Sterile neutrinos

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- introduction
- active-sterile mixing and oscillations
- cosmological constraints
- experimental situation and fits
- implications for beta and double beta decays

9ème Rencontre SPP/IPhT: Les neutrinos
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Introduction

Several oscillation results or anomalies (reactor antineutrino anomaly, LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ data...) cannot be explained within 3-flavour oscillations
$\Rightarrow$ need at least a fourth neutrino

But constraint from the invisible decay width of the Z boson [LEP]:

$$N_\nu = 2.9840 \pm 0.0082$$

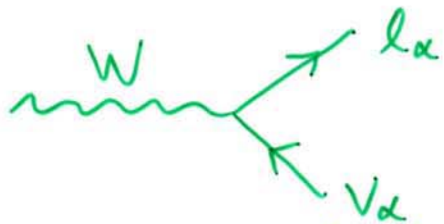
$\Rightarrow$ additional neutrinos must be sterile (i.e. electroweak singlets) or be heavier than Mz /2

Sterile neutrinos are SM gauge singlets - only interact via their mixing with the active neutrinos $\Rightarrow$ oscillations $\nu_{e,\mu,\tau} \leftrightharpoons \nu_s$

Other motivations for sterile neutrinos from cosmology, e.g. keV sterile neutrino as warm dark matter [Shaposhnikov] or to explain pulsar velocities [Kusenko, Segrè]

Active-sterile neutrino mixing

Standard case (3 flavours):



$[\alpha = e, \mu, \tau]$

$$\underbrace{\nu_\alpha}_{\text{flavour eigenstate}} \equiv \sum_i U_{\alpha i} \underbrace{\nu_i}_{\substack{\text{mass eigenstate} \\ \text{with mass } m_i}} \qquad [i = 1, 2, 3]$$

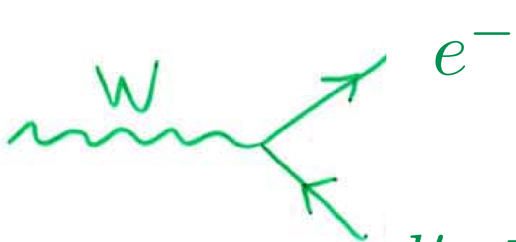
Add a sterile neutrino:

$$\nu_\alpha = \sum_{i=1}^{4} U_{\alpha i}\, \nu_i \qquad [\alpha = e, \mu, \tau]$$

ν_s flavour eigenstate
ν_4 mass eigenstate (m4)

U = 4x4 unitary matrix

Only ν_e, ν_μ, ν_τ couple to electroweak gauge boson, but all four mass eigenstate are produced in a beta decay:



$$\nu_e = \sum_{i=1}^{4} U_{ei}\, \nu_i$$

2-flavour oscillations:

$$P(\nu_\alpha \to \nu_\beta) \;=\; \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad\qquad \Delta m^2 \;\equiv\; m_2^2 - m_1^2$$

N-flavour oscillations:

$$\begin{aligned} P_{\nu_\alpha\to\nu_\beta(\bar\nu_\alpha\to\bar\nu_\beta)} \;&=\; \delta_{\alpha\beta} - 4\sum_{i<j} \mathrm{Re}\left(U_{\alpha i}U^\star_{\beta i}U^\star_{\alpha j}U_{\beta j}\right)\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) \\ &\mp 2\sum_{i<j}\mathrm{Im}\left(U_{\alpha i}U^\star_{\beta i}U^\star_{\alpha j}U_{\beta j}\right)\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right) \end{aligned}$$

3+1 case:

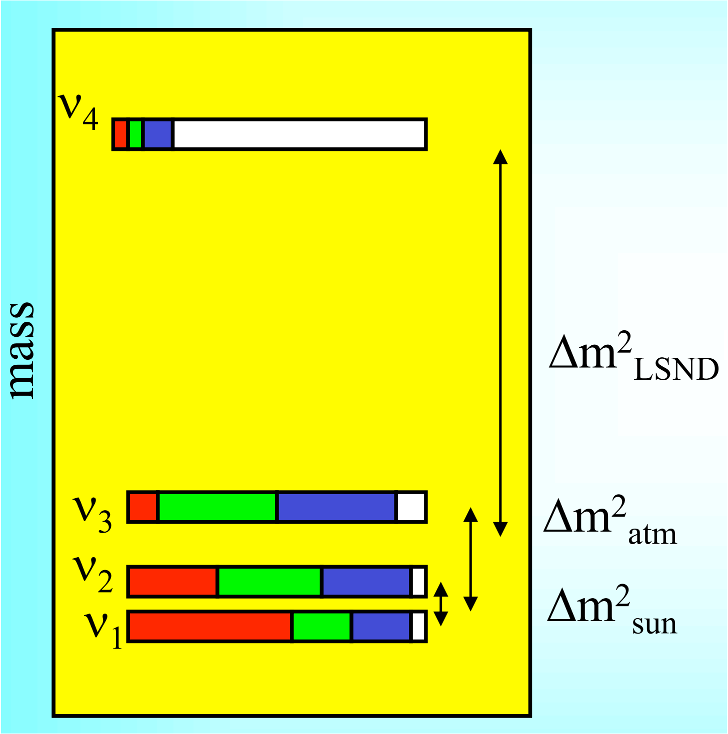
Since $\Delta m^2_{SBL} \gg \Delta m^2_{atm.}, \Delta m^2_{sun}$, it is natural (and cosmologically preferred) to assume $m_4 \gg m_3, m_2, m_1$

Then $\Delta m^2_{SBL} \equiv \Delta m^2_{41} \simeq \Delta m^2_{42} \simeq \Delta m^2_{43} \;\gg\;$ all other Δm^2_{ij}'s

All data but short baseline oscillations well described by 3-flavour oscillations

$\Rightarrow$ $\nu_{1,2,3}$ mainly composed of $\nu_{e,\mu,\tau}$ + small admixture of ν_s, and

ν_4 mainly composed of ν_s + small admixture of $\nu_{e,\mu,\tau}$



Smirnov

We are interested in short baseline oscillations with

$$\frac{\Delta m_{41}^2 L}{4E} \lesssim 1 \quad \Longrightarrow \quad \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right) \gg \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right),\ \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

$$\begin{aligned} P_{\nu_\alpha \to \nu_\alpha} &\simeq 1 - 4\left(|U_{\alpha 1}|^2 + |U_{\alpha 2}|^2 + |U_{\alpha 3}|^2\right)|U_{\alpha 4}|^2 \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right) \\ &\equiv 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right) \end{aligned}$$

where $\sin^2 2\theta_{\alpha\alpha} \equiv 4\,(1 - |U_{\alpha 4}|^2)|U_{\alpha 4}|^2$

$$\begin{aligned} P_{\nu_\alpha \to \nu_\beta} &\simeq -4\,\mathrm{Re}\left[\left(U_{\alpha 1}U_{\beta 1}^* + U_{\alpha 2}U_{\beta 2}^* + U_{\alpha 3}U_{\beta 3}^*\right)U_{\alpha 4}^* U_{\beta 4}\right] \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right) \\ &\equiv \sin^2 2\theta_{\alpha\beta} \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right) \end{aligned}$$

where $\sin^2 2\theta_{\alpha\beta} \equiv 4\,|U_{\alpha 4}U_{\beta 4}|^2$

3+2 case:

Assume $m_5 \sim m_4 \gg m_3, m_2, m_1$

$\Rightarrow$ two relevant squared mass differences Δm^2_{51} and Δm^2_{41}

$\Rightarrow$ CP-violating effects possible due to interference between the two oscillations frequencies

$$P_{\nu_\alpha \to \nu_\beta (\bar{\nu}_\alpha \to \bar{\nu}_\beta)} = 4\,|U_{\alpha 4} U_{\beta 4}|^2 \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) + 4\,|U_{\alpha 5} U_{\beta 5}|^2 \sin^2\left(\frac{\Delta m^2_{51} L}{4E}\right)$$
$$+ 8\,|U_{\alpha 4} U_{\beta 4} U_{\alpha 5} U_{\beta 5}| \sin\left(\frac{\Delta m^2_{41} L}{4E}\right) \sin^2\left(\frac{\Delta m^2_{51} L}{4E}\right) \cos\left(\frac{\Delta m^2_{54} L}{4E} \mp \eta\right)$$

$$\eta \equiv \arg\left[U_{\alpha 4} U^*_{\beta 4} U^*_{\alpha 5} U_{\beta 5}\right]$$

Cosmological constraints

Light sterile neutrinos are in thermal equilibrium in the early universe due to oscillations (unless small active-sterile mixing)

$\Longrightarrow$ increase the number of relativistic species

$\Longrightarrow$ affect BBN, CMB anisotropies and large-scale structure formation

<u>Hamann, Hannestad, Raffelt, Wong [1108.4136]:</u>

within ΛCDM, CMB+LSS and BBN prefer extra relativistics dofs:

$$N_{eff} = 3.90^{+0.39}_{-0.56} \qquad (95\% \text{ C.L.})$$

However, a sterile neutrino with an eV mass violates the cosmological bound on neutrino masses

$\Longrightarrow$ $m_4 \lesssim 0.5\,\mathrm{eV}$ or must depart from ΛCDM: e.g. additional relativistic dofs help relax this bound, but inconsistent with BBN (allows at most one extra relativistic dof) unless introduce a neutrino chemical potential

If eV-scale sterile neutrinos are really around, seem to require a significant modification of the standard cosmological scenario

Experimental situation

Several experimental anomalies suggest the existence of sterile neutrinos

<u>LSND:</u> $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations

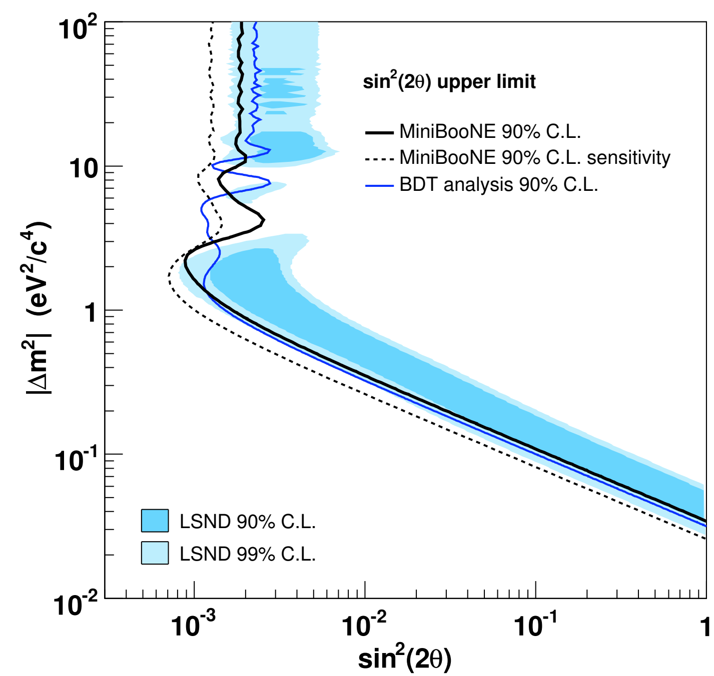
Excess of $\bar{\nu}_e$ events over background at 3.8 σ (still controversial)
Not observed by KARMEN

<u>MiniBooNE:</u>

$\nu_\mu \to \nu_e$ data: no excess in the 475-1250 MeV range, but unexplained 3σ ν_e excess at low energy

$\bar{\nu}_\mu \to \bar{\nu}_e$ data: $\bar{\nu}_e$ excess in the E > 475 MeV region consistent with LSND-like oscillations, but also (after the 2011 update) with a background-only hypothesis

A low-energy $\bar{\nu}_e$ excess is also seen



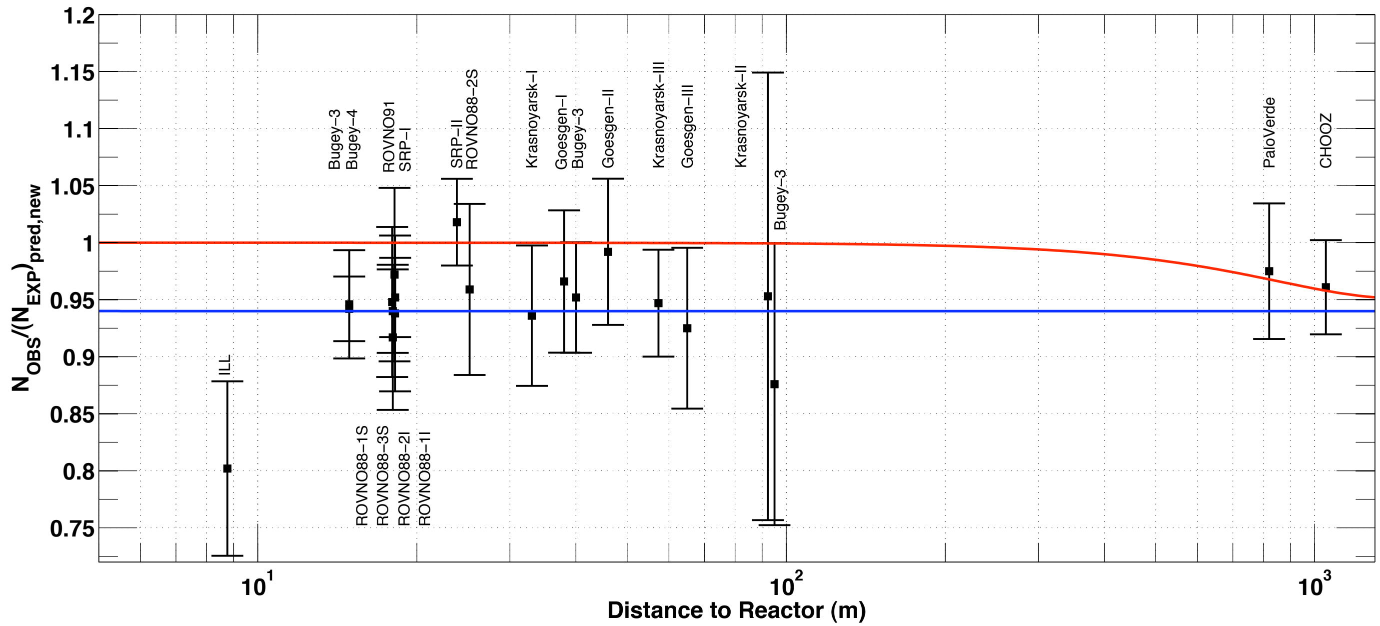
Reactor antineutrino anomaly:

New computation of the reactor antineutrino spectra

$\Rightarrow$ increase of the flux by about 3%

$\Rightarrow$ deficit of antineutrinos in SBL reactor experiments

mean observed to predicted rate 0.943 ± 0.023



G. Mention et al.

FIG. 5. Illustration of the short baseline reactor antineutrino anomaly. The experimental results are compared to the prediction without oscillation, taking into account the new antineutrino spectra, the corrections of the neutron mean lifetime, and the off-equilibrium effects. Published experimental errors and antineutrino spectra errors are added in quadrature. The mean averaged ratio including possible correlations is 0.943 ± 0.023. The red line shows a possible 3 active neutrino mixing solution, with $\sin^2(2\theta_{13}) = 0.06$. The blue line displays a solution including a new neutrino mass state, such as $|\Delta m^2_{\rm new,R}| \gg 1$ eV^2 and $\sin^2(2\theta_{\rm new,R}) = 0.12$ (for illustration purpose only).

Gallex-SAGE calibration experiments:

Calibration of the Gallex and SAGE experiments with radioactive sources
$\Rightarrow$ observed deficit of ν_e with respect to predictions

R = 0.86 ± 0.05

[tension with ν_e - Carbon cross-section measurements at LSND and KARMEN, 1106.5552]

Combined analysis of SBL reactor data, gallium calibration experiments and MiniBooNE neutrino data [G. Mention et al.]:

$$|\Delta m^2_{SBL}| > 1.5\,\mathrm{eV}^2\,, \quad \sin^2 2\theta_{ee} = 0.14 \pm 0.08 \quad (95\%\ \mathrm{C.L.})$$

However, no coherent picture of the data with an additional (or even 2) sterile neutrinos (even if the global fit has improved with the new reactor antineutrino flux):

1) tension between appearance (LSND/MiniBooNE antineutrino data) and disappearance experiments (reactors, ν_μ disappearence experiments)

Reactors: $$P_{\bar{\nu}_e \to \bar{\nu}_e} \simeq 1 - \sin^2 2\theta_{ee} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

require relatively small $\sin^2 2\theta_{ee} \equiv 4\,(1-|U_{e4}|^2)|U_{e4}|^2 \simeq 4\,|U_{e4}|^2$

(using info from solar neutrino data)

CDHS: $$P_{\nu_\mu \to \nu_\mu} \simeq 1 - \sin^2 2\theta_{\mu\mu} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

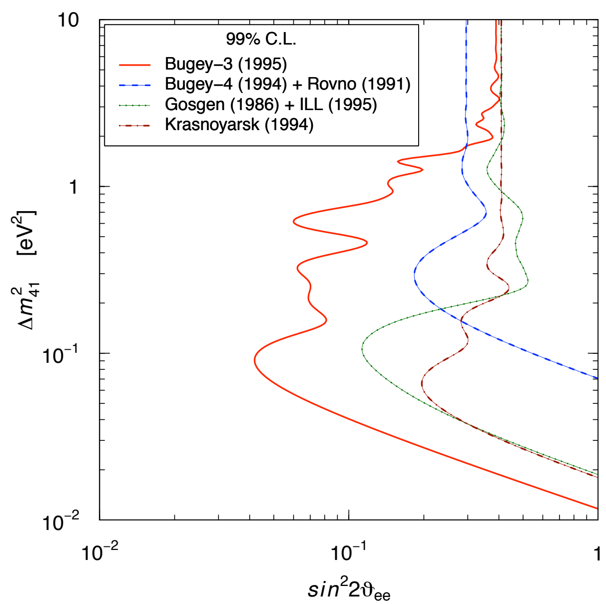
require relatively small $\sin^2 2\theta_{\mu\mu} \equiv 4\,(1-|U_{\mu 4}|^2)|U_{\mu 4}|^2 \simeq 4\,|U_{\mu 4}|^2$

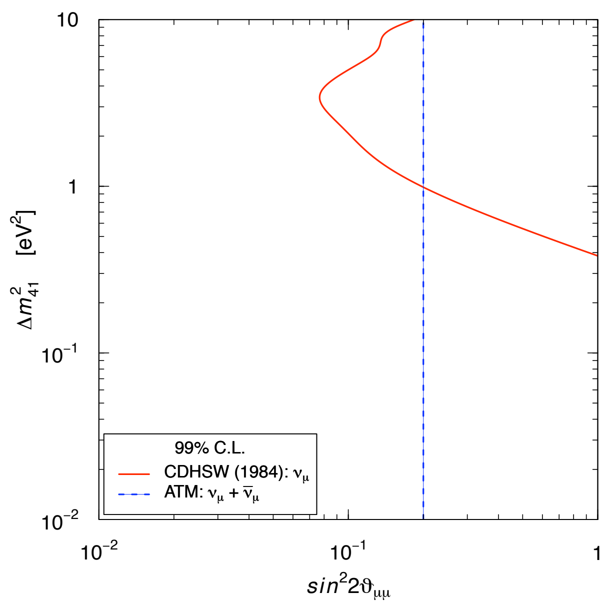
(using info from atm. neutrino data)

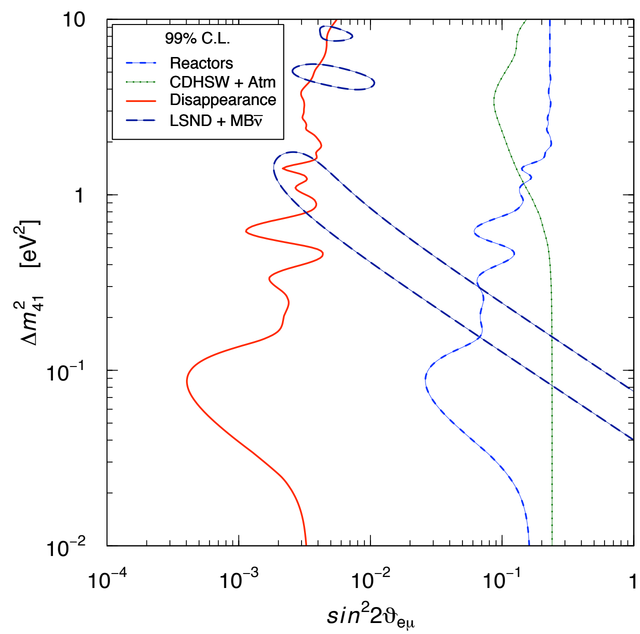
Appearance experiments (LSND/MiniBooNE antineutrino data):

$$P_{\bar{\nu}_\mu \to \bar{\nu}_e} \simeq \sin^2 2\theta_{e\mu} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\theta_{e\mu} \equiv 4\,|U_{e4}U_{\mu 4}|^2 \simeq \frac{1}{4}\,\sin^2 2\theta_{ee}\,\sin^2 2\theta_{\mu\mu}$$

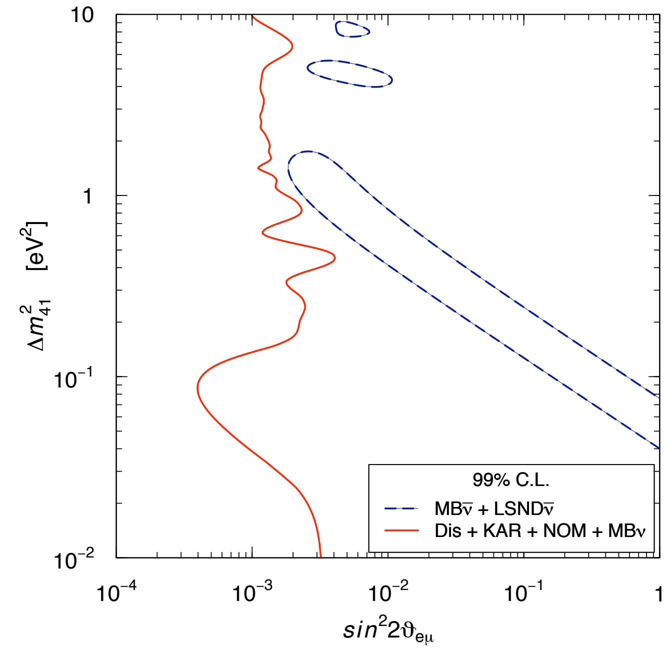




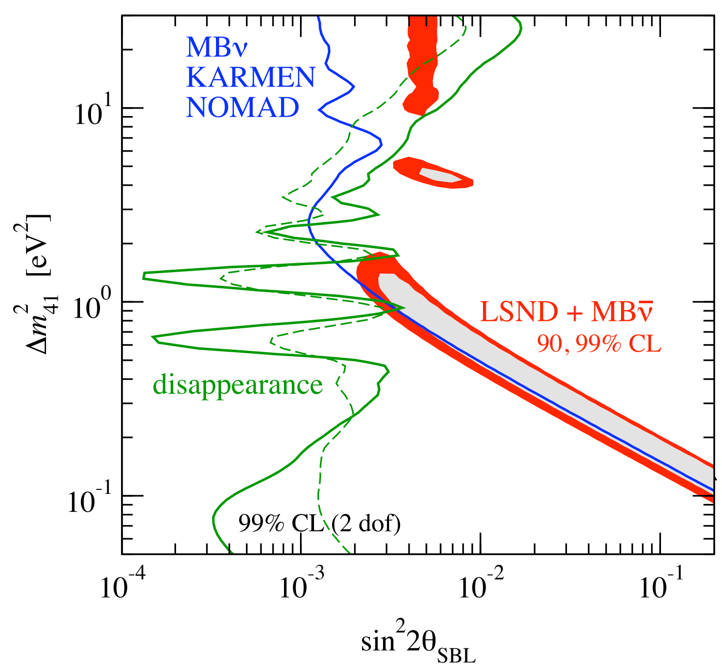


Giunti, 1110.3914

2) tension between LSND and MiniBooNE neutrino data (+ null result of NOMAD and KARMEN)



Giunti, 1110.3914



Kopp, Maltoni, Schwetz, 1103.4570

→ 3+1 case does not provide a very satisfactory fit of all the data

Best fit point of a global analysis [Giunti, Laveder, 1111.1069 - incl. MiniBooNE 2011]:

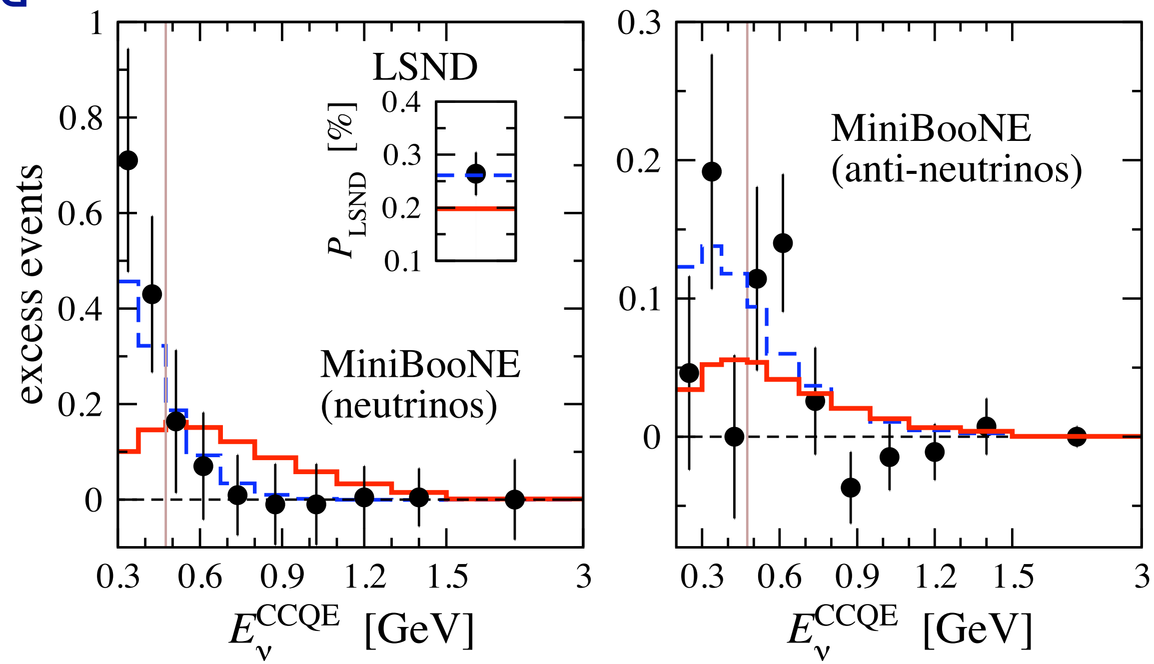
$$|\Delta m^2_{41}| = 1.6\,\mathrm{eV}^2\,, \quad |U_{e4}|^2 = 0.036\,, \quad |U_{\mu 4}|^2 = 0.0084$$

$$\left[\sin^2 2\theta_{e\mu} = 1.2\times 10^{-3}\right]$$

3+2 case [Kopp, Maltoni, Schwetz]

Allows for CP violation $\Rightarrow P(\bar\nu_\mu \to \bar\nu_e) \neq P(\nu_\mu \to \nu_e)$

$\Rightarrow$ can reconcile MiniBooNE neutrino data with LSND/MiniBooNE 2010 antineutrino data (less motivated after inclusion of 2011 data)



Much better fit of pre-2011 data than in the 3+1 case

[low-energy excess of MiniBooNE not included in the fit]

Other implications of sterile neutrinos

<u>Tritium beta decay:</u>

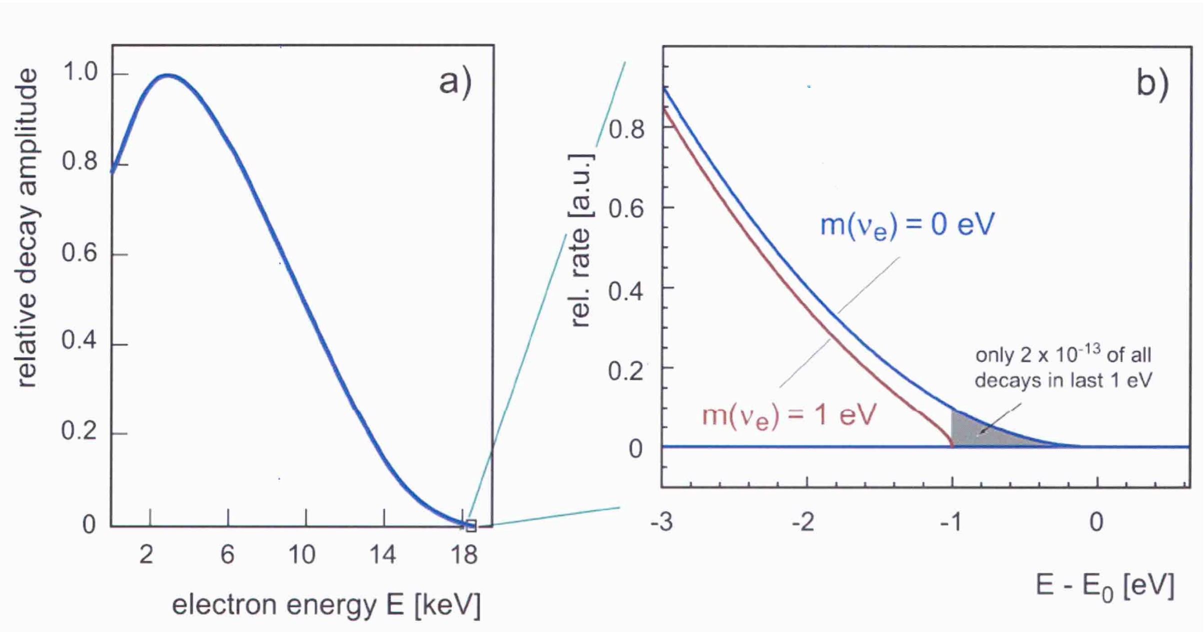
$$^3H \rightarrow\ ^3He + e^- + \bar{\nu}_e \qquad\qquad E_0 = m_{^3H} - m_{^3He}$$

The electron energy spectrum is given by:

$$\frac{dN}{dE_e} = R(E_e)\sqrt{(E_0 - E_e)^2 - m_\nu^2} \qquad\qquad E_e = E_0 - E_\nu$$

Effect of the non-vanishing neutrino mass: $E_e^{max} = E_0 \rightarrow E_0 - m_\nu$

$\Rightarrow$ distorsion of the Ee spectrum close to the endpoint



Present bound (Troitsk/Mainz): $m_{\nu_e} < 2.2\,\mathrm{eV} \quad (95\%\ \mathrm{C.L.})$

KATRIN will reach a sensitivity of about 0.3 eV

In pratice, there is no electron neutrino mass, but 3 (or more) strongly mixed mass eigenstates, and

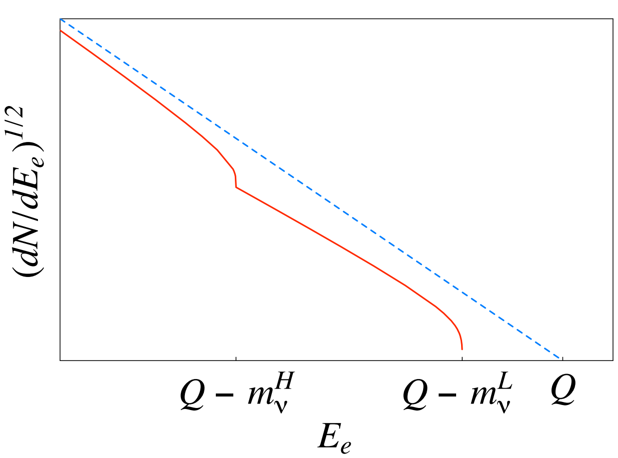
$$\frac{dN}{dE_e} = R(E_e) \sum_i |U_{ei}|^2 \sqrt{(E_0 - E_e)^2 - m_i^2}\, \Theta(E_0 - E_e - m_i)$$

If all mi are smaller than the energy resolution, this can be rewritten as:

$$\frac{dN}{dE_e} = R(E_e) \sqrt{(E_0 - E_e)^2 - m_\beta^2} \qquad m_\beta^2 \equiv \sum_i m_i^2 |U_{ei}|^2$$

If there is an eV-scale sterile neutrino (comparable to the energy resolution of KATRIN), its mass may be resolved (but difficult measurement):

$$\frac{1}{R(E_e)} \frac{dN}{dE_e} = (1 - |U_{e4}|^2) \sqrt{(E_0 - E_e)^2 - m_\beta^2}$$
$$+ |U_{e4}|^2 \sqrt{(E_0 - E_e)^2 - m_4^2}\, \Theta(E_0 - E_e - m_4)$$

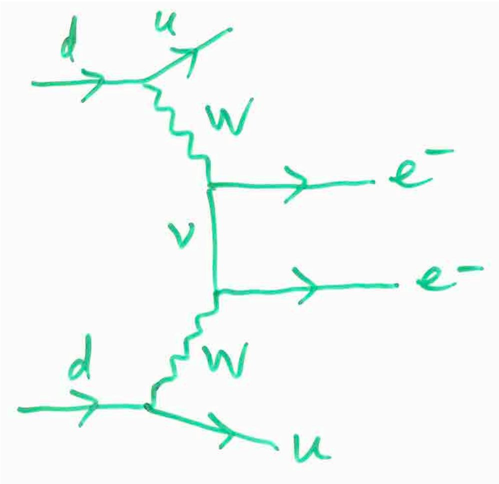


(also: upper bound on m4 from beta decay)

Neutrinoless double beta decay:

$$(A, Z) \rightarrow (A, Z+2) + e^- + e^-$$

Possible if lepton number violated (Majorana neutrinos), in nuclei where the single beta decay is forbidden

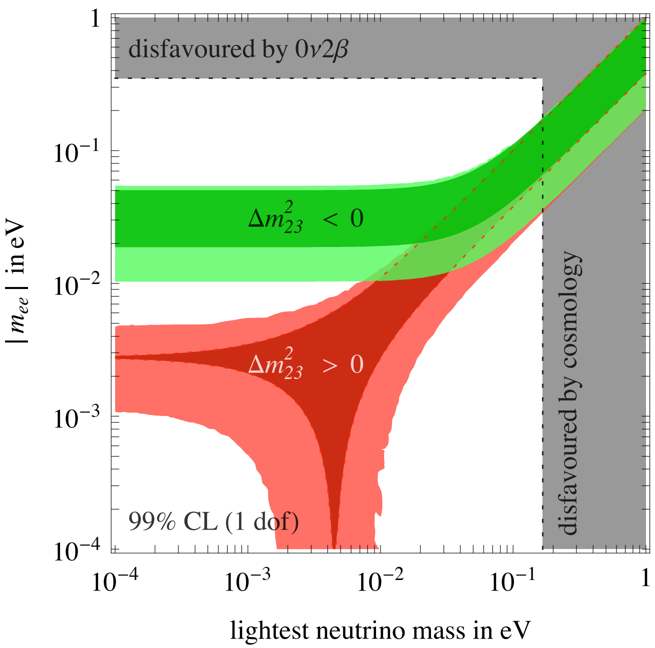


Sensitive to the effective mass parameter:

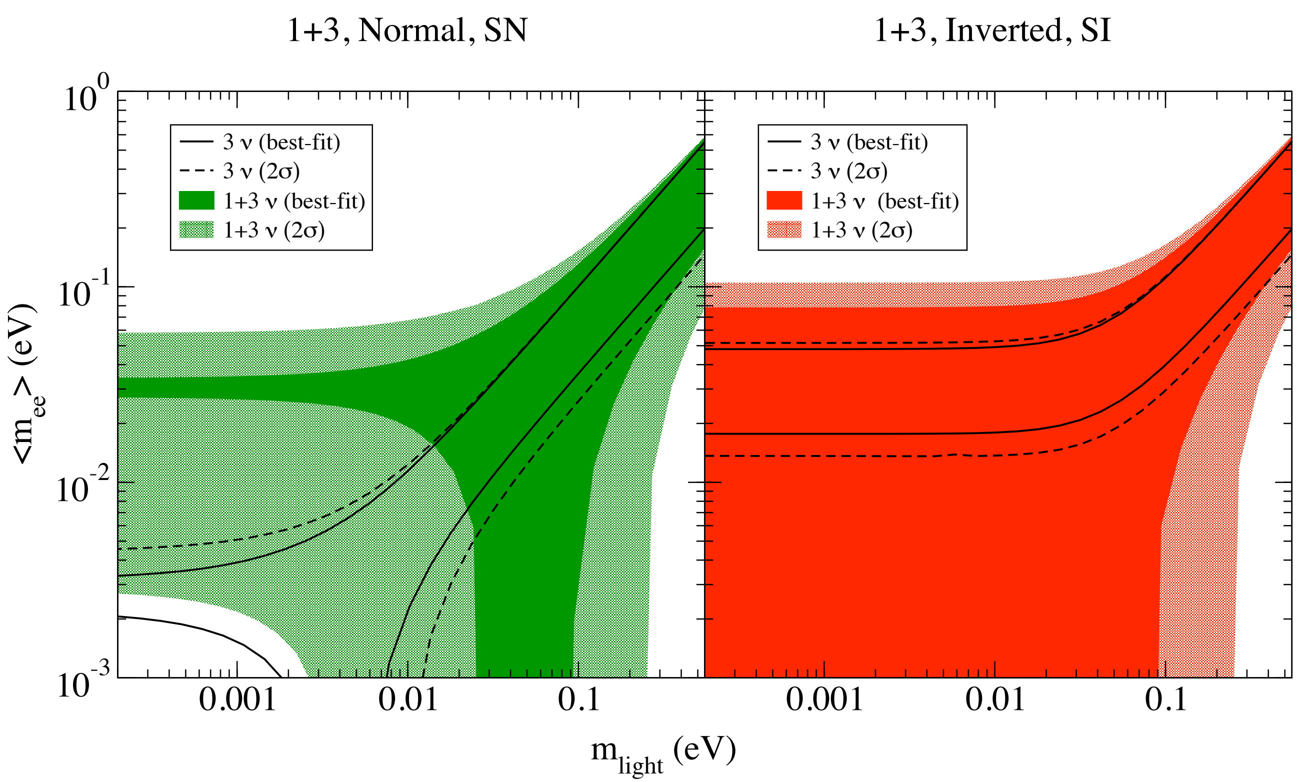
$$m_{\beta\beta} \equiv \sum_i m_i U_{ei}^2$$

possible cancellations in the sum (phases in U)

3-neutrino case
(Strumia, Vissani)



An additional sterile neutrino will contribute $m_4|U_{e4}|^2 e^{i\gamma}$ to the effective mass $m_{\beta\beta} \equiv \sum_i m_i U_{ei}^2$; depending on the active neutrino parameters it may dominate or lead to cancellations



Barry, Rodejohann, Zhang, 1105.3911

using the fit of Kopp, Maltoni and Schwetz:

	parameter	Δm_{41}^2 [eV]	$\lvert U_{e4}\rvert^2$
3+1/1+3	best-fit	1.78	0.023
	2σ	1.61–2.01	0.006–0.040