Chapter 22: Cosmology - Back to the Beginning of Time

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

Future of universe depends on the total amount of dark and normal matter.

Lots of dark matter

Critical density of matter

Not enough dark matter

Amount of matter is ~25% of the critical density suggesting fate is eternal expansion.

Brightness of distant white-dwarf supernovae tells us how much universe has expanded since they exploded.

Accelerating universe is best fit to supernova data.
Acceleration of universe: mystery of dark energy. Estimated age depends on both dark matter and dark energy.

Deep Mysteries

**Dark Matter:** An undetected form of mass that emits little or no light but whose existence we infer from its gravitational influence.

**Dark Energy:** An unknown form of energy that seems to be the source of a repulsive force causing the expansion of the universe to accelerate.

Contents of Universe

Summary

- Current measurements indicate that there is not enough dark matter to prevent the universe from expanding forever.
- An accelerating universe is the best explanation for the distances we measure when using white dwarf supernovae as standard candles.

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.
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.

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.*

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

Forces become similar (unify) at higher temperatures

Fundamental Particles: based on mass, charge, spin

- **Integer spin**
- **Half integer spin**

**Quarks**

- Protons and neutrons are made of quarks
- *Up quark* (u) has charge +2/3
- *Down quark* (d) has charge -1/3
Masses of quarks and Z, W bosons related to Higgs field and Higgs boson (CERN discovery 7/4/2012)

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

**Planck Era:**
- First $10^{-43}$ sec
- No theory of quantum gravity yet

**GUT Era:**
- Strong and weak nuclear forces and electromagnetism are all unified

**Inflationary Epoch**
- Between GUT and electroweak epochs, separation of strong and electroweak forces may have released energy to cause sudden expansion, cosmic inflation.
- Explains (1) why regions of universe now separated by > speed of light x age can have similar properties (originally very close) and (2) why it is so smooth.

**Electroweak Era:**
- Lasts until electroweak force separates into weak and electromagnetic forces ($10^{-10}$ sec)
**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

**Era of Nucleo-synthesis:**
Protons, neutrons begin to fuse (H, He) but larger nuclei broken by collisions

**Era of Nuclei:**
Most of He made by 3 minutes
Too hot for electrons and nuclei to combine

**Era of Atoms:**
Atoms form at age ~ 380,000 years
Background radiation released*
First stars formed

**Era of Galaxies:**
Galaxies form at age ~ 1 billion years
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