Lecture 3: Big Bang Nucleosynthesis
"The First Three Minutes"

Last time:

particle anti-particle soup

--> quark soup

--> neutron-proton soup

p / n ratio at onset of ^{2}D formation

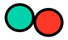
Today:

- Form ^{2}D and ^{4}He
- Form heavier nuclei?
- Discuss primordial abundances X_p, Y_p, Z_p .
- Constraint on cosmic baryon density Ω_b .

Onset of Big Bang Nucleosynthesis

Deuterium (D) production

$$n + p \rightarrow D + \gamma\,(2.2\,\mathrm{MeV})$$



Delayed until the high energy tail of blackbody photons can no longer break up D. Binding energy: $E = 2.2$ MeV.

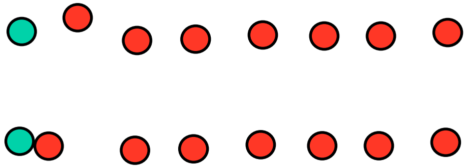
$$E\,/\,k\,T \sim \ln\left(\,N_\gamma / N_B\,\right) = \ln\left(10^9\right) \sim 20$$

$$k\,T \sim 0.1\ \mathrm{MeV}\ \ (\,T \sim 10^9\ \mathrm{K}\ \ \ t \sim 400\ \mathrm{s}\,)$$

Thermal equilibrium

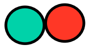
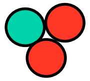
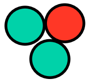
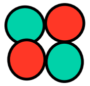
+ neutron decay: $N_p / N_n \sim 7$

Thus, at most, $N_D / N_p = 1/6$



But: **Deuterium readily assembles into heavier nuclei.**

Key Fusion Reactions

	product:	binding energy:
$n + p \rightarrow D + \gamma$	Deuterium (pn) 	2.2 MeV
$D + D \rightarrow {}^3He^{++} + n$ $p + D \rightarrow {}^3He^{++} + \gamma$	${}^3He$ (ppn) 	7.72 MeV
$n + D \rightarrow T + \gamma$ $D + D \rightarrow T + p$ $n + {}^3He^{++} \rightarrow T + p$	Tritium (pnn) 	8.48 MeV
$n + {}^3He^{++} \rightarrow {}^4He^{++} + \gamma$ $D + {}^3He^{++} \rightarrow {}^4He^{++} + p$ $p + T \rightarrow {}^4He^{++} + \gamma$ $D + T \rightarrow {}^4He^{++} + n$ ${}^3He^{++} + {}^3He^{++} \rightarrow {}^4He^{++} + 2p$	${}^4He$ (ppnn) 	28.3 MeV

Deuterium Bottleneck

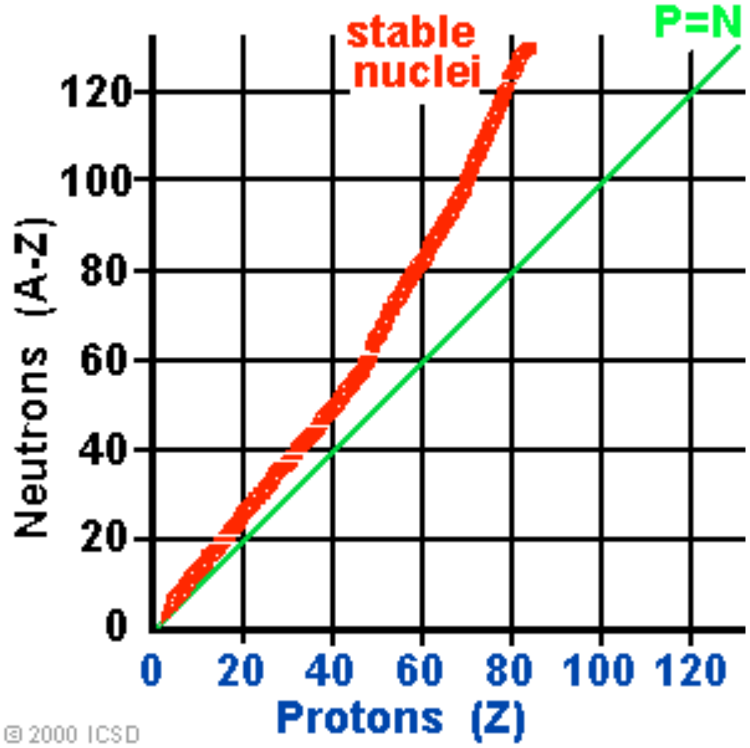
Note:

1) D has the lowest binding energy (2.2 MeV)
   (D easy to break up)
2) Nuclei with A > 2 cannot form until D is produced.
   (would require 3-body collisions)

→ **Deuterium bottleneck**

- Nucleosynthesis is delayed until D forms.
- Then nuclei immediately form up to ^{4}He.

What about Heavier Nuclei?

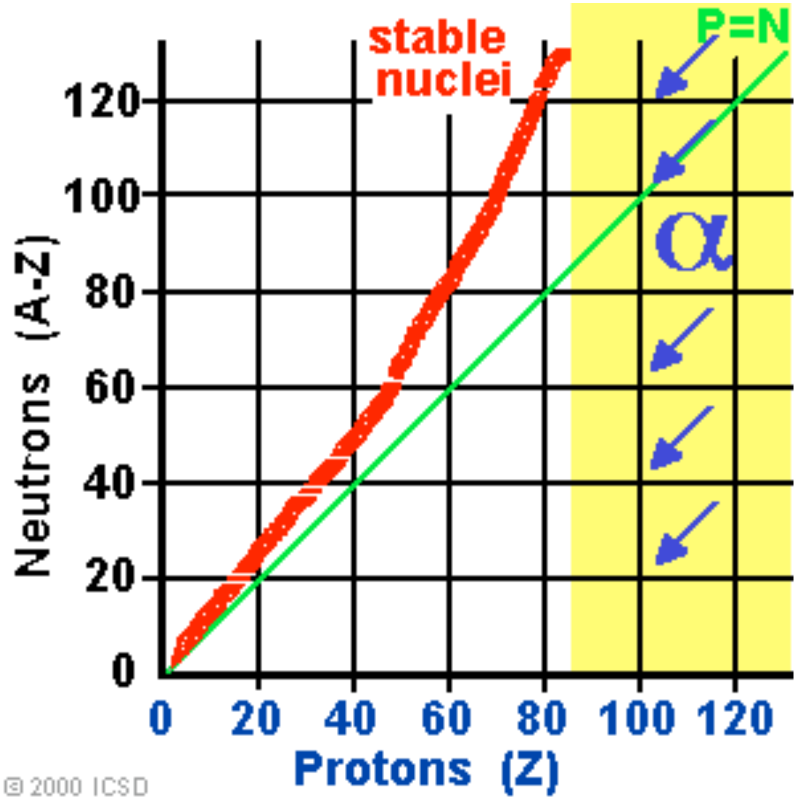


Z = number of protons
A = atomic weight
= protons + neutrons

As protons increase, neutrons must increase faster for stable nuclei.

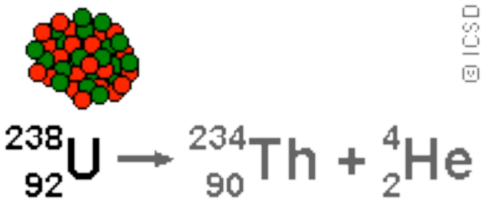
Nuclei with Z > 83 or >126 neutrons UNSTABLE.

e.g. α-decay (emit ^{4}He)
β-decay (emit e^-)



Lose 2 neutrons and 2 protons

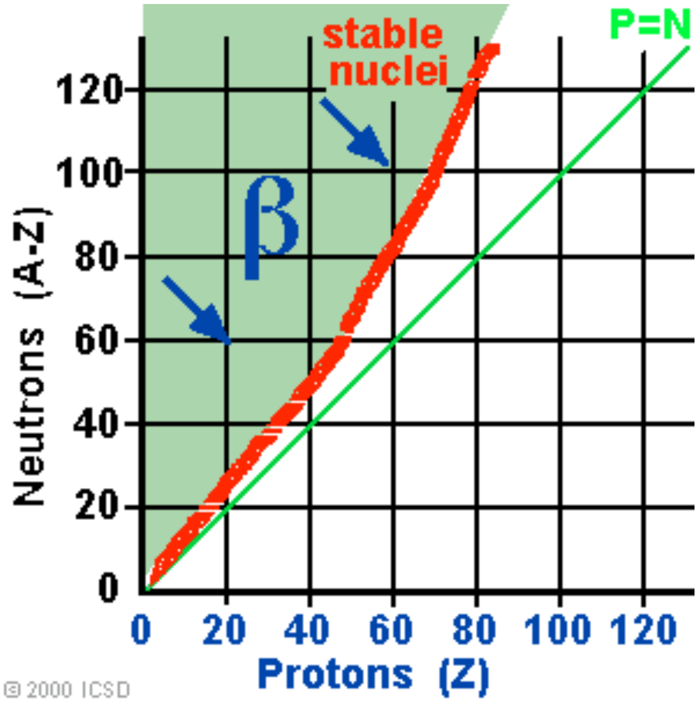
α decay

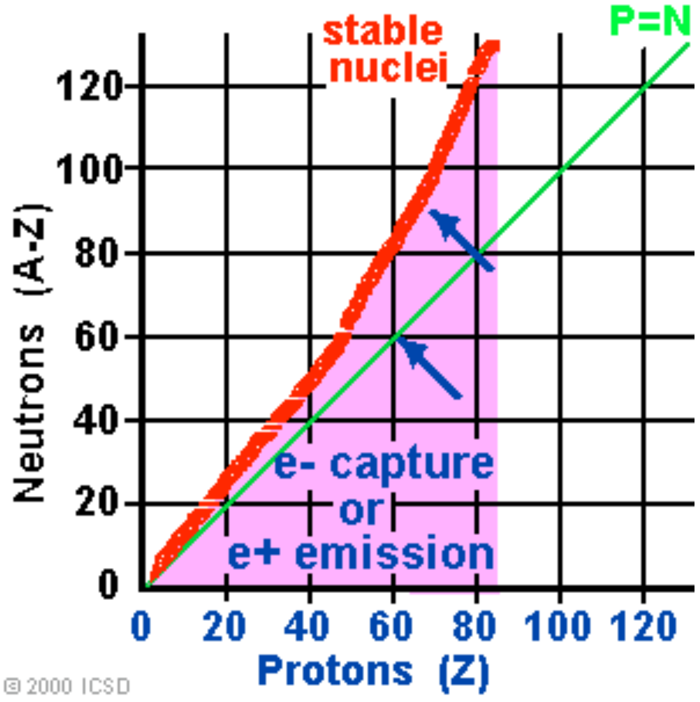


$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He$

$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He + 2\,^{0}_{0}\gamma$

Photon emission





β decay

n => p + e^-

$${}^{131}_{53}I \rightarrow {}^{131}_{54}Xe + {}^{0}_{-1}e$$

Positron emission

p => n + e^+

$${}^{11}_{6}C \rightarrow {}^{11}_{5}B + {}^{0}_{1}e$$

Electron capture

$${}^{81}_{37}Rb + {}^{0}_{-1}e \rightarrow {}^{81}_{36}Kr$$

p + e^- => n

BBN stalls

The main problem:

^{4}He is very stable, (28 MeV binding energy).

No stable nuclei with A = 5.

So can't use ^{4}He + p or ^{4}He + n, only much rarer ^{4}He + ^{4}He collisions make progress.

Thus further fusion is slow (low binding energies), leading to only traces of heavier nuclei, up to ^{7}Li.

$$^3He^{++} + {}^4He^{++} \rightarrow {}^7Li^{+++} + e^+ + \gamma$$

$$^3He^{++} + {}^4He^{++} \rightarrow {}^7Be^{4+} + \gamma$$

$$^7Be^{4+} + n \rightarrow {}^7Li^{+++} + p$$

$$^7Li^{+++} + p \rightarrow 2\ {}^4He^{++}$$

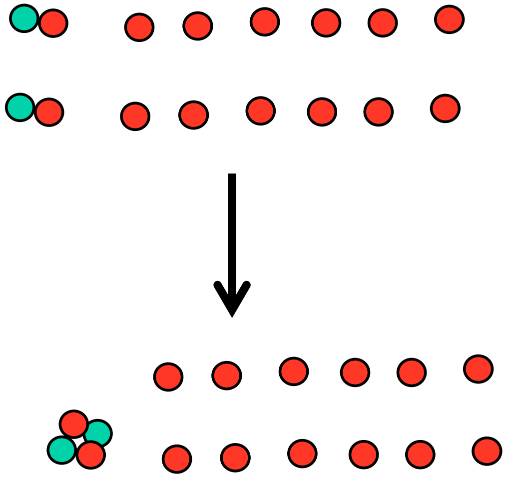
(In stars, fusion proceeds because high density and temperature overcome the ^{4}He binding energy.*)*

Primordial Abundances

Because ^{4}He is so stable, all fusion pathways lead to ^{4}He, and further fusion is rare.

Thus almost all neutrons end up in ^{4}He, and

residual protons remain free. [p+p -> ^{2}He does not occur]



To first order, with $N_p / N_n \sim 7$,

$$X_p \equiv \frac{\text{mass in H}}{\text{total mass}} = \frac{N_p - N_n}{N_p + N_n} = \frac{6}{8} = 0.75$$

$$Y_p \equiv \frac{\text{mass in He}}{\text{total mass}} = \frac{2N_n}{N_p + N_n} = \frac{2}{8} = 0.25$$

Primordial abundances of H & He (by mass, not by number).

Primordial Metals

In astronomy, all nuclei with A > 4 (or with Z > 2) are called metals (Li, Be, ...)

BBN yields H, He, and traces of D, T, ^{6}Li, ^{7}Li, ^{7}Be.

$$Z_p \equiv \frac{\text{mass of metals}}{\text{total mass}} \approx 0$$

Since the 1960's, computers simulating Big Bang Nucleosynthesis, using known reaction rates, give detailed abundance predictions:

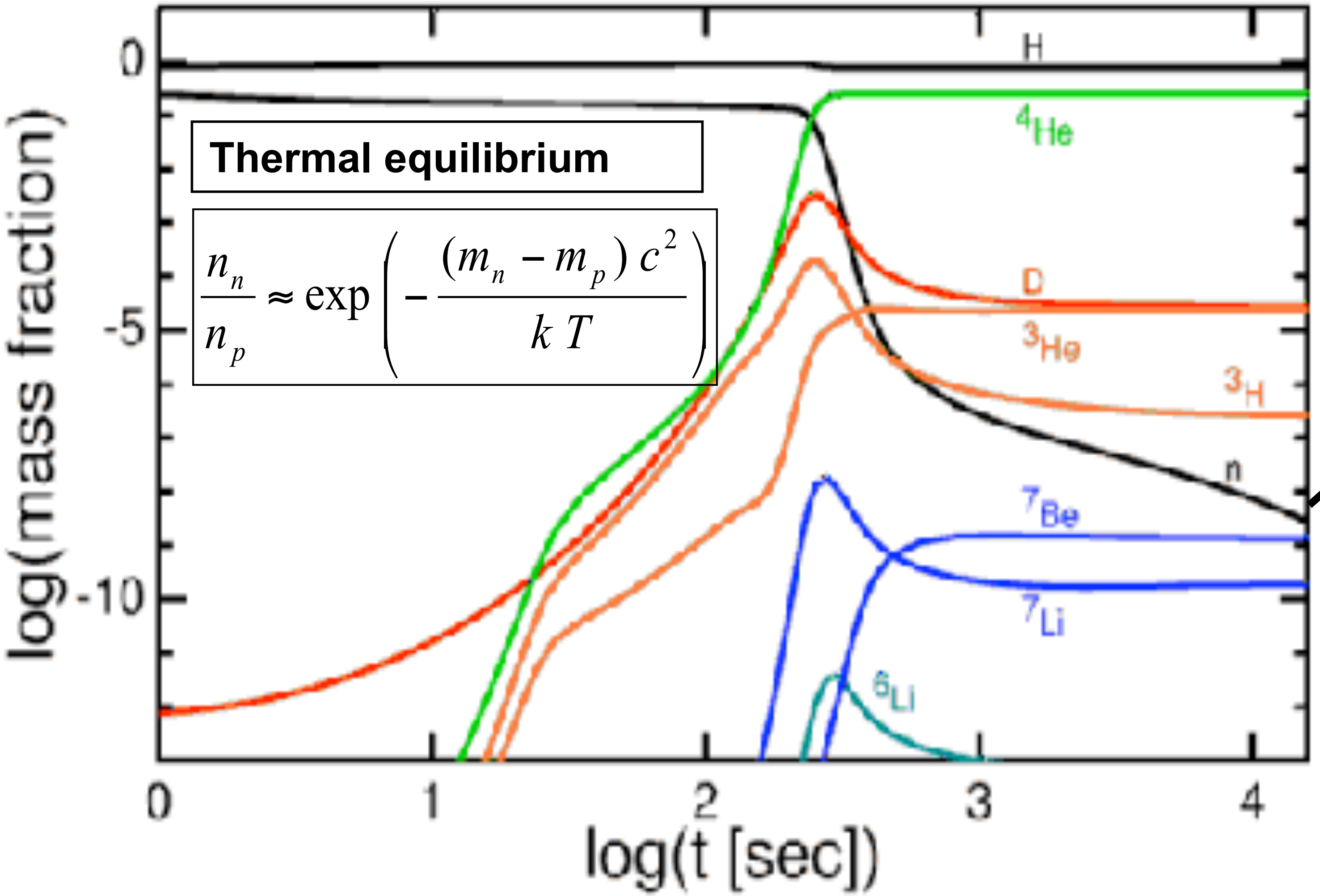
$$\boldsymbol{X_p} = 0.75 \qquad \boldsymbol{Y_p} = 0.25 \qquad \boldsymbol{Z_p} \sim 10^{-9}$$

BBN Predictions

Expansion, cooling

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

$X_p \approx 0.75 \quad Y_p \approx 0.25$



Thermal equilibrium

$$\frac{n_n}{n_p} \approx \exp\left(-\frac{(m_n - m_p)\,c^2}{k\,T}\right)$$

Reactions "freeze out" due to expansion

$D/H = 5 \times 10^{-5}$

neutrons decay into protons

$Z_p \sim 10^{-9}$

Sensitivity to Parameters

Abundances depend on two parameters:

1) photon/baryon ratio (sets *T* at which D forms)

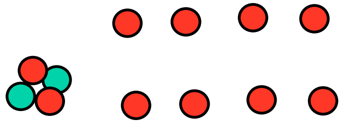
2) cooling time / neutron decay time

(determines the proton / neutron ratio)

If cooling much faster, no neutrons decay

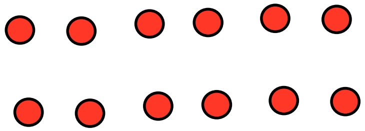
and $N_p / N_n \sim 5$

→ $\boldsymbol{X_p} = 4/6 = 0.67$ $\boldsymbol{Y_p} = 2/6 = 0.33$



If cooling much slower, all neutrons decay

→ $\boldsymbol{X_p} = 1$ $\boldsymbol{Y_p} = 0$



Baryon Density Constraint

Abundances (especially D) are sensitive to these 2 parameters.

Why?

Fewer baryons/photon, D forms at lower *T*, longer cooling time, more neutrons decay ==> less He.

At lower density, lower collision rates, D burning incomplete ==> more D.

Conversely, higher baryon/photon ratio ==> more He and less D.

Photon density is well known, but baryon density is not.

→ The measured D abundance constrains the baryon density!!

A very important constraint.

$$\Omega_b \approx 0.04$$

Baryon Density Constraint

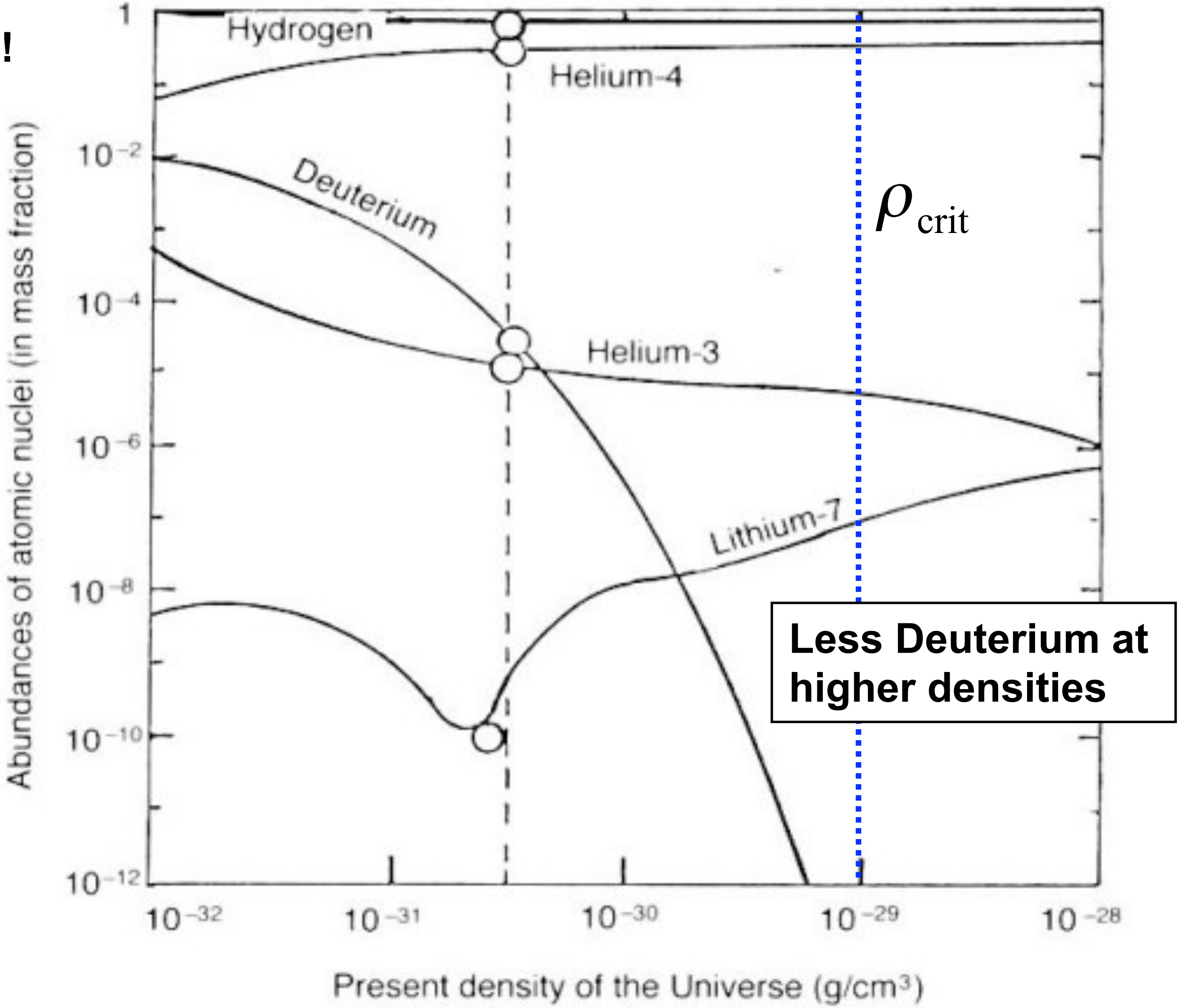
Observed He/H matches !

Observed D/H requires:

$$\Omega_b \left(\frac{H_0}{70}\right)^2 = 0.040 \pm 0.004$$

~4% baryons

Confirmed by an independent result from the CMB ripples.

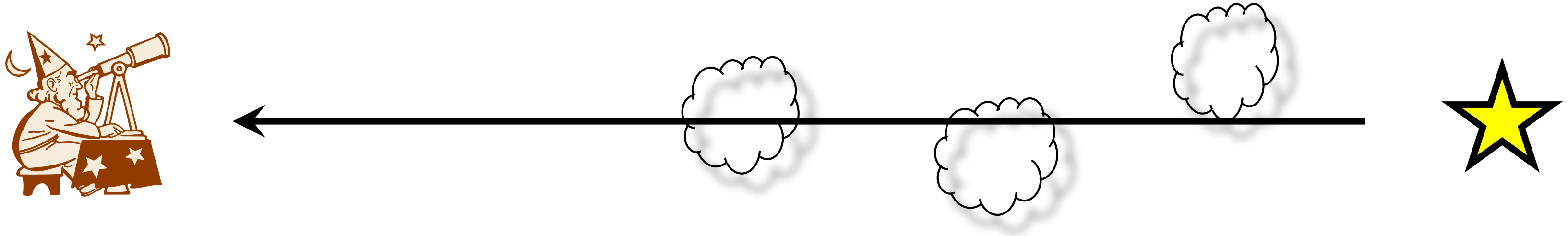


Less Deuterium at higher densities

Can we find primordial gas ?

Observations can check the BBN predictions.
But we **must find primordial gas, not yet polluted by stars**.

1) D/H ratio from "Lyman-alpha clouds":



Quasar spectra show a "forest" of Lα absorption lines, formed in gas clouds at various redshifts along the line of sight.

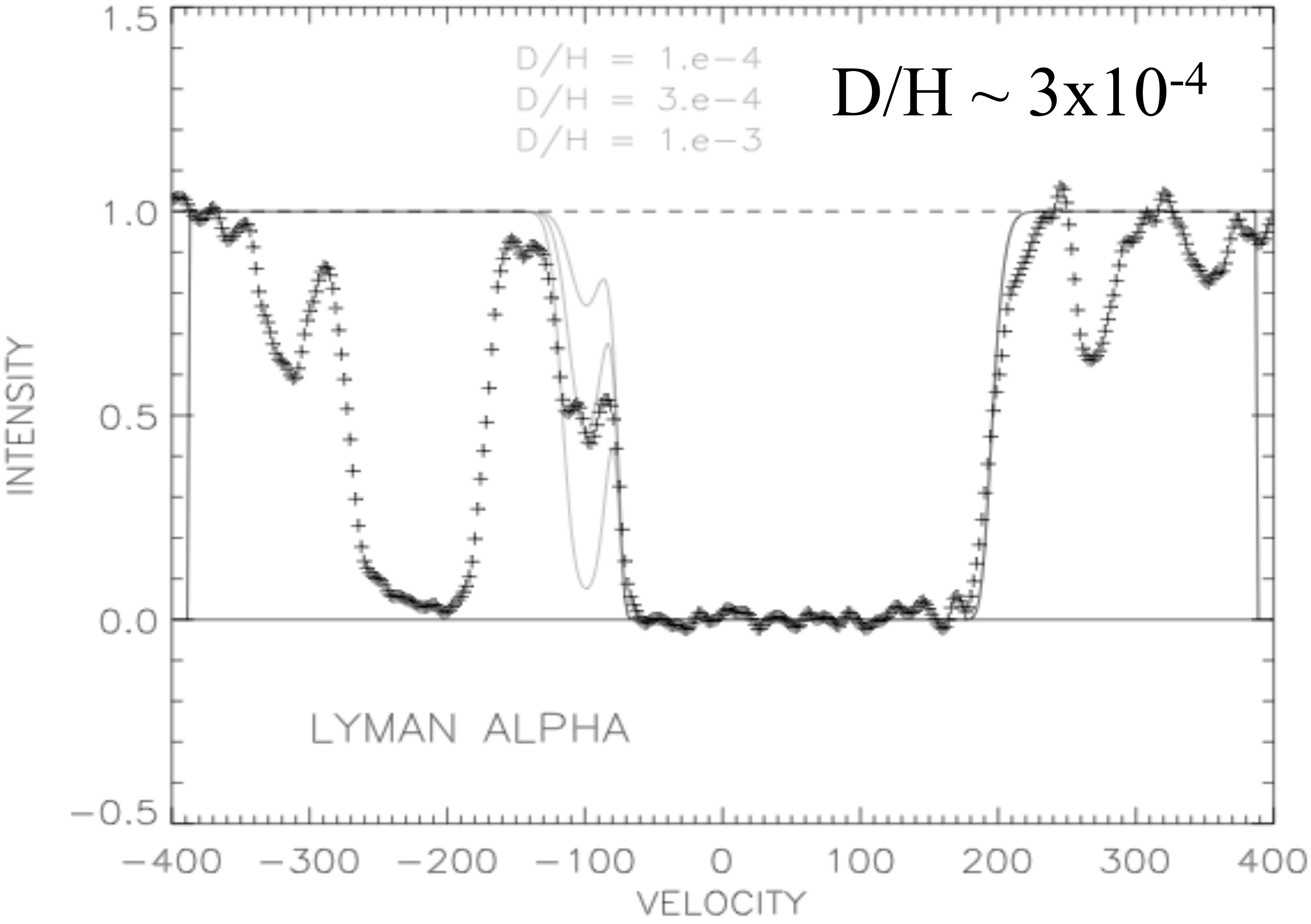
Line strengths give D/H abundance in primordial gas clouds (where few or no stars have yet formed).

2) He/H ratio from nearby low-metalicity dwarf galaxies:

High gas/star ratio and low metal/H from emission lines in HII regions suggest that interstellar medium still close to primordial

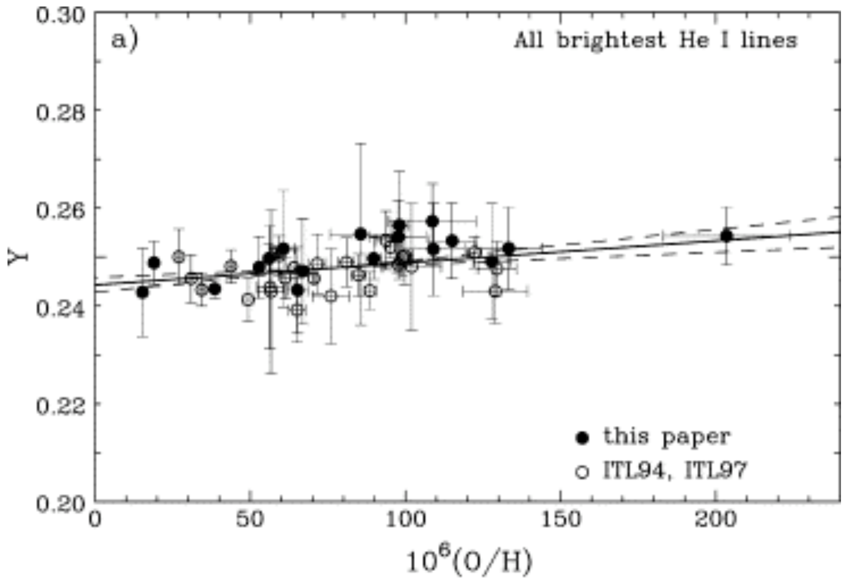
Primordial D/H from Lα clouds

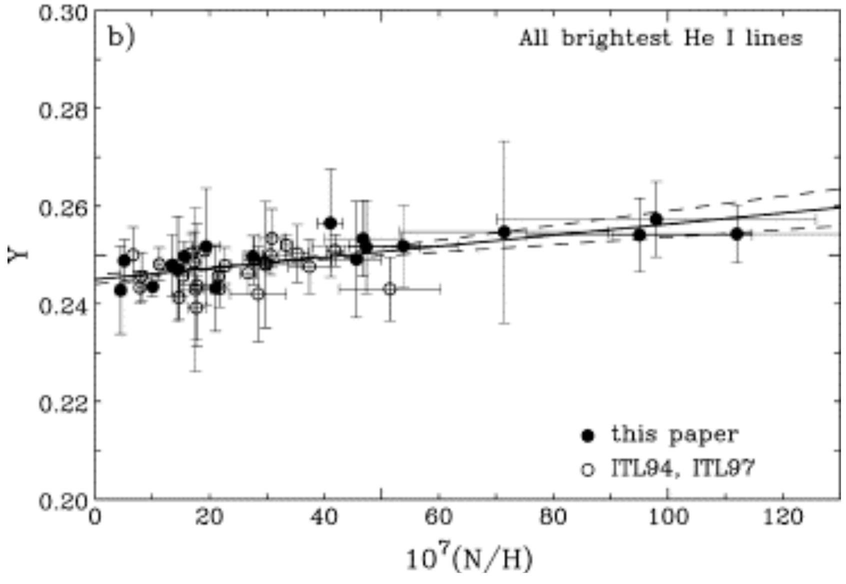
Lα (+Deuterium Lα) line in quasar spectrum:



Yp = primordial He/H from dwarf galaxies

- Emission lines from H II regions in low-metalicity galaxies.
- Measure abundance ratios: He/H, O/H, N/H, …
- Stellar nucleosynthesis increases He along with metal abundances.
- Find $Y_p = 0.245$ by extrapolating to zero metal abundance.





Summary of BBN

Mostly H (75%) and ^{4}He (25%) emerge from the Big Bang, plus traces of metals (~0%) up to ^{7}Li.

The strong binding energy of ^{4}He largely prevents formation of heavy metals.

Observed primordial abundances confirm predictions, and measure the baryon density

$$\Omega_b \approx 0.04$$

Next time: ***Matter-radiation decoupling***

Formation of the CMB