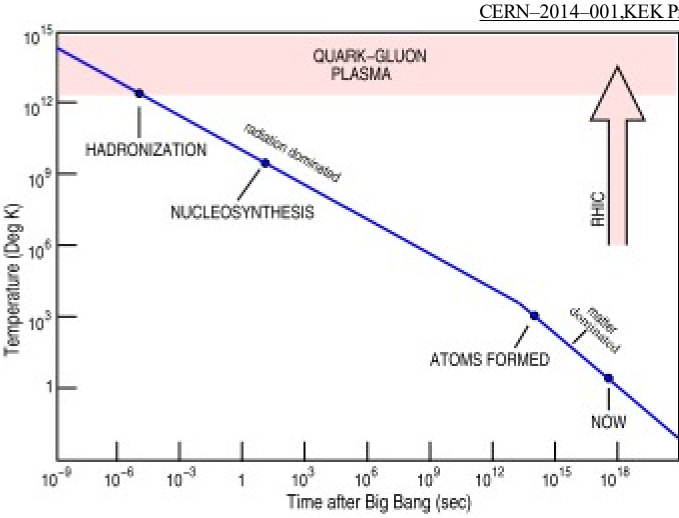
XXIX. Early Universe Models: Quark-Gluon Plasma

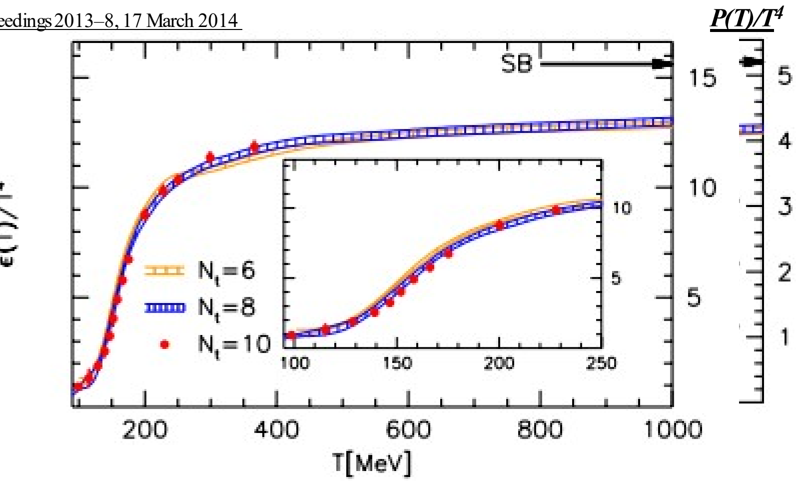
Refer to Section IIC. Hypothetical and Observable Thermal Sequence for the ΛCDM Theory

Quark–Gluon plasma (QGP or quark soup) is a state of matter of Quantum Chromodynamics (QCD) of an interacting localized assembly of quarks and gluons at thermal (local kinetic) and (close to) chemical (abundance) equilibrium. The word plasma signals that free color charges are allowed. It can be said that QGP emerges to be the new phase of strongly interacting matter which manifests its physical properties in terms of nearly free dynamics of practically massless gluons and quarks. Both quarks and gluons must be present in conditions near chemical (yield) equilibrium with their color charge open for a new state of matter to be referred to as QGP.
In the Big Bang theory, quark–gluon plasma filled the entire Universe before matter as we know it was created.
Quark–gluon plasma is a state of matter in which the elementary particles that make up the hadrons of baryonic matter are freed of their ***Strong Force*** attraction (deconfinment) for one another under extremely high energy densities.

CERN–2014–001,KEK Proceedings 2013–8, 17 March 2014



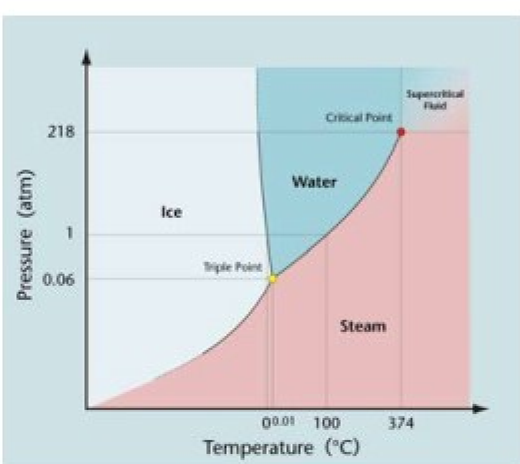
Temperature history of the universe.



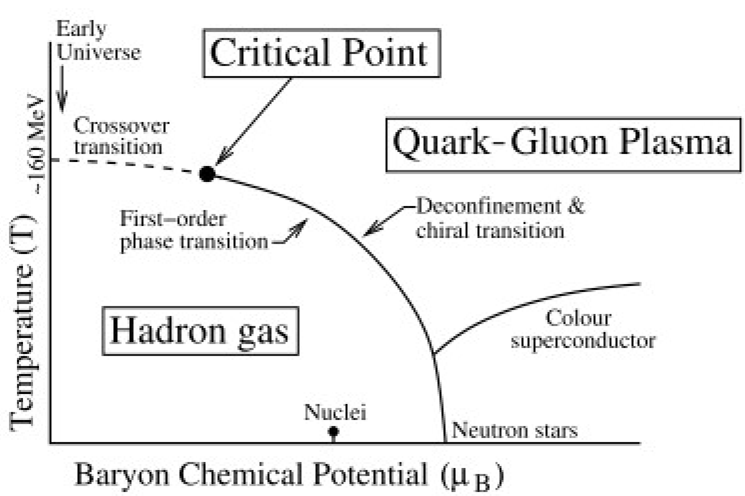
Energy density ***ε(T)*** and Pressure ***P(T)*** normalized by T^4 as a function of temperature (***T***). N_t is the number of lattice points in the temporal direction. The Stefan-Boltzmann (SB) limits are indicated by arrows.

The phase diagram (pressure vs temperature) of water below shows three broad regions separated by phase transition lines, the triple point where all three phases coexist, and the critical point where the vapour pressure curve terminates and two distinct coexisting phases, namely liquid and gas, become identical. The QCD phase diagram is known only schematically, except for the lattice QCD predictions at vanishing or small μB , in particular the prediction of a crossover transition around T ~ 150-170 MeV for vanishing Baryon Chemcial potential μ_B.

Note that both energy density (ε) and pressure (P) rise rapidly around T = 160 MeV,



Phase diagram of Water



QCD phase diagram.

Early Universe Models: Nucelosynthesis - Metallicity - Population III Stars

Modeling Hydrogen Orbitals (We will use the Maple Programming Language for Model)

$Y(l, m, \theta, \phi)$ is the spherical harmonic or angular part of an orbital, where l is the angular momentum (azimuthal) quantum number and m is the magnetic quantum number. θ is the angle with the z axis in spherical coordinates and ϕ is the angle around the z axis in spherical coordinates. These angles follow the quantum mechanics convention, used here and in the VectorCalculus package, which is different from the math convention used in the rest of Maple.

A d_{z^2} orbital has $l = 2$ and $m = 0$ and an angular part that is the spherical harmonic $Y(2, 0, \theta, \phi)$. (This worksheet makes liberal use of atomic variables to make nice looking variables such as d_{z^2}, check "Atomic Variables" in the view menu to highlight these.)
The function *cartesian* converts the spherical harmonic to the usual form in terms of x, y, z and r (use the function *fullcartesian* to remove the last r)

> $d_{z^2} := Y(2, 0, \theta, \phi);$

$$d_{z^2} := \frac{1}{4} \frac{\sqrt{5}\,(3\cos(\theta)^2 - 1)}{\sqrt{\pi}}$$

$$-\frac{1}{4} \frac{\sqrt{5}\,(x^2 + y^2 - 2z^2)}{r^2\sqrt{\pi}}$$

The plots of orbitals usually seen are just plots of the squares of their angular parts (for contour plots of the wavefunction with both radial and angular parts, see below). Recall again that Maple's (θ, ϕ) is (ϕ, θ) in quantum mechanics, so put ϕ before θ in the plot command. A useful way to color these is by phase. Since this spherical harmonic is real, the phase simply indicates the sign: red for positive (phase = 0), cyan for negative (phase = π).

> $plot3d\left(d_{z^2}^{\,2}, \phi = 0..2\pi, \theta = 0..\pi, coords = spherical, style = patchnogrid, scaling = constrained, color = \text{argument}(d_{z^2}) / (2\pi), grid = [50, 50], axes = none\right)$

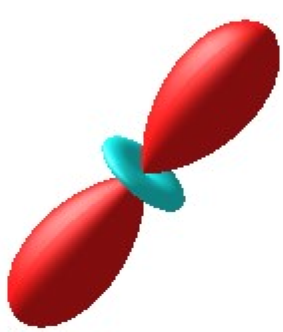
Only the spherical harmonics with $m = 0$ are real. For example, for $l = 2, m = 1$ we have

> $d_1 := Y(2, 1, \theta, \phi)$

$$d_1 := \frac{1}{4} \frac{\sqrt{30}\,\sin(\theta)\cos(\theta)\,e^{I\phi}}{\sqrt{\pi}} \qquad \textbf{(3.2)}$$

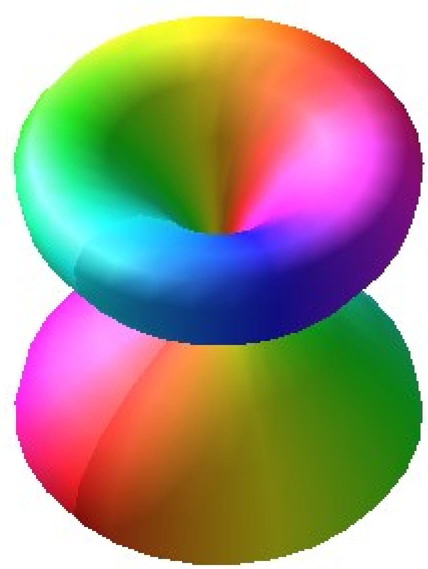
The square of the absolute value can be plotted in the same way as above. The colors now show phases other than 0 and π.

> $plot3d\left(|d_1|^2, \phi = 0..2\pi, \theta = 0..\pi, coords = spherical, style = patchnogrid, scaling = constrained, color = \text{argument}(d_1) / (2\pi), grid = [30, 30], axes = none\right)$



Maple Plots:

The square of the absolute value can be plotted in the same way as the spherical harmonic at the left.
The colors now show phases other than 0 and π.



Nucelosynthesis in the Early Universe: Ratio of Neutrons to Protons

Introduction to Cosomology, Ryden

"The basic building blocks for nucleosynthesis are neutrons and protons. As the Universe cools, protons and neutrons become stable particles and they, in turn, bind into nuclei. With a decay time of only fifteen minutes, the existence of a free neutron is as fleeting as fame; once the universe was several hours old, it contained essentially no free neutrons. However, a neutron which is bound into a stable atomic nucleus is preserved against decay. There are still neutrons around today, because they've been tied up in deuterium, helium, and other atoms.

The Boltzmann distribution for the number density of nonrelativistic nuclei of atomic weight A is: $n_A \approx T^{3/2} e^{(\mu A - m A)/k}$.

Given the masses of the particles in Mega Electron Volts (MeV), the number density for neutrons and protons is:"

$MeV := 1.60218 \times 10^{-13} \cdot J$ $\quad m_n := 939.565420 MeV$ $\quad m_p := 938.272088 MeV$ $\quad m_n - m_p = 1.293 \cdot MeV$

$$n_n = g_n \cdot \left(\frac{m_n \cdot k \cdot T}{2\pi\hbar^2}\right)^{\frac{3}{2}} \cdot e^{\frac{-m_n \cdot c^2}{k_b \cdot T}} \qquad n_p = g_p \cdot \left(\frac{m_p \cdot k \cdot T}{2\pi\hbar^2}\right)^{\frac{3}{2}} \cdot e^{\frac{-m_p \cdot c^2}{k_b \cdot T}}$$

Since the statistical weights of protons and neutrons are equal, with $g_p = g_n = 2$, the neutron-to-proton ratio is then given by the equation:

$$Ratio_{n\_p}(T) := \left(\frac{m_n}{m_p}\right)^{\frac{3}{2}} \cdot e^{-(m_n - m_p) \cdot \frac{c_v^2}{k_b \cdot T \cdot K}}$$

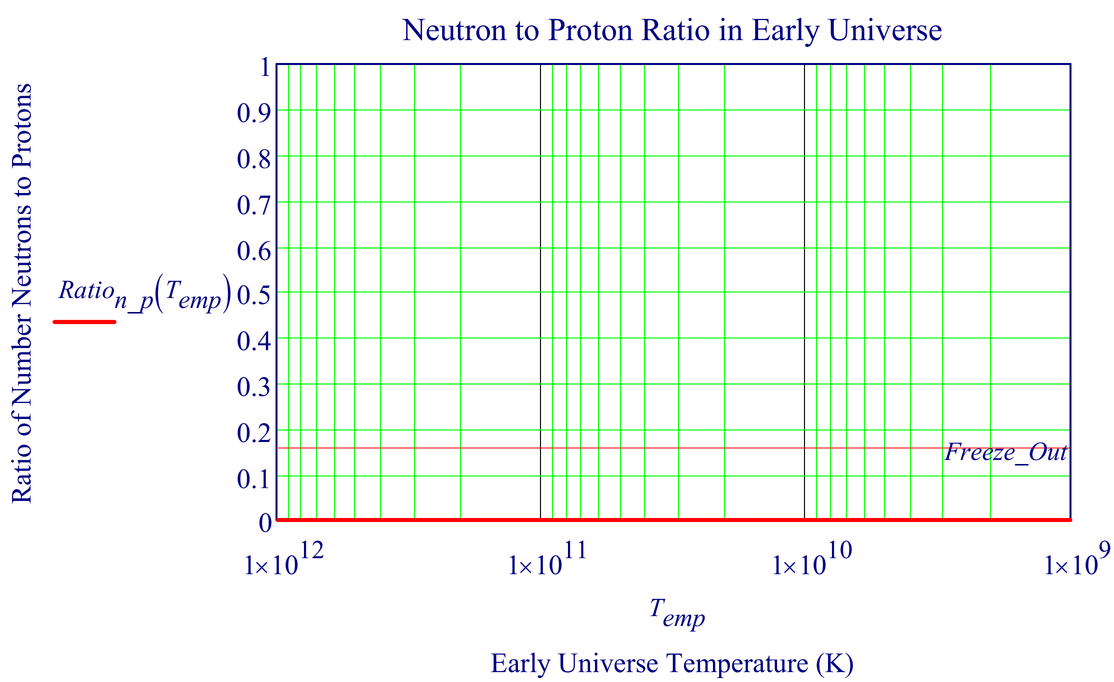
These reactions continued until the decreasing temperature and density caused the reactions to become too slow, which occurred at about T = 0.7 MeV (time around 1 second) and is called the freeze out temperature.

Freeze Out Temperature in Kelvin, K

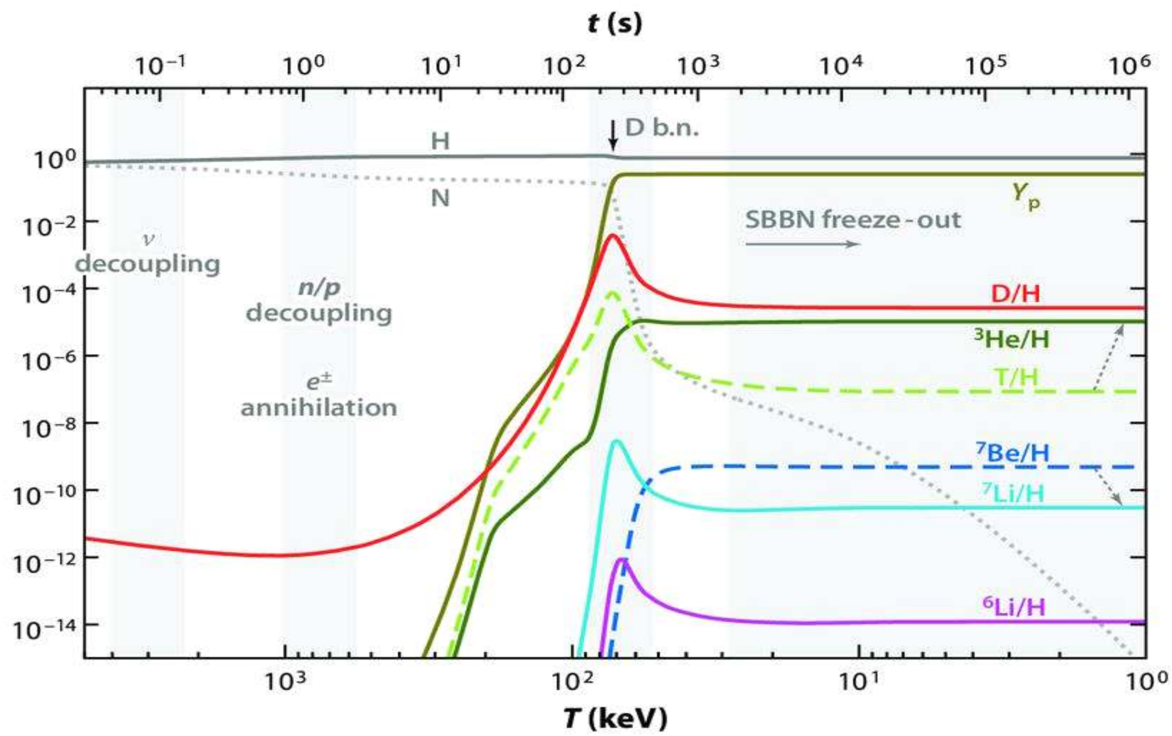
$$T_{Freeze\_Out} := \frac{0.7 \cdot MeV}{k_b \cdot K} = 2.865 \times 10^{68} s$$

Ratio of Neutrons to Protons in Early Universe

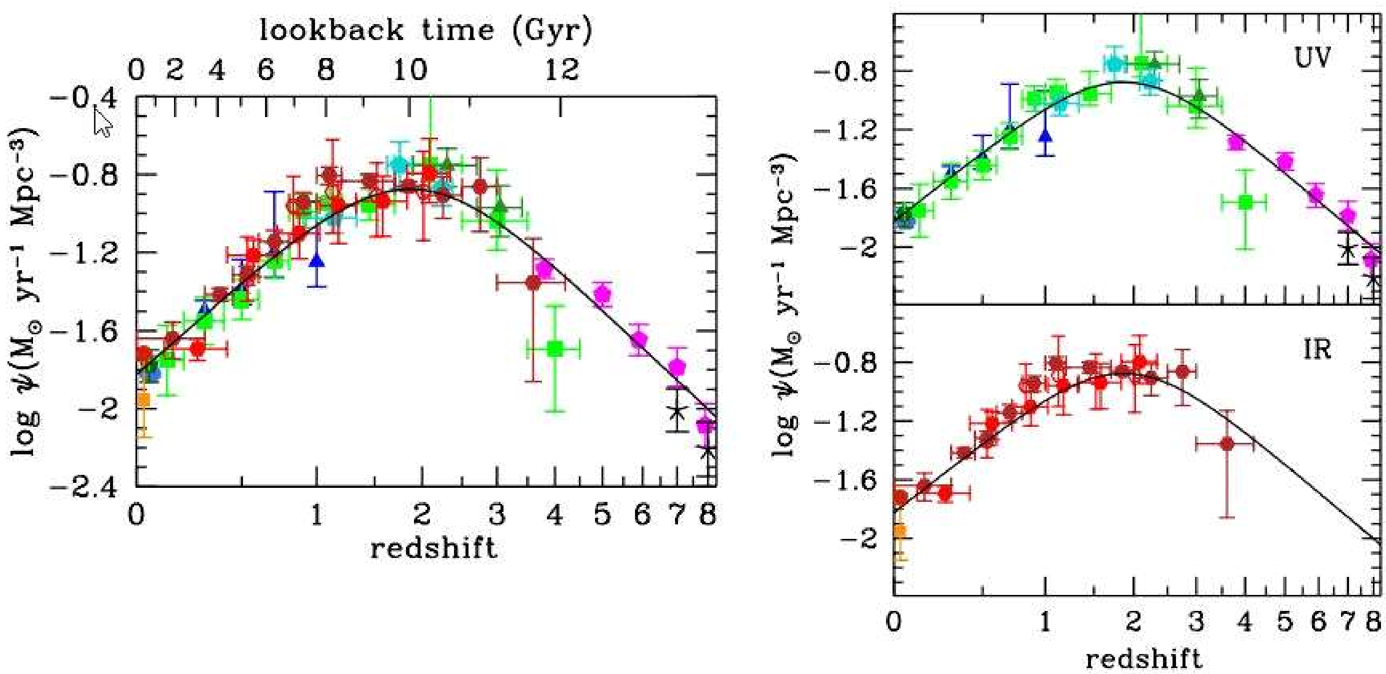
$$Freeze\_Out := Ratio_{n\_p}(T_{Freeze\_Out}) = 0.158$$



Abundance of the light elements over time



<u>This plot shows the abundance of the light elements over time, as the Universe expands and cools</u> during the various phases of Big Bang Nucleosynthesis. By the time the first stars form, the initial ratios of hydrogen, deuterium, helium-3, helium-4, and lithium-7 are all fixed by these early nuclear processes. *Credit:* M. Pospelov & J. Pradler, Annual Review of Nuclear and Particle Science, 2010



<u>The star-formation rate in the Universe is a function of redshift</u>, which is itself a function of cosmic time. The overall rate, (left) is derived from both ultraviolet and infrared observations, and is remarkably consistent across time and space. Note that star formation, today, is only a few percent of what it was at its peak (between 3-5%), and that the **majority of stars were formed in the first ~5 billion years** of our cosmic history. Only about ~15% of all stars, at maximum, have formed over the past 4.6 billion years, with the cumulative history of star-formation transforming about 1% of all atoms, by mass, into oxygen. *Credit*: P. Madau & M. Dickinson, 2014, ARAA