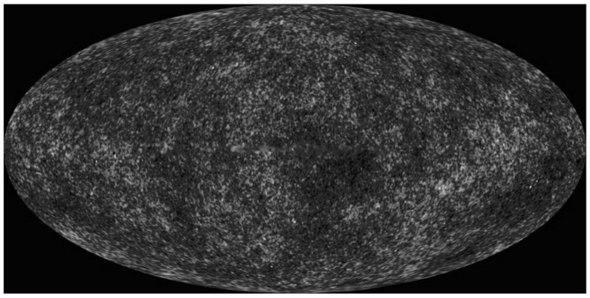
Chapter 22
Birth of the Universe



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Expansion of the Universe

- Hubble's Law: all galaxies see all others moving away from them
- Whole universe is in state of expansion
- Current expansion implies whole universe much more compact in past
- Hubble Law gives idea of time since universe began: Big Bang theory

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Age of the Universe

- Time since any galaxy left origin is d/v (distance/velocity)
- Velocity is given by Hubble's law, v=Hd
- Age = d/v = d/ (Hd) = 1/ H
- H = 70 km/s / Mpc (1 Mpc = 10^6 pc) = 70 km/s / (3.1×10^{19} km) = 2.3×10^{-18} /s
- Age = 1/H = 4.4×10^{17} s = 14×10^9 years (compare to age of Earth 4.5×10^9 years)

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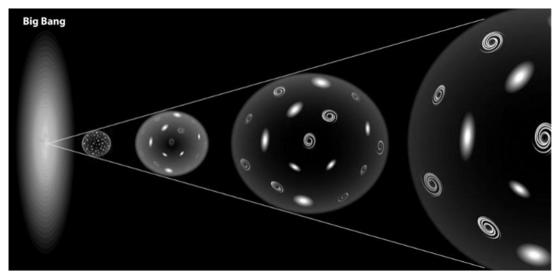

The universe began as a hot, dense singularity that has expanded and cooled over time.

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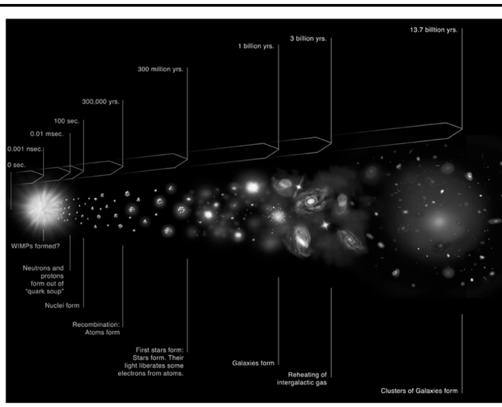

Expansion of Universe implies dense, hot start: **Big Bang**

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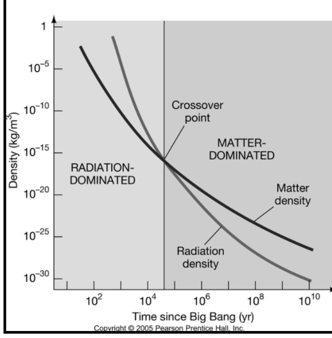
Back to the Big Bang

The early Universe was both dense and hot.



Equivalent mass density of radiation ($E=mc^2$) was much greater than matter density.

As the universe cooled, it went from being radiation-dominated to being matter-dominated.

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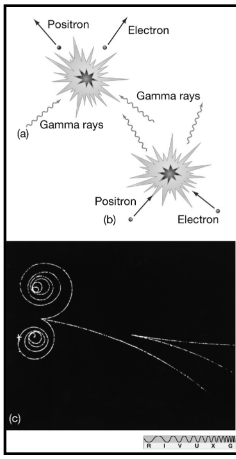

New particles formed by collisions of photons (when photon energies exceeded particle equivalent energy): pair production/annihilation

(creates particle & anti-particle)

Above: 2 gamma rays make an electron–positron pair, and vice versa.

Left: Tracks of electron and positron in a high-energy particle accelerator.

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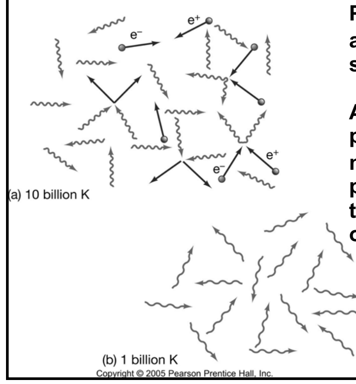

Pair production and annihilation processes started in equilibrium.

As temperature fell, photons lost energy and no longer created massive particles. Any particles that survived were "frozen out" (origin of matter).

Slight excess of regular matter over anti-matter.

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Physics of Early Universe: Fundamental Forces

- Strong Force (holds nuclei together)
  - Exchange particle: gluons
- Electromagnetic Force (holds electrons in atoms)
  - Exchange particle: photons
- Weak force (mediates nuclear reactions)
  - Exchange particle: weak bosons
- Gravity (holds large-scale structures together)
  - Exchange particle: gravitons

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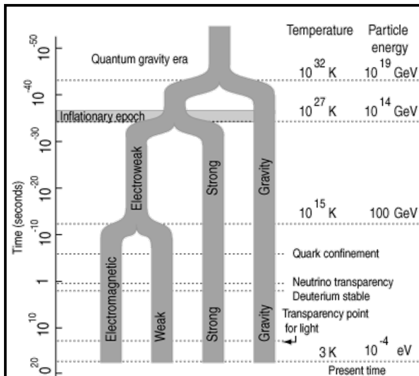

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Grand unified theory (GUT)

Electroweak force

Four forces

forces become similar (unify) at higher temperatures

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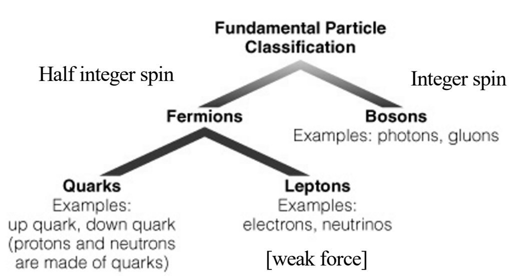
Fundamental Particles: based on mass, charge, spin



[strong force]

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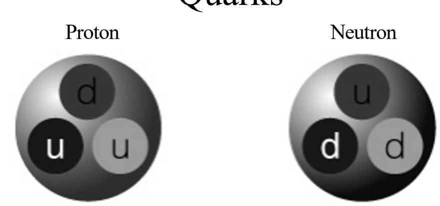
Quarks



- Protons and neutrons are made of quarks
- *Up quark* (u) has charge +2/3
- *Down quark* (d) has charge -1/3

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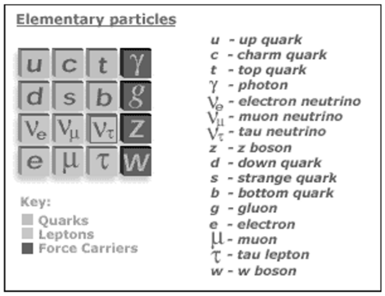

Masses of quarks and Z, W bosons related to Higgs field and Higgs boson (CERN discovery 7/4/2012)
https://www.youtube.com/watch?v=ehHoOYqAT_U

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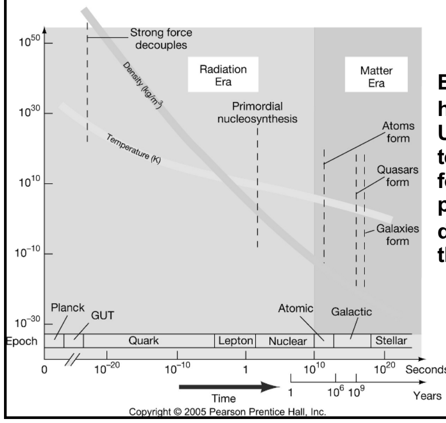

Epochs in the history of the Universe in terms of forces and particles that dominated at that time

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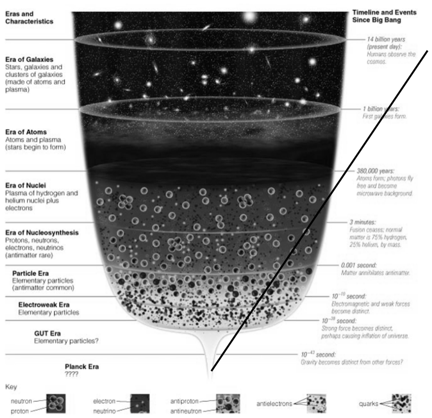

Planck Era:

First 10^{-43} sec

No theory of quantum gravity yet

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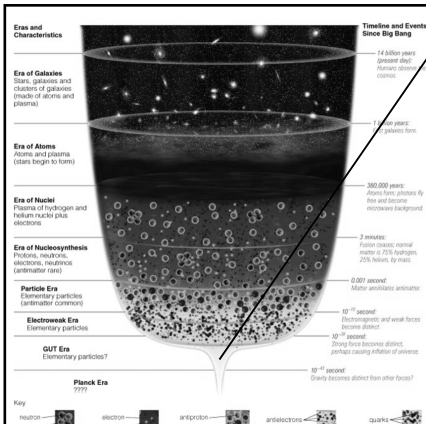

GUT Era:

strong and weak nuclear forces and electromagnetism are all unified

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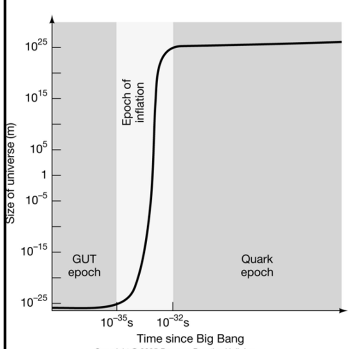
Inflationary Epoch



Between GUT and electroweak epochs, separation of strong and electroweak forces may have released energy to cause sudden expansion, cosmic inflation*.

Explains why regions of universe now separated by > speed of light x age can have similar properties (originally very close).

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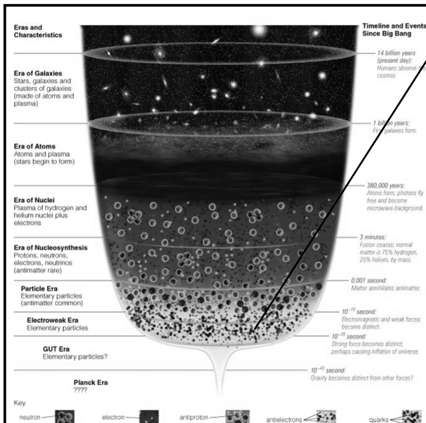

Electroweak Era:

Lasts until electroweak force separates into weak and electromagnetic forces (10^{-10} sec)

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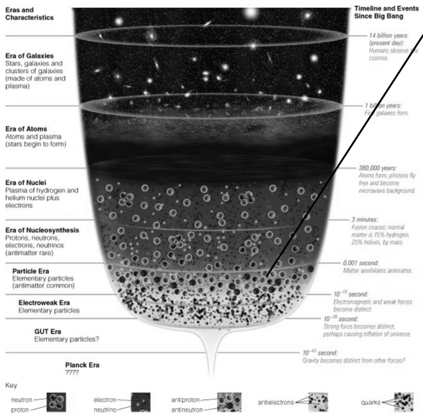

Particle Era:
Amounts of matter and antimatter nearly equal
(1 extra proton for every 10^9 proton-antiproton pairs!)

First heavier (quarks) then lighter (leptons, WIMPs) particles form as Universe cools

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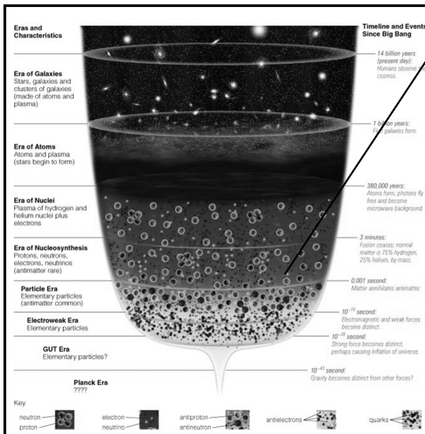

Era of Nucleo-synthesis:

Protons, neutrons begin to fuse (H, He) but larger nuclei broken by collisions

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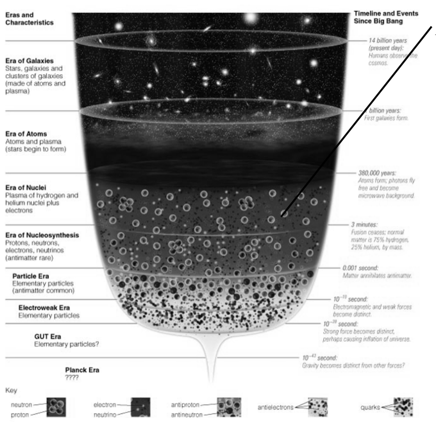

Era of Nuclei:

Most of He made by 3 minutes

Too hot for electrons and nuclei to combine

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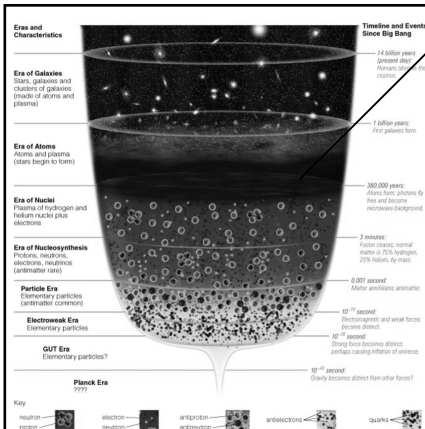

Era of Atoms:

Atoms form at age ~ 380,000 years

Background radiation released*

First stars formed

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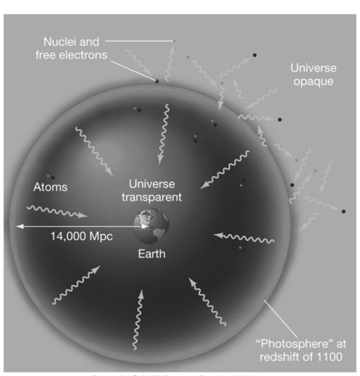

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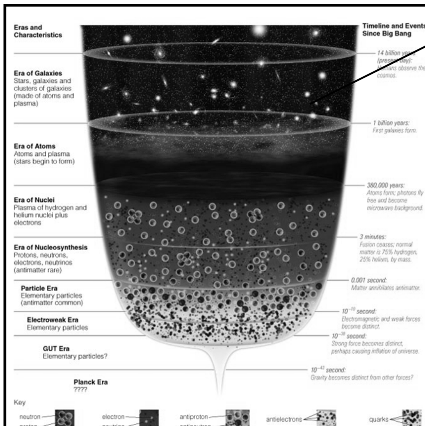

Era of Galaxies:

Galaxies form at age ~ 1 billion years

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Summary

– The early universe was so hot and so dense that radiation was constantly producing particle-antiparticle pairs and vice versa
– 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
– Stars formed from dense clouds
– Galaxies formed from stars and gas

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Primary Evidence

1) Expansion of the Universe (Hubble's Law).
2) Detection of the radiation from the Big Bang.
3) Abundances of helium and light elements.
4) Structure in the Universe.

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

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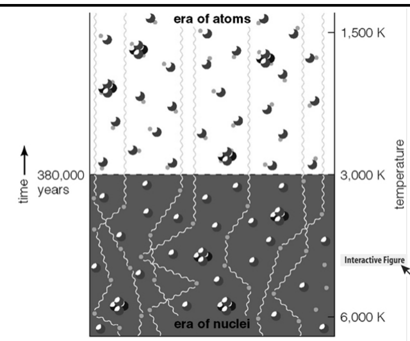

Background radiation from Big Bang has been freely streaming across universe since atoms formed at temperature ~ 3,000 K: *visible/IR*

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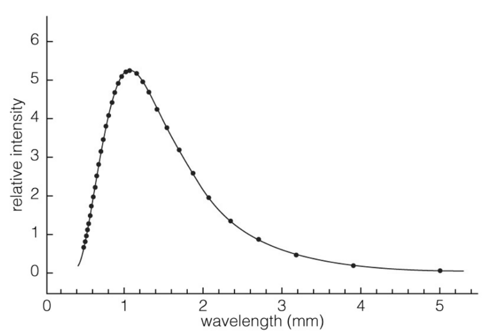

Expansion of universe has redshifted thermal radiation from that time to ~1000 times longer wavelength: *microwaves*

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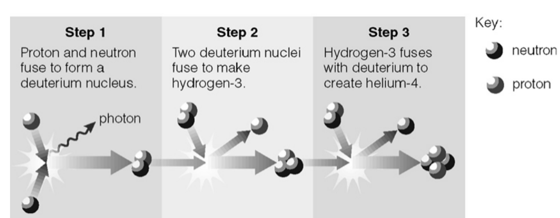

Protons and neutrons combined to make long-lasting helium nuclei when universe was ~ 3 minutes old

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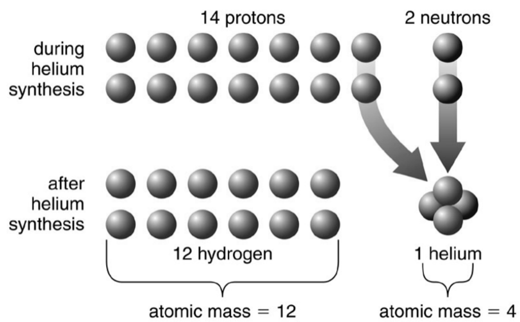

Big Bang theory prediction: 75% H, 25% He (by mass)

Matches observations of nearly primordial gases

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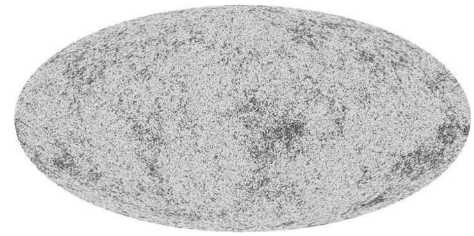
Structure in the Universe

Tiny ripples in cosmic background radiation found by NASA Wilkinson Microwave Anisotropy Probe (map.gsfc.nasa.gov) and the ESA Planck Space Telescope: https://www.youtube.com/watch?v=Fn0FgOwyu0w

These structures provide the seeds for later development of galaxies and clusters of galaxies.



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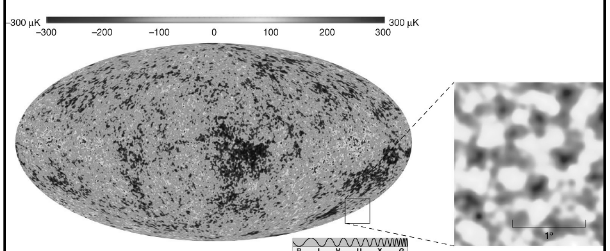
Ancient Structures in the Universe

WMAP ripples of +/- 0.01% (25 arcmin resolution).
Inset: Cosmic Background Imager (9 arcmin resolution).
Structures seen with size of about 1 degree.



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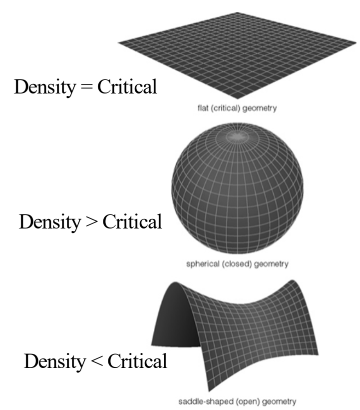

Overall (spacetime) geometry of the universe is closely related to total density of matter & energy

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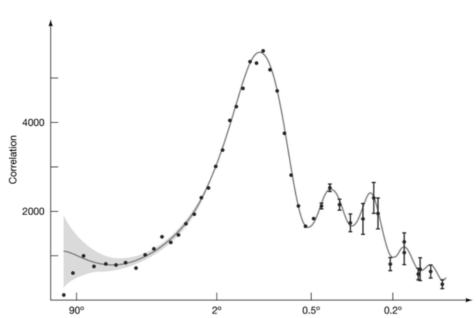
Observed and predicted angular scale clumping for critical density (flat Universe) are excellent match.



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Summary: Cosmic Microwave Background

- **Universe is about 13.8 billion years old**
- **First stars appeared 200 million years after Big Bang**
- **CMB is from 379,000 years after Big Bang**
- **Universe contains**
  4% Atoms, 23% Cold Dark Matter, 73% Dark Energy
  (more on this next time)

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The Universe As An 80-year-old Person ...

Time Since the Big Bang	The Universe	Human Equivalent
379,000 years	Time when the pattern of CMB light was set. Universe was cool enough for atoms to form.	Baby just 19 hours old.
200 million years	The matter in the Universe has condensed by gravity sufficiently to make the first stars.	Baby of 13 months (first steps).
1 billion years	The first galaxies began to form.	Child just under six years old.
9.1 billion years	Sun and Earth form.	Adult at 53.
13.7 billion years	The present day Universe of stars and galaxies.	Adult at 80.

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