Re-cap from last lecture

Discovery of the CMB- logic

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 and a lot hotter AT R=0 have the Big Bang

the CMB is the 'relic' of the Big Bang

Its extremely uniform and can be well fit by a black body spectrum of T=2.7k

Re-cap from last lecture

The energy density of the universe in the form of radiation and matter density change differently with redshift

$\rho_{matter} \propto (R_0/R(t))^3=(1+z)^3$

$\rho_{radiation} \propto (R_0/R(t))^4=(1+z)^4$

Strong connection between temperature of the CMB and the scale factor of the universe T~1/R

Energy density of background radiation *increases* as cosmic scale factor *R(t)* *decreases* at earlier time *t*:

How Does the Temperature Change with Redshift

Remember from eq 10.10 in the book that
$\mathbf{R_{now}/R_{then}=1+z}$
where z is the redshift of objects at
observed when the universe had scale factor R_{then}

Putting this into eq 12.2 one gets
$T(z)=T_0(1+z)$
where the book has conveniently relabeled variables
$R_0=R_{now}$

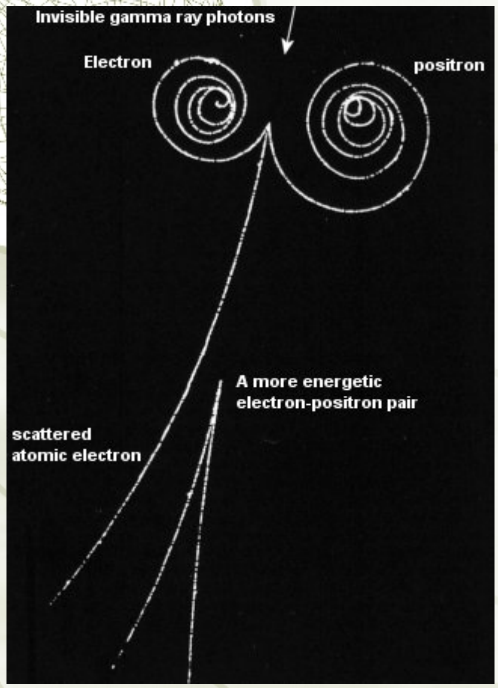
- At a given temperature, each particle or photon has the same average energy:

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

  - k_B is called "Boltzmann's constant" (has the value of $k_B=1.38\times10^{-23}$ J/K)

- 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*

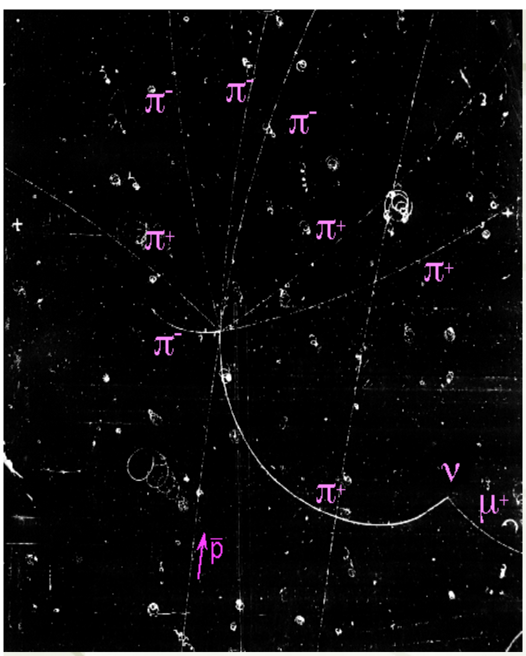
Particle production



- 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 can be created.

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

- 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
  - Electrons : $T \approx 4\times10^9$K

lets calculate the temperature at which the univese is hot enough to create *protons*

$T=\{(2/3)*1.67x10^{-27}x(3x10^8)^2\}/1.38\times10^{-23}$

- $7x10^{12}$ K
- so since T~1/R and T today is 2.7k the universe was $3.7x10^{-13}$ its present size when it was this hot… the early universe.

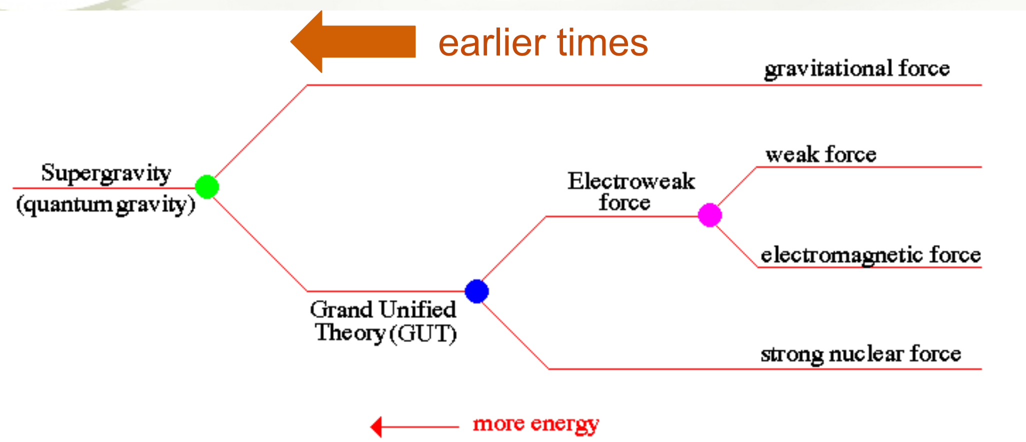
- Above the threshold temperature…(or alternatively at earlier times, smaller R)
  - Continual creation/destruction of particles and anti-particles (equilibrium)

- Below threshold temperature…
  - Can no longer create pairs
  - The particles and anti-particles that were created when the universe was hot annihilate each other
  - 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.

Stages of the early Universe

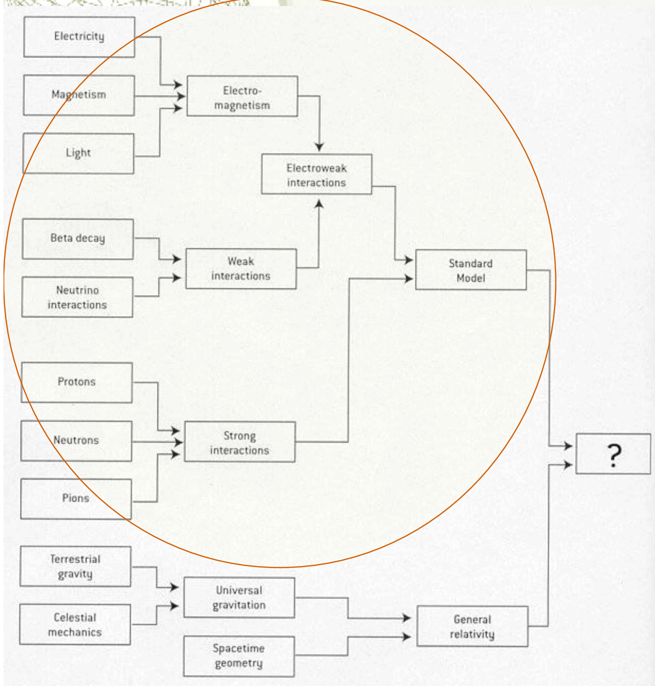
- In the high-temperature very, very early universe, the 4 forces were all unified (in the same way that electricity and magnetism are unified today).
- As universe cooled down, they started to “decouple” from each other.-

Complex quantum mechanics



Graphics: University of Oregon Astronomy Dept

Theories and unification of phenomena



How are the forces of nature connected?

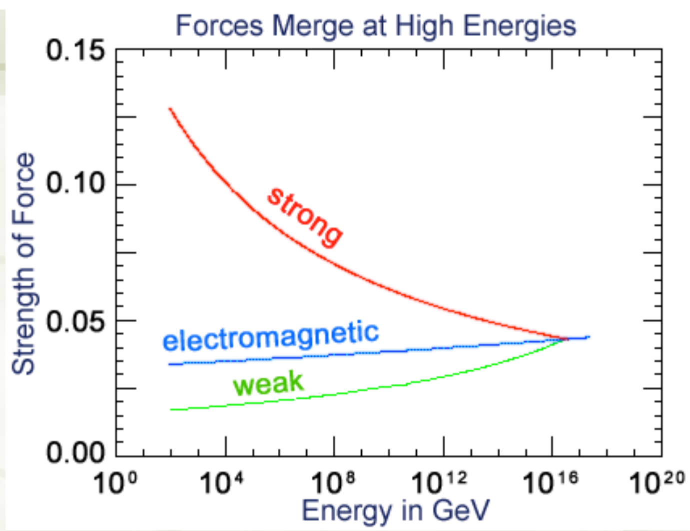
The 'standard model' of quantum mechanics connects 3 of the 4 forces (all except gravity)

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

- 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

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 recently in the news)
- The early universe was a 'equal opportunity' place and if a particle could be created it was (lots more later)
- I will not go into this in any detail

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

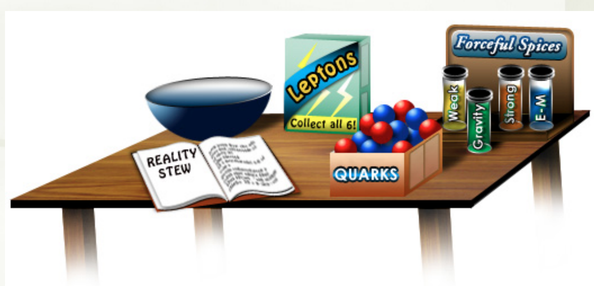
- hadrons made of 2-3 quarks- 2 families
  - •baryons+ (proton, neutron)
  - •mesons
- leptons* (electrons, muons, neutrinos...)

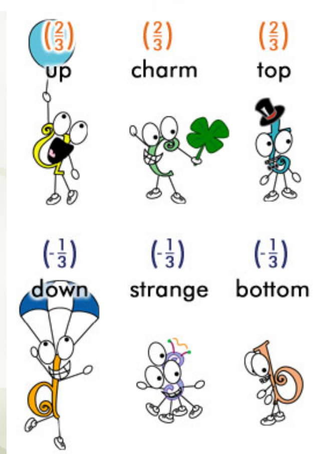
+ From Greek word (barys) for "heavy"
•From Greek (leptos), "fine, small, thin"

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

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





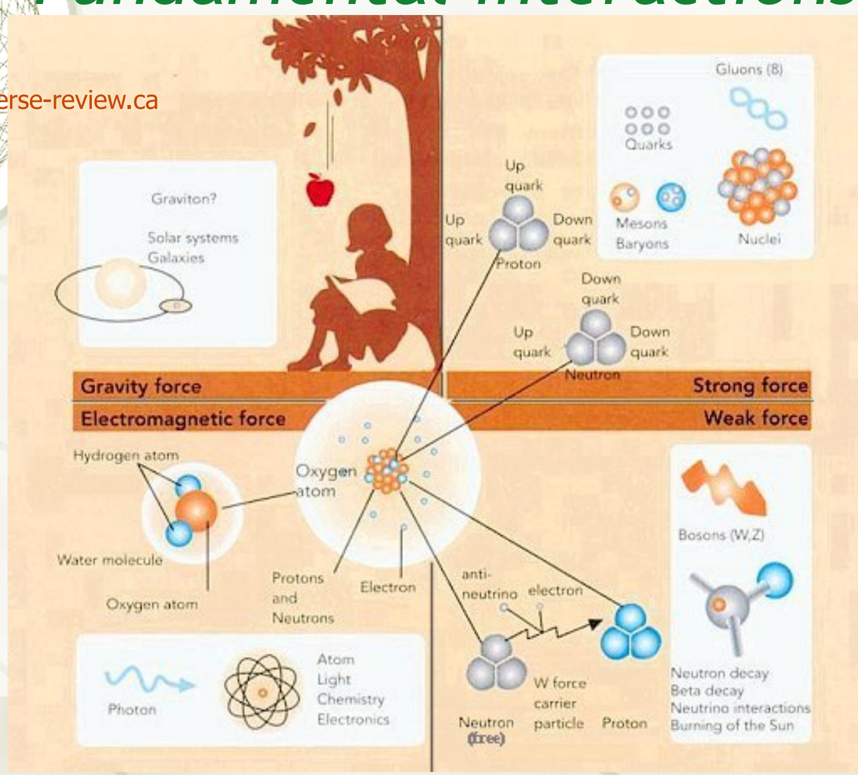
http://www.particleadventure.org/standard_model.html

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



- http://cds.cern.ch/record/1165534/files/CERN-Brochure-2009-003-Eng.pdf

LEPTONS

Make up matter		
	Electron Together with the nucleus, it makes up the atom	**Electron neutrino** Particle with no electric charge, and very small mass; billions fly through your body every second
	Muon A heavier relative of the electron; it lives for two-millionths of a second	**Muon neutrino** Created along with muons when some particles decay
	Tau Heavier still; it is extremely unstable. It was discovered in 1975	**Tau neutrino** Discovered in 2000

QUARKS

Make up matter		
	Up Has an electric charge of plus two-thirds; protons contain two, neutrons contain one	**Down** Has an electric charge of minus one-third; protons contain one, neutrons contain two
	Charm A heavier relative of the up; found in 1974	**Strange** A heavier relative of the down.
	Top Heavier still; found in 1995	**Bottom** Heavier still; measuring bottom quarks is an important test of electroweak theory

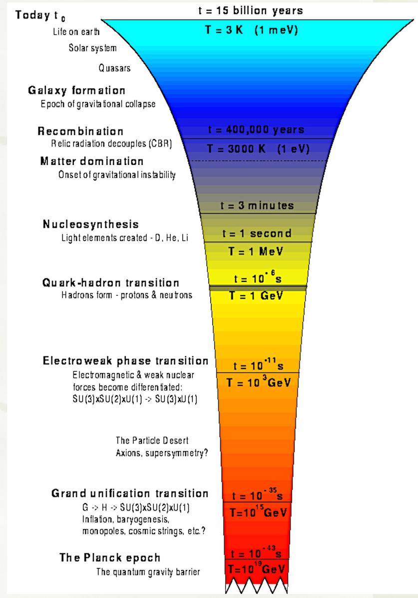
- Many of the particles are very unstable and only exist for very short times after being created in particle accelerators.
- The heavier leptons and hadrons, are not found in ordinary matter at all. This is because they decay very quickly
- however they existed in the very early universe

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}	...

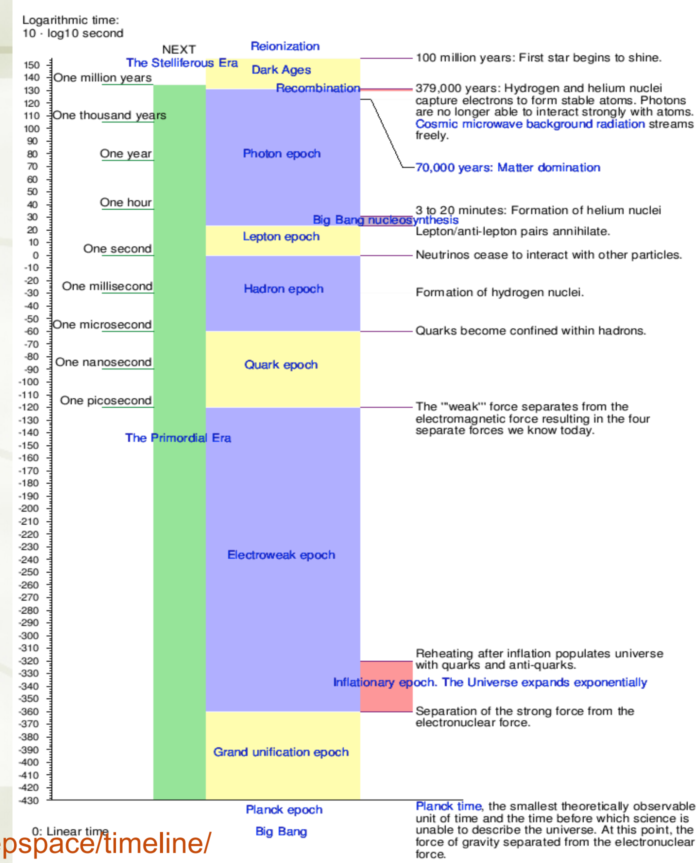
✦The Big Bang! (t=0) *Planck epoch*

- The "Planck" Epoch ($t<10^{-43}$s)
  - Particle Horizon is $c\ t<10^{-35}$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



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

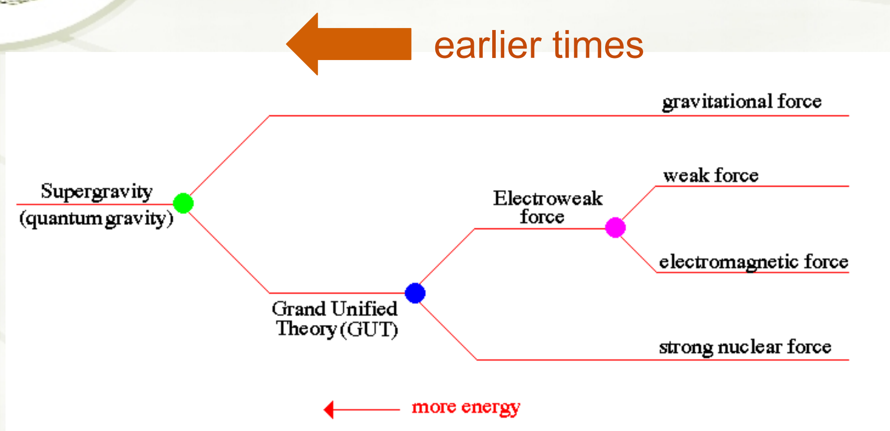
- After inflation, 10^{-6} seconds after the Big Bang, the universe continues to expand but not nearly so quickly.
- As it expands, it becomes less dense and cools. The most basic forces in nature become distinct: first gravity, then the strong force, which holds nuclei of atoms together, followed by 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.



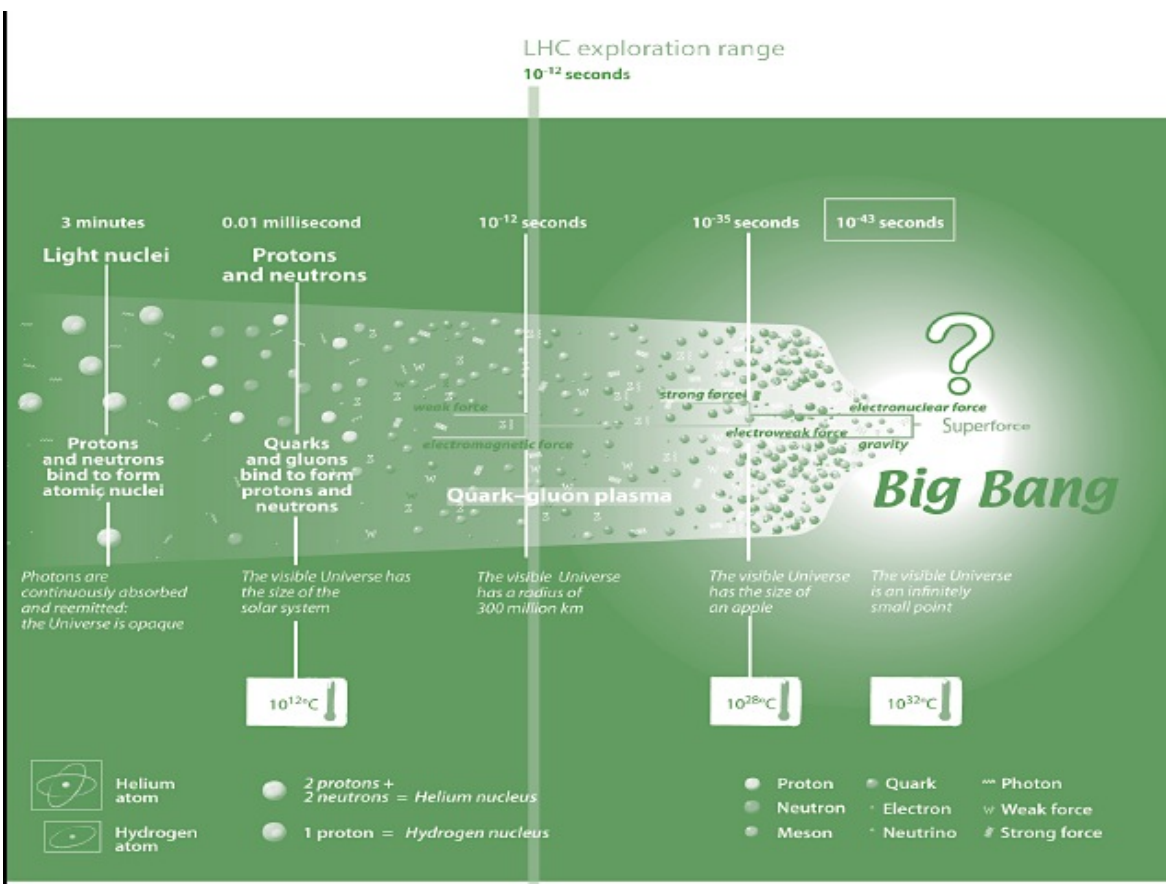
http://www.pbs.org/deepspace/timeline/

Stages of the early Universe

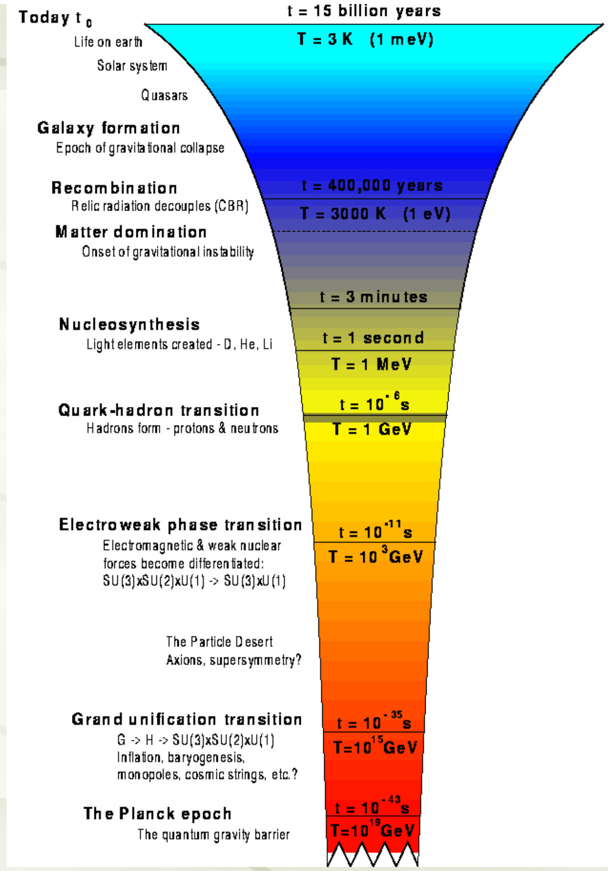
- In the high-temperature very, very early universe, these forces were all unified (in the same way that electricity and magnetism are unified today).
- As universe cooled down, they started to “decouple” from each other.



Graphics: University of Oregon Astronomy Dept

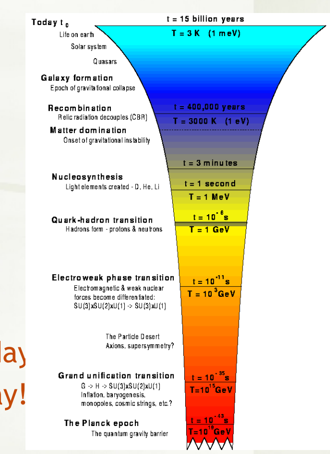


- End of the Planck Epoch ($t=10^{-43}$s)
  - Gravity decouples from other forces
  - Classical General Relativity starts to describe gravity very well
  - Gravitons cease their interactions with other particles… start free streaming through space
  - Produces a background of gravitational waves



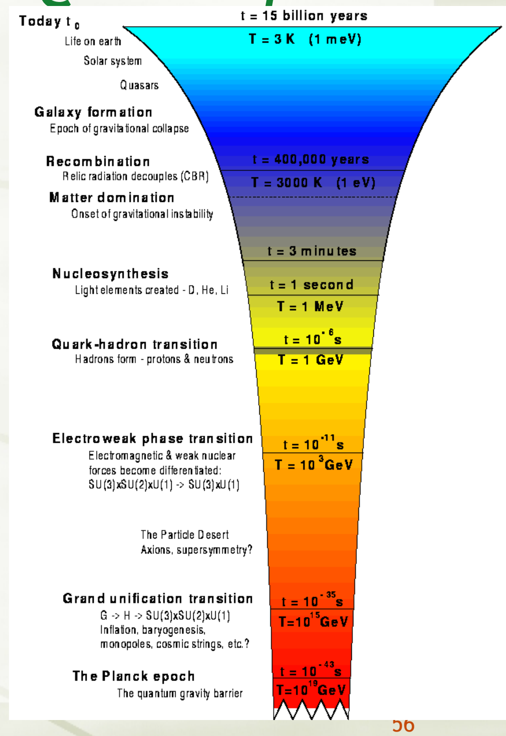
Unified epoch

- 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 $x10^9$
  - 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.



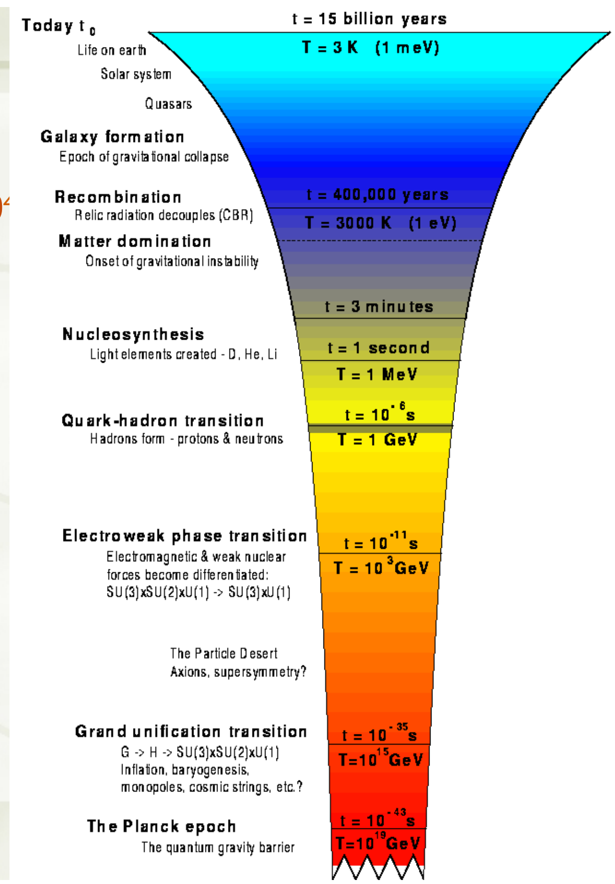
Quark epoch

- 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

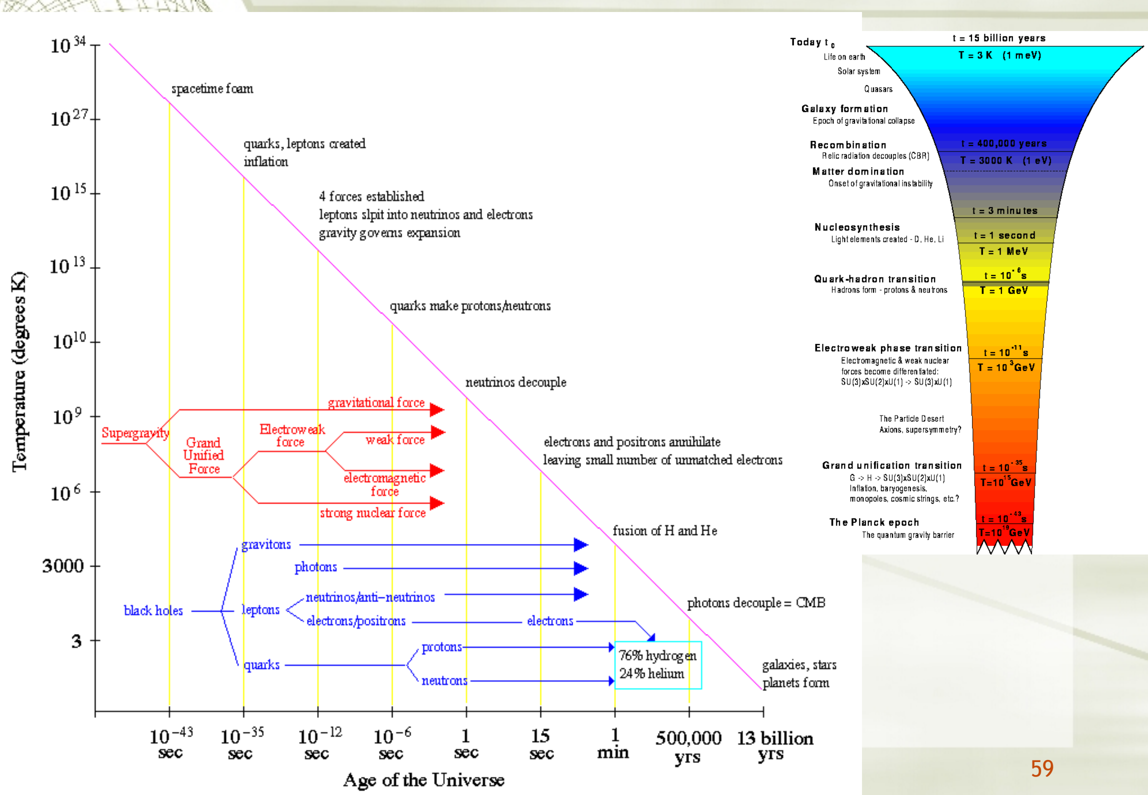
- Lepton Epoch ($t=10^{-4}$ – 15 s)
  - Universe was "soup" of photons, neutrinos, electons, positrons, plus much smaller number of protons & neutrons leftover from hadron epoch
  - Abundant ongoing production of electron/positron and pairs by interacting photons
  - Equilibrium between protons and neutrons

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

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

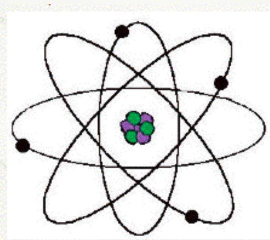
ν is a neutrino

  - 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



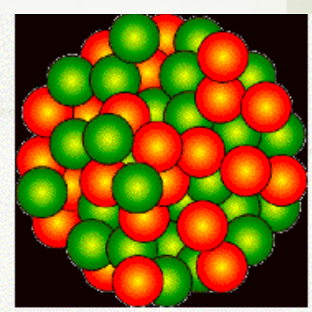
I: THE STRUCTURE OF MATTER

- 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.

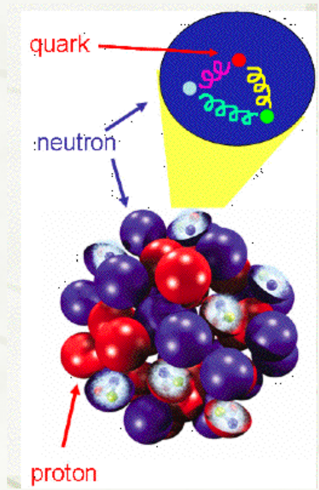
Elements & isotopes



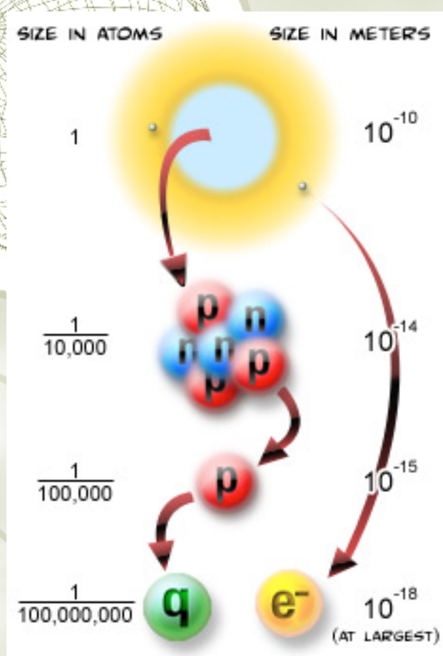
- Number of protons determines the element:
  - Hydrogen – 1 proton
  - Helium – 2 protons
  - Lithium – 3 protons
  - Beryllium – 4 protons
  - Boron – 5 protons
  - Carbon – 6 proton
  - …
- Number of neutrons determines the isotope
- e.g., for hydrogen (1 proton), there are three isotopes
  - Normal Hydrogen (H or p) – no neutrons
  - Deuterium (d) – 1 neutron
  - Tritium (t) – 2 neutrons

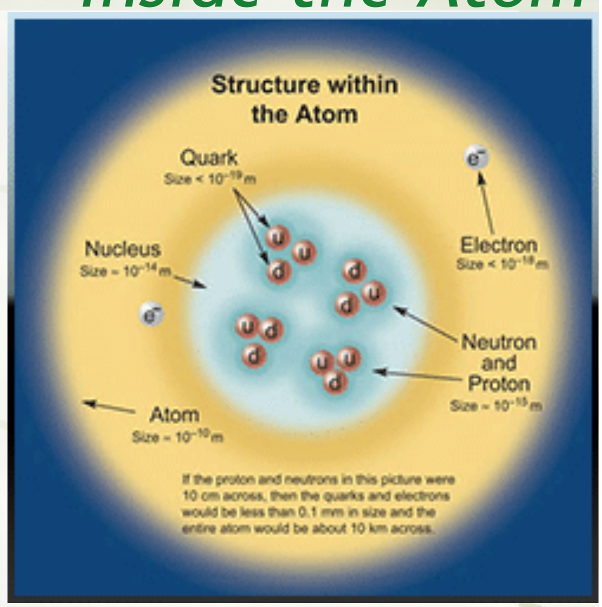
Atomic nuclei

- 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")



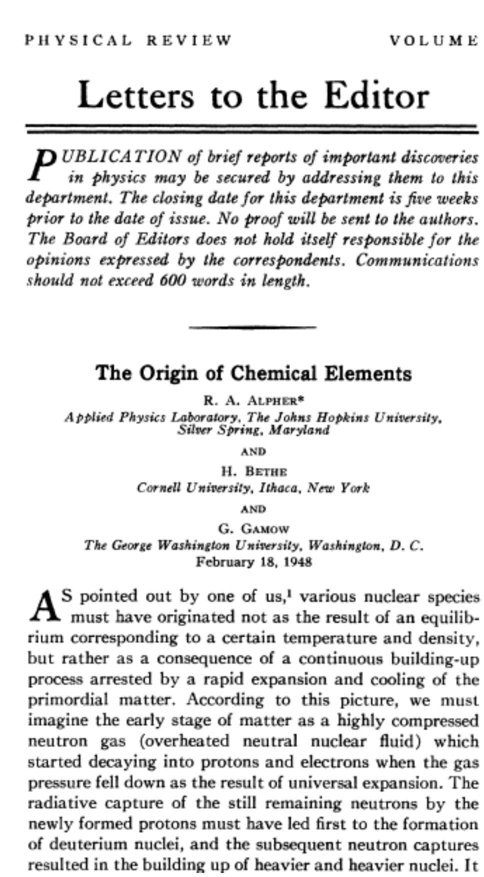
Inside the Atom





- enormous range in scales

- 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

PUBLICATION of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is five weeks prior to the date of issue. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length.

The Origin of Chemical Elements

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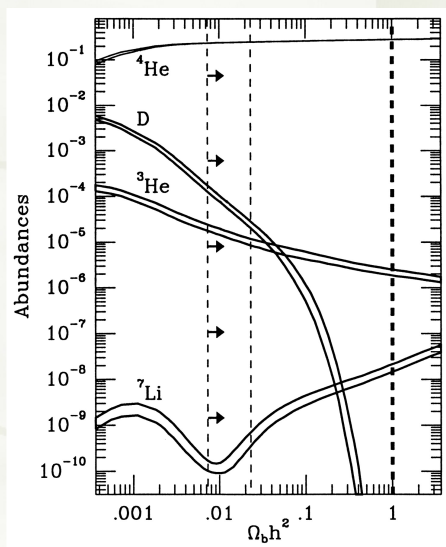
AND
G. GAMOW
The George Washington University, Washington, D. C.
February 18, 1948

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

Primordial Nucleosynthesis

- Some light elements 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 lacks some of the speculative uncertainties that characterize earlier periods in the life of the universe.
- 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.



Next lecture…

- End of radiation-dominated era