# 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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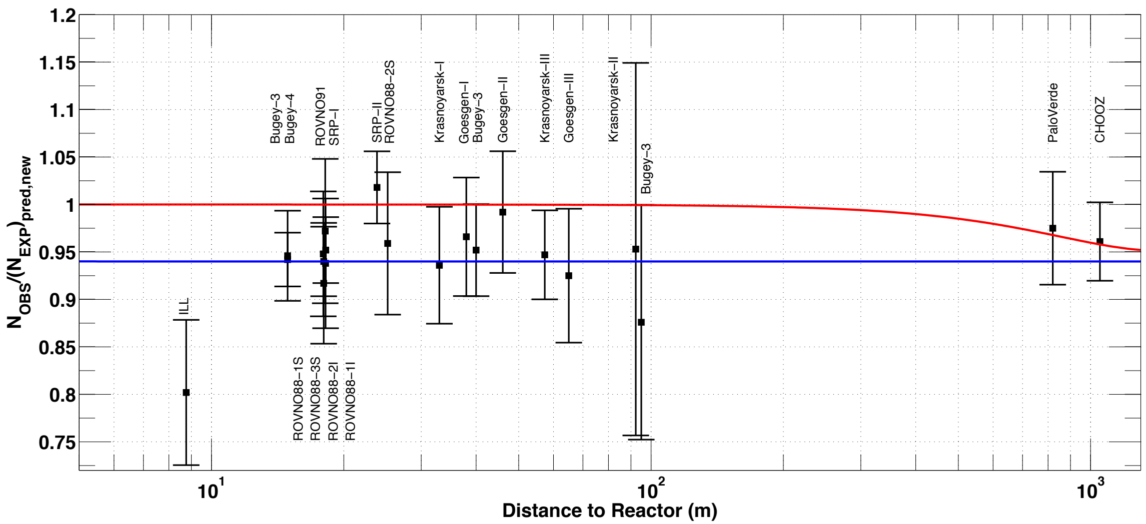
# Introduction and motivations

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]

# Experimental situation

Several experimental anomalies suggest the existence of sterile neutrinos

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

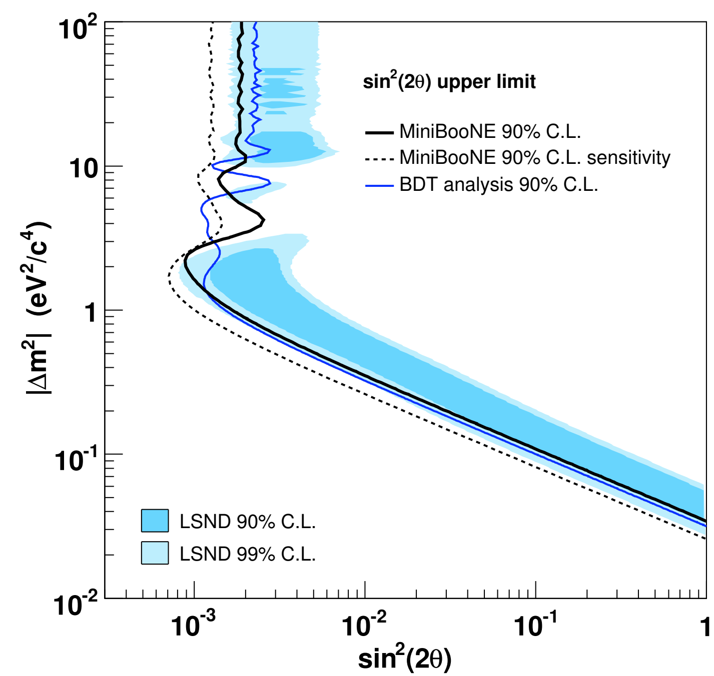
Excess of $\bar{\nu}_e$ events over background at 3.8 $\sigma$ (still controversial)
Not observed by KARMEN

MiniBooNE:

$\nu_\mu \to \nu_e$ data: no excess in the 475-1250 MeV range, but unexplained 3$\sigma$ $\nu_e$ 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

G. Mention et al.

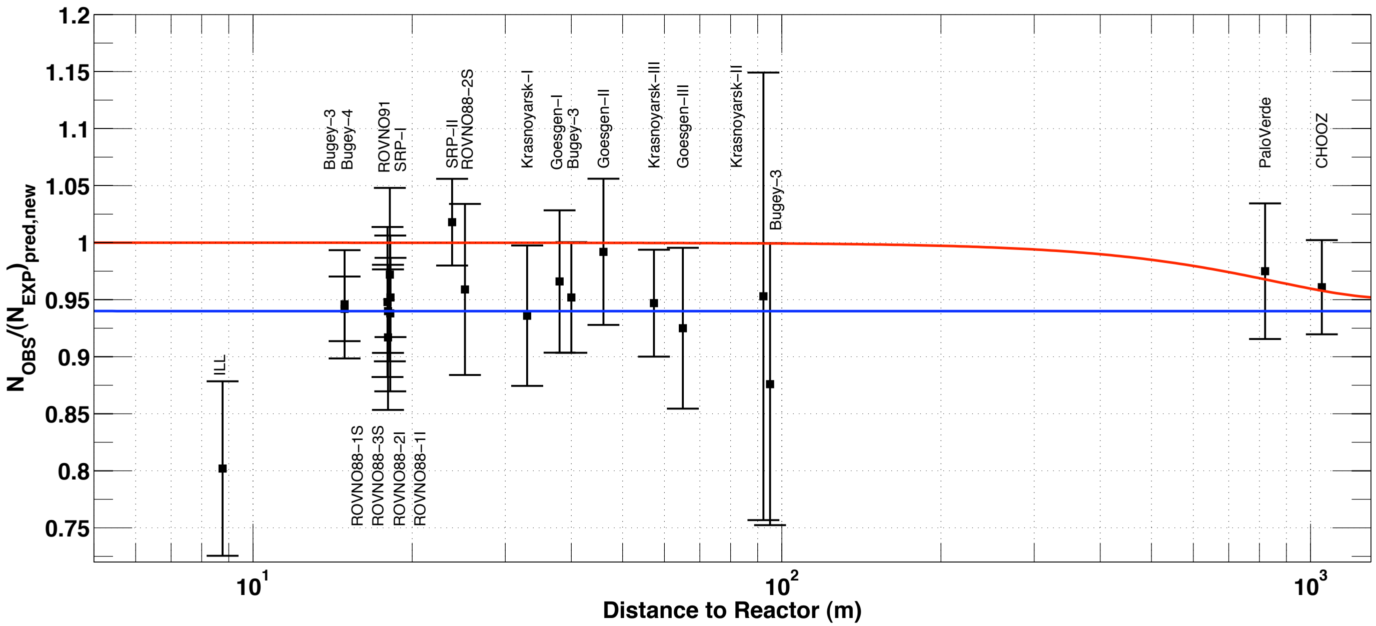



FIG. 5. Illustration of the short baseline reactor antineutrino anomaly. The experimental results are compared to the prediction without oscillation, taking into account the new antineutrino spectra, the corrections of the neutron mean lifetime, and the off-equilibrium effects. Published experimental errors and antineutrino spectra errors are added in quadrature. The mean averaged ratio including possible correlations is $0.943 \pm 0.023$. 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 $\nu_e$ with respect to predictions
R = 0.86 ± 0.05
[tension with $\nu_e$ - 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 all data with an additional (or even 2) sterile neutrinos: tension between appearance (LSND/MiniBooNE antineutrino data) and disappearance experiments (reactors, $\nu_\mu$ disappearence experiments)
+ tension between LSND and MiniBooNE neutrino data

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 $\nu_{L1}$ and $\nu_{L2}$ are admixtures of the active neutrino $\nu_L$ 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

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

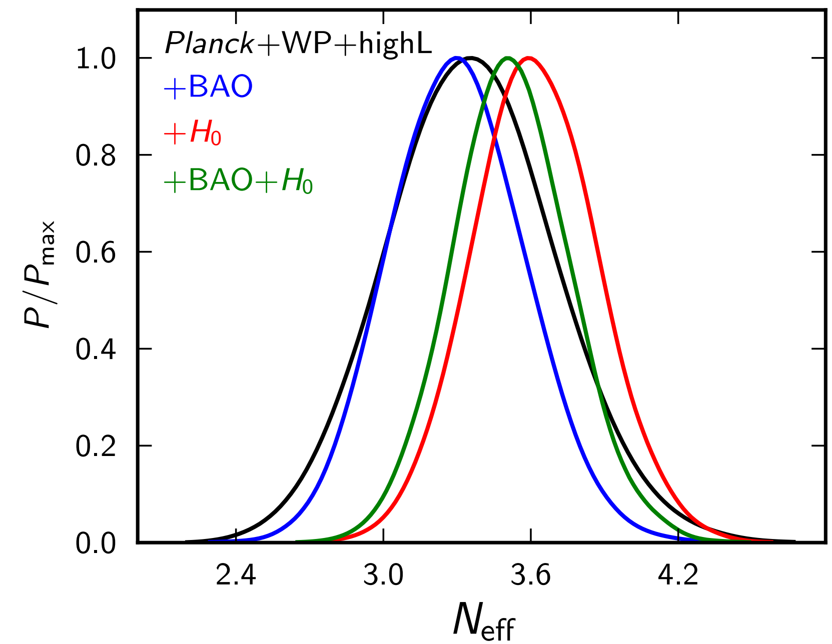
$$N_{\rm eff} = 3.30^{+0.54}_{-0.51} \quad (95\%\,{\rm C.L.})$$

[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]

# 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 U(1) 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 $A \to A + i\eta f$

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 $\int d^4\theta \, \frac{1}{M_P} (A + A^\dagger)^2 (X + X^\dagger) \; , \quad \langle X \rangle = F\theta^2$

⇒ low-scale supersymmetry breaking needed

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

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

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

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

After minimization of the scalar potential, $H_u$, $L_\alpha$ get vevs (assume <A> = 0)
$\Rightarrow$ non-canonical kinetic terms for $H_u$ and $L_\alpha$

→ redefine $H_u$ and $L_\alpha = (H_d, L_i)$ 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) $\lambda^e_{0jk} = \lambda^e_j \delta_{jk}$, $\lambda^e_j$ 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 $H_u^0, H_d^0, \nu^i, A$ are not canonical, the neutralino mass matrix receives contribution from the Kähler potential and mixes $\chi$ 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 $\mu_i/\mu$ 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

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

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 $C_{ud}, C_u, C_{\bar{d}d}, C_{\bar{\imath}\jmath}$ (Rp-conserving) and $C_{u\imath}, C_{\bar{d}\imath}$ (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 $i, j \to \alpha, \beta = e, \mu, \tau$

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 the active neutrino parameters are known (neglecting CPV), one can "reconstruct" the sterile neutrino parameters using [if the first term dominates]

$$m_2 \simeq -\frac{E^2}{F}\,\vec{\zeta}^{\,2}\,, \qquad m_3 \simeq D\,, \qquad U_{\alpha 1} \simeq (\zeta_e, \zeta_\mu, \zeta_\tau)\,/\,|\vec{\zeta}|\,,$$

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

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

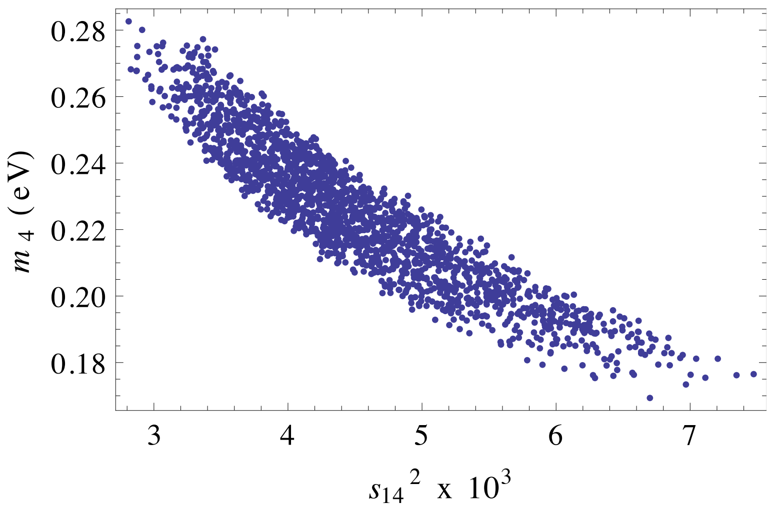
and $\kappa \equiv \left(|\xi_\mu\,\xi_\tau|^2 + |\xi_e\,\xi_\tau|^2 + |\xi_e\,\xi_\mu|^2\right)^{1/4}$

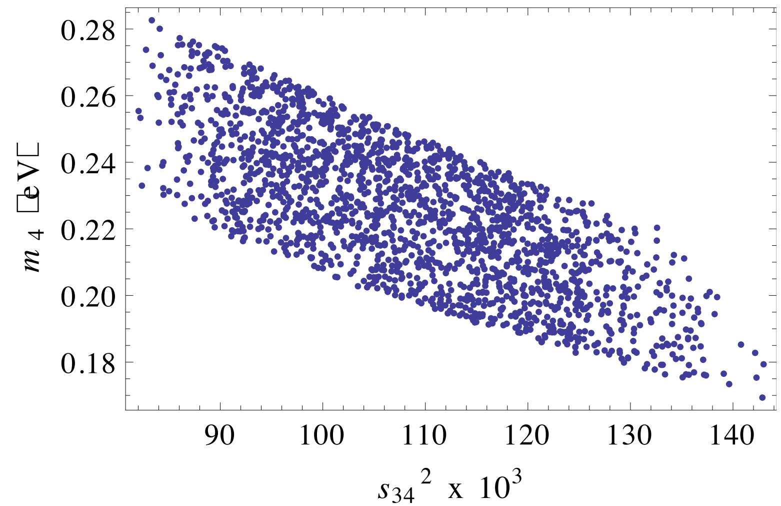
In the reconstruction process, one obtains the $\zeta_\alpha^2$ as a function of $\kappa/\vec{\zeta}^{\,2}$, which is the solution of a polynomial of degree 4. Among the solutions, only the ones that satisfy the constraint $\vec{\zeta}^{\,2} \le 1$ (if any) are acceptable

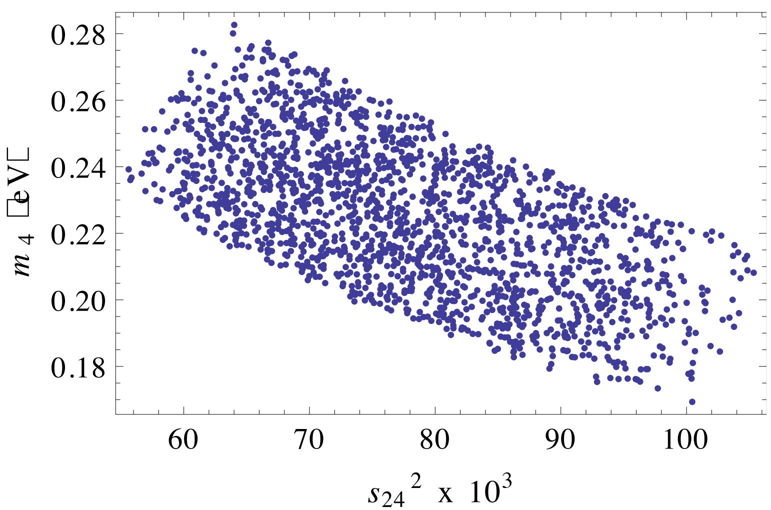
Finally, one identifies $\dfrac{E^2}{F}\,\eta_\alpha \eta_\beta \equiv m_4\,U_{\alpha 4} U_{\beta 4} \;\Rightarrow$ correlations

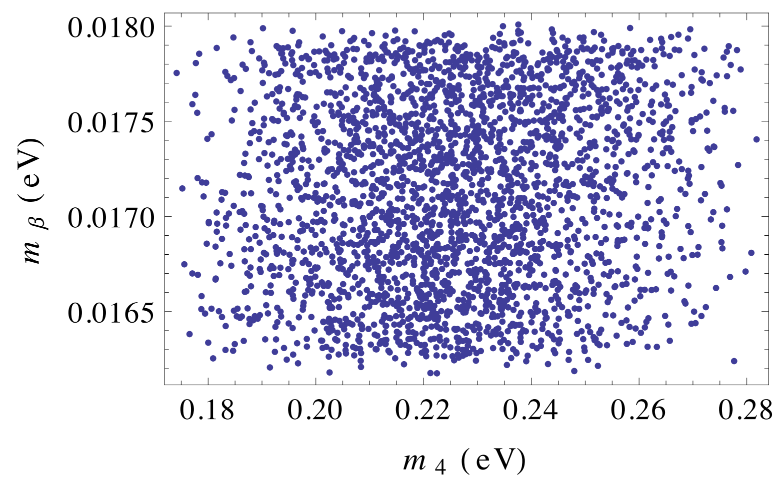
# Numerical results

## Normal hierarchy, solution 1



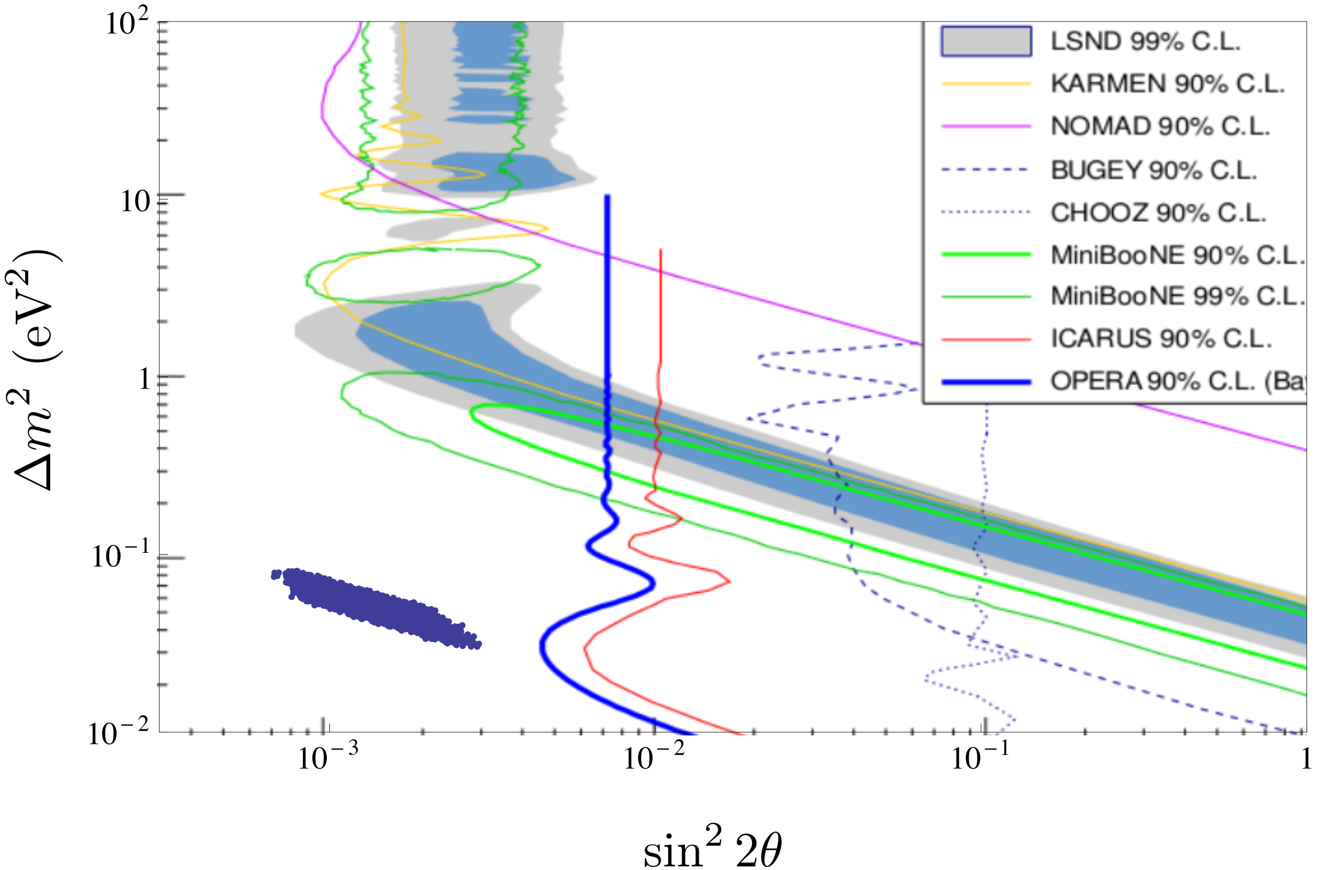



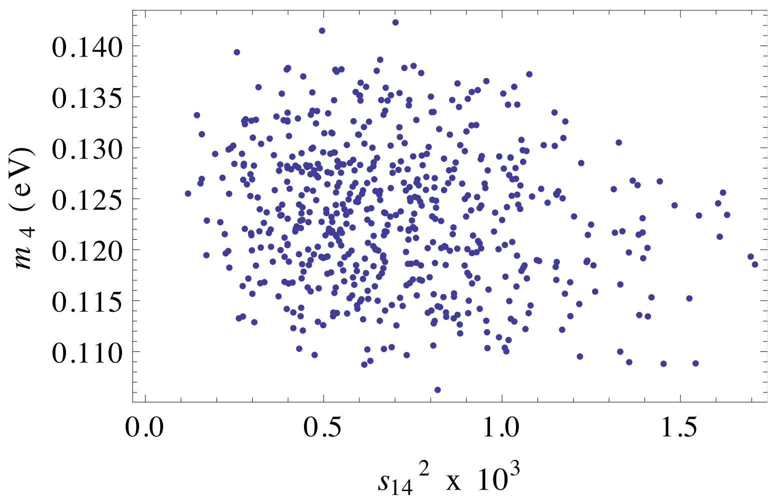



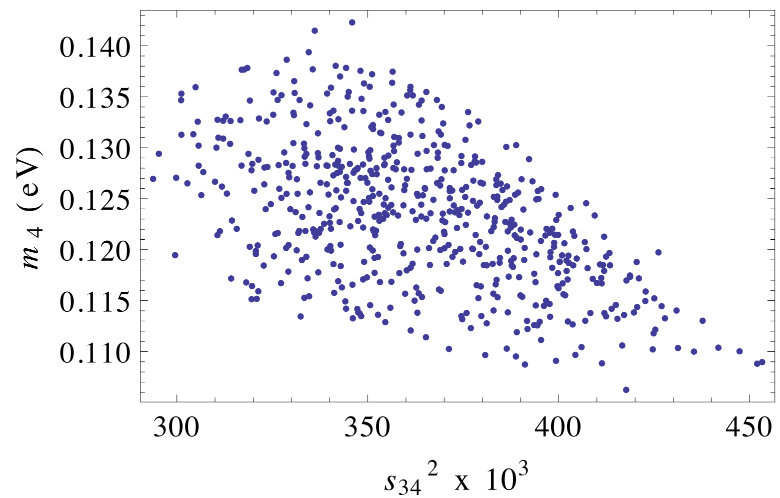
Not relevant to the reactor anomaly

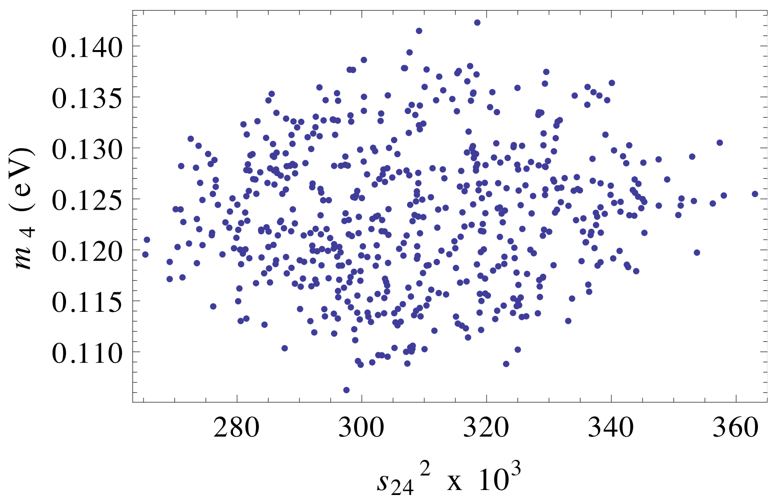
Not relevant to LSND / MiniBooNE

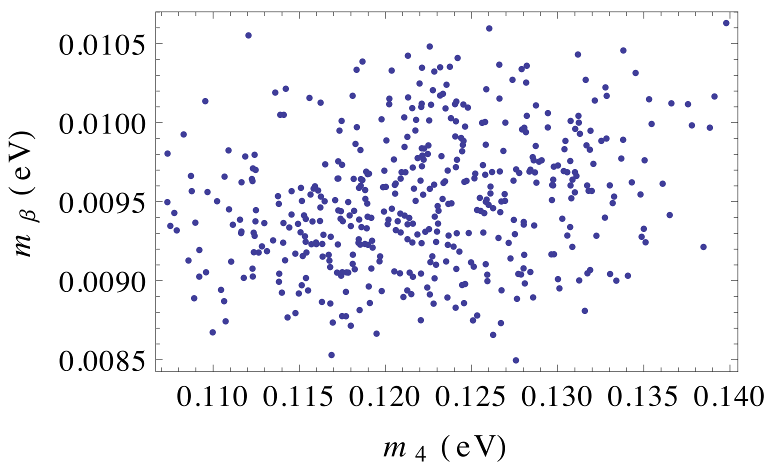


# Normal hierarchy, solution 2



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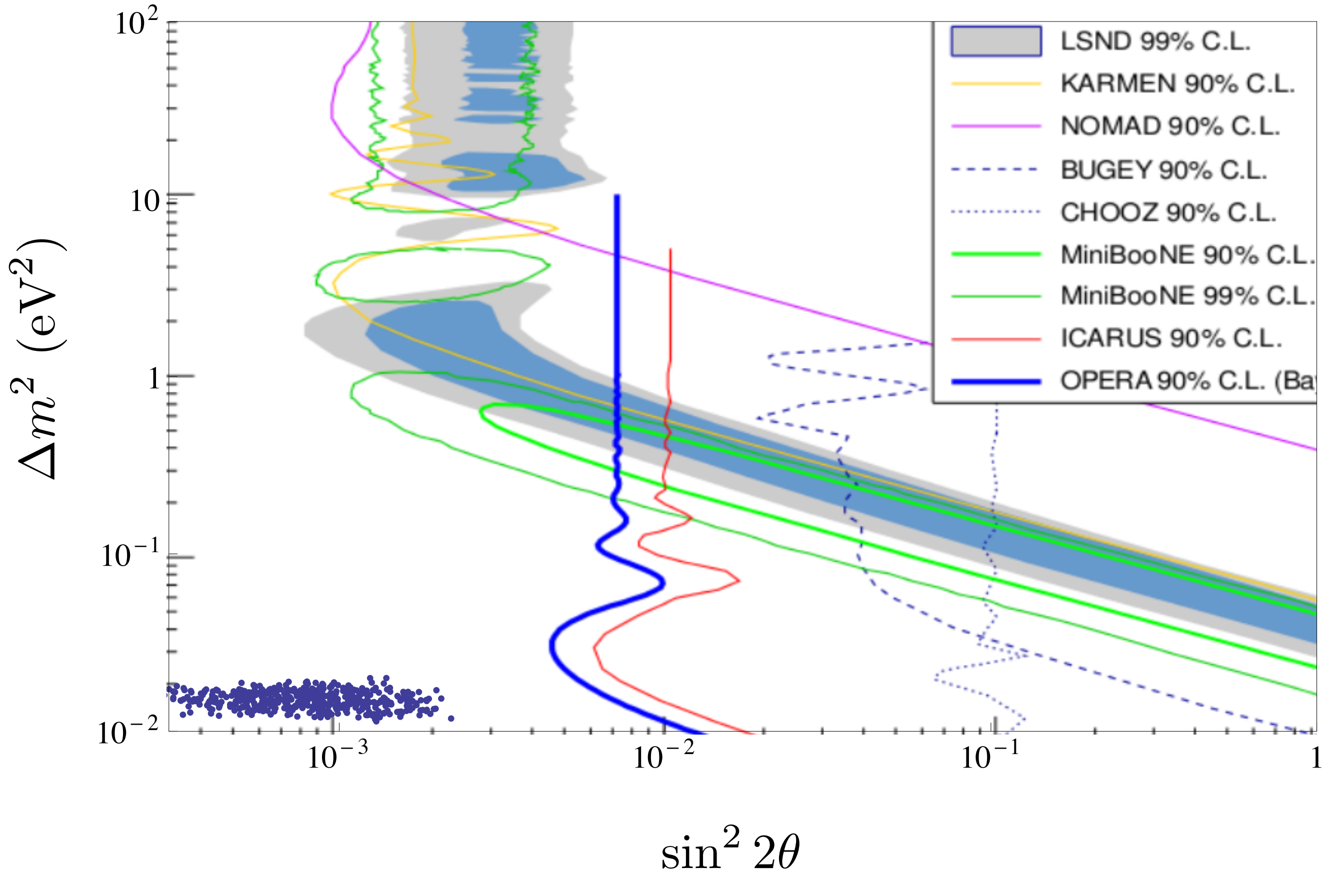


## Inverted hierarchy

In this case one has $(m_\nu)_{\alpha\beta} = \sum_{i=1}^{2} m_i\, U_{\alpha i} U_{\beta i} = D\, \epsilon_\alpha \epsilon_\beta - \frac{E^2}{F}\, \eta_\alpha \eta_\beta$

with $m_2 \simeq m_1$ and $m_3 = 0$

This requires a tuning of $D \simeq E^2/F$ at the $1\%$ level

Furthermore the structure of the mass matrix implies

$$m_4 \sum_\alpha (U_\nu)^2_{\alpha 4} \geq \sqrt{\Delta m^2_{\mathrm{atm}}} \simeq 0.05\,\mathrm{eV}$$

$$m_4 \leq 1\,\mathrm{eV} \implies \sum_\alpha (U_\nu)^2_{\alpha 4} \geq 0.05$$

This may allow to accommodate the LSND signal and/or the reactor anomaly (to be checked numerically)

→ 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)

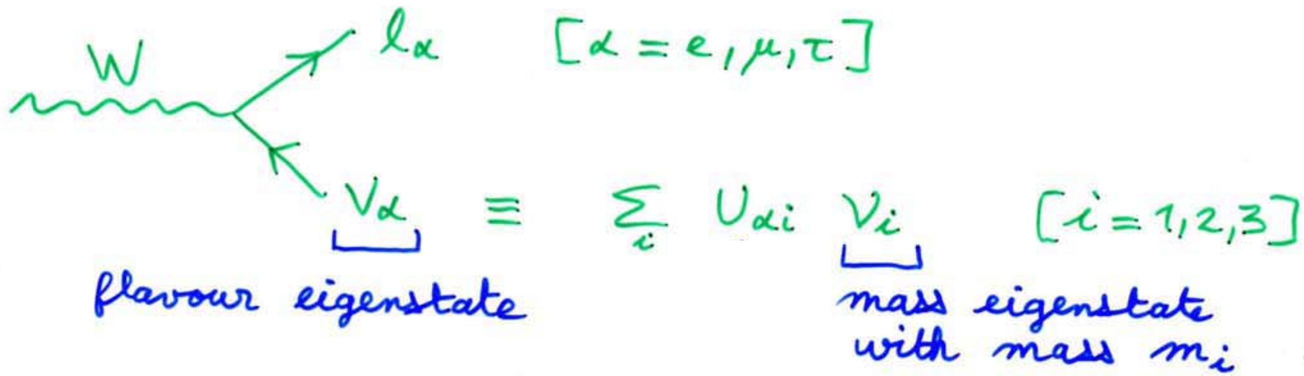
Normal hierarchy case: does not explain the reactor neutrino anomaly nor LSND/MiniBooNE, but could be tested in future appearance experiments

Inverted hierarchy case under investigation

# BACK UP

# Active-sterile neutrino mixing

Standard case (3 flavours):



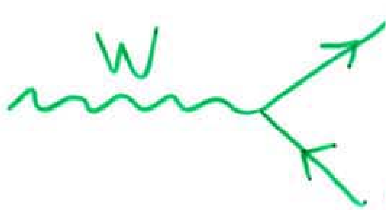

Add a sterile neutrino:

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

$\nu_s$ flavour eigenstate
$\nu_4$ mass eigenstate (m4)

U = 4x4 unitary matrix

Only $\nu_e, \nu_\mu, \nu_\tau$ 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:

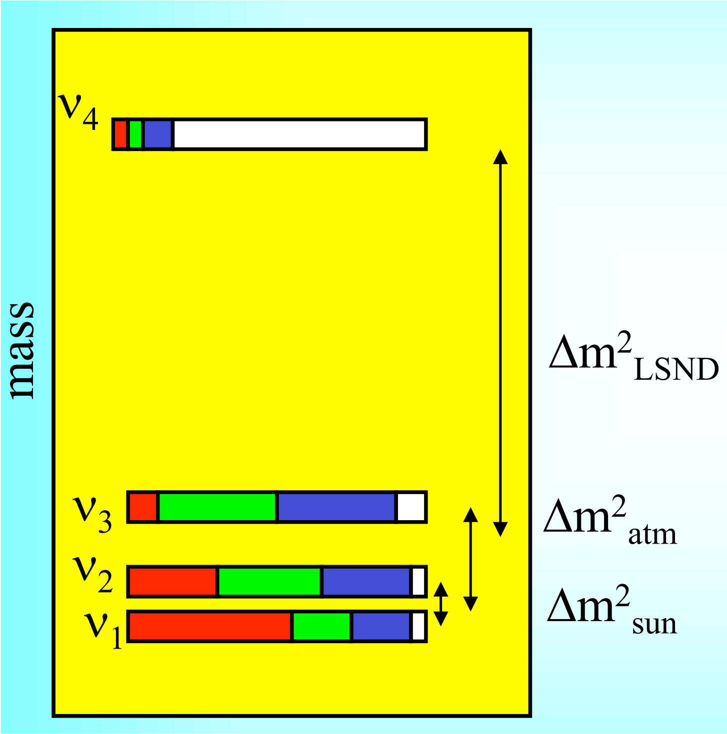
$$P_{\nu_\alpha \to \nu_\beta (\bar\nu_\alpha \to \bar\nu_\beta)} = \delta_{\alpha\beta} - 4 \sum_{i<j} \mathrm{Re}\left(U_{\alpha i} U^\star_{\beta i} U^\star_{\alpha j} U_{\beta j}\right) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$
$$\mp 2 \sum_{i<j} \mathrm{Im}\left(U_{\alpha i} U^\star_{\beta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

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 $\Delta m^2_{ij}$'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 $\nu_s$, and
$\nu_4$ mainly composed of $\nu_s$ + 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 $\sin^2 2\theta_{\alpha\beta} \equiv 4\,|U_{\alpha 4}U_{\beta 4}|^2$