# BBN and sterile neutrinos: A mini-review

F. L. Villante – Univ. AQ and INFN-LNGS

# OUTLINE

- The physics of BBN

- Active-Sterile oscillations in early universe

- Is there evidence for non standard physics from BBN?

# The physics of BBN

The abundances of $^4$He, D, $^3$He, $^7$Li produced by BBN depends on the following quantities:

- Baryon density

$$\eta \equiv \frac{n_B}{n_\gamma}$$

$$\Omega_B h^2 = 3.7 \times 10^7 \eta$$

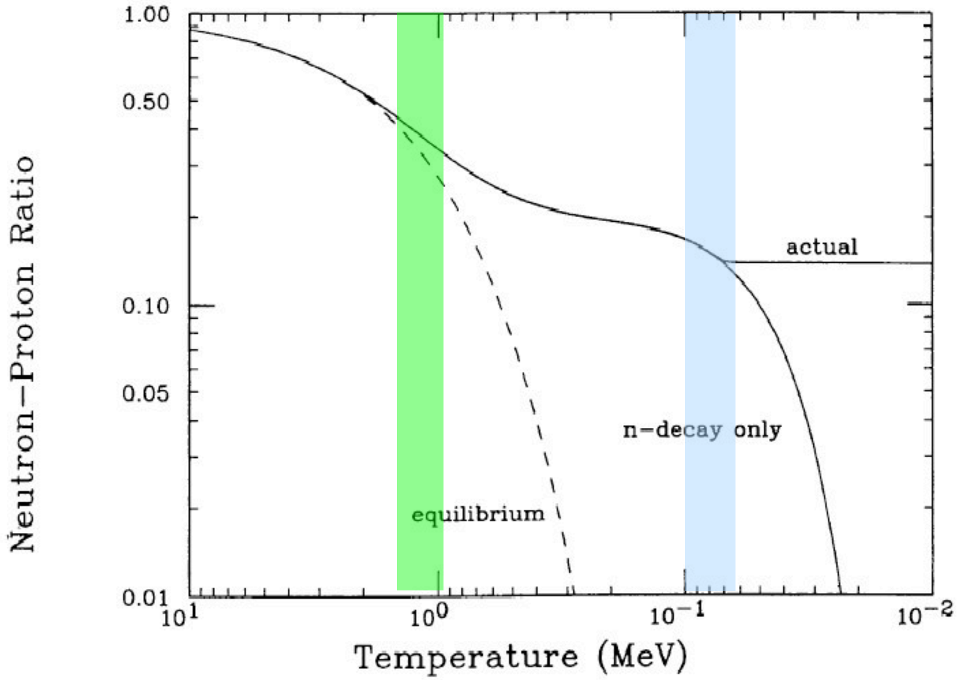
- Hubble expansion rate

$$H \simeq g_\star^{1/2} G_N^{1/2} T^2$$

$$g_\star = 10.75 + \frac{7}{4}(N_\nu - 3)$$

$\Gamma_W$ = Weak rate ($\nu_e$ + n ↔ p + e)

Deuterium bottleneck $T_N \sim -\frac{B_d}{\ln(\eta)} \sim 0.1\,\text{MeV}$




$$\frac{H}{\Gamma_W} = 1$$ →

Weak interaction freeze-out $T_W \sim 1\,\text{MeV} \cdot (g_\star/10.75)^{1/6}$

# The Physics of BBN

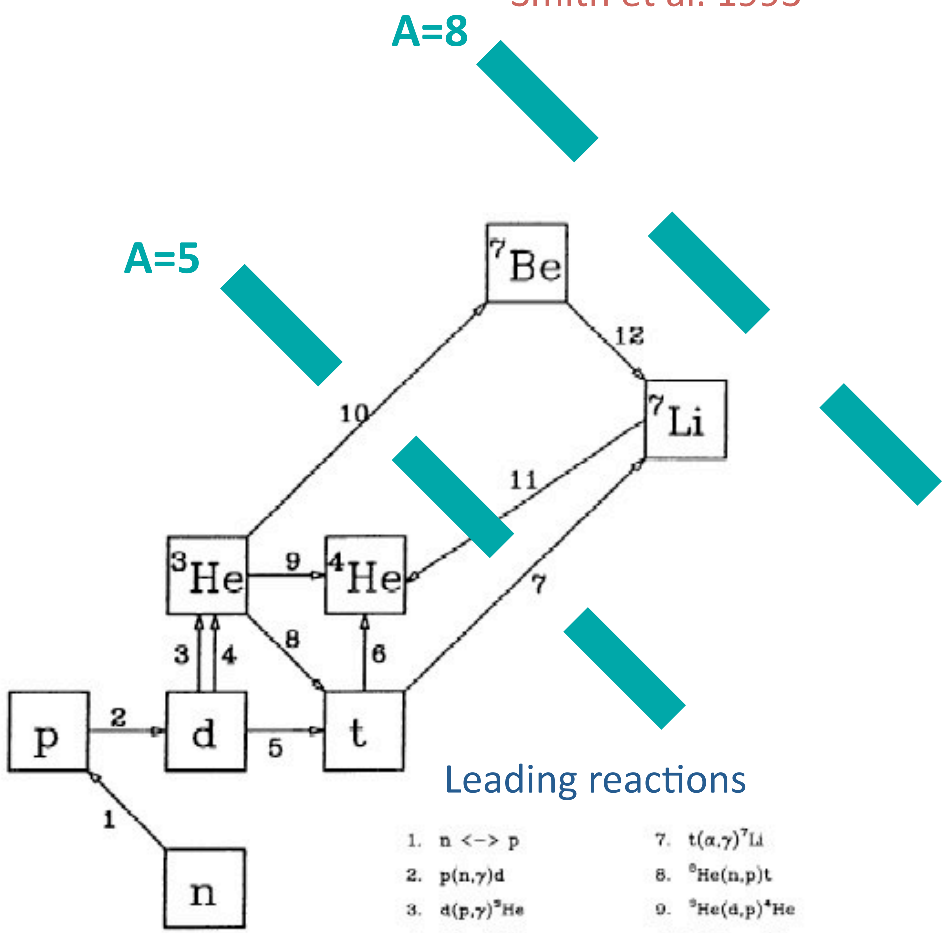
Essentially all neutrons which survive till the onset of BBN are used to build $^4$He:

$$Y_\mathrm{p} = \frac{2(n/p)}{1+(n/p)} \simeq 0.25$$

The abundance of D, $^3$He, $^7$Li is determined by a complex nuclear reaction network.

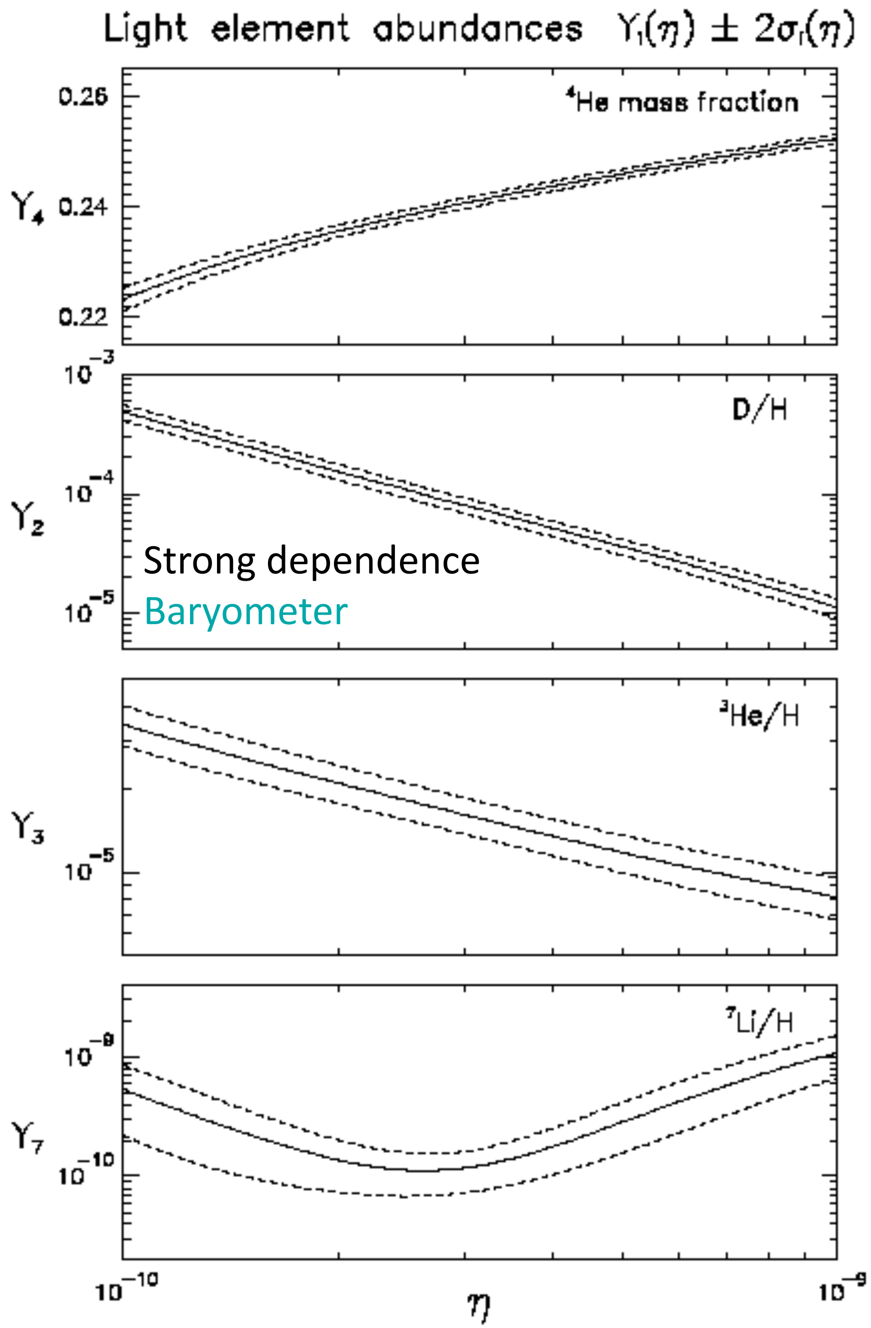
No stable nuclei with A=5 or A=8
$\longrightarrow$ No heavy nuclei are produced.

Smith et al. 1993




Leading reactions

1. $n \leftrightarrow p$
2. $p(n,\gamma)d$
3. $d(p,\gamma)^3He$
4. $d(d,n)^3He$
5. $d(d,p)t$
6. $t(d,n)^4He$
7. $t(\alpha,\gamma)^7Li$
8. $^3He(n,p)t$
9. $^3He(d,p)^4He$
10. $^3He(\alpha,\gamma)^7Be$
11. $^7Li(p,\alpha)^4He$
12. $^7Be(n,p)^7Li$



Light element abundances $Y_i(\eta) \pm 2\sigma_i(\eta)$
$^4$He mass fraction
$Y_4$
0.26
0.24
0.22
D/H
$Y_2$
$10^{-3}$
$10^{-4}$
$10^{-5}$
Strong dependence
Baryometer
$^3$He/H
$Y_3$
$10^{-5}$
$^7$Li/H
$Y_7$
$10^{-9}$
$10^{-10}$
$10^{-10}$
$10^{-9}$
$\eta$

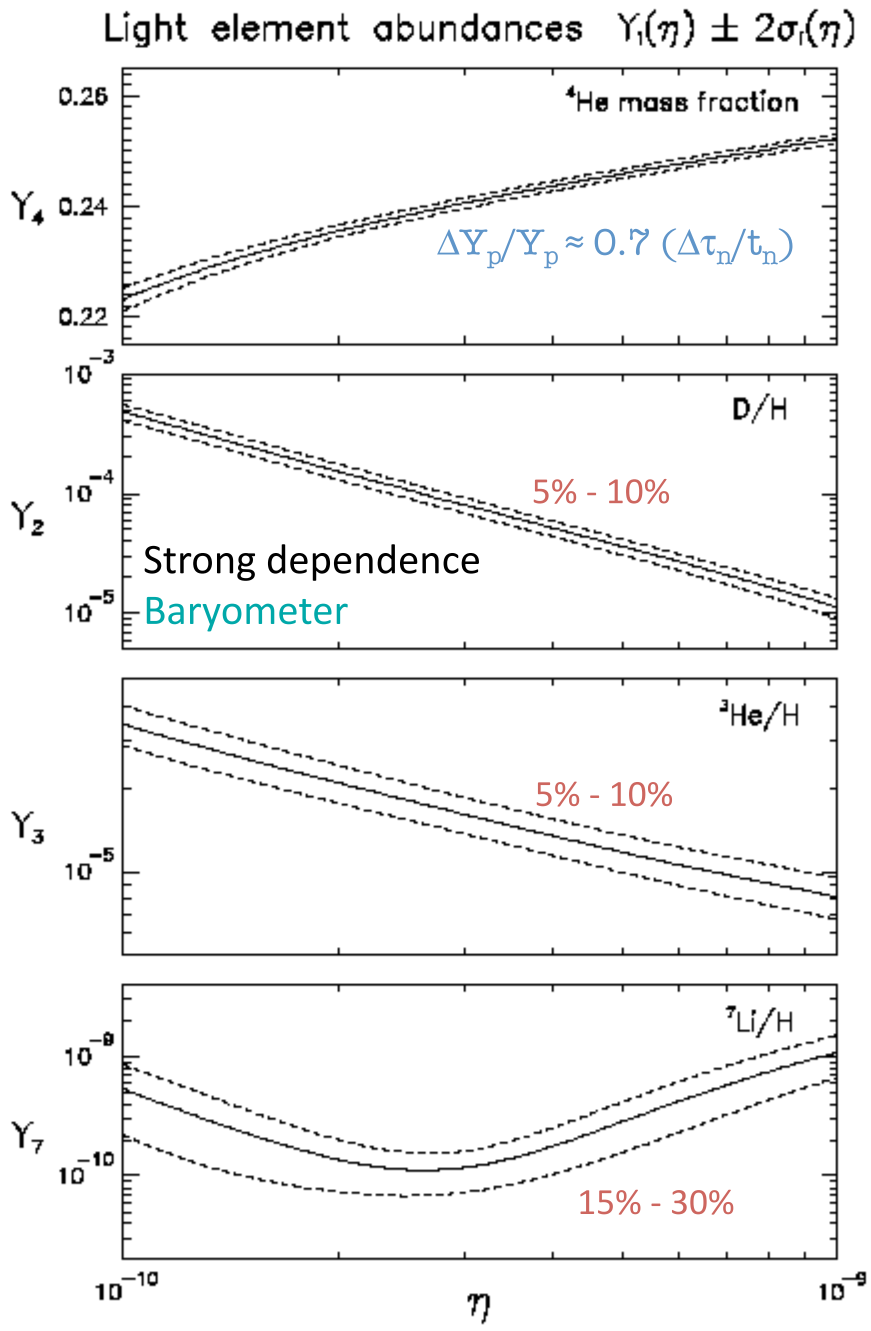
# Accuracy and Uncertainties ...

Accuracy of $^4$He calculation at the level of 0.1%.

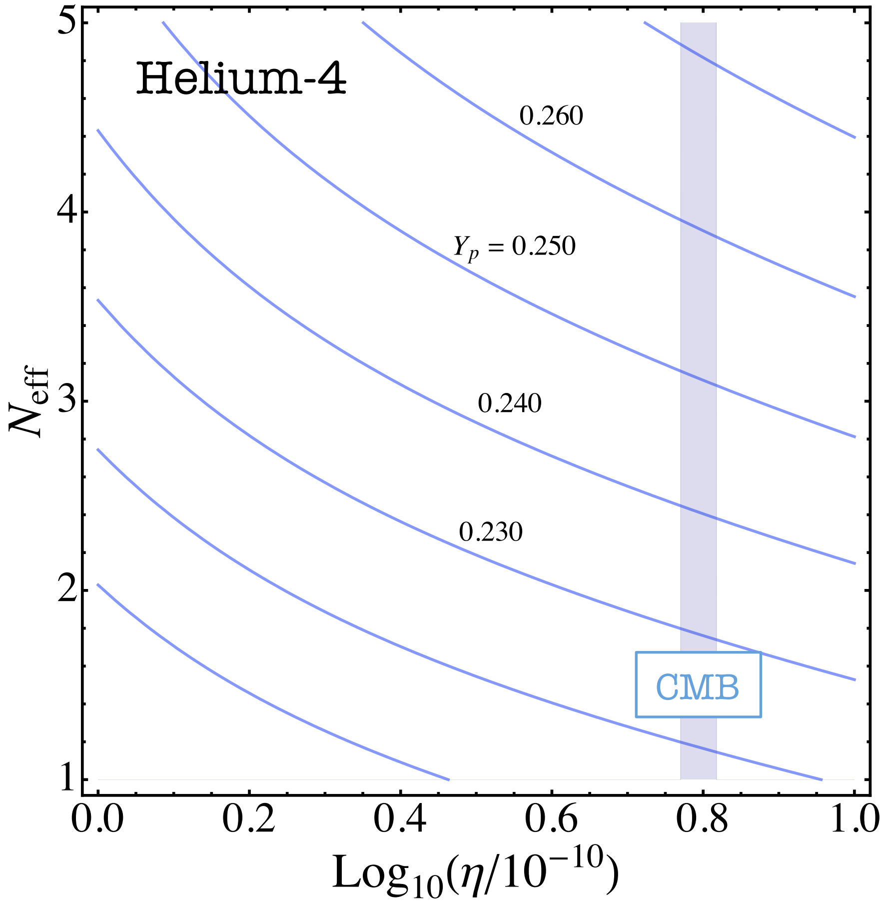
High precision codes (Lopez & Turner 1999, Esposito et al. 1999) take directly into account effects due to :
- zero and finite temperature radiative processes; non equilibrium neutrino heating during e± annihilation; finite nucleon masses; ...

These effects are included "a posteriori" in the "standard" code (Wagoner 1973, Kawano 1992).

Reaction rate uncertainties translate into uncertainties in theoretical predictions → **sub-dominant** with respect to systematic observational errors (see later).



# Understanding the dependence on Nν …

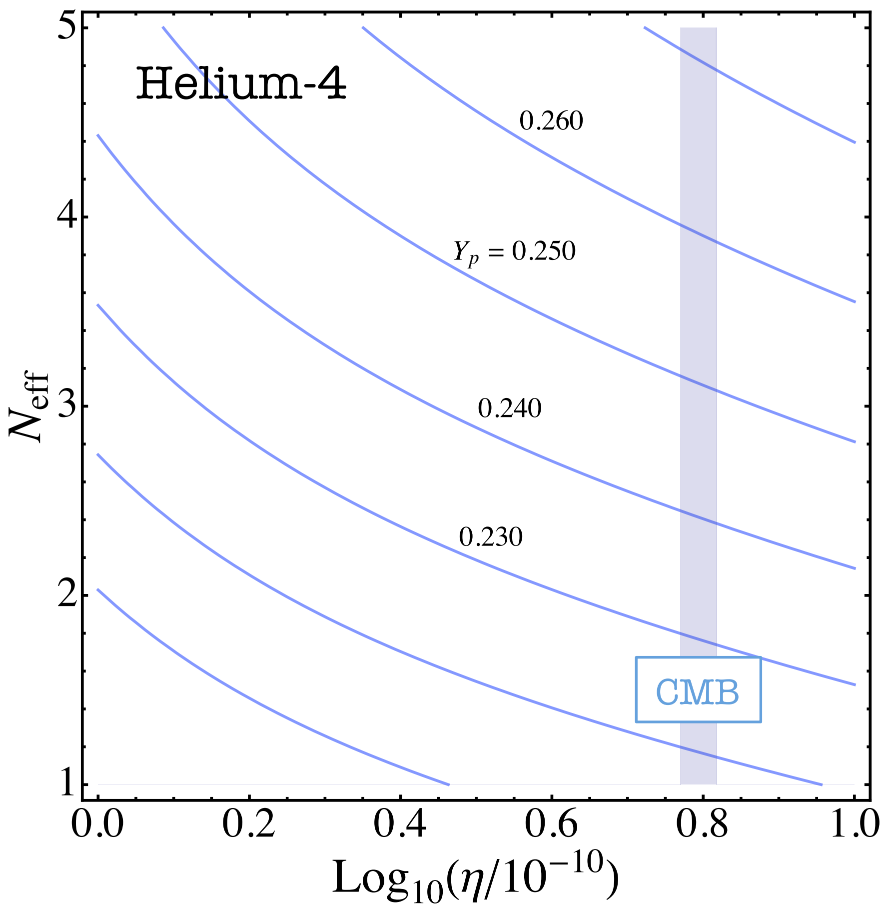



$$Y_{\rm p} = \frac{2(n/p)}{1+(n/p)} \simeq 2\frac{\exp\left(-\Delta m/T_{\rm W}\right)}{1+\exp\left(-\Delta m/T_{\rm W}\right)}\exp(-t_{\rm d}/\tau_{\rm n})$$

$$\frac{\Gamma_{\rm W}}{H} \simeq \frac{G_{\rm F}^2\, T_{\rm W}^3}{g_\star^{1/2}\, G_{\rm N}^{1/2}} \simeq 1$$

$$\Rightarrow \begin{cases} T_{\rm W} \sim 1\,\mathrm{MeV}\cdot(g_\star/10.75)^{1/6} \\ g_\star = 10.75 + \dfrac{7}{4}\left(N_\nu - 3\right) \end{cases}$$

# Understanding the dependence on Nν ...




$$\Delta Y_{\rm p} \sim 0.012\ \Delta N_\nu$$

One extra neutrino corresponds to 5% variation of $Y_p$

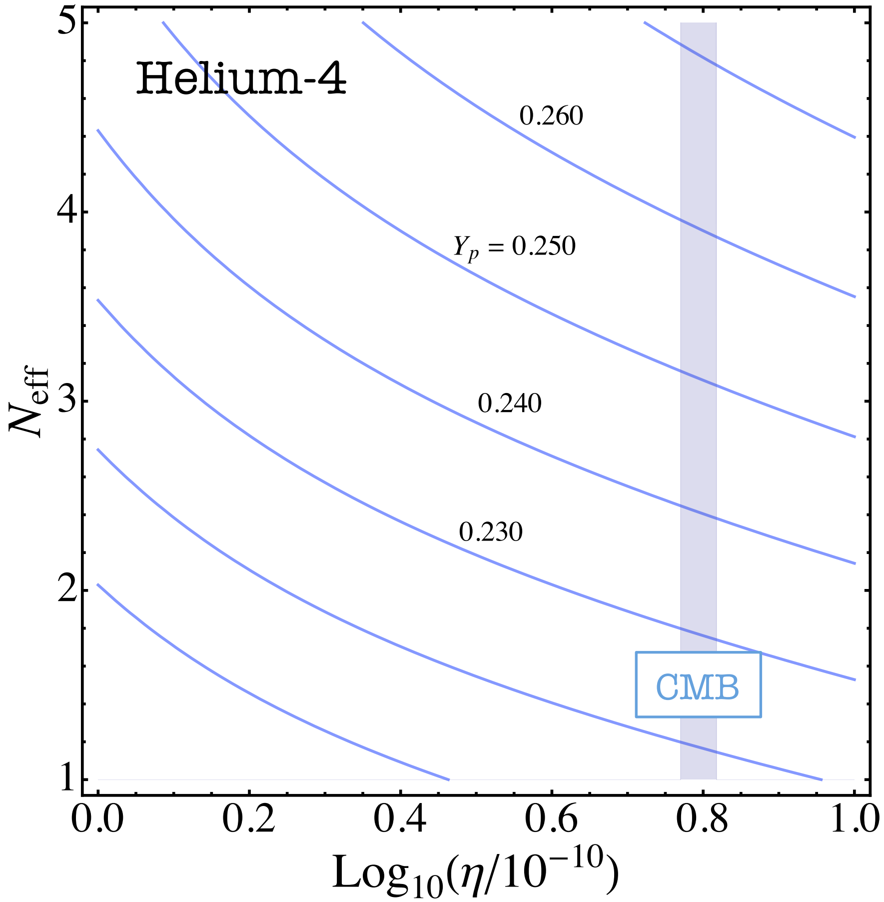
Remember that $\Delta N_\nu$ is an "effective" number.
Helium-4 is sensitive to:

$$\left.\frac{\Gamma_W}{H}\right|_{T\sim 1MeV}$$

- The expansion rate H at T=1 MeV
→ New light particles, $G_N$, $\xi_i$......

- The weak reaction rate $\Gamma_W$ at T=1 MeV
→ $G_F$ ($\tau_n$), $\xi_e$, ......

# Understanding the dependence on Nν ...




$$\Delta Y_{\rm p} \sim 0.012\ \Delta N_\nu$$

One extra neutrino corresponds to 5% variation of $Y_p$

Remember that $\Delta N_\nu$ is an "effective" number.
Helium-4 is sensitive to:

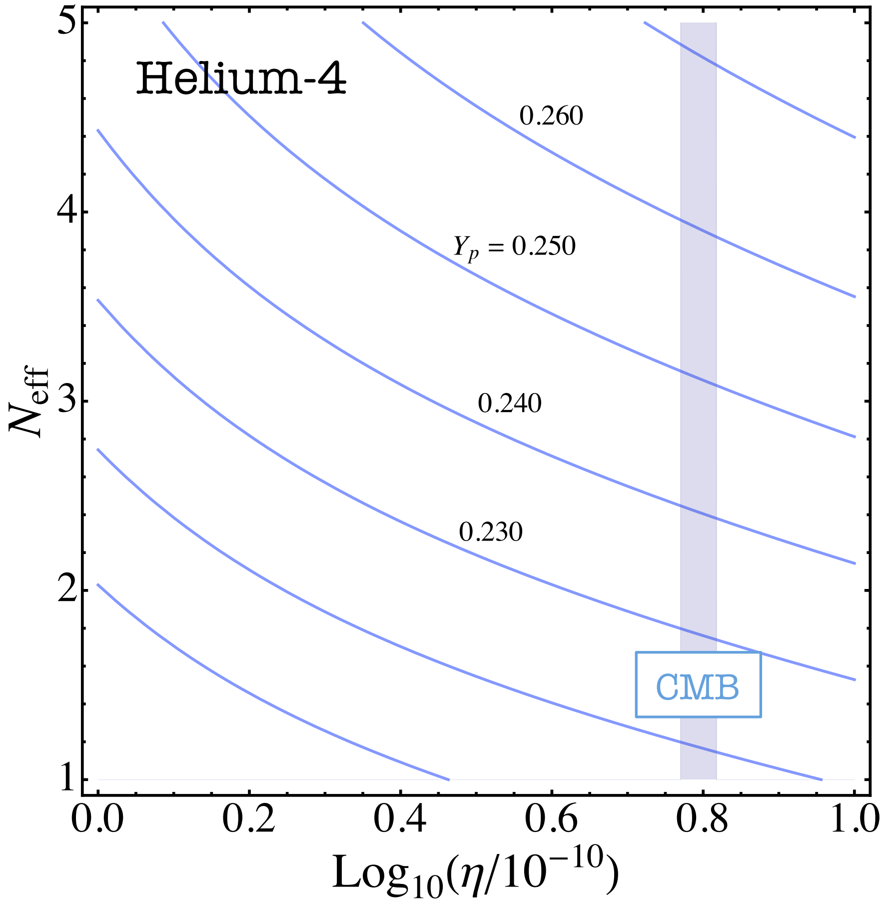
$$\left.\frac{\Gamma_W}{H}\right|_{T\sim 1MeV}$$

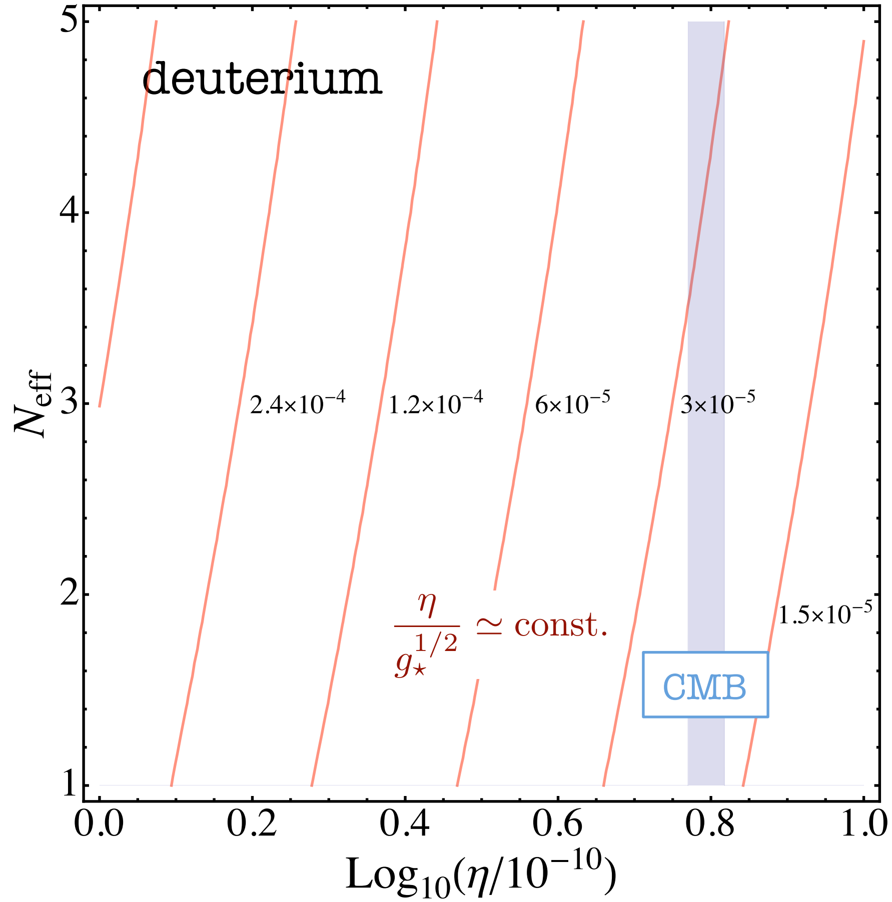
- The expansion rate H at T=1 MeV
→ New light particles, $G_N$, $\xi_i$......

- The weak reaction rate $\Gamma_W$ at T=1 MeV
→ $G_F$ ($\tau_n$), $\xi_e$, ......

$\Delta Y_p/Y_p \approx 0.7\ (\Delta\tau_n/t_n)$

# Understanding the dependence on Nν ...




$$\frac{dY_{\rm i}}{dt} \propto \eta \sum_{+,-} Y \times Y \times \langle \sigma v \rangle_{\rm T}$$

$$\frac{dY_{\rm i}}{dT} \propto \frac{\eta}{g_\star^{1/2}} T^{-3} \sum_{+,-} Y \times Y \times \langle \sigma v \rangle_{\rm T}$$

# Active-Sterile neutrino oscillations in the early universe

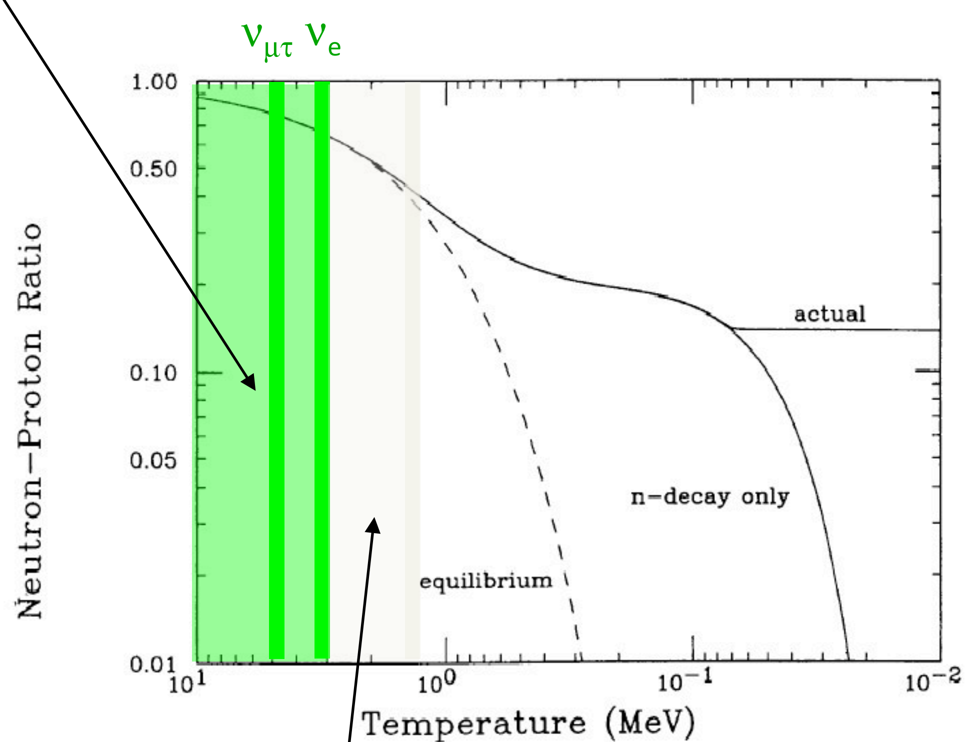
| | |
|---|---|
| A. Dolgov, Phys.Rept. 2002 | *Review and references* |
| A. Dolgov and F.L. Villante, Nucl.Phys.B 2005.<br>M. Cirelli, et al., Nucl.Phys.B 2005. | *3+1 oscillations* |
| Y. Chu and M. Cirelli, Phys.Rev.D74 2006 | *(3+1) and lepton asymmetries* |
| A.Melchiorri et al., JCAP 2007. | *3+2 oscillations* |
| L. Krauss et al., arXiv:1009.4666<br>J. Hamann et al., Phys.Rev.Lett. 2010<br>E. Giusarma et al. arXiv:1102:4774 | *Recent dicussions.* |

*+ many other notable refs*

# A closer look at relevant epochs for neutrinos:

Kinetic + chemical equilibrium
Ann./creat. neutrino reactions

$$\nu\nu \leftrightarrow ll$$




Kinetic equilibrium
Elastic scattering

$$\nu l \leftrightarrow \nu l$$

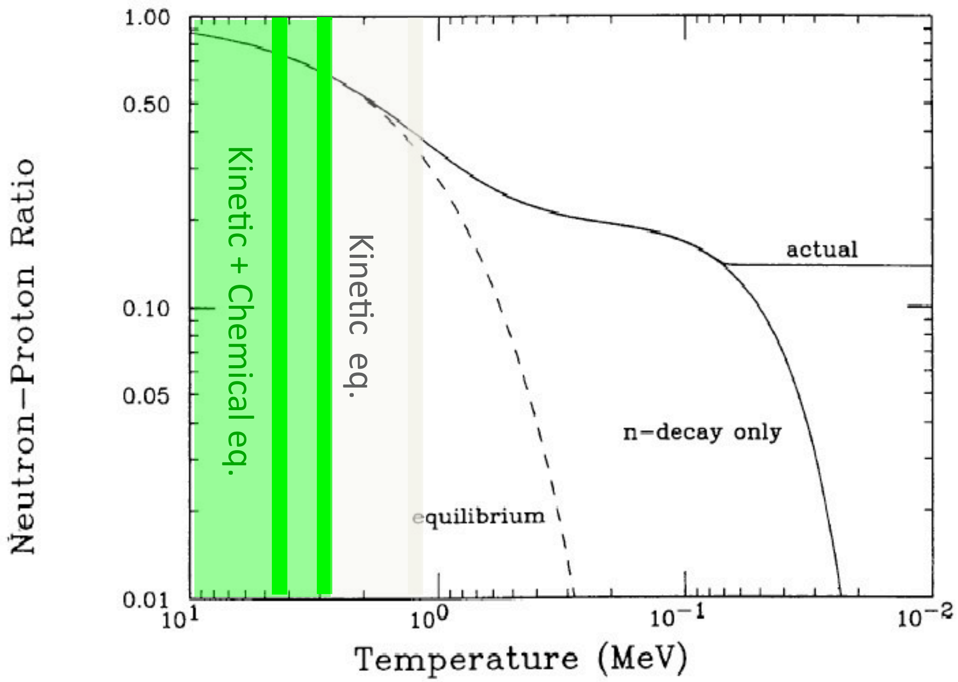
# Sterile neutrinos ...

Sterile neutrinos can be brought into equilibrium by oscillations
→ Boost the Universe exp. rate

$\nu_e$ - $\nu_s$ oscillations after chemical decoupling reduce $\nu_e$ number density
→ affect n/p interconversion rate.

$\nu_e$ - $\nu_s$ oscillations after kinetic decoupling may produce $\nu_e$ spectral distortion
→ affect n/p interconversion rate.

A large lepton asymmetry in the sector of active neutrinos can be generated by MSW-resonance.
(not considered in the following)




*Energy density increase*

$$\Delta N_\nu^{\rm BBN} = \frac{4}{7}\left[\frac{10.75 + (7/4)\Delta N_\nu}{((1+n_e)/2)^2} - 10.75\right]$$

*$\nu_e$ depletion*

# Neutrino oscillations in the early universe

Described by kinetic equations:

$$\left(\frac{\partial}{\partial t} - \tilde{H} p \frac{\partial}{\partial p}\right) \rho = i\left[H_0 + V_{\rm eff}, \rho\right] + \text{c.b.t.}$$

ρ = neutrino density matrix

Coherence breaking terms due to:

- Annihilation $\nu\nu \leftrightarrow l\,l \quad \nu_i\,\nu_i \leftrightarrow \nu_\beta\nu_\beta$
- Elastic scattering $\nu\, l \leftrightarrow \nu\, l$

$$H_0 = U \frac{M^2}{2p} U^\dagger$$

$$(V_{\rm eff})_{\rm aa} = \pm C_1\, \eta_{\rm a}\, G_{\rm F} T^3 + C_{2,\rm a} \frac{G_{\rm F}^2\, T^4\, E}{\alpha}$$

Generally dominant term in potential

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

U = neutrino mixing matrix

Among all the references:
Dolgov,Barbieri 1990

# Neutrino oscillations: 1 active + 1 sterile

$$
\begin{aligned}
x &\equiv m/T \\
y &\equiv E/T
\end{aligned}
$$

Analytic estimates are possible:

$$
\begin{aligned}
\mathcal{H} &= \text{neutrino hamiltonian} \\
\gamma &= \text{neutrino interact. rates}
\end{aligned}
$$

$$
\begin{aligned}
Hx\,\partial_x \rho_{aa} &= i\mathcal{H}_{as}(\rho_{as} - \rho_{sa}) - I_{\rm coll(q)} \\
Hx\,\partial_x \rho_{ss} &= -i\mathcal{H}_{as}(\rho_{as} - \rho_{sa}) \\
Hx\,\partial_x \rho_{as} &= -i\left[(\mathcal{H}_{aa} - \mathcal{H}_{ss}) - i\gamma_{as}\right]\rho_{as} + i\mathcal{H}_{as}(\rho_{aa} - \rho_{ss})
\end{aligned}
$$

For $\delta m^2 > 10^{-6}$ eV$^2$, sterile neutrino production occurs at "high" temperatures:

$$
T^{\nu_s}_{\rm prod} \sim 10\,{\rm MeV}\ (3/y)^{1/3}\ \left(\delta m^2/{\rm eV}^2\right)^{1/6}
$$

Neutrino interaction rates ($\gamma_{as}$) are large compared to hubble expansion rate ($H$)
→ Quasi stationary approximation for off-diagonal components:

$$
\rho_{as} = \frac{\mathcal{H}_{as}}{(\mathcal{H}_{aa} - \mathcal{H}_{ss}) - i\gamma_{as}}\,(\rho_{aa} - \rho_{ss})
$$

In presence of "late" resonance ($H_{aa} - H_{ss} = 0$) the behaviour of $\rho_{as}$ through resonace can be obtained by saddle-point integration.

Dolgov and Villante 2004

# Non-resonance case

$m_s > m_a$ in the small mixing angle limit

The rate of $\nu_s$ production is:

$$\Gamma_s = ( \Gamma_{act} / 4 ) \sin^2(2\theta_{matter})$$

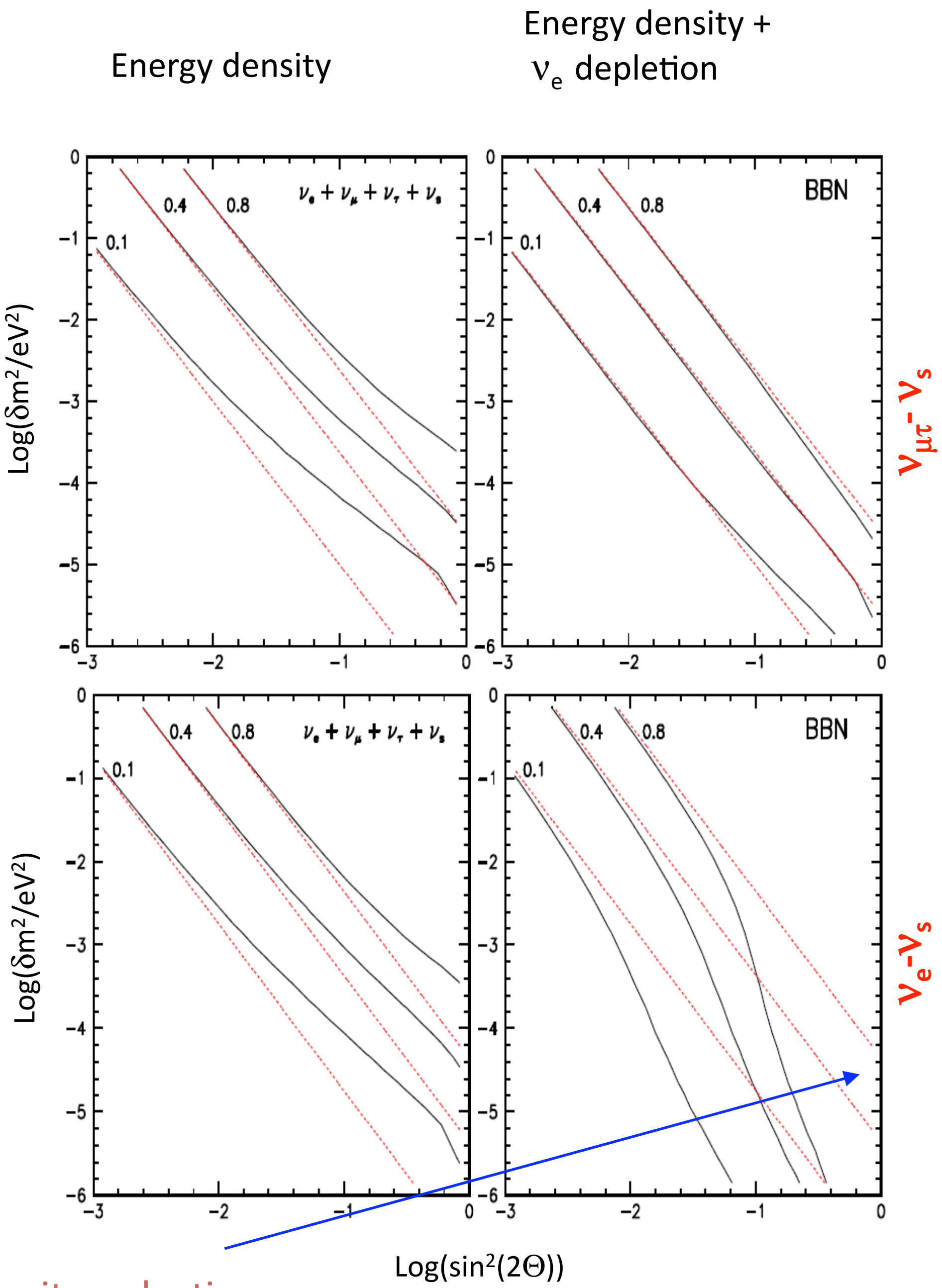
This gives (re-adapted from Dolgov 2001):

$$\Delta N_\nu \simeq 1 - \exp(-M/A_\alpha) \sim M/A_\alpha$$

where:

$$M = \left(\frac{\delta m^2}{\mathrm{eV}^2}\right)^{1/2} \frac{\sin^2(2\theta)}{4}$$

$$\begin{cases} A_e = 1.4 \times 10^{-3} & \nu_e - \nu_s \text{ mixing} \\ A_{\mu\tau} = 1.0 \times 10^{-3} & \nu_\mu - \nu_s \text{ mixing} \end{cases}$$




$\nu_e$ number density reduction.
Relevant effect for small mass differences.

# Resonance Case

$m_s < m_a$ in the small mixing angle limit

Our anlytic results coincide (in the proper limit) with the Landau-Zener description of resonance crossing:

$\nu_\mu$ - $\nu_s$ mixing

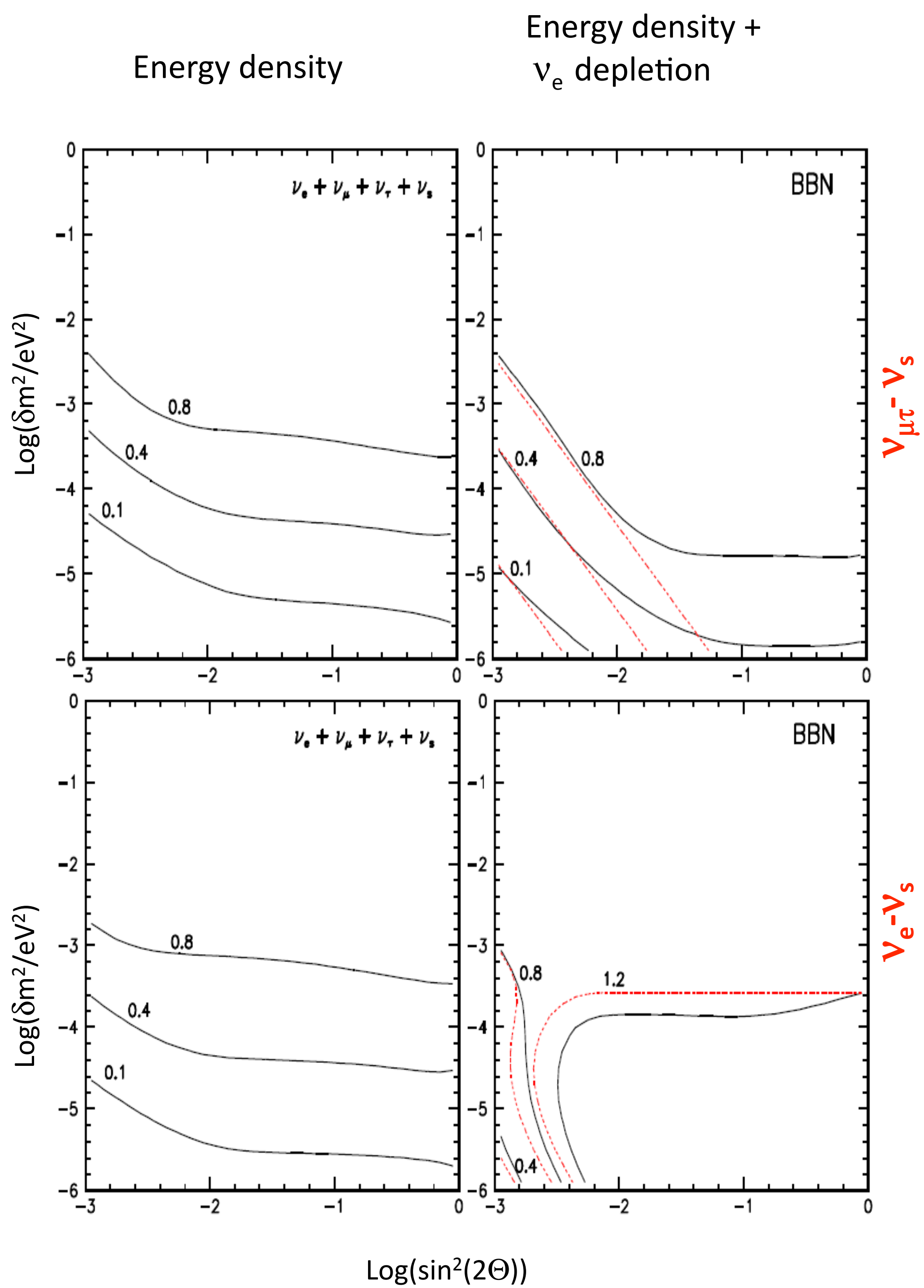
$$(\delta m^2 / eV^2) \sin^4(2\theta) < 1.9 * 10^{-9} (\Delta N\nu)^2$$

$\nu_e$ - $\nu_s$ mixing

$$(\delta m^2 / eV^2) \sin^4(2\theta) < 5.9 * 10^{-10} (\Delta N\nu)^2$$

Dolgov and FLV 2004

Our results show larger effects respect to previous estimates (e.g. by Enqvist et a. 1992, Shi et al. 1993)

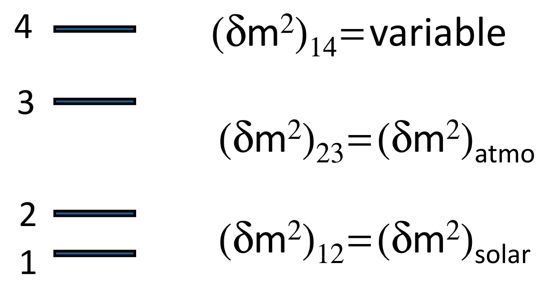


# Neutrino oscillations: 3 active + 1 sterile

Active neutrinos are now known to be mixed.
Their mixing should be taken into account together with $\nu_{act} - \nu_s$ mixing:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} & U_{ACT} & & \eta_1 \\ & & & \eta_2 \\ & & & \eta_3 \\ \varepsilon_1 & \varepsilon_2 & \varepsilon_3 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

$$\vec{\eta} = -\overleftrightarrow{U}_{ACT} \cdot \vec{\varepsilon}$$




$\nu_s$ mixing with one flavour eigenstate (e.g. $\eta_1 \neq 0$, $\eta_2, \eta_3 = 0$)
→ three different $\delta m^2$ ($\varepsilon_1, \varepsilon_2, \varepsilon_3 \neq 0$), new resonances ….

$\nu_s$ mixing with one mass eigenstate (e.g. $\varepsilon_1 \neq 0$, $\varepsilon_2, \varepsilon_3 = 0$)
→ one $\delta m^2$, oscillation into mixed flavours ($\eta_1, \eta_2, \eta_3 \neq 0$)

N.B. Mixing among active neutrinos cannot be rotated away, because BBN is flavour sensitive.

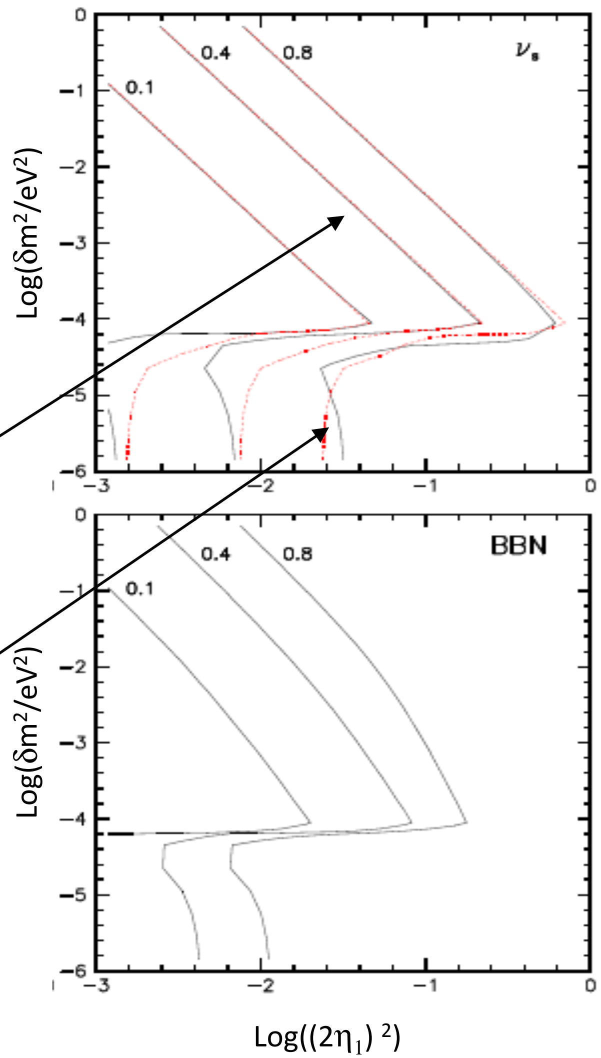
# Neutrino oscillations: 3 active + 1 sterile

Problem partially simplificated considering that early universe does not distinguish $\nu_\mu$ and $\nu_\tau$

$$\begin{pmatrix} \nu_e \\ \nu_\mu' \\ \nu_\tau' \\ \nu_s \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & & \eta_1' \\ -s_{12} & c_{12} & & \eta_2' \\ & & 1 & \eta_3' \\ \varepsilon_1 & \varepsilon_2 & \varepsilon_3 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

$$\vec{\eta}' = -\vec{U}_{ACT}' \cdot \vec{\varepsilon}$$

Complete numerical calculation




Analytic estimates: $\eta_3'$

$$\begin{aligned} (\delta m^2{}_{43}/\mathrm{eV}^2)\,(2\,\eta_3')^4 &= 1.74 \cdot 10^{-5} \ln^2(1-\Delta N_\nu) \quad \text{for} \quad m_4 \geq m_3 \\ (|\delta m^2{}_{43}|/\mathrm{eV}^2)\,(2\,\eta_3')^4 &= 1.9 \cdot 10^{-9} \ln^2(1-\Delta N_\nu) \quad \text{for} \quad m_4 < m_3 \end{aligned}$$

Analytic estimates: $\eta_1'$ and $\eta_2'$

$$\begin{aligned} (\delta m^2{}_{41}/\mathrm{eV}^2)\,(2\,\eta_1')^4 &= 3.16 \cdot 10^{-5} \ln^2(1-\Delta N_\nu) \\ (\delta m^2{}_{42}/\mathrm{eV}^2)\,(2\,\eta_2')^4 &= 1.74 \cdot 10^{-5} \ln^2(1-\Delta N_\nu) \\ & \text{for} \quad m_4 \geq m_2 > m_1 \end{aligned}$$

$$\begin{aligned} (|\delta m^2{}_{42}|/\mathrm{eV}^2)\,[2\,(\eta_1' \sin(\theta_{12}) + \eta_2' \cos\theta_{12})]^4 &= 1.9 \cdot 10^{-9} \ln^2(1-\Delta N_\nu) \\ & \text{for} \quad m_2 \geq m_4 > m_1 \end{aligned}$$

$$\begin{aligned} (|\delta m^2{}_{41}|/\mathrm{eV}^2)\,(2\,\eta_1')^4 &= 5.2 \cdot 10^{-10} \ln^2(1-\Delta N_\nu) \\ (|\delta m^2{}_{42}|/\mathrm{eV}^2)\,(2\,\eta_2')^4 &= 1.9 \cdot 10^{-9} \ln^2(1-\Delta N_\nu) \\ & \text{for} \quad m_2 > m_1 > m_4 \end{aligned}$$

Dolgov and Villante 2004 – see also Cirelli et al. 2005

## 3 active + 1 sterile: the case for large $\delta m^2$

If $m_4$ is large, we can assume $\delta m^2_{12} \approx \delta m^2_{13} \approx 0$:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} 1 & & & \eta_1 \\ & 1 & & \eta_2 \\ & & 1 & \eta_3 \\ \varepsilon_1' & \varepsilon_2' & \varepsilon_3' & 1 \end{pmatrix} \begin{pmatrix} \nu_1' \\ \nu_2' \\ \nu_3' \\ \nu_4 \end{pmatrix} \qquad \vec{\eta} = -\vec{\varepsilon}\,'$$

The relevant parameter is:

$$M = (\delta m^2_{41}/\mathrm{eV}^2)^{1/2}(|\eta_e|^2 + |\eta_\mu|^2 + |\eta_\tau|^2)$$

$$\Delta N_\nu \simeq 1 - \exp(-M/A) \sim \frac{(\delta m^2_{41}/\mathrm{eV}^2)^{1/2}}{10^{-3}}(|\eta_e|^2 + |\eta_\mu|^2 + |\eta_\tau|^2)$$

$$\Omega_\nu h^2 \simeq (m_4/93.5\mathrm{eV})\ \Delta N_\nu \sim \frac{(\delta m^2_{41}/\mathrm{eV}^2)}{10^{-1}}(|\eta_e|^2 + |\eta_\mu|^2 + |\eta_\tau|^2)$$

$$\left\{\begin{array}{lcl} \Omega_\nu h^2 & \sim & 0.01 \\ \Delta N_\nu & \sim & 1 \end{array}\right.$$

cross for: $\delta m^2_{41} \sim 1\ \mathrm{eV}^2$

# The LSND anomaly interpreted as 3+1

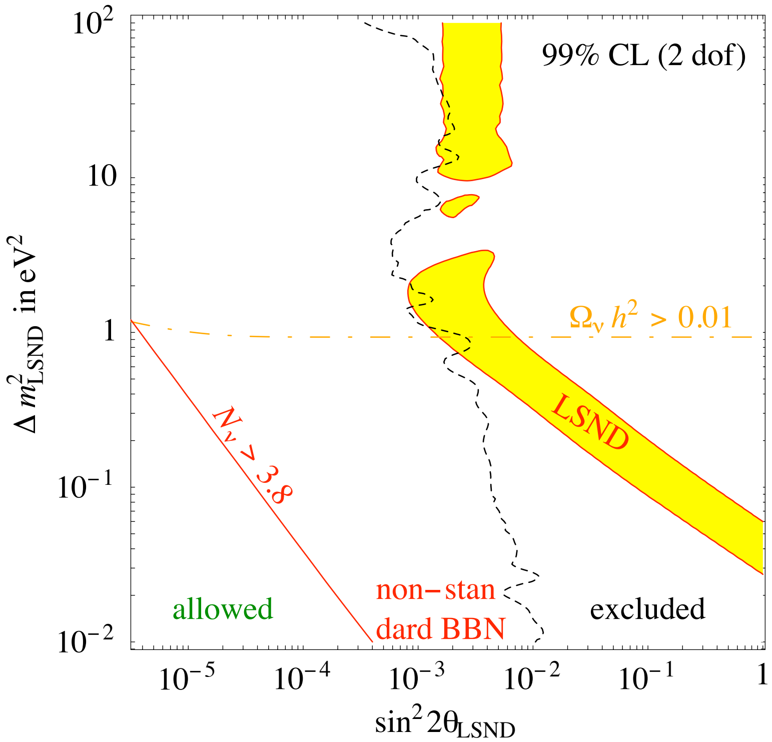
The LSND mixing angle is:

$$\theta_{LSND} \sim \eta_e \, \eta_\mu$$

$$\theta_{LSND}^{1/2} = \eta_e = \eta_\mu$$

To minimze cosmological effects

Cirelli et al. 2005




The relevant parameter is:

$$M = (\delta m^2_{41}/\mathrm{eV}^2)^{1/2}(|\eta_e|^2 + |\eta_\mu|^2 + |\eta_\tau|^2)$$

$$\Delta N_\nu \simeq 1 - \exp(-M/A) \sim \frac{(\delta m^2_{41}/\mathrm{eV}^2)^{1/2}}{10^{-3}}(|\eta_e|^2 + |\eta_\mu|^2 + |\eta_\tau|^2) \sim \frac{2\,(\delta m^2_{41}/\mathrm{eV}^2)^{1/2}\,\theta_{\rm LSND}}{10^{-3}}$$

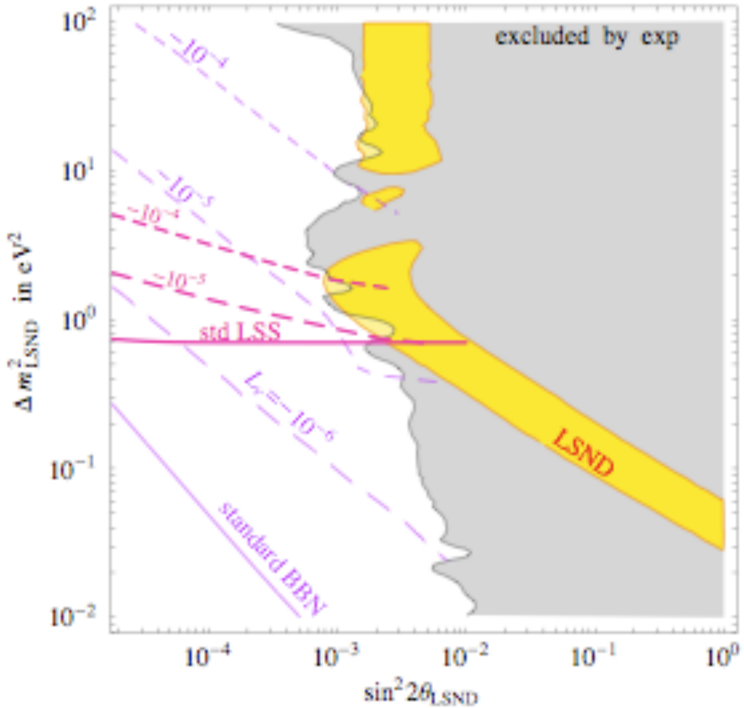
$$\Omega_\nu h^2 \simeq (m_4/93.5\mathrm{eV})\,\Delta N_\nu \sim \frac{(\delta m^2_{41}/\mathrm{eV}^2)}{10^{-1}}(|\eta_e|^2 + |\eta_\mu|^2 + |\eta_\tau|^2) \sim \frac{2\,(\delta m^2_{41}/\mathrm{eV}^2)\,\theta_{\rm LSND}}{10^{-1}}$$

# The LSND anomaly interpreted as 3+1

N.B. A relatively large lepton asymmetry can prevent extra neutrino thermalization.

Y. Chu et al. 2006 – $L_\nu \approx 10^{-4}$ is required to relax conflict with LSND.

Y. Chu and M.Cirelli et al. 2006




The relevant parameter is:

$$M = (\delta m^2_{41}/\mathrm{eV}^2)^{1/2}(|\eta_e|^2 + |\eta_\mu|^2 + |\eta_\tau|^2)$$

$$\Delta N_\nu \simeq 1 - \exp(-M/A) \sim \frac{(\delta m^2_{41}/\mathrm{eV}^2)^{1/2}}{10^{-3}}(|\eta_e|^2 + |\eta_\mu|^2 + |\eta_\tau|^2) \sim \frac{2\,(\delta m^2_{41}/\mathrm{eV}^2)^{1/2}\,\theta_{\rm LSND}}{10^{-3}}$$

$$\Omega_\nu h^2 \simeq (m_4/93.5\mathrm{eV})\,\Delta N_\nu \sim \frac{(\delta m^2_{41}/\mathrm{eV}^2)}{10^{-1}}(|\eta_e|^2 + |\eta_\mu|^2 + |\eta_\tau|^2) \sim \frac{2\,(\delta m^2_{41}/\mathrm{eV}^2)\,\theta_{\rm LSND}}{10^{-1}}$$

$$\theta^{1/2}_{LSND} = \eta_e = \eta_\mu$$

To minimize cosmological effects

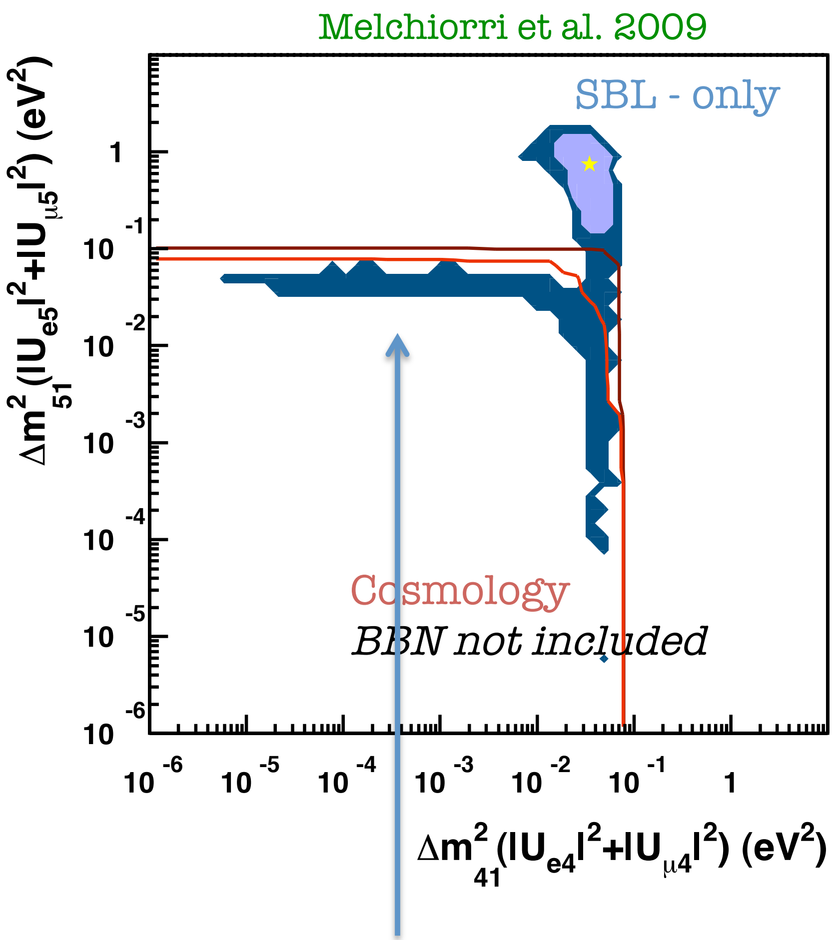
# 3+2 schemes in cosmology

Melchiorri et al. 2009 considered compatibility of SBL data and cosmology in 3+2 scenarios:

$$U_{\alpha i} = \begin{pmatrix} 0.81 & 0.55 & 0 & \pm|U_{e4}| & \pm|U_{e5}| \\ -0.51 & 0.51 & 0.70 & \pm|U_{\mu 4}| & \pm|U_{\mu 5}| \\ 0.28 & -0.67 & 0.70 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\Delta N_{\nu,h} \simeq 6.6 \times 10^{-3} \sqrt{\frac{\Delta m^2_{j1}}{\text{eV}^2}} \sum_a \frac{g_a}{\sqrt{C_a}} \left(\frac{U_{aj}}{10^{-2}}\right)^2$$

$$\Omega_h\, h^2 \simeq 7 \times 10^{-5} \left(\frac{\Delta m^2_{j1}}{\text{eV}^2}\right) \sum_a \frac{g_a}{\sqrt{C_a}} \left(\frac{U_{aj}}{10^{-2}}\right)^2$$



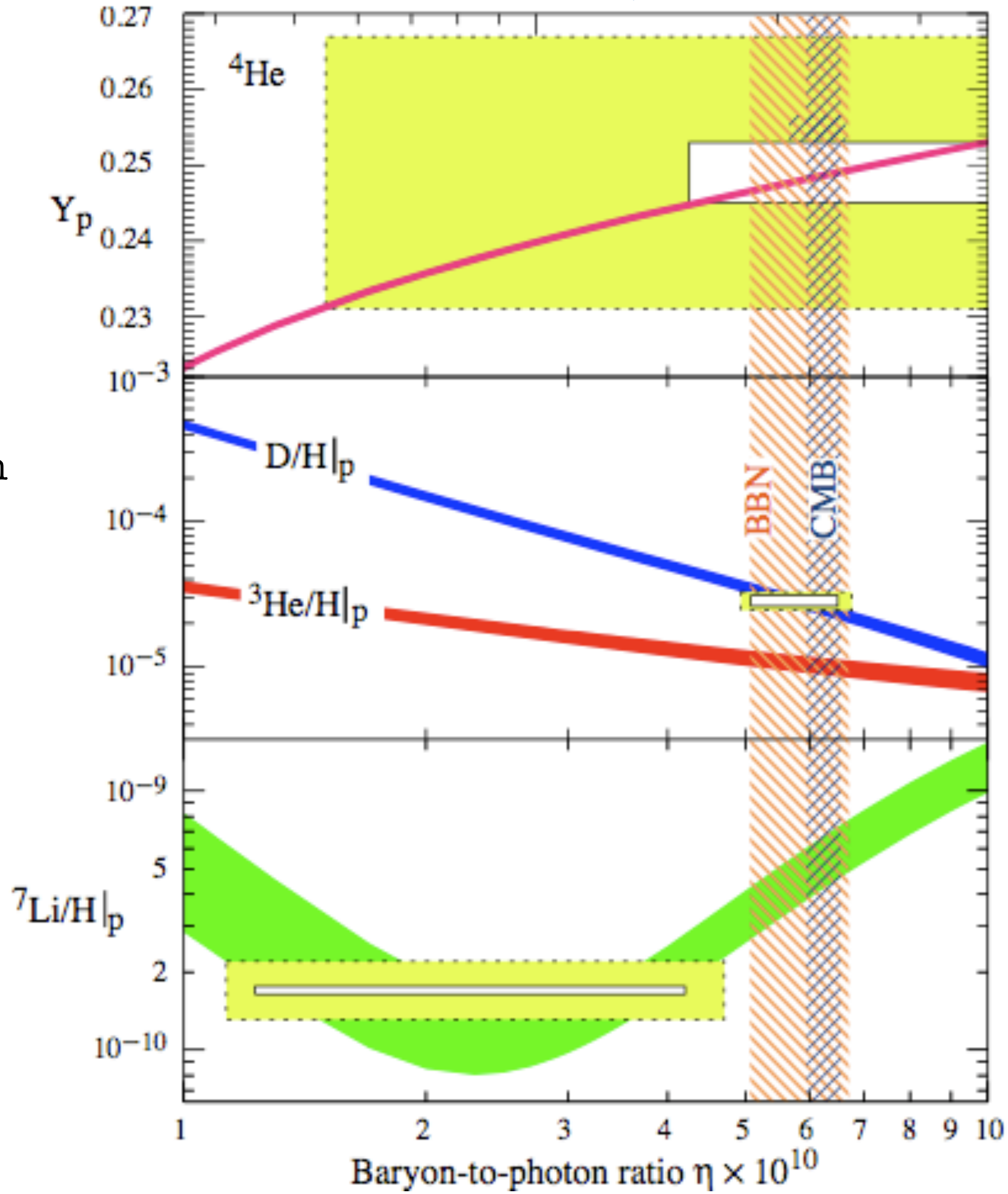

Message

In relevant regions of parameter space, extra neutrinos may not fully thermalize.

# Is there evidence for non standard physics from BBN?

# Theory .vs. observations

PDG 2010, Fields and Sarkar




Deuterium – observed in the high resolution spectra of QSO absorption systems at high redshift.

Lithium-7 – Factor 2-3 discrepancy with theoretical predictions. Cannot be cured by extra radiation.

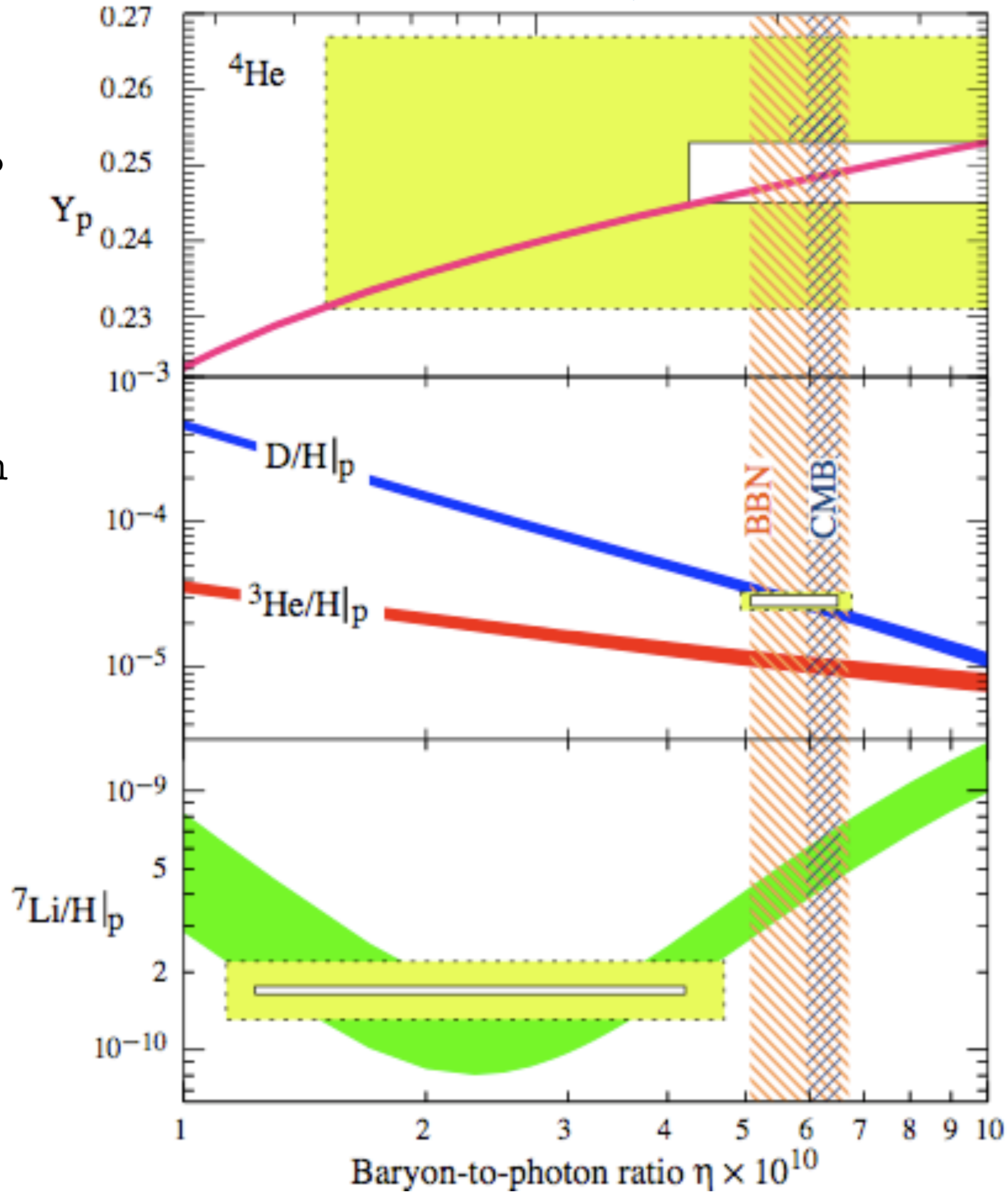
# Theory .vs. observations

Is there evidence for extra radiation from Helium-4 data?

Deuterium – observed in the high resolution spectra of QSO absorption systems at high redshift:

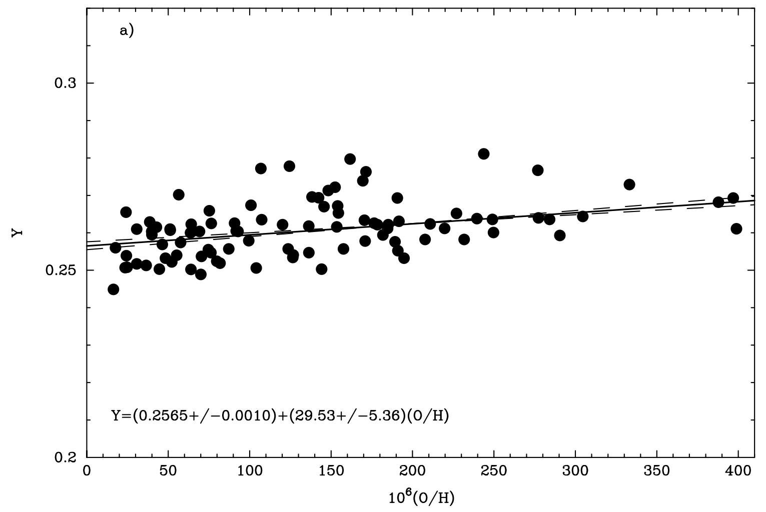
Lithium-7 – Factor 2-3 discrepancy with theoretical predictions. Cannot be cured by extra radiation.

PDG 2010, Fields and Sarkar



# Observations: Helium-4

Izotov et al. 2010




$Y_p$ is determined by extrapolating to Z=0 the (Y,Z) relation or by averaging Y in extremely metal poor objects (N and O used as metallicity tracers). In particular:

✓ $^4$He is observed in clouds of ionized hydrogen (HII regions).

✓ The most metal poor HII regions are in Dwarf Blue Compact Galaxies (BCGs).

Present situation:

✓ Statistical uncertainties at the level of 1% (or less ...)

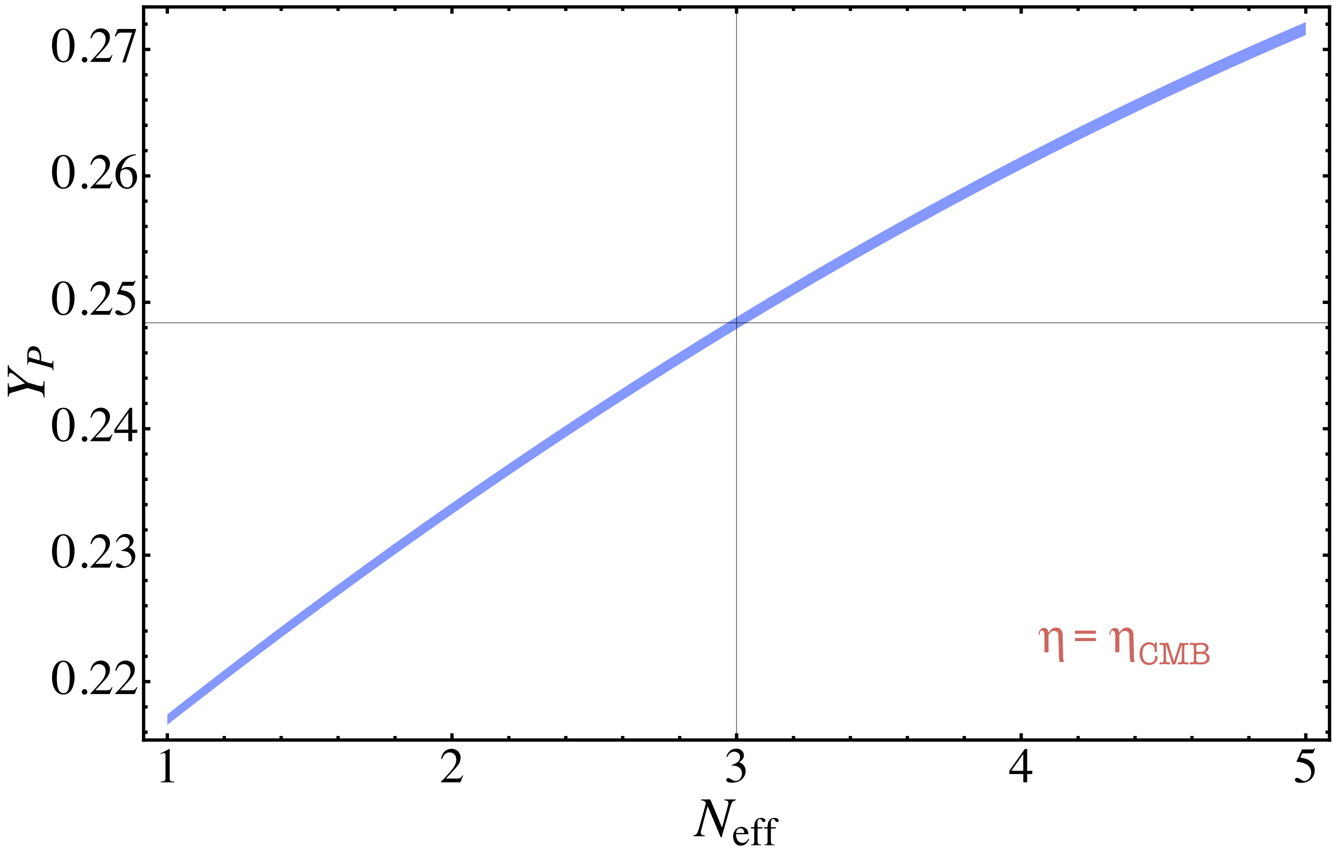
✓ Systematic uncertainties at the level of 2% (or more ...)

✓ Several physical mechanism acting in HII regions still not completely understood (ionization correction factor, underlying stellar absorption, temperature structure ...).

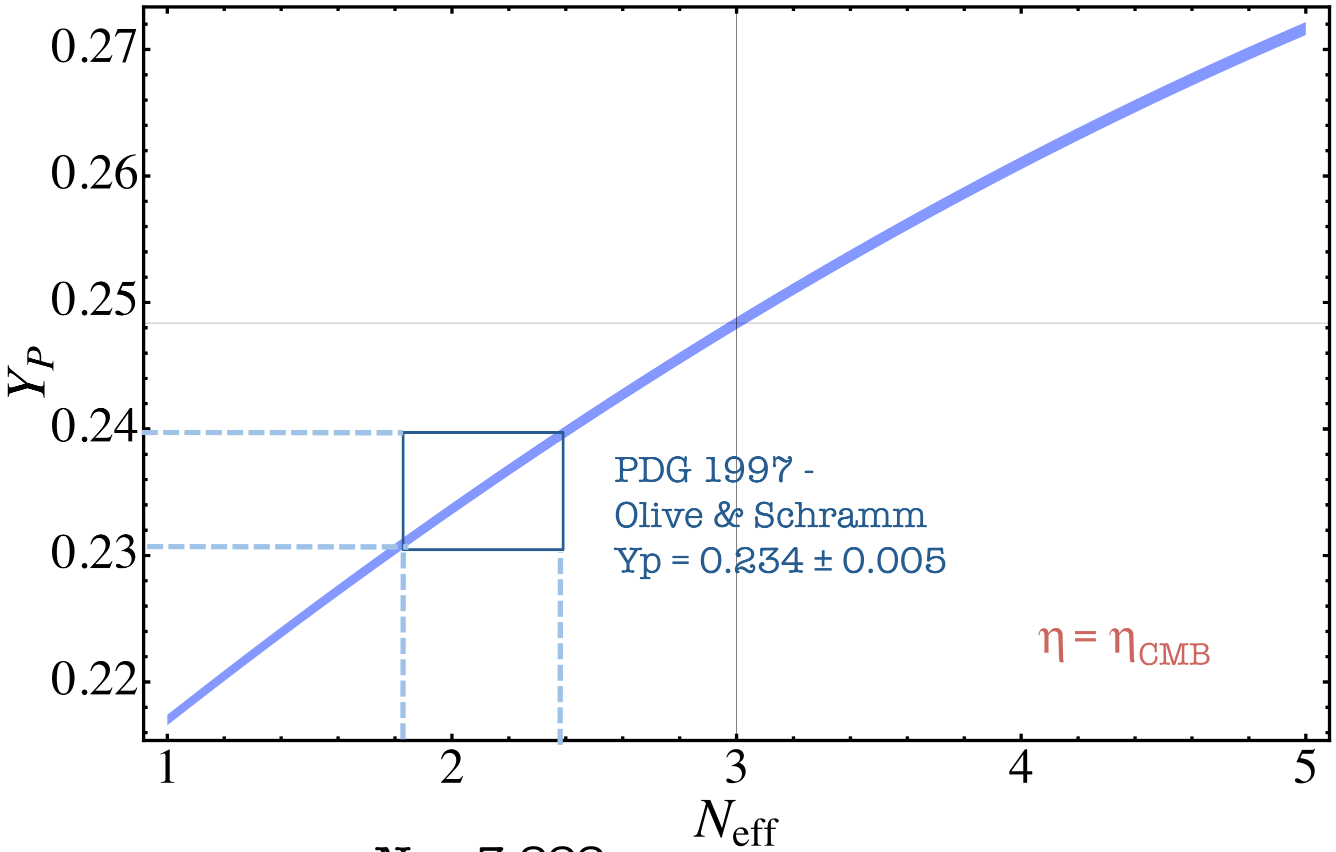
# Compilation of $Y_p$ determinations

| $Y_p$ | | |
|---|---|---|
| 0.244 ± 0.002 | Izotov et al. 1998 | Regression using 45 BCGs – O/H |
| 0.245 ± 0.001 | | N/H |
| 0.235 ± 0.003 | Olive et al. 1997 | Regression using 62 BCGs |
| 0.238 ± 0.002 | Fields and Olive 1998 | Re-analysis (update) of Olive et al. 1997 |
| 0.2345 ± 0.0026 | Peimbert et al 2000 | HII regions of the Small Magellanic Cloud |
| 0.2384 ± 0.0025 | Peimbert et al 2001 | Average of the 5 most metal poor BCGs |
| 0.239 ± 0.002 | Luridiana et al 2003 | 5 metal poor HII regions |
| 0.249 ± 0.009 | Olive et al. 2004 | Re-analysis of a subsample of Izotov et al. 1998 |
| 0.2472 ± 0.0012 | Izotov et al. 2007 | Regression using 86 extra-galactic HII regions |
| 0.2516 ± 0.0011 | | |
| 0.2474 ± 0.0028 | Peimbert et al 2007 | 5 metal poor extra-galactic HII regions |
| | | |
| 0.2565 ± 0.001 ± 0.005 | Izotov et al. 2010 | 86 Low metallicity HII regions |
| 0.256 ± 0.0108 | Aver et al. 2010 (a) | better treat. of syst. Err. (reanalysis of Olive et al. 2004) |
| 0.256 + 0.0032 -0.0108 | | only positive slopes in the regression |
| 0.2609 ± 0.0117 | Aver et al. 2010 (b) | MCMC analisys of stat. and syst. uncertainties |
| 0.2573 + 0.0033 – 0.0088 | | only positive slopes in the regression |
| < 0.2631 (95 %) | Mangano et al. 2011 | Upper limit – no regression. |

# The “time evolution” of the primordial helium …

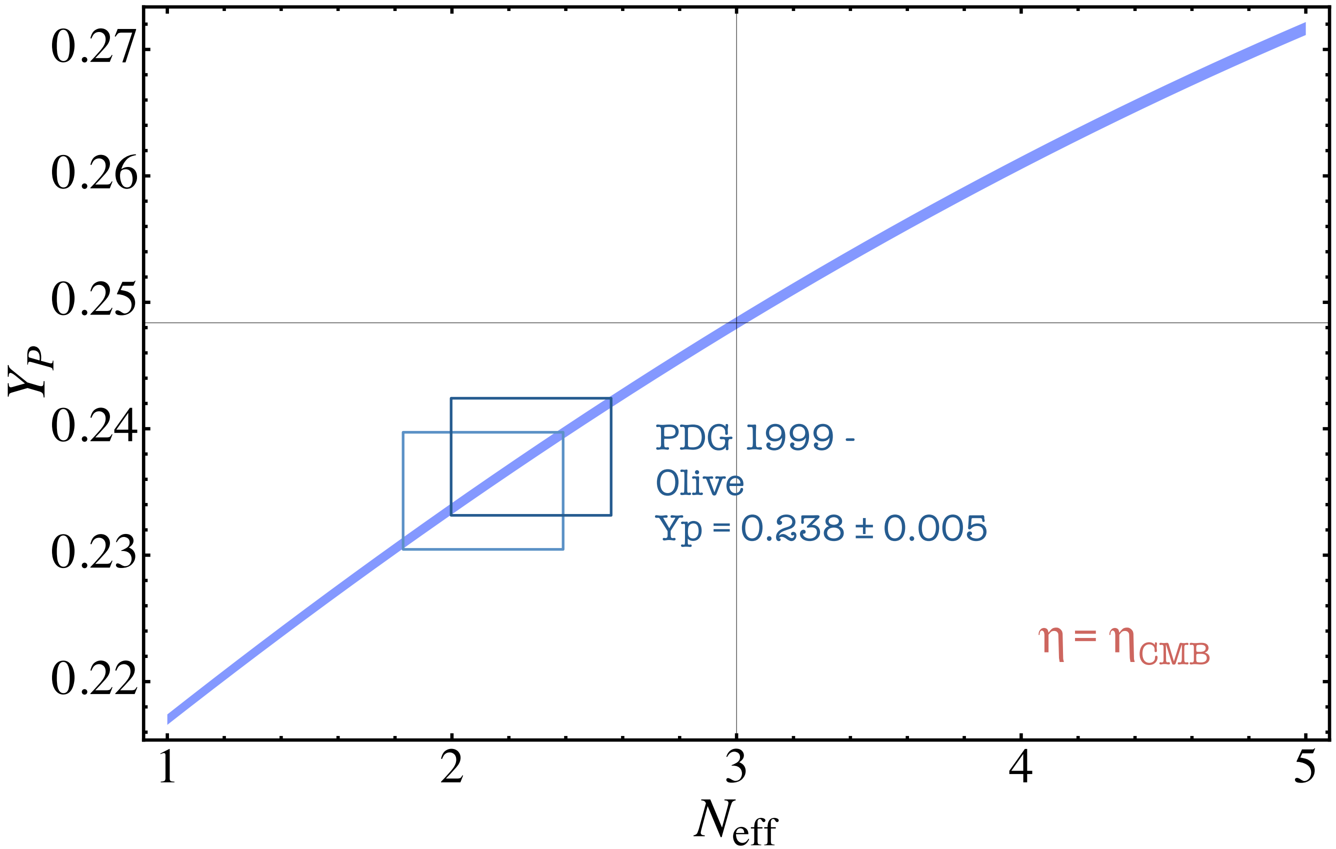


# The “time evolution” of the primordial helium ...

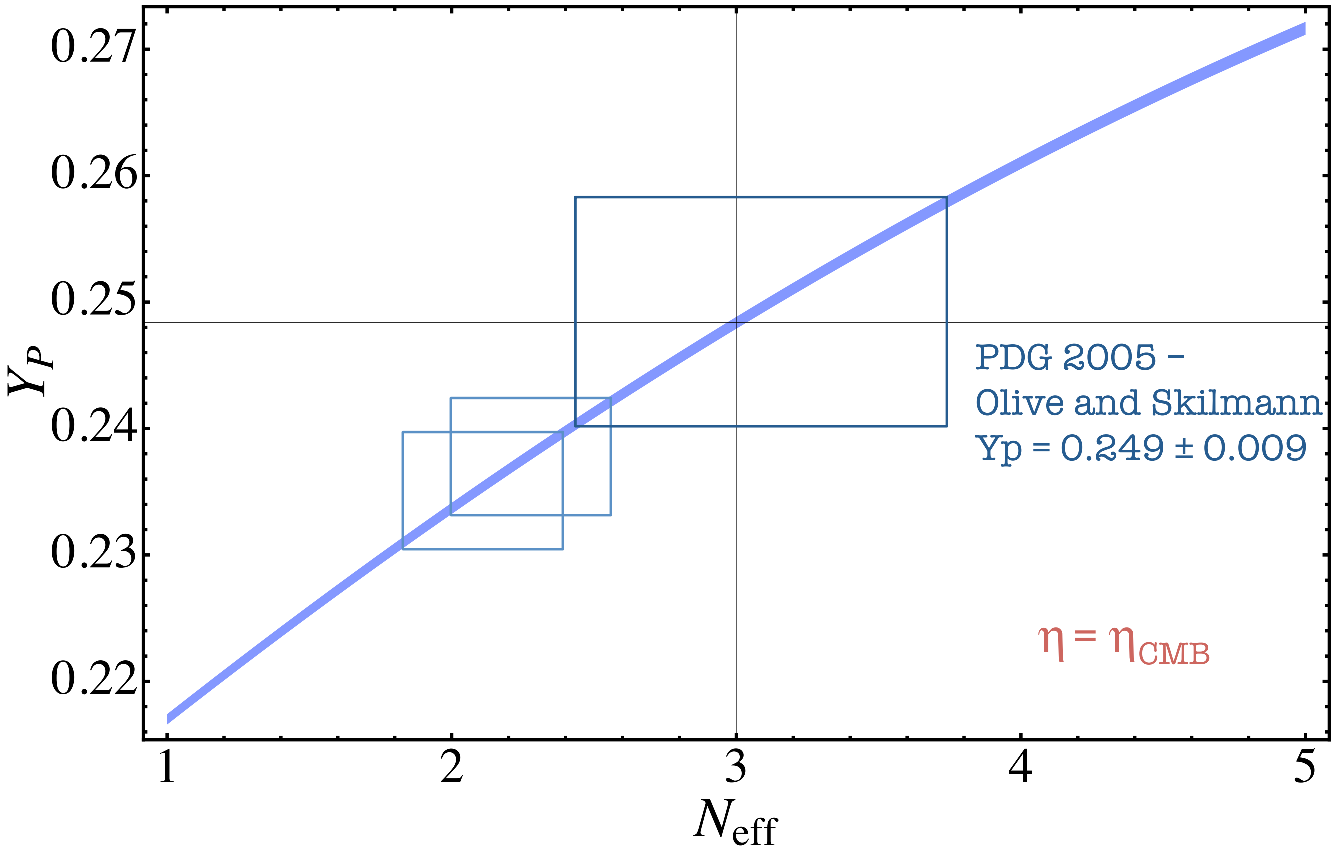



$N_\nu < 3$ ???

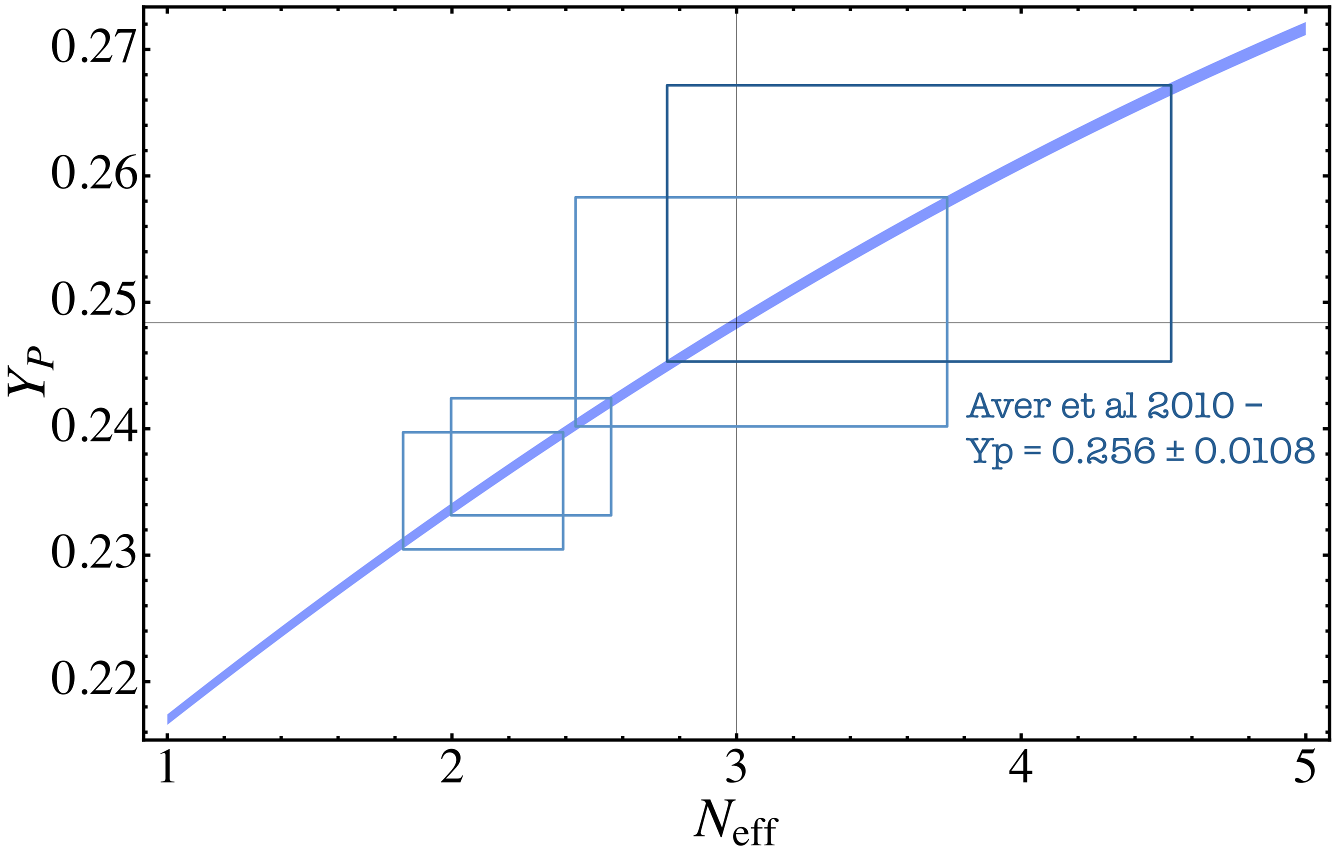
# The "time evolution" of the primordial helium ...



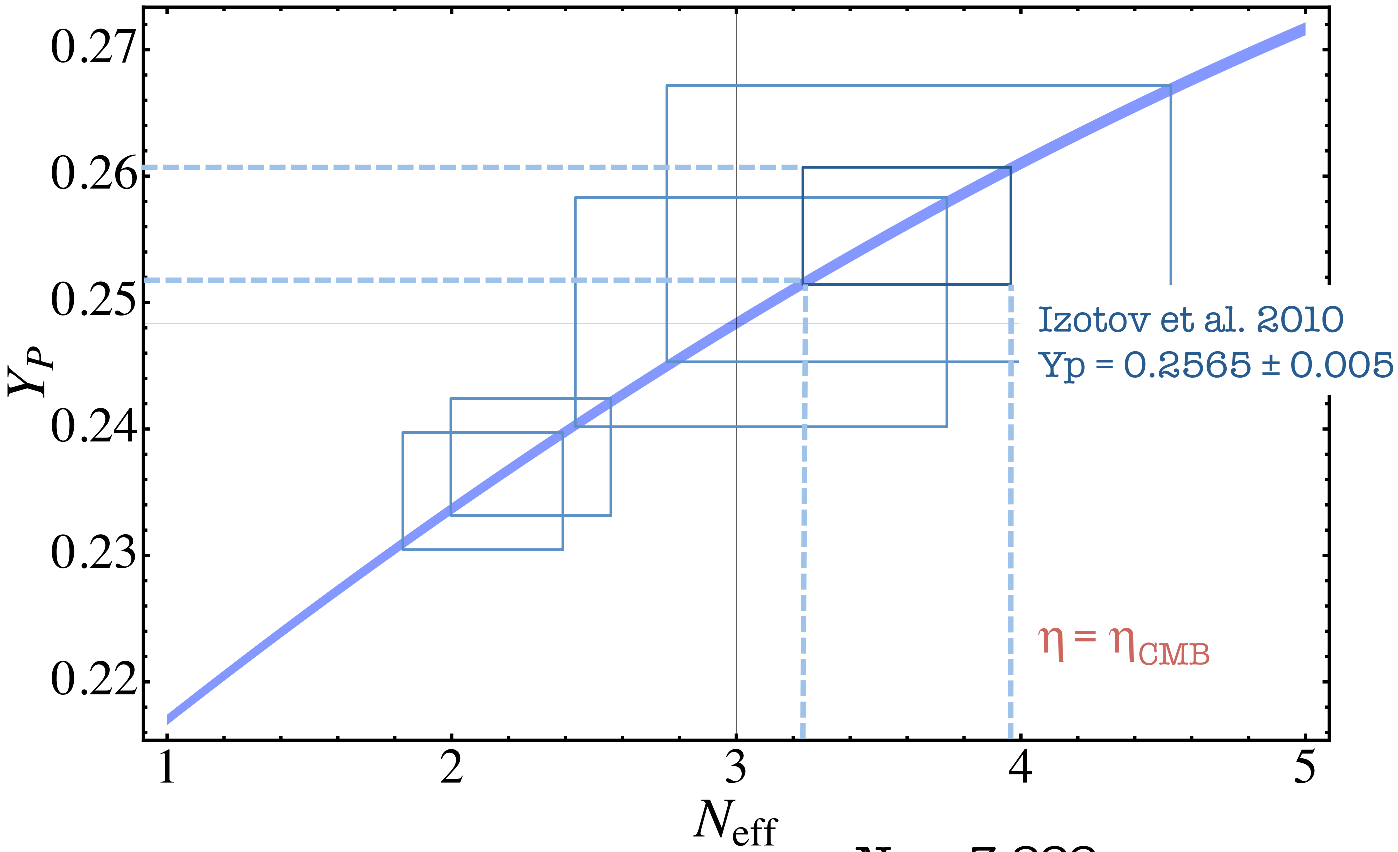
# The “time evolution” of the primordial helium ...



# The “time evolution” of the primordial helium ...

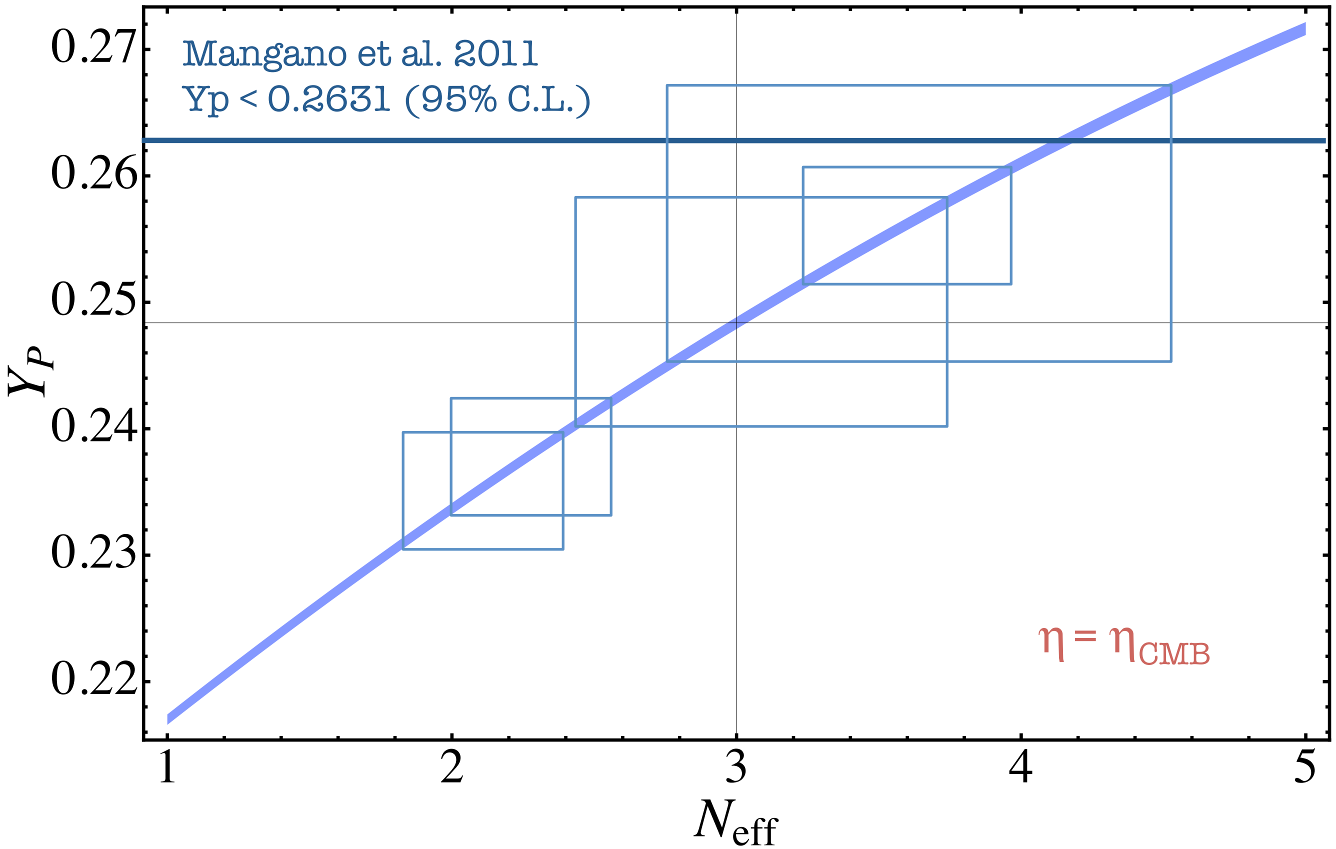


# The “time evolution” of the primordial helium …



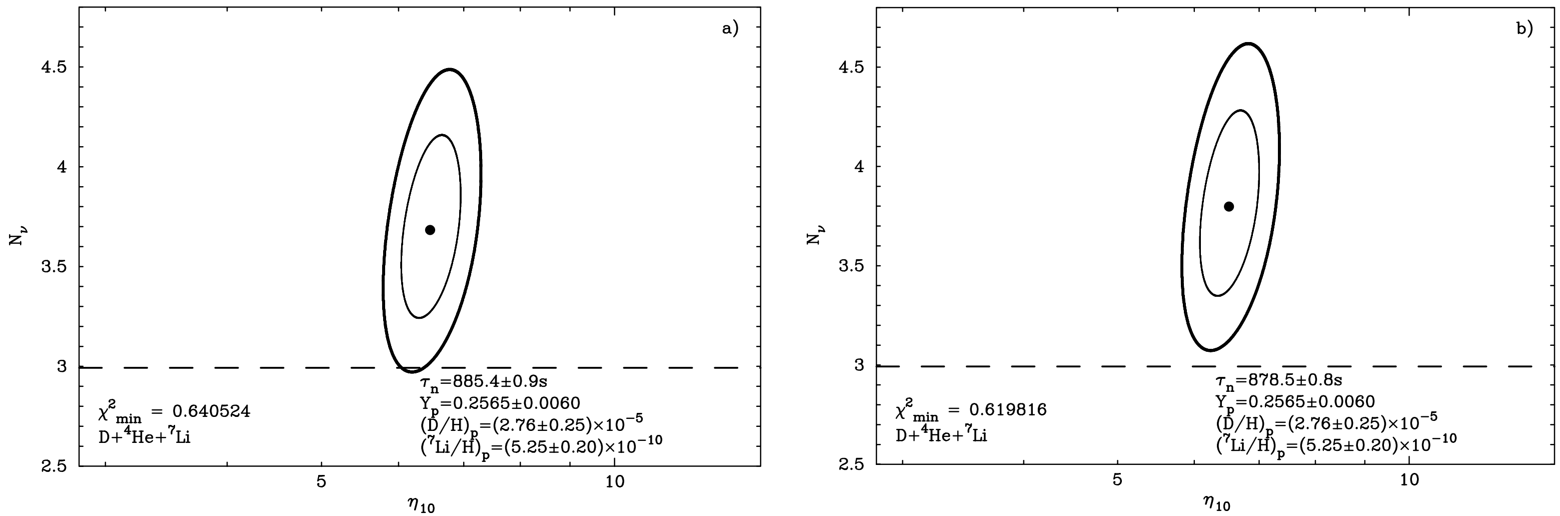

$N_\nu > 3$ ???

# The “time evolution” of the primordial helium …



# Is there evidence for non standard BBN ($N_\nu$ >3)?

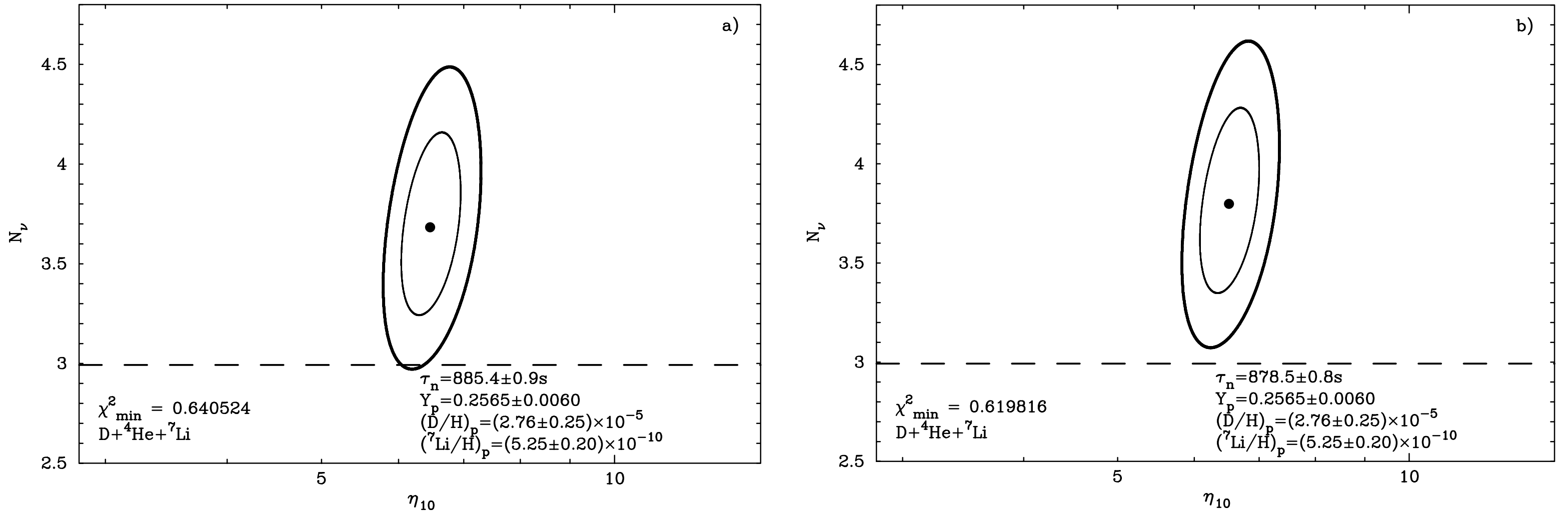
Izotov et al. 2010




Izotov and Thuan 2011 claim that $N_\nu$=3 is escluded at 2σ.

# Is there evidence for non standard BBN ($N_\nu > 3$)?

Izotov et al. 2010

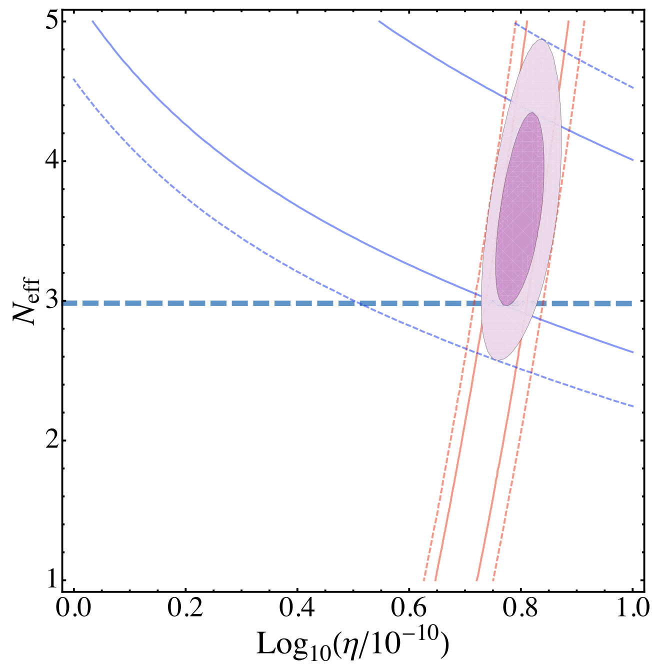



Izotov and Thuan 2011 claim that $N_\nu$=3 is escluded at $2\sigma$.

I am unable to reproduce their analisys:

$1\sigma \rightarrow$ (68.3 C.L.) $\rightarrow$ $\chi^2 - \chi^2_{min} = 2.3$ (not 1!)

$2\sigma \rightarrow$ (95.4 C.L.) $\rightarrow$ $\chi^2 - \chi^2_{min} = 6.2$ (not 2.7!)



# Are two extra neutrinos allowed?

By requiring that primordial helium is less than what observed in astrophysical systems (no regression) , Mangano & Serpico 2011, obtain:

$$Y_p < 0.2631 \ (95\ \%)$$

Mangano et al. 2011

Consistent with Aver et al 2010(a) and Aver et al 2010 (b) when only positive slope is allowed in the regression:

$$Y_p = 0.2573 + 0.0033 - 0.0088$$

Aver et al 2010(a)

$$Y_p = 0.256 + 0.0032 -0.0108$$

Aver et al 2010(b)

# Are two extra neutrinos allowed?

By requiring that primordial helium is less than what observed in astrophysical systems (no regression) , Mangano & Serpico 2011, obtain:

$Y_p < 0.2631$ (95 %)

Mangano et al. 2011

Consistent with Aver et al 2010(a) and Aver et al 2010 (b) when only positive slope is allowed in the regression:

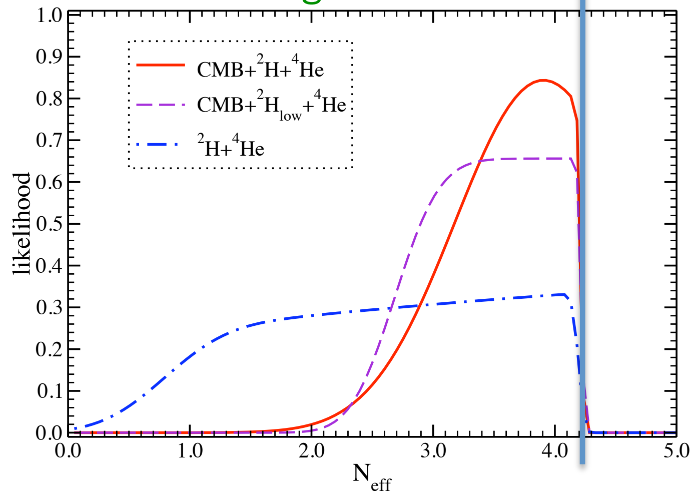
$Y_p = 0.2573 + 0.0033 - 0.0088$

Aver et al 2010(a)

$Y_p = 0.256 + 0.0032 - 0.0108$

Aver et al 2010(b)

Mangano et al. 2011




$N_\nu < 4.2$ at 95% (C.L.)

# Conclusions

BBN can provides **important clues** in favor of sterile neutrinos and/or bounds for sterile neutrino masses and mixing parameters ...

# Conclusions

BBN can provides **important clues** in favor of sterile neutrinos and/or bounds for sterile neutrino masses and mixing parameters ...

... if a **robust** determination of primordial helium abundance is obtained!

# Conclusions

BBN can provides **important clues** in favor of sterile neutrinos and/or bounds for sterile neutrino masses and mixing parameters ...

... if a **robust** determination of primordial helium abundance is obtained!

At this moment:

*Is there a* ***robust*** *evidence for non standard BBN* ($N_\nu > 3$)?

Not yet, in my opinion!
$N_\nu > 3$ is favored but $N_\nu = 3$ is still allowed at about $1\sigma$.

# Conclusions

BBN can provides **important clues** in favor of sterile neutrinos and/or bounds for sterile neutrino masses and mixing parameters ...

... if a **robust** determination of primordial helium abundance is obtained!

At this moment:

*Is there a **robust** evidence for non standard BBN ($N_\nu > 3$)?*

Not yet, in my opinion!
$N_\nu > 3$ is favored but $N_\nu = 3$ is still allowed at about $1\sigma$.

*Is there a **robust** upper limit on $N_\nu$?*

$N_\nu < 4.2$ (95 C.L.) Mangano et al. 2011
No constrains for 3+1 scenarios
May be significant for 3+2 scenarios

# Additional slides

# Theoretical uncertainties

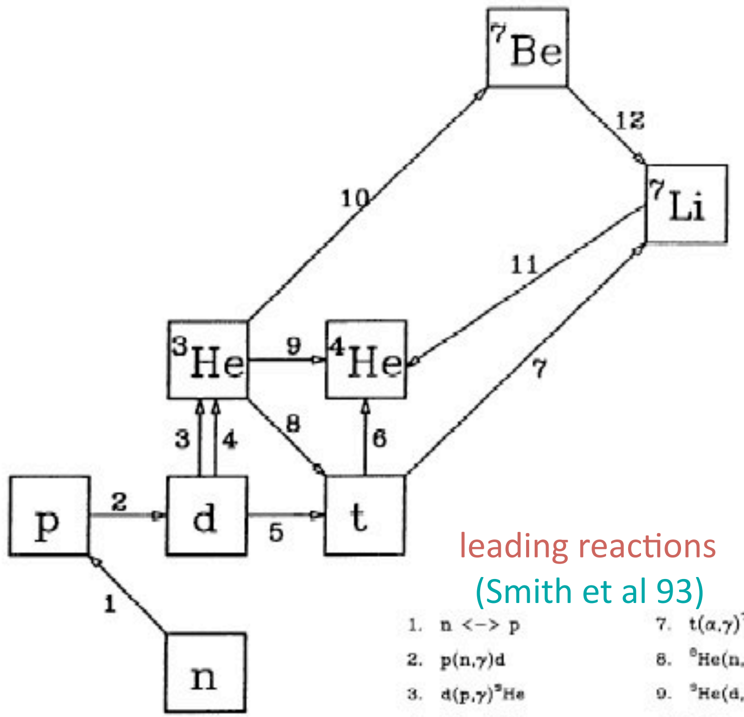
Reaction rate uncertainties translate into uncertainties in theoretical predictions:

Monte-Carlo evaluation of uncertainties
Krauss & Romanelli 90,
Smith et al 93,
Kernan & Krauss 94

Semi-analytical evaluation of the error matrix
Fiorentini et al 98
Lisi et al. 00

Re-analysis of nuclear data
Nollet & Burles 00, Cyburt et al 01,
Descouvement et al. 04, Cyburt et al. 04,
Serpico et al. 04

Recent new data and compilations
NACRE Coll. Database
LUNA: $D(p,\gamma)^3He$, $^3He(a,\gamma)^7Be$




leading reactions
(Smith et al 93)

| | |
|---|---|
| 1. $n \leftrightarrow p$ | 7. $t(\alpha,\gamma)^7Li$ |
| 2. $p(n,\gamma)d$ | 8. $^3He(n,p)t$ |
| 3. $d(p,\gamma)^3He$ | 9. $^3He(d,p)^4He$ |
| 4. $d(d,n)^3He$ | 10. $^3He(\alpha,\gamma)^7Be$ |
| 5. $d(d,p)t$ | 11. $^7Li(p,\alpha)^4He$ |
| 6. $t(d,n)^4He$ | 12. $^7Be(n,p)^7Li$ |

Sub-leading reactions
(see Serpico et al. 04)