Solar neutrinos and the neutrino magnetic moment

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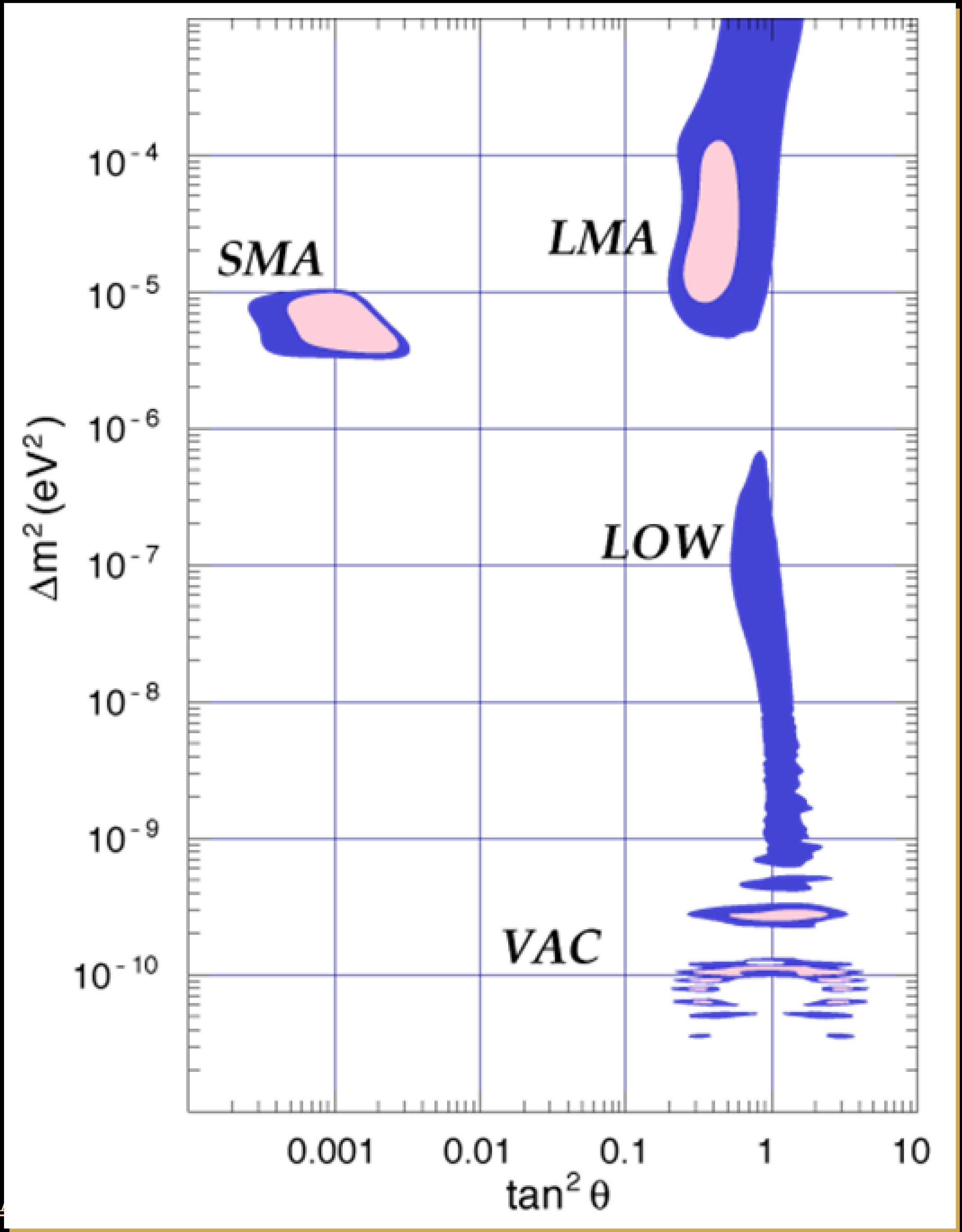
Goal

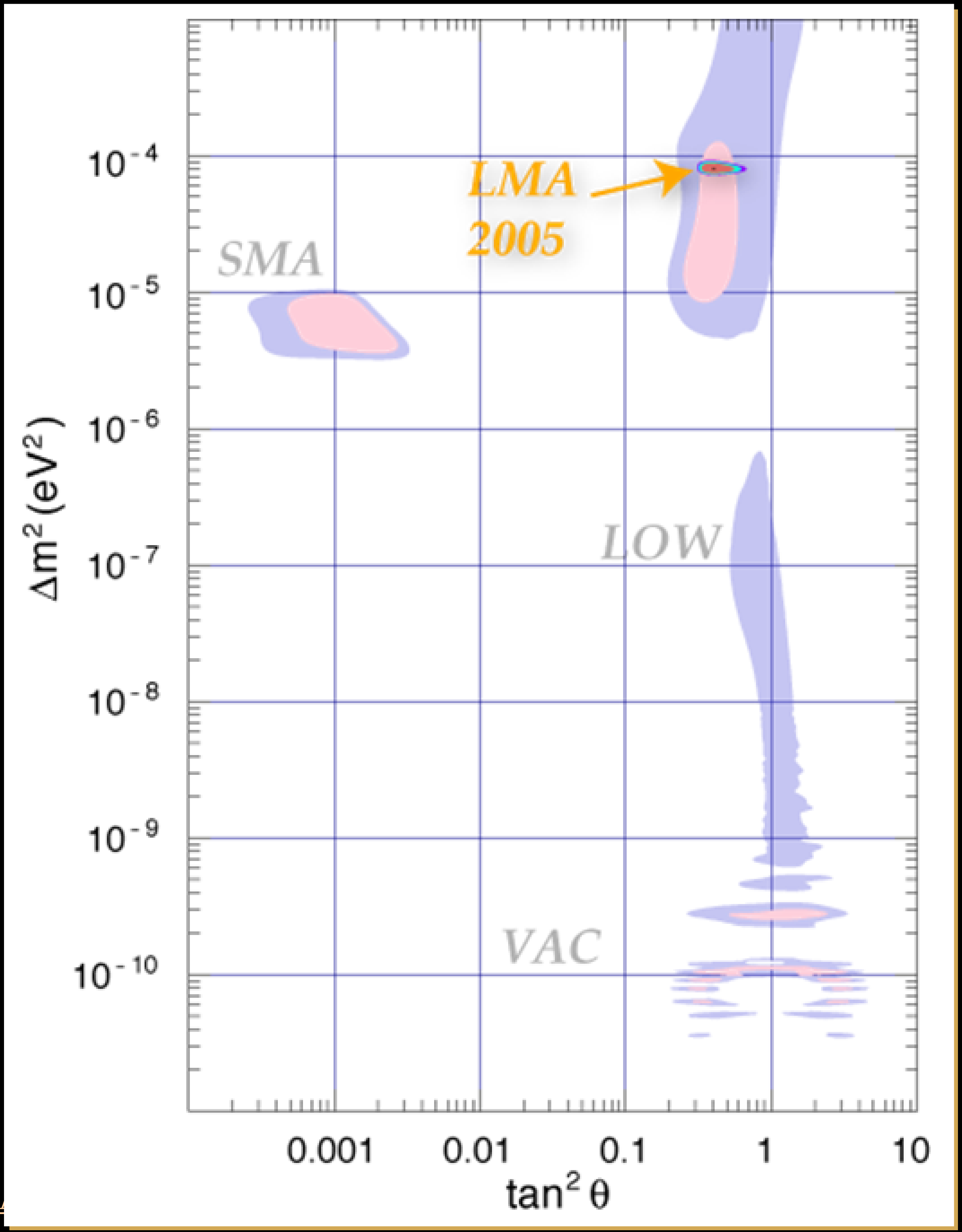
- To see if the solar neutrinos are sensitive to the neutrino magnetic moment
- On a more detailed level: where in the Sun? Consider all possibilities

- Allowed values of oscillation parameters as of 2000…

(from PLB 490 125, 2000)



- … and now, five years later



Not done yet!

- Neutrino properties, besides masses and mixings:
  1. interactions with matter
  2. interactions with EM fields
  3. exotic decays
  4. novel neutrino states
  5. …
- *Full implications of the data remain to be understood!*

- New physics at $\gtrsim M_{EW}$ could cause subdominant effects, detectable with precision measurements. If found, implications would be profound

Digression: philosophy

- Light scalars are in general unnatural in QFT.
- All the particles observed so far are fermions or gauge bosons (good!)
- But, a scalar (the Higgs) lies just around the corner
- New physics at the TeV scale?
- Search for this new physics:
  - write down effective operators suppressed by the new scale
  - Search for their effects with precision “low” energy measurements
- A lot of effort in the quark and charge lepton sector (e.g., precision EW tests, exotic FV decays, proton decay)
- What can be done with neutrinos?

Neutrino magnetic moment: basics

- Dimension 5 operator

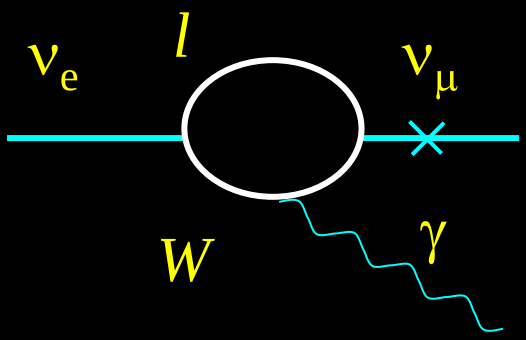
$$\mathcal{L}_{EM} = -\frac{1}{2}\mu_{ab}(\nu^{\alpha})_a(\sigma^{\mu\nu})_{\alpha}{}^{\beta}(\nu_{\beta})_b F_{\mu\nu} + \text{h.c.}$$
$$= \mu_{ab}(\chi)_a\vec{\sigma}(\nu)_b(\vec{E} + i\vec{B}) + \text{h.c.}$$

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

Neutrino magnetic moment: basics

- Generated in the Standard Model
  - Because the SM is left-handed, highly suppressed:

$$\mu_\nu \sim e G_F m_\nu \sim 3 \times 10^{-19} \mu_B (m_\nu / eV)$$



- Extensions of the SM could easily have larger contributions
  - E.g, in left-right symmetric models

$$\mu_\nu \sim e G_F m_l \sin 2\eta$$

Neutrino magnetic moment: bounds

- Direct bounds: $\mu < 1\times 10^{-10}\ \mu_B$ (NUMU experiment, Phys. Lett. B564, 190, 2003);
- BBN bound: wrong helicity ν production (*Dirac only*) $\mu \lesssim 5\times 10^{-10}\ \mu_B$ (Fukugida&Yazaki, PRD36,3817,1987)
- CMB: Searches for spectral distortion caused by ν decay: $\mu \lesssim 0.3\times 10^{-10}\ \mu_B\ (eV/m_\nu)^{2.3}$ (Ressel&Turner)
- Astrophysics: red giant cooling, $\mu \lesssim 3\times 10^{-12}\ \mu_B$ (G. Raffelt, PRL64, 2856, 1990)
- Astrophysics: solar neutrinos, $\mu \lesssim 3\times 10^{-12}\ \mu_B$ (Miranda, Rashba, Rez, Valle, PRL93, 051304, 2004; PRD70, 113002, 2004)

??

Could μ_ν have an effect on solar ν's?

- Interaction with solar magnetic fields: $\nu_e \to$ anti-ν_μ (Majorana neutrinos)
- Flavor oscillations: anti-$\nu_\mu \to$ anti-ν_e
- KamLAND is VERY sensitive to anti-ν_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: $\lesssim 3 \times 10^{-4}$ $\nu_e \to$ anti-ν_e conversion (*KamLAND*: Phys. Rev. Lett. 92, 071301 (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
    - weaker upper bounds than in the CZ

Traditional wisdom

- Radiative zone: resonance level crossing for measured value of $\Delta m^2 \rightarrow$ measurable antineutrino production possible
  - E. Akhmedov, J. Pulido, Phys.Lett.B553:7, 2003
  - B. Chauhan, J. Pulido, E. Torrente-Lujan, PRD68, 033015, 2003
  - A.B. Balantekin, C. Volpe, hep-ph/0411148
  - ….
- Convective zone: enhanced production in the turbulent magnetic field $\rightarrow$ measurable antineutrino production possible $\rightarrow$ even a bound claimed
  - E. Torrente-Lujan, JHEP0304, 054, 2003
  - Miranda, Rashba, Rez, Valle, PRL93, 051304, 2004
  - Miranda, Rashba, Rez, Valle, PRD70, 113002, 2004
  - ….

Radiative Zone fields: basics

- possible primordial fields
  - Ohmic decay time $\sim 10^{10}$ years (Cowling, MNRAS, 1945)
  - Eight toroidal eigenmodes with lifetimes greater than the solar age, 4.6 Gyrs (A.F., A. Gruzinov, Astrophys. J. 601, 570, 2004)
- Strength constrained to be $\lesssim$ a few MG (A.F., A. Gruzinov, Astrophys. J. 601, 570, 2004)
  - Solar oblateness
  - Stability of field configurations ("double-diffusive instability")
  - Helioseismology

Radiative zone fields: some history

- Solar neutrino problem
  - D. Bartenwerfer, Astron. Astrophys. 25, 455 (1973).
  - S. M. Chitre, D. Ezer, R. Stothers, Astrophys. Lett. 14, 37 (1973).
- "Princeton" solar oblateness measurements:
  - R. H. Dicke, Astrophys. Space Sci. 55, 275 (1978); Astrophys. J. 228, 898 (1979); Solar Phys. 78, 3 (1982).
- Solar rotation profiles
  - D. Gough, M. E. Mcintyre, Nature 394, 755 (1998)

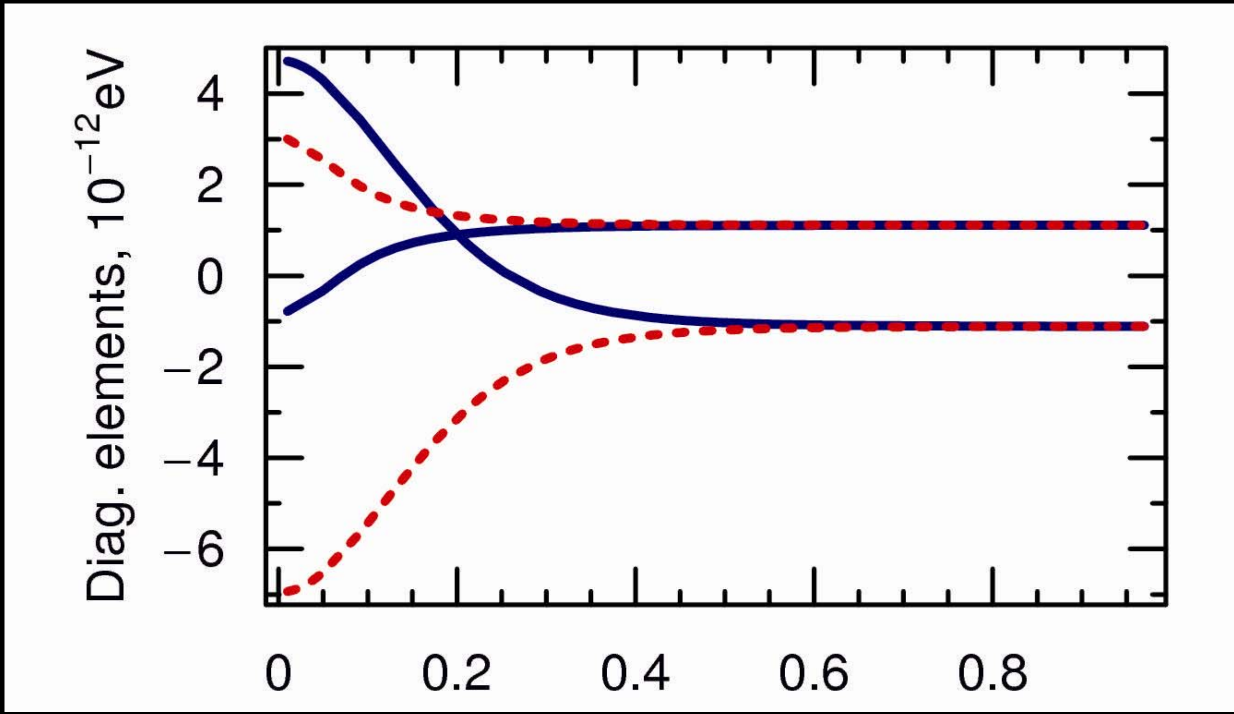
Neutrino Hamiltonian

- In the basis $(\nu_e, \nu_\mu, \bar{\nu}_e, \bar{\nu}_\mu)$

$$H = \begin{pmatrix} -\Delta\cos 2\theta & \Delta\sin 2\theta & 0 & \mu_\nu B \\ \Delta\sin 2\theta & \Delta\cos 2\theta & -\mu_\nu B & 0 \\ 0 & -\mu_\nu B & -\Delta\cos 2\theta & \Delta\sin 2\theta \\ \mu_\nu B & 0 & \Delta\sin 2\theta & \Delta\cos 2\theta \end{pmatrix} + \sqrt{2}G_F \begin{pmatrix} N_e - N_n/2 & 0 & 0 & 0 \\ 0 & -N_n/2 & 0 & 0 \\ 0 & 0 & -N_e + N_n/2 & 0 \\ 0 & 0 & 0 & N_n/2 \end{pmatrix}$$

Mechanism: the resonance

- For measured $\Delta m^2 \simeq 8 * 10^{-5}$ eV^2, high energy ($\sim$ 10 MeV) ^{8}B neutrinos
- Diagonal entries of the Hamiltonian: two resonances
  - $\nu_e \rightarrow$ anti-ν_μ
  - $\nu_e \rightarrow \nu_\mu$



Evolution factorized

- *Standard argument:* the resonance is narrow
  $\rightarrow$ magnetic spin-flip in near the resonance, followed by flavor oscillations

$$P(\nu_e \rightarrow \bar{\nu}_e) = P(\nu_e \rightarrow \bar{\nu}_\mu)|_{res} \times P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)|_{fl.osc.}$$

- Toroidal magnetic field in the rad. zone is bounded to be $\lesssim$ 5-7 MG from the analysis of the solar shape + stability of the field configuration (A.F., A. Gruzinov, Astrophys.J.601:570, 2004)
- Within this bound, and given the factorized expression above, can get large antineutrino flux
  - at the bound up to 5-10% conversion

This is nice… but doesn't work!

- Trivially checked by putting the neutrino evolution equation on the computer

What went wrong? Physics behind the resonance description

- Large diagonal entries of the Hamiltonian suppress oscillations

$$H = \begin{pmatrix} -\Delta & \delta \\ \delta & \Delta \end{pmatrix} \longrightarrow \text{for } \Delta \gg \delta, \ \text{(osc.prob.)} \sim \left(\frac{\delta}{\Delta}\right)^2$$

- Resonance: if levels cross, Δ is small in some region
- In that region, δ can drive conversion

Factorization not justified!

- When mixing angle θ is large, even when the diagonal terms cancel, the off-diagonal terms dominate the Hamiltonian $\rightarrow$ cannot apply the standard resonance logic

$$H = \begin{pmatrix} -\Delta\cos 2\theta & \Delta\sin 2\theta & 0 & \mu_\nu B \\ \Delta\sin 2\theta & \Delta\cos 2\theta & -\mu_\nu B & 0 \\ 0 & -\mu_\nu B & -\Delta\cos 2\theta & \Delta\sin 2\theta \\ \mu_\nu B & 0 & \Delta\sin 2\theta & \Delta\cos 2\theta \end{pmatrix} + \sqrt{2}G_F \begin{pmatrix} N_e - N_n/2 & 0 & 0 & 0 \\ 0 & -N_n/2 & 0 & 0 \\ 0 & 0 & -N_e + N_n/2 & 0 \\ 0 & 0 & 0 & N_n/2 \end{pmatrix}$$

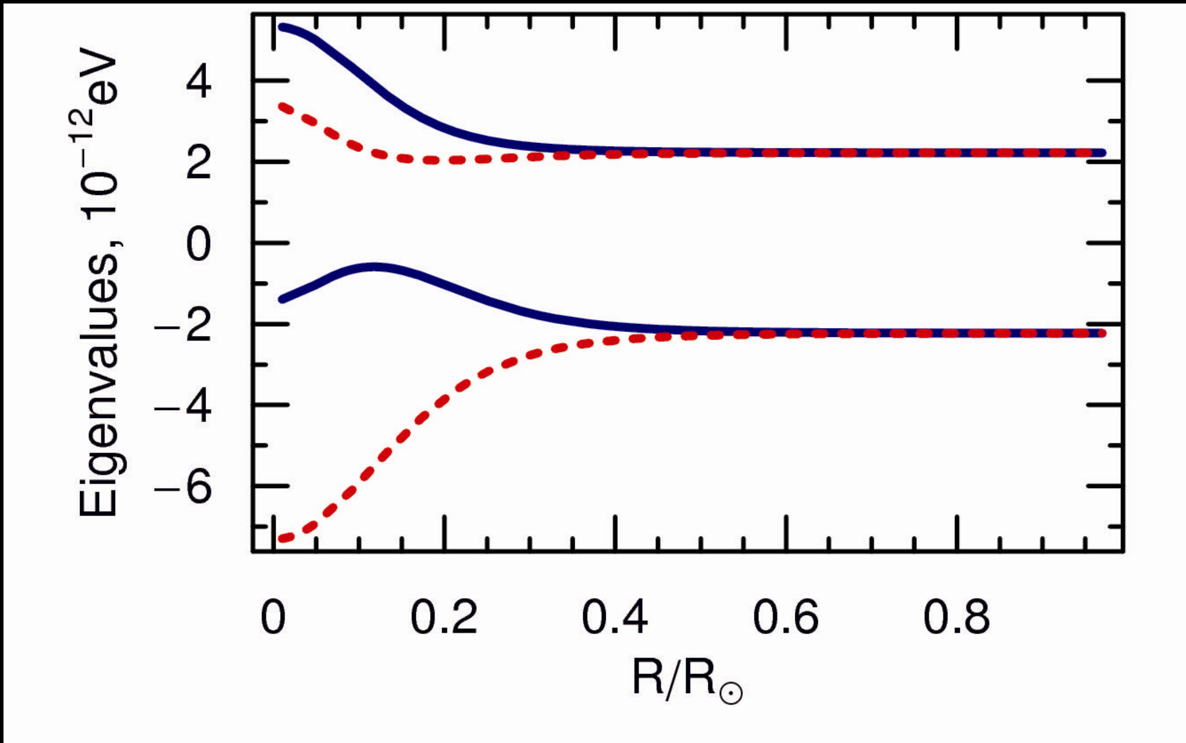
Mass eigenbasis

- The right way to think about the problem is to go to the mass basis, where all the large terms are on the diagonal

$$H = \begin{pmatrix} -\Delta_m & 0 & \mu_\nu B \sin(\theta_m - \bar{\theta}_m) & \mu_\nu B \cos(\theta_m - \bar{\theta}_m) \\ 0 & \Delta_m & -\mu_\nu B \cos(\theta_m - \bar{\theta}_m) & \mu_\nu B \cos(\theta_m - \bar{\theta}_m) \\ \mu_\nu B \sin(\theta_m - \bar{\theta}_m) & -\mu_\nu B \cos(\theta_m - \bar{\theta}_m) & -\bar{\Delta}_m & 0 \\ \mu_\nu B \cos(\theta_m - \bar{\theta}_m) & \mu_\nu B \sin(\theta_m - \bar{\theta}_m) & 0 & \bar{\Delta}_m \end{pmatrix}$$

- Now, check to see if mass eigenvalues in matter cancel anywhere…

- No, they don't!
- Large mixing pushes levels apart!
- No neutrino-antineutrino transition



Correct resonance condition

- *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 right condition is

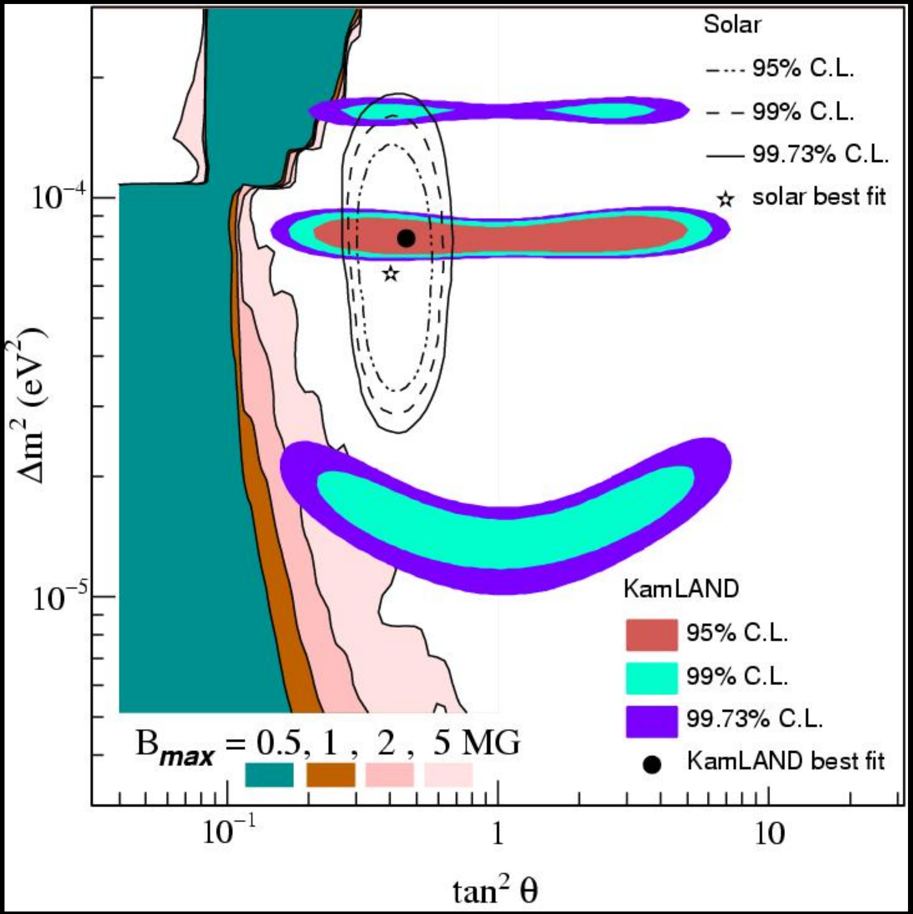
$$\frac{\Delta m^2}{2E_\nu} = \sqrt{2}G_F(n_e - n_n)\sqrt{\frac{n_e^2 - (n_e - n_n)^2}{n_e^2\cos^2 2\theta - (n_e - n_n)^2}}.$$

- Agree only for zero θ! The dependence on θ is completely different! The resonance disappears for

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

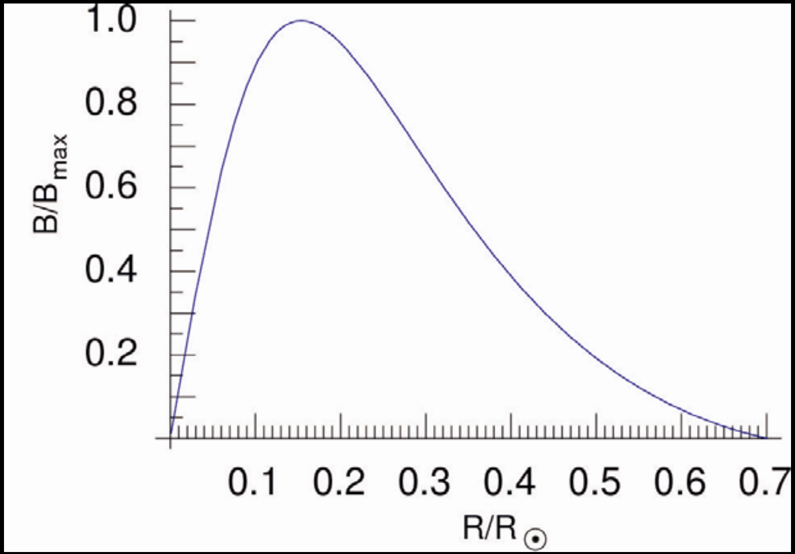
Magnetic anti-ν_e production: quantitative analysis

- The region of the parameter space where anti-ν_e can be produced does not include the experimentally measured oscillation parameters



Result is general

- Used BP04 solar model; longest living toroidal mode



A.F., A. Gruzinov,
Astropart. Phys. 19, 575 (2003)
Astrophys. J. 601, 570 (2004)

- Not essential, could have included other modes. Important physics: field smooth (adiabaticity!)
  - features smaller than $R_\odot/10$ must have decayed away
  - axisymmetric + vanishing at the RZ/CZ boundary

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 2×10^{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 $\rightarrow$ random walk in the flavor space
  - transitions that are normally (in smooth fields) suppressed by large diagonal mass splitting become allowed

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

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

Model I: Uniform Kolmogorov turbulence

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

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

- 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 net effect comes out too small!

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

Model II: Isolated flux tubes

- Possible 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 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 $\rightarrow$ 300 km, close to optimal!
- Comparing with total flux, 10^{24} Mx, neutrino encounters only several tubes

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

Summary

- Given the measured large value of the solar neutrino mixing angle, possible magnetic fields in the solar radiative interior *cannot affect neutrino evolution*
- Previous conclusions to the contrary did not treat neutrino evolution properly (large mixing!)
- The 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.