BIG BANG NUCLEOSYNTHESIS

Theoretical estimation of primordial abundances and comparison with current observations

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Outline

- Nuclear Statistical Equilibrium (NSE)

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- Initial Conditions

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- BBN step by step

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- BBN as a constraint for new physics
- Sumary

Nuclear Statistical Equilibrium (NSE)

Kinetic equilibrium among the light nuclear species:

$$n_A = g_A \left(\frac{m_A T}{2\pi} \right)^{3/2} \exp\left\{ \frac{\mu_A - m_A}{T} \right\} \tag{1}$$

Nucleus A is produced out of Z protons and (A-Z) neutrons, If $(A-Z)n + Zp \rightarrow A$ occurs rapidly compared to the expansion rate, chemical equilibrium is attained:

$$\mu_A = Z\mu_p + (A-Z)\mu_n$$

Regarding the definition of the binding energy :

$$B_A = m_A - (A-Z)m_n - Zm_p$$

$$n_A = g_A A^{3/2} 2^{-A} \left(\frac{2\pi}{m_N T} \right)^{3(A-1)/2} n_p^Z n_n^{A-Z} \exp\{B_A/T\} \qquad (2)$$

Some binding energies

^{Z}A	B_A [MeV]	g_A
^{2}H	2.22	3
^{3}H	6.92	2
^{3}He	7.72	2
^{4}He	28.3	1
^{12}C	92.2	1

Nucleon density:

$$n_N = n_n + n_p + \sum_i (A n_A)_i$$

Abundances

$$X_A = \frac{A n_A}{n_N} \qquad \sum_i X_i = 1$$

Using $\eta \equiv n_N/n_\gamma = 2.68 \cdot 10^{-8}(\Omega_B h^2)$ The abundance of specie A is:

$$X_A = g_A[\zeta(3)^{(A-1)}\pi^{(1-A)/2}2^{3(A-1)/2}]A^{5/2}(T/m_N)^{3(A-1)/2}$$
$$\times\, \eta^{(A-1)} X_p^Z X_n^{(A-Z)} \exp\{B_A/T\}$$

Initial Conditions ($T \gg 1$ MeV, $t \ll 1$ s)

At this stage the proton-neutron balance is maintained through:

Chemical equilibrium maintained for slow expansion!

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

$$n + \nu_e \leftrightarrow p + e^-$$

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

$$\mu_n + \mu_\nu = \mu_p + \mu_e$$

In thermal equilibrium:

$$n/p \equiv \frac{n_n}{n_p} = \frac{X_n}{X_p} = \exp\{-Q/T + (\mu_e - \mu_\nu)/T\}$$

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

How to estimate $(\mu_e - \mu_\nu)$?

$$\mu_e/T \sim (n_e/n_\gamma) = (n_p/n_\gamma) = \eta \sim 10^{-10}$$ Negligible!

$\uparrow$ Charge neutrality of the universe

What about μ_ν/T?

$$\mu_{\nu e}/T \sim (n_{\nu e}/n_\gamma)$$

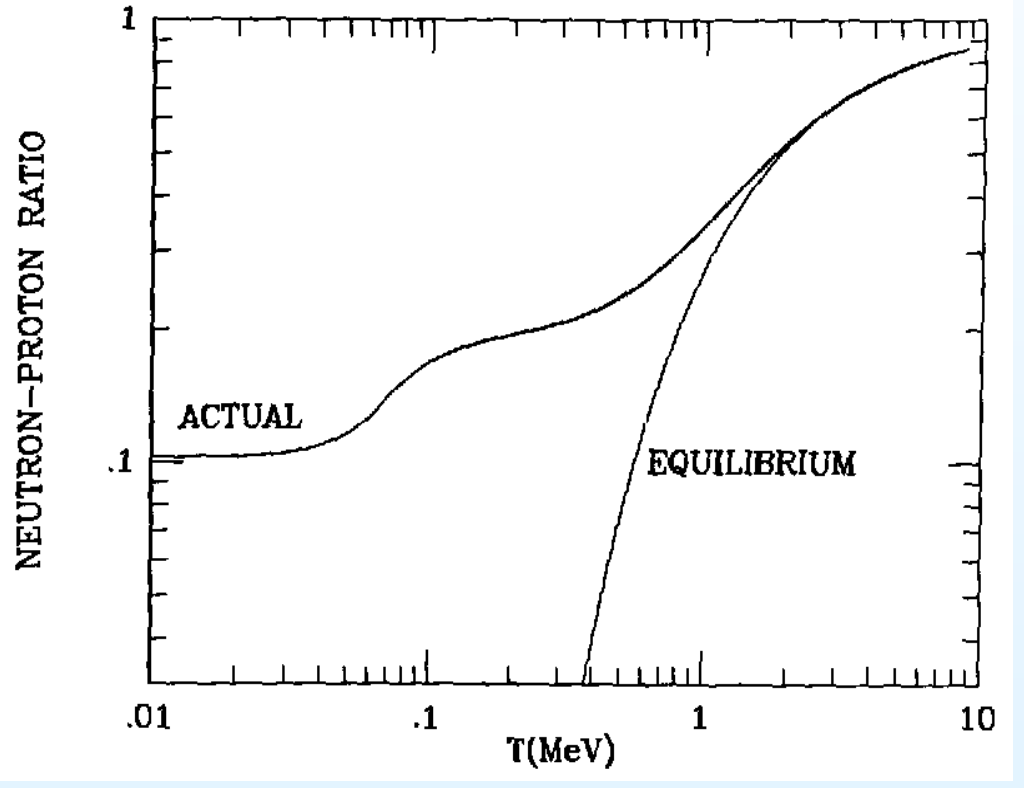
- Neutrino background have not yet been measured
- None of the neutrino lepton numbers is known
- Assume they are small $\Rightarrow |\mu_{\nu e}|/T \ll 1$
- This term might be of relevance in non standard BBN scenarios!

Under the last assumption:

$$\left(\frac{n}{p}\right)_{\text{EQ}} = \exp\{-Q/T\}$$

Kolb, Turner; The Early Universe:

n-p ratio as function of temperature.



Weak Rates and Neutrino freeze-out Temperature

$$\Gamma_{pe\to\nu n} = \int f_e(E_e)[1 - f_\nu(E_\nu)]|\mathcal{M}|^2\delta^4(p + e - n - \nu)$$
$$\times \frac{d^3p_e}{2E_e}\frac{d^3p_n}{2E_n}\frac{d^3p_\nu}{2E_\nu}$$

β decay matrix element:

$$|\mathcal{M}|^2 \propto G_F^2(1 + 3g_A^2); \qquad g_A \simeq 1.26$$

Related to the unweighted neutron decay rate:

$$\tau_n^{-1} = \Gamma_{n\to pe\nu} = \frac{G_F^2}{2\pi^3}(1 + 3g_A)m_e^5\lambda_0; \qquad \lambda_0 = 1.636$$

Using the above result:

$$\Gamma_{pe\to\nu n} = (\tau_n\lambda_0)^{-1}\int_q^\infty d\epsilon \frac{\epsilon(\epsilon-q)^2(\epsilon^2-1)^{1/2}}{[1+\exp\{\epsilon z\}][1+\exp\{(q-\epsilon)z_\nu\}]}$$

$$q = Q/m_e \qquad \epsilon = E_e/m_e \qquad z = m_e/T \qquad z_\nu = m_e/T_\nu$$

Identical procedures can be applied to obtain $\Gamma_{n\to pe\nu}$ (weighted), $\Gamma_{ne\to p\nu}$, $\Gamma_{n\nu\to pe}$, $\Gamma_{pe\nu\to n}$, $\Gamma_{p\nu\to ne}$ and $\Gamma_{pe\to n\nu}$.

Group them:

$$\Gamma_n = \Gamma_{n\to pe\nu} + \Gamma_{ne\to p\nu} + \Gamma_{n\nu\to pe} = (\tau_n\lambda_0)^{-1}\lambda_n$$

$$\Gamma_p = \Gamma_{pe\nu\to n} + \Gamma_{p\nu\to ne} + \Gamma_{pe\to n\nu} = (\tau_n\lambda_0)^{-1}\lambda_p$$

neutron and proton number densities determined by Boltzmann eqns.:

$$\dot{n}_n + 3Hn_n = (\tau_n \lambda_0)^{-1}[\lambda_p n_p - \lambda_n n_n]$$

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...computer code required...However, for $T \geq m_e \Rightarrow \Gamma_p \simeq G_F^2 T^5$.

$H = 1.66 g_*^{1/2} T^2 / m_p l$, $g_* = 10.75$:

$$\Gamma_p / H \sim (T/0.8 \text{ MeV})^3$$

Since $e^+ + e^- \leftrightarrow \nu + \bar{\nu}$ has a smaller cross section $T_F = 0.8$ MeV is the neutrino freeze-out temperature!

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- 0.8 MeV $< T <$ 1 MeV; n-p ratio equal to its equilibrium value
- What about other nuclear species at $T \sim$ 1 MeV?
  Nuclear reactions that build up the light nuclei are faster than the expansion rate $\Rightarrow$ NSE abundances should occur!

Playing with NSE abundances

The toys: neutrons, protons, D (**2**), ^{3}He (**3**), ^{4}He (**4**), ^{12}C (**12**)
(Some heavy nucleus).
The rules:

$$X_n = X_p \exp\{-Q/T\}$$

$$X_2 = 16.3(T/m_N)^{3/2}\eta \exp\{B_2/T\} X_p X_n$$

$$X_3 = 57.4(T/m_N)^{3}\eta^2 \exp\{B_3/T\} X_p^2 X_n$$

$$X_4 = 113(T/m_N)^{9/2}\eta^4 \exp\{B_4/T\} X_p^2 X_n^2$$

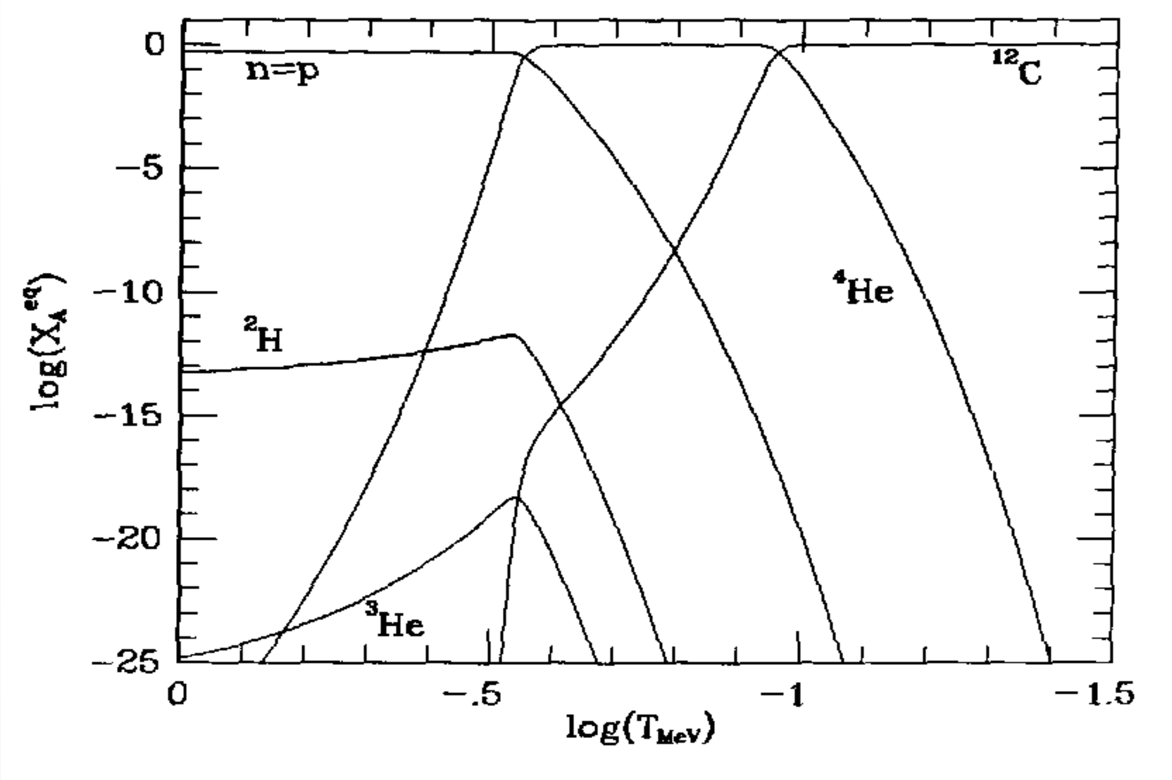
$$X_{12} = 3.22 \cdot 10^5 (T/m_N)^{33/2}\eta^{11} \exp\{B_{12}/T\} X_p^6 X_n^6$$

$$X_p + X_n + X_2 + X_3 + X_4 + X_{12} = 1$$

When a specie A is thermally favored?

Kolb, Turner; The Early Universe:

NSE abundances ($X_n = X_p$).



No significant fractions are produced before neutrino freeze out!

BBN Step by Step I ($t \simeq 10^{-2}$ s, $T \simeq$ 10 MeV)

- Radiation dominated universe:

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- Light elements are in NSE, but η so small $\Rightarrow$ small abundances

$$X_n = X_p \simeq 0.5 \qquad X_2 \simeq 6{\cdot}10^{-12} \qquad X_3 \simeq 2{\cdot}10^{-23} \qquad X_4 \simeq 2{\cdot}10^{-34}$$

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As T decreases (n/p) is reduced by neutron decays.
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- NSE abundances, but still very small!

$$X_n \simeq 1/7 \quad X_p \simeq 6/7 \quad X_2 \simeq 10^{-12} \quad X_3 \simeq 10^{-23} \quad X_4 \simeq 10^{-28}$$

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- At $T =$ 0.3 MeV, NSE abundance for ^{4}He gets of the order of 1. However, for $T \leq$ 0.5 MeV X_4 falls below its NSE value! Reactions leading to ^{4}He are not fast enough.

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  - T decreasing $\Rightarrow$ Significant Coulomb Barrier suppression!

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  - Rates proportional to $\eta \Rightarrow$ abundances should decrease with increasing η.

Standard BBN Predictions

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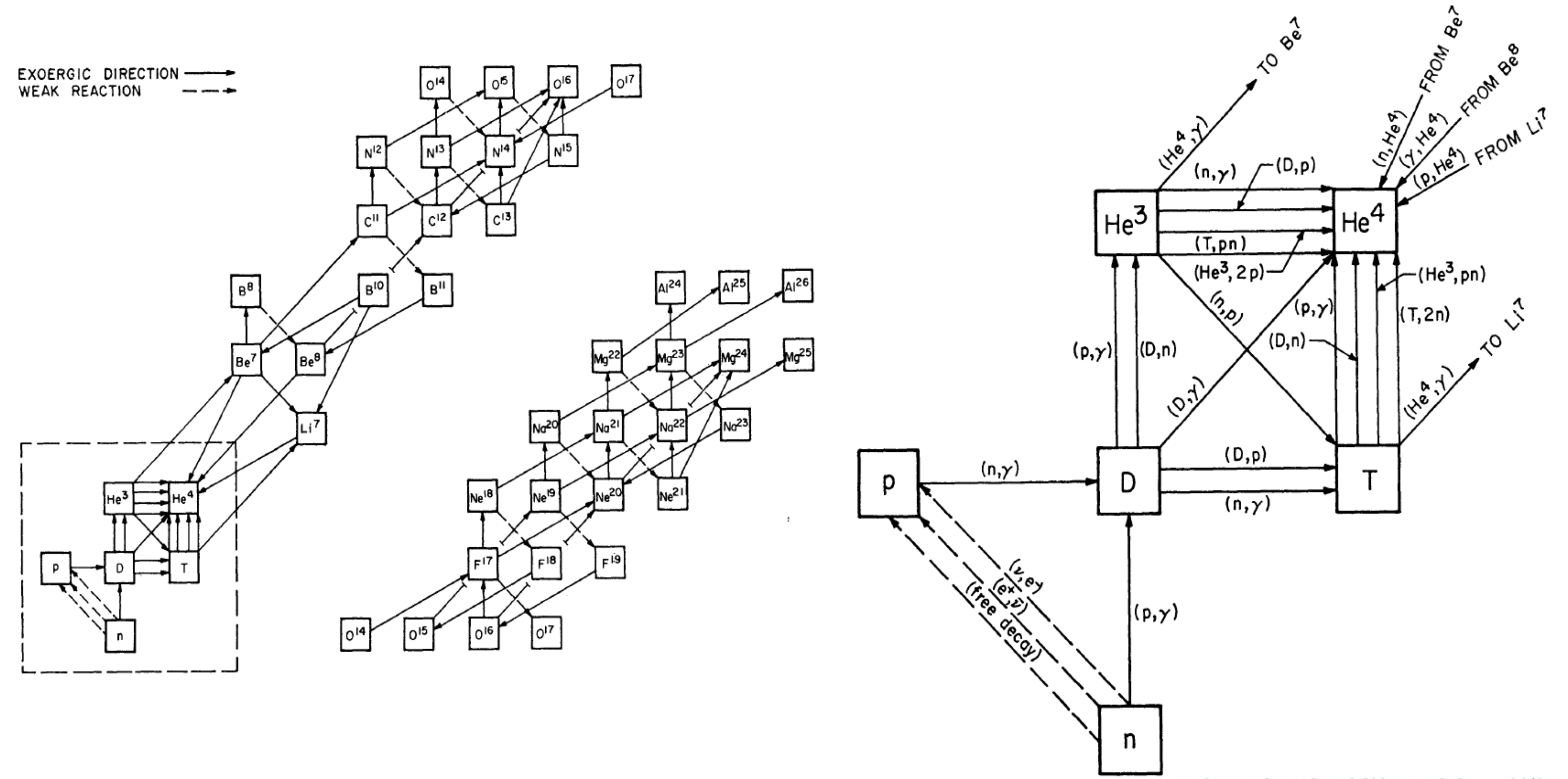
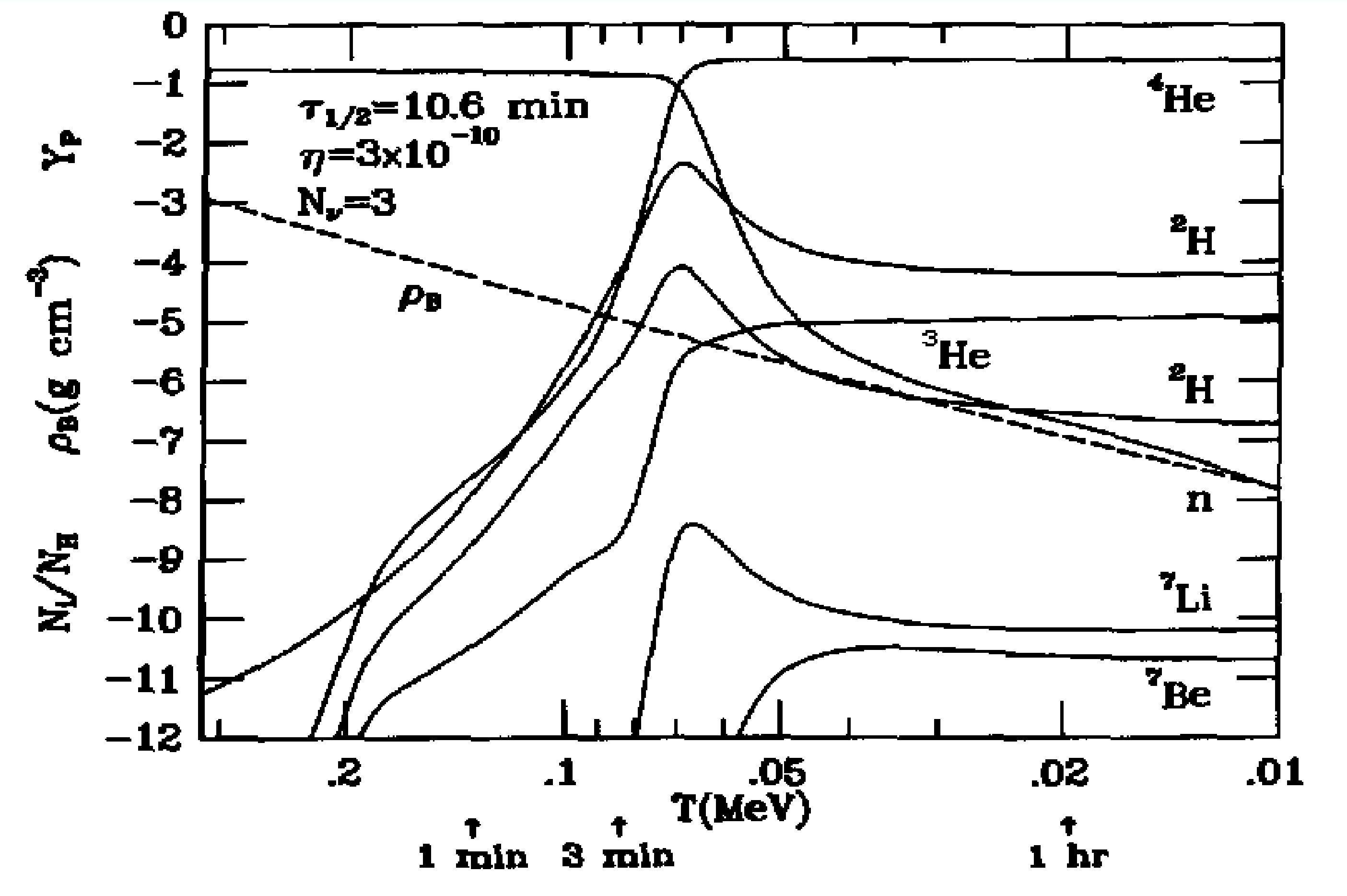
  - Include electromagnetic and weak rates, Universe dynamics and...a lot of nuclear reaction rates!.

Wagoner *et. al.*, Ap. J.,**148**, 3 (1967)



Kolb, Turner; The Early Universe: The development of BBN.



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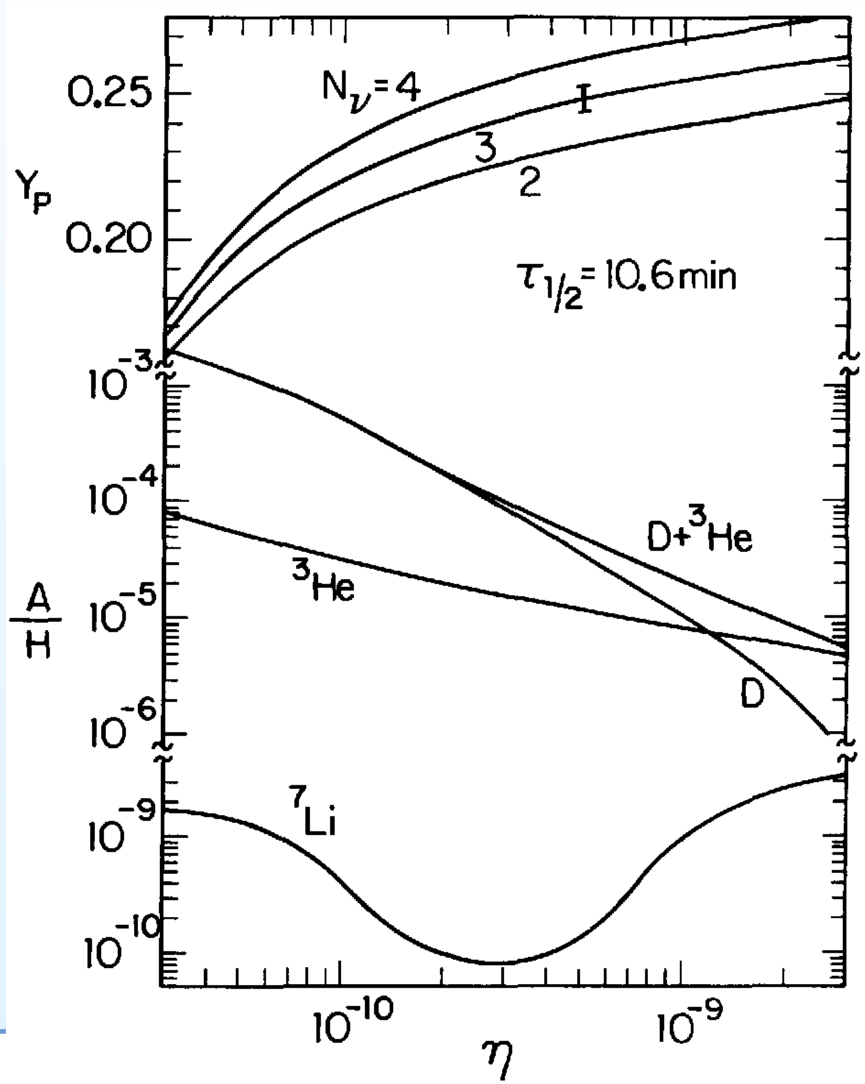
  - η determines the NSE abundances $\Rightarrow$ Plays a role in the thermally averged reaction rates.
  - $g_*(T_F)$ plays an important role in determination of the freeze out temperature.

Kolb, Turner; The Early Universe: BBN abundaces vs. η.



- $\tau_{1/2}$: $\Gamma \propto T^5/\tau_{1/2} \Rightarrow T_F \propto \tau_{1/2}^{1/3}$
- g_*: $H \propto g_*^{1/2} T^2 \Rightarrow T_F \propto g_*^{1/6}$
- η: $X_A \propto \eta^{(A-1)}$

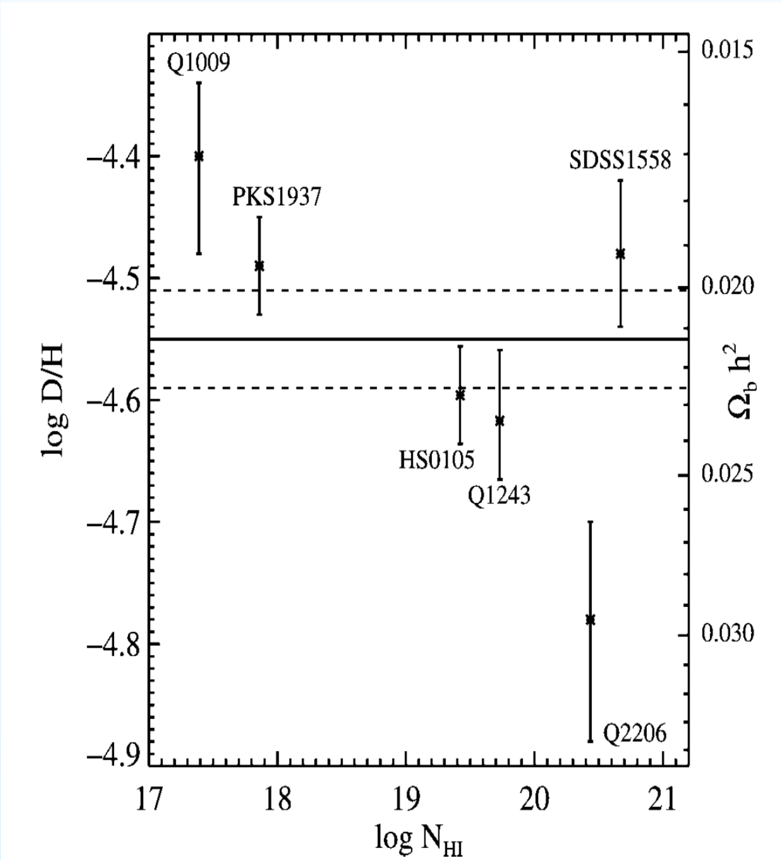
Primordial Abundance Observations

...Stars do not help

- Deuterium

J.M. O’Meara *et al*., Astrophys. J. Lett. **649**, L61 (2006).

The best measurements of $(D/H)_P$.



- Deuterium is not efficiently produced in stellar processes.
- Any abundance measurement imposes a lower bound on $(D/H)_P \Rightarrow$ upper bound on η
- D presence is revealed by high-resolution spectra of high-red shift low-metalicity absorption quasars.
- Astration may have reduced galactic ISM by a factor of 1.12 ± 0.13.
- Average of the six most accurate abundances in quasar systems:

$$(D/H)_P = (2.82 \pm 0.12[1\sigma]\{0.21[3\sigma]\}) \cdot 10^{-5}$$

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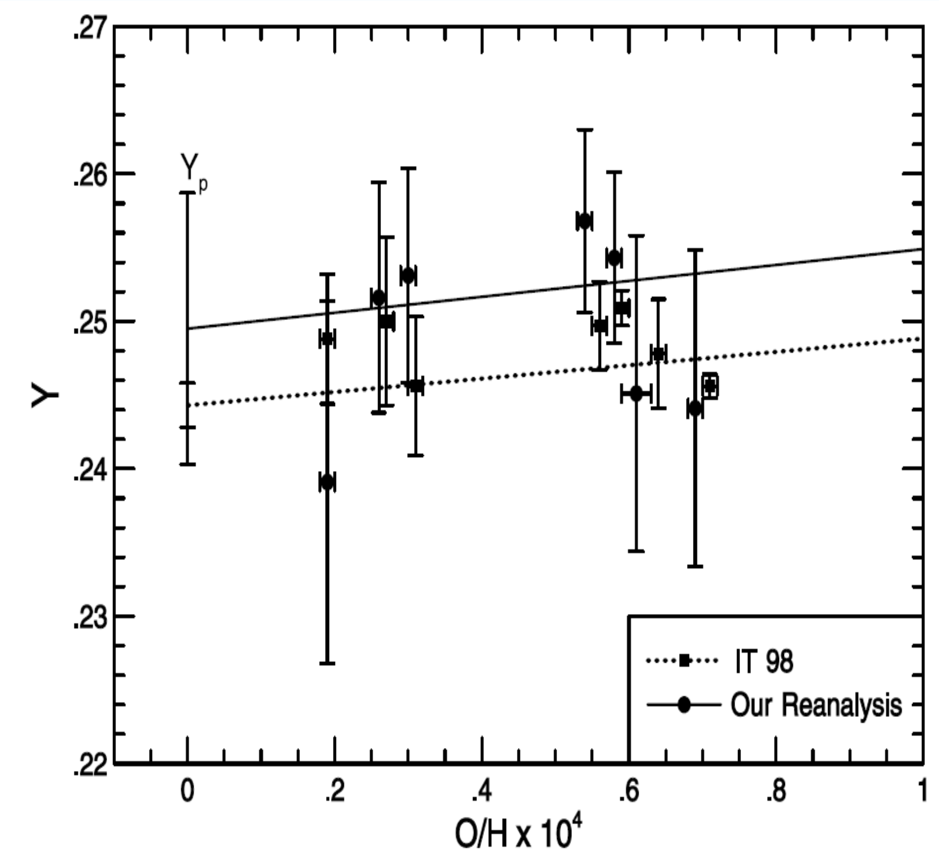
$$\left(\frac{\mathrm{D} +^3 \mathrm{He}}{\mathrm{H}}\right)_{\mathrm{P}} \leq 8 \cdot 10^{-5} \quad \Rightarrow \quad \eta \geq 4 \cdot 10^{-10}$$

- ^{4}He

K.A. Olive & E. Skillman, Astrophys. J. **617**, 29 (2004).
Helium abundance vs. Metalicity.



- Measurement of recombination lines in HII galactic and extragalactic regions.
- Correlation between metalicity and ^{4}He abundance.
- Extrapolate to zero metalicity:

$$Y_{\mathrm{P}} = 0.249 \pm 0.009$$

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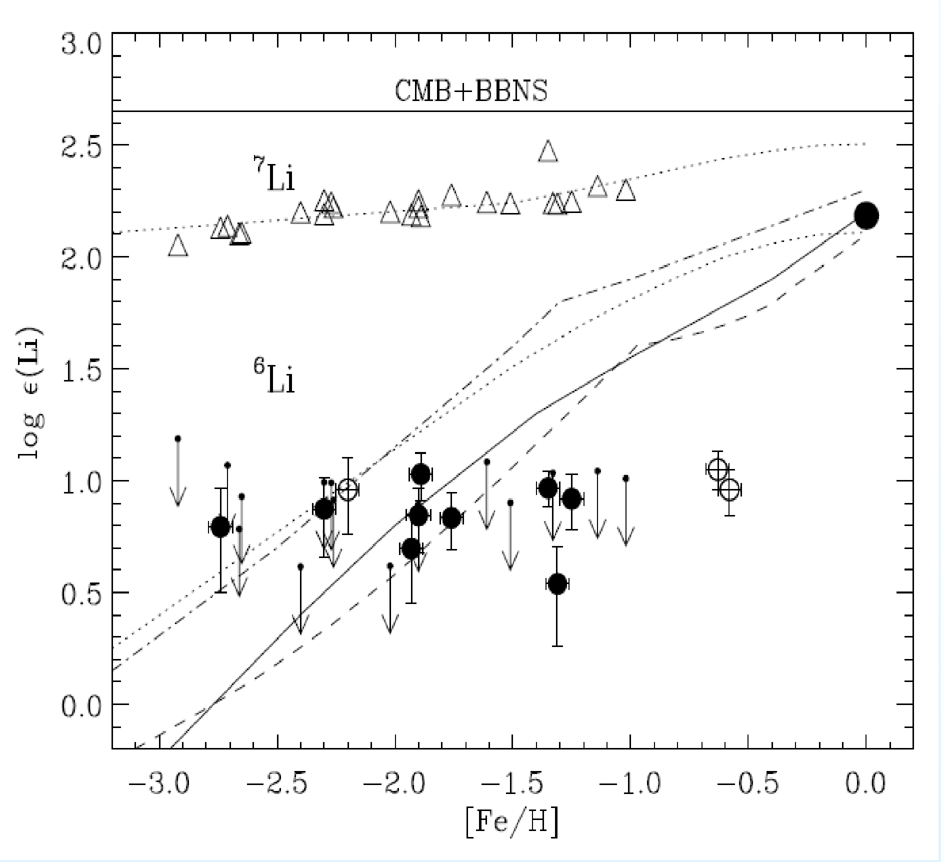
- Evidence for primordial ^{6}Li?

M. Asplund *et al*., Astrophys. J. **644**, 229 (2006).

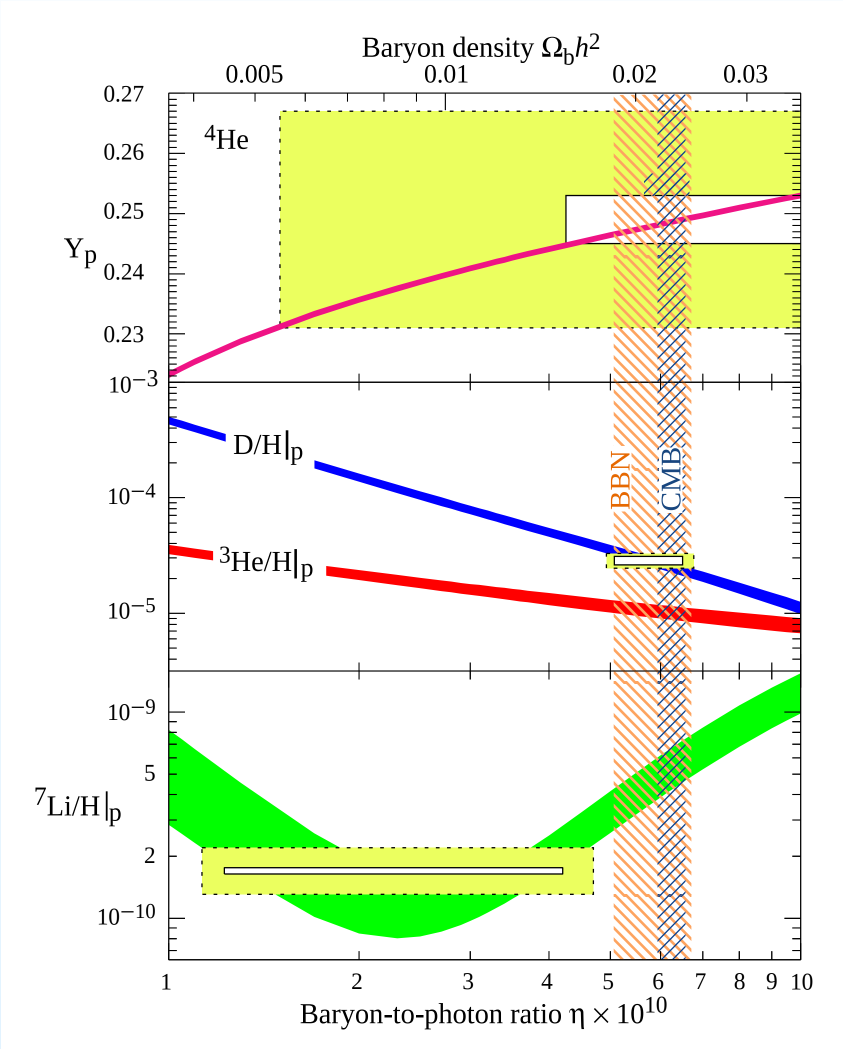
Spite plateau for lithium isotopes.



- Current spectral resolution permits to determine the isotopic fraction in Pop II stars:

$$\frac{^6\text{Li}}{^7\text{Li}} \leq 0.15$$

- Spite plateau is also observed for ^{6}Li.
- Can be generated by convection processes.
- The plateau is interpreted as an upper bound for primordial ^{6}Li.



Amsler *et al.* (PDG), Phys. Lett. **B667**, 1 (2008).

Theory and Observation altogether

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- Set bound on the mass of NR particles decaying during BBN. If they decay to SM particles, light nuclei can be affected.

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- Extra dimensions can set modifications for the expansion rate in the early universe.

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- Consistency between current measurements and SBBN necessarily forces one (maybe two) Lithium problem.
- $(H/D)_P$ agreement with CMB values for the baryon density.
- Extensions of SM have to explain ^{7}Li (^{6}Li) primordial abundance and predict abundances for ^{4}He and D in agreement with SBBN.

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