INFN Naples Astroparticle Physics Group
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# *Dynamics of Neutrino Asymmetries and BBN*


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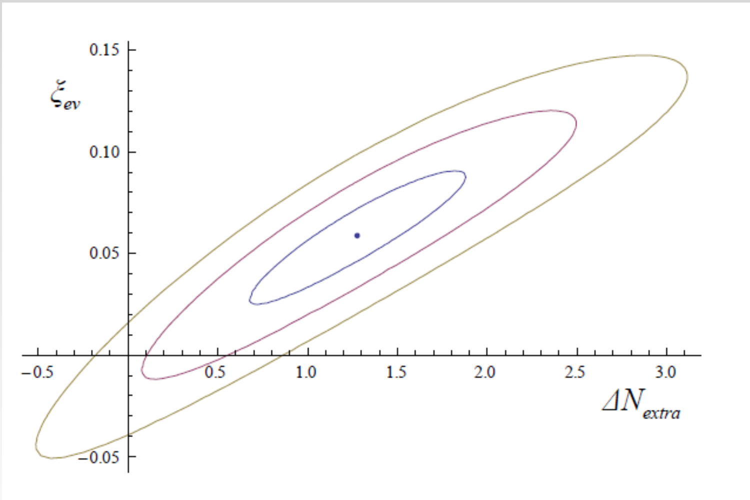
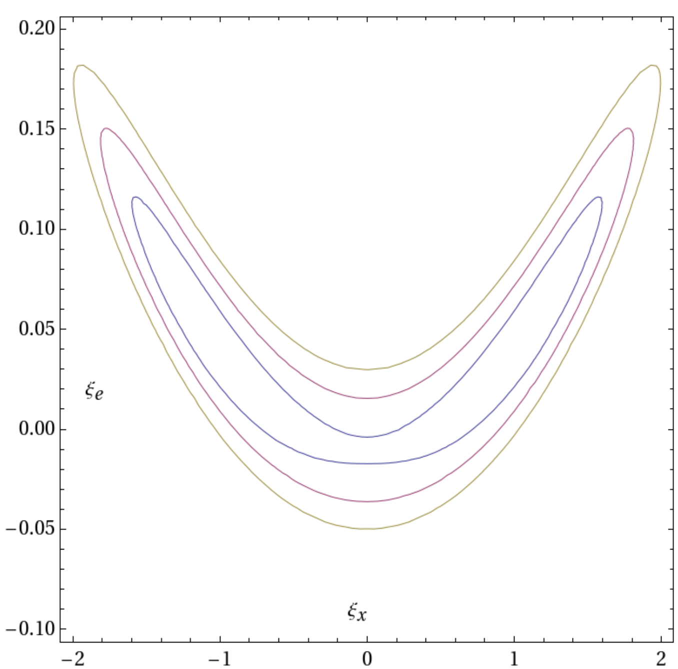
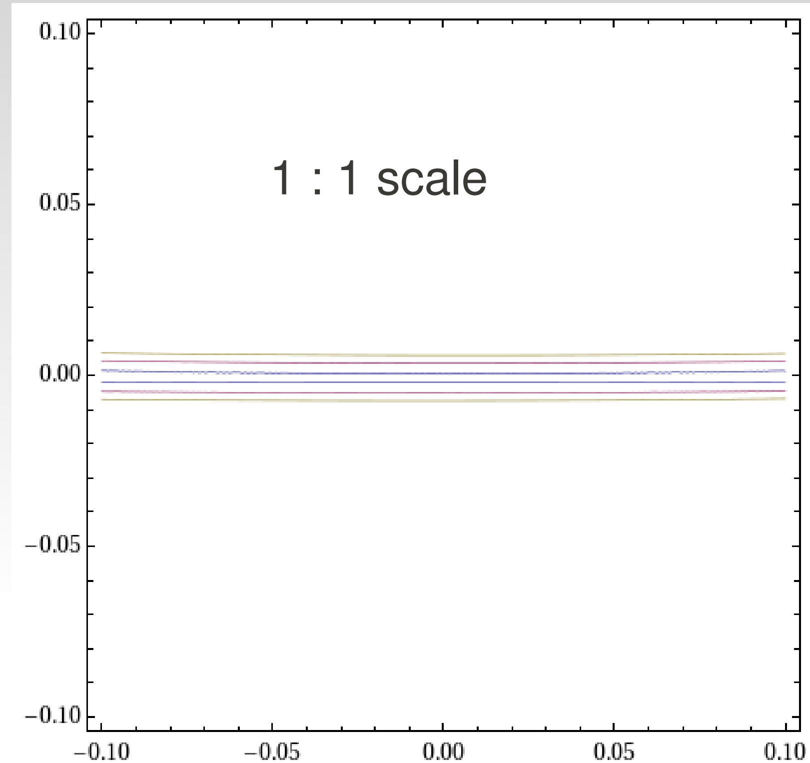
Obsolete no-oscillation-case:




$$\Delta N_\nu = \frac{15}{7}\left[\left(\frac{\xi}{\pi}\right)^4 + 2\left(\frac{\xi}{\pi}\right)^2\right]$$




PHYSICAL REVIEW D, VOLUME 65, 023511

**Constraining neutrino physics with big bang nucleosynthesis and cosmic microwave background radiation**

(Received 4 June 2001; published 21 December 2001)

We perform a likelihood analysis of the recent results on the anisotropy of cosmic microwave background radiation from the BOOMERanG and DASI experiments to show that they single out an effective number of neutrinos in good agreement with standard big bang nucleosynthesis. We also consider degenerate big bang nucleosynthesis to provide new bounds on effective relativistic degrees of freedom $N_\nu$ and, in particular, on the neutrino chemical potential $\xi_\alpha$. When including supernova type Ia data we find, at $2\sigma$, $N_\nu \leqslant 7$ and $-0.01 \leqslant \xi_e \leqslant 0.22$, $|\xi_{\mu,\tau}| \leqslant 2.6$.

## Oscillations:

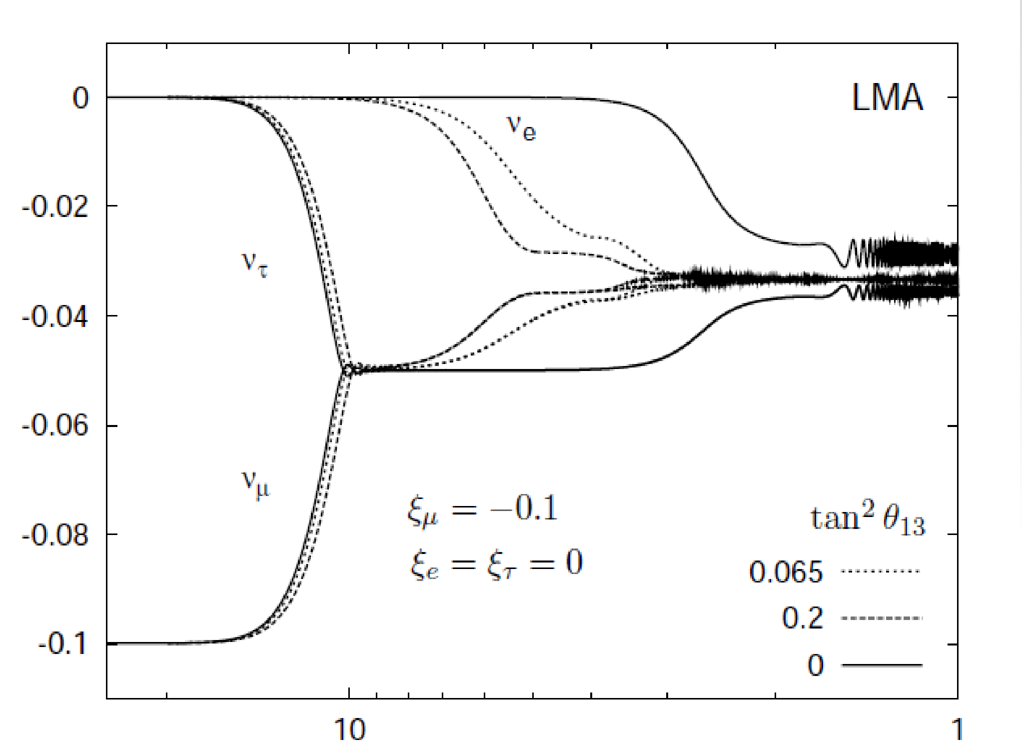
A. D. Dolgov et al., Nucl.Phys. B **632** (2002) 363

The equations are written for the usual 3x3 matrix:

$$\rho(p,t) = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} & \rho_{e\tau} \\ \rho_{\mu e} & \rho_{\mu\mu} & \rho_{\mu\tau} \\ \rho_{\tau e} & \rho_{\tau\mu} & \rho_{\tau\tau} \end{pmatrix}$$

The QKE should take into account:

- vacuum oscillations
- effects of the background plasma
- effects of the neutrino background (self-interaction)
- collisions



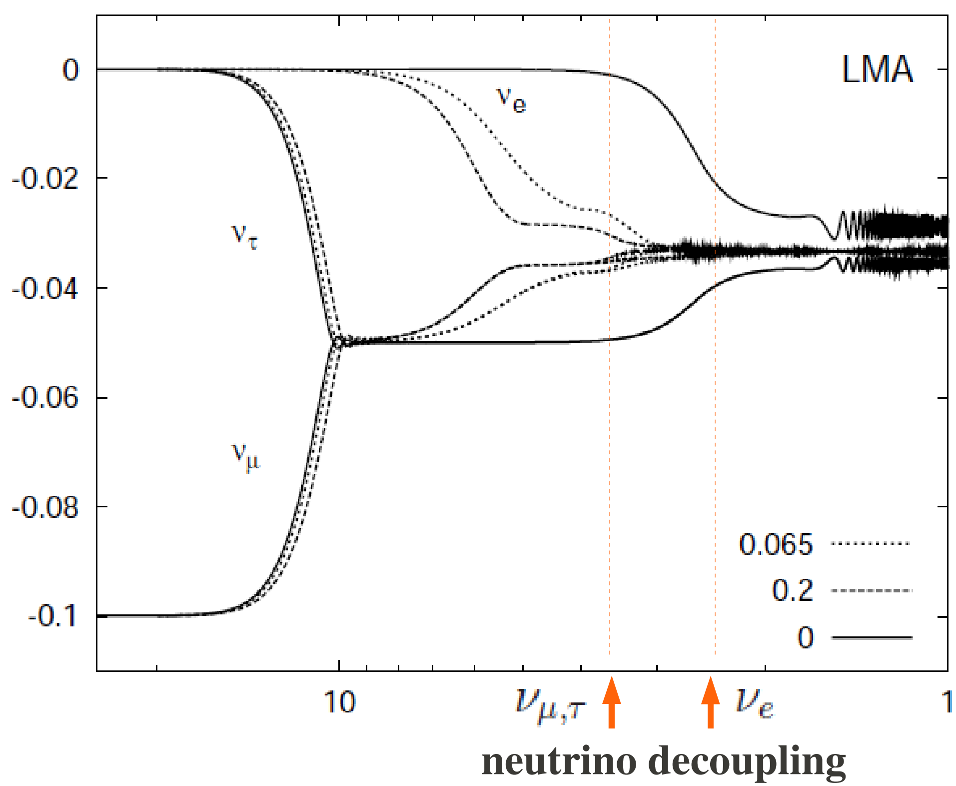

*"We conclude that in the LMA region the neutrino flavors essentially* ***equilibrate long before n/p freeze out****, even when $\theta_{13}$ is vanishingly small"*

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

$$i\partial_t \rho_p = +\left[\frac{M^2}{2p}, \rho_p\right] + \sqrt{2}G_F\left[\left(-\frac{8p}{3m_W^2}E + \rho - \bar{\rho}\right), \rho_p\right] + C[\rho_p]$$

# However...

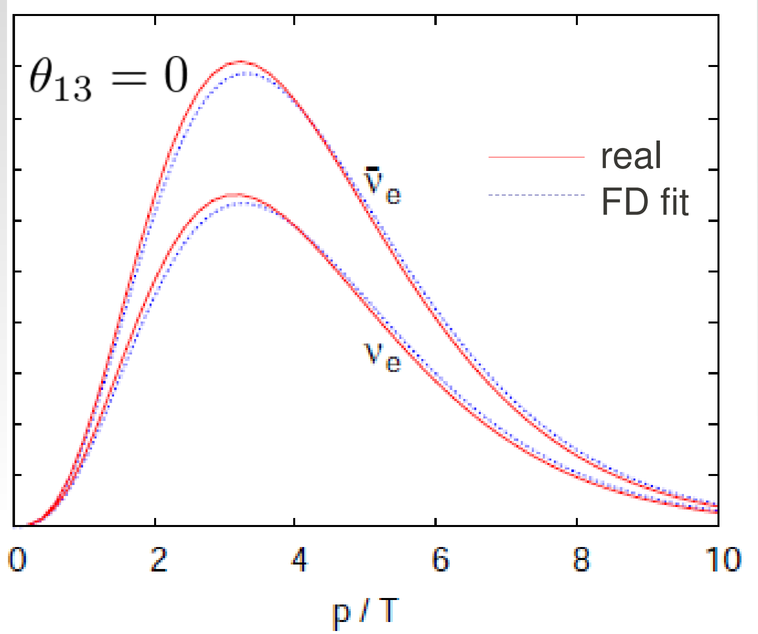
A. D. Dolgov et al., Nucl.Phys. B **632** (2002) 363




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

Once neutrinos decouple, flavour conversions continue to lead to equipartition among all flavours, but there is no process driving them to kinetic and chemical equilibrium.

* An average of two equilibrium Fermi-Dirac distributions is ***not necessarily a FD distribution!***



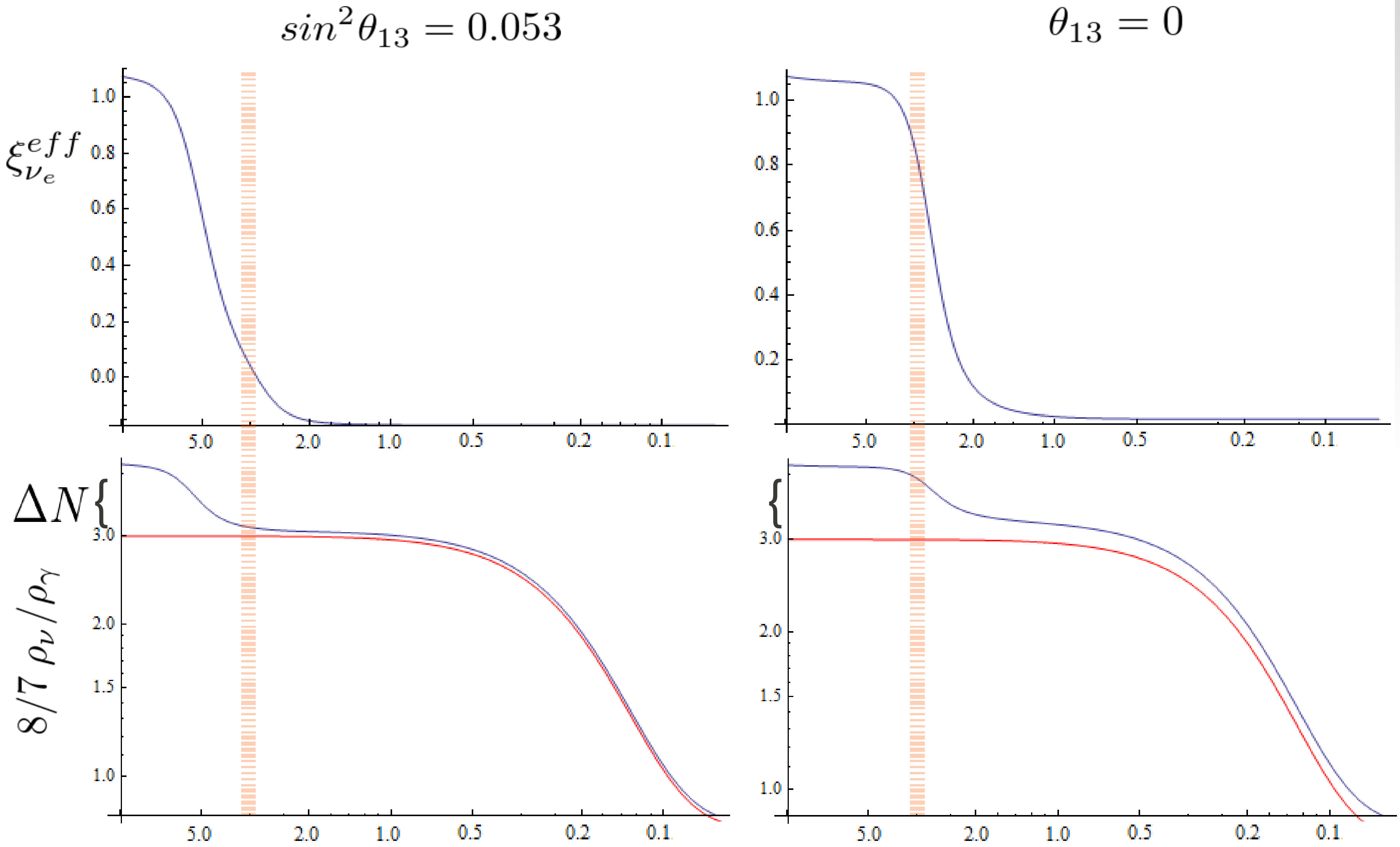

Distribution could be approximated as equilibrium Fermi-Dirac with two ***effective parameters*** $T_\nu^{eff}$ and $\xi_\nu^{eff}$, producing the same:

- ***asymmetry L*** and
- ***contribution to energy density ΔN***.

*Def: "Comoving" asymmetry:

$$L_a = (n_{\nu_a} - n_{\bar{\nu}_a}) \times T^{-3}$$
$$= \frac{1}{6}\left(\xi_{\nu_e} + \frac{\xi^3_{\nu_e}}{\pi^2}\right)$$

Example:




$$L_{\nu_e}^{init} = 0.2,\ L_{tot} = -0.1$$

Method:

Choose a point in $(L_{\nu_e}^{init}, L^{tot})$ plane

Solve QKE for neutrinos

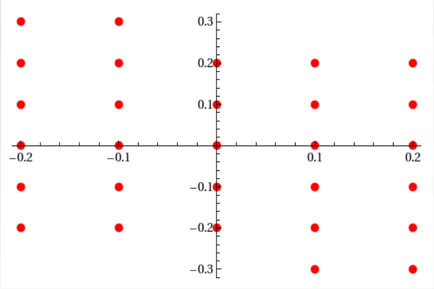
Neutrino evolution files

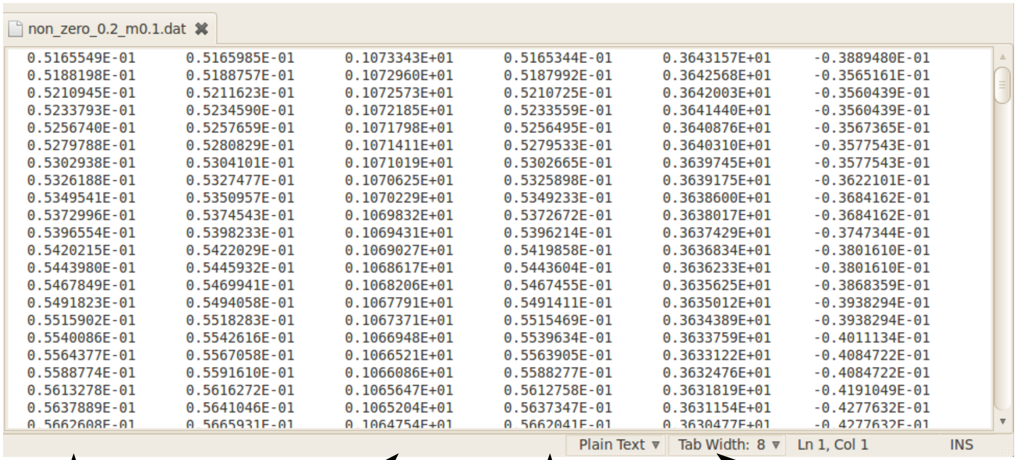
Run PArthENoPE

Pars outputs

$^4He, D$

Draw likelihood





non_zero_0.2_m0.1.dat

| | | | | | |
|---|---|---|---|---|---|
| 0.5165549E-01 | 0.5165985E-01 | 0.1073343E+01 | 0.5165344E-01 | 0.3643157E+01 | -0.3889480E-01 |
| 0.5188198E-01 | 0.5188757E-01 | 0.1072960E+01 | 0.5187992E-01 | 0.3642568E+01 | -0.3565161E-01 |
| 0.5210945E-01 | 0.5211623E-01 | 0.1072573E+01 | 0.5210725E-01 | 0.3642003E+01 | -0.3560439E-01 |
| 0.5233793E-01 | 0.5234590E-01 | 0.1072185E+01 | 0.5233559E-01 | 0.3641440E+01 | -0.3560439E-01 |
| 0.5256740E-01 | 0.5257659E-01 | 0.1071798E+01 | 0.5256495E-01 | 0.3640876E+01 | -0.3567365E-01 |
| 0.5279788E-01 | 0.5280829E-01 | 0.1071411E+01 | 0.5279533E-01 | 0.3640310E+01 | -0.3577543E-01 |
| 0.5302938E-01 | 0.5304101E-01 | 0.1071019E+01 | 0.5302665E-01 | 0.3639745E+01 | -0.3577543E-01 |
| 0.5326188E-01 | 0.5327477E-01 | 0.1070625E+01 | 0.5325898E-01 | 0.3639175E+01 | -0.3622101E-01 |
| 0.5349541E-01 | 0.5350957E-01 | 0.1070229E+01 | 0.5349233E-01 | 0.3638600E+01 | -0.3684162E-01 |
| 0.5372996E-01 | 0.5374543E-01 | 0.1069832E+01 | 0.5372672E-01 | 0.3638017E+01 | -0.3684162E-01 |
| 0.5396554E-01 | 0.5398233E-01 | 0.1069431E+01 | 0.5396214E-01 | 0.3637429E+01 | -0.3747344E-01 |
| 0.5420215E-01 | 0.5422029E-01 | 0.1069027E+01 | 0.5419858E-01 | 0.3636834E+01 | -0.3801610E-01 |
| 0.5443980E-01 | 0.5445932E-01 | 0.1068617E+01 | 0.5443604E-01 | 0.3636233E+01 | -0.3801610E-01 |
| 0.5467849E-01 | 0.5469941E-01 | 0.1068206E+01 | 0.5467455E-01 | 0.3635625E+01 | -0.3868359E-01 |
| 0.5491823E-01 | 0.5494058E-01 | 0.1067791E+01 | 0.5491411E-01 | 0.3635012E+01 | -0.3938294E-01 |
| 0.5515902E-01 | 0.5518283E-01 | 0.1067371E+01 | 0.5515469E-01 | 0.3634389E+01 | -0.3938294E-01 |
| 0.5540086E-01 | 0.5542616E-01 | 0.1066948E+01 | 0.5539634E-01 | 0.3633759E+01 | -0.4011134E-01 |
| 0.5564377E-01 | 0.5567058E-01 | 0.1066521E+01 | 0.5563905E-01 | 0.3633122E+01 | -0.4084722E-01 |
| 0.5588774E-01 | 0.5591610E-01 | 0.1066086E+01 | 0.5588277E-01 | 0.3632476E+01 | -0.4084722E-01 |
| 0.5613278E-01 | 0.5616272E-01 | 0.1065647E+01 | 0.5612758E-01 | 0.3631819E+01 | -0.4191049E-01 |
| 0.5637889E-01 | 0.5641046E-01 | 0.1065204E+01 | 0.5637347E-01 | 0.3631154E+01 | -0.4277632E-01 |
| 0.5662608E-01 | 0.5665931E-01 | 0.1064754E+01 | 0.5662041E-01 | 0.3630477E+01 | -0.4277632E-01 |

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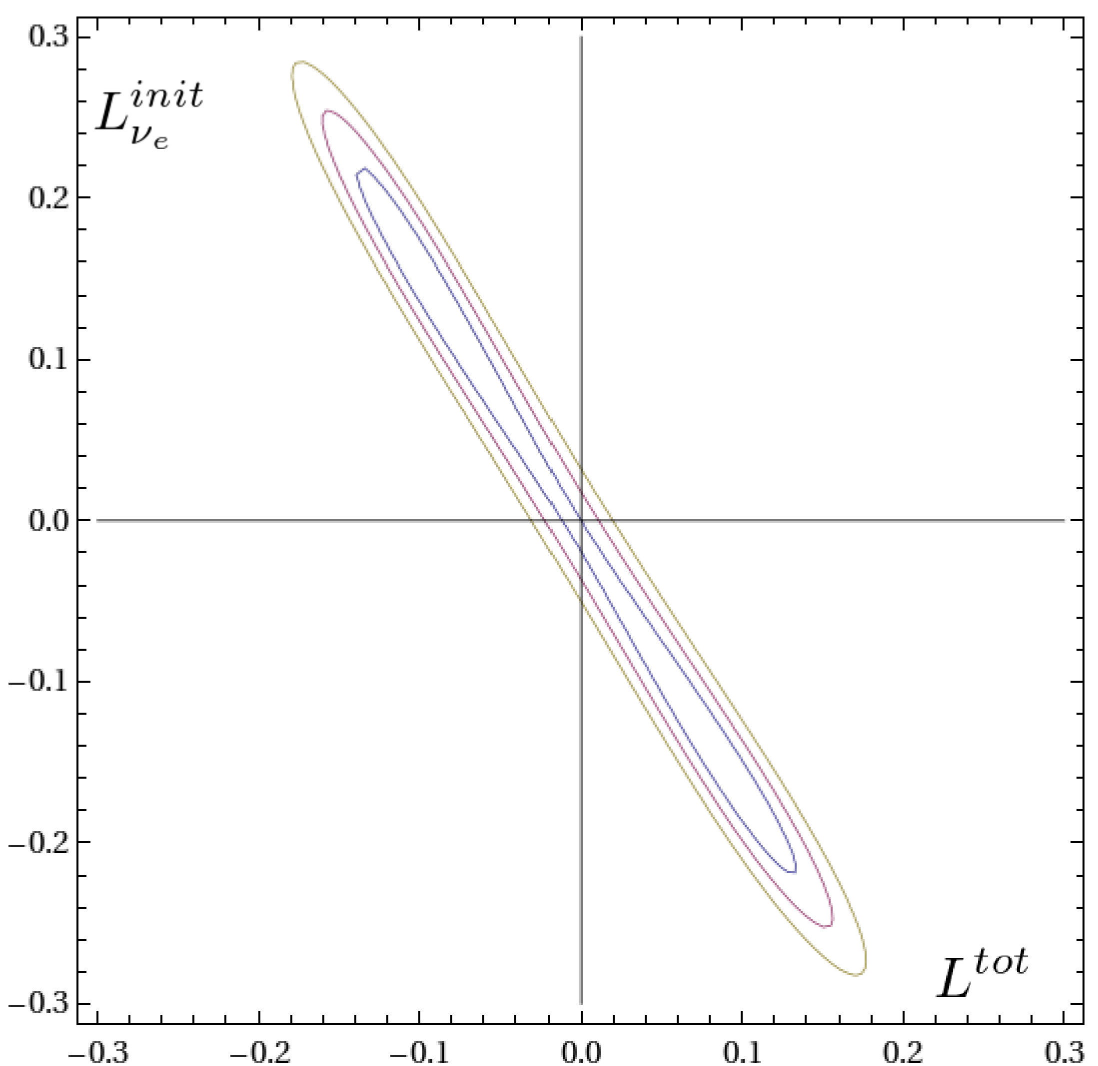
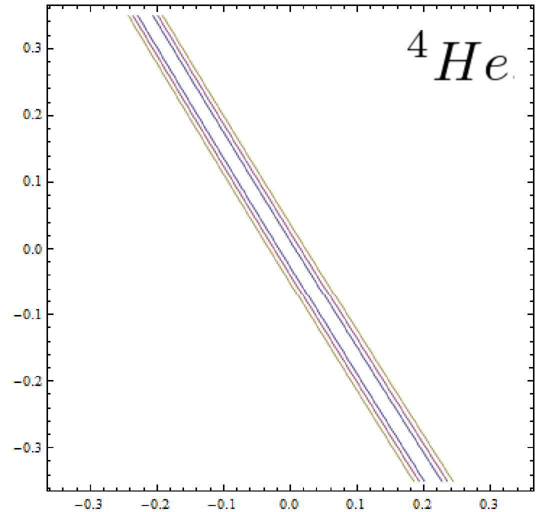
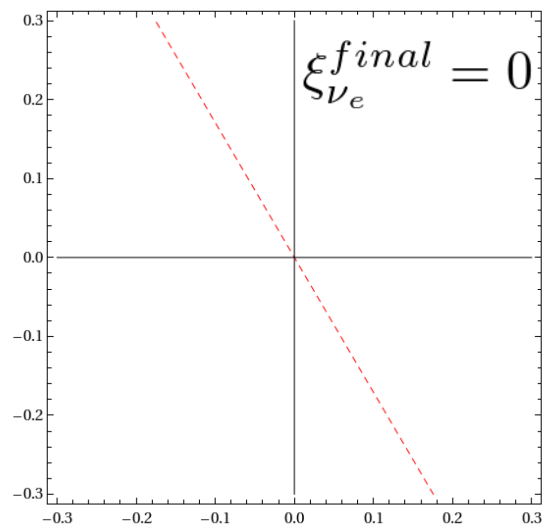
$$z = \frac{m_e}{T_\gamma} \qquad \xi_\nu^{eff} \qquad z_\nu = \frac{m_e}{T_\nu^{eff}} \qquad \frac{\rho_\nu}{\rho_\gamma}$$

Results:




$$\theta_{13} = 0$$

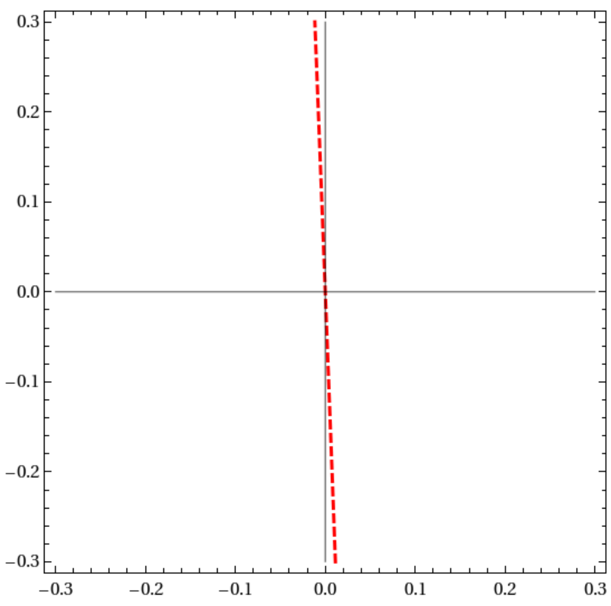
$\theta_{13} > 0$ case:

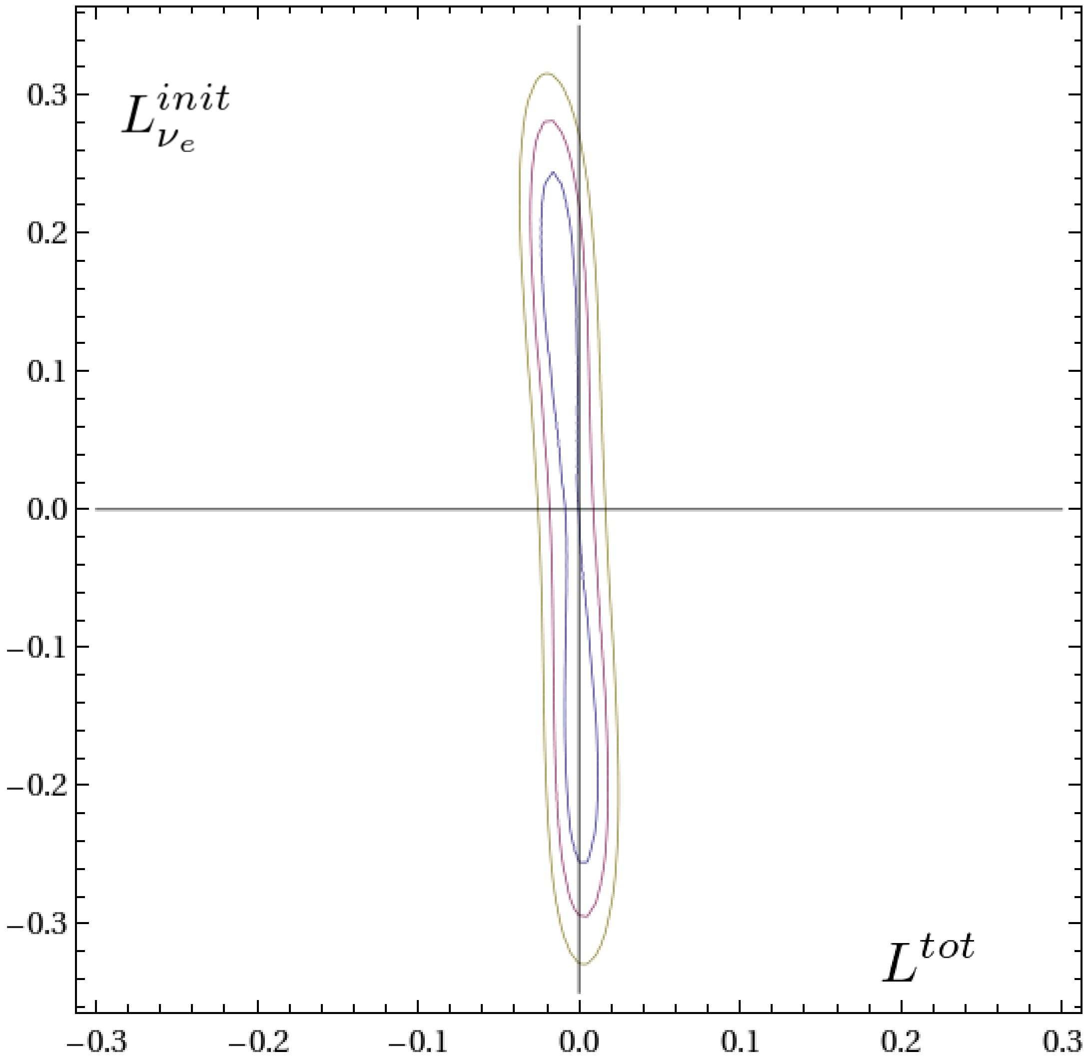
Neutrino chemical potential have more time to equilibrate:

$$\xi_{\nu_e} \approx \xi_{\nu_x}$$

$\xi_{\nu_e}^{final} = 0$ line is closer to $L^{tot} = 0$

Results prefer $\xi_{\nu_e} \approx 0$

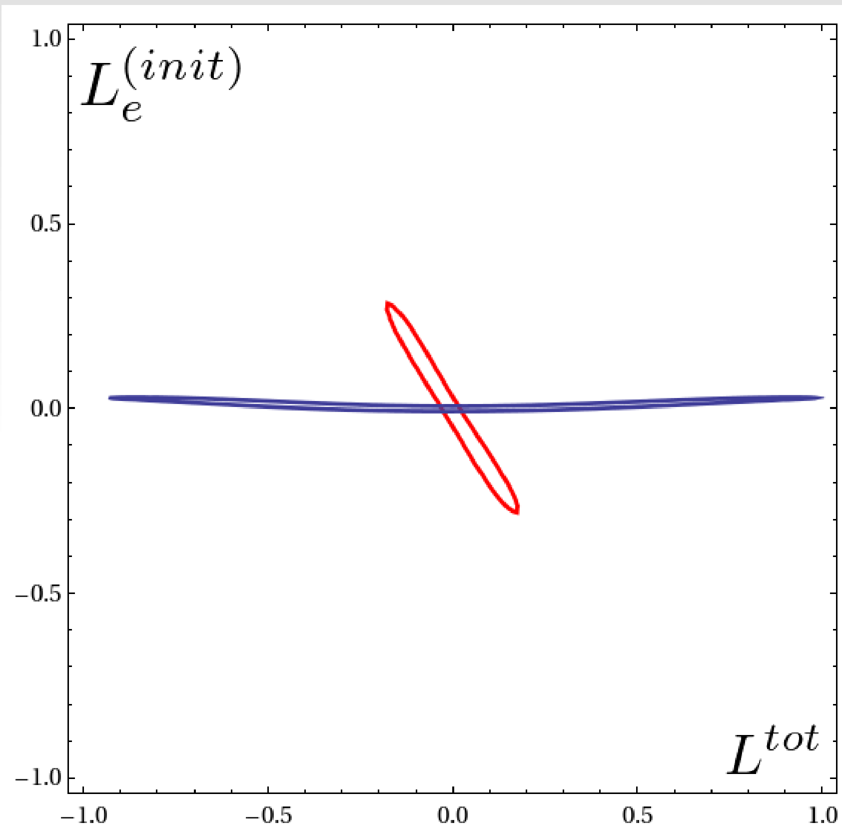


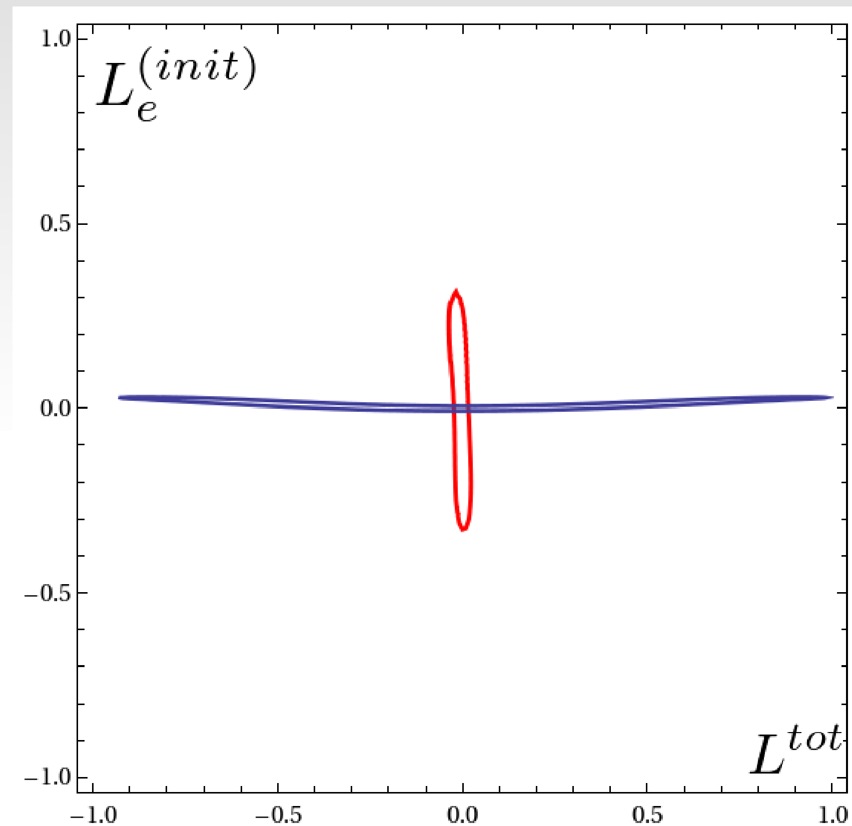

$$sin^2\theta_{13} = 0.053$$

Comparison of constraints in case of no oscillations and the new ones:

3-$\sigma$ plots




$\theta_{13} = 0$

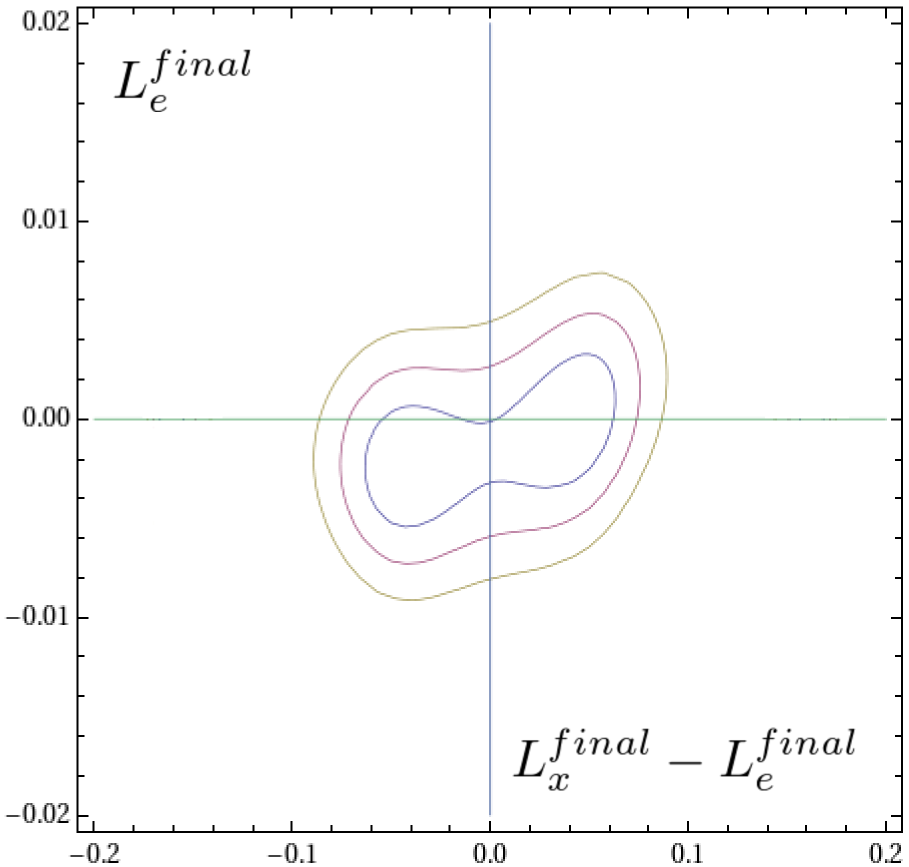



$sin^2\theta_{13} = 0.053$

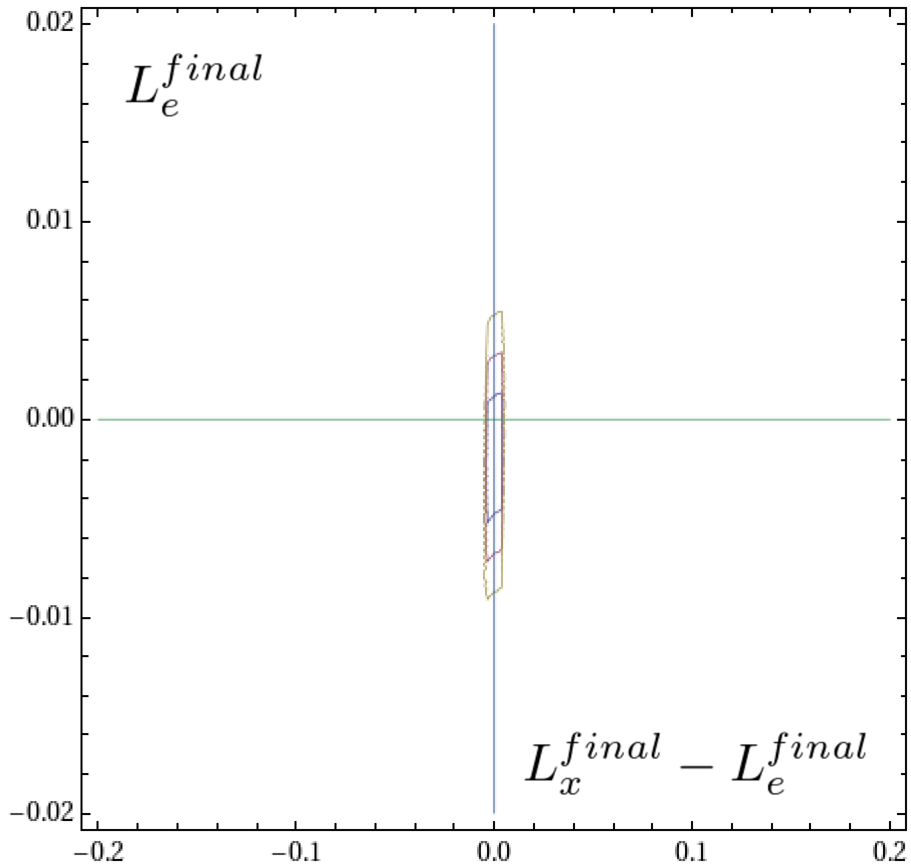
*no oscillations*

*our results*

## Constraints in the plane $(L_e^{final}, L_x^{final} - L_e^{final})$




$\theta_{13} = 0$




$sin^2\theta_{13} = 0.053$

Summary:

- Starting from QKE, for various points in $(L_{\nu_e}{}^{init}, L^{tot})$ plane, the distribution function for neutrinos was calculated explicitly, considering the inefficiency of the collisions at $T \lesssim 2 - 3$ MeV.
- These results are used as inputs for PArthENoPE to calculate abundances of deuterium and helium-4.
- PArthENoPE results were processed by likelihod analysis in $(L_{\nu_e}{}^{init}, L^{tot})$ and $(L_{\nu_e}{}^{final}, \Delta L^{final})$ planes.

- at 1-$\sigma$ C.L.

| | $\theta_{13} = 0$ | $sin\theta_{13} = 0.053$ |
|---|---|---|
| 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 $n_\gamma$ | $\lvert L_{\nu_e}^{init}\rvert < 0.86$ | $\lvert L_{\nu_e}^{init}\rvert < 0.98$ |
| residual neutrino asymmetry ($\times 10^3$) | $-5 < L_{\nu_e}^{final} < 3$ | $-5 < L_{\nu_e}^{final} < 1$ |
| final difference btw $L_e$ an $L_x$ ($\times 10^3$) | $\lvert L_{\nu_e}^{fin} - L_{\nu_x}^{fin}\rvert < 62$ | $\lvert L_{\nu_e}^{fin} - L_{\nu_x}^{fin}\rvert < 4$ |

- Further extension would be to include some additional d.o.f. (e.g. steriles), corresponding to varying $\Delta N$ as well.