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Probing the Nature of Heavy Neutral Leptons with DUNE and $0\nu\beta\beta$

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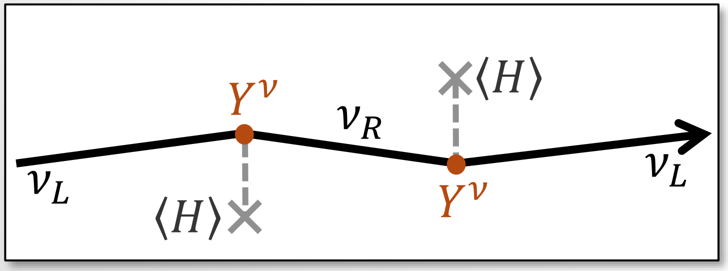
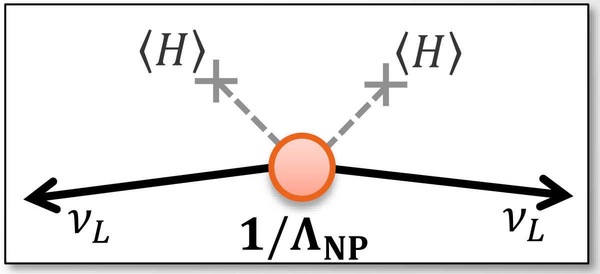
Dirac vs Majorana

- Origin of neutrino masses beyond the Standard Model
- Two possibilities to define neutrino mass

Dirac mass analogous to other fermions but with ${}^{m_\nu}/_{\Lambda_{EW}} \approx 10^{-12}$ couplings to Higgs



Majorana mass, using only a left-handed neutrino
→ Lepton Number Violation



Beta Decays and Neutrinos

- Single beta decay

$$(A,Z) \to (A,Z+1) + e^- + \bar{\nu}_e$$

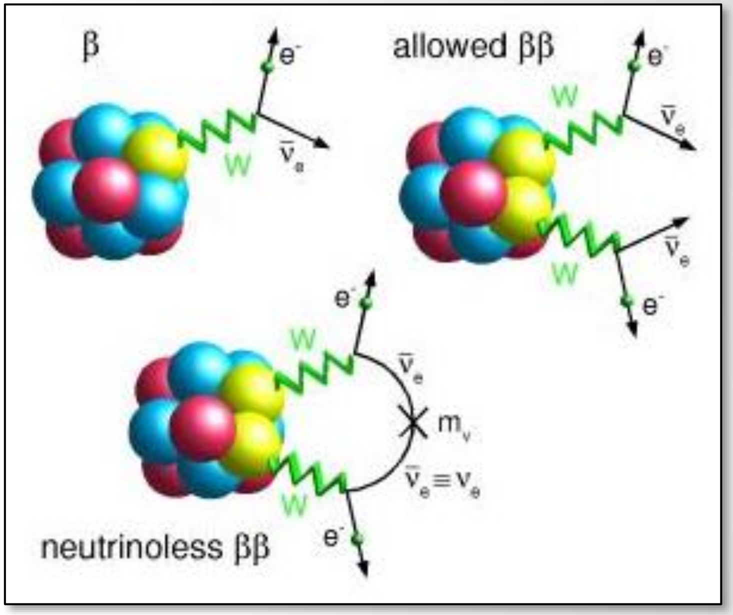
  - Kinematic neutrino mass measurement
- Allowed double beta ($\boldsymbol{2\nu\beta\beta}$) decay

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

- Neutrinoless double beta ($\boldsymbol{0\nu\beta\beta}$) decay

$$(A,Z) \to (A,Z+2) + 2e^-$$

  - Violation of lepton number
  - Mediated by Majorana neutrinos
  - Alternatives:
    - $0\nu\beta^+\beta^+$: $(A,Z) \to (A,Z-2) + 2e^+$
    - $0\nu\beta^+\mathrm{EC}$: $(A,Z) + e^- \to (A,Z-2) + e^+$
    - $0\nu\mathrm{ECEC}$: $(A,Z) + 2e^- \to (A,Z-2)$



$0\nu\beta\beta$

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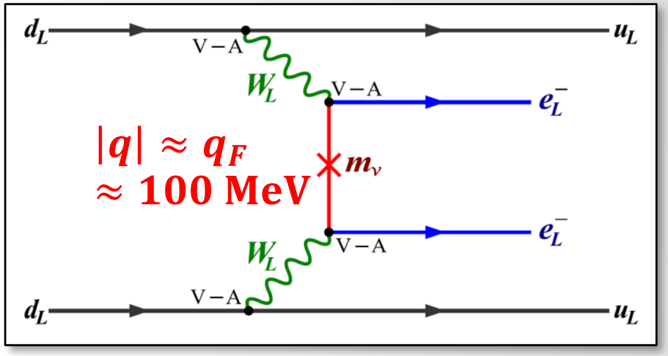


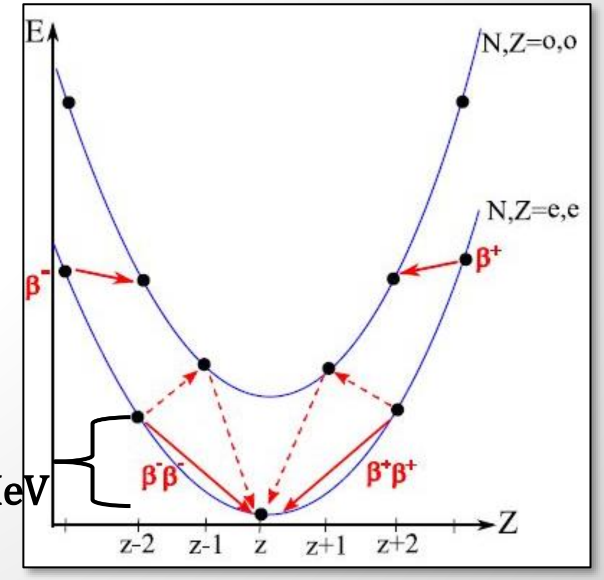
- Half-life

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

- Particle Physics

$$\mathcal{A}_{\mu\nu}^{lep} = \frac{1}{4}\sum_{i=1}^{3} U_{ei}^2\, \gamma_\mu (1+\gamma_5) \frac{\not{q} + m_{\nu_i}}{q^2 - m_{\nu_i}^2} \gamma_\nu (1-\gamma_5) \approx \frac{\gamma_\mu (1+\gamma_5)\gamma_\nu}{4q^2} \boxed{\sum_{i=1}^{3} U_{ei}^2\, m_{\nu_i}} \rightarrow m_{\beta\beta}$$

- Atomic Physics
  - Leptonic phase space $G^{0\nu} \propto Q^5$
- Nuclear Physics
  - Nuclear transition matrix element $M^{0\nu} \approx 1$



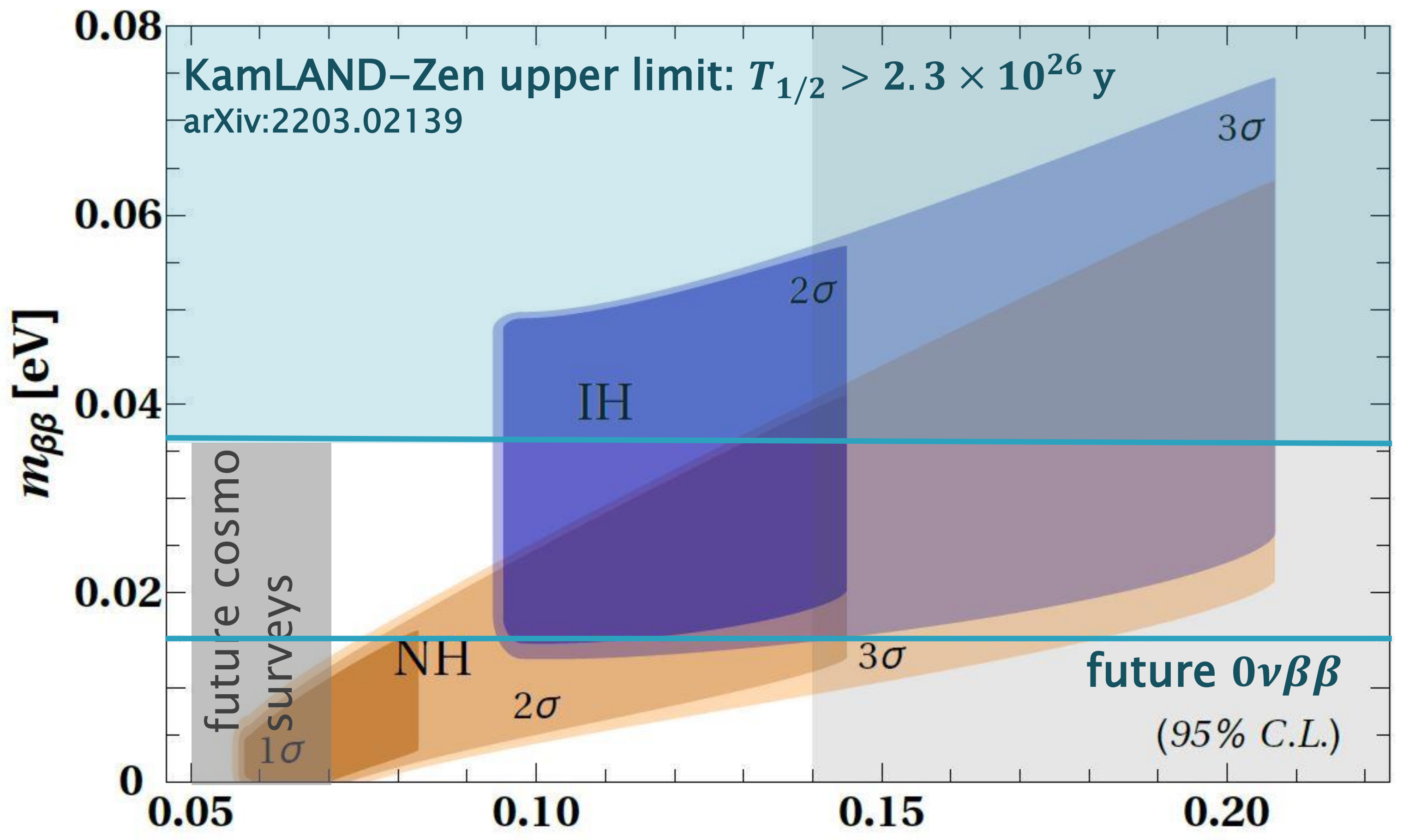
$$\boxed{T_{1/2}^{-1} \propto |m_{\beta\beta}|^2 q_F^2 G_F^4 Q^5}$$

$$\boxed{\frac{10^{25}\,\mathrm{y}}{T_{1/2}} \approx \left(\frac{|m_{\beta\beta}|}{\mathrm{eV}}\right)^2}$$

$Q + 2m_e \approx$ 3−5 MeV

Three Active Neutrinos

- Effective $0\nu\beta\beta$ Mass



Dell'Oro, Marcocci, Viel, Vissani,
Adv. High Energy Phys. (2016) 2162659

HNL in $0\nu\beta\beta$

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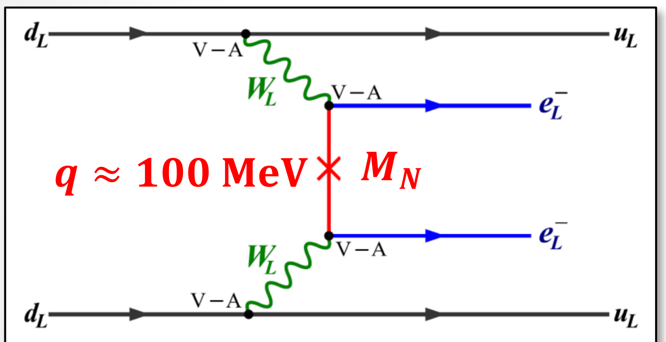
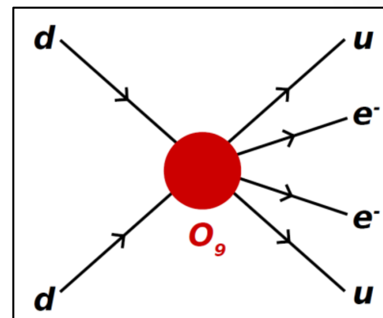
- with masses larger than ≈ 100 MeV

$$\mathcal{A}_{\mu\nu}^{lep} = \frac{1}{4}\sum_{i=1}^{n} V_{ei}^2\, \gamma_\mu(1+\gamma_5)\frac{\not{q} + M_{N_i}}{q^2 - M_{N_i}^2}\gamma_\nu(1-\gamma_5) \approx \frac{-\gamma_\mu(1+\gamma_5)\gamma_\nu}{4}\boxed{\sum_{i=1}^{n}\frac{V_{ei}^2}{M_{N_i}}} \longrightarrow \left\langle \frac{1}{M_N} \right\rangle_{\beta\beta}$$

- Short-distance on nuclear scale





- Light neutrino mass via seesaw

$$\mathrm{diag}(m_\nu, M_N, M_N + \Delta M_N) = V \cdot \begin{array}{c} \begin{array}{ccc} \nu & N_1 & N_2 \end{array} \\ \begin{pmatrix} 0 & m_D & 0 \\ m_D & \mu_R & M \\ 0 & M & \mu_S \end{pmatrix} \end{array} \cdot V^T$$

'Vanilla' seesaw $\mu_R \gg m_D$

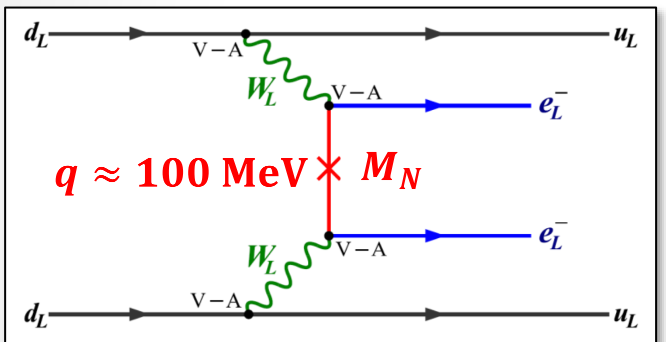
$$\frac{m_\nu}{0.1\ \mathrm{eV}} = \frac{V_{eN}^2}{10^{-12}}\frac{M_N}{100\ \mathrm{GeV}}$$

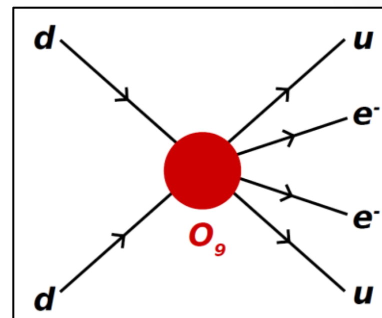
HNL in $0\nu\beta\beta$

- with masses larger than ≈ 100 MeV

$$\mathcal{A}^{lep}_{\mu\nu} = \frac{1}{4}\sum_{i=1}^{n} V_{ei}^2\, \gamma_\mu(1+\gamma_5)\frac{\not{q} + M_{N_i}}{q^2 - M_{N_i}^2}\gamma_\nu(1-\gamma_5) \approx \frac{-\gamma_\mu(1+\gamma_5)\gamma_\nu}{4}\boxed{\sum_{i=1}^{n}\frac{V_{ei}^2}{M_{N_i}}} \rightarrow \left\langle \frac{1}{M_N}\right\rangle_{\beta\beta}$$

- Short-distance on nuclear scale





- Light neutrino mass via seesaw

$$\mathrm{diag}(m_\nu, M_N, M_N + \Delta M_N) = V \cdot \begin{array}{c} \begin{array}{ccc} \nu & N_1 & N_2 \end{array} \\ \begin{pmatrix} 0 & m_D & 0 \\ m_D & \mu_R & M \\ 0 & M & \mu_S \end{pmatrix} \end{array} \cdot V^T$$

Inverse seesaw

$M \gg \mu_S, \mu_R, m_D$

$$\frac{m_\nu}{0.1\text{ eV}} = \frac{V_{eN}^2}{10^{-4}}\frac{\mu_S}{\text{keV}}$$

Quasi-Dirac N

Approximate L conservation

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$1\nu + 2$HNL: Pheno Parametrization

- Parametrization

$$
\mathrm{diag}(m_\nu, M_N, M_N + \Delta M_N) = V \cdot \begin{array}{c} \begin{matrix} \nu & N_1 & N_2 \end{matrix} \\ \begin{pmatrix} 0 & m_D & 0 \\ m_D & \mu_R & M \\ 0 & M & \mu_S \end{pmatrix} \end{array} \cdot V^T
$$

$$
V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{12} & \sin\theta_{12} \\ 0 & -\sin\theta_{12} & \cos\theta_{12} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{e2} & 0 & \sin\theta_{e2} e^{i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{e2} e^{i\delta} & 0 & \cos\theta_{e2} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{e1} & \sin\theta_{e1} & 0 \\ -\sin\theta_{e1} & \cos\theta_{e1} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot D
$$

- Contribution of heavy and light neutrinos to $0\nu\beta\beta$
  - See, e.g., Lopez-Pavon, Pascoli, Wong, Phys. Rev. D 87, 093007; Hernández, Jones-Pérez, Suarez-Navarro, Eur. Phys. J. C (2019) 79: 220
- Masses and observable active-sterile mixing as input
  - Large mass-splitting $\Delta m_N = m_{N_2} - m_{N_1}$ lead to large loop-contribution to light neutrino mass

$1\nu + 2$HNL: Pheno Parametrization

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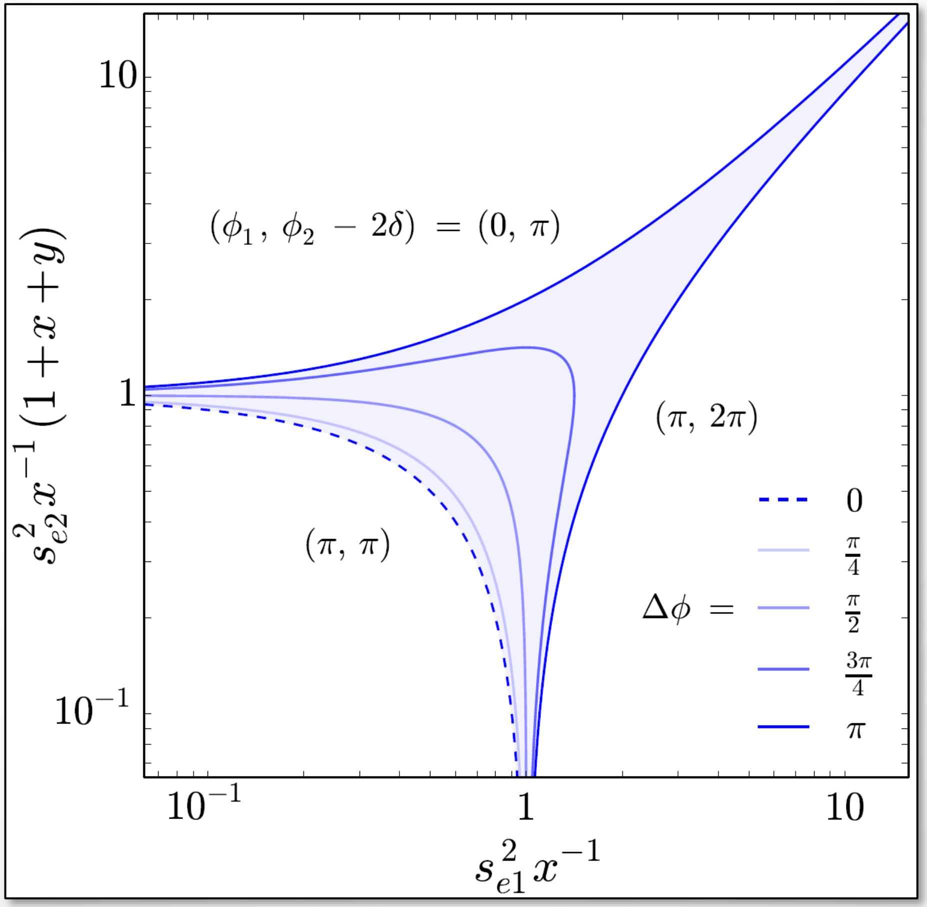
- Relation between active-sterile mixing angles (tree level)



HNL – Current Limits

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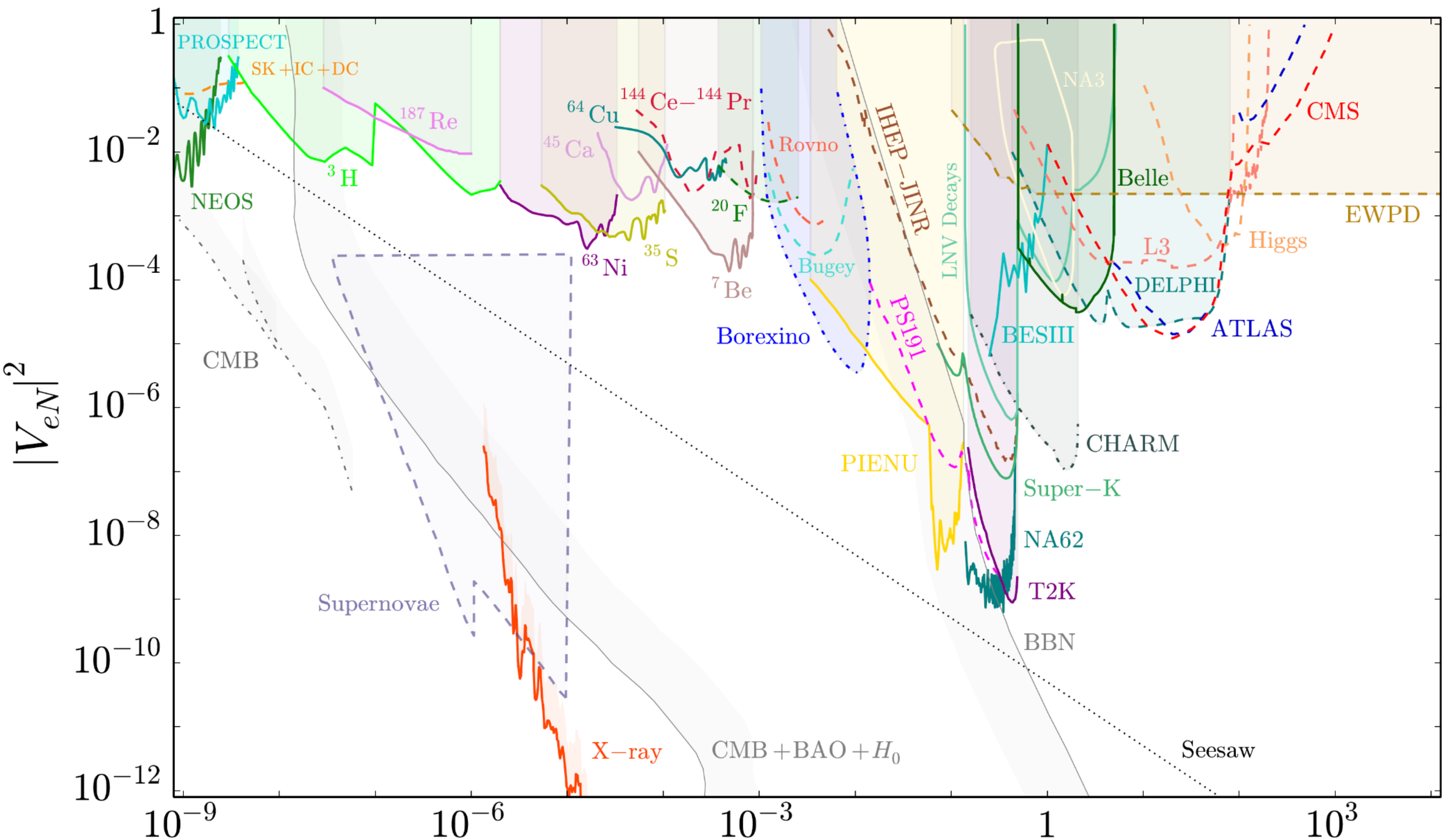
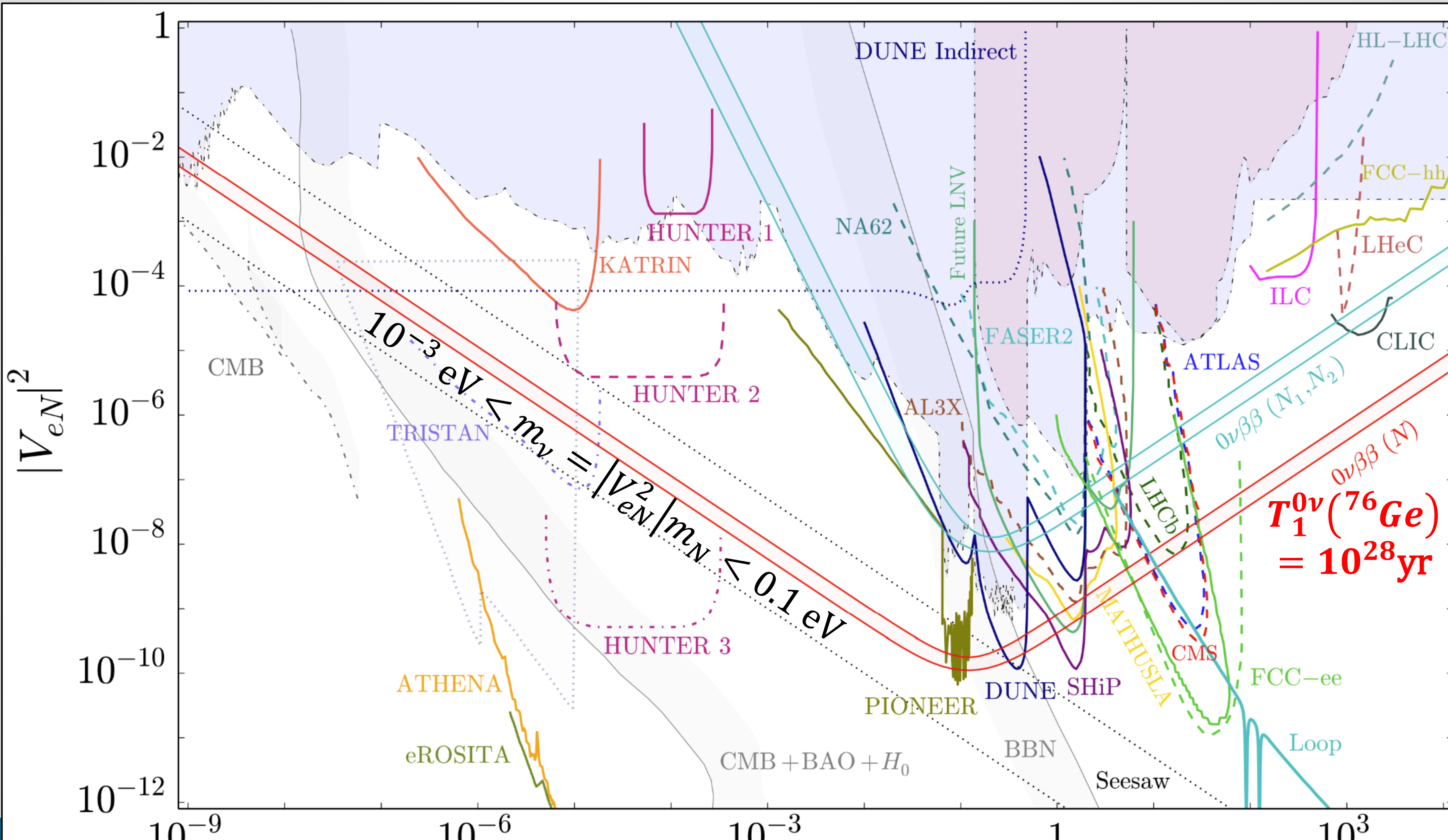


Bolton, FFD, Dev Moriond 2022

Direct search limits: sterile-neutrino.org

HNL – Future Sensitivities



Bolton, FFD, Dev Moriond 2022

Direct search limits: sterile-neutrino.org

HNL – Comparison with $0\nu\beta\beta$

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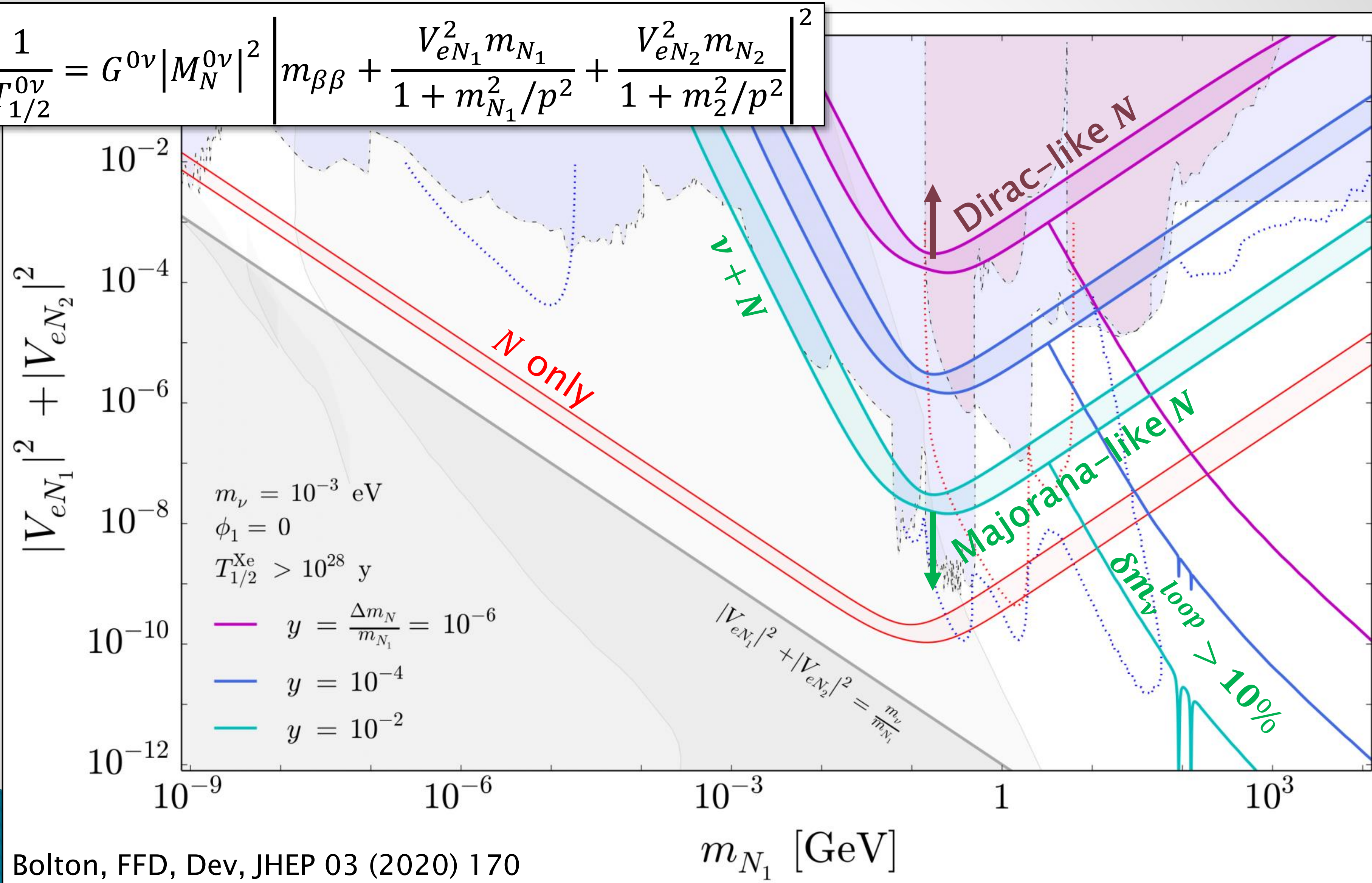
$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}|M^{0\nu}_N|^2 \left| m_{\beta\beta} + \frac{V^2_{eN_1} m_{N_1}}{1 + m^2_{N_1}/p^2} + \frac{V^2_{eN_2} m_{N_2}}{1 + m^2_2/p^2} \right|^2$$

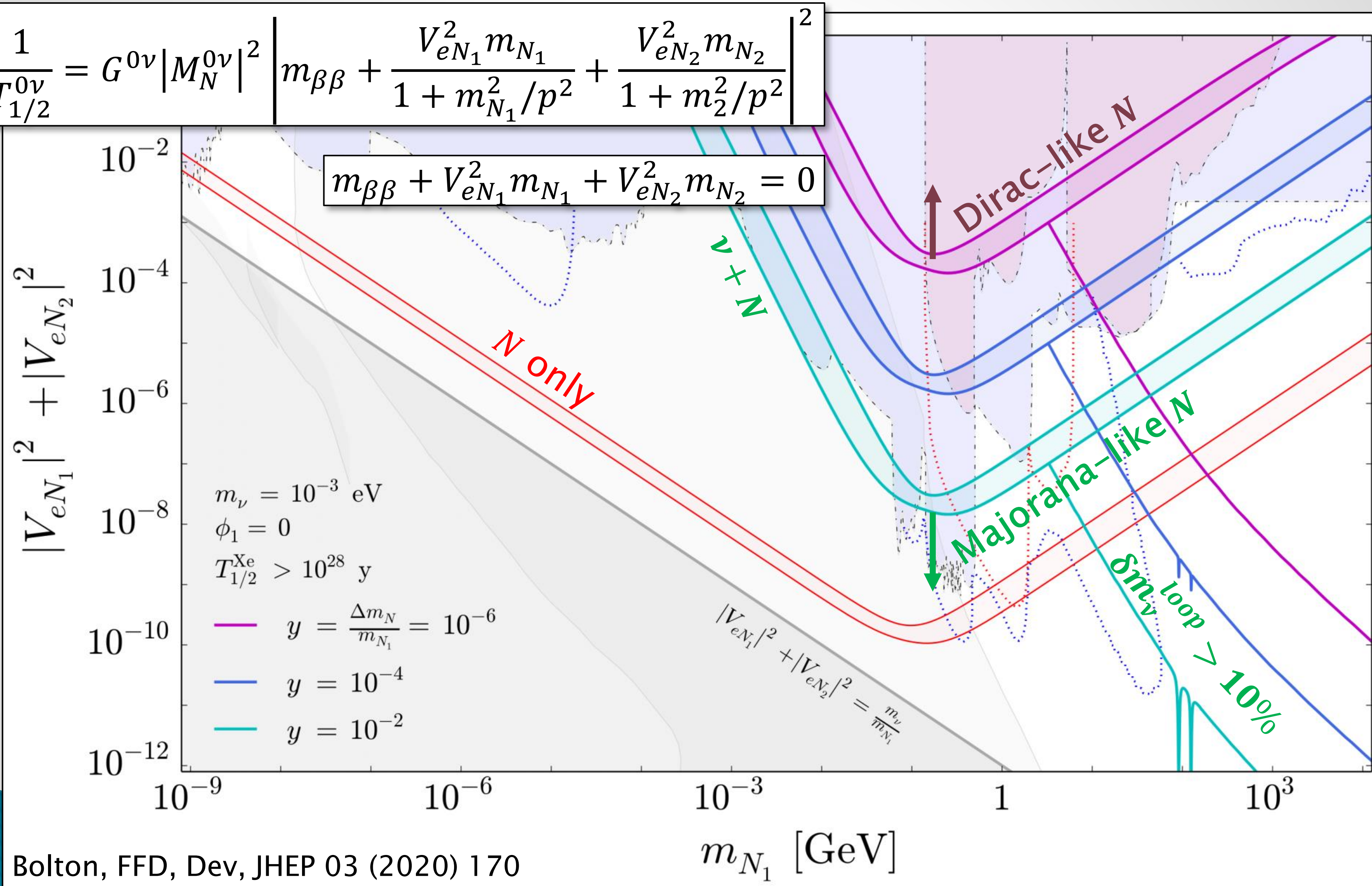


Bolton, FFD, Dev, JHEP 03 (2020) 170

HNL – Comparison with $0\nu\beta\beta$

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}|M_N^{0\nu}|^2 \left| m_{\beta\beta} + \frac{V_{eN_1}^2 m_{N_1}}{1+m_{N_1}^2/p^2} + \frac{V_{eN_2}^2 m_{N_2}}{1+m_2^2/p^2} \right|^2$$

$$m_{\beta\beta} + V_{eN_1}^2 m_{N_1} + V_{eN_2}^2 m_{N_2} = 0$$



Bolton, FFD, Dev, JHEP 03 (2020) 170

HNL – Comparison with $0\nu\beta\beta$

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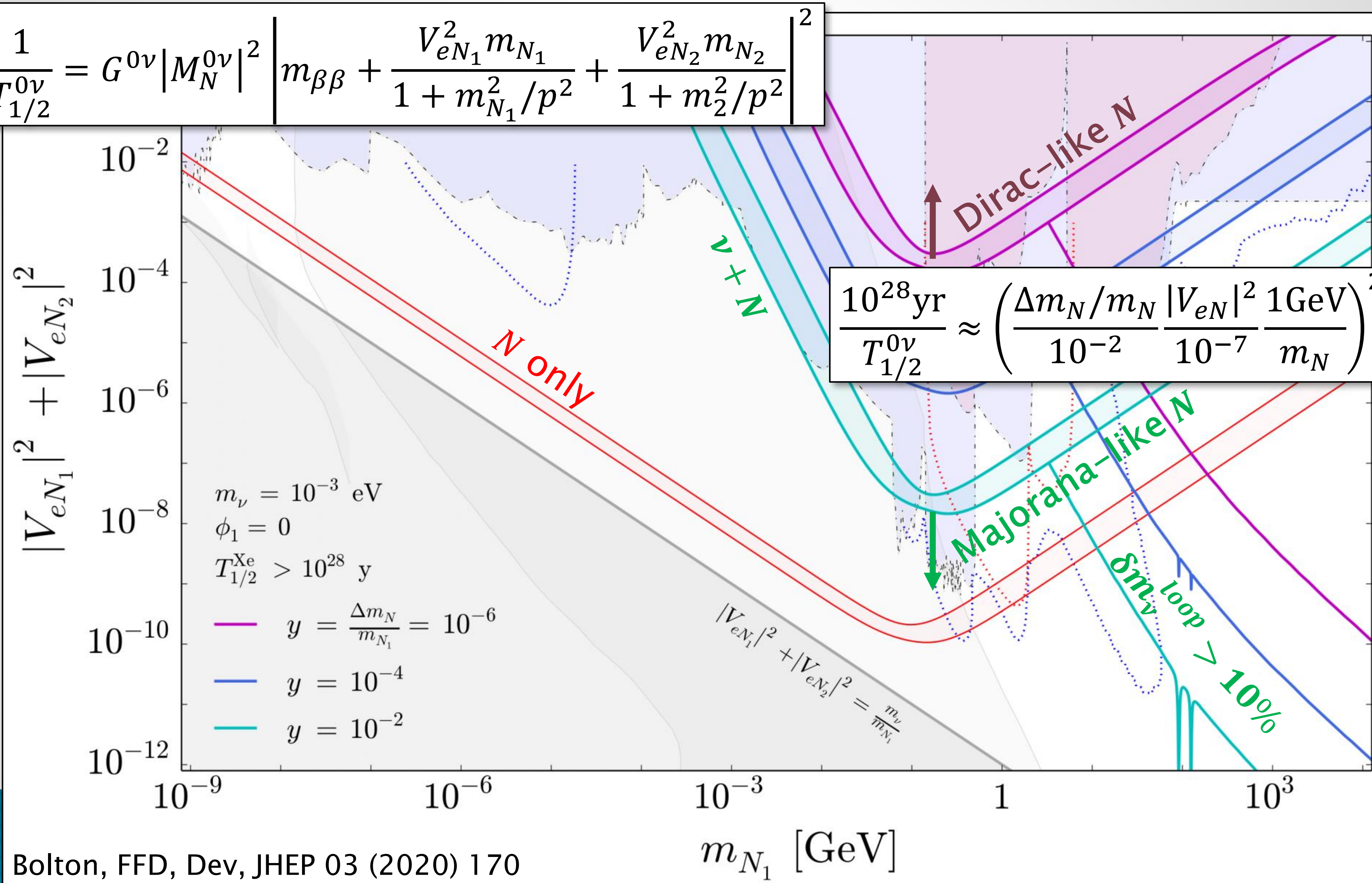
$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}\left|M_N^{0\nu}\right|^2 \left| m_{\beta\beta} + \frac{V_{eN_1}^2 m_{N_1}}{1+m_{N_1}^2/p^2} + \frac{V_{eN_2}^2 m_{N_2}}{1+m_2^2/p^2} \right|^2$$

$$\frac{10^{28}\text{yr}}{T_{1/2}^{0\nu}} \approx \left(\frac{\Delta m_N/m_N}{10^{-2}} \frac{|V_{eN}|^2}{10^{-7}} \frac{1\text{GeV}}{m_N}\right)^2$$



Bolton, FFD, Dev, JHEP 03 (2020) 170

DUNE Simulation

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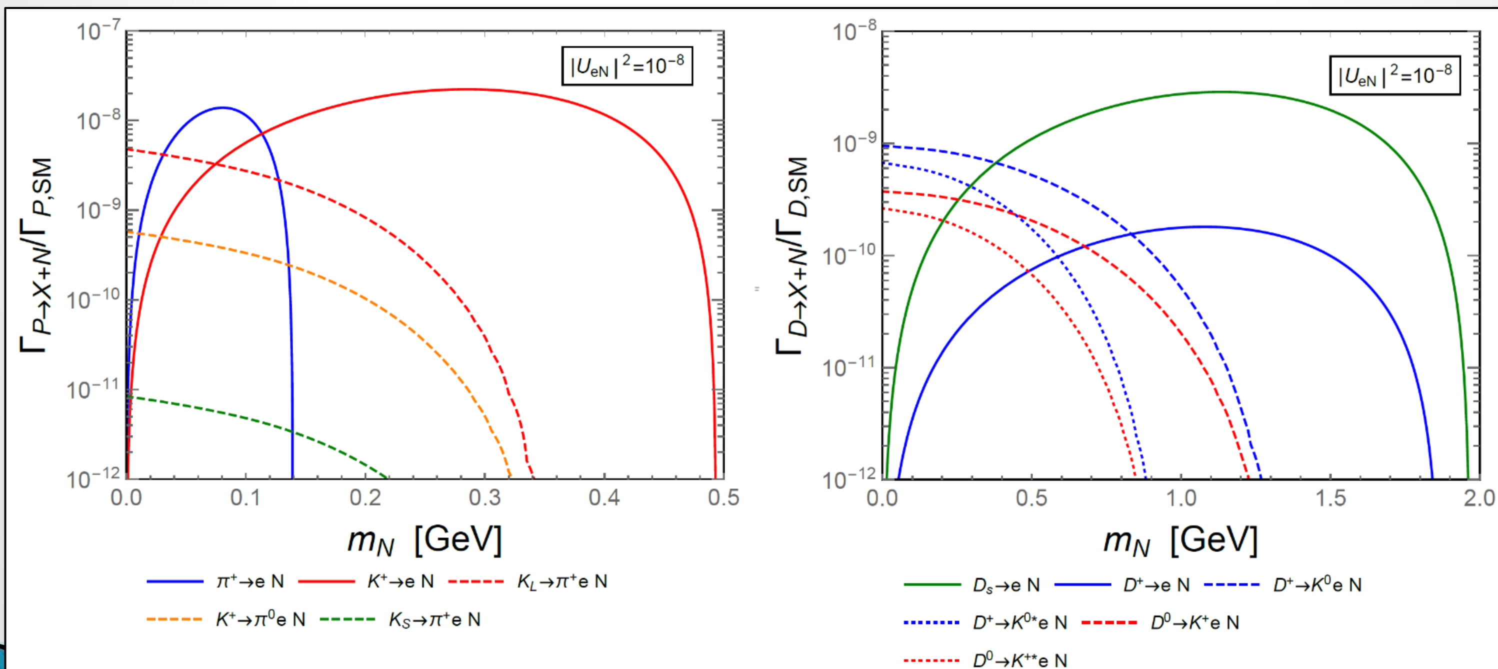
- Meson Production and Decay using Pythia

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}



DUNE Simulation

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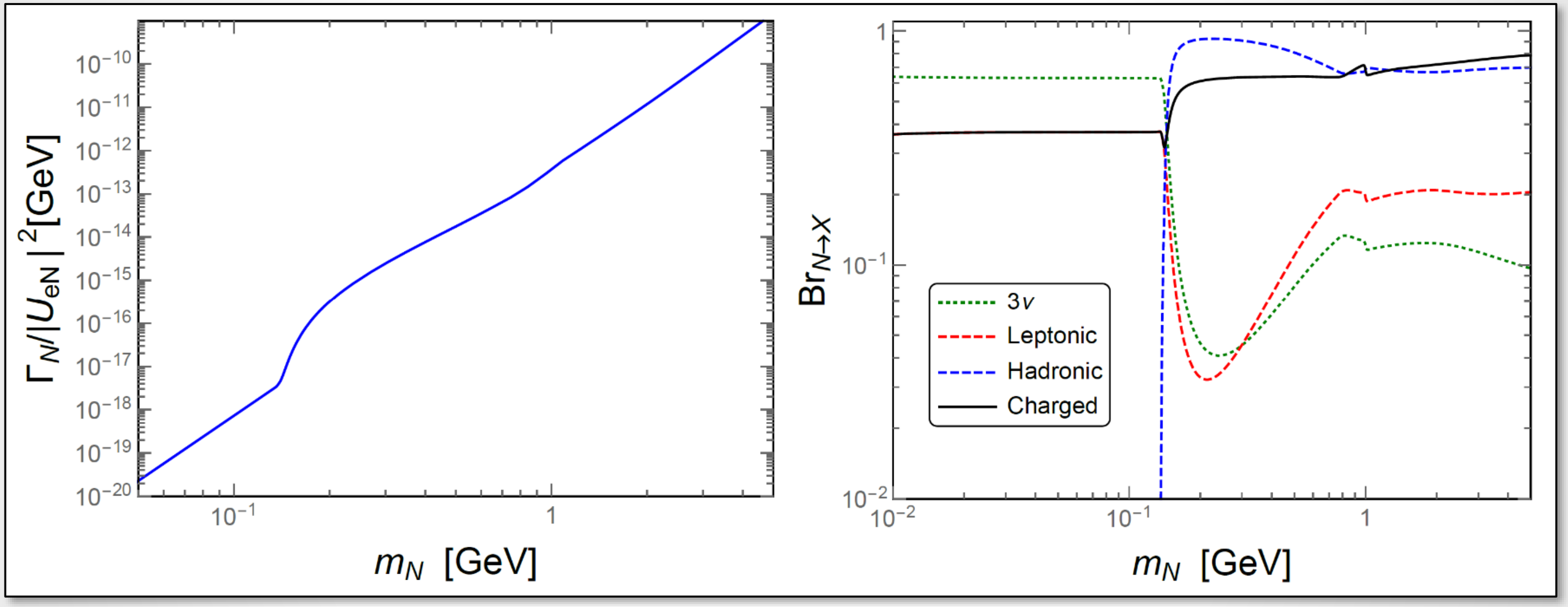
- HNL Production and Decay



- Simplified Detection at Near Detector

Experiment	Beam type	ΔA_{det} [m^2]	$\Delta \ell_{\text{det}}$ [m]	ℓ_{det} [m]	N_{POT}
DUNE	120 GeV, p	12	5	574	6.6×10^{21}
SHiP	400 GeV, p	50	45	50	2.0×10^{20}

DUNE Simulation

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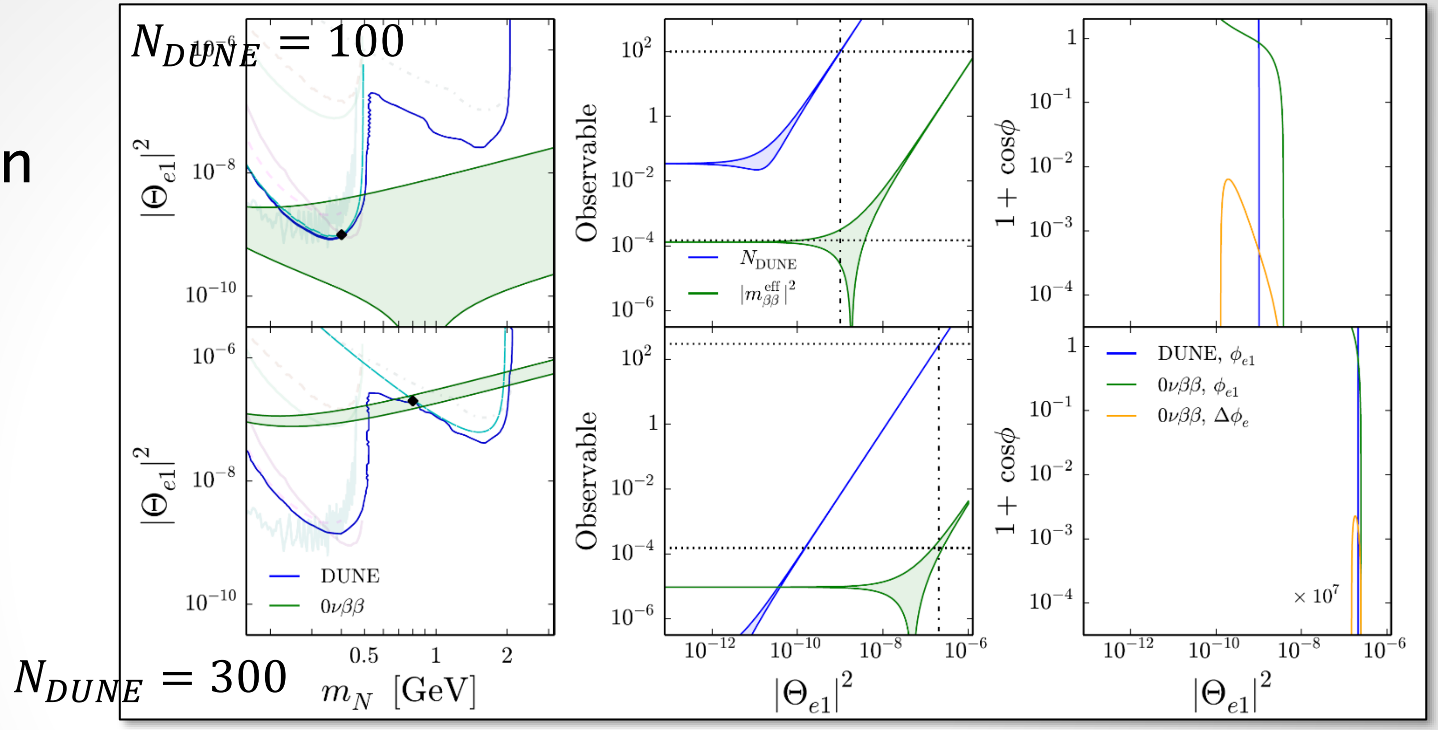
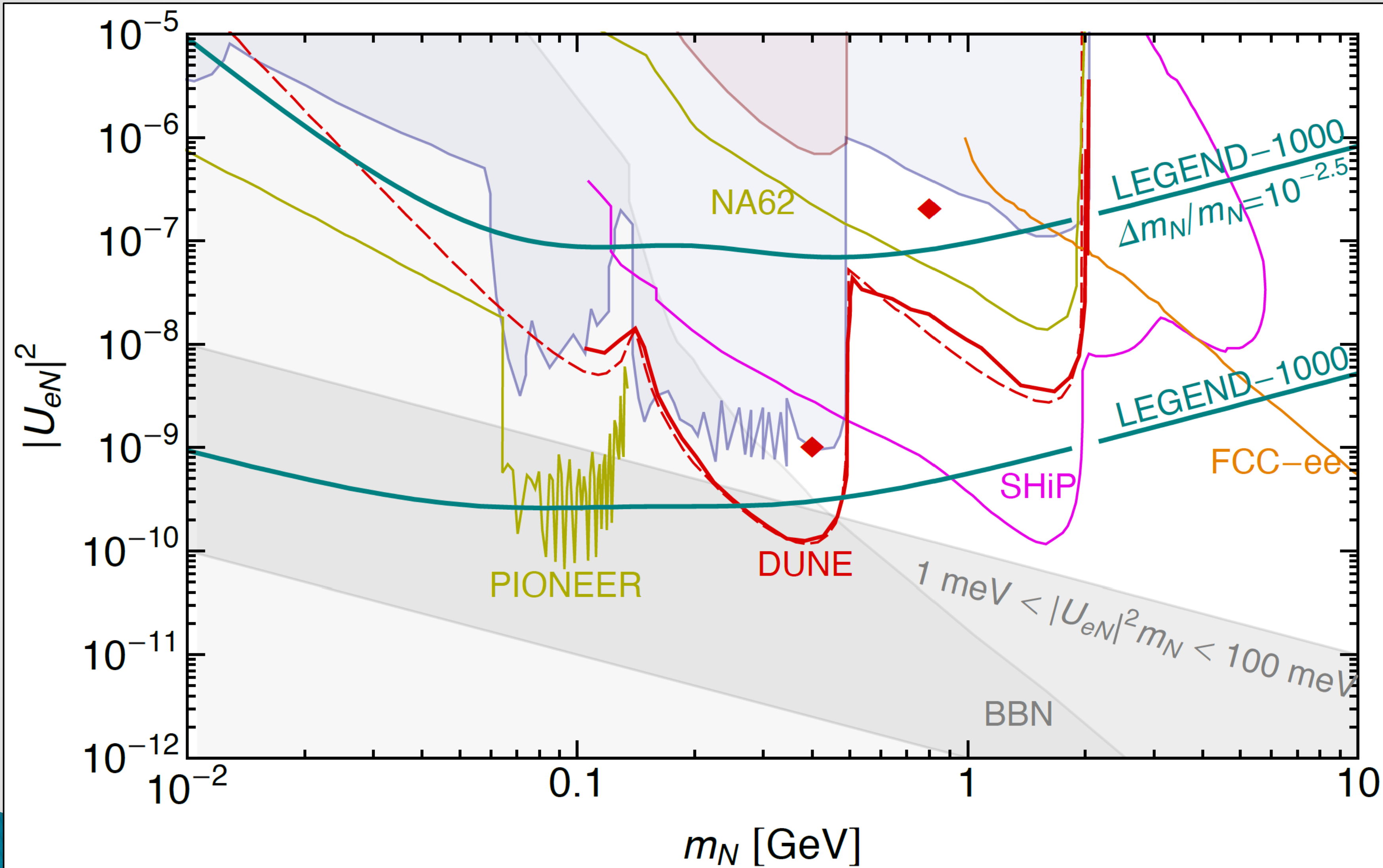
- Analytic Comparison



$$|\Theta_{e1}|^2 \approx 2 \times 10^{-7} \left(\frac{N_{\rm DUNE}^{\rm exp}}{300}\right)^{1/2} \left(\frac{6.6 \times 10^{21}}{N_{\rm POT}}\right)^{1/2} \left(\frac{5\ \rm m}{\Delta\ell_{\rm det}}\right)^{1/2} \left(\frac{7.3 \times 10^3\ \rm MeV^2}{\mathcal{A}_{PP'}(m_N)}\right)^{1/2}$$

$$r_\Delta \sim 1.5 \times 10^{-3} \left(\frac{2 \times 10^{-7}}{|\Theta_{e1}|^2}\right) \left(\frac{m_N}{800\ \rm MeV}\right) \left(\frac{10^{28}\ \rm yr}{T_{1/2}^{0\nu}}\right)^{1/2}$$

Benchmark Scenarios



Benchmark Scenarios

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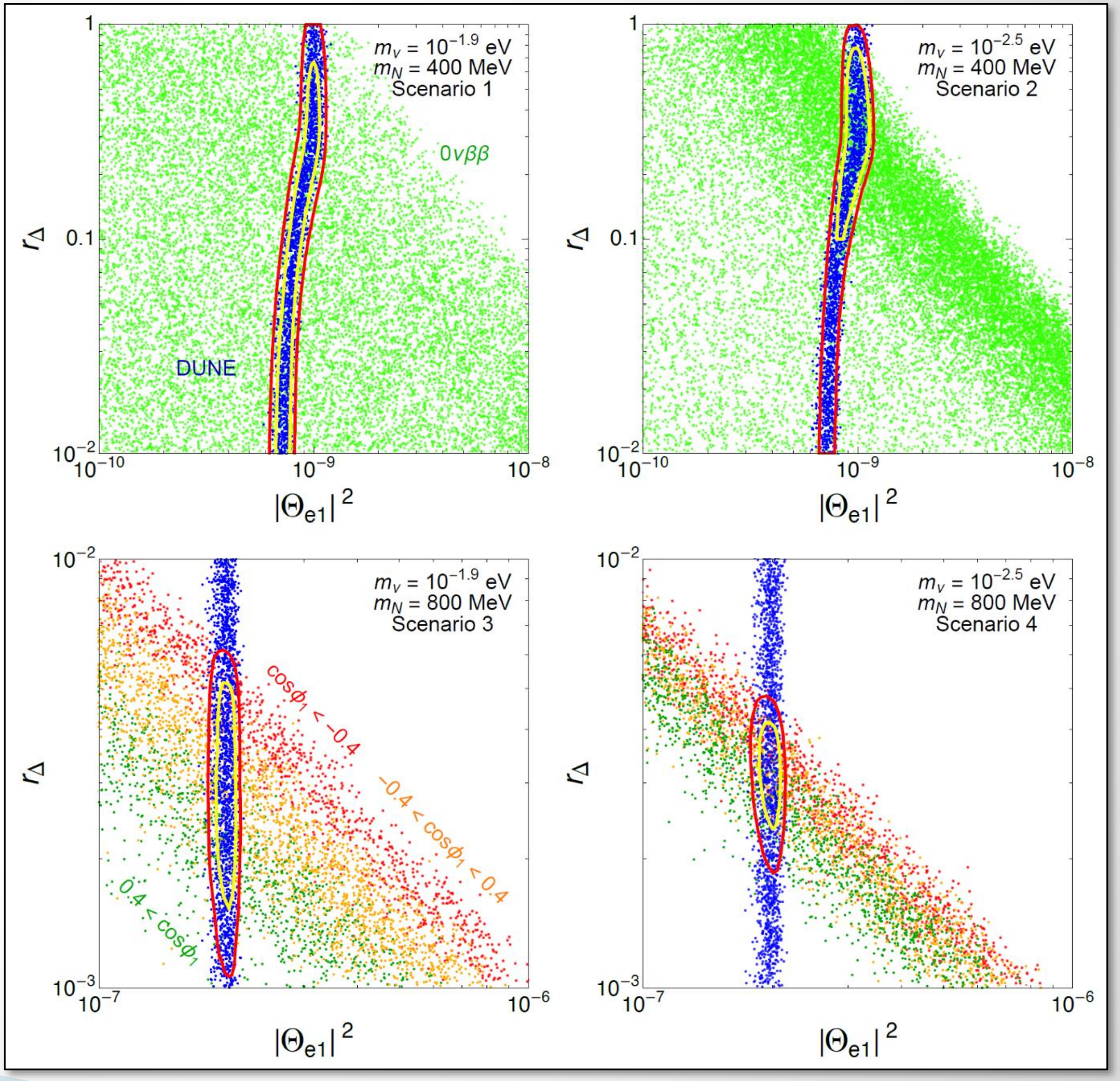
- Observation at DUNE and LEGEND-1000

Scenario	m_N [MeV]	$\lvert\Theta_{e1}\rvert^2$	r_Δ	m_ν [eV]	λ_{DUNE}	$\lambda_{0\nu}$	$T^{0\nu}_{1/2}$ [yr]
1	400	$10^{-9.0}$	$10^{-0.5}$	$10^{-1.9}$	76.7	5.94	$10^{27.8}$
2	400	$10^{-9.0}$	$10^{-0.5}$	$10^{-2.5}$	76.7	2.73	$10^{28.1}$
3	800	$10^{-6.7}$	$10^{-2.5}$	$10^{-1.9}$	325	15.5	$10^{27.4}$
4	800	$10^{-6.7}$	$10^{-2.5}$	$10^{-2.5}$	325	12.3	$10^{27.5}$

Bayesian Analysis

- Observation at DUNE and LEGEND-1000



Bayesian Analysis

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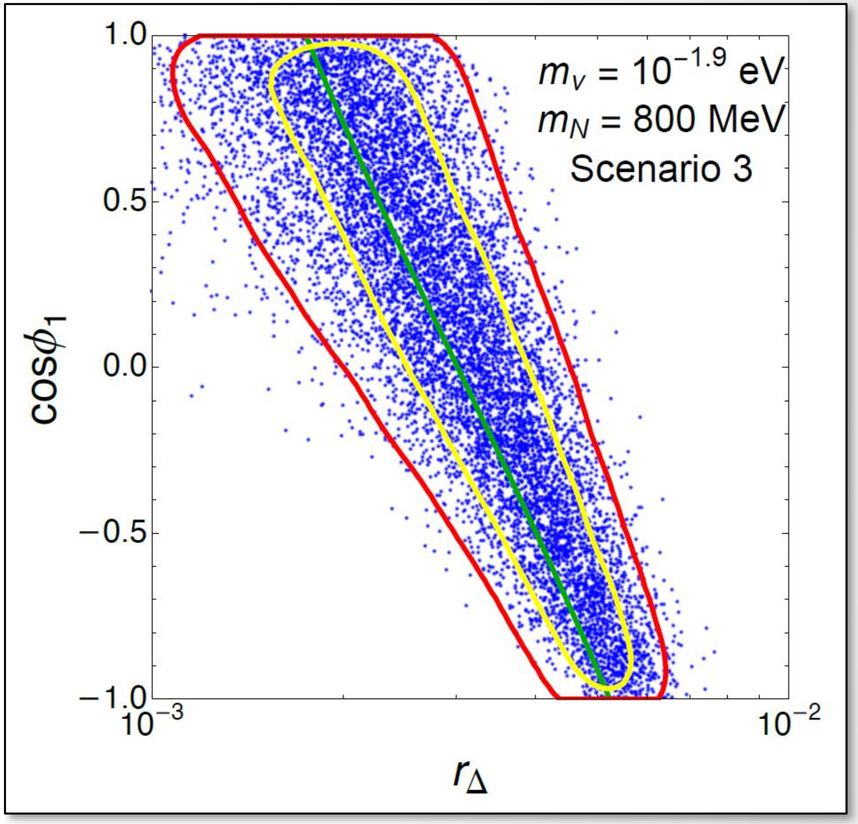
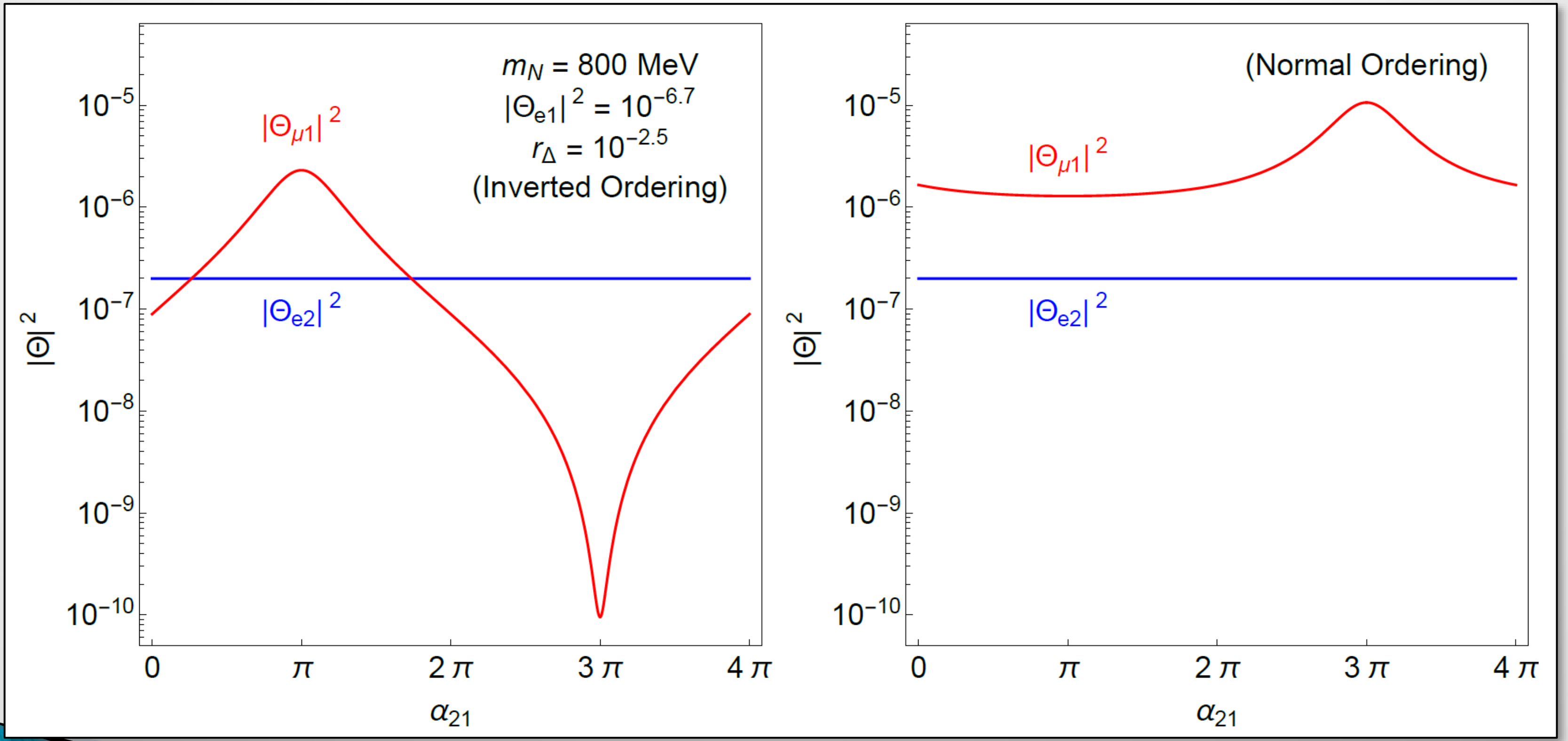


Bayesian Analysis

- Observation at DUNE and LEGEND-1000
- Identifying electron and muon flavours (3+2 scenario)



Bayesian Analysis

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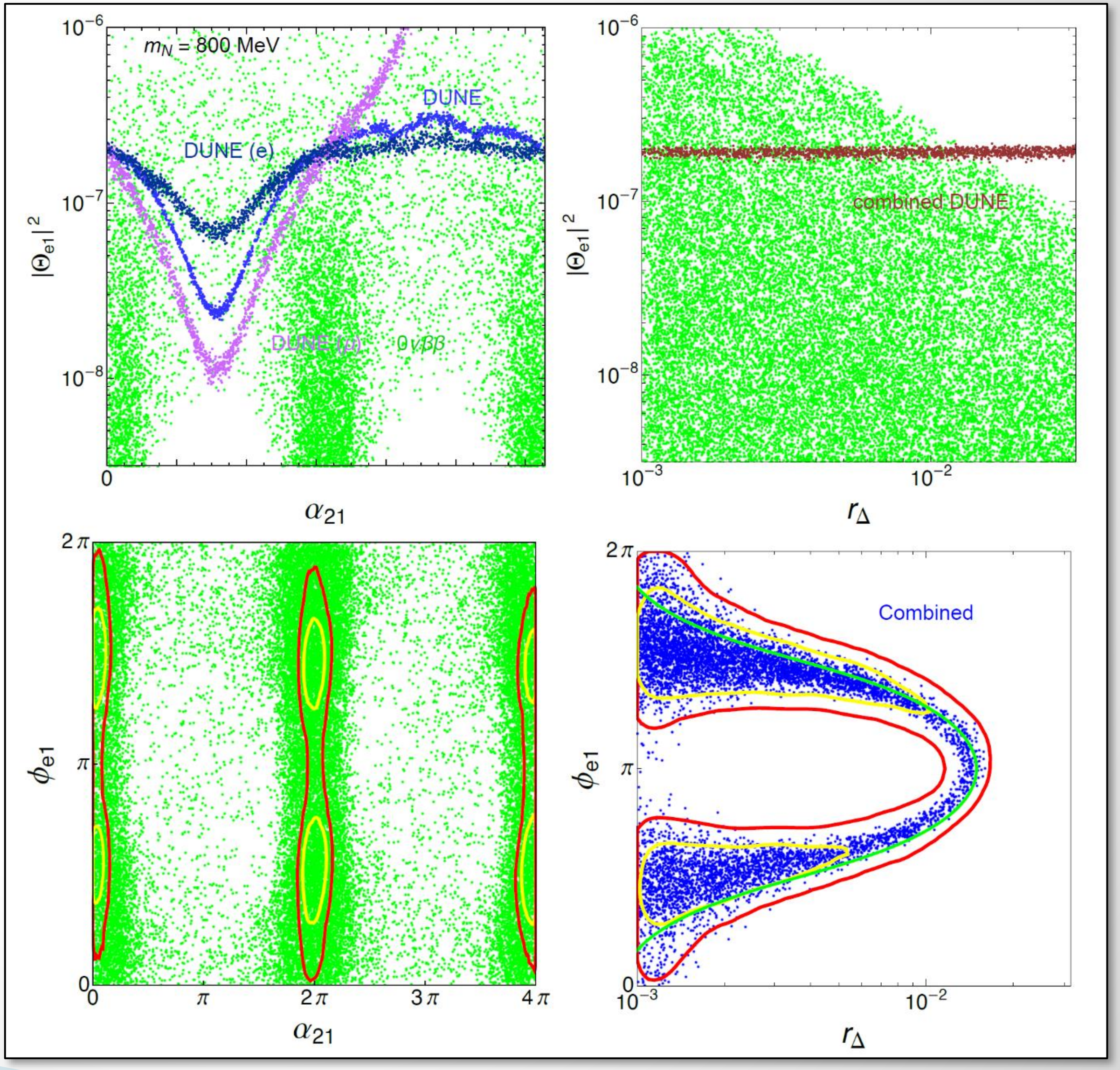

Conclusion

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- **Neutrinos much lighter than other fermions**
  - Mechanism of mass generation
  - Dirac or Majorana?
- **$0\nu\beta\beta$ is crucial probe for BSM physics**
  - Effective $0\nu\beta\beta$ mass $m_{\beta\beta} \approx 10 - 100\ \mathrm{meV}$ probes New Physics near GUT scale
  - Sensitive to Majorana HNL for $0.1\ \mathrm{eV} < m_N < 10\ \mathrm{TeV}$
  - Sensitive to nature of HNL: Dirac vs Quasi-Dirac vs Majorana
- **HNLs aka sterile neutrinos are natural extension to SM**
  - Sensitivity in $0\nu\beta\beta$ and direct searches such as DUNE
  - Complementarity in probing properties of HNLs for $m_N \approx 1 - 10\ \mathrm{GeV}$
    - Mass splitting between HNLs and relative CP phase