Open problems and perspectives in neutrino physics: a theorist view

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Virtual Seminar at Albert Einstein Center, Bern

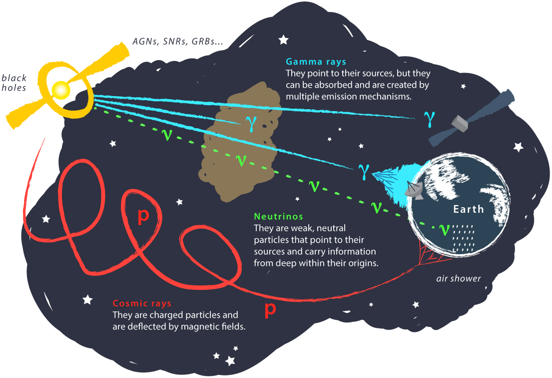
10 March 2021

Open problems that require New Physics

- From experiment:
  - Neutrino masses.
  - Dark Matter (keV sterile neutrino is a candidate).
  - Dark Energy (connection with the neutrino mass scale?).
  - Matter-antimatter asymmetry in the Universe (neutrino-induced leptogenesis).
- From theory:
  - Too many free numerical parameters ($19 + 7$ neutrino masses and mixing).
  - Why neutrino masses are so small? (seesaw Majorana neutrino masses?)
  - Why neutrino mixing is so different from quark mixing? (due to Majorana neutrino masses?)
  - Hierarchy problem (why the electroweak scale is so much smaller than the Planck or GUT scales?): BSM models with new neutrino states.
  - Accidental conservation of $B - L$ global symmetry (broken by Majorana neutrino masses?).
  - The strong CP problem.
  - Quantum gravity and the unification of all forces.

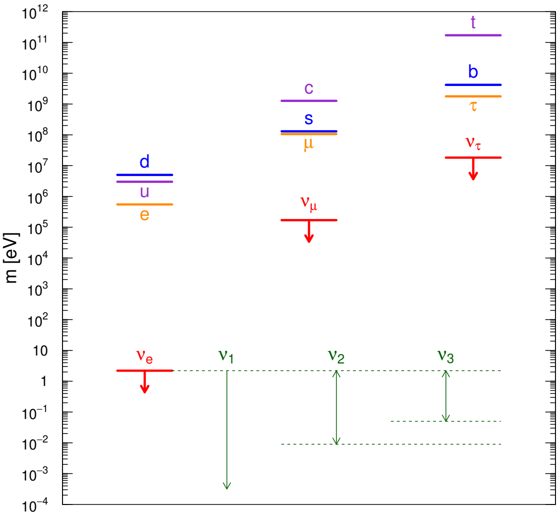
Neutrinos in Multimessenger Astrophysics

- Neutrinos are neutral and the weakest-interacting known particles.



- Fantastic astrophysical messenger in the arising multimessenger era.
- Sensitive to the effects of new states and very weak new interactions beyond the Standard Model:
  - Sterile neutrinos.
  - Non-standard neutrino interactions.
  - Electromagnetic interactions (neutrino magnetic moments and charges).

Neutrino Masses



Three-Neutrino Mixing

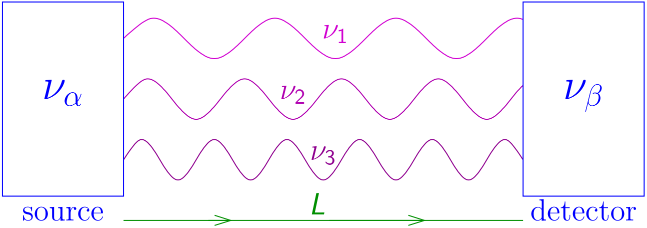
- Flavor Neutrinos: ν_e, ν_μ, ν_τ produced in Weak Interactions
- Massive Neutrinos: ν_1, ν_2, ν_3 propagate from Source to Detector
- Neutrino Mixing: Flavor Neutrinos are superpositions of Massive Neutrinos

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

- U is the 3×3 unitary Neutrino Mixing Matrix

Neutrino Oscillations

$$|\nu(t=0)\rangle = |\nu_\alpha\rangle = U_{\alpha 1}\,|\nu_1\rangle + U_{\alpha 2}\,|\nu_2\rangle + U_{\alpha 3}\,|\nu_3\rangle$$



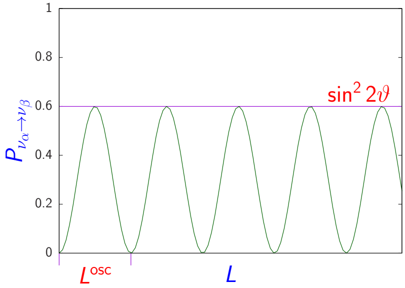
$$|\nu(t>0)\rangle = U_{\alpha 1}\,e^{-iE_1 t}\,|\nu_1\rangle + U_{\alpha 2}\,e^{-iE_2 t}\,|\nu_2\rangle + U_{\alpha 3}\,e^{-iE_3 t}\,|\nu_3\rangle \neq |\nu_\alpha\rangle$$

$$E_k^2 = p^2 + m_k^2 \qquad\qquad t = L$$

$$P_{\nu_\alpha \to \nu_\beta}(L) = |\langle \nu_\beta | \nu(L)\rangle|^2 = \sum_{k,j} U_{\beta k} U_{\alpha k}^* U_{\beta j}^* U_{\alpha j} \exp\left(-i \frac{\Delta m_{kj}^2 L}{2E}\right)$$

The oscillation probabilities depend on U and $\Delta m_{kj}^2 \equiv m_k^2 - m_j^2$

2ν-mixing: $P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\vartheta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \implies \boxed{L^{\text{osc}} = \frac{4\pi E}{\Delta m^2}}$



Tiny neutrino masses lead to observable macroscopic oscillation distances!

$$\frac{L}{E} \lesssim \begin{cases} 10 \, \frac{\text{m}}{\text{MeV}} \, \left(\frac{\text{km}}{\text{GeV}}\right) & \text{short-baseline experiments} & \Delta m^2 \gtrsim 10^{-1} \, \text{eV}^2 \\ 10^3 \, \frac{\text{m}}{\text{MeV}} \, \left(\frac{\text{km}}{\text{GeV}}\right) & \text{long-baseline experiments} & \Delta m^2 \gtrsim 10^{-3} \, \text{eV}^2 \\ 10^4 \, \frac{\text{km}}{\text{GeV}} & \text{atmospheric neutrino experiments} & \Delta m^2 \gtrsim 10^{-4} \, \text{eV}^2 \\ 10^{11} \, \frac{\text{m}}{\text{MeV}} & \text{solar neutrino experiments} & \Delta m^2 \gtrsim 10^{-11} \, \text{eV}^2 \end{cases}$$

Neutrino oscillations are the optimal tool to reveal tiny neutrino masses!

Three-Neutrino Mixing Matrix

Standard Parameterization of Mixing Matrix (as CKM)

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

$$= \begin{pmatrix} c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta_{13}} \\ -s_{12} c_{23} - c_{12} s_{23} s_{13} e^{i\delta_{13}} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i\delta_{13}} & s_{23} c_{13} \\ s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta_{13}} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i\delta_{13}} & c_{23} c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

$c_{ab} \equiv \cos\vartheta_{ab}$ $\quad s_{ab} \equiv \sin\vartheta_{ab}$ $\quad 0 \leq \vartheta_{ab} \leq \dfrac{\pi}{2}$ $\quad 0 \leq \delta_{13}, \lambda_{21}, \lambda_{31} < 2\pi$

OSCILLATION PARAMETERS
- 3 Mixing Angles: ϑ_{12}, ϑ_{23}, ϑ_{13}
- 1 CPV Dirac Phase: δ_{13}
- 2 independent $\Delta m^2_{kj} \equiv m^2_k - m^2_j$: Δm^2_{21}, Δm^2_{31}

2 CPV Majorana Phases: λ_{21}, λ_{31} $\Longleftrightarrow$ $|\Delta L| = 2$ processes

Three-Neutrino Mixing Parameters

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Solar
$\nu_e \to \nu_\mu, \nu_\tau$

(SNO, Borexino; Super-Kamiokande; GALLEX/GNO, SAGE; Homestake, Kamiokande)

VLBL Reactor
$\bar{\nu}_e$ disappearance

(KamLAND)

$\rightarrow$

$$\Delta m^2_{\mathrm{S}} = \Delta m^2_{21} = (7.36 \pm 0.155) \times 10^{-5}\,\mathrm{eV}^2$$
($\sim 2.3\%$ accuracy)

$$\sin^2\vartheta_{\mathrm{S}} = \sin^2\vartheta_{12} = 0.303 \pm 0.013$$
($\sim 4.5\%$ accuracy)

[A. Marrone, talk at NeuTel 2021]
[Capozzi, Di Valentino, Lisi, Marrone, Melchiorri, Palazzo, arXiv:2003.08511]
[de Salas, Forero, Gariazzo, Martinez-Mirave, Mena, Ternes, Tortola, Valle, arXiv:2006.11237]
[Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, arXiv:2007.14792]

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Atmospheric
$\nu_\mu \to \nu_\tau$
(Super-Kamiokande, Kamiokande, IMB, MACRO, Soudan-2)

LBL Accelerator
ν_μ disappearance
(K2K, MINOS, T2K, NOνA)

LBL Accelerator
$\nu_\mu \to \nu_\tau$
(OPERA)

$\rightarrow$

$$\Delta m^2_{\mathrm{A}} = |\Delta m^2_{31} + \Delta m^2_{32}|/2$$
$$= (2.475 \pm 0.028) \times 10^{-3}\,\mathrm{eV}^2$$
($\sim$ 1.1% accuracy) (NO)
$$= (2.455 \pm 0.028) \times 10^{-3}\,\mathrm{eV}^2$$
($\sim$ 1.2% accuracy) (IO)

$$\sin^2\vartheta_{\mathrm{A}} = \sin^2\vartheta_{23}$$
$$= 0.569 \pm 0.017$$
($\sim$ 5.4% accuracy)

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LBL Accelerator $\nu_\mu \to \nu_e$ (T2K, MINOS, NOνA)

LBL Reactor $\bar{\nu}_e$ disappearance (Daya Bay, RENO, Double Chooz)

$$\rightarrow \begin{cases} \Delta m^2_{\text{A}} = |\Delta m^2_{31} + \Delta m^2_{32}|/2 \\ \sin^2\vartheta_{\text{A}} = \sin^2\vartheta_{13} = 0.0223 \pm 0.0006 \quad (\sim 2.9\% \text{ accuracy}) \end{cases}$$

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CP Violation

$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \delta_{\alpha\beta} \underbrace{- 4 \sum_{k>j} \mathrm{Re}\left[U_{\alpha k}^* \, U_{\beta k} \, U_{\alpha j} \, U_{\beta j}^* \right] \sin^2\left(\frac{\Delta m_{kj}^2 L}{4E} \right)}_{\text{CP conserving}}$$

$$\underbrace{+ 2 \sum_{k>j} \mathrm{Im}\left[U_{\alpha k}^* \, U_{\beta k} \, U_{\alpha j} \, U_{\beta j}^* \right] \sin\left(\frac{\Delta m_{kj}^2 L}{2E} \right)}_{\text{CP violating}}$$

- The oscillation probabilities depend on the quartic rephasing invariants

$$U_{\alpha k}^* \, U_{\beta k} \, U_{\alpha j} \, U_{\beta j}^*$$

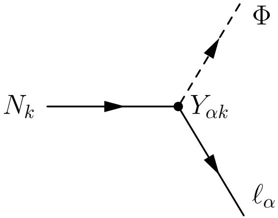
- CP violation depends on the Jarlskog invariant

$$J_{\mathrm{CP}} = \pm \, \mathrm{Im}\left[U_{\alpha k}^* \, U_{\beta k} \, U_{\alpha j} \, U_{\beta j}^* \right] = c_{12} s_{12} c_{23} s_{23} c_{13}^2 s_{13} \sin\delta_{13}$$

Leptogenesis

- Off-equilibrium L and CP violating heavy Majorana neutrino decays at $T \sim M_N$:

$$\mathcal{L}_I \sim \overline{L}\, \widetilde{\Phi}\, Y\, \nu_R$$



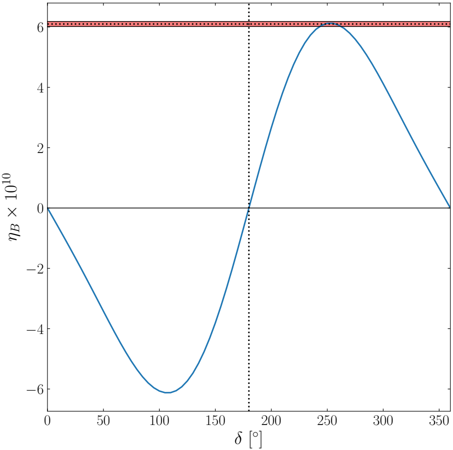
$$A_L \sim \frac{\sum_{k,\alpha} \left[\Gamma(N_k \to \Phi \ell_\alpha) - \Gamma(N_k \to \bar{\Phi} \bar{\ell}_\alpha) \right]}{\sum_{k,\alpha} \left[\Gamma(N_k \to \Phi \ell_\alpha) + \Gamma(N_k \to \bar{\Phi} \bar{\ell}_\alpha) \right]}$$

- The lepton asymmetry A_L is converted into a baryon asymmetry A_B at $T \sim 100\,\text{GeV}$ by electroweak sphalerons that conserve $B - L$ and break $B + L$.

- Seesaw $\Rightarrow$ $Y \sim \frac{1}{v} \underbrace{M_R^{1/2}\, R}_{\text{inaccessible}}\, \underbrace{m_\nu^{1/2}\, U_{3\times 3}}_{\text{measurable}}$ $\qquad (RR^T = 1)$

  [Casas, Ibarra, arXiv:hep-ph/0103065]

- CP-violating $U_{3\times3}$ $\Rightarrow$ plausible CP-violating Y



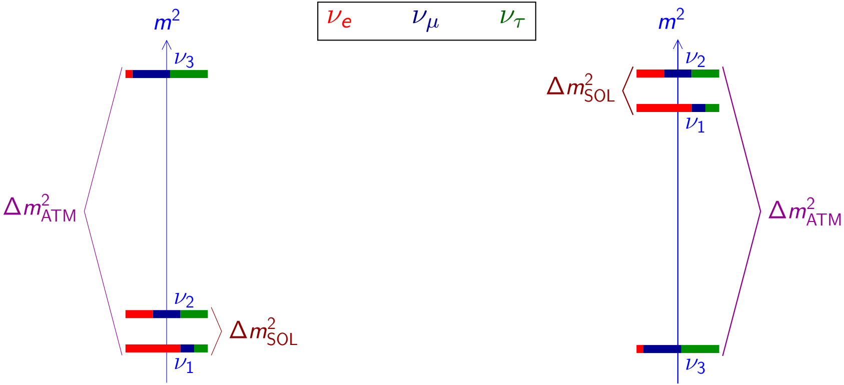
$M_1 \simeq 5 \times 10^{10}$ GeV

$M_1 \ll M_1 \ll M_3$

[Moffat, Pascoli, Petcov, Turner, arXiv:1809.08251]

- The discovery of L violation ($\beta\beta_{0\nu}$ decay due to Majorana neutrinos) and CP violation in the lepton sector (through neutrino oscillations) would be a strong indication in favor of leptogenesis as the origin of the matter-antimatter asymmetry in the Universe.

Neutrino Mass Ordering



Normal Ordering

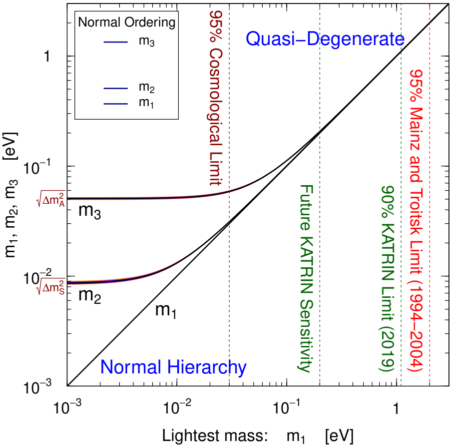
$$\Delta m^2_{31} > \Delta m^2_{32} > 0$$

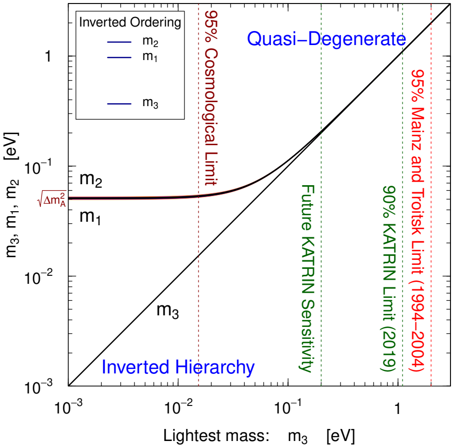
Inverted Ordering

$$\Delta m^2_{32} < \Delta m^2_{31} < 0$$

absolute scale is not determined by neutrino oscillation data

Absolute Neutrino Mass Scale





$$m_2^2 = m_1^2 + \Delta m_{21}^2 = m_1^2 + \Delta m_S^2$$
$$m_3^2 = m_1^2 + \Delta m_{31}^2 = m_1^2 + \Delta m_A^2$$

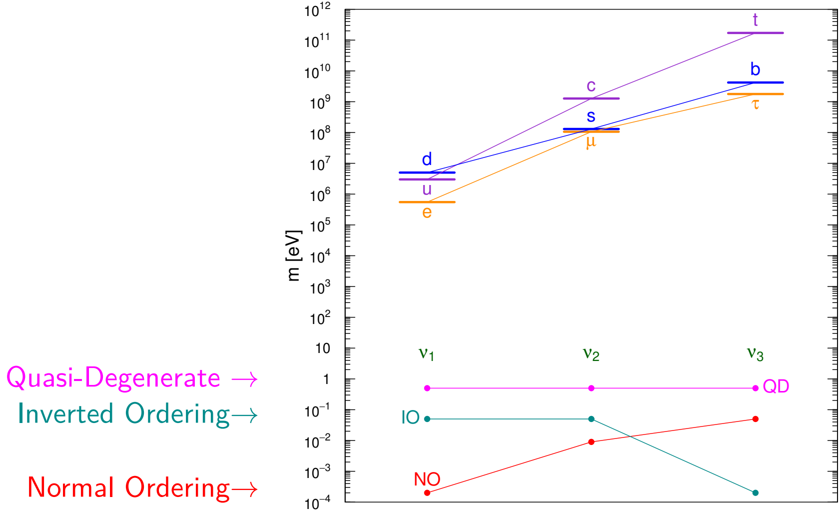
$$m_1^2 = m_3^2 - \Delta m_{31}^2 = m_3^2 + \Delta m_A^2$$
$$m_2^2 = m_1^2 + \Delta m_{21}^2 \simeq m_3^2 + \Delta m_A^2$$

$$m_\beta = \sqrt{\sum_k |U_{ek}|^2 m_k^2} < 1.1\,\text{eV}\ (90\%\ \text{CL})$$

[KATRIN, arXiv:1909.06048]

$$\sum_k m_k < 0.12\,\text{eV}\ (95\%\ \text{CL})$$

[Planck, arXiv:1807.06209]



It is most important to determine the neutrino mass ordering in order to

- Simplify most phenomenological analyses.
- Reduce dramatically the allowed models.

Origin of Neutrino Masses

	1st Generation	2nd Generation	3rd Generation
Quarks:	$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \begin{matrix} u_R \\ d_R \end{matrix}$	$\begin{pmatrix} c_L \\ s_L \end{pmatrix} \quad \begin{matrix} c_R \\ s_R \end{matrix}$	$\begin{pmatrix} t_L \\ b_L \end{pmatrix} \quad \begin{matrix} t_R \\ b_R \end{matrix}$
Leptons:	$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} \quad \begin{matrix} \boxed{\nu_{eR}} \\ e_R \end{matrix}$	$\begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix} \quad \begin{matrix} \boxed{\nu_{\mu R}} \\ \mu_R \end{matrix}$	$\begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix} \quad \begin{matrix} \boxed{\nu_{\tau R}} \\ \tau_R \end{matrix}$

- Standard Model extension: $\nu_R \Rightarrow$ Dirac mass term $\mathcal{L}_{\mathrm{D}} \sim m_{\mathrm{D}}\, \overline{\nu_L} \nu_R$

- This is Standard Model physics, because m_{D} is generated by the standard Higgs mechanism:

$$y\, \overline{L_L} \widetilde{\Phi} \nu_R \xrightarrow[\text{Breaking}]{\text{Symmetry}} y\, v\, \overline{\nu_L} \nu_R \quad \Rightarrow \quad m_{\mathrm{D}} \sim y\, v = y\, 246\,\mathrm{GeV}$$

- Extremely small Yukawa couplings are needed to get $m_{\mathrm{D}} \lesssim 1\,\mathrm{eV}$:

$$y \lesssim 10^{-11}$$

It is considered unnatural, unless there is a protecting BSM symmetry.

Beyond the Standard Model

- The introduction of ν_R leads us beyond the Standard Model because they can have the Majorana mass term

$$\mathcal{L}_{\text{M}} \sim m_{\text{M}} \overline{\nu_R} \nu_R^c \qquad \text{singlet under SM symmetries!}$$

- This is beyond the Standard Model because m_{M} is not generated by the Higgs mechanism of the Standard Model $\Rightarrow$ new physics is required.

- The Majorana mass term can be avoided by imposing lepton number conservation which should anyway be explained by some physics beyond the Standard Model.

Seesaw Mechanism

without lepton number conservation

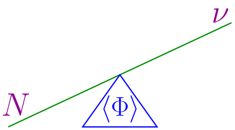
$$\mathcal{L}^{\mathrm{D+M}} = -\frac{1}{2} \begin{pmatrix} \overline{\nu_L^c} & \overline{\nu_R} \end{pmatrix} \begin{pmatrix} 0 & m_{\mathrm{D}} \\ m_{\mathrm{D}} & m_{\mathrm{M}} \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} + \mathrm{H.c.}$$

m_{M} can be arbitrarily large (not protected by SM symmetries)

$m_{\mathrm{M}} \sim$ scale of new physics beyond Standard Model $\Rightarrow m_{\mathrm{M}} \gg m_{\mathrm{D}}$

diagonalization of $\begin{pmatrix} 0 & m_{\mathrm{D}} \\ m_{\mathrm{D}} & m_{\mathrm{M}} \end{pmatrix} \Longrightarrow m_\nu \simeq \frac{m_{\mathrm{D}}^2}{m_{\mathrm{M}}} \qquad m_N \simeq m_{\mathrm{M}}$

natural explanation of smallness
of light neutrino masses



seesaw mechanism

massive neutrinos are Majorana $\Rightarrow$ $\boxed{\beta\beta_{0\nu}}$

$$\nu \simeq -i\left(\nu_L - \nu_L^c\right) \qquad N \simeq \nu_R + \nu_R^c$$

3-GEN $\Rightarrow$ effective low-energy 3-ν mixing

Majorana Neutrinos

There are compelling arguments in favor of Majorana Neutrinos:

- A Majorana field is simpler than a Dirac field:
  - A Majorana field corresponds to the fundamental spinor representation of the Lorentz group.
  - A Dirac field is made of two Majorana fields degenerate in mass.

  Therefore, if there is no additional constraint (as L conservation), a neutral elementary particle as the neutrino is naturally Majorana.

- The seesaw mechanism if ν_R is introduced to generate neutrino masses.

- A general Effective Field Theory argument from high-energy new physics:

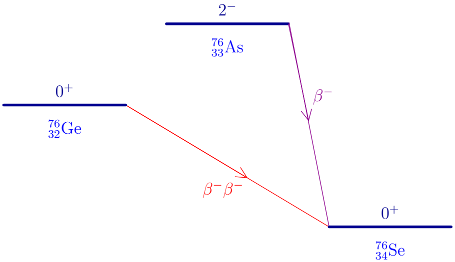
$$\mathscr{L} = \mathscr{L}_{\text{SM}} + \frac{g_5}{\mathcal{M}}\,\mathscr{O}_5 + \frac{g_6}{\mathcal{M}^2}\,\mathscr{O}_6 + \ldots$$

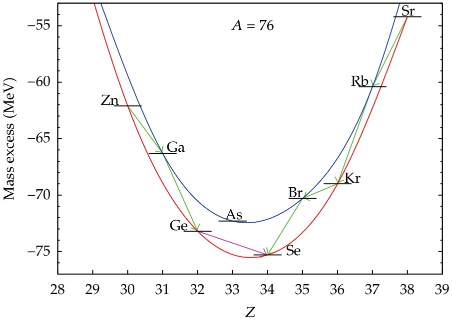
  - $\mathscr{O}_5$: Majorana neutrino masses (Lepton number violation and $\beta\beta_{0\nu}$ decay).

$$\mathscr{O}_5 = (\overline{L}\,\widetilde{\Phi})\,(\widetilde{\Phi}^T L^c) \qquad L = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix} \qquad \widetilde{\Phi} = \begin{pmatrix} \phi_0 \\ -\phi_+ \end{pmatrix}$$

  - $\mathscr{O}_6$: Baryon number violation (proton decay), neutrino Non-Standard Interactions (NSI), neutrino magnetic moments.

Neutrinoless Double-Beta Decay





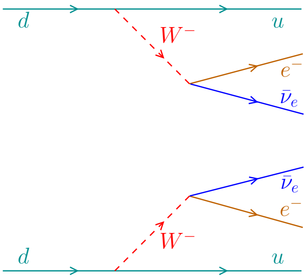
Effective Majorana Neutrino Mass: $$m_{\beta\beta} = \sum_k U_{ek}^2\, m_k$$

Two-Neutrino Double-β Decay: $\Delta L = 0$

$$\mathcal{N}(A,Z) \to \mathcal{N}(A,Z+2) + e^- + e^- + \bar{\nu}_e + \bar{\nu}_e$$

$$(T_{1/2}^{2\nu})^{-1} = G_{2\nu}\,|\mathcal{M}_{2\nu}|^2$$

second order weak interaction process in the Standard Model

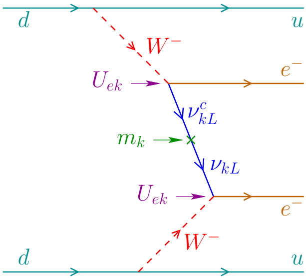


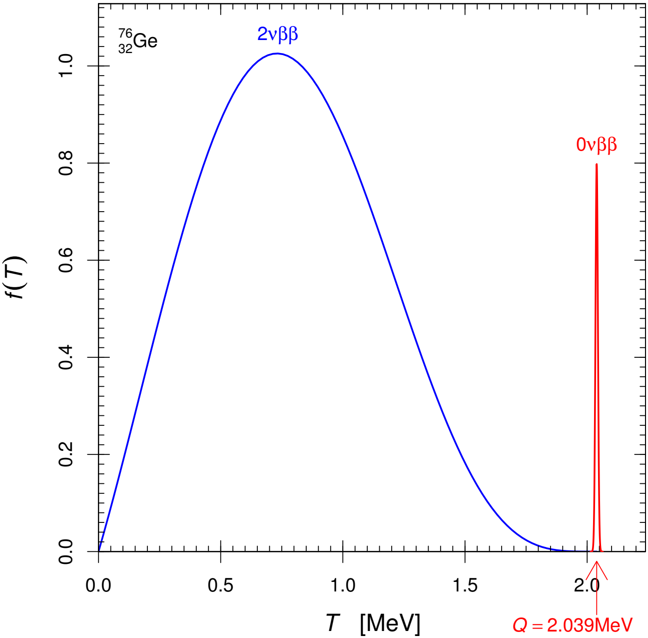
Neutrinoless Double-β Decay: $\Delta L = 2$

$$\mathcal{N}(A,Z) \to \mathcal{N}(A,Z+2) + e^- + e^-$$

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu}\,|\mathcal{M}_{0\nu}|^2\,|m_{\beta\beta}|^2$$

effective Majorana mass $\quad |m_{\beta\beta}| = \left|\sum_k U_{ek}^2\, m_k\right|$



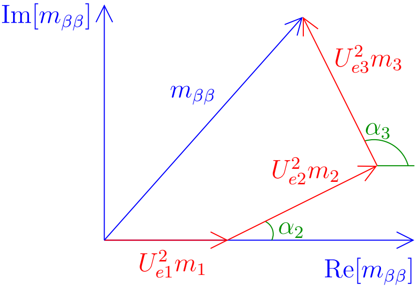

$^{76}_{32}$Ge
$2\nu\beta\beta$
$0\nu\beta\beta$
$f(T)$
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.5
1.0
1.5
2.0
T [MeV]
$Q = 2.039$MeV

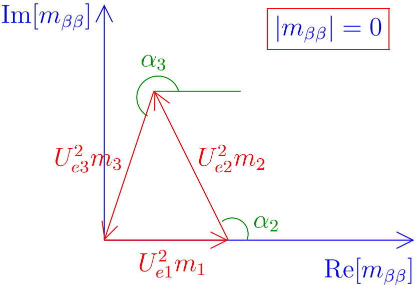
Effective Majorana Neutrino Mass

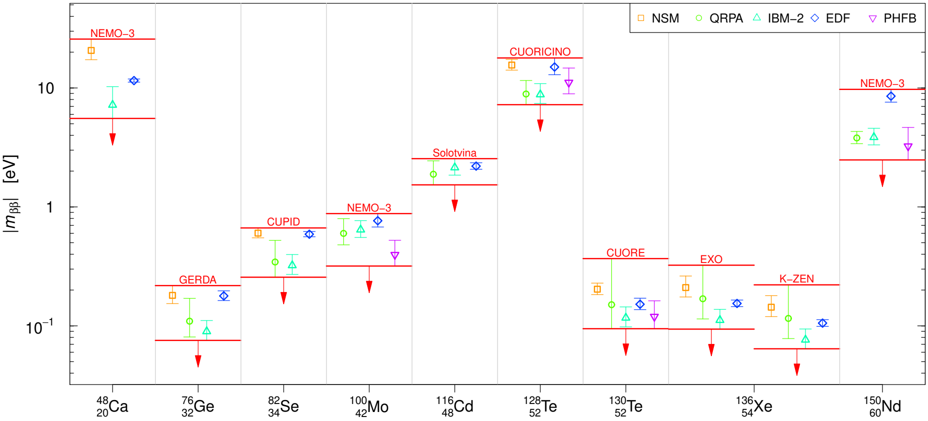
$$m_{\beta\beta} = \sum_k U_{ek}^2 \, m_k$$ complex U_{ek} $\Rightarrow$ possible cancellations

$$m_{\beta\beta} = |U_{e1}|^2 \, m_1 + |U_{e2}|^2 \, e^{i\alpha_2} \, m_2 + |U_{e3}|^2 \, e^{i\alpha_3} \, m_3$$

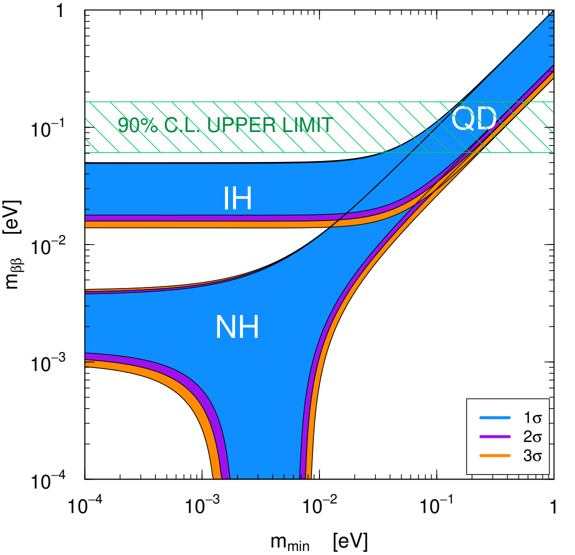
$$\alpha_2 = 2\lambda_2 \qquad \alpha_3 = 2\left(\lambda_3 - \delta_{13}\right)$$





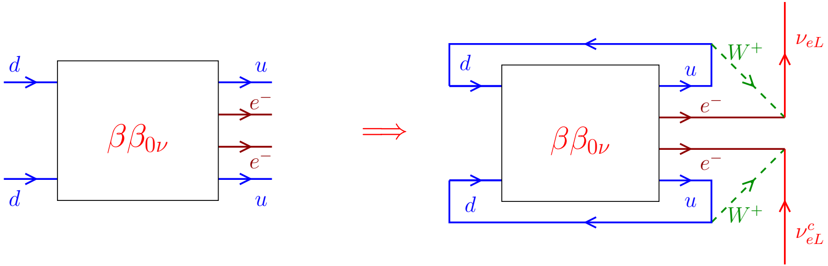

NSM
QRPA
IBM–2
EDF
PHFB
NEMO–3
GERDA
CUPID
NEMO–3
Solotvina
CUORICINO
CUORE
EXO
K–ZEN
NEMO–3
$|m_{\beta\beta}|$ [eV]
10
1
10^{-1}
$^{48}_{20}$Ca
$^{76}_{32}$Ge
$^{82}_{34}$Se
$^{100}_{42}$Mo
$^{116}_{48}$Cd
$^{128}_{52}$Te
$^{130}_{52}$Te
$^{136}_{54}$Xe
$^{150}_{60}$Nd

Predictions of 3ν-Mixing Paradigm



$\beta\beta_{0\nu}$ Decay $\Leftrightarrow$ Majorana Neutrino Mass

- $|m_{\beta\beta}|$ can vanish because of unfortunate cancellations among the ν_1, ν_2, ν_3 contributions or because neutrinos are Dirac particles.
- However, $\beta\beta_{0\nu}$ decay can be generated by another mechanism beyond the Standard Model.
- In this case, a Majorana mass for ν_e is generated by radiative corrections:



[Schechter, Valle, PRD 25 (1982) 2951; Takasugi, PLB 149 (1984) 372]

- Majorana Mass Term: $\boxed{\mathcal{L}^{\mathrm{M}}_{eL} = -\frac{1}{2}\, m_{ee} \left(\overline{\nu^c_{eL}}\, \nu_{eL} + \overline{\nu_{eL}}\, \nu^c_{eL} \right)}$
- Very small four-loop diagram contribution: $m_{ee} \sim 10^{-24}\,\mathrm{eV}$

[Duerr, Lindner, Merle, JHEP 06 (2011) 091 (arXiv:1105.0901)]

- In any case finding $\beta\beta_{0\nu}$ decay is important for
  - Finding total Lepton number violation $(\Delta L = \pm 2)$.
  - Establishing the Majorana (or pseudo-Dirac) nature of neutrinos.
- On the other hand, even if $\beta\beta_{0\nu}$ decay is not found, it is not possible to prove experimentally that neutrinos are Dirac particles, because
  - A Dirac neutrino is equivalent to 2 Majorana neutrinos with the same mass.
  - It is impossible to prove experimentally that the mass splitting is exactly zero.

Light Sterile Neutrinos

- The seesaw mechanism is a very attractive and compelling way to generate small neutrino masses.
- The seesaw mechanism requires the existence of heavy ν_R's or other appropriate BSM physics at very high energies.
- However, in general there is no constraint on the number and mass scale of the ν_R's.
- It is possible and interesting that there is low-energy new physics (maybe connected with dark matter).
- Light neutral BSM fermions can mix with neutrinos: they are ν_R's.

- Light left-handed anti-ν_R are light sterile neutrinos

$$\nu_R^c \to \nu_{sL} \qquad \text{(left-handed)}$$

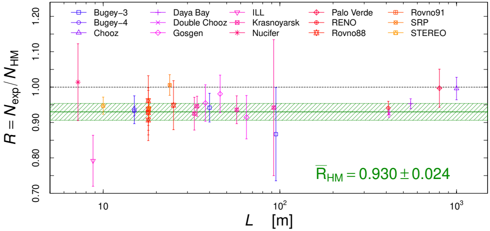
- Sterile means no standard model interactions

[Pontecorvo, Sov. Phys. JETP 26 (1968) 984]

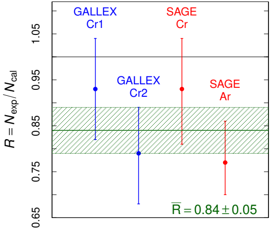
- The active left-handed neutrinos ν_{eL}, $\nu_{\mu L}$, $\nu_{\tau L}$ can oscillate into sterile neutrinos ν_{sL}.

Short-Baseline Anomalies

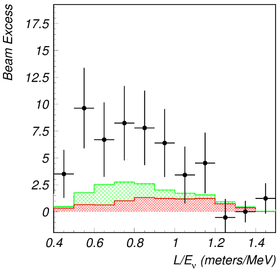
Reactor Anomaly: $\bar{\nu}_e \to \bar{\nu}_x$ ($\sim 3\sigma$)



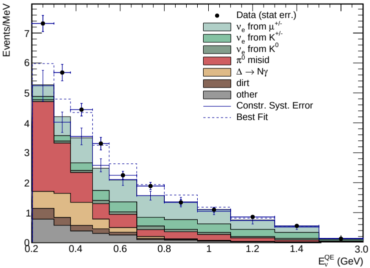
Gallium Anomaly: $\nu_e \to \nu_x$ ($\sim 3\sigma$)



LSND Anomaly: $\bar{\nu}_\mu \to \bar{\nu}_e$ ($\sim 4\sigma$)



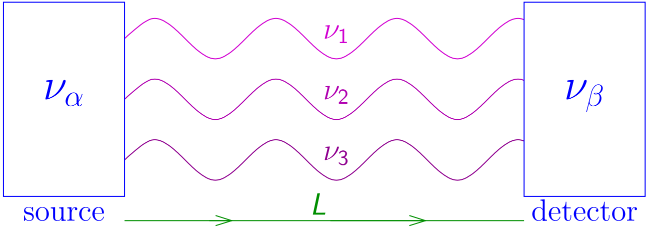
MiniBooNE Anomaly: $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ (4.8σ)



Short-Baseline Neutrino Oscillations

Three-Neutrino Mixing

$$|\nu_{\text{source}}\rangle = |\nu_\alpha\rangle = U_{\alpha 1}\,|\nu_1\rangle + U_{\alpha 2}\,|\nu_2\rangle + U_{\alpha 3}\,|\nu_3\rangle$$



$$|\nu_{\text{detector}}\rangle \simeq U_{\alpha 1}\,e^{-iEL}\,|\nu_1\rangle + U_{\alpha 2}\,e^{-iEL}\,|\nu_2\rangle + U_{\alpha 3}\,e^{-iEL}\,|\nu_3\rangle = e^{-iEL}|\nu_\alpha\rangle$$

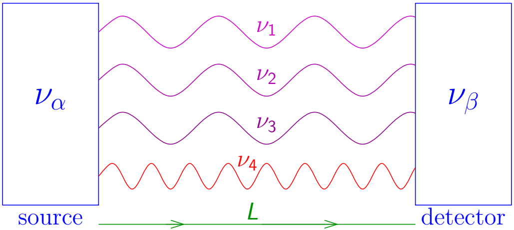
$$P_{\nu_\alpha \to \nu_\beta}(L) = |\langle \nu_\beta | \nu_{\text{detector}} \rangle|^2 \simeq |e^{-iEL} \langle \nu_\beta | \nu_\alpha \rangle|^2 = \delta_{\alpha\beta}$$

No Observable Short-Baseline Neutrino Oscillations!

Short-Baseline Neutrino Oscillations

3+1 Neutrino Mixing

$$|\nu_{\text{source}}\rangle = |\nu_\alpha\rangle = U_{\alpha 1}\,|\nu_1\rangle + U_{\alpha 2}\,|\nu_2\rangle + U_{\alpha 3}\,|\nu_3\rangle + U_{\alpha 4}\,|\nu_4\rangle$$



$$|\nu_{\text{detector}}\rangle \simeq e^{-iEL}\left(U_{\alpha 1}\,|\nu_1\rangle + U_{\alpha 2}\,|\nu_2\rangle + U_{\alpha 3}\,|\nu_3\rangle\right) + U_{\alpha 4}\,e^{-iE_4 L}\,|\nu_3\rangle \neq |\nu_\alpha\rangle$$

$$P_{\nu_\alpha \to \nu_\beta}(L) = |\langle \nu_\beta | \nu_{\text{detector}} \rangle|^2 \neq \delta_{\alpha\beta}$$

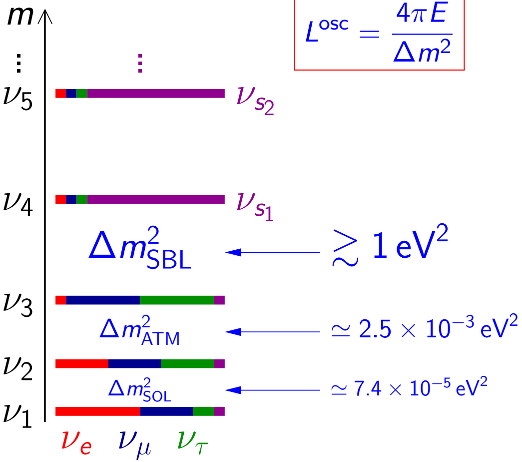
Observable Short-Baseline Neutrino Oscillations!

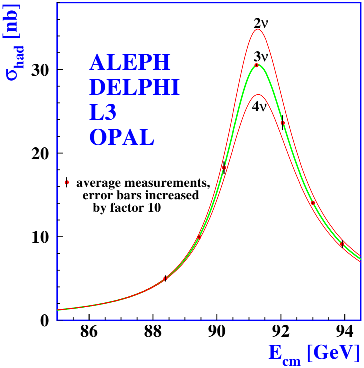
The oscillation probabilities depend on U and

$$\Delta m^2_{\text{SBL}} = \Delta m^2_{41} \simeq \Delta m^2_{42} \simeq \Delta m^2_{43}$$

Beyond Three-Neutrino Mixing: Sterile Neutrinos

$$\boxed{L^{\text{osc}} = \frac{4\pi E}{\Delta m^2}}$$





$$N_{\nu_{\text{active}}}^{\text{LEP}} = 2.9840 \pm 0.0082$$

$$\boxed{N_{\nu_{\text{active}}} = 2.9963 \pm 0.0074}$$

[Janot, Jadach, arXiv:1912.02067]

Terminology: a eV-scale sterile neutrino

means: a eV-scale massive neutrino which is mainly sterile

Effective 3+1 SBL Oscillation Probabilities

Appearance ($\alpha \neq \beta$)

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

Disappearance

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right)$$

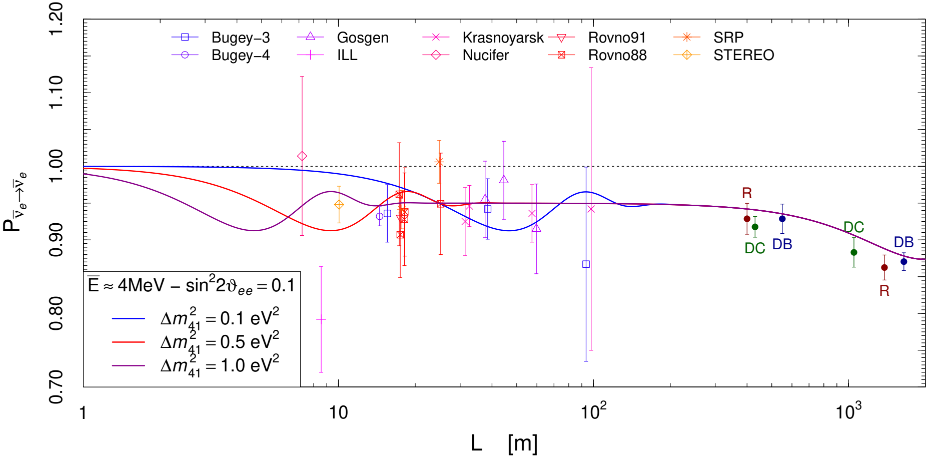
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

SBL

- 6 mixing angles
- 3 Dirac CP phases
- 3 Majorana CP phases

- $\Delta m^2_{\text{SBL}} = \Delta m^2_{41} \simeq \Delta m^2_{42} \simeq \Delta m^2_{43}$
- CP violation is not observable in SBL experiments!
- Observable in LBL accelerator exp. sensitive to Δm^2_{ATM} [de Gouvea et al, arXiv:1412.1479, arXiv:1507.03986, arXiv:1605.09376; Palazzo et al, arXiv:1412.7524, arXiv:1509.03148; Kayser et al, arXiv:1508.06275, arXiv:1607.02152] and solar exp. sensitive to Δm^2_{SOL} [Long, Li, Giunti, arXiv:1304.2207]

Short-Baseline Reactor Neutrino Oscillations



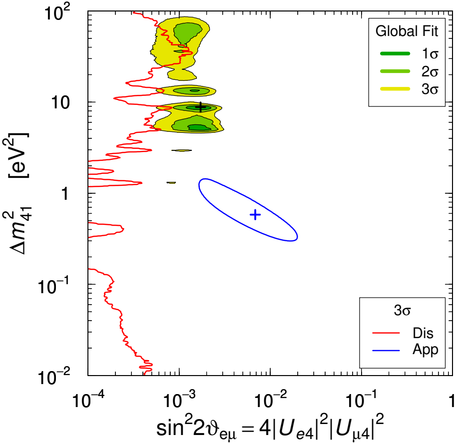
$$\Delta m^2_{\text{SBL}} \gtrsim 0.5\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}}$$

Global Appearance-Disappearance Tension

ν_e DIS
$\sin^2 2\vartheta_{ee} \simeq 4|U_{e4}|^2$

ν_μ DIS
$\sin^2 2\vartheta_{\mu\mu} \simeq 4|U_{\mu4}|^2$

$\nu_\mu \to \nu_e$ APP
$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4}\sin^2 2\vartheta_{ee}\sin^2 2\vartheta_{\mu\mu}$$



- $\nu_\mu \to \nu_e$ is quadratically suppressed!
- Global Fit:

  $\chi^2/\text{NDF} = 843.6/794$

  $\text{GoF} = 11\%$

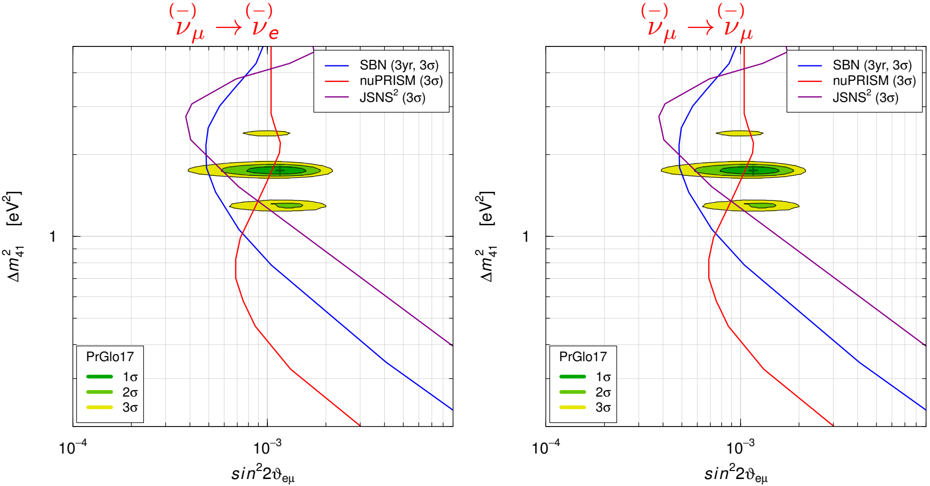
  $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 46.7/2$

  $\text{GoF}_{\text{PG}} = 7 \times 10^{-11}$ $\leftarrow$ ☹
- Similar tension in

  $3+2, \quad 3+3, \quad \ldots, \quad 3+N_s$

[Giunti, Zavanin, arXiv:1508.03172]

New Dedicated Experiments



[Global Fit: Gariazzo, Giunti, Laveder, Li, arXiv:1703.00860]

Non-Unitary Lepton Mixing

Standard Light Massive Neutrinos

ν_1, ν_3, ν_3

Heavy Neutral Leptons $(m_k \gtrsim 100\,\text{GeV})$

$\nu_4, \ldots, \nu_N$

$N_s = N - 3$ Heavy Sterile Neutrinos

$\nu_{s_1}, \ldots, \nu_{N_s}$

$$U^{N \times N} = \begin{array}{c} \begin{array}{ccccc} \phantom{U_{e1}} & N & \phantom{U_{e3}} & & \phantom{U_{eN}} \end{array} \\ \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \cdots & U_{eN} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \cdots & U_{\mu N} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \cdots & U_{\tau N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ U_{s_{N_s} 1} & U_{s_{N_s} 2} & U_{s_{N_s} 3} & \cdots & U_{s_{N_s} N} \end{pmatrix} \end{array}$$

Effective Low-Energy Mixing of Active Neutrinos $(\alpha = e, \mu, \tau)$

$$|\nu_\alpha\rangle = \sum_{k=1}^{3} U_{\alpha k}^{N \times N} |\nu_k\rangle = \sum_{k=1}^{3} N_{\alpha k} |\nu_k\rangle$$

Non-Unitary Effective 3×3 Mixing Matrix N

Convenient parameterization: $\boxed{N = N^{\text{NP}} U}$ [Schechter, Valle, PRD 22 (1980) 2227; Xing, PLB 660 (2008) 515; Escrihuela, Forero, Miranda, Tortola, Valle PRD 92 (2015) 053009]

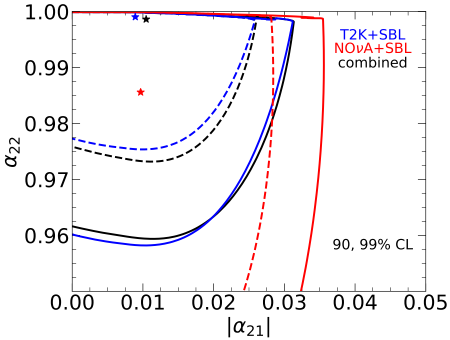
$$N^{\text{NP}} = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix}$$

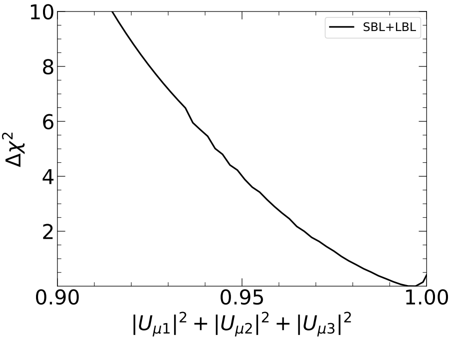
Real: $\alpha_{11}, \alpha_{22}, \alpha_{33}$

Complex: $\alpha_{21}, \alpha_{31}, \alpha_{32}$

$$|\alpha_{ij}| \leq \sqrt{(1-\alpha_{ii}^2)(1-\alpha_{jj}^2)}$$

$$\sum_{k=1}^{3} |U_{\mu k}|^2 = |\alpha_{21}|^2 + \alpha_{22}^2$$





[Forero, Giunti, Ternes, Tortola, arXiv:2103.01998]

Neutrino Non-Standard Interactions

- Observable non-renormalizable effective NSI of left-handed neutrinos:

Charged-Current-like NSI: $(\alpha, \beta = e, \mu, \tau)$

$$\mathcal{H}_{\text{NSI}}^{\text{CC}} = 2\sqrt{2} G_{\text{F}} V_{ud} \sum_{\alpha,\beta} \left(\overline{\ell_{\alpha L}} \gamma_{\rho} \nu_{\beta L} \right) \left[\varepsilon_{\alpha\beta}^{udL} \overline{u_L} \gamma^{\rho} d_L + \varepsilon_{\alpha\beta}^{udR} \overline{u_R} \gamma^{\rho} d_R \right] + \text{H.c.}$$

$$+ 2\sqrt{2} G_{\text{F}} \sum_{\alpha,\beta} \left(\overline{\nu_{\alpha L}} \gamma_{\rho} \nu_{\beta L} \right) \sum_{\sigma \neq \delta} \left[\varepsilon_{\alpha\beta}^{\sigma\delta L} \overline{\ell_{\sigma L}} \gamma^{\rho} \ell_{\delta L} + \varepsilon_{\alpha\beta}^{\sigma\delta R} \overline{\ell_{\sigma R}} \gamma^{\rho} \ell_{\delta R} \right]$$

Neutral-Current-like or Matter NSI: $(\varepsilon_{\alpha\beta}^{fP} = \varepsilon_{\beta\alpha}^{fP*})$

$$\mathcal{H}_{\text{NSI}}^{\text{NC}} = 2\sqrt{2} G_{\text{F}} \sum_{\alpha,\beta} \left(\overline{\nu_{\alpha L}} \gamma_{\rho} \nu_{\beta L} \right) \sum_{f=e,u,d} \left[\varepsilon_{\alpha\beta}^{fL} \overline{f_L} \gamma^{\rho} f_L + \varepsilon_{\alpha\beta}^{fR} \overline{f_R} \gamma^{\rho} f_R \right]$$

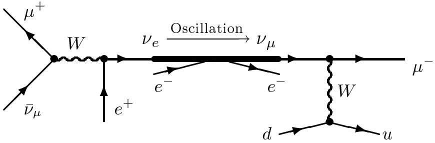
- Obtained in Effective Field Theory from operators of dimension 6 and higher:

$$\mathscr{O}_6 = \sum_{\alpha,\beta,\sigma,\delta} C_{\alpha\beta\sigma\delta} \left(\overline{L_{\alpha}} \gamma^{\rho} L_{\beta} \right) \left(\overline{L_{\sigma}} \gamma_{\rho} L_{\delta} \right) + \ldots$$

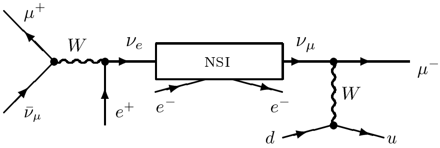
Constraints are required to suppress unobserved large charged lepton transitions as $\mu \to 3e$. [see: Gavela, Hernandez, Ota, Winter, PRD 79 (2009) 013007]

NSI Effects on Oscillations

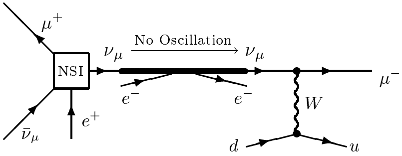
- Standard oscillations with matter effects:

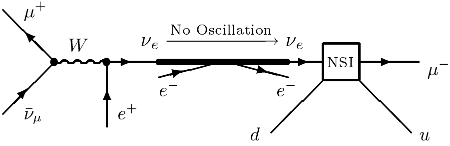


- NC NSI in neutrino propagation in matter $\sim \varepsilon$:



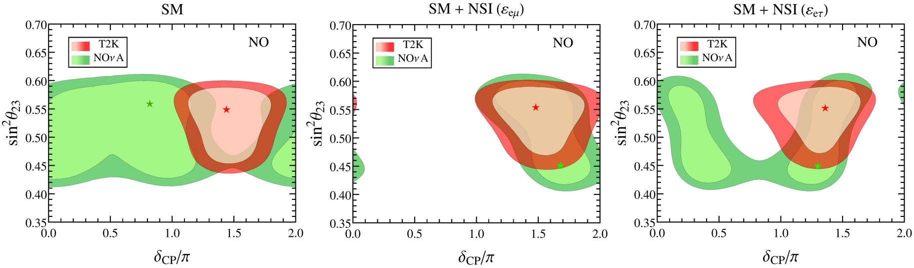
- CC NSI in neutrino production and detection $\sim \varepsilon^2$:





[Kopp, Lindner, Ota, PRD 76 (2007) 013001]

NSI as a solution to the NOνA and T2K discrepancy

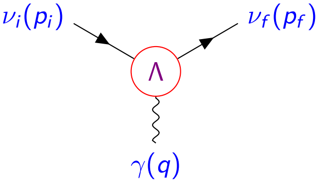


[Chatterjee, Palazzo, PRL 126 (2021) 051802, arXiv:2008.04161]

Neutrino Electromagnetic Interactions

- Effective Hamiltonian: $\mathcal{H}_{\text{em}}^{(\nu)}(x) = j_{\mu}^{(\nu)}(x) A^{\mu}(x) = \sum_{k,j=1} \overline{\nu_k}(x) \Lambda_{\mu}^{kj} \nu_j(x) A^{\mu}(x)$

- Effective electromagnetic vertex:



$$\langle \nu_f(p_f) | j_{\mu}^{(\nu)}(0) | \nu_i(p_i) \rangle = \overline{u_f}(p_f) \Lambda_{\mu}^{fi}(q) u_i(p_i)$$

$$q = p_i - p_f$$

- Vertex function:

$$\Lambda_{\mu}(q) = \left(\gamma_{\mu} - q_{\mu} \not{q}/q^2\right) \left[F_Q(q^2) + F_A(q^2) q^2 \gamma_5\right] - i \sigma_{\mu\nu} q^{\nu} \left[F_M(q^2) + i F_E(q^2) \gamma_5\right]$$

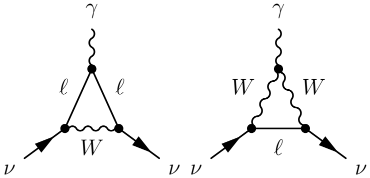
Lorentz-invariant form factors:	charge	anapole	magnetic	electric
$q^2 = 0 \quad \Longrightarrow$	q	a	μ	ε

Neutrino Charge Radii

- In the Standard Model neutrinos are neutral and there are no electromagnetic interactions at the tree-level.

- Radiative corrections generate an effective electromagnetic interaction vertex

$$\Lambda_\mu(q) = \left(\gamma_\mu - q_\mu \not{q}/q^2\right) F(q^2)$$



- $F(q^2) = \cancel{F(0)} + q^2 \left. \dfrac{dF(q^2)}{dq^2} \right|_{q^2=0} + \ldots = q^2 \dfrac{\langle r^2 \rangle}{6} + \ldots$

- In the Standard Model:

[Bernabeu et al, PRD 62 (2000) 113012, NPB 680 (2004) 450]

$$\langle r^2_{\nu_\ell} \rangle_{\text{SM}} = -\frac{G_{\text{F}}}{2\sqrt{2}\pi^2} \left[3 - 2 \log \left(\frac{m^2_\ell}{m^2_W} \right) \right]$$

$$\langle r^2_{\nu_e} \rangle_{\text{SM}} = -8.2 \times 10^{-33}\,\text{cm}^2$$
$$\langle r^2_{\nu_\mu} \rangle_{\text{SM}} = -4.8 \times 10^{-33}\,\text{cm}^2$$
$$\langle r^2_{\nu_\tau} \rangle_{\text{SM}} = -3.0 \times 10^{-33}\,\text{cm}^2$$

Experimental Bounds

Method	Experiment	Limit [cm^2]	CL	Year
Reactor $\bar{\nu}_e\, e^-$	Krasnoyarsk	$\|\langle r^2_{\nu_e}\rangle\| < 7.3 \times 10^{-32}$	90%	1992
	TEXONO	$-4.2 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 6.6 \times 10^{-32}$	90%	2009
Accelerator $\nu_e\, e^-$	LAMPF	$-7.12 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 10.88 \times 10^{-32}$	90%	1992
	LSND	$-5.94 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 8.28 \times 10^{-32}$	90%	2001
Accelerator $\nu_\mu\, e^-$	BNL-E734	$-5.7 \times 10^{-32} < \langle r^2_{\nu_\mu}\rangle < 1.1 \times 10^{-32}$	90%	1990
	CHARM-II	$\|\langle r^2_{\nu_\mu}\rangle\| < 1.2 \times 10^{-32}$	90%	1994

[see the review Giunti, Studenikin, RMP 87 (2015) 531, arXiv:1403.6344

and the update in Cadeddu, Giunti, Kouzakov, Y.F. Li, Studenikin, Y.Y. Zhang, PRD 98 (2018) 113010, arXiv:1810.05606]

- Neutrino charge radii contribute coherently to standard neutral-current weak interactions $\Rightarrow$ shifts $\sin^2\vartheta_W \to \sin^2\vartheta_W \left(1 + \frac{1}{3} m_W^2 \langle r^2_{\nu_\ell}\rangle\right)$
- The current limits are not too far from the SM prediction: about 1 order of magnitude.
- Powerful precision test of the SM.
- A failure to measure the SM values would imply BSM physics!

Neutrino Magnetic and Electric Moments

- Extended Standard Model with right-handed neutrinos and $\Delta L = 0$:

$$\mu_{kk}^{\mathrm{D}} \simeq 3.2 \times 10^{-19} \mu_{\mathrm{B}} \left(\frac{m_k}{\mathrm{eV}} \right) \qquad \varepsilon_{kk}^{\mathrm{D}} = 0$$

$$\left. \begin{array}{r} \mu_{kj}^{\mathrm{D}} \\ i\varepsilon_{kj}^{\mathrm{D}} \end{array} \right\} \simeq -3.9 \times 10^{-23} \mu_{\mathrm{B}} \left(\frac{m_k \pm m_j}{\mathrm{eV}} \right) \sum_{\ell=e,\mu,\tau} U_{\ell k}^{*} U_{\ell j} \left(\frac{m_\ell}{m_\tau} \right)^2$$

off-diagonal moments are GIM-suppressed

[Fujikawa, Shrock, PRL 45 (1980) 963; Pal, Wolfenstein, PRD 25 (1982) 766; Shrock, NPB 206 (1982) 359; Dvornikov, Studenikin, PRD 69 (2004) 073001, JETP 99 (2004) 254]

- Extended Standard Model with Majorana neutrinos ($|\Delta L| = 2$):

$$\mu_{kj}^{\mathrm{M}} \simeq -7.8 \times 10^{-23} \mu_{\mathrm{B}} \, i \, (m_k + m_j) \sum_{\ell=e,\mu,\tau} \mathrm{Im}\left[U_{\ell k}^{*} U_{\ell j} \right] \frac{m_\ell^2}{m_W^2}$$

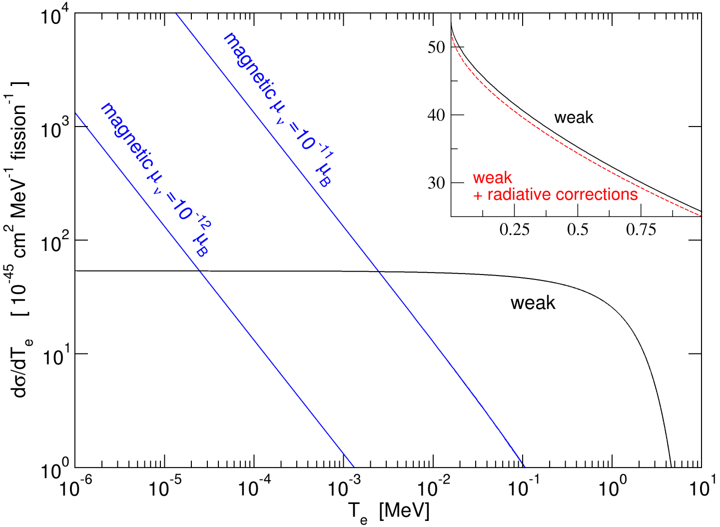
$$\varepsilon_{kj}^{\mathrm{M}} \simeq 7.8 \times 10^{-23} \mu_{\mathrm{B}} \, i \, (m_k - m_j) \sum_{\ell=e,\mu,\tau} \mathrm{Re}\left[U_{\ell k}^{*} U_{\ell j} \right] \frac{m_\ell^2}{m_W^2}$$

[Shrock, NPB 206 (1982) 359]

GIM-suppressed, but additional model-dependent contributions of the scalar sector can enhance the Majorana transition dipole moments

[Pal, Wolfenstein, PRD 25 (1982) 766; Barr, Freire, Zee, PRL 65 (1990) 2626; Pal, PRD 44 (1991) 2261]

$$\left(\frac{d\sigma_{\nu e^-}}{dT_e}\right)_{\rm mag} = \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_e}-\frac{1}{E_\nu}\right)\left(\frac{\mu_\nu}{\mu_{\rm B}}\right)^2$$



Method	Experiment	Limit $[\mu_B]$	CL	Year
Reactor $\bar{\nu}_e\, e^-$	Krasnoyarsk	$\mu_{\nu_e} < 2.4 \times 10^{-10}$	90%	1992
	Rovno	$\mu_{\nu_e} < 1.9 \times 10^{-10}$	95%	1993
	MUNU	$\mu_{\nu_e} < 9 \times 10^{-11}$	90%	2005
	TEXONO	$\mu_{\nu_e} < 7.4 \times 10^{-11}$	90%	2006
	GEMMA	$\mu_{\nu_e} < 2.9 \times 10^{-11}$	90%	2012
Accelerator $\nu_e\, e^-$	LAMPF	$\mu_{\nu_e} < 1.1 \times 10^{-9}$	90%	1992
Accelerator $(\nu_\mu, \bar{\nu}_\mu)\, e^-$	BNL-E734	$\mu_{\nu_\mu} < 8.5 \times 10^{-10}$	90%	1990
	LAMPF	$\mu_{\nu_\mu} < 7.4 \times 10^{-10}$	90%	1992
	LSND	$\mu_{\nu_\mu} < 6.8 \times 10^{-10}$	90%	2001
Accelerator $(\nu_\tau, \bar{\nu}_\tau)\, e^-$	DONUT	$\mu_{\nu_\tau} < 3.9 \times 10^{-7}$	90%	2001
Solar $\nu_e\, e^-$	Super-Kamiokande	$\mu_S(E_\nu \gtrsim 5\,\text{MeV}) < 1.1 \times 10^{-10}$	90%	2004
	Borexino	$\mu_S(E_\nu \lesssim 1\,\text{MeV}) < 2.8 \times 10^{-11}$	90%	2017

[see the review Giunti, Studenikin, RMP 87 (2015) 531, arXiv:1403.6344]

- Gap of about 8 orders of magnitude between the experimental limits and the $\lesssim 10^{-19}\,\mu_B$ prediction of the minimal Standard Model extensions.
- $\mu_\nu \gg 10^{-19}\,\mu_B$ discovery $\Rightarrow$ non-minimal new physics beyond the SM.
- Neutrino spin-flavor precession in a magnetic field

[Lim, Marciano, PRD 37 (1988) 1368; Akhmedov, PLB 213 (1988) 64]

Conclusions

- Important first determination: neutrino mass ordering.
- Neutrinos can be powerful messengers of the physics beyond the SM.
- The discovery of L violation through $\beta\beta_{0\nu}$ decay is of paramount importance $\Longrightarrow$ Majorana neutrinos.
- The additional discovery of CP violation in the lepton sector in LBL neutrino oscillation experiments will represent a strong indication in favor of leptogenesis as the origin of the matter-antimatter asymmetry in the Universe.
- The search for sterile neutrinos may open a cornucopia of new phenomena.
- Look out for Non-Unitary Mixing neutrino Non-Standard Interactions, and Electromagnetic Interactions.