Pair Creation of Particles

- Mass energy: $E=mc^2$
  - Mass can be converted into energy
- Energy can also be converted into mass
  - Energy can create particles!
- Creation of particles always occurs in pairs:
  - Energy → Particle + Anti-particle
  - Particle and anti-particle have the same masses
  - Required energy: $E = mc^2 + mc^2 = \mathbf{2}mc^2$
- Pair annihilation
  - Particle + Anti-particle → Energy: $E=2mc^2$

Pair Creation in the Early Universe

- A lot of energy is out there in the early universe– but, particles are not so easy to create!
  - As we go back in time, photons get more energy
  - The lightest (hence easiest) particles to create from photons are electrons
  - Pair creation occurs in pairs: *electrons* and *positrons*
- The mass of electrons=$9.11\text{x}10^{-31}$ kg
  - $E=2mc^2=1.6\text{x}10^{-13}$ joules → About **12 billion K**

The Lepton Era

- Leptons
  - Electron, positron
  - Muon, anti-muon
  - Tauon, anti-tauon
  - Electron-neutrino, Anti-electron-neutrino
  - Muon-neutrino, Anti-muon-neutrino
  - Tauon-neutrino, Anti-tauon-neutrino
- Leptons are minorities at T<10 billion K (1 second)
  - T>10 billion K: a lot of electrons and positrons will be created
  - The mass of muons = 207 times the mass of electrons
  - The mass of tauons = 3500 times the mass of electrons
  - **The era of leptons**
- Neutrinos?
  - Neutrinos are almost massless (they do have masses, but very small)
  - However, photons cannot create neutrinos

Decoupling of Neutrinos

- Like photons get scattered by electrons, neutrinos also get scattered by the corresponding "—ons".
  - They don't travel freely until the scattering by the corresponding "—ons" have annihilated
- **Neutrino decoupling**
  - (c.f.) Photon decoupling (z~1100)
  - Electron-neutrino decoupling ($z\sim4\text{x}10^{9}$)
  - Muon-neutrino decoupling ($z\sim4\text{x}10^{11}$)
  - Tauon-neutrino decoupling ($z\sim10^{13}$)
- **Cosmic Neutrino Background** allows us to "see" through the universe in much earlier epochs.
  - The neutrino background is slightly cooler: 1.96 K

Hadrons

- Hadrons can interact via the *strong forces*
- *Baryons*
  - Proton, Anti-proton
  - Neutron, Anti-neutron
  - Lambda, Anti-lambda
    - A lot of others
- *Mesons*
  - Pions, Anti-pions
  - K-ons, Anti-K-ons
    - A lot of others
- Too many hadrons -- are they elementary particles?
  - Quarks and gluons

The Hadron Era

- Baryons are heavy:
  - The mass of protons ~ 2000 times the mass of electrons
- At T>20 trillion K (~1/10,000 seconds), the pair-creation of protons and neutrons occurs.
  - **The era of hadrons**
    - Energy → Protons + Anti-protons
    - Energy → Neutrons + Anti-neutrons

Baryon Annihilation Riddle

- At T<20 trillion K, protons and neutrons annihilate away
  - Protons + Anti-protons → Energy
  - Neutrons + Anti-neutrons → Energy
- Have all the protons and neutrons annihilated?
  - **Of course not!** If they had, we weren't born…
- Apparently, there was more matter than anti-matter: WHY?
  - Even more puzzling:
    - 1,000,000,001 protons for 1,000,000,000 anti-protons
    - The required excess of matter is *tiny*!! WHY??
- **Baryogenesis** – challenge for the final theory