New Physics in Future Neutrino Experiments (?)

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This is a Talk About Unknown Unknowns . . .

"...there are known knowns. There are things we know that we know. There are known unknowns. That is to say, there are things that we now know we don't know. But there are also unknown unknowns. There are things we do not know we don't know."

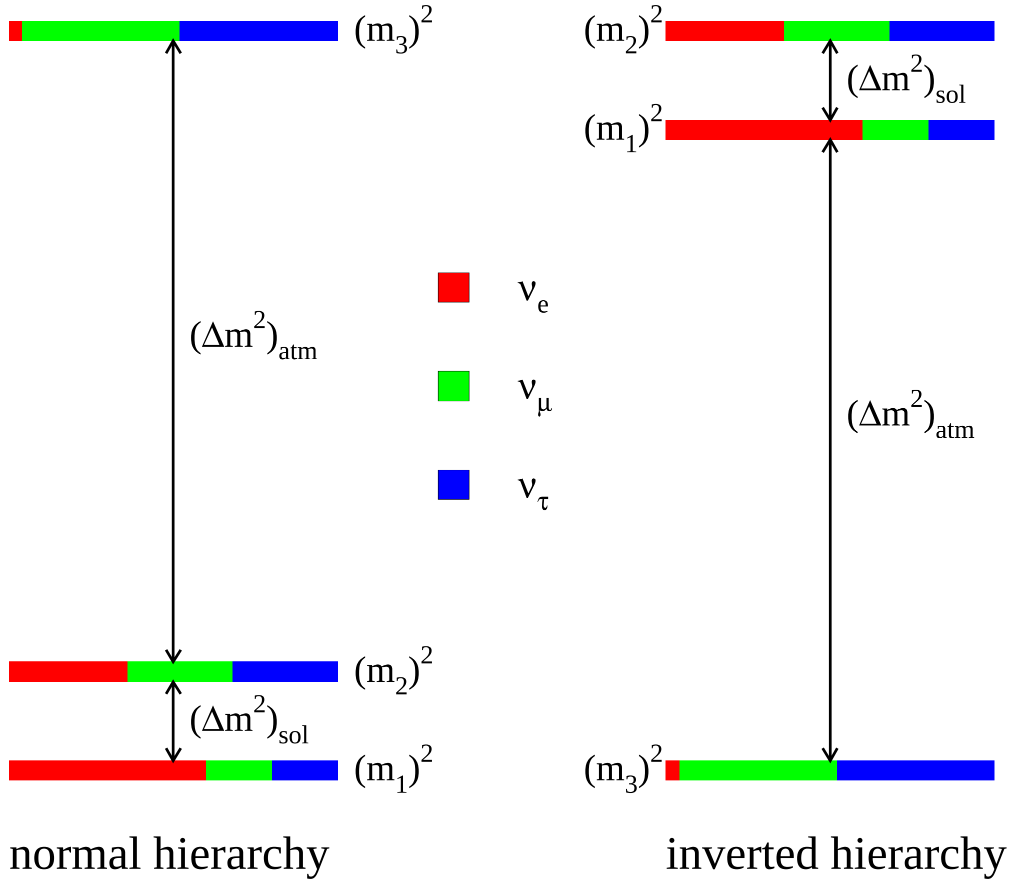
– Donald Rumsfeld, Feb. 12, 2002†

†Winner of 2003 "Foot in Mouth" Award (http://www.plainenglish.co.uk/)

Outline

- Known Unknowns – What are We Really After?;
- Sterile Neutrinos, One Concrete Example;
- Non-Standard Neutrino Interactions;
- How Do We Look for Unknown Unknowns? – Examples;
- Concluding Remarks

What is the "Real" Goal of Neutrino Oscillation Experiments?



- What is the ν_e component of ν_3? $(\theta_{13} \neq 0?)$
- Is CP-invariance violated in neutrino oscillations? $(\delta \neq 0, \pi?)$
- Is ν_3 mostly ν_μ or ν_τ? $(\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4?)$
- What is the neutrino mass hierarchy? $(\Delta m^2_{13} > 0?)$

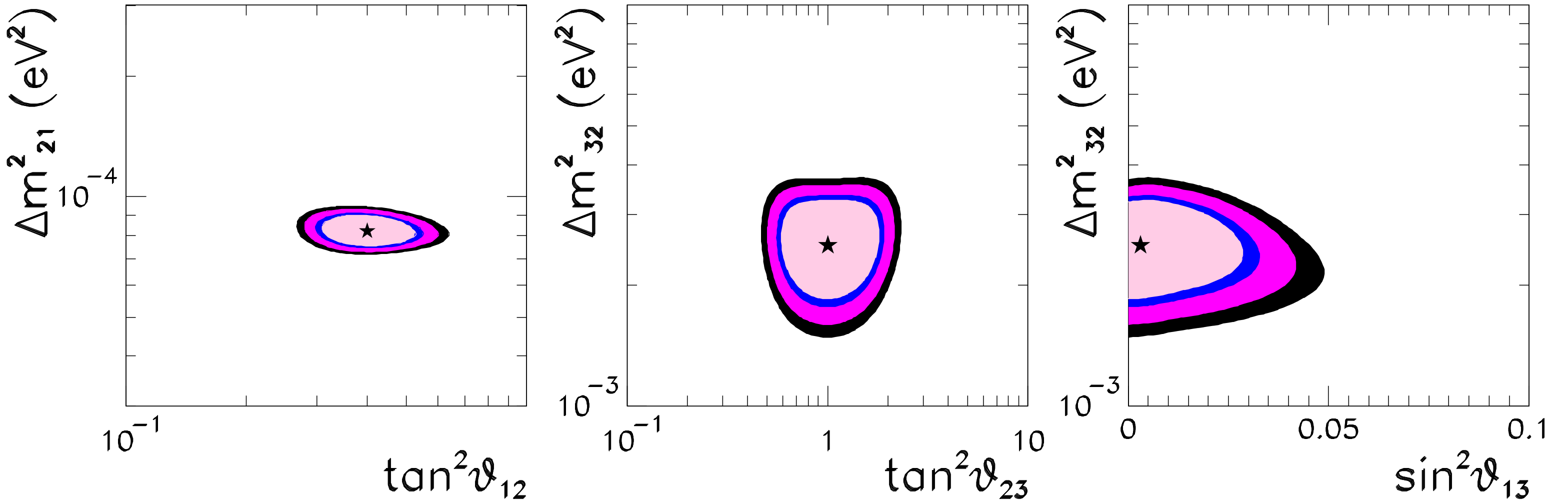
...

MORE IMPORTANT:

test the three neutrino mixing hypothesis. Are we missing anything?

More New ν Physics? → What Could It Be?

Reminder. . . [WARNING: slightly old fit]



(“update,” Gonzalez-Garcia, Maltoni, hep-ph/0406056)

(“update,” Gonzalez-Garcia, Peña-Garay, hep-ph/0306001)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{e\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$m_1^2 < m_2^2$$

$$m_2^2 - m_1^2 \ll |m_3^2 - m_{1,2}^2|$$

$\tan^2\theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2}$; $\tan^2\theta_{23} \equiv \frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2}$;

$U_{e3} \equiv \sin\theta_{13} e^{-i\delta}$

$\Delta m^2_{13} > 0$ – Normal Mass Hierarchy

$\Delta m^2_{13} < 0$ – Inverted Mass Hierarchy

But what have we **really measured** (very, very roughly):

- Two mass-squared differences, at several percent level – many probes;
- $|U_{e2}|^2$ – solar data;
- $|U_{\mu 2}|^2 + |U_{\tau 2}|^2$ – solar data;
- $|U_{e2}|^2(1 - |U_{e2}|^2)$ – KamLAND;
- $|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2)$ – atmospheric data, K2K, MINOS;
- $|U_{e3}|^2(1 - |U_{e3}|^2)$ (upper bound) – mostly reactor data.

We still have a ways to go!

(Some of) What We Don't Know We Don't Know

Given that neutrinos have mass and we are in position to probe whether neutrino are endowed with other "unexpected" properties, including,

- a "large" electric/magnetic dipole moment;
- a finite but not infinitely long lifetime.

We are also able to search for

- New neutrino contact interactions;
- New neutrino degrees of freedom (sterile neutrinos).

Finally, we can ask whether the leptonic sector respects a variety of fundamental symmetries, including

- Lorentz invariance;
- CPT invariance.

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 can be searched, for example, in neutrino oscillation experiments, where they mediate anomalous matter effects:

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

Sterile Neutrinos – Why Not?

Sterile neutrinos are gauge singlet fermions, and qualify, along with a gauge singlet scalar, as the most benign, trivial extension of the SM matter sector. "Hidden Sector"

More interesting is the fact that gauge singlets only communicate to the SM (at the renormalizable level) in two ways:

- Scalars couple to the Higgs boson;
- Fermions couple to neutrinos (via Yukawa coupling $\rightarrow$ mixing).

$\rightarrow$ Active–sterile neutrino mixing provides one of only two ways to communicate with gauge singlet fields that may be out there!

Of course, one may ask if there is any evidence for such a hidden sector. The answer is "we don't know." …

…However:

- Dark matter could be a very weakly coupled "weak-scale" mass particle. And it can certainly be either one of the Hidden sector particles!
- Light sterile neutrinos in particular may be a good warm dark matter candidate.
- It is often speculated that light sterile neutrinos may play an important role in supernova explosions. They may aid on the synthesis of heavy elements and may be the reason behind the large peculiar velocity of neutron stars (pulsar kicks).
- Sterile neutrinos are often a side-effect of active neutrino masses. Remember:

  Sterile Neutrino = Right-Handed Neutrino = Gauge Singlet Fermion

Concrete Example: The Seesaw Lagrangian, No Prejudices

A simple[a], renormalizable Lagrangian that allows for neutrino masses is

$$\mathcal{L}_\nu = \mathcal{L}_{\rm old} - \lambda_{\alpha i} L^\alpha H N^i - \sum_{i=1}^{3} \frac{M_i}{2} N^i N^i + H.c.,$$

where N_i ($i = 1, 2, 3$, for concreteness) are SM gauge singlet fermions. $\mathcal{L}_\nu$ is the most general, renormalizable Lagrangian consistent with the SM gauge group and particle content, plus the addition of the N_i fields.

After electroweak symmetry breaking, $\mathcal{L}_\nu$ describes, besides all other SM degrees of freedom, six Majorana fermions: **six neutrinos.**

[a] Only requires the introduction of three fermionic degrees of freedom, no new interactions or symmetries.

What We Know About M:

- $M=0$: the six neutrinos "fuse" into three Dirac states. Neutrino mass matrix given by $\mu_{\alpha i} \equiv \lambda_{\alpha i} v$.

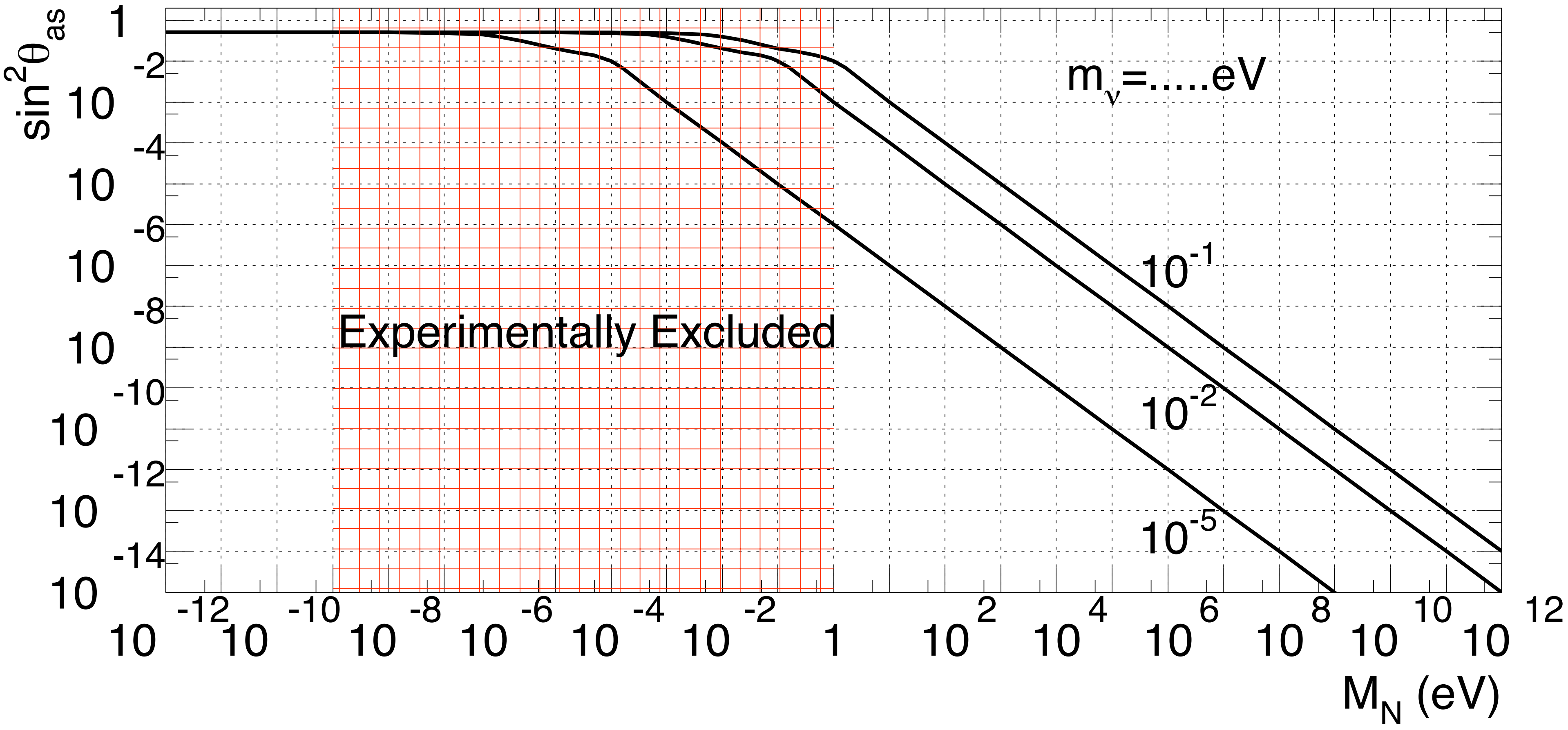
  The symmetry of $\mathcal{L}_\nu$ is enhanced: $U(1)_{B-L}$ is an exact global symmetry of the Lagrangian if all M_i vanish. Small M_i values are 'tHooft natural.

- $M \gg \mu$: the six neutrinos split up into three mostly active, light ones, and three, mostly sterile, heavy ones. The light neutrino mass matrix is given by $m_{\alpha\beta} = \sum_i \mu_{\alpha i} M_i^{-1} \mu_{\beta i}$ $[m \propto 1/\Lambda \;\Rightarrow\; \Lambda = M/\mu^2]$.

  This the **seesaw mechanism.** Neutrinos are Majorana fermions. Lepton number is not a good symmetry of $\mathcal{L}_\nu$, even though L-violating effects are hard to come by.

- $M \sim \mu$: six states have similar masses. Active–sterile mixing is very large. This scenario is (generically) ruled out by active neutrino data (atmospheric, solar, KamLAND, K2K, etc).

Constraining the Seesaw Lagrangian



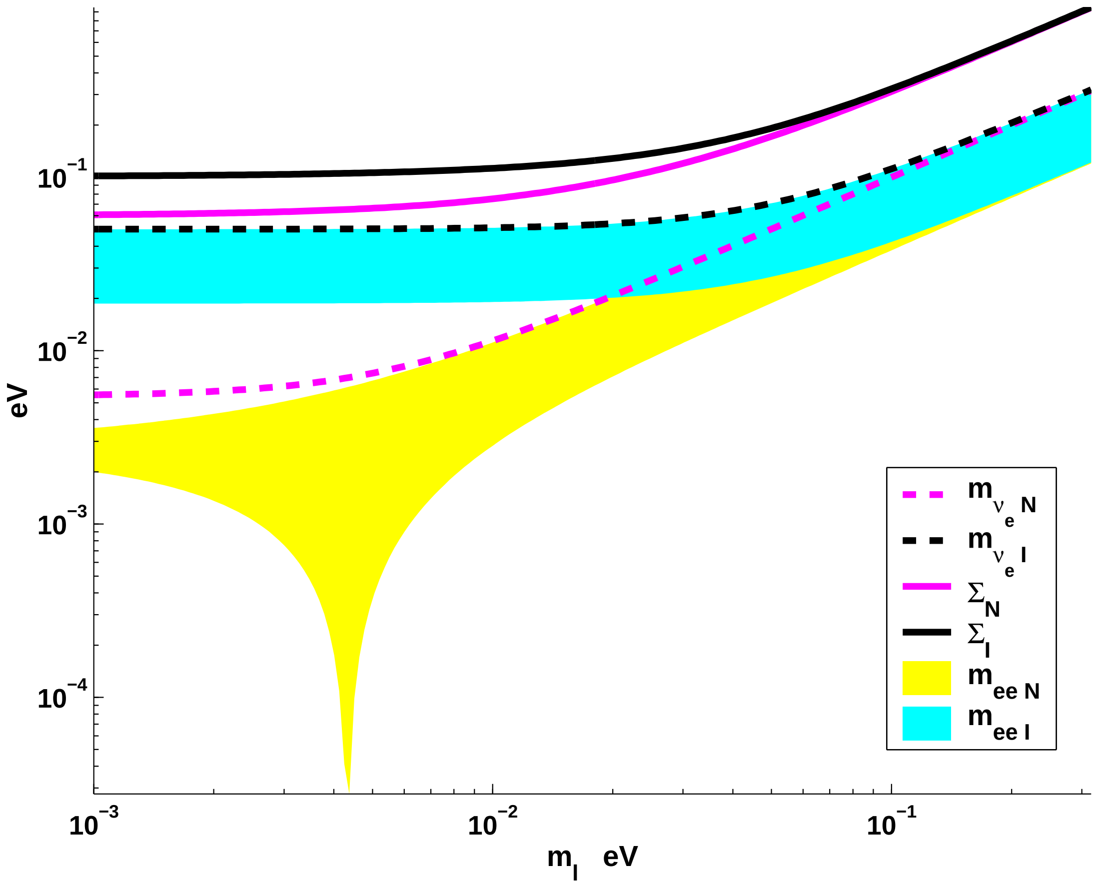
[AdG, Huang, Jenkins, arXiv:0906.1611]

Looking for Unknown Unknowns, Examples

m_l is the lightest neutrino mass

$m_l = m_1$ for the normal hierarchy,

$m_l = m_3$ for the inverted hierarchy.

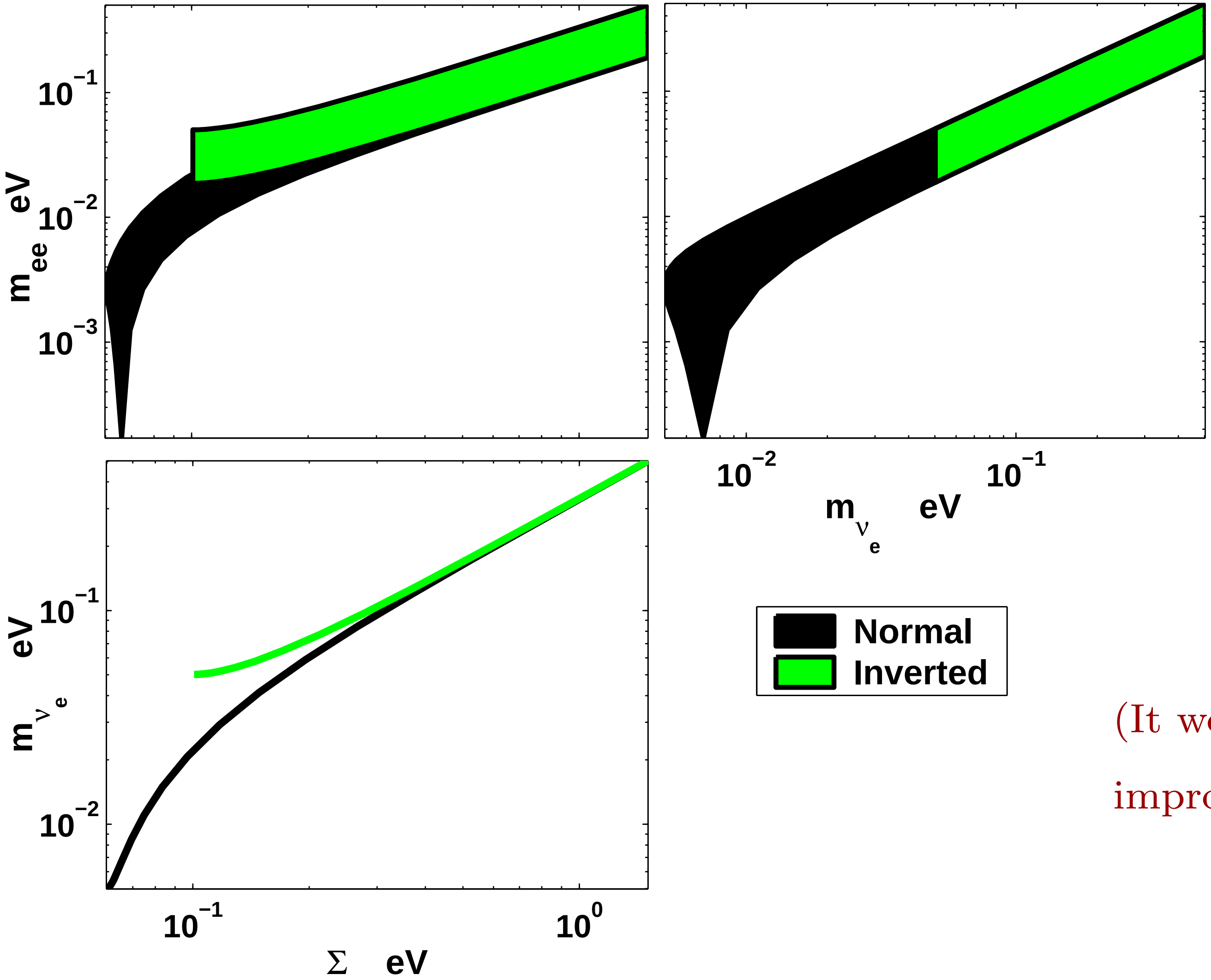


Neutrino Mass Observables:

- m_{ν_e}: kinematical neutrino mass
- m_{ee}: double-beta decay
- Σ: sum of masses, "cosmology"

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

The Power of Combining the Different Observables: $2 \gg 1$



Very Strong Correlations!

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

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

Low-Energy Seesaw and **Neutrinoless Double-Beta Decay**

The exchange of Majorana neutrinos mediates lepton-number violating neutrinoless double-beta decay, $0\nu\beta\beta$: $Z \to (Z+2)e^-e^-$.

For light enough neutrinos, the amplitude for $0\nu\beta\beta$ is proportional to the effective neutrino mass

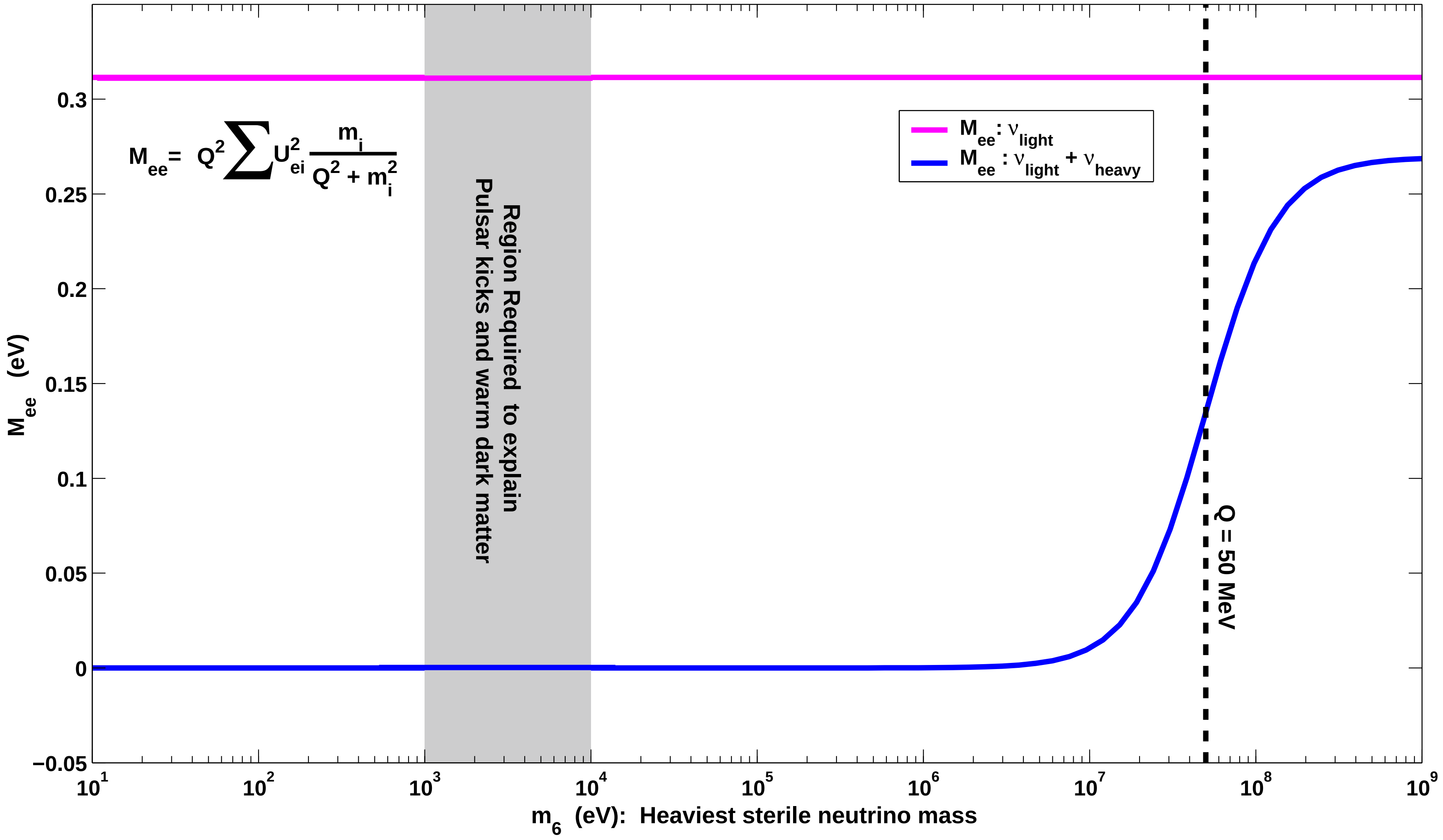
$$m_{ee} = \left|\sum_{i=1}^{6} U_{ei}^2 m_i\right| \sim \left|\sum_{i=1}^{3} U_{ei}^2 m_i + \sum_{i=1}^{3} \vartheta_{ei}^2 M_i\right|.$$

However, upon further examination, $m_{ee} = 0$ in the eV-seesaw. **The contribution of light and heavy neutrinos exactly cancels!** This seems to remain true to a good approximation as long as $M_i \ll 1$ MeV.

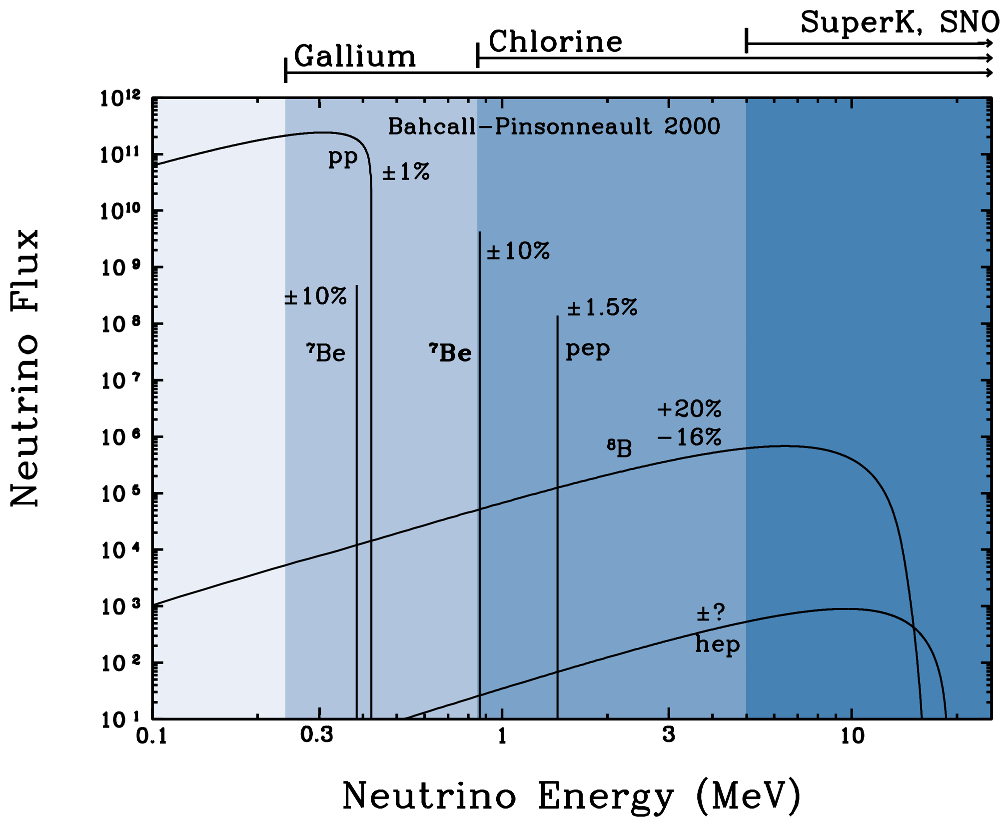
$$\left[\ \mathcal{M} = \begin{pmatrix} 0 & \mu^{\rm T} \\ \mu & M \end{pmatrix} \ \rightarrow\ m_{ee} \text{ is identically zero!}\ \right]$$

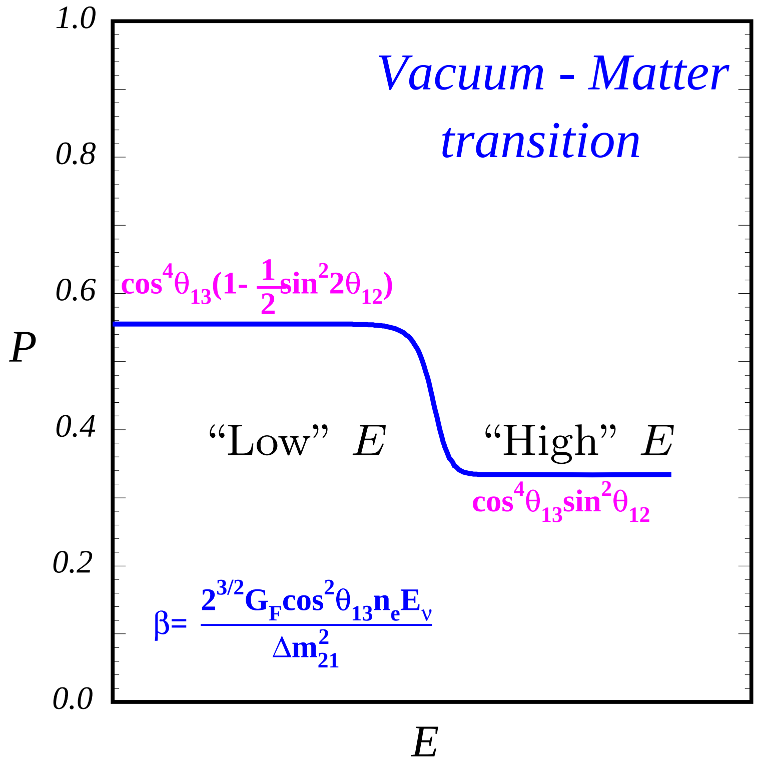
(lack of) sensitivity in $0\nu\beta\beta$ due to seesaw sterile neutrinos

[AdG, Jenkins, Vasudevan, hep-ph/0608147]

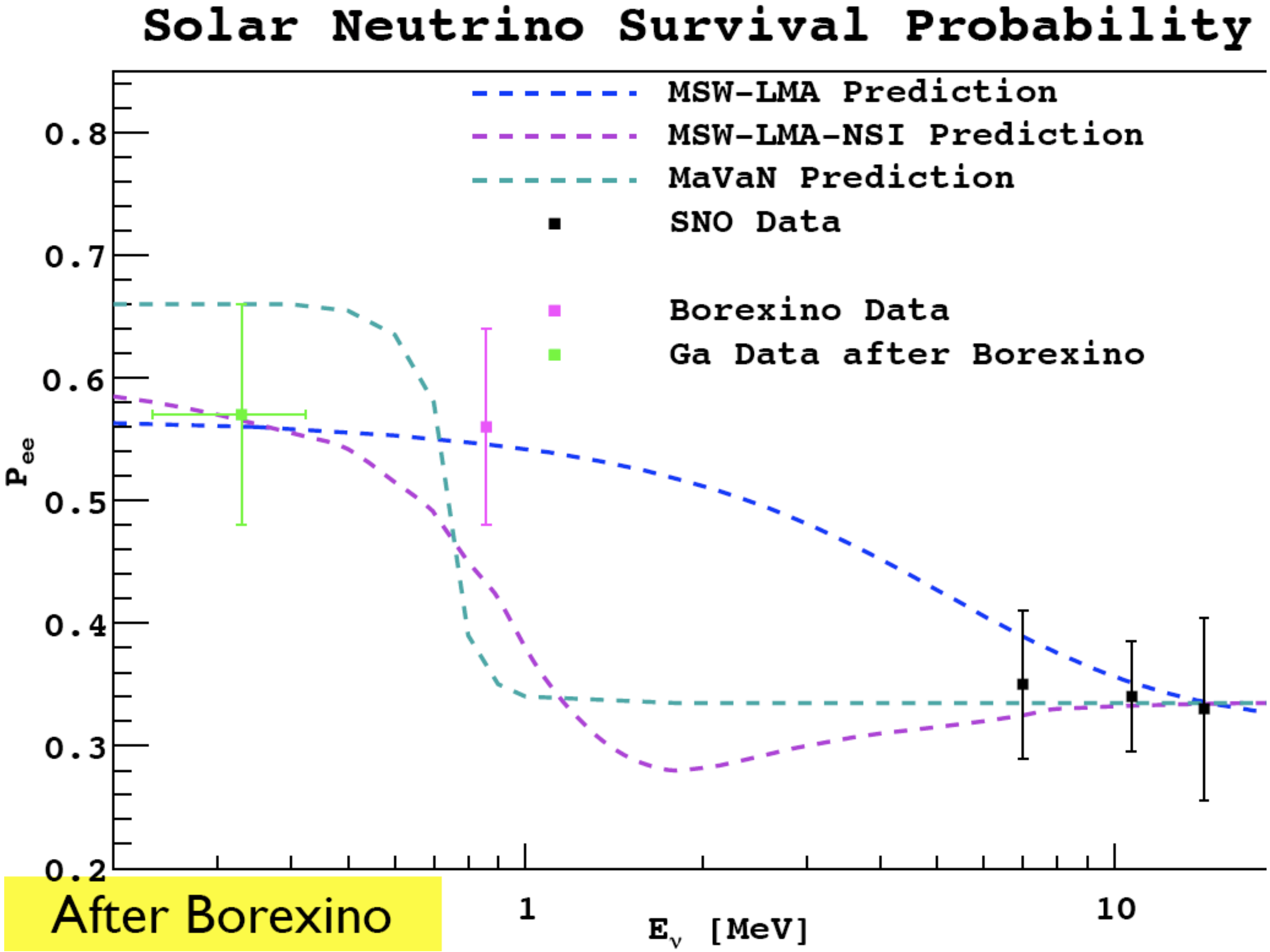


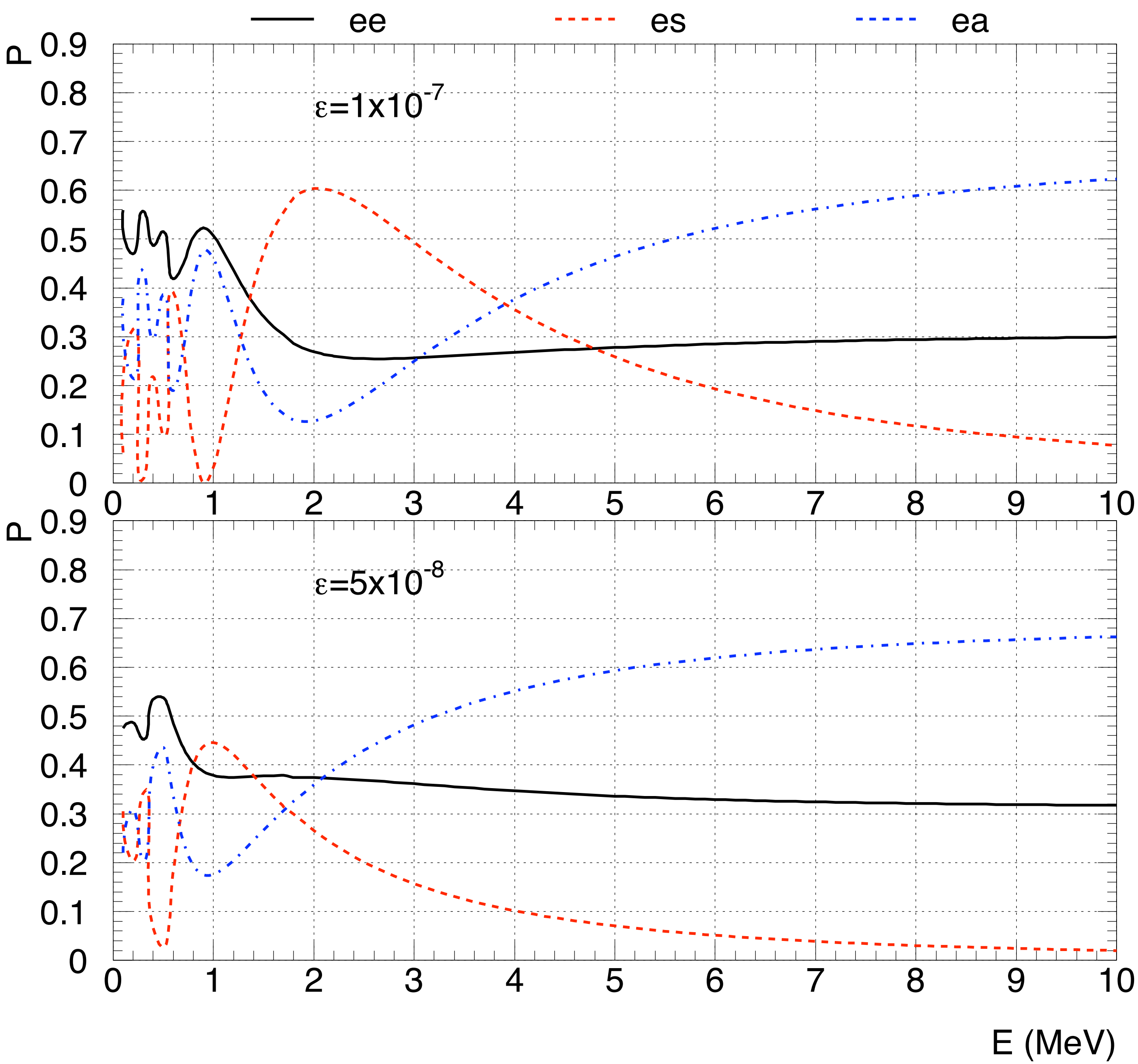
We Have Only Precisely Studied a Tiny Fraction of the Solar νs!





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


Solar Neutrino Survival Probability
MSW-LMA Prediction
MSW-LMA-NSI Prediction
MaVaN Prediction
SNO Data
Borexino Data
Ga Data after Borexino
0.8
0.7
0.6
0.5
0.4
0.3
0.2
P_{ee}
1
10
E_ν [MeV]
After Borexino



Sterile Neutrinos with:

- tiny new $\Delta m^2 = \epsilon \Delta m^2_{12}$,
- maximal mixing!

[AdG, Huang, Jenkins, arXiv:0906.1611]

Back to Over-constraining the Formalism

General Idea:

1. Assume three active neutrino oscillation formalism;
2. Measure parameters as well as possible in as many different ways as possible;
3. Are all fits "good"?;
4. Are different measurements of the different parameters consistent?
5. Rinse and repeat ...

New ν Physics in Neutrino Oscillations

Unexpected phenomena can occur at three points of a neutrino oscillation experiment. Of course, you need to consider the consequences of your favorite new physics to all of them. In more detail:

- New Physics at Production: instead of, say, $\pi \to \nu_\mu$, you get $\pi \to \nu_\mu + \epsilon\nu_\tau$. This can be a consequence of new charged-current-like interactions, or the existence of new heavy mass eigenstates. This leads, for example, to zero-baseline flavor-change.
- New Physics at Detection: instead of, say, $\nu_\mu \to \mu^-$, you get $\nu_\mu \to \mu^- + \epsilon e^-$. This can be a consequence of new charged-current-like interactions, or the existence of new heavy mass eigenstates. As above, this can lead to zero-baseline flavor-change.

- New Physics During Flight: neutrino propagation relies on several things. First, that there are three neutrinos with a well-defined mass that satisfy the following dispersion relation, in vacuum

$$E^2 - |\vec{p}|^2 = m^2.$$

Second, when propagating in matter, the matter potential is uniquely specify by the weak interactions and the local density and composition of the medium.

This can be modified by new neutrino mass-eigenstates (sterile neutrinos), anomalous matter effects (non-standard neutrino interactions), the violation of Lorentz invariance ($E^2 - |\vec{p}|^2 \neq m^2$), disappearing neutrinos (neutrino decay), new media (dark energy!), etc.

There are several possible consequences of this. One of them includes a deviation from the standard L/E behavior of neutrino oscillations. Note: the L/E behavior of the neutrino flavor transitions is not a feature of oscillations, but a general consequence of Lorentz Invariance.

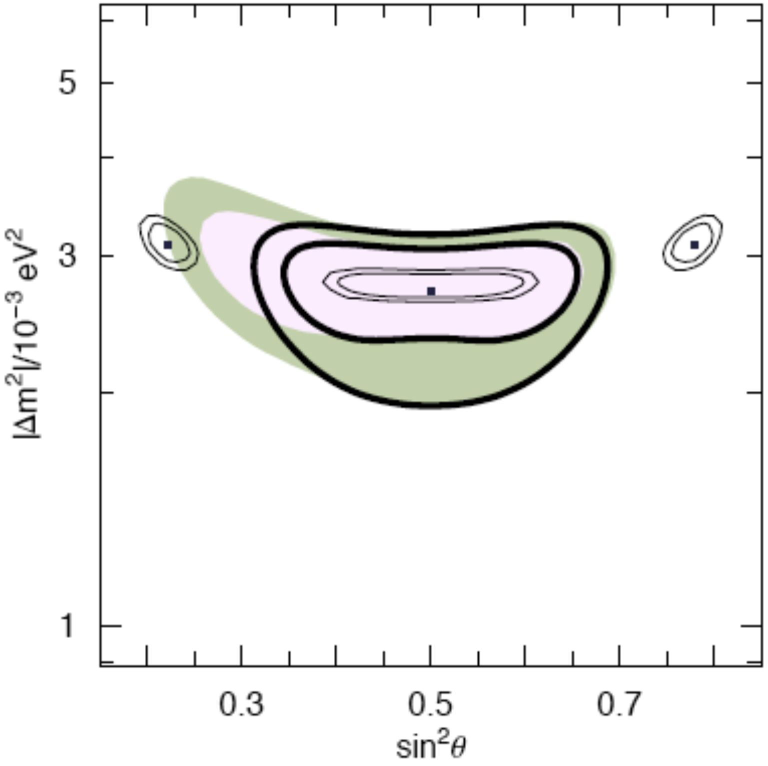
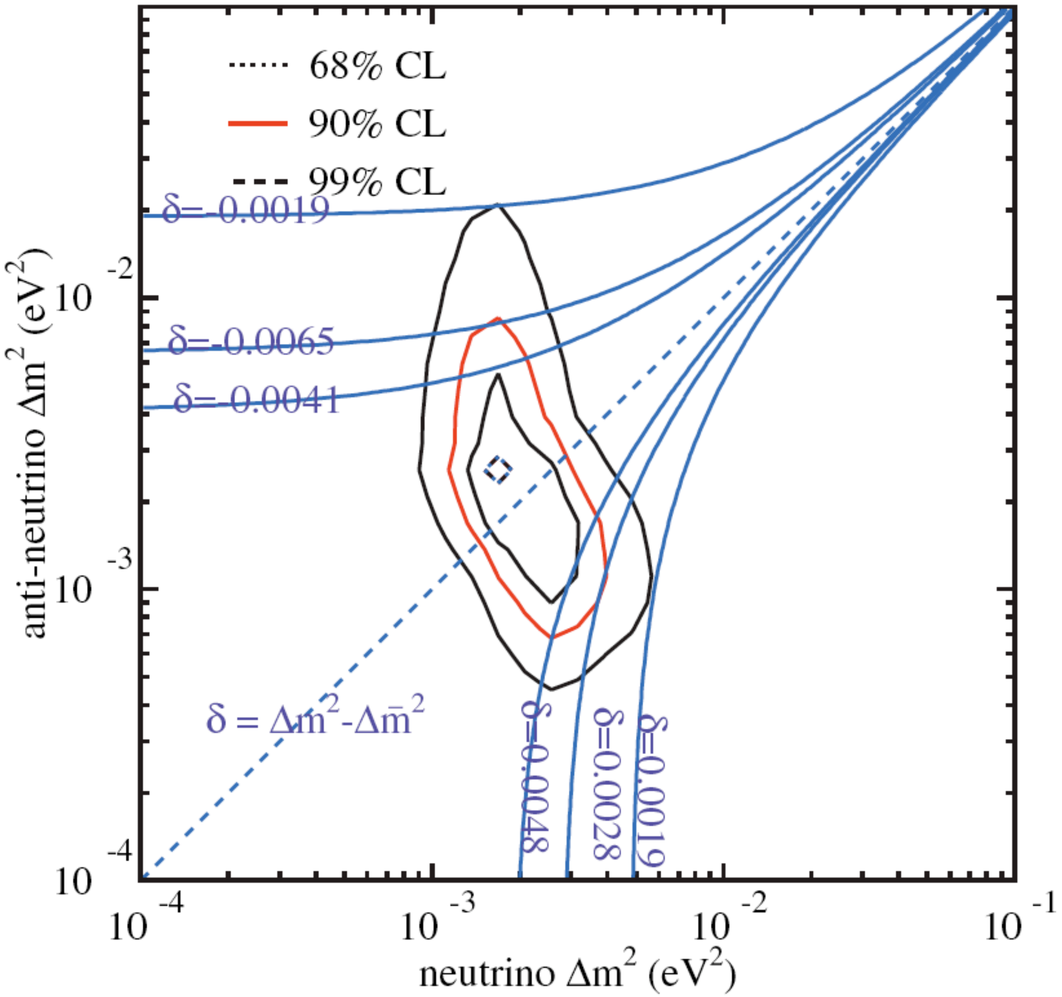


FIG. 3: Results of fits to simulated MINOS data with statistics increased from the current $0.93 \cdot 10^{20}$ to $25 \cdot 10^{20}$ protons on target (thin contours). 90% and 99% C.L. regions are shown. The "data" were simulate for two sets of NSI and "true" oscillation parameters: (i) no NSI, $\sin^2\theta = 0.5$ and $\Delta m^2 = 2.7 \cdot 10^{-3}$ eV^2, (ii) $\epsilon_{ee} = 0$, $\epsilon_{\tau\tau} = 0.81$, $\epsilon_{e\tau} = 0.9$, $\sin 2\theta = 0.27$ and $\Delta m^2 = 3.1 \cdot 10^{-3}$ eV^2. The fits were done in both cases in the assumption of no NSI. For reference, we also show the regions allowed currently by all the data combined, at 90% and 99% C.L. with (filled area) and without NSI (thick contours), as in Fig. 1. See text for details.

[Friedland and Lunardini, Phys.Rev.D74:033012 (2006)]

Are neutrinos and antineutrino mass-squared differences the same?

[E. Kearns, talk at Neutrino 2004]



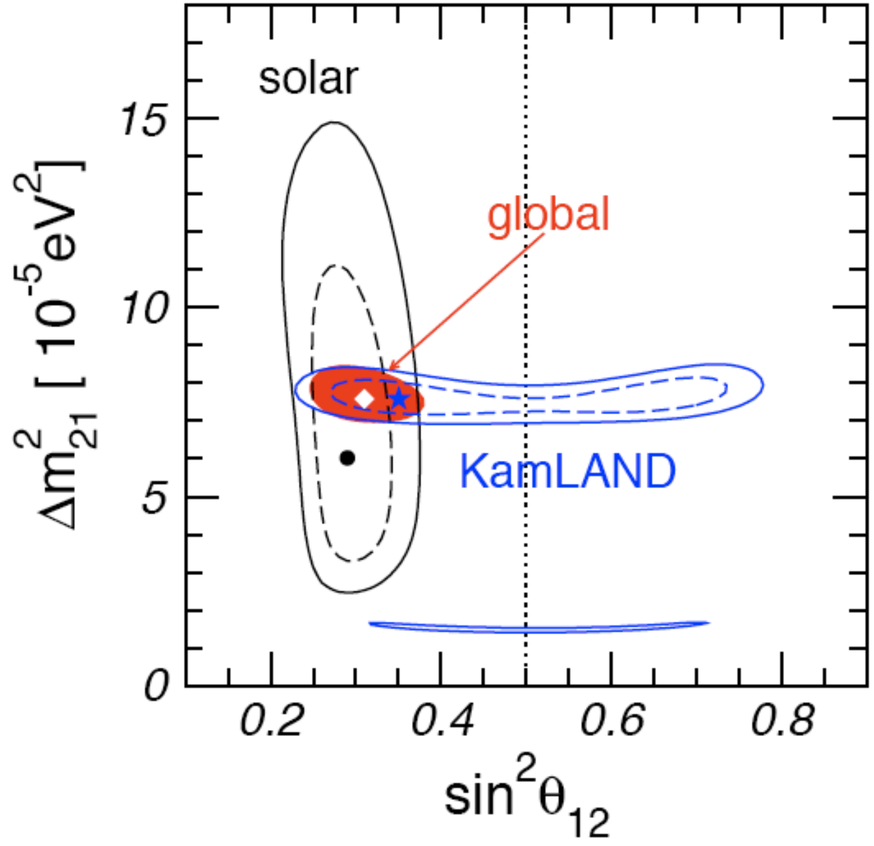


Figure 1: Determination of the leading "solar" and
allowed regions at 90% and 99.73% CL (2 dof) for sola
(right), as well as the 99.73% CL regions for the respe

Can We Do Better? ⇒ MINOS will start taking $\bar{\nu}_\mu$ very soon!

[Maltoni and Schwetz, arXiv: 0812.3161]

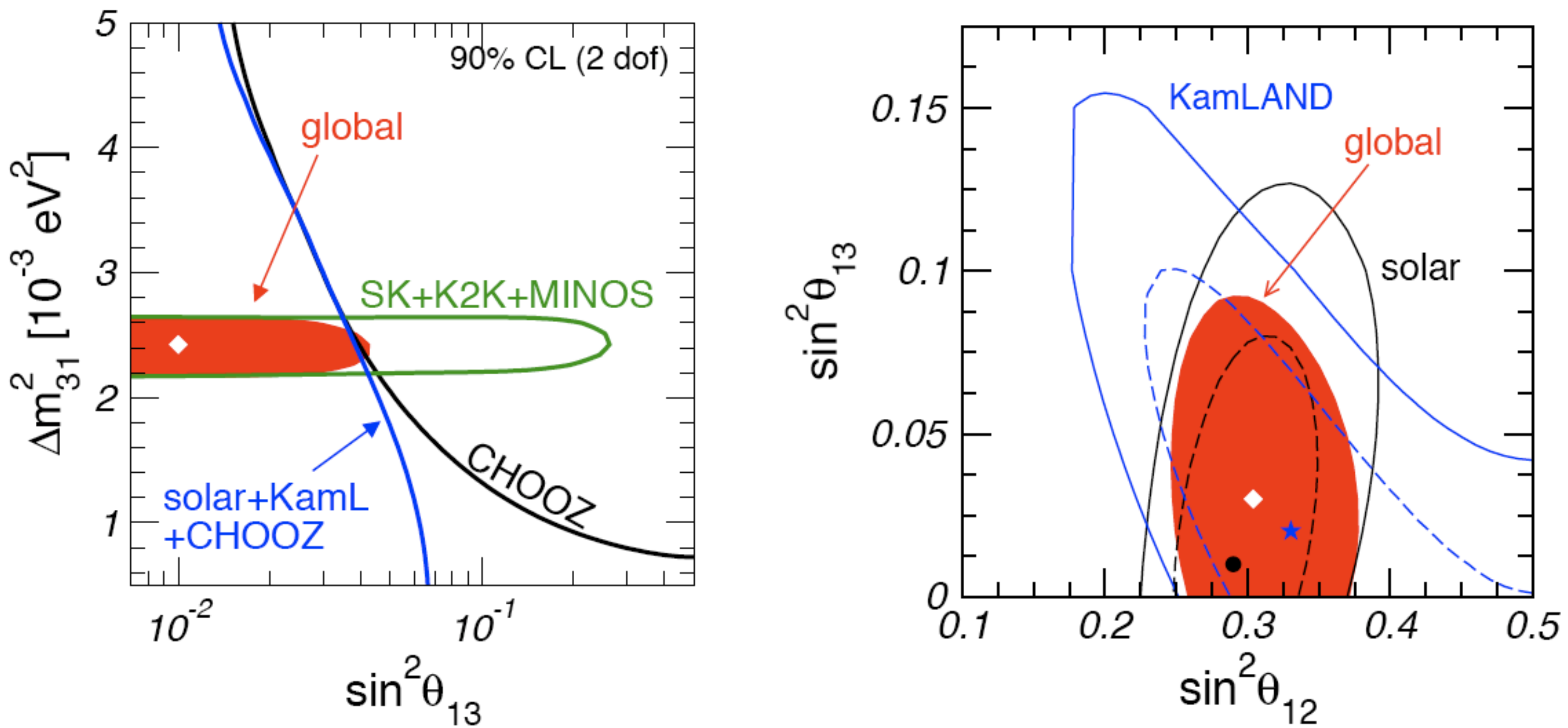


Figure 2: Left: Constraints on $\sin^2\theta_{13}$ from the interplay of different parts of the global data. Right: Allowed regions in the $(\theta_{12} - \theta_{13})$ plane at 90% and 99.73% CL (2 dof) for solar and KamLAND, as well as the 99.73% CL region for the combined analysis. Δm^2_{21} is fixed at its best fit point. The dot, star, and diamond indicate the best fit points of solar, KamLAND, and combined data, respectively.

"Hint" for non-zero $\sin^2\theta_{13}$? You decide. . . (see claim by Fogli et al., arXiv:0806.2649)

Concluding Remarks

1. We have a very **successful parameterization** of the physics revealed by the last decade of neutrino experiments: three massive, active neutrinos, plus unitary flavor mixing. What we learn from this framework guides the future neutrino experimental program, as it should be.

2. We have learned a lot, but not enough. We are still in the process of testing the standard paradigm: there are lots of holes to be filled. There is plenty of **room for surprises**, as neutrinos are very narrow but deep probes of all sorts of physical phenomena. Remember that neutrino oscillations are "quantum interference devices" – potentially very sensitive to whatever else may be out there (e.g., $\Lambda \simeq 10^{14}$ GeV).

3. Gauge singlet fermions (**sterile neutrinos**) are a simple, benign extension of the standard model (Hidden Sector). They **will only manifes themselves through mixing with the active neutrinos**. They are probably the simplest (most boring), most likely new physics we will run into in neutrino experiments.

4. There are **many other possibilities**, ranging from new weaker-than-weak interactions involving neutrinos to the violation of Lorentz or CPT invariance to modified gravity. Remember that we don't know the mechanism behind neutrino masses. It could be due to new physics that will show up in next-generation neutrino mass-related experiments!

5. It is important to keep an eye out for different possibilities. It is also imperative to measure the same parameters in as many different ways as we can imagine – this is what we did in the quark sector. We can only claim to have pieced the neutrino puzzle once we have safely **over-constrained the three flavor hypothesis**!