The Early Universe

Notes based on Teaching Company lectures, and associated undergraduate text – with some additional material added.

1) From 1 μs to 1 s: quark confinement; particle freezout.

2) From 1 s to 3 minutes: Big Bang Nucleosynthesis.

3) Before 1 ns: Supersymmetry; baryogenesis; unification.

Overview: The Early Universe

Simple Friedmann equation for the radiation era:

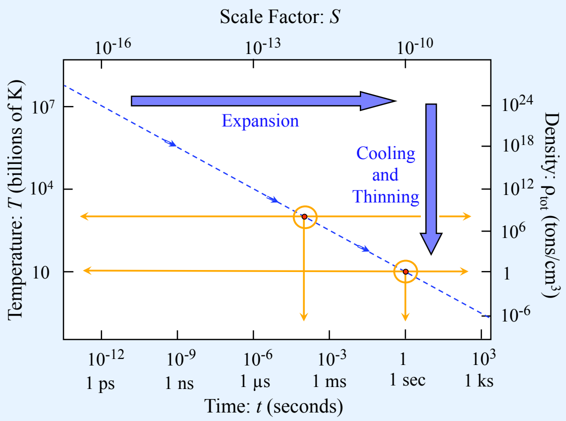
$$E(a) = \Omega_{r,o}{}^{1/2}\, a^{-2} \quad \text{gives (using } \Omega_{r,o} = 8.4 \times 10^{-5}\text{)}$$

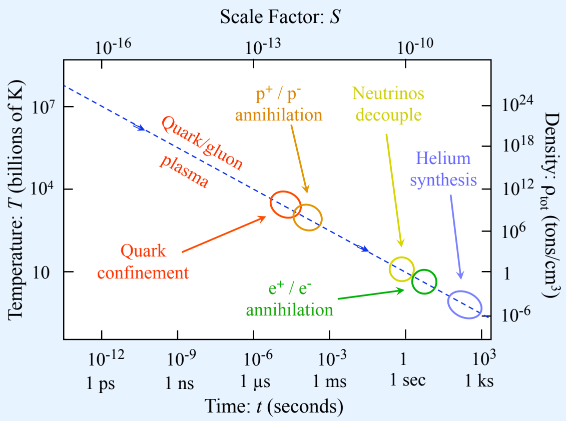
$$a = 2.09 \times 10^{-10}\, h_{72}{}^{½}\, t_s{}^{½}$$

$$T = 1.31 \times 10^{10}\, h_{72}{}^{-½}\, t_s{}^{-½}\ \text{K} \;=\; 1.14\, h_{72}{}^{-½}\, t_s{}^{-½}\ \text{MeV}$$

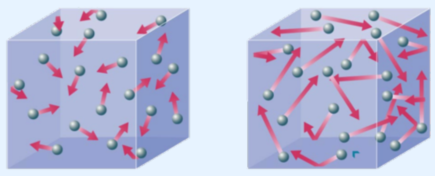
$$\boxed{\left(\frac{t}{1\ \text{s}}\right)^{-1/2} \approx \frac{T}{10^{10}\,\text{K}} \approx \frac{k_B T}{1\ \text{MeV}} \approx \left(\frac{\rho}{10^{7}\,\text{gm cm}^{-3}}\right)^{1/4} \approx \left(\frac{\rho_m}{1\ \text{gm cm}^{-3}}\right)^{1/3} \approx \frac{1+z}{10^{10}}}$$

Note: this relation is modified somewhat at earlier times when other species (e.g. e^+, e^-) are thermally produced.





Accelerators recreate the early universe



Lower Temperature
Slower Motion

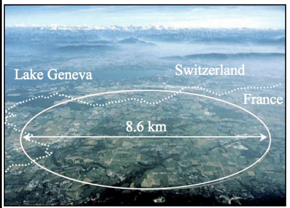
Higher Temperature
Faster Motion

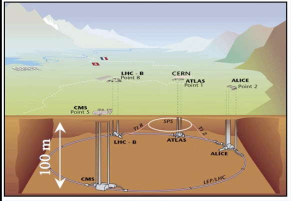
High temperatures = high energy collisions

→ Particle accelerators reproduce these collisions

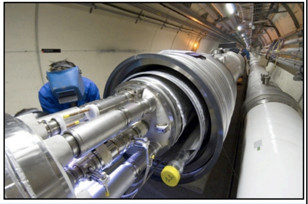
→ They recreate the conditions of the early universe.

Large Hadron Collider (LHC)



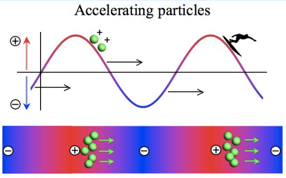


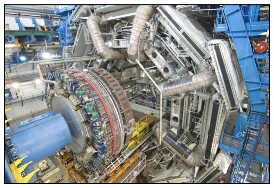
Accelerator beam pipes

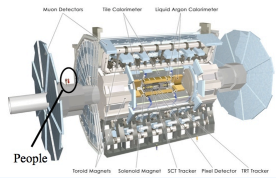


Electric fields accelerate the particles

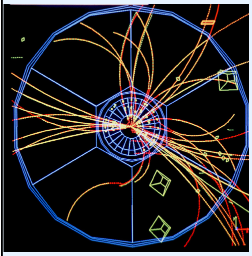
Detectors are immense

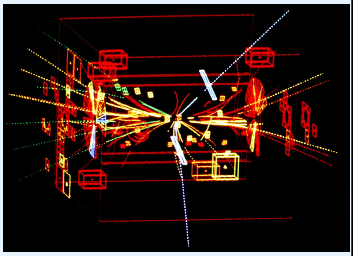

Accelerating particles


ATLAS detector at CERN



Particle creation and detection

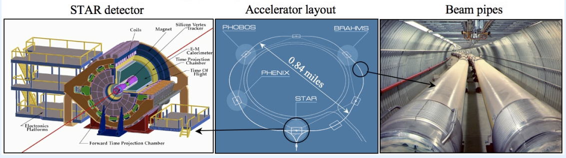

Z0 decay at DELPHI detector


Z0 detection at UA1 detector

Many accelerators collide single particles head on (e^+e^-, pp)
→ Fundamental laws of physics

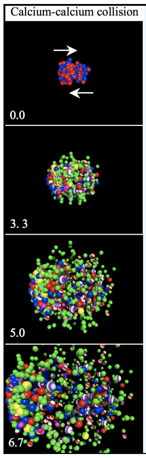
Also possible to collide whole nuclei (Pb-Pb or Au-Au)
→ Recreates the quark gluon plasma

Making a quark-gluon plasma at Brookhaven's RHIC

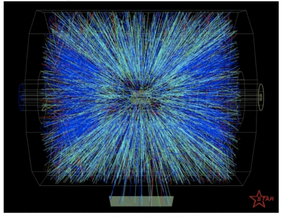

STAR detector

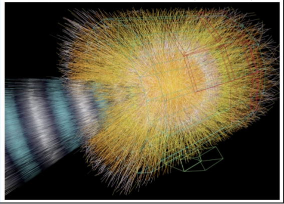
Accelerator layout

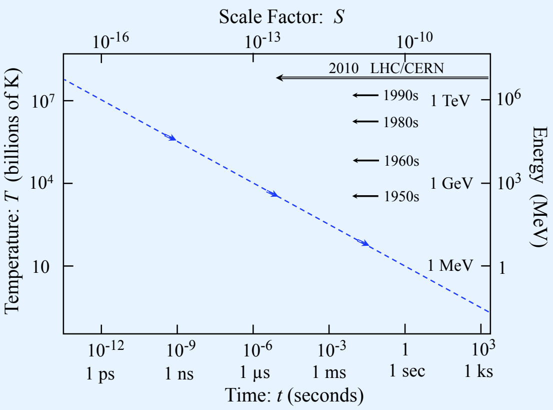
Beam pipes


Calcium-calcium collision

Primary result: the quark-gluon plasma behaves like a liquid!


Gold-gold colision in STAR (real data)


Lead-lead collision in ALICE (simulation)



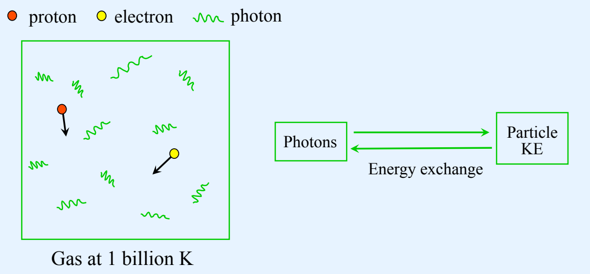
Above/below threshold temperatures: particle creation and annihilation

With high enough energy, particle collisions can generate particle-antiparticle pairs: e.g. $\gamma + \gamma \rightarrow x^+ + x^-$

Need thermal energy: $k_B T \geq m_x c^2$ to generate this.
So $k_B T_{\text{threshold}} \sim m_x c^2$ provides a *threshold* temperature.
(e.g. e^+/e^- at 0.5 MeV = 6 GK (5s); p^+/p^- at 1 GeV = 10^{13} K (1μs))

However, at *any* temperature, particle-antiparticle annihilation can occur: e.g. $x^+ + x^- \rightarrow \gamma + \gamma$

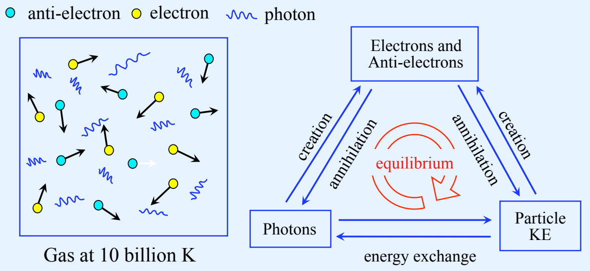
Below the threshold temperature



At LTE the photons have a planck function, with energy density:

$$u_\gamma = \rho_\gamma c^2 = g_\gamma \frac{8\pi^5 (k_B T)^4}{30 (hc)^3} \quad \text{where } g_\gamma = 2 \text{ for both spins}$$

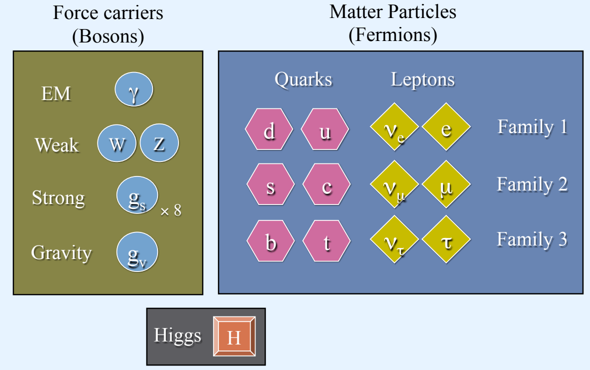
Above the threshold temperature

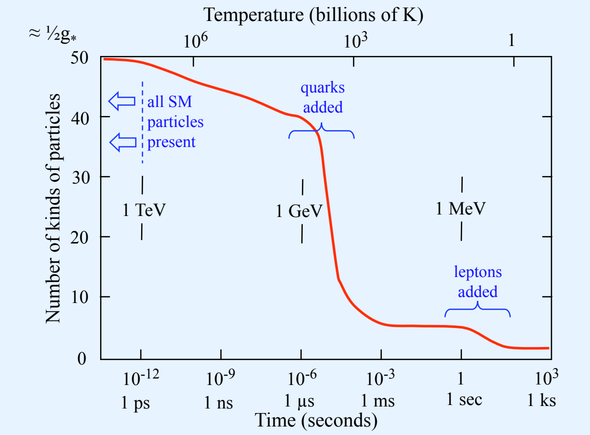


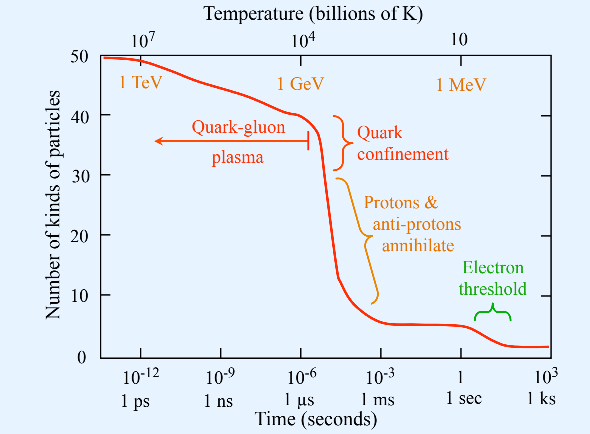
We now have γ, e^+ and e^- all present, with total energy density:

$$u = \rho c^2 = g_* \frac{8\pi^5 (k_B T)^4}{30 (hc)^3} \quad \text{where } g_* = 5.5 \ \ (=2 + (2+2)\times\tfrac{7}{8})$$

The Standard Model Particles







Higher g_* shortens expansion timescale

Since $t_H = 1/H = (3/8\pi G\rho)^{1/2}$ and $\rho c^2 = g_* \dfrac{8\pi^5 (k_B T)^4}{30 (hc)^3}$

Then g_* enters a(t), giving faster expansion timescales at earlier times than our simple relation.

In terms of temp/energy: $T_{MeV} \sim 1.5\, g_*^{-1/4}\, t_s^{-1/2}$

Big Bang Nucleosynthesis

Late 1940s: Robert Herman George Gamow and Ralph Alpher analyze nuclear reactions in a hot big bang. Their aim was to make *all* the elements.

Near 1 minute, T ~ 10^8 K, and nuclear reactions can occur. Unlike stars, there are free neutrons, which can form deuterium, and then He-4. The conditions don't allow heavier elements to form.

Neutron/proton equilibrium

The neutron/proton number ratio is a key parameter.

Before 1 sec, an eqlm population is maintained by *neutrino* reactions:

$$n + \nu_e \rightarrow p + e^- + energy$$

$$p + \bar{\nu}_e + energy \rightarrow n + e^+$$

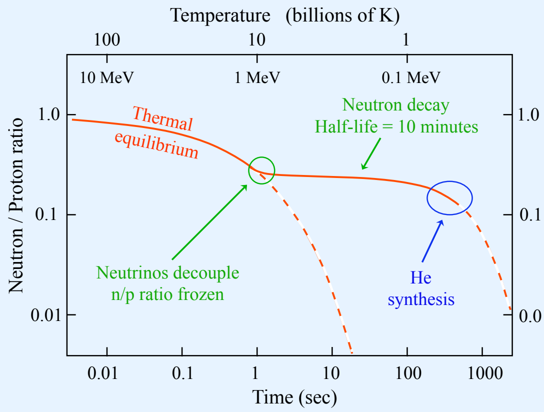
Recall, neutrons are slightly heavier than protons:

$\Delta m = m_n - m_p = 939.6 - 938.3 = 1.3$ MeV

Hence eqlm population ratio given by Boltzmann factor:

$$\frac{N_n}{N_p} = \left(\frac{m_n}{m_p}\right)^{3/2} \exp\left(-\frac{(m_n - m_p)c^2}{k_B T}\right)$$

So, when $k_B T >> 1$MeV, $(N_n/N_p) \approx 1$.
This drops below 1.0 near 1sec, as T drops below 1 MeV



Neutrino decoupling freezes the neutron/proton ratio

Near 1 sec, the neutrino's *decouple* and the interconversion of neutrons and protons ceases. We say the reaction *freezes out*.

What's going on: Reaction timescale: $t_{reac} = 1/(n<\sigma v>)$
With: $n \sim a^{-3}$, $\sigma_W \sim T^2 \sim a^{-2}$, $v \sim c$; so $t_{reac} \sim a^5$ is *slowing down*

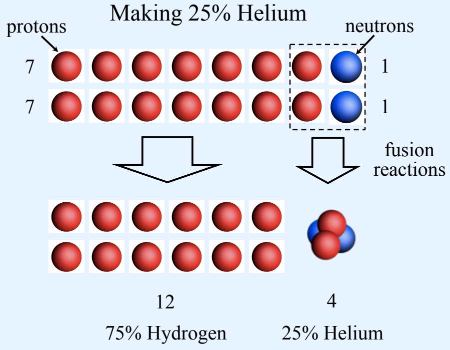
Expansion timescale: $t_H = 2t_{age} \sim a^2$ is also slowing down, but not as fast.

When $t_{reac} > t_H$ then the number of "collisions" drops to zero.

→ The reaction is frozen.

This occurs near 1 sec (T ~ 0.8 MeV), when $N_n/N_p \sim 1/5$.
The further delay of ~5 minutes until deuterium formation brings this ratio down to 1/7.3 (neutron half-life = 10.2 min)

Making 25% Helium



Helium Abundance

In simple form, helium abundance arises from full conversion of neutrons into He-4. Hence:

$$N_{He} = ½ N_n$$

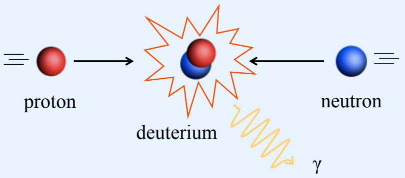
Hence the *mass* fraction of helium is:

$$Y_{He} = (4 \times ½ N_n) / (N_n + N_p) = 2/(1 + N_p/N_n)$$

Hence, for $N_p/N_n = 7.3$, we have $Y_{He} = 0.24$

Making Helium

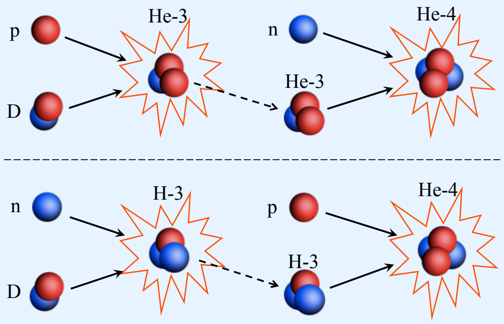
Making deuterium



Notice: this is a strong reaction, and quite different from the weak reaction that occurs within stars:

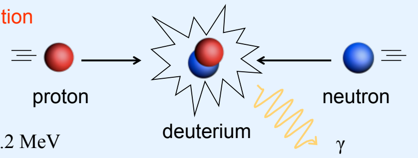
$$p + p \rightarrow D + e^{+} + \nu_e$$

Making Helium-4



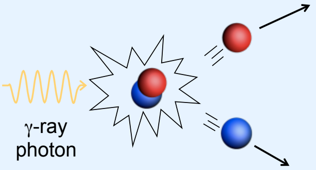
The Deuterium Bottleneck

Formation

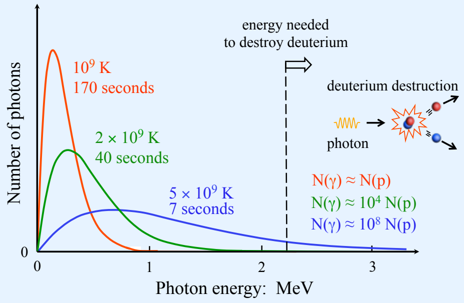


$BE_D \sim 2.2$ MeV

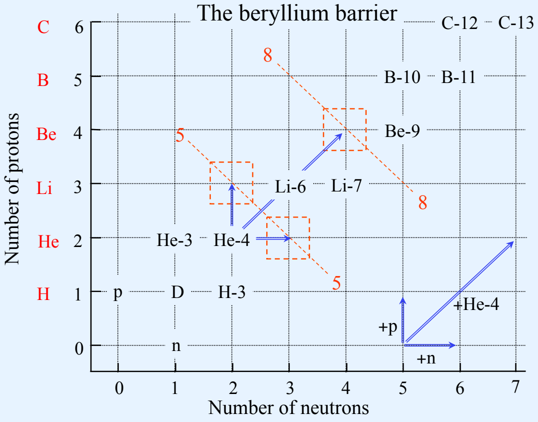
Destruction

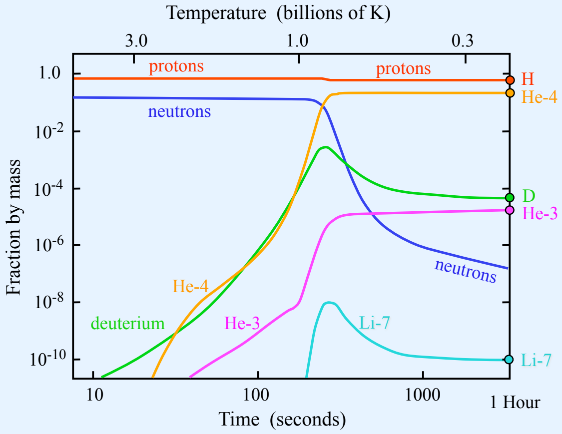


The deuterium bottleneck



The beryllium barrier



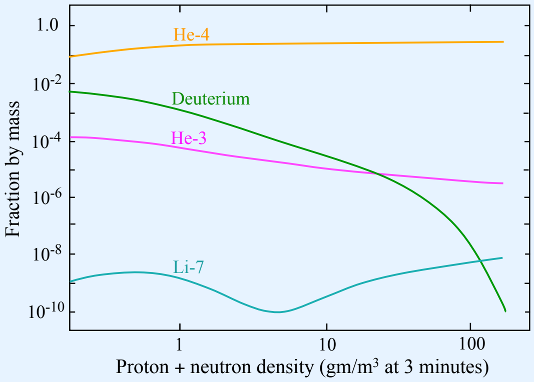


The final abundances depend somewhat on the cosmic parameters, in particular the photon/nucleon ratio or, equivalently, the nucleon density.

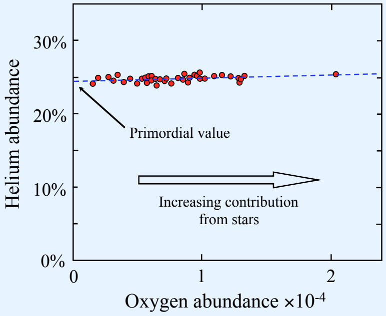
Comparison with measured primordial abundances then allows one to “measure” the baryon density during BBNS.

Because we know the scale factor during BBNS (because we know the temperature), then we can convert the baryon density during BBNS to a baryon density today $\rightarrow \Omega_b$

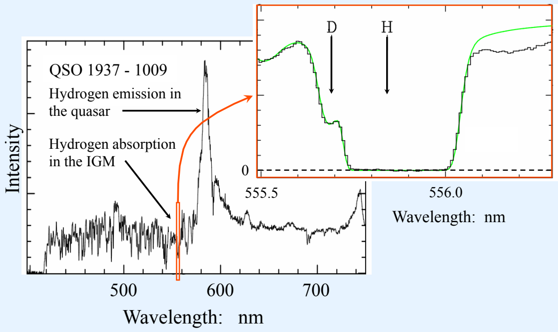
Element production depends on furnace density

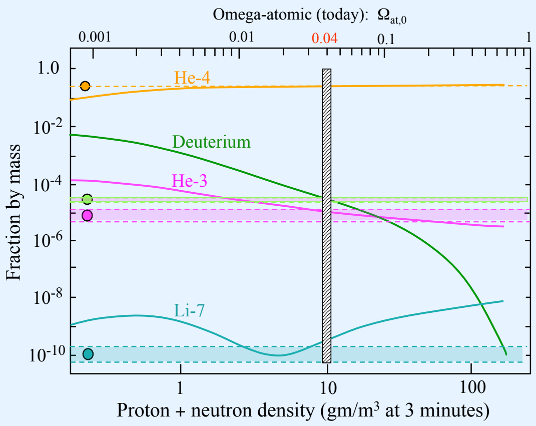


Measuring primoridal helium

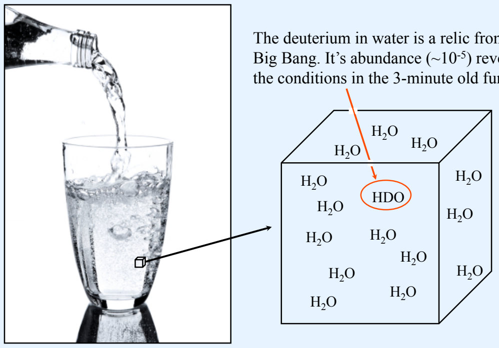


Measuring deuterium in the intergalactic medium





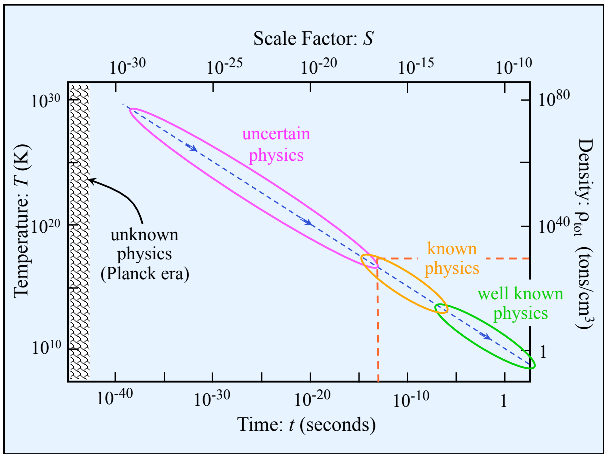
Cosmic history in a glass of water

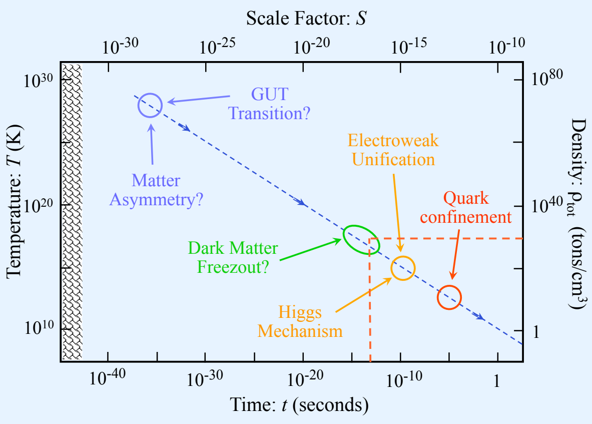


The deuterium in water is a relic from the Big Bang. It’s abundance (~10^{-5}) reveals the conditions in the 3-minute old furnace.

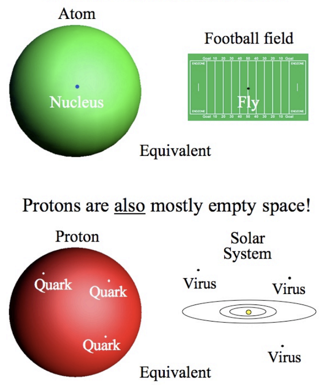
Even Earlier Times

1) Supersymmetric particle creation and dark matter
2) Force unification: electroweak and GUT
3) Baryogenesis: matter/antimatter asymmetry.

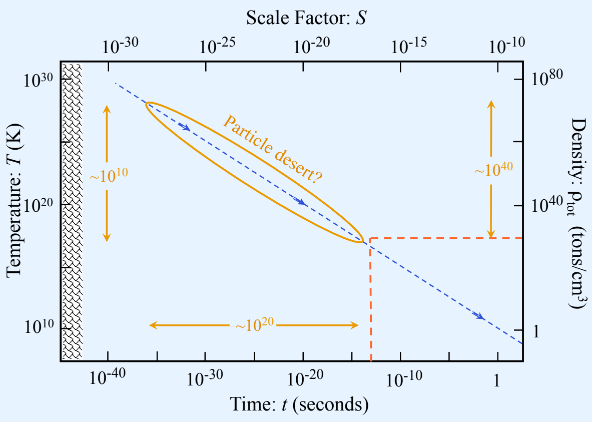




Atoms are mostly empty space

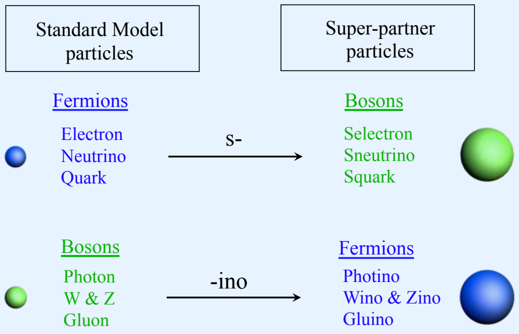


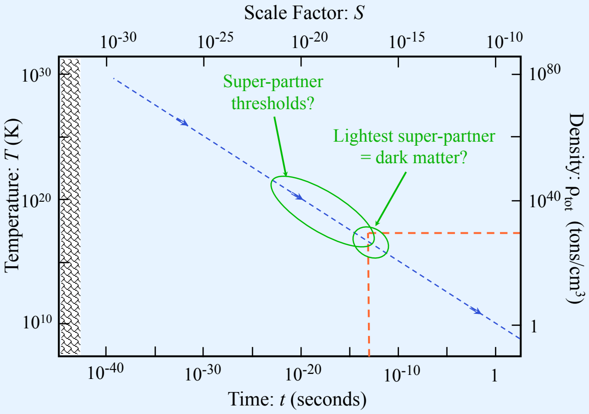
Protons are also mostly empty space!



Super-symmetry

Super-symmetric particles





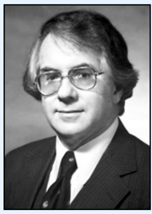
Force unification

Forces depend on temperature due to vacuum polarization

The Forces of Nature

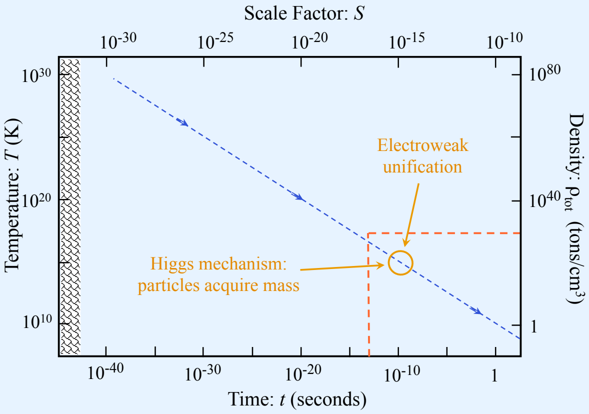
	Gravity	**Weak**	**Electro-magnetism**	**Strong**
Example	Planetary orbits	Radioactive decay	Electrons in atoms	Protons in nucleus
Acts on	All	All	Charged particles	Quarks & gluons
Carrying boson	Graviton	W & Z	Photon	Gluons
Relative strength	10^{-38}	10^{-4}	10^{-2}	1

Electro-weak unification

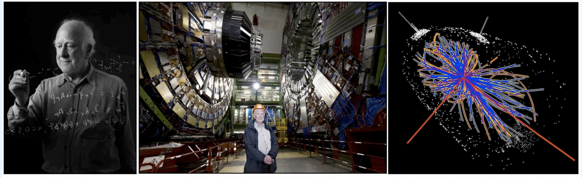

Sheldon Glashow
b. 1932


Abdus Salam
1926 - 1996


Steven Weinberg
b. 1933



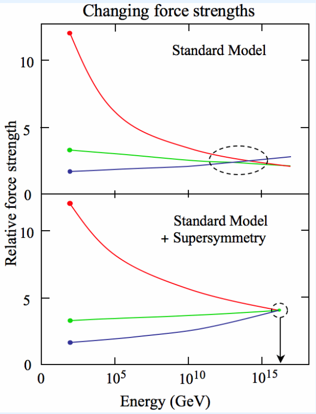
Peter Higgs and the Higgs boson

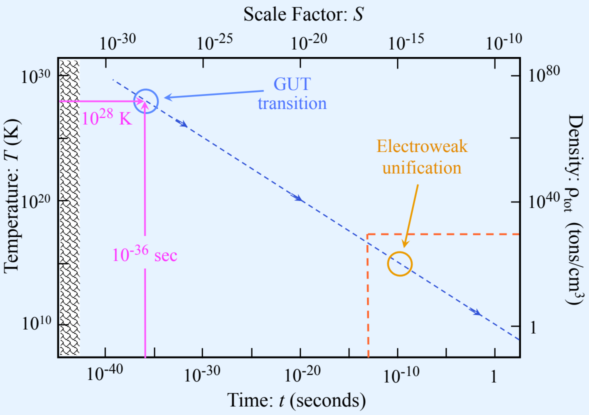


Peter Higgs
b. 1929

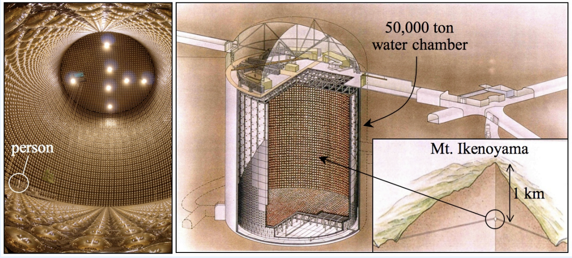
Higgs visits the CMS detector at
CERN's LHC in 2008

Simulation of Higgs boson production
(and decay) in the CMS detector





Super-Kamiokande II: proton decay and neutrino detector



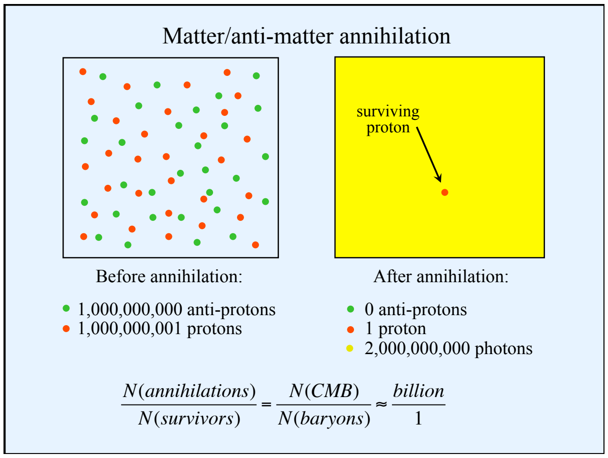
Baryogenesis

Conditions for matter/anti-matter asymmetry

Andrei Sakharov
(1921 - 1989)

1) Quarks and leptons must be able to interconvert.
2) Matter and anti-matter reactions must differ somehow
3) The process must occur in a non-equilibrium state, that happens during times of rapid change.

Hunt for CP violation currently a primary goal of the LHC.



Matter/anti-matter annihilation

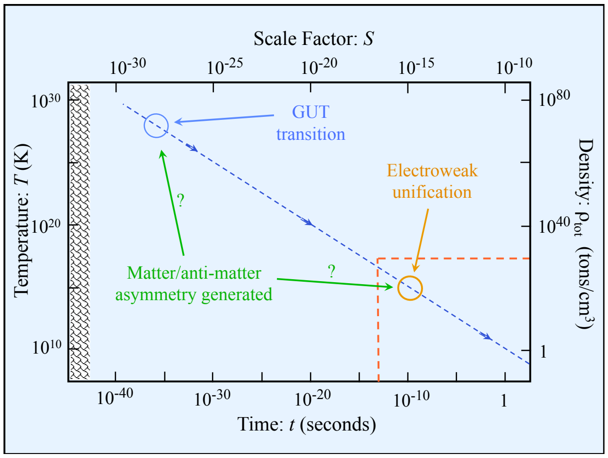
Before annihilation:

- ● 1,000,000,000 anti-protons
- ● 1,000,000,001 protons

After annihilation:

- ● 0 anti-protons
- ● 1 proton
- ● 2,000,000,000 photons

$$\frac{N(annihilations)}{N(survivors)} = \frac{N(CMB)}{N(baryons)} \approx \frac{billion}{1}$$



End of Early Universe