The Beginning of the Universe: The Big Bang

Chapter 22

Midterm 3 is June 12

- Midterm on June 12 2025
- multi-choice and text questions

- Covers material through (lectures 19-26)
  - **Special Relativity** (S2), **General Relativity** (S3),
  - **Milky Way, Galaxies and Galaxies evolution** (Ch 19-20-21)
  - **The Big Bang** (Ch 22) **Dark Energy, Dark matter and acceleration** (Ch 23)
- Exam is not cumulative, but much of this material builds on what we learned in the first 1/3rd of the course

Recap of last time: Galaxy Evolution

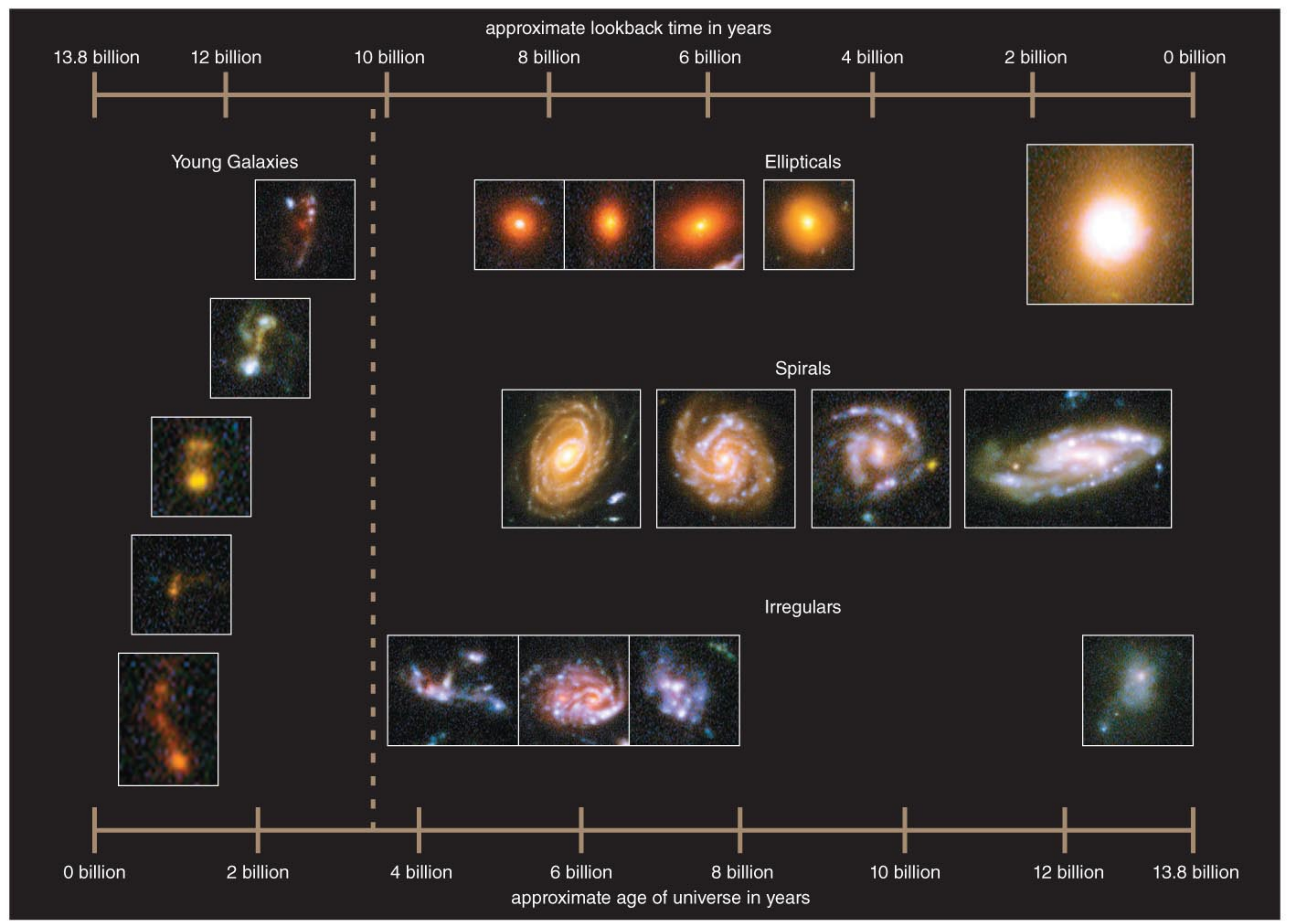
Galaxies grow and evolve over time. We can observe this process by studying distant galaxies.

(“Time Machine”: large distance means we see back in time, due to finite speed of light!)

The very short version:

- Galaxies start as mostly gas
- Stars form out of gas
  - And create new, heavier elements
- Galaxies end up as mostly stars

The process of star formation and evolution fundamentally changes galaxies

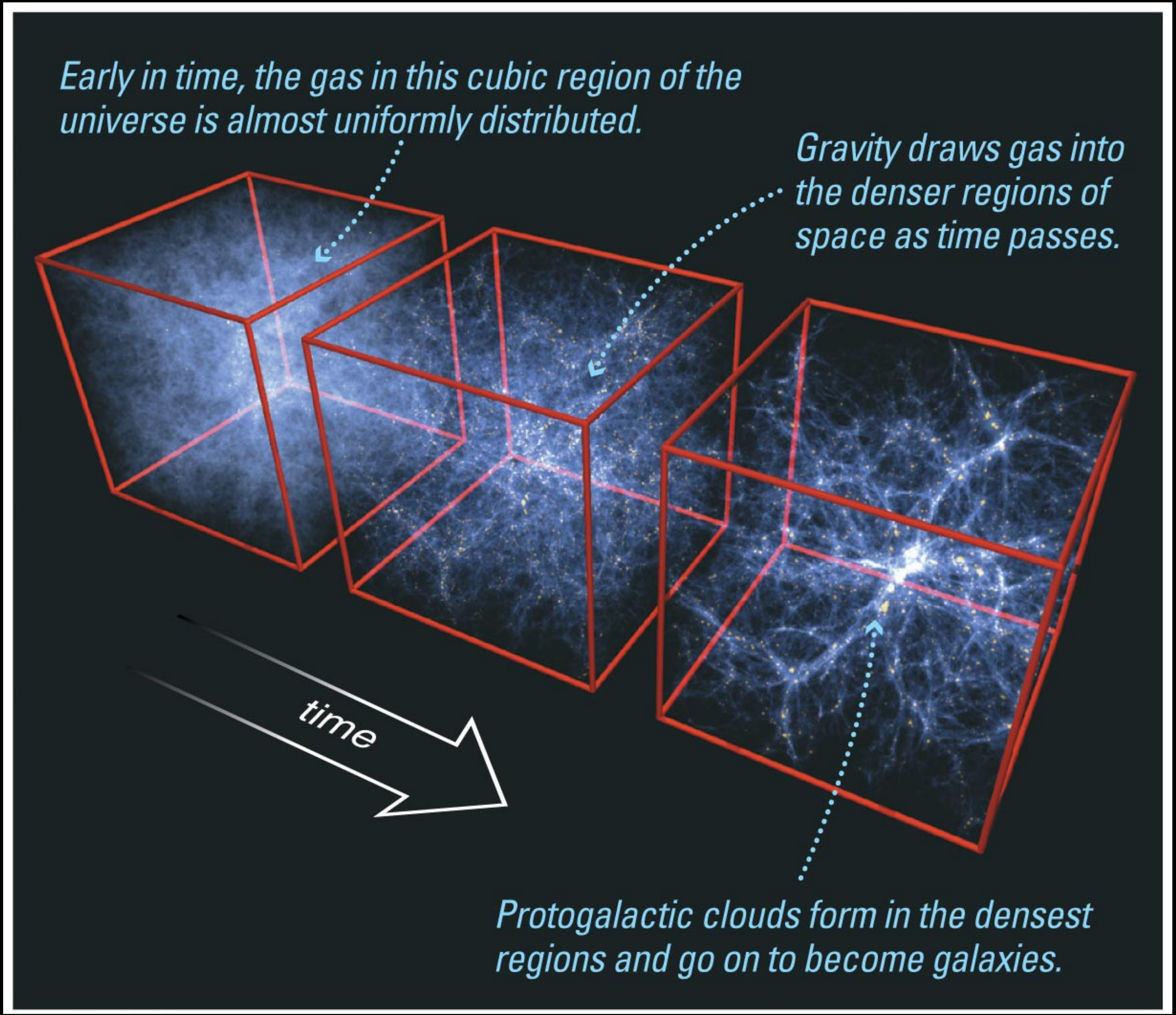


← Big Bang Today→

The Hubble Ultra-Deep Field: Generations of galaxies in formation (reaching 13 billion years ago!)

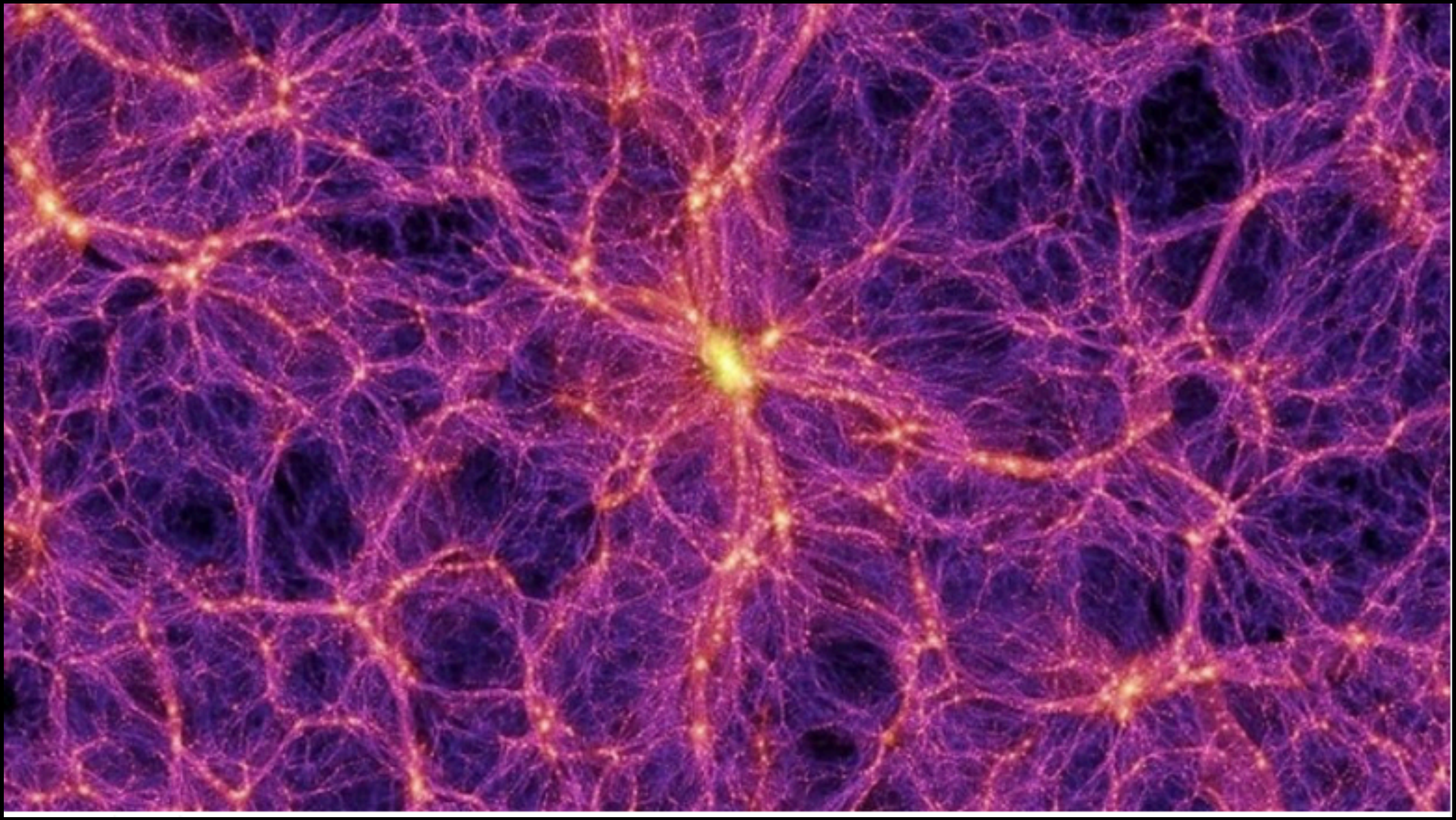
How did galaxies start out?

- H and He filled space more or less uniformly ~1 million years after Big Bang
- However, uniformity was not perfect
- Galaxies began to form in regions of slightly higher density
  - Greater pull of gravity in these regions attracts matter (slowing, and reversing, the overall expansion)
  - This matter began to contract into protogalactic clouds which eventually form galaxies



Early in time, the gas in this cubic region of the universe is almost uniformly distributed.
Gravity draws gas into the denser regions of space as time passes.
time
Protogalactic clouds form in the densest regions and go on to become galaxies.

the “cosmic web”



the structure of our universe.

https://apod.nasa.gov/apod/ap120813.html

Infall of gas from the "cosmic web"

- Galaxies continue to form stars
  - Just enough gas in galaxy disks today to form stars for a few billion years
  - Fresh gas must keep it going
- Fraction of heavy elements (not H or He) in stars is lower than expected
  - Fresh Hydrogen must be flowing in
  - Gas is also ejected from galaxies, by supernova explosions and other effects

Putting it all together:
computer simulations of galaxies over time

Pleiades Supercomputer

Galaxy simulation movie: what to look for

- Starts out as all gas, and no stars
- At the beginning, gas is almost the same density everywhere
  - H and He filled space more or less uniformly ~1 million years after Big Bang

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  - Galaxies! They start forming stars
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Galaxy simulation movie: what to look for

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  - Galaxies! They start forming stars
  - Gas continues to flow in from the "cosmic web"
  - Gas also gets ejected (mostly by supernova)
- At first, galaxies are small and **irregular**, and they frequently collide ("merge")
- Regular spiral disk galaxy does not emerge until about halfway through

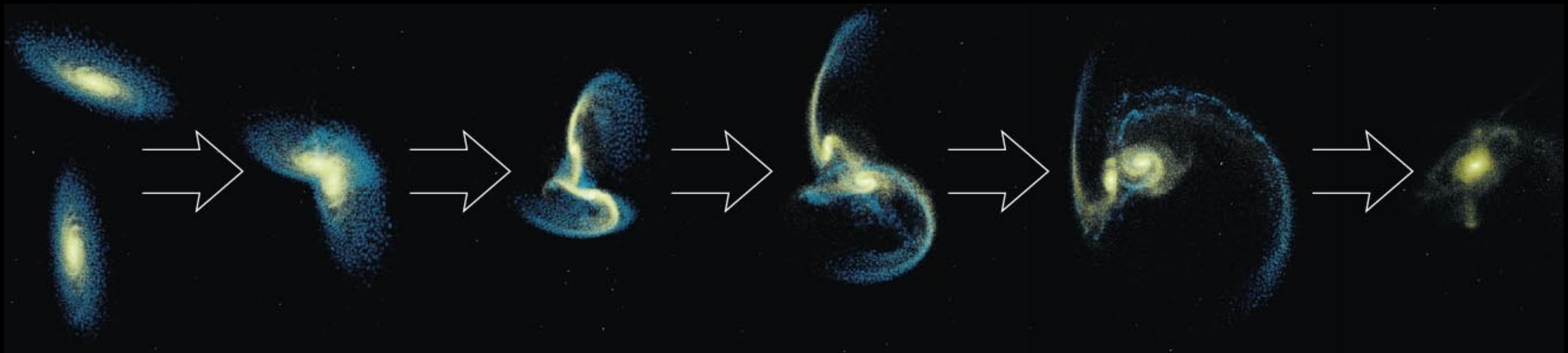
The formation of galaxies

Protogalactic cloud birth condition may be responsible of the type of galaxy we see today

Protogalactic cloud with low angular momentum will not flat producing elliptical galaxies

Protogalactic cloud with high density gas may use all the gas to quickly form stars before flattening

Some of the elliptical galaxies today are probably coming from the collision of spiral galaxies



Recap: what have we learned?

- **How do we observe the histories of galaxies?**
  - Light takes a long time to reach us from distant galaxies
  - By looking at galaxies at different distances, we see them at different ages
  - We can see galaxies as far back as ~13 billion years ago!
- **How do we study galaxy formation?**
  - We observe how galaxies change over time, and use our knowledge of physics to construct models for how they behave
  - We can run these models on supercomputers, and compare them with actual galaxies

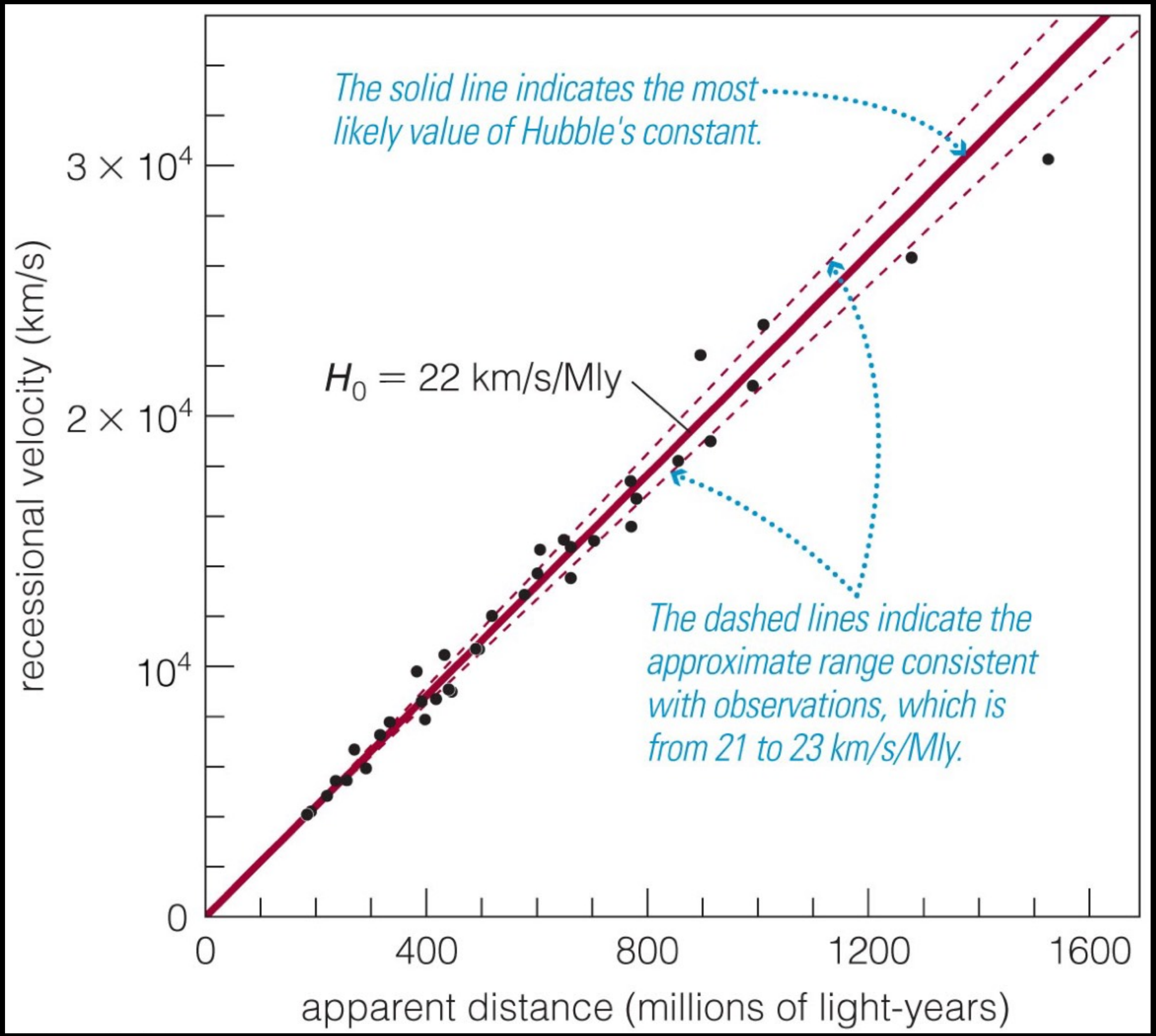
The Big Bang and the Beginning of the Universe

Chapter 22

Questions of the day

- What were physical conditions like in the early Universe?
- How did the early Universe change with time?

Recap: Hubble's Law



Distant galaxies appear to be moving away from us.
Hubble's Law:
$v = H_0 \times D$

We understand this as an expansion of space.

- The Universe was smaller yesterday
  - And smaller the day before
  - Et cetera

About 14 billion years ago, the Universe was an infinitely small point!

The beginning of the Universe: we call this the **BIG BANG!**

Extrapolating into the past: the Big Bang

What happens to the Universe if it is compressed?

What happens to matter if it is compressed?

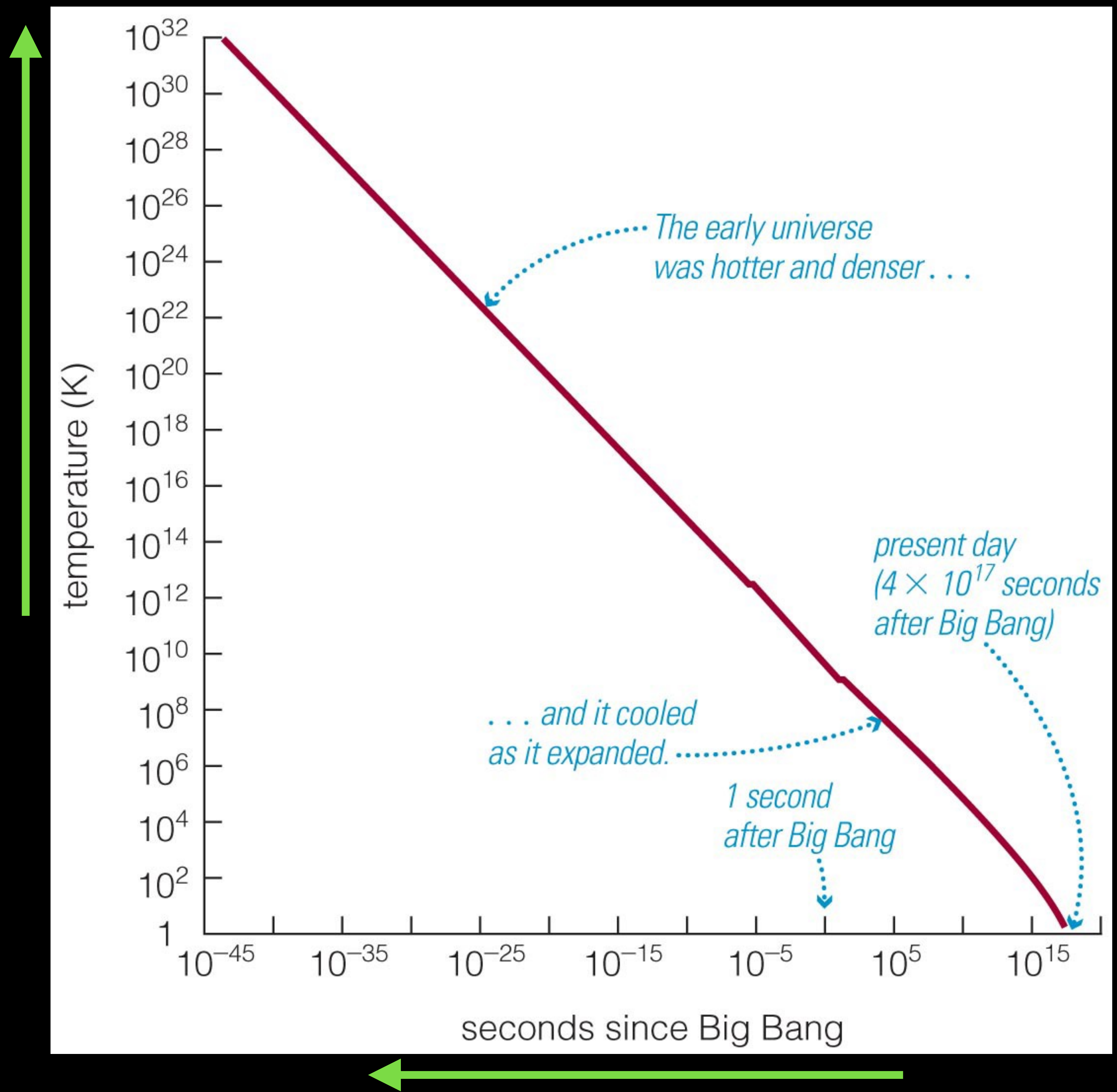
- It heats up!
- What would be the observable consequences of this?

Extrapolating into the past: the Big Bang

The early Universe:

- Smaller!
- Denser!
- Hotter!

Temperature



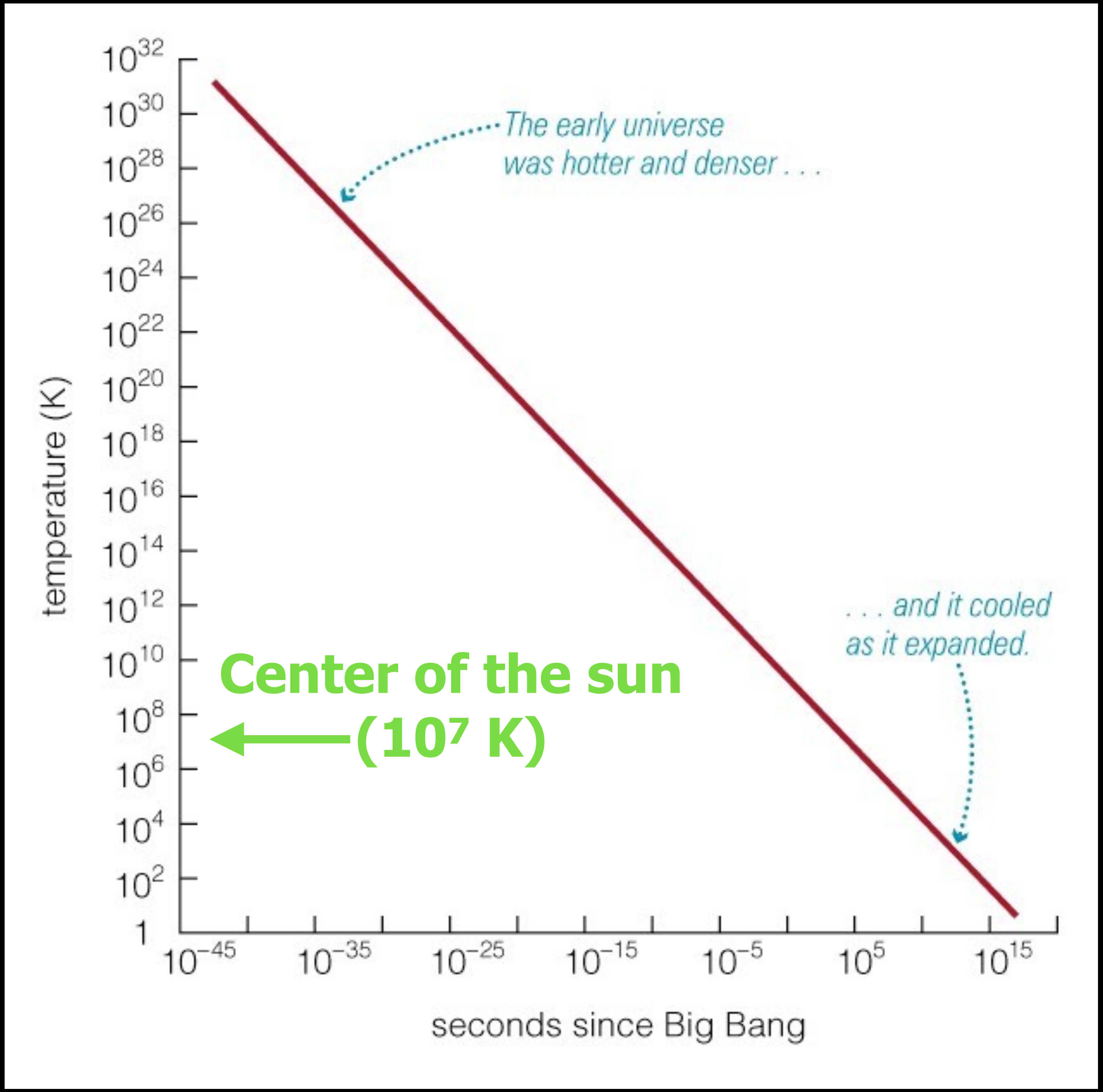
Looking back in time

The "Hot Big Bang"

What happens to the Universe if it is compressed?

What happens to matter if it is compressed?

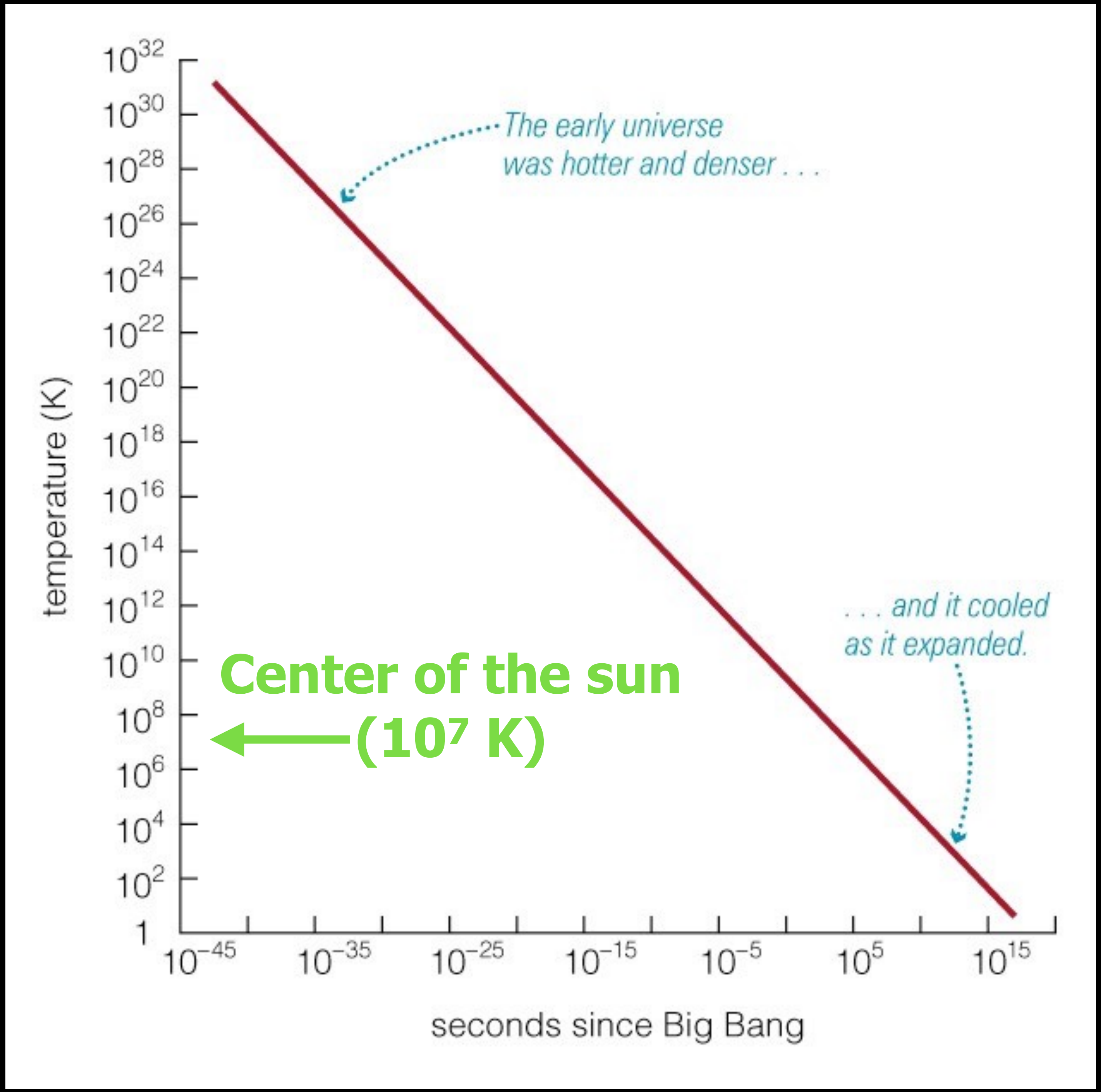
- It heats up!
- What would be the observable consequences of this?



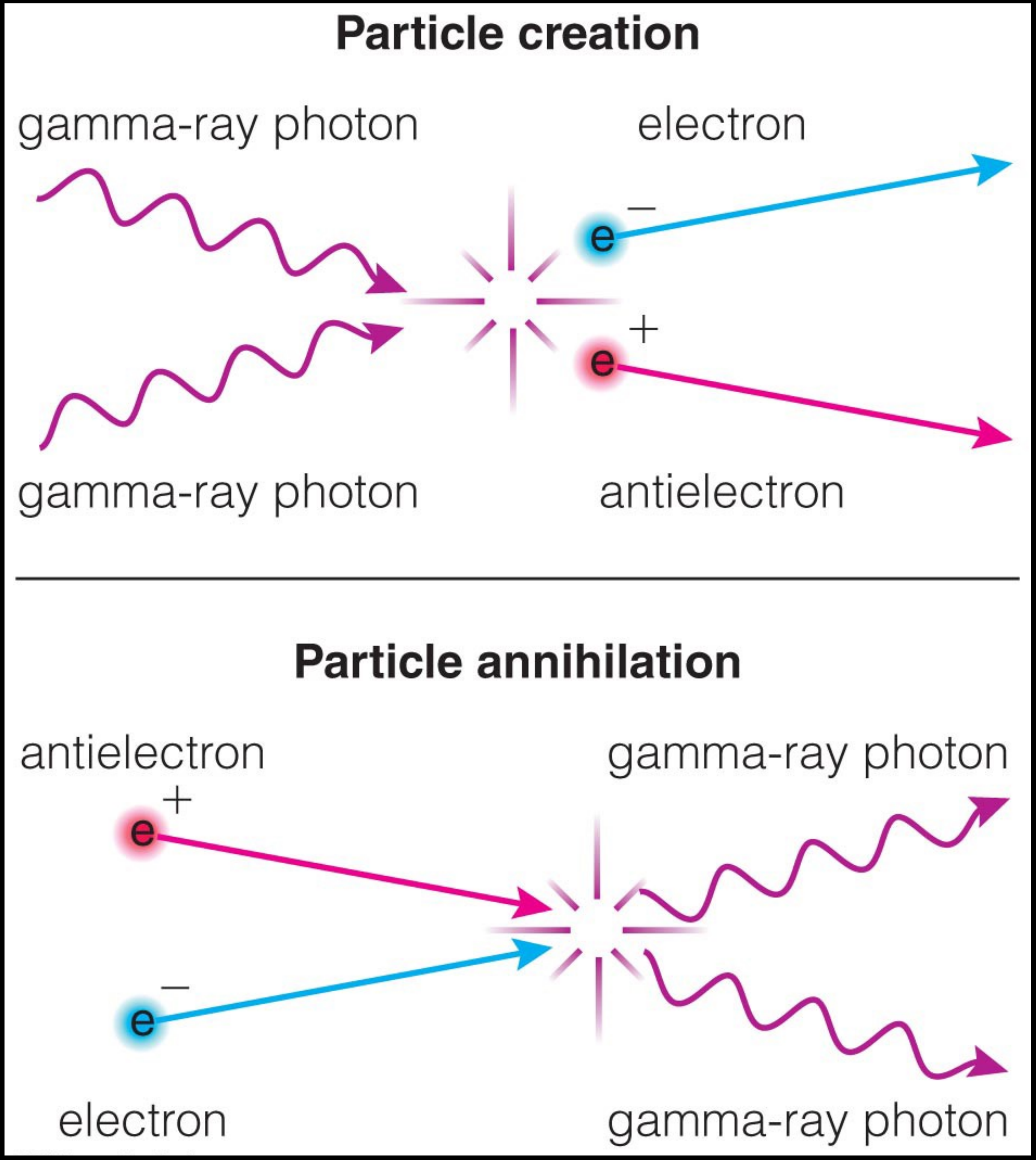
The "Hot Big Bang"

The Universe was smaller, denser, and hotter in the past.
What happens when you heat matter?

- Solid
- Liquid
- Gas
- Plasma (ionized atoms and free electrons)
- Nuclei ripped apart (protons, neutrons, electrons)
- Protons & neutrons ripped apart ("quark-gluon plasma", lots of antimatter)
- …



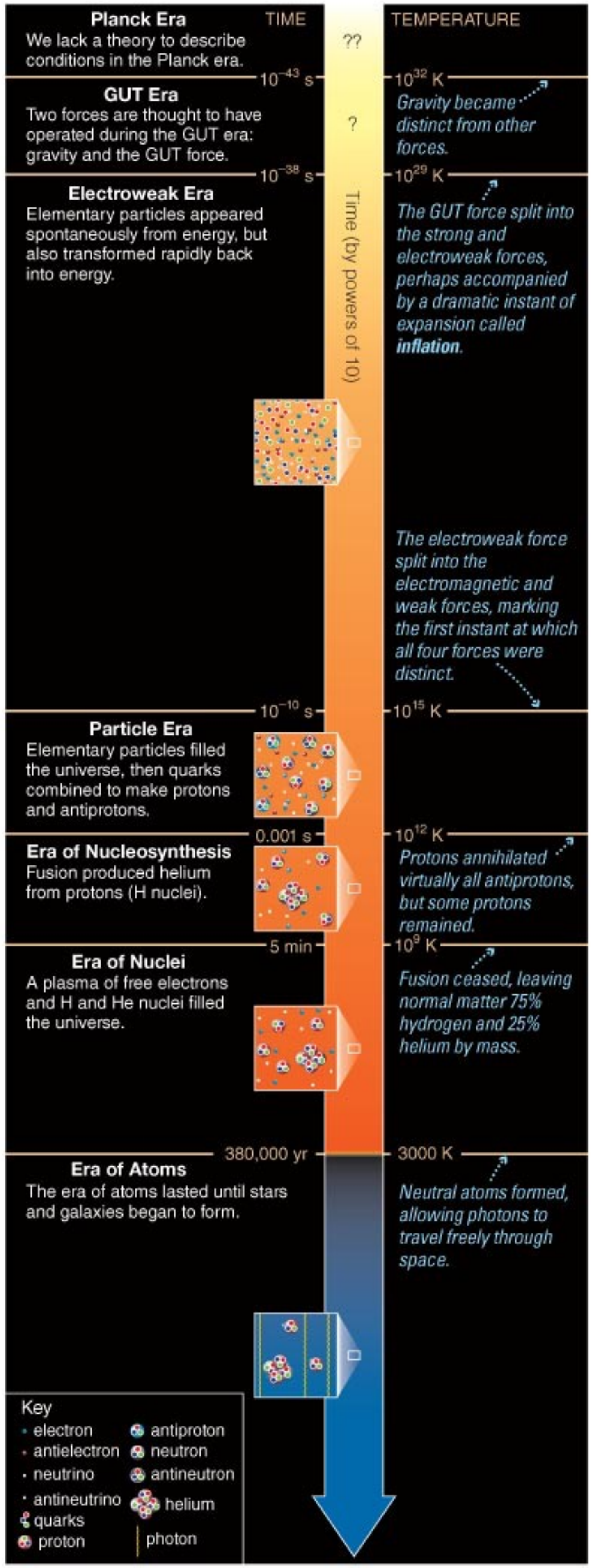
Very high temperatures at early times

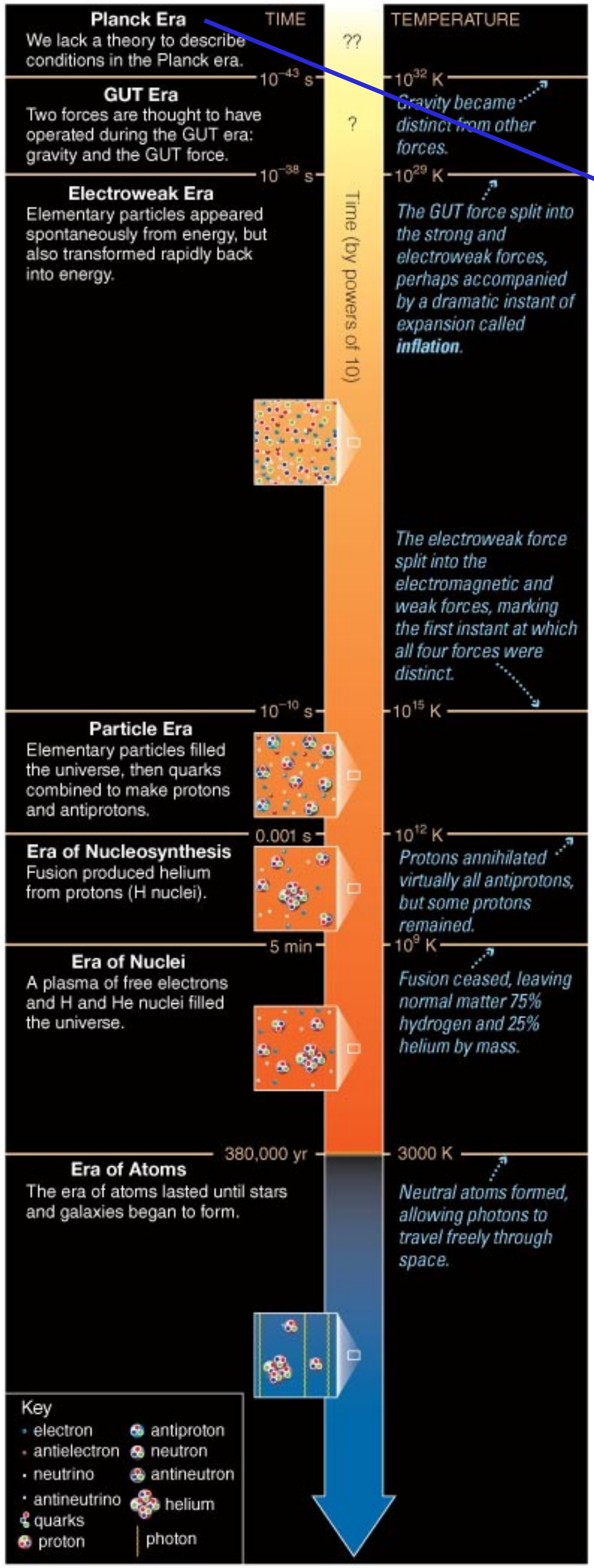


Recall thermal radiation: higher temperature = bluer = photons with higher energy

- Photon energy **E = hf**, and particle mass-energy **$E = mc^2$**
- When photons collide, their energy is so large that they create new particles and **anti**particles (antimatter!)
- Matter and antimatter collide and annihilate, creating high-energy photons

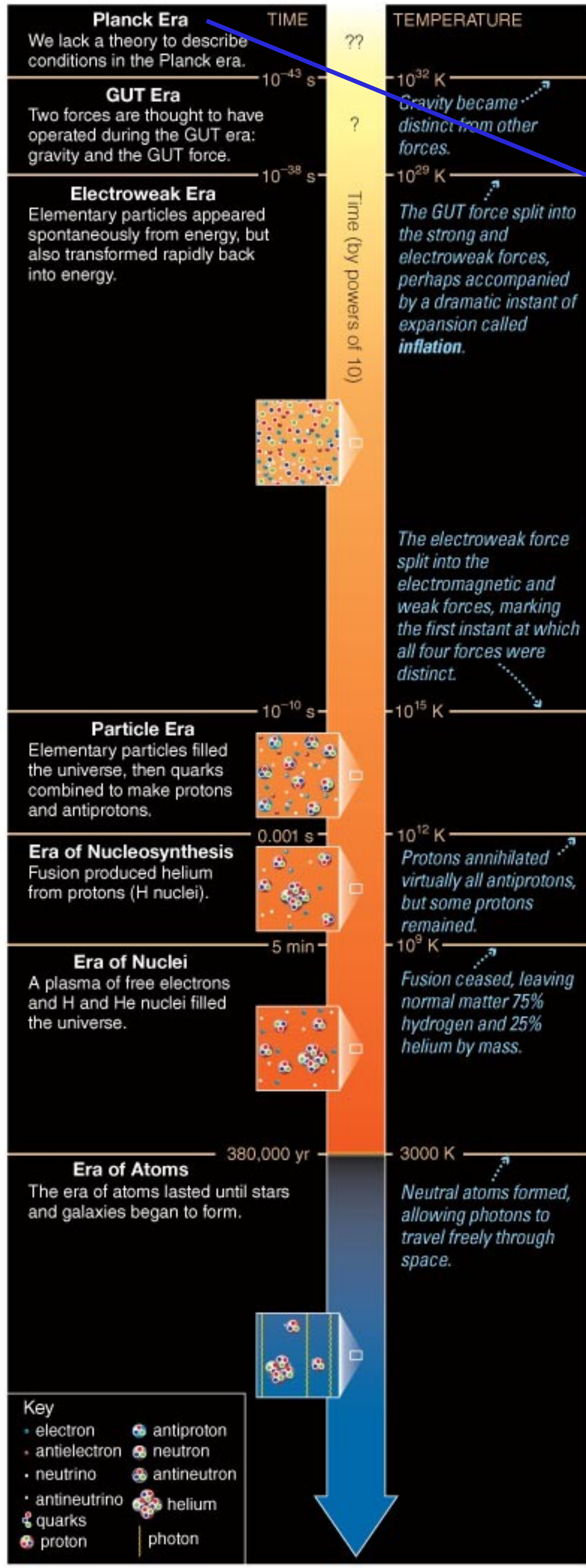
The **hot** early universe was full of energetic photons, matter, and antimatter!


Planck Era
We lack a theory to describe conditions in the Planck era.
TIME
??
TEMPERATURE
10^{-43} s
10^{32} K
GUT Era
Two forces are thought to have operated during the GUT era: gravity and the GUT force.
?
Gravity became distinct from other forces.
10^{-38} s
10^{29} K
Electroweak Era
Elementary particles appeared spontaneously from energy, but also transformed rapidly back into energy.
Time (by powers of 10)
The GUT force split into the strong and electroweak forces, perhaps accompanied by a dramatic instant of expansion called **inflation**.
The electroweak force split into the electromagnetic and weak forces, marking the first instant at which all four forces were distinct.
10^{-10} s
10^{15} K
Particle Era
Elementary particles filled the universe, then quarks combined to make protons and antiprotons.
0.001 s
10^{12} K
Era of Nucleosynthesis
Fusion produced helium from protons (H nuclei).
Protons annihilated virtually all antiprotons, but some protons remained.
5 min
10^{9} K
Era of Nuclei
A plasma of free electrons and H and He nuclei filled the universe.
Fusion ceased, leaving normal matter 75% hydrogen and 25% helium by mass.
380,000 yr
3000 K
Era of Atoms
The era of atoms lasted until stars and galaxies began to form.
Neutral atoms formed, allowing photons to travel freely through space.
Key
electron
antielectron
neutrino
antineutrino
quarks
proton
antiproton
neutron
antineutron
helium
photon



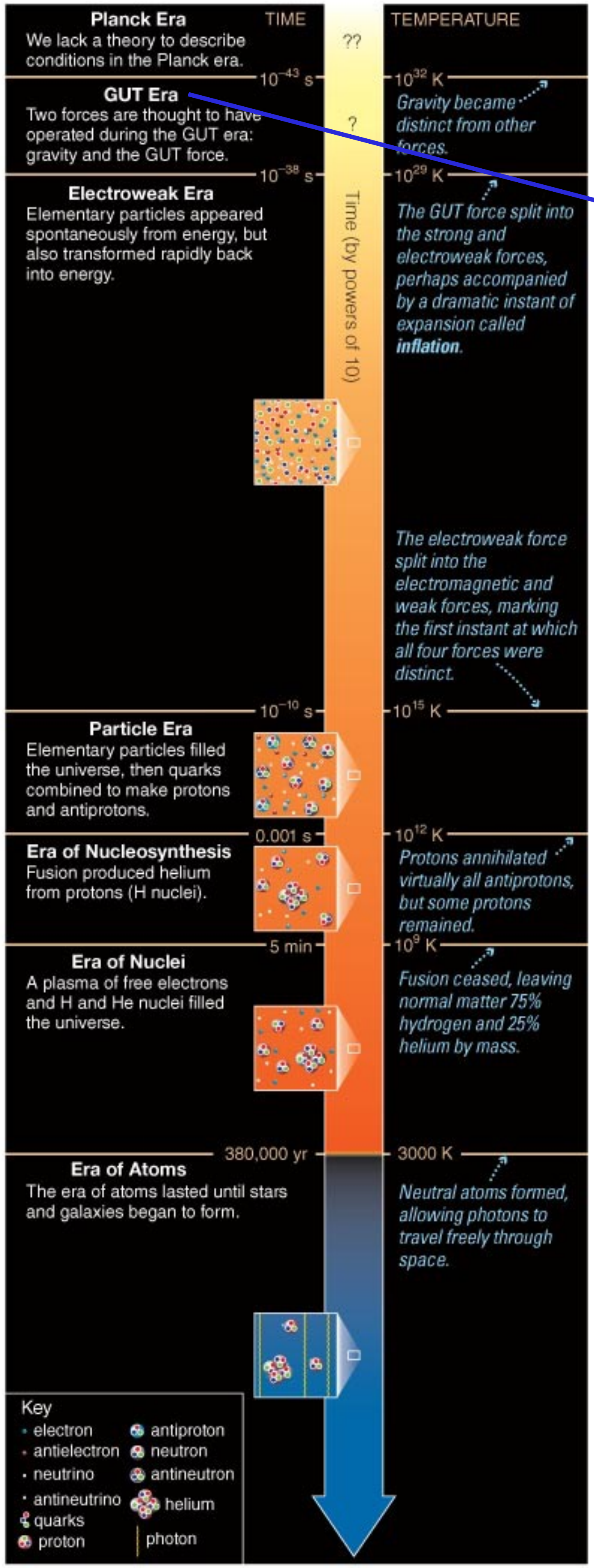
Planck era

- Before Planck time ($\sim 10^{-43}$ second)
- No theory of quantum gravity
- We don't know what happens at this time! No physical theory!



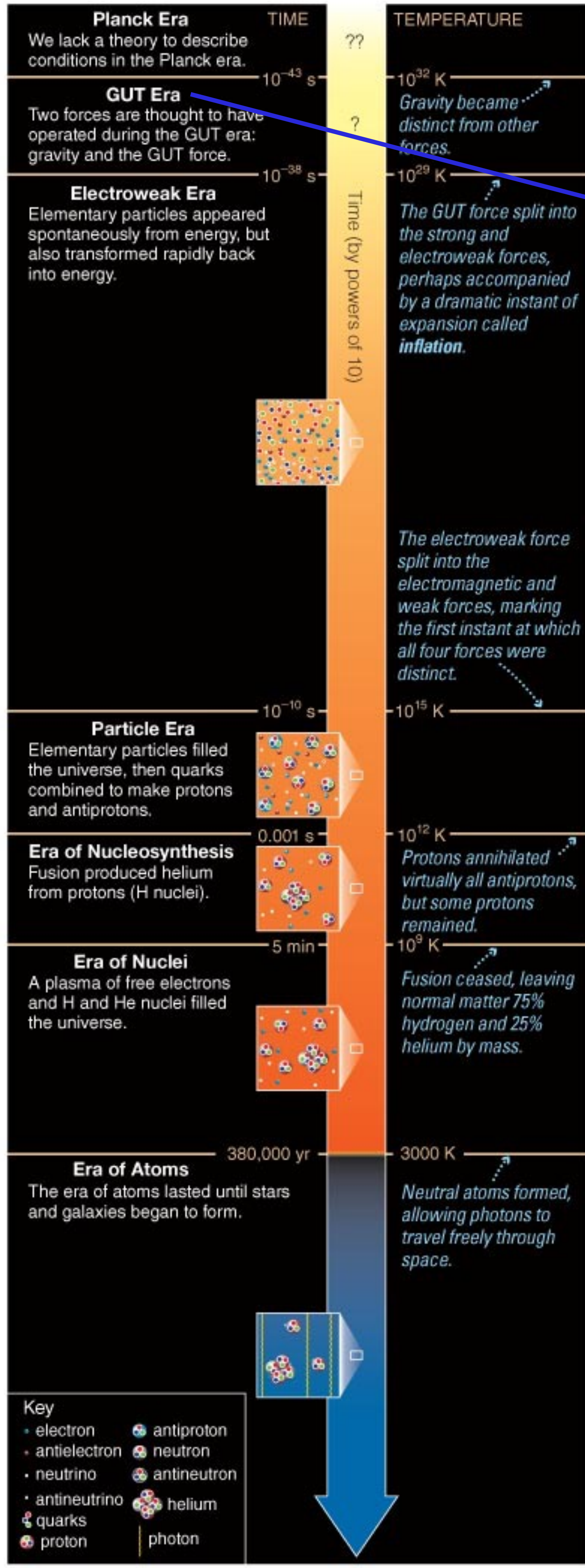
Planck era

- Before Planck time ($\sim 10^{-43}$ second)
- No theory of quantum gravity
- We don't know what happens at this time! No physical theory!
- substantial energy fluctuations that may have produced primordial gravitational waves



GUT era

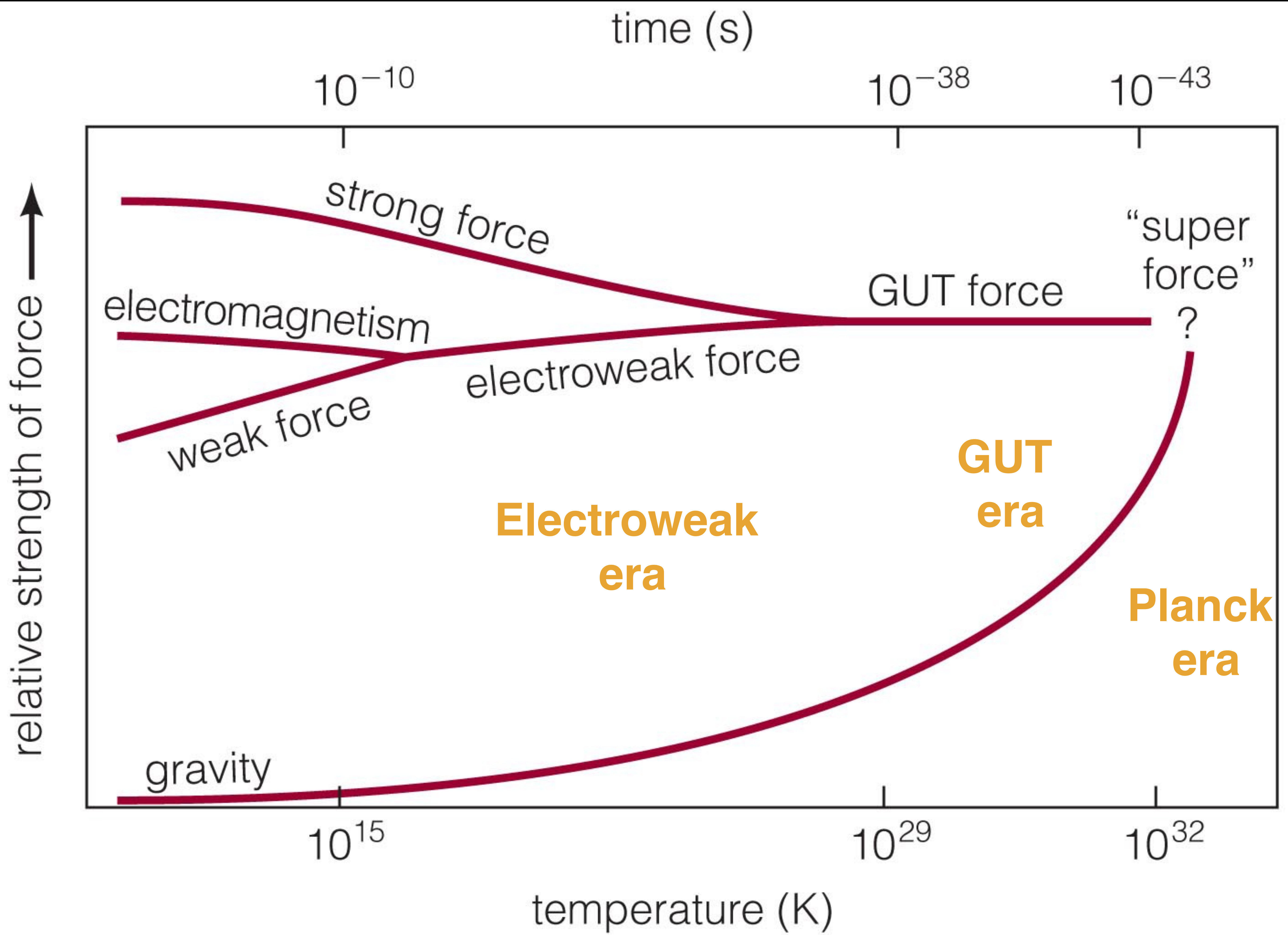
- Lasts from Planck time (~10^{-43} second) to end of GUT force (~10^{-38} second)

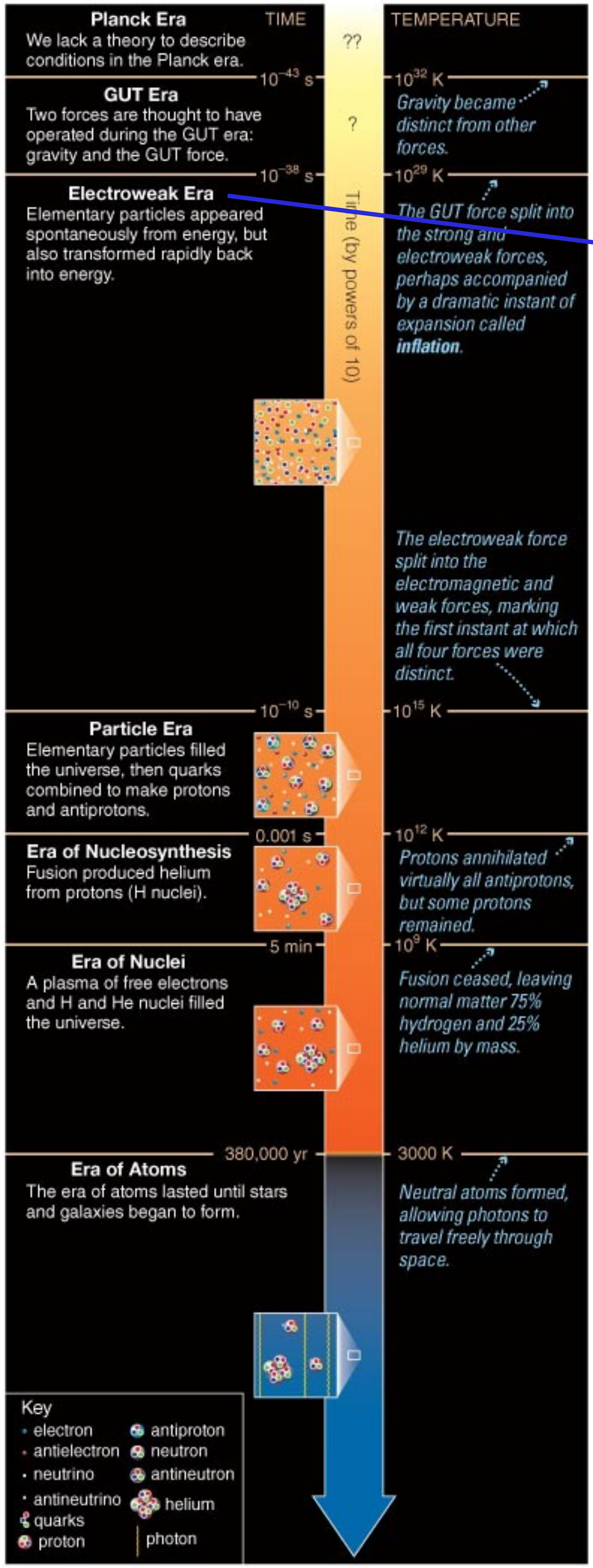


GUT era

- Lasts from Planck time (~10^{-43} second) to end of GUT force (~10^{-38} second)

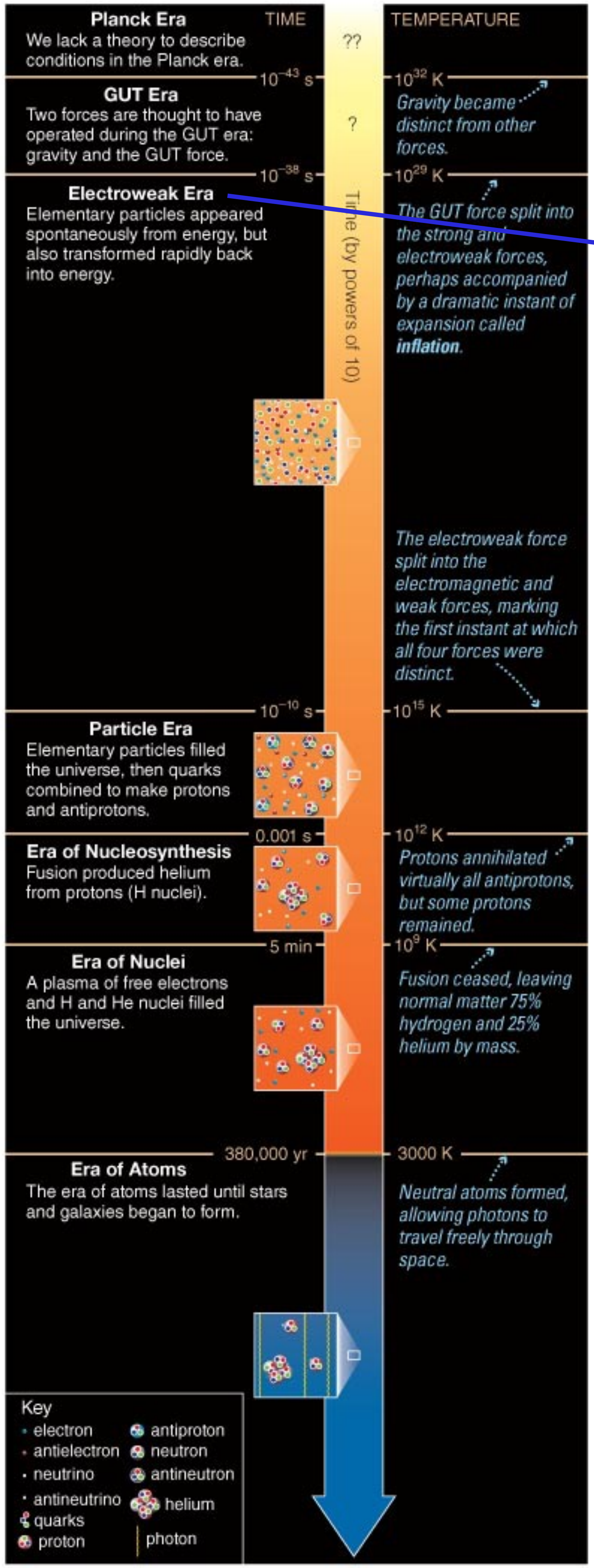
- Gravity and Gut force (electromagnetic, weak and strong)
- We know very little on the physics of this epoch


time (s)
10^{-10}
10^{-38}
10^{-43}
relative strength of force
strong force
electromagnetism
weak force
electroweak force
GUT force
"super force"
?
gravity
Electroweak era
GUT era
Planck era
10^{15}
10^{29}
10^{32}
temperature (K)



Electroweak era

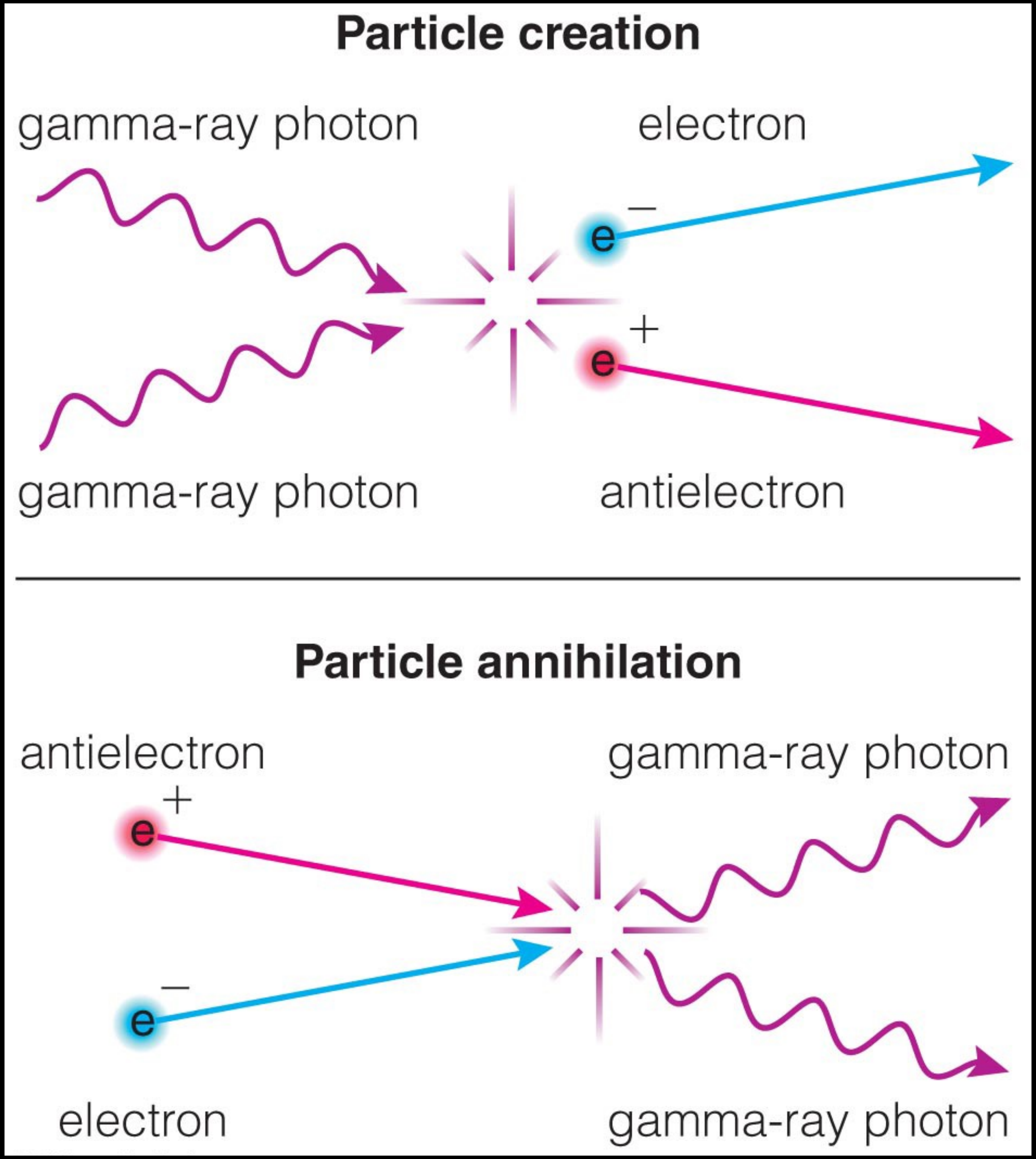
- Lasts from end of GUT force (~10^{-38} second) to end of electroweak force (~10^{-10} second)



Electroweak era

- Lasts from end of GUT force (~10^{-38} second) to end of electroweak force (~10^{-10} second)
- The unification of weak and electromagnetic force predict the existence of new particles (W and Z boson) that have been observed in particle accelerator experiments

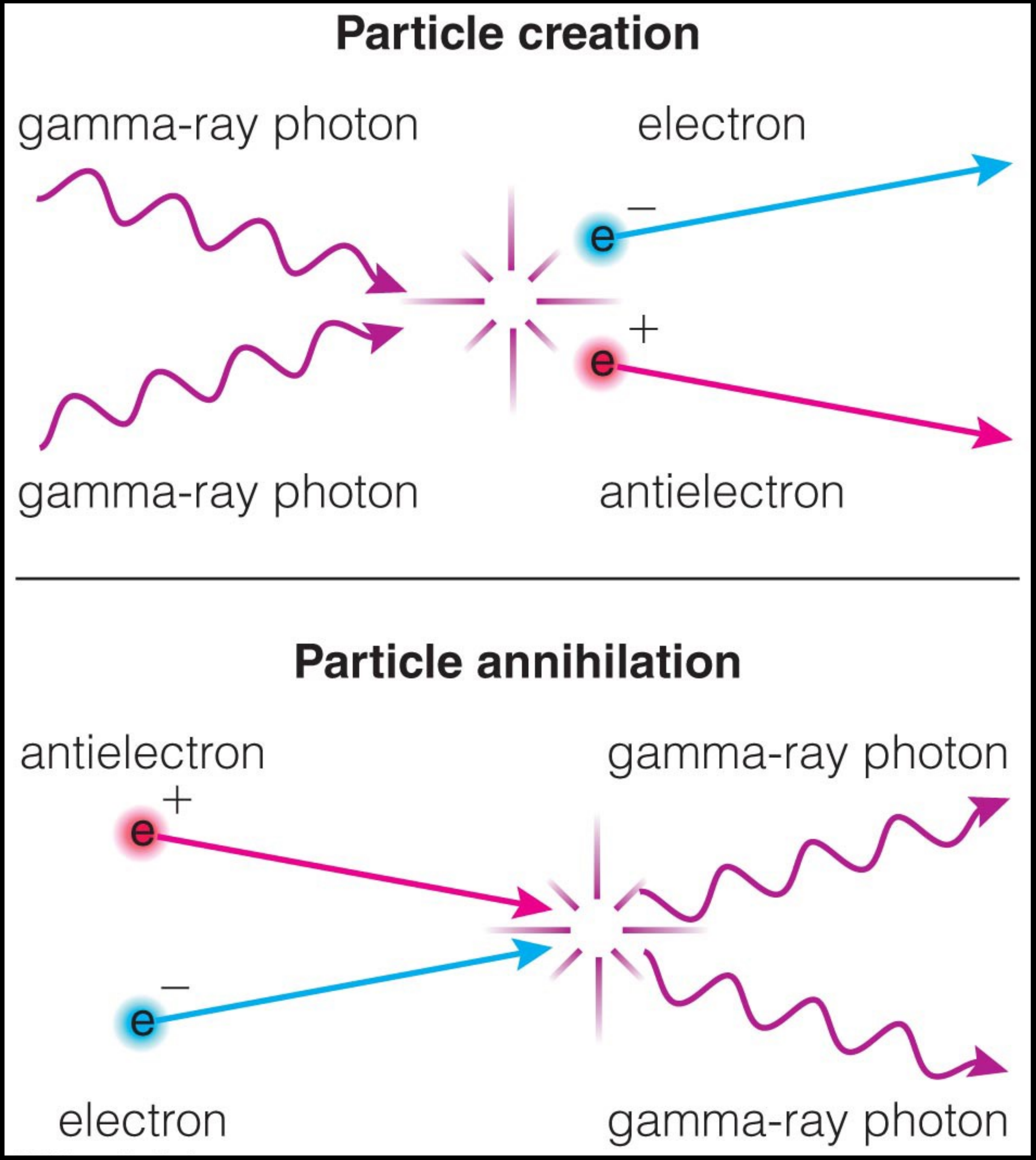
Very high temperatures at early times



Very high energy photons

- Particle are created and annihilated continuously
- Matter and antimatter collide and annihilate, creating high-energy photons

Very high temperatures at early times

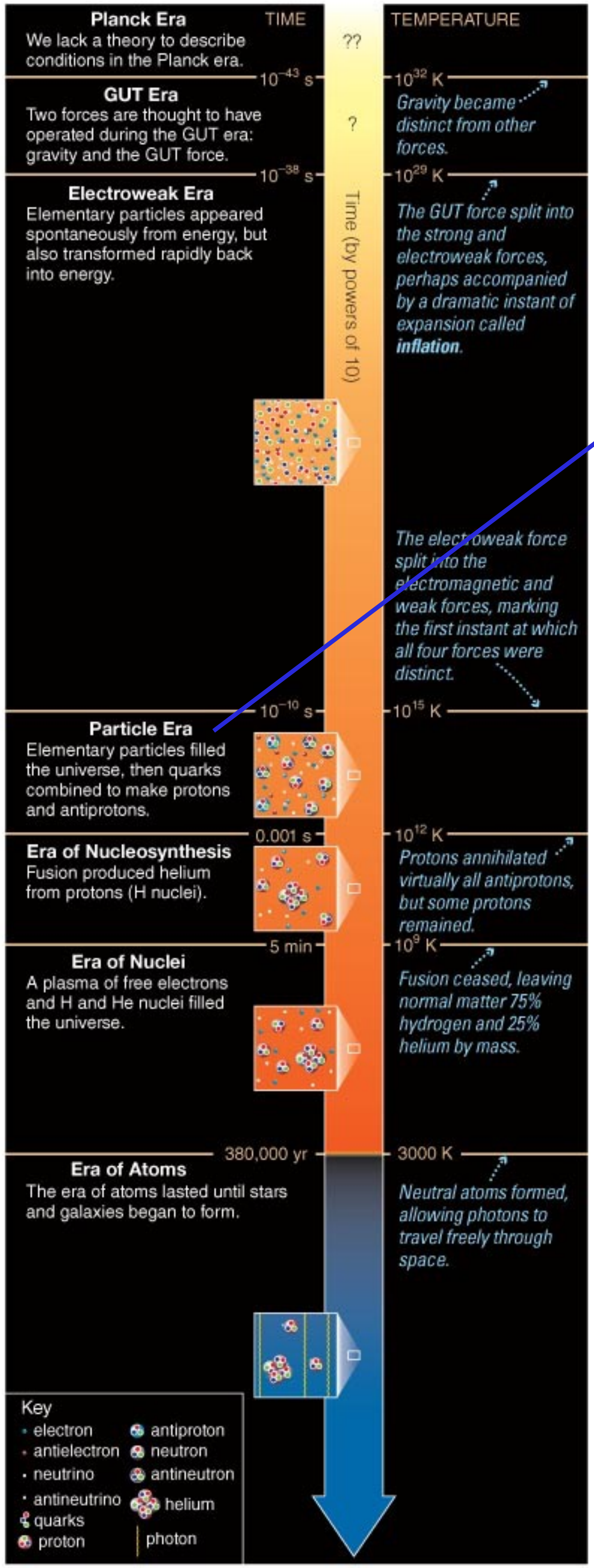


Very high energy photons

- Particle are created and annihilated continuously
- Matter and antimatter collide and annihilate, creating high-energy photons

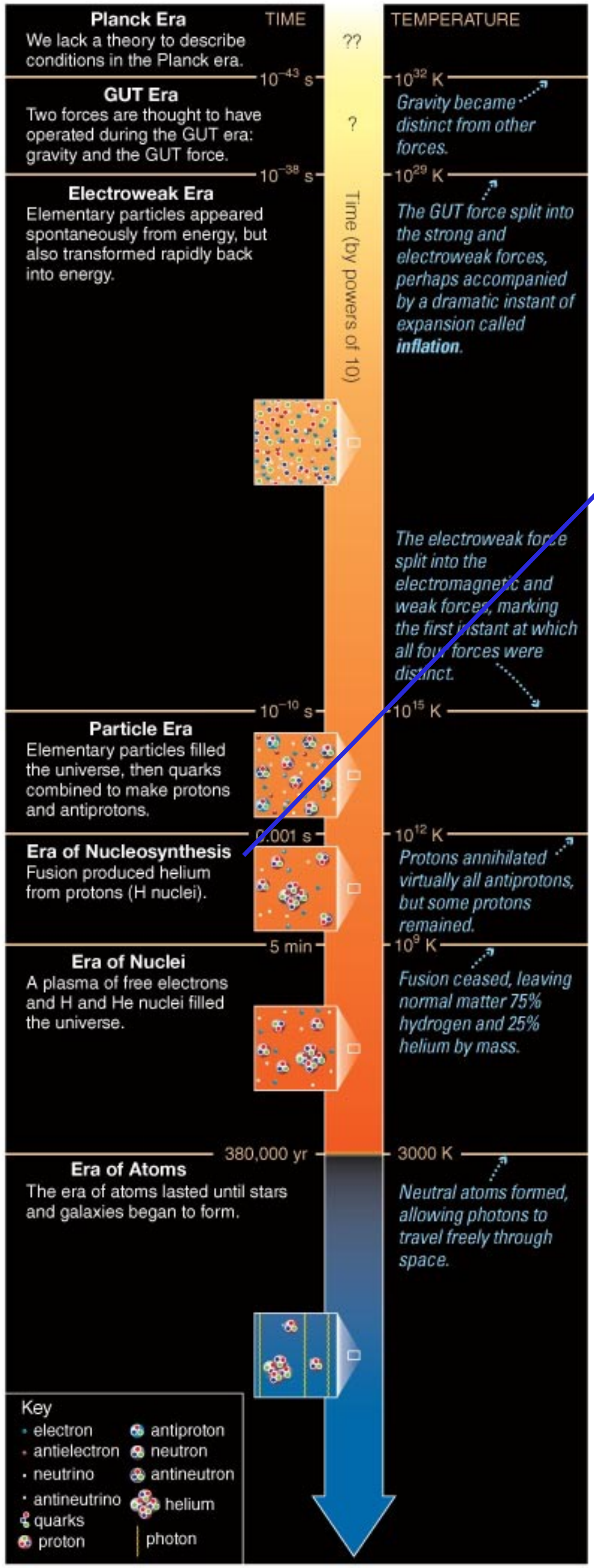
Density and temperature is going down….

- The energy is not high enough to create proton and antiproton
- proton and antiproton annihilate and the small access of protons is left over.



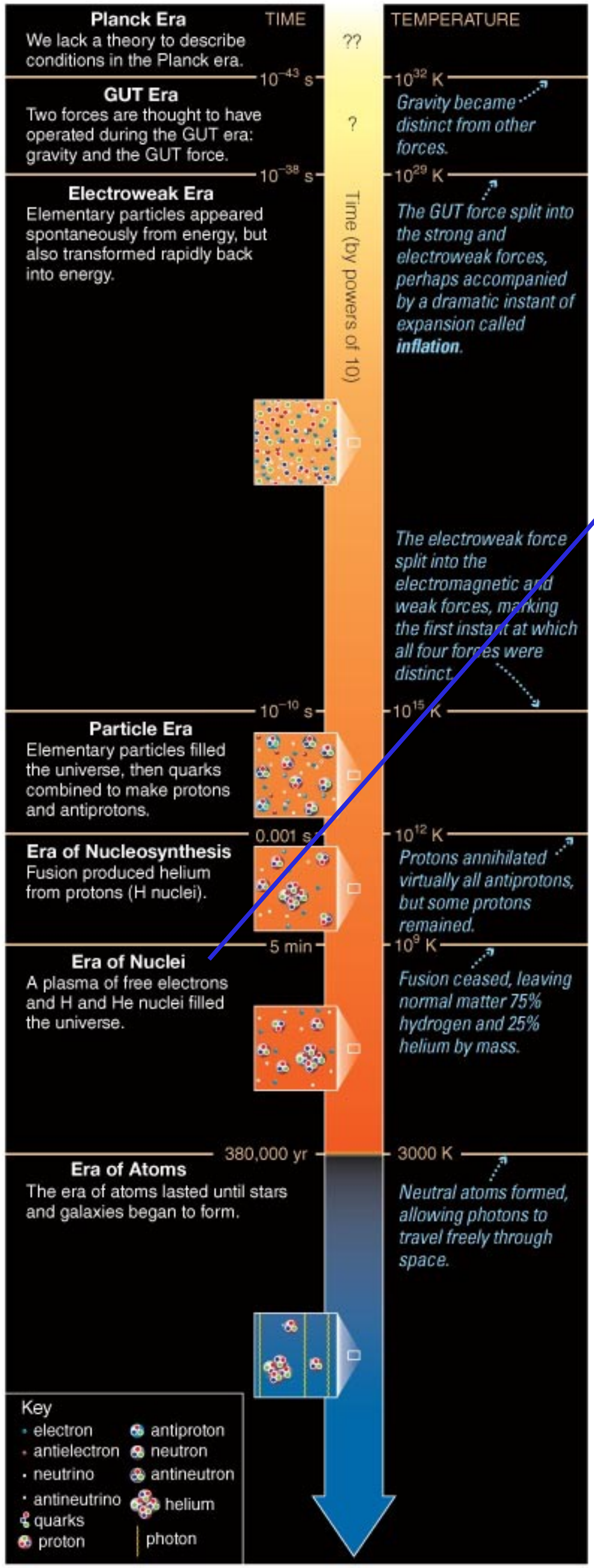
Particle era

- Basic particles of atoms (electrons, protons, neutrons) are created
- High-energy photons, matter, and antimatter
- At end of particle era, all the antimatter is annihilated and only a small amount of matter is left
- Lots and lots of photons



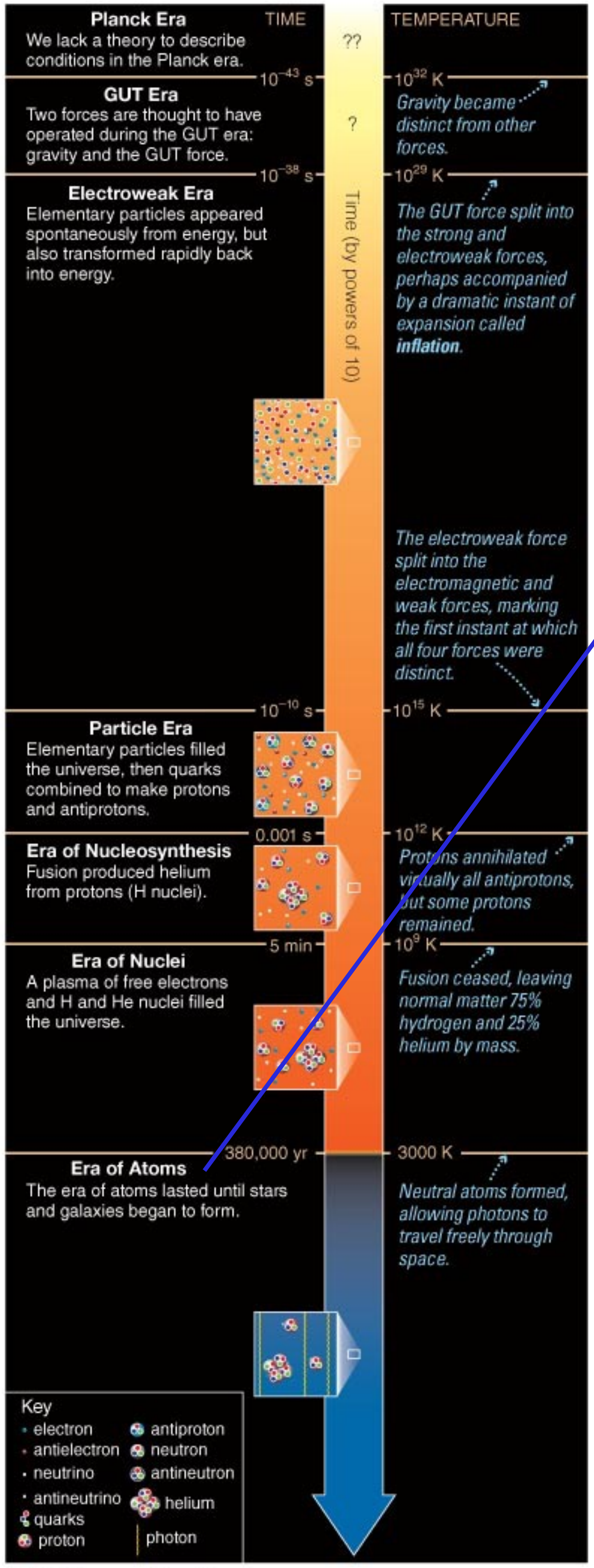
Era of nucleosynthesis

- Protons and neutrons begin to fuse
- They form Helium (and a little bit of Lithium)



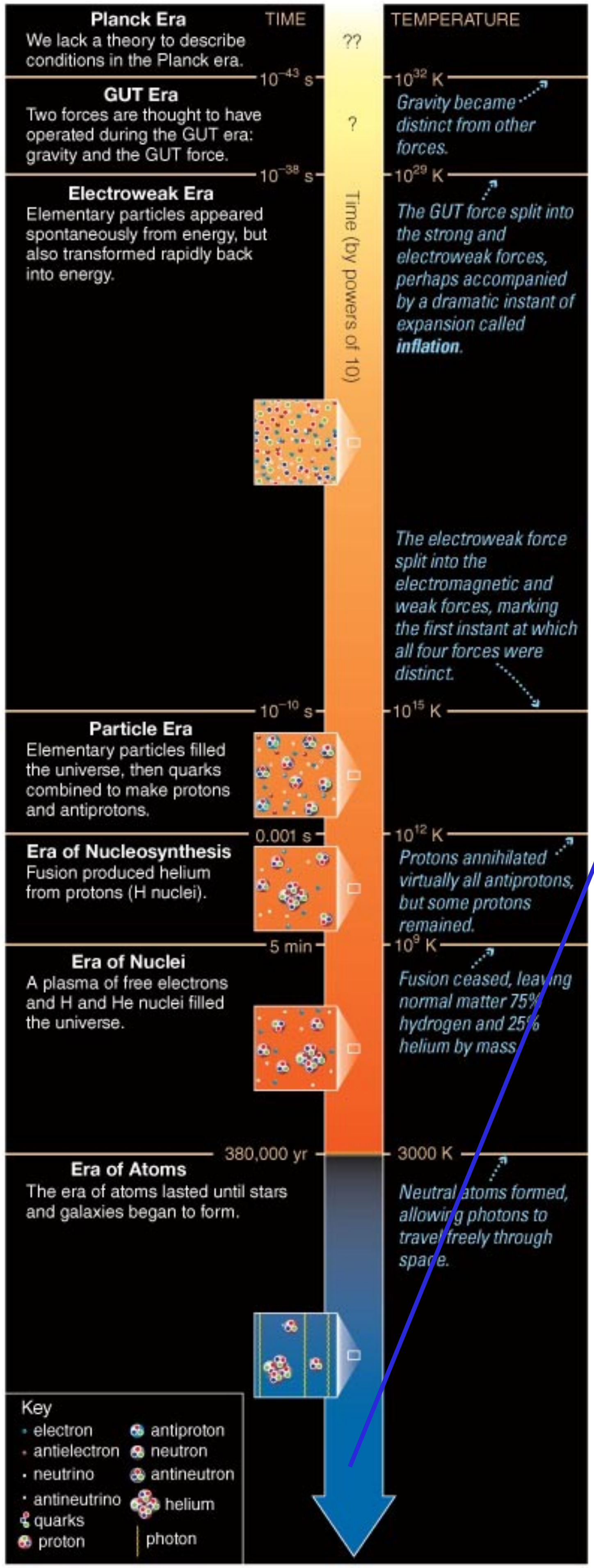
Era of nuclei

- Nucleosynthesis ends at age ~3 minutes
- Universe is too cool to fuse heavier elements
- Mostly Hydrogen left over, with lots of Helium and tiny amounts of other stuff (Lithium, Deuterium)
- Very hot! All atoms are fully ionized.



Era of (neutral) atoms

- Atoms form at age ~380,000 years
- Electrons combine with atomic nuclei
- Photons are able to travel freely through space — “background radiation”



Era of galaxies

- First stars and galaxies form at age ~ few hundred million years

Recap: what have we learned?

- **What were physical conditions like in the early Universe?**
  - **The Universe was hotter and denser at early times**
  - At age < 3 minutes, hot enough for nuclear fusion!
  - At age < 1 second, so hot that radiation was constantly producing particle-antiparticle pairs!

- **How did the early Universe change with time?**
  - **The Universe cooled as it expanded**
  - Particle production stopped, leaving some matter (and no antimatter)
  - Nuclear fusion created Helium (age ~3 minutes)
  - Ionized nuclei combined into neutral atoms (age ~380,000 years)
  - Eventually the first stars and galaxies formed (within 1 billion years)

Further question

- What evidence do we have to support the Big Bang theory?

Primary evidence: leftover radiation

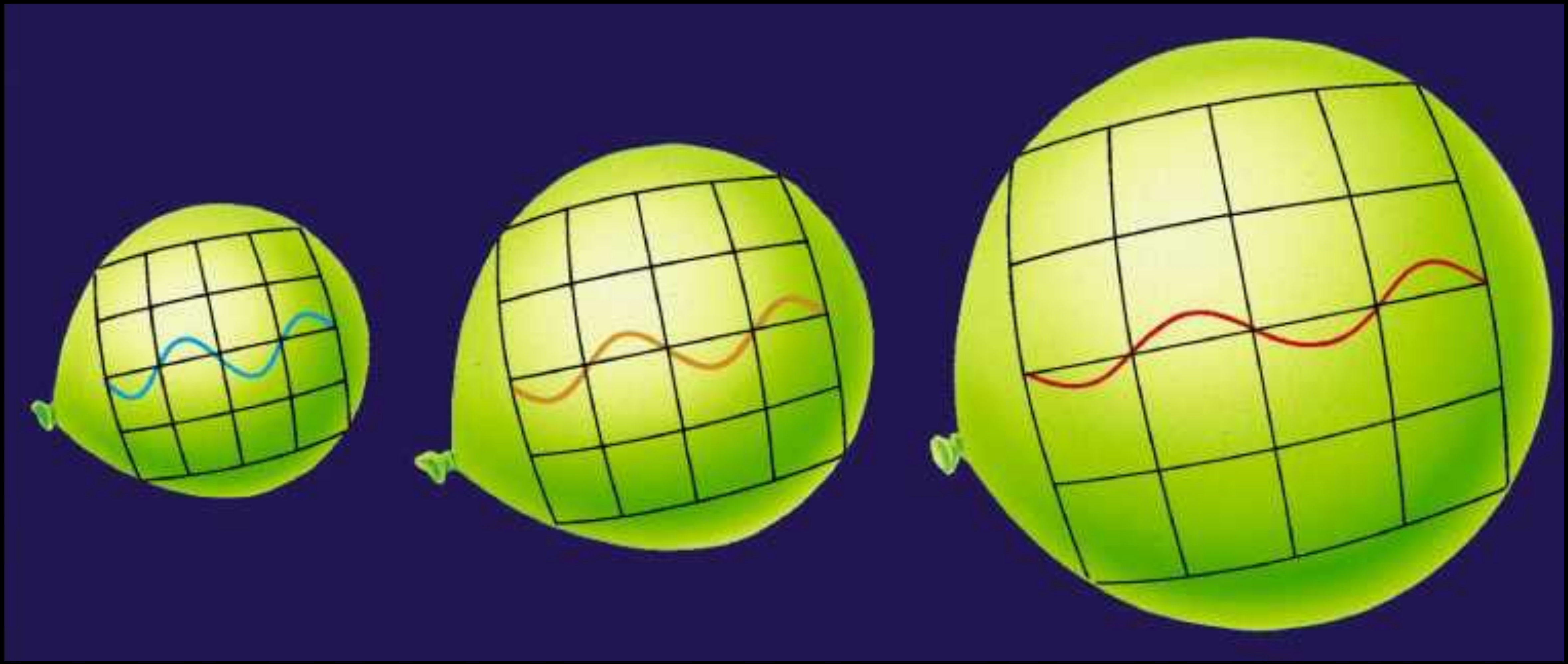
Before 380,000 years: "era of nuclei"

- Temperature > 3000 K
- All matter is ionized (plasma)
- Light scatters off of charged particles, just like it does inside the Sun. The Universe is opaque.

After 380,000 years: "era of atoms"

- Temperature < 3000 K
- Matter is neutral (H, He atoms with neutral charge)
- Photons do not scatter. The Universe is transparent!
- These photons have not interacted with matter since that time!

Recall: the "Cosmological Redshift"



- As the Universe expands, the wavelength of photons do too! → **REDDER**!
- Photons that travel longer (from further away), have experienced more expansion.

Bigger Distance = Bigger Redshift

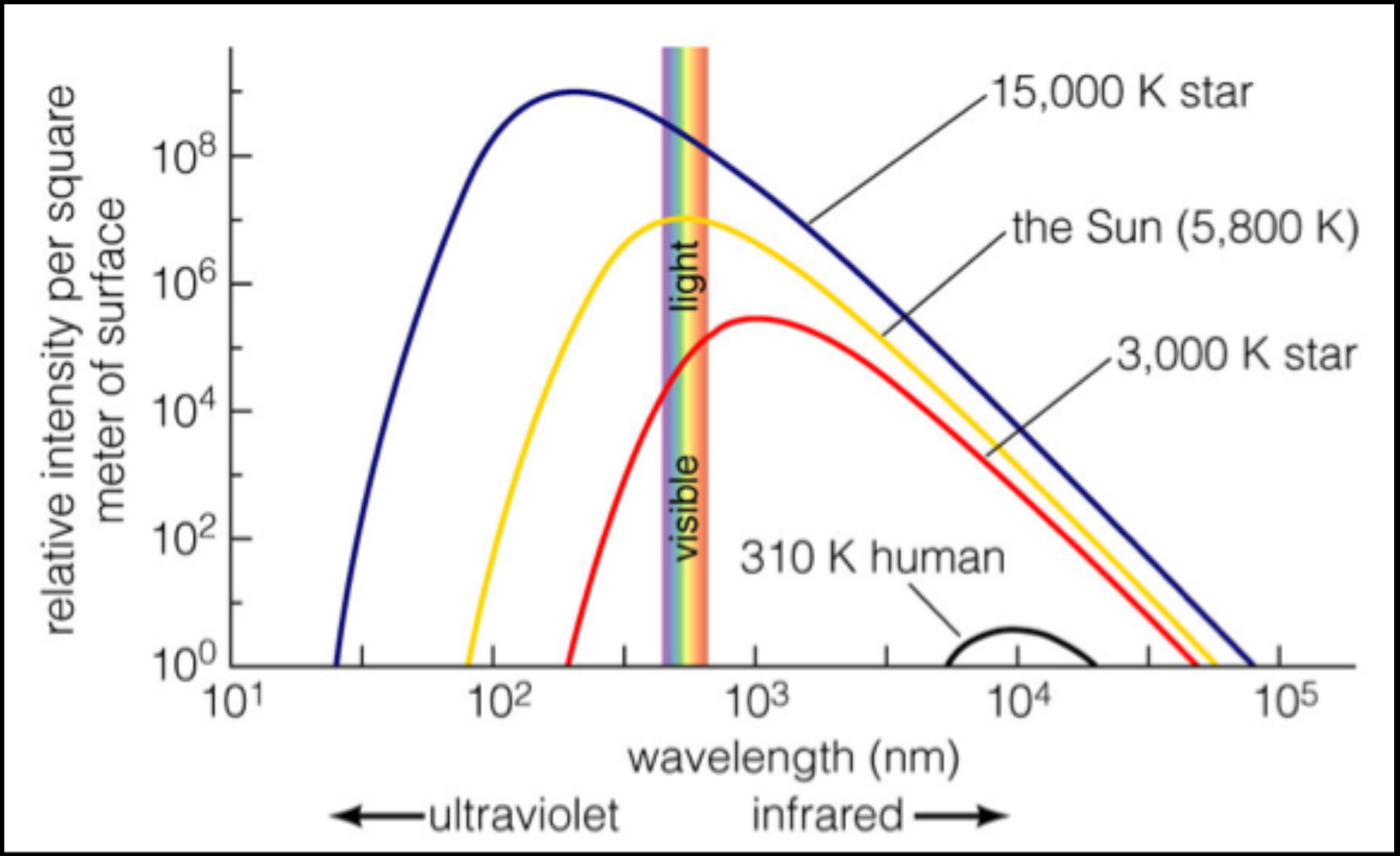
Recall: thermal radiation spectrum

- Hotter means the peak is at a SHORTER wavelength.

  $T = 2{,}900{,}000 \text{ nm} / \lambda_{peak}$

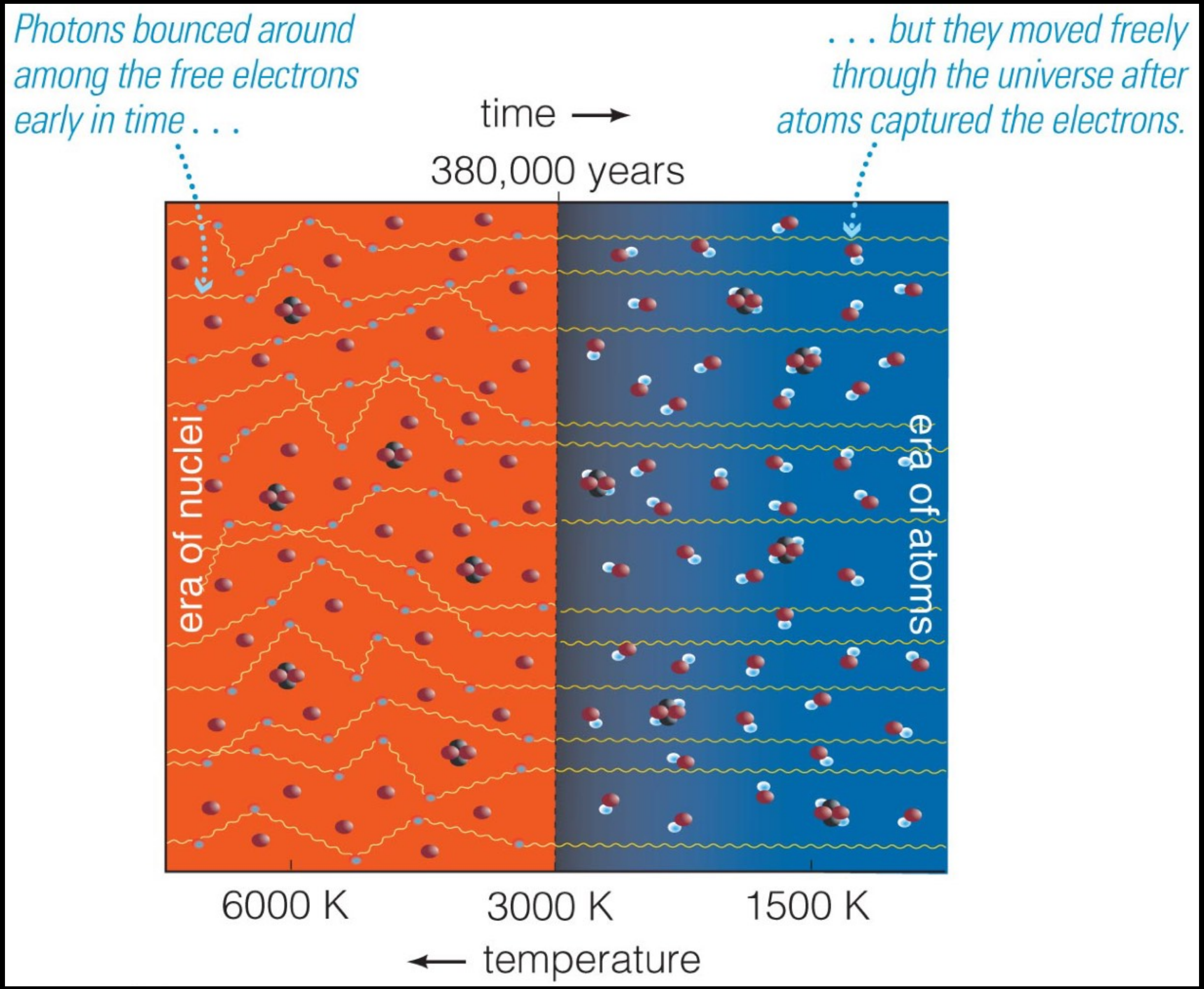
  Redshift: longer wavelength ⟷ lower T

  If space expands to 10x larger, T will be 10x lower



HIGH ENERGY **LOW ENERGY**

Primary evidence of Big Bang: leftover radiation

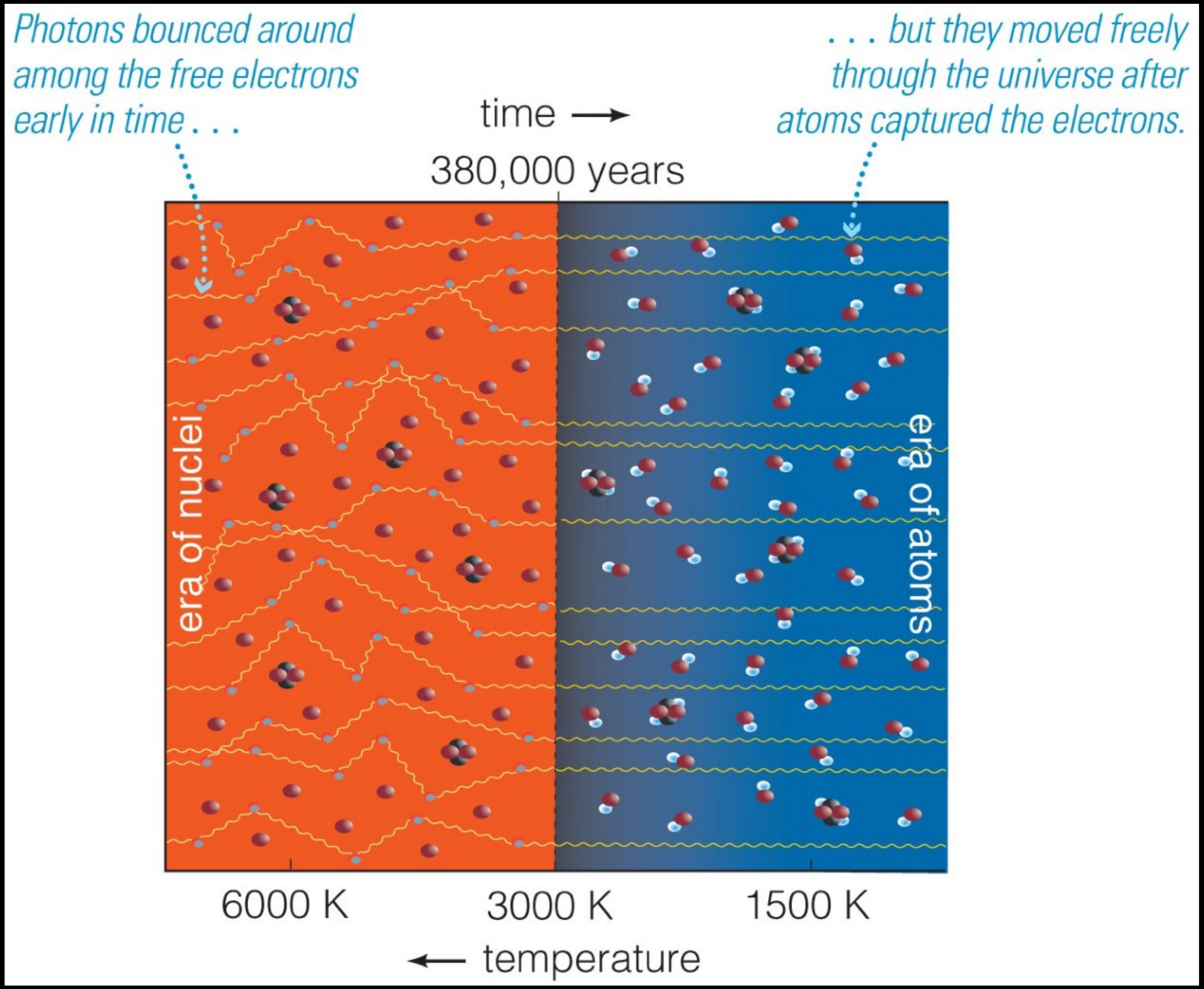


Background radiation from the Big Bang has been freely streaming across universe since atoms formed.

Temperature ~ 3,000 K: *visible/IR thermal radiation*

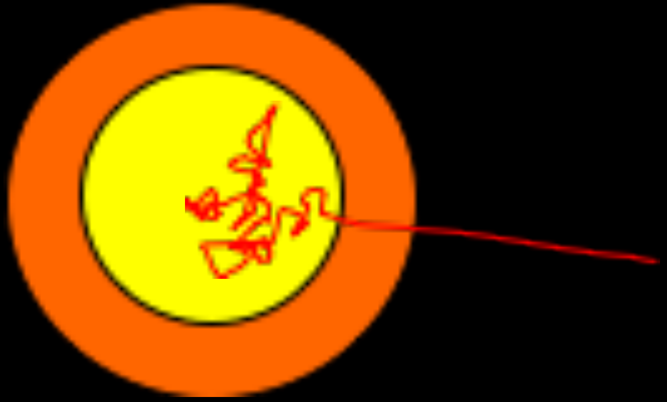
Universe has since expanded by ~1,000× to current T ~ 3 K: *microwave*

Primary evidence: leftover radiation

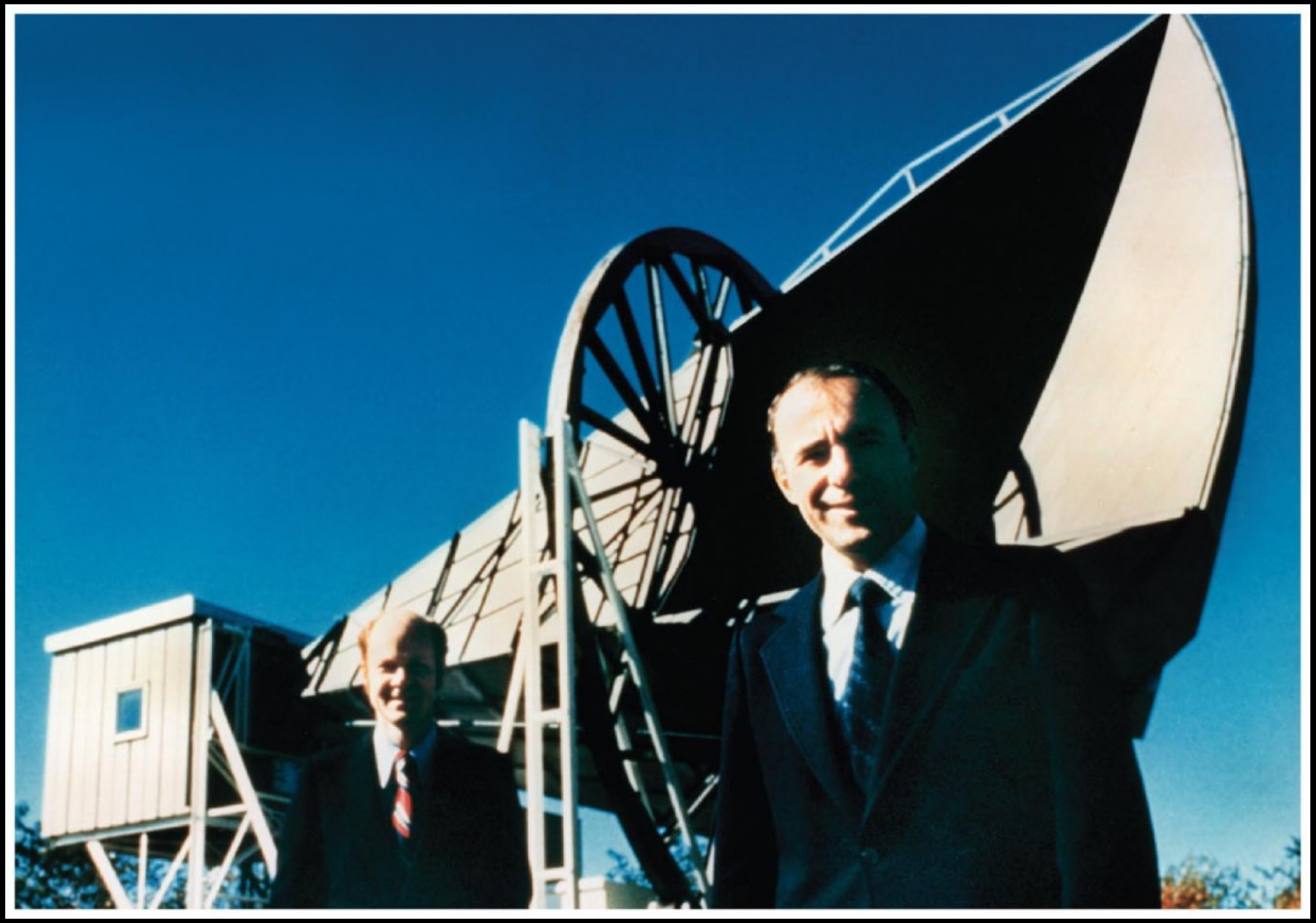


When the Universe cools to ~3000 K, atoms become neutral and radiation travels freely

- Predicted in 1948
- Should have a thermal spectrum, with low temperature (initial guesses ~5-50 K)
- Scientists began looking for this radiation…



The "Cosmic Microwave Background" (CMB) Radiation



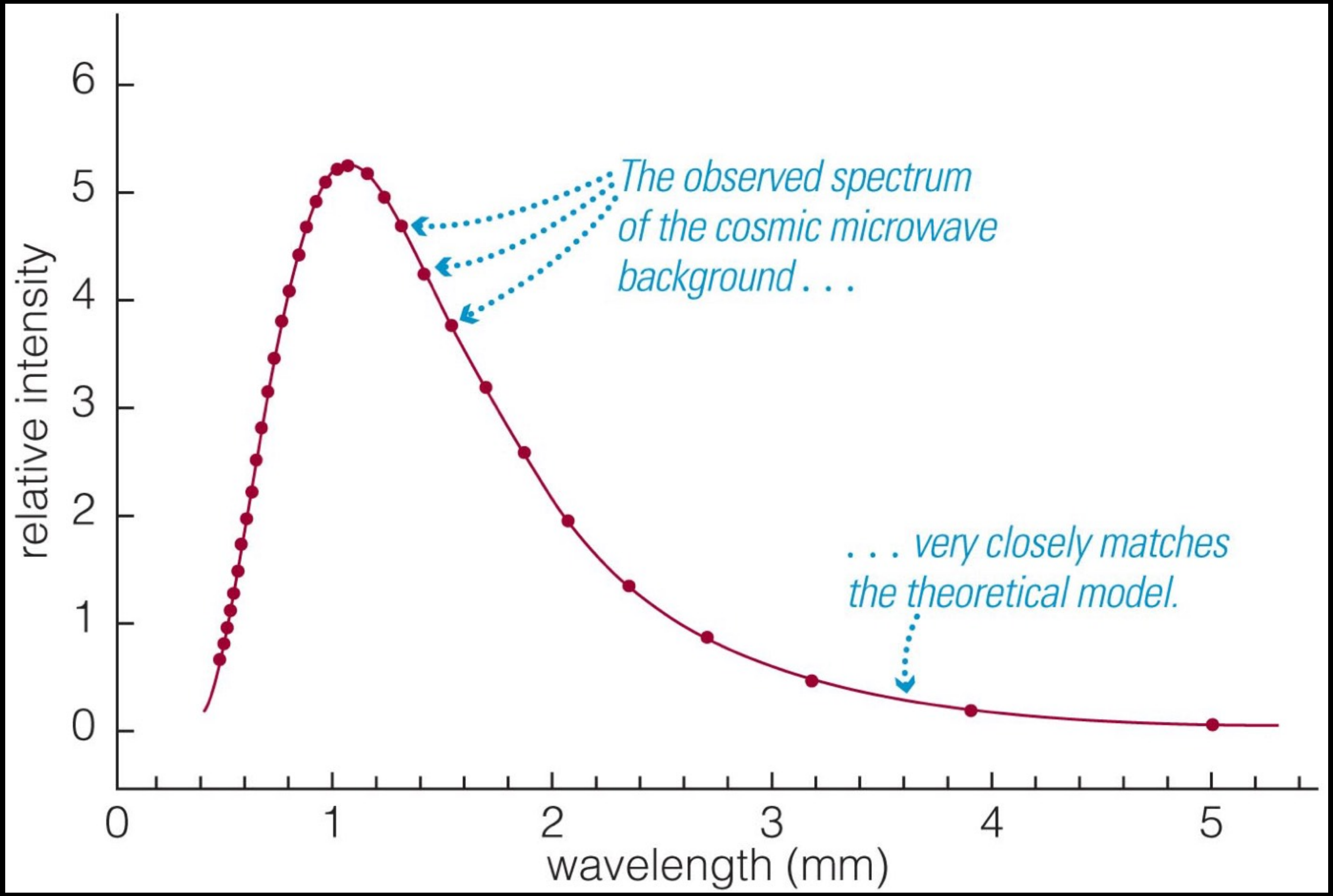
- The ***cosmic microwave background*** — the radiation left over from the Big Bang, observed at microwave wavelengths — was detected by Penzias and Wilson in 1965 (Nobel Prize in 1978)

- Jim Peebles (and Robert Dicke and David Wilkinson and others) predicted this!
- Nobel Prize in 2019!

Spectrum of the CMB: thermal!

Critical **prediction** of the Big Bang model: the Universe should have a thermal radiation spectrum

- Created when temperature of the Universe was ~3000 K, and now **redshifted** to a much lower T ~ 3 K



Measurement: near-perfect thermal spectrum with T = 2.73 K

Spectrum of the CMB: thermal!

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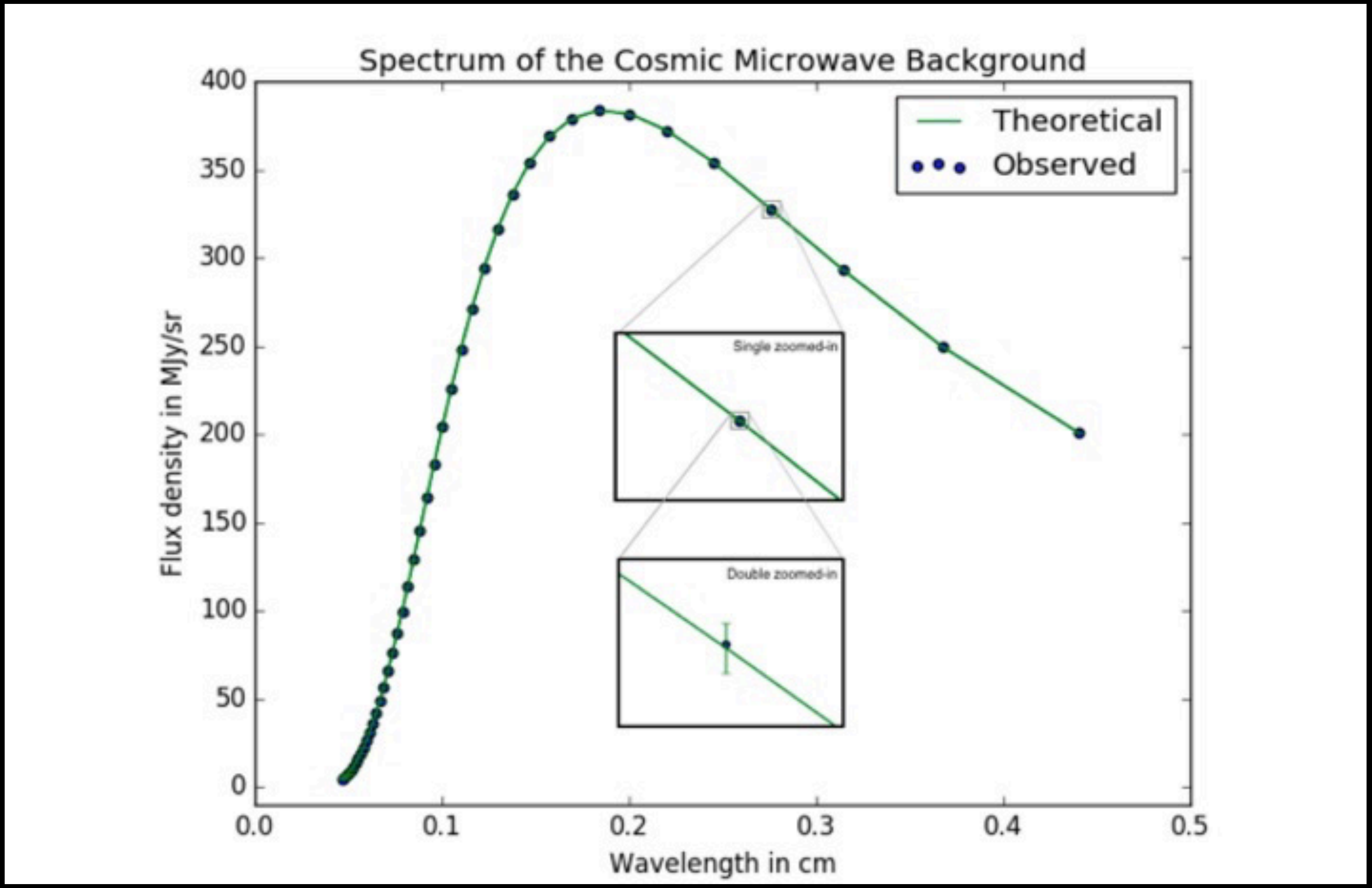
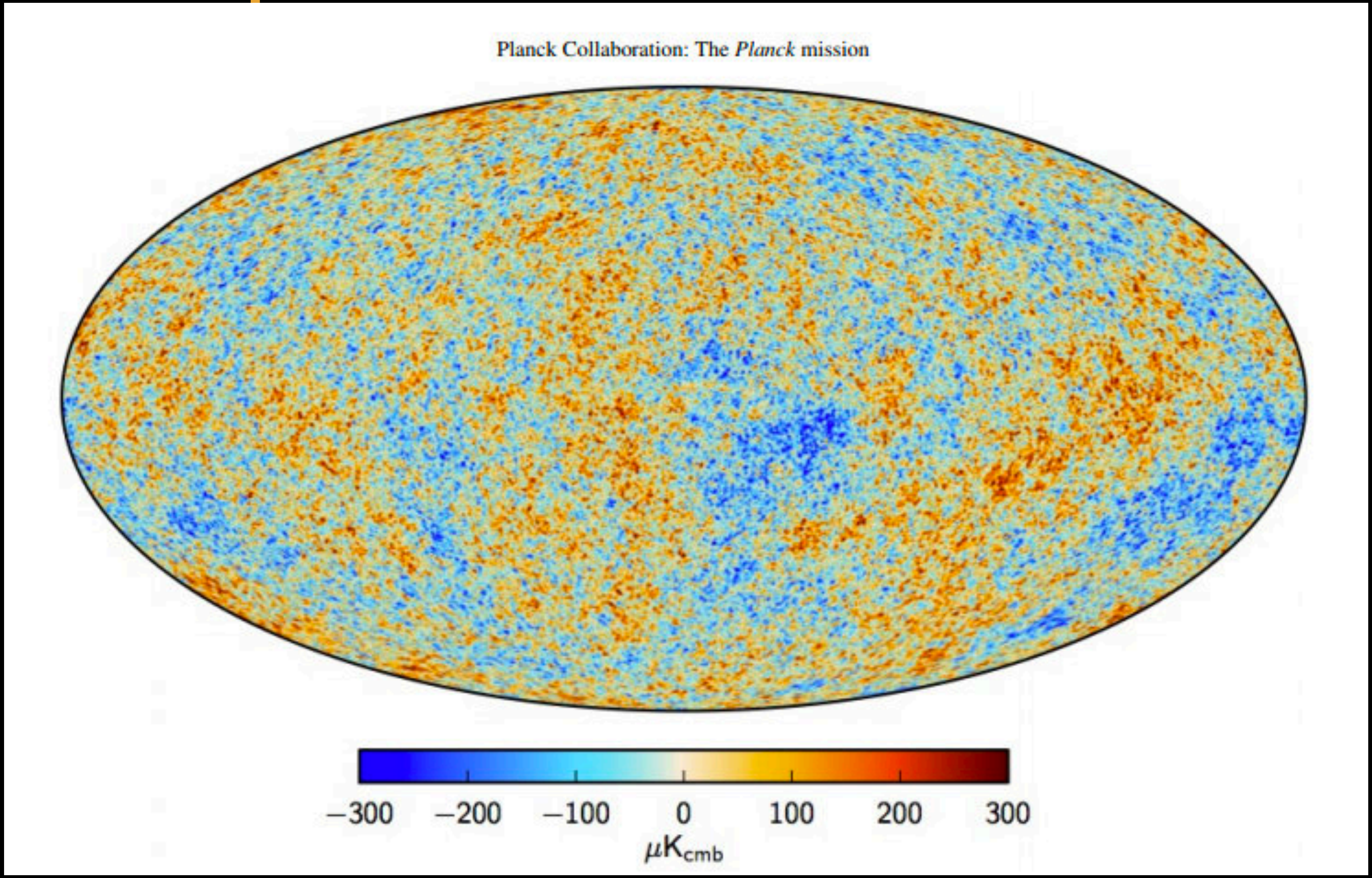


Measurement: near-perfect thermal spectrum with T = 2.73 K

Map of the CMB: uniform!

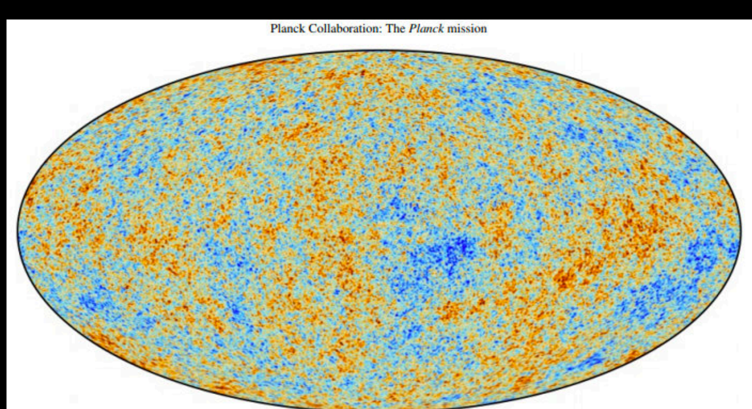


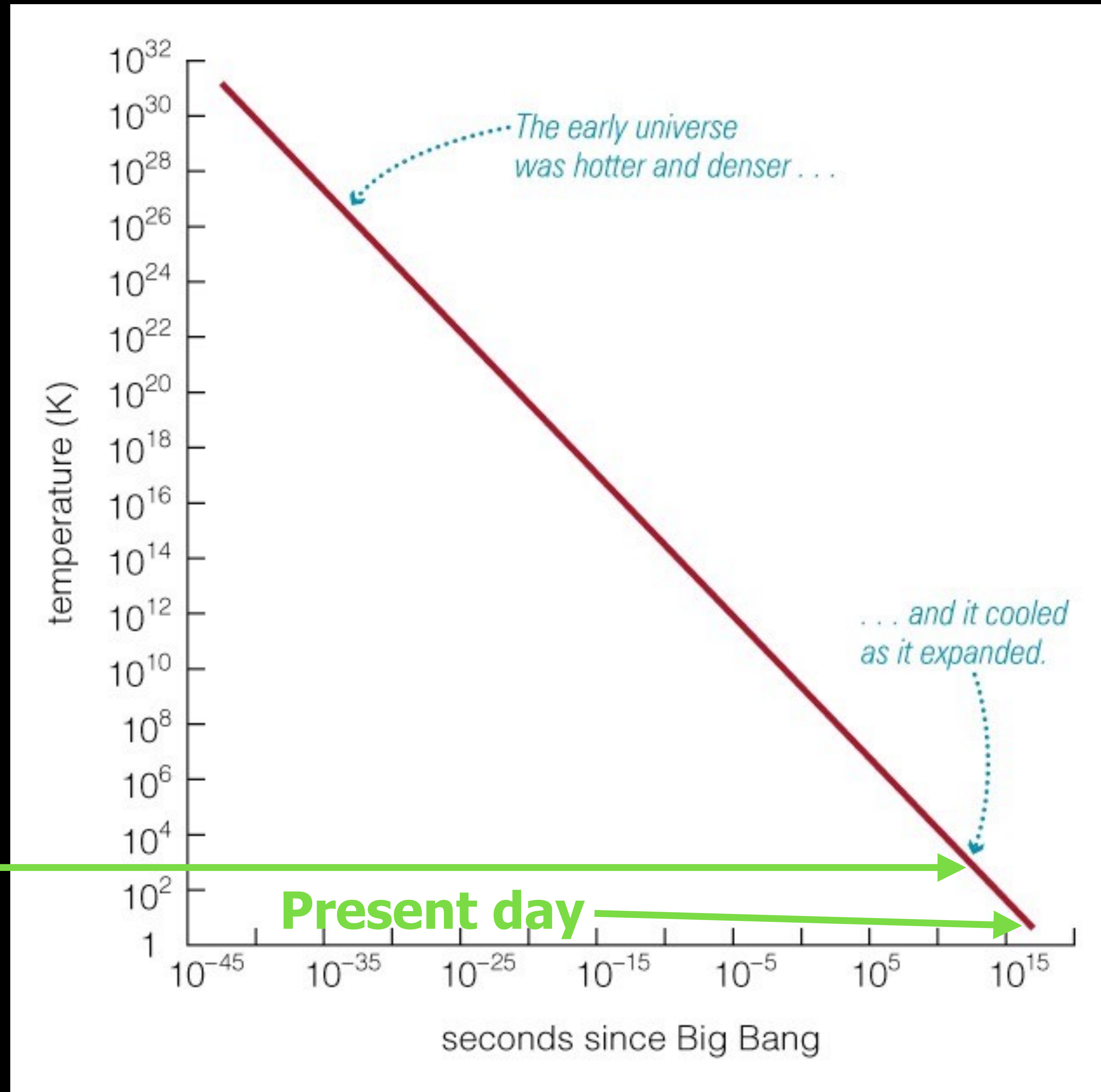
Nearly constant temperature everywhere in the sky

- T = 2.73, with variations of ~0.0001 K
- Tiny fluctuations: the hotter & denser regions are where galaxies will eventually start to form!

Timescale of the CMB

CMB: T ~ 3000 K
Age ~ 380,000 years

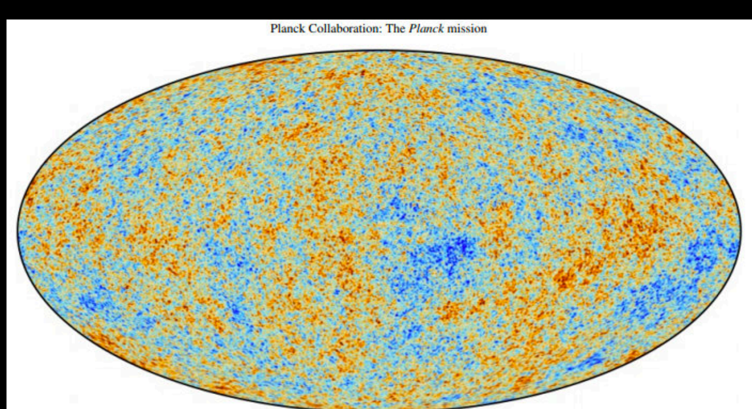


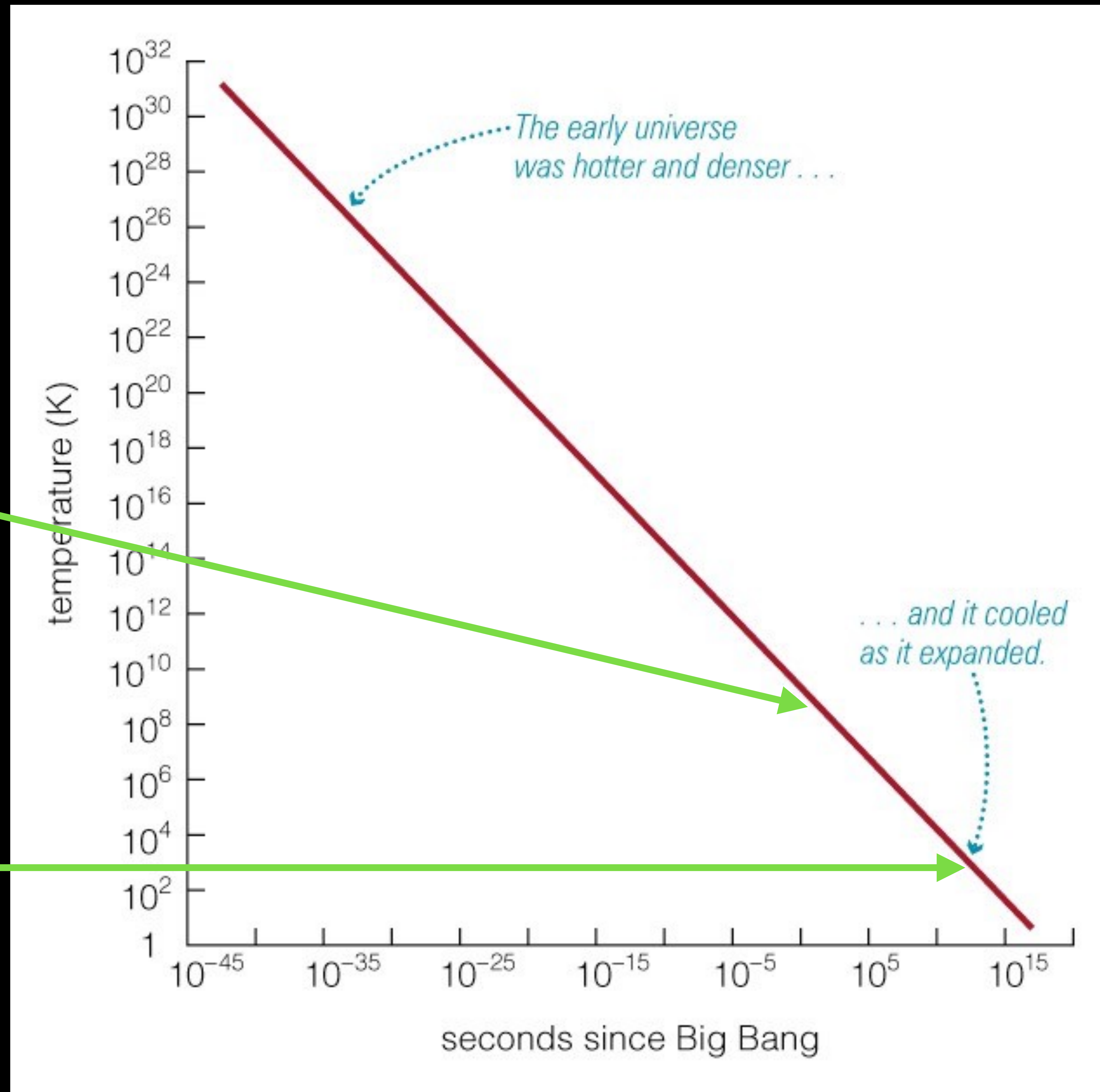


We can probe even earlier!

Nucleosynthesis:
T ~ 10^9 K
Age ~ 1-3 minutes

CMB: T ~ 3000 K
Age ~ 380,000 years



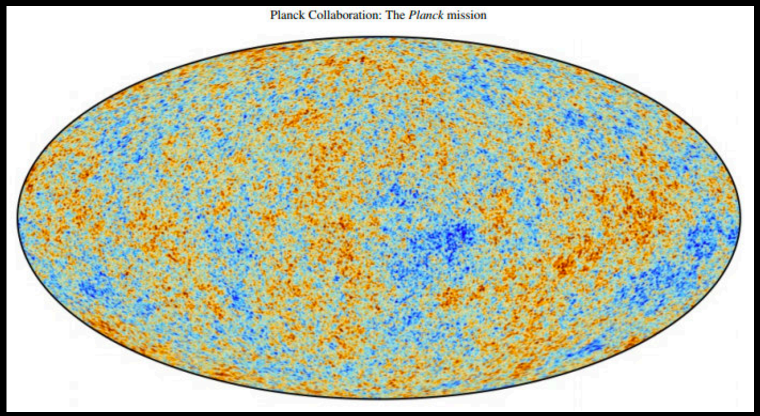


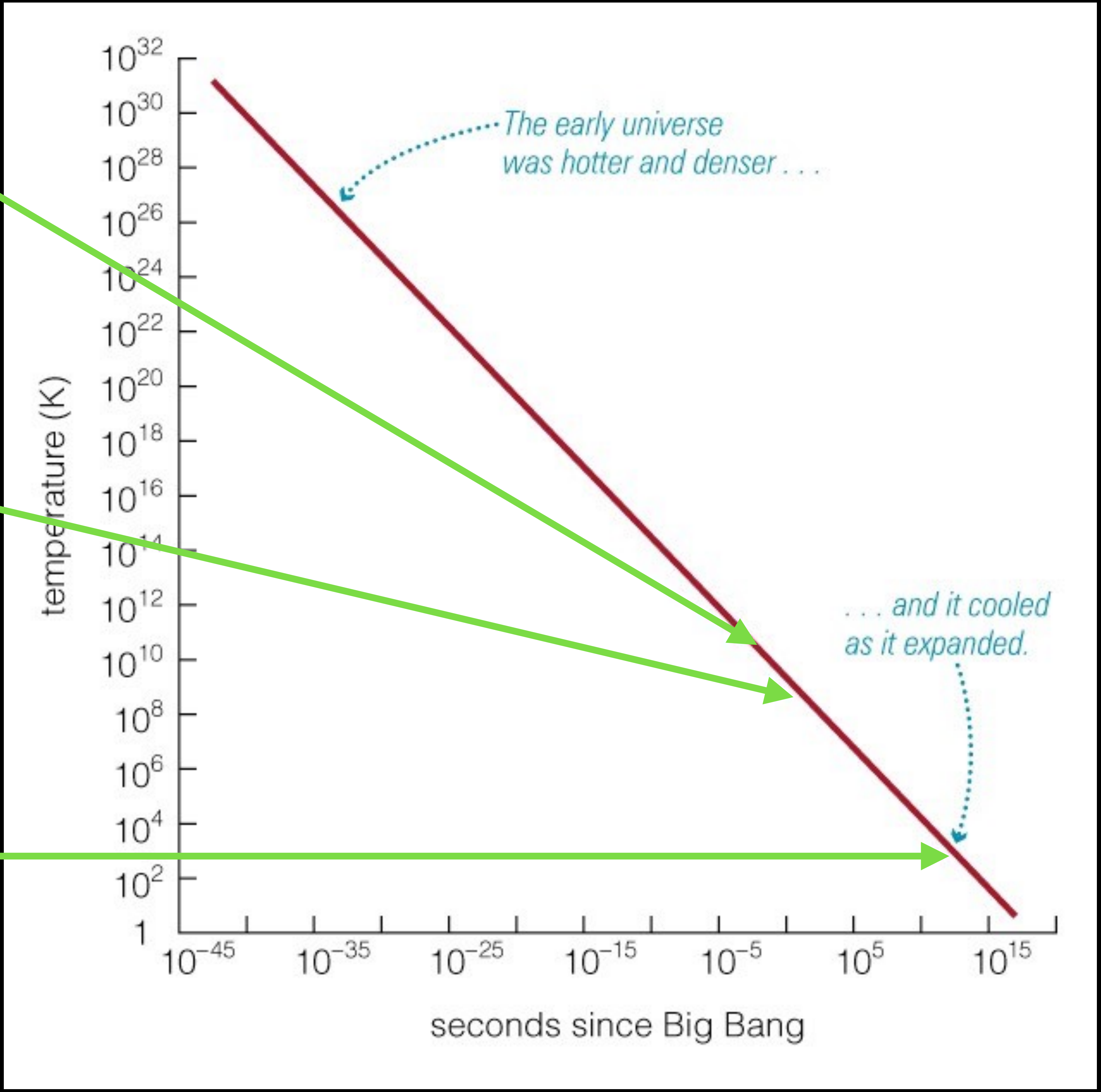
We can probe even earlier!

Age < 1 minute:
nuclei ripped apart
(by energetic photons)

Nucleosynthesis:
T ~ 10^9 K
Age ~ 1-3 minutes

CMB: T ~ 3000 K
Age ~ 380,000 years

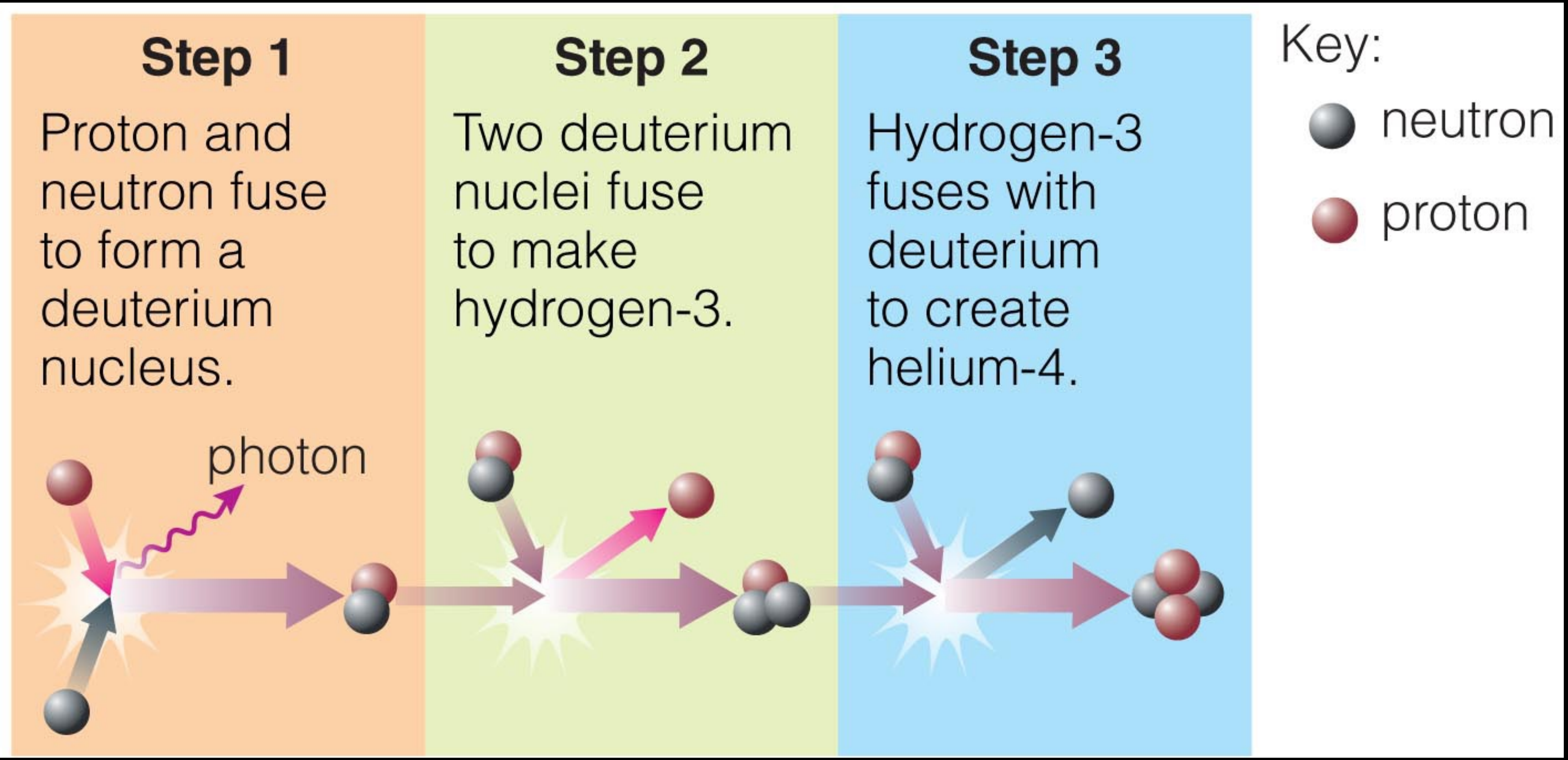




Big Bang Nucleosynthesis (BBN)

After ~1 minute, the Universe is cool enough for atomic nuclei to survive.

- Within first ~1-3 minutes, the Universe is hot & dense enough for nuclear fusion reactions to occur
- Exact reaction is different than in stars, but similar product: mostly Helium-4



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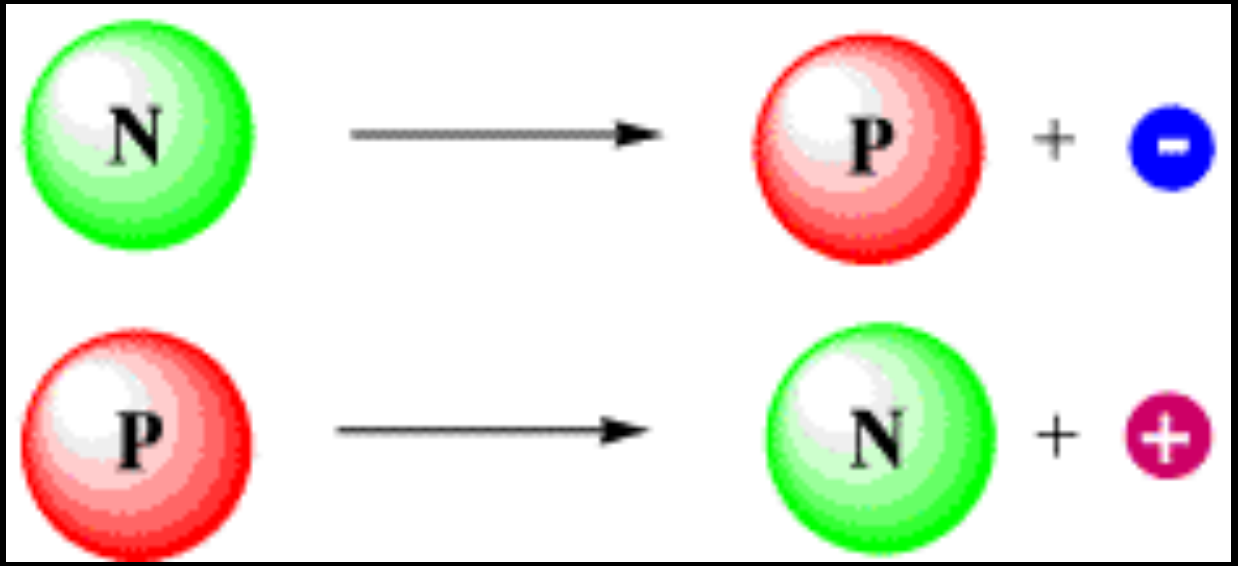

produce Energy

need Energy

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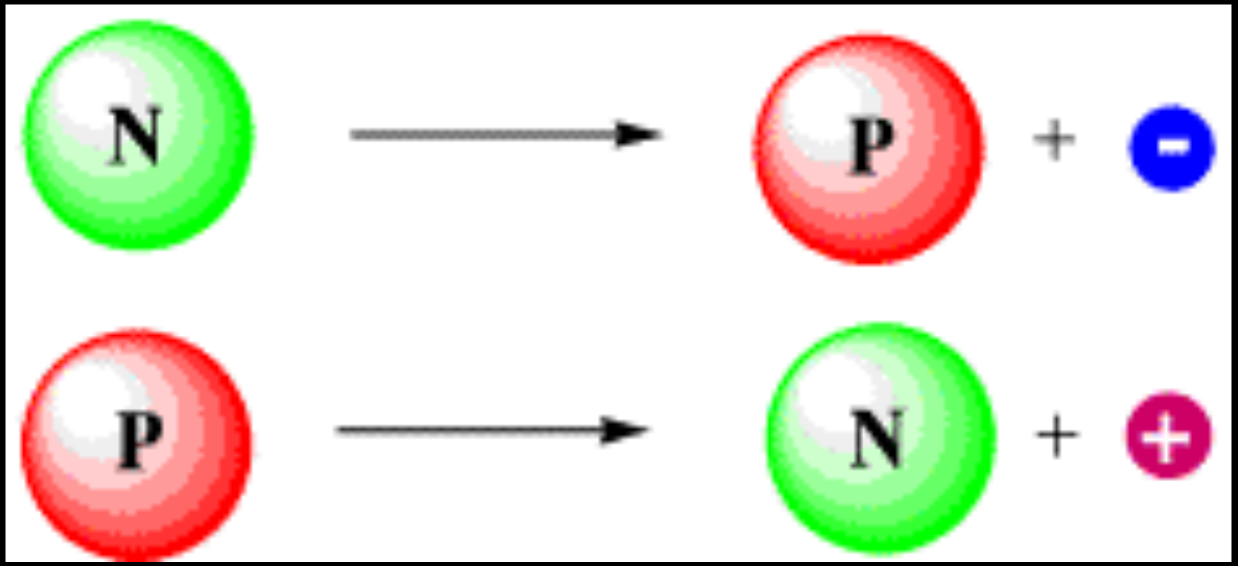

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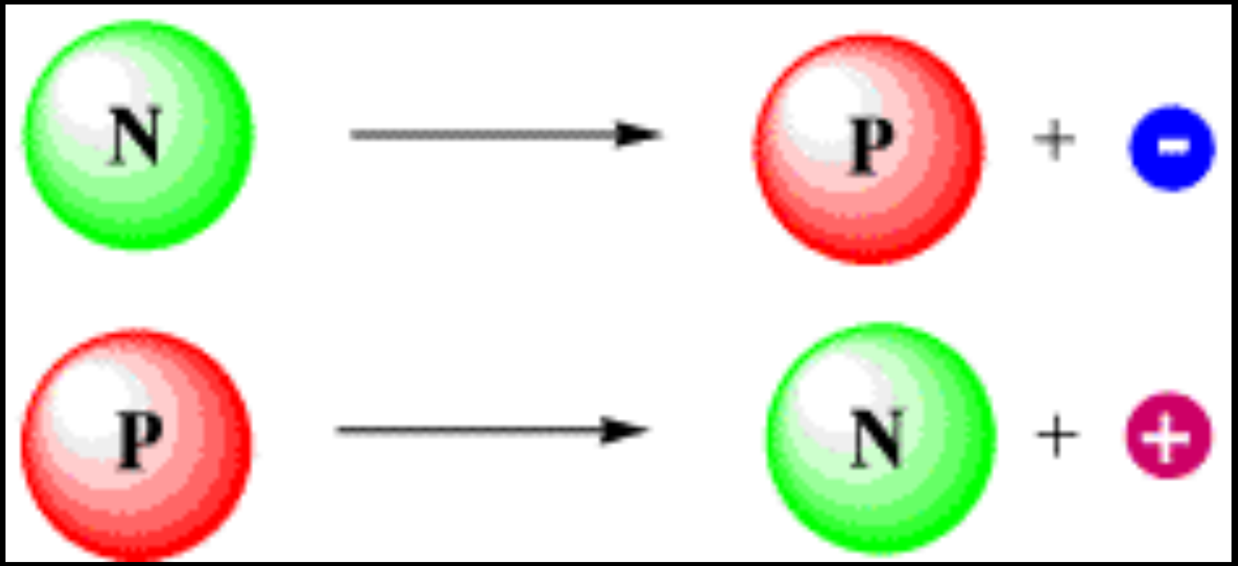

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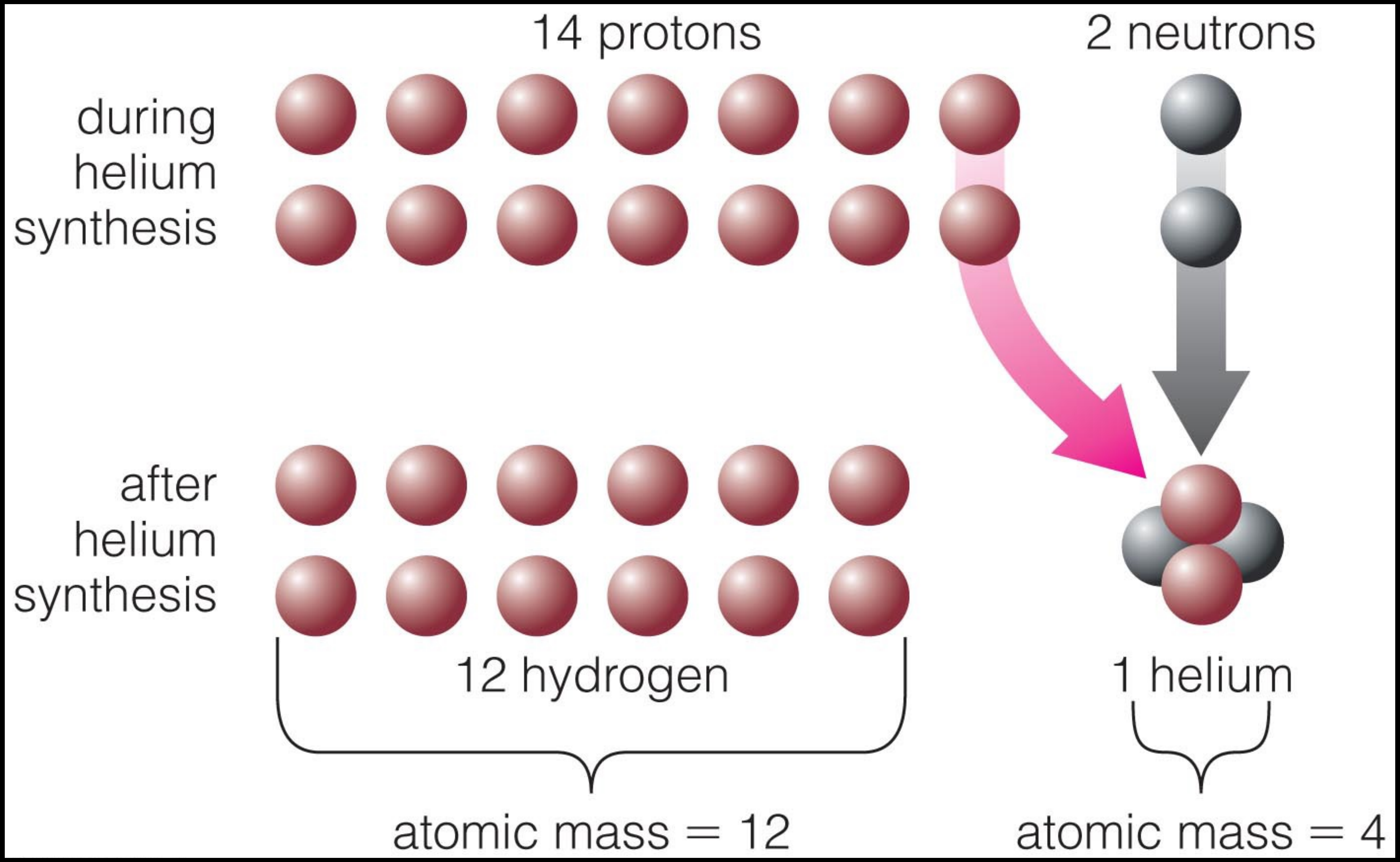
No energetic photons -> **7 protons for 1 neutrons**

Big Bang Nucleosynthesis (BBN)



Prediction of Big Bang theory: 75% H-1, 25% He-4 (by mass), + tiny amounts of other nuclei

- This agrees very well with **measurements** of “primordial” gas

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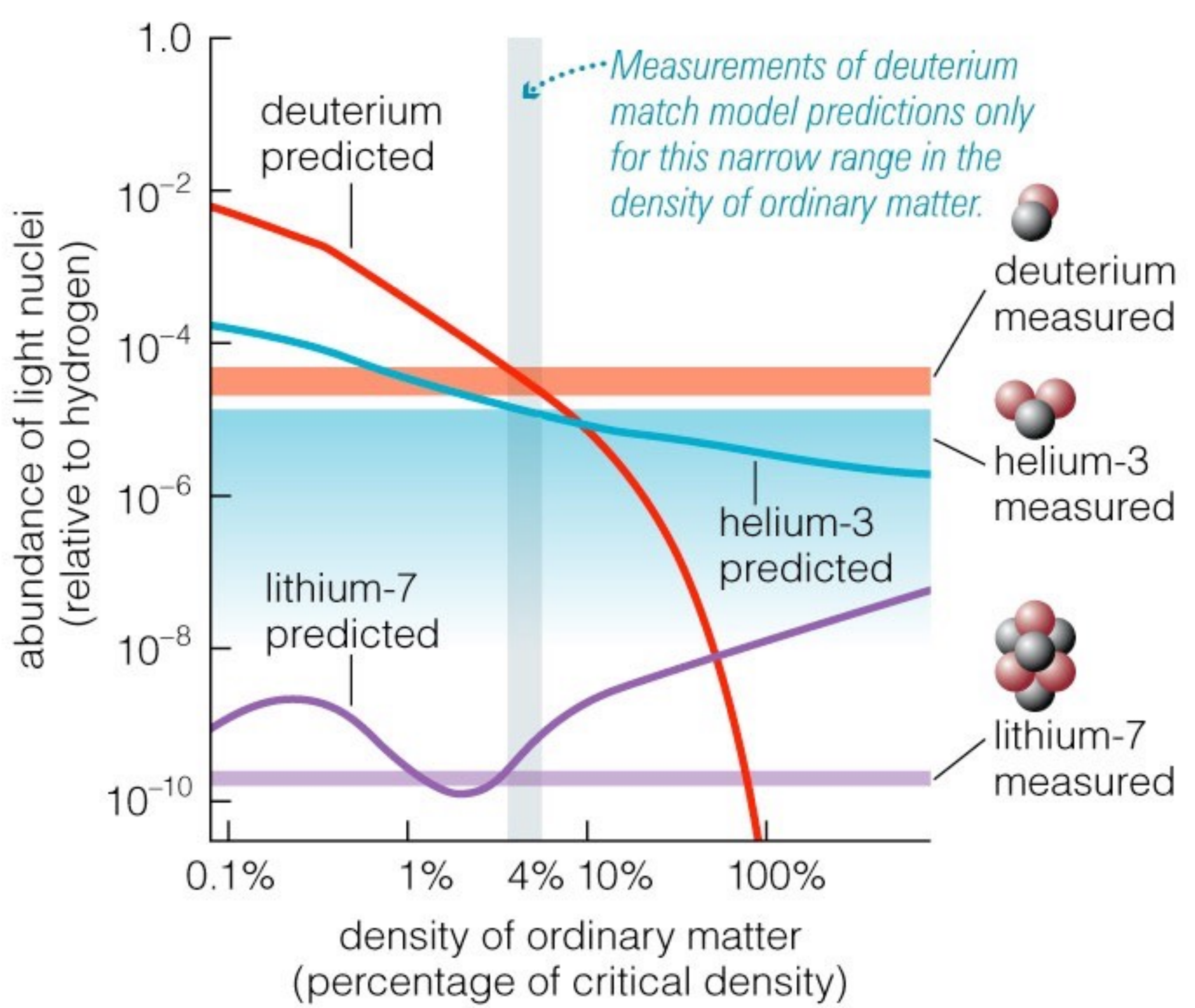


Prediction of Big Bang theory: 75% H-1, 25% He-4 (by mass), + tiny amounts of other nuclei

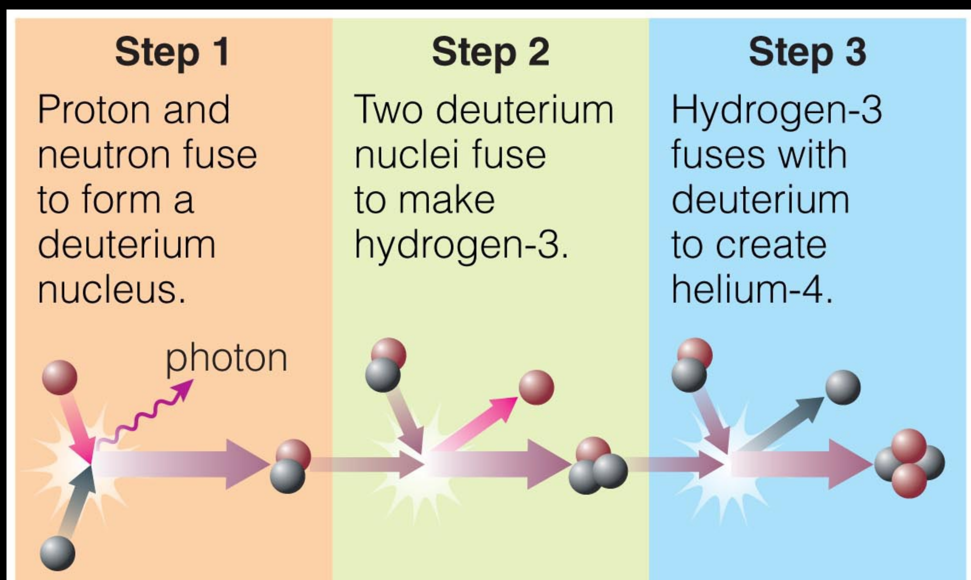
Data agree very well with predictions of theory!
- Deuterium (H-2)
- He-3
- Li-7

Theory predicts the number of CMB photons for every Hydrogen atom… and measurements agree!
- More photons → fewer heavy atoms (they would be broken apart)

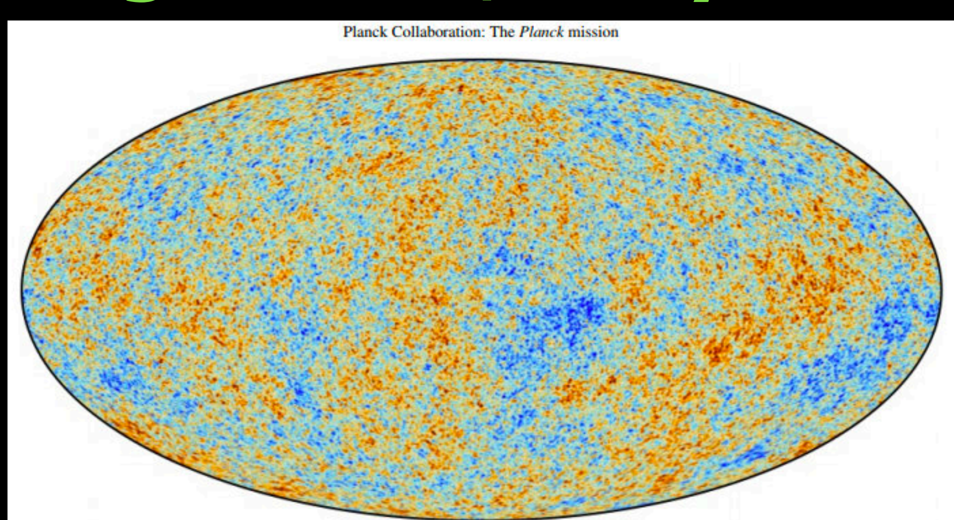
Be amazed!!!

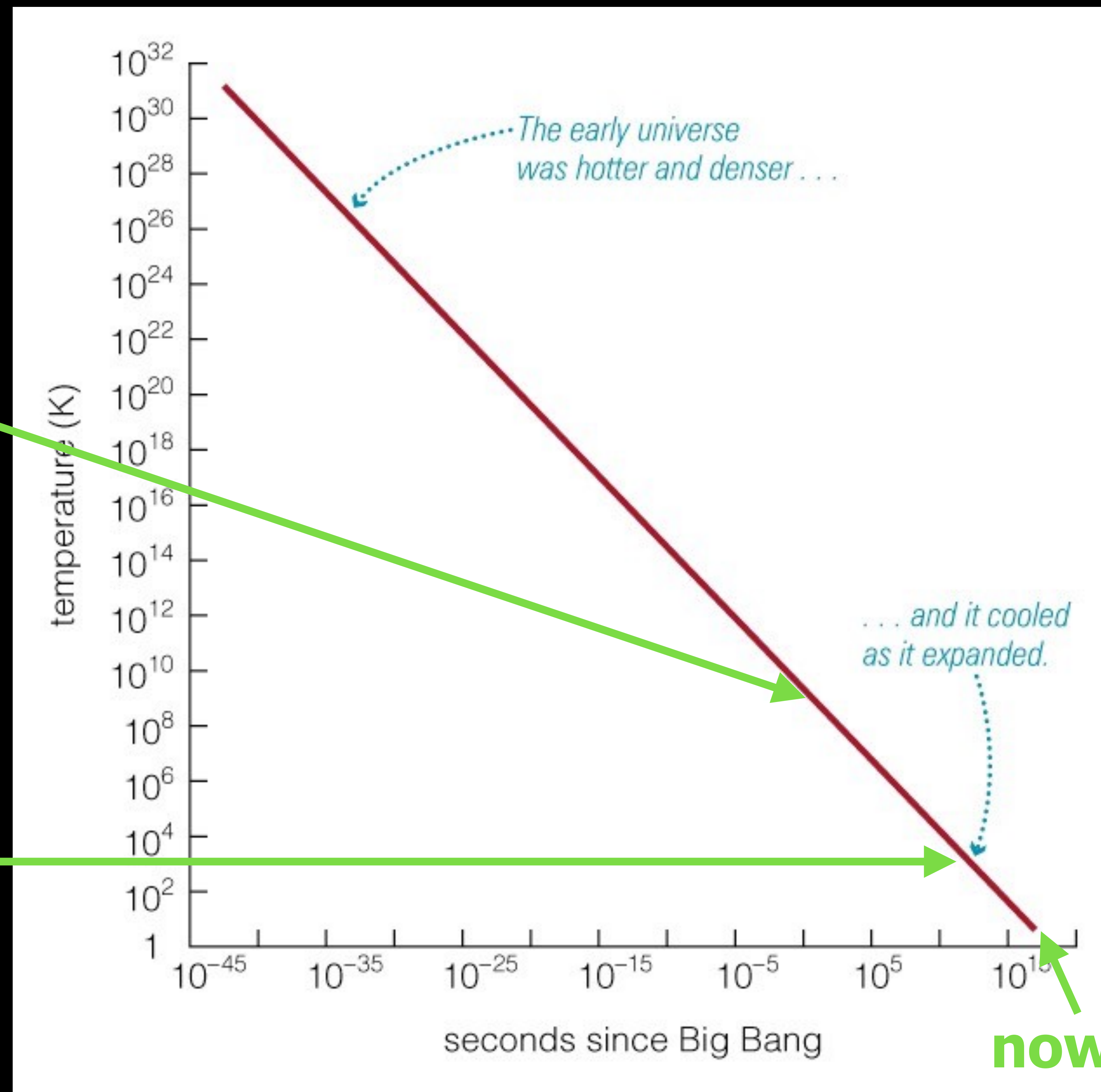
We can predict what happened billions of years ago, in the first few minutes of the Universe. A triumph of modern science!!

BBN: T ~ 10^9 K
Age ~ 1-3 minutes



CMB: T ~ 3000 K
Age ~ 380,000 years





Recap: what have we learned?

- **What evidence do we have to support the Hot Big Bang theory?**
  - **The Cosmic Microwave Background (CMB)**
  - Radiation left over from the Big Bang is now in the form of microwaves (millimeter wavelengths), which we observe with radio telescopes
  - Near-perfect thermal spectrum matches predictions of Big Bang theory

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  - **Big Bang Nucleosynthesis (BBN)**
  - Nuclear fusion created large amounts of Helium (age ~1-3 minutes) and small amounts of other light elements
  - Measurements of Helium and other elements agree with the predictions for fusion in the Big Bang theory