Constraining flavor-dependent long range forces from neutrino experiments

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Extra $U(1)_X$ gauge symmetries

- Minimal extensions of the SM
- $X = L_e - L_\mu, L_e - L_\tau, L_\mu - L_\tau$: anomaly-free
- Corresponding vector gauge bosons $\mathcal{B}_\mu$
- Interaction $\mathcal{L}_X = g_X \overline{\Psi} \gamma^\mu \mathcal{B}_\mu X \Psi$
- Additional neutral current processes
- If $\mathcal{B}$ are massless / extremely light, the force is long range

Limits from gravity experiments

- Long range forces: $1/r^2$ just like gravity, but only between leptons (flavor dependent)
- Should have signatures in gravity experiments that test the violation of equivalence principle
- Lunar ranging and torsion balance experiments: $\alpha_{e\ \mu/\tau} < 3.4 \times 10^{-49}$

Adelberger, Heckel, Nelson, hep-ph/0307284

Breaking of $L_e - L_{\mu/\tau}$ symmetry

- $L_e - L_\mu$ has to be broken for nonzero, nonmaximal mixing angles:

$$m_{\text{eff}} = \begin{pmatrix} 0 & m_{e\mu} & 0 \\ m_{e\mu} & 0 & 0 \\ 0 & 0 & m_{\tau\tau} \end{pmatrix}$$

- Gauge bosons $\mathcal{B}$ should have a mass $m_{\mathcal{B}} \sim g\langle v \rangle$
- Range $R \gtrsim R_{\text{ES}} \sim 10^{13}$ cm and $g \lesssim 10^{-25}$ possible with the symmetry breaking scale $\langle v \rangle \sim 1$ GeV
- Similarly with $L_e - L_\tau$

Effective potential with $L_e - L_\mu$

- Additional forward scattering NC amplitude:
  $A(\nu_e e^- \rightarrow \nu_e e^-) \propto +g^2/q^2$
  $A(\nu_\mu e^- \rightarrow \nu_\mu e^-) \propto -g^2/q^2$
  $A(\nu_\tau e^- \rightarrow \nu_\tau e^-) = 0$

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- Effective potentials in flavor basis:
  $V_{(ee)} = +\alpha \int d^3r \; n_e(\vec{r})/r \equiv V_{e\mu}$
  $V_{(\mu\mu)} = -\alpha \int d^3r \; n_e(\vec{r})/r \equiv -V_{e\mu} \; ,$
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  $V_{(\tau\tau)} = 0$
- Potential due to large spherical “electron sources”:

$$V_{e\mu}^{\odot}(r) = \frac{4\pi\alpha_{e\mu}}{r} \int_0^{r_\odot} r''^2 n_e(r'') dr'' = \frac{\alpha_{e\mu}}{r} N_e^{\odot}$$

LR Potential at the Earth

- Potential due to the Sun:

$$V_{e\beta}^{\odot}(r_{ES}) = \frac{\alpha N_e^{\odot}}{R_{ES}} \approx 1.3 \times 10^{-11}\mathrm{eV}\left(\frac{\alpha_{e\beta}}{10^{-50}}\right)$$

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- Potential due to the Earth at its surface:

$$V^{E}_{e\mu} \sim \frac{M_E}{M_{\odot}}\frac{R_{ES}}{R_E} V_{e\mu}(r_{ES}) \approx 0.1\; V_{e\mu}(r_{ES})$$

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A. Joshipura and S. Mohanty, PLB 584 (2004) 103

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A. Joshipura and S. Mohanty, PLB 584 (2004) 103

- Atmospheric $\Delta m^2/E \sim 10^{-12}$ eV
  $\Rightarrow$ even $\alpha \sim 10^{-50}$ may cause significant effects

A galactic conspiracy

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A. Dolgov and G. Raffelt, hep-ph/9503438

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- Initial analysis with $R_{LR} \ll R_{\rm gal}$
  Later add the modifications due to the galaxy

Atmospheric neutrino oscillations

- Effective 2-ν Hamiltonian in ν_μ-ν_τ basis:

$$H_{\text{eff}} = \frac{1}{2}\begin{pmatrix} -\Delta\cos 2\theta_{23} - 2V_{e\mu} & \Delta\sin 2\theta_{23} \\ \Delta\sin 2\theta_{23} & \Delta\cos 2\theta_{23} \end{pmatrix} \quad , \quad \Delta = \frac{\Delta m^2_{32}}{2E}$$

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$$\tan 2\theta_{23m} \approx \frac{\Delta\sin 2\theta_{23}}{\Delta\cos 2\theta_{23} + V_{e\mu}}$$

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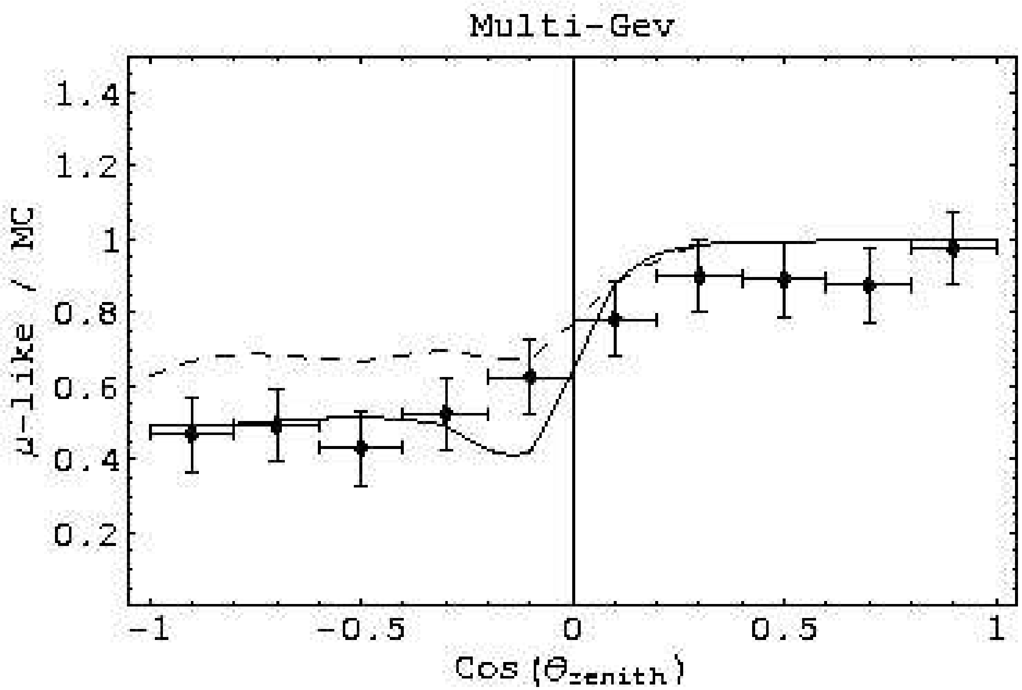
- 2-ν treatment enough since θ_{13} small and $\Delta_{21} \ll \Delta_{32}$
- Oscillation probability changes:

$$P_{\mu\mu} = 1 - \sin^2 2\theta_{23m}\sin^2\left(\frac{(m^2_{3m} - m^2_{2m})L}{4E}\right)$$

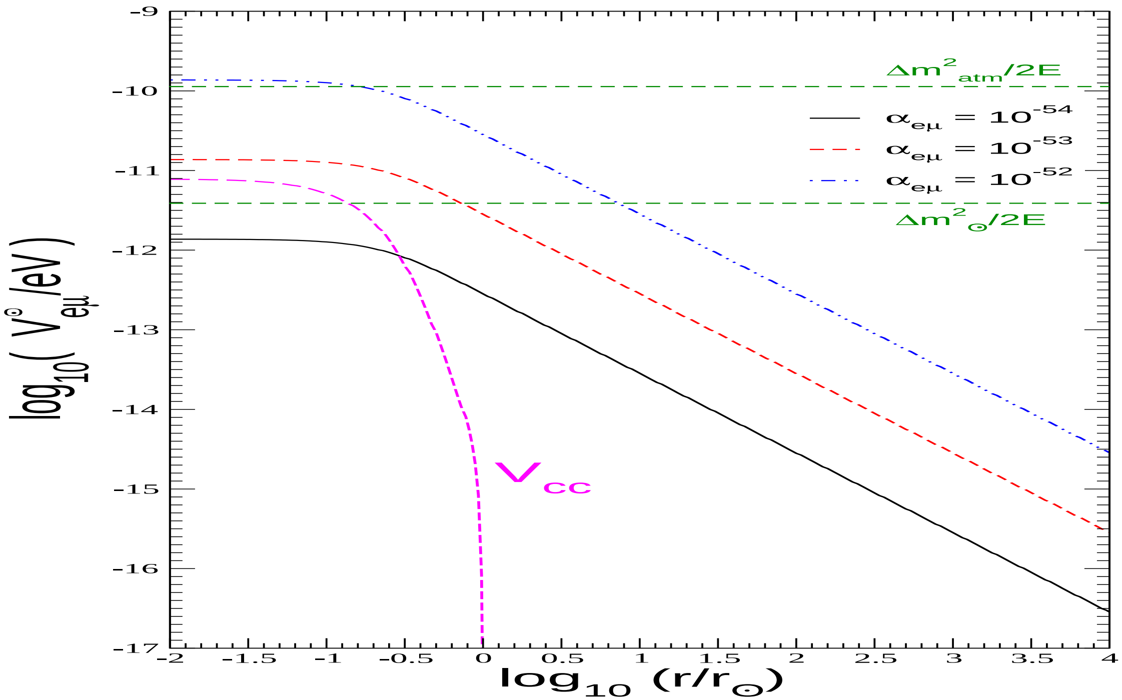
Limit on $\alpha_{e\mu}$ from atmospheric neutrinos



(Dotted curve with $\alpha_{e\mu} = 5.5 \times 10^{-52}$)

- Matter effects suppress mixing, increase $P_{\mu\mu}$
- Larger α values ruled out:
  $\alpha_{e\mu} < 5.5 \times 10^{-52}$, $\alpha_{e\tau} < 6.4 \times 10^{-52}$ (90% C.L.)
  A. Joshipura and S. Mohanty, PLB 584 (2004) 103
- Improvement by almost 2.5 orders of magnitude !

LR potential from the Sun



(For $E = 10$ MeV)

- Dominates over V_{CC} for $\alpha_{e\beta} \gtrsim 10^{-53}$

  M.C. Gonzalez-Garcia, P.C. de Holanda, E. Masso, R. Zukanovich Funchal, hep-ph/0609094

- Exceeds $\Delta m^2_{\rm atm}/(2E)$ for $\alpha_{e\beta} > 10^{-52}$

Effective masses and mixing angles

- The effective Hamiltonian:

$$H_f = \Delta_{32} \times$$

$$\begin{pmatrix} x s_{12}^2 + y_c + y_{e\mu} & x c_{12} s_{12} c_{23} + s_{13} s_{23} & -x c_{12} s_{12} s_{23} - s_{13} c_{23} \\ x c_{12} s_{12} c_{23} + s_{13} s_{23} & s_{23}^2 + x c_{12}^2 c_{23}^2 - y_{e\mu} & c_{23} s_{23} (1 - x c_{12}^2) \\ -x c_{12} s_{12} s_{23} - s_{13} c_{23} & c_{23} s_{23} (1 - x c_{12}^2) & c_{23}^2 + x c_{12}^2 s_{23}^2 \end{pmatrix}$$

$$x \equiv \frac{\Delta_{21}}{\Delta_{32}} \approx 0.03 \ , \ y_c \equiv \frac{V_{cc}}{\Delta_{32}} = \frac{2EV_{cc}}{\Delta m_{32}^2} \ , \ y_{e\mu} \equiv \frac{V_{e\mu}}{\Delta_{32}} = \frac{2EV_{e\mu}}{\Delta m_{32}^2}$$

- Can be diagonalized keeping terms linear in x and s_{13} (except in a small range of $y_{e\mu}$)

A. Bandyopadhyay, AD, A. Joshipura, hep-ph/0610263

Mixing angles in matter

$$\tan 2\theta_{23m} \approx \frac{\sin 2\theta_{23}(1 - xc_{12}^2)}{\cos 2\theta_{23}(1 - xc_{12}^2) + y_{e\mu}}$$

$$\tan 2\theta_{13m} \approx \frac{2(xs_{12}c_{12}S + s_{13}C)}{C^2 + x(c_{12}^2 S^2 - s_{12}^2) - y_c - y_{e\mu}(1 + \sin^2\theta_{23m})}$$

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$$\delta\theta_{23} = \theta_{23m} - \theta_{23}\ ,\ S = \sin\delta\theta_{23}\ ,\ C = \cos\delta\theta_{23}$$

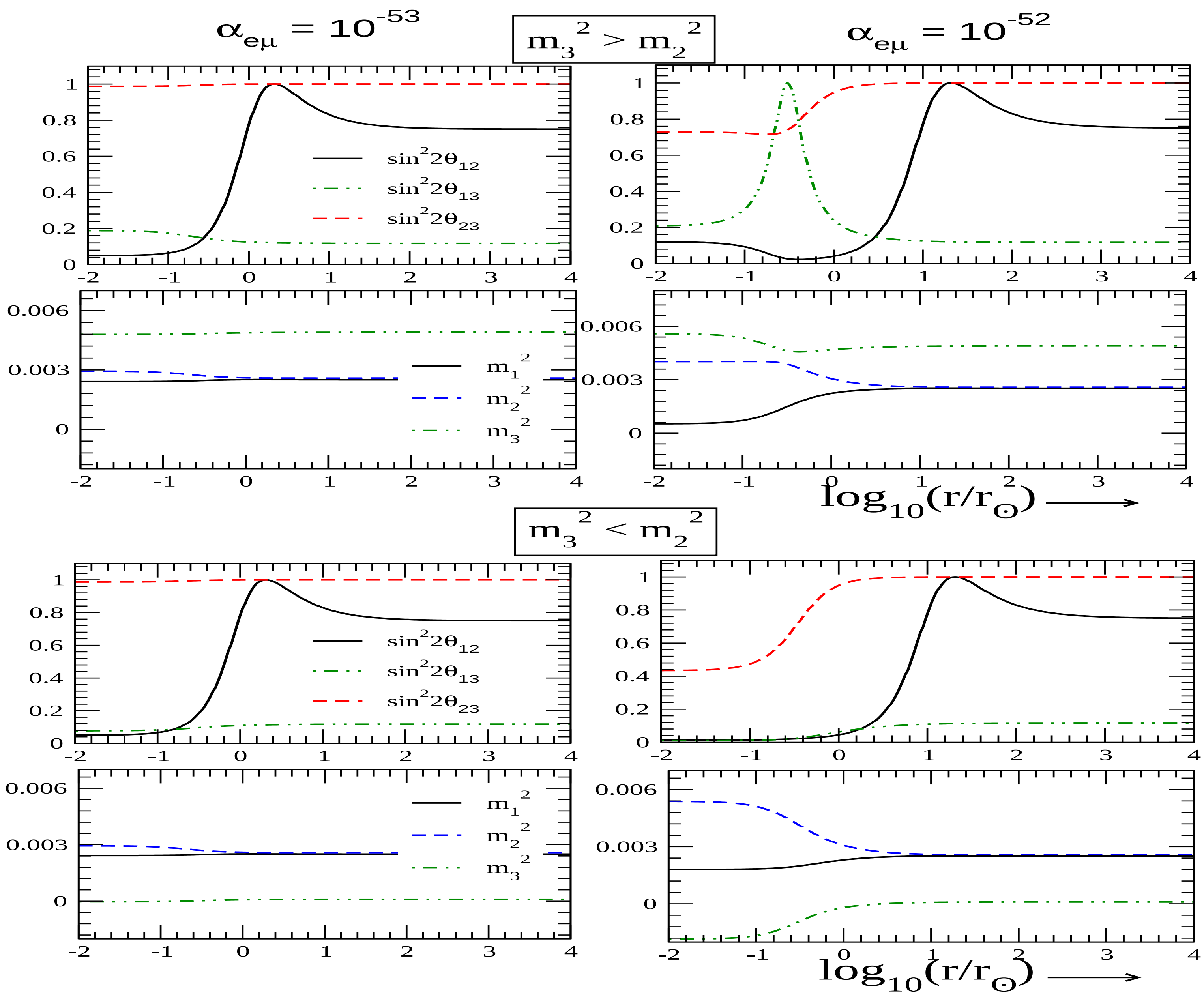
- Valid as long as the denominator in θ_{13m} equation is nonvanishing, i.e. θ_{13m} is not too large
- When θ_{13m} is large (resonance), numerical means have to be used. This happens around $y_{e\mu} \approx 2/3$

Neutrino masses in matter

$$
\begin{aligned}
m_{1m}^2 &\approx \Delta_{32}E\left[x(c_{12}^2C^2+S^2)+y_c+y_{e\mu}\sin^2\theta_{23m}+S^2-D^{1/2}\right] \ , \\
m_{2m}^2 &\approx \Delta_{32}E\left[x(c_{12}^2C^2+S^2)+y_c+y_{e\mu}\sin^2\theta_{23m}+S^2+D^{1/2}\right] \ , \\
m_{3m}^2 &= 2\Delta m_{\rm atm}^2E(C^2+xc_{12}^2S^2-y_{e\mu}\sin^2\theta_{23m}) \ ,
\end{aligned}
$$

$$
\begin{aligned}
D &= \left[S^2+x(c_{12}^2C^2-s_{12}^2)-y_c-y_{e\mu}(1+\cos^2\theta_{23m})\right]^2 \\
&\quad + 4\left(xs_{12}c_{12}C-s_{13}S\right)^2
\end{aligned}
$$

r-dependence of m_i^2 and $\sin^2\theta_{ij}$



For $\alpha_{e\mu} \lesssim 10^{-52}$

- $y_{e\mu} \ll 1$, so that $\delta\theta_{23} \sim -y_{e\mu} \sin 2\theta_{23}/2$. At larger $y_{e\mu}$, this causes problems with atmospheric neutrinos

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- Resonance at $\Delta m^2_{21} \cos 2\theta_{12} \approx 2E \left[V_{cc} + V_{e\mu}(1 + c^2_{23m})\right]$
  Shifted outside the sun for $\alpha \gtrsim 10^{-53}$!

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- Adiabaticity always obeyed for $\alpha_{e\mu} \gtrsim 10^{-58}$:

$$\begin{aligned}\gamma_{12R} &\equiv \frac{\Delta m^2_{12}}{2E} \frac{\sin^2 2\theta_{12}}{\cos 2\theta_{12}} \left| \frac{1}{\mathcal{V}_{12}} \frac{d\mathcal{V}_{12}}{dr} \right|^{-1}_{res} \\ &\approx \alpha_{e\mu} N_e \tan^2 2\theta_{12} (1 + \cos^2 \theta_{23}) \approx 1.4 \times 10^{58} \alpha_{e\mu}\end{aligned}$$

Survival probability for solar ν_e

$$\begin{aligned} P_{ee}(E) &= (1-P_L)\cos^2\theta_{13P}\cos^2\theta_{12P}\cos^2\theta_{13E}\cos^2\theta_{12E} \\ &+ P_L\cos^2\theta_{13P}\sin^2\theta_{12P}\cos^2\theta_{13E}\cos^2\theta_{12E} \\ &+ (1-P_L)\cos^2\theta_{13P}\sin^2\theta_{12P}\cos^2\theta_{13E}\sin^2\theta_{12E} \\ &+ P_L\cos^2\theta_{13P}\cos^2\theta_{12P}\cos^2\theta_{13E}\sin^2\theta_{12E} \\ &+ \sin^2\theta_{13P}\sin^2\theta_{13E}\ . \end{aligned}$$

(P: production point, E: Earth)

For $\alpha_{e\mu} \gtrsim 10^{-52}$

- θ_{13m} resonantly enhanced when
  $C^2 + x(S^2 c_{12}^2 - s_{12}^2) - y_c - y_{e\mu}(1 + s_{23m}^2) \approx 0$.

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- H–L resonance structure *a la* supernova !
- L resonance outside the Sun, and hence always adiabatic $(\alpha \gtrsim 10^{-52})$
- Near the ν_{2m}-ν_{3m} level crossing (H),
  effective potential $\mathcal{V}_{23} = V_{cc} + V_{e\mu}(1 + s_{23m}^2)$

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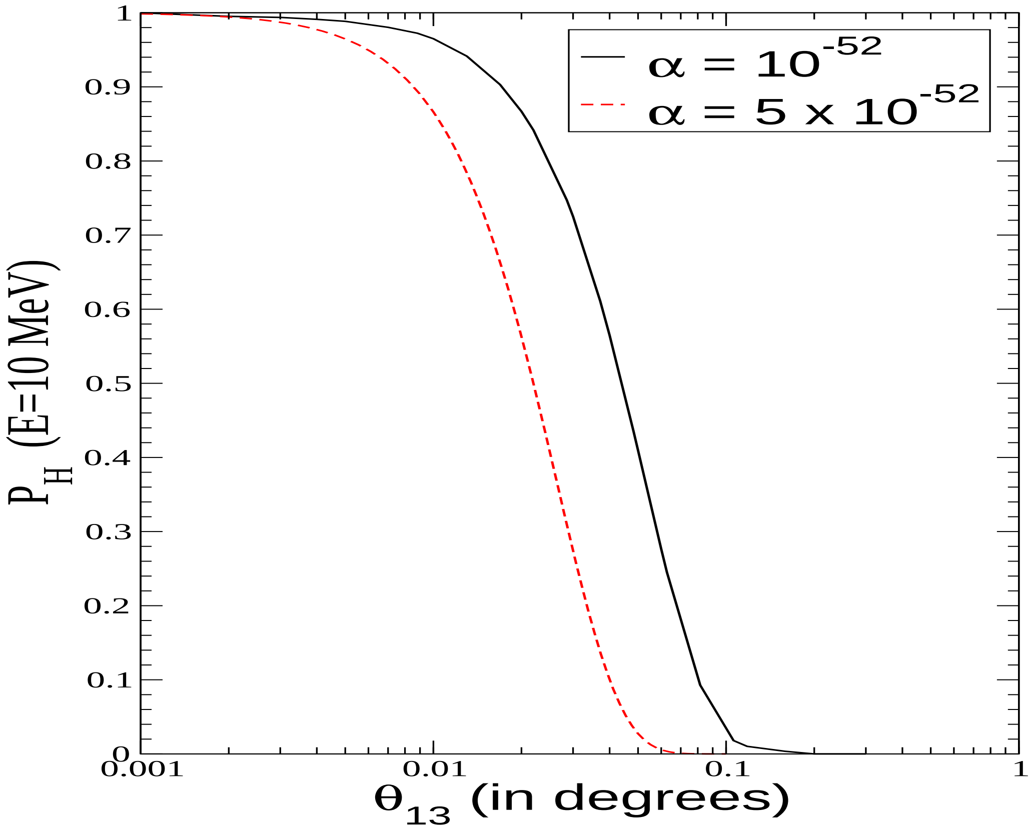
P_{ee}(E) &= \cos^2\theta_{13P}\cos^2\theta_{12P}\cos^2\theta_{13E}\cos^2\theta_{12E} \\
&+ (1-P_H)\cos^2\theta_{13P}\sin^2\theta_{12P}\cos^2\theta_{13E}\sin^2\theta_{12E} \\
&+ P_H\sin^2\theta_{13P}\cos^2\theta_{13E}\sin^2\theta_{12E} \\
&+ (1-P_H)\sin^2\theta_{13P}\sin^2\theta_{13E} \\
&+ P_H\cos^2\theta_{13P}\sin^2\theta_{12P}\sin^2\theta_{13E}\ ,
\end{aligned}
$$

$$
P_H \approx \exp\left[-\frac{\pi}{2}\left|\frac{m_3^2-m_2^2}{2E\ d\theta_{13m}/dr}\right|_{\rm res}\right]
$$

θ_{13}- dependence of P_H



- When $P_H \neq 0$ or 1, it has a strong energy dependence

The χ^2 analysis

- For total event rates:

$$\chi^2_{\rm rates} = \sum_{i,j=1}^{N_{\rm expt}} (P_i^{\rm th} - P_i^{\rm expt}) \left[({\sigma_{ij}}^{rates})^2\right]^{-1} (P_j^{\rm th} - P_j^{\rm expt})$$

- For spectral data:

$$\chi^2_{\rm spec} = \sum_{i,j=1}^{N_{\rm bins}} (S_i^{\rm th} - S_i^{\rm expt}) \left[({\sigma_{ij}}^{spec})^2\right]^{-1} (S_j^{\rm th} - S_j^{\rm expt})$$

- Global analysis:

$$\chi^2 = \chi^2_{\rm Cl,Ga\ rates} + \chi^2_{\rm SK\ spec} + \chi^2_{\rm SNO\ spec} + \chi^2_{\rm KamLAND} \ .$$

KamLAND survival probabilty

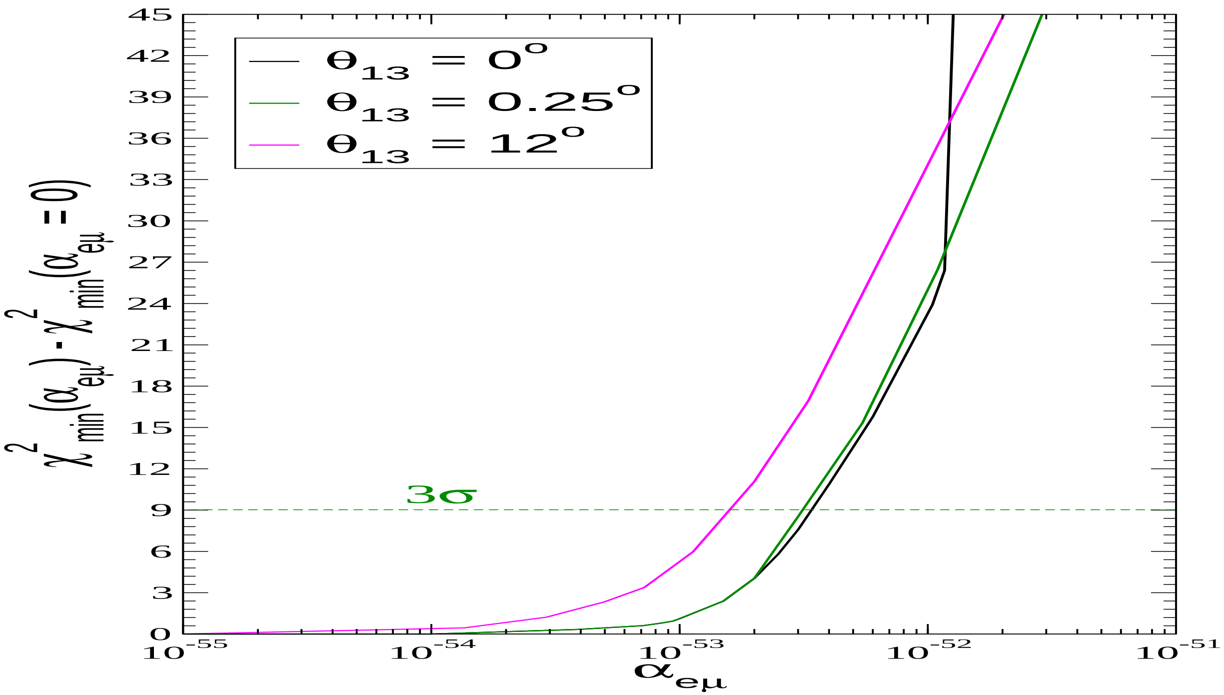
$$P_{\bar{e}\bar{e}}^{KL} =$$

$$1 - \cos^4\theta_{13}\left[\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)\right] - \sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

$$+\sin^2 2\theta_{13}\sin^2\theta_{12}\left[\sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) - \sin^2\left(\frac{(\Delta m_{31}^2 - \Delta m_{21}^2)L}{4E}\right)\right]$$

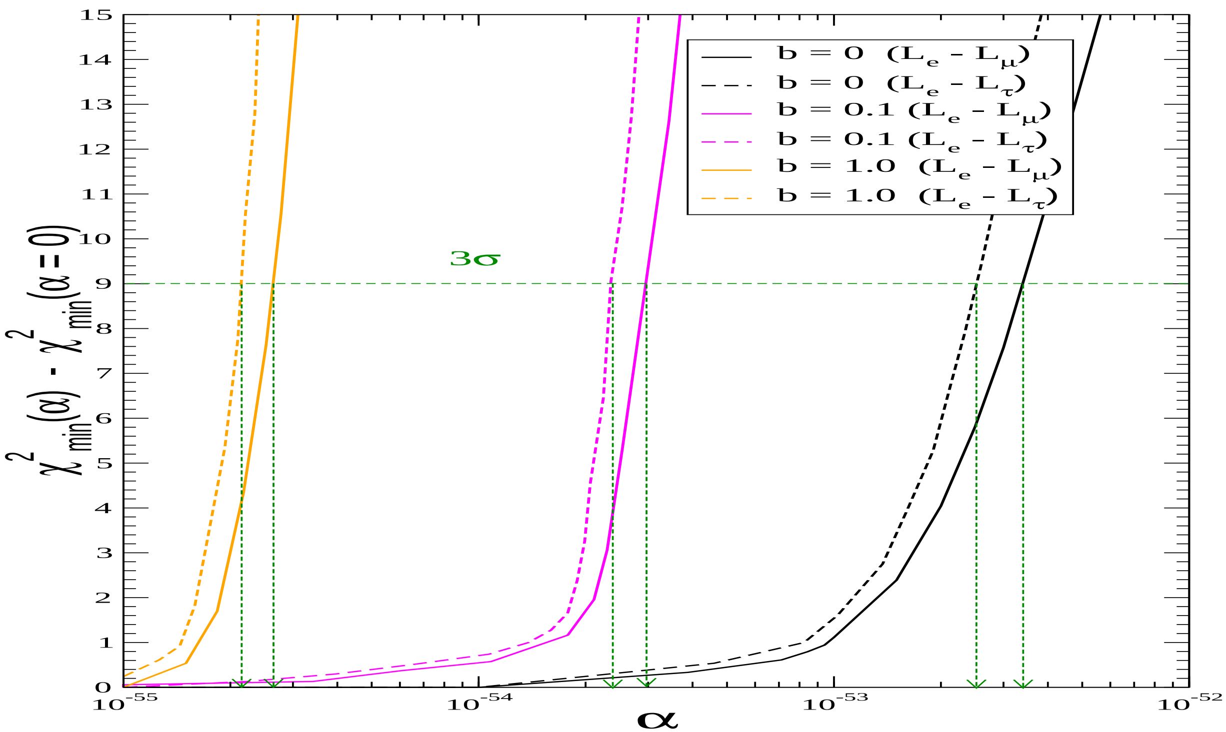
- All quantities computed at the Earth, and for antineutrinos

Bounds as a function of θ_{13}



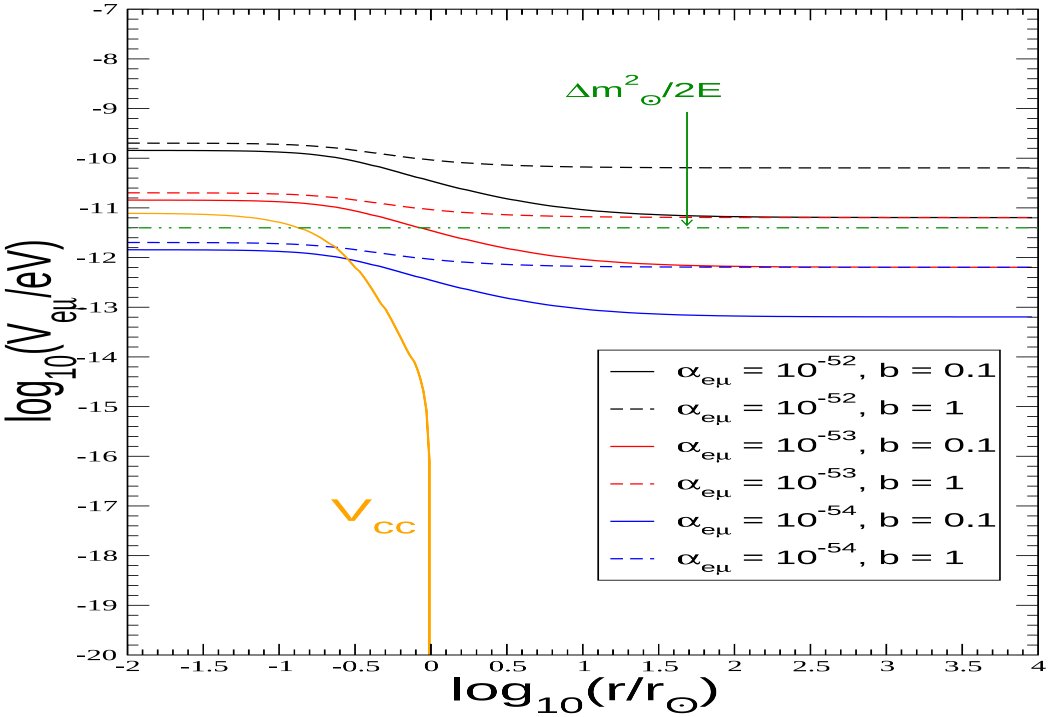
- $\theta_{13} = 0 \Rightarrow P_H = 1$, no energy dependence
- $0 < \theta_{13} \lesssim 1^\circ$: large energy dependence
  $\Rightarrow$ large χ^2 for $\alpha \gtrsim 10^{-52}$
- $\theta_{13} \gtrsim 1^\circ \Rightarrow P_H \approx 1$, no energy dependence
- Most conservative limits with $\theta_{13} = 0$

Bounds for $L_e - L_\mu$ and $L_e - L_\tau$



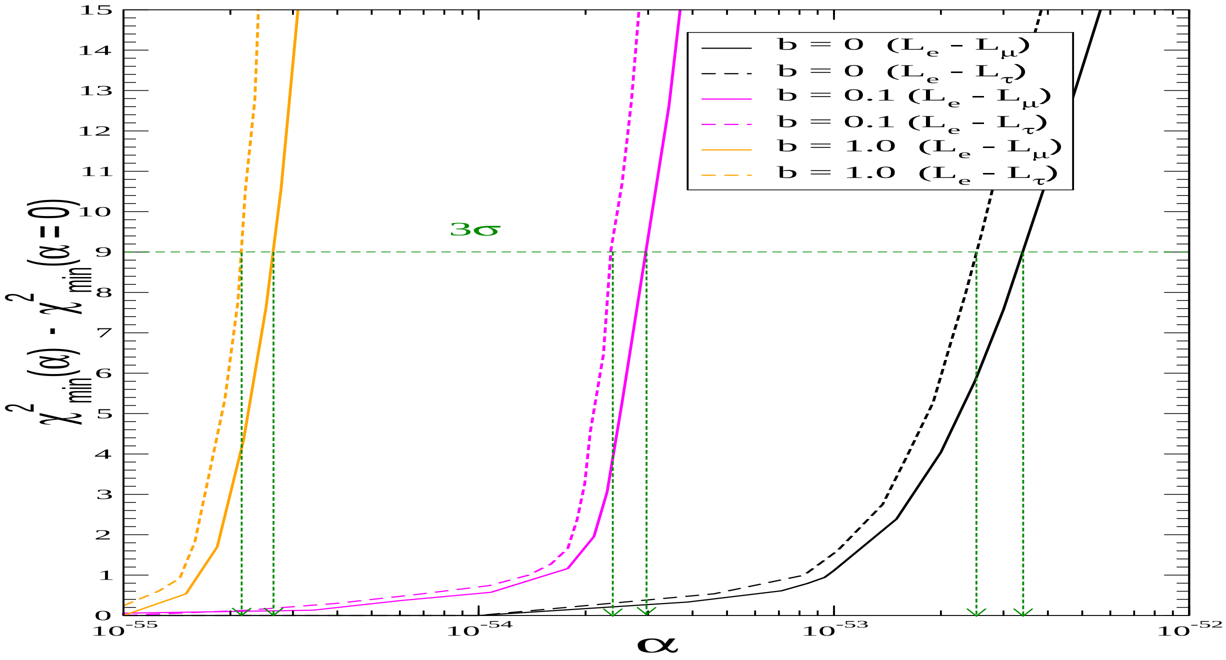
- $R_{LR} \ll R_{\rm gal} \Rightarrow b = 0$:
  $\alpha_{e\mu} < 3.4 \times 10^{-53}$ $\alpha_{e\tau} < 2.5 \times 10^{-53}$
- An order of magnitude better than the earlier limit !

LR potential due to the galaxy



- $V_{e\mu}^{\rm gal} \gg \Delta m^2_\odot/(2E) \Rightarrow$ No MSW resonance
  $b\alpha \gtrsim 10^{-53}$ ruled out
- $V_{e\mu}^{\rm gal} \gtrsim V_{CC}$ inside the sun $\Rightarrow$ MSW adiabatic for low E
  Conflicts with radiochemical data

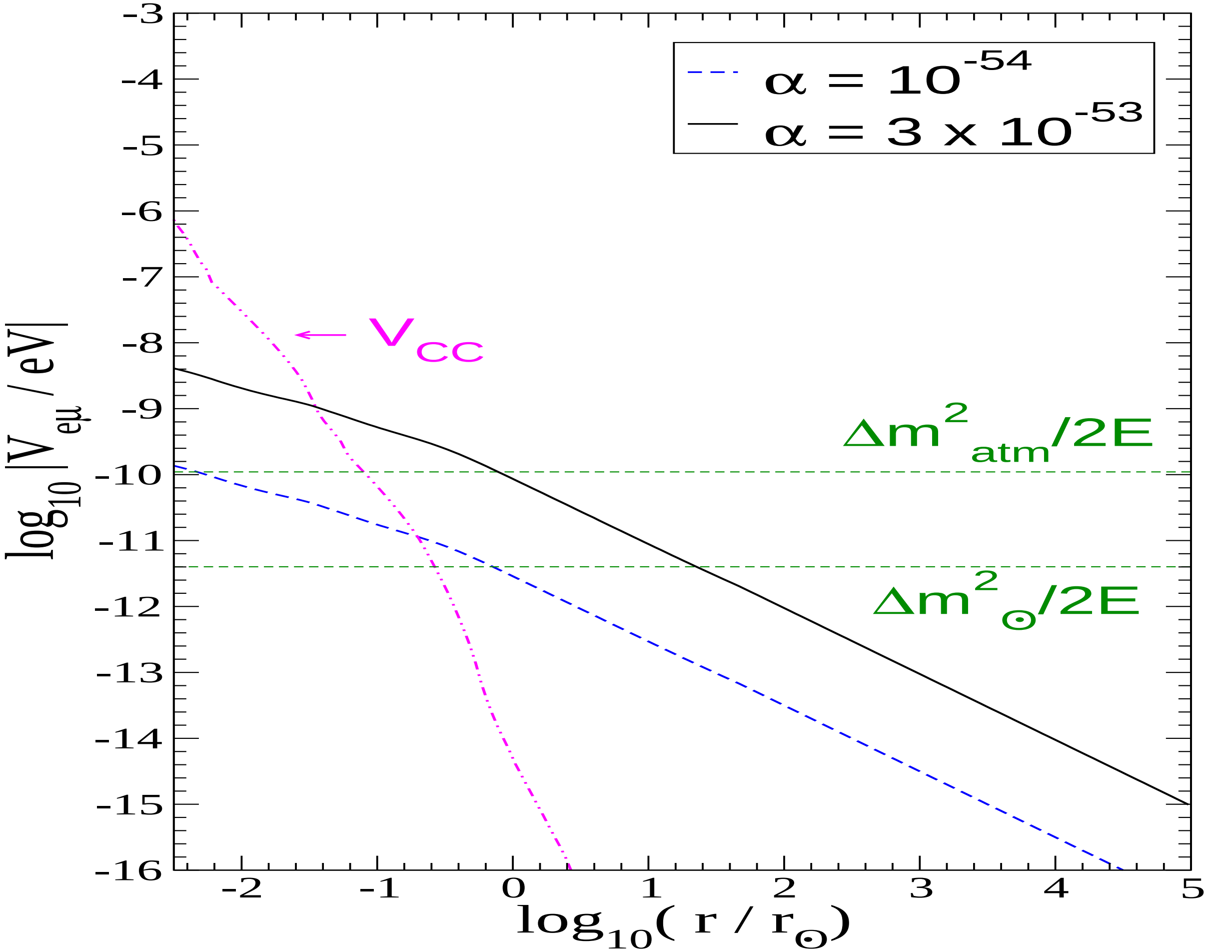
$L_e - L_{\mu/\tau}$ constraints with galaxy



- $L_e - L_\mu$:
  $\alpha_{e\mu} < 2.9 \times 10^{-54}$ $(b = 0.1)$, $\alpha_{e\mu} < 2.6 \times 10^{-55}$ $(b = 1)$
- $L_e - L_\tau$:
  $\alpha_{e\tau} < 2.3 \times 10^{-54}$ $(b = 0.1)$, $\alpha_{e\tau} < 2.1 \times 10^{-55}$ $(b = 1)$
- Orders of magnitude better than the earlier limits !

A. Bandyopadhyay, AD, A. Joshipura, hep-ph/0610263

LR forces and supernova



$M = 15M_{\odot}$, solar metallicity

S. E. Wooseley, A. Heger and T. A. Weaver, RMP 74, 1025 (2002)

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- Observation of Earth matter effects / shock wave effects will put much stronger bounds on α (for $R_{LR} \ll R_{\rm gal}$)

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- Neutrino burst from SN may improve the constraints if $R_{LR} \ll R_{\rm gal}$