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# Big Bang Nucleosynthesis

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- Big Bang Nucleosynthesis

BBN predicts the abundances of the light elements at the end of the first three minutes, in good agreement with observations.

BBN offers the deepest reliable probe of the early Universe, based on the well-understood Standard Model of physics.

BBN gives strong constraints on the deviations from the standard cosmology, and on new physics beyond Standard Model.

# PERIODIC TABLE OF THE ELEMENTS

http://www.ktf-split.hr/periodni/en/

GROUP

RELATIVE ATOMIC MASS (1)
GROUP IUPAC — 13
GROUP CAS — IIIA
ATOMIC NUMBER — 5
SYMBOL — B
ELEMENT NAME — BORON
(10.811)

- Metal
- Semimetal
- Nonmetal
- 1 Alkali metal
- 2 Alkaline earth metal
- Transition metals
- Lanthanide
- Actinide
- 16 Chalcogens element
- 17 Halogens element
- 18 Noble gas

STANDARD STATE (25 °C; 101 kPa)
Ne - gas  Fe - solid
Ga - liquid  Tc - synthetic

| PERIOD | 1 IA | 2 IIA | 3 IIIB | 4 IVB | 5 VB | 6 VIB | 7 VIIB | 8 VIIIB | 9 | 10 | 11 IB | 12 IIB | 13 IIIA | 14 IVA | 15 VA | 16 VIA | 17 VIIA | 18 VIIIA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 1.0079 H HYDROGEN | | | | | | | | | | | | | | | | | 2 4.0026 He HELIUM |
| 2 | 3 6.941 Li LITHIUM | 4 9.0122 Be BERYLLIUM | | | | | | | | | | | 5 10.811 B BORON | 6 12.011 C CARBON | 7 14.007 N NITROGEN | 8 15.999 O OXYGEN | 9 18.998 F FLUORINE | 10 20.180 Ne NEON |
| 3 | 11 22.990 Na SODIUM | 12 24.305 Mg MAGNESIUM | | | | | | | | | | | 13 26.982 Al ALUMINIUM | 14 28.086 Si SILICON | 15 30.974 P PHOSPHORUS | 16 32.065 S SULPHUR | 17 35.453 Cl CHLORINE | 18 39.948 Ar ARGON |
| 4 | 19 39.098 K POTASSIUM | 20 40.078 Ca CALCIUM | 21 44.956 Sc SCANDIUM | 22 47.867 Ti TITANIUM | 23 50.942 V VANADIUM | 24 51.996 Cr CHROMIUM | 25 54.938 Mn MANGANESE | 26 55.845 Fe IRON | 27 58.933 Co COBALT | 28 58.693 Ni NICKEL | 29 63.546 Cu COPPER | 30 65.39 Zn ZINC | 31 69.723 Ga GALLIUM | 32 72.64 Ge GERMANIUM | 33 74.922 As ARSENIC | 34 78.96 Se SELENIUM | 35 79.904 Br BROMINE | 36 83.80 Kr KRYPTON |
| 5 | 37 85.468 Rb RUBIDIUM | 38 87.62 Sr STRONTIUM | 39 88.906 Y YTTRIUM | 40 91.224 Zr ZIRCONIUM | 41 92.906 Nb NIOBIUM | 42 95.94 Mo MOLYBDENUM | 43 (98) Tc TECHNETIUM | 44 101.07 Ru RUTHENIUM | 45 102.91 Rh RHODIUM | 46 106.42 Pd PALLADIUM | 47 107.87 Ag SILVER | 48 112.41 Cd CADMIUM | 49 114.82 In INDIUM | 50 118.71 Sn TIN | 51 121.76 Sb ANTIMONY | 52 127.60 Te TELLURIUM | 53 126.90 I IODINE | 54 131.29 Xe XENON |
| 6 | 55 132.91 Cs CAESIUM | 56 137.33 Ba BARIUM | 57-71 La-Lu Lanthanide | 72 178.49 Hf HAFNIUM | 73 180.95 Ta TANTALUM | 74 183.84 W TUNGSTEN | 75 186.21 Re RHENIUM | 76 190.23 Os OSMIUM | 77 192.22 Ir IRIDIUM | 78 195.08 Pt PLATINUM | 79 196.97 Au GOLD | 80 200.59 Hg MERCURY | 81 204.38 Tl THALLIUM | 82 207.2 Pb LEAD | 83 208.98 Bi BISMUTH | 84 (209) Po POLONIUM | 85 (210) At ASTATINE | 86 (222) Rn RADON |
| 7 | 87 (223) Fr FRANCIUM | 88 (226) Ra RADIUM | 89-103 Ac-Lr Actinide | 104 (261) Rf RUTHERFORDIUM | 105 (262) Db DUBNIUM | 106 (266) Sg SEABORGIUM | 107 (264) Bh BOHRIUM | 108 (277) Hs HASSIUM | 109 (268) Mt MEITNERIUM | 110 (281) Uun UNUNNILIUM | 111 (272) Uuu UNUNUNIUM | 112 (285) Uub UNUNBIUM | | 114 (289) Uuq UNUNQUADIUM | | | | |

LANTHANIDE

| 57 138.91 La LANTHANUM | 58 140.12 Ce CERIUM | 59 140.91 Pr PRASEODYMIUM | 60 144.24 Nd NEODYMIUM | 61 (145) Pm PROMETHIUM | 62 150.36 Sm SAMARIUM | 63 151.96 Eu EUROPIUM | 64 157.25 Gd GADOLINIUM | 65 158.93 Tb TERBIUM | 66 162.50 Dy DYSPROSIUM | 67 164.93 Ho HOLMIUM | 68 167.26 Er ERBIUM | 69 168.93 Tm THULIUM | 70 173.04 Yb YTTERBIUM | 71 174.97 Lu LUTETIUM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

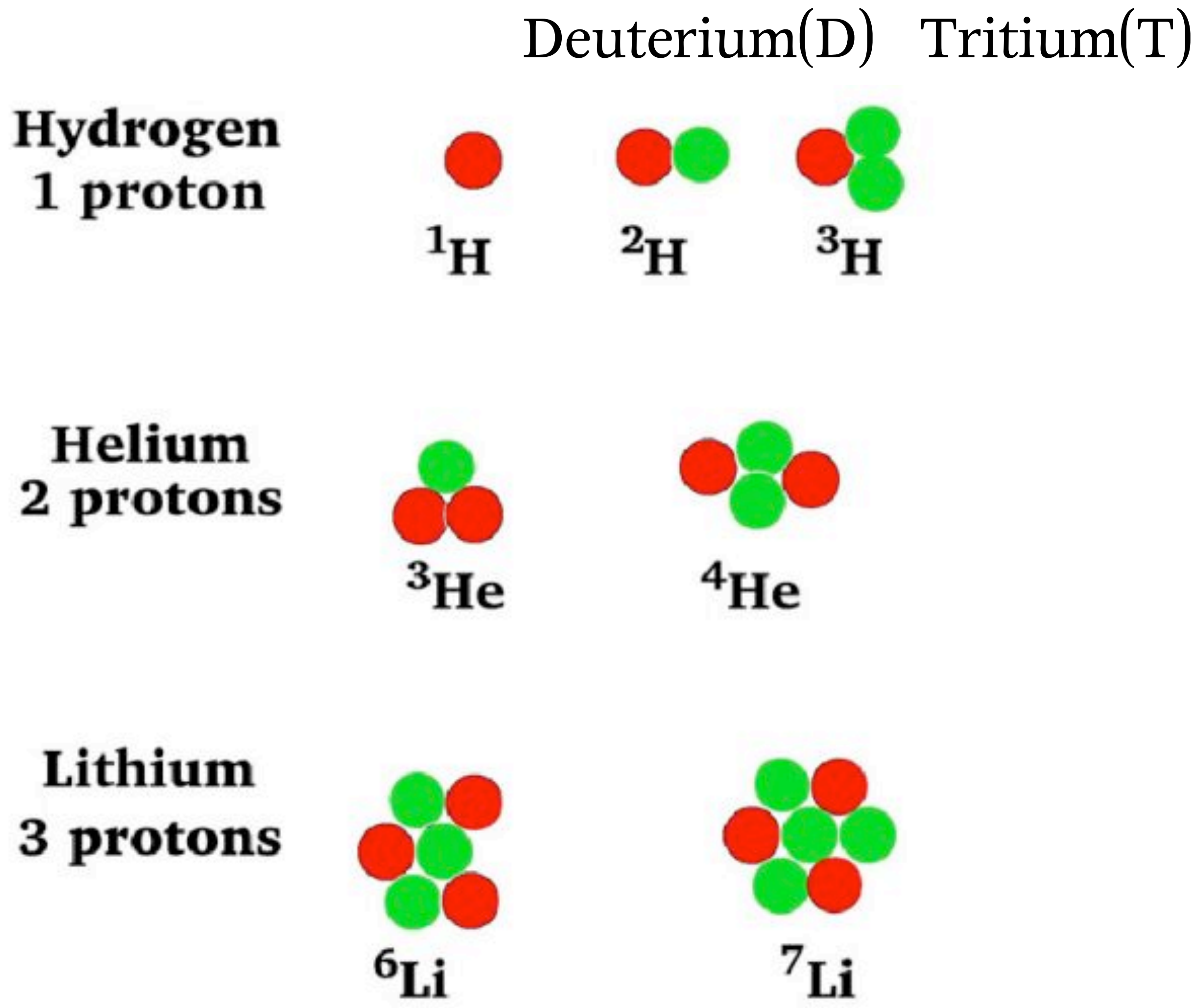
ACTINIDE

| 89 (227) Ac ACTINIUM | 90 232.04 Th THORIUM | 91 231.04 Pa PROTACTINIUM | 92 238.03 U URANIUM | 93 (237) Np NEPTUNIUM | 94 (244) Pu PLUTONIUM | 95 (243) Am AMERICIUM | 96 (247) Cm CURIUM | 97 (247) Bk BERKELIUM | 98 (251) Cf CALIFORNIUM | 99 (252) Es EINSTEINIUM | 100 (257) Fm FERMIUM | 101 (258) Md MENDELEVIUM | 102 (259) No NOBELIUM | 103 (262) Lr LAWRENCIUM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

(1) Pure Appl. Chem., 73, No. 4, 667-683 (2001)
Relative atomic mass is shown with five significant figures. For elements have no stable nuclides, the value enclosed in brackets indicates the mass number of the longest-lived isotope of the element.
However three such elements (Th, Pa, and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated.

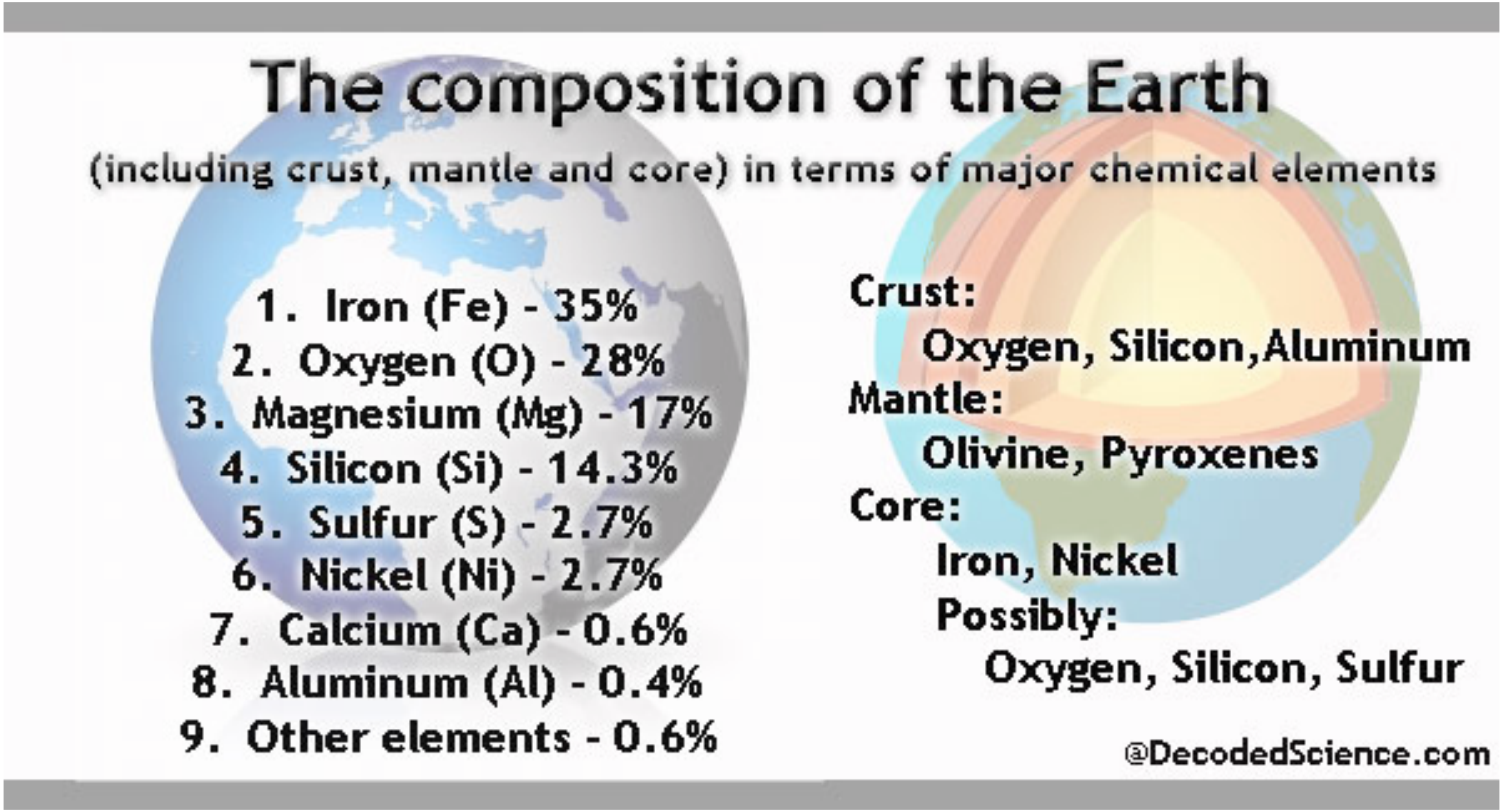
Editor: Aditya Vardhan (adivar@netllinx.com)

- Isotopes (stable)



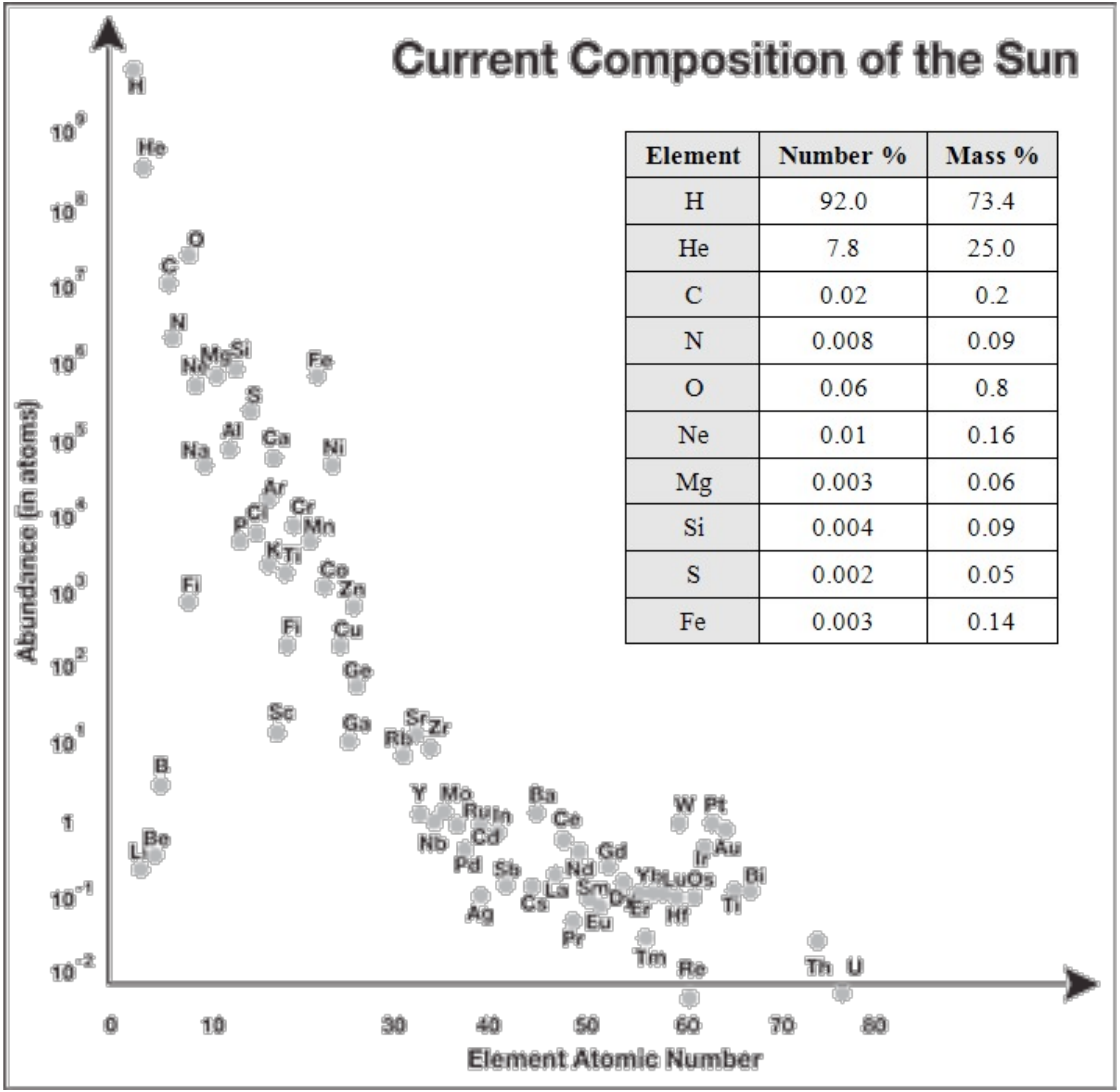

Lifetime of free neutron is around 880 seconds but it is stable in the bound state.

- Composition of Earth




Olivine: 감람석
$(Mg,Fe)2SiO4$

Pyroxenes: 휘석
$(Ca,Mg,Fe)_2(Si,Al)_2O_6$




| Element | Number % | Mass % |
|---|---|---|
| H | 92.0 | 73.4 |
| He | 7.8 | 25.0 |
| C | 0.02 | 0.2 |
| N | 0.008 | 0.09 |
| O | 0.06 | 0.8 |
| Ne | 0.01 | 0.16 |
| Mg | 0.003 | 0.06 |
| Si | 0.004 | 0.09 |
| S | 0.002 | 0.05 |
| Fe | 0.003 | 0.14 |

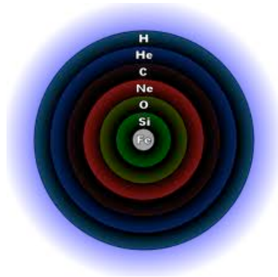
- The Universe and the formation of the elements

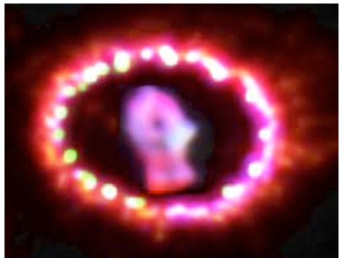
Big Bang

H, He

Stellar fusion

He - Fe

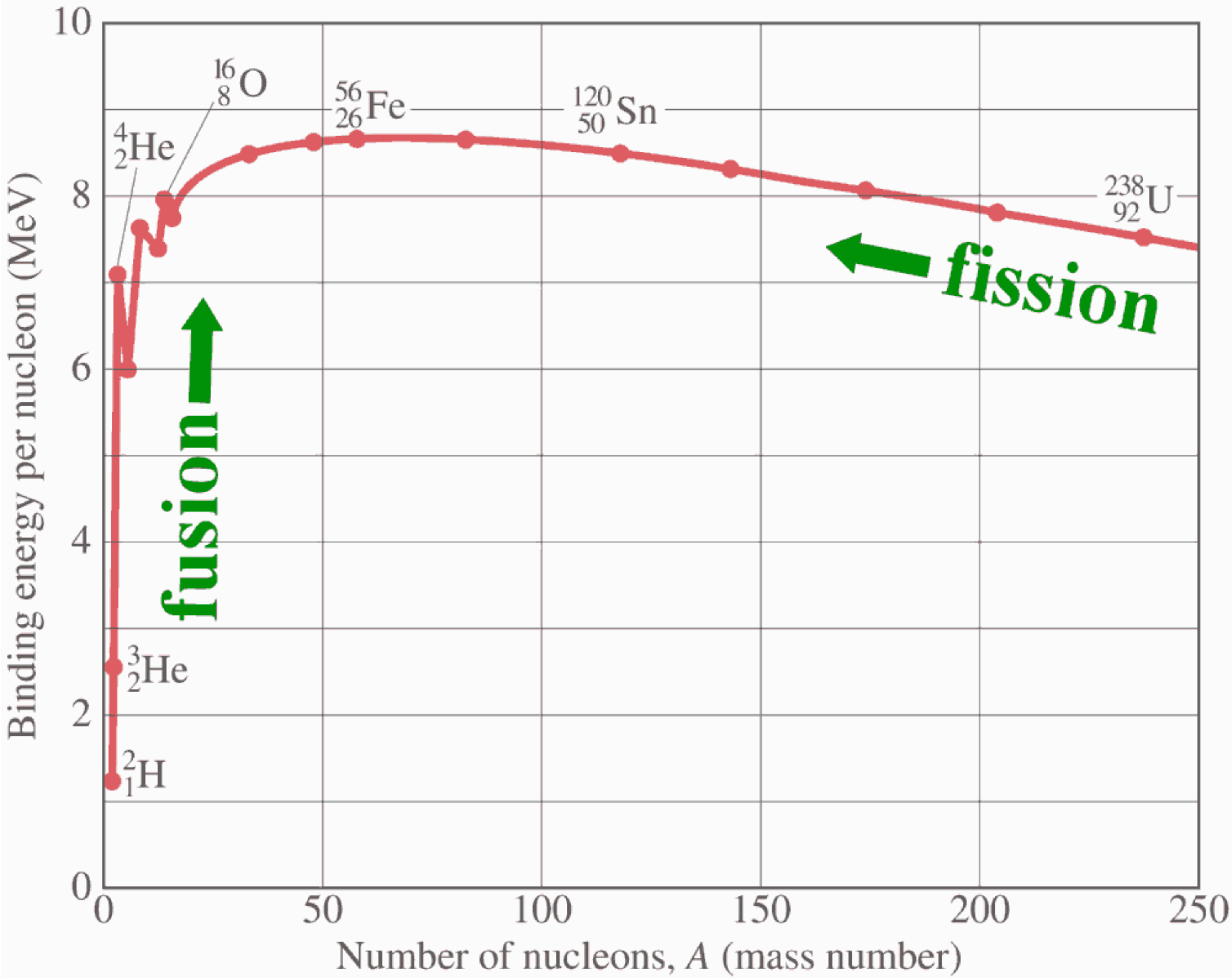


Heavier than Fe

Supernova

The present abundances observed are altered in the astrophysical processes with increase of metals such as C, N, O and Fe.



Binding energy per nucleon (MeV)
10
8
6
4
2
0
$^{16}_{8}$O
$^{56}_{26}$Fe
$^{120}_{50}$Sn
$^{4}_{2}$He
$^{238}_{92}$U
fission
fusion
$^{3}_{2}$He
$^{2}_{1}$H
0
50
100
150
200
250
Number of nucleons, A (mass number)

- Primordial light element abundances

Examine the high-redshift, low-metallicity spectrums.

## Deuterium

No known production mechanism in the astrophysical sources, and the abundance only decreases. The observed value gives lower limit on the primordial value, thus upper limit on $\eta$ .

Averaging the seven most precise observations of deuterium in quasar absorption systems gives

$$\boxed{\mathrm{D/H}_p = (2.82 \pm 0.21) \times 10^{-5}}$$

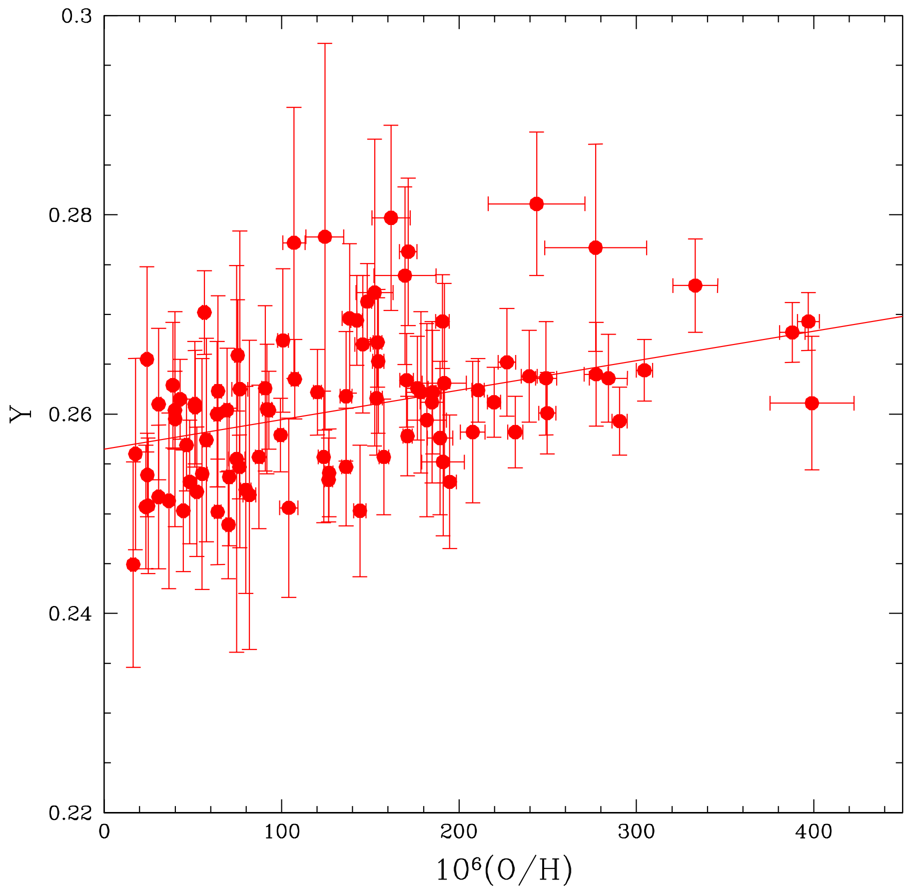
[Pettini etal, 2008]

## Helium 3

The only data from the Solar system and high-metallicity H II regions in our Galaxy. So difficult to know the primordial He3 value.

# Helium 4

Observing the spectral line in metal poor extragalactic H II region (clouds of ionized hydrogen).




[Steigman, 1208.0032]

$$\boxed{Y_P = 0.2565 \pm 0.0060.}$$

[Steigman, 1208.0032]

$$\boxed{Y_p = 0.249 \pm 0.009.}$$

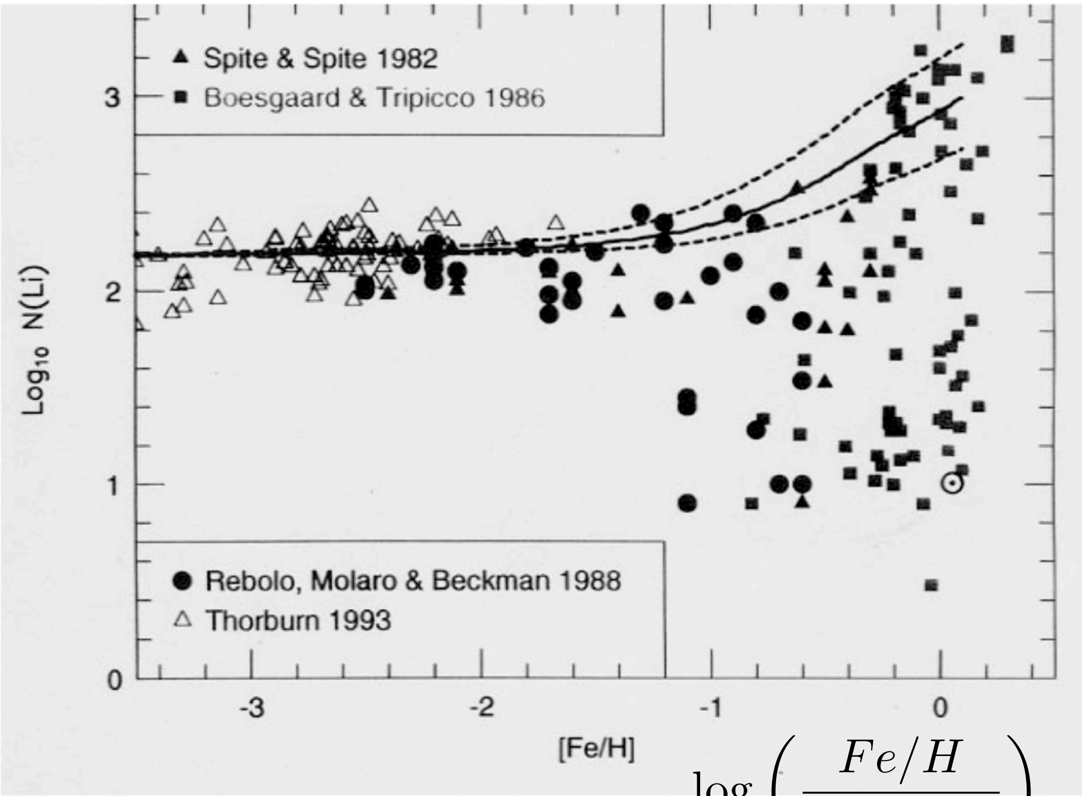
[Olive, Skillman, 2004]

## Lithium

From metal-poor stars (Pop II) of our Galaxy less than $10^{-4}$ of Solar value. It shows ‘Spite plateau’ .

$$\boxed{\mathrm{Li/H}|_\mathrm{p} = (1.7 \pm 0.06 \pm 0.44) \times 10^{-10}.}$$

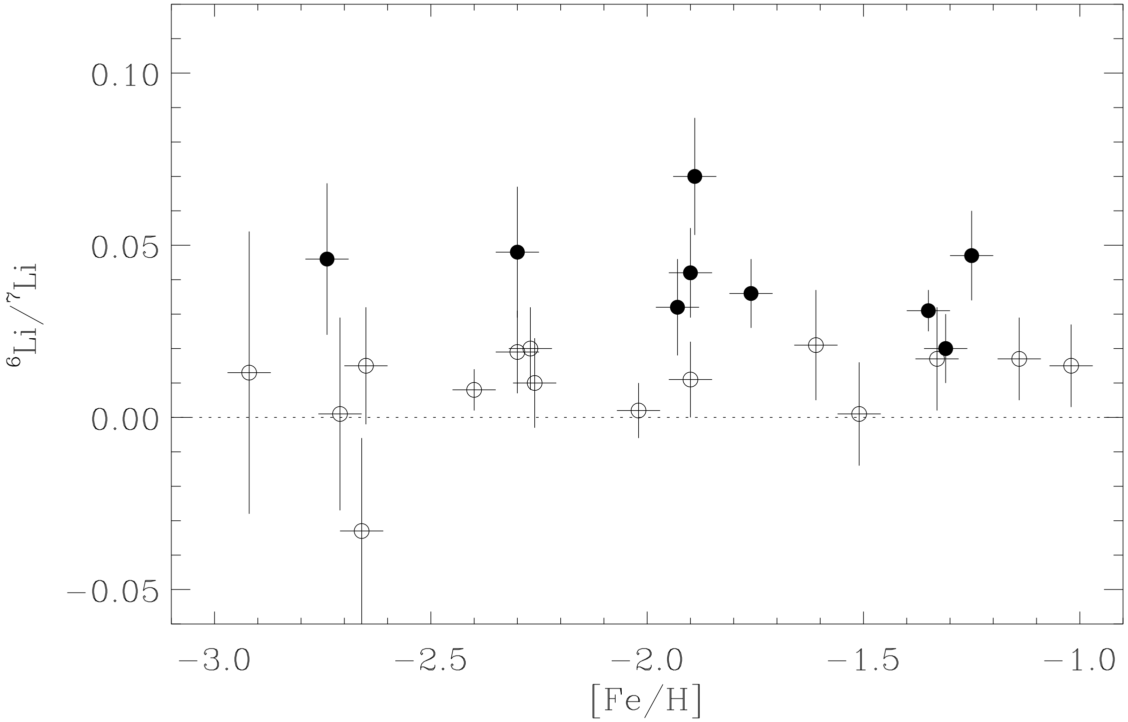
[Fields, Sarkar, PDG 2012]




$$\log\left(\frac{Fe/H}{(Fe/H)_\odot}\right)$$

## Lithium 6

The recent high precision measurements shows probable Li6 plateau.




$$\boxed{Li6/Li7 = 0.046 \pm 0.022}$$

[Asplund, 2006]

However caution must be exercised since convective motion in the stars may generates similar results. [Fields, Sarkar, PDG 2012]

# Big Bang Nucleosynthesis

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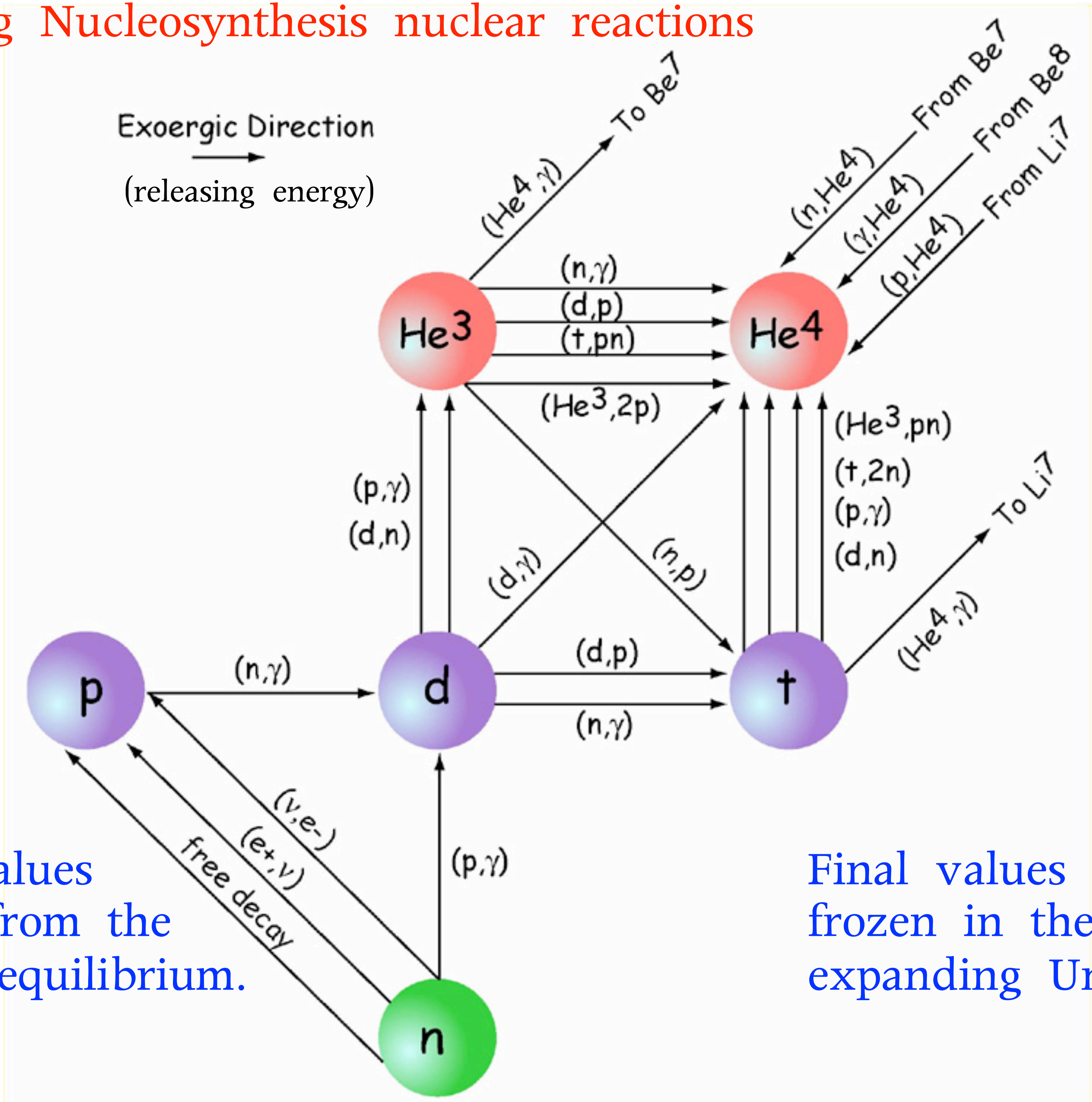
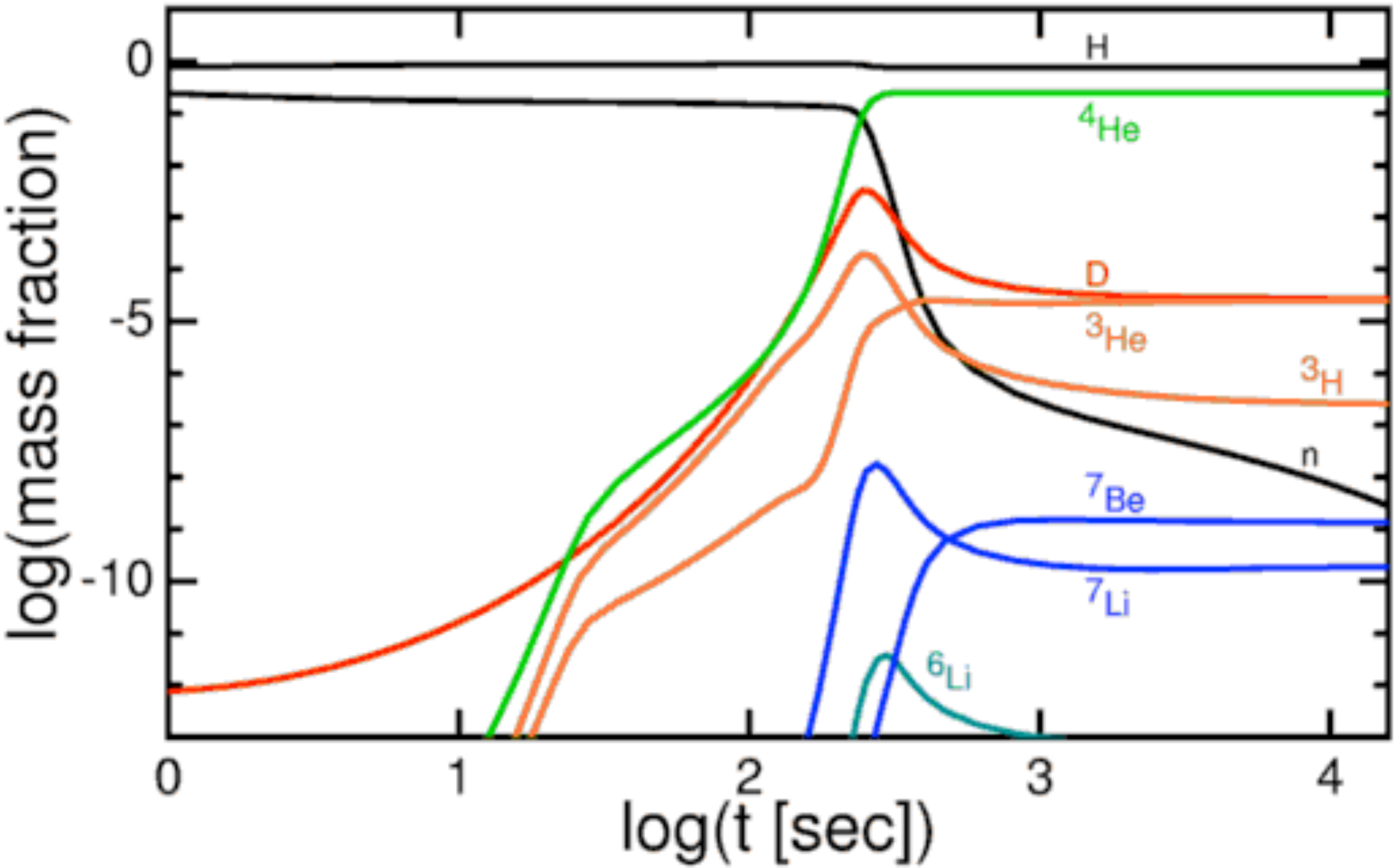
# Big Bang Nucleosynthesis nuclear reactions




Initial values are set from the thermal equilibrium.

Final values are frozen in the expanding Universe.

# Big Bang Nucleosynthesis :
## evolution of the abundances in the first three minutes




Initial condition

Nuclear reaction

Frozen

$T \gg 1$ MeV $(t \ll 1$ sec$)$

**Local Thermal Equilibrium of protons and neutrons**

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

$T \sim 1$ MeV $(t \sim 1$ sec$)$

**Weak freeze-out**

$$\frac{n}{p} = e^{-(m_n - m_p)/T} \simeq \frac{1}{6}$$

**Decay of free neutrons**

$$\tau_n \simeq 880\,\mathrm{sec}$$

$$n + p \leftrightarrow D + \gamma$$

**Deuterium bottleneck**

$T \sim 0.07$ MeV $(t \sim 3$ min$)$

$$n/p \simeq 1/7$$

most neutrons to He4
small D, He3 Li7

$$n = g\left(\frac{mT}{2\pi}\right)^{3/2} e^{-(m-\mu)/T} \qquad m_n - m_p \simeq 1.29\ \mathrm{MeV}$$

## Initial condition : Nuclear statistical equilibrium

We consider now the temperature much larger than 1 MeV and below 100 MeV.

In kinetic equilibrium, the number density of light nuclear species follow

$$n = g\left(\frac{mT}{2\pi}\right)^{3/2} e^{-(m-\mu)/T}$$

In chemical equilibrium, with reactions much faster than expansion

$$Nucleus(A, Z) \leftrightarrow Z\,p + (A - Z)\,n$$

then the chemical potentials are related by

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

For proton number density,

$$n_p = g_p \left( \frac{m_p T}{2\pi} \right)^{3/2} \exp \left( \frac{\mu_p - m_p}{T} \right)$$

For neutron number density,

$$n_n = g_n \left( \frac{m_n T}{2\pi} \right)^{3/2} \exp \left( \frac{\mu_n - m_n}{T} \right)$$

For nucleus (mass number A, proton number Z) number density,

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

In the chemical equilibrium, $\mu_A = Z\mu_p + (A - Z)\mu_n$

$$\exp \left( \frac{\mu_A}{T} \right) = n_p^Z n_n^{A-Z} \left( \frac{2\pi}{m_N T} \right)^{3A/2} 2^{-A} \exp \left[ (Z m_p + (A - Z) m_n)/T \right]$$

For nucleus (mass number A, proton number Z) number density,

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

with using $m_N = m_p = m_n \quad m_A = Am_N$

In the equilibrium, the number density is determined by those of proton and neutron at a given temperature.

$$B_A \equiv Zm_p + (A-Z)m_n - m_A$$

## Binding energy of nuclei

$$B_{^2H} = 2.22\,\mathrm{MeV}$$

$$B_{^3H} = 26.92\,\mathrm{MeV}$$

$$B_{^3He} = 27.72\,\mathrm{MeV}$$

$$B_{^4He} = 28.3\,\mathrm{MeV}$$

Total nucleon density, $n_N = n_n + n_p + \sum_i (An_A)_i$

The mass fraction is defined by

$$X_A \equiv \frac{An_A}{n_N} \quad \text{and} \quad \sum_i X_i = 1$$

The mass fraction of species A(Z) in nuclear thermal equilibrium

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

$$\boxed{\eta \equiv \frac{n_N}{n_\gamma} = 2.67\times 10^{-8}(\Omega_B h^2)}$$

Remains constant below MeV until now.

## $\boxed{\text{Initial condition}}$ : equilibrium by weak interaction

Protons and neutrons are balanced by the weak interactions. Thus the chemical potentials satisfy

$$\boxed{\mu_n + \mu_\nu = \mu_p + \mu_e}$$

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

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

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

Therefore in chemical equilibrium,

$$\frac{n_n}{n_p} = \frac{X_n}{X_p} = \exp\left[-\frac{Q}{T} + \frac{\mu_e - \mu_\nu}{T}\right]$$

$$\simeq \exp\left[-\frac{Q}{T}\right]$$

$$n = g\left(\frac{mT}{2\pi}\right)^{3/2} e^{-(m-\mu)/T}$$

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

with charge neutrality

$$\frac{\mu_e}{T} \sim \frac{n_e}{n_\gamma} = \frac{n_p}{n_\gamma} \sim \eta \sim 10^{-9}$$

and assuming small $\dfrac{|\mu_\nu|}{T} \ll 1$

$\boxed{\text{T} = 10\ \text{MeV}}$ : still in the thermal equilibrium

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

$\boxed{\text{T} = 1\ \text{MeV}}$ : weak interaction frozen

$$\left.\frac{n_n}{n_p}\right|_{freeze-out} = \exp\left[-\frac{1.293\,\mathrm{MeV}}{0.8\,\mathrm{MeV}}\right] \simeq \frac{1}{6}$$

The light nuclei are still in the nuclear statistal equilibrium,

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

$\boxed{\text{T = 0.3 MeV to 0.1 MeV}}$

(t=1 to 3 minutes)

The free neutrons still decays and produce protons.

$$\tau_n = 880.1 \pm 1.1\,\mathrm{sec}$$

$$\left.\frac{n_n}{n_p}\right|_{T\simeq 0.1\,\mathrm{MeV}} \simeq \frac{1}{7}$$

At around this temperature, the D, H3 and He3 abundances grows and they quickly bound into most stable light element He4. All the free neutrons are bound into He4. The resulting mass fraction of H4 is

$$X_4 = \frac{4n_4}{n_N} = \frac{4\times n_n/2}{n_n+n_p} = \frac{2\times \left.\frac{n_n}{n_p}\right|_{T\simeq 0.1\,\mathrm{MeV}}}{1+\left.\frac{n_n}{n_p}\right|_{T\simeq 0.1\,\mathrm{MeV}}} = \frac{1}{4}$$

## How He4 are produced?

1. Direct production of 4-particle scattering: the probability is too small

$$p + p + n + n \to {}^{4}\mathrm{He}$$

2. First produce Deuterium and then T or He3 to combine He4

$$p + n \to D + \gamma \quad \longrightarrow \quad \begin{array}{l} D + D \to He3 + n \\ D + D \to T + p \end{array} \quad \longrightarrow \quad \begin{array}{l} T + D \to He4 + n \\ He3 + D \to He4 + p \end{array}$$

He4 cannot be produced until enough Deuteriums are produced.

$$\boxed{\text{Deuterium bottleneck}}$$

There is no stable nuclei for A=5, 8

Production of Li6, Li7 and Be7

$$He4 + T \rightarrow Li7 + \gamma$$
$$He4 + He3 \rightarrow Be7 + \gamma$$
$$He4 + D \rightarrow Li6 + \gamma$$

Be7 captures electron and decays to Li7.

$$Be7 + e^- \rightarrow Li7 + \nu_e$$

First calculated by Gamow, Alpher and Herman (1940)

Computer code by Wagoner (1969, 1973)

Updated by Kawano (1992) and etc...

Public code

| | |
|---|---|
| FASTBBN | Lisi,Sarkar,Villante (1990) |
| PArthENoPE | Pisanti et al (2008) |

Public code and review papers for BBN at

http://www-thphys.physics.ox.ac.uk/people/SubirSarkar/bbn.html

# Numerical calculation of BBN

Nuclear reactions

$$N_i({}^{A_i}Z_i) + N_j({}^{A_j}Z_j) \leftrightarrow N_k({}^{A_k}Z_k) + N_l({}^{A_l}Z_l)$$

Solve Boltzmann equation

$$\frac{dY_i}{dt} = \sum_{j,k,l} N_i \left( -\frac{Y_i^{N_i} Y_j^{N_j}}{N_i! N_j!}[ij]_k + \frac{Y_l^{N_l} Y_k^{N_k}}{N_l! N_k!}[lk]_j \right)$$

with initial equilibrium conditions and input parameters.

The nuclear reaction rates are given from experiments and nuclear models.

# Nuclear reaction rate

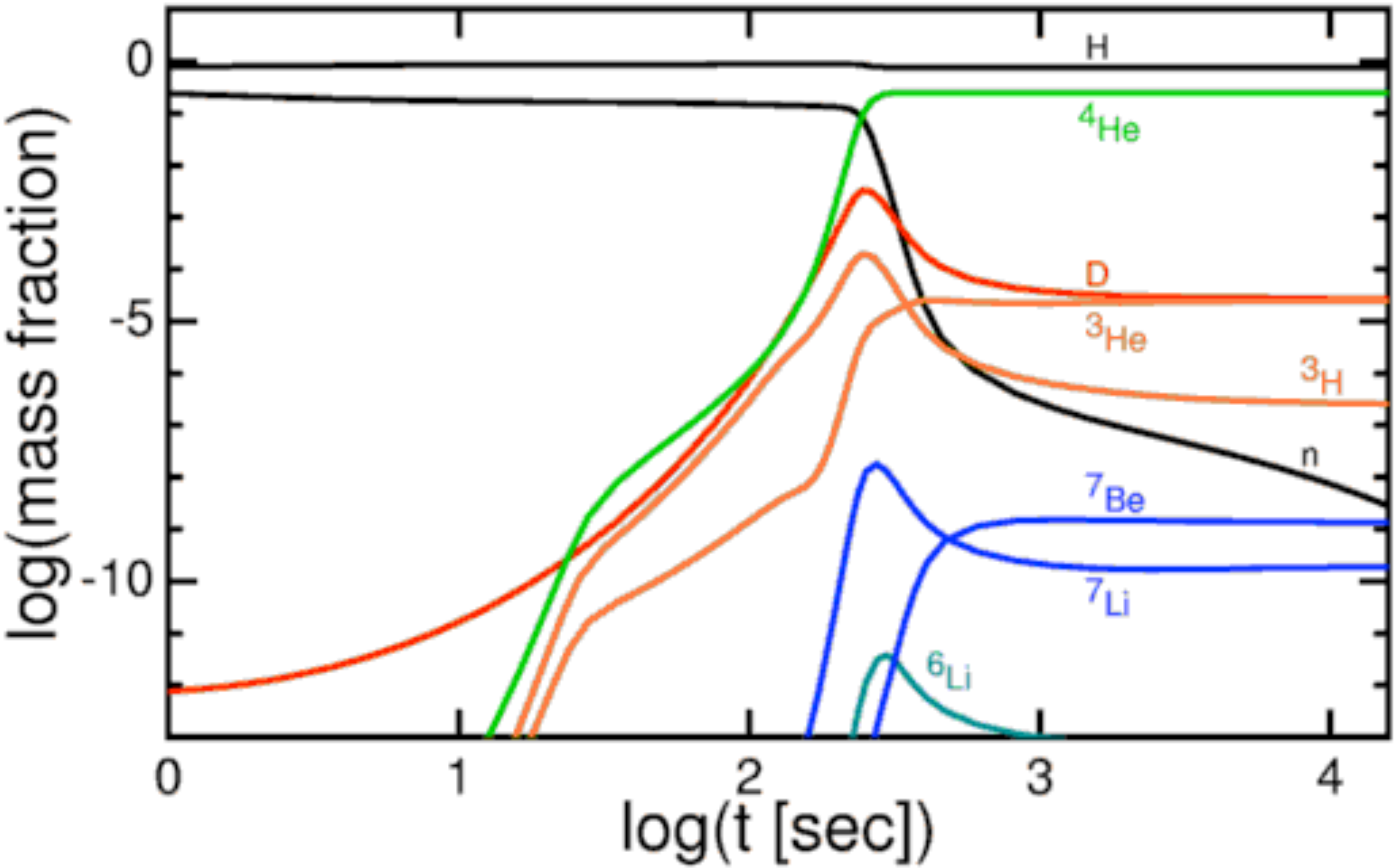
Table 2.

[Kawano, 1992]

DEDUCED RATES AND UNCERTAINTIES OF 12 MAJOR BBN REACTIONS

| | Reaction | Nuclear Reaction Rate ($cm^3 s^{-1} mole^{-1}$) | $1\sigma$ Uncertainty |
|---|---|---|---|
| 1. | neutron $\tau$ | 888.5 seconds | 3.7 sec |
| 2. | $p(n,\gamma)d$ | $4.742\times10^4$<br>$\times(1.-.850T_9^{1/2}+.490T_9-.0962T_9^{3/2}$<br>$+8.47\times10^{-3}T_9^2-2.80\times10^{-4}T_9^{5/2})$ | 7% |
| 3. | $d(p,\gamma)^3He$ | $2.65\times10^3T_9^{-2/3}\exp(-3.720/T_9^{1/3})$<br>$\times(1.+.112T_9^{1/3}+1.99T_9^{2/3}+1.56T_9+.162T_9^{4/3}+.324T_9^{5/3})$ | 10 |
| 4. | $d(d,n)^3He$ | $3.95\times10^8T_9^{-2/3}\exp(-4.259/T_9^{1/3})$<br>$\times(1.+.098T_9^{1/3}+.765T_9^{2/3}+.525T_9+9.61\times10^{-3}T_9^{4/3}+.0167T_9^{5/3})$ | 10 |
| 5. | $d(d,p)t$ | $4.17\times10^8T_9^{-2/3}\exp(-4.258/T_9^{1/3})$<br>$\times(1.+.098T_9^{1/3}+.518T_9^{2/3}+.355T_9-.010T_9^{4/3}-.018T_9^{5/3})$ | 10 |
| 6. | $t(d,n)^4He$ | $1.063\times10^{11}T_9^{-2/3}\exp[-4.559/T_9^{1/3}-(T_9/.0754)^2]$<br>$\times(1.+.092T_9^{1/3}-.375T_9^{2/3}-.242T_9+33.82T_9^{4/3}+55.42T_9^{5/3})$<br>$+8.047\times10^8T_9^{-2/3}\exp(-0.4857/T_9)$ | 8 |
| 7. | $t(\alpha,\gamma)^7Li$ | $3.032\times10^5T_9^{-2/3}\exp(-8.090/T_9^{1/3})$<br>$\times(1.+.0516T_9^{1/3}+.0229T_9^{2/3}+8.28\times10^{-3}T_9$<br>$-3.28\times10^{-4}T_9^{4/3}-3.01\times10^{-4}T_9^{5/3})$<br>$+5.109\times10^5T_{9a}^{5/6}T_9^{-3/2}\exp(-8.068/T_{9a}^{1/3})$<br>$T_{9a}=T_9/(1.+.1378T_9)$ | $T_9>10$ :<br>8.1<br>$T_9\leq10$ :<br>$29.-5.9T_{9b}^{1/2}-7.2T_{9b}+4.0T_{9b}^{3/2}-.56T_{9b}^2$<br>$T_{9b}=T_9+.0419$ |
| 8. | $^3He(n,p)t$ | $7.21\times10^8(1.-.508T_9^{1/2}+.228T_9)$ | 10 |
| 9. | $^3He(d,p)^4He$ | $5.021\times10^{10}T_9^{-2/3}\exp[-7.144/T_9^{1/3}-(T_9/.270)^2]$<br>$(1.+.058T_9^{1/3}+.603T_9^{2/3}+.245T_9+6.97T_9^{4/3}+7.19T_9^{5/3})$<br>$+5.212\times10^8T_9^{-1/2}\exp(-1.762/T_9)$ | 8 |
| 10. | $^3He(\alpha,\gamma)^7Be$ | $4.817\times10^6T_9^{-2/3}\exp(-14.964/T_9^{1/3})$<br>$\times(1.+.0325T_9^{1/3}-1.04\times10^{-3}T_9^{2/3}-2.37\times10^{-4}T_9$<br>$-8.11\times10^{-5}T_9^{4/3}-4.69\times10^{-5}T_9^{5/3})$<br>$+5.938\times10^6T_{9a}^{5/6}T_9^{-3/2}\exp(-12.859/T_{9a}^{1/3})$<br>$T_{9a}=T_9/(1.+.1071T_9)$ | $T_9>10$ :<br>9.7<br>$T_9\leq10$ :<br>$27.-15.T_{9b}^{1/2}+4.0T_{9b}-.25T_{9b}^{3/2}-.02T_{9b}^2$<br>$T_{9b}=T_9+.783$ |
| 11. | $^7Li(p,\alpha)^4He$ | $1.096\times10^9T_9^{-2/3}\exp(-8.472/T_9^{1/3})$<br>$-4.830\times10^8T_{9a}^{5/6}T_9^{-3/2}\exp(-8.472/T_{9a}^{1/3})$<br>$+1.06\times10^{10}T_9^{-3/2}\exp(-30.442/T_9)$<br>$+1.56\times10^5T_9^{-2/3}\exp[-8.472/T_9^{1/3}-(T_9/1.696)^2]$<br>$\times(1.+.049T_9^{1/3}-2.50T_9^{2/3}+.860T_9+3.52T_9^{4/3}+3.08T_9^{5/3})$<br>$+1.55\times10^6T_9^{-3/2}\exp(-4.478/T_9)$<br>$T_{9a}=[T_9/(1.+.759T_9)]$ | 8 |
| 12. | $^7Be(n,p)^7Li$ | $2.675\times10^9$<br>$\times(1.-.560T_9^{1/2}+.179T_9-.0283T_9^{3/2}+2.21\times10^{-3}T_9^2-6.85\times10^{-5}T_9^{5/2})$<br>$+9.391\times10^8T_{9a}^{3/2}T_9^{-3/2}+4.467\times10^7T_9^{-3/2}\exp(-0.07486/T_9)$<br>$T_{9a}=[T_9/(1.+13.08T_9)]$ | 9 |

# Big Bang Nucleosynthesis :
evolution of the abundances in the first three minutes




Initial condition

Nuclear reaction

Frozen

Most dominant elements are

75% Hydrogen $\left(^1\mathrm{H}\right)$ : 1p

25% Helium4 $\left(^4\mathrm{He}\right)$ : 2p + 2n

* the number ratio of proton : neutron $\sim$ 7:1

Small amount of the light elements are

$$\mathrm{D},\ \mathrm{T} \quad : \quad \frac{n}{n_p} \sim 10^{-5} \qquad\qquad {}^7\mathrm{Li} \quad : \quad \frac{n}{n_p} \sim 10^{-10}$$

These light elements cannot be produced in the stellar evolution. They was created in the early hot Universe.

# Test of Standard Big Bang Cosmology

- Determination of Baryon density

One free parameter is the baryon-to-photon ratio, $\eta$ .

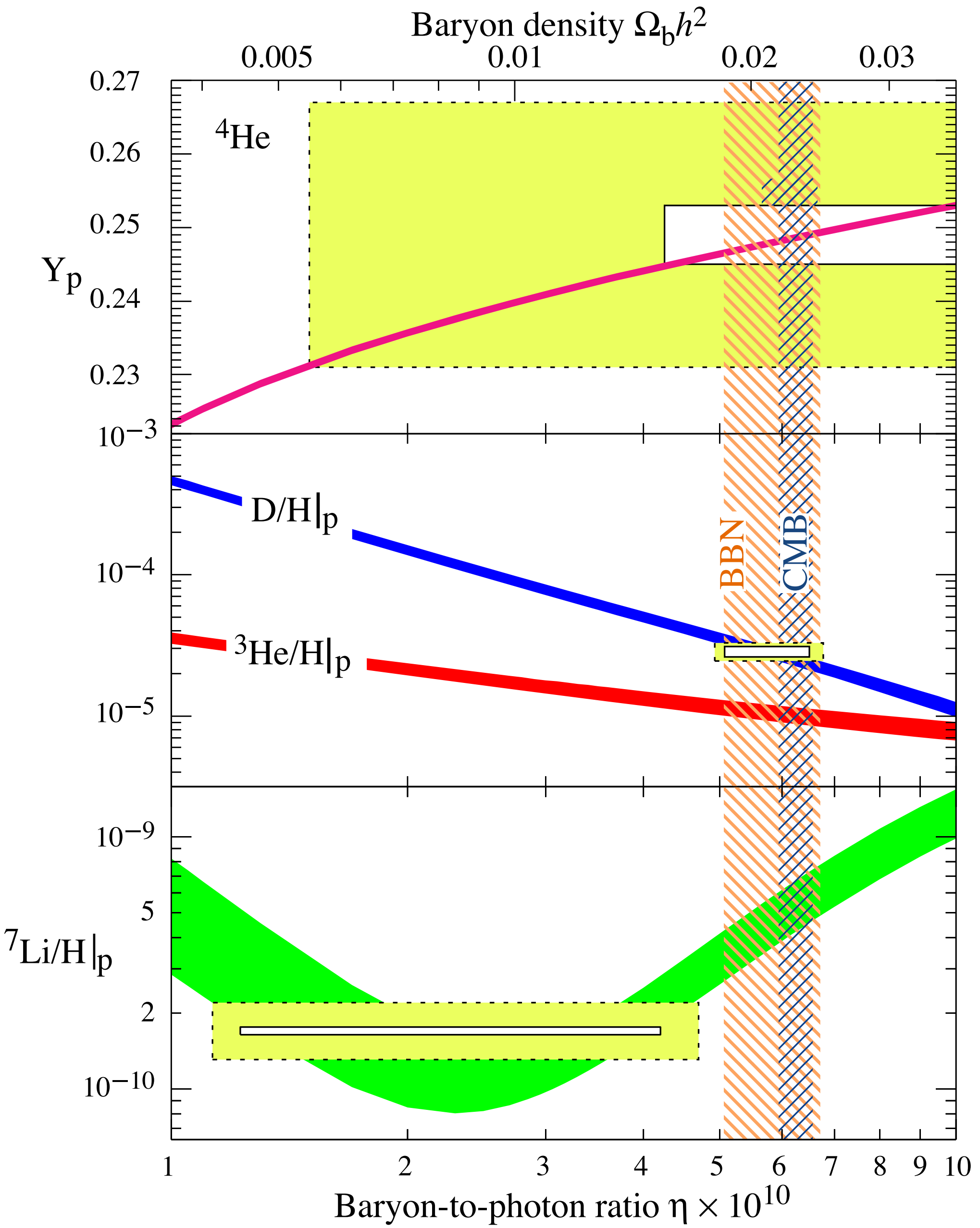
Since the photon number density is fixed, baryon number is determined from this parameter. Then in the thermal equilibrium, all abundance of the nuclei are given as initial conditions.

For a larger value of $\eta$, the abundances of D, T, He3 build up slightly earlier and He4 synthesis starts earlier, when neutron-to-proton ratio is larger. Thus He4 fraction is higher.

The abundance of D, He3 is more sensitive to $\eta$, with decreasing as $\eta$ increases.

Li7 has trough at a value around $\eta \simeq 3 \times 10^{-10}$ . This is due to two different production processes dominate depending on the value of $\eta$

- Determination of Baryon density




Box: 2sigma stat, 2sigma stat + syst

The comparison between the observed light element abundances and the theoretical calculation shows that the baryon-to-photon ratio

$$\eta_{10} \equiv \frac{n_b}{n_\gamma} \times 10^{10}$$

must be

$$5.1 \leq \eta_{10} \leq 6.5 \ (95\%\mathrm{CL})$$

It corresponds to Baryon energy density

$$0.019 \leq \Omega_b h^2 \leq 0.024 \ (95\%\mathrm{CL})$$

cf) $\Omega h^2_{\mathrm{lum}} \simeq 0.0024$

It is consistent with independent determination from CMB anisotropy.

$$\eta_{10} = 6.23 \pm 0.17$$

- Lithium problems

  SBBN predicts more Li7 by a factor at least 2.4 and by at least 4.2 sigma. CMB value of baryon abundance increases the discrepancy to as much as 5.3 sigma.

  If Li6 plateau reflects a primordial Li6, then 1000 times larger than expected from SBBN.

  Where these mismatch come from?

  Systematic errors in the observed abundances?

  Uncertainties in stellar astrophysics?

  Uncertainties in nuclear inputs?

  New physics: decay of heavy particles around BBN epoch?

## • Additional relativistic degrees of freedom

After electron-positron annihilation, with three neutrino species,

$$g_* = 3.36$$

determines the expansion rate,

$$H^2 \simeq \frac{8\pi G}{3}\rho \qquad\qquad \rho_R = \frac{\pi^2}{30} g_* T^4$$

With additional relativistic degrees of freedom,

$$H \propto g_*^{1/2} T^2$$

makes the freeze-out of the weak interaction earlier, then the neutron-to-proton ratio increases. Thus, the He4 mass fraction increases.

Particle physics beyond Standard Model is usually constrained from this additional energy budget and thus from He4 abundance.

The energy density of the relativistic neutrinos

$$\rho_\nu(a) \to \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\rho_\gamma(a) \simeq 0.2271 N_{\rm eff}\rho_\gamma(a),$$

For 3 species of neutrinos in the Standard Model

$$N_{\rm eff} = 3.046$$ [Mangano et al, 2005]

slight increase from 3 due to the residual heating of the neutrino fluid from the electron-positron annihilation.

The additional contribution to the 3 flavors of neutrino is parametrized by

$$\boxed{\Delta N_{\rm eff} = N_{\rm eff} - N_{\rm eff}^{\rm SM}}$$

The computed He4 abundance scales as

$$\Delta Y_p \simeq 0.013 \Delta N_{\rm eff}$$

# $N_{\rm eff}$ at BBN epoch

[Mangano et al, 2011]

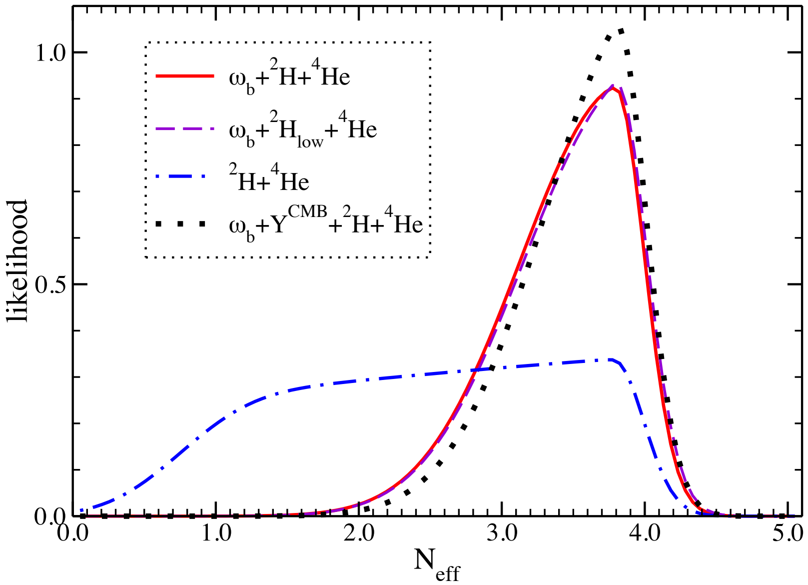



FIG. 1: Marginalized 1-D likelihood functions $\mathcal{L}$ versus $N_{\rm eff}$ using the different combinations of data as in Table I. Solid (red) and dashed (purple) curves are obtained using CMB measurement of $\omega_b$, with the dotted (black) one also adds CMB information on $Y_p$. In all cases the quite sharp cut-off at $N_{\rm eff} \sim 4$ is due to $^4$He abundance upper limit.

| Datasets | $N_{\rm eff}^{\rm max}$ | $N_{\rm eff}^{\rm min}$ | $L(N_{\rm eff} \leq N_{\rm eff}^{\rm SM})$ |
|---|---|---|---|
| $\omega_b$+$^2$H+$^4$He | 4.05 | 2.56 | 0.20 |
| $\omega_b$+$^2$H$_{\rm low}$ +$^4$He | 4.08 | 2.57 | 0.19 |
| $^2$H+$^4$He | 3.91 | 0.80 | 0.67 |
| $\omega_b + Y_p^{\rm CMB}$+$^2$H+$^4$He | 4.08 | 2.71 | 0.15 |

TABLE I: Constraints on $N_{\rm eff}$ corresponding to different datasets used: i) first row: Eq. (6), Eqs. (1;3), Eq. (4); ii) second row: Eq. (6), Eqs. (1;3), Eq. (5); iii) third row: Eqs. (1;3) and Eq. (4); fourth row: as the first one, with the additional CMB measurement of $Y_p$ of Eq. (7). The last column shows the likelihood that $N_{\rm eff}$ is smaller than the standard value 3.046 [19].

- Test of non-standard physics

The limit on $N_{\mathrm{eff}}$ can be translated to limit on other types of particles that affect the expansion rate of the Universe during BBN. Dark Radiation

Any changes in the strong, weak, electromagnetic couplings, or gravitational coupling constants can change the expansion rate or the interaction rate, and thus can be constrained from BBN.

For heavy particles which decay during BBN, the mass and lifetime are constrained. Gravitino, axino Charged massive particles, etc.

Large annihilation cross section of dark matter is constrained by BBN.

# Big Bang Nucleosynthesis

BBN marks the boundary between the established and speculative in Big Bang cosmology. The Standard Model provides a description to the weak scale, however there is no observable relics from this epoch have been identified.

The concordance of the light element abundances, D, He4 and also with CMB is profound and remains as non-trivial success. BBN makes one of the pillars of the standard Big Bang cosmology.

BBN is used to test non-standard cosmology and particle physics.