Oscillations and sterile neutrinos

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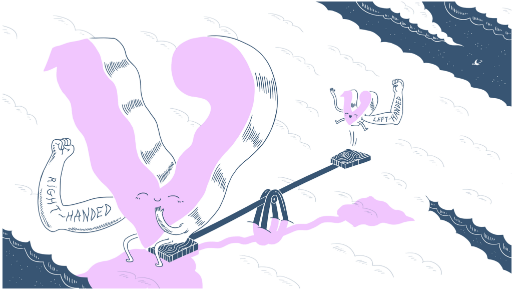
Three burning questions

- Why neutrinos are massive? (Heaviest neutrino has mass 0.05 – 1.1 eV)
- What is dark matter? ($\Omega_{\text{DM}} \sim 1/4$)
- Why is the matter-antimatter asymmetry larger than expected? ($\eta \sim 10^{-10} \gg 10^{-20} = \eta_{\text{SM}}$)



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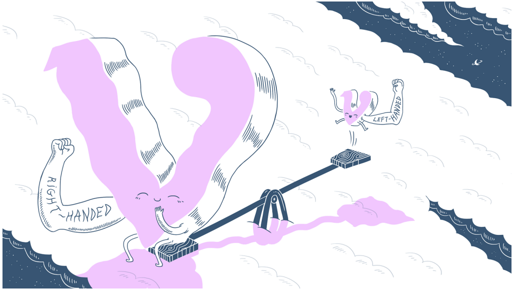
Popular solution: Neutrinos have mass due to existence of sterile neutrinos N_1, N_2, ... which are gauge singlets with respect to SM gauge symmetry.

No hints on active-sterile mixing or mass $\Rightarrow$ different approaches needed to constrain the (U_ℓ^2, M_N) parameter space.



Different experiments are sensitive to different mass regions

10^{15} **GeV**	Natural scale.
TeV	LHC scale.
GeV	Meson and Z decays.
MeV	Meson peak searches.
keV	β decay kink searches. Dark matter.
eV	Neutrino oscillation anomalies.

FASER/FASER2 will be useful constraining active-sterile mixing for $M_N \in [0.5, 3]$ GeV (slightly more powerful on $\nu_\tau - N$ mixing).

Background

Extra terms in Lagrangian include:

$$\Delta\mathcal{L}^{\nu} = \underbrace{\frac{1}{2}\overline{\nu_R}(i\partial\!\!\!/ - \mathbf{M}_N)(\nu_R)^c}_{\text{Kinetic and Majorana mass term}} - \underbrace{\overline{\nu_R}\mathbf{Y}_\nu\varepsilon_{\alpha\beta}L_{L\alpha}\phi_\beta}_{\text{Dirac mass term after SSB}} + \text{h.c.} + \cdots$$

Mass terms can be collected to block matrix form

$$-\mathcal{L}^{\nu}_{m} = \frac{1}{2}\begin{pmatrix}\nu_L \\ (\nu_R)^c\end{pmatrix}^T C \begin{pmatrix}\mathbf{0}_3 & \mathbf{M}_D^T \\ \mathbf{M}_D & \mathbf{M}_N\end{pmatrix}\begin{pmatrix}\nu_L \\ (\nu_R)^c\end{pmatrix}$$

"$3+n$" neutrino scenario. ($n \geq 2$)

$$\nu_L = \begin{pmatrix}\nu_{L,e} \\ \nu_{L,\mu} \\ \nu_{L,\tau}\end{pmatrix}, \quad \nu_R = \begin{pmatrix}N_{R,1} \\ \vdots \\ N_{R,n}\end{pmatrix}, \quad \mathbf{M}_D = \frac{v}{\sqrt{2}}\mathbf{Y}_\nu$$

$$\mathbf{M}_L = -\mathbf{M}_D\mathbf{M}_N^{-1}\mathbf{M}_D^{\dagger} + \text{(subleading terms)},$$

Active — sterile -mixing

The mass matrix can be diagonalized with a unitary matrix $\mathbf{U}$:

$$\mathbf{U} = \begin{pmatrix} \mathbf{U}_\nu & \theta \\ \theta'^T & \mathbf{U}_N \end{pmatrix}, \quad \theta \approx \mathbf{M}_D \mathbf{M}_R^{-1}, \quad \mathbf{U}_\nu \approx \left(\mathbf{1} - \frac{1}{2}\theta^\dagger \theta\right) \mathbf{U}_{\text{PMNS}}$$

$$\mathbf{U}^T \begin{pmatrix} \mathbf{0}_3 & \mathbf{M}_D^T \\ \mathbf{M}_D & \mathbf{M}_N \end{pmatrix} \mathbf{U} = \text{diag}(m_1, m_2, m_3, m_4, \ldots, m_{3+n})$$

Physical sterile neutrino states have an active component:

$$\begin{cases} \nu_i \approx (\mathbf{U}_\nu^\dagger)_{i\alpha} \nu_{L,\alpha} - (\mathbf{U}_\nu^\dagger \theta)_{ij} \nu_{R,j}^c \\ N_{R,i} \approx \nu_{R,i} + \theta_{\alpha i} \nu_{L,\alpha}^c, \end{cases}$$

Expected mixing:

$$|\theta|^2 = \frac{m_{\text{active}}}{m_{\text{sterile}}} = \mathcal{O}(10^{-11}) \times \frac{\text{GeV}}{m_{\text{sterile}}}$$

We measure the active weight of (e, μ, τ) flavour component in sterile neutrino state, which is interpreted as the probability of detecting $\nu_{e,\mu,\tau}$ after production of N_R.

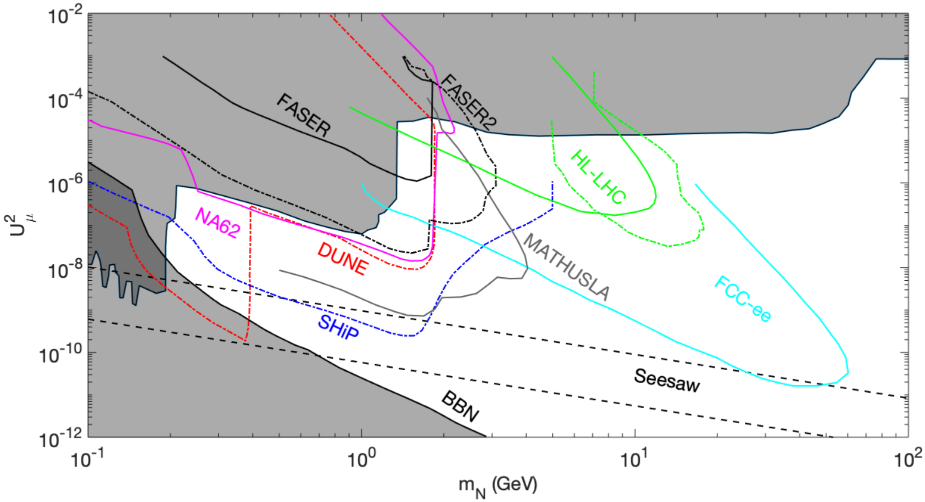
$$\boxed{U_e^2 = \sum_{i=4}^{3+n} |U_{ei}|^2}, \quad \boxed{U_\mu^2 = \sum_{i=4}^{3+n} |U_{\mu i}|^2}, \quad \boxed{U_\tau^2 = \sum_{i=4}^{3+n} |U_{\tau i}|^2}$$

Data from FASER/FASER2 is from Ariga et al., Phys.Rev.D 99 (2019) 9, 095011

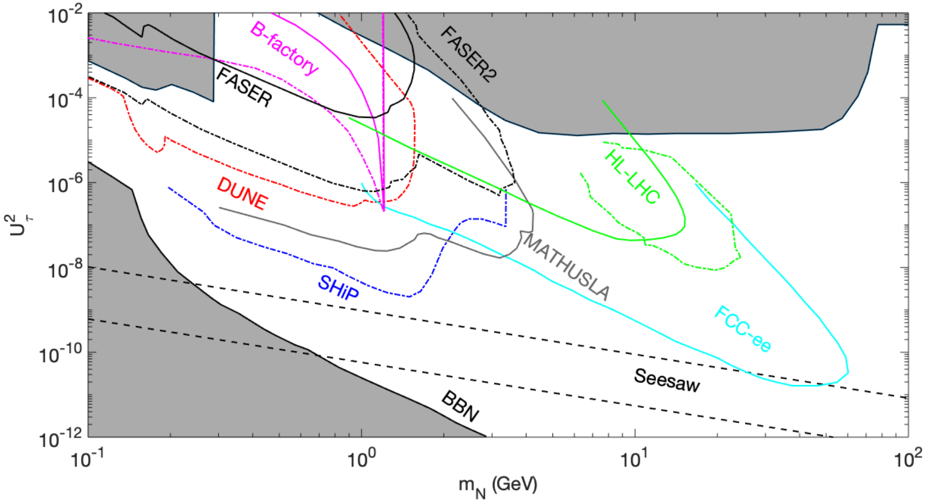
Simple benchmark models:

1. $U_e^2 : U_\mu^2 : U_\tau^2 = 1 : 0 : 0$
2. $U_e^2 : U_\mu^2 : U_\tau^2 = 0 : 1 : 0$
3. $U_e^2 : U_\mu^2 : U_\tau^2 = 0 : 0 : 1$

Experimental constraints for U_μ^2



Experimental constraints for U_τ^2



- FASER and FASER2 can not access the expected scale for mixing in canonical seesaw scenario.
- Present experimental limits are improved for U_μ^2 and U_τ^2 for FASER, and also for U_e^2 for FASER2.
- FASER and FASER2 are competitive with other planned experiments aiming on detecting the active-sterile neutrino mixing.

Thank you!

Experimental constraints for U_e^2