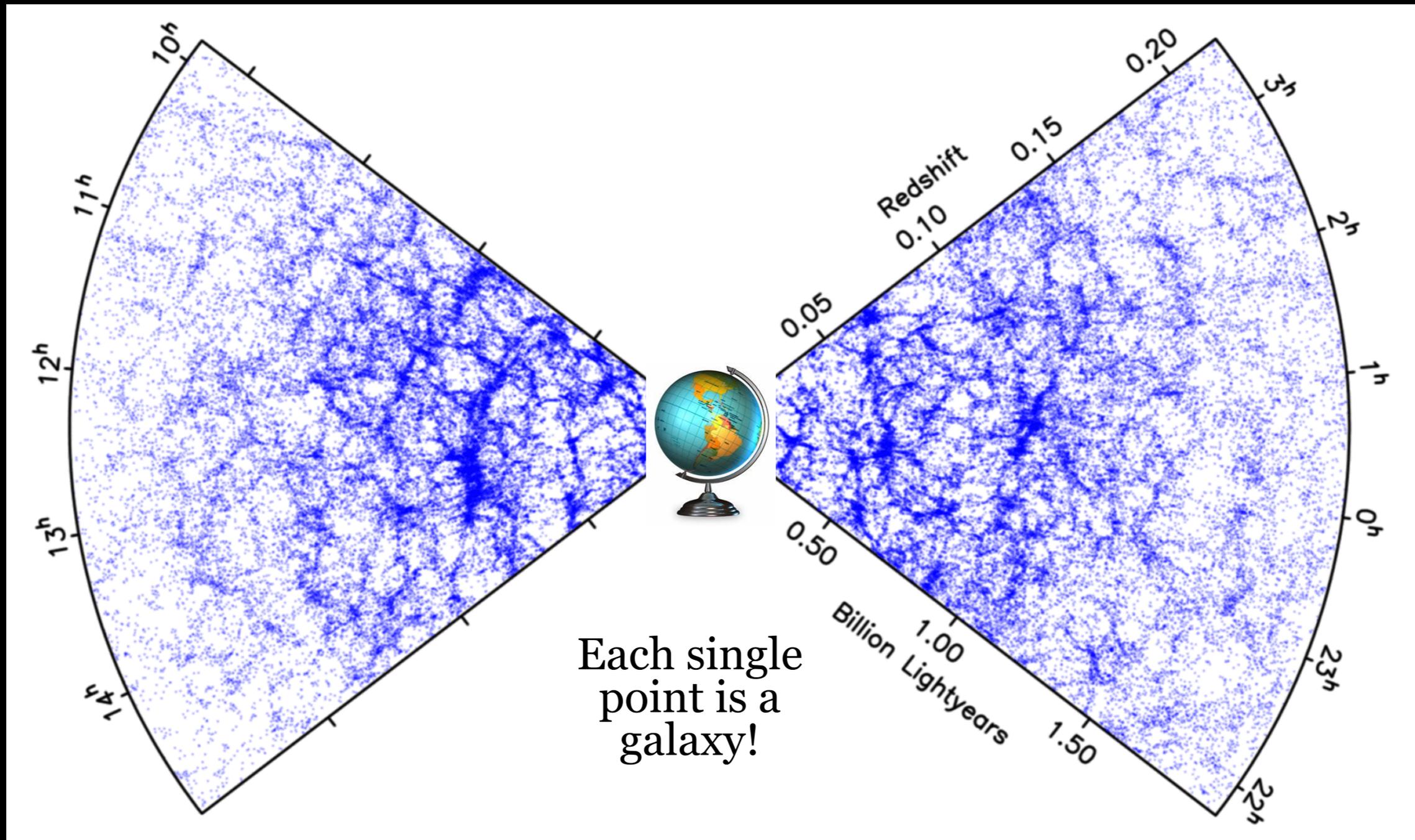
E = Energy (GeV)

## Key

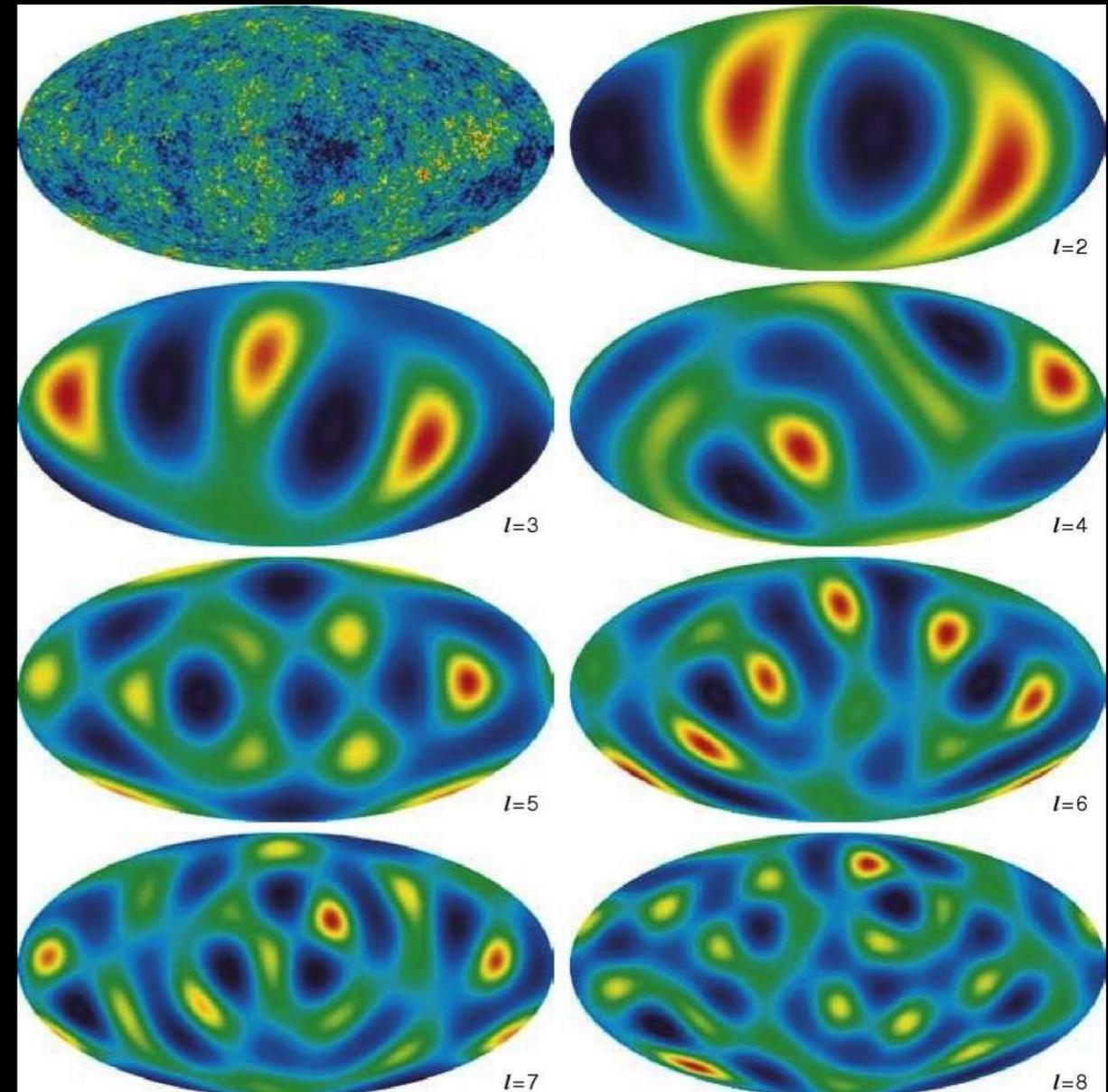
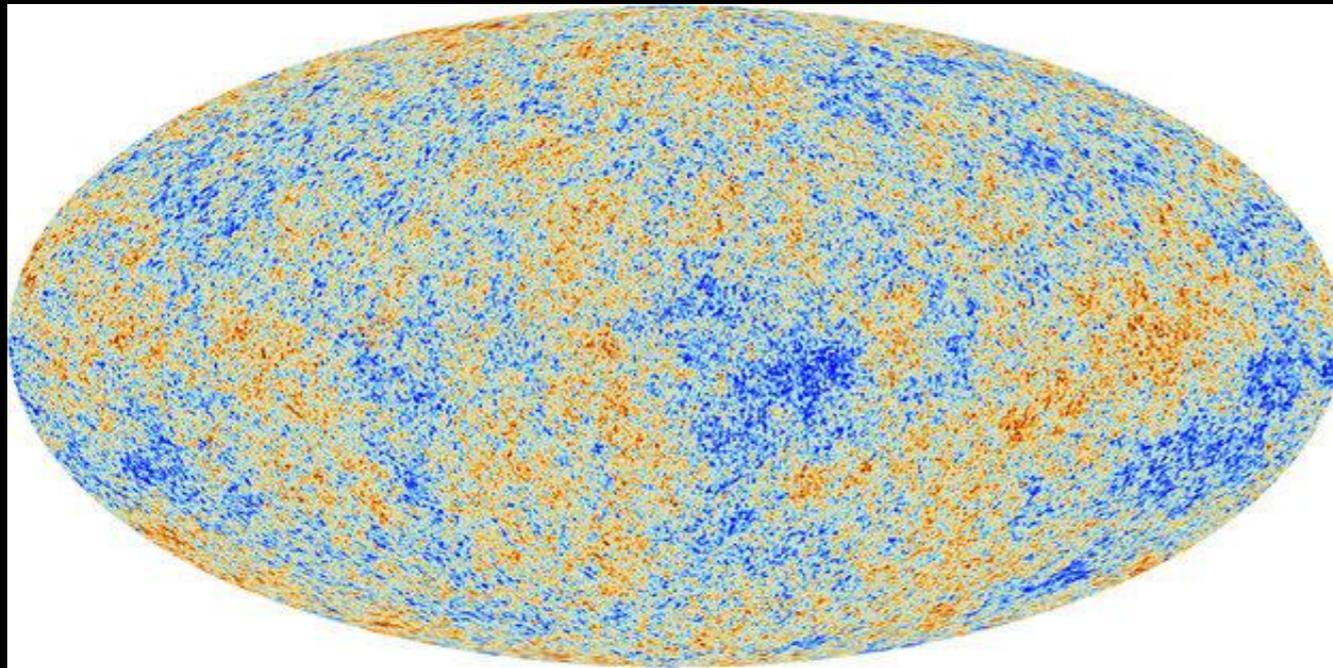
	quark		neutrino		ion		star
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	electron		meson		photon		black hole
	muon		baryon				
	tau						

# Galaxy Distribution

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

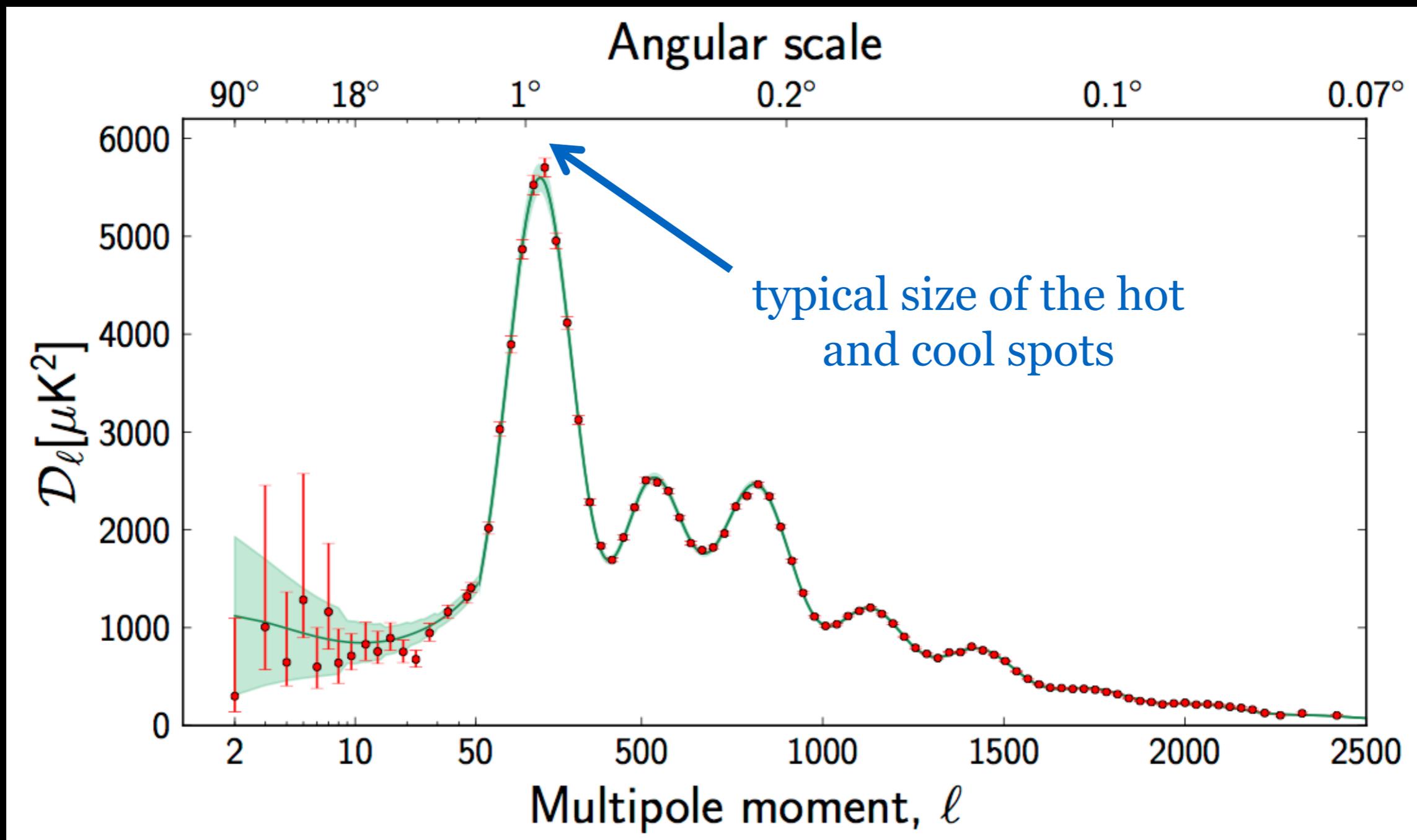


# From the map to the spectrum...

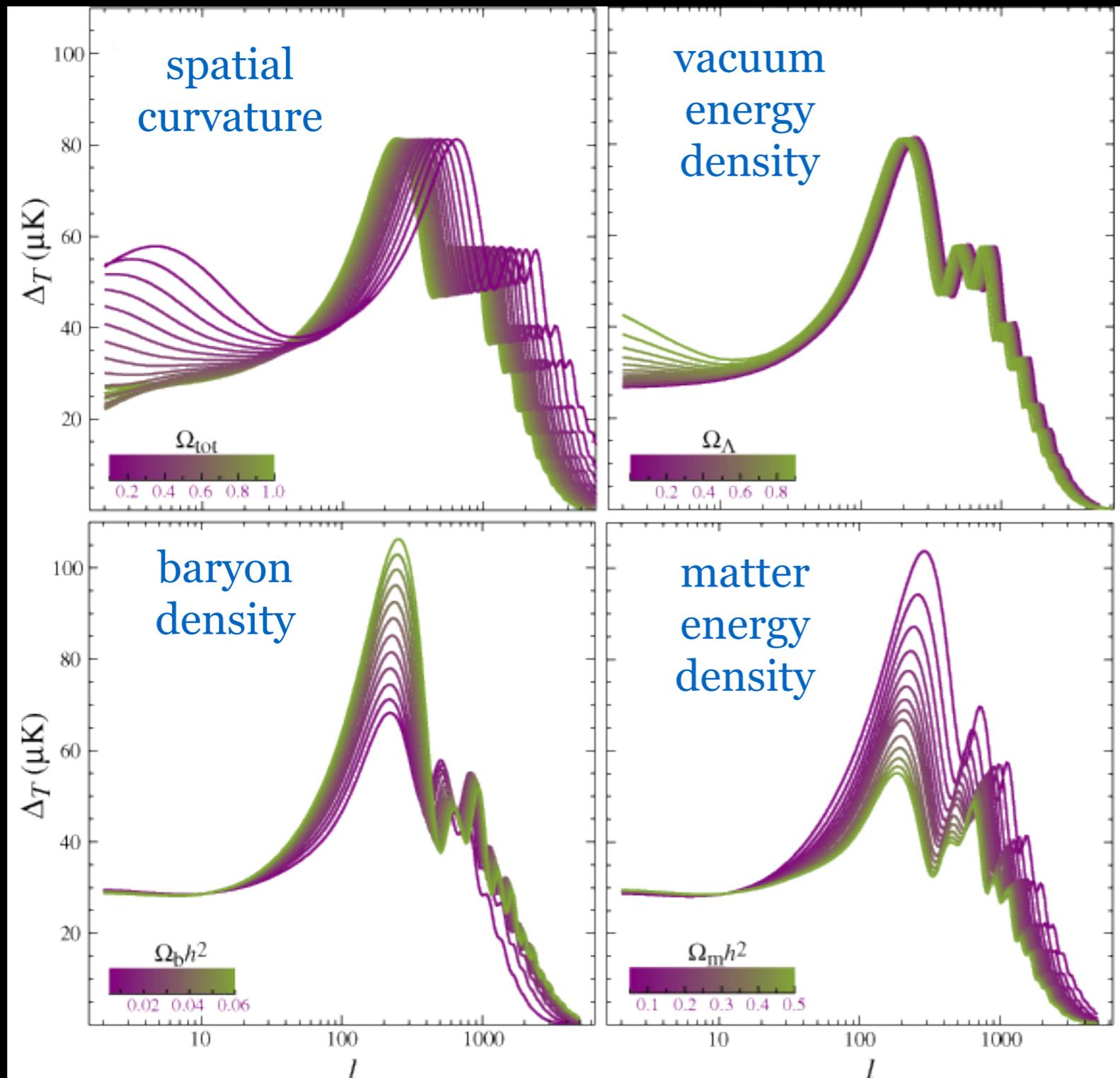


- theory is not able to predict the exact position of individual hot or cool spots
- instead: prediction of statistical properties of the temperature map (for example mean value, variance, correlations,...)

# The Angular Power Spectrum of the CMB



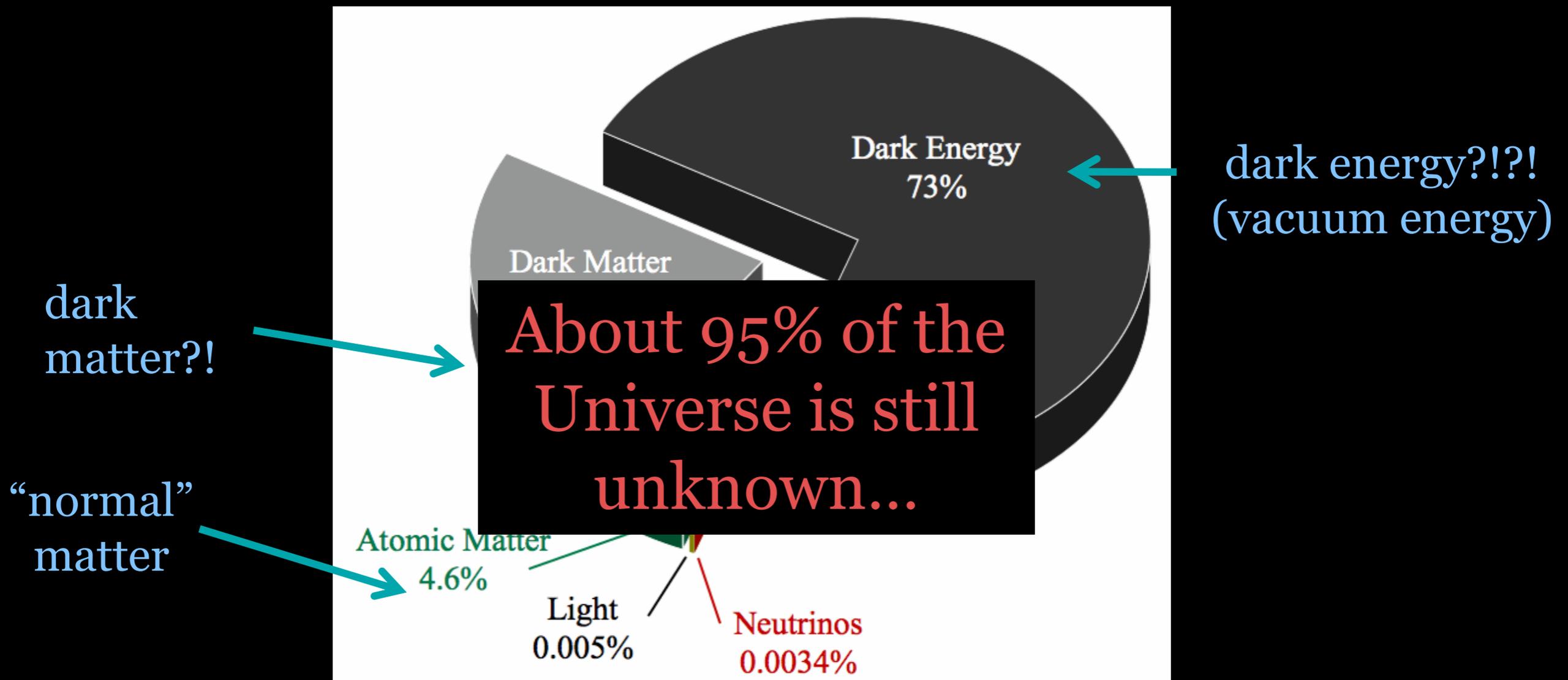
# Theoretical Predictions of the CMB Spectrum



- 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!)



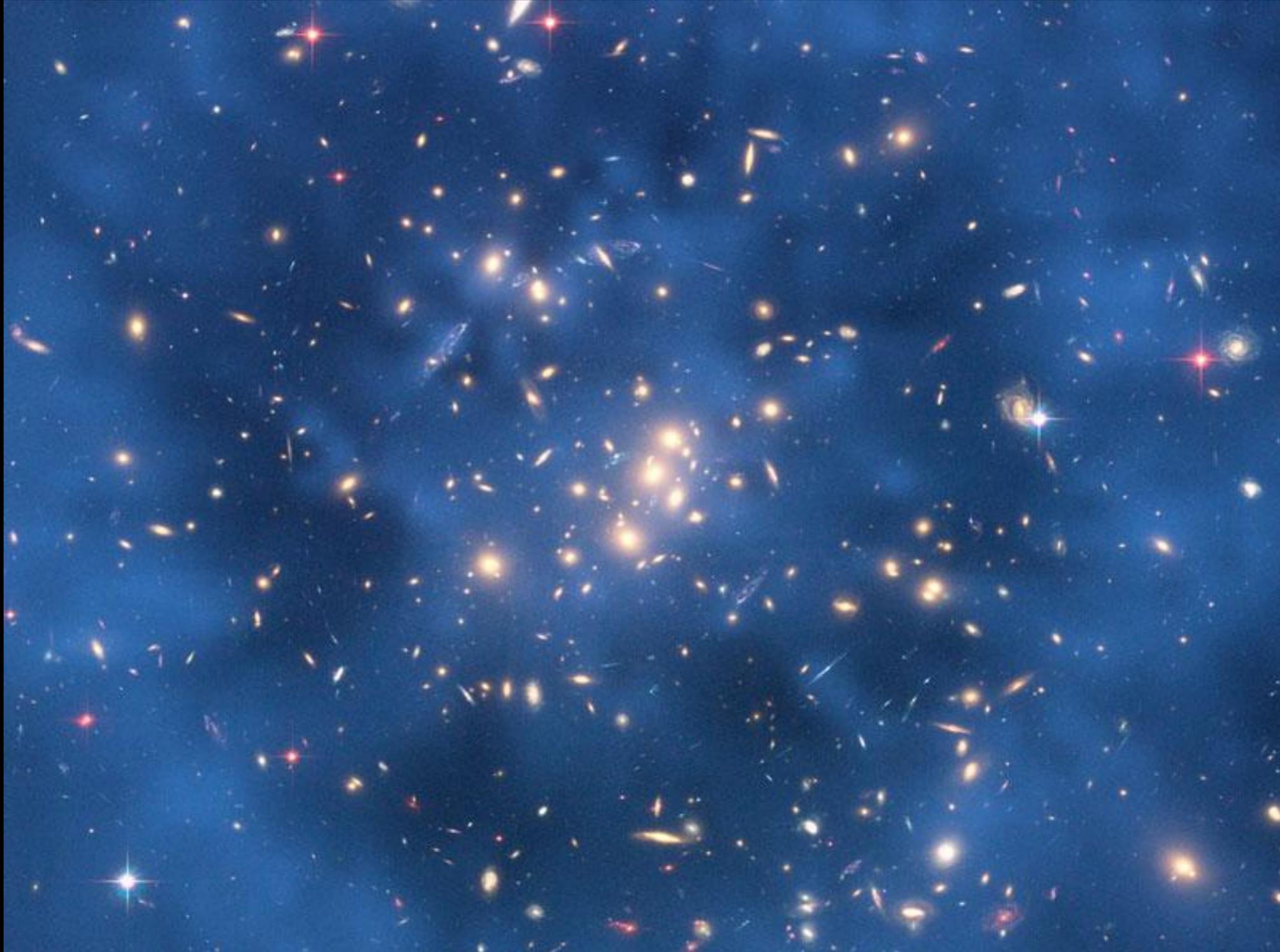
# Mysteries of the Universe

What is dark matter?

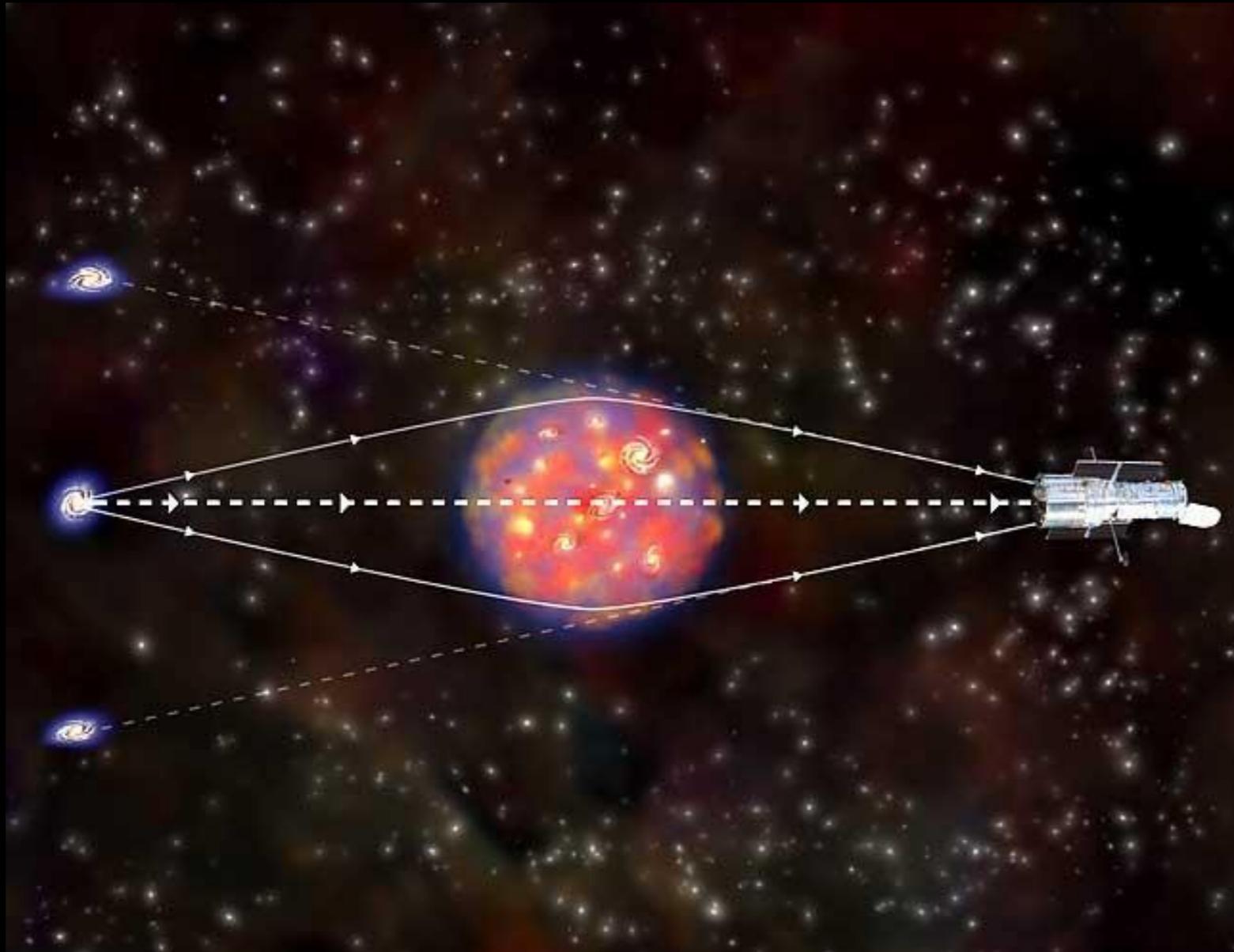
# Rotation Curves of Galaxies



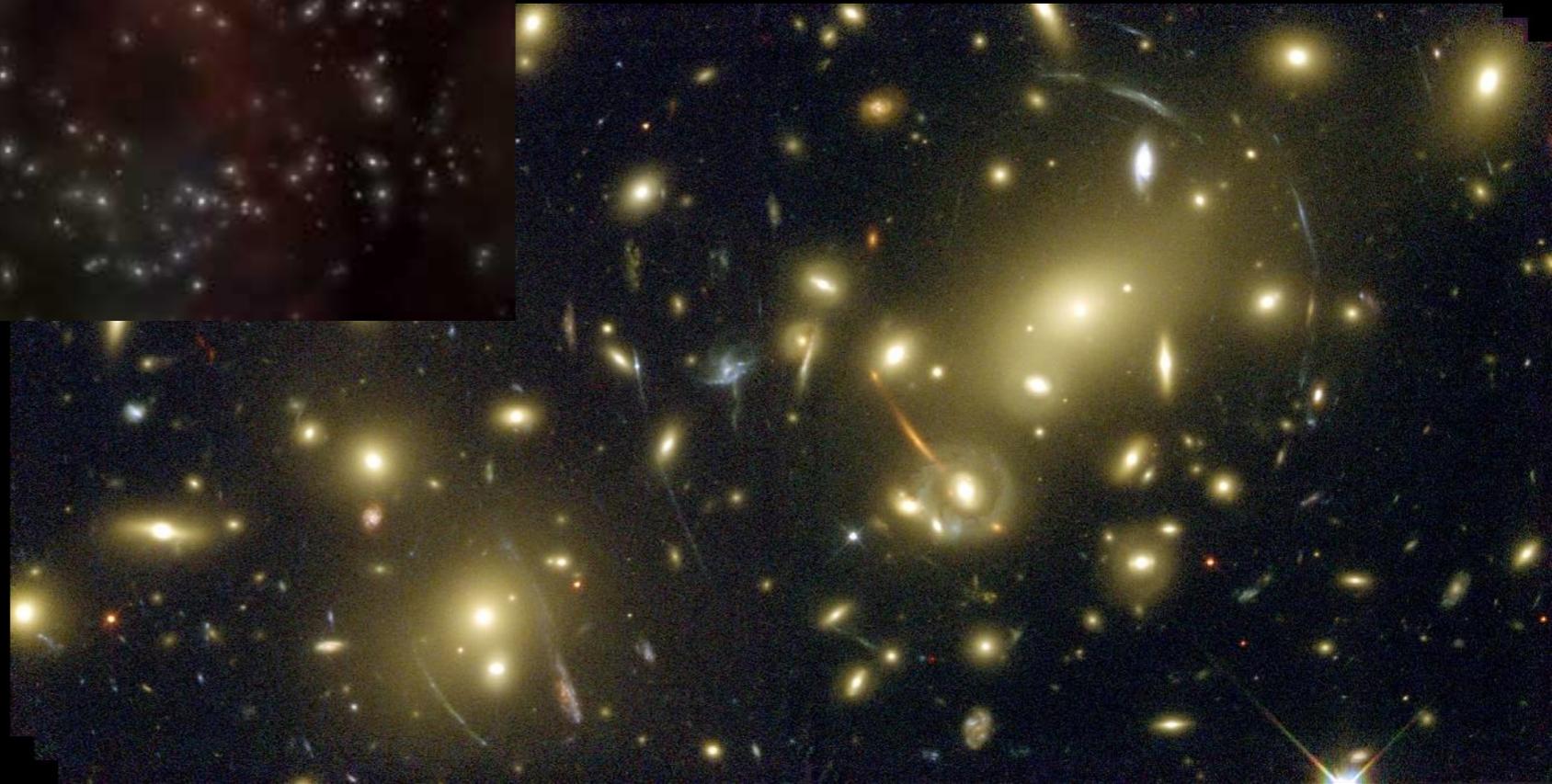
# Galaxy Cluster CL0024+17



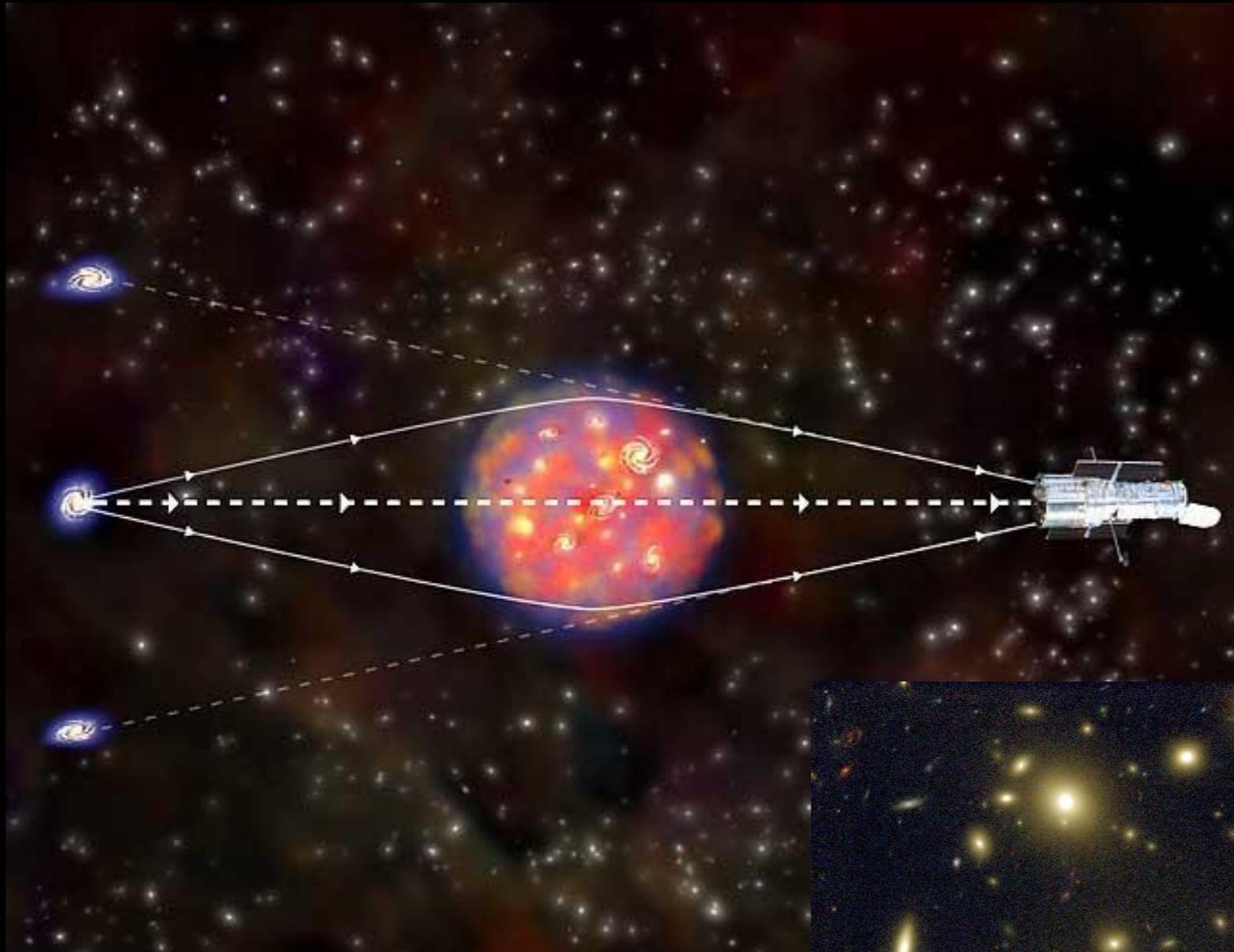
# Gravitational Lenses



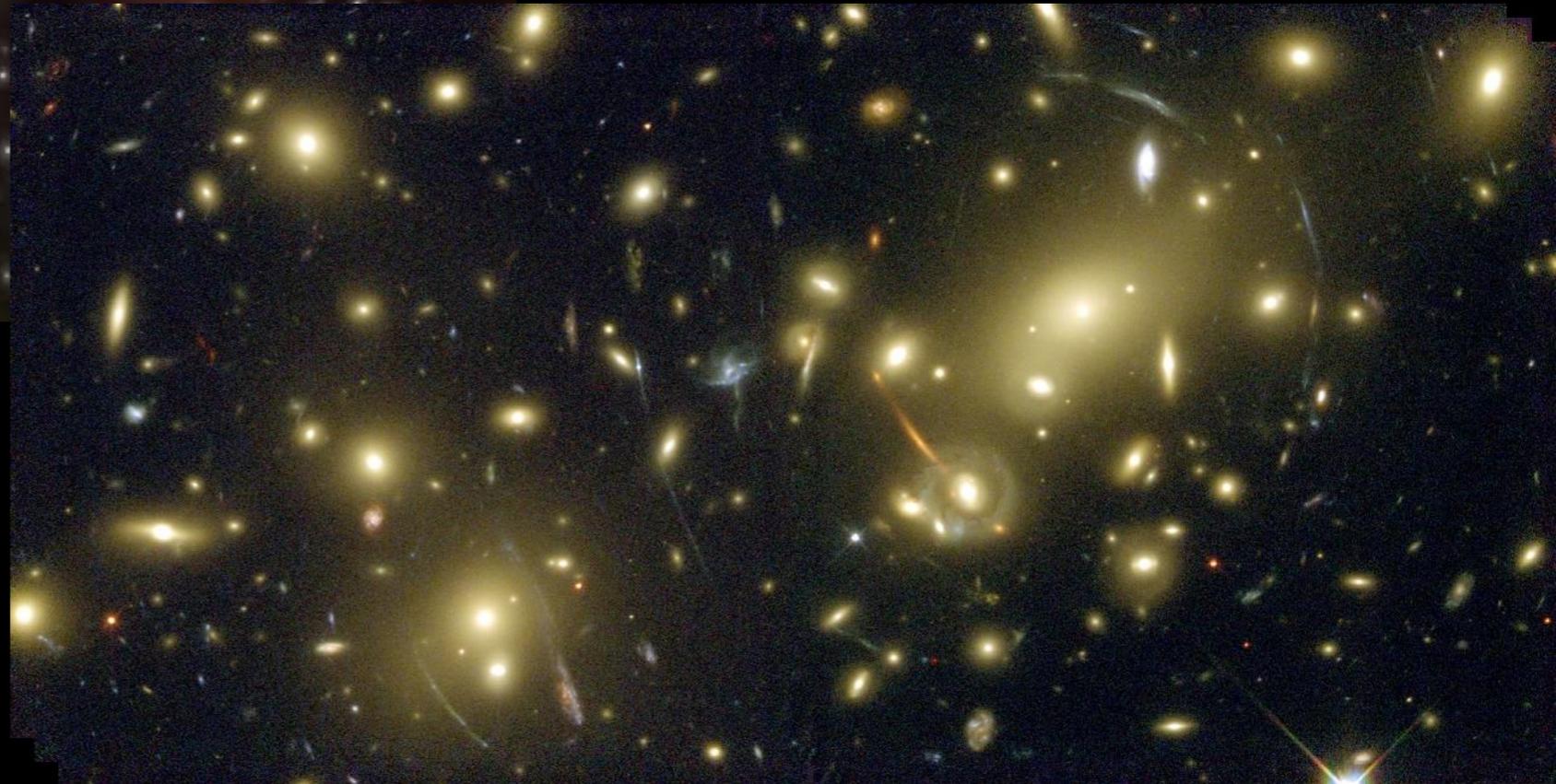
Massive objects curve space-time and therefore distort the light of the objects behind.



# Gravitational Lenses



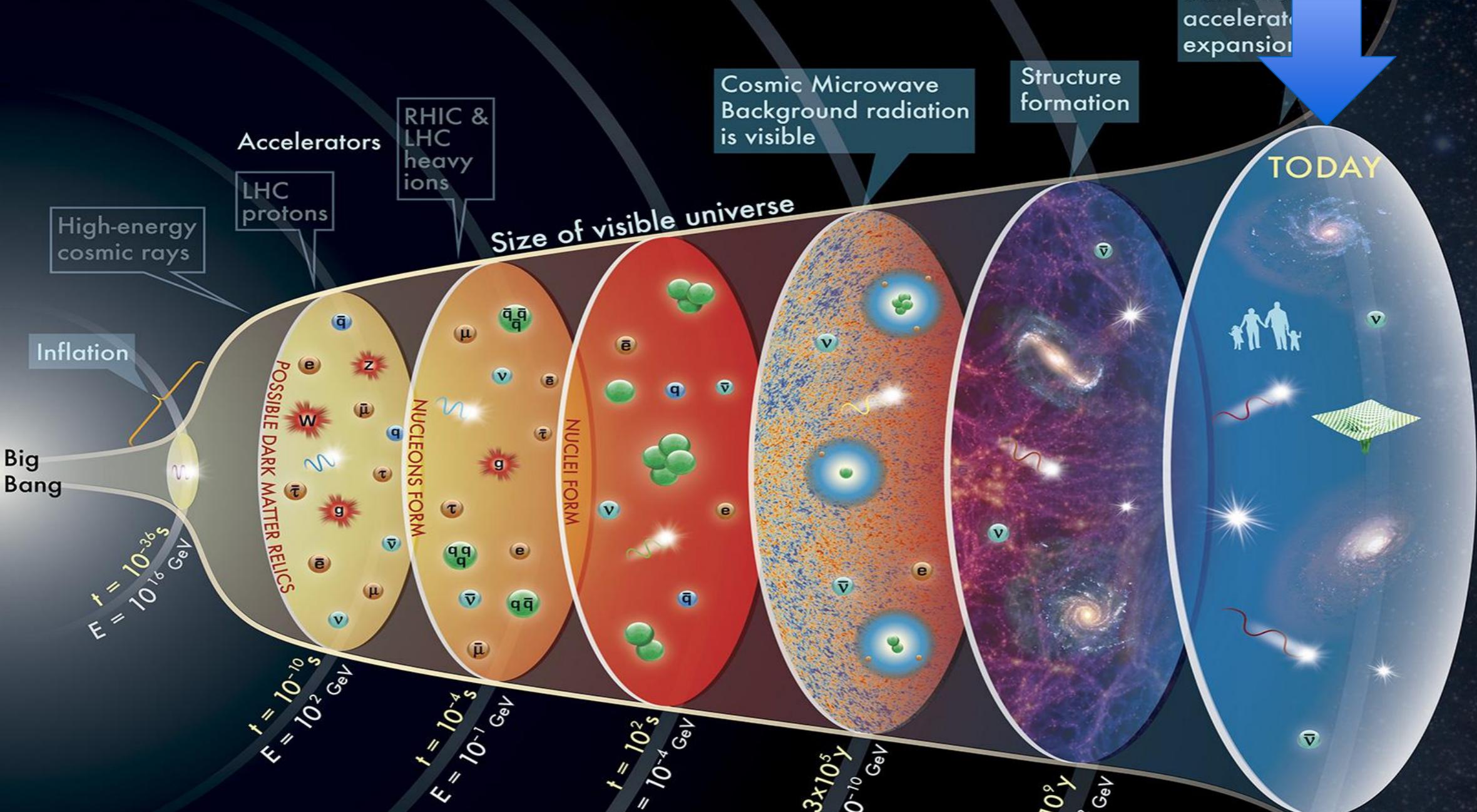
galaxy cluster Abell 2218



Thereby light arcs of the objects behind are visible.

# HISTORY OF THE UNIVERSE

era of the dark energy



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

## Key

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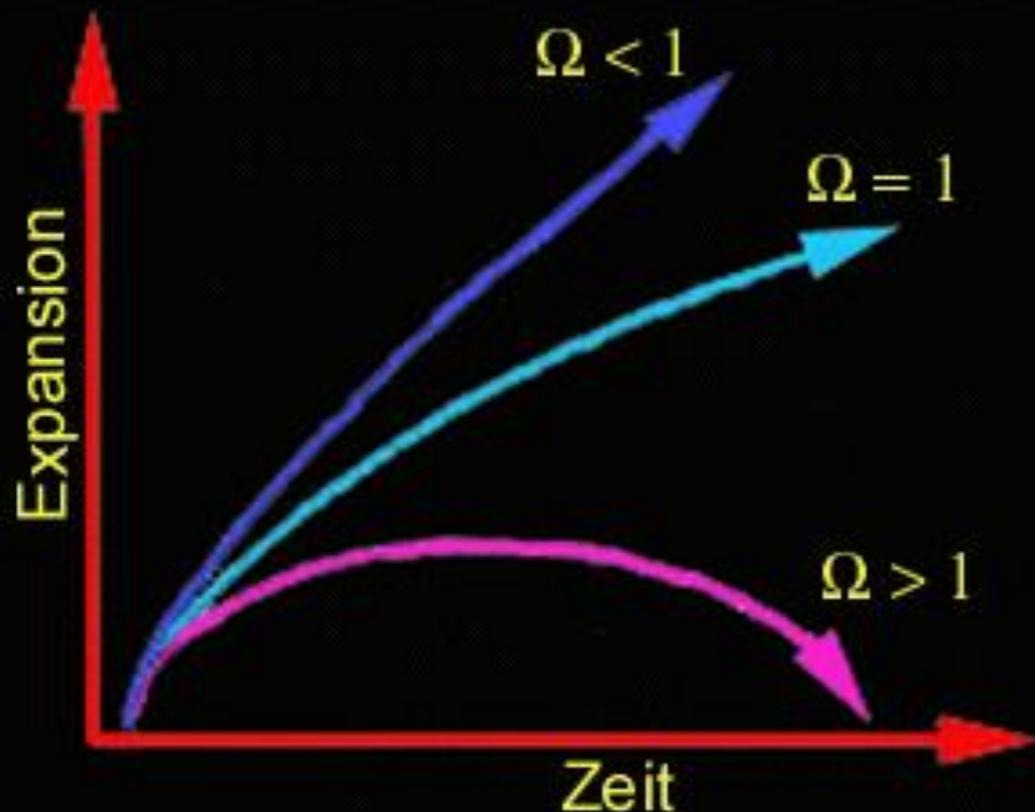
# The Fate of the Universe...

... depends on the balance between contraction and expansion

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

$\rho_{\text{krit}}$  is the critical density, which is necessary to stop the expansion:

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



- $\Omega > 1$   
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 21<sup>st</sup> 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?

