# *(Some thoughts on) Neutrino properties and oscillation experiments*

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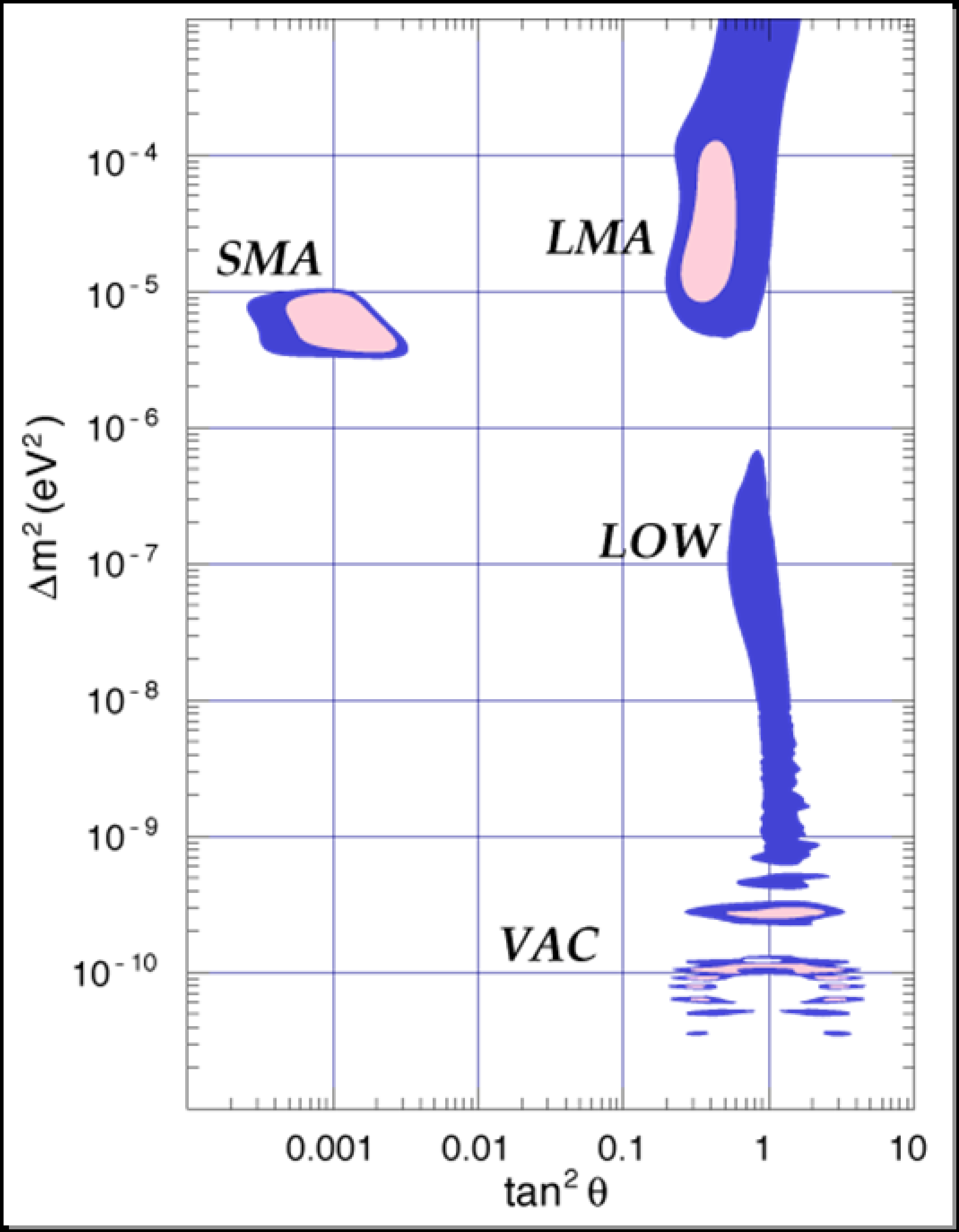
# *A long-long time ago…*

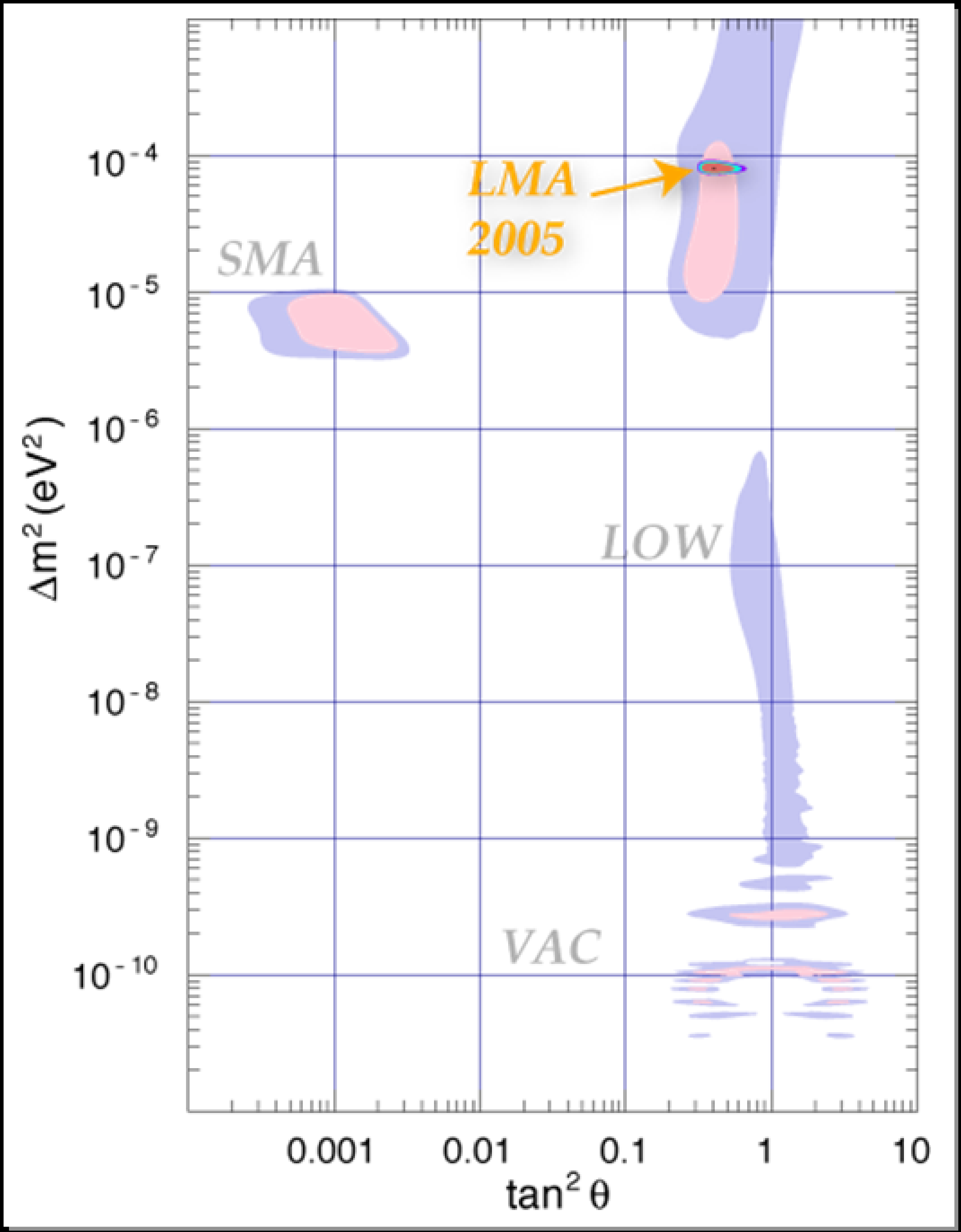
- …some people were suspecting that neutrinos could have unusual properties:
  - $\nu$'s could be massive and oscillate
    - Pontecorvo (1957); Gribov & Pontecorvo (1969),…
  - $\nu$'s could have non-standard interaction with matter
    - Wolfenstein (1978);…
  - $\nu$'s could have magnetic moments and precess in the solar magnetic fields
    - Cisneros (1971); Okun, Voloshin & Vysotsky (1986)…

- Then humans learned some more about neutrinos…

(state of things circa 2000)



- … and more!


LMA
2005
SMA
LOW
VAC
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
$10^{-10}$
$\Delta m^2$ (eV$^2$)
0.001
0.01
0.1
1
10
$\tan^2\theta$

# *Now that we know so much…*

- What can we say about neutrinos?
  - They do have masses, they mix, they oscillate ☑
  - Do they have non-standard interactions? ?
  - Do they have magnetic moments? ?
  - Anything else? (Majorana/Dirac, sterile states, etc, etc, not in this talk)
- By searching for nonstandard properties we may be probing new physics above the EW scale

# *Some neutrino interactions are very poorly known*

- Parameterize additional contributions due to heavy scalar/vector exchange as

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

- Well established only for the $\mu$-neutrino

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

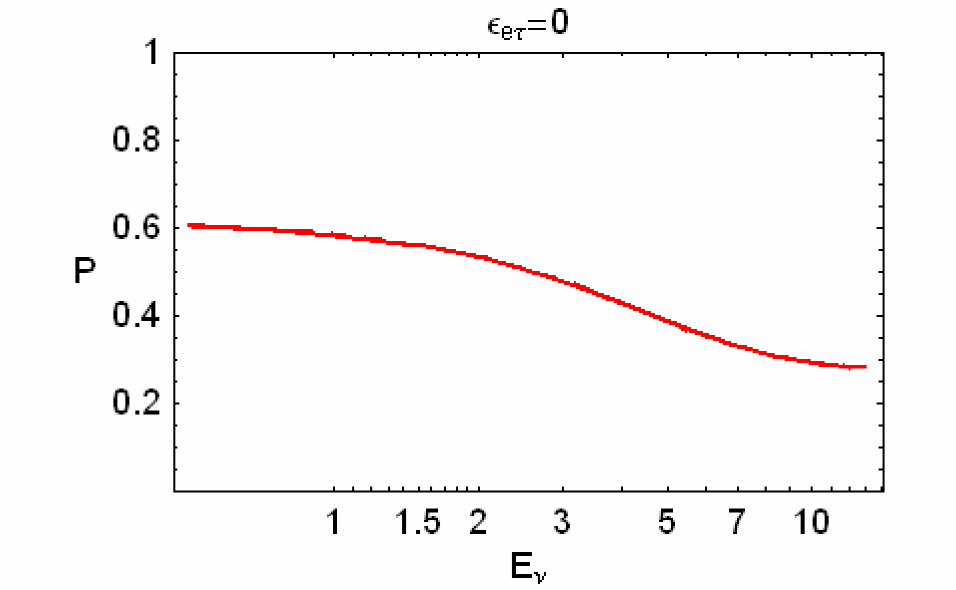
- poorly known for the e-neutrino and <u>especially the $\tau$-neutrino (not using SU(2))</u>

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

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

# *Flavor-changing NSI: effects on solar neutrino energy spectrum*

- Transition from "vacuum regime" (low $E_\nu$) to matter dominated regime (high $E_\nu$) deviates from the canonical MSW profile

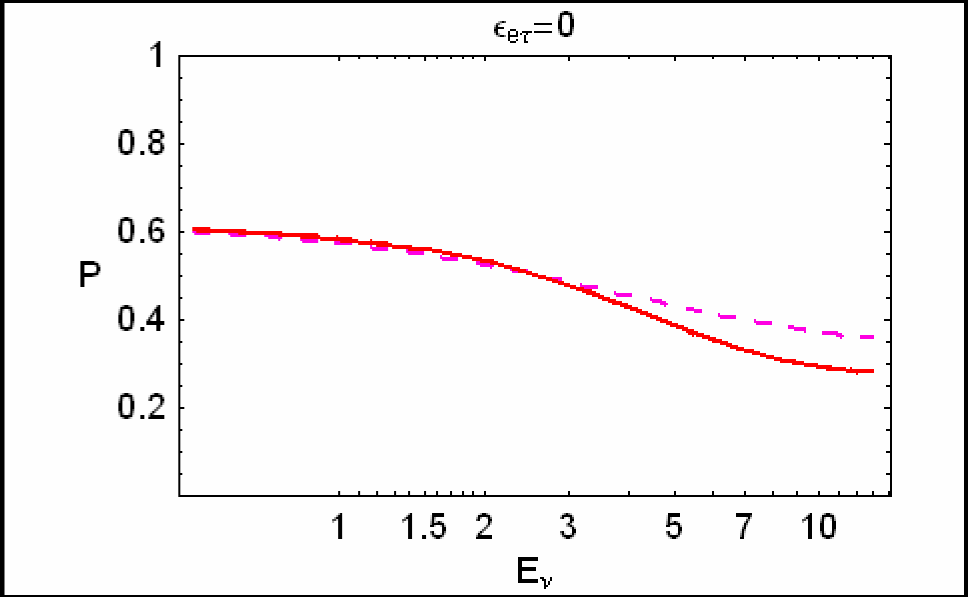


$$\epsilon_{e\tau} \equiv \sum_{f=u,d,e} \epsilon^f_{e\tau} n_f / n_e$$

$$\epsilon^f_{e\tau} \equiv \epsilon^{fL}_{e\tau} + \epsilon^{fR}_{\alpha\beta}$$

# *Flavor-changing NSI: effects on solar neutrino energy spectrum*

- Survival probability at SNO could show more or less energy dependence, depending on the *sign* of the NSI!
- Low-energy bin critical!



$$\epsilon_{\alpha\beta} \equiv \sum_{f=u,d,e} \epsilon^{f}_{\alpha\beta} n_f / n_e$$

$$\epsilon^{f}_{\alpha\beta} \equiv \epsilon^{fL}_{\alpha\beta} + \epsilon^{fR}_{\alpha\beta}$$

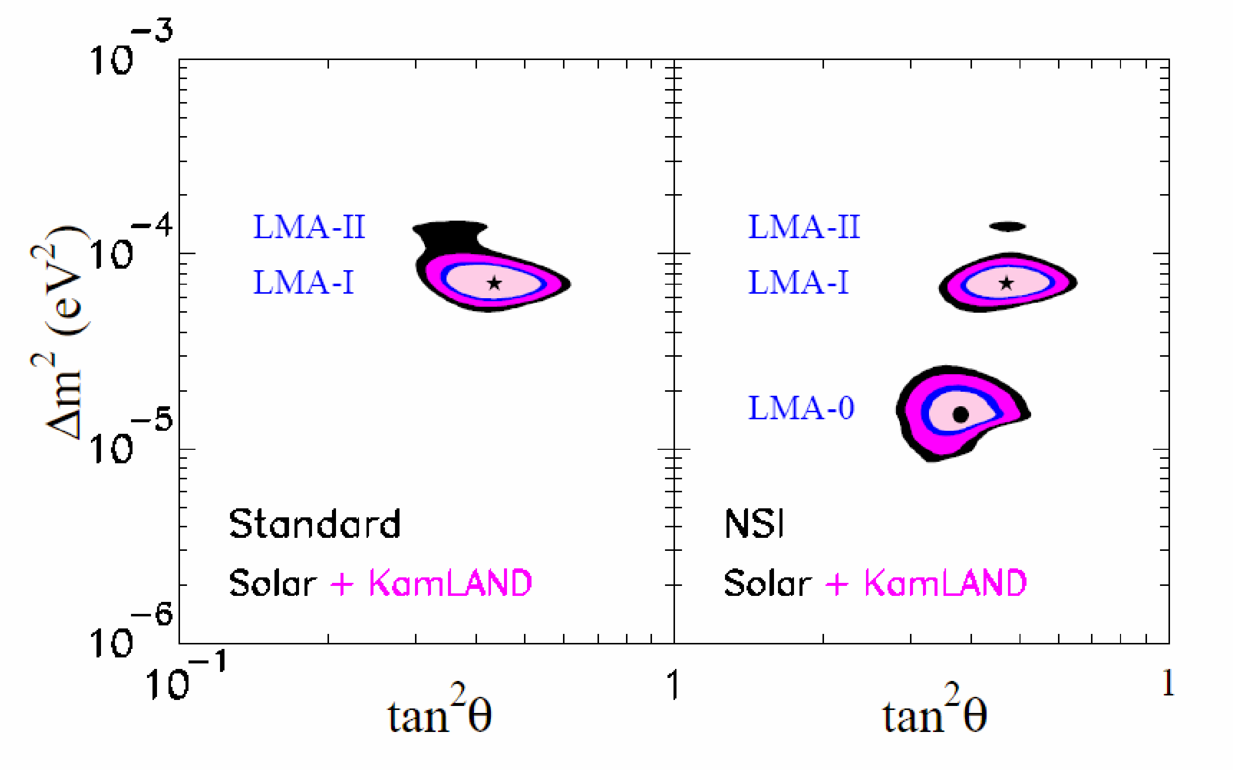
# *NSI can even lead to a new solution: LMA-0…*

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

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

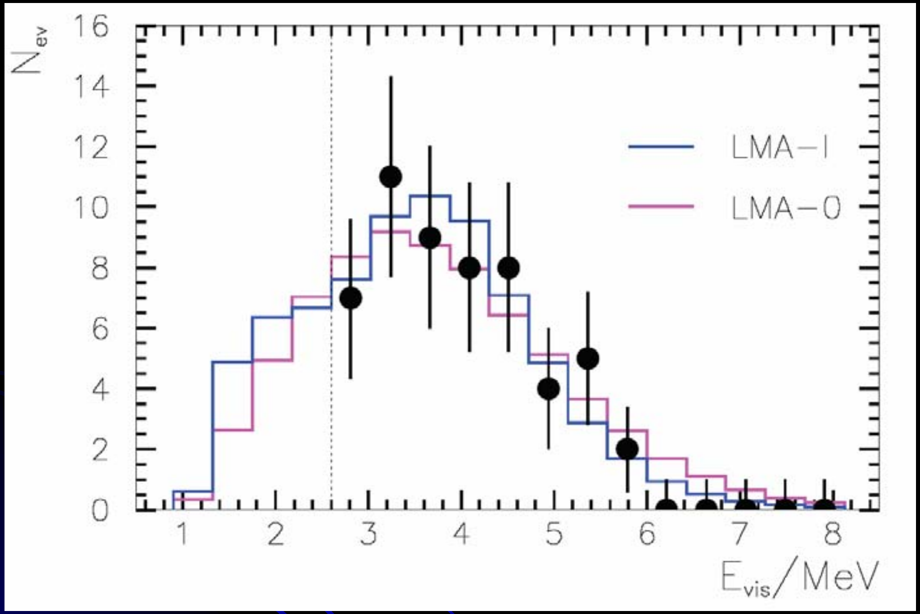
$\varepsilon_{e\tau}^{d} = \varepsilon_{e\tau}^{u} = 0.11$,

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

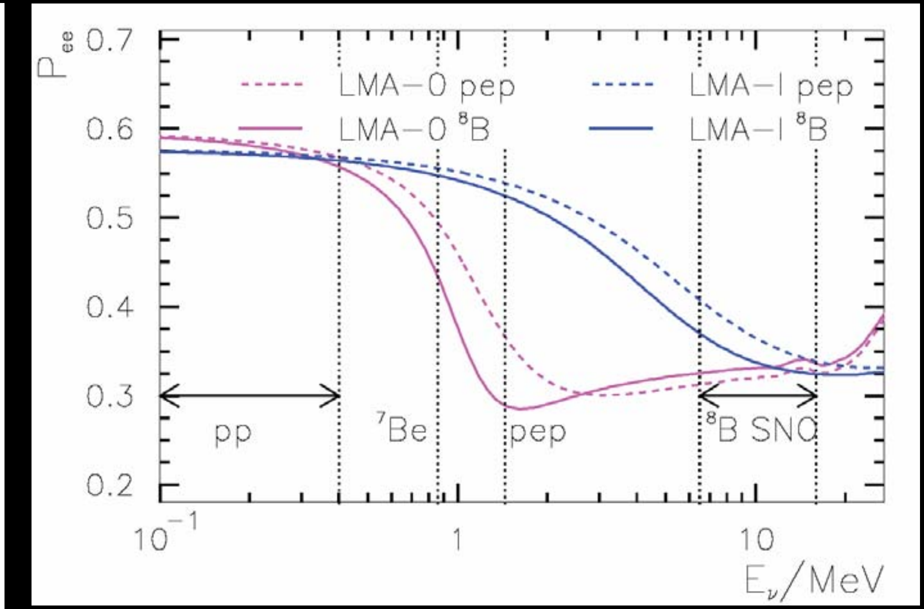


# *…with completely non-trivial and testable properties*

## **KamLAND**



## **Solar neutrino experiments**



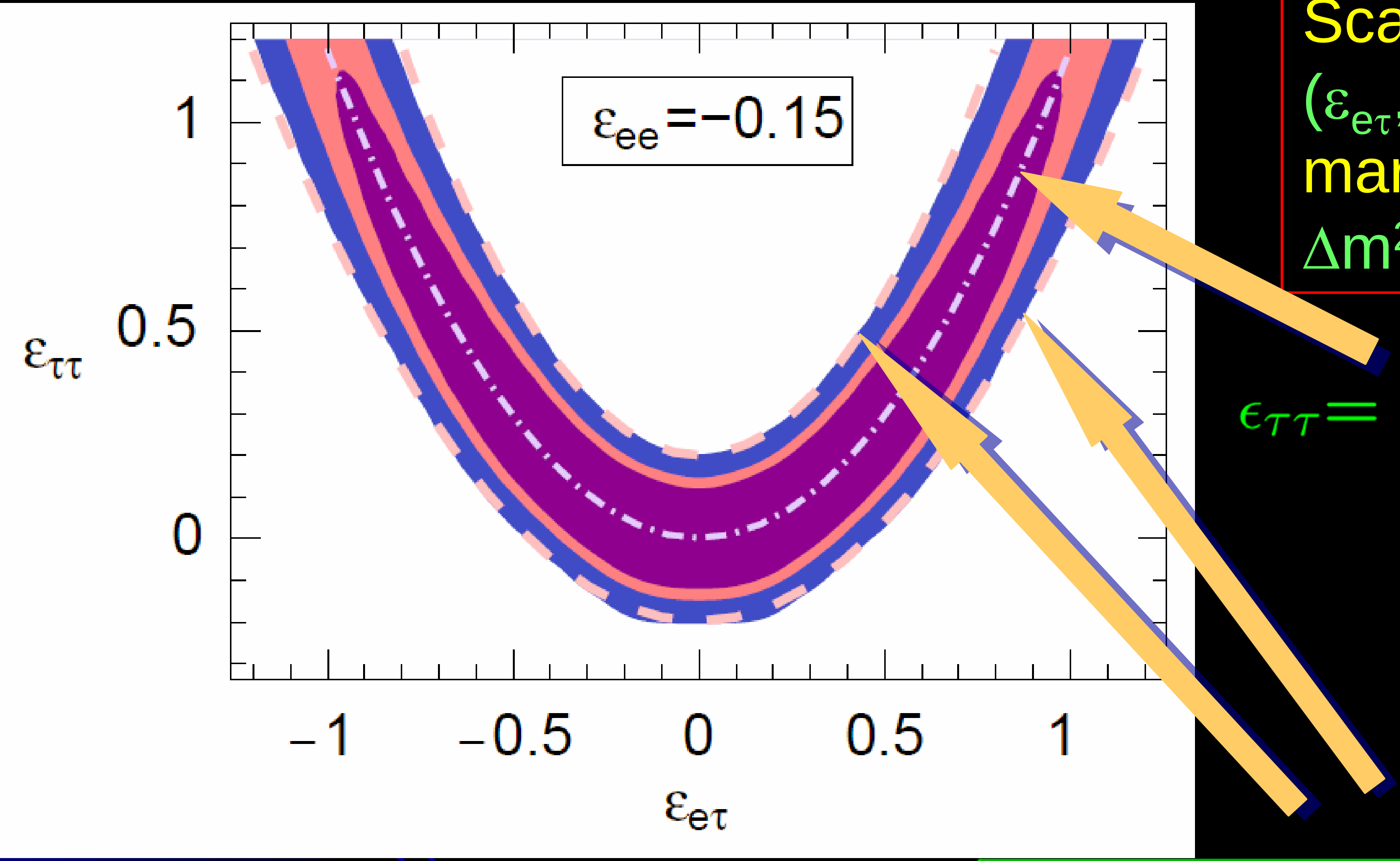
*A. F., C. Lunardini, C. Peña-Garay, PLB594:347,2004 [hep-ph/0402266]*

# *Atmospheric neutrinos and NSI*

- It was thought that such large NSI are excluded by the atmospheric $\nu$ data but that was based on a 2-family $\nu_\mu \leftrightarrow \nu_\tau$ analysis
- The atmospheric analysis DOES NOT reduce to a 2x2 $\nu_\mu$-$\nu_\tau$ system!
  - 3-family analysis finds that large NSI ($\varepsilon_{e\tau} \sim \varepsilon_{\tau\tau} \sim 1$) can be consistent with the data

*A. F., C. Lunardini, M. Maltoni, PRD 70:111301,2004 [hep-ph/0408264]*
*A. F., C. Lunardini, PRD 72:053009,2005 [hep-ph/0506143]*

# Allowed NSI range: fit and predictions



Scanned 4-D space ($\varepsilon_{e\tau}$, $\varepsilon_{\tau\tau}$, $\Delta m^2$, $\theta$); marginalized over $\Delta m^2$, $\theta$

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

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

# *Effect of NSI on the oscillation fit*

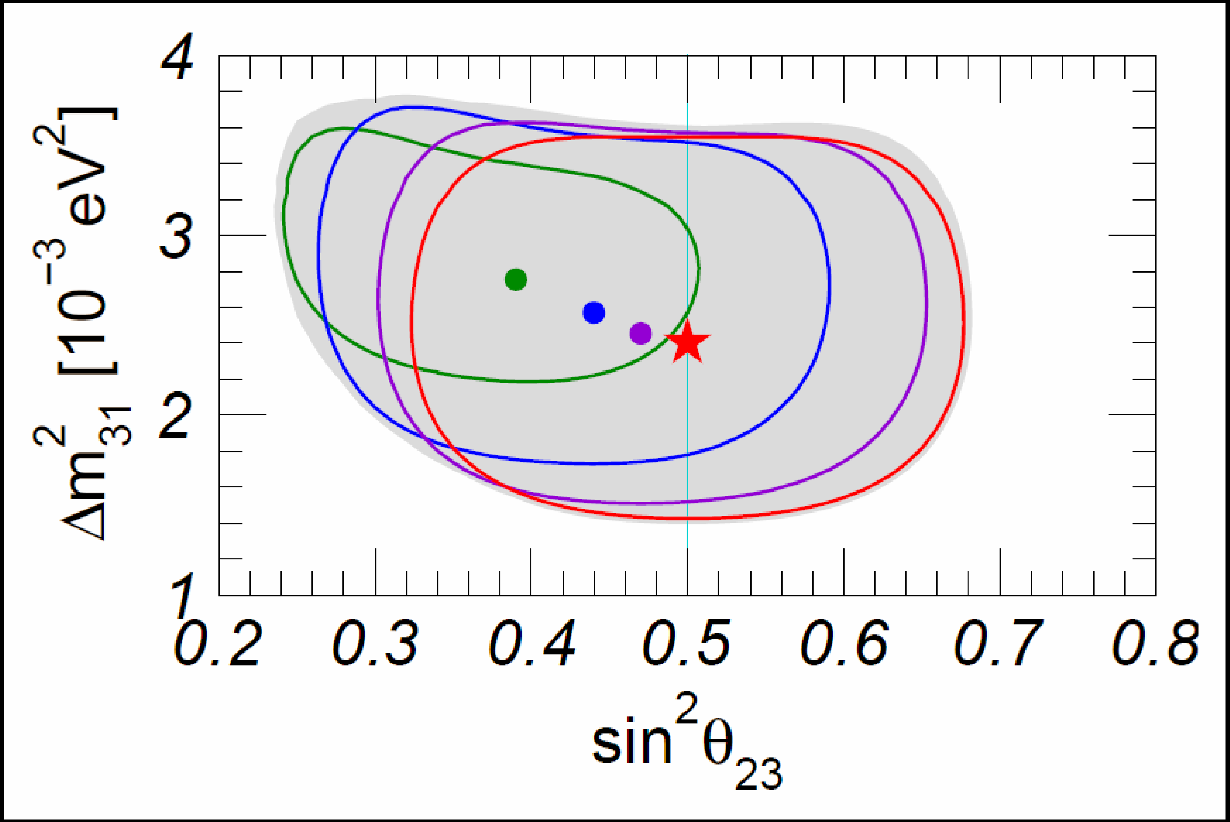
- The best-fit region shifts to smaller θ and larger $\Delta m^2$: $\cos 2\theta \simeq s_\beta^2/(1+c_\beta^2)$; $\Delta m^2 \simeq \Delta m_m^2(1+\cos^{-2}\beta)/2$

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

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

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

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



# *Testing the NSI*

- Lower threshold at SNO, to look for the upturn in $P_{ee}$
- $^7$Be line (Borexino, KamLAND?), to see if the flux is lower, as predicted by LMA-0
- Pep neutrinos!
- 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!

# *Neutrino magnetic moment: basics*

- Dimension 5 operator

$$\begin{aligned}\mathcal{L}_{EM} &= -\frac{1}{2}\mu_{ab}(\nu^{\alpha})_a(\sigma^{\mu\nu})_{\alpha}{}^{\beta}(\nu_{\beta})_b F_{\mu\nu} + \text{h.c.}\\ &= i\mu_{ab}(\tilde{\chi})_a\vec{\sigma}(\nu)_b(\vec{E}+i\vec{B}) + \text{h.c.}\end{aligned}$$

- Majorana neutrino: flavor-diagonal moments vanish identically (spinors anticommute); flavor-changing (transition) moments are allowed
- Ultrarel. $\nu$ precesses in an external magnetic field if either the magnetic or electric moments are non-zero

# *Neutrino magnetic moment: bounds*

- Direct bounds: $\mu < 1\times 10^{-10}\ \mu_B$ (NUMU experiment, Phys. Lett. B564, 190, 2003)
- BBN bound: wrong helicity $\nu$ production (*Dirac only*) $\mu \lesssim 5\times 10^{-10}\ \mu_B$ (Fukugida&Yazaki, PRD36,3817,1987)
- SK spect. distort. $\mu < 1.5\times 10^{-10}\ \mu_B$ (Beacom&Vogel, PRL83,5222,1999)
- CMB: Searches for spectral distortion caused by $\nu$ decay: $\mu \lesssim 0.3\times 10^{-10}\ \mu_B\ (\mathrm{eV}/m_\nu)^{2.3}$ (Ressel&Turner)
- Astrophysics: red giant cooling, $\mu \lesssim 3\times 10^{-12}\ \mu_B$ (G. Raffelt, PRL64, 2856, 1990)

# Use KamLAND?

- Interaction with solar magnetic fields: $\nu_e \rightarrow$ anti-$\nu_\mu$ (Majorana neutrinos)
- Flavor oscillations: anti-$\nu_\mu \rightarrow$ anti-$\nu_e$
- KamLAND is VERY sensitive to anti-$\nu_e$ from the Sun
  - looks for events above 8.3 MeV where there are no reactor antineutrinos; if any excess over predicted background observed, should be due to conversions of solar $^8$B neutrinos
  - Current bound: $\lesssim 3 \times 10^{-4}$ $\nu_e \rightarrow$ anti-$\nu_e$ conversion (*KamLAND*: Phys. Rev. Lett. 92, 071301 (2004))

E. Torrente-Lujan, 2003;
B. C. Chauhan, J. Pulido and E. Torrente-Lujan, 2003;
O. G. Miranda, T. I. Rashba, A. I. Rez and Valle, 2004
…

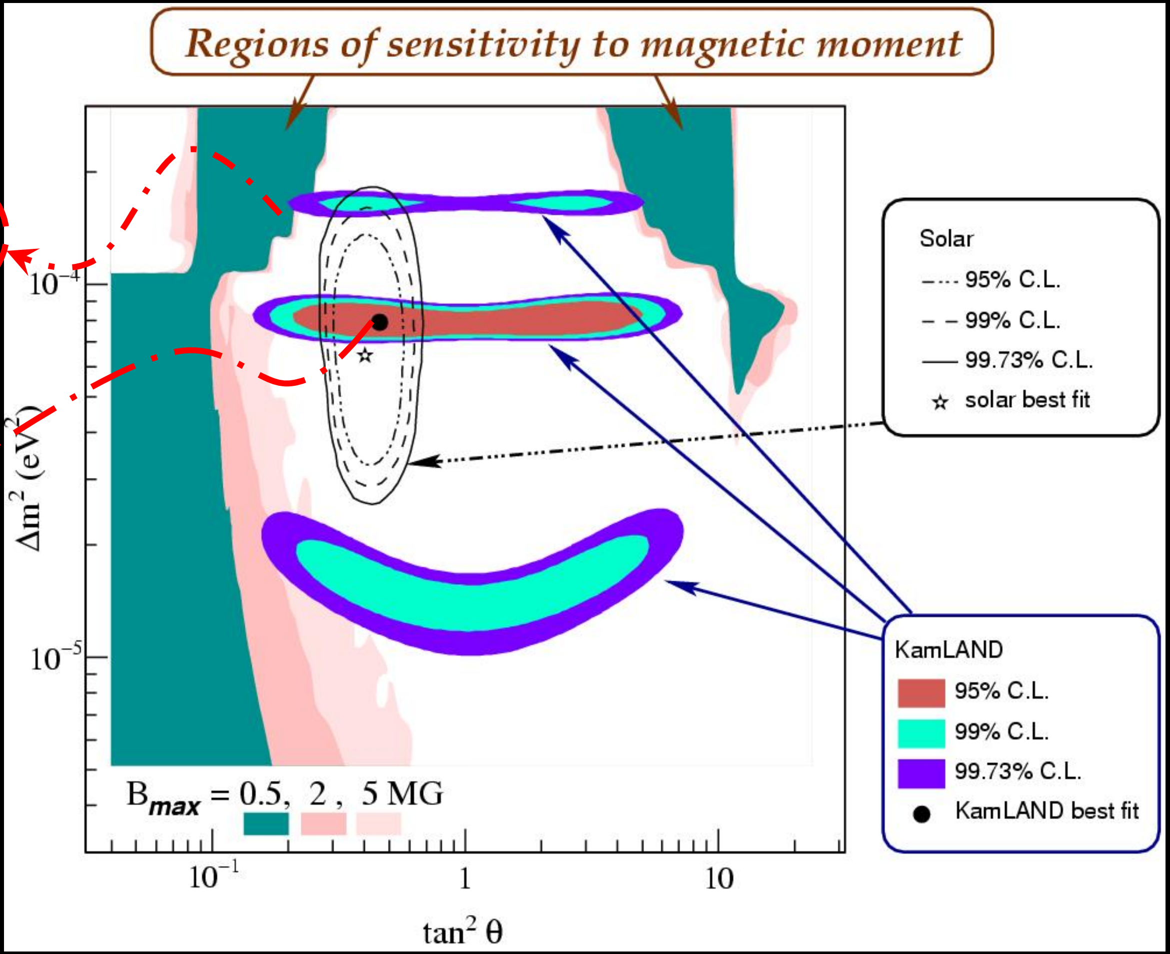
# *If in the Sun, where?*

- Two places with very different physics:
  - convective zone ($r > 0.7\ R_{SUN}$)
    - Magnetic fields KNOWN TO EXIST
    - sunspots, flares, prominences, etc
    - generated by turbulence and shear
    - 11-year (22-year) solar cycle
  - radiative zone ($r < 0.7\ R_{SUN}$)
    - No active mechanism to generate fields
    - Only hints that magnetic field may exist
    - High conductivity (very long Ohmic decay time)
    - possible primordial fields (T.G.Cowling, 1945)
    - weaker upper bounds than in the CZ, $B \lesssim 5\text{-}7$ MG (A.F., A. Gruzinov, Astrophys. J., 601, 570, 2004)

# *Radiative zone: no antineutrino production, even for* $\mu_\nu \sim 10^{-11}\,\mu_B$

$$\Delta m^2 \sim 1.5\times 10^{-4}\,\mathrm{eV}^2$$
$$\theta \sim 24^\circ$$

$$\Delta m^2 \sim 8\times 10^{-5}\,\mathrm{eV}^2$$
$$\theta \sim 32^\circ$$



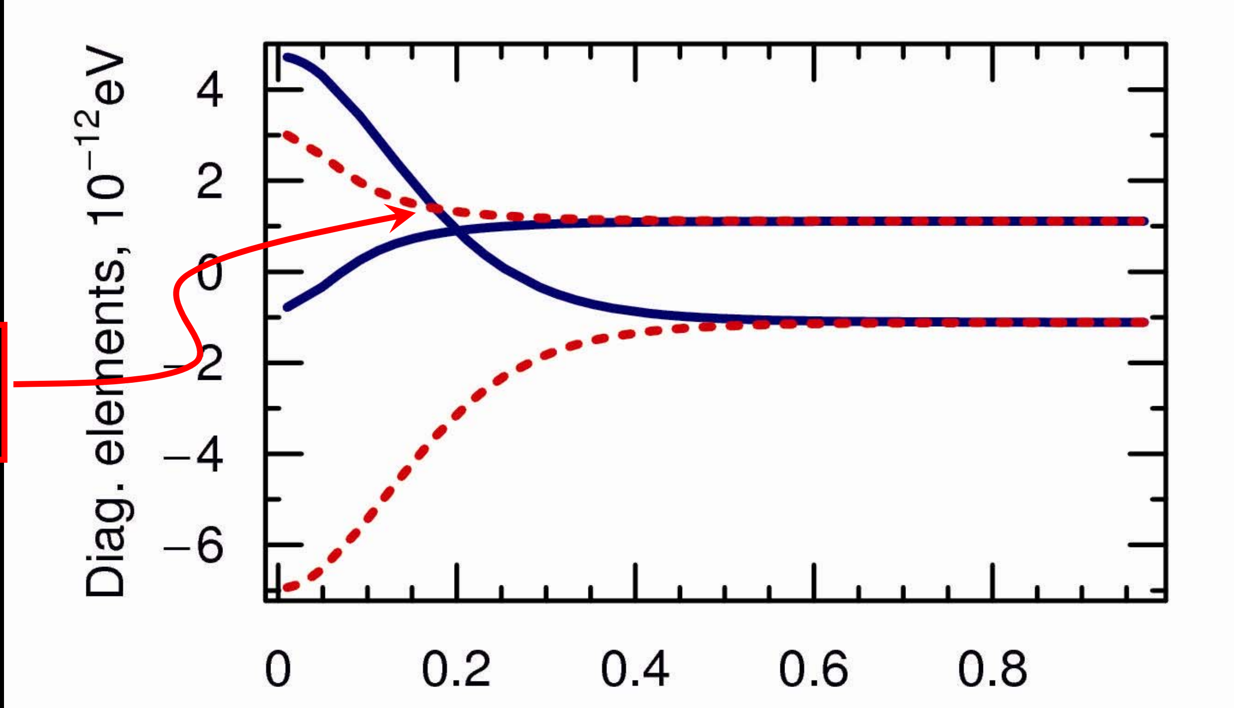
# *Paradox?*

- It is well-known that we should have large $\nu_e \to$ anti-$\nu_\mu$ conversion if the RSFP resonance condition

$$\frac{\Delta m^2}{2E_\nu}\cos 2\theta = \sqrt{2}G_F(n_e - n_n),$$

is satisfied

- For measured $\Delta m^2 \simeq 8 * 10^{-5}$ eV$^2$, $^8$B neutrinos ($\sim$ 10 MeV) *it is satisfied*



# Resolution: correct resonance condition

- Check if *mass* eigenstates in matter cross
- Instead of the classical condition,

$$\frac{\Delta m^2}{2E_\nu}\cos 2\theta = \sqrt{2}G_F(n_e - n_n),$$

the correct condition is

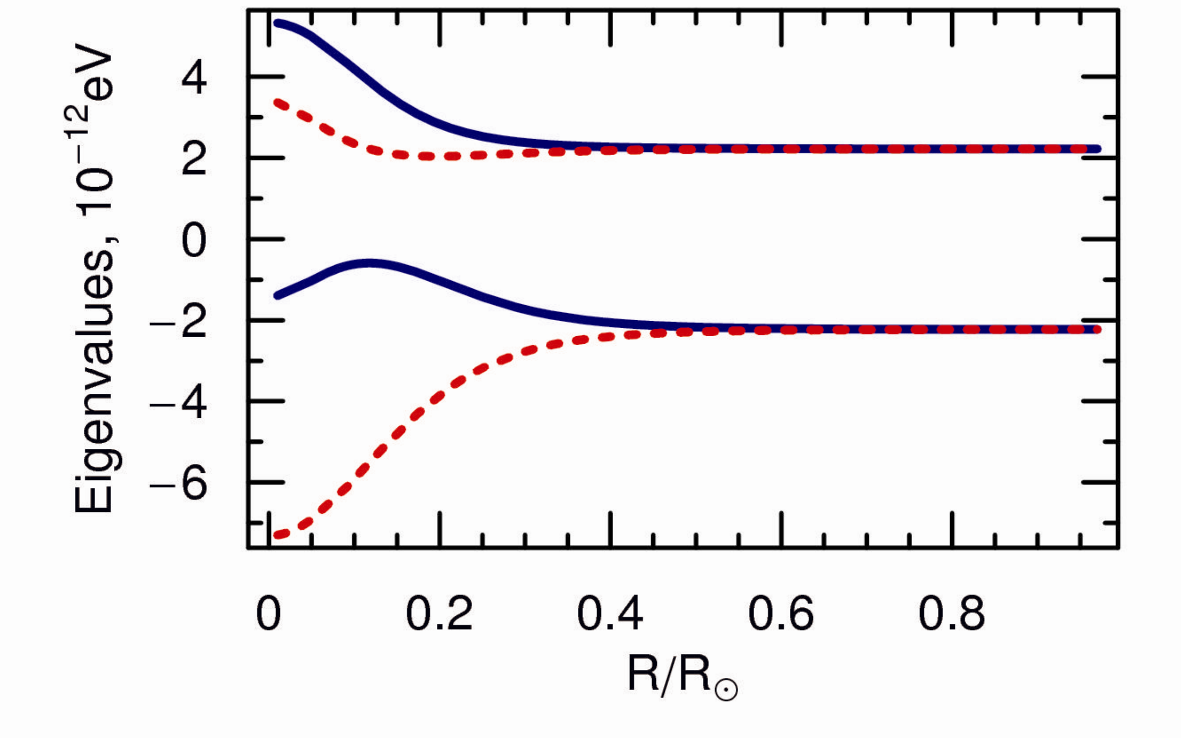
$$\boxed{\frac{\Delta m^2}{2E_\nu} = \sqrt{2}G_F(n_e-n_n)\sqrt{\frac{n_e^2-(n_e-n_n)^2}{n_e^2\cos^2 2\theta-(n_e-n_n)^2}}.}$$

- The two agree only for zero θ! The dependence on θ is completely different! In particular, the resonance disappears for

$$\boxed{\cos 2\theta_{\rm crit} \simeq (1-n_n/n_e) \qquad \tan^2\theta_{\rm crit} \sim (0.09-0.33).}$$

# *Resolution: correct resonance condition*

- Large mixing pushes levels apart!
- No resonant neutrino-antineutrino conversion



# *Convective Zone, Model I: Uniform Kolmogorov turbulence*

- Assume magnetic field scales in a way typical for turbulent systems

$$B_\lambda \propto \lambda^\alpha, \quad \alpha \sim 1/3(\text{Kolmogorov})$$

- Estimate the field on the largest scales (0.1 $R_\odot$) of the turbulence from equipartition:

$$B_{L\text{max}} \sim \rho^{1/6} L_\odot^{1/3} r^{-2/3} \sim 10\text{kG}$$

- The effect comes out too small!

$$P(\nu_e \to \bar{\nu}_e) \sim \cos^2\theta(\mu B_{\lambda_\text{osc}})^2 L\lambda_\text{osc} \sim 10^{-5}$$

# *Convective Zone, Model II: Isolated flux tubes*

- Plausible that the field in the CZ has a ``fibril'' nature, i.e., it is expelled by the turbulence and combines in isolated flux tubes. It was argued (E. Parker, 1984) that the total energy of the CZ (thermal + gravitational + magnetic) is reduced by the fibril state by avoiding the magnetic inhibition of convection
- Sunspot flux $10^{20}$ Mx, assume 100 kG fields → 300 km, close to optimal (neutrino oscillation length)!
- Comparing with total flux through the CZ, $10^{24}$ Mx, neutrino encounters only several tubes

$$P(\nu_e \to \bar{\nu}_e) \sim (\text{a few}) \times 10^{-4}$$

# *Summary on magnetic moment*

- Given the measured large value of the solar neutrino mixing angle, possible magnetic fields in the solar radiative interior *cannot affect neutrino evolution*
- Correct "magnetic resonance" condition derived
- "Bounds" based on the CZ spin-flip are greatly exaggerated: did not treat magnetic field correctly
- Makes sense that KamLAND has not seen any antineutrinos from the Sun. May be on the edge of probing the optimistic scenario.

# *Convective Zone fields: basics*

- Fields created and destroyed during each solar cycle by convection + differential rotation. The exact picture still an active subject of research. Nevertheless,
  - Sunspots (B $\sim$ sev. kG) usually come in pairs of opposite polarity; thought to be manifestations of large-scale magnetic structures residing in the CZ.
  - Total flux that emerges on the surface during the solar cycle is around $2 \times 10^{25}$ Mx; total toroidal flux in the CZ at sunspot maximum $\sim 10^{24}$ Mx (tubes emerge more than once)
  - Turbulent equipartition B $\sim$ 10 kG
  - Stronger fields (B $\sim$ 100 kG), if exist, must have a small filling fraction (total flux + energy arguments)

# *Neutrino in turbulent fields*

- "Noisy" background field resets oscillation phase → random walk in the flavor space
  - transitions that are normally (in smooth fields) suppressed by large diagonal mass splitting become allowed

$$P \sim (\mu B \lambda_{\text{osc}})^2 \text{ smooth field}$$

$$P \sim \begin{cases} (\mu B \lambda_{\text{corr}})^2 L/\lambda_{\text{corr}}, & \lambda_{\text{corr}} \lesssim \lambda_{\text{osc}} \\ (\mu B \lambda_{\text{osc}})^2 L/\lambda_{\text{corr}}, & \lambda_{\text{corr}} \gtrsim \lambda_{\text{osc}}, \text{ sharp edge} \\ \text{exp. suppressed}, & \lambda_{\text{corr}} \gtrsim \lambda_{\text{osc}}, \text{ smooth edge} \end{cases}$$

Balantekin&Loreti 1994, Burgess&Michaud 1996, …