Nucleosynthesis in the Early Universe

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PhD course in Cosmolgy
grad U 2005

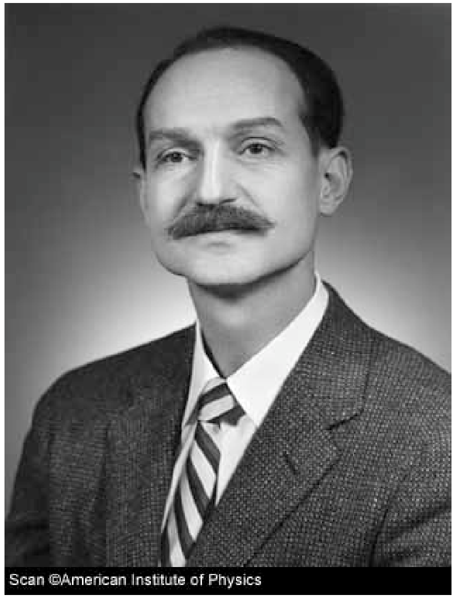
Outline

- Historical remarks
- Basic physics
- Predictions from theory
- Observations
- Remaining problems
- Out of dark age
- Future?

George Gamow (1904-68)
Ralph Alpher (1921 -)
Robert Herman (1914-97)

Alpher, Bethe and Gamow (1948), Phys. Rev.

Alpher, Herman and Gamow (1948-49), Phys Rev.



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Alpher, Herman and Gamow:

Early universe made of neutrons

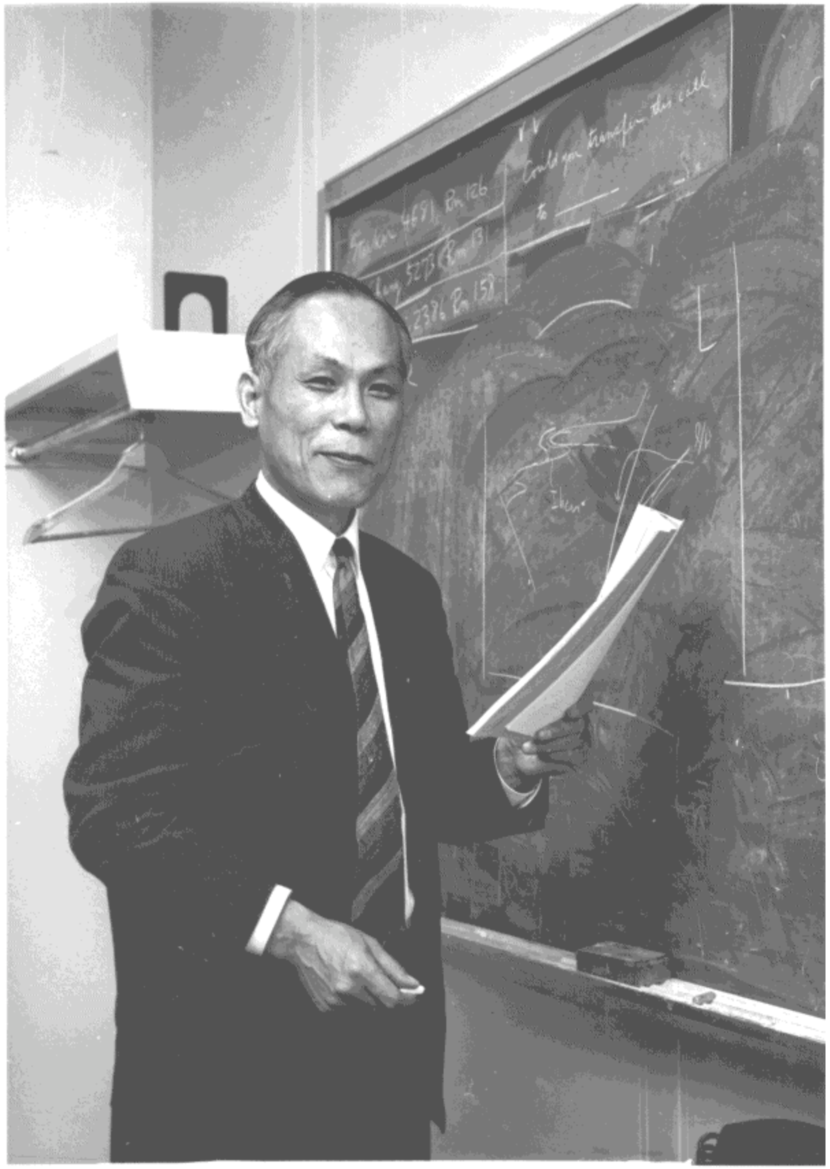
n -> p + e + $\square_e$

U will cool so that heavy elements do not disintegrate. Obs of abudances of light elements require $N_{\square}/N_B = 10^9$ =>

5K present background radiation.

- Improved as regards □ processes etc by C. Hayashi (1950) and

  Alpher, Herman and Follin Jr. (1953).



NASA G-68-10,414

A frustrated continuation

- None of these people set out to discover the radiation (could technically have been done during the 50’ies). Alpher and Herman do not discuss it further.
- Gamow repeats the prediction but on fallacious grounds 1953. These were out for a greater goal!
- Dicke and Peebles start trying obs. in early 60:ies.
- Penzias and Wilson happen to discover it in 1965.
- Wagoner, Fowler and Hoyle make first detailed predictions of BB nucleosynthesis 1967.
- For further details, see S. Weinberg: *The first three minutes*, Chapter VI.

Basic physics

(a) Dynamics of the expansion

Isotropy, homogeneity => Robertson-Walker metric:

$H^2 = [1/a\,(da/dt)]^2 = 8\pi/3\ G\rho - k\,c^2/a^2 + \Lambda/3$

Non-relativistic conserved particles: $n \sim a^{-3}$

Relativistic particles: $n \sim a^{-4}$

Early on, radiation dominated universe:

$H^2 \approx 8\pi/3\ G\rho_R$, integrate: $32\,\pi/3\ G\rho_R t^2 = 1$ (1)

$\rho_R \sim T^4$ => $T \sim t^{-1/2}$. Note that the total number density of all relativistic particles, known and unknown, are in play here!

After 1s: $kT \sim 1$ MeV, $T \sim 10^{10}$ K.

Basic physics

(b) Particles

like e^-, e^+, $\square_e$, $\square_e$, $\square$, a few p, n, ...

- $n + e^+ \langle\text{-->} p + \square_e$
- $n + \square_e \langle\text{-->} p + e^-$
- $n \langle\text{-->} p + e^- + \square_e$ (half life 887 s)

In equilibrium:

$N_n/N_p = \exp[-\square mc^2/kT] = \exp[\,-1.5\text{x}10^{10}\text{ K }/T\,]$ (2)

Equilibrium?

Equilibrium?

Typical density of photons: $n_{\square} \approx 10^{-7.5}$ $T^{3(}$MeV) f^{-3}

(1f $=10^{-13}$ cm).

Length scale: $l_{\square} \approx 300\ T^{-1}$ (MeV) f $\approx l_e \approx l_{\square}$.

Quite dilute! Nucleons (p and n) at hundred times greater distance. Causal horizon scale: 10^{21} times larger!

Typical reaction rates (weak interaction):

$R_{WI} \approx (T/10^{10.135}\ \mathrm{K})^5$ (3)

Thus, R_{WI} drops very rapidly with T.

At expansion, the weak interactions are suddenly swiched off; ”*neutron freeze out*”.

Comparison between expansion rate (1) and R_{WI} gives freeze out around 1 MeV <-> 10^{10}K, t ≈ 1 s.

What is then the neutron density?

(2) => $N_n/N_p \approx 1/7$.

Another freeze out:

Weak interaction reactions also keep *neutrinos* in equilibrium; The last important reaction is

□+□ <--> $e^- + e^+$

Neutrinos freeze out (decouple) at somewhat higher T (matrix element^2 for nuclear interaction x5 due to axial coupling), at about $3\text{x}10^{10}$ K. Must be taken into account in detailed calculations.

Neutrino background forms. Electron gas keeps interacting with photons,

$e^- + e^+$ <□> □+□;   e + □<□> e + □.

When T < 1.03 MeV, pair production stops, annihilations heat photon gas and $T_□/T_□$ -> $(11/4)^{1/3.}$ Presently 400 microwave photons per cm^3, 109 neutrinos per cm^3.

What happens to the neutrons ?

Nuclear reactions:

Neutrons react with protons -- in time before decay?

$n + p \rightarrow {}^2D + \square$

${}^2D$ binding energy $\square = 2.225$ MeV

$m_e c^2 = 0.52$ MeV; $m_n - m_p = 1.31$ MeV.

But photon/baryon ratio is high ($\sim 10^{10}$) so that photons disintegrate D:s efficiently below T=2.225 MeV.

Saha equation:

$N_d/N_p = N_n \text{ const } T^{-3/2} \exp(\square/kT)$.

N_d stays low until crossover at about $T \approx 10^{8.9}$ K.

This is after about 3 minutes = 180 s.

Exact integration (including n decay) gives

$N_n/N_p \approx 0.163\ (\square_{\square}\, h^2)^{0.04}\ (N_{\square}/3)^{0.2}$ (4)

What happens with the deutrons?

Further reactions:

$^{2}D(n, \square)^{3}H$, $^{2}D(d, p)^{3}H$

$^{2}D(p, \square)^{3}He$, $^{2}D(d, n)^{3}He$

$^{3}He(n, p)^{3}H$, $^{3}H \rightarrow {}^{3}He + e^{-} + \square_{e}$

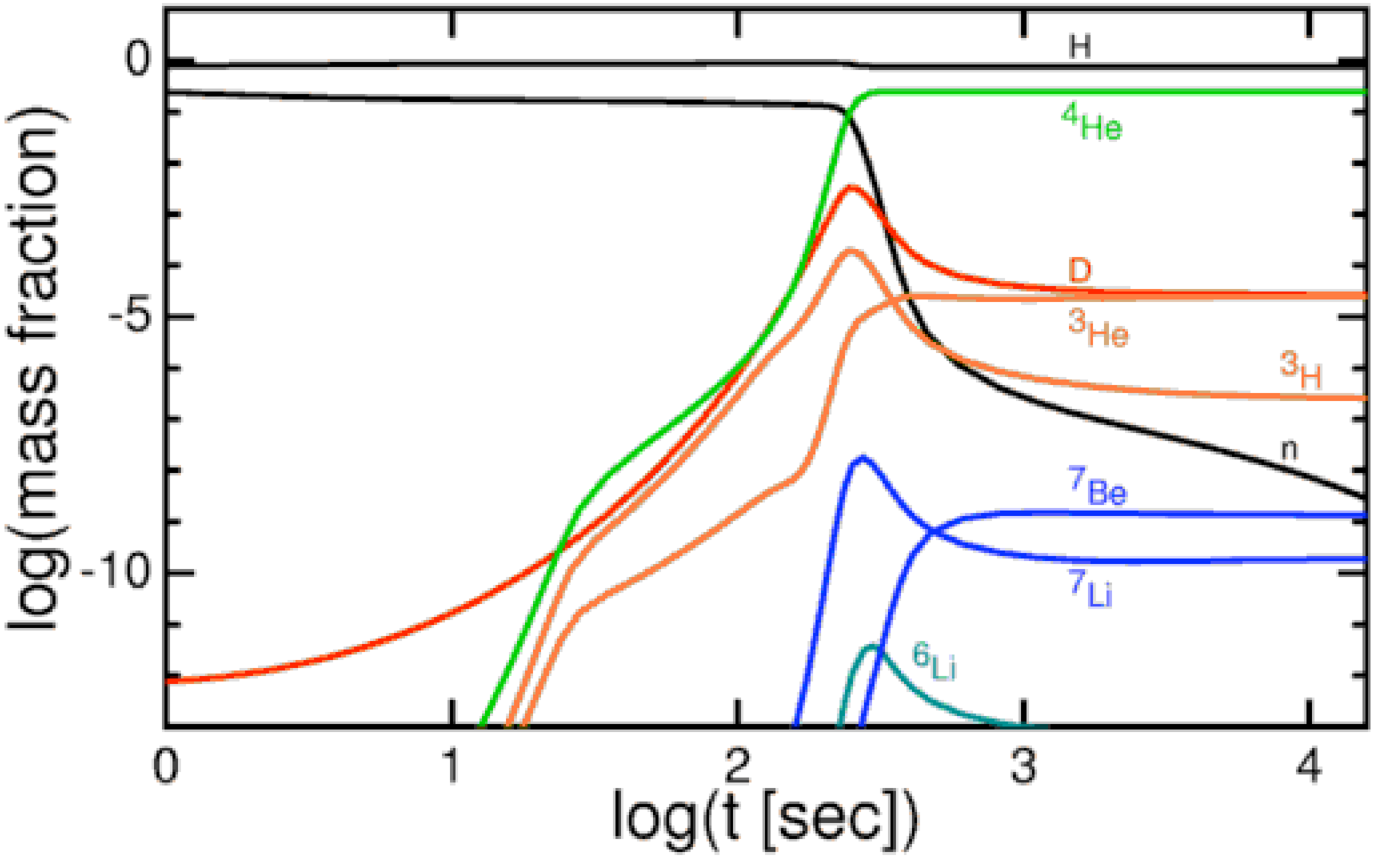
$^{3}He(n, \square)^{4}He$, $^{3}H(d, n)^{4}He$, $^{3}He(^{3}He, 2p)^{4}He$

To calculate: a system of ordinary diff. equations.

In equilibrium, one may show that

$N_{Z,A} = f(Z,A)\, T^{-3(A-1)/2}\, N_{p}^{Z} N_{n}^{(A-Z)} \exp(\square/kT)$ (5)

^{4}He is favoured by large □, however higher A disfavoured by A dependence of f and T term.



The evolution of nuclear abundances in the standard Big Bang model. From Burles, Nollett and Turner (1999), here assuming $\Omega_B h^2 = 0.029$.

Still further reactions:

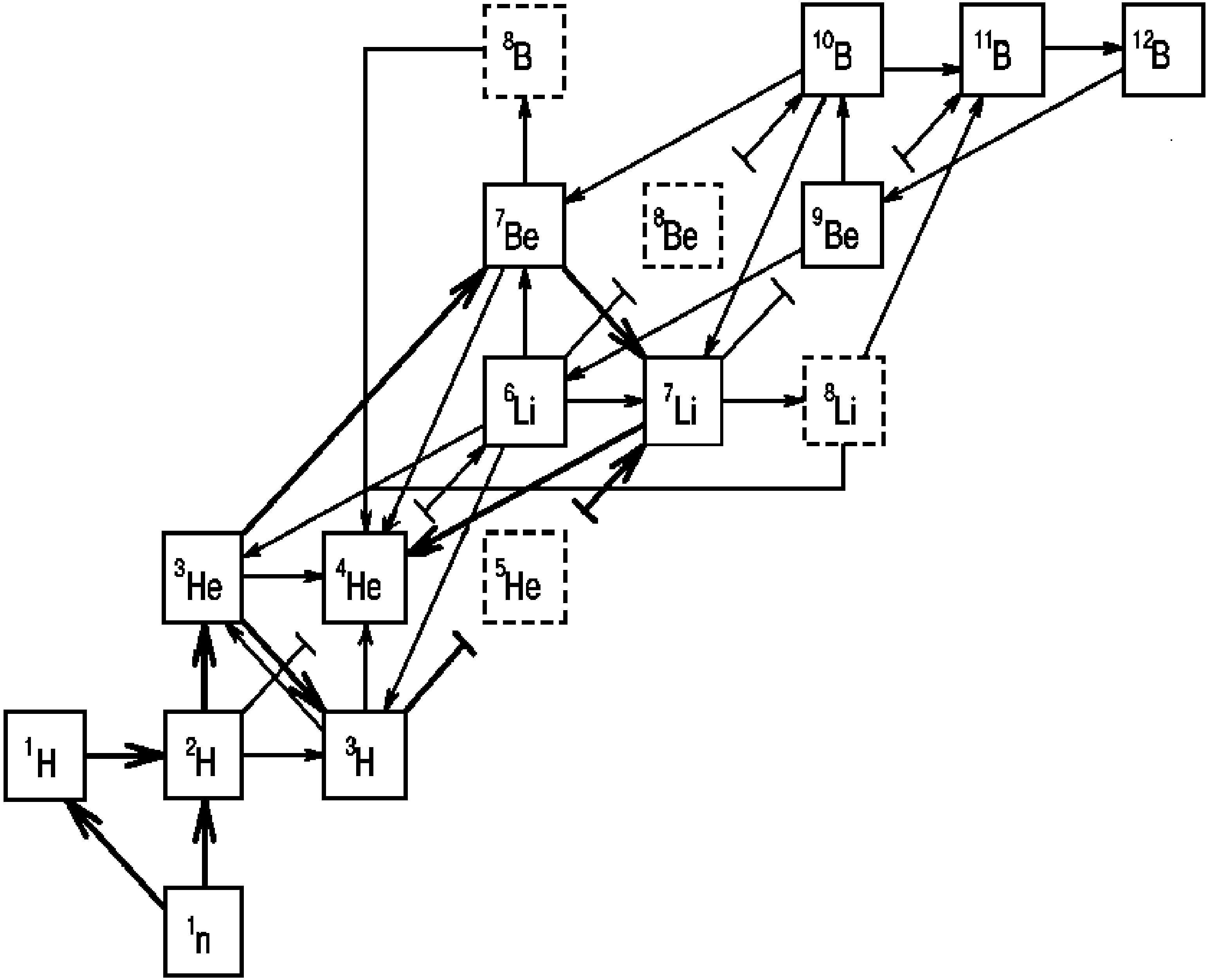
Coulomb barriers (exp ($\square$/kT) in (5)), the cooling universe and no stable nuclei at A=5 and 8 prevent higher elements to form. However,

$^{4}\mathrm{He}(^{3}\mathrm{H}, \square)^{7}\mathrm{Li}$

$^{4}\mathrm{He}(^{3}\mathrm{He}, \square)\ ^{7}\mathrm{Be}(e^{-}, \square_{e})^{7}\mathrm{Li}$

$^{7}\mathrm{Li}(p, \square)\ ^{4}\mathrm{He}$

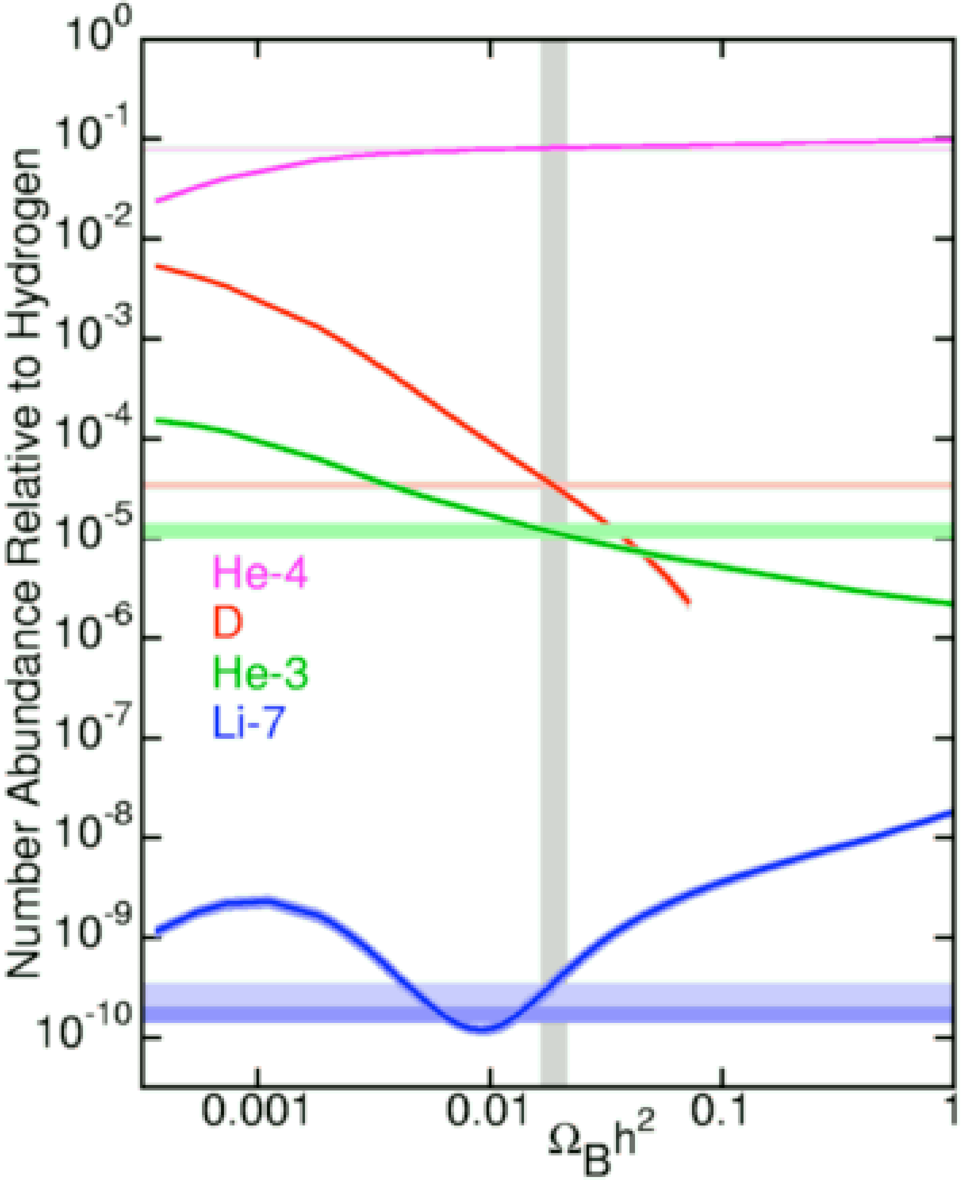
give traces of ^{7}Li and some ^{7}Be.



calculations

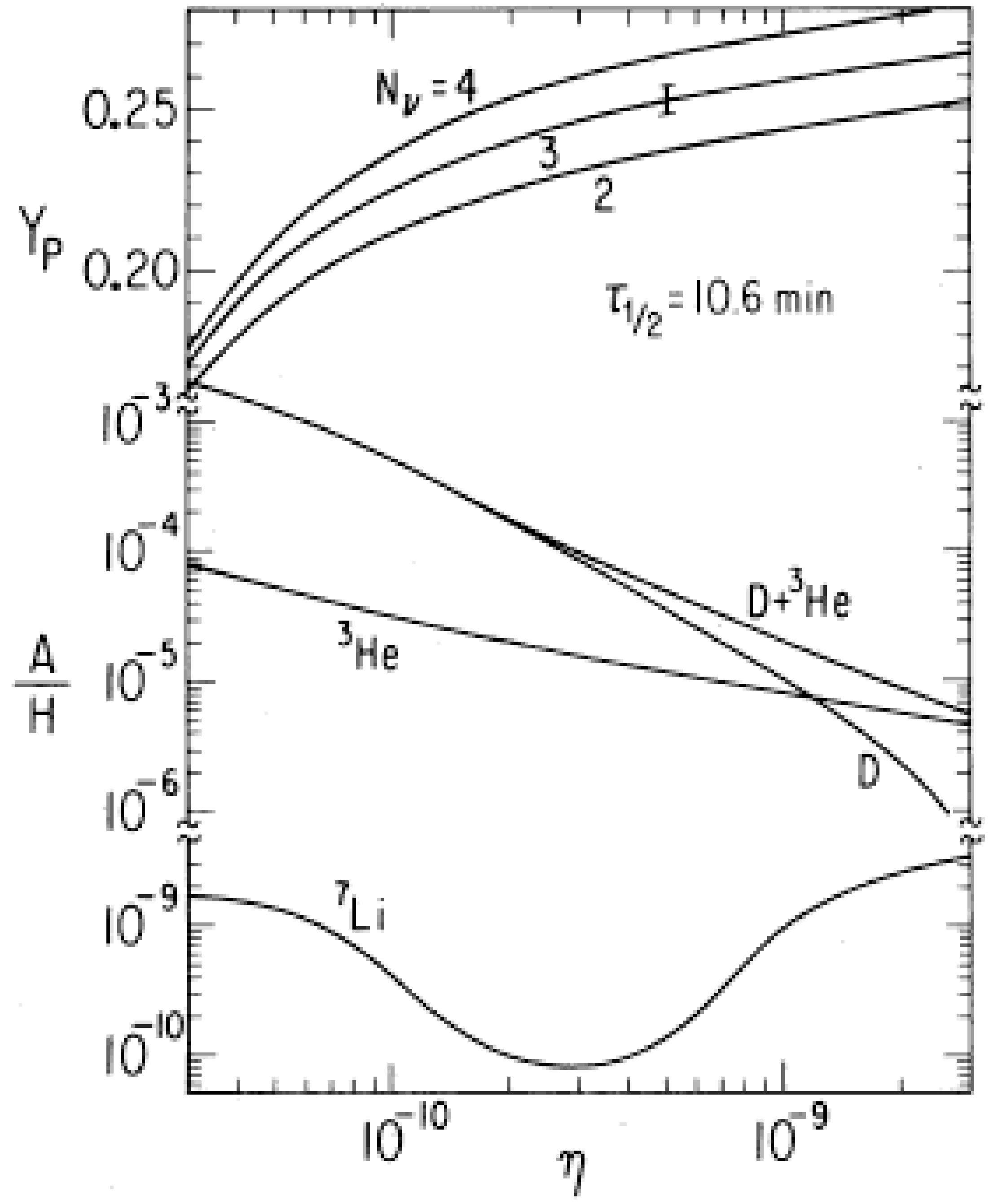
Predictions from theory

and observed abundances of light elements. $N_{\square} = 3$.



$$\square = N_B/N_{\square}$$

$$= 2.7 \cdot 10^{-8} \, \square_B h^2$$


Y_P
0.25
0.20
$N_\nu = 4$
3
2
$\tau_{1/2} = 10.6$ min
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$\frac{A}{H}$
D+^{3}He
^{3}He
D
10^{-9}
10^{-10}
^{7}Li
10^{-10}
10^{-9}
η

N_ν?

Increase in N_ν increases expansion rate (ρ_R in (1)).

Then more n survive until nucleosynthesis starts =>

greater He abundance.

Experimental limit, LEP (Cern):

Z by e^+e^- collisions, energy width of Z

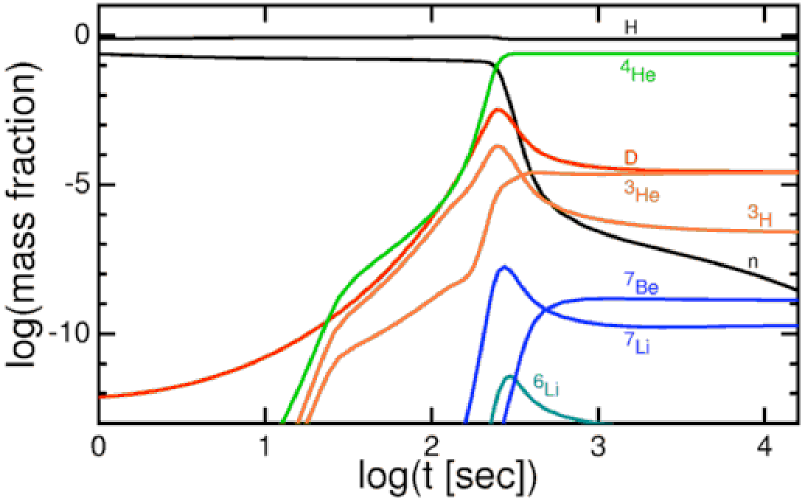
=> $N_\nu = 2.984 \pm 0.008$ (2001)

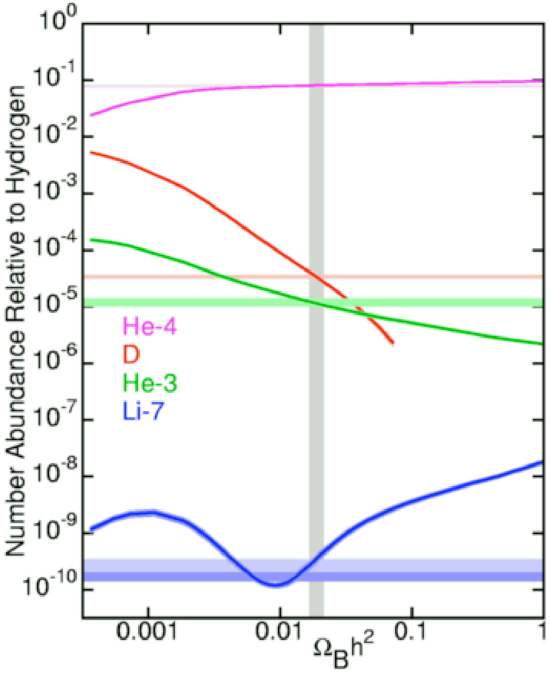
From BB + He abundance: $N_\nu = 3 \pm 0.3$.

A victory (1990)!

Constraints on other particles, see below!

Discussion of abundances: ^{2}D



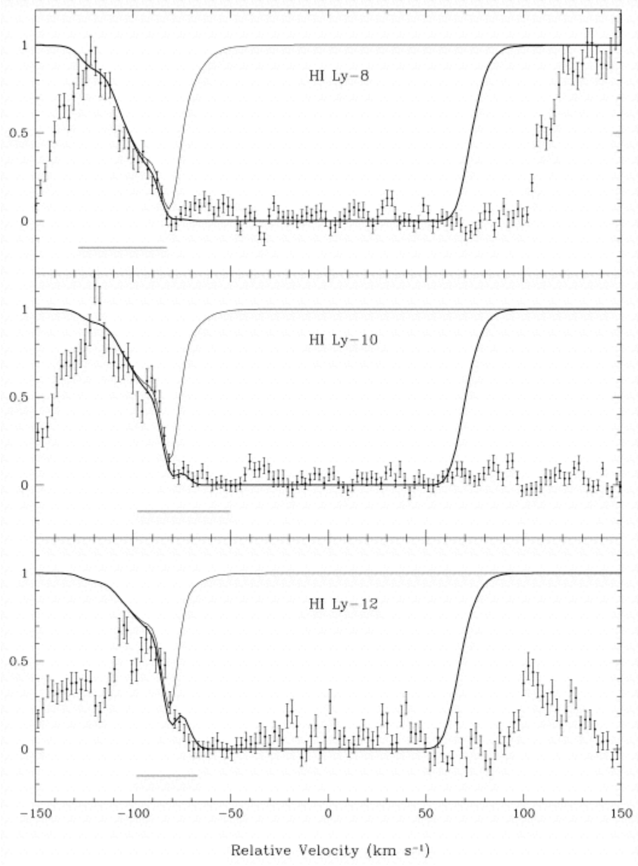


- ^{2}D starts growing by p(n,□)^{2}D, rather late due to photodisintegration
- ^{2}D is then consumed by ^{2}D+p etc.

- ^{2}D decreases in proportion to □$^{-1.7}$ due to incr. two-body collisions.
- ^{2}D is not easy to observe spectroscopically, and is also destroyed in stars, but

not made!

Observations of ^{2}D



- Only upper limjt to ▯
- Measurement in low metallicity clouds seen against distant quasars

<= Levshakov et al. (2002)

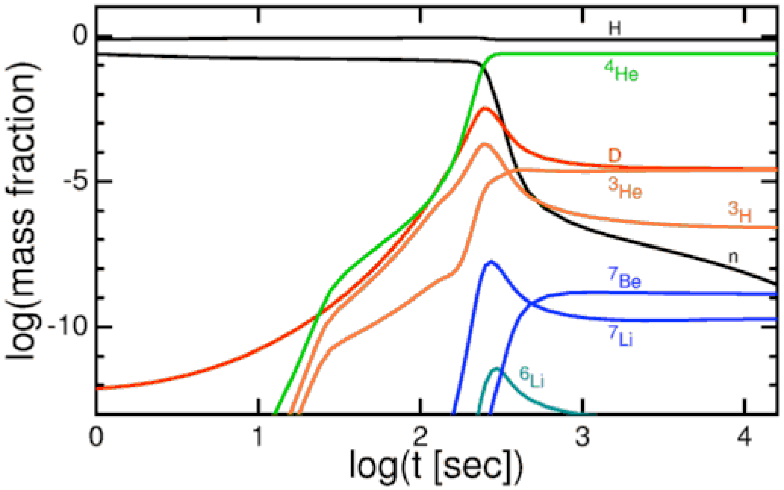
Q 0347-3819, $z_{abs}= 3.02$

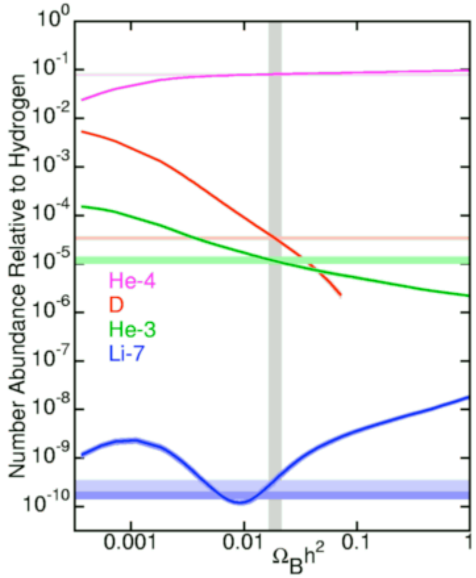
- Complex velocity structures of clouds. Isotope shifts hard to distinguish from velocity-shifted H.
- Conflicting results, like

$3 \cdot 10^{-5} < D/H < 4 \cdot 10^{-5}$ or

$10 \cdot 10^{-5} < D/H < 20 \cdot 10^{-5}$

Discussion of abundances, ^{3}He





^{3}He is produced by D+p -> ^{3}He, then ^{3}He+n -> ^{4}He

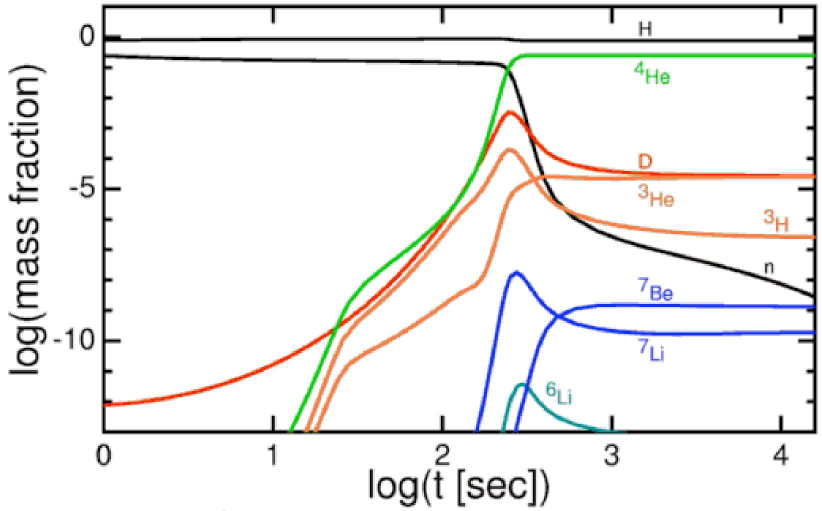
^{3}He rizes as ^{4}He but is always less due to lower binding energy

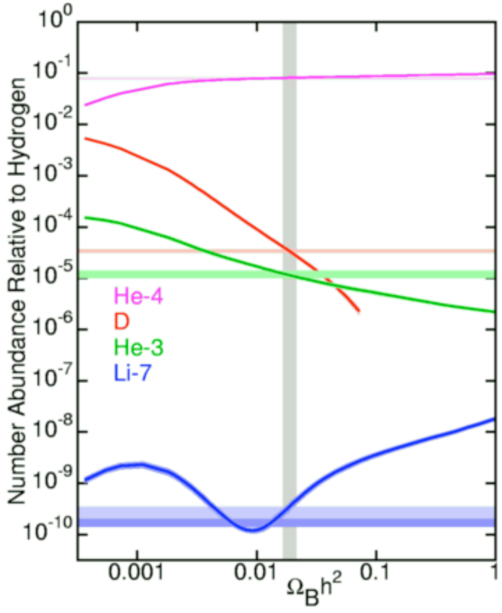
(7.72 MeV and 28.3 Mev, respectively).

^{3}He pressure sensitive as is ^{2}D.but less so due to higher binding energy.

^{3}He is produced in stars by ^{2}D burning, ^{3}He + ^{2}D = unchanged.

Discussion of abundances, ^{4}He



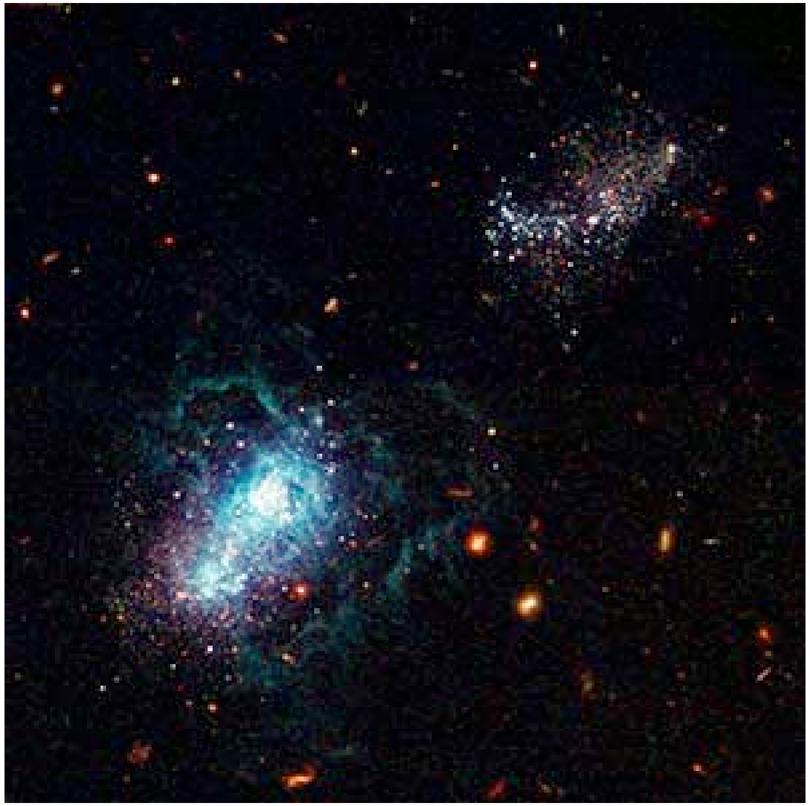


High binding energy => almost all remaining n goes into ^{4}He. Simple counting arguments:

$Y \approx 2(N_n/N_p)/[1+(N_n/N_p)] = 0.25$ for $N_n/N_p=1/7$.

Y changes little with time in the Galaxy.

$Y=Y_p+\square Y/\square Z\ \square Z$



- I Zwicky18

  O/H ≈ 0.02 solar
- Several recent bursts, the most recent about 4 10^6 years ago, oldest about 500 $\cdot 10^6$ years,

Discussion of abundances, ^{4}He, cont.

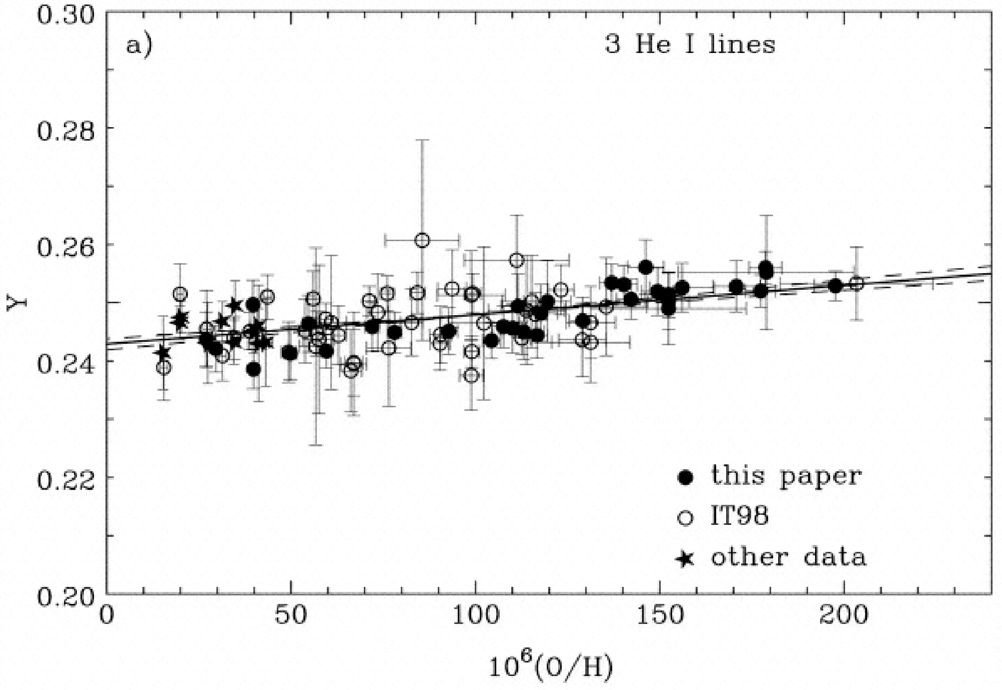
$Y=Y_p+\Delta Y/\Delta Z\ \Delta Z$

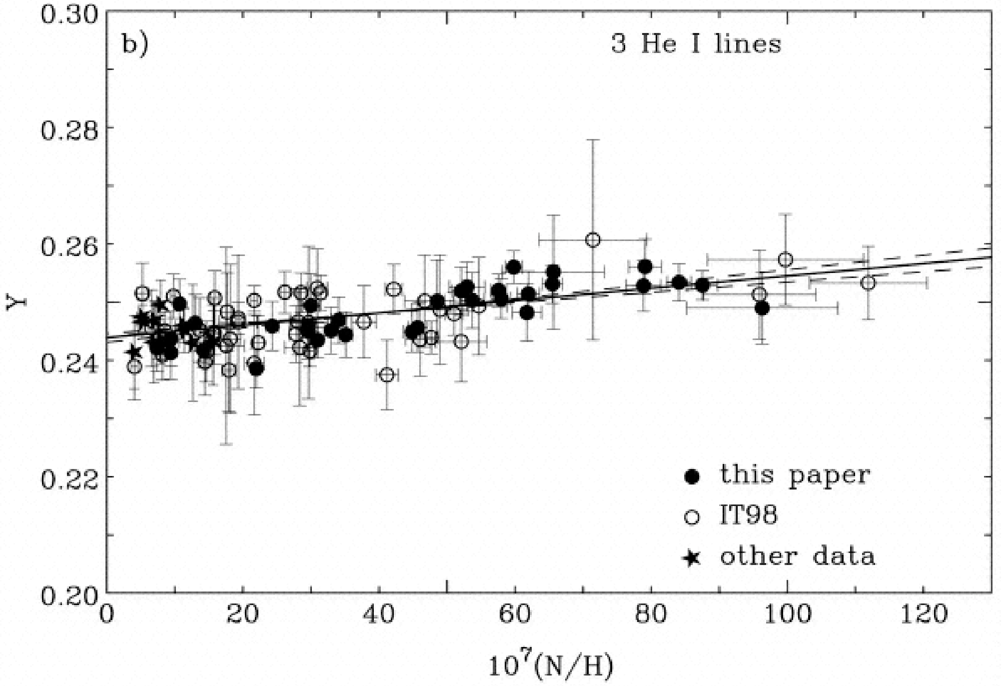
$\Delta Y/\Delta Z$ estimated from gaseous nebulae in Blue Compact Galaxies

E.g. Izotov & Thuan (2004) => $\Delta Y/\Delta Z = 3.7 \pm 1.2$ =>

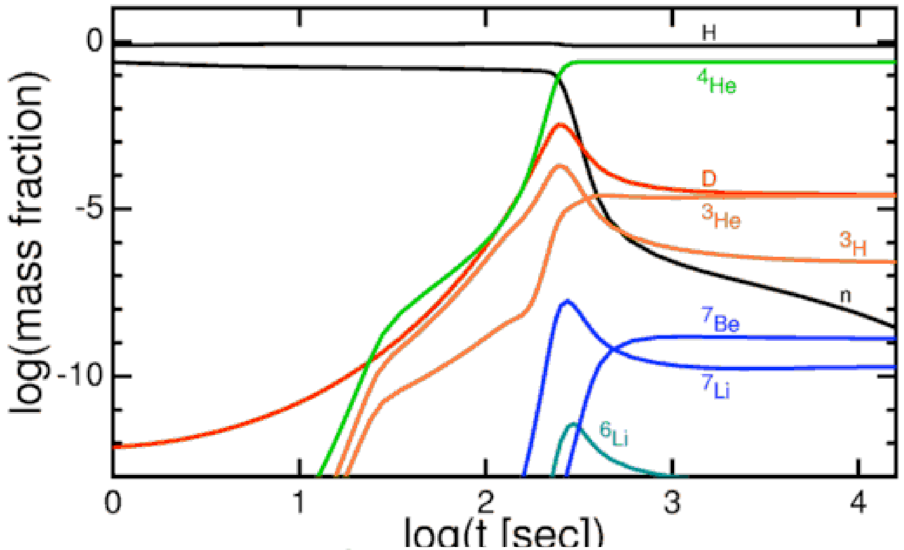
$Y_p = 0.242 \pm 0.002$.

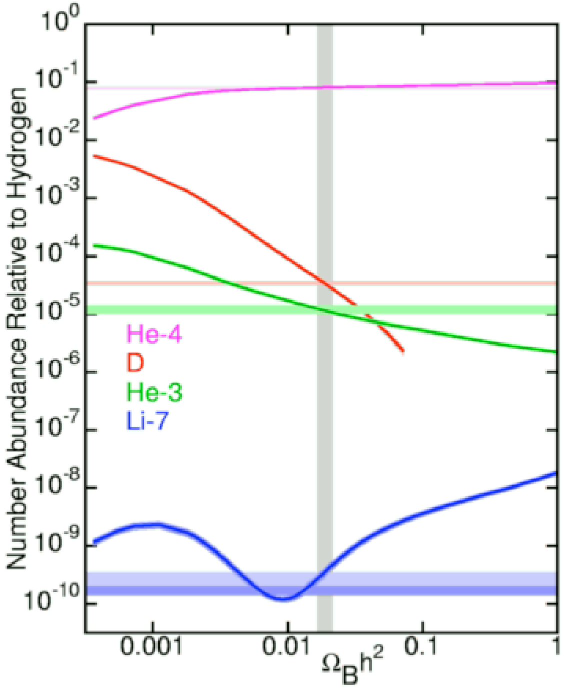
Other groups get lower values, such as 0.234 ±0.003, Peimbert et al. (2000)





Discussion of abundances, ^{7}Li





At low ($< 3\cdot10^{-10}$) ^{7}Li is produced by ^{4}He(^{3}H,)^{7}Li and burned away by ^{7}Li(p,)^{4}He.

For greater the production channel ^{7}Be(e^{-}, $_{e}$) ^{7}Li takes over when ^{7}Be becomes available.

Since ^{7}Be is unstable, this works more efficiently the higher

^{7}Li is destroyed by burning in stars at temperatures $T>10^{6}$ K

How much mixing of surface layers of stars?

The Li plateau (Spite & Spite 1982)

F. Spite and M. Spite: Lithium in Halo Stars

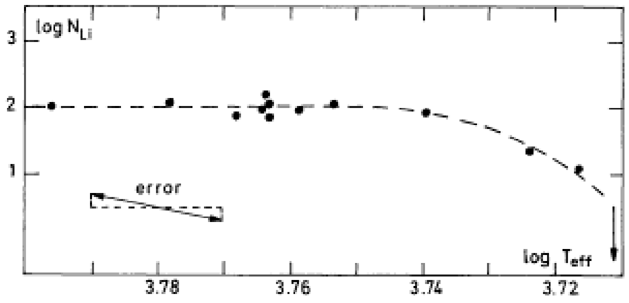
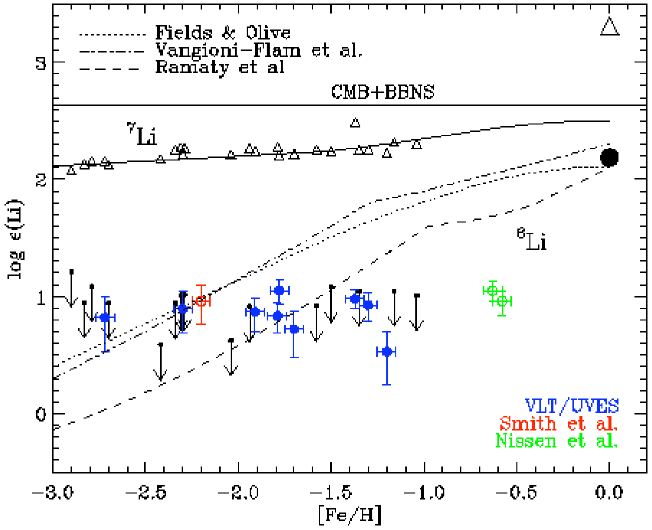


Fig. 5. N_{Li} versus $\log T_{\mathrm{eff}}$ for old halo stars



Predicted abundance: $A(\mathrm{Li}) = 2.6 \pm 0.02$
Observed mean LTE abundance $\langle A(\mathrm{Li})_{-2.8}\rangle = 2.12 \pm 0.02$

Corrections to apply:

(1) GCE/GCR	-0.11	+0.07/-0.09
(2) Stellar depletion	+0.02	+0.08/-0.02
(3) T_{eff}-scale zeropoint	+0.08	± 0.08
(4) 1-D model atmosphere	0.00	+0.10/-0.00
(5) model temperature gradients	0.00	+0.08/-0.00
(6) NLTE	-0.02	± 0.01
(7) *gf* values	0.00	± 0.04
(8) anomalous/pathological obj.	0.00	± 0.01
Total correction	-0.03	+0.19/-0.13

Inferred primordial abundance

A(Li) 2.09 +0.19/-0.13
Ryan (2005)

Even a ^{6}Li plateau??

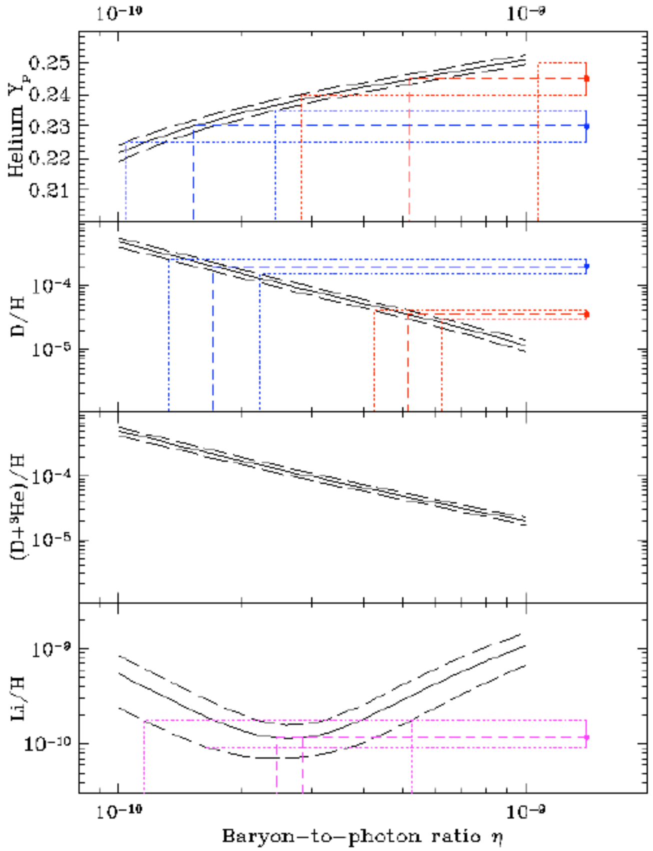
Errors in predictions?

- 0.4% for Y (coming from n half life 887±2 s)
- ~ 10% for ^{2}D and 20% for ^{7}Li.
- WMAP settles parameters

  Ω_B=0.0224±0.0009 => D/H$_{pred}$ = 2.6 ±0.2 $\cdot 10^{-5}$

  somewhat less than observed.

Comparison to observ.



Is there a unique value of η where predictions agree with observations?

Does this value agree with η(WMAP)?

Observed

η = (1.7-3.9)·10^{-10} (95% conf.)

WMAP:

η = (6.1-6.7) ·10^{-10}

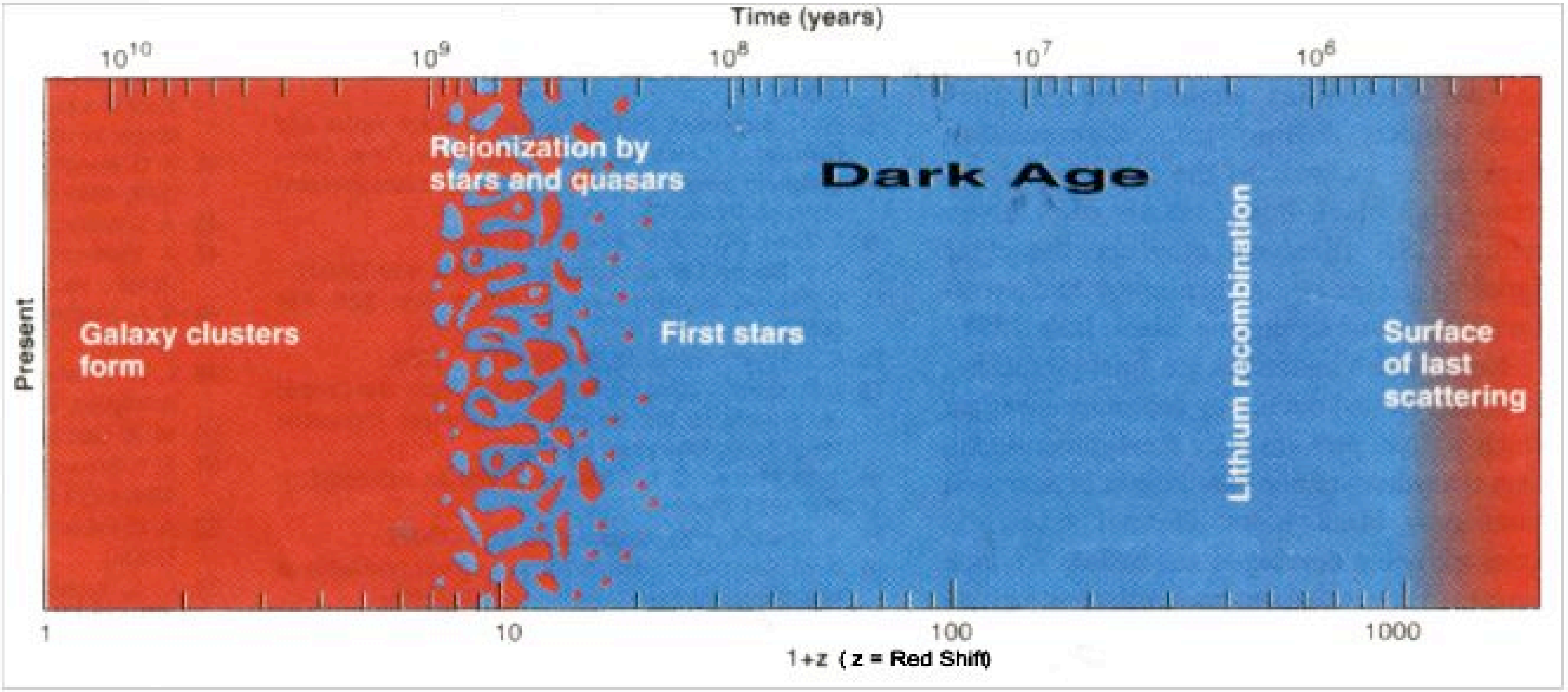
But systematic errors may remain in observed abundances!

What else do we learn?

- SBB is successful

  (if systematic errors explain abundances)
- Rather heavy constraints on more particles, as well as on (MeV) masses for e.g. $\square_{\square}$, cf. Olive et al. (2000).
- Empirical grip on a(t) during first minutes even if Robertson-Walker or GR is wrong.
- Neutrino asymmetry ($\square_{\square} \neq \square_{\square}$)?? Strong constraints from nucleosynthesis.
- Upper limits concerning decaying massive particles X, e.g. gravitinos or NLSP (cf. Kawasaki et al., astro-ph/0408426). Note ^{6}Li may result for half life > 10^{2} s!

And what comes next in nucleosynthesis?



The Dark Age of the Cosmos
Figure 16a

- WMAP polarization => re-ionization (by first stars) after about 200 million years

First stars?

- Cooling of gas problem -- by H_2, DH, HeH etc.
- Limits masses to at least 100 M_{sun} ?
- What remains? What SNe?

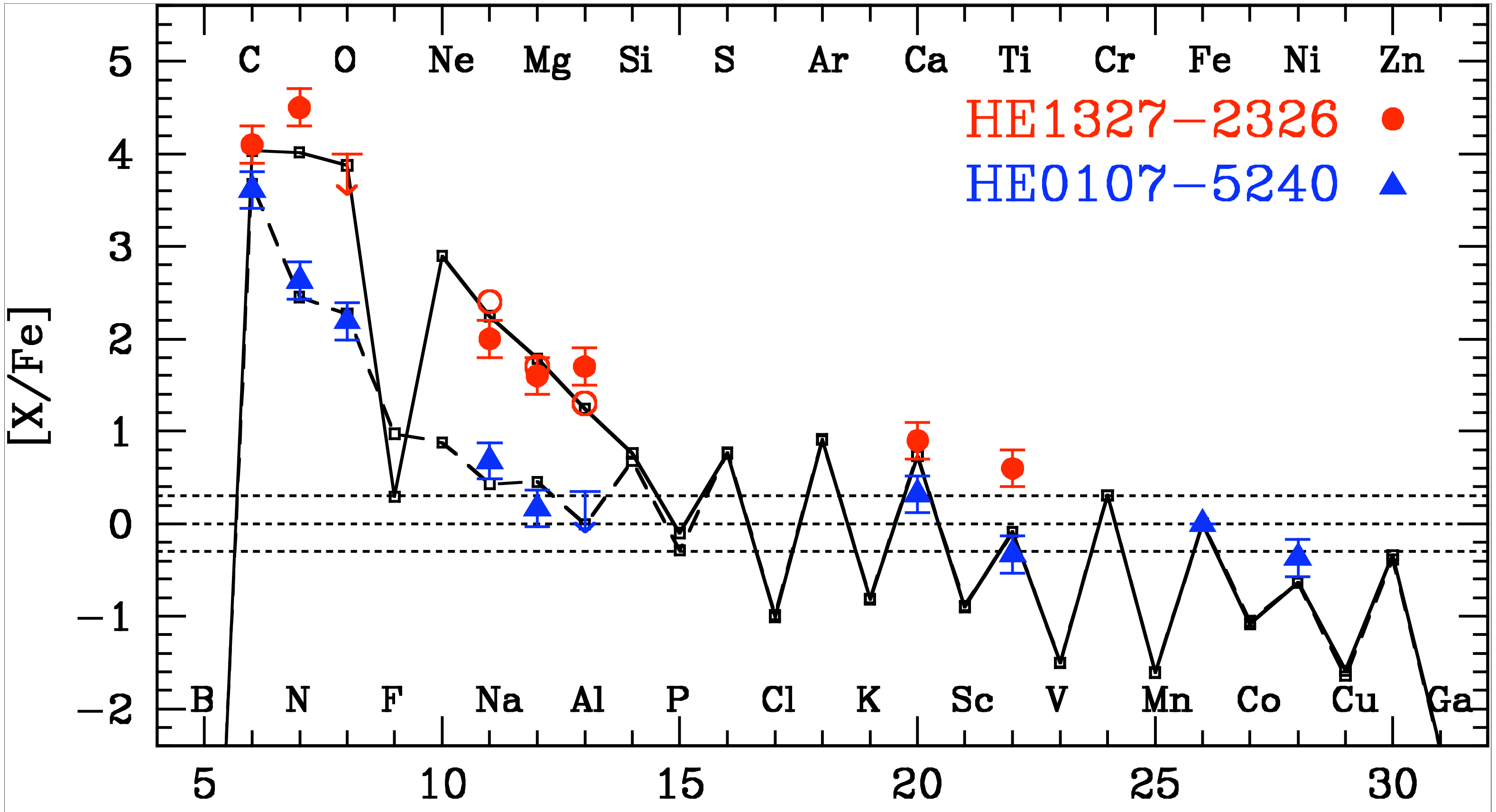
  Pair-instability SNe?? □-> e^++e^- -> $\square_e$+$\square_e$

Search the most metal-poor stars!

We have found low-mass stars with □(Fe) ≈ $10^{-5}\square(\mathrm{Fe})_{\mathrm{Sun}}$

Quite odd chemical composition.

May reflect the nucleosynthesis of the first stars.



- The composition of the most metal-poor stars found, compared with two SN models.
- Fall-back (low energy) SNe, 3 free parameters!

Mass = 25 M_{sun}. *Not understood yet!*

With the end of Dark Age starts NON-LINEAR processes:

the Astrophysical World!