Lecture 17 : The Early Universe I

- Cosmic radiation and matter densities
- The hot big bang
- Fundamental particles and forces
- Stages of evolution in the early Universe

This week: read Chapter 12 in textbook

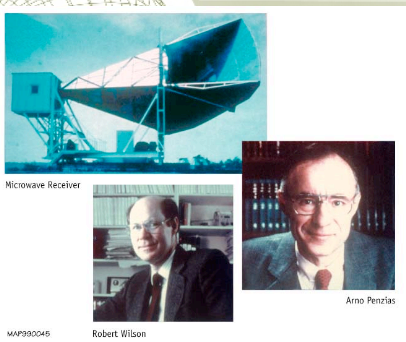
Quiz

- What is the expansion rate of a universe dominated by a cosmological constant?

Cosmic evolution

- From Hubble's observations, we know the Universe is expanding
  - This can be understood theoretically in terms of solutions of GR equations
- Earlier in time, all the matter must have been squeezed more tightly together
  - If crushed together at high enough density, the galaxies, stars, etc could not exist as we see them now -- everything must have been different!
- What was the Universe like long, long ago?
  - What were the original contents?
  - What were the early conditions like?
  - What physical processes occurred under those conditions?
  - How did changes over time result in the contents and structure we see today?

Cosmic radiation



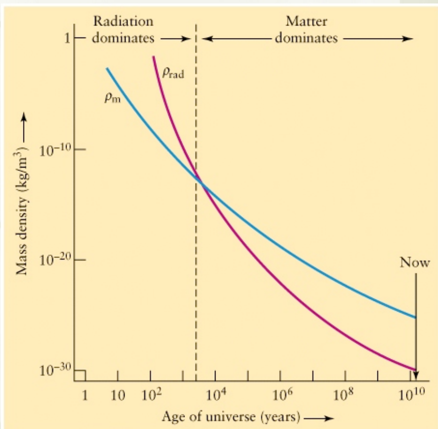
- Since the 1960's, it has been known that in addition to starlight, space is filled with a nearly-uniform, very faint radiation field
  - Pervasive throughout Universe
  - Range of wavelengths, with peak in microwave range
  - Present density is 411 photons/cubic centimeter
  - Known as ***cosmic background radiation***, or ***CBR (or CMB, for Cosmic Microwave Background, since there are other backgrounds)***
  - We'll discuss CBR discovery & properties in detail later on

Cosmic radiation

- At earlier times, this radiation field must have been *more intense*
- Energy density of background radiation *increases* as cosmic scale factor $R(t)$ *decreases* at earlier time t:
  - Multiply current number of photons/volume by $(R_0/R(t))^3=(1+z)^3$
  - Multiply current energy per photon by $(R_0/R(t))=(1+z)$
    - Why? Because photon energy is inversely proportional to wavelength, and wavelength at earlier time = present wavelength × $(R(t)/R_0)$
  - Overall, radiation energy density must vary as $(1+z)^4$

Matter and radiation densities compared

- Already know matter density varies inversely with volume
- Thus:
  - $\rho_{matter} \propto (R_0/R(t))^3=(1+z)^3$
  - $\rho_{radiation} \propto (R_0/R(t))^4=(1+z)^4$
- At early times, energy density of CBR must have exceeded energy density of matter!
- When radiation field is strong, matter is heated up
- Therefore earlier and earlier in the Universe, it must have been hotter and hotter
- This suggests that origin of the Universe was a ***hot*** *Big Bang*!



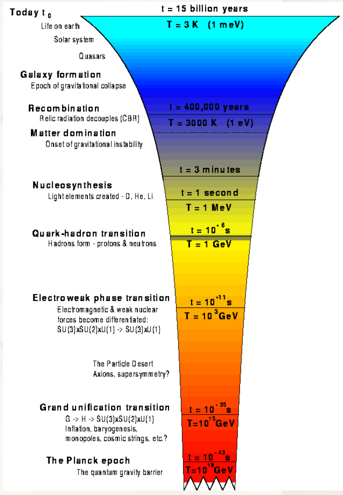
Hot big bang

- In fact, hot early Universe was previously (1948) predicted by George Gamow, with Alpher and Herman
  - They suggested that the universe started off in an extremely hot state of matter and radiation mixed together
  - High temperatures and densities would provide conditions where atomic nuclei could form!
  - As the Universe expands, the radiation energy would be spread over in increasing volume of space, and cool
  - **They predicted "relic radiation" with temperature about 5K**
- Work not fully recognized until revived by Jim Peebles in 1960s
- Original observation of CBR that confirmed hot big bang theory was serendipitous!

Planck data

A brief look at the stages of the Universe's life…

- We will discuss this diagram in detail in future classes…
- Crude overview:
  - t=0: The Big Bang
  - For first 400,000 yrs, an expanding "soup" of tightly coupled radiation and matter
    - Earliest epochs were "extreme" physics
    - Then more "normal" physics: protons & neutrons form
    - Then came nucleosynthesis
  - After 400,000 yrs, atoms form ("recombination") and radiation and matter "decouple"
  - Following decoupling, matter and radiation evolve independently
  - Galaxies, stars, planets, etc can then form and evolve



SOME TERMINOLOGY

- Our terminology…
  - Very Early Universe: from BB to t=10^{-35} s
  - Early Universe: from t=10^{-35} s to t=3 mins
- The study of the early universe:
  - No direct observations to constrain theories…
  - .. but, the basic physics governing the universe is well understood and tested in laboratories on Earth (particle accelerators).
- The study of the very early universe:
  - Still no observations to constrain theories…
  - … and the basic physics gets less and less certain as one considers times closer and closer to the big bang.

THE TEMPERATURE OF THE UNIVERSE

- The universe started off very hot and cooled as it expanded.
- In fact, the radiation temperature is inversely proportional to the scale factor

$$T \propto \frac{1}{R}$$

- The evolving temperature is crucial in determining what goes on when in the early (and very early) universe

10/24/18 11

- At a given temperature, each particle or photon has the same average energy:

$$E = \frac{3}{2} k_B T$$

  - k_B is called “Boltzmann’s constant” (has the value of $k_B = 1.38 \times 10^{-23}$ J/K)
- In early Universe, the average energy per particle or photon increases
- In early Universe, temperature was high enough that electrons had energies too high to remain bound in atoms
- In very early Universe, energies were too high for protons and neutrons to remain bound in nuclei
- In addition, photon energies were high enough that matter particle pairs could be created

10/24/18 12

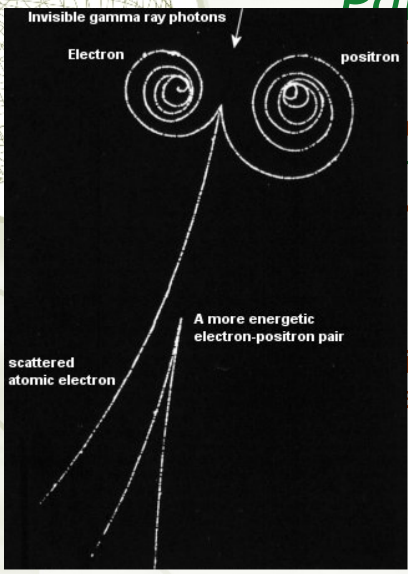
Particle production

- Suppose two very early Universe photons collide
- If they have sufficient combined energy, a particle/ anti-particle pair can be formed.
- So, we define ***Threshold Temperature***: the temperature above which particle and anti-particle pairs can be created.

$$T_{thres} = \frac{2mc^2}{3k_B}$$

- Different particles with different masses have different threshold temperatures
  - Protons : $T \approx 10^{13}$K
  - Electrons : $T \approx 5 \times 10^{9}$K

Particle production



ly Universe photons collide
t combined energy, a particle/
be formed.
hold Temperature: the
vhich particle and anti-particle

ith different masses have
emperatures

- Above the threshold temperature…
  - Continual creation/destruction of particles and anti-particles (equilibrium)
- Below threshold temperature…
  - Can no longer create pairs
  - Particles and anti-particles annihilate
  - Small residual of particles (matter) left over

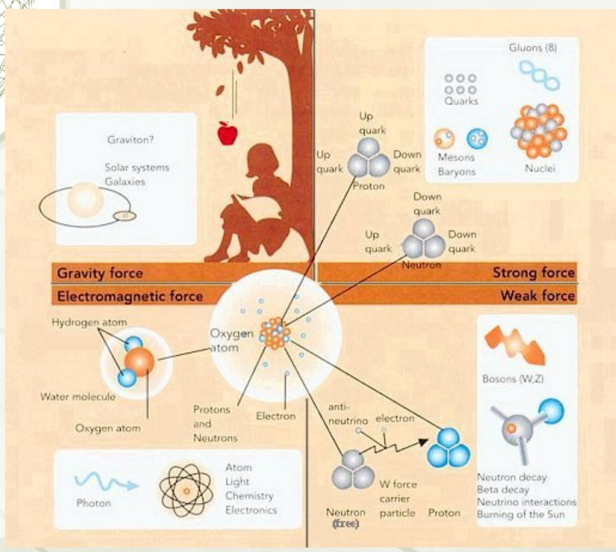
Types of particles

- Particles created/annihilated in the very early Universe were more than the ordinary types of particles abundant today (protons, neutrons, electrons, photons, neutrinos)
- Other more massive and unusual particles could be created/ annihilated
- These types of particles are observed today only as products of collisions in high-energy accelerators
- Two types of particles: **fermions** and **bosons** (see Ch. 4)
  - Primary duty of fermions is to make up matter
  - Primary duty of bosons is to mediate forces
- **Fermions** include:
  - Those particles based on **quarks**, called ***hadrons***
    - **Baryons** are made of 3 quarks (e.g. proton, neutron)
    - **Mesons** are made of 2 quarks (e.g. pion)
  - Those particles that are not, called ***leptons***
    - Electrons, muons, tauons
    - Neutrinos
  - The hadrons are generally more massive than leptons

Forces

- There are four fundamental forces in the Universe
  - Each has an associated particle (a boson) that mediates the force by constant "exchanges"
- Electromagnetic force (mediated by photons)
  - Electric & Magnetic fields are familiar in everyday life!
- Strong nuclear force (mediated by gluons)
  - Holds the nuclei of atoms together
  - Binds quarks together into hadrons
  - Does not affect leptons
- Weak nuclear force (mediated by W and Z particles)
  - Responsible for neutron decay
- Gravitational force (mediated by gravitons)
  - Gravitons have never been detected… still theoretical

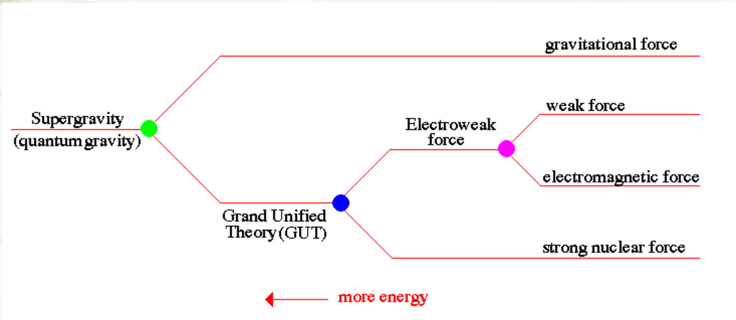
Fundamental interactions



From http://universe-review.ca

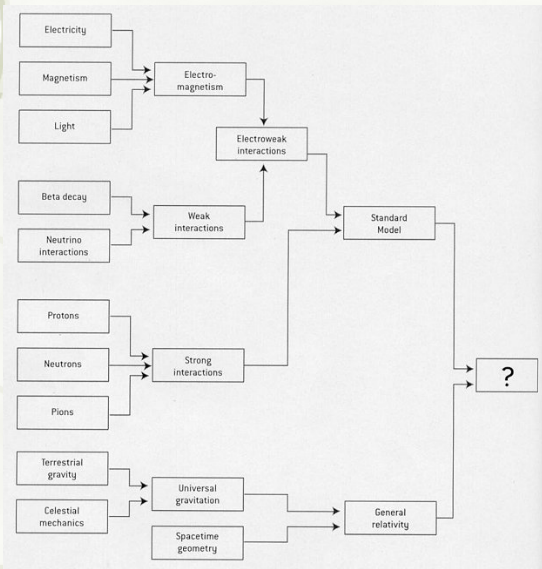
Stages of the early Universe

- In the high-temperature very, very early universe, these forces were all unified (in the same way that electricity and magnetism are unified today).
- As universe cooled down, they started to "decouple" from each other.



Graphics: University of Oregon Astronomy Dept

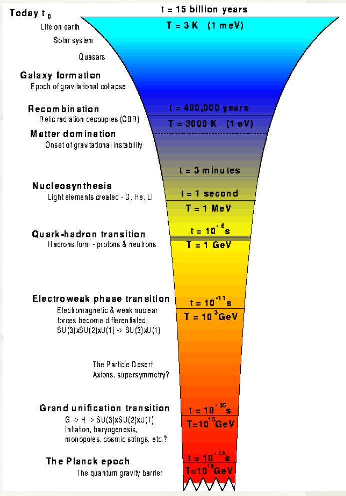
Theories and unification of phenomena



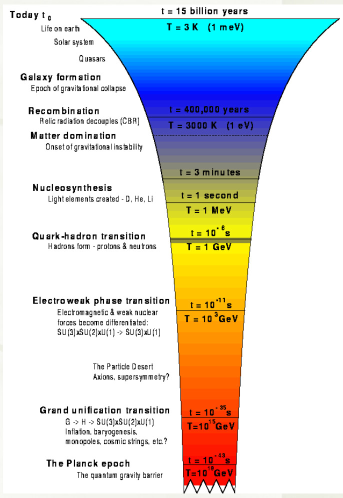
From http://universe-review.ca

Planck epoch

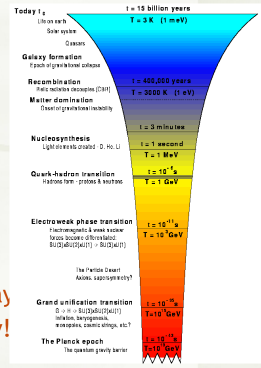
- The Big Bang! (t=0)
- The "Planck" Epoch ($t<10^{-43}$s)
  - Particle Horizon is c $t<10^{-35}$m
  - All fundamental forces are coupled, including gravity
  - Very difficult to describe the universe at this time – something completely outside of our experience.
  - Full theory of quantum gravity needed to describe this period of the Universe's life
  - Such a theory doesn't yet exist…



- End of the Planck Epoch ($t=10^{-43}$s)
  - Gravity decouples from other forces
  - Classical General Relativity starts to describe gravity very well
  - Gravitons cease their interactions with other particles… start free streaming through space
  - Produces a background of gravitational waves (almost completely redshifted away by the present day)

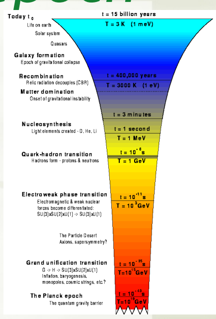


Unified epoch



- The Unified Epoch ($t=10^{-43}$ - 10^{-35}s)
- Two forces operate
  - Gravity (described by GR)
  - All other forces (described by Grand Unified Theories; GUTs): Strong, Weak, Electromagnetic
- Baryogenesis
  - Slight asymmetry developed between particles & antiparticles
  - Get more matter than antimatter by 1 part in 1.6×10^9
  - Same as ratio of number of baryons to CMB photons today
  - This produces the matter dominance that we have today!
- During unified epoch ($\sim 10^{-37}$s), Universe is believed to have undergone a period of exponential expansion, called ***inflation***
  - Size of universe expanded by factor 10^{100} or 10^{1000}
  - We'll discuss evidence for this later on!
- At end of epoch, GUT force splits into Strong and Electroweak force.

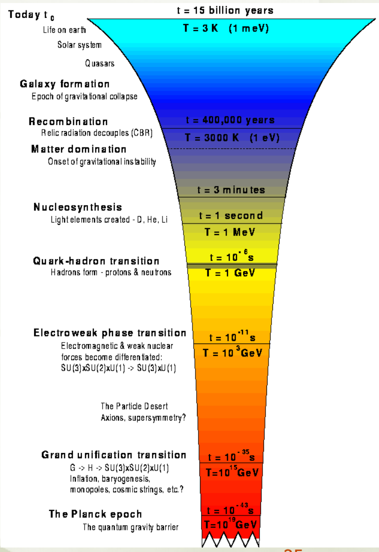
Quark epoch



- The quark epoch (10^{-35} -10^{-6} s)
- Universe consists of soup of
  - Quarks
  - Gluons
  - Electroweak force particles
  - Photons
  - leptons
  - Other more exotic particles
- Electroweak force symmetry breaks at $t=10^{-11}$s
  - Electroweak force particles were transformed into
    - Weak carriers: W, Z bosons (massive; 1st detected in 1983 in CERN)
    - Electomagnetic carriers: photons (massless)
- Quark epoch ends with "quark-hadron phase transition"
  - quarks pull themselves together into particles called hadrons (baryons are a subclass of this).

Hadron epoch

- Hadron Epoch ($t=10^{-6}$ - 10^{-4} s)
  - Particle horizon $D=10^2$ - 10^4 m
  - Soup of protons, neutrons, photons, W & Z particles + exotics
  - Matter/anti-matter asymmetry from GUT era gives baryon/anti-baryon asymmetry.
  - End of epoch given when temperature falls below proton threshold temperature



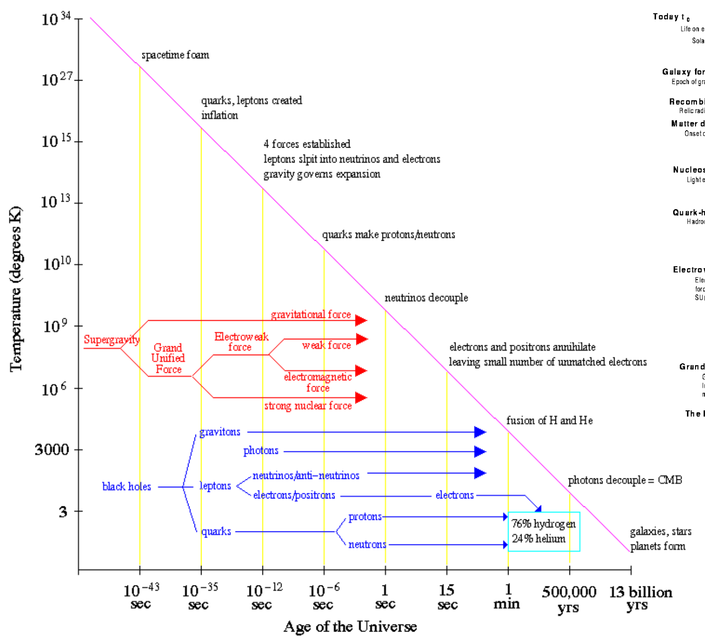
Lepton epoch

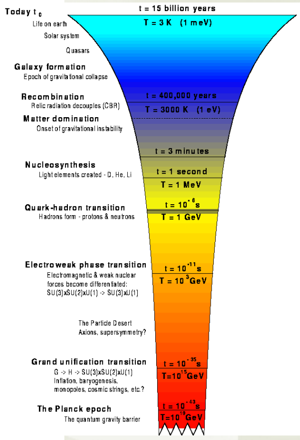
- Lepton Epoch ($t=10^{-4}$ - 15 s)
  - Universe was "soup" of photons, neutrinos, electons, positrons, plus much smaller number of protons & neutrons leftover from hadron epoch
  - Abundant ongoing production of electron/positron and pairs by interacting photons
  - Equilibrium between protons and neutrons

$$\bar{\nu} + p \leftrightarrow e^+ + n$$

$$\nu + n \leftrightarrow e^- + p$$

  - Number of protons same as number of neutrons until t=0.1 s
    - Afterwards, protons favored since they have lower mass
  - After t=1 s, neutrinos ceased interacting with other particles
  - Lepton epoch ended when temperature falls below electron threshold temperature, 5×10^9K, at t=14 s
  - Proton/Neutron ratio frozen in at this point:
    - 14% neutrons
    - 86% protons
  - Most of e^+ and e^- annihilated, leaving just enough e^- to balance charge of protons





Next lecture…

- Nucleosynthesis
- End of radiation-dominated era