# Recent results from BBN and Planck 2015

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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 $\nu$'s

# SUMMARY

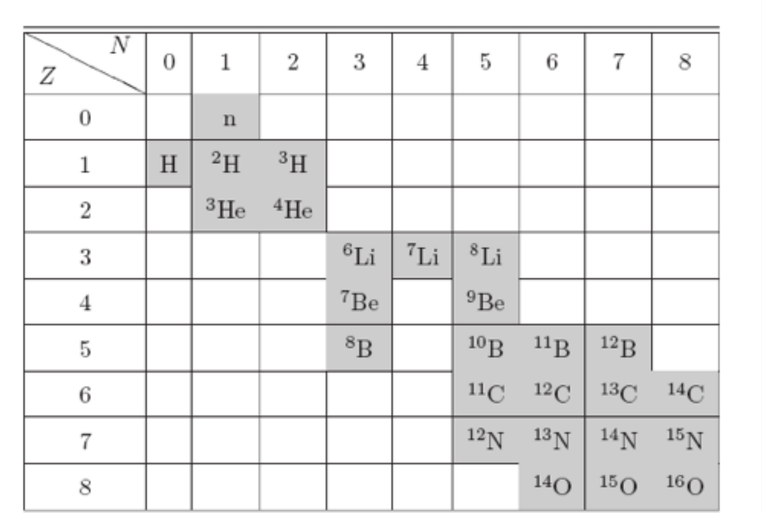
- Overview of status of BBN theory
- DATA. A robust upper bound on primordial $^4$He
- RESULTS
  - standard scenario
  - extra relativistic species from BBN and CMB
  - sterile states

# BBN: almost seventy years after **αβγ** seminal paper( Alpher, Bethe & Gamow 1948)

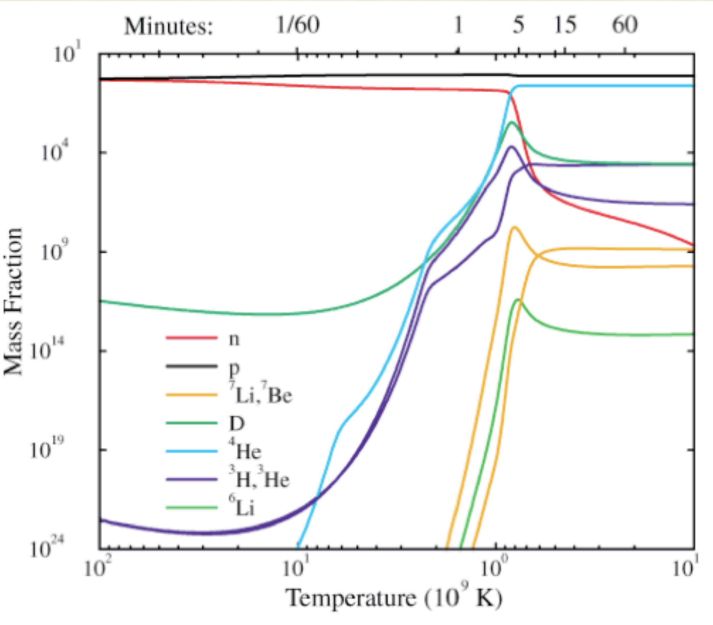
- Theory reasonably under control (per mille level for $^4$He (neutron lifetime), 1-2 % for $^2$H);
- Increased precision in nuclear reaction cross sections at low energy (underground lab's);
- $\Omega_b h^2$ measured by WMAP/Planck with high precision;
- Decreasingly precise data ($^4$He, but see later),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

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

PArthENoPE
Public Algorithm Evaluating Nucleosynthesis
of Primordial Elements

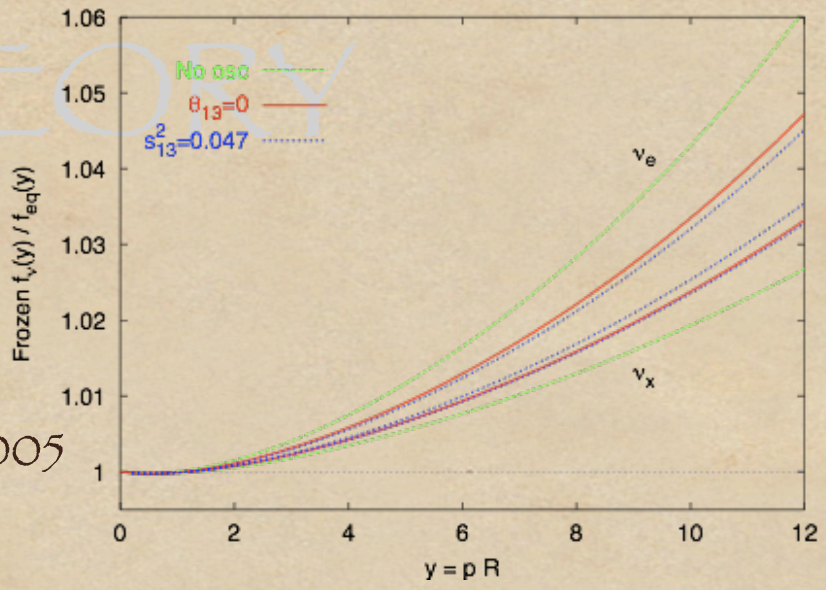
THEORY

## Weak rates:

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

$N_{eff}$=3.046

G.M. et al 2005

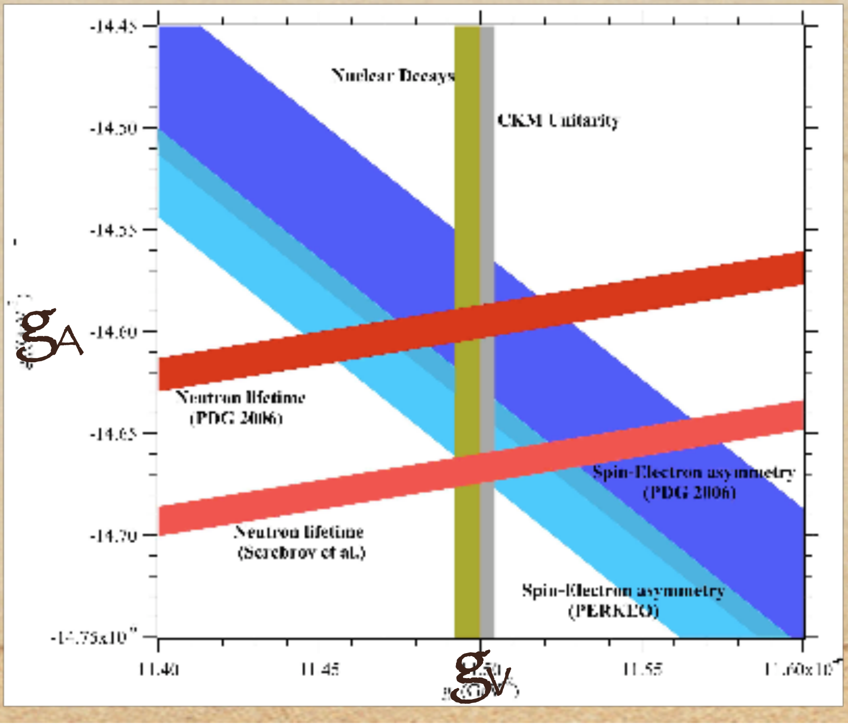


Main uncertainty: neutron lifetime
$\tau_n$= 885.6 ± 0.8 sec (old PDG mean)
$\tau_n$=878.5 ± 0.8 sec (Serebrov et al 2005)

Presently:

$\tau_n$=880.3 ± 1.1 sec

$^4$He mass fraction $Y_P$ linearly increases with $\tau_n$: 0.246 - 0.249

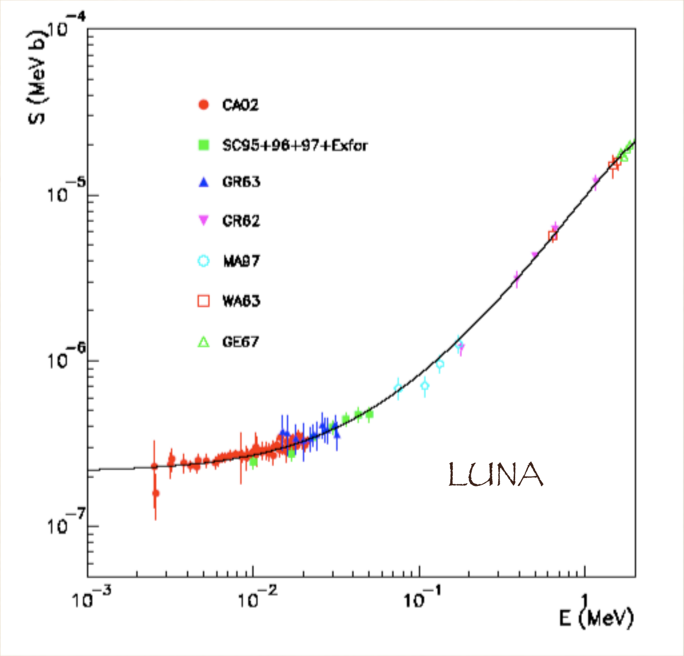


Nico & Snow 2006

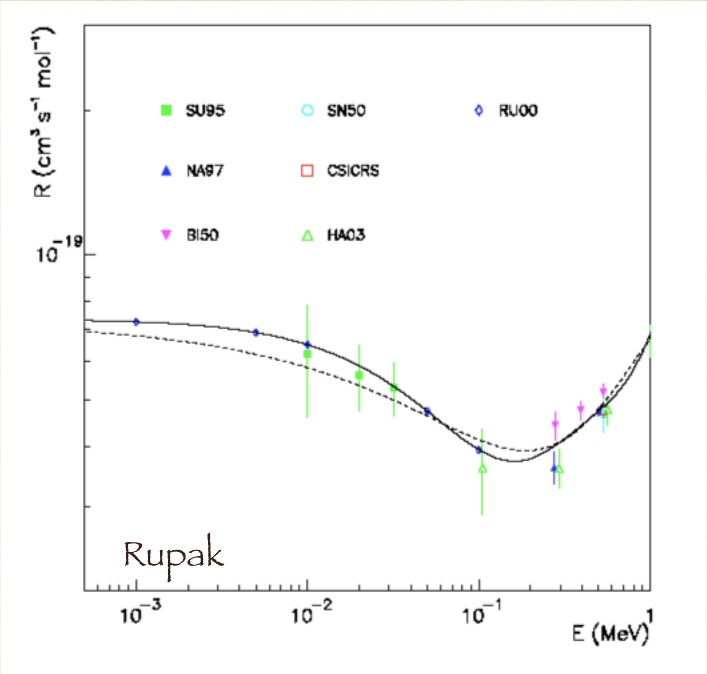
# Nuclear rates:

THEO

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



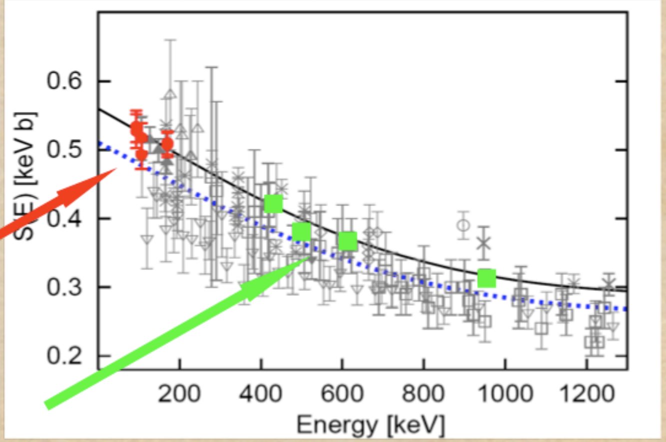
$^2H(p,\gamma)^3He$



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

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

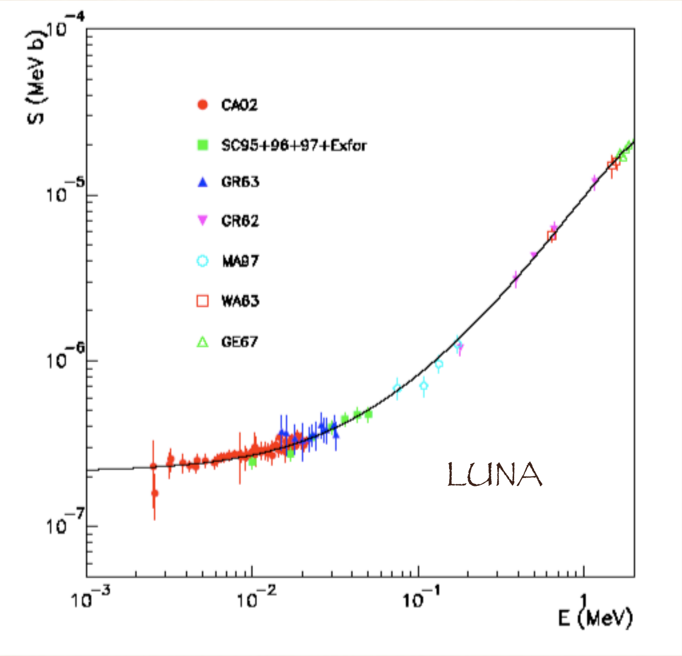
# Nuclear rate error budget:

| | | |
|---|---|---|
| $^4$He | $\tau_n$ | $\approx$100% (0.0003) |
| $^2$H/H | d(p,$\gamma$)$^3$He | 78% (0.06) |
| | d(d,n)$^3$He | 19% (0.02) |
| | d(d,p)$^3$H | 3% (0.013) |

# THEORY

THEORY

Nuclear rates: for d(p,γ) $^3$He also available ab initio calculations (Viviani et al 2000 PRC, Marcucci et al 2005 PRC, …,Marcucci et al 2016 PRL)



$^2$H(p,γ)$^3$He

Larger cross section than present data fit! (Adelberger et al, 2011, Rev. Mod. Phys.)

Important to check experimentally this result! LUNA 2017?

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

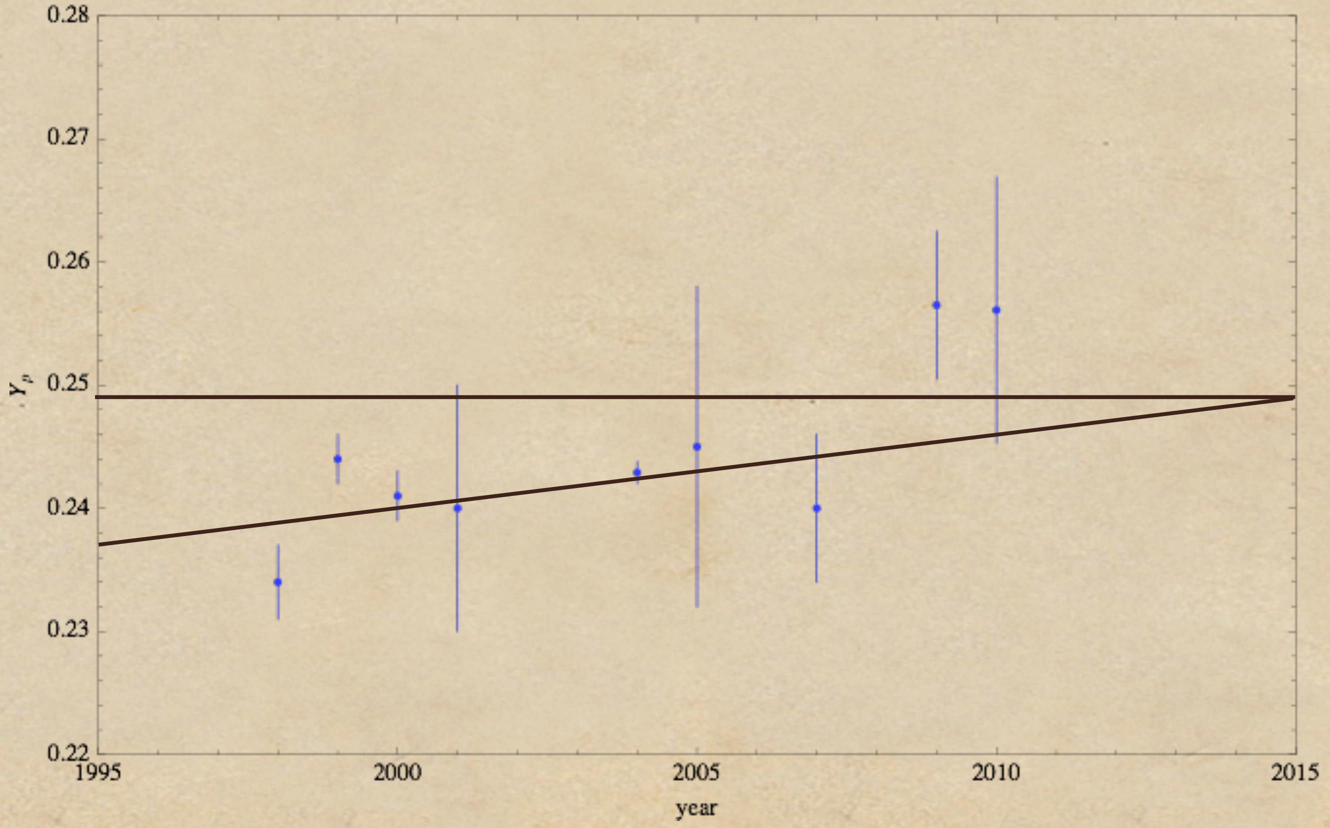
# DATA

## 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

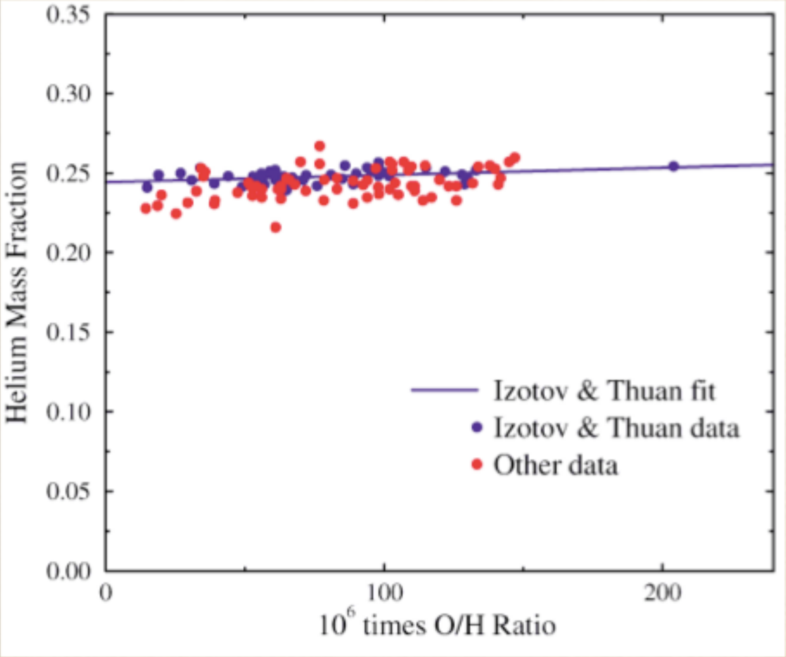
He recombination lines in ionized $H_{II}$ regions in BCG & regression to zero metallicity.

Small statistical error but large systematics

Recent analyses:

Izotov & Thuan 2014

Aver, Olive & Skillmann 2015



# DATA

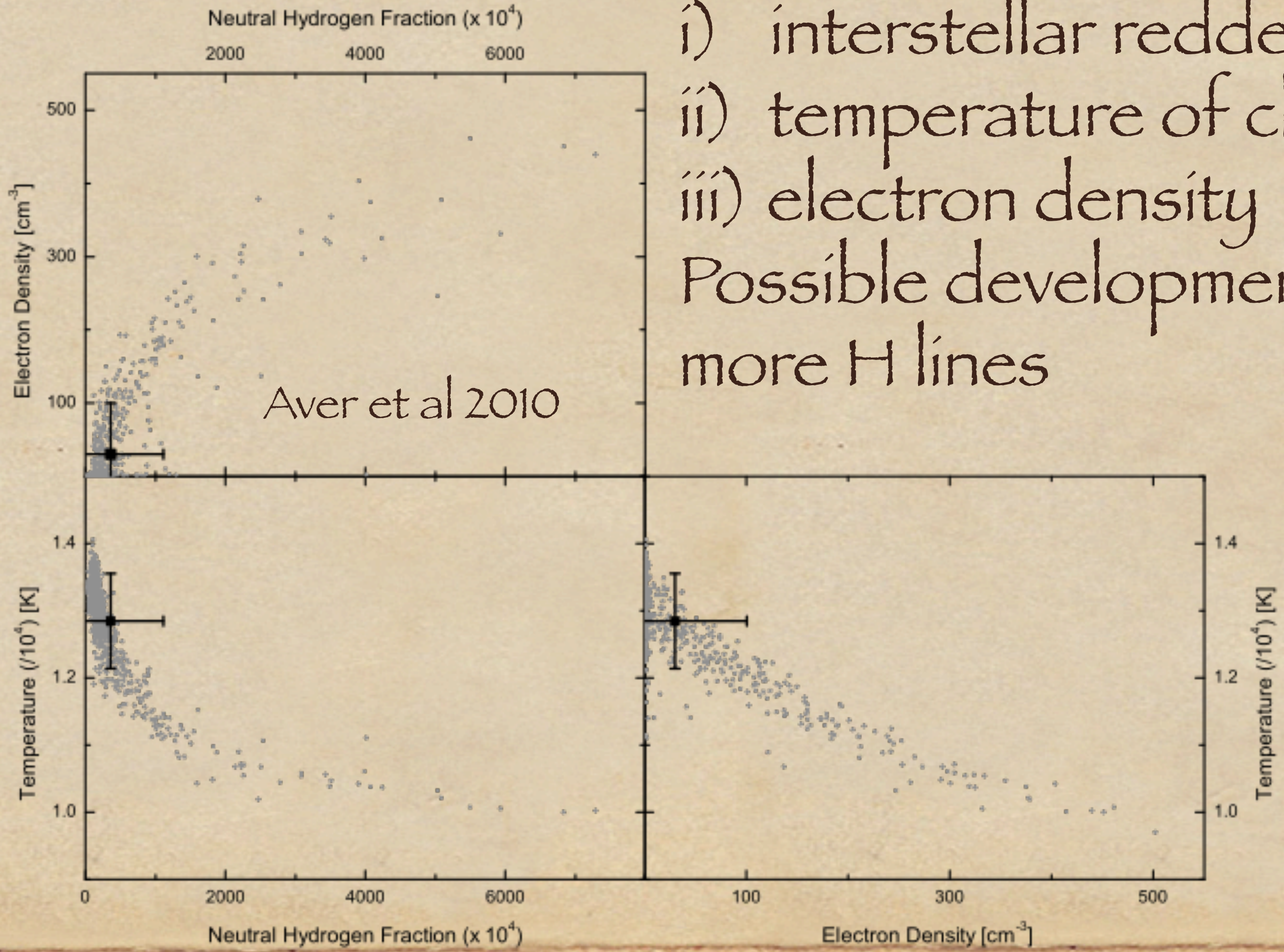
Main sources of systematics:

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

# New recent analysis use also the infrared I λ10830

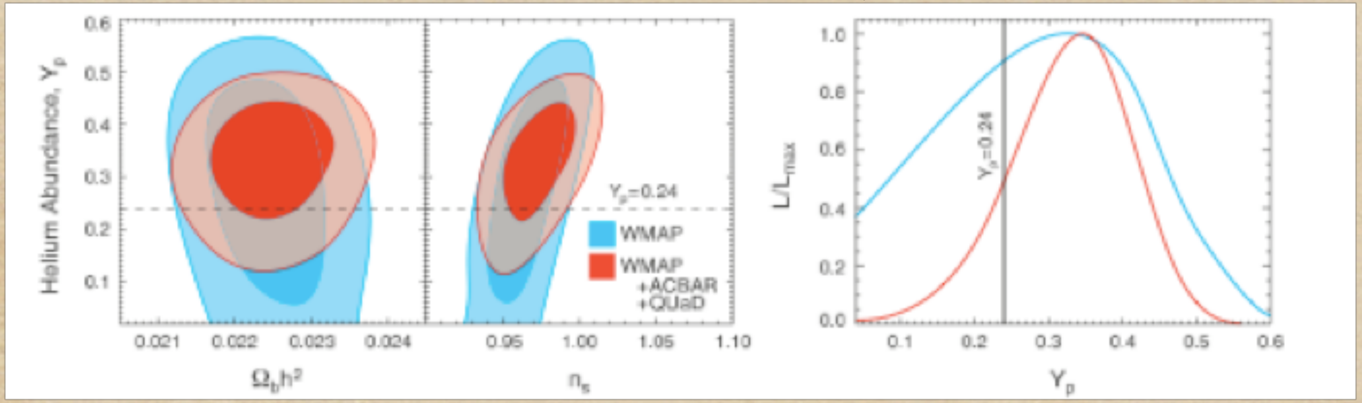
$Y_p = 0.2551 \pm 0.0022$ Izotov et al 2014

$Y_p = 0.2449 \pm 0.0040$ Aver et al 2015

# $^4$He from CMB?

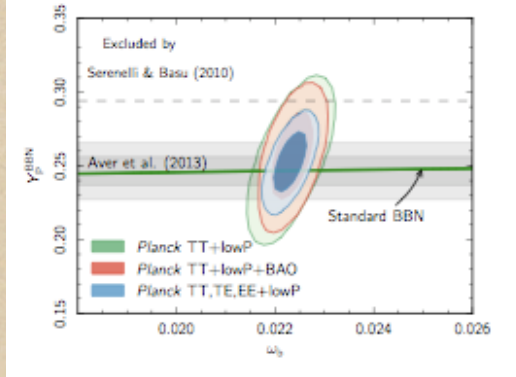
## $^4$He recombines before photon decoupling

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



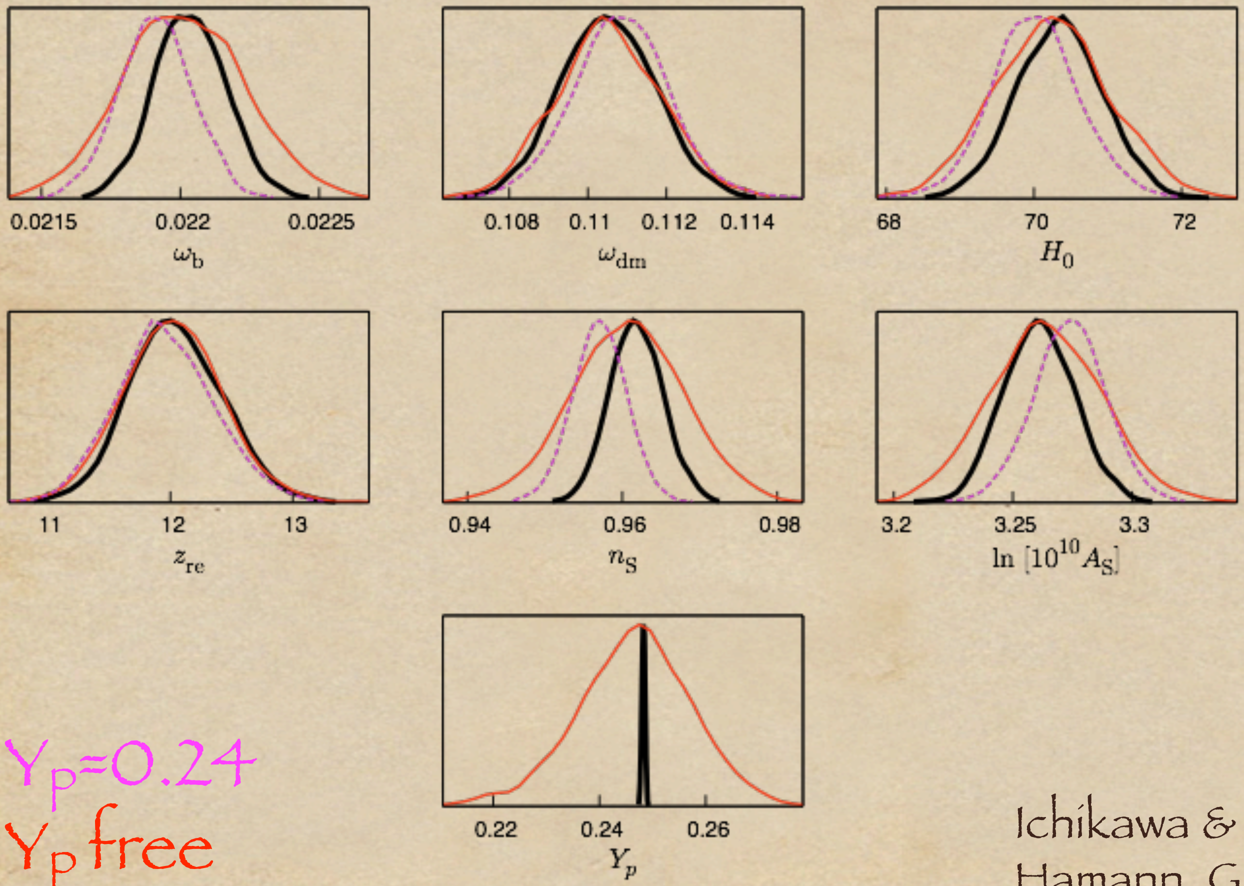
WMAP-7

PLANCK 2015



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

# Wrong $^4$He can bias parameter estimation



$Y_P$=0.24

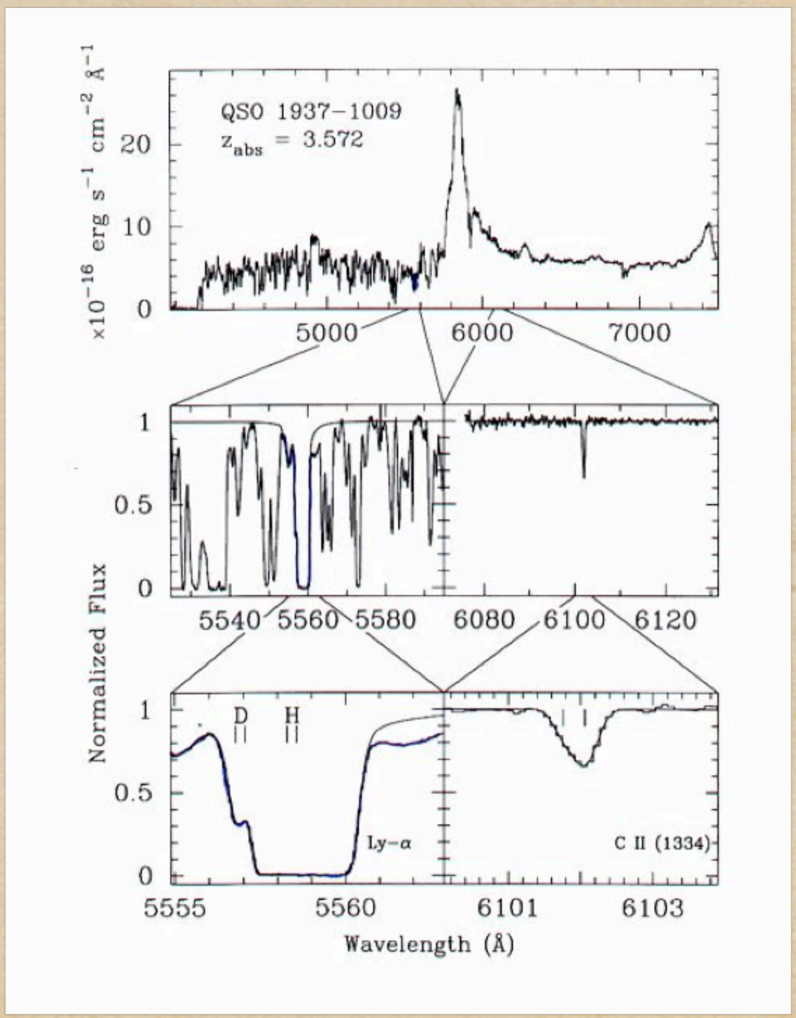
$Y_P$ free

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

Ichikawa & Takahashi 2006

Hamann, G.M. & Lesgourgues 2008

# DATA

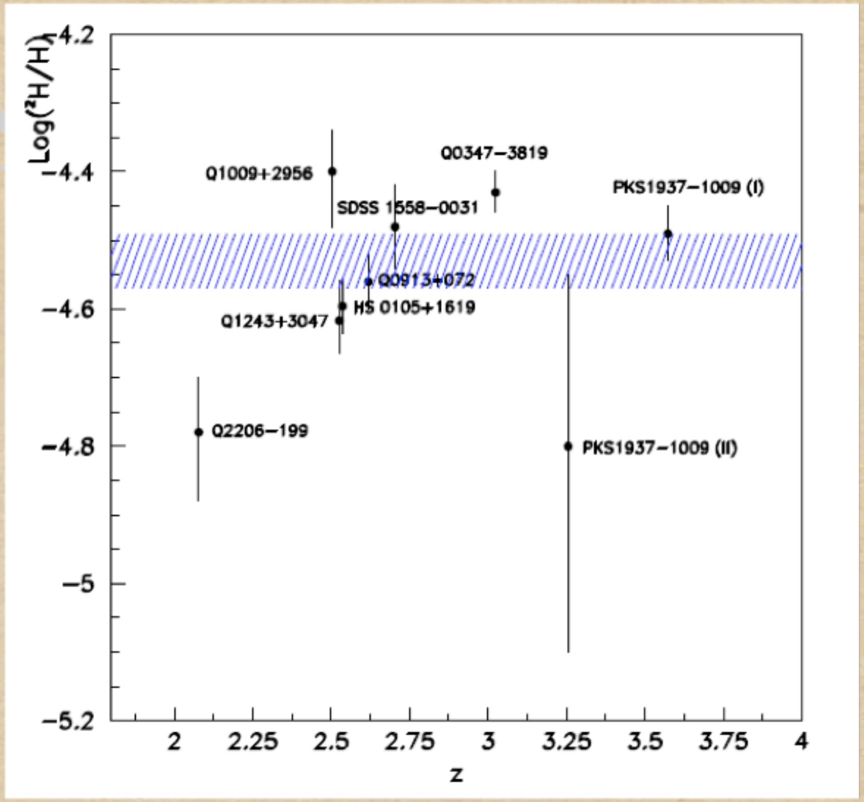


$^2$H measures baryon fraction. Quite good agreement with Planck determination:

$$\Omega_b h^2 = 0.02225 \pm 0.00032$$

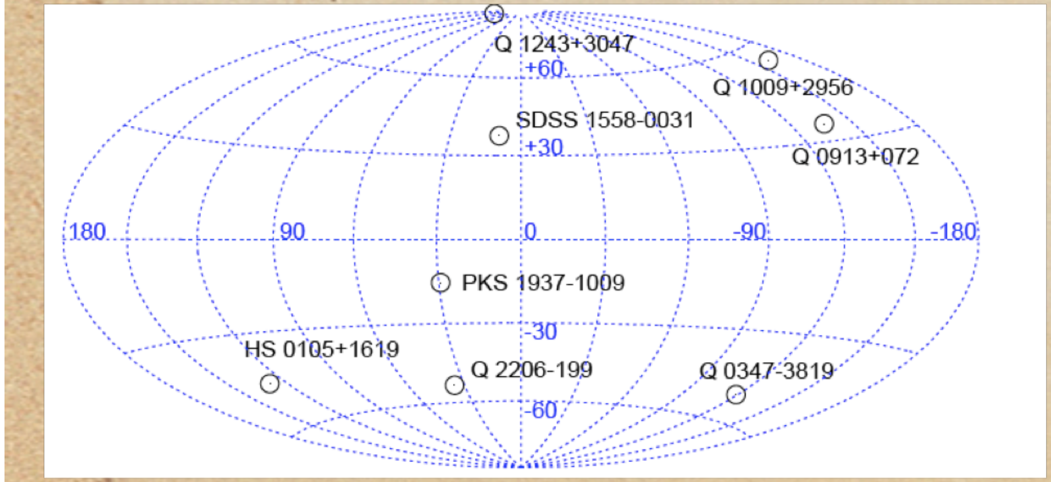
Observations: absorption lines in clouds of light from high redshift background QSO

DA



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

Iocco et al 2009



$^{2}\mathrm{H/H}(10^{-5}) \approx 2.53 \pm 0.04$

Cooke et al, 2014, ApJ

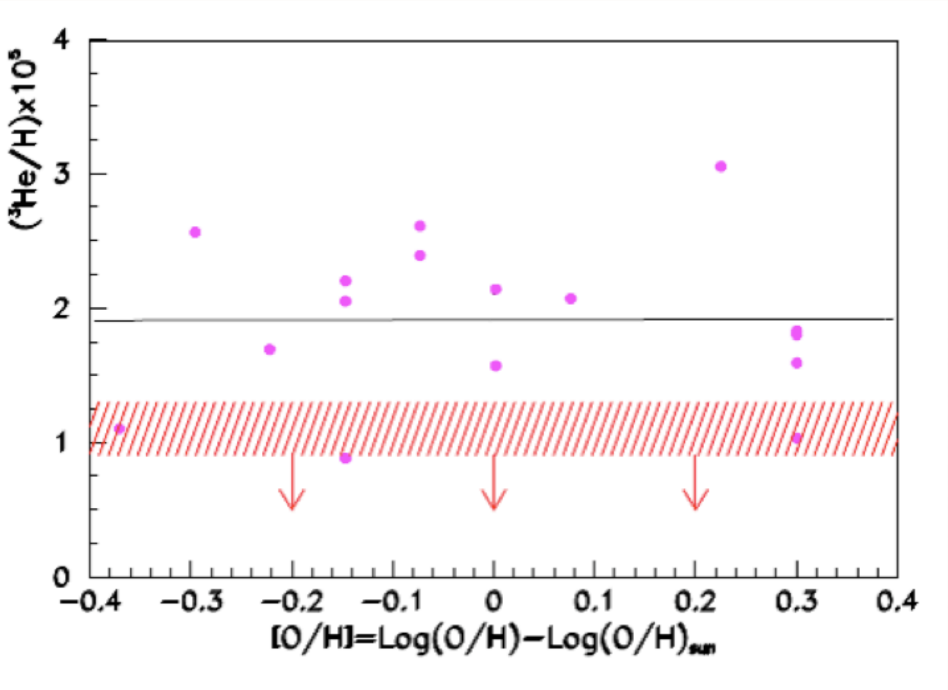
# DATA

$^{3}He$

observed on Earth (nuclear weapons)
observed in the Solar System (Sun): $^{2}H \rightarrow {}^{3}He$
observed in the ISM $^{3}He/H = 0.1$
observed in planetary nebulae and $H_{II}$ regions
outside the solar system ($^{3}He^{+}$ spin flip 3.46 cm wavelength band)

# DATA

No clear evidence for dependence upon metallicity

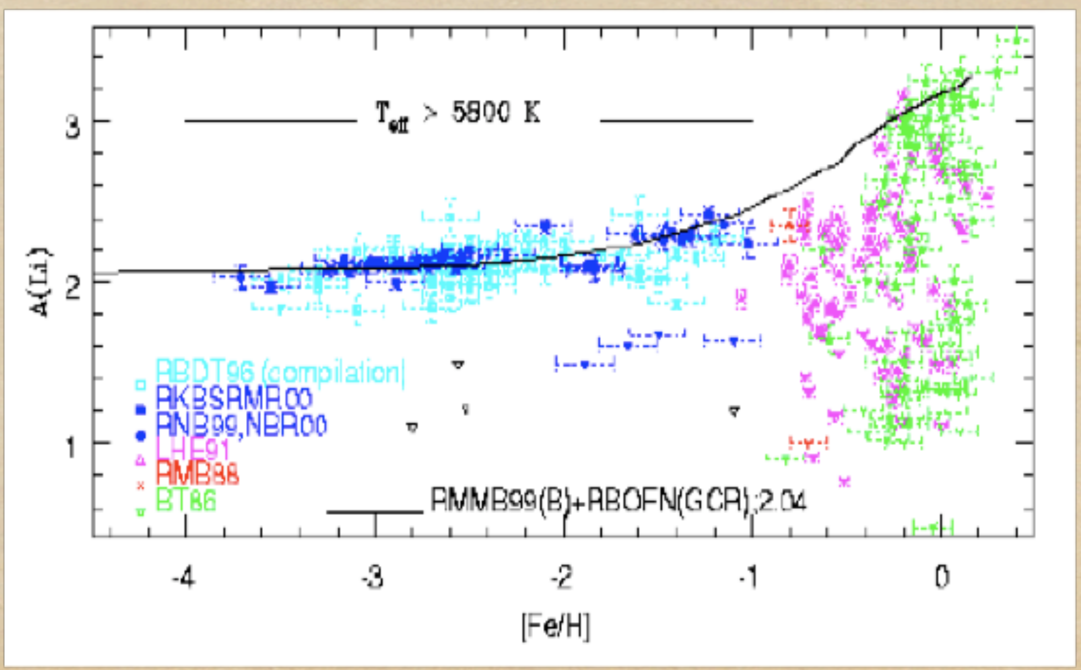


Bania et al 2002

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

# DATA

$^7$Li (and $^6$Li) still a puzzle. Spite plateau in metal poor dwarfs 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+PLANCK 2015 baryon density and ${}^3$He upper bound

# DATA

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

# RESULTS

## Standard scenario

# DATA

## MINIMAL SCENARIO: ALL FIXED!

$\Omega_b h^2 = 0.02225 \pm 0.00032$

$Y_p = 0.2467 \pm 0.0001 \pm 0.0003$ PLANCK 2015

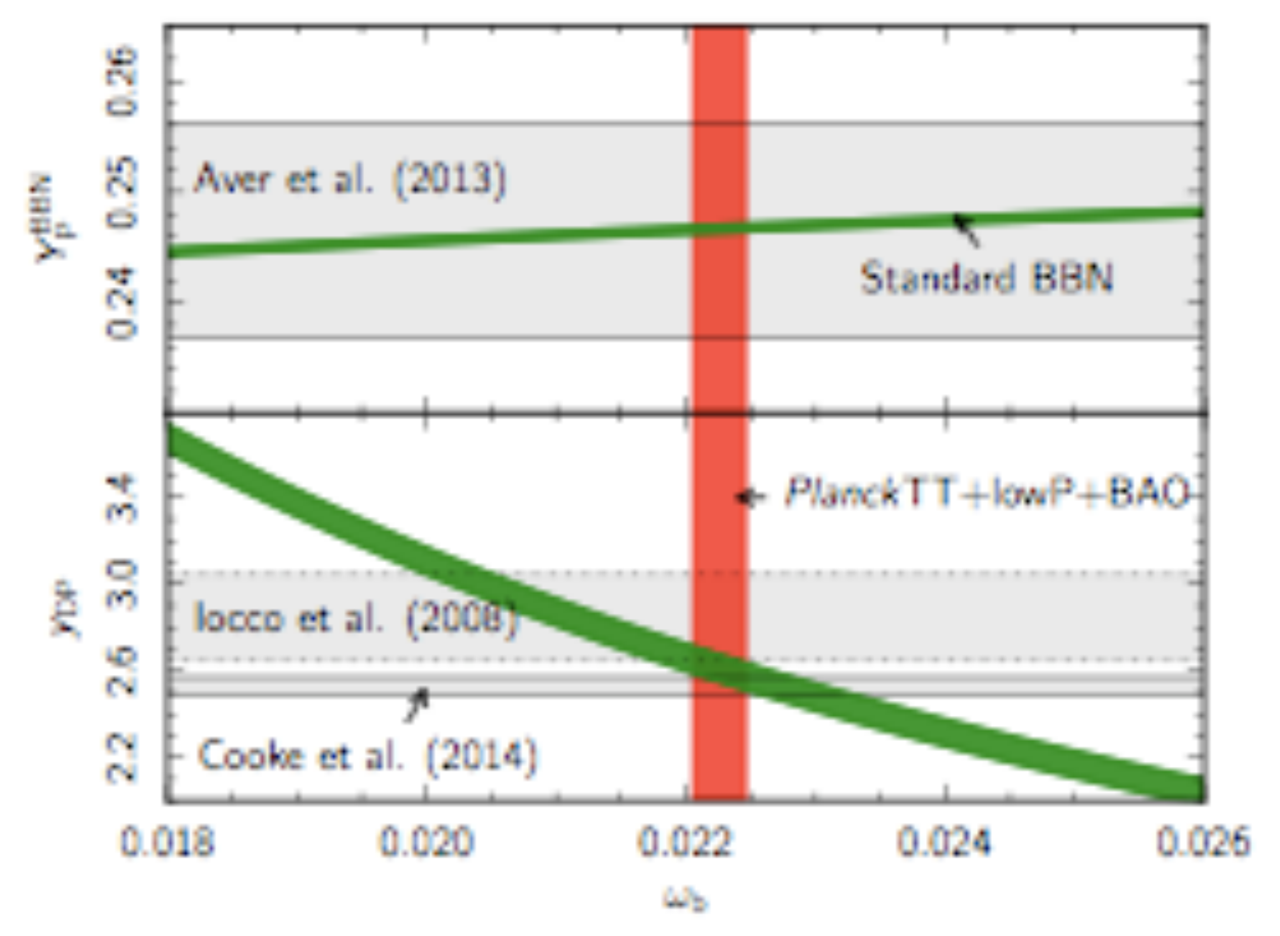
$^2H/H = 2.60 \pm 0.03 \pm 0.07$

EXP:

$Y_p = 0.2551 \pm 0.0022$ !!!

$Y_p = 0.2449 \pm 0.0040$ !

$^2H/H\,(10^{-5}) = 2.53 \pm 0.04$ !!


$Y_P^{BBN}$
0.24
0.25
0.26
Aver et al. (2013)
Standard BBN
$y_{DP}$
2.2
2.6
3.0
3.4
Planck TT+lowP+BAO
Iocco et al. (2008)
Cooke et al. (2014)
0.018
0.020
0.022
0.024
0.026
$\omega_b$

PLANCK 2015

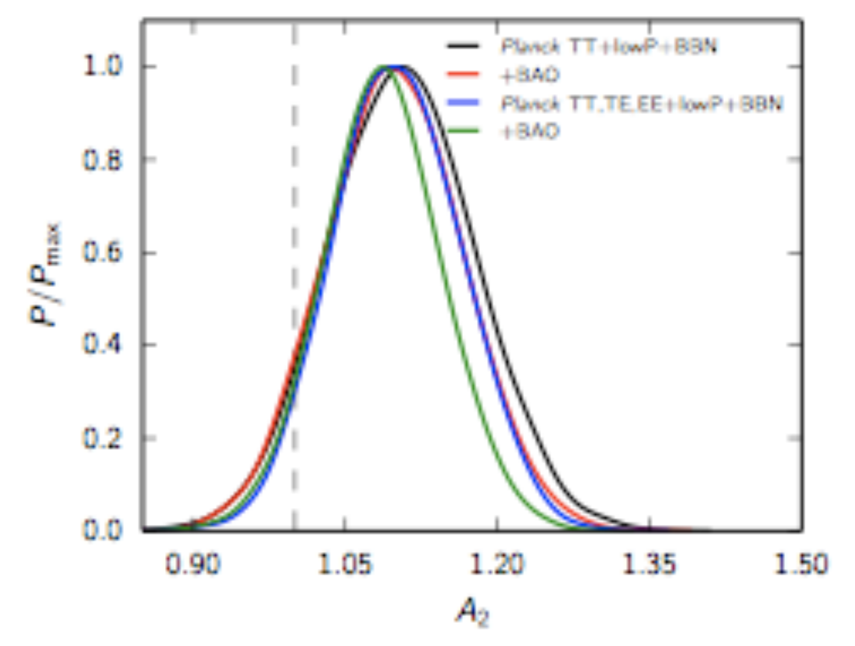
Discrepancies at worst 3 σ :

✓ New physics?

✓ systematics/uncertainties

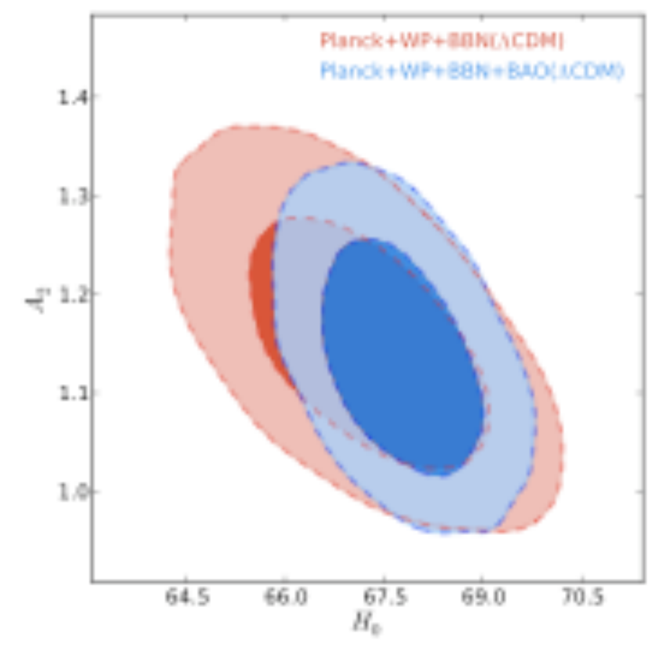
DATA

Example: increasing $d(p,\gamma)^3He$ (as from by ab initio calculations) deuterium decreases, better agreement with Planck $\Omega_b h^2$ (Di Valentino et al 2014, Planck 2015)



PLANCK 2015

$$A_2 = R(d,p)/R^{exp}(d,p)$$



$$A_2 = R^{th}(d,p)/R^{exp}(d,p) = 1.17$$

Marcucci et al. 2016

# RESULTS

## Exotic scenarios

# 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 $\nu$ decoupling value for $T_\nu / T_\gamma$

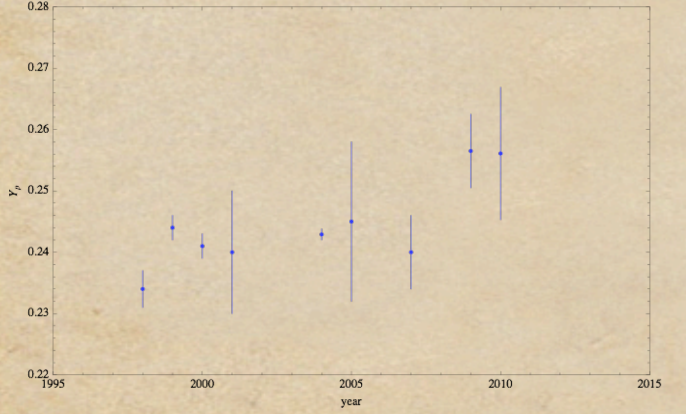
CMB and BBN scrutinize different "mass" scales!

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



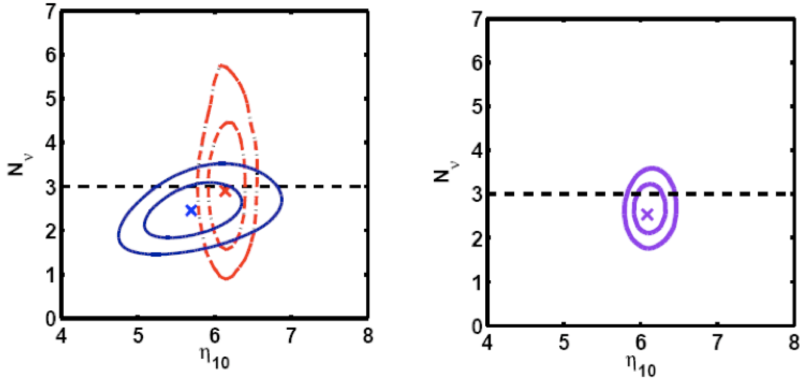


Figure 4:
(Left) In blue (solid), the 68% and 95% contours in the $N_\nu$ - $\eta_{10}$ plane derived from a comparison of the observationally-inferred and BBN-predicted primordial abundances of D and $^4$He. In red (dashed), the 68% and 95% contours derived from the combined WMAP 5-year data, small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

# 2-3 σ claim ! (Izotov & Thuan 2010,2014)

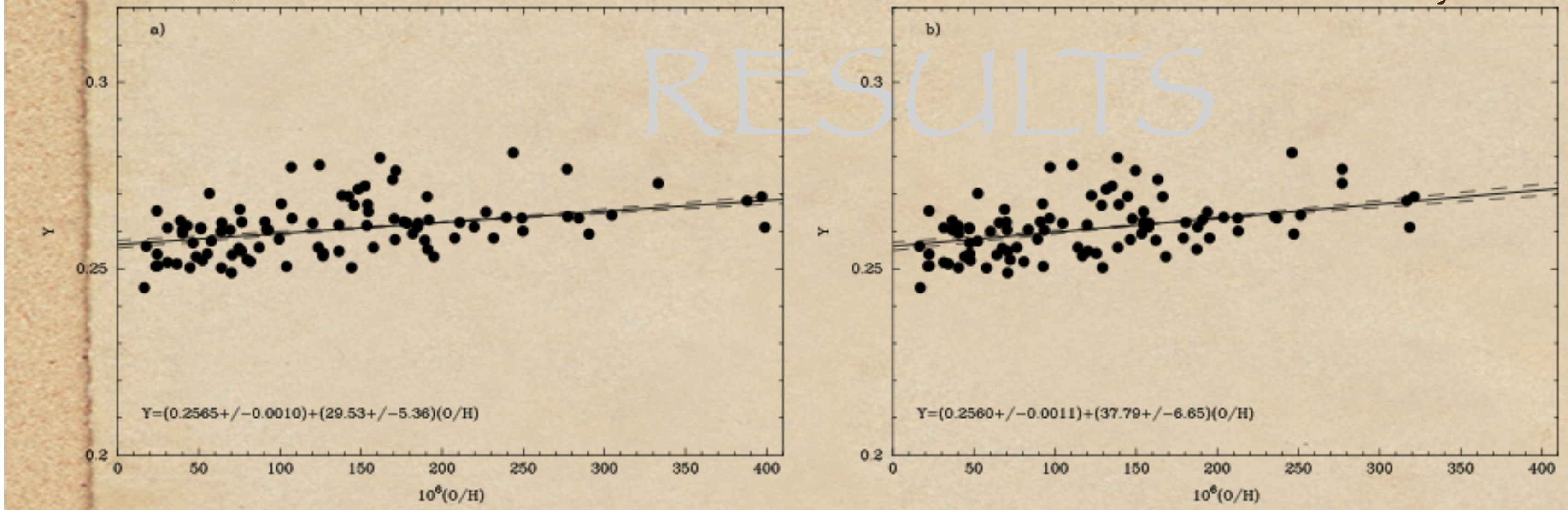
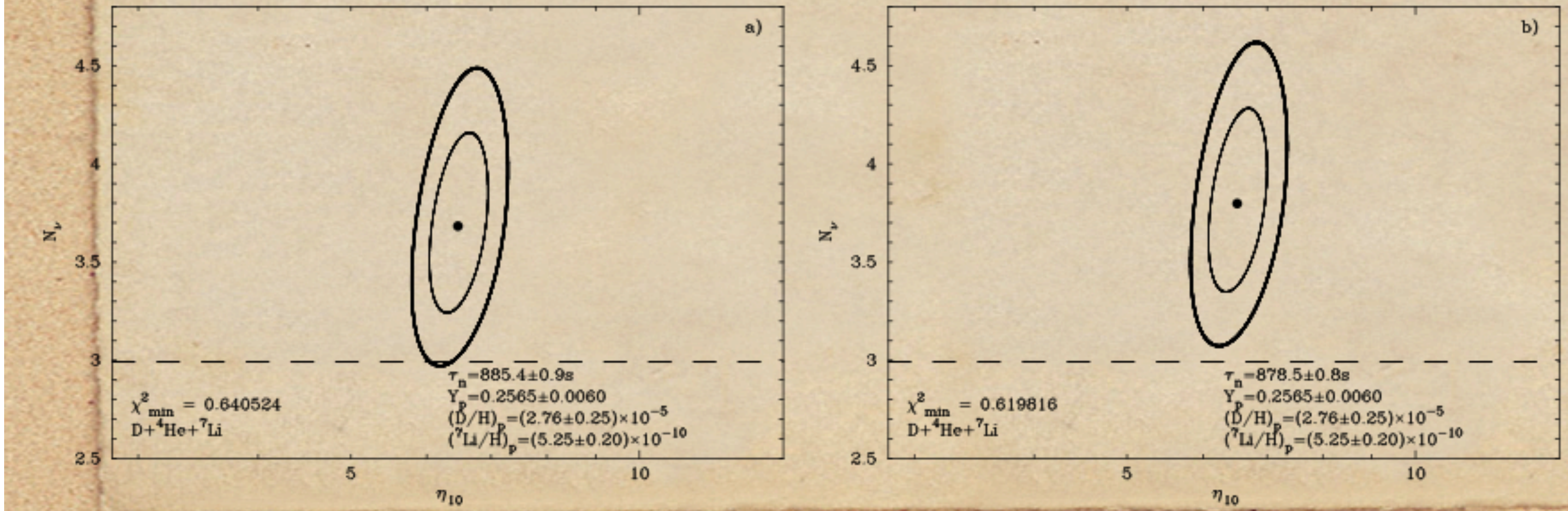


FIG. 1.— Linear regressions of the helium mass fraction $Y$ vs. oxygen abundance for H II regions in the HeBCD sample. The $Y$s are derived with the He I emissivities from Porter et al. (2005). The electron temperature $T_e(\mathrm{He}^+)$ is varied in the range $(0.95-1)\times T_e(\mathrm{O\ III})$.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



Izotov et al 2014

$N_{eff} = 3.7 \pm 0.2$

But using Aver et al. 2015 (larger error)

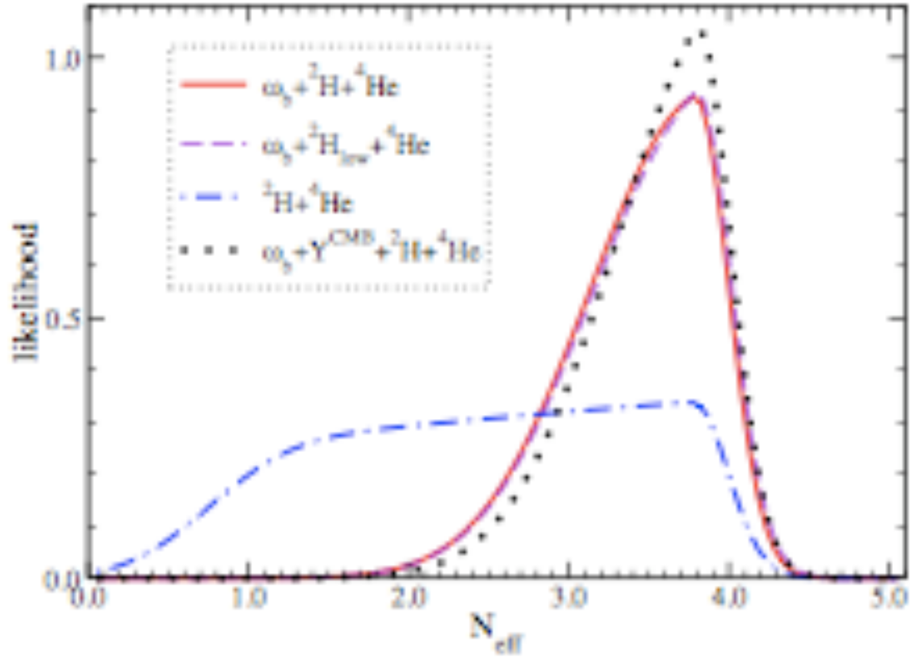
$N_{eff} = 2.9 \pm 0.3$

Planck 2015: $N_{eff} = 3.04 \pm 0.18$ !!

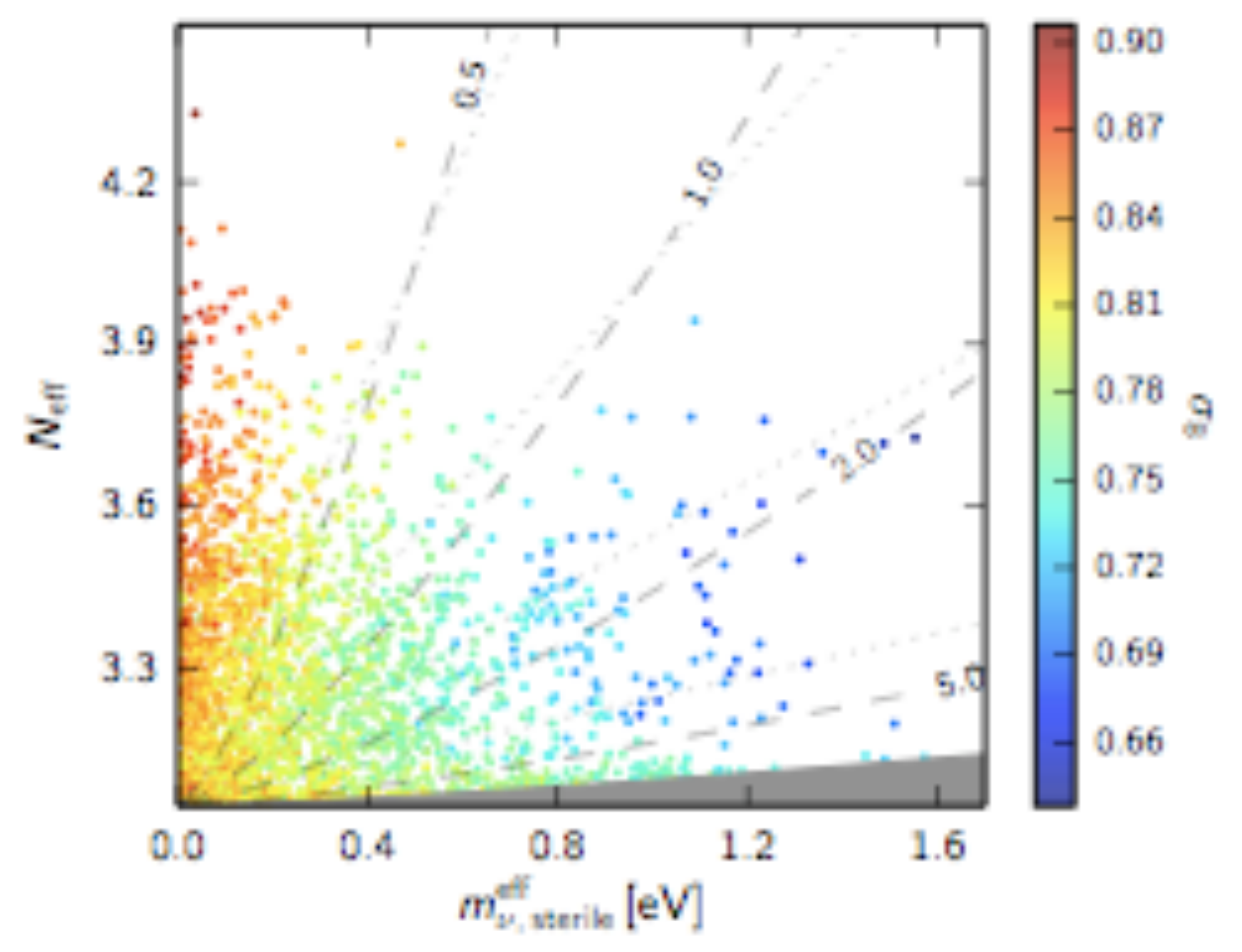
Remember: CMB and BBN
scrutinize different “mass” scales!

# Bounds with a conservative $^4$He limit

2 extra relativistic states excluded if well thermalized

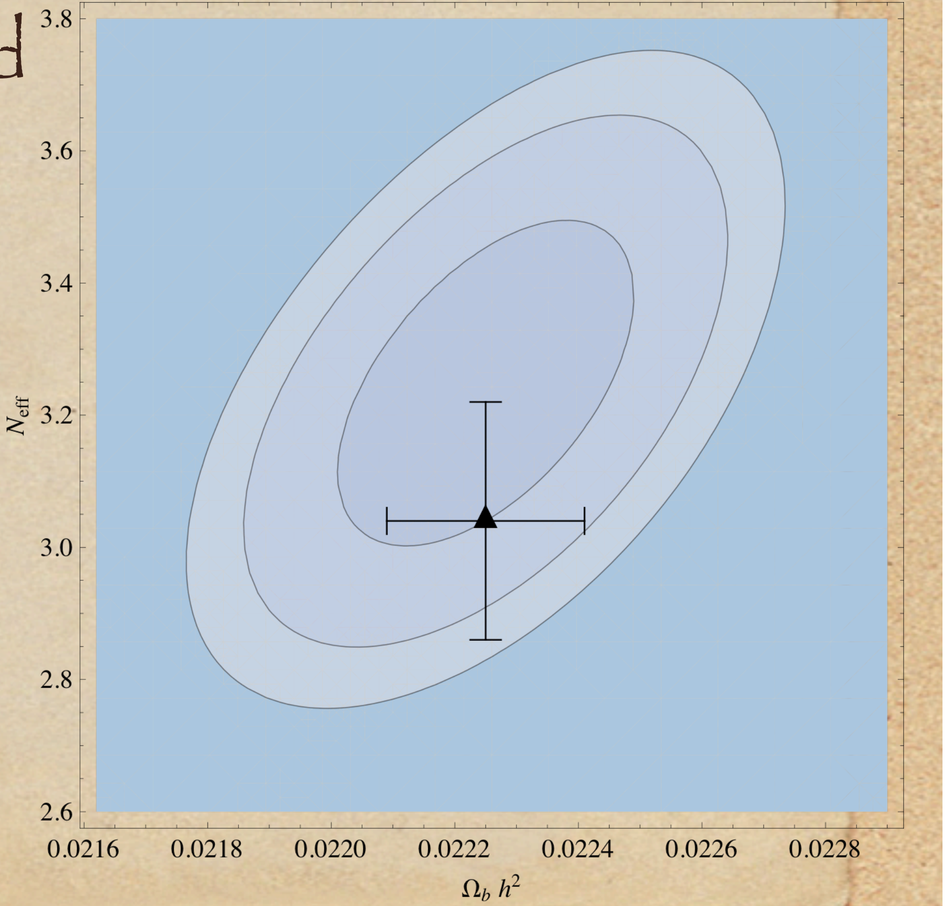


# Planck results also depends upon neutrino masses and $\sigma_8$



# Deuterium constraint: crucial the $d(p,\gamma)^3He$ !

Present data fit (Adelberger et al) leads to a slightly deuterium overproduction which might be compensated by a smaller expansion rate ($N_{eff}$=2.84)



Ab initio calculation gives a larger cross section and lower deuterium yield!
In this case better a larger expansion rate ($N_{eff}$=3.2)

# What could it be this putative extra radiation?

## Sterile neutrinos?

Succesfull picture of 3-active neutrino mixing in terms of 2 mass differences and 3 mixing angles.

Few parameters describe a lot of data: solar $\nu$ flux, atmospheric $\nu$'s, accelerator $\nu$ beams!

Yet, few anomalies (2-3 $\sigma$) :

1) LSND-MiniBooNE (short baseline exp's);
2) Reactor anomaly;
3) Gallium anomaly.

LSND+ MiniBooNE: evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

MiniBooNE: excess of $\nu_\mu \rightarrow \nu_e$

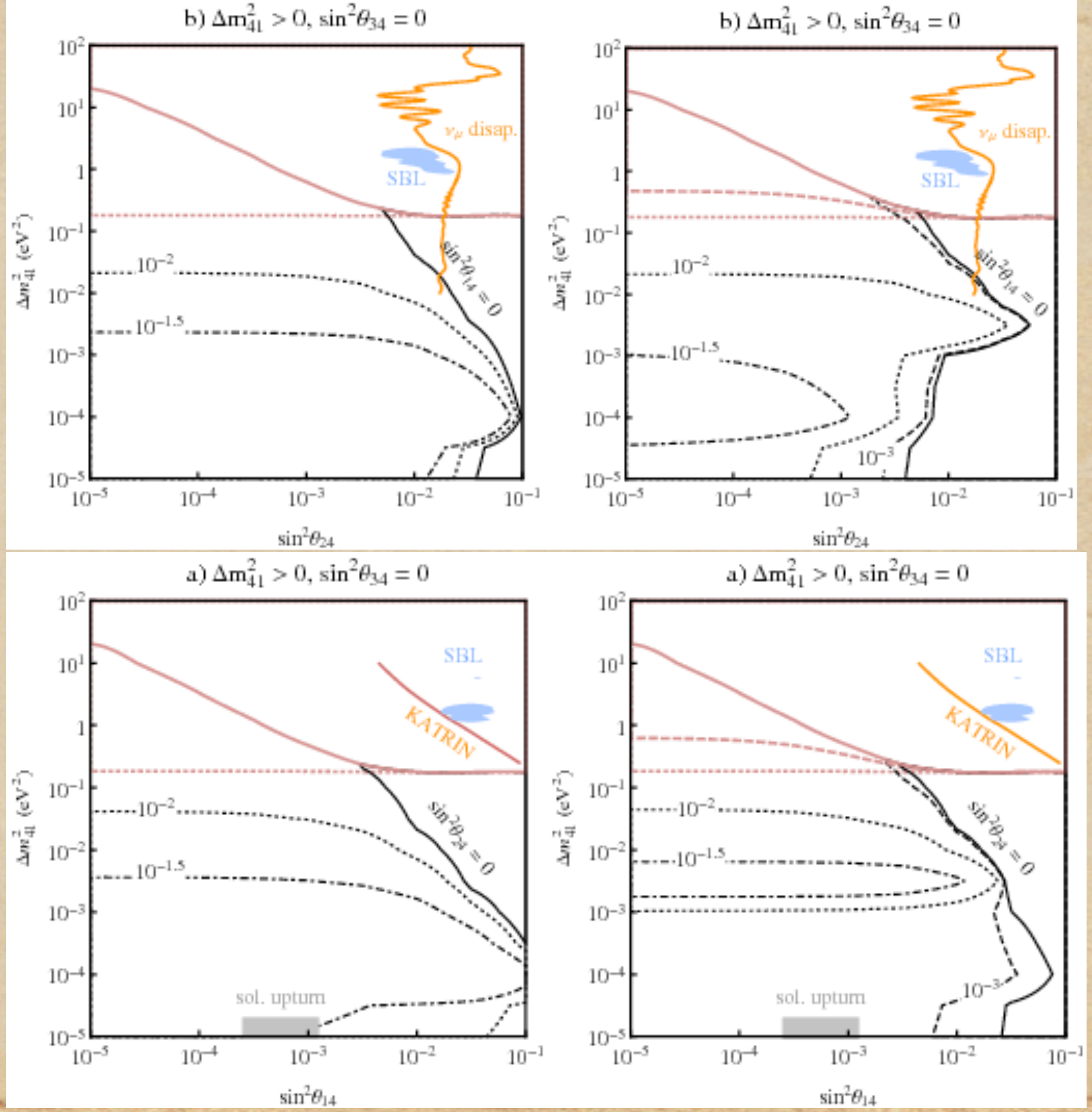
Interpretation: order 1 eV massive extra sterile neutrino with large mixing angle

$$\Delta m^2 \approx \mathrm{eV}^2$$
$$\sin^2 2\theta \approx 10^{-3} - 1$$

$$P_{e\mu} = \sin^2 2\theta \, \sin^2(1.27\, \Delta m^2\, L/E)$$

(L in meters, E in MeV)

# But for such large mixing angles sterile neutrino too much produced ($N_{eff} = 1$)



The standard case, after Planck 2013

$N_{eff} < 3.30 \pm 0.27$
$m_s < 0.38$ eV

New Planck analysis even stronger!

(Planck XIII 2015)

$N_{eff} = 3.04 \pm 0.22$
$m_s < 0.38$ eV

# Conclusions

- BBN theory quite accurate, at % level (or better) for main nuclides;
- Problem: systematics in $^4$He measurements;
- d(p, )$^3$He should be accurately measured in the BBN energy range (30 – 300 keV)
- 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

Maybe still Planck,… (and Katrin) result will tell us more in few years!

# Backup slides

# RESULTS

## The Lepton number of the Universe

Neutrino chemical potentials change the expansion rate parameter H (larger ν energy density);
$\nu_e$ chemical potential changes the n-p chemical equilibrium (weak rates);

Kang & Steigman 1992

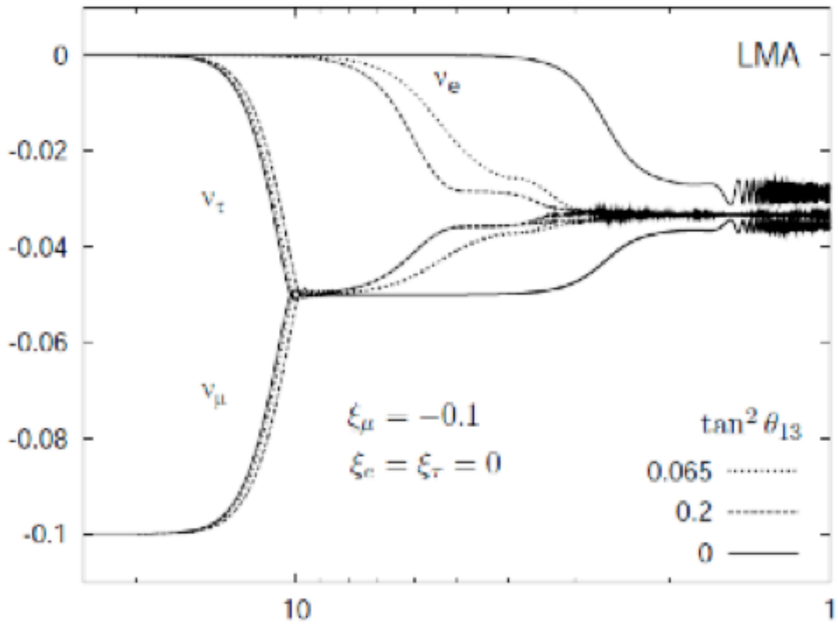
ν's oscillates in flavor space: before BBN $\nu_e$, $\nu_\mu$ & $\nu_\tau$ mix their chemical potential.

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

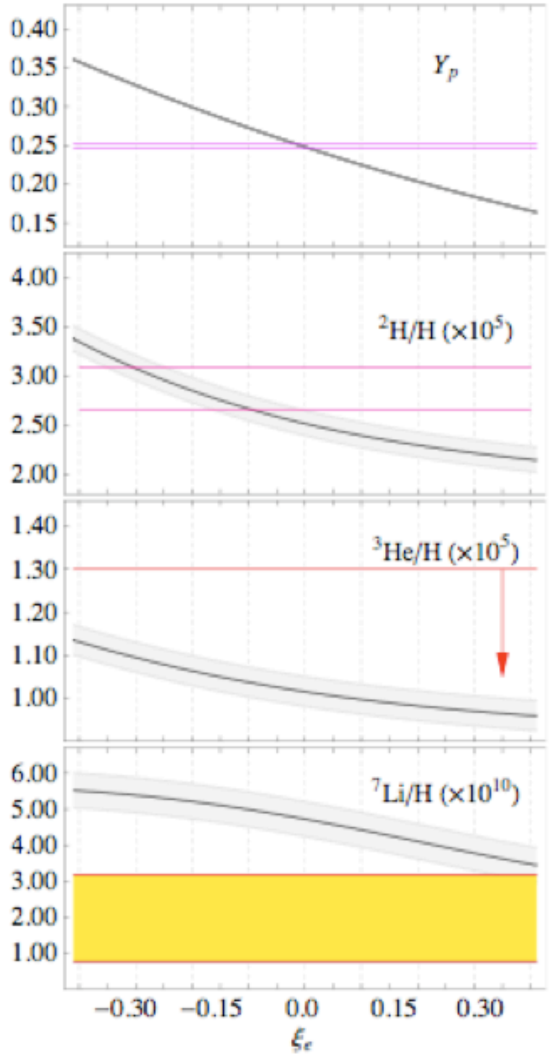
Dolgov et al 2002



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

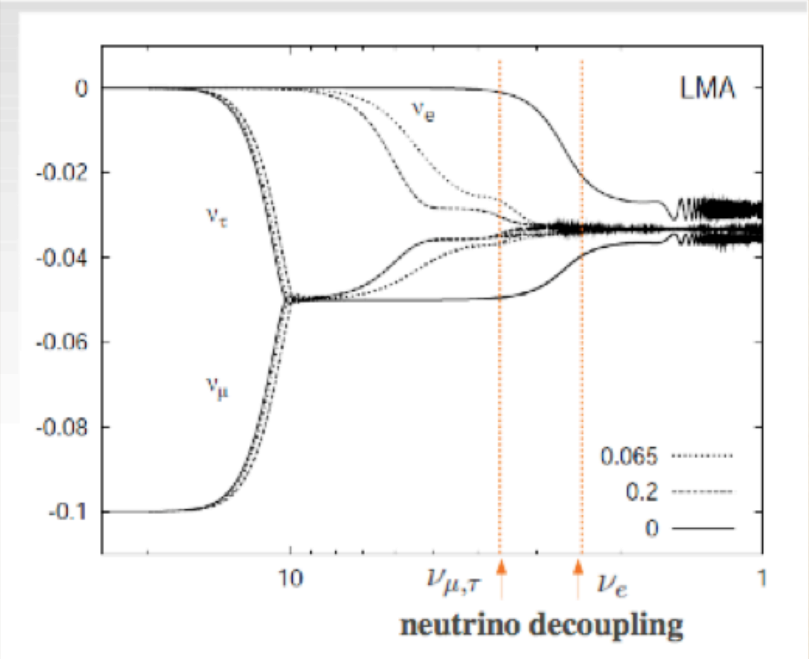
*"...the BBN limit on the $\nu_e$ degeneracy parameter,* ***$|\xi_\nu| < 0.07$, now applies to all flavors."***

Iocco et al 2009



# RESULTS

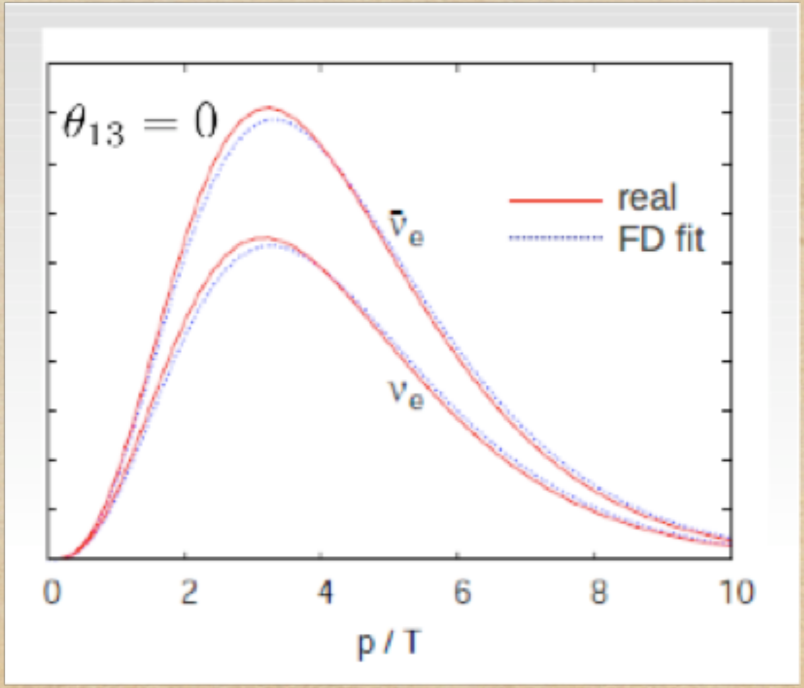
## However...

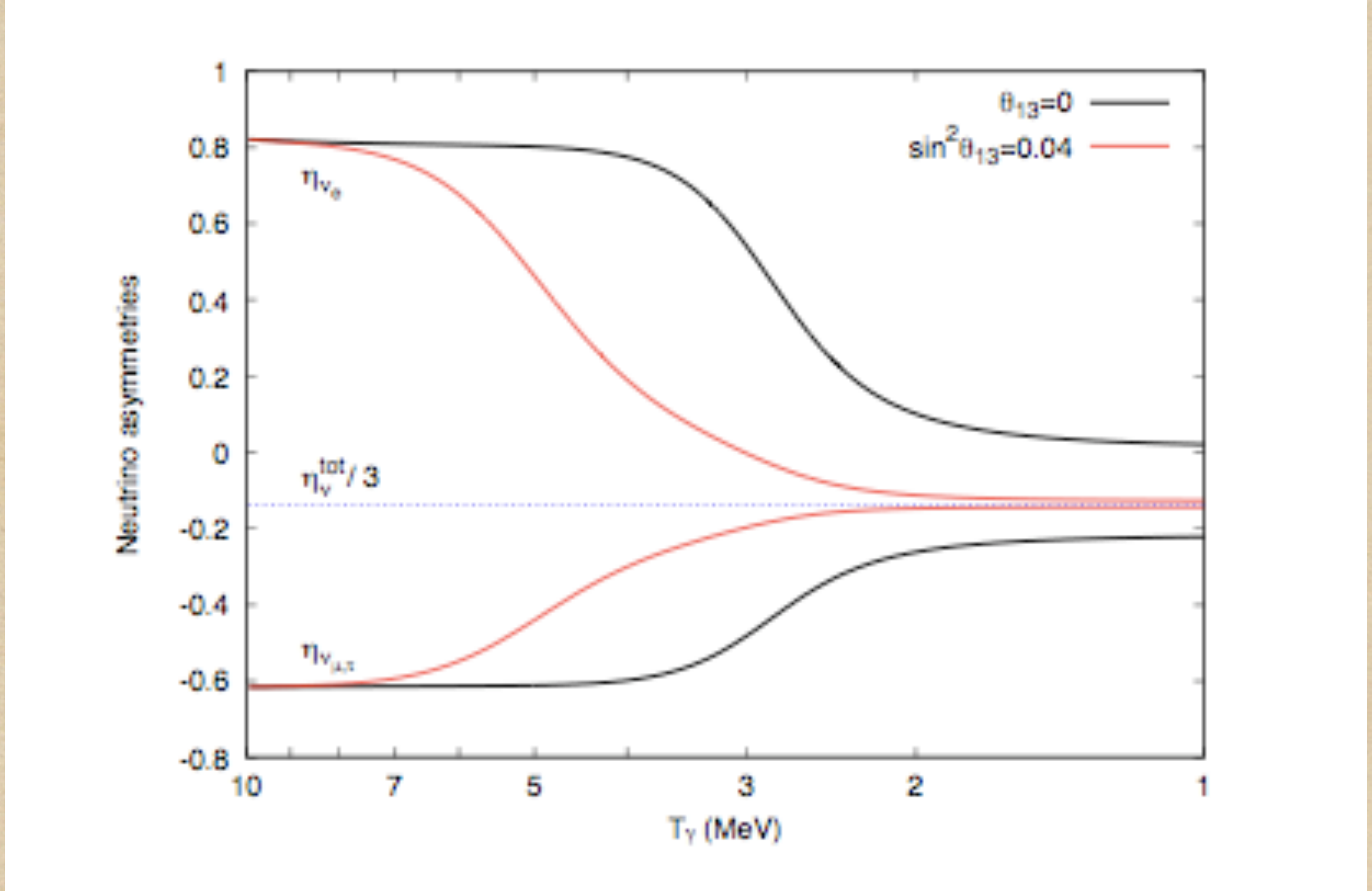


S. Pastor et al.,Phys. Rev. Lett. **102**, 241302 (2009)

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

Not a perfect FD (in general)!

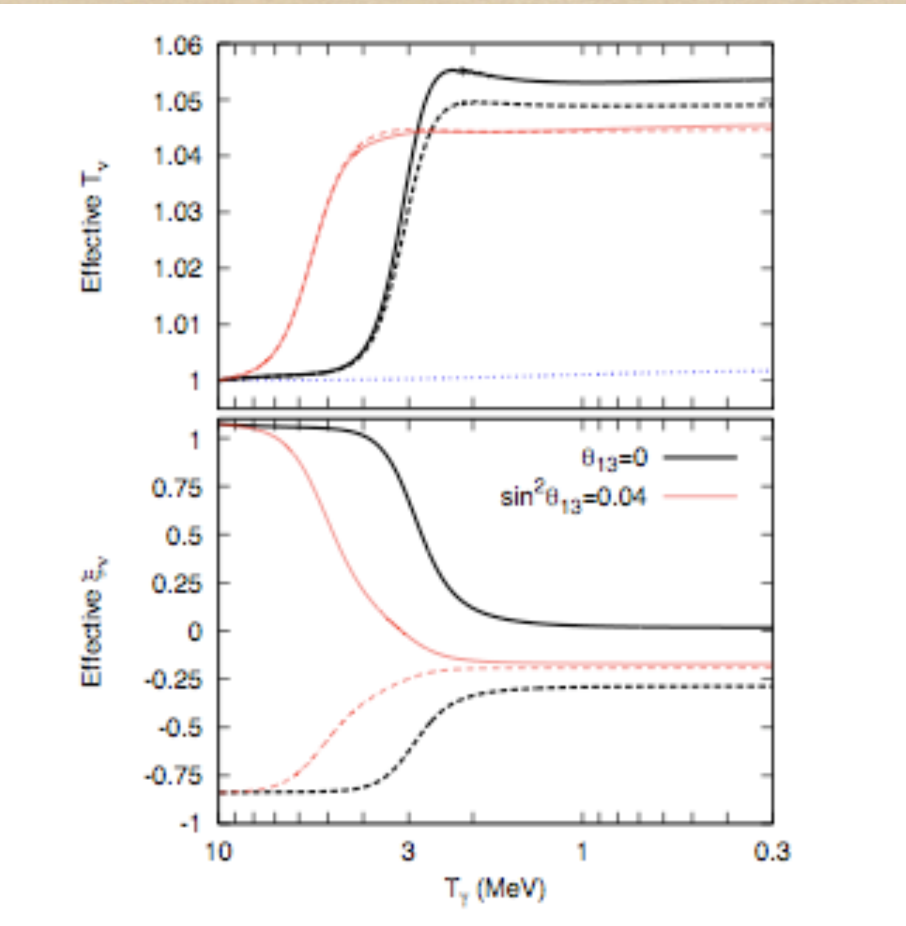


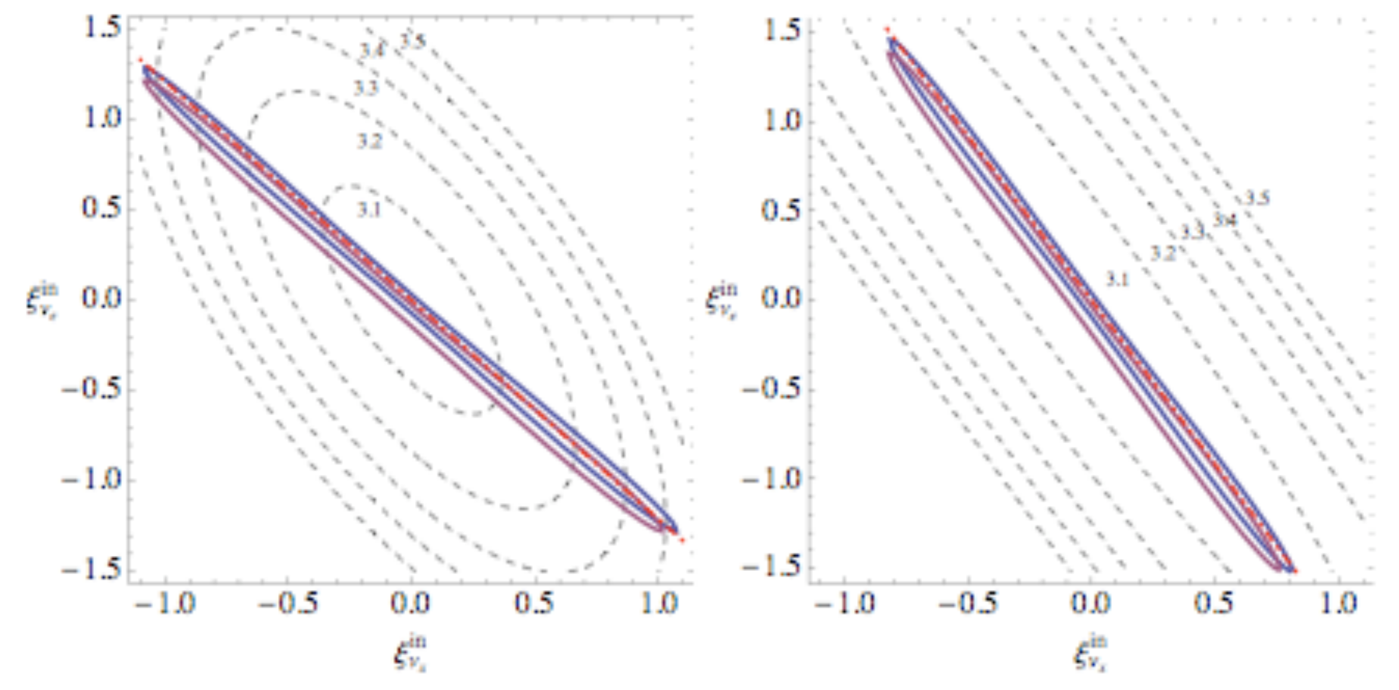


We must follow ν distribution through BBN dynamics

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

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





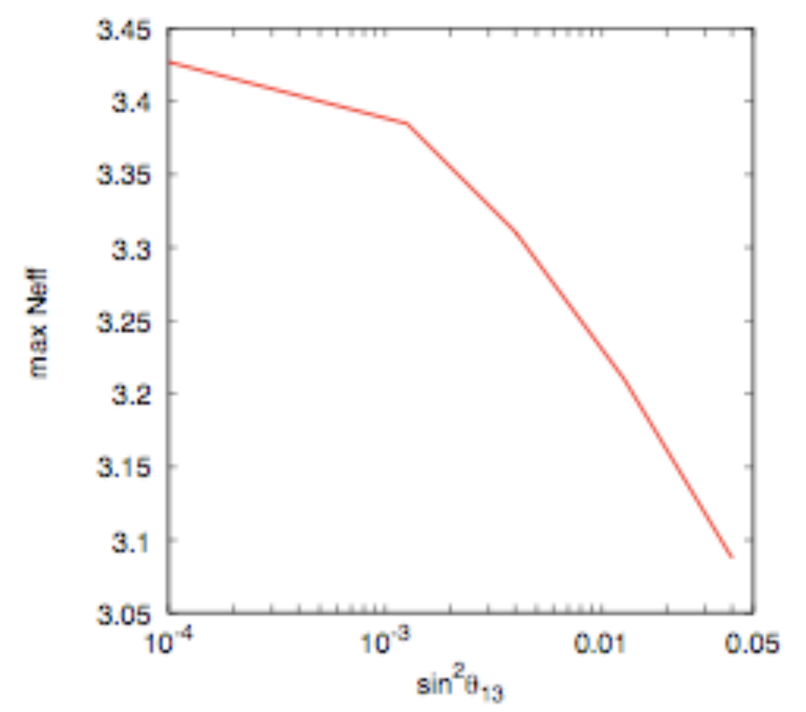
$\sin^2\theta_{13}=0$ $\sin^2\theta_{13}=0.04$

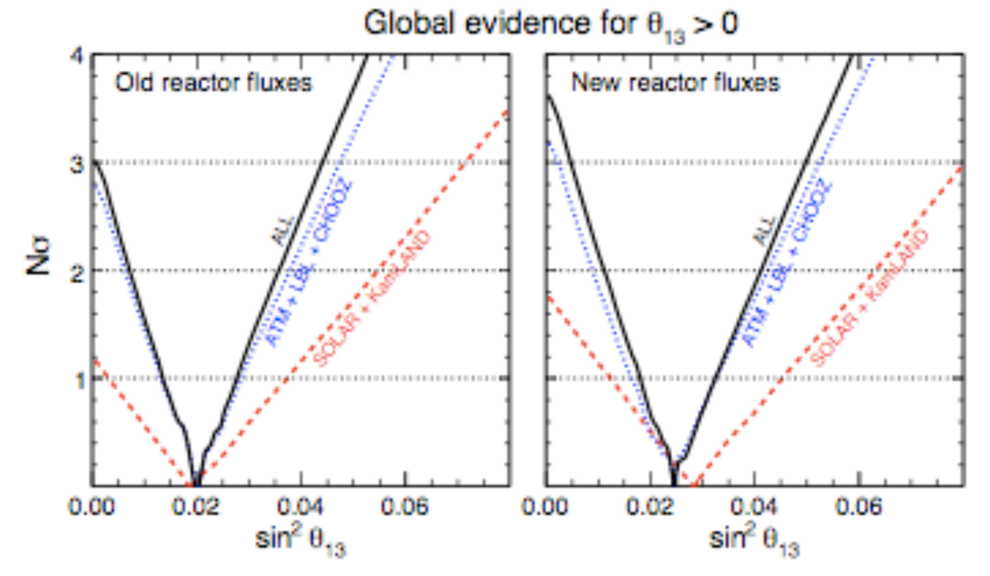
# Dependence on $\theta_{13}$

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

# Maximal $N_{eff}$ vs $\theta_{13}$

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

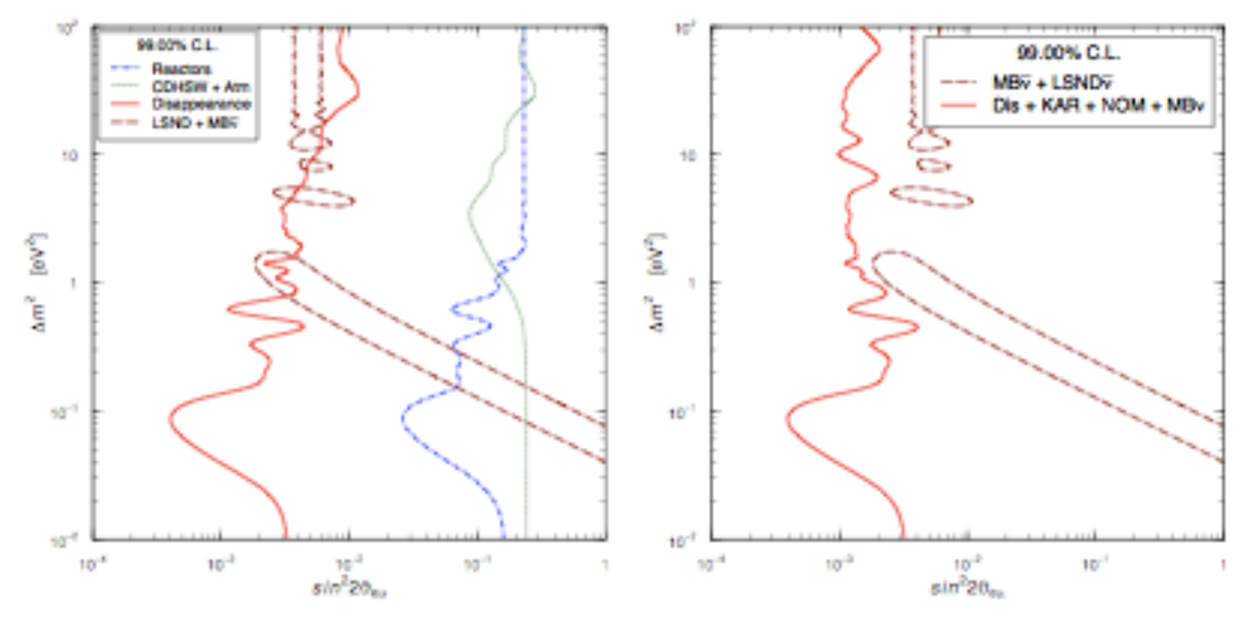




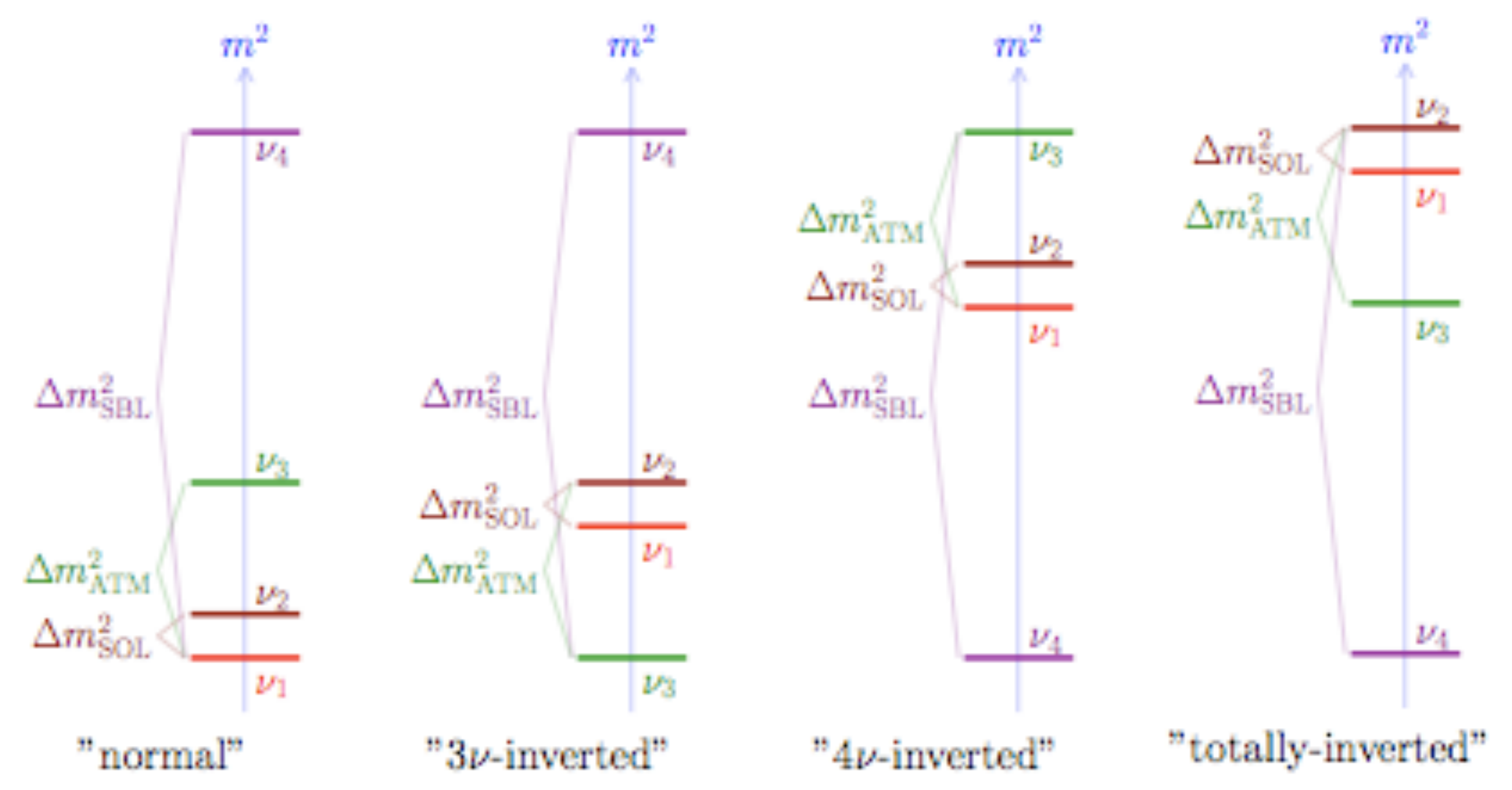
# After T2K results

Fogli et al '11

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



C. Giunti, '11



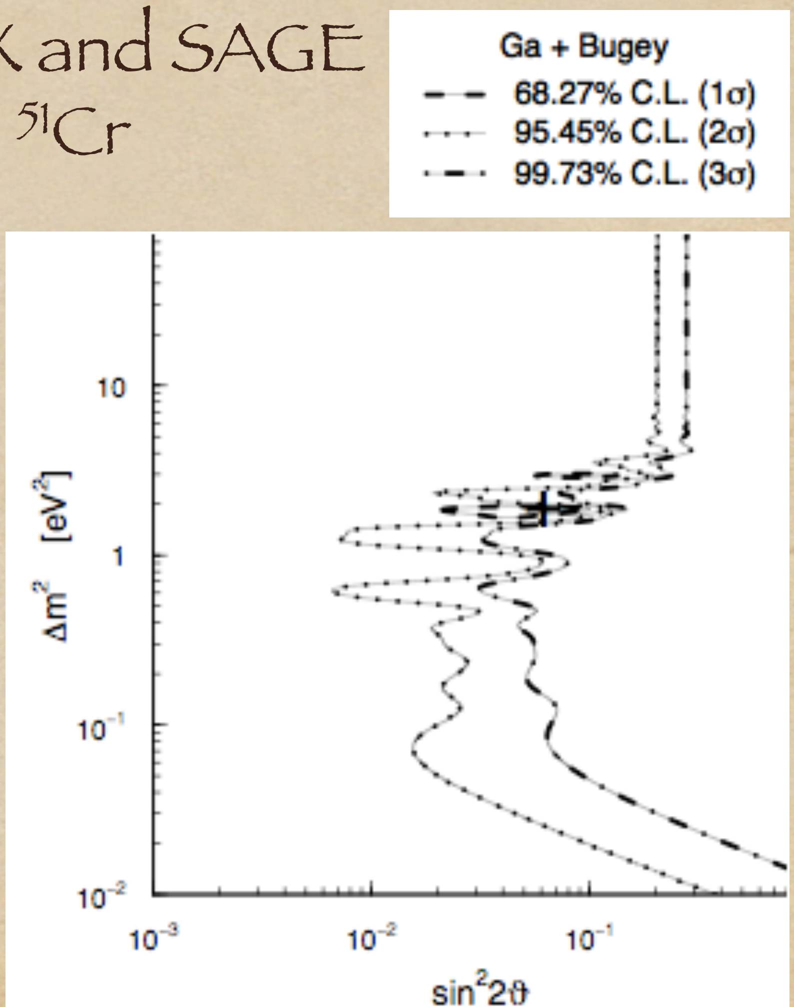
3+2 schemes?

Disfavoured by cosmology

# Neutrino anomalies and sterile neutrinos

Chemical experiments GALLEX and SAGE tested with intense $\nu_e$ flux from $^{51}Cr$ and $^{37}Ar$, detected by

$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$



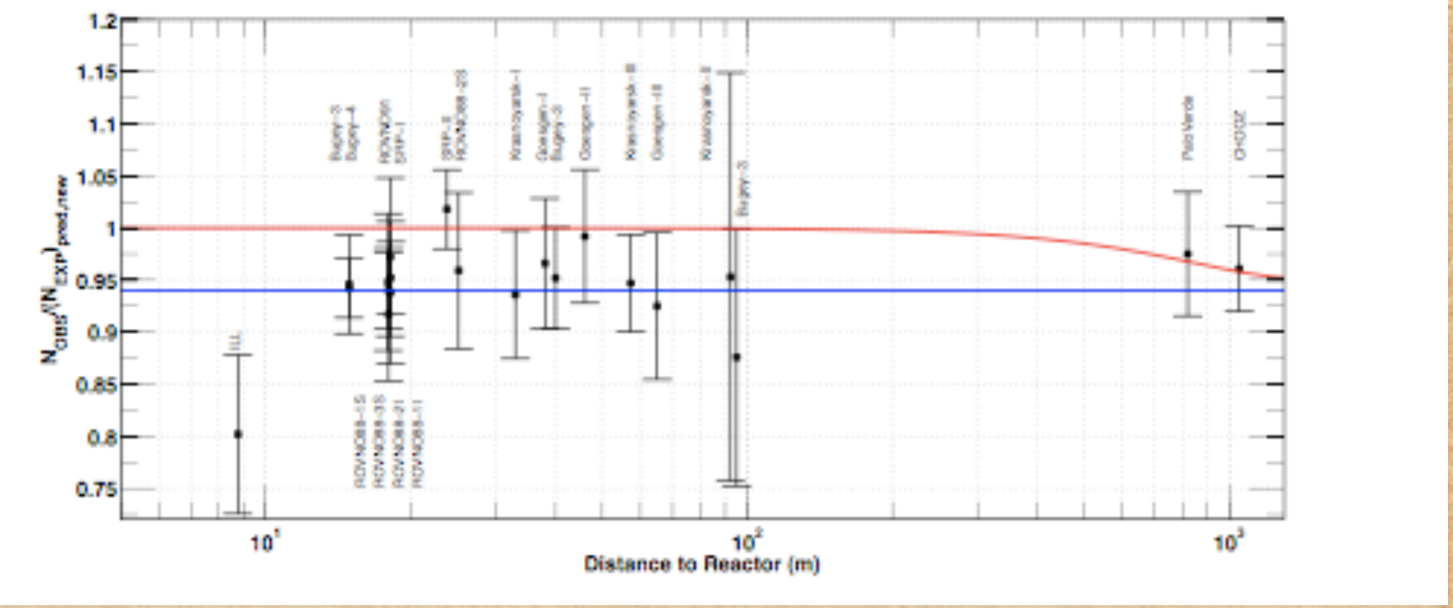
Exp/Th ≈0.88 ±0.05
3+1 mixing analysis
weak evidence

See e.g.Acero et al 0711.4222

# Neutrino anomalies and sterile neutrinos

(anti) neutrinos from nuclear reactors: ILL-Grenoble, Goesgen, Rovno, Krasnoyarsk, Savannah River, Bugey, observed at short baselines (< 100 m). New calculation of initial neutrino flux results in a small increase (3%), leading to a few percent deficit

Exp/Th = 0.943 ± 0.023



See 1101.2755