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The cosmological information on neutrino mixing

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Goals

General particle cosmology pattern:

Particle Physics Model

↘

Kinetic Equations

↘

Cosmological observables

particle physics model: **neutrino mixing**

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \\ \cdot \\ \cdot \\ \cdot \\ \cdot \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \dots & \dots & \dots & \dots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \dots & \dots & \dots & \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \\ \cdot \\ \cdot \\ \cdot \\ \cdot \end{pmatrix}$$

Cosmological observations

CMBR anisotropies $\Rightarrow$ baryon content

BOOMERanG and DASI find exactly the same result (see also the combined analysis by Wang, Tegmark and Zaldarriaga); at 68% c.l.:

$$\Omega_b\, h^2 \;=\; 0.022^{+0.004}_{-0.003} \Rightarrow \eta_{10}^{CBR} = 6.0^{+1.1}_{-0.8};$$

$\eta_{10} \equiv (n_N/n_\gamma)\, 10^{10} \simeq 273\, \Omega_b\, h^2$

Primordial Nuclear abundances (68%c.l.)

$$(Y_p^{\rm exp})^{\rm high} \;=\; 0.245 \pm 0.002 \;\; \text{(Izotov et.al. 1999)}$$
$$(Y_p^{\rm exp})^{\rm low} \;=\; 0.234 \pm 0.003 \;\; \text{(Olive et. al. 1997)}$$

$(D/H)^{\rm exp} = (3.0 \pm 0.4) \cdot 10^{-5}$ (O'Meara et. al. 2001)

Standard BBN (SBBN)

- 3 ordinary neutrinos with $m_i \ll 1\,MeV$
- standard neutrino distributions:

$$f_{\nu_\alpha} = f_{\bar{\nu}_\alpha} = 1/(1+e^{E/T})$$

$$\Rightarrow Y_p = Y_p^{SBBN}(\eta), \quad (D/H) = (D/H)^{SBBN}(\eta)$$

test of compatibility SBBN-CMBR:

$$\begin{cases} Y_p^{SBBN}(\eta^{CBR}) & = & Y_p^{\exp} \\ (D/H)^{SBBN}(\eta^{CBR}) & = & (D/H)^{\exp} \end{cases}$$

$$\begin{cases} Y_p^{SBBN}(\eta^{CBR}) & \simeq & 0.2467 + 0.01\ \ln(\frac{\eta_{10}^{CBR}}{5}) & = & 0,2485^{+0,0017}_{-0,0014} \\ (D/H)^{SBBN}(\eta^{CBR}) & \simeq & 3.6\cdot 10^{-5}\,(\frac{\eta_{10}^{CBR}}{5})^{-1.7} & = & (2.7^{+0.7}_{-0.7})\cdot 10^{-5} \end{cases}$$

- good agreement with $(Y_p^{\exp})^{\text{high}}$ and with $(D/H)^{\exp}$;
- more than 3σ discrepancy with $(Y_p^{\exp})^{\text{low}}$

Non standard BBN models

Two different kinds of deviations from the standard BBN:

1. change of energy density degrees of freedom

$$H = \sqrt{\frac{8\pi\,\rho}{3\,M_{PL}^2}} \simeq \frac{1.66\sqrt{g_\rho}}{M_{PL}}\,T^2$$

$$g_\rho = \frac{11}{2} + \frac{21}{4}\left(\frac{T_\nu}{T}\right)^4 + \frac{7}{4}\Delta N_\nu^\rho \left(\frac{T_\nu}{T}\right)^4$$

$$\Delta N_\nu^\rho = \sum_\alpha \frac{\rho_{\nu_\alpha} + \rho_{\bar\nu_\alpha}}{2\rho_\nu^0} - 3 \;\Rightarrow \Delta Y_p^\rho \simeq 0.012\,\Delta N_\nu^\rho$$

$$\rho_\nu^0 \equiv \frac{1}{2\pi^2}\int_0^\infty dp\,p^3\,f_\nu^0, \qquad f_\nu^0 \equiv (1+e^{p/T_\nu})^{-1}$$

2. deviations of electron neutrino distributions

   Electron neutrinos and anti-neutrinos have a special role in the neutron-proton interconvertion reactions:

$$\begin{aligned} n &\leftrightarrow p + e^- + \bar\nu_e \\ n + e^+ &\leftrightarrow p + \bar\nu_e \\ n + \nu_e &\leftrightarrow p + e^- \end{aligned}$$

$$\delta f_{\nu_e} \equiv f_{\nu_e} - f_\nu^0 \;\Rightarrow\; \Delta Y_p^{f_{\nu_e}} = \Delta Y_p^{\rm tot} - \Delta Y_p^\rho$$

   By convention we can define:

$$\Delta N_\nu^{f_{\nu_e}} \equiv \frac{\Delta Y_p^{f_{\nu_e}}}{0.012}$$

$$\Rightarrow \Delta N_\nu^{\rm tot} = \Delta N_\nu^\rho + \Delta N_\nu^{f_{\nu_e}}$$

Constraints on non-SBBN

$$\begin{cases} Y_p^{BBN}(\eta^{CBR}, \Delta N_\nu^\rho, \delta f_{\nu_e}) & = & Y_p^{\rm exp} \\ (D/H)^{BBN}(\eta^{CBR}, \Delta N_\nu^\rho, \Delta N_\nu^{f_{\nu e}}) & = & (D/H)^{\rm exp} \end{cases}$$

$$Y_p^{BBN}(\eta^{CBR}, \Delta N_\nu^\rho, \Delta N_\nu^{f_{\nu e}}) \simeq 0.2466 + 0.01\ \ln(\eta_{10}^{CBR}/5) + 0.012\,(\Delta N_\nu^\rho + \Delta N_\nu^{f_{\nu e}})$$

at 3σ:

$$\Rightarrow \begin{cases} \Delta N_\nu^{\rm tot} = -0.3 \pm 0.6 & \text{high values} \\ \Delta N_\nu^{\rm tot} = -1.2 \pm 0.8 & \text{low values} \end{cases}$$

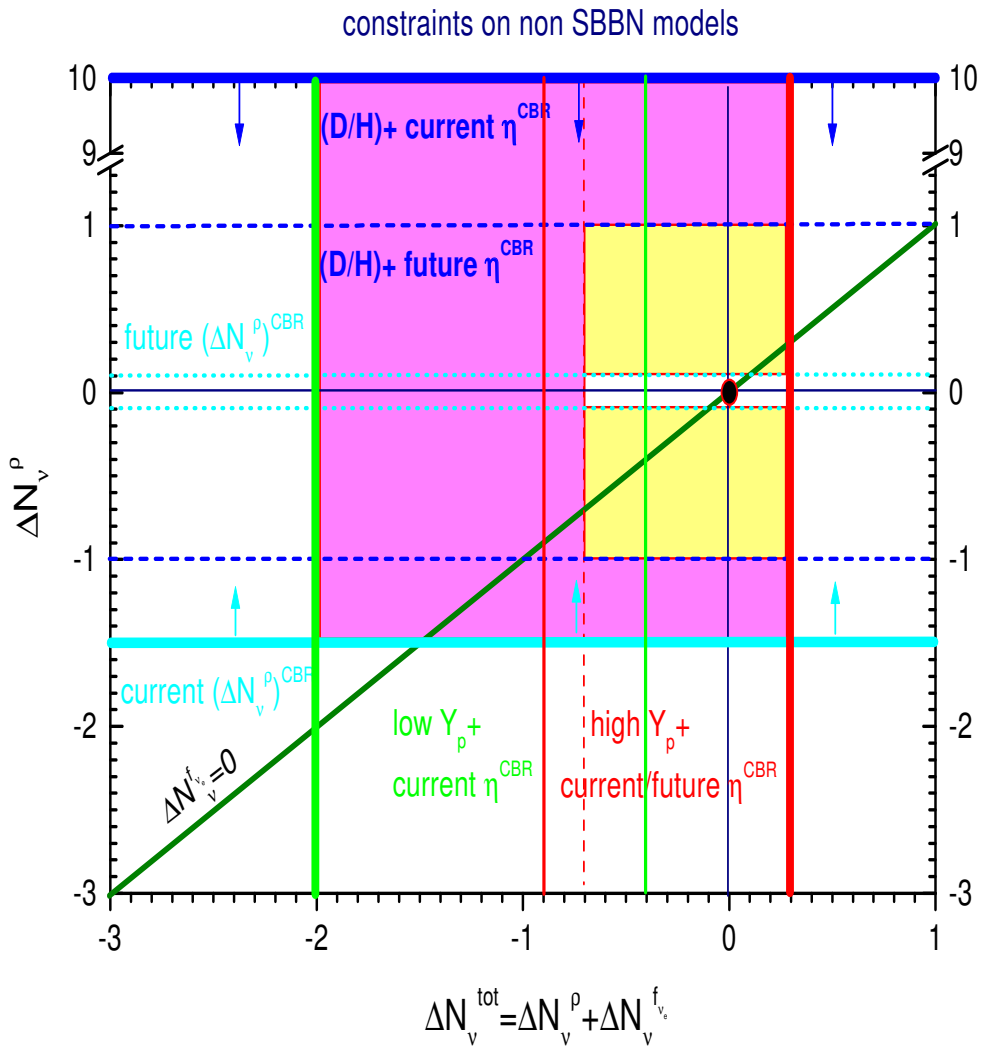
Sarkar 1999:

$$(D/H)^{BBN}(\eta^{CBR}, \Delta N_\nu^\rho, \Delta N_\nu^{f_{\nu e}}) \simeq 3.6 \cdot 10^{-5}\,(\eta_{10}^{CBR}/5)^{-1.7} \times \exp[0.117\,\Delta N_\nu^\rho]$$

$$\Rightarrow \Delta N_\nu^\rho \lesssim 10$$

- Realistically in future : $\delta[\Delta N_\nu^\rho] \lesssim 1$
- Moreover from satellite experiments we will measure directly $(\Delta N_\nu^\rho)^{CBR}$ with an error (Lopez et.al. '98,) : $\delta[(\Delta N_\nu^\rho)^{CBR}] = 10^{-3} - 10^{-1}$. At the moment very loose constraints (CBR+H_0+LSS): $11 \gtrsim (\Delta N_\nu^\rho)^{CBR} \gtrsim -1.5$ (Hannestad 2001)
- A comparison of $(\Delta N_\nu^\rho)^{CMB}$ with $\Delta(N_\nu^\rho)^{BBN}$ will give information on the quantity $\alpha \propto m_{\nu_i}^2 \tau$ (Hannestad 2000)

we can plot the constraints in a plane $\Delta N_\nu^{\rm tot} - \Delta N_\nu^\rho$:



Standard Model

The standard model of particle physics + BBN $\neq$ SBBN:

$$(\Delta N_\nu^{\rm tot})^{SM} \simeq 0.012$$
$$(\Delta N_\nu^{\rho})^{SM} \simeq 0.034$$

(Dolgov, Fukugita'92; Dodelson, Turner '92; Hannestad, Madsen '95; Gnedin & Gnedin '97; Dolgov,Hansen & Semikoz '98)

CBR anisotropies + CBR polarization should manage to get $\delta[\Delta N_\nu^{\rho}] = 10^{-3}$–$10^{-2}$ and thus to distinguish the small effect of neutrino heating + finite temperature QED that makes $(\Delta N_\nu^{\rho})^{SM} \neq 0$ (Lopez et. al. '98)

Bimaximal Mixing

(Vissani '97, Barger et. al. '98, Altarelli and Feruglio '98,. . .)

It is the most economical and favoured solution to explain neutrino mixing experiments excluding LSND:

$$s \equiv \sin\theta_{13}, \quad c \equiv \cos\theta_{13}, \quad \text{CHOOZ} \Rightarrow \theta_{13} \ll 1$$

$$U_{\text{bm}} = \begin{pmatrix} c/\sqrt{2} & c/\sqrt{2} & s \\ (-1-s)/2 & (1-s)/2 & c/\sqrt{2} \\ (1-s)/2 & (-1-s)/2 & c/\sqrt{2} \end{pmatrix}$$

The bimaximal mixing modifies $(\Delta N_\nu^\rho)^{\text{SM}}$ in a too tiny way to see it. There should be also modifications of $\Delta N_\nu^{\text{tot}}$ (i.e. of Y_p) (Langacker et. al. '87, Shi et. al '92), again beyond the precision of the observations. Can one hope to see them in future ?

$\nu_\alpha \leftrightarrow \nu_{\text{sterile}}$

only two mixing parameters: $\delta m^2 \equiv m_4^2 - m_\alpha^2$ and $\sin^2 2\theta_0$ $(\alpha = e, \mu, \tau)$

- In most of the mixing parameters space one has that:

$$\Delta N_\nu^{f_{\nu_e}} \geq 0 \Rightarrow \Delta N_\nu^{\text{tot}} \geq \Delta N_\nu^{\rho} \geq 0$$

and this yields restrictive constraints

(Kainulainen '90; Dolgov,Barbieri'90; Enqvist et. al.'92; Shi et. al '93; Kirillova,Chizhov '96)

- But in the region of mixing parameters:

$$\delta m^2 < 0, \quad \sin^2 2\theta_0 \ll 10^{-3}$$

a large α-neutrino asymmetry is generated

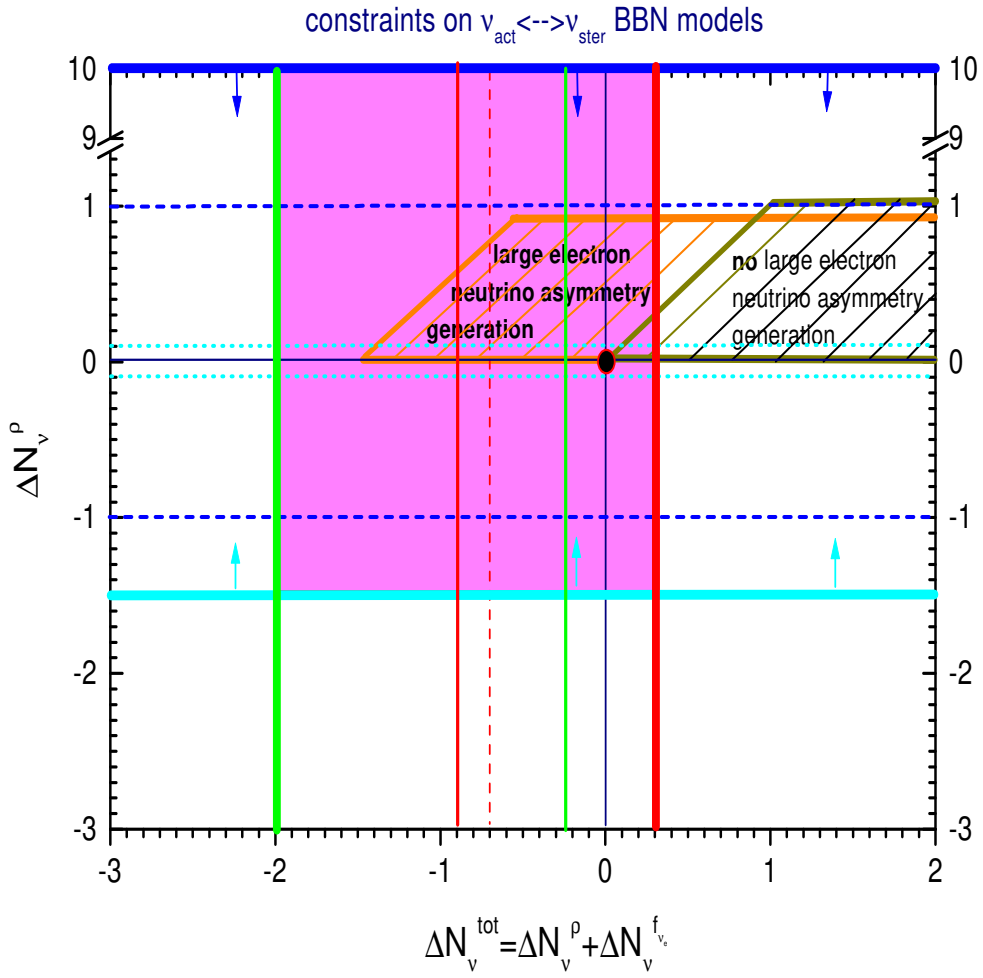
(Foot,Thomson,Volkas '96; Foot,Volkas '97)

If $\alpha = e \Rightarrow \Delta N_\nu^{f_{\nu_e}}$ can be also **negative** with:

$|\Delta N_\nu^{f_{\nu_e}}| \lesssim 1.5$ and $0 \leq \Delta N_\nu^{\rho} \lesssim 0.9$

In this way one can get $\Delta N_\nu^{\text{tot}}$ **negative**

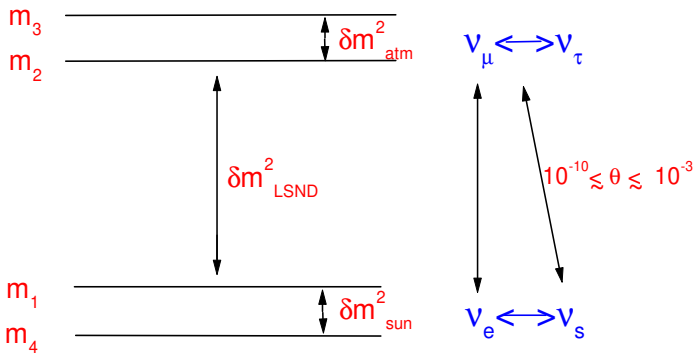
in the plot $\Delta N_\nu^{\rm tot} - \Delta N_\nu^\rho$:



it is remarkable that neutrino asymmetry generation can occur for mixing angles as small as 10^{-10} due to the adiabaticity of the MSW effect that amplifies the asymmetry to large values after a collision dominated phase (PDB,Foot 2001) $\Rightarrow$ this is important in more realistic multiflavor mixing models

4 neutrino mixing

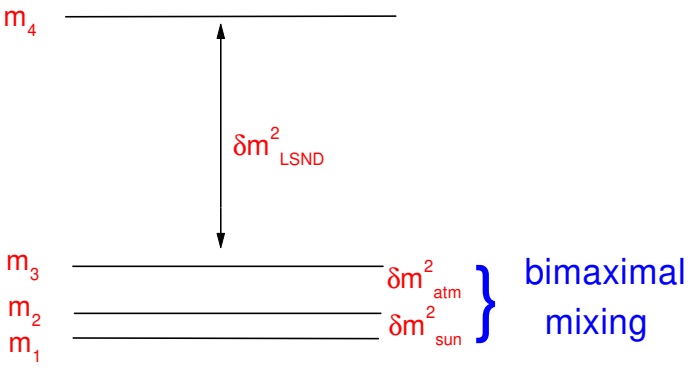
2+2 model



$\Rightarrow \quad \Delta N_\nu^\rho \ll 1 \qquad \Delta N_\nu^{f_{\nu e}} \simeq +0.3, -0.3$

(Bell, Foot and Volkas '98)

3+1 model



naïvely:

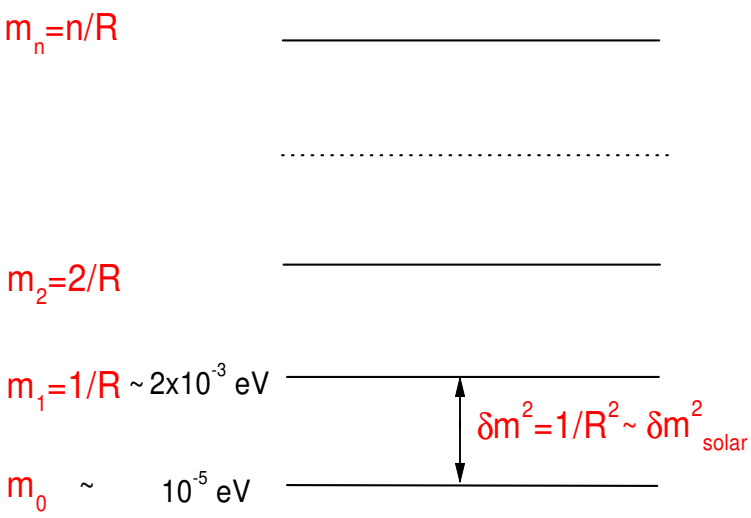
$\ln(1-\Delta N_\nu^\rho)^{-1} \sim 2 \cdot 10^2 \, (\sin^2 2\theta_{LSND}) \sqrt{\delta m^2_{LSND}/\mathrm{eV}^2} \sim 0.5$

It would be interesting to have an accurate calculation

Large extra dimensions

KK tower

(Dienes,Dudas,Gherghetta'99;Dvali,Smirnov'99)



$$\nu_e \simeq \nu_0 \quad \nu_e \leftrightarrow \nu_n^{\text{bulk}} \quad \theta_n \simeq \sqrt{2}\, m_0\, R/n \ll 1$$

$$\Rightarrow \delta m_n^2 \sin^2 2\theta_n \simeq 10^{-8}\,\text{eV}^2 \Rightarrow (\Delta N_\nu^\rho)_n \simeq 0.001/n$$

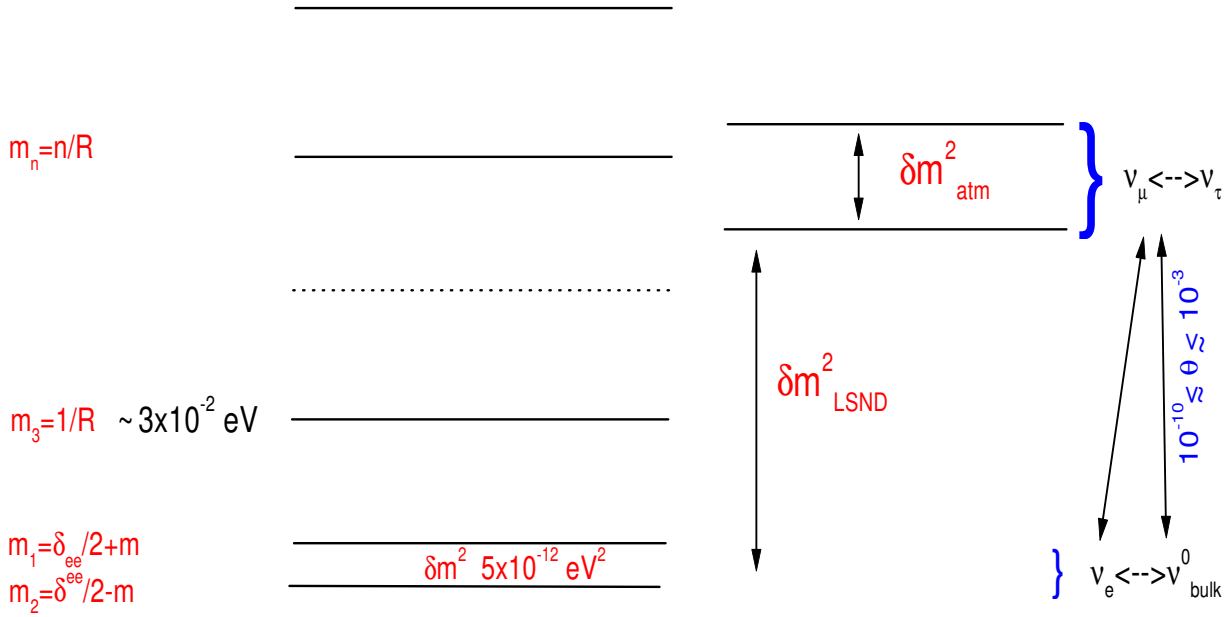
$$\Rightarrow \Delta N_\nu^\rho \simeq \sum_1^{10^5} (\Delta N_\nu^\rho)_n \simeq 0.01 \qquad \text{maybe detectable !}$$

$$\text{no asymmetry generation} \Rightarrow \Delta N_\nu^{f_{\nu_e}} = 0$$

However asymmetry generation can be naturally obtained in an extended version

KK tower+Majorana mass matrix

(Caldwell, Mohapatra, Yellin 2000)



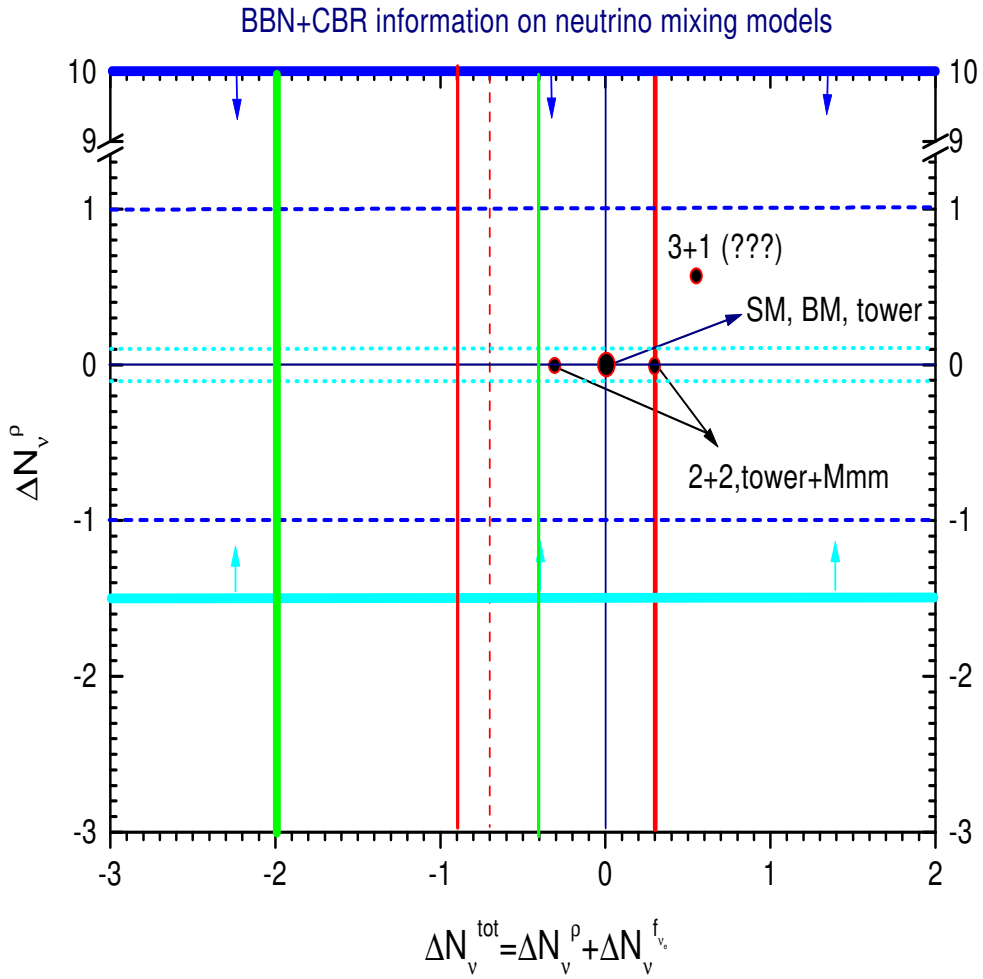
Due to the asymmetry generation:

$\Rightarrow \Delta N_\nu^\rho$ approximately halved

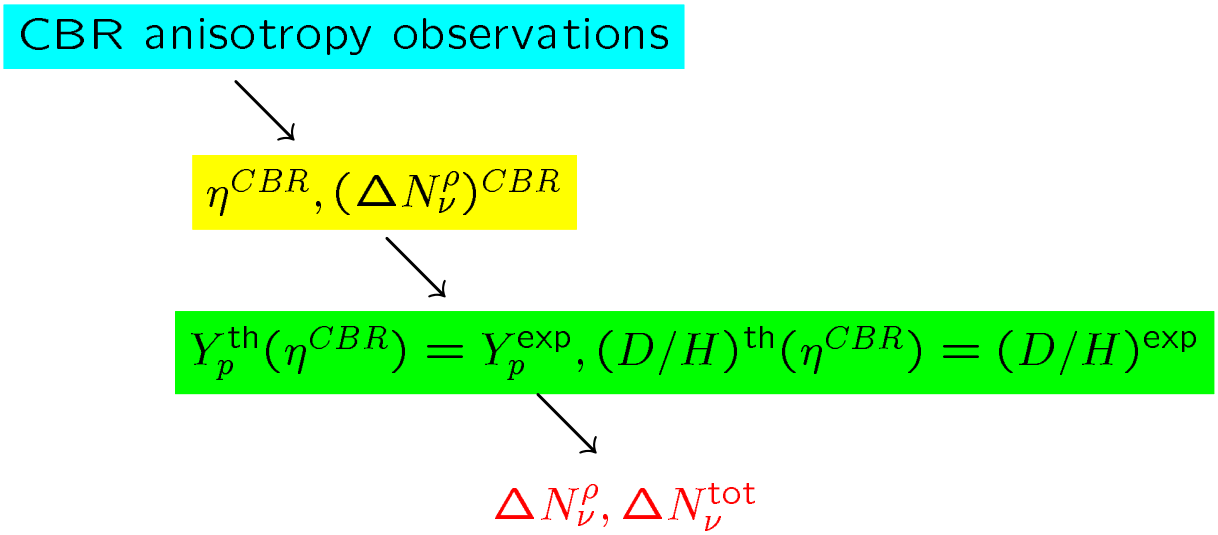
(suppression of bulk modes production for $\delta m_n^2 \gtrsim \delta m^2_{LSND}$)

$$\Delta N^{f_{\nu_e}} \simeq (\Delta N^{f_{\nu_e}})^{2+2\text{model}}$$

Summary


BBN+CBR information on neutrino mixing models
3+1 (???)
SM, BM, tower
2+2,tower+Mmm
ΔN_ν^ρ
$\Delta N_\nu^{tot}=\Delta N_\nu^\rho+\Delta N_\nu^{f_{\nu_e}}$

Conclusions



more restrictive constraints on non SBBN models

(plots in the $\Delta N_\nu^\rho - \Delta N_\nu^{\rm tot}$ plane)

The early Universe is highly sensitive to a possible mixing between the ordinary and a sterile neutrino sector (if this exists) $\Rightarrow$ complementary information to Earth experiments

special relevance for neutrino mixing models arising in theories with large or warped extra dimensions

confirmation of the peculiar sensitivity of early cosmology to new physics.