Measuring neutrino interactions with solar and atmospheric neutrinos

Alexander Friedland

Los Alamos National Lab

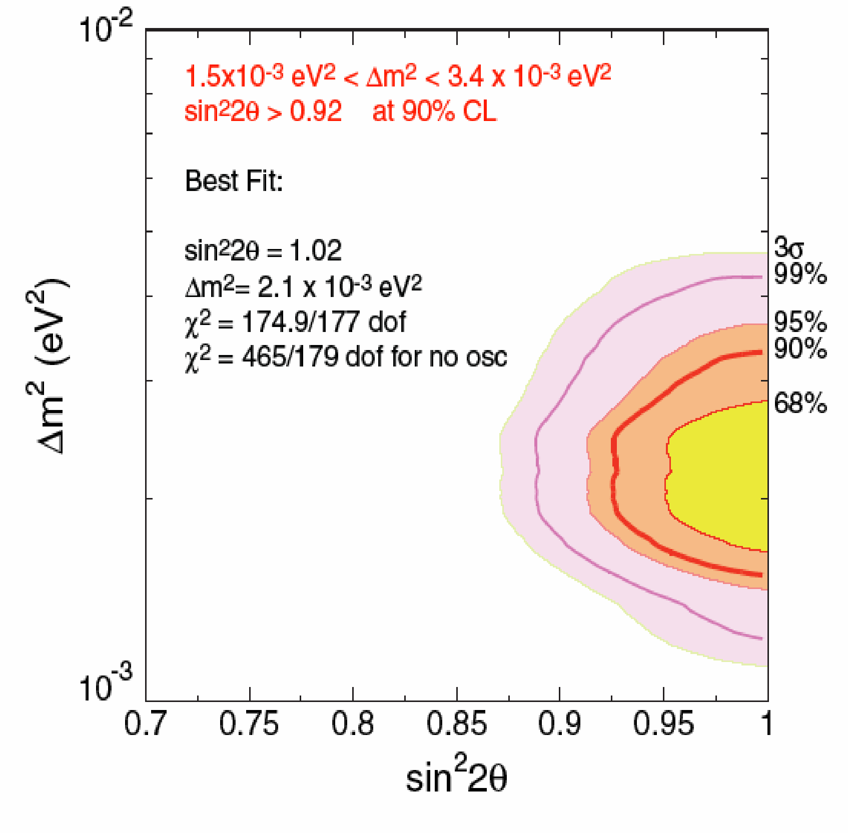
With C. Lunardini, C. Peña-Garay

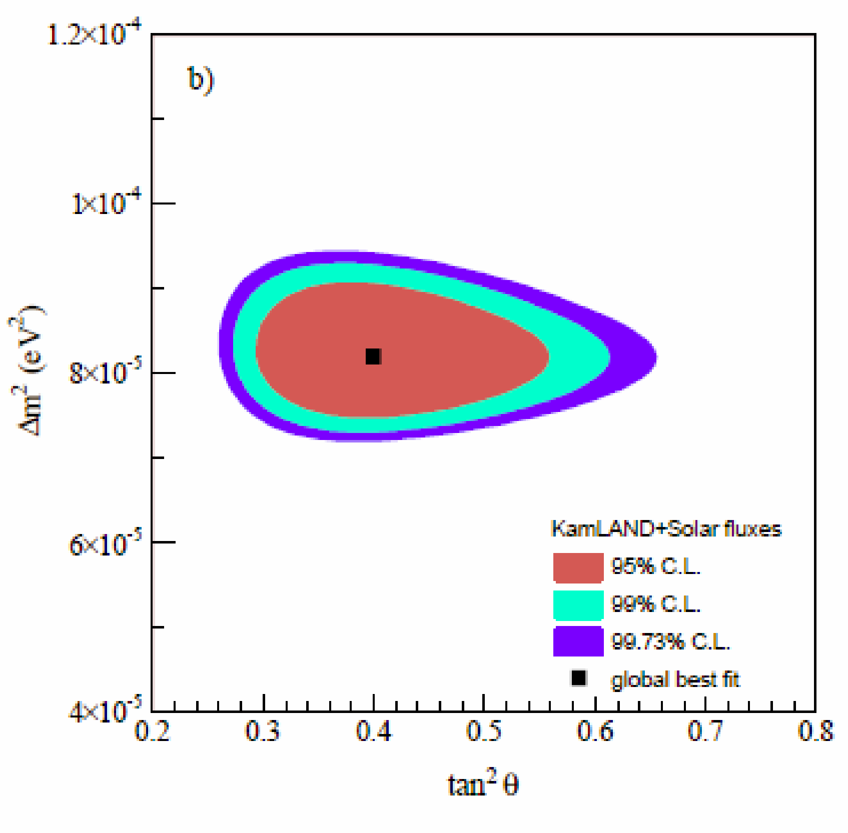
Phys. Lett. B594, 347 (2004) [hep-ph/0402266];

With C. Lunardini, M. Maltoni

[hep-ph/0408264]

Oscillations established





- What next?

“Things we know we don’t know”

- The third neutrino mixing angle, θ_{13}
- Neutrino mass hierarchy (normal or inverted)
- Absolute mass scale
- Dirac or Majorana (both?)
- CP violation
- more than 3 states? (sterile neutrinos?)

Why continue solar and atmospheric experiments?

Are we missing something very important?

What is often not realized is that our knowledge of neutrino-matter interactions is embarrassingly incomplete!

Neutrino interactions with matter

- New contributions due to heavy scalar/vector exchange

$$L^{NSI} = -2\sqrt{2}G_F(\bar{\nu}_\alpha\gamma_\rho\nu_\beta)(\epsilon^{f\tilde{f}L}_{\alpha\beta}\bar{f}_L\gamma^\rho\tilde{f}_L + \epsilon^{f\tilde{f}R}_{\alpha\beta}\bar{f}_R\gamma^\rho\tilde{f}_R) + h.c.$$

- Well established only for the μ-neutrino

$$\epsilon_{e\mu} \lesssim 10^{-3},\ \epsilon_{\mu\mu} \lesssim 10^{-3} - 10^{-2}$$

- poorly known for the e-neutrino and especially the τ-neutrino

$$-0.4 < \epsilon^{uuR}_{ee} < 0.7,\ |\epsilon^{uu}_{\tau e}| < 0.5,\ |\epsilon^{dd}_{\tau e}| < 0.5,$$
$$|\epsilon^{uuR}_{\tau\tau}| < 3$$

S. Davidson et al, JHEP 0303, 011 (2003)

Key advantage of solar and atm. ν's

- Both solar and atmospheric neutrinos partially oscillate into the tau-neutrino state
- Modified interactions of ν_τ with matter may make the oscillation pattern incompatible with the data (propagation effect)
  - In addition, one should keep in mind potential detection effects

NSI in solar and atm. neutrinos: summary

- Solar neutrinos:
  - Constrain the parameter space, beyond what is possible with accelerators
  - In the remaining part of the parameter space, the NSI effects are non-negligible! Can give a new solution, LMA-0, → uncertainty in the determination of the osc. parameters.
- Atmospheric neutrinos:
  - 2-family $\nu_\mu \leftrightarrow \nu_\tau$ analysis gave very tight constraints on $\varepsilon_{\mu\tau}$, $\varepsilon_{\tau\tau}$
  - 3-family analysis gives qualitatively new effects: large NSI ($\varepsilon_{e\tau} \sim \varepsilon_{\tau\tau} \sim 1$) can be consistent with the data
  - The large NSI change the osc. fit: $\theta < \pi/4$, $\Delta m^2 \uparrow$
- Both solar and atm. neutrinos are sensitive to new physics in the 10^2-10^3 GeV range; data expected in the next ~ 3 years!

Setup

- Take the matter term in the osc. Hamiltonian to have the form

$$H_{\text{mat}} = \sqrt{2} G_F n_e \begin{pmatrix} 1+\epsilon_{ee} & 0 & \epsilon^*_{e\tau} \\ 0 & 0 & 0 \\ \epsilon_{e\tau} & 0 & \epsilon_{\tau\tau} \end{pmatrix}.$$

- The solar problem reduces to a 2x2 ν_e-ν_μ' system

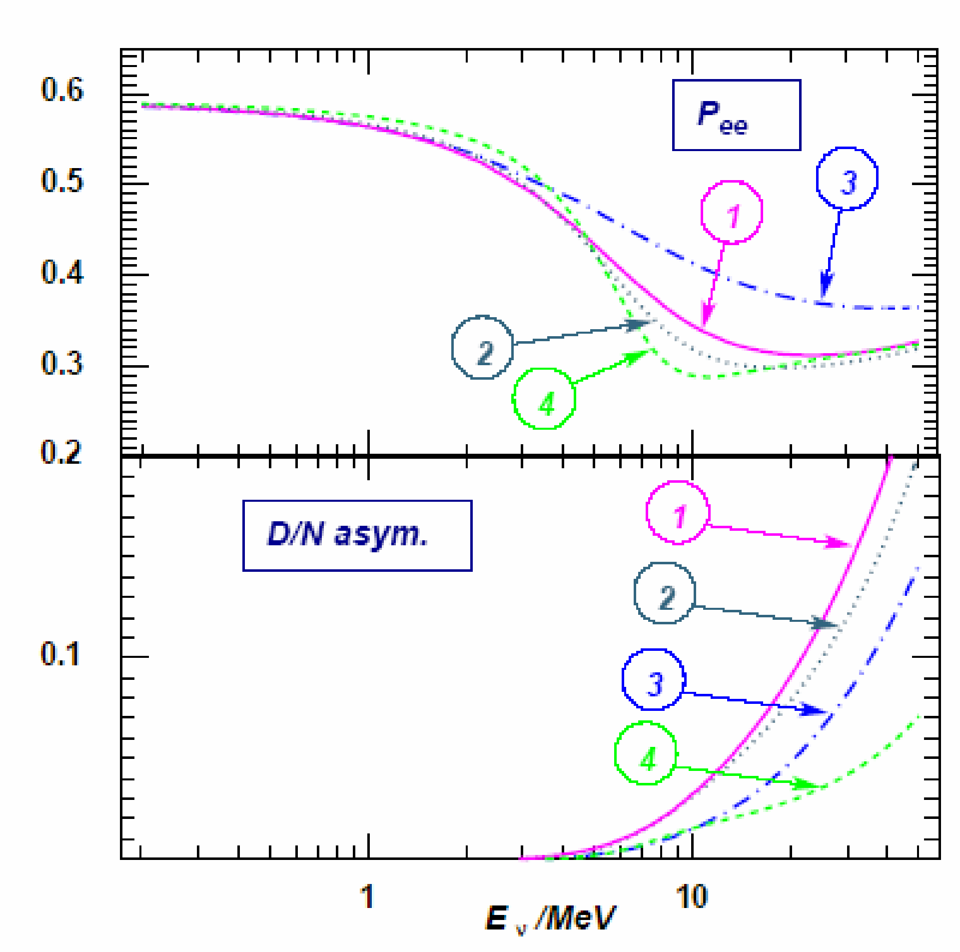
$$H^{2\times 2}_{\text{mat}} = \sqrt{2} G_F n_e \begin{pmatrix} 1+\epsilon_{ee} & -\epsilon^*_{e\tau}\sin\theta_{23} \\ -\epsilon_{e\tau}\sin\theta_{23} & \epsilon_{\tau\tau}\sin^2\theta_{23} \end{pmatrix}.$$

- The atmospheric analysis DOES NOT reduce to a 2x2 ν_μ-ν_τ system!

Effect of the NSI on the solar survival probability and day/night asymmetry

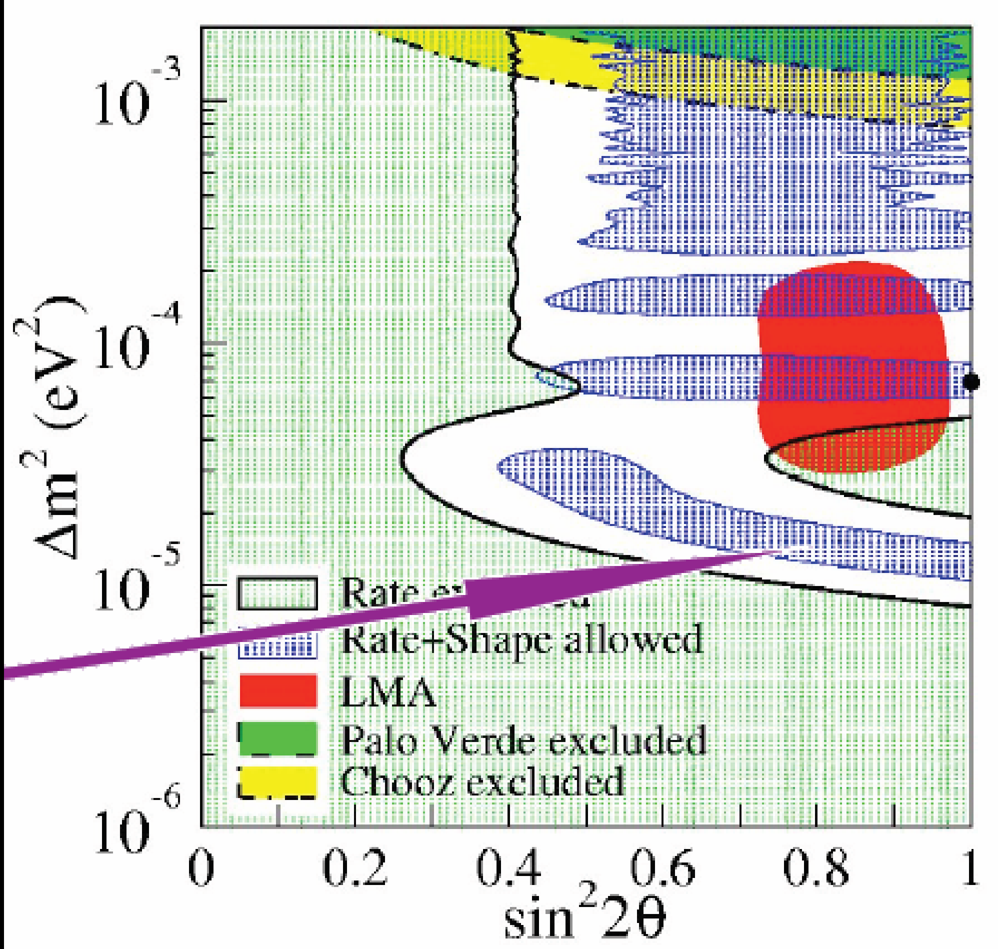
- Effect depends on the sign of $\varepsilon_{e\tau}$!

1. $\varepsilon_{11}^{u}=\varepsilon_{11}^{d}=\varepsilon_{12}^{u}=\varepsilon_{12}^{d}=0$
2. $\varepsilon_{11}^{u}=\varepsilon_{11}^{d}=-0.008$, $\varepsilon_{12}^{u}=\varepsilon_{12}^{d}=-0.06$;
3. $\varepsilon_{11}^{u}=\varepsilon_{11}^{d}=-0.044$, $\varepsilon_{12}^{u}=\varepsilon_{12}^{d}=0.14$;
4. $\varepsilon_{11}^{u}=\varepsilon_{11}^{d}=-0.044$, $\varepsilon_{12}^{u}=\varepsilon_{12}^{d}=-0.14$.



LMA=0: physics

- The d/n effect is proportional to sin(2θ-2α), where θ is the vacuum angle and α is the mixing in H_{mat}.
- When the d/n effect is suppressed, the allowed solar region extends to low Δm^2



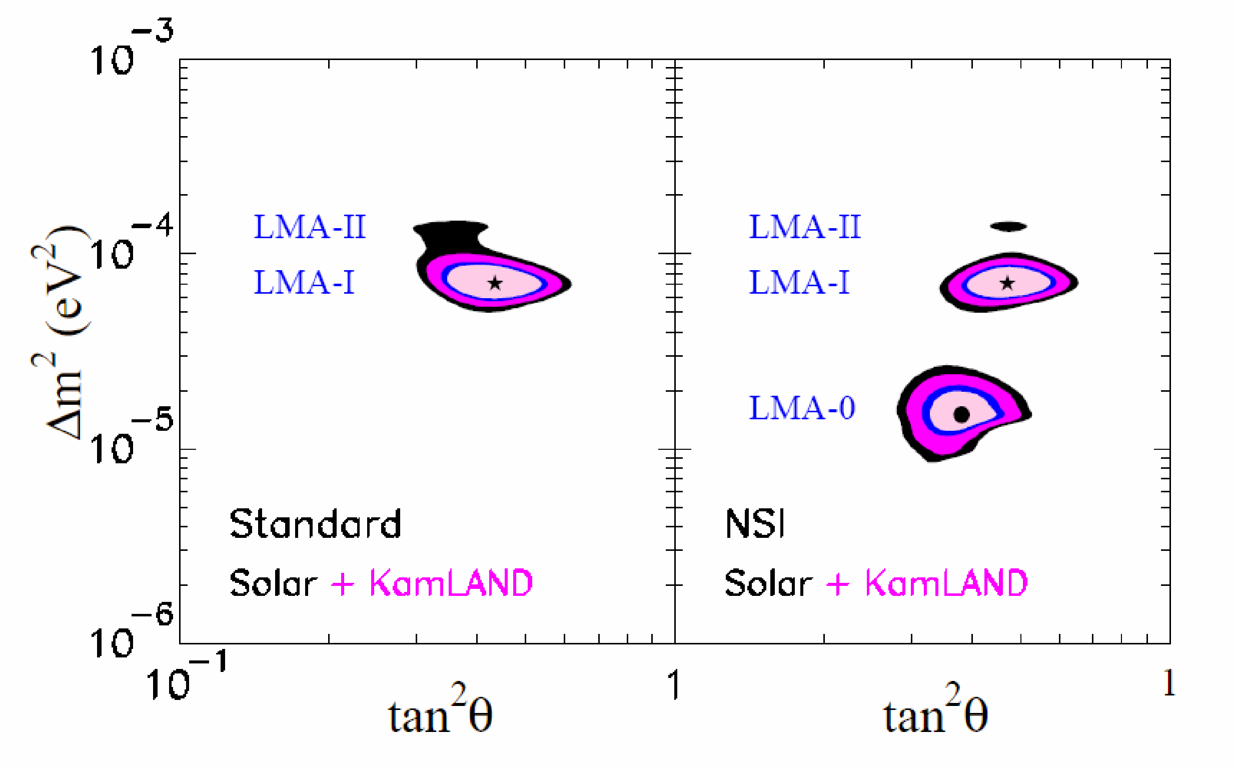
LMA-0: fit

- Choose a point that cancels the d/n effect:

$\varepsilon_{ee}^{d} = \varepsilon_{ee}^{u} = -0.025$,

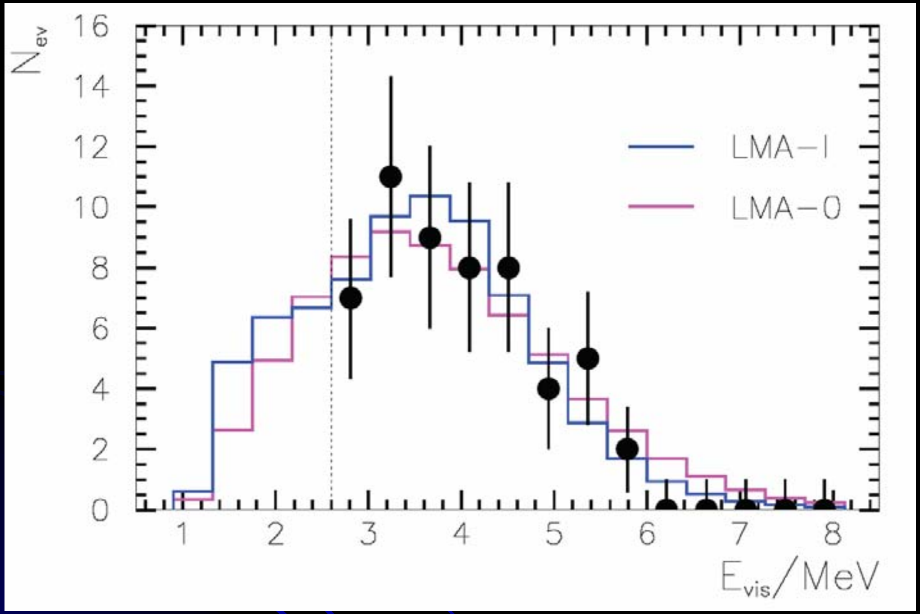
$\varepsilon_{e\tau}^{d} = \varepsilon_{e\tau}^{u} = 0.11$,

$\varepsilon_{\tau\tau}^{d} = \varepsilon_{\tau\tau}^{u} = 0.08$.

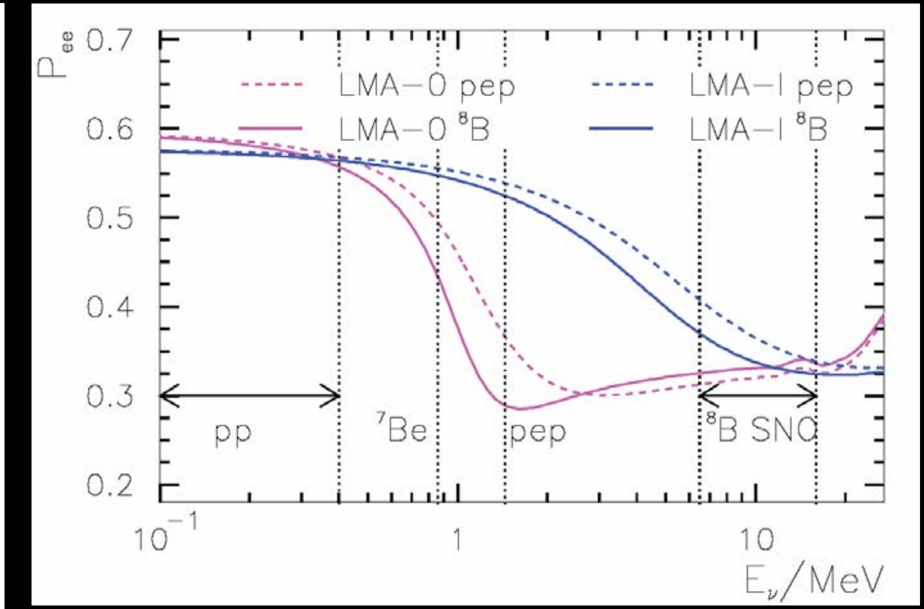


Testing LMA-0

KamLAND



Solar neutrino experiments



Atmospheric neutrinos: physics

- Matter effects generically first show up at high E_ν
- The muon data are well-fit by vacuum oscillations

$$H_{\text{vac}} \simeq \frac{\Delta m^2_{\text{atm}}}{4E_\nu}\begin{pmatrix} -1 & 0 & 0 \\ 0 & -\cos 2\theta & \sin 2\theta \\ 0 & \sin 2\theta & \cos 2\theta \end{pmatrix},$$

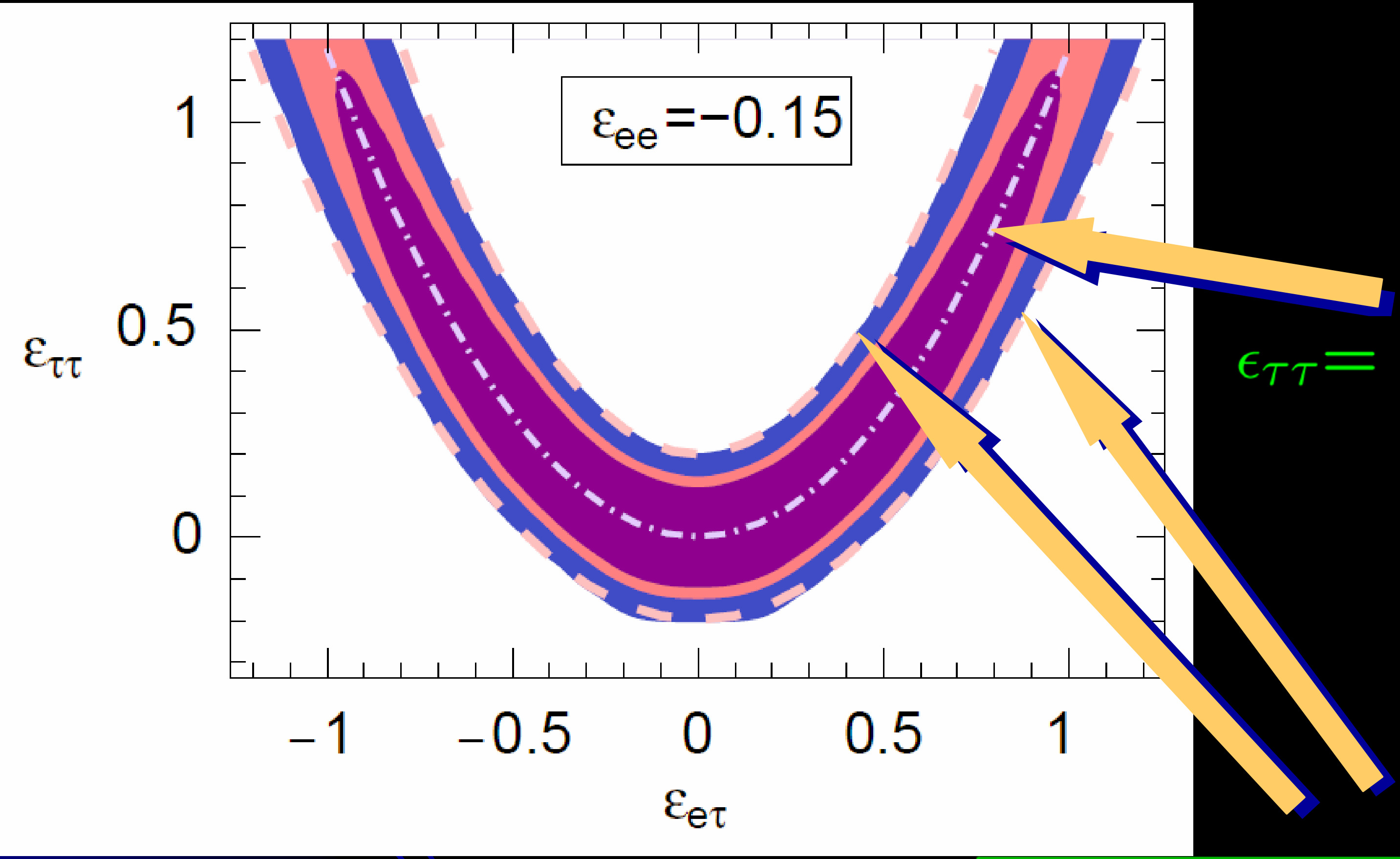
- The introduction of NSI

$$H_{\text{mat}} = \sqrt{2}G_F n_e \begin{pmatrix} 1+\epsilon_{ee} & 0 & \epsilon^*_{e\tau} \\ 0 & 0 & 0 \\ \epsilon_{e\tau} & 0 & \epsilon_{\tau\tau} \end{pmatrix}.$$

will suppress these oscillations, unless one of the eigenvalues $\lambda_1 < \Delta m^2/4E_\nu$

- The last condition DOES NOT require that NSI themselves be small!

Allowed NSI range: fit and predictions



$$\epsilon_{\tau\tau} = |\,\epsilon_{e\tau}\,|^2/(1+\epsilon_{ee})$$

$$|1+\epsilon_{ee}+\epsilon_{\tau\tau}-\sqrt{(1+\epsilon_{ee}-\epsilon_{\tau\tau})^2+4|\,\epsilon_{e\tau}\,|^2}| \lesssim 0.4.$$

Effect of NSI on the oscillation fit

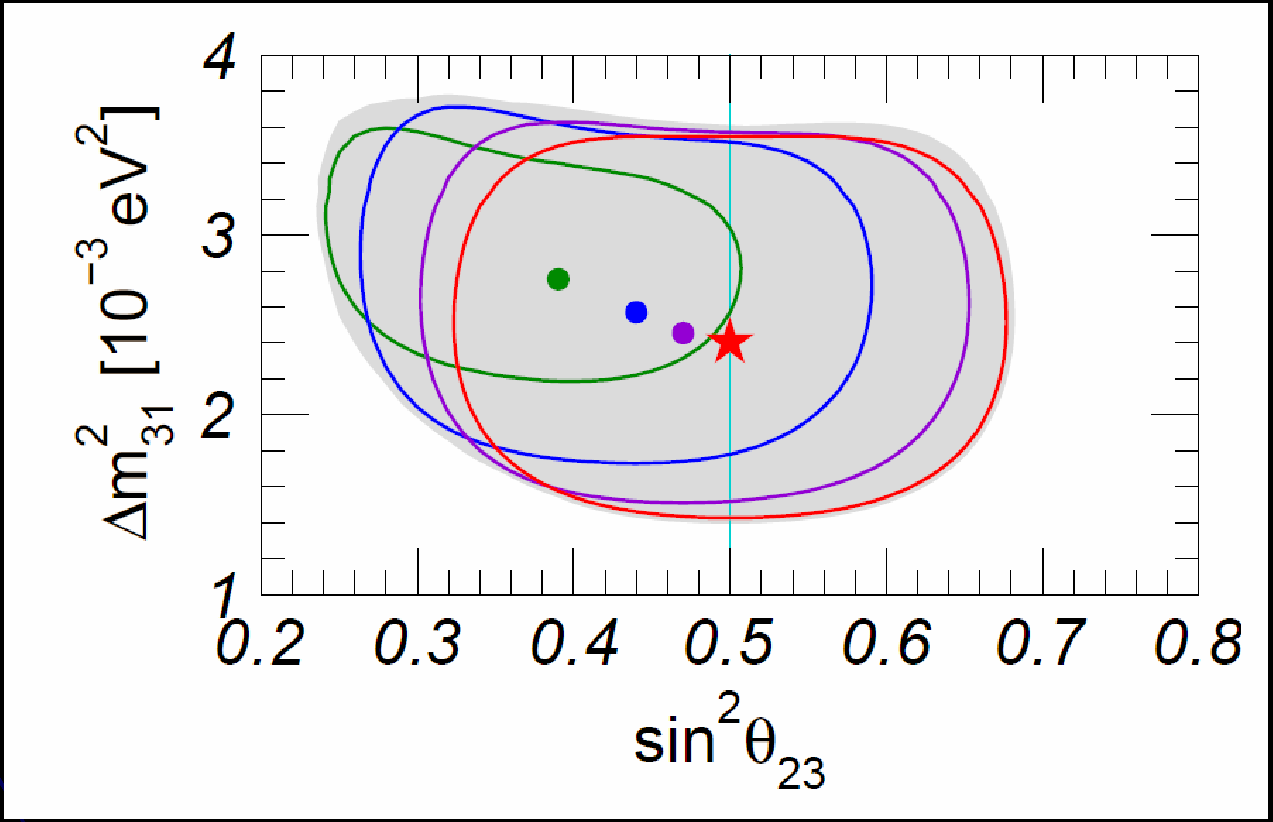
- The best-fit region shifts to smaller θ and larger Δm^2: $\cos 2\theta \simeq s_\beta^2/(1+c_\beta^2)$; $\Delta m^2 \simeq \Delta m_m^2(1+\cos^{-2}\beta)/2$

$\epsilon_{e\tau} = 0, \epsilon_{\tau\tau} = 0;$

$\epsilon_{e\tau} = 0.30, \epsilon_{\tau\tau} = 0.106;$

$\epsilon_{e\tau} = 0.60, \epsilon_{\tau\tau} = 0.424;$

$\epsilon_{e\tau} = 0.90, \epsilon_{\tau\tau} = 0.953.$



Testing the NSI

- SNO should lower its threshold to look for the upturn in P_{ee}
- Borexino should measure ^{7}Be line, to see if the flux is lower, as predicted by LMA-0
- Atmospheric mixing angle should be probed by MINOS: will test the large NSI possibility
- NO-LOSE situation: confirmation of the standard scenario would place strong bounds on the NSI. In the opposite case, new physics at the 10^2-10^3 GeV!

"As we know, there are known knowns. There are things we know we know. We also know there are known unknowns. That is to say we know there are some things we do not know. But there are also unknown unknowns, the ones we don't know we don't know."

— Donald Rumsfeld, Feb. 12, 2002