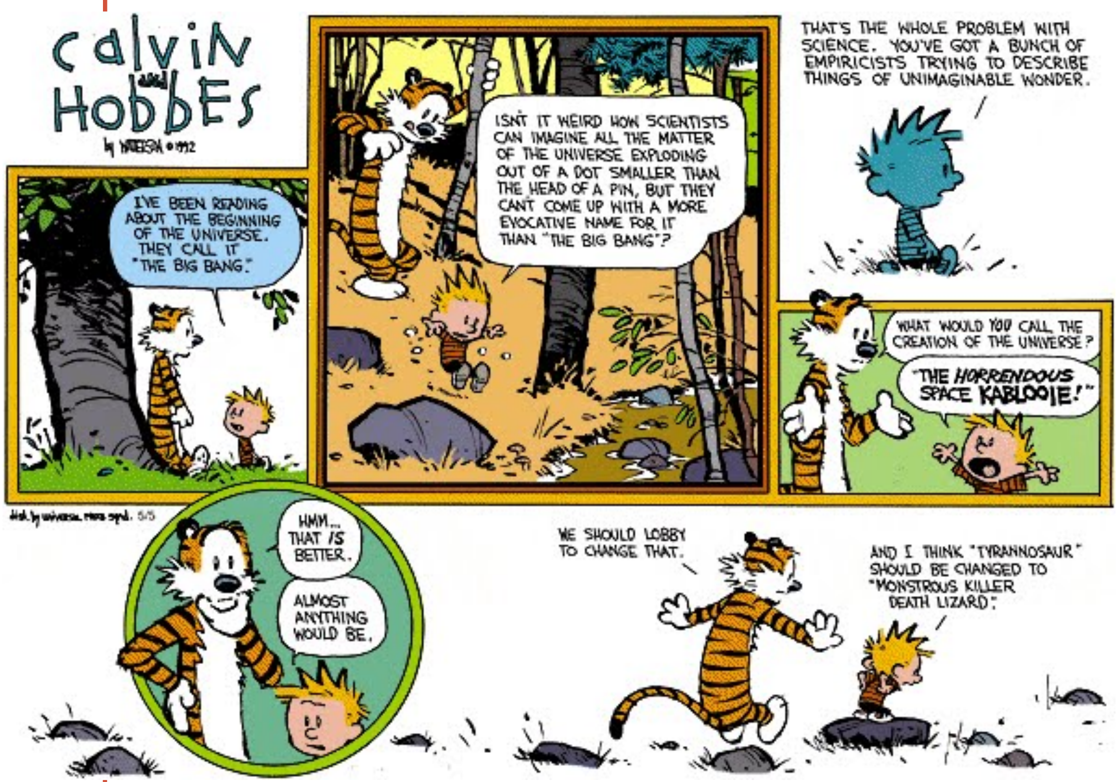
[22] The Big Bang (4/24/18)

Upcoming Items

- Homework #6 due in two weeks.
- Read Ch. 22.2 by next class and do the self-study quizzes.



LEARNING GOALS

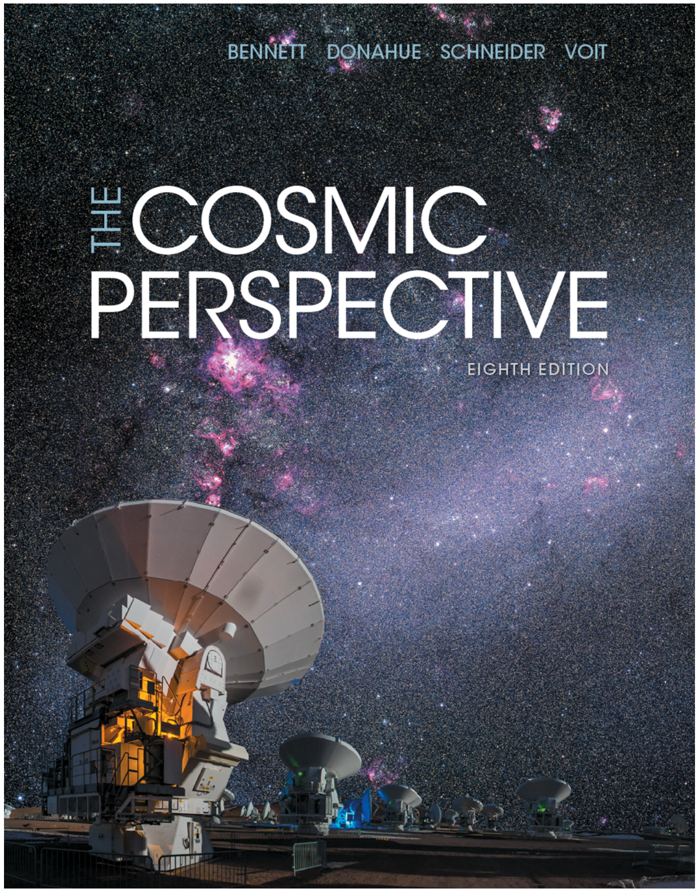
Chapter 22.1

For this class, you should be able to…

… *explain what observational evidence suggests the universe must have been hotter and denser in the past;*

… *determine the minimum temperature needed to create a particle of a given mass;*

… *explain the reason for the cosmic background radiation, and why it peaks in the microwaves today.*

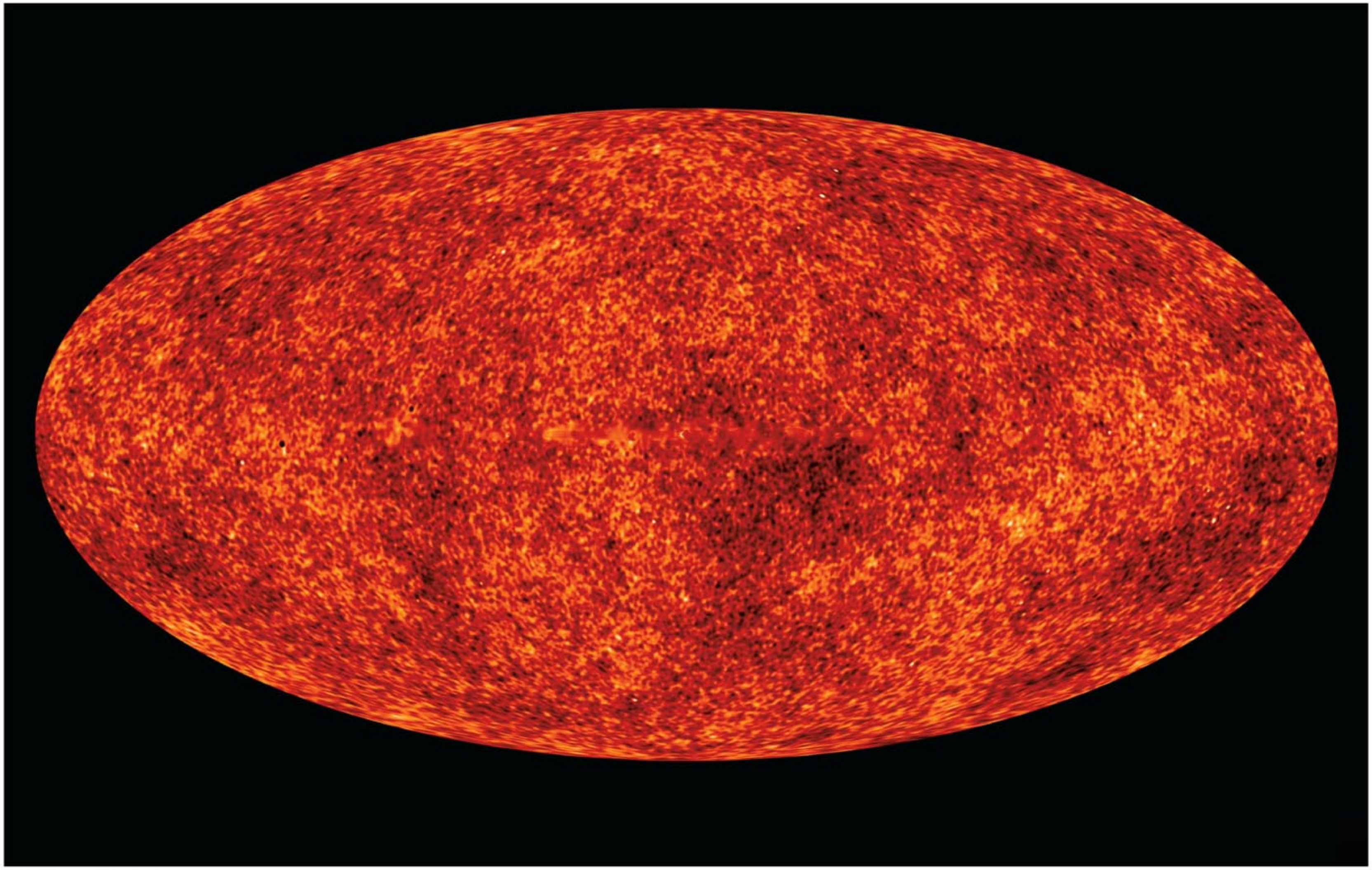


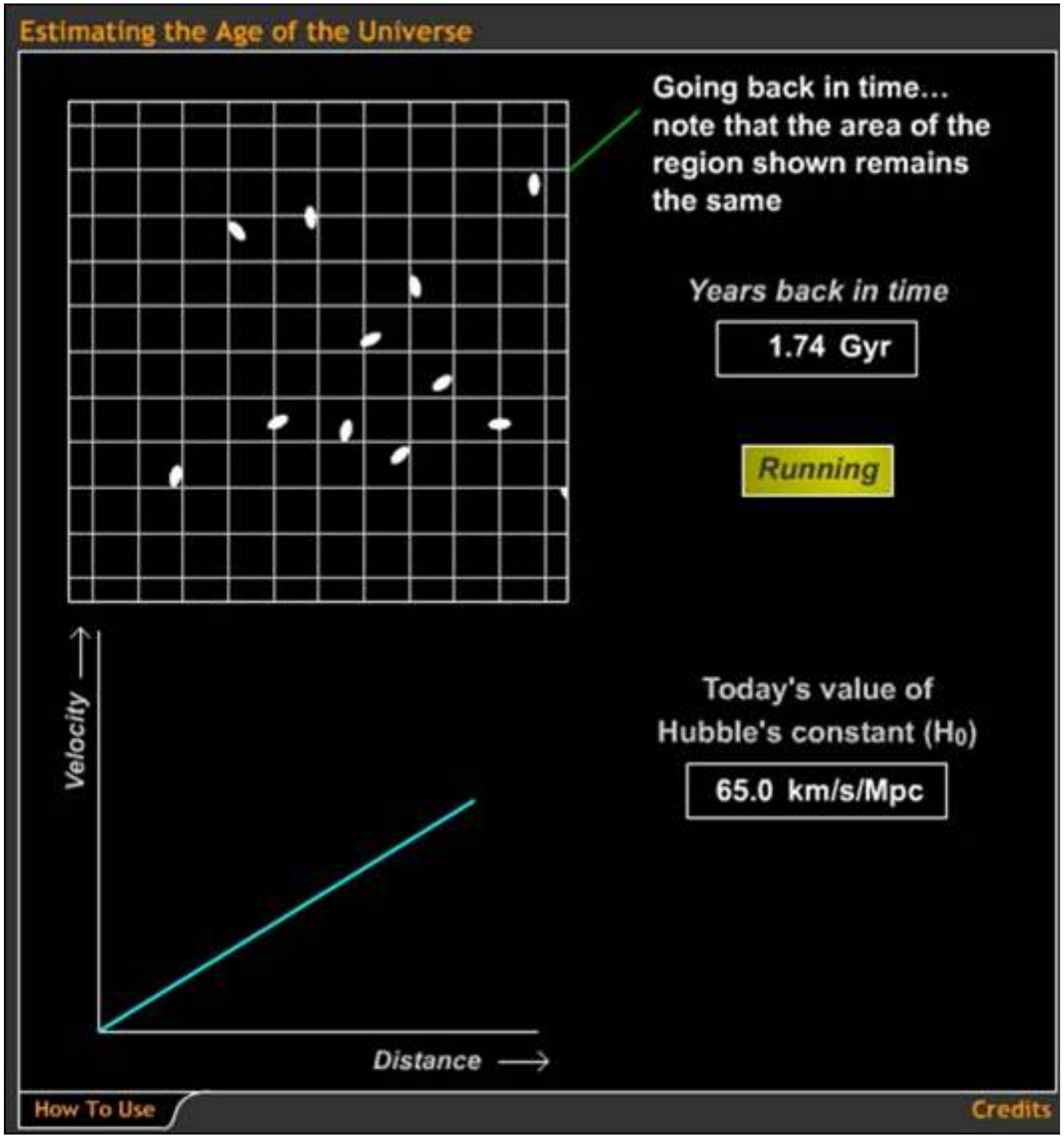
Any astro questions?

The Big Bang

- Because of the observed expansion, the universe must have been much denser and hotter in the past.
- Cosmologists divide the early history of the universe into eras distinguished by the constituent forces and particles.
  - Initially so hot that fundamental forces behave as "superforces."
  - Particle creation and annihilation in balance at high temperature.
  - Some "relic" particles persist after it is too cold for them to remain in thermal equilibrium with photons; massive particles freeze out first.
  - For some reason very slightly more matter was created than antimatter.
  - Conditions were briefly right for hydrogen to fuse to helium, but the universe cooled quickly enough to prevent any heavier fusion.
  - Eventually the universe was cool enough for electrons to combine with protons, releasing the cosmic background radiation.

What were conditions like in the early universe?

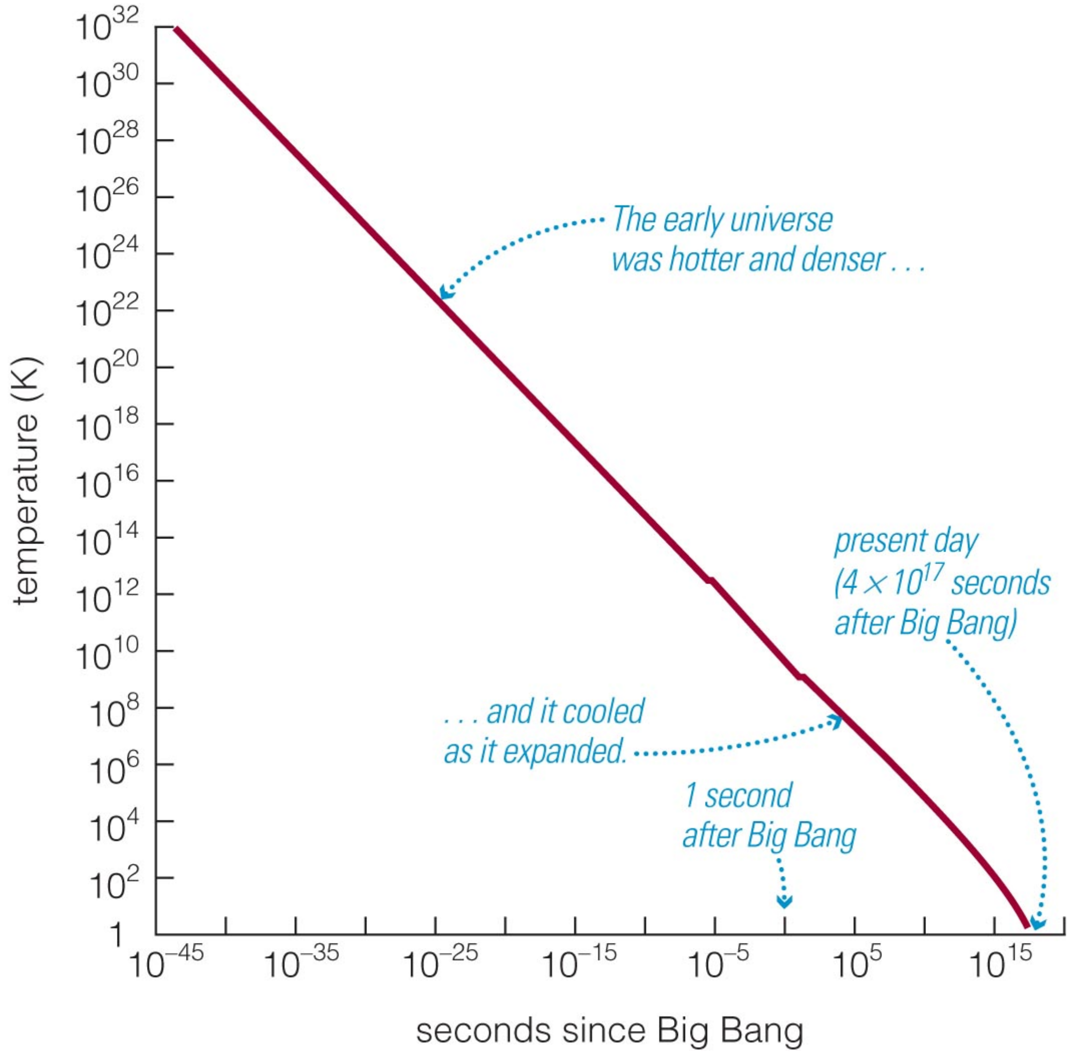




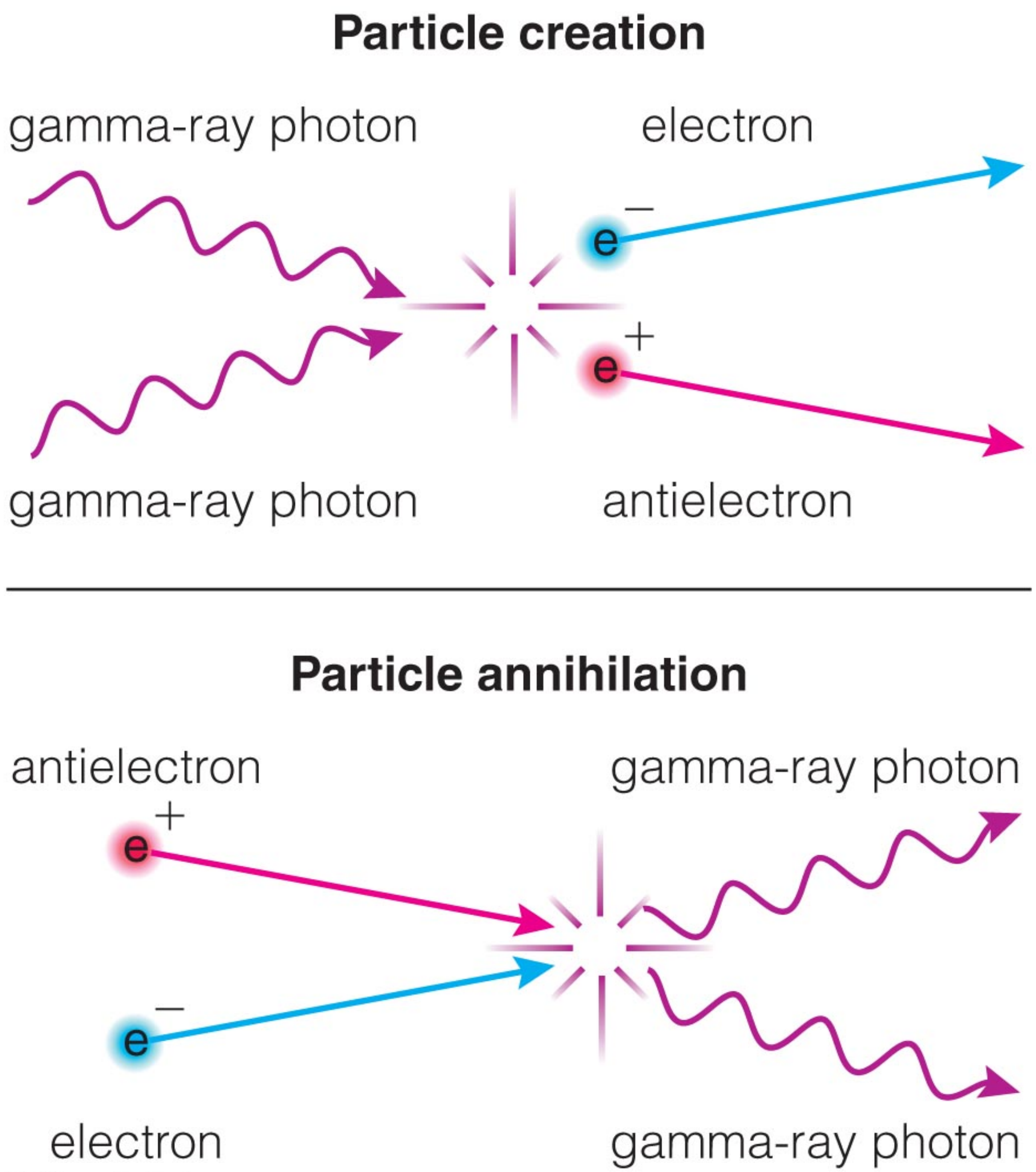
- The universe must have been much hotter and denser early in time. Why?
  1. Smaller scale factor, so a given amount of mass & energy was contained in a smaller volume.
  2. Temperature corresponding to emitted photons was higher, by Wien's law.

The Hot Big Bang Model

- Observation: the universe is 25% helium by mass.
  - Too much to come from stars alone.
  - How would we know that? From what observations?
- To explain this, astrophysicists suggested the universe started off in an extremely hot state.
  - So hot that the entire universe underwent thermonuclear reactions!
- As the universe expands, the energy within the universe is spread over an increasing volume of space…
- **Thus the universe cools down as it expands**.



The early universe must have been extremely hot and dense.



- The early universe was full of particles and radiation because of its high temperature.

$$E = mc^2$$

- Photons converted into particle-antiparticle pairs and vice versa.

Particle Creation and Annihilation

- To turn a photon into a particle, the photon must have energy equal to at least the rest energy of the particle. Actually need *two* photons to turn in to *two* particles

(1 eV = 1.6×10^{-19} J)

Particle	Energy ($E = mc^2$)	Temperature
proton	938 MeV	$\sim 10^{13}$ K
neutron	940 MeV	$\sim 10^{13}$ K
electron	511 keV	$\sim 6\times10^{9}$ K

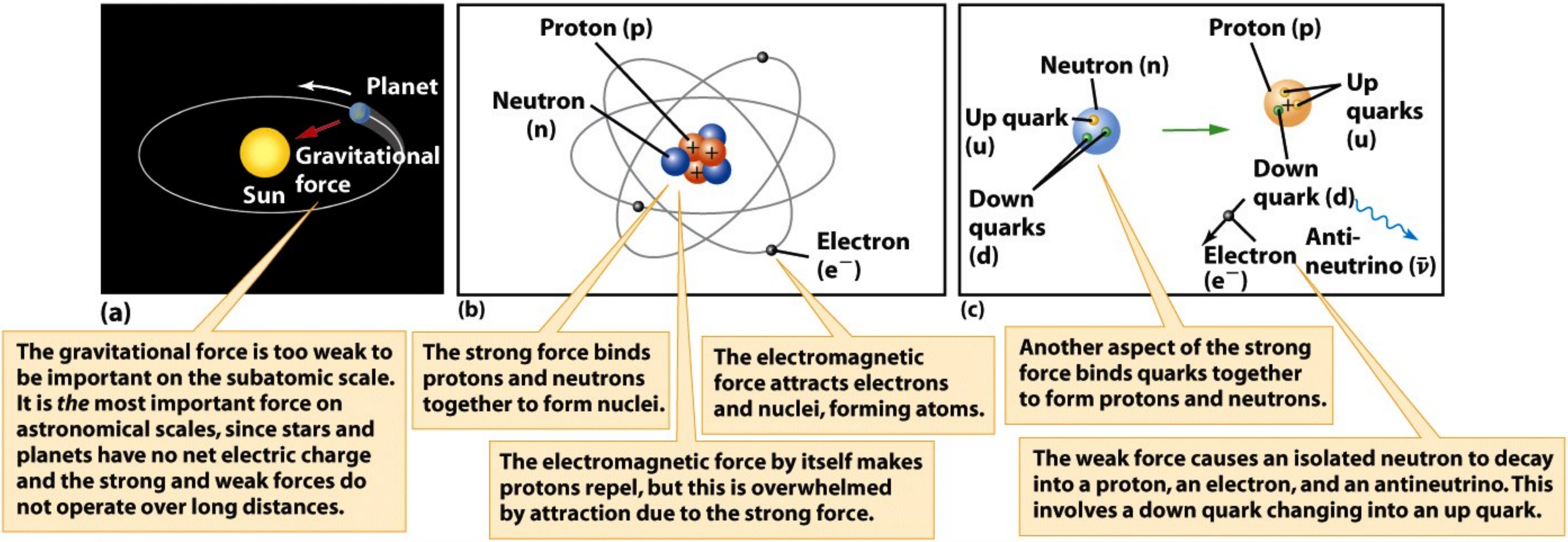
$E = k_B T$

- First particles to stop forming are protons and neutrons (and their antiparticles). (Actually, quarks form earliest.)
  - Requires $T < 10^{13}$ K.
  - This happens at $t = 10^{-12}$ s… What about before that?...

The Fundamental Forces

- To understand conditions in the early universe, we need to understand how particles interact at very high energies.
- Four known forces in the universe govern all interactions:

1. Gravitation.
   - Long-range force that dominates over astronomical distances.
2. Electromagnetism.
   - Usually dominates over gravity on small scales, but on large scales the universe is electrically neutral and weakly magnetized.
3. Strong force.
   - Binds nuclei together. Stronger than electromagnetism, but only on scales of 10^{-15} m, about the diameter of a proton.
4. Weak force.
   - Also short range, governs radioactive decay, e.g., $n \rightarrow p + e^{-} + \overline{\nu}$.

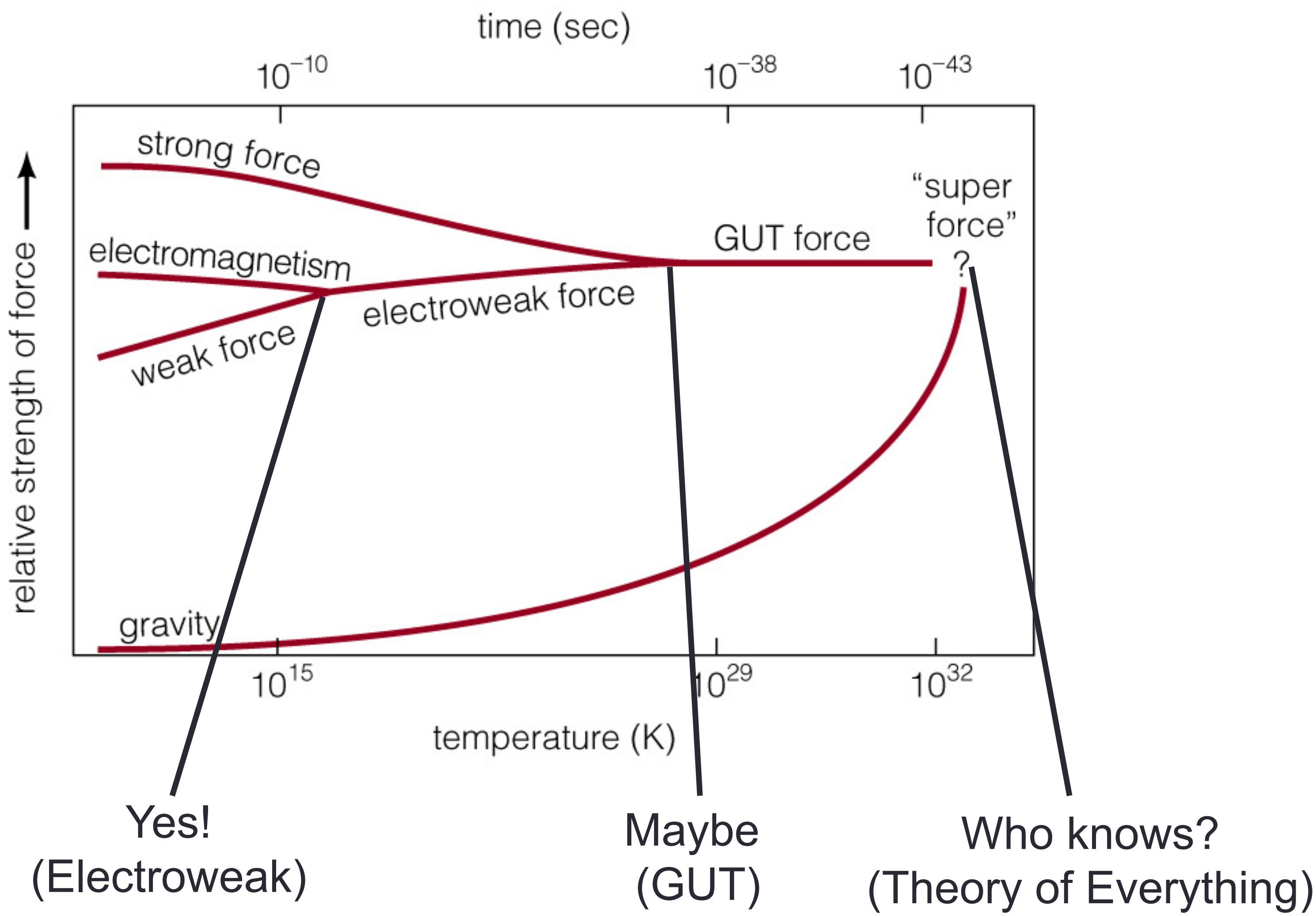


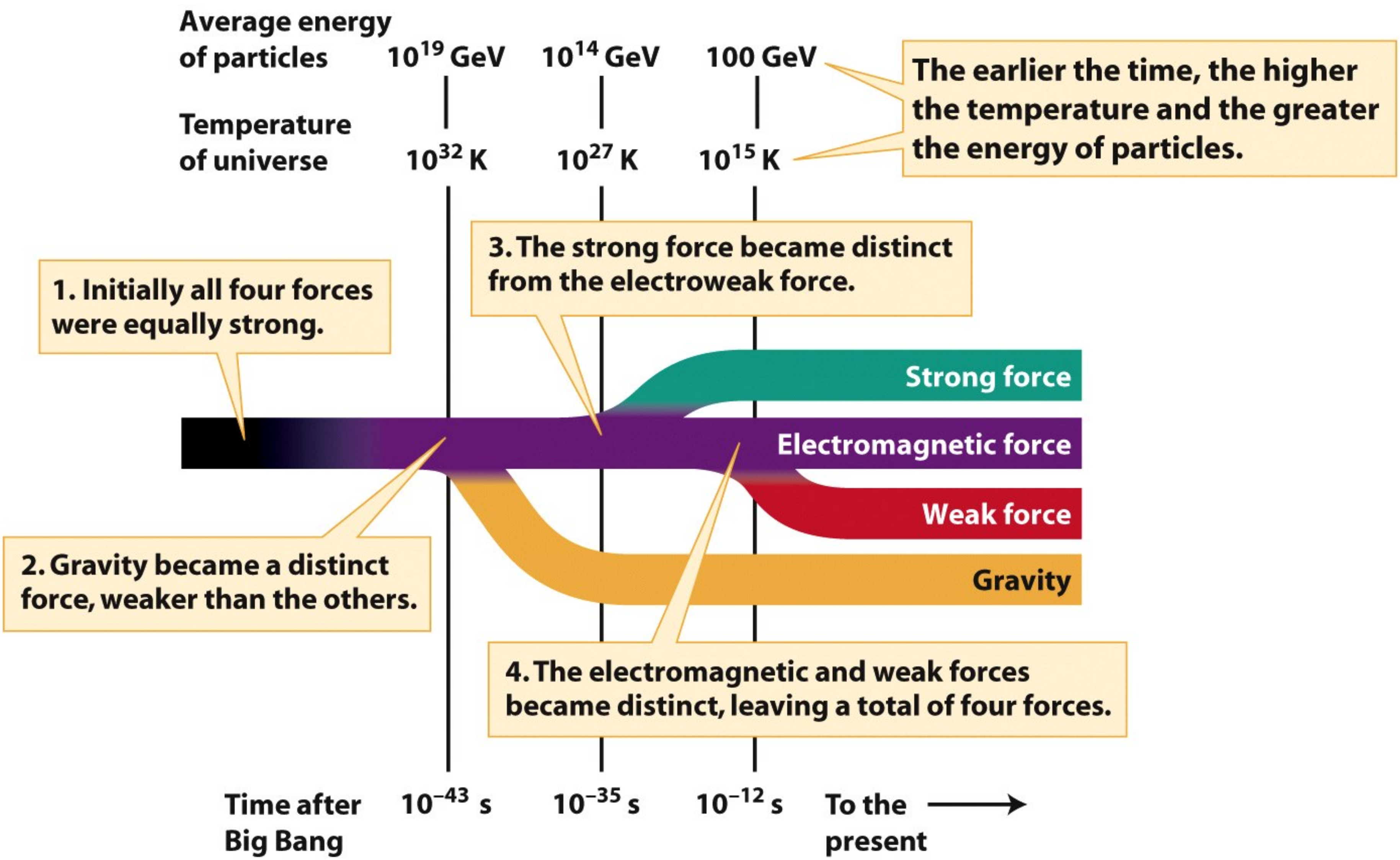
Force	Relative strength	Particles exchanged	Particles on which the force can act	Range	Example
Strong	1	gluons	quarks	10^{-15} m	holding protons, neutrons, and nuclei together
Electromagnetic	1/137	photons	charged particles	infinite	holding atoms together
Weak	10^{-4}	intermediate vector bosons	quarks, electrons, neutrinos	10^{-16} m	radioactive decay
Gravitational	6×10^{-39}	gravitons	everything	infinite	holding the solar system together

Defining Eras of the Universe

- The earliest eras are defined by the kinds of *forces* present in the universe.
- Later eras are defined by the kinds of *particles* present in the universe.

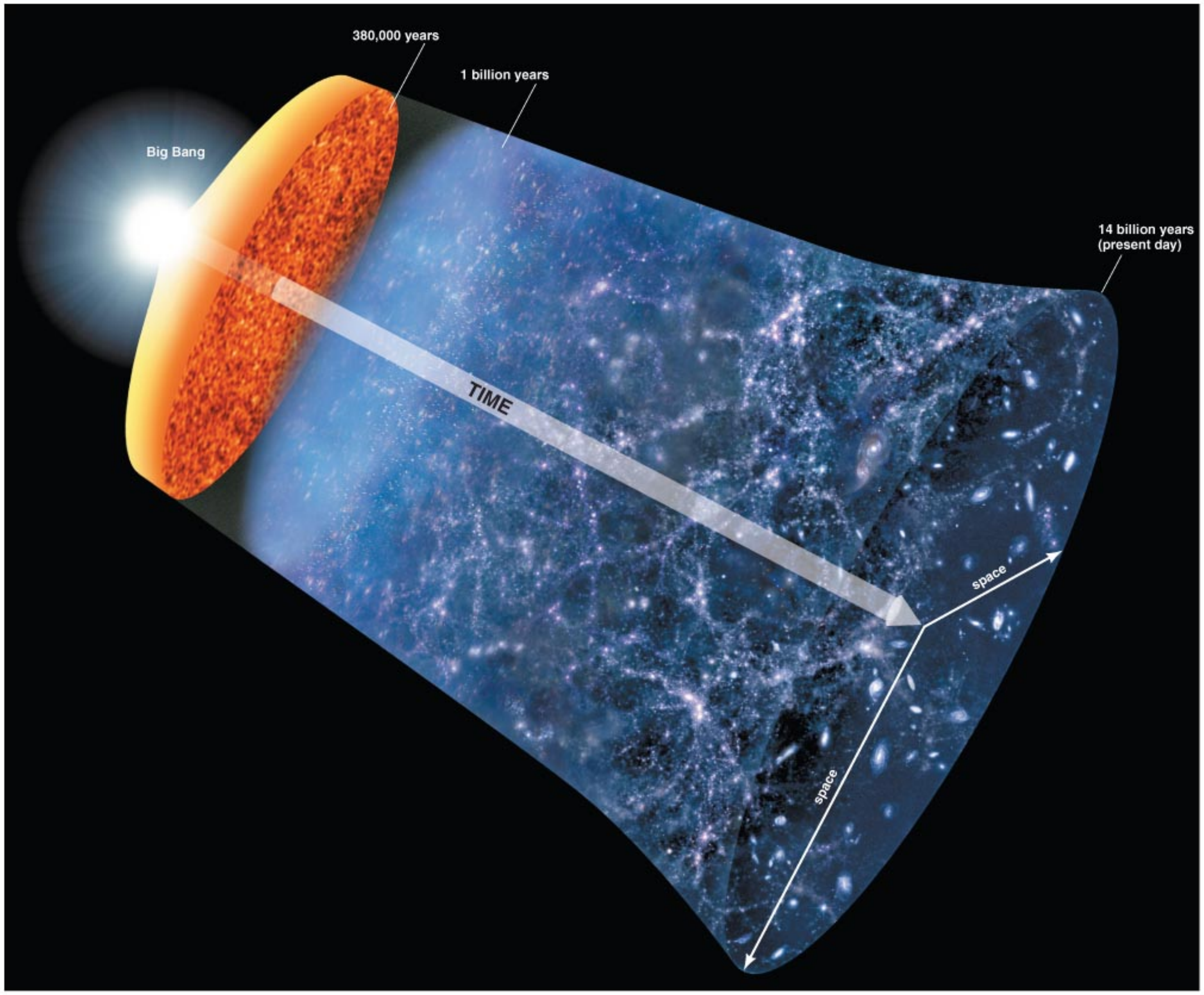
Do forces unify at high temperatures?

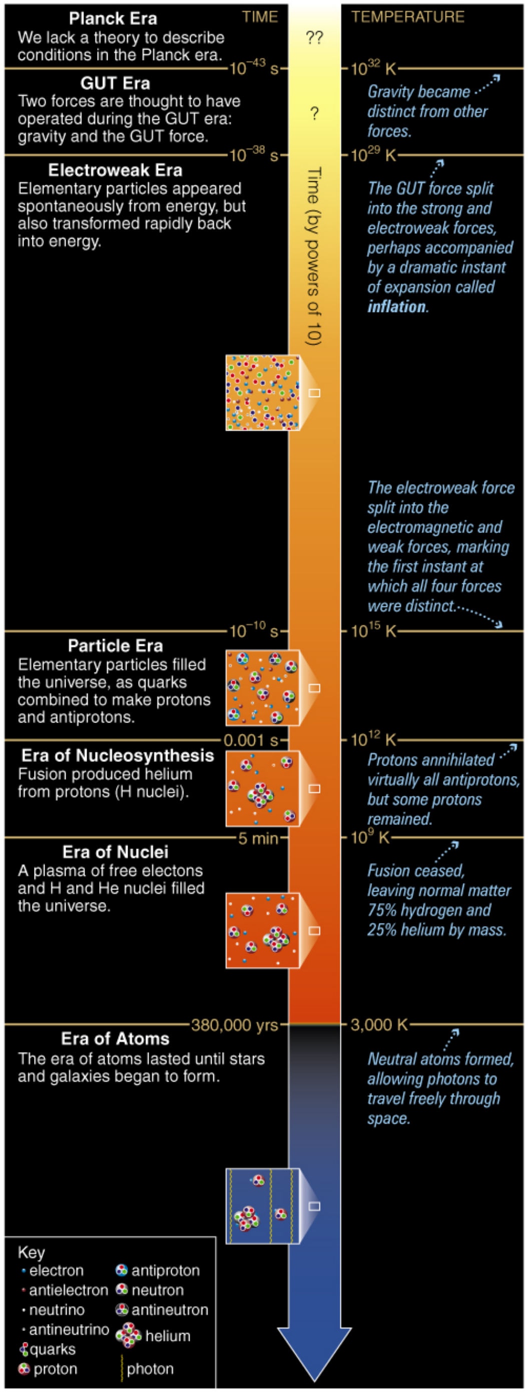




How the four forces behave at different energies and temperatures

How did the early universe change with time?





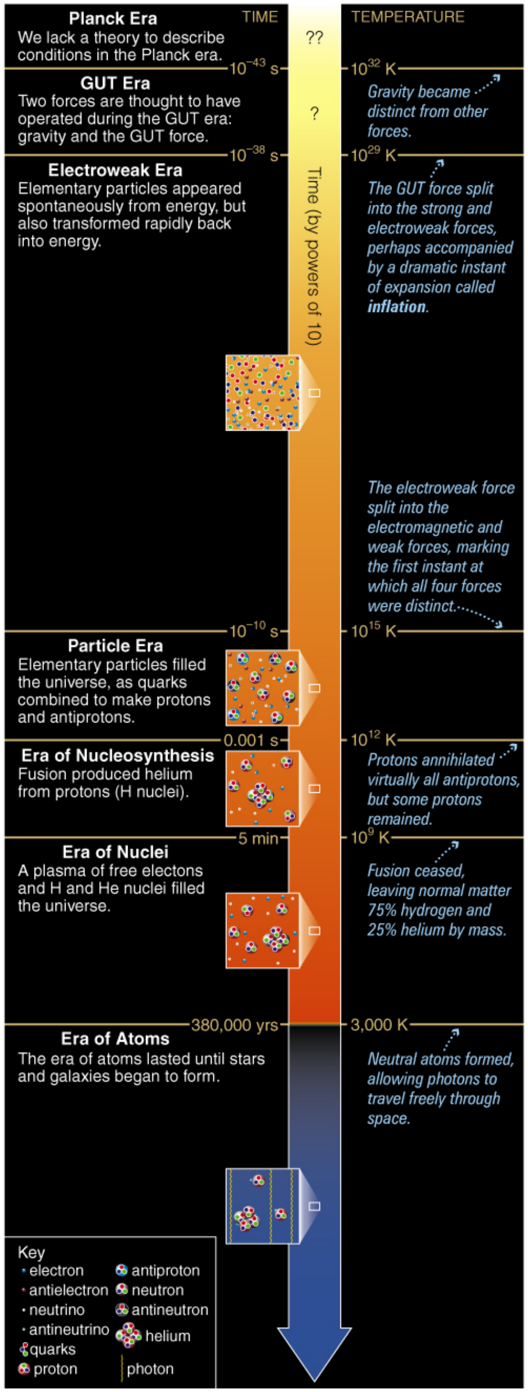
Planck Era

Time: < 10^{-43} sec
Temp: > 10^{32} K

No theory of quantum gravity.

All forces may have been unified.

$$\text{Planck time} = \sqrt{\frac{Gh}{c^5}} = 1.35 \times 10^{-43}\ \text{s}$$

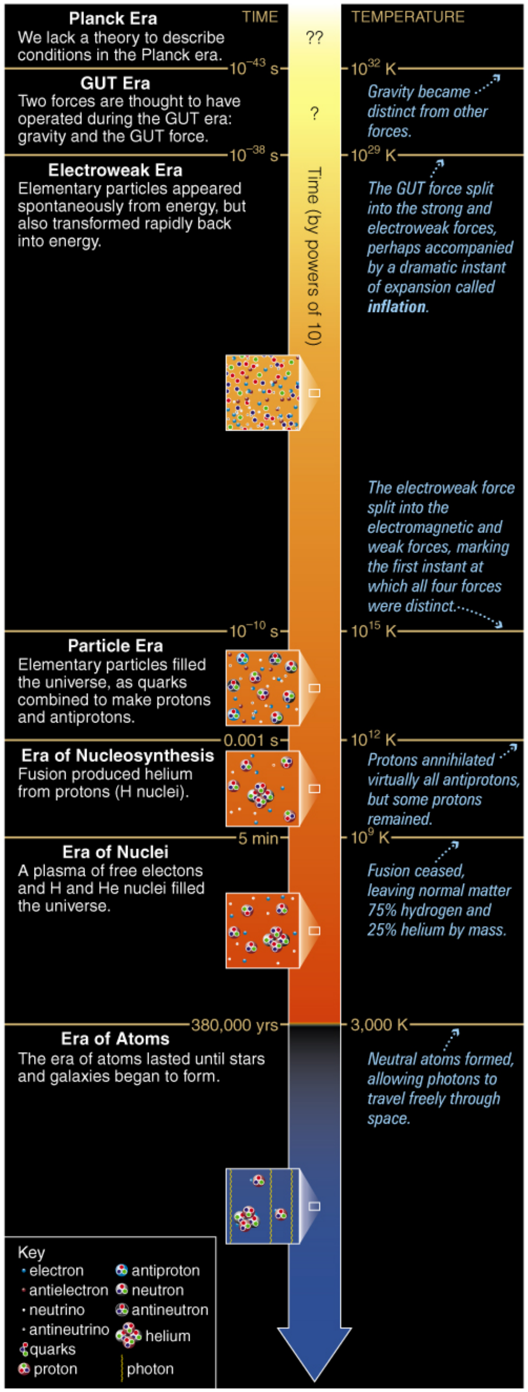


GUT Era

Time: $10^{-43} - 10^{-38}$ sec
Temp: $10^{32} - 10^{29}$ K

Era began when gravity became distinct from other forces.

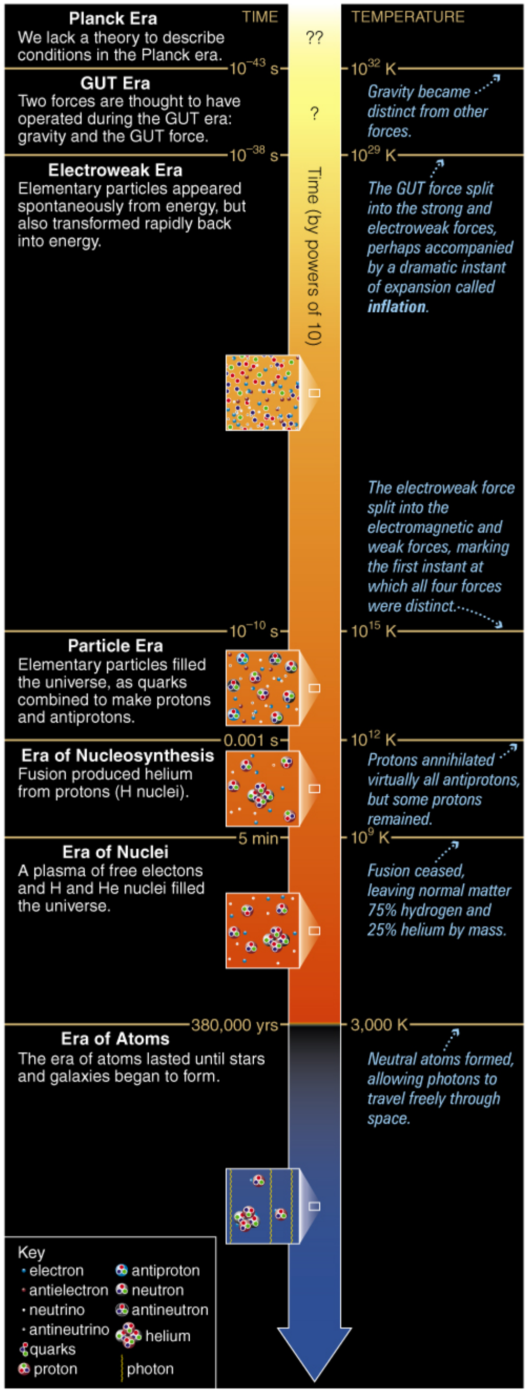
Era may have ended with sudden burst of *inflation* (more later).



Electroweak Era

Time: 10^{-38} – 10^{-10} sec
Temp: 10^{29} – 10^{15} K

Era ended when all four forces became distinct.

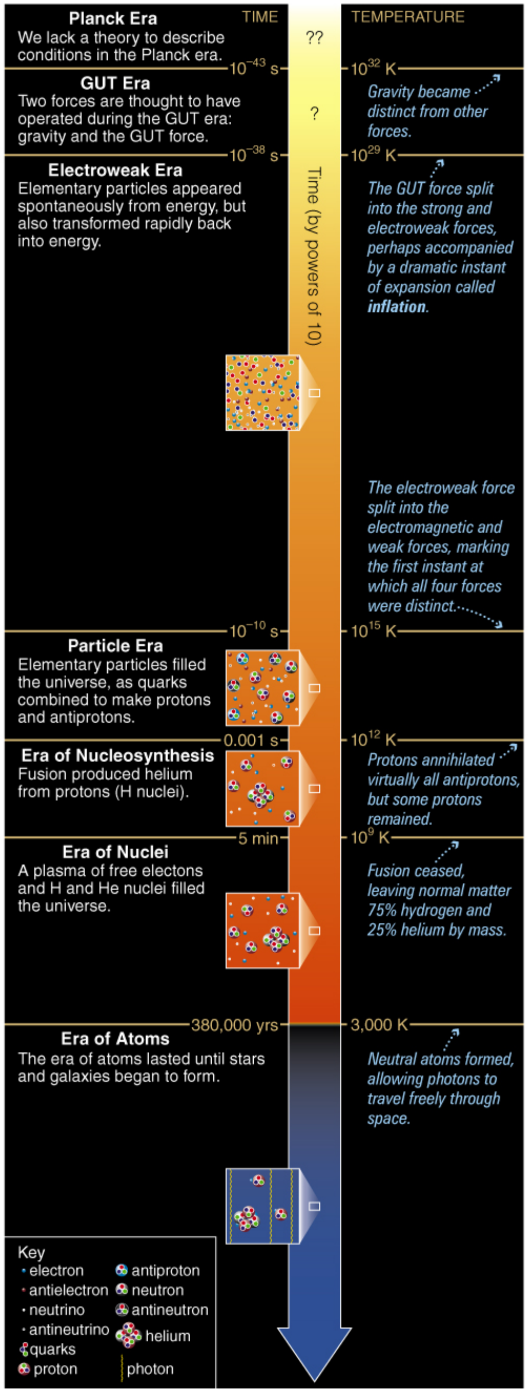


Particle Era

Time: 10^{-10} – 0.001 sec
Temp: 10^{15} – 10^{12} K

Amounts of matter and antimatter nearly equal.

(Roughly one extra proton for every 10^{9} proton-antiproton pairs!)



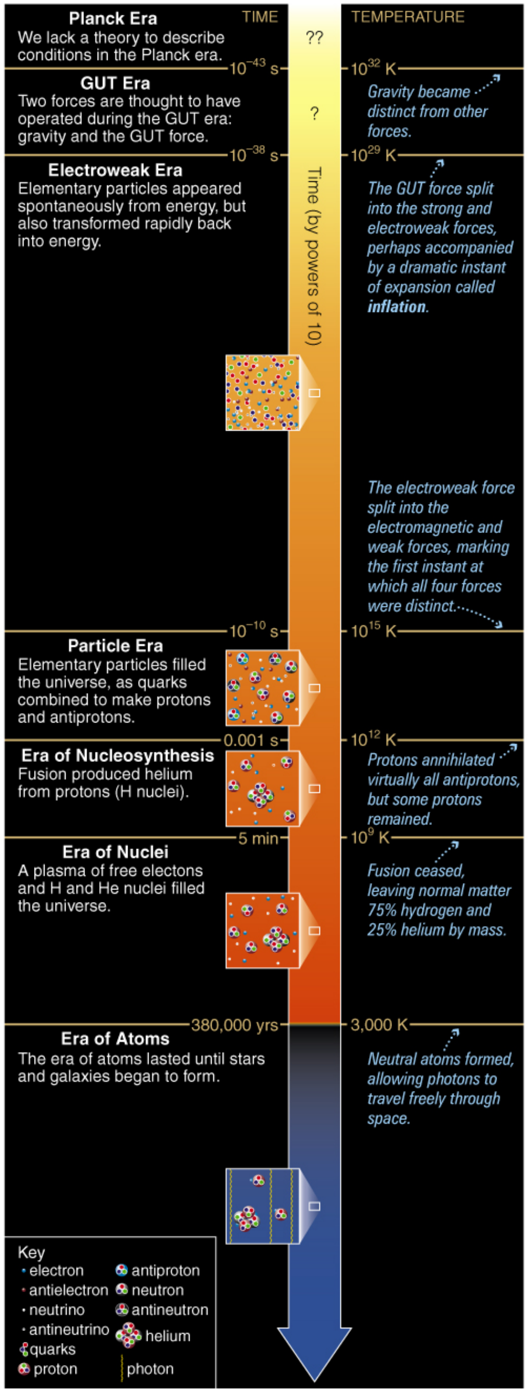
Era of Nucleosynthesis

Time: 0.001 sec – 3 min

Temp: 10^{12} – 10^{9} K

Began when matter annihilated remaining antimatter at ~ 0.001 sec.

Nuclei began to fuse.

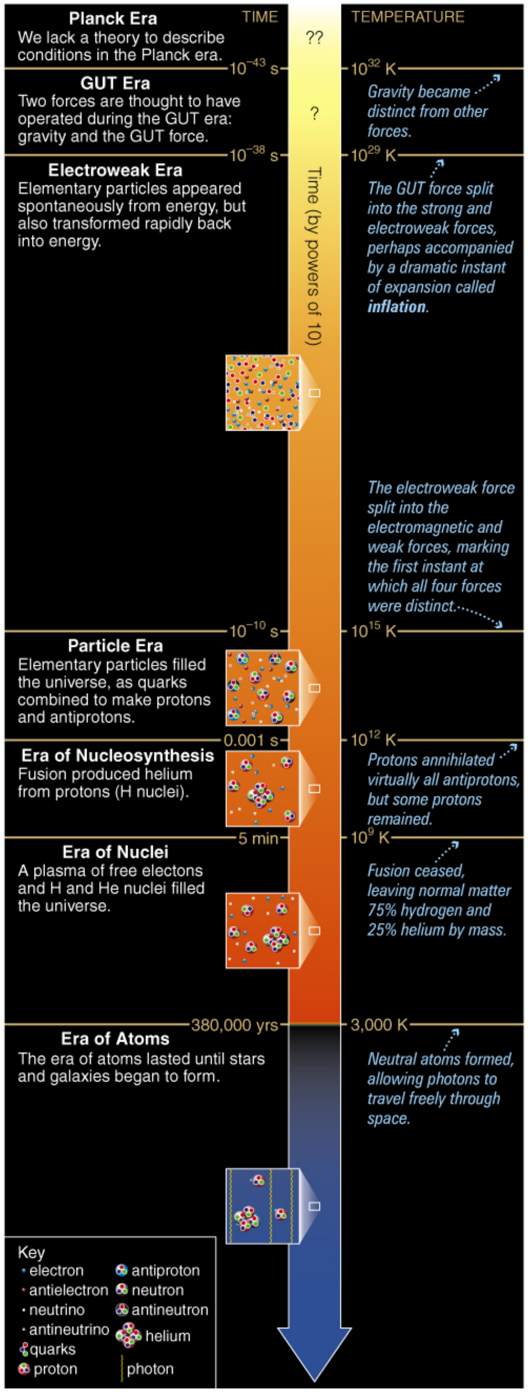


Era of Nuclei

Time: 3 min – 380,000 yr
Temp: 10^9 – 3,000 K

Helium nuclei formed at age ~3 minutes.

The universe became too cool to blast helium apart.

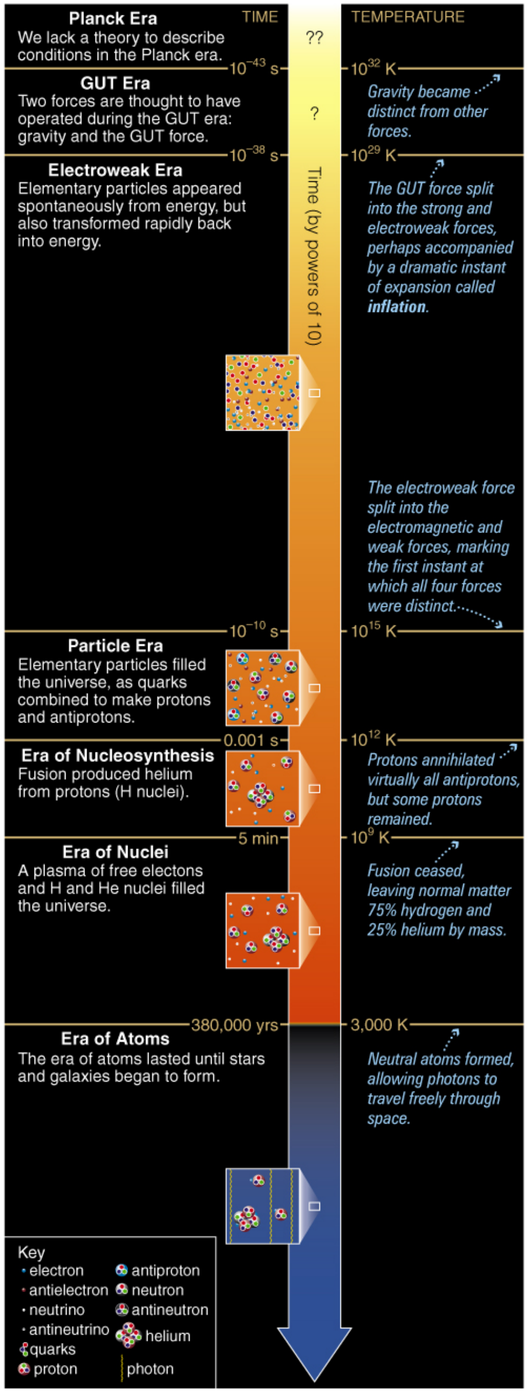


Era of Atoms

Time: 380,000 years –
1 billion years
Temp: 3,000 – 20 K

Atoms formed at age ~380,000 years.

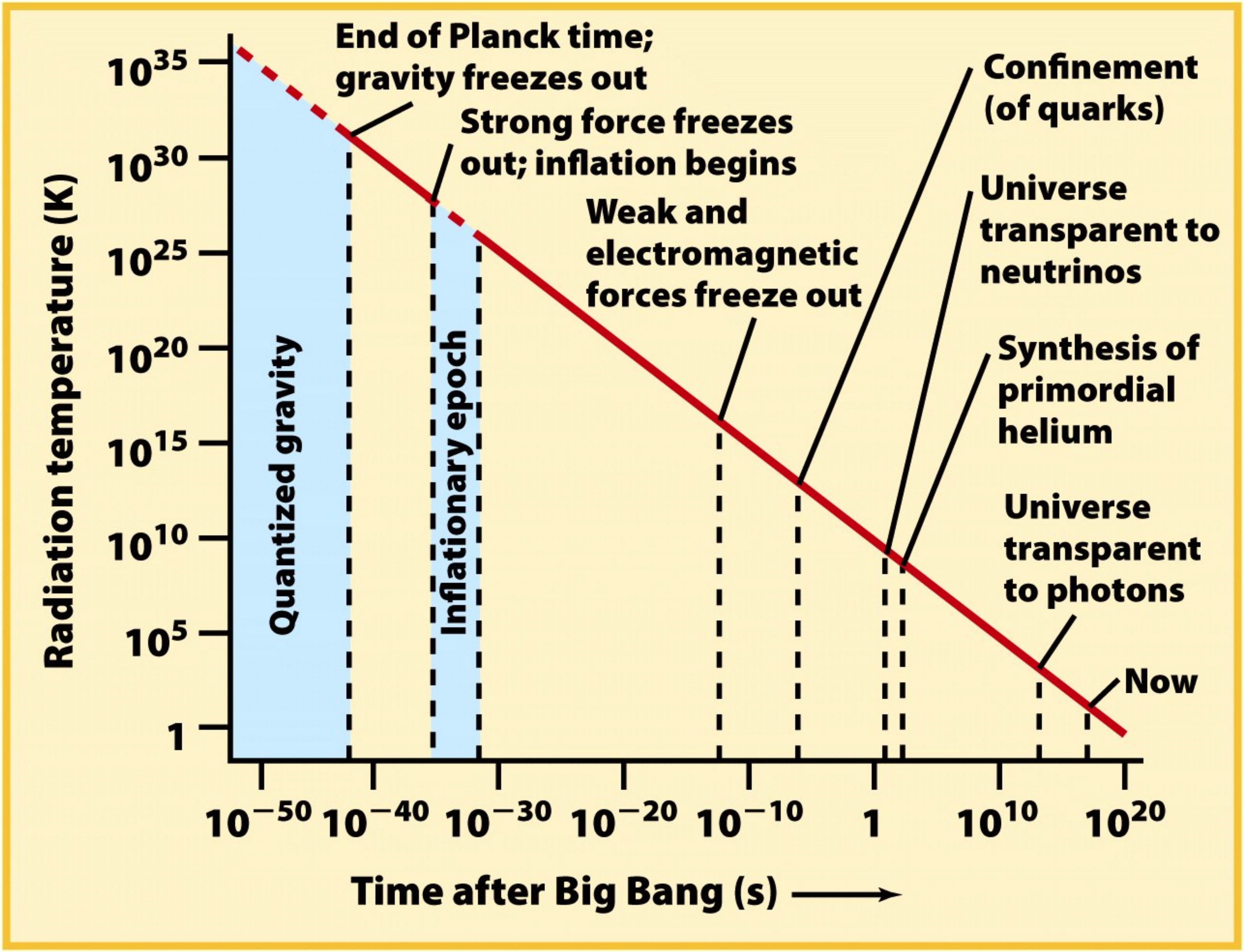
Background radiation is released.



Era of Galaxies

Time: ~1 billion years – present
Temp: 20 – 3 K

The first stars and galaxies formed by ~1 billion years after the Big Bang.


End of Planck time; gravity freezes out
Strong force freezes out; inflation begins
Weak and electromagnetic forces freeze out
Confinement (of quarks)
Universe transparent to neutrinos
Synthesis of primordial helium
Universe transparent to photons
Now
Quantized gravity
Inflationary epoch
Radiation temperature (K)
10^{35}
10^{30}
10^{25}
10^{20}
10^{15}
10^{10}
10^{5}
1
10^{-50} 10^{-40} 10^{-30} 10^{-20} 10^{-10} 1 10^{10} 10^{20}
Time after Big Bang (s)

Details: A Very Brief Early History of our Universe…

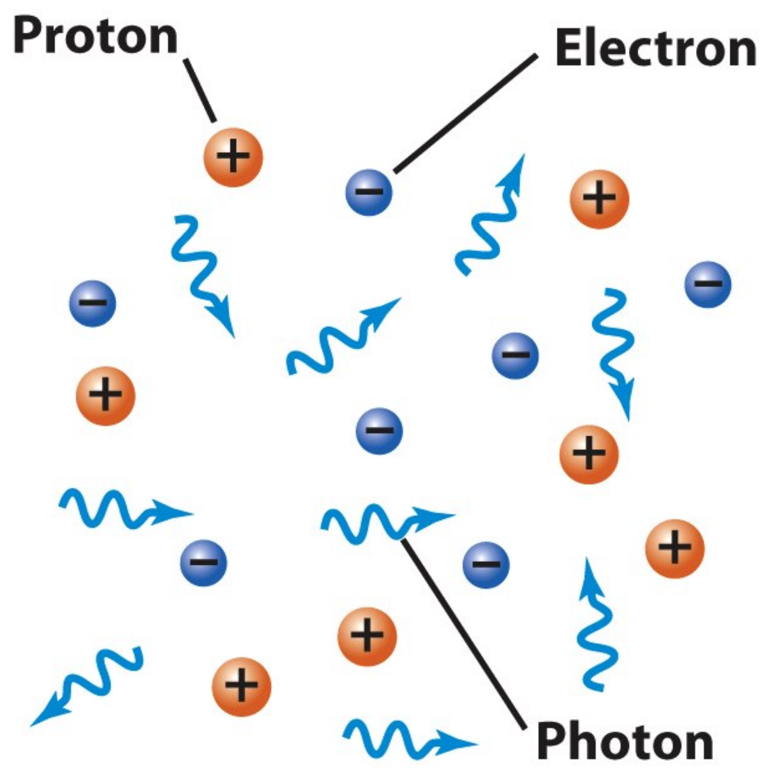
- The Big Bang ($t = 0$).
- The first second… LOTS and LOTS happens:
  - The four fundamental forces come into being (successively splitting off from one “superforce”).
  - Inflation (more later!).
  - A slight asymmetry between particle and antiparticle leads to the creation of slightly more matter than antimatter (by 1 part in 10^9).
  - Quarks are formed and condense to create protons, neutrons, etc.
  - By end of first second, universe is an expanding “soup” of photons, protons, neutrons, electrons, and neutrinos… it is ***radiation-dominated*** (a lot more energy in the radiation than the matter).

The History of the Universe, Continued…

- Primordial nucleosynthesis ($t \sim 3$ mins):
  - The universe has cooled to $T = 10^9$ K.
  - This is cool enough that deuterium (^{2}H) can survive.
  - Deuterium formation is the first step in fusion of hydrogen to helium… reactions proceed very rapidly!
  - What determines how much helium is produced? It's a race against time, driven by 2 factors:
    - Rate of nuclear reactions (depends on density and temperature, both of which are dropping in the expanding universe).
    - Neutrons are decaying with a half-life of ~10 minutes.
  - Predictions agree well with observations (next lecture).

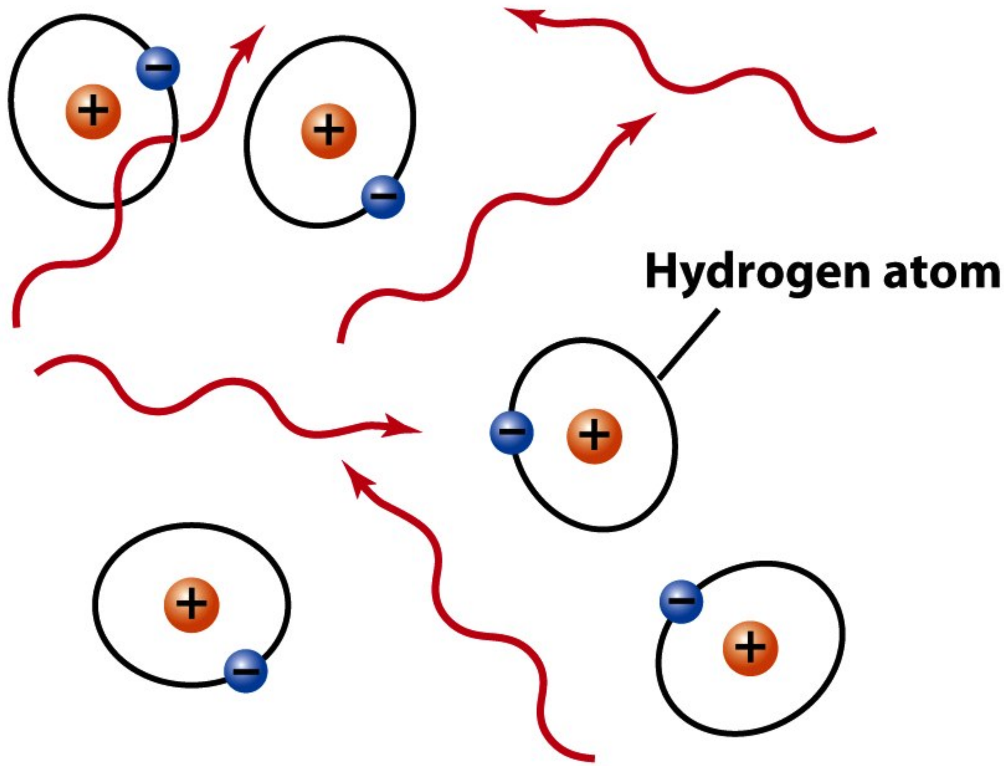
What happens next?

- Universe continues to expand and cool.
  - Consists of ionized hydrogen and helium, free electrons, and lots and lots of photons.
  - Photons are efficiently scattering off the free electrons.
- Recombination ($t = 380{,}000$ years).
  - The universe cools to about $3{,}000$ K.
  - Electrons and hydrogen nuclei start to combine to form neutral atoms.
  - With the free electrons gone, photons now “free stream” through the universe.
  - At this point, photons have spectrum of a $T = 3{,}000$ K black body.
  - This radiation gets redshifted and becomes the *cosmic microwave background* (CMB) we see today.



Before recombination:

- **Temperatures were so high that electrons and protons could not combine to form hydrogen atoms.**
- **The universe was opaque: Photons underwent frequent collisions with electrons.**
- **Matter and radiation were at the same temperature.**



After recombination:

- **Temperatures became low enough for hydrogen atoms to form.**
- **The universe became transparent: Collisions between photons and atoms became infrequent.**
- **Matter and radiation were no longer at the same temperature.**