Open Questions – The Big Picture (II)

André de Gouvêa

Northwestern University

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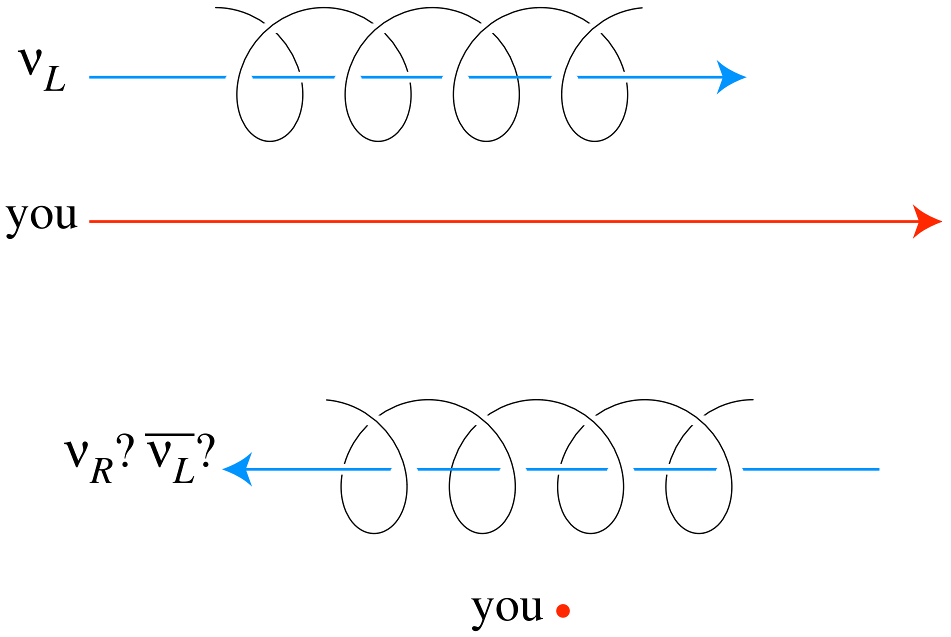
Tentative Outline for this Lecture

1. Are Neutrinos Their Own Antiparticles?; (very, very brief)
2. How Light is the Lightest Neutrino?;
3. Do Neutrinos Couple to Photons?;
4. Do Neutrinos Decay?;
5. What We Don't Know We Don't Know:
   - New Neutrino Interactions?
   - New Neutrino Degrees of Freedom?

[note: Questions are ALWAYS welcome]

1– What We Know We Don't Know – Are Neutrinos Majorana Fermions?



A massive charged fermion (s=1/2) is described by 4 degrees of freedom:

$$(e^-_L \leftarrow \text{CPT} \rightarrow e^+_R)$$
$$\updownarrow \text{Lorentz}$$
$$(e^-_R \leftarrow \text{CPT} \rightarrow e^+_L)$$

A massive neutral fermion (s=1/2) is described by 4 or 2 degrees of freedom:

$$(\nu_L \leftarrow \text{CPT} \rightarrow \bar{\nu}_R)$$
$$\updownarrow \text{Lorentz} \qquad \text{“DIRAC”}$$
$$(\nu_R \leftarrow \text{CPT} \rightarrow \bar{\nu}_L)$$

$$(\nu_L \leftarrow \text{CPT} \rightarrow \bar{\nu}_R)$$
$$\text{“MAJORANA”} \qquad \updownarrow \text{Lorentz}$$
$$(\bar{\nu}_R \leftarrow \text{CPT} \rightarrow \nu_L)$$

How many degrees of freedom are required to describe massive neutrinos?

Why Don't We Know the Answer (Yet)?

If neutrino masses were indeed zero, this is a nonquestion: there is no distinction between a massless Dirac and Majorana fermion.

Processes that are proportional to the Majorana nature of the neutrino vanish in the limit $m_\nu \to 0$. Since neutrinos masses are very small, the probability for these to happen is very, very small: $A \propto m_\nu / E$.

The "smoking gun" signature is the observation of LEPTON NUMBER violation. This is easy to understand: Majorana neutrinos are their own antiparticles and, therefore, cannot carry "any" quantum numbers — including lepton number.

Weak Interactions are Purely Left-Handed (Chirality):

For example, in the scattering process $e^- + X \to \nu_e + X$, the electron neutrino is, in a reference frame where $m \ll E$,

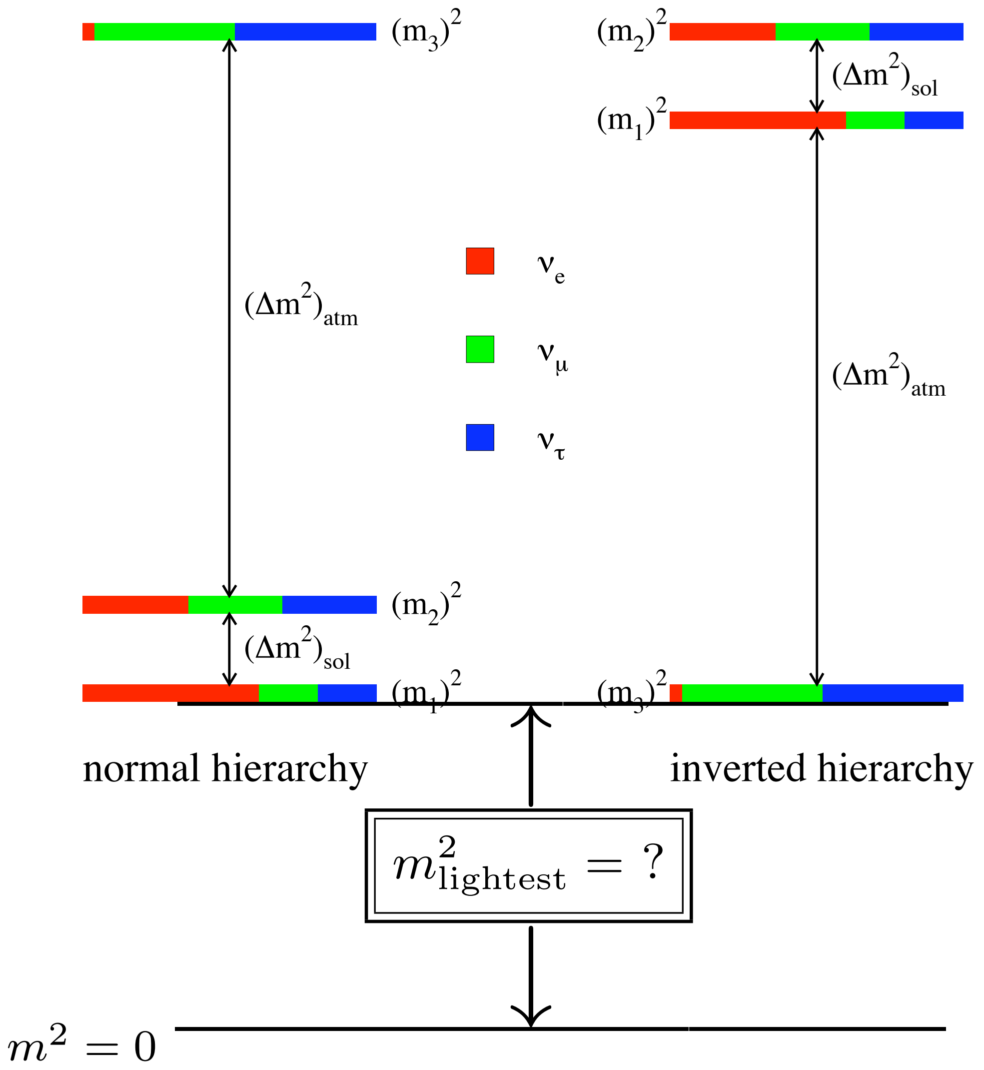
$$|\nu_e\rangle \sim |L\rangle + \left(\frac{m}{E}\right)|R\rangle.$$

If the neutrino is a Majorana fermion, $|R\rangle$ behaves mostly like a "$\bar{\nu}_e$," (and $|L\rangle$ mostly like a "ν_e,") such that the following process could happen:

$$e^- + X \to \nu_e + X, \quad \text{followed by} \quad \nu_e + X \to e^+ + X, \qquad P \simeq \left(\frac{m}{E}\right)^2$$

Lepton number can be violated by 2 units with small probability. Typical numbers: $P \simeq (0.1~\text{eV}/100~\text{MeV})^2 = 10^{-18}$. VERY Challenging!

2 – What We Know We Don't Know: How Light is the Lightest Neutrino?



So far, we've only been able to measure neutrino mass-squared differences.

The lightest neutrino mass is only poorly constrained: $m^2_{\rm lightest} < 1~{\rm eV}^2$

qualitatively different scenarios allowed:

- $m^2_{\rm lightest} \equiv 0$;
- $m^2_{\rm lightest} \ll \Delta m^2_{12,13}$;
- $m^2_{\rm lightest} \gg \Delta m^2_{12,13}$.

Need information outside of neutrino oscillations.

Handle on the Overall Scale of the Neutrino Mass (1): The effective mass for neutrinoless double-beta decay

$$\Gamma_{0\nu\beta\beta} \propto \left|\sum_i U_{ei}^2 \frac{m_i}{Q^2+m_i^2}\mathcal{M}(m_i^2,Q^2)\right|^2,$$

$Q^2 \sim 50^2$ MeV^2. Neutrino masses are known to be small enough that, in practice,

$$\Gamma_{0\nu\beta\beta} \propto |m_{ee}|^2,$$

where[a]

$$m_{ee} \equiv \sum_i U_{ei}^2 m_i \equiv m_1|U_{e1}|^2 e^{i\alpha_1} + m_2|U_{e2}|^2 e^{i\alpha_2} + m_3|U_{e3}|^2 e^{-2i\delta}.$$

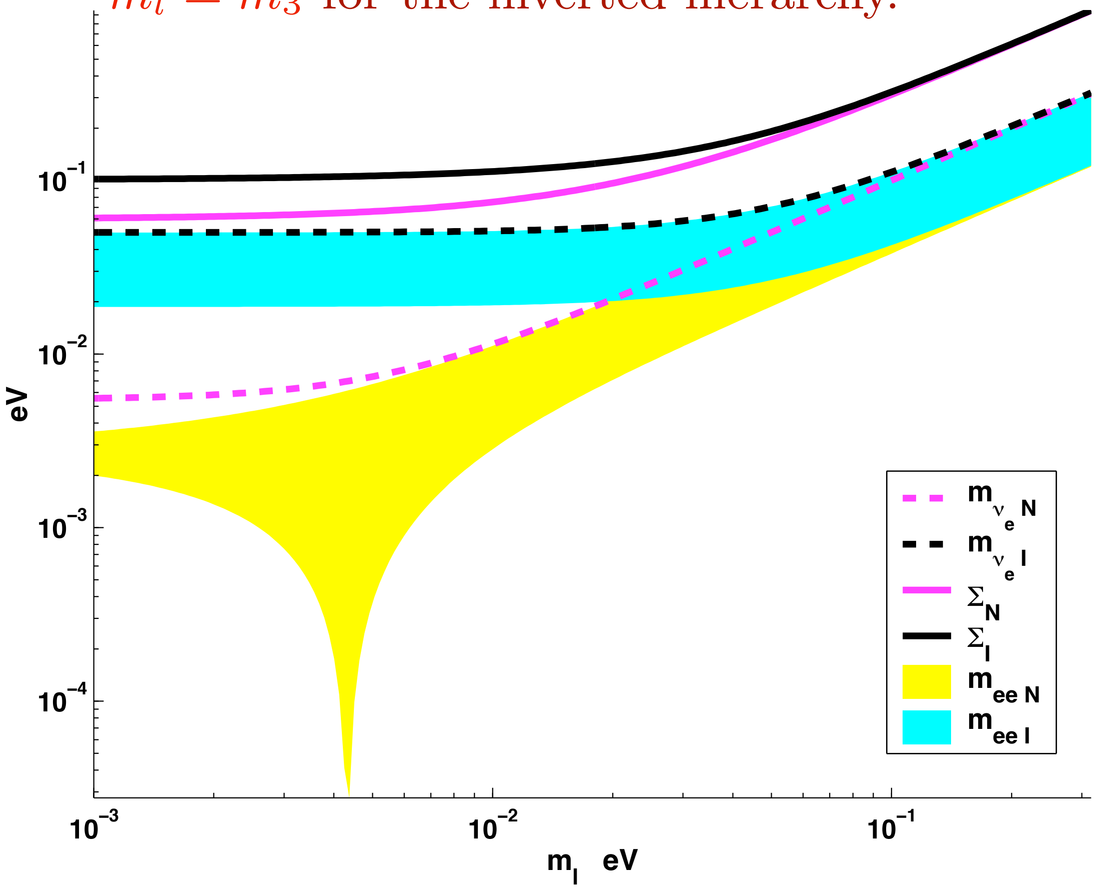
We assume that this is all one can hope to measure in the foreseeable future.

[a] α_i are Majorana phases.

m_l is the lightest neutrino mass.

$m_l = m_1$ for the normal hierarchy.

$m_l = m_3$ for the inverted hierarchy.



Not very clean observable, not guaranteed to be there (neutrinos could be Dirac).

Huge theoretical uncertainties:

- Nuclear Matrix Elements,
- Other L-breaking effects.

Current bound: $m_{ee} < 0.91$ eV (99% CL)

Near Future Sensitivity: $m_{ee} > 0.1$ eV

Plans for $m_{ee} > 0.01$ eV sensitivity

[see lectures by S. Elliott]

$U_{e3} = 0,\ \Delta m^{2+}_{13} = +2.50 \times 10^{-3}\ \text{eV}^2,\ \Delta m^{2-}_{13} = -2.44 \times 10^{-3}\ \text{eV}^2$

Handle on the Neutrino Mass Scale (2): Cosmological Observables

Studies of several "cosmological observables" constrain the amount of hot dark matter in the universe.

Neutrinos qualify as hot dark matter. They are expected to be there according to "concordance cosmology" (there is even some evidence for primordial neutrinos from BBN!) and, if they compose all the hot dark matter, their masses leave an imprint in the universe.

Here, I'll assume that, out of these data, one can extract the **sum** of the neutrino masses:

$$\Sigma = m_1 + m_2 + m_3$$

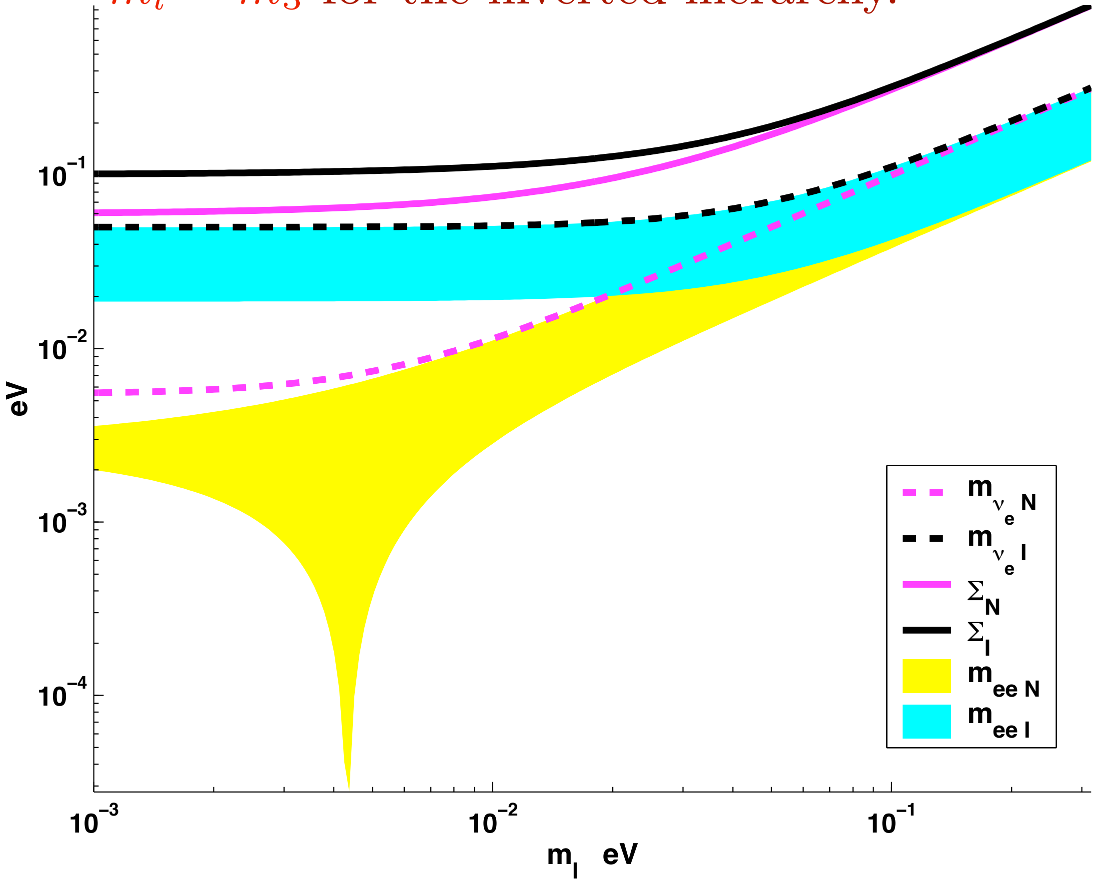
Note that m_i are positive-definite.

[see lecture by S. Dodelson]

m_l is the lightest neutrino mass.

$m_l = m_1$ for the normal hierarchy.

$m_l = m_3$ for the inverted hierarchy.



Not very clean observable, not guaranteed to be there (nonstandard cosmology).

What else is out there?

Current bound: $\Sigma < 0.68$ eV (95% CL)

Near Future Sensitivity: $\Sigma > 0.1$ eV

Plans for $\Sigma > 0.03$ eV ?

$U_{e3} = 0$, $\Delta m^{2+}_{13} = +2.50 \times 10^{-3}$ eV^2, $\Delta m^{2-}_{13} = -2.44 \times 10^{-3}$ eV^2

Handle on the Neutrino Mass Scale (3):

The "safest" probe of the lightest neutrino mass – precision measurements of β-decay

The effect of non-zero neutrino masses should also be observable **kinematically**.

When a neutrino is produced, some of the energy exchanged in the process should be spent by the non-zero neutrino mass.

Typical effects are very, very small – we've never seen them! The most sensitive observable is the electron energy spectrum from tritium decay.

$$^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \underset{\Uparrow}{\bar{\nu}}$$

(which (anti)neutrino is this? Is it $\bar{\nu}_e$? is it $\bar{\nu}_1$?)

Why tritium? Small Q value, reasonable abundances. Required sensitivity proportional to m^2/Q^2.

If we can "see" the neutrino mass, the proper description of β-decay is

$$^3\text{H} \to {}^3\text{He} + e^- + \bar{\nu}_1 \text{ with Prob.} = |U_{e1}|^2;$$
$$^3\text{H} \to {}^3\text{He} + e^- + \bar{\nu}_2 \text{ with Prob.} = |U_{e2}|^2;$$
$$^3\text{H} \to {}^3\text{He} + e^- + \bar{\nu}_3 \text{ with Prob.} = |U_{e3}|^2.$$

The maximum attainable electron energy is, roughly, $Q - m_i$, different for each of the three distinct decay modes.

This is exactly like, say, c-quark semi-leptonic decays:

$$c(D) \to d(\pi) + \ell + \nu_\ell \text{ with Prob.} \propto |V_{cd}|^2;$$
$$c(D) \to s(K) + \ell + \nu_\ell \text{ with Prob.} \propto |V_{cs}|^2.$$

{Sort of related QUESTION: do neutrinos from tritium β-decay oscillate?}

The "electron neutrino mass"

β-decay spectrum can be schematically written as:

$$|U_{e1}|^2 F(m_1^2/E_\nu^2, E_\nu) + |U_{e2}|^2 F(m_2^2/E_\nu^2, E_\nu) + |U_{e3}|^2 F(m_3^2/E_\nu^2, E_\nu).$$

One should, in principle, be able to "see" all three neutrino masses → trivially resolves the hierarchy! In the real world, however, life is not so simple. Neutrino masses are small enough that the expression above is well approximated by

$$F_0 \left(1 + \frac{m_{\nu_e}^2}{E_\nu^2}\frac{F_0'}{F_0} + O\left(\frac{m_i^4}{E_\nu^4}\right)\right),$$

where

$$m_{\nu_e}^2 \equiv \sum_i |U_{ei}|^2 m_i^2$$

We assume that this is all one can hope to measure in the foreseeable future.

Experiments measure the **shape** of the end-point of the spectrum, not the value of the end point. This is done by counting events as a function of a low-energy cut-off. note: LOTS of Statistics Needed!

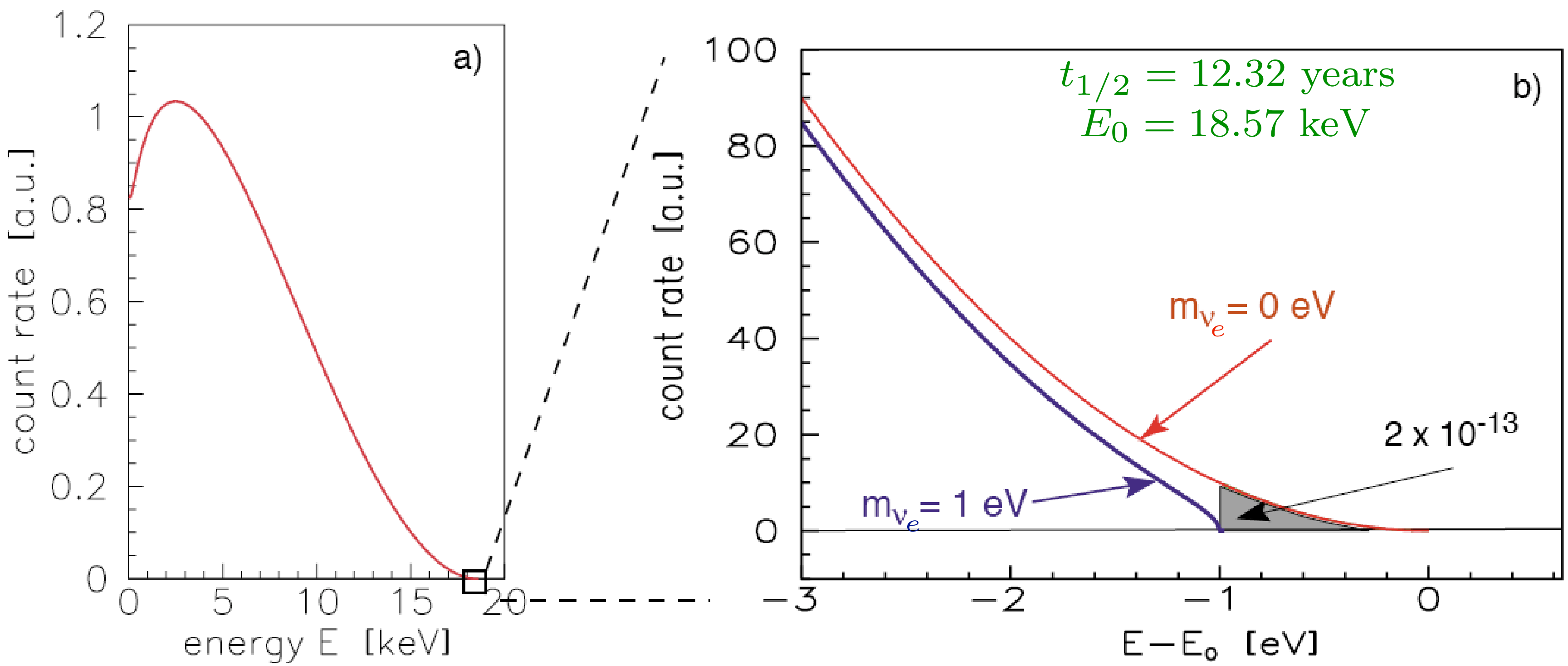


Figure 2: The electron energy spectrum of tritium β decay: (a) complete and (b) narrow region around endpoint E_0. The β spectrum is shown for neutrino masses of 0 and 1 eV.

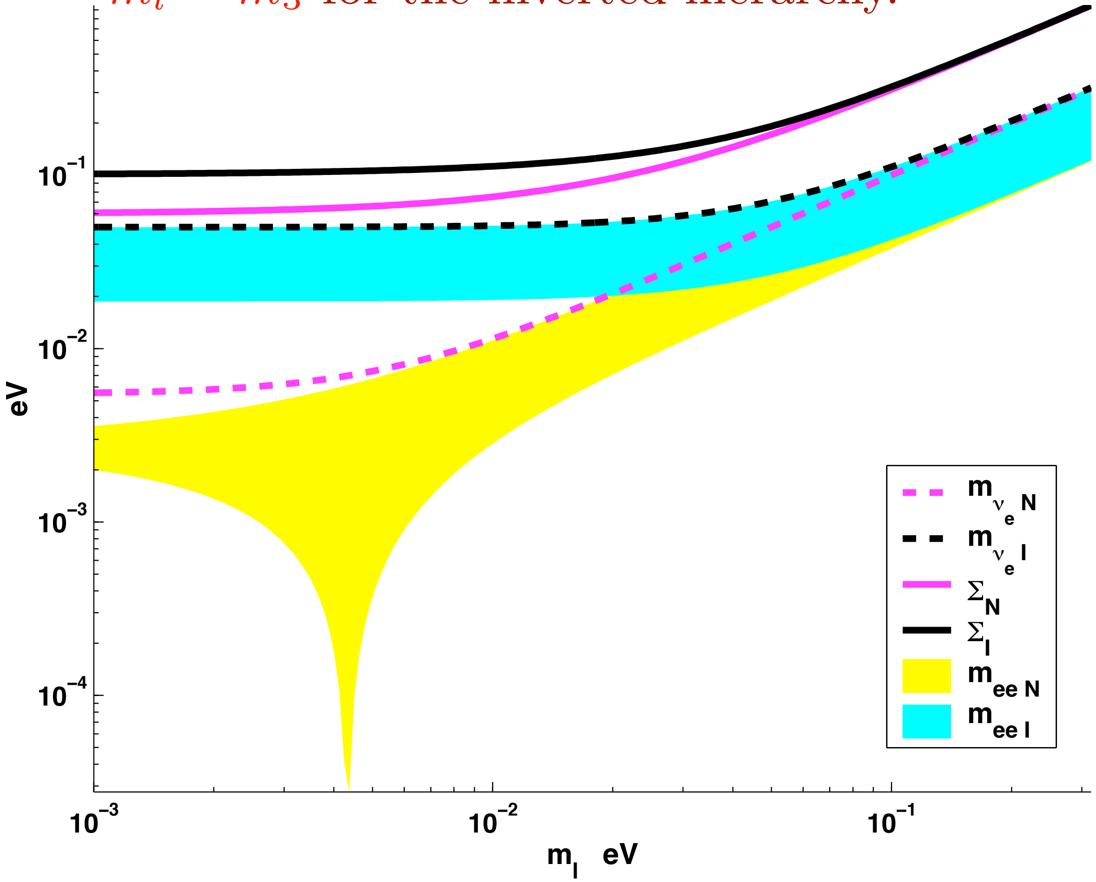
NEXT GENERATION: The Karlsruhe Tritium Neutrino (KATRIN) Experiment:

(not your grandmother's table top experiment!)

m_l is the lightest neutrino mass.

$m_l = m_1$ for the normal hierarchy.

$m_l = m_3$ for the inverted hierarchy.



Very clean observable, guaranteed to be there.

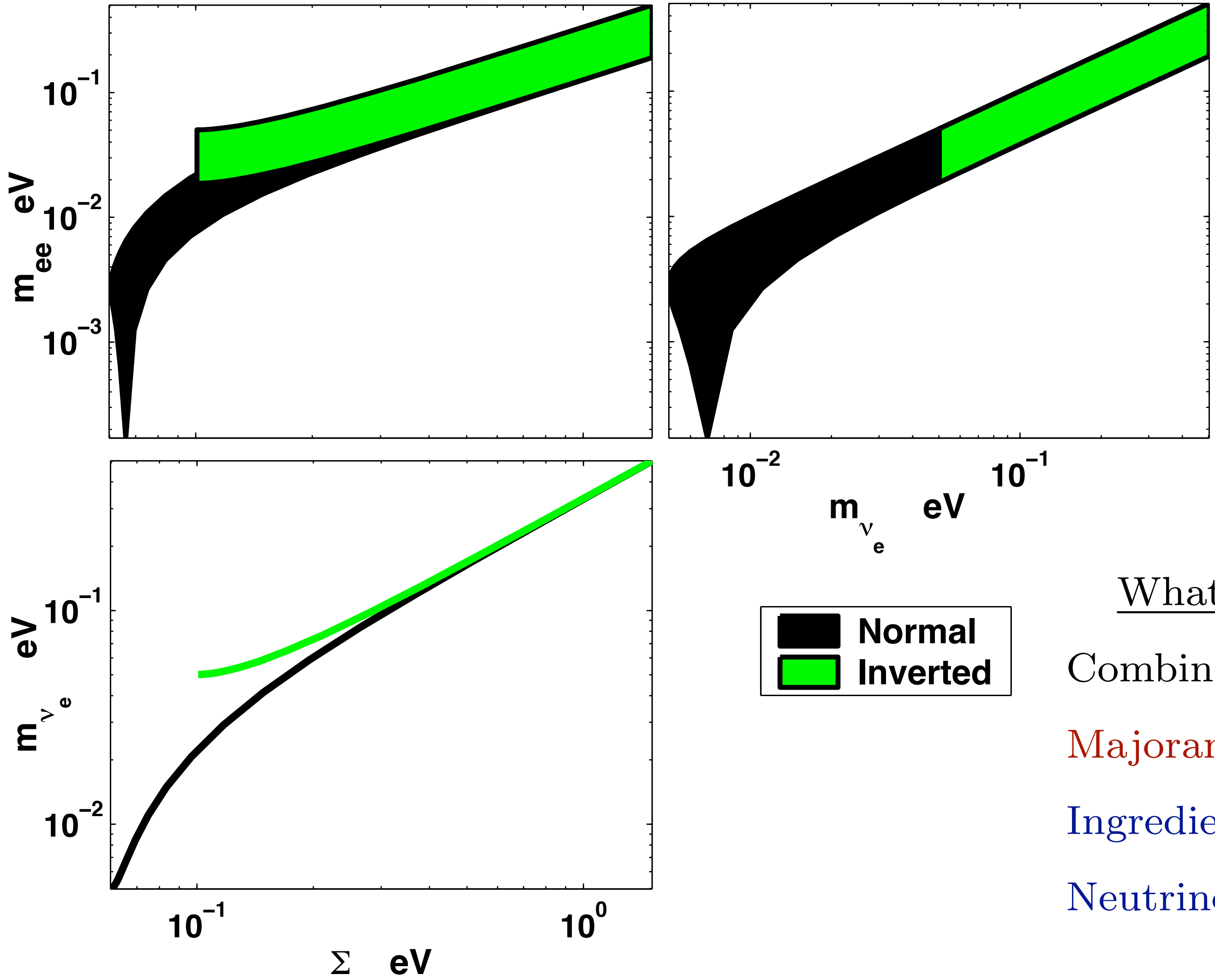
Current bound: $m^2_{\nu_e} < 4$ eV^2 (99% CL)

Near Future Sensitivity: $m^2_{\nu_e} > 0.04$ eV^2

Can anyone do better? Unknown.

$U_{e3} = 0$, $\Delta m^{2+}_{13} = +2.50 \times 10^{-3}$ eV^2, $\Delta m^{2-}_{13} = -2.44 \times 10^{-3}$ eV^2

Combining the Different Observables: Can We Determine $m_{\rm lightest}$?



(It would be great if we could improve the sensitivity to m_{ν_e}!)

What else can we learn:

Combination is powerful probe of Majorana vs. Dirac, New Cosmological Ingredients, Other L-violating Physics, Neutrino Mass Hierarchy, etc.

$U_{e3} = 0$, $\Delta m^{2+}_{13} = +2.50 \times 10^{-3}$ eV^2, $\Delta m^{2-}_{13} = -2.44 \times 10^{-3}$ eV^2

3 – What We Know We Don't Know: Do Neutrinos Couple to Photons?

Neutrinos have NO electric charge (hence their name). However, since they interact with charge particles via the weak interactions, they are expected to talk to photons "indirectly" (like, say, the neutron). That is guaranteed to happen, unless protected by a symmetry → this is exactly what happens when neutrinos are massless!

Now that neutrinos have mass, they are "allowed" to have a nonzero magnetic moment μ_ν.

The nature of μ_ν will depend on whether the neutrino is its own antiparticle:

$$\mathcal{L}_{m.m.} = \mu_\nu^{ij}(\nu_i \sigma_{\mu\nu} \nu_j F^{\mu\nu}) + H.c.,$$

$$\mu_\nu^{ij} = -\mu_\nu^{ji}, \quad i,j = 1,2,3 \ \rightarrow \ \text{Majorana Magnetic Moment}$$

or

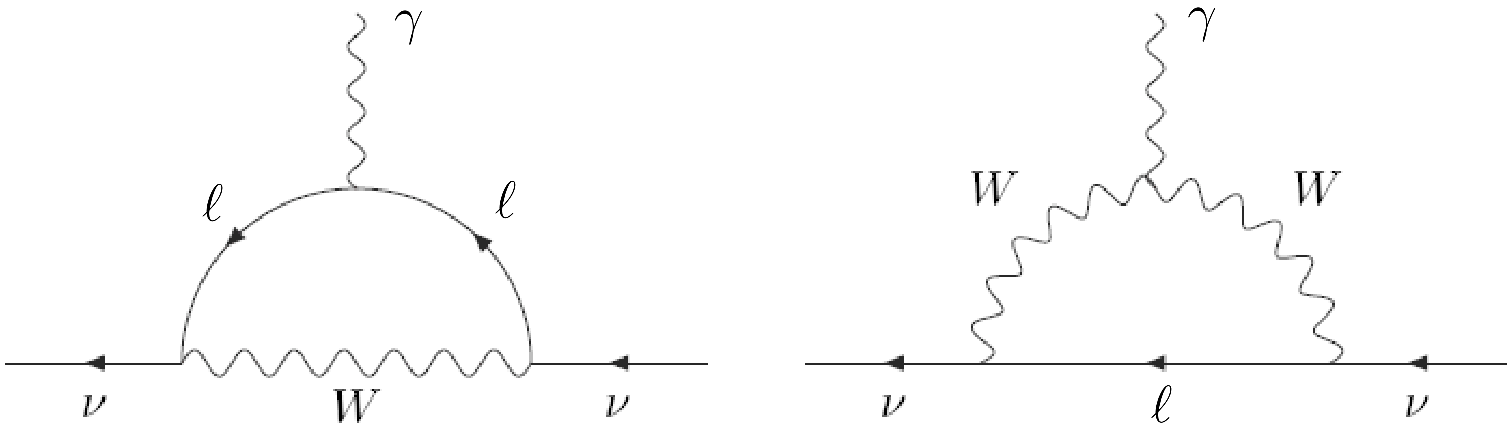
$$\mathcal{L}_{m.m.} = \mu_\nu^{ij}(\bar{\nu}_i \sigma_{\mu\nu} N F^{\mu\nu}) + H.c.,$$

$$i,j = 1,2,3 \ \rightarrow \ \text{Dirac Magnetic Moment}$$

in new SM, whether neutrinos are Majorana or Dirac fermions, μ is really small:

$$\mu_{ij} \leq \sum_\alpha U_{\alpha i} U^*_{\alpha j} \frac{3eG_F}{8\sqrt{2}\pi^2} m_\nu = 3 \times 10^{-20} \mu_B \left(\frac{m_\nu}{10^{-1}\ \mathrm{eV}}\right) \sum_\alpha U_{\alpha i} U^*_{\alpha j} \qquad \left(\mu_B = \frac{e}{2m_e}\right)$$

[Dirac case]



Generic new, electroweak-scale physics effects yield much larger neutrino magnetic moments. *E.g.*,

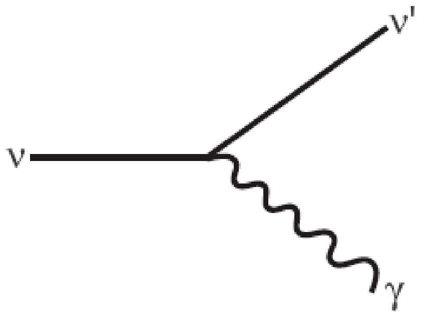
$$\mu \sim \frac{e\lambda^2}{M^2_{\rm new}} m_f \qquad\qquad f = e, \mu, \tau, \ldots$$

Searches for neutrino magnetic moments constrain the new physics scale (M) and coupling (λ) like searches for new physics in the charged-lepton sector: $\mu \to e\gamma$, $(g-2)_{\mu}$, muon and electron electric dipole moments, etc. After all, they all come from the same effective operator!

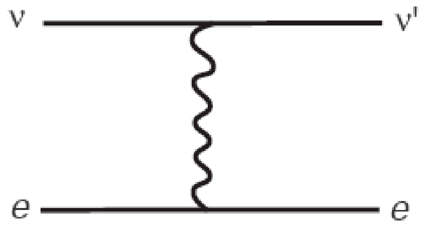
One can place bounds on (or find "evidence" for)

- SUSY,
- large extra dimensions ($\bar{\nu}_e e^- \to \sum_{\rm kk} \bar{\nu}_{\rm kk} e^-$),
- $\ldots$ (the usual suspects).

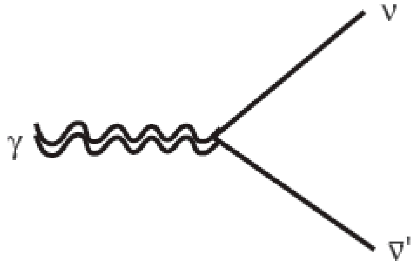
How To See the Neutrino and the Photon Interacting



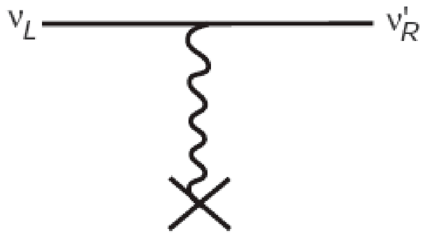
ν decay or Cherenkov radiation



$\nu - e$ scatt. or e^+-e^- annigilation



Plasmon decay



Spin (flavor) precession

Bounds come from a variety of sources and constrain different linear combinations of elements of μ_ν.

- $\bar{\nu}_e e^- \to \nu_\beta\ (\bar{\nu}_\beta)\ e^-,\ \forall\beta\ (\beta = e, \mu, \tau)$ TEXONO, MUNU reactor expt's.

$$\frac{d\sigma}{dT}(\bar{\nu}_e e \to \nu_x e) = \frac{2G_\mu^2 m_e}{\pi E_\nu^2}\left[(\sin^2\theta_W)^2 E_\nu^2 + \left(\frac{1}{2} + \sin^2\theta_W\right)^2 (E_\nu - T)^2 + \right.$$
$$\left. - \sin^2\theta_W\left(\frac{1}{2} + \sin^2\theta_W\right) m_e T\right] + \mu^2\frac{\pi\alpha^2}{E_\nu m_e^2}\left(\frac{E_\nu}{T} - 1\right),$$

where $\mu^2 = \sum_\alpha |\mu_{e\alpha}|^2$ is a particular combination of magnetic moments ($\mu_{\alpha\beta} = U_{\alpha i}\mu_{ij}U^*_{\beta j}$). T is the recoil electron kinetic energy, E_ν is the incoming neutrino energy.

- searches for electron antineutrinos from the Sun ($\nu_e \stackrel{(m.m.)}{\longrightarrow} \bar{\nu}_\beta \stackrel{(osc)}{\longrightarrow} \bar{\nu}_e$). Applies only in the case of Majorana neutrinos.

  Uncertainties: $\vec{B}$ in the Sun (measure only μB)?, how well oscillation parameters are known?

  KamLAND: $\Phi^{\odot}_{\bar{\nu}_e} < 2.8 \times 10^{-4} \Phi^{^8\mathrm{B}}_{\nu_e}$

- astrophysics red giants, SN1987A, …

$$\Rightarrow \boxed{\mu_\nu < 1.5 \times 10^{-10} \mu_B} \quad \text{(PDG accepted bound);}$$

also $O(10^{-[12\div 11]})$ bounds from astrophysics and solar neutrinos.

- μ leads to subleading effects, on top of oscillations.

- time dependency was another option...

$$H = \begin{pmatrix} H_\nu & (B_x - iB_y)M^\dagger \\ (B_x + iB_y)M & H_{\bar{\nu}} \end{pmatrix},$$

where $B_{x,y}$ are the transverse components of the
netic field and the 2×2 submatrices are given by

$$\begin{aligned} M &= \begin{pmatrix} 0 & -\mu_{e\mu} \\ \mu_{e\mu} & 0 \end{pmatrix}, \\ H_\nu &= \begin{pmatrix} -\Delta\cos 2\theta + A_e & \Delta\sin 2\theta \\ \Delta\sin 2\theta & \Delta\cos 2\theta + A_\mu \end{pmatrix}, \\ H_{\bar{\nu}} &= \begin{pmatrix} -\Delta\cos 2\theta - A_e & \Delta\sin 2\theta \\ \Delta\sin 2\theta & \Delta\cos 2\theta - A_\mu \end{pmatrix}. \end{aligned} \quad (8)$$

Here $\Delta \equiv \Delta m^2/4E_\nu$, $A_e \equiv \sqrt{2}G_F(n_e - n_n/2)$ and $A_\mu \equiv \sqrt{2}G_F(-n_n/2)$. Δm^2 is the neutrino mass-squared splitting, E_ν is its energy, and n_e and n_n are the electron and neutron number densities.

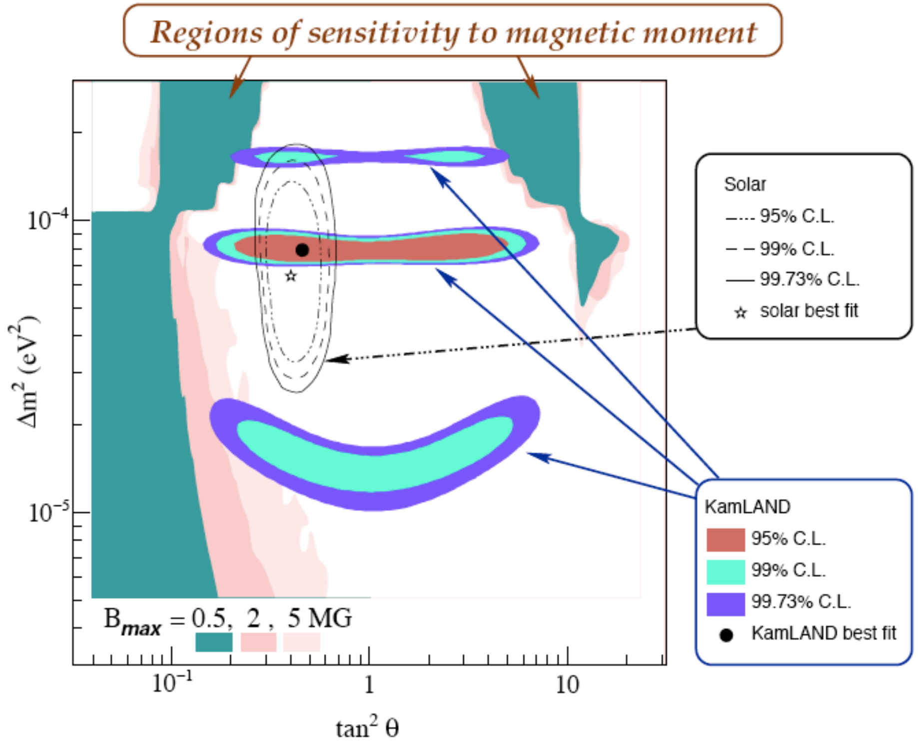


FIG. 4: The regions of the oscillation parameter space where one may expect the electron antineutrino flux above the KamLAND bound [8] (three different shadings correspond to three different normalizations of the magnetic field). A very optimistic value of the transition moment, $\mu = 1 \times 10^{-11}\mu_B$, was taken. Also shown are the regions allowed by the analysis of the KamLAND data [14] (shaded regions in the middle) and the region allowed by the solar data (unfilled contours).

$$\mu = 1 \times 10^{-11}\mu_B$$

[Friedland, hep-ph/0505165]

4– What We Know We Don't Know? – Do Neutrinos Decay?

Now that neutrinos have mass, the **two heavier neutrino mass eigenstates are unstable** and will eventually decay into the lightest mass eigenstates plus X $[\nu_{\rm heavy} \to \nu_{\rm light} + X]$. In the new SM, X are photons and other light (anti)neutrinos.

$\nu_i \to \nu_j \gamma$ is governed by the same type of operators as magnetic moments, and expectations for the life-time are absurdly long:

$$\boxed{\tau > 10^{38}\ \text{years}} \quad \text{for } m_\nu \sim 1\ \text{eV (GIM suppressed).}$$

For comparison purposes, the number of **solar neutrinos** that hit the Earth **per year** is of order 10^{37} (don't forget a γ-factor larger than 10^5).

Other new SM induced decays are also rare beyond all reason:

$$\tau_{\nu\to 3\nu} > 10^{39}\ \text{years.}$$

Similar to magnetic moments, observable neutrino decays are a sign for physics beyond the new SM. The new physics effects are either of the "bread and butter" $1/M_{\rm new}$-type, or involve the presence of very light, yet to be observed degrees of freedom (say, (quasi-)massless (pseudo)scalars, like "Majorons").

Experimental bounds are very dependent on the decay mode (and the kinematics of the decay) and vary from the billion of years scale (bounds on UV light) to the hundreds of microseconds scale (model independent bounds from the sun).

e.g., Constraints on μ severely constrain neutrino lifetimes already:

$$\tau > 5\times 10^{11}\left(\frac{10^{-10}\mu_B}{\mu_\nu}\right)^2 \text{ years}, \qquad m_\nu \sim 1 \text{ eV}.$$

Best model independent bound comes from solar neutrinos. In order to disentangle the oscillation effects from the decay effects we profit from a combination of solar and KamLAND data. It is easy to see that the constraints are very mild:

$$\gamma\tau > 500\text{ s} \Rightarrow \tau > 500\ s\frac{m}{E} \sim 10^{-4}\text{ s}\left(\frac{m}{\text{eV}}\right)\left(\frac{5\text{ MeV}}{E}\right)$$

Much better (many orders of magnitude) constraints are expected

- high energy cosmic neutrinos at Ice-Cube (*e.g.*, large violations of 1:1:1 flavor ratios with dependency on mixing parameters),
- relic supernova neutrinos,
- ...

Decaying Neutrinos From Very Far Away: [see lectures by F. Halzen]

Imagine that very high energy neutrinos are produced by the $\pi \to \mu + \nu_\mu \to (e + \nu_e + \nu_\mu) + \nu_\mu$ decay chain, like atmospheric neutrinos. What is the flavor distribution on the Earth?

- at the source 2 parts ν_μ + 1 part ν_e + 0 parts ν_τ
- What arrives at the Earth is an incoherent mixture of ν_1, ν_2 and ν_3, with relative weight given by $2|U_{\mu i}|^2 + |U_{ei}|^2$ for mass eigenstate ν_i.
- Hence, probability to detect ν_α is proportional to $\sum_i \left(2|U_{\mu i}|^2 + |U_{ei}|^2\right) |U_{\alpha i}|^2$. This turns out to lead to – given observations: 1 part ν_μ + 1 part ν_e + 1 part ν_τ
- If the neutrinos decay, this changes. Lets say ν_2 and ν_3 decay away, so that only ν_1 gets here. In this case the probability to detect ν_α is proportional to $\left(2|U_{\mu 1}|^2 + |U_{e1}|^2\right) |U_{\alpha 1}|^2$. In this case we get about 1 part ν_μ + 4 parts ν_e + 1 part ν_τ.
- Can we see this difference? How about "systematic" effects due to an uncertain source?

[for details, see Beacom *et al.*, hep-ph/0211305]

What We Don't Know We Don't Know

Are we missing anything? Is our picture of the ν world qualitatively incomplete?

Is there more new physics out there that can be best probed by neutrino experiments? What kind of experiments?

Neutrinos are expected to add non-trivial information, especially via neutrino oscillations. Remember the quantum interferometer aspect of neutrino oscillations – "deep" probe of very small effects. (This is the ONLY WAY we have been able to see neutrino masses after all!).

Example: New Neutrino–Matter Interactions

These are parameterized by effective four-fermion interactions, of the type:

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

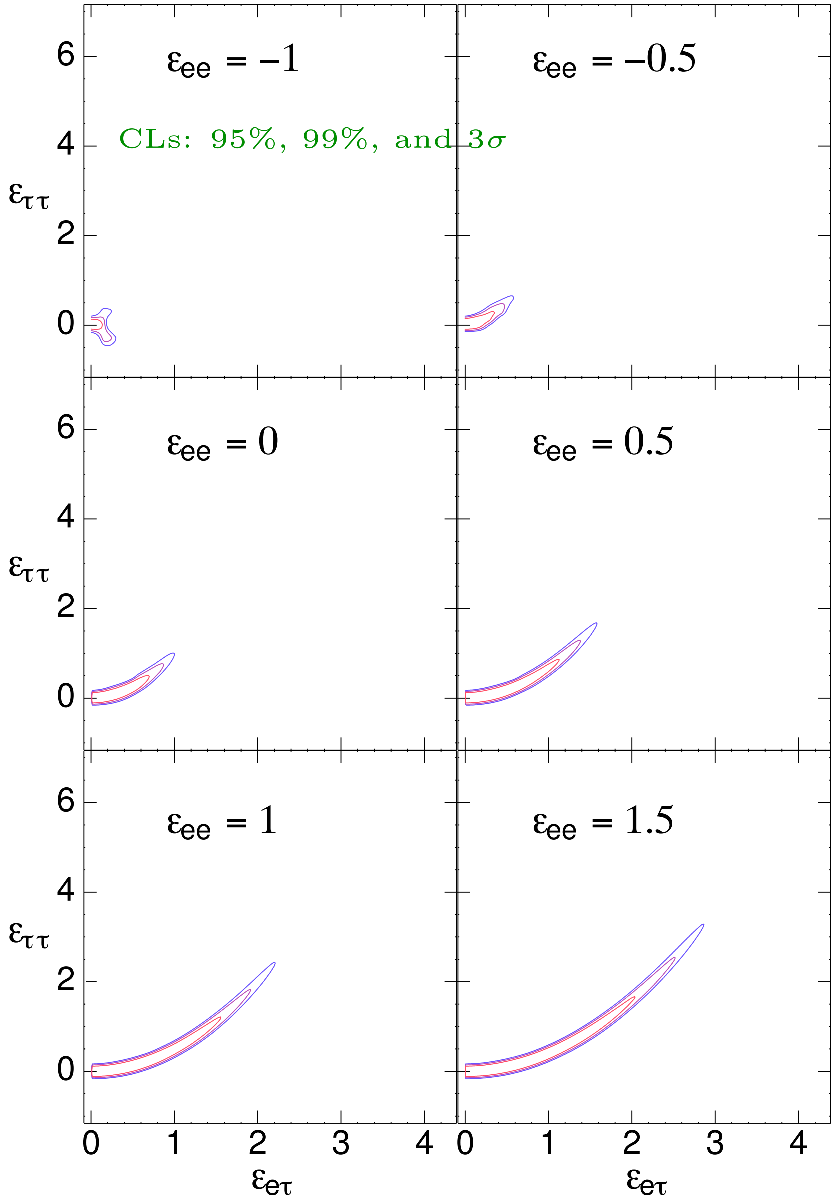
where $f, \tilde{f} = u, d, \ldots$ and $\epsilon_{\alpha\beta}^{f\tilde{f}}$ are dimensionless couplings that measure the strength of the four-fermion interaction relative to the weak interactions.

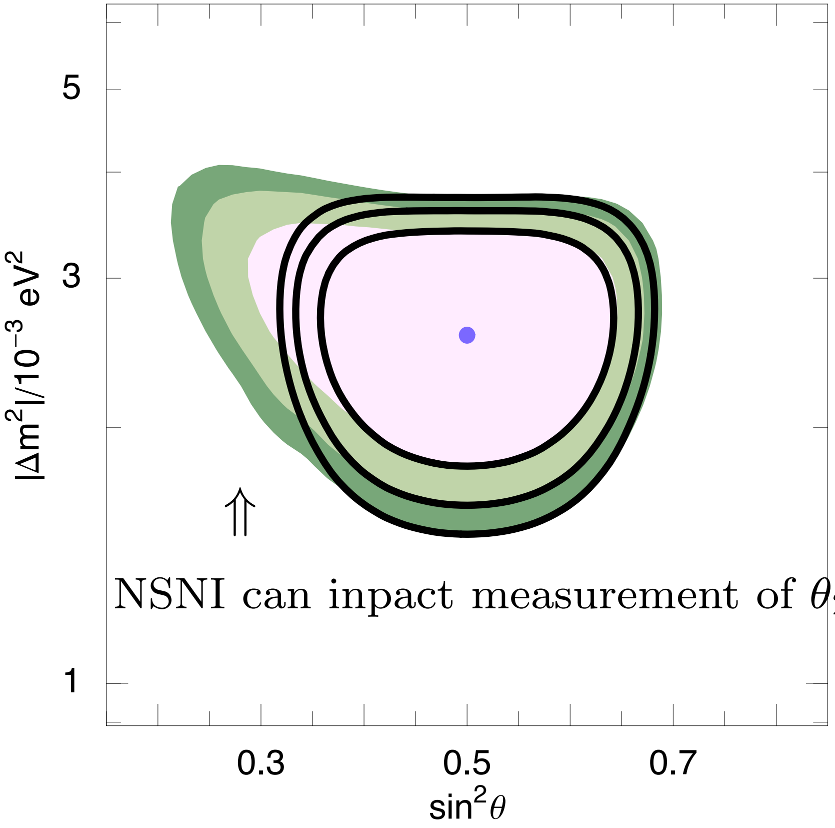
While some of the ϵs are well constrained (especially those involving muons), some are only very poorly known. These are best searched for in neutrino oscillation experiments, where they mediate anomalous matter effects:

$$H_{\rm mat} = \sqrt{2}G_F n_e\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu}^* & \epsilon_{e\tau}^* \\ \epsilon_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}^* \\ \epsilon_{e\tau} & \epsilon_{\mu\tau} & \epsilon_{\tau\tau}\end{pmatrix}, \qquad \epsilon_{\alpha\beta} = \sum_{f=u,d,e}\epsilon_{\alpha\beta}^{ff}\frac{n_f}{n_e}$$

IMPORTANT: sensitive to ϵ, not ϵ^2

Atmospheric Neutrinos and Non-Standard Interactions





⇑

NSNI can inpact measurement of θ_{23}

⇐ current constraint on such subleading effects.

More stringent bounds expected from MINOS.

Improved sensitivity from new ATM and LBL.

[Friedland and Lunardini, PRD72, 053009 (2005)].

Solar Neutrinos

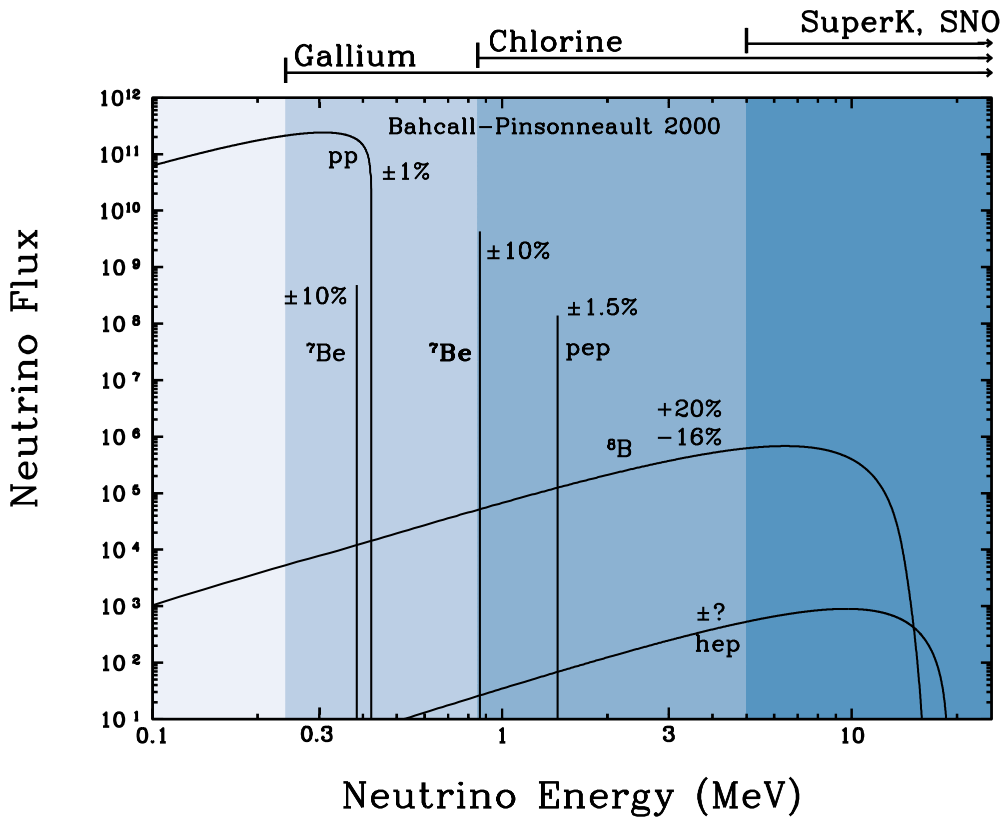
SuperK and SNO have measured, with great precision, "high energy" solar neutrinos, $E_\nu > 5$ MeV. The next natural step is to measure low energy ($E_\nu < 1$ MeV) "solar neutrinos".

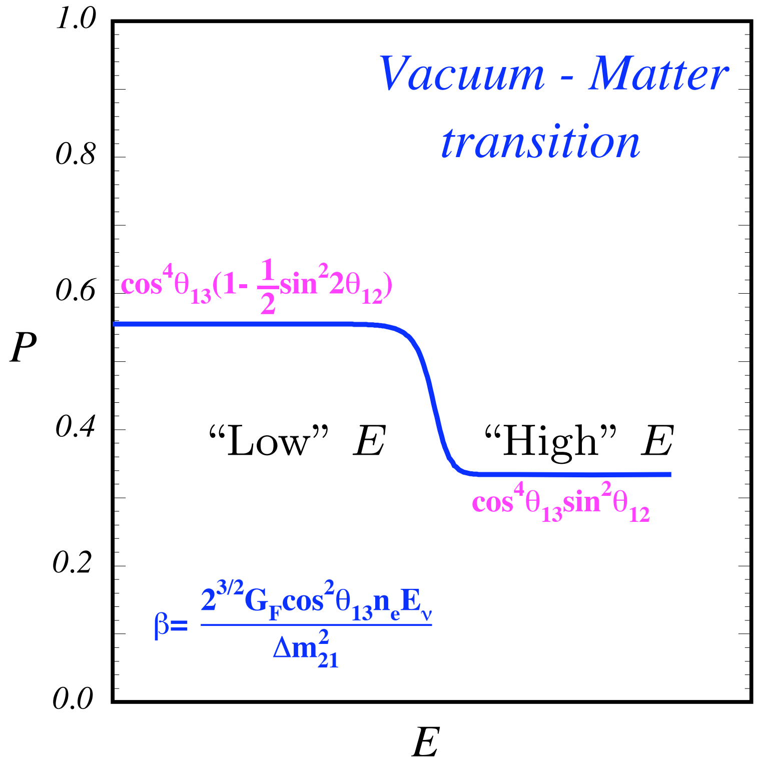
In order to do this, we need deep underground detectors. These are **not** your typical LBL detector. Different techniques have been proposed in order to obtain sensitivity to sub-MeV neutrinos and reduce radioactive backgrounds.

We don't expect significant improvements as far as solar parameters are concerned, but solar neutrinos could play a big role in the case of new new physics (and I won't talk about astrophysics at all).

Important ingredients: strong magnetic fields (time dependency?), large, smoothly varying matter density, very low neutrino energies.

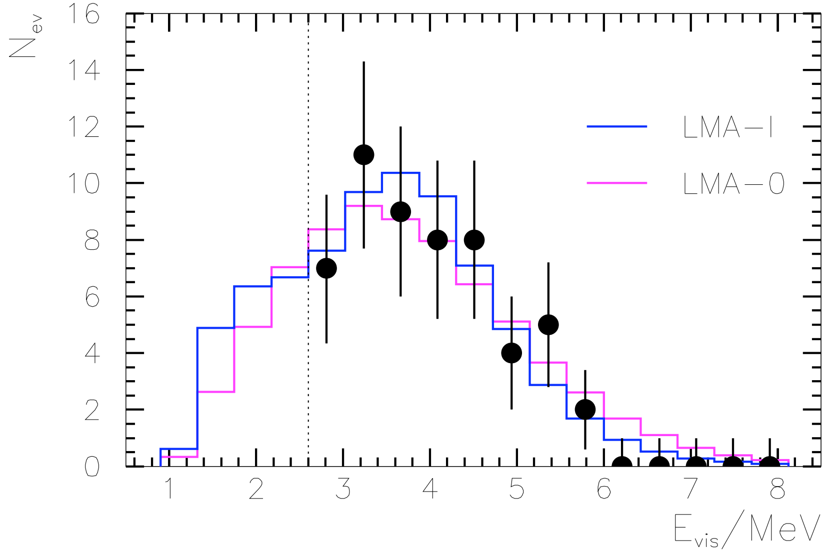
We Have Only Precisely Studied a Tiny Fraction of the Solar νs!

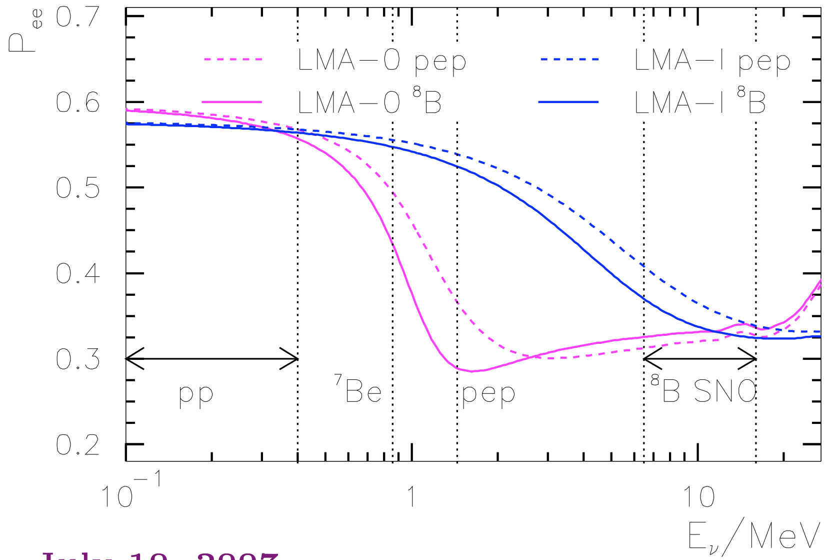




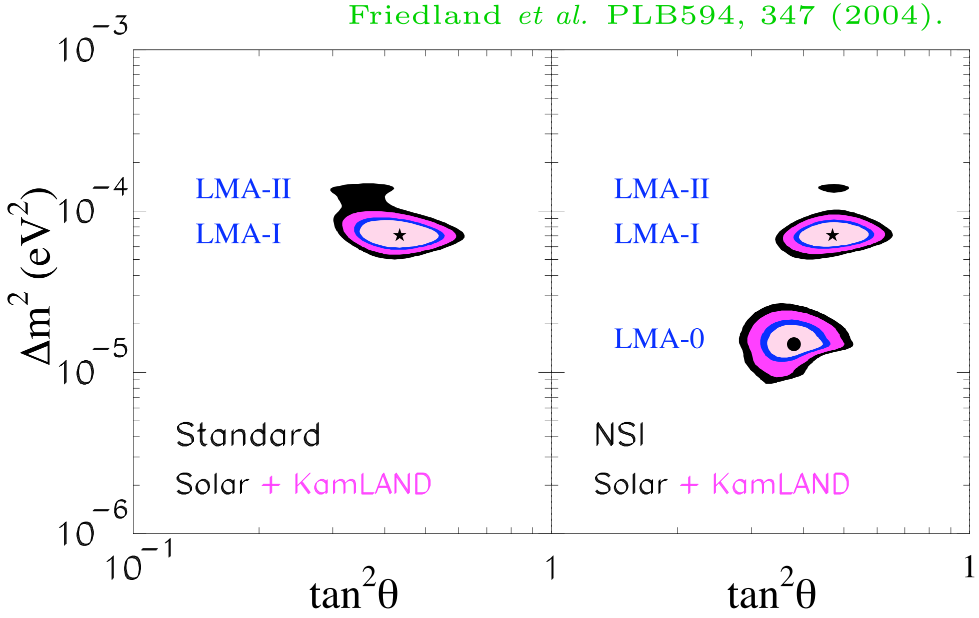
...and we have only looked at the "boring side" of the LMA solution!

Non-Standard ν Interactions and Low-Energy Solar νs





Friedland *et al.* PLB594, 347 (2004).

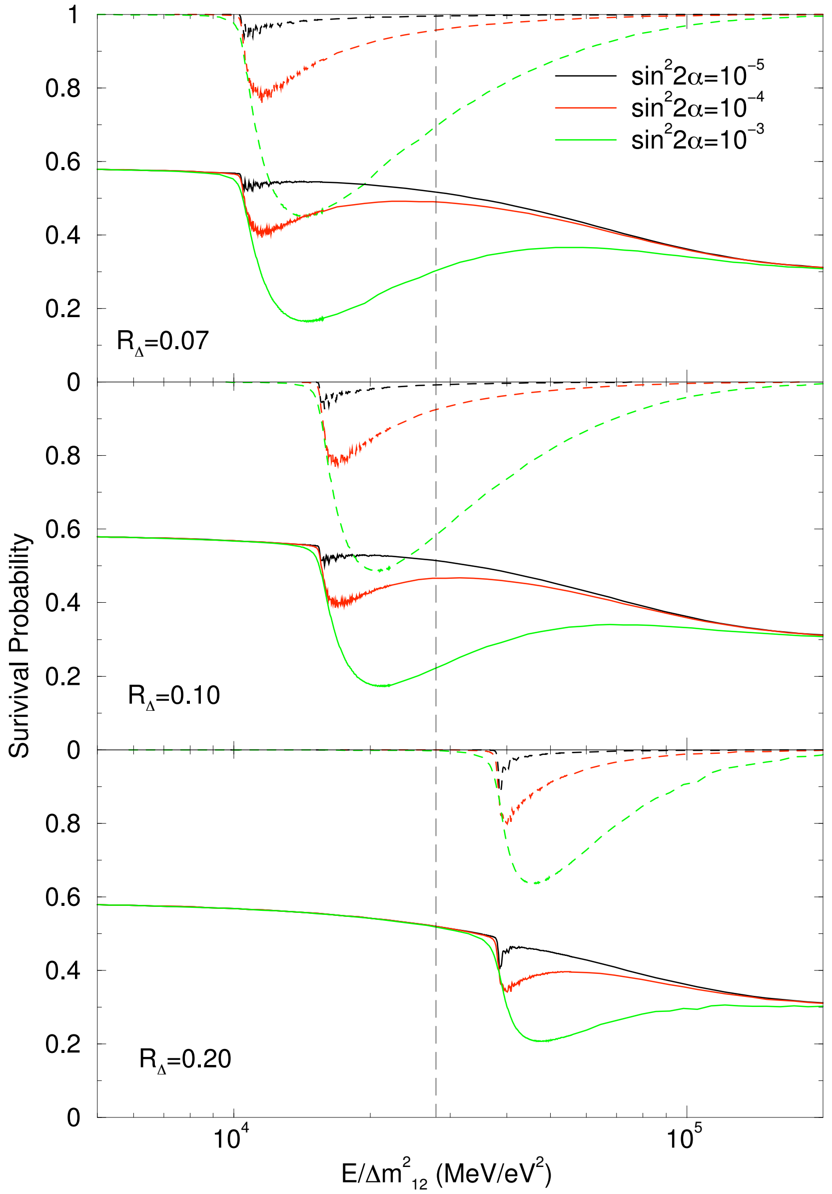


$$\text{LMA 0} \Rightarrow \epsilon_{ee} - \epsilon_{\tau\tau}\sin^2\theta_{23} = -0.065$$

$$2\epsilon_{e\tau}\sin\theta_{23} = 0.15$$

[WARNING: This is slightly outdated KamLAND data]

Other New New Physics Effects Look "The Same" – Sterile Solar νs



de Holanda, Smirnov, PRD69, 113002 (2004).

- $R_\Delta = \frac{\Delta m^2_{01}}{\Delta m^2_{12}} \rightarrow$ very light, mostly sterile state
- solid line: P_{ee}
- dashed line: $1 - P_{es}$

^{7}Be neutrinos at 1.1×10^4 MeV/eV^2

Low Energy ^{8}B neutrinos at 6.3×10^4 MeV/eV^2

All the action in around $E_\nu = 1$ MeV

$\Rightarrow$ ^{7}Be and pep. (Borexino/KamLAND, SNO+)

END LECTURE # 2

(To Be Continued . . .)