NOW 2008

Primordial Nucleosynthesis: from precision cosmology to fundamental physics

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Gennaro Miele

University of Naples “Federico II”

In coll. with F. Iocco, G. Mangano, O. Pisanti and P.D. Serpico

BBN in **few words**

During the expansion after the Big Bang, for:

$1\ s \lesssim t \lesssim 3600\ s$ (1 MeV $\gtrsim$ T $\gtrsim$ 10 keV)

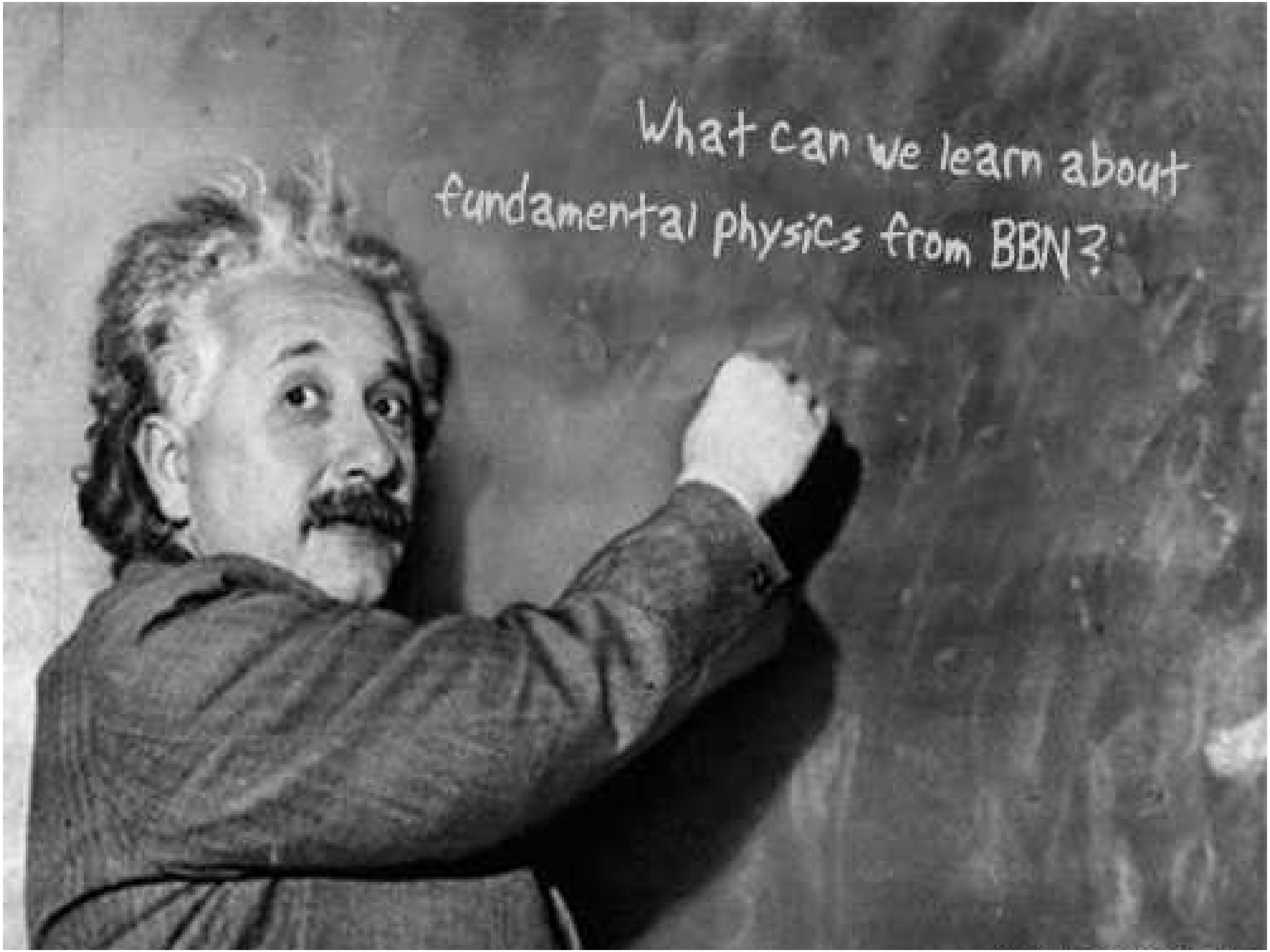
when the radiation was still dominating the energy

The Universe made of n, p, $e^{\pm}$, γ, ν anti- ν and X?

behaved as a **nuclear reactor**,

producing sensible amount of light nuclei,

H, ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li .....


What can we learn about
fundamental physics from BBN?

Physics Beyond the Standard Model

- **BBN and Neutrino physics**
  - Bounds on electromagnetic interactions of neutrinos
  - Bounds on other exotic interactions of neutrinos
  - Neutrino asymmetry
  - Sterile Neutrinos and BBN

- **Inhomogeneous nucleosynthesis**
  - Baryon inhomogeneous models
  - Matter-antimatter inhomogeneities

- **Constraints on fundamental interactions**
  - Extra-Dimensions and BBN
  - Variation of fundamental constants

- **Massive Particles & BBN**
  - Cascade Nucleosynthesis
  - Catalyzed BBN

BBN Evolution History

- 1946 Gamow: nuclear reactions in the early universe might explain the abundances of elements.
- Fermi and Turkevich: lack of stable nuclei with mass 5 and 8 prevents significant production of nuclei more massive than ^{7}Li.
- 1964 Peebles, Hoyle and Tayler: $Y_P \approx 0.25$.
- 1967 Wagoner, Fowler and Hoyle: first detailed calculation of light nuclei abundances.

……..Schramm, Turner, Steigman, Olive, ……

-1988 & 1992 Kawano, release of a user friendly code

- 2008 PArthENoPE, our release of a new generation code

website: http://parthenope.na.infn.it/

Prerequisites (The Hot Big Bang)

Einstein equations: $$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = 8\pi G_N T_{\mu\nu} + \Lambda\, g_{\mu\nu}$$

FLRW universe: spatial homogeneity and isotropy

Equilibrium vs non equilibrium: **Out of equilibrium phases are crucial in the history of the universe.**

Thermodynamics would have make everything much boring! **Tool: Boltzmann transport equations**

BBN Machinery

Set of nuclides typically considered

Z \ N	0	1	2	3	4	5	6	7	8
0		n							
1	H	^{2}H	^{3}H						
2		^{3}He	^{4}He						
3				^{6}Li	^{7}Li	^{8}Li			
4				^{7}Be		^{9}Be			
5				^{8}B		^{10}B	^{11}B	^{12}B	
6						^{11}C	^{12}C	^{13}C	^{14}C
7						^{12}N	^{13}N	^{14}N	^{15}N
8							^{14}O	^{15}O	^{16}O

They are described by their relative abundances $X_a = n_a/n_B$. With short convenient notations

$$\frac{^{2}H}{H} \equiv \frac{X_{^{2}H}}{X_p} \qquad \frac{^{3}He}{H} \equiv \frac{X_{^{3}He}}{X_p} \qquad Y_p = 4X_{^{4}He} \qquad \frac{^{7}Li}{H} \equiv \frac{X_{^{7}Li}}{X_p}$$

BBN set of coupled differential equations

$$H \equiv \frac{\dot a}{a} = \sqrt{\frac{8\pi}{3 m_{Pl}^{2}}\rho}$$

$$\frac{\dot n_B}{n_B} = -3H$$

$$\dot\rho = -3H(\rho + P)$$

$$n_B \sum_j Z_j X_j = n_{e^-} - n_{e^+} \ldots \pi^2 \ldots \left(\ldots T\right) \left(\frac{\ldots}{e^{\zeta - \frac{\mu_e}{T}} + 1} \ldots \frac{\ldots}{e^{\zeta + \frac{\mu_e}{T}} + 1} \right)$$

$$\dot X_a = \sum_{b,c,d} N_a \left(\Gamma_{c+d\to a+b} \frac{(X_c)^{N_c}}{N_c!} \frac{(X_d)^{N_d}}{N_d!} - \Gamma_{a+b\to c+d} \frac{(X_a)^{N_a}}{N_a!} \frac{(X_b)^{N_b}}{N_b!} \right)$$

$$\left(\frac{\partial}{\partial t} - H|\vec p| \frac{\partial}{\partial |\vec p|} \right) f_{\nu_\alpha}(|\vec p|, t) = I_{\nu_\alpha}\left[f_{\nu_e}, f_{\bar\nu_e}, f_{\nu_x}, f_{\bar\nu_x}, f_{e^-}, f_{e^+} \right]$$

$$\rho = \rho_\gamma + \rho_e + \rho_\nu + \rho_B \qquad P = P_\gamma + P_e + P_\nu + P_B$$

We can solve it separately

The neutrinos decoupling

BBN Input:

- baryon density: $\eta = n_B/n_\gamma \approx 274\ 10^{-10}\ \Omega_b h^2$
- energy density in relativistic degrees of freedom historically described as "effective number of neutrinos", N_ν , but it can account for:
  1) non instantaneous decoupling effects
  2) non standard neutrino physics
  3) extra relativistic degrees of freedom

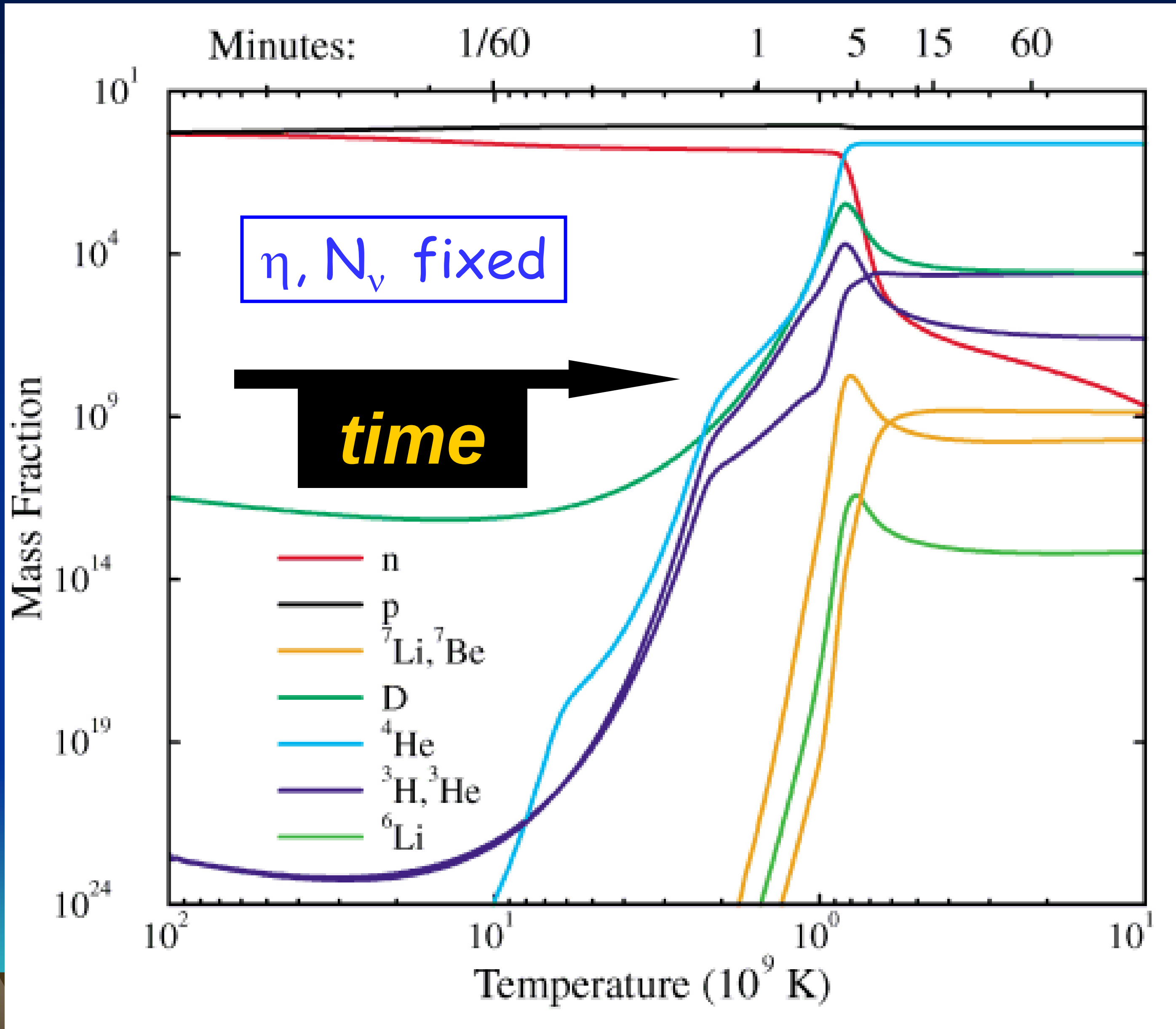
$$\rho_\nu + \rho_X(?) \equiv \frac{N_\nu}{3}\rho_{\nu,0} \equiv N_\nu \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\rho_\gamma$$

Output: $X_a\ (\eta, N_\nu)$

BBN in four steps

i)	Initial conditions	$T > 1$ MeV
ii)	n/p ratio freeze out	$T \approx 1$ MeV
iii)	Deuterium bottleneck	$T \approx 0.1$ MeV
iv)	Nuclear chain	$0.1 \text{ MeV} > T > 0.01$ MeV

Time -Temperature^{-1} evolution



Primordial Yields Dependence on ω_b

When η increseases:

^2H a larger baryon density shifts the onset of ^2H production towards larger temperatures, burning into ^4He is more efficient;

^4He weakly increasing for more efficient burning;

^7Li for small η, ^7Li decreases as a result of the balance of the two processes

$$^4He(^3H,\gamma)^7Li \, , \, ^7Li(p,^4He)^4He$$

for larger η, ^7Li starts growing due to larger ^7Be production, leading to ^7Li via electron capture:

$$^4He(^3He,\gamma)^7Be(e^-,\nu_e)^7Li$$

Dependence on relativistic d.o.f. ≡ N_ν

When N_ν increases:

^2H, ^7Li only slightly affected

^4He a larger value for $N_\nu \rightarrow$ a larger expansion rate $H(\rho_\nu+\rho_\gamma+\rho_e+\rho_b)$

This implies an earlier freeze out (larger T) of the n/p ratio, and so a larger value for Y_P. More neutrons → more ^4He.

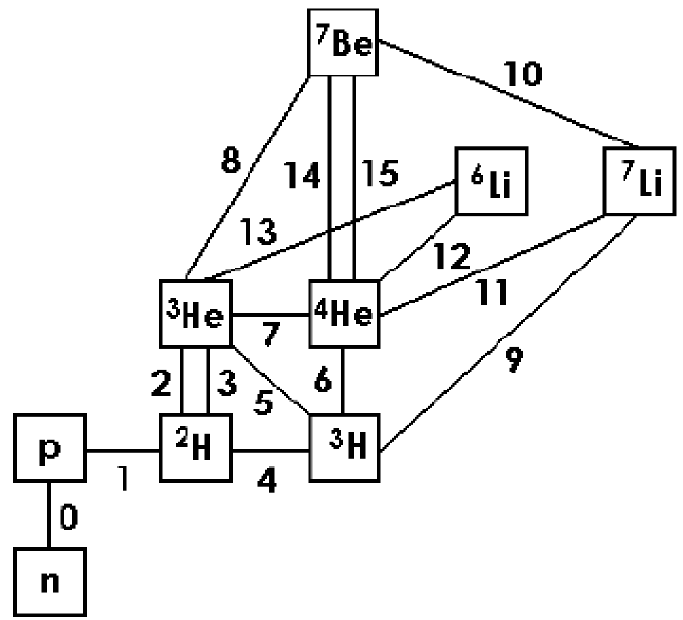
$$\frac{n}{p} = \exp\left(\frac{m_p - m_n}{T}\right)$$

Nuclear chain

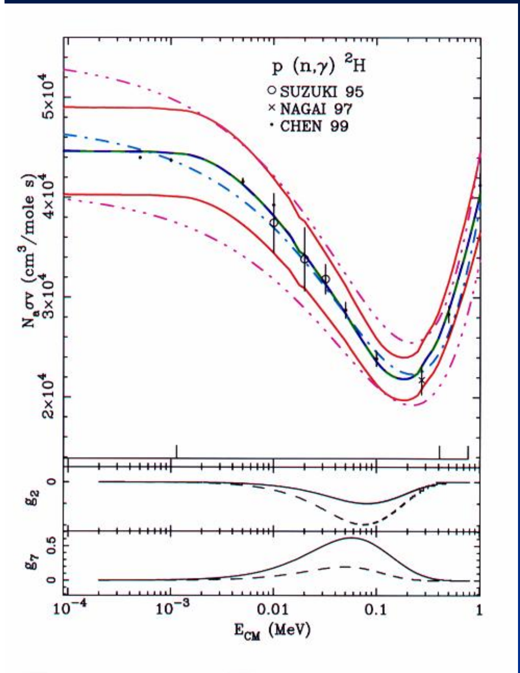
Once D is produced, ^{4}He is rapidly formed, along with small fractions of ^{3}H. ^{3}He, ^{6}Li, ^{7}Li and ^{7}Be.

Nuclear processes during BBN proceed in an environment very different with respect to the stellar plasmas, where stellar nucleosynthesis takes place. In stars the plasma is dense and species are mostly in chemical equilibrium.

For BBN we have a hot and low density plasma with a significant population of free neutrons, which expands and cools down very rapidly, resulting in peculiar “out of equilibrium" nucleosynthetic yields.

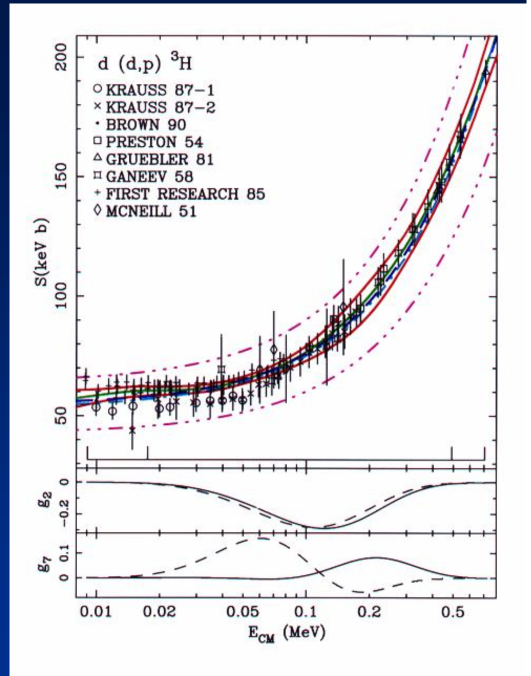


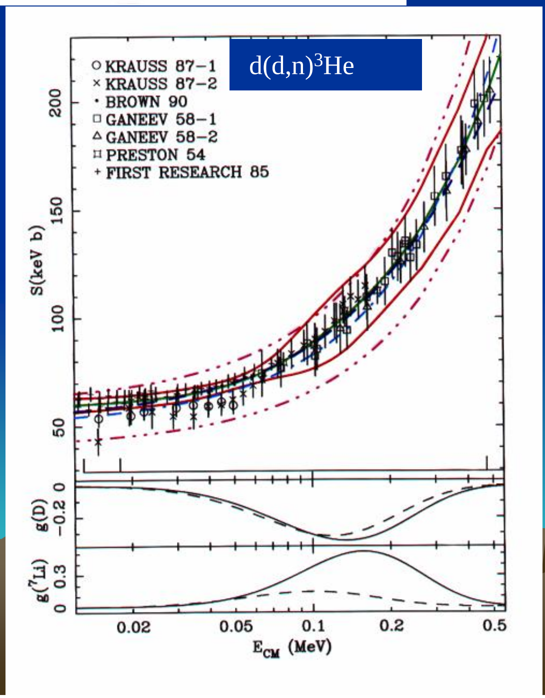
The main net. , but ~ 100 reac. are involved

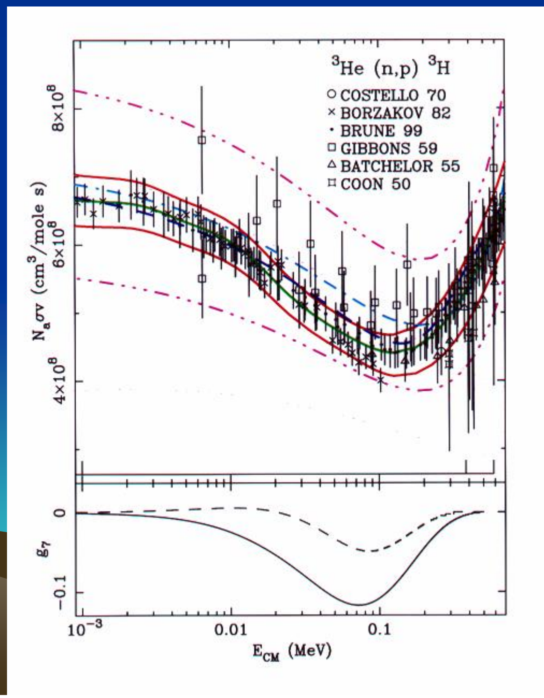


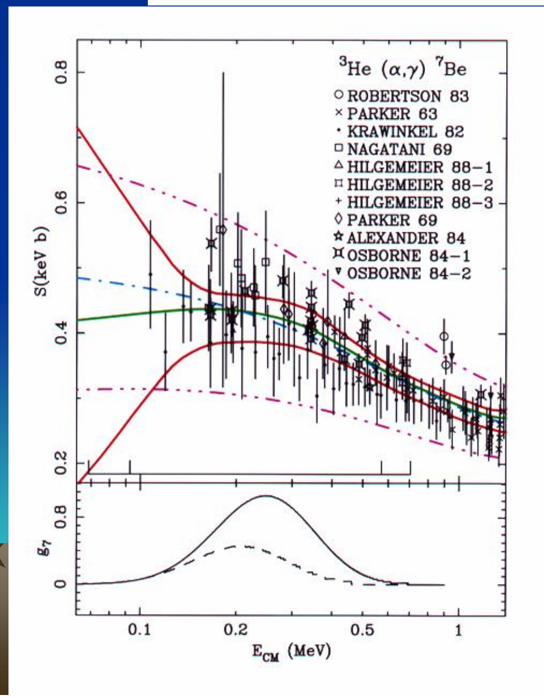
Uncertainties

From nuclear rates ultimately propagate onto the final errors on the nuclides.









For two body collisions, like $i + j \rightarrow k + l$, the nuclear reaction rates enter the eq. via

$$\Gamma_{i j \rightarrow k l} = \langle \sigma_{i j \rightarrow k l} \, v \rangle$$

Where the average is over the nuclei distributions

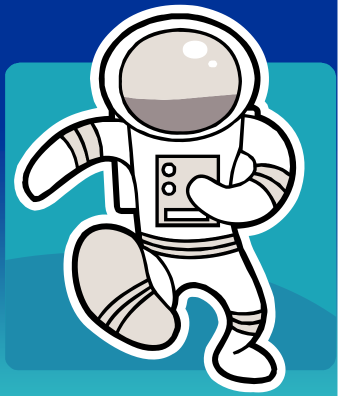
$$\left\langle \sigma_{i\,j \rightarrow k\,l}\, v \right\rangle \propto T^{-3/2} \int_0^\infty dE\, \sigma_{i\,j \rightarrow k\,l}(E)\, E\, e^{-E/T}$$

For ω_b=0.0224

nuclide i	central value	σ_{ω_b}	σ_{ii}	rate	$\delta\sigma^2/\sigma^2 (\%)$
$^2\mathrm{H/H}\,(10^{-5})$	2.58	$^{+0.19}_{-0.16}$	± 0.04	R_2	49
				R_3	37
				R_4	14
$^3\mathrm{He/H}\,(10^{-5})$	1.03	$^{+0.02}_{-0.03}$	± 0.03	R_7	80.7
				R_2	16.8
Y_p	0.2479	$^{+0.0004}_{-0.0004}$	± 0.0002	R_0	98.5
$^6\mathrm{Li/H}\,(10^{-14})$	1.1	± 0.1	$^{+1.7}_{-1.1}$	R_{13}	~ 100
$^7\mathrm{Li/H}\,(10^{-10})$	4.6	± 0.4	± 0.4	R_{14}	40.9
				R_8	25.1
				R_{15}	16.2
				R_7	8.6

Symbol	Reaction
R_0	τ_n
R_1	$p(n,\gamma)d$
R_2	$^2\mathrm{H}(p,\gamma)^3\mathrm{He}$
R_3	$^2\mathrm{H}(d,n)^3\mathrm{He}$
R_4	$^2\mathrm{H}(d,p)^3\mathrm{H}$
R_5	$^3\mathrm{He}(n,p)^3\mathrm{H}$
R_6	$^3\mathrm{H}(d,n)^4\mathrm{He}$
R_7	$^3\mathrm{He}(d,p)^4\mathrm{He}$
R_8	$^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$
R_9	$^3\mathrm{H}(\alpha,\gamma)^7\mathrm{Li}$
R_{10}	$^7\mathrm{Be}(n,p)^7\mathrm{Li}$
R_{11}	$^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$
R_{12}	$^4\mathrm{He}(d,\gamma)^6\mathrm{Li}$
R_{13}	$^6\mathrm{Li}(p,\alpha)^3\mathrm{He}$
R_{14}	$^7\mathrm{Be}(n,\alpha)^4\mathrm{He}$
R_{15}	$^7\mathrm{Be}(d,p)2\,^4\mathrm{He}$

ASTROPHYSICAL OBSERVATIONS



Main problem

We cannot observe directly primordial abundances, since stars have changed the chemical composition of the universe

1) Observations in systems negligibly contaminated by stellar evolution;

2) Carefull account for galactic chemical evolution.

Deuterium

It is commonly believed that there are no astrophysical sources of deuterium. Since it is destroyed by stellar evolution processes and non-thermal production channels have been constrained to be negligible, any astrophysical observation can provide a lower bound for the primordial abundance.

Galactic measurements

Far-Ultraviolet Spectroscopic Explorer (FUSE) has provided several Galactic $^2H/H$ measurements, but the picture is puzzling

- In the Local Bubble (a cavity in the ISM of the Orion Arm < 100 pc from sun we are travelling through) D is almost constant

$$^2H/H = (1.56 \pm 0.04)\ 10^{-5}$$

- beyond this bound an unexpected scatter of a factor $\sim$ 2 on $^2H/H$ is observed and a correlation with heavy elements $\rightarrow$ stellar astration (?)
- The measurements in the Jupiter atm. By Infrared Space Observatory indicate a value for the protosolar cloud of

$$^2H/H_{psc} = (2.1 \pm 0.4)\ 10^{-5}$$

High redshift measurements

The astrophysical environments which seem most appropriate are the hydrogen-rich clouds absorbing the light of background QSO's at high redshifts.

To apply the method one must require:

(i) neutral hydrogen column density in the range

$$17 < \log[N(H_I)/cm^{-2}] < 21;$$

(H_I regions are interstellar cloud made of neutral atomic hydrogen)

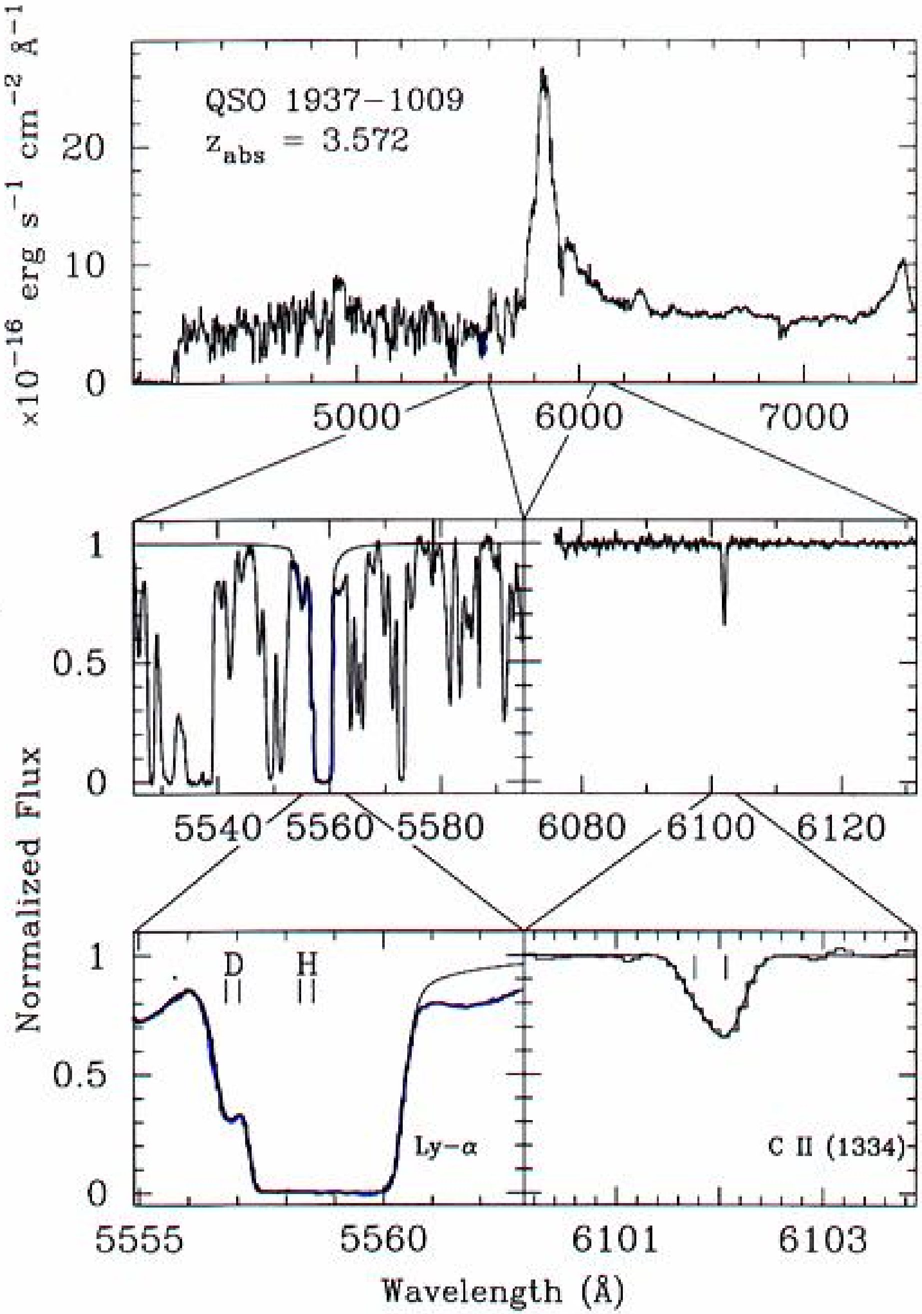
(ii) low metallicity [M/H] to reduce the chances of deuterium astration;

(iii) low internal velocity dispersion of the atoms of the clouds, allowing the isotope shift of only 81.6 km/s to be resolved.

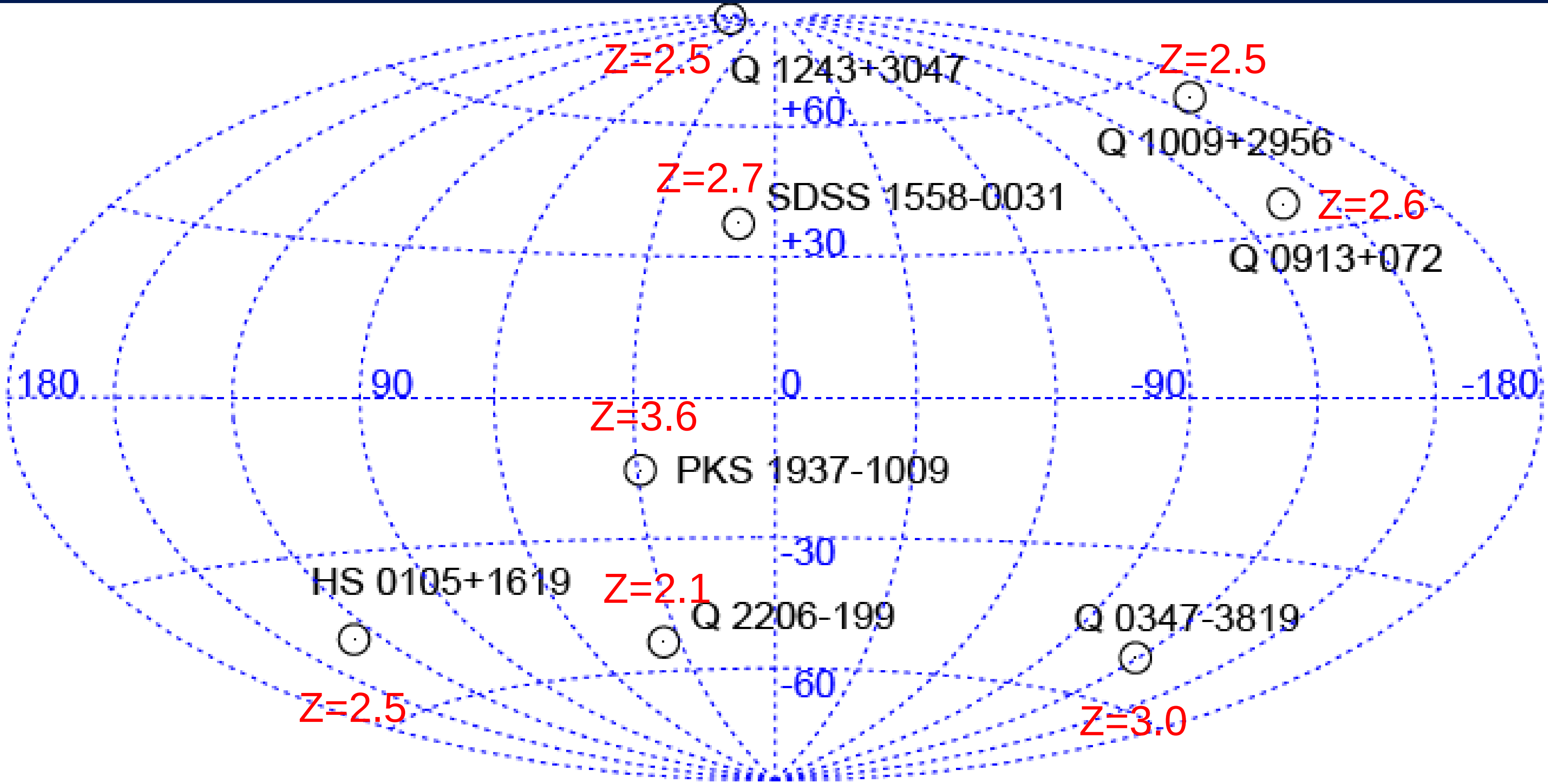
Only a small bunch (~ 14) of QAS's pass the first exam!

Observation of Lyman absorption lines in gas clouds in QAS's at high red-shift ($z \approx 2 - 3$) with low metallicity

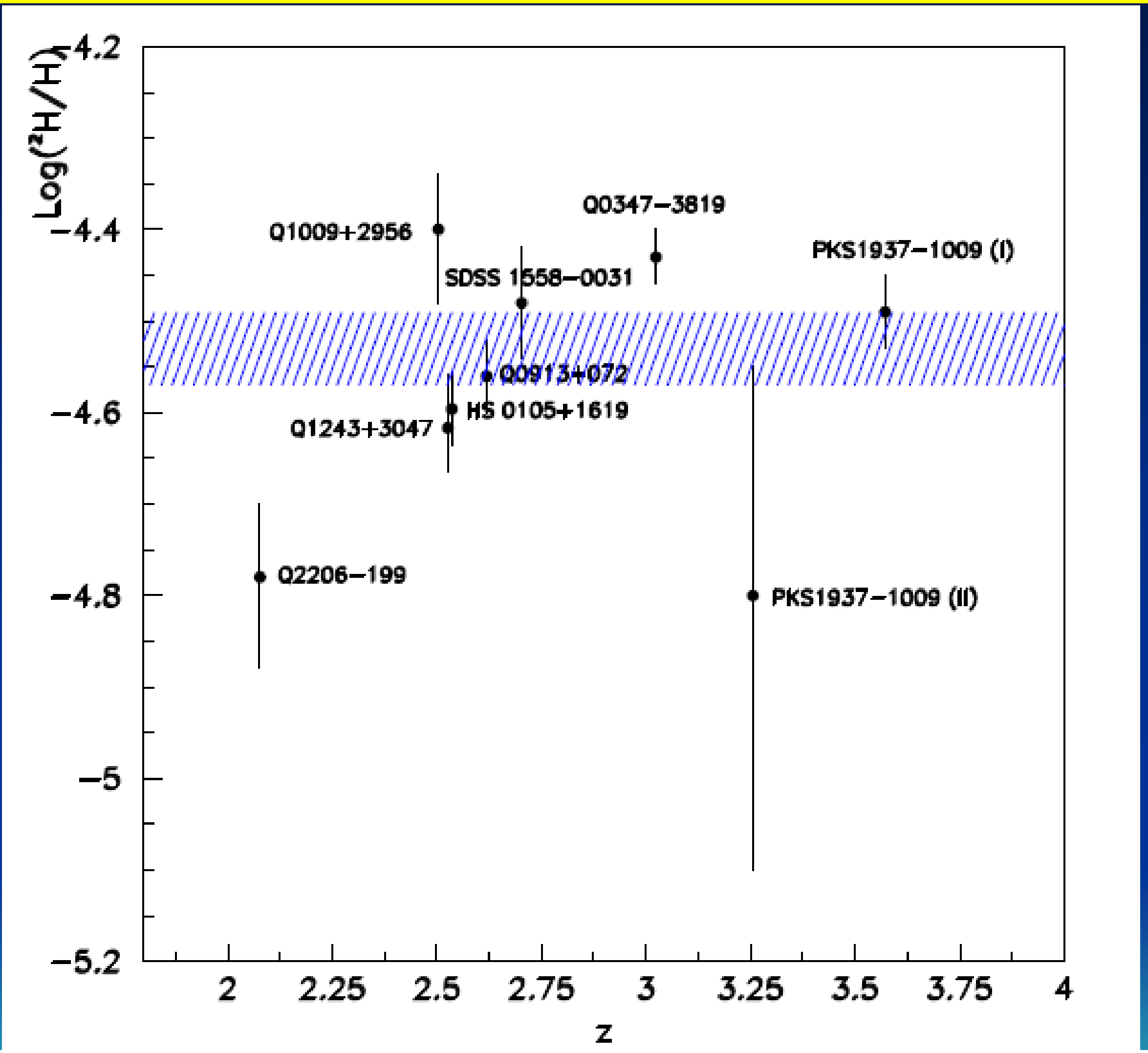
$C/H \approx 0.01 - 0.001\ (C/H)_{solar}$



The best 8 QAS's in Galactic coordinates



Our determination $^2H/H = (2.87\,^{+0.22}_{-0.21})\ 10^{-5}$



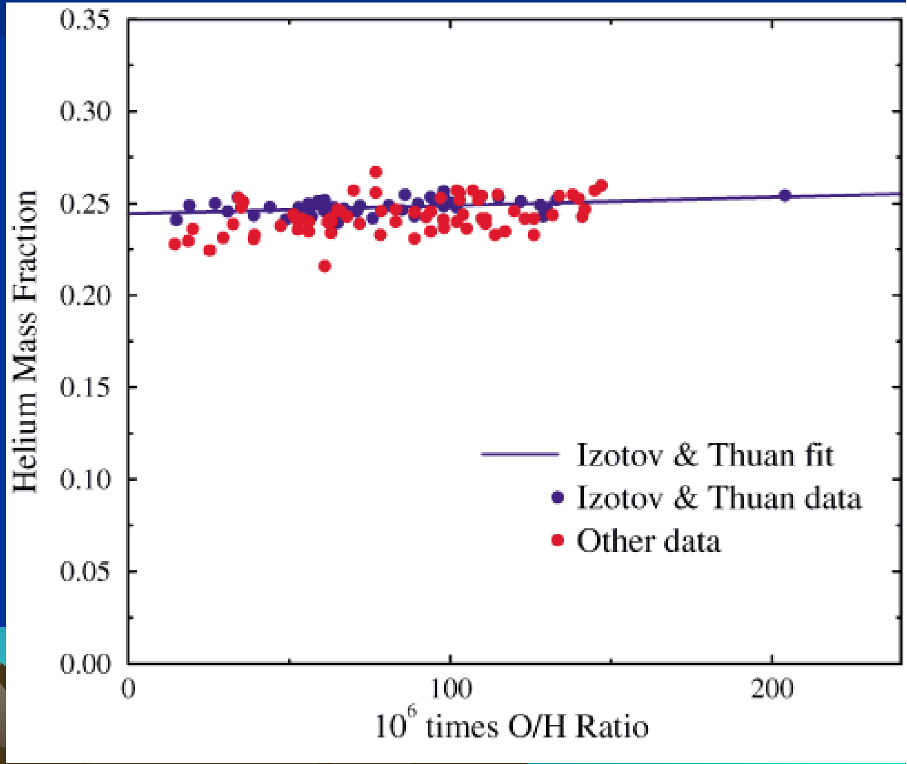
Combining measurements with asymmetric errors!

$$\chi_i^2(\mu) = \left(\frac{\overline{x}_i - \mu}{\sigma_i}\right)^2 \left(1 - 2\,A_i \left(\frac{\overline{x}_i - \mu}{\sigma_i}\right) + 5\,A_i^2 \left(\frac{\overline{x}_i - \mu}{\sigma_i}\right)^2\right) \quad \sigma_i \equiv \frac{\sigma_i^+ + \sigma_i^-}{2} \qquad A_i \equiv \frac{\sigma_i^+ - \sigma_i^-}{\sigma_i^+ + \sigma_i^-}$$

^{4}He

^{4}He evolution can be simply understood in terms of nuclear stellar processes which through successive generations of stars have burned hydrogen into ^{4}He and heavier elements, hence increasing the ^{4}He abundance above its primordial value. Since the history of stellar processing can be tagged by measuring the *metallicity* (*Z*) of the particular astrophysical environment, the primordial value of ^{4}He mass fraction Y_p can be derived by extrapolating the Y_p-O/H and Y_p - N/H correlations to O/H and N/H → 0

- Observation of ionized gas (He II → HeI recombination lines in H_{II} regions) in Blue Compact Galaxies (BCGs) which are are the least chemically evolved known galaxies
- Y_P in different galaxies plotted as function of O and N abundances.
- Regression to "zero metallicity"



Different analyses

i) Izotov et al. 04 reported the estimate $Y_p = 0.2421 \pm 0.0021$

ii) Olive et al 04 quoted the value $Y_p = 0.249 \pm 0.009$. A small sample size used and large uncertainties affecting analysis are responsible in this case for the very large error

iii) Fukugita et al. 06, based on a reanalysis of a sample of 33 H_{II} regions from i) determined a value of $Y_p = 0.250 \pm 0.004$

iv) Peimbert et al 07, present a new ^{4}He mass fraction determination, yielding $Y_p = 0.2477 \pm 0.0029$. This result is based on new atomic physics computations together with observations and photoionization models of metal-poor extragalactic H_{II} regions.

All recent estimates are dominated by systematics. We take as central value of Y_p the average (without weights) of the four determinations, while the systematic error is estimated as the semi-width of the distribution of the four best values

$$Y_p = 0.247 \pm 0.002_{stat} \pm 0.004_{syst}$$

Finally, CMB anisotropies are sensitive to the reionization history, and thus to fraction of baryons in the form of ^4He. Present data only allow a marginal detection of a non-zero Y_p, and even with PLANCK the error bars from CMB will be larger than the present systematic spread of the astrophysical determinations

^3He

In stellar interior it can be either produced by ^2H-burning or destroyed in the hotter regions $\rightarrow$ all the ^3He nuclides surviving the stellar evolution phase contribute to the chemical composition of the InterStellar Medium (ISM). Stellar and galactic evolution models are necessary to track back the primordial ^3He abundance from the post-BBN data, at least in the regions where stellar matter is present.

Terrestrial measurements

- From balloon measurements $^3He/^4He \sim 10^{-6}$
- From continental rock$\sim$ $^3He/^4He \sim 10^{-8}$

Large spread of values, confirm the idea that the terrestrial He has no cosmological nature. Most of it is ^4He produced by the radioactive decay of elements such as uranium and thorium. No natural radioactive decay produces ^3He, hence its observed terrestrial traces can be ascribed to unusual processes such as the testing of nuclear weapons or the infusion of extraterrestrial material.

In the Solar System

The most accurate value was measured in Jupiter's atmosphere by the Galileo Probe. Support the idea of a conversion of D initially present in the outer parts of the Sun into ^{3}He via nuclear reactions.

- ProtoSolar Material (PSM) $^3He/^4He = (1.66 \pm 0.05)\ 10^{-4}$
- Meteoritic gases $^3He/^4He = (1.5 \pm 0.3)\ 10^{-4}$

In the Local ISM

By counting the helium ions in the solar wind, the Ulysses spacecraft has measured

- LISM $^3He/^4He = (2.48\ ^{+0.68}_{-0.62})\ 10^{-4}$ note that $^4He/H \sim 0.1$

not inconsistent with the dea that ^{3}He at our galaxy location might have grown in the last 4.6 billion years since the birth of the Sun.

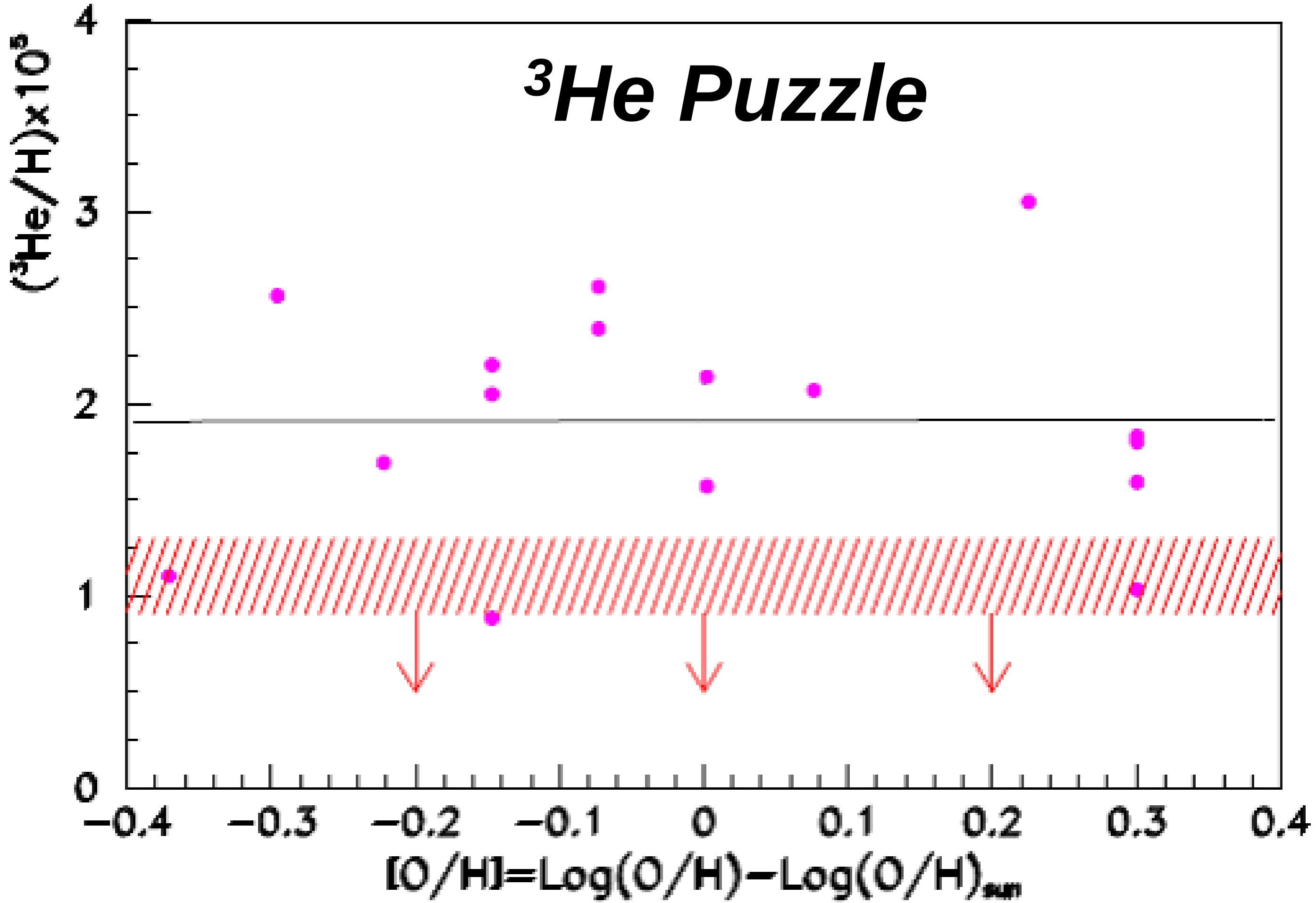
Beyond Local ISM

Only one spectral transition allows detection of ^3He, namely the 3.46 cm spin-flip transition of $^3He^+$, the analog of the widely used 21-cm line of hydrogen.

A powerful tool for the isotope identification, as there is no corresponding transition in $^4He^+$.

The emission is quite weak, hence ^3He has been observed outside the solar system only in a few HII regions and Planetary Nebula in the Galaxy.

The values found in PN result one order of magnituded larger than in PSM and LISM $^3He/H = (2 - 5)\ 10^{-4}$ confirming a net stellar production of ^3He in at least some stars. From the expected correlation between metallicity of the particular galactic environment and its distance from the center of galaxy, one would expect a gradient in ^3He abundance versus metallicity and/or distance.

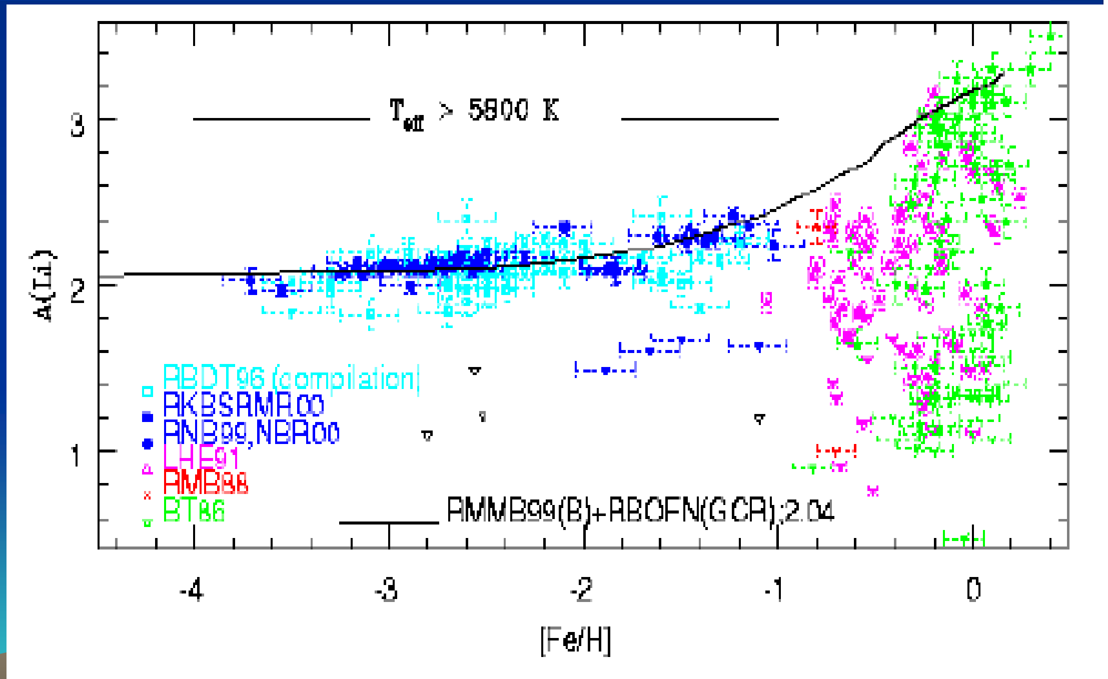


No ^{3}He dependence on environment metallicity, as predicted by chemical evolution models of Galaxy.Known as ^{3}He problem. Thus a conservative approach: ^{3}He/H $<$ (1.1 $\pm$ 0.2) 10^{-5}. In alternative, by using ^{2}H/H estimate and the theoretical stability of ratio $(^2H+^3He)/H = (3.6\pm0.5)10^{-5} \Longrightarrow\ ^3He/H = (0.7 \pm 0.5)\ 10^{-5}$

^{7}Li

Lithium's two stable isotopes, ^{6}Li and ^{7}Li, continue to puzzle astrophysicists and cosmologists. Spite & Spite (1982) showed that the lithium abundance in the warmest metal-poor dwarfs was independent of metallicity for [Fe/H]< -1.5. This is commonly called *the Spite plateau and* may be the lithium abundance in pre-Galactic gas provided by the BBN.

The very metal-poor stars in the halo of the Galaxy or in similarly metal poor galactic globular cluster (GGC) thus represent ideal targets for probing the primordial abundance of lithium.



Several technical and conceptual difficulties have been responsible for quite a long tale of ^7Li determinations:

$$[^7Li/H] \equiv 12 + \log_{10}(^7Li/H)$$

1. (Bonifacio et al. 97) $[^7Li/H] = 2.24 \pm 0.01$
2. (Ryan et al. 99, 00) $[^7Li/H] = 2.09^{+0.19}_{-0.13}$
3. (Bonifacio et al. 02) $[^7Li/H] = 2.34 \pm 0.06$
4. (Melendez et al. 04) $[^7Li/H] = 2.37 \pm 0.05$
5. (Charbonnel et al. 05) $[^7Li/H] = 2.21 \pm 0.09$
6. (Asplund et al. 06) $[^7Li/H] = 2.095 \pm 0.055$
7. (Korn et al. 06) $[^7Li/H] = 2.54 \pm 0.10$

It is unclear how to combine the different determinations in a single estimate, or if the value measured is truly indicative of a primordial yield.

A conservative approach (similar to the one used for ^{4}He) is to quote the simple (un-weighted) average and half-width of the above distribution of data as best estimate of the average and "systematic“ error on ^{7}Li/H, obtaining

$$\left[\frac{^7\mathrm{Li}}{\mathrm{H}}\right] = 2.27 \pm 0.23 \Longrightarrow \left(\frac{^7\mathrm{Li}}{\mathrm{H}}\right) = \left(1.86^{+1.30}_{-1.10}\right) \times 10^{-10}$$

We have a substantial disagreement, as a factor 1.5 – 2, between BBN prediction and observations. What could be the reason?

i) a factor 1.5 - 2 lower value of η at the BBN time with respect to the best fit deduced from CMB data is excluded by the agreement between D observations and CMB value of η, and also by the inferred upper limit of the primordial ^{3}He abundance.

ii) underestimated errors in the adopted nuclear reaction rates are now excluded: the laboratory measurements of the crucial ^{3}He$(\alpha,\gamma)^7$Be cross section, its inferred rate from solar neutrino data and the measurement of the proposed alternative channel for ^{7}Be destruction ^{7}Be$(d; p)2\,\alpha$

iii) Systematic errors in the analysis, although in principle still possible, seem very unlikely. 3D model atmospheres did not result in a significant upward revision of results obtained from more primitive 1D atmospheres.

Perhaps, and more likely, the lithium abundance of very metal-poor stars is not the one of the primordial gas

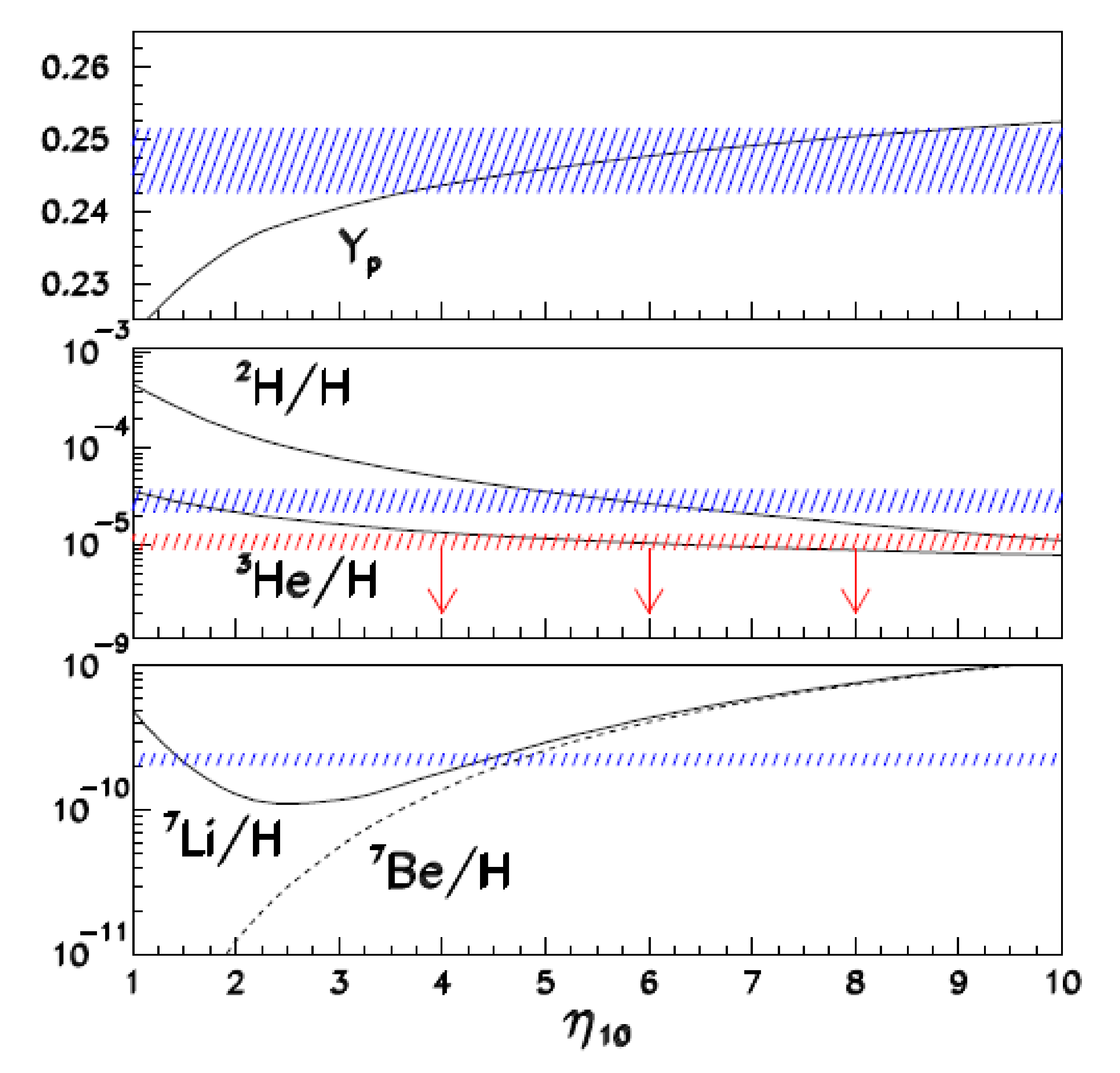
Even assuming some diffusion and turbulent mixing mechanism to explain the ^{7}Li problem, still an issue remains with ^{6}Li.

The presence of the fragile ^{6}Li isotope, which is produced during BBN at the level of $^{6}Li/H \sim 10^{-15} - 10^{-14}$, has been recently confirmed in a few metal-poor halo stars, with some hint of a plateau vs. metallicity with abundance as high as $^{6}Li/H \sim 6 \times 10^{-16}$

A great help in solving this issue might come from detecting lithium in a different environment !

BBN, BARYON FRACTION AND NEUTRINOS

Abundances dependence on ω_b (N_ν=3)



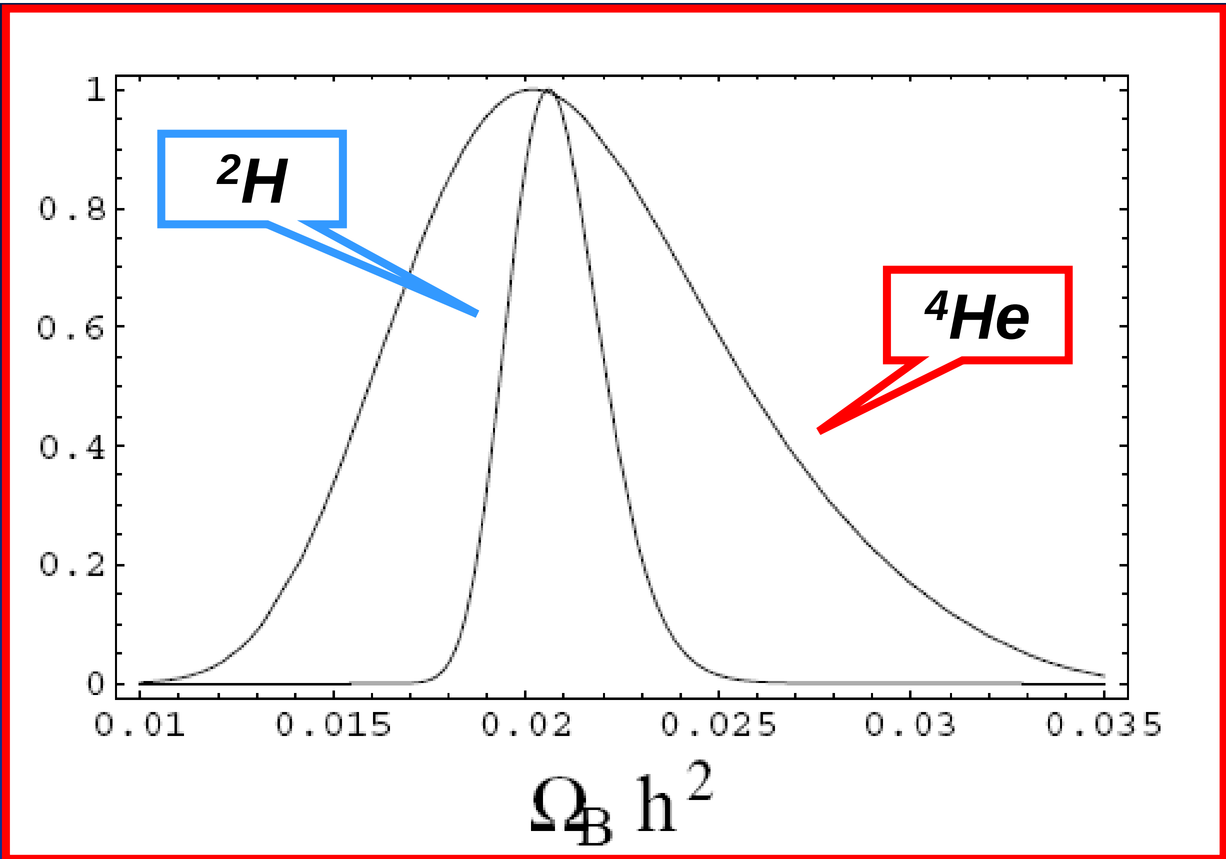
Likelihood analysis

- Run a BBN code (PArthENoPE) to get $Y_P(N_{\nu,}\eta)$, $X_D(N_{\nu,}\eta)$
- Construct for each abundance the likelihood function:

$$L_i(N_\nu,\eta) = \frac{1}{2\pi\sigma_i^{th}(N_\nu,\eta)\sigma_i^{ex}} \int dx \exp\left(-\frac{(x - Y_i^{th}(N_\nu,\eta))^2}{2\sigma_i^{th}(N_\nu,\eta)^2} \right) \exp\left(-\frac{(x - Y_i^{ex})^2}{2\sigma_i^{ex\,2}} \right)$$

$$^2\mathrm{H}/\mathrm{H} = 2.87^{+0.22}_{-0.21} \times 10^{-5}, \qquad \mathrm{Y}_p = 0.247 \pm 0.002_{\mathrm{stat}} \pm 0.004_{\mathrm{syst}}$$

- Define a total likelihhod function $L = L_{4He}\, L_D$
- Plot the 68%, 95% and 99% cl contours in the $(N_{\nu,}\eta)$ plane.



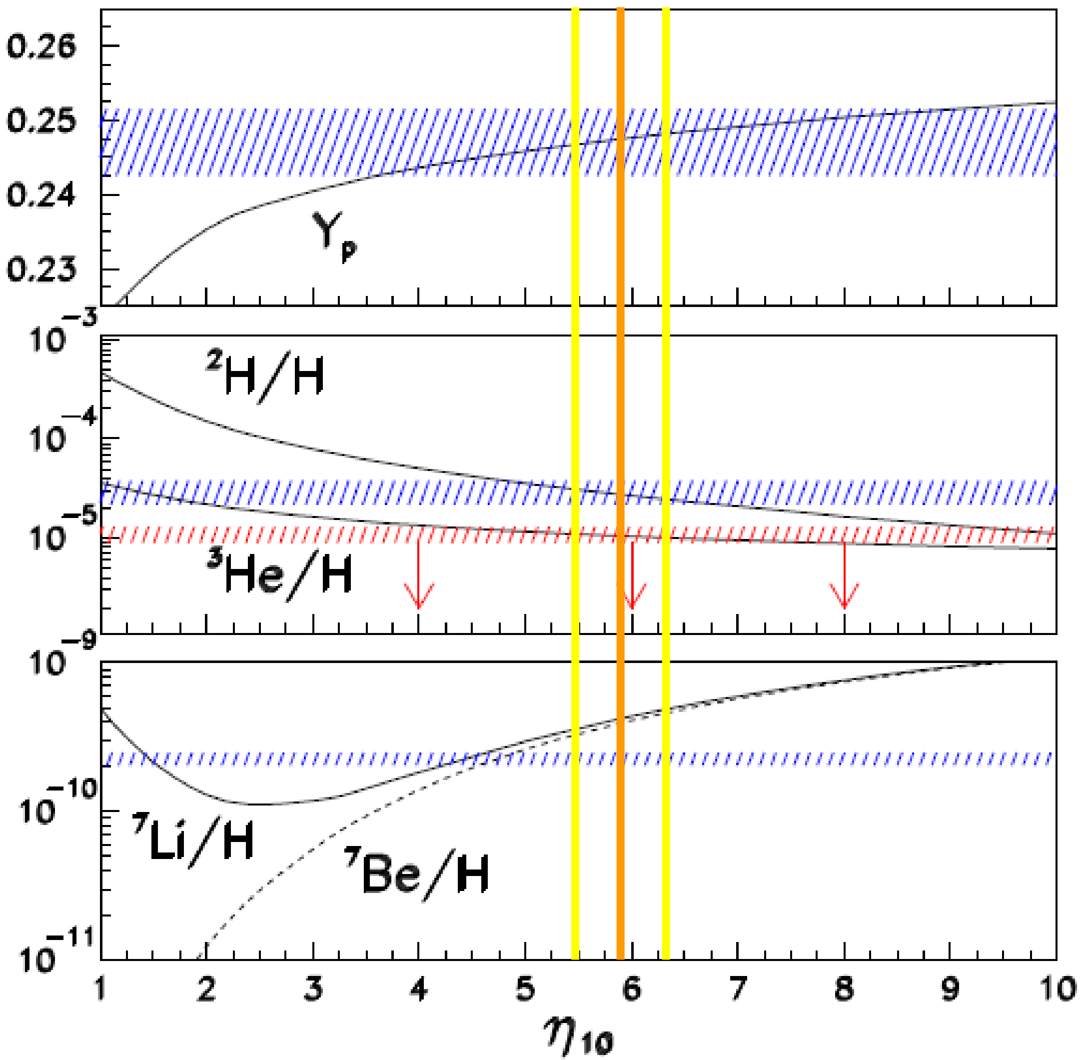
- Only ^{2}H → $\Omega_B h^2 = 0.021 \pm 0.002$ at 95% CL
- Only ^{4}He stat. → $\Omega_B h^2 = 0.020^{+0.010}_{-0.006}$ at 95% CL
- WMAP 5-years → $\Omega_B h^2 = 0.02273 \pm 0.00062$

The slight tension could affect primordial scalar perturbation spectral index n_s determination (^{2}H is a prior)

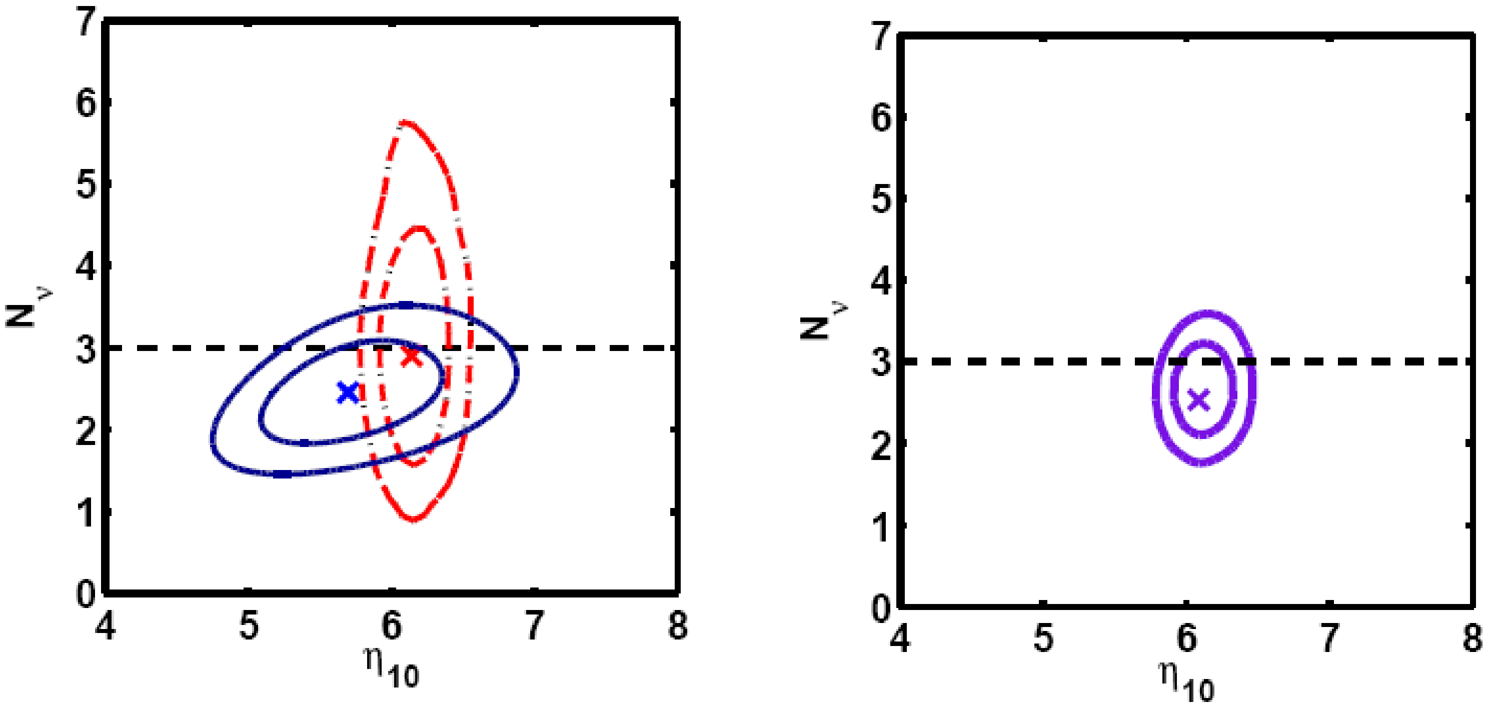
After marginalization we get

$N_\nu = 2.97^{+0.29}_{-0.27}$ (95% CL) add. Syst. $2.4 \leq N_\nu \leq 3.6$ (95% CL)

$\Omega_B h^2 = 0.021 \pm 0.002$ (95% CL)



Combining with other observables



G. Steigman ArXiv:0807.3004v1 [astro-ph]

Figure 4:

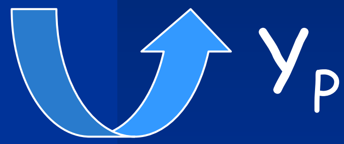
(Left) In blue (solid), the 68% and 95% contours in the N_ν - η_{10} plane derived from a comparison of the observationally-inferred and BBN-predicted primordial abundances of D and ^{4}He. In red (dashed), the 68% and 95% contours derived from the combined WMAP 5-year data, small scale CMB data, SNIa, and the HST Key Project prior on H_0 along with the LSS matter power spectrum data. (Right) The 68% and 95% joint BBN-CMB-LSS contours in the $N_\nu - \eta_{10}$ plane.

BBN and Neutrino Asymmetry: a leptometer

Large neutrino chemical potentials are not forbidden. They affect BBN!

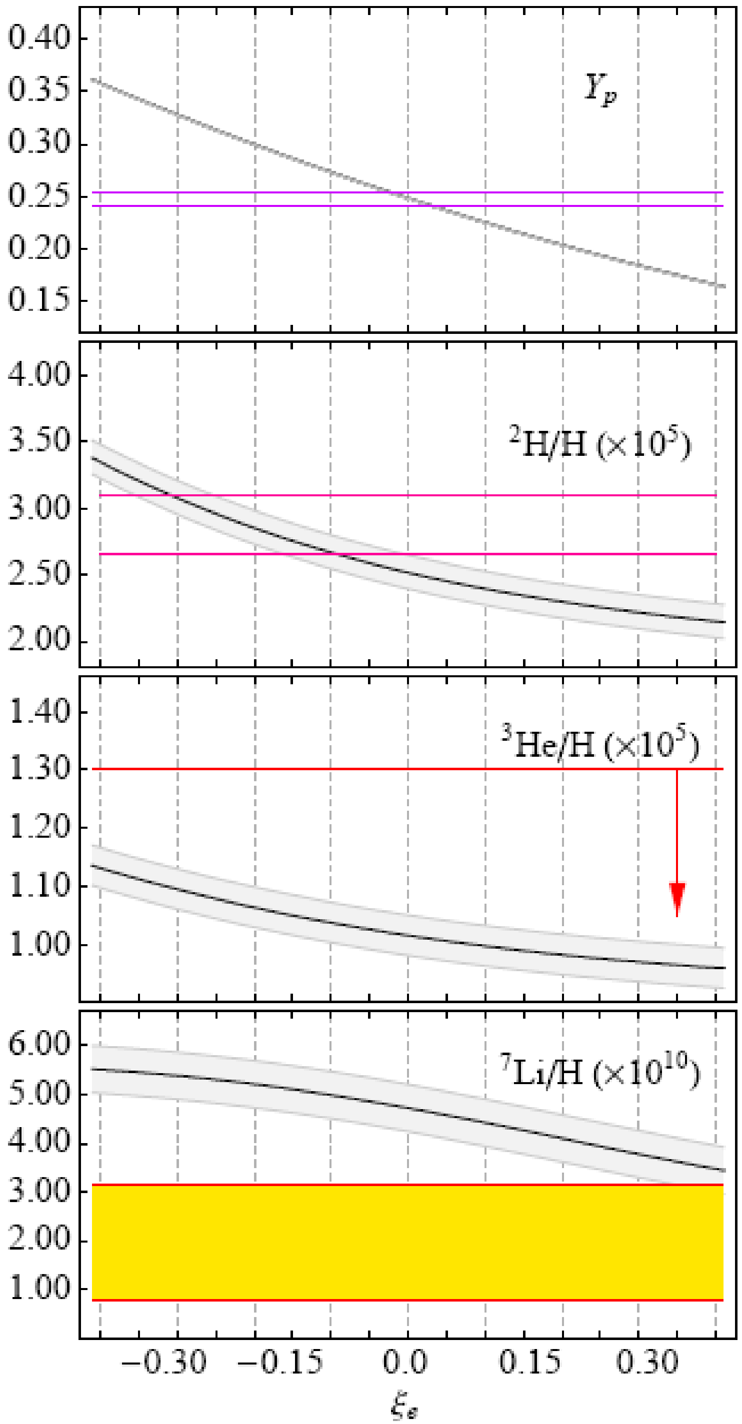
1) chemical potentials contribute to N_ν (if no extra d.o.f.)

$$N_\nu = 3 + \sum_i \left(\frac{30\xi_i^{\,2}}{7\pi^2} + \frac{15\xi_i^{\,4}}{7\pi^4} \right) + \ldots.$$



2) a positive electron neutrino chemical potential ξ_e (more neutrinos than antineutrinos) favour n $\rightarrow$ p with respect to p $\rightarrow$ n processes.

3) Neutrino oscillations mix ξ_e , ξ_μ , ξ_τ. We can take all of them equal.



From Y_p

$\xi_e = 0.004 \pm 0.017_{stat}(2\ \sigma) \pm 0.017_{sys}$

Even with a sensitivity of $\delta N_\nu \sim 0.1$ implies $|\xi| < 0.3$

BBN the best leptometer

But Neutrino Asymmetry is back!

According to the recent (arXiv:0808.3137 [astro-ph]) by S. Pastor, T. Pinto and G.G. Raffelt we have a degenerate (fine-tuned) direction, where for some value of θ_{13} one does not get thermodynamical equilibrium

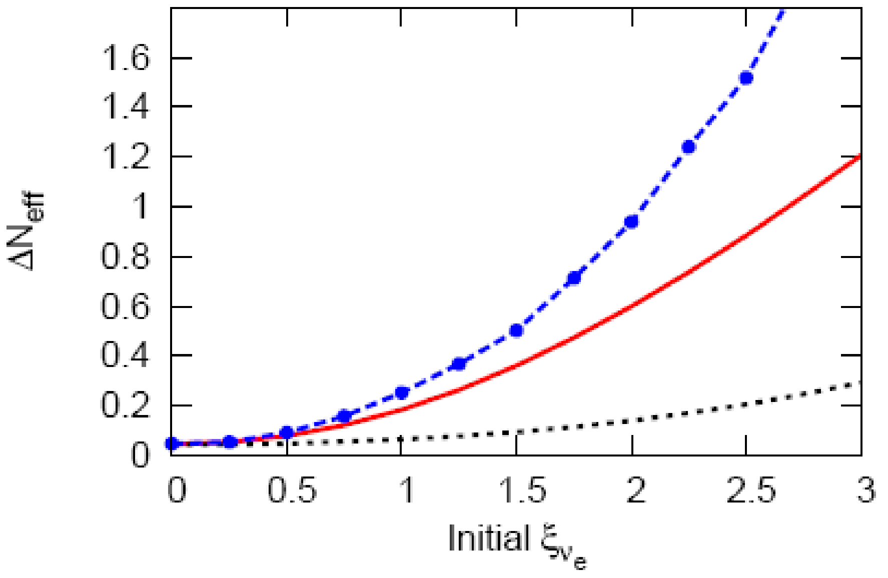


FIG. 3: Parameters for the final ν_e and $\bar{\nu}_e$ spectra as well as the final $\Delta N_{\rm eff}$ as a function of the initial ξ_{ν_e}. The solid lines correspond to $\theta_{13} = 0$, the dotted lines to $\sin^2\theta_{13} = 0.04$. In the bottom panel, the dashed line is the surviving $\Delta N_{\rm eff}$ when the final ξ_{ν_e} is in the range allowed by BBN.

Some Conclusions

- BBN fixes the baryon abundance $\Omega_B h^2$ mainly through ^{2}H

$\Omega_B h^2 = 0.021 \pm 0.002$ (2σ) 2σ agreement with WMAP-5y

- only serious discrepancy with ^{7}Li (a factor 3)
- too much ^{6}Li is found
- Assuming extra dof: $N_\nu = 3.0 \pm 0.3_{stat}$ (2σ) $\pm\, 0.3_{syst}$
- Assuming deg. ν's $\xi = 0.004 \pm 0.017_{stat}$ **(2σ)** $\pm\, 0.017_{syst}$
- Some models invoked to explain the disagreement will be soon tested at LHC

A Planetary Nebula is a glowing shell of gas and plasma formed by certain types of stars when they die

NGC6543 - Cat's Eye Nebula

A HII regions, also known as emission nebula, is a cloud of glowing gas and plasma, sometimes several hundred light-years across, in which star formation is taking place

NGC 604, a giant H_{II} region in the Triangulum Galaxy.

A **Blue Compact dwarf Galaxy** (**BCG galaxy**) is a small galaxy which contains large clusters of young, hot, massive stars.

NGC 1705, a nearby example of a blue compact dwarf galaxy .

A **Globular Cluster** is a spherical collection of stars that orbits a galactic core as a satellite

_The Messier 80 globular cluster in the constellation Scorpius