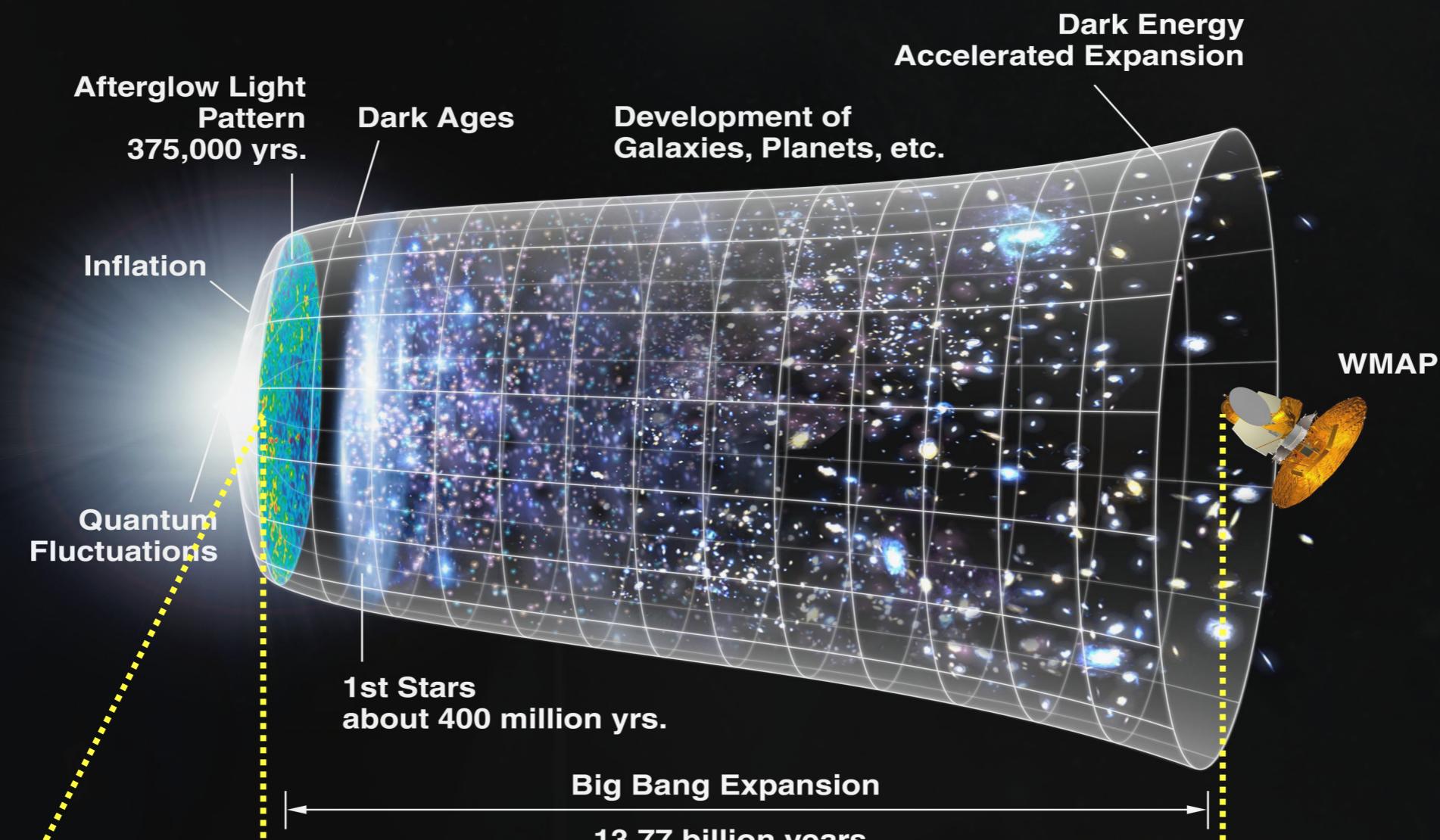


# **Evolution of the universe:**

## **Latest ~13.8 billions of years...**

**P. Milenovic, June 2022**

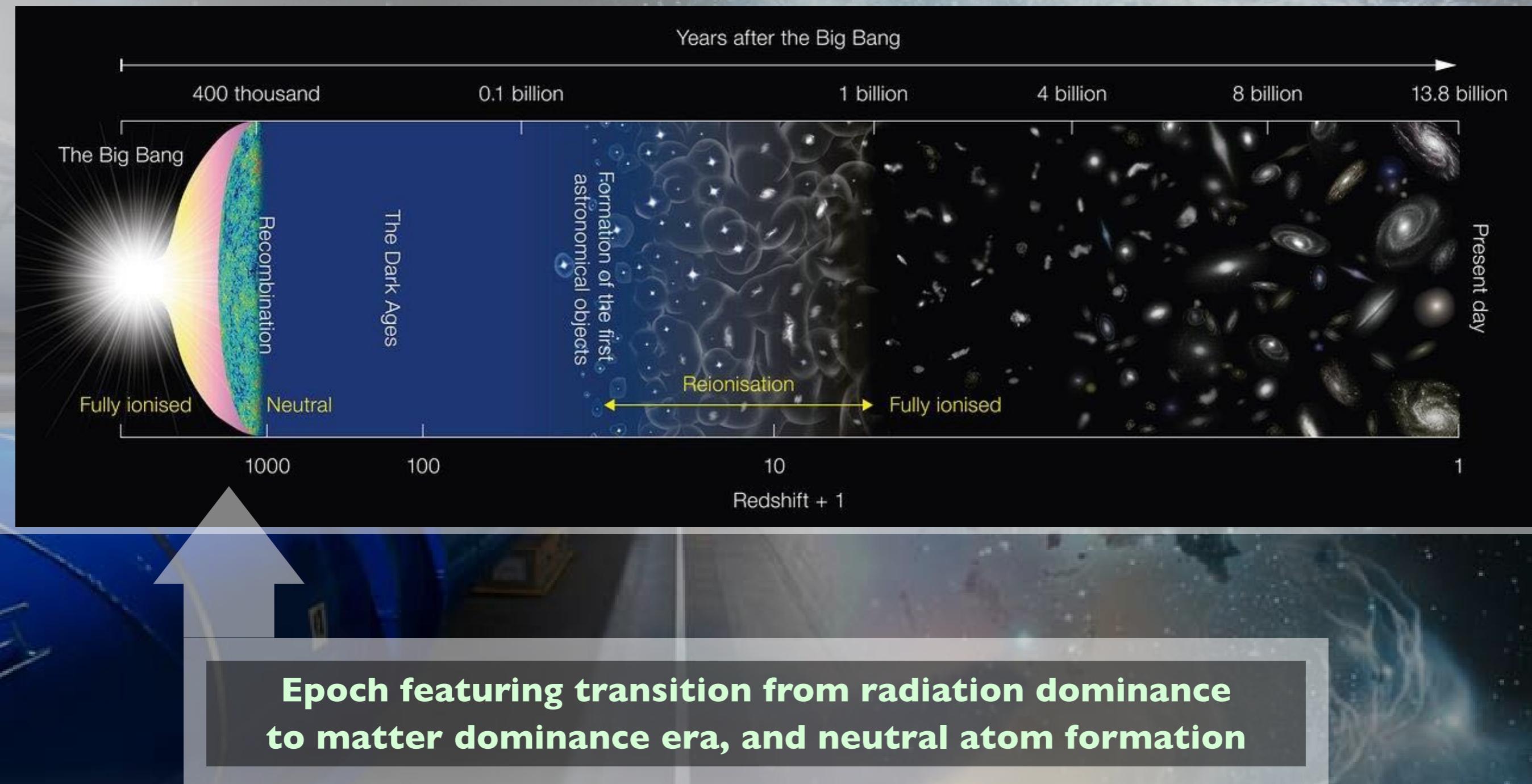
# Evolution of the universe



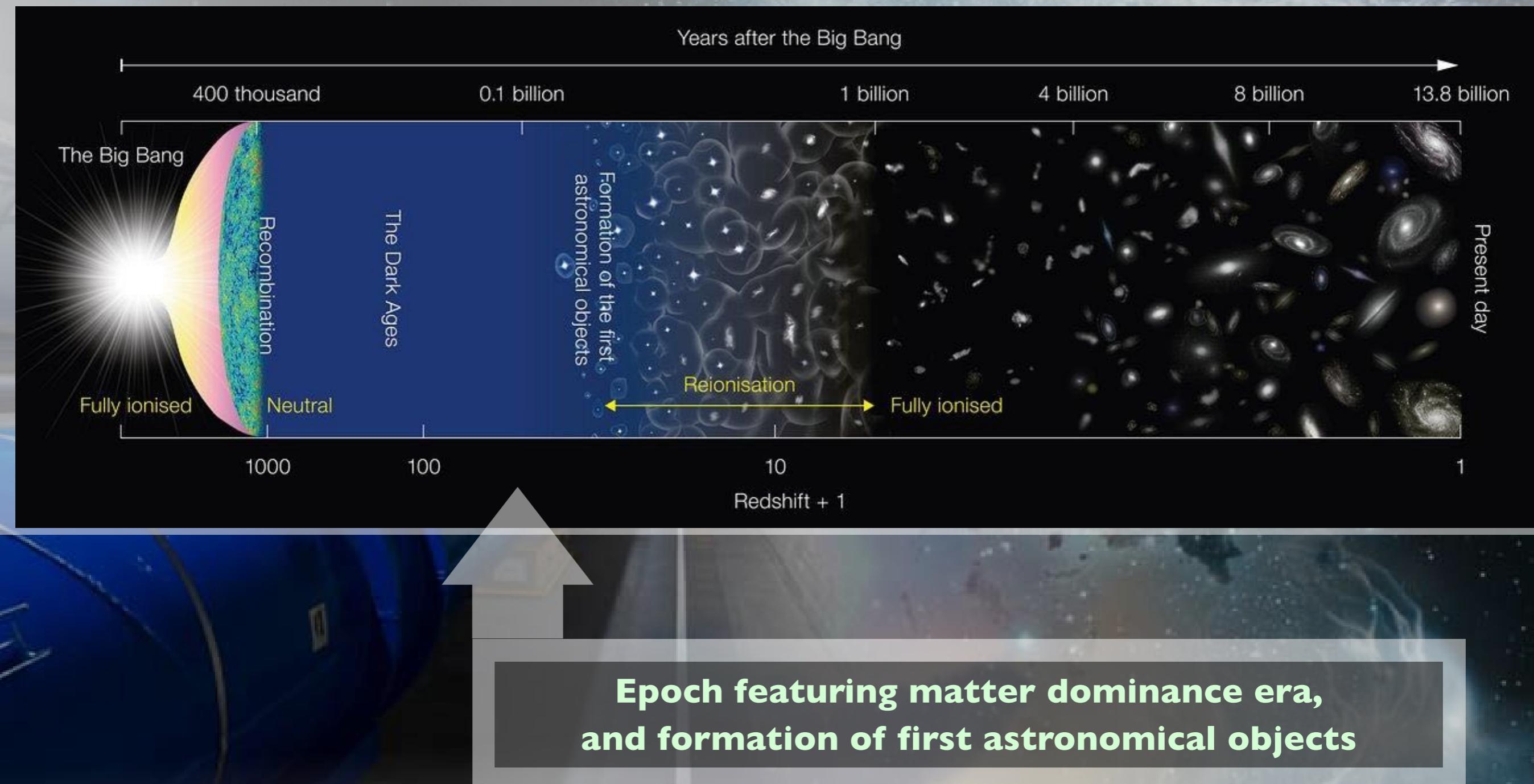
~3 min.

~13.8 billion years

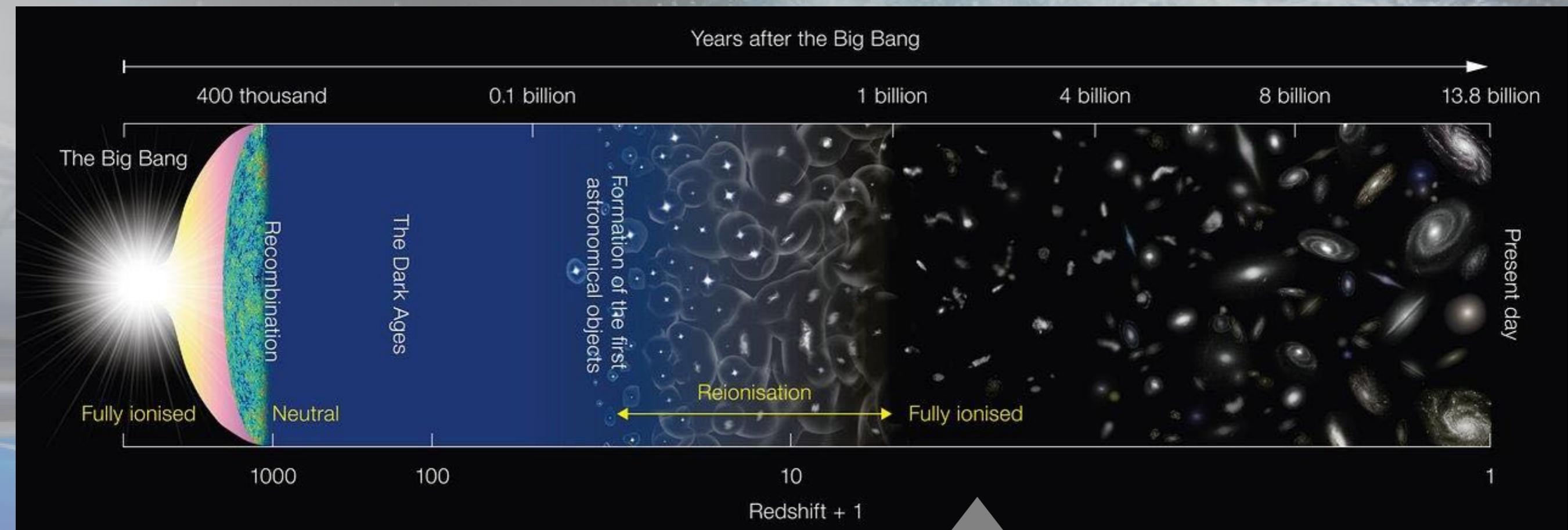
# Epochs of the universe



# Epochs of the universe

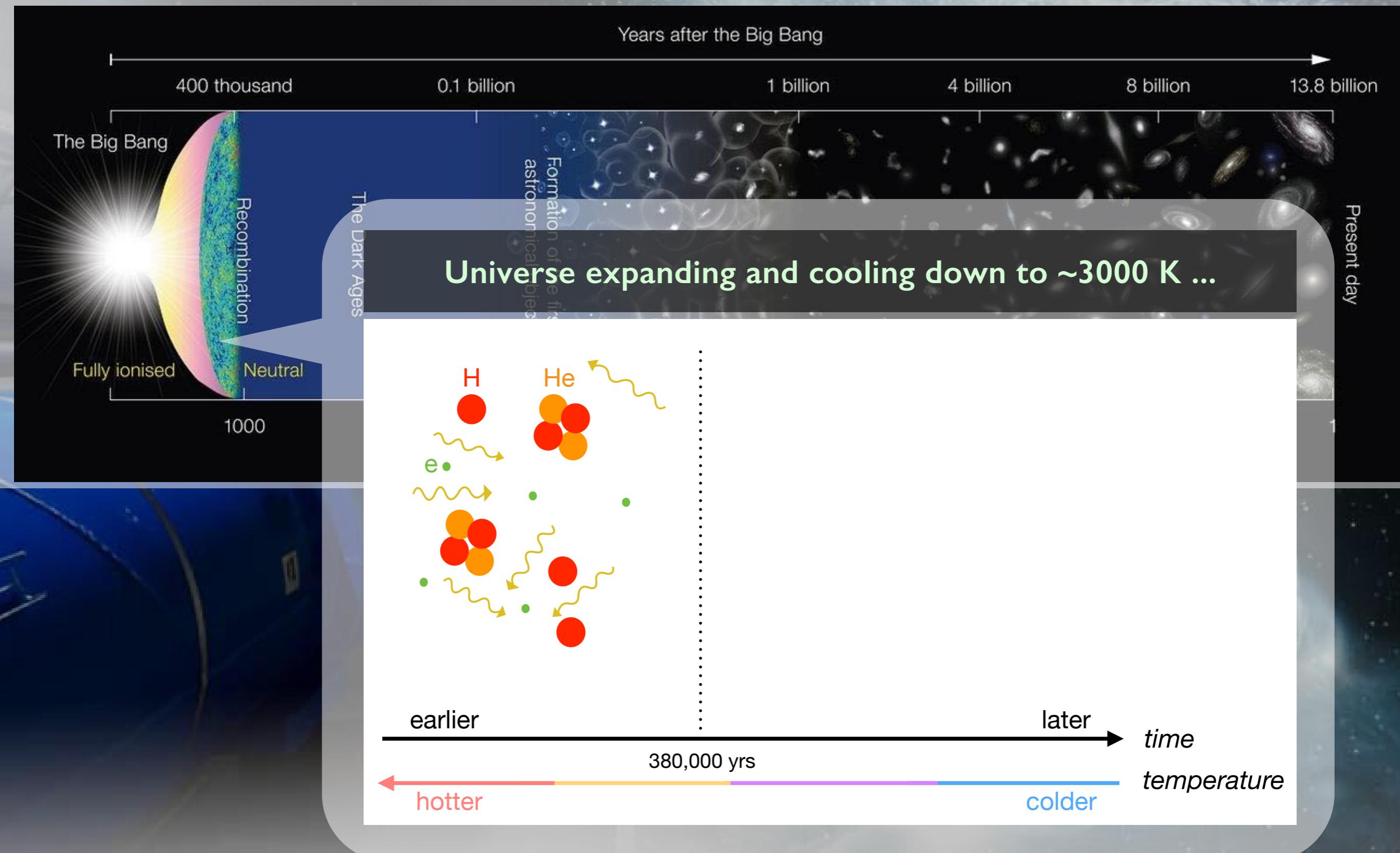


# Epochs of the universe

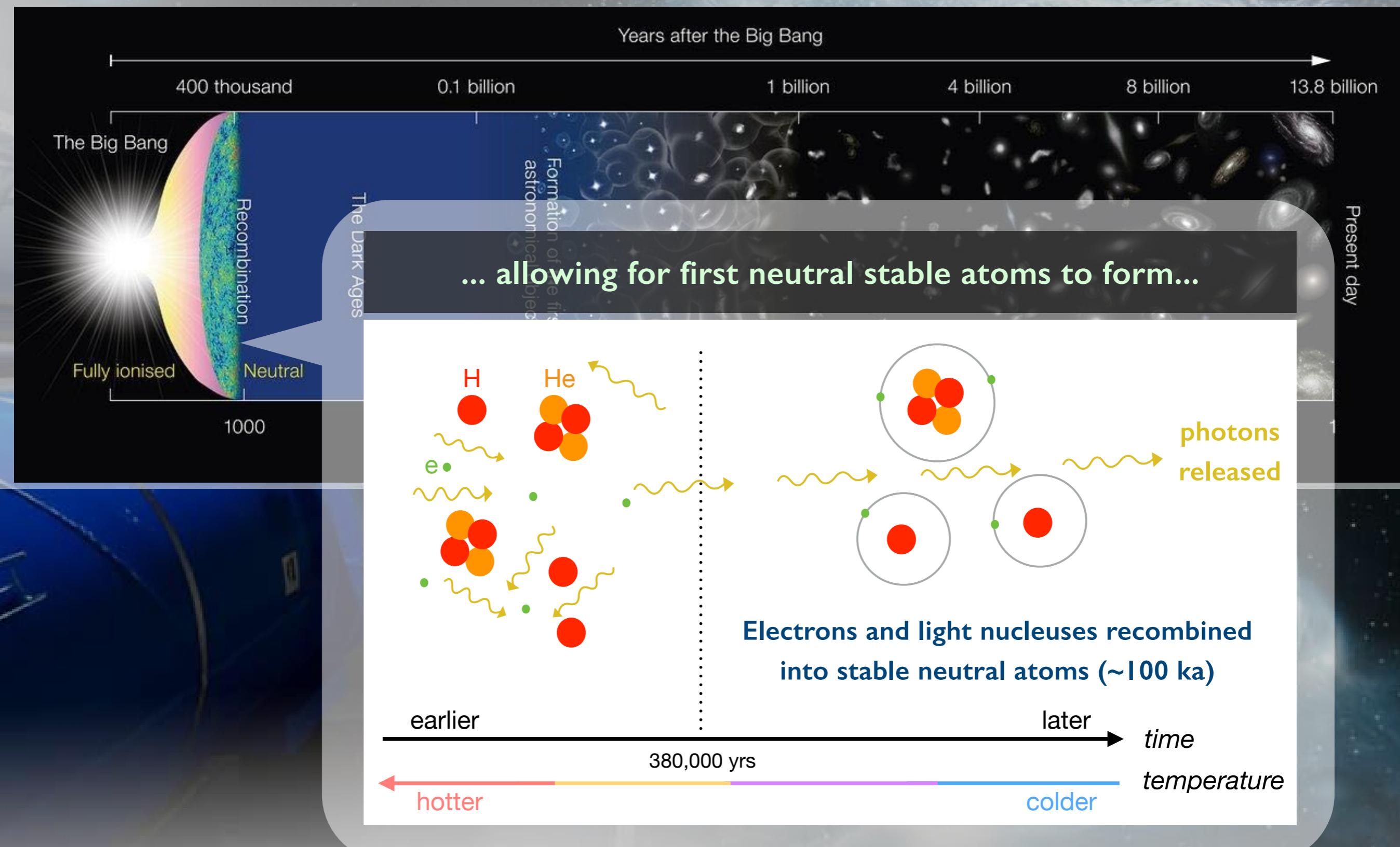


**Epoch featuring formation and evolution of astronomical objects, and transition from matter dominance to dark energy dominance era**

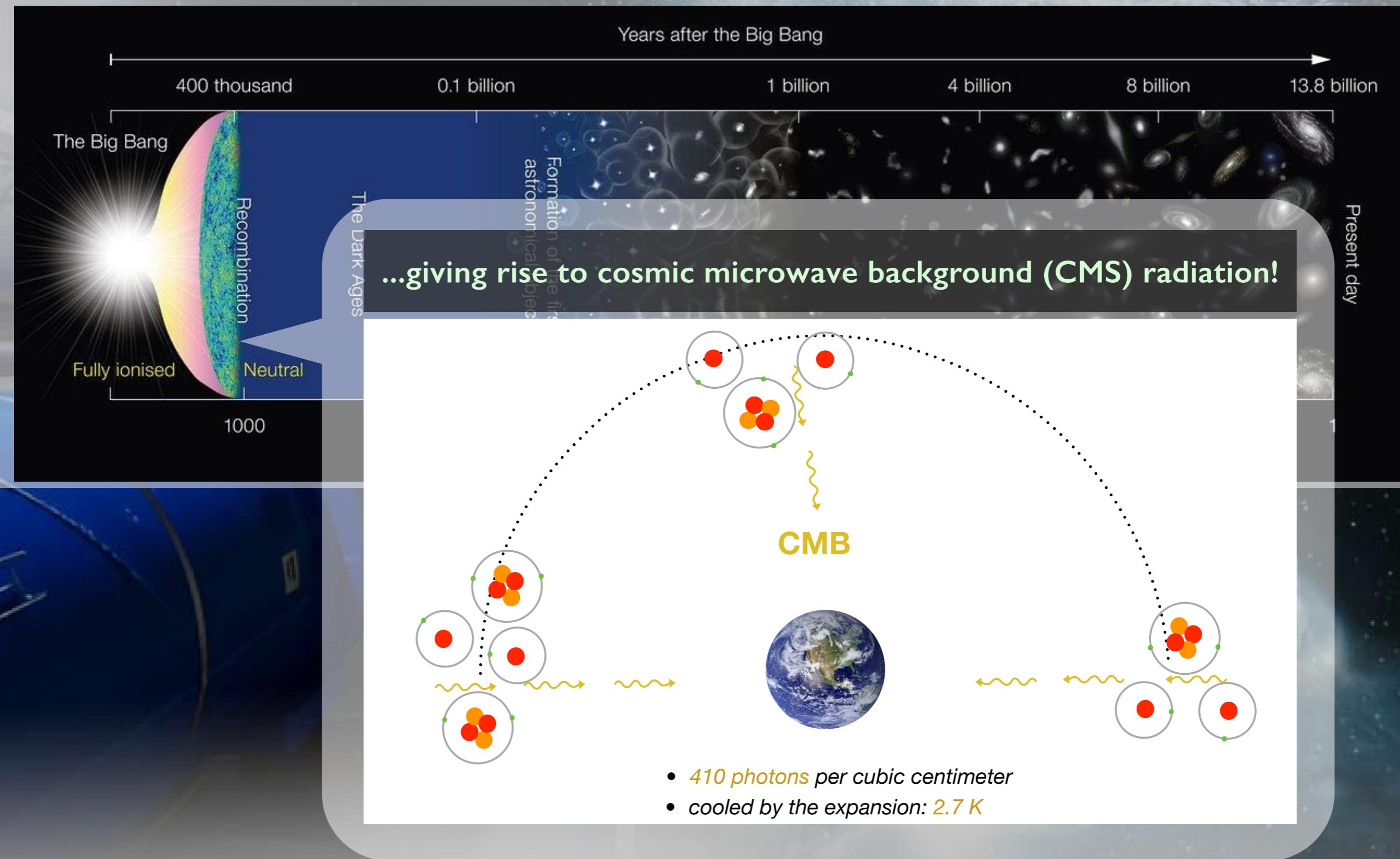
# From radiation-dominated era to recombination



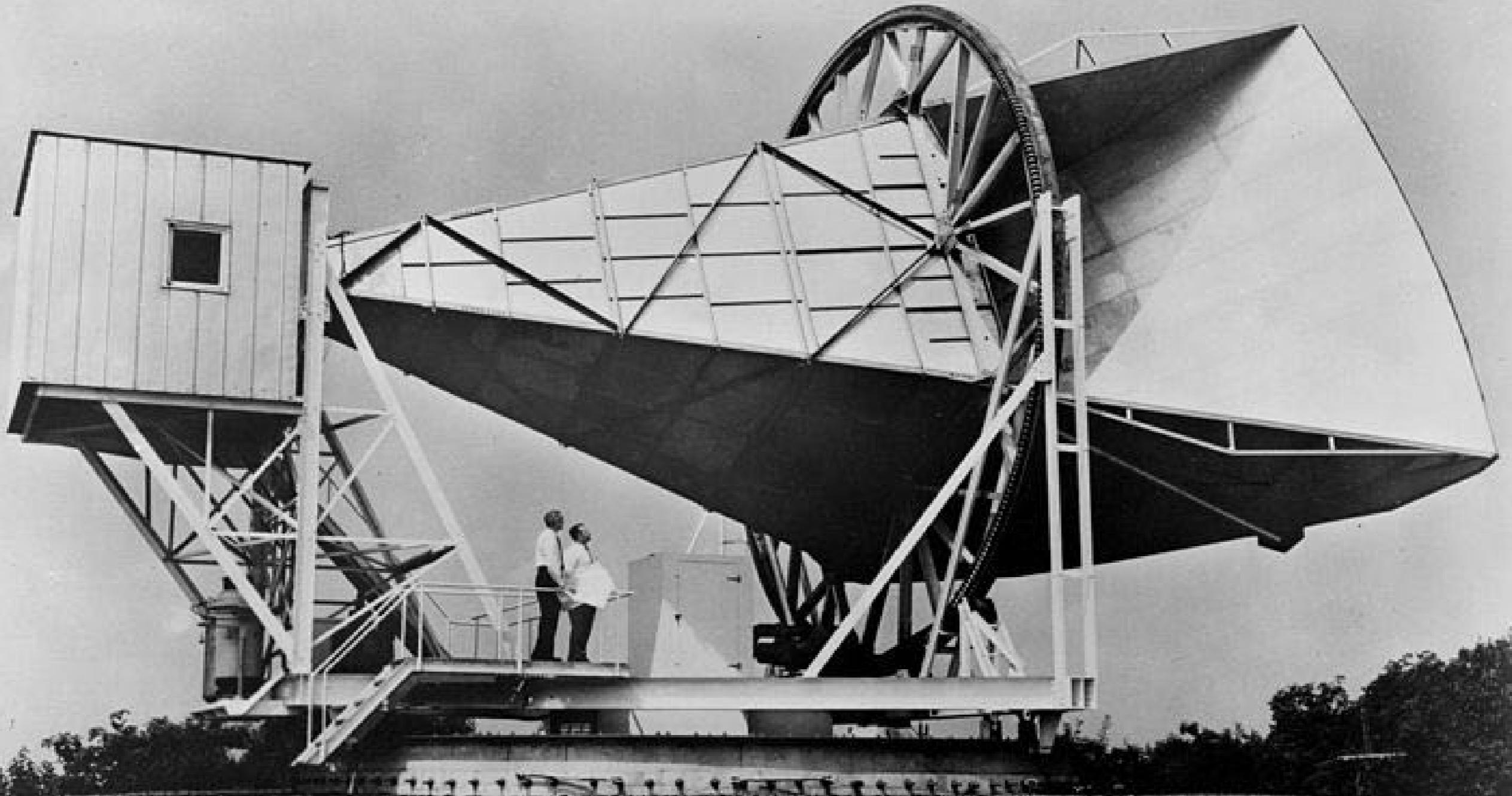
# From radiation-dominated era to recombination



# From radiation-dominated era to recombination



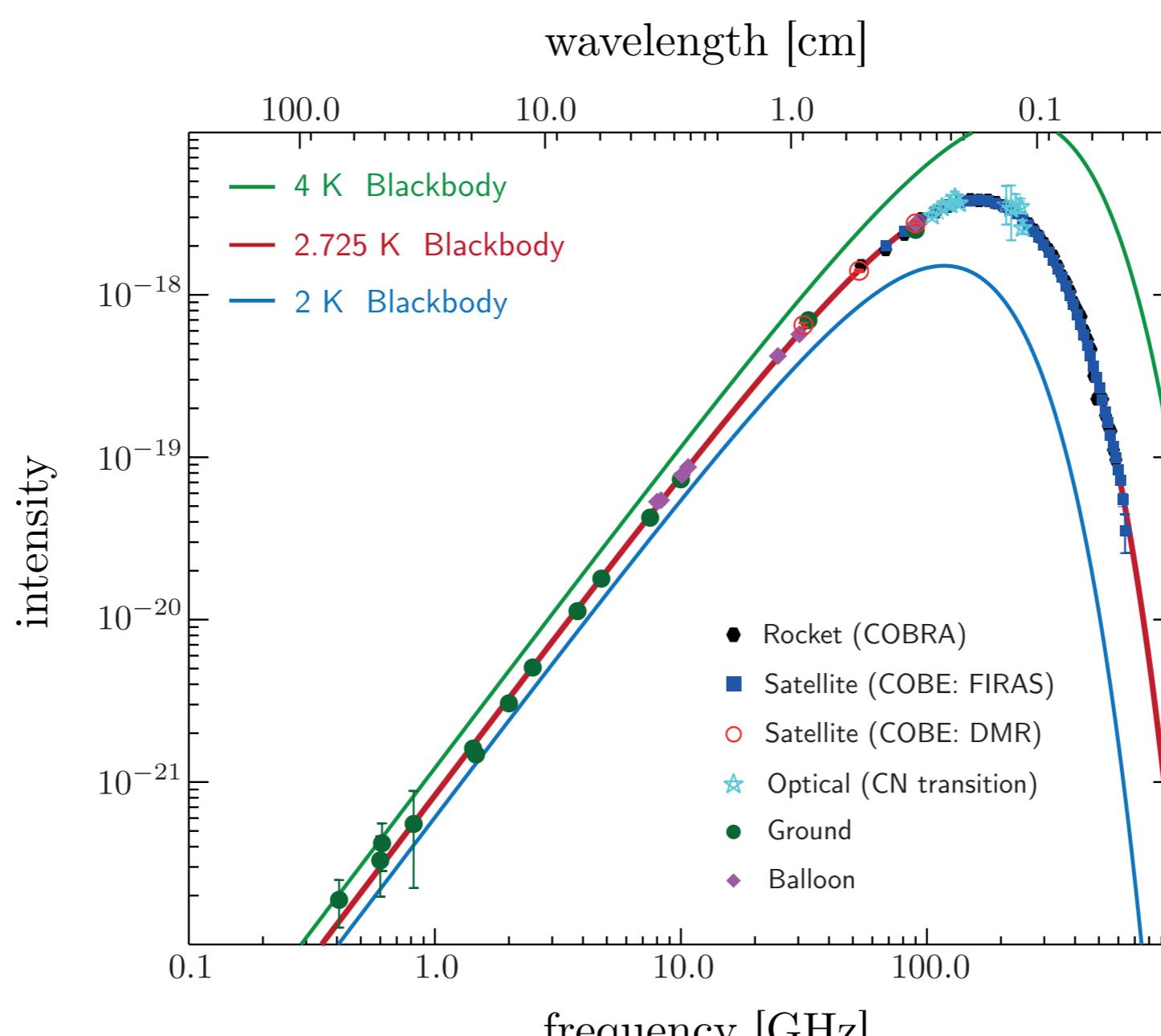
# Afterglow of the Big Bang



**Penzias & Wilson discovered the Cosmic Microwave Background (CMB) in 1965**

# Afterglow of the Big Bang

They found is the most perfect blackbody spectrum in Nature...



Penzias & Wilson discovered the Cosmic Microwave Background (CMB) in 1965  
Observed in every direction and has no single origin point...

# Observing the CMB radiation

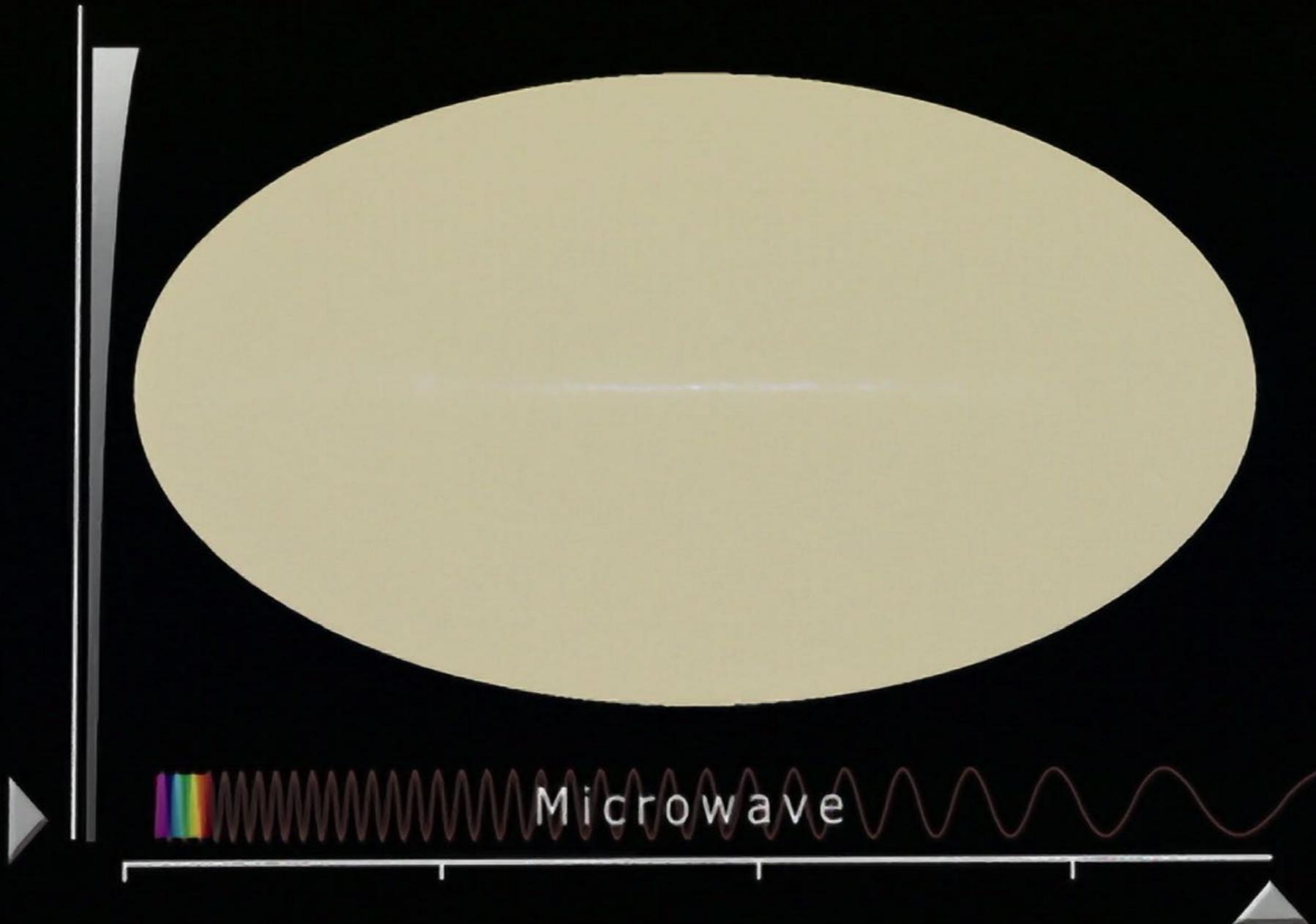


# Observing the CMB radiation

**Initial CMB spectrum measurements confirmed perfect uniform black-body radiation of 2.75 K!**

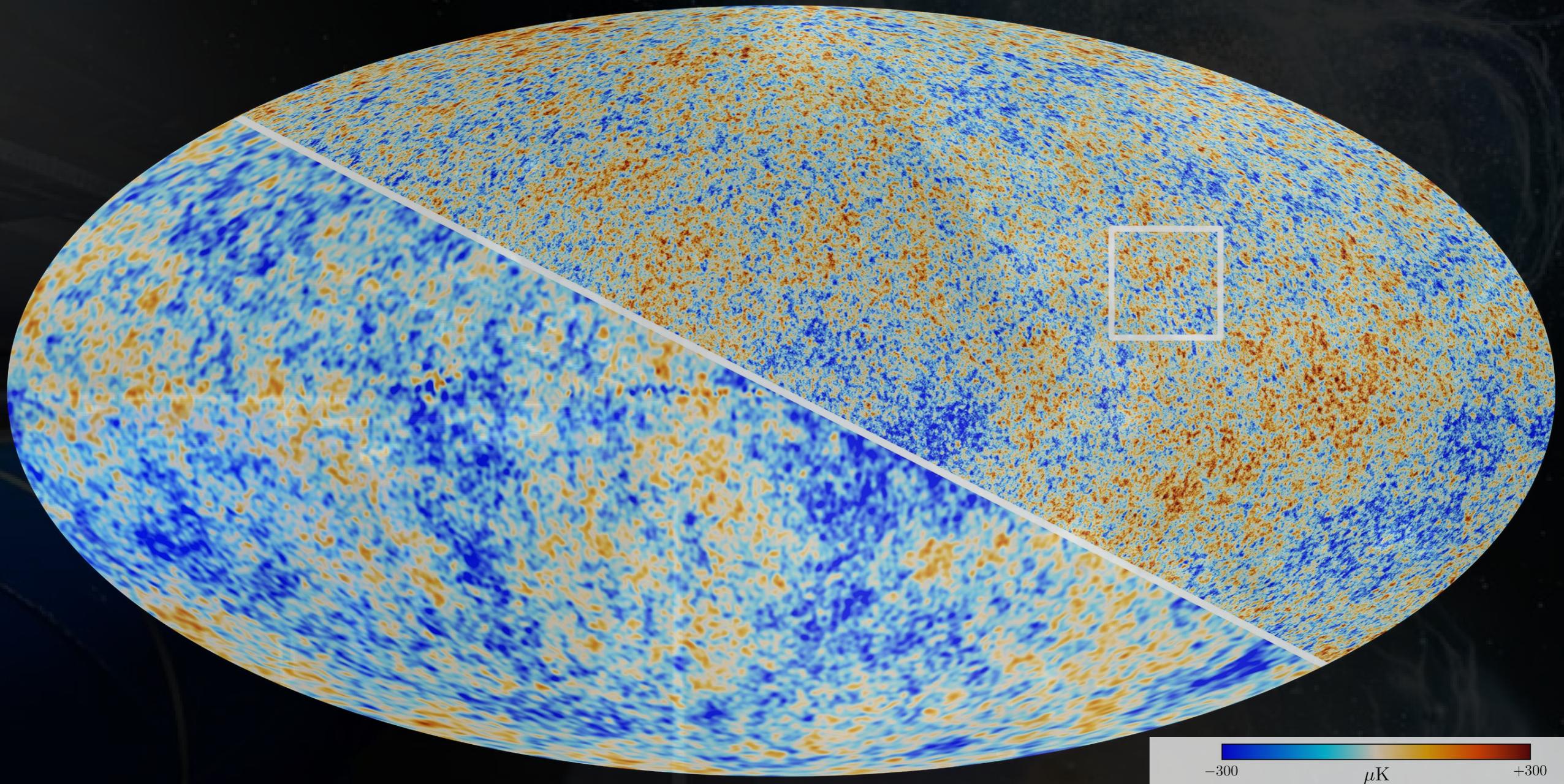


# Observing the CMB radiation



**With ever-more precise space-based experiments (COBE, WMAP, Planck)  
CMB spectrum measured at extraordinary details!**

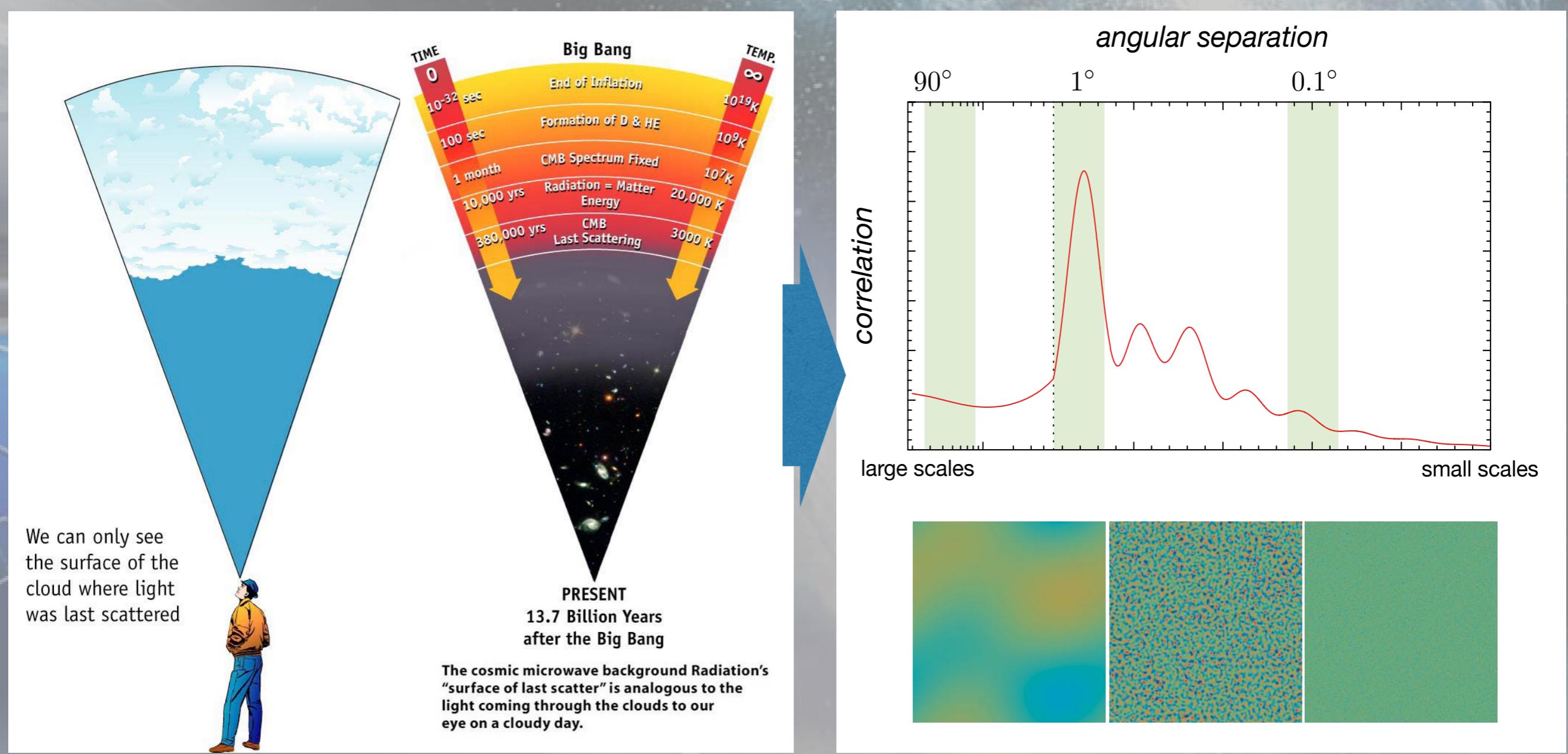
# Observing the CMB radiation



**Temperature of the CMB found to vary with direction...  
...with tiny variations, just 1 part in 10,000!**

# CMB : Fingerprinting the universe

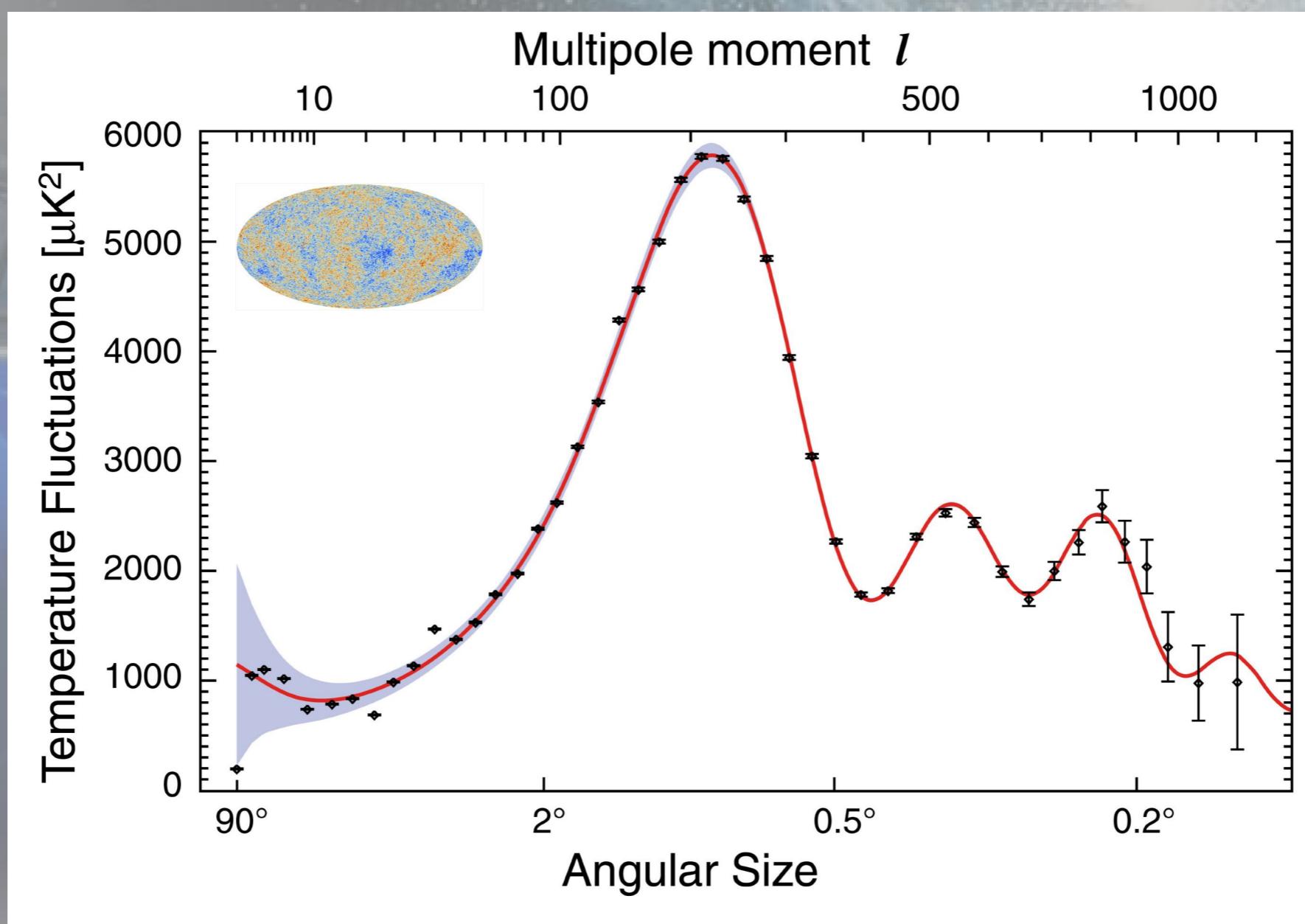
**Matter/density variations in an early universe imprinted in tiny CMB "ripples".**  
**Initial CMB cooled down gradually with the expansion of the universe.**



**CMB pattern today allows to infer: age, shape, and composition of our universe!**

# CMB : Fingerprinting the universe

**Matter/density variations in an early universe imprinted in tiny CMB "ripples".**  
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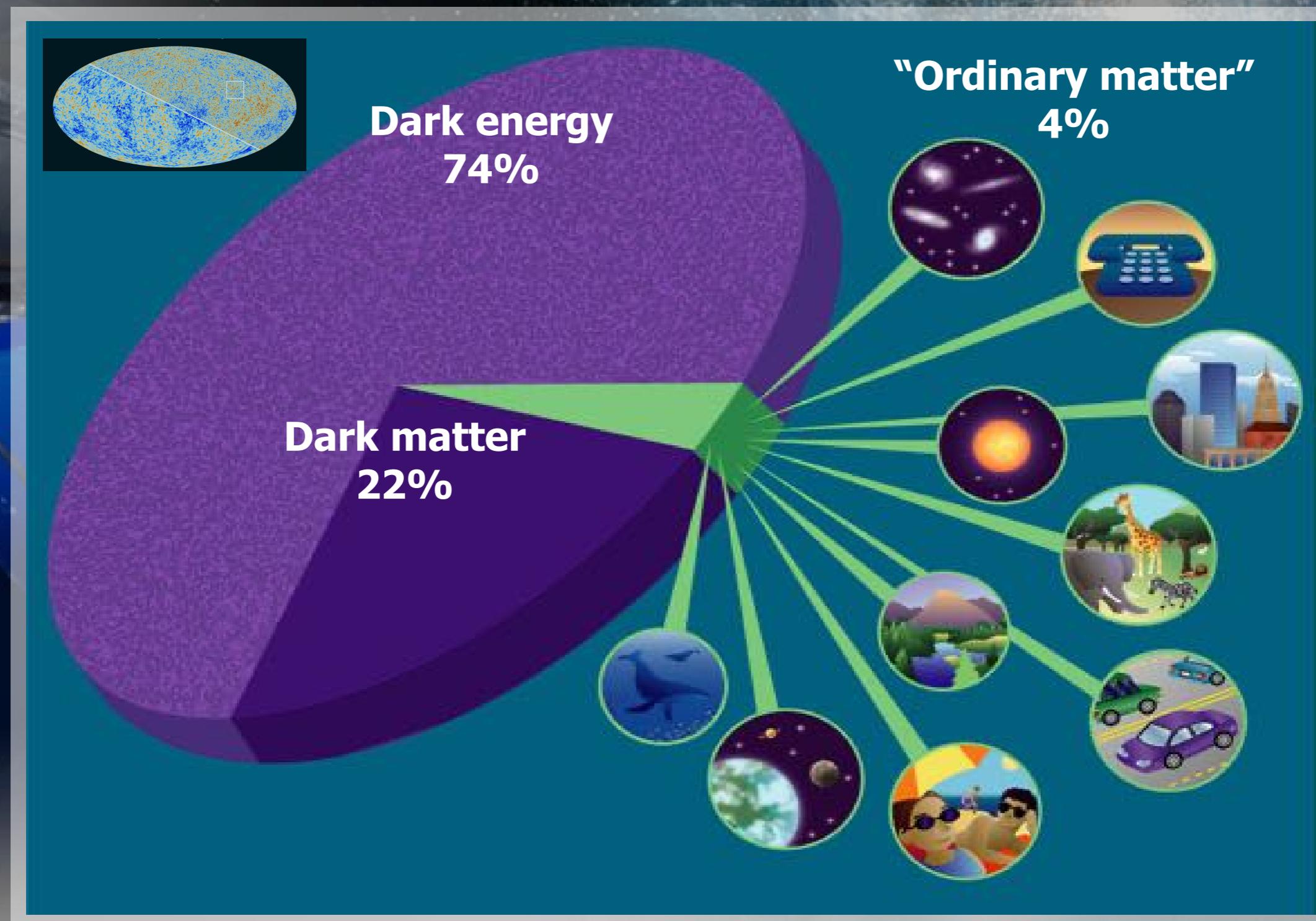
# CMB : Fingerprinting the universe

**Shape: Universe predominantly has flat geometry!**

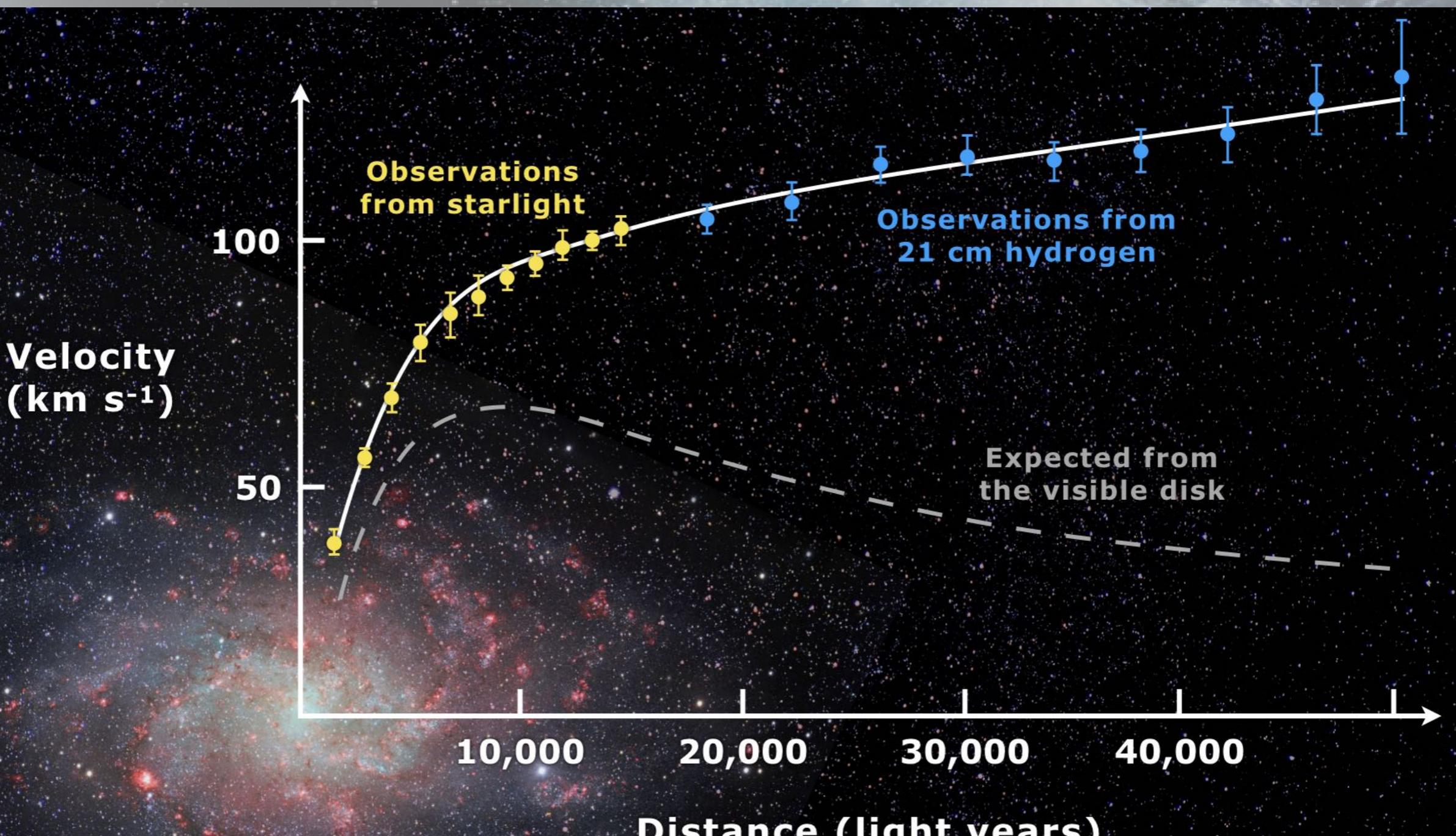


# CMB : Fingerprinting the universe

**Composition:** Universe seems to be dominated by non-ordinary forms of matter!



# Dark matter: indirect evidences



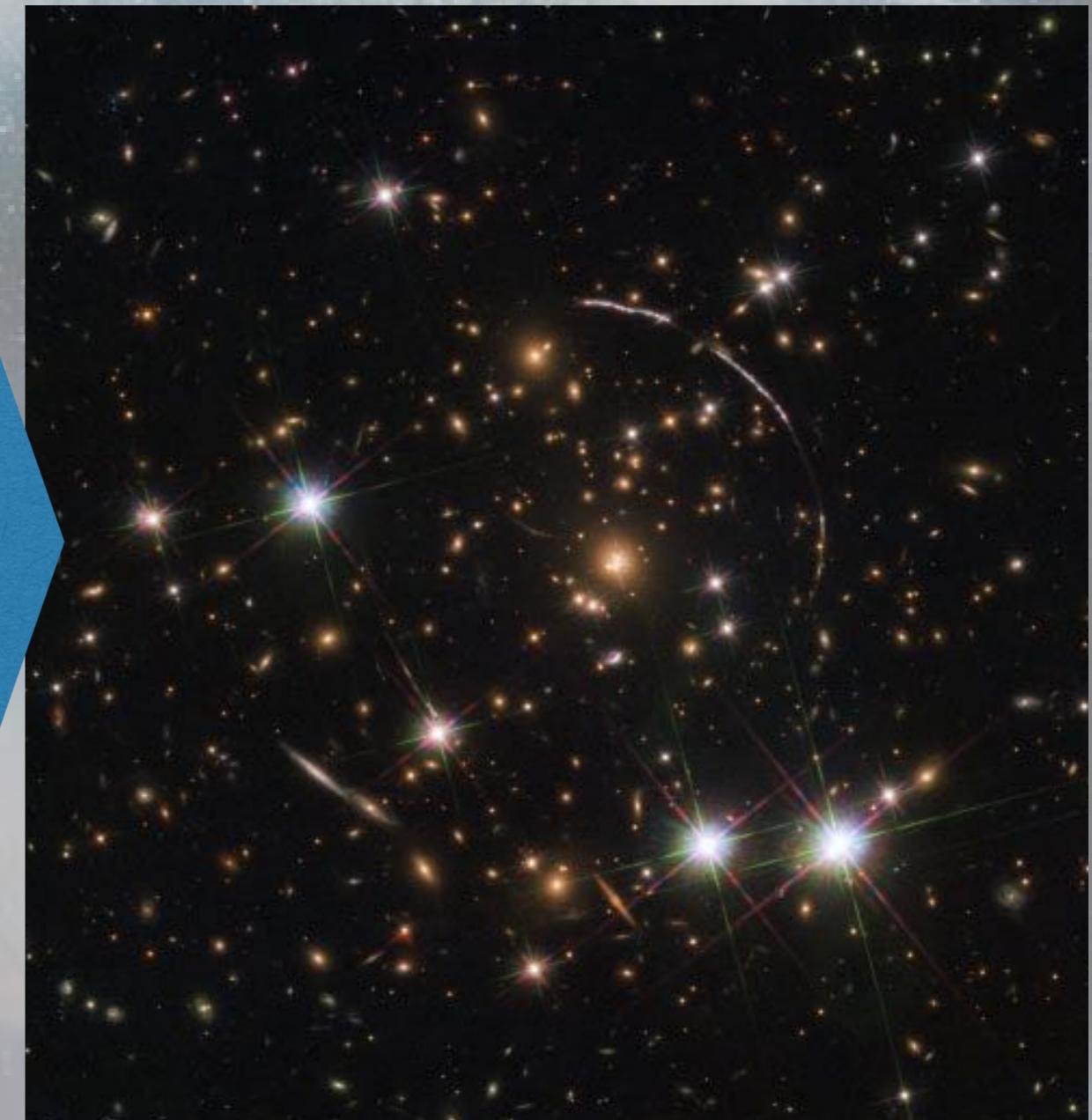
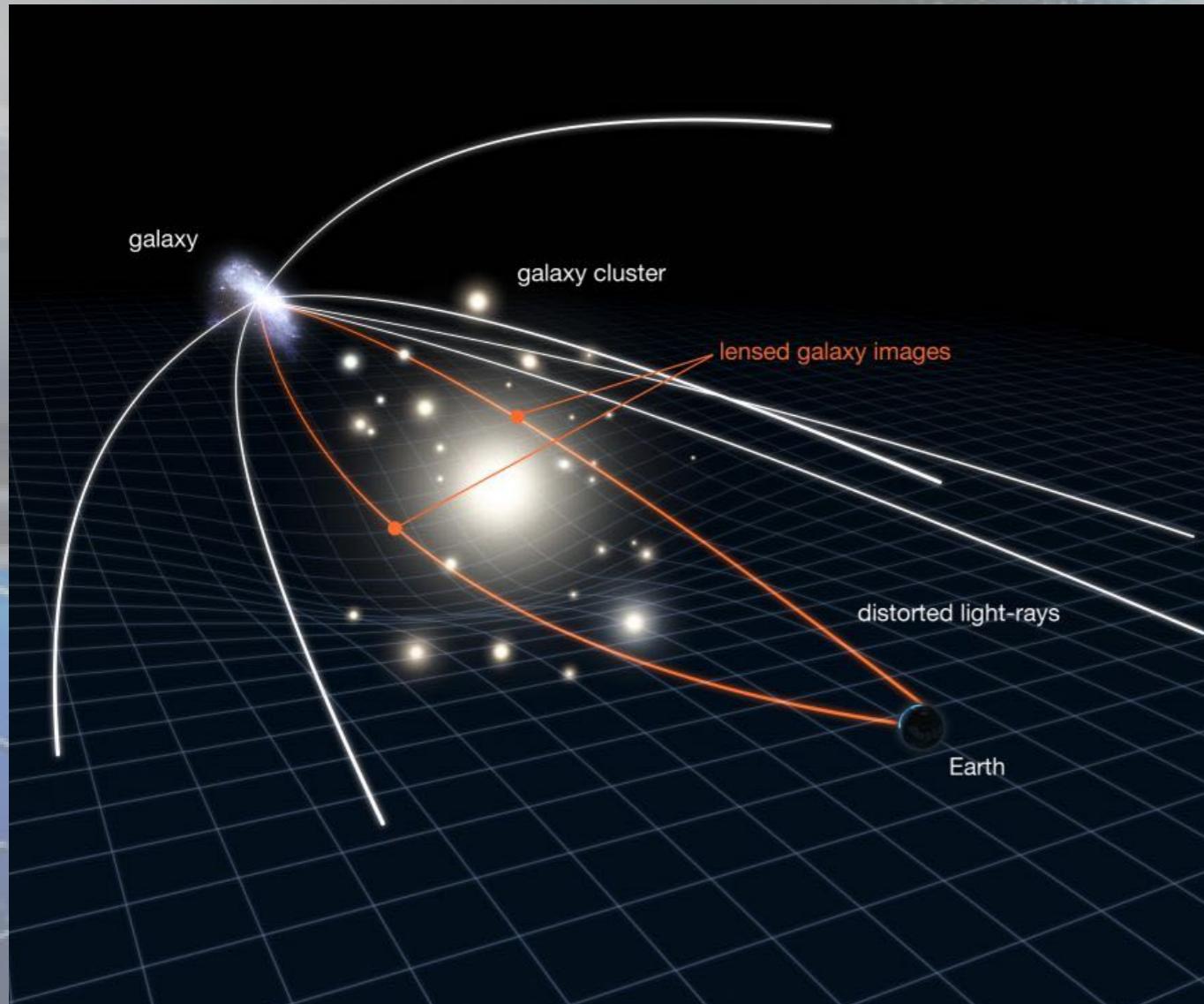
Galaxy rotation curves and stars velocity dispersions  
consistent with presence of dark matter!

# Dark matter: indirect evidences



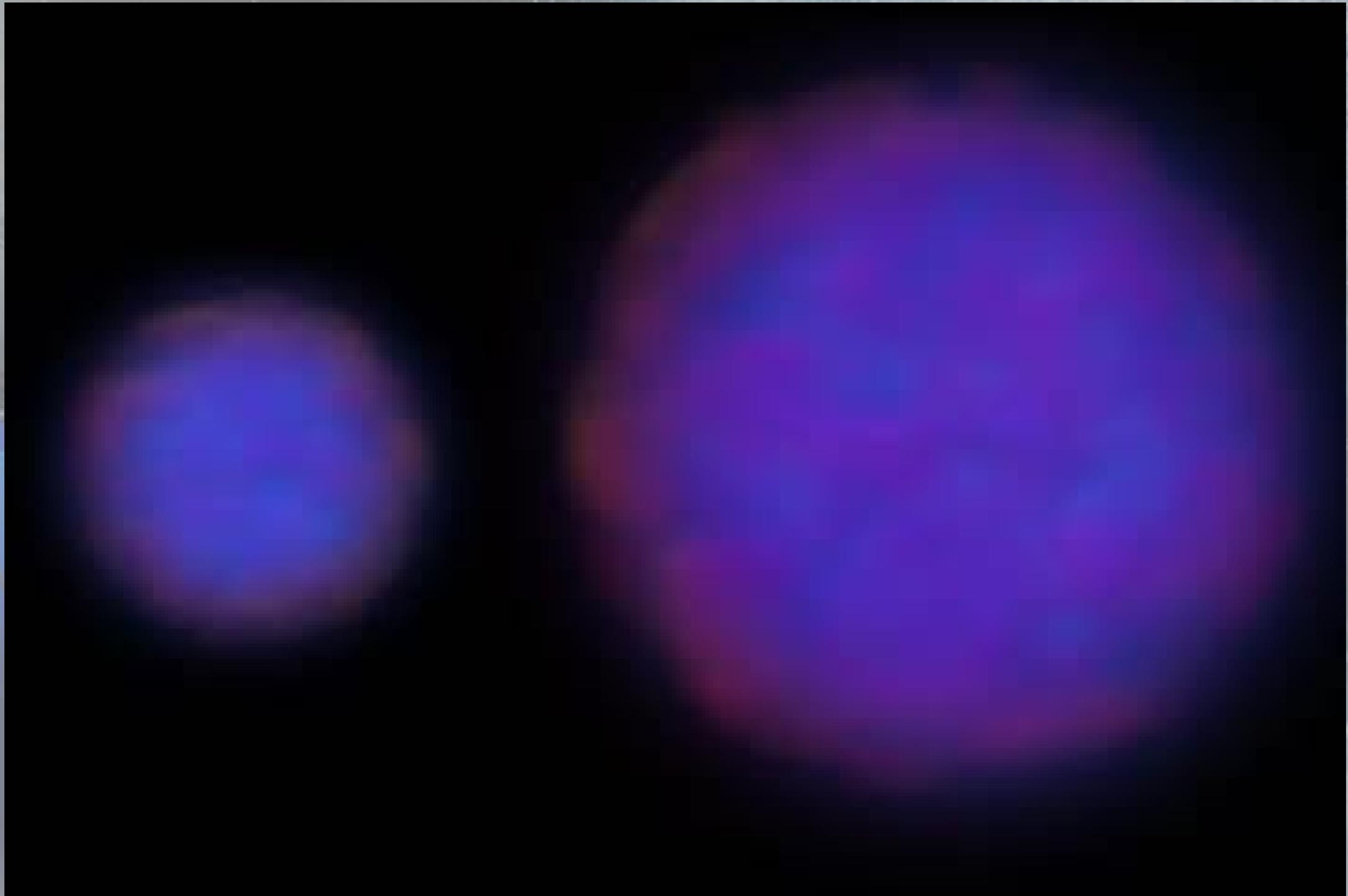
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# Dark matter: indirect evidences



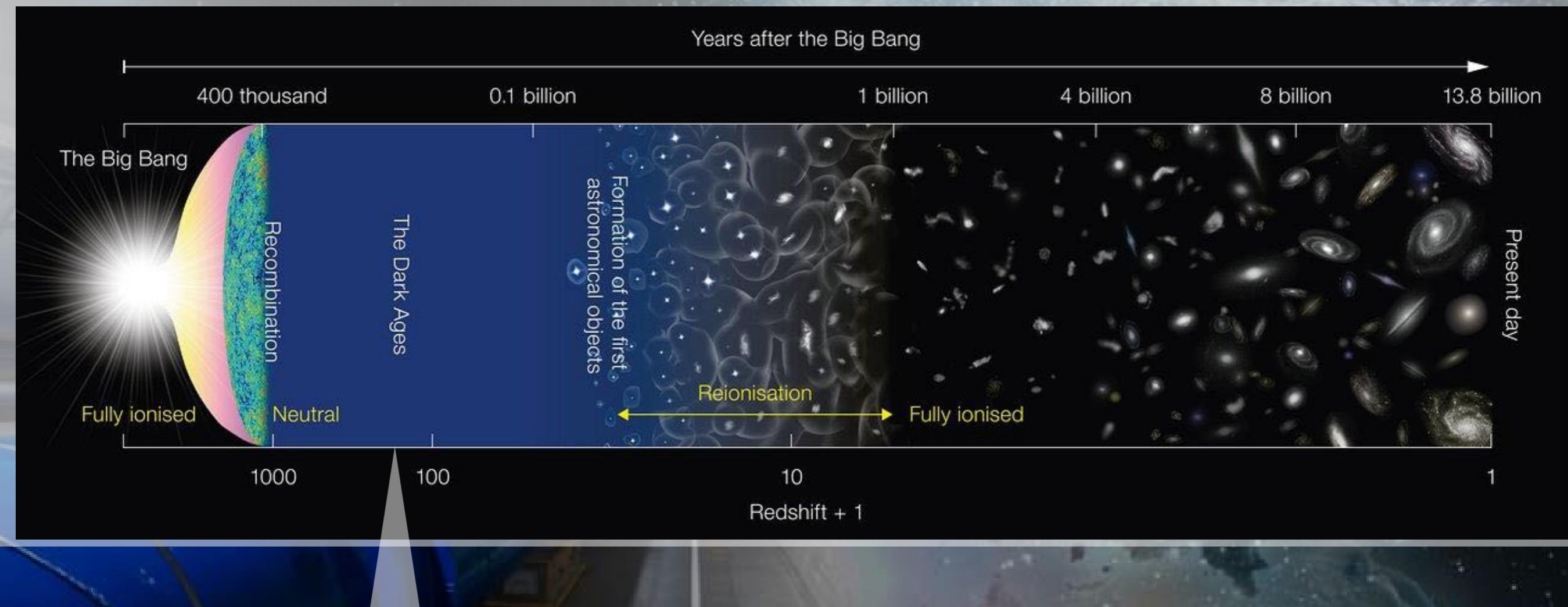
**Dark matter bends space-time resulting in lensing effect:  
observations consistent with presence of dark matter!**

# Dark matter: (almost) direct evidences



**Distribution of matter during the collisions of two clusters of galaxies:  
most of the mass exhibits interaction consistent with dark matter!**

# Emerging from the Dark Ages

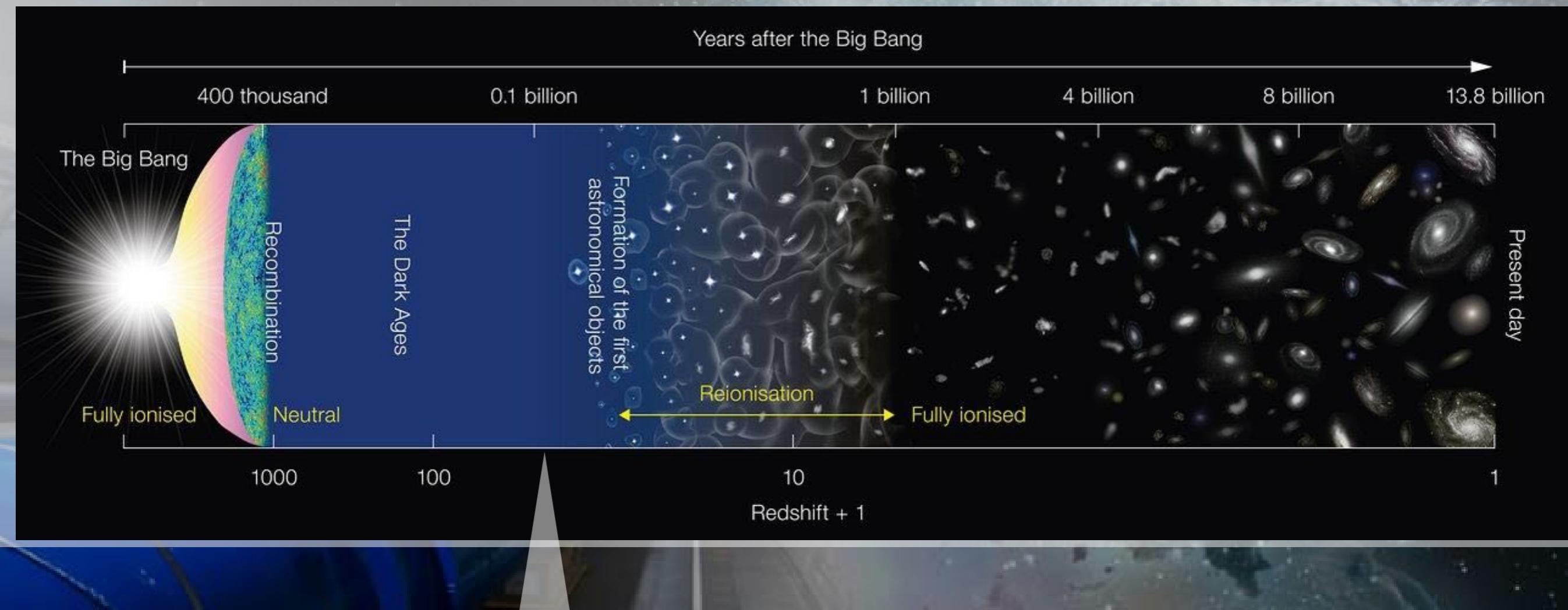


## Epoch of dark ages:

**CMB temperature cooled down from  $\sim 3000$  K to  $\sim 60$  K,  
no visible light photons, hydrogen/helium density stable.**

**~15 ma: CMB had a temperature of a "warm summer day on Earth"**

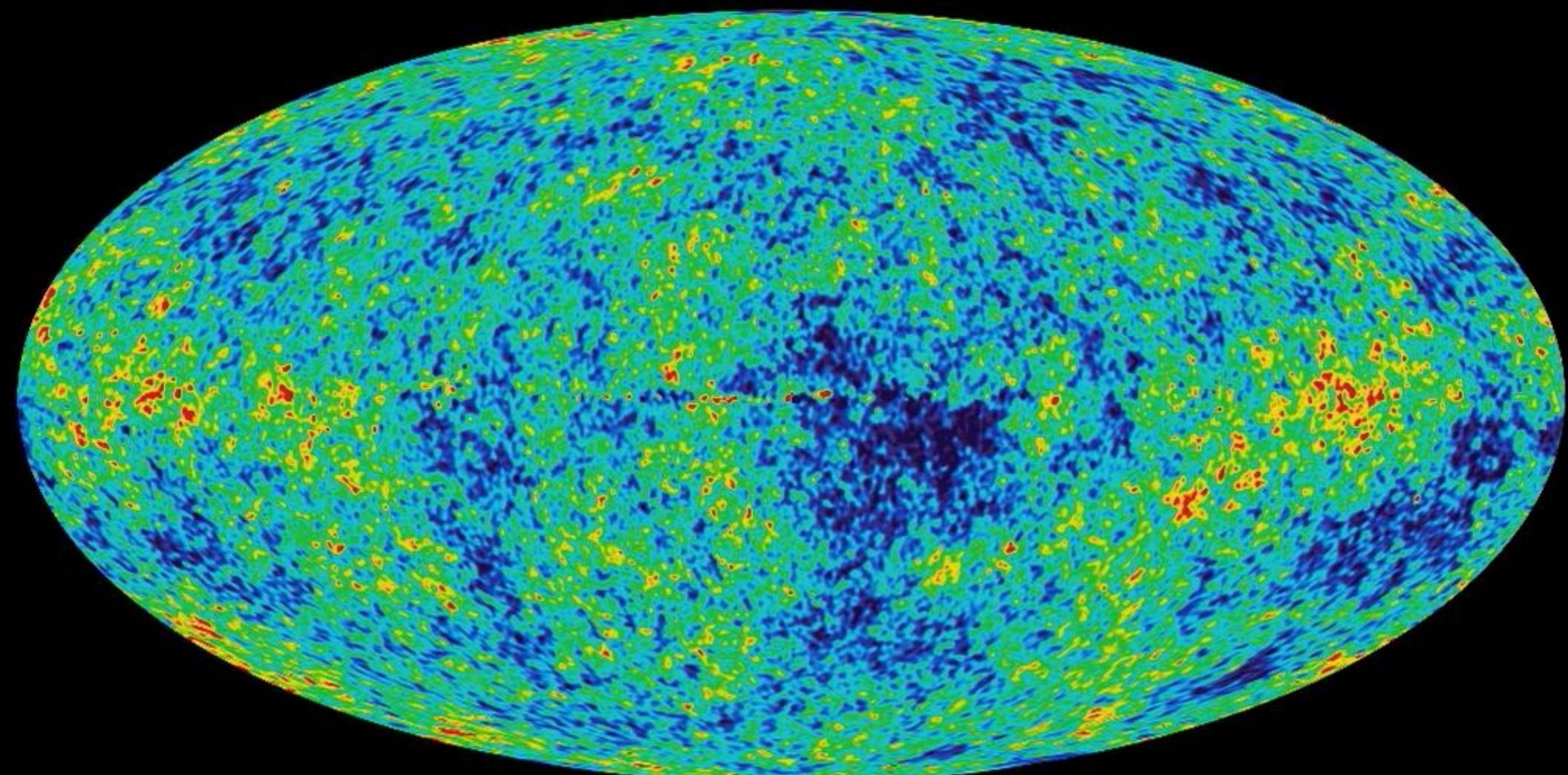
# Emerging from the Dark Ages



**Gravitational collapse:**  
ordinary matter falls into the structures created by dark matter,  
first smaller and larger non-linear structures begin to take shape.

**UV light starts to ionize neutral gas**

# From quantum fluctuations to large-scale structures



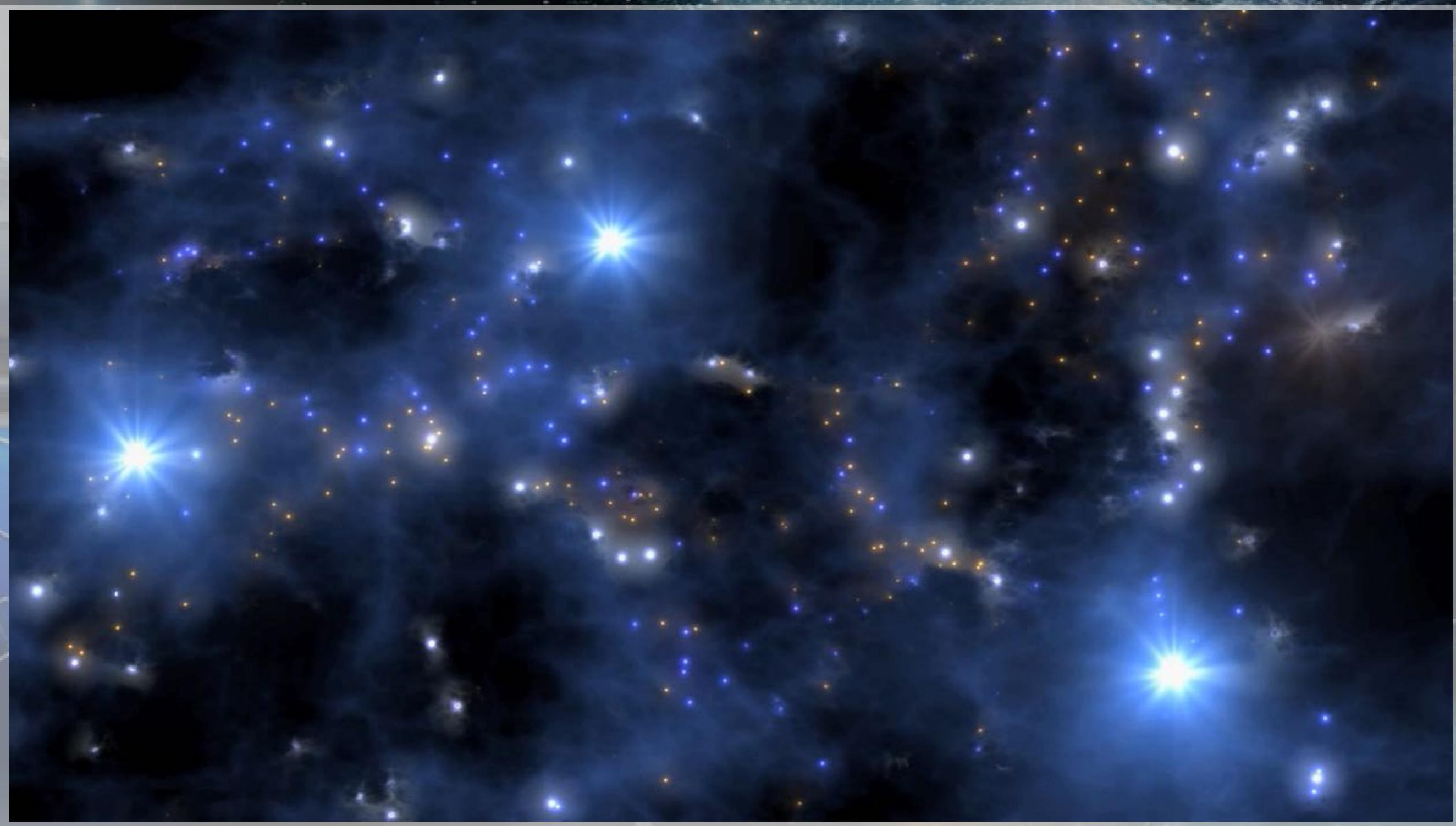
**Quantum fluctuation in space-time induced variations in matter density  
ordinary matter falls into the structures created by dark matter!**

# From quantum fluctuations to large-scale structures



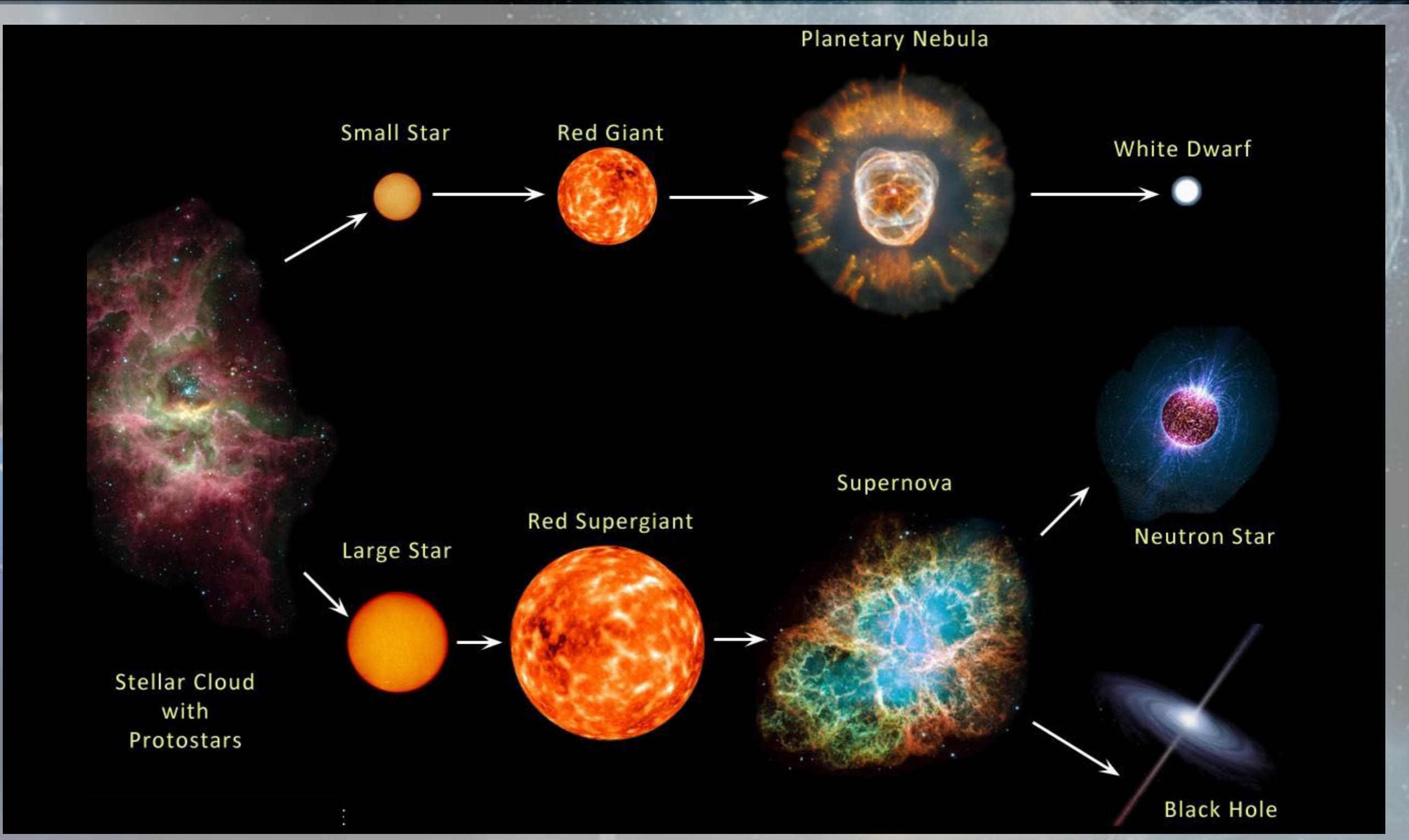
**First smaller and larger non-linear structures begin to take shape (100 ma)  
first proto-stars made of hydrogen and helium begin to shine (200-300 ma)!**

# From quantum fluctuations to large-scale structures



**Large-scale astronomical objects (protogalaxies, quasars) begun forming  
proto-stars producing heavy elements allowing for "metallic" stars (>300 ma) !**

# Evolution of stars



**Stellar evolution is complex/cyclic process, often with compact final objects:  
white/brown dwarfs, neutron stars, and black holes !**

# Origin of elements

## Element Origins

1 H																				2 He
3 Li	4 Be																			
11 Na	12 Mg																			
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr			
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe			
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn			
87 Fr	88 Ra																			
57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu						
89 Ac	90 Th	91 Pa	92 U																	

Merging Neutron Stars  
Dying Low Mass Stars

Exploding Massive Stars  
Exploding White Dwarfs

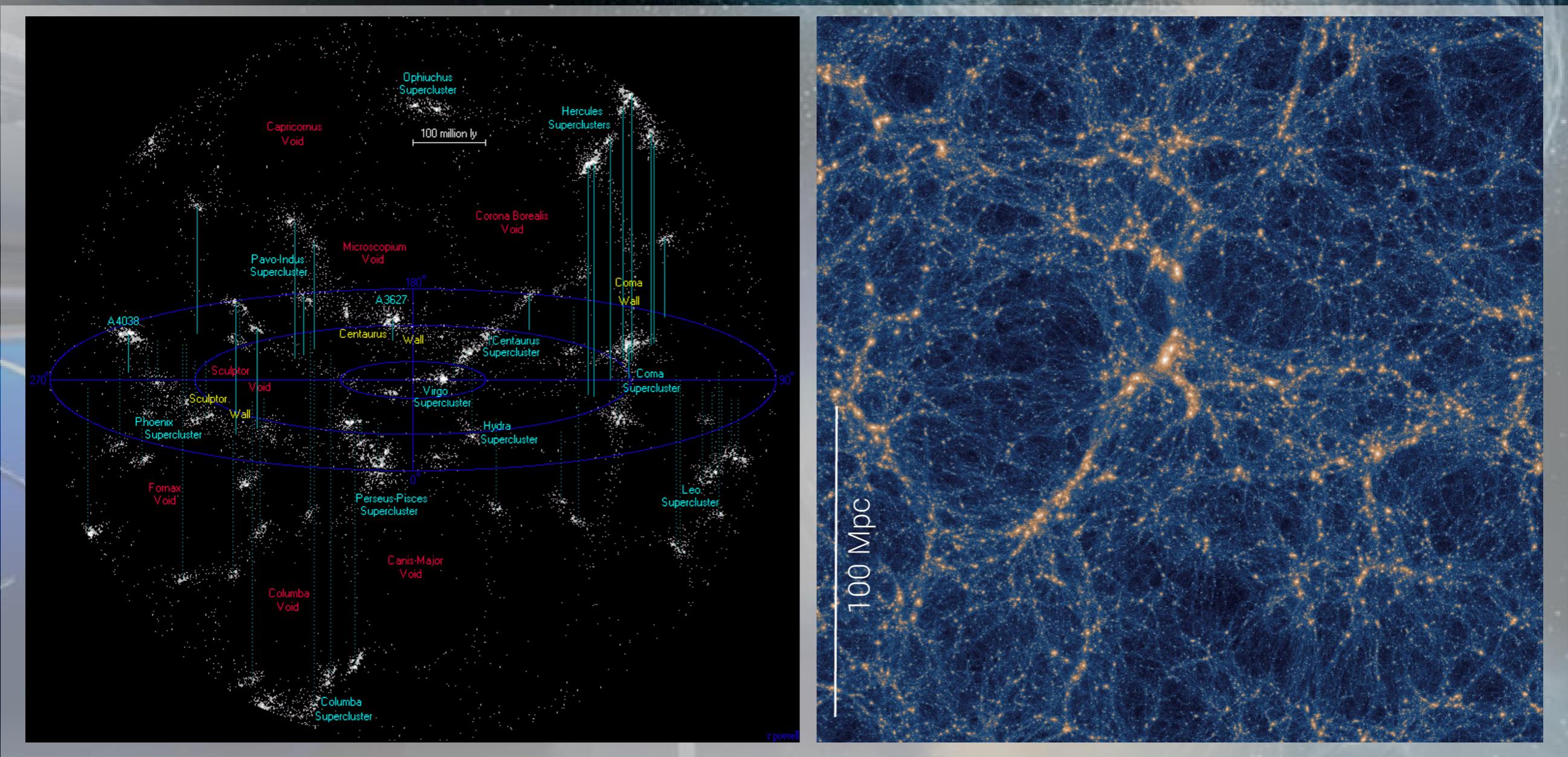
Big Bang  
Cosmic Ray Fission

Based on graphic created by Jennifer Johnson

All heavy chemical elements have stellar origin:  
from stellar merging/dying/exploding events !

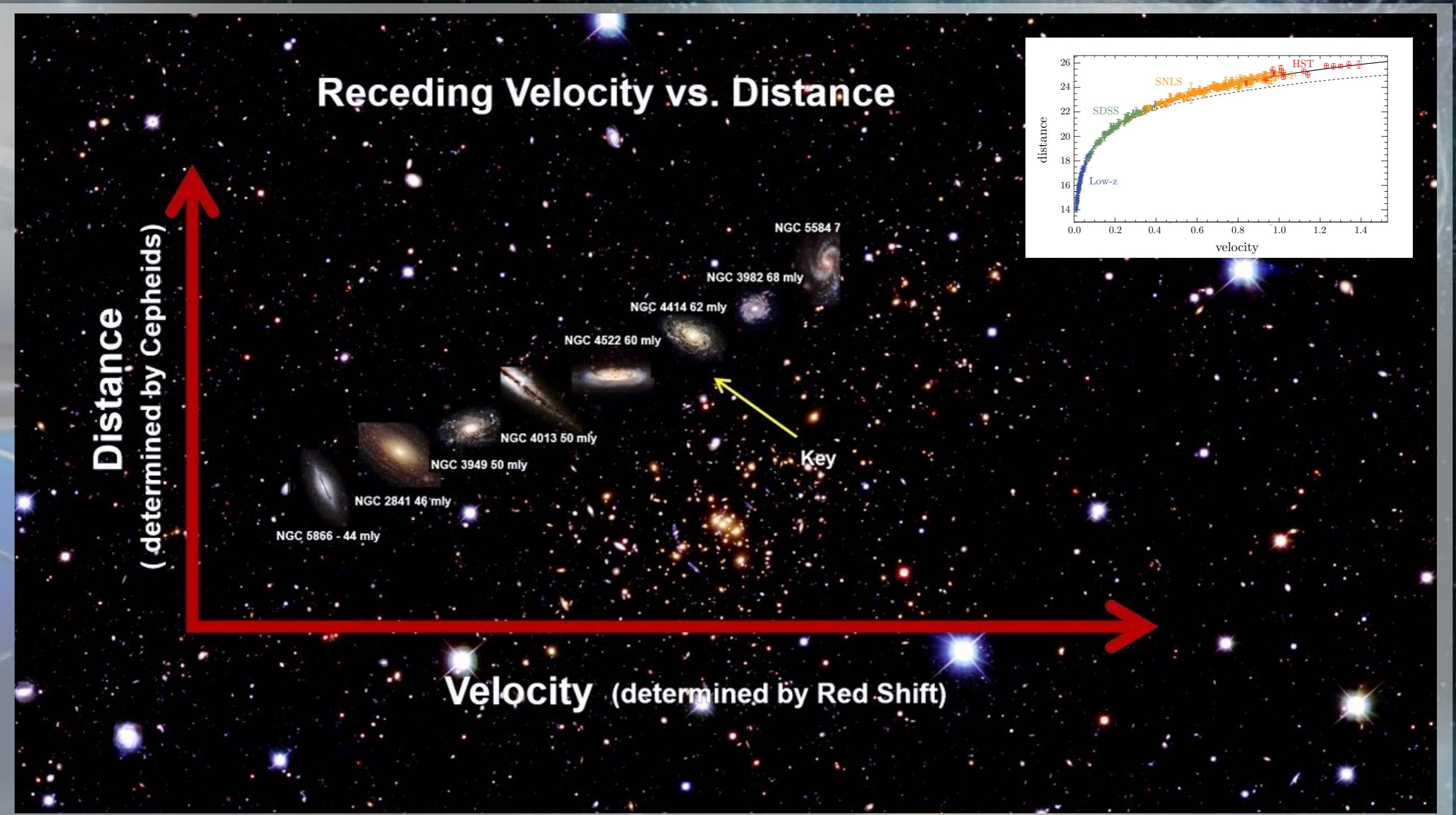
# Large-scale structures of the universe

**From Sky surveys and mappings: Cosmic structures follow a hierarchical model with organization up to the scale of superclusters and filaments (not beyond).**



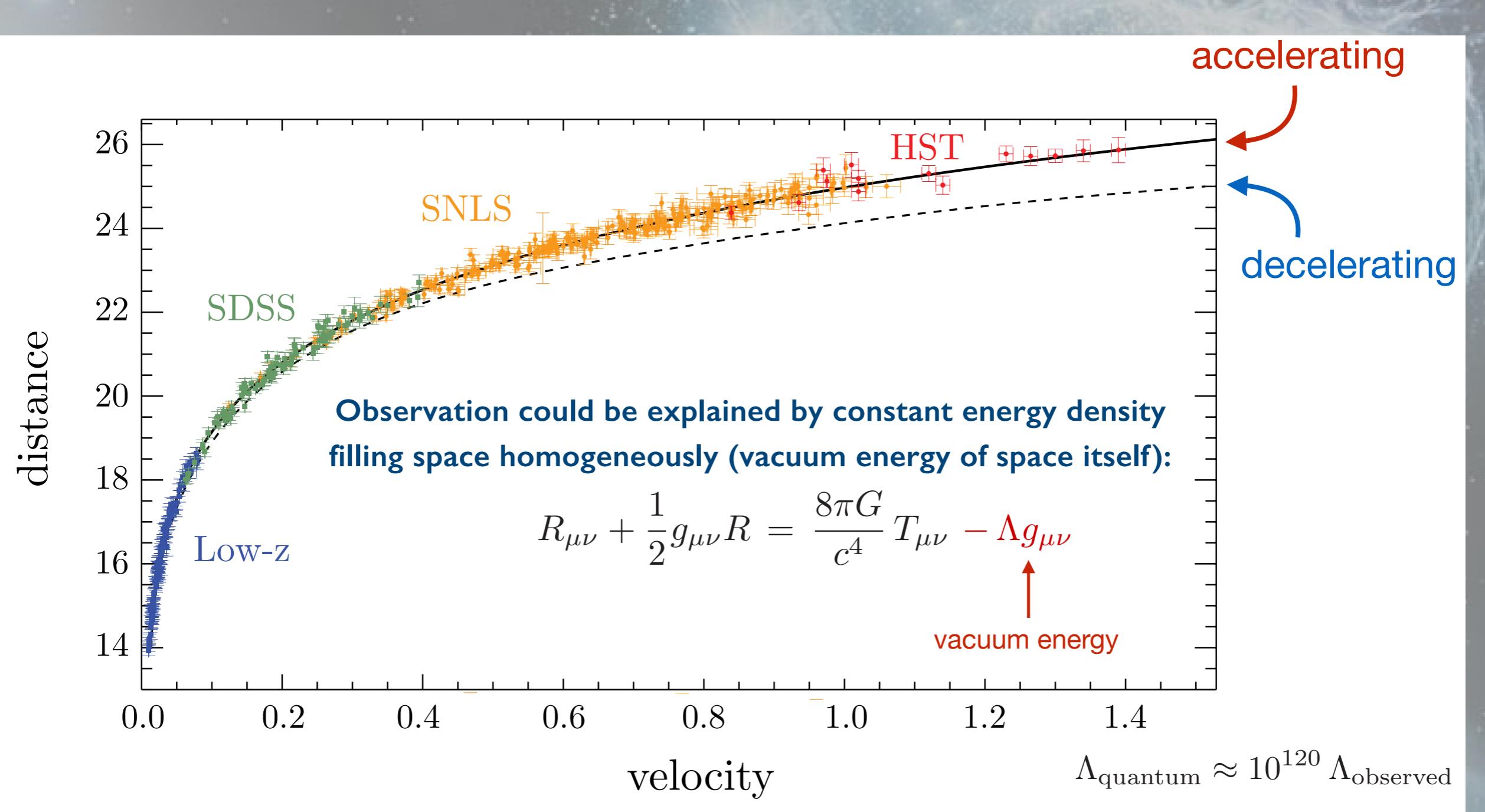
**Simulations of the Universe reproduce its key structural features  
still the largest structures observed are larger than expected (~10 billion ly) !**

# Expansion of the universe: Hubble's law



**Galaxies are moving away from Earth at speeds proportional to their distance giving observational basis for the expansion of the universe !**

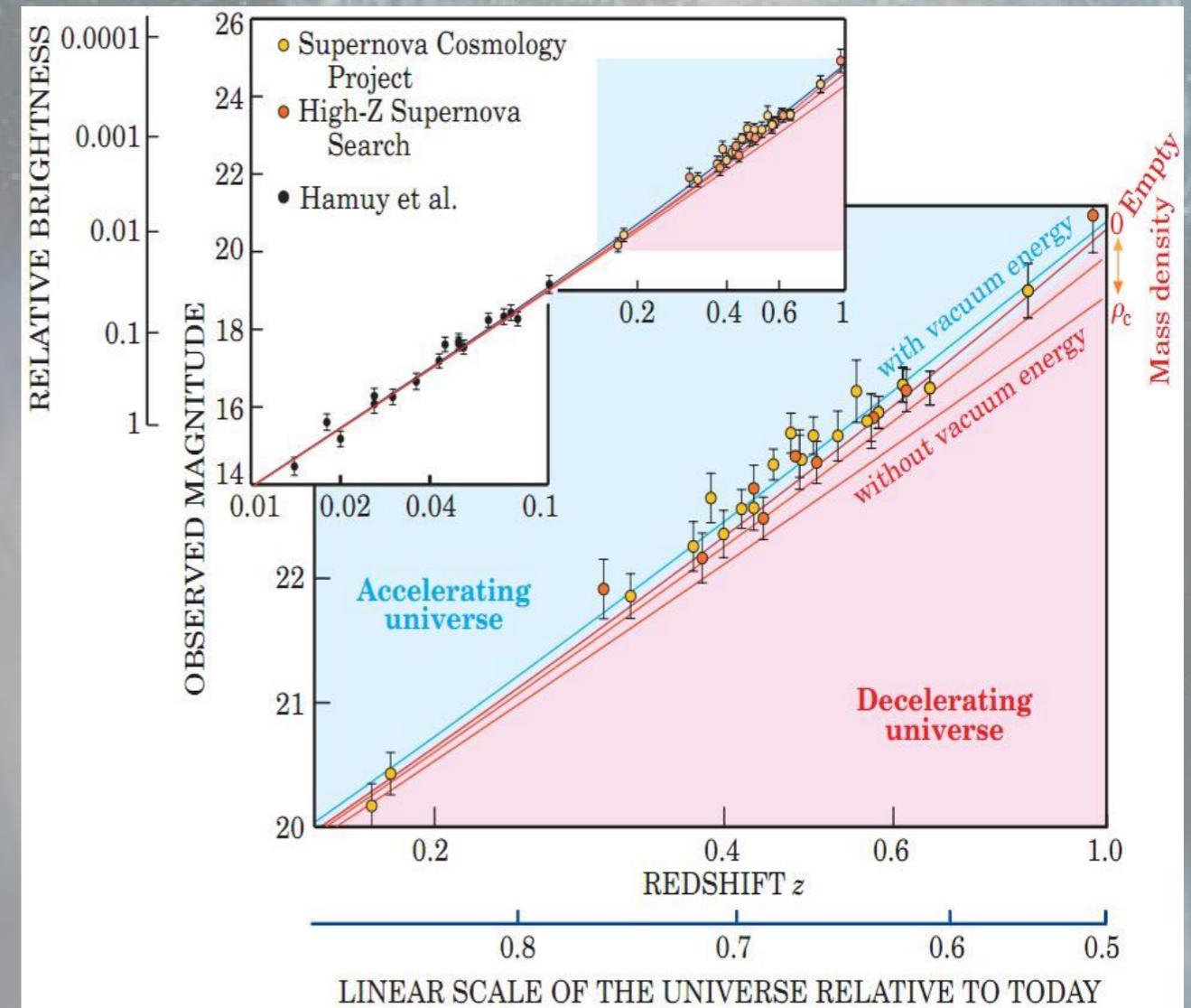
# Accelerated expansion of the universe



Observed accelerated expansion of the universe can be explained by the dark energy (e.g. vacuum energy or scalar field) !

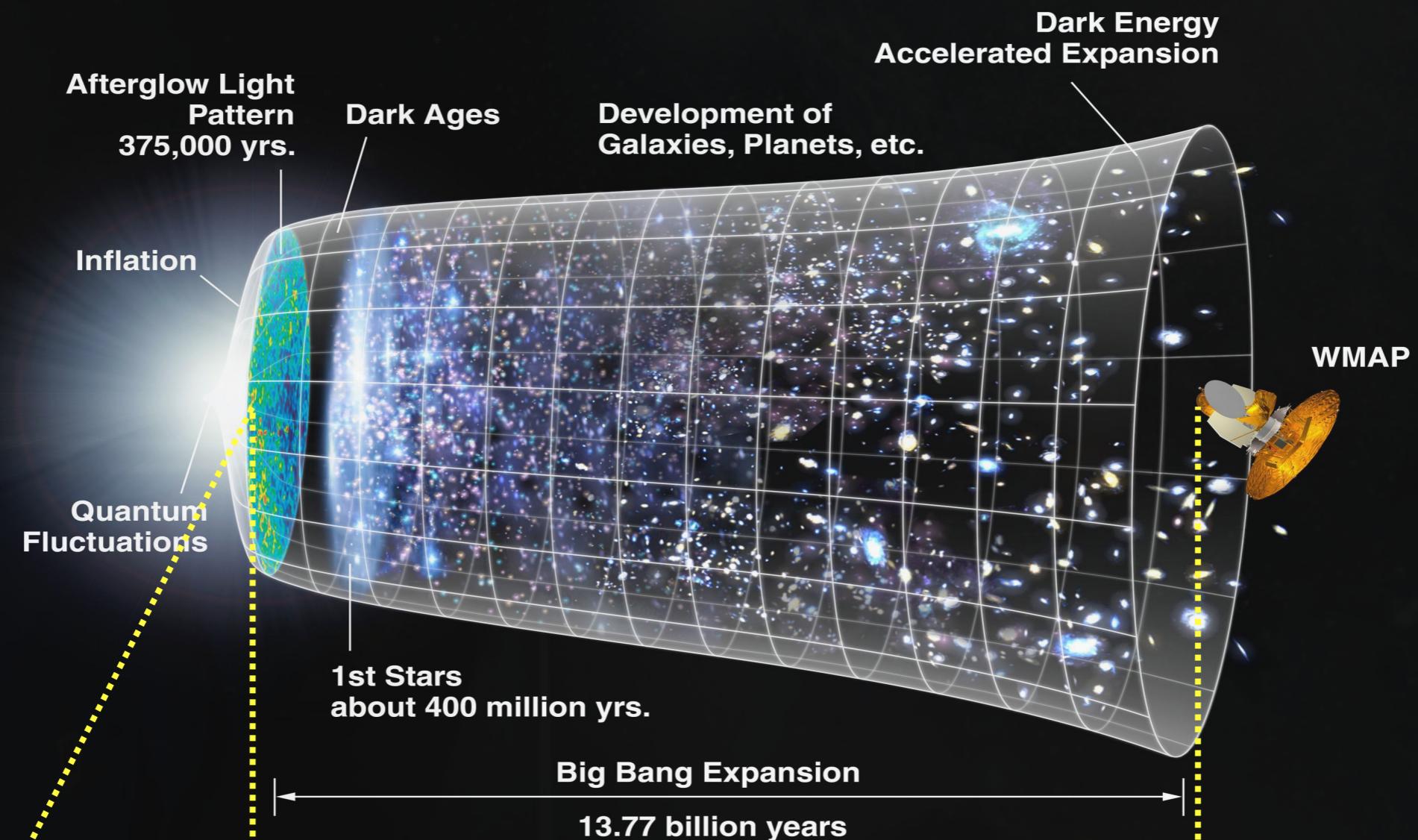
# Dark energy & accelerated expansion

Confirmed by studying distribution/distance/velocity of Supernovae Type Ia  
(Nobel Prize in Physics 2011).



Dark energy also consistent with need for the observationally flat universe,  
and observed large-scale wave-patterns of mass density in the universe!

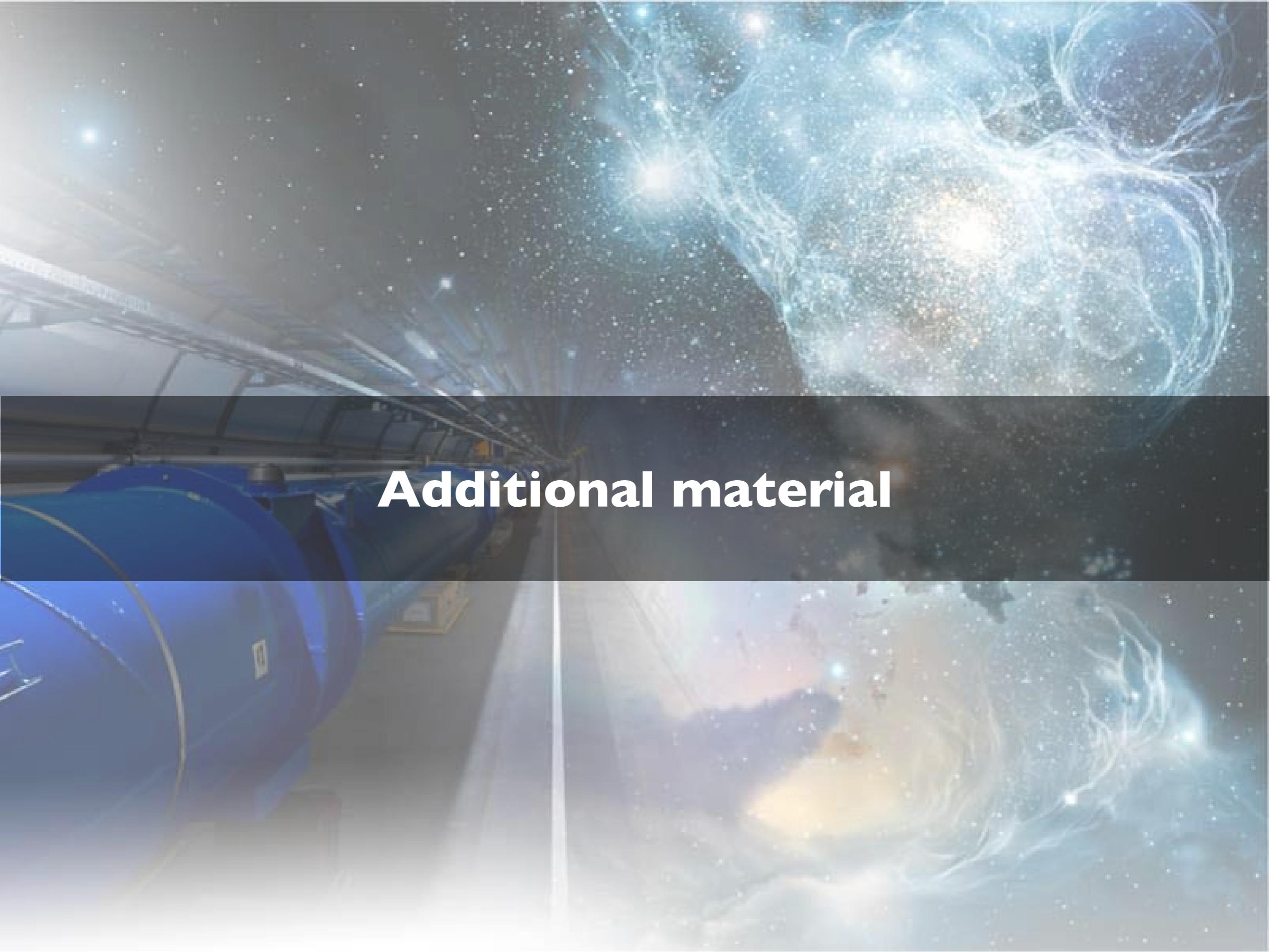
# Evolution of the universe



~3 min.

~13.8 billion years

...until the end.

The background of this slide is a collage of three distinct images. The left image shows a perspective view of a long, dark tunnel or corridor. Along the floor and walls are several large, blue cylindrical objects, possibly storage tanks or industrial equipment. The middle image is a wide-angle photograph of a night sky filled with numerous stars of varying brightness. The right image is a close-up, high-resolution view of a celestial body, likely a planet or a large moon, showing intricate cloud patterns in shades of blue, white, and yellow.

**Additional material**

# Our location at the Universe

EARTH

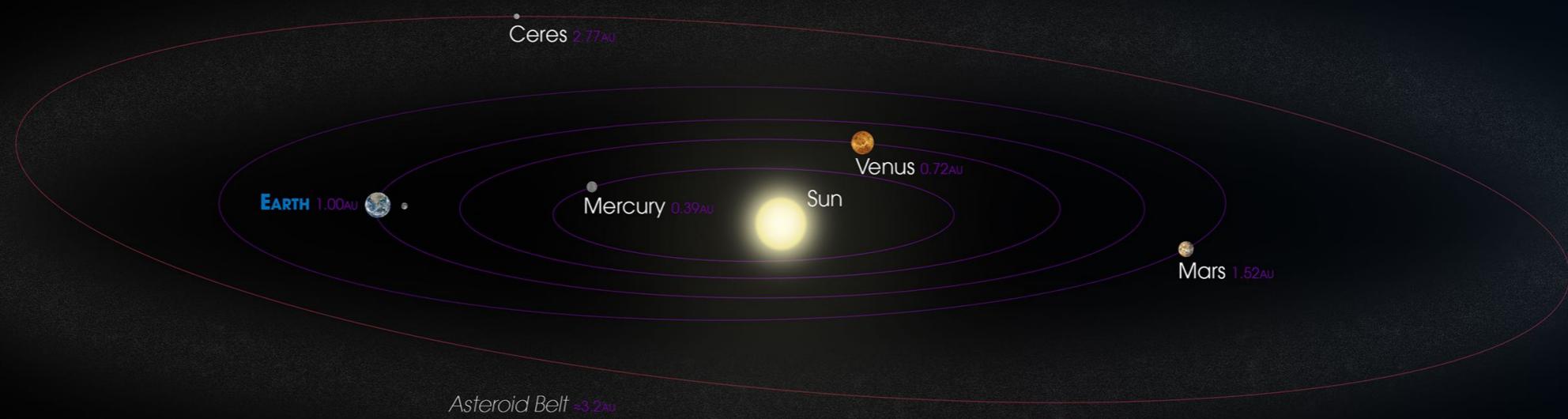


Moon 384402km



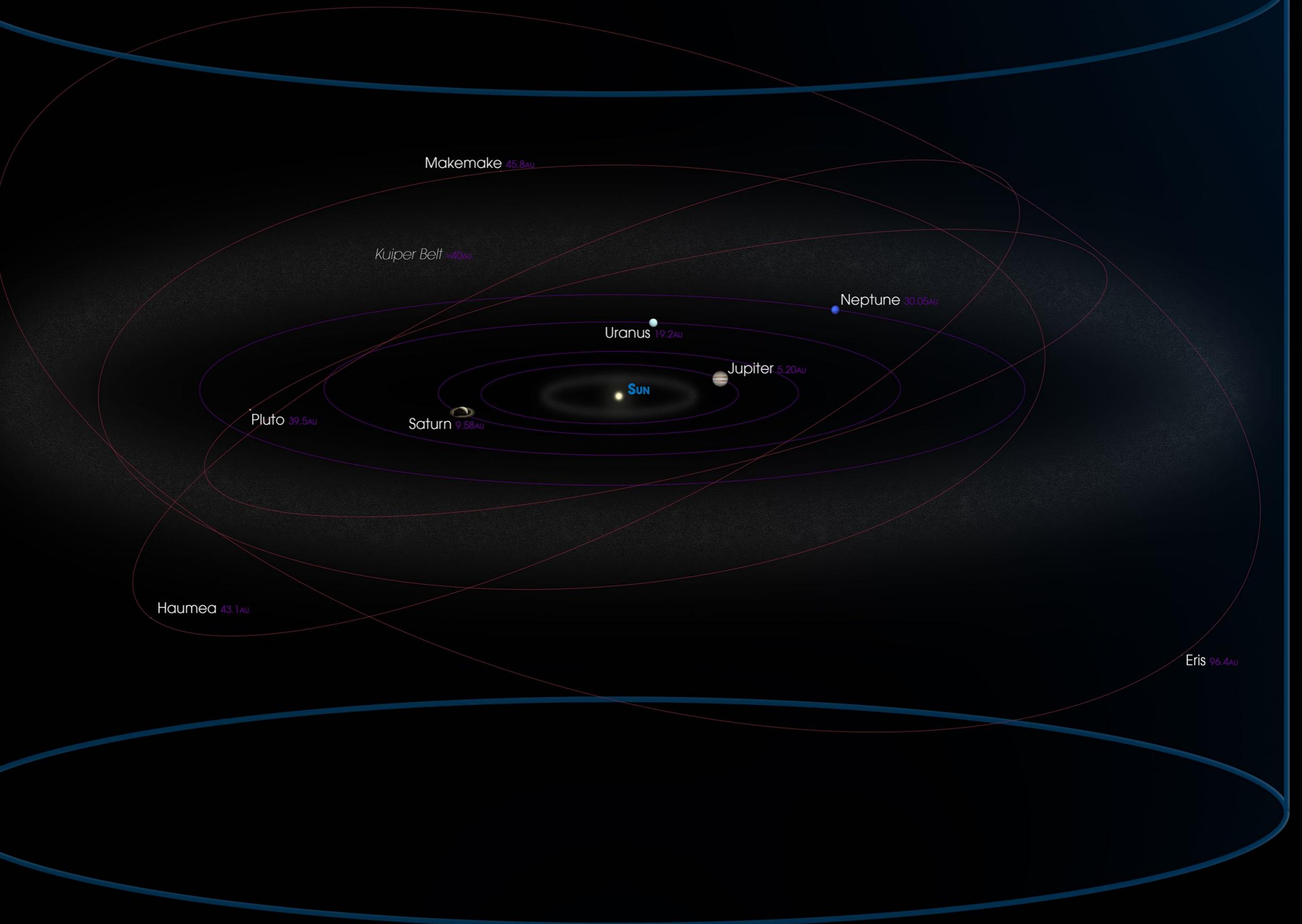
# Our location at the Universe

INNER SOLAR SYSTEM



# Our location at the Universe

OUTER SOLAR SYSTEM



# CLOSEST STARS

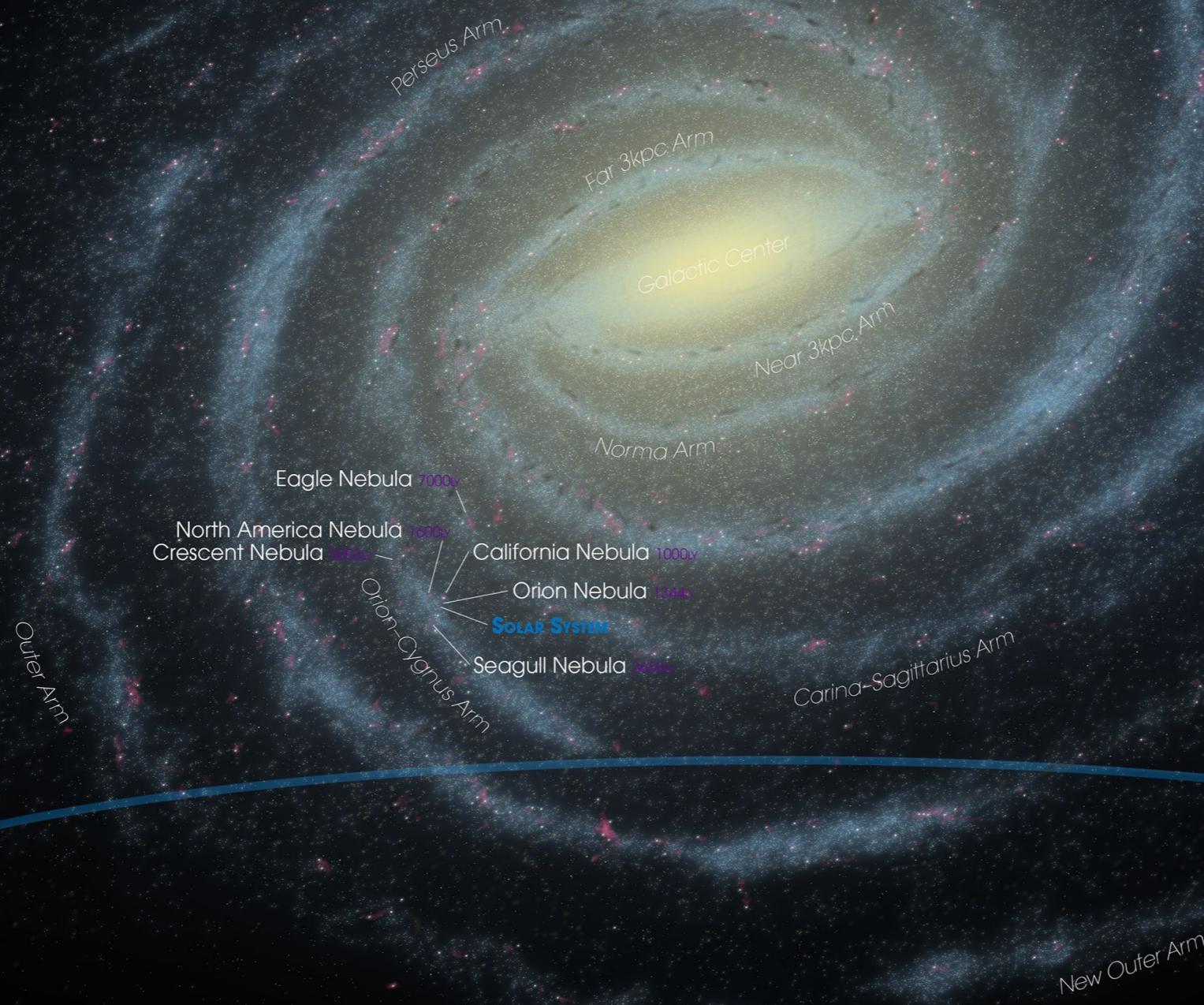
# Our location at the Universe



# MILKY WAY GALAXY

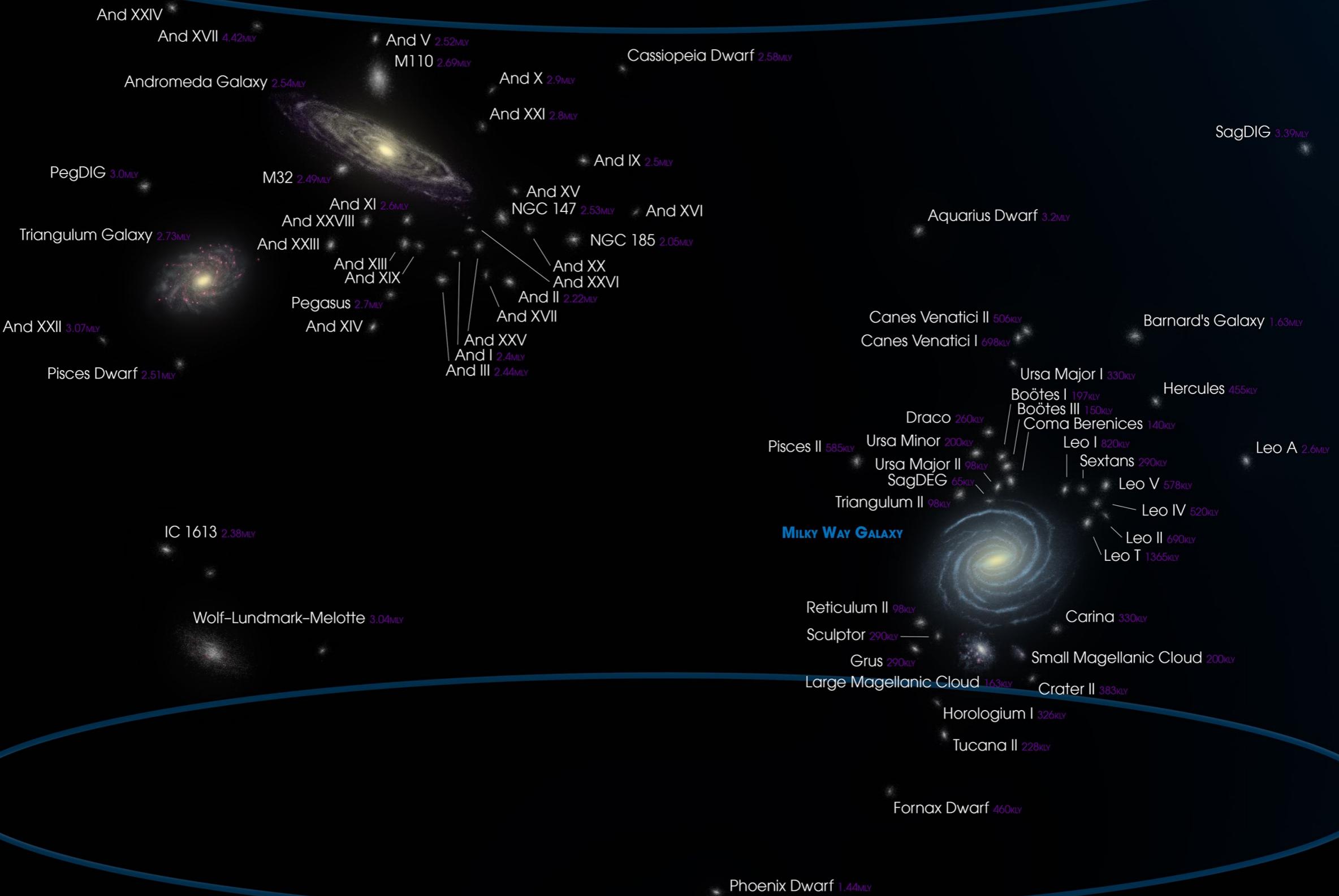
# Our location at the Universe

Scutum-Centaurus Arm



# LOCAL GROUP

# Our location at the Universe



# LANIAKEA

# Our location at the Universe

PAVO-INDUS  
SUPERCLUSTER

Cygnus Void

NGC 6769 Group 185Mly

Teloskopium Group 125Mly

CENTAURUS  
SUPERCLUSTER

NGC 5419/5488 Group 190Mly

Pegasus Cluster 180Mly

Pavo Cluster 180Mly

NGC 6753 Group 150Mly

Local Void

VIRGO  
SUPERCLUSTER

Virgo III Groups 65-85Mly

A3565-Group 165Mly

Centaurus Cluster 170Mly

NGC 7172 Group 125Mly

NGC 7329 Group 150Mly

Centaurus A/M83 Group 11.9Mly  
Sculptor Group 12.7Mly

M94 Group 12.4Mly

Canes II Group 26.5Mly  
M101 Group 21Mly

Virgo Cluster 52Mly

Coma I Group 47.3Mly

Ursa Major Cluster 60Mly

Corvus Void

Leo Void

Hydra Cluster 190.1Mly

SOUTHERN  
SUPERCLUSTER

Eridanus Void

Eridanus Cluster 75Mly

Fornax Cluster 62Mly

Taurus Void

NGC 1417 Group 189Mly

Puppis Cluster 95Mly

Antlia Cluster 132.7Mly

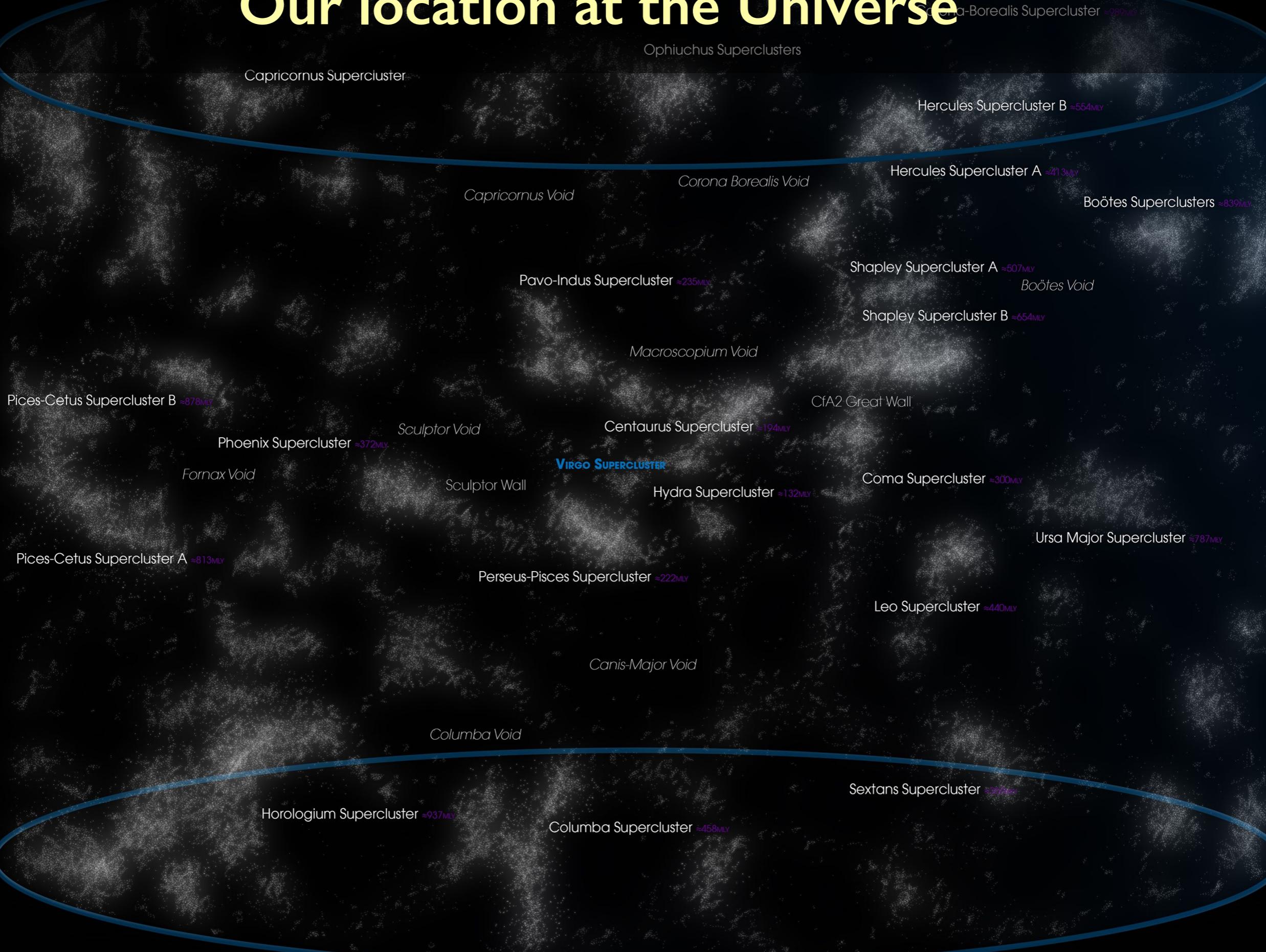
HYDRA  
SUPERCLUSTER

Gemini Void

Cancer Cluster 200Mly

# LOCAL SUPERCLUSTERS

## Our location at the Universe



# OBSERVABLE UNIVERSE

## Our location at the Universe

Local SUPERCLUSTERS