Sterile neutrino as a pseudo-Goldstone fermion

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- introduction and motivations
- theoretical framework
- numerical results: correlations among sterile parameters
- conclusions

based on a work in progress with Enrico Bertuzzo (IPhT Saclay)

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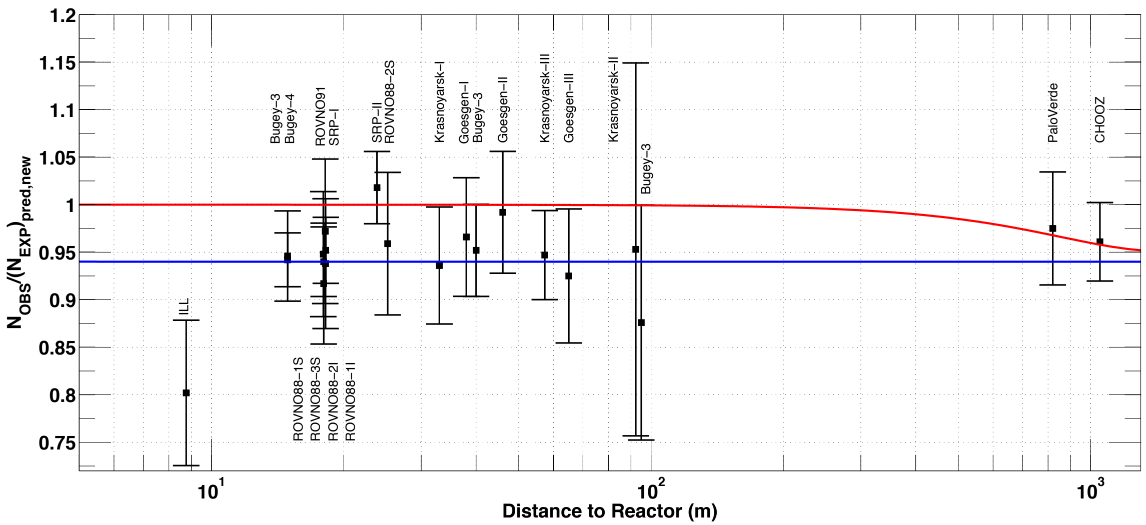
Introduction and motivations

Renewed interest in the past few years for sterile neutrinos, mainly driven by experimental anomalies and cosmology:

- the reactor anti-neutrino anomaly (deficit of $\overline{\nu}_e$ in short-baseline reactor experiments) could be due to oscillations into sterile neutrinos



G. Mention et al. (arXiv:1101.2755)

- measurement of CMB anisotropies and other cosmological data are consistent with extra light degrees of freedom

$N_{\rm eff} = 4.34^{+0.86}_{-0.88} \quad (68\%\,{\rm C.L.})$ [WMAP 7yr + BAO + H0]

$N_{\rm eff} = 3.84 \pm 0.40 \quad (68\%\,{\rm C.L.})$ [WMAP 9yr + eCMB + BAO + H0]

Recent Planck data leave less room for a sterile neutrino. One usually quotes:

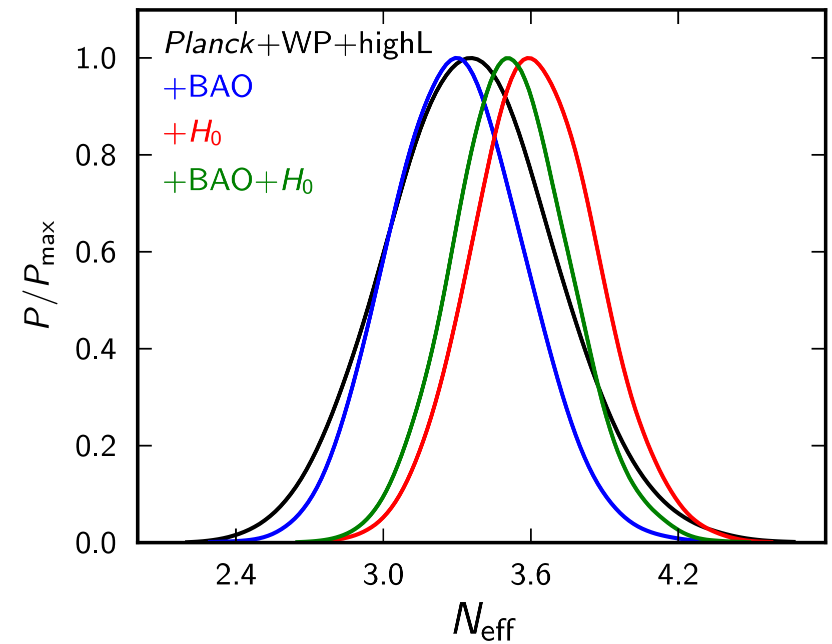
$$N_{\rm eff} = 3.30^{+0.54}_{-0.51} \quad (95\%\,{\rm C.L.})$$

[Planck + WMAP + highL + BAO]

However the constraint strongly depends on the set of data used:

$$N_{\rm eff} = 3.52^{+0.48}_{-0.45} \quad (95\%\,{\rm C.L.})$$

[Planck + WMAP + highL + BAO + H_0]



arXiv:1303.5076

Assuming a fully thermalized massive sterile neutrino, the constraint becomes:

$$N_{\rm eff} < 3.91\,, \quad m_{\nu_s} < 0.59\,{\rm eV} \quad (95\%\,{\rm C.L.})$$ [Planck + WMAP + highL]

$$N_{\rm eff} < 3.80\,, \quad m_{\nu_s} < 0.42\,{\rm eV} \quad (95\%\,{\rm C.L.})$$ [Planck + WMAP + highL + BAO]

These bounds are in tension with the sterile neutrino interpretation of the neutrino anomalies, which require $m_{\nu_s} \sim 1\,\mathrm{eV}$
[see e.g. Mirizzi et al., arXiv:1303.5368]

e.g. a combined analysis of SBL reactor data, gallium calibration experiments and MiniBooNE neutrino data gives [G. Mention et al., arXiv:1101.2755]:

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

From a theoretical point of view, sterile neutrinos also pose a problem: since they are gauge singlets, their mass is not protected by any symmetry

Sterile neutrinos are present e.g. in the seesaw mechanism:

$$-m\,\overline{\nu}_L \nu_R - \frac{1}{2} M \nu_R^T C \nu_R + \mathrm{h.c.} = -\frac{1}{2} \left(\bar{\nu}_L\ \bar{\nu}^c_L \right) \begin{pmatrix} 0 & m \\ m & M \end{pmatrix} \begin{pmatrix} \nu^c_R \\ \nu_R \end{pmatrix} + \mathrm{h.c.}$$

the mass eigenstates ν_{L1} and ν_{L2} are admixtures of the active neutrino ν_L and of the sterile neutrino $\nu^c_L \equiv C\,\overline{\nu}^T_R$

However, for m << M, the sterile neutrino $\nu^c_L \simeq \nu_{L2}$ is very heavy and has negligible mixing with the active neutrino

Theoretical scenarios for naturally light sterile neutrinos

1) (very) low-energy seesaw with M < 10 eV [de Gouvêa, Huang, arXiv:1110.6122]
   but the seesaw explanation of small neutrino masses is lost

2) singular seesaw mechanism [Glashow '91]
   det M = 0 leading to a fourth light mass eigenstate
   accidental or due to symmetries of the neutrino sector

3) flat extra dimensions [arkani-Hamed et al. '98; Dienes et al. '98]
   a massless bulk RH neutrino generates a tower of Kaluza-Klein sterile neutrinos with masses n/R

4) singlet fermions (modulinos) in supersymmetry/string theory
   [Benakli, Smirnov '97; Dvali, Nir '98]

5) pseudo-Goldstone fermion [Chun, Joshipura, Smirnov '95; Chun '99]
   supersymmetric partner of the Goldstone boson of a spontaneously broken global symmetry (e.g. lepton number or Peccei-Quinn)

Theoretical framework

Some global symmetry spontaneously broken at a scale f >> M_{SUSY}

The supersymmetric effective field theory below f involves a (pseudo-)Goldstone multiplet

$$A = \frac{s + ia}{\sqrt{2}} + \sqrt{2}\theta\chi + \theta^2 F$$

with a shift symmetry $A \to A + i\alpha f$

In the supersymmetric limit and in the absence of explicit global symmetry breaking, all components *s*, *a*, χ are massless

Supersymmetry breaking can give a mass to χ and *s*, while some explicit breaking of the global symmetry is needed to give a mass to *a* (or the symmetry must be anomalous)

Irreducible χ mass from supersymmetry breaking [Cheung, Elor, Hall, 1104.0692]

$m_\chi \sim m_{3/2}$ from $\displaystyle\int d^4\theta \, \frac{1}{M_P} (A + A^\dagger)^2 (X + X^\dagger) \, , \quad \langle X \rangle = F\theta^2$

$\Rightarrow$ low-scale supersymmetry breaking needed

Assuming no R-parity (but baryon number), the most general Lagrangian compatible with the shift symmetry $A \to A + i\alpha f$ is (α = 0, 1, 2, 3):

$$W = \mu_\alpha H_u L^\alpha + \frac{1}{2}\lambda^e_{\alpha\beta k} L^\alpha L^\beta \overline{e}^k + \lambda^d_{\alpha jk} L^\alpha Q^j \overline{d}^k - \lambda^u_{jk} H_u Q^j \overline{u}^k$$

$$K = \frac{1}{2}(A + A^\dagger)^2 + H_u^\dagger H_u + L^{\alpha\dagger} L^\alpha + C_u\, H_u^\dagger H_u \frac{A + A^\dagger}{f}$$
$$+ C_{\overline{\alpha}\beta}\, L^{\alpha\dagger} L^\beta \frac{A + A^\dagger}{f} + \left(C_{u\alpha}\, H_u L^\alpha \frac{A + A^\dagger}{f} + \text{h.c.} \right) + \cdots$$

V_{soft} = generic MSSM soft terms with leptonic RPV

After minimization of the scalar potential, H_u, L_α get vevs (assume <A> = 0)
⇒ non-canonical kinetic terms for H_u and L_α

→ redefine H_u and L_α = (H_d, L_i) such that

(i) the charged fields H_u^+, H_d^-, e_i^- have canonical kinetic terms

(ii) the sneutrino vevs $\langle \tilde{\nu}_i \rangle$ vanish

(iii) $\lambda^e_{0jk} = \lambda^e_j\, \delta_{jk}$, λ^e_j real

Neutralino and chargino mass matrices

As a consequence of the bilinear RPV terms ($\mu_i H_u L_i$), leptons mix with charginos and neutralinos.

Furthermore, since the kinetic terms of the neutral fields H_u^0, H_d^0, ν^i, A are not canonical, the neutralino mass matrix receives contribution from the Kähler potential and mixes χ with the standard neutrinos and neutralinos

<u>Charginos:</u>

$$\begin{pmatrix} \widetilde{W}^- & \widetilde{H}_d^- & e_i^- \end{pmatrix} \begin{pmatrix} M_2 & g v_u & 0_{1\times 3} \\ g v_d & \mu & 0_{1\times 3} \\ 0_{3\times 1} & \mu_i & \lambda_i^e v_d \delta_{ij} \end{pmatrix} \begin{pmatrix} \widetilde{W}^+ \\ \widetilde{H}_u^+ \\ \overline{e}_k^+ \end{pmatrix}$$

2 heavy mass eigenstates (charginos)

3 light mass eigenstates (charged leptons) with masses $m_i = \lambda_i^e v_d$

chargino / charged lepton mixing suppressed by μ_i/μ or smaller

Neutralinos:

The neutralino mass matrix, written in the basis $(\widetilde{W}^3, \widetilde{B}, \widetilde{H}_u^0, \widetilde{H}_d^0, \nu_i, \chi)$ is a 8x8 matrix with a seesaw structure

$$M_N = \begin{pmatrix} M_{4\times 4} & \mu_{4\times 4} \\ \mu^T_{4\times 4} & m_{4\times 4} \end{pmatrix} \qquad\qquad m,\, \mu \ll M$$

hence the neutrino masses and mixing are given by the diagonalization of the 4x4 effective neutrino mass matrix

$$M_\nu = m - \mu^T M^{-1} \mu = \begin{pmatrix} A\,\frac{\mu_i}{\mu}\frac{\mu_j}{\mu} & \left(B\,\frac{\mu_i}{\mu} + D_i\right)\frac{v}{f} \\ \left(B\,\frac{\mu_j}{\mu} + D_j\right)\frac{v}{f} & C\,\frac{v^2}{f^2} + m_\chi \end{pmatrix}$$

where $A = \frac{\mu^2 M_{11} M_Z^2 \cos^2\beta}{\det M}$ depends only on MSSM parameters, while B, Di and C depend also on the Kähler parameters $C_{ud}, C_u, C_{\overline{d}d}, C_{\overline{\imath}\jmath}$ (Rp-conserving) and $C_{u\imath}, C_{\overline{d}\imath}$ (RPV). Assuming the former are of order 1, one has $B, C = \mathcal{O}(\mu)$

One gets a consistent neutrino phenomenology by assuming that all RPV parameters ($\mu_i, C_{ui}, C_{\overline{d}i}$) are small, while the Rp-conserving Kähler parameters are of order 1

In practice, need $\frac{\mu_i}{\mu} \lesssim 10^{-5}, \quad C_{\overline{d}i} \lesssim 10^{-6}, \quad \frac{v}{f} \lesssim 10^{-6}, \quad m_\chi \lesssim 1\,\mathrm{eV}$

Can rewrite the 4x4 neutrino mass matrix in a more compact form:

$$M_\nu = \begin{pmatrix} D\epsilon_\alpha\epsilon_\beta & E\eta_\alpha \\ E\eta_\beta & F \end{pmatrix} \qquad \sum_\alpha \epsilon_\alpha^2 = \sum_\alpha \eta_\alpha^2 = 1$$

where we have renamed the indices $i, j \rightarrow \alpha, \beta = e, \mu, \tau$

This structure implies:

1) the matrix has rank 3, so $m_1 = 0$

2) the active-sterile mixing is given by $U_{\alpha 4} \simeq \frac{E}{F}\eta_\alpha \qquad (m_4 \simeq F)$

3) at order 1 in the active-sterile mixing, the active neutrino parameters are given by the matrix

$$(m_\nu)_{\alpha\beta} = D\,\epsilon_\alpha\epsilon_\beta - \frac{E^2}{F}\eta_\alpha\eta_\beta$$

$$(m_\nu)_{\alpha\beta} = \sum_{i=2}^{3} m_i U_{\alpha i} U_{\beta i} = D\,\epsilon_\alpha \epsilon_\beta - \frac{E^2}{F}\,\eta_\alpha \eta_\beta$$

Since we know the active neutrino parameters (neglecting CPV), we can "reconstruct" the sterile neutrino parameters using [when the first term dominates]

$$m_2 \simeq -\frac{E^2}{F}\,\vec{\zeta}^{\,2}\,, \qquad m_3 \simeq D$$

$$U_{\alpha 2} \simeq -\left(\xi_\mu \xi_\tau, \xi_e \xi_\tau, \xi_e \xi_\mu\right)/\kappa\,, \qquad U_{\alpha 3} \simeq (\epsilon_e, \epsilon_\mu, \epsilon_\tau)$$

where $\vec{\zeta} \equiv \vec{\epsilon} \times \vec{\eta} \qquad \xi_\alpha \equiv \zeta_\beta \zeta_\gamma + \vec{\zeta}^{\,2}\,\epsilon_\beta \epsilon_\gamma \quad (\alpha, \beta, \gamma \text{ all different})$

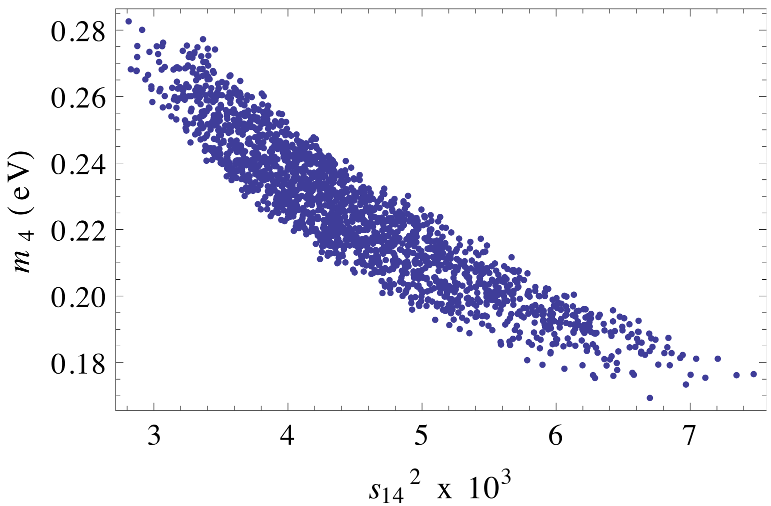
and $\kappa \equiv \left(|\xi_\mu \xi_\tau|^2 + |\xi_e \xi_\tau|^2 + |\xi_e \xi_\mu|^2\right)^{1/4}$

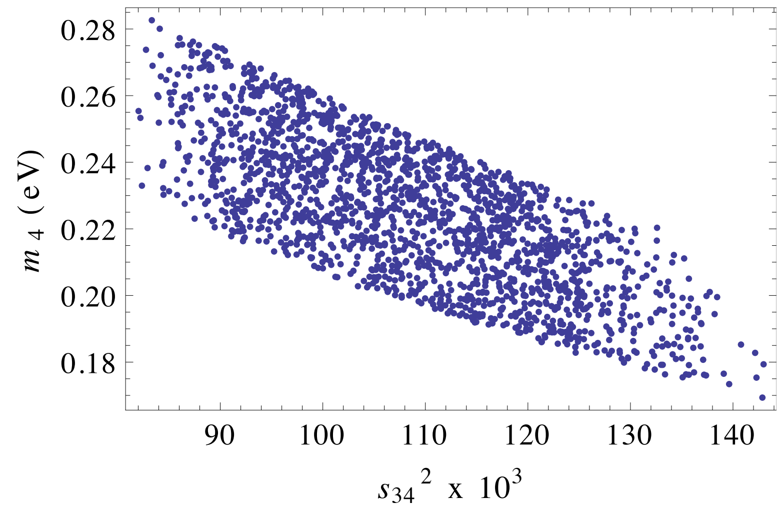
In the reconstruction process, one obtains the ζ_α^2 as a function of $\kappa/\vec{\zeta}^{\,2}$, which is the solution of a polynomial of degree 4. Among the solutions, only the ones that satisfy the constraint $\vec{\zeta}^{\,2} \leq 1$ (if any) are acceptable

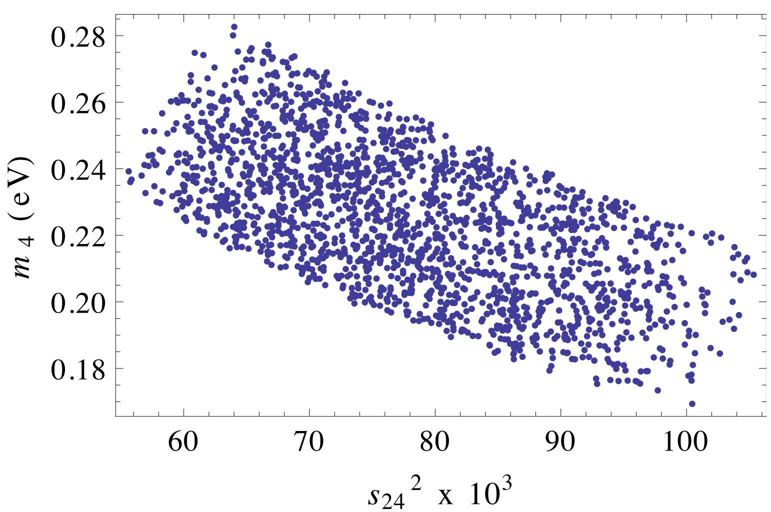
Finally, one identifies $\dfrac{E^2}{F}\,\eta_\alpha \eta_\beta \equiv m_4 U_{\alpha 4} U_{\beta 4} \Rightarrow$ <u>correlations</u>

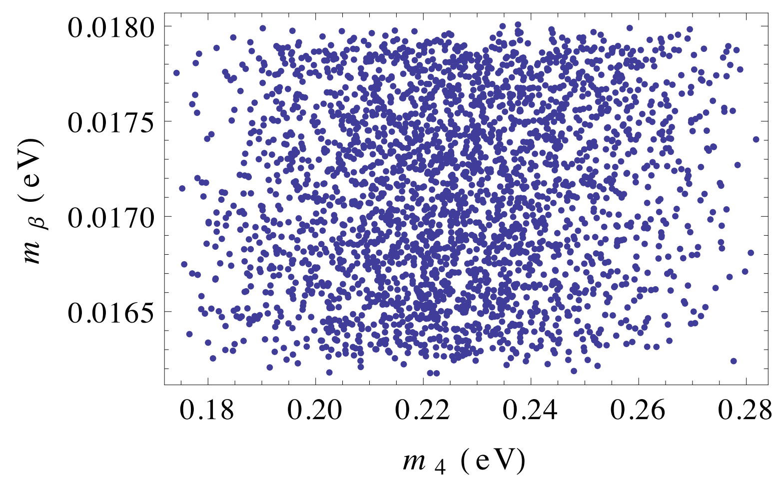
Numerical results

Normal hierarchy, case 1 $D\,\epsilon_\alpha^2 \ll (E^2/F)\,\eta_\alpha^2$



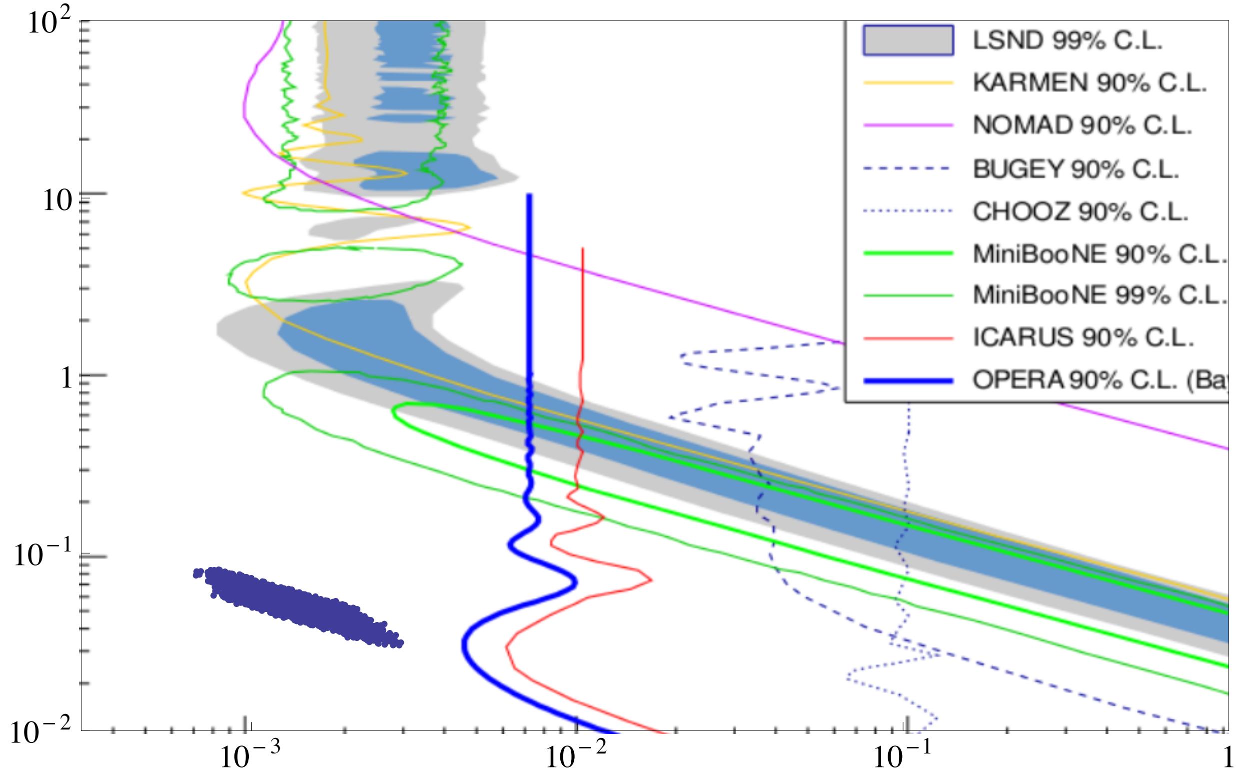




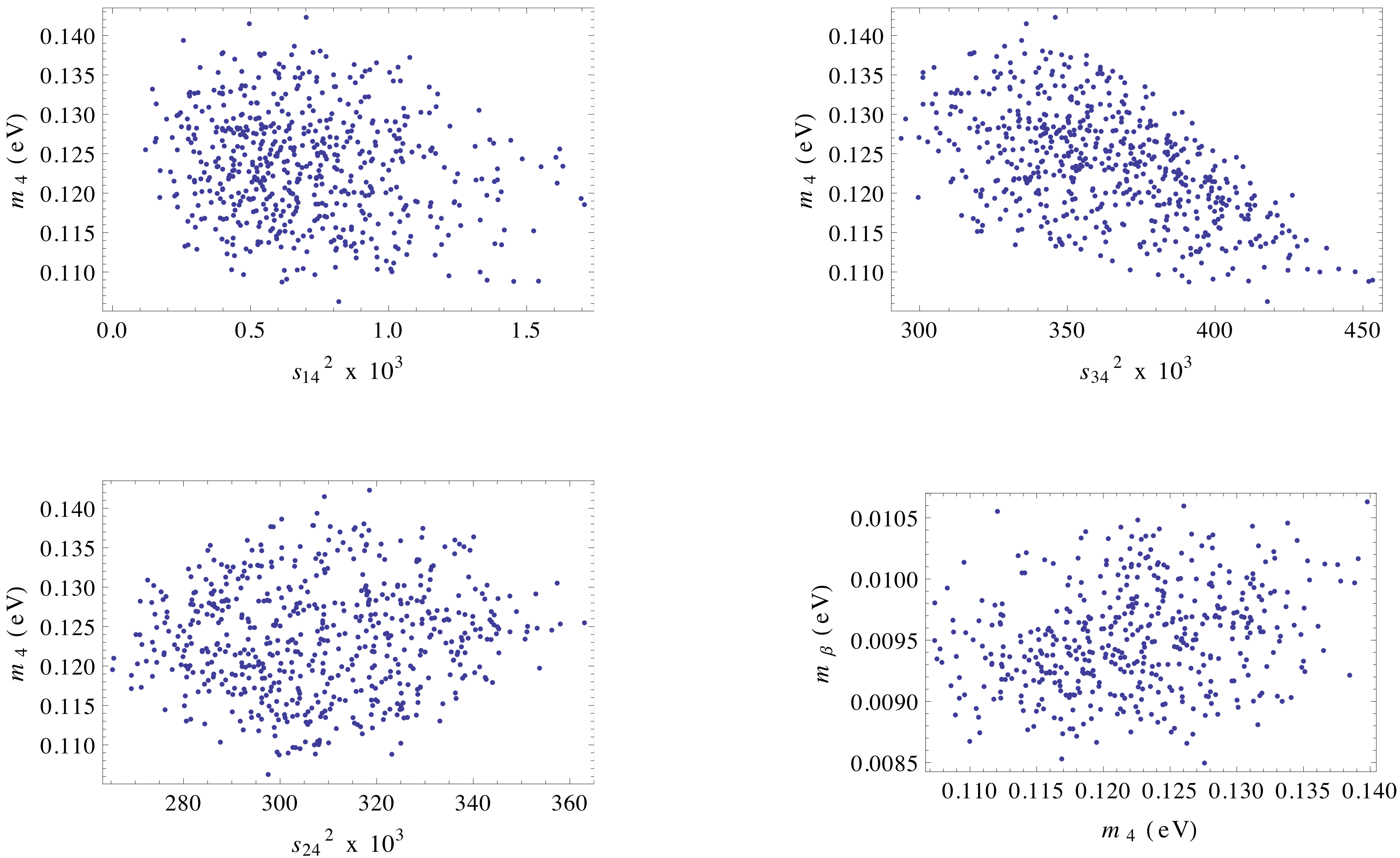


Not relevant to the reactor anomaly

Not relevant to LSND / MiniBooNE

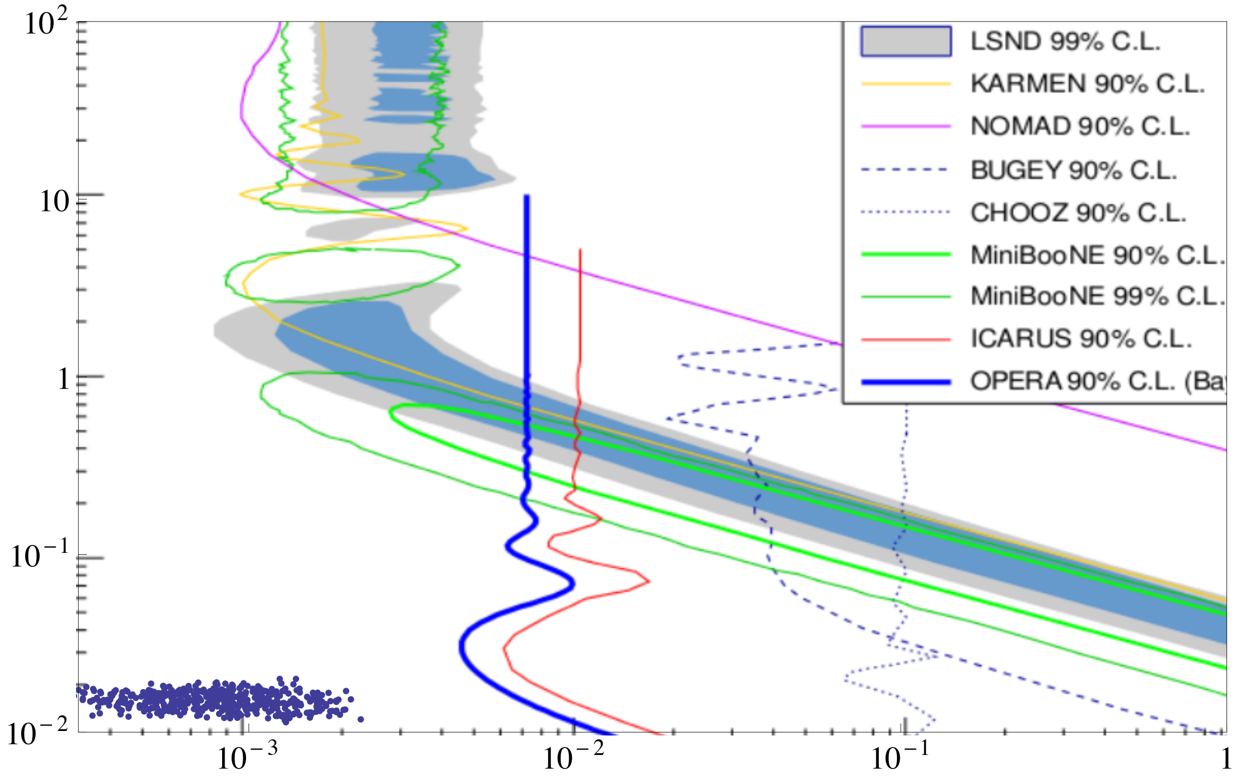


Normal hierarchy, case 2 $\quad (E^2/F)\,\eta_\alpha^2 \ll D\,\epsilon_\alpha^2$



Not relevant to the reactor anomaly

Not relevant to LSND / MiniBooNE



Inverted hierarchy

No numerical solution found so far

Under study

Conclusions

Sterile neutrino as a pseudo-Goldstone fermion within R-parity violating supersymmetry provides a surprisingly predictive scenario

Correlations between the sterile neutrino mass and the active-sterile mixing (in spite of a large number of parameters)

Does not explain the reactor neutrino anomaly nor LSND/MiniBooNE, but could be tested in future appearance experiments

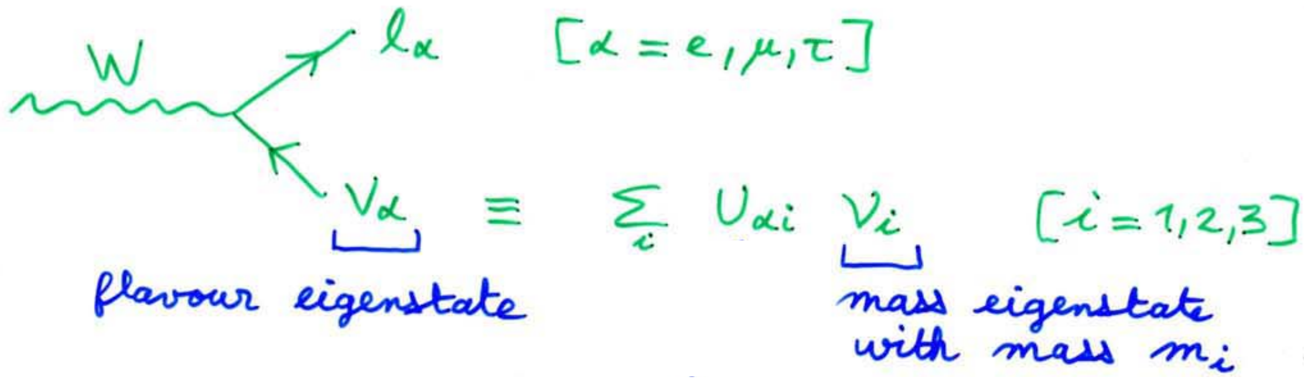
Does not seem to be consistent with an inverted hierarchy in the active neutrino sector (to be confirmed)

In progress...

BACK UP

Active-sterile neutrino mixing

Standard case (3 flavours):



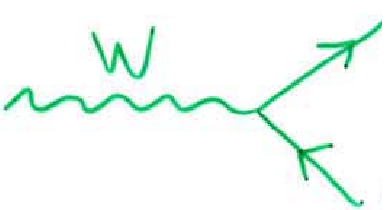
Add a sterile neutrino:

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

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:



e^-

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

2-flavour oscillations:

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

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

N-flavour oscillations:

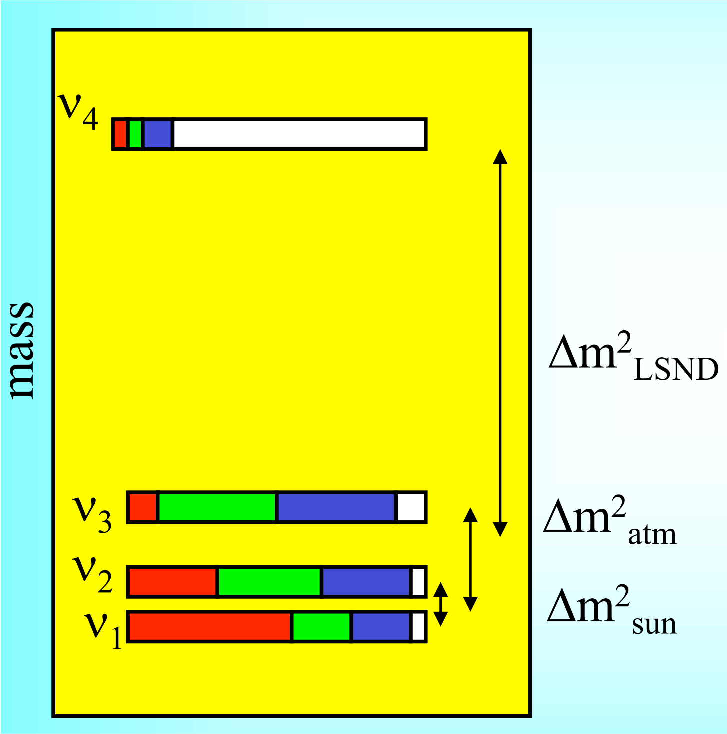
$$\begin{aligned} P_{\nu_\alpha \to \nu_\beta (\bar\nu_\alpha \to \bar\nu_\beta)} \;=\; & \delta_{\alpha\beta} - 4 \sum_{i<j} \mathrm{Re}\left(U_{\alpha i} U^\star_{\beta i} U^\star_{\alpha j} U_{\beta j}\right) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) \\ & \mp 2 \sum_{i<j} \mathrm{Im}\left(U_{\alpha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

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

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

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

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

Experimental situation

Several experimental anomalies suggest the existence of sterile neutrinos

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

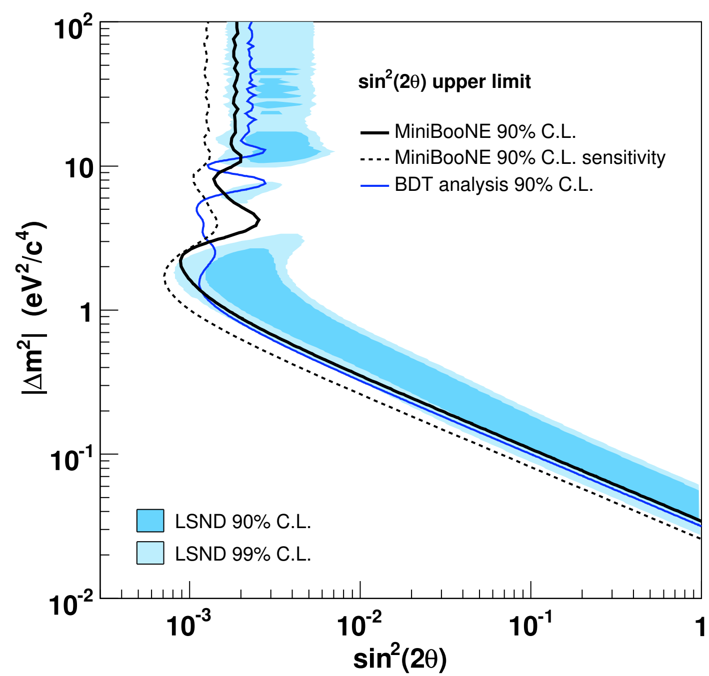
Excess of $\bar{\nu}_e$ events over background at 3.8 σ (still controversial)
Not observed by KARMEN

<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

⇒ increase of the flux by about 3%

⇒ deficit of antineutrinos in SBL reactor experiments

mean observed to predicted rate 0.943 ± 0.023

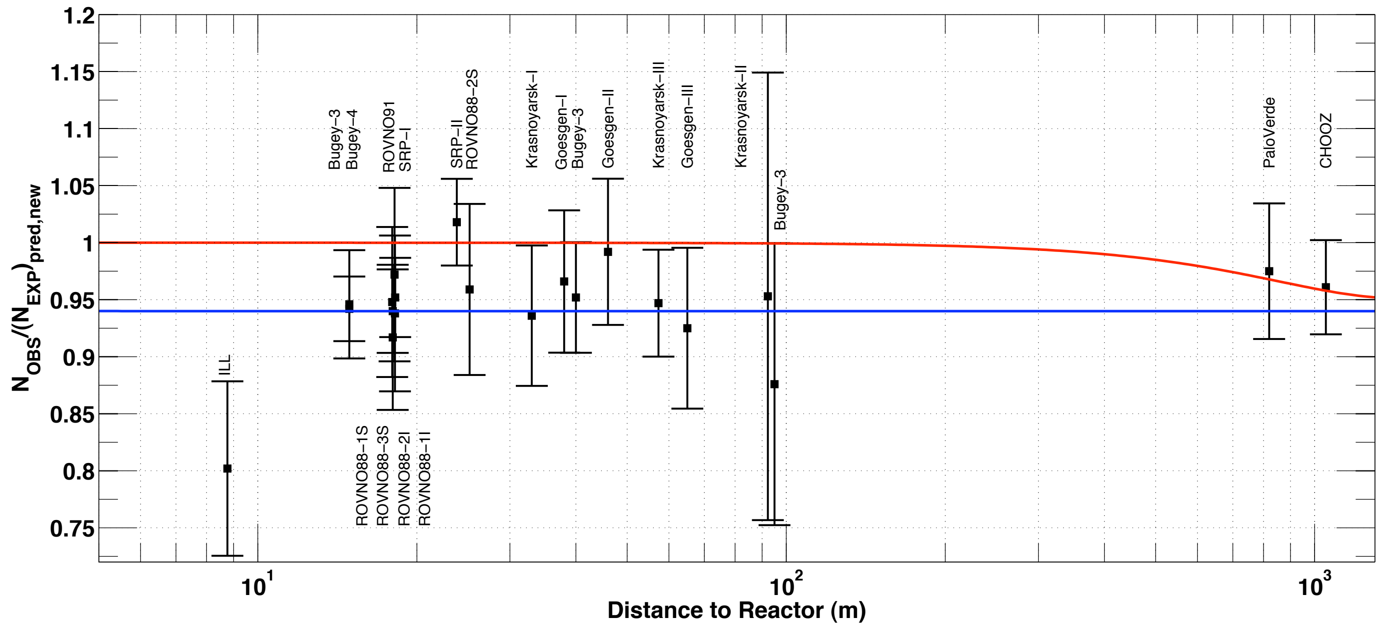


FIG. 5. Illustration of the short baseline reactor antineutrino anomaly. The experimental results are compared to the prediction without oscillation, taking into account the new antineutrino spectra, the corrections of the neutron mean lifetime, and the off-equilibrium effects. Published experimental 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).

G. Mention et al.

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)

Other implications of sterile neutrinos

<u>Tritium beta decay:</u>

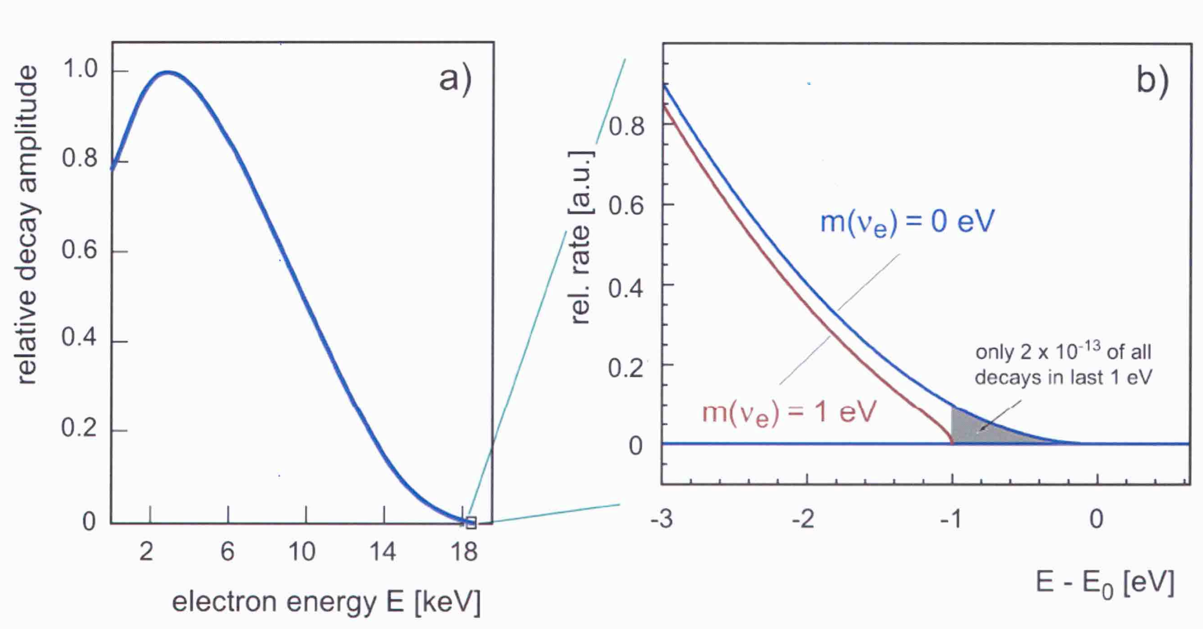
$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$ $\qquad E_0 = m_{^3H} - m_{^3He}$

The electron energy spectrum is given by:

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

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): $m_{\nu_e} < 2.2\,\text{eV} \quad (95\%\ \text{C.L.})$

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

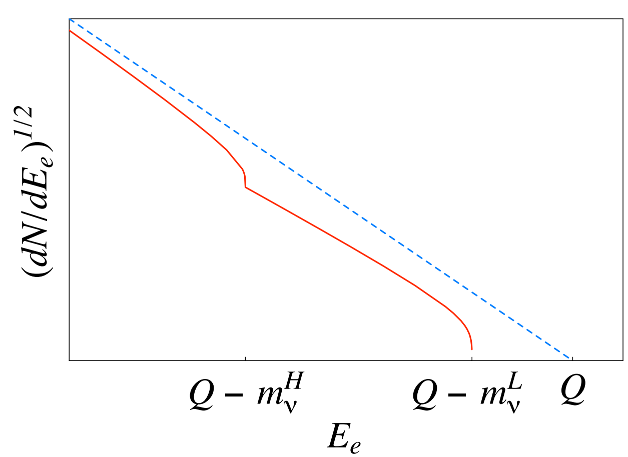
$$\frac{dN}{dE_e} = R(E_e) \sum_i |U_{ei}|^2 \sqrt{(E_0 - E_e)^2 - m_i^2}\, \Theta(E_0 - E_e - m_i)$$

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):

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

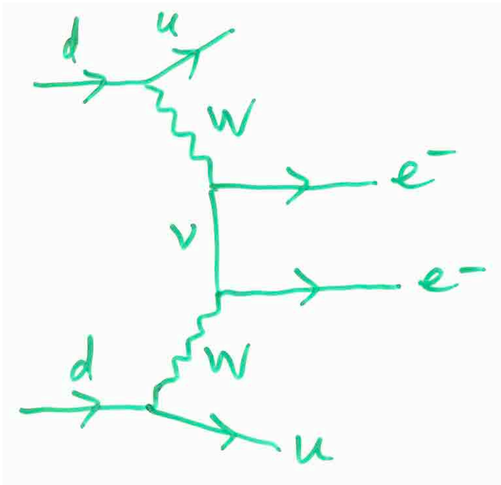


(also: upper bound on m4 from beta decay)

Neutrinoless double beta decay:

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

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

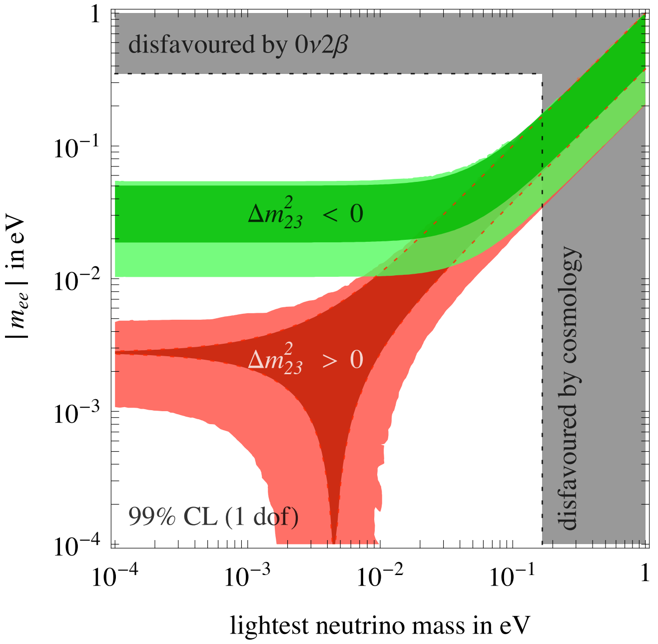


Sensitive to the effective mass parameter:

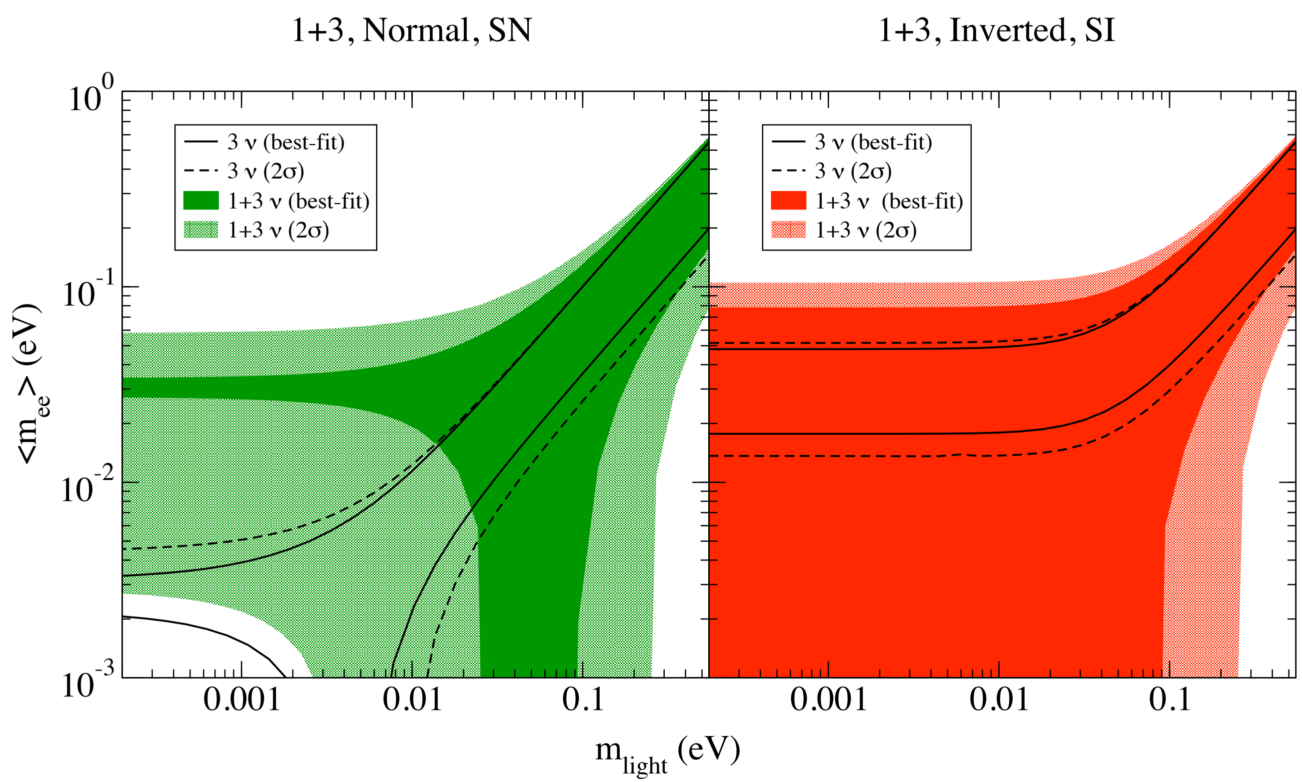
$$m_{\beta\beta} \equiv \sum_i m_i U_{ei}^2$$

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



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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