What did we learn ?

- Universe cools adiabatically during expansion
- $T(t) = 1.3E10\ K/t^{1/2}[s]$
- Particles are in thermodynamical equilibrium
- Annihilation for $kT << m\ c^2$
- Nucleons and Antiparticles annihilate at 1E12 K

=> overabundance of matter over anti-matter

needed by about 3E-8 (h^2 * omega)

- proton and neutrons are seeds for nucleosynthesis (t<200 sec)
- components with kT > binding energy are destroyed

Nucleosynthesis of the Big Bang

- Summary from last week
- Thermodynamical Equilibrium & FreezeOut
- Probing the Universe before Recombination

Source: Weinberg, 2008, in: Cosmology, Chap. 3.1 and 3.2, (and references therein)

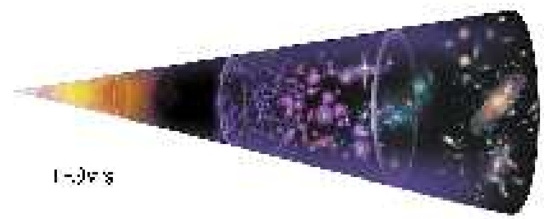
Particles at T(t)=1E12

Thermodynamical equilibrium -> chemical equilibrium

- protons, neutrons, photons and leptons
- weak interactions couple leptons and protons/neutron

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

•Summary: Thermal Evolution of the Universe



- $T \sim 10^{15}\ K$, $t \sim 10^{-[illegible]}$ sec: Primordial soup of fundamental [illegible]
- $T \sim 10^{13}\ K$, $t \sim 10^{-6}$ sec: Protons and neutrons form.
- $T \sim 10^{10}\ K$, $t \sim 3$ min: Nucleosynthesis: nuclei form.
- $T \sim 3000\ K$, $t \sim 300,000$ years: Atoms form.
- $T \sim 10\ K$, $t \sim 10^{[illegible]}$ years: Galaxies form.
- $T \sim 3\ K$, $t \sim 10^{10}$ years: Today.

Formation of Heavy Elements & NSE

Abundances in NSE (see earlier lesson)

$$X_i = \frac{g_i}{2} X_p^{Z_i} X_n^{A_i - Z_i} A_i^{3/2} \epsilon^{A_i - 1} e^{B_i/k_B T}$$

with $\epsilon \equiv \frac{1}{2} n_N h^3 (2\pi m_N k_B T)^{-3/2}$

$$= 2.96 \times 10^{-11} \left(\frac{a}{10^{-10} a_0}\right)^{-3} \left(\frac{T}{10^{10}\mathrm{K}}\right)^{-3/2} \Omega_B h^2$$

After freeze out

$$\epsilon = 1.46 \times 10^{-12} \left(\frac{T}{10^{10}\mathrm{K}}\right)^{+3/2} \Omega_B h^2 \quad => \quad T_i \simeq \frac{B_i}{k(A_i - 1)|\ln \epsilon|}$$

Evolution of the n/p Ratio

Rem: kT << m(neutron/proton)

$$\begin{aligned} E_e - E_\nu &= Q \quad \text{for } n + \nu \rightleftharpoons p + e^- \\ E_\nu - E_e &= Q \quad \text{for } n + e^+ \rightleftharpoons p + \overline{\nu} \\ E_\nu + E_e &= Q \quad \text{for } n \rightleftharpoons p + e^- + \overline{\nu} \end{aligned}$$

$$Q = m_n - m_p = 1.293 \text{ MeV} .$$

Formation Temperature of Elements

Element drops out of equilibrium
if the binding energy is larger than kT.

4He : 3.1E9 (almost all neutrons go into 4He)
2H : 0.75E9 K
3H : 1.4E9K
3He: 1.3E9K

Evolution of the Neutron Concentration

$$\frac{dX_n}{dt} = -\lambda(n \to p) X_n + \lambda(p \to n)(1 - X_n)$$

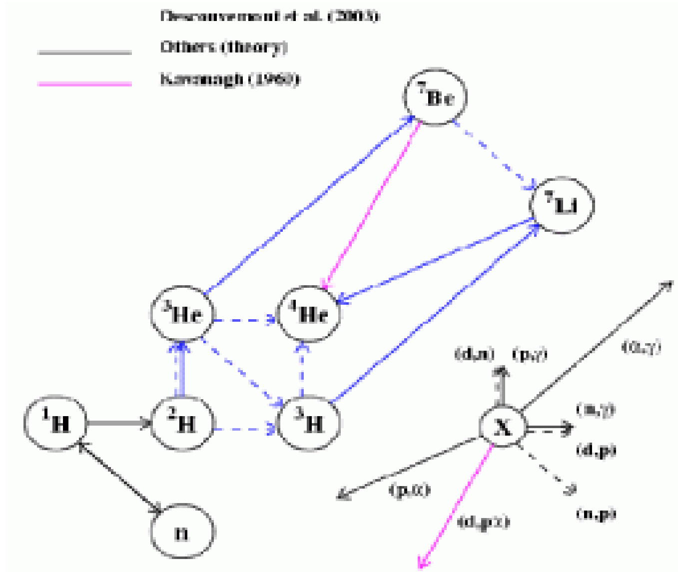
a) Start value for neutron concentration at T > 3E10 K statistical equilibrium:

$$\frac{X_n}{X_p} = \frac{X_n}{1 - X_n} = \exp\left(-Q/k_B T\right)$$

b) At about 7E9K (freeze out), electron-positron annihilation stops the equilibrium
=> Evolution is governed by neutron decay with a time scale of 886sec

$$X_n \to 0.1609 \exp\left(\frac{-t}{885.7 \text{ sec}}\right)$$

The BNN Network



Role of the Deuterium Bottleneck for BNN

Deuterium is d in equilibrium n+p <-> d + gamma

- low baryon to photon ratio (η=1E-9) and low binding energy

=> low concentration of d

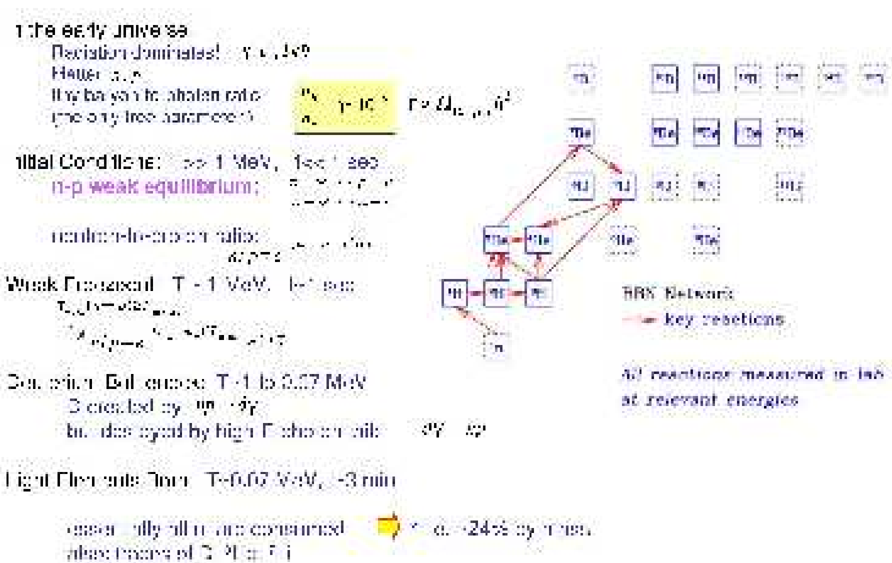
- allmost all neutrons go to 4He because high binding energy

- temperature too low for heavy elements when D forms

- Fast reactions from D to 7Li

- No stable isotopes with Z=5-8 => BNN stops at 7Li

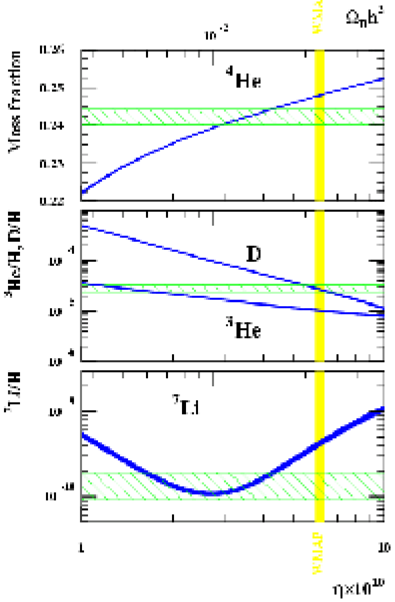
Summary of Big Bang Nucleosynthesis

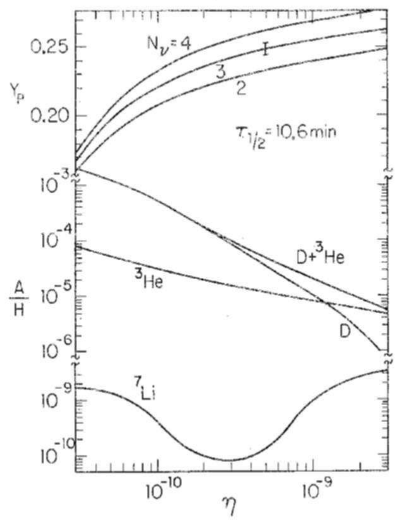


The BNN Network

$$d(p,\gamma)^3He \qquad d(n,\gamma)^3H$$
$$d(d,n)^3He \qquad d(d,p)^3H$$
$$^3He(d,p)^4He \qquad ^3H(d,n)^4He$$
$$^3He(^3He,2p)^4He \qquad ^4He(^3He,\gamma)^7Be$$
$$^4He(^3H,\gamma)^7Li \qquad ^7Be(e^-\nu)^7Li$$

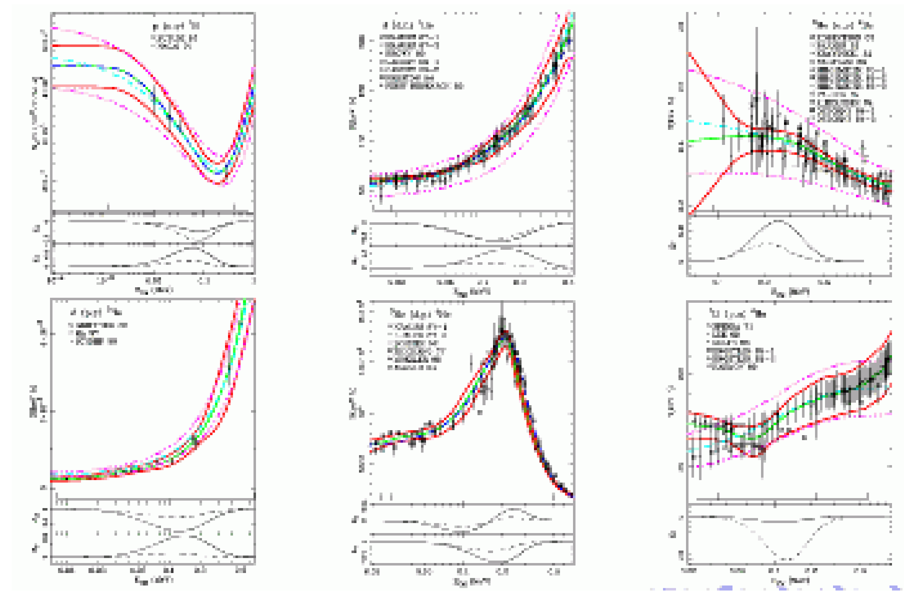
Abundances and Neutrino Flavors





Uncertainty: Neutron half life

Accuracy of the Nuclear Rates



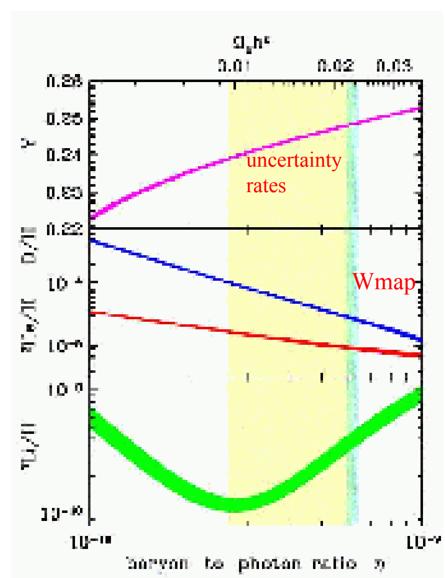
Big Open Questions for the Future: Baryon Asymmetry

Sakharov's Conditions (1967):

- baryon number violation (GUT)
- C and CP violation
- non-equilibrium conditions

Rem: parity violation in weak reactions
CP violation observed in neutral kaions
nec requires slow coupling compared
to expansion at early phase (T>1E12K)

Predictions of the BBN vs. WMap

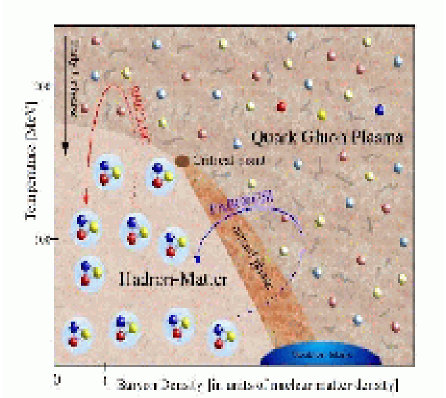


- close but slightly different photon to baryon ratio

Inhomogenous Big Bang ???

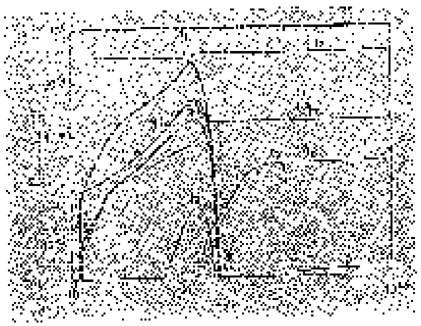
Idea: Make use of phase transition at 170MeV predicted by QCD when going from gluon-quark plasma to normal matter

Phase diagram (see Cern)



Possible Test:
Old neutron and proton rich stars

(Schramm et al. 1996)



protonrich

neutronrich