Primordial Nucleosynthesis (BBN) and the radiation content of the early universe

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A short review of BBN: recent data and theoretical status

Sixty years after the seminal $\alpha\beta\gamma$ paper (Alpher, Bethe, Gamow, 1948):

- Theoretical (standard) framework well established
- Increasingly precise data on Deuterium, ^4He(?), and ^7Li
- Increasingly precise data on nuclear process rates from lab experiments at low energies (10 KeV – MeV)
- Baryon fraction measured very accurately by CMB and Deuterium, and they agree!!

COSMOLOGY

ASTROPHYSICS

→

FUNDAMENTAL

MICROPHYSICS

BBN Input:

- baryon density: $\eta = n_B/n_\gamma \approx 274\ 10^{-10}\ \Omega_b h^2$ (Now from CMB)
- energy density in relativistic degrees of freedom historically described as "effective number of neutrinos", but it can account partially for:

1) non instantaneous decoupling effects
2) non standard ν-interactions, ν-asymmetries
3) extra relativistic degrees of freedom,exotic physics

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

BBN Output: X_a (nuclide abundances)

We can get information about Cosmological Neutrinos + extra relativistic d.o.f. !

Solving numerically BBN dynamics

1. Weak interactions freeze out at T ~1 MeV
2. Deuterium forms via p n $\rightarrow$D γ at T ~ 0.1 MeV
3. Nuclear chain

$$\frac{\dot{a}}{a} = H = \sqrt{\frac{8\,\pi G_N}{3}\,\rho} \quad ,$$

$$\frac{\dot{n}_B}{n_B} = -\,3\,H \quad ,$$

$$\dot{\rho} = -\,3\,H\,(\rho + P) \quad ,$$

$$\dot{X}_i = \sum_{j,k,l} N_i \left(\Gamma_{kl\rightarrow ij}\,\frac{X_k^{N_k}\,X_l^{N_l}}{N_k!\,N_l!} - \Gamma_{ij\rightarrow kl}\,\frac{X_i^{N_i}\,X_j^{N_j}}{N_i!\,N_j!} \right) \equiv \Gamma_i \quad ,$$

$$n_B \sum_j Z_j\,X_j = n_{e^-} - n_{e^+} \equiv L\left(\frac{m_e}{T}, \phi_e\right) \equiv T^3\,\hat{L}\left(\frac{m_e}{T}, \phi_e\right) \quad ,$$

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

Neutrino decoupling can be computed independently of nuclear abundances

BBN accuracy I

Weak rates:

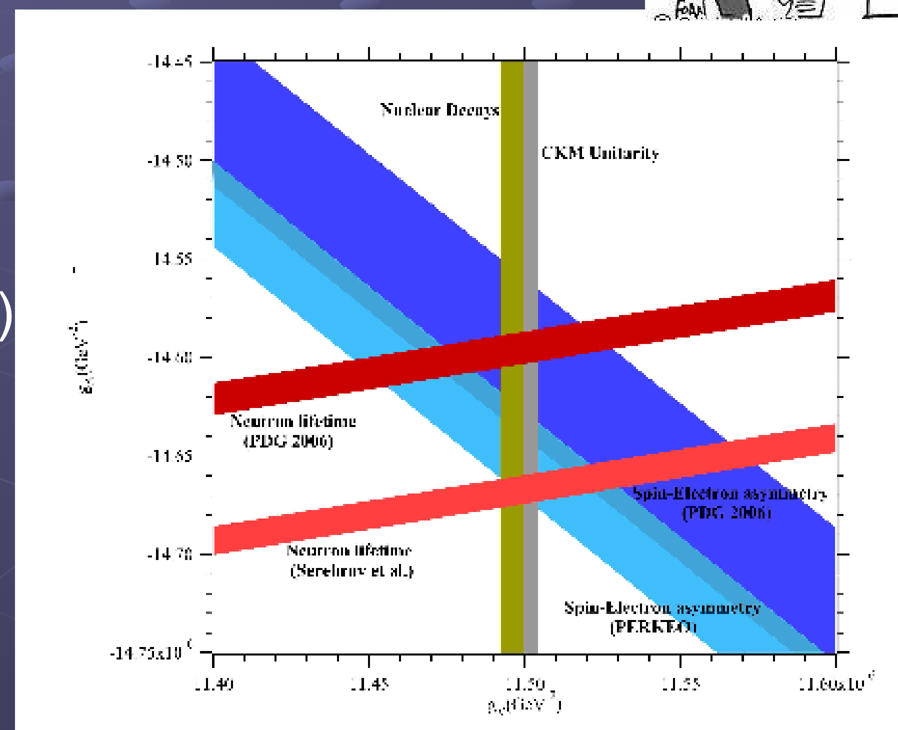
- radiative corrections $O(\alpha)$
- finite nucleon mass $O(T/M_N)$
- plasma effects $O(\alpha T/m_e)$
- neutrino decoupling $O(G_F^2 T^3 m_{Pl})$

Main uncertainty: neutron lifetime

τ_n= 885.7 ± 0.8 sec (PDG)

τ_n=878.5 ± 0.8 sec (Serebrov et al 2005)

^{4}He mass fraction Y_P linearly increases with τ_n: 0.246 - 0.249



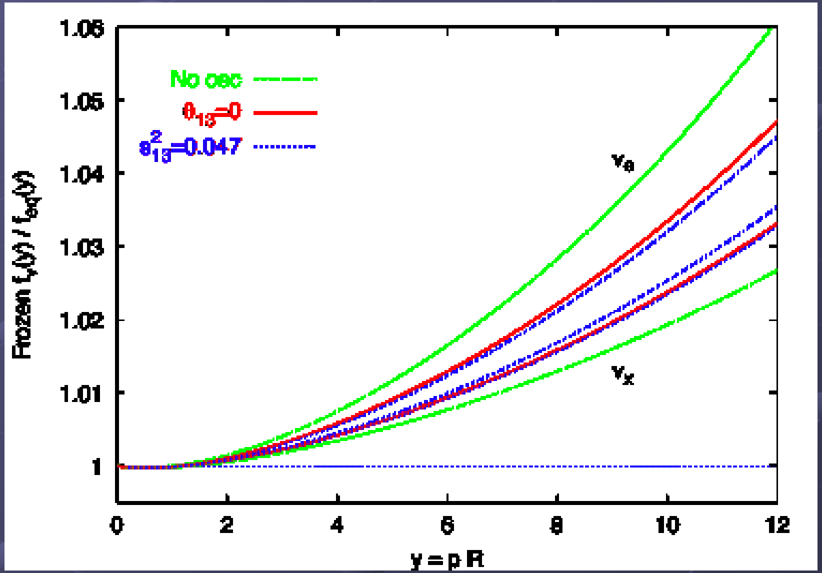
Nico & Snow, **Ann.Rev.Nucl.Part.Sci.55:27-69,2005**

Neutrino decoupling in details

- Non standard neutrino-electron interactions — NPBB756:100 (2006)
- Including oscillation effects — NPB729:221 (2005)
- E.M. plasma effects — PLB534:8 (2002)
- Neutrino chemical potentials — NPB590:539 (2000)

but revisited after S.Pastor et al PRL102:241302 (2009)

z=T a	$\delta\rho_e$	$\delta\rho_x$	N_ν^{eff}
1.4	0.73%	0.52%	3.046



Neglecting ν-asymmetries

$$N_\nu^{\rm eff} = \left(\frac{z^0}{z^{\rm fin}}\right)^4 \left(3 + \frac{\delta\rho_{\nu_e}}{\rho_\nu^0} + 2\frac{\delta\rho_{\nu_x}}{\rho_\nu^0}\right) \simeq \left(3 - 12\frac{\delta z}{z^0} + \frac{\delta\rho_{\nu_e}}{\rho_\nu^0} + 2\frac{\delta\rho_{\nu_x}}{\rho_\nu^0}\right)$$

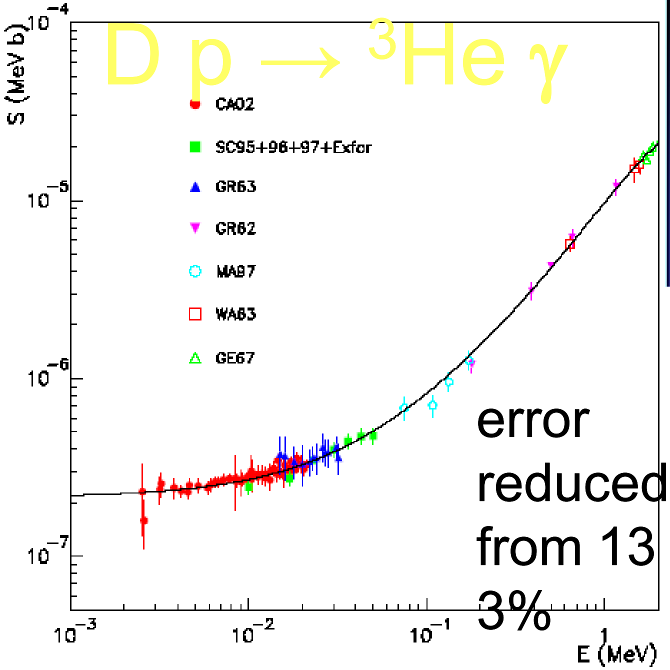
Small effect on ^{4}He mass fraction: $\delta Y_p = 2\ 10^{-4}$

BBN accuracy II

Nuclear rate benchmarks:
Caughlan and Fowler ‘88
Smith, Kawano and Malaney ‘93
NACRE

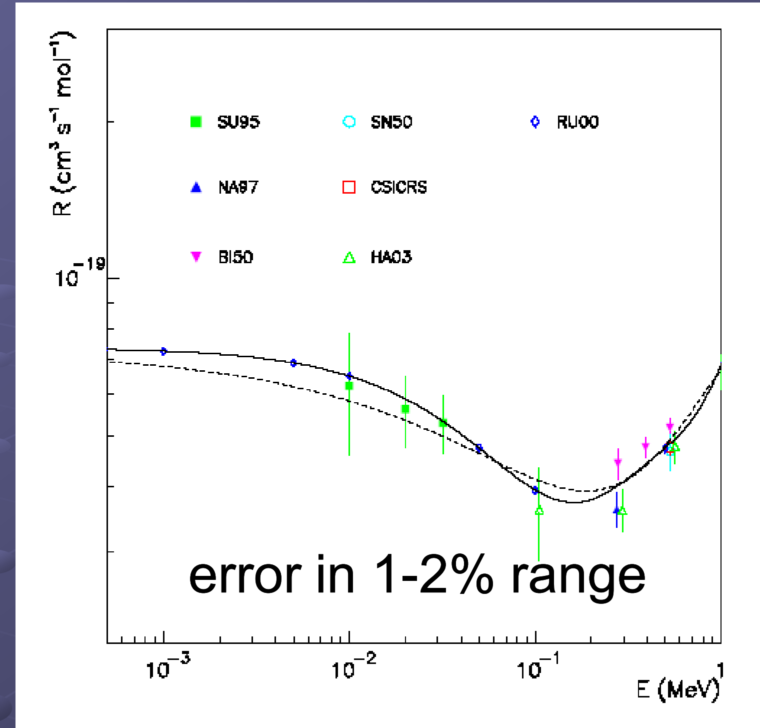
Recent efforts: reanalysis of the whole network including recent experimental results (e.g. LUNA) and theoretical calculations (e.g. $p\ n \rightarrow D\ \gamma$). Main improvements: underground measurements in low energy range (100 KeV)

D p → ^{3}He γ



error reduced from 13 to 3%

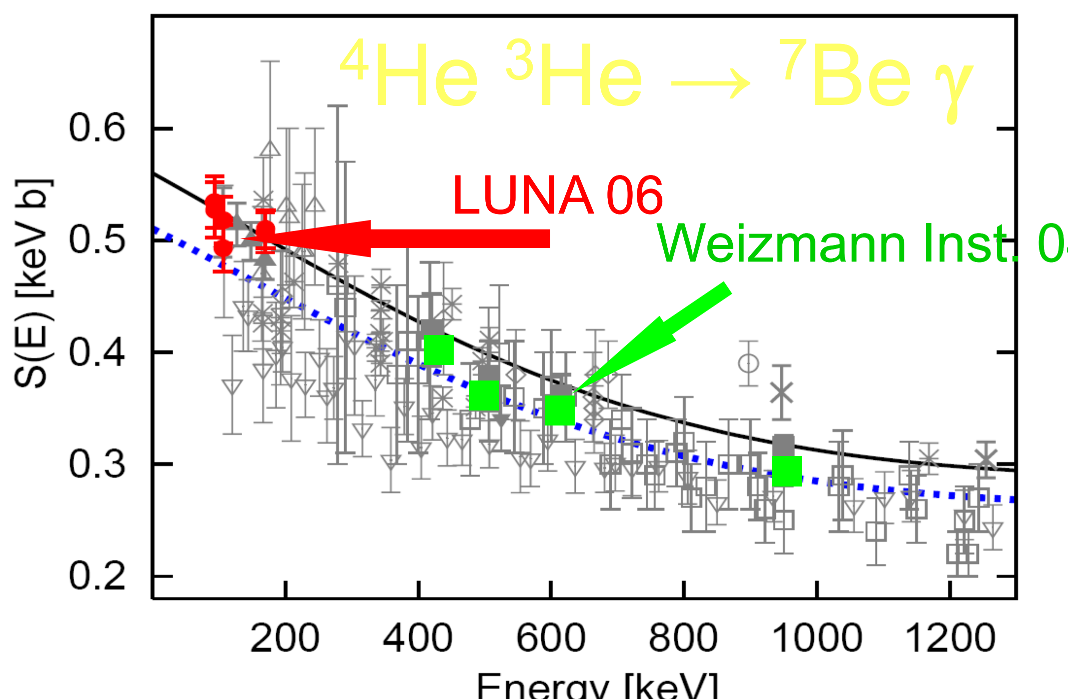
p n → D γ



error in 1-2% range

Pionless effective field theory at N^{2}LO and N^{4}LO (Rupak)

^{4}He ^{3}He → ^{7}Be γ



results seem to worsen the ^{7}Li problem

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

PArthENoPE

Public Algorithm Evaluating Nucleosynthesis of Primordial Elements

Comput.Phys.Commun.178:956,2008

Nuclides considered

nuclide i	central value	σ_{ω_b}	σ_{ii}	rate	$\delta\sigma^2/\sigma^2(\%)$
Y_p	0.2480	$^{+0.0002}_{-0.0003}$	±0.0002	R_0	98.5
^{2}H/H $\times10^5$	2.53	±0.11	±0.04	R_2	49
				R_3	37
				R_4	14
^{3}He/H $\times10^5$	1.02	$^{+0.01}_{-0.02}$	±0.03	R_7	80.7
				R_2	16.8
^{7}Li/H $\times10^{10}$	4.7	±0.3	±0.4	R_{14}	40.9
				R_8	25.1
				R_{15}	16.2
				R_7	8.6
^{6}Li/H $\times10^{14}$	1.1	±0.1	$^{+1.7}_{-1.1}$	R_{13}	~ 100

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

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

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

The astrophysical environments which seem the 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

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

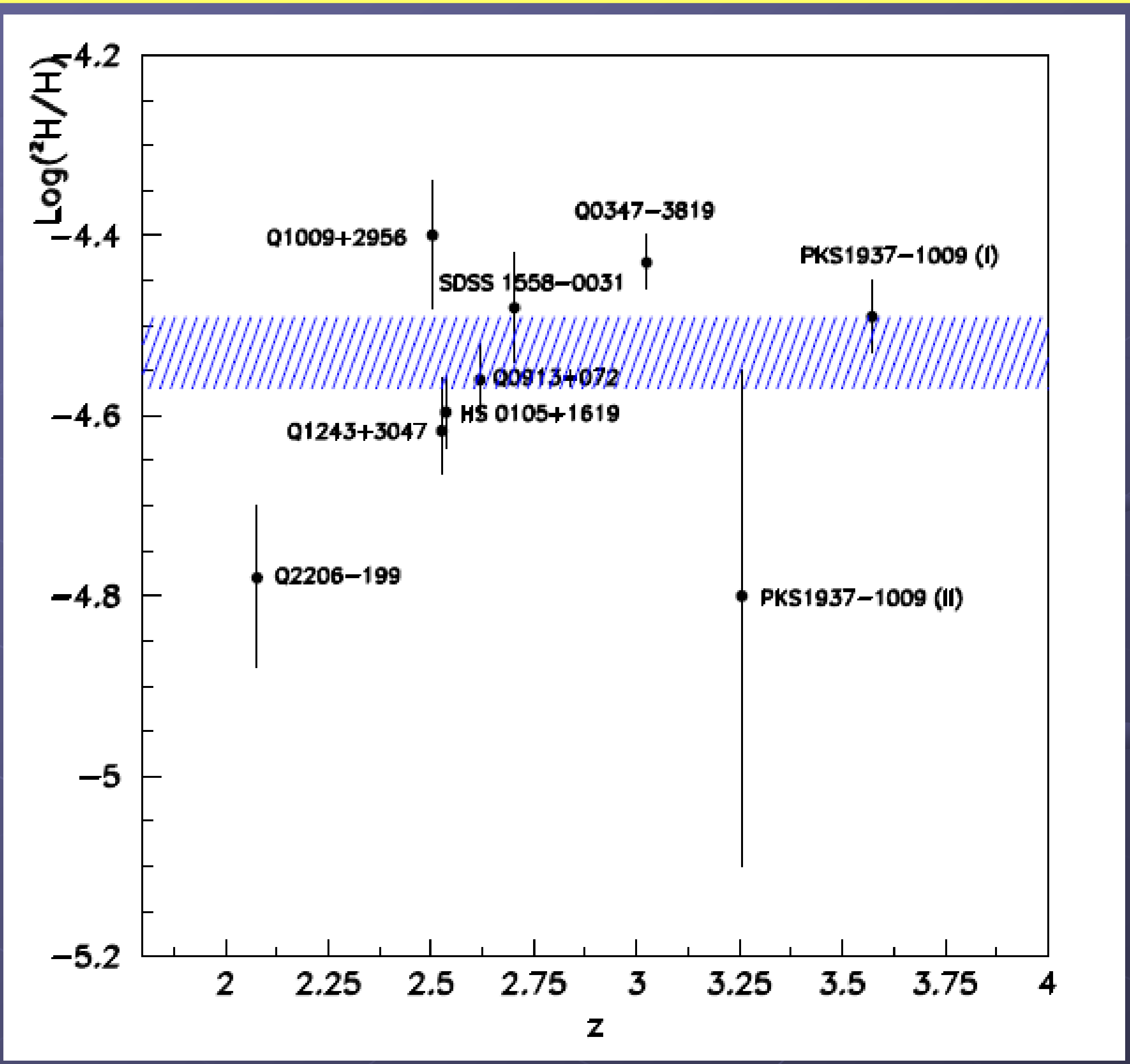
(H_I regions are interstellar cloud made of neutral atomic hydrogen)

(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 few QASs pass the exam!

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



Iocco et al. PR472, 1 (2009)

^{4}He

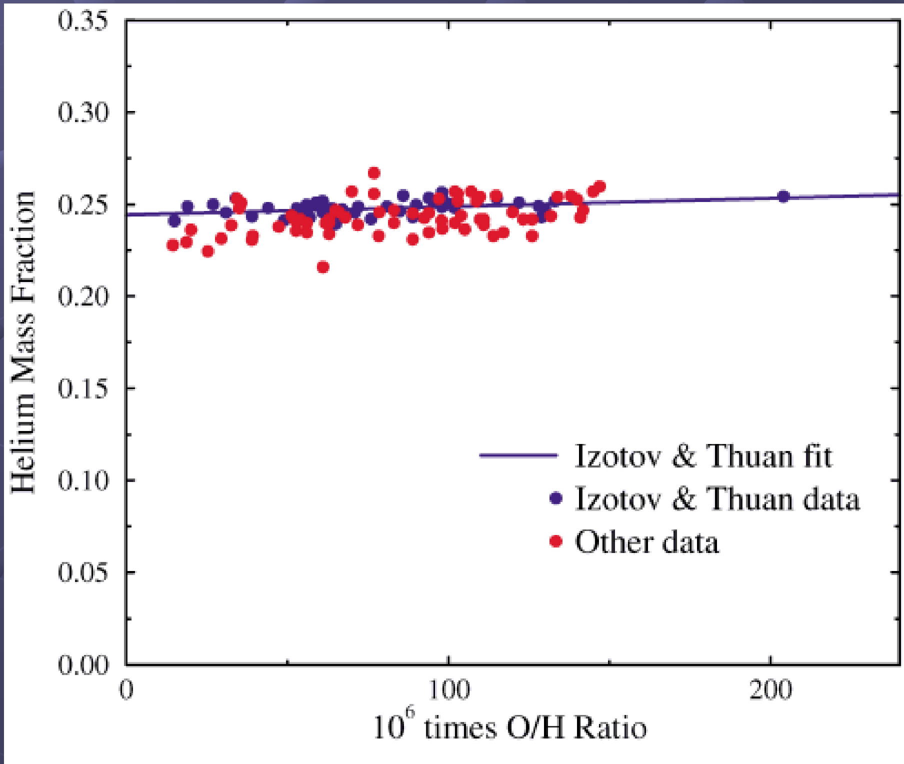
Nuclear stellar processes through successive generations of stars have burned hydrogen into ^{4}He and heavier elements, hence increasing the primordial ^{4}He

Since the history of stellar processing is measured by *metallicity* (Z) the primordial value of ^{4}He mass fraction Y_p can be derived by extrapolating to O/H and N/H ➔ 0

- Observation of ionized gas (HeII ✹ HeI recombination lines in H_{II} regions) in Blue Compact Galaxies (BCGs)

which are the least chemically evolved known galaxies

- Y_P in different galaxies plotted as function of O and N abundances.
- Regression to "zero metallicity"



Small statistical error but large systematics

Recent analyses:
Izotov & Thuan 2010
Aver, Olive & Skillmann 2010
Aver, Olive & Skillmann arXiv:1012.2385

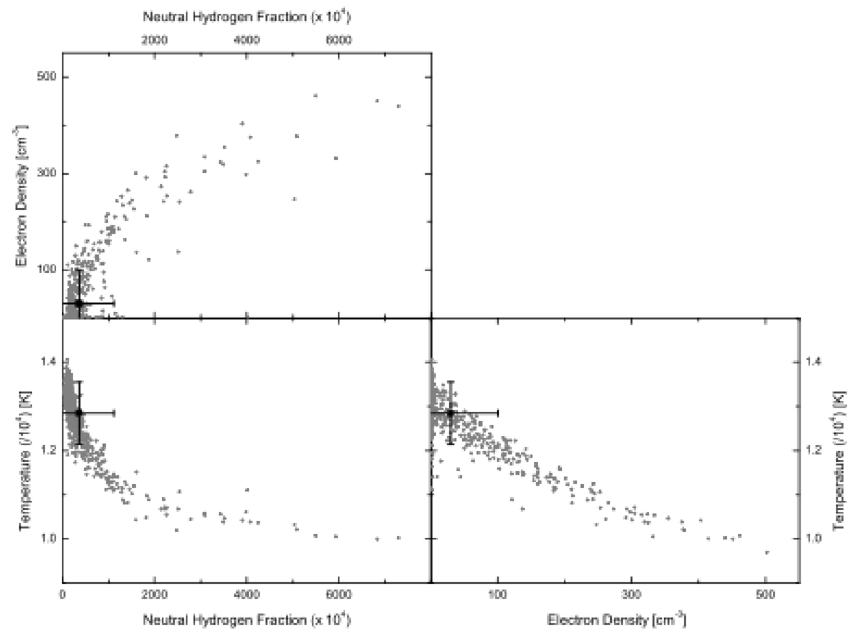


Fig. 10.— Monte Carlo plots (1000 points) of density, temperature, and neutral hydrogen fraction for NGC 346. The strong correlation between the three parameters demonstrates the difficulty in solving for them independently.

Main sources of systematics:
i) interstellar reddening
ii) temperature of clouds
iii) electron density

Possible developments: using more H lines

All recent determinations are dominated by systematics.

- $Y_p = 0.250 \pm 0.003$ Iocco et al. PR472, 1 (2009)
- $Y_p = 0.2565 \pm 0.0010(stat) \pm 0.0050(syst)$ Izotov & Thuan 2010
- $Y_p = 0.2561 \pm 0.0108$ Aver et al. 2010
- $Y_p = 0.2573 \pm 0.0033$ Aver et al. arXiv:1012.2385

CMB anisotropies are sensitive to the reionization history, and thus to fraction of baryons in the form of ^{4}He.

Ony a marginal detection of a non-zero Y_p, and even with PLANCK the uncertainty will be larger than the present systematic spread of the astrophysical determinations.

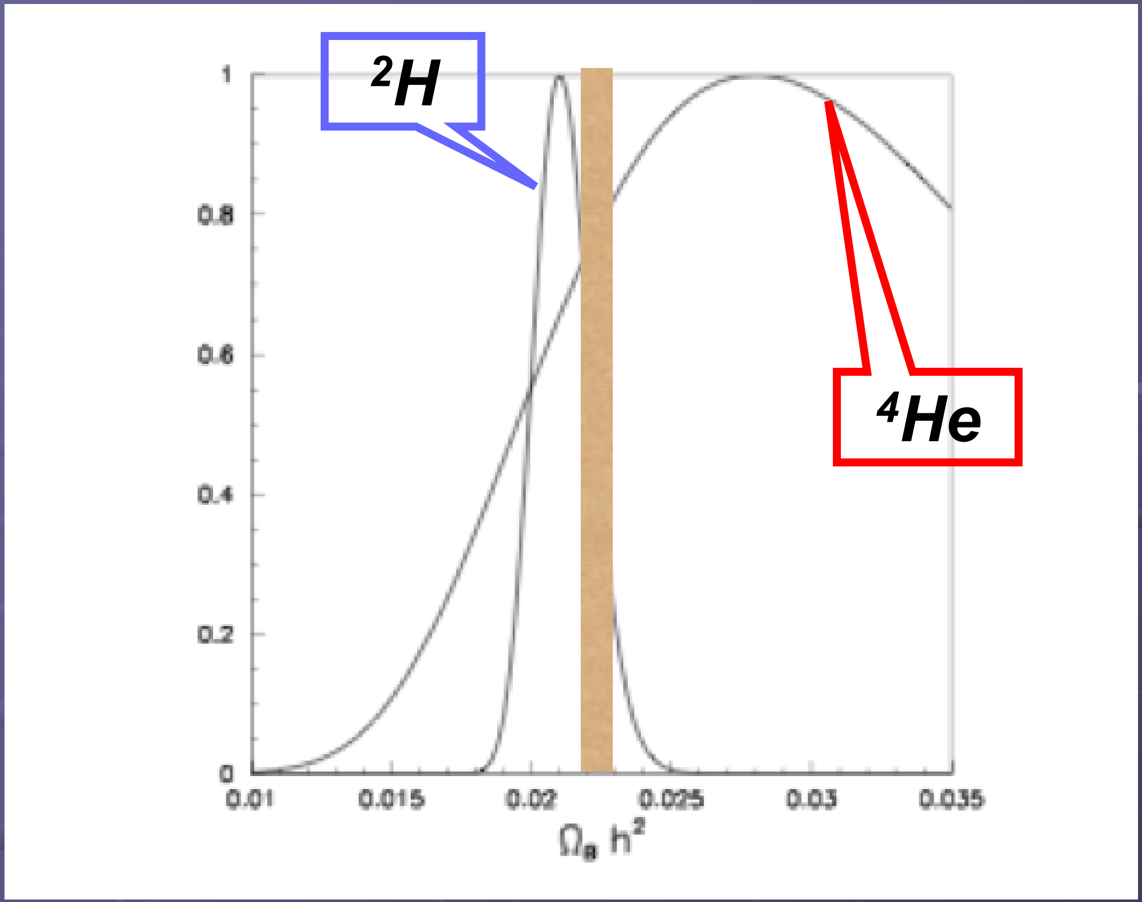
Likelihood analysis

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

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

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

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



- Only ^{2}H ✸ $\Omega_B h^2 = 0.021 \pm 0.001$
- Only ^{4}He ✸ $\Omega_B h^2 = 0.028^{+0.011}_{-0.007}$
- WMAP 7-years ✸ $\Omega_B h^2 = 0.0226 \pm 0.0005$

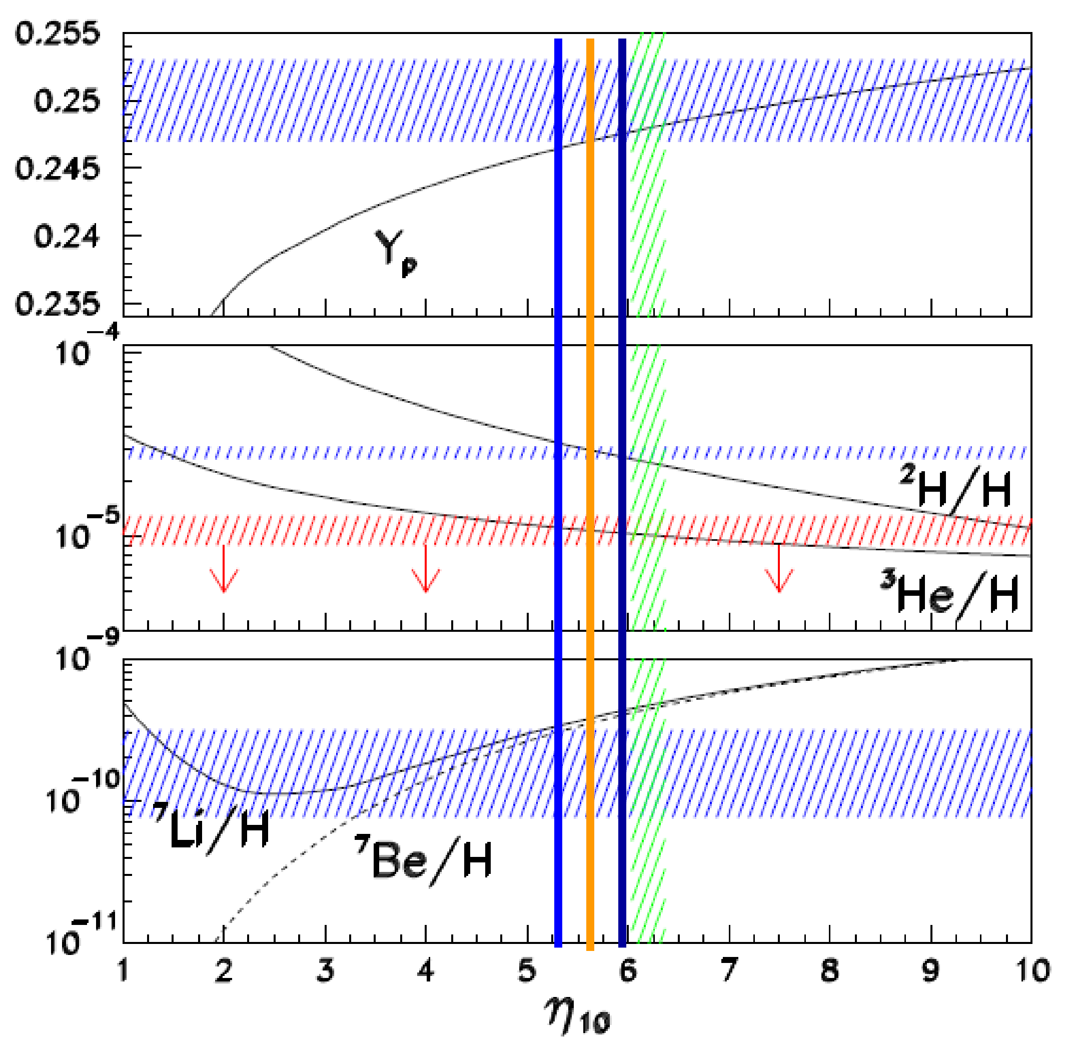
Compatible results at order 1.5 σ

After marginalization

Iocco et al. PR472, 1 (2009)

$N_\nu = 3.18^{+0.22}_{-0.21}$ (68% CL) $2.8 \le N_\nu \le 3.6$ (95% CL)

$\Omega_B h^2 = 0.021 \pm 0.001$ (68% CL)



Using Y_P from IT10

$3.0 \le N_\nu \le 4.5$ (95% CL)

Due to the largest value of Y_P

Again Tension in BBN?

BBN and Neutrino Asymmetry: a leptometer

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

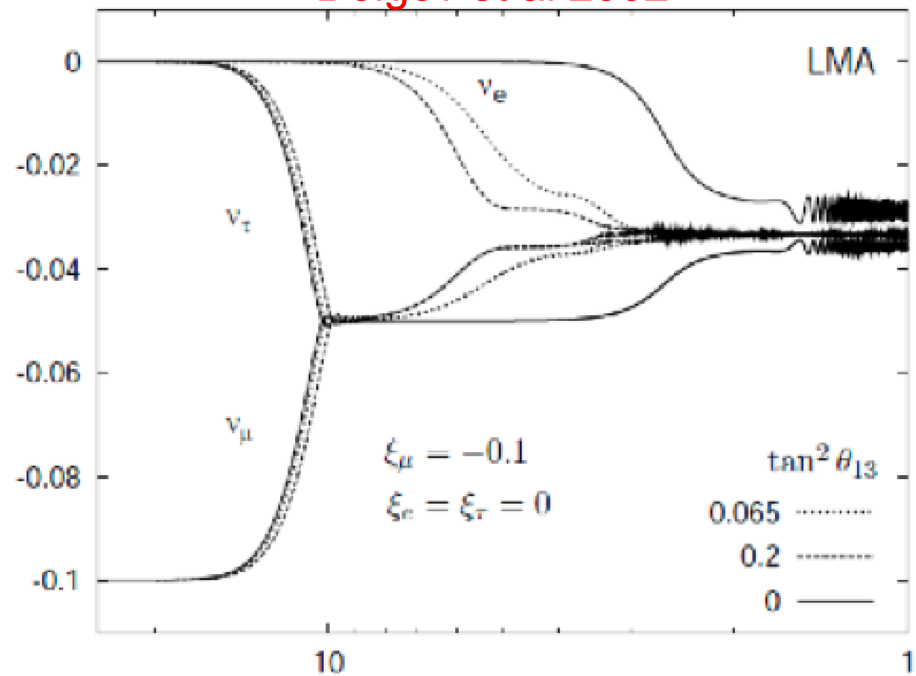
1) chemical potentials contribute to N_ν (if no extra d.o.f. and assuming T.E.)

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

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

3) Neutrino oscillations mix ξ_e , ξ_x .They equilibrate if θ_{13} is not too small

Dolgov et al 2002

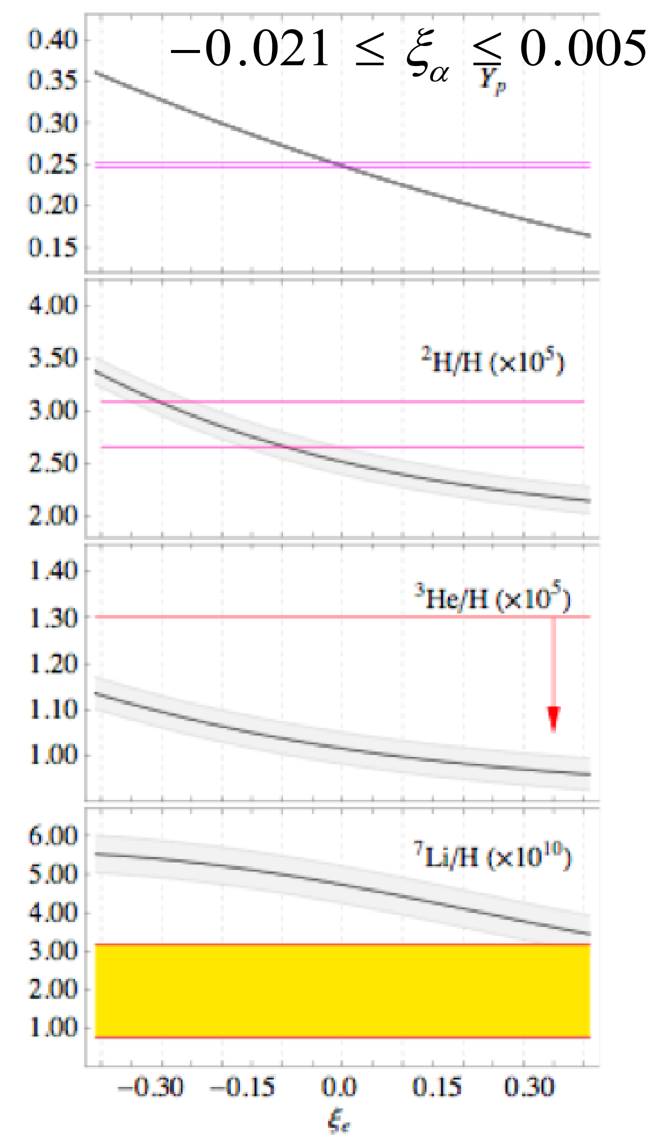


"We conclude that in the LMA region the neutrino flavors essentially ***equilibrate long before n/p freeze out****, even when θ_{13} is vanishingly small"*

"...the BBN limit on the ν_e degeneracy parameter, ***$|\xi_\nu| < 0.07$, now applies to all flavors."***

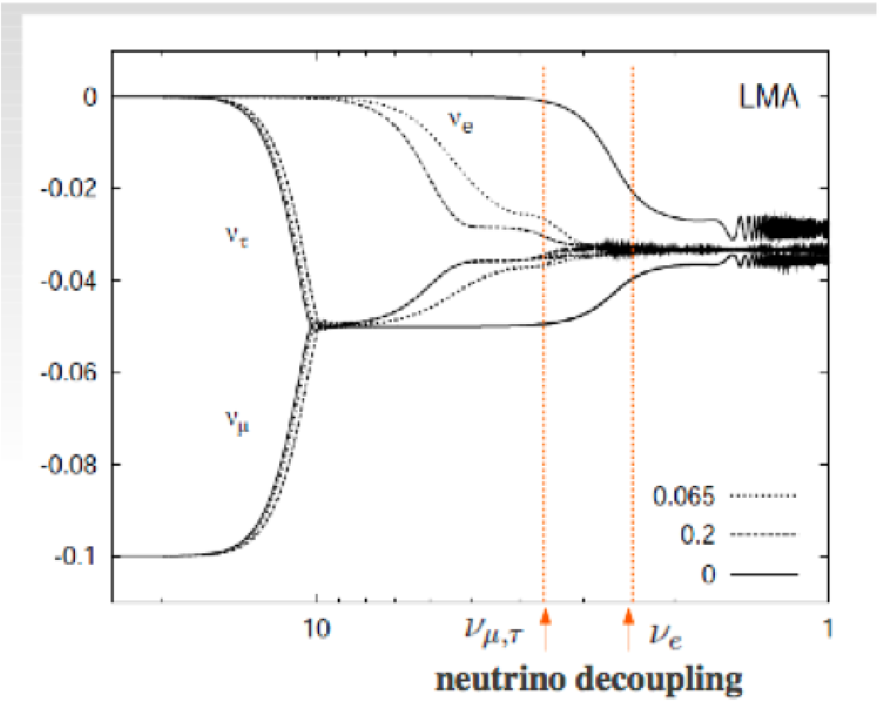
$$\Delta N_\nu = \sum_i \left(\frac{30\,\xi_i^2}{7\pi^2} + \frac{15\,\xi_i^4}{7\pi^4} \right) \le 0.006$$

Iocco et al 2009



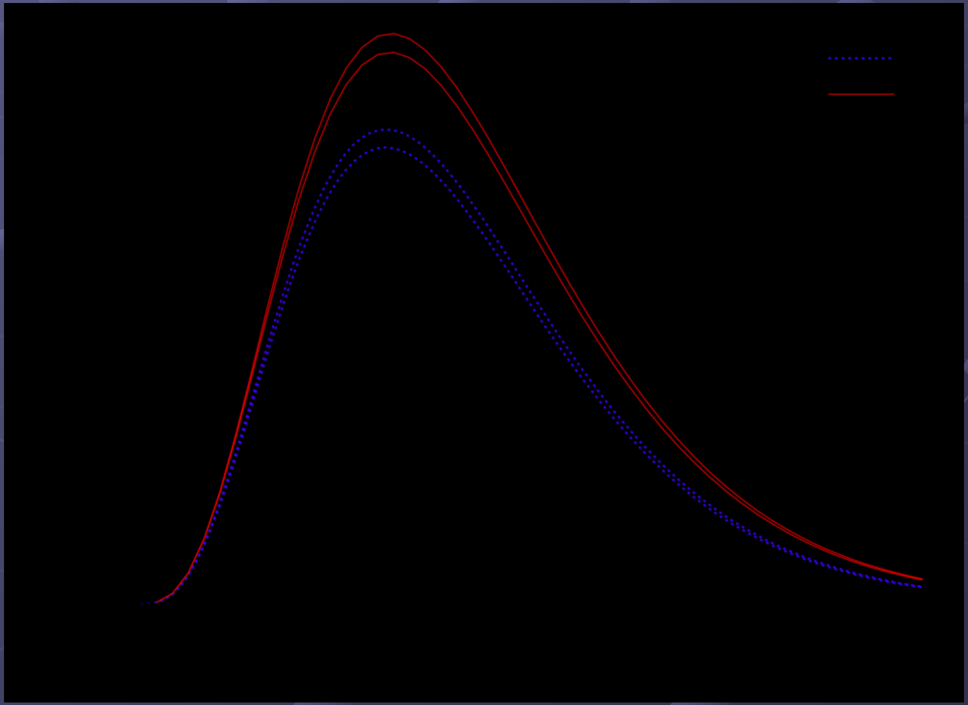
Even smaller than 0.046 due to non instantaneous decoupling

However...



S. Pastor et al.,Phys. Rev. Lett. **102**, 241302 (2009)

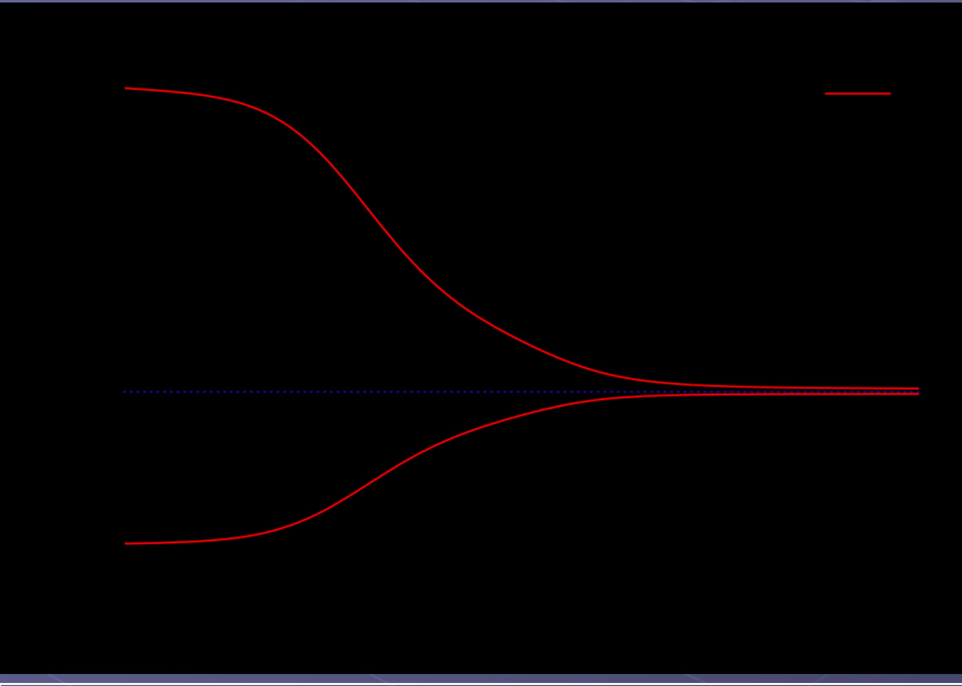
ν decouple from the thermal bath, and scatterings & pair processes may be inefficient to re-adjust their distribution.
Not a perfect FD (in general)!



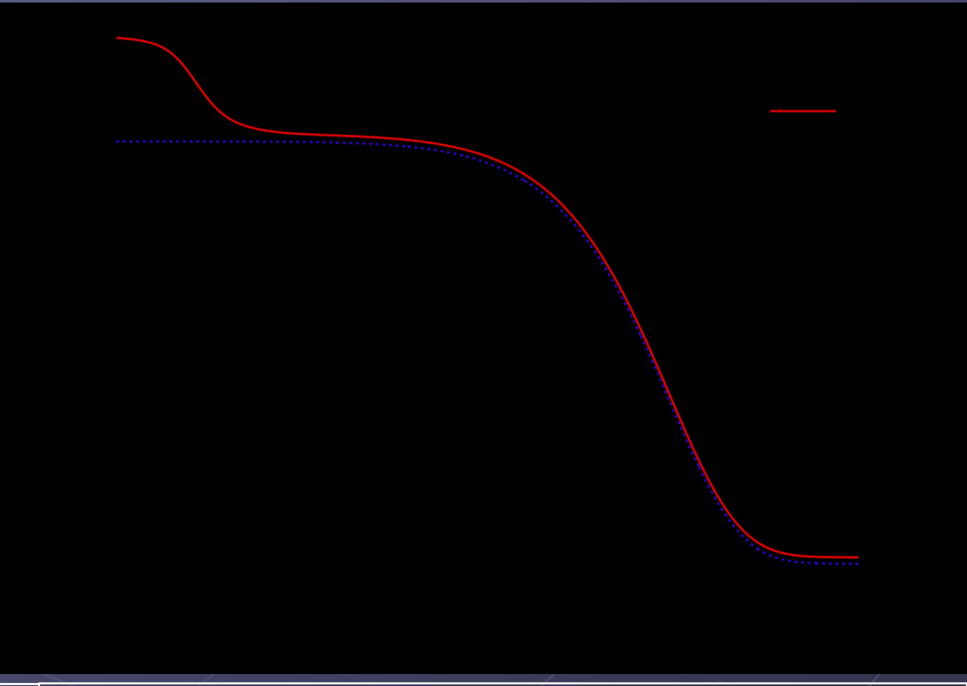
We must follow neutrino decoupling during BBN

G. Mangano, G. M., S. Pastor, Pisanti, S. Sarikas **JCAP 1103 (2011) 035**

We evolve ρ_ν starting from initial values of the total neutrino asymmetry η_ν and $\eta_{\nu e}$. The oscillation parameters are fixed at the fitted values apart of θ_{13}.

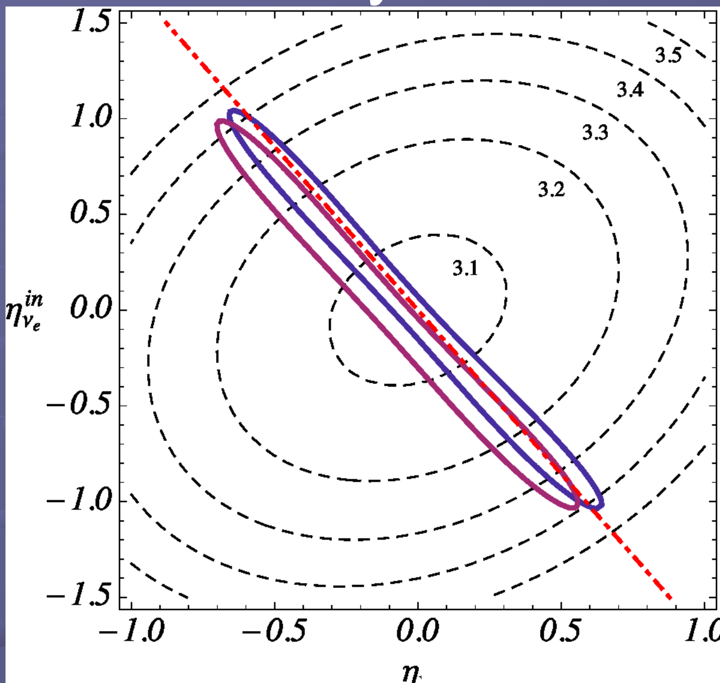


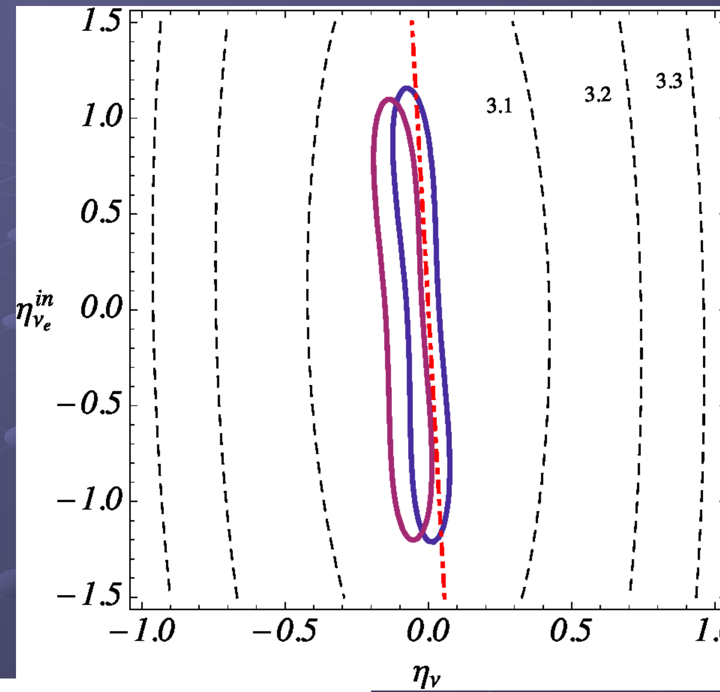
Case for an intial $\eta_\nu = -0.41$, and $\eta_{\nu e}^{in} = 0.82$. The total neutrino asymmetry is constant and equal to three times the value shown (blue dotted line).



Same initial asymmetries. The blue dotted line shows the case of vanishing asymmetries

Spanning on the initial values of asymmetries and including the neutrino dynamics in PArthENoPE we can performe a likelihood analysis for ^{2}H and ^{4}He

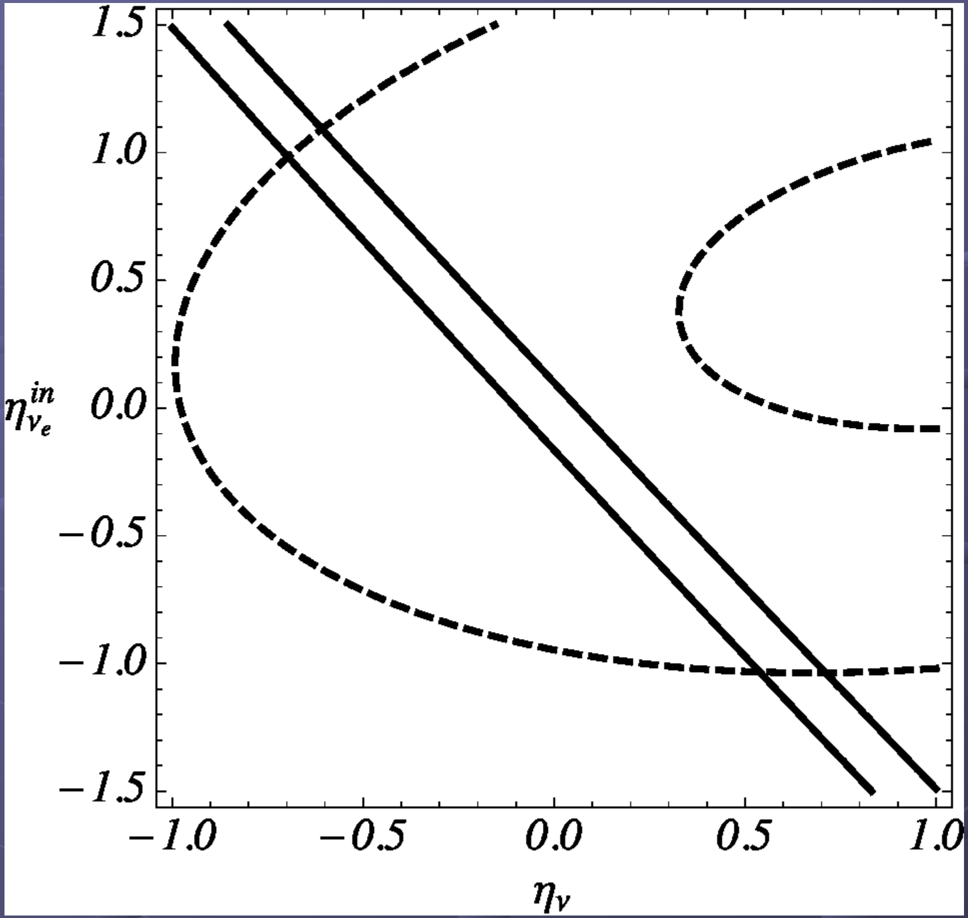




	$\theta_{13} = 0$	$\sin^2\theta_{13} = 0.04$
$Y_p = 0.250 \pm 0.003$	$-0.66 < \eta_\nu < 0.63$	$-0.13 < \eta_\nu < 0.07$
$Y_p = 0.2573 \pm 0.0033$	$-0.71 < \eta_\nu < 0.56$	$-0.20 < \eta_\nu < 0.02$

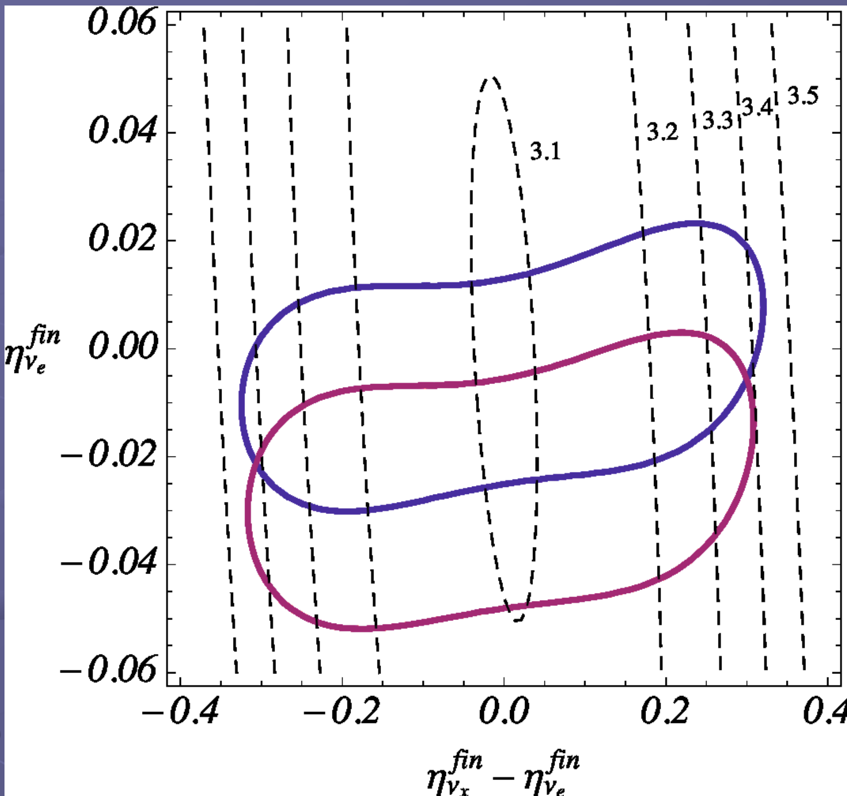
The 95% C.L. contours from BBN analysis for $\theta_{13} = 0$ (left) and $\sin^2\theta_{13} = 0.04$ (right). The two contours correspond to the different choices for the primordial 4He abundances. The (red) dot-dashed line is the set of values which evolve towards a vanishing final value of electron neutrino asymmetry. annihilation stage.

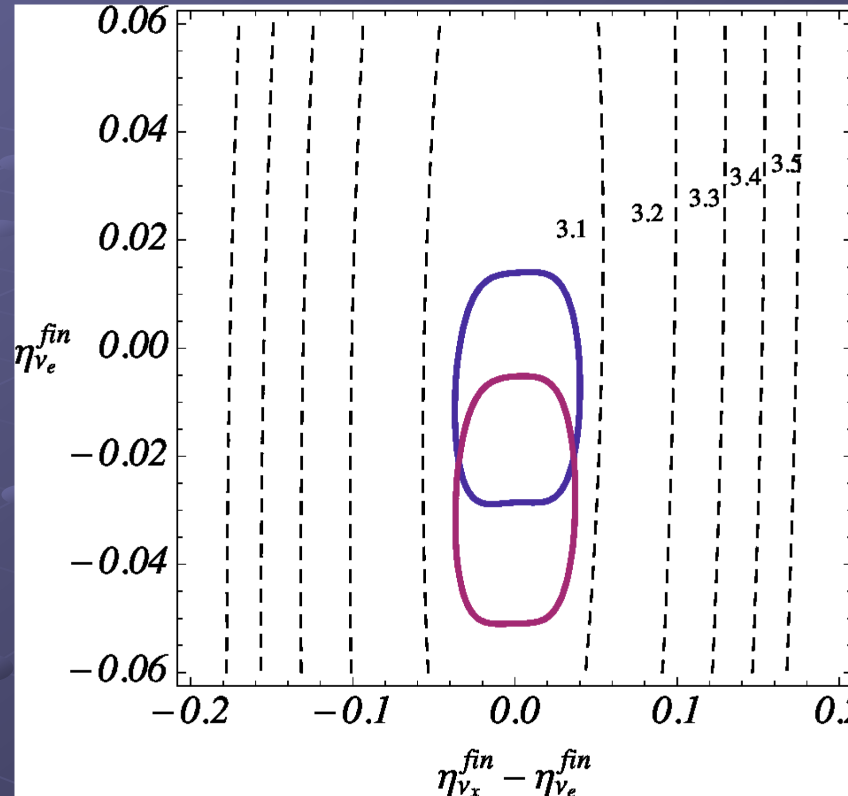
Deuterium removes the degeneracy



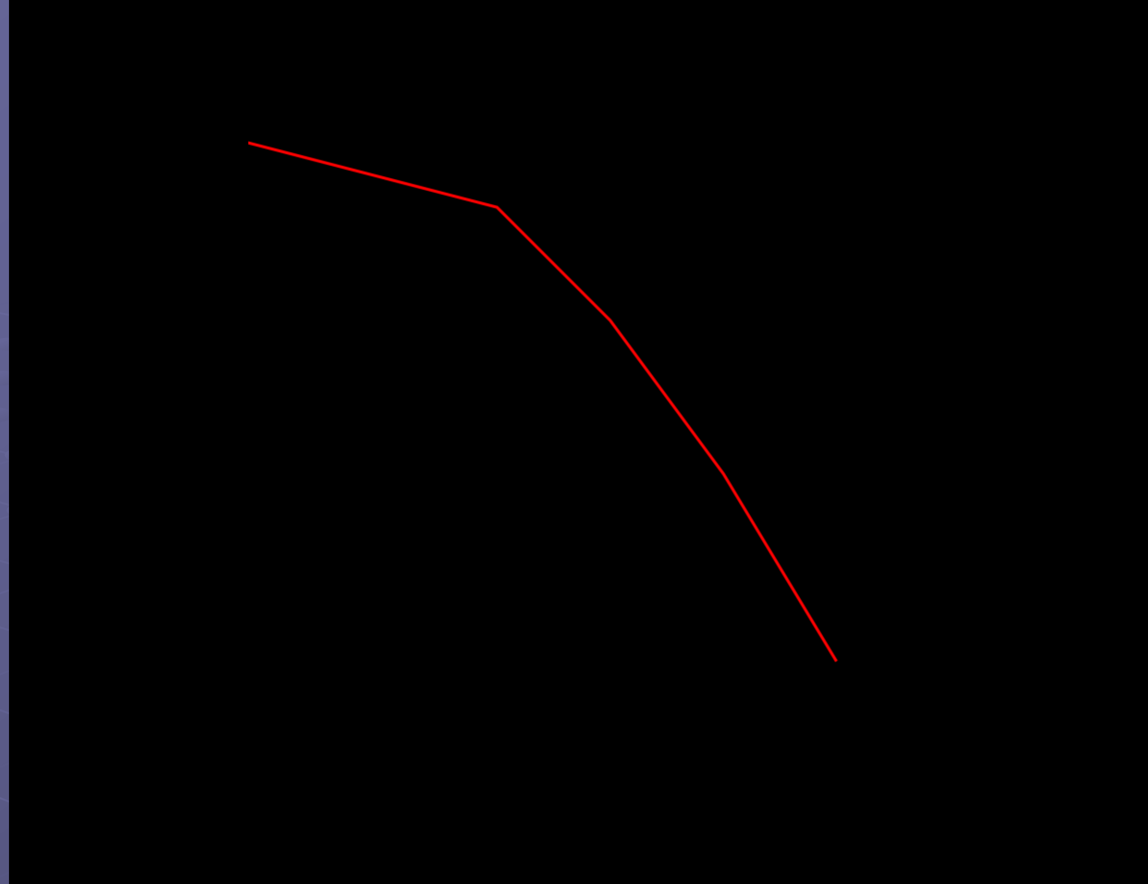
Areas between the lines correspond to 95% C.L. regions singled out by the ^4He mass fraction (solid lines), and Deuterium (dashed lines)

The same but for final asymmetries: at the onset of BBN



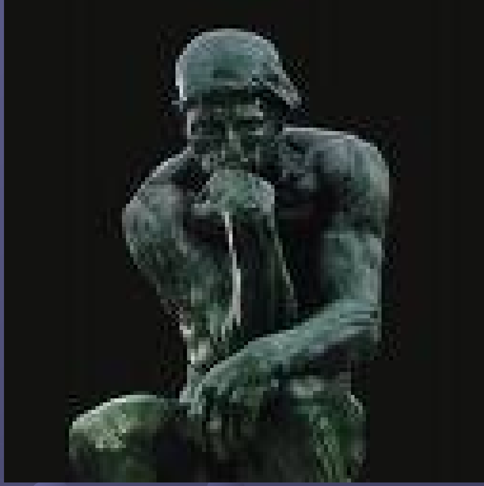


For small values of θ_{13}, N_{eff} can be as large as 3.4 still being compatible with BBN



- Planck satellite will reach a sensitivity for N_{eff} of the order of 0.4 at 2σ
- A detection of a ΔN_{eff} = 0.4 – 0.5 could imply a large degeneracy but only for almost vanishing θ_{13}, but in this case a measurement of such angle larger than almost 0.03 would mean extra d.o.f.
- A detection of a ΔN_{eff} > 0.5 would mean in anycase extra d.o.f.
- We have a robust limit from BBN: $\Delta N_{eff} \leq 1.2$ at 2σ arXiv:1103:1261v1 [astro-ph.CO]

Conclusions



- BBN theory quite accurate, at
% level (or better) for main nuclides;
- Problem: systematics in ^{4}He measurements, and Lithium still puzzling; new observational strategies !
- BBN + CMB (PLANCK): a tool to constrain new physics.
- Relevant the interplay with measurements in lab which could fix better the range for θ_{13}