Probing the Seesaw Scale: From neV to MeV

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Outline

1. darkgreen Light Sterile Neutrinos – General Comments;
2. The SM Plus Gauge Singlet Fermions;
3. Goal: Making predictions, testing the model;
4. Low-Energy Seesaw.
5. $M \ll yv$ – Quasi-Dirac Neutrinos;

Sterile Neutrinos – General Comments

Here I'll concentrate on LIGHT sterile neutrinos ($M_{\nu_s} < 1$ MeV). Such states only interact with the SM via mixing with the active neutrinos we know and love.

People often talk about "sterile neutrinos." **Why?** There are many theoretical complaints related to light sterile neutrinos:

- Who ordered that? What are sterile neutrinos good for?
- Why would they be light? Sterile neutrinos are "theoretically expected" to be very heavy...
- If there are sterile neutrinos, can we say anything about their properties? Say, is the sterile–active neutrino mixing angle calculable? Are there preferred regions of the sterile neutrino parameter space?
- ...

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).

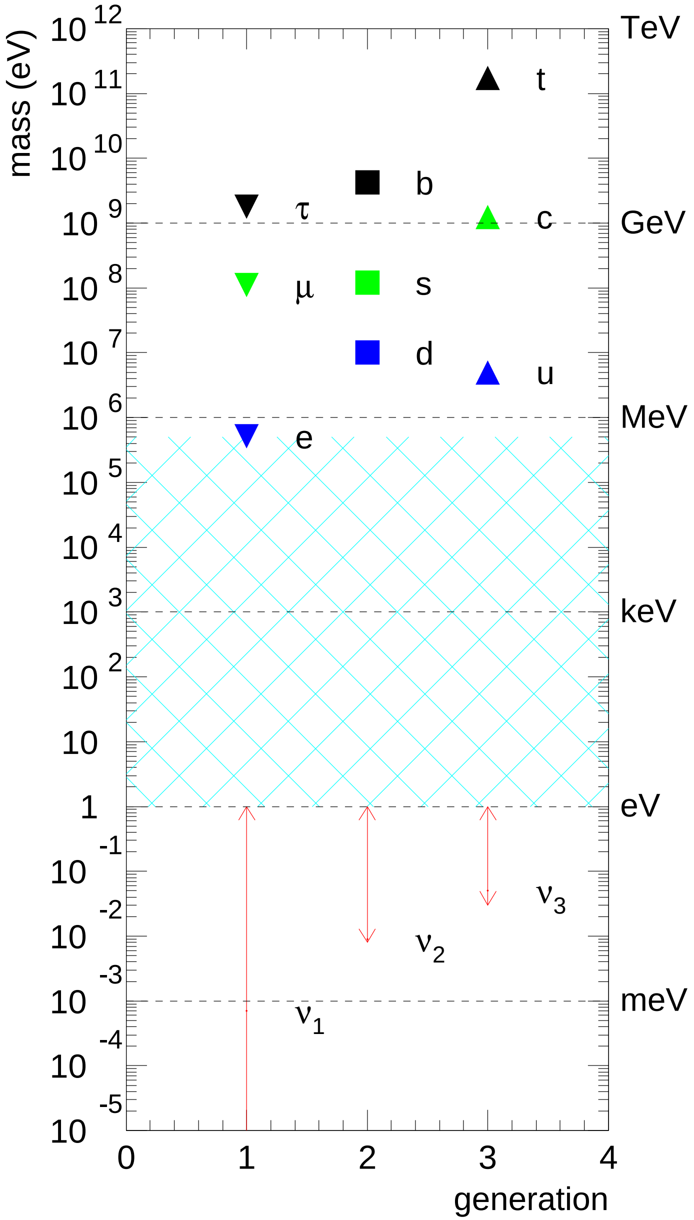
$\rightarrow$ Active–sterile neutrino mixing provides one of only two ways to communicate with gauge singlet fields that may be out there!

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



What We Are Trying To Understand:

⇐ **NEUTRINOS HAVE TINY MASSES**

⇓ **LEPTON MIXING IS "WEIRD"** ⇓

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & \mathbf{0.2} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

$\boxed{\text{What Does It Mean?}}$

What is the New Standard Model? [νSM]

The short answer is – WE DON'T KNOW. Not enough available info!

$$\Updownarrow$$

Equivalently, there are several completely different ways of addressing neutrino masses. The key issue is to understand what else the νSM candidates can do. [are they falsifiable?, are they "simple"?, do they address other outstanding problems in physics?, etc]

We need more experimental input, and it looks like it may be coming in the near/intermediate future!

νSM – One Possibility

SM as an effective field theory – non-renormalizable operators

$$\mathcal{L}_{\nu\mathrm{SM}} \supset -y_{ij}\frac{L^i H L^j H}{2\Lambda} + \mathcal{O}\left(\frac{1}{\Lambda^2}\right) + H.c.$$

There is only one dimension five operator [Weinberg, 1979]. If $\Lambda \gg 1$ TeV, it leads to only one observable consequence...

$$\text{after EWSB } \mathcal{L}_{\nu\mathrm{SM}} \supset \frac{m_{ij}}{2}\nu^i\nu^j; \quad m_{ij} = y_{ij}\frac{v^2}{\Lambda}.$$

- Neutrino masses are small: $\Lambda \gg v \to m_\nu \ll m_f$ ($f = e, \mu, u, d$, etc)
- Neutrinos are Majorana fermions – Lepton number is violated!
- νSM effective theory – not valid for energies above at most Λ.
- What is Λ? First naive guess is that Λ is the Planck scale – does not work. Data require $\Lambda \sim 10^{14}$ GeV (related to GUT scale?) [note $y^{\max} \equiv 1$]

What else is this "good for"? Depends on the ultraviolet completion!

The “Seesaw” Lagrangian

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.

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 (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 larger than 10^9 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 $m_{\alpha\beta} = \sum_i \mu_{\alpha i} M_i^{-1} \mu_{\beta i}$ $[m \propto 1/\Lambda \;\Rightarrow\; \Lambda = M/\mu^2]$.

  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).

Why are Neutrino Masses Small?

If $\mu \ll M$, below the mass scale M,

$$\mathcal{L}_5 = \frac{LHLH}{\Lambda}.$$

Neutrino masses are small if $\Lambda \gg \langle H \rangle$. Data require $\Lambda \sim 10^{14}$ GeV.

In the case of the seesaw,

$$\Lambda \sim \frac{M}{\lambda^2},$$

so neutrino masses are small if either

- they are generated by physics at a very high energy scale $M \gg v$ (high-energy seesaw); or
- they arise out of a very weak coupling between the SM and a new, hidden sector (low-energy seesaw); or
- cancellations among different contributions render neutrino masses small (symmetries, or accidents).

Low-Energy Seesaw ($M \gg \mu$) [AdG PRD72,033005)]

The other end of the M spectrum ($M < 1$ MeV). What do we get?

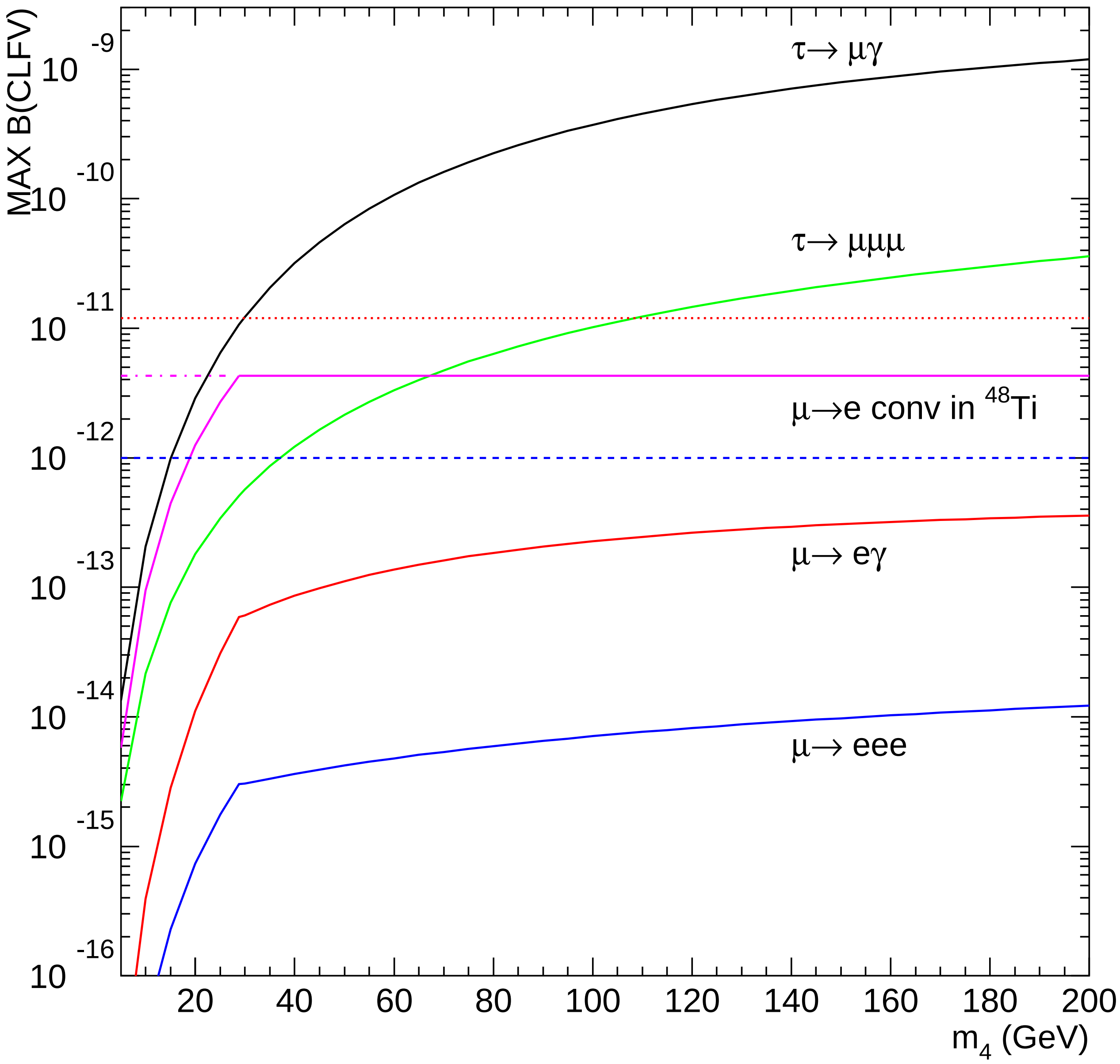
- Neutrino masses are small because the Yukawa couplings are very small $\lambda \in [10^{-8}, 10^{-11}]$;
- No standard thermal leptogenesis – right-handed neutrinos way too light;
- No obvious connection with other energy scales (EWSB, GUTs, etc);
- Right-handed neutrinos are propagating degrees of freedom. They look like sterile neutrinos $\Rightarrow$ sterile neutrinos associated with the fact that the active neutrinos have mass;
- sterile–active mixing can be predicted – hypothesis is falsifiable!
- Small values of M are natural (in the 'tHooft sense). In fact, theoretically, no value of M should be discriminated against!

Most Relevant for this Meeting:

Most of the constraints we heard about yesterdat do not apply at all!

- No large $\mu \to e\gamma$ – sterile neutrinos too light!
- No large effects in meson decays, muon decays, Z-boson decays – sterile neutrinos too light!
- "Only" manifest themselves in neutrinos!

e.g.: SeeSaw Mechanism [minus "Theoretical Prejudice"]



arXiv:0706.1732 [hep-ph]

More Details, assuming three right-handed neutrinos N:

$$m_\nu = \begin{pmatrix} 0 & \lambda v \\ (\lambda v)^t & M \end{pmatrix},$$

M is diagonal, and all its eigenvalues are real and positive. The charged lepton mass matrix also diagonal, real, and positive.

To leading order in $(\lambda v)M^{-1}$, the three lightest neutrino mass eigenvalues are given by the eigenvalues of

$$m_a = \lambda v M^{-1}(\lambda v)^t,$$

where m_a is the mostly active neutrino mass matrix, while the heavy sterile neutrino masses coincide with the eigenvalues of M.

6×6 mixing matrix U $[U^t m_\nu U = \text{diag}(m_1, m_2, m_3, m_4, m_5, m_6)]$ is

$$U = \begin{pmatrix} V & \Theta \\ -\Theta^\dagger V & 1_{n\times n} \end{pmatrix},$$

where V is the active neutrino mixing matrix (MNS matrix)

$$V^t m_a V = \text{diag}(m_1, m_2, m_3),$$

and the matrix that governs active–sterile mixing is

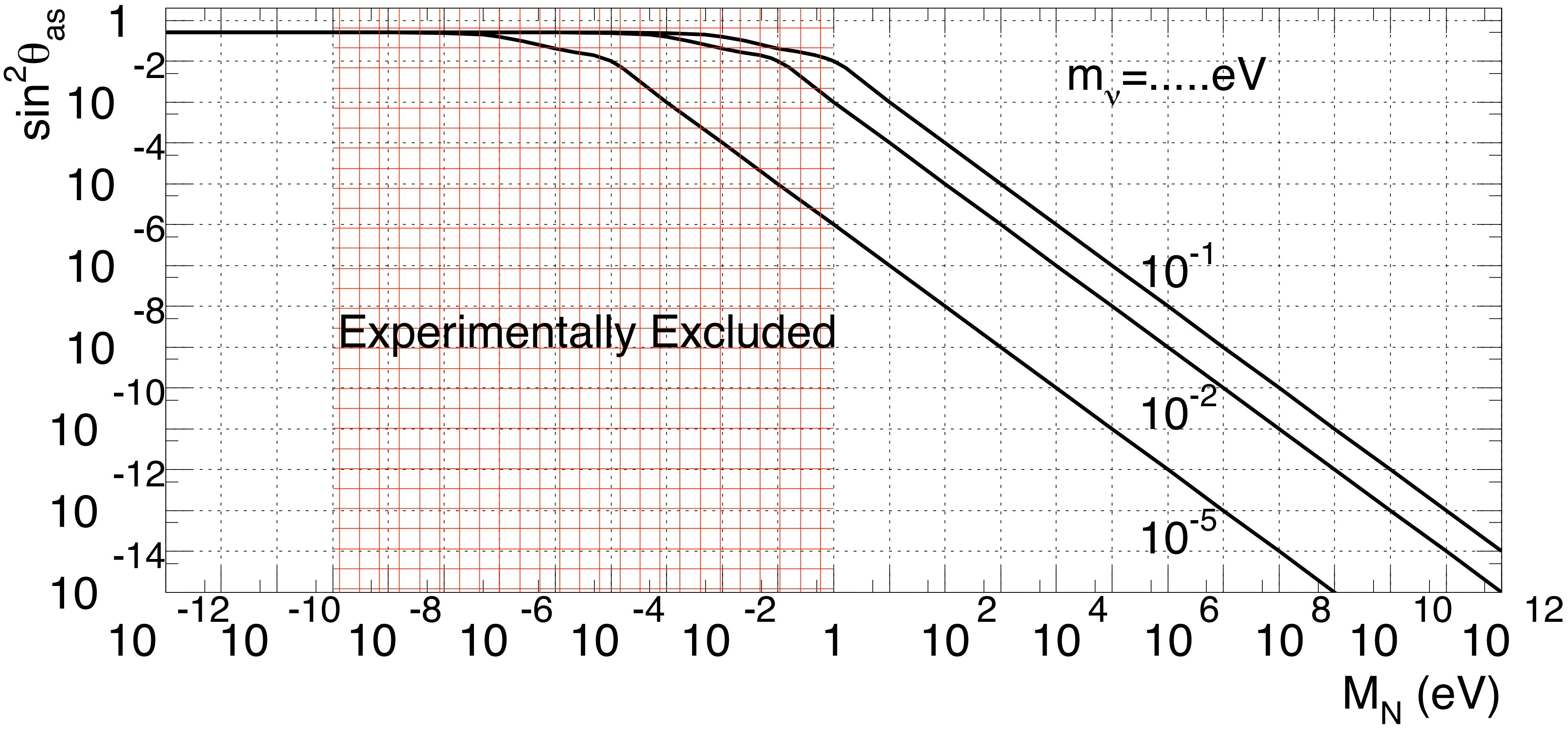
$$\Theta = (\lambda v)^* M^{-1}.$$

One can solve for the Yukawa couplings and re-express

$$\Theta = V \sqrt{\text{diag}(m_1, m_2, m_3)} R^\dagger M^{-1/2},$$

where R is a complex orthogonal matrix $RR^t = 1$.

Constraining the Seesaw Lagrangian



[AdG, Huang, Jenkins, arXiv:0906.1611]

Prediction for low-energy seesaw: **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

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

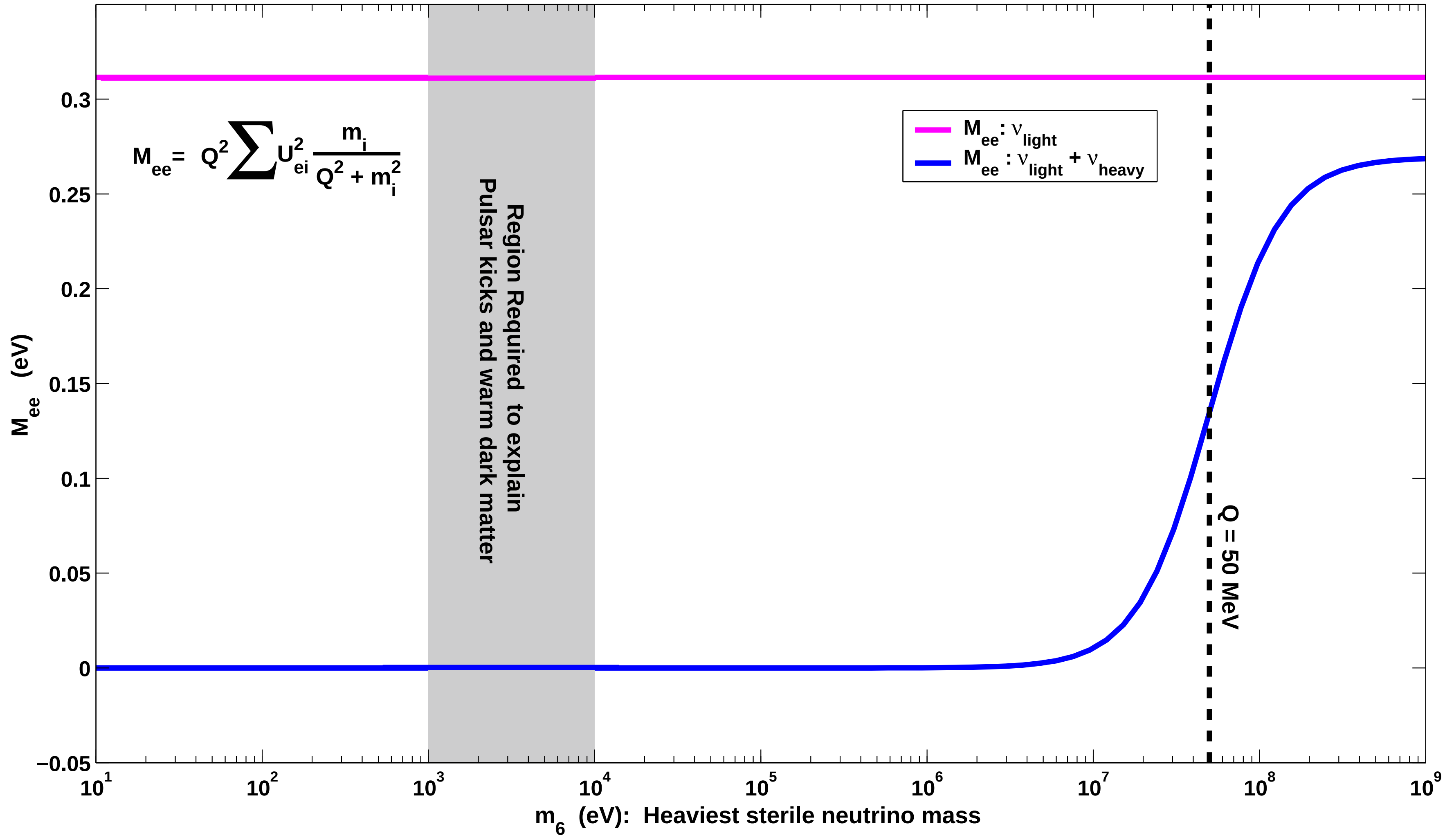
However, upon further examination, $m_{ee} = 0$ in the eV-seesaw. **The contribution of light and heavy neutrinos exactly cancels!** This seems to remain true to a good approximation as long as $M_i \ll 1$ MeV.

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

[AdG PRD 72, 033005 (2005)]

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

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



Other predictions: **Tritium beta-decay**

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

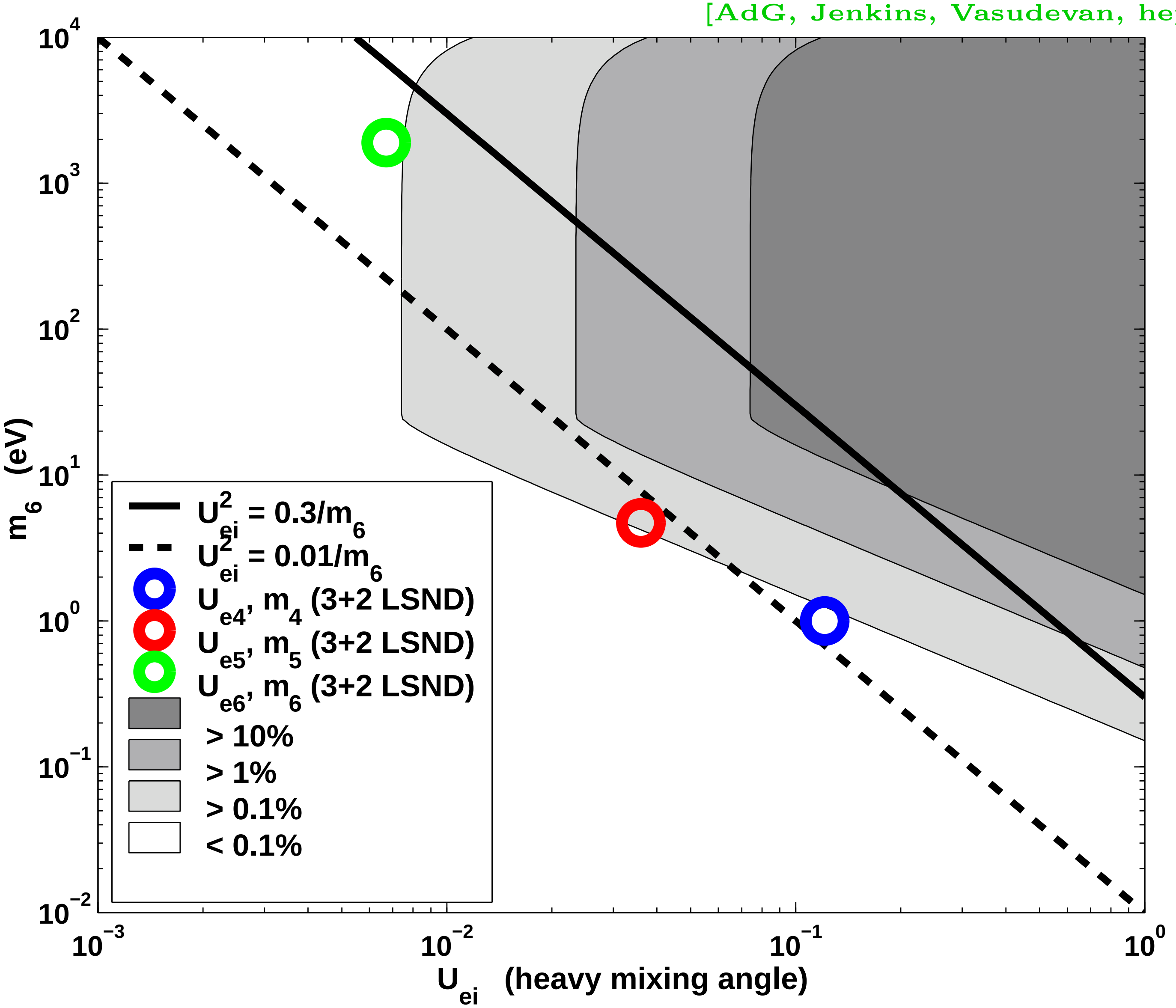
$$m_\beta^2 = \sum_{i=1}^{6} |U_{ei}|^2 m_i^2 \simeq \sum_{i=1}^{3} |U_{ei}|^2 m_i^2 + \sum_{i=1}^{3} |U_{ei}|^2 m_i M_i,$$

as long as M_i is not too heavy (above tens of eV). For example, in the case of a 3+2 solution to the LSND anomaly, the heaviest sterile state (with mass M_1) contributes the most: $m_\beta^2 \simeq 0.7~\text{eV}^2 \left(\frac{|U_{e1}|^2}{0.7}\right) \left(\frac{m_1}{0.1~\text{eV}}\right) \left(\frac{M_1}{10~\text{eV}}\right)$.

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

sensitivity of tritium beta decay to seesaw sterile neutrinos

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



On Early Universe Cosmology / Astrophysics

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

eV-seesaw → nonstandard particle physics and cosmology.

On the other hand...

- Right-handed neutrinos may make good warm dark matter particles.

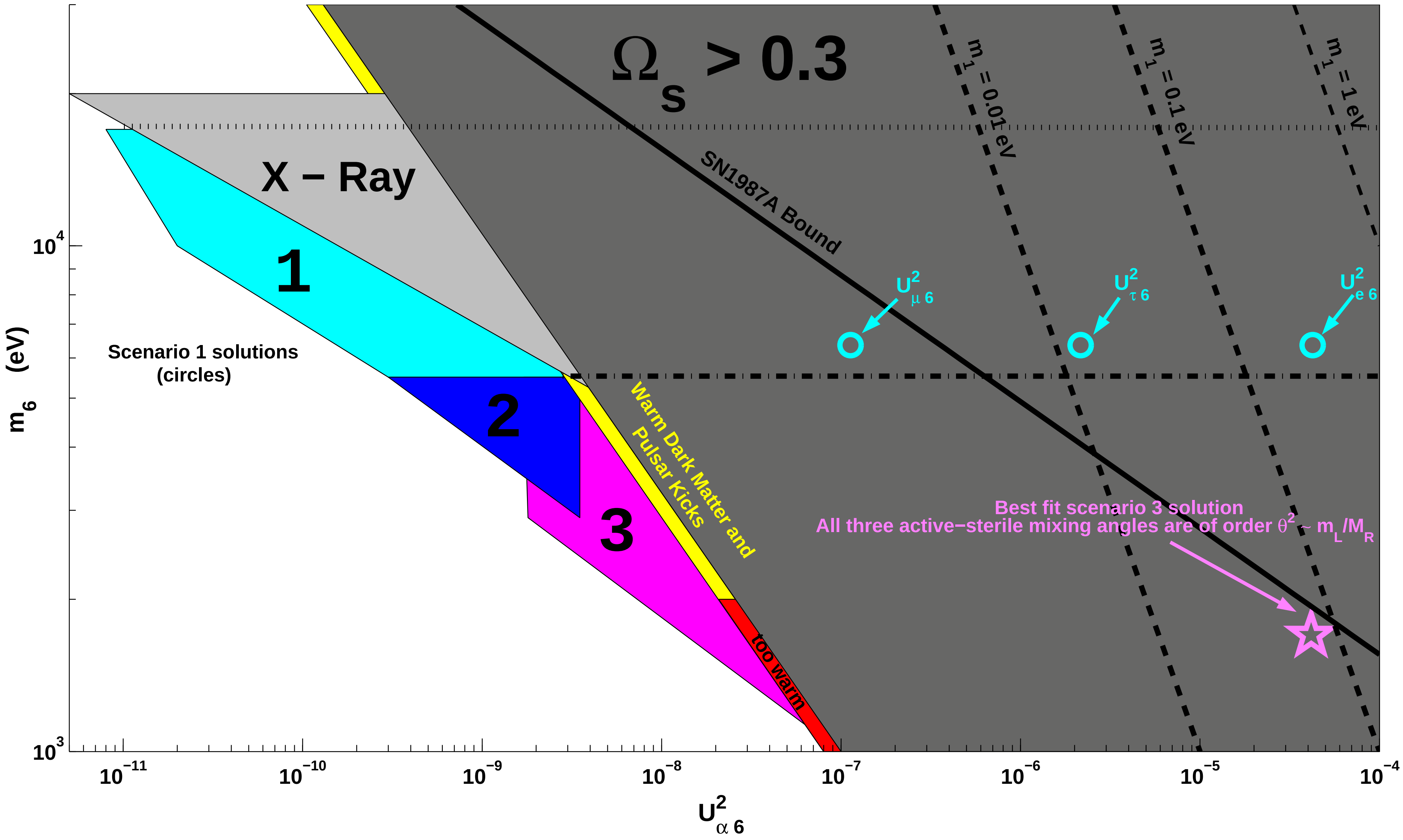
  Asaka, Blanchet, Shaposhnikov, hep-ph/0503065.

- Sterile neutrinos are known to help out with r-process nucleosynthesis in supernovae, ...

- ...and may help explain the peculiar peculiar velocities of pulsars.

On Astrophysical / Cosmological Bounds

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



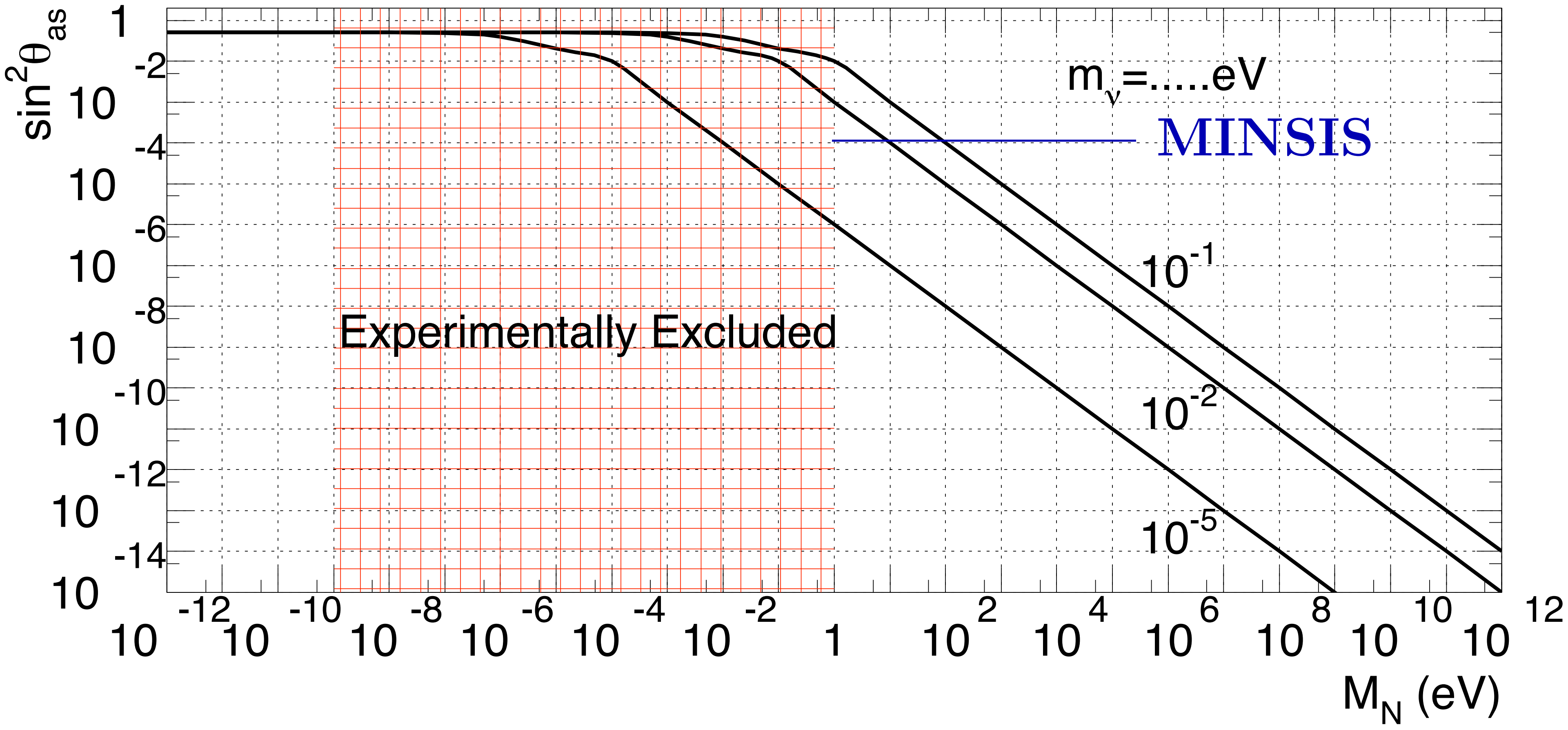
Other predictions: **Supernova Neutrino Flavor Transitions**

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.

MINSIS – Can we improve our sensitivity?



[AdG, Huang, Jenkins, arXiv:0906.1611]

Quick comment: model independent constraints?

Constraints depend, unfortunately, on m_i and M_i and R. E.g.,

$$U_{e4} = U_{e1} A \sqrt{\frac{m_1}{m_4}} + U_{e2} B \sqrt{\frac{m_2}{m_4}} + U_{e3} C \sqrt{\frac{m_3}{m_4}},$$

$$U_{\mu 4} = U_{\mu 1} A \sqrt{\frac{m_1}{m_4}} + U_{\mu 2} B \sqrt{\frac{m_2}{m_4}} + U_{\mu 3} C \sqrt{\frac{m_3}{m_4}},$$

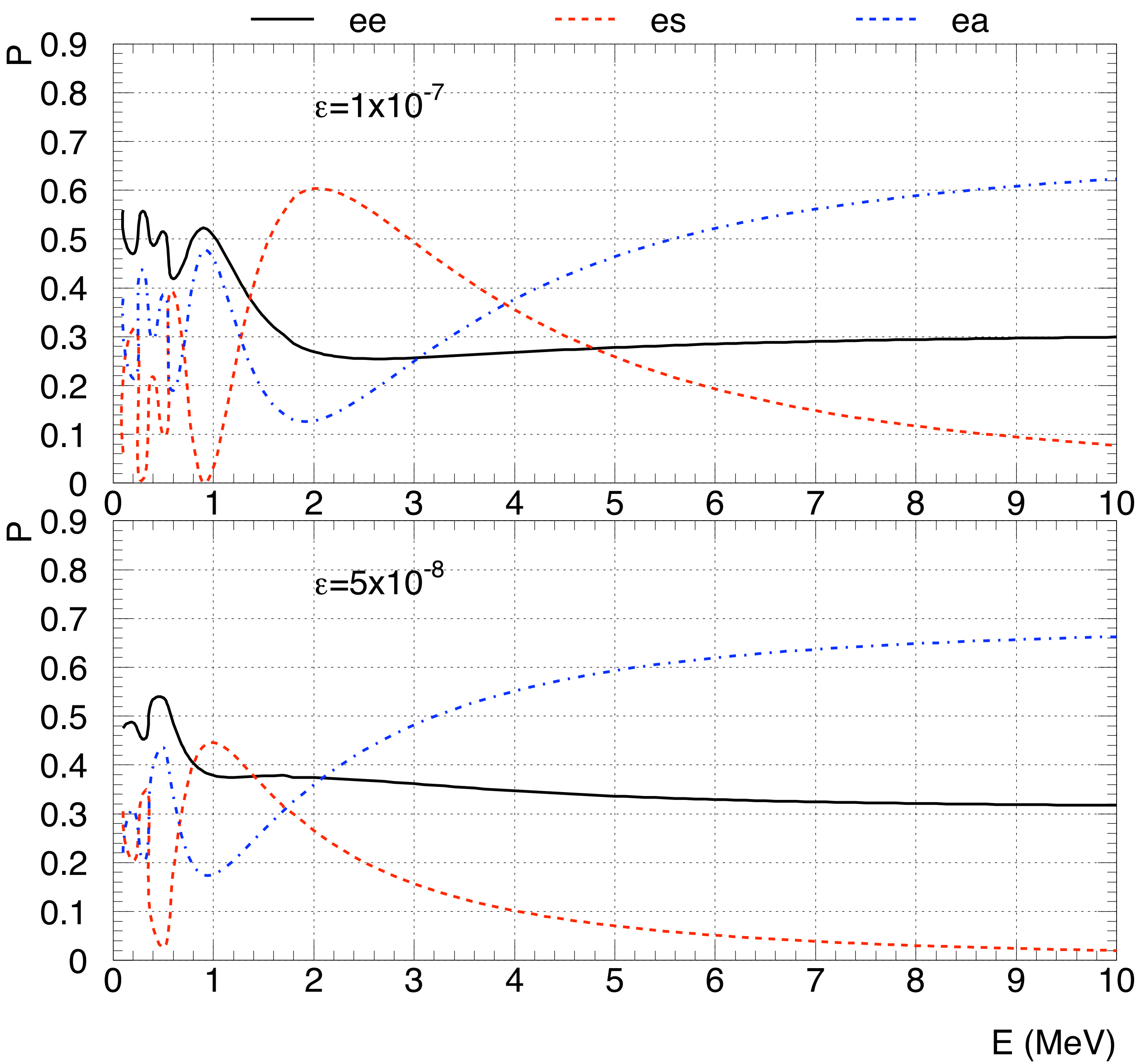
$$U_{\tau 4} = U_{\tau 1} A \sqrt{\frac{m_1}{m_4}} + U_{\tau 2} B \sqrt{\frac{m_2}{m_4}} + U_{\tau 3} C \sqrt{\frac{m_3}{m_4}},$$

where

$$A^2 + B^2 + C^2 = 1.$$

One can pick A, B, C such that two of these vanish. But the other one is maximized, along with $U_{\alpha 5}$ and $U_{\alpha 6}$.

Hope on (a) constraining the seesaw scale with combined bounds on $U_{\alpha 4}$ and (b) testing the low energy seesaw if nonzero $U_{\alpha 4}$ are discovered? $\rightarrow$ I don't know!

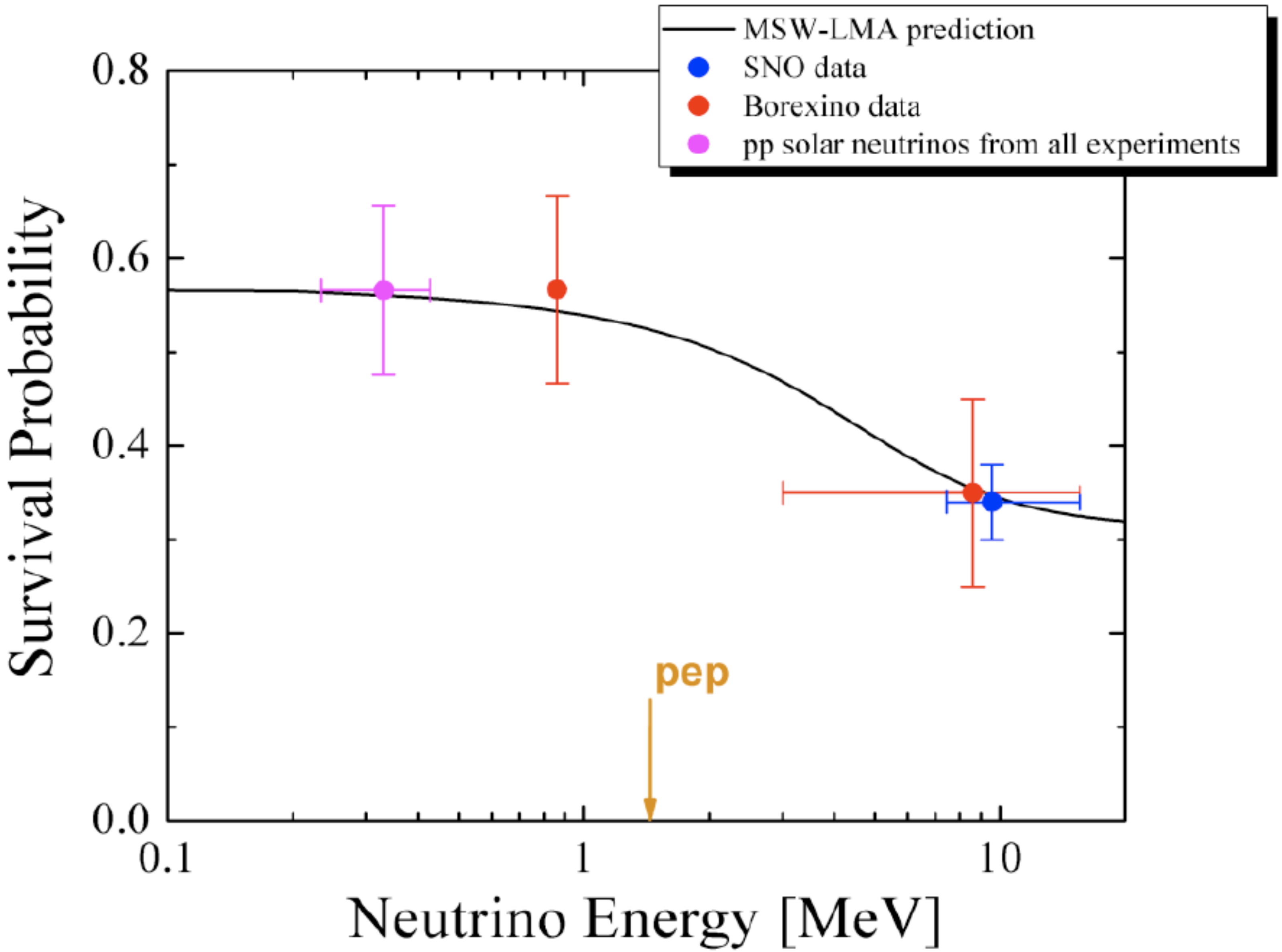


Quasi-Sterile Neutrinos

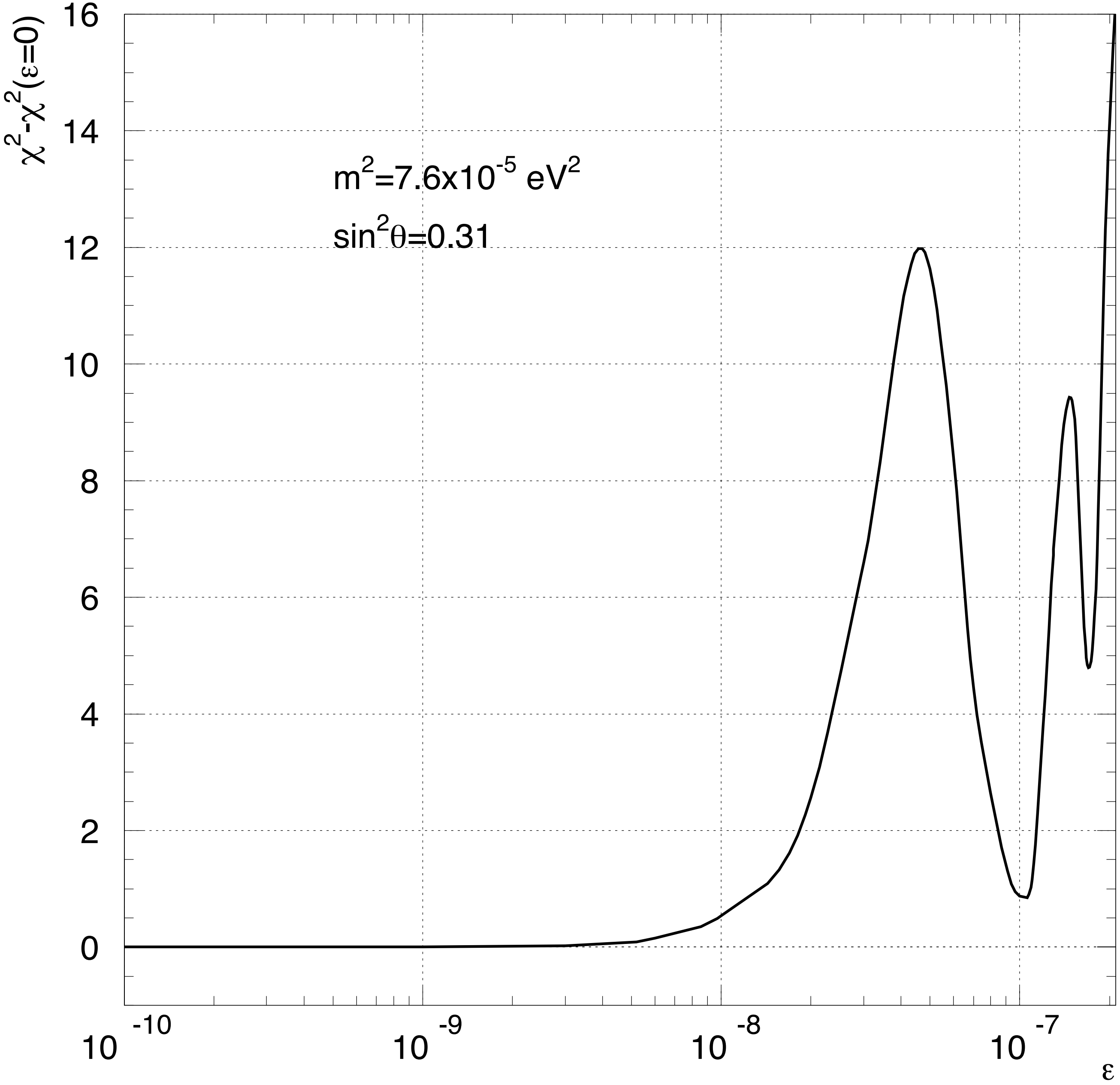
- tiny new $\Delta m^2 = \epsilon \Delta m^2_{12}$,
- maximal mixing!
- Effects in Solar νs

[AdG, Huang, Jenkins, arXiv:0906.1611]

(Almost) All We Know About Solar Neutrinos



2+1 Case



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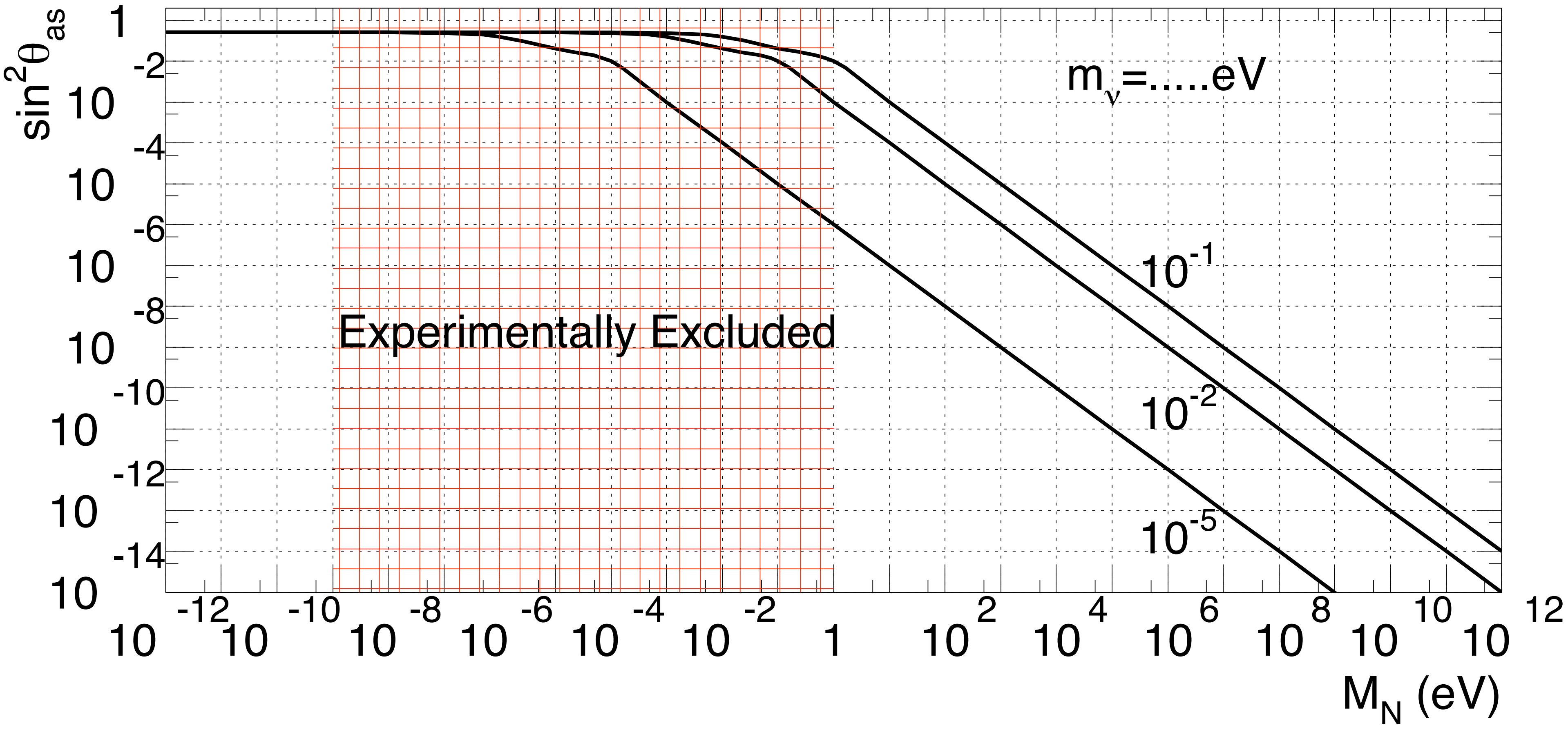

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