Theory of neutrino masses and oscillations

Lecture 3

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- Dirac and Majorana neutrinos
- mechanisms of neutrino mass generation
- sterile neutrinos

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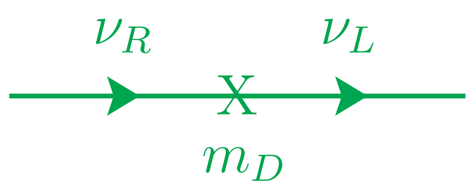
Massive neutrinos – Dirac versus Majorana

Dirac mass term

The simplest way to describe a massive neutrino is to add a ν_R to the SM and to write a Dirac mass term, as for the other fermions:

$$\mathcal{L}^{\text{Dirac}}_{\text{mass}} = -m_D\left(\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L\right) \equiv -m_D\, \bar{\nu}_D \nu_D \qquad \nu_D \equiv \nu_L + \nu_R$$

The massive neutrino ν_D is a Dirac fermion (2 independent chiralities)



$$\Delta L = 0 \qquad \Delta T^3 = \frac{1}{2}$$

[note: ν_R is an SM gauge singlet]

not invariant under $SU(2)_L \times U(1)_Y$ but can be generated from a Yukawa coupling to the SM Higgs doublet (which has weak isospin 1/2)

$$\mathcal{L}_{\text{Yuk.}} = -y_D\, \bar{L}\, i\sigma^2 H^* \nu_R + \text{h.c.} \quad \longrightarrow \quad m_D = y_D \frac{v}{\sqrt{2}}$$

$$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \qquad \langle H \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \qquad m_\nu \lesssim 1\,\text{eV} \;\Rightarrow\; y_D \lesssim 10^{-11}$$

caveat : possible to write a Majorana mass term for ν_R $\Rightarrow$ end up with two Majorana neutrinos rather than one Dirac neutrino (see later)

Majorana mass term

Preliminary remark: can form a RH spinor from ν_L $\qquad (\, C\gamma_\mu^T C^{-1} = -\gamma_\mu \,)$

$$\nu_R^c \equiv C\,\overline{\nu}_L^T \quad \sim \quad \text{CP conjugate of } \nu_L \qquad (\bar{\nu}_L \equiv \nu_L^\dagger \gamma^0)$$

C = charge conjugation matrix; enters the charge conjugate of a Dirac spinor

$$\psi(x) \;\rightarrow\; \psi^c(x) \equiv C\bar{\psi}^T(x) \quad \text{describes the corresponding antifermion}$$

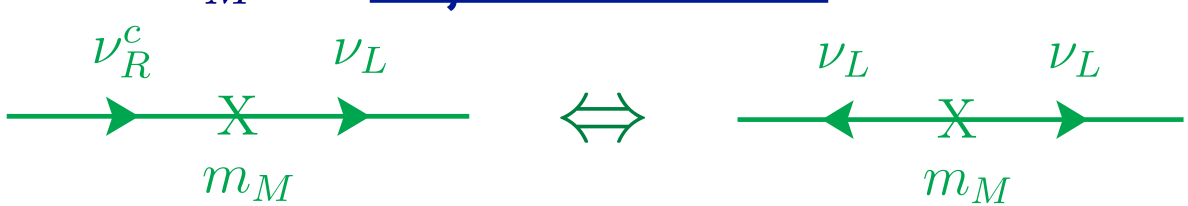
$\Rightarrow$ the existence of a LH neutrino (ν_L) implies the existence of a RH antineutrino ($C\bar{\nu}_L^T \equiv \nu_R^c \sim \bar{\nu}_R$)

Now, with ν_L and ν_R^c, can write a (Majorana) mass term :

$$\mathcal{L}_{\rm mass}^{\rm Maj.} = -\frac{1}{2}\, m_M \left(\bar{\nu}_L \nu_R^c + \bar{\nu}_R^c \nu_L\right) \equiv -\frac{1}{2}\, m_M\, \bar{\nu}_M \nu_M \qquad \nu_M \equiv \nu_L + \nu_R^c$$

The massive neutrino $\nu_M = \nu_L + \nu_R^c$ satisfies the Majorana condition

$\nu_M = \nu_M^c \;\rightarrow$ Majorana fermion



$\Delta L = 2 \qquad \Delta T^3 = 1$

A Majorana mass term violates lepton number (signature of a Majorana neutrino). It cannot be generated from a coupling to the SM Higgs doublet, which has a T = 1/2 $\Rightarrow$ neutrino masses require an extension of the SM

Dirac versus Majorana neutrino

A Dirac neutrino is different from its antiparticle ($\nu \neq \nu^c$)

$\Rightarrow$ describes 4 degrees of freedom: $\nu\uparrow, \ \nu\downarrow, \ \bar{\nu}\uparrow, \ \bar{\nu}\downarrow$ [or $\nu_R, \nu_L, \bar{\nu}_R, \bar{\nu}_L$]

Described by a 4-component spinor $\nu_D = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$, with independent LH and RH components

A Majorana neutrino satisfies the condition $\nu = \nu^c = C\bar{\nu}^T$

$\Rightarrow$ describes only 2 degrees of freedom: $\nu\downarrow, \ \bar{\nu}\uparrow$ [or $\nu_L, \bar{\nu}_R$]

Can be described by a 4-component spinor $\nu_M = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$, but the LH and RH components are not independent, as $\nu_M = \nu_M^c \Rightarrow \nu_R = \nu_R^c = C\bar{\nu}_L^T$

The Majorana condition is inconsistent with any conserved additive quantum number: if ψ possesses a conserved quantum number q,

$$\psi \to e^{i\theta q}\,\psi \quad \Rightarrow \quad \psi^c \to e^{-i\theta q}\,\psi^c$$

Thus only neutrinos (not quarks, charged leptons) can be Majorana fermions

For the same reason, one cannot rephase a Majorana neutrino

$\Rightarrow$ 2 additional physical phases in the PMNS matrix wrt the Dirac case

How to distinguish Majorana from Dirac neutrinos?

Dirac and Majorana neutrinos have the same gauge interactions, since weak interactions only involve ν_L and its antiparticle $\bar{\nu}_R \sim \nu_R^c$ (ν_R , if it exists, is an SM gauge singlet and does not interact at all)

For the same reason, oscillations probabilities are the same for Dirac and Majorana neutrinos (production and detection are weak interaction processes: only ν_L and $\bar{\nu}_R$ can be produced and detected) (*)

The only practical difference between Dirac and Majorana neutrinos lies in their mass term, which violates lepton number by 2 units in the Majorana case

→ the Majorana nature of neutrinos can be established in $\Delta L = 2$ processes such as neutrinoless double beta decay

(*) note: $P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$ corresponds to CP violation, not C violation, and is possible both for Dirac and Majorana neutrinos, precisely because $\bar{\nu}_\alpha \equiv \bar{\nu}_{R\alpha} =$ CP conjugate of $\nu_\alpha \equiv \nu_{L\alpha}$

Mechanisms of neutrino mass generation

Simplest possibility: add a RH neutrino to the SM

In addition to the Dirac mass term $-m_D\,\bar{\nu}_L N_R + \mathrm{h.c.}$, must write a Majorana mass term for the RH neutrino, which is allowed by all (non-accidental) symmetries of the SM (or justify its absence):

$$-\frac{1}{2}\,M\,\bar{N}^c_L N_R + \mathrm{h.c.} = -\frac{1}{2}\,M\,N_R^T C N_R + \mathrm{h.c.} \qquad \Delta L = 2 \qquad \Delta T^3 = 0$$

[only lepton number, if imposed, can forbid this term]

Mass eigenstates : write the mass terms in a matrix form and diagonalize

$$\mathcal{L}_{\mathrm{mass}} = -\frac{1}{2}\begin{pmatrix}\bar{\nu}_L & \bar{N}^c_L\end{pmatrix}\begin{pmatrix}0 & m_D \\ m_D & M\end{pmatrix}\begin{pmatrix}\nu^c_R \\ N_R\end{pmatrix} + \mathrm{h.c.}$$

$$= -\frac{1}{2}\begin{pmatrix}\bar{\nu}_{L1} & \bar{\nu}_{L2}\end{pmatrix}\begin{pmatrix}m_1 & 0 \\ 0 & m_2\end{pmatrix}\begin{pmatrix}\nu^c_{R1} \\ \nu^c_{R2}\end{pmatrix} + \mathrm{h.c.}$$

where $\begin{cases}\nu_{L1} = \cos\theta\,\nu_L - \sin\theta\,N^c_L \\ \nu_{L2} = \sin\theta\,\nu_L + \cos\theta\,N^c_L\end{cases}$

Defining $\nu_{Mi} \equiv \nu_{Li} + \nu^c_{Ri}$ (such that $\nu_{Mi} = \nu^c_{Mi}$), one can see that the mass eigenstates are 2 Majorana neutrinos with masses m1 and m2 :

$$\mathcal{L}_{\rm mass} = -\frac{1}{2} \sum_{i=1,2} m_i \, \bar{\nu}_{Li} \nu^c_{Ri} + \text{h.c.} = -\frac{1}{2} \sum_{i=1,2} m_i \, \bar{\nu}_{Mi} \nu_{Mi}$$

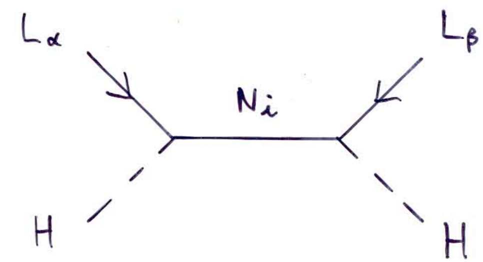
<u>"Seesaw" limit :</u> $M \gg M_W \gtrsim m_D$

Minkowski - Gell-Mann, Ramond, Slansky
Yanagida - Mohapatra, Senjanovic

(N_R = gauge singlet $\Rightarrow$ M unconstrained by electroweak symmetry breaking)

$$m_1 \simeq -m_D^2/M \ll M_W \qquad m_2 \simeq M \gg M_W$$

$$\sin\theta \simeq \frac{m_D}{M} \ll 1 \quad \Rightarrow \quad \nu_{L1} \simeq \nu_L \,, \quad \nu^c_{R2} \simeq N_R$$



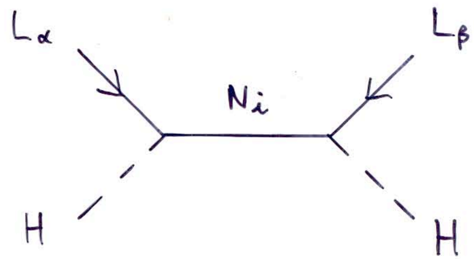
→ the light Majorana neutrino is essentially the SM neutrino

→ natural explanation of the smallness of neutrino masses

<u>New physics interpretation :</u> M = scale of the new physics responsible for lepton number violation – can a priori lie anywhere between $\sim 10^{15}\,\text{GeV}$ (a larger M would give $m_\nu < \sqrt{|\Delta m^2_{31}|} \simeq 0.05\,\text{eV}$, unless $y_D > 1$) and the weak scale (low-scale seesaw mechanism), or even below

3-generation (type I) seesaw mechanism ($i = 1, 2, 3;\ \alpha = e, \mu, \tau$)

$$\mathcal{L}^{I}_{\text{seesaw}} = -Y_{i\alpha}\overline{N}_{Ri}L_\alpha H - \frac{1}{2}M_i\overline{N}_{Ri}N^c_{Ri} + \text{h.c.}$$



$$\Longrightarrow \qquad (M_\nu)_{\alpha\beta} = -\sum_i \frac{Y_{i\alpha}Y_{i\beta}}{M_i}v^2$$

Light neutrino mass matrix: $M_\nu = -Y^T M^{-1} Y v^2 = U^* D_\nu U^\dagger$

U = lepton mixing (PMNS) matrix $\qquad \nu_\alpha = \sum_i U_{\alpha i}\,\nu_i$

$$D_\nu = \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix} \qquad U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i(\sigma+\delta)} \end{pmatrix}$$

Natural realization of the seesaw mechanism in Grand Unified Theories (GUTs) based on the SO(10) gauge group

- SM quarks and leptons fit in a single 16-dimensional representation of SO(10), which also contains a right-handed neutrino:

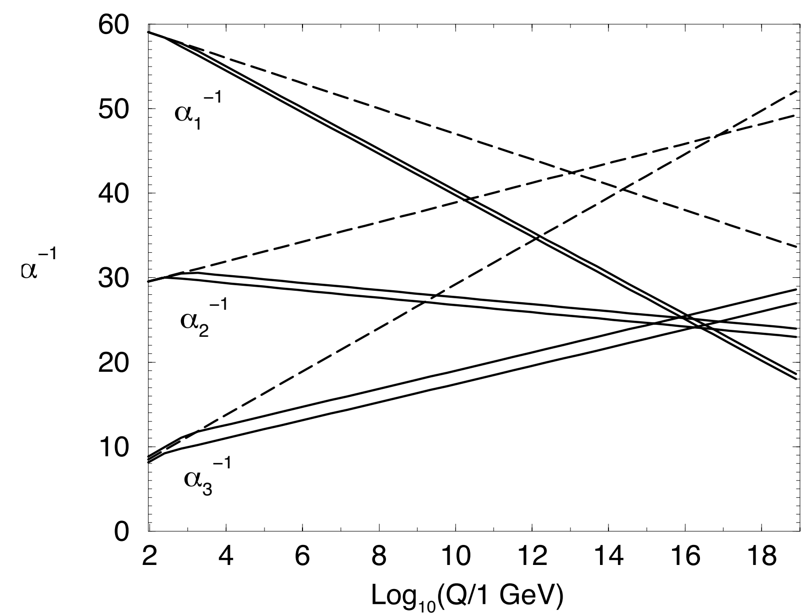
$$\mathbf{16}_i = (Q_i, u_i^c, d_i^c, L_i, e_i^c, N_i^c) \qquad (i = 1, 2, 3)$$

- the scale of RH neutrino masses is associated with the breaking of the B-L symmetry, which is a generator of SO(10), and is typically broken at or a few orders of magnitude below the GUT scale M_{GUT}

$$M_i \ \longleftrightarrow \ M_{B-L} \ \longleftrightarrow \ SO(10) \text{ gauge symmetry breaking}$$

(≠ arbitrary scale, even if model dependent)

- natural values of the Dirac Yukawa coupling $y_D = \sqrt{2}\, m_D / v$ (i.e. $y_D \sim 1$) give $m_\nu = m_D^2 / M \sim 0.05\,\mathrm{eV}$ for $M \sim 10^{15}\,\mathrm{GeV}$, near the unification scale in supersymmetric extensions of the SM, $M_{\mathrm{GUT}} \approx 2 \times 10^{16}\,\mathrm{GeV}$



Right-handed neutrinos imply a deep (even if minimal) modification of the SM

- without RHNs, gauge invariance and renormalizability imply that B and L are global symmetries of the SM, only broken by quantum effects (anomalies)

- with RHNs, this is no longer true: a $\Delta L = 2$ Majorana mass term is allowed both by gauge invariance and renormalizability

Dirac neutrinos remain a viable possibility, but lepton number has to be imposed: no longer automatic

<u>Theoretical prejudices against Dirac neutrinos:</u>

- must impose lepton number

- need very small Yukawa couplings: $m_\nu = y_\nu \langle H \rangle \qquad \langle H \rangle = 174\,\mathrm{GeV}$

$$m_\nu \lesssim 1\,\mathrm{eV} \quad \Longrightarrow \quad y_\nu \lesssim 10^{-12} \qquad\qquad (y_e \lesssim 10^{-6})$$

[this makes the SM flavour puzzle, i.e. the unexplained hierarchy of fermion masses / Yukawa couplings even stronger, but it might be explained by a theory of flavour]

Theoretical prejudices for Majorana neutrinos:

- lepton number violated in many extensions of the SM

- any mechanism generating neutrino masses without RHNs gives Majorana neutrinos

- natural in SO(10) Grand Unified Theories (GUTs), left-right symmetric theories (based on the gauge group $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ or larger), supersymmetry without R-parity

- possible explanation of the small neutrino masses (seesaw mechanism...)

- open the possibility of generating the baryon asymmetry of the Universe via leptogenesis (B-L violation and CP violation are necessary ingredients of baryogenesis)

While Majorana neutrinos are theoretically compelling, only experiment (neutrinoless double beta decay, or possibly some other $\Delta L = 2$ leptonic process) will tell whether neutrinos are Dirac or Majorana particles

Alternative mechanisms of neutrino (Majorana) mass generation :

- other versions of the seesaw mechanism with heavy SU(2) triplets (scalar [type II seesaw] or fermionic [type III seesaw]). Can be realized at high or low energy (with possibly new states accessible at colliders in the latter case)

- radiative models: neutrino masses generated at the one-loop (Zee model, supersymmetry with trilinear R-parity violation), two loop level (Babu-Zee model) or more. These are typically low-scale models, which can be tested at colliders and predict flavour-violating processes involving charged leptons

- more exotic: supersymmetric models with R-parity violation (in which lepton number is violated), extra spatial dimensions (*)…

(*) the minimal model with a flat extra dimensions, ν_L on the SM brane and ν_R in the bulk, predicted a mixing of ν_e with an infinite tower of sterile neutrinos, ans has been excluded by Super-Kamiokande and SNO

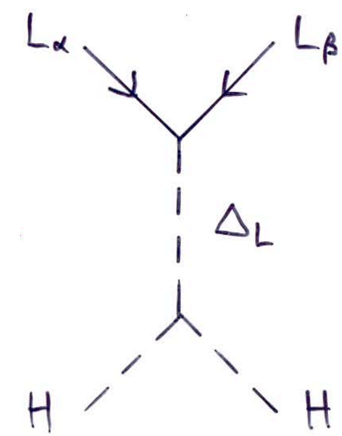
Type II seesaw mechanism: heavy scalar triplet exchange

The Majorana mass term $\mathcal{L}_{\rm m}^{\rm Maj.} = -\frac{1}{2}\, m_\nu\, \nu_L^T C \nu_L + \text{h.c.}$ has $\Delta T_3 = 1$
$\Rightarrow$ can be generated from a coupling to a Higgs triplet: [Gelimini, Roncadelli]

$$-\tfrac{1}{2}\, f_{\alpha\beta}\, L_\alpha^T C i\sigma^2 \Delta_L L_\beta + \text{h.c.} \qquad \Delta_L = \begin{pmatrix} \Delta^+ & \sqrt{2}\,\Delta^{++} \\ \sqrt{2}\,\Delta^0 & -\Delta^+ \end{pmatrix}$$

violation of lepton number in the scalar potential: $\frac{\mu}{2}\, H^T i\sigma^2 \Delta_L^\dagger H + \text{h.c.}$

need small vev v_Δ and/or small Yukawa coupling $f_{\alpha\beta}$



<u>Natural limit: heavy Higgs triplet</u> $\Rightarrow m_\nu$ suppressed by μ/M_Δ^2

→ type II seesaw mechanism Magg, Wetterich - Lazarides, Shafi, Wetterich
Mohapatra, Senjanovic - Schechter, Valle

$$(M_\nu)_{\alpha\beta} = f_{\alpha\beta}\, \frac{\mu}{M_\Delta^2}\, v^2$$

no need for small μ or $f_{\alpha\beta}$

also possibility of decoupling triplet mass / lepton number breaking scale :
low-scale lepton number breaking (<< GeV) possible

More economical in parameters than type I: $M_{\alpha\beta} \leftrightarrow f_{\alpha\beta}$

Type II seesaw can be realized in SO(10) GUTs, using the $SU(2)_L$ triplets present in the 54- and 126-dimensional Higgs representations

Type I and II can be simultaneously present in SO(10) models or in left-right symmetric theories with $SU(2)_L$ and $SU(2)_R$ triplets:

$$M_\nu = f_L v_L - Y f_R^{-1} Y \frac{v^2}{v_R} \qquad\qquad v_L = \mu v^2 / M_\Delta^2$$

f_L, f_R (v_L, v_R) = $SU(2)_L$ and $SU(2)_R$ triplet couplings (vevs)

Often an underlying left-right symmetry ensures $f_L = f_R \equiv f$

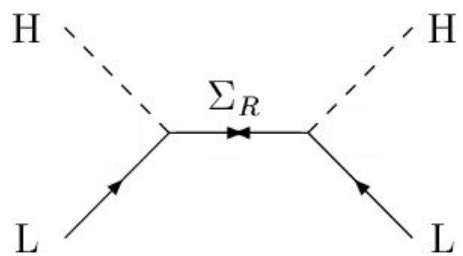
Type III seesaw mechanism: heavy fermion triplet exchange

The Majorana mass term $\mathcal{L}_{\rm m}^{\rm Maj.} = -\frac{1}{2} m_\nu \nu_L^T C \nu_L + \text{h.c.}$ can also be generated from a coupling to a fermion Higgs triplet:

$$-Y_\alpha^\Sigma \bar{L}_\alpha \Sigma \, i\sigma^2 H^* + \text{h.c.} \qquad\qquad \Sigma = \begin{pmatrix} \Sigma^0 & \sqrt{2}\,\Sigma^+ \\ \sqrt{2}\,\Sigma^- & -\Sigma^0 \end{pmatrix}$$

<u>Natural limit: heavy Higgs triplet</u> $\Rightarrow m_\nu$ suppressed by $1/M_\Sigma$

→ type III seesaw mechanism   Foot, Lew, He, Joshi - Ma



$$(M_\nu)_{\alpha\beta} = \frac{Y_\alpha^\Sigma Y_\beta^\Sigma}{M_\Sigma} v^2$$

With a single Σ, M_ν has rank one $\Rightarrow$ a single massive neutrino

$\Rightarrow$ at least two fermion triplets needed

Can be realized in SU(5) GUTs with a fermion in the adjoint representation

$$24_F \ni (1,3)_0 \oplus (1,1)_0 \qquad \bar{5}_\alpha \, 24_F 5_H \qquad \bar{5}_\alpha = (L_\alpha, d_\alpha^c),\ 5_H = (H, T)$$

→ type I+III seesaw mechanism

Radiative neutrino mass models

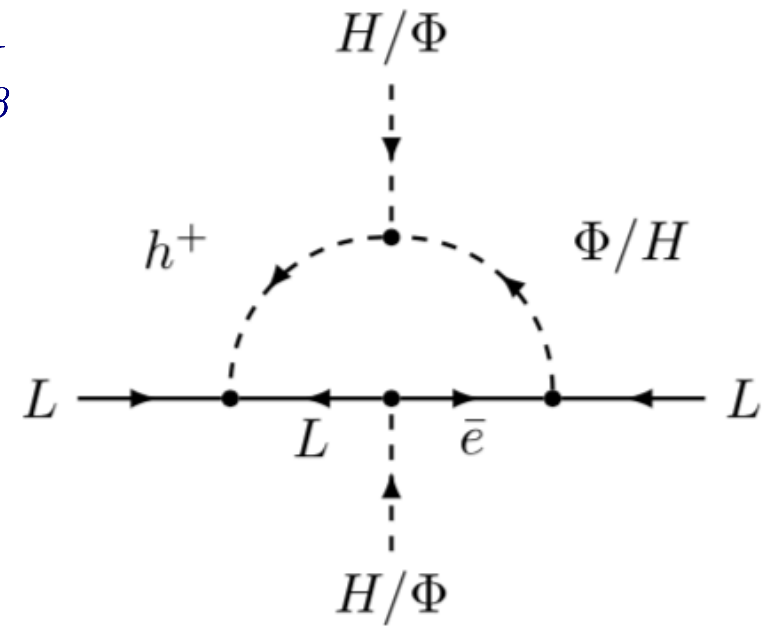
Zee model (1-loop)

Adding to the SM a second Higgs doublet Φ and a charged SU(2) singlet h^+ leads to the following leptonic Yukawa couplings + scalar trilinear coupling

$$\mathcal{L}_{\text{Zee}} \ni -Y^H_{\alpha\beta} \bar{L}_\alpha H e_{R\beta} - Y^\Phi_{\alpha\beta} \bar{L}_\alpha \Phi\, e_{R\beta} - f_{\alpha\beta} L^T_\alpha C^{-1} i\sigma^2 L_\beta - \mu H^\dagger i\sigma^2 \Phi^* h^+ + \text{h.c.}$$

where $f_{\beta\alpha} = -f_{\alpha\beta}$ and both H and Φ acquire a vev

$\Rightarrow$ charged lepton masses depend on both $Y^H_{\alpha\beta}$ and $Y^\Phi_{\alpha\beta}$, and neutrino masses arise at 1-loop

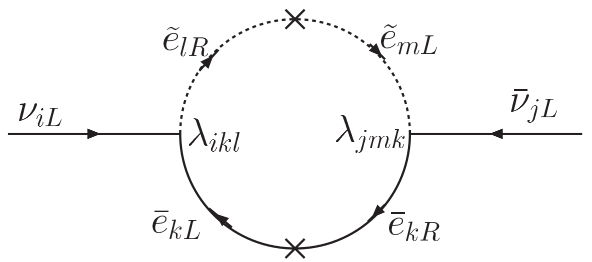


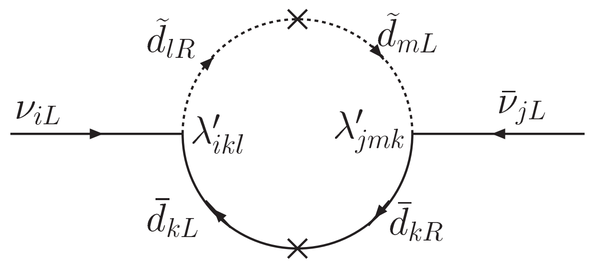
The testable signatures of this mechanism are exotic scalars and flavour-violating charged lepton decays such as $\mu \to e\,\gamma$

<u>Note</u>: the original Zee model had $Y^\Phi_{\alpha\beta} = 0$ and was predicting an inverted mass ordering with a near-maximal solar mixing angle, which is excluded by the data

Supersymmetry with trilinear R-parity breaking (1-loop)

Neutrino masses arise from quark-squark and lepton-slepton loops

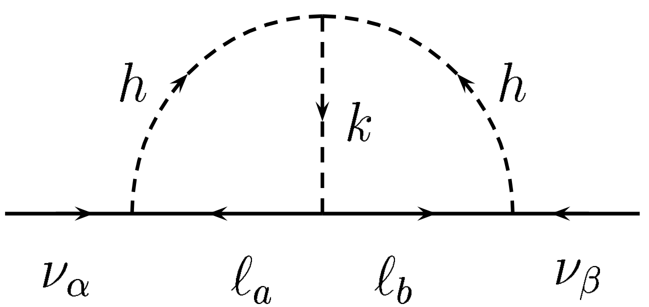




Zee-Babu model (2-loop)

introduce 2 charged SU(2) singlet scalars, h^+ and k^{++}, with couplings to leptons:

$$f_{\alpha\beta}\, L_\alpha^T C i\sigma^2 L_\beta h^+ + h'_{\alpha\beta} e_{R\alpha}^T C e_{R\beta} k^{++} + \text{h.c.}$$



Lepton number is violated by scalar couplings: $\mu\, h^+ h^+ k^{--} + \text{h.c.}$

Neutrino mass matrix: $(M_\nu)_{\alpha\beta} \sim \dfrac{8\mu}{(16\pi^2)^2 m_h^2} f_{\alpha\gamma} m_{e_\gamma} h_{\gamma\delta} m_{e_\delta} f_{\delta\beta}$

In addition to new exotic scalars, this mechanism predicts flavour-violating processes involving charged leptons, such as $\mu \to e\,\gamma$

Sterile neutrinos

Only 3 light neutrinos ($m_\nu < M_Z/2$) couple to the Z boson :

$$N_\nu \equiv \Gamma_Z^{\rm invisible} / \Gamma(Z \to \nu\bar{\nu})_{\rm SM} = 2.9840 \pm 0.0082 \qquad [\text{LEP}]$$

Still additional light neutrino species without electroweak interactions may exist. These "sterile neutrinos" would interact only through their mixing with the "active neutrinos" ν_e, ν_μ, ν_τ and affect their oscillations.

(eV-scale) sterile neutrinos have been invoked to explain experimental anomalies that cannot be accounted for within 3-flavour oscillations

Sterile neutrinos are present in models where the SM neutrino masses arise from their coupling to RH neutrinos with a Majorana mass. In the seesaw limit, the sterile neutrinos are very heavy and mix very weakly with the SM neutrinos. But in general, their masses may lie anywhere between the eV and the Grand Unification scale. Generic prediction : the lighter the sterile neutrinos, the stronger their mixing with active neutrinos

$$m_\nu \sim \frac{m_D^2}{M}\,, \quad m_s \sim M\,, \quad \sin\theta \sim \frac{m_D}{M} \qquad \Rightarrow \qquad \sin\theta \sim \sqrt{\frac{m_\nu}{m_s}}$$

Active-sterile neutrino mixing

Standard case (3 flavours)

3x3 lepton mixing matrix (PMNS)

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\, \nu_i$$

3 flavour eigenstates $(\alpha = e, \mu, \tau)$

3 mass eigenstates with masses mi $(i = 1, 2, 3)$

Add a sterile neutrino :

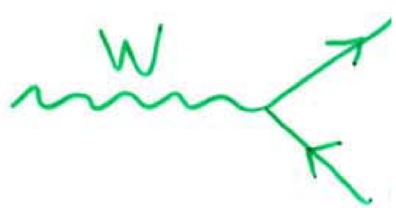
$$\nu_\alpha = \sum_{i=1}^{4} U_{\alpha i}\, \nu_i \qquad (\alpha = e, \mu, \tau, s)$$

ν_s flavour eigenstate

ν_4 mass eigenstate (m_4)

lepton mixing matrix U = 4x4 unitary matrix

Only ν_e, ν_μ, ν_τ couple to electroweak gauge boson, but all four mass eigenstates are produced in a weak process like beta decay



e^-

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

(if kinematically accessible, as assumed in the following)

New oscillation parameters : $\Delta m^2_{43}\,,\ \Delta m^2_{42}\,,\ \Delta m^2_{41}$

$\theta_{14}\,,\ \theta_{24}\,,\ \theta_{34} \qquad (\text{or } U_{e4},\, U_{\mu 4},\, U_{\tau 4})$

<u>Consider short baseline oscillations with</u> $\Delta m^2_{41} \gg \Delta m^2_{31}$

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

→ approximate $\Delta m^2_{31} = \Delta m^2_{21} = 0\,, \quad \Delta m^2_{43} = \Delta m^2_{42} = \Delta m^2_{41} \equiv \Delta m^2_{\mathrm{SBL}}$

$$P_{\nu_\alpha \to \nu_\alpha} \simeq 1 - 4\left(|U_{\alpha 1}|^2 + |U_{\alpha 2}|^2 + |U_{\alpha 3}|^2\right)|U_{\alpha 4}|^2 \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\equiv 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

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

$$P_{\nu_\alpha \to \nu_\beta} \simeq -4\,\mathrm{Re}\left[\left(U_{\alpha 1} U^*_{\beta 1} + U_{\alpha 2} U^*_{\beta 2} + U_{\alpha 3} U^*_{\beta 3}\right) U^*_{\alpha 4} U_{\beta 4}\right] \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\equiv \sin^2 2\theta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

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

Experimental status of oscillation anomalies

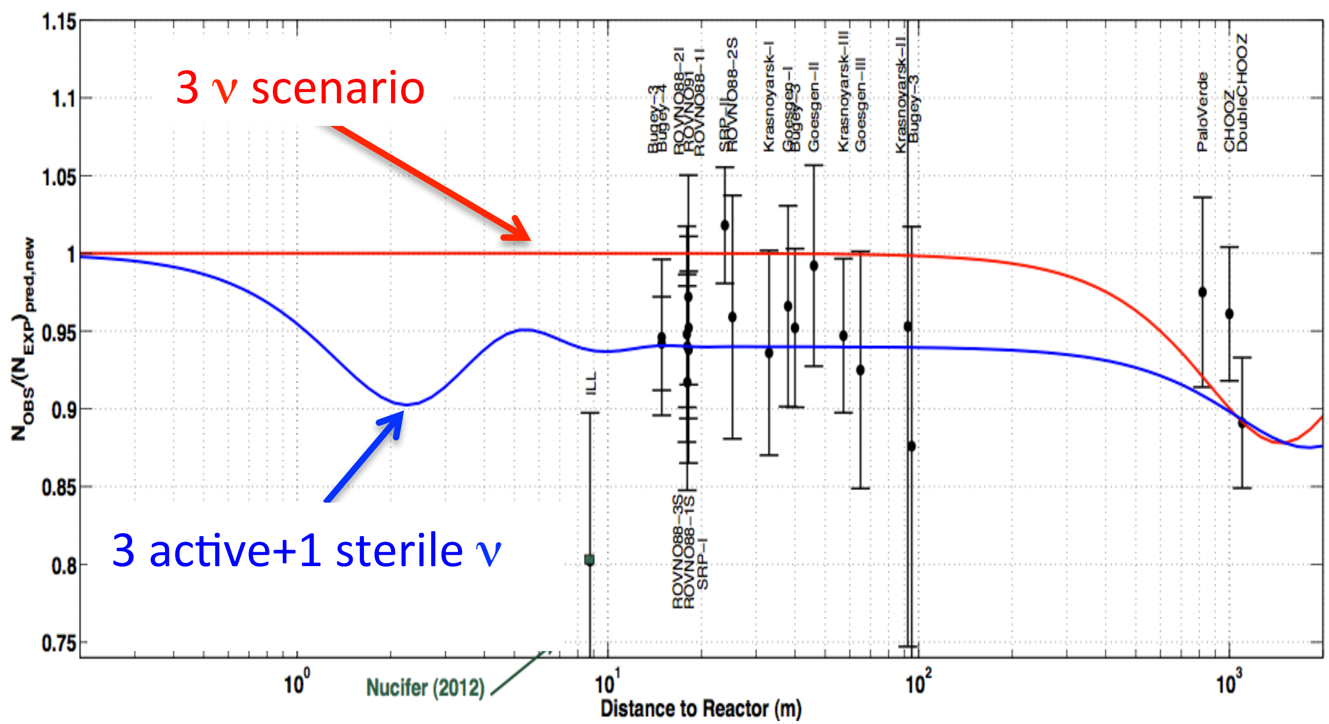
<u>Short-baseline $\nu_e(\bar{\nu}_e)$ disappearance experiments</u>

<u>The reactor antineutrino anomaly (RAA) [2011]</u>

New computation of the reactor $\bar{\nu}_e$ spectra [Th. Mueller et al., 2011 - P. Huber, 2011]
$\Rightarrow$ increase of the flux by about 3.5%
$\Rightarrow$ deficit of antineutrinos in SBL reactor experiments

Mean observed to predicted rate 0.943 ± 0.023 [G. Mention et al., arXiv:1101.2755]
(significance of 2.6 σ)

can be explained by
$\bar{\nu}_e \to \bar{\nu}_s$ oscillations
with $\Delta m^2_{41} \sim 1\,\mathrm{eV}^2$
and $\sin^2 2\theta_{ee} \sim 0.1$

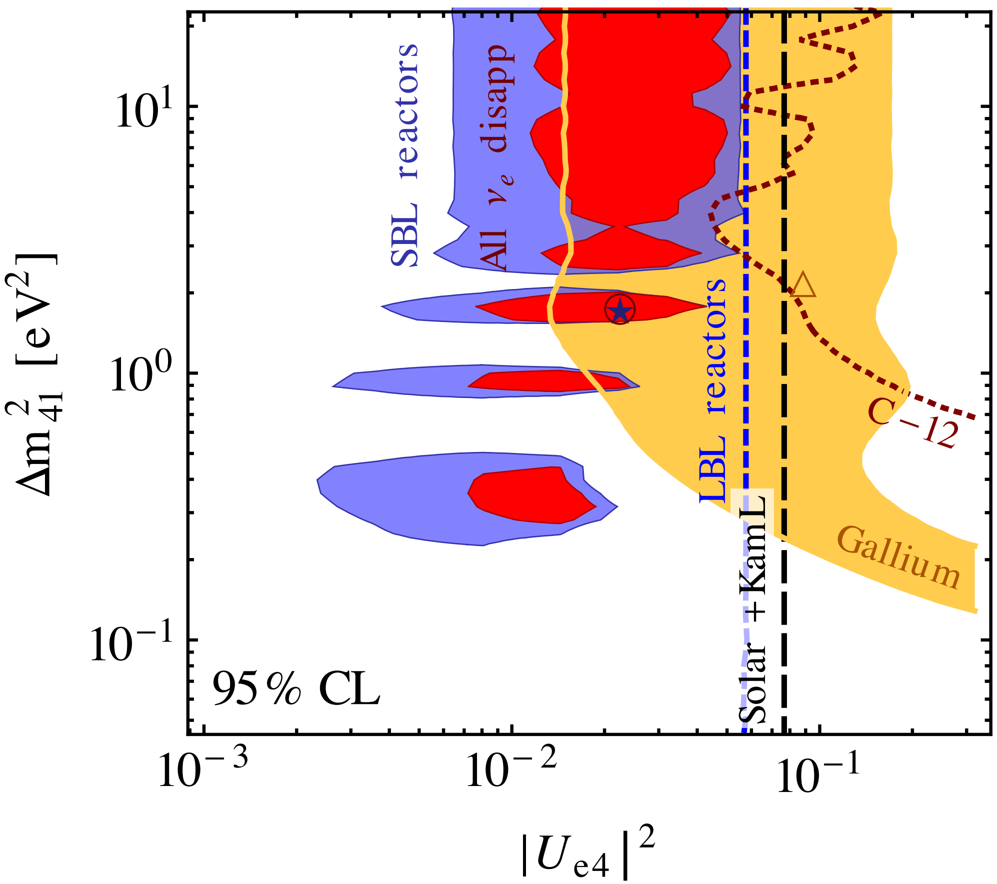


[D. Lhuillier, talk at IPA 2016]

<u>The Gallium anomaly</u>

Calibration of the Gallex and SAGE experiments with radioactive sources
$\Rightarrow$ observed 3σ deficit of ν_e with respect to predictions (R = 0.84 ± 0.05)

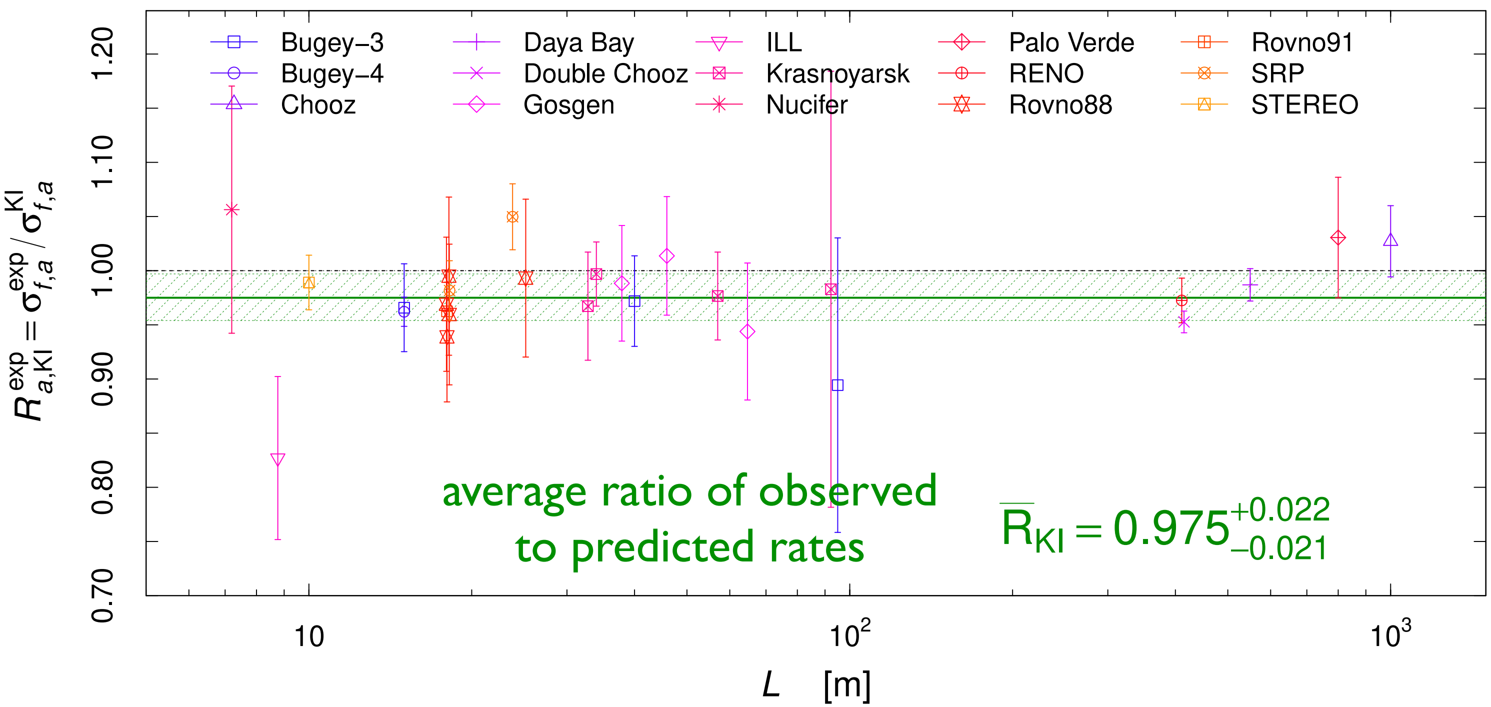
The reactor and gallium anomalies suggest oscillations into a sterile neutrino with $\Delta m^2_{41} \gtrsim 1\,\mathrm{eV}^2$ and $\sin^2 2\theta_{ee} \sim 0.1$ $\qquad [\,\sin^2 2\theta_{ee} \equiv 4(1-|U_{e4}|^2)|U_{e4}|^2\,]$



[Kopp et al., arXiv:1303.3011]

Recent results on the reactor antineutrino anomaly

Kopeikin et al. (arXiv:2103.01684): new computation of the reactor $\bar{\nu}_e$ spectra using recent measurements at the Kurchatov Institute (KI). Find a smaller $^{235}\mathrm{U}$ antineutrino flux than Mueller and Huber, in agreement with the dependence of the antineutrino flux on the fuel composition (proportion of $^{235}\mathrm{U}$, $^{238}\mathrm{U}$, $^{239}\mathrm{Pu}$, $^{241}\mathrm{Pu}$) observed by the Daya Bay and RENO experiments, and confirmed by PROSPECT and STEREO.



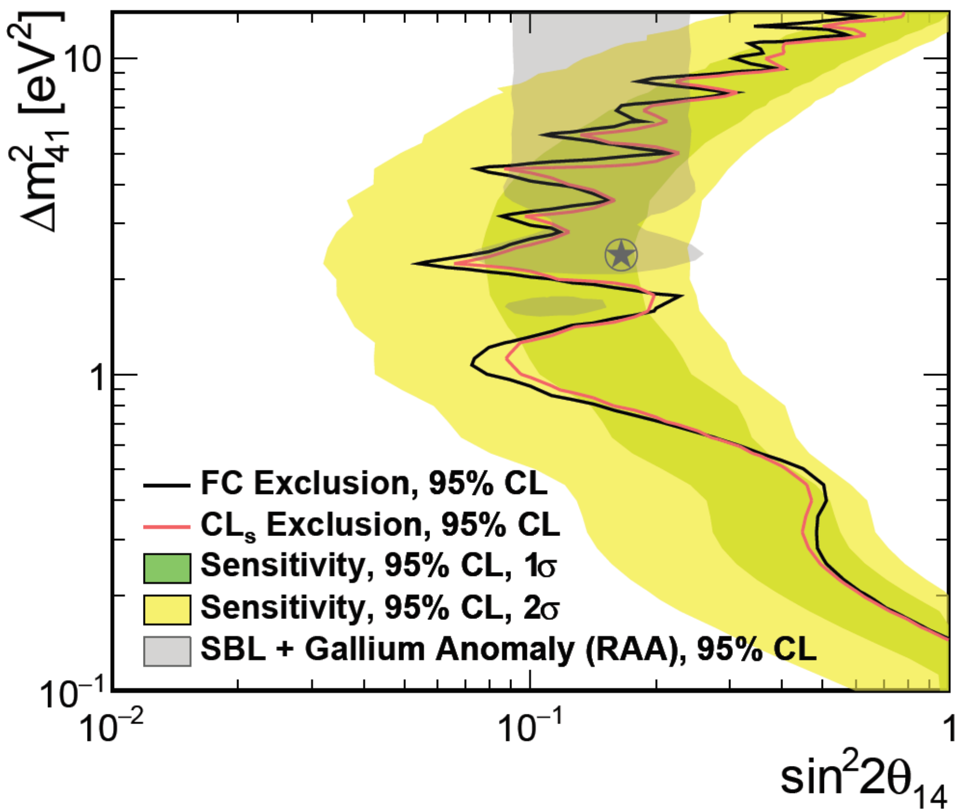
Giunti et al., arXiv:2110.06820

$\Rightarrow$ the significance of the RAA decreases to $1.1\ \sigma$ [similar conclusion with an independent flux computation by Estienne et al. (2019) using a different method]

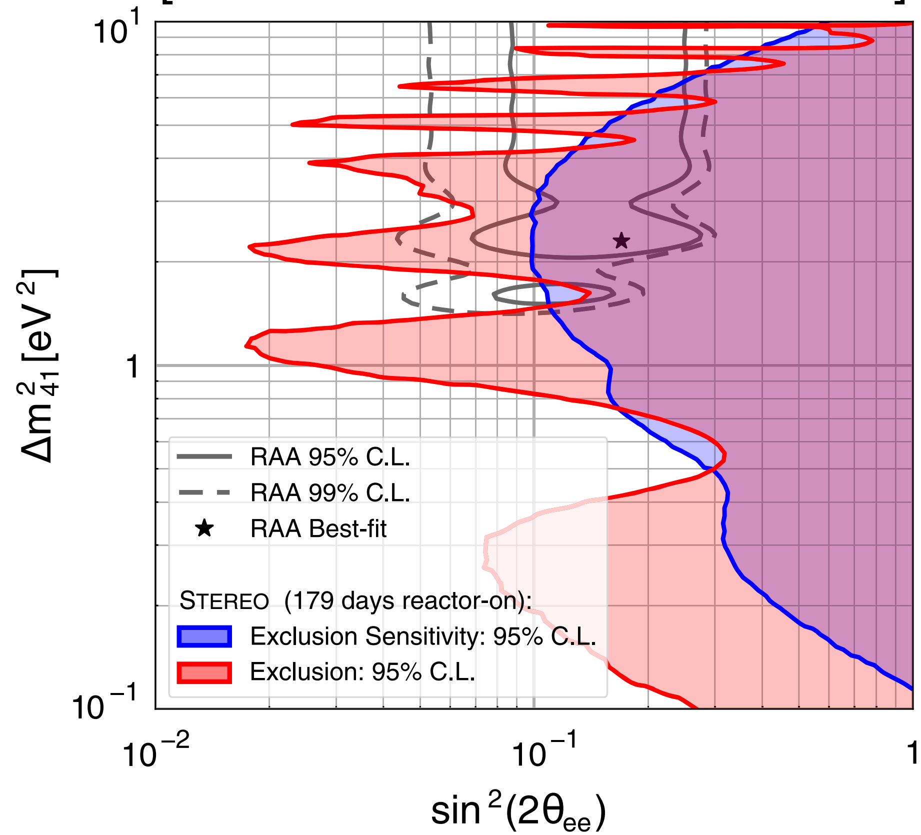
Searches for short-baseline $\bar{\nu}_e$ disappearance

NEOS, DANSS, STEREO and PROSPECT exclude a significant portion of the reactor antineutrino anomaly parameter space

[PROSPECT Collaboration, arXiv:2006.11210]



[STEREO Collaboration, arXiv:1912.06582]



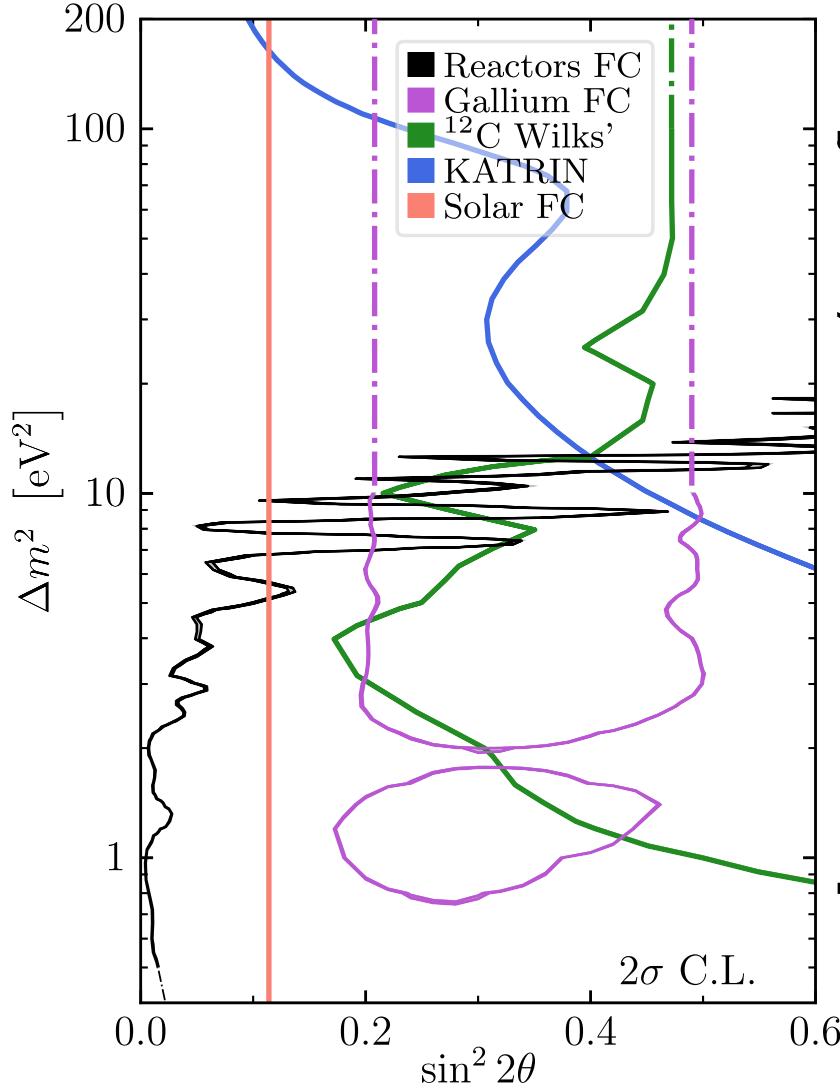
⇒ the reactor antineutrino anomaly is disfavored by SBL reactor experiments and no longer supported by reactor antineutrino flux computations

Update on the gallium anomaly

Recently confirmed by the BEST experiment (arXiv:2109.11482), with anincreased statistical significance of 4σ

Oscillation explanation requires a large active-sterile mixing, $\sin^2 2\theta_{ee} \geq 0.2$, in conflict with reactor data for $\Delta m^2_{41} \lesssim 10\,\mathrm{eV}^2$ and with solar neutrino data, which excludes $\sin^2 2\theta_{ee} > 0.11$ at 2σ

⇒ very confusing situation



[J.M. Berryman et al., arXiv:2111.12530]

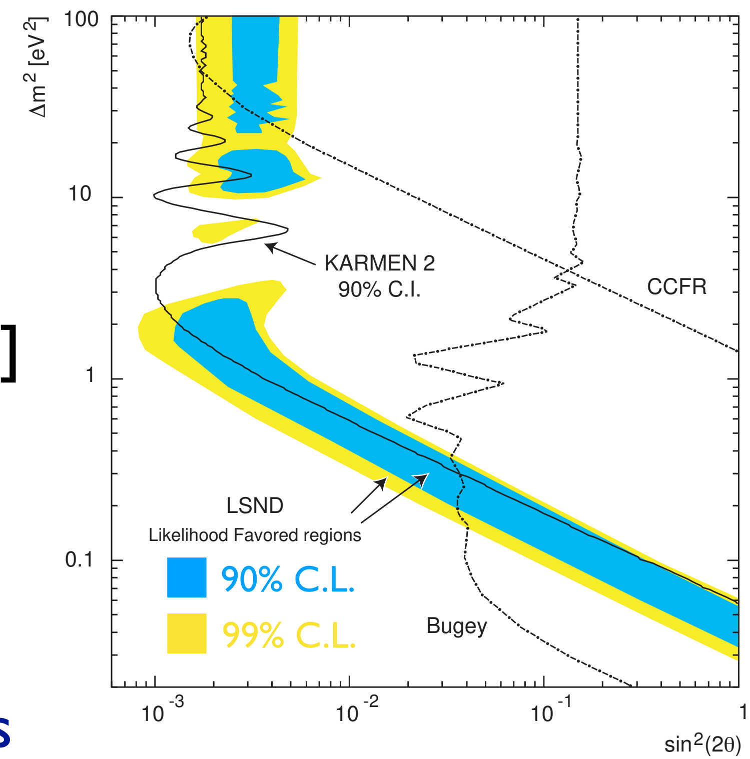
Short-baseline appearance experiments [$\nu_e(\bar{\nu}_e)$ appearance in a $\nu_\mu(\bar{\nu}_\mu)$ beam]

LSND (1993-1998) [$\bar{\nu}_\mu$ beam, $L \approx 35\,\mathrm{m}$]

Excess of $\bar{\nu}_e$ events over background at 3.8 σ interpreted by LSND as $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations

Not observed by KARMEN

[LSND allowed region in the $(\sin^2 2\theta, \Delta m^2)$ plane (2-neutrino fit) - hep-ex/0203021]



$$\sin^2 2\theta_{\mu e} \equiv 4|U_{e4}U_{\mu 4}|^2$$

MiniBooNE (2002-2017) [ν_μ and $\bar{\nu}_\mu$, $L = 541\,\mathrm{m}$]

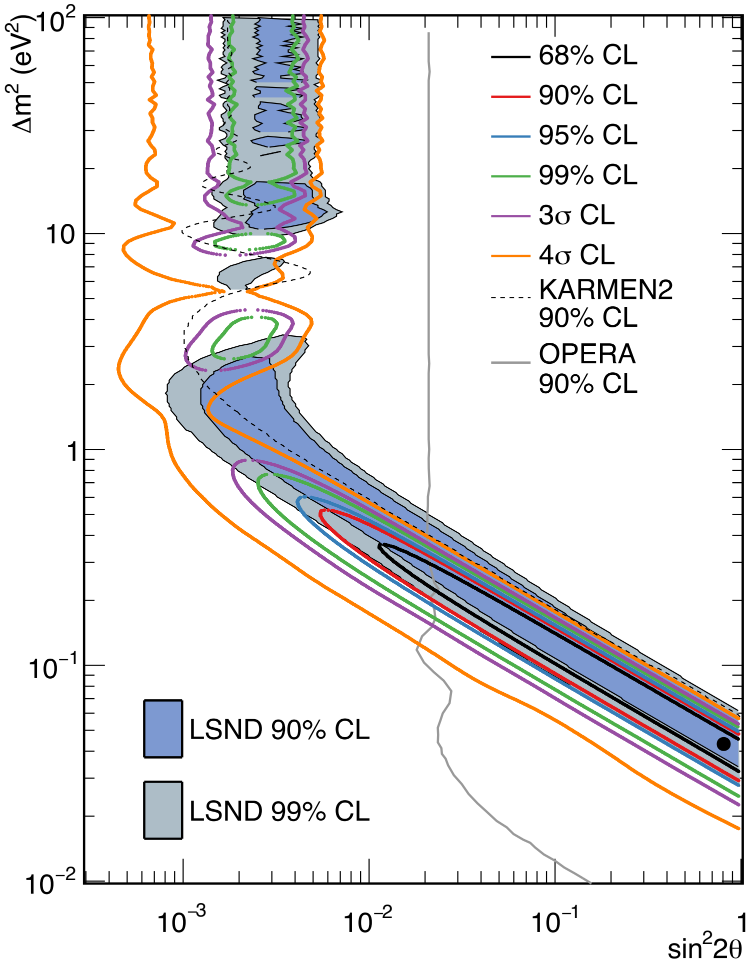
Designed to test the LSND anomaly with a different L but a similar L/E

2002-2012 : inconclusive/contradictory results

Full 2002-2019 data : excess of $\nu_e(\bar{\nu}_e)$ CC events both in the ν and $\bar{\nu}$ modes (4.8 σ in total), mainly in the low-energy region, consistent with LSND

→ suggests $\nu_\mu \to \nu_e$ / $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations

2002-2019 MiniBooNE results



[MiniBooNE Collaboration, arXiv:2006.16883]

FIG. 20: MiniBooNE allowed regions for combined neutrino mode (18.75×10^{20} POT) and antineutrino mode (11.27×10^{20} POT) data sets for events with $200 < E_\nu^{QE} < 3000$ MeV within a two-neutrino oscillation model. The shaded areas show the 90% and 99% C.L. LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ allowed regions. The black point shows the MiniBooNE best fit point. Also shown are 90% C.L. limits from the KARMEN [26] and OPERA [27] experiments.

MiniBooNE + LSND excesses : 6.1 σ significance

Oscillation interpretation requires a 4th massive neutrino in the eV range

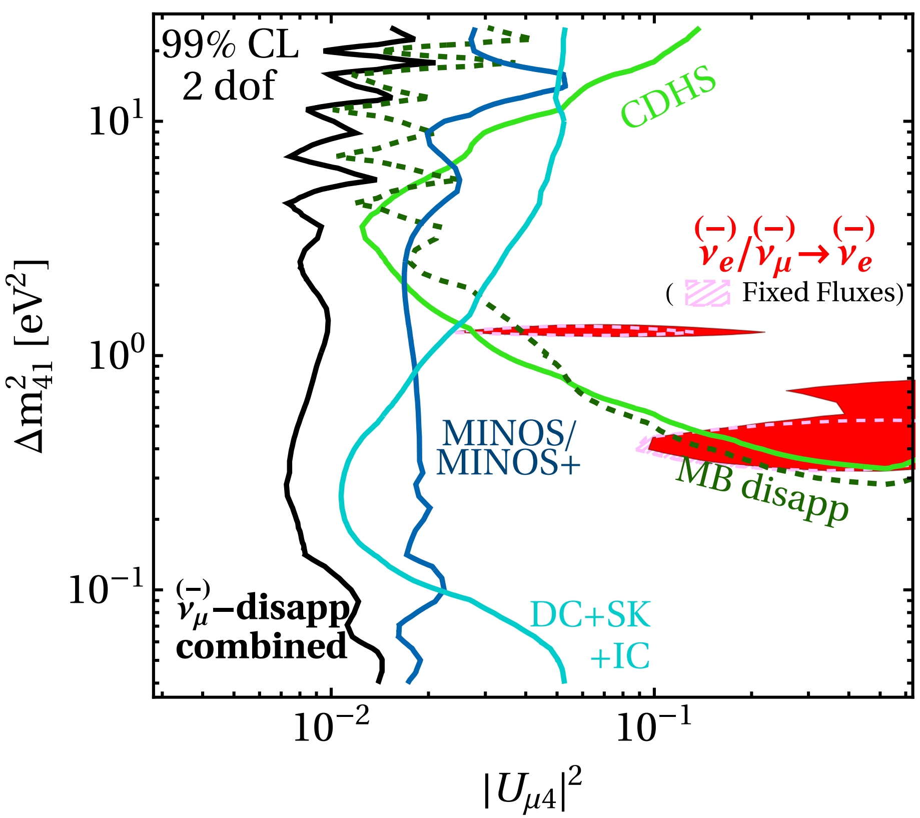
$$\Delta m^2_{41} \gtrsim 0.1\,\mathrm{eV}^2, \quad \sin^2 2\theta_{\mu e} \approx (10^{-3} - 10^{-2})$$

However, this interpretation is essentially excluded by $\nu_\mu(\bar{\nu}_\mu)$ disappearance data :

- MINOS/MINOS+ (long-baseline oscillation experiment)
- IceCube (neutrino telescope located under the Antarctic ice: atmospheric neutrino data)

MINOS/MINOS+ : long-baseline oscillation experiment (L_{near} = 1.04 km, L_{far}= 735 km). Has analyzed both charged current data ($\nu_\mu/\bar{\nu}_\mu$ disappearance) and neutral current data, which is sensitive to the total flux of active neutrinos, hence to $\nu_\mu \to \nu_s$ oscillations

IceCube : a sterile neutrino in the eV range would affect the survival probability of atmospheric $\bar{\nu}_\mu$ passing through the Earth (MSW resonance) $\Rightarrow$ sensitivity to Δm^2_{41} and $\sin^2 2\theta_{\mu\mu}$



strong conflict between appearance data (LSND + MiniBooNE, allowed regions in red) and disappearance data (exclusion curves from CDHS, MINOS/MINOS+, MiniBooNE disappearance data, SK + IceCube)

[M. Dentler et al., arXiV:1803.10661]

Origin of the conflict between appearance (LSND + MiniBooNE) and disappearance experiments (reactors, accelerators, IceCube…)

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

($|U_{e4}|^2 \approx 1$ excluded by SNO)

MINOS, IceCube… : $\nu_\mu (\bar{\nu}_\mu)$ disappearance not observed

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

($|U_{\mu 4}|^2 \approx 1$ excluded by SK and LBL experiments)

Appearance experiments (LSND + MiniBooNE) :

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

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

Quantifying the tension between appearance and disappearance data

(M. Dentler et al., arXiV:1803.10661)

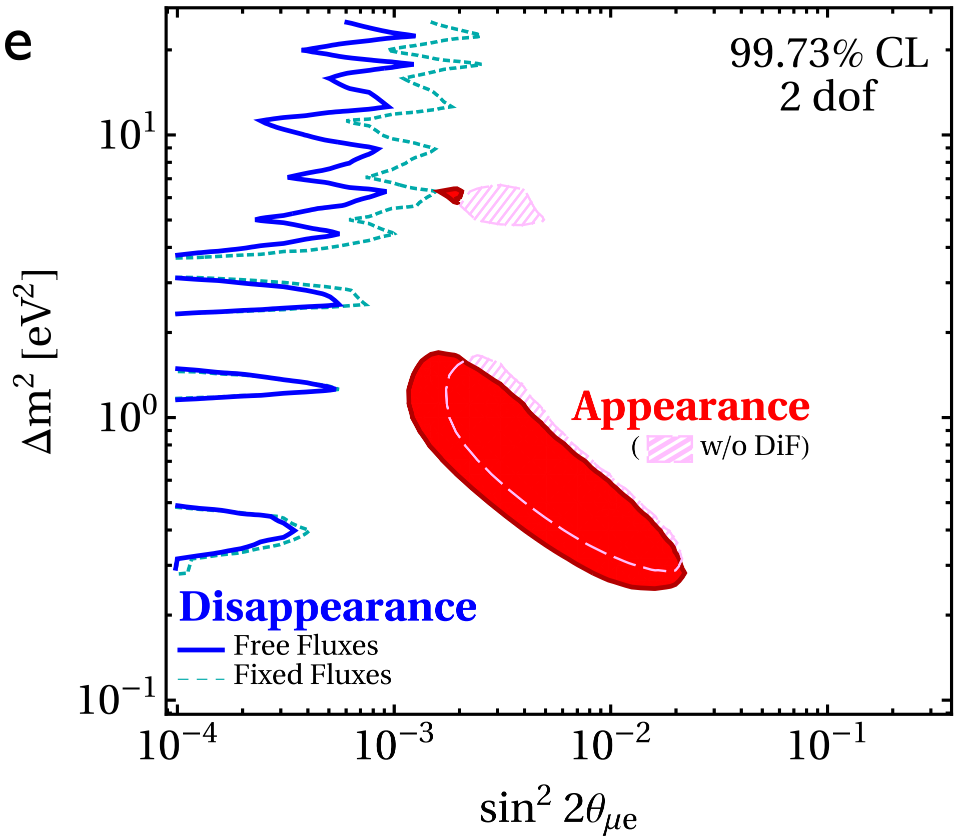
$\left(\sin^2 2\theta_{\mu e} \equiv 4|U_{e4}U_{\mu 4}|^2,\, \Delta m^2_{41}\right)$ plane

red region is allowed at 3σ
by appearance data

[pink hatched: without LSND DiF]

blue curve defines 3σ excluded
region by disappearance data

[dashed = fixed reactor fluxes]



[M. Dentler et al., arXiV:1803.10661]

→ sterile neutrino interpretation of LSND and MiniBooNE data
excluded at the 4.7 σ level

This tension persists for 2 sterile neutrinos [M. Maltoni at Neutrino 2018]

Cosmological constraints on sterile neutrinos

Cosmological measurements constrain the number of stable, relativistic degrees of freedom (other than photons) in the early Universe :

$$N_{\rm eff} = 2.99^{+0.34}_{-0.33} \quad (95\,\%,\ \text{TT,TE,EE+lowE+lensing} \ \text{+BAO}).$$ [Planck 2018]

A given species contributes to Neff proportionally to its contribution to the relativistic energy density (normalization : Neff = 1 for a neutrino)

The Standard Model value, due to neutrinos, is $N_{\rm eff} = 3.044$

[not exactly 3, since neutrino decoupling is not fully completed when e+ and e- annihilate]

In the presence of a sterile neutrino, the cosmological constraint becomes :

$$\left.\begin{aligned} N_{\rm eff} &< 3.29, \\ m_{\nu,\,\rm sterile}^{\rm eff} &< 0.65\ \text{eV}, \end{aligned}\right\} \ 95\,\%,\ \textit{Planck}\ \text{TT,TE,EE+lowE} \ \text{+lensing+BAO},$$ [Planck 2018]

A sterile neutrino with the mixing angles suggested by oscillation anomalies would be fully thermalized and contribute as $\Delta N_{\rm eff} = 1$

→ strongly disfavored by standard cosmology [at 6σ according to Planck]

<u>Ways out :</u> non-standard cosmological model, sterile neutrino interactions that would prevent thermalization… however no compelling proposal so far

Conclusions on sterile neutrinos

- ν_e disappearance: the reactor antineutrino anomaly is fading away, but the gallium anomaly is reinforced by the BEST results, which are in tension with solar neutrino and reactor data

- ν_e appearance (LSND, MiniBooNE) is in strong conflict with disappearance experiments. Might be due to an unidentified background process or to some new physics other than oscillations

- will be tested by the short baseline neutrino program at Fermilab (SBN)

- eV-scale sterile neutrino with significant mixing with active neutrinos are disfavored by cosmology

- heavier sterile neutrinos (keV, MeV, GeV, TeV and above) are a less constrained possibility and may play a role in the origin of SM neutrino masses, dark matter and the baryon asymmetry of the Universe