Constraining sterile neutrinos with AMANDA and IceCube atmospheric neutrino data

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In collaboration with F. Halzen and Arman Esmaili-
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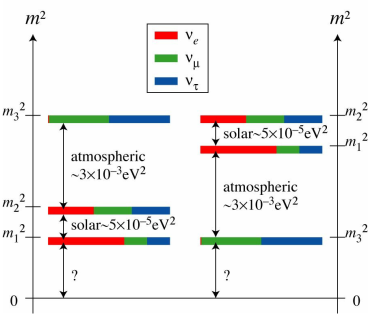
Standard scenario for neutrino oscillations

- Most (all data) can be understand if we assume that Neutrino flavor states are linear combination of mass eigenstates. a Mixing matrix, named Pontecorvo, Maki-Nakagawa-Sakata (PMNS).
  For 3 flavor neutrinos we have a 3 $\times$ 3 matrix,

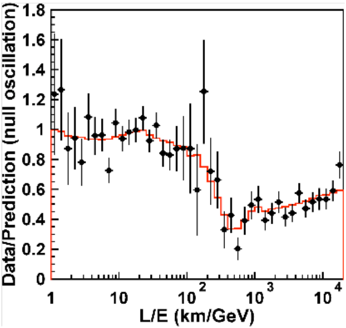
$$|\nu_\alpha\rangle = \sum^{n} U^*_{\alpha i}|\nu_i\rangle \qquad \mathbf{U}_{\mathrm{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$



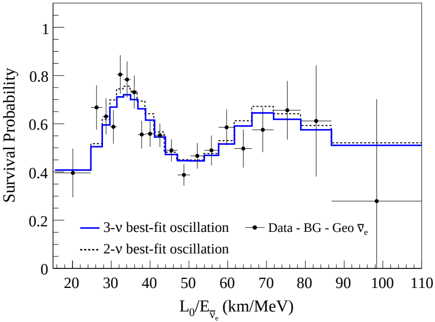
Standard scenario for neutrino oscillations

- In different experiments, it was proved that neutrinos oscillate,

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2}{(\mathrm{eV})^2}\frac{\mathrm{L/Km}}{\mathrm{E/GeV}}\right)$$



(a) SK ν_μ data



(b) KamLand $\bar{\nu}_e$ data

$$\Delta M^2 = 2.5\,10^{-3}\mathrm{eV}^2 \qquad \Delta m^2 = 7.5\,10^{-5}\mathrm{eV}^2$$

Sterile neutrino phenomenology

- Recently, there are a few anomalies that did not fit in the standard view of three light neutrinos:
  LSND anomaly and related [1]
  The reactor neutrino anomaly [2]
  The Gallium anomaly
  The Dark radiation
  The absence of up-turn in solar neutrino data

[1] See talk by Aguilar-Arevalo (Th4)
[2] See the talk by Thierry Lasserre at this conference

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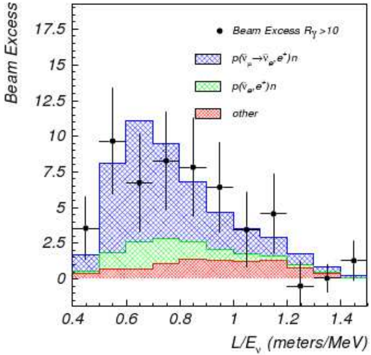
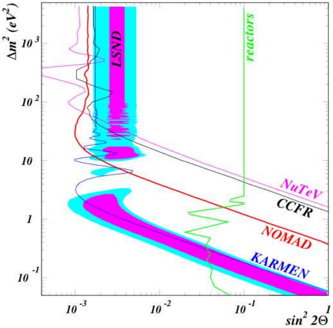
- LSND experiment (2001)[1]: $\bar{\nu}_\mu \to \bar{\nu}_e$ L $\sim$ 30m $E_\nu \sim 20 - 200$ MeV



(c)



(d)

$$\Delta m^2_{LSND} \sim 1 \text{ eV}^2 \gtrsim \Delta m^2_{21}, \Delta m^2_{31}$$
$$\Delta m^2_{21} = 2.5 \times 10^{-3} \text{ eV}^2, \Delta m^2_{31} = 7 \times 10^{-5} \text{ eV}^2$$

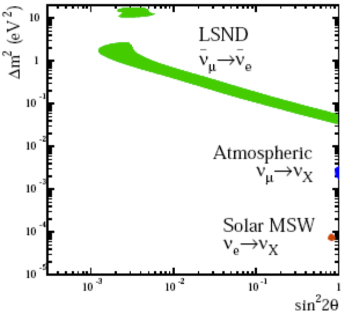
[1] LSND, PRD 64 (2001) 112007, hep-ex/0104049]

Sterile neutrino phenomenology

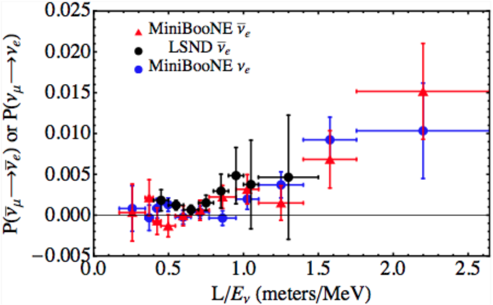
- to explain LSND experiment require: $\frac{L}{E_\nu} \sim \frac{1m}{MeV} \sim \frac{1Km}{GeV}$ that it is not compatible with the results from other oscillation experiment : $\frac{L}{E_\nu} >\sim \frac{10^3 Km}{GeV}$.

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2}{(\mathrm{eV})^2}\frac{\mathrm{L/Km}}{\mathrm{E/GeV}}\right)$$

A possible explanation is to have $\Delta m^2_{LSND} \sim$ 1eV ^{2}



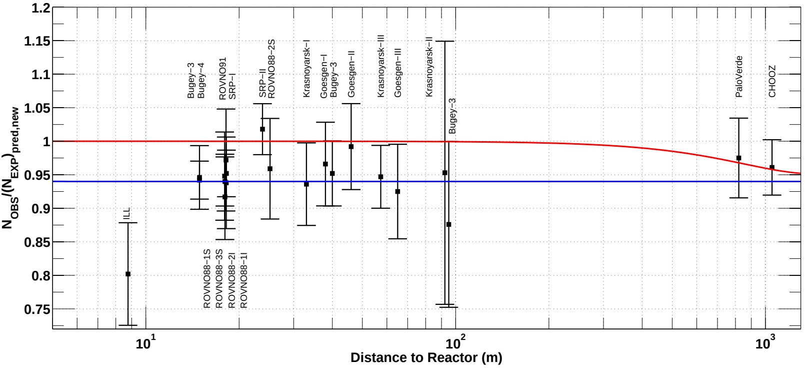
- A new generation experiment MINI-BOONE [1] was designed to test the LSND result If we compare the probabilities of three experiments: LSND, Mini-Boone neutrino and Mini-Boone anti-neutrino (the three have the same L/E_ν but different L and different E_ν.)



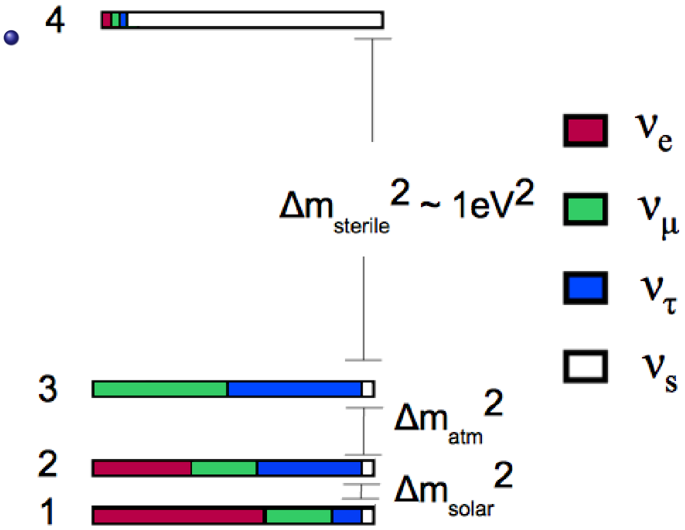
[1] See talk by Aguilar-Arevalo (Th4)

Sterile neutrino phenomenology

- Reactor $\bar{\nu}_e$ anomaly:
  Recent reevaluation of expected reactor $\bar{\nu}_e$ flux is 3.5% higher than previous prediction: Mueller et al. arXiv:1101.2663, confirmed by P. Huber arXiv:1106.0687.
- Reactor anomaly: With new fluxes there is a deficit of $\bar{\nu}_e$



Framework: 3+1 model



Framework: 3+1 model

- The mixing matrix for the 3+1 mass scheme

$$\mathbf{U}_{\mathrm{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & \boxed{U_{e3}} & \boxed{U_{e4}} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \boxed{U_{\mu 4}} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \boxed{U_{\tau 4}} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

for disapparence channel, P($\nu_\alpha \to \nu_\alpha$) we did not see neutrino oscillation and a very small signal for appearence channel: P($\nu_\mu \to \nu_e$)

The 3+1 properties

For very short baselines, we can write down the survival probability as

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2(2\theta_{\alpha\alpha}) sin^2\left(1.27 \frac{\Delta m^2}{(\mathrm{eV})^2} \frac{\mathrm{L/Km}}{\mathrm{E/GeV}}\right)$$

where $\sin^2(2\theta_{\alpha\alpha}) = 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)$
and the conversion probability as

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta_{\alpha\beta}) sin^2\left(1.27 \frac{\Delta m^2}{(\mathrm{eV})^2} \frac{\mathrm{L/Km}}{\mathrm{E/GeV}}\right)$$

where $\sin^2(2\theta_{\alpha\beta}) = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2$

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The 3+1 properties

From $\sin^2(2\theta_{\alpha\alpha}) = 4|U_{\alpha 4}|^2(1-|U_{\alpha 4}|^2)$ and $\sin^2(2\theta_{\alpha\beta}) = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2$ and because all parameters $|U_{\alpha 4}|^2$ are small, we can write down $\sin^2(2\theta_{\mu\mu}) \sim 4|U_{\mu 4}|^2$, and $\sin^2(2\theta_{\mu e}) = 4|U_{\mu 4}|^2|U_{e4}|^2$.
This allow us to relate the survival amplitude with the conversion amplitude [1]:

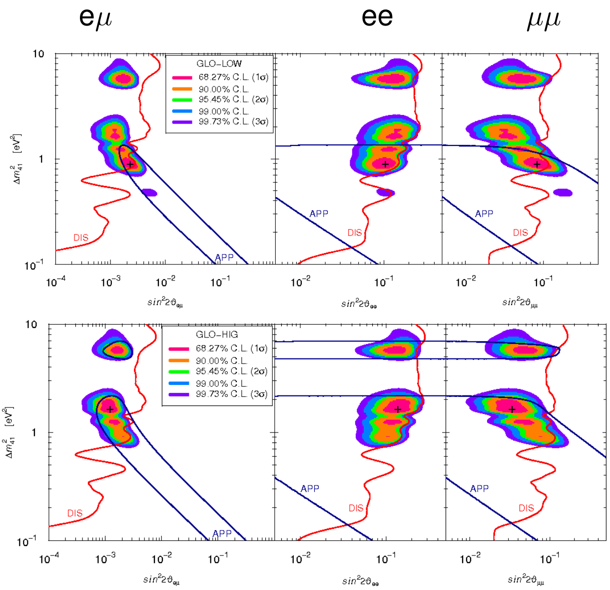
$$\sin^2(2\theta_{\mu e}) = \frac{1}{4}\sin^2(2\theta_{\mu\mu})\sin^2(2\theta_{ee})$$

To have a sizeable $\sin^2(2\theta_{\mu e})$ we should also have sizeable $\sin^2(2\theta_{\mu\mu}), \sin^2(2\theta_{ee})$. if we assume that $\sin^2(2\theta_{\mu\mu}) \sim \sin^2(2\theta_{ee}) \sim \epsilon^2$, where ϵ is a small parameter then

$$\sin^2(2\theta_{\mu e}) \sim \epsilon^4/4 << 1!!$$

[1] O. L. G. P. and A. Y. .Smirnov, Nucl. Phys. B **599**, 3 (2001) [hep-ph/0011054].

Combined analysis of sterile 3+1 scenario



3+1 summary

• A 3+1 scenario in principle can fit now both LSND and MINI-BOONE neutrino e anti-neutrino.

• Still the model have problems coinciling the disappearence constrains and appearence signal: $\sin^2(2\theta_{\mu e}) \sim \epsilon^4/4$ and $\sin^2(2\theta_{\mu\mu}) \sim \sin^2(2\theta_{ee}) \sim \epsilon^2$.

• We need to confirm the reactor neutrino anomaly, new experiments are been planned.

• A positive signal 10% for $\nu_\mu \to \nu_\mu$ and $\nu_e \to \nu_e$ disappearence is expected, new short-baseline experiments?, ICECUBE, KATRIN?Can we search for that? [2]

[2] *Light Sterile Neutrinos: A White Paper* K. N. Abazajian *et al.*, arXiv:1204.5379 [hep-ph].

Fishing Sterile neutrino in ICE-CUBE

The complete evolution equation for sterile neutrinos (3+1 mass scheme) is given by

$$\frac{d}{dr}\nu_f = \left[U_4 \frac{M^2}{2E_\nu} U_4^\dagger + A\right] \nu_f,$$

where $\nu_f = (\nu_e \nu_\mu \nu_\tau \nu_s)^T$ and E_ν is the neutrino energy. We get from Reference[3] the mixing matrix for the 3+1 case

$$\begin{aligned} U_4 = {} & \mathbf{R^{34}}(\theta_{34})\widetilde{\mathbf{R}}^{\mathbf{24}}(\theta_{24},\delta_2)\widetilde{\mathbf{R}}^{\mathbf{14}}(\theta_{14},\delta_1) \\ & \mathbf{R^{23}}(\theta_{23})\widetilde{\mathbf{R}}^{\mathbf{13}}(\theta_{13},\delta)\mathbf{R^{12}}(\theta_{12}) \end{aligned}$$

The mixing matrix is parameterized by twelve real parameters: the six mixing angles $\theta_{12}, \theta_{13}, \theta_{23}, \theta_{14}, \theta_{24}, \theta_{34}$, the three Dirac phases $\delta, \delta_1, \delta_2$.

[3] A. de Gouvea and J. Jenkins, Phys. Rev. D **78**, 053003 (2008) arXiv:0804.3627 [hep-ph]].

Fishing Sterile neutrino in ICE-CUBE

$$H = \frac{1}{2E_\nu} U_{4\times4} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 & 0 \\ 0 & 0 & \Delta m^2_{31} & 0 \\ 0 & 0 & 0 & \Delta m^2_{41} \end{pmatrix} U^\dagger_{4\times4} + \begin{pmatrix} A_{CC} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & A_{NC} \end{pmatrix}$$

where $U_{4\times4} = \begin{pmatrix} a & b \\ c & d \end{pmatrix}_{4\times4} \begin{pmatrix} U_{3\times3} & 0 \\ 0 & I \end{pmatrix}$,

and $A_{CC} = \sqrt{2} G_f n_e$ and $A_{NC} = \frac{1}{\sqrt{2}} G_f n_n$

Consequences for sterile neutrino phenomenology:

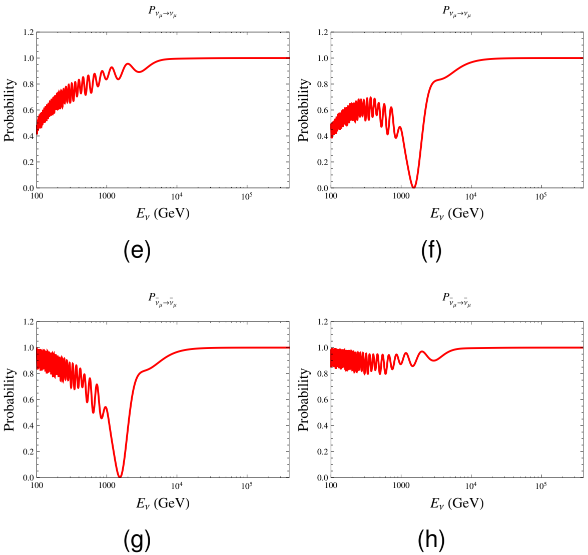
- New MSW effects, resonant conditions are:[3]

$$E_\nu \sim (2-5)\text{TeV}\left(-\frac{\Delta m^2_{41}}{1eV^2}\right)$$

For positive Δm^2_{41}, we have resonance for antineutrinos, for negative Δm^2_{41}, we have resonance for neutrinos.

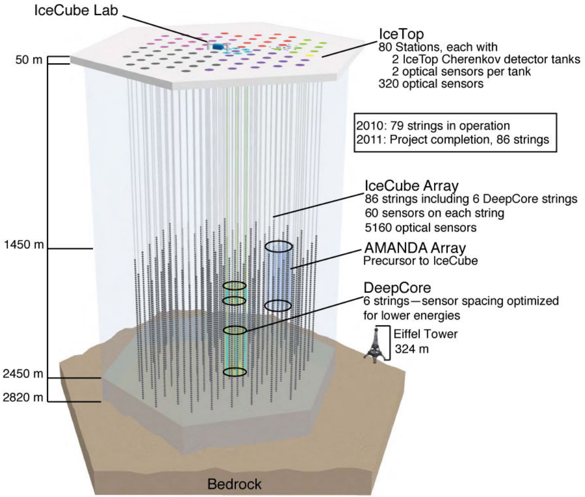
[3] O. Yasuda, hep-ph/0102166; H. Nunokawa, O. L. G. P. and R. Z. Funchal, Phys. Lett. B **562**, 279 (2003)
S. Choubey, JHEP **0712**, 014 (2007) ; S. Razzaque and A. Y. .Smirnov, JHEP **1107**, 084 (2011)
V. Barger, Y. Gao and D. Marfatia, Phys. Rev. D **85**, 011302 (2012)
A. Esmaili, F. Halzen and O. L. G. P., arXiv:1206.6903 [hep-ph].

Fishing Sterile neutrino in ICE-CUBE

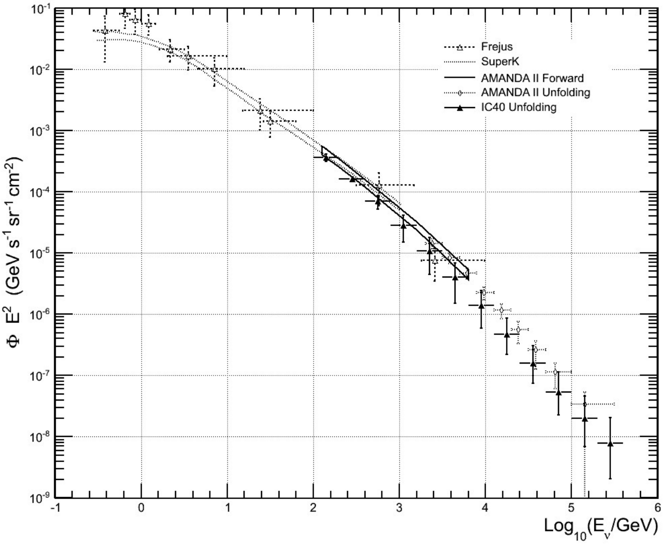


Fishing Sterile neutrino in ICE-CUBE

A new generation of neutrino observatories: The experiment

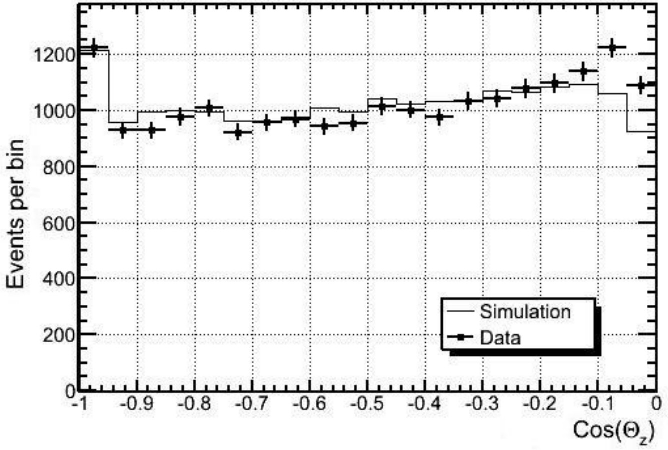


The highest atmospheric neutrino sample ever measured!!



Fishing Sterile neutrino in ICE-CUBE

The experiment ICECUBE see only upward-going neutrinos:
matter effect!!



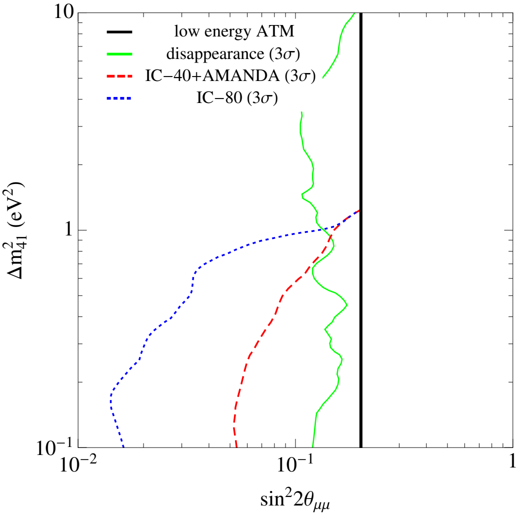
Fishing Sterile neutrino in ICE-CUBE

A χ^2 analysis

$$\chi^2(\Delta m^2_{41}, \theta_{34}, \theta_{24}; \alpha) = \sum_i \frac{\left(N_i^{\rm data} - \alpha N_i^{3+1}(\Delta m^2_{41}, \theta_{34}, \theta_{24})\right)^2}{\sigma_i^2} + \frac{(1-\alpha)^2}{\sigma_\alpha^2} \; ,$$

where α fix the normalization uncertainty.

Fishing Sterile neutrino in ICE-CUBE



The best constrains on $\sin^2 2\theta_{\mu\mu}$ parameter

Conclusions

• From a series of experiment there is evidence for a new species of neutrinos: a sterile neutrino that mix with the other neutrinos.

• A direct consequence of this scenario is the muon neutrino disappearence signal with $\sin^2 2\theta_{\mu\mu} \sim 10^{-1}$ for typical $\Delta m^2 \sim 0.1 - 1$ eV^2.

• It was predicted some yeas ago that the 3+1 scenario can be tested in neutrino telescope experiments. We made the analysis using the data from ICECUBE and from AMANDA and we have found that the sterile scenario is disvafored by the ICECUBE/AMANDA data.

We have put the the best constrains on $\sin^2 2\theta_{\mu\mu}$ mixing angle so far.

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ν masses in lab experiments

- Kinematics of β decay, absolute mass scale m_β

A effective neutrino mass can be used (for 3ν) $m_\beta^2 = \sum_i |U_{ei}|^2 m_i^2$.
Present limits are $m_\beta < 2.0$ eV.

KATRIN (2013?) expected to have sensitivity of $m_\beta = 0.23$ eV.

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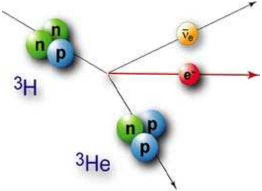
New generation (and probably the last) search for ν mass in β decay experiment. Lowest Q-value in β decay:Q$= 18571.8 \pm 1.2$ eV.

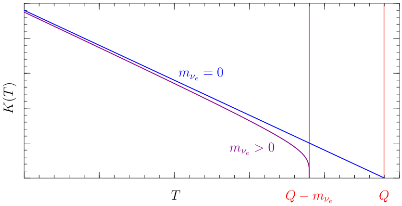


$$\beta(T_e, m_0, R_{\rm ED}) = N_s F^Z \sum_k p_k \mathcal{E}_k \sum_{i=1}^{3} |U^{ei}|^2 \sqrt{\mathcal{E}_k^2 - m_i^2} \;, \tag{1}$$

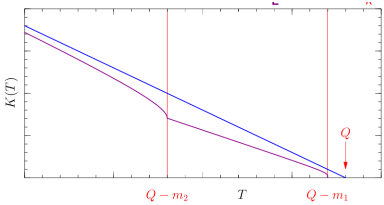
where $F^Z)$ is the Fermi function, $\mathcal{E}_i = Q - W_i - K_e$, E_e and p_e; W_i and p_i are respectively the excitation energy and transition probability for the excited state i of the daughter nucleus.

Effect of neutrino mass in β spectrum. For 3ν we can use $m_\beta^2 = \sum_i |U_{ei}|^2 m_i^2$, for other cases for KATRIN it is not possible to use this expression.

3ν



>4ν



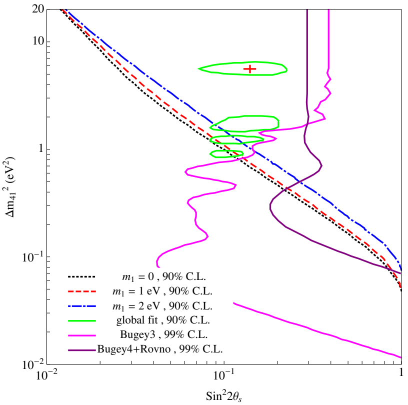
Integrated measurement

$$S(Q, qU, [U_{ei}], [m_\nu]) = \int_0^\infty \beta(K_e, Q, [U_{ei}], [m_\nu]) T'(K_e, qU) \, \mathrm{d}K_e \,,$$

- Thick Tritium source: atomic/molecular levels
- Energy loss of electrons inside source
- Sanity test: We recover the quoted limite for 3ν neutrinos:

$m_\beta < 0.23$ at 90 % C.L.

Testing 3+1 model in KATRIN



Arman Esmaili and O. L. G. P, A. Esmaili and O. L. G. Peres, Phys. Rev. D **85**, 117301 (2012) [arXiv:1203.2632 [hep-ph]].

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