Status of Big Bang Nucleosynthesis

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Sixty years after αβγ seminal paper

(Alpher, Bethe & Gamow 1948)

- Theory reasonably under control (per mille level for ^{4}He (neutron lifetime), 1-2 % for ^{2}H);
- Increased precision in nuclear reaction cross sections at low energy (underground lab's);
- $\Omega_b h^2$ measured by WMAP with high precision;
- Decreasingly precise data (^{4}He), ^{7}Li not understood, ^{2}H fixes $\Omega_b h^2$ value in good agreement with CMB data.

SUMMARY

- THEORY
- DATA
- RESULTS
  standard scenario
  exotic scenarios

Iocco et al, Phys Rept. 472, 1 (2009)

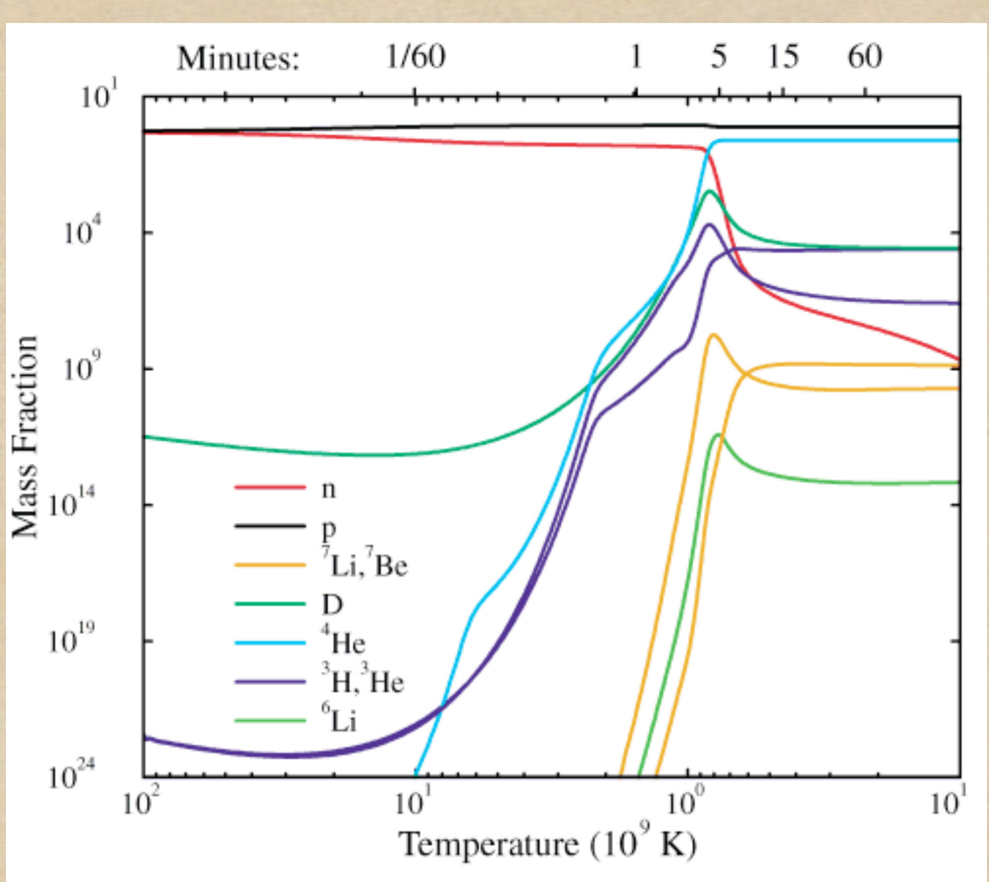
THEORY

weak rate freeze out (1 MeV);

^{2}H forms at T~0.08 MeV;

nuclear chain;

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



Public numerical codes:Kawano, PArthENoPE

private numerical codes: many...

PArthENoPE

Public Algorithm Evaluating Nucleosynthesis of Primordial Elements

THEORY

Weak rates:

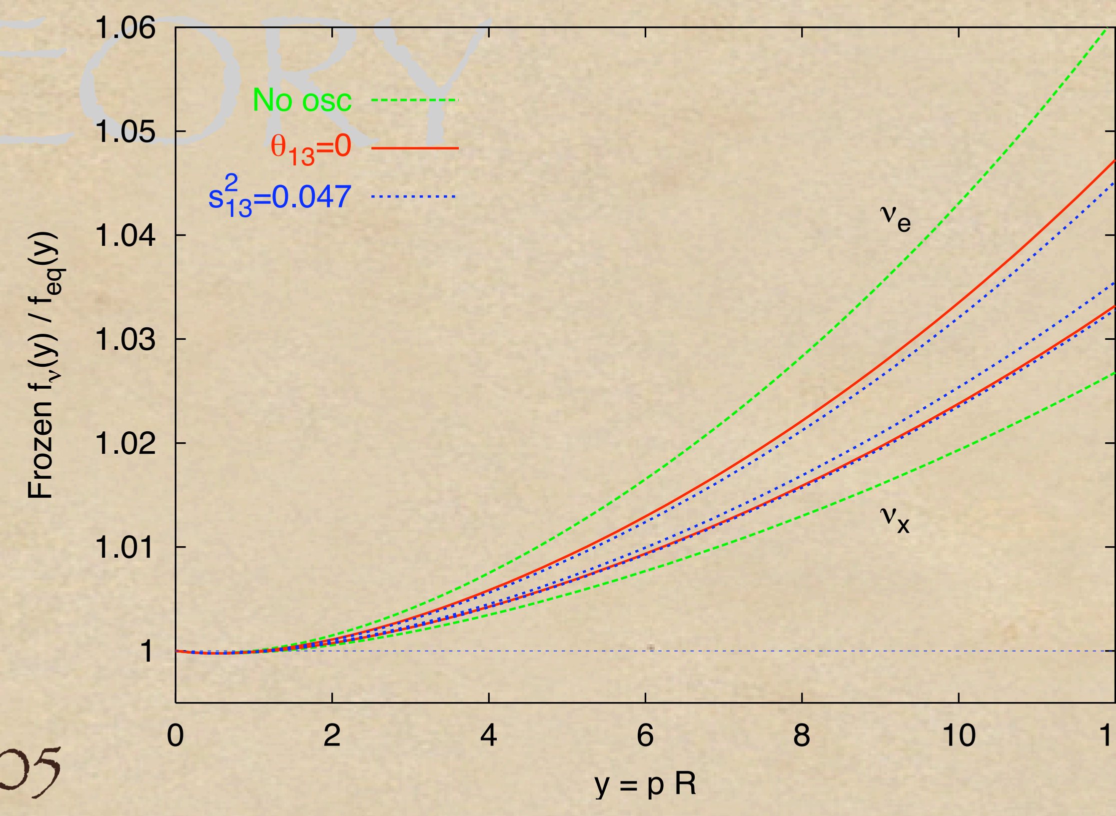
radiative corrections $O(\alpha)$

finite nucleon mass $O(T/M_N)$

plasma effects $O(\alpha T/m_e)$

neutrino decoupling $O(G_F^2 T^3 m_{Pl})$

$N^{eff}_{\nu}=3.046$



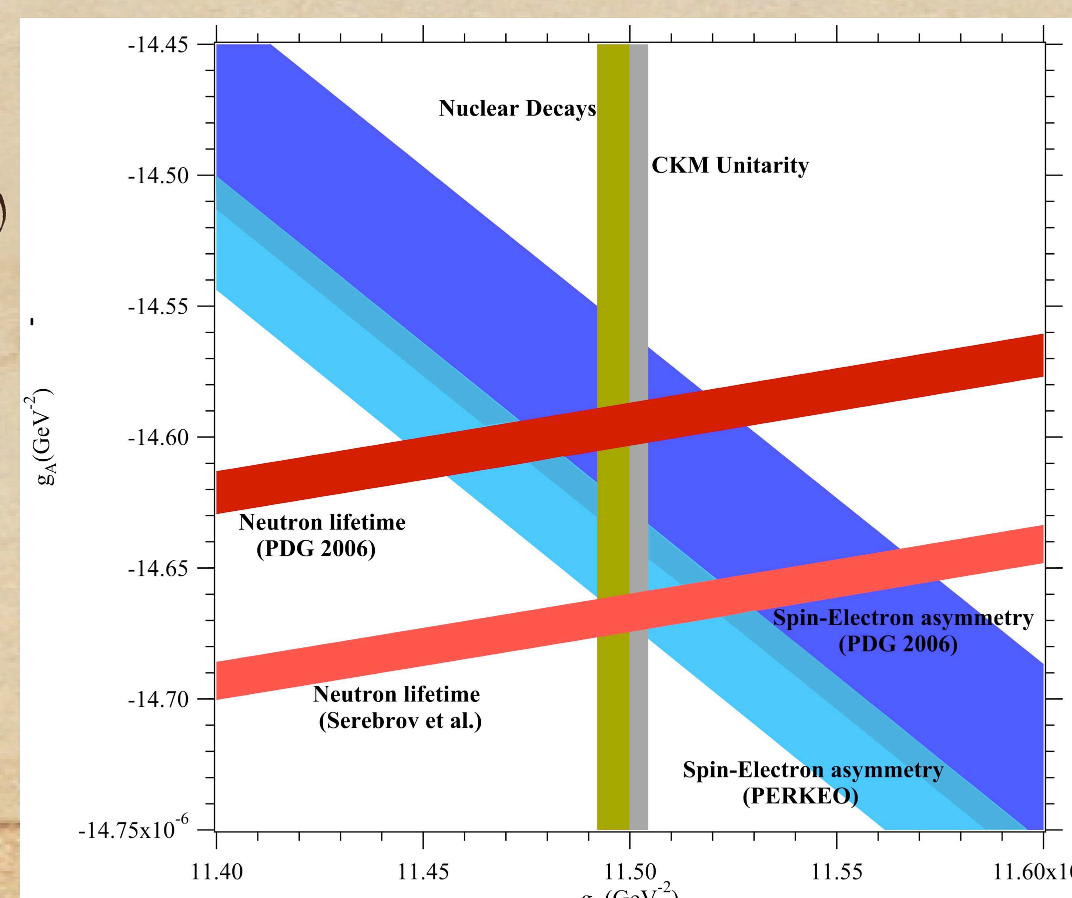
G.M. et al 2005

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



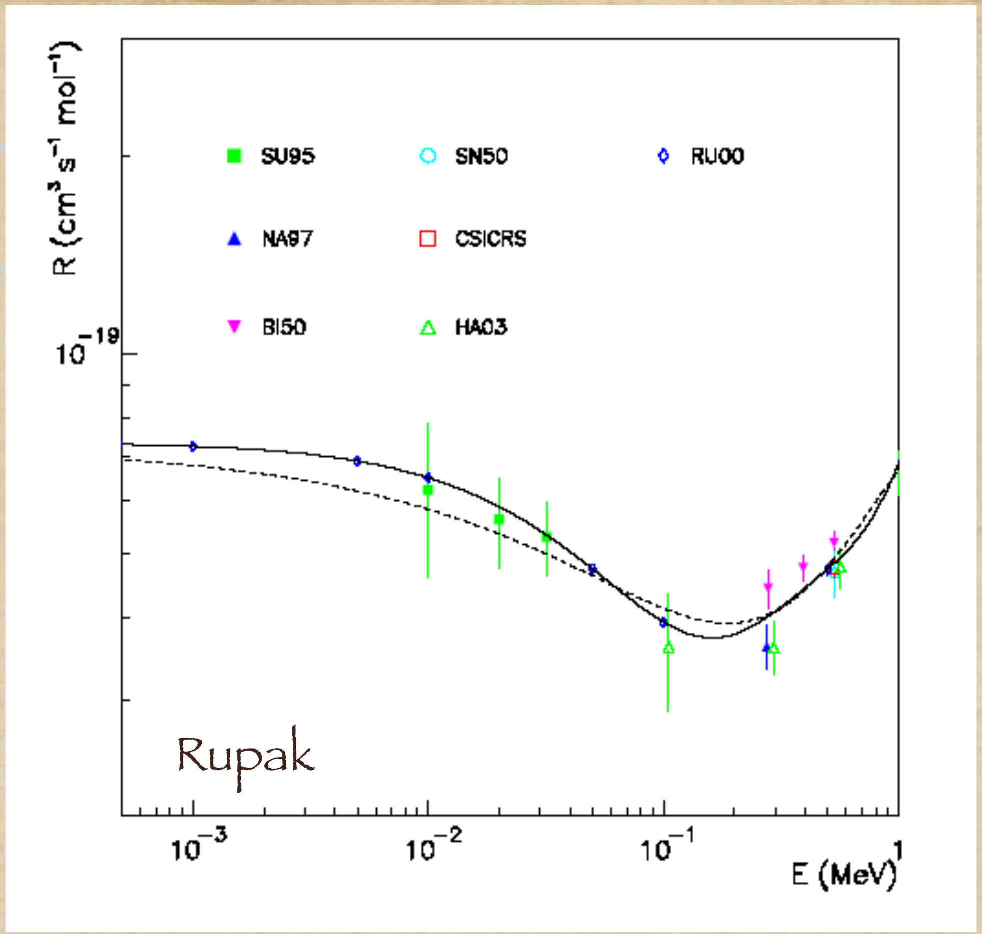
Nico & Snow 2006

Nuclear rates:

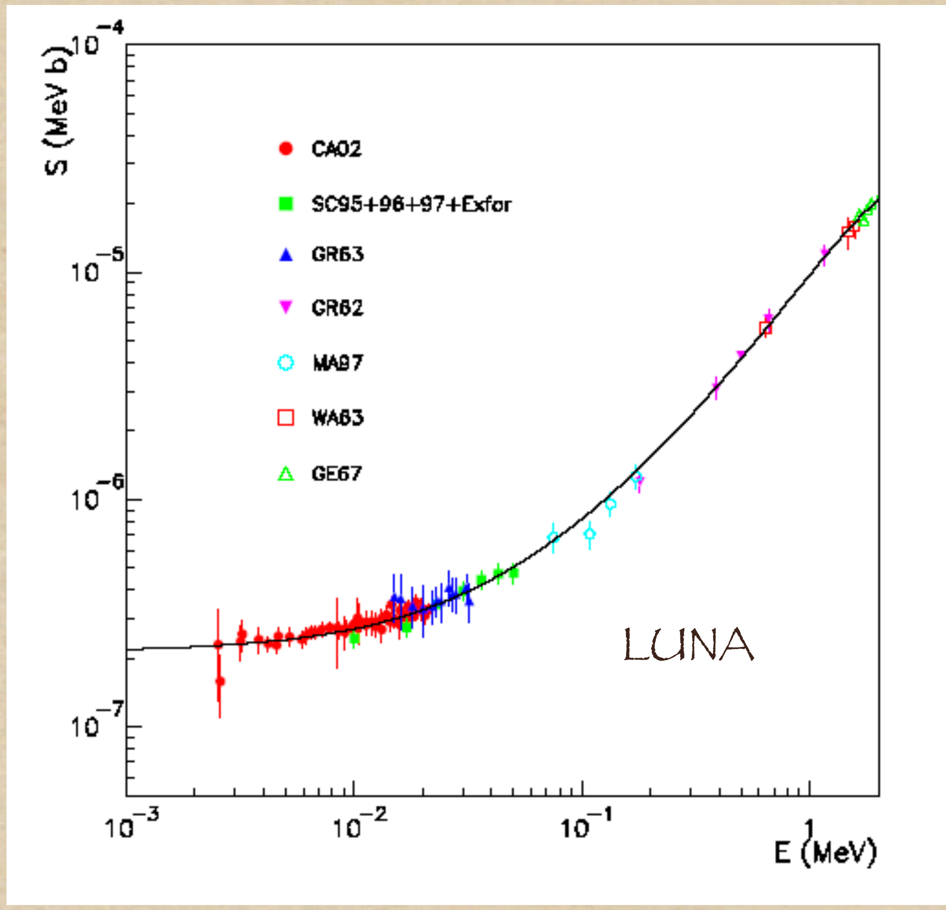
main input from experiments

low energy range (10^2 KeV)

major improvement: underground measurements (e.g. LUNA at LNGS)

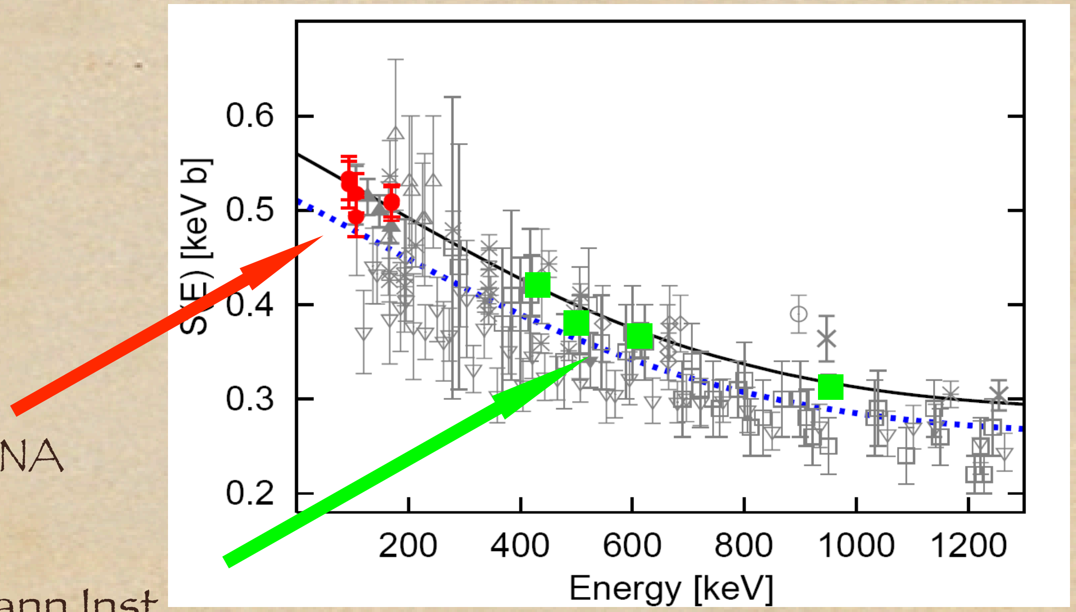


$n(p,\gamma)^2H$



$^2H(p,\gamma)^3He$

LUNA



Weitzmann Inst.

$^3He(\alpha,\gamma)^7Be$

ERNA: S(0)=0.57±0.04 KeV b Di Leva et al 2010

Table 4
The most relevant reactions for BBN.

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}	$^7\mathrm{Be}(d,p)2^4\mathrm{He}$

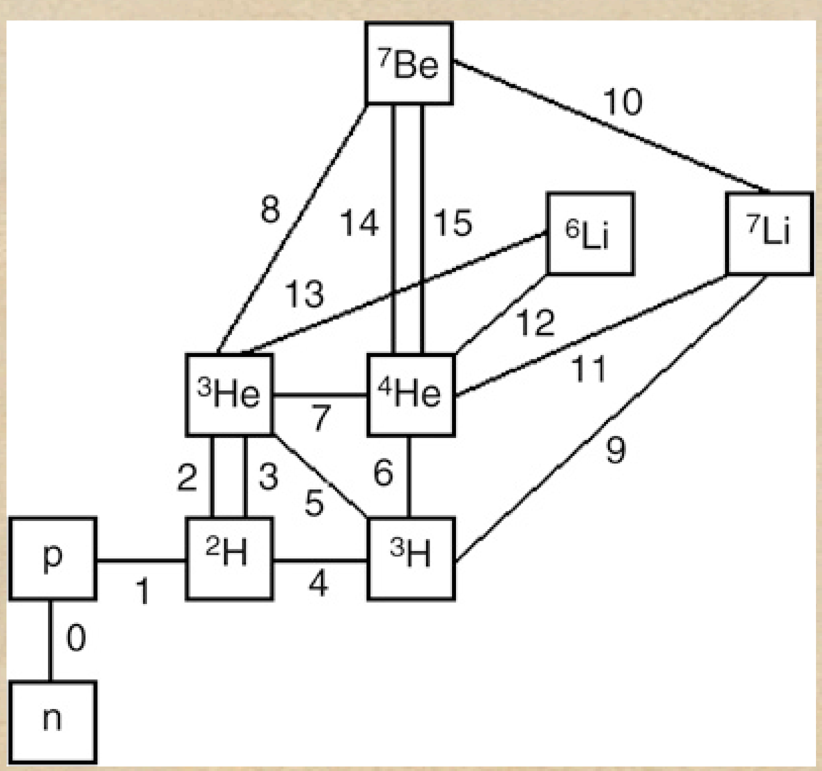


Fig. 5. The most relevant reactions for BBN.

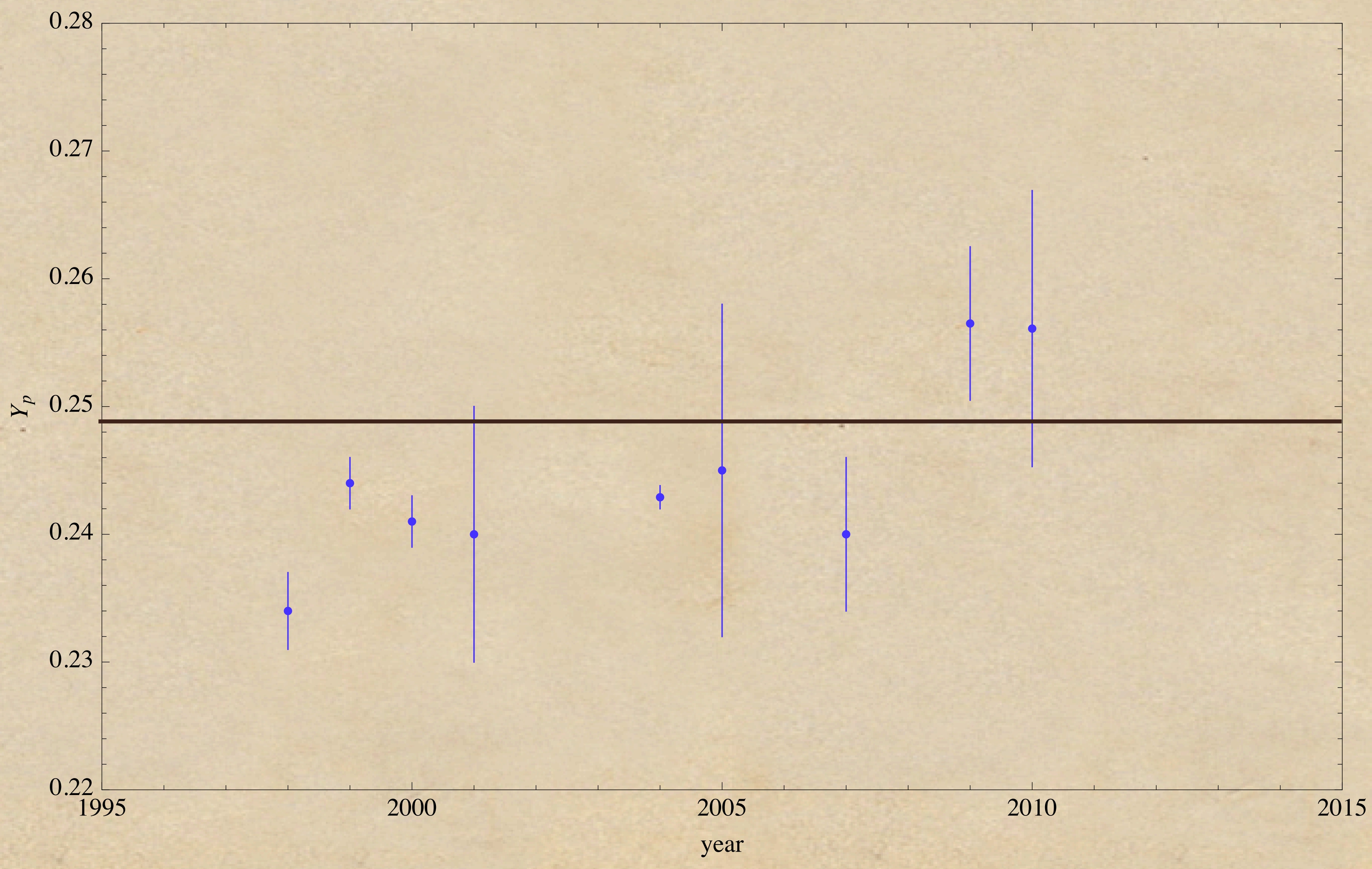
DATA

The quest for primordiality

- Observations in systems negligibly contaminated by stellar evolution (e.g. high redshift);
- Careful account for galactic chemical evolution.

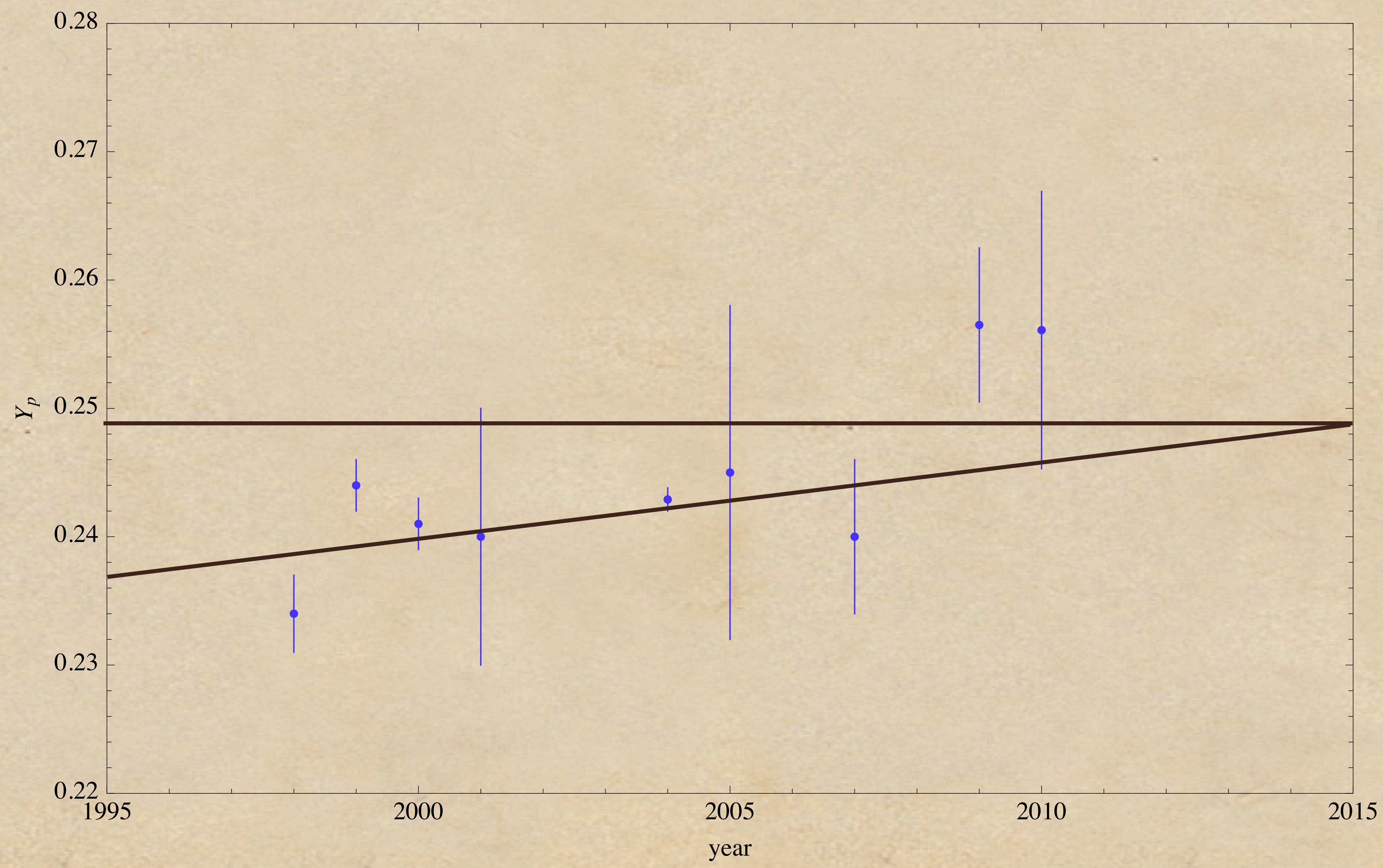
DATA

^{4}He "evolution"



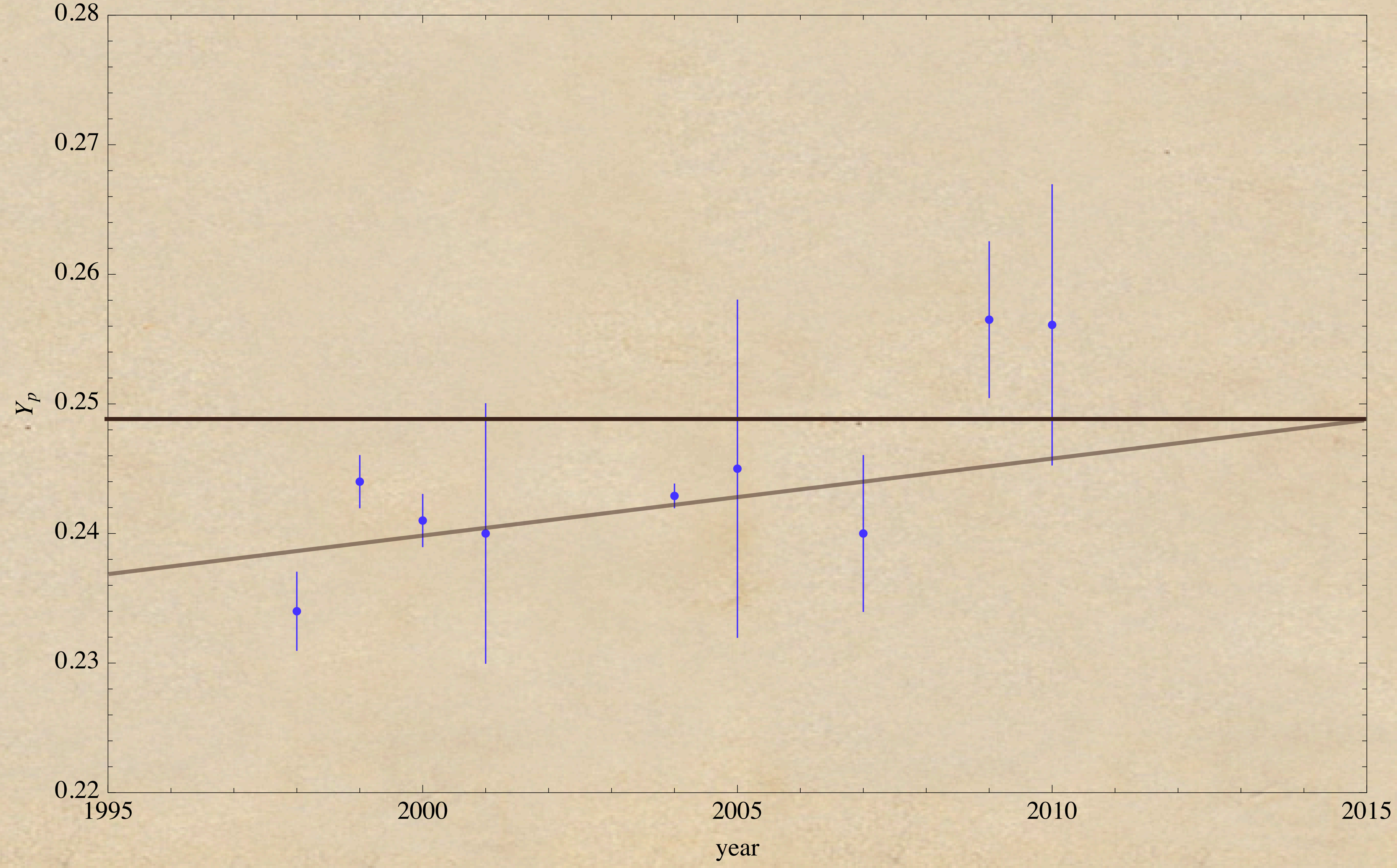
DATA

^{4}He "evolution"



DATA

^{4}He "evolution"



DATA

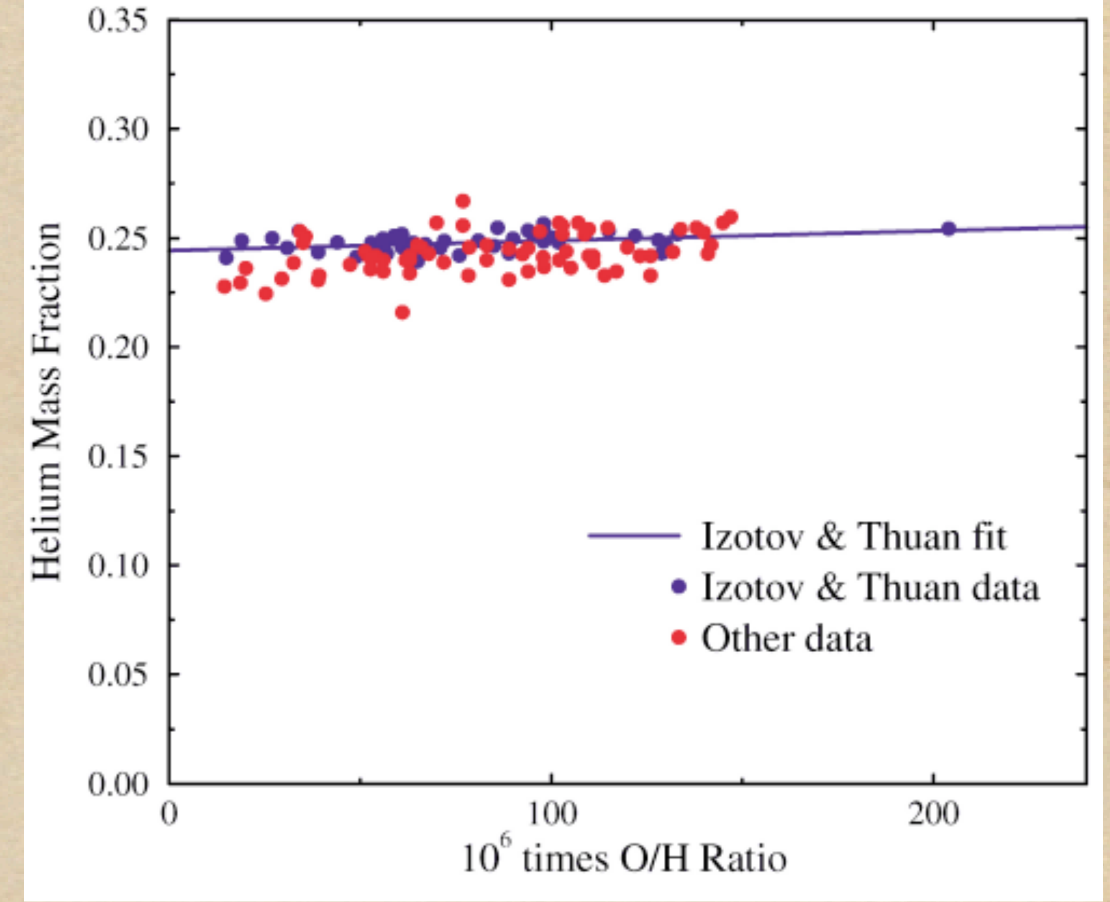
He recombination lines in ionized H_{II} regions in BCG & regression to zero metallicity.

Small statistical error but large systematics

Recent analyses:

Izotov & Thuan 2010

Aver, Olive & Skillmann 2010



DATA

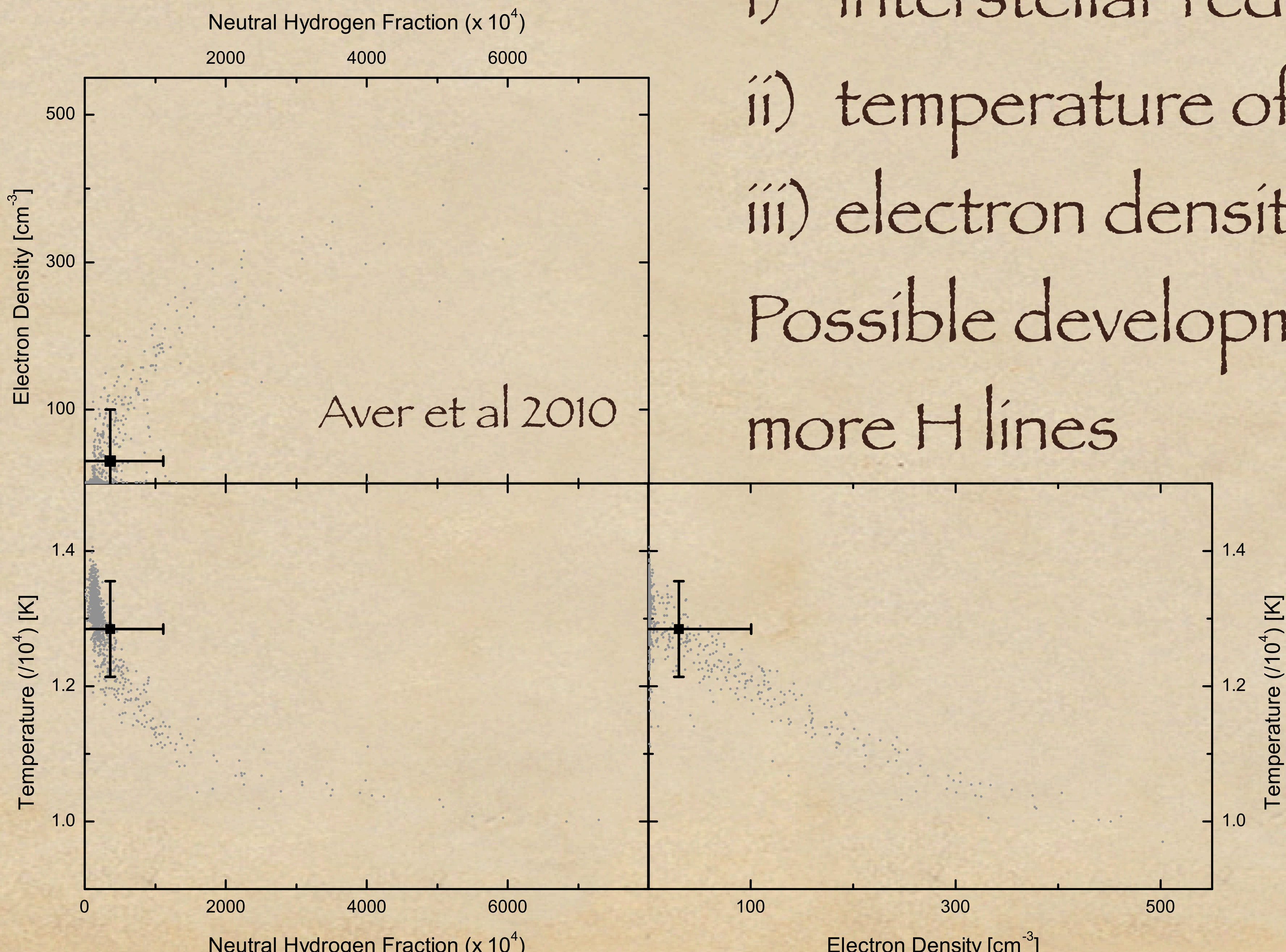
Main sources of systematics:

i) interstellar reddening

ii) temperature of clouds

iii) electron density

Possible developments: using more H lines

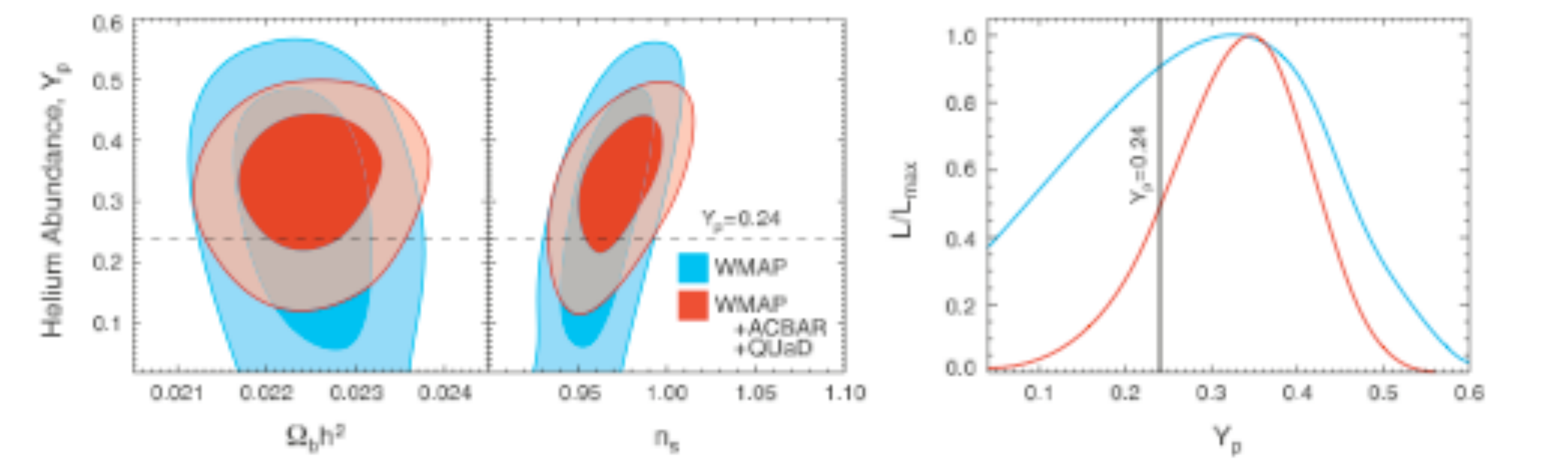


^{4}He from CMB?

DATA

^{4}He recombines before photon decoupling

$$n_e \propto (1-Y_p)\ \Omega_b h^2$$

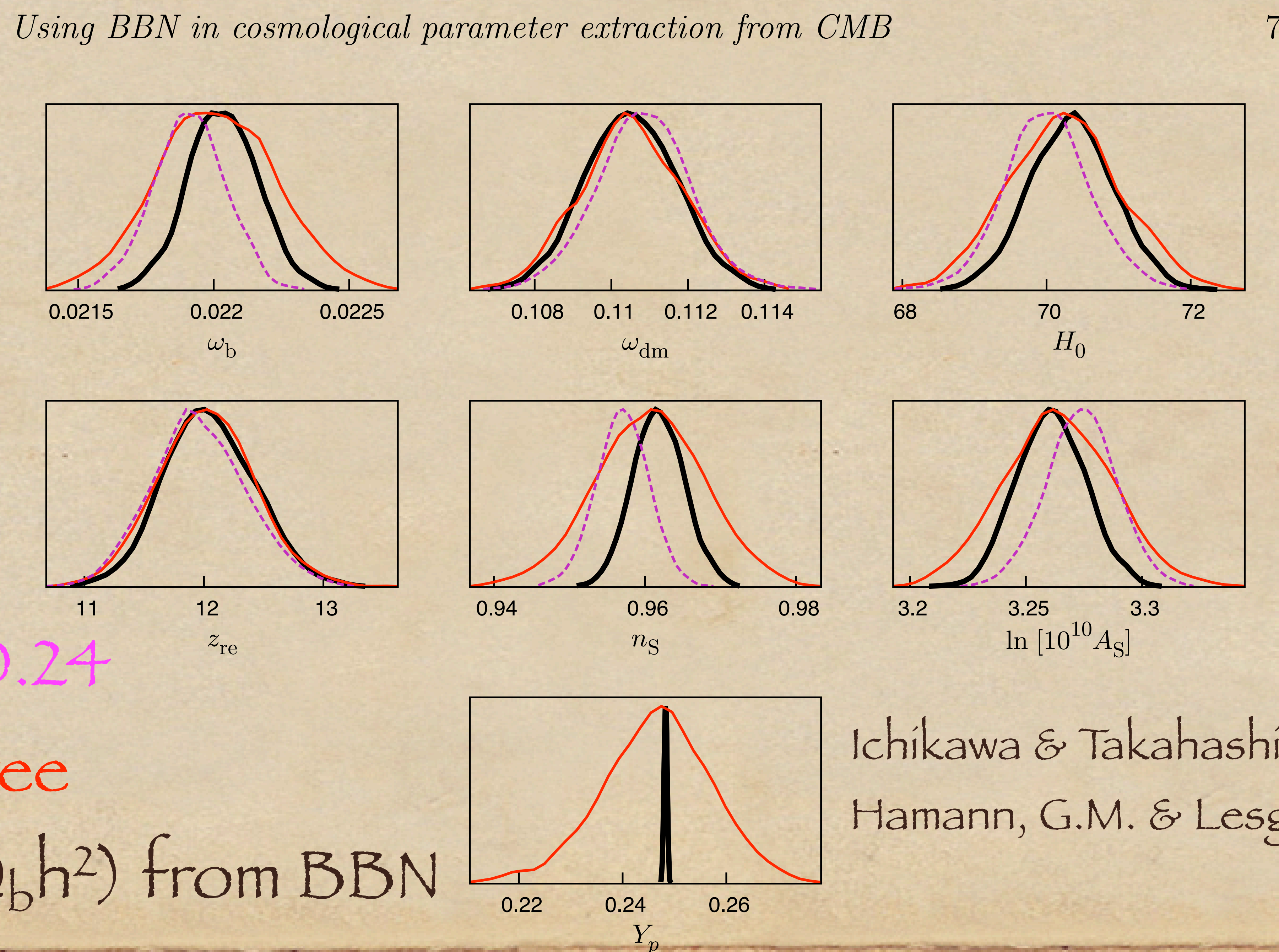


WMAP-7

More meaningful: use $Y_p(\Omega_b h^2)$ from BBN and not as a free parameter in CMB analysis

DATA

Wrong ^{4}He can bias parameter estimation



Y_p=0.24

Y_p free

$Y_p(\Omega_b h^2)$ from BBN

Ichikawa & Takahashi 2006

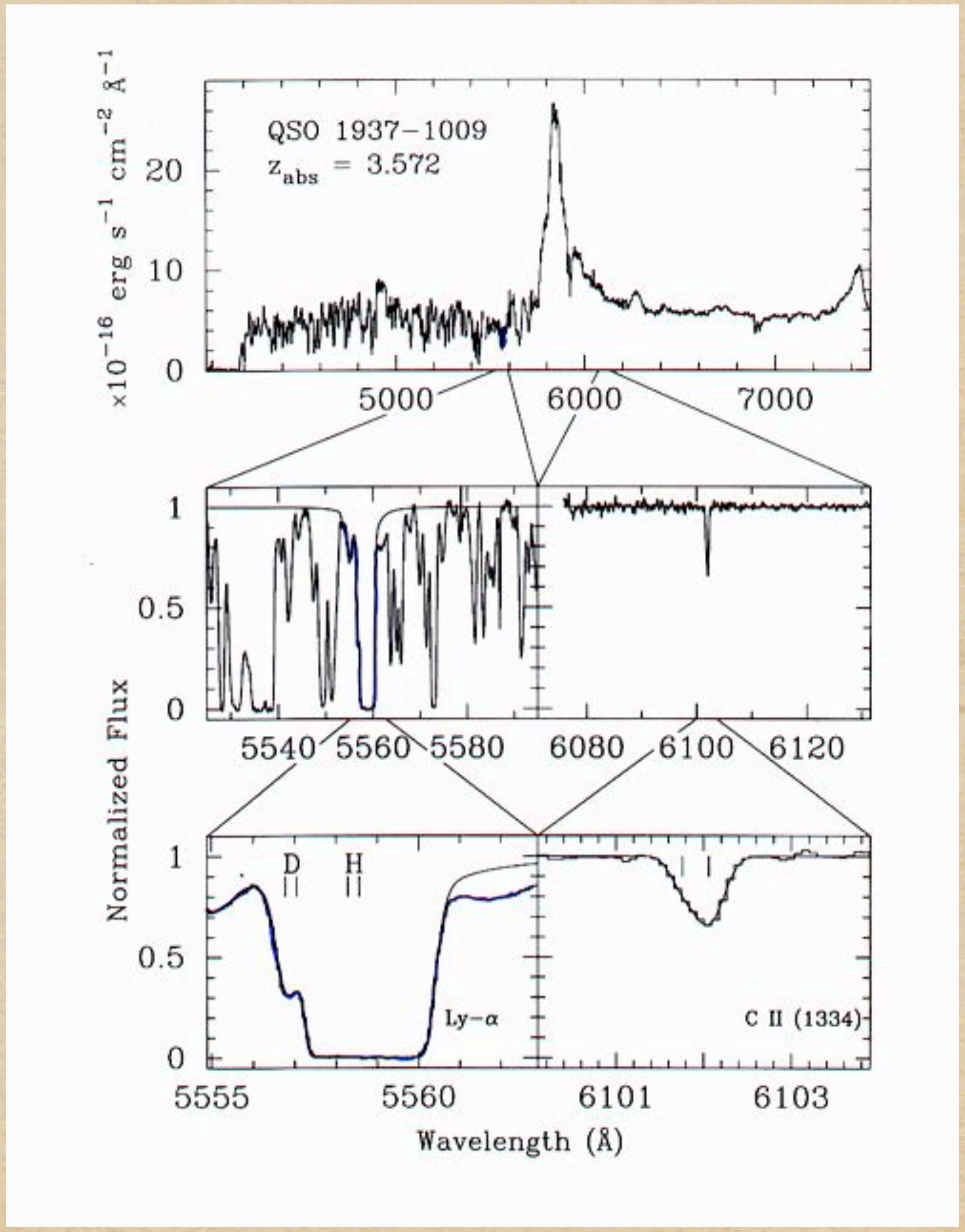
Hamann, G.M. & Lesgourgues 2008

DATA

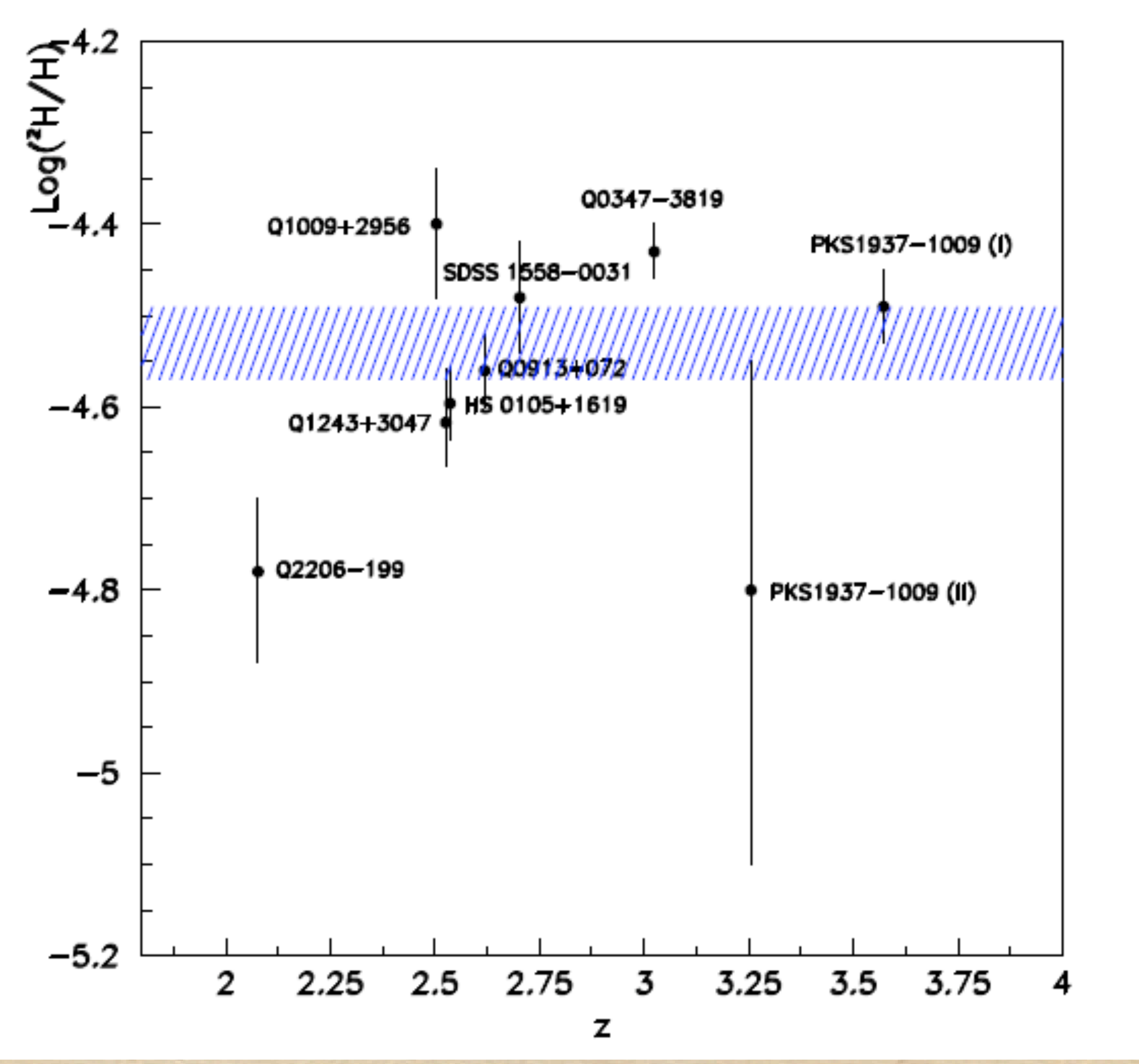
^{2}H measures baryon fraction. Quite good agreement with WMAP determination:

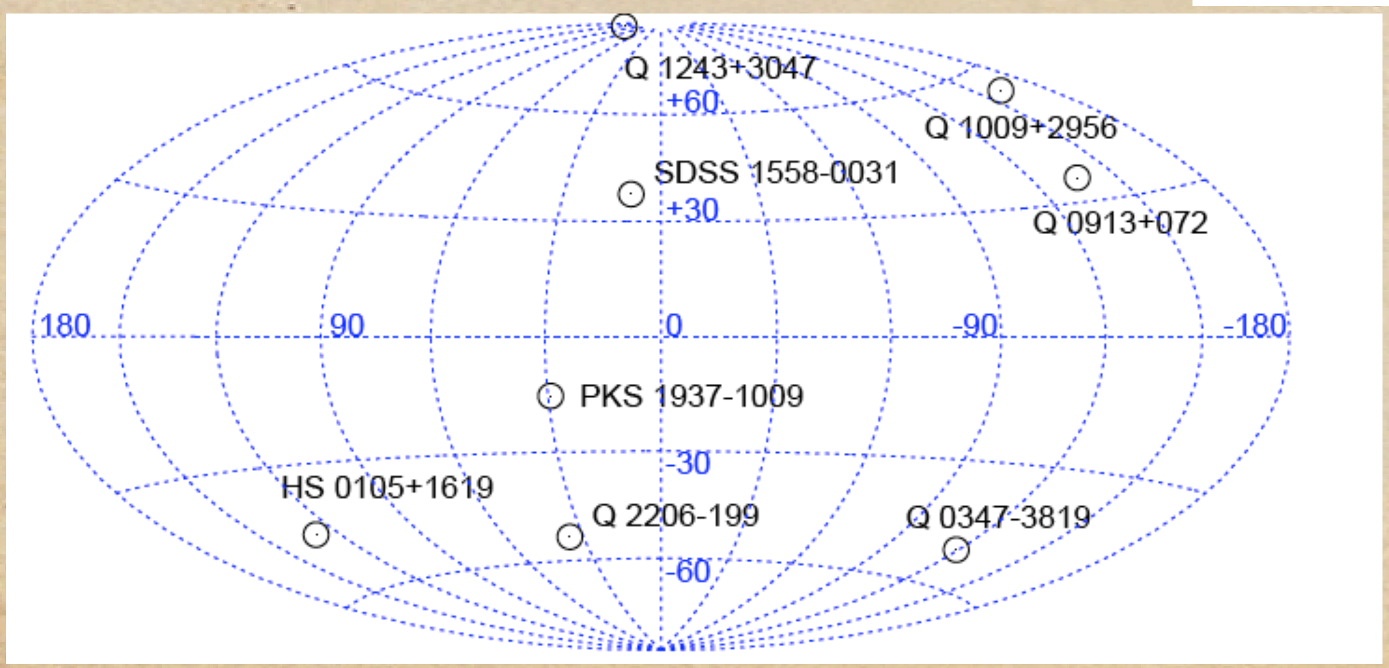
$$\Omega_b h^2 = 0.0226 \pm 0.0005$$

Observations: absorption lines in clouds of light from high redshift background QSO



$^{2}H/H(10^{-5}) = 2.87 \pm 0.22$





Iocco et al 2009

DATA

^{3}He

observed on Earth (nuclear weapons)

observed in the Solar System (Sun): $^2H \Rightarrow {}^3He$

observed in the ISM $^3He/H= 0.1$

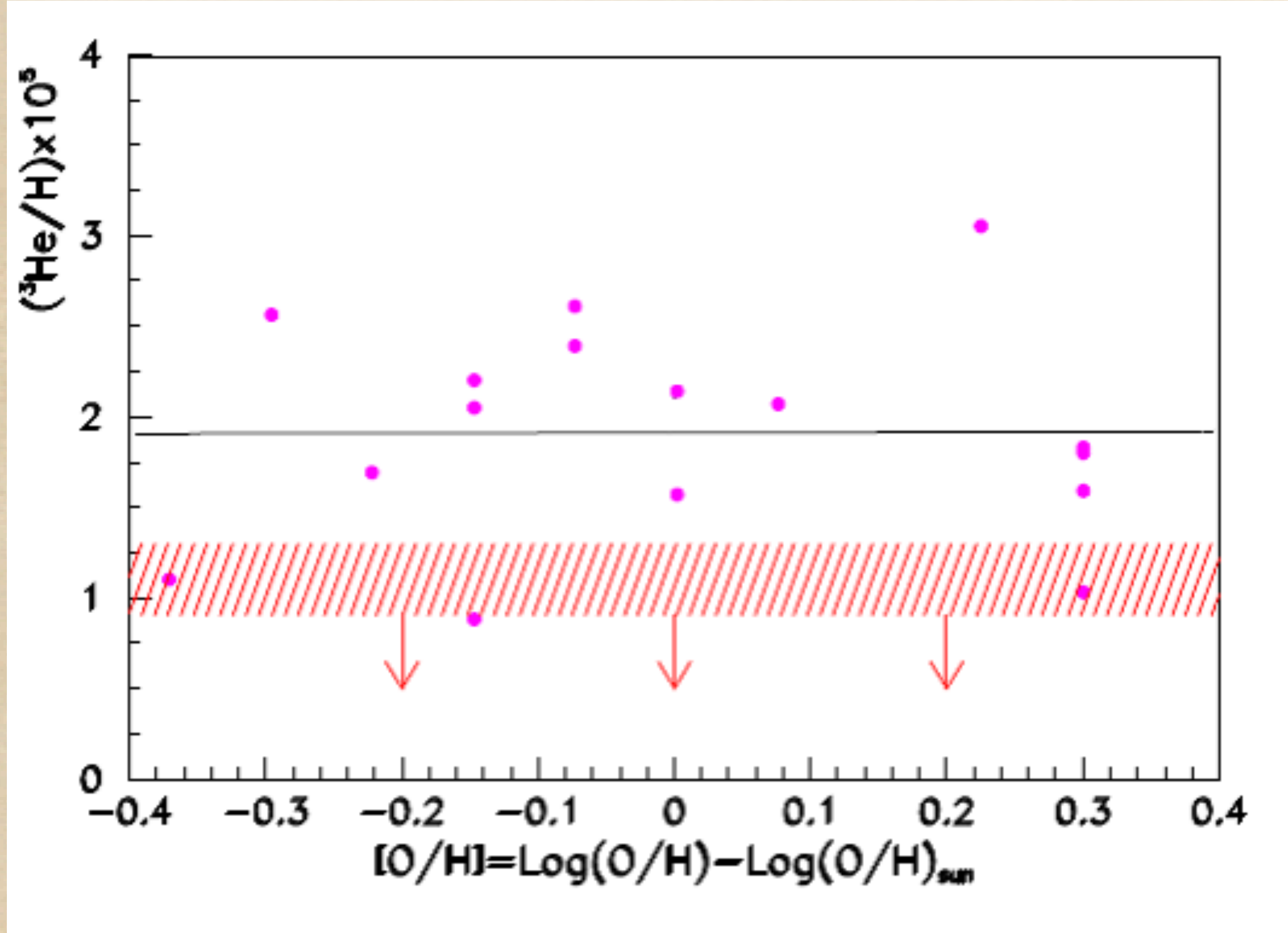
observed in planetary nebulae and H_{II} regions

outside the solar system ($^3He^+$ spin flip 3.46 cm wavelength band)

DATA

No clear evidence for dependence upon metallicity

Bania et al 2002

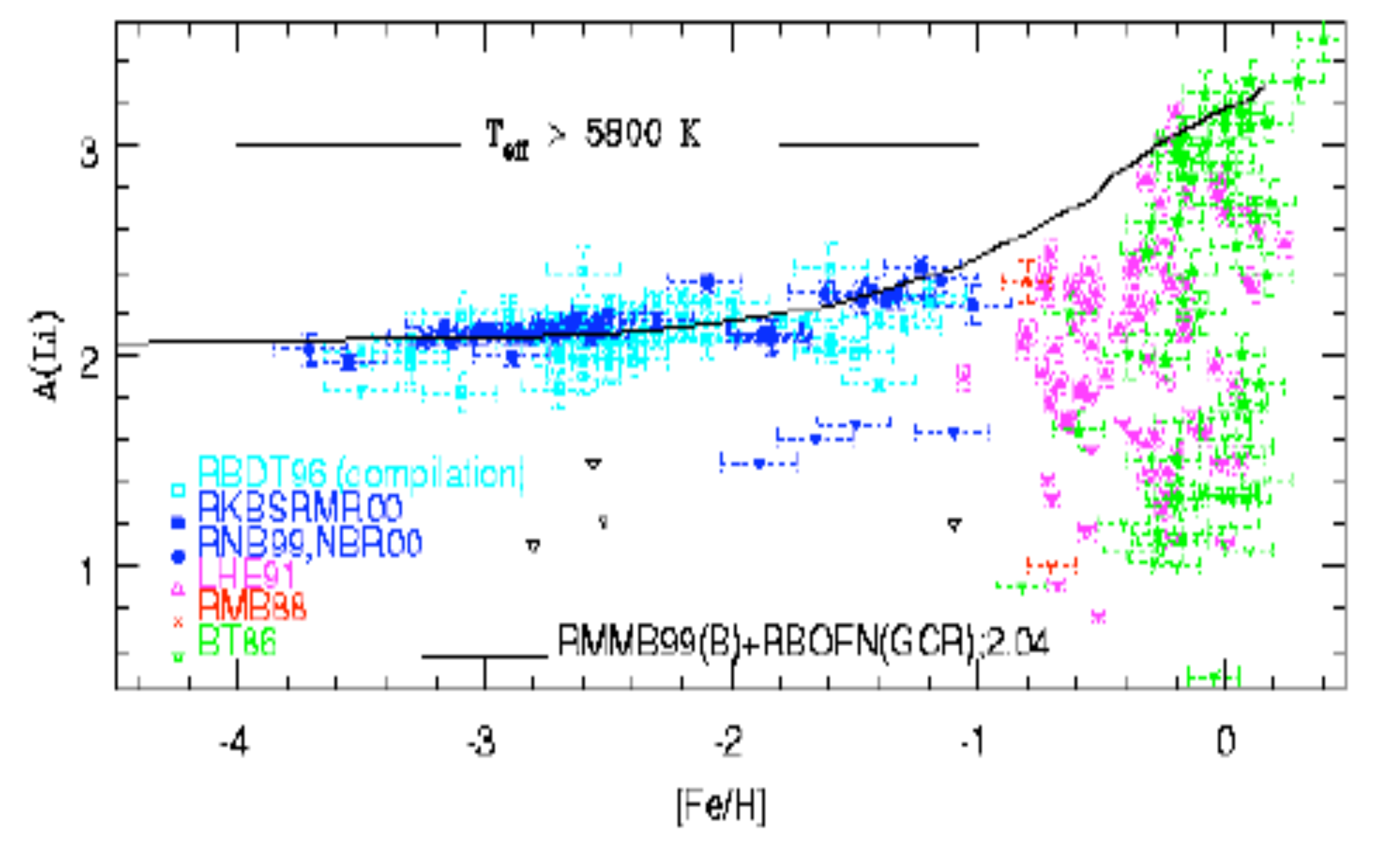


$^3He/H<(1.1\pm0.2)\ 10^{-5}$

DATA

^{7}Li (and ^{6}Li) still a puzzle.

Spite plateau in metal poor dwarfs and GGC questioned



DATA

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

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

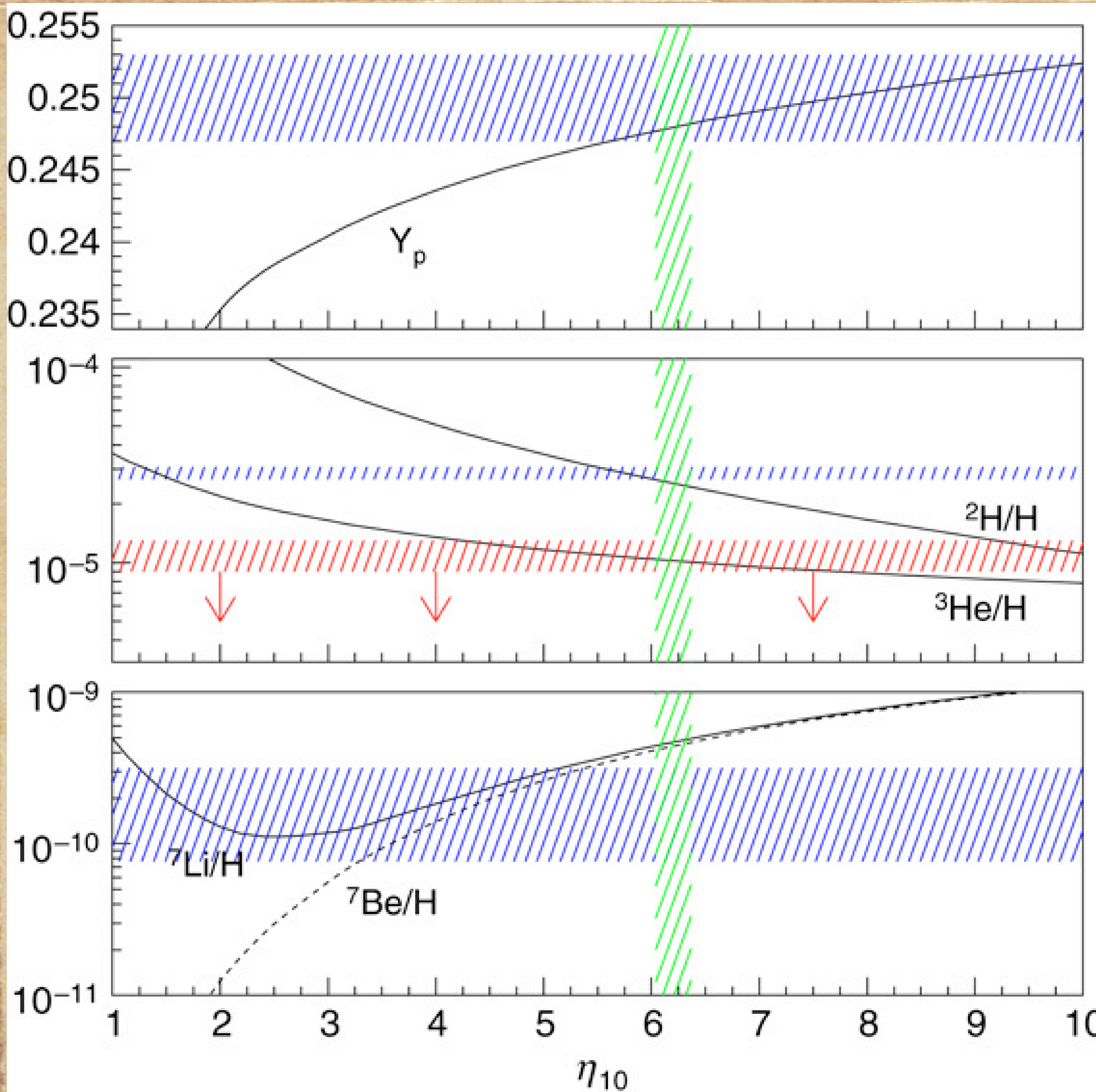
A factor 2 or more below BBN prediction, trusting ^{2}H+WMAP baryon density and ^{3}He upper bound

DATA

- Nuclear rates under control ($^3He(\alpha,\gamma)^7Be$ & ^7Be (d,p)2 α)
- Systematics in measurements?
- Non standard BBN (catalyzed BBN)? (see Prof. Jedamzik talk)
- Observed values NOT primordial

RESULTS

Standard scenario



Iocco et al 2009

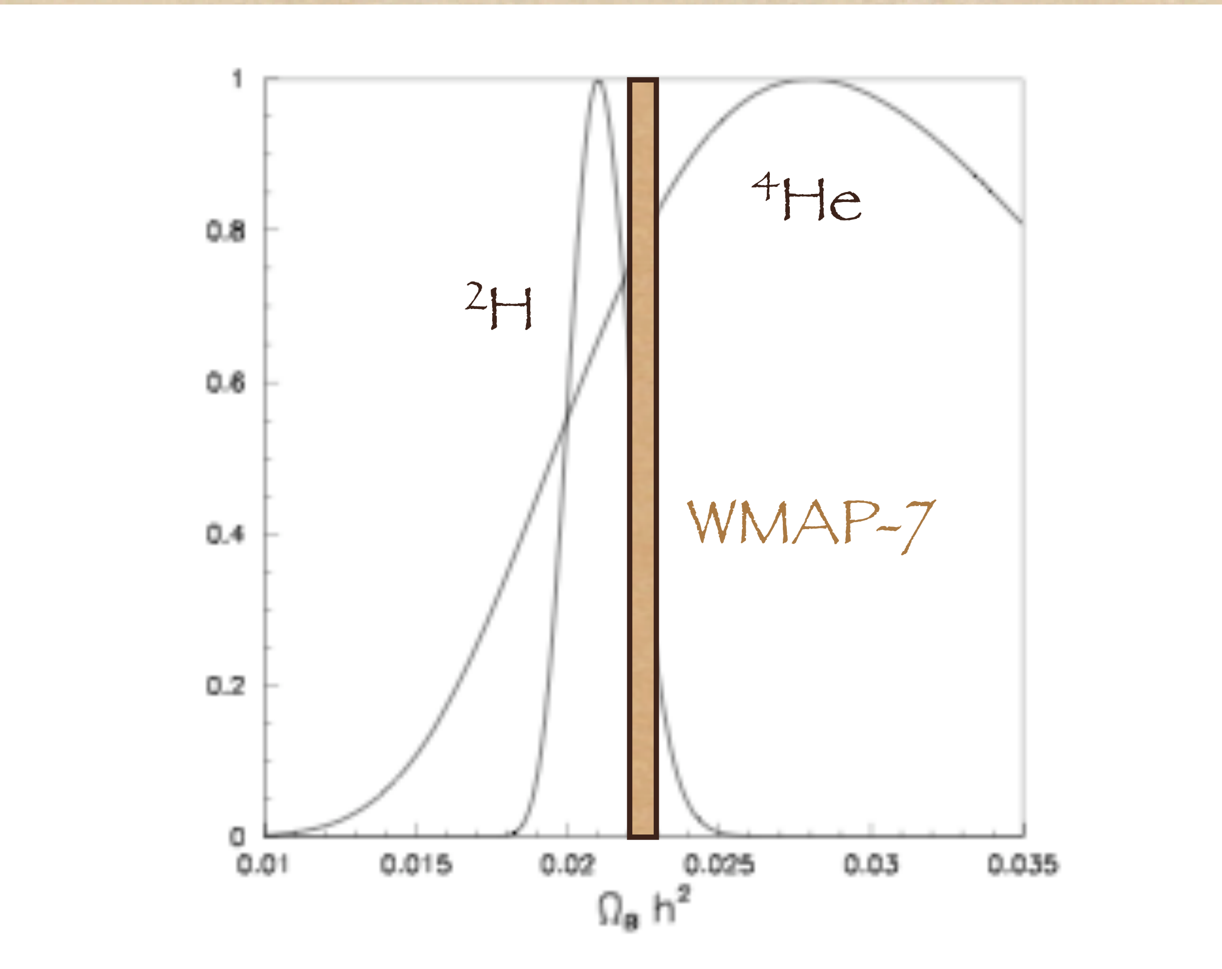
RESULTS

Determinations of $\Omega_b h^2$:

^{2}H: 0.021± 0.001

^{4}He: 0.028± 0.010

WMAP-7: 0.0226± 0.0005



Iocco et al 2009

Picture fully consistent at slightly more than 1 σ

RESULTS

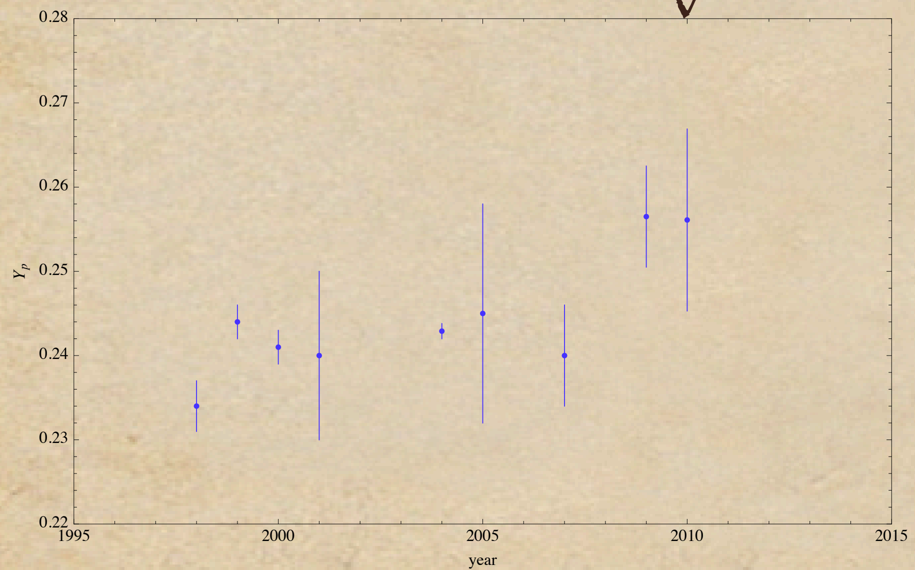
Exotic scenarios

RESULTS

Room for extra light particles?

$$\rho_R = \rho_\gamma + \rho_\nu + \rho_x = \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N^{eff}{}_\nu\right)\rho_\gamma$$

^{4}He grows with $N^{eff}{}_\nu$



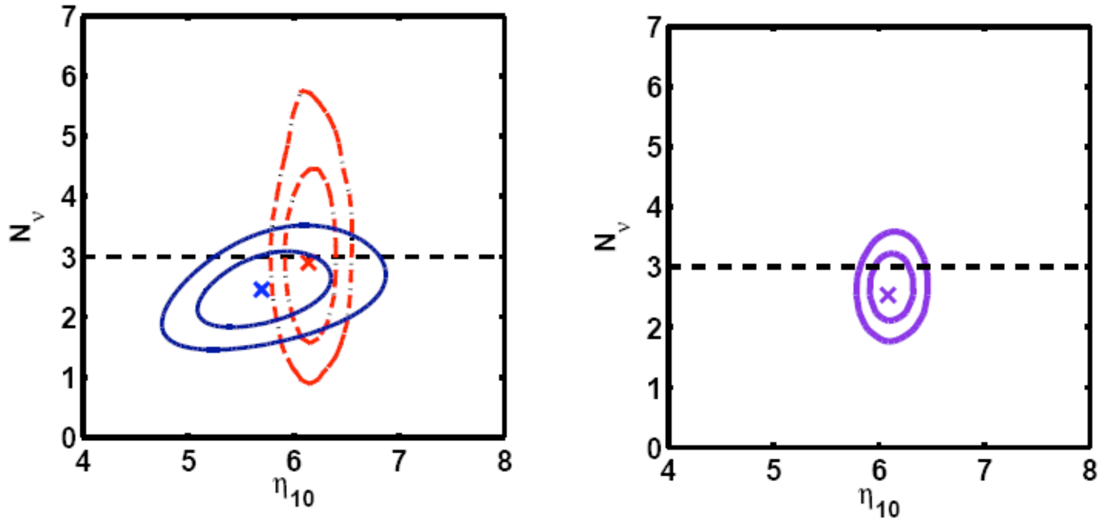


Figure 4:
(Left) In blue (solid), the 68% and 95% contours in the N$_\nu$ - η_{10} plane derived from a comparison of the observationally-inferred and BBN-predicted primordial abundances of D and ^{4}He. In red (dashed), the 68% and 95% contours derived from the combined WMAP 5-year data, small scale 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$_\nu$ − η_{10} plane.

Steigman 2008

2 σ claim ! (Izotov & Thuan 2010)

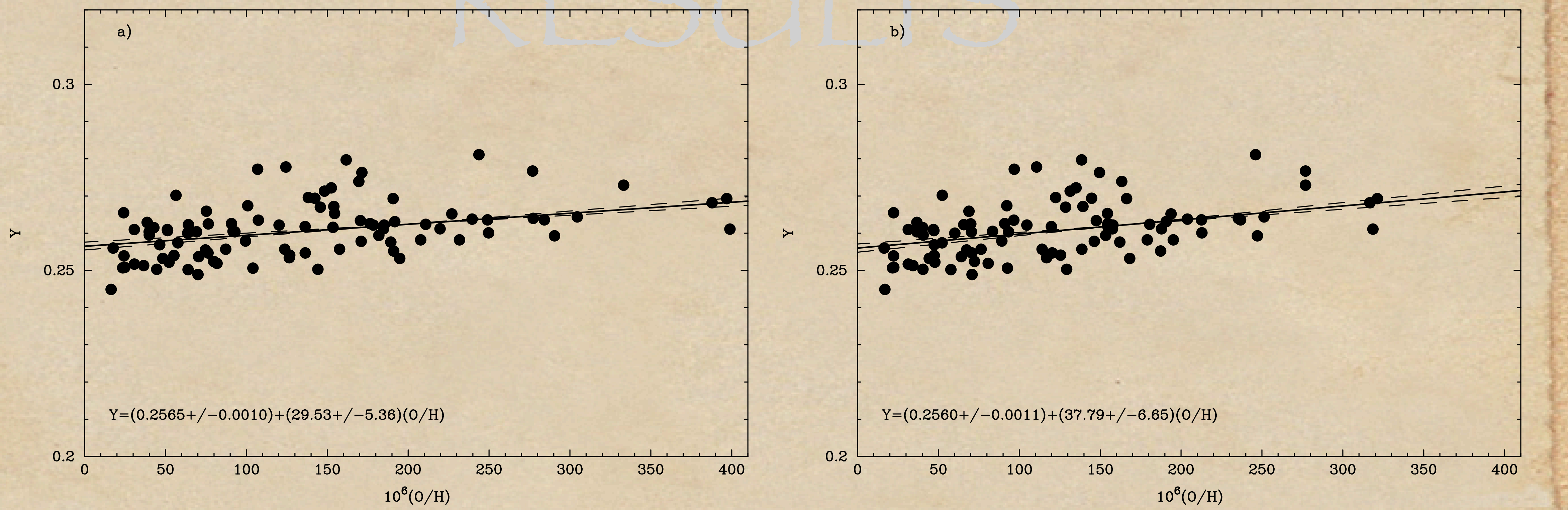
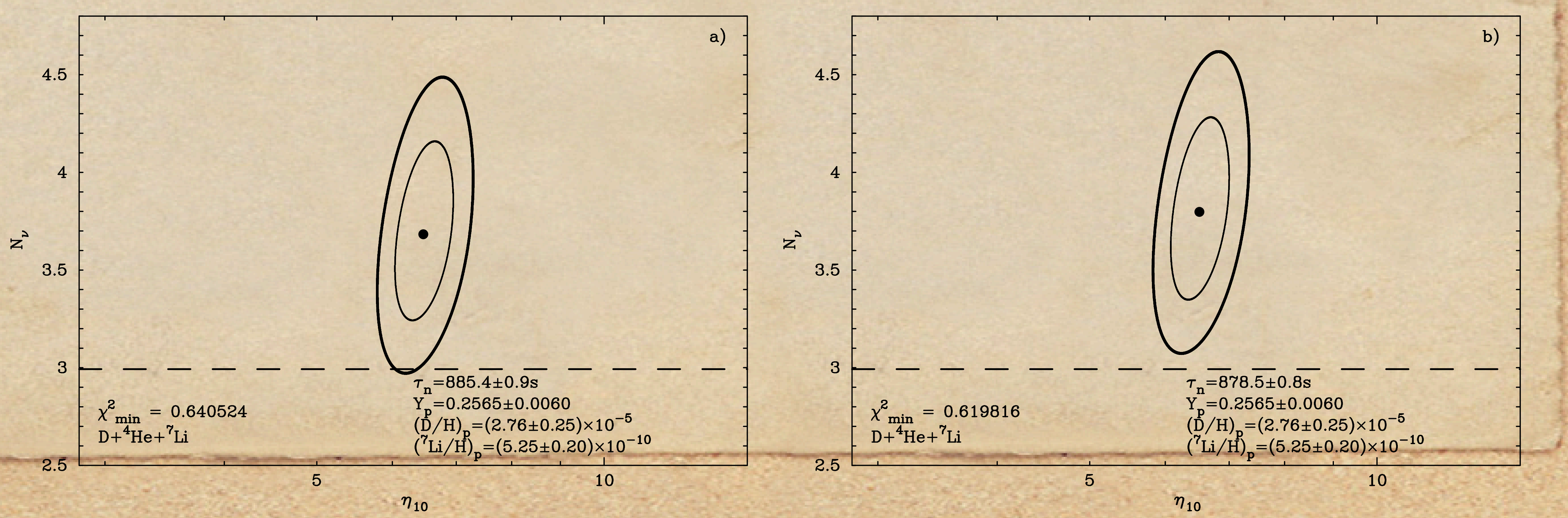


FIG. 1.— Linear regressions of the helium mass fraction Y vs. oxygen abundance for H II regions in the HeBCD sample. The Ys are derived with the He I emissivities from Porter et al. (2005). The electron temperature $T_e(\mathrm{He}^+)$ is varied in the range $(0.95-1)\times T_e(\mathrm{O\ III})$. The oxygen abundance is derived adopting an electron temperature equal to $T_e(\mathrm{He}^+)$ in a) and to $T_e(\mathrm{O\ III})$ in b).



RESULTS

The Lepton number of the Universe

Neutrino chemical potentials change the expansion rate parameter H (larger ν energy density);

ν_e chemical potential changes the n-p chemical equilibrium (weak rates); Kang & Steigman 1992

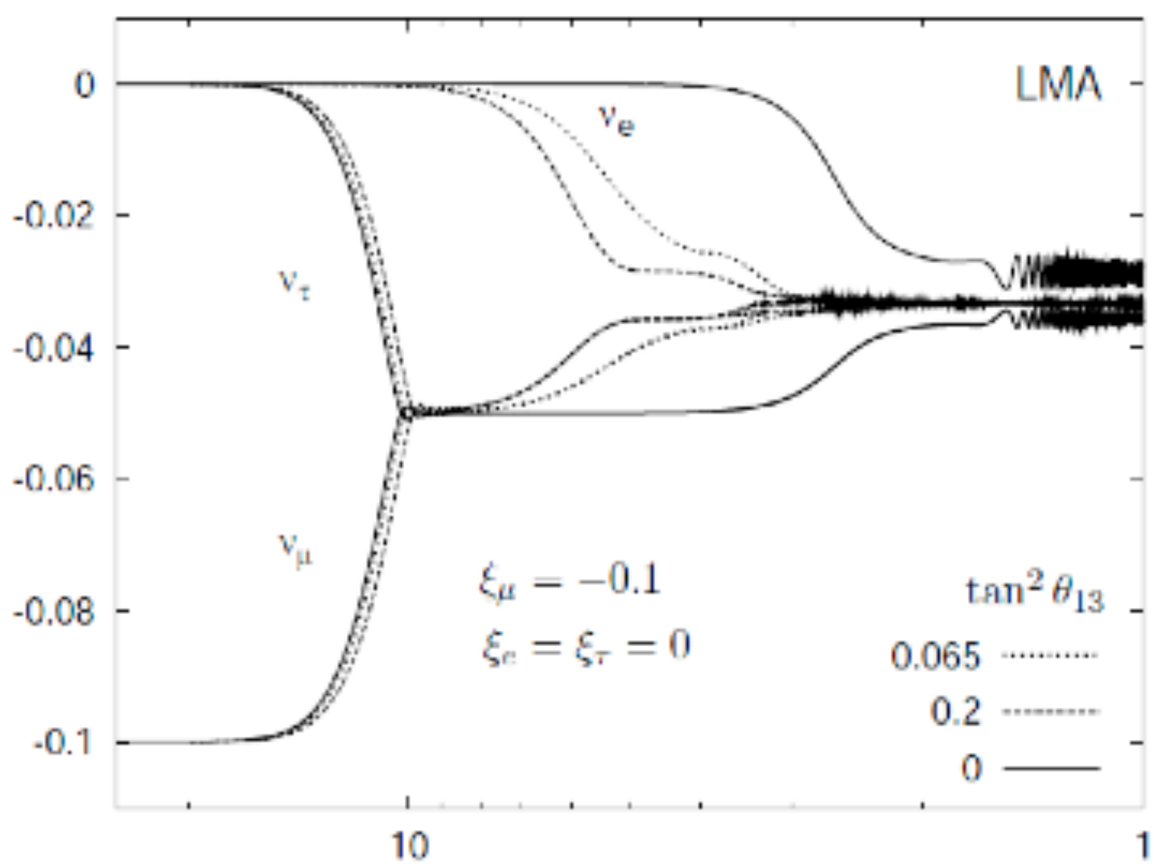
ν's oscillates in flavor space: before BBN ν_e, ν_μ & ν_τ share the same chemical potential.

Dolgov et al 2002

$$i\rho' = [\Omega, \rho] + C \quad \Omega = M^2/2p + \sqrt{2}\, G_F(-8p/m_W^2\ E + \rho - \bar{\rho})$$

RESULTS

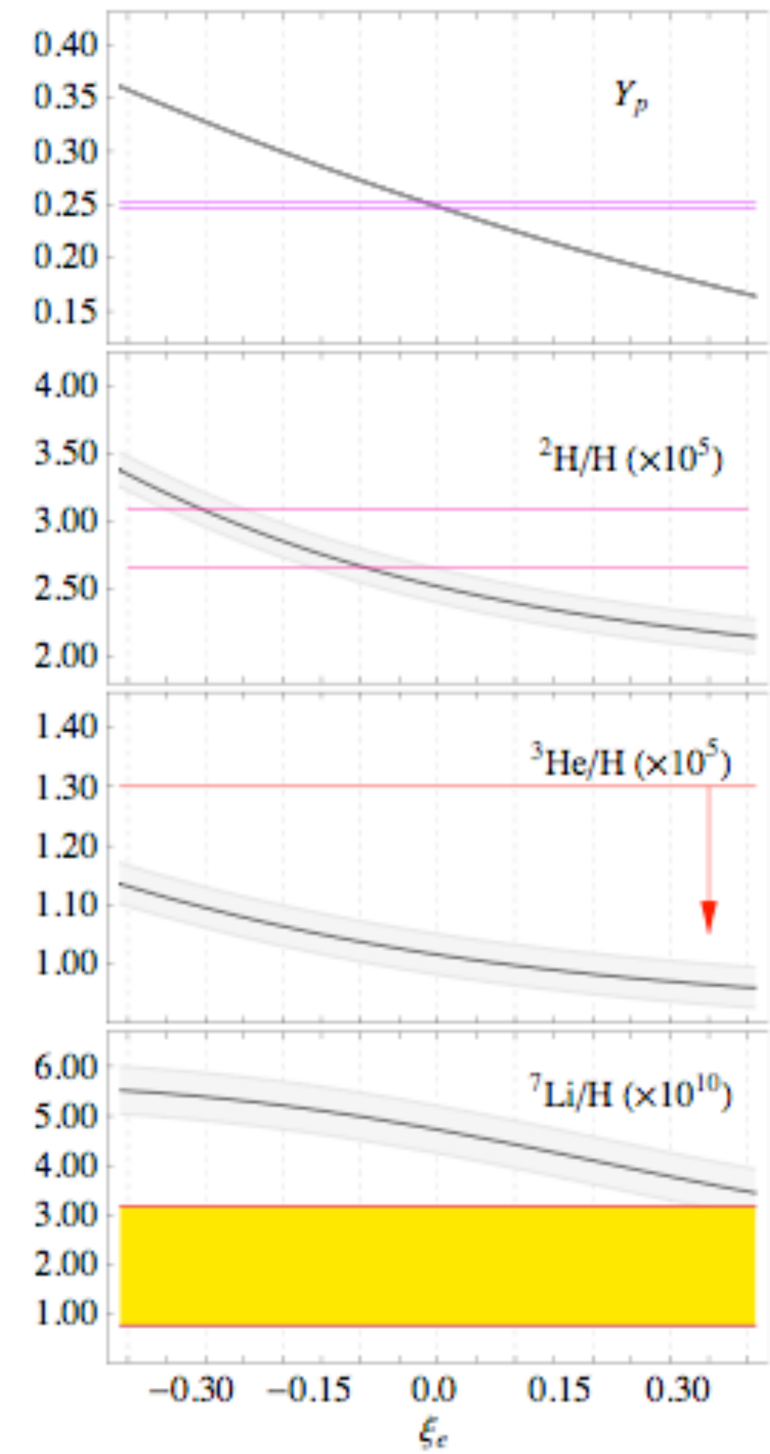
Dolgov et al 2002



"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"*

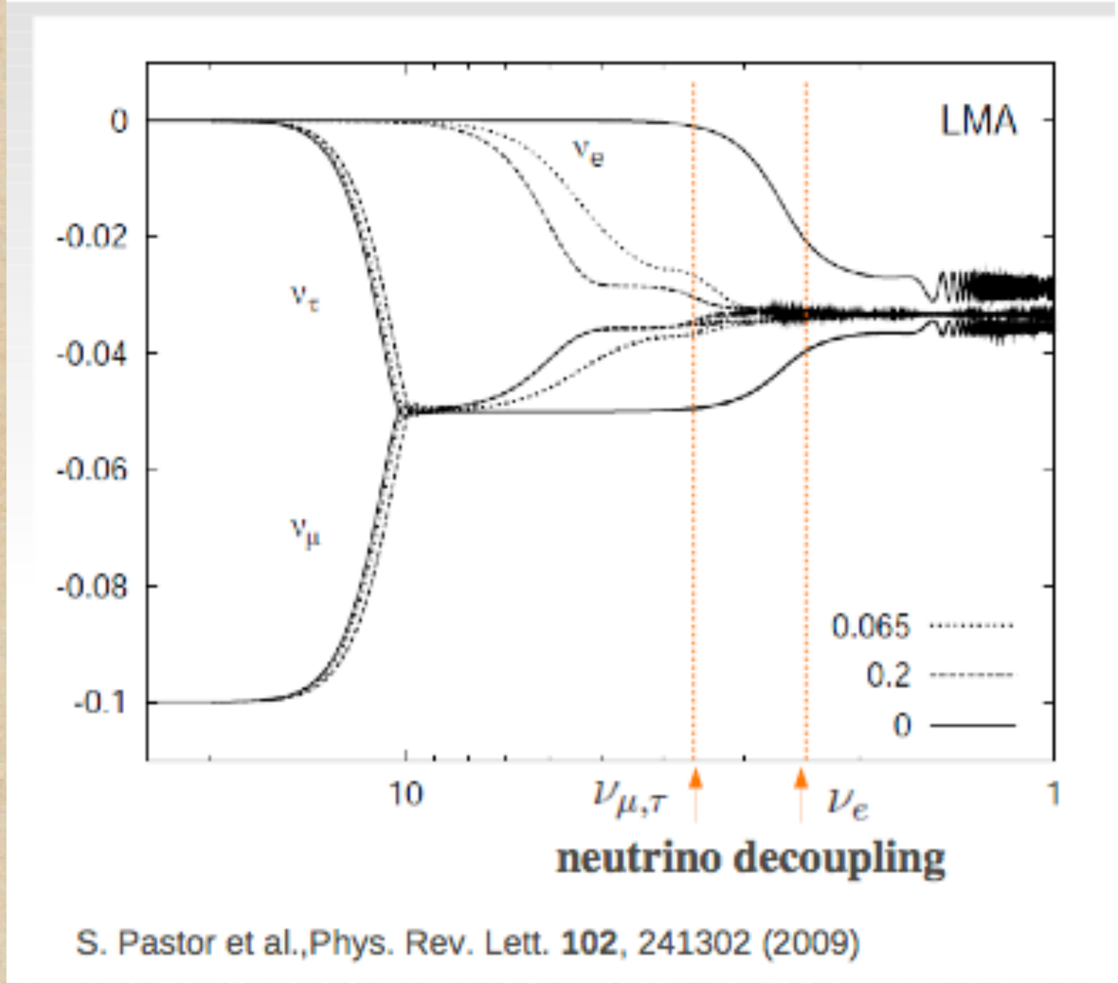
"...the BBN limit on the ν_e degeneracy parameter, ***$|\xi_\nu| < 0.07$, now applies to all flavors.****"*

Iocco et al 2009



RESULTS

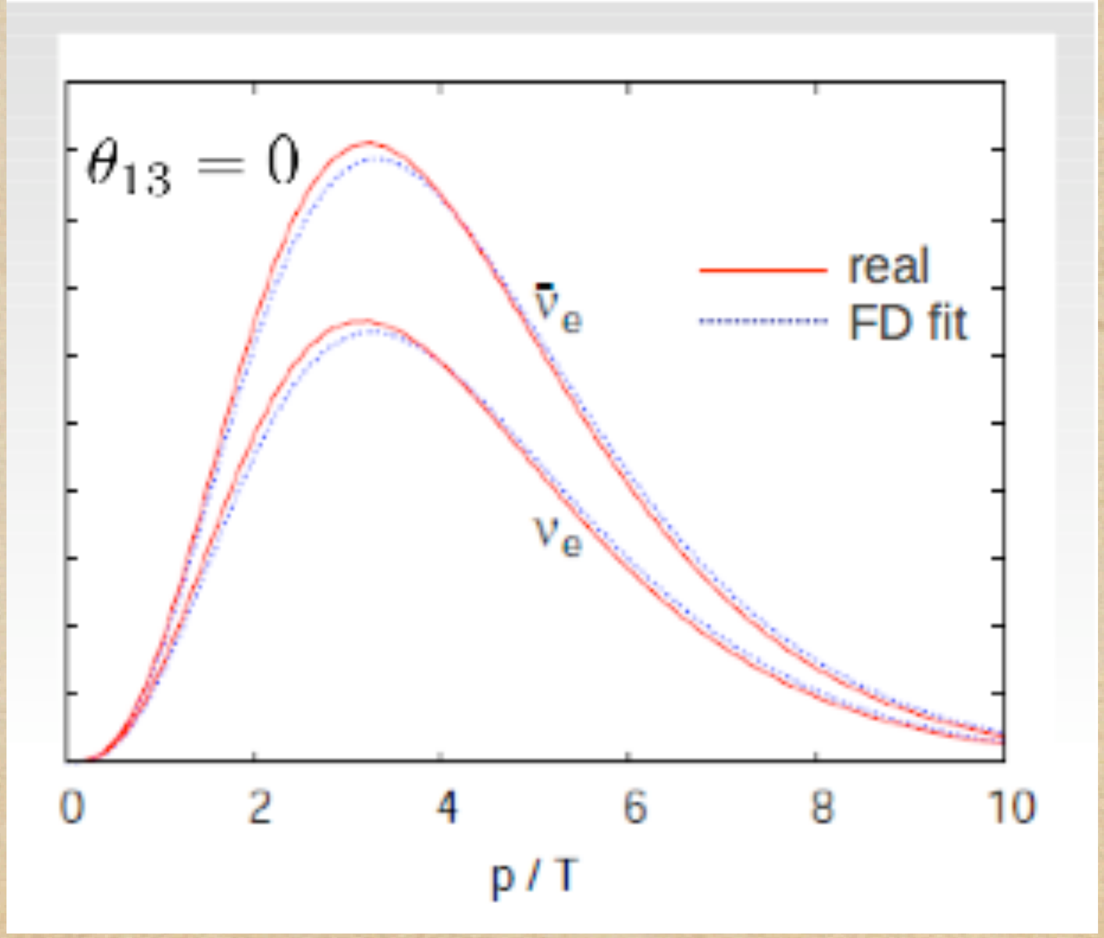
However...

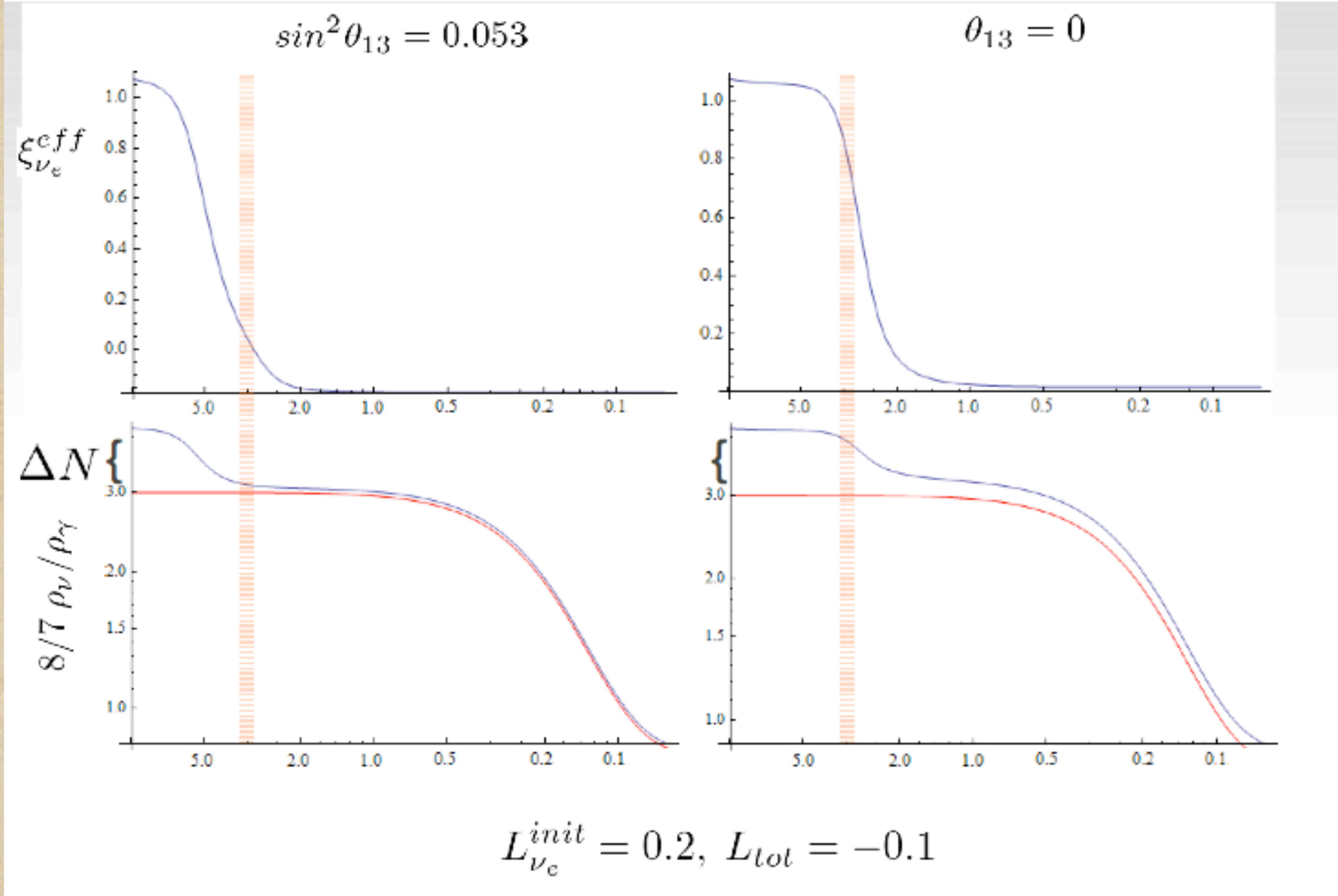


S. Pastor et al.,Phys. Rev. Lett. **102**, 241302 (2009)

ν decouple from the thermal bath, and scatterings & pair processes may be inefficient to re-adjust their distribution.

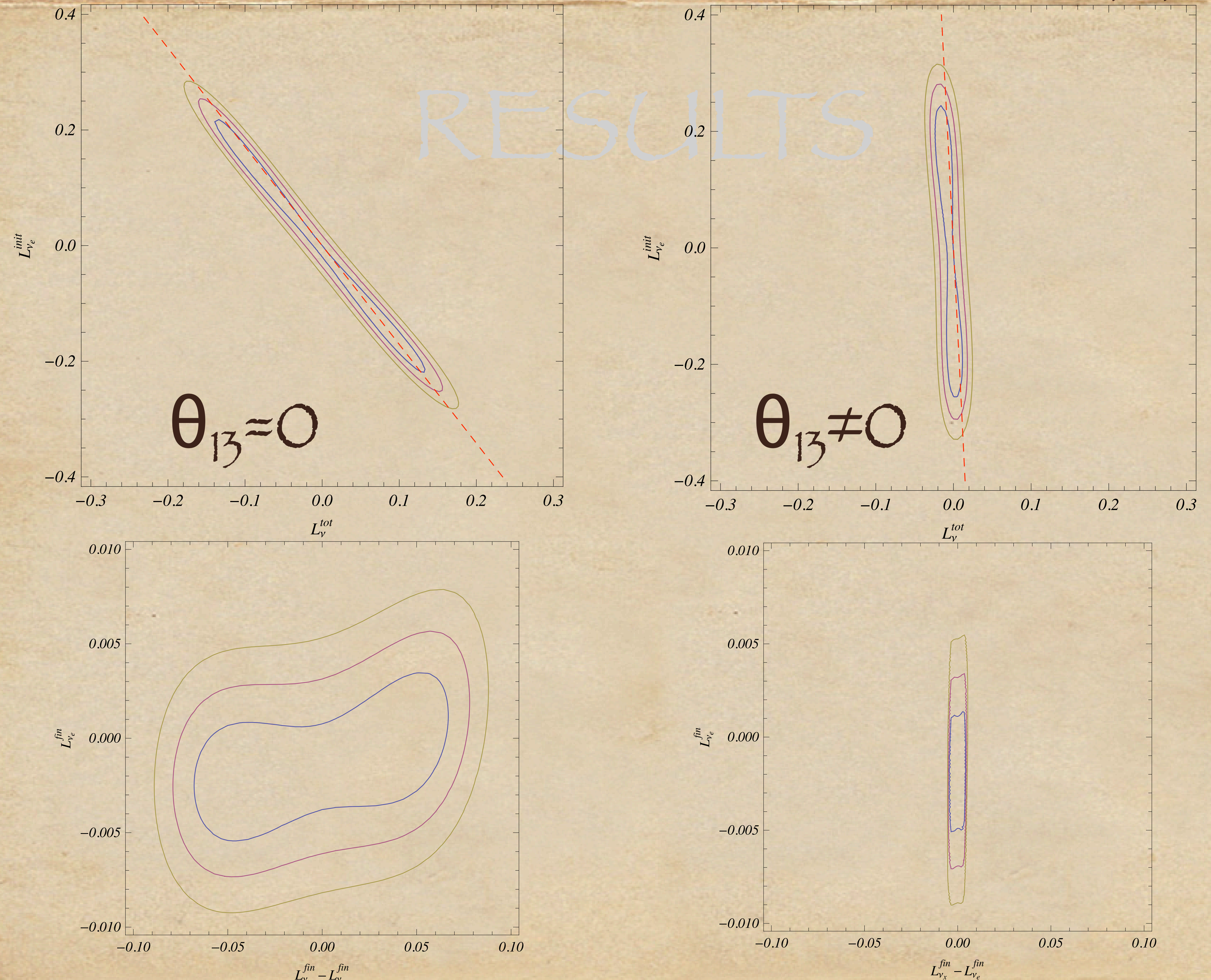
Not a perfect FD (in general)!





We must follow ν distribution through BBN dynamics

RESULTS



$\theta_{13}{\approx}0$
$\theta_{13}{\neq}0$
$L^{init}_{\nu_e}$
L^{tot}_{ν}
$L^{fin}_{\nu_e}$
$L^{fin}_{\nu_x} - L^{fin}_{\nu_e}$
0.4
0.2
0.0
−0.2
−0.4
−0.3
−0.2
−0.1
0.1
0.3
0.010
0.005
0.000
−0.005
−0.010
−0.10
−0.05
0.00
0.05
0.10

RESULTS

	$\theta_{13} = 0$	$sin\theta_{13} = 0.053$
initial neutrino asymmetry	$\lvert L_{\nu_e}^{init}\rvert < 0.21$	$\lvert L_{\nu_e}^{init}\rvert < 0.24$
initial neutrino chemical potential	$\lvert \xi_{\nu_e}^{init}\rvert < 1.21$	$\lvert \xi_{\nu_e}^{init}\rvert < 1.38$
initial $L_{\nu_e}^{init}$ rescaled by n_γ	$\lvert L_{\nu_e}^{init}\rvert < 0.86$	$\lvert L_{\nu_e}^{init}\rvert < 0.98$
residual neutrino asymmetry $(\times 10^3)$	$-5 < L_{\nu_e}^{final} < 3$	$-5 < L_{\nu_e}^{final} < 1$
final difference btw L_e an L_x $(\times 10^3)$	$\lvert L_{\nu_e}^{fin} - L_{\nu_x}^{fin}\rvert < 62$	$\lvert L_{\nu_e}^{fin} - L_{\nu_x}^{fin}\rvert < 4$

G.M. et al, in preparation

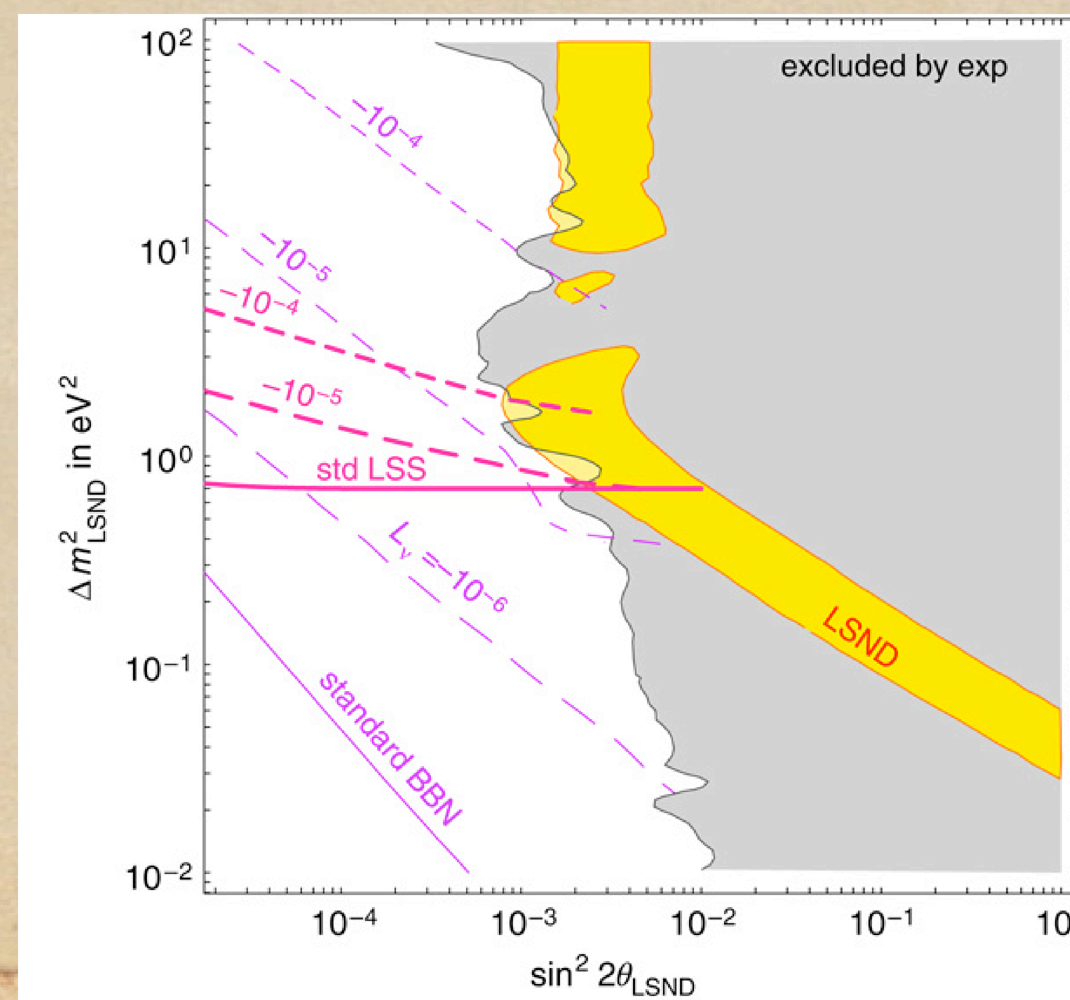
Sterile neutrinos

Change the value of N^{eff}_{ν};

production after active ν decoupling change n/p ratio;

asymmetry too.

F. Iocco et al. / Physics Reports 472 (2009) 1–76



Chuzoy & Shapiro 2006

RESULTS

Variation of fundamental "constants"

An old idea, Dirac 1937.

Problems:

i) too many "constants";

ii) no unique theoretical framework.

RESULTS

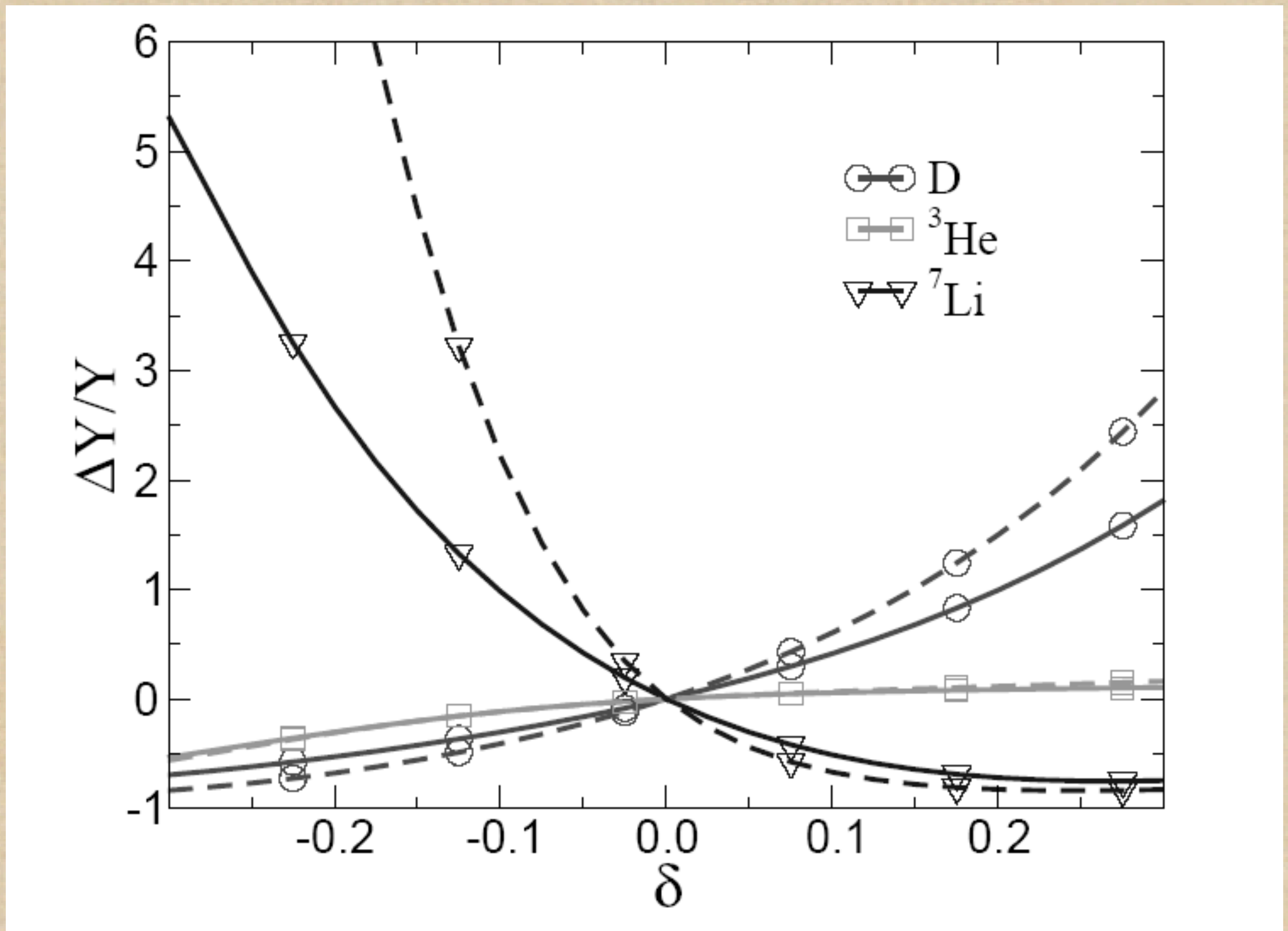
An example : α & BBN

Change the n/p mass difference and thus the n-p chemical equilibrium: $\Delta m = 2.05 - 0.76(1 + \Delta\alpha / \alpha)$

Change the charged nuclide interaction rates (Coulomb barrier):

$$\sigma(E) \approx S(E)\ \exp(-2\pi\,\eta)/E$$

$$\eta = Z_1 Z_2 \alpha \sqrt{\mu / 2E}$$



Nollet et al 2002

Typical bounds from BBN at the level of %

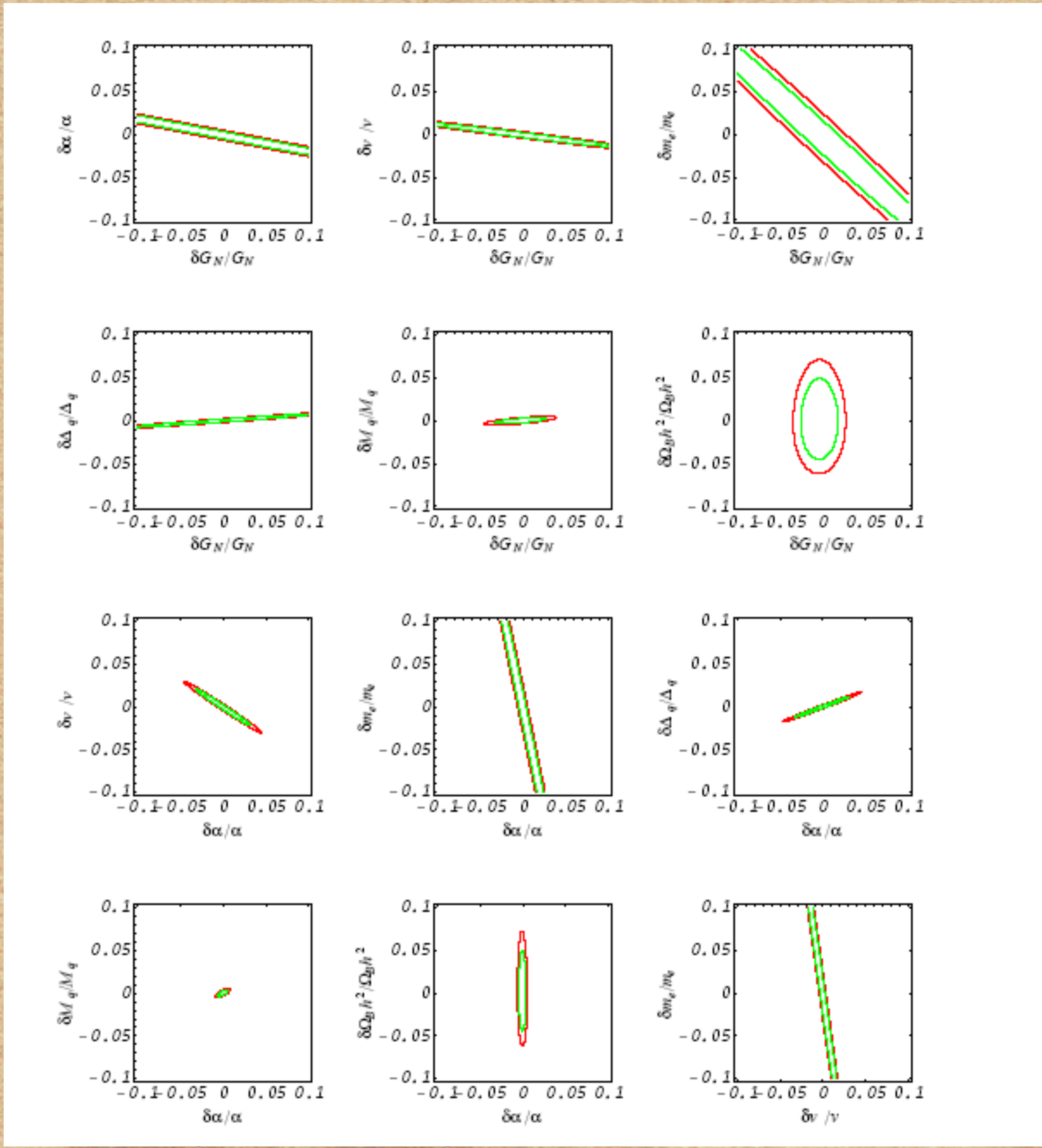
^{7}Li problem unsolved (unless one considers less radiation too, $N^{eff}_{\nu} < 3$)

Bounds on various parameters

Iocco et al 2009

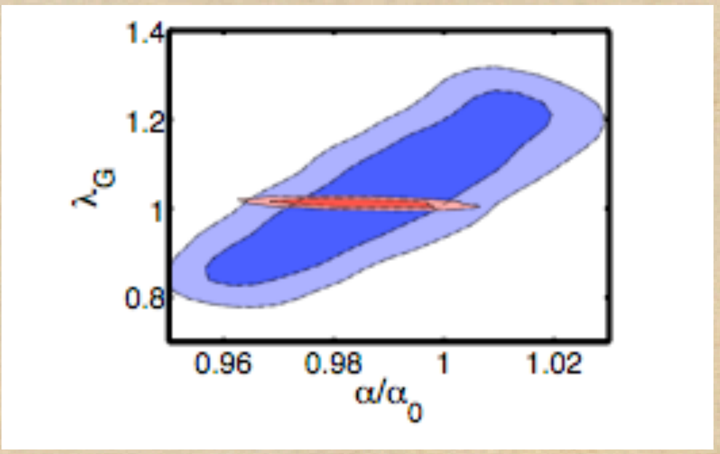
	Data	Range	Ref.
$\delta\alpha/\alpha$	$Y_p = 0.244 \pm 0.002$		
	${}^2\mathrm{H/H} = (3.0 \pm 0.4) \times 10^{-5}$	-0.016 ÷ 0.002 (95 % C.L.)	(Ave01)
$\delta\alpha/\alpha$	$Y_p = 0.244 \pm 0.002$		
	${}^2\mathrm{H/H} = (3.0 \pm 0.4) \times 10^{-5}$	-0.024 ÷ 0.003 (95 % C.L.)	(Nol02)
$\delta\alpha/\alpha$	$Y_p = 0.247 \pm 0.002_{\mathrm{stat}} \pm 0.004_{\mathrm{syst}}$		this paper
	${}^2\mathrm{H/H} = \left(2.95^{+0.028}_{-0.026}\right) \times 10^{-5}$	-0.015 ÷ 0.014 (95 % C.L.)	(using (Den07))
$\delta v/v$	$Y_p = 0.238 \pm 0.005$		
	${}^2\mathrm{H/H} = \left(3.0^{+1.0}_{-0.5}\right) \times 10^{-5}$	-0.007 ÷ 0.02	(Yoo03)
$\delta v/v$	$Y_p = 0.247 \pm 0.002_{\mathrm{stat}} \pm 0.004_{\mathrm{syst}}$		
	${}^2\mathrm{H/H} = \left(2.95^{+0.028}_{-0.026}\right) \times 10^{-5}$	-0.01 ÷ 0.01 (95 % C.L.)	this paper
$\delta\Lambda_{QCD}/\Lambda_{QCD}$	$Y_p = 0.238 \pm 0.005$		
	${}^2\mathrm{H/H} = (2.6 \pm 0.4) \times 10^{-5}$	$\sim$ -0.1 ÷ $\sim$ 0.1	(Kne03b)
$\delta\Lambda_{QCD}/\Lambda_{QCD}$	${}^2\mathrm{H/H} = (1 \div 10) \times 10^{-5}$	$\sim$ -0.06 ÷ $\sim$ 0.06	(Fla02)

Degeneracies



Fisher matrix analysis using response matrix of Dent et al 2007

$\lambda_G = (G_N/G^0_N)^{1/2}$



Martins et al 2010: CMB+BBN

Conclusions

- BBN theory quite accurate, at % level (or better) for main nuclides;
- Problem: systematics in ^{4}He measurements;
- Lithium still puzzling ;
- new observational strategies !
- BBN + CMB (PLANCK): a tool to constrain new physics.