Heavy Neutral Leptons via Mixing and Transition Dipole Moments

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Why Heavy Neutral Leptons?

Heavy Neutral Leptons: Motivation

Heavy neutral leptons (HNLs) are a well motivated extension to the SM:

- SM: Only the left-handed field ν_L
  $\Leftrightarrow$ Neutrinos are massless to all orders in perturbation theory

- Introduce ν_R: $\mathcal{L} \supset -M_D \bar{\nu}_L \nu_R + \text{h.c.}, \;\; M_D = \frac{vY_\nu}{\sqrt{2}}$
  $\Rightarrow$ Why is $Y_\nu \ll Y_e, Y_u, Y_d$?

- Lepton number (accidental global symmetry of the SM) forbids $\mathcal{L} \supset -\frac{1}{2} M_R \bar{\nu}_R^c \nu_R + \text{h.c.}$
  $\Rightarrow$ This symmetry need not hold in the UV and *a priori*, M_R of arbitrary value

Extended neutral lepton sector:

- Dynamically generate the light neutrino masses
- Interesting phenomenology: **$3 + n$ oscillations** (C. Giunti, S. Urrea Gonzalez talks), **$0\nu\beta\beta$ decay** (G. Benato, A Giuliani, W. Dekens talks), **cLFV** processes, **direct production** in β decay, beam dumps and colliders, **DM** (J. Kersten, A. Vicente, L. Strigari talks), **leptogenesis** (J. Klaric, S. Sandner talks)
- This talk: Mixing and dipole portals to HNLs

Heavy Neutral Leptons in the SM Effective Field Theory

Adding singlet fermion N_R to the SM (respecting $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$)

$$\mathcal{L}_{\mathrm{SMEFT}+N} = \mathcal{L}_{\mathrm{SM}} + i\bar{N}_R \partial\!\!\!/ N_R - \left[\frac{1}{2} M_R \bar{N}_R^c N_R + Y_\nu \bar{L}\tilde{H} N_R + \mathrm{h.c.}\right] + \sum_{d>5} \mathcal{L}^{(d)}$$

where $\tilde{H} = i\sigma_2 H^*$ and $\Psi^c = C\bar{\Psi}^T$

[Grzadkowski, Iskrzyński, Misiak, Rosiek, 10]
[Jenkins, Manohar, Trott, 13]
[Lehman, 14]

- $d = 5$ operators:

$$\mathcal{L}^{(5)} = C_\nu^{(5)} (\bar{L}\tilde{H})(H^\dagger L^c) + M_R^{(5)} (\bar{N}_R^c N_R)(H^\dagger H) + d_R^{(5)} (\bar{N}_R^c \sigma_{\mu\nu} N_R) B^{\mu\nu} + \mathrm{h.c.}$$

[Weinberg, 79]
[Aparici, Kim, Santamaria, Wudka, 09]
[Caputo, Hernández, López-Pavón, Salvado, 17]

- $d = 6$ operators:

$$\begin{aligned}\mathcal{L}^{(6)} \supset\ & Y_\nu^{(6)} \bar{L}\tilde{H} N_R (H^\dagger H) + C_{duNe}^{(6)} (\bar{d}_R \gamma_\mu u_R)(\bar{N}_R \gamma^\mu e_R) + C_{fN}^{(6)} (\bar{f}\gamma_\mu f)(\bar{N}_R \gamma^\mu N_R) \\ & + C_{LNLe}^{(6)} (\bar{L} N_R)\epsilon(\bar{L} e_R) + C_{LNQd}^{(6)} (\bar{L} N_R)\epsilon(\bar{Q} d_R) + C_{LdQN}^{(6)} (\bar{L} d_R)\epsilon(\bar{Q} N_R) \\ & + C_B^{(6)} g' (\bar{L}\sigma_{\mu\nu} N_R)\tilde{H} B^{\mu\nu} + C_W^{(6)} g (\bar{L}\sigma_{\mu\nu} N_R)\tau^I \tilde{H} W^{I\mu\nu} + \mathrm{h.c.}\end{aligned}$$

[Bhattacharya, Wudka, 16]
[Liao, Ma, 17]

Below the Electroweak Scale

Replace H with $\langle H \rangle = \frac{v}{\sqrt{2}}$ and integrate out degrees of freedom heavier than m_W.
Theory now respects $\mathrm{SU}(3)_c \times \mathrm{U}(1)_{\mathrm{em}}$

$$\mathcal{L}_{\mathrm{LEFT}+N} = \mathcal{L}'_{\mathrm{SM}} + i\bar{N}_R \partial\!\!\!/ N_R - \left[\frac{1}{2} M_L \bar{\nu}_L \nu_L^c + \frac{1}{2} M_R \bar{N}_R^c N_R + M_D \bar{\nu}_L N_R + \mathrm{h.c.}\right] + \sum_{\bar{d}>5} \mathcal{L}^{(\bar{d})}$$

- $\bar{d} = 5$ operators:

$$\mathcal{L}^{(\bar{5})} = \frac{1}{2} d_L (\bar{\nu}_L \sigma_{\mu\nu} \nu_L^c) F^{\mu\nu} + \frac{1}{2} d_R (\bar{N}_R^c \sigma_{\mu\nu} N_R) F^{\mu\nu} + d_{\nu N} (\bar{\nu}_L \sigma_{\mu\nu} N_R) F^{\mu\nu} + \mathrm{h.c.}$$

- $\bar{d} = 6$ operators: Four-fermion scalar, vector and tensor operators (neutrino NSIs)

UV theory above Λ $\Longleftrightarrow$ Low-energy interactions of N

1) UV predicts combination of SMEFT+N coefficients $C_i(\mu = \Lambda)$
2) RG evolution of operators down to $\mu = v$
3) Match onto LEFT+ N operators
4) RG evolution down to experimental scale

[Chala, Titov, 20]
[Li, Ma, Schmidt, 20]
[Chala, Titov, 21]

Mixing Portal

Mixing Portal

Introducing n_S sterile states, mass terms can be written as an $N \times N$ ($N = 3 + n_S$) matrix

$$\mathcal{L}_m = -\frac{1}{2}\bar{\mathcal{N}}_L \mathcal{M}_\nu \mathcal{N}_L^c + \text{h.c.}\,, \quad \mathcal{M}_\nu = \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix}, \quad \mathcal{N}_L = \begin{pmatrix} \nu_L \\ N_R^c \end{pmatrix}$$

Now diagonalise $\mathcal{M}_\nu$ as

$$U^\dagger \mathcal{M}_\nu U^* = \text{diag}(m_1, m_2, m_3, m_{N_1}, m_{N_2}, \dots)\,, \quad \nu_L = P_L \mathcal{P} U n\,, \quad N_R^c = P_L \mathcal{P}_S U n$$

where $n = (\nu_1, \nu_2, \nu_3, N_1, \cdots)^T$ contains Majorana fields

U: Unitary matrix parametrised by $\frac{1}{2}N(N-1)$ angles and $\frac{1}{2}N(N+1)$ phases
$\mathcal{P}$ and $\mathcal{P}_S$: Project out the top 3 and bottom n_S rows of U respectively

$\Rightarrow$ Insert expression for ν_L into SM weak interactions

$$\mathcal{L}_{W^\pm} = -\frac{g}{\sqrt{2}}(\bar{e}_L \gamma^\mu \mathcal{P} U n_L) W_\mu^- + \text{h.c.}\,, \quad \mathcal{L}_Z = -\frac{g}{2c_W}(\bar{n}_L \gamma^\mu \mathcal{C} n_L) Z_\mu \quad (\mathcal{C} = U^\dagger \mathcal{P}^\dagger \mathcal{P} U)$$

$\Rightarrow$ Mixing portal: Directly produce HNLs in SM processes (sensitive to $\mathcal{P}U$)

Reproducing Light Neutrino Data

It's common to split the matrix U up as

$$U = \begin{pmatrix} \mathcal{P} U \\ \mathcal{P}_S U \end{pmatrix} = \begin{pmatrix} U_\nu & U_{\nu N} \\ U_{N\nu} & U_N \end{pmatrix}$$

Writing $\mathcal{M}_\nu = U \,\mathrm{diag}(m_1, m_2, m_3, m_{N_1}, \ldots)\, U^T$ with $M_L = 0$ then gives

$$\underbrace{\sum_i^3 (U_\nu)_{\alpha i} (U_\nu)_{\beta i} m_i}_{\Delta m^2, U_{\mathrm{PMNS}}, m_\beta, m_{\beta\beta}, \Sigma m_\nu} = -\sum_k^{n_S} (U_{\nu N})_{\alpha k} (U_{\nu N})_{\beta k} m_{N_k}$$

For large m_{N_k}, two ways to reproduce the light neutrino data:

1) Suppressed active-sterile mixings $(U_{\nu N})_{\alpha k} \equiv U_{\alpha N_k}$
   $\Rightarrow$ Not conducive to direct production of HNLs with $m_N \lesssim 1$ TeV in, e.g., colliders
   $\Rightarrow$ Prediction of *type-I seesaw*
2) Cancellations among the HNLs N_k
   $\Rightarrow$ For example, $m_{N_1} \approx m_{N_2}$ and $U_{\alpha N_1} = i U_{\alpha N_2}$ ($U_{\alpha N_k}$ can in principle be large)
   $\Rightarrow$ Prediction of *inverse seesaw*

Extension: Inverse Seesaw

Introduce an extended sterile sector with the mass matrix

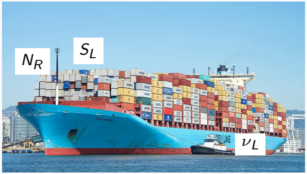
$$\mathcal{L}_m = -\frac{1}{2}\bar{\mathcal{N}}_L \begin{pmatrix} 0 & M_D & \mu_F \\ M_D^T & \mu_R & M_S \\ \mu_F^T & M_S^T & \mu_S \end{pmatrix} \mathcal{N}_L^c + \text{h.c.}\,, \qquad \mathcal{N}_L = \begin{pmatrix} \nu_L \\ N_R^c \\ S_L \end{pmatrix}$$

'Technically natural' for the parameters μ_R and μ_S to be small
$\Rightarrow \mu_{R,S} \to 0$ restores lepton number symmetry

In the limit $\mu_{R,S} \ll M_D \ll M_S$:

$$M_\nu = M_D M_S^{-1} \mu_S (M_S^T)^{-1} M_D^T$$

Sterile states N_1 and N_2 form a pseudo-Dirac HNL with splitting $\Delta m_N \sim \mu_S$ and opposite CP phases



Key point: HNLs with $m_N \lesssim 1$ TeV can have large enough mixings to be produced directly in experiments

Phenomenological Approach

We can consider the toy $1+2$ model

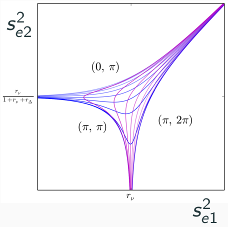
$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D & \mu_R & m_S \\ 0 & m_S & \mu_S \end{pmatrix} = U \begin{pmatrix} m_\nu & 0 & 0 \\ 0 & m_N & 0 \\ 0 & 0 & m_N(1+r_\Delta) \end{pmatrix} U^T$$

where U is a 3×3 unitary matrix containing 2 active-sterile mixings

The $(1,1)$-element gives the following constraint:

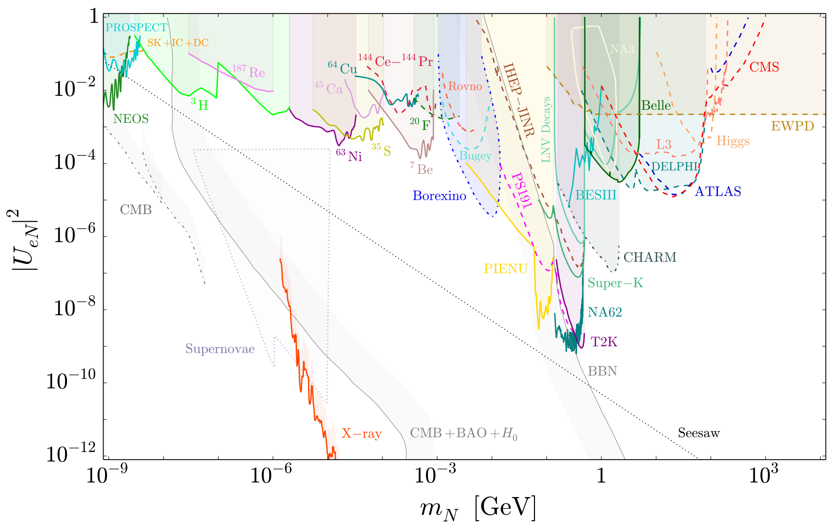
$$m_\nu c_{e1}^2 c_{e2}^2 + m_N s_{e1}^2 c_{e2}^2 e^{i\phi_1} + m_N(1+r_\Delta) s_{e2}^2 e^{i\phi_2} = 0$$

- $\phi_1 = \phi_2 = \pi \quad \Rightarrow \quad s_{e2}^2 = \frac{m_\nu/m_N - s_{e1}^2}{1+r_\Delta}$ (type-I seesaw-like)
- $\phi_1 = 0,\ \phi_2 = \pi \quad \Rightarrow \quad s_{e2}^2 = \frac{s_{e1}^2}{1+r_\Delta}$ (inverse seesaw-like)



[PDB, Deppisch, Dev, JHEP **03**, 107 (2019)]

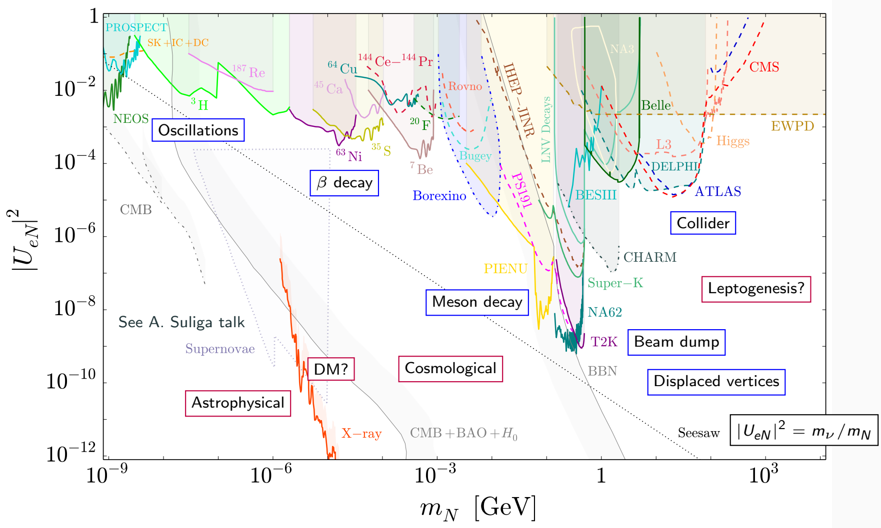
Current $|U_{eN}|^2$ Constraints



[PDB, Deppisch, Dev, JHEP **03**, 107 (2019)]

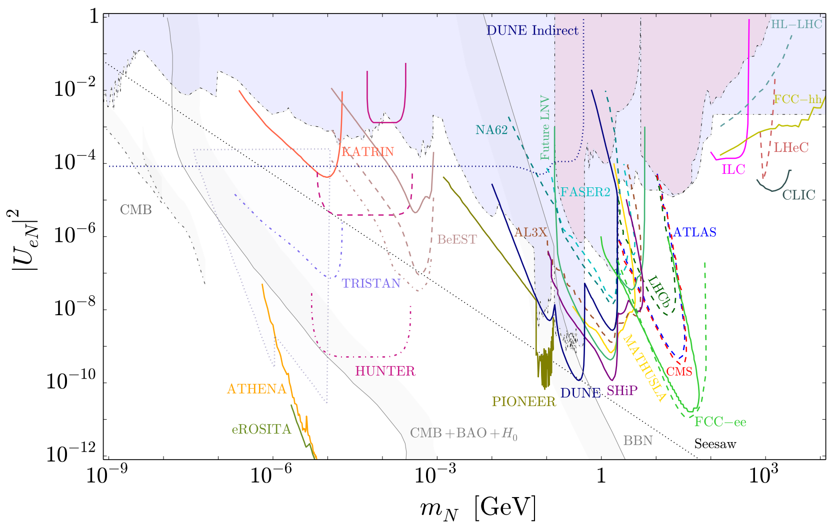
Note: ‘Heavy’ here means more massive than ~ 1 eV

Current $|U_{eN}|^2$ Constraints



[PDB, Deppisch, Dev, JHEP **03**, 107 (2019)]

Future $|U_{eN}|^2$ Sensitivities



[PDB, Deppisch, Dev, JHEP **03**, 107 (2019)]

For current constraints and future sensitivities on $|U_{\mu N}|^2$ and $|U_{\tau N}|^2$, see `www.sterile-neutrino.org`. *Work in progress*!

Dipole Portal

Recall: Introducing N_R produces the following LEFT+N operators at $\bar{d}=5$:

$$\mathcal{L}^{(\bar{5})} = \frac{1}{2} d_L (\bar{\nu}_L \sigma_{\mu\nu} \nu_L^c) F^{\mu\nu} + \frac{1}{2} d_R (\bar{N}_R^c \sigma_{\mu\nu} N_R) F^{\mu\nu} + d_{\nu N} (\bar{\nu}_L \sigma_{\mu\nu} N_R) F^{\mu\nu} + \text{h.c.}$$

Consider two scenarios:

$$\text{Nature of } \nu \text{ and } N \begin{cases} \nu = \nu_L + \nu_R, \;\; N = N_L + N_R & \text{(Dirac)} \\ \nu = \nu_L + \nu_L^c, \;\; N = N_R^c + N_R & \text{(Majorana)} \end{cases}$$

In the Dirac case (ν in flavour basis and N in mass basis),

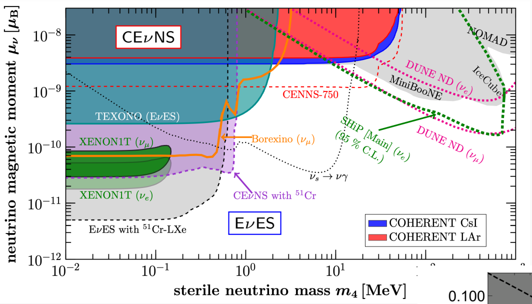
$$\mathcal{L}_d = \frac{\mu_{\nu N}^{\alpha}}{2} (\bar{\nu}_{\alpha L} \sigma_{\mu\nu} P_R N) F^{\mu\nu} + \frac{\zeta_{\nu N}^{\alpha}}{2} (\bar{\nu}_{\alpha R} \sigma_{\mu\nu} P_L N) F^{\mu\nu} + \text{h.c.}$$

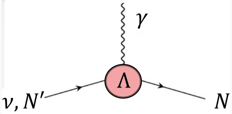
In the Majorana case,

$$\mathcal{L}_d = \frac{\mu_{\nu N}^{\alpha}}{2} (\bar{\nu}_{\alpha L} \sigma_{\mu\nu} P_R N) F^{\mu\nu} + \text{h.c.} = \frac{\mu_{\nu N}^{\alpha}}{2} (\bar{\nu}_{\alpha} \sigma_{\mu\nu} N) F^{\mu\nu}$$

where we have used that $(\mu_{\nu N}^{\alpha})^* = -\mu_{\nu N}^{\alpha}$ for Majorana fields

Dipole Portal Constraints





CEνNS: $\nu A \to N A$

EνES: $\nu e^- \to N e^-$

Beam dump: $\pi^+, K^+ \to \mu^+(\nu_\mu^* \to \gamma N)$

Collider: $e^+ e^- \to Z \to (N \to \nu\gamma)\bar{\nu}$

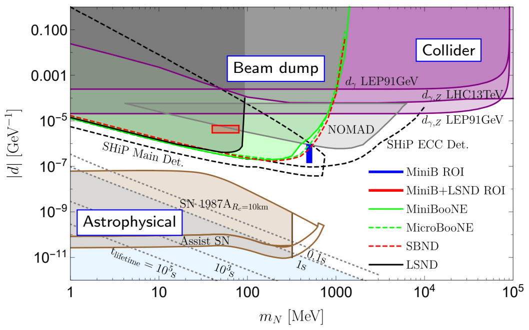
$q_i \bar{q}_i \to Z \to (N \to \nu\gamma)\bar{\nu}$

Supernovae: $\nu e^- \to N e^-$

$\nu p \to N p$

$e^+ e^- \to \bar{\nu} N$

$\gamma\nu \to N$



[Magill, Plestid, Pospelov, Tsai, 18]
[Miranda, Papoulias, Sanders, Tórtola, Valle, 21]

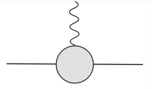
Naturalness Bounds

Recall the $d = 6$ operators:

$$\mathcal{L}^{(6)} \supset Y_\nu^{(6)} \bar{L}\tilde{H}N_R(H^\dagger H) + C_B^{(6)} g'(\bar{L}\sigma_{\mu\nu}N_R)\tilde{H}B^{\mu\nu} + C_W^{(6)} g(\bar{L}\sigma_{\mu\nu}N_R)\tau^I \tilde{H}W^{I\mu\nu} + \text{h.c.}$$

In the Dirac case,

$$\frac{\mu_{\nu N}}{\mu_B} = 8\sqrt{2}m_e v(C_B^{(6)} + C_W^{(6)}), \quad \delta m_{\nu N} = -\frac{v^3}{2\sqrt{2}} Y_\nu^{(6)}$$



which gives

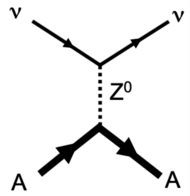
$$\frac{\mu_{\nu N}}{\mu_B} = -\frac{32 m_e}{v^2} \frac{C_B^{(6)}(v) + C_W^{(6)}(v)}{Y_\nu^{(6)}(v)} \delta m_{\nu N} \quad \Rightarrow \quad \frac{|\mu_{\nu N}|}{\mu_B} \sim 10^{-15} \left(\frac{\delta m_{\nu N}}{1 \text{ eV}}\right)$$

[Bell, Cirigliano, Ramsey-Musolf, Vogel, Wise, 05]
[Bell, Gorchtein, Ramsey-Musolf, Vogel, Wise, 06]
[Chala, Titov, 20]

However, if Dirac HNL (e.g. produced in inverse seesaw) is approximately decoupled from the mass generation of the light neutrinos, constraint needs not apply

Naturalness constraints on Majorana magnetic moments less stringent due to antisymmetric nature of $\mu_{\nu N}$

CEνNS Bounds



Neutrino scattering elastically from a nucleus A

$$E_\nu < 1/R_{\text{nucleus}} \sim \mathcal{O}(10 \text{ MeV}), \quad \sigma \propto Z^2$$

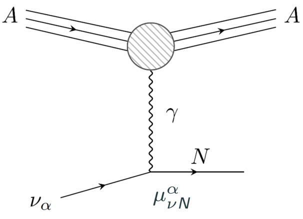
Very low nuclear recoils

$$E_R < 2E_\nu^2/m_A \sim \mathcal{O}(\text{keV})$$

Experiments:

- COHERENT; 6.7σ observation, compatible with SM (see I. Bernardi talk) [Akimov et al., 17]
- NUCLEUS; $\bar{\nu}_e$ from CHOOZ, low E_R threshold (see J. Rothe talk)
- CONUS (MPIK, see C. Buck talk), MINER (US), RICOCHET (US+FR), CONNIE (int.)

Transition magnetic moment ⇒ Primakoff upscattering

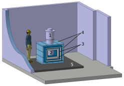


'Left-handed incoming ν_α (right-handed $\bar{\nu}_\alpha$)
⇒ Not sensitive to Dirac vs. Majorana nature of N

$$\mathcal{L}_d = \frac{\mu^\alpha_{\nu N}}{2}\left(\bar{\nu}_\alpha \sigma_{\mu\nu}(P_R + P_L)N\right)F^{\mu\nu}$$

Primakoff Upscattering at NUCLEUS

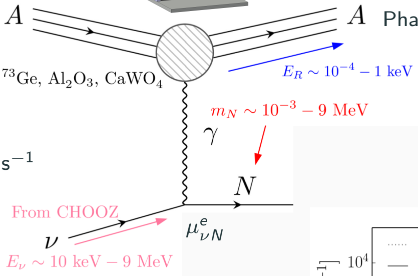
Image: Kåre Fridell



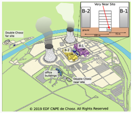
Cryogenic calorimeter (CEνNS target):
Phase I: 10 g of $Al_2O_3/CaWO_4$
Phase II: 1 kg of ^{73}Ge

[Angloher et al., 19]

See J. Rothe talk

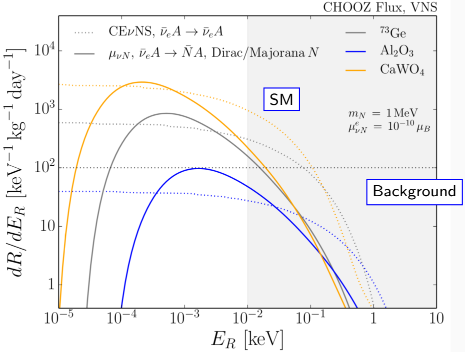


$10^{12}\ \bar{\nu}_e\ \text{cm}^{-2}\ \text{s}^{-1}$

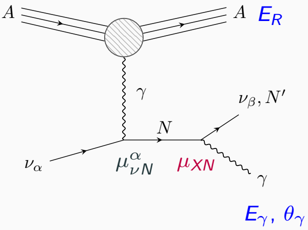


$$\frac{dR_{\bar{\nu}_e A \to NA}}{dE_R} \propto \int_{E_\nu^{\text{min}}}^{E_\nu^{\text{max}}} dE_\nu \frac{d\phi_{\bar{\nu}_e}}{dE_\nu} \frac{d\sigma_{\bar{\nu}_e A \to NA}}{dE_R},$$

No excess over SM CEνNS + Background
$\Rightarrow$ Upper bound on $\mu^e_{\nu N}$ as a function of m_N



Consider $\nu_\alpha A \to NA$ followed by $N \to X\gamma$, $X = \{\nu_\beta, N', \ldots\}$, i.e. N decays via



$$\mathcal{L}_d = \frac{\mu^\beta_{\nu N}}{2}(\bar{\nu}_{\beta L}\sigma_{\mu\nu}P_R N)F^{\mu\nu} + \frac{\mu_{N'N}}{2}(\bar{N}'\sigma_{\mu\nu}P_R N)F^{\mu\nu} + \text{h.c.}$$

Using the narrow width approximation:

$$\frac{d\sigma_{\nu_\alpha A \to XA\gamma}}{dE_R} = \frac{d\sigma_{\nu_\alpha A \to NA}}{dE_R} \underbrace{\frac{\Gamma_{N\to X\gamma}}{\Gamma_N}}_{\mathcal{B}_{N\to X\gamma}}$$

Probability that the decay $N \to X\gamma$ occurs inside the detector length L_{det} is

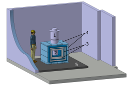
$$\mathcal{B}_{N\to X\gamma}P_N^{\text{det}} = \frac{\Gamma_{N\to X\gamma}}{\Gamma_N}\left[1 - \exp\left(\frac{L_{\text{det}}\Gamma_N}{\beta\gamma}\right)\right], \quad \beta\gamma = \sqrt{\gamma^2 - 1}, \quad \gamma = \frac{E_N}{m_N}$$

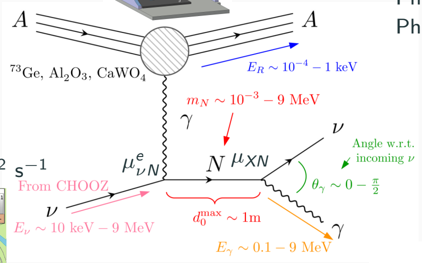
Assuming that the decay length $\ell_N = \beta\gamma\tau_N = \beta\gamma/\Gamma_N \gg L_{\text{det}}$:

$$\mathcal{B}_{N\to X\gamma}P_N^{\text{det}} \approx \frac{L_{\text{det}}\Gamma_{N\to X\gamma}}{\beta\gamma}$$

Radiative Upscattering at NUCLEUS

Image: Kåre Fridell



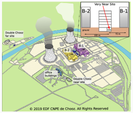


Cryogenic calorimeter (CEνNS target):
Phase I: 10 g of Al_2O_3/$CaWO_4$, $L_{\rm det} = 5$ cm
Phase II: 1 kg of ^{73}Ge, $L_{\rm det} = 25$ cm

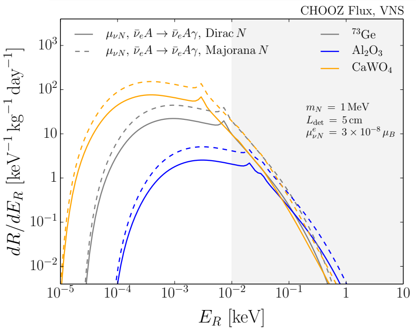
[Angloher et al., 19]

See J . Rothe talk

10^{12} $\bar{\nu}_e$ cm^{-2} s^{-1}



$$\frac{dR_{\bar{\nu}_e A \to XA\gamma}}{dE_R} \propto \int_{E_\nu^{\min}}^{E_\nu^{\max}} dE_\nu \frac{d\phi_{\bar{\nu}_e}}{dE_\nu} \frac{d\sigma_{\bar{\nu}_e A \to NA}}{dE_R} \frac{L_{\rm det}\Gamma_{N\to X\gamma}}{\beta\gamma}$$



Signal is the coincidence of E_R + MeV energy γ

$\Rightarrow$ Assume negligible background

$\Rightarrow$ No excess $\Rightarrow$ Upper bound on $\mu^e_{\nu N}\sum_X \mu_{XN}$

Benchmark Scenarios

N can decay via $\mu^e_{\nu N}$, $\mu^\mu_{\nu N}$, $\mu^\tau_{\nu N}$, $\mu_{N'N}$ ..., *or* via an invisible channel $N \to \text{inv}$

[*Note*: N can decay via mixing with Z exchange, $N \to 3\nu$

$\Rightarrow$ For $m_N \sim 1$ MeV, $|U_{eN}|^2 \lesssim 10^{-2}$ (^{7}Be β-decay), $\Gamma_{N\to 3\nu} \approx \frac{G_F^2 m_N^5}{96\pi^3}|U_{eN}|^2 \sim 10^{-27}$ MeV]

To derive limits on $\mu^e_{\nu N}$, we consider three benchmark scenarios:

1) $\mu^e_{\nu N} \neq 0$, $\mu_{XN} = 0$

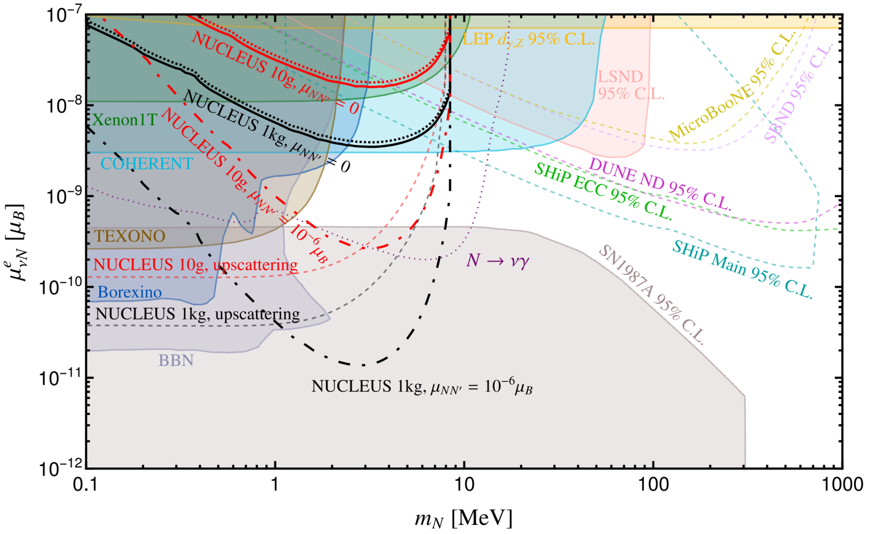
2) $\mu^e_{\nu N} \neq 0$, $\mu_{N'N} = 10^{-6}\ \mu_B$
   $\Rightarrow \mu_{N'N} \lesssim 10^{-4}\ \mu_B$ from $\phi \to N'N$ decays [Li, Ma, Schmidt, 20]
   $\Rightarrow \mu_{N'N} \lesssim 10^{-6}\ \mu_B$ from $e^+e^- \to Z \to (N \to N'\gamma)\bar{\nu}$ at LEP [Magill, Plestid, Pospelov, Tsai, 18]

3) $\mu^e_{\nu N} \neq 0$, $\mu_{XN} = 0$ with invisible N decays to a light 'dark' sector

$$\Gamma_N \approx \Gamma_N^{\text{inv}}, \quad \ell_N = \beta\gamma/\Gamma_N = L_{\text{det}}$$

However, $\mathcal{B}_{N\to X\gamma} P_N^{\text{det}}$ is effectively independent of Γ_N up to this value

Constraints



[PDB, Deppisch, Fridell, Harz, Hati, Kulkarni, PRD **106**, 035036 (2022)]

Dirac vs. Majorana Nature of N

We saw that for Majorana fields,

$$\mathcal{L}_d = \frac{\mu_{XN}}{2}(\bar{X}\sigma_{\mu\nu}N)F^{\mu\nu}$$

$N \to X\gamma$ decay for Majorana N is twice that for Dirac N ($m_X \ll m_N$)

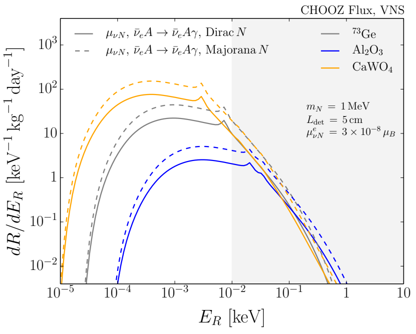
$$\Gamma^{\rm M}_{N\to X\gamma} = 2\Gamma^{\rm D}_{N\to X\gamma} = \frac{|\mu_{XN}|^2 m_N^3}{4\pi}$$

Likewise,

$$\frac{d\sigma_{\nu_\alpha A\to XA\gamma}}{dE_R}P_N^{\rm det} = \frac{d\sigma_{\nu_\alpha A\to NA}}{dE_R}\frac{L_{\rm det}\Gamma^{\rm D(M)}_{N\to X\gamma}}{\beta\gamma}$$

⇒ Factor of two difference can be absorbed into the measured value of μ_{XN}

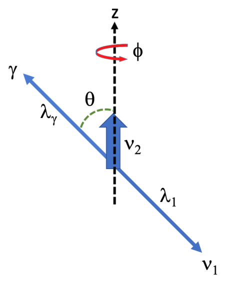
⇒ Instead consider distributions in E_γ and θ_γ



Distributions in the Rest and Lab Frames

In the rest frame of N, purely from CPT and rotational invariance,

$$\frac{d\Gamma_{N\to X\gamma}}{d\cos\theta_\gamma} \propto \cos^2\frac{\theta_\gamma}{2}|\mathcal{A}_{-\frac{1}{2},-1}|^2 + \sin^2\frac{\theta_\gamma}{2}|\mathcal{A}_{+\frac{1}{2},+1}|^2$$



[Balantekin, Kayser, 18]

Therefore obtain for Dirac and Majorana N:

$$\frac{d\Gamma^{\rm D}_{N\to X\gamma}}{d\cos\theta_\gamma} = \frac{\Gamma^{\rm D}_{N\to X\gamma}}{2}(1+\cos\theta_\gamma)\,, \quad \frac{d\Gamma^{\rm M}_{N\to X\gamma}}{d\cos\theta_\gamma} = \frac{\Gamma^{\rm M}_{N\to X\gamma}}{2}$$

Boost to the lab frame:

$$\cos\theta_\gamma^{\rm lab} = \frac{\beta-\cos\theta_\gamma}{1-\beta\cos\theta_\gamma}\,, \quad E_\gamma^{\rm lab} = \frac{\gamma m_N}{2}(1-\beta\cos\theta_\gamma)\,, \quad E_\gamma = \frac{m_N}{2}$$

Distinct distributions in $E_\gamma^{\rm lab}$ in the Dirac and Majorana cases:

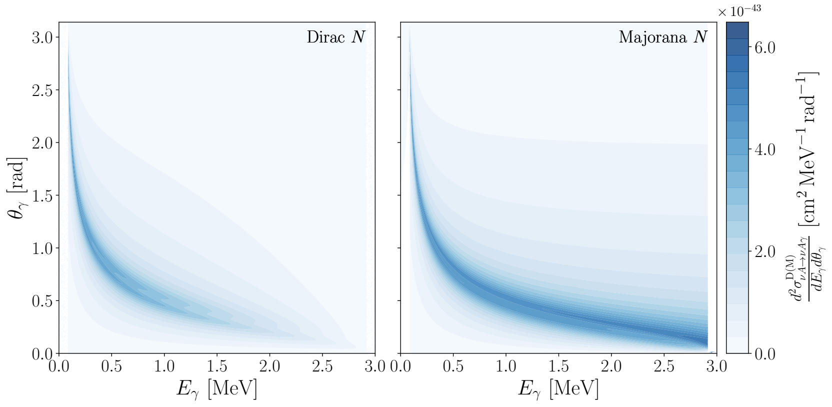
$$\frac{d\Gamma^{\rm D}_{N\to X\gamma}}{dE_\gamma^{\rm lab}} = \frac{\Gamma^{\rm D}_{N\to X\gamma}}{p_N^{\rm lab}}\left(1+\frac{E_N^{\rm lab}}{p_N^{\rm lab}} - \frac{2E_\gamma^{\rm lab}}{p_N^{\rm lab}}\right), \quad \frac{d\Gamma^{\rm M}_{N\to X\gamma}}{dE_\gamma^{\rm lab}} = \frac{\Gamma^{\rm M}_{N\to X\gamma}}{p_N^{\rm lab}}\,,$$

with $E_N^{\rm lab} = \gamma m_N$, $p_N^{\rm lab} = \beta\gamma m_N$

Double Differential Cross Sections in the Lab Frame

Double differential cross section in E_γ and θ_γ in lab frame can be calculated in full:

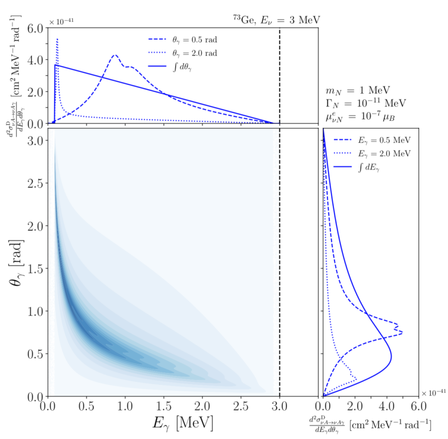
$$\left.\frac{d^2\sigma^{\mathrm{D(M)}}_{\nu_\alpha A\to XA\gamma}}{dE_\gamma\, d\theta_\gamma}\right|_{\mathrm{NWA}} \propto (\mu^\alpha_{\nu N})^2 \sum_X (\mu_{XN})^2 \frac{E_\gamma \sin\theta_\gamma}{E_\nu} \int_{E_R^-}^{E_R^+} dE_R \left.\frac{L^{\gamma,\mathrm{D(M)}}_{\mu\nu} H^{\mu\nu}}{E_R^2\sqrt{-\Delta_4}}\right|_{p_N^2=m_N^2}$$



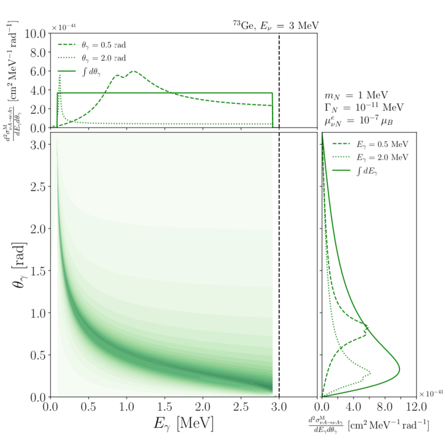
[PDB, Deppisch, Fridell, Harz, Hati, Kulkarni, PRD **106**, 035036 (2022)]

Double Differential Cross Sections in the Lab Frame

Dirac:



Majorana:



More forward emissions of high energy γ in Majorana vs. Dirac case

Clear distrinction for $E_\gamma > E_\nu/2$

[PDB, Deppisch, Fridell, Harz, Hati, Kulkarni, PRD **106**, 035036 (2022)]

Conclusions

Heavy neutral leptons (HNLs) remain a well motivated extension to the SM:

- Dynamically generate the light neutrino masses

∴ Detection could provide a hint towards to nature of light neutrinos

- Generic prediction of a number of UV models
- A wide field of phenomenology via the so-called mixing and dipole portals

Mixing portal:

- Constraints on active-sterile mixings $|U_{\alpha N}|^2$ from 3+n oscillations, β-decay, $0\nu\beta\beta$ decay, meson decays, beam dumps, colliders, astrophysics and cosmology

Dipole portal:

- Constraints on active-sterile transition moments $\mu^{\alpha}_{\nu N}$ from CEνNS, EνES, beam dumps, colliders, astrophysics and cosmology
- Radiative upscattering process, if observed, could provide further hints on the HNL nature

⇒ Keep looking in all possible parameter space

Thank you for your attention!

Backup Slides

Differential Rates in E_γ and θ_γ at NUCLEUS