Probing neutrino magnetic moments with CEvNS

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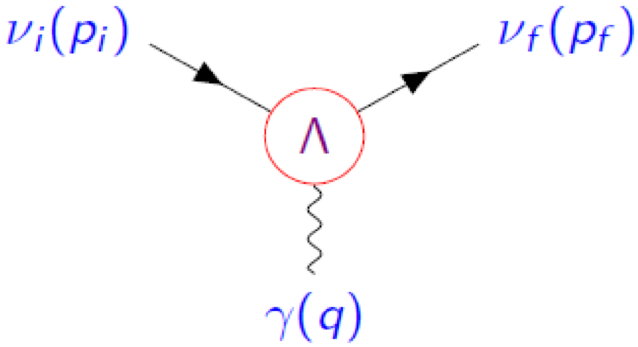
Neutrino Electromagnetic Interactions

- Effective Hamiltonian: $\mathcal{H}_{\text{em}}^{(\nu)}(x) = j_{\mu}^{(\nu)}(x) A^{\mu}(x) = \sum_{k,j=1} \overline{\nu_k}(x) \Lambda_{\mu}^{kj} \nu_j(x) A^{\mu}(x)$

- Effective electromagnetic vertex:



$$\langle \nu_f(p_f) | j_{\mu}^{(\nu)}(0) | \nu_i(p_i) \rangle = \overline{u_f}(p_f) \Lambda_{\mu}^{fi}(q) u_i(p_i)$$

$$q = p_i - p_f$$

- Vertex function:

$$\Lambda_{\mu}(q) = \left(\gamma_{\mu} - q_{\mu} \not{q}/q^2\right) \left[F_Q(q^2) + F_A(q^2) q^2 \gamma_5\right] - i \sigma_{\mu\nu} q^{\nu} \left[F_M(q^2) + i F_E(q^2) \gamma_5\right]$$

Lorentz-invariant form factors: charge, anapole, magnetic, electric

$q^2 = 0 \quad \Longrightarrow$

charge → q

anapole → a

magnetic → μ

electric → ε

helicity-conserving

helicity-flipping

Neutrino magnetic and electric moments

- Extended Standard Model with right-handed neutrinos and $\Delta L = 0$:

$$\mu^{\rm D}_{kk} \simeq 3.2 \times 10^{-19} \mu_{\rm B} \left(\frac{m_k}{\rm eV} \right) \qquad\qquad \varepsilon^{\rm D}_{kk} = 0$$

$$\left. \begin{matrix} \mu^{\rm D}_{kj} \\ i\varepsilon^{\rm D}_{kj} \end{matrix} \right\} \simeq -3.9 \times 10^{-23} \mu_{\rm B} \left(\frac{m_k \pm m_j}{\rm eV} \right) \sum_{\ell=e,\mu,\tau} U^*_{\ell k} U_{\ell j} \left(\frac{m_\ell}{m_\tau} \right)^2$$

off-diagonal moments are GIM-suppressed

[Fujikawa, Shrock, PRL 45 (1980) 963; Pal, Wolfenstein, PRD 25 (1982) 766; Shrock, NPB 206 (1982) 359; Dvornikov, Studenikin, PRD 69 (2004) 073001, JETP 99 (2004) 254]

- Extended Standard Model with Majorana neutrinos ($|\Delta L| = 2$):

$$\mu^{\rm M}_{kj} \simeq -7.8 \times 10^{-23} \mu_{\rm B}\, i\, (m_k + m_j) \sum_{\ell=e,\mu,\tau} {\rm Im}\left[U^*_{\ell k} U_{\ell j} \right] \frac{m_\ell^2}{m_W^2}$$

$$\varepsilon^{\rm M}_{kj} \simeq 7.8 \times 10^{-23} \mu_{\rm B}\, i\, (m_k - m_j) \sum_{\ell=e,\mu,\tau} {\rm Re}\left[U^*_{\ell k} U_{\ell j} \right] \frac{m_\ell^2}{m_W^2}$$

[Shrock, NPB 206 (1982) 359]

GIM-suppressed, but additional model-dependent contributions of the scalar sector can enhance the Majorana transition dipole moments

[Pal, Wolfenstein, PRD 25 (1982) 766; Barr, Freire, Zee, PRL 65 (1990) 2626; Pal, PRD 44 (1991) 2261]

CEνNS with ν magnetic moments

- Neutrino magnetic (and electric) moment contributions to CEνNS $\nu_\ell + \mathcal{N} \to \sum_{\ell'} \nu_{\ell'} + \mathcal{N}$:

$$\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\left[g_V^n N F_N(|\vec{q}|^2) + g_V^p Z F_Z(|\vec{q}|^2)\right]^2$$
$$+ \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right) Z^2 F_Z^2(|\vec{q}|^2) \sum_{\ell' \neq \ell} \frac{|\mu_{\ell\ell'}|^2}{\mu_B^2}$$

- The magnetic moment interaction adds incoherently to the weak interaction because it flips helicity.

- The m_e is due to the definition of the Bohr magneton: $\mu_B = e/2m_e$.

Experimental Bounds

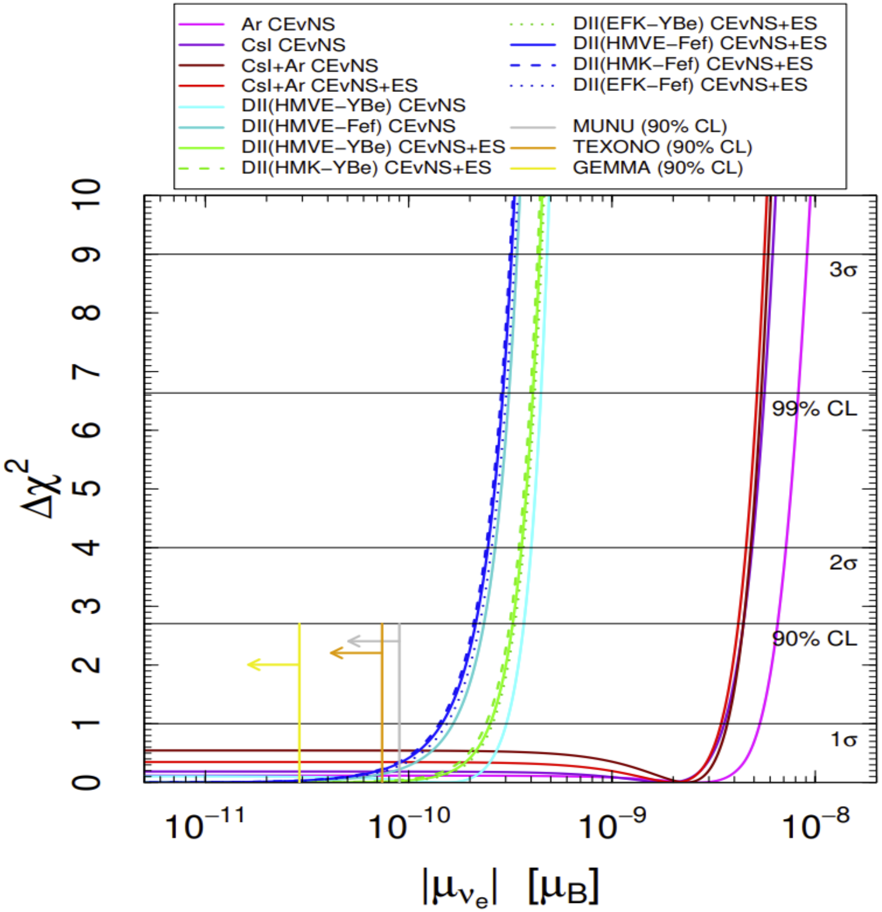
Method	Experiment	Limit [μ_B]	CL	Year
Reactor $\bar{\nu}_e\, e^-$	Krasnoyarsk	$\mu_{\nu_e} < 2.4 \times 10^{-10}$	90%	1992
	Rovno	$\mu_{\nu_e} < 1.9 \times 10^{-10}$	95%	1993
	MUNU	$\mu_{\nu_e} < 9 \times 10^{-11}$	90%	2005
	TEXONO	$\mu_{\nu_e} < 7.4 \times 10^{-11}$	90%	2006
	GEMMA	$\mu_{\nu_e} < 2.9 \times 10^{-11}$	90%	2012
Accelerator $\nu_e\, e^-$	LAMPF	$\mu_{\nu_e} < 1.1 \times 10^{-9}$	90%	1992
Accelerator $(\nu_\mu, \bar{\nu}_\mu)\, e^-$	BNL-E734	$\mu_{\nu_\mu} < 8.5 \times 10^{-10}$	90%	1990
	LAMPF	$\mu_{\nu_\mu} < 7.4 \times 10^{-10}$	90%	1992
	LSND	$\mu_{\nu_\mu} < 6.8 \times 10^{-10}$	90%	2001
Accelerator $(\nu_\tau, \bar{\nu}_\tau)\, e^-$	DONUT	$\mu_{\nu_\tau} < 3.9 \times 10^{-7}$	90%	2001
Solar $\nu_e\, e^-$	Super-Kamiokande	$\mu_S(E_\nu \gtrsim 5\,\text{MeV}) < 1.1 \times 10^{-10}$	90%	2004
	Borexino	$\mu_S(E_\nu \lesssim 1\,\text{MeV}) < 2.8 \times 10^{-11}$	90%	2017

[see the review Giunti, Studenikin, arXiv:1403.6344]

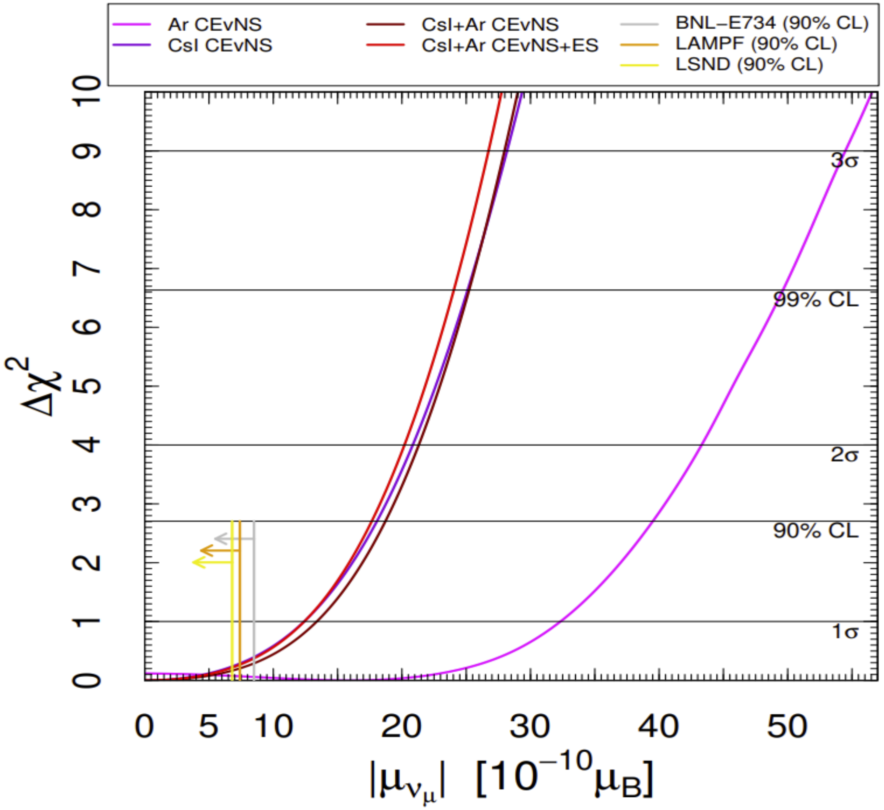
- Gap of about 8 orders of magnitude between the experimental limits and the $\lesssim 10^{-19}\,\mu_B$ prediction of the minimal Standard Model extensions.
- $\mu_\nu \gg 10^{-19}\,\mu_B$ discovery $\Rightarrow$ non-minimal new physics beyond the SM.
- Neutrino spin-flavor precession in a magnetic field

[Lim, Marciano, PRD 37 (1988) 1368; Akhmedov, PLB 213 (1988) 64]

COHERENT constraints on ν magnetic moment



More details in Corona, … YFL, et al, 2205.09484



$$|\mu_{\nu_e}| < 2.13 \times 10^{-10}\,\mu_B \quad \mathrm{Dresden-II\,(CE\nu NS + ES)},$$
$$|\mu_{\nu_\mu}| < 18 \times 10^{-10}\,\mu_B \quad \mathrm{CsI\,(CE\nu NS + ES) + Ar\,(CE\nu NS)}$$

$\Longleftrightarrow$

$$|\mu_{\nu_e}| \;<\; 10.3 \times 10^{-12}\,\mu_B$$
$$|\mu_{\nu_{\mu/\tau}}| \;<\; 15.6 \times 10^{-12}\,\mu_B$$

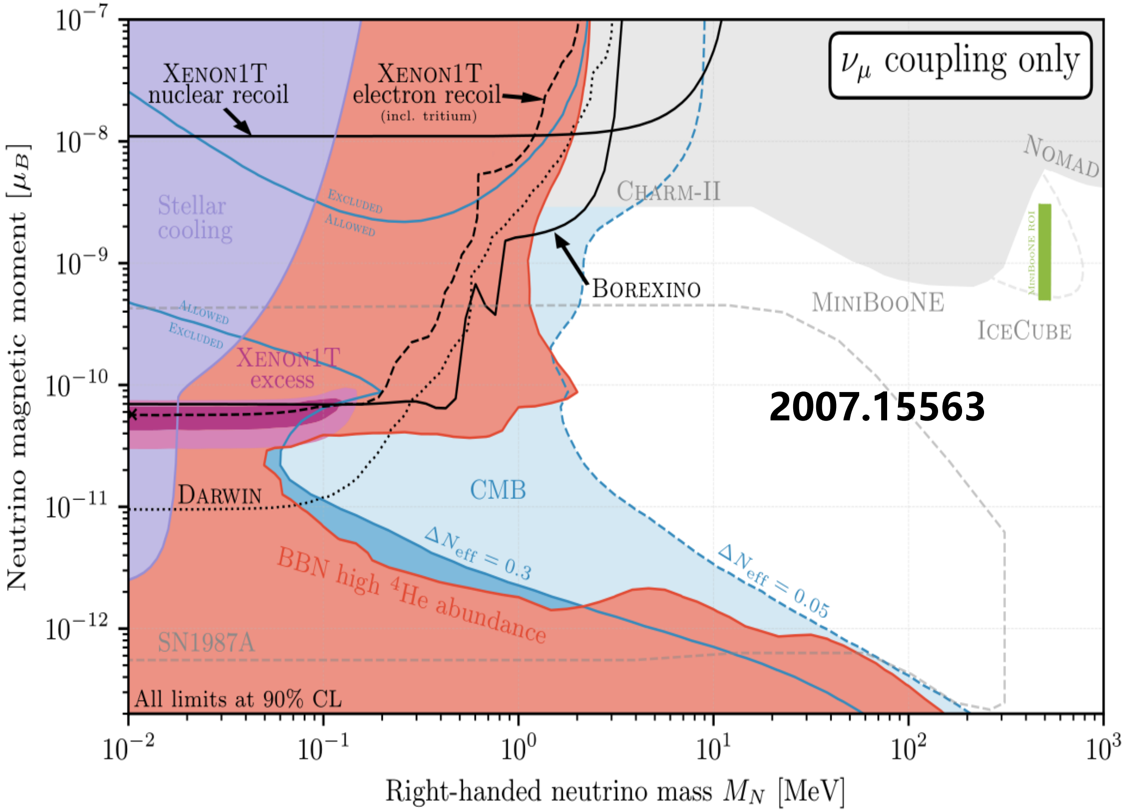
A combined analysis of DM direct detection experiments (see 2309.17380)

Active-sterile ν magnetic moment: dipole portal

$$\mathcal{L}_{\rm NDP} = \frac{d_\alpha}{2}(\bar{N}\sigma_{\mu\nu}\nu^\alpha F^{\mu\nu}) + \text{h.c.}$$

$$d_\alpha = \frac{\sqrt{\pi\alpha_{\rm EM}}}{m_e}\left|\frac{\mu_{\nu_\alpha}}{\mu_B}\right| \simeq 296 \left|\frac{\mu_{\nu_\alpha}}{\mu_B}\right| \quad \text{GeV}^{-1}$$

An important portal to the dark sector



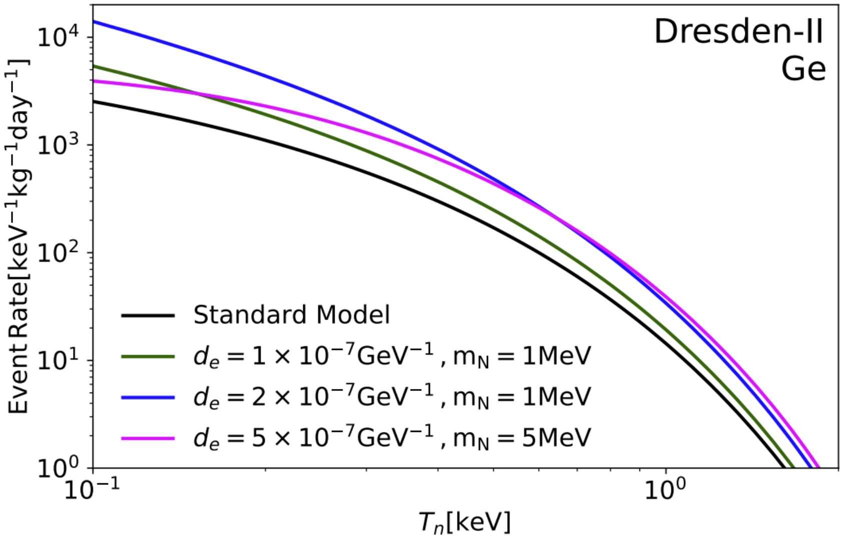
2007.15563

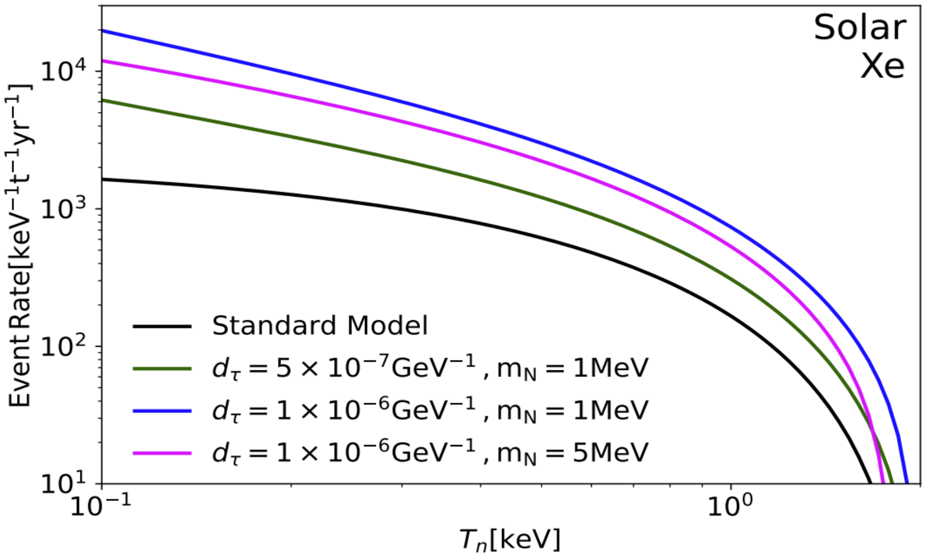
- ➢ **Above GeV:**
  LEP/LHC with 10^{-3} GeV^{-1}
- ➢ **Below MeV:**
  strong BBN bound
- ➢ **Sub GeV: SN1987A**
- ➢ **MeV — GeV:**
  ν scattering plays an important role!
  Borexino, CHARM-II etc.

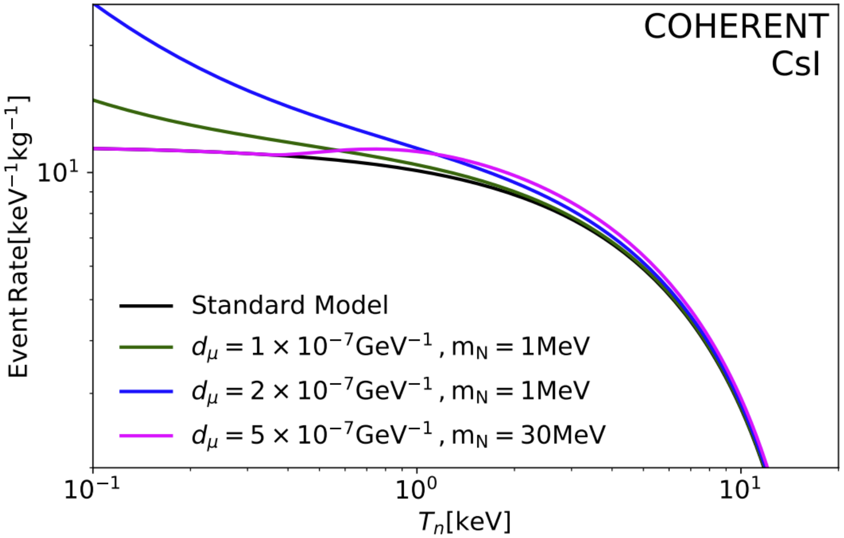
CEvNS: MeV to 50 MeV

NDP from low-Energy ν-nucleus scattering data

Li, YFL, Xia, 2406.07477







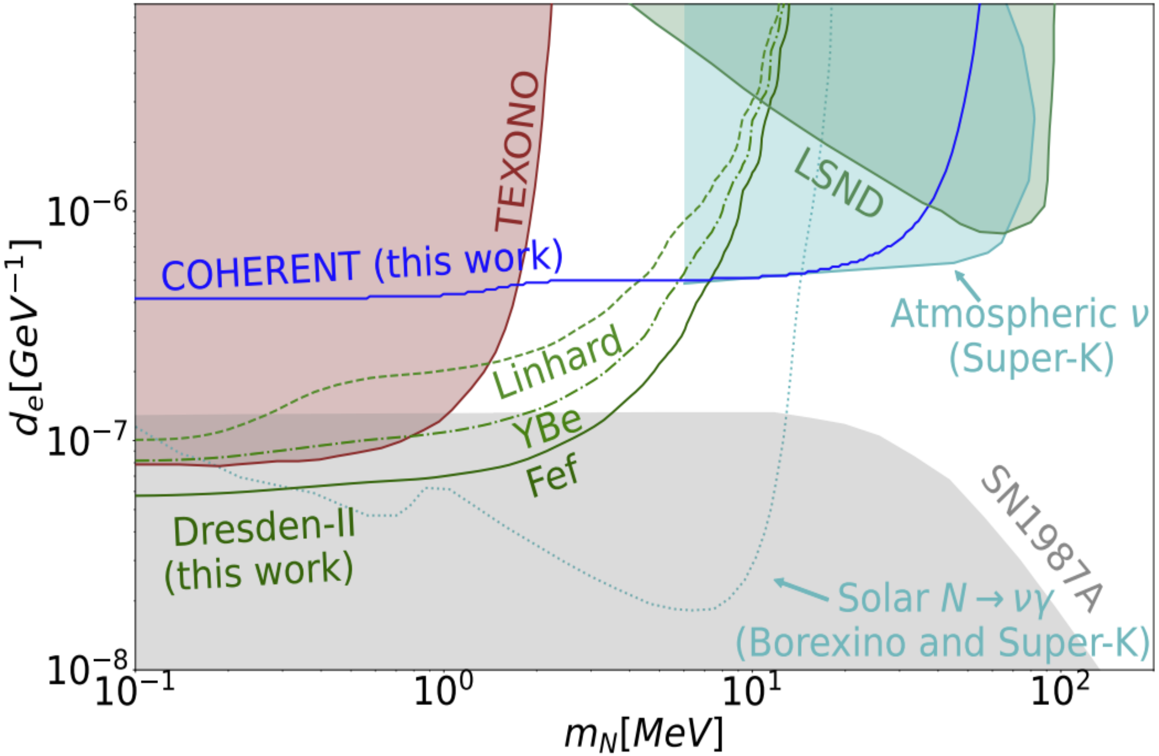
- **We consider Dresden-II, full set of CsI, and Xe-based low threshold data (PandaX-4t and Xenon-1t)**

- **All enhance the energy spectra:**

low mass scenario have more distortion at low energies;
while, high mass case will be more significant at high energies.

NDP: e-flavor scenario

Li, YFL, Xia, 2406.07477

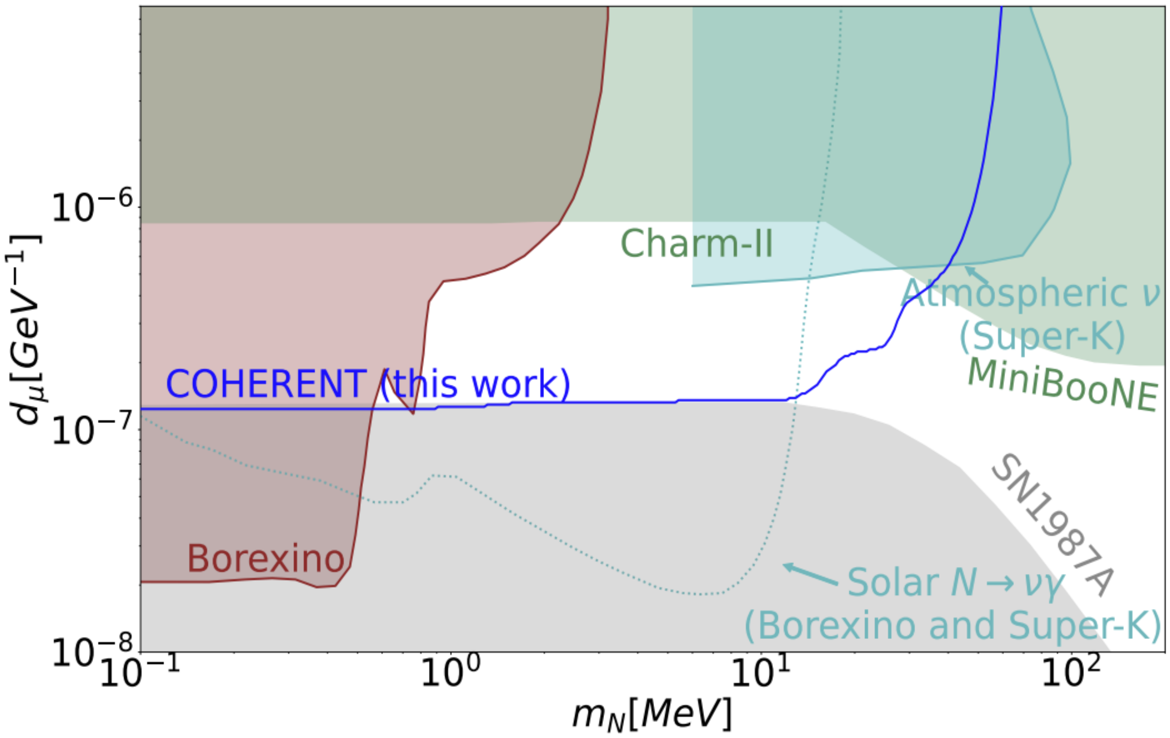


- **Dresten-II provides the leading constraints for the MeV range, but the quenching factor matters at lower energies.**

- **COHERENT data present weaker constraints, but can extend to tens of MeV, comparable to the limits from LSND and SK**

NDP: μ-flavor scenario

Li, YFL, Xia, 2406.07477

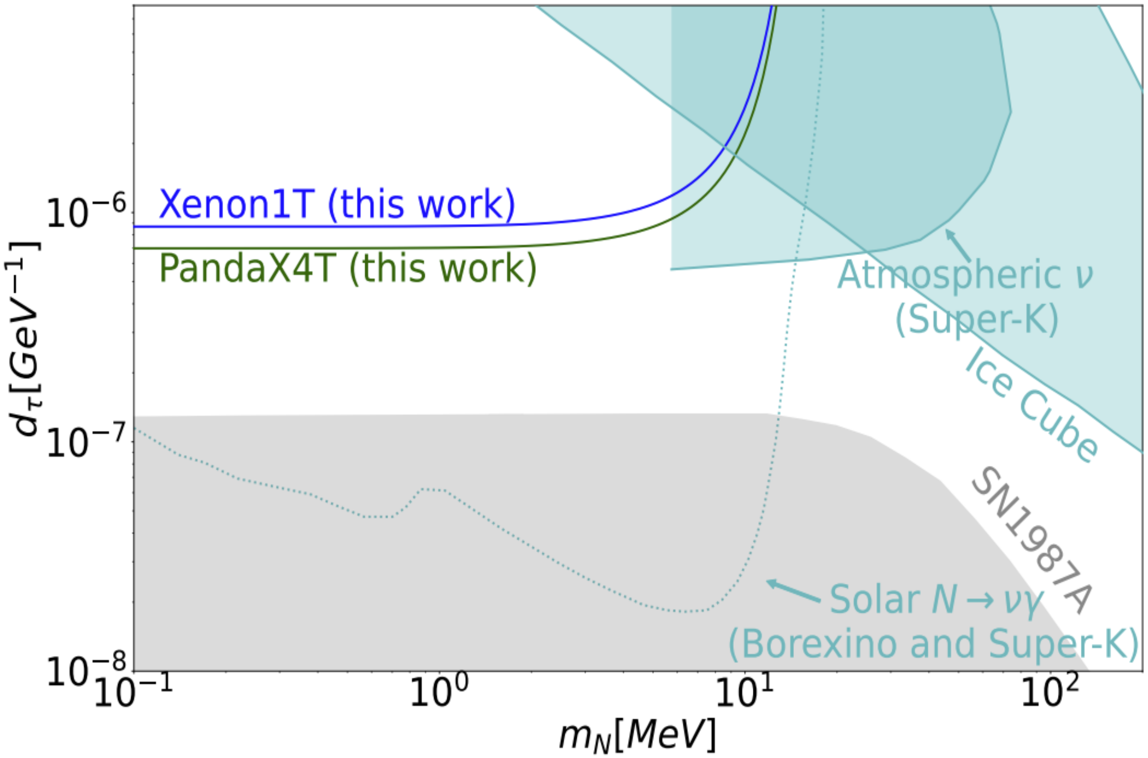


- **COHERENT data provide leading constraints for 10—50 MeV, and extend to MeV range at the level of 10^{-7} GeV^{-1}**

- **Our limit is around one order of magnitude better than previous works, because of additional time information, more stats., better systematics.**

NDP: τ-flavor scenario

Li, YFL, Xia, 2406.07477



Nature sources, such as solar and atmospheric vs, have abundant τ-flavor fluxes at detectors.

- **The solar ν-nucleus scattering in DM direct detection exp. provides independent constraints up to 10 MeV, compared to the electron scattering at Borexino & SuperK.**
- **Our constraints are a factor of three better than previous work because of low threshold data are employed.**

Conclusion

- **The low energy coherent neutrino nucleus data are unique probe of the neutrino magnetic moment!**

- **Active neutrino magnetic moment:**

$$\begin{array}{ll} |\mu_{\nu_e}| < 2.13 \times 10^{-10}\,\mu_{\mathrm{B}} & \mathrm{Dresden-II\,(CE\nu NS + ES)}, \\ |\mu_{\nu_\mu}| < 18 \times 10^{-10}\,\mu_{\mathrm{B}} & \mathrm{CsI\,(CE\nu NS + ES) + Ar\,(CE\nu NS)} \end{array}$$

- **Active-sterile neutrino magnetic moment:**

  (a) leading constraints at the MeV mass range (e-flavor)
  (b) leading constraints at the 10 MeV mass range (μ-flavor)
  (c) independent constraints for the τ-flavor scenario

- **A window for new physics beyond the standard model: promising prospects with future measurements**

Thanks!

Backup

Electromagnetic Vertex Function

$$\Lambda_\mu(q) = (\gamma_\mu - q_\mu \not{q}/q^2)\left[F_Q(q^2) + F_A(q^2)q^2\gamma_5\right] - i\sigma_{\mu\nu}q^\nu\left[F_M(q^2) + iF_E(q^2)\gamma_5\right]$$

Lorentz-invariant form factors:	charge	anapole	magnetic	electric
$q^2 = 0 \quad \Longrightarrow$	q	a	μ	ε

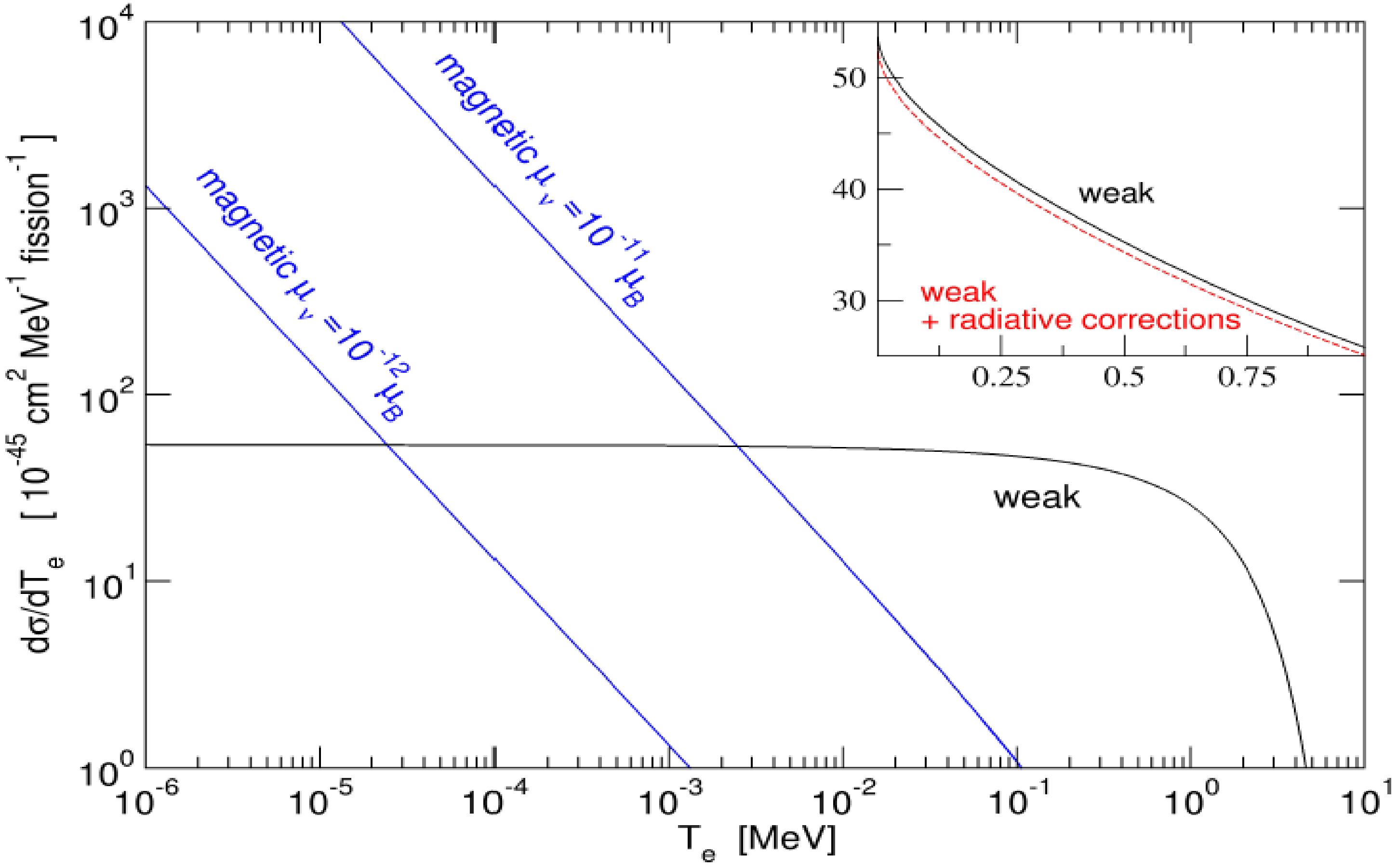
- Hermitian form factors: $F_Q = F_Q^\dagger$, $F_A = F_A^\dagger$, $F_M = F_M^\dagger$, $F_E = F_E^\dagger$
- Majorana neutrinos: $F_Q = -F_Q^T$, $F_A = F_A^T$, $F_M = -F_M^T$, $F_E = -F_E^T$

no diagonal charges and electric and magnetic moments in the mass basis

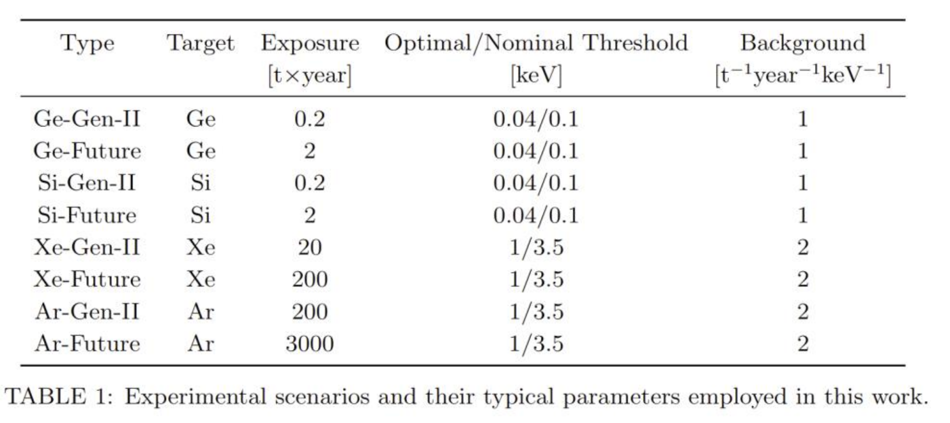
- For left-handed ultrarelativistic neutrinos $\gamma_5 \to -1 \Rightarrow$ The phenomenology of the charge and anapole are similar and the phenomenology of the magnetic and electric moments are similar.
- For ultrarelativistic neutrinos the charge and anapole terms conserve helicity, whereas the magnetic and electric terms invert helicity.

Neutrino scattering with magnetic moments

$$\left(\frac{d\sigma_{\nu e^-}}{dT_e}\right)_{\text{mag}} = \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_e} - \frac{1}{E_\nu}\right)\left(\frac{\mu_\nu}{\mu_B}\right)^2$$

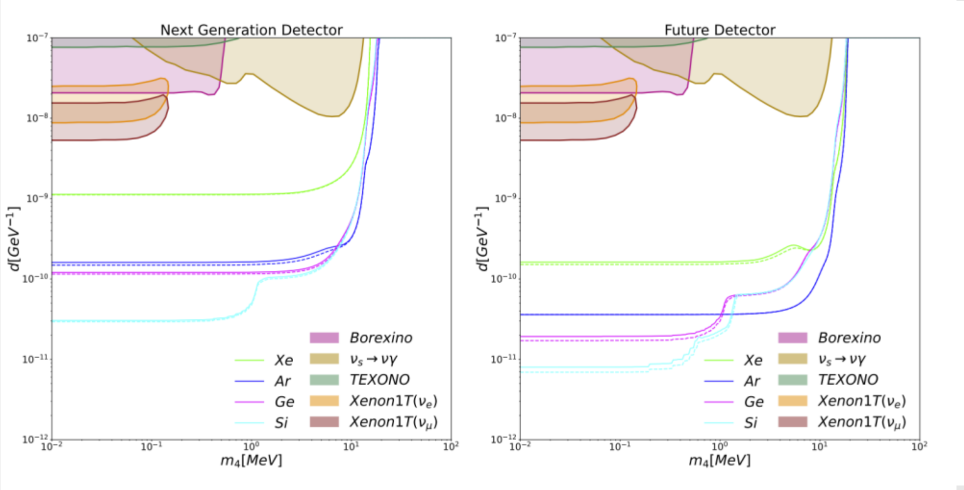


CEνNS with solar neutrinos



Type	Target	Exposure [t×year]	Optimal/Nominal Threshold [keV]	Background [$\mathrm{t^{-1}year^{-1}keV^{-1}}$]
Ge-Gen-II	Ge	0.2	0.04/0.1	1
Ge-Future	Ge	2	0.04/0.1	1
Si-Gen-II	Si	0.2	0.04/0.1	1
Si-Future	Si	2	0.04/0.1	1
Xe-Gen-II	Xe	20	1/3.5	2
Xe-Future	Xe	200	1/3.5	2
Ar-Gen-II	Ar	200	1/3.5	2
Ar-Future	Ar	3000	1/3.5	2

TABLE 1: Experimental scenarios and their typical parameters employed in this work.



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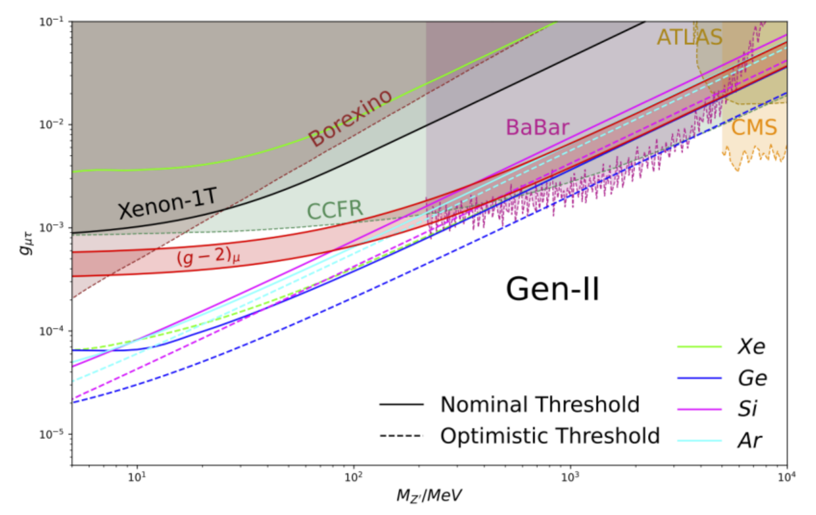
- ➢ ***Active neutrino magnetic moment:***
  limited by the threshold
- ➢ ***Active-sterile magnetic moment (dipole portal)***
  promising prospect !



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