Probing the Sterile Neutrino Dipole Portal with Coherent Elastic Solar Neutrino-Nucleus Scattering

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Outline

Sterile Neutrino Dipole Portal

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- The observation of neutrino flavor oscillation implies non-zero neutrino masses (Fukuda *et al.*, 1998; Ahmad *et al.*, 2002).
- This indicate that the standard model (SM) need to be expanded to include neutrino masses.
- Many known mechanisms involve fermionic neutral SM-gauge-group singlets, or heavy neutral leptons, or simply **sterile neutrinos** (Pontecorvo, 1967; Kusenko, 2009, Dasgupta & Kopp, 2021).

- The idea is often motivated by solving anomalies, found in short-baseline oscillation and reactor experiments: **LSND** (Athanassopoulos *et al.*, 1998), **MiniBoone** (Aguilar-Arevalo *et al.*, 2010), **MicroBoone** (Arguelles *et al.*, 2022).
- The eV-mass scale of sterile neutrinos could explain these anomalies and potentially play an important role in core-collapse supernovae (McLaughlin, Fetter, Balantekin, & Fuller, 1999).
- In the higher mass ranges, sterile neutrino could also be a **DM candidate** (Dodelson & Widrow, 1994).
- Other area that could influenced by sterile neutrinos: extra dimensions (Khan, 2023), evolution of the Early Universe (Mirizzi *et al.*, 2012), effective neutrino magnetic-moment (Balantekin & Vassh, 2014).

The Lagrangian

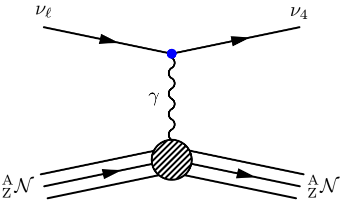
- The ν_4 could be produced by neutrino beams electromagnetically up-scattered on nuclei by the presence of a transition magnetic moment between active neutrinos and sterile neutrino.
- The relevant Lagrangian is

$$\mathcal{L}_{\rm int} \supset \frac{\mu_{\nu_{\ell 4}}}{2} \bar{\nu}_{\ell L} \sigma^{\mu\nu} P_R \nu_4 F_{\mu\nu} + h.c., \tag{1}$$

- It is only valid at energies below the electroweak (EW) scale.
- The coherent elastic neutrino-nuclues scattering (CEνNS) occurs at energies well below the EW scale and thus it remains applicable.

- An incoming active neutrino ν_ℓ exchanges a photon with a target nucleus $\mathcal{N}$ and up-scatters to a sterile neutrino ν_4. The matrix element of this process can be written as

$$i\mathcal{M} = (\mu_{\nu_{\ell 4}})^* [\bar{u}_{\nu_4} \sigma^{\mu\nu} P_L q_\nu u_{\nu_\ell}] (\frac{-ig_{\mu\lambda}}{q^2}) j^\lambda_{\mathcal{N}}, \qquad (2)$$



with the hadronic current of the nucleus

$$j^\lambda_{\mathcal{N}} = -ieZ(\bar{u}_{\mathcal{N}} \gamma^\lambda u_{\mathcal{N}}) F(|\vec{q}|^2), \qquad (3)$$

where the target nucleus is considered as a spin-1/2 particle.

The cross-section

- The differential cross section, concerning spin-1/2 nuclei, is

$$\left[\frac{d\sigma}{dT_{nr}}\right] = \frac{\pi\alpha_{\mathrm{EM}}^2}{m_e^2}\left|\frac{\mu_{\nu_{\ell 4}}}{\mu_B}\right|^2 Z^2 F^2(|\vec{q}|^2) \times \left[\frac{1}{T_{nr}} - \frac{1}{E_\nu} - \frac{m_4^2}{2T_{nr}E_\nu m_{\mathcal{N}}}\left(1 - \frac{T_{nr}}{2E_\nu} + \frac{m_{\mathcal{N}}}{2E_\nu}\right) - \frac{m_4^4}{8m_{\mathcal{N}}T_{nr}^2E_\nu^2}\left(1 - \frac{T_{nr}}{m_{\mathcal{N}}}\right)\right], \quad (4)$$

- As $m_4 = 0$ we obtain the conventional active neutrino magnetic moment cross-section (Vogel, 1989).
- The m_4 must satisfy the following kinematic constraint

$$m_4^2 \leq 2m_{\mathcal{N}}T_{nr}\left(\sqrt{\frac{2}{m_{\mathcal{N}}T_{nr}}}E_\nu - 1\right). \quad (5)$$

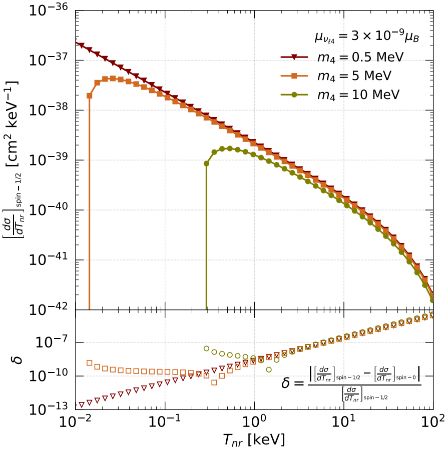
- For complementary, the cross section for spin-0 nuclei can be written as

$$\left[\frac{d\sigma}{dT_{nr}}\right]_{\text{spin-0}} = \left[\frac{d\sigma}{dT_{nr}}\right]_{\text{spin-1/2}} + \frac{\pi\alpha_{\mathrm{EM}}^2}{m_e^2}\left|\frac{\mu_{\nu_{\ell 4}}}{\mu_B}\right|^2 Z^2 F^2(|\vec{q}|^2) \times \left[\frac{T_{nr}}{4E_\nu^2} - \frac{m_4^2}{8m_{\mathcal{N}}E_\nu^2}\left(1 + \frac{m_4^2}{m_{\mathcal{N}}T_{nr}}\right)\right], \quad (6)$$

- To show the effect from the two assumption, we define relative difference δ

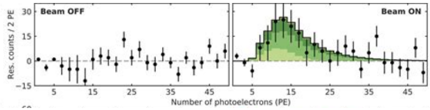
$$\delta = \frac{\left|\left[\frac{d\sigma}{dT_{nr}}\right]_{\text{spin-1/2}} - \left[\frac{d\sigma}{dT_{nr}}\right]_{\text{spin-0}}\right|}{\left[\frac{d\sigma}{dT_{nr}}\right]_{\text{spin-1/2}}}. \quad (7)$$

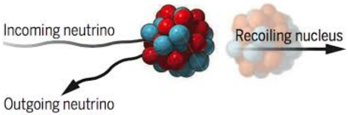
- Both cross-section have the same order of magnitude.
- The varied initial values are due to m_4.
- For T_{nr} increases, all lines begin to overlap as $T_{nr} > 10$ keV.
- The relative difference δ is in order of 10^{-5} to 10^{-13} for the considered T_{nr}.
- Hence the different spin states do not significantly alter the result.

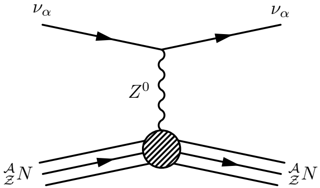


Coherent Elastic Neutrino Nucleus Scattering (CEνNS)

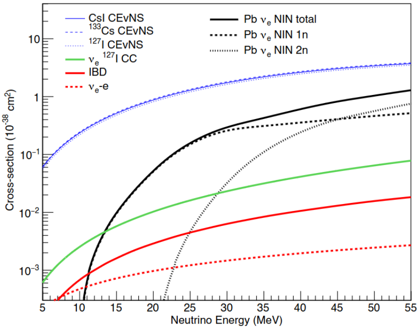
CEνNS Process







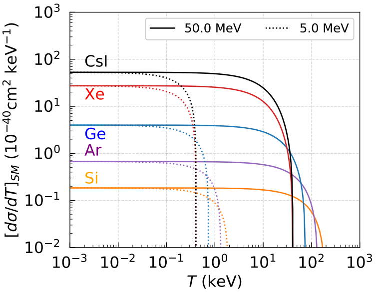
- It is an SM process in which neutrinos interact with nucleus as a whole through Z-boson exchange, followed by recoiled nucleus.
- Theoretically proposed: (Freedman, 1974). Experimentally observed: COHERENT collaboration (Akimov *et al*, 2017).
- To observe the process: $E_\nu \lesssim 50$ MeV, $T_{nr} \lesssim 50$ keV.



(Akimov *et. al.*, 2017)

- The largest observable among other processes involving neutrinos.
- It is difficult to observe; the nuclear recoil energy in low keV scales.
- Offering a novel framework for investigating fundamental parameters of the SM and testing physics scenarios beyond the SM (BSM).
- It triggers development of sensitive detector technology.

CEνNS Cross-Section



the transfer momentum satisfies: $Q^2 \equiv -q^2 = 2m_N T_{nr}$

The CEνNS cross section is

$$\left[\frac{d\sigma}{dT_{nr}}\right]_{\rm SM} = \frac{G_F^2 m_N}{\pi} Q_{\rm SM}^2 \left(1 - \frac{m_N T_{nr}}{2E_\nu^2}\right) \times \left|F(|\vec{q}|^2)\right|^2, \tag{8}$$

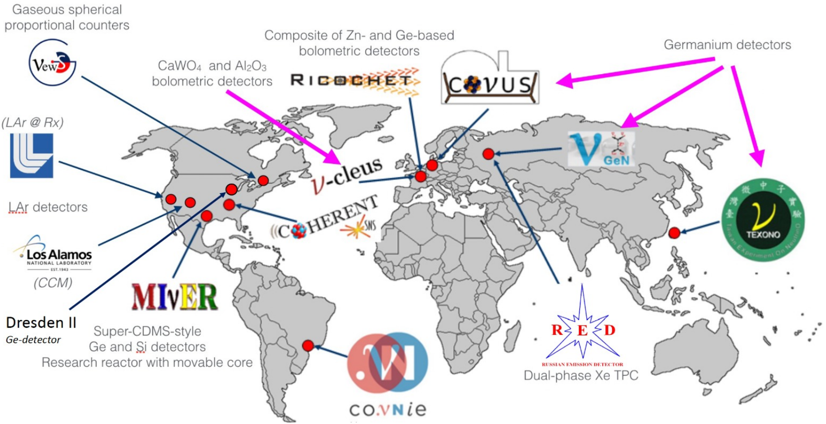
with the weak charge coupling:

$$Q_{\rm SM} = g_V^p \mathcal{Z} + g_V^n \mathcal{N} \tag{9}$$

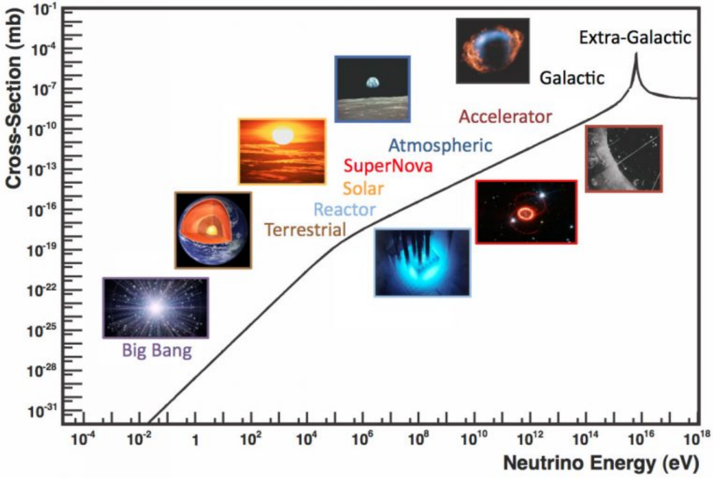
$g_V^p = 1/2(1 - 4\sin^2\theta_W) \approx 0.0229$, $g_V^n = -1/2$. Form factor: Klein-Nystrand (Klein & Nystrand, 1999)

$$F(|\vec{q}|^2) = 3\frac{J_1(|\vec{q}|R_A)}{|\vec{q}|R_A}\left(\frac{1}{1+|\vec{q}|^2 a_k^2}\right). \tag{10}$$

CEνNS Related Experiments



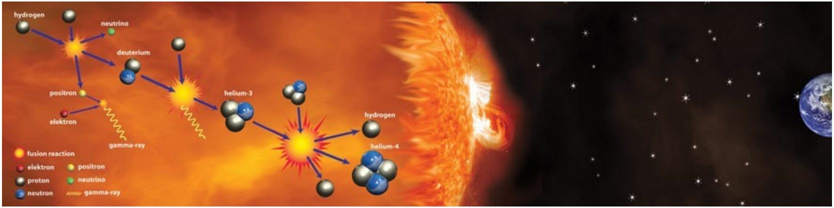
Neutrino Sources



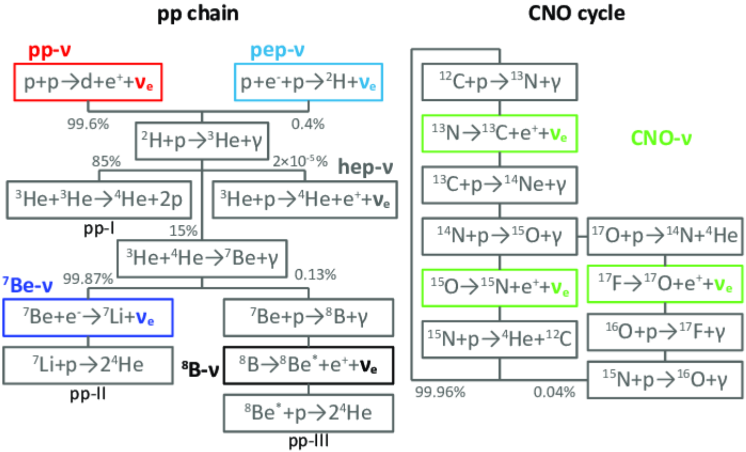
Credit: Formaggio & Zeller, 2012.

Solar Neutrinos

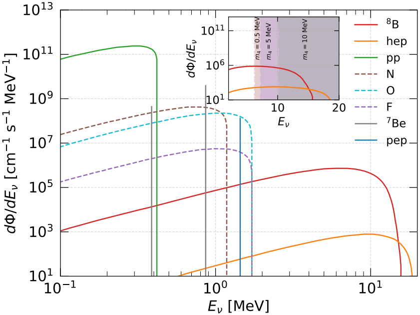
Neutrinos from the Sun



- It is one of the most intensive natural neutrino sources on the earth.
- Neutrinos produced as electron neutrino by the nuclear fusion inside the Sun.
- The general information of solar neutrino is part of the Standard Solar Model.
- Two main process: pp chain and CNO cycle.


pp chain
CNO cycle
pp-ν
p+p→d+e⁺+νₑ
pep-ν
p+e⁻+p→²H+νₑ
99.6%
0.4%
²H+p→³He+γ
85%
2×10⁻⁵%
hep-ν
³He+³He→⁴He+2p
³He+p→⁴He+e⁺+νₑ
pp-I
15%
³He+⁴He→⁷Be+γ
⁷Be-ν
99.87%
0.13%
⁷Be+e⁻→⁷Li+νₑ
⁷Be+p→⁸B+γ
⁷Li+p→2⁴He
⁸B-ν
⁸B→⁸Be*+e⁺+νₑ
pp-II
⁸Be*+p→2⁴He
pp-III
¹²C+p→¹³N+γ
¹³N→¹³C+e⁺+νₑ
CNO-ν
¹³C+p→¹⁴Ne+γ
¹⁴N+p→¹⁵O+γ
¹⁷O+p→¹⁴N+⁴He
¹⁵O→¹⁵N+e⁺+νₑ
¹⁷F→¹⁷O+e⁺+νₑ
¹⁵N+p→⁴He+¹²C
¹⁶O+p→¹⁷F+γ
99.96%
0.04%
¹⁵N+p→¹⁶O+γ

- Solar neutrino fluxes with their uncertainties from the high-metallicity solar neutrino model BS05(OP).



Components	Flux [cm^{-2}s^{-1}]	Uncertainty [%]
pp	5.99×10^{10}	0.8%
pep	1.42×10^{8}	1.3%
hep	7.93×10^{3}	15.4%
^{8}B	5.69×10^{6}	12.6%
^{7}Be	4.84×10^{9}	9.3%
^{13}N	3.07×10^{8}	20.2%
^{15}O	2.33×10^{8}	23.3%
^{17}F	5.84×10^{6}	25.1%

Survival Probabilities

- Solar neutrinos oscillate as they propagate from the Sun to the Earth.
- They arrive at a detector as a mixture of ν_e, ν_μ, ν_τ.
- The survival probabilities for each flavor can be written as

$$\Phi^i_{\nu_e} = \Phi^{i\,\odot}_{\nu_e} P_{ee}, \tag{11}$$

$$\Phi^i_{\nu_\mu} = \Phi^{i\,\odot}_{\nu_e} (1 - P_{ee}) \cos^2 \vartheta_{23}, \tag{12}$$

$$\Phi^i_{\nu_\tau} = \Phi^{i\,\odot}_{\nu_e} (1 - P_{ee}) \sin^2 \vartheta_{23}, \tag{13}$$

  where $\Phi^{i\,\odot}_{\nu_e}$ is the electron-neutrino flux, with $i = hep$ and ^{8}B, etc.
- The P_{ee} is the survival probability of ν_e which can be written by

$$P_{ee} =(c^2_{13} c^{m\,2}_{13}) \left(\frac{1}{2} - \frac{1}{2} \cos 2\vartheta^m_{12} \cos 2\vartheta_{12} \right) + (s^2_{13} s^{m\,2}_{13}) \tag{14}$$

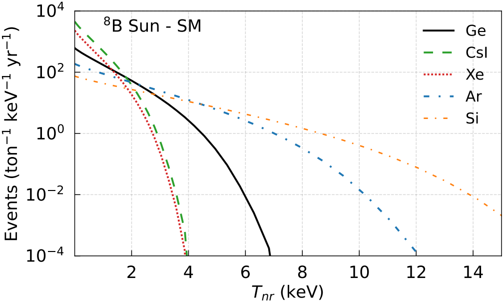
- In the notation, $c_{13} = \cos\vartheta_{13}$, $s_{13} = \sin\vartheta_{13}$ and the label m represents the matter effect.
- The $\cos 2\vartheta_{12}^{m}$ is the matter angle. We consider the day-night asymmetry due to the Earth matter effect in the calculation of the survival probabilities.
- We take the normal-ordering neutrino oscillation parameters from the latest 3-ν oscillation of NuFit-5.3, without the Super-Kamiokande atmospheric data (Esteban *et al.*, 2020).

Event Rate

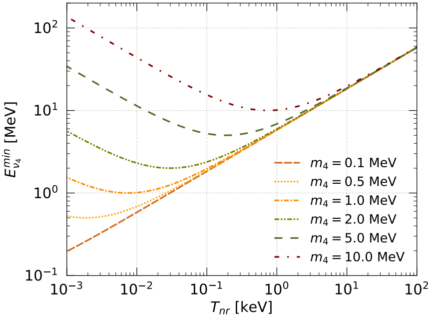
Event Rate

- The maximum nuclear recoil energy obeys $T_{nr}^{max} = \frac{2E_\nu^2}{2E_\nu + m_N}$.
- The differential event rate of the CEνNS:

$$\frac{dR}{dT_{nr}} = N_T \int_{E_\nu^{min}}^{E_\nu^{max}} dE_\nu \frac{d\Phi(E_\nu)}{dE_\nu} \frac{d\sigma(E_\nu, T_{nr})}{dT_{nr}}. \qquad (15)$$



- The minimum neutrino energy, for the active case, satisfies $E_{\nu}^{min} = \frac{T_{nr}}{2}\left(1+\sqrt{1+\frac{2m_N}{T_{nr}}}\right)$,
- Meanwhile, for the sterile case the minimum energy is $E_{\nu_4}^{\min} = \frac{m_4^2+2m_{\mathcal{N}}T_{nr}}{2(\sqrt{T_{nr}(T_{nr}+2m_{\mathcal{N}})}-T_{nr})}$



Quenching Factor

- The observed physical quantity is electron equivalent energy. To relate this with nuclear recoil energy, quenching factor $Y(T_{nr})$ is needed.
- For this purpose, we utilize the Lindhard quenching factor (Lindhard *et. al.*, 1963):

$$Y(T_{nr}) = \frac{kg(\epsilon)}{1 + kg(\epsilon)}, \tag{16}$$

with

$$\begin{aligned} g(\epsilon) &= 3\epsilon^{0.15} + 0.7\epsilon^{0.6} + \epsilon \\ \epsilon &= 11.5\mathcal{Z}^{-7/3} T_{nr}, \end{aligned} \tag{17}$$

where $k = 0.16$, closely matches the recent low-energy measurement (Bonhomme *et. al.*, 2022).

- The Linhard formula is acceptable for high recoil energy, namely $0.254\ \text{keV} < T_{nr} < 10\ \text{keV}$.
- Below this range, in the range of $0.04\ \text{keV} < T_{nr} < 0.254\ \text{keV}$ (Essig *et. al.*, 2018), we consider for Ge target

$$Y(T_{nr}) = 0.18 \left[1 - \exp\left(\frac{15 - T_{nr}}{71.03}\right)\right] \tag{18}$$

- The T_{nr}(keV) can be converted into T_{ee}(keV) by

$$T_{ee} = Y(T_{nr})T_{nr}. \tag{19}$$

- Hence, the differential rate in term of the electron equivalency is given by

$$\frac{dR}{dT_{ee}} = \frac{dR}{dT_{nr}} \frac{1}{Y(T_{nr}) + T_{nr}\frac{dY(T_{nr})}{dT_{nr}}}. \tag{20}$$

Analysis and Results

The Data

- We are interested testing the **CDEX-10** result (Geng *et. al.*, 2023) to constraint active-sterile transition magnetic moment through CEνNS process.
- The collaboration reported 20 data points in their effort on searching for DM signal.
- We obtain the data via communication with one of the CDEX-10 member.
- It is given in terms of electron-equivalent recoil energy. We convert this into the nuclear recoil energy using the Linhard quenching factor.
- We further accommodate **three projections** regarding experimental advancement in the near future.
  - Next-generation $\rightarrow$ 150 kg year, 1 keVnr.
  - Future 1 $\rightarrow$ 1.5 ton year, 1 keVnr.
  - Future 2 $\rightarrow$ 1.5 ton year, 0.1 keVnr.

χ^2-Analysis

- We adopt the pull approach of the χ^2 function (Fogli *et. al.*, 2002):

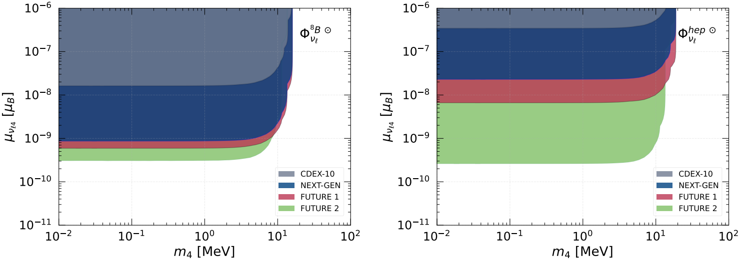
$$\chi^2 = \min_{(\xi_j)} \sum_{i=1}^{20} \left(\frac{R^i_{obs} - R^i_{exp} - B - \sum_j \xi_j c^i_j}{\Delta^i} \right)^2 + \sum_j \xi_j \tag{21}$$

.

- R^i_{obs} and R^i_{exp} are the observed and expected event rates, respectively. in the i-th energy bin.
- Δ^i denotes the experimental uncertainty.
- The solar neutrino flux uncertainty is represented by c^i_j.

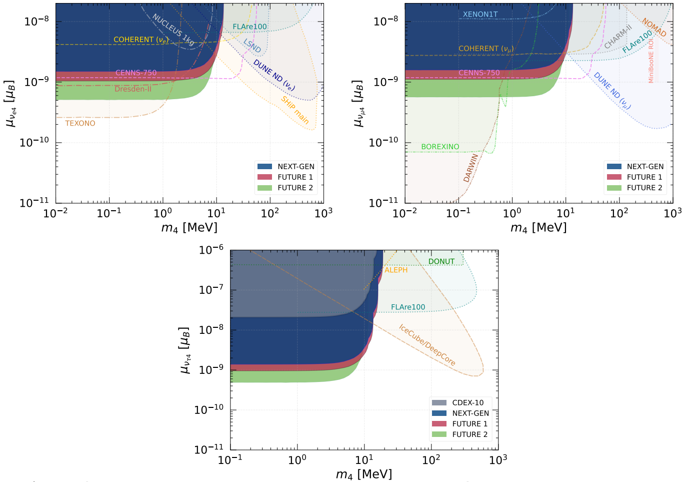
Single-Flux Case

- The CDEX-10 data can address the $\mu_{\nu_{\ell 4}}$.
- ^{8}B provides stringent constraints than the hep.
- The projection results address an improvement to the existing limits.



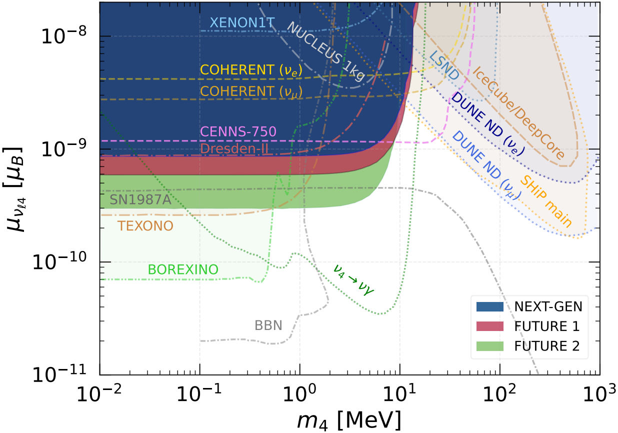
Flavor-dependent Cases

- Dominates stopped-pion results, previous DD, and others in low m_4 region.
- Yet to reach neutrino-electron channels.



Effective Case

- In addition to the previous, the projection can reach constraint from supernova, cover most of the $\nu_4 \to \nu\gamma$.



Summary

Summary

- Sterile neutrino is an interesting scenario to explore with CEνNS utilizing solar neutrino.
- The considered CDEX-10 data can address constraints of the active-sterile transition magnetic moment.
- Our configured projections provide a better constraints which could cover some of the available limits in the literature.
- High exposure and small nuclear energy threshold indicate the possible obtainment of stringent limits.

Thank You for Your Time!

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