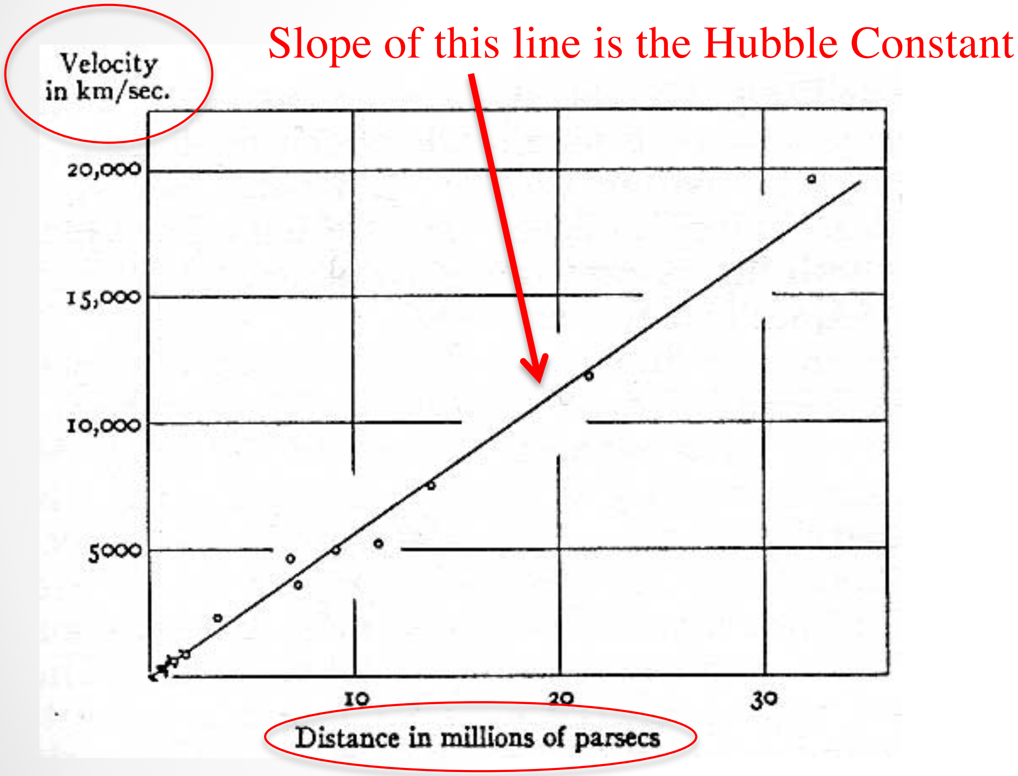
AY2 Announcements

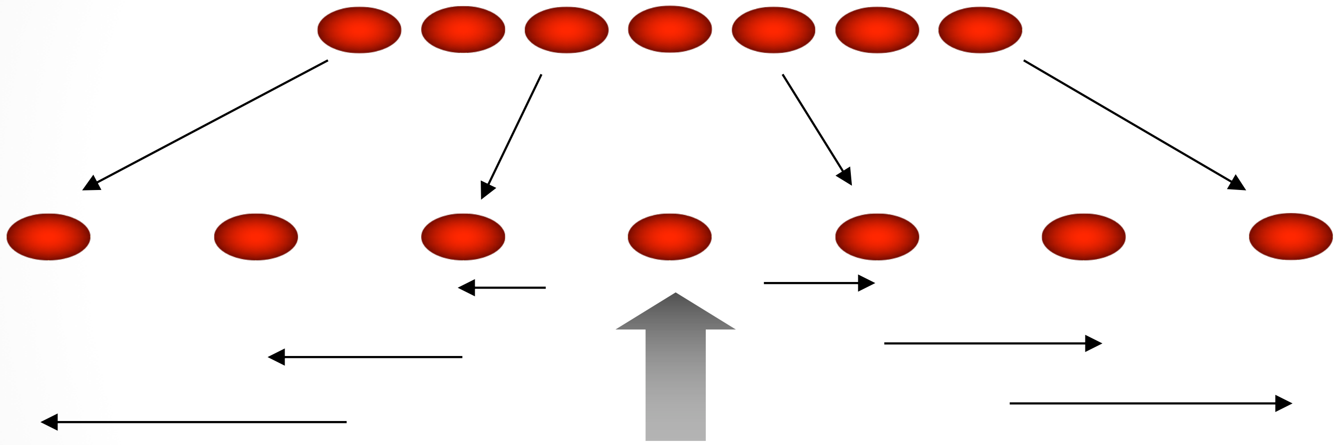
- Quiz 4: Thursday Dec 5 (last day of class)
- Final: Dec 12, noon – 3pm
  - Final is cumulative and largely drawn from the quizzes
- Final study session with Miranda: Dec 10, 9am – noon in Thimann 3 (right here). Will be Zoom broadcast and recorded.

Expanding Universe



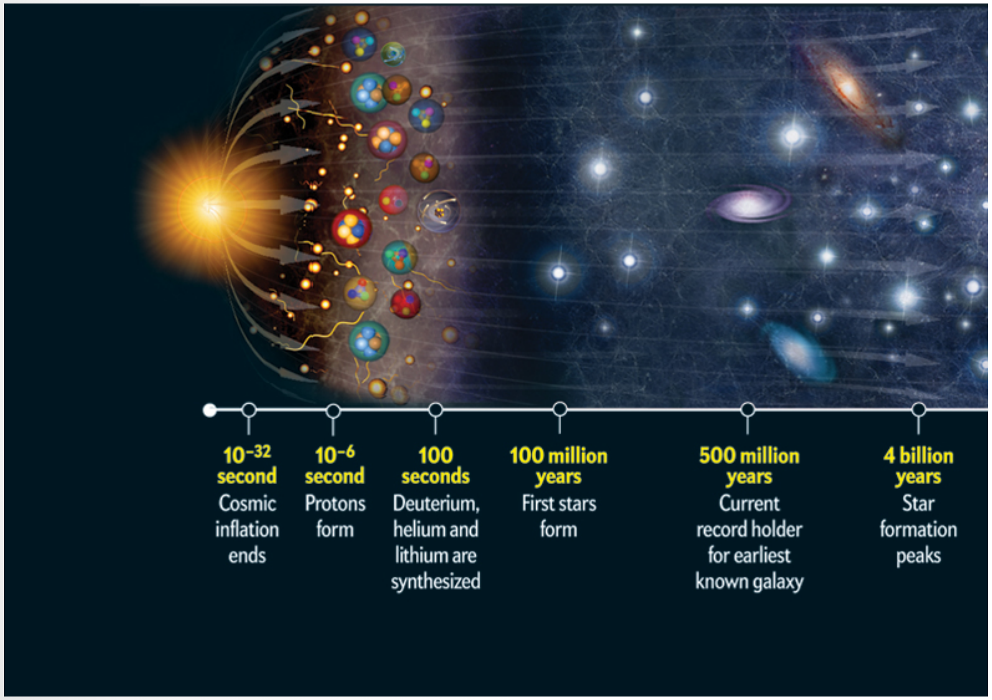
In 1931, Hubble and Humason published a second paper on the distances and velocities of galaxies using additional distance indicators calibrated by the Cepheid work

The Expanding Universe



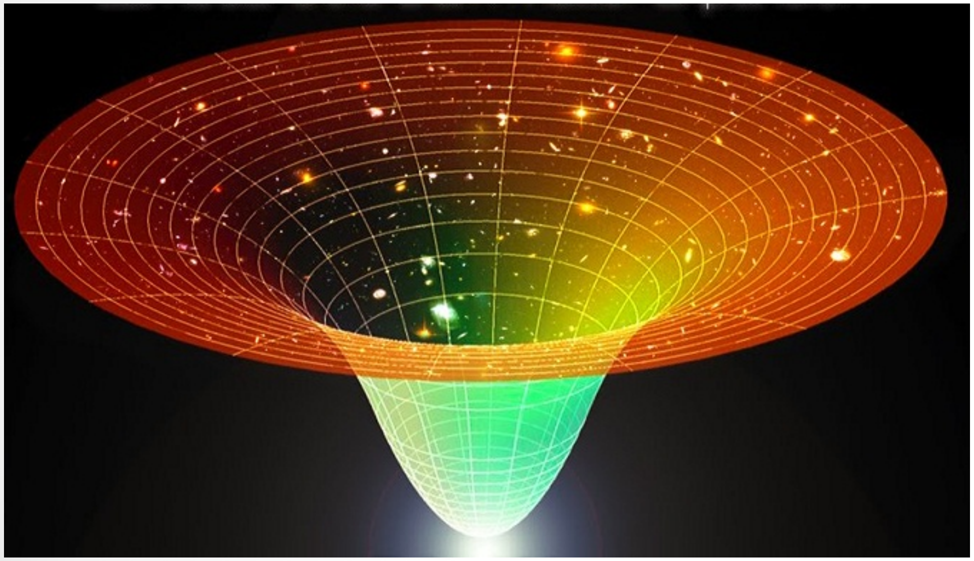
These people measure their nearest neighbors to have moved one unit, the next galaxies to have moved 2 units…

The Big Bang thought experiment

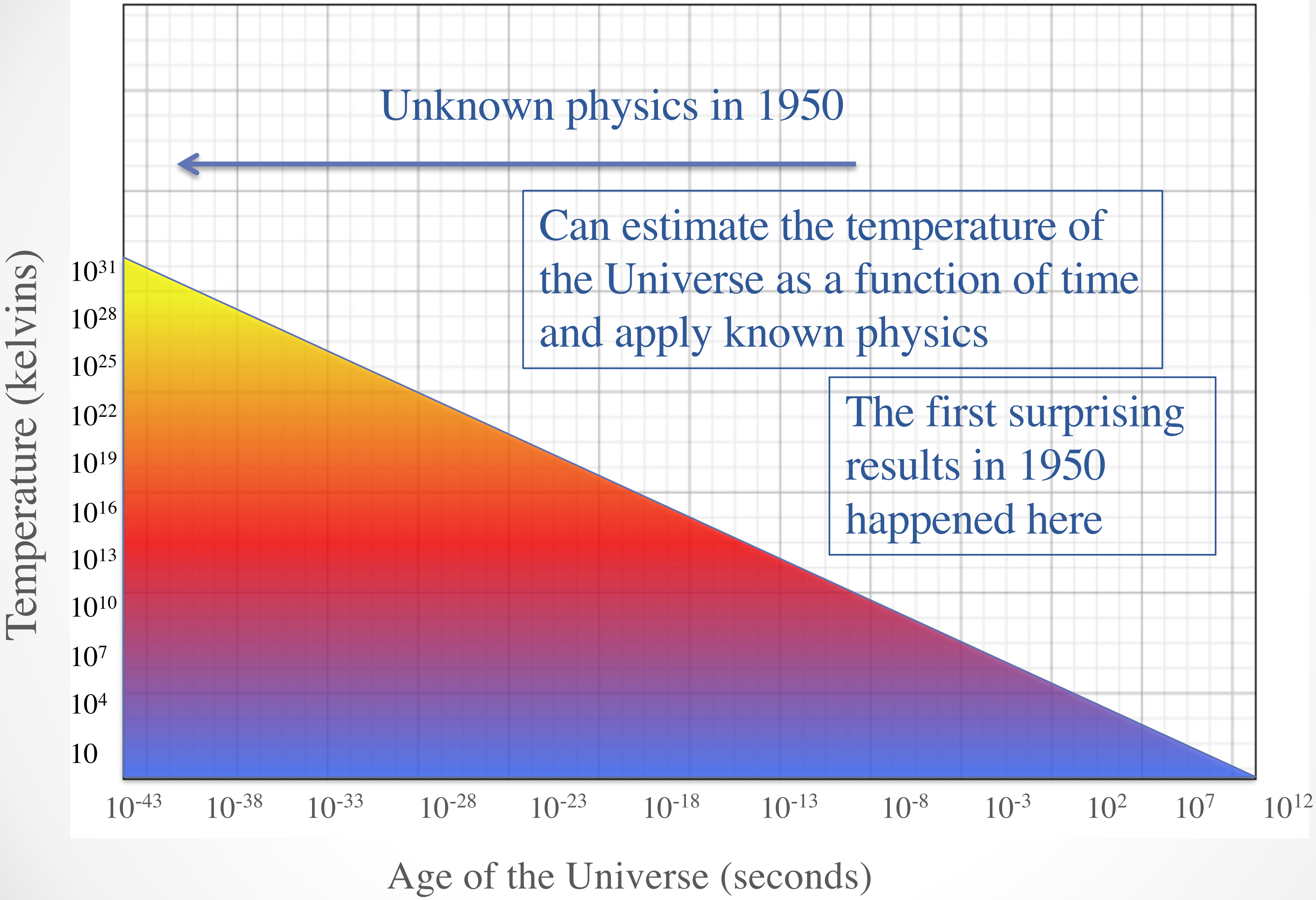


Lemaitre in 1927 discussed the concept of a Universe that started as an extremely dense and hot point and expanded, cooled and evolved into the Universe we live in today

Moving back to the Beginning



- Run the Universe timeline backward
- Density and temperature go up, apply physics as we know it
- Need to think about “phase transitions”
- This first was considered in the 1950’s when much of the early Universe physics had still not been developed

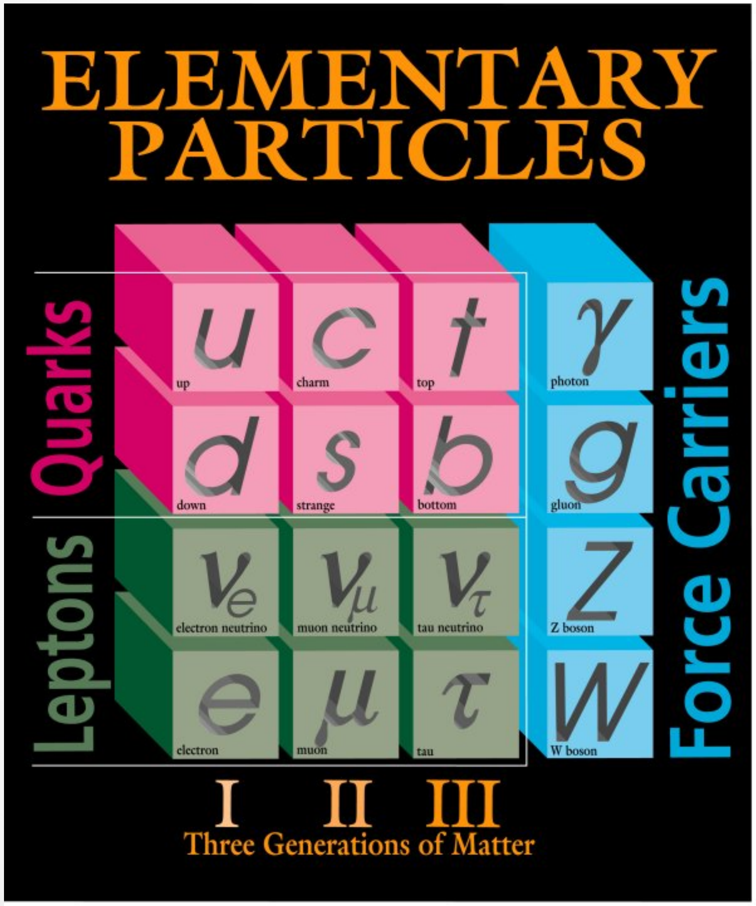


Unknown physics in 1950

Can estimate the temperature of the Universe as a function of time and apply known physics

The first surprising results in 1950 happened here

Background: Fundamental Particles



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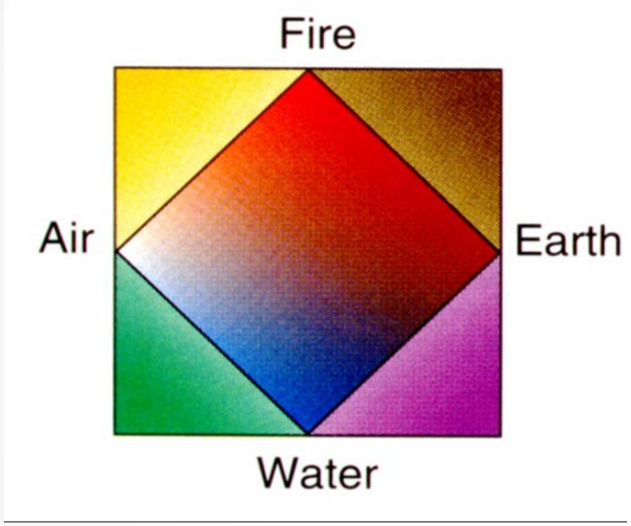
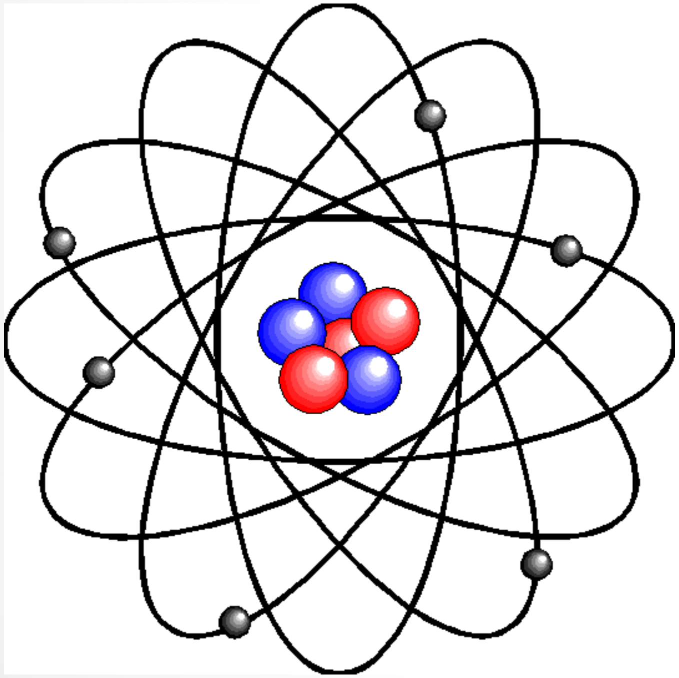
- Identifying the fundamental building blocks of the Universe is a long-time activity of humans
- Like the history of cosmology, there are striking similarities in history and cultures

Earth, Wind, Fire, Water



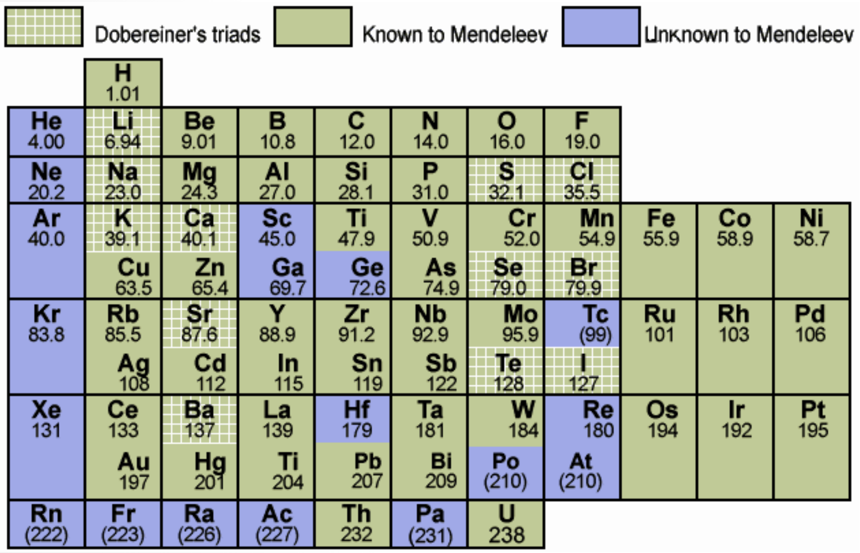
- Greeks: EWFW
- Hindu: Earth, air, fire, water, void (nothing)
- China: Earth, wood, metal, fire, water
- Japan: EWFW, spirit
- Buddhism: EWFW

Atoms



Democritus (greek philosopher and contemporary of Aristotle) considered what would happen if you took matter, divided it in two, then again and again and again, eventually you would have an “atom” that could not be divided further: atomos “not to be cut”

Atoms II: inferences from chemistry

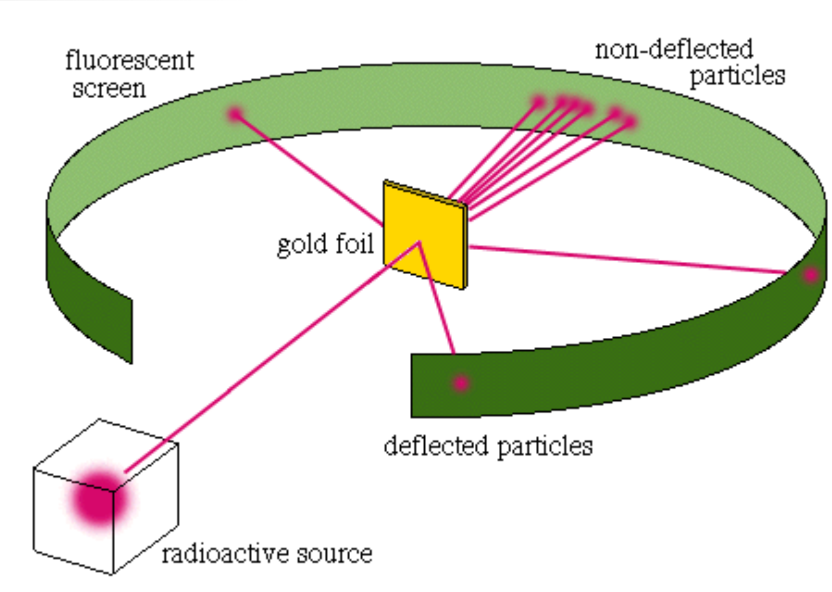


▨ Dobereiner's triads
🟩 Known to Mendeleev
🟦 Unknown to Mendeleev

	H 1.01									
He 4.00	Li 6.94	Be 9.01	B 10.8	C 12.0	N 14.0	O 16.0	F 19.0			
Ne 20.2	Na 23.0	Mg 24.3	Al 27.0	Si 28.1	P 31.0	S 32.1	Cl 35.5			
Ar 40.0	K 39.1	Ca 40.1	Sc 45.0	Ti 47.9	V 50.9	Cr 52.0	Mn 54.9	Fe 55.9	Co 58.9	Ni 58.7
	Cu 63.5	Zn 65.4	Ga 69.7	Ge 72.6	As 74.9	Se 79.0	Br 79.9			
Kr 83.8	Rb 85.5	Sr 87.6	Y 88.9	Zr 91.2	Nb 92.9	Mo 95.9	Tc (99)	Ru 101	Rh 103	Pd 106
	Ag 108	Cd 112	In 115	Sn 119	Sb 122	Te 128	I 127			
Xe 131	Ce 133	Ba 137	La 139	Hf 179	Ta 181	W 184	Re 180	Os 194	Ir 192	Pt 195
	Au 197	Hg 201	Ti 204	Pb 207	Bi 209	Po (210)	At (210)			
Rn (222)	Fr (223)	Ra (226)	Ac (227)	Th 232	Pa (231)	U 238				

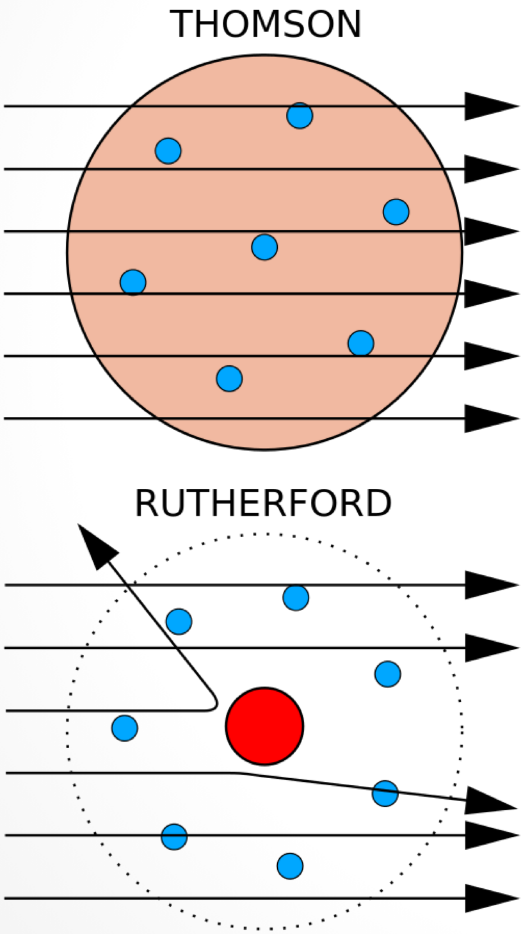
- 1830 John Dalton identified elements with particular types of atom and compounds as combinations of elements
- 1869 Mendeleev proposed the periodic table
- 1897 Thomson discovered electrons and it was realized that atoms were not fundamental but could be further divided

Rutherford and the modern theory



- 1911 Rutherford inferred that atoms had a strongly centralized mass distribution: he discovered the nucleus
- This is all experimentally difficult because of the tiny size of atoms
  - 10^{-10} meters in diameter
  - Human hair is 10^6 atoms across
  - Water drop contains ~10^{21} atoms of oxygen

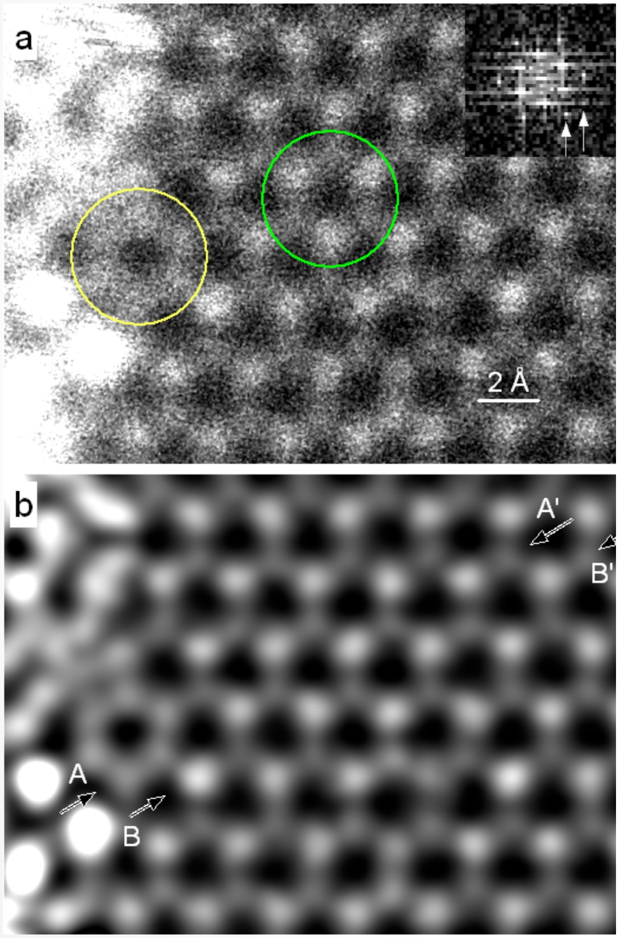
Rutherford Model



- Before Rutherford, the structure of the atom was thought the be like a "plum pudding" with electrons milling around in a diffuse charged medium
- The large-angle deflections of alpha particles showed there was a dense, charged center of the atom

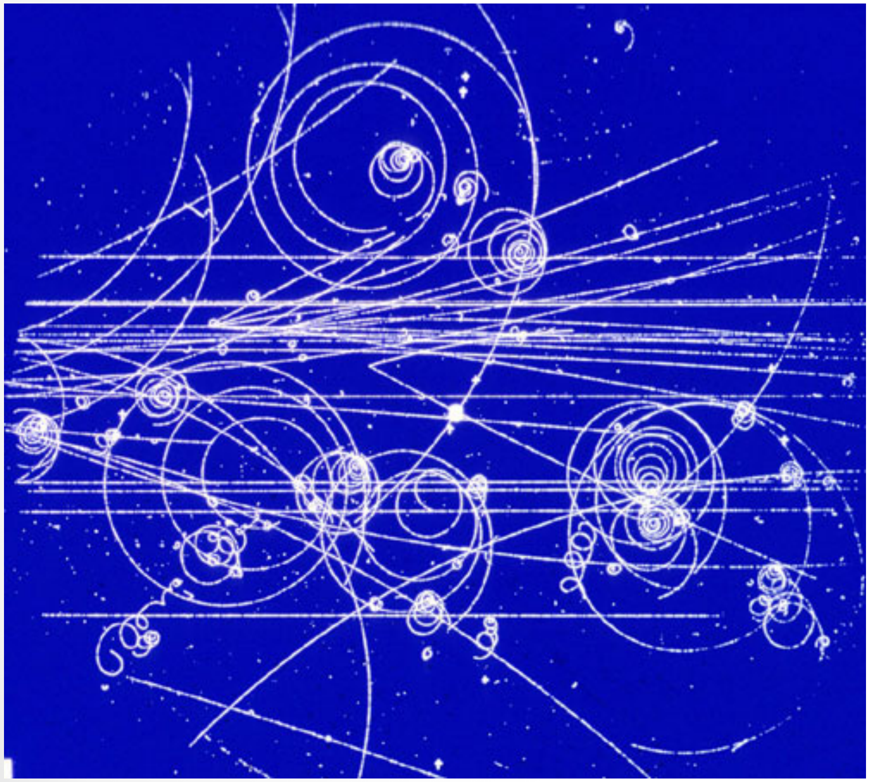
Nucleus not to scale!

Quantum Physics

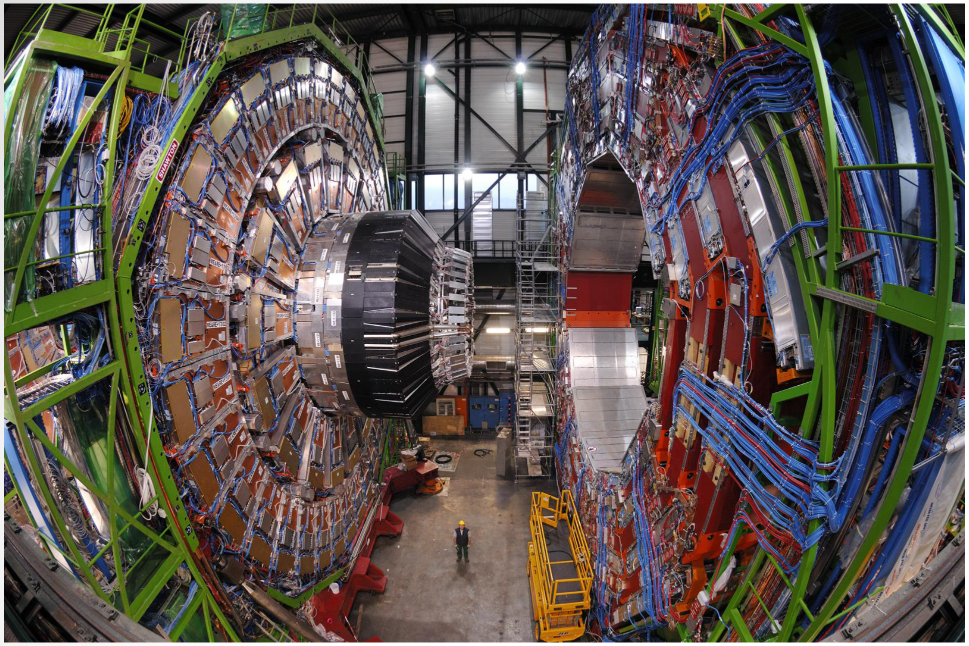


- From 1911 – 1935 our knowledge of the structure of atoms and matter was the subject of intense study "quantum mechanics"
- Fundamental building blocks of everything were thought to be electrons, protons and neutrons

Three Quarks for Muster Mark



- Cosmic ray studies and particle accelerators had been demonstrating a whole slew of unexpected massive particles coming out of energetic collisions
- Particle physics theorists proposed all could be explained by three (then four) truly fundamental particles that got names "quarks" (1964)



- Modern accelerators are incredible machines
- Large Hadron Collider accelerates protons to 0.9999991c
- Super-cooled, vacuum of space
- 10,000 scientists, 100 countries
- 14 x 10^{12} eV (TeV)collisions
- 80,000 computers on private internet
- $6.5B (US)

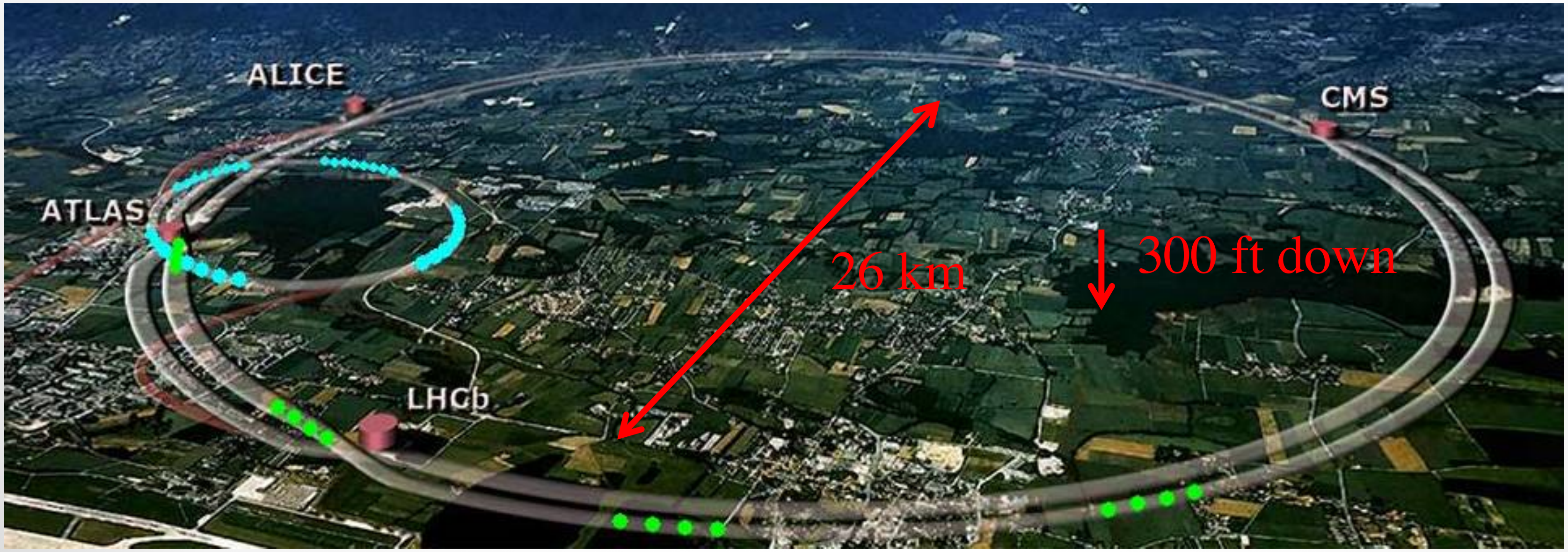
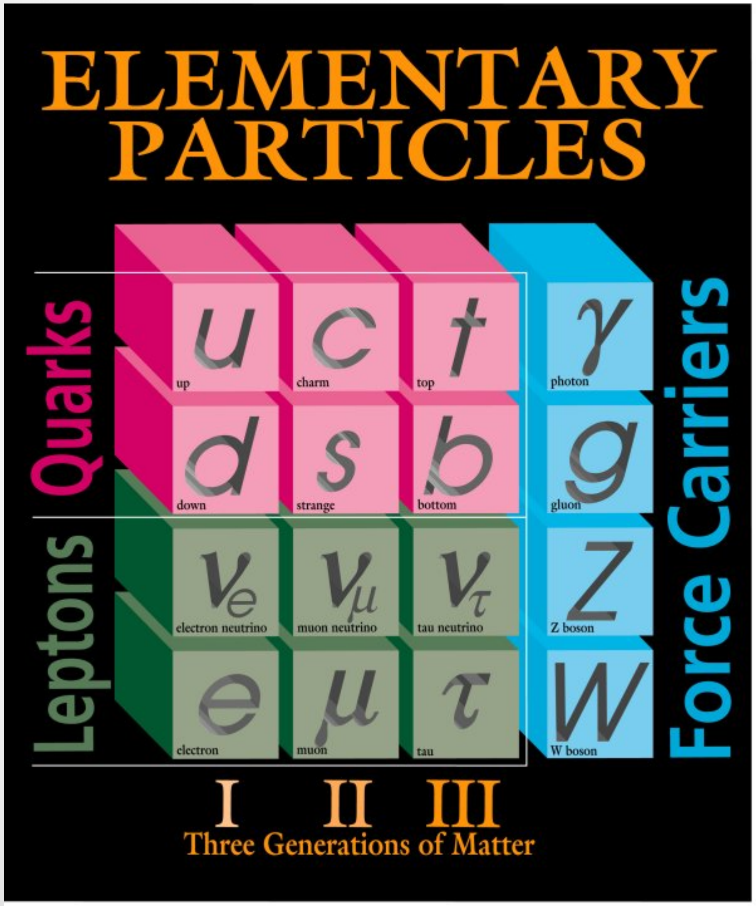


Table of Fundamental Building Blocks



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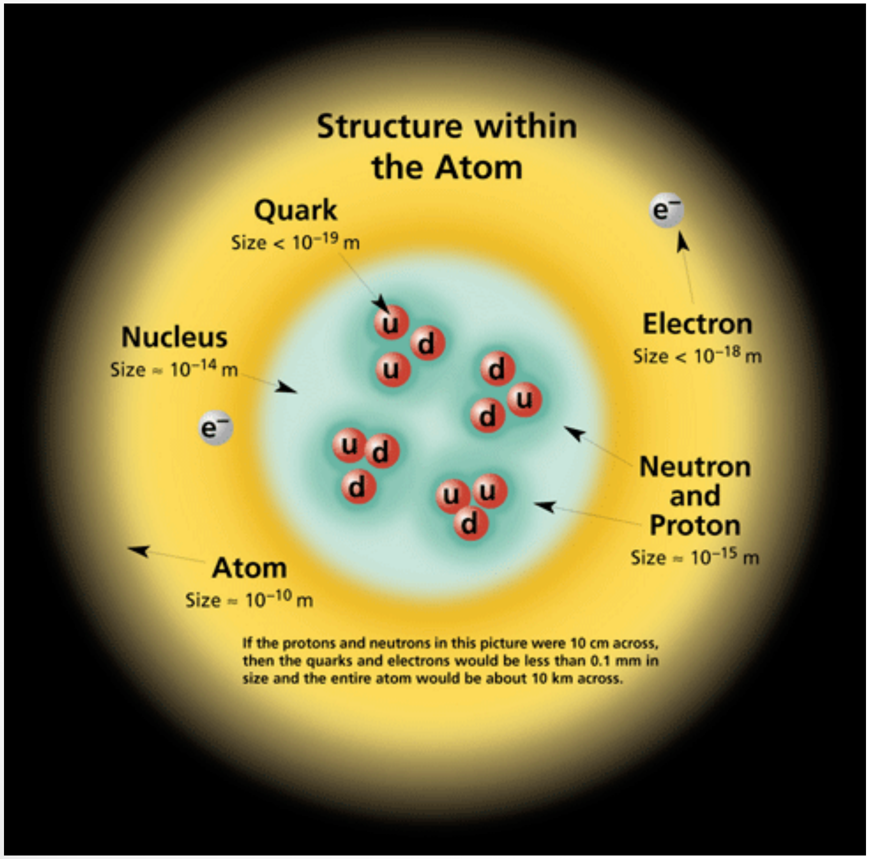
- Fermions: fundamental particles.
  - Leptons
  - Quarks
- Hadrons: combinations of Fermions (i.e. proton, neutron)
- Bosons: particles that exchange forces

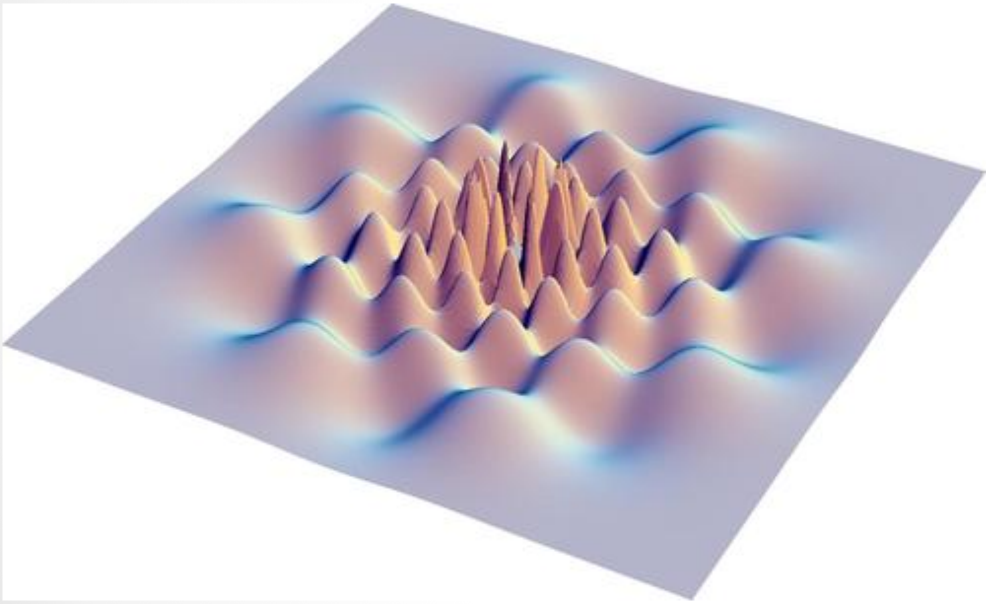
Quarks


Structure within the Atom

If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

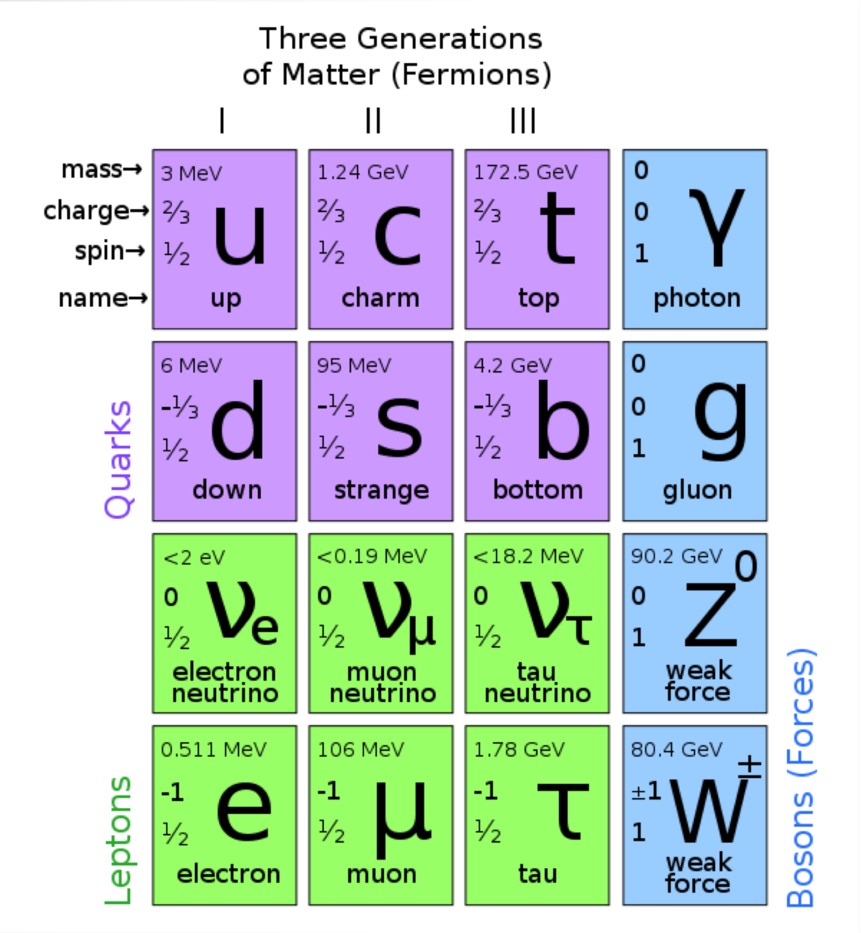
- Postulating the existence of quarks allowed physicists to understand the zoo of new particles
- Six in total with the two lowest mass (up and down) the most stable
- Always confined in nuclei
- In 1968 at the Stanford Linear Accelerator first observational evidence was gathered
- https://en.wikipedia.org/wiki/List_of_baryons

Leptons



- Near massless, no structure, unknown, but very, very small size
  - Electron, electron neutrino
  - Muon, muon neutrino
  - Tau, Tau neutrino
  - Anti-matter partners

Fermions: Quarks



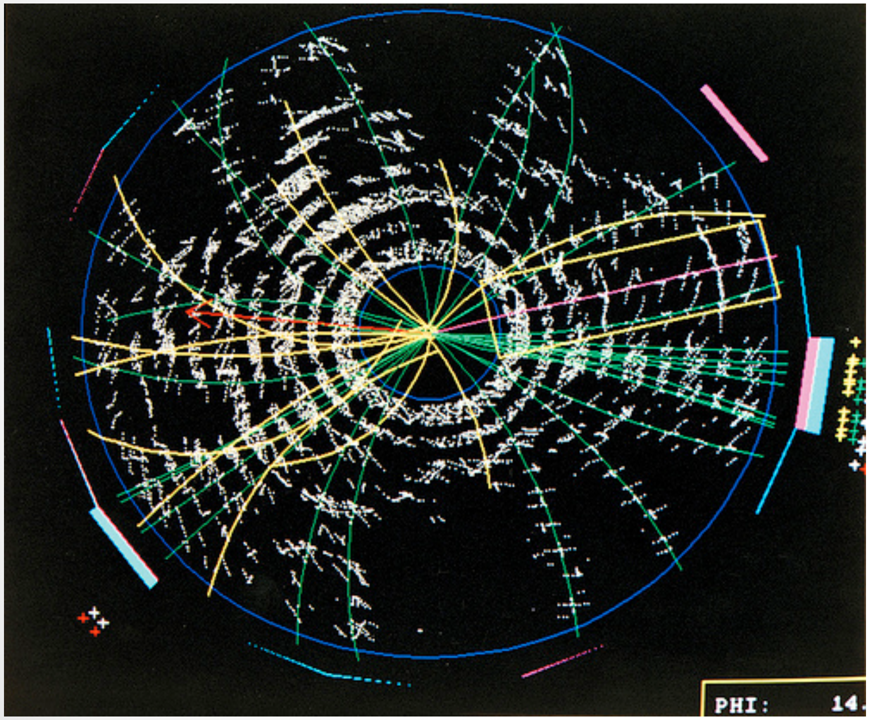
Three Generations of Matter (Fermions)

		I	II	III	
	mass→ charge→ spin→ name→	3 MeV ⅔ ½ u up	1.24 GeV ⅔ ½ c charm	172.5 GeV ⅔ ½ t top	0 0 1 γ photon
Quarks		6 MeV -⅓ ½ d down	95 MeV -⅓ ½ s strange	4.2 GeV -⅓ ½ b bottom	0 0 1 g gluon
		<2 eV 0 ½ ν_e electron neutrino	<0.19 MeV 0 ½ ν_μ muon neutrino	<18.2 MeV 0 ½ ν_τ tau neutrino	90.2 GeV 0 1 Z^0 weak force
Leptons		0.511 MeV -1 ½ e electron	106 MeV -1 ½ μ muon	1.78 GeV -1 ½ τ tau	80.4 GeV ±1 1 $W^{\pm}$ weak force

Bosons (Forces)

- Proton: 2u + 1d quarks (uud)
  - Charge: [(2 x 2/3) + (-1/3)]=+1
  - Held together by 3 Gluons
  - Mass=1.672x10^{-27}kg=938.3Mev/c^2
- Neutron: 1u + 2d quarks (udd)
  - Charge: [2/3 + 2 x (-1/3)]=0
  - Held together by 3 Gluons
  - Mass=1.675x10^{-27}kg=939.6Mev/c^2
  - "free" neutrons are unstable and decay via βdecay to become protons with a half-life of 15 minutes

Why do we believe this?



- All this is part of the "Standard Model" for particle physics
- Model calculations (very complex) get made for the production of particles at different energies and the last 40 years of accelerator experiments have shown the models to be remarkably accurate

Energy and Mass

- Common to give particle mass in electron volts (eV), e.g. proton mass=938.3 MeV (should have $/c^2$)
  - Useful for understanding the conditions in which massive particles are created (in accelerators or in the Big Bang)
  - Useful for reminding us about $E=mc^2$
  - Useful for reminding us about binding energy
  - $1 eV=1.602 \times 10^{-19}$ Joules

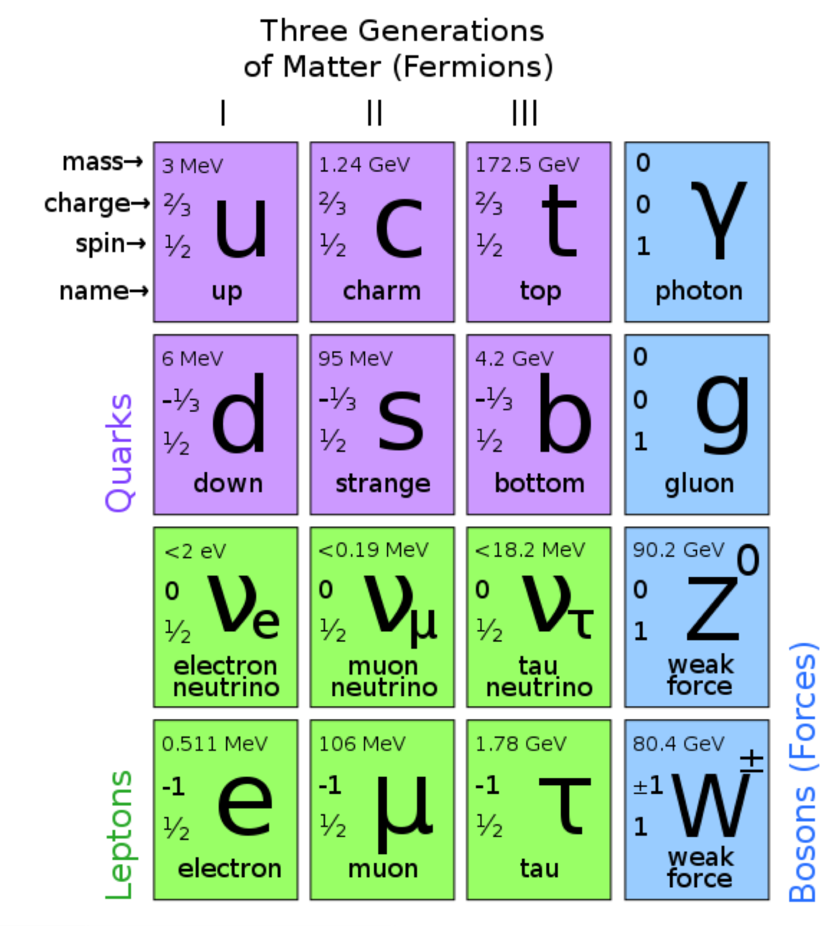
Example: Proton mass = 1.672×10^{-27} kg

$E=mc^2=(1.672 \times 10^{-27})x(3 \times 10^8)^2=1.5 \times 10^{-10} J$

$1.5 \times 10^{-10} J \times (1 eV)/(1.602 \times 10^{-19} J)$

$=938.3 \times 10^6$ eV=938.3 MeV (energy equivalent of mass)

An Aside about Proton Mass



Three Generations of Matter (Fermions)

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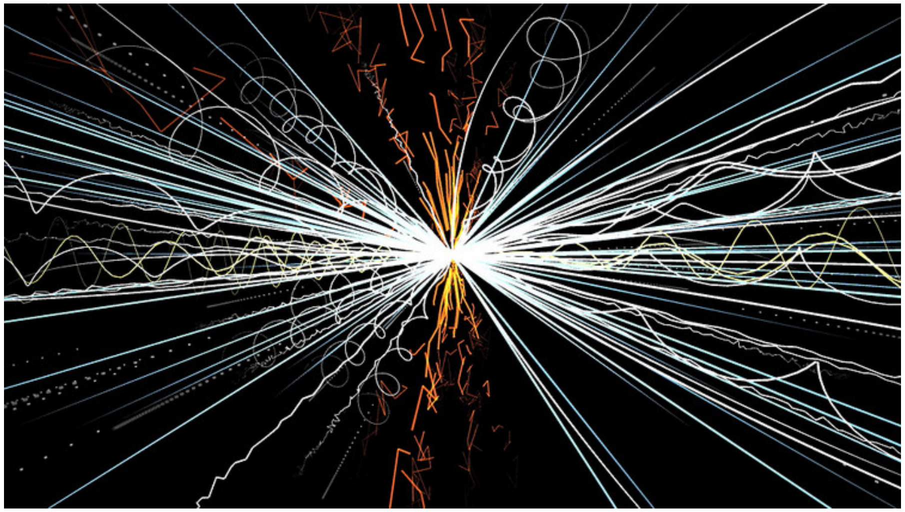
- Proton mass is 938.3 MeV/c^2
  - Up quark mass is 3 MeV/c^2
  - Down quark mass is 6 MeV/c^2
  - Gluon mass is zero
- So, components of proton (uud) only add up to 12 MeV/c^2. The remainder of the rest mass is in the binding energy bonds and some kinetic energy of the quarks in the proton

iclicker

Which of the following are fundamental particles?

A. Atom
B. Electron
C. Proton
D. All of the above

Creation of Matter

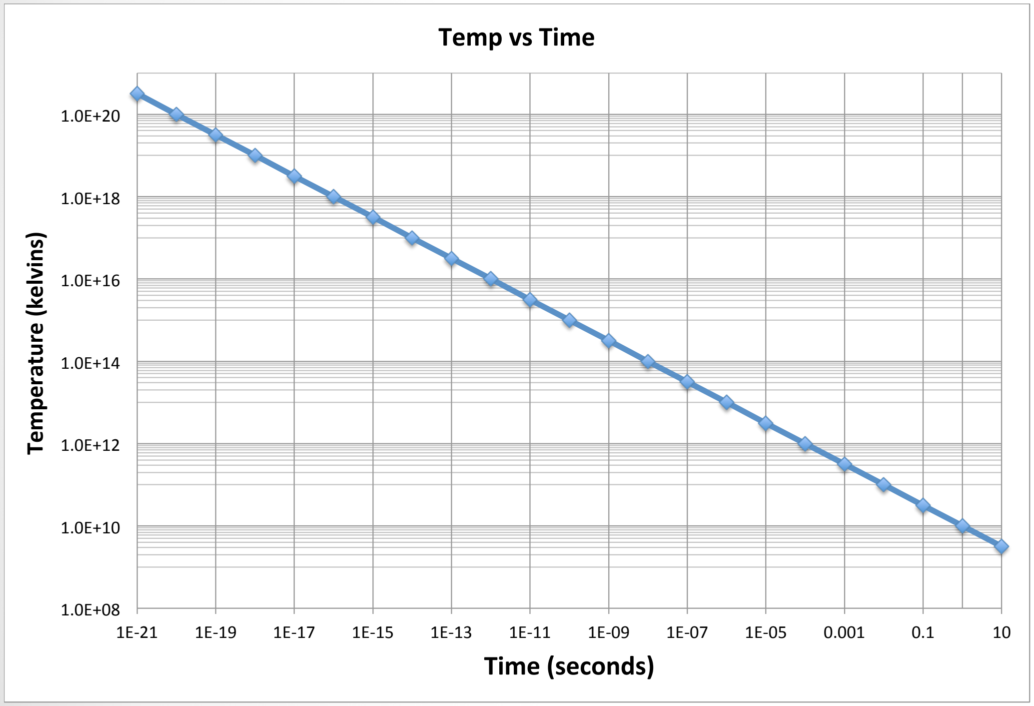


- The threshold energy for creating a particle is its "rest mass energy" given by $E=mc^2$
- In an accelerator, as the beam energy goes up, so does the mass of the particles created in the collisions
- In the early universe, as the temperature goes up so does the mass of particles created

Creation of Matter

- At very high temperatures, radiation is more stable than matter. Very massive matter/anti-matter particle pairs get created and destroyed (broken back into radiation or quarks) regularly: Quark-Gluon Plasma (quark soup)
- The formation of matter and its ability to survive subsequent energetic encounters and native stability is what determines the matter content of the Universe today

Putting these ideas to work



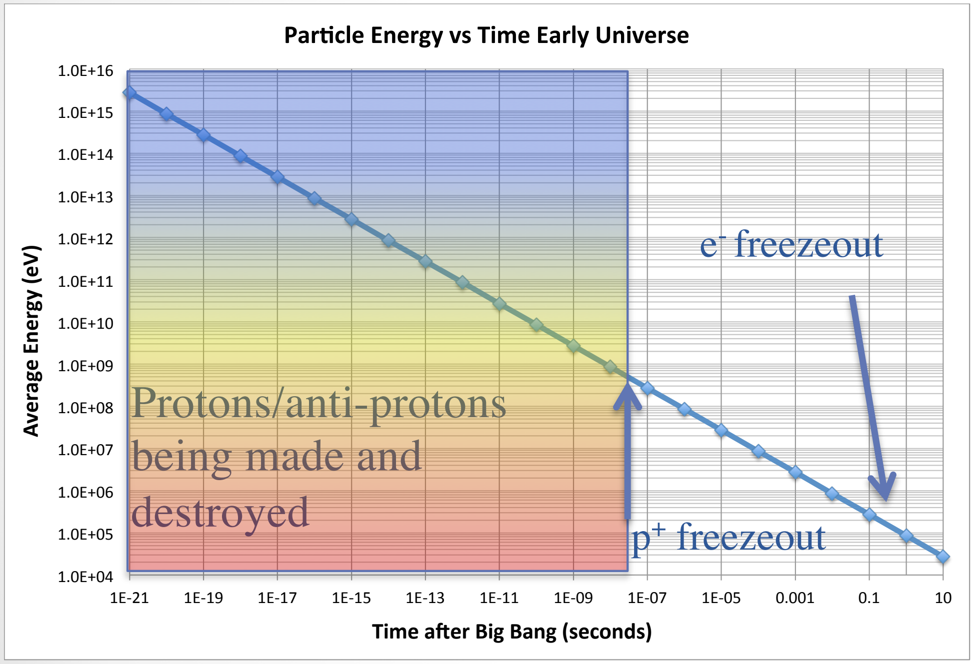
- The temperature of the Universe after the Big Bang is given by:

$$T(\text{kelvin}) = \frac{10^{10}}{\sqrt{t\ (\text{seconds})}}$$

- The average energy of a particle in the gas is given by:

$$E(\text{eV}) = \frac{8.6\times10^{5}}{\sqrt{t(\text{seconds})}}$$

Formation of protons

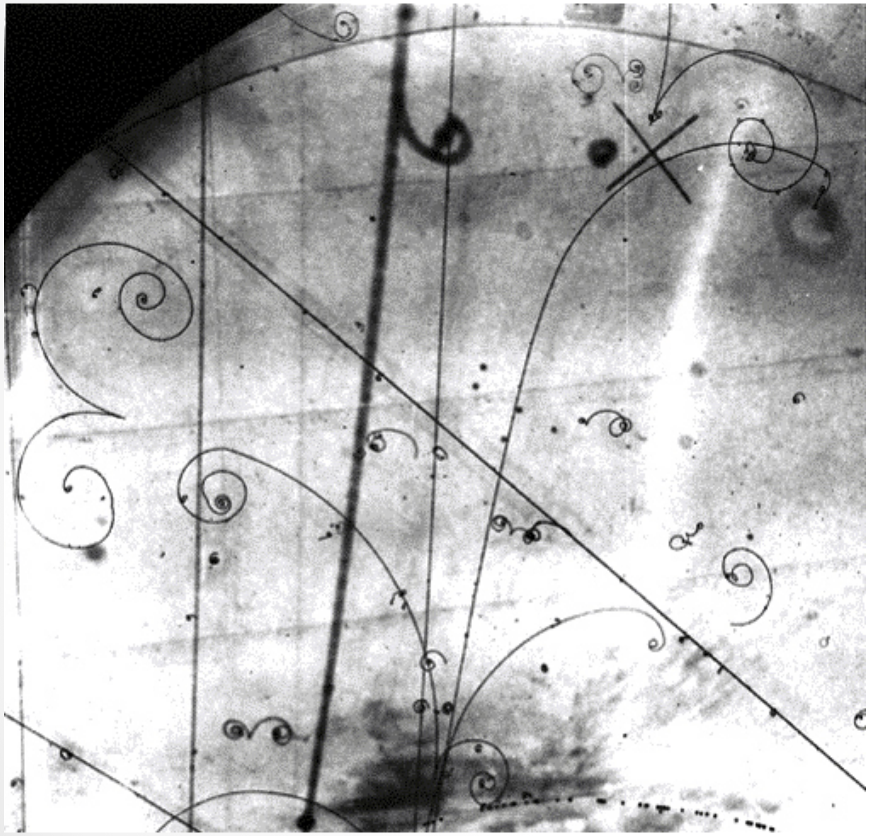


- When is the last time after the Big Bang that proton-antiprotons can be formed?
  - Mass equivalent is twice 938.3 MeV: ~2×10^9 eV
  - $E(eV)=(8.6 \times 10^5)/\mathrm{sqrt}(t)$
  - $t=(860000)^2/(2 \times 10^9)^2$

    $=1.84 \times 10^{-7}$ seconds

Note: only true in a statistical mean sense

A Really Good Question



- Every particle was produced with an anti-particle
- Yet, we live in a matter (not anti-matter) Universe
- Somehow for every billion anti-particles formed, there were a billion and one particles
- Why and how?

- How close to the Big Bang have we probed with the LHC accelerator if it has achieved beam energies of 1.5 TeV (1.5 x 10^{12} eV)?

$$E(\mathrm{eV}) = \frac{8.6\times10^{5}}{\sqrt{t(\mathrm{seconds})}}$$

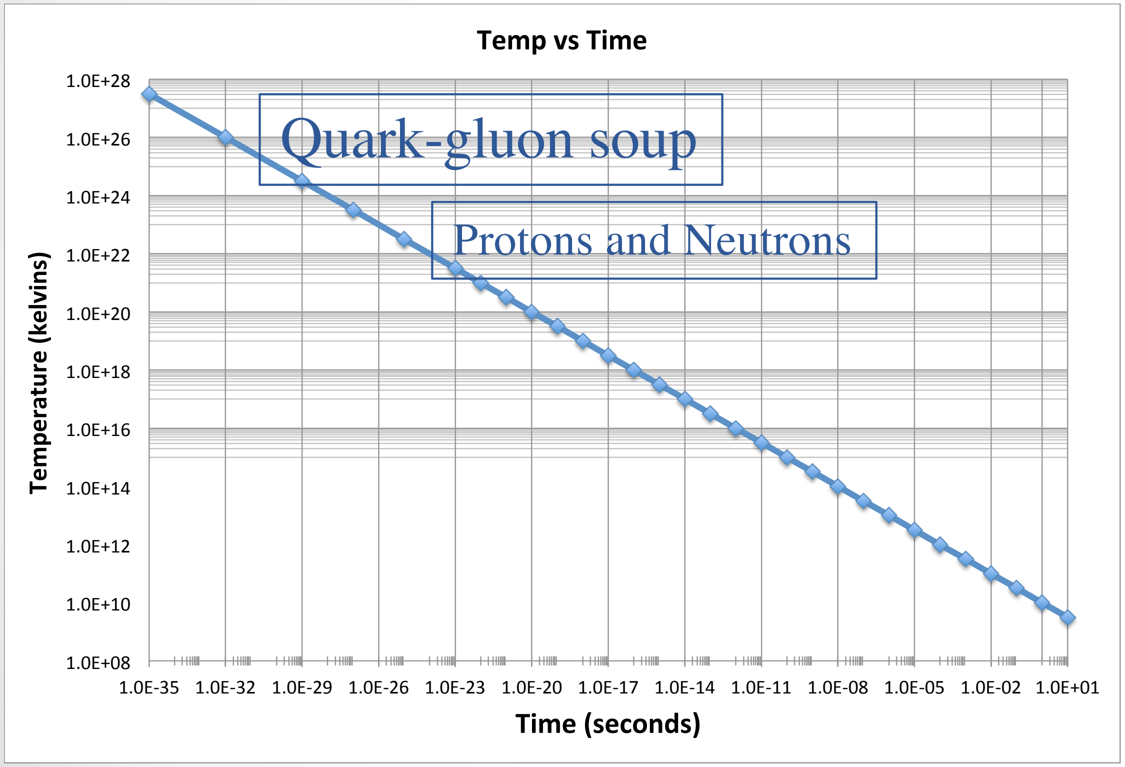
$$t = \frac{(8.6\times10^{5})^{2}}{E^{2}} = \frac{7.4\times10^{11}}{E^{2}}(\mathrm{sec}) = \frac{7.4\times10^{11}}{(1.5\times10^{12})^{2}}$$

$$= \frac{7.4\times10^{11}}{1.5^{2}\times10^{24}} = \frac{7.4}{1.5^{2}}\times10^{(11-24)} = \frac{7.4}{1.5^{2}}\times10^{(-13)}\mathrm{s}\ (\mathrm{C})$$

Hot Big Bang Nucleosynthesis

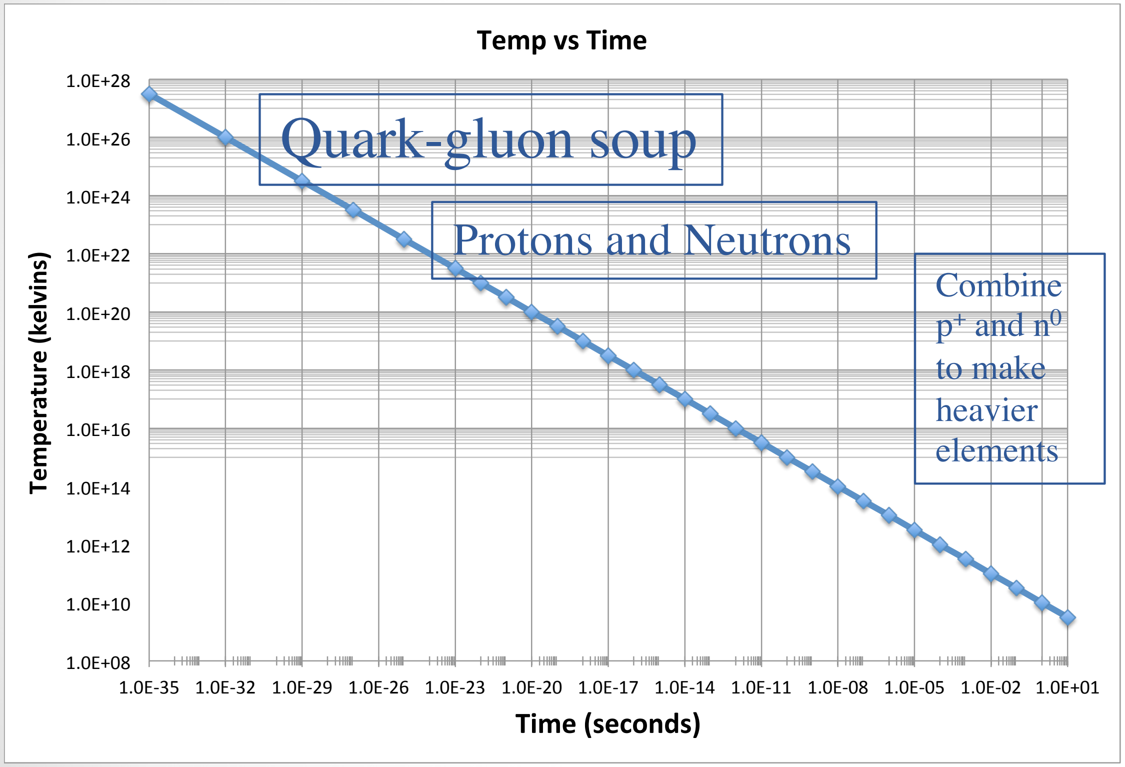
- George Gamov was a nuclear physicist political refugee from Russia who looked in detail at the early times in an expanding Universe run backward
- Made the first predictions of the era of nucleosynthesis and got a big surprise

Early Universe



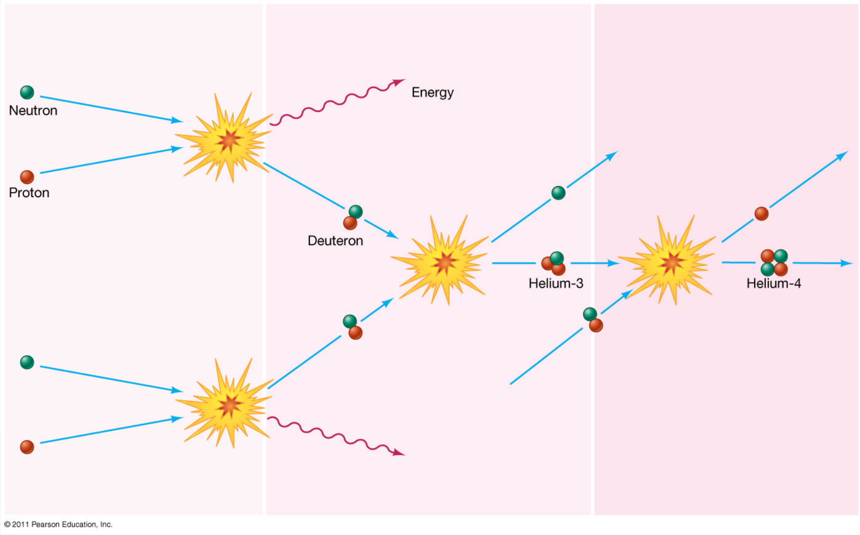
- Have all the background in place to finally get to the Gamov HBB nucleosynthesis predictions
- At very early times, quark soup produces hadrons, they get broken apart, till the temperature is low enough that p^+ and n^0 can survive
- Neutrons/protons/electrons and positrons combine and decay to produce an equilibrium ratio of p^+ to n^0

Early Universe



- After 10^{-7} seconds, stop forming p^+ and n^0 and have confined the quarks in these nucleons
- At around 1 second after the BB, the neutron-proton-e^--e^+ reaction stops and the building blocks for “primordial nucleosynthesis” are in place
- Note! Free neutrons are unstable to decay with a half life of 10 minutes which is the window to produce the heavier elements

Primordial Nucleosynthesis



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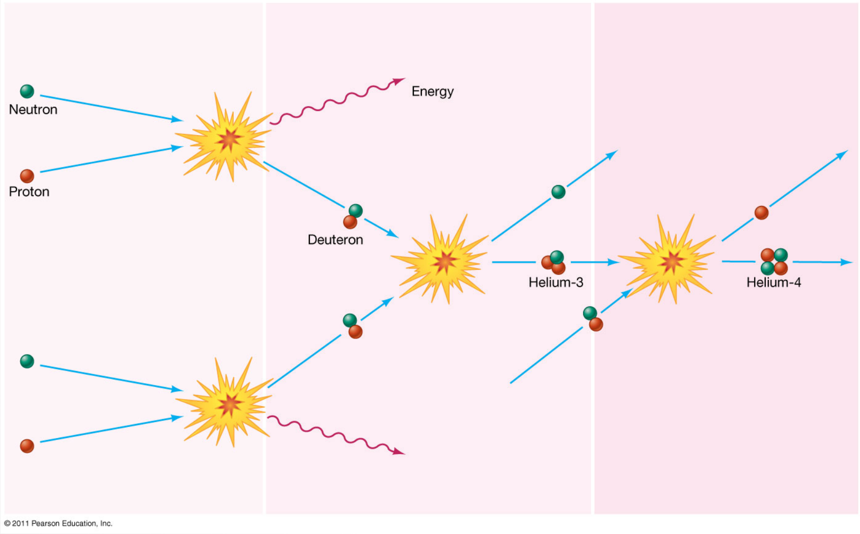
- Gamov and Alpher started with the conditions at a few tenth's of a second after the BB
- Need: temperature, density, # of protons and neutrons, *nuclear physics cross-sections for reactions*

Primordial Nucleosynthesis



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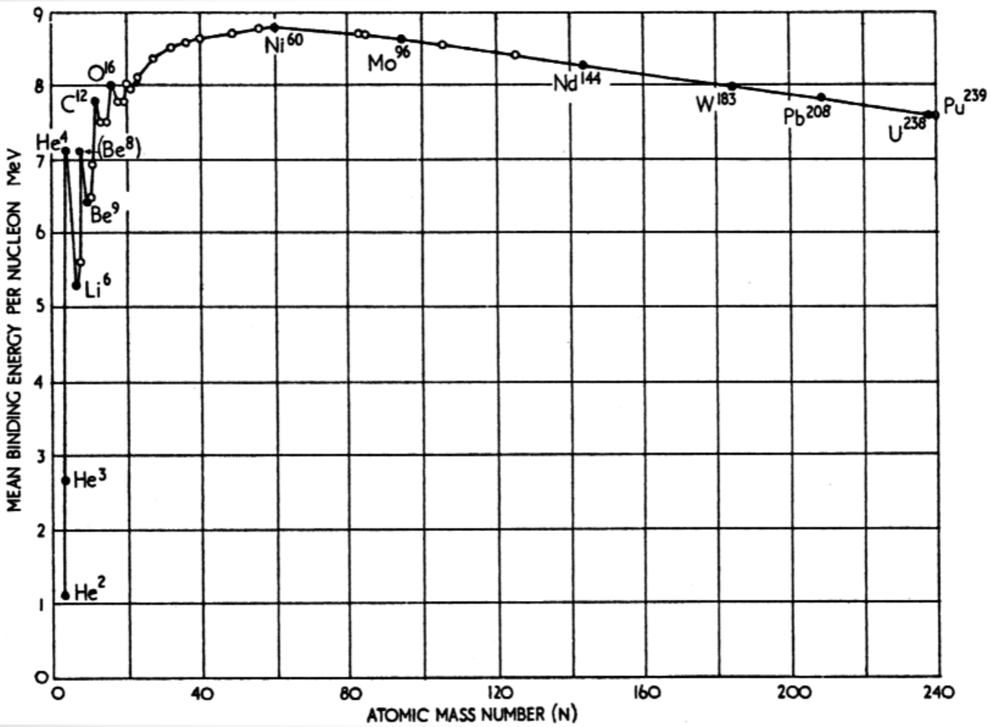
Principle fusion chain:

- $p^{+}+n^{0} \rightarrow H^{2}$ (deuterium)
  - No electrical repulsion
- $H^{2}+H^{2} \rightarrow He^{3}+n^{0}$
- $He^{3}+H^{2} \rightarrow He^{4}+p^{+}$

H^{2} is relatively easily broken apart by energetic photons.

This is what starts the nucleosynthesis chain going: Universe cools to the point where very energetic photons are rare and H^{2} is available

The Surprise



Natural next steps:

- $He^4+He^4 \rightarrow Be^8$

Be^8 is unstable with a half life of $7x10^{-17}$seconds!

- $He^4 + p^+ \rightarrow Li^5$

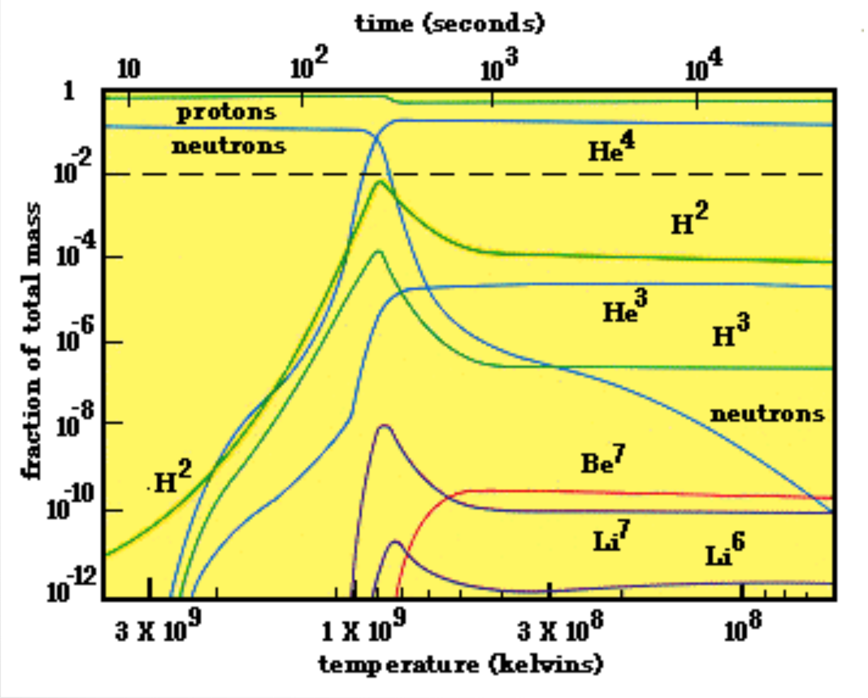
Unstable again

- Other isotopes of Be and Li are stable, but energetically not favored. Makes these in small amounts

The Surprise

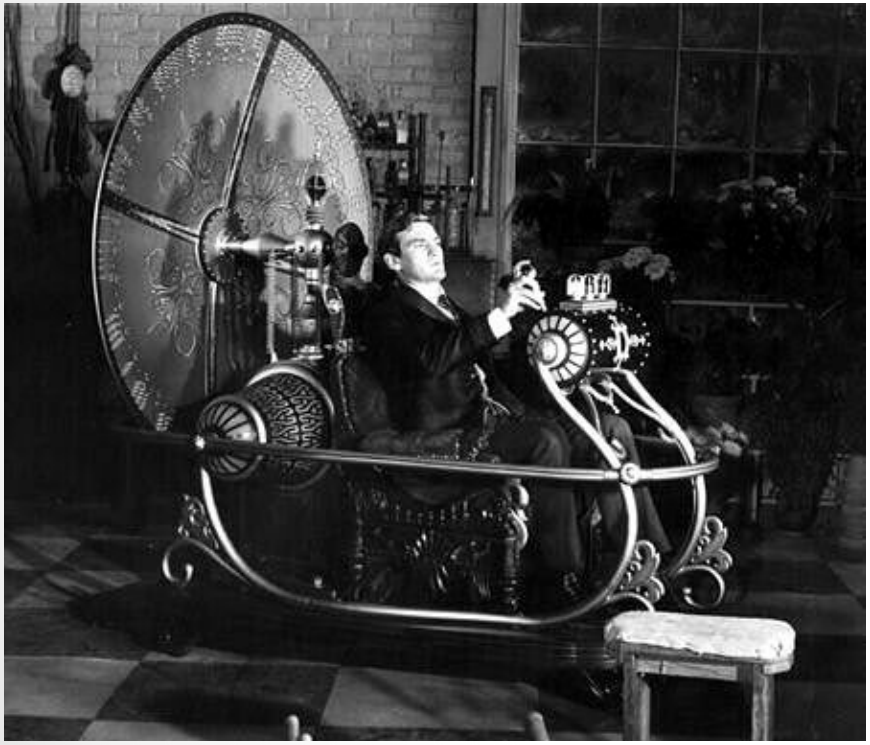
- By 10^3 seconds after the BB, the temperature of the Universe has dropped to values too low to support fusion reactions
- Produced lots of hydrogen, 25% by mass of He^4, some H^2, $H^{3,}$ He^3, Li^7, Li^6, Be^7
- This was used as an argument against the Hot Big Bang model: where did all the other elements come from?
- Required a slight asymmetry in matter vs anti-matter (1 extra matter particle per billion)

Big Bang Nucleosynthesis

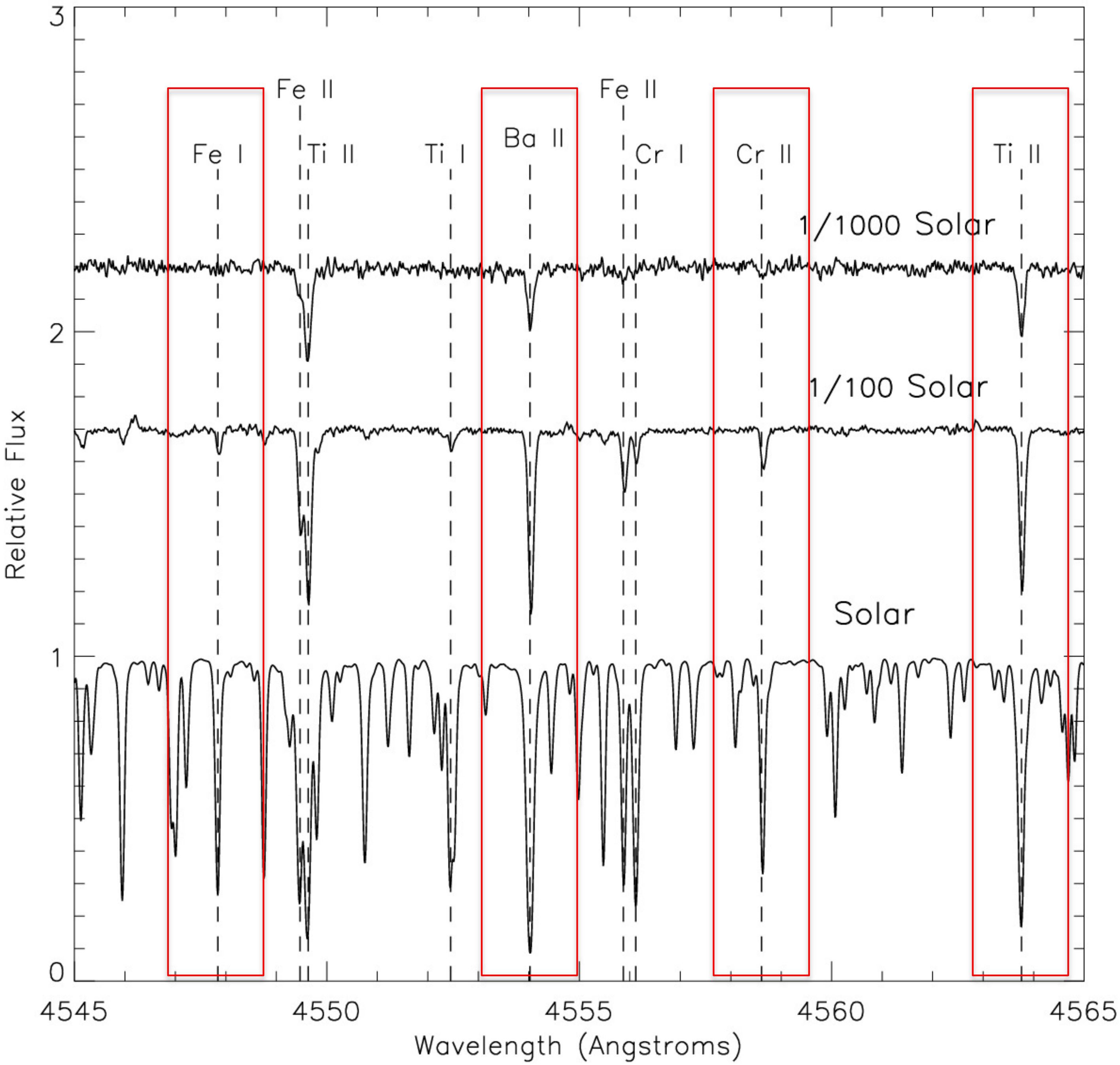


- BB+1 second: electrons, photons, neutrons, protons
- BB+2 minutes: some H^2 (p+n) produced
- BB+4 minutes: He production+tiny amount of Be, B and Li
- That's all! Universe has expanded to 10^9K and a density of only 10 g/cm^2

Fossils and time machines



- Stars like the Sun live for 10 billion years and some in the Galaxy are very old: these preserve the properties of the chemical composition of the Galaxy from the time of their formation
- Searching for "first stars" has been going on since 1970s


Fe I
Fe II
Ti II
Ti I
Ba II
Fe II
Cr I
Cr II
Ti II
1/1000 Solar
1/100 Solar
Solar
Relative Flux
0
1
2
3
4545
4550
4555
4560
4565
Wavelength (Angstroms)

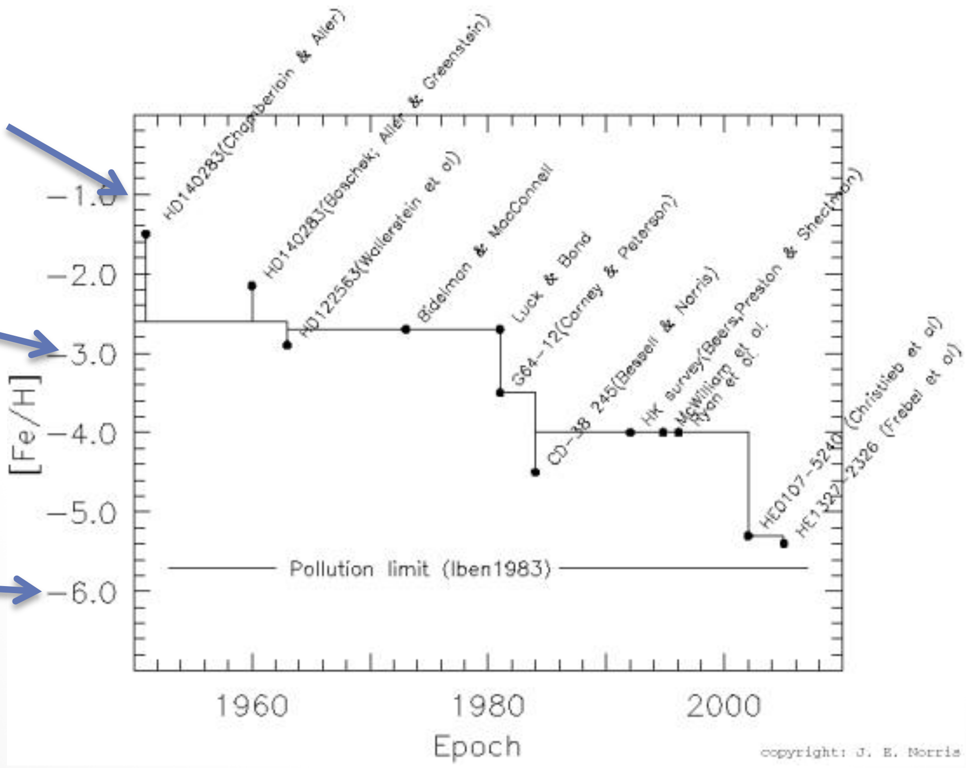
Big Bang Nucleosynthesis

- Is this story right? Makes some predictions:
  - The oldest stars in the Galaxy are deficient in the abundance of elements heavier than Helium

Factor 10 lower abundance of Fe compared to the Sun

Factor 10^3 lower abundance of Fe compared to the Sun

Factor 10^6 lower abundance of Fe compared to the Sun



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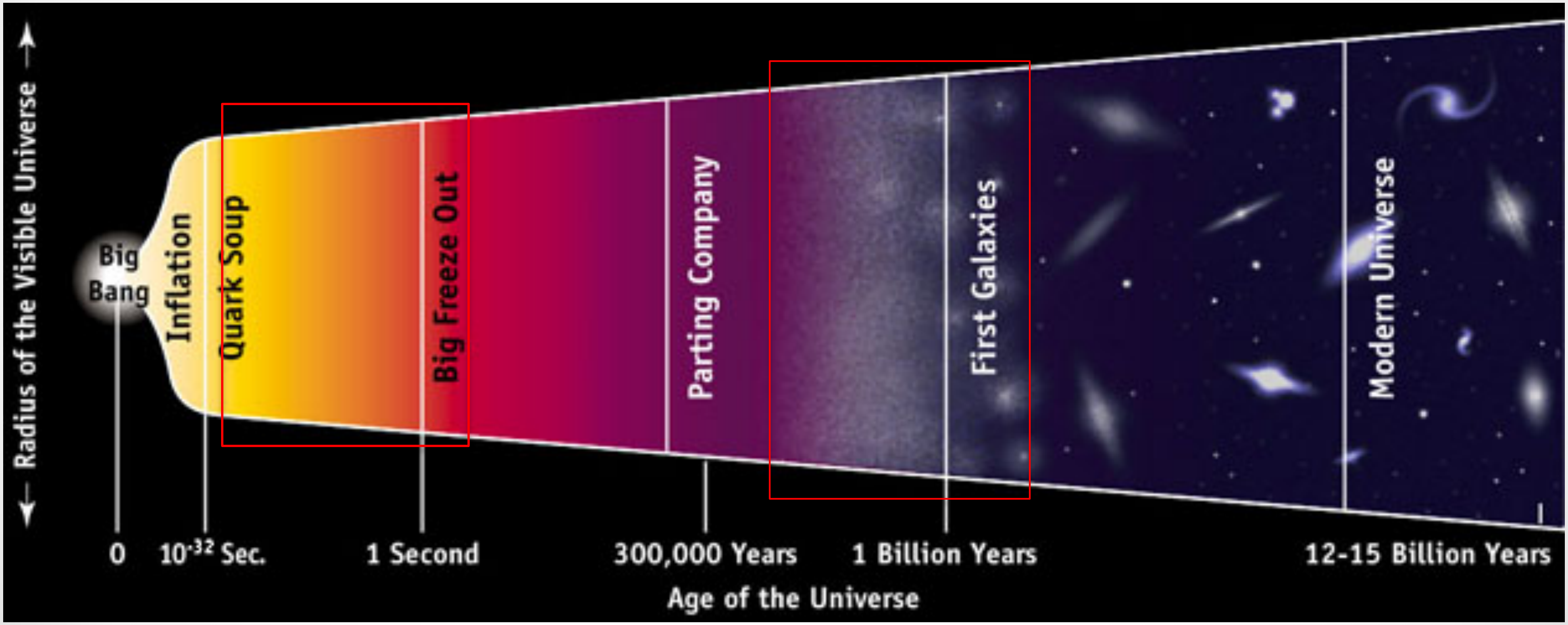
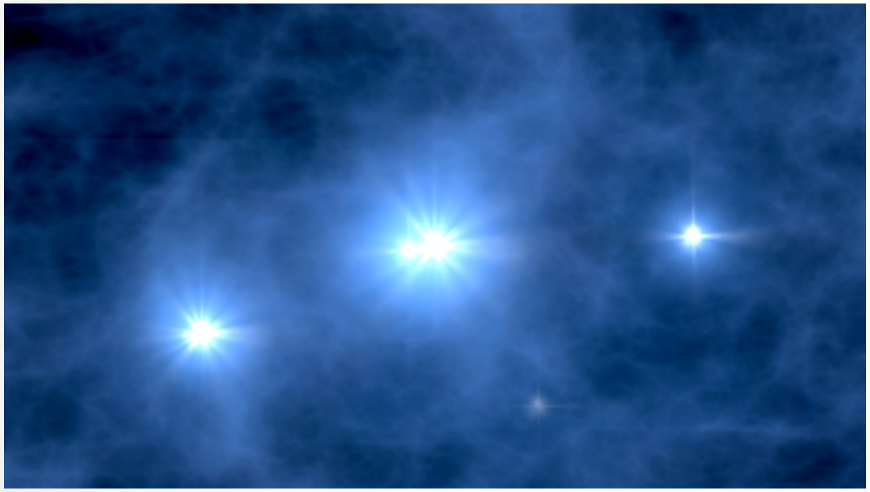
Universe Timeline



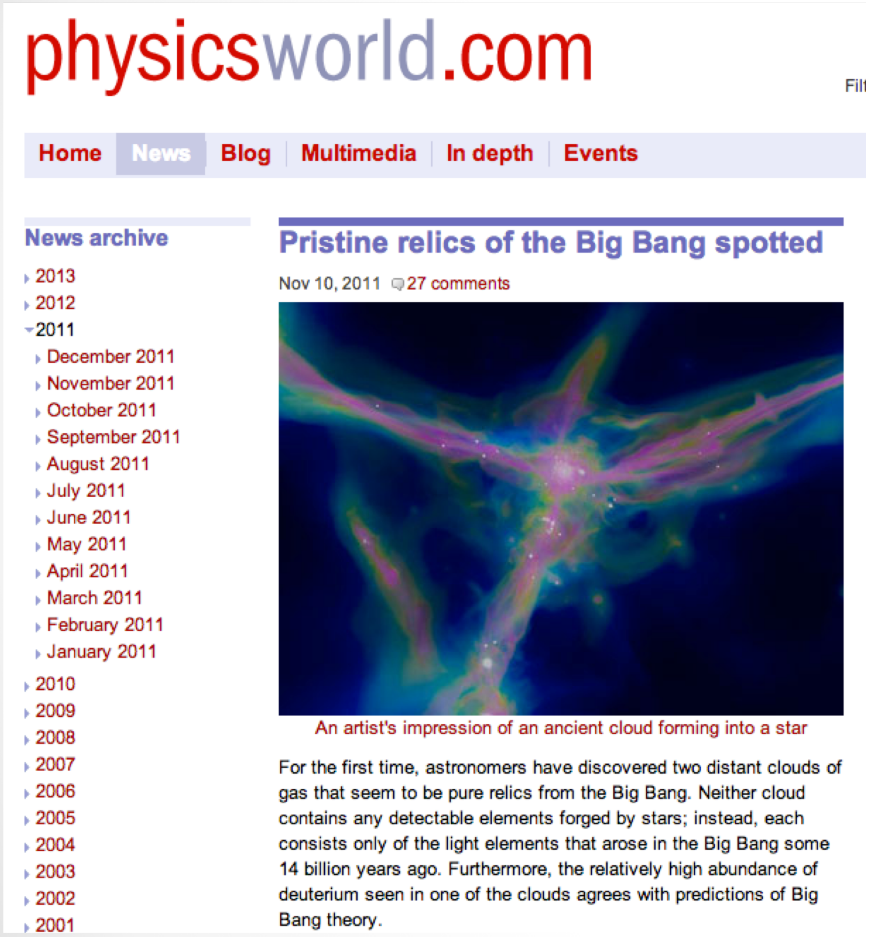
It was too hot for stars or galaxies to form for the first 200-400 million years, but at some point the First Stars formed from "primordial" material

The First Stars



- Have looked hard for stars composed of only HBB material
- Have gotten very close, but there may not be any true first-generation stars in the Galaxy
  - Galaxy formed from enriched gas
  - Stars made of only H and He all have masses $>0.9M_{Sun}$ and lifespans <12 Gyr

Pristine Gas in the Early Universe



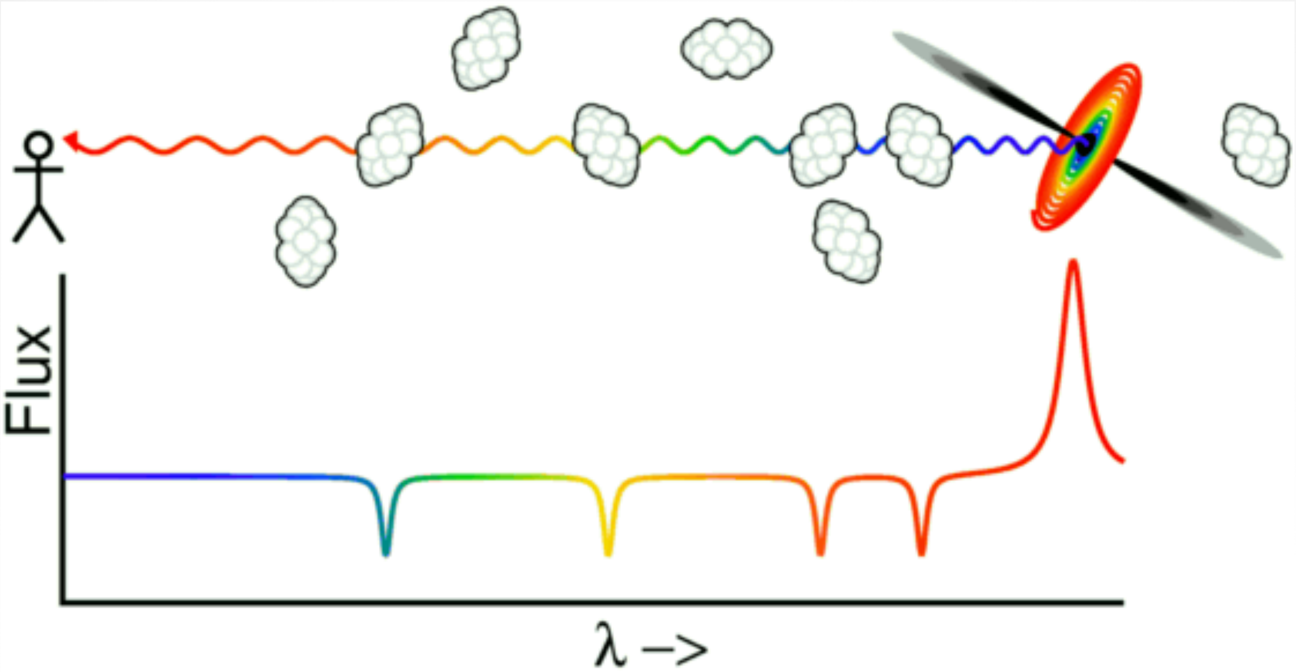
Pristine relics of the Big Bang spotted

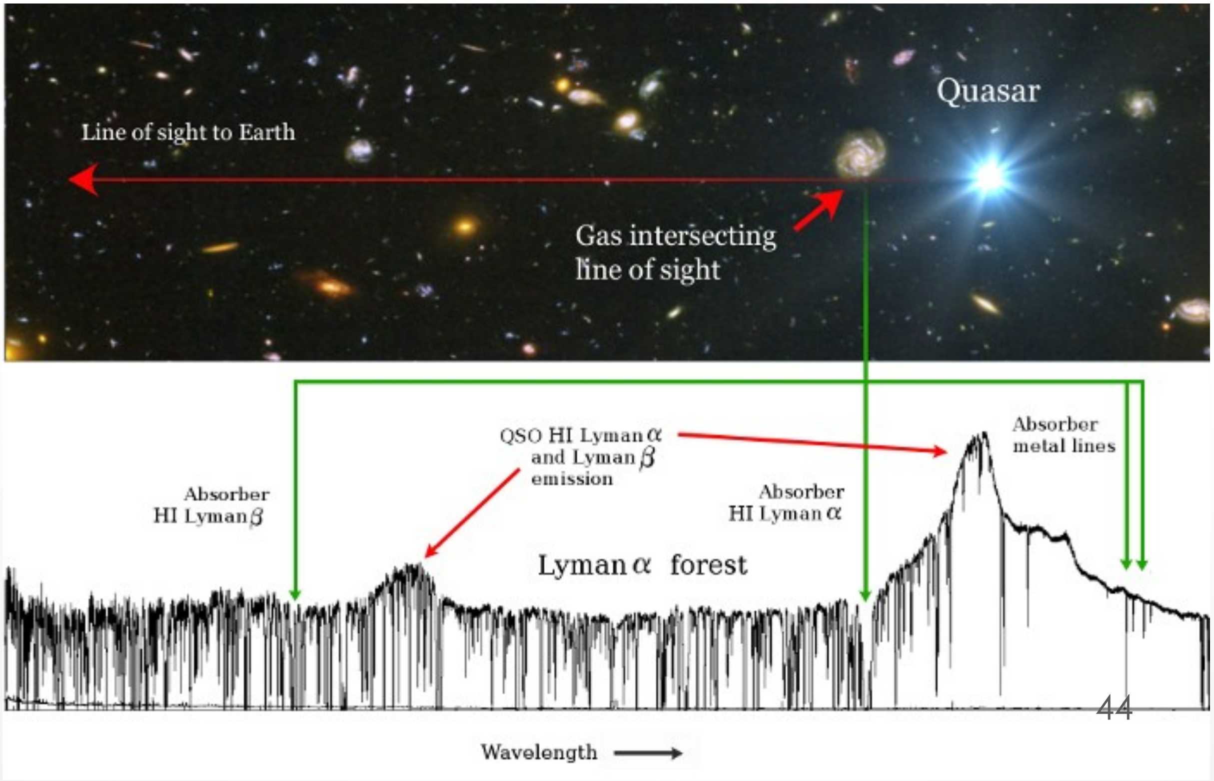
Nov 10, 2011 27 comments

An artist's impression of an ancient cloud forming into a star

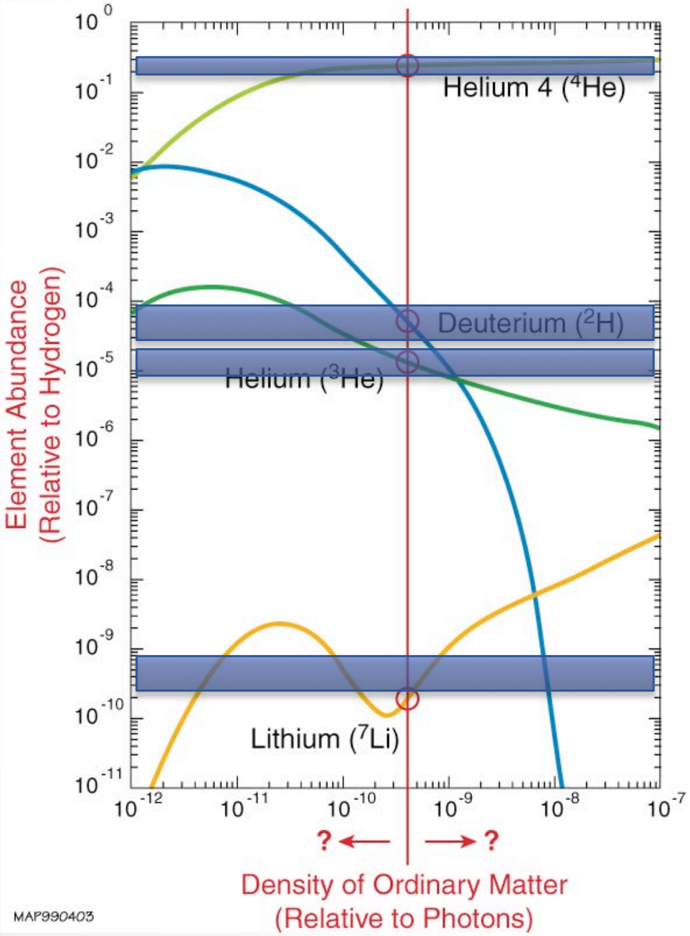
For the first time, astronomers have discovered two distant clouds of gas that seem to be pure relics from the Big Bang. Neither cloud contains any detectable elements forged by stars; instead, each consists only of the light elements that arose in the Big Bang some 14 billion years ago. Furthermore, the relatively high abundance of deuterium seen in one of the clouds agrees with predictions of Big Bang theory.

- In addition to looking for old stars made of primordial material, can look directly back in time at large look-back times
- 2011, UCSC astronomers made the first discovery of pristine clouds of primordial material


Flux
λ –>


Quasar
Line of sight to Earth
Gas intersecting line of sight
QSO HI Lyman α and Lyman β emission
Absorber HI Lyman β
Absorber HI Lyman α
Absorber metal lines
Lyman α forest
Wavelength →

HBB Nucleosynthesis



- Calculations also make specific predictions for the "primordial" abundance of H, H^2, He^3, He^4 and Li^7
- Depends on the ratio of "baryons" to photons at the time of nucleosynthesis (plus a few other interesting things like the number of neutrino families)

HBB nucleosynthesis looks pretty good!

Run through the Standard Model physics for the Universe evolving from ~10^{-30} to 10^{3} seconds and we predict quite accurately the abundances of primordial elements and match particle accelerator results

Origin of the Elements

HBB stars SNI r- and s-process (SNII and AGB stars