Midterm topics for FINAL EXAM

Midterm #1 topics: Background Physics

1. Scientific units, notations, exponents, trigonometry
2. Kepler's Laws + Newton's vers. of 3rd law
3. Newton's laws and gravity
4. Conservation laws: Energy, momentum, angular momentum
5. Kinetic & Potential Energy
6. Circular Motion
7. Escape velocity
8. Electromagnetic spectrum
9. Blackbody radiation
10. Photons & Spectroscopy
11. Doppler effect
12. Nuclear particles & P-P chain fusion

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Midterm #2 Topics: Stellar Astronomy

A. Telescopes, angular resolution
B. Our Sun
C. Luminosity, magnitude
D. Luminosity vs mass, H-R diagram
E. Main sequence stellar evolution
F. Red giant, planetary nebula, white dwarf
G. Pauli exclusion principle
H. Evolution of massive stars
I. Type 2 supernova physics, neutrinos
J. Neutron stars, pulsars
K. Origin of the elements
L. Special relativity: length contraction, time dilation
M. General relativity, gravitational waves
N. Black holes

Topics since Midterms for FINAL EXAM

Exoplanets, protoplanetary systems, exolife.

Milky Way galaxy.

Galaxy structure, galaxy formation.

Dark matter, galaxy rotation curve.

Distance ladder: Parallax, Cepheid variables, Tully-Fisher, type 1a supernovae.

Hubble's law and red shift.

Galaxy types: Spirals, Ellipticals, irregulars, dwarfs … globular clusters.

Quasars, active galactic nuclei, accretion disks, jets.

Galaxy collisions and mergers.

Groups, clusters, and superclusters.

Expanding universe, critical density, accelerating expansion.

Composition of universe: matter, dark matter, dark energy.

The Big Bang: Nucleosynthesis, Cosmic Microwave Background.

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The Big Bang: Nucleosynthesis, Cosmic Microwave Background.

Today !!

Today's Topics

Friday, May 1, 2026 (Week 13, lecture 37) – Chapter 29.

1. Composition of Universe.
2. The Big Bang.
3. Big Bang Nucleosynthesis.
4. Big Bang Blackbody Radiation.

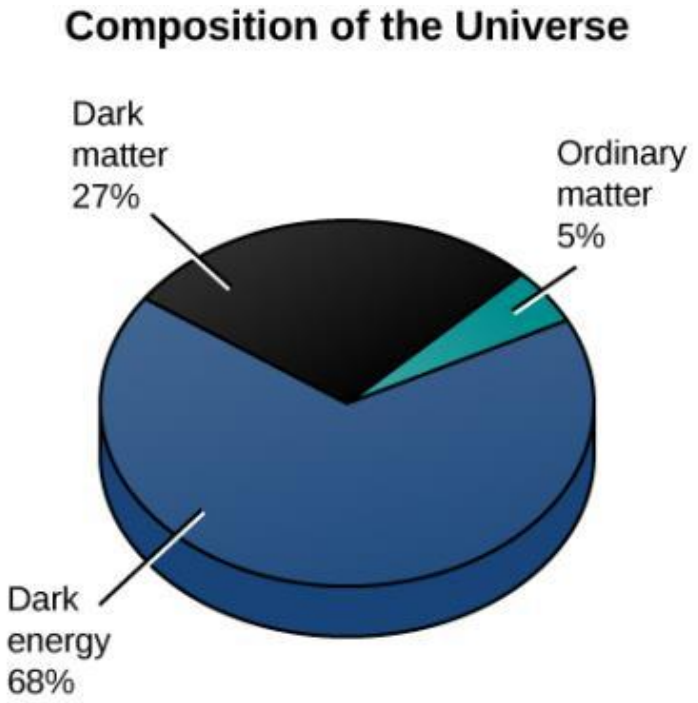
Final Exam is on Wednesday, May 6 at 9:00 am – noon, in this room

Composition of the Universe

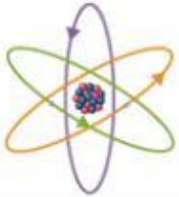
95% of matter-energy is made of stuff we have never directly observed

Dark matter
27%

Dark energy
68%



Ordinary matter
4% H and He
<1% Stars
<1% Other



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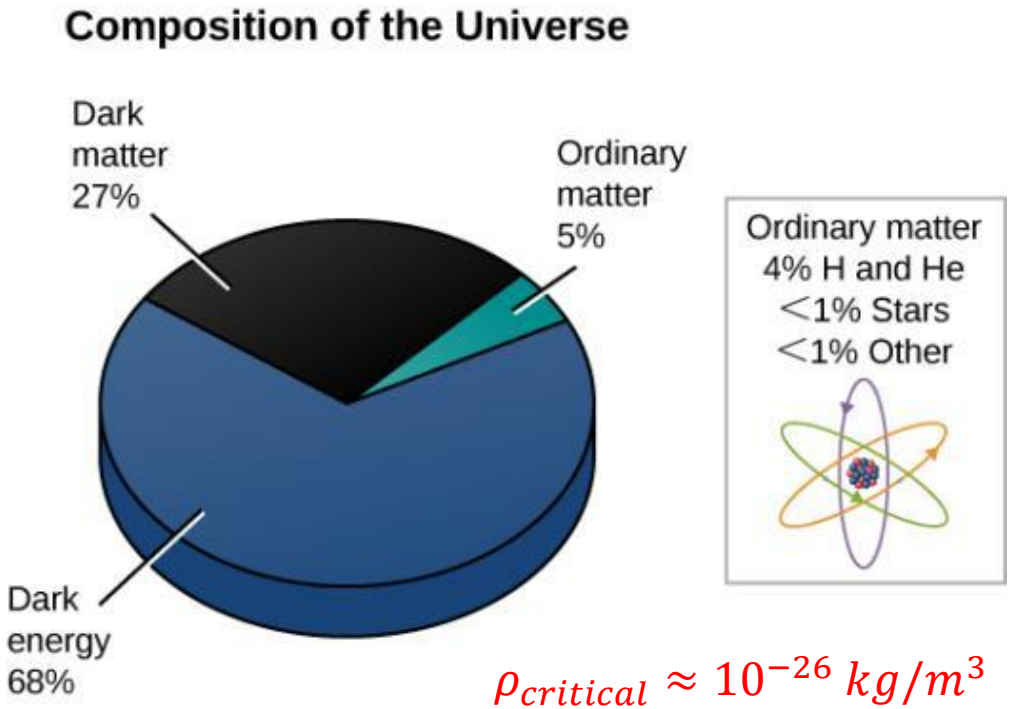


$\rho_{critical} \approx 10^{-26}\ kg/m^3$
(for present day Hubble constant)

Object	Density as a Percent of Critical Density
Luminous matter (stars, etc.)	<1
Hydrogen and helium in interstellar and intergalactic space	4
Dark matter	27
Equivalent mass density of the dark energy	68

only indirect evidence for these

The Big Bang & The Universe

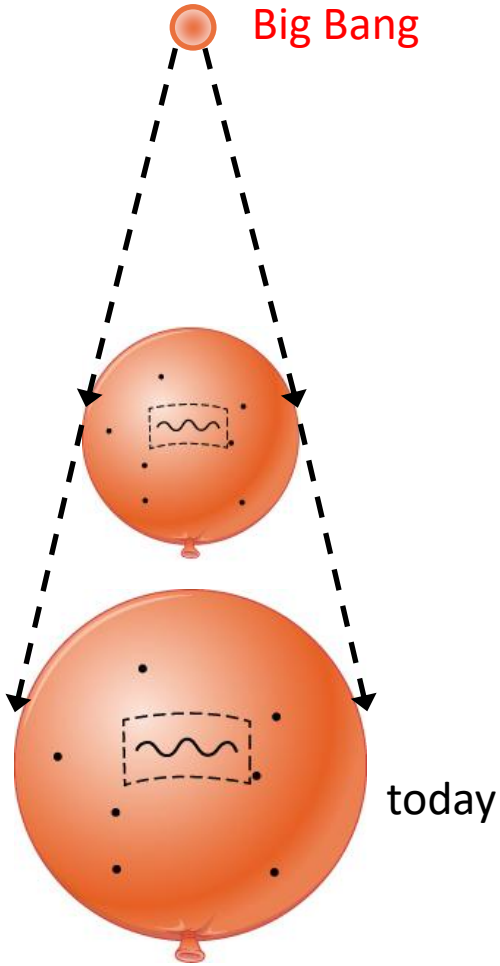
The universe started 13.8 billion years ago … and has expanded ever since then.

If we play the movie backwards, there are two main possibilities:

1) Universe is finite

Universe started as a **very very small**, **very very dense**, and **very very hot** ball of material and energy

In the present, the **universe and space have expanded considerably**, but they are still very much **finite** (matter/energy are conserved), though the observable universe is a fraction of full universe.



The Big Bang & The Universe

The universe started 13.8 billion years ago … and has expanded ever since then.

If we play the movie backwards, there are two main possibilities:

2) Universe is infinite

Universe started as **spatially infinite** **very very dense**, and **very very hot** material and energy.

→ The universe started infinitely large (spatially) and started with an infinite amount of matter and energy.

→ The matter density and energy density are finite, but still very very large.

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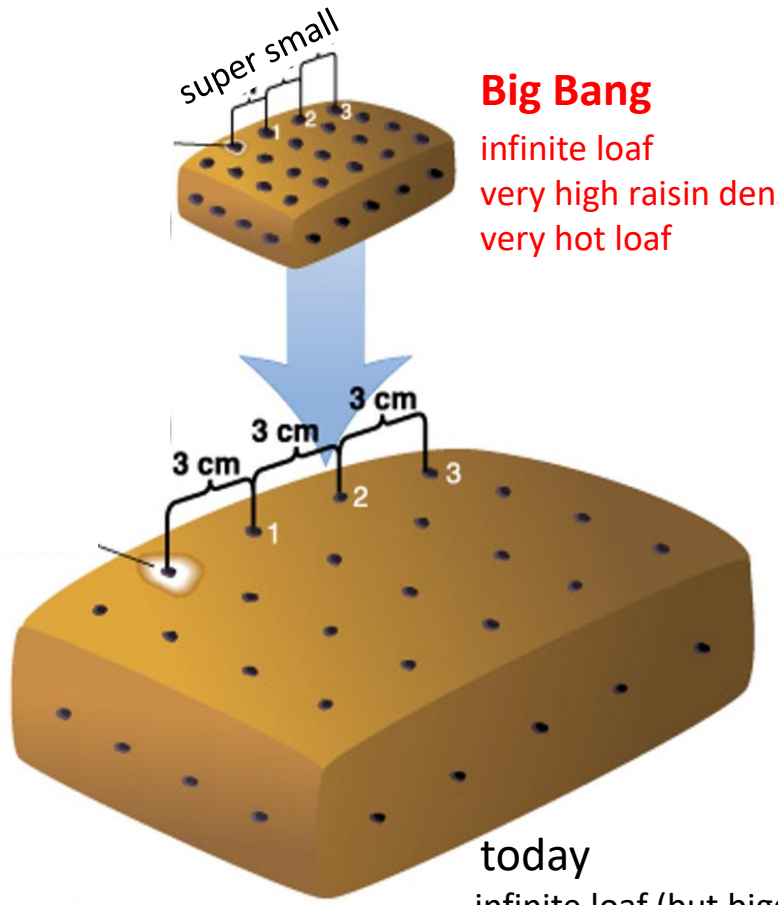

Big Bang
infinite loaf
very high raisin density
very hot loaf

today
infinite loaf (but bigger)
very low raisin density
very cold loaf

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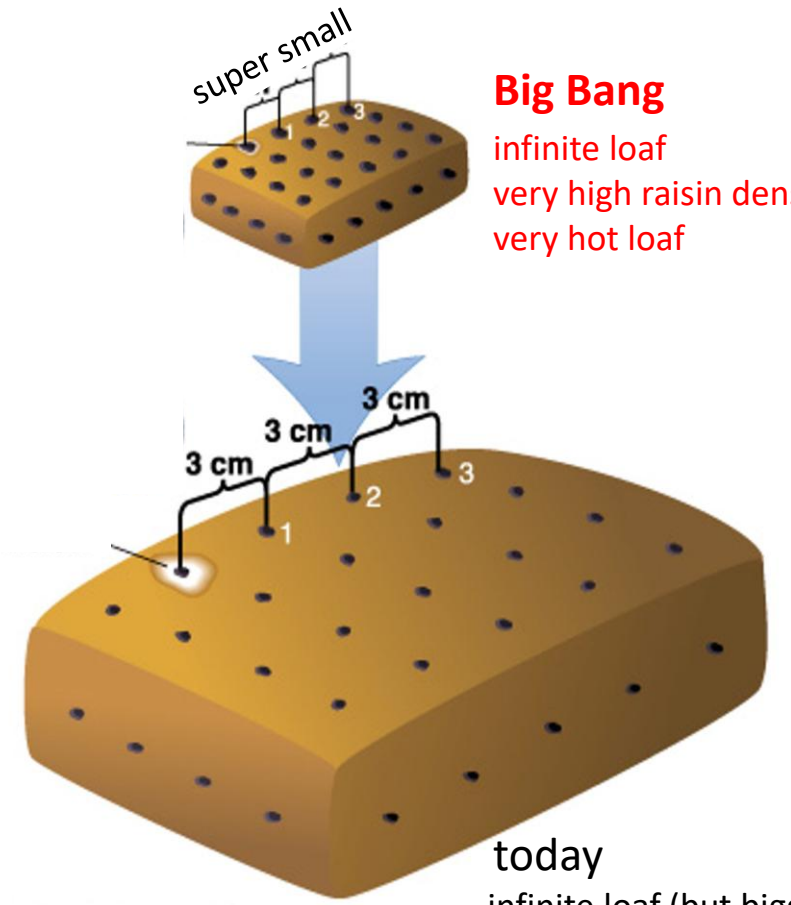

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The Big Bang

What happened 13.8 billion years ago?

The Big Bang

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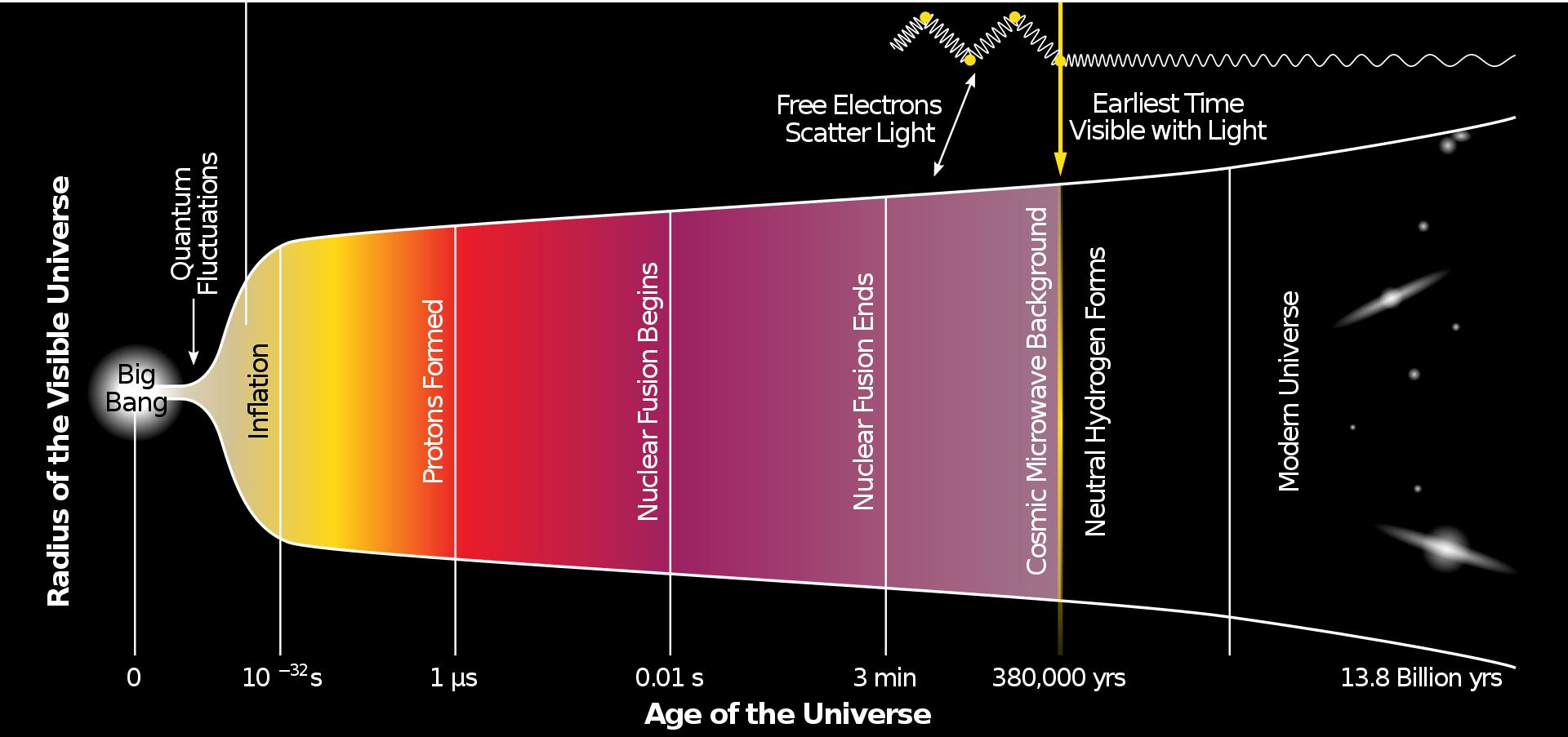
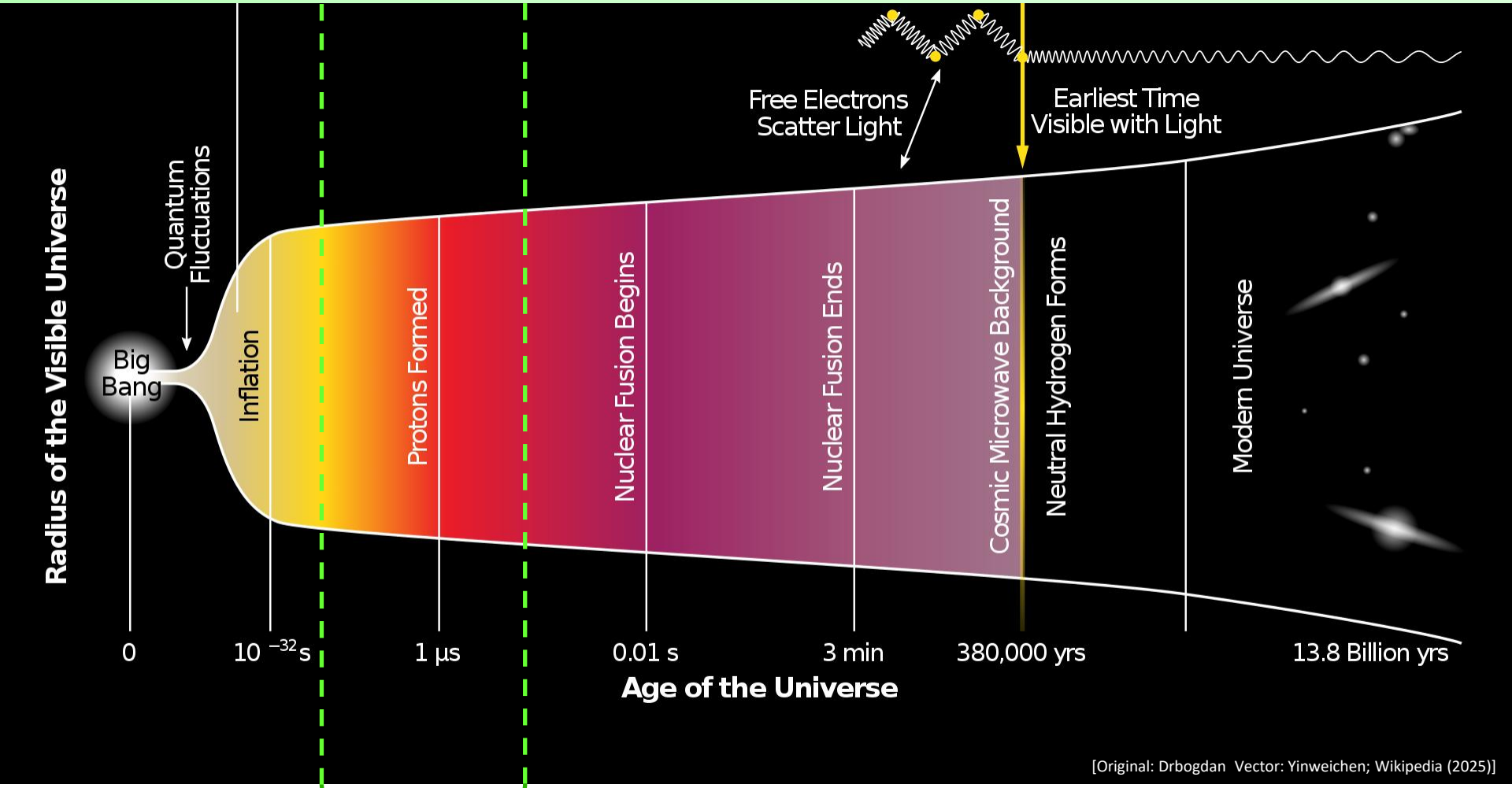


[Original: Drbogdan Vector: Yinweichen; Wikipedia (2025)]

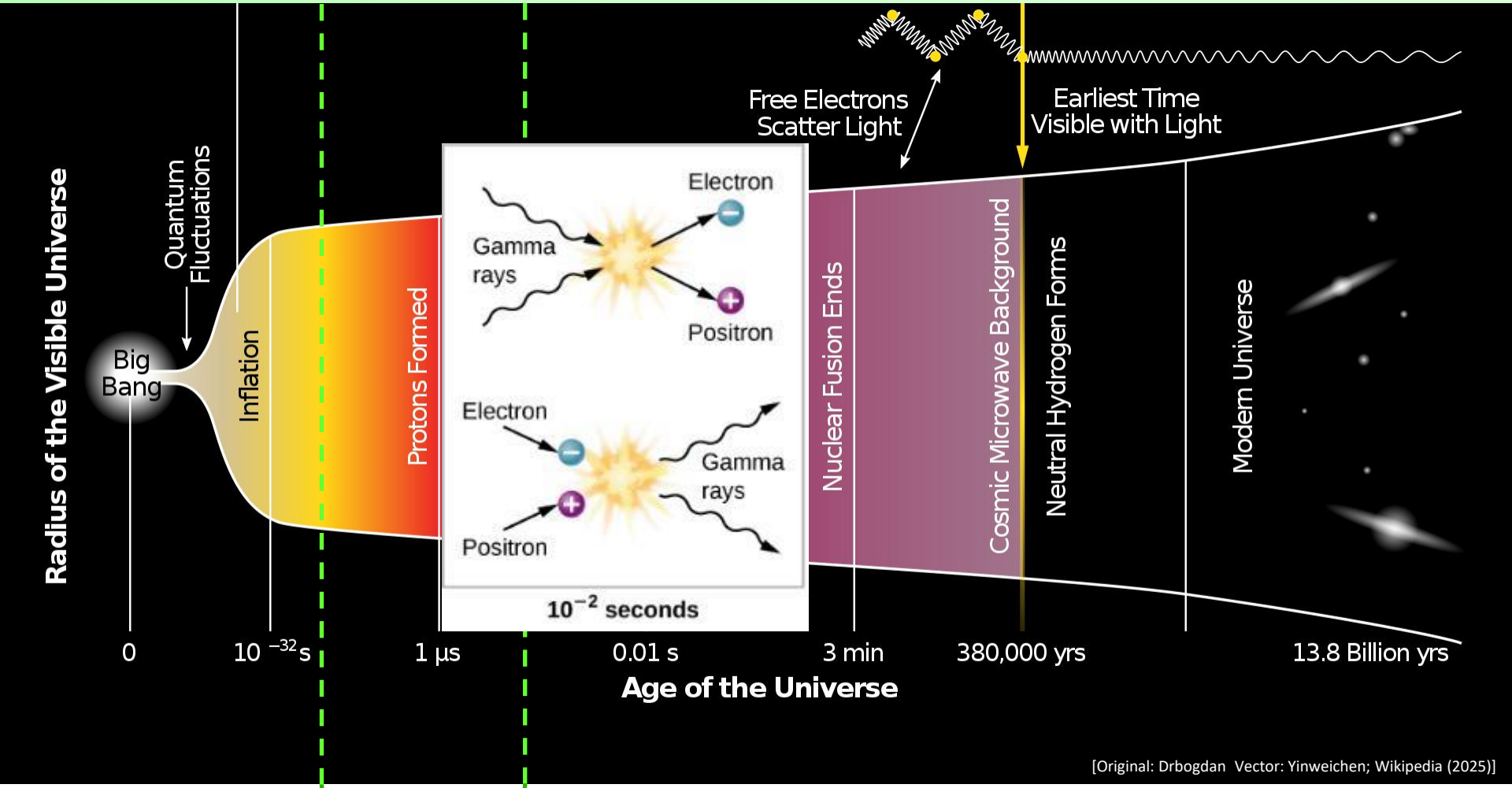
The Big Bang



Baryogenesis

matter/antimatter asymmetry (unexplained)

The Big Bang



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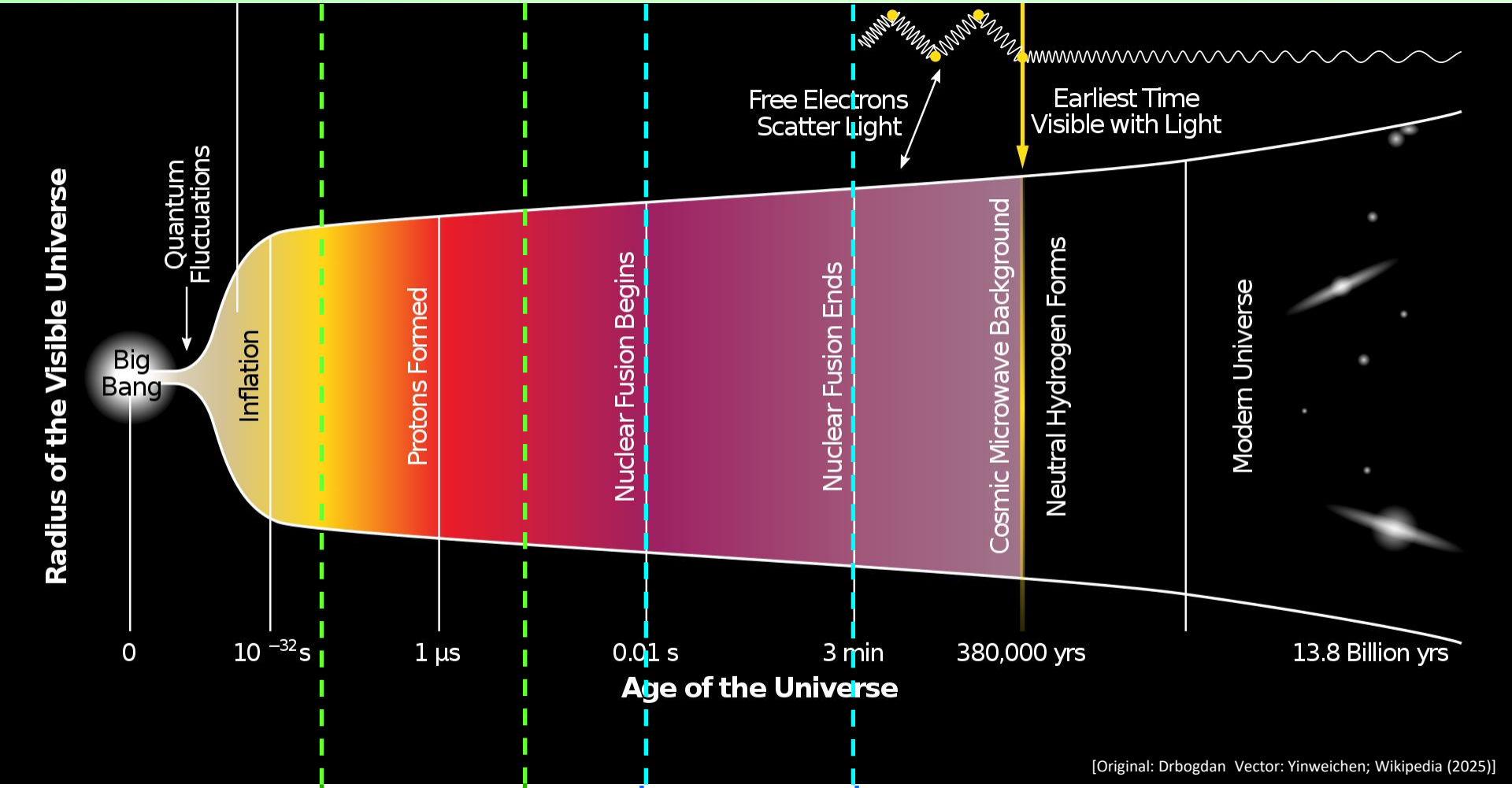

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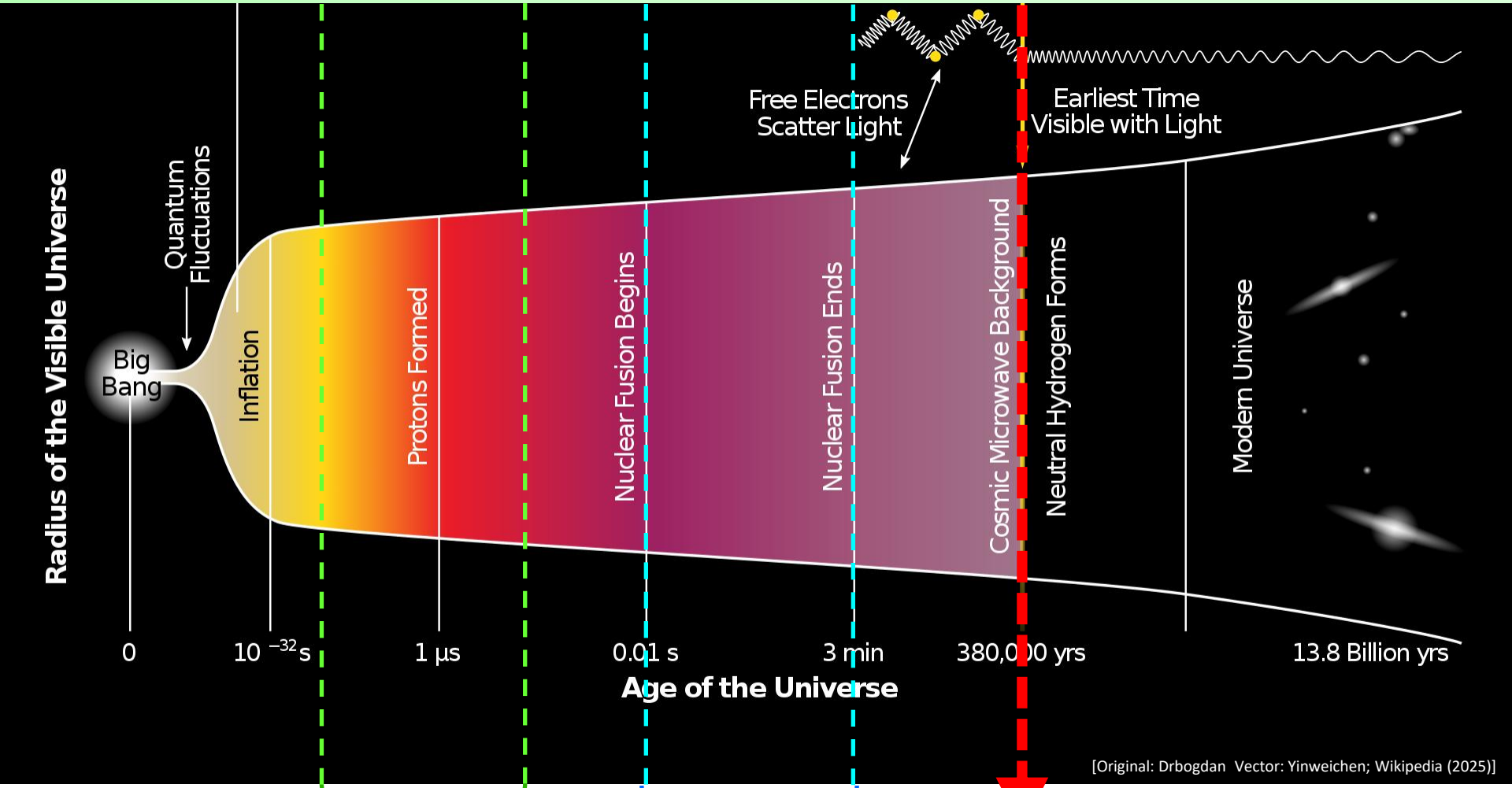
Nucleosynthesis
primordial deuterium, helium, lithium (well understood)

The Big Bang



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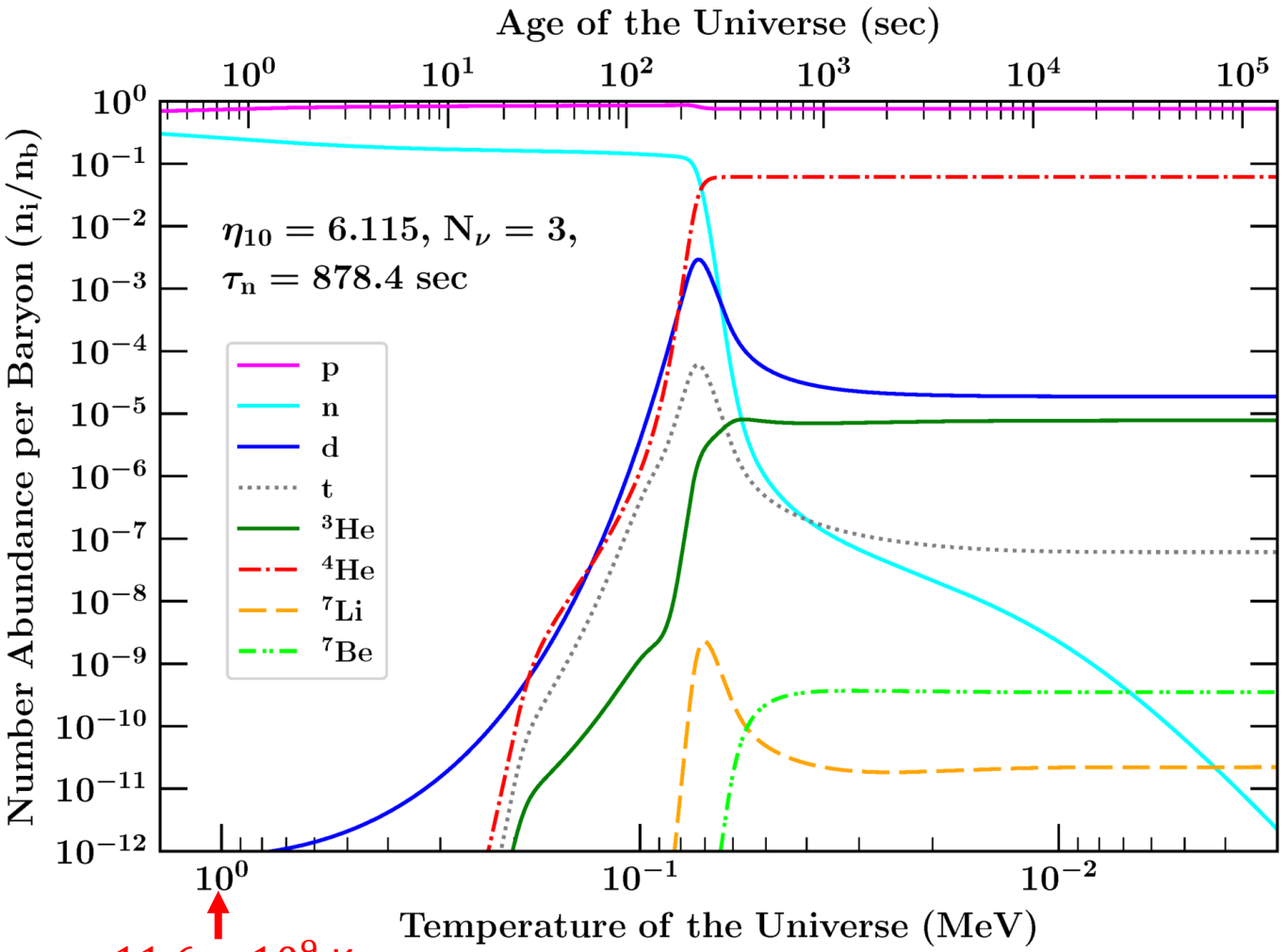
Blackbody radiation decouples from matter
"cosmic microwave background"

Big Bang Nucleosynthesis

10 s to 20 minutes after start of Universe:
- Universe is like giant star that can fuse hydrogen (protons).
- Formation of primordial **hydrogen**, **deuterium**, and **helium**.



[Tsung-Han Yeh, Keith A. Olive and Brian D. Fields - https://www.mdpi.com/2218-1997/9/4/183; https://doi.org/10.3390/universe9040183]; Wikipedia (2025)]

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Predicted mass fractions:

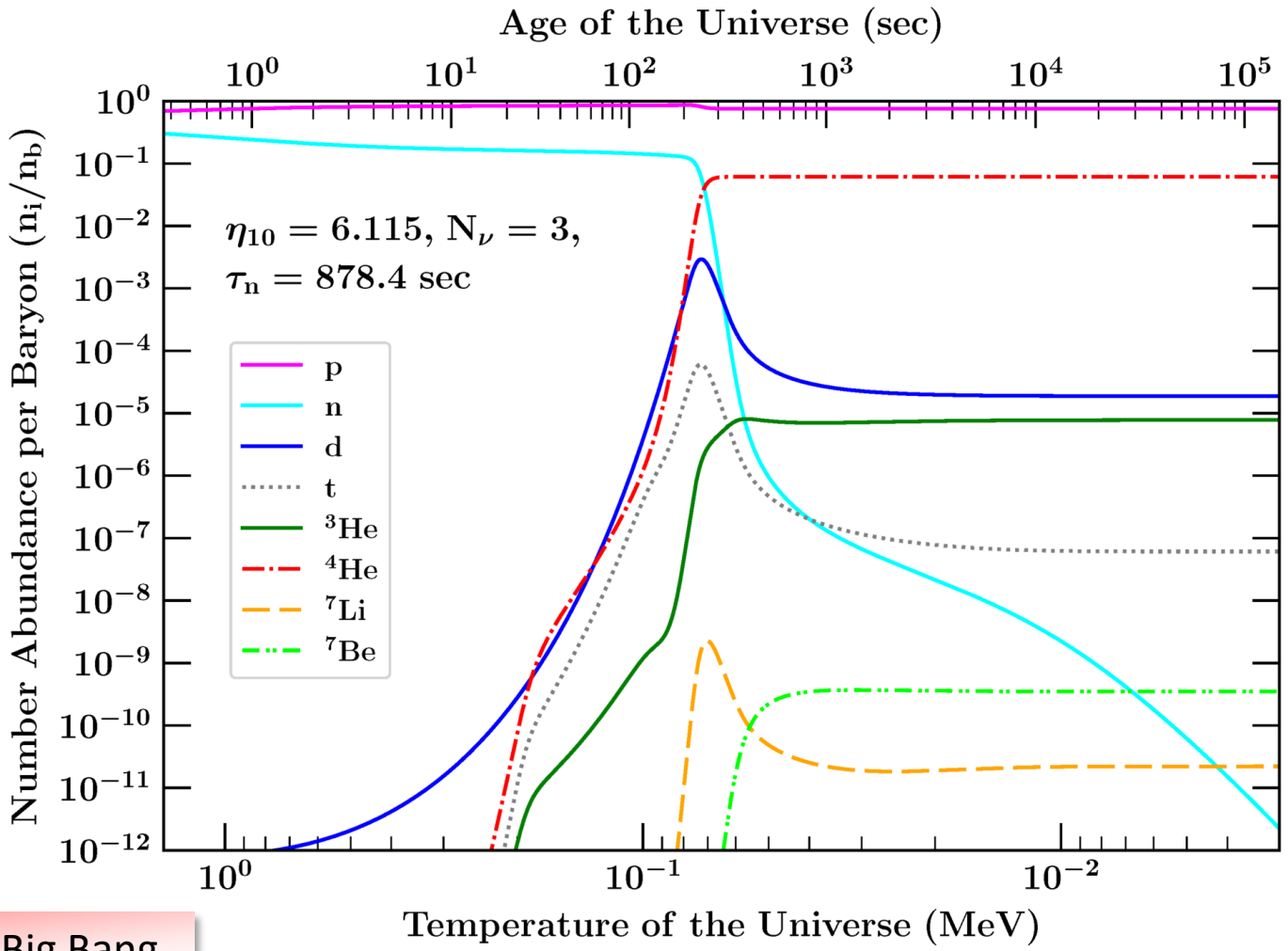
Hydrogen: 75%

Deuterium: 0.01%

Helium-3: 0.01%

Helium 4: 25%

These fractions agree well with observations of primordial gas clouds.



Strong evidence for HOT Big Bang.

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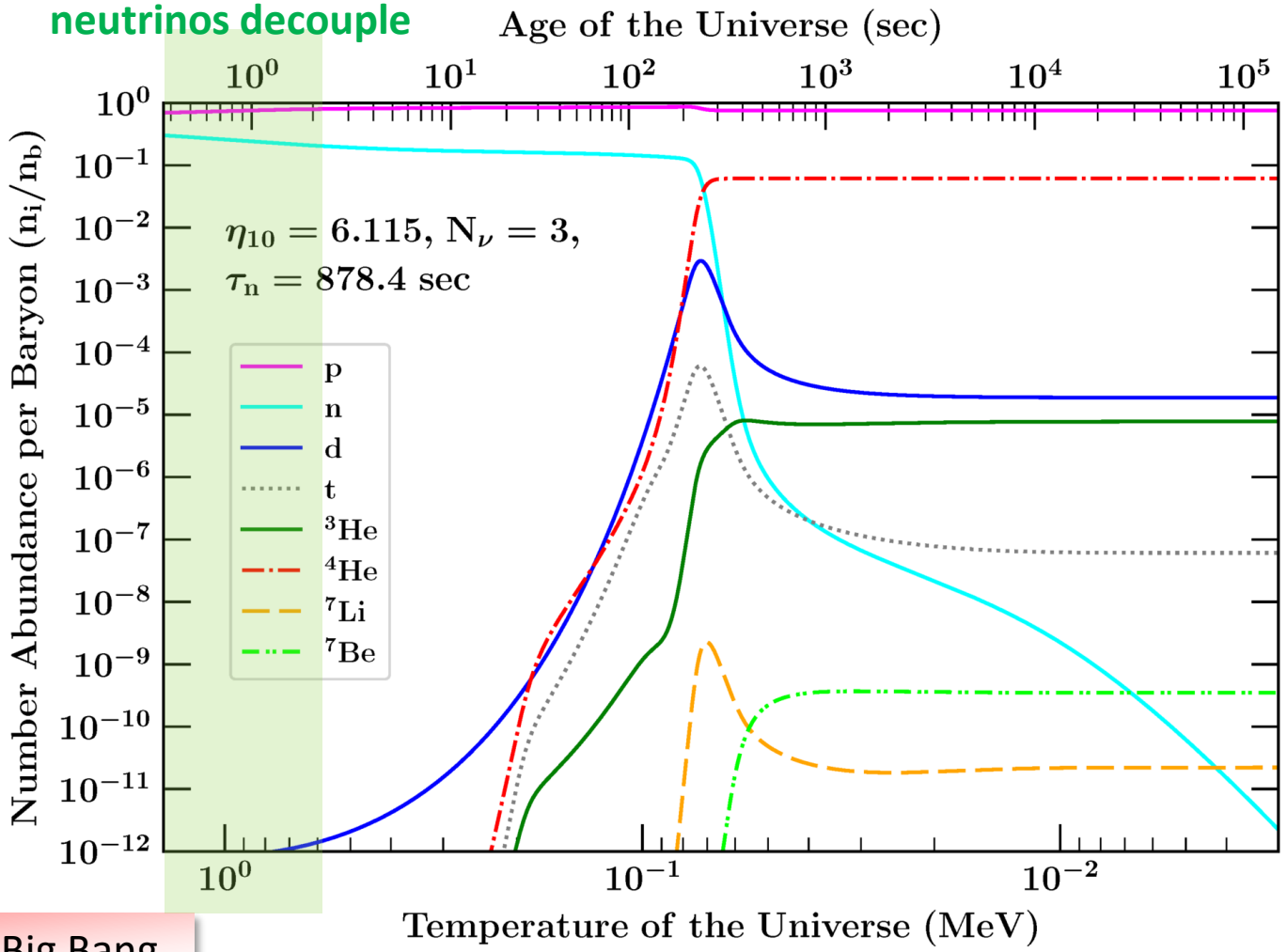

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The Cosmic Microwave Background

Robert Wilson (left) and Arno Penzias (right) standing in front of the horn-shaped antenna used to accidentally discover the cosmic background radiation.

The Cosmic Microwave Background

About 380,000 years after the start of the universe, two things happened:

1) The universe cooled to about 3000 K, which allowed **neutral atoms to form**.

2) Neutral atoms are largely transparent to electromagnetic radiation, so **this blackbody radiation (at 3000 K) stopped having a significant interaction with matter** at this point.

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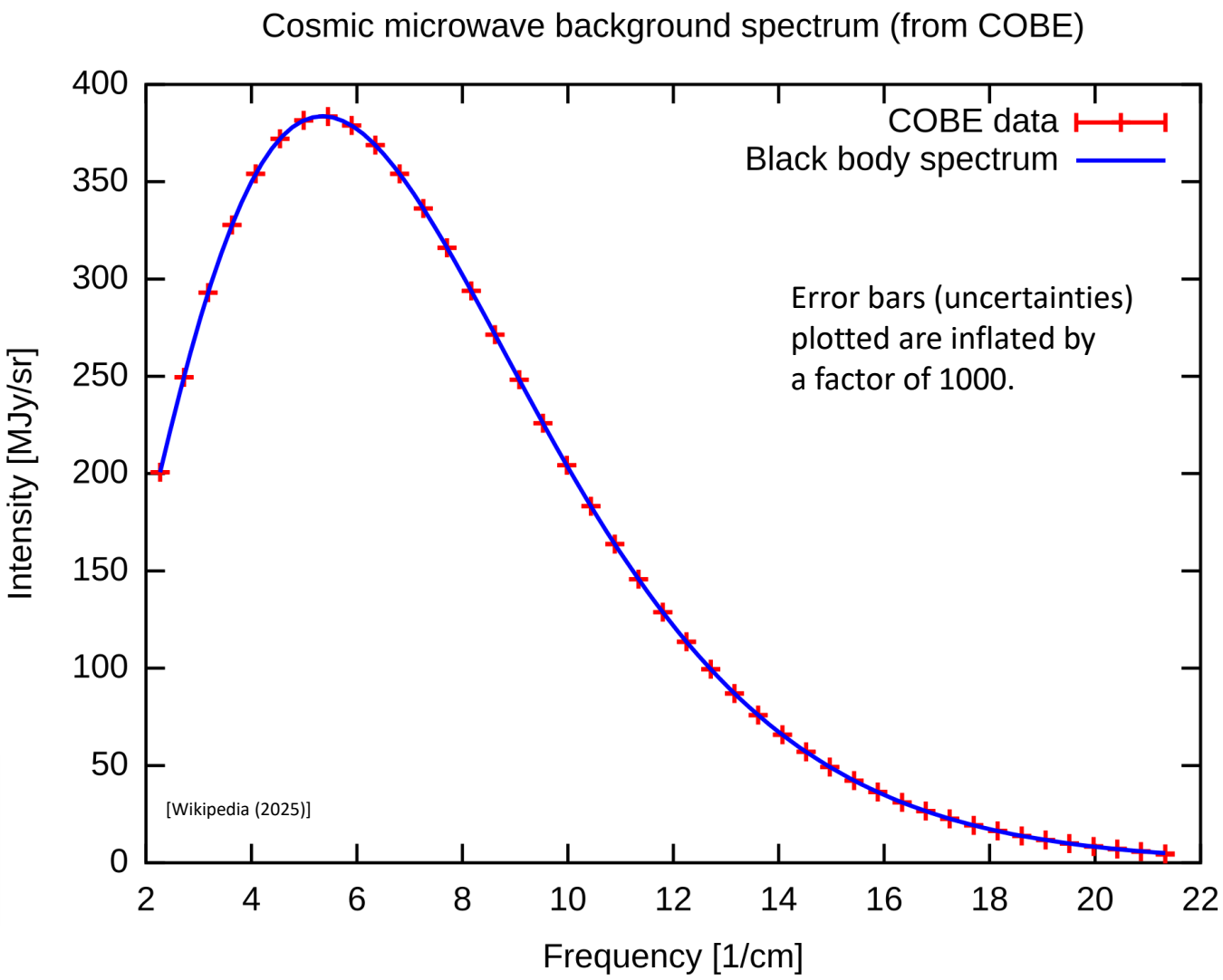
Since then, the universe has expanded about 1000 times its size, so this remnant primordial blackbody radiation should be at the equivalent of about 3 K.

The Cosmic Microwave Background

- COBE satellite results (1992) confirmed incredibly precise blackbody curve.
- Most precisely measured blackbody spectrum *in all of nature*.
- The CMB is the same in all directions !!

Blackbody spectrum has a temperature of $T = 2.725\ K$.



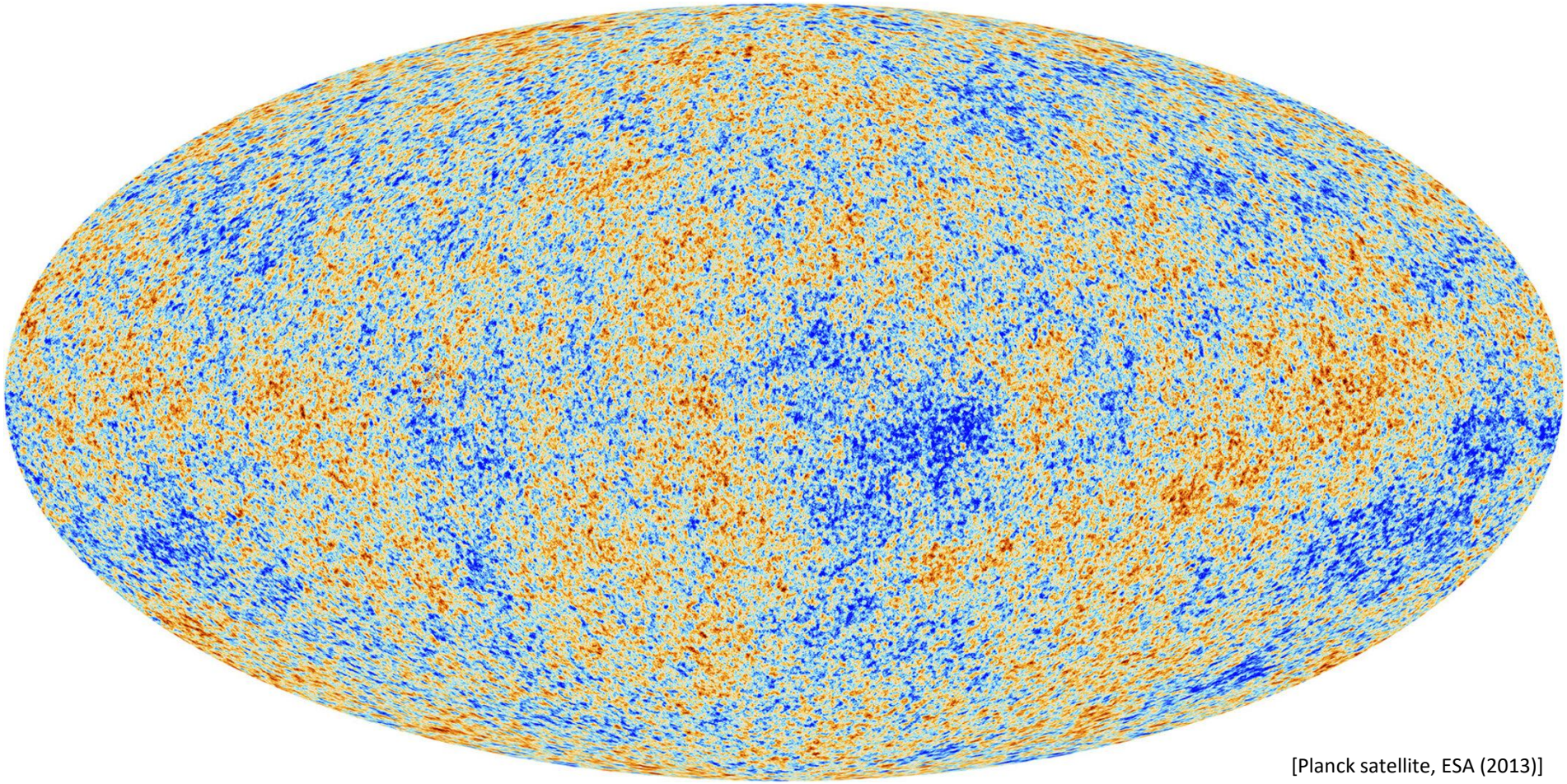
The CMB is very strong evidence for our current model of the big bang

“Pointing” Structure in the CMB

Measurements by the WMAP and Planck satellites reveal that there are temperature variations in the CMB in different directions of the sky at the 1 part per 100,000 level.

Orange = slightly hotter → due to slightly lower matter density

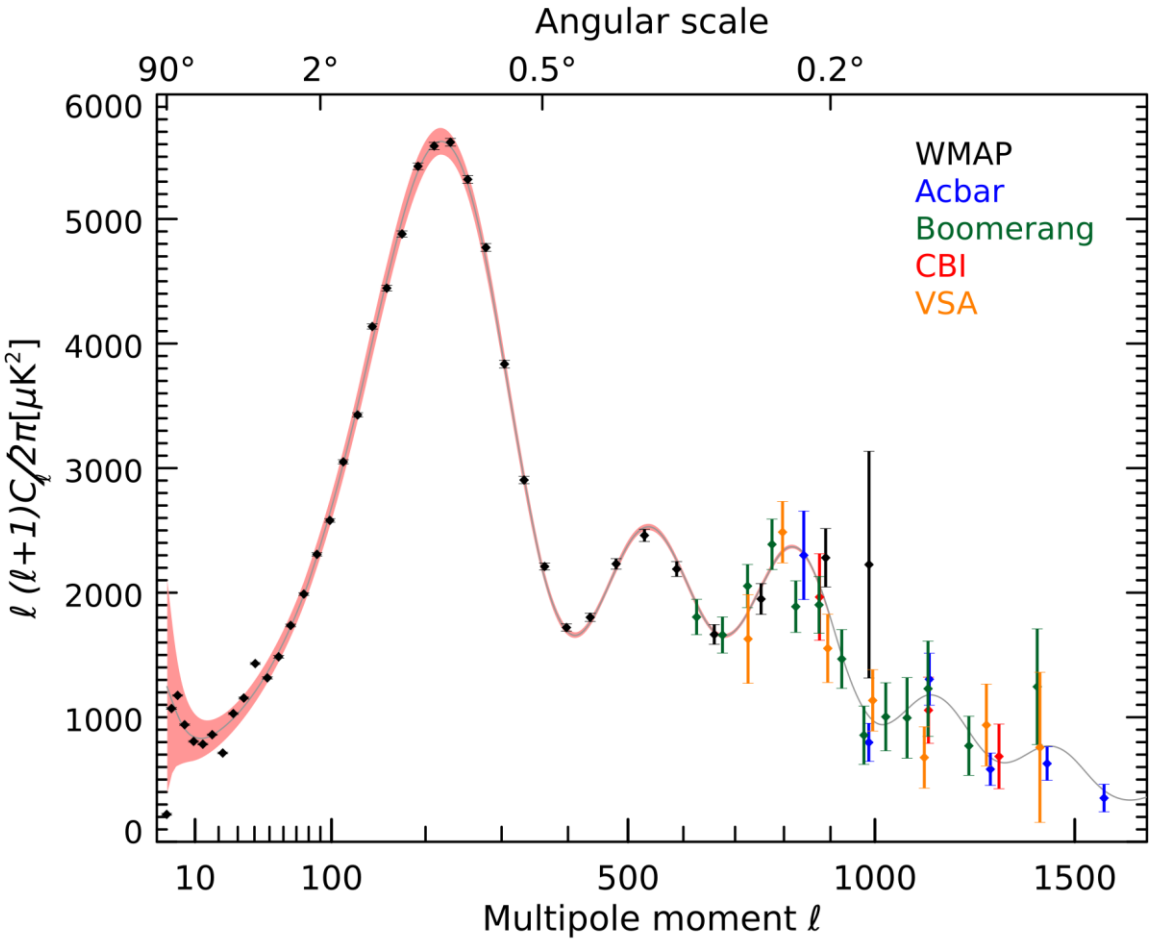
Blue = slightly colder → due to slightly higher matter density



[Planck satellite, ESA (2013)]

Angular "Power" Spectrum of CMB

Plot of size of temperature fluctuations vs. angular separation scale (in essence).



[NASA/WMAP team]

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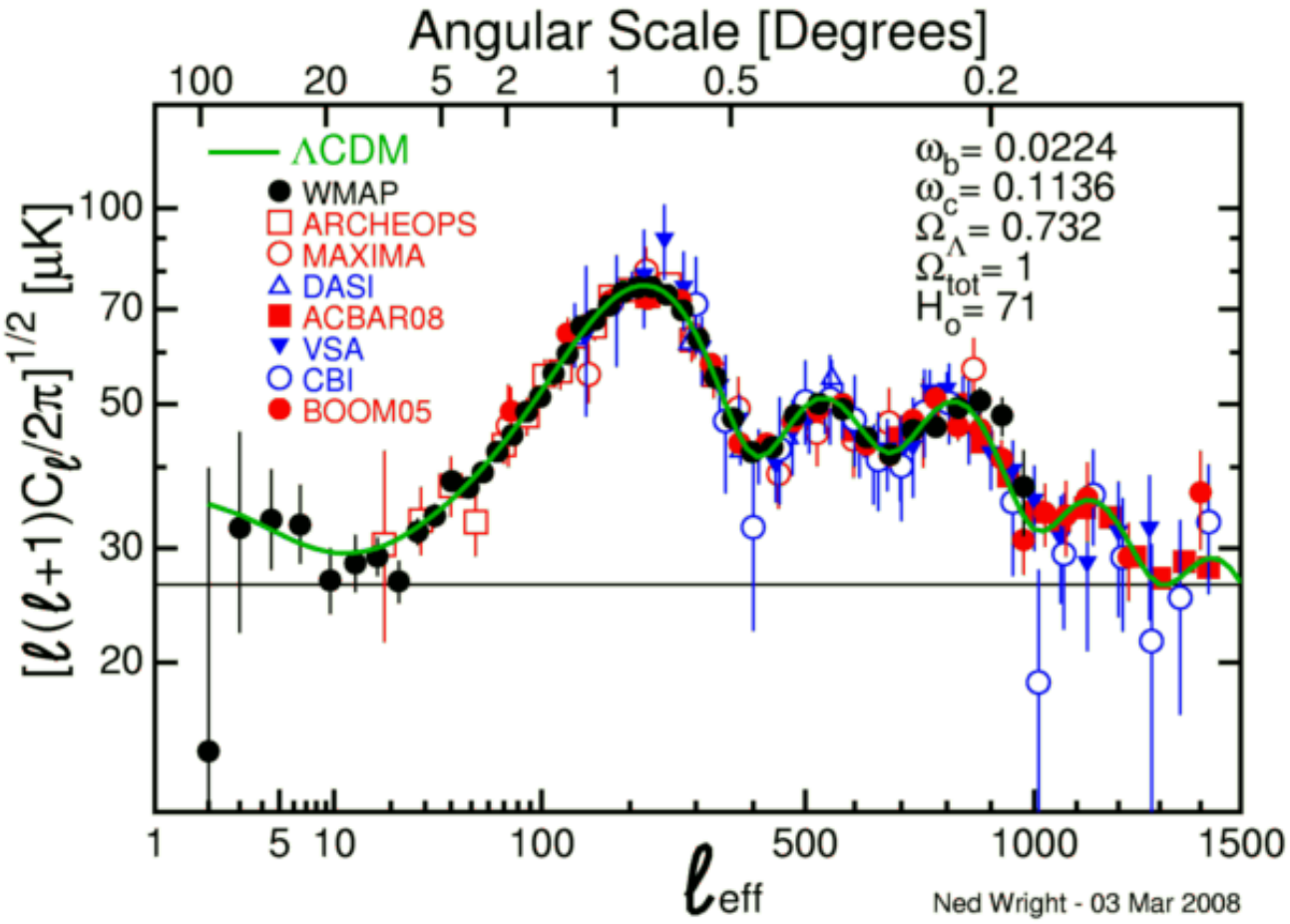

Green curve (ΛCDM) is prediction from the Big Bang model (assuming that dark matter is cold, and the existence of dark energy).