MSW Oscillations - LMA and Subdominant Effects

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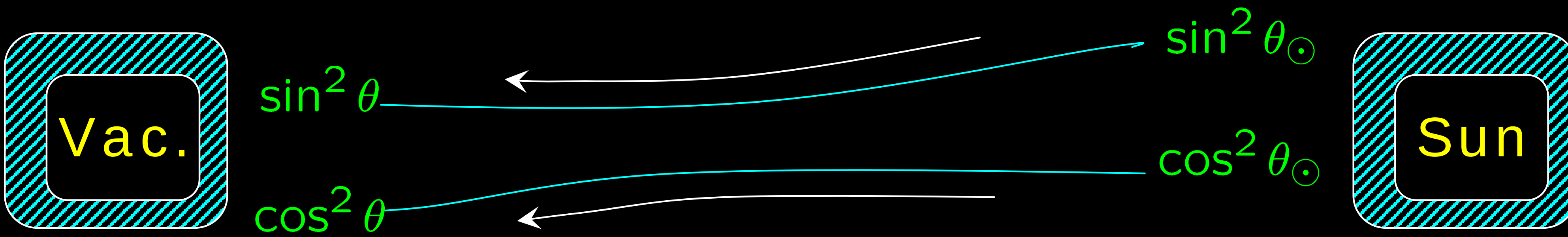
Outline

- Standard LMA solution: basic features
- Subdominant effects: status and prospects
  - 3-ν oscillations (briefly)
  - Searching for non-standard ν interactions
  - Searching for ν magnetic moments
- Solar neutrinos must be considered together with atmospheric, reactor, and ν beam experiments + astrophysics/colliders
  - Precision neutrino physics $\rightarrow$ important mode of searching for new physics
- By no means exhaustive; not considered here
  - effects of density fluctuations (negligible)
  - sterile neutrinos
  - neutrino couplings to hypothetical light scalars
  - …

How does LMA work?

- ^8B survival probability is ~30%, approx. flat in E_ν + day/night is small
- GALLIUM experiments see about 54% of the SSM prediction $\rightarrow$ survival probability must be higher for low energy *pp* neutrinos

Adiabatic survival probability



$$P_{ee}^{AD} = \cos^2\theta_\odot \cos^2\theta + \sin^2\theta_\odot \sin^2\theta$$

Two limits:

- ***Matter dominates*** $\Delta m^2/2E < 2^{1/2} G_F N_\odot \Rightarrow \theta_\odot \rightarrow \pi/2$

  $\Rightarrow P_{ee} \rightarrow \sin^2\theta$

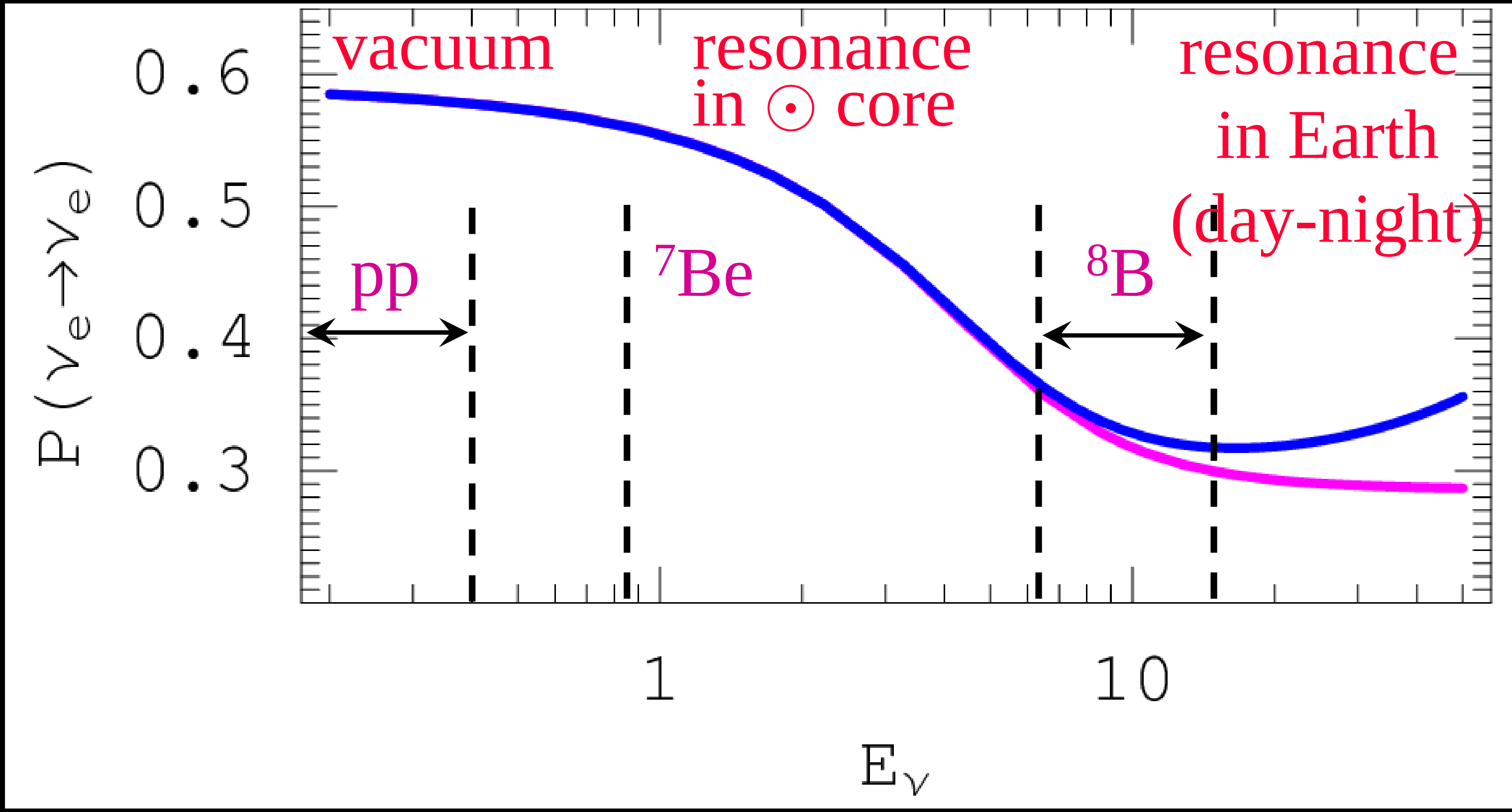
- ***Vacuum dominates*** $\Delta m^2/2E > 2^{1/2} G_F N_\odot \Rightarrow \theta_\odot \rightarrow \theta$

  $\Rightarrow P_{ee} \rightarrow \cos^4\theta + \sin^4\theta = 1 - (\sin^2 2\theta)/2 \geq 1/2$

  averaged vacuum oscillations

Designing LMA

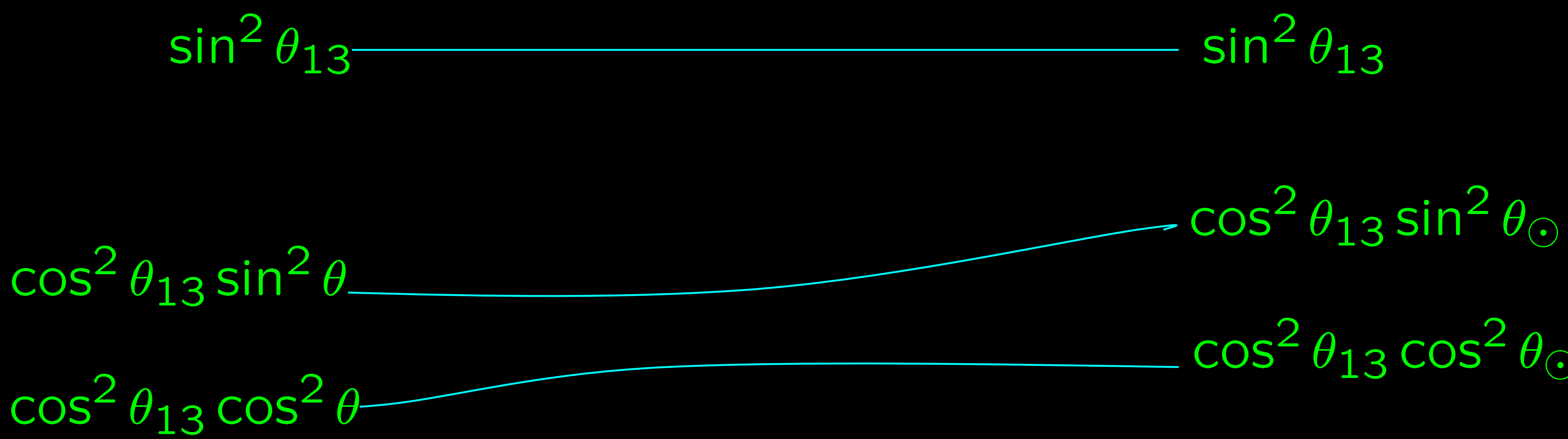
- Fine-tune Δm^2 such that the transition between the regimes occurs at the intermediate solar energies
  $\Delta m^2 \sim G_F N_\odot\ (10^6 eV) \sim$ a few $\times\ 10^{-5}\ eV^2$
- Remarkably, checks with KamLAND reactor ν osc.!



Designing the whole spectrum

- Tune solar splitting to matter potential in solar center
    - $\Delta m^2 \sim G_F N_\odot\ (10^6 eV) \sim$ a few $\times\ 10^{-5}\ eV^2$
  - make mixing angle large, so that could be checked with reactor antineutrinos (basically oscillations in vacuum)
- The 2nd splitting should be discoverable with atmospheric neutrinos:
    - set vacuum oscillation length for typical $E_{atm} \sim 10^9$ GeV to be $\sim 10^3$ km $\rightarrow \Delta m^2_{atm} \sim 10^{-3}\ eV^2$
  - make mixing angle large (basically oscillations in vacuum)
- Make θ_{13} small, so as not to confuse people
  - two-neutrino analysis for both solar and atmospheric neutrinos

Subdominant effect I: θ_{13}



$$P_{ee}^{3\nu} \simeq \sin^4\theta_{13} + \cos^4\theta_{13} P_{ee}^{2\nu}$$

- CHOOZ (+ global): $\sin^2\theta_{13} \lesssim 0.02$
  - at the limit, $P_{ee}^{3\nu} \simeq 4\times 10^{-4} + 0.96 \times P_{ee}^{2\nu}$
  - a few percent change

see, e.g., G.L. Fogli, E. Lisi, A. Marrone, A. Palazzo, hep-ph/0506083 for a recent analysis and refs.

Subdominant effect II: novel neutrino NC interactions

- Idea is as old as matter effects in neutrino oscillations
  - (L. Wolfenstein, PRD 17, 2369 (1978))

PHYSICAL REVIEW D VOLUME 17, NUMBER 9 1 MAY 1978

Neutrino oscillations in matter

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(Received 6 October 1977; revised manuscript received 5 December 1977)

The effect of coherent forward scattering must be taken into account when considering the oscillations of neutrinos traveling through matter. In particular, for the case of massless neutrinos for which vacuum oscillations cannot occur, oscillations can occur in matter if the neutral current has an off-diagonal piece connecting different neutrino types. Applications discussed are solar neutrinos and a proposed experiment involving transmission of neutrinos through 1000 km of rock.

  - J. W. F. Valle, Phys. Lett. B199, 432 (1987)
  - E. Roulet, Phys.Rev. D44 935, (1991)
  - M.M. Guzzo, A. Masiero, S.T. Petcov, Phys.Lett. B260, 154 (1991)
  - … and many, many others

Some neutrino interactions are very poorly known to this day!

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

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

- 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 for the τ-neutrino

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

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

Bounds from charged leptons don't necessarily apply

- In addition to the SU(2)-preserving operators

$$\frac{1}{M^2} L L q_R q_R \rightarrow \frac{1}{M^2} (\bar{q}_R \gamma^\mu q_R)(\bar{\nu}\gamma_\mu \nu)$$

there could be large potential contributions from SU(2) breaking operators*, e.g.,

$$\frac{1}{M^4} \bar{q}_R (H^\dagger \sigma^a L)(\bar{L}\sigma^a H) q_R \rightarrow \frac{v^2}{M^4} (\bar{q}_R \gamma^\mu q_R)(\bar{\nu}\gamma_\mu \nu)$$

*charge lepton operators would be induced at one loop

- Berezhiani & Rossi, Phys.Lett.B535, 207 (2002)
- Davidson, Peña-Garay, Rius, Santamaria, JHEP 0303, 011 (2003)

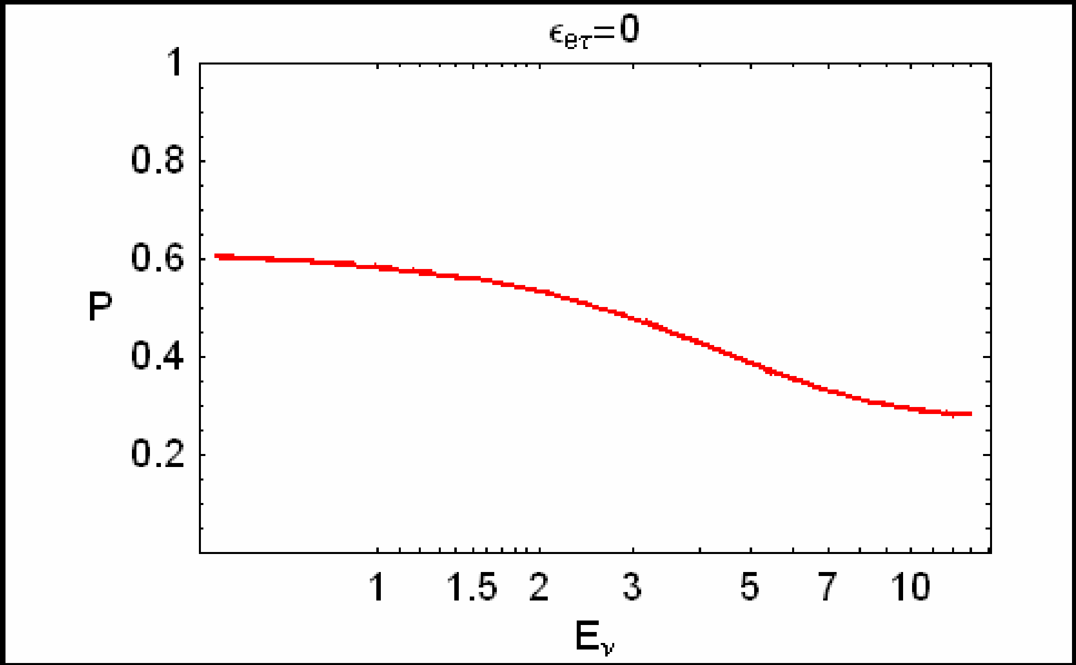
- Important if new physics is close to EW scale

Need a "ν_τ beam"!

- Both solar and atmospheric neutrinos partially oscillate into the tau-neutrino state
  - In the standard case, the oscillation parameters are quite well known by now
- Neutrino beams (K2K, MINOS) also produce ν_τ by oscillations
- Look for anomalies in the NC event rate caused by ν_τ (detection effect)
- Modified interactions of ν_τ with matter may make the oscillation pattern incompatible with the data (propagation effect)

Flavor-changing NSI: effects on solar neutrino energy spectrum

- Transition from the "vacuum regime" (low E_ν) to the matter dominated regime (high E_ν) deviates from the canonical MSW prediction



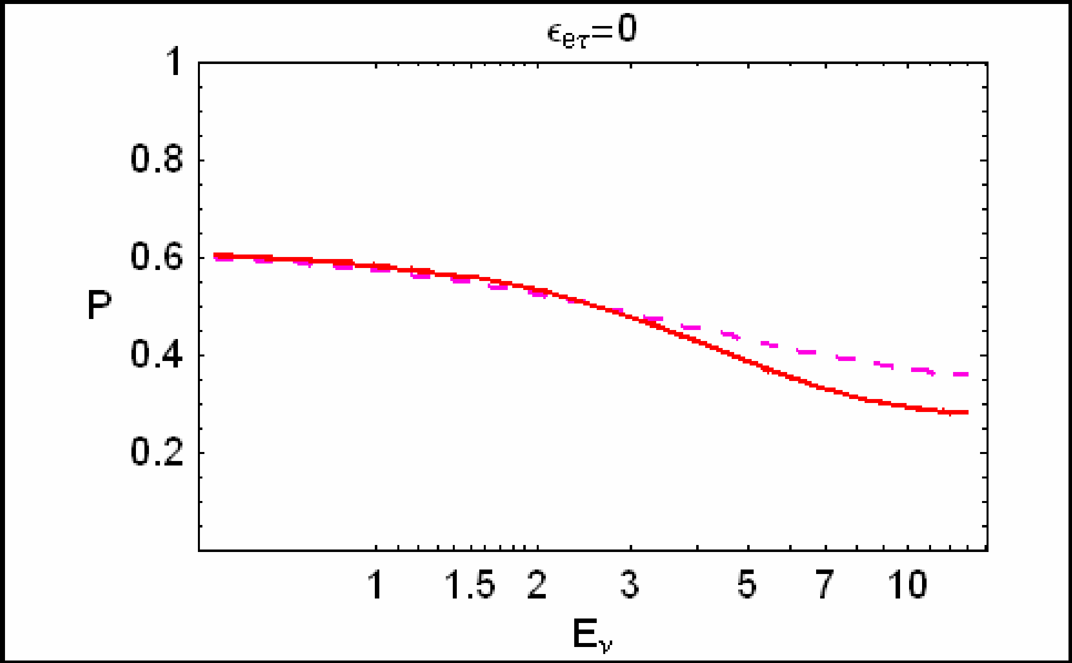
ε per quark ~ 10^{-1} of the SM

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

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

Flavor-changing NSI: effects on solar neutrino energy spectrum

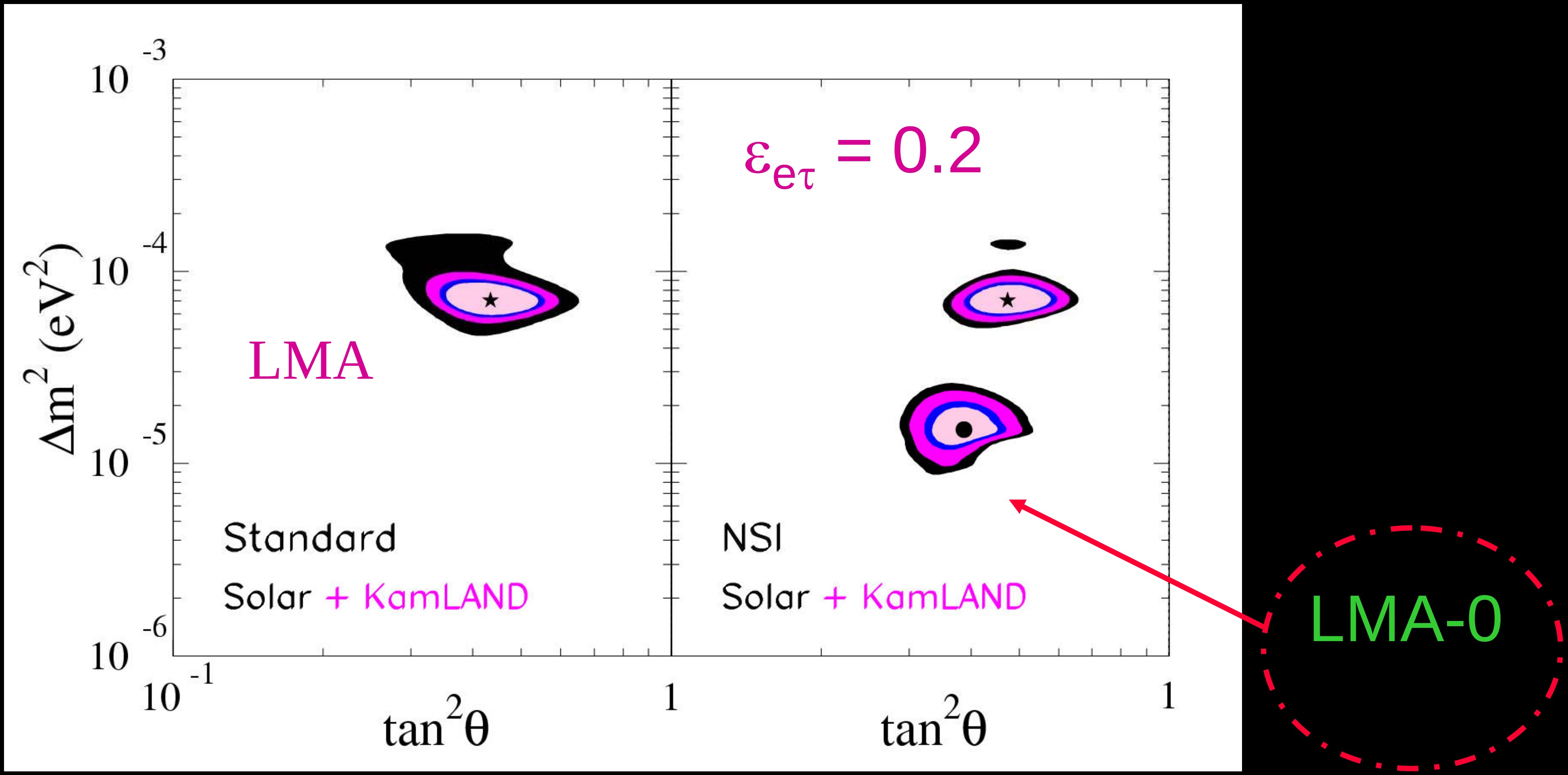
- Survival probability at SNO could show more or less energy dependence, depending on the *sign (phase)* of the NSI!
- Low-energy bin at SNO/SK critical!



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

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

More radical effects on solar ν's



Friedland, Lunardini, Peña-Garay, Phys. Lett. B594, 347 (2004);

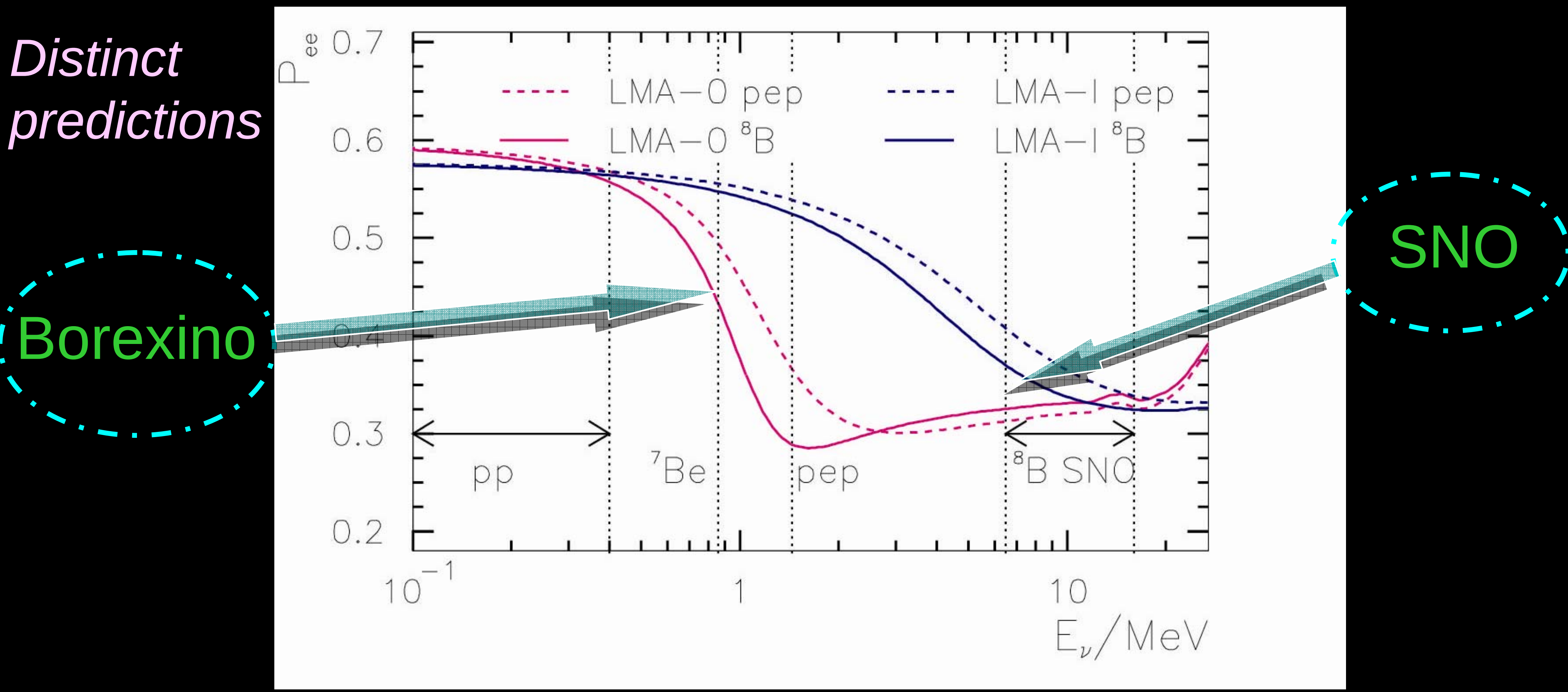
Guzzo, de Holanda, Peres, Phys.Lett. B591, 1 (2004);

Miranda, Tortola, Valle, hep-ph/0406280

Survival probability for LMA-0

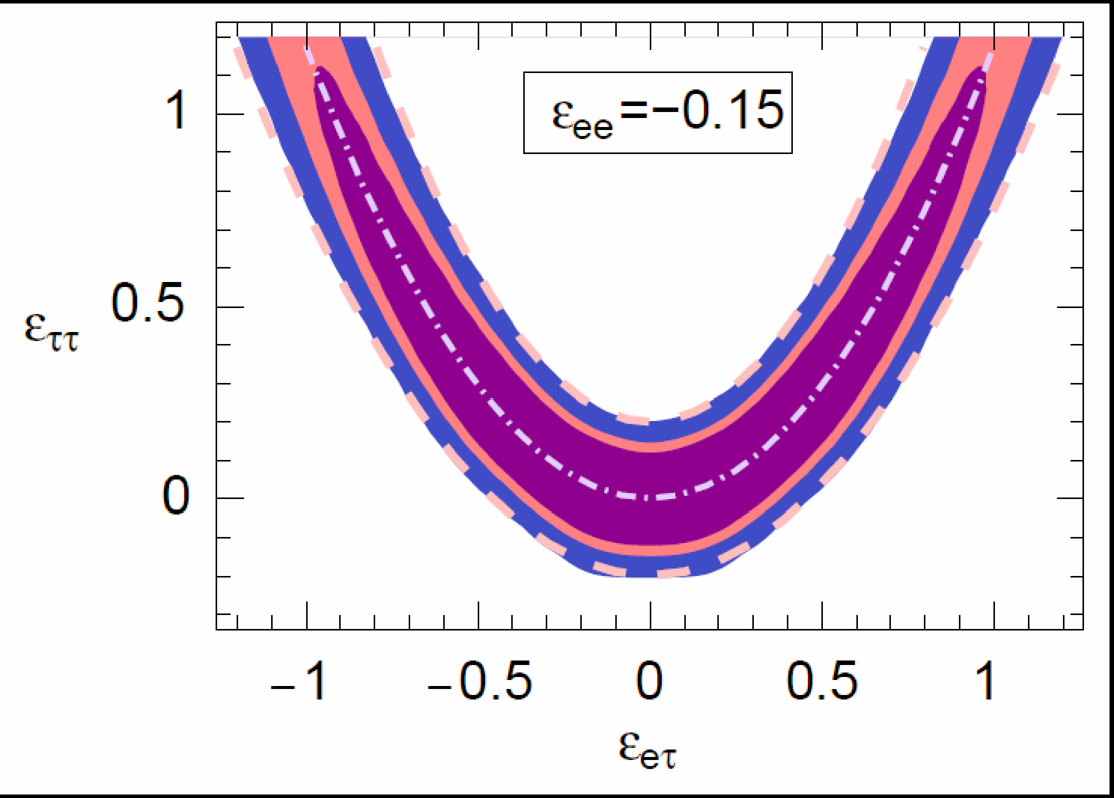
Phys. Lett. B594, 347 (2004)

Distinct predictions



Atmospheric neutrino oscillations and new interactions

- *The same* flavor-changing neutrino interactions can be probed with atmospheric neutrinos!
- *Large NSI cannot be excluded by present data; ε_{ee}, $\varepsilon_{e\tau}$, $\varepsilon_{\tau\tau}$ NSI parameters correlated in a certain way*
- The key is to do a full 3-generation analysis



A.F., C. Lunardini, M. Maltoni, Phys. Rev. D70, 111301 (2004);

A.F., C. Lunardini, Phys. Rev. D72, 053009 (2005)

Effect of NSI on the oscillation fit

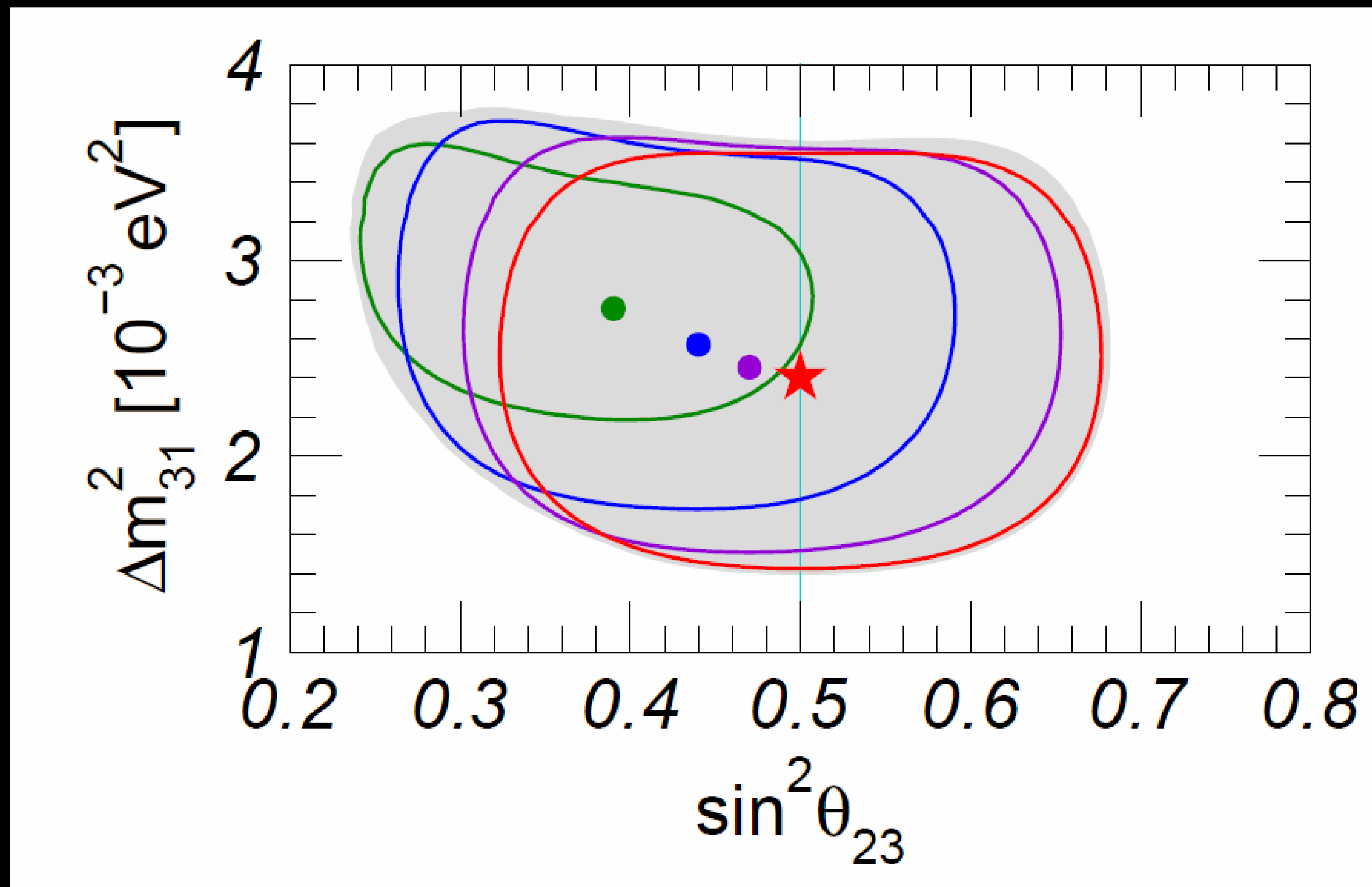
- The best-fit region shifts to smaller θ and larger Δm^2:

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

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

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

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

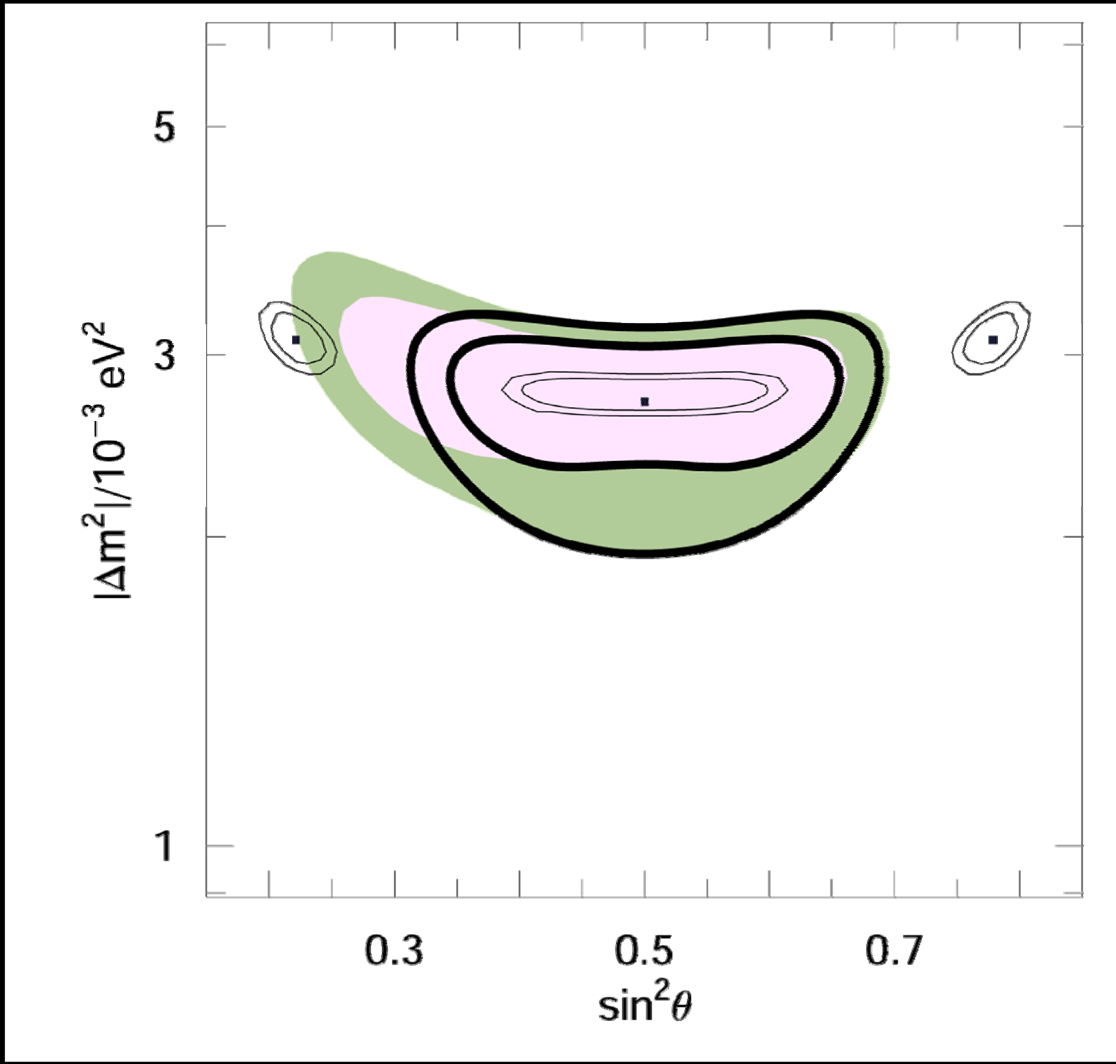


Phys.Rev.D70 111301, (2004)

MINOS, $\nu_\mu \to \nu_\tau$ mode

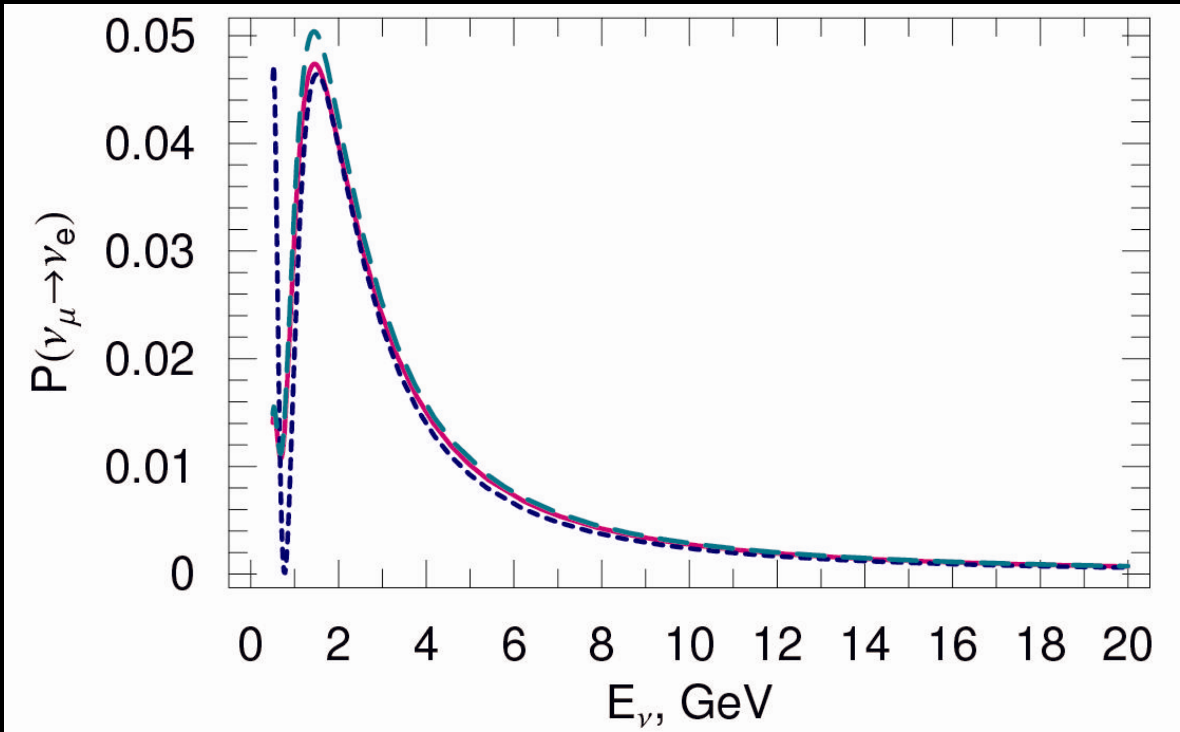
- $\nu_\mu \to \nu_\tau$ mode: measure “true” vacuum parameters
- $25*10^{20}$ protons on target
- Either discover new physics, or place best constraints

hep-ph/0606101



MINOS, $\nu_\mu \rightarrow \nu_e$ mode

- $\nu_\mu \rightarrow \nu_e$ mode: direct conversion due to new flavor changing interactions
- 25×10^{20} protons on target: shrinks currently allowed parameter space by a factor of 2
- θ_{13} or New interactions?



hep-ph/0606101

Subdominant effect III: magnetic (transition) moment

- Again, as an alternative to oscillations, a very old idea
  - A. Cisneros, Astrophys. Space Sci. 10, 87 (1971).
- Renaissance in mid-1980's, to explain Homestake time variation
  - M. B. Voloshin, M. I. Vysotsky, L. B. Okun, Zh. Eksp. Teor. Fiz. 91, 446 (1986) [Sov. Phys. JETP64, 446 (1986)].
  - E. Kh. Akhmedov, Phys. Lett. B 213, 64 (1988).
  - C. Lim & W. Marciano, Phys. Rev. D 37, 1368 (1988).
  - … and many others
- As late as 2002 (before KamLAND) could still fit all solar data with this mechanism (spin-flavor flip in the radiative zone)
  - A. F. & A. Gruzinov, Astropart.Phys. 19, 575 (2003)

Neutrino magnetic moment: basics

- Effective low-energy operator

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

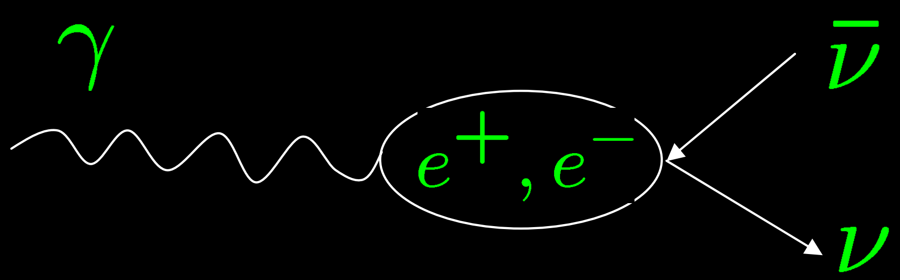
- Dim 7 when SU(2)×U(1) structure restored

$$[O_B]_{ab} = g'(\overline{\ell^c}_a\epsilon H)\sigma^{\mu\nu}(H\epsilon P_L\ell_b)B_{\mu\nu},$$
$$[O_W]_{ab} = ig\varepsilon_{mnp}(\overline{\ell^c}_a\epsilon\tau^m P_L\ell_b)(H\epsilon\tau^n H)W^p_{\mu\nu}$$

- *Majorana neutrino*: flavor-diagonal moments vanish identically (spinors anticommute); flavor-changing (transition) moments are allowed
- Ultrarelativistic Majorana ν undergoes *spin-flavor precession* in external magnetic fields

Majorana neutrino transition moment: bounds (short version)

- Direct bounds: $2\mu_{\varepsilon\beta} < 0.9\times 10^{-10}\ \mu_B$ $\mu_B \equiv e/(2m_e)$
  - reactor antineutrino scattering
    - NUMU experiment, Phys.Lett. B615, 153 (2005)
- Astrophysics $\mu \lesssim 3\times 10^{-12}\ \mu_B$
  - red giant cooling via plasmon decay to $\nu\bar{\nu}$
    - G. Raffelt, Phys. Rev. Lett. 64, 2856 (1990)



Magnetic moment and mass: naturalness considerations

- Magn. mom. operator radiatively generates neutrino mass
  - While for Dirac neutrinos this leads to a naturalness bound

$$\mu_\nu \lesssim 10^{-14}\mu_B$$

    - N. Bell, V. Cirigliano, M. Ramsey-Musolf, P. Vogel, M. Wise, Phys.Rev.Lett.95, 151802 (2005)
  - for Majorana neutrinos the analogous bound is much weaker (because of the Voloshin symmetry, Voloshin 1987)

$$\mu_\nu \lesssim 10^{-10}\mu_B$$

    - S. Davidson, M. Gorbahn, A. Santamaria, Phys.Lett.B626, 151 (2005)
- Again, new physics scale required to be close to EW scale to be near the bound

Searching for μ_ν with solar ν's at KamLAND

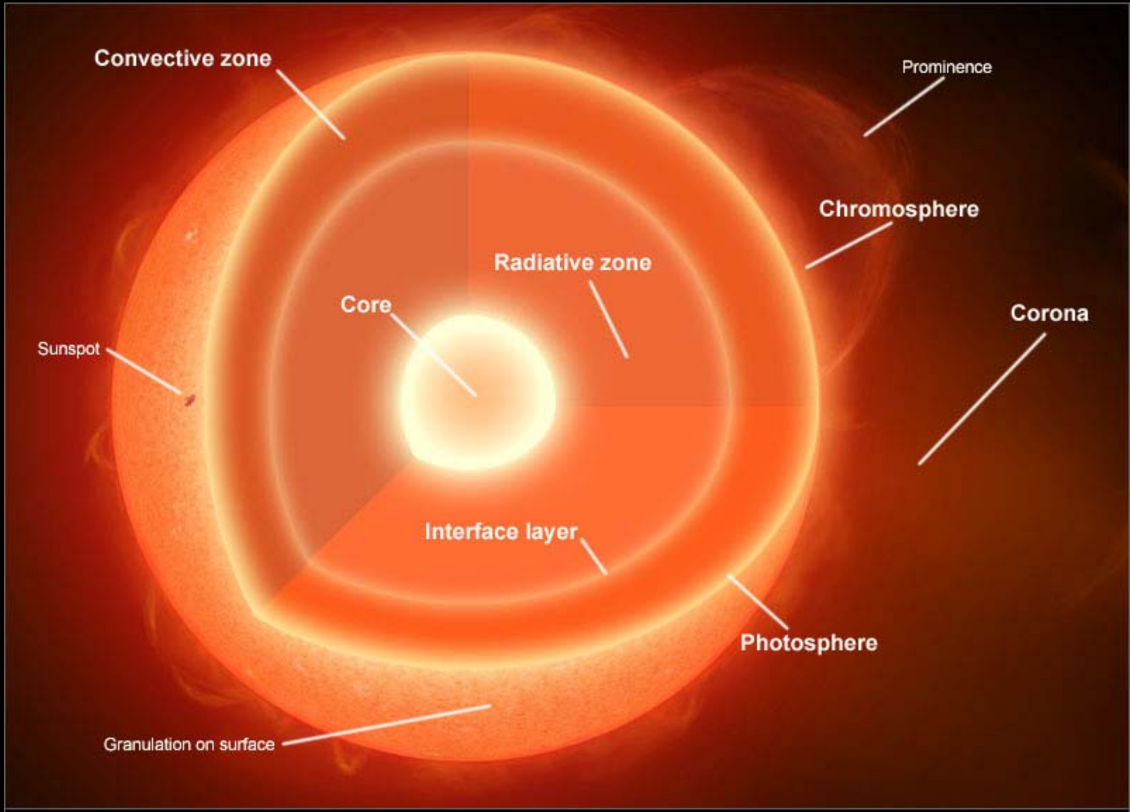
- Interaction with solar magnetic fields + flavor oscillations: $\nu_e \rightarrow$ anti-ν_e (Majorana neutrinos)

- KamLAND is VERY sensitive to anti-ν_e from the Sun
  - looks for events above 8.3 MeV where there are no reactor antineutrinos; excess over predicted background would indicate conversions of solar ^{8}B neutrinos
  - Current bound: $\lesssim 3 \times 10^{-4}$ $\nu_e \rightarrow$ anti-ν_e conversion

    (KamLAND: Phys. Rev. Lett. 92, 071301 (2004))

Solar magnetic fields

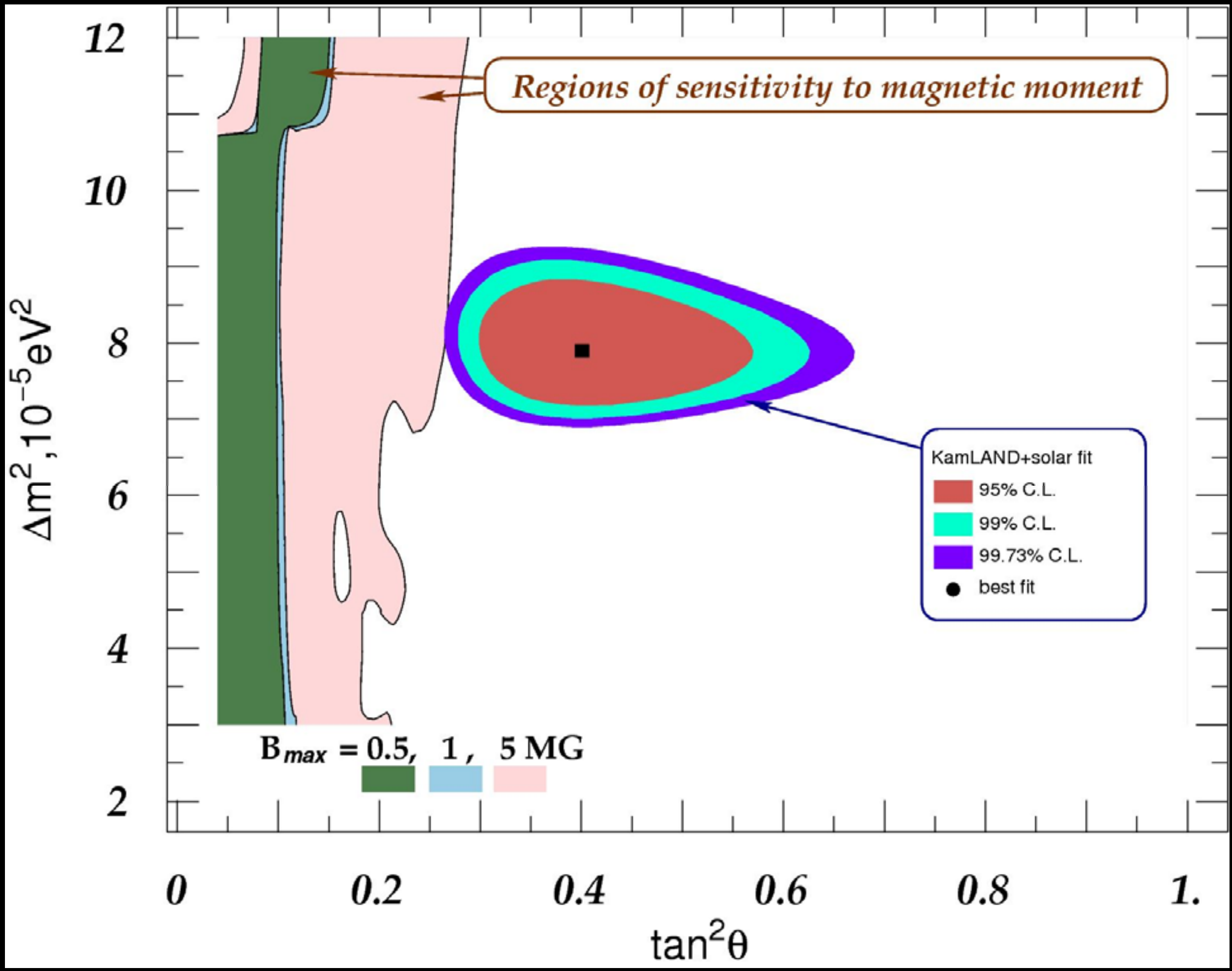
- radiative zone ($r < 0.7\ R_{SUN}$)
  - possible primordial fields
  - Strength constrained to be $\lesssim$ a few MG by oblateness, stability arguments (A.F., A. Gruzinov, Astrophys. J. 601, 570, 2004)
- convective zone ($r > 0.7\ R_{SUN}$)
  - fields generated by turbulence
  - bounds on B from observations at the surface, turbulent equipartition, energy arguments (e.g, Y. Fan, Rev. Solar Phys. 1, 1 (2004))



Radiative zone: quantitative analysis

- The effect could be large (order one!) for small mixing angles (resonance)
- For large mixing angles, *including the experimentally measured oscillation parameters* ***the effect is (as yet unobservably) small***
- CAUTION: For large mixing angles resonance condition modified!

A.F., hep-ph/0505165



$\mu = 10^{-11}\ \mu_B$

Convective zone: neutrino in turbulent fields

- "Turbulent" magnetic field resets oscillation phase $\rightarrow$ random walk in the flavor space
  - Kolmogorov turbulence: Miranda, Rashba, Rez, Valle, Phys.Rev.D70, 113002 (2004)
- Depending on the model for the magnetic field, get

$$P(\nu_e \rightarrow \bar{\nu}_e) \sim (10^{-5} - 10^{-4}) \left(\frac{\mu}{10^{-11}\mu_B} \right)^2$$

A.F., hep-ph/0505165

- Sensitivity already competitive with laboratory experiments; may improve with the next KamLAND data release

Searching for new physics with neutrinos

- New physics at $\gtrsim M_{EW}$ could generate effective low-energy operators that modify
  1. ν interactions with matter
  2. ν interactions with EM fields
- Resulting subdominant effects could be detectable with precision measurements (SNO, Borexino, KamLAND, MINOS)
  - Solar, atmospheric, reactor and beams all probe NC interactions; combined analyses needed
  - If deviations from SM found, implications would be profound
  - Even if not, we will learn about neutrino properties
    - At present neutral current interactions of ν_τ are basically unknown
- Solar neutrinos may reveal neutrino transition moment. Future KamLAND data on anti-ν_e from the Sun very important!