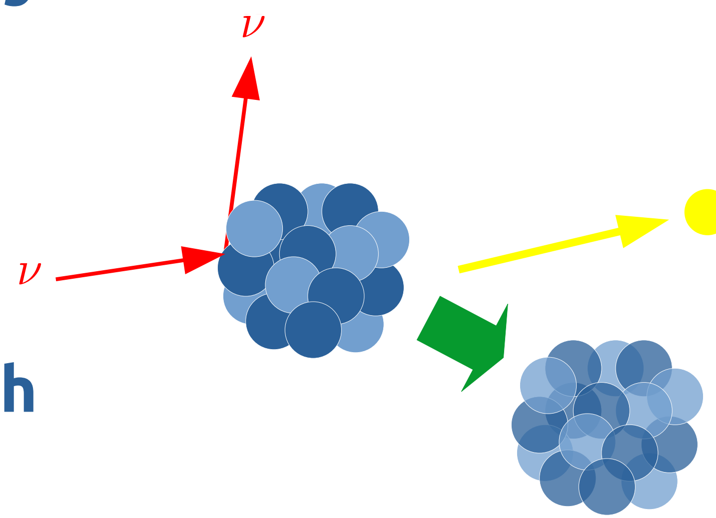
CEvNS with Photon Emission as Smoking Gun Signal of New Physics



Julia Harz, Technical University of Munich

in collaboration with

Patrick Bolton, Frank Deppisch, Chandan Hati, Kåre Fridell, Suchita Kulkarni

Bologna, July 8th 2022
ICHEP 2022

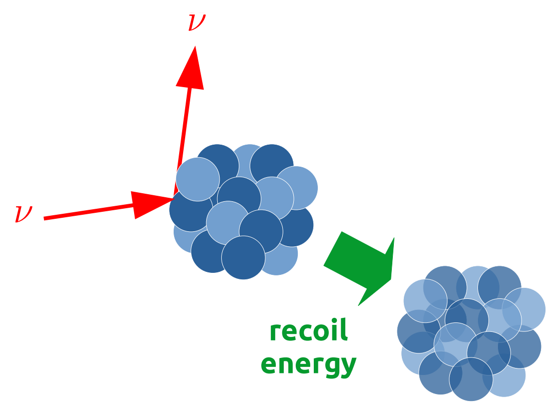
based on arxiv:hep-ph/2110.02233

Technische Universität München

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

Previously a hubris – now a reality

Coherent elastic neutrino nucleus scattering – postulated in 1974 by D. Freedman



PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790

(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm^2 on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \to \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering. We will discuss these problems at the end of this note, but first we wish to present the theoretical ideas relevant to the experiments.

Window to New Physics: CEvNS

Neutrino energy for coherence:

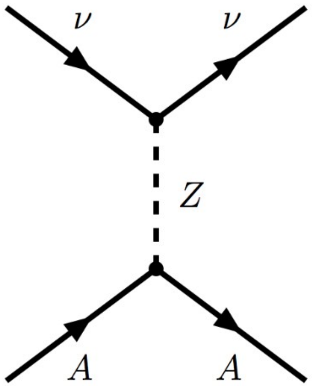
$$E_\nu \leq \frac{hc}{R_N} \approx O(50\text{MeV})$$

extension of nucleus

Maximal nucleus recoil energy:

$$E_r^{\max} = \frac{2E_\nu^2}{M_A} \approx O(\text{keV})$$

mass nucleus



Many running and upcoming experiments, e.g.

- COHERENT: 6.7σ observation, compatible with SM (Akimov et al. 2017)
- CONUS, MINER, RICOCHET, CONNIE, NUCLEUS, RED100, TEXONO ...

Rich physics opportunities:

- Light mediators, neutrino NSIs, neutrino magnetic moments, CPV mediators
  Billard et al. (2019), Lindner et al. (2017), Bischer et al. (2019), Kosmas et al. (2015), Miranda et al. (2019), Sierra et al. (2019), ...
- Link to dark matter, neutrino oscillations, supernovae dynamics
  Brdar et al. (2018), Colama et al. (2017), Wilson et al., ...
- Link to nuclear physics, form factors, neutron radius
  Amanik + McLaughlin, Patton et al. (2012), Caddedu et al. (2017), ...

Window to New Physics: CEvNS

Neutrino energy for coherence:

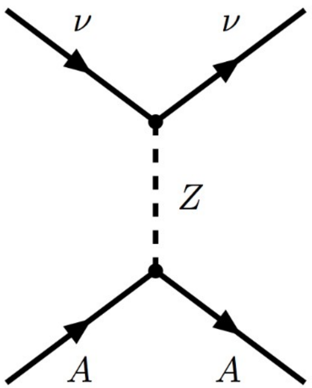
$$E_\nu \leq \frac{hc}{R_N} \approx O(50\mathrm{MeV})$$

extension of nucleus

Maximal nucleus recoil energy:

$$E_r^{\max} = \frac{2E_\nu^2}{M_A} \approx O(\mathrm{keV})$$

mass nucleus



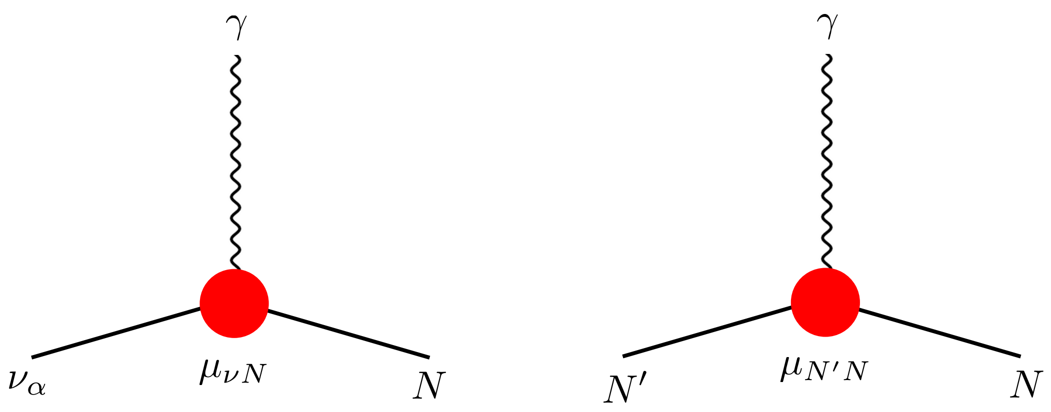
Many running and upcoming experiments, e.g.

- COHERENT: 6.7σ observation, compatible with SM (Akimov et al. 2017)
- CONUS, MINER, RICOCHET, CONNIE, NUCLEUS, RED100, TEXONO ...

Rich physics opportunities:

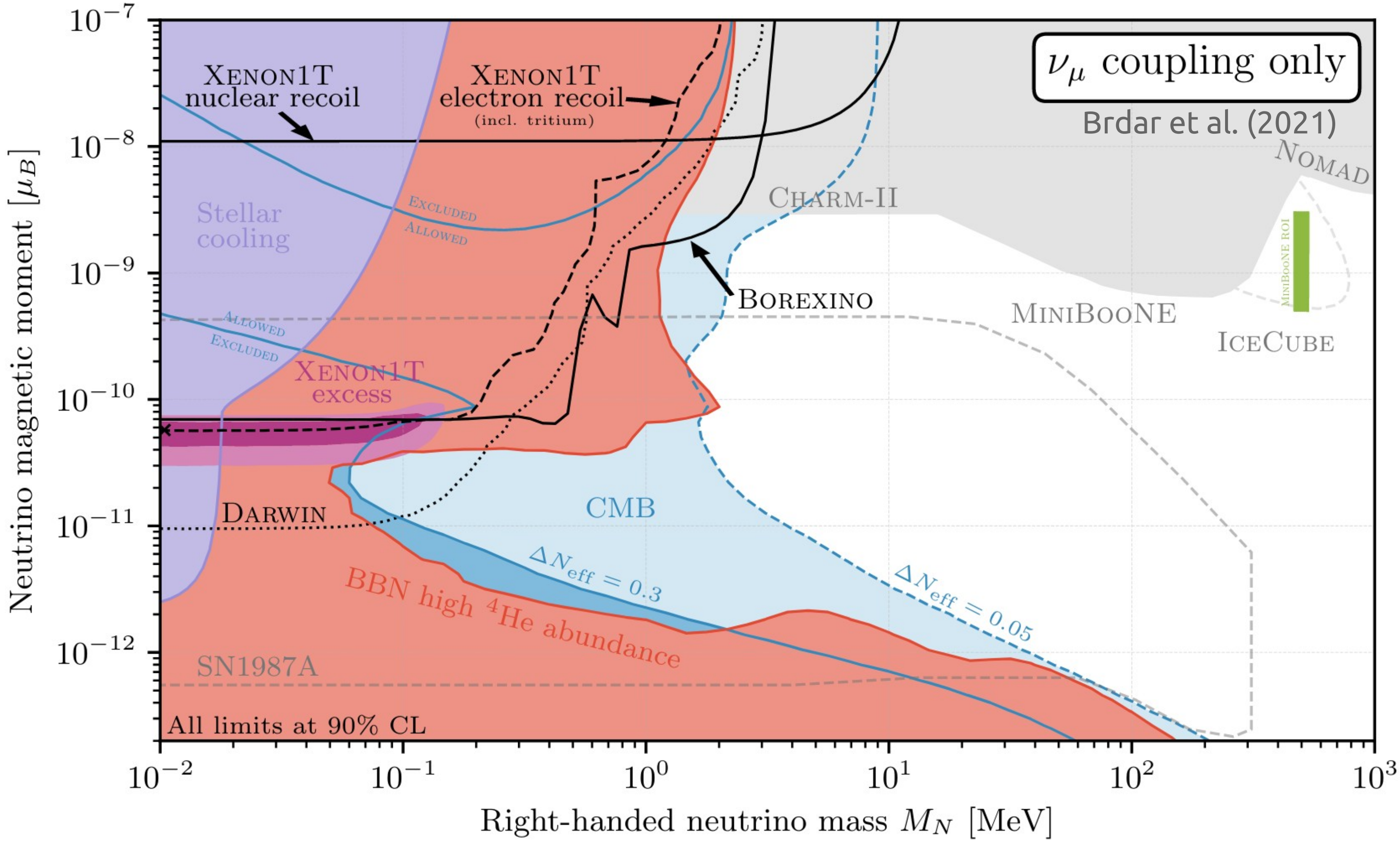
- Light mediators, neutrino NSIs, **neutrino magnetic moments**, CPV mediators
  Billard et al. (2019), Lindner et al. (2017), Bischer et al. (2019), Kosmas et al. (2015), Miranda et al. (2019), Sierra et al. (2019), ...
- Link to dark matter, neutrino oscillations, supernovae dynamics
  Brdar et al. (2018), Colama et al. (2017), Wilson et al., ...
- Link to nuclear physics, form factors, neutron radius
  Amanik + McLaughlin, Patton et al. (2012), Caddedu et al. (2017), ...

Neutrino transition magnetic moments



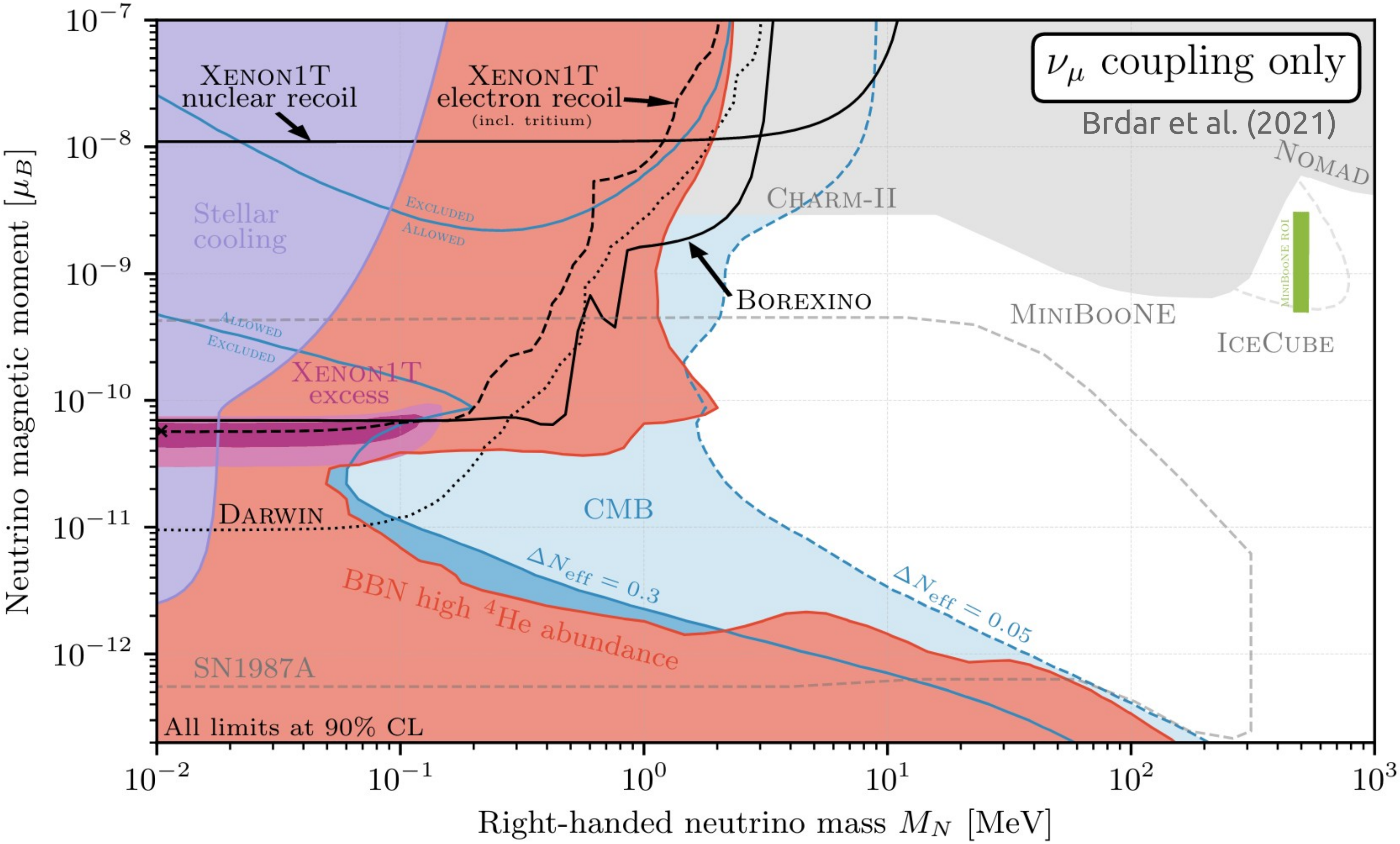
$$\mathcal{L} \supset \mu^{\alpha}_{\nu N} \bar{\nu}_{\alpha L} \sigma_{\mu\nu} P_R N F^{\mu\nu} + \mu^{\alpha}_{N' N} \bar{N}' \sigma_{\mu\nu} P_R N F^{\mu\nu} + \text{h.c.}$$

Latest constraints on neutrino magnetic moment



Brdar et al. (2021)

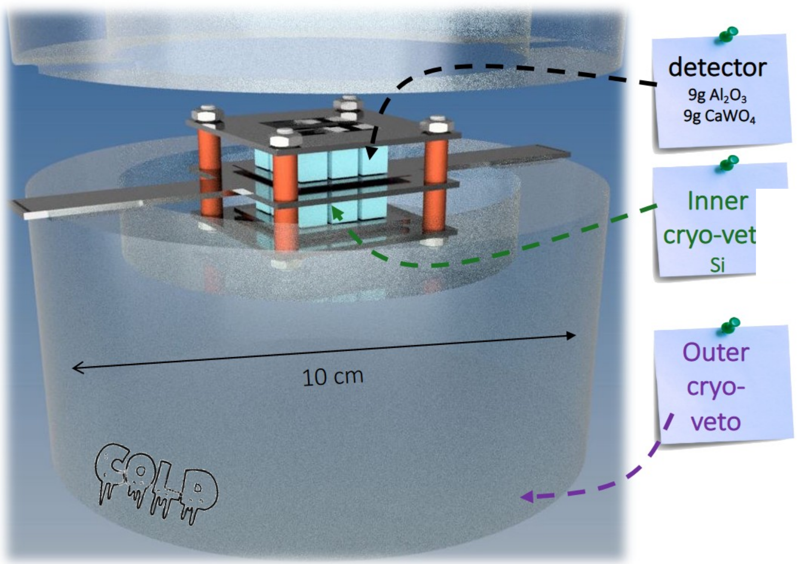
Latest constraints on neutrino magnetic moment



How does coherent elastic neutrino nucleus scattering compare?

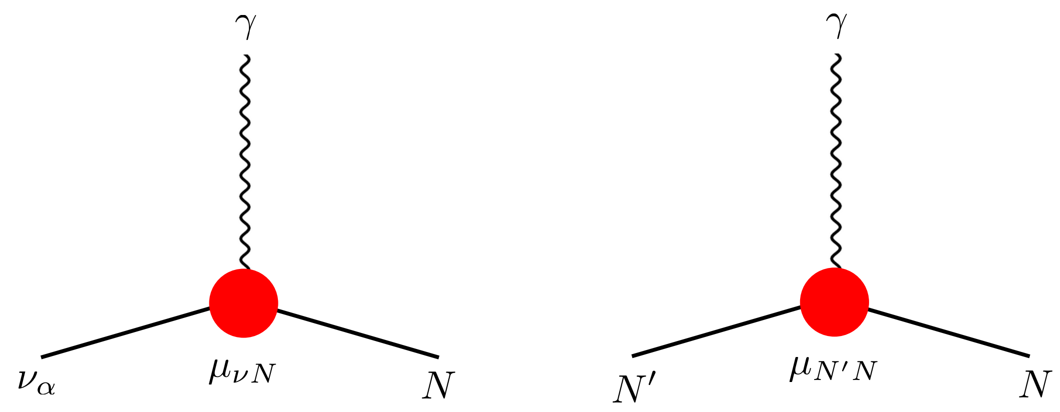
The NUCLEUS experiment

- **At the very near site (VNS) of Double-Chooz**
- **NUCLEUS-phase 1: 10g $Al_2O_3/CaWO_4$**
- **NUCLEUS-phase 2: 1kg ^{73}Ge upgrade**
- **Energy threshold: 10 eV**
- **Sensitivity to photon energy: 1keV to 10 MeV**
- **Distance to cryogenic outer veto L_{det} = 5cm for phase 1, L_{det} = 25cm for phase 2**



T. Lasserre

Neutrino transition magnetic moments



$$\mathcal{L} \supset \mu^\alpha_{\nu N} \bar{\nu}_{\alpha L} \sigma_{\mu\nu} P_R N F^{\mu\nu} + \mu^\alpha_{N'N} \bar{N}' \sigma_{\mu\nu} P_R N F^{\mu\nu} + \text{h.c.}$$

Dirac: $\nu_\alpha = \nu_{\alpha L} + \nu_{\alpha R}$

Majorana: $\nu_\alpha = \nu_{\alpha L} + \nu^c_{\alpha L}$

Dirac: $N = N_L + N_R$

Majorana: $N = N^c_R + N_R$

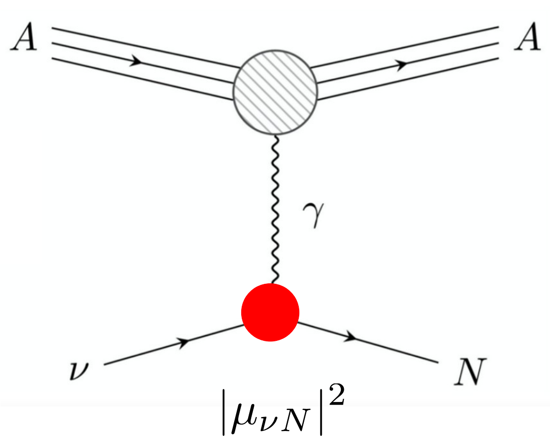
For scales much larger than the light active neutrinos $m_\nu \ll E_\nu$, rates are identical for Dirac and Majorana active neutrinos → agreement with Dirac-Majorana confusion theorem

- **→ How sensitive is the NUCLEUS experiment to neutrino transition magnetic moments?**
- **→ Can we distinguish Dirac vs. Majorana right-handed neutrinos (RHNs)?**

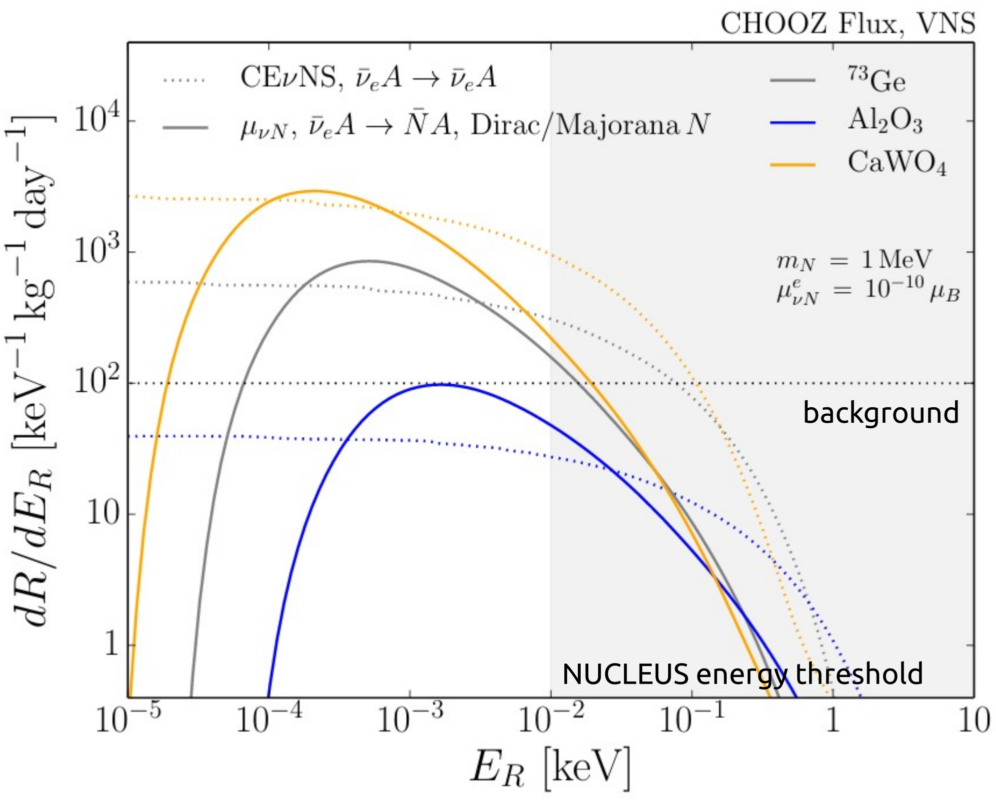
Probing neutrino magnetic moments with CEvNS

$$\frac{dR^{\rm D(M)}_{\bar\nu_e A\to\bar\nu_e A}}{dE_R} \propto \int_{E_\nu^{\rm min}}^{E_\nu^{\rm max}} dE_\nu \, \frac{d\phi_{\nu_\alpha}}{dE_\nu} \frac{d\sigma^{\rm D(M)}_{\bar\nu_e A\to\bar\nu_e A}}{dE_R}$$

$$\frac{d\sigma^{\rm D(M)}_{\bar\nu_e A\to\bar\nu_e A}}{dE_R} \approx (\mu^\alpha_{\nu N})^2 \alpha Z^2 \left[\frac{1}{E_R} - \frac{m_N^2}{4E_R E_\nu^2}\right] \quad \text{for} \quad m_N \ll m_A$$

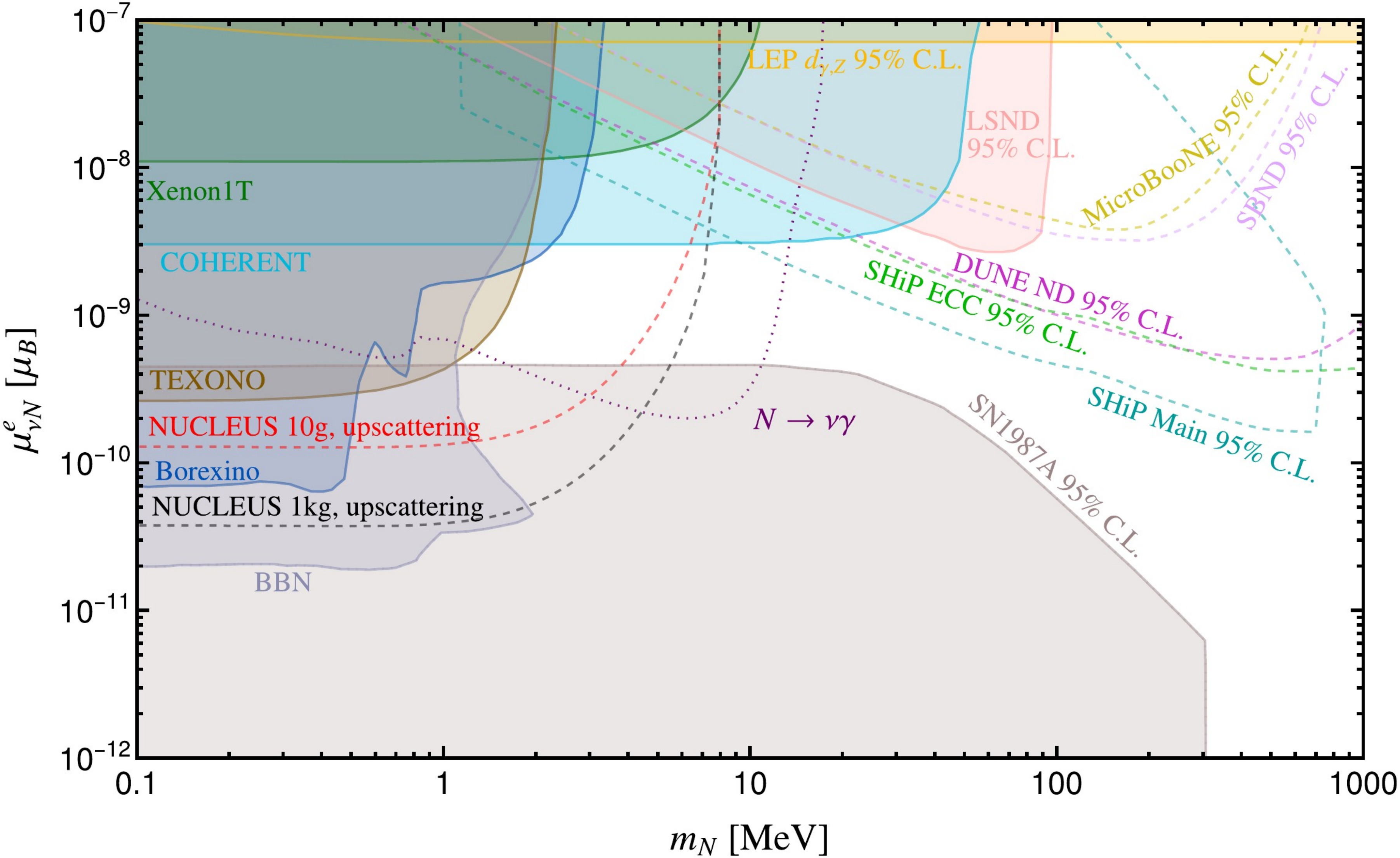


Primakoff-upscattering



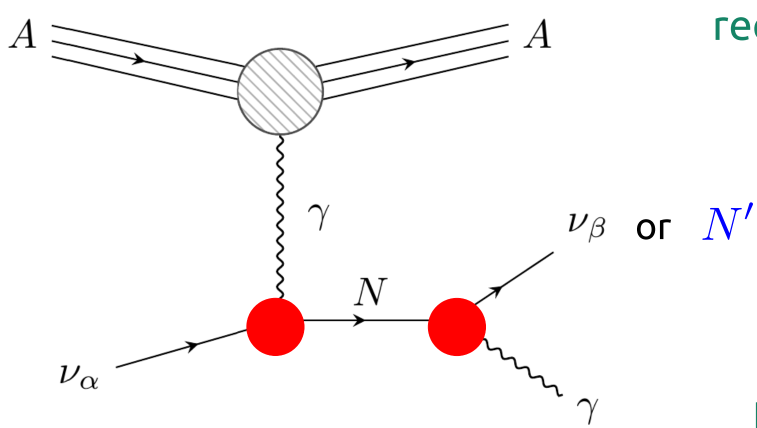
- **no access over SM + background → constraint on $\mu^e_{\nu N}$**
- **no difference between Majorana or Dirac right-handed neutrino**

Sensitivity of NUCLEUS to CEvNS



Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)
see also for other CEvNS limits e.g. Miranda, Papoulias, Sanders, Tortola, Valle (2021)

CEvNS with Photon Emission



$|\mu^{\alpha}_{\nu N}\mu^{\beta}_{\nu N}|^2$ or $|\mu^{\alpha}_{\nu N}\mu_{NN'}|^2$

recoil energy E_R

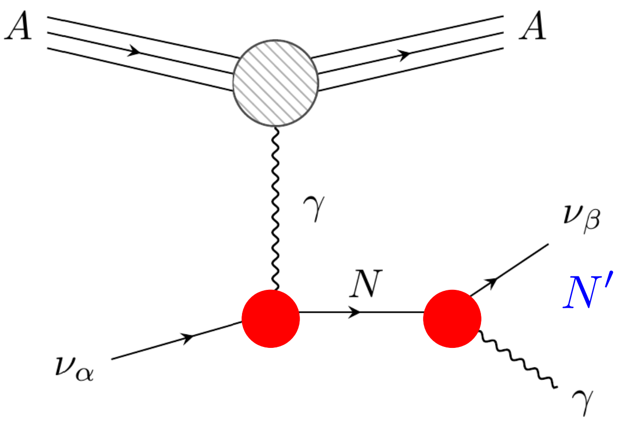
not detected

photon energy and angular distribution E_γ θ_γ

Primakoff-upscattering with photon emission

Suppressed, but new smoking gun signal due to coincidence event: recoil energy plus photon detection!

CEvNS with Photon Emission



$$i\mathcal{M}^{\mathrm{D}}_{\nu_\alpha A\to\nu_\beta A\gamma} = \mu^{\alpha}_{\nu N}\mu^{\beta}_{\nu N}[\bar{u}_{\nu_\beta}\sigma_{\mu\nu}P_R(p_N+m_N)\sigma_{\rho\sigma}P_L u_{\nu_\alpha}]X^{\mu\nu\rho\sigma}$$

$$i\mathcal{M}^{\mathrm{M}}_{\nu_\alpha A\to\nu_\beta A\gamma} = \mu^{\alpha}_{\nu N}\mu^{\beta}_{\nu N}[\bar{u}_{\nu_\beta}\sigma_{\mu\nu}(p_N+m_N)\sigma_{\rho\sigma}P_L u_{\nu_\alpha}]X^{\mu\nu\rho\sigma}$$

Electron-recoil distribution:

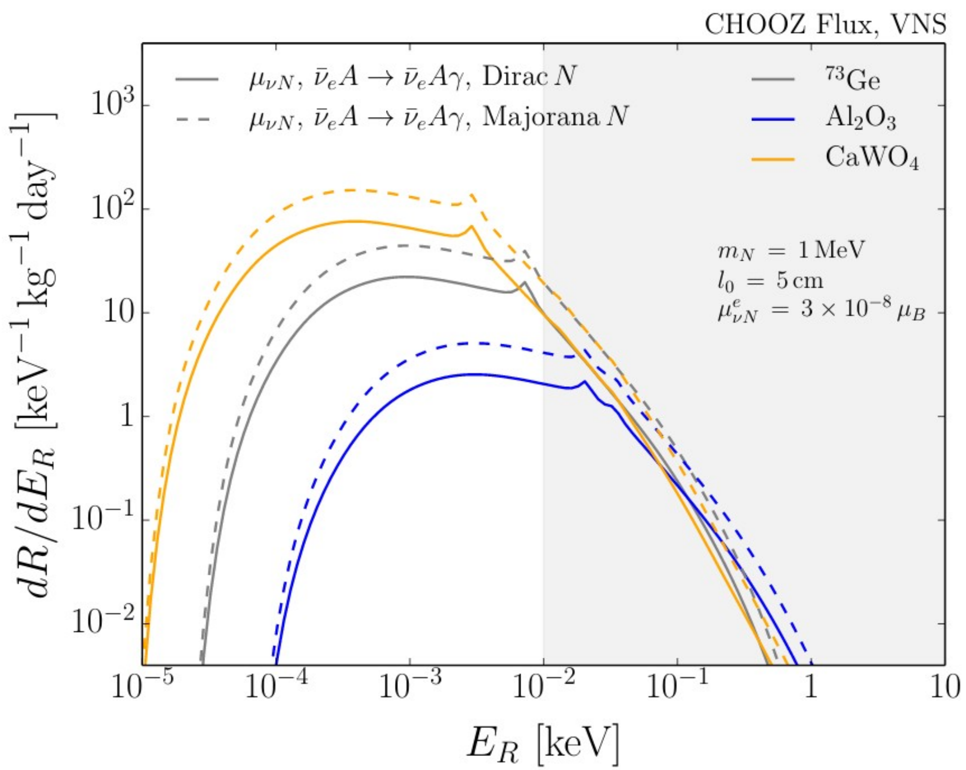
$$\left.\frac{d\sigma^{\mathrm{D(M)}}_{\nu_\alpha A\to\nu_\beta A\gamma}}{dE_R}\right|_{\mathrm{NWA}} = \frac{d\sigma_{\nu_\alpha A\to NA}}{dE_R}\frac{\Gamma^{\mathrm{D(M)}}_{N\to\nu_\beta\gamma}+\Gamma^{\mathrm{D(M)}}_{N\to N'\gamma}}{\Gamma_N}$$

Differential rate wrt to the nuclear recoil energy for coincidence event:

$$\frac{dR_{\nu_\alpha A\to\nu_\beta A\gamma}}{dE_R} \propto \int_{E_\nu^{\min}}^{E_\nu^{\max}} dE_\nu \frac{d\phi_{\nu_\alpha}}{dE_\nu}\frac{d\sigma^{\mathrm{D(M)}}_{\nu_\alpha A\to NA}}{dE_R}\mathcal{B}_{N\to X\gamma}\left(1-\exp\left(-\frac{L_{\det}\Gamma_N}{\beta\gamma}\right)\right)$$

Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

Majorana vs Dirac RHN – nuclear recoil



$$\left.\frac{d\sigma^{\mathrm{D(M)}}_{\nu_\alpha A \to \nu_\beta A \gamma}}{dE_R}\right|_{\mathrm{NWA}} = \frac{d\sigma_{\nu_\alpha A \to N A}}{dE_R} \frac{\Gamma^{\mathrm{D(M)}}_{N \to X\gamma}}{\Gamma_N}$$

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

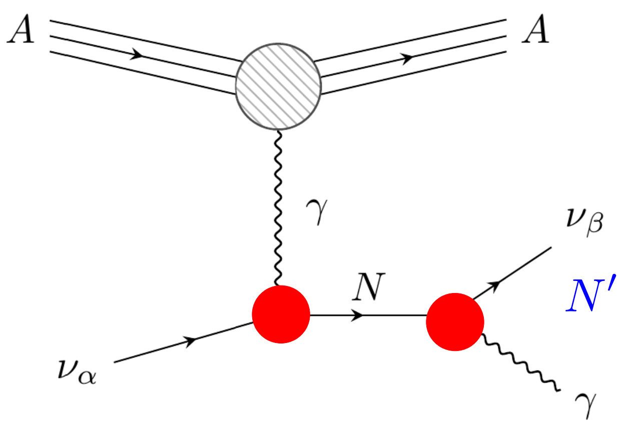
With nuclear recoil only no possibility to disentangle Dirac vs Majorana nature, as factor 2 can be absorbed into magnetic moment.

Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

Sensitivity to CEvNS with Photon Emission

$$i\mathcal{M}^{\mathrm{D}}_{\nu_\alpha A\to\nu_\beta A\gamma} = \mu^{\alpha}_{\nu N}\mu^{\beta}_{\nu N}[\bar{u}_{\nu_\beta}\sigma_{\mu\nu}P_R(p_N+m_N)\sigma_{\rho\sigma}P_L u_{\nu_\alpha}]X^{\mu\nu\rho\sigma}$$

$$i\mathcal{M}^{\mathrm{M}}_{\nu_\alpha A\to\nu_\beta A\gamma} = \mu^{\alpha}_{\nu N}\mu^{\beta}_{\nu N}[\bar{u}_{\nu_\beta}\sigma_{\mu\nu}(p_N+m_N)\sigma_{\rho\sigma}P_L u_{\nu_\alpha}]X^{\mu\nu\rho\sigma}$$



Electron-recoil distribution:

$$\left.\frac{d\sigma^{\mathrm{D(M)}}_{\nu_\alpha A\to\nu_\beta A\gamma}}{dE_R}\right|_{\mathrm{NWA}} = \frac{d\sigma_{\nu_\alpha A\to NA}}{dE_R}\frac{\Gamma^{\mathrm{D(M)}}_{N\to\nu_\beta\gamma}+\Gamma^{\mathrm{D(M)}}_{N\to N'\gamma}}{\Gamma_N}$$

Differential rate wrt to the nuclear recoil energy for coincidence event:

$$\frac{dR_{\nu_\alpha A\to\nu_\beta A\gamma}}{dE_R} \propto \int_{E_\nu^{\min}}^{E_\nu^{\max}} dE_\nu \frac{d\phi_{\nu_\alpha}}{dE_\nu}\frac{d\sigma^{\mathrm{D(M)}}_{\nu_\alpha A\to NA}}{dE_R}\mathcal{B}_{N\to X\gamma}\left(1-\exp\left(-\frac{L_{\mathrm{det}}\Gamma_N}{\beta\gamma}\right)\right)$$

Number of coincidence events:

$$N^{\gamma}_{\mathrm{exp}} = T_{\mathrm{run}}m_{\mathrm{det}}\int_{E_R^{\min}}^{E_R^{\max}} dE_R\frac{dR_{\nu_\alpha A\to\nu_\beta A\gamma}}{dE_R} < 2.30 \quad (90\ \%\mathrm{C.L.})$$

Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

Sensitivity to CEvNS with Photon Emission

For coincidence signal, photon needs to decay within the detector (NUCLEUS: L_{det} = 5cm):

$$\frac{dR_{\nu_\alpha A\to\nu_\beta A\gamma}}{dE_R} \supset \frac{\Gamma_{N\to\nu_\beta\gamma}+\Gamma_{N\to N'\gamma}}{\Gamma_{N\to\nu_\beta\gamma}+\Gamma_{N\to N'\gamma}+\Gamma_{N\to\mathrm{inv}}}\left(1-\exp\left(-\frac{L_{\mathrm{det}}(\Gamma_{N\to\nu_\beta\gamma}+\Gamma_{N\to N'\gamma}+\Gamma_{N\to\mathrm{inv}})}{\beta\gamma}\right)\right)$$

To cover different possible realizations, we distinguish three cases:

(1) Only active-to-sterile transition

$$\mu_{\nu N}\neq 0, \mu_{NN'}=0, \Gamma_{N\to\mathrm{inv}}=0$$

$$\mathcal{B}_{N\to X\gamma}=1$$

$$P_N^{\mathrm{det}}=\Gamma_{N\to X\gamma}L_{\mathrm{det}}/\beta\gamma\ll 1$$

(2) Active-to-sterile transition + invisible decays

$$\mu_{\nu N}\neq 0, \mu_{NN'}=0, \Gamma_{N\to\mathrm{inv}}=\beta\gamma/L_{\mathrm{det}}\gg\Gamma_{N\to X\gamma}$$

$$\mathcal{B}_{N\to X\gamma}\ll 1$$

$$P_N^{\mathrm{det}}=0.63$$

(3) Active-to-sterile + sterile-to-sterile transition

$$\mu_{\nu N}\neq 0, \mu_{NN'}=10^{-6}\ \mu_B, \Gamma_{N\to\mathrm{inv}}=0$$

$$\mathcal{B}_{N\to X\gamma}=1$$

$$P_N^{\mathrm{det}}\sim 1$$

Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

Sensitivity to CEvNS with Photon Emission

For coincidence signal, photon needs to decay within the detector (NUCLEUS: L_{det} = 5cm):

$$\frac{dR_{\nu_\alpha A\to\nu_\beta A\gamma}}{dE_R} \supset \frac{\Gamma_{N\to\nu_\beta\gamma}+\Gamma_{N\to N'\gamma}}{\Gamma_{N\to\nu_\beta\gamma}+\Gamma_{N\to N'\gamma}+\Gamma_{N\to \mathrm{inv}}}\left(1-\exp\left(-\frac{L_{\mathrm{det}}(\Gamma_{N\to\nu_\beta\gamma}+\Gamma_{N\to N'\gamma}+\Gamma_{N\to \mathrm{inv}})}{\beta\gamma}\right)\right)$$

To cover different possible realizations, we distinguish three cases:

(1) Only active-to-sterile transition

$$\mu_{\nu N}\neq 0, \mu_{NN'}=0, \Gamma_{N\to\mathrm{inv}}=0$$

$$\mathcal{B}_{N\to X\gamma}=1$$

$$P_N^{\mathrm{det}}=\Gamma_{N\to X\gamma}L_{\mathrm{det}}/\beta\gamma\ll 1$$

(2) Active-to-sterile transition + invisible decays

$$\mu_{\nu N}\neq 0, \mu_{NN'}=0, \Gamma_{N\to\mathrm{inv}}=\beta\gamma/L_{\mathrm{det}}\gg\Gamma_{N\to X\gamma}$$

$$\mathcal{B}_{N\to X\gamma}\ll 1$$

$$P_N^{\mathrm{det}}=0.63$$

(3) Active-to-sterile + sterile-to-sterile transition

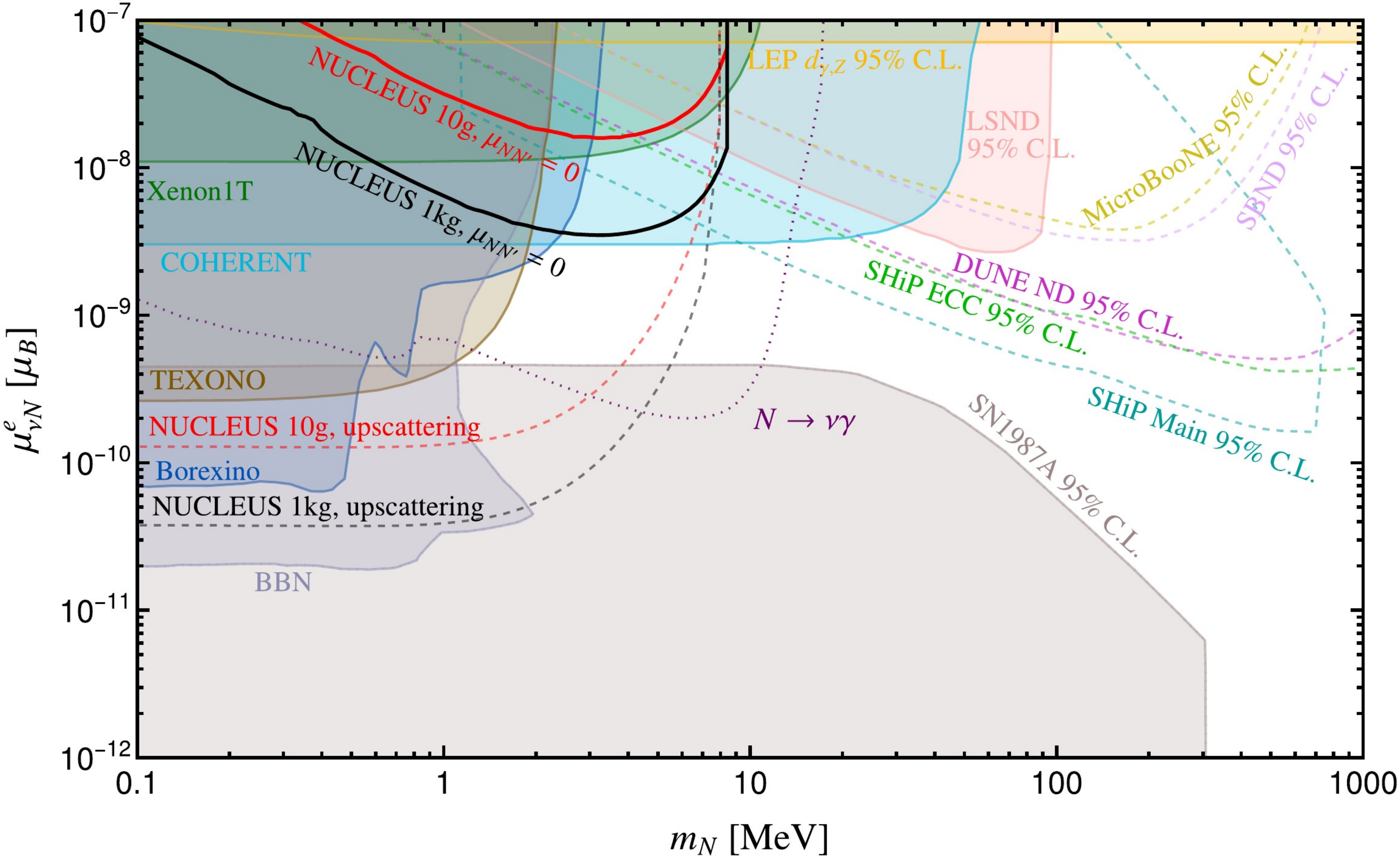
$$\mu_{\nu N}\neq 0, \mu_{NN'}=10^{-6}\ \mu_B, \Gamma_{N\to\mathrm{inv}}=0$$

$$\mathcal{B}_{N\to X\gamma}=1$$

$$P_N^{\mathrm{det}}\sim 1$$

Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

Sensitivity to CEvNS with Photon Emission



Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

Sensitivity to CEvNS with Photon Emission

For coincidence signal, photon needs to decay within the detector (NUCLEUS: L_{det} = 5cm):

$$\frac{dR_{\nu_\alpha A\to\nu_\beta A\gamma}}{dE_R} \supset \frac{\Gamma_{N\to\nu_\beta\gamma}+\Gamma_{N\to N'\gamma}}{\Gamma_{N\to\nu_\beta\gamma}+\Gamma_{N\to N'\gamma}+\Gamma_{N\to\mathrm{inv}}}\left(1-\exp\left(-\frac{L_{\mathrm{det}}(\Gamma_{N\to\nu_\beta\gamma}+\Gamma_{N\to N'\gamma}+\Gamma_{N\to\mathrm{inv}})}{\beta\gamma}\right)\right)$$

To cover different possible realizations, we distinguish three cases:

(1) Only active-to-sterile transition

$$\mu_{\nu N}\neq 0, \mu_{NN'}=0, \Gamma_{N\to\mathrm{inv}}=0$$

$$\mathcal{B}_{N\to X\gamma}=1$$

$$P_N^{\mathrm{det}}=\Gamma_{N\to X\gamma}L_{\mathrm{det}}/\beta\gamma\ll 1$$

(2) Active-to-sterile transition + invisible decays

$$\mu_{\nu N}\neq 0, \mu_{NN'}=0, \Gamma_{N\to\mathrm{inv}}=\beta\gamma/L_{\mathrm{det}}\gg\Gamma_{N\to X\gamma}$$

$$\mathcal{B}_{N\to X\gamma}\ll 1$$

$$P_N^{\mathrm{det}}=0.63$$

(3) Active-to-sterile + sterile-to-sterile transition

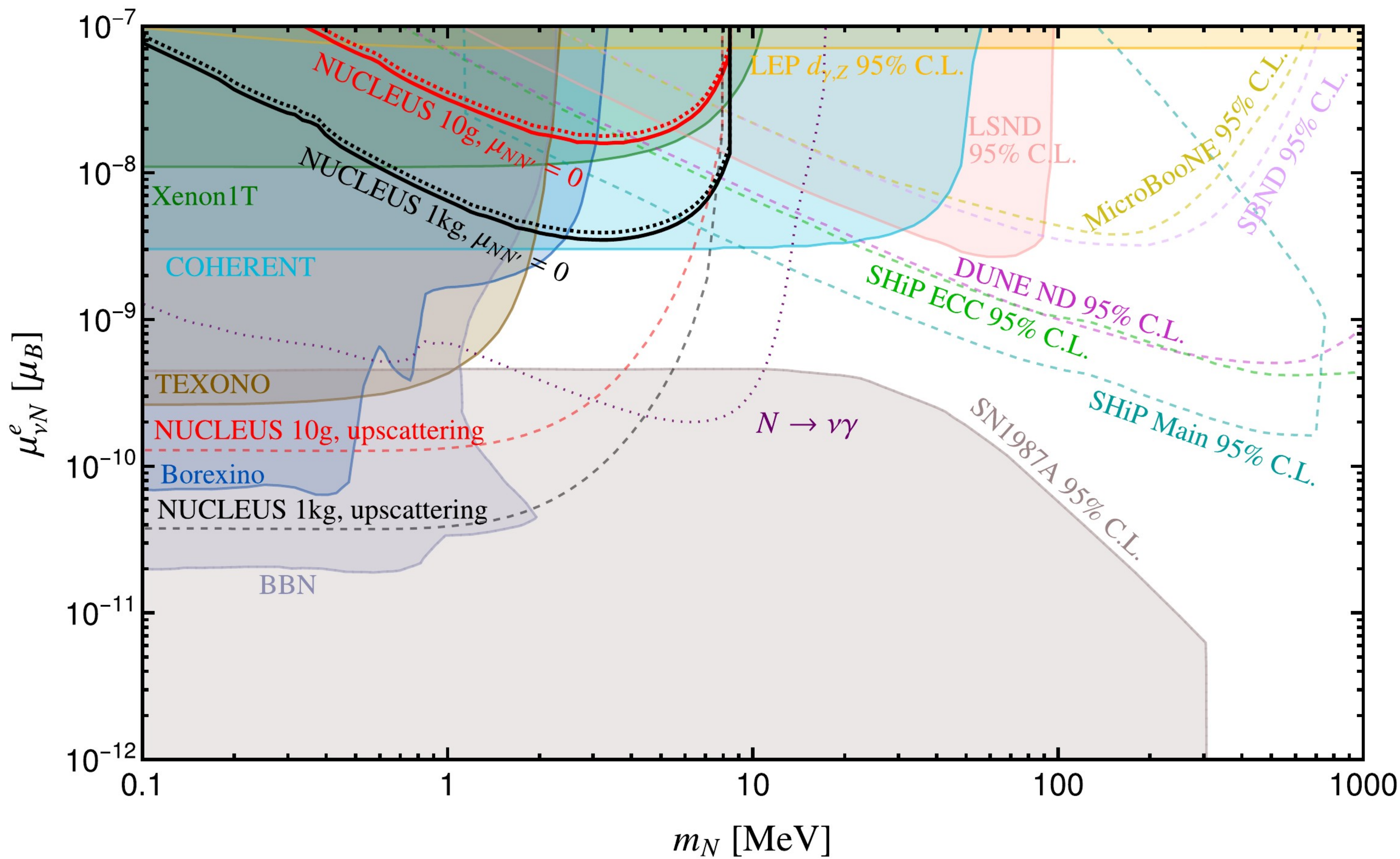
$$\mu_{\nu N}\neq 0, \mu_{NN'}=10^{-6}\ \mu_B, \Gamma_{N\to\mathrm{inv}}=0$$

$$\mathcal{B}_{N\to X\gamma}=1$$

$$P_N^{\mathrm{det}}\sim 1$$

Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

Sensitivity to CEvNS with Photon Emission



Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

Sensitivity to CEvNS with Photon Emission

For coincidence signal, photon needs to decay within the detector (NUCLEUS: L_{det} = 5cm):

$$\frac{dR_{\nu_\alpha A\to\nu_\beta A\gamma}}{dE_R} \supset \frac{\Gamma_{N\to\nu_\beta\gamma}+\Gamma_{N\to N'\gamma}}{\Gamma_{N\to\nu_\beta\gamma}+\Gamma_{N\to N'\gamma}+\Gamma_{N\to\mathrm{inv}}}\left(1-\exp\left(-\frac{L_{\mathrm{det}}(\Gamma_{N\to\nu_\beta\gamma}+\Gamma_{N\to N'\gamma}+\Gamma_{N\to\mathrm{inv}})}{\beta\gamma}\right)\right)$$

To cover different possible realizations, we distinguish three cases:

(1) Only active-to-sterile transition

$$\mu_{\nu N}\neq 0, \mu_{NN'}=0, \Gamma_{N\to\mathrm{inv}}=0$$

$$\mathcal{B}_{N\to X\gamma}=1$$

$$P_N^{\mathrm{det}}=\Gamma_{N\to X\gamma}L_{\mathrm{det}}/\beta\gamma \ll 1$$

(2) Active-to-sterile transition + invisible decays

$$\mu_{\nu N}\neq 0, \mu_{NN'}=0, \Gamma_{N\to\mathrm{inv}}=\beta\gamma/L_{\mathrm{det}} \gg \Gamma_{N\to X\gamma}$$

$$\mathcal{B}_{N\to X\gamma}\ll 1$$

$$P_N^{\mathrm{det}}=0.63$$

(3) Active-to-sterile + sterile-to-sterile transition

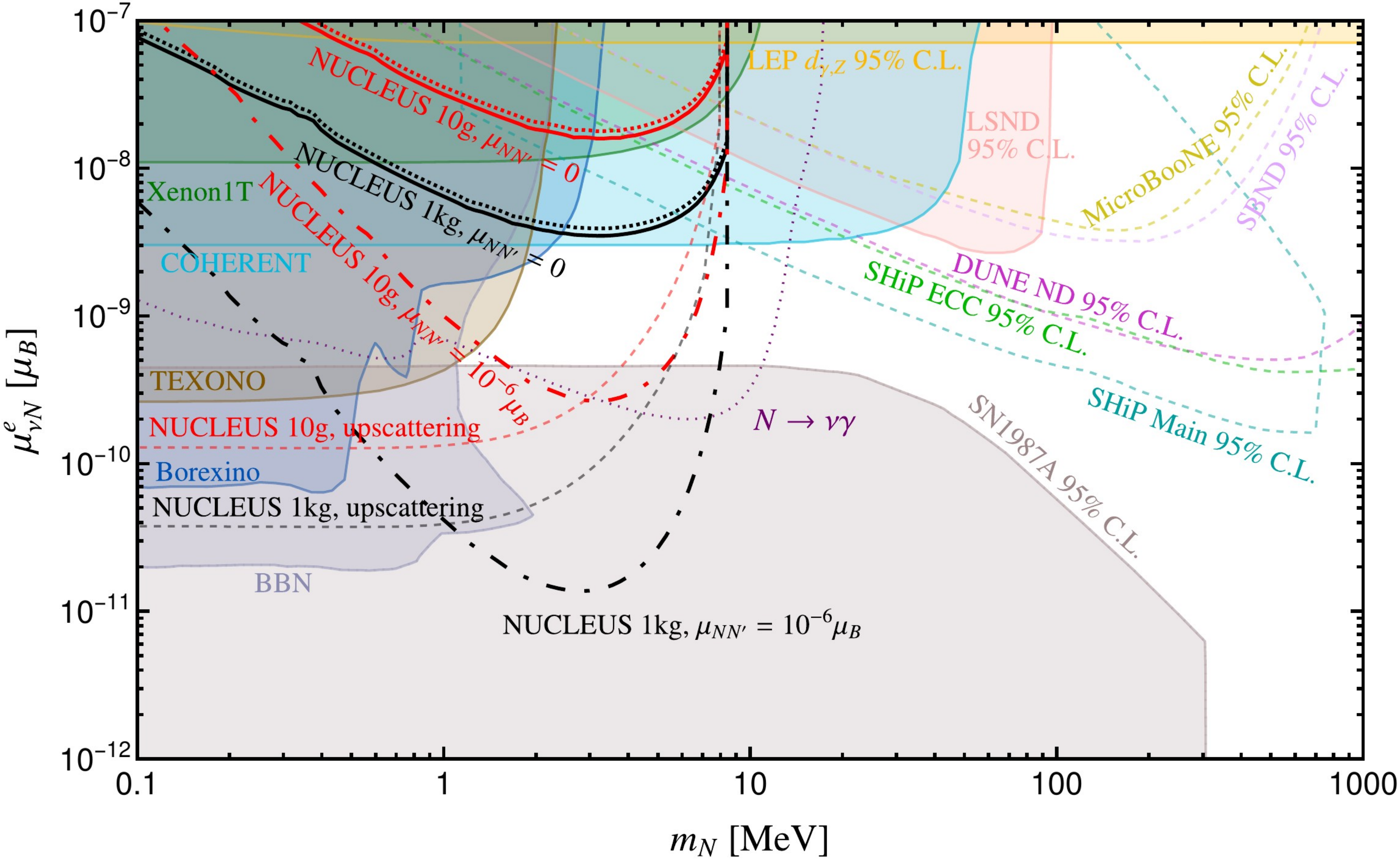
$$\mu_{\nu N}\neq 0, \mu_{NN'}=10^{-6}\;\mu_B, \Gamma_{N\to\mathrm{inv}}=0$$

$$\mathcal{B}_{N\to X\gamma}=1$$

$$P_N^{\mathrm{det}}\sim 1$$

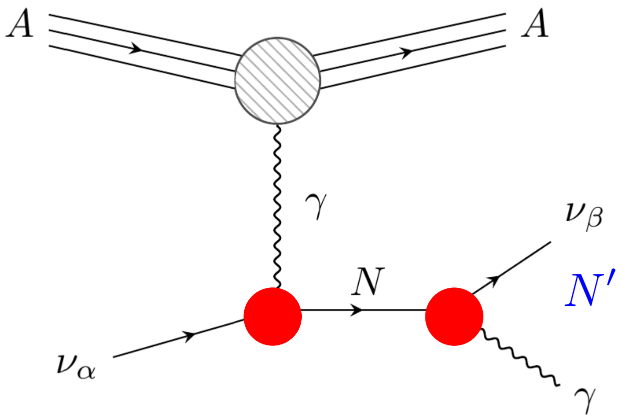
Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

Sensitivity to CEvNS with Photon Emission



Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

Majorana vs Dirac – photon spectrum



$$i\mathcal{M}^{\mathrm{D}}_{\nu_\alpha A\to\nu_\beta A\gamma} = \mu^\alpha_{\nu N}\mu^\beta_{\nu N}[\bar{u}_{\nu_\beta}\sigma_{\mu\nu}P_R(p_N+m_N)\sigma_{\rho\sigma}P_L u_{\nu_\alpha}]X^{\mu\nu\rho\sigma}$$

$$i\mathcal{M}^{\mathrm{M}}_{\nu_\alpha A\to\nu_\beta A\gamma} = \mu^\alpha_{\nu N}\mu^\beta_{\nu N}[\bar{u}_{\nu_\beta}\sigma_{\mu\nu}(p_N+m_N)\sigma_{\rho\sigma}P_L u_{\nu_\alpha}]X^{\mu\nu\rho\sigma}$$

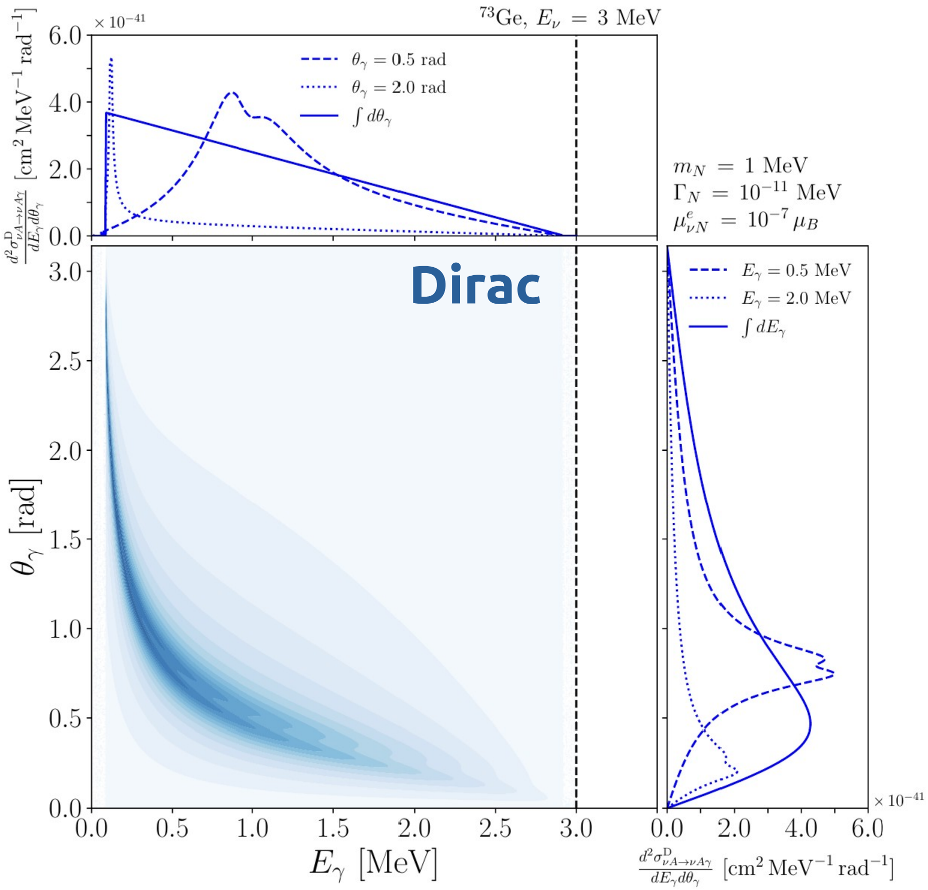
Energy and angular distribution of the photon:

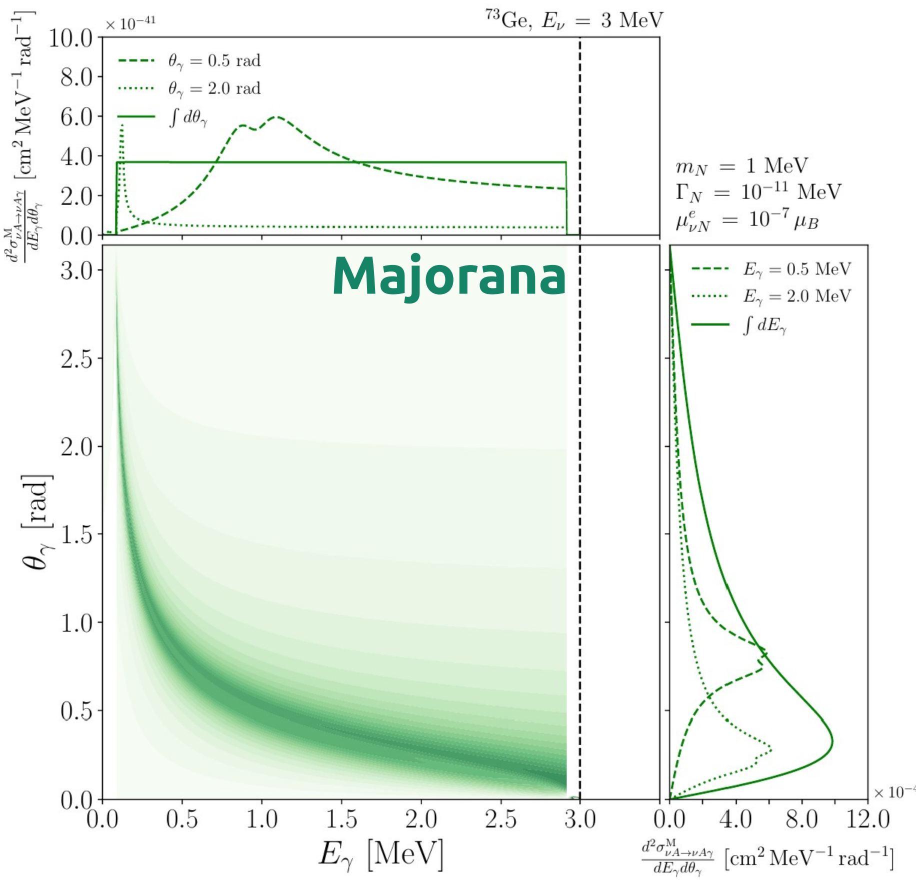
$$\left.\frac{d^2\sigma^{\mathrm{D(M)}}_{\nu_\alpha A\to\nu_\beta A\gamma}}{dE_\gamma d\theta_\gamma}\right|_{\mathrm{NWA}} = |\mu^\alpha_{\nu N}\mu^\beta_{\nu N}|^2\frac{\alpha Z^2 E_\gamma\sin\theta_\gamma}{128\pi^2 m_A E_\nu m_N\Gamma_N}\int_{t_1^-}^{t_1^+}dt_1\left.\frac{L^{\gamma,\,\mathrm{D(M)}}_{\mu\nu}H^{\mu\nu}\mathcal{F}^2(t_1)}{t_1^2\sqrt{-\Delta_4}}\right|_{s_1=m_N^2}$$

Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

Majorana vs Dirac – photon spectrum

$$E_\nu = 3\mathrm{MeV}, m_N = 1\mathrm{MeV}, \mu_{\nu N}^{\alpha} = 3\times 10^{-8}\mu_B, \Gamma_N = 10^{-11}\mathrm{MeV}$$





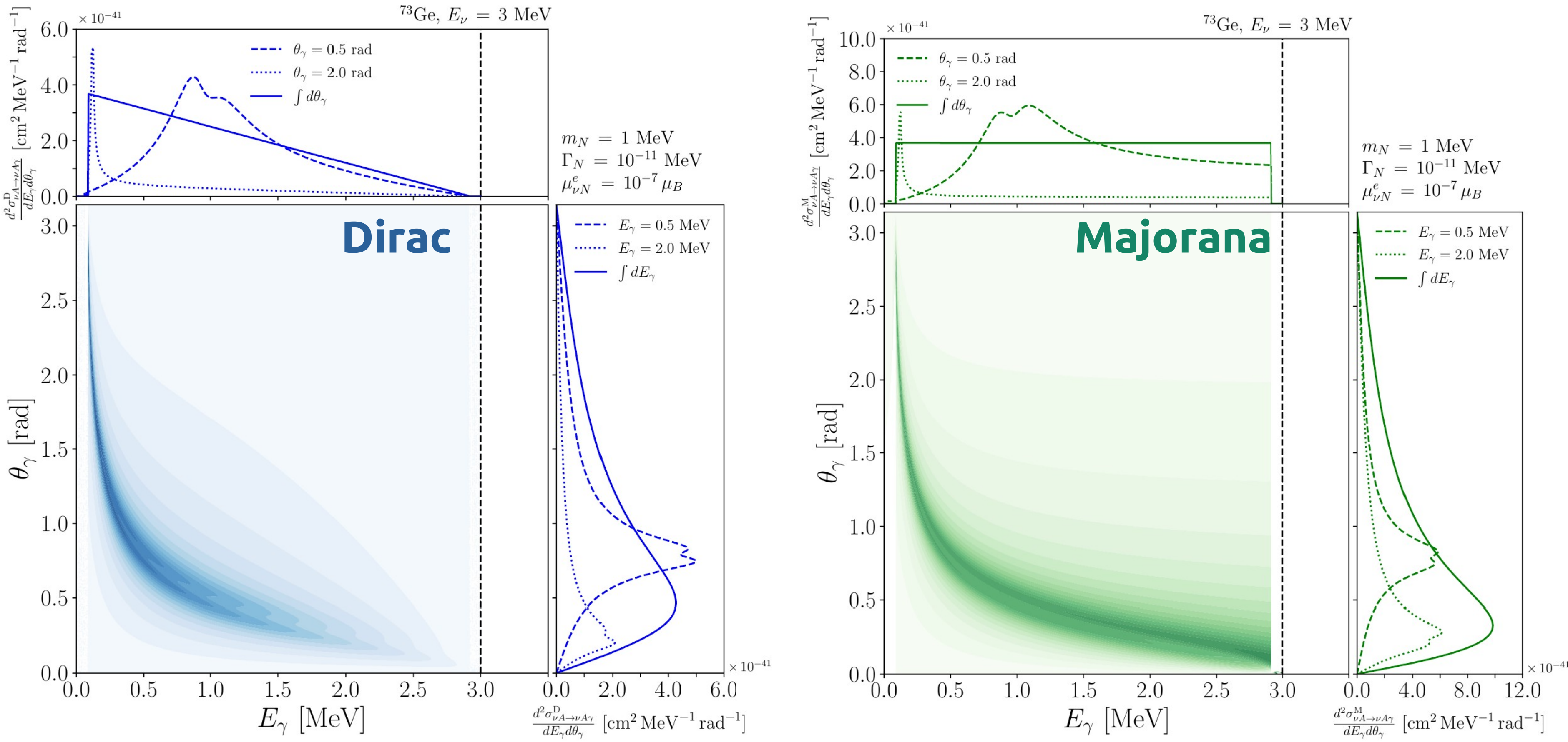
$$\frac{d^2\sigma^{\mathrm{M}}_{\nu_\alpha A\to\nu_\beta A\gamma}}{ds_1 dt_1} \Big/ \frac{d^2\sigma^{\mathrm{D}}_{\nu_\alpha A\to\nu_\beta A\gamma}}{ds_1 dt_1} = 1 + \frac{m_N^2}{s_1}$$

$\nu_\alpha A \to \nu_\beta A\gamma$ $\quad$ $\nu_\alpha A \to \bar{\nu}_\beta A\gamma$

Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

Majorana vs Dirac – photon spectrum

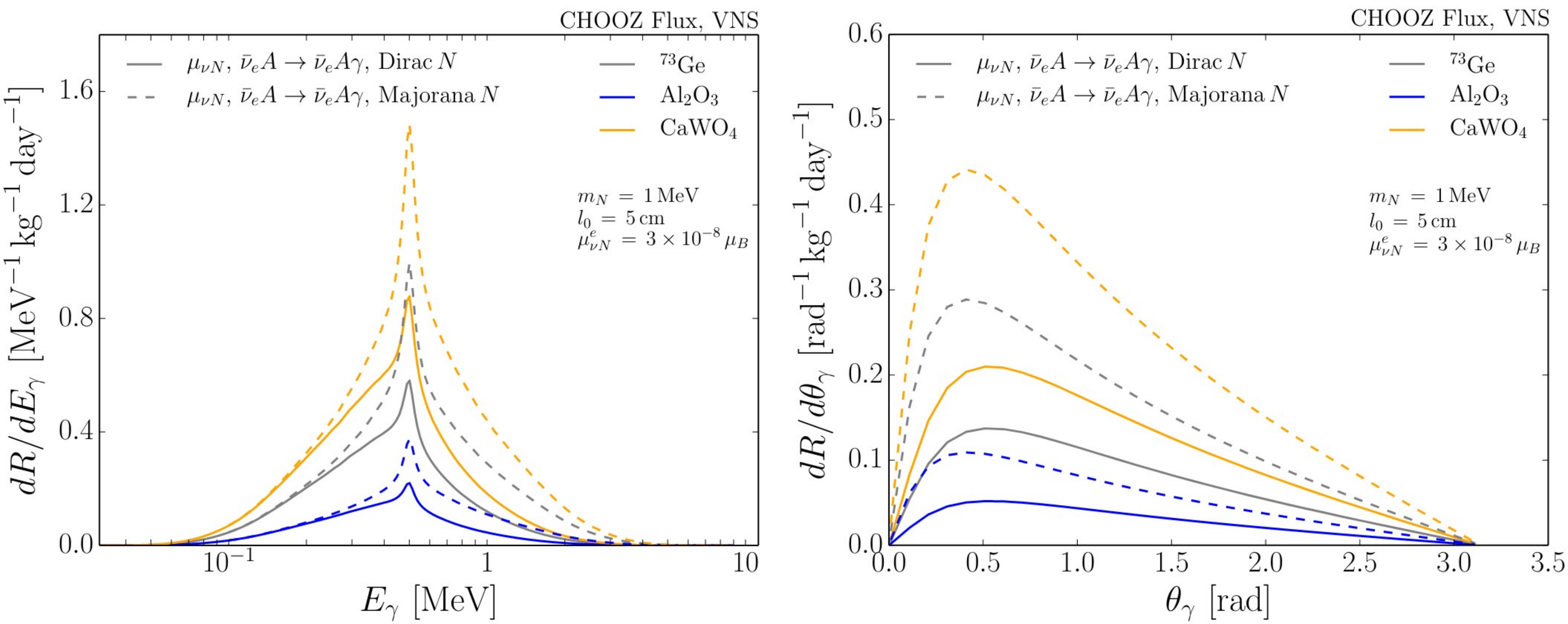
$$E_\nu = 3\text{MeV}, m_N = 1\text{MeV}, \mu^\alpha_{\nu N} = 3\times 10^{-8}\mu_B, \Gamma_N = 10^{-11}\text{MeV}$$



→ **Majorana vs Dirac nature shows clear difference for larger photon energies / smaller angles**

Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

Majorana vs Dirac – photon spectrum



$$\frac{dR^{\mathrm{D(M)}}_{\bar{\nu}_e A \to \bar{\nu}_e A\gamma}}{dE_\gamma} = \frac{1}{m_A} \int_{E_\nu^{\min}(E_\gamma)}^{E_\nu^{\max}} dE_\nu \, \frac{d\phi_{\bar{\nu}_e}}{dE_\nu} \, \frac{d\sigma^{\mathrm{D(M)}}_{\bar{\nu}_e A \to \bar{\nu}_e A\gamma}}{dE_\gamma}$$

→ **Different angular and energy distribution of photons for Dirac vs. Majorana RHNs**

Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

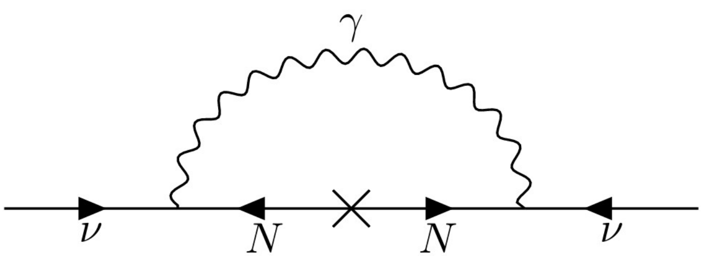
Insight in the nature of active neutrinos

- **In case of contribution consistent to Dirac RHN:**

  → no conclusive statement possible

- **In case of contribution consistent to Majorana RHN:**

$$m_\nu \sim \frac{1}{16\pi^2}\mu_{\nu N}^2 m_N \Lambda^2$$
$$\sim \left(\frac{\mu_{\nu N}}{\mu_B}\right)^2 \frac{\alpha}{16\pi}\frac{m_N \Lambda^2}{m_e^2}$$



→ implies lepton-number violation and a Majorana mass term for active neutrinos

→ complementary probe to LNV at LHC or neutrinoless double beta decay

For example, $m_N \sim 1$ MeV, $\Lambda \sim 1$ TeV and $m_\nu < 1$ eV → $\frac{|\mu_{\nu N}|}{\mu_B} < 10^{-8}$

Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

Conclusions

- **Photon emission off Primakoff-upscattering as new smoking gun signature for the detection of neutrino magnetic moments**

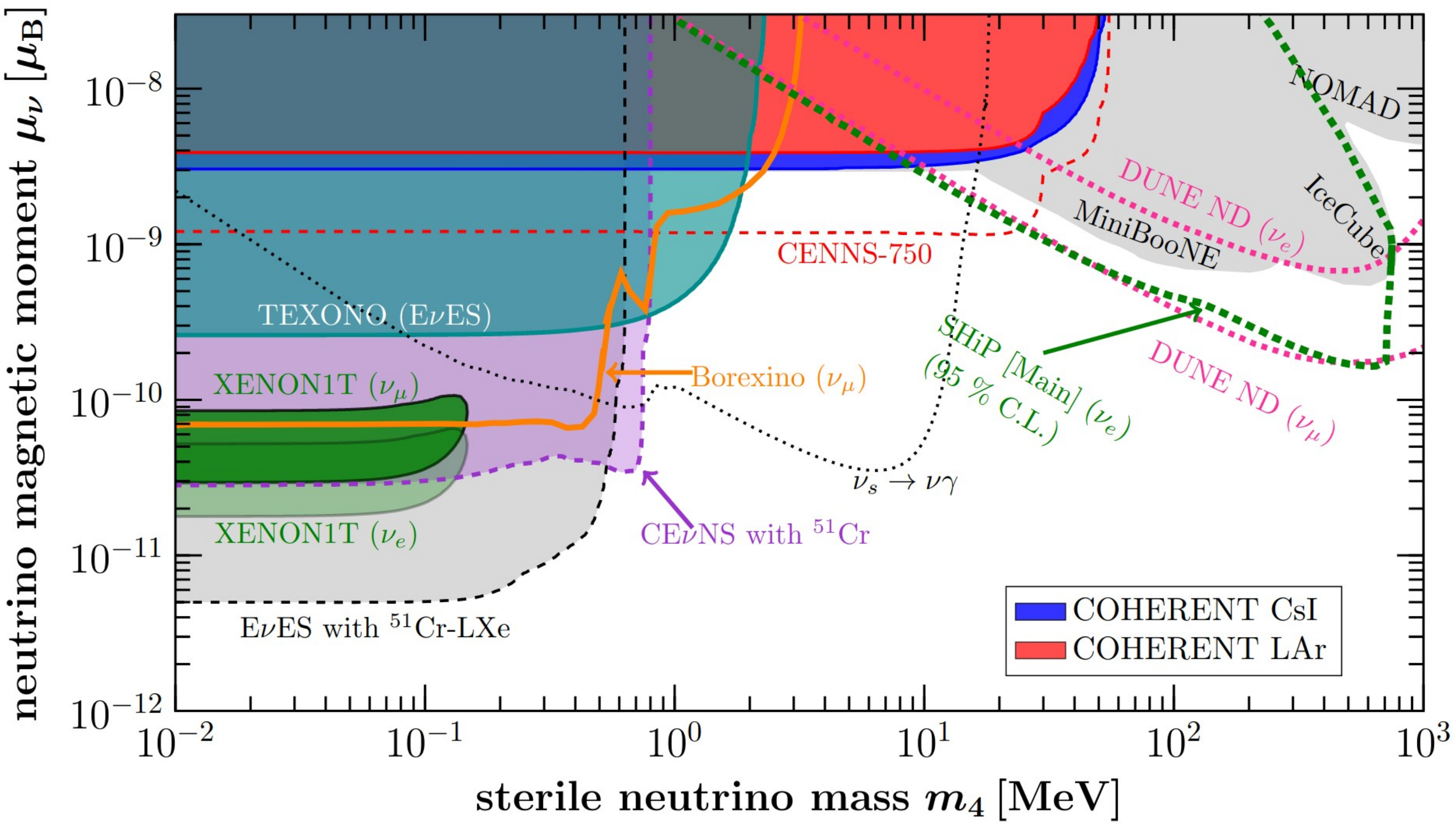
- **Photon detection allows for identifying Majorana vs Dirac nature of RHNs**

- **Identification of RHN give hints towards the Majorana vs Dirac nature of active neutrinos**

→ Maybe yet a hubris, but motivation to probe beyond nuclear recoil energy

Thank you for your attention!

Probing neutrino magnetic moments with CEvNS

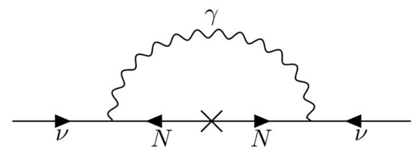


Miranda, Papoulias, Sanders, Tortola, Valle (2021)

Hint towards the neutrino mass mechanism?

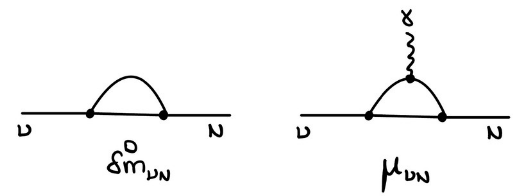
- **Majorana mass term**

$$\delta m_\nu^M \sim \left(\frac{\mu_{\nu N}}{\mu_B}\right)^2 \frac{\alpha}{16\pi}\frac{m_N \Lambda^2}{m_e^2}$$



- **if transition magnetic moment gets loop induced via heavy NP**

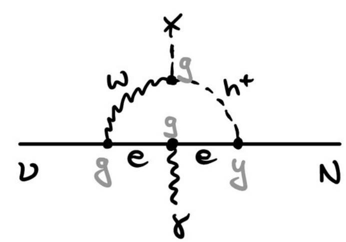
$$\mu_{\nu N} \sim \frac{e}{\Lambda^2}\delta m_{\nu N}^D \qquad \frac{\mu_{\nu N}}{\mu_B} \sim \frac{m_e \delta m_{\nu N}^D}{\Lambda^2}$$



$$\frac{|\mu_{\nu N}|}{\mu_B} \sim 10^{-13}\frac{\delta m_{\nu N}^D}{1keV}$$

- **active-to-sterile mixing**

$$\mu_{\nu N} \sim \frac{g^3 y v}{16\pi^2 m_W^2} \qquad \frac{\mu_{\nu N}}{\mu_B} \sim \frac{m_{\nu N}^D m_e G_F}{16\pi^2\sqrt{2}}$$



$$\frac{|\mu_{\nu N}|}{\mu_B} \sim 10^{-14}\frac{m_{\nu N}^D}{1keV}$$

For example, see-saw type I with m_N ~ 50 MeV, Λ ~ 1 TeV and $m^D_{\nu N}$ ~ 1 keV → m_ν ~ 0.2eV

A sign for radiative CEvNS would imply a neutrino mass mechanism beyond see-saw type I!

Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

How magnetic can the neutrino be?

$$\mathcal{L}_{\text{eff}} = \sum_{n,j} \frac{C_j^n(\mu)}{\Lambda^{n-4}} \, \mathcal{O}_j^{(n)}(\mu) \; + \; \text{h.c.}$$

$$\begin{aligned}
\mathcal{O}_1^{(6)} &= g' \bar{L}\tilde{H}\sigma_{\mu\nu} N_R B^{\mu\nu} \\
\mathcal{O}_2^{(6)} &= g \bar{L}\tau^a \tilde{H}\sigma_{\mu\nu} N_R W^{a\mu\nu} \\
\mathcal{O}_3^{(6)} &= \bar{L}\tilde{H} N_R \left(H^\dagger H\right)
\end{aligned}$$

$$C_3^{(6)}(\mu = \Lambda_{\text{NP}}) = 0 \;\Rightarrow\; C_3^{(6)}(\mu = v) \neq 0$$

$$\delta m_{\nu N} = \frac{v^2}{16 m_e} \, \frac{C_3^{(6)}(v)}{C_1^{(6)}(v) + C_2^{(6)}(v)} \, \frac{\mu_{\nu N}}{\mu_B}$$

$$\frac{|\mu_{\nu N}|}{\mu_B} \sim 10^{-15} \left(\frac{\delta m_{\nu N}}{1 \text{ eV}}\right)$$

Bell, Cirigliano, Ramsey-Musolf, Vogel, Wise (2005)

Discrepancies would help to disentangle mass mechanism!