Probing Heavy Neutral Leptons with Direct Searches & Neutrinoless Double Beta Decay

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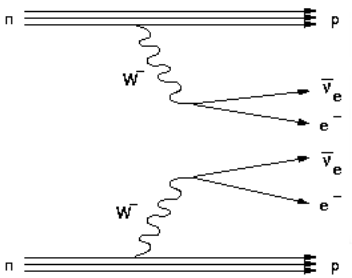
Outlines

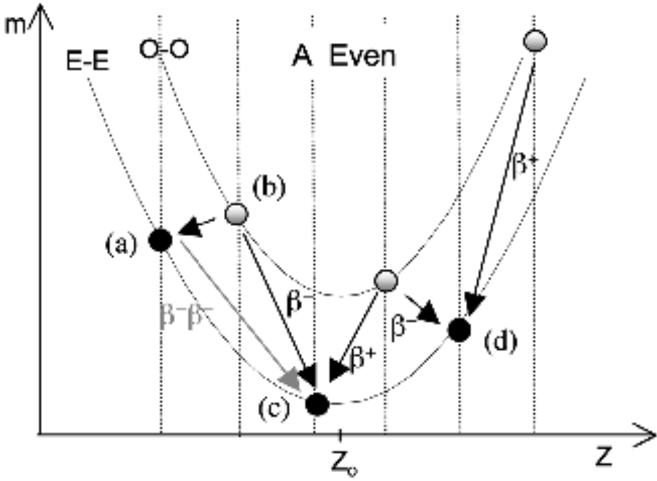
1. Neutrinoless Double Beta Decay (DBD)
2. Direct Searches & DUNE Experiment
3. Seesaw Mechanism & Heavy Neutral Lepton
4. Inverse-Seesaw Mechanism & 0ν DBD
5. Current Constraints on HNLs
6. Results
7. Conclusion

Beta Decay & Double Beta Decay (DBD)

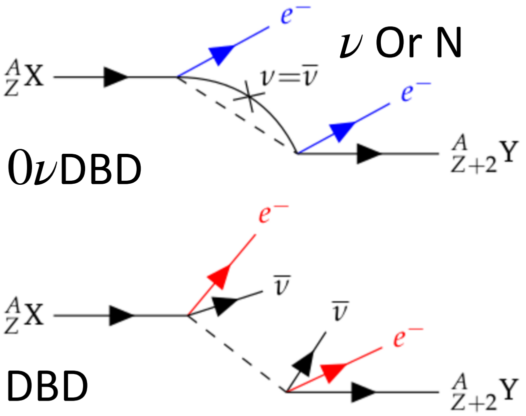


$$^A_Z\mathrm{X} \rightarrow {}^{A}_{Z+2}\mathrm{Y} + 2e^- + 2\bar{\nu}$$

$$T^{-1}_{1/2} = \left|m_{\beta\beta}\right|^2 G^{0\nu} \left|M^{0\nu}\right|^2$$



Neutrinoless Double Beta Decay (0νDBD)



$$^A_Z\mathrm{X} \rightarrow {}^{A}_{Z+2}\mathrm{Y} + 2e^-$$

Atomic phase space

Decay half-life: $T^{-1}_{1/2} = \boxed{\left|m_{\beta\beta}\right|^2} G^{0\nu} \boxed{\left|M^{0\nu}\right|^2}$

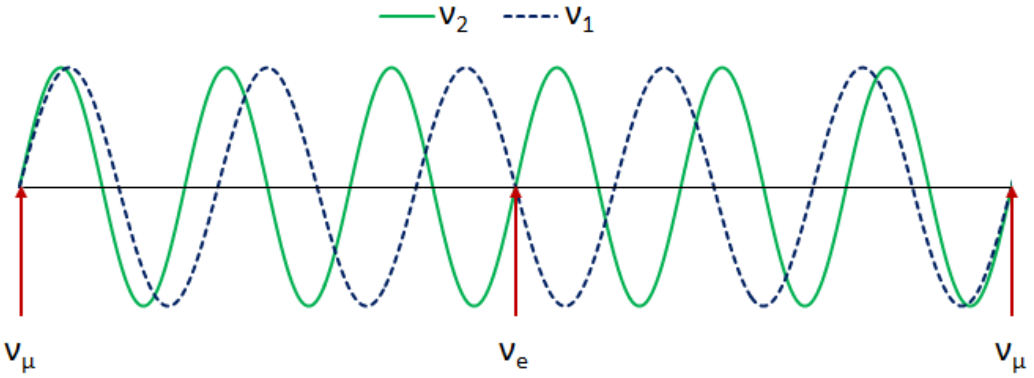
Particle Physics: $m_{\beta\beta} = \sum_{i=1}^{3} U^2_{ei} m_{\nu_i}$

Nuclear Physics

Mixing & Oscillation Recap

$$\left|\nu_\alpha\right\rangle = \sum_i^3 U_{\alpha i}\left|\nu_i\right\rangle \quad (\alpha = e, \mu, \tau)$$

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta}\delta_{CP} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



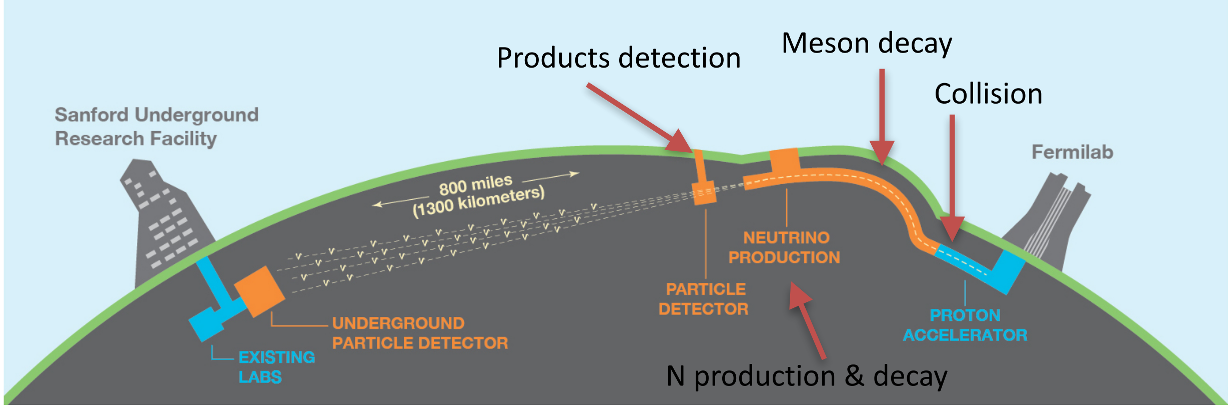
2 neutrino oscillation:

$$P_{\nu_\alpha \to \nu_\beta} \equiv \left|\left\langle \nu_\beta \mid \nu_\alpha(t) \right\rangle\right|^2$$

$$= \left|\sum_i U^*_{\alpha i} U_{\beta i} e^{-i\frac{m_i^2}{2E_{\mathrm{q}}}}\right|^2$$

$$\approx \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

DUNE Experiment



Proton-target interaction

Mesons

$$K/\pi^+ \rightarrow l^\pm N \rightarrow l^\pm \nu$$

Detected at ND

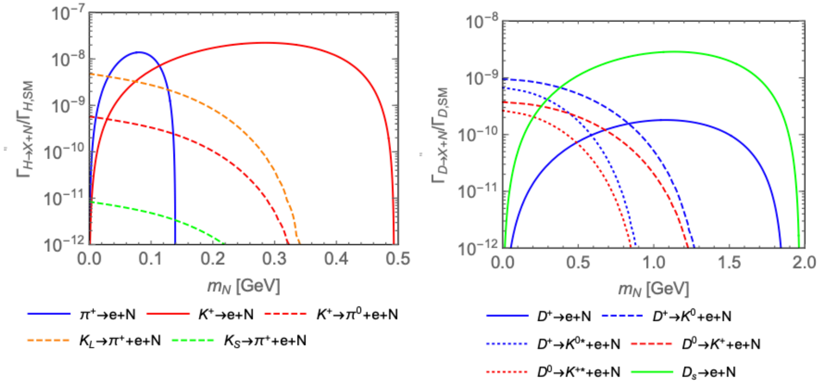
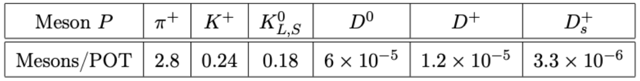


Figure 5: HNL production channels via the decays of pions and kaons (left) and D mesons (right), with $U_e = 10^{-4}$. The ratios here corresponds to the decay width of mesons to HNL, and we compare it to the Standard Model decay width for π, K (left) and D mesons (right)[18].



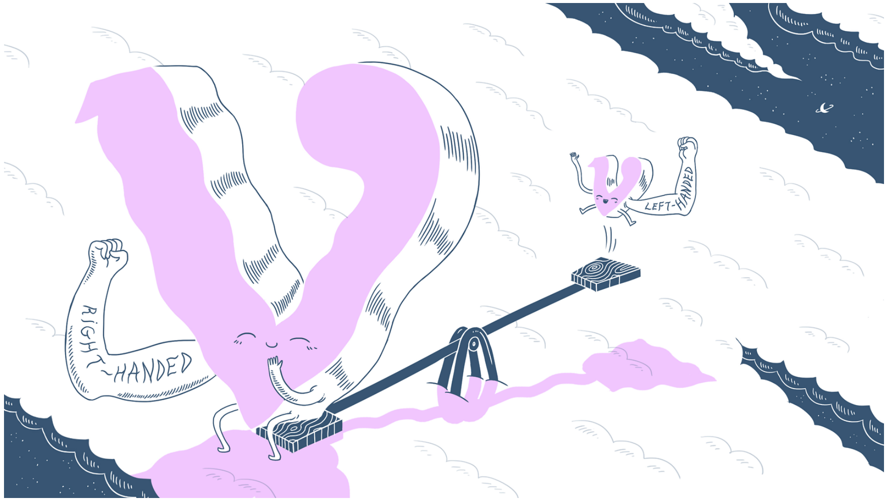
Meson P	π^+	K^+	$K^0_{L,S}$	D^0	D^+	D^+_s
Mesons/POT	2.8	0.24	0.18	6×10^{-5}	1.2×10^{-5}	3.3×10^{-6}

Table 3: Positively-charged and neutral pseudoscalar mesons produced from proton collisions in the DUNE target. We give the average number N_P^{POT} of each meson produced per POT for a 120 GeV proton beam.

Seesaw Mechanism

Motivation:Massless SM neutrinos

HNLs give mass to light active neutrinos



Dirac mass by **Right-Handed Neutrinos**:

$$\mathscr{L}_{Dirac} = -Y_\nu \bar{L} \cdot H \nu_R + \text{h.c.}$$

Majorana Right-Handed Neutrinos:

$$\mathscr{L}_{Majorana} = -Y_\nu \bar{N} L \cdot H - 1/2 \bar{N}^c M_R N + \text{ h.c.}$$

$$\mathscr{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} = U \begin{pmatrix} m_\nu & 0 \\ 0 & m_N \end{pmatrix} U^T$$

Light Neutrino Mass:

$$m_\nu \simeq \frac{m_D^2}{M_R} \simeq \frac{(1)^2}{10^{10}} \text{GeV} = 0.1 \text{eV}$$

$$|V_{eN}|^2 \simeq \frac{m_\nu}{M_R}$$ Active-Sterile mixing

Inverse Seesaw & Parameterization

$$\mathscr{M}_\nu = \begin{pmatrix} 0 & m_{D,1} & m_{D,2} \\ m_{D,1} & \mu_R & M_R \\ m_{D,2} & M_R & \mu_S \end{pmatrix} = U \begin{pmatrix} m_\nu & 0 & 0 \\ 0 & m_N & 0 \\ 0 & 0 & m_N\left(1 + r_\Delta\right) \end{pmatrix} U^T$$

HNL mass splitting

Lepton Number Violation Mass

Light Neutrino Mass:

$$m_\nu \simeq \frac{m_D^2 \mu_S}{M_R^2} \simeq \frac{1^2(10^{-6})}{(10^3)}\text{GeV} = 0.1\text{eV}$$

General Expression for type-II Seesaw:

$$\begin{pmatrix} 0 & m_{D,1} & m_{D,2} \\ m_{D,1} & 0 & M_1 \\ m_{D,2} & M_1 & 0 \end{pmatrix} = W \begin{pmatrix} 0 & m_D & 0 \\ m_D & \mu_R & M_2 \\ 0 & M_2 & \mu_S \end{pmatrix} W^T$$

Linear Seesaw   Typical Inverse Seesaw

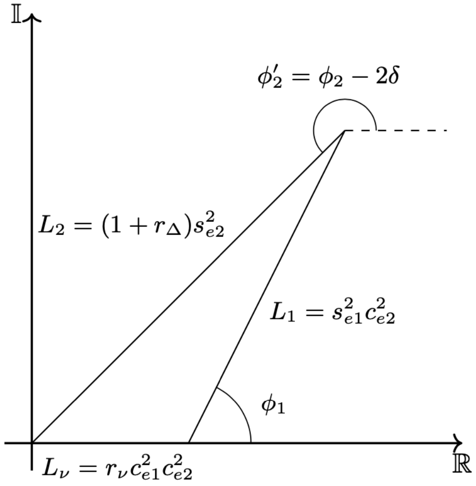
One generation analysis:

$$U_{1g} \approx \begin{pmatrix} 1 & s_{e1} & s_{e2}e^{-i\delta} \\ -s_{e1}c_{12} - s_{e2}s_{12}e^{i\delta} & c_{12} & s_{12} \\ s_{e1}s_{12} - s_{e2}c_{12}e^{i\delta} & -s_{12} & c_{12} \end{pmatrix} \cdot diag(1,e^{i\phi_1}, e^{i\phi_2}) + \mathcal{O}\left(s_{ei}^2\right)$$

Dirac CP Phase

Majorana CP Phases

$$\left(\mathcal{M}_\nu\right)_{11} = 0 \Rightarrow c_{e1}^2 c_{e2}^2 \frac{m_\nu}{m_{N_1}} + s_{e1}^2 c_{e2}^2 e^{i\phi_1} + s_{e2}^2 \frac{m_{N_2}}{m_{N_1}} e^{i(\phi_2 - 2\delta)} = 0$$



Unitary Condition:

$$\max\left(L_\nu, L_1, L_2\right) \leq \min\left(L_\nu, L_1, L_2\right) + \mathrm{med}\left(L_\nu, L_1, L_2\right)$$

5 Free Parameters: $m_\nu, m_N, s_{e1}^2, \phi_1, r_\Delta$

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0νDBD Decay Time

DBD Decay Time (effective mass)

Light neutrino contribution

$$\boxed{\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu} g_A^4 m_p^2 \left| m_\nu M_\nu^{0\nu} + \sum_{i=1}^{2} V_{eN_i}^2 m_{N_i} M^{0\nu}\left(m_{N_i}\right) \right|^2}$$

Two HNL contributions

$$\left|m_{\beta\beta}^{\text{eff}}\right| = \left|\alpha m_\nu + \beta m_N s_{e1}^2 e^{i\phi_1}\right| = m_N \sqrt{\alpha^2 r_\nu^2 + \beta^2 s_{e1}^4 + 2\alpha\beta r_\nu s_{e1}^2 \cos\phi_1}$$

$$\alpha \equiv 1 - \frac{\langle \mathbf{p}^2\rangle \mathscr{F}\left(m_N\left(1+r_\Delta\right)\right)}{\left(\langle \mathbf{p}^2\rangle + m_N^2\left(1+r_\Delta\right)\right)^2} \qquad \beta \equiv \frac{\langle \mathbf{p}^2\rangle \mathscr{F}\left(m_N\right)}{\langle \mathbf{p}^2\rangle + m_N^2} - \frac{\langle \mathbf{p}^2\rangle \mathscr{F}\left(m_N\left(1+r_\Delta\right)\right)}{\left(\langle \mathbf{p}^2\rangle + m_N^2\left(1+r_\Delta\right)\right)^2}$$

NME related parameters

Fixing $\left|m_{\beta\beta}^{\text{eff}}\right|$ from experimental limit and future sensitivity

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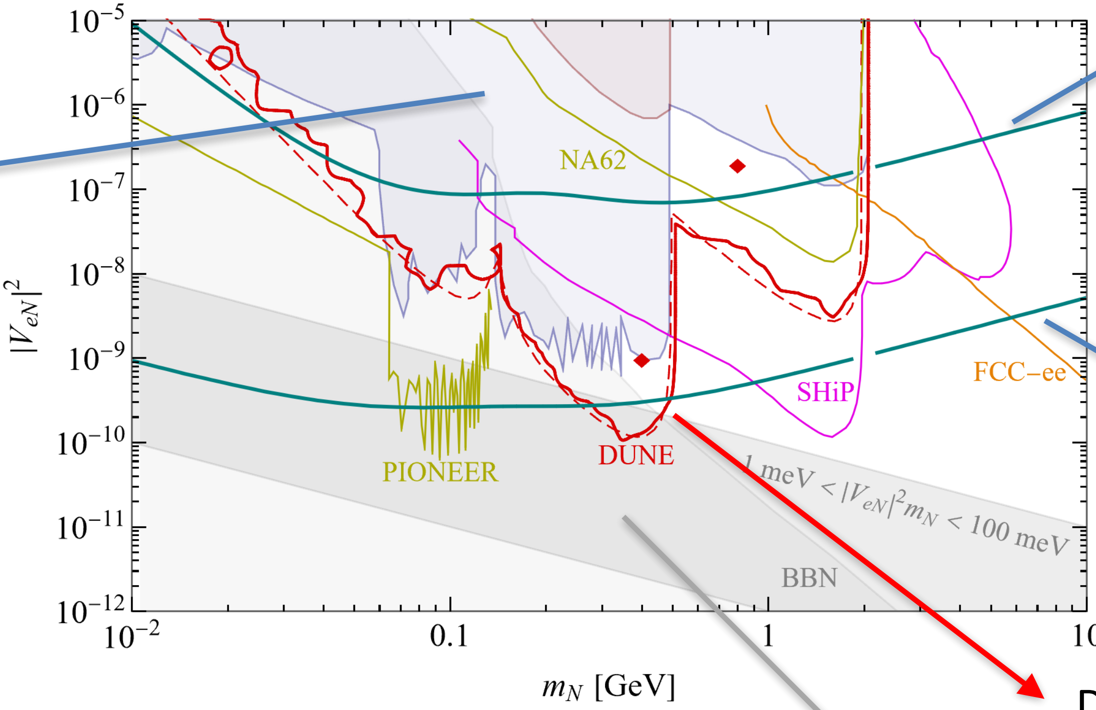
DUNE & DBD Benchmarks

Shaded current excluded region by direct searches



DBD current limit: 10^{26} years

DBD future sensitivity: 10^{28} years (Legend-1000)

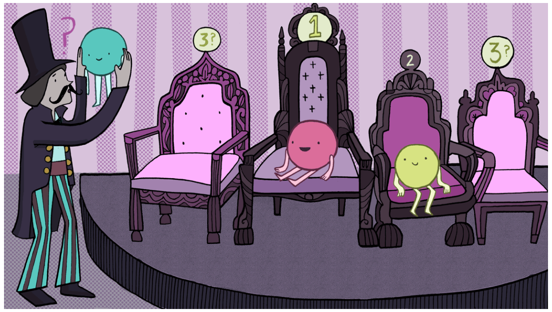
DUNE sensitivity

Standard Seesaw relation limit by $|V_{eN}|^2 = m_\nu / m_N$

Benchmarks: 400MeV at $|V_{eN}|^2 = 10^{-9}$

800MeV at $|V_{eN}|^2 = 2 \times 10^{-7}$

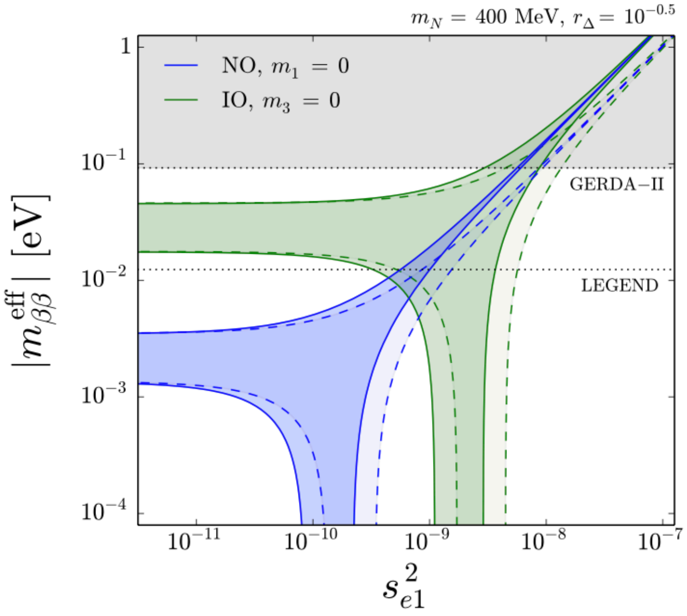
Light Neutrino Masses & Ordering

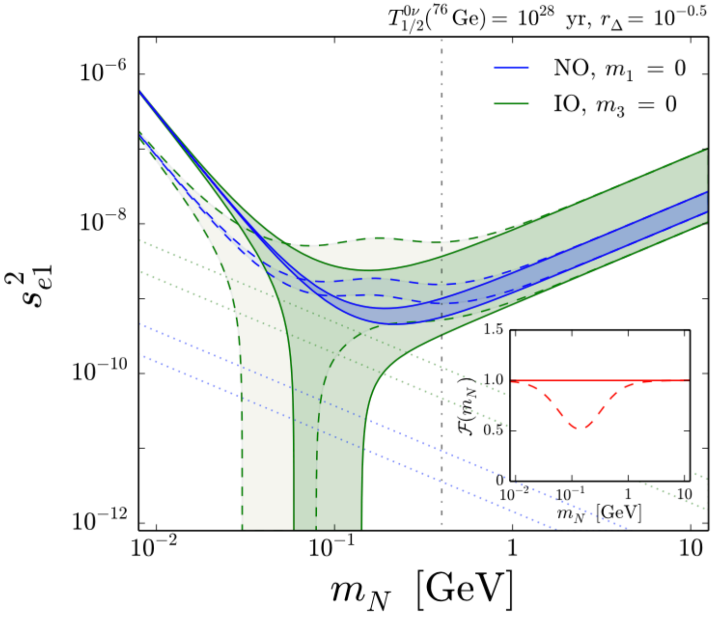


3 > 2 > 1 Normal Ordering?

2 > 1 > 3 Inverted Ordering?

Ordering matters in case of 3 + 2 model





Results

Benchmark:

400MeV at $|V_{eN}|^2 = 10^{-9}$

800MeV at $|V_{eN}|^2 = 2 \times 10^{-7}$

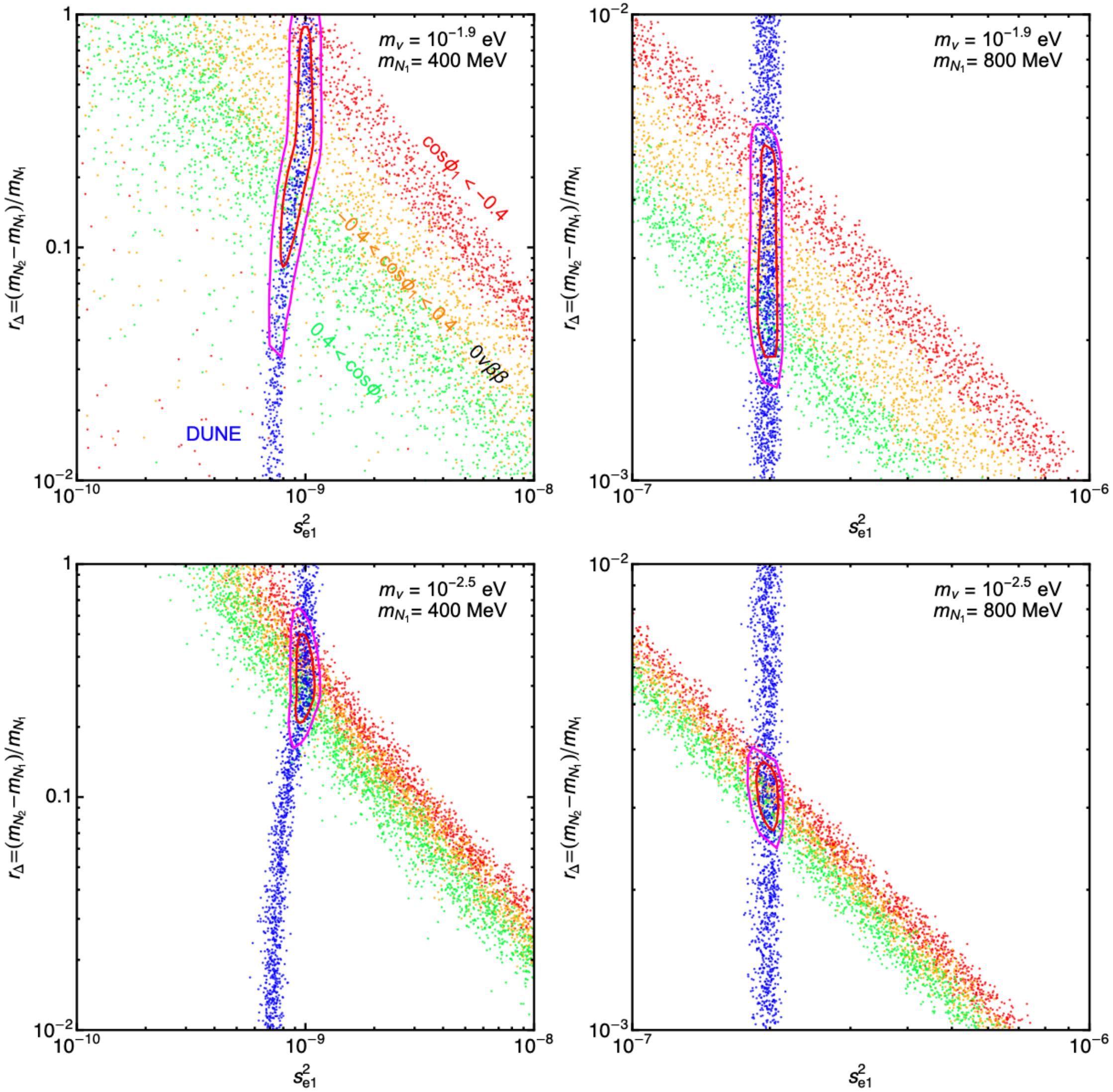
Light masses:

$10^{-1.9}$ eV near saturation

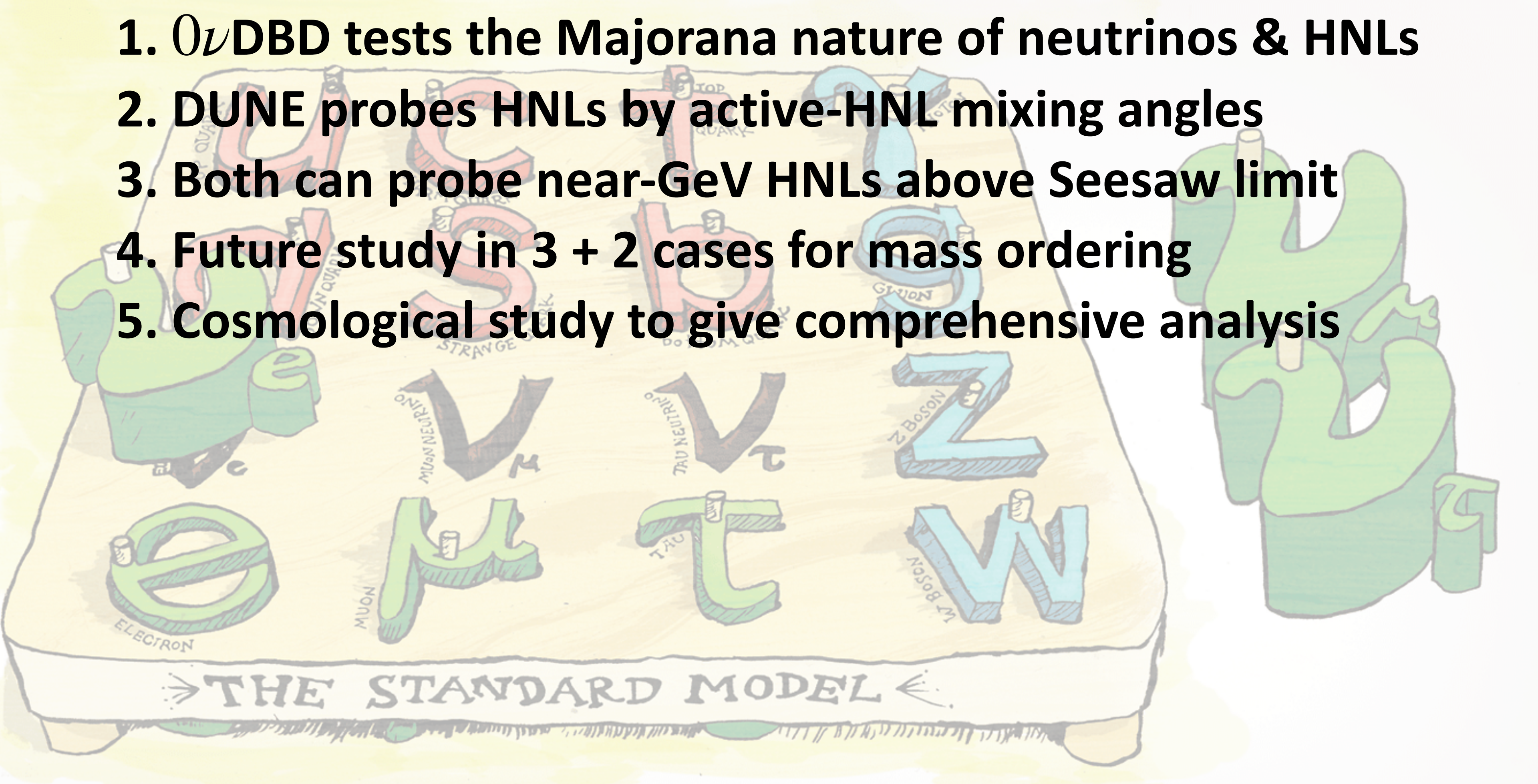
$10^{-2.5}$ eV below saturation

1. DUNE sensitive to $|V_{eN}|^2$
2. DBD sensitive to r_Δ
3. Larger light mass gives larger overlap region

$$\boxed{s_{e1}^2 \approx \frac{m_N \left| m_{\beta\beta}^{\text{exp}} \right|}{\langle \mathbf{p}^2 \rangle} \frac{(1+r_\Delta)^2}{r_\Delta (2+r_\Delta)}}$$



Conclusion



1. 0νDBD tests the Majorana nature of neutrinos & HNLs
2. DUNE probes HNLs by active-HNL mixing angles
3. Both can probe near-GeV HNLs above Seesaw limit
4. Future study in 3 + 2 cases for mass ordering
5. Cosmological study to give comprehensive analysis

Thanks for listening

Any Questions?