Seesaw Energy Scale & The LSND Anomaly*

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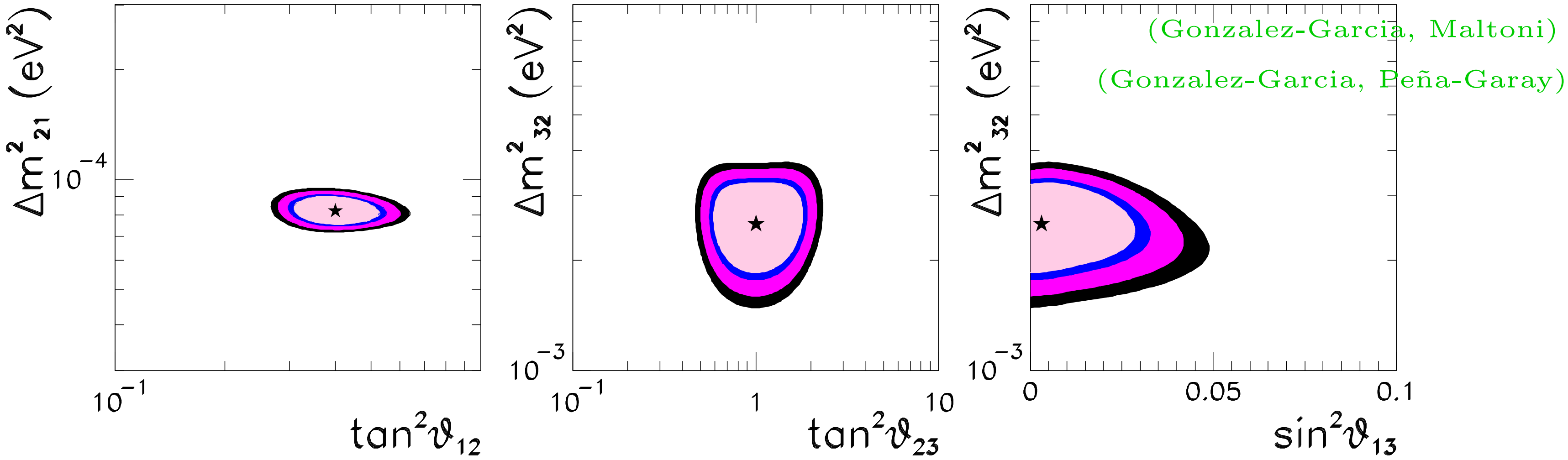
INFO Workshop, Santa Fe, July 11 – 15, 2005

*based on hep-ph/0501039

Outline

1. Rendering the Neutrinos Massive, and The Seesaw Mechanism;
2. The LSND Anomaly;
3. Solving the LSND Anomaly;
4. The eV Seesaw;
5. Other Interesting Consequences, and Downsides;
6. Conclusions.

Neutrinos Have Mass



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{e\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$m_1^2 < m_2^2$$

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

$$\tan^2\theta_{12} \equiv \frac{|U_{e2}^2|}{|U_{e1}^2|}; \quad \tan^2\theta_{23} \equiv \frac{|U_{\mu3}^2|}{|U_{\tau3}^2|};$$

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

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

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

Massive Neutrinos and the Seesaw Mechanism

In the SM, neutrinos are massless. There are several qualitatively distinct ways of modifying the SM in order to introduce neutrino masses.

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. Other "similar" option is to introduce a Higgs $SU(2)$ Triplet.

To be determined from data: λ and M.

The data can be summarized as follows: there is evidence for three neutrinos, mostly "active" (linear combinations of ν_e, ν_μ, and ν_τ). At least two of them are massive and, if there are other neutrinos, they have to be "sterile."

This provides very little information concerning the magnitude of M_i (I assume $M_1 \sim M_2 \sim M_3$)

Theoretically, there is prejudice in favor of very large M: $M \gg v$. Popular examples include $M \sim M_{\rm GUT}$ (GUT scale), or $M \sim 1$ TeV (EWSB scale).

Furthermore, $\lambda \sim 1$ translates into $M \sim 10^{14}$ GeV, while thermal leptogenesis requires the lightest M_i to be around 10^{10} GeV.

we can impose very, very few experimental constraints on M

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 $m_{\alpha\beta} = \sum_i \lambda_{\alpha i} M_i^{-1} \lambda_{\beta i}$.

  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).

And now, for something completely different:

The LSND Anomaly

The LSND experiment looks for $\bar{\nu}_e$ coming from

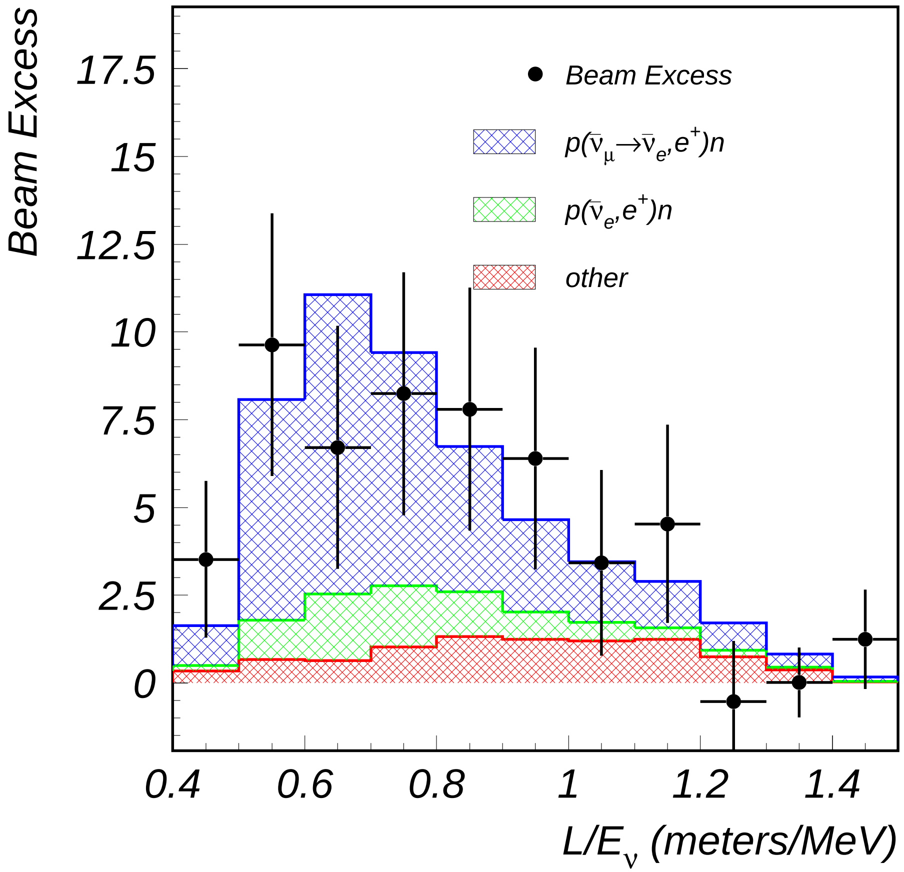
- $\pi^+ \to \mu^+ \nu_\mu$ decay in flight;
- $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ decay at rest;

produced some 30 meters away from the detector region.

It observes a statistically significant excess of $\bar{\nu}_e$-candidates. The excess can be explained if there is a very small probability that a $\bar{\nu}_\mu$ interacts as a $\bar{\nu}_e$, $P_{\mu e} = (0.26 \pm 0.08)\%$.

However: the LSND anomaly (or any other consequence associated with its resolution) is yet to be observed in another experimental setup.

strong evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$



If oscillations $\Rightarrow \Delta m^2 \sim 1$ eV^2

× does not fit into 3 ν picture;

× $2+2$ scheme ruled out (solar, atm);

○? $3+1$ scheme disfavored (sbl searches);

× 3 ν's CPTV ruled out (KamLAND, atm);

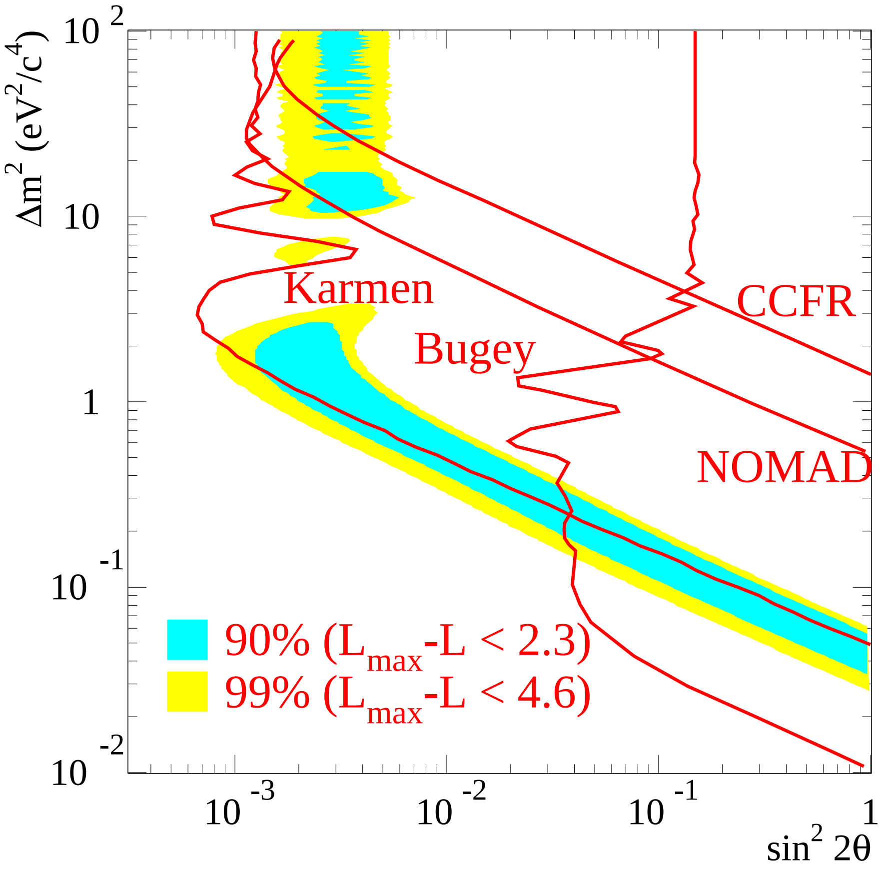
× $\mu \to e\nu_e\bar{\nu}_e$ ruled out (KARMEN, TWIST);

○ $3+1+1$ scheme works (finely tuned?);

○ 4 ν's CPTV

○ "heavy" decaying sterile neutrinos;

○ something completely different.



Karmen has a similar sensitivity to

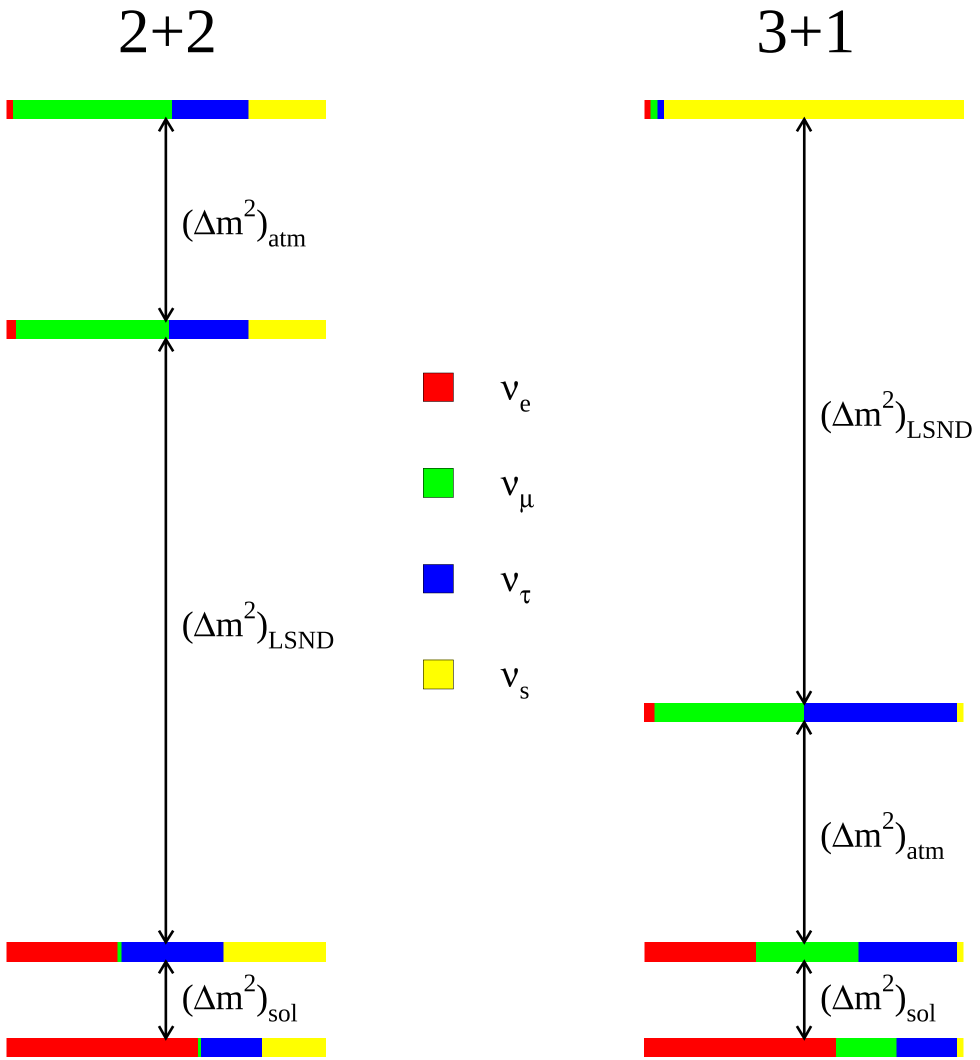
$\bar{\nu}_\mu \to \bar{\nu}_e$, but a shorter baseline ($L = 18$ m)

Other curves are failed searches for

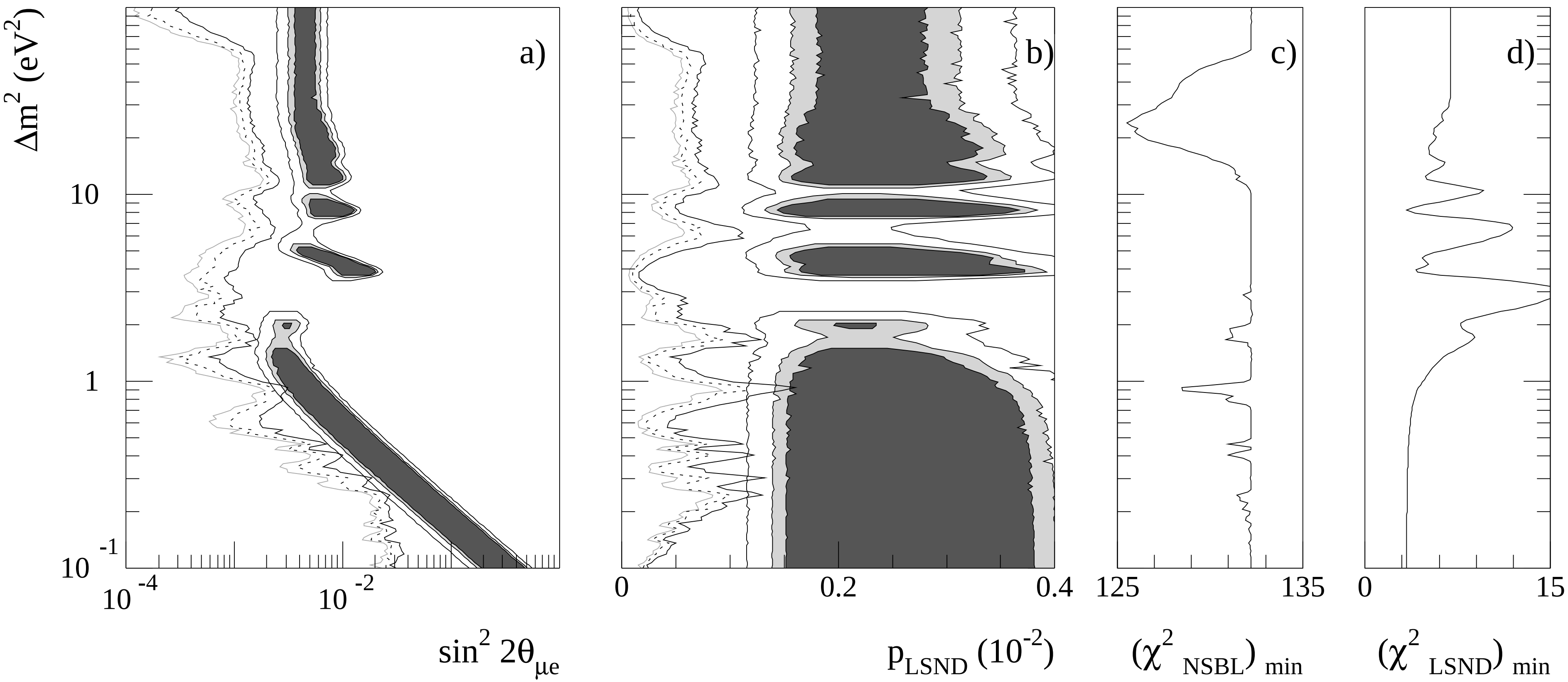
ν_μ disappearance (CCFR),

$\bar{\nu}_e$ disapperance (Bugey), etc

Remember: $P_{\mu e} = \sin^2 2\theta \sin^2 \left[1.27 \left(\frac{\Delta m^2}{\text{eV}^2}\right) \left(\frac{L}{\text{m}}\right) \left(\frac{\text{MeV}}{E}\right)\right]$



$\Rightarrow$ 2+2 requires large sterile effects in either solar or atmospheric oscillations, not observed

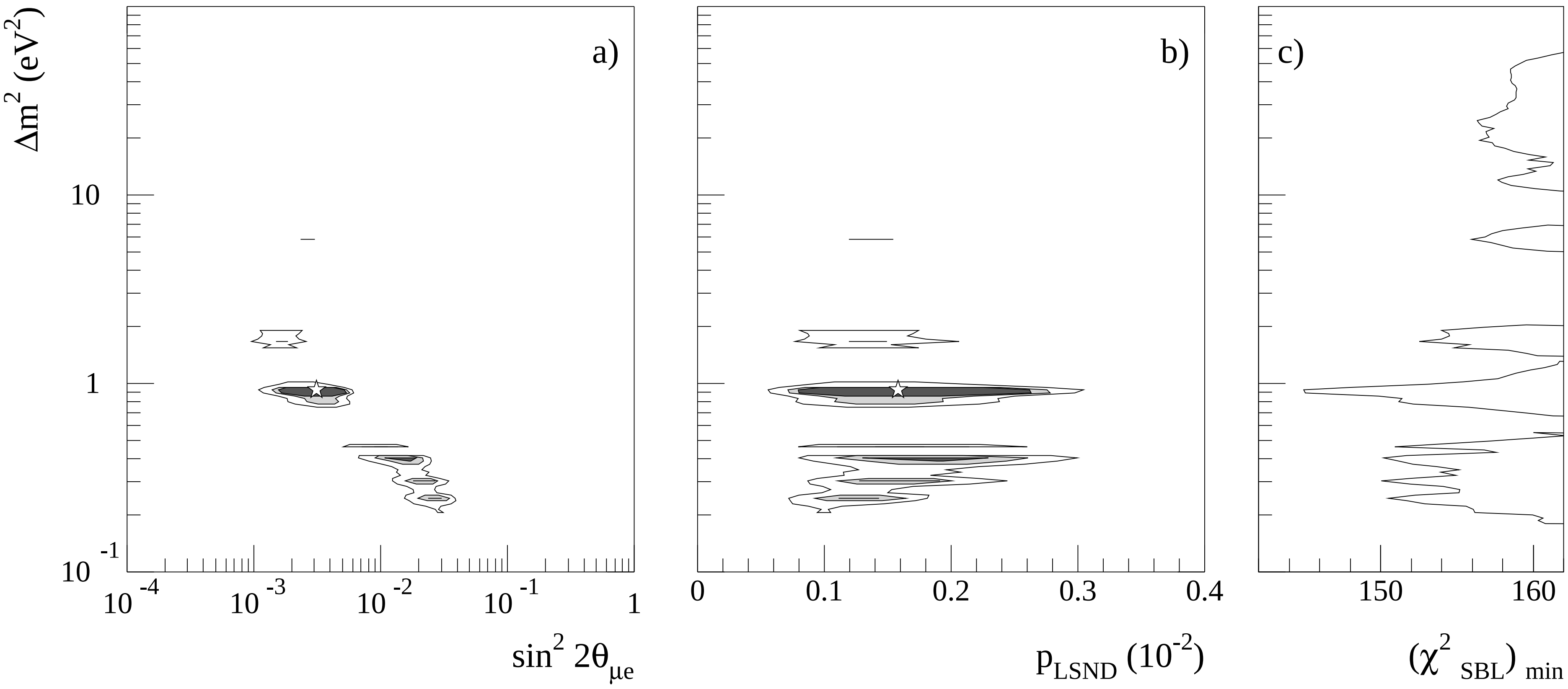


In 3+1, $\sin^2 2\theta_{\rm LSND} = \sin^2 2\theta_{\mu e} \simeq 4|U_{e4}|^2|U_{\mu 4}|^2$, while for

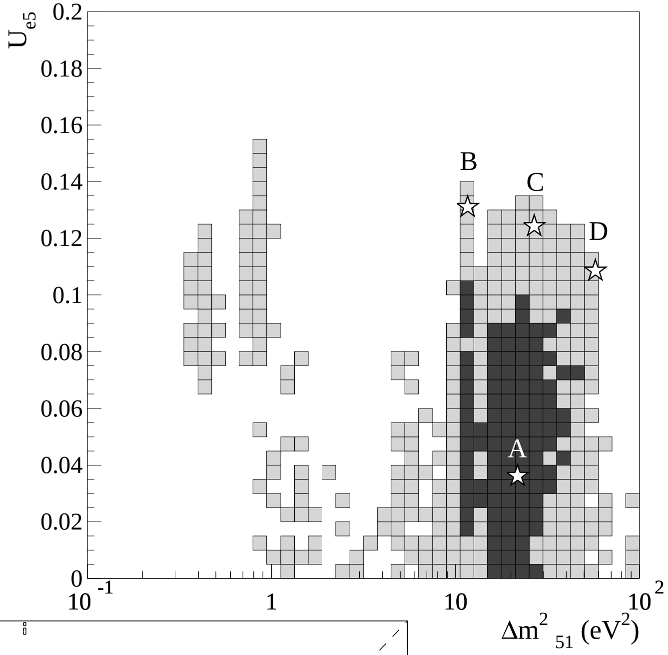
disappearance searches $\sin^2 2\theta_{\alpha\alpha} \simeq 4|U_{\alpha 4}|^2(1-|U_{\alpha 4}|^2)$.

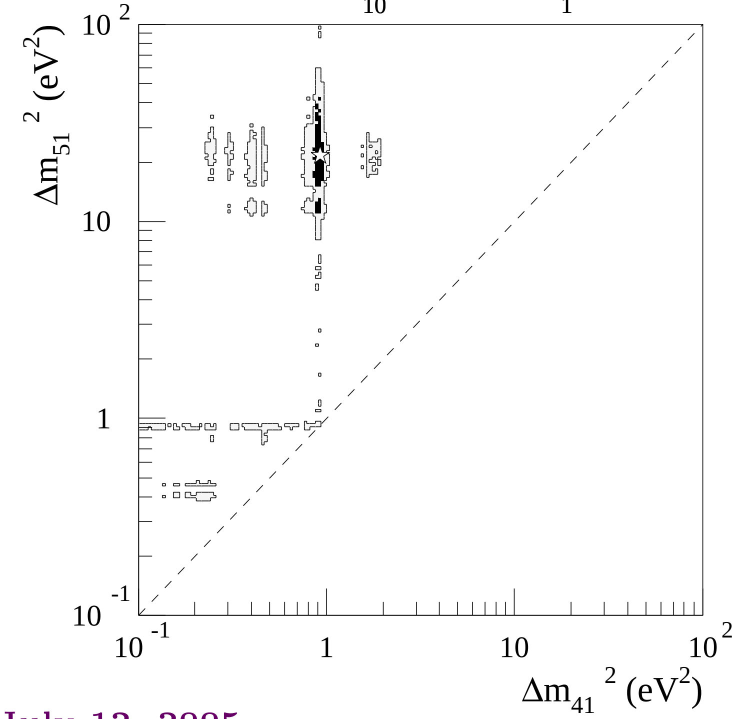
nontrivial constraints from short-baseline disappearance searches!. . .

...but one can still speak of a "best fit" region.



3+1+1 Fits Introduce an Extra Δm^2 and Effective Mixing Angle.

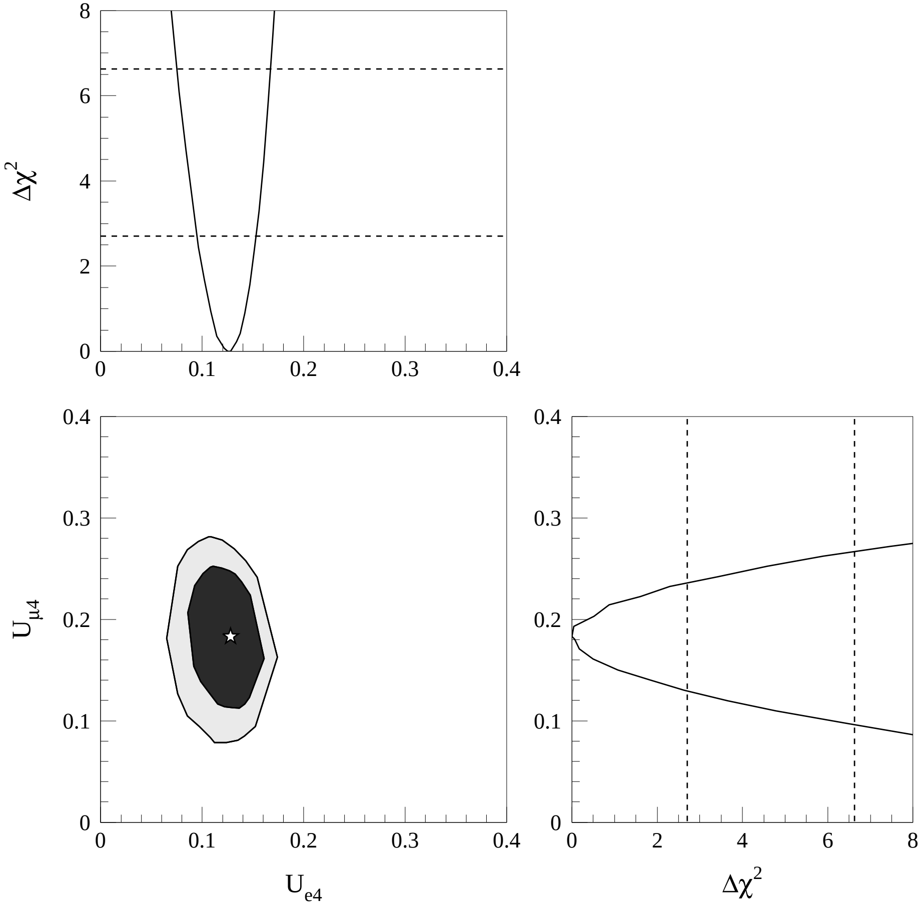


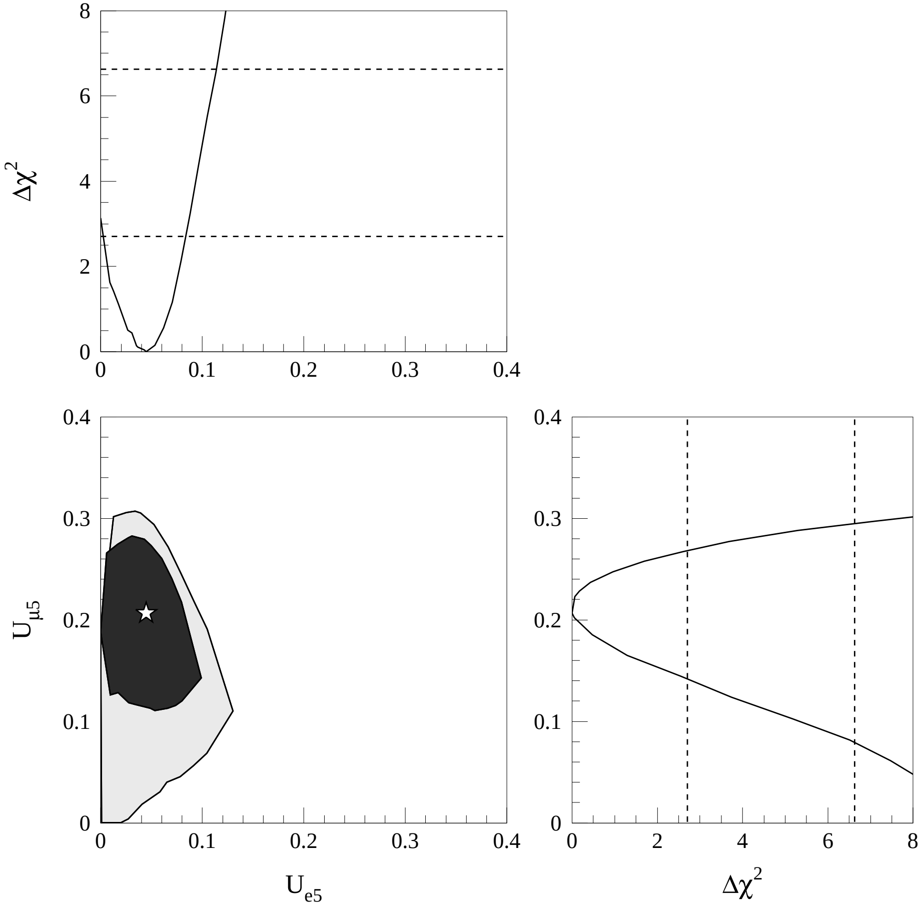


Can only be better than 3+1 fit (decoupling)

The fit works by "splitting" the constraints imposed by short baseline data between the two frequencies, whose effect add up at LSND.

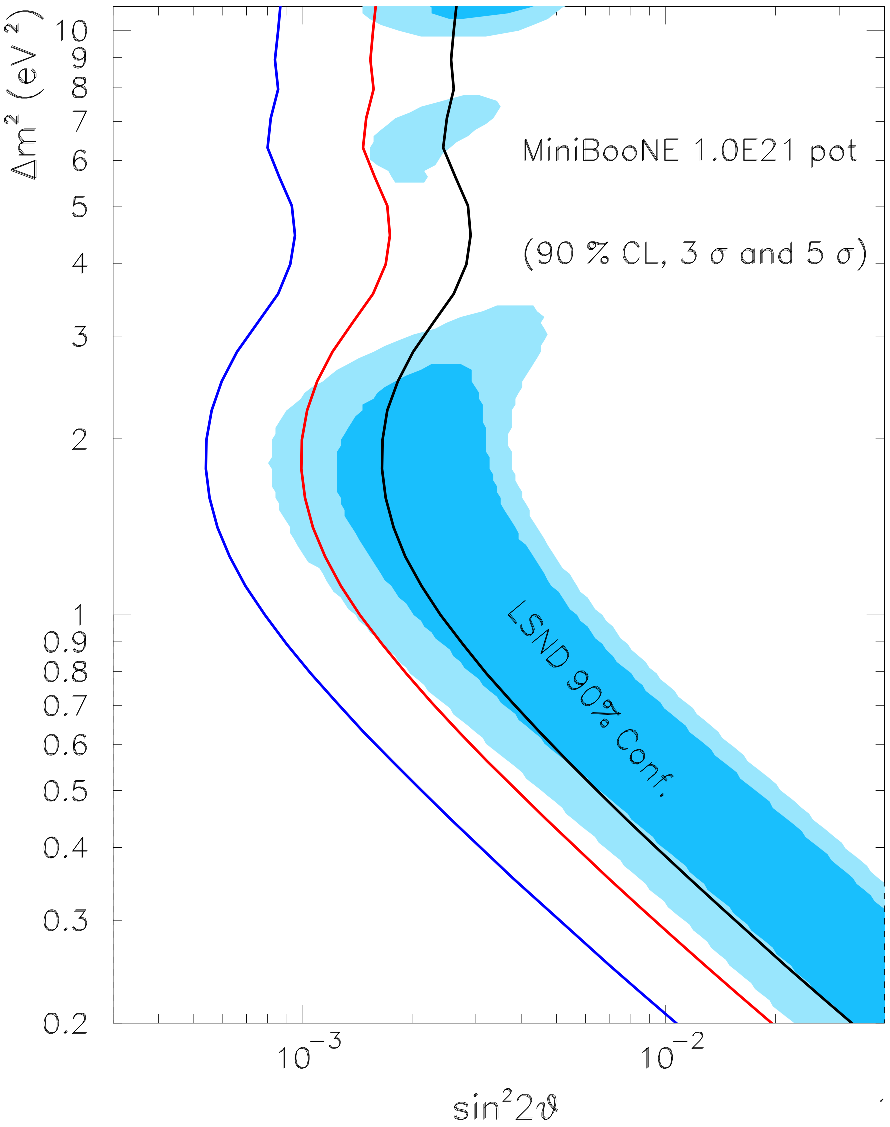
Is this "finely tuned"? In what sense?





[Courtesy of Michel Sorel]

LSND Anomaly to be resolved by the MiniBooNE experiment:



Ongoing experiment at Fermilab designed to definitively test the LSND anomaly with different beam and systematics.

LSND: $\mu^+ \to \bar{\nu}_\mu \to \bar{\nu}_e$

MiniBooNE: $\pi^+ \to \nu_\mu \to \nu_e$

Results expected by the end of 2005!

In summary, the best solution (my opinion) to the LSND anomaly we have been able to concoct is **3+2 neutrino oscillations** (or 3+3, 3+4, etc).

While a good fit can be obtained, it seems to be "taylor made." Why haven't LSND effects been observed in disappearance experiments?

There are many left-over theoretical complaints.

- What are these sterile neutrinos? [LEP data tell us there are only three light neutrinos that couple to the Z-boson...]
- Why are they so light? Sterile neutrinos are "theoretically expected" to be very heavy...
- Can we say anything about the expected sterile–active neutrino mixing? Can LSND oscillations be predicted?
- . . .

The main point I wish make is that the LSND anomaly provides the only experimental positive hint for a new neutrino physics scale. I'll take this seriously and use it to fix the mostly unknown seesaw energy scale:

$$\boxed{M \sim \sqrt{\Delta m^2_{\rm LSND}} \sim 1~\textbf{eV.}}$$

In return, an **eV-seesaw** naturally explains why there are sterile neutrino around 1 eV (and what they are). Solves two out of the three "theoretical complaints" in the previous slide.

More exciting, however, is that it turns out that the active sterile mixing angles are determined as a function of the "active" mixing angles, and the masses. $\Rightarrow$ falsifiable hypothesis!

The key property of $\mathcal{L}_\nu$ is that it **does not** lead, after EWSB, to the most general active–sterile mass-matrix:

$$\mathcal{M} = \begin{pmatrix} 0 & \mu^{\mathrm{T}} \\ \mu & M \end{pmatrix},$$ μ = Dirac mass matrix; $M = N_i$ Majorana mass matrix.

In the limit $\mu \ll M$ (the seesaw limit),

$$m_\nu^{\alpha\beta} = \sum_i \frac{\mu_{\alpha i}\mu_{\beta i}}{M_i} = \sum_i U_{\alpha i} U_{\beta i} m_i,$$

where U is the active neutrino mixing matrix (MNS matrix). In this case, it is easy to solve for μ in terms of active neutrino observables and M:

$$\mu_{\alpha i} = U_{\alpha i}\sqrt{M_i m_i}$$

Active–sterile mixing:

$$\langle\nu_\alpha|M_i\rangle \equiv \vartheta_{\alpha i} = \frac{\mu_{\alpha i}}{M_i} + O\left(\frac{\mu^2}{M^2}\right) = U_{\alpha i}\sqrt{\frac{m_i}{M_i}} + O\left(\frac{m}{M}\right),$$

such that, for example, $|U_{e4}|^2 = |U_{ej}|^2\frac{m_j}{M_j}$, where M_j is the lightest of the M_i.

(I'll talk about ν_4, ν_5 and ν_6, with masses, respectively, $m_4 < m_5 < m_6$. In the seesaw limit, $m_4 =$ lightest M_i, $m_5 =$ second lightest M_i and $m_6 =$ heaviest M_i, where $i = 1, 2, 3$. The i index refers to the position of M_i in $\mathcal{M}$)

Can this explain the LSND data?

Depends on the active neutrino mass hierarchy. It is easy to explore 3+1 schemes, which are obtained if some $M_i \sim 1$ eV, while the other two are large enough, say > 10 eV.

Normal hierarchy: $m_3^2 \sim \Delta m_{13}^2$, and

$$\sin^2 2\theta_{\rm LSND} = 4|U_{e3}|^2|U_{\mu 3}|^2\frac{\Delta m_{13}^2}{M_3^2} < 5\times 10^{-4} \qquad \rightarrow \text{too small}$$

For an inverted mass hieararchy $(m_1^2 \sim m_2^2 \sim \Delta m_{13}^2 \gg m_3^2)$

$$|U_{e4}|^2 \simeq 0.020\left(\frac{|U_{e2}|^2}{0.3}\right)\sqrt{\left(\frac{\Delta m_{13}^2}{3\times 10^{-3}~\rm eV^2}\frac{0.92~\rm eV^2}{M_2^2}\right)},$$

$$|U_{\mu 4}|^2 \simeq 0.024\left(\frac{|U_{\mu 2}|^2}{0.42}\right)\sqrt{\left(\frac{\Delta m_{13}^2}{3\times 10^{-3}~\rm eV^2}\frac{0.92~\rm eV^2}{M_2^2}\right)}.$$

$\rightarrow$ works quite well!

Finally, 3+2 or 3+3 solutions to LSND are generically expected in the eV-seesaw. For example, say $M_3 = 5$ eV, $M_2 = 1$ eV, $M_1 \sim 10$ eV (or larger) and the active neutrino masses are quasi-degenerate.

$$\Delta m^2_{15} \sim 25\ \mathrm{eV}^2,$$

$$\Delta m^2_{14} \sim 1\ \mathrm{eV}^2,$$

$$|U_{e4}|^2 \sim 0.02,\ |U_{\mu 4}|^2 \sim 0.03,$$

$$|U_{e5}|^2 \sim 0.001,\ |U_{\mu 5}|^2 \sim 0.01.$$

It Works!

Other predictions: **Tritium beta-decay**

Heavy neutrinos participate in tritium β-decay. Their contribution can be parameterized by

$$m_\beta^2 = \sum_{i=1}^{6} |U_{ei}|^2 m_i^2 \simeq \sum_{i=1}^{3} |U_{ei}|^2 m_i^2 + \sum_{i=1}^{3} |U_{ei}|^2 m_i M_i,$$

as long as M_i is not too heavy (above tens of eV). For example, in the 3+2 scenario of the previous slide, $m_\beta^2 \simeq 0.7~\text{eV}^2 \left(\frac{|U_{e1}|^2}{0.7}\right)\left(\frac{m_1}{0.1~\text{eV}}\right)\left(\frac{M_1}{10~\text{eV}}\right)$.

NOTE: next generation experiments will be sensitive to $O(10^{-1})$ eV^2.

Other predictions: **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.

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

Other predictions: **Supernova Neutrino Flavor Transitions**

In the environment of type-IIA supernovae, $\nu_a \to \nu_s$ or $\bar{\nu}_a \to \bar{\nu}_s$ transitions can be resonantly enhanced in the eV-seesaw.

The only information we have so far is from SN1987A. Unfortunately, theoretical uncertainties and low-statistics do not allow one to say very much...

$\Rightarrow$ very interesting effects are expected for the next galactic supernova explosion.

Other predictions: **Brief Comment on Early Universe Cosmology**

A combination of the SM of particle physics plus the "concordance cosmological model" severely constrain light, sterile neutrinos with significant active-sterile mixing. Main constraints from

- Big Bang Nucleosynthesis;
- Hot Dark Matter (Large Scale Structure plus CMB data).

If all is taken at face value, not only is the eV-seesaw ruled out, but so are all oscillation solutions to the LSND anomaly.

Hence, **eV-seesaw $\rightarrow$ nonstandard particle physics and cosmology**. There are plenty of examples of these in the literature (e.g., low reheat temperature, "late neutrino masses," etc).

Down-Sides

- No clear connection between the seesaw scale and other interesting energy scales (GUT scale, EWSB scale, etc). → Relationship to UV physics is more subtle. [in progress]
- We haven't "explained" why the neutrino masses are so small: $\lambda \sim 10^{-11}$ for $M \sim 1$ eV. → "More" new physics needed (flavor physics, UV connection?) [in progress]
- Traditional thermal leptogenesis does not work. → However, there are other CP-invariance violating phases. Any relation to baryon asymmetry of the Universe?
- ...

Summary, Conclusions

- The introduction of right-handed neutrinos renders the neutrinos massive. Furthermore, the introduction of the most general, renormalizable Lagrangian consistent with the enlarged field content and gauge invariance describes, after EWSB, six Majorana fermions.
- This seesaw Lagrangian contains several free parameters, which are to be determined from experiment. In particular, the seesaw energy scale M is only very poorly bound.
- Theoretical prejudice favors $M \gg$ EWSB scale. However, there is no concrete reason for M very large — **any value of M is "natural."** Remeber, the symmetry of the Lagrangian is enhanced when $M = 0$.
- The LSND anomaly may come to the rescue. It provides the only experimental evidence for a new physics scale, which happens to be around 1 electron-volt — is $M \sim 1$ eV?

The eV-seesaw is falsifiable, but not currently ruled out. It will be severely tested in the near future.

- Mini-BooNE has to see a signal, consistent with neutrino oscillations;
- Either the active neutrino mass hierarchy is inverted, or the active neutrino masses are quasi-degenerate;
- Effective neutrino mass probed by tritium β-decay is "large;"
- Neutrinos are Majorana fermions, but their contribution to neutrinoless double beta decay vanishes (very tricky to experimentally see "Majorananess" of the neutrinos);
- Strong active-sterile mixing of supernova neutrinos;
- Concordance cosmology is incomplete.

Finally, sterile–active, sterile–sterile neutrino mixing "non-generic" — strongly correlated to active–active mixing.