Lecture 3: Big Bang Nucleosynthesis

Last time:

particle anti-particle soup

--> quark soup

--> neutron-proton soup.

Today:

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

Big Bang Nucleosynthesis

Starts with Deuterium formation

$$n + p \rightarrow D + \gamma$$

when the high energy tail of blackbody photons no longer breaks up D. Binding energy E=2.2 MeV.

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

$$k\,T \sim 0.1 \text{ MeV} \;\; (T \sim 10^9 \text{ K} \quad t \sim 100 \text{ s})$$

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

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

Deuterium readily assembles into heavier nuclei.

Key Fusion Reactions

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

Deuterium Bottleneck

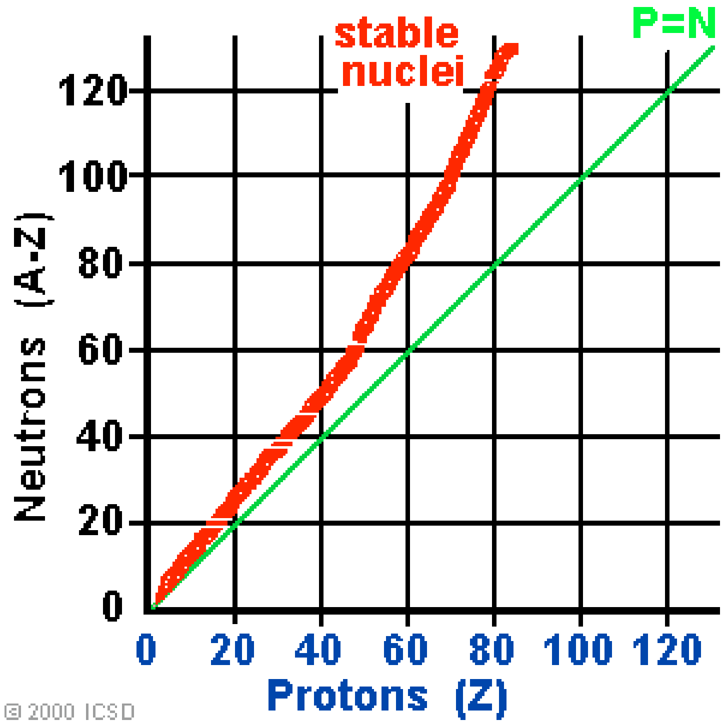
Note:

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

→ **Deuterium bottleneck**

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

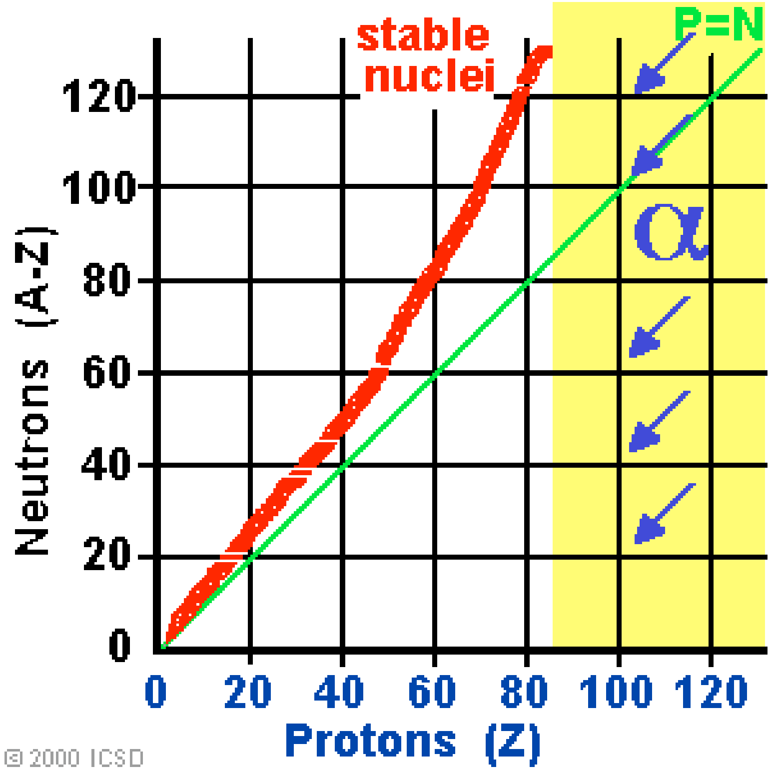
What about Heavier Nuclei?



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^-)



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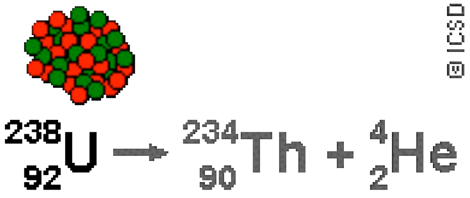
α decay



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

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

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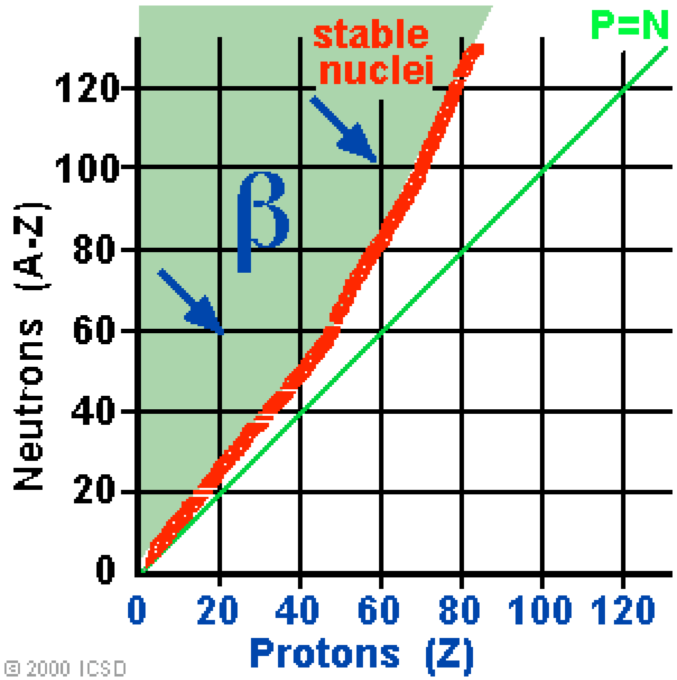
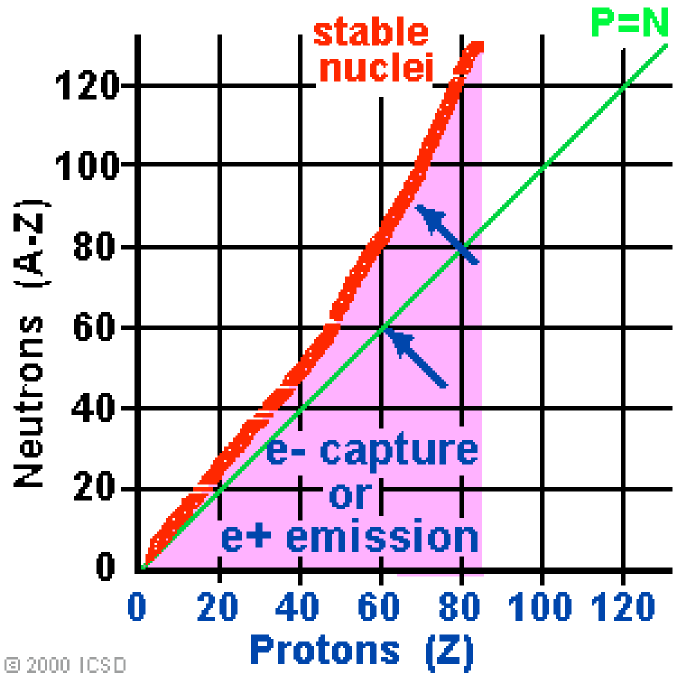
Photon emission



β decay

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



Positron emission

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

Electron capture

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

BBN stalls

The main problem:

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

Nuclei with A = 5 are unstable!

Further fusion is rare (lower binding energies):

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

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

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

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

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. [i.e., p+p 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

Residual D, T, ^{7}Li, ^{7}Be.

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

Note*: In astronomy all nuclei with A > 4 are known as metals.*

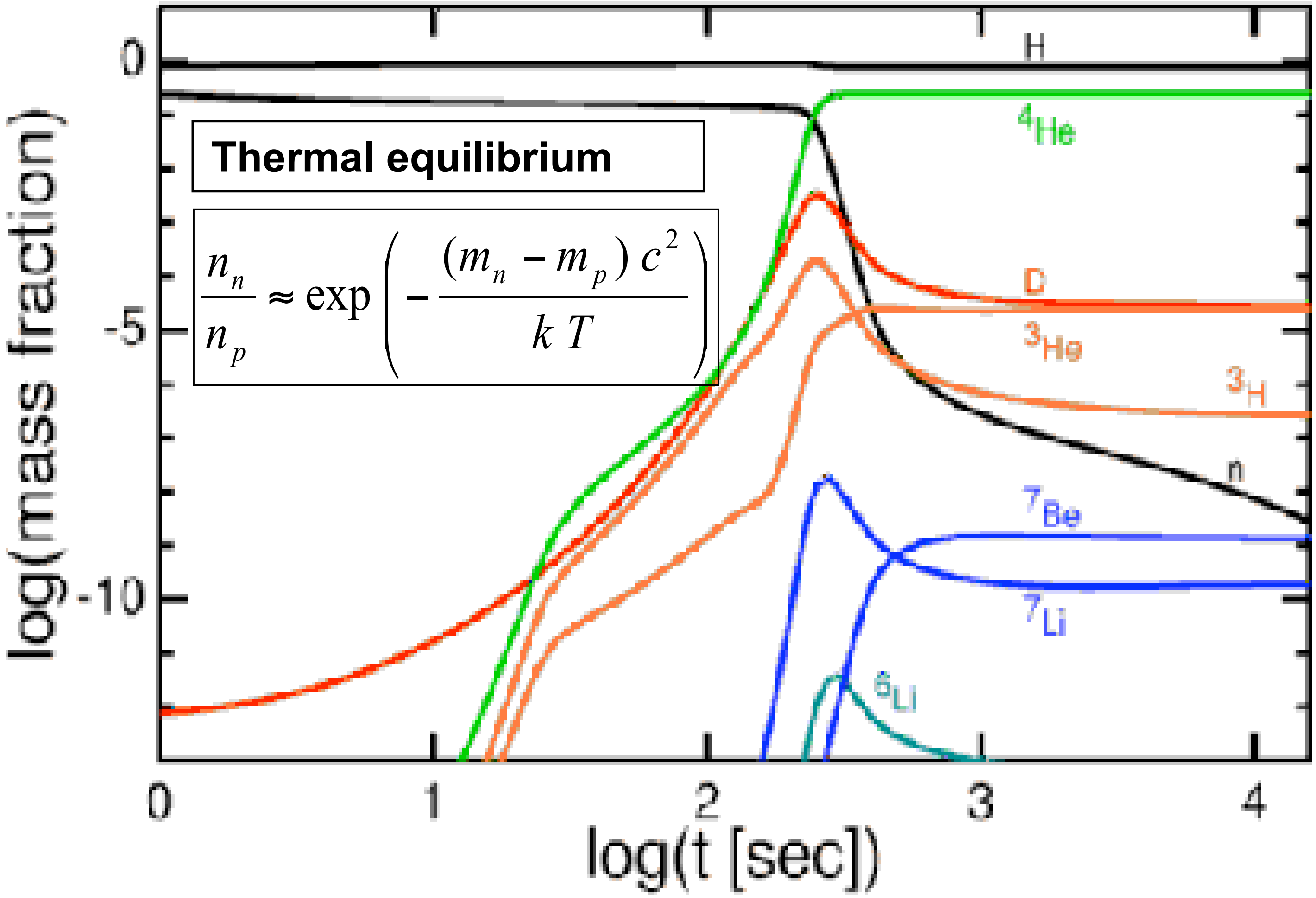
Since the 1960's, computers simulating Big Bang Nucleosynthesis using known reaction rates give detailed abundance predictions:

$\boldsymbol{X_p} = 0.75$ $\boldsymbol{Y_p} = 0.25$ $\boldsymbol{Z_p} = 5\text{x}10^{-5}$

Big Bang Nucleosynthesis

Expansion, cooling

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



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

neutrons decay

Sensitivity to Parameters

Abundances depend on two parameters:

1) cooling time vs neutron decay time

(proton - neutron ratio)

2) photon-baryon ratio

(*T* at which D forms)

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) sensitive to these 2 parameters.

Why?

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

Also, 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.

$$\Omega_b \approx 0.04$$

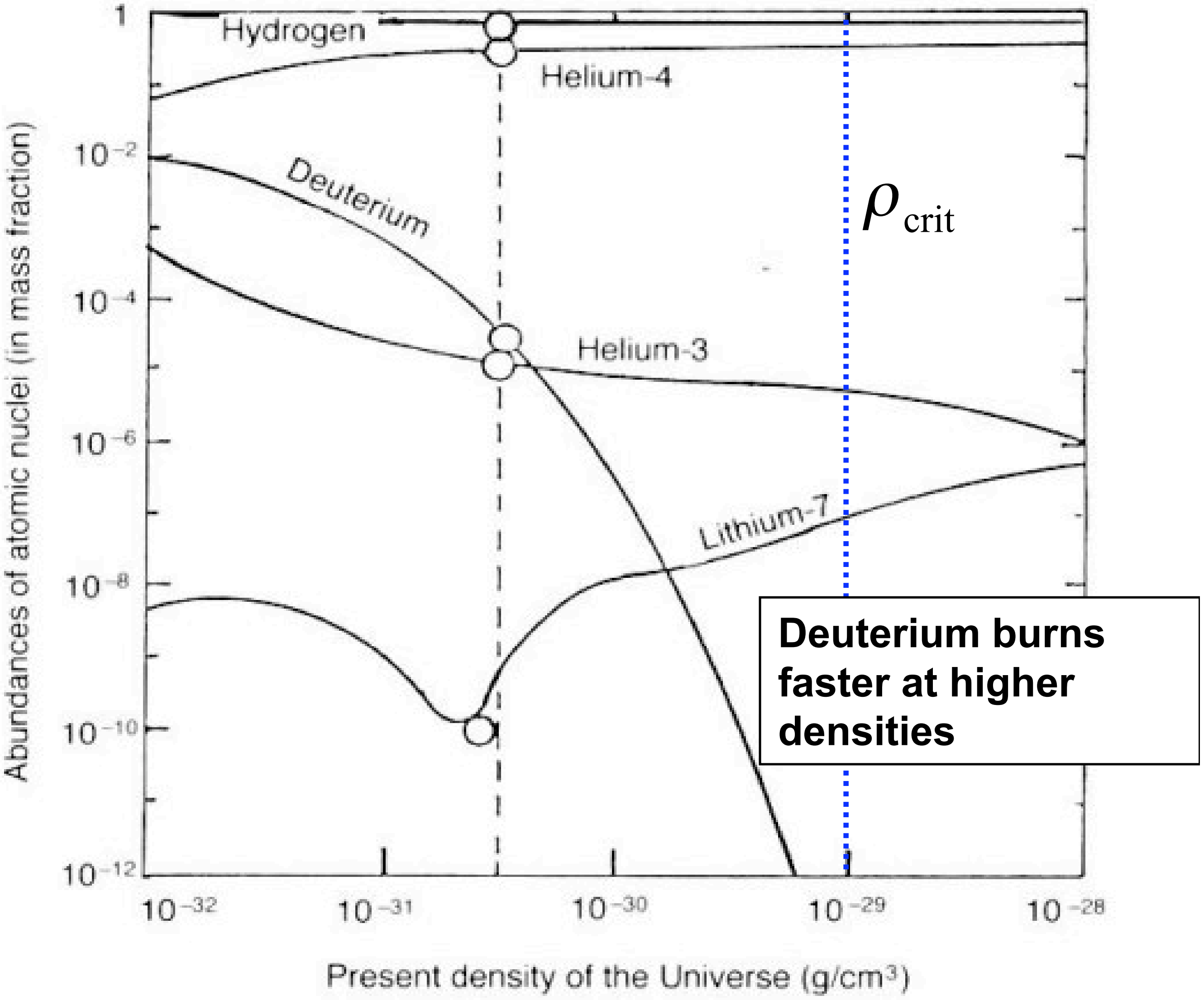
Baryon Density Constraint

Observed abundances require

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

~4% baryons

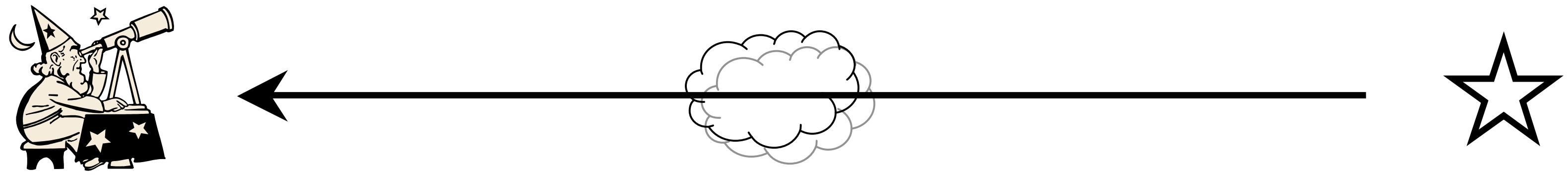
consistent with CMB



Deuterium burns faster at higher densities

Observations can check the predictions, but must find places not yet polluted by stars.

- Lyman-alpha clouds

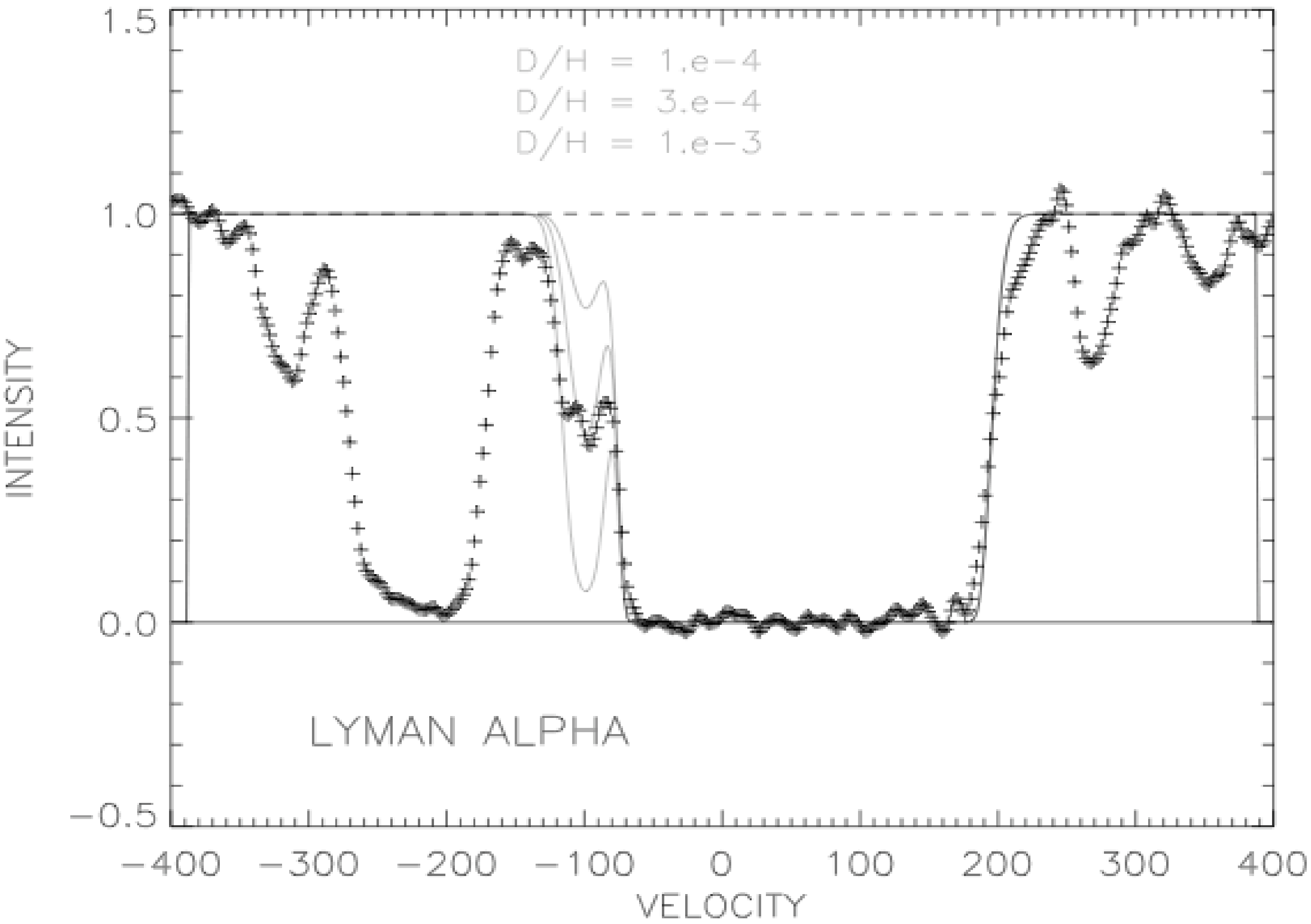


Quasar spectra show absorption lines. Line strengths give abundances in primordial gas clouds (where few or no stars have yet formed).

- nearby dwarf galaxies

High gas/star ratio and low metal/H in gas suggest that interstellar medium still close to primordial.

D/H measurement



Summary

Mostly H (75%) and ^{4}He (25%) emerge from the Big Bang, plus a few 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