# Today's Topics

Friday, May 2, 2025 (Week 13, lecture 36) – Chapter 29.

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

**Final Exam** is on Thursday, May 8 at 9:00 am – noon, in this room

# 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.

# Course Evaluations

Please fill out.

Interested in the following info:

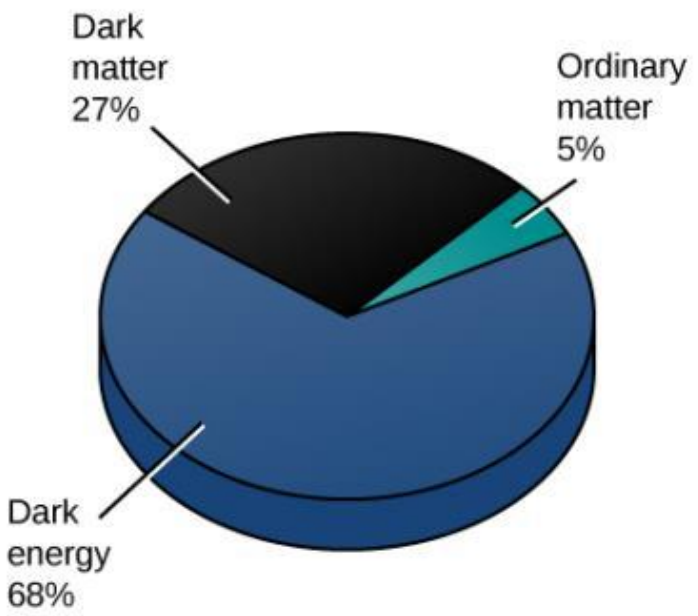
- Quality of textbook.
- Quality of ExpertTA & problems.
- Quality of Interlude 1 & 2 topics.
- Comments on Midterm tests.
- Comments on grading (essays and midterms)
- More quantitative vs less quantitative.
- More PowerPoint vs more handwritten notes.
- Comments on structure of lectures.
- Did you use the free tutoring (Thursdays 6-8 pm, Small Hall 122)?
- Comments on office hours.

# Composition of the Universe

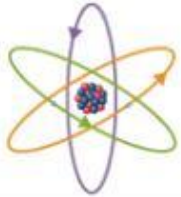
95% of matter-energy is made of stuff we have never directly observed

Dark matter
27%

Dark energy
68%




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



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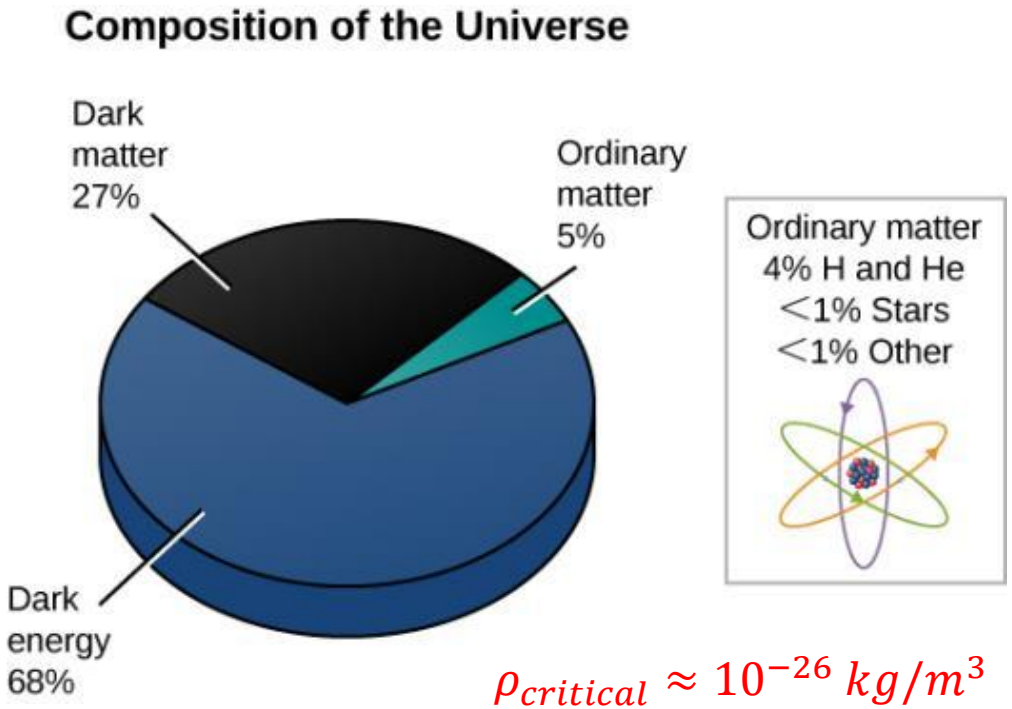



$\rho_{critical} \approx 10^{-26}\ kg/m^3$
(for present day Hubble constant)

| 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

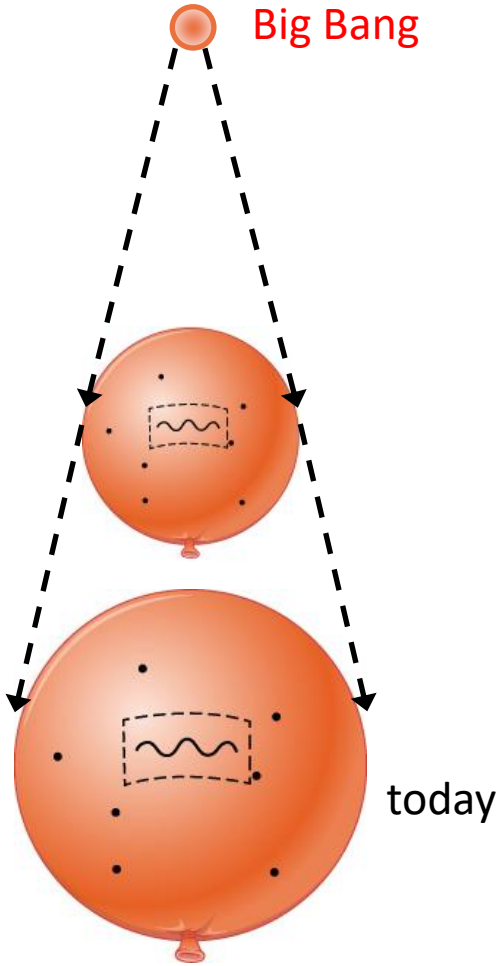
The universe started 13.8 billion years ago … and has expanded ever since then.

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 an **infinite** **very very dense**, and **very very hot** ball of 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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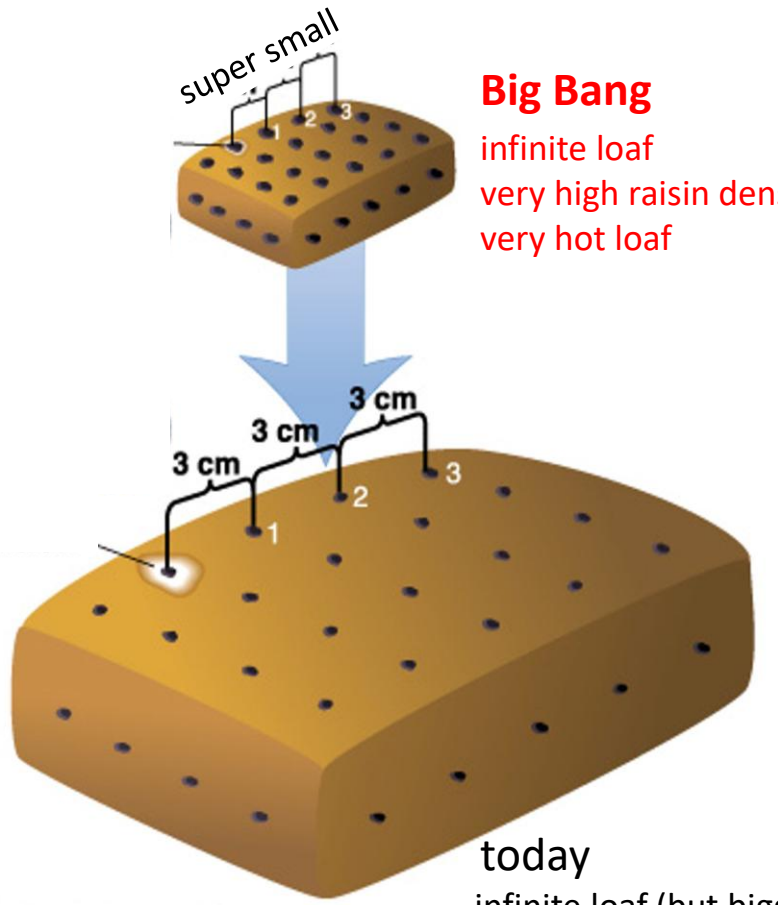


**Big Bang**
infinite loaf
very high raisin density
very hot loaf

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

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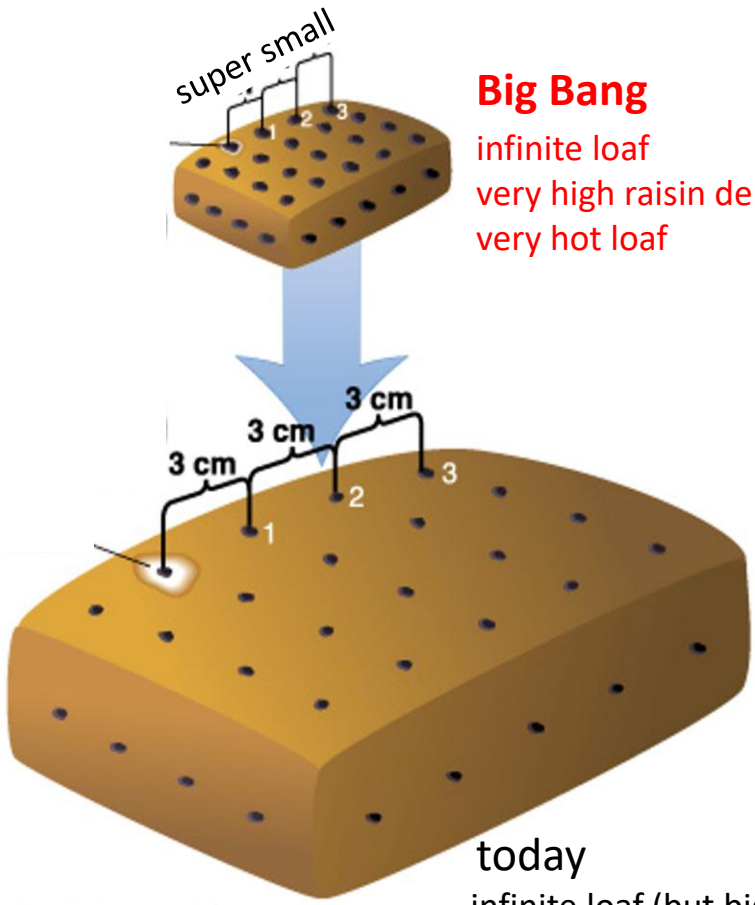


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# The Big Bang

What happened 13.8 billion years ago?

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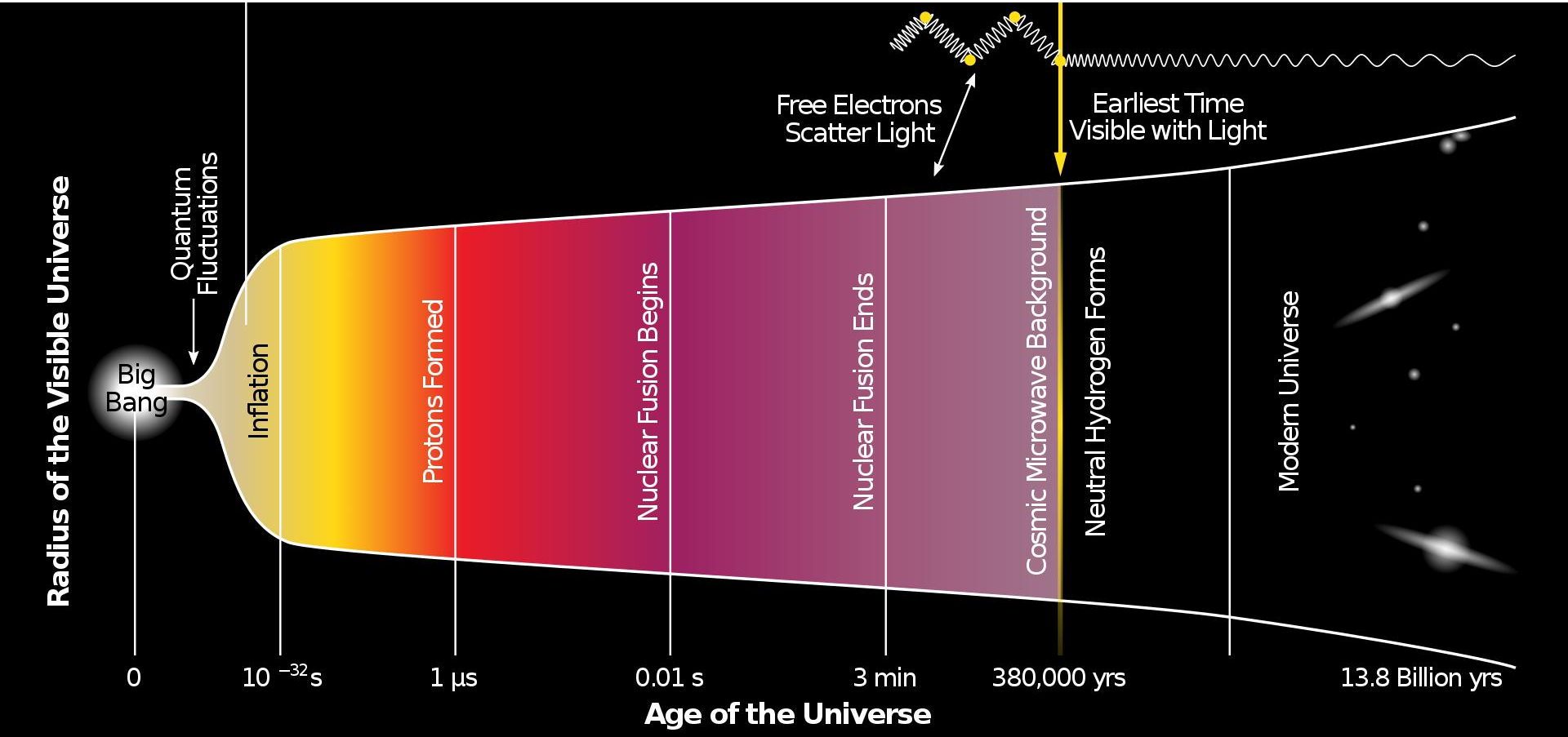
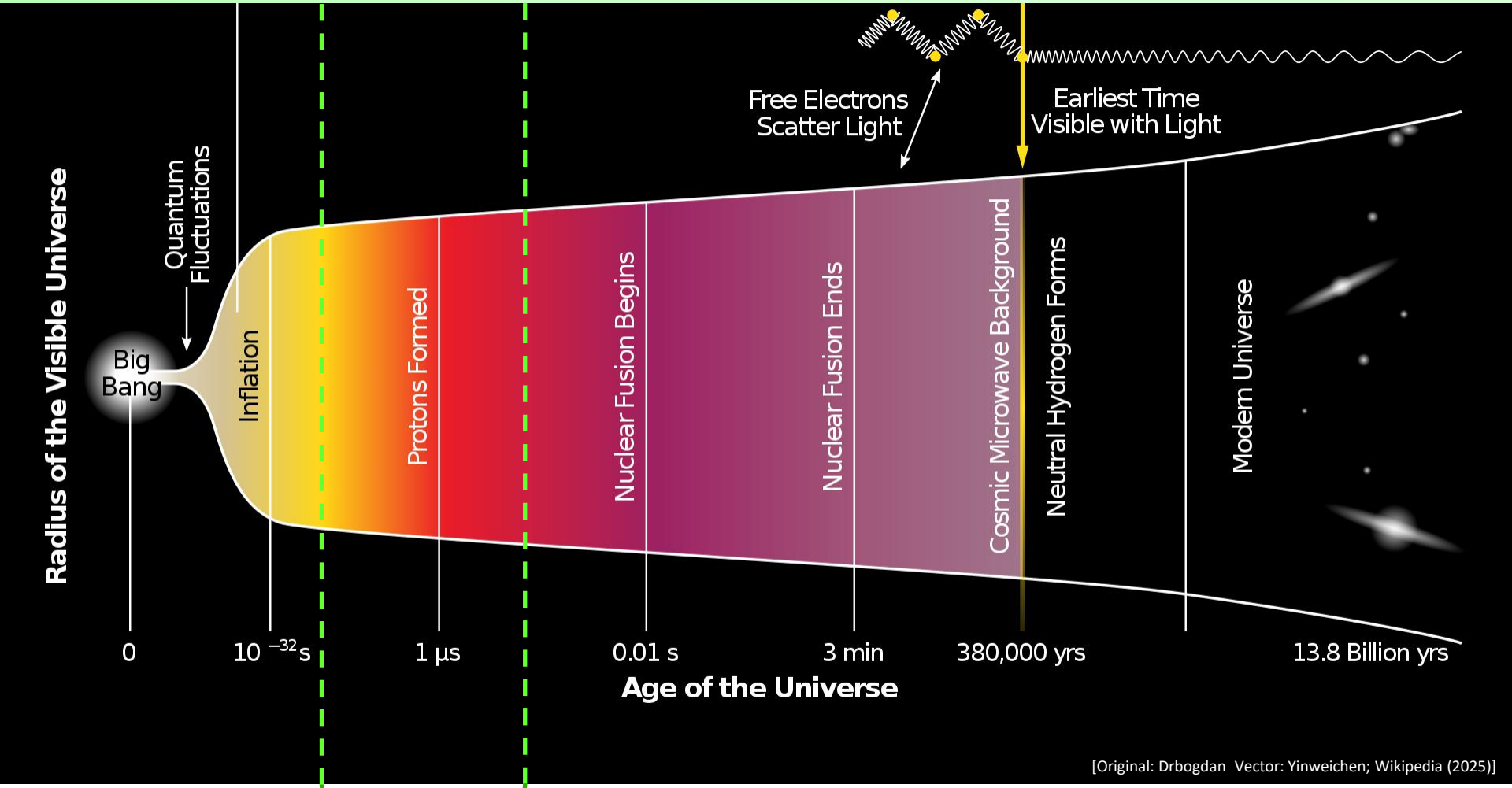



[Original: Drbogdan Vector: Yinweichen; Wikipedia (2025)]

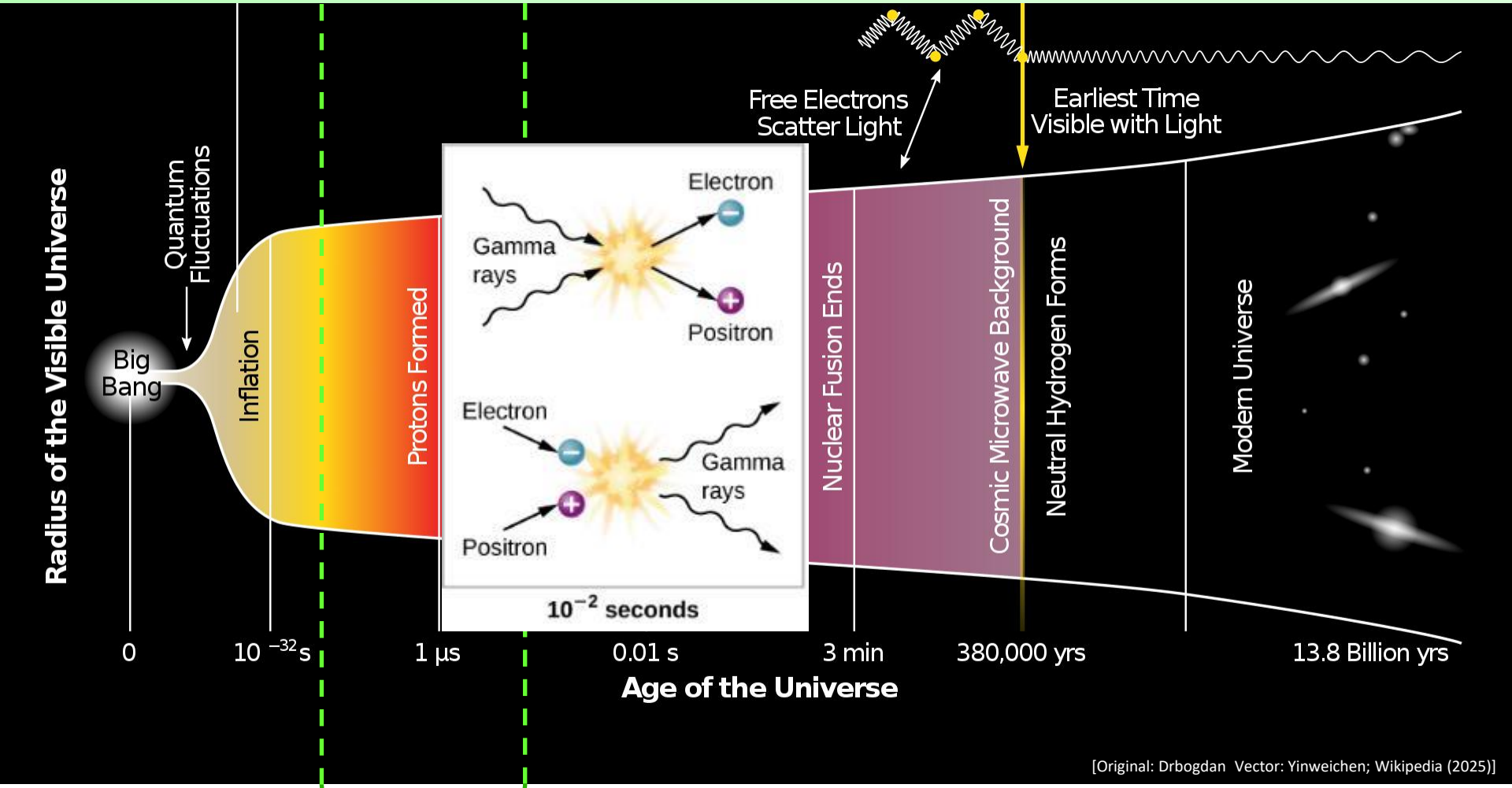
# The Big Bang




**Baryogenesis**

**matter**/antimatter asymmetry (unexplained)

# The Big Bang

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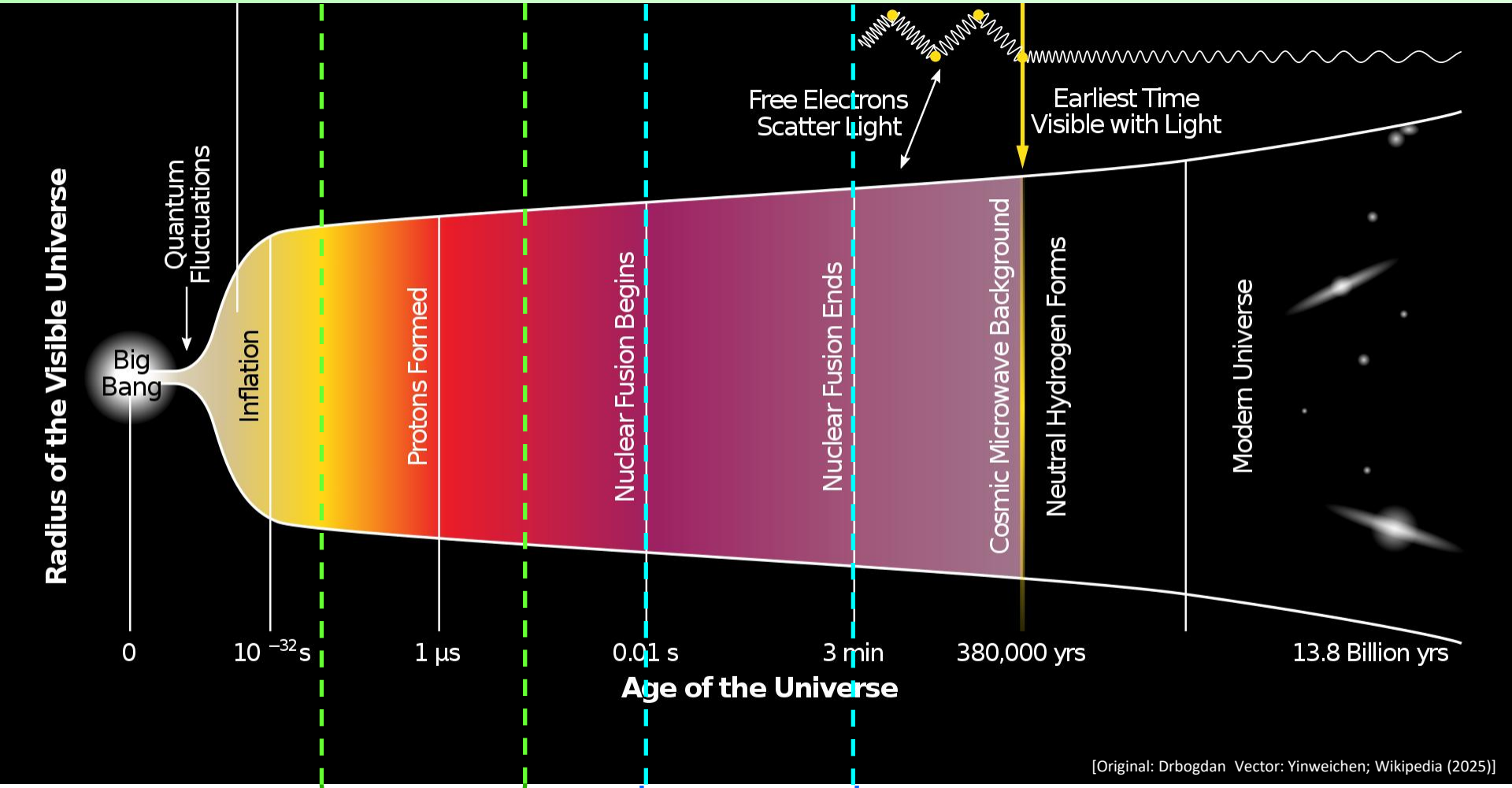


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**Nucleosynthesis**
primordial deuterium, helium, lithium (well understood)

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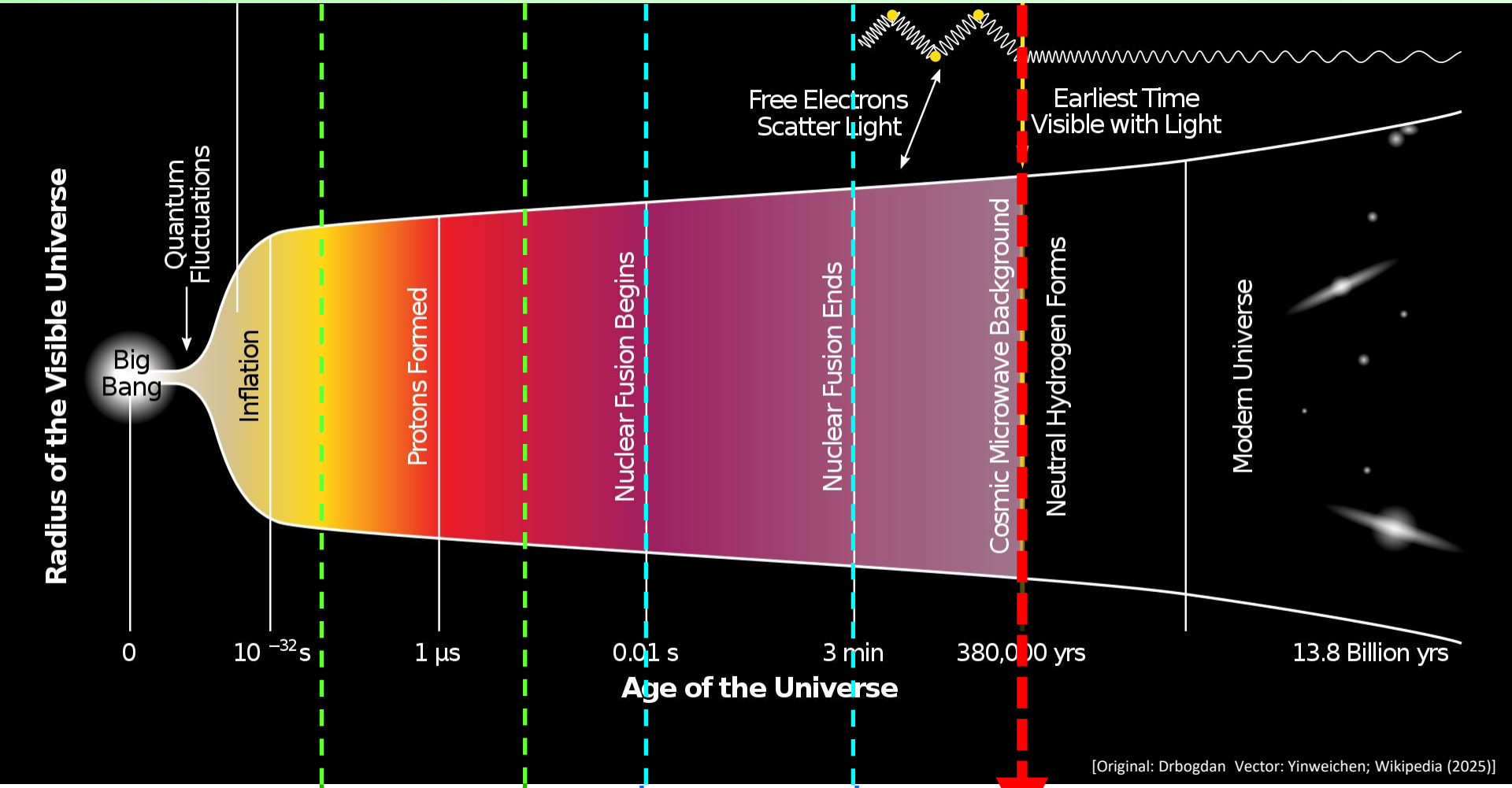


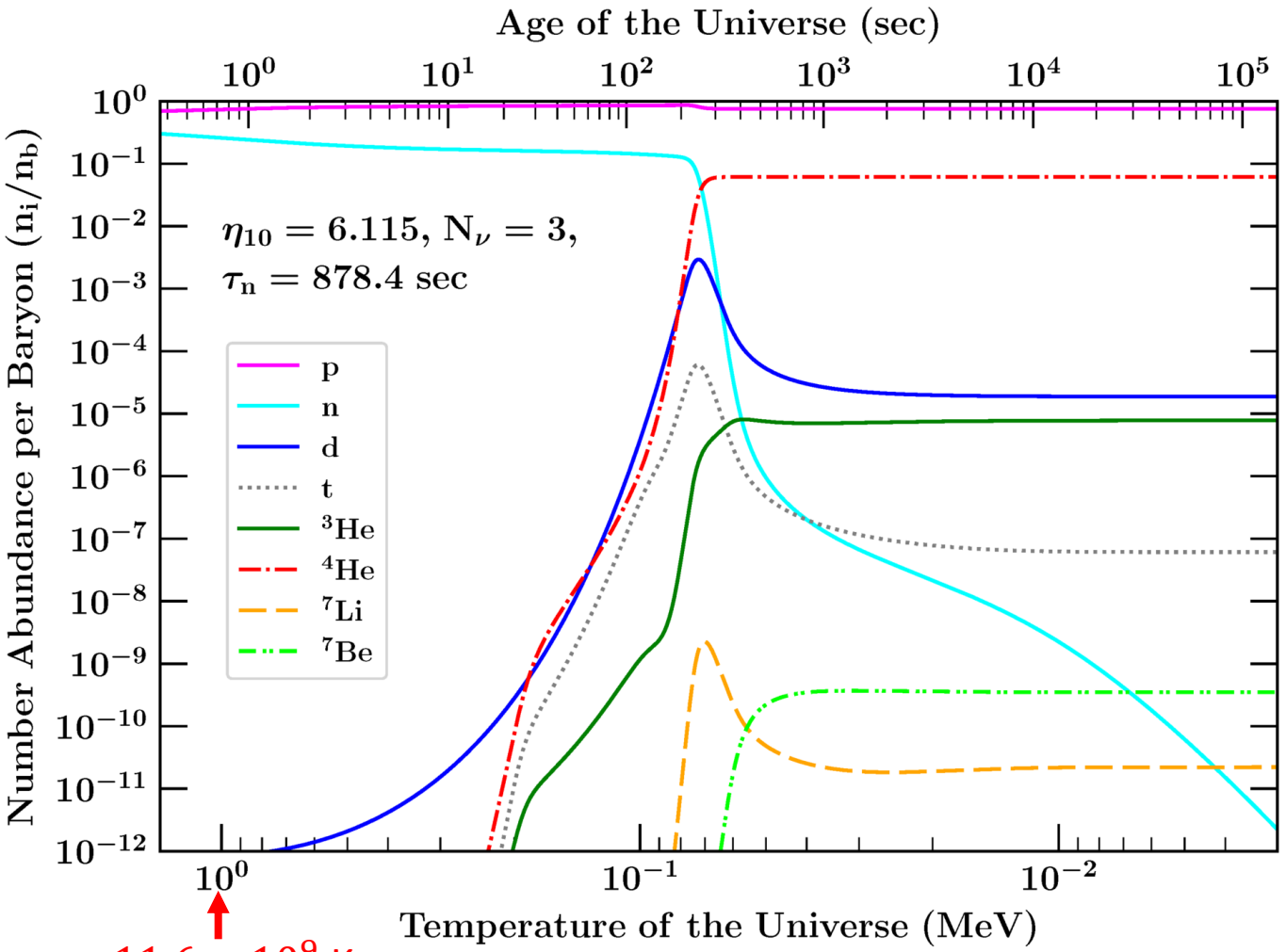

**Baryogenesis**
**matter**/antimatter asymmetry (unexplained)

**Nucleosynthesis**
primordial deuterium, helium, lithium (well understood)

**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)]

# Big Bang Nucleosynthesis

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- Formation of primordial **hydrogen**, **deuterium**, and **helium**.

**Predicted mass fractions:**

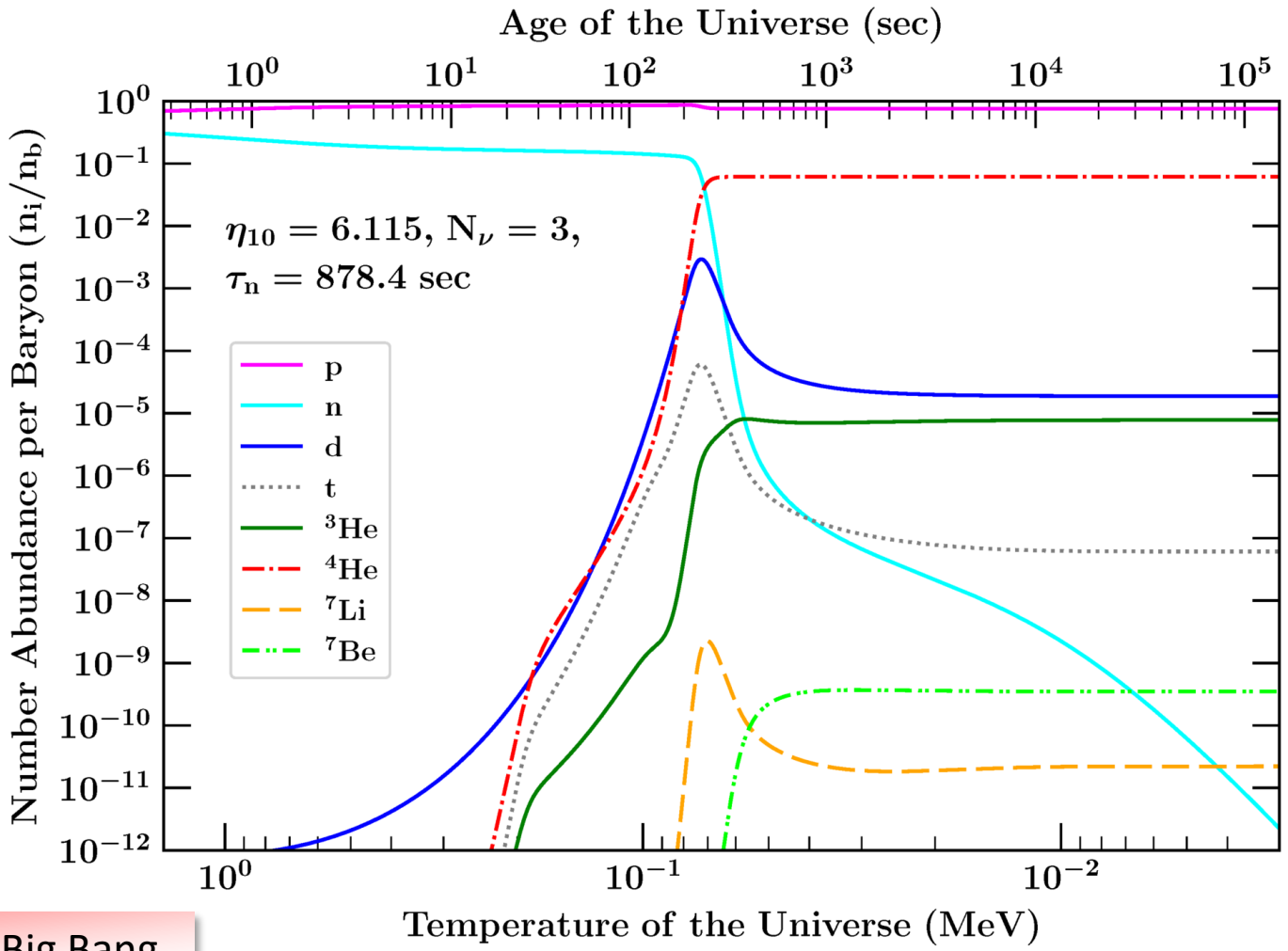
Hydrogen: 75%

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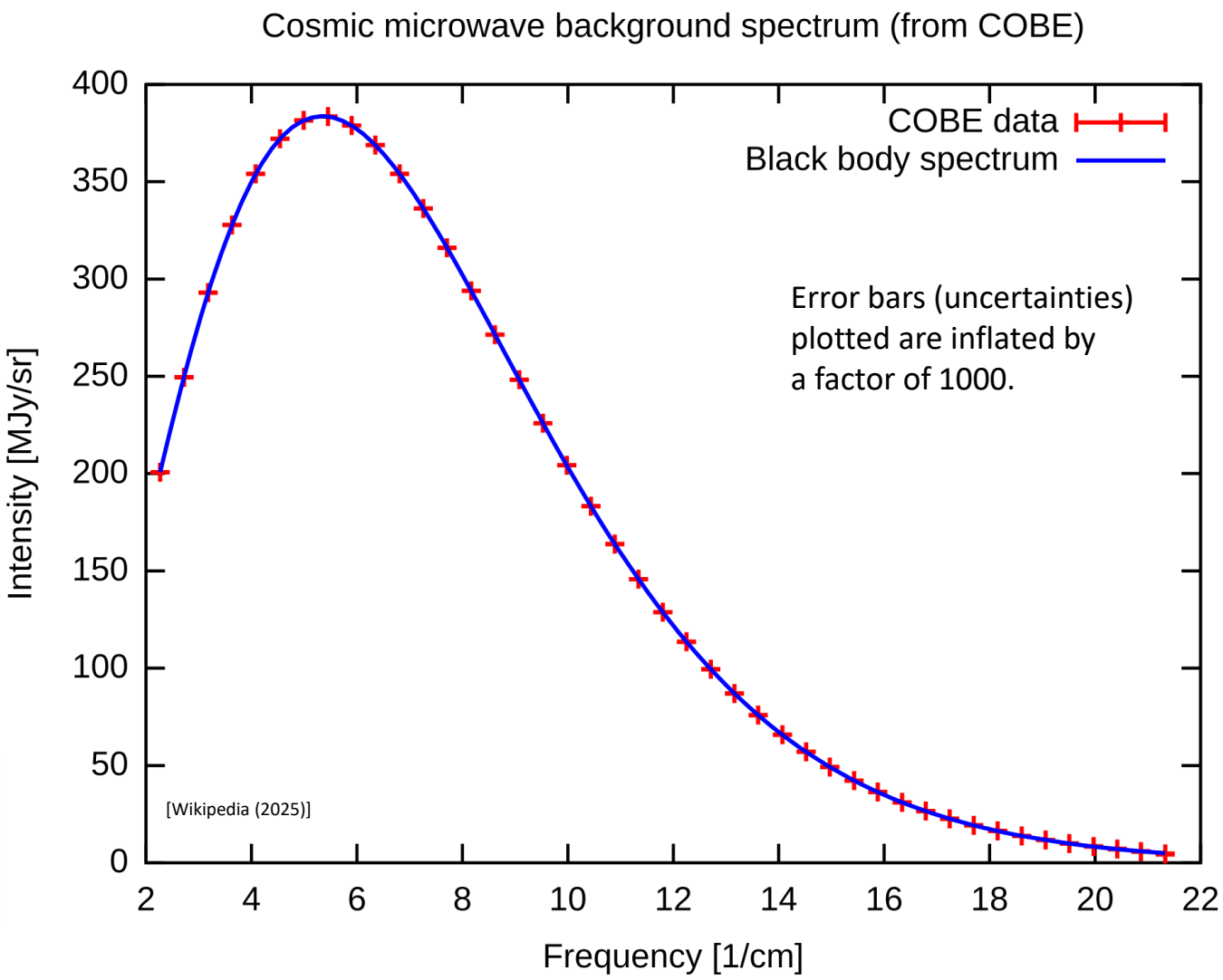
Since then, the universe has expanded about 1000 times its size, so this remnant primordial blackbody radiation should be at the equivalent of about 3 K.

# 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 $T = 2.725\ K$.



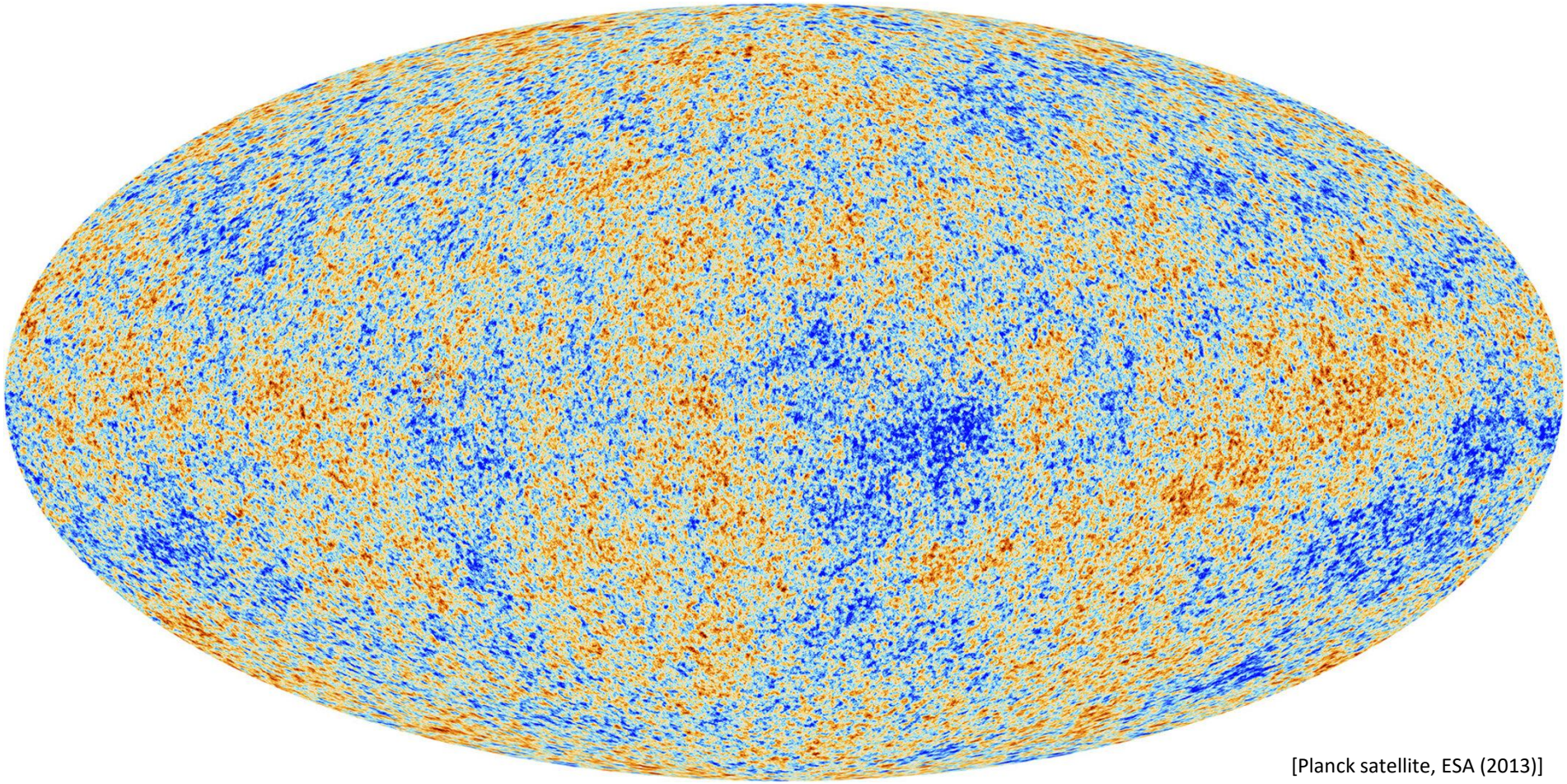

The CMB is very strong evidence for our current model of the big bang

# “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

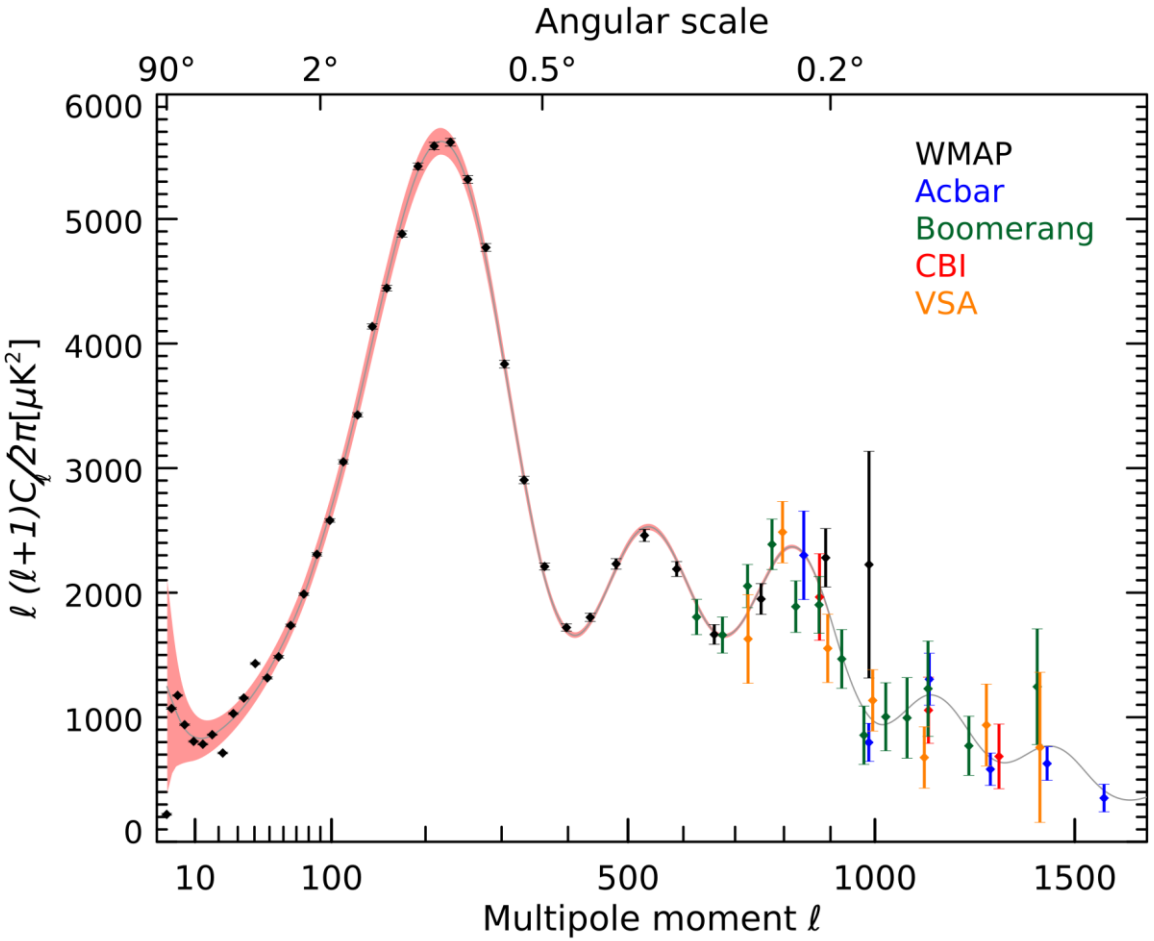
Blue = slightly colder → due to slightly higher matter density



[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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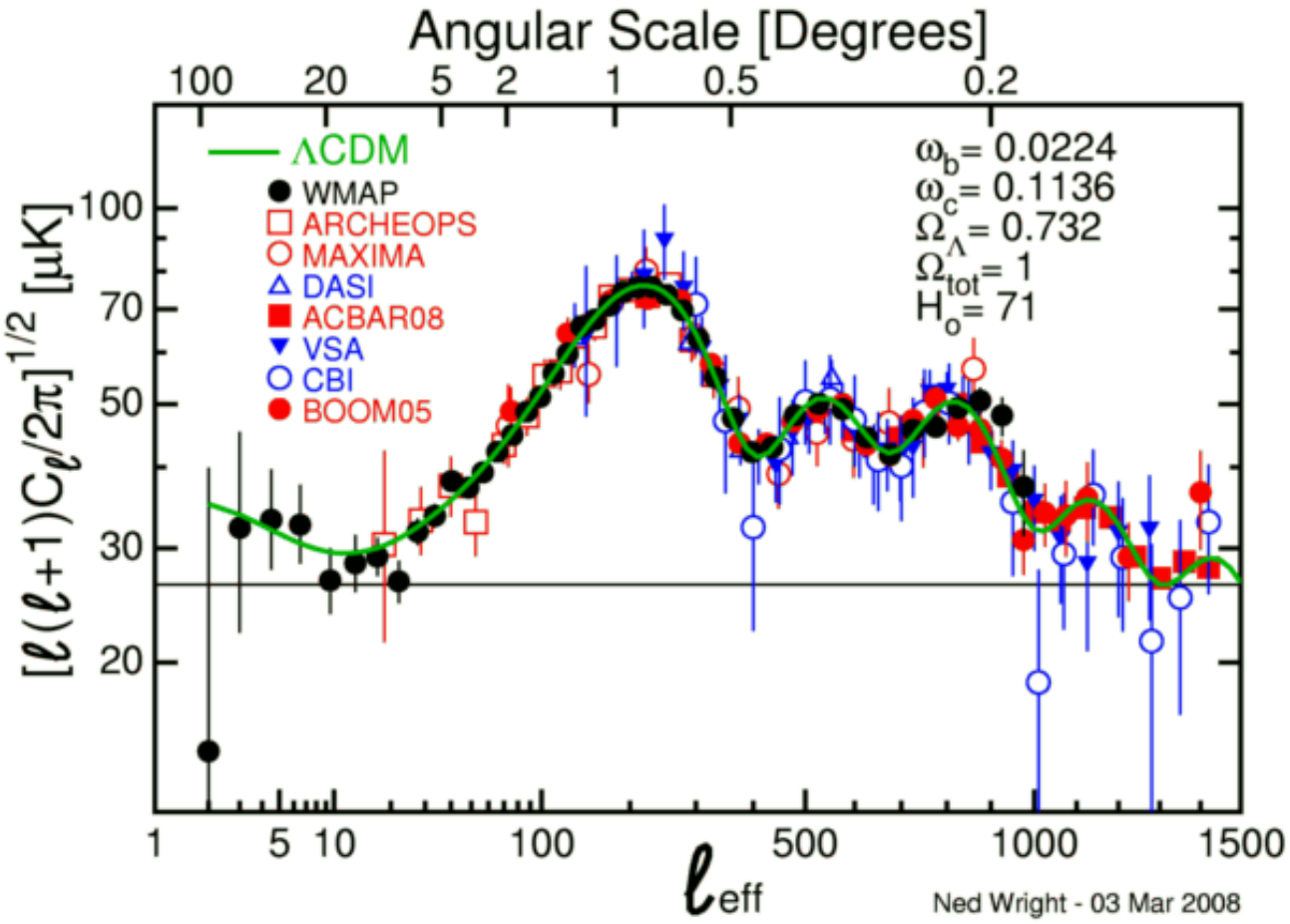


Green curve (ΛCDM) is prediction from the Big Bang model (assuming that dark matter is cold, and the existence of dark energy).