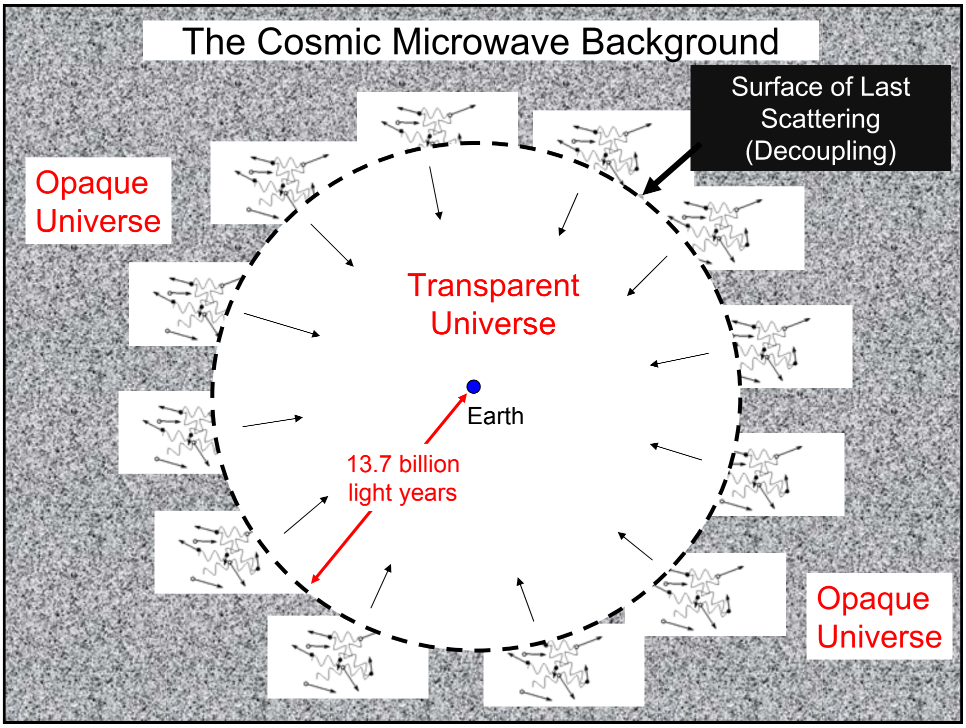


When did decoupling occur?

- Saha equation: <u>Collisional</u> ionization rate = Recombination rate

$$\frac{N_{H^+}}{N_{H^0}} = \frac{4}{N_e}\left(\frac{2\pi m_e k T}{h^2}\right)^{3/2} e^{-\Delta E / kT} \qquad (8.8)$$

  - Solve for $\frac{N_{H^+}}{N_{H^0}} = 1$, using $T = \frac{T_0}{R}$, $N_e \sim \frac{\rho_0}{m_H}\frac{1}{R^3}$ = electron density

    ➔ $R \sim 7.2\text{x}10^{-4}$
    $T \sim 3800$ K

  - Taking composition and radiative transfer into account:

    $T_{dec} = 2970\text{K}$ $\qquad z_{dec} = 1089$
    $R_{dec} = 9\text{x}10^{-4}$ $\qquad t_{dec} = 118{,}000$ yrs.

Decoupling also called “**re**combination”

The Radiation Era

$T_0 = RT$

$T = \frac{T_0}{R}$

Energy density (integrated over wavelength):

$$u_{rad} = \frac{4\sigma T^4}{c} = aT^4$$

See [CO pg. 234]

$$\rho_{rad} = \frac{u_{rad}}{c^2} = \frac{aT^4}{c^2} = \frac{\rho_{rad,0}}{R^4}$$

$$\rho_{matter} = \frac{\rho_{matter,0}}{R^3}$$

$$\frac{\rho_{rad}}{\rho_{matter}} \propto \frac{1}{R}$$

$\rho_{matter} = \rho_{rad}$ at

$$R = \frac{a T_0^4}{\rho_0 c^2} = \frac{8\pi G a T_0^4}{3 H_0^2 c^2 \Omega_0} \sim 2.5\times10^{-5}\,\Omega_0^{-1} h^{-2}$$

$$z = \frac{1}{R} - 1 \sim 4\times10^4\,\Omega_0 h^2$$

when $T = \frac{T_0}{R} \sim 1.1\times10^5\,\Omega_0 h^2$ K

Knowing *R(t)* as function of *t* ➔ Age of U ~ 3200 yrs

for $\Omega_0 = 1$, h = 0.71

During the Radiation Era:

$$\left[\left(\frac{1}{R}\frac{dR}{dt}\right)^2 - \frac{8}{3}\pi G \rho_{RAD}\right] R^2 = -kc^2$$

$\uparrow k \sim 0$

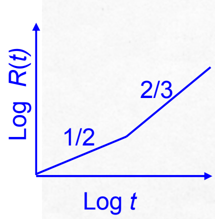
$$\left(\frac{1}{R}\frac{dR}{dt}\right)^2 = \frac{8}{3}\pi G \frac{\rho_{RAD,0}}{R^4}$$

$$\left(\frac{dR}{dt}\right)^2 \propto \frac{1}{R^2}$$

$$R\,dR \propto dt$$

$$R \propto t^{1/2}$$

instead of $R \propto t^{2/3}$ in matter era.



also, $T_0 = RT \Rightarrow T \propto t^{-1/2}$

Terminology…

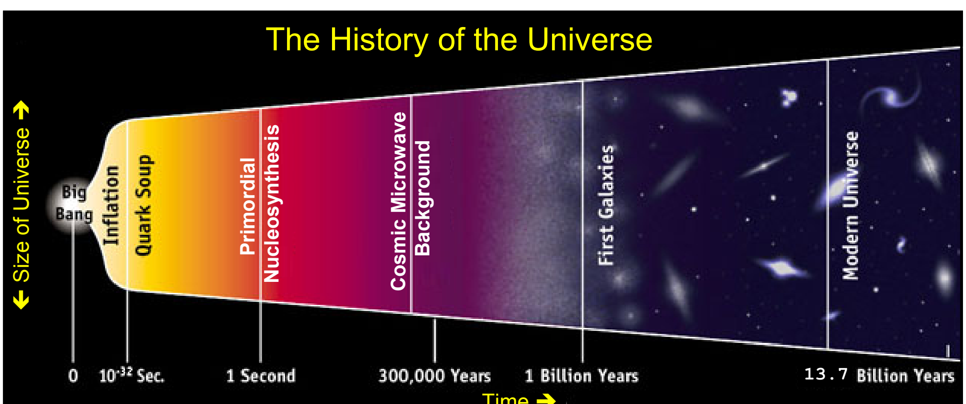
$$\left(\left(\frac{1}{R}\frac{dR}{dt}\right)^2 - \frac{8}{3}\pi G\rho\right)R^2 = -kc^2$$

$$\left(\left(\frac{1}{R}\frac{dR}{dt}\right)^2 - \frac{8}{3}\pi G(\rho_{matter} + \rho_{rel})\right)R^2 = -kc^2$$

CO call it $\rho_{\text{relativistic}}$
= photons + neutrinos

$$\rho_{rel} = \frac{u_{rel}}{c^2}$$

$$\Omega_{rel}(t) = \frac{\rho_{rel}(t)}{\rho_{crit}(t)}$$



Planck time

Inflation

Formation of H, He, Li

Decoupling of CMB

Galaxy Formation

Now

Hot → Cool

(10^{32} K) (10^9 K) (3000 K) (3 K)

High density → Low density

Primordial Nucleosynthesis

Radiation era

$R(t) \propto t^{1/2}$

$T(t) \propto t^{-1/2}$

$t = 10^{-4}$ s, $T = 10^{12}$K

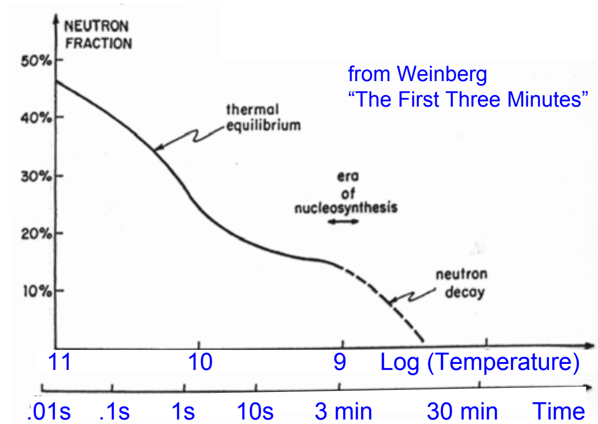
$p^+ + e^- \rightleftarrows n + \nu_e$, etc.

$\gamma \rightleftarrows e^- + e^+$

Statistical equilibrium

$$\frac{n_n}{n_p} = e^{-\Delta E/kT}$$

$$= e^{-1.5\times10^{10}\,K/T}$$



from Weinberg
"The First Three Minutes"

$t \sim 1$ s, $T = 10^{10}$K

Neutrons freeze out

- redshifting of neutrinos.
- lower γ energies

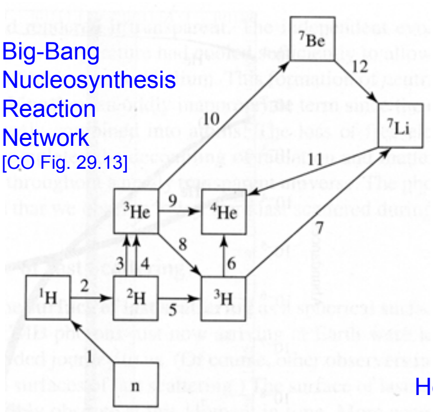
$$\frac{n_n}{n_p} = 0.223$$

Subsequent β decays ➔ $$\frac{n_n}{n_p} \approx 0.176$$

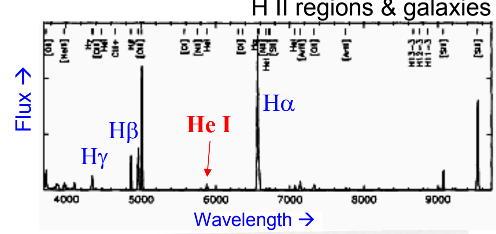
Primordial Nucleosynthesis

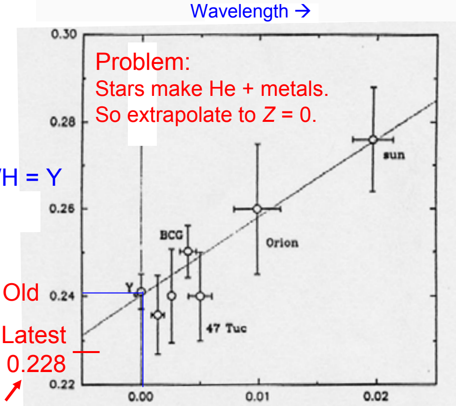
Big-Bang Nucleosynthesis Reaction Network

[CO Fig. 29.13]



H II regions & galaxies





He/H = Y

Old

Latest
= 0.228

Metallicity Z ➔
(from C/H. N/H, O/H etc.)

He production

~ all neutrons used up in ^{4}He

➔ Mass fraction of ^{4}He / total

$$= \frac{2n_n}{n_n + n_p} \approx 0.299$$

Confirms Big Bang!

Measuring Baryonic Matter Density – Version I

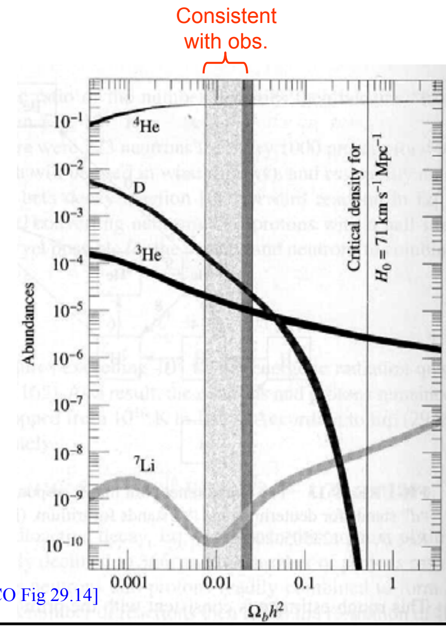
- ^{4}He/total ➔ doesn't depend on details
- But trace element abundances depend strongly on $\rho_{BARYON}(t)$, $T(t)$

➔ $\rho_{B,o}$ from RT = constant,

$$\rho = \rho_o/R^3 \propto \rho_o T^3$$

Baryons:
Particles made of 3 quarks
= protons, neutrons, + …
= "normal matter"

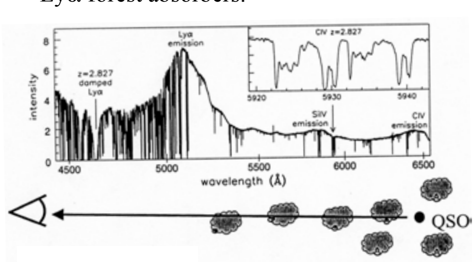
A Problem: d, ^{3}He, ^{7}Li easily destroyed in stars. How to measure primordial values?

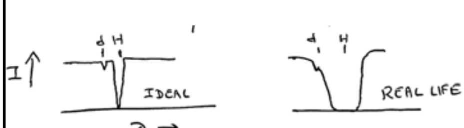


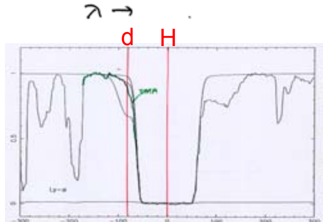
[CO Fig 29.14]

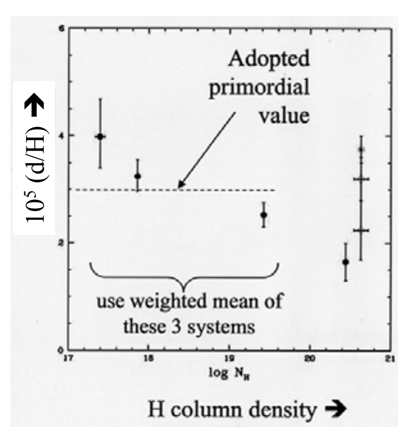
Example: the Primordial Deuterium Abundance

Lyα forest absorbers.









$\Omega_{Baryons}$

- d, ^{7}Li, ^{3}He ➔

$$\Omega_B = \frac{\rho_{B,o}}{\rho_{c,o}} = 0.02 - 0.05$$

- Luminous baryonic matter:

$$\Omega_{LUM} \sim 0.005$$

(x-ray emission from hot gas filling galaxy clusters).

➔ most baryonic matter is in Lyα forest clouds.

- But better determination now from CMB fluctuations (WMAP)

$$\Omega_B = 0.044$$

CO Reading

[27.1] The Extragalactic Distance Scale.
[27.2] The Expansion of the Universe.
[29.1] Newtonian Cosmology
[29.2] The Cosmic Microwave Background
[17] General Relativity & Black Holes ← WE ARE HERE!
[29.3] Relativistic Cosmology

Important to read through Chapter 17 (Relativity) before I start lecturing on it.

Pay particular attention to 17.2 "Intervals & Geodesics"
- What is a metric?
- The Schwarzschild metric (= non-rotating black hole)
- "The orbit of a satellite" (somewhat flakey example)

I will present additional material assuming that you have read at least 17.2.