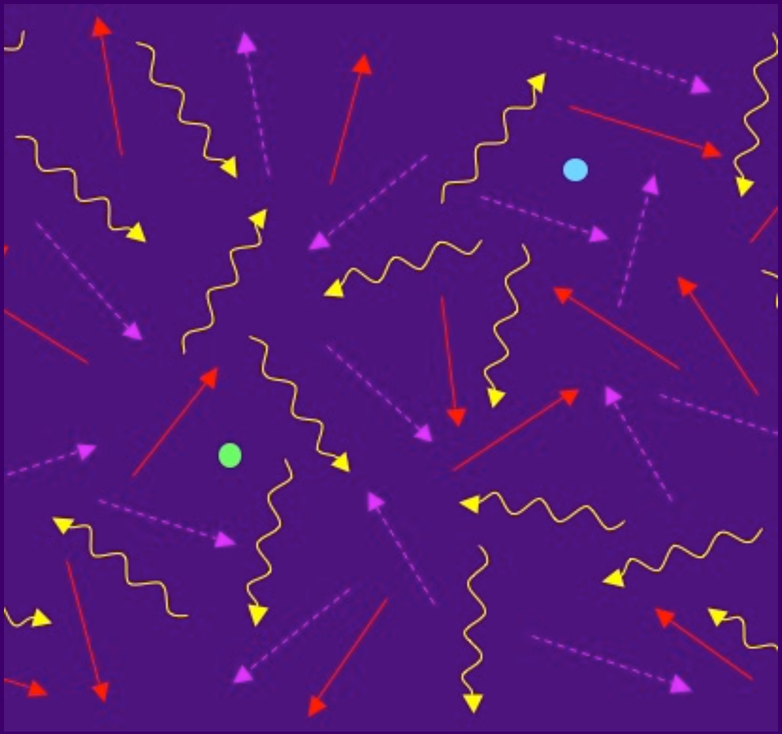
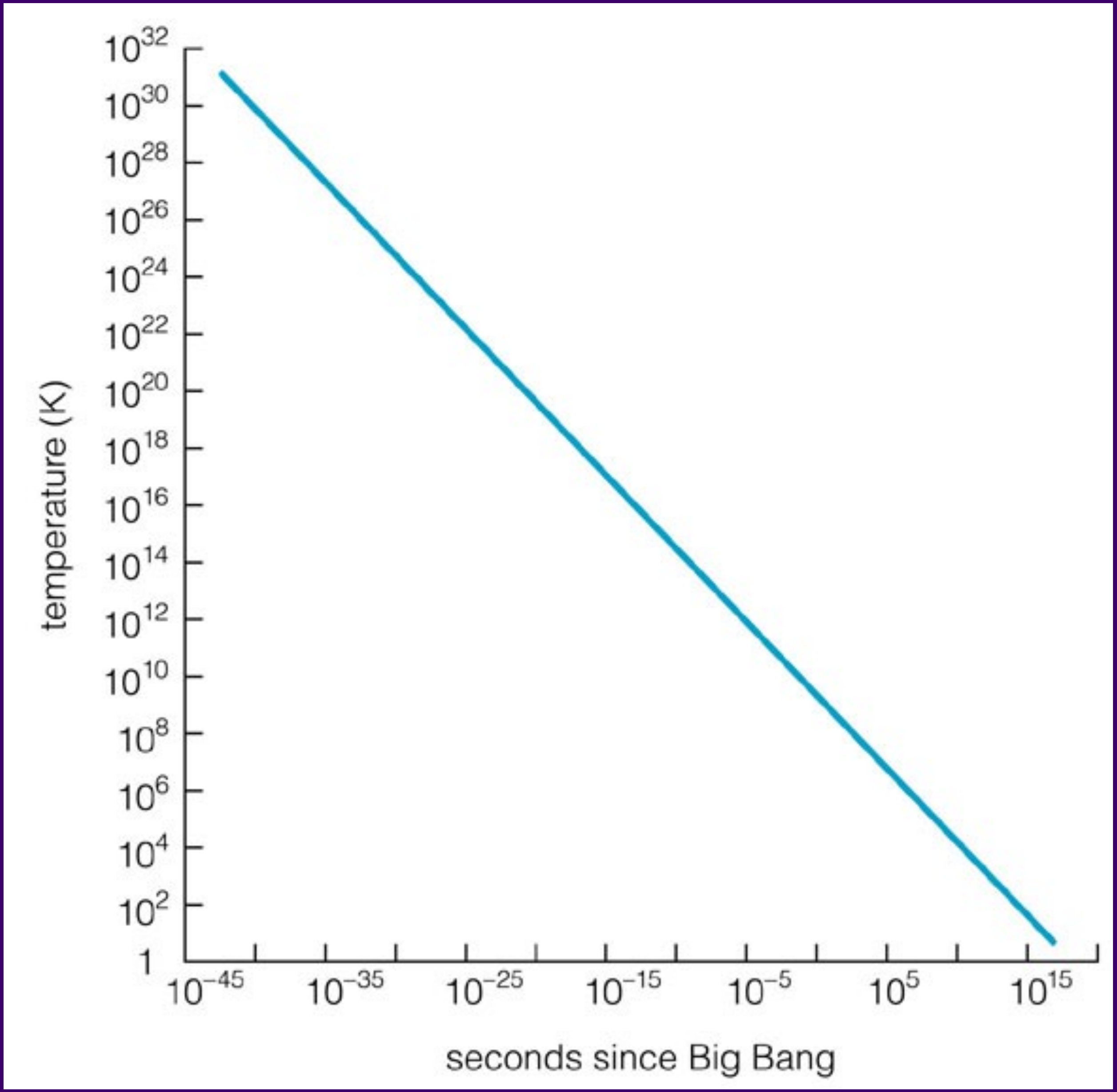


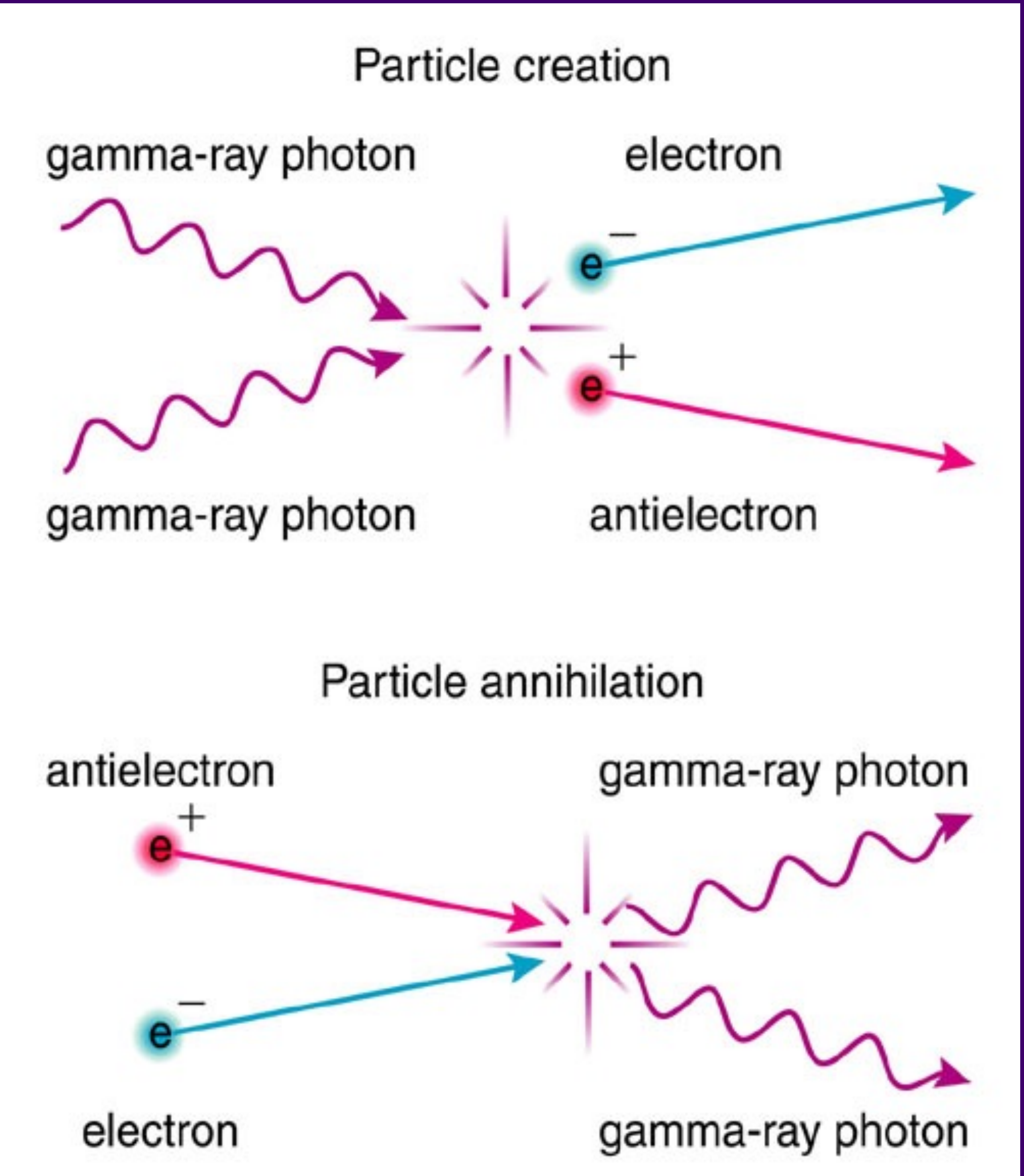
The Early Universe


the BIG BANG THEORY

Most people are familiar with the term 'Big Bang' theory. However when astronomer Sir Fred Hoyle first coined the phrase 'Big Bang' he did so in order to mock the theory. Hoyle was a firm believer in the alternative steady state theory which gives the universe no start or end. However the name stuck and the term Big Bang is now widely used although the irony has been lost.



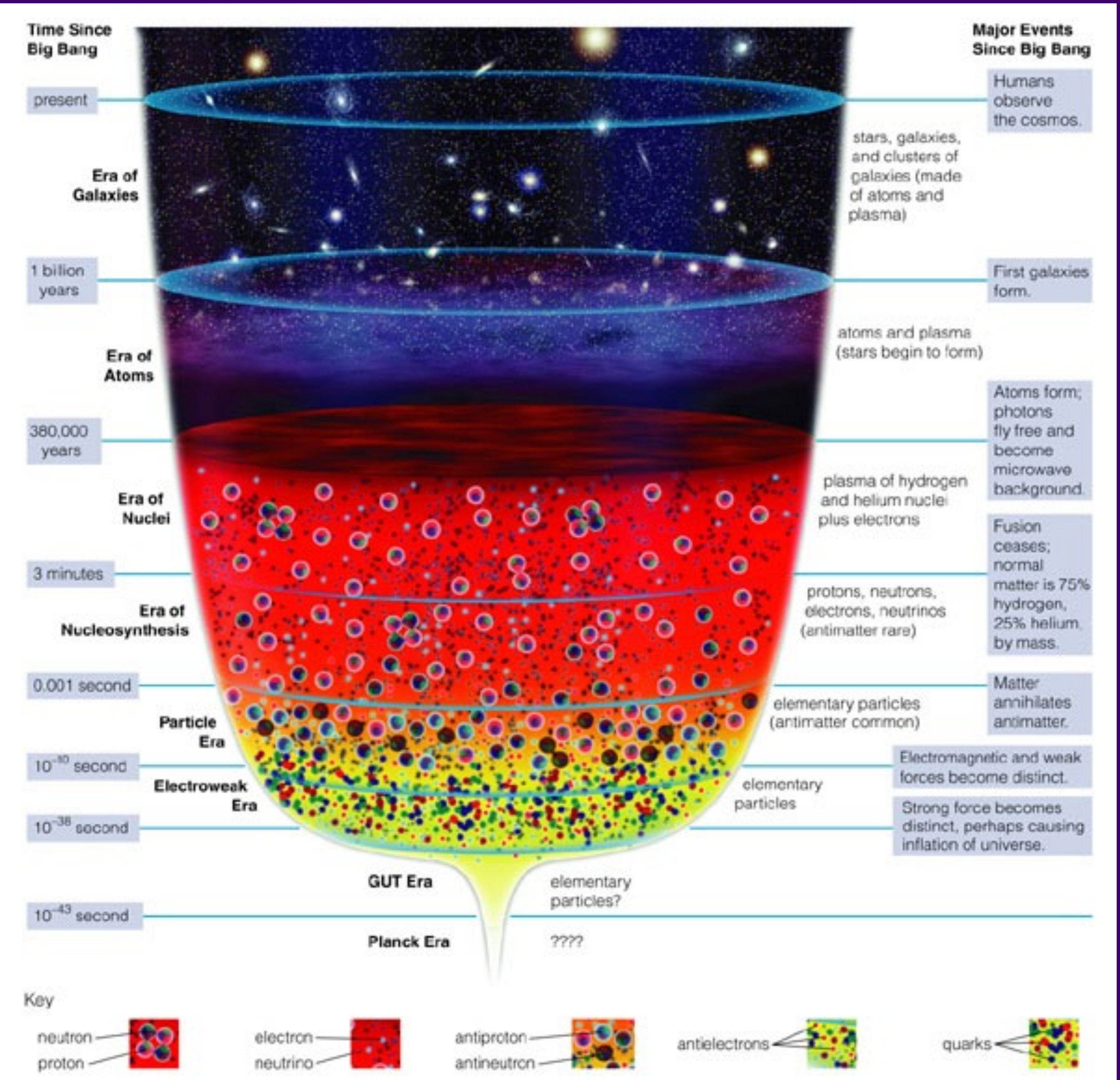
The early universe must have been extremely hot and dense



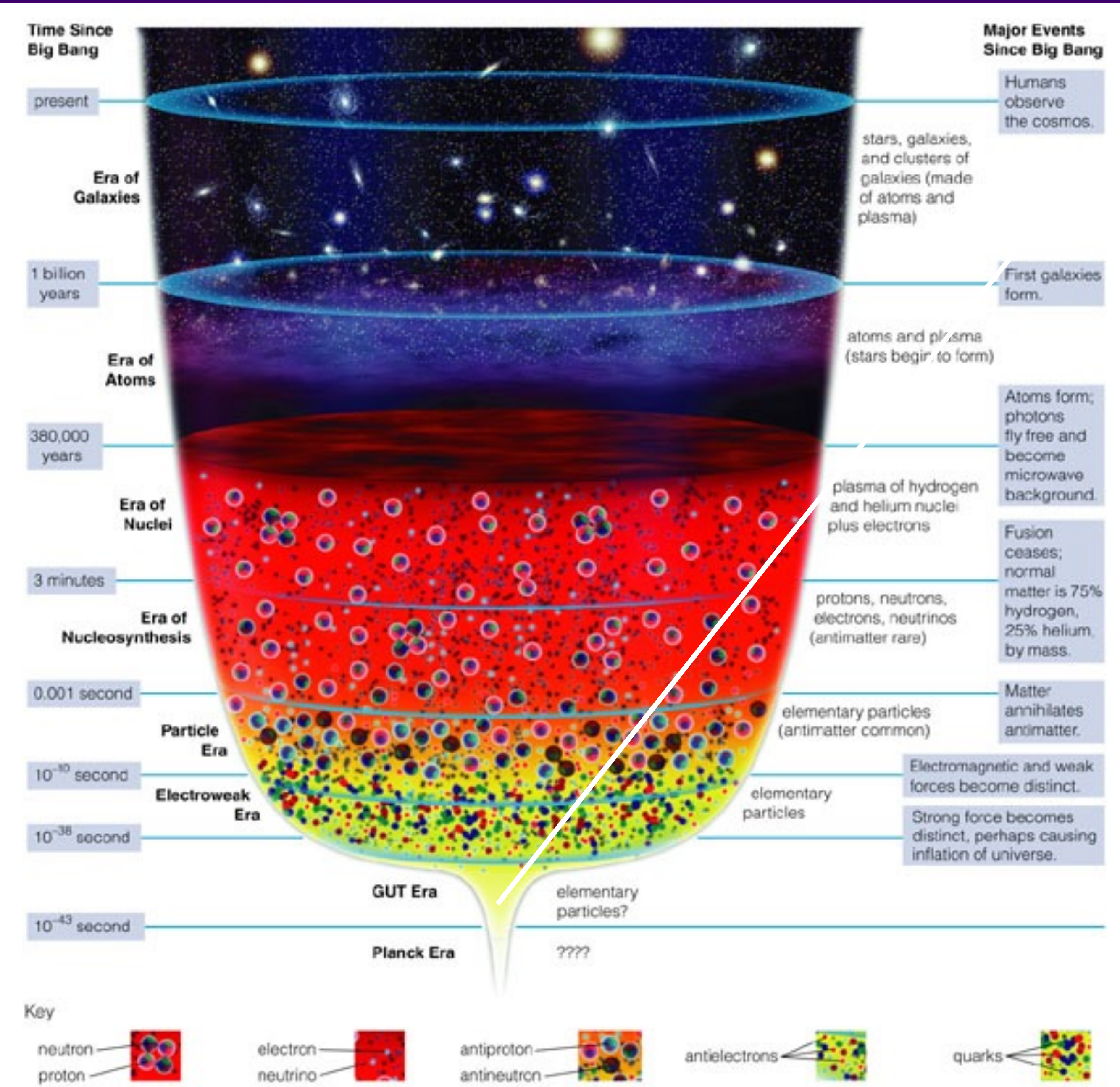
Photons converted into particle-antiparticle pairs and vice-versa

$$E = mc^2$$

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



Time Since Big Bang
Major Events Since Big Bang
present
Humans observe the cosmos.
stars, galaxies, and clusters of galaxies (made of atoms and plasma)
Era of Galaxies
1 billion years
First galaxies form.
atoms and plasma (stars begin to form)
Era of Atoms
380,000 years
Atoms form; photons fly free and become microwave background.
plasma of hydrogen and helium nuclei plus electrons
Era of Nuclei
Fusion ceases; normal matter is 75% hydrogen, 25% helium, by mass.
3 minutes
protons, neutrons, electrons, neutrinos (antimatter rare)
Era of Nucleosynthesis
0.001 second
Matter annihilates antimatter.
elementary particles (antimatter common)
Particle Era
10^{-10} second
Electromagnetic and weak forces become distinct.
Electroweak Era
elementary particles
10^{-38} second
Strong force becomes distinct, perhaps causing inflation of universe.
GUT Era
elementary particles?
10^{-43} second
Planck Era
????
Key
neutron
proton
electron
neutrino
antiproton
antineutron
antielectrons
quarks



Planck Era

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

No theory of quantum gravity

The Planck Regime: 2 Theories:

2 important length scales:

$$r_{sch} = \frac{2Gm}{c^2}$$

$$\lambda_{compton} = \frac{h}{mc}$$

Gravitation

Quantum Mechanics

$$\frac{2Gm}{c^2} = \frac{h}{mc}$$

$$Gm^2 = \hbar c$$

$$m^2 = \frac{\hbar c}{G}$$

factor of p!

$$\left(\hbar = \frac{h}{2\pi} \right)$$

[redacted]

The Planck mass

$$m_{pl} = \sqrt{\frac{\hbar c}{G}}$$

Planck mass = 5.46 x 10^{-5} gm

$$\lambda_{pl} = \left(\frac{G\hbar}{c^3}\right)^{1/2}$$

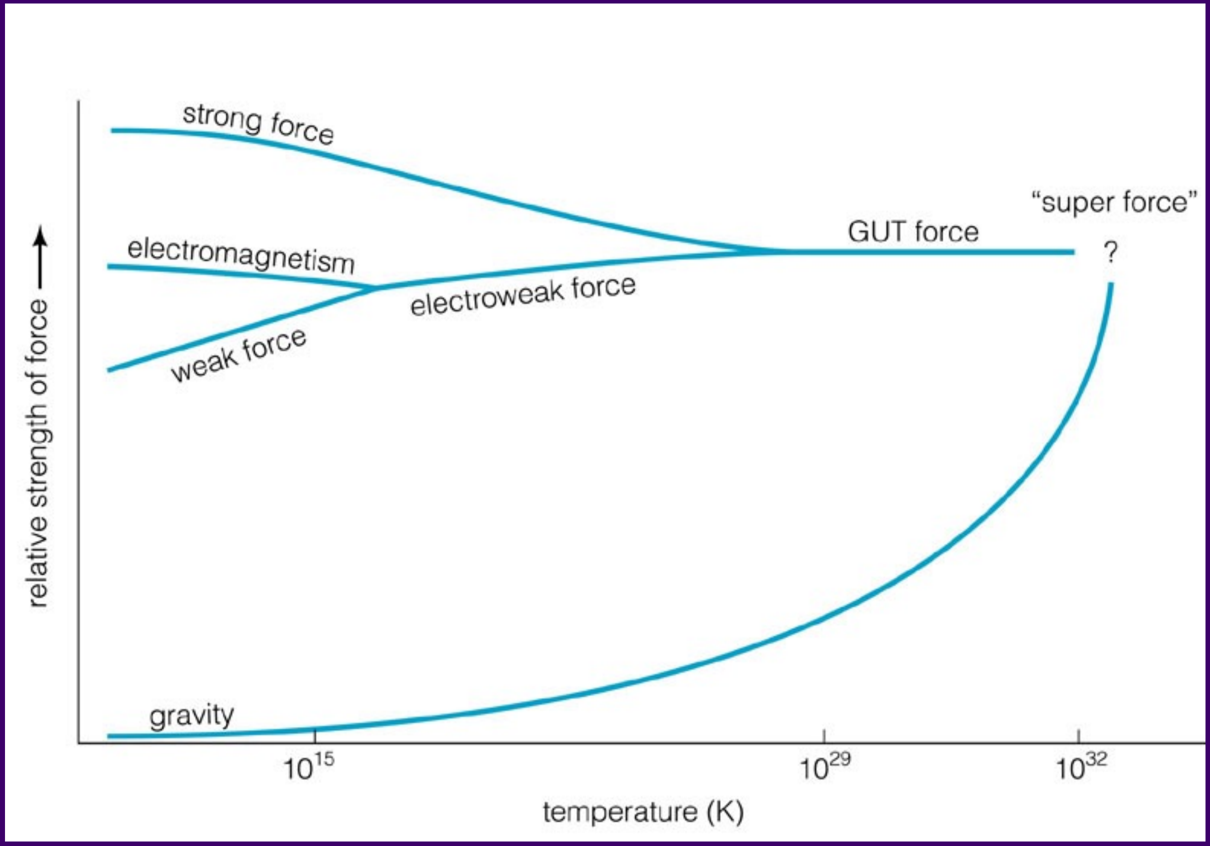
Planck length ~ 10^{-33} cm

$$t_{pl} = \left(\frac{G\hbar}{c^5}\right)^{1/2}$$

Planck time ~ 10^{-43} sec

$$E_{pl} = \sqrt{\frac{\hbar c^5}{G}}$$

Planck energy ~ 10^{19} GeV



Four known forces in universe:

Strong Force

Electromagnetism

Weak Force

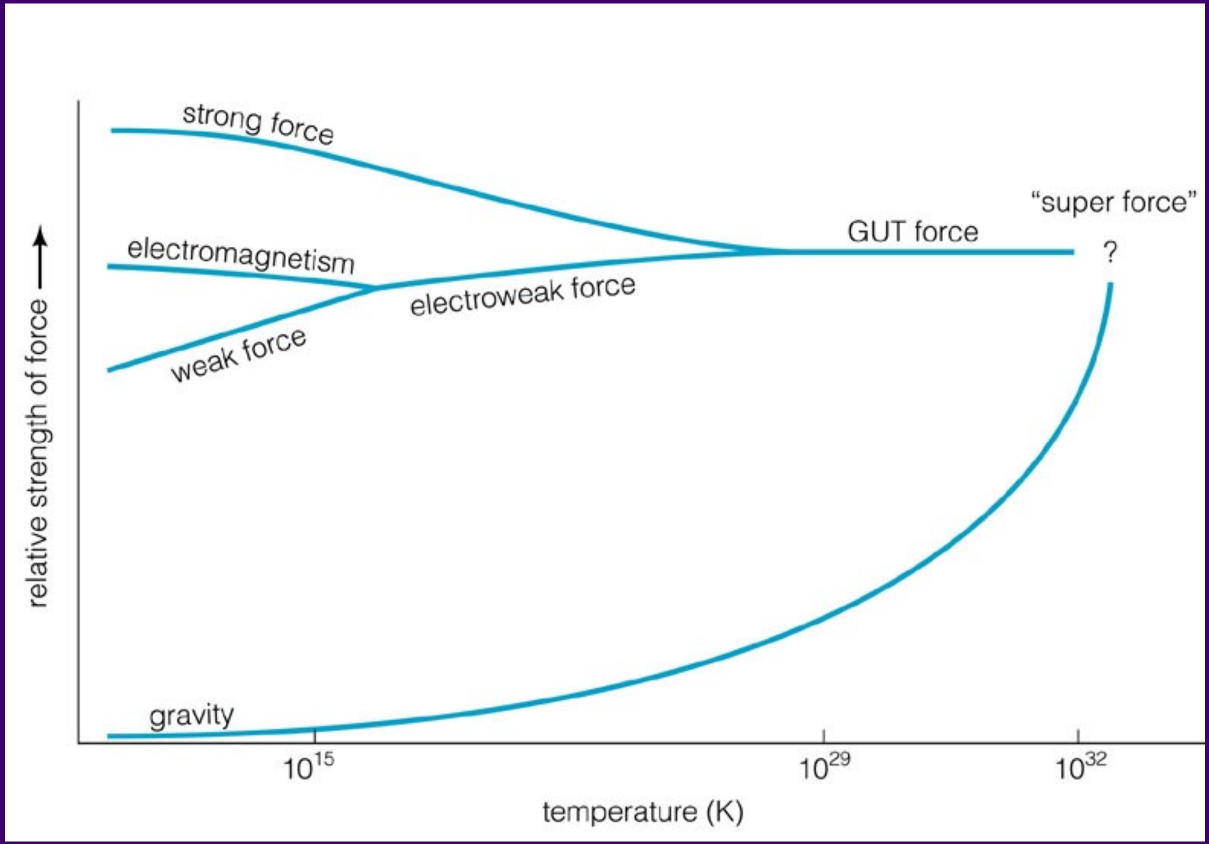
Gravity

Thought Question

Which of the four forces keeps you from sinking to the center of the Earth?

A. Gravity
B. Electromagnetism
C. Strong Force
D. Weak Force

Do forces unify at high temperatures?



Four known forces in universe:

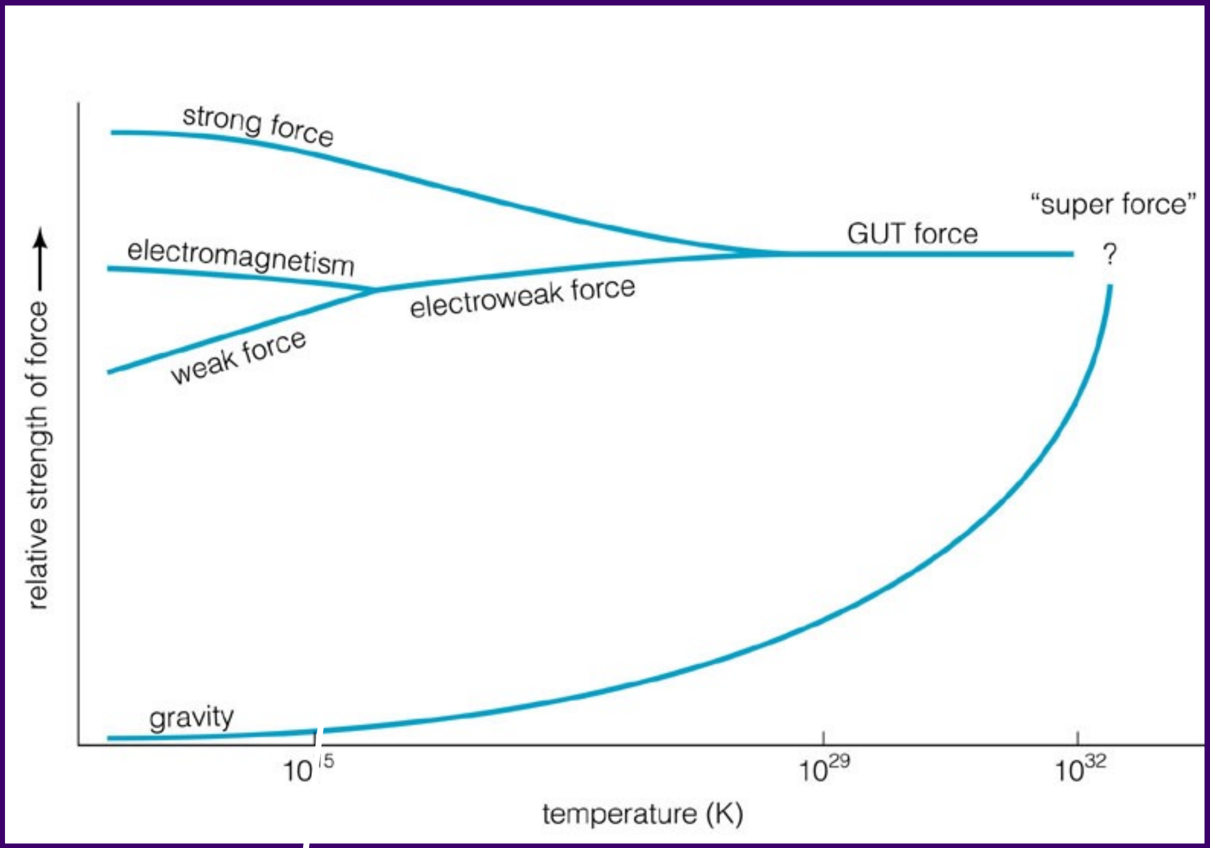
Strong Force

Electromagnetism

Weak Force

Gravity

Do forces unify at high temperatures?



Yes!
(Electroweak)

Four known forces in universe:

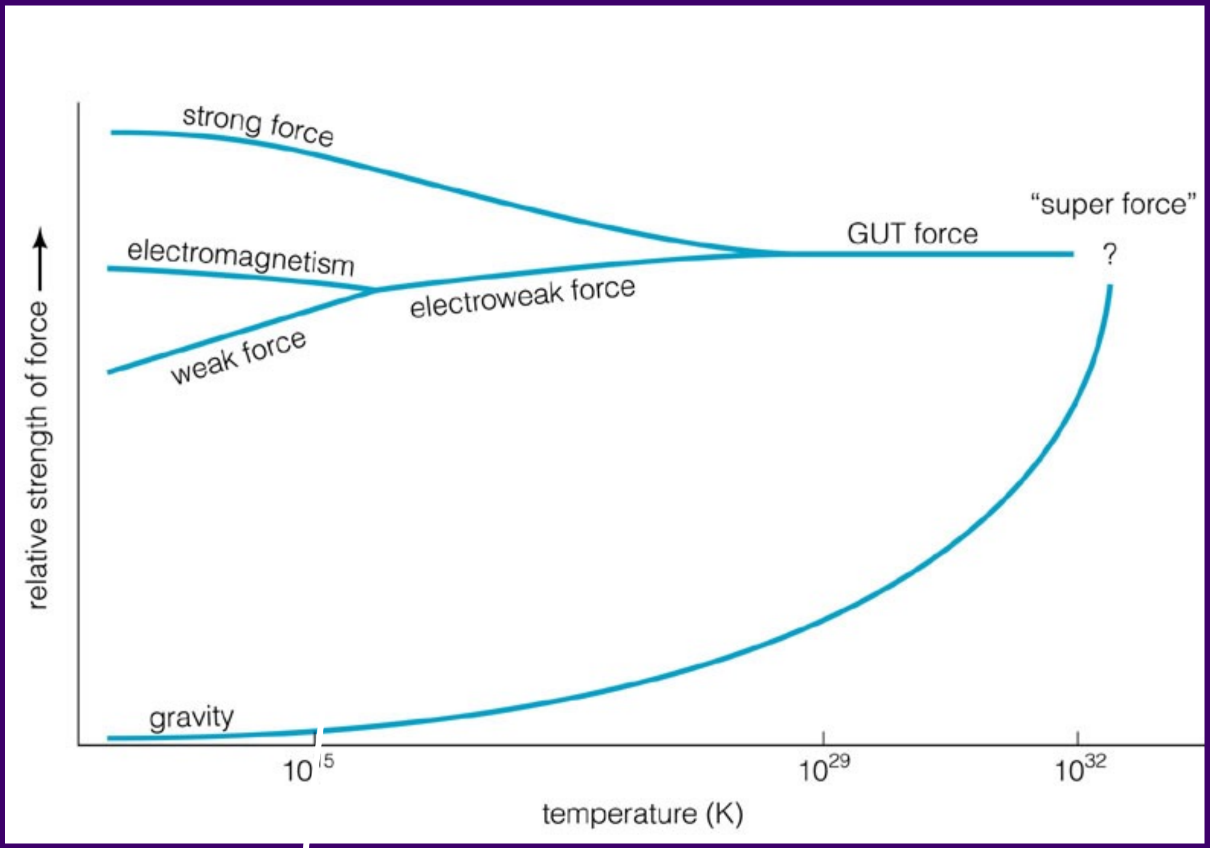
Strong Force

Electromagnetism

Weak Force

Gravity

Do forces unify at high temperatures?



Four known forces in universe:

Strong Force

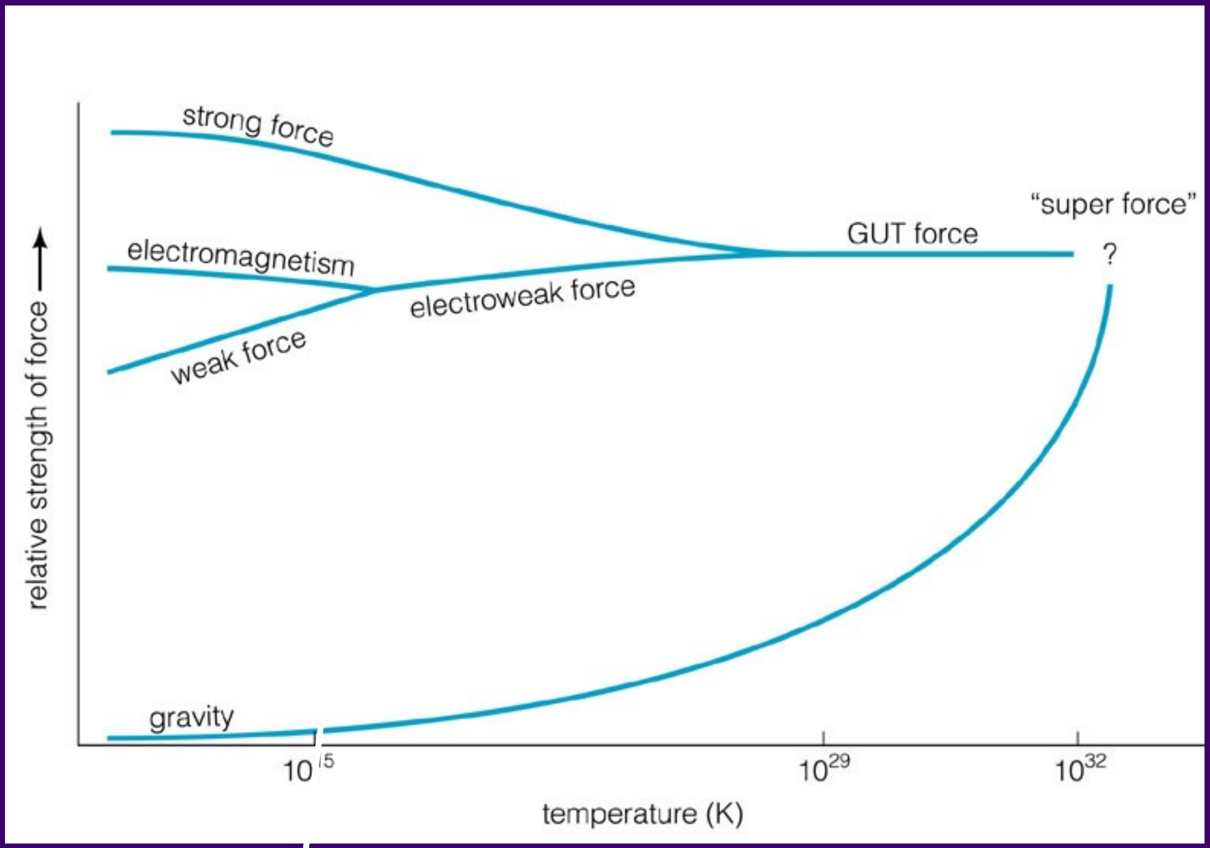
Electromagnetism

Weak Force

Gravity

Yes!
(Electroweak)

Do forces unify at high temperatures?



Four known forces in universe:

Strong Force

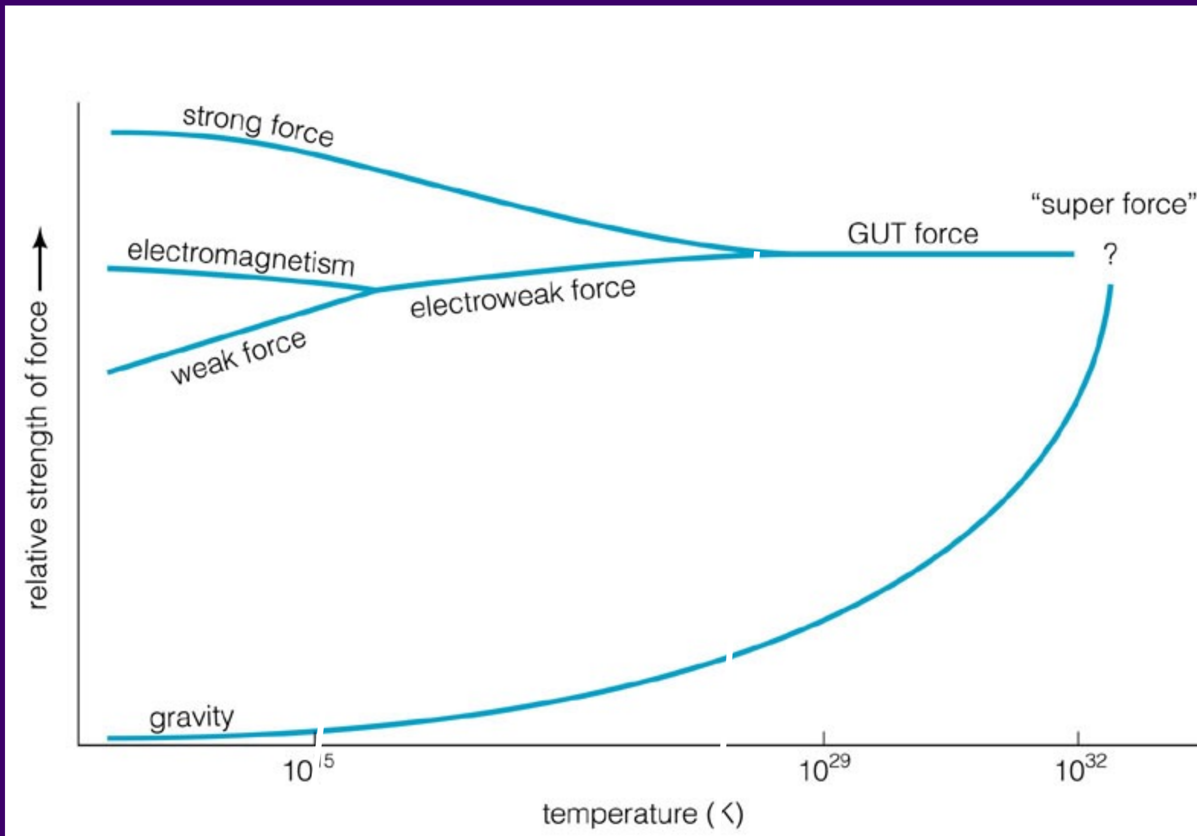
Electromagnetism

Weak Force

Gravity

Yes!
(Electroweak)

Do forces unify at high temperatures?



Four known forces in universe:

Strong Force

Electromagnetism

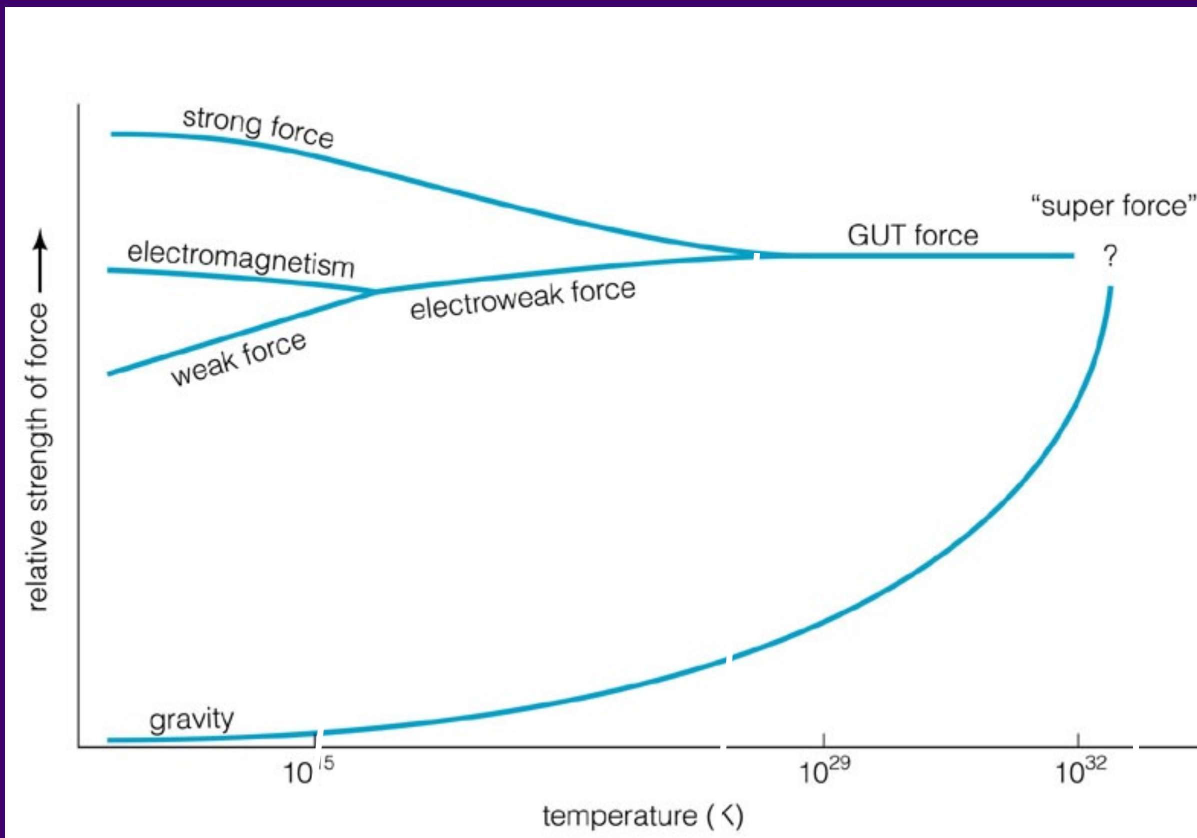
Weak Force

Gravity

Yes!
(Electroweak)

Maybe
(GUT)

Do forces unify at high temperatures?



Four known forces in universe:

Strong Force

Electromagnetism

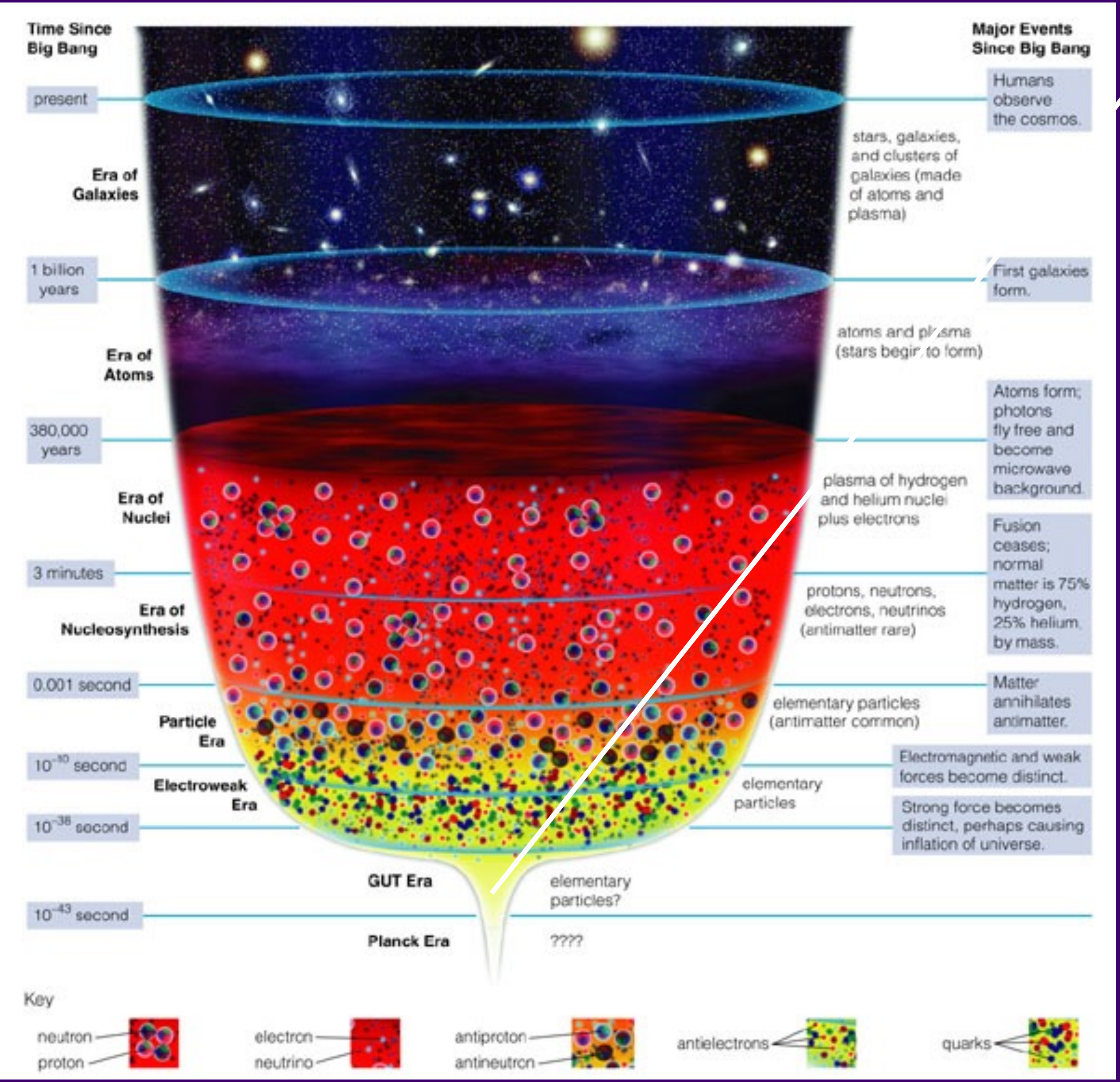
Weak Force

Gravity

Yes!
(Electroweak)

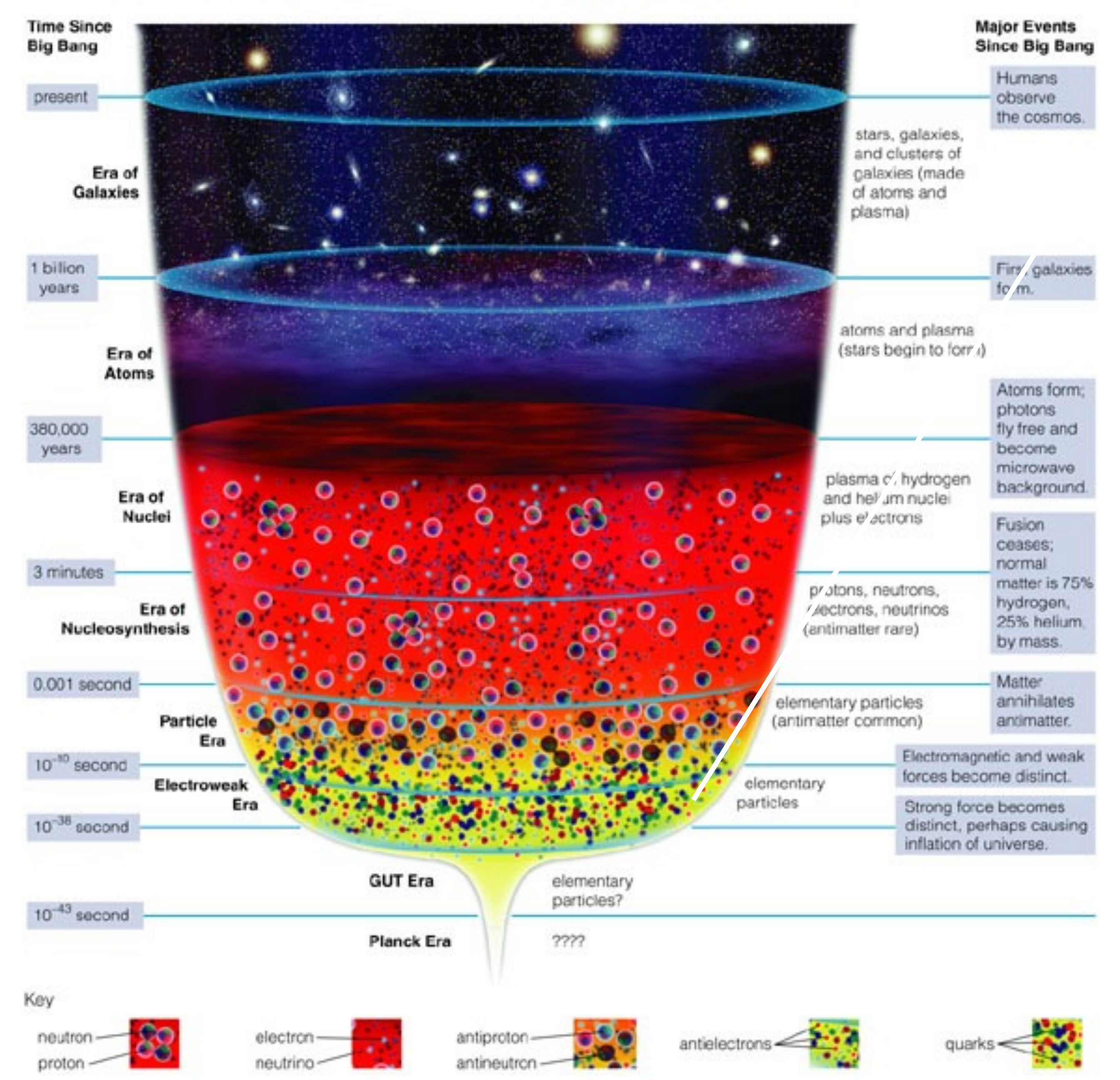
Maybe
(GUT)

Who knows?
(String Theory)



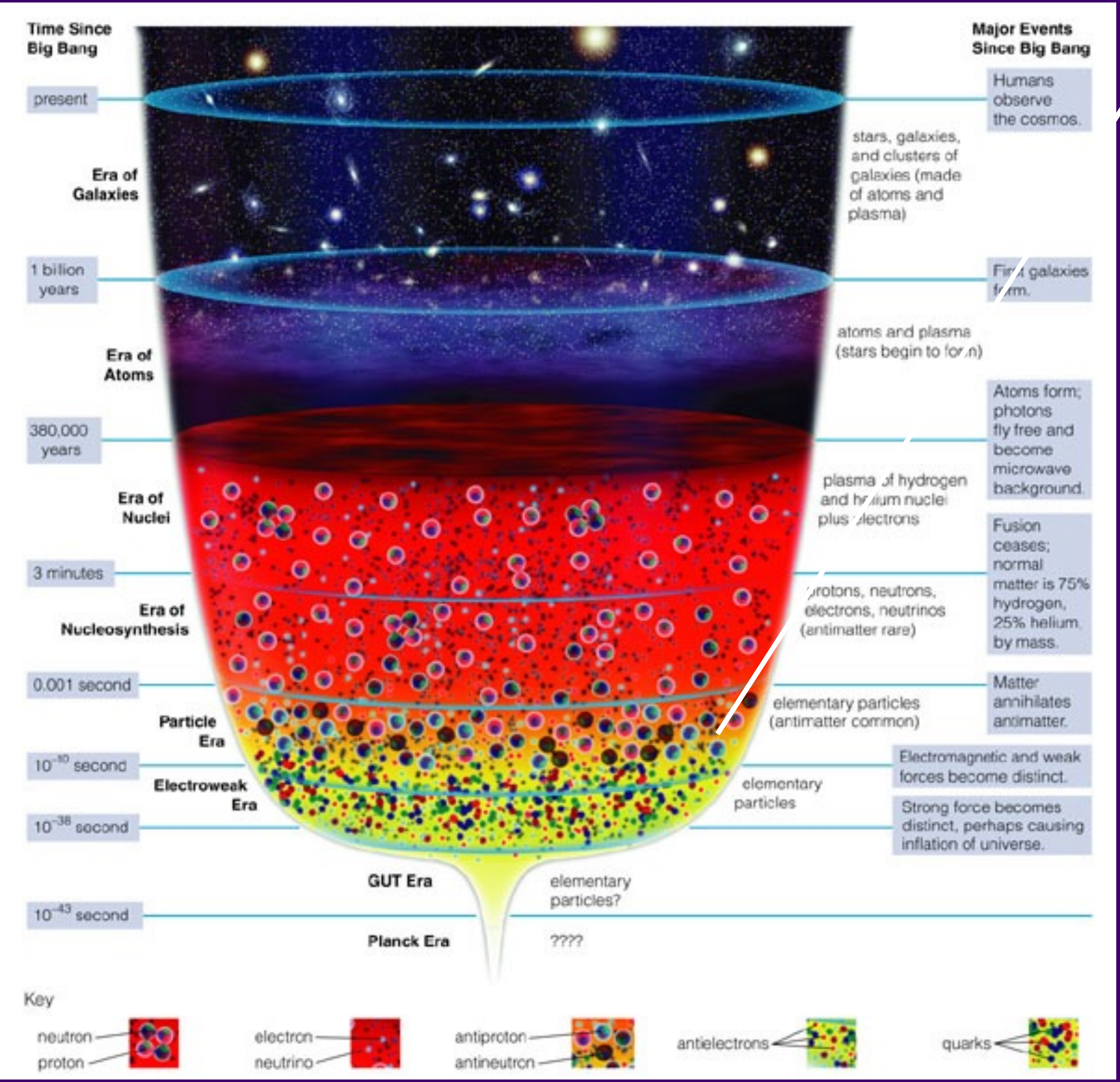
GUT Era

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



Electroweak Era

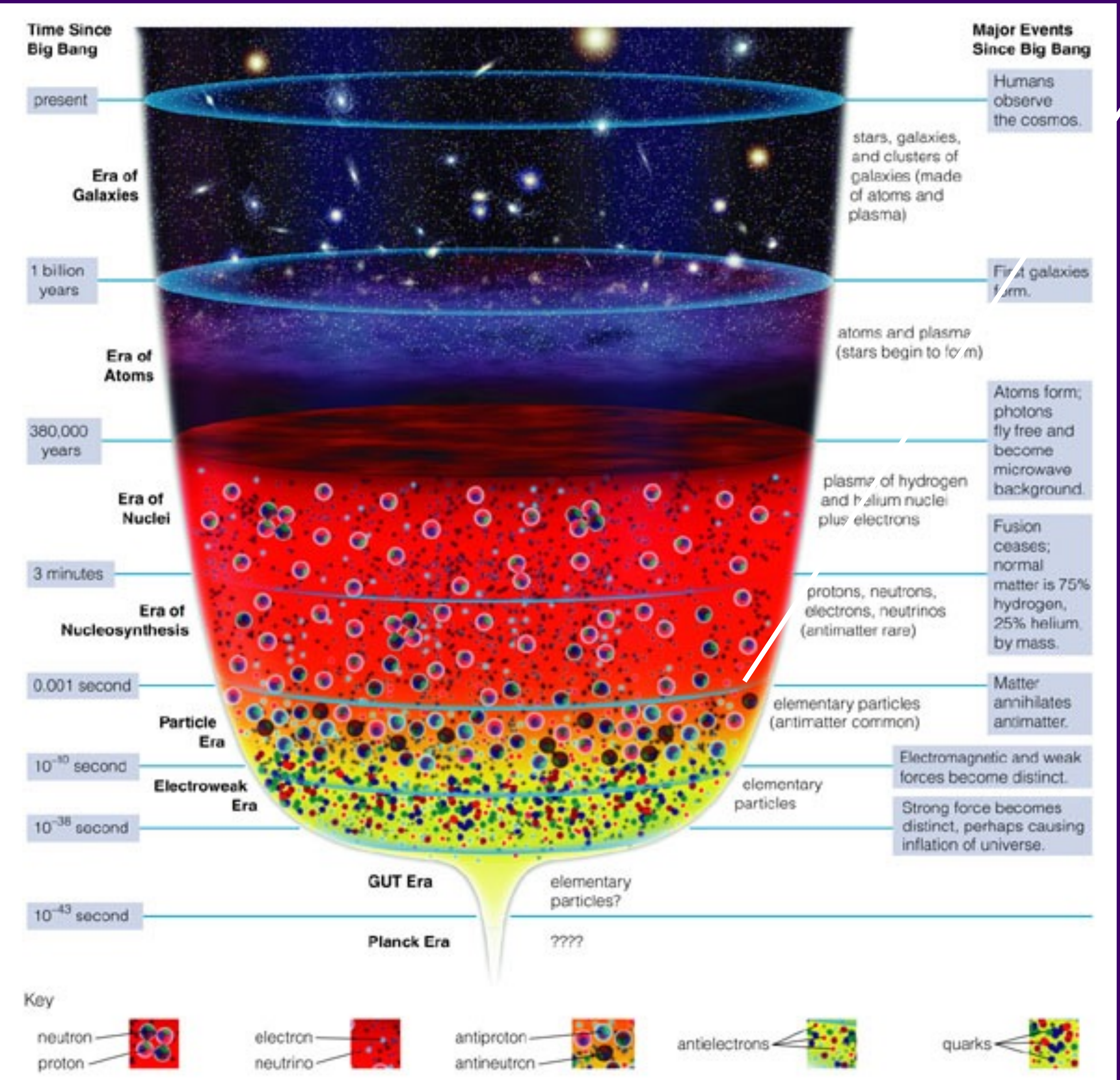
Lasts from end of GUT force (~10^{-38} sec) to end of electroweak force (~10^{-10} sec)



Particle Era

Amounts of matter and antimatter nearly equal

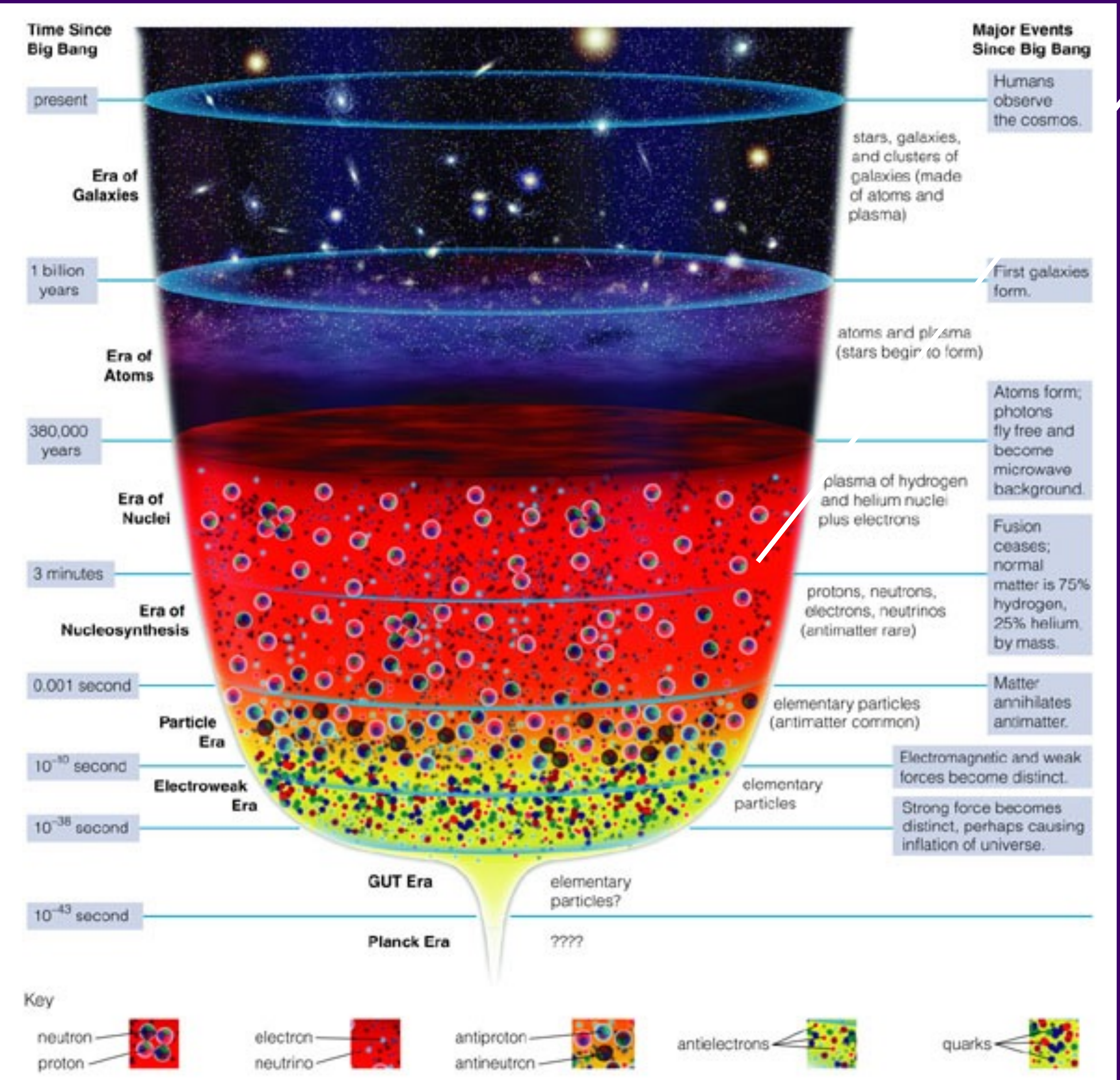
(Roughly 1 extra proton for every 10^9 proton-antiproton pairs!)



Era of Nucleo-synthesis

Begins when matter annihilates remaining antimatter at ~ 0.001 sec

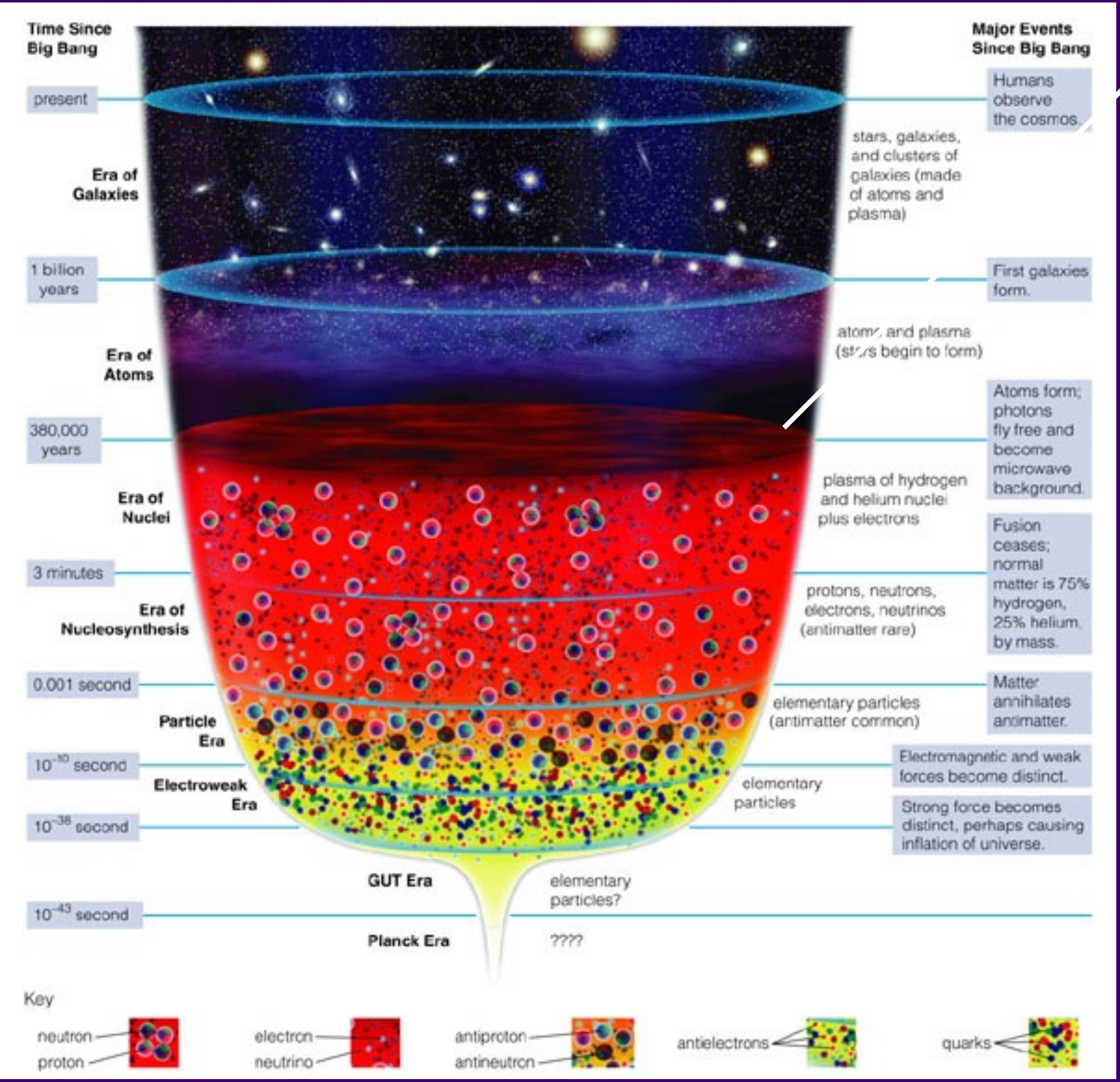
Nuclei begin to fuse



Era of Nuclei

Helium nuclei form at age ~ 3 minutes

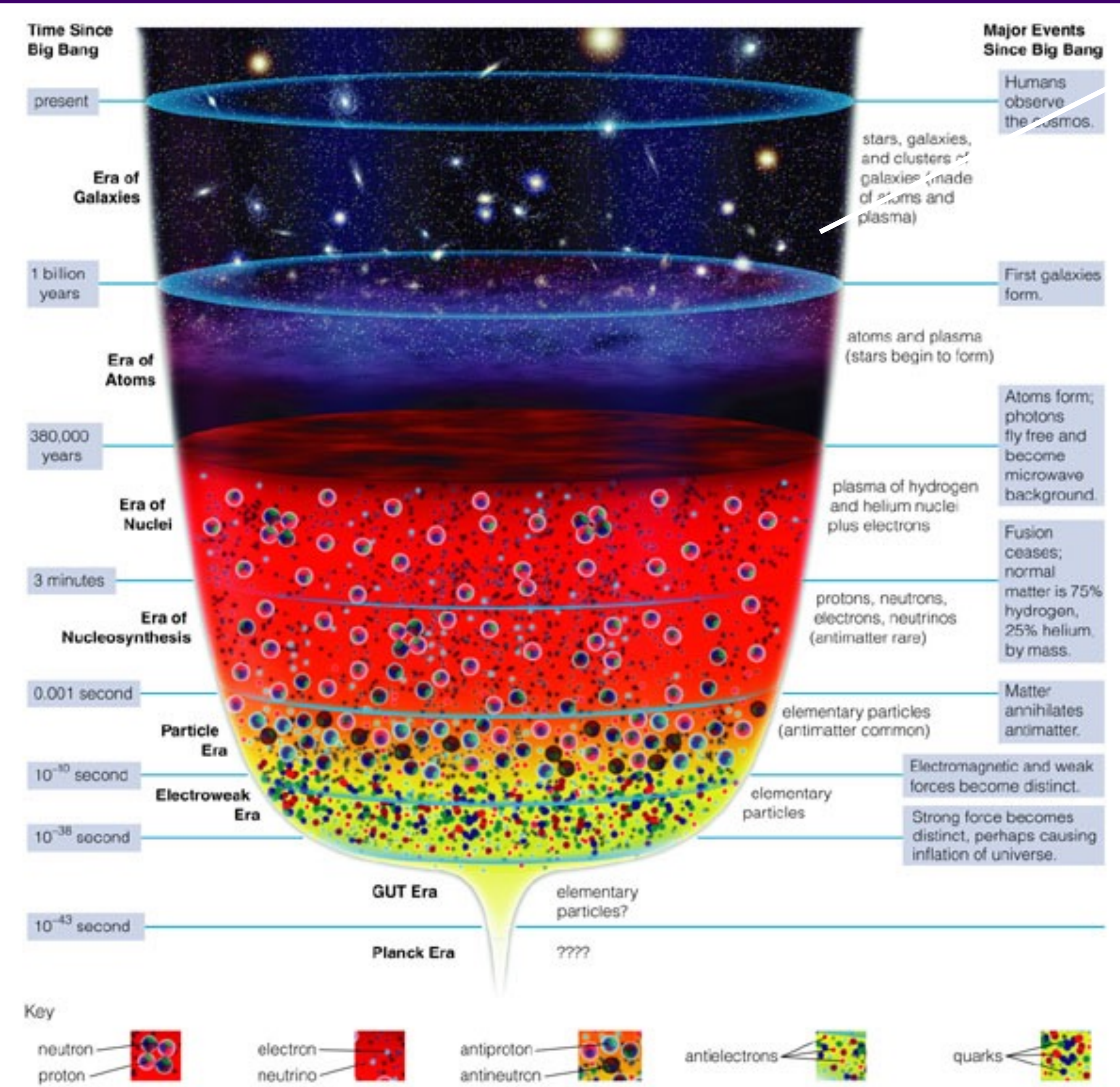
Universe has become too cool to blast helium apart



Era of Atoms

Atoms form at age of ~ 380,000 years

Background radiation released



Era of Galaxies

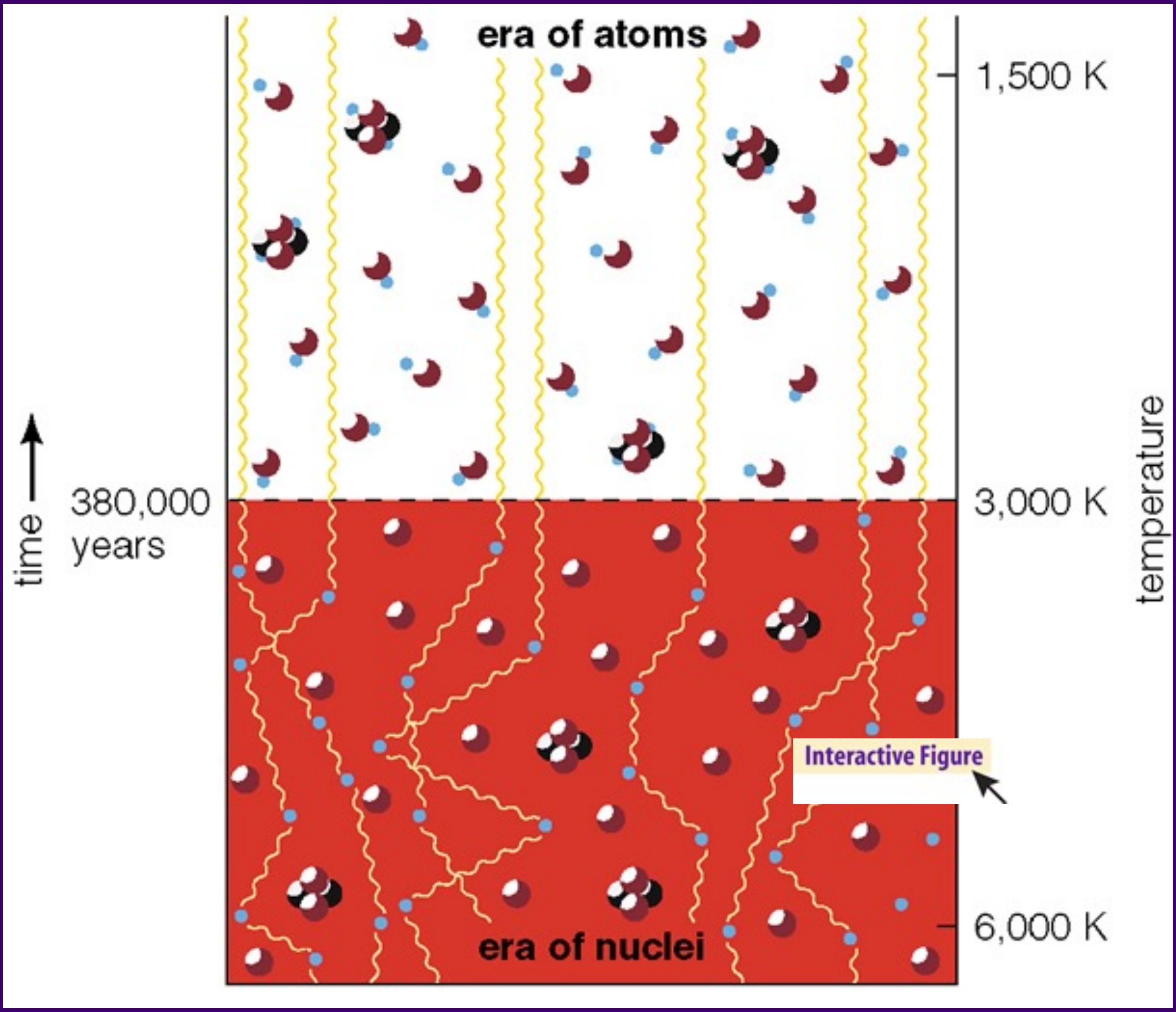
Galaxies form at age ~ 1 billion years

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.

Evidence #1



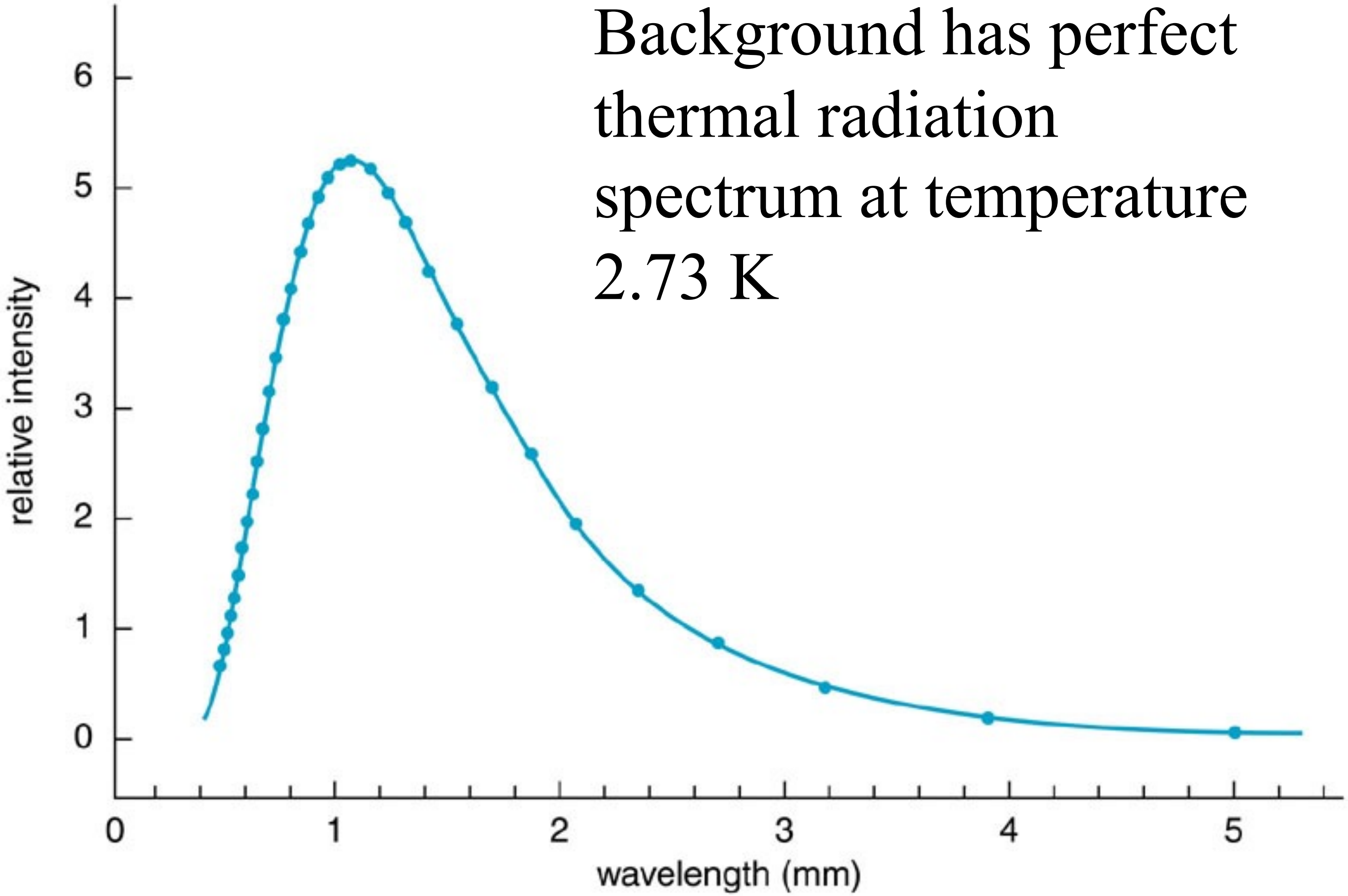
Background radiation from Big Bang has been freely streaming across universe since atoms formed at temperature ~ 3,000 K: *visible/IR*

The radiation left over from the Big Bang – how do we observe it?

The ***cosmic microwave background*** – the radiation left over from the Big Bang – was detected by Penzias & Wilson in 1965 (they won the Nobel prize in 1978 for this discovery)

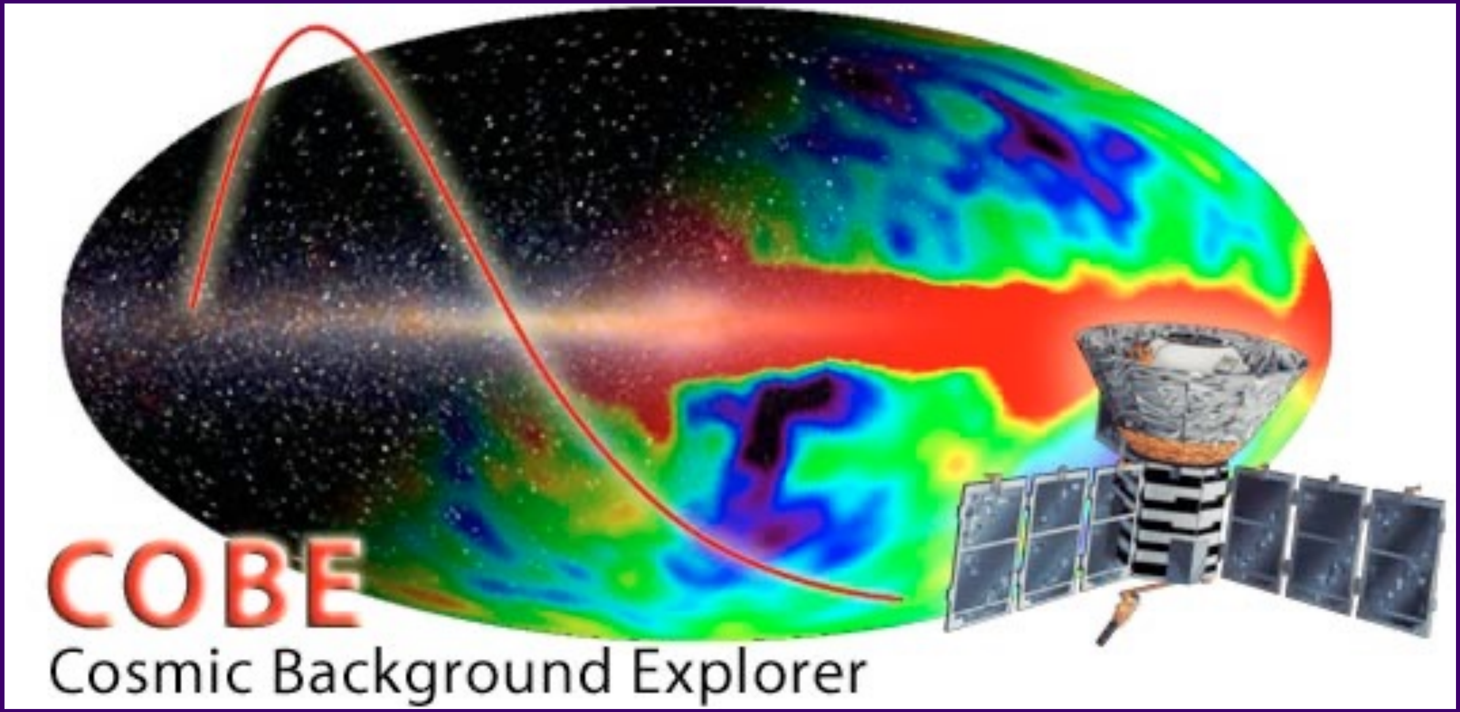
Bob Dicke and his Princeton group – which included Dave Wilkinson and Jim Peebles – were building a radiometer to look for the relic radiation from the early universe. Pensias and Wilson had already discovered it – but they didn't know what it was!!!

Bernie Burke at MIT (a radio astronomer) had heard the complaints of Pensias and Wilson and knew of Dicke's program. He suggested that Penzias contact Dicke… and the rest is history.



Background has perfect thermal radiation spectrum at temperature 2.73 K

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



COBE detected the seeds of future structure formation

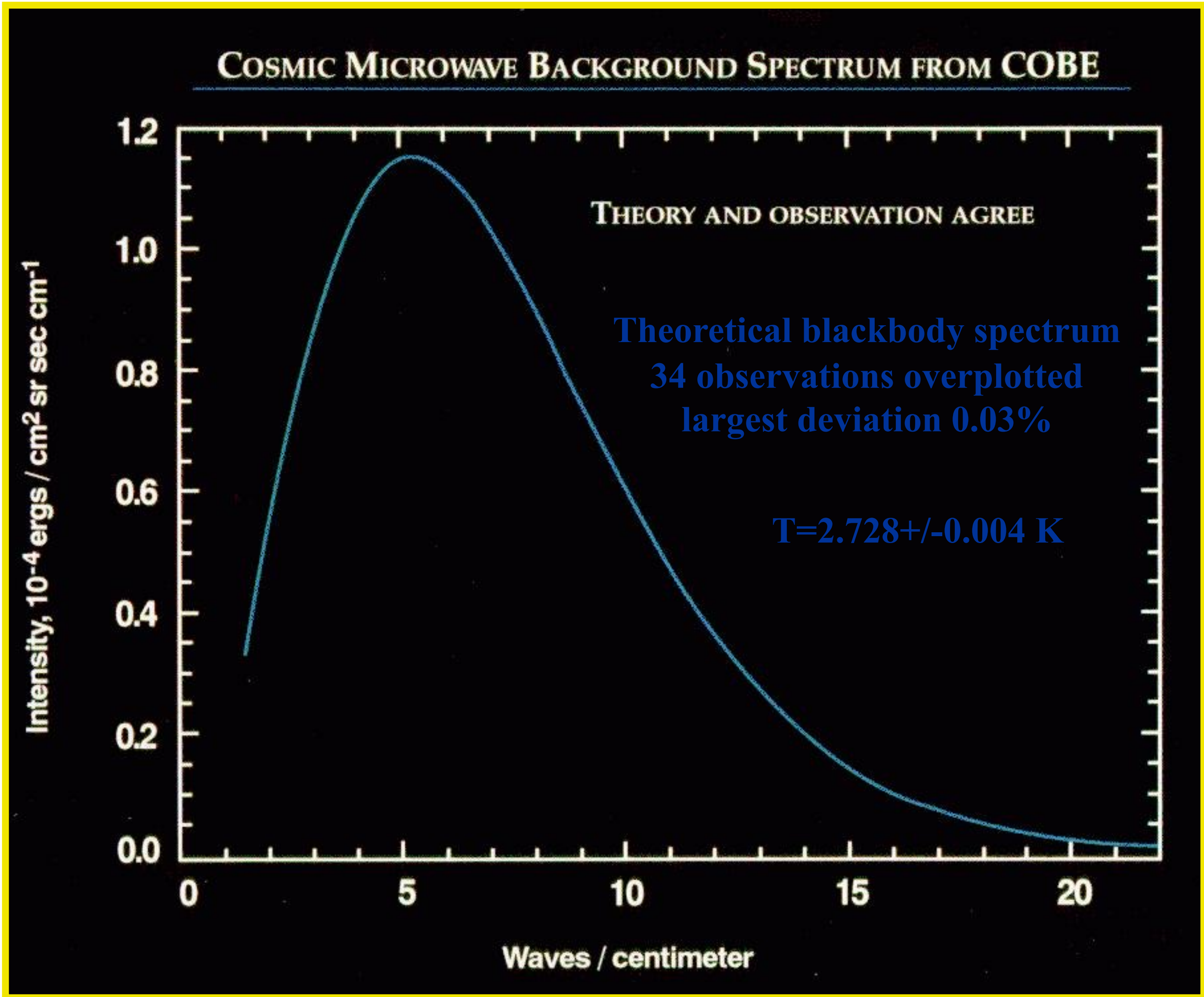
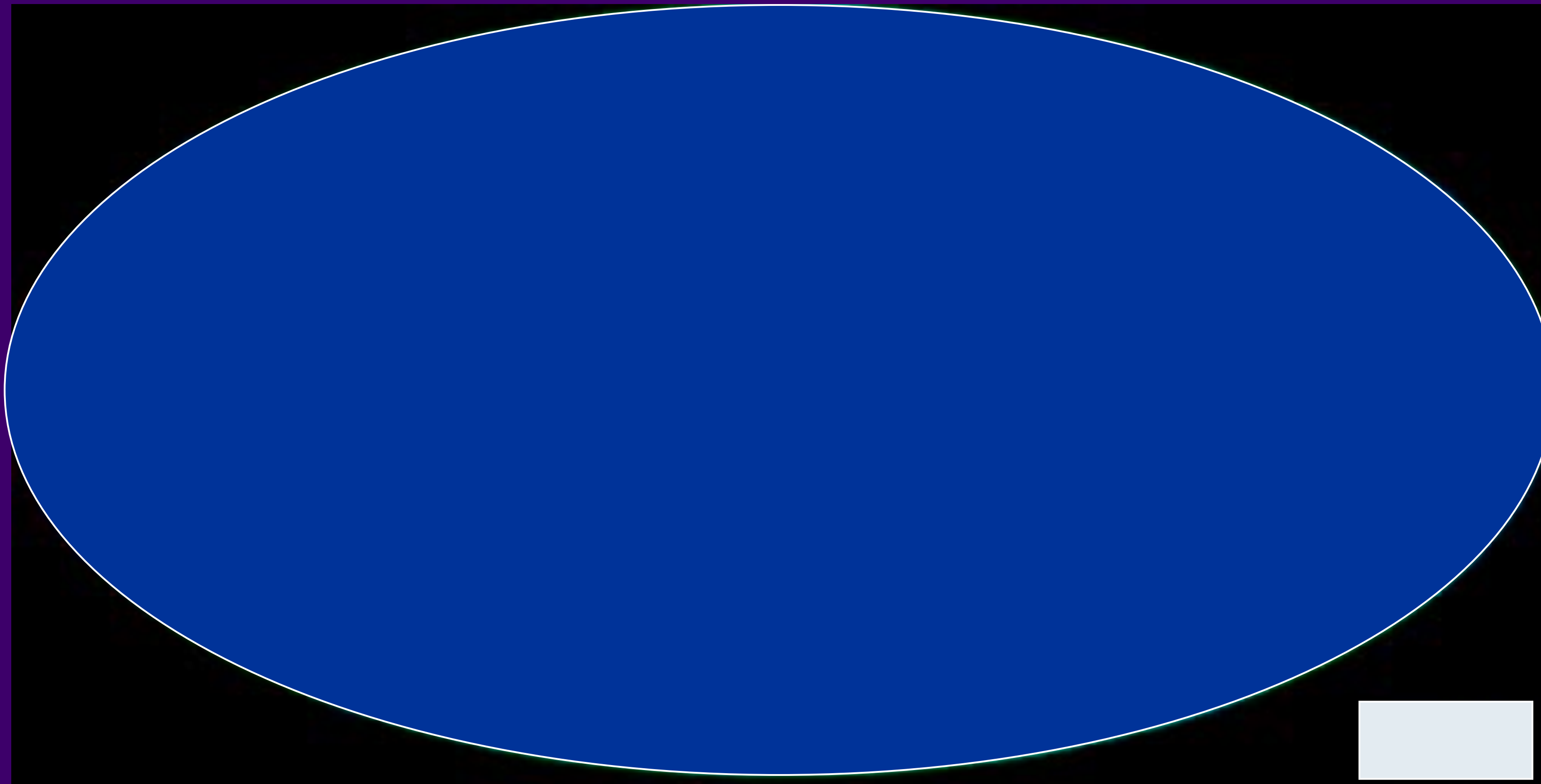
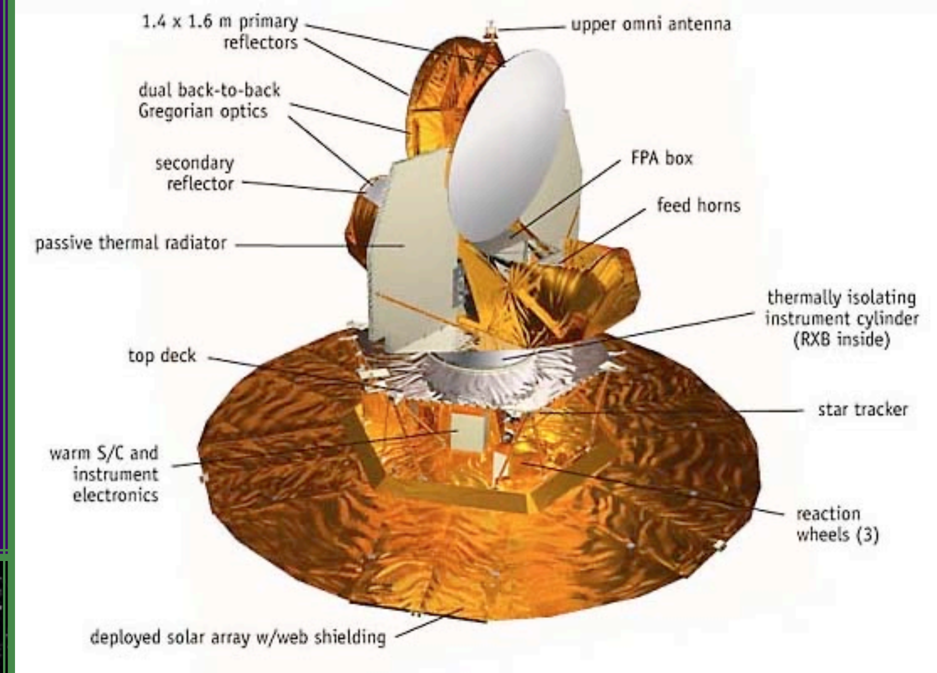


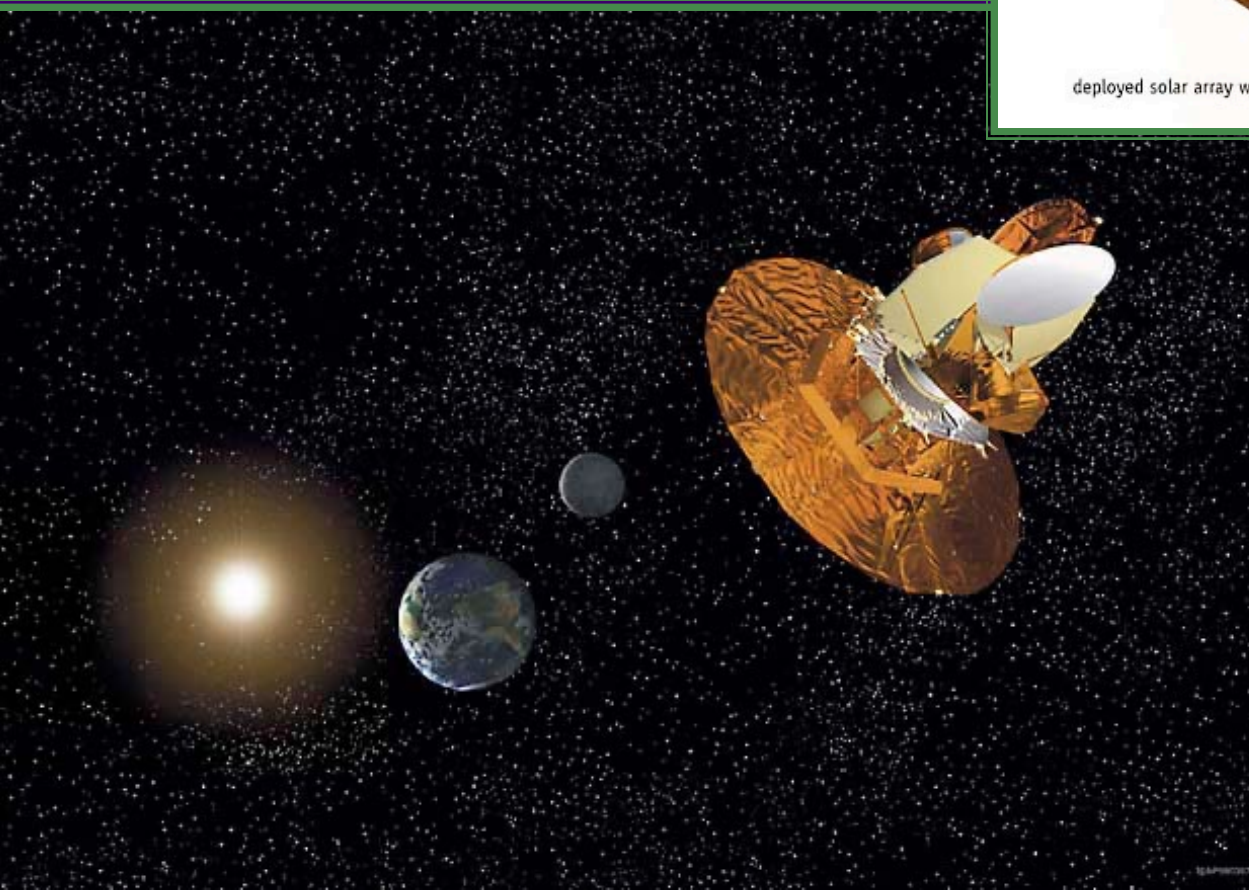
Image courtesy COBE homepage.

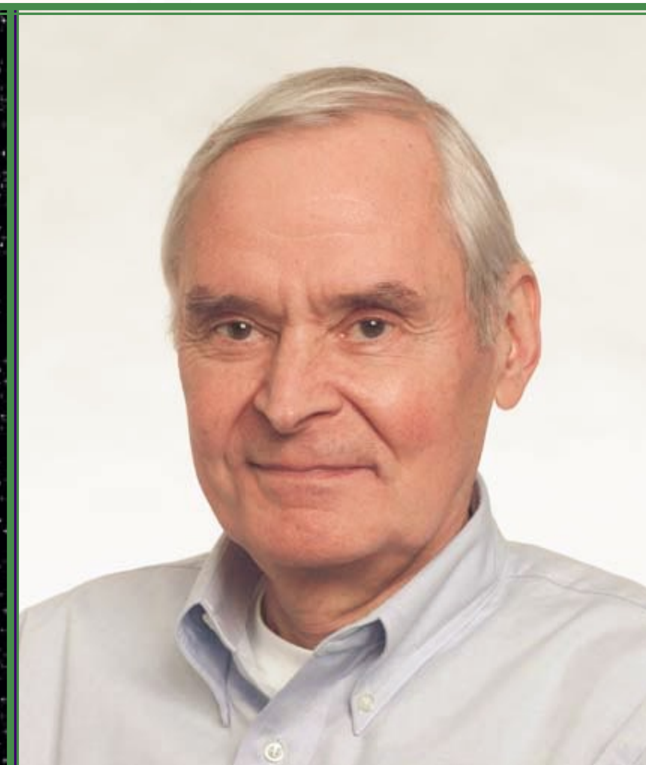


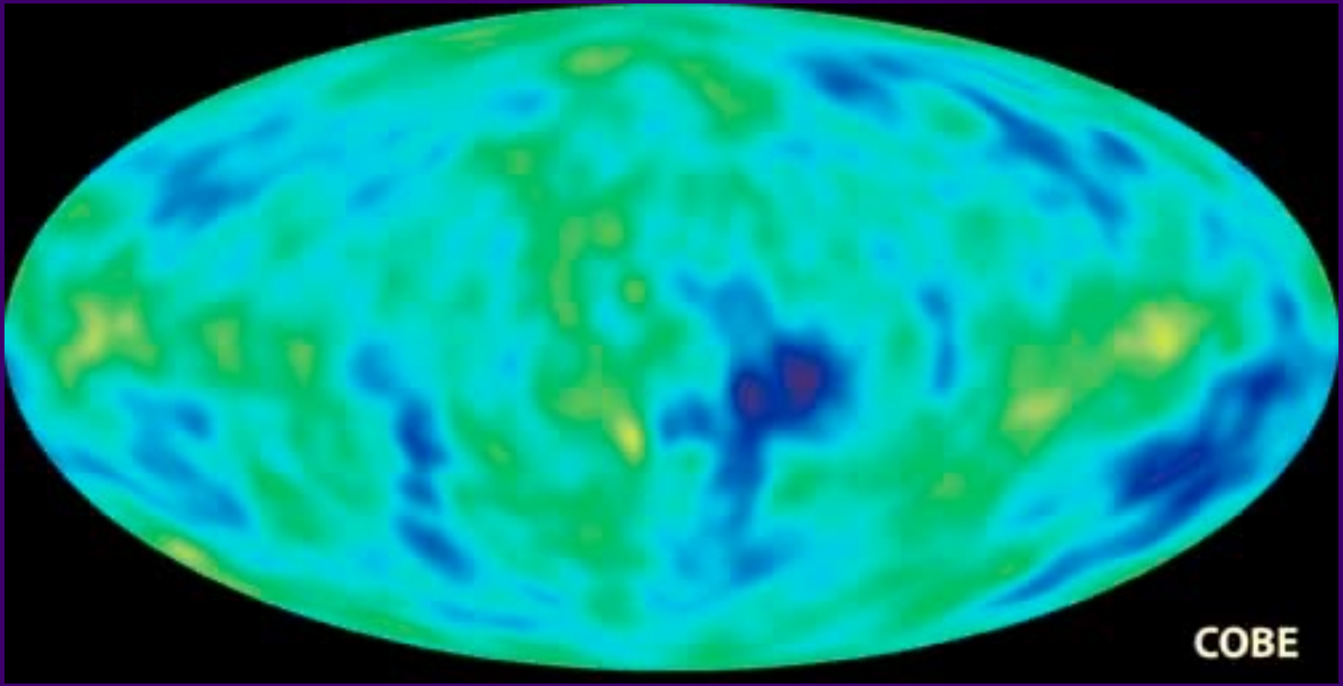
$DT/T \sim 10^{-5}$

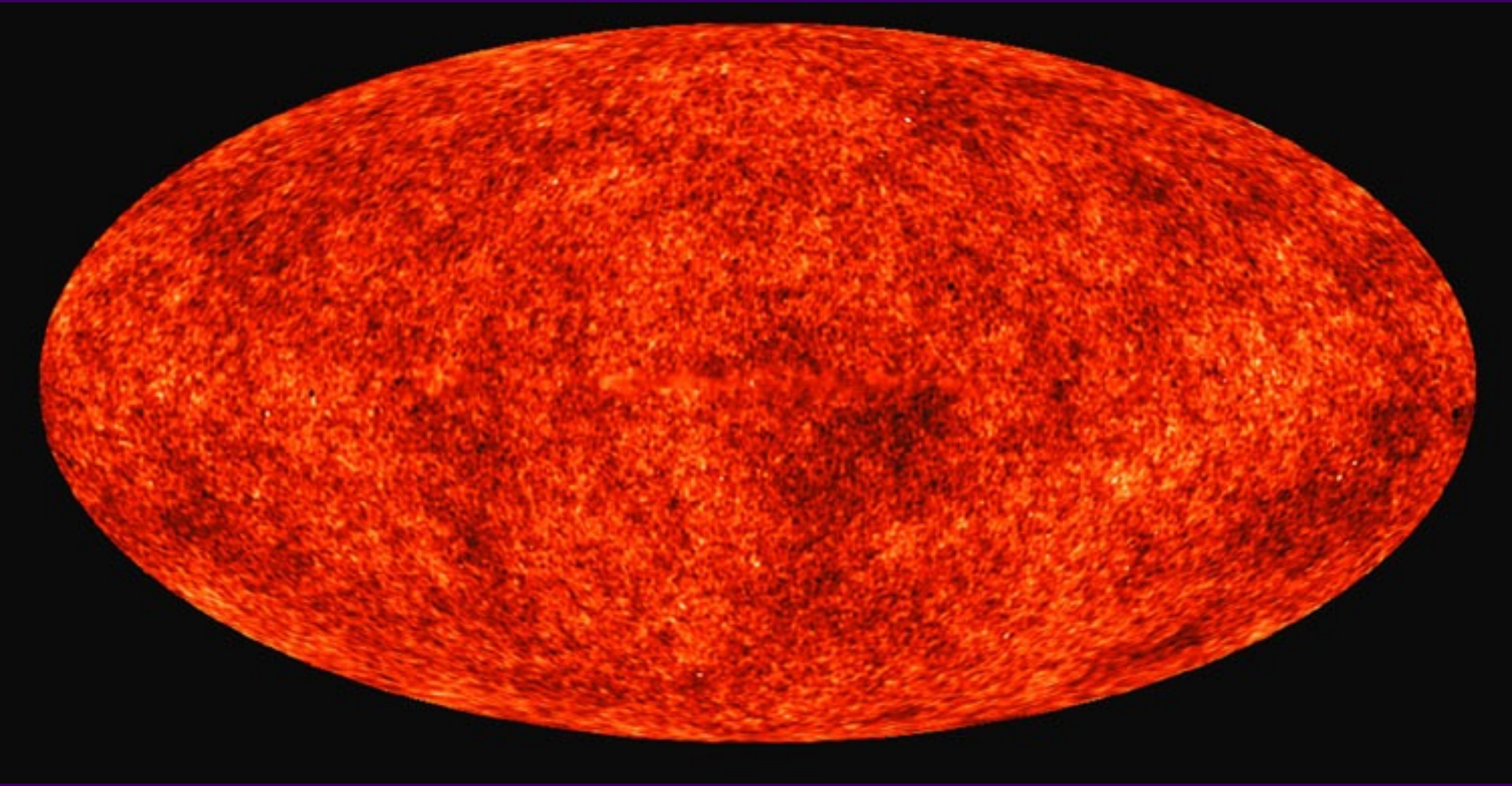
WMAP


1.4 x 1.6 m primary reflectors
upper omni antenna
dual back-to-back Gregorian optics
secondary reflector
FPA box
feed horns
passive thermal radiator
thermally isolating instrument cylinder (RXB inside)
top deck
star tracker
warm S/C and instrument electronics
reaction wheels (3)
deployed solar array w/web shielding

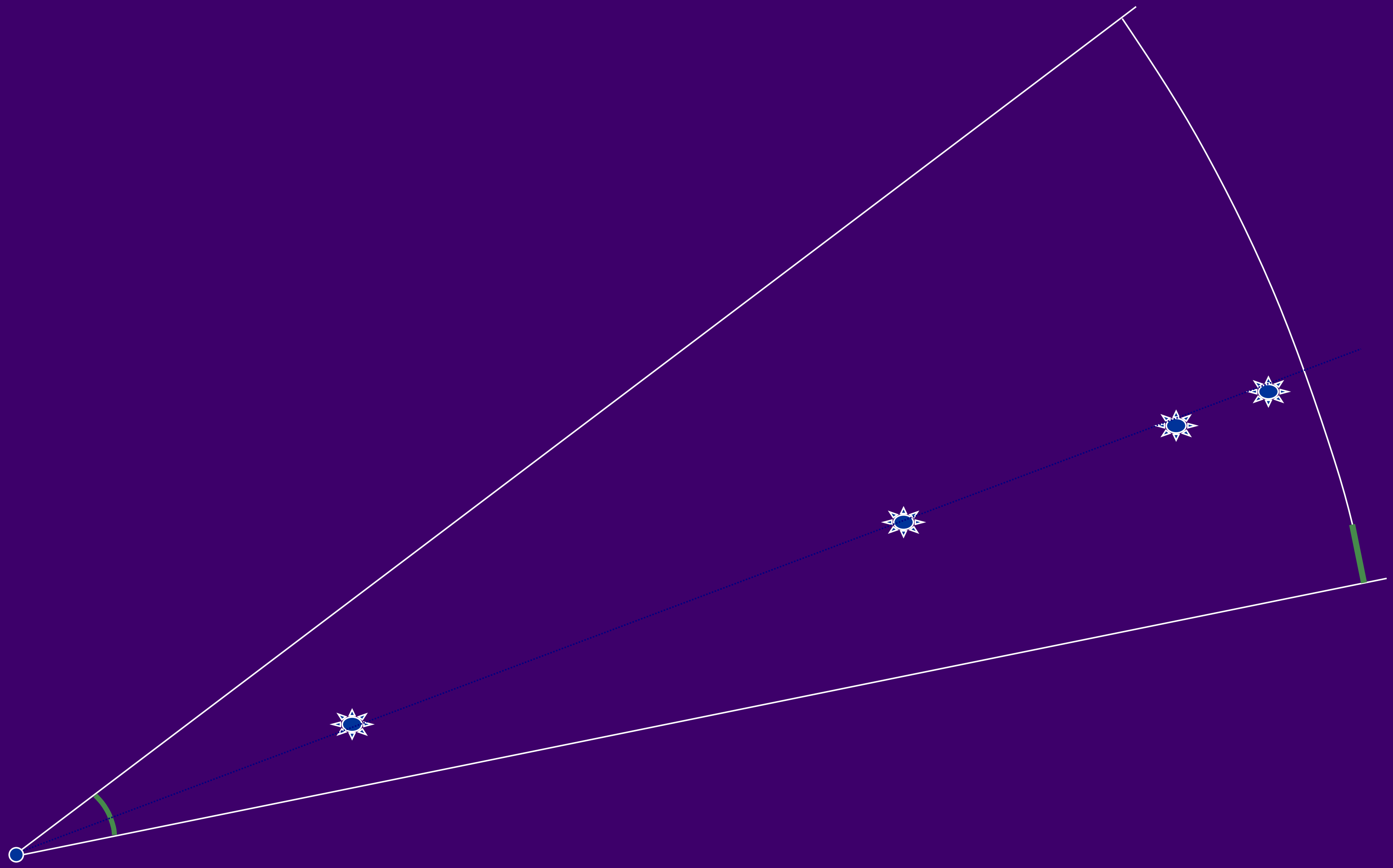




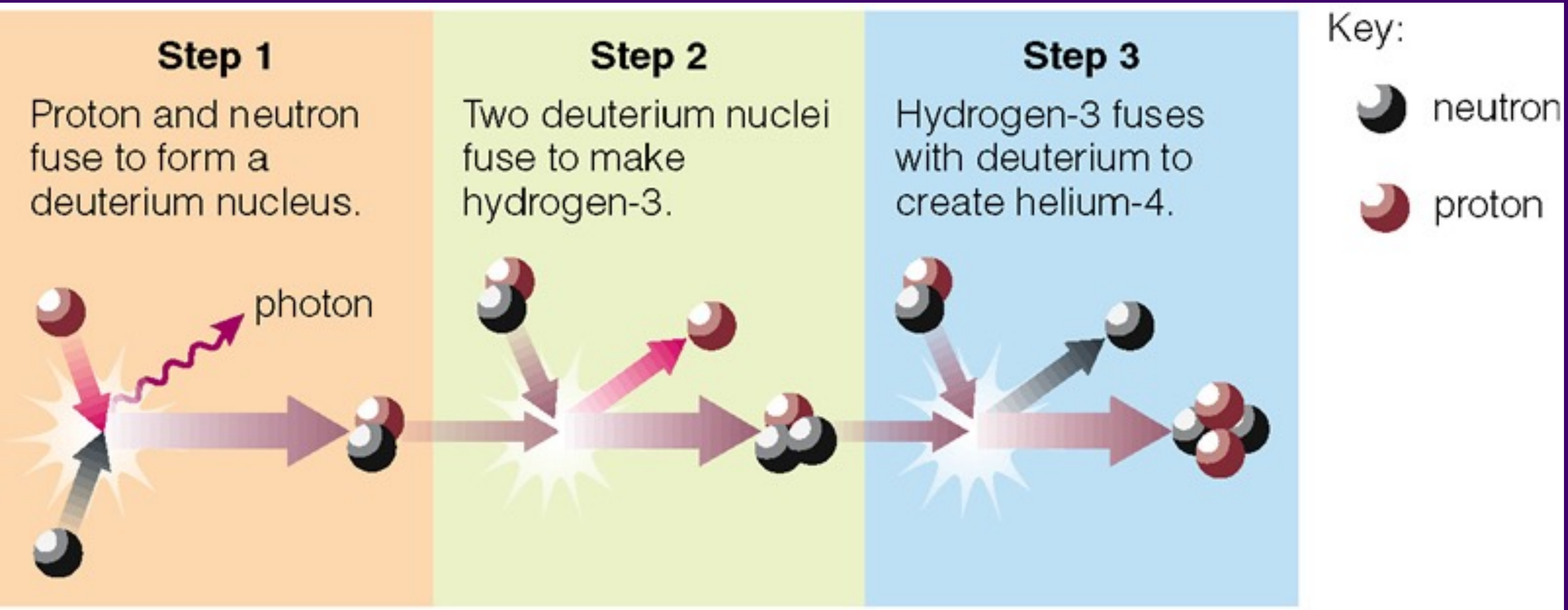

COBE



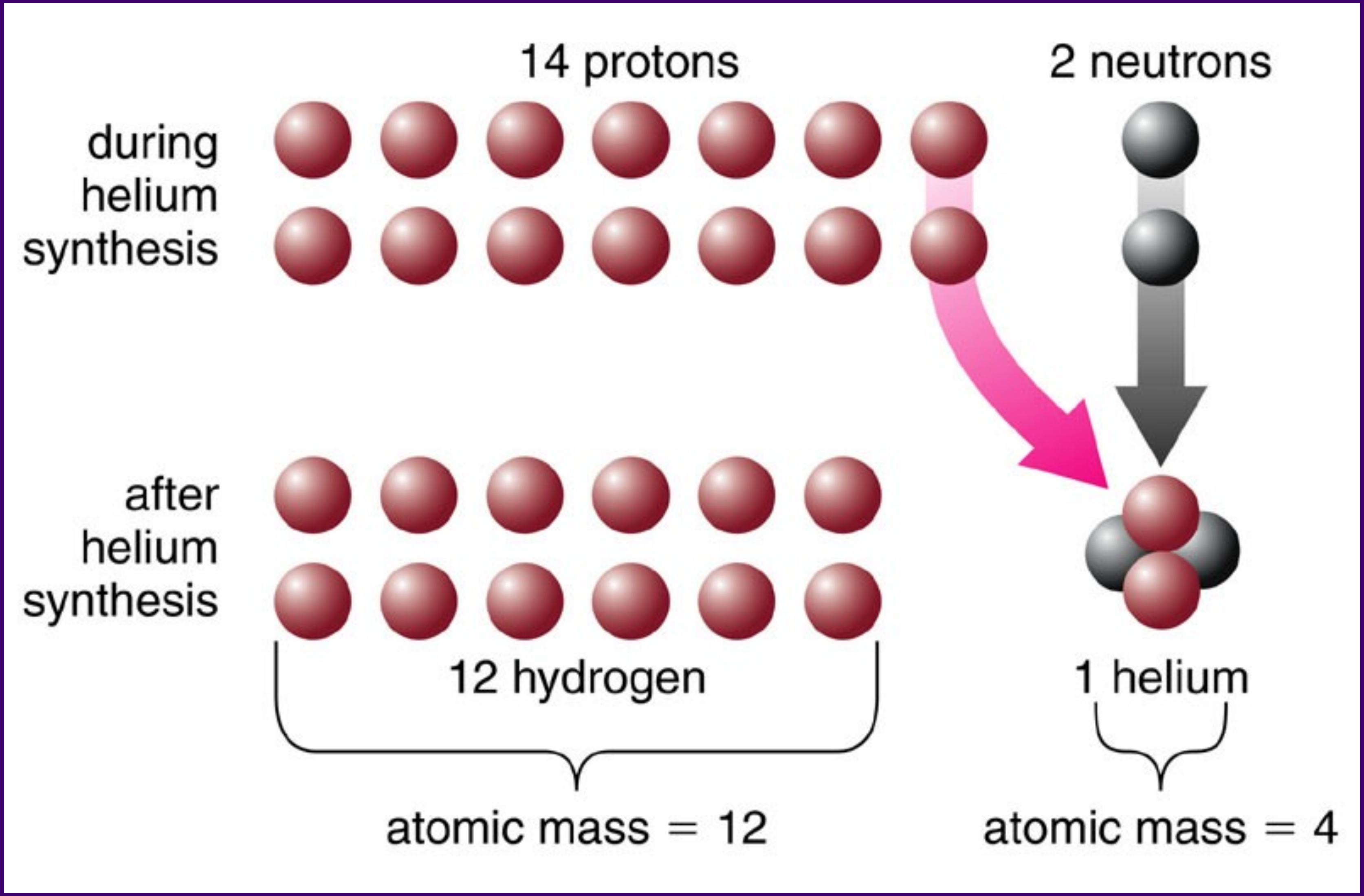
WMAP gives us detailed baby pictures of structure in the universe



EVIDENCE #2: How do the abundances of elements support the Big Bang?

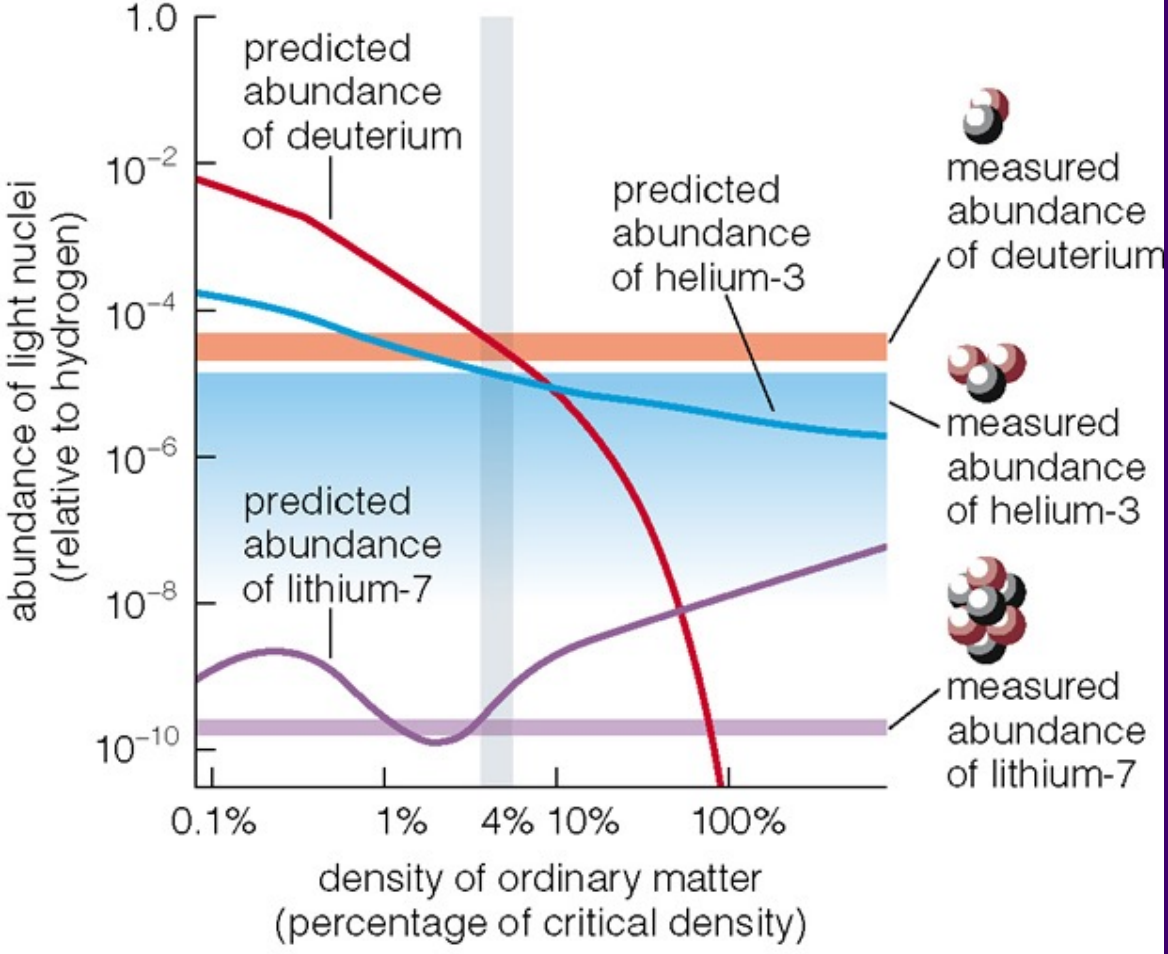


Protons and neutrons combined to make long-lasting helium nuclei when universe was ~ 3 minutes old



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

Matches observations of nearly primordial gases



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

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?

Mysteries Needing Explanation

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

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

An early episode of rapid inflation can solve these problems!

Last topics –

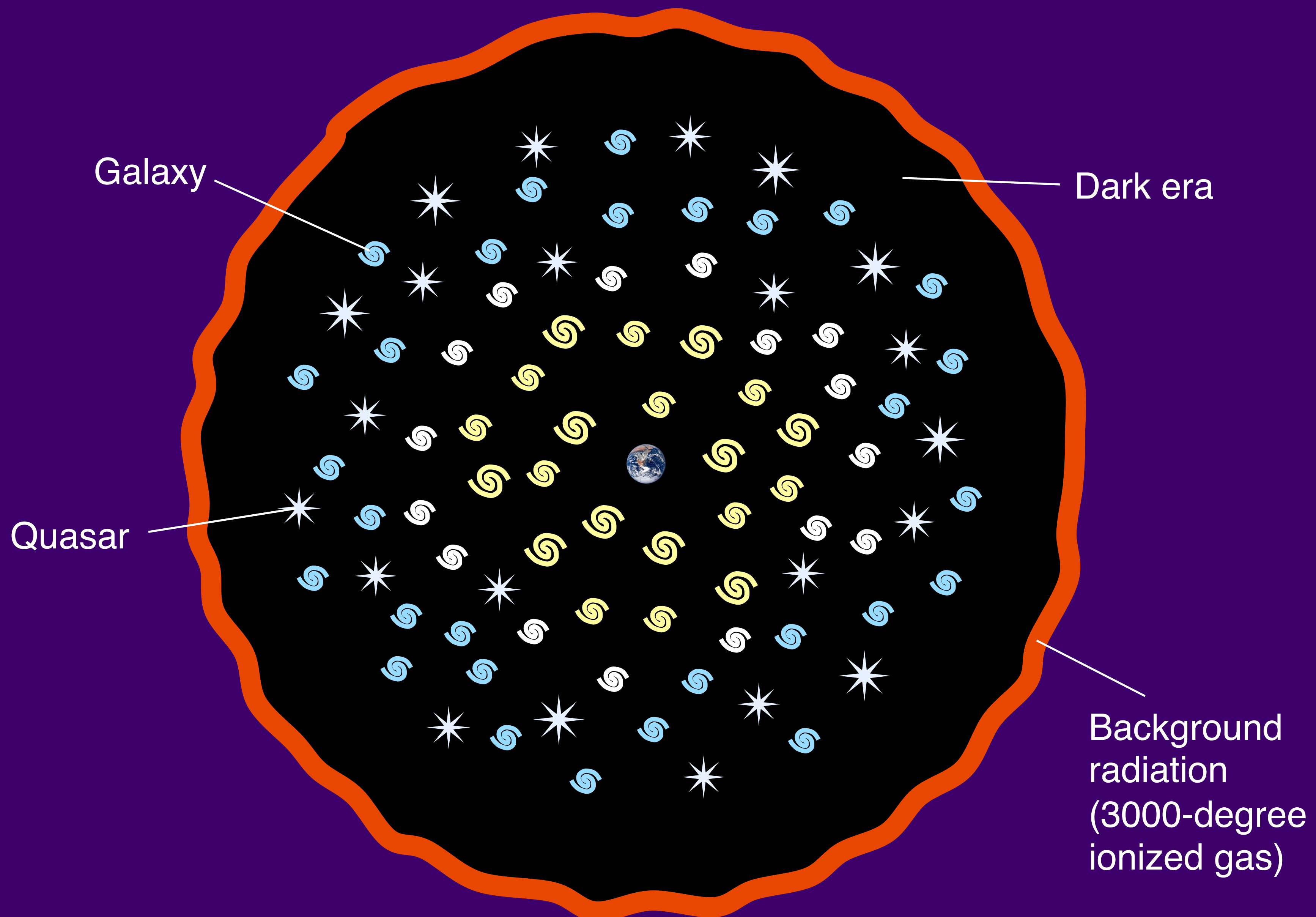
- Thirty meter science etc
- Inflation
- Big bang
- Elementary particles
- End of it all
- Cosmic microwave background
- Wormholes
- Dark matter / Dark energy
- Gravitational waves

want any others???

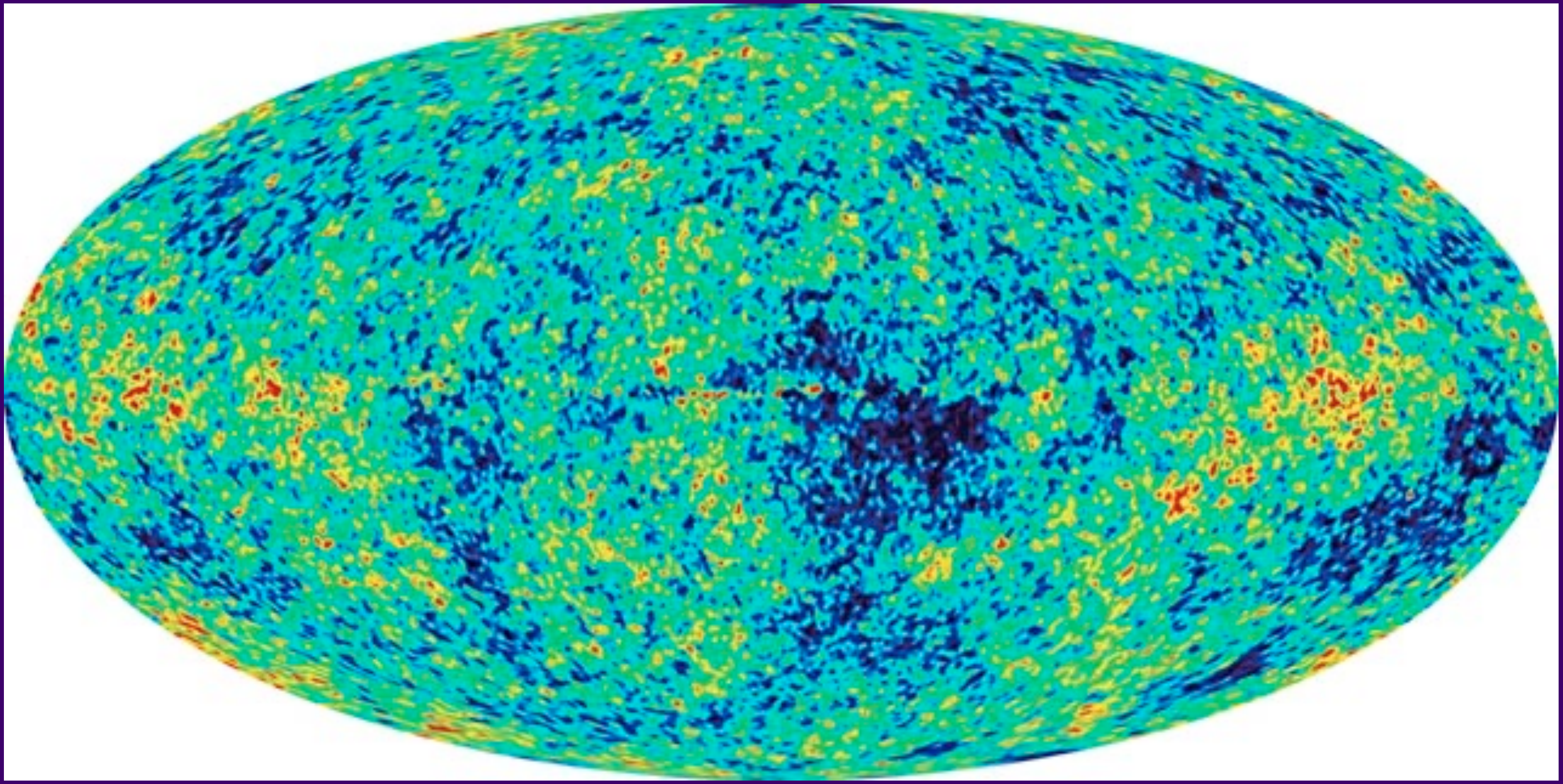
Summary of Cosmological Facts

- The universe is expanding: the galaxies are gradually moving apart from each other (on average).
- About 13 - 14 billion years ago, everything that we see would have been in about the same place.
- By looking far enough out into space, we can look back into time and see what the universe was like 10 billion years ago: quasars were common; galaxies were smaller and bluer.
- From still farther distances and earlier times, we see the cosmic background radiation: a faint microwave and infrared “static” coming from all directions, with an effective temperature of 2.7 K.

The Observable Universe



Our best picture of the early univese



After subtracting out the effect of our motion and the foreground radiation from our galaxy, we're left with tiny variations of 1 part in 100,000. These are slight variations in the density of the hot gases that filled the early universe!

How big is the universe?

- The limit to how far we can see is a limit in *time*, not space: We can’t see galaxies from before there were galaxies, and we can’t see anything from before the universe became transparent to light.

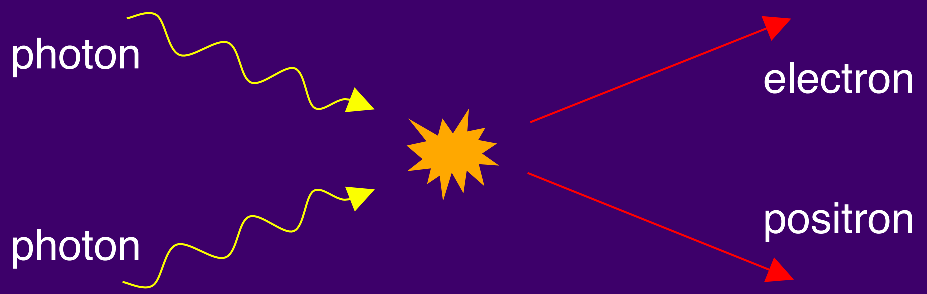
- How big is the *whole* universe? We have no idea, but it’s probably *much* larger than what we can see.

The Cosmic Background Radiation

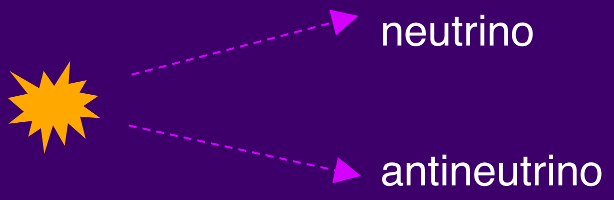
- Each cubic meter of space contains about 400 million photons of low-energy background radiation.
- Compare the density of ordinary matter, which on average is only about one atom per cubic meter.
- In the early universe, the densities would have been much higher, but still there would have been a few hundred million photons for every proton or neutron.
- So let’s extrapolate back even further…

The Hot, Early Universe

- Photon energies increase (un-redshift) as we go back further in time.
- At sufficiently early times, the total photon energy outweighed the mass of the protons and neutrons.
- At still earlier times, photons had enough energy to produce electron-positron pairs:



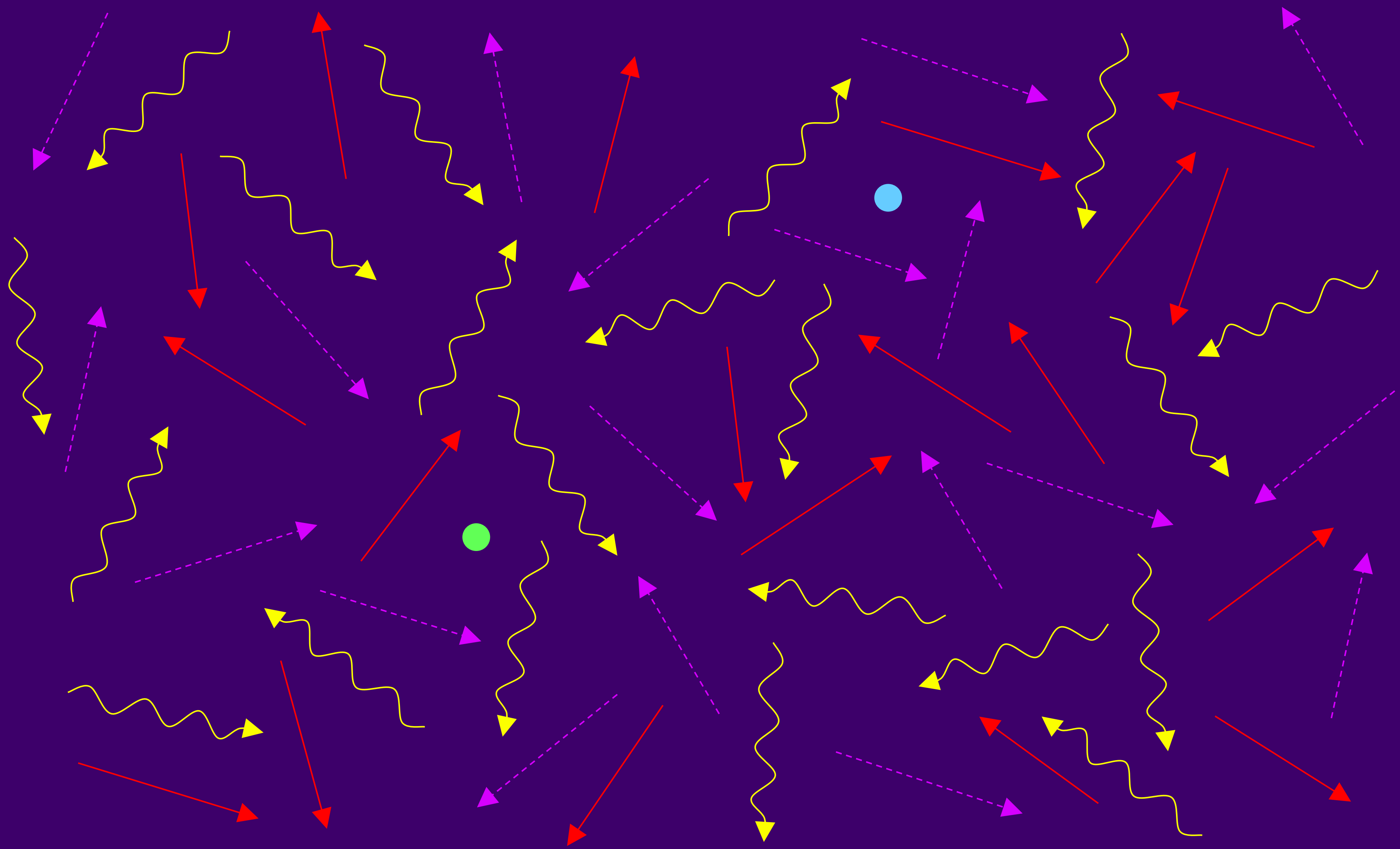
- At *still* earlier times, collisions could also produce neutrino-antineutrino pairs:



Recipe for a Hot Universe

- Photons (high-energy gamma rays)
- Electrons (about as abundant as photons)
- Positrons (nearly as abundant as electrons)
- Neutrinos (also very abundant)
- Antineutrinos (ditto)
- Protons (one for every half billion of each of the above)
- Neutrons (slightly less abundant than protons)

The Hot Early Universe



Neutron-Proton Conversion

- Neutron + Positron <---> Proton + Antineutrino

- Neutron + Neutrino <---> Proton + Electron

- Neutron ---> Proton + Electron + Antineutrino

Three quantities never change: (1) total electric charge; (2) total number of protons + neutrons; (3) total number of electrons + neutrinos – positrons – antineutrinos.

The First Three Minutes

- The universe is expanding and cooling…
- At temperature 10^{11} K, protons and neutrons are about equally abundant.
- As the temperature drops, neutrons convert to protons faster than the reverse.
- Neutrinos soon stop interacting with other particles; electrons and positrons annihilate into photons.
- After about three minutes, the temperature is low enough (10^9 K) for neutrons and protons to stick together to form ^{2}H, ^{3}He, ^{4}He, ^{7}Li. (By this time the density of nuclei is too low to form ^{12}C.)
- **Prediction:** Pristine material left over from the early universe should consist of 75% hydrogen, 25% ^{4}He, trace amounts of ^{2}H, ^{3}He, ^{7}Li.
- A few hundred thousand years later (at $T = 3000$ K), leftover electrons combine with nuclei to form atoms. The universe becomes transparent, and the photons are free to travel great distances.
- 200 million years later, the first stars form…

What is the solar system made of?

- 74% hydrogen
- 25% helium
- 1% everything else (esp. carbon, oxygen, silicon, iron)

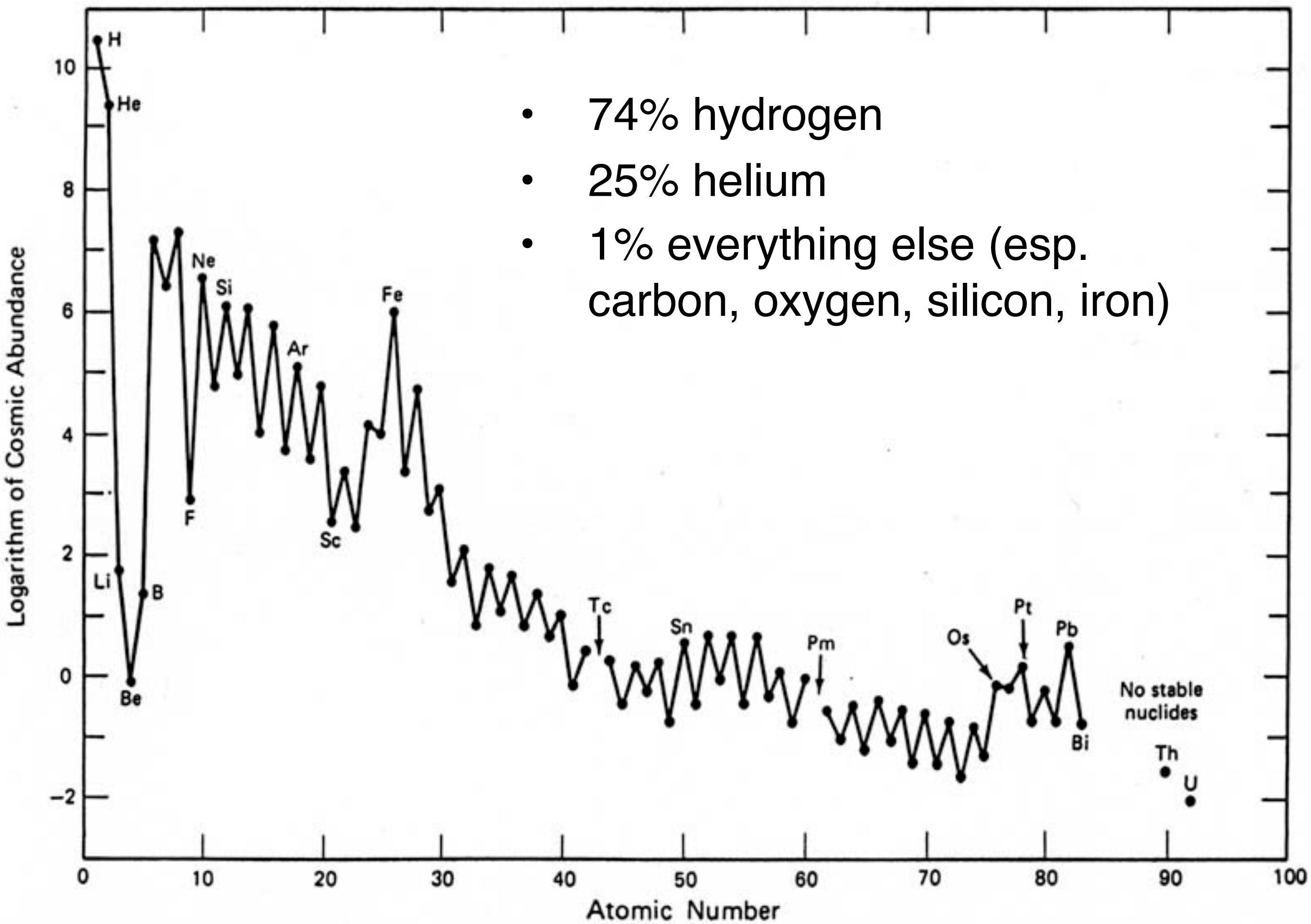
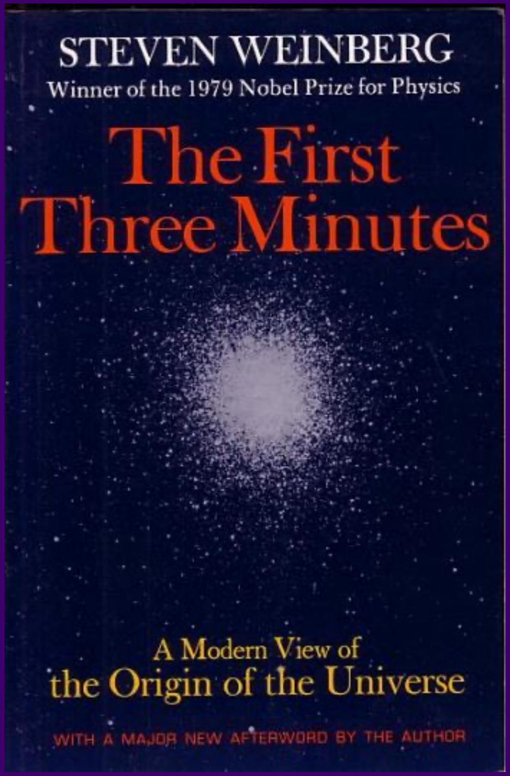


Figure 2.4 Plot of the abundances of the elements in the solar system versus their atomic number. The abundances are expressed as the logarithm of the number of atoms of each element relative to 10^6 atoms of silicon. (Data are listed in Table 2.2 after Anders and Ebihara, 1982.)

Book Recommendation

The First Three Minutes, by Steven Weinberg

Describes the history of the early universe, and the history of how we learned about the early universe.



What happened before *that*?

- At still higher temperatures, even more exotic particles would have been abundant.

- There was probably a brief period of *very* rapid expansion (“inflation”), which smoothed out the universe. (Otherwise, how could space be so flat, and how could the background radiation be the same temperature in all directions?)

- And before that? Quantum fluctuations may have created the seeds for the slight density variations that eventually grew to become galaxies.

- And before that? Who knows? (The question may have no meaning.)

Where is the universe headed?

- Recent results show that the expansion is probably accelerating.
- In this case, the expansion will continue “forever”.
- Eventually, all stars will burn out, leaving white dwarfs, neutrons stars, and black holes.
- Protons themselves are probably unstable (with a very long half-life), decaying into positrons and neutrinos. Then black holes would be the only remaining concentrated form of matter. Electrons and positrons would gradually annihilate into photons that become ever more redshifted.
- Even black holes eventually evaporate into photons via Hawking radiation.

Intolerable heat . . . endless cold . . .

- This picture of the universe is not as well established as the fact that the earth orbits the sun.
- But don't reject it just because you don't like it. 400 years ago, most people didn't like Copernicanism either, but it turned out to be mostly correct.
- Eventually, we grow accustomed to whatever science teaches us about the universe.