Extra radiation? Recent results from BBN (and CMB)

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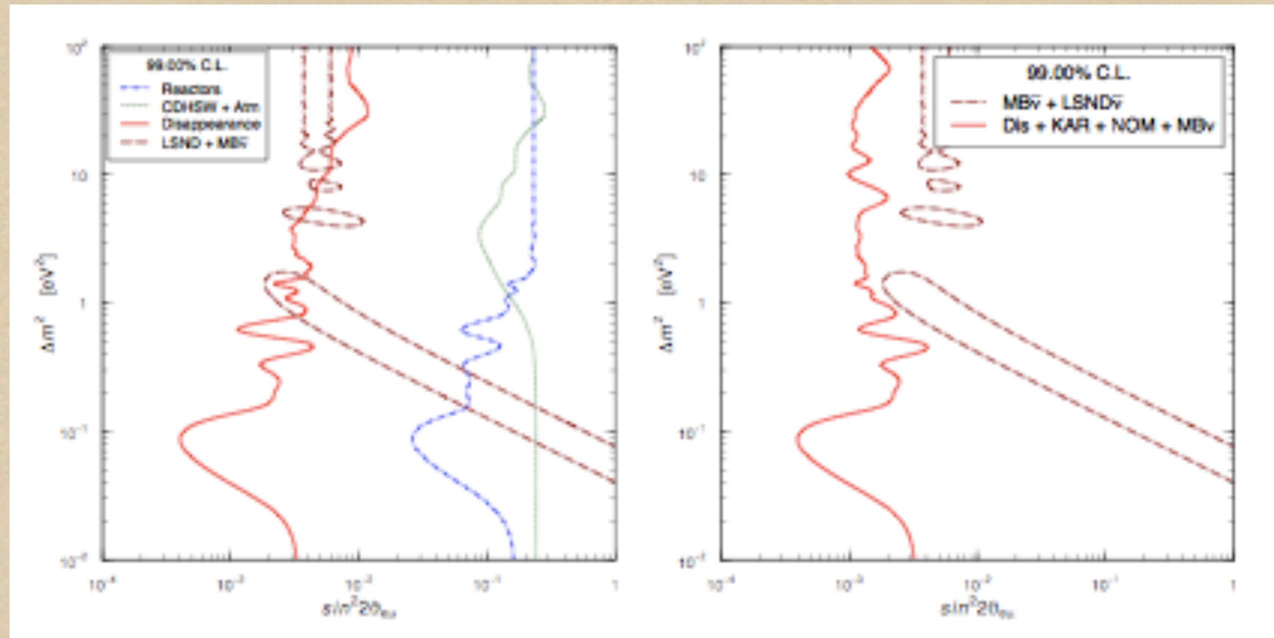
To the memory of
Robert Brout

Cosmology: a powerful tool to constrain relativistic degrees of freedom (light particles)

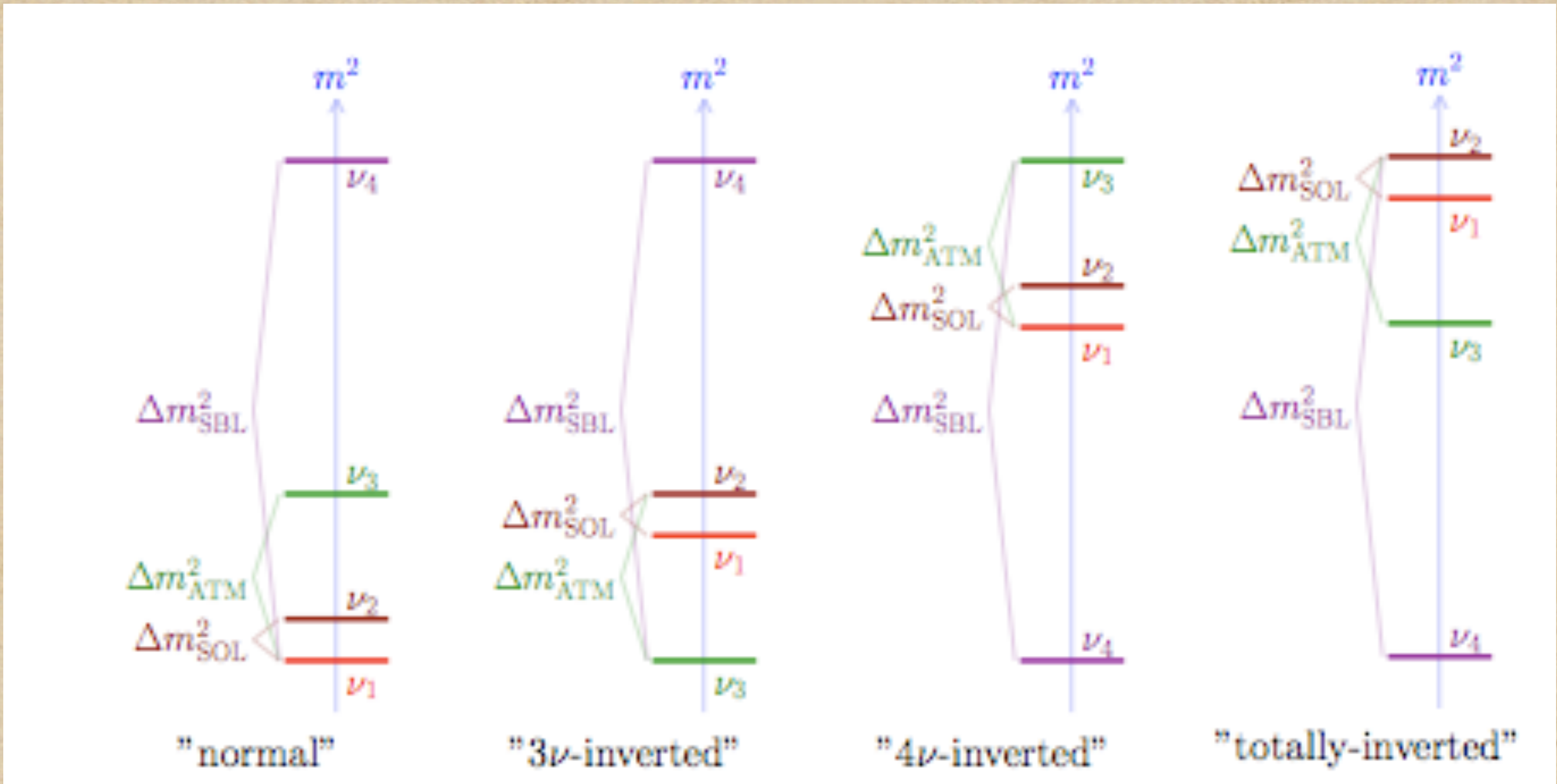
BBN bounds on (active) neutrino generations already used well before LEP results

Recent interests on possible sterile states, which mix with active ν's

MiniBooNE (and LSND) results: oscillations into a sterile state, $\Delta m^2 \approx eV^2$



C. Giunti, '11



3+2 schemes?

Disfavoured by cosmology

For several cosmological observables, all in a single parameter

$$\rho_{rad} = \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right)\frac{\pi^2}{15} T_\gamma^4$$

Instantaneous ν decoupling value for T_ν / T_γ

CMB and BBN scrutinize different "mass" scales!

SUMMARY

- Overview of status of BBN theory
- DATA. A robust upper bound on primordial ^{4}He
- RESULTS
  - standard scenario
  - extra relativistic species from BBN and CMB
  - the role of neutrino asymmetries

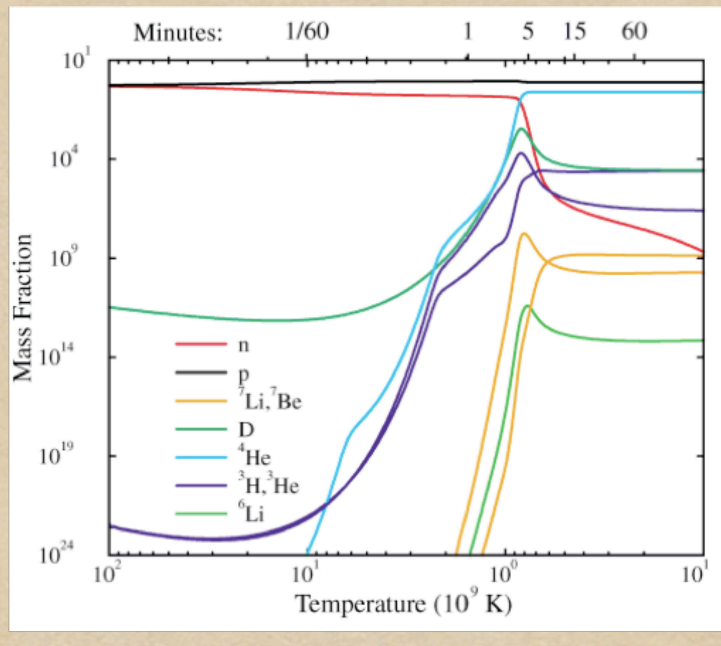
BBN: sixty years after αβγ seminal paper
(Alpher, Bethe & Gamow 1948)

- Theory reasonably under control (per mille level for ^4He (neutron lifetime), 1-2 % for ^2H);
- 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 (^4He, but see later), ^7Li not understood, ^2H fixes $\Omega_b h^2$ value in good agreement with CMB data.

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

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

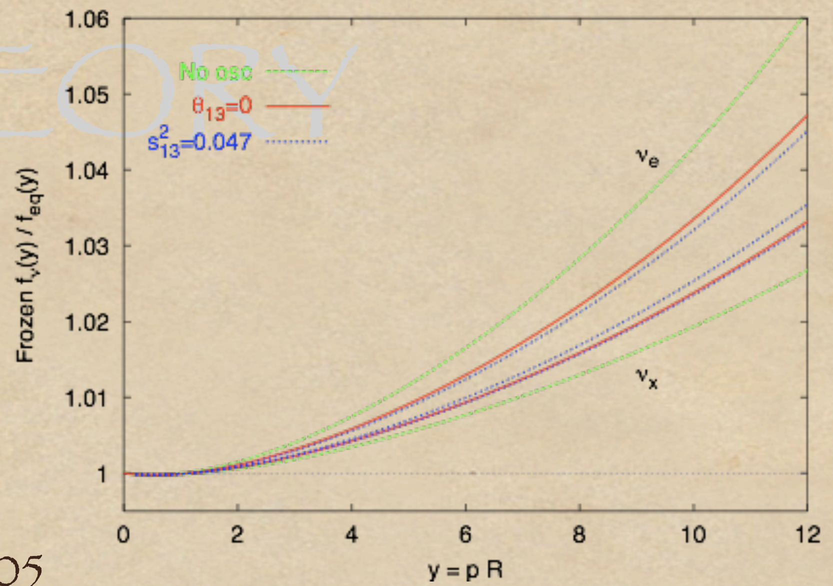
THEORY

Weak rates:

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

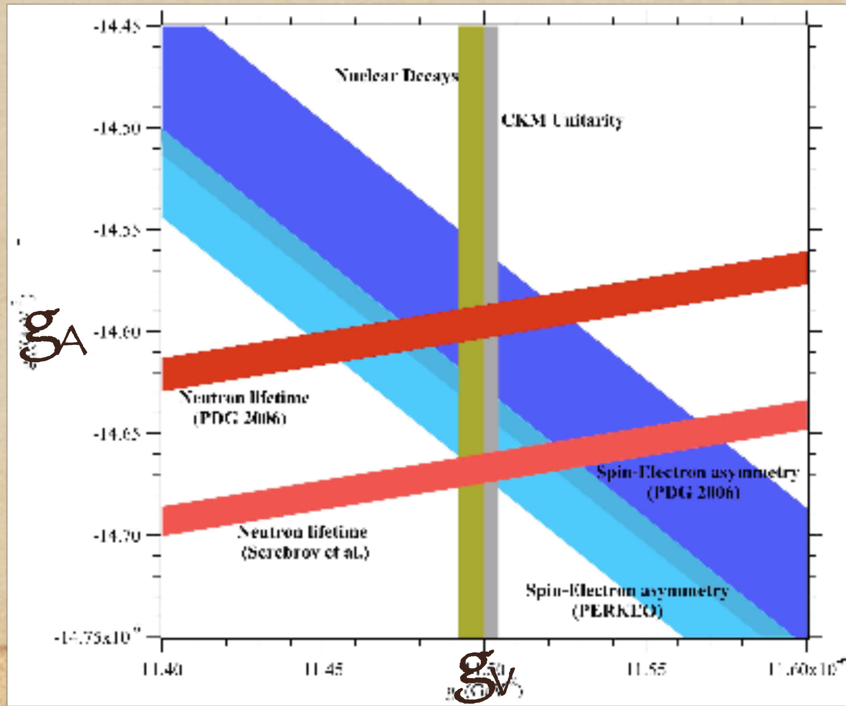
N_{eff}=3.046

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)

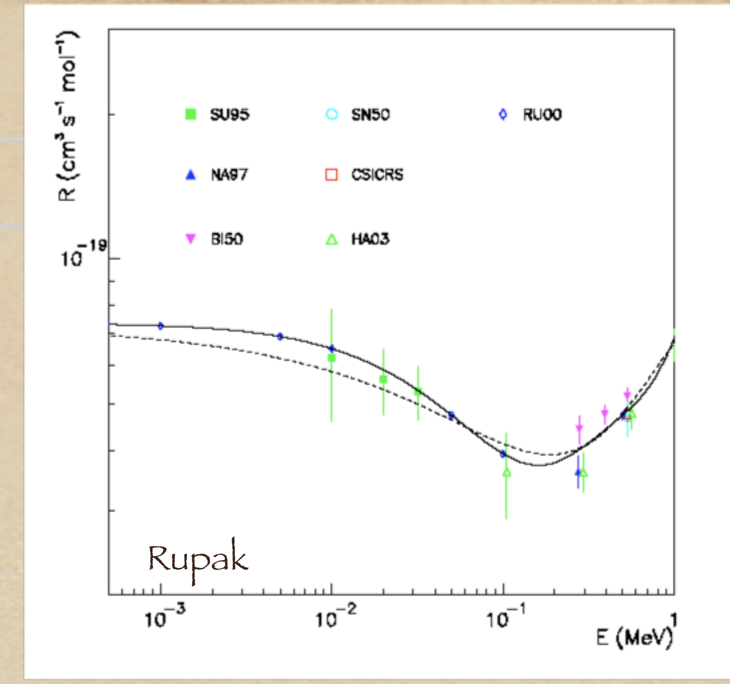
^{4}He mass fraction Y_P linearly increases with τ_n: 0.246 - 0.249



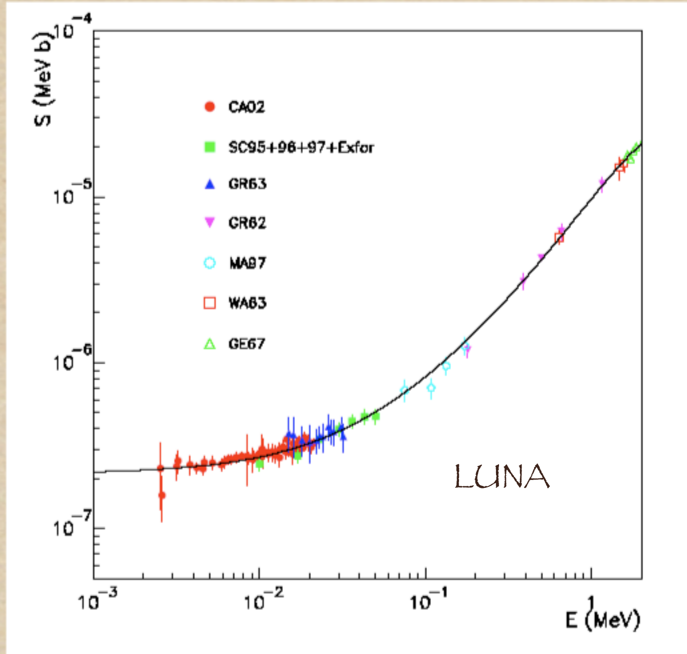
Nico & Snow 2006

Nuclear rates:

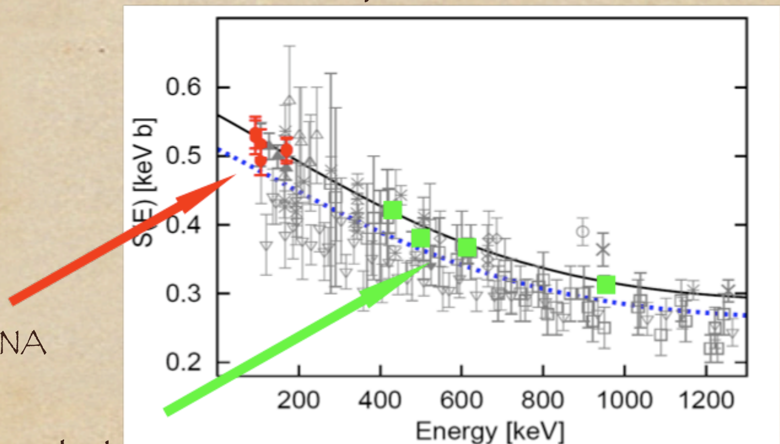
main input from experiments
low energy range (10^2 KeV)
major improvement: underground
measurements (e.g. LUNA at LNGS)



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



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



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

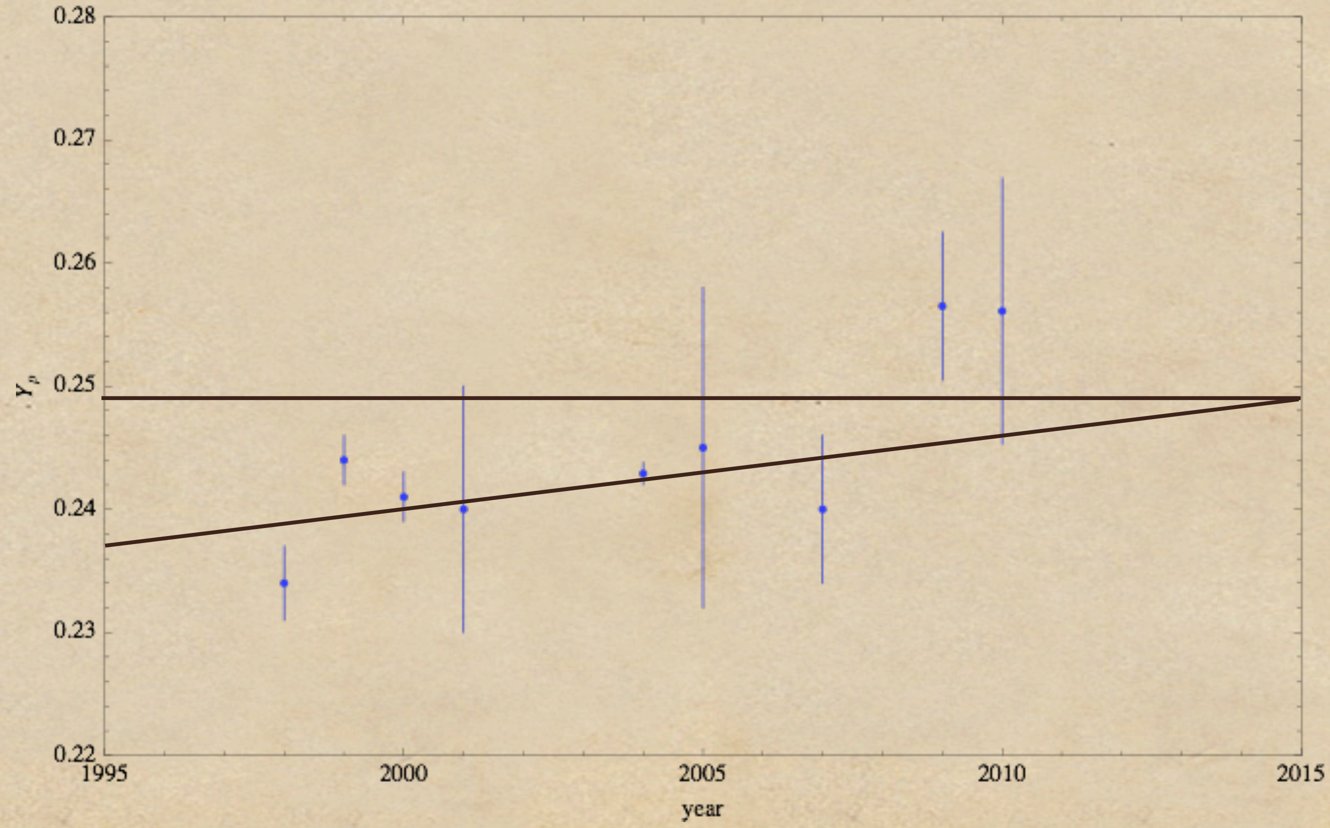
DATA

The quest for primordiality

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

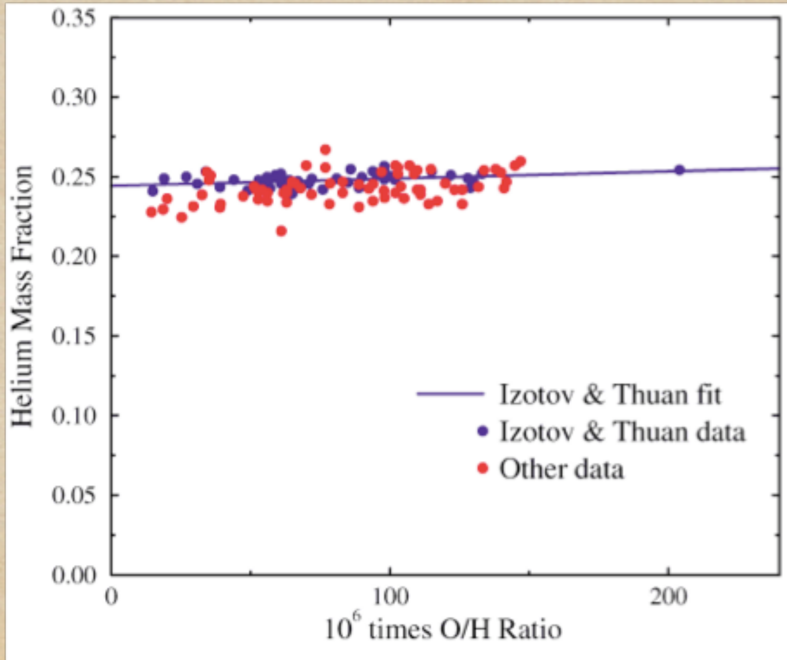
DATA

^{4}He "evolution"



DATA

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

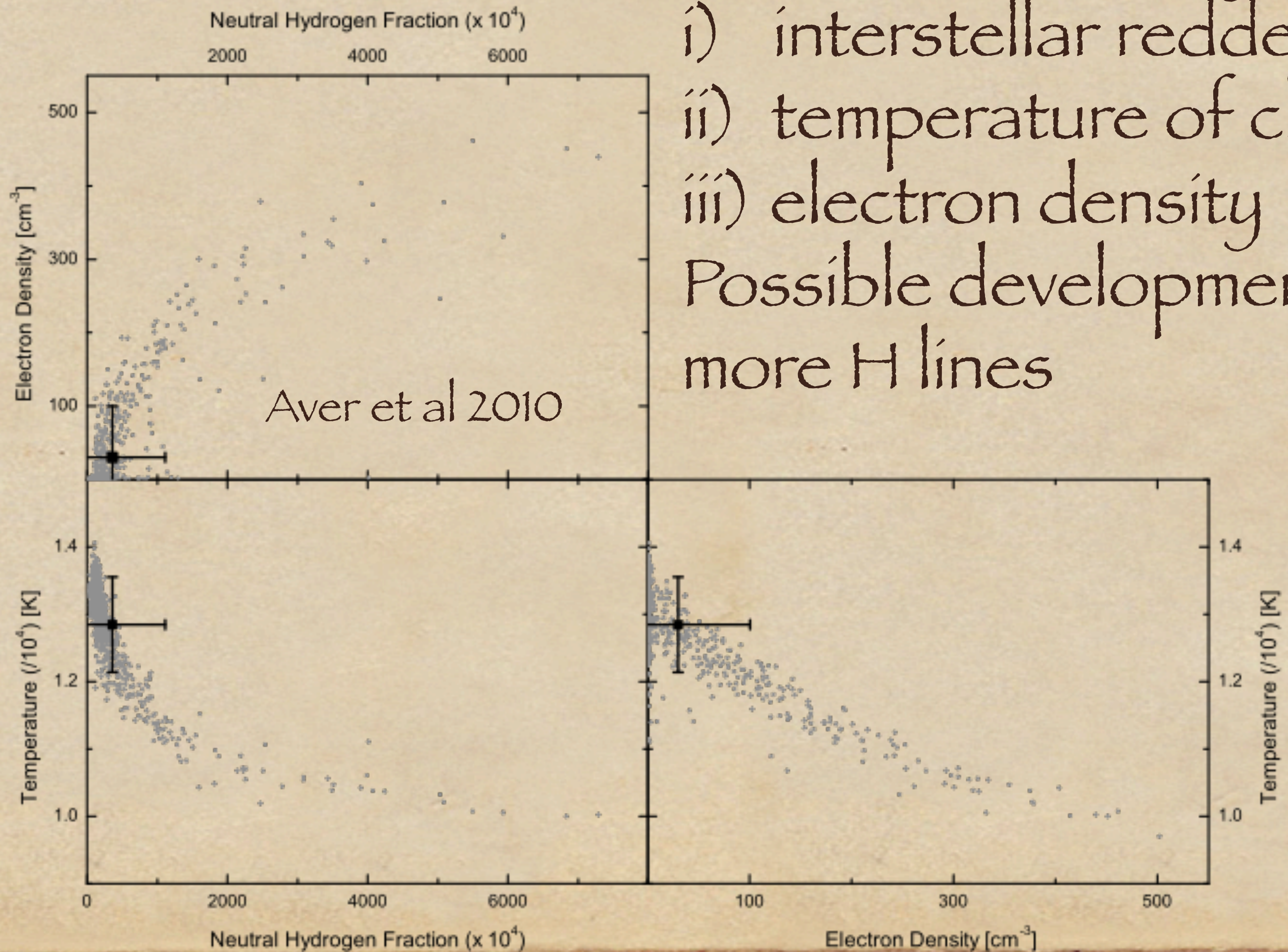
Main sources of systematics:

i) interstellar reddening

ii) temperature of clouds

iii) electron density

Possible developments: using more H lines



Further problem: what is the ^{4}He produced by POP III early stars?

$\Delta Y \approx 10^{-2} - 10^{-3}$

Salvaterra & Ferrara '03
Vangioni et al 2010

For our purposes a robust upper bound on ^{4}He (and lower bound on D) is more than enough

No regression to zero-metallicity but fit with a constant value + $dY/dZ>0$

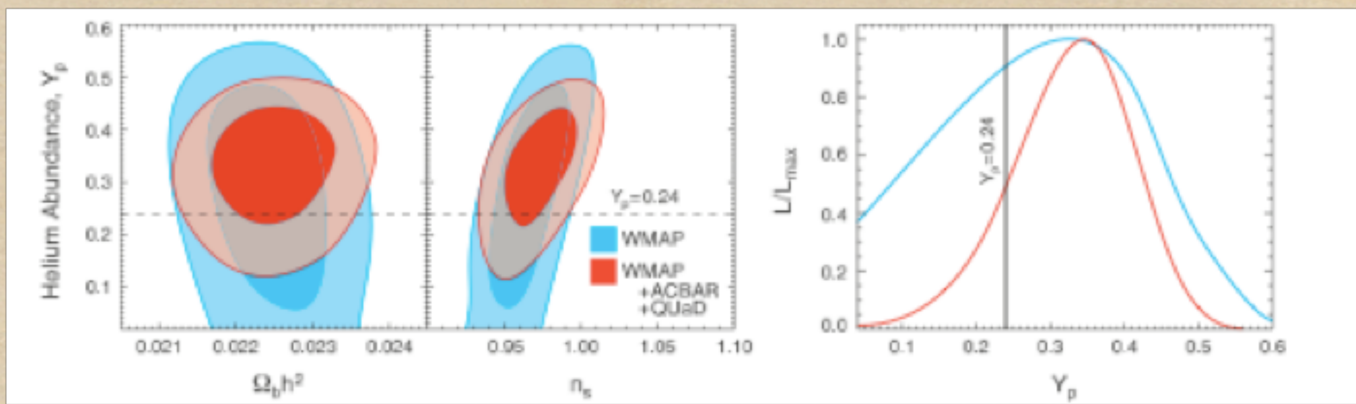
$Y < 0.2631$ @ 95 C.L.

G.M. e P.Serpico '11

^{4}He from CMB?

^{4}He recombines before photon decoupling

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

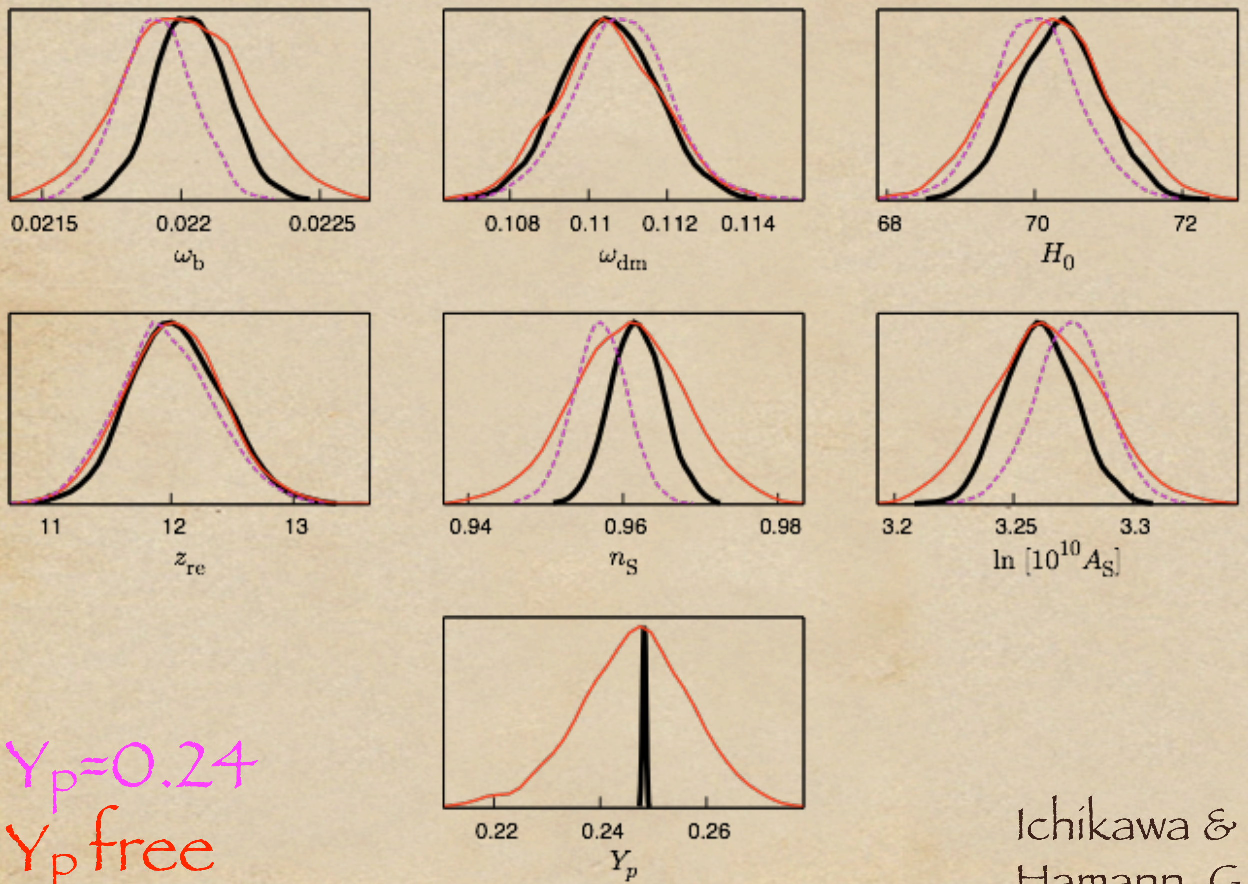


WMAP-7

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

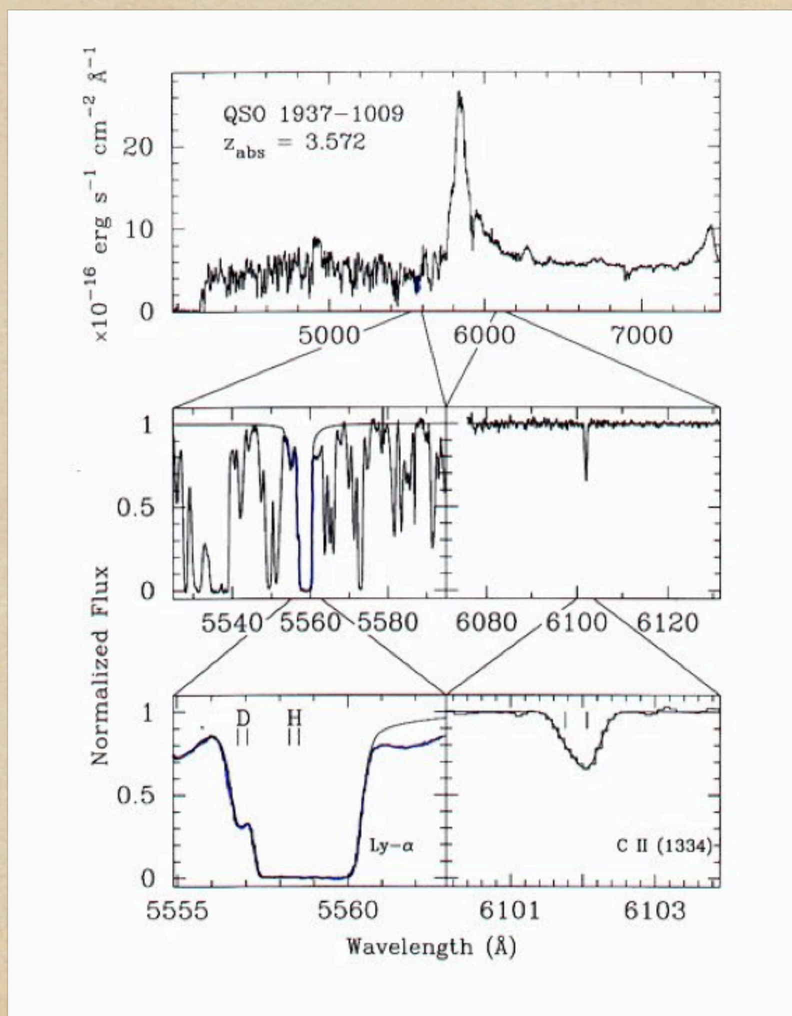
Hamann, G.M. & Lesgourgues 2008

DATA

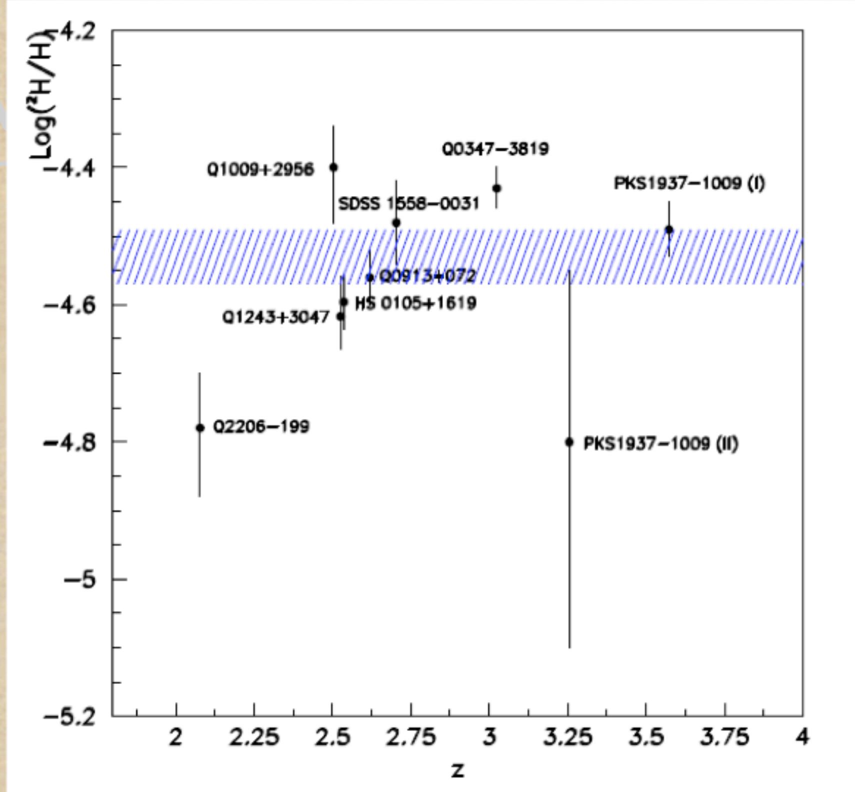
^2H measures baryon fraction. Quite good agreement with WMAP determination:

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

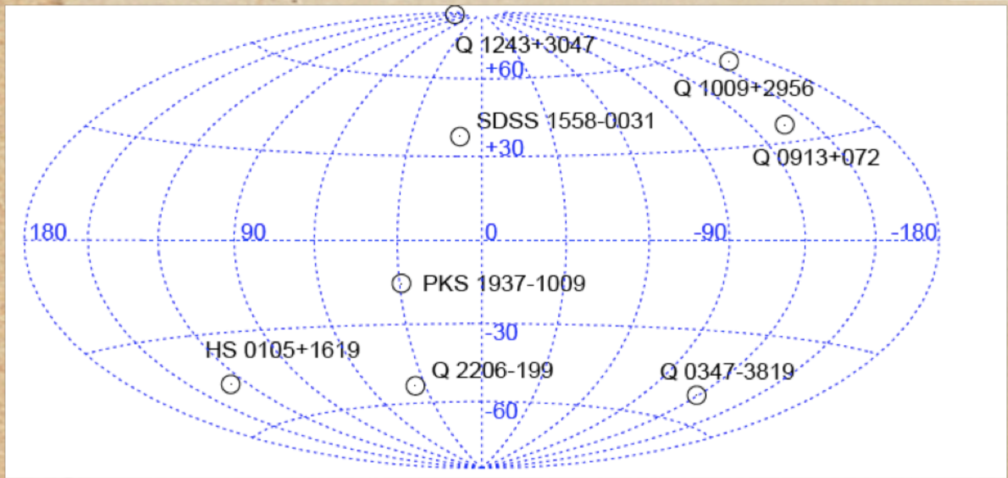
Observations: absorption lines in clouds of light from high redshift background QSO



DA



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



Iocco et al 2009

$^2H/H(10^{-5}) > 2.45$ @ 95 C.L.

DATA

^3He

observed on Earth (nuclear weapons)

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

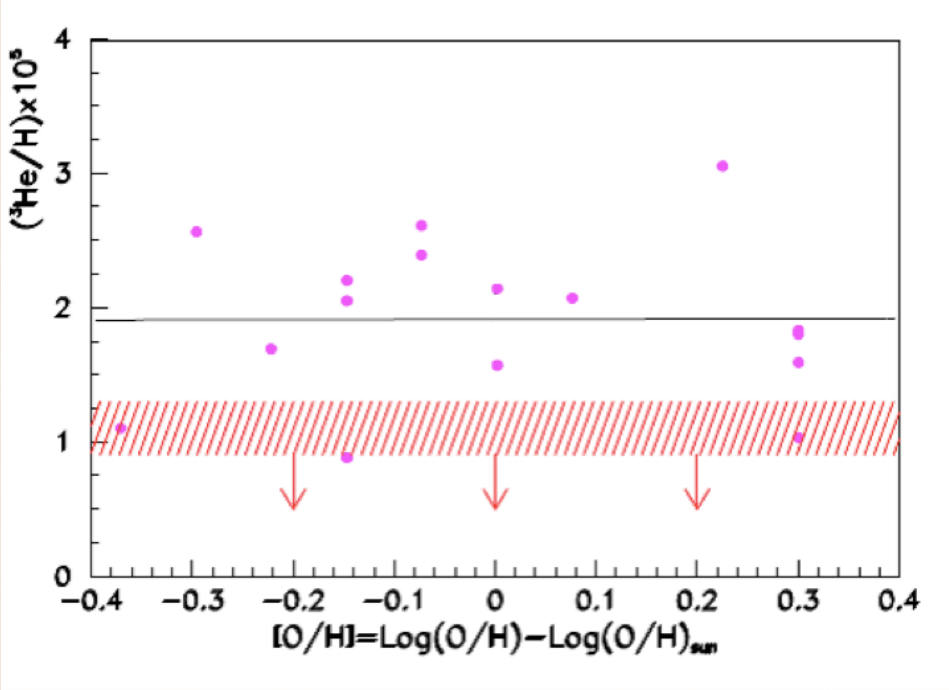
observed in the ISM $^3He/H = 0.1$

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

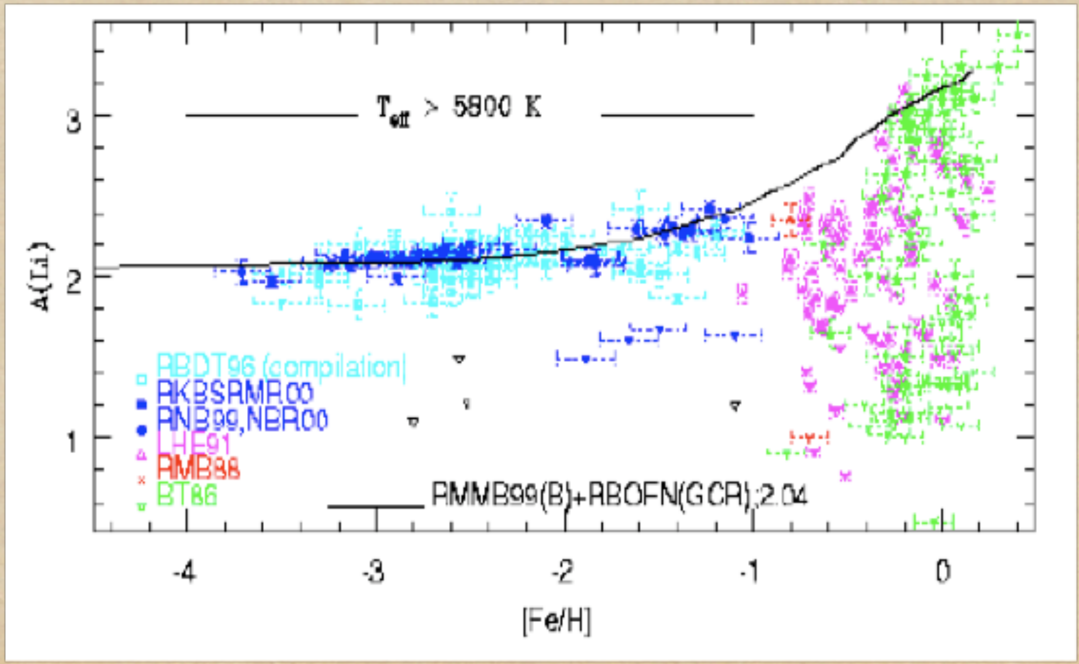


Bania et al 2002

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

DATA

^{7}Li (and ^{6}Li) still a puzzle.
Spite plateau in metal poor dwarfs and GGC questioned



DATA

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

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

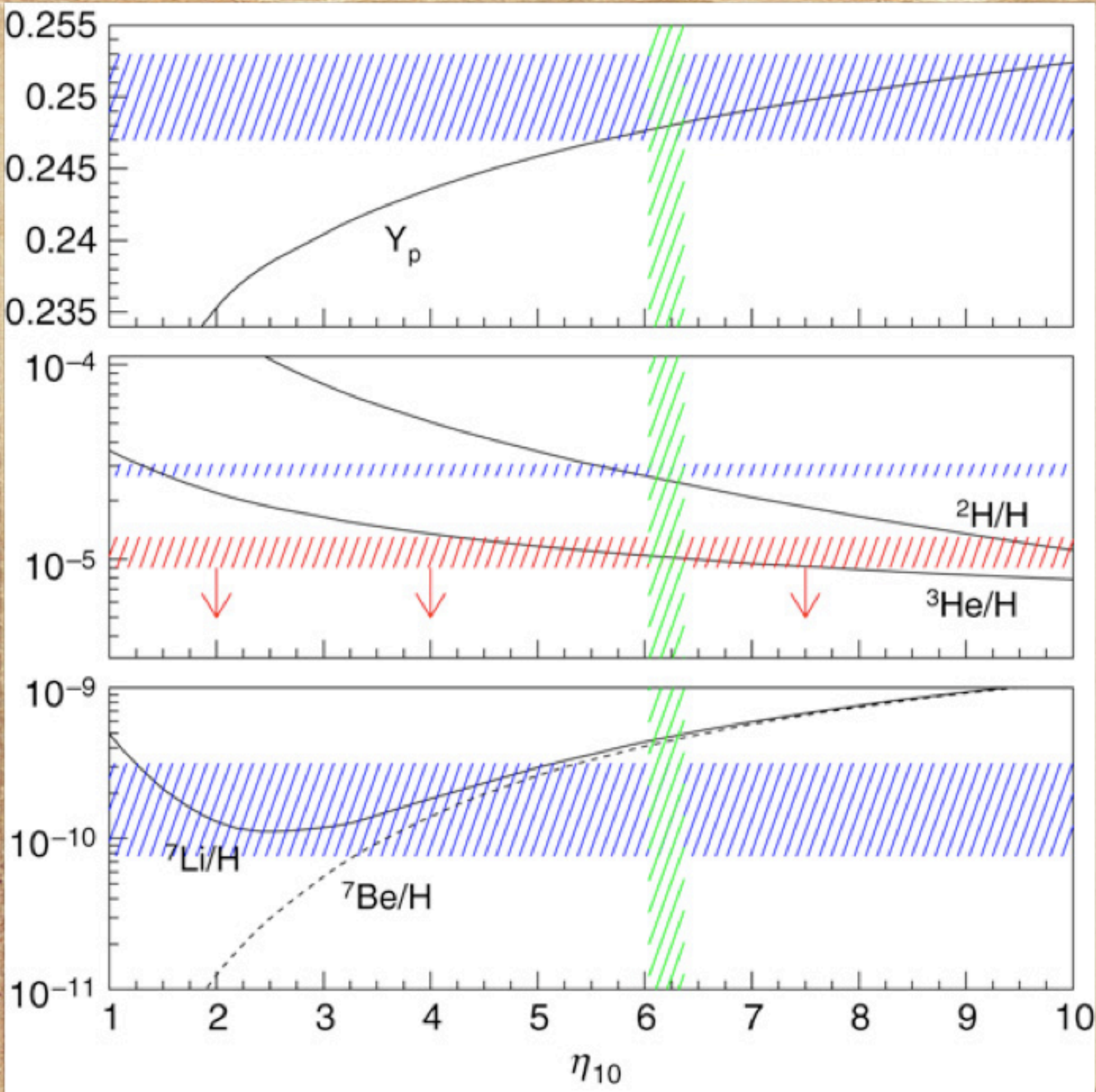
A factor 2 or more below BBN prediction, trusting ^2H+WMAP baryon density and ^3He upper bound

DATA

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

RESULTS

Standard scenario



Iocco et al 2009

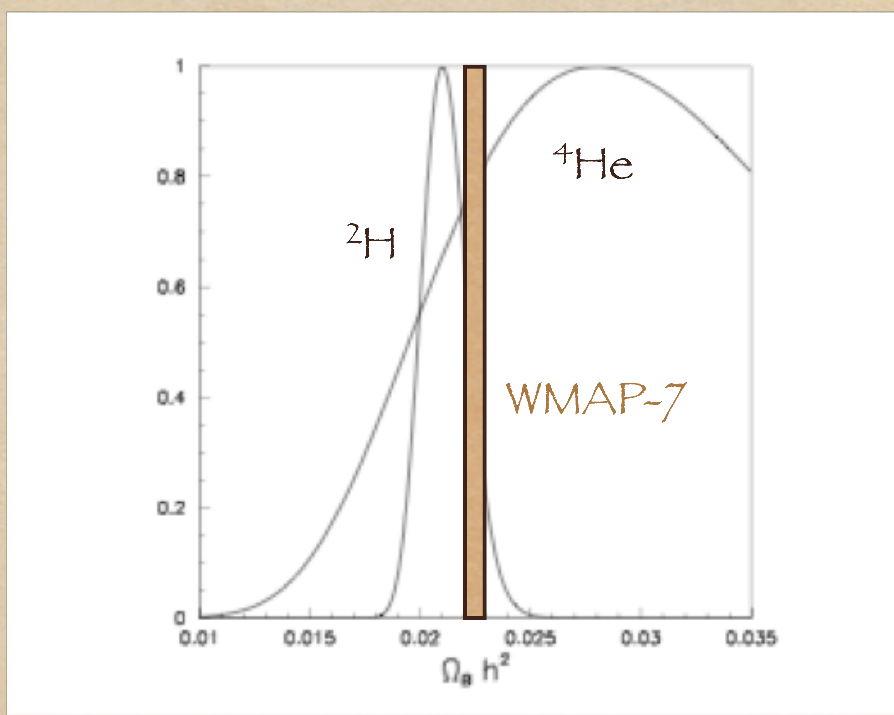
RESULTS

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

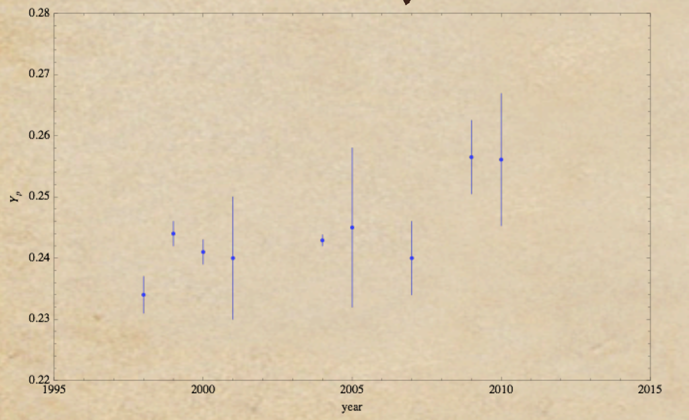
Exotic scenarios

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



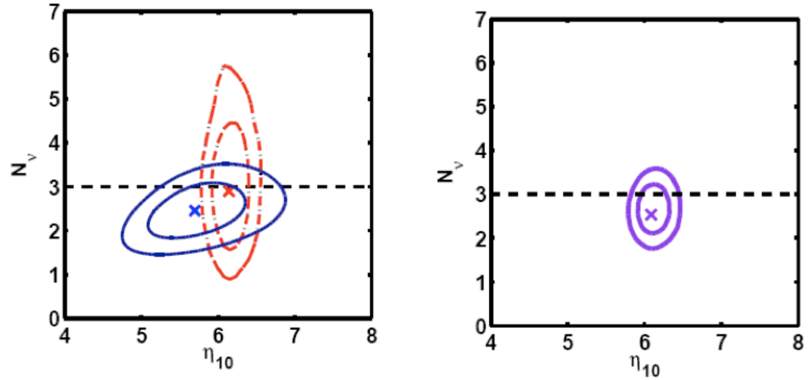


Figure 4:
(Left) In blue (solid), the 68% and 95% contours in the N_ν - η_{10} plane derived from a comparison of the observationally-inferred and BBN-predicted primordial abundances of D and ^{4}He. In red (dashed), the 68% and 95% contours derived from the combined WMAP 5-year data, small scale CMB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

Steigman 2008

2 σ claim ! (Izotov & Thuan 2010)

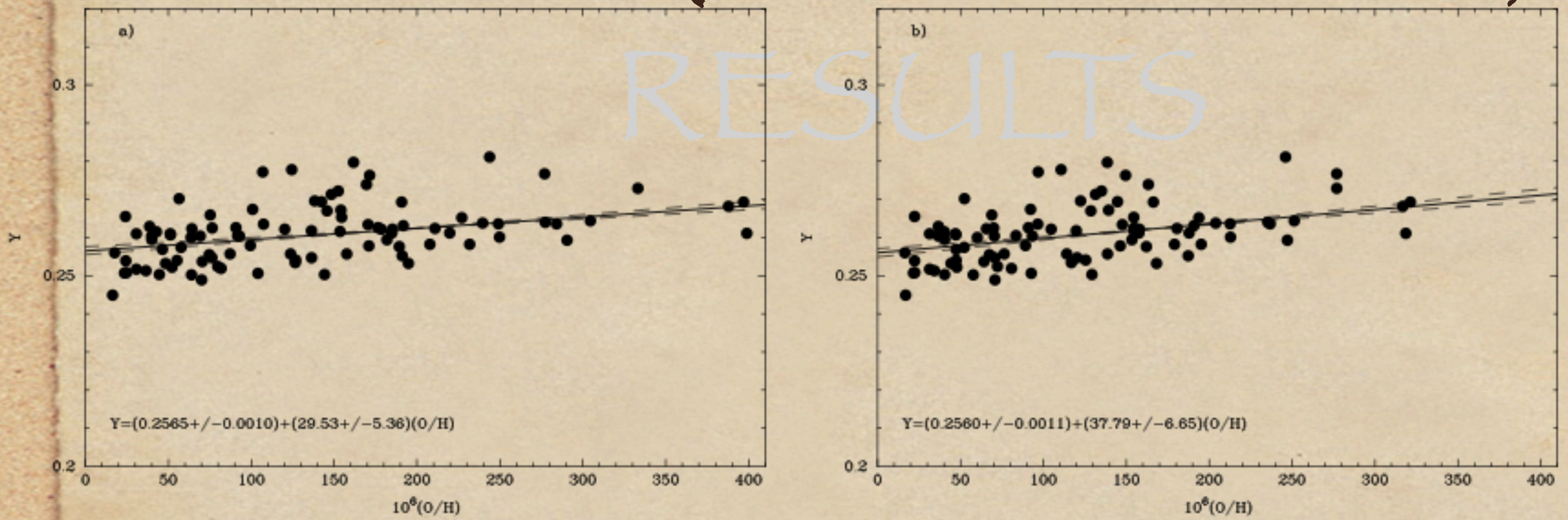
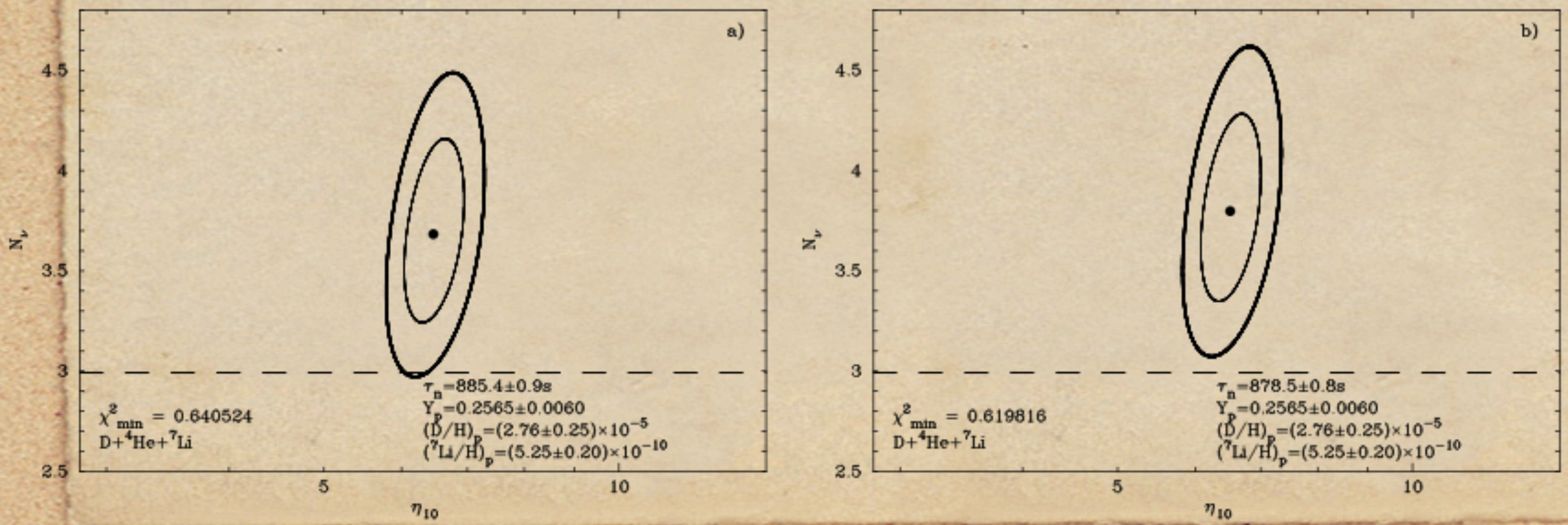
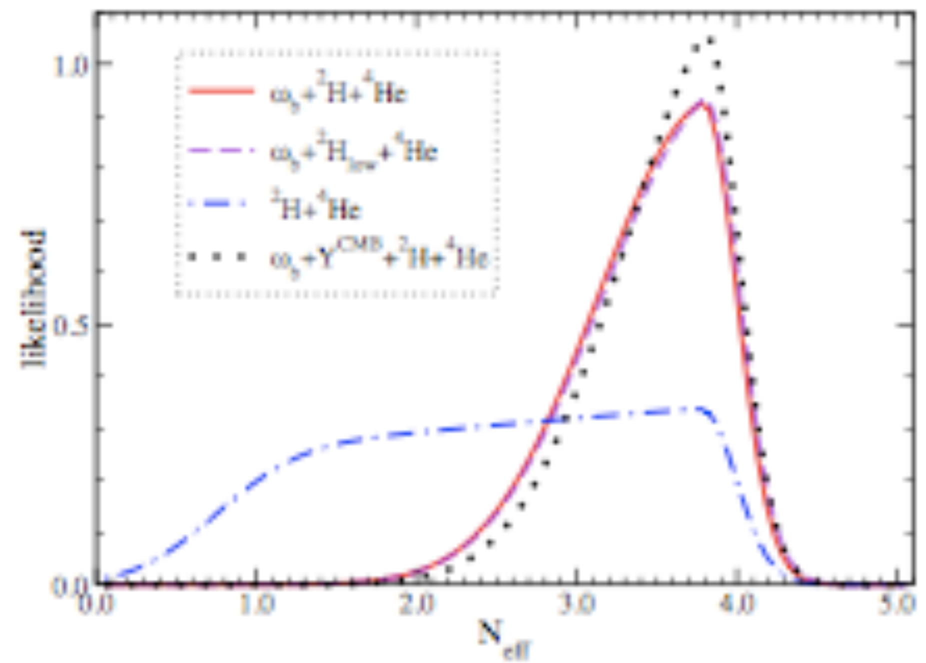


FIG. 1.— Linear regressions of the helium mass fraction Y vs. oxygen abundance for H II regions in the HeBCD sample. The Ys are derived with the He I emissivities from Porter et al. (2005). The electron temperature $T_e(He^+)$ is varied in the range $(0.95-1)\times T_e$(O III). The oxygen abundance is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



Bounds with a conservative ^{4}He limit

2 extra sterile ν's excluded if well thermalized (large mixings)

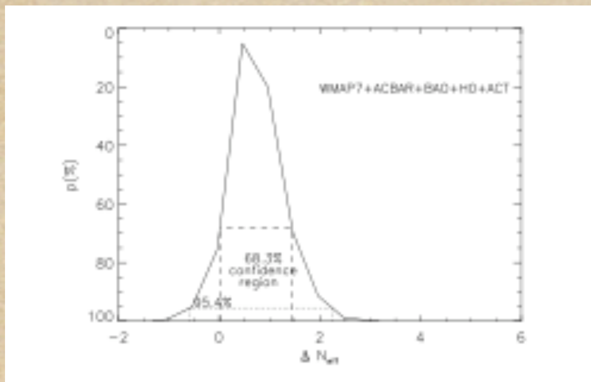


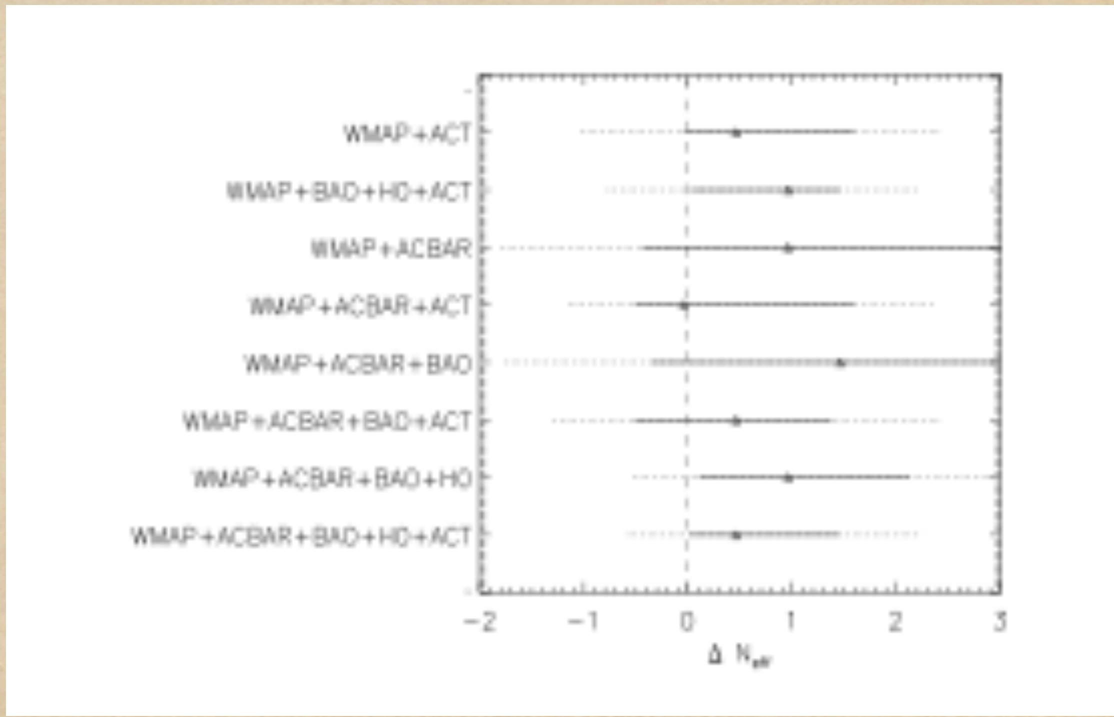
	Δm^2_{41} [eV^2]	$\lvert U_{e4}\rvert$	Δm^2_{51} [eV^2]	$\lvert U_{e5}\rvert$	χ^2/dof
3+1	1.78	0.151			50.1/67
3+2	0.46	0.108	0.89	0.124	46.5/65

Kopp et al '11

New CMB results (frequentists vs Bayesians: the effect of priors)

Gonzales-Morales et al '11



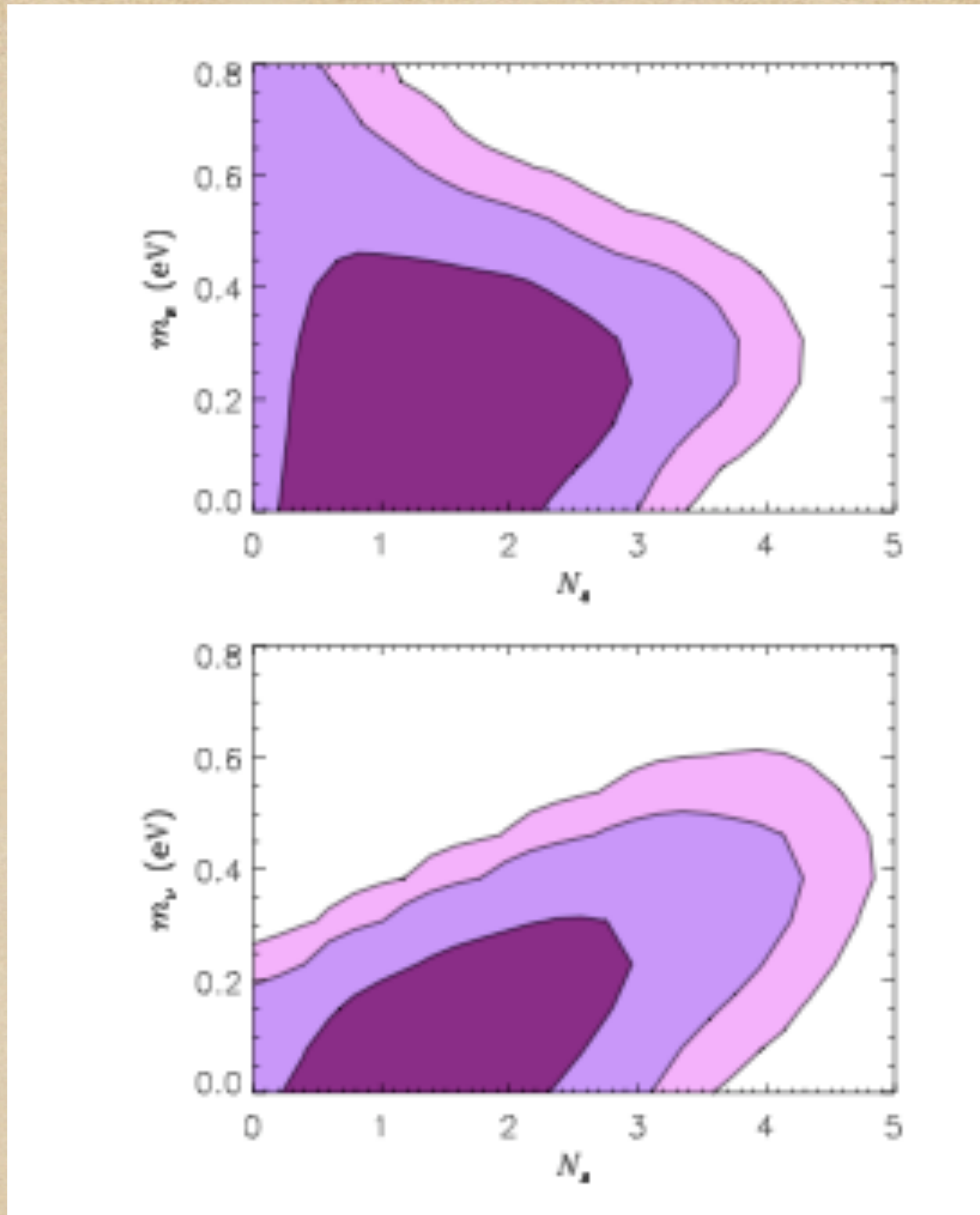


Also depends upon neutrino masses

3+N

Hamann et al '06

N+3



RESULTS

The Lepton number of the Universe

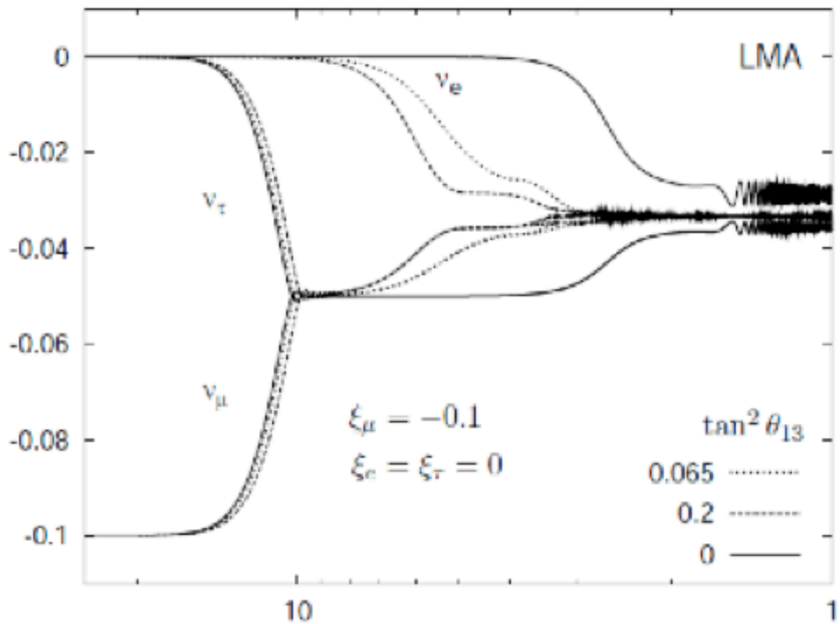
Neutrino chemical potentials change the expansion rate parameter H (larger ν energy density);
ν_e chemical potential changes the n-p chemical equilibrium (weak rates); Kang & Steigman 1992
ν's oscillates in flavor space: before BBN ν_e, ν_μ & ν_τ mix their chemical potential.

Dolgov et al 2002

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

RESULTS

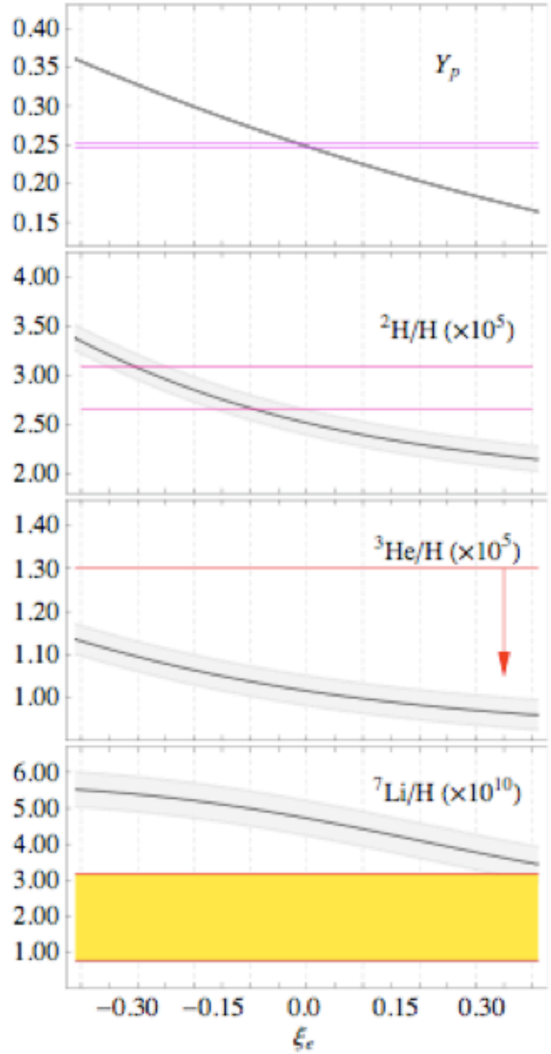
Dolgov et al 2002



"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"*

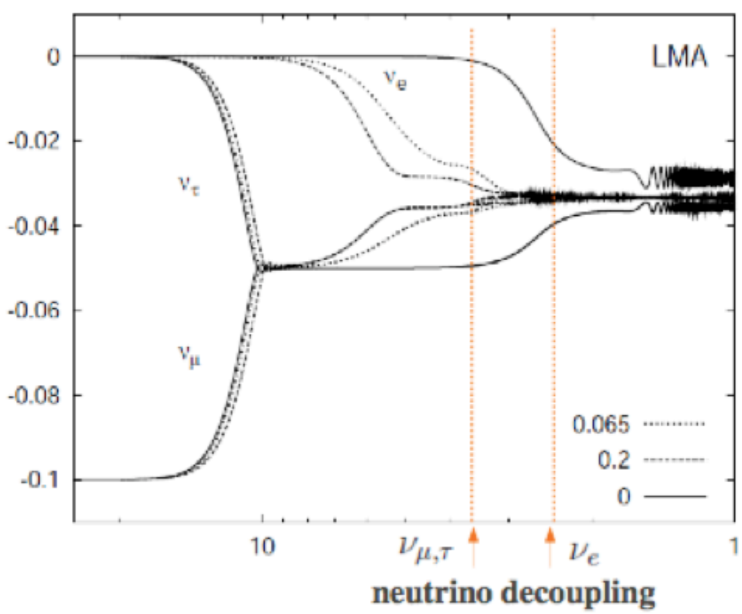
"...the BBN limit on the ν_e degeneracy parameter, ***$|\xi_\nu| < 0.07$, now applies to all flavors.****"*

Iocco et al 2009



RESULTS

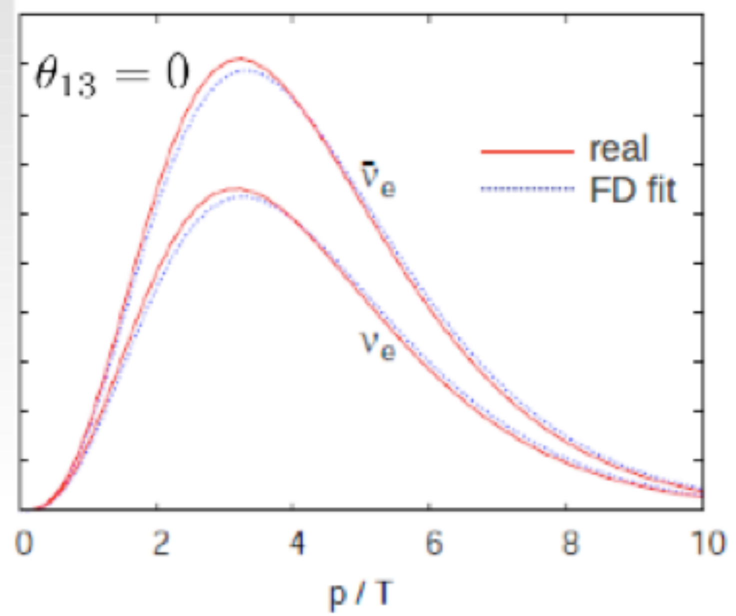
However...

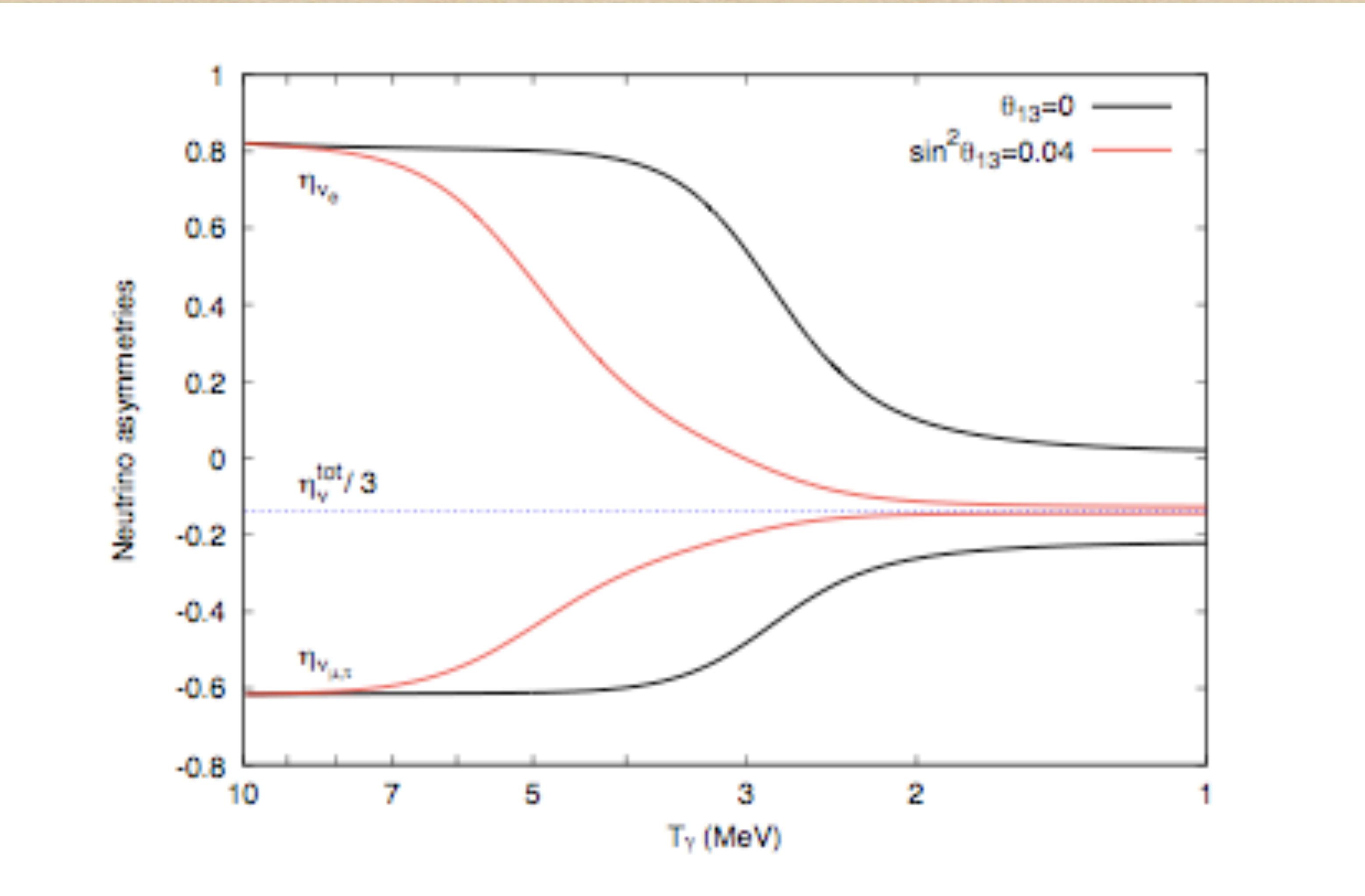


S. Pastor et al.,Phys. Rev. Lett. **102**, 241302 (2009)

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

Not a perfect FD (in general)!

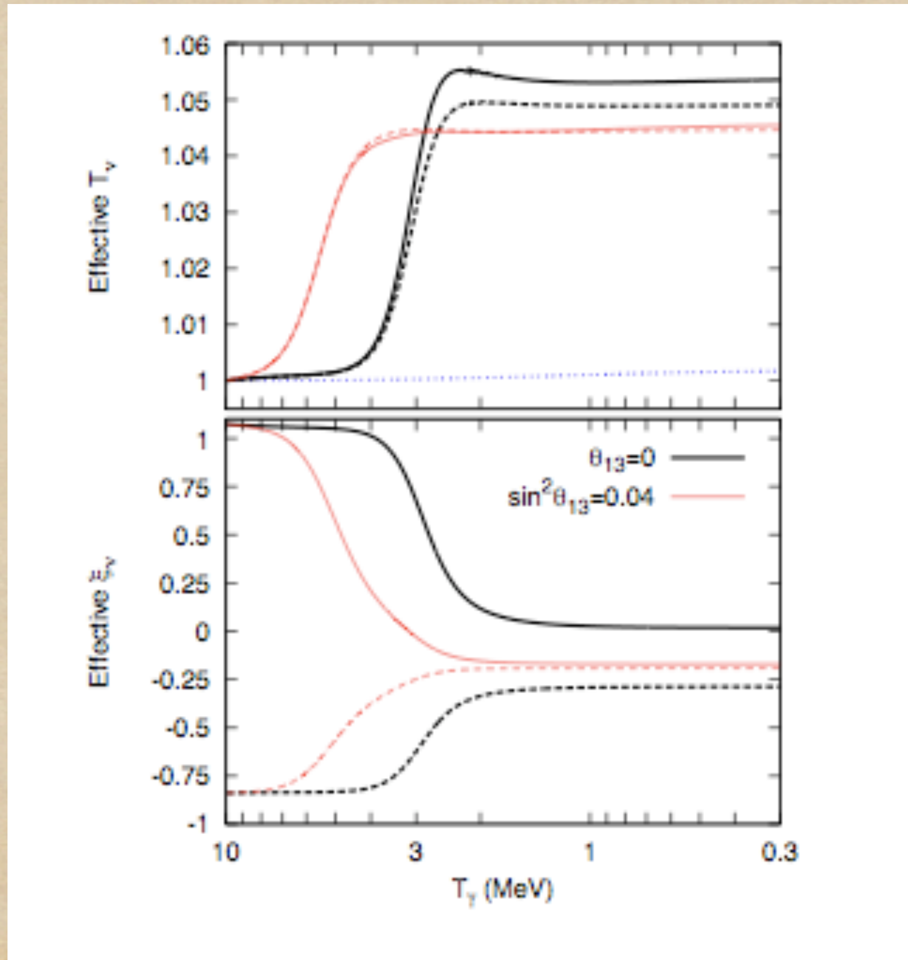




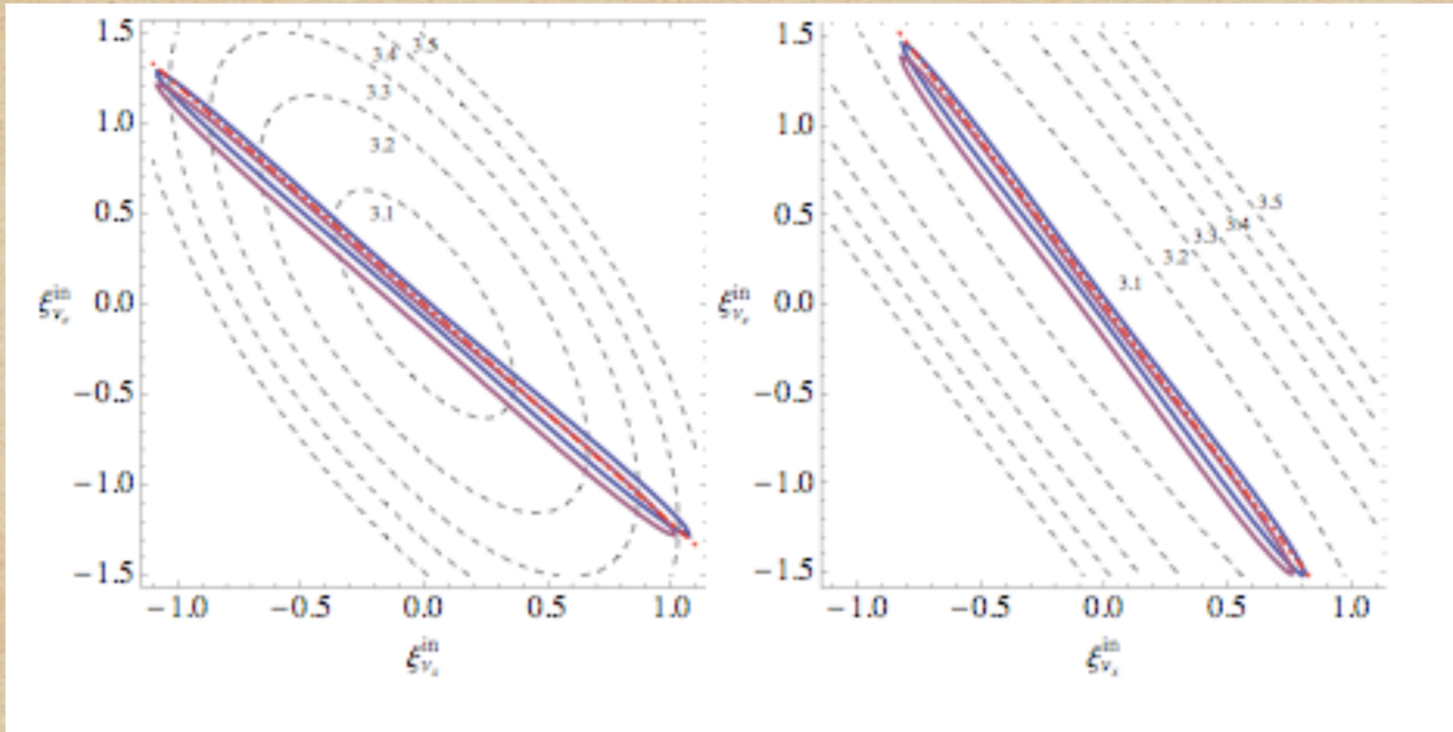
We must follow ν distribution through BBN dynamics

Neutrino distribution is not a pure FD: ν's slightly hotter

RESULTS



G.M., Miele, Pastor, Pisanti and Sarikas, '10



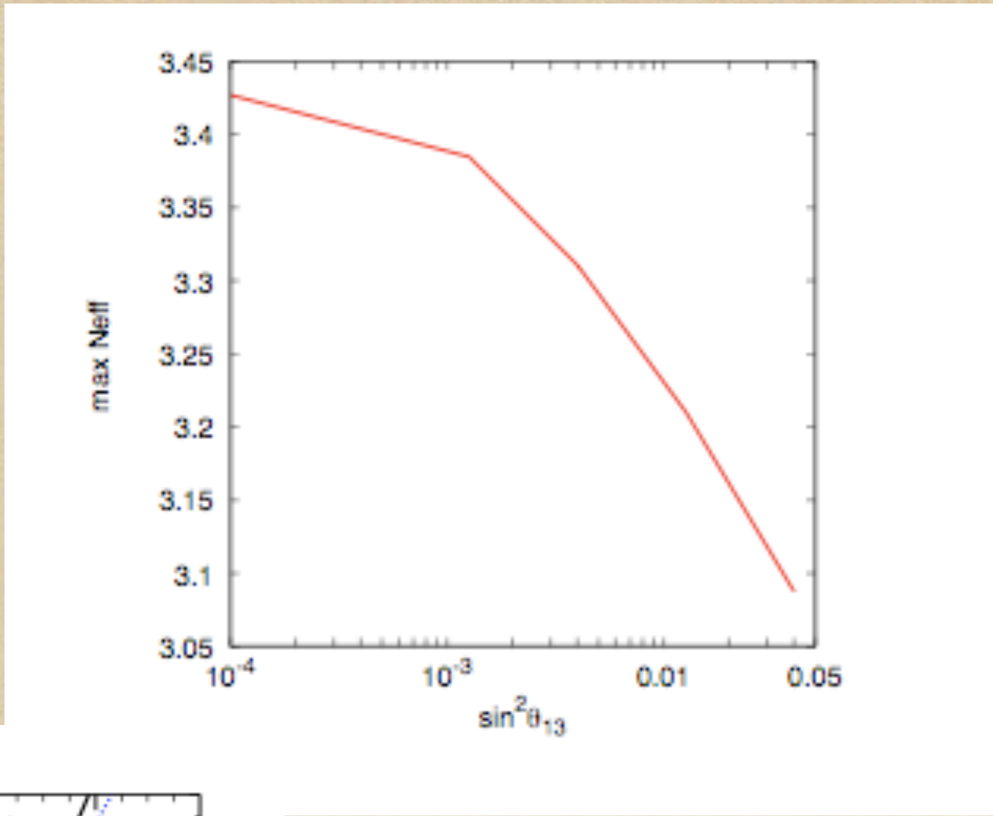
$\sin^2 \theta_{13}=0$ $\sin^2 \theta_{13}=0.04$

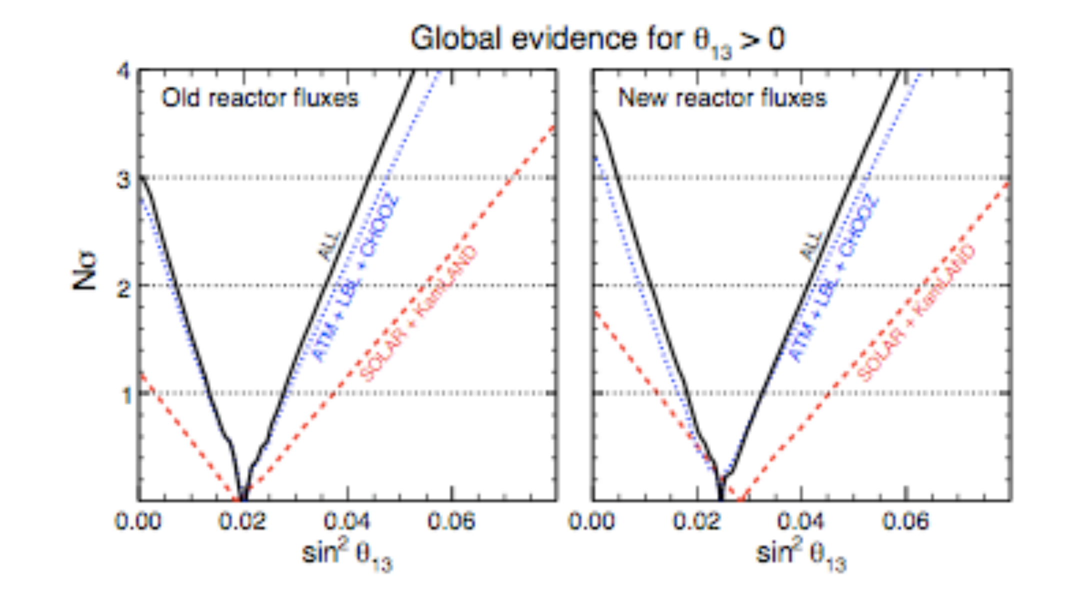
Dependence on θ_{13}

Planck sensitivity $\Delta N_{eff} \approx 0.1 - 0.2$

Maximal N_{eff} vs θ_{13}

G.M., Miele, Pastor, Pisanti and Sarikas, '10





After T2K results

Fogli et al '11

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.

One extra “effective” neutrino allowed by data (maybe slightly preferred)

No room for two thermalized sterile states

Planck (and Katrin) results will tell us more in 1-2 years!