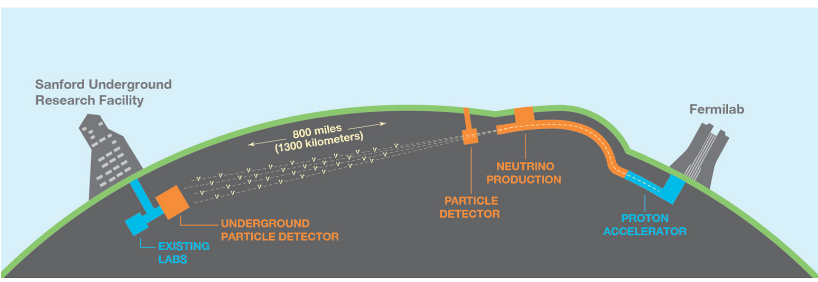
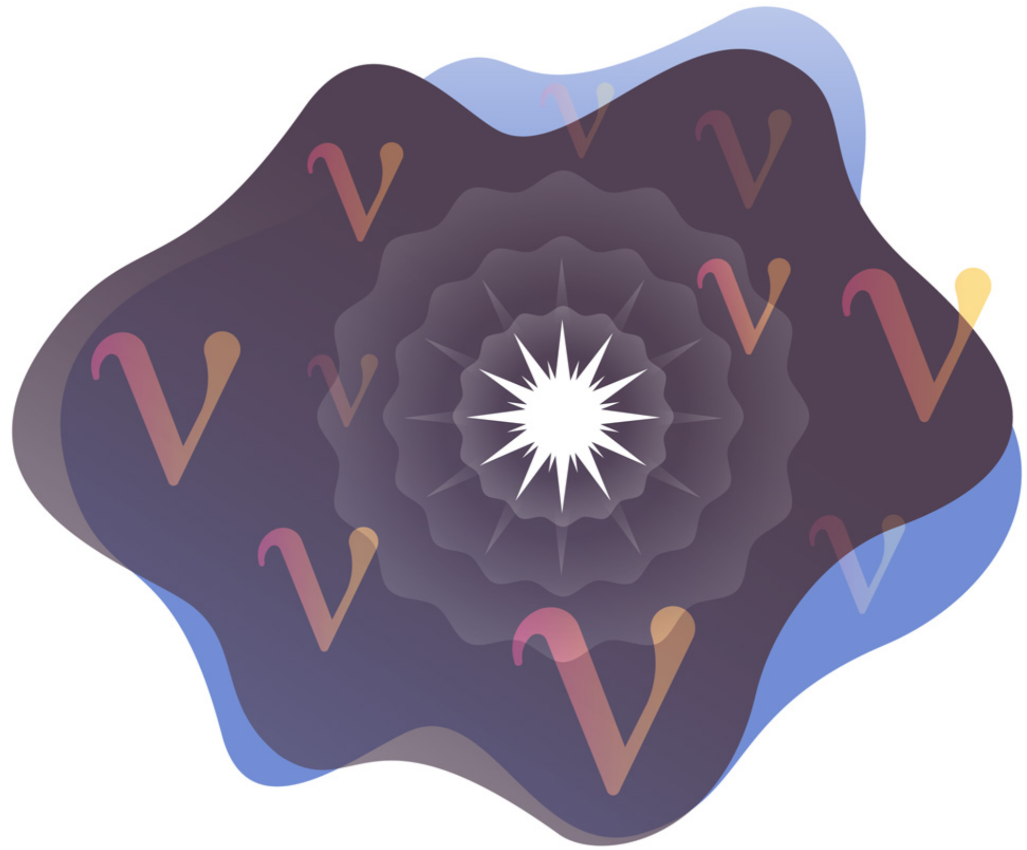



中国科学技术大学 University of Science and Technology of China

*Ying-Ying Li* (李英英)

arXiv: 2302.10965, 2211.02028
in collaboration with
Vedran Brdar, Andr´e de Gouvˆea
and Pedro A. N. Machado

# Neutrino magnetic moment portal and supernova:

## new constraints and multi_messenger opportunities

***July 7, 2023 WIN2023***

# Heavy Neutral Lepton - Sterile Neutrino

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

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

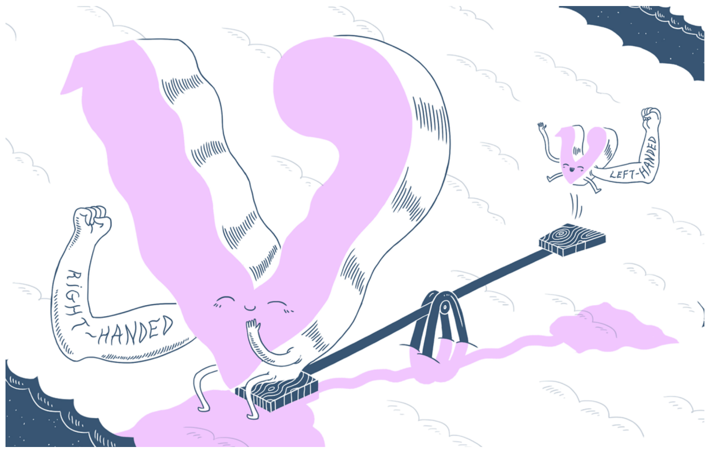
Neutrino mass:

type-I seesaw

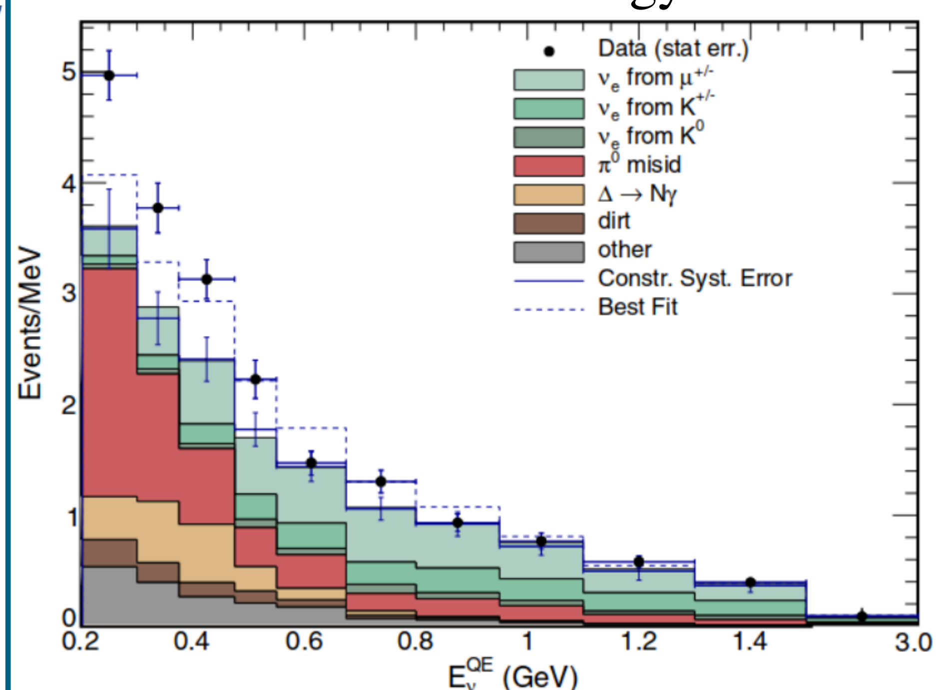
mechanism

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

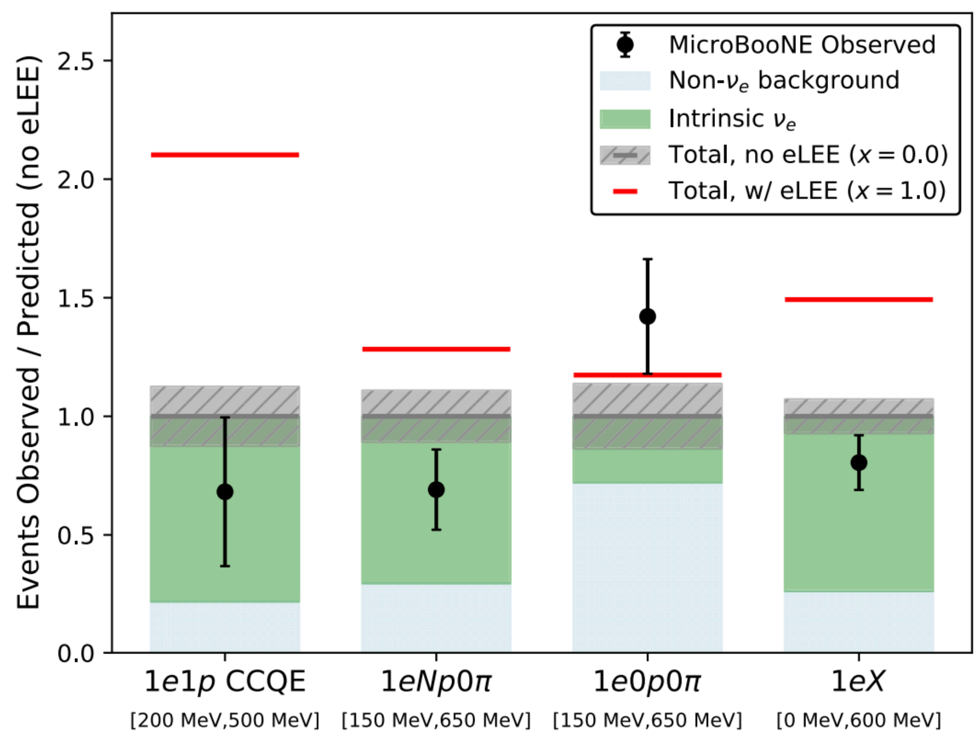
$$m_\nu = -M_D M_R^{-1} M_D^T$$




MiniBooNE low energy excess

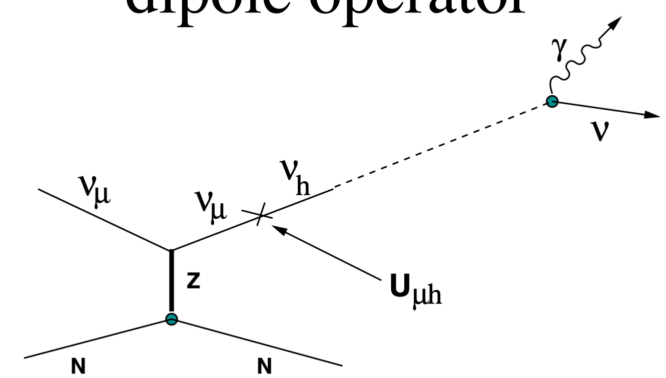



[PRL 128, 241801 (2022)]




Via mixing and

dipole operator



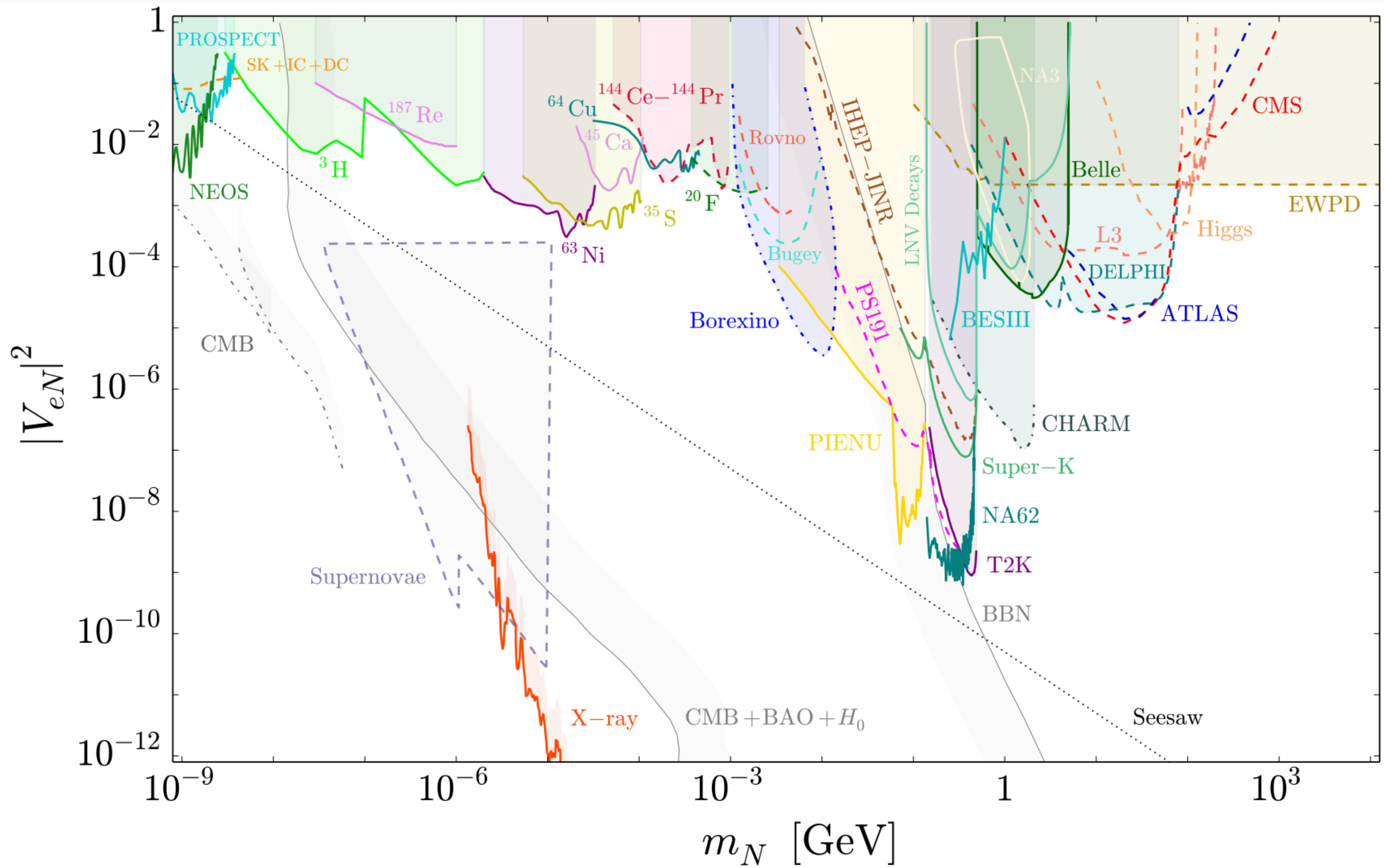

$$\theta^2 \sim 10^{-3}$$

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

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

# Heavy Neutral Lepton - Mixing Portal

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



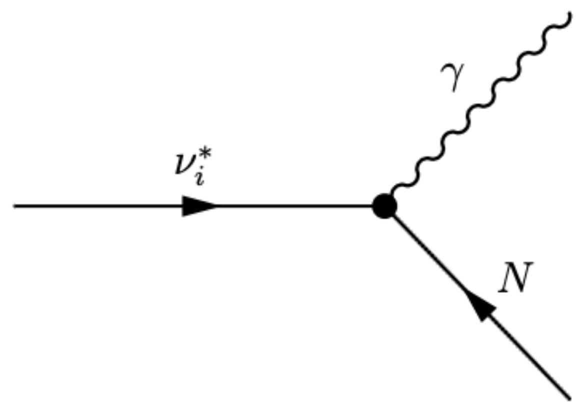

[P. D. Bolton, F. F. Deppisch, P. S. B. Dev, arXiv: 1912.03058]

# Heavy Neutral Lepton - Dipole Portal

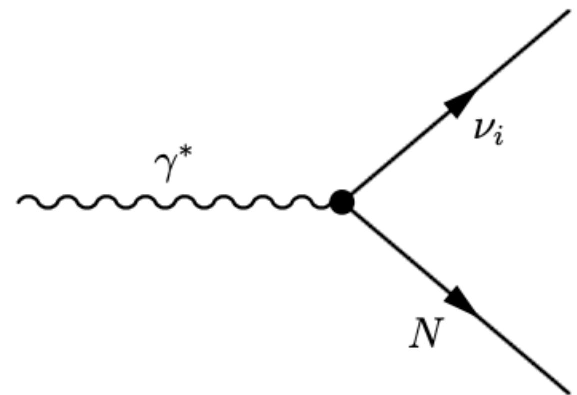
When the mixing effect is subdominant, …

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

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

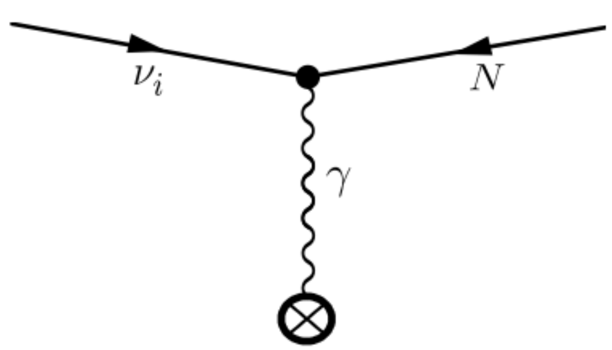



(a) Weak meson decays

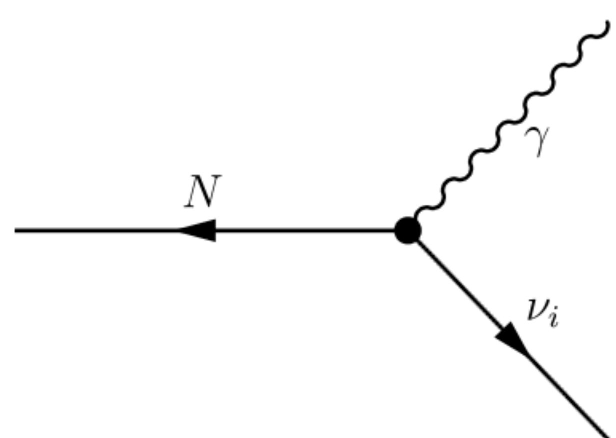



(b) Dalitz-like decay

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




(c) Primakoff upscattering




(d) $N \to \gamma\nu$ (signal)

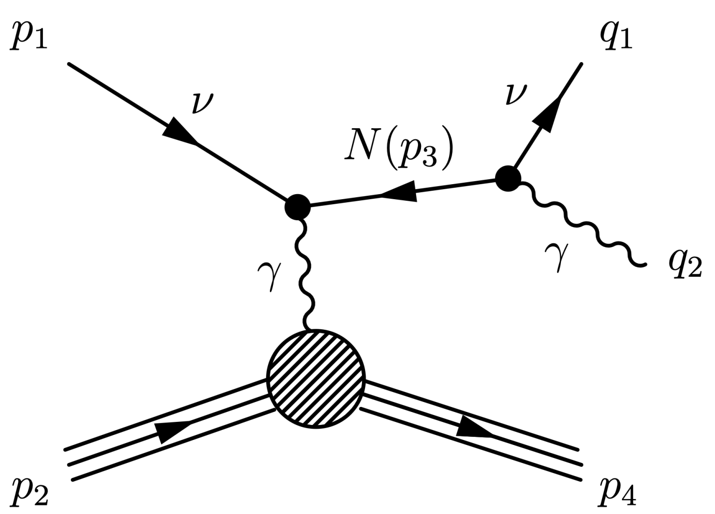
$$\Gamma_N = \frac{6}{4\pi}\mu_\nu^2 M_N^3$$

(flavor universal)

# Current Probes: terrestrial experiments

Beam dump experiments:

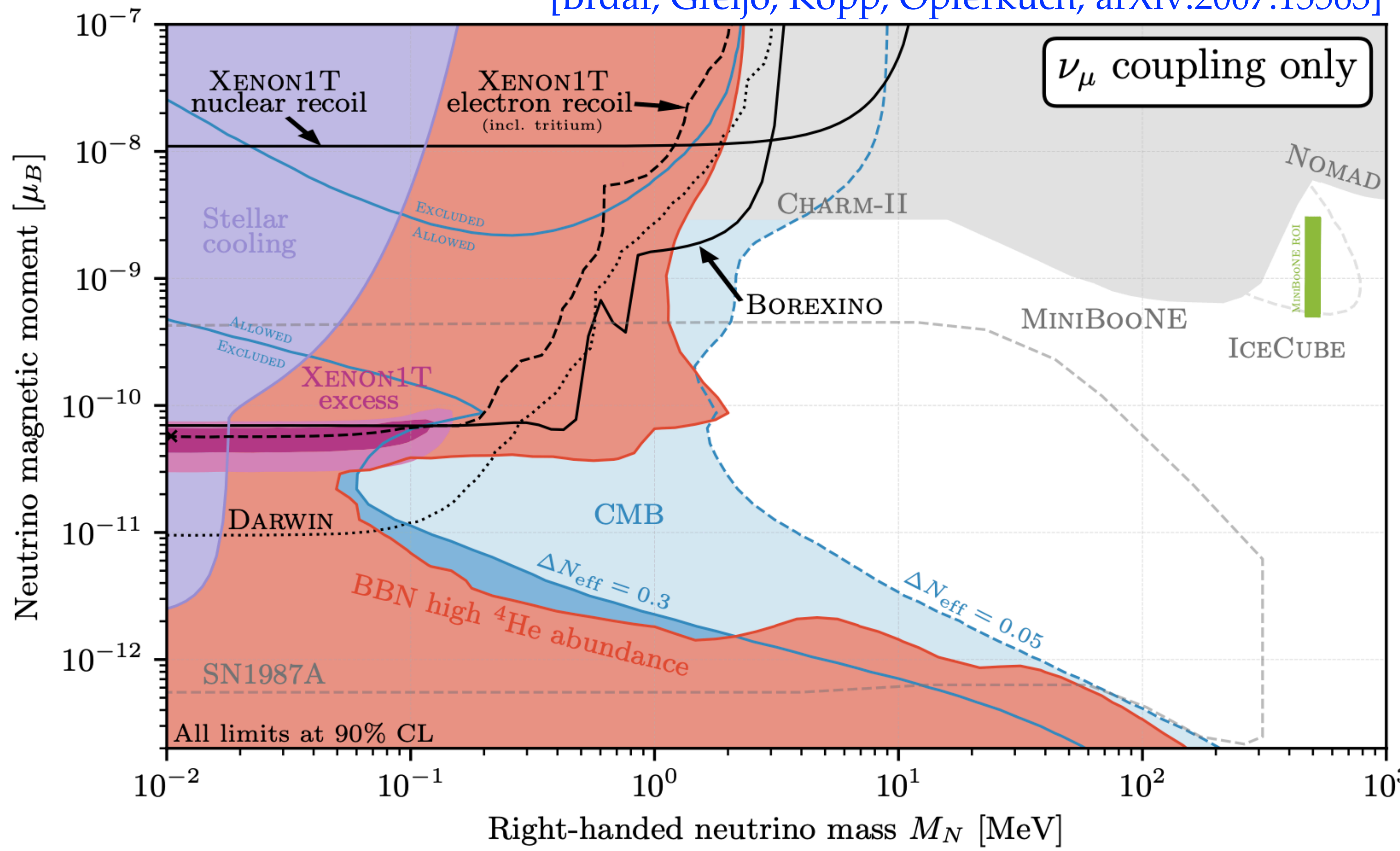
MiniBoone, NONAD




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

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

[Brdar, Greljo, Kopp, Opferkuch, arXiv:2007.15563]




relevant for transition magnetic moments between $\nu_\mu$ and $N$

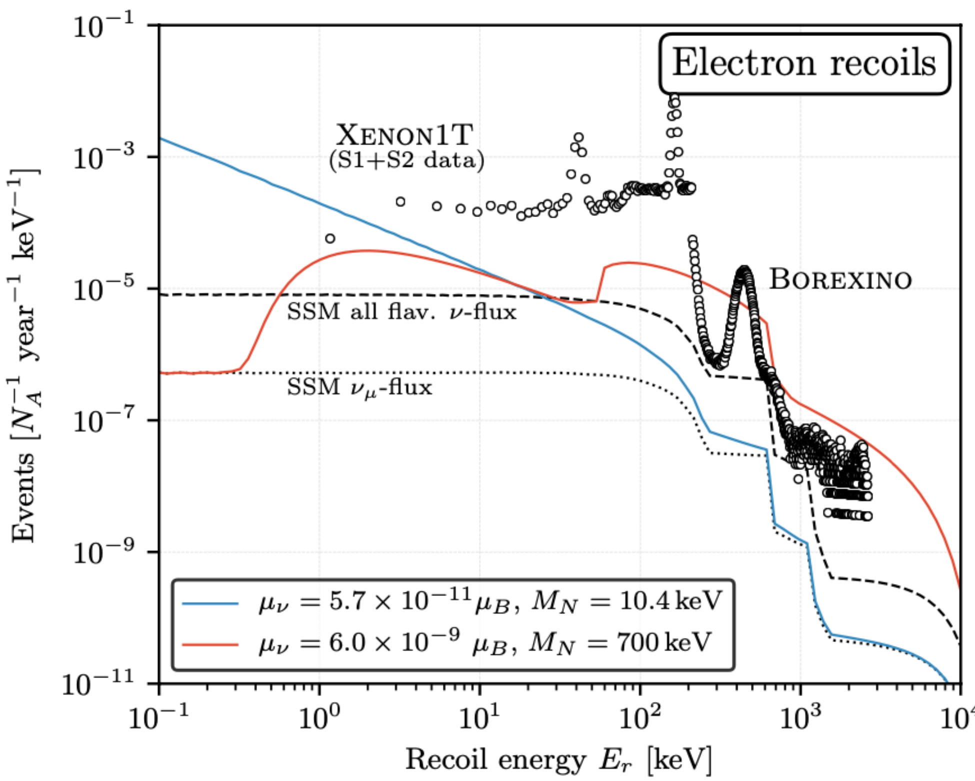
# Current Probes: terrestrial experiments

Solar neutrino spectrum:

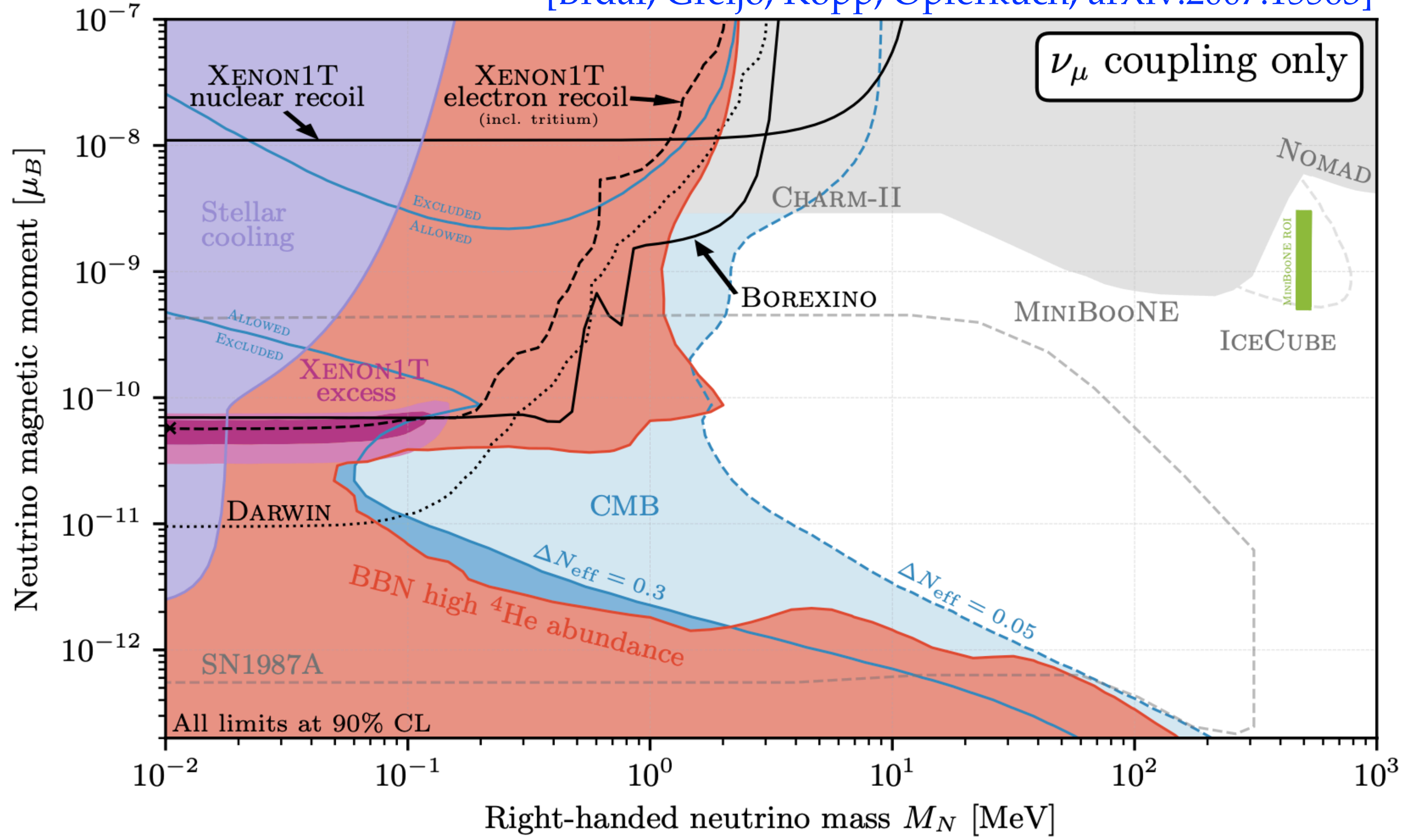
Xenon1T, Borexino

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

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




[Brdar, Greljo, Kopp, Opferkuch, arXiv:2007.15563]




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

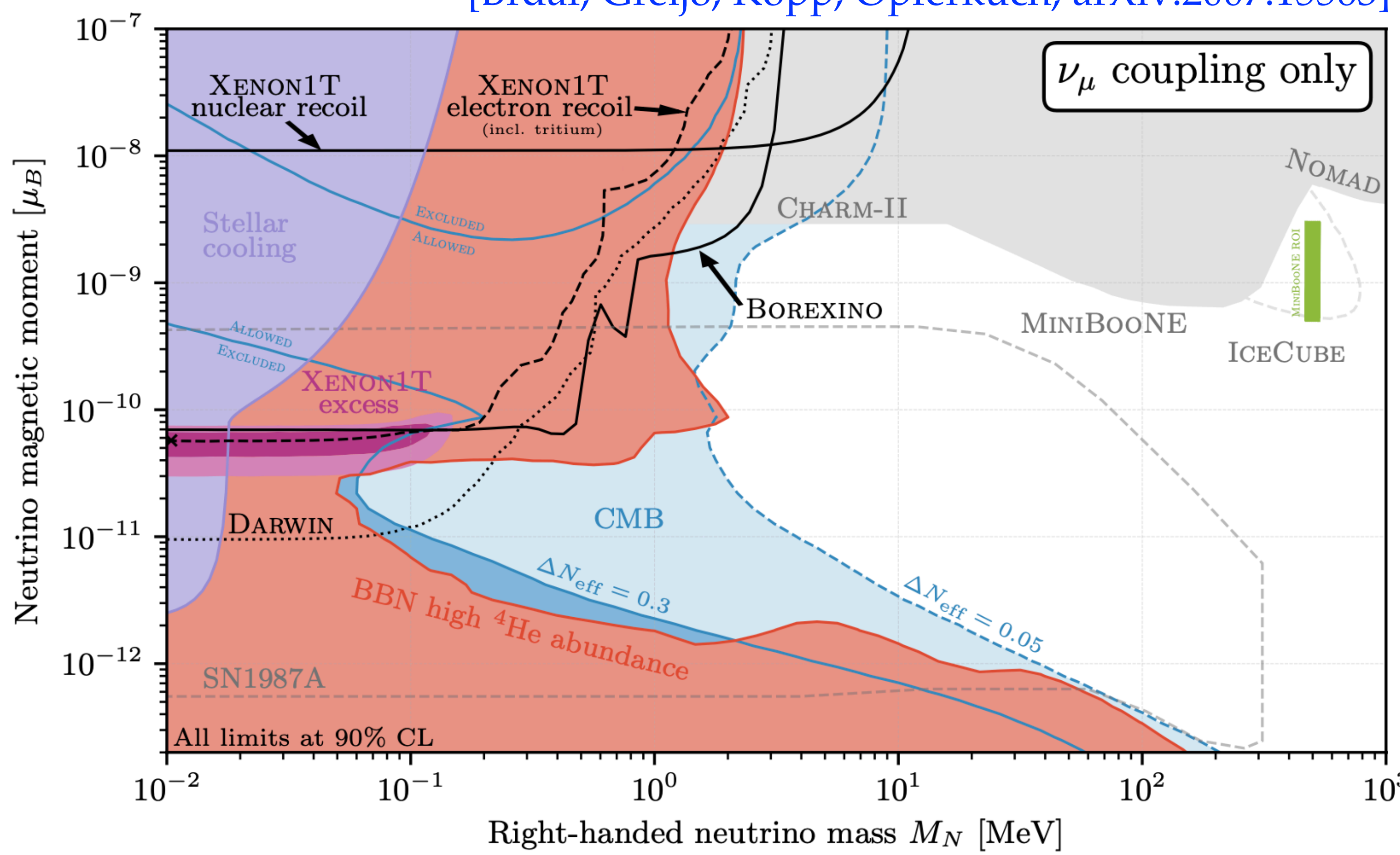
# Current Probes: cosmology

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

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

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

[Brdar, Greljo, Kopp, Opferkuch, arXiv:2007.15563]




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

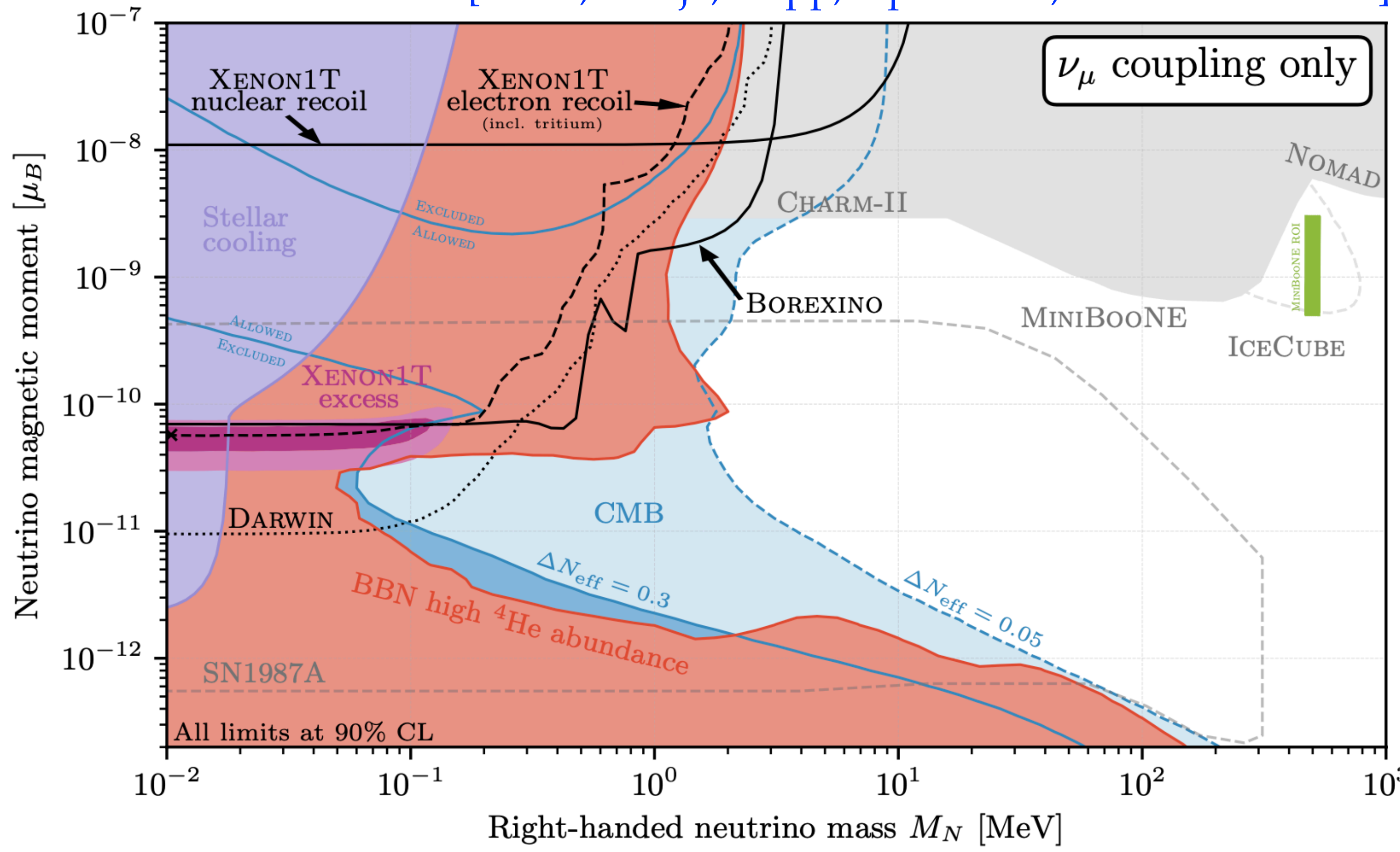
# Current Probes: Supernova

10% of energy loss

to sterile neutrino

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

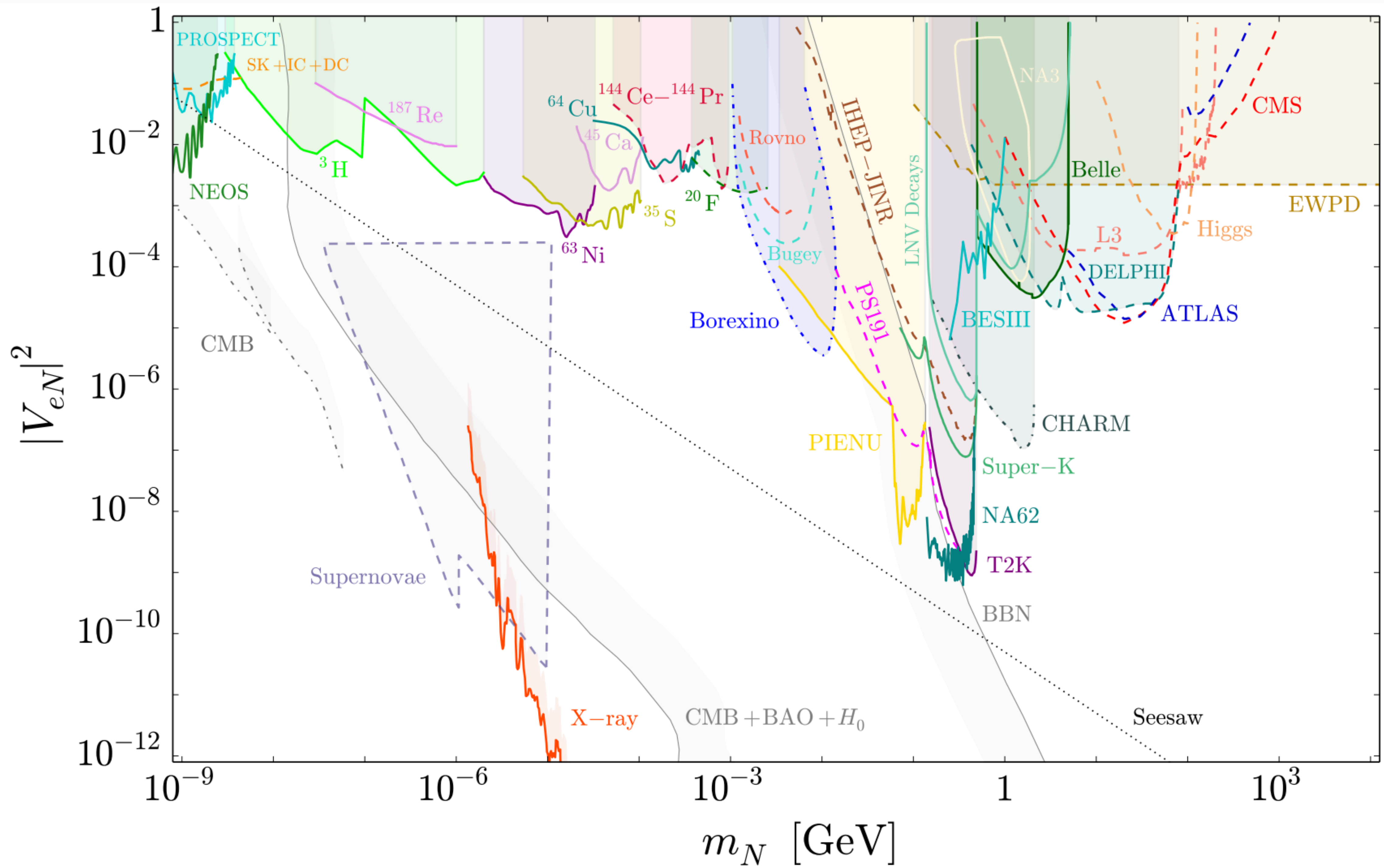
[Brdar, Greljo, Kopp, Opferkuch, arXiv:2007.15563]



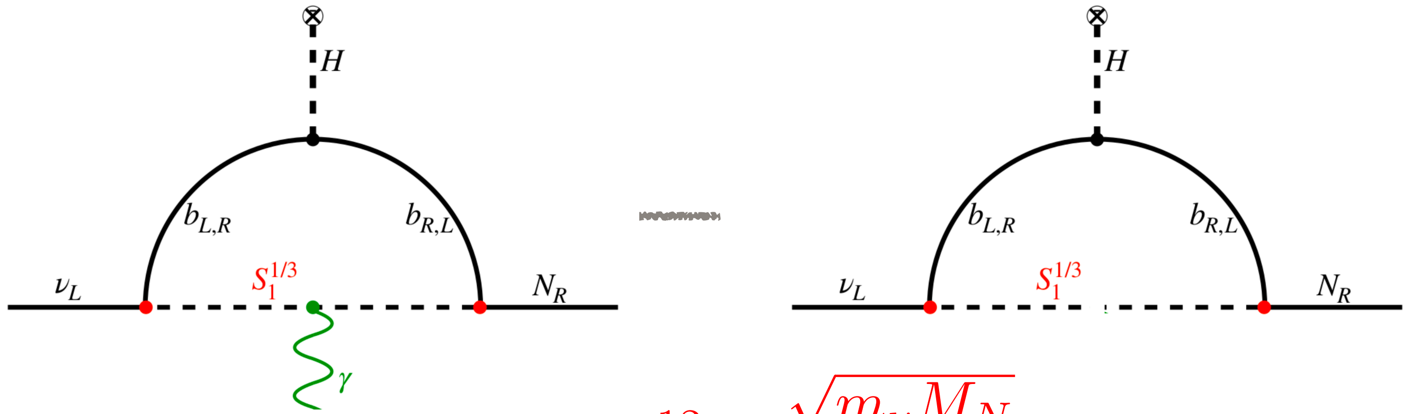
# UV completion

In what theory the effect of mixing is subdominant...

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



# UV completion




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

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

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

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

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

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

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

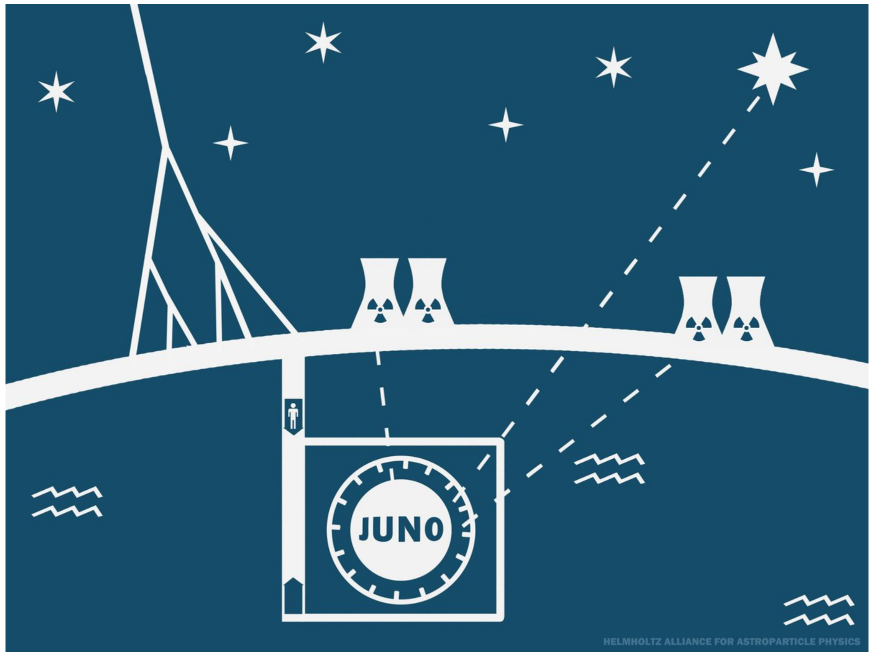
$$m_\nu \sim 0.1\text{eV}, \mu_\nu \sim 10^{-11} \mu_B$$

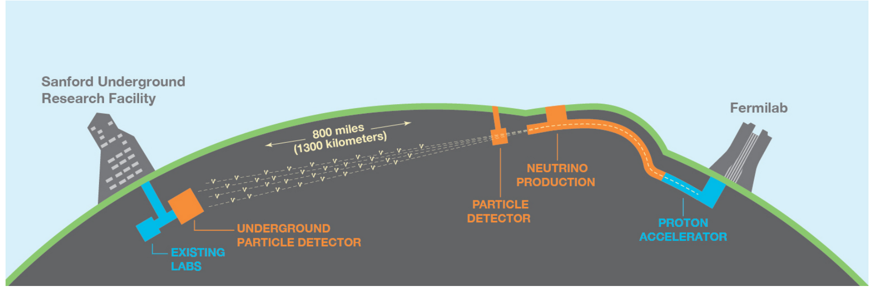
# Multimessenger Signals

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

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

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




[V. Brdar, A. D. Gouv^ea, YYL, P. A. N. Machado, arXiv:2302.10965]

# Multimessenger Signals

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

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

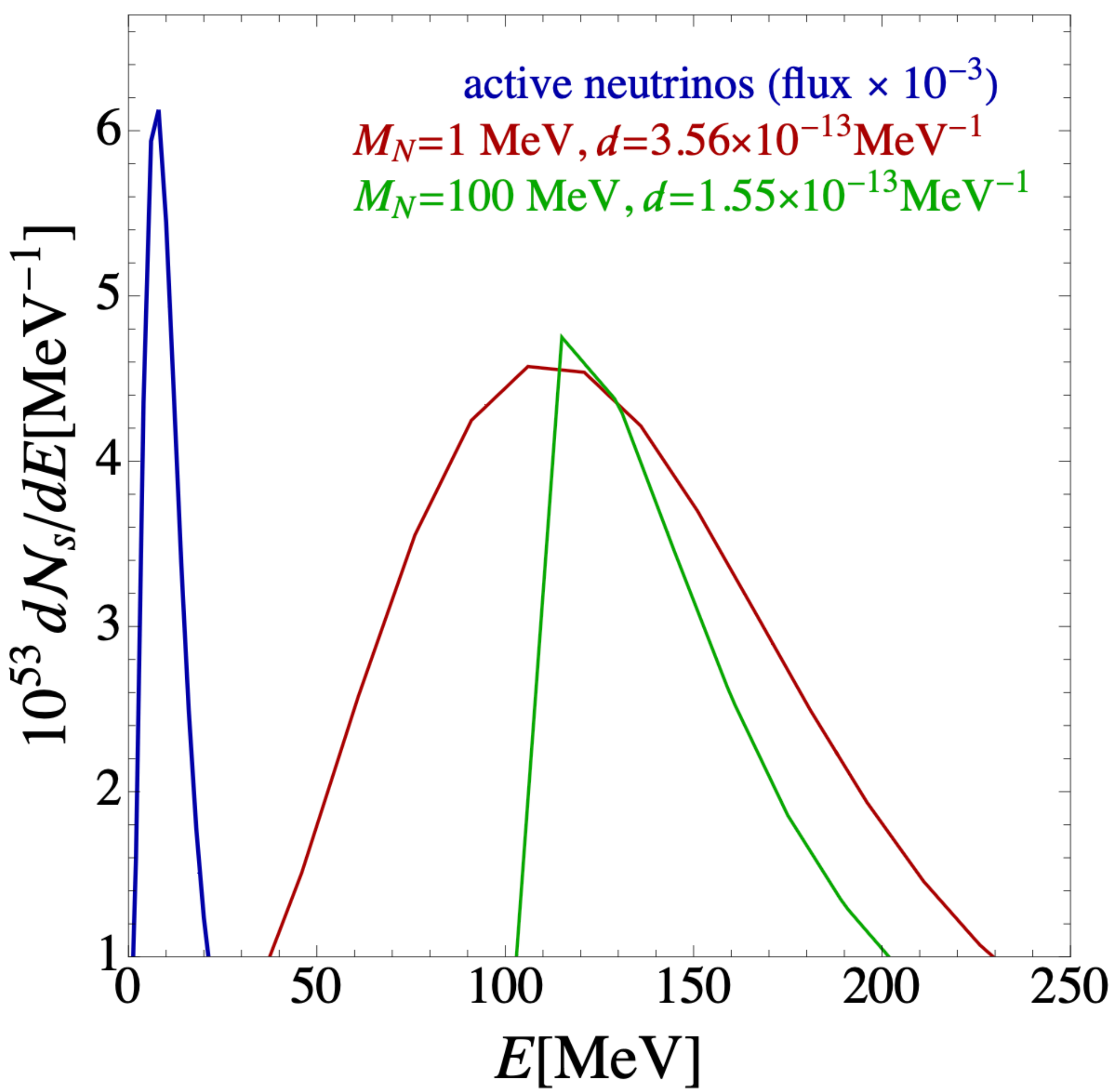
$$e^{+} + e^{-} \to \bar{\nu} + N$$

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

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

using data associated to the simulation performed by the Garching group of an 8.8M⊙ progenitor star

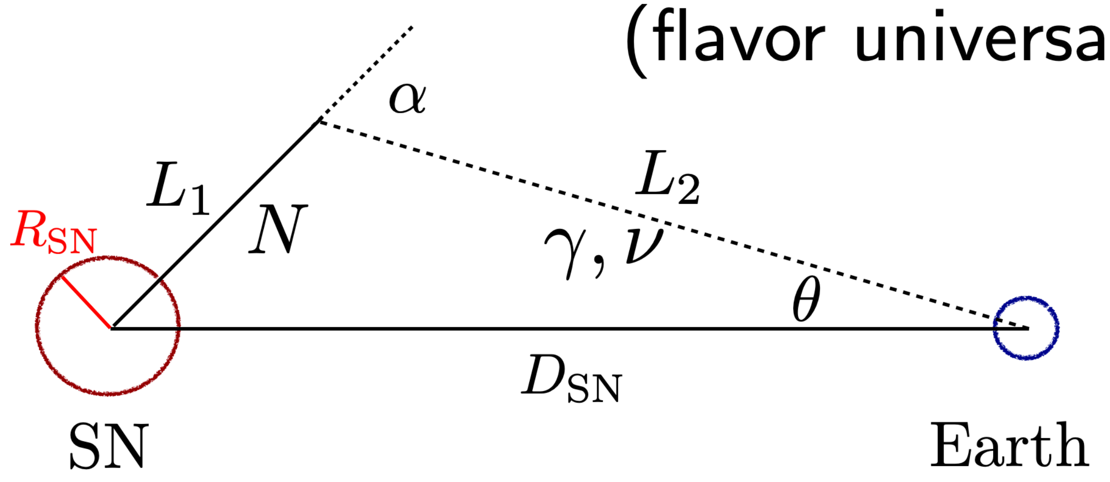
[V. Brdar, A. D. Gouv^ea, YYL, P. A. N. Machado, arXiv:2302.10965]




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

# Multimessenger Signals

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



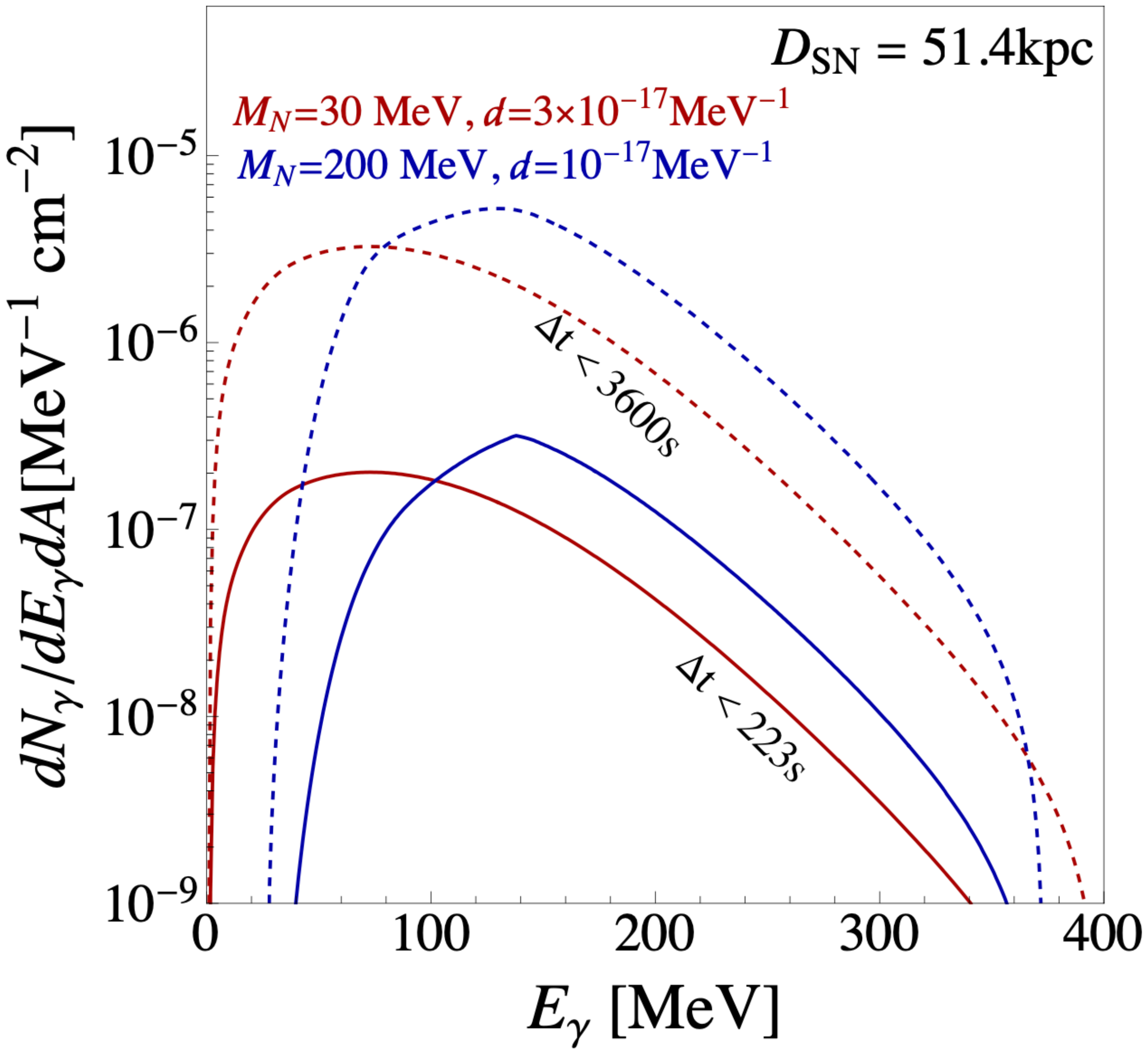

$$\cos\alpha = \frac{2E_N E_{\gamma/\nu} - M_N^2}{2E_{\gamma/\nu}\sqrt{E_N^2 - M_N^2}}$$

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

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

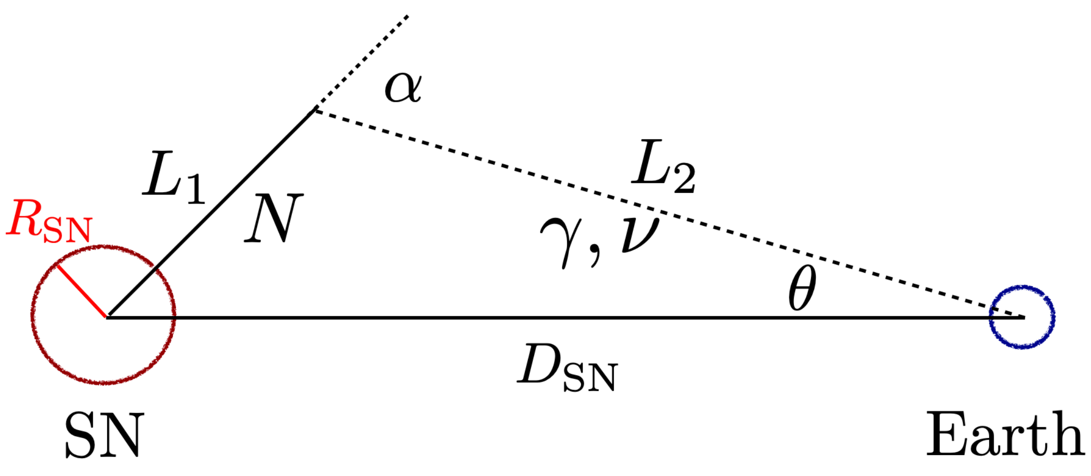
$$R_{\rm SN}^{\gamma/\nu} \le L_1 \le L_1^{\rm max}$$

$$R_{\rm SN}^{\gamma} = 3\times 10^{10}\,{\rm m}$$
$$R_{\rm SN}^{\nu} = 30\ {\rm km}$$



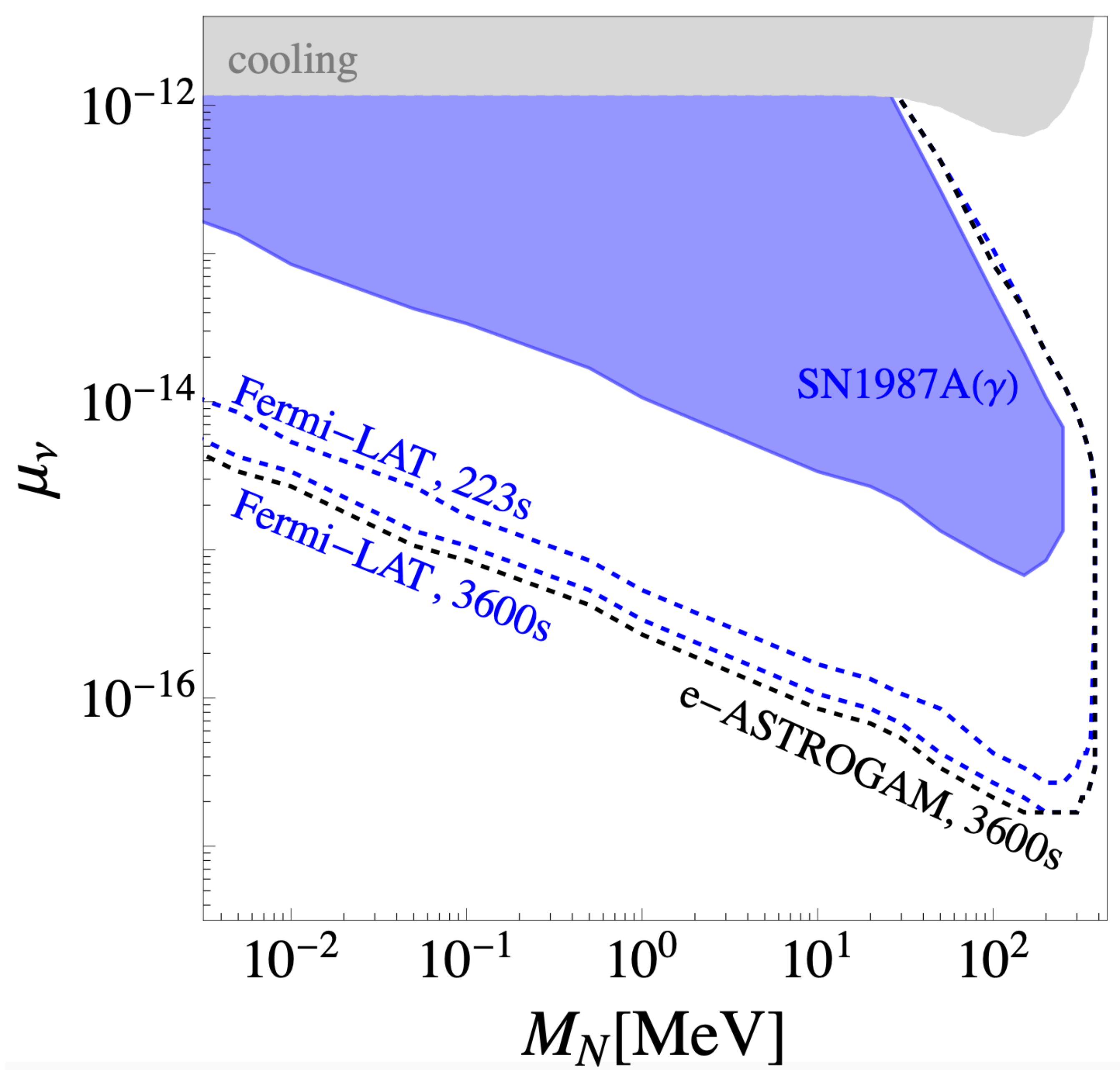

[V. Brdar, A. D. Gouv^ea, YYL, P. A. N. Machado, arXiv:2302.10965]

# Multimessenger Signals : $\gamma$ − 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: $E_\gamma > 1\text{MeV}, \theta < 1.25^\circ$

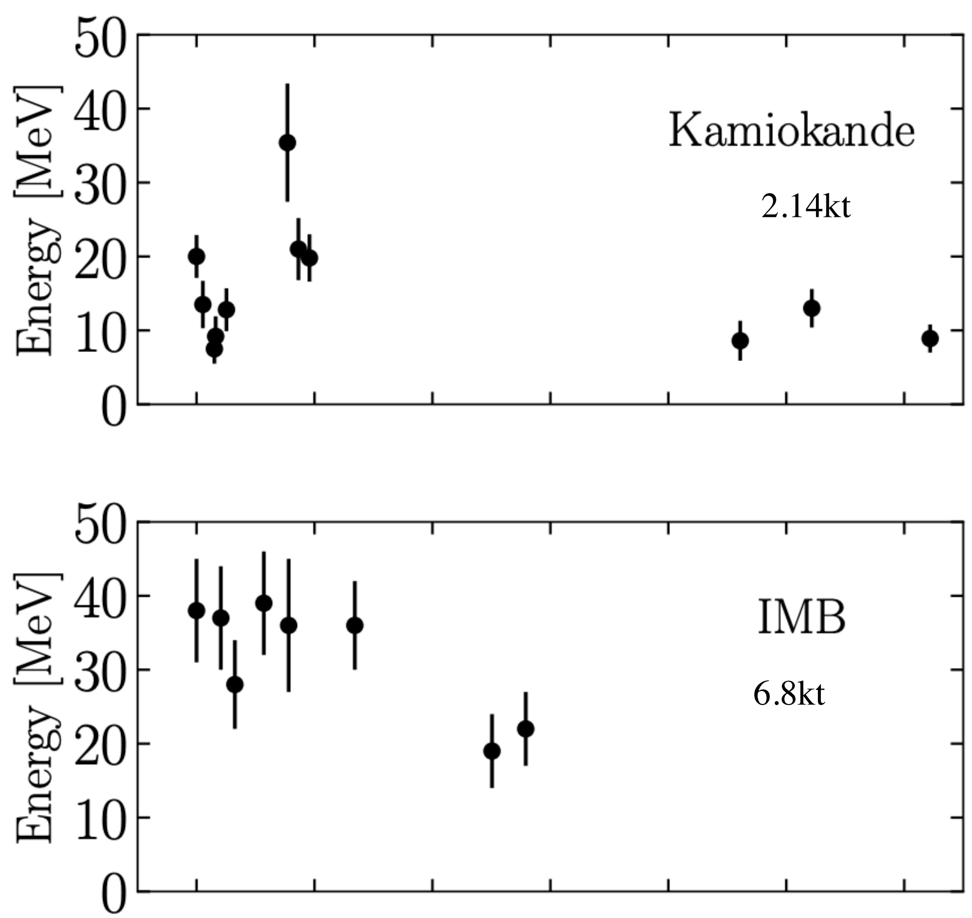



[V. Brdar, A. D. Gouv^ea, YYL, P. A. N. Machado, arXiv:2302.10965]

# Multimessenger Signals : neutrino detection

## SN1987A, neutrino events

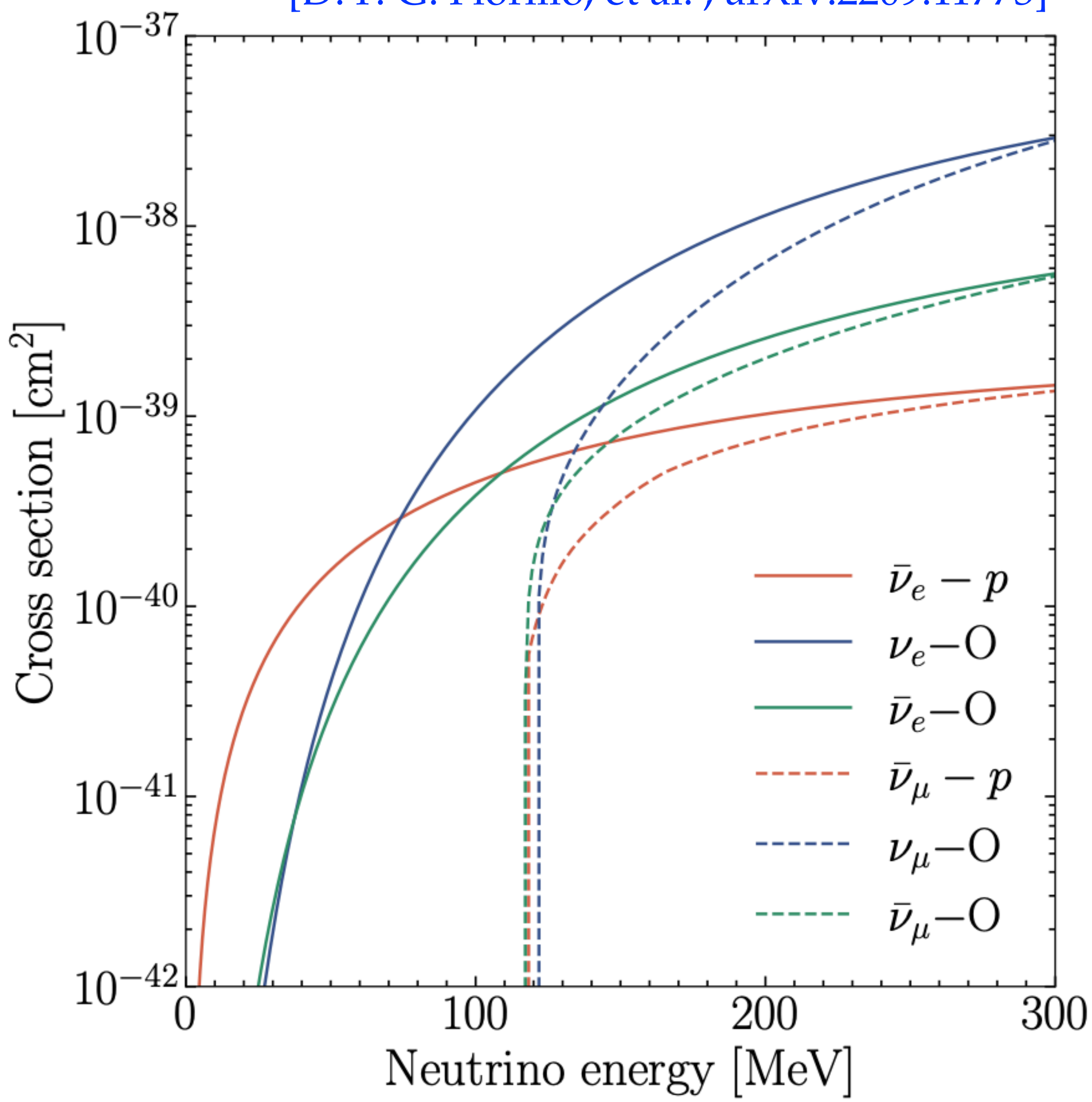
water-Cherenkov detectors




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

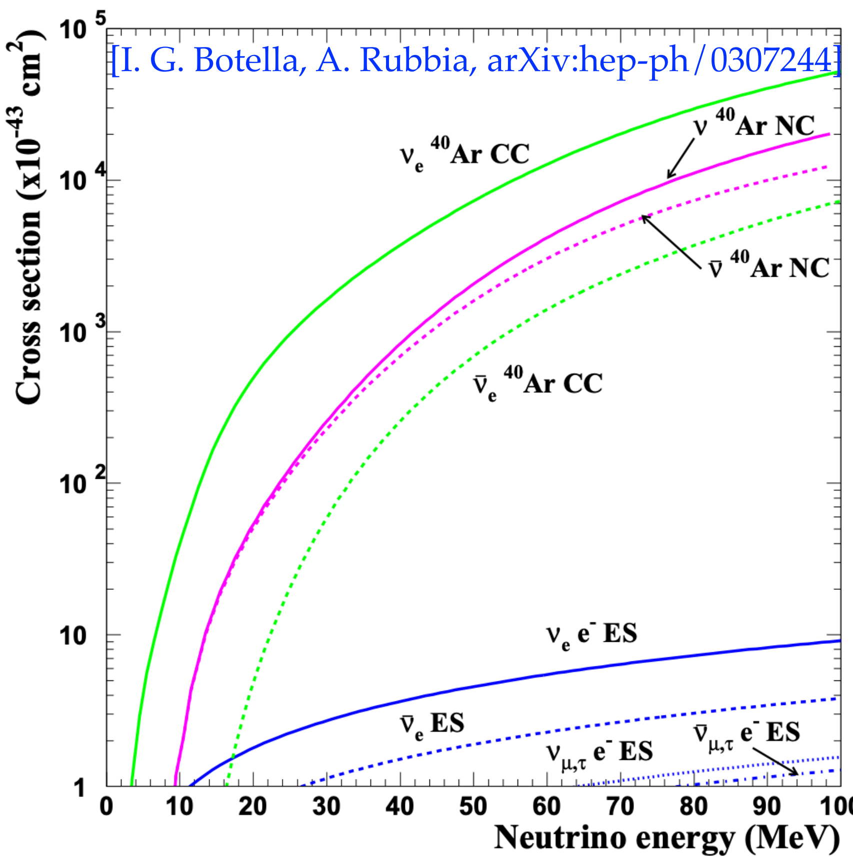
$$N_\nu^{\rm BSM} = N_{\rm tgt} \int dE_\nu \frac{dN_\nu}{dE_\nu dA}(E_\nu)\, \sigma_{\rm IBD}(E_\nu)\, \varepsilon(E_\nu)$$

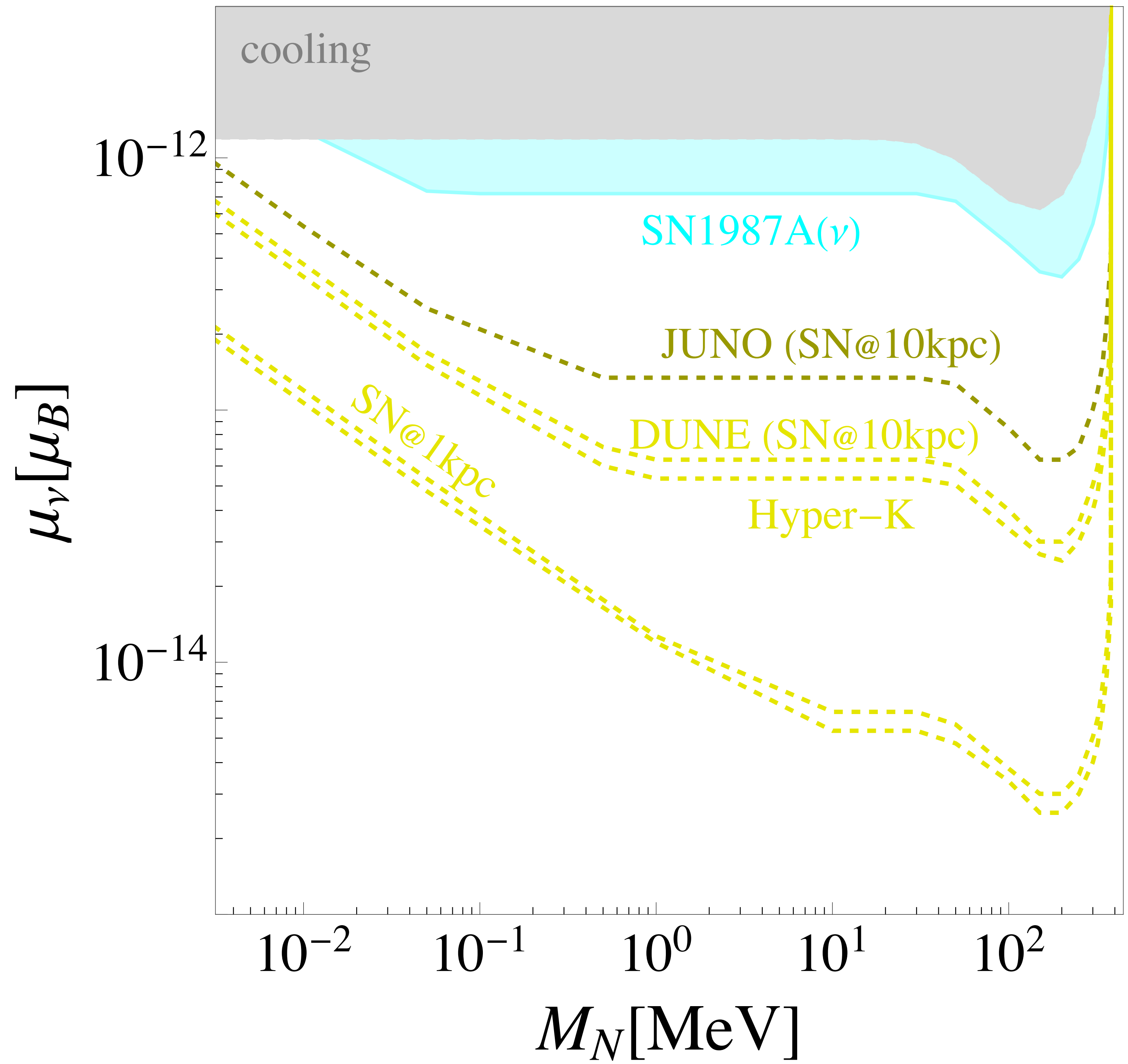
[D. F. G. Fiorillo, et al. , arXiv:2209.11773]



# Multimessenger 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



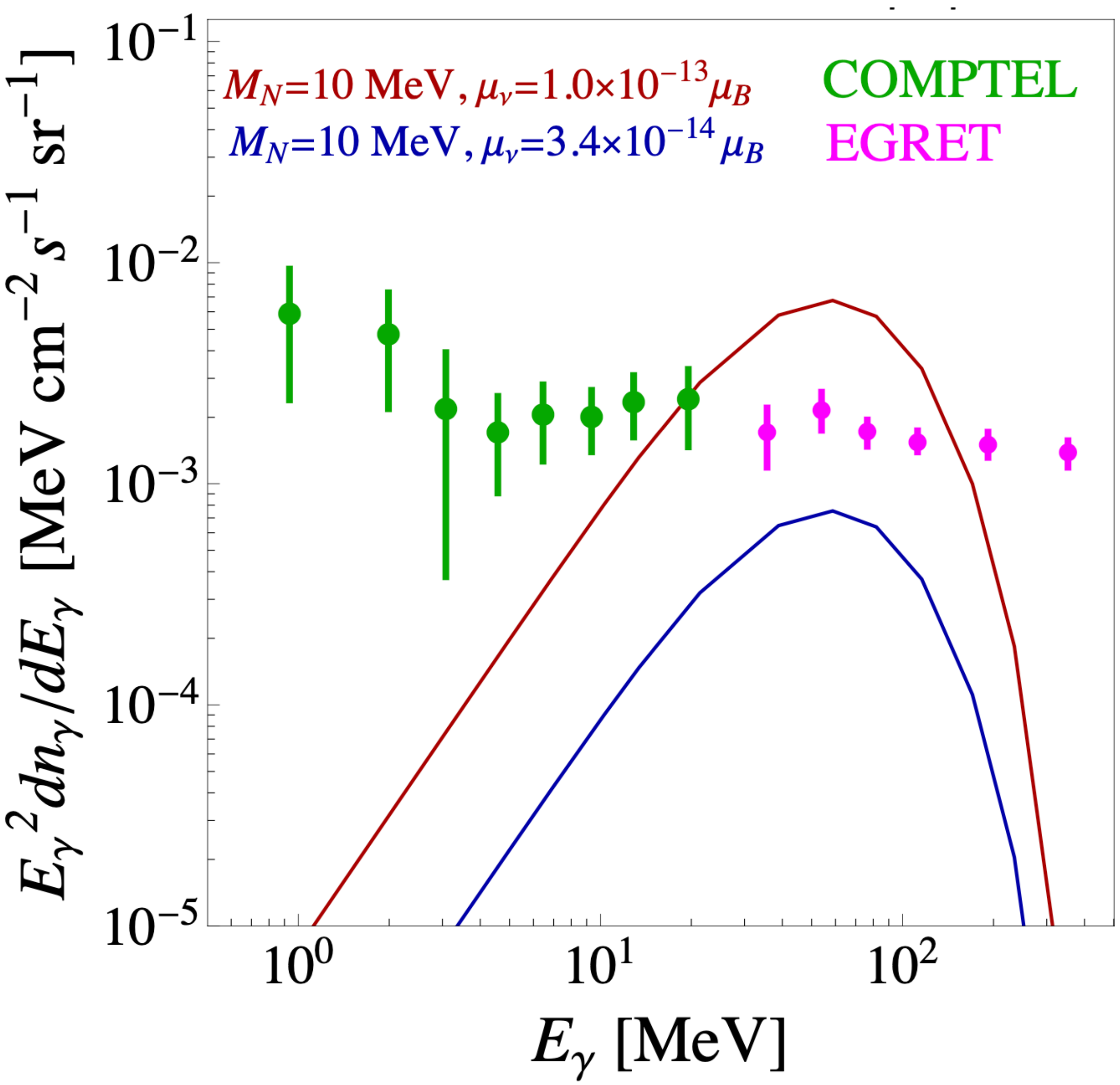



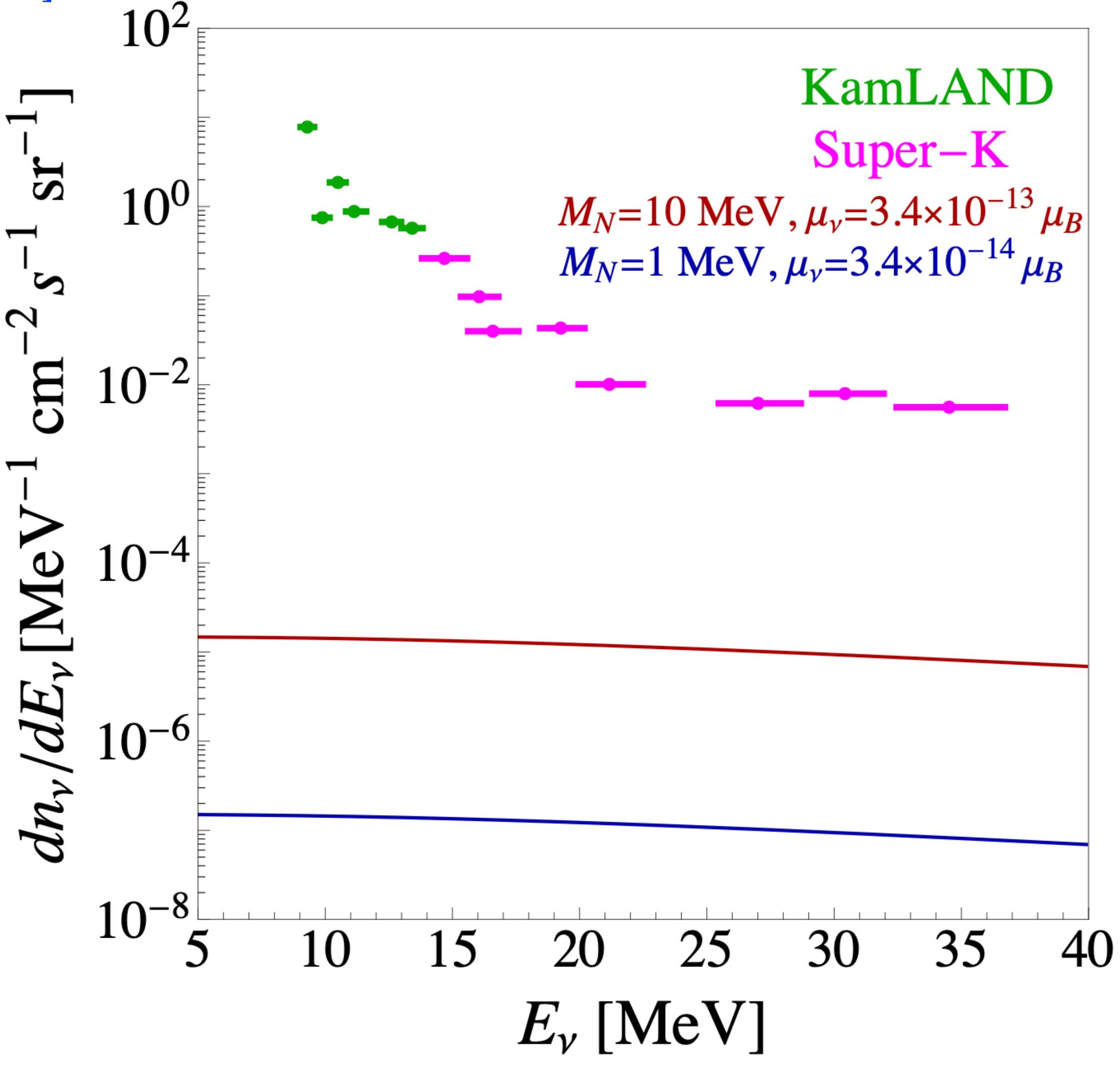

[V. Brdar, A. D. Gouv^ea, YYL, P. A. N. Machado, arXiv:2302.10965]

# Multimessenger 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. D. Gouv^ea, YYL, P. A. N. Machado, arXiv:2302.10965]



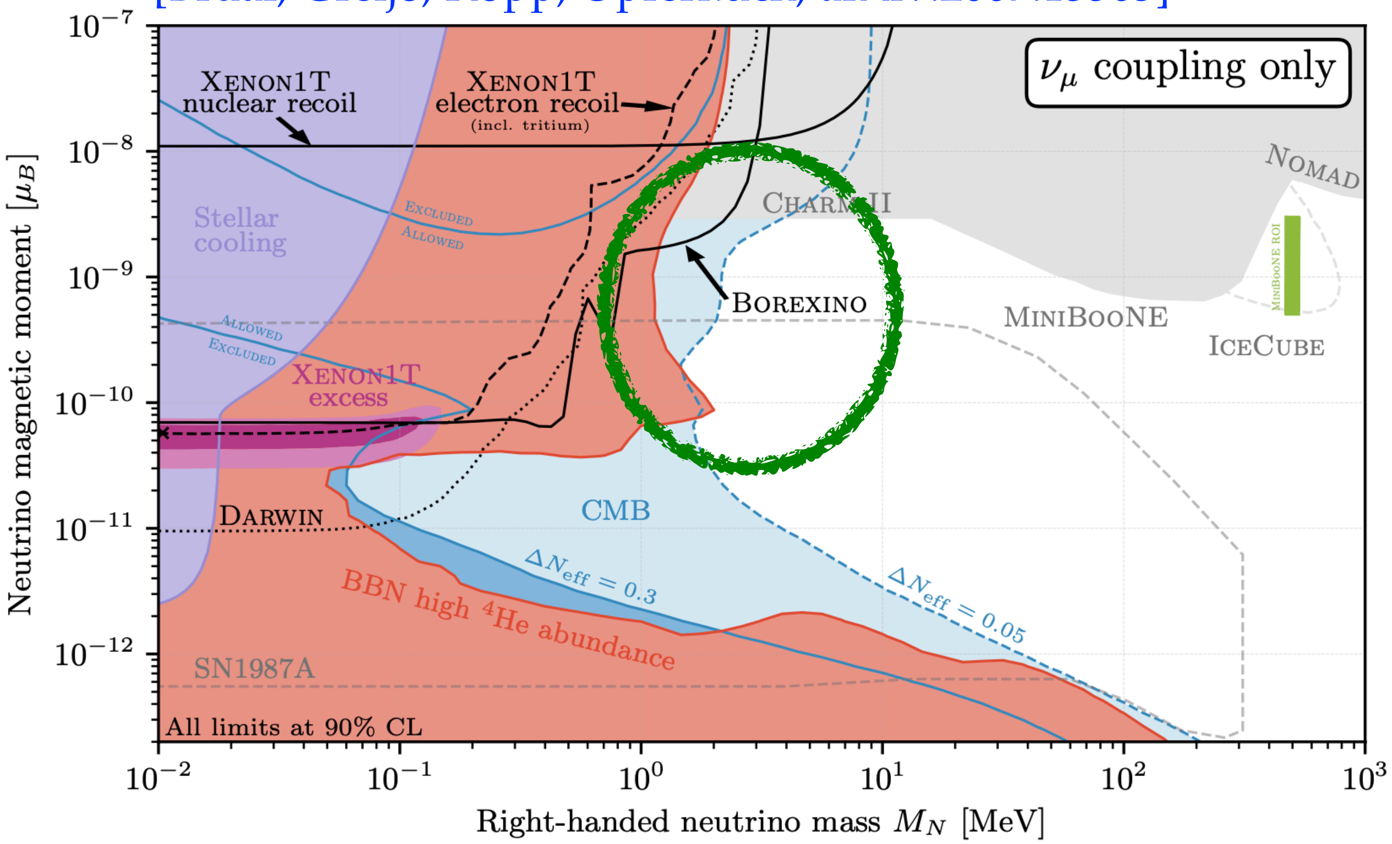

extragalactic background light

# Conclusion? Outlooks

Solar neutrino —

Can JUNO cover the green circle region, given that its bigger than Borexino, also probes electron recoils below 100keV.

[Brdar, Greljo, Kopp, Opferkuch, arXiv:2007.15563]



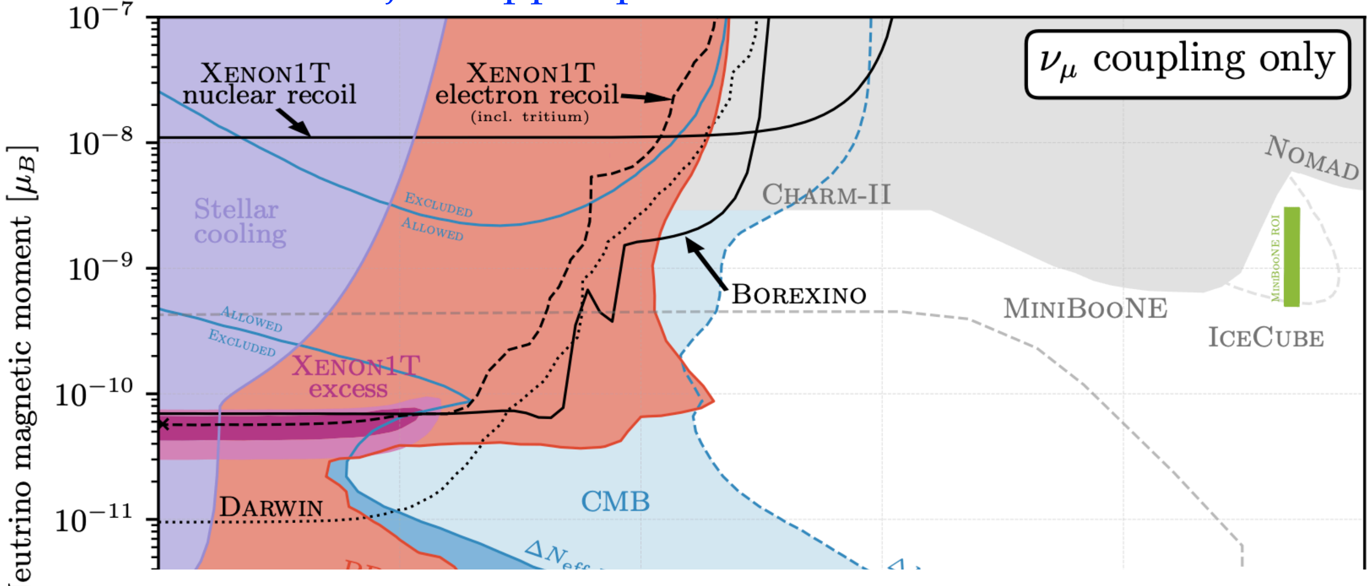

[Z. Ye, F. Zhang, D. Xu, J. Liu, arXiv:2103.11771]

$\mu_\nu < 10^{-11} \mu B$ can be reached at an

energy threshold greater than 40keV (SM case)

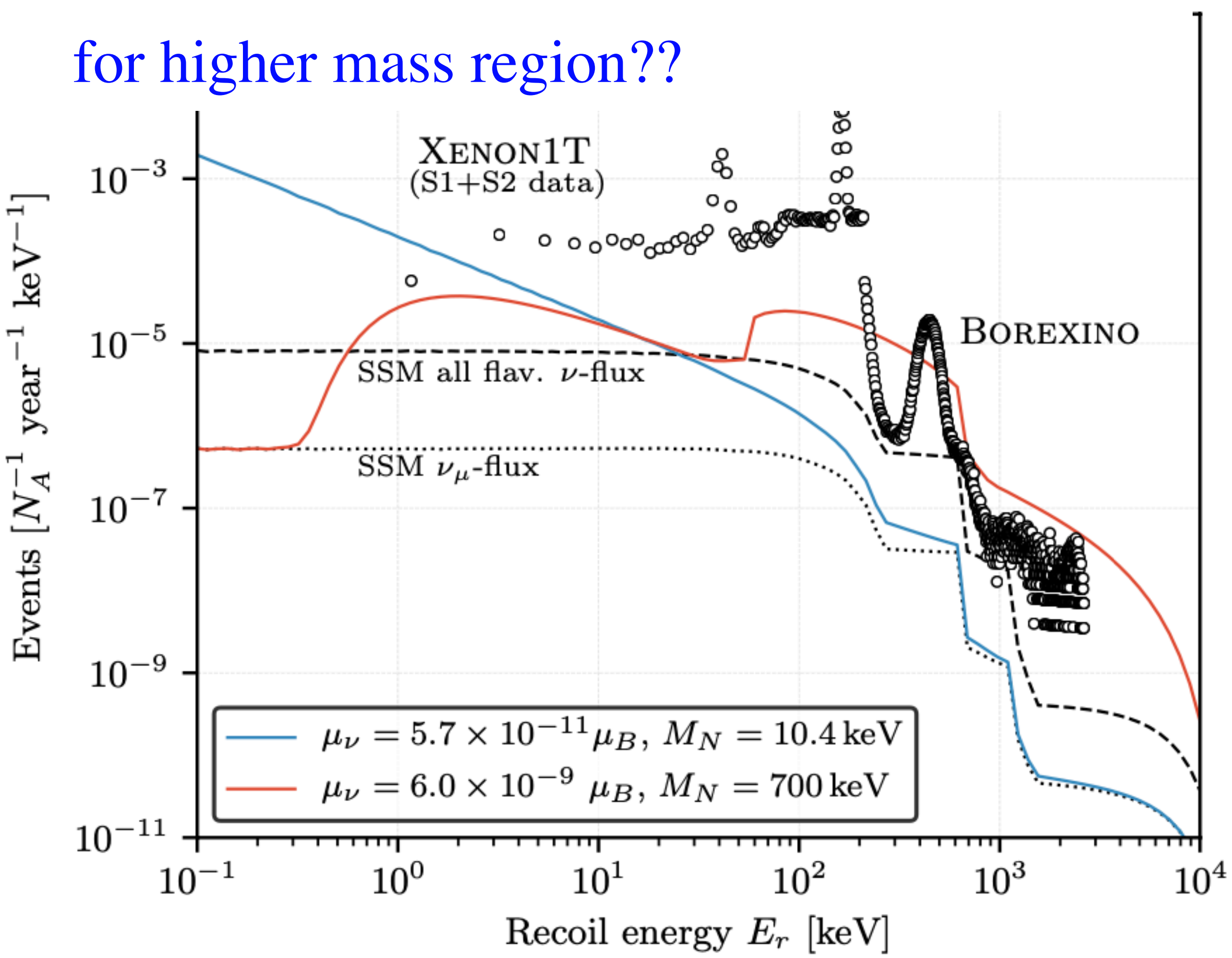
# Conclusion? Outlooks

[Brdar, Greljo, Kopp, Opferkuch, arXiv:2007.15563]

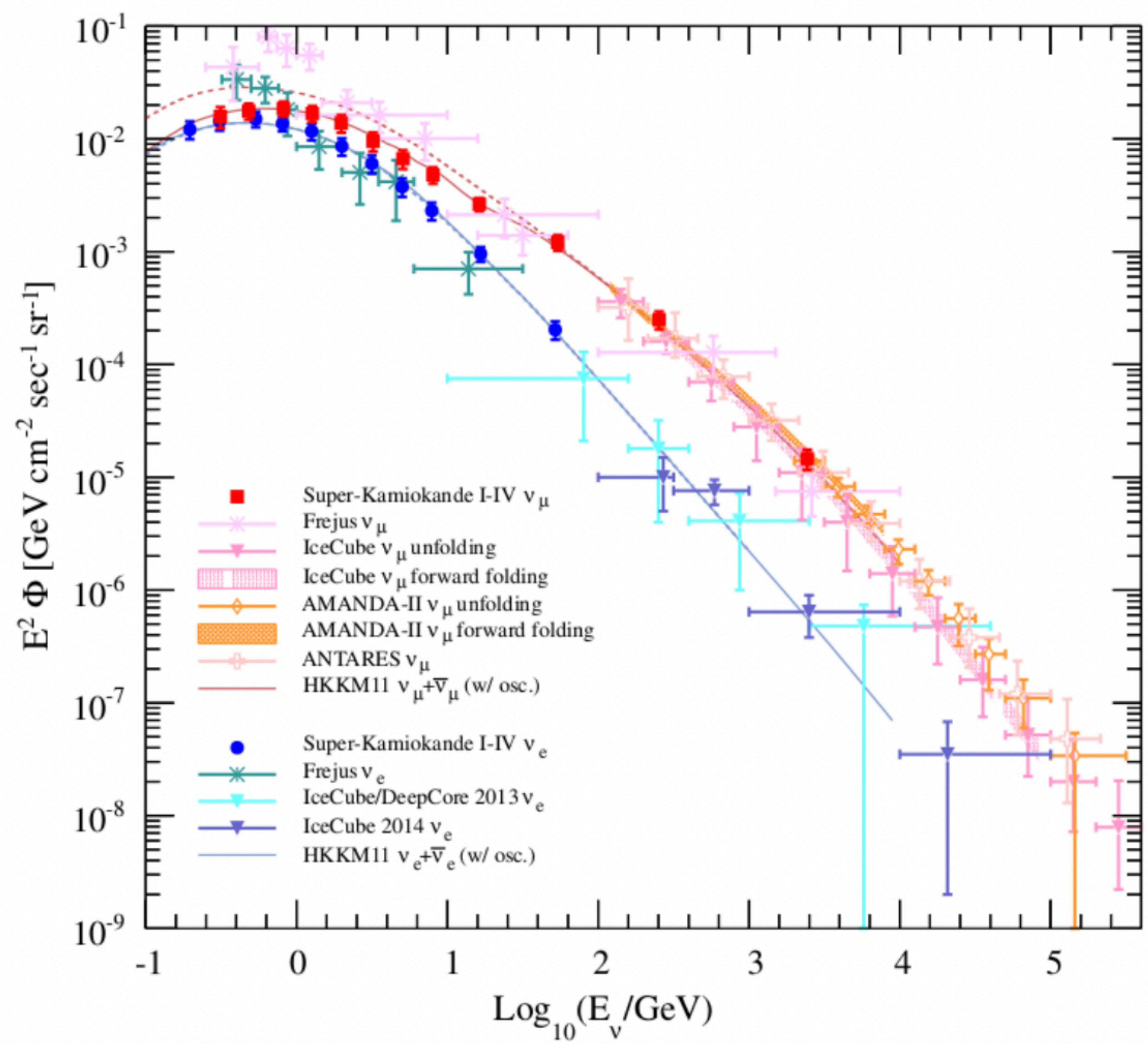



atmospheric neutrino spectrum

for higher mass region??




[JUNO, arXiv:2103.09908]

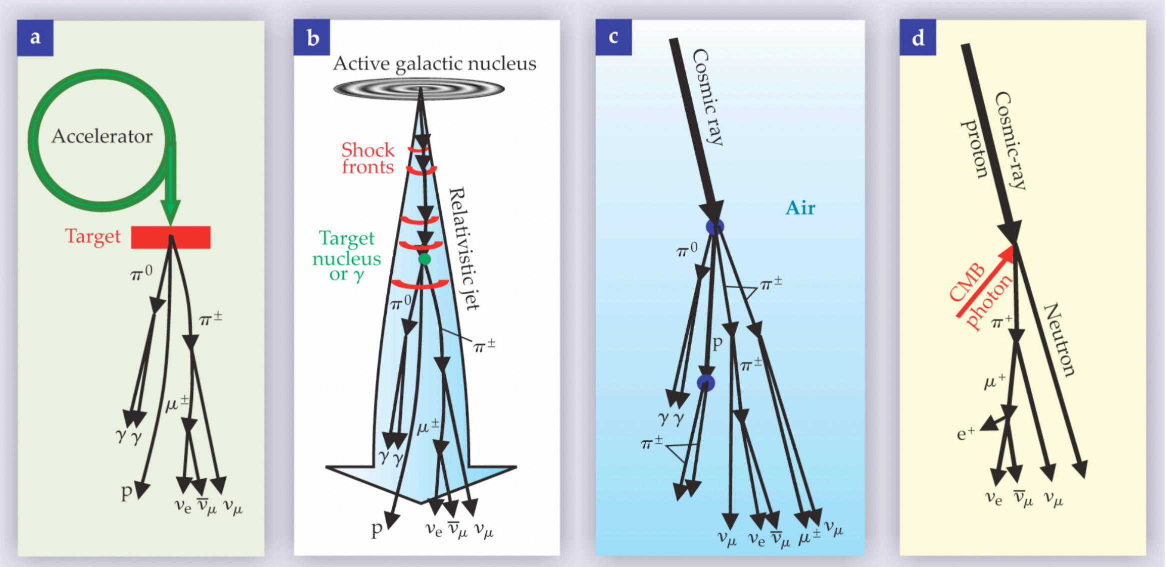


## Sterile Neutrino: Multi-messenger signals for

## Photon detection and Neutrino experiments

- Astrophysical neutrinos

Halzen Klein 2008




Sterile neutrino N production via mixing: $\nu \to N$

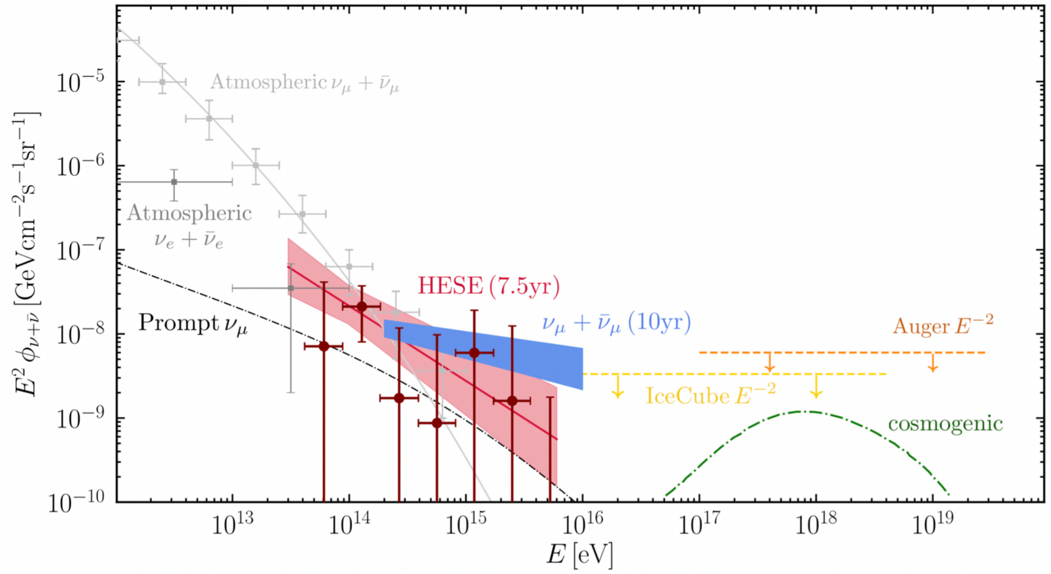
N decaying to photon that can be observed by photon detectors: $N \to \nu + \gamma$

- Diffused neutrinos fluxes being observed or bounded

**LHAASO's measurements of diffused TeV photon flux**

**might already constrains parameter space of sterile neutrino?**

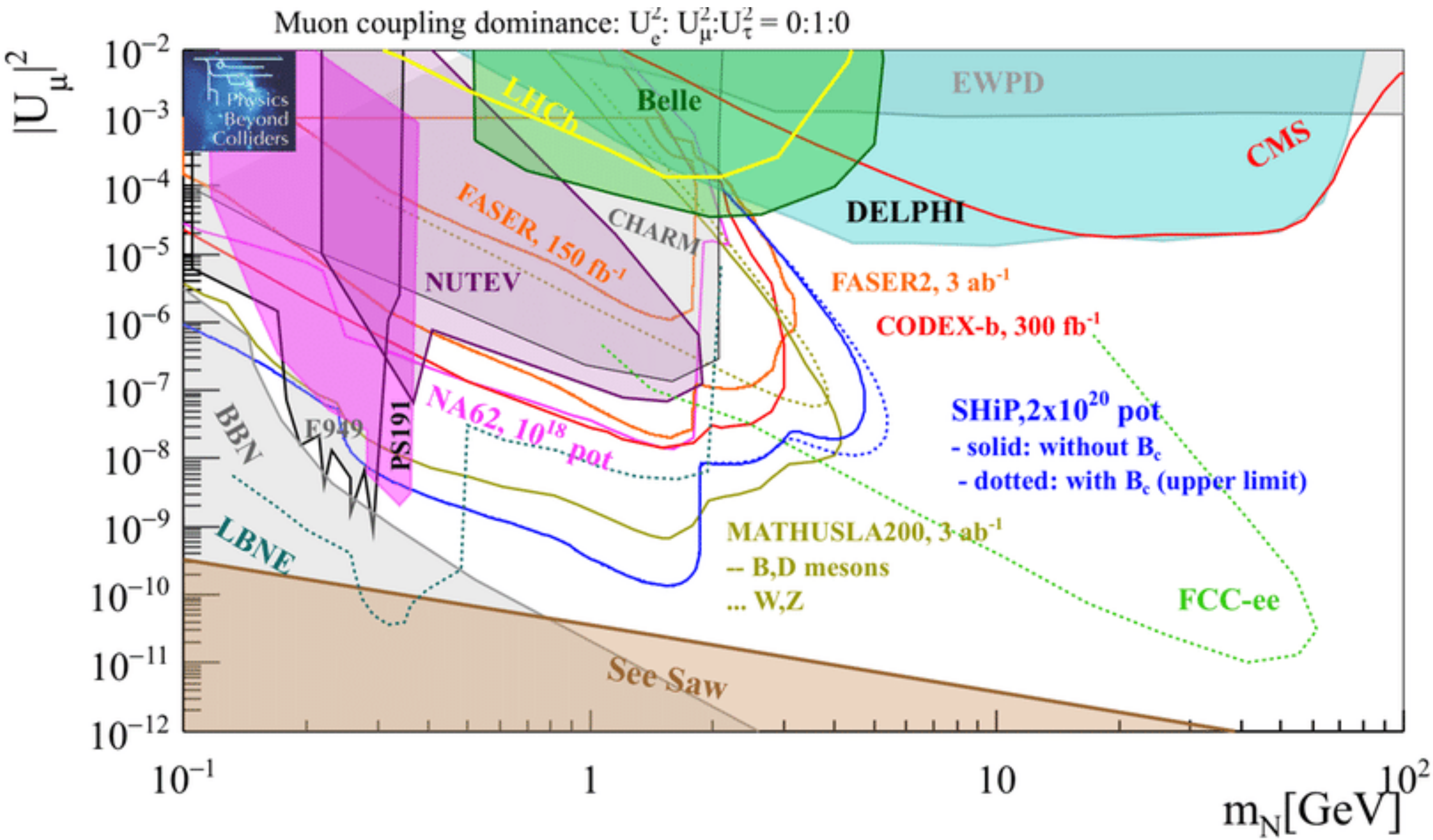
Halzen Kheirandish 2202.00694



Thank you

# BACK UP

[J. Beacham, arXiv:1901.09966]



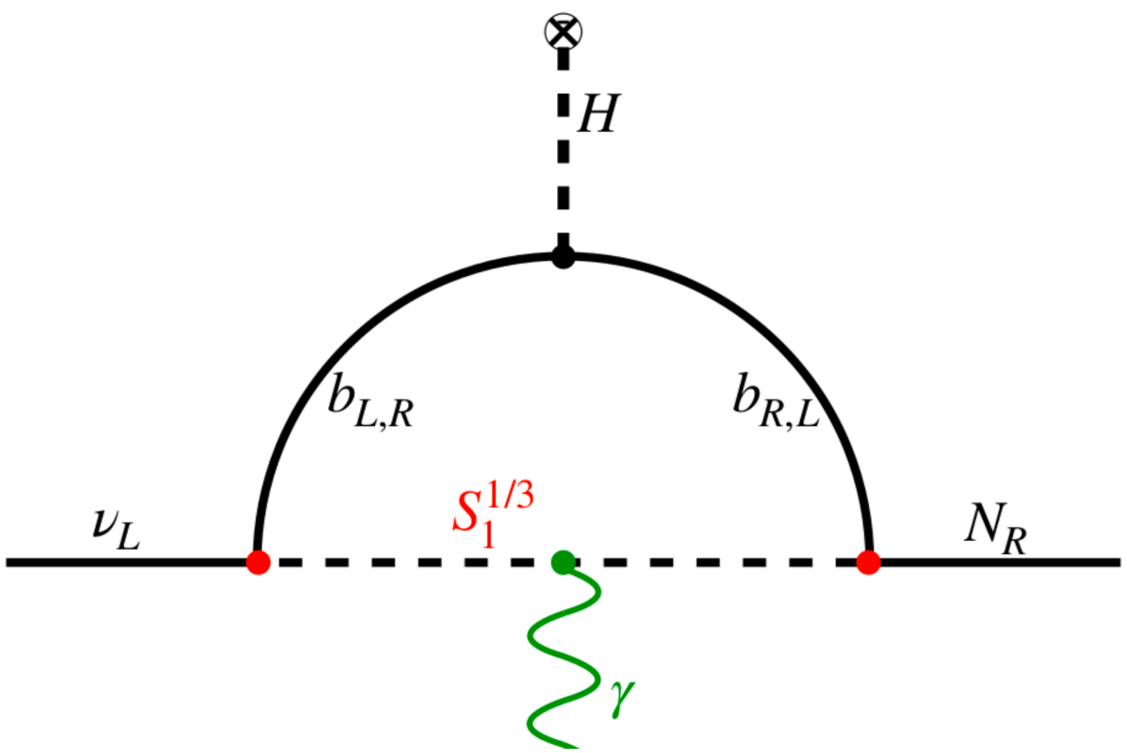
# UV completion

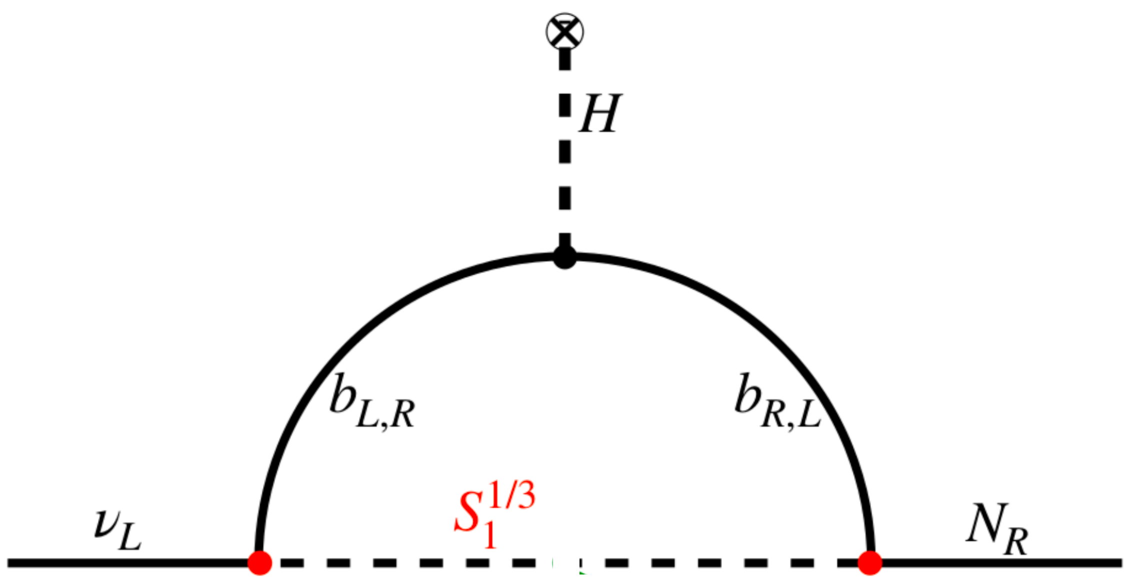
In what theory the effect of mixing is subdominant...

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

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

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




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

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

# UV completion

In what theory the effect of mixing is subdominant... $\theta^2 \sim \frac{m_\nu}{M_N}, \mathrm{keV} < M_N < 100\mathrm{MeV}$

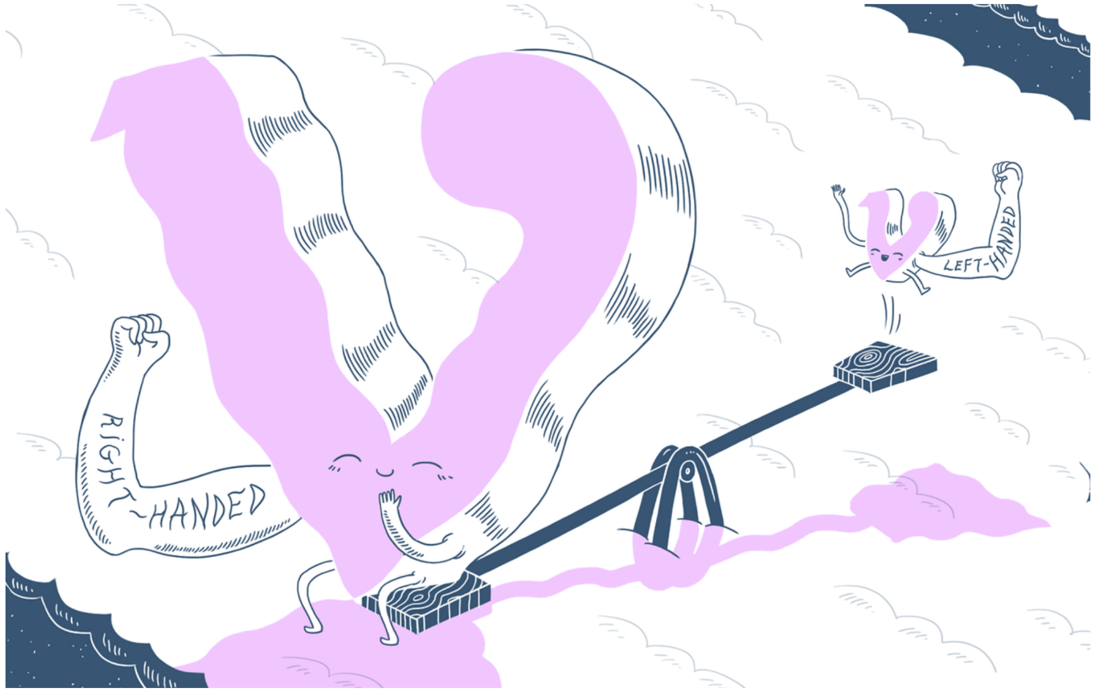
- Consider heavy scalar lepto-quark $S_1 \sim (\bar{3}, 1, 1/3)$

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

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

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

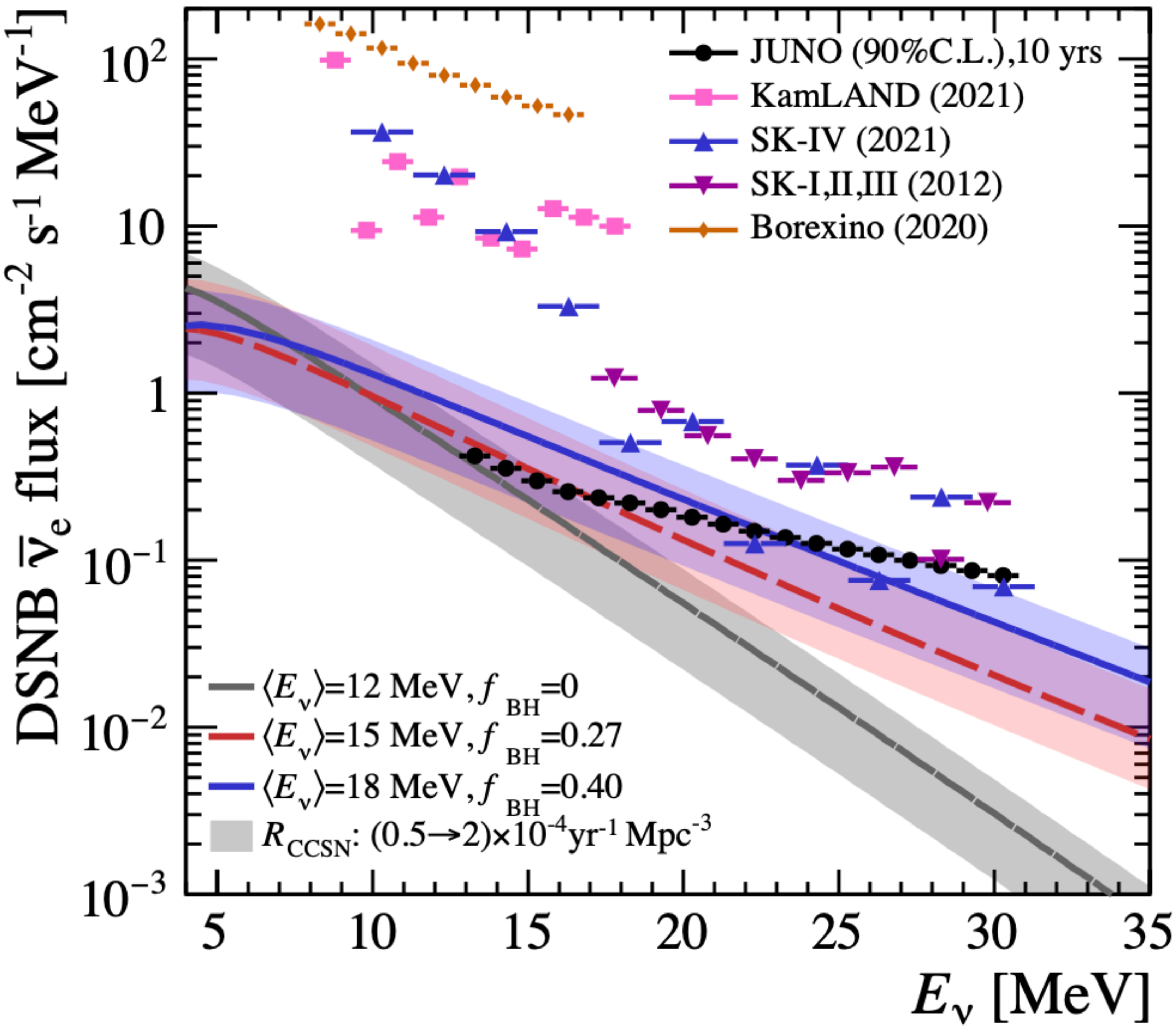
$$\mu_\nu \sim 10^{-12} \mu_B \frac{\sqrt{m_\nu M_N}}{\mathrm{MeV}}$$




for lepto-quark masses at the TeV scale

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

# Multimessenger Signals : diffused BSM Photon and neutrino background




[A. Abusleme, arXiv:2205.08830]