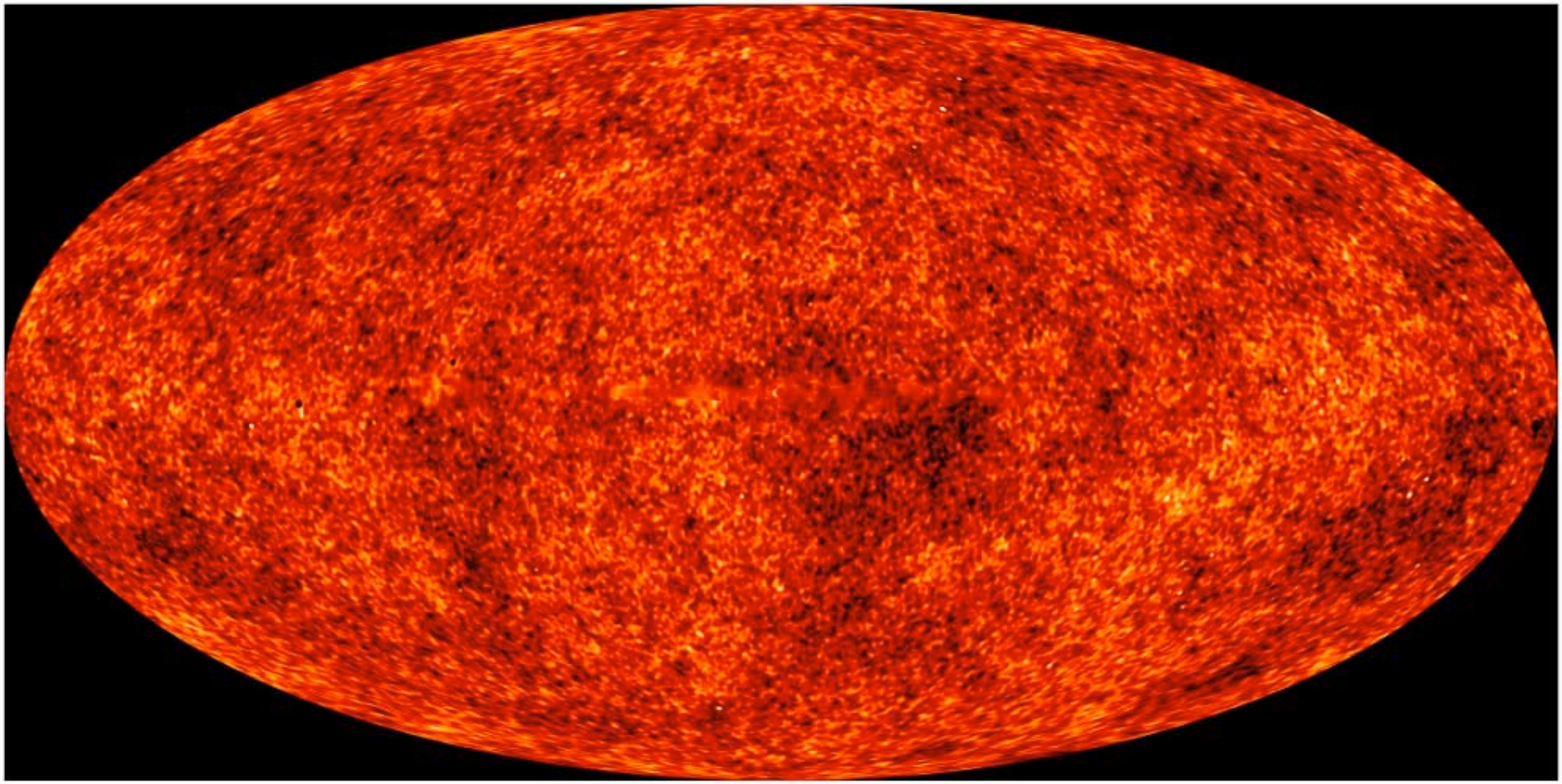
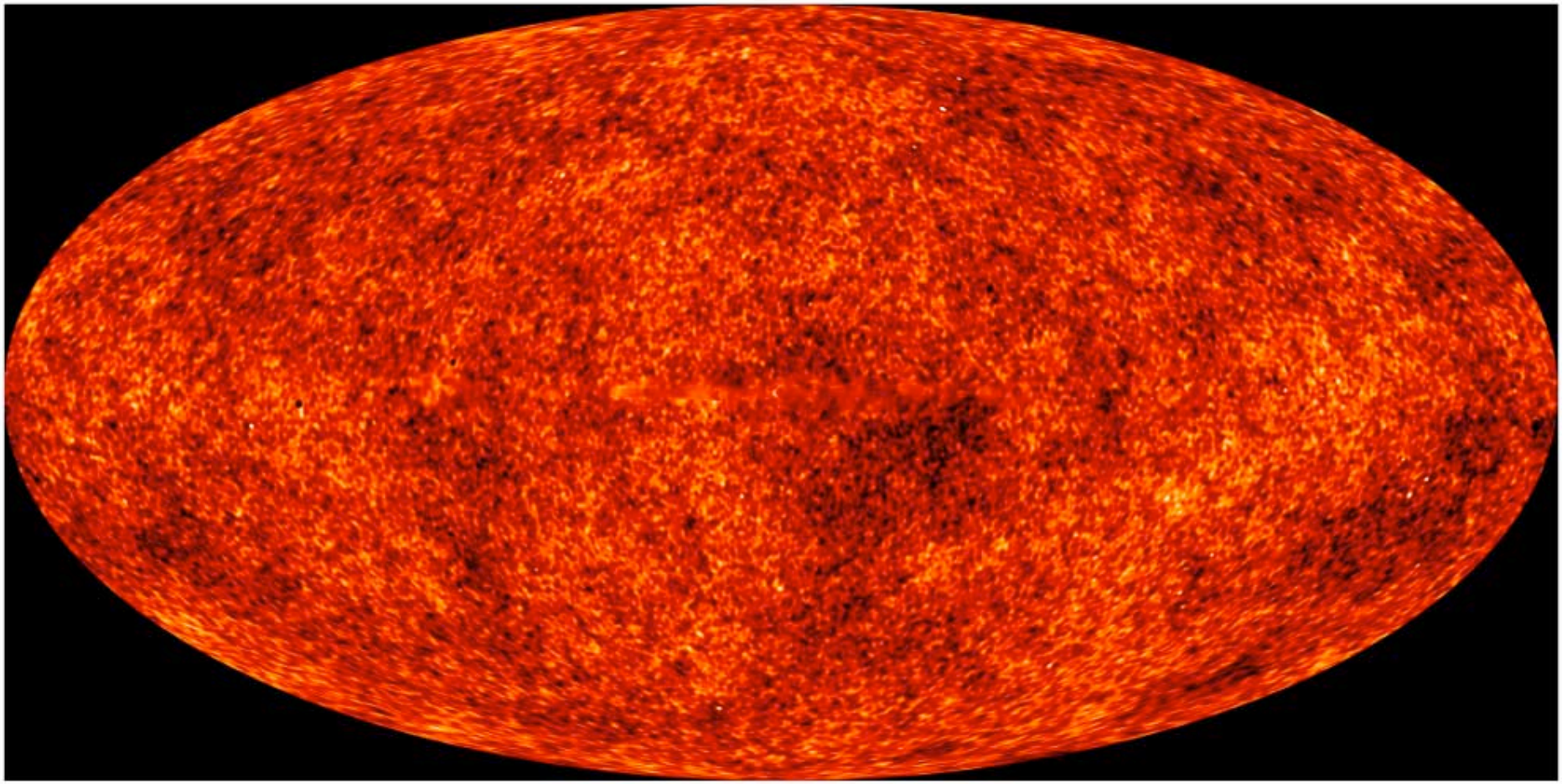
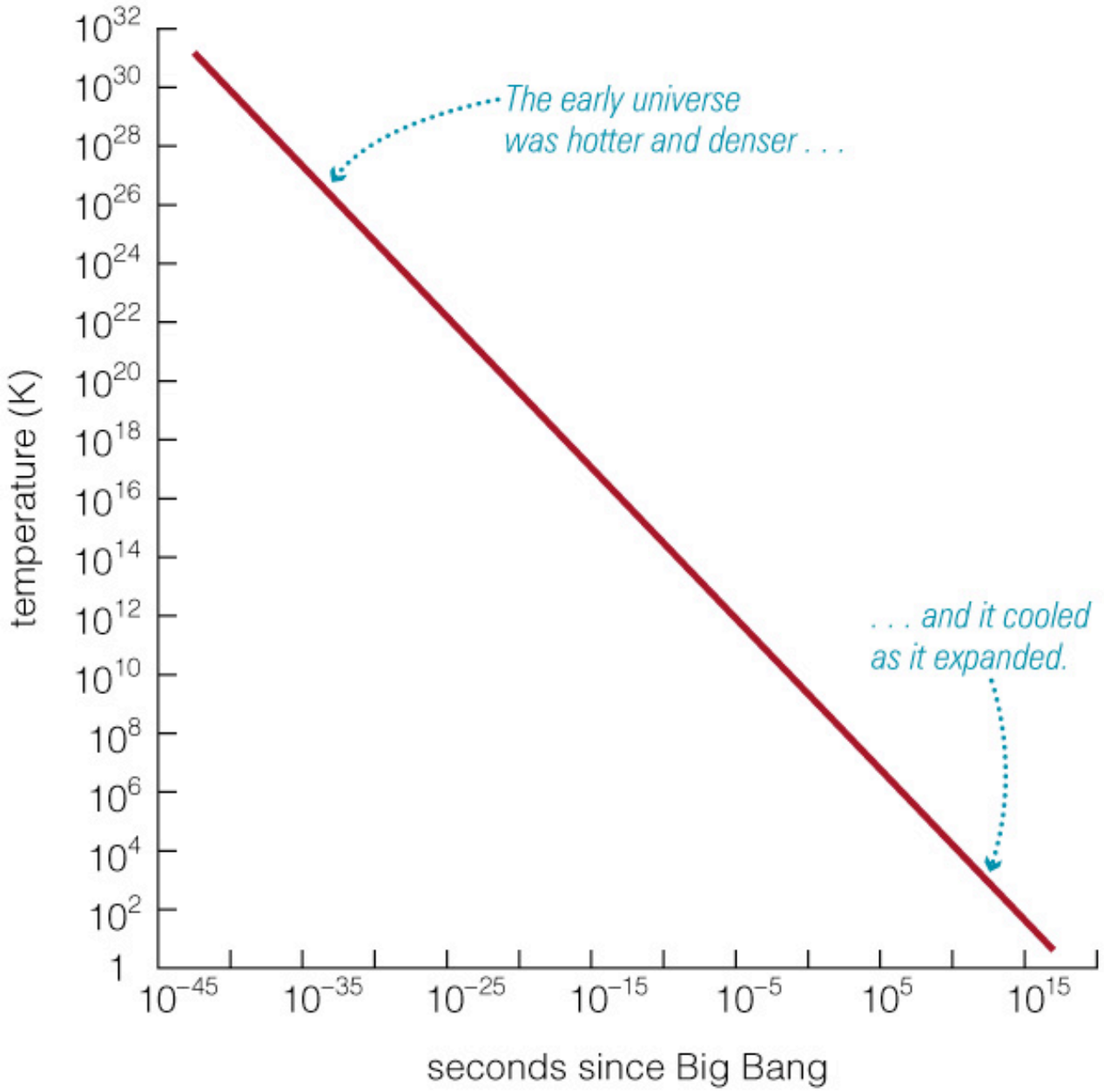
The ‘Big Bang’
The Beginning of Time

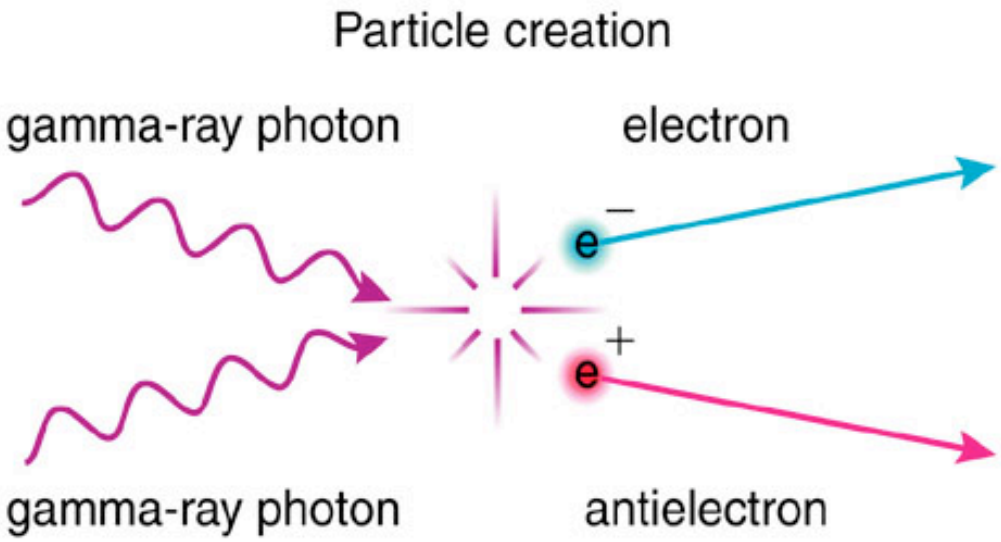


What were conditions like in the early universe?



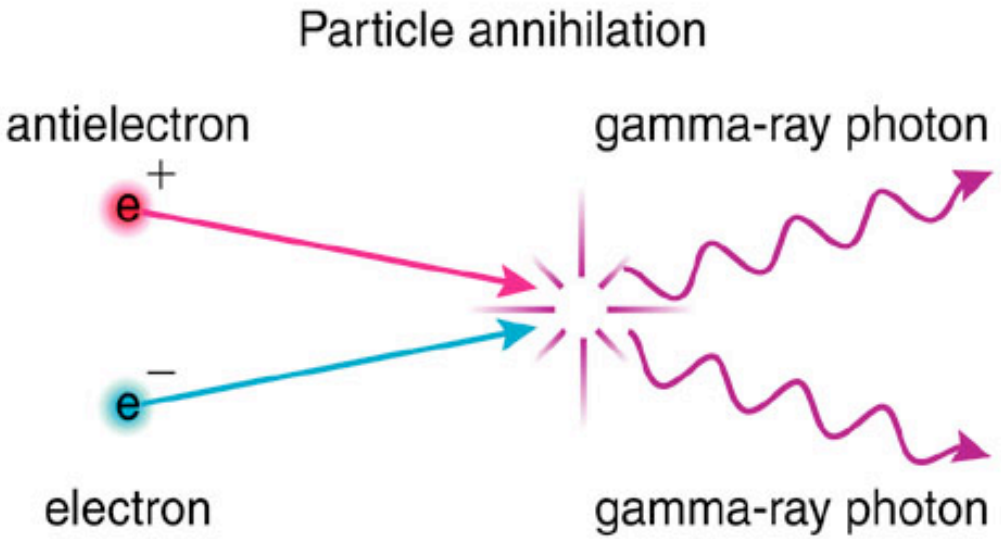


The early universe must have been extremely hot and dense



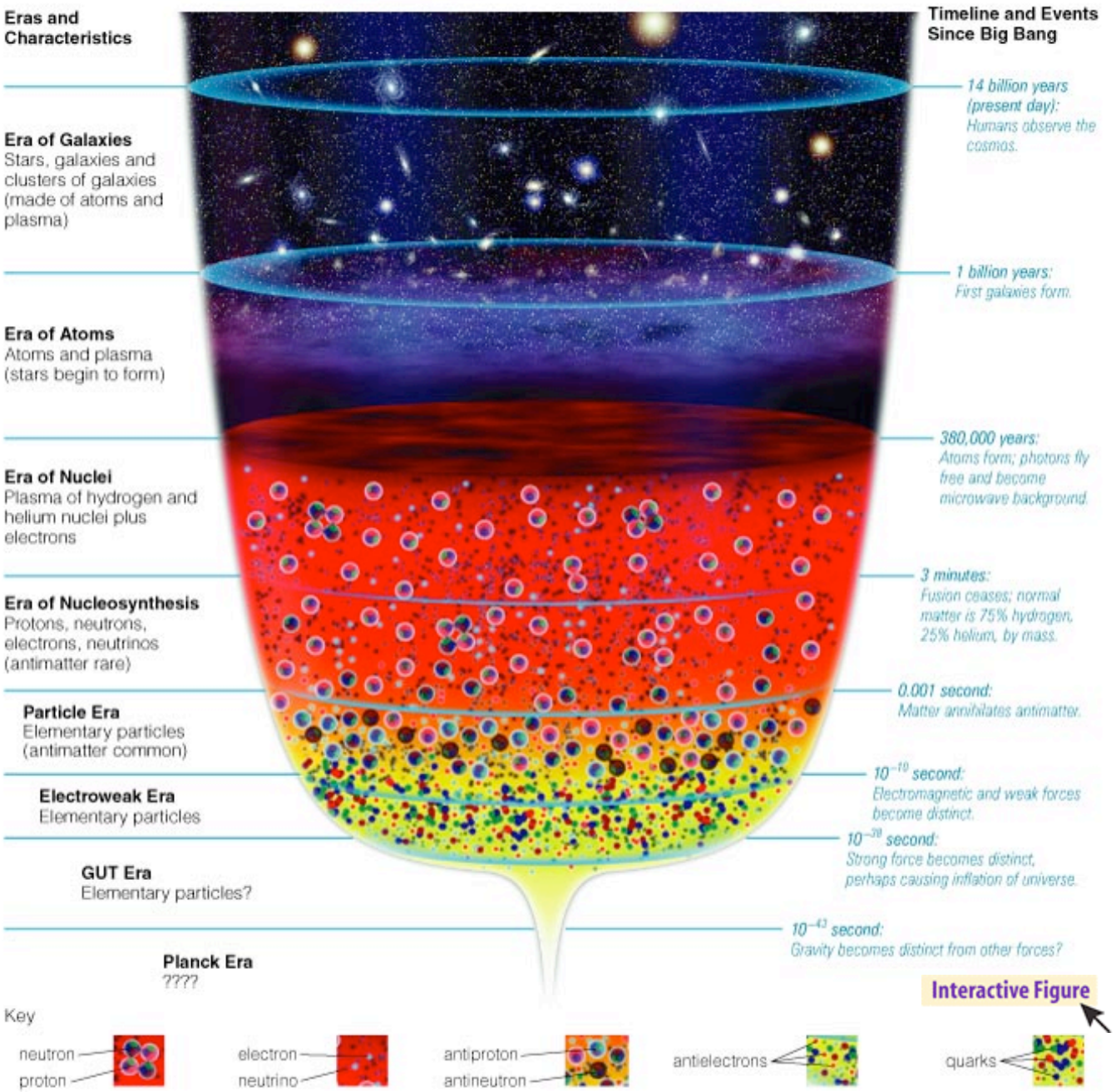
Photons converted into particle-antiparticle pairs and vice-versa

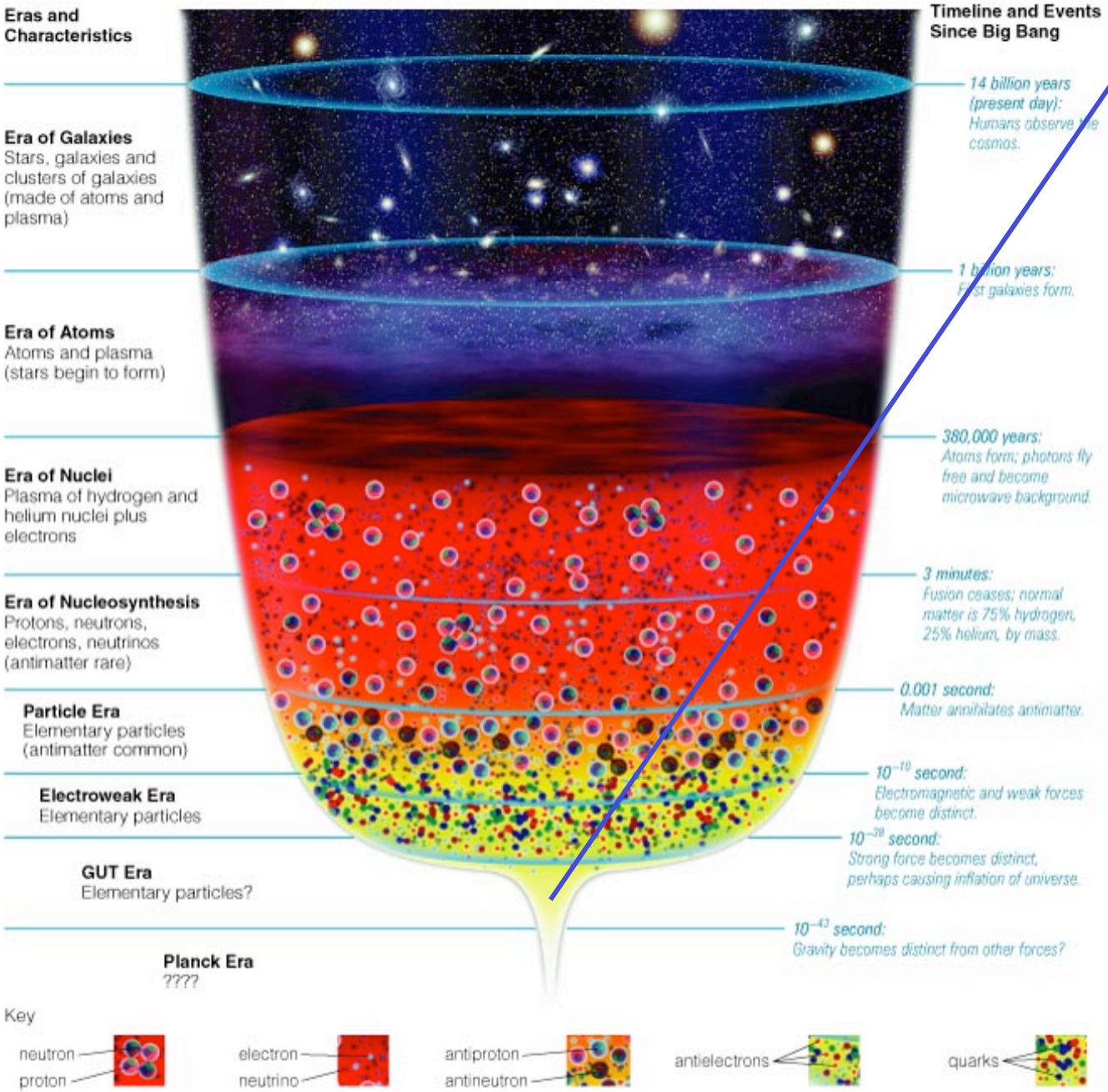
$$E = mc^2$$



Early universe was full of particles and radiation because of its high temperature

History of the Universe



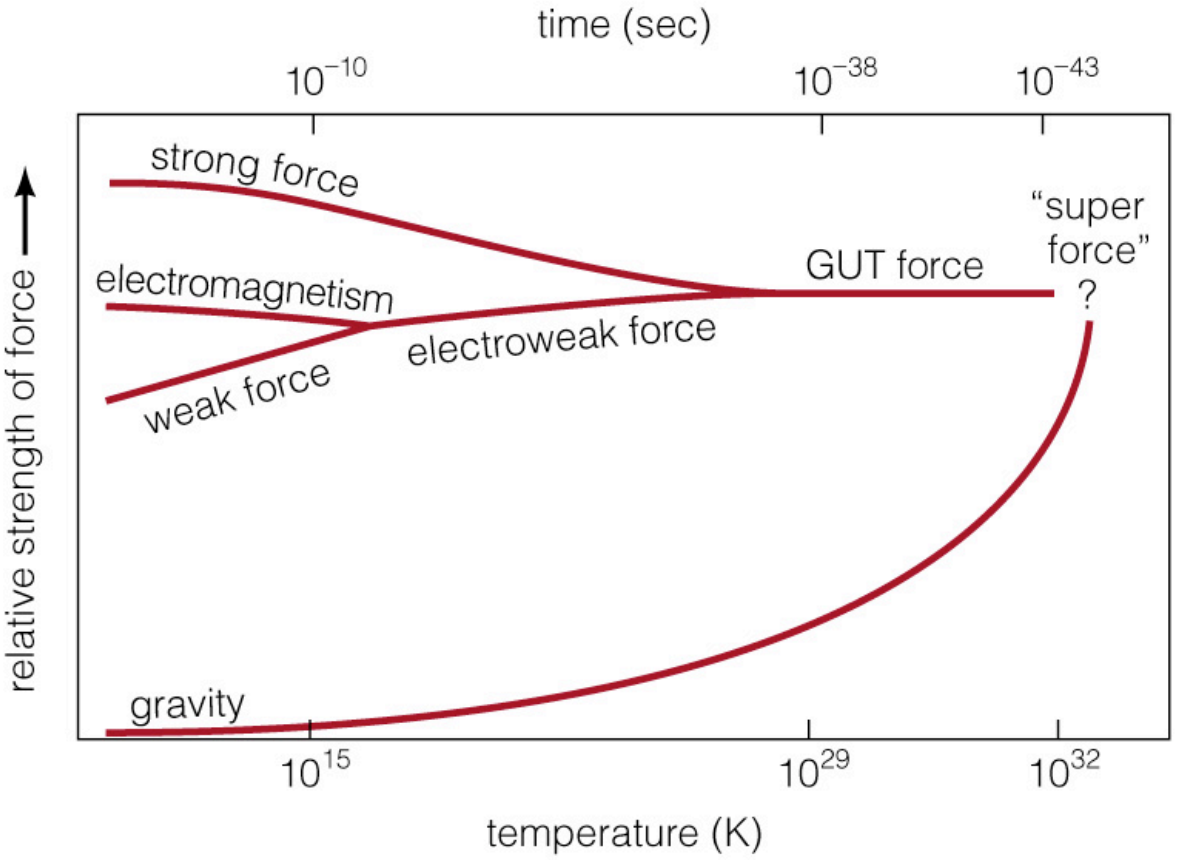


Planck Era

Before Planck time (~10^{-43} sec)

No theory of quantum gravity

Do forces unify at high temperatures?



Four known forces in universe:

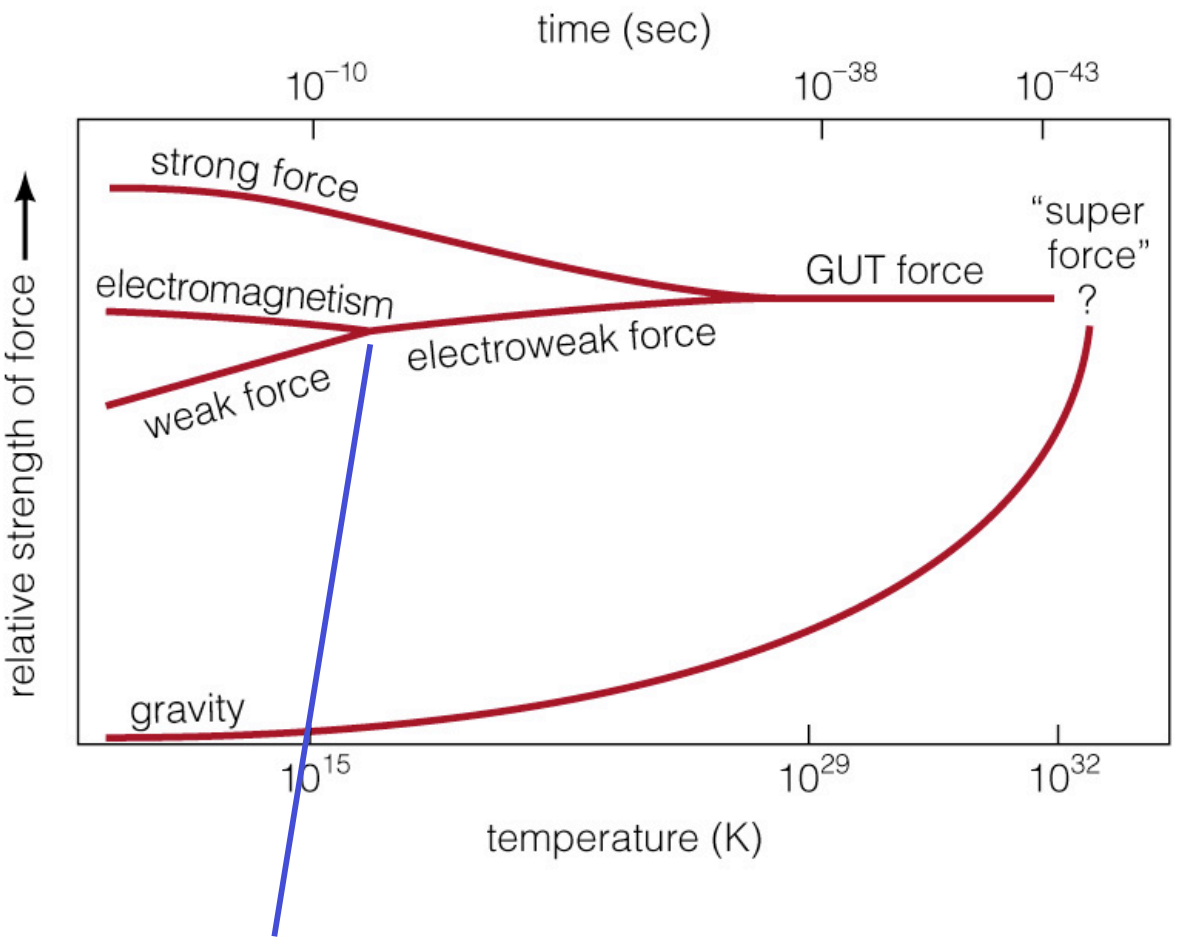
Strong Force

Electromagnetism

Weak Force

Gravity

Do forces unify at high temperatures?



Yes!
(Electroweak)

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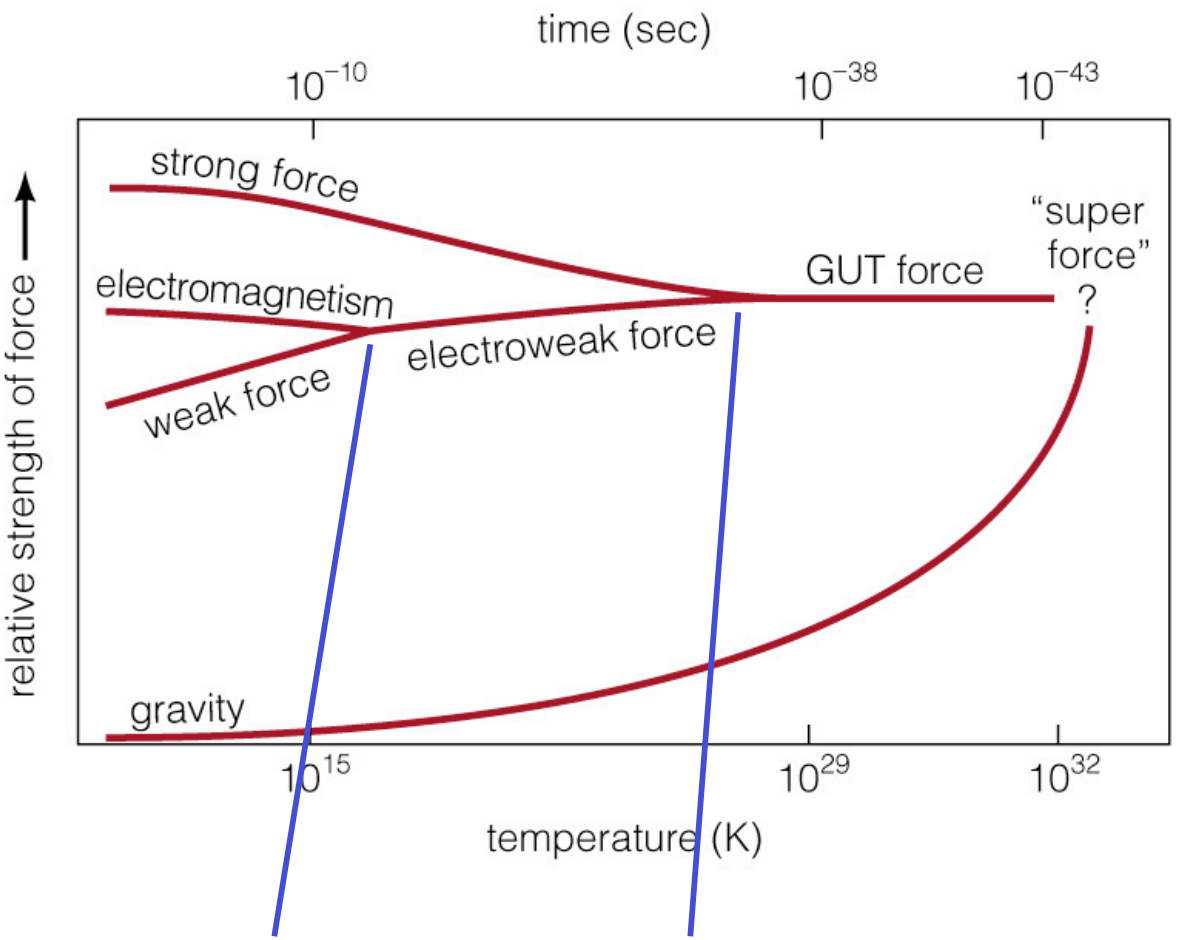

Yes!
(Electroweak)

Maybe
(GUT)

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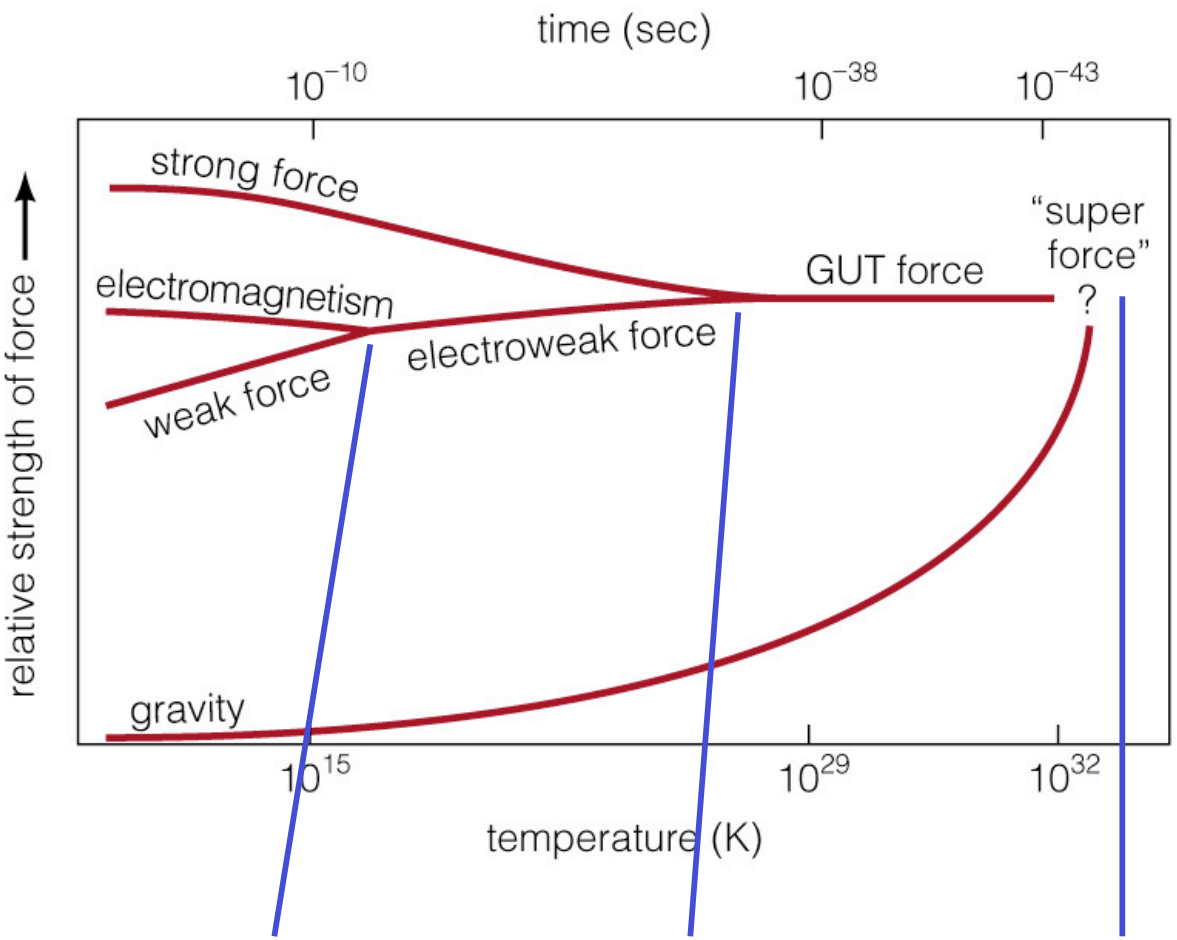


Four known forces in universe:

Strong Force

Electromagnetism

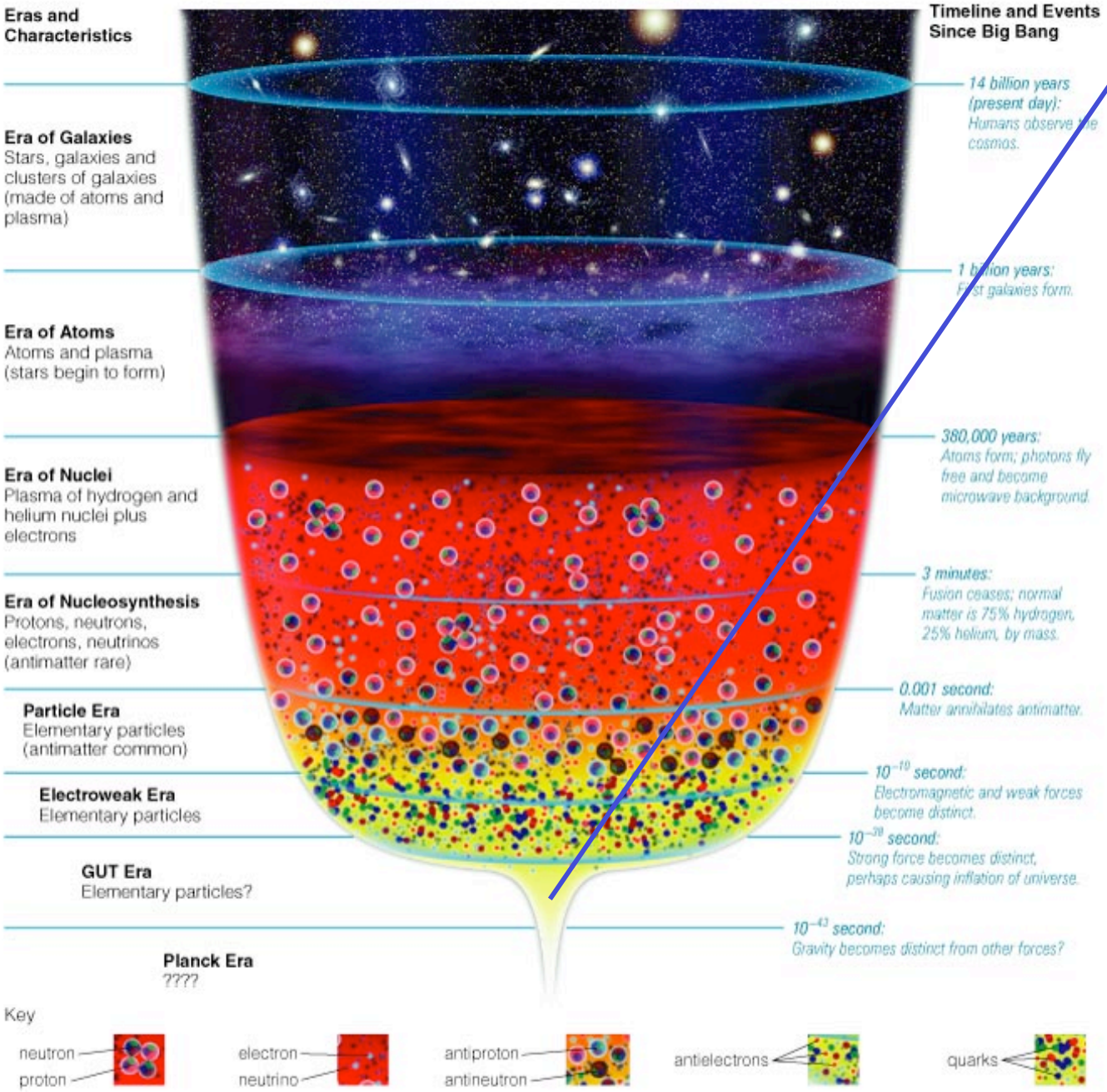
Weak Force

Gravity

Yes! (Electroweak)

Maybe (GUT)

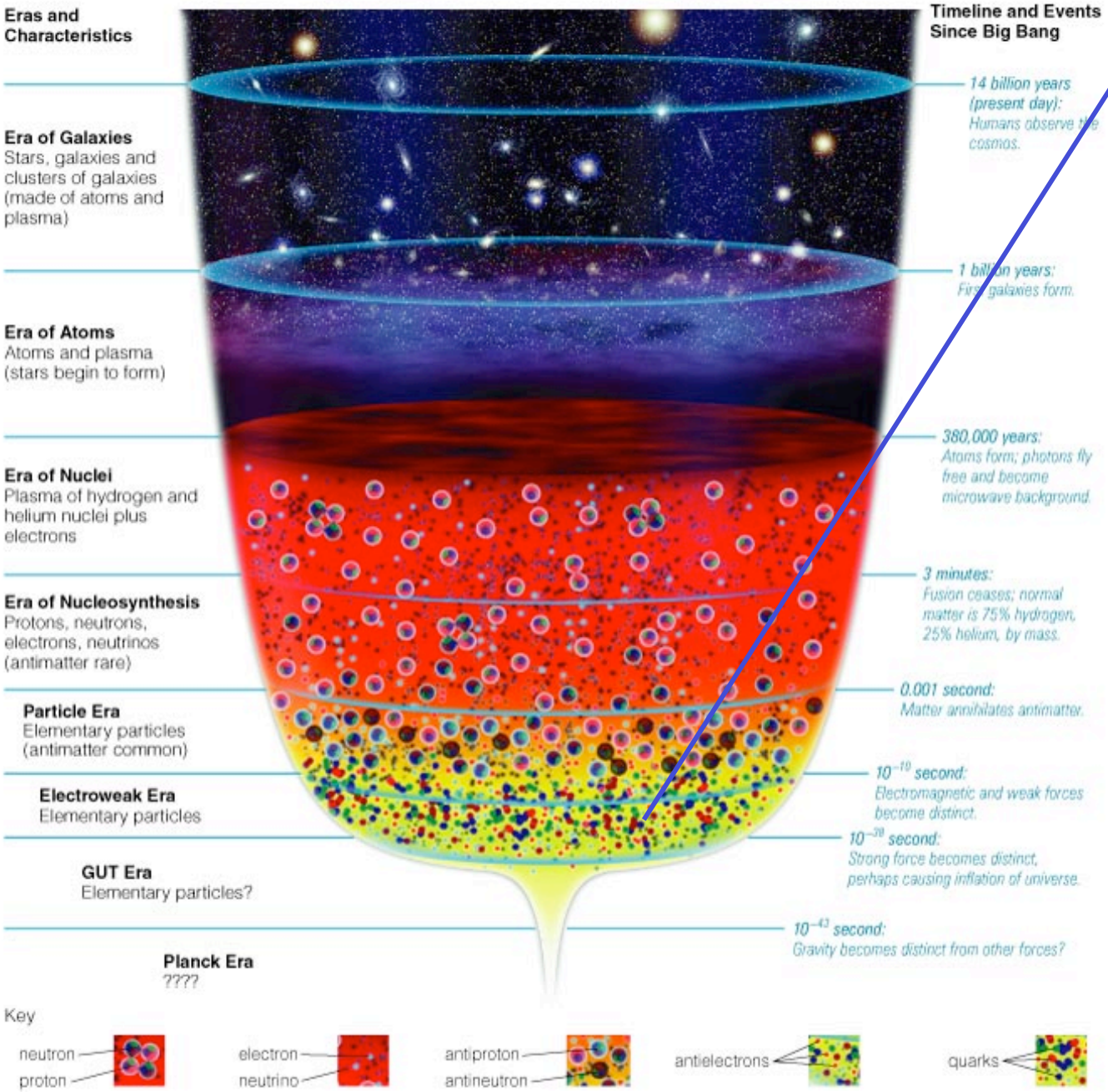
Who knows? (String Theory???)



GUT Era

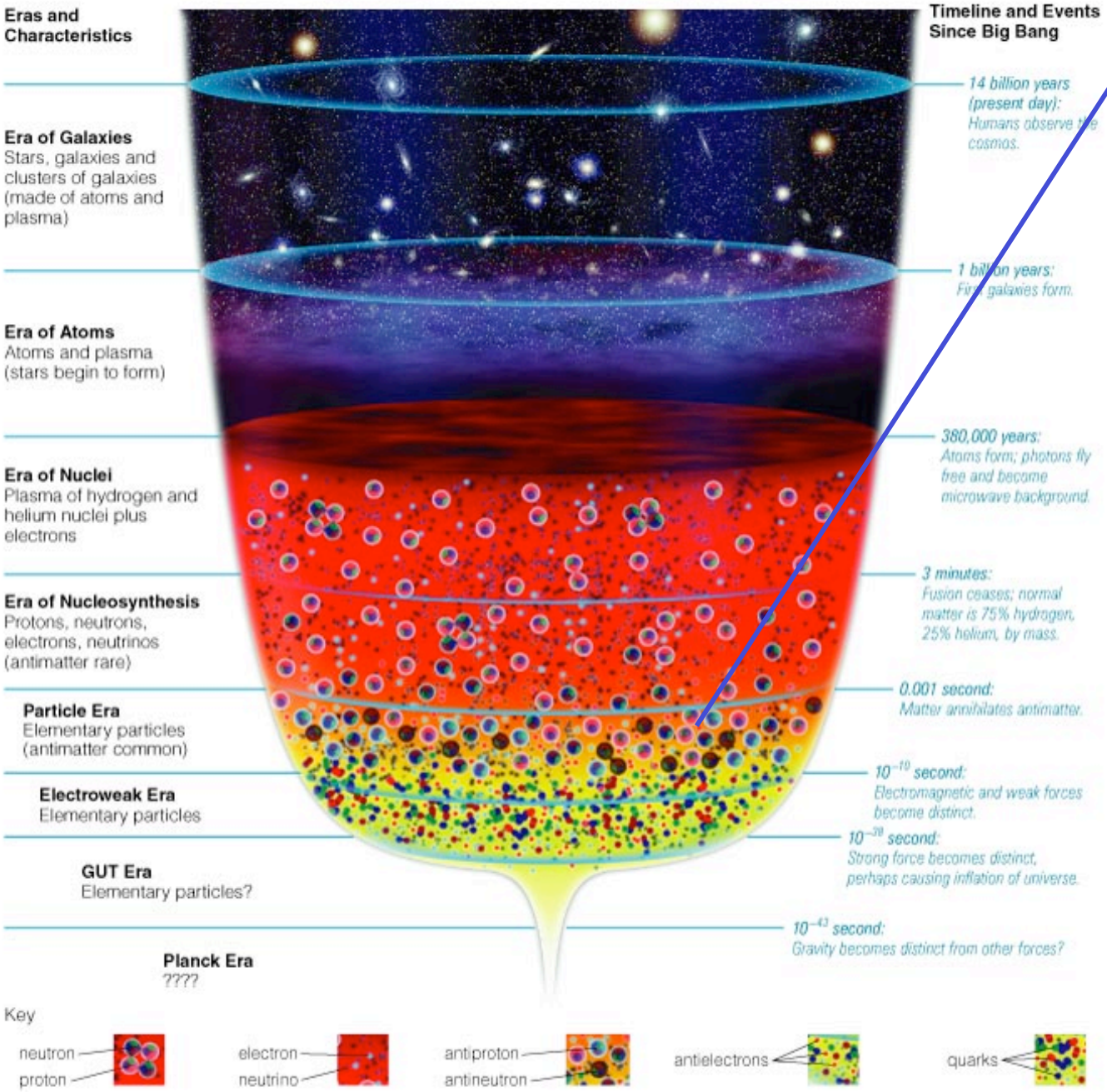
Lasts from Planck time ($\sim 10^{-43}$ sec)
to end of GUT force
($\sim 10^{-38}$ sec)

Inflation - due to energy from force 'symmetry breaking'?



Electroweak Era

Lasts from end of GUT force (~10^{-38} sec) to end of electroweak force (~10^{-10} sec)

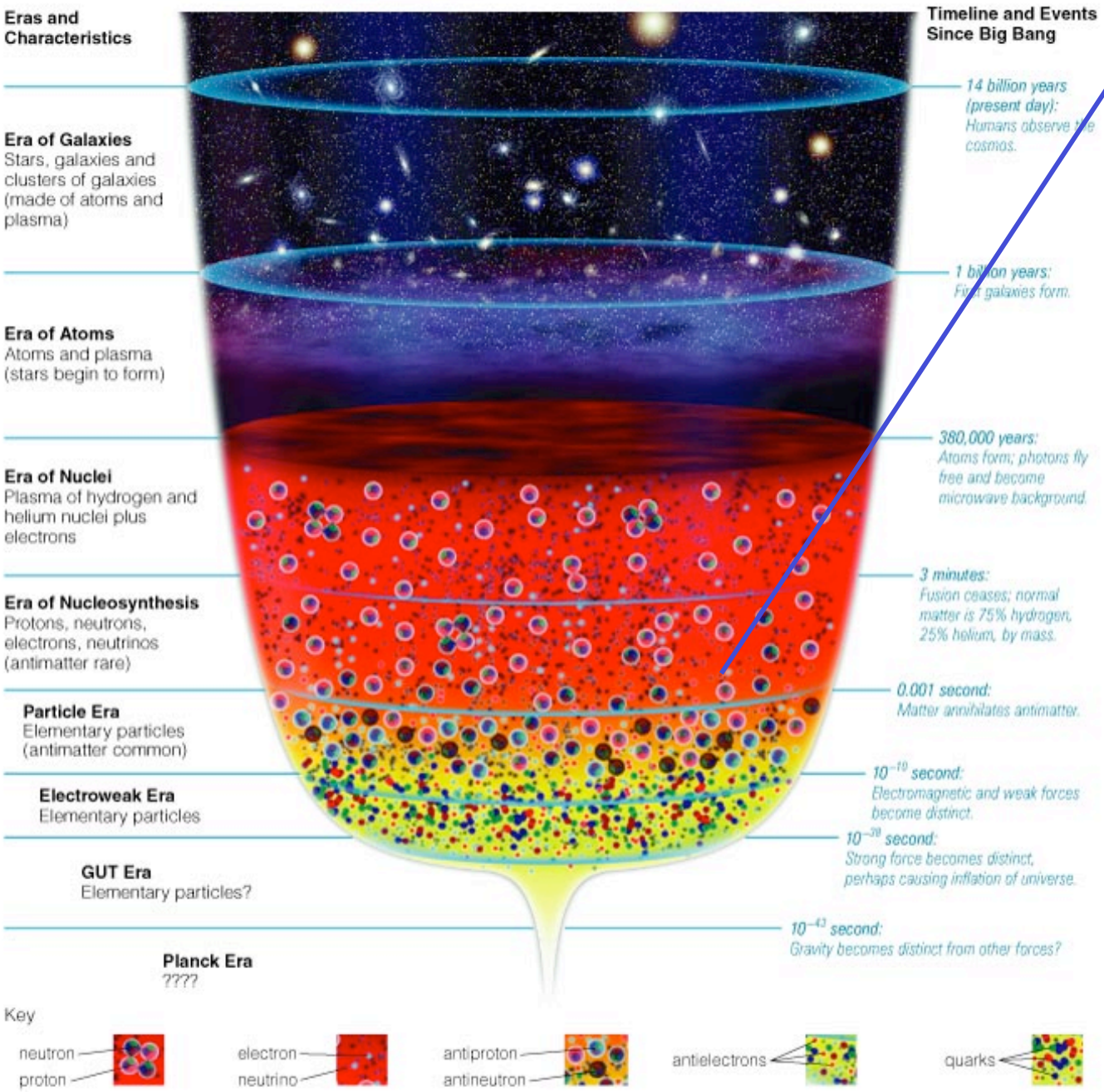


Particle Era

Amounts of matter and antimatter nearly equal

(Roughly 1 extra proton for every 10^9 proton-antiproton pairs!)

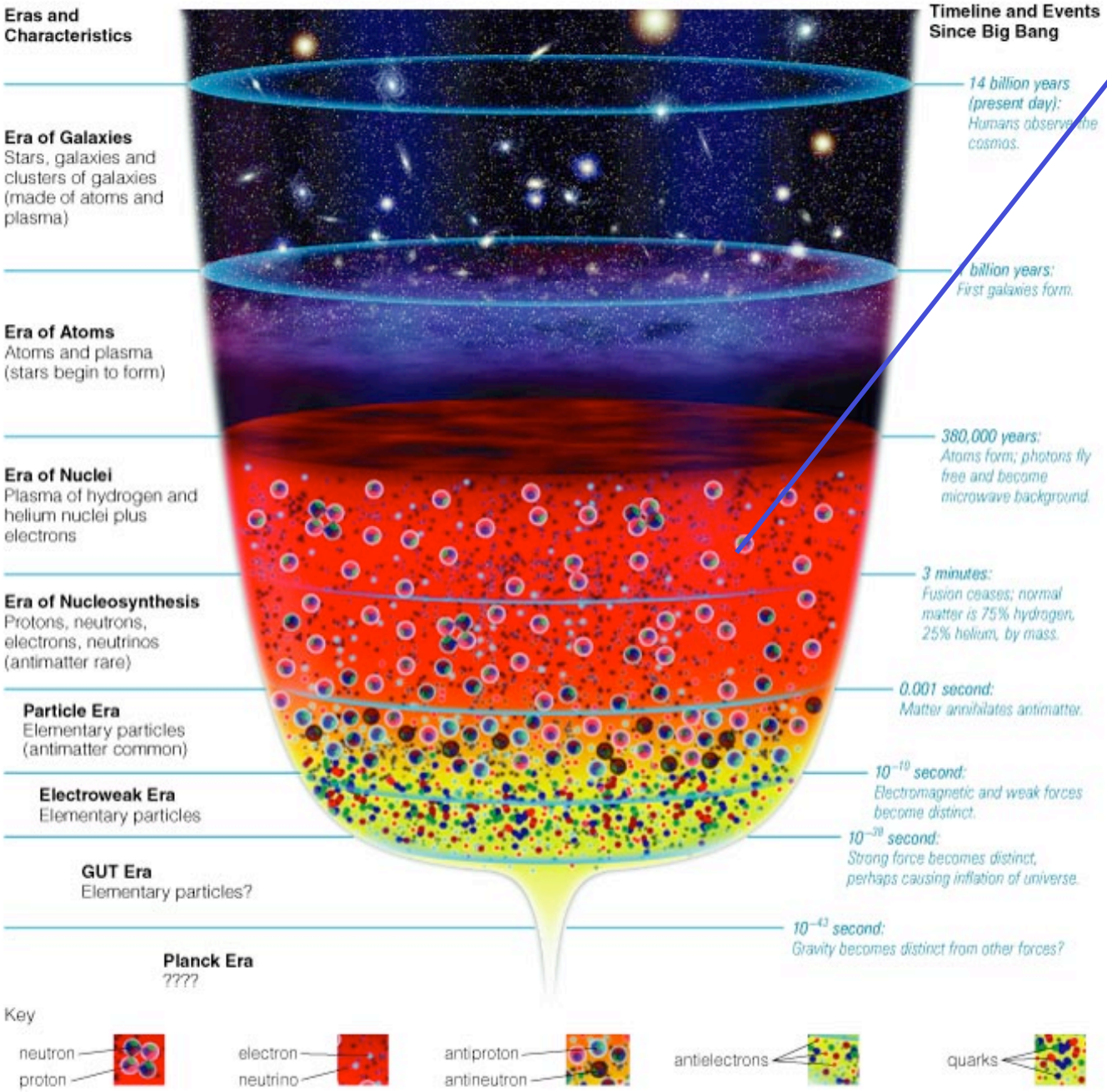
Why?



Era of Nucleo-synthesis

Begins when matter annihilates remaining antimatter at ~ 0.001 sec

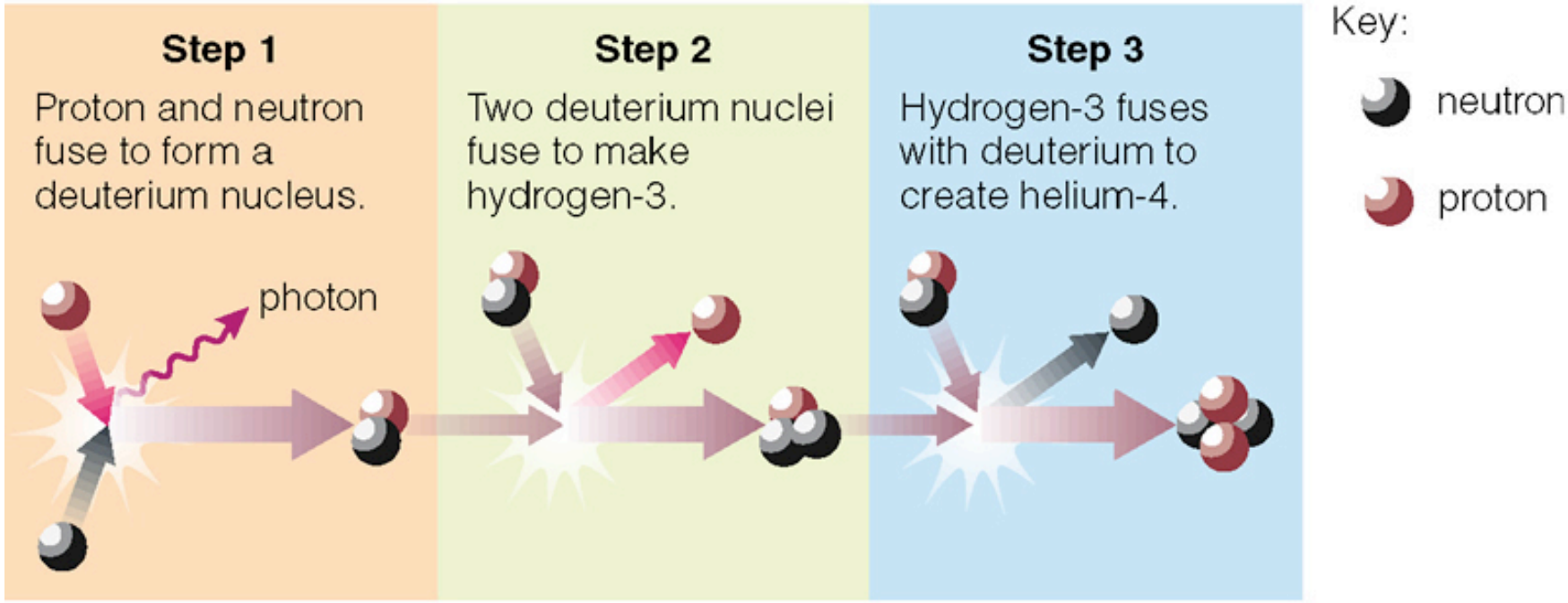
Universe heats up by 35%



Era of Nuclei

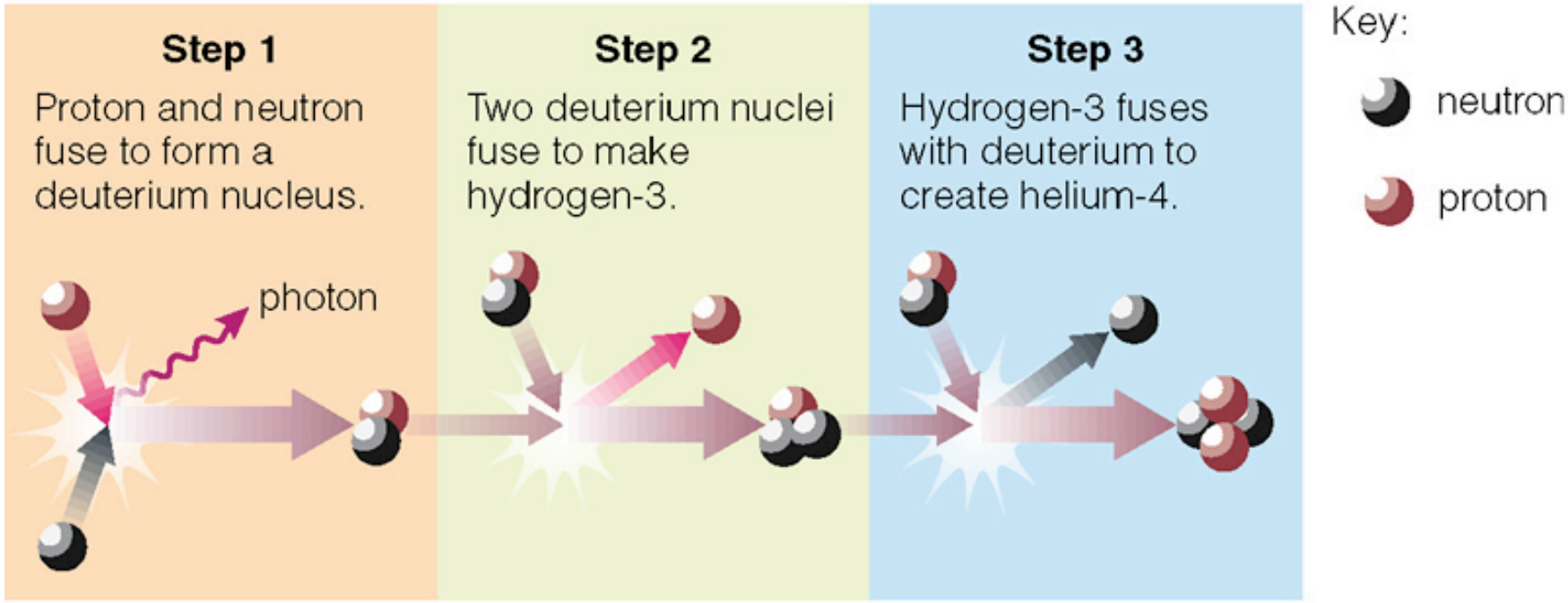
Helium nuclei begin to form from age ~ 3 minutes to 30 minutes

Universe has become too cool to blast helium apart



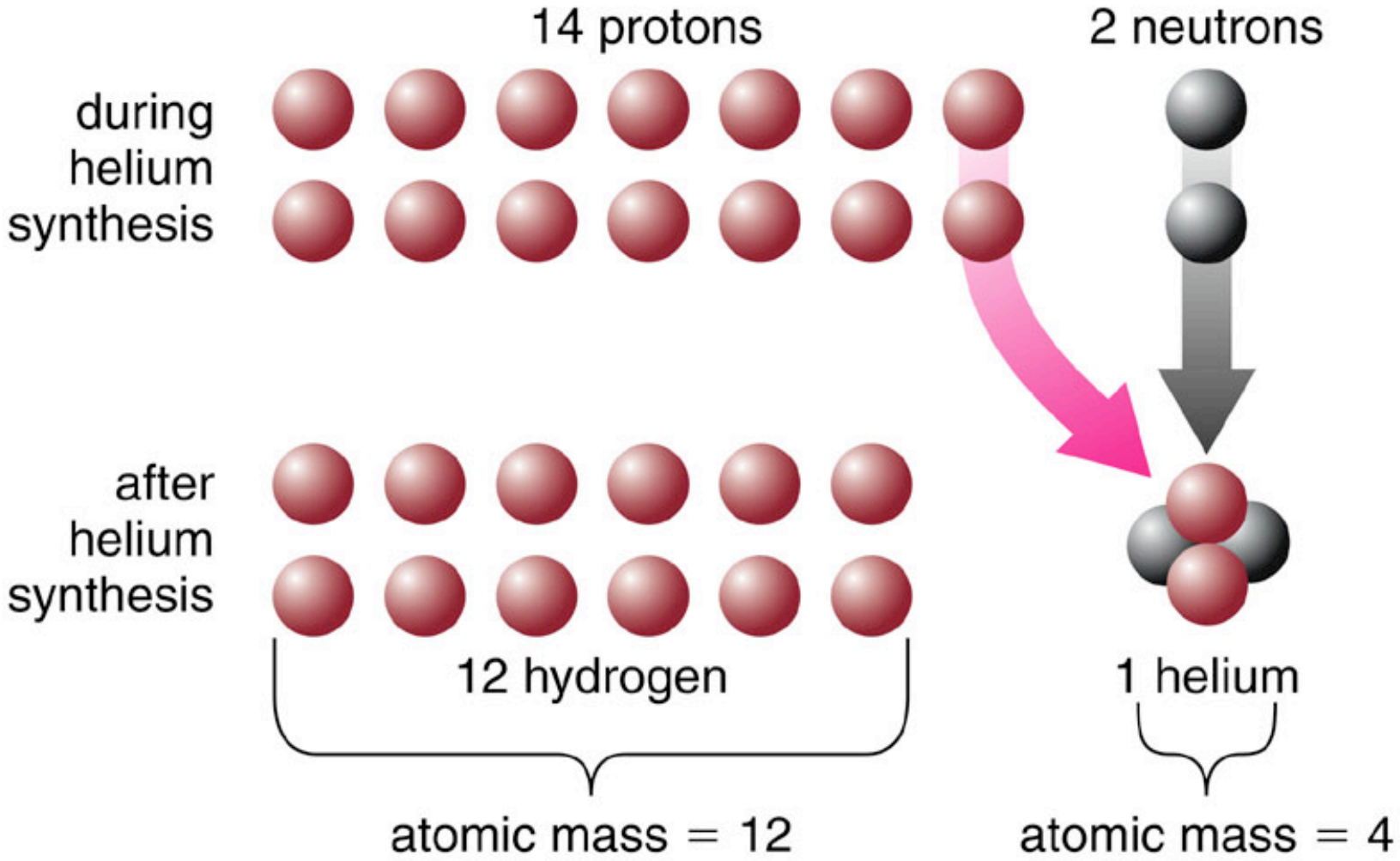
Protons and neutrons combined to make long-lasting helium nuclei.

Question: *Why is Big Bang Nucleosynthesis different from Stellar Nucleosynthesis?*



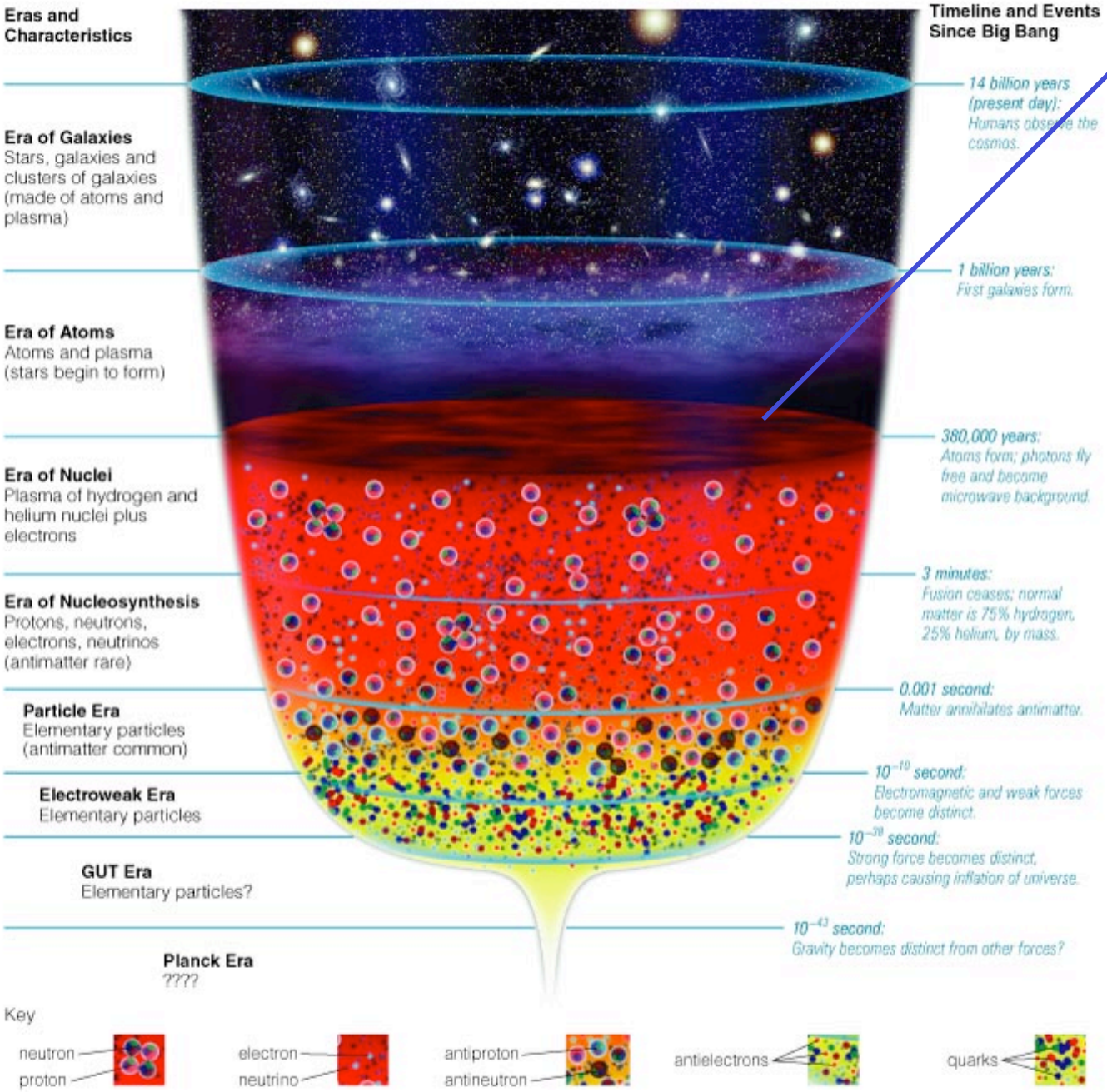
Question: *Why is Big Bang Nucleosynthesis different from Stellar Nucleosynthesis?*

1. ***There are no free neutrons in stars (all used up in Big Bang)***
2. ***Densities are much lower when nuclear fusion occurs in the Big Bang; cannot get Triple-α process - $^4He + {}^4He + {}^4He \rightarrow {}^{12}C$***
   There is not much fusion beyond He (get a bit of Li, Be, B)



Big Bang theory prediction: 75% H, 25% He (by mass)

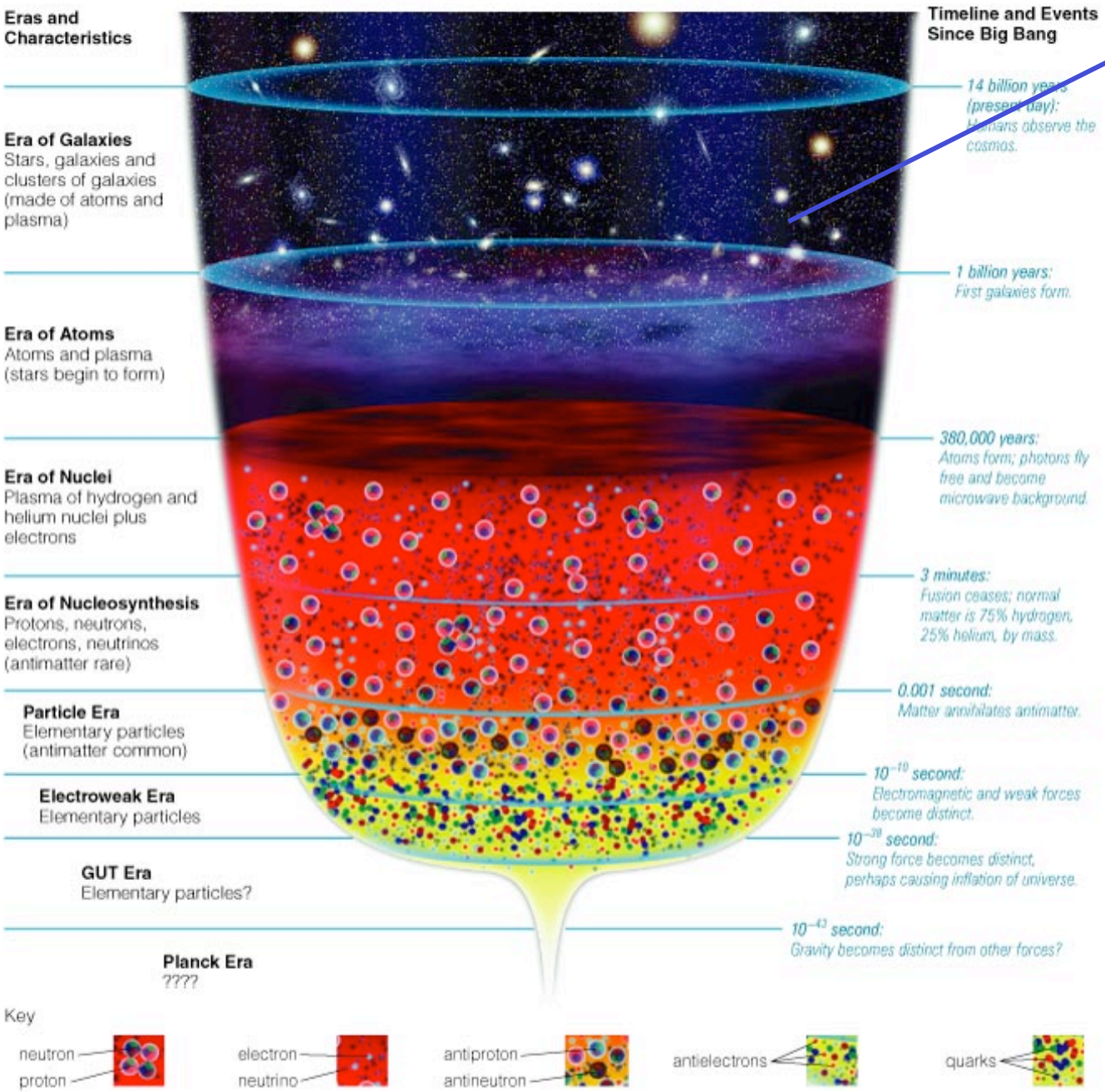
Matches observations of nearly primordial gases



Era of Atoms

Atoms form at age ~ 380,000 years

Background radiation ‘decouples from matter’



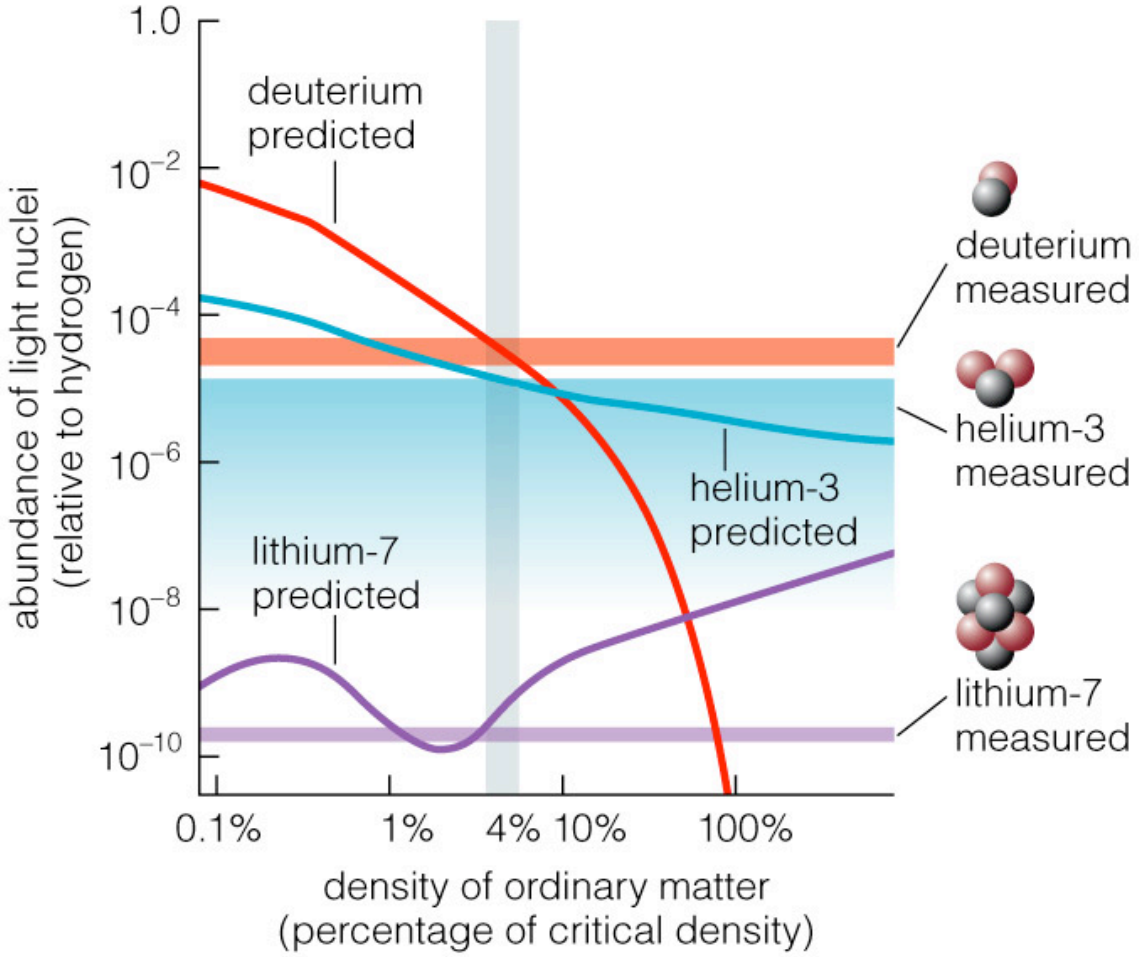
Era of Galaxies

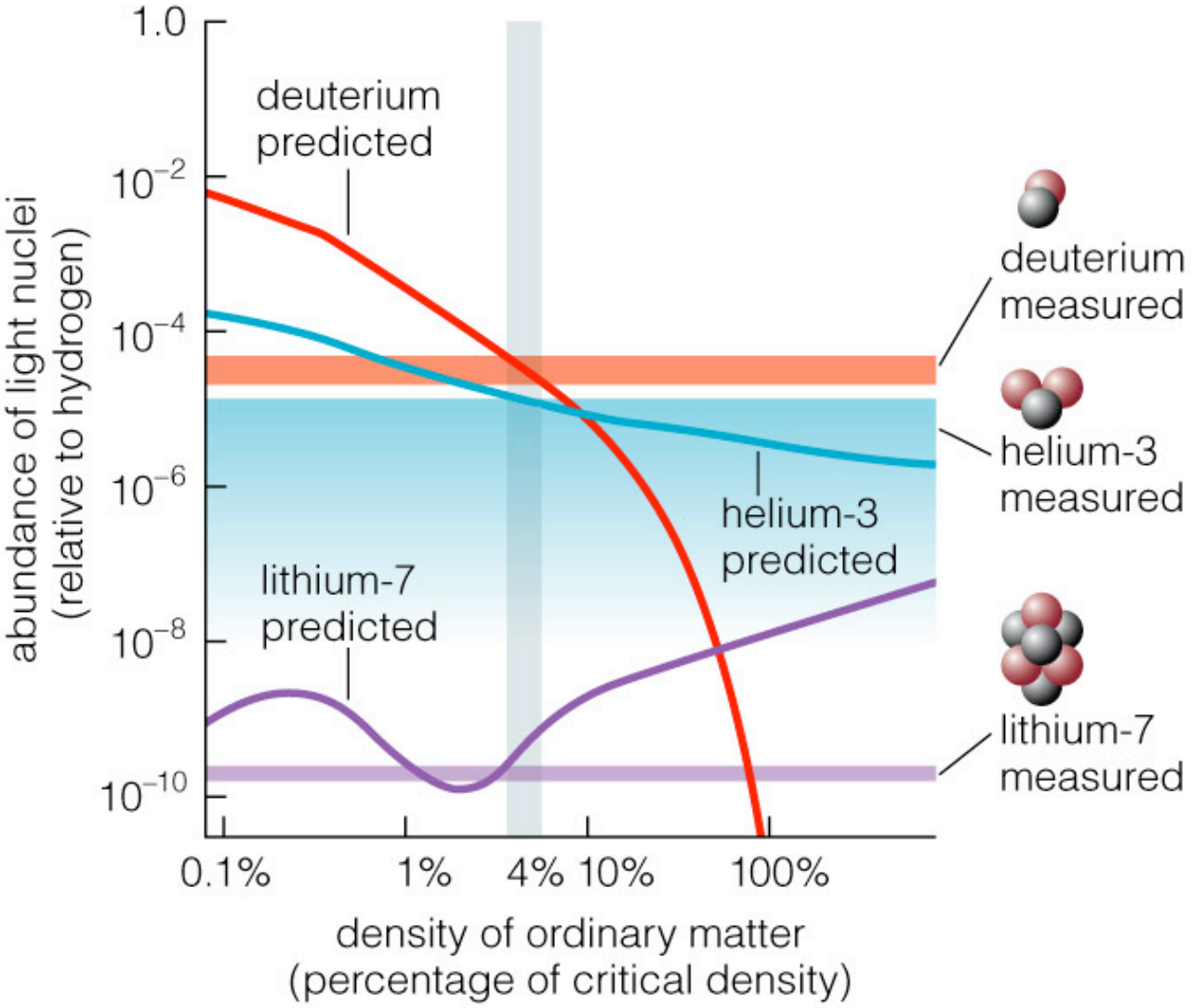
Galaxies form at age ~ 1 billion years

Summary

- What were conditions like in the early universe?
  - The early universe was so hot and so dense that radiation was constantly producing particle-antiparticle pairs and vice versa
- What is the history of the universe according to the Big Bang theory?
  - As the universe cooled, particle production stopped, leaving matter instead of antimatter
  - Fusion turned remaining neutrons into helium
  - Radiation traveled freely after formation of atoms

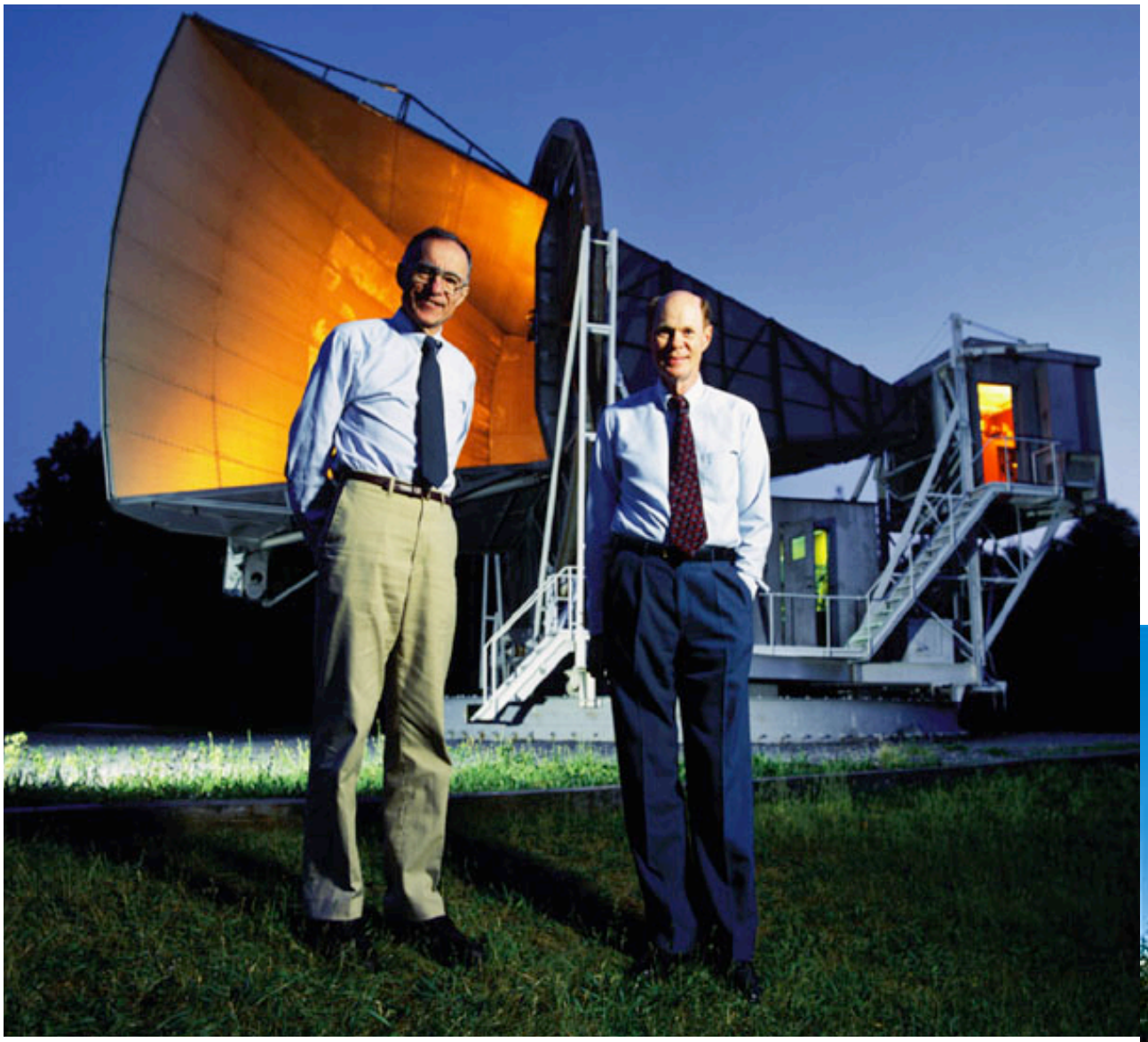
How do the abundances of elements support the Big Bang theory?



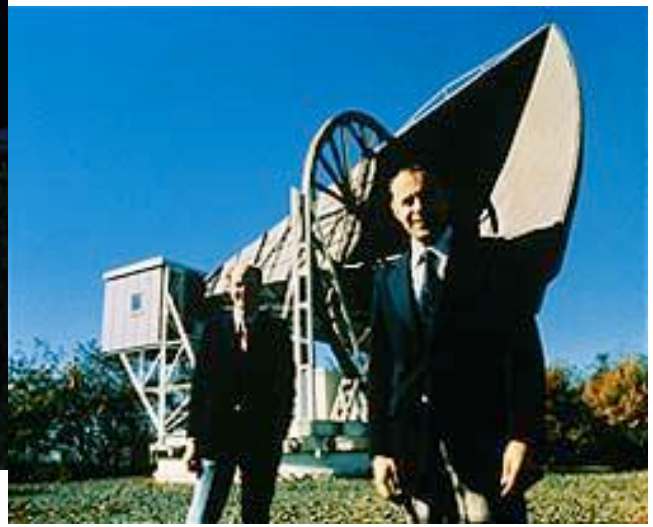


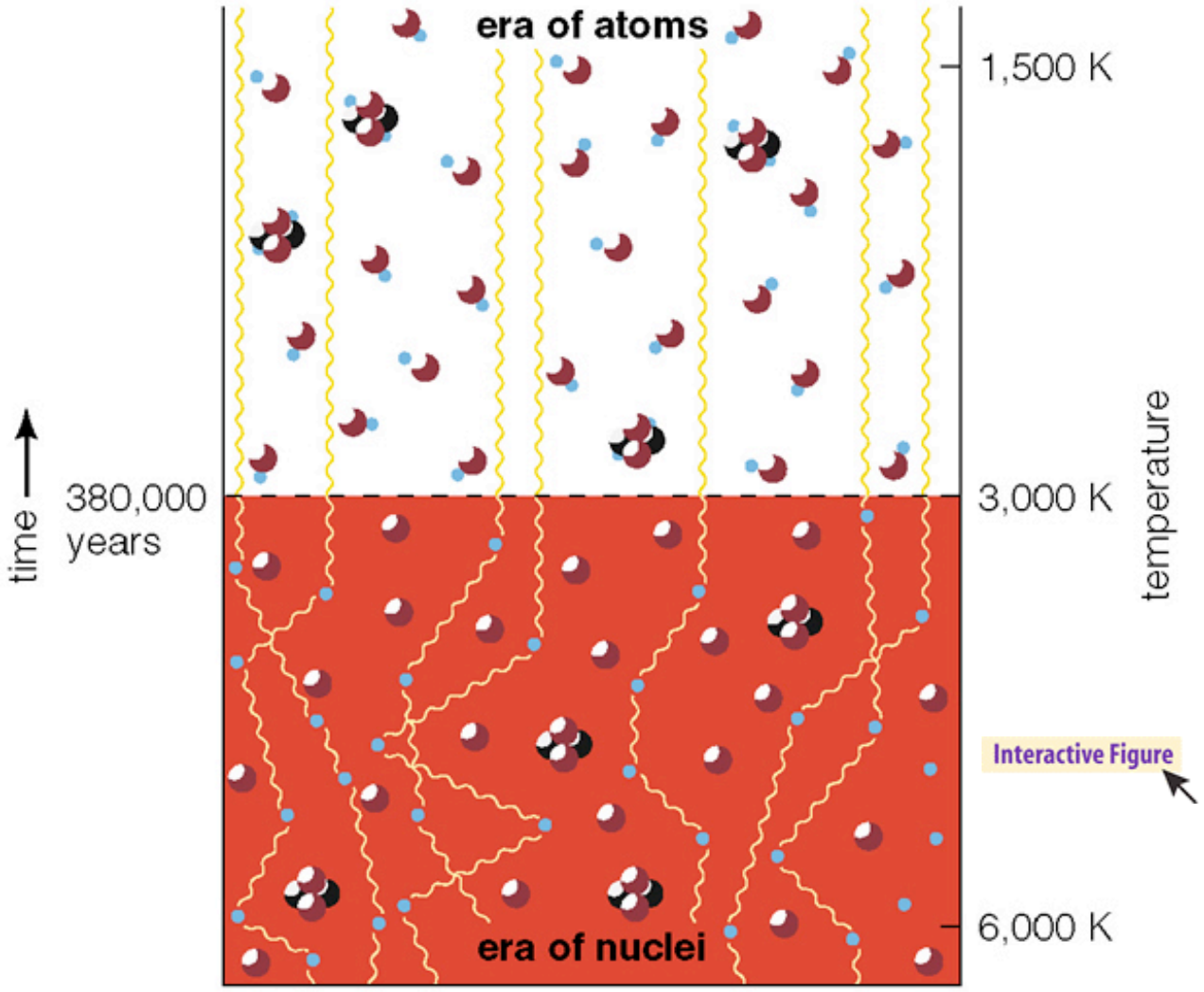
Abundances of other light elements agree with Big Bang model having 4.4% normal matter – *more evidence for WIMPS!*

Cosmic Background Radiation

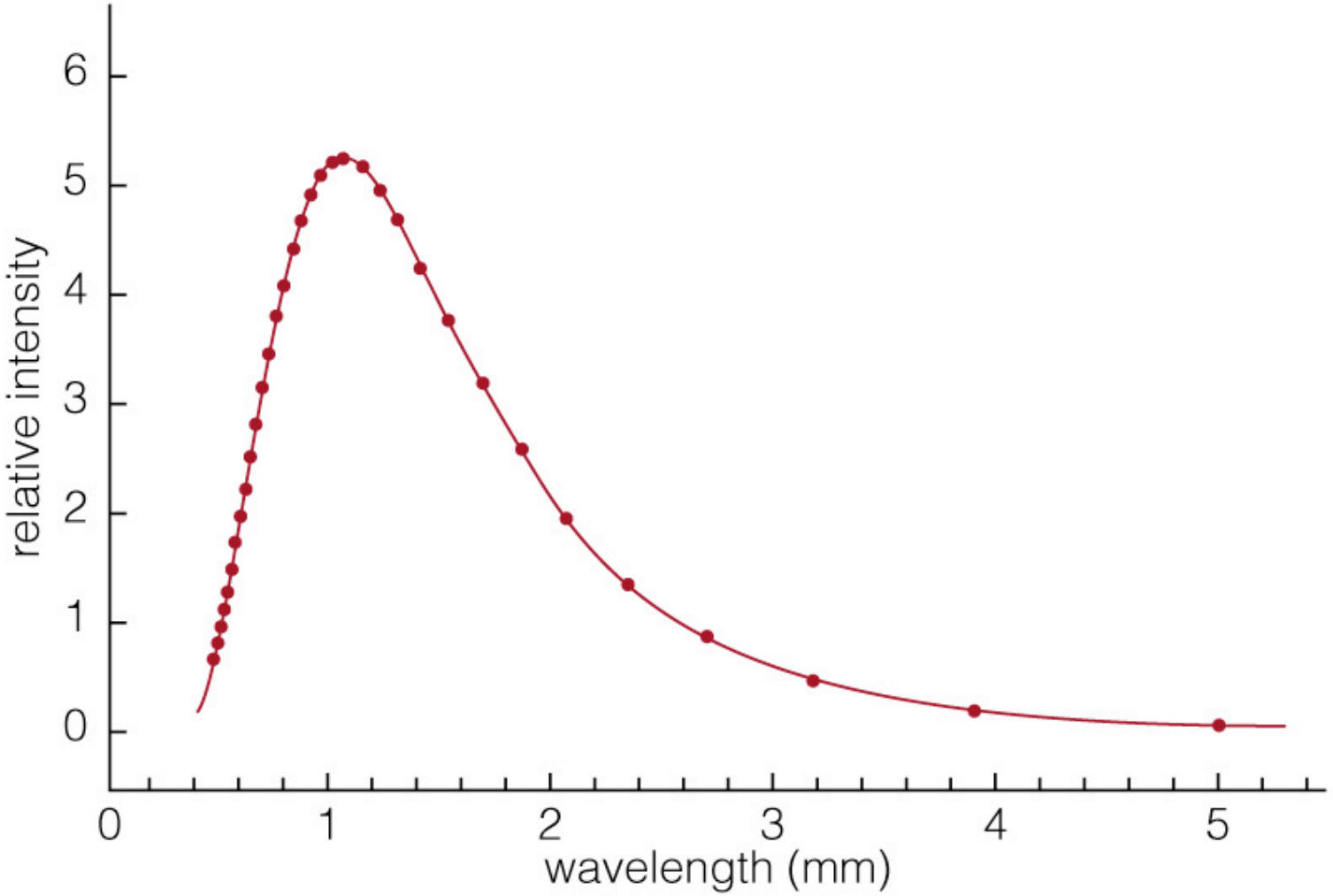


The ***cosmic microwave background*** – the radiation left over from the Big Bang – was detected by Penzias & Wilson in 1965
(Nobel Prize 1978)

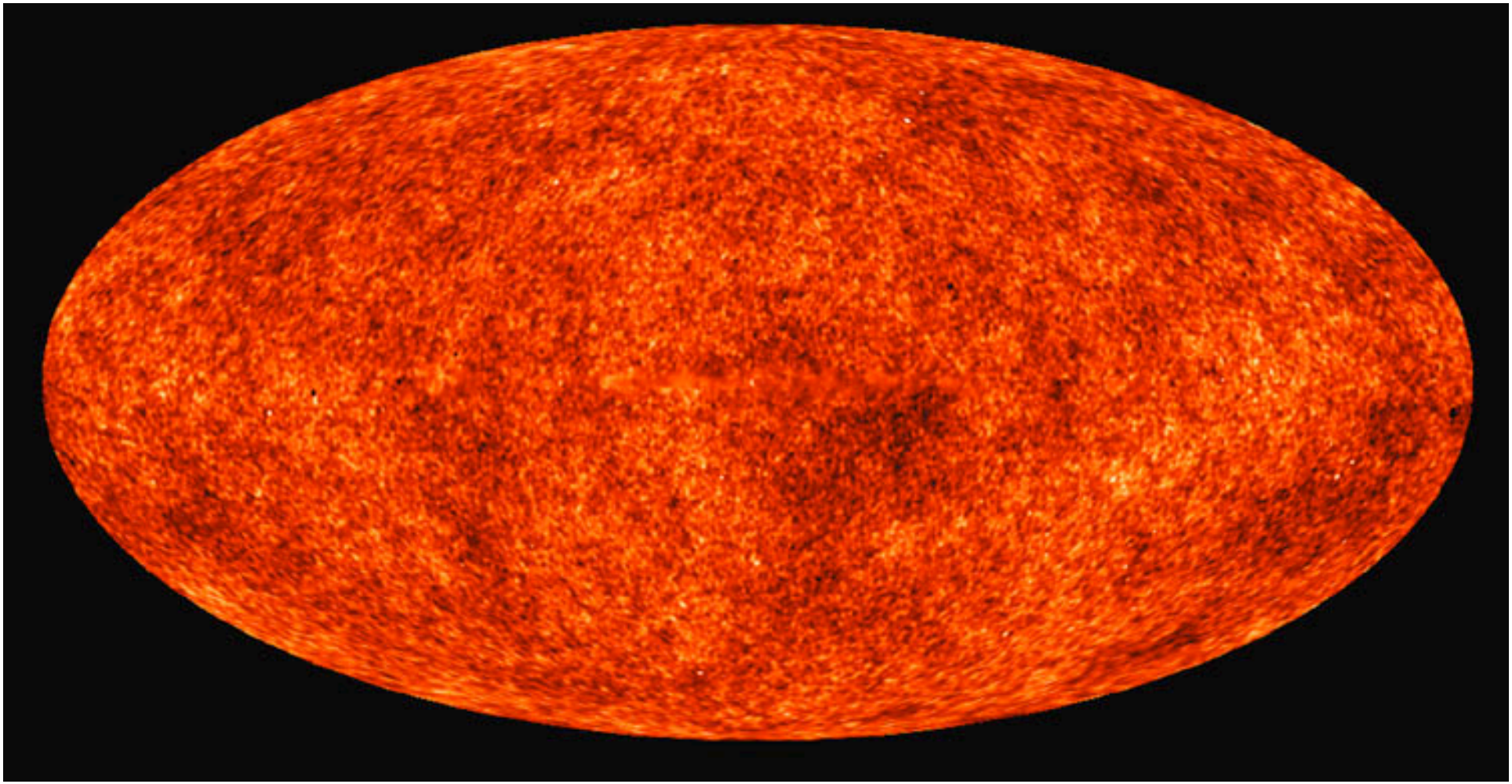




Background radiation from Big Bang has been freely streaming across universe since atoms formed at temperature ~ 3,000 K: *visible/IR*



Expansion of universe has redshifted thermal radiation from that time to ~1000 times longer wavelength: *microwaves*



WMAP gives us detailed baby pictures of structure in the universe

Primary Evidence

1) We have detected the leftover radiation from the Big Bang.

2) The Big Bang theory correctly predicts the abundance of helium and other light elements.

Three Mysteries about the Big Bang

1) Where does structure come from?

2) Why is the overall distribution of matter so uniform?

3) Why is the density of the universe so close to the critical density?

Mysteries Needing Explanation

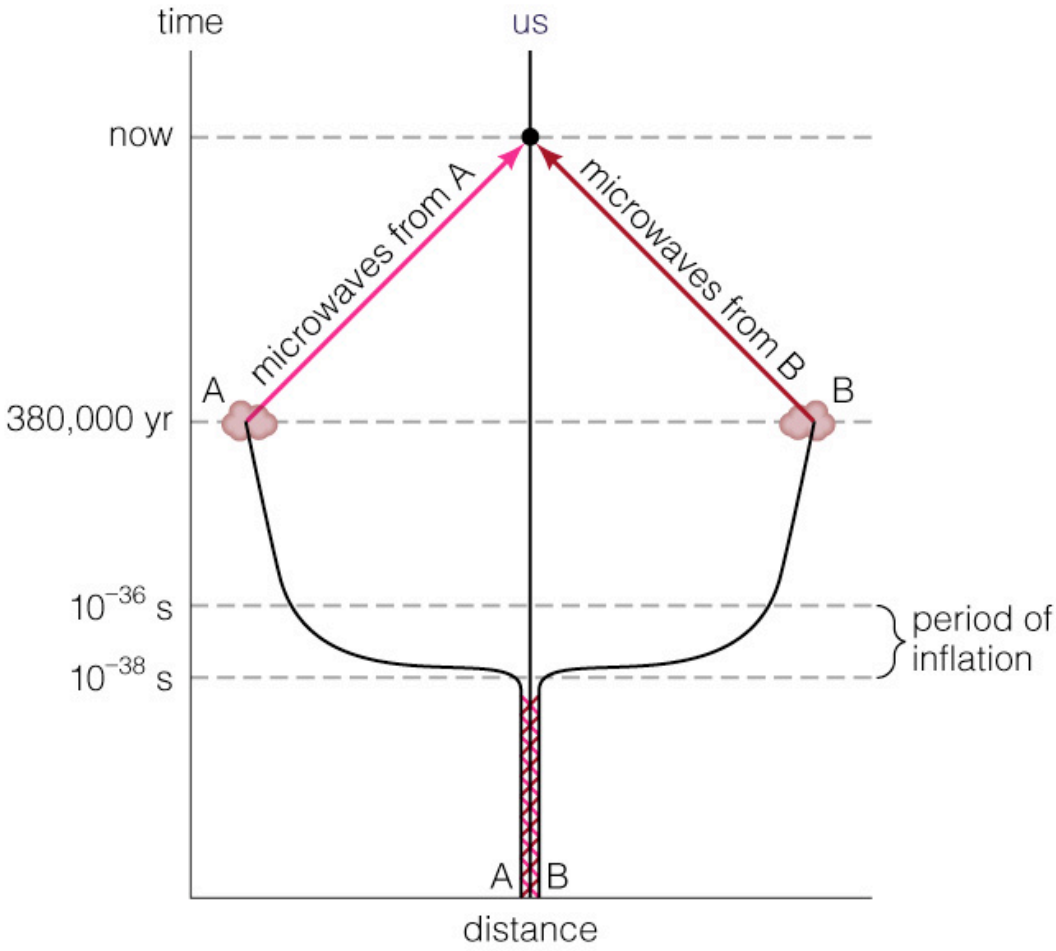
1) Where does structure come from?

2) Why is the overall distribution of matter so uniform?

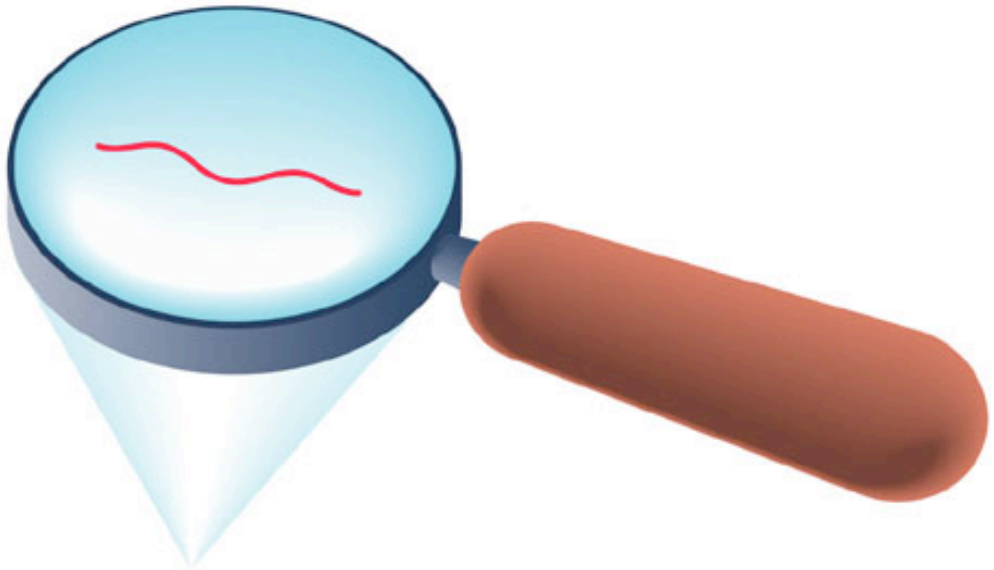
3) Why is the density of the universe so close to the critical density?

An early episode of rapid inflation can solve all three mysteries!

How does inflation explain these features?



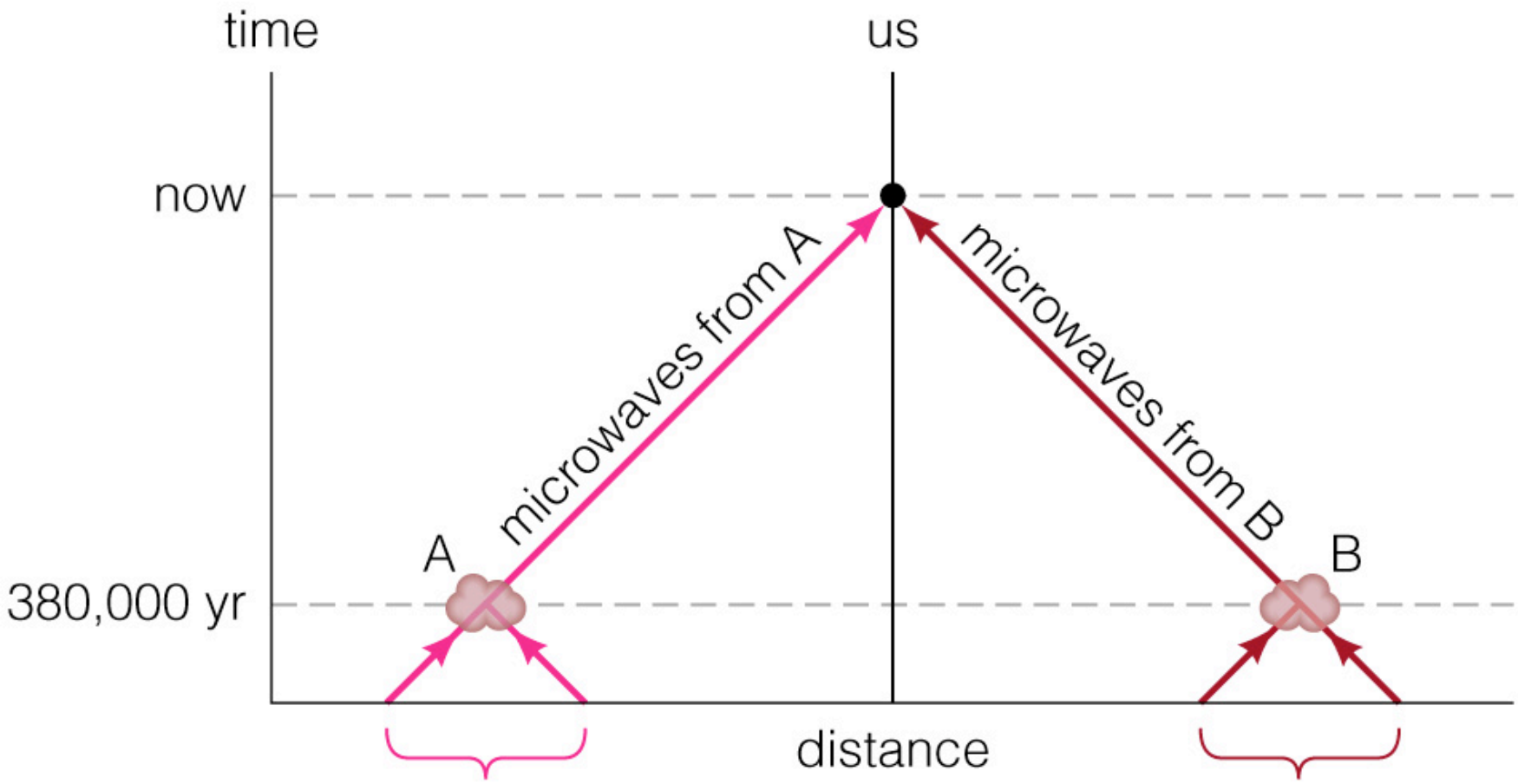
size of ripple before inflation = size of atomic nucleus



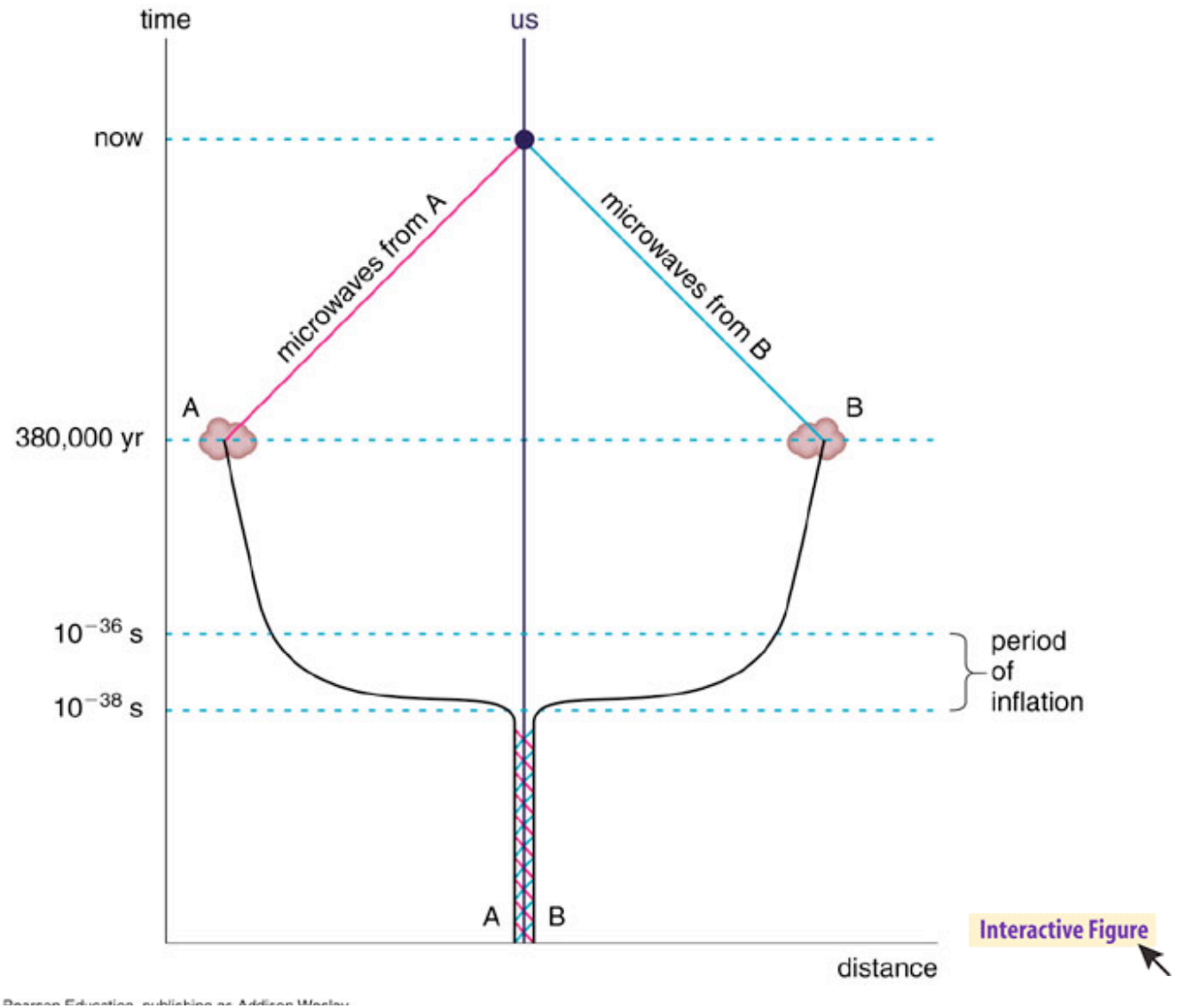
size of ripple after inflation = size of solar system

Inflation can make all the structure by stretching tiny quantum ripples to enormous size

These ripples in density then become the seeds for all structures

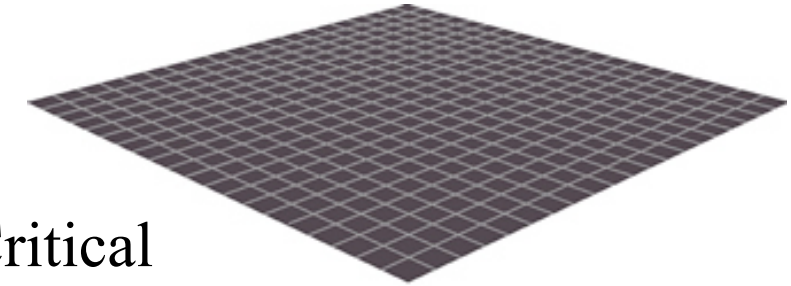


How can microwave temperature be nearly identical on opposite sides of the sky?



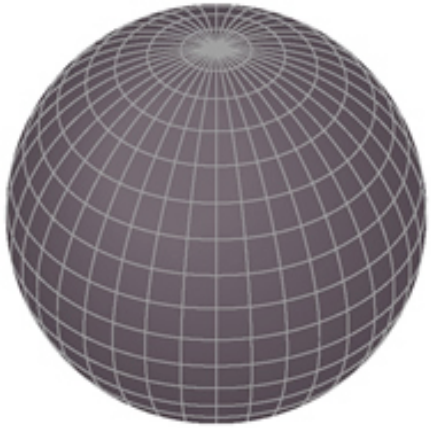
Regions now on opposite sides of the sky were close together before inflation pushed them far apart

Density = Critical



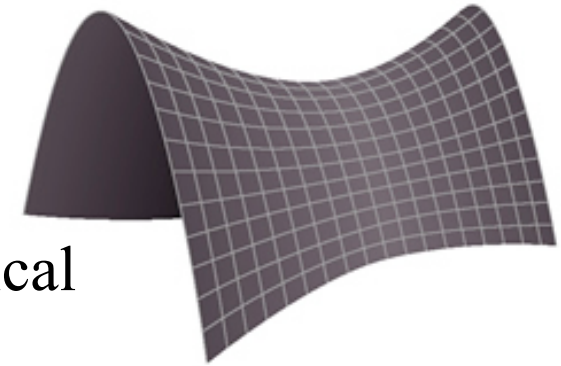
flat (critical) geometry

Density > Critical



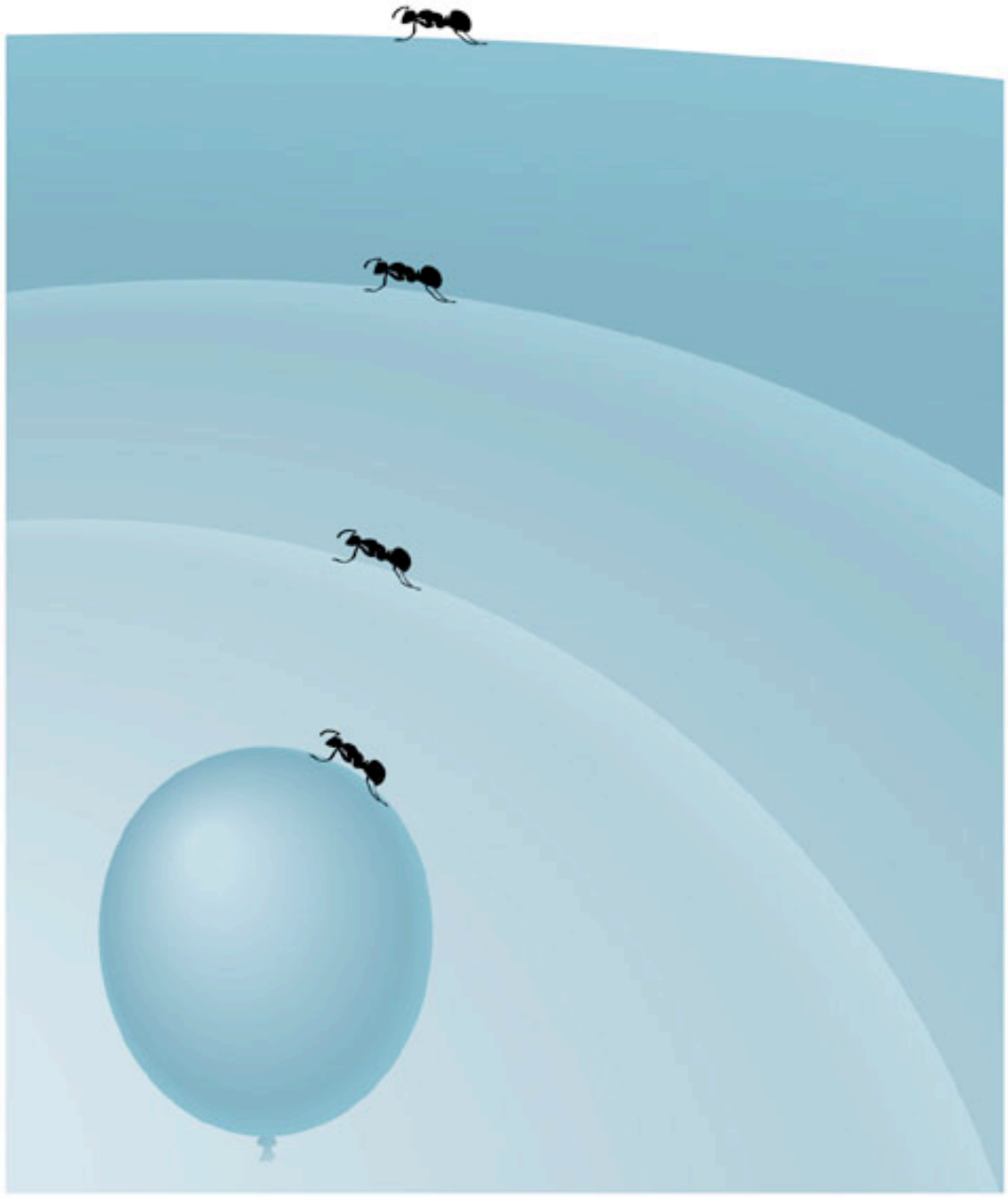
spherical (closed) geometry

Density < Critical



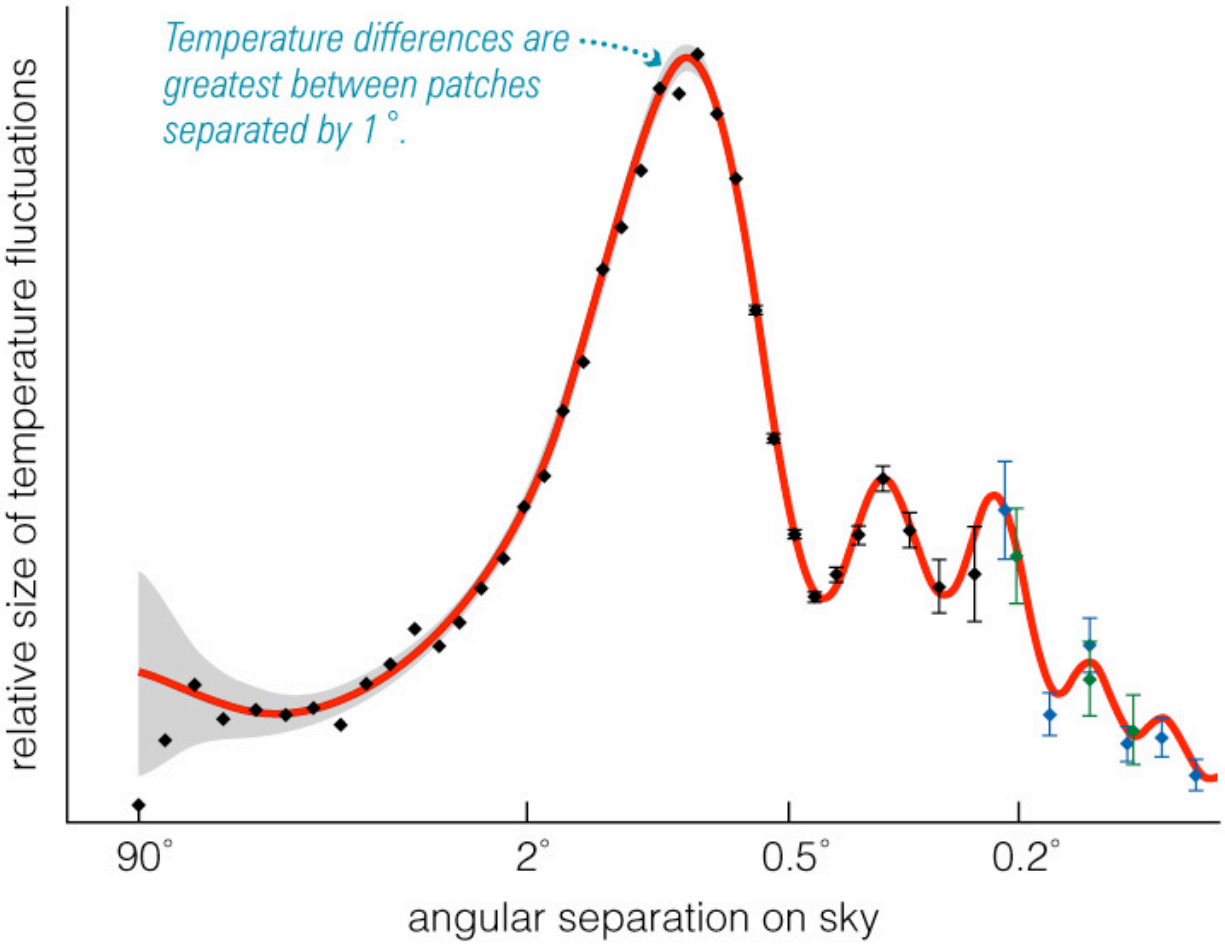
saddle-shaped (open) geometry

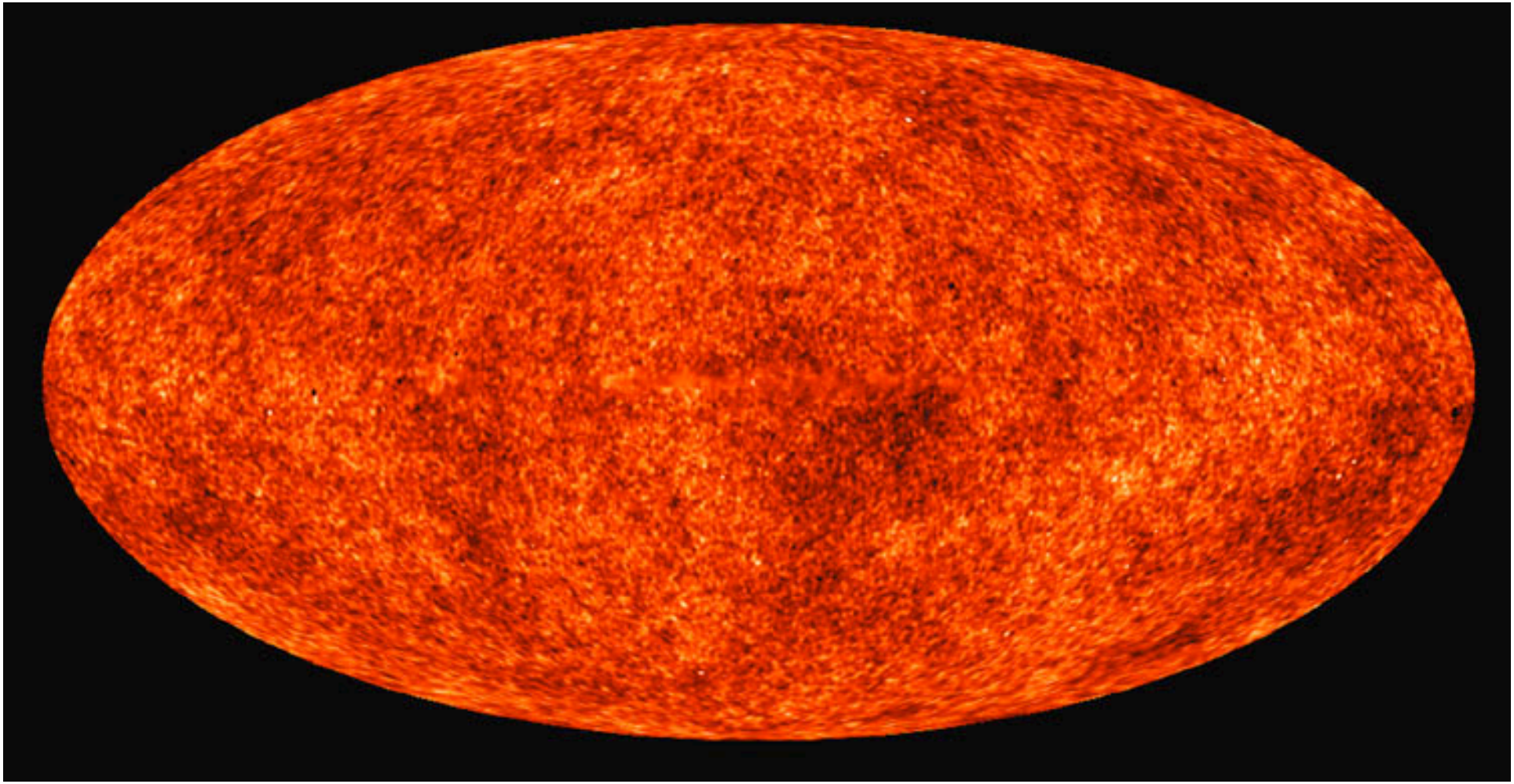
Overall geometry of the universe is closely related to total density of matter & energy



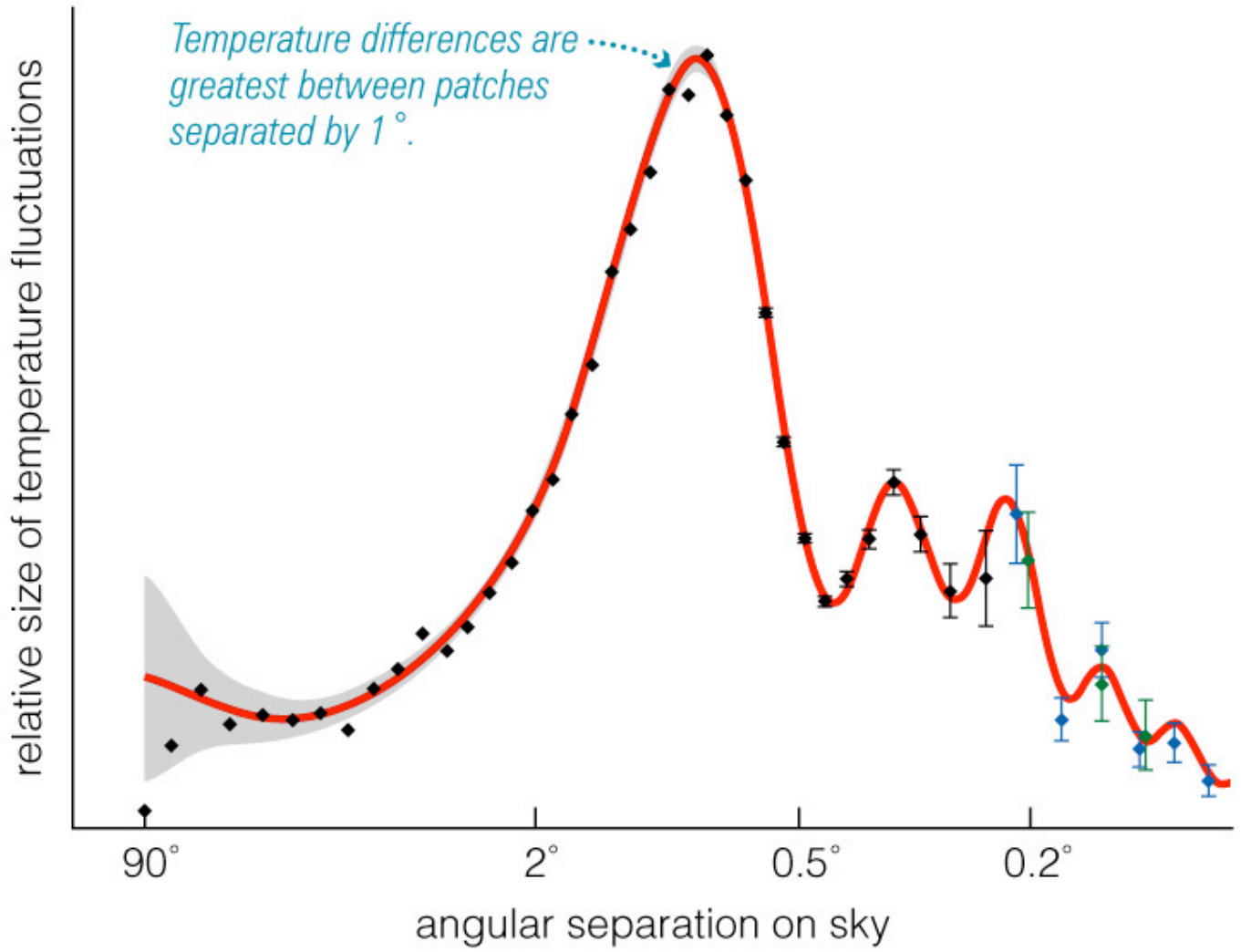
Inflation of universe flattens overall geometry like the inflation of a balloon, causing overall density of matter plus energy to be very close to critical density

How can we test the idea of inflation?





Patterns of structure observed by WMAP show us the "seeds" of universe



Observed patterns of structure in universe agree (so far) with the "seeds" that inflation would produce

“Seeds” Inferred from CMB

- Overall geometry is flat
  - Total mass+energy has critical density
- Ordinary matter ~ 4.4% of total
- Total matter is ~ 27% of total
  - Dark matter is ~ 23% of total
  - Dark energy is ~ 73% of total
- Age of 13.7 billion years

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- Ordinary matter ~ 4.4% of total
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  - Dark matter is ~ 23% of total
  - Dark energy is ~ 73% of total
- Age of 13.7 billion years

In excellent agreement with observations of present-day universe and models involving inflation and WIMPs!

What have we learned?

- What aspects of the universe were originally unexplained with the Big Bang theory?
  - The origin of structure, the smoothness of the universe on large scales, the nearly critical density of the universe
- How does inflation explain these features?
  - Structure comes from inflated quantum ripples
  - Observable universe became smooth before inflation, when it was very tiny
  - Inflation flattened the curvature of space, bringing expansion rate into balance with the overall density of mass-energy

Why is the darkness of the night sky evidence for the Big Bang?

Olbers' Paradox

If universe were

1) infinite

2) unchanging

3) everywhere the same

Then, stars would cover the night sky

Olbers' Paradox

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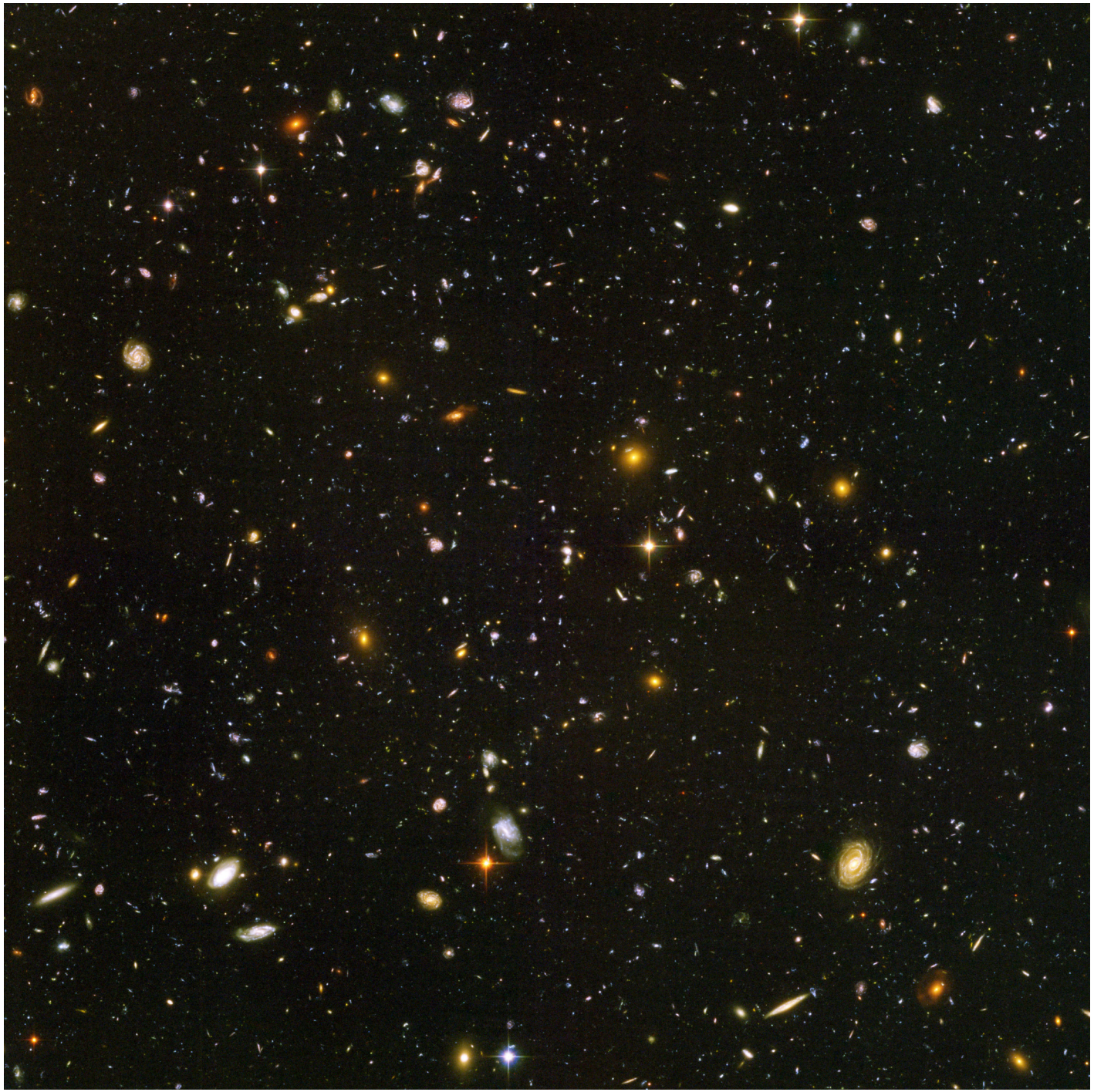
Night sky is dark because the universe changes with time

As we look out in space, we can look back to a time when there were no stars



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