Class 18
The early universe and nucleosynthesis

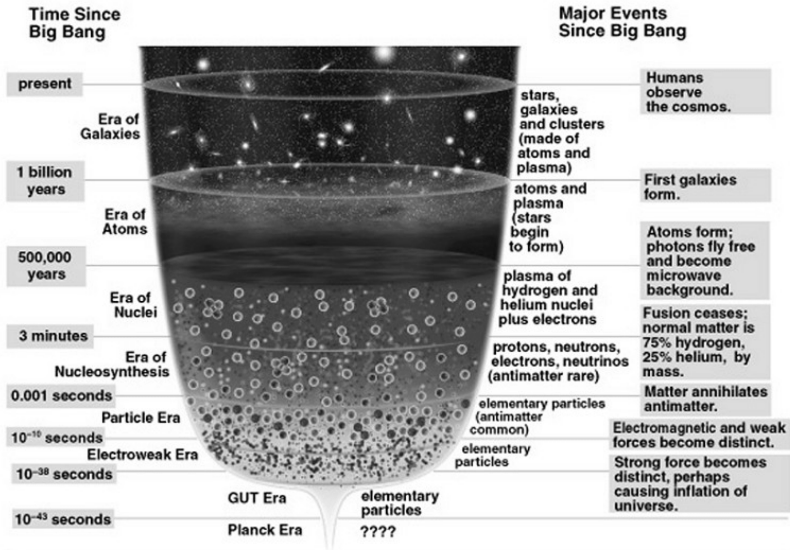
- ch 12 of book

- Why did Gamov and Peebles suggest hot big band model?

- If the early Universe was hot (full of energy), a lot of features of the current universe could be explained…
  - Could explain where the matter that we see around us came from (**baryogenesis** occurred well within first second)- Gamow first calculated that this could be important in 1948
  - Could explain the observed ratio of H,He Li *****

  (**nucleosynthesis** occurred within first few minutes)
  - This scenario predicted that there should be left over radiation in the present Universe…
  - This radiation redshifts as the Universe expands… nowadays should be redshifted to microwave/radio wave frequencies- the **CMB.**

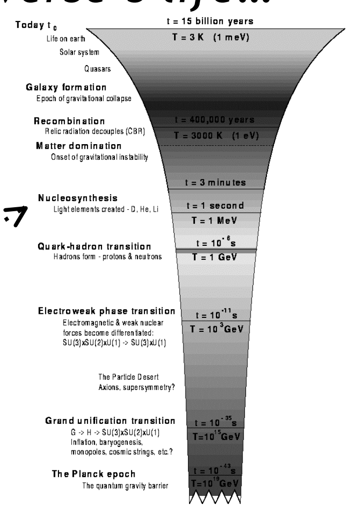
  ***** cannot explain the existence and amount of 'heavier'elements (e.g. C,N, O, ...Fe) which are created in stars and supernova (later lecture)

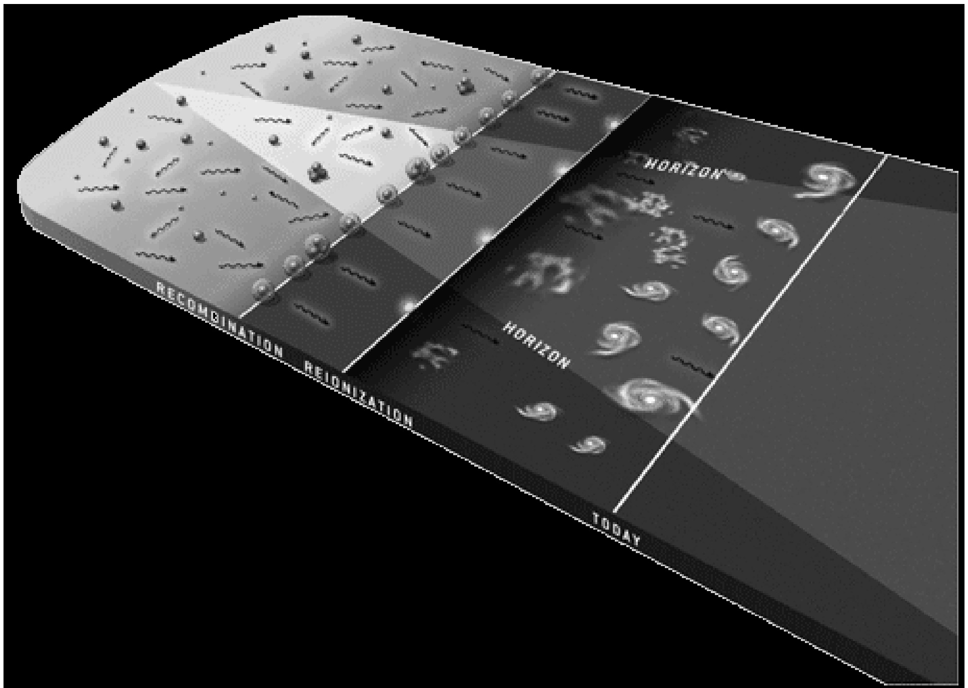


(*Lots* of technical details in this diagram – don't need to understand it all. Will cover some of this next time.)

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

- The big picture
- 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 early 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 discovery of 'B mode' polarization the other week means we are a lot closer to understanding the physics of the early universe

THE TEMPERATURE OF THE UNIVERSE

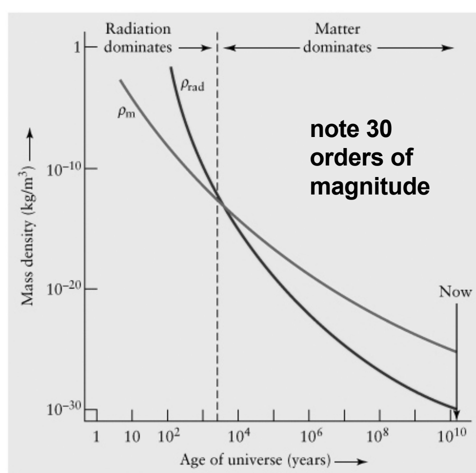
- The universe started off very hot and cooled as it expanded.
- In fact, the radiation temperature is inversely proportional to the scale factor

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

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

Matter and radiation densities compared

- Already know how matter density and CMB temperature vary with redshift
- 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*!



Remember its the sum of matter energy that is conserved

- 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=1.38×10^{-23} J/K)- physics formula the relates energy to temperature

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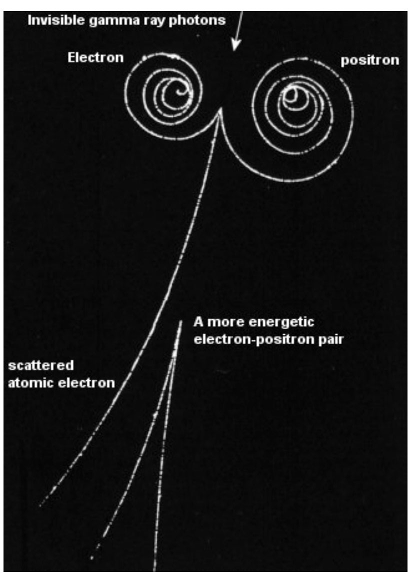
- In early Universe, the average energy per particle or photon increases enormously
- *In early Universe, temperature was high enough that electrons had energies too high to remain bound in atoms*
- *In very early Universe, energies were too high for protons and neutrons to remain bound in nuclei*
- *In addition, photon energies were high enough that matter-anti matter particle pairs could be created*

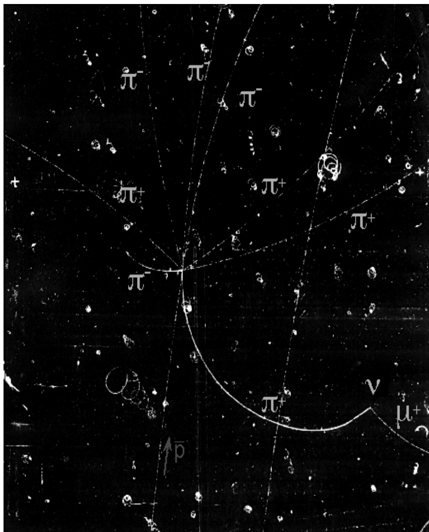
Particle production



- 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 of given mass can be created.

$$T_{thres} = \frac{2\boxed{m}c^2}{3k_B}$$

- This comes from equating $E=mc^2$ to $E=3/2k_BT$,



actual bubble chamber photograph of an antiproton (entering from the bottom of the picture), colliding with a proton and annihilating. 8 pions were produced. One decayed into μ+ and ν. The paths of positive and negative pions curve opposite ways in the magnetic field, and the neutral ν leaves no track.

Particle production

- Different particles with different masses have different threshold temperatures
  - Protons mass=$1.6x10^{-27}$ kg : $T \approx 10^{13}K$
  - Electrons : $T \approx 4 \times 10^9 K$

  incredibly hot

  lets calculate the proton temperature

  $T=\{(2/3)*1.67x10^{-27}x(3x10^8)^2\}/1.38 \times 10^{-23}$

- $7x10^{12}$ K
- so since T~1/R and T today is 2.7k the universe was $3.7x10^{-13}$ its present size - (.005lt-yr)

What Else is There Besides Atoms, Neutrons Protons and Electrons

- There are a 'slew' of other particles (we have already encountered the muon and the neutrino was in the news last year)
- The early universe was a 'equal opportunity' place and if a particle could be created it was (more later)
- I will not go into this in any detail

The two big families of particles which make up matter (fermions)

• hadrons made of 2-3 quarks- 2 families
    •baryons+ (proton, neutron)
    •mesons

• leptons* (electrons, muons, neutrinos...)

+ From Greek word (barys) for "heavy"
•From Greek (leptos), "fine, small, thin"

•The other type of particle (bosons) "carry forces" (e.g. photons)

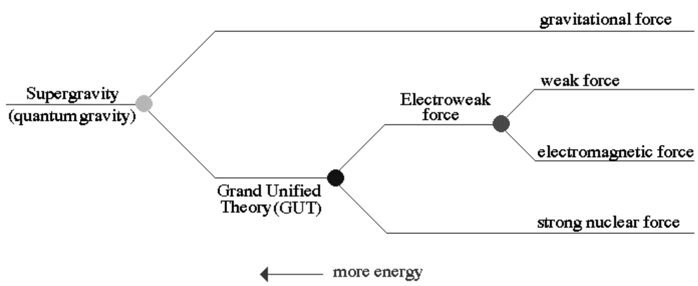
- Above the threshold temperature…
  - Continual creation/destruction of particles and anti-particles (equilibrium)
- Below threshold temperature…
  - Can no longer create pairs
  - The particles and anti-particles that were created, when the universe was hot, annihilate or decay
  - Small residual of particles (matter) left over ???-Since one needs an asymmetry between baryons and antibaryons in the very early universe, to produce the substantial amounts of matter that make up the universe today. This is a an unsolved problem called baryogenesis.

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

Stages of the early Universe

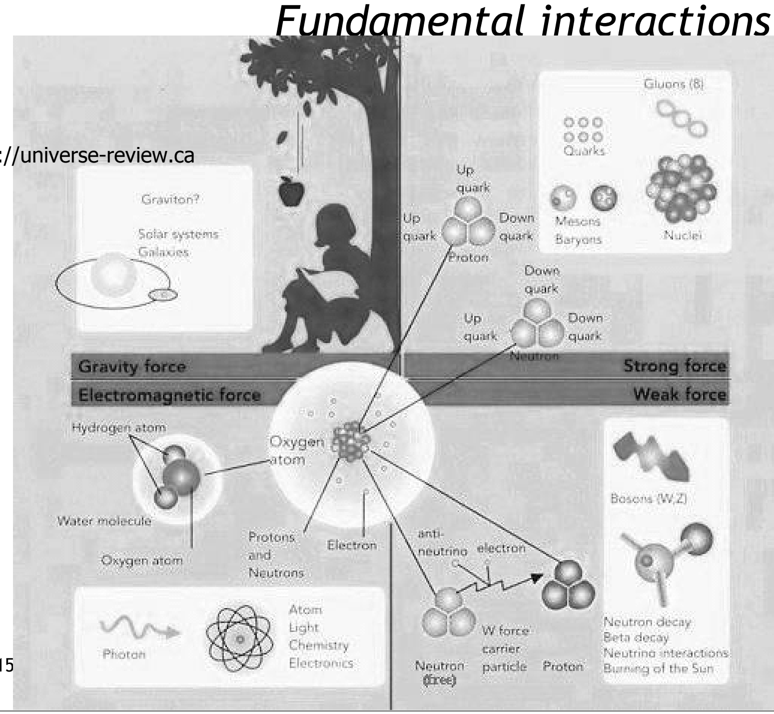
- In the high-temperature very, very early universe, all the forces were unified (in the same way that electricity and magnetism are unified today).
- As universe cooled down, they started to “decouple” from each other.



Graphics: University of Oregon Astronomy Dept

Fundamental interactions

From http://universe-review.ca



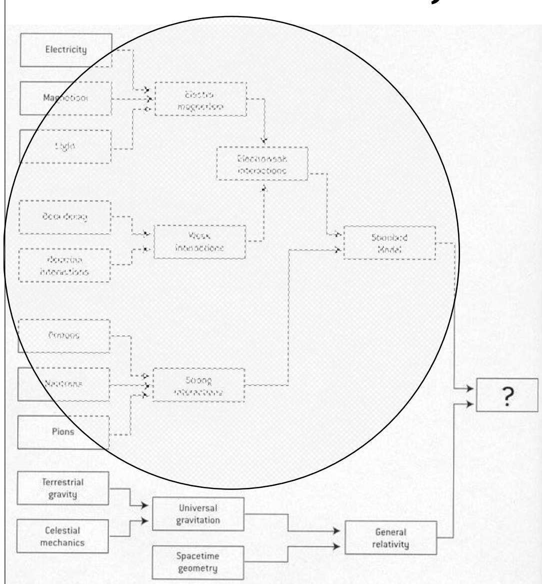
Some Strange New Words

Spontaneous symmetry breaking-a process by which a system in a symmetrical state ends up in an asymmetrical state.

To quote from hyperphysics

The snowflake: Both the hydrogen and oxygen molecules are quite symmetric. But when the temperature is lowered they form a water molecule, and the symmetry of the individual atoms is broken as they form a molecule with 105 degrees between the hydrogen-oxygen bonds. Since this loss of symmetry occurs without any external intervention, it is called spontaneous symmetry breaking.

Theories and unification of phenomena



How are the forces of nature connected?

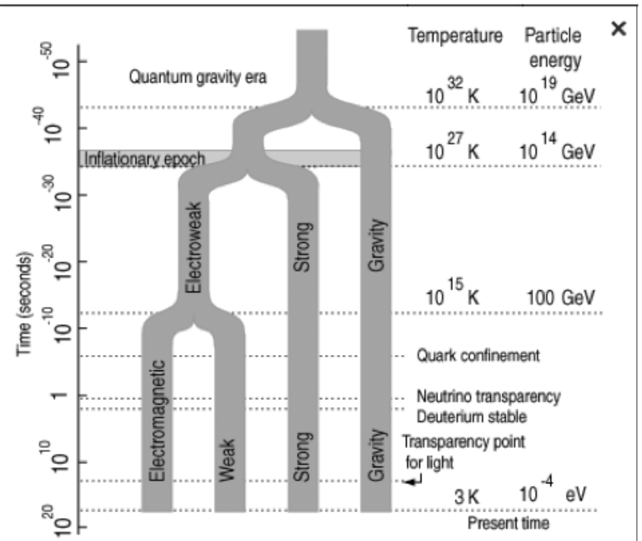
The 'standard model' of quantum mechanics connects 3 of the 4 forces (all except gravity)

In the early universe they were "unified"

We are still unable to connect gravity with the other 3 - do not have a Grand Unified Theory (GUT)

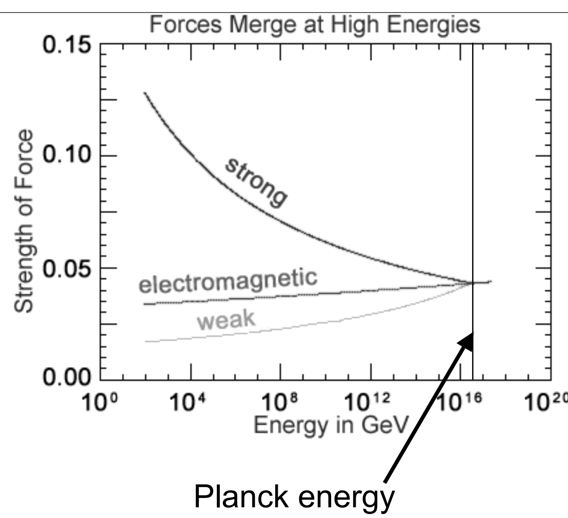
From http://universe-review.ca

- Each separation of forces is due to a 'new' symmetry breaking



http://hyperphysics.phy-astr.gsu.edu/hbase/astro/unify.html

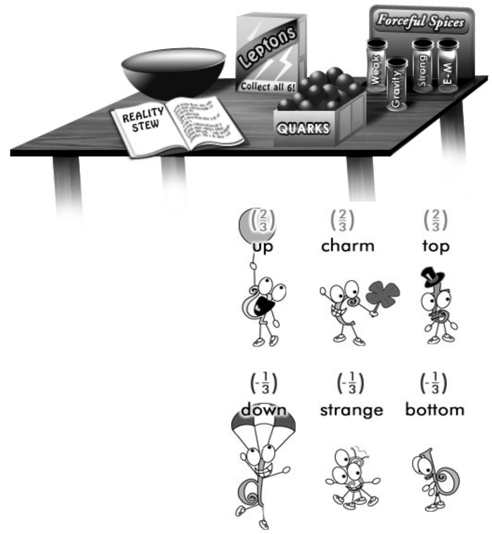
- The unification of forces occurs at high energies- the early universe was a very high energy place (very hot → very energetic)



http://www.particleadventure.org/grand.htm

Standard Model

- The Standard Model that explains what the world is and what holds it together. It is a simple and comprehensive theory that explains all the hundreds of particles and complex interactions with only:
- 6 quarks- which make up most of the mass .
- 6 leptons. The best-known lepton is the electron.
- Force carrier particles, like the photon



http://www.particleadventure.org/standard_model.html

- Many of the particles are very unstable and only exist for very short times after being created in particle accelerators.
- The heavier leptons and hadrons, are not found in ordinary matter at all. This is because when they are produced they very quickly decay
- however they existed in the very early universe

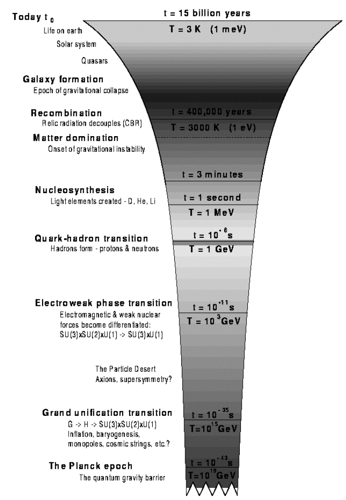
Table of Baryons

Particle	Symbol	Makeup	Rest mass MeV/c^2	Spin	B	S	Lifetime (seconds>	Decay Modes
Proton	p	uud	938.3	1/2	+1	0	Stable	...
Neutron	n	ddu	939.6	1/2	+1	0	920	$pe^- \underline{\nu}_e$
Lambda	Λ^0	uds	1115.6	1/2	+1	-1	2.6 $x10^{-10}$	$p\pi^-$, $n\pi^0$
Sigma	Σ^+	uus	1189.4	1/2	+1	-1	0.8 $x10^{-10}$	$p\pi^0$, $n\pi^+$
Sigma	Σ^0	uds	1192.5	1/2	+1	-1	$6x10^{-20}$	$\Lambda^0\gamma$
Sigma	Σ^-	dds	1197.3	1/2	+1	-1	1.5 $x10^{-10}$	$n\pi^-$
Delta	Δ^{++}	uuu	1232	3/2	+1	0	0.6 $x10^{-23}$	$p\pi^+$
Delta	Δ^+	uud	1232	3/2	+1	0	0.6 $x10^{-23}$	$p\pi^0$
Delta	Δ^0	udd	1232	3/2	+1	0	0.6 $x10^{-23}$	$n\pi^0$
Delta	Δ^-	ddd	1232	3/2	+1	0	0.6 $x10^{-23}$	$n\pi^-$
Xi Cascade	Ξ^0	uss	1315	1/2	+1	-2	2.9 $x10^{-10}$	$\Lambda^0\pi^0$
Xi Cascade	Ξ^-	dss	1321	1/2	+1	-2	1.64 $x10^{-10}$	$\Lambda^0\pi^-$
Omega	Ω^-	sss	1672	3/2	+1	-3	0.82 $x10^{-10}$	$\Xi^0\pi^-$, Λ^0K^-
Lambda	Λ^+_c	udc	2281	1/2	+1	0	$2x10^{-13}$	...

✦The Big Bang! (t=0)

Planck epoch

- ✦ The "Planck" Epoch ($t<10^{-43}s$)
  - ✦ Particle Horizon is $ct<10^{-35}m$
  - ✦ At this length concepts of size and distance break down, as quantum indeterminacy becomes virtually absolute.
  - ✦ 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



http://www.guardian.co.uk/science/2008/apr/26/universe.physics

Planck Units

- ✦ Form dimensionless units of length,mass,time from fundamental constants-
  - ✦ Planck's constant h (from the uncertainty principle and the energy of light)
  - ✦ Gravitational constant (G)
  - ✦ Speed of light (c)
  - ✦ Boltzman constant (k_B) relate temperature to energy

- ✦ $Length_{Planck}$=sqrt(hG/c^3)
- ✦ $Mass_{Planck}$ =sqrt(hG/c)
- ✦ $Time_{Planck}$ =sqrt(hG/c^5)
- ✦ $Temp_{Planck}$ =sqrt(hc^5/Gk_B^2)

Quantity	SI equivalent
Planck time	5.39121×10^{-44} s
Planck mass	2.17645×10^{-8} kg
Planck length (ℓ_P)	$1.616\,252 \times 10^{-35}$ m

Why Planck Scale Important in the early universe

- Uncertainty Principle

$\Delta E \Delta t = h$

define length as $L = c\Delta t$ then

- $\Delta E \Delta t = hc/L$
- Use $\Delta E = mc^2$ and thus cannot known anything about something with a mass less than $h/2cL$ (Planck mass)

Now we know that mass and length are related by the Schwarschild radius of a black hole

$R = 2Gm/c^2$

so lets put them together

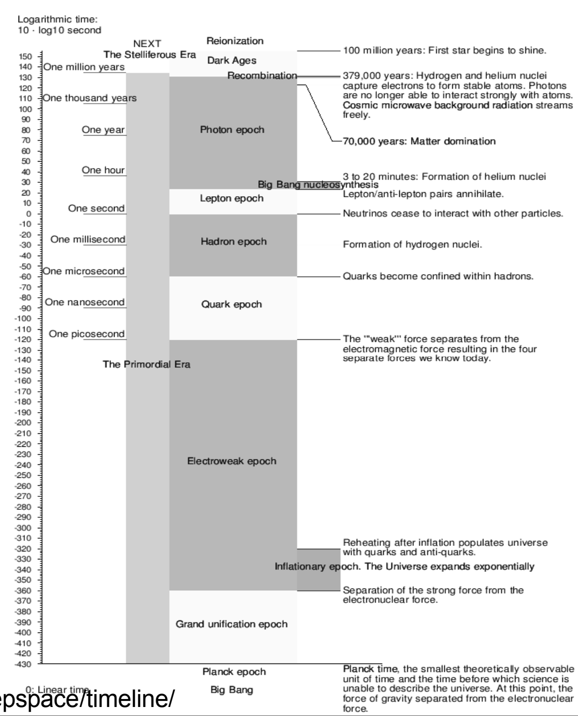
(L=R) and we get

$L = \text{sqrt}(G/c^3) \sim 10^{-35}$ m, $\Delta t = L/c$

it is the smallest length that can be operationally defined-If try to measure a smaller distance, the time interval would be smaller, the uncertainty in rest energy larger, the uncertainty in mass larger, and the region of space would be indistinguishable from a black hole. Since nothing inside a black hole is 'visible', we cannot see inside and thus cannot make smaller measurement

---

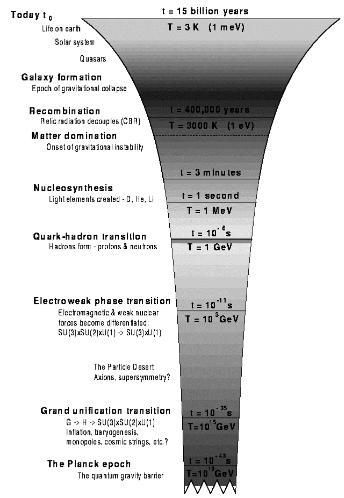
- After inflation, 10^{-6} seconds after the Big Bang, the universe continues to expand but not nearly so quickly.
- As it expands, it becomes less dense and cools. The most basic forces in nature become distinct: first gravity, then the strong force, which holds nuclei of atoms together, followed by the weak and electromagnetic forces.
- By the first second, the universe is made up of fundamental particles and energy: quarks, electrons, photons, neutrinos and less familiar types. These particles smash together to form protons and neutrons.



http://www.pbs.org/deepspace/timeline/

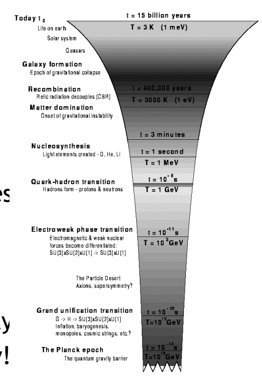
End of the Planck Epoch

- End of the Planck Epoch ($t=10^{-43}$s)
  - Gravity <u>decouples</u> 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 <u>gravitational waves</u> (almost completely redshifted away by the present day)**- very recently detected ! (BICEP2)**

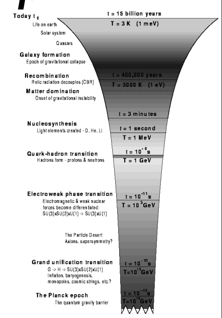


Unified epoch

- 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 must have developed between particles & antiparticles
  - Need only more matter than antimatter by 1 part in 1.6 $\times 10^9$
  - Same as ratio of number of baryons to CMB photons today
  - This produces the matter dominance that we have today!
- During unified epoch (~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.



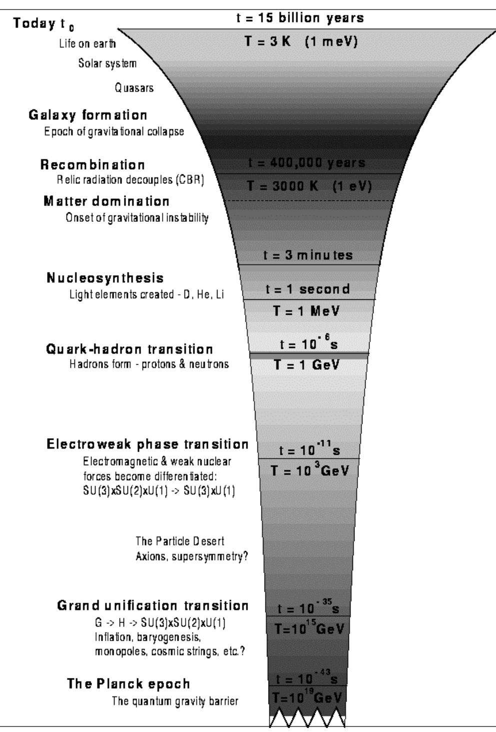
Quark epoch



- 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**



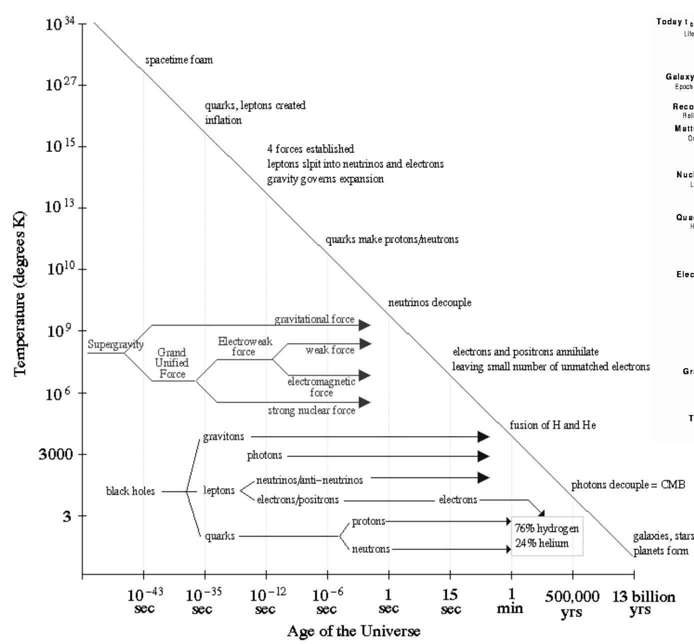
Lepton epoch

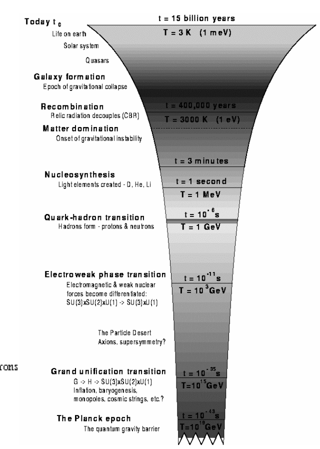
- Lepton Epoch ($t=10^{-4}$ – 15 s)
  - Universe was "soup" of photons, neutrinos, electons, positrons, plus much smaller number of protons & neutrons leftover from hadron epoch
  - Abundant ongoing production of electron/positron and pairs by interacting photons
  - Equilibrium between protons and neutrons

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

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

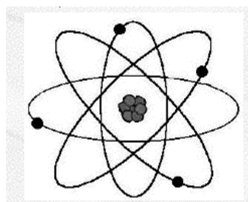
  - Number of protons same as number of neutrons until t=0.1 s
    - Afterwards, protons favored since they have lower mass
  - After t=1 s, neutrinos ceased interacting with other particles
  - Lepton epoch ended when temperature falls below electron threshold temperature, 5×10^{9}K, at t=14 s
  - Proton/Neutron 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





THE STRUCTURE OF MATTER+ Nucleosyntheis

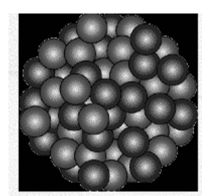
- Atom is made up of…
  - Nucleus (very tiny but contains most off mass)
  - Electrons (orbit around the nucleus)



  - Atom held together by (electromagnetic) attraction between positively-charged nucleus and negatively-charged electrons.

Elements & isotopes

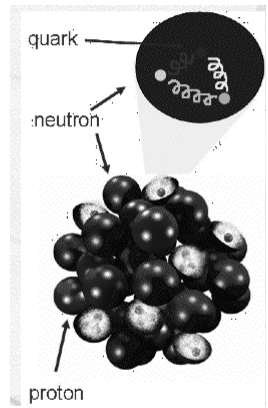
- Number of protons determines the element:
  - Hydrogen – 1 proton
  - Helium – 2 protons
  - Lithium – 3 protons
  - Beryllium – 4 protons
  - Boron – 5 protons
  - Carbon – 6 proton
  - etc



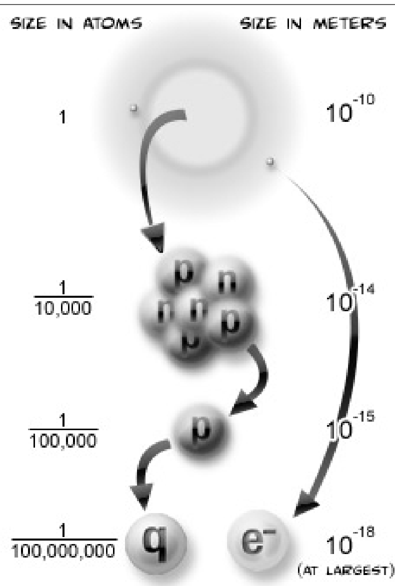
- Number of neutrons determines the isotope
- e.g., for hydrogen (1 proton), there are three isotopes
  - Normal Hydrogen (H or p) – no neutrons
  - Deuterium (d) – 1 neutron
  - Tritium (t) – 2 neutrons

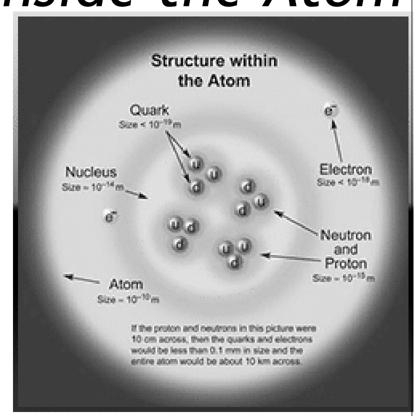
Atomic nuclei

- The nucleus is itself made up of:
  - Protons, **p** (positively charged)
  - Neutrons, **n** (neutral; no charge)
  - Collectively, these particles are known as **baryons (made up of 3 quarks)**
  - **p** is **slightly** less massive than **n** (0.1% difference)
  - Protons and neutrons bound together by the strong nuclear force (exchange of "gluons")



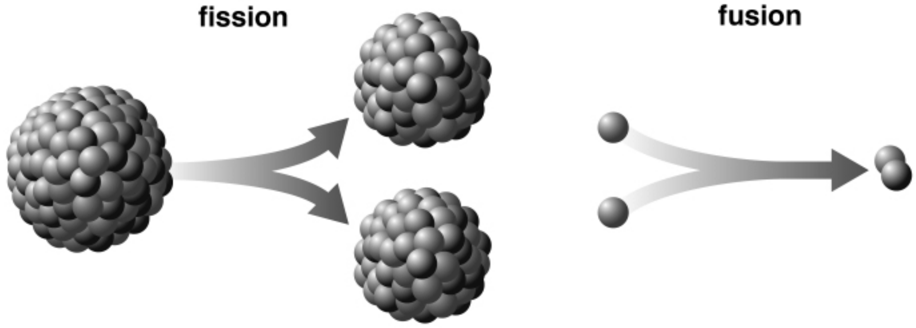
Inside the Atom



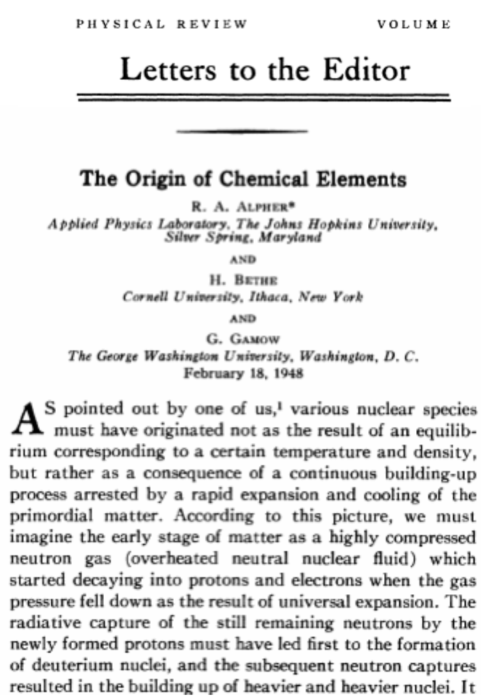


- enormous range in scales

Fission and fusion



- Enough was known about nuclear physics after 1945 (the atomic bomb project) that an attempt to understand the origin of the elements (nucleosynthesis) in the early universe was made
- The idea is that the very early on the hot universe could make protons,neutrons,electrons
- as it cooled nuclei could exist



PHYSICAL REVIEW VOLUME

Letters to the Editor

The Origin of Chemical Elements

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The George Washington University, Washington, D. C.
February 18, 1948

AS pointed out by one of us,[1] various nuclear species must have originated not as the result of an equilibrium corresponding to a certain temperature and density, but rather as a consequence of a continuous building-up process arrested by a rapid expansion and cooling of the primordial matter. According to this picture, we must imagine the early stage of matter as a highly compressed neutron gas (overheated neutral nuclear fluid) which started decaying into protons and electrons when the gas pressure fell down as the result of universal expansion. The radiative capture of the still remaining neutrons by the newly formed protons must have led first to the formation of deuterium nuclei, and the subsequent neutron captures resulted in the building up of heavier and heavier nuclei. It

NUCLEOSYNTHESIS IN THE EARLY UNIVERSE

- Nucleosynthesis: the production of different elements via nuclear reactions
- Consider universe at t=180s
  - i.e. 3 minutes after big bang
  - Universe has cooled down to 1 billion (10^9) K
  - Filled with
    - Photons (i.e. parcels of electromagnetic radiation)
    - Protons (p)
    - Neutrons (n)
    - Electrons (e)
    - [also Neutrinos, but these were freely streaming]

The first three minutes…

- Protons and Neutrons can **fuse** together to form deuterium (d)

$$n + p \rightarrow D + \gamma$$

- But, deuterium is quite fragile…
- Before t=180s, Universe is hotter than 1 billion degrees.
  - High-T means that photons carry a lot of energy
  - Deuterium is destroyed by energetic photons as soon as it forms

$$D + \gamma \rightarrow n + p$$

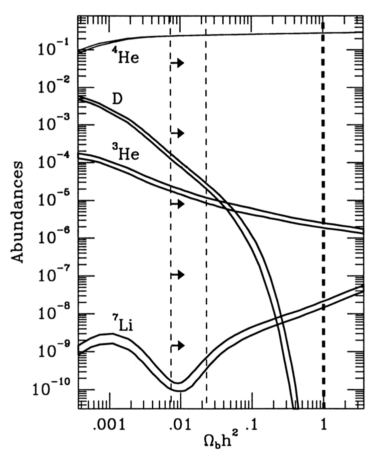
✦Further reactions can give Lithium (Li)

$$^4He + T \rightarrow {}^7Li + \gamma$$

✦Reactions cannot easily proceed beyond Lithium due to the "stability gap"… - lots of other detailed physics is needed but the bottom line is

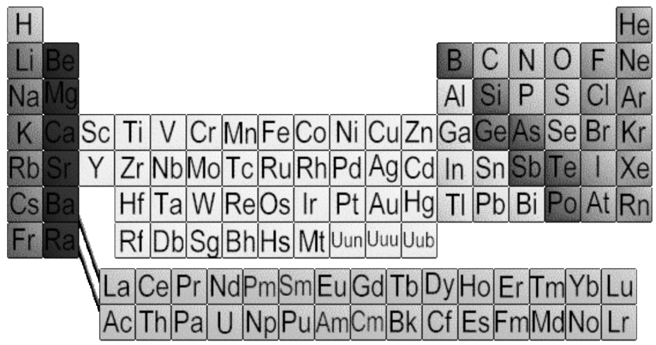
Primordial Nucleosynthesis

- The light elements (H,He,D, Li) were manufactured during the Big-Bang- the universe was only hot enough for this to happen for ~20 minutes
- the physical laws and constants that govern the behavior of matter at these energies are very well understood, and hence BBN is a strong constraint on cosmology.
- The abundances of those elements tells us about the density of the Universe
- Big Bang nucleosynthesis produced no elements heavier than beryllium, due to a bottleneck: the absence of a stable nucleus with 8 or 5 nucleons.

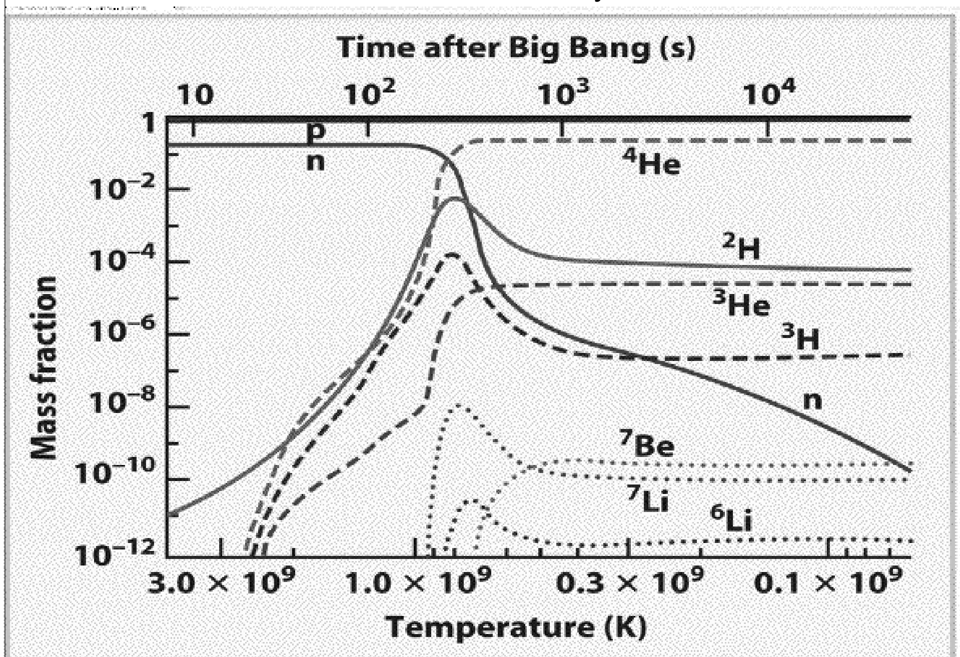


All the Heavy Stuff is Made in Stars

- ✦Fusion in 1st generation of stars…
- ✦…mostly makes more Helium!
- ✦Helium combines to make more Carbon, etc.



When did Nucleosynthesis Occur



Next lecture…

- End of radiation-dominated era