Do neutrino flavor oscillations forbid large lepton asymmetries?

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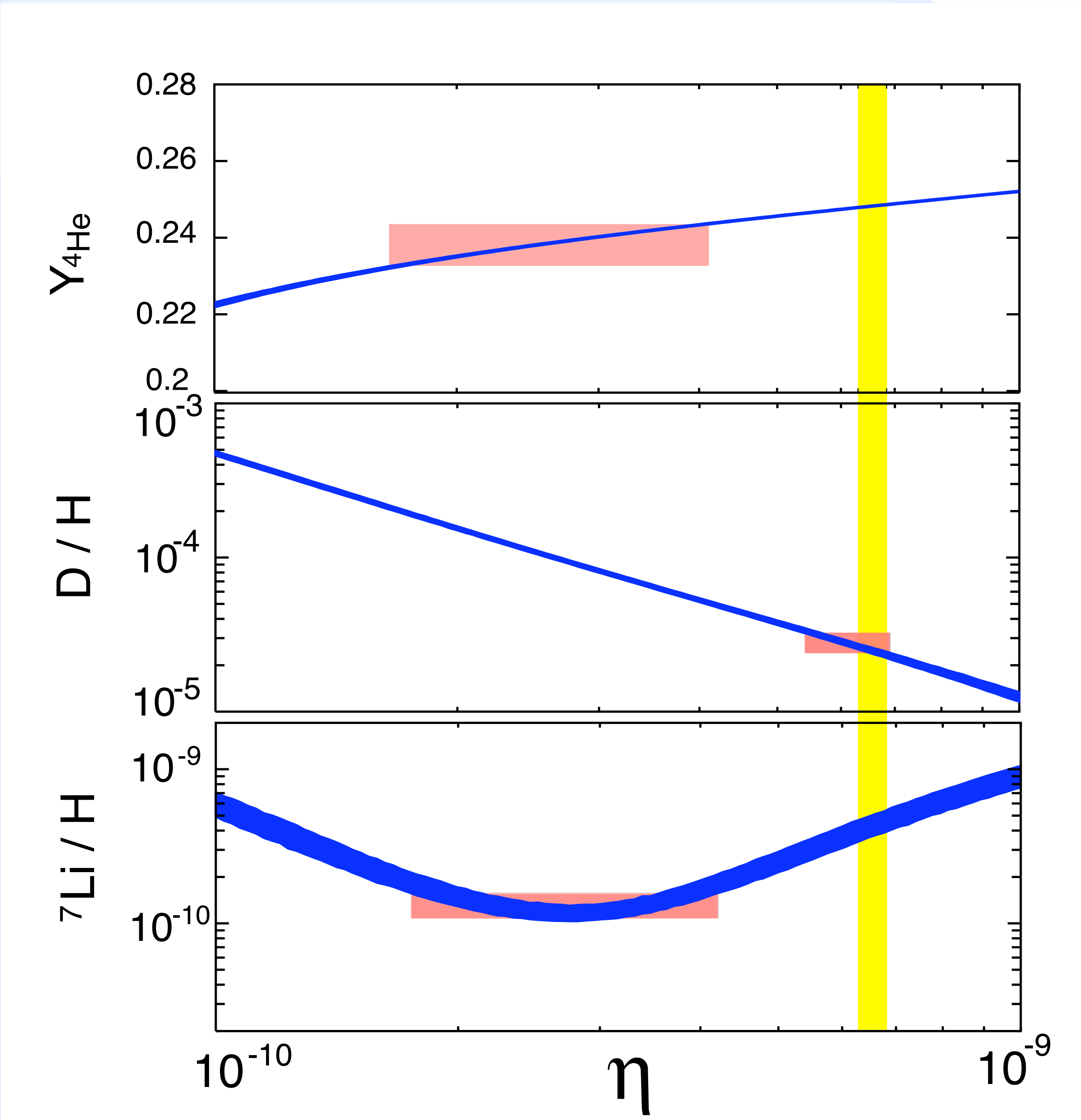
A.D. Dolgov and F.T. Nucl.Phys.B 688, 189 (2004)
(hep-ph/0402066)

Preliminaries

- The abundance of light elements:



Ichikawa, Kawasaki and F.T., '04

How to solve the descrepancy？

lepton asymmetries, varying alpha,etc....

1.Introduction

- Cosmological lepton asymmetry is constrained by BBN and CMB

$$\xi \equiv \frac{\mu}{T}$$:dimensionless chemical potential

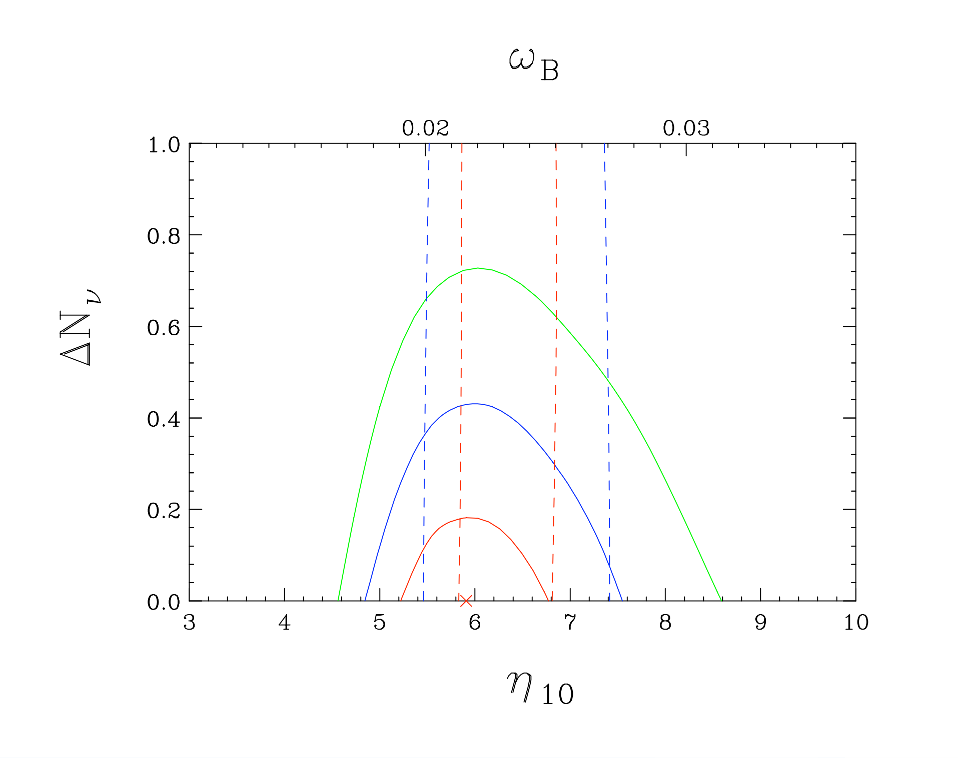
- Lepton asymmetry of electron type directly affects the beta equilibrium: $\nu_e\, n \leftrightarrow e^- p \qquad \bar{\nu}_e\, p \leftarrow e^+ n$
- Lepton asymmetry of muon or tauon type changes the expansion rate:

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

Constraints on $\xi_{e,\mu,\tau}$

(Kohri, Kawasaki, Sato '97)
(Barger et al '03)

$$|\xi_e| < 0.1 \qquad |\xi_{\mu,\tau}| < 0.9 \ \ (\Delta N_\nu < 0.4)$$

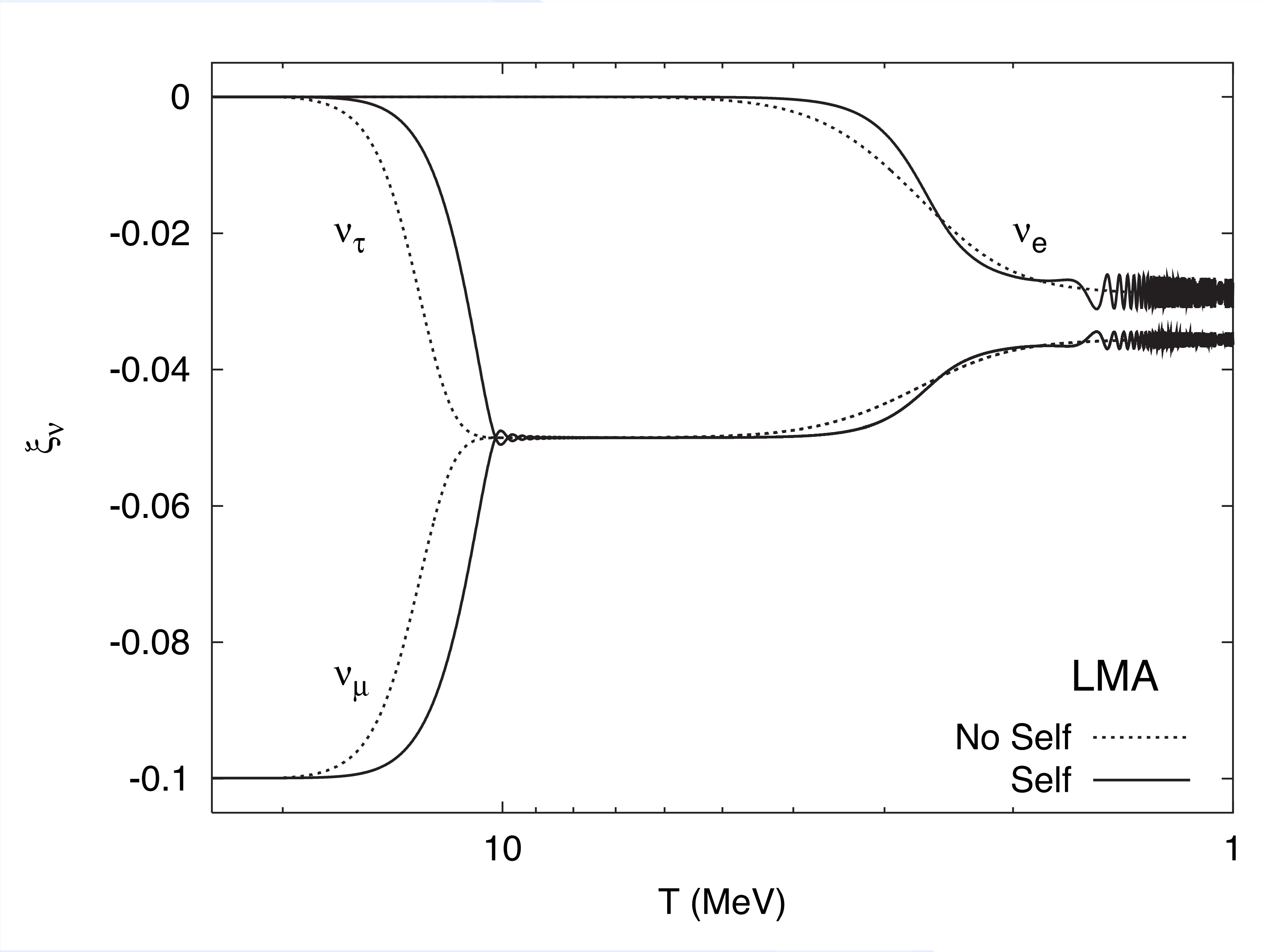


If a conspiracy between ξ_e and $\xi_{\mu,\tau}$ is allowed, the limits become weaker.

$$|\xi_e| < 0.2, \quad |\xi_{\mu,\tau}| < 2.6$$

(Hansen et al '02)

○ However, if neutrino oscillations equilibrate the lepton asymmetries,



(Dolgov et al '02)

$$\rightarrow \quad |\xi_{e,\mu,\tau}| < 0.07$$

- What we did:
  - We have shown that the neutrino-majoron interaction can suppress neutrino oscillations at the relevant BBN epoch, reopening a window for a large lepton asymmetry.

2.Neutrino Oscillation

Density Matrices:

$$\nu_i(x) = \int d\mathbf{p}\, \left(a_i(\mathbf{p})u_{\mathbf{p}} + b_i(-\mathbf{p})^\dagger v_{-\mathbf{p}}\right) e^{-ip^0 t + i\mathbf{p}\,\mathbf{x}},$$

$$\begin{aligned} \left\langle a_j^\dagger(\mathbf{p})\, a_i(\mathbf{p}')\right\rangle &= (2\pi)^3 \delta^{(3)}(\mathbf{p}-\mathbf{p}')\, [\rho_{\mathbf{p}}]_{ij}\,, \\ \left\langle b_i^\dagger(\mathbf{p})\, b_j(\mathbf{p}')\right\rangle &= (2\pi)^3 \delta^{(3)}(\mathbf{p}-\mathbf{p}')\, [\bar\rho_{\mathbf{p}}]_{ij}\,. \end{aligned}$$

$$\{i,\ j\} = \{e,\ \mu,\ \tau\}$$

Equation of Motion (in vacuum)

$$\begin{aligned} i\partial_t \rho_{\mathbf{p}} &= \left[\Omega^0_{\mathbf{p}}, \rho_{\mathbf{p}}\right] \\ i\partial_t \bar\rho_{\mathbf{p}} &= -\left[\Omega^0_{\mathbf{p}}, \bar\rho_{\mathbf{p}}\right] \end{aligned}$$

$$\Omega^0_{\mathbf{p}} = \sqrt{\mathbf{p}^2 + M^2}$$

EOM for density matrices :

Heisenberg equation

$$\partial_t \rho_{\mathbf{p}} = -i\left[\Omega^0_{\mathbf{p}}, \rho_{\mathbf{p}}\right] + i\left\langle\left[H_{\rm int}(B(t), \nu(t)), \mathcal{D}_{\mathbf{p}}\right]\right\rangle$$

$B(t)$:background field

$\mathcal{D}_{\mathbf{p}ij} \equiv a^\dagger_j(\mathbf{p})\, a_i(\mathbf{p})$

In a first-order perturbative approximation,

$$\partial_t \rho_{\mathbf{p}} = -i\left[\Omega^0_{\mathbf{p}}, \rho_{\mathbf{p}}\right] + i\left\langle\left[H^0_{\rm int}(t), \mathcal{D}^0_{\mathbf{p}}\right]\right\rangle$$

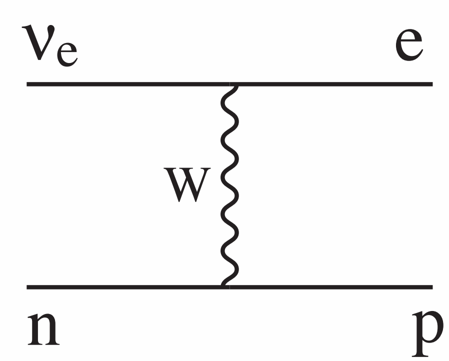
forward-scattering
or
refractive effect

Assuming no correlations between the neutrinos and the b.g.,

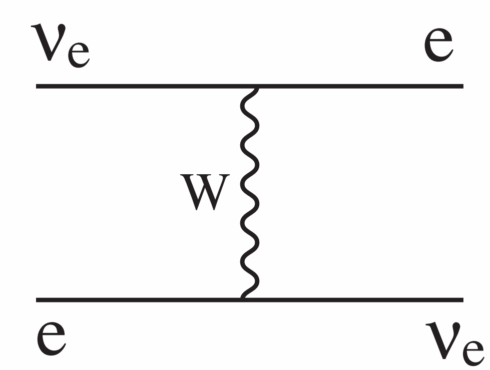
$$\sim \langle \text{background} \rangle \, \langle \text{neutrinos} \rangle$$

Relevant interactions:

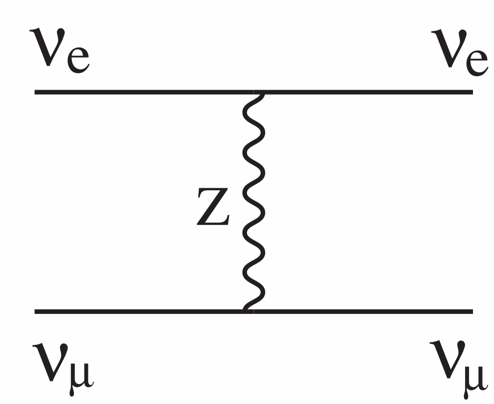
$$H_{CC} = \frac{G_F}{\sqrt{2}} \int d\mathbf{x} \bar{\chi}(\mathbf{x}) \nu(\mathbf{x}) + h.c.,$$



$$H_{NC} = \sqrt{2} G_F \int d\mathbf{x}\, B^\mu\, \bar{\nu}(\mathbf{x}) \gamma_\mu G \nu(\mathbf{x}),$$



$$H_S = \frac{G_F}{\sqrt{2}} \int d\mathbf{x}\, \bar{\nu}_a(\mathbf{x}) \gamma^\mu \nu_a(\mathbf{x})\, \bar{\nu}_b(\mathbf{x}) \gamma_\mu \nu_b(\mathbf{x}),$$



$$i\partial_t \rho_{\mathbf{p}} = [V_{\text{eff}}, \rho_{\mathbf{p}}]$$

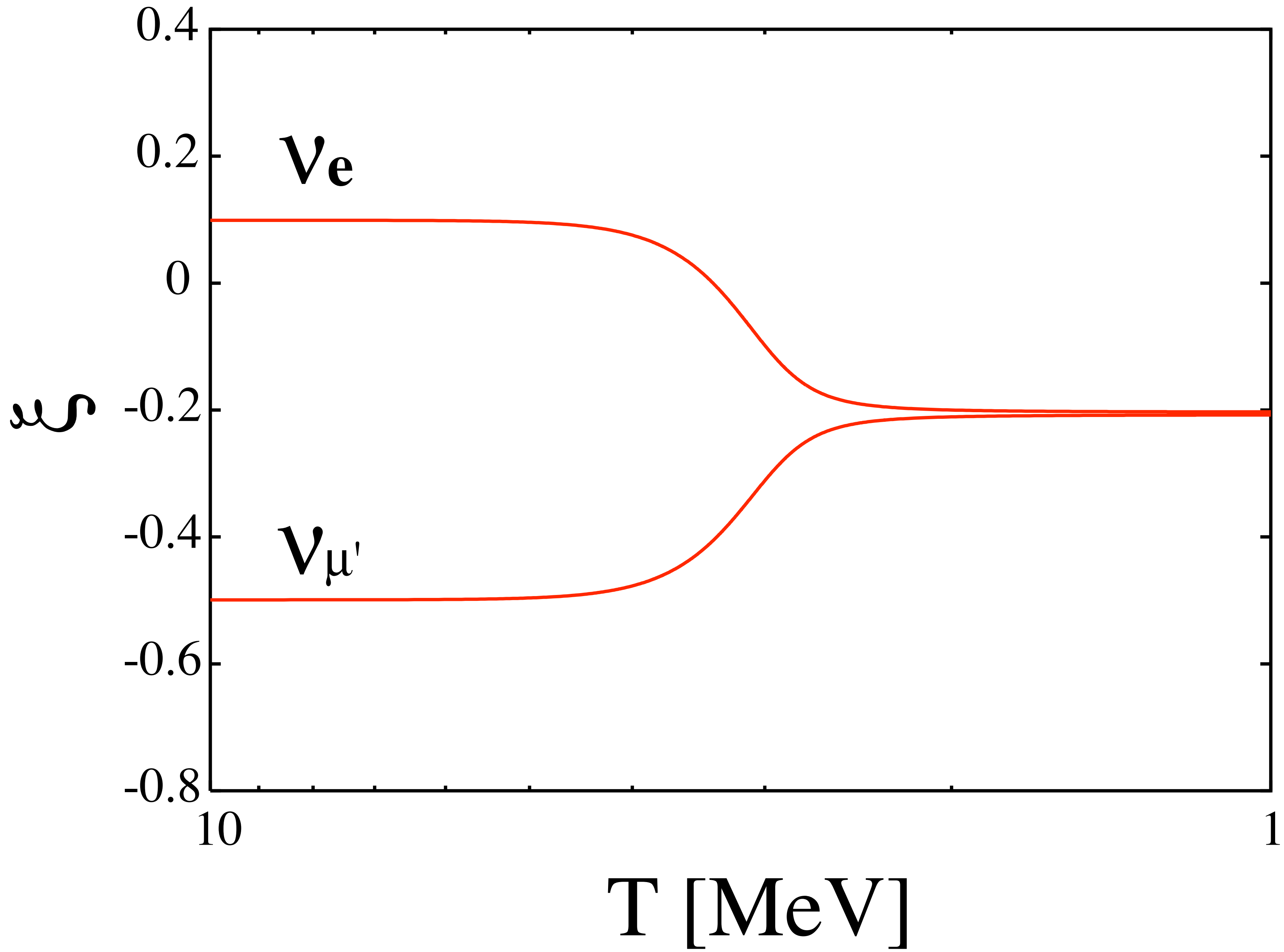
$$V_{\text{eff}} = \frac{M^2}{2p} + \sqrt{2} G_F (\rho - \bar{\rho})$$

$$\begin{pmatrix} X & 0 \\ 0 & Y \end{pmatrix}$$ neutrino oscillations can be suppressed.

$$\begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$$ neutrino oscillations are NOT suppressed.

Flavor Equilibration between ξ_e and $\xi_{\mu'}$

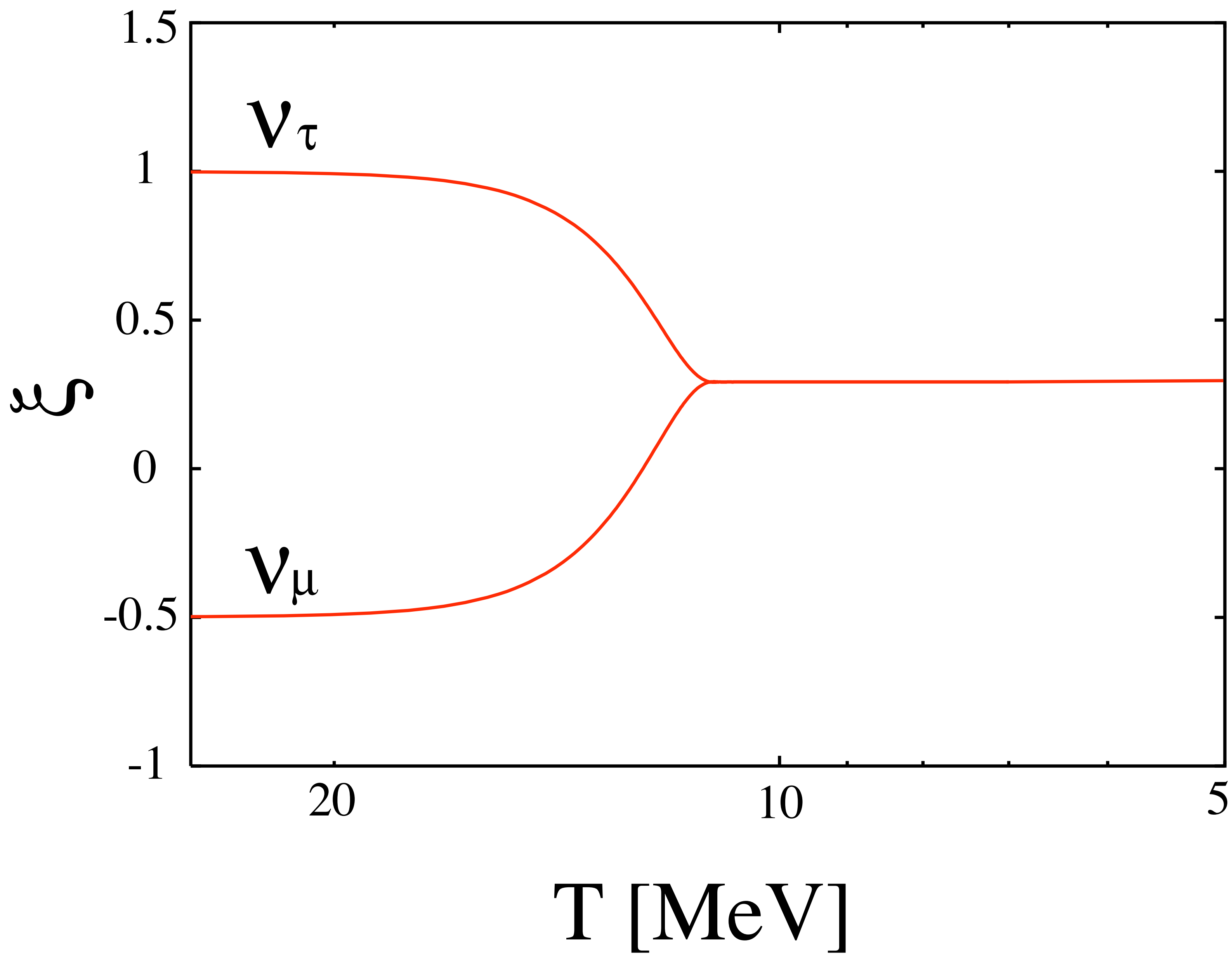
$\delta m^2_{21} = 7.3 \times 10^{-5} \mathrm{eV}^2$
$\sin^2\theta = 0.315$



(Dolgov and F.T. '04)

Flavor Equilibration between ξ_μ and ξ_τ

$\delta m^2_{32} = 2.5 \times 10^{-3} \mathrm{eV}^2$
maximal mixing



(Dolgov and F.T. '04)

3.Neutrino-Majoron interaction

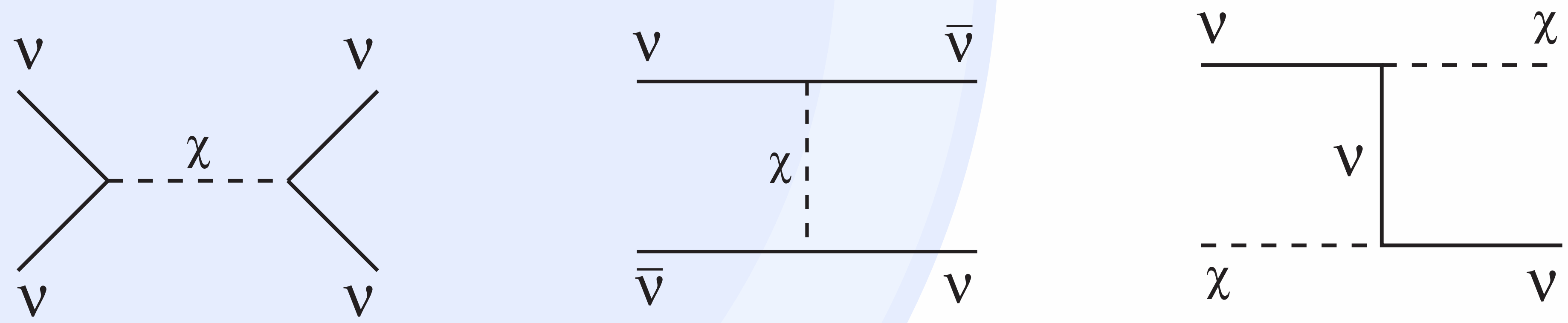
- **Lagrangian:**

$$\mathcal{L}_{int} = \frac{i}{2}\chi\left(g_{ab}\,\nu_a^T C\nu_b + g^*_{ab}\,\nu_b^\dagger C\nu_a^*\right),$$

$$C \equiv i\gamma^2\gamma^0$$

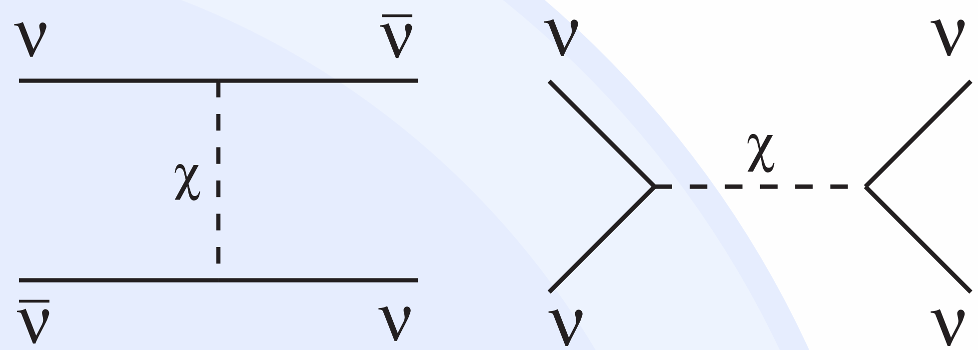
the effective potential:

$$\left[V_{\mathbf{p}}^{(\chi)}\right]_{ab} = \int d\mathbf{q}\ \frac{1}{4\,|\mathbf{p}|\,|\mathbf{q}|}\left[g^\dagger\left(\rho_{\mathbf{q}}^T + \overline{\rho}_{\mathbf{q}}^T + f_\chi(\mathbf{q})\cdot\mathbf{1}\right)g\right]_{ab},$$



For simplicity, let us take

$$g_{ab} = \begin{pmatrix} g_1 & 0 \\ 0 & g_2 \end{pmatrix} \Rightarrow V_\chi \sim T \begin{pmatrix} g_1 g_1 & g_1 g_2 \\ g_1 g_2 & g_2 g_2 \end{pmatrix}$$

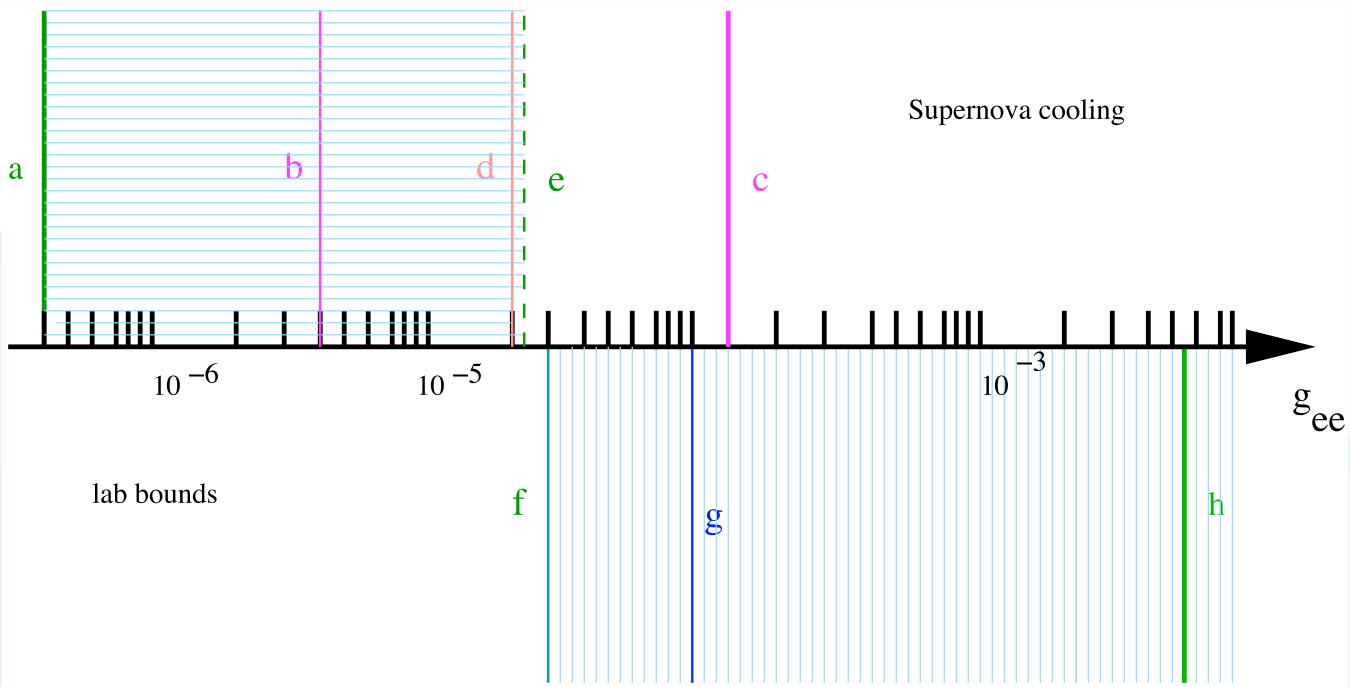


If $g_1 \ll g_2 \Rightarrow V_\chi \sim T g_2^2 \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$

Can g satisfy astrophysical bounds, while $V_\chi \gg V_{ew}$?

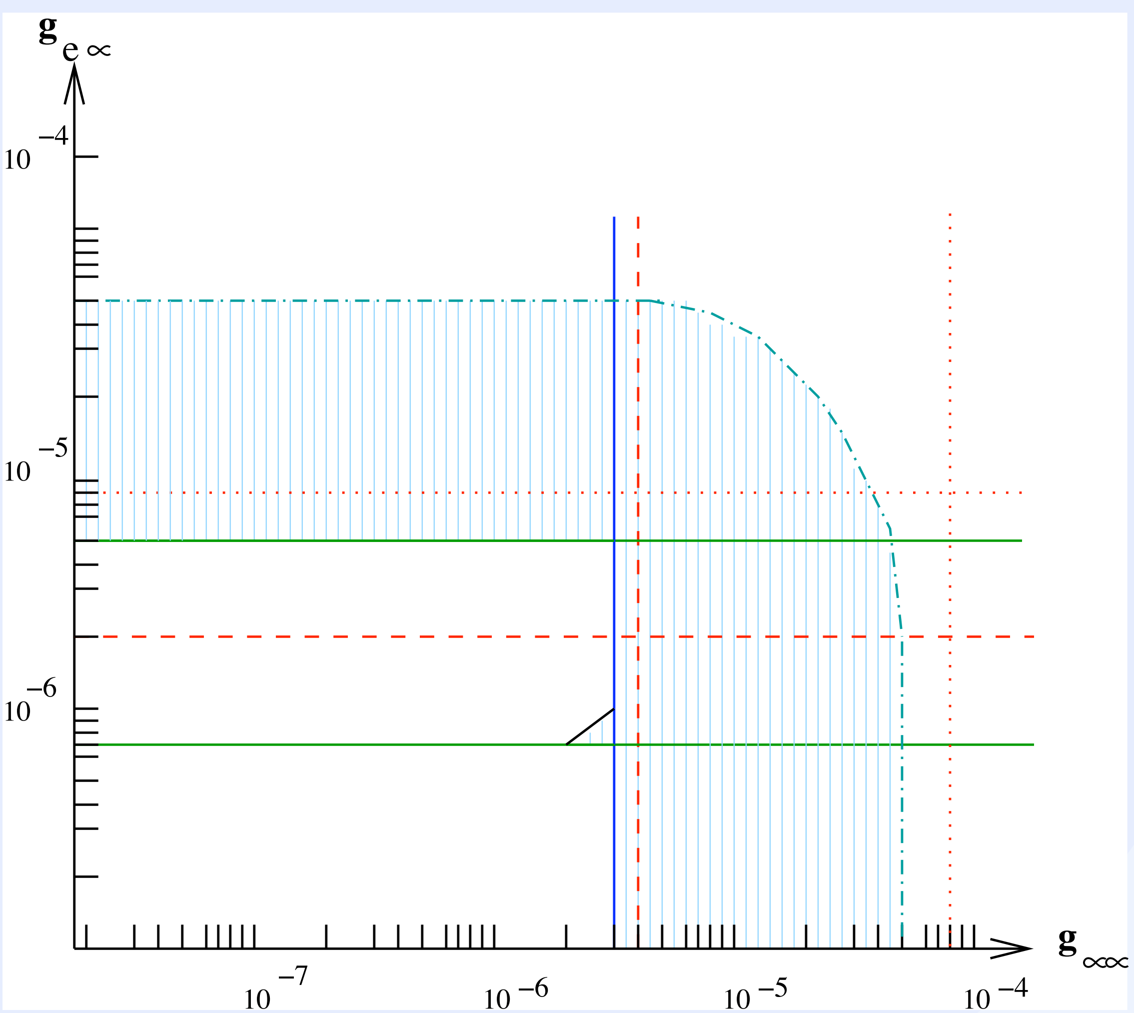
Do the lepton asymmetries survive in the presence of the neutrino-majoron interactions?

Astrophysical bounds on g: (Farzan,'03)



$$g_{ee} < 4 \times 10^{-7}$$

$$2 \times 10^{-5} < g_{ee} < 3 \times 10^{-5}$$



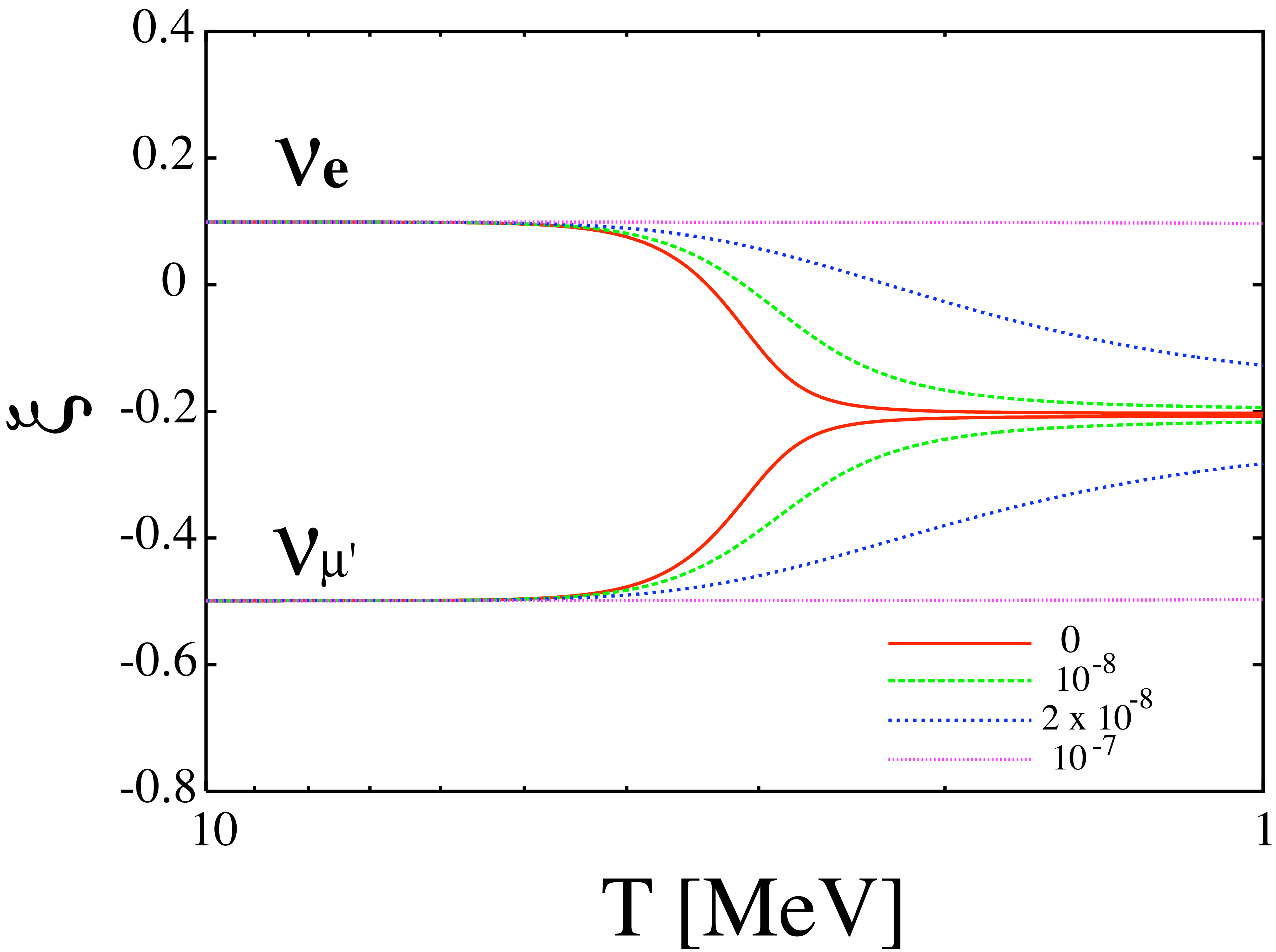
$$g_{aa} < (3 \sim 5) \times 10^{-6}$$

$$g_{aa} > (3 \sim 5) \times 10^{-5}$$

4.Numerical Results

$$\delta m_{21}^2 = 7.3 \times 10^{-5} \mathrm{eV}^2$$
$$\sin^2\theta = 0.315$$

$$g_{ab} = \begin{pmatrix} 0 & 0 \\ 0 & g \end{pmatrix}$$



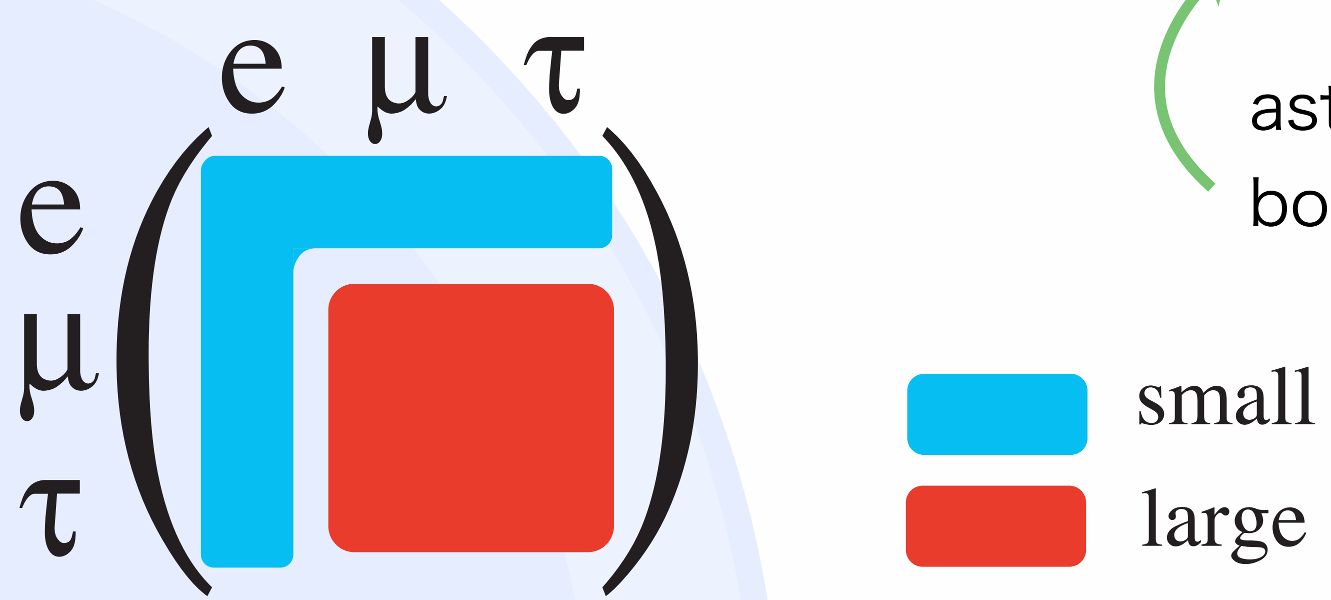
(Dolgov and F.T. '04)

Results:

$$
\begin{aligned}
|g_{ee}|,\ |g_{e\mu}|,\ |g_{e\tau}| \quad & \ll 10^{-7}, \\
10^{-7} \lesssim \quad \mathrm{Max}\,[\,|g_{\tau\tau}|,\ |g_{\mu\tau}|,\ |g_{\mu\mu}|\,] \quad & \lesssim 5 \times 10^{-6}.
\end{aligned}
$$

astrophysical bound

$g \sim$



e.g.)

In simplest class of majoron models, $g \propto m_\nu$.

$$
m_\nu \propto \begin{pmatrix} 0 & 0 & \lambda \\ 0 & 1 & 1 \\ \lambda & 1 & 1 \end{pmatrix} \ \text{or} \ \begin{pmatrix} \lambda^2 & \lambda & \lambda \\ \lambda & 1 & 1 \\ \lambda & 1 & 1 \end{pmatrix}
$$

for the normal mass hierarchy

$$\lambda \sim 0.2$$

5. Summary

- Neutrino-majoron interaction can suppress the neutrino oscillations at the BBN, which reopens a window for a large L.
- Other ways of cancellation between ξ_e and ΔN_ν was also obtained.

- For lepton asymmetries not to be erased,

$$g_{aa} \lesssim 10^{-5}$$

If $g_{aa} \gtrsim 10^{-5}$,

- Lepton asymmetry is erased.
- Majorons would be in equlibrium:

$$\Delta N_\nu = \frac{4}{7}$$