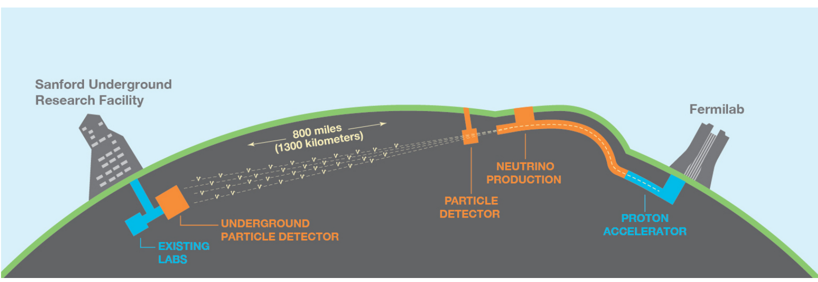

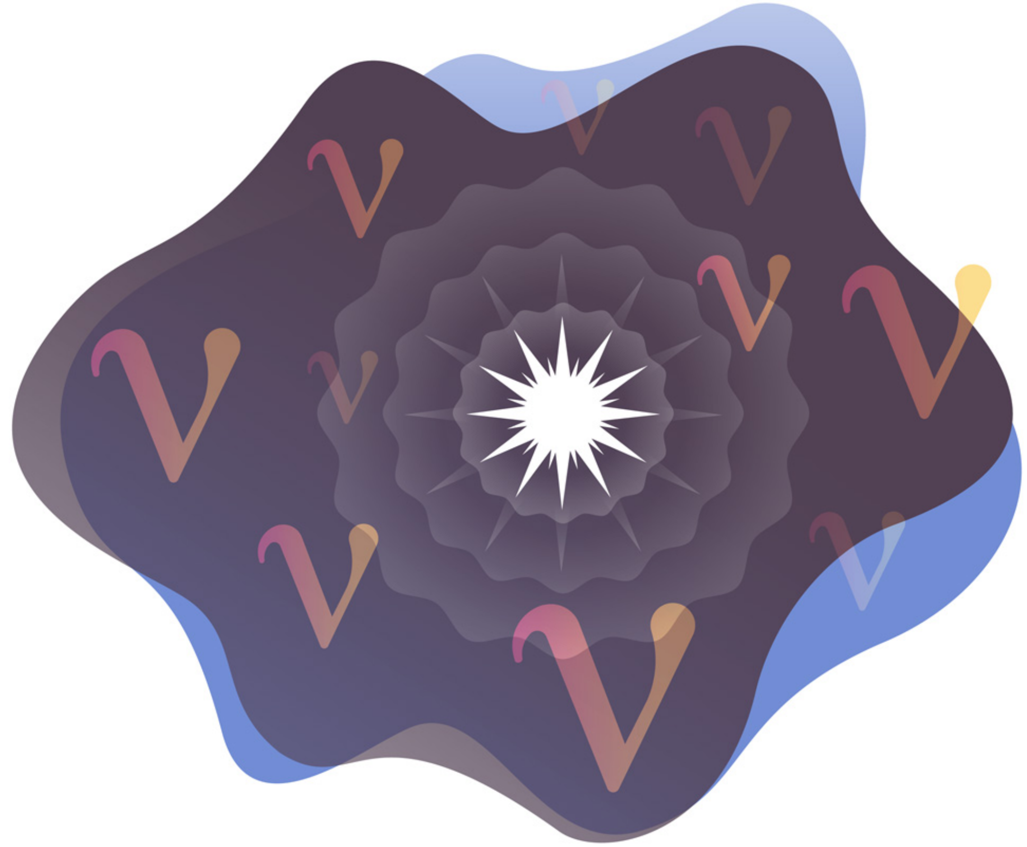

arXiv: 2302.10965, 2401.xxxxx, 2402.xxxxx

中国科学技术大学
University of Science and Technology of China
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in collaboration with
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P. A. N. Machado, G. Li,
Y.-L. Zhou

Multi-messenger Opportunities for Heavy Neutral Leptons

Jan 09, 2024 @ ICISE, Quy Nhon

Heavy Neutral Lepton - Sterile Neutrino

[Minkowski, Mohapatra, Senjanovi´c, Gell-Mann, Ramond, Slansky, Yanagida]

Neutrino mass:

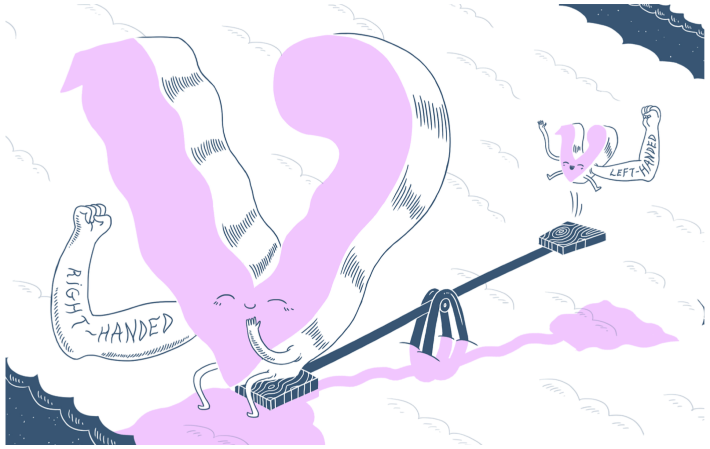
type-I seesaw

mechanism

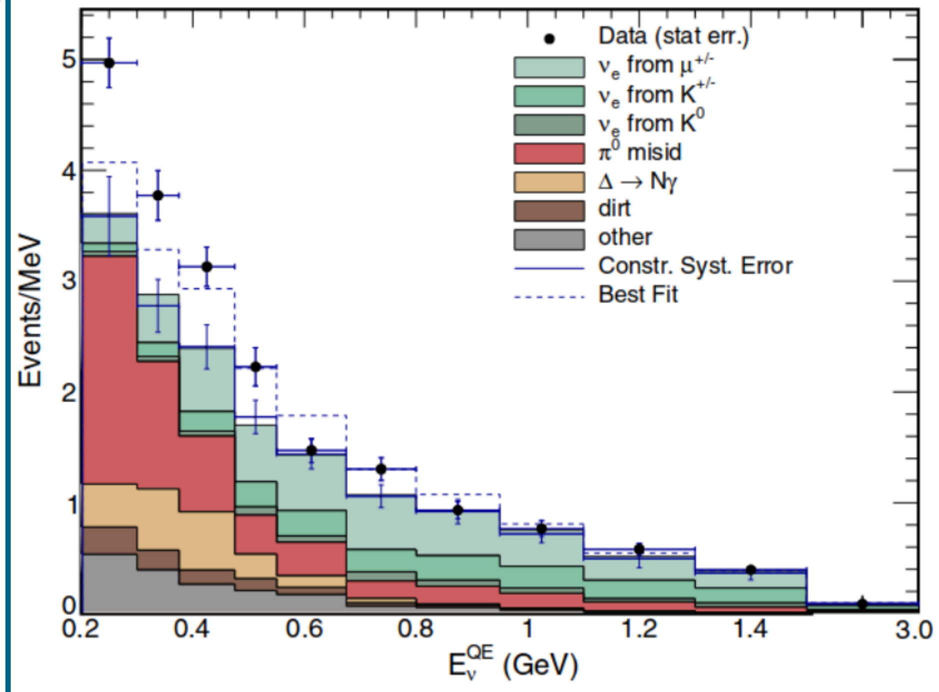
$$\mathcal{L} \supset \frac{1}{2}\overline{N^c} M_R N + \bar{L} Y_\nu \tilde{H} N + \text{h.c.}$$

$$\mathcal{M} = \begin{pmatrix} 0 & M_D \\ M_D & M_R \end{pmatrix}$$

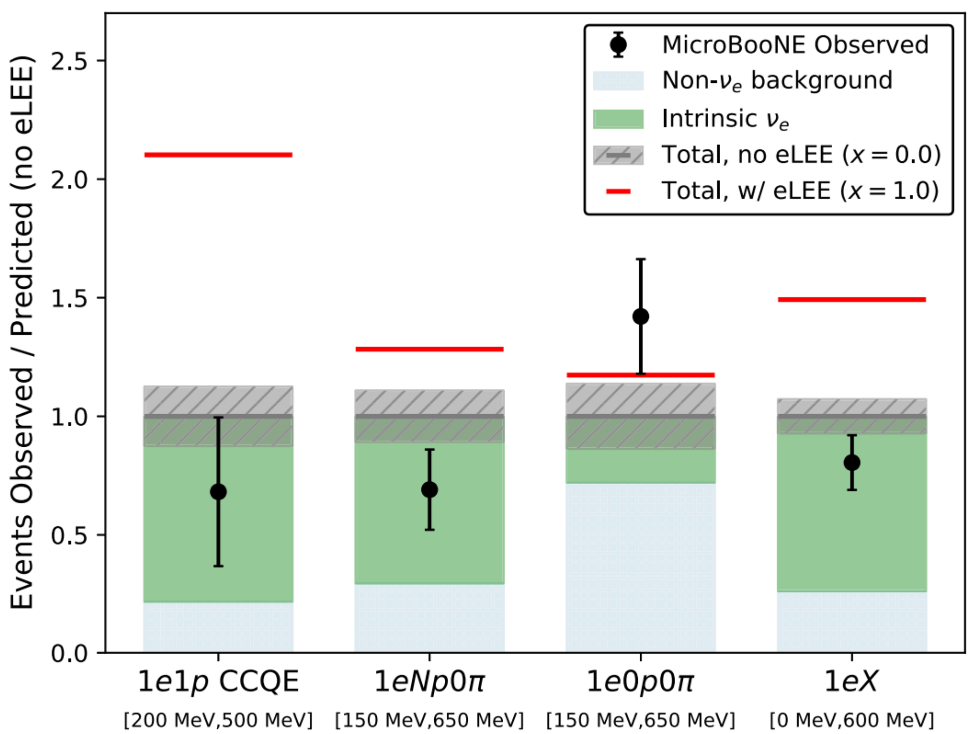
$$m_\nu = -M_D M_R^{-1} M_D^T$$



MiniBooNE low energy excess

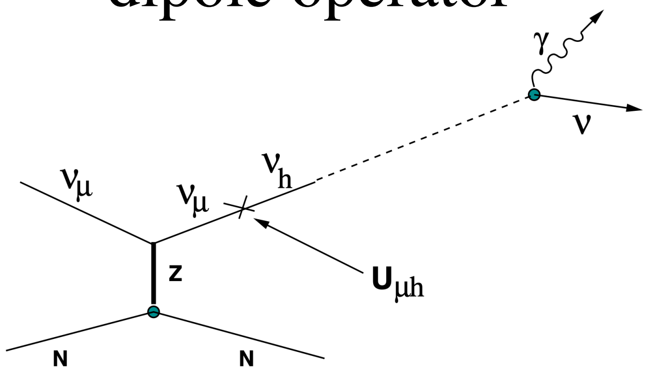


[PRL 128, 241801 (2022)]



Via mixing and

dipole operator



$$\theta^2 \sim 10^{-3}$$

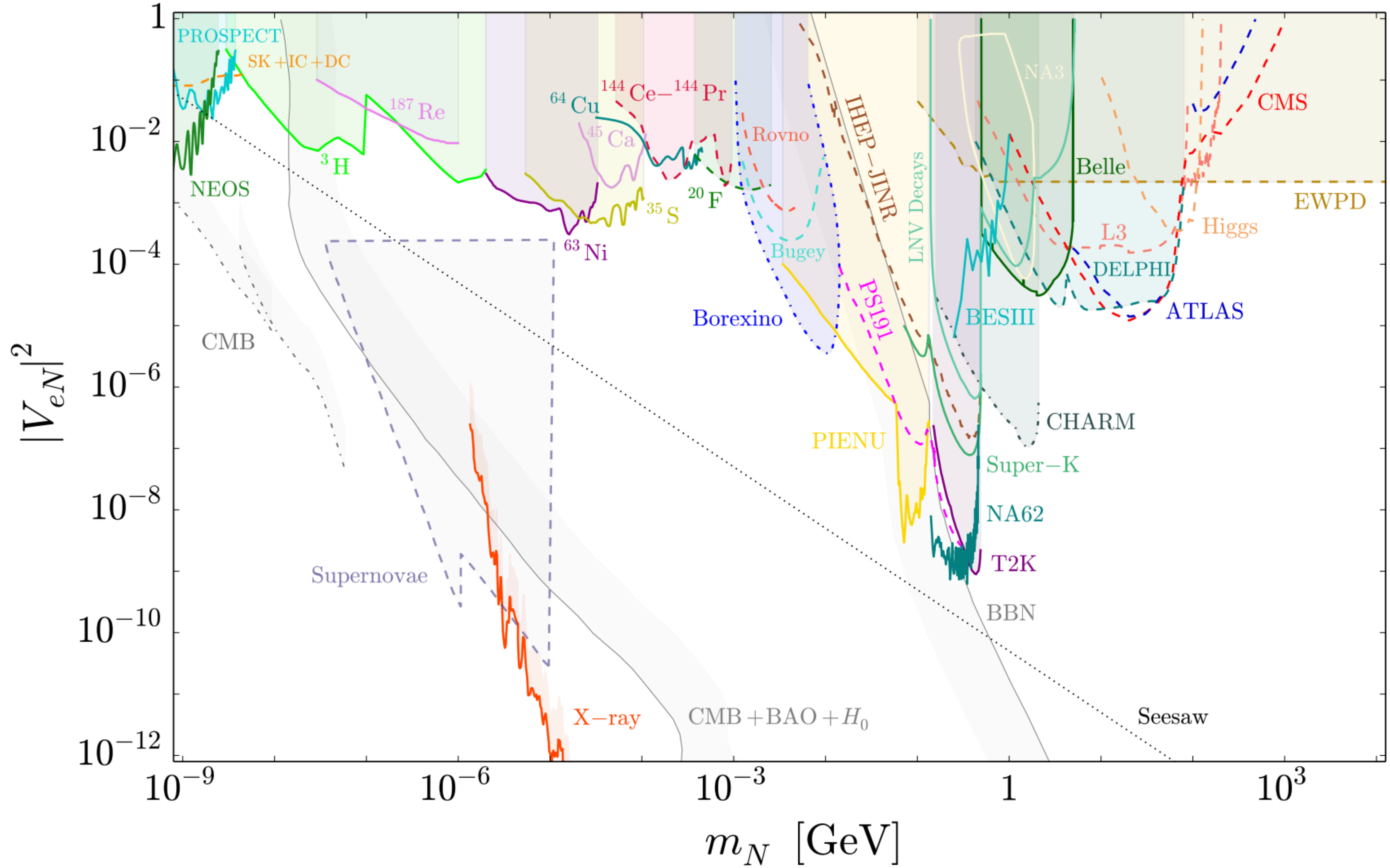
$$\mu \sim 10^{-9} \mu_B$$

[S. N. Gninenko, PRL 103, 241802 (2009)]

Heavy Neutral Lepton - Mixing Portal

$$\Gamma_{\nu_s \to \nu_a \gamma} = 1.38 \cdot 10^{-29}\ \mathrm{sec}^{-1} \left(\frac{\sin^2 2\theta}{10^{-7}}\right)\left(\frac{m_s}{1\ \mathrm{keV}}\right)^5.$$

$$\theta^2 \sim \frac{m_\nu}{M_N}, \mathrm{keV} < M_N < 100\mathrm{MeV}$$



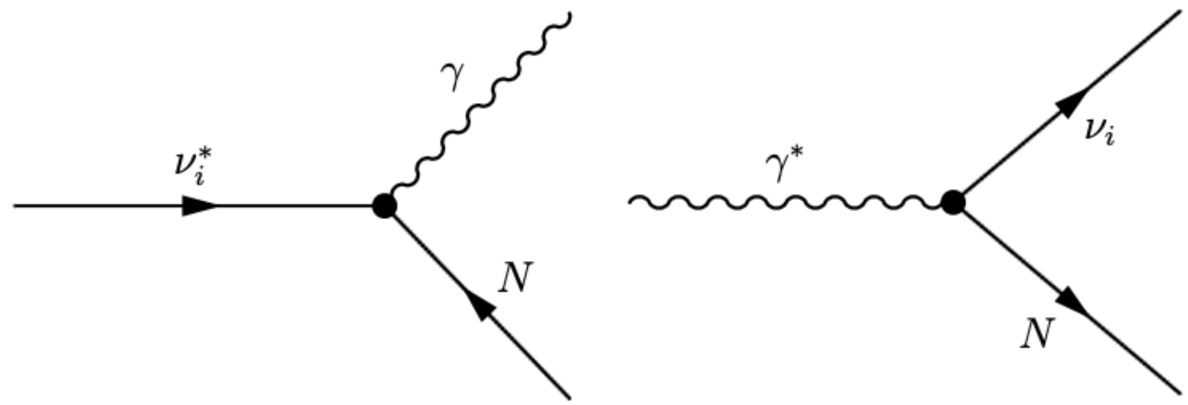
[P. D. Bolton, F. F. Deppisch, P. S. B. Dev, arXiv: 1912.03058]

Heavy Neutral Lepton - Dipole Portal

When the mixing effect is subdominant, …

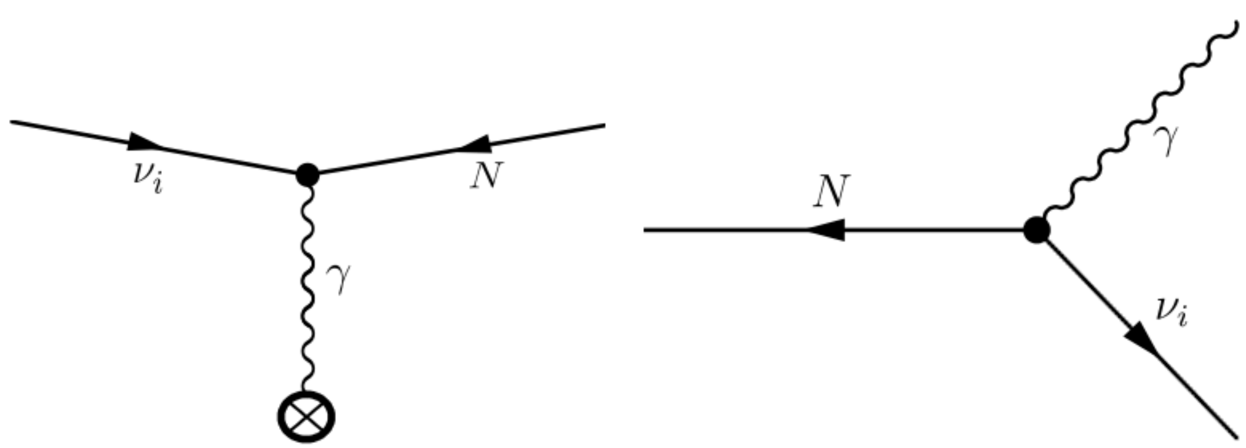
$$\mathcal{L} \supset \frac{1}{2}\mu_\nu \bar{\nu}_L^\alpha \sigma^{\mu\nu} N F_{\mu\nu}$$

$$\pi^\pm, K^\pm \to \mu^\pm \left(\overset{(-)}{\nu}_\mu{}^* \to \gamma \overset{(-)}{N}\right) \quad \pi^0, \eta \to \gamma(\gamma^* \to \nu_a N)$$



(a) Weak meson decays (b) Dalitz-like decay

$$\mathrm{Br}(M \to N) \propto \mu_\nu^2 m_M^2$$



(c) Primakoff upscattering (d) $N \to \gamma\nu$ (signal)

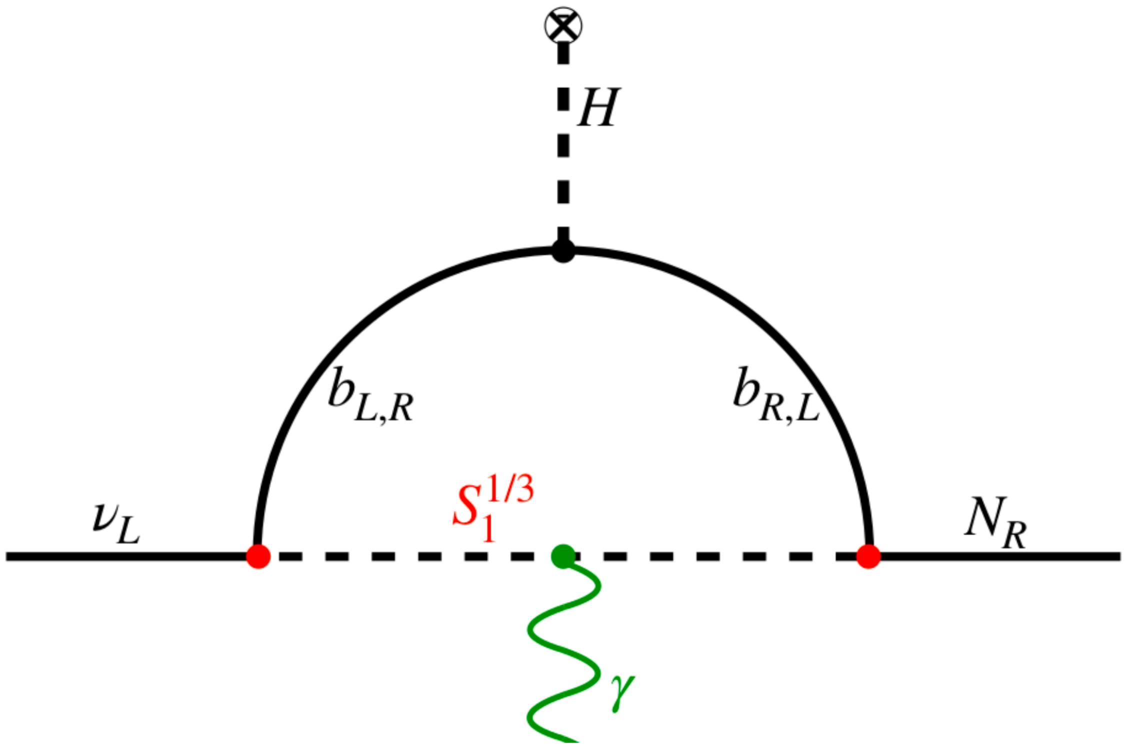
$$\Gamma_N = \frac{6}{4\pi}\mu_\nu^2 M_N^3$$
(flavor universal)

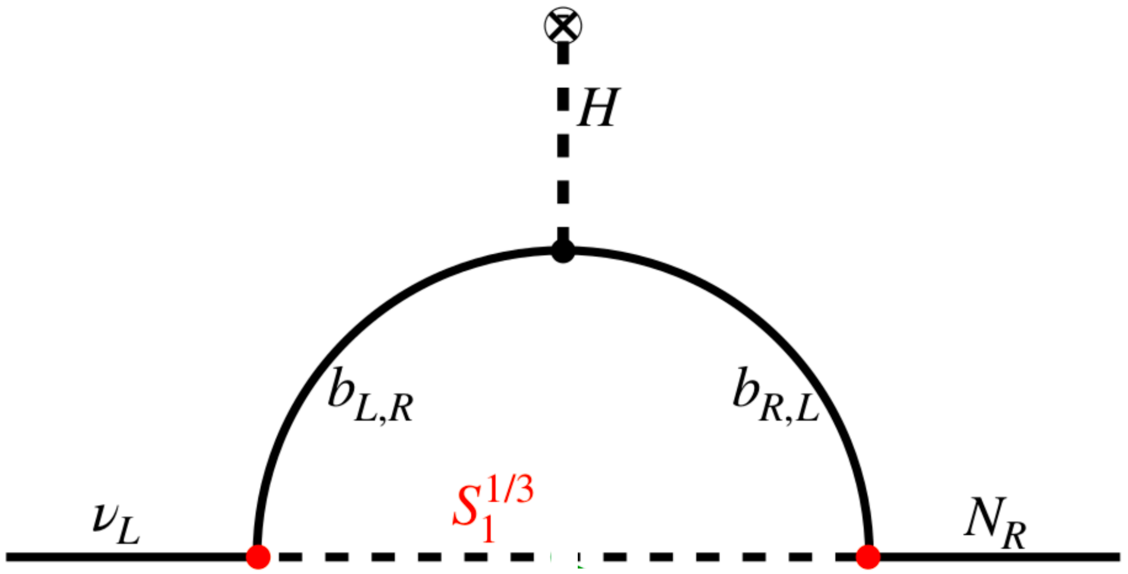
[Magill, Plestid, Pospelov, Tsai, arXiv:1803.03262]

UV completion – Mixing vs Dipole

- Consider heavy scalar lepto-quark $S_1 \sim (\bar{3}, 1, 1/3)$

$$\mathcal{L} \supset y_1 \bar{b}_R^c N S_1 + y_2 \bar{Q}_L^3 L_L^{i\,c} S_1^\dagger + h.c.$$





$$\mu_\nu \approx \frac{e\, y_1 y_2}{8\pi^2 m_{LQ}^2} m_b \log \frac{m_b^2}{m_{LQ}^2}$$

$$m_{\nu N} \sim \frac{\mu_\nu}{\mu_B} \frac{m_{LQ}^2}{2 m_e}$$

UV completion – Mixing vs Dipole

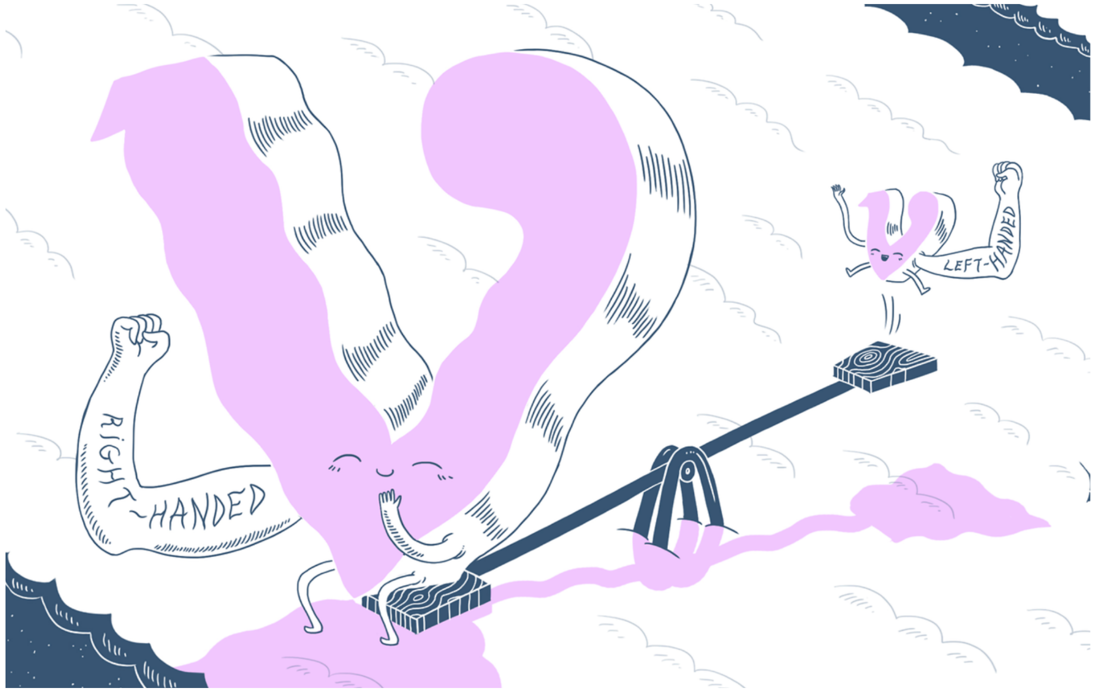
- Consider heavy scalar lepto-quark $S_1 \sim (\bar{3}, 1, 1/3)$

$$\mathcal{L} \supset y_1 \bar{b}_R^c N S_1 + y_2 \bar{Q}_L^3 L_L^{i\,c} S_1^\dagger + h.c.$$

$$m_{\nu N} \sim \frac{\mu_\nu}{\mu_B} \frac{m_{LQ}^2}{2m_e}$$

$$m_\nu \sim \frac{m_{\nu N}^2}{M_N}$$

$$\mu_\nu \sim 10^{-12} \mu_B \frac{\sqrt{m_\nu M_N}}{\text{MeV}}$$



for lepto-quark masses at the TeV scale

$$m_\nu \sim 0.1\text{eV}, \mu_\nu \sim 10^{-15} \mu_B$$

UV completion – Mixing vs Dipole

[Lindner et al., arXiv:1706.02555]

- Voloshin-type symmetry $SU(2)_\nu$

$$(N_R^C, \nu_L)^T \in \mathbf{2} \qquad SU(2)_L \to SU(3)_L$$

$$\bar{\nu}_L N_R \to -\bar{\nu}_L N_R \qquad \bar{\nu}_L \sigma_{\mu\nu} N_R F^{\mu\nu} \to \bar{\nu}_L \sigma_{\mu\nu} N_R F^{\mu\nu}$$

$$m_{\nu N} \sim \frac{\mu_\nu}{\mu_B} \frac{\alpha}{4\pi} \frac{m_V^2}{2m_e}$$

$$\mu_\nu \sim 10^{-8} \mu_B \frac{\sqrt{m_\nu M_N}}{\mathrm{MeV}}$$

$SU(2)_\nu$ Symmetry-breaking scale m_V at the TeV scale

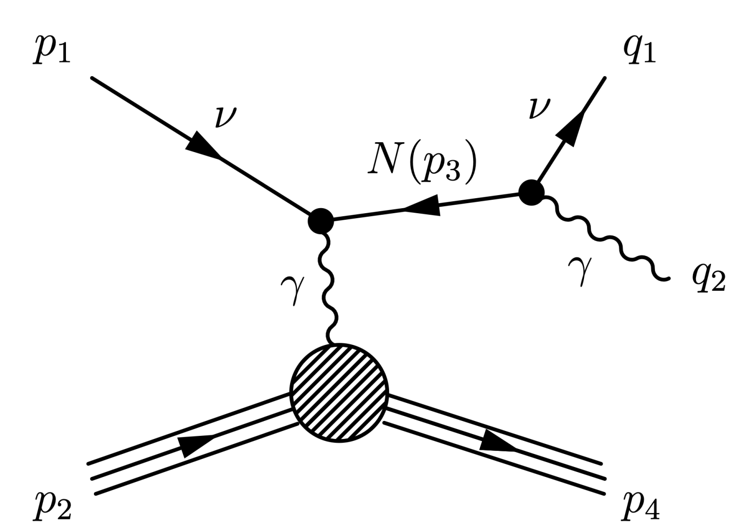
$$m_\nu \sim 0.1\mathrm{eV}, \mu_\nu \sim 10^{-11} \mu_B$$

Current Probes: terrestrial experiments

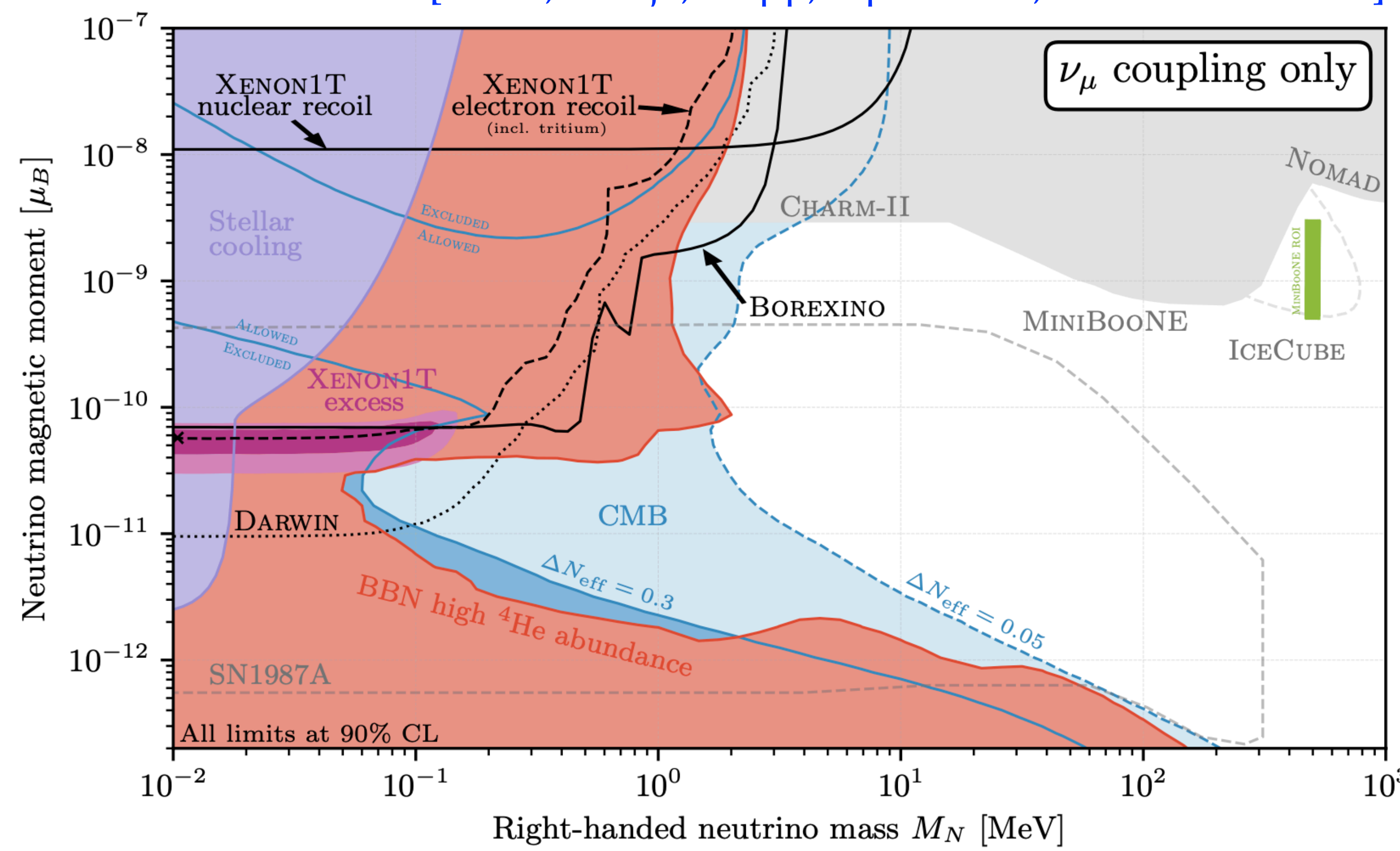
Beam dump experiments:

MiniBoone, NONAD, CHARM

production via:



[Magill, Plestid, Pospelov, Tsai, arXiv:1803.03262]
[Brdar, Greljo, Kopp, Opferkuch, arXiv:2007.15563]



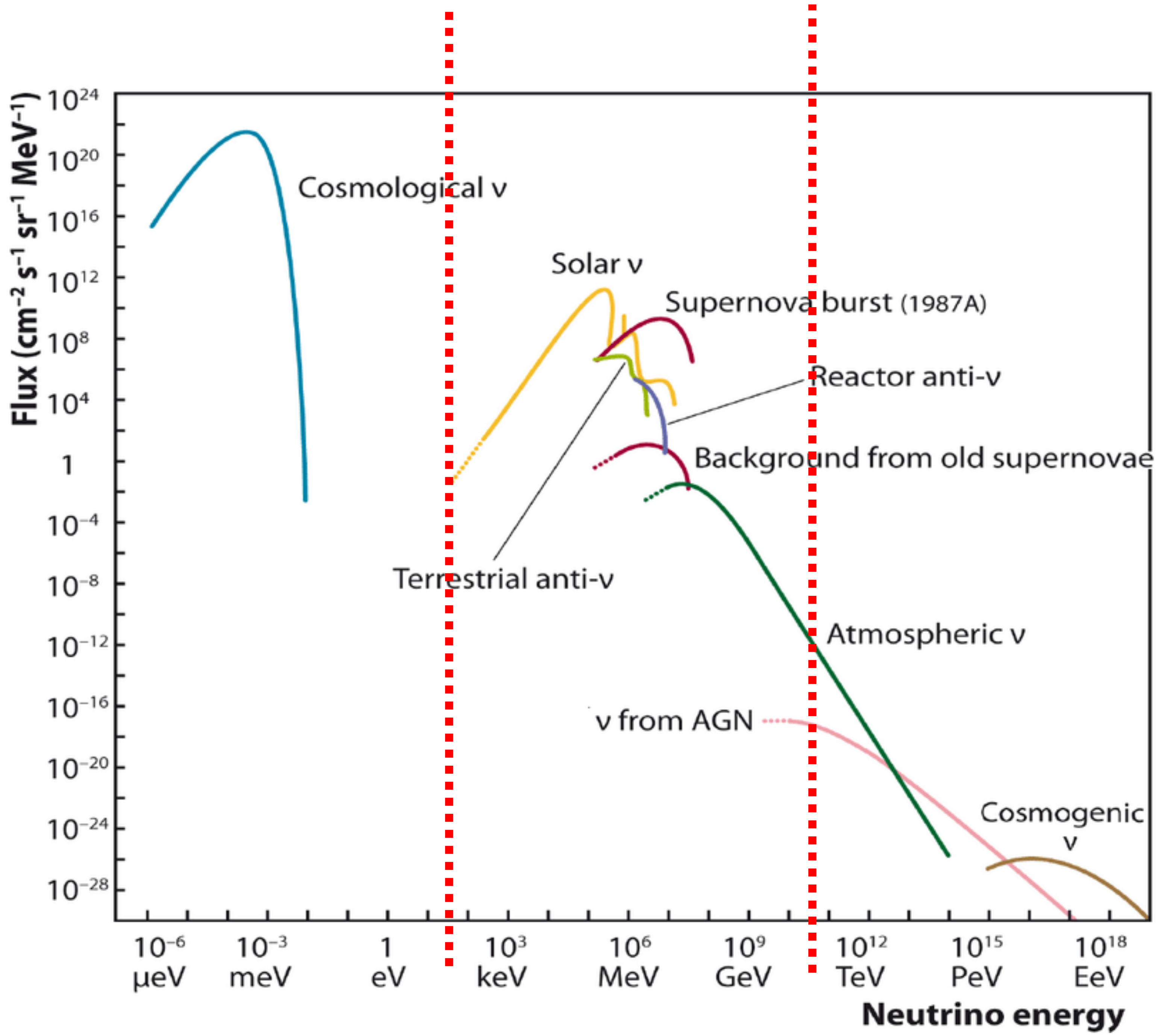
$$\pi^0, \eta \to \gamma(\gamma^* \to \nu_a N)$$

$$\pi^\pm, K^\pm \to \mu^\pm \left(\overset{(-)}{\nu}_\mu{}^* \to \gamma \overset{(-)}{N} \right)$$

relevant for transition magnetic moments between ν_μ and N

Current Probes: terrestrial experiments

- looking to the sky



Current Probes: terrestrial experiments

Solar neutrino spectrum:

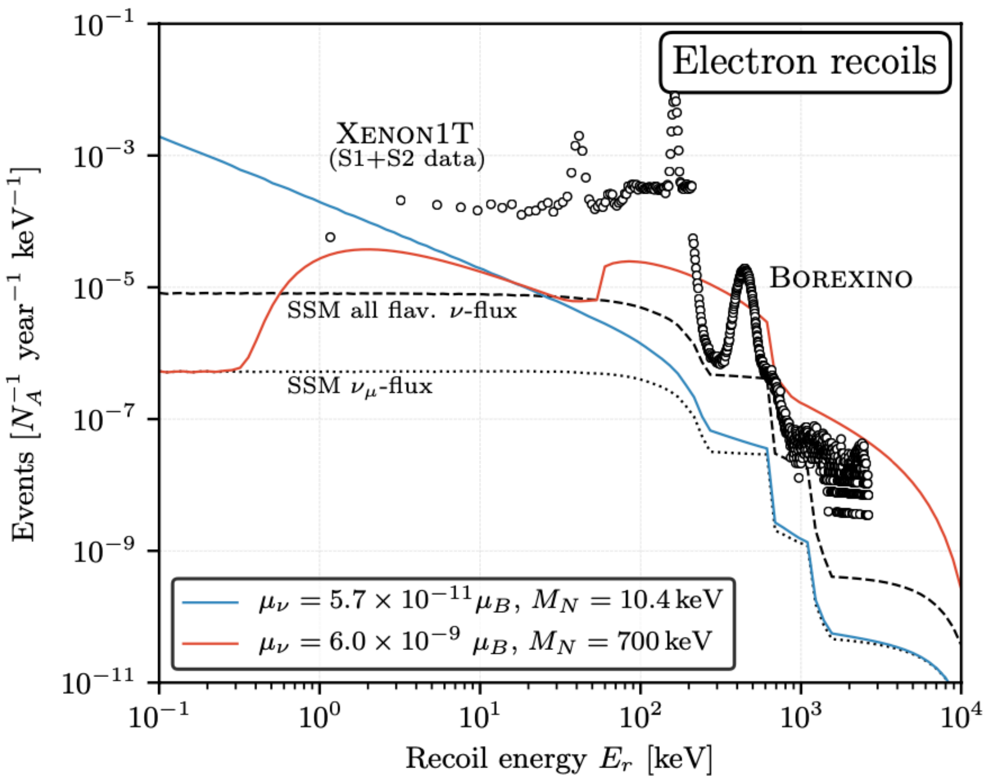
Xenon1T, Borexino

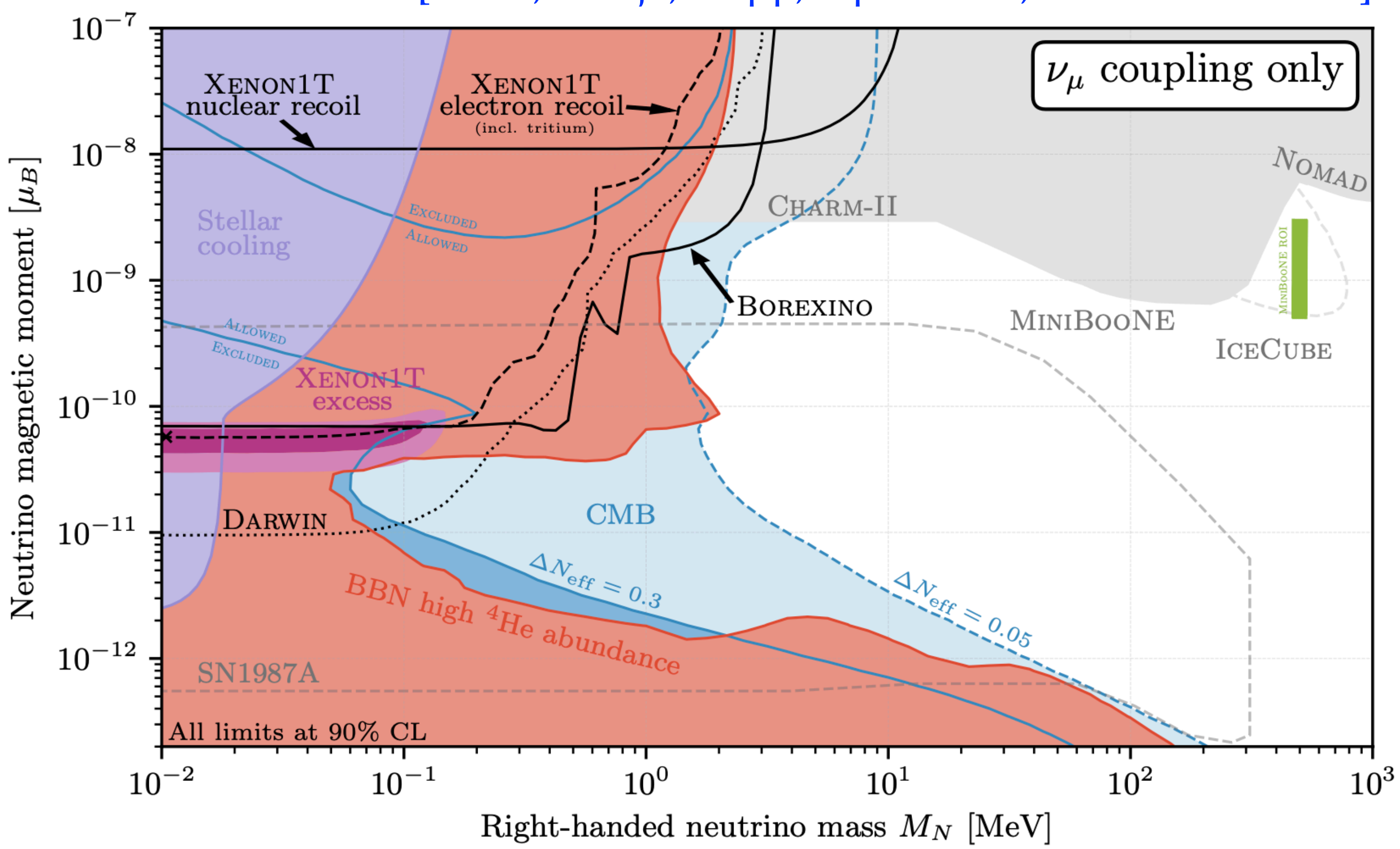
detection via:

$$\nu_L + e^- \to N + e^-$$

$$\nu_L + X_Z^A \to N + X_Z^A$$

[Magill, Plestid, Pospelov, Tsai, arXiv:1803.03262]
[Brdar, Greljo, Kopp, Opferkuch, arXiv:2007.15563]



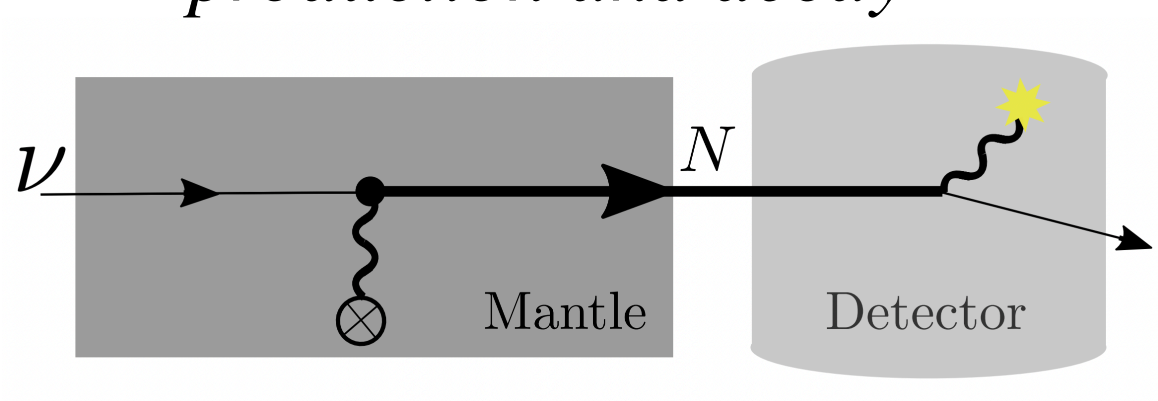


Current Probes: terrestrial experiments

Solar neutrino

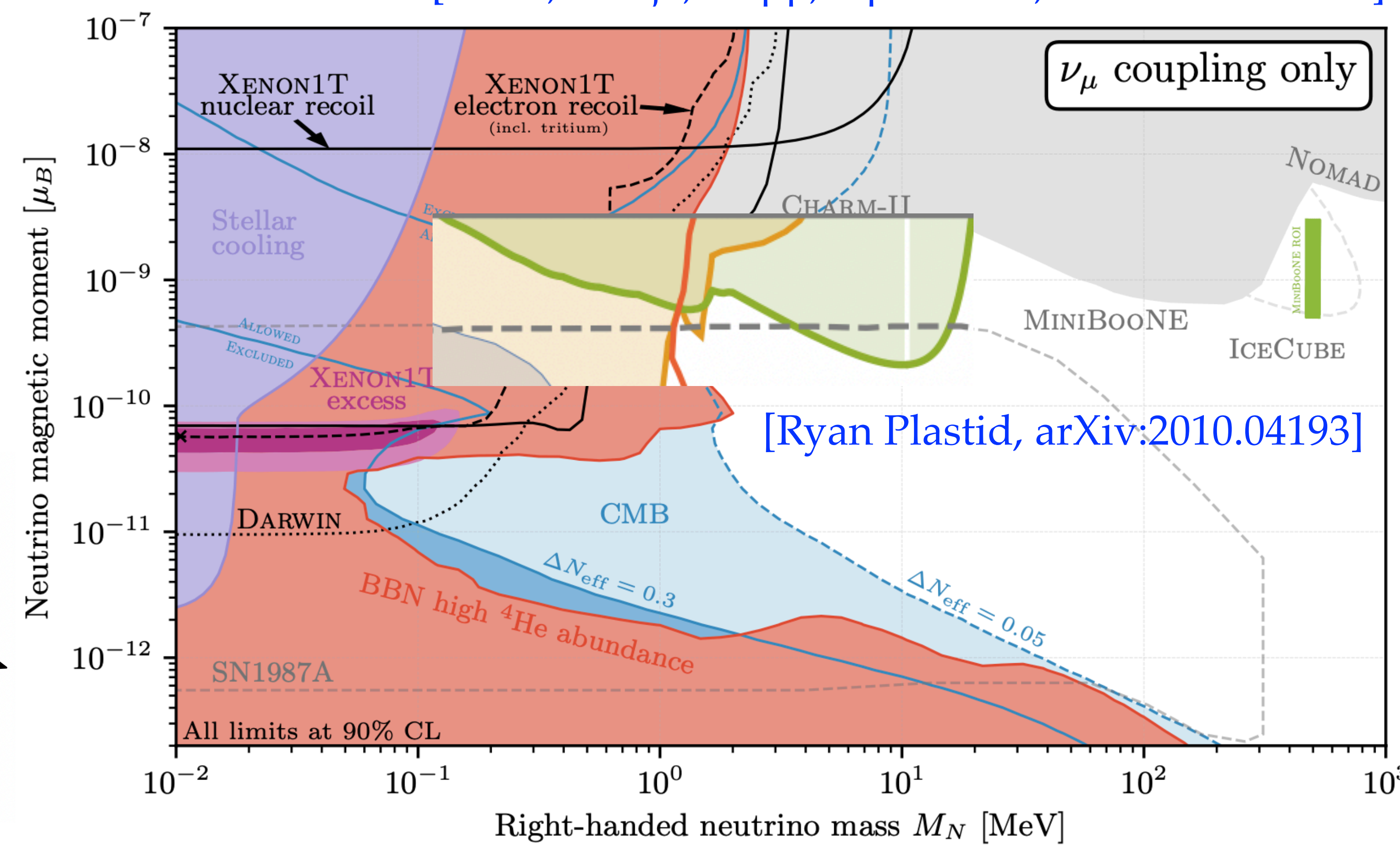
up-scattering and decays

production and decay



Borexino, SuperK

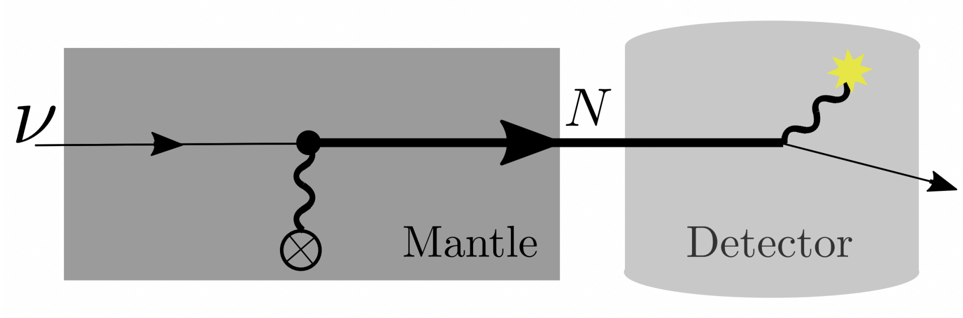
[Magill, Plestid, Pospelov, Tsai, arXiv:1803.03262]
[Brdar, Greljo, Kopp, Opferkuch, arXiv:2007.15563]



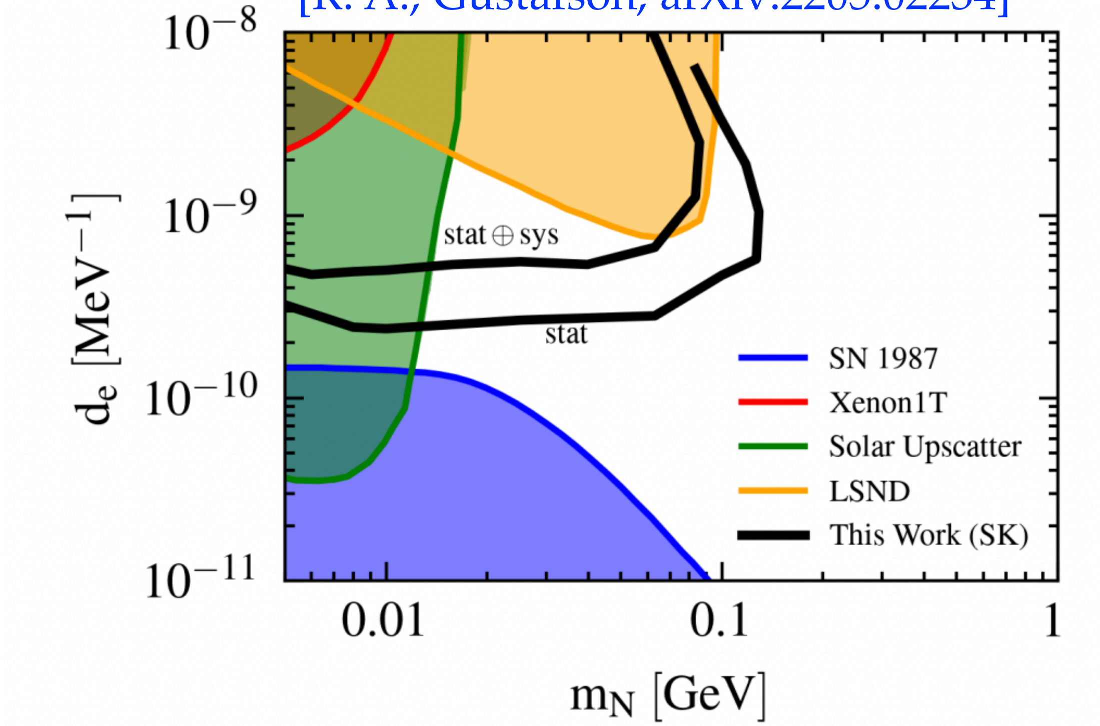
[Ryan Plastid, arXiv:2010.04193]

Current Probes: terrestrial experiments

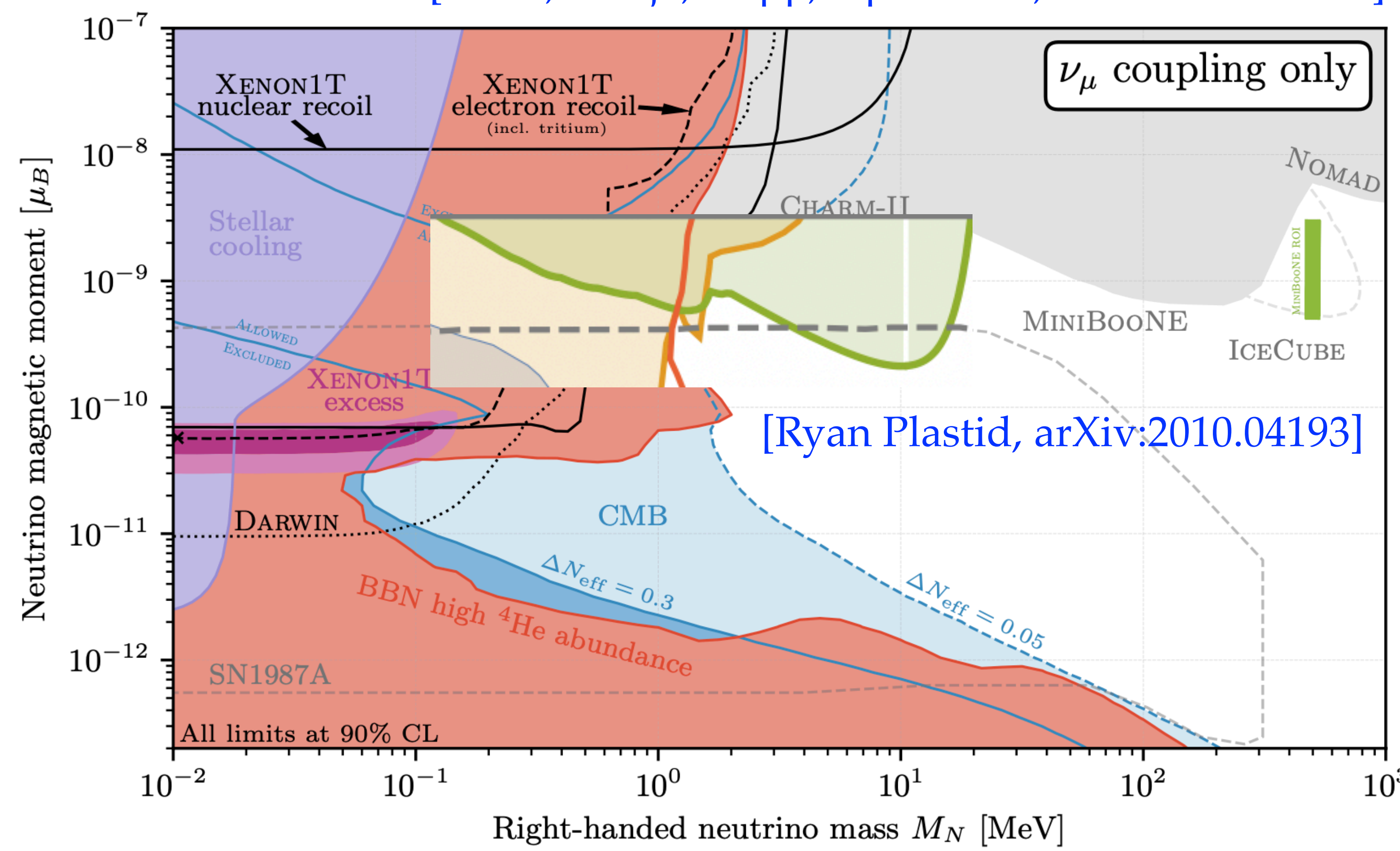
Atmospheric neutrino DUNE, Super-K



[R. A., Gustafson, arXiv:2205.02234]



[Magill, Plestid, Pospelov, Tsai, arXiv:1803.03262]
[Brdar, Greljo, Kopp, Opferkuch, arXiv:2007.15563]



$$M_N \gtrsim 6\text{GeV (LHC, LEP)}: \; e^+e^-(q\bar{q}) \to (N \to \gamma\nu)\bar{\nu} + h.c.$$

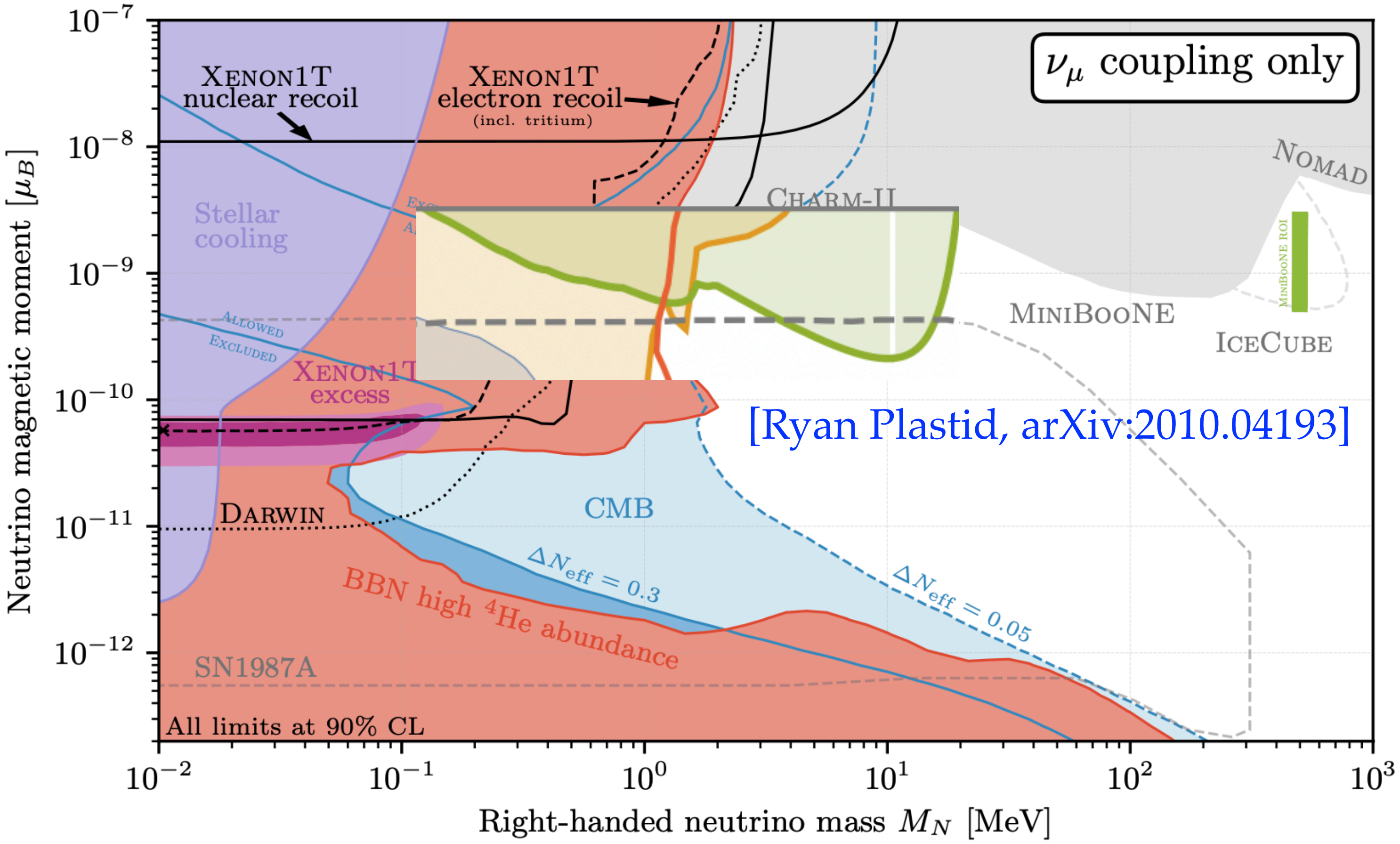
Current Probes: cosmology

CMB, BBN: $N_{\rm eff}$

- Relativistic: $N_{\rm eff}$
- Inject extra photons $N \to \nu\gamma$

$$\tau_N = \frac{16\pi}{\mu_\nu^2 M_N^3}$$
$$= 3760\,\text{sec} \times \left(\frac{1\times 10^{-11}\,\mu_{\rm B}}{\mu_\nu}\right)^2 \left(\frac{\rm MeV}{M_N}\right)^3$$

[Magill, Plestid, Pospelov, Tsai, arXiv:1803.03262]
[Brdar, Greljo, Kopp, Opferkuch, arXiv:2007.15563]



[Ryan Plastid, arXiv:2010.04193]

$$T_{\rm dec} \simeq 1.28\,\text{GeV}\left(\frac{10^{-11}\,\mu_B}{\mu_\nu}\right)^2$$

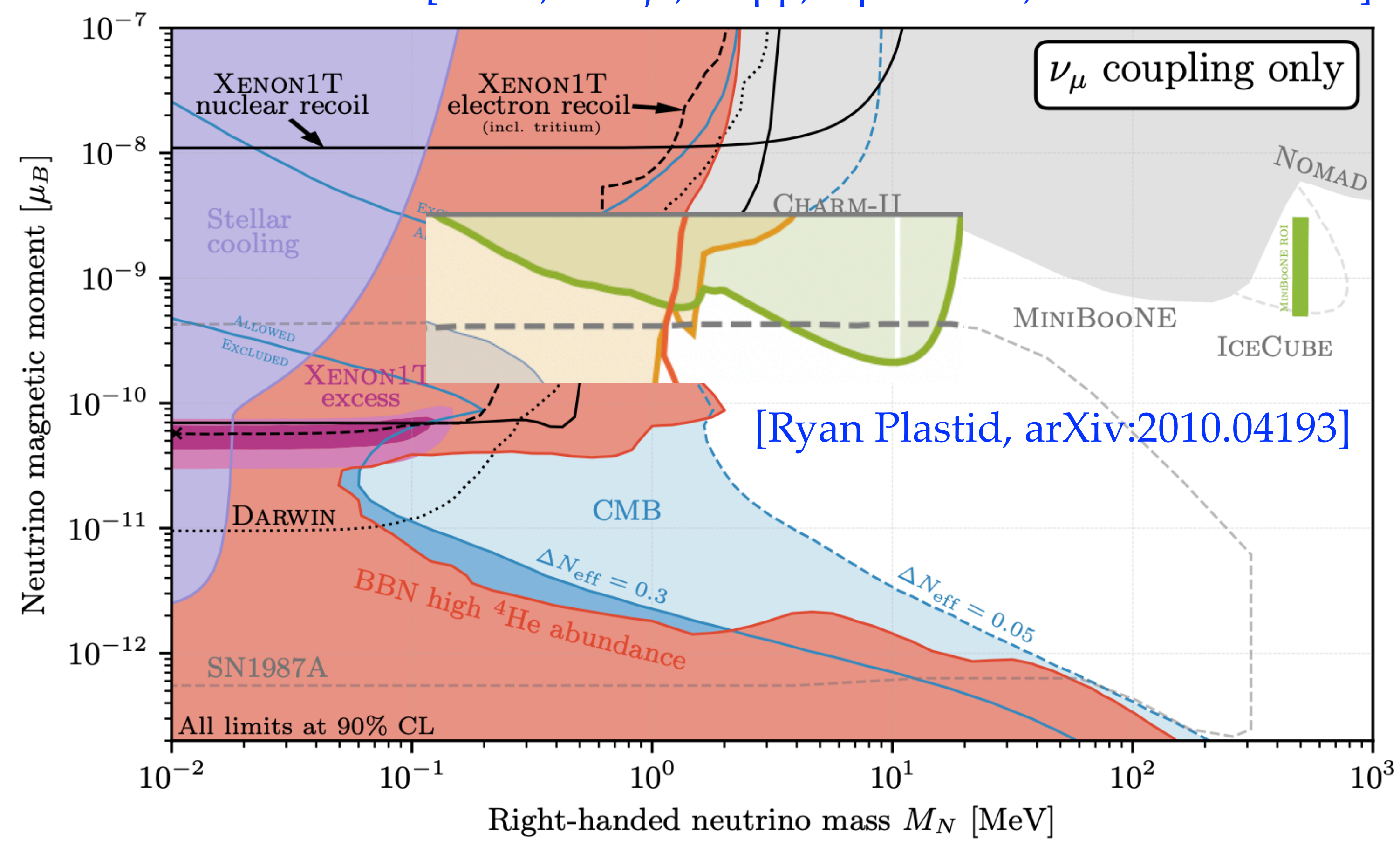
Current Probes: Supernova

10% of energy loss

to sterile neutrino

$$\nu + e^{\pm} \to N + e^{\pm}$$
$$\nu + p \to N + p$$
$$e^{+} + e^{-} \to \overline{\nu} + N$$
$$\gamma + \nu \to N$$

[Magill, Plestid, Pospelov, Tsai, arXiv:1803.03262]
[Brdar, Greljo, Kopp, Opferkuch, arXiv:2007.15563]



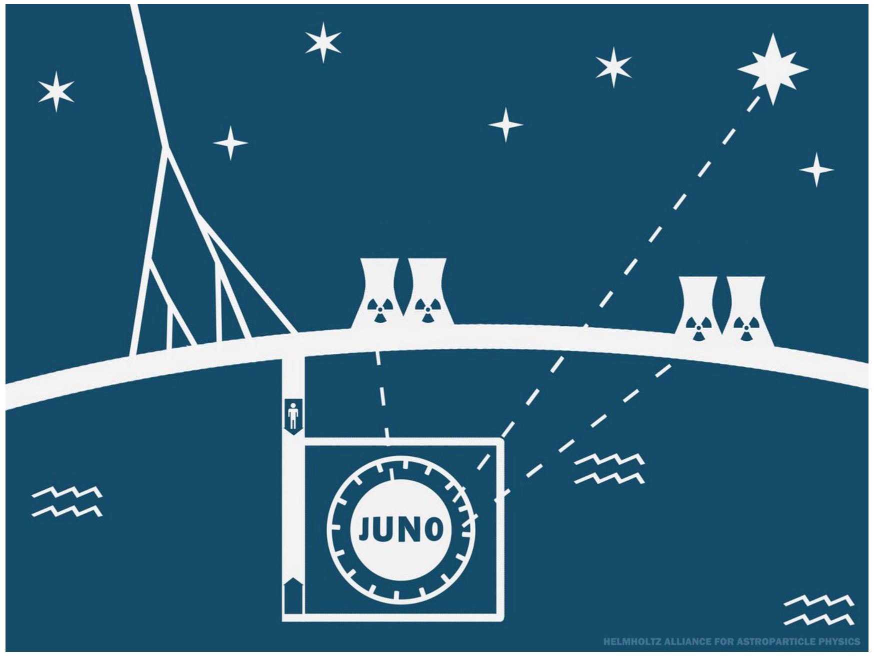
[Ryan Plastid, arXiv:2010.04193]

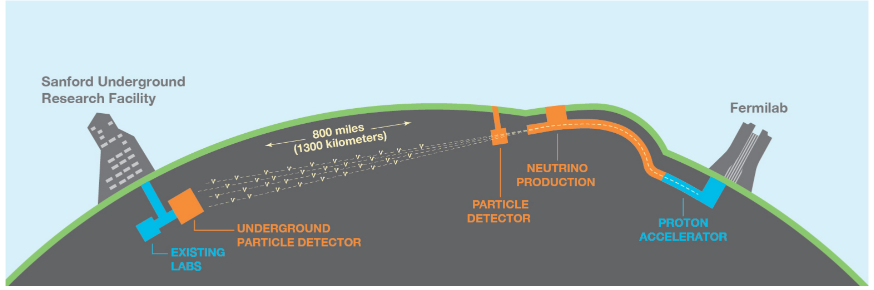
Multi-messenger Signals

$$\nu + e^{\pm} \to N + e^{\pm}$$
$$\nu + p \to N + p$$
$$e^{+} + e^{-} \to \overline{\nu} + N$$
$$\gamma + \nu \to N$$

$$\mathcal{L} \supset \frac{1}{2}\mu_\nu \bar{\nu}_L^\alpha \sigma^{\mu\nu} N F_{\mu\nu}$$

$$N \to \nu + \gamma$$





[V. Brdar, A. de Gouvêa, YYL, P. A. N. Machado, arXiv:2302.10965]

Multi-messenger Signals

[V. Brdar, A. de Gouvêa, YYL, P. A. N. Machado, arXiv:2302.10965]

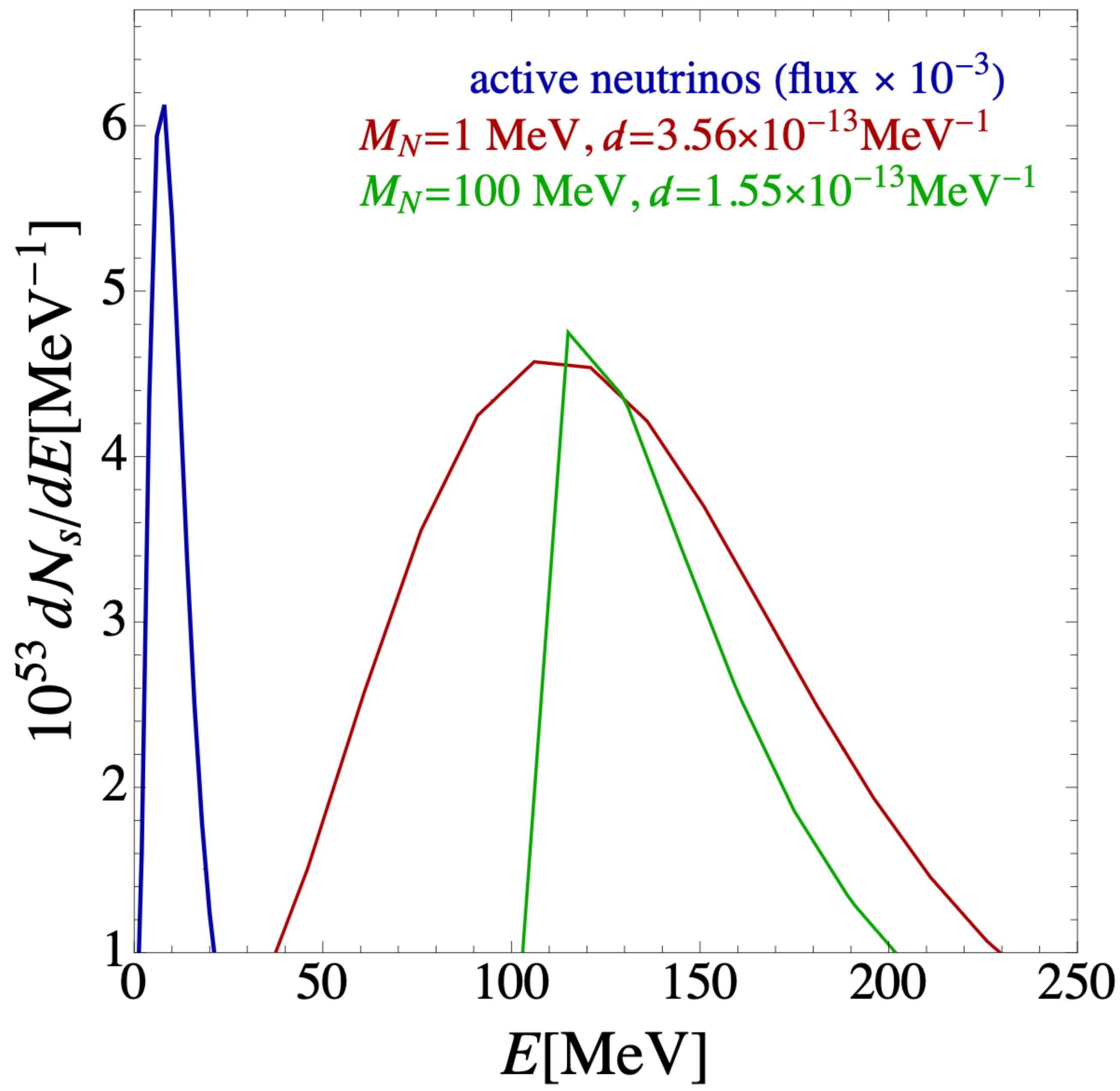
$$\nu + e^{\pm} \to N + e^{\pm}$$

$$\nu + p \to N + p$$

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

$$\gamma + \nu \to N$$

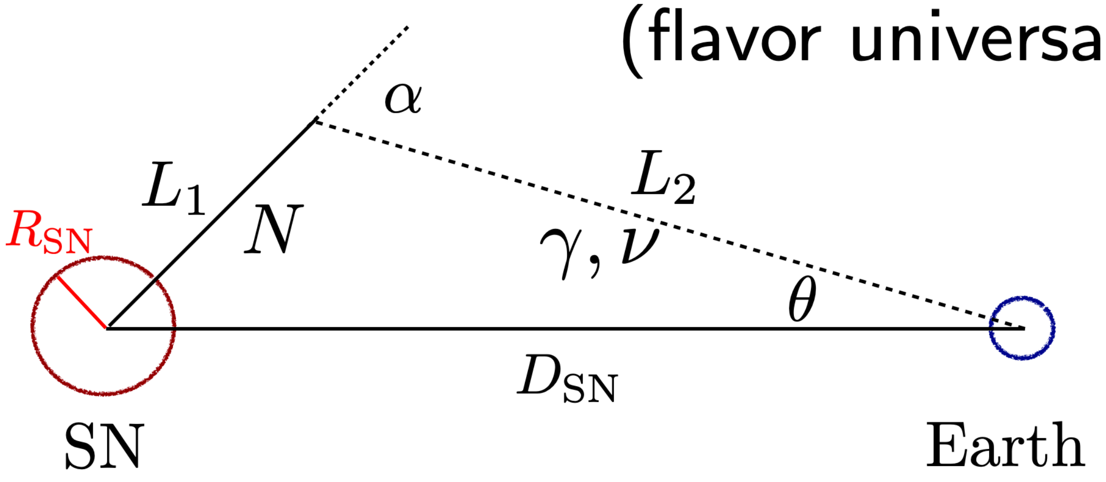
$$\frac{1}{4\pi r^2}\frac{\partial^2}{\partial r \partial t}\left(\frac{d\mathcal{N}_s}{dE_N}\right) = \sigma n_e \frac{dn_\nu}{dE}$$



HNL are produced in a dense T ~ 100 MeV core and leave subsequently the star without further interactions

Multi-messenger Signals

$$\Gamma_N = \frac{6}{4\pi}\,\mu_\nu^2 M_N^3$$
(flavor universal)



$$\cos\alpha = \frac{2E_N E_{\gamma/\nu} - M_N^2}{2E_{\gamma/\nu}\sqrt{E_N^2 - M_N^2}}$$

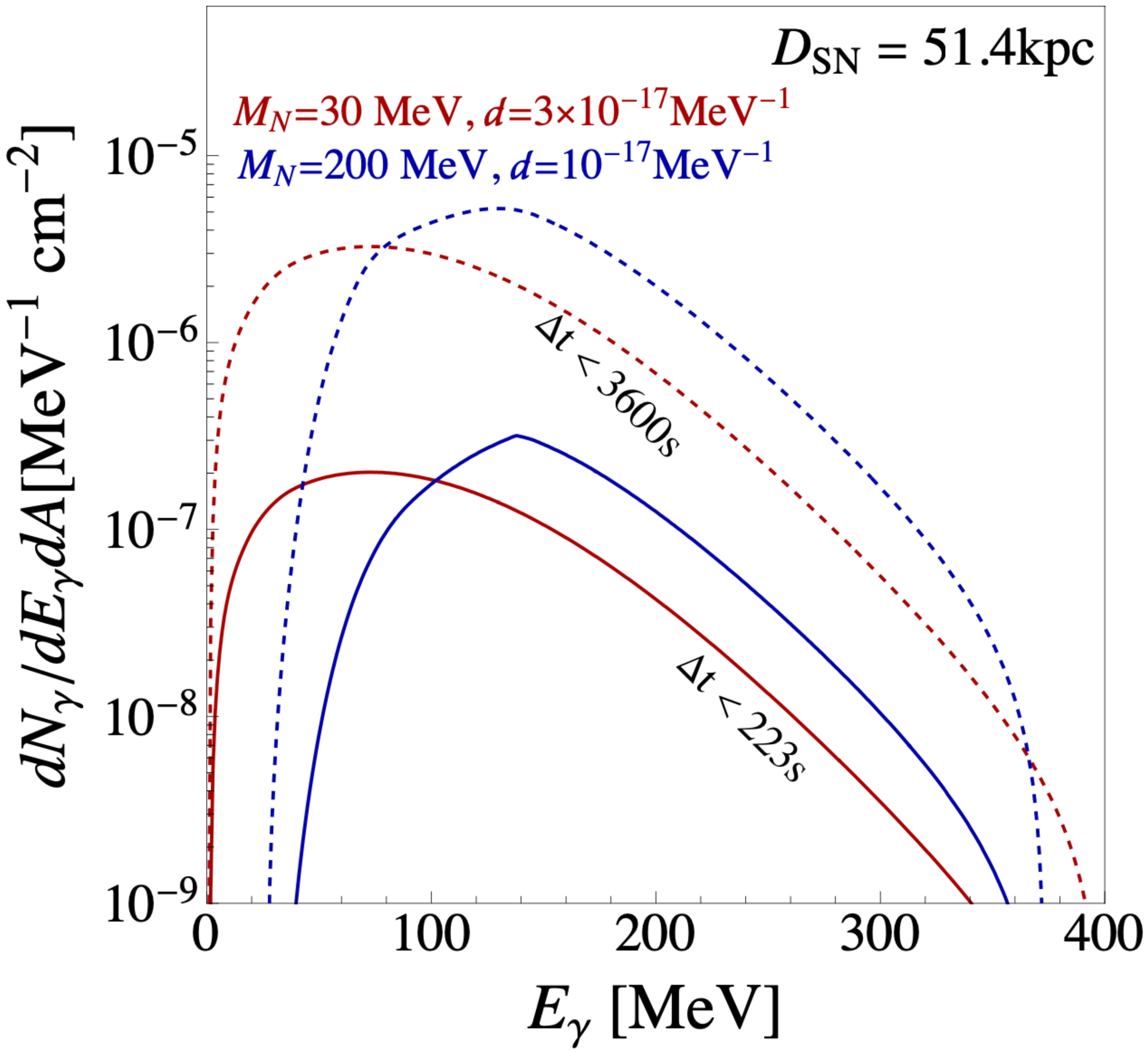
$$\Delta t = L_1/\beta + L_2 - D_{\rm SN}$$

$$\beta = \sqrt{E_N^2 - M_N^2}/E_N$$

$$R_{\rm SN}^{\gamma/\nu} \leq L_1 \leq L_1^{\max}$$

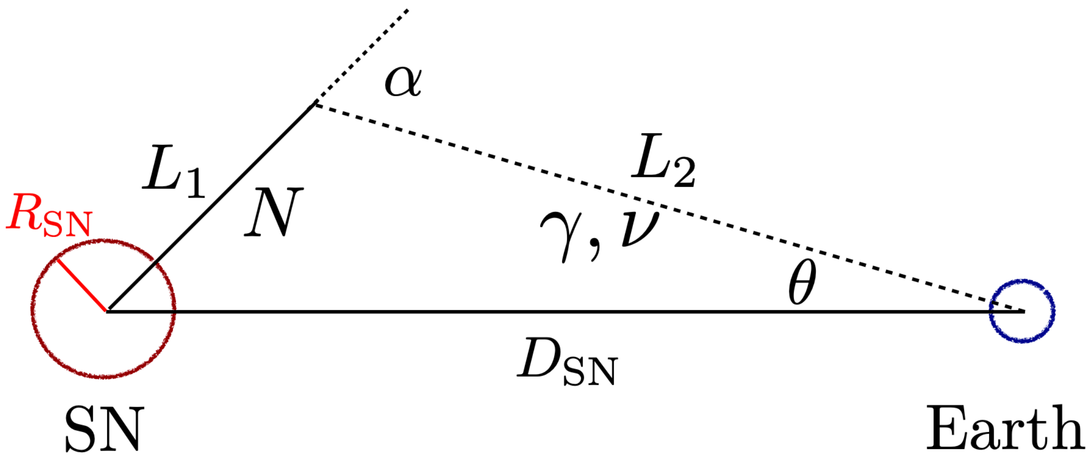
$$R_{\rm SN}^{\gamma} = 3\times 10^{10}\,{\rm m}$$

$$R_{\rm SN}^{\nu} = 30\ {\rm km}$$



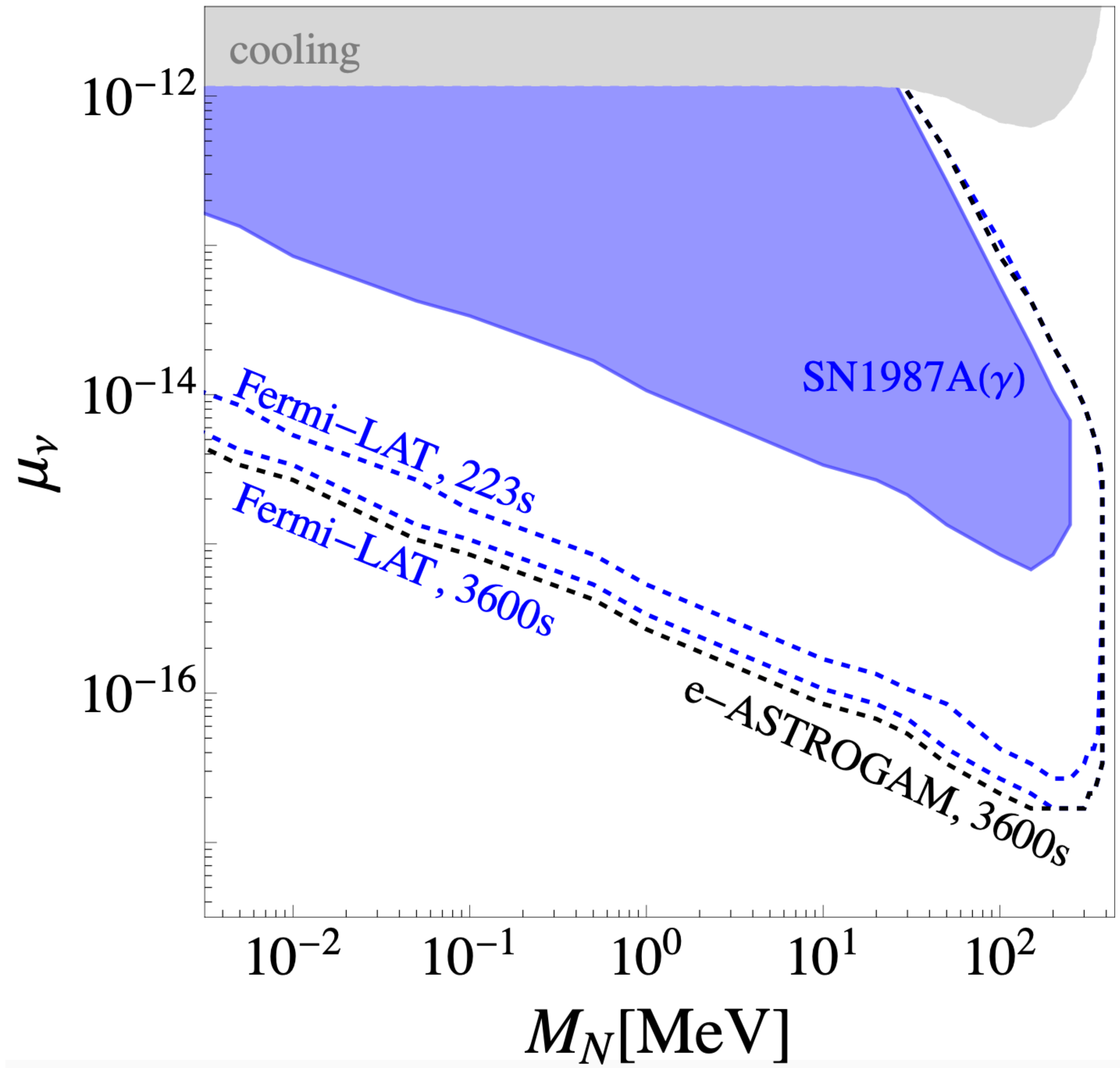
[V. Brdar, A. de Gouvêa, **YYL**, P. A. N. Machado, arXiv:2302.10965]

Multi-messenger Signals : γ − ray detection



- At the time of SN1987A, the Gamma-Ray Spectrometer (GRS) observed Nobs = 1393 photons with energy 25-100 MeV at $\Delta t < 223s$

- Assuming a SN event happens in the galaxy at a distance of D_SN = 10kpc,
  Fermi-LAT: $E_\gamma > 100\text{MeV}, \theta < 5^\circ$
  e-ASTROGAM: $E_\gamma > 1\text{MeV}, \theta < 1.25^\circ$

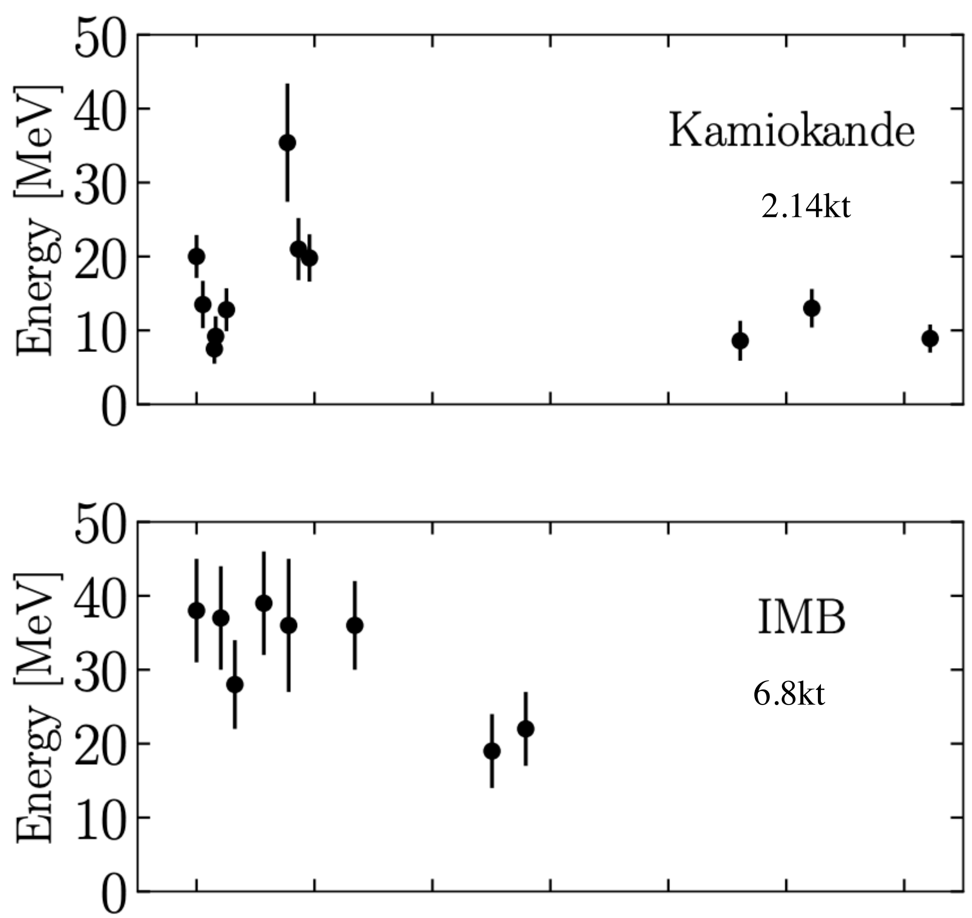


[V. Brdar, A. de Gouvêa, **YYL**, P. A. N. Machado, arXiv:2302.10965]

Multi-messenger Signals : neutrino detection

SN1987A, neutrino events

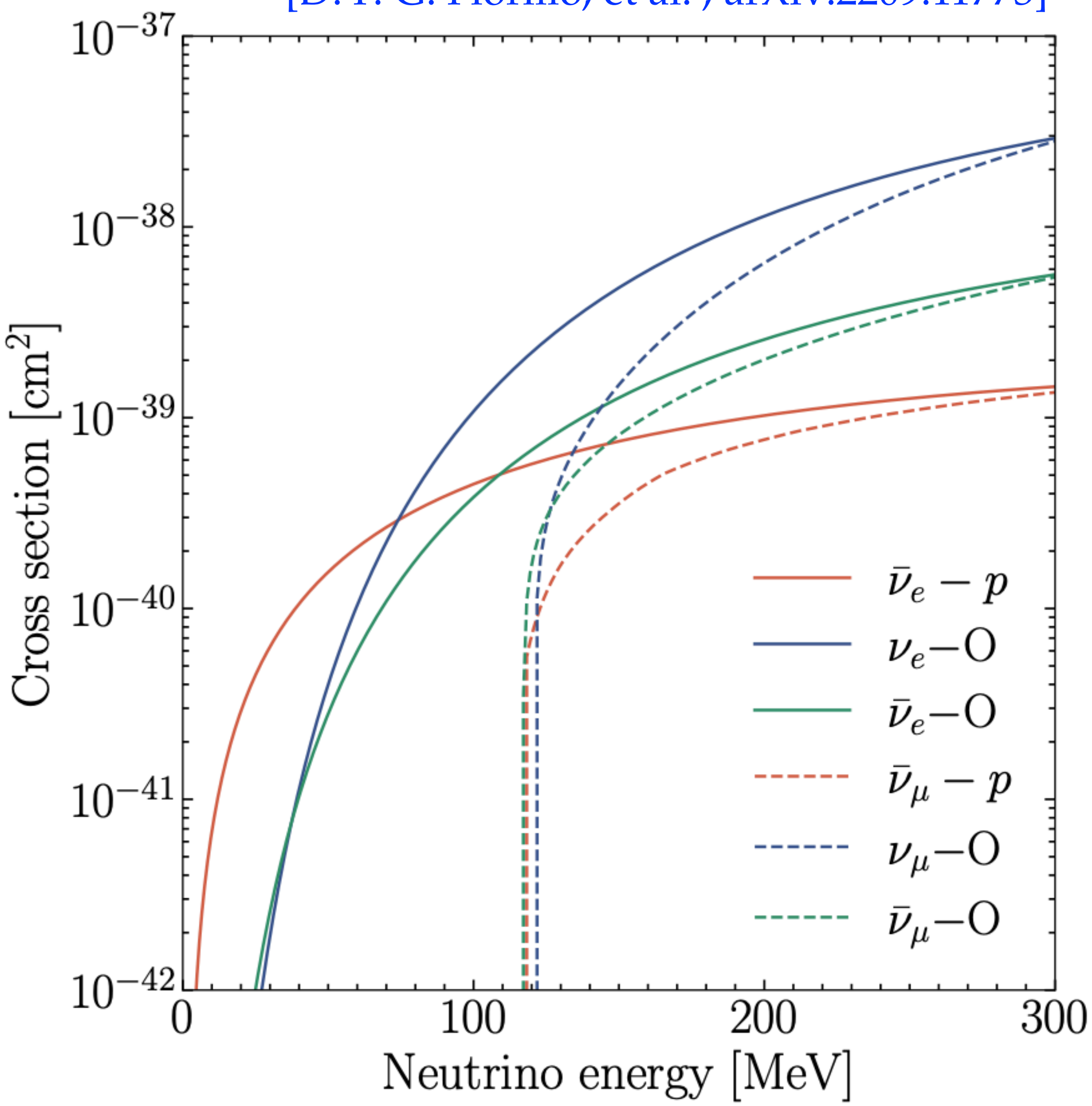
water-Cherenkov detectors



- No significant excess was observed by Kamiokande-II and IMB for $E_\nu > 50\text{MeV}, \Delta t < 2$ days

$$N_\nu^{\rm BSM} = N_{\rm tgt} \int dE_\nu \frac{dN_\nu}{dE_\nu dA}(E_\nu)\, \sigma_{\rm IBD}(E_\nu)\, \varepsilon(E_\nu)$$

[D. F. G. Fiorillo, et al. , arXiv:2209.11773]



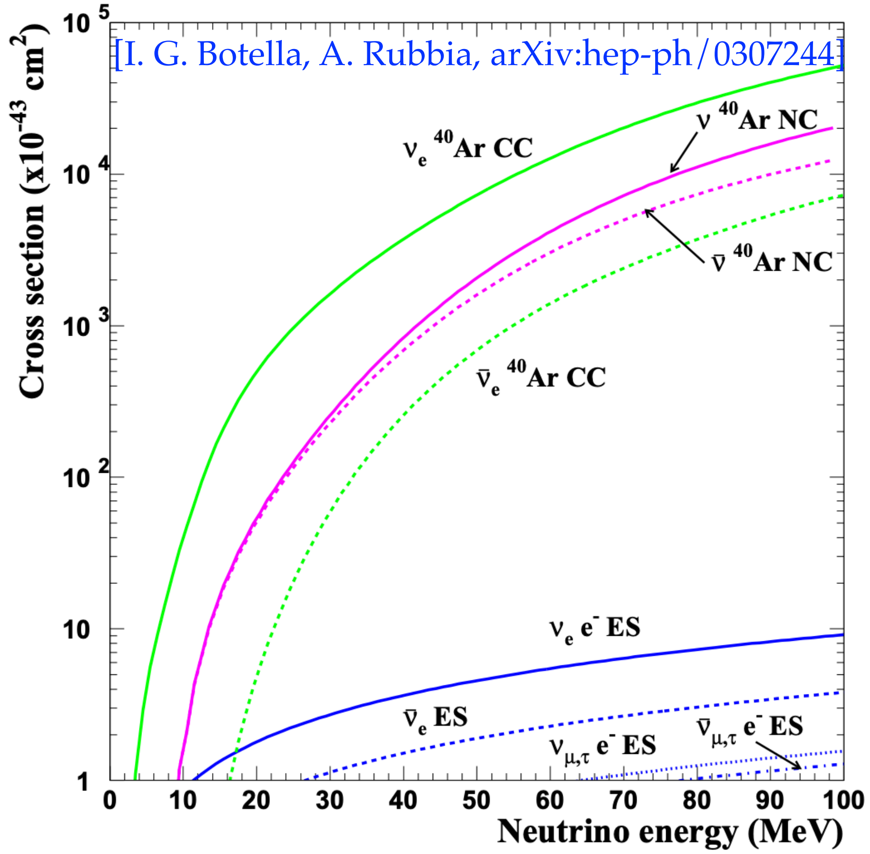
Multi-messenger Signals : neutrino detection

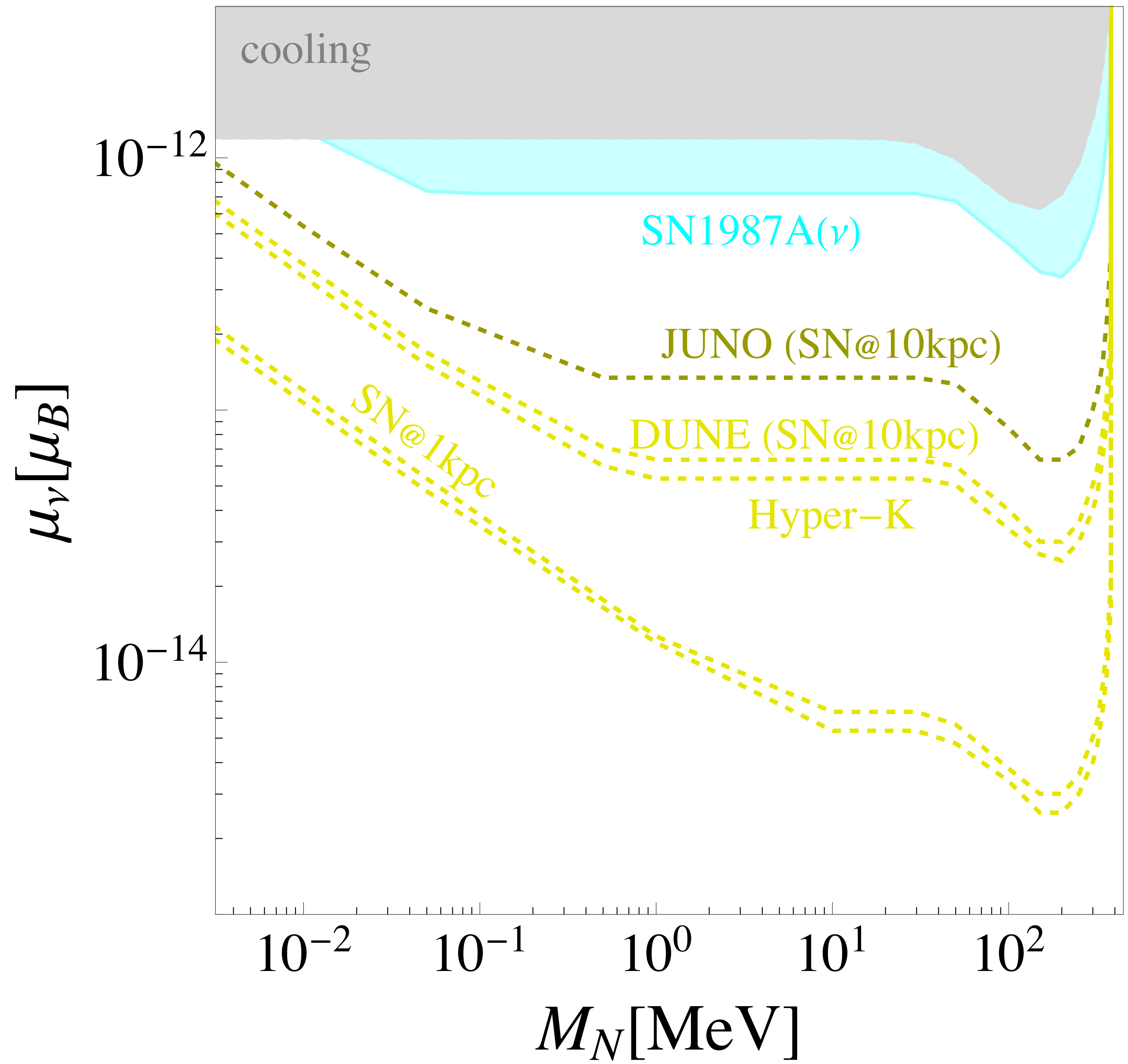
- Assuming a SN event happens in the galaxy at a distance of D_SN = 10kpc,

  JUNO: 20kt fiducial volume, liquid scintillator detector

  DUNE: 40kt, liquid argon

  Hyper-K: 188kt fiducial volume water Cherenkov



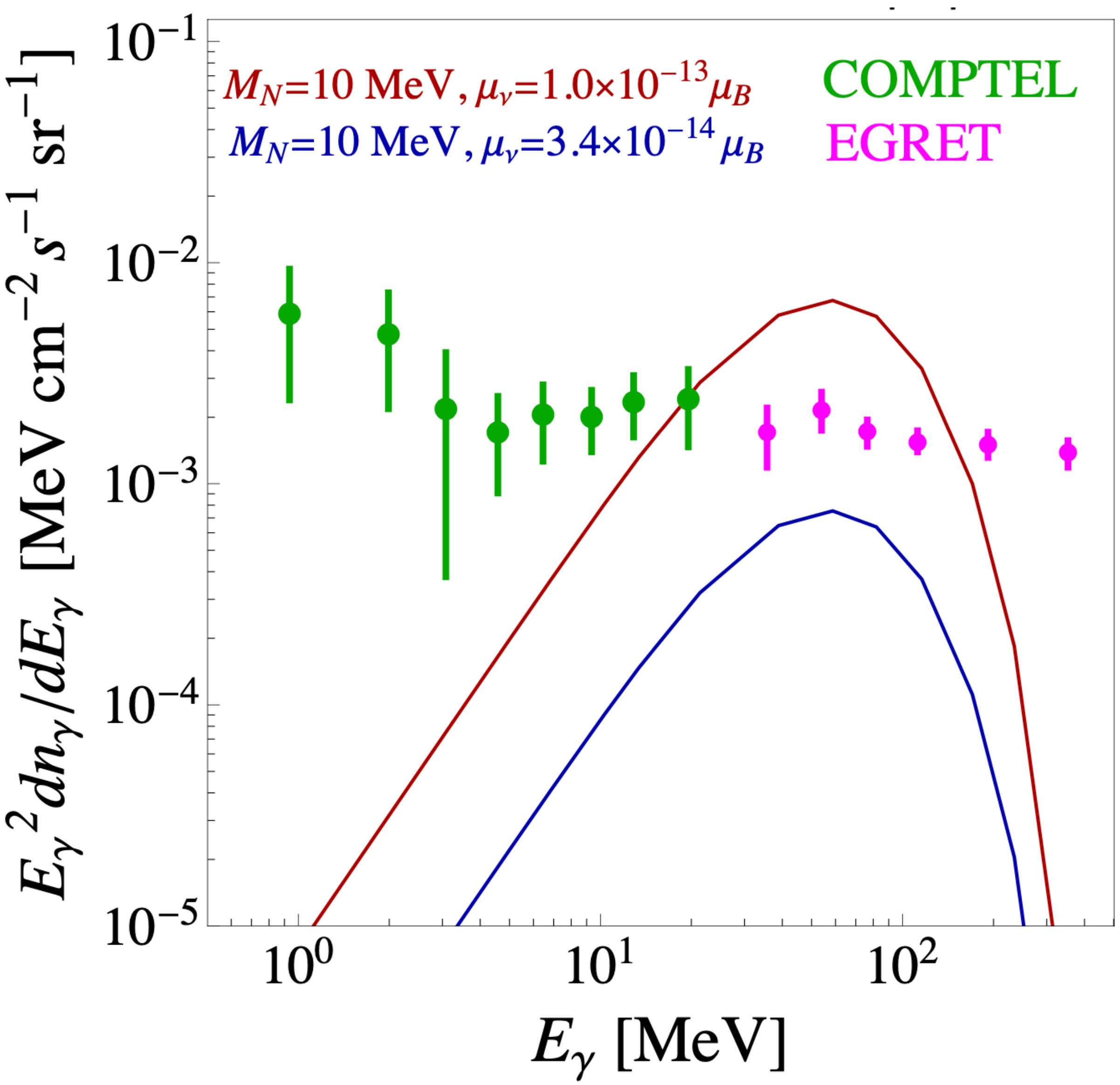


[V. Brdar, A. de Gouvêa, **YYL**, P. A. N. Machado, arXiv:2302.10965]

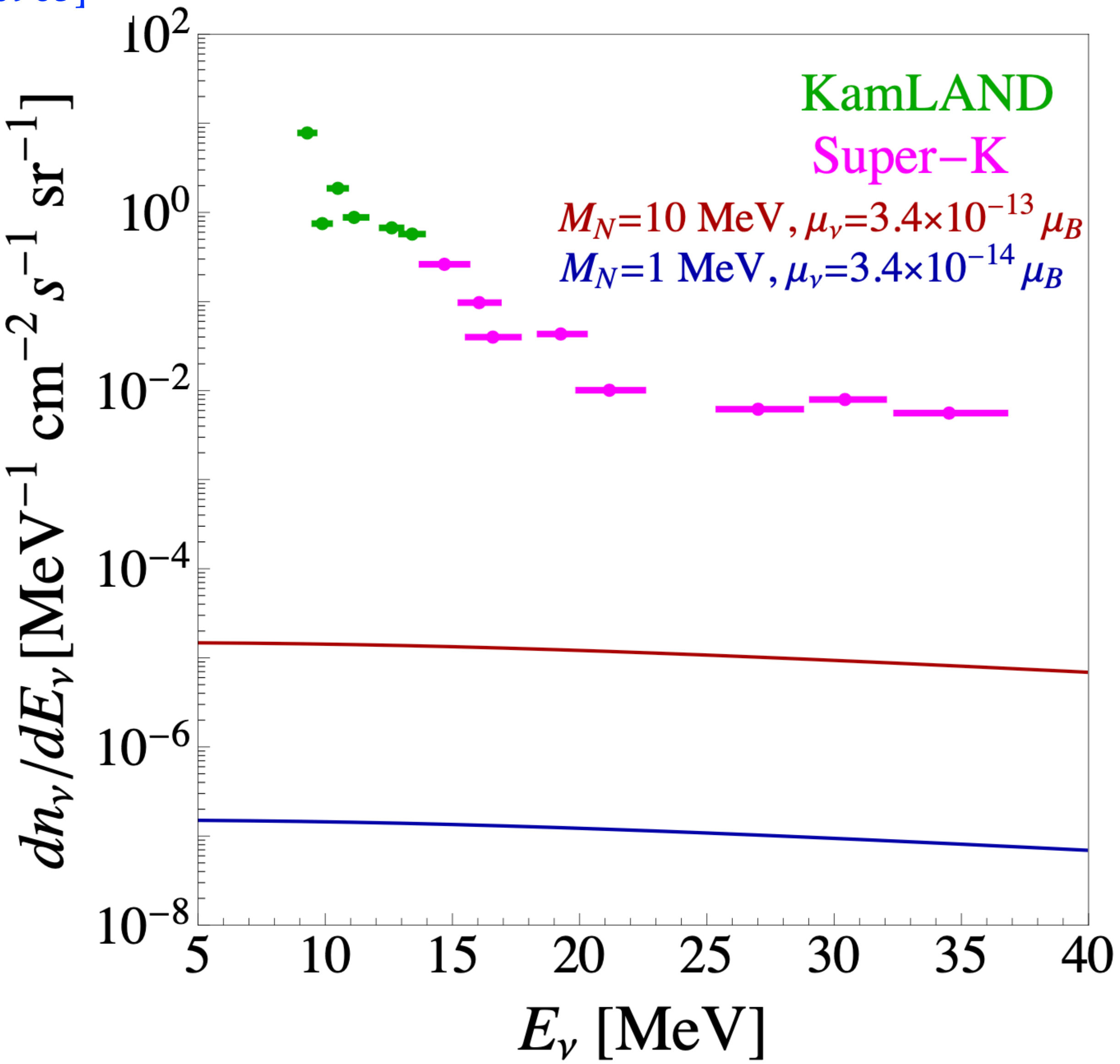
Multi-messenger Signals : diffused BSM Photon and neutrino background

$$\frac{dn_N}{dE} = \frac{c}{4\pi}\int_0^\infty dz(1+z)\, n'_{cc}(z)\,\frac{d\mathcal{N}_s}{dE}(E_z)$$

[V. Brdar, A. de Gouvêa, **YYL**, P. A. N. Machado, arXiv:2302.10965]



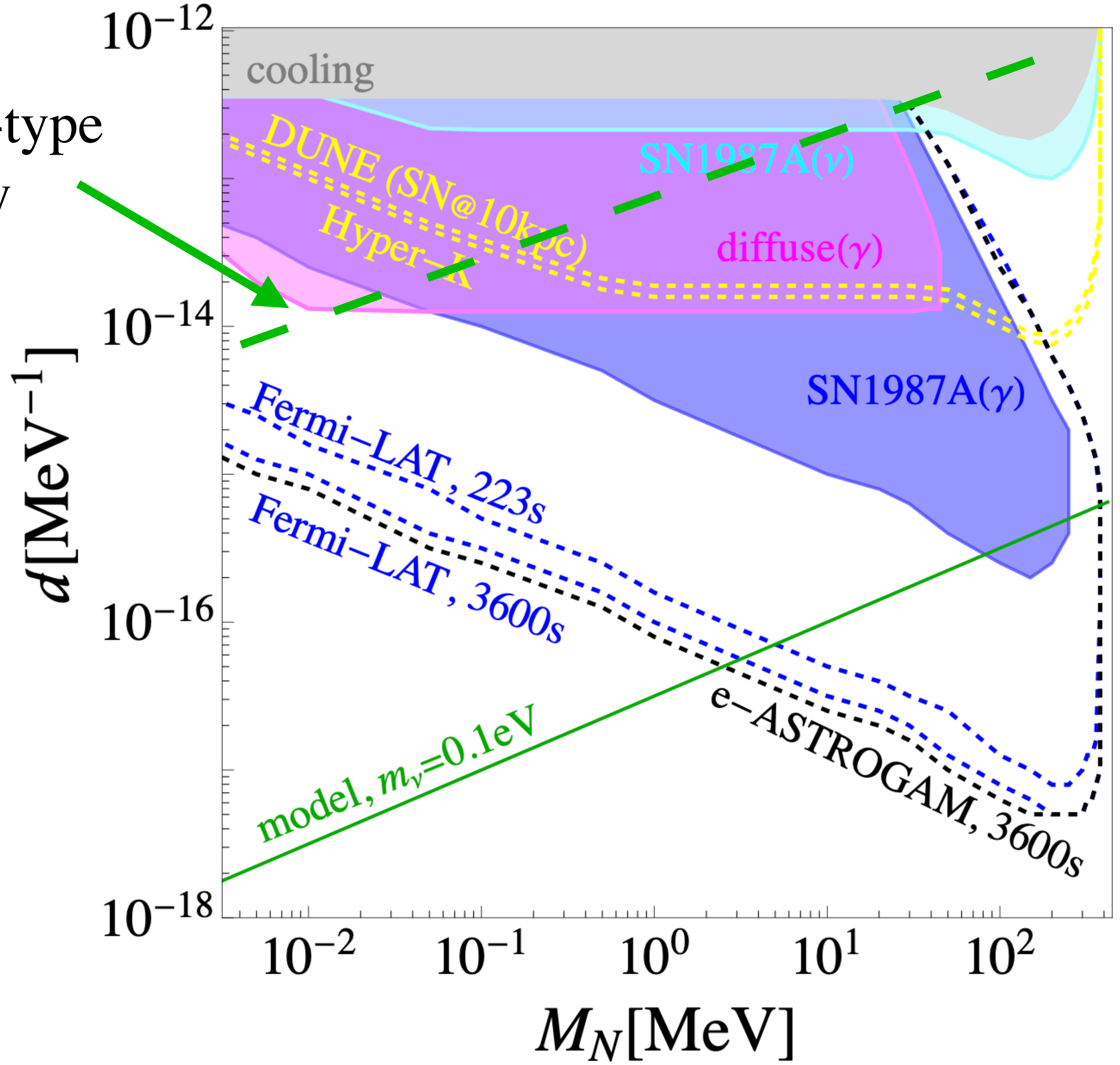
extragalactic background light



Multi-messenger Signals : diffused BSM Photon and neutrino background

$$\mathcal{L} \supset \frac{1}{2}\mu_\nu \bar{\nu}_L^\alpha \sigma^{\mu\nu} N F_{\mu\nu}$$

Voloshin-type symmetry



[V. Brdar, A. de Gouvêa, **YYL**, P. A. N. Machado, arXiv:2302.10965]

Left - Right symmetric model

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$
$$\rightarrow SU(2)_L \times U(1)_Y \rightarrow U(1)_Q$$

$$\begin{pmatrix} W_L^\pm \\ W_R^\pm \end{pmatrix} = \begin{pmatrix} \cos\zeta & -\sin\zeta \\ \sin\zeta & \cos\zeta \end{pmatrix} \begin{pmatrix} W_1^\pm \\ W_2^\pm \end{pmatrix}$$

$$Q_L^i\left(\tfrac{1}{2},0,\tfrac{1}{3}\right): \begin{pmatrix} u_L \\ d_L \end{pmatrix}^\alpha, \quad \begin{pmatrix} c_L \\ s_L \end{pmatrix}^\alpha, \quad \begin{pmatrix} t_L \\ b_L \end{pmatrix}^\alpha$$

$$Q_R^i\left(0,\tfrac{1}{2},\tfrac{1}{3}\right): \begin{pmatrix} u_R \\ d_R \end{pmatrix}^\alpha, \quad \begin{pmatrix} c_R \\ s_R \end{pmatrix}^\alpha, \quad \begin{pmatrix} t_R \\ b_R \end{pmatrix}^\alpha$$

$$\Psi_L^a\left(\tfrac{1}{2},0,-1\right): \begin{pmatrix} \nu_{eL} \\ e_L^- \end{pmatrix}, \quad \begin{pmatrix} \nu_{\mu L} \\ \mu_L^- \end{pmatrix}, \quad \begin{pmatrix} \nu_{\tau L} \\ \tau_L^- \end{pmatrix},$$

$$\Psi_R^a\left(0,\tfrac{1}{2},-1\right): \begin{pmatrix} N_{eR} \\ e_R^- \end{pmatrix}, \quad \begin{pmatrix} N_{\mu R} \\ \mu_R^- \end{pmatrix}, \quad \begin{pmatrix} N_{\tau R} \\ \tau_R^- \end{pmatrix}$$

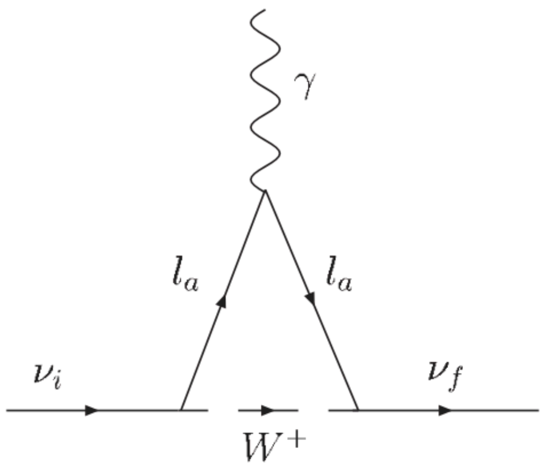
bi-doublet

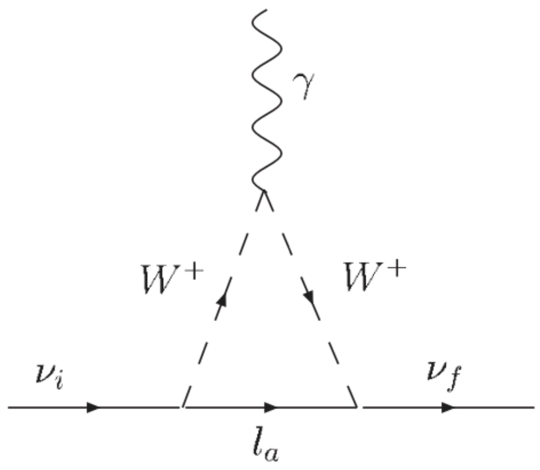
$$\mathscr{L}^L_{\text{Yukawa}} = \{\overline{L}_{Li}(h_{ij}\phi + \tilde{h}_{ij}\tilde{\phi})L_{Rj} + \text{h.c.}\}$$
$$+ \{\overline{L}^c_{Ri}(h_M)_{ij}\Sigma_L L_{Lj} + \overline{L}^c_{Li}(h_M)_{ij}\Sigma_R L_{Rj} + \text{h.c.}\}$$

triplet

type-II seesaw dominance

$$U = \begin{pmatrix} U_L & 0_{3\times3} \\ 0_{3\times3} & U_R^* \end{pmatrix}$$

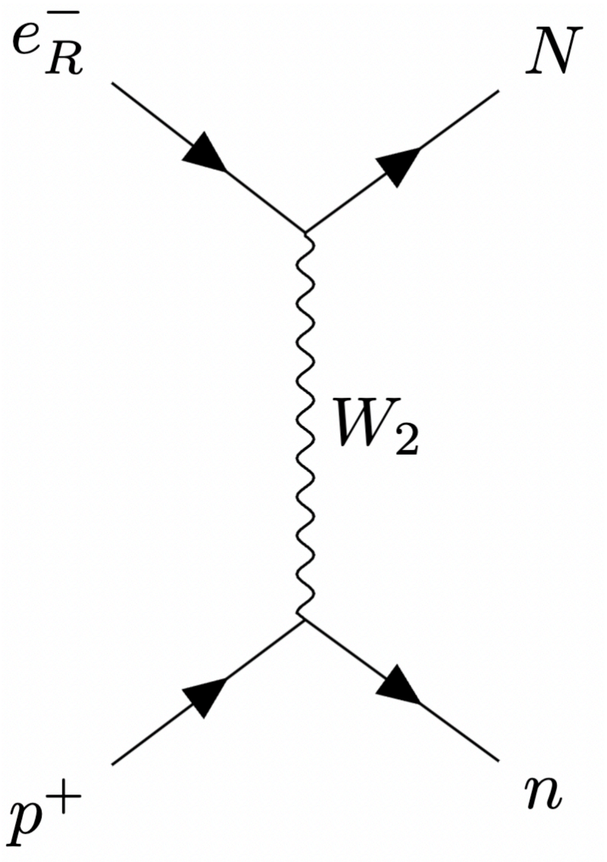




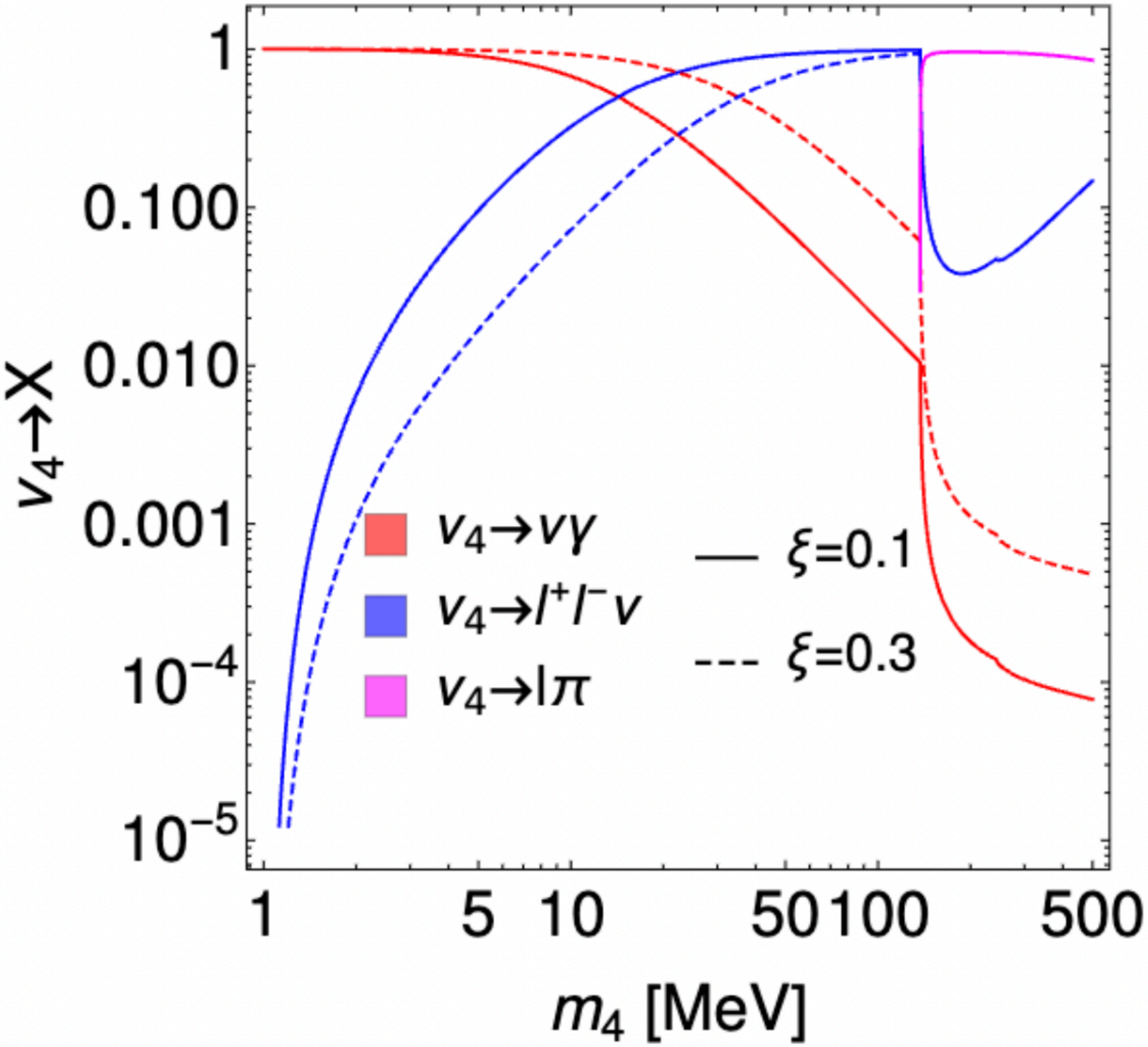
$$\mu_{ji} = \frac{eG_F}{2\sqrt{2}\pi^2}\sin 2\zeta \sum_{\alpha=1}^{3} m_{\ell\alpha}\,\text{Im}\left[(PU^*)_{\alpha j}(P_s U^*)_{\alpha i}\right]$$

Left - Right symmetric model

Tree level production in SN



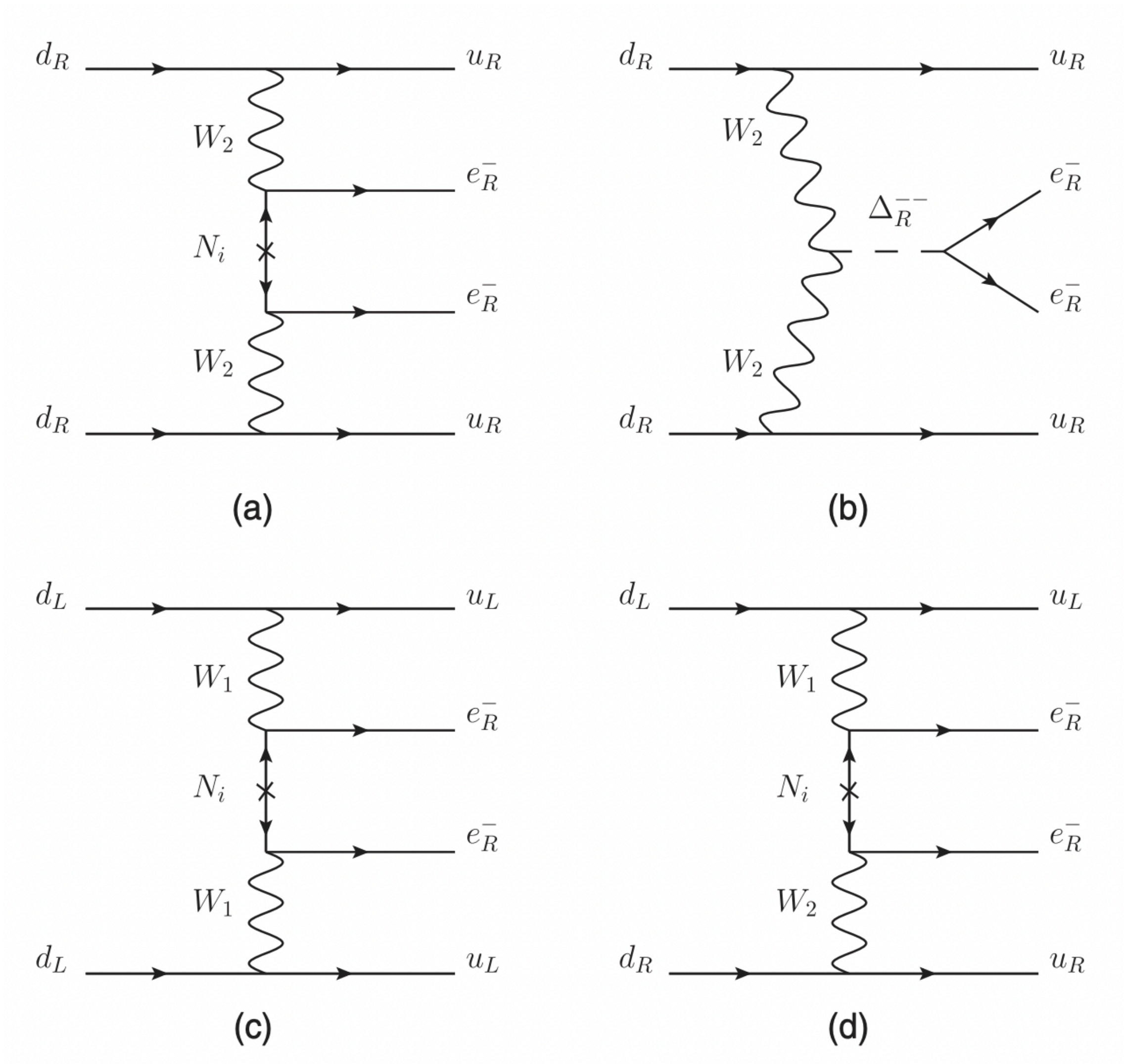
including three-body decay channel



[G. Li, **YYL**, Y.-L. Zhou, in preparation]

Left - Right symmetric model

Majorana Case

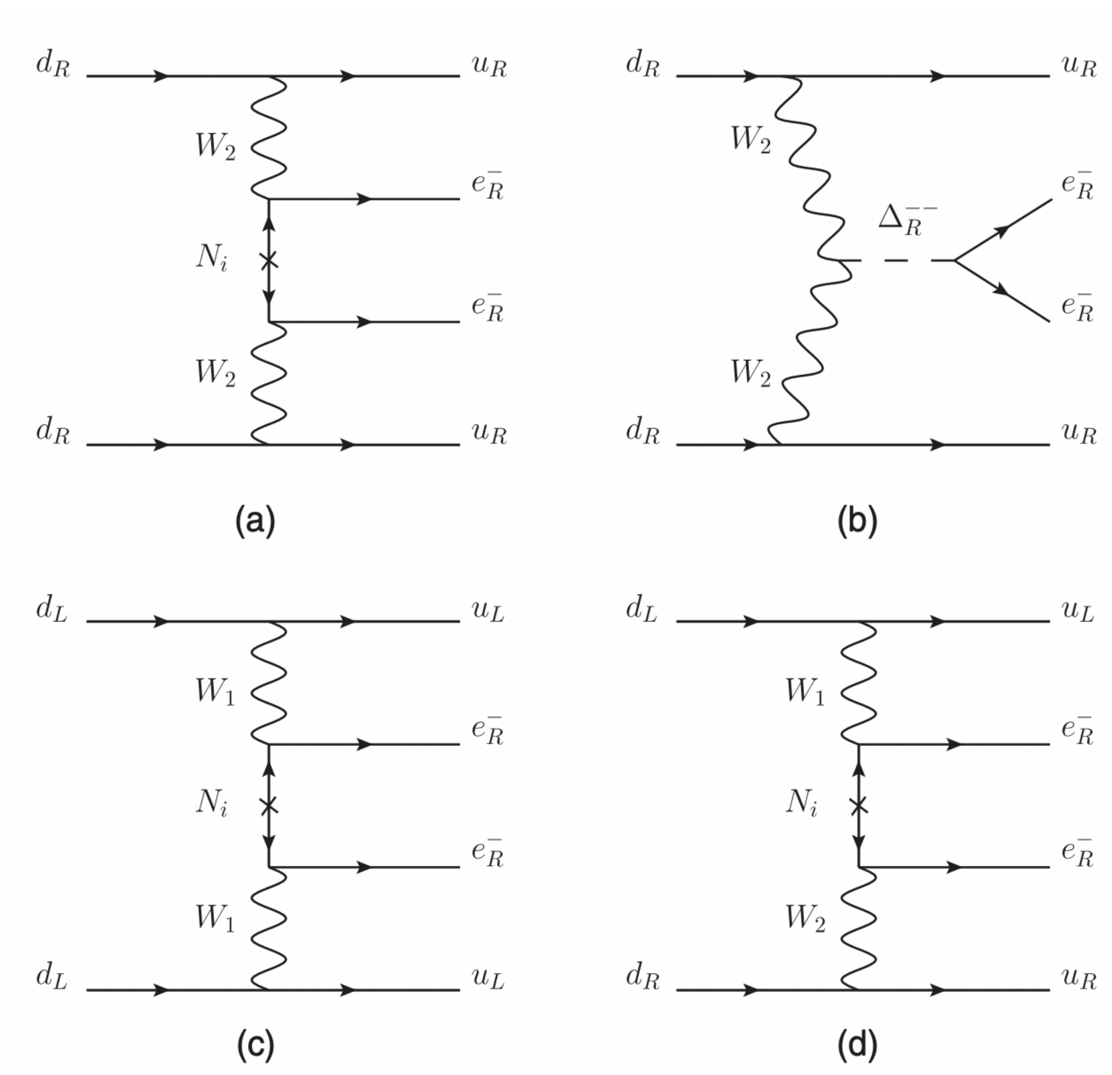


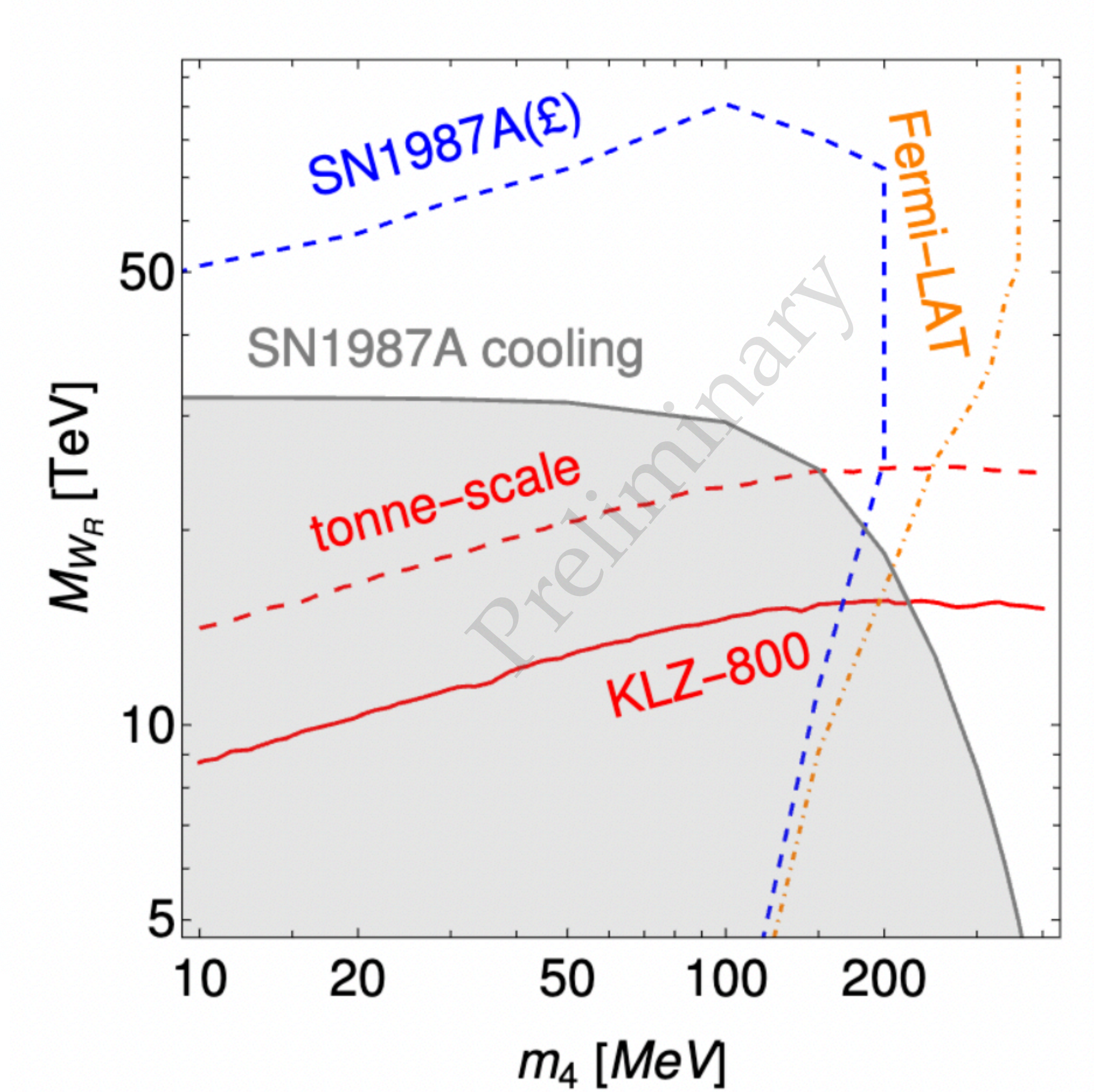
next generation of 0νββ decay searches with ton-scale detectors

[G. Li et al., arXiv:2009.01257]

Left - Right symmetric model

Majorana Case





next generation of 0νββ decay searches with ton-scale detectors

[G. Li et al., arXiv:2009.01257]

[G. Li, **YYL**, Y.-L. Zhou, in preparation]

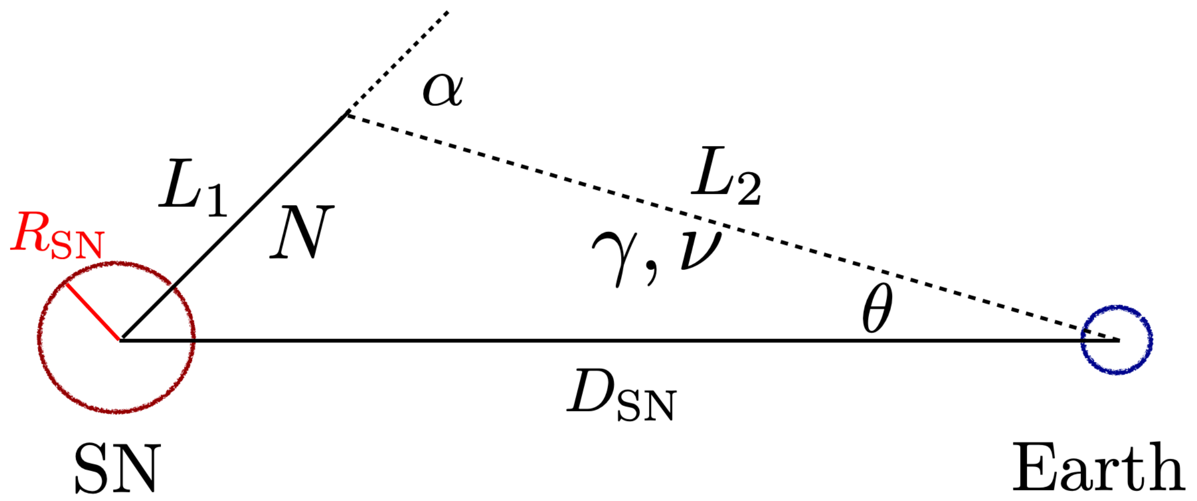
Conclusion

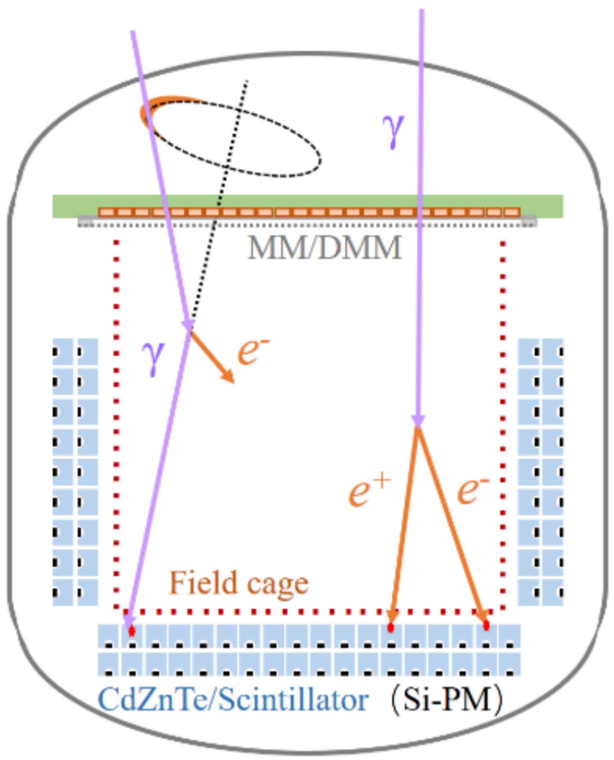
Multi-messenger Signals: Photon + Neutrino

Neutrino Timing Information

Outlooks

photon polarization





CP violation in neutral lepton transition dipole moment?

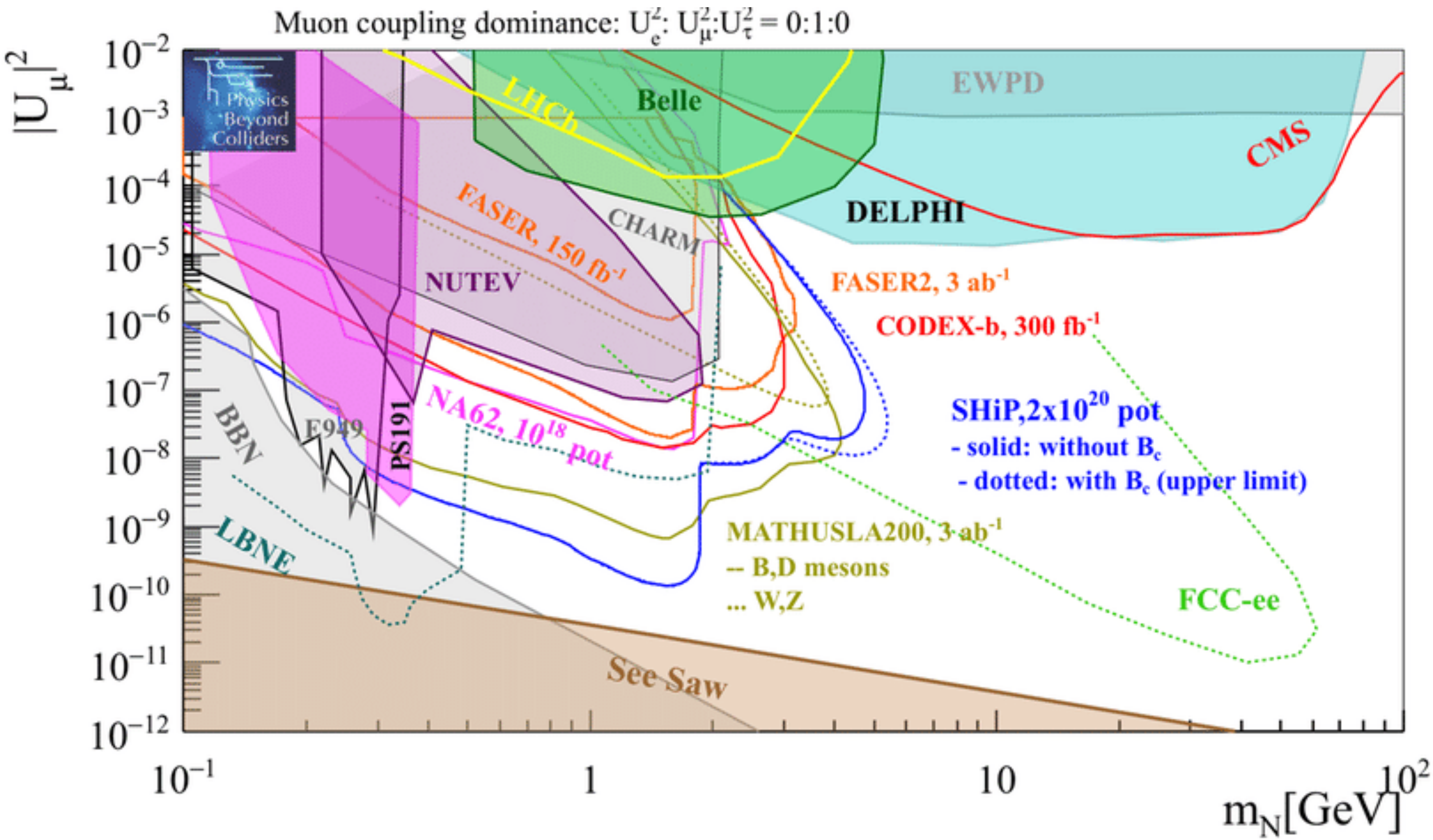
Photon signals from sterile neutrino decay or axion decay?

DSEL
DEEP SPACE EXPLORATION LAB
深空探测实验室

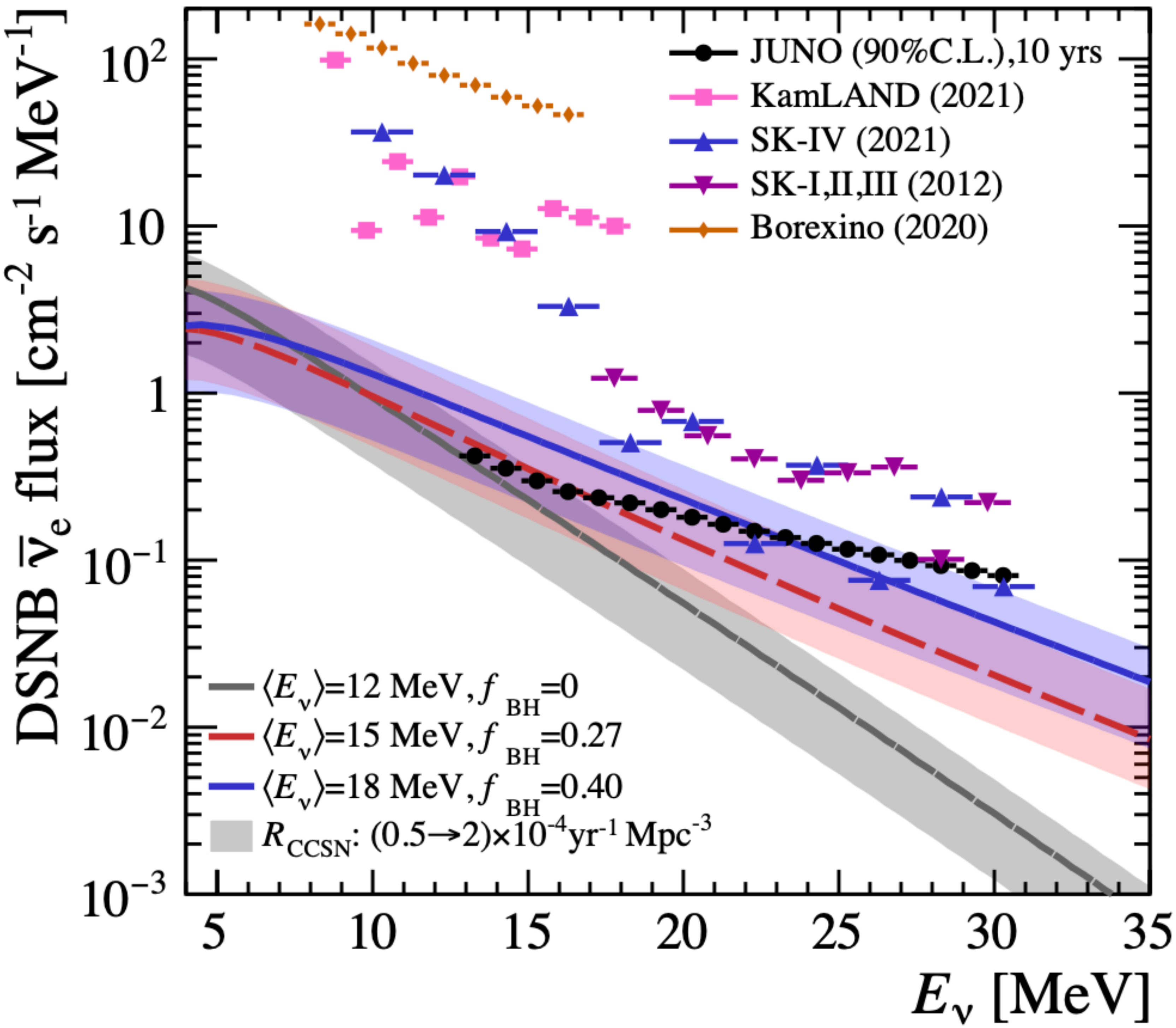
Thank you

BACK UP

[J. Beacham, arXiv:1901.09966]



Multimessenger Signals : diffused BSM Photon and neutrino background



[A. Abusleme, arXiv:2205.08830]