Implications of first LZ and XENONnT results: a comparative study of neutrino properties and light mediators.

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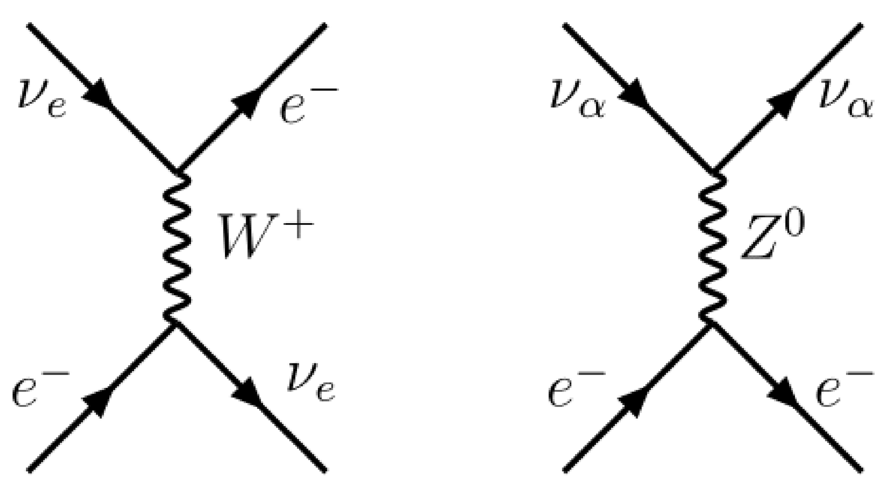
Overview

Current and prospective direct dark matter detection experiments with multi-ton mass scale and sufficiently low-threshold capabilities are promising facilities to probe neutrino properties and study light novel mediators expected in scenarios beyond the Standard Model (BSM). The LUX-ZEPLIN (LZ) [1] and XENONnT [2] experiments have published initial data from their hunt for Weakly-Interacting-Massive-Particles (WIMPs). In these experiments, elastic neutrino-electron scattering (EνES) induced by solar neutrinos is reported to be one of the main background components. Therefore, the new data allow us to place stringent constraints on various neutrino properties within and beyond the Standard Model (SM). Here we have performed a comparative study [3] of neutrino electromagnetic properties and neutrino-generalized-interactions (NGIs) with light mediators, using neutrino-electron scattering exploiting the recent LZ and XENONnT data.

Theoretical Framework

Standard Model physics: Neutrino-electron scattering is a purely leptonic process in which a neutrino scatters off an electron by exchanging a virtual vector boson, as depicted in the following Feynman diagrams.



The observation of ν–e scattering was a turning point in the elementary particle physics, as it demonstrates the existence of weak neutral current process. At the tree level, the EνES SM differential cross section:

$$\left[\frac{d\sigma_{\nu_\alpha}}{dE_{er}}\right]_{\text{SM}}^{\nu e} = \frac{G_F^2 m_e}{2\pi}\Big[(g_V \pm g_A)^2 + (g_V \mp g_A)^2\left(1-\frac{E_{er}}{E_\nu}\right)^2 - (g_V^2 - g_A^2)\frac{m_e E_{er}}{E_\nu^2}\Big], \tag{1}$$

with SM couplings $g_V = -\frac{1}{2} + 2\sin^2\theta_W + \delta_{\alpha e}$, $\quad g_A = -\frac{1}{2} + \delta_{\alpha e}$, while the weak mixing angle is taken by RGE extrapolation in the minimal subtraction ($\overline{\text{MS}}$) renormalization scheme: $\sin^2\theta_W = 0.23857 \pm 0.00005$.

EνES through beyond the Standard Model: Within the BSM framework we analyse neutrino electromagnetic properties and consider new type of scalar (S), pseudoscalar (P), vector (V), axial-vector (A), and tensor (T) interaction, namely neutrino generalized interactions (NGI). In the latter, we consider the interactions mediated through light bosons.

Neutrino electromagnetic properties: The existence of non-vanishing neutrino masses shown by oscillation data suggests the possibility of non-trivial electromagnetic neutrino characteristics. The helicity-flipping neutrino magnetic moment contribution to the EνES cross section adds incoherently to the SM, shown in Eq.(1), and reads,

$$\left[\frac{d\sigma_{\nu_\alpha}}{dE_{er}}\right]_{\text{mag}}^{\nu e} = \frac{\pi a_{\text{EM}}^2}{m_e^2}\left[\frac{1}{E_r} - \frac{1}{E_\nu}\right]\left(\frac{\mu_{\nu_\alpha}^{\text{eff}}}{\mu_B}\right)^2, \tag{2}$$

On the other hand the helicity-preserving EM contributions for millicharge (q_{ν_α}), anapole moment (a_{ν_α}) and neutrino charge radius (r_{ν_α}) are taken via the substitutions of SM couplings:

$$g_V \to g_V + \frac{\sqrt{2}\pi\alpha}{G_F}\left[\frac{\langle r_{\nu_\alpha}^2\rangle}{3} - \frac{a_{\nu_\alpha}}{18} - \frac{1}{m_e E_{er}}\left(\frac{q_{\nu_\alpha}}{e}\right)\right], \tag{3}$$

Neutrino generalized interactions: Simplified $\mathbb{U}(1)'$ scenarios with an additional light vector (V) and axial vector (A) can be considered by the substitutions of SM couplings:

$$g'_{V/A} = g_{V/A} + \frac{g_{\nu V/A}\cdot g_{eV/A}}{2\sqrt{2}G_F(2m_e E_{er} + m_{V/A}^2)}. \tag{4}$$

Other relevant interactions:

$$\left[\frac{d\sigma_{\nu_\alpha}}{dE_{er}}\right]_S^{\nu e} = \left[\frac{g_{\nu S}^2\cdot g_{eS}^2}{4\pi(2m_e E_{er} + m_S^2)^2}\right]\frac{m_e^2 E_{er}}{E_\nu^2}, \tag{5}$$

$$\left[\frac{d\sigma_{\nu_\alpha}}{dE_{er}}\right]_P^{\nu e} = \left[\frac{g_{\nu P}^2\cdot g_{eP}^2}{8\pi(2m_e E_{er} + m_P^2)^2}\right]\frac{m_e E_{er}^2}{E_\nu^2}, \tag{6}$$

$$\left[\frac{d\sigma_{\nu_\alpha}}{dE_{er}}\right]_T^{\nu e} = \frac{m_e\cdot g_{\nu T}^2\cdot g_{eT}^2}{\pi(2m_e E_{er} + m_T^2)^2}\cdot\left[1 + 2\left(1-\frac{E_{er}}{E_\nu}\right) + \left(1-\frac{E_{er}}{E_\nu}\right)^2 - \frac{m_e E_{er}}{E_\nu^2}\right]. \tag{7}$$

Simulation of events rate

The estimated differential events rate at the detector:

$$\left[\frac{dR}{dE_{er}}\right]_X^{\nu e} = t_{\text{run}} N_{\text{target}}\mathcal{A}(E_{er})\sum_{i=\text{solar}}\int_{E_\nu^{min}}^{E_\nu^{max}} dE_\nu \frac{d\Phi_i^{\nu_e}(E_\nu)}{dE_\nu}\left(P_{ee}\left[\frac{d\sigma_{\nu_e}}{dE_{er}}\right]_X^{\nu e} + P_{ef}\left[\frac{d\sigma_{\nu_f}}{dE_{er}}\right]_X^{\nu e}\right), \tag{8}$$

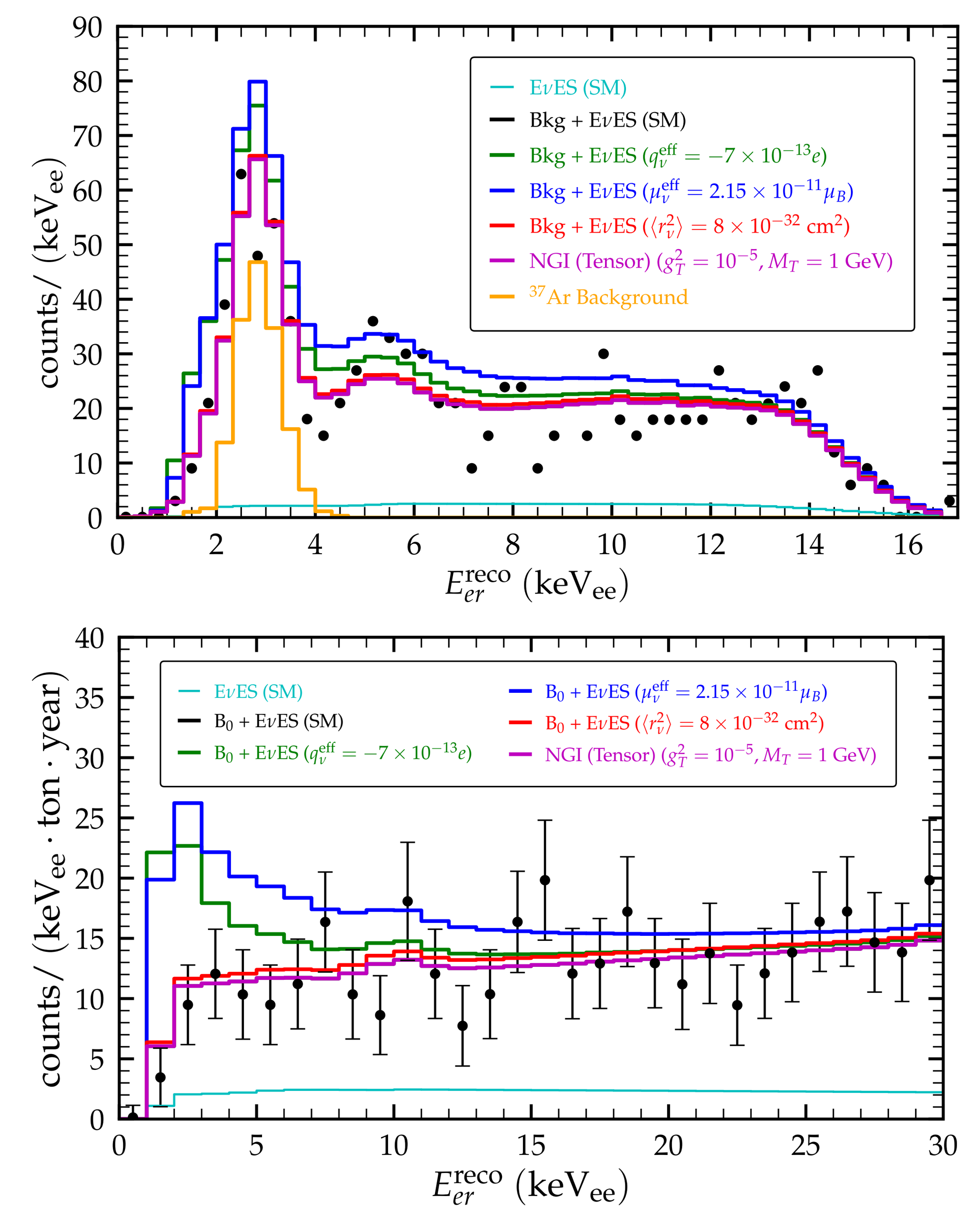


Fig.1 Expected signal and comparison with the experimental data at LZ (top) and XENONnT (bottom). Various examples of possible new physics contributions to EνES are shown.

Statistical analysis

In order to explore the new physics parameter(s) of interest ξ with the LZ data, our statistical analysis is based on the Poissonian χ^2 function

$$\chi^2(\xi) = 2\sum_{i=1}^{51}\left[R_{\text{pred}}^i(\xi;\alpha,\beta,\delta) - R_{\text{exp}}^i + R_{\text{exp}}^i \ln\left(\frac{R_{\text{exp}}^i}{R_{\text{pred}}^i(\xi;\alpha,\beta,\delta)}\right)\right] + \left(\frac{\alpha}{\sigma_\alpha}\right)^2 + \left(\frac{\beta}{\sigma_\beta}\right)^2 + \left(\frac{\delta}{\sigma_\delta}\right)^2, \tag{9}$$

For the case of XENONnT we employ a Gaussian χ^2 function

$$\chi^2(\xi) = \sum_{i=1}^{30}\left(\frac{R_{\text{pred}}^i(\xi;\beta) - R_{\text{exp}}^i}{\sigma^i}\right)^2 + \left(\frac{\beta}{\sigma_\beta}\right)^2, \tag{10}$$

Results

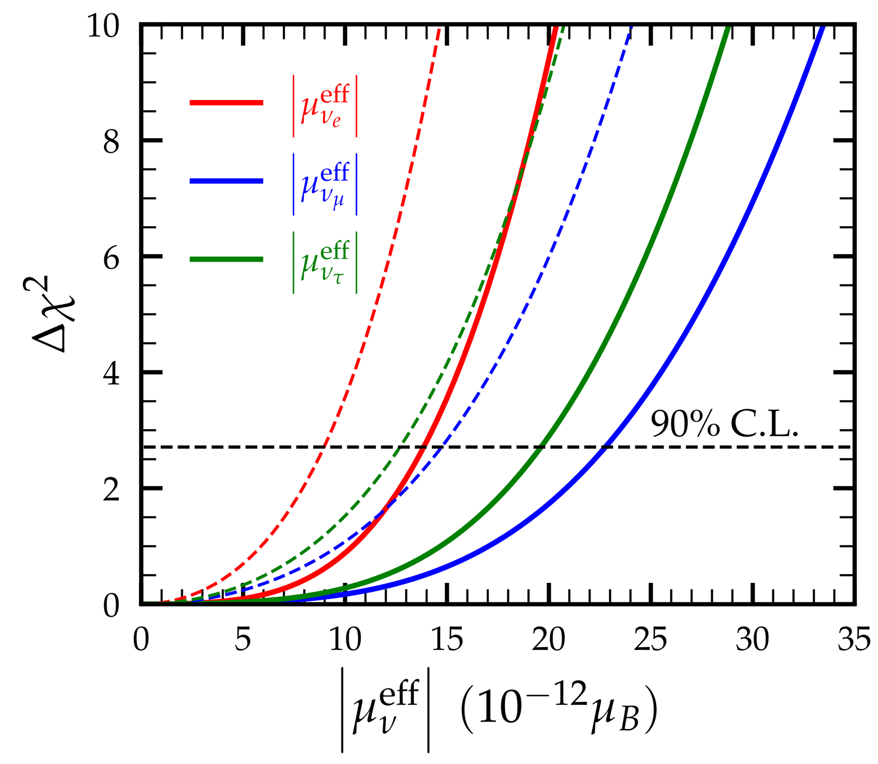


Fig.2 $\Delta\chi^2$ profiles of the flavor dependent neutrino magnetic moment parameters from the analysis of LZ (solid lines) and XENONnT (dashed lines) data.

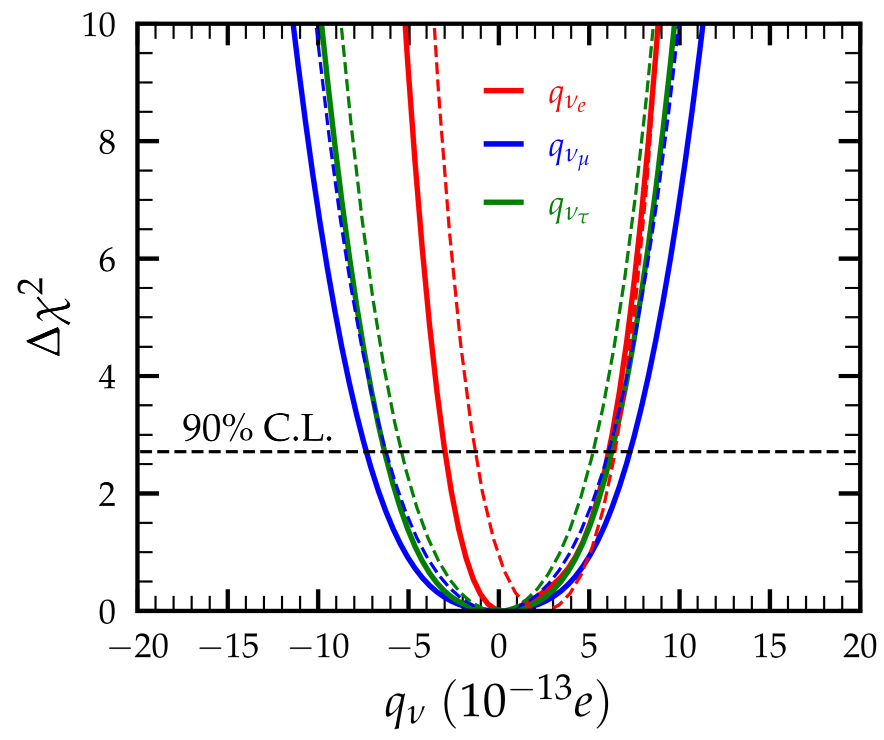


Fig.3 $\Delta\chi^2$ profiles of the flavor dependent neutrino millicharge parameters from the analysis of LZ (solid lines) and XENONnT (dashed lines) data.

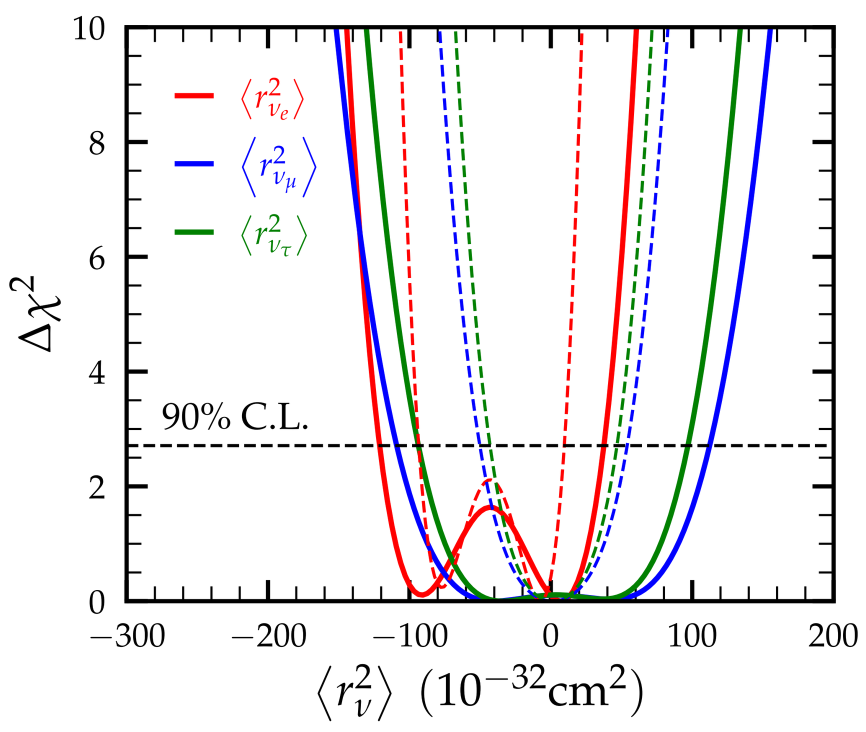


Fig.4 $\Delta\chi^2$ profiles of flavor dependent neutrino charge radius from the analysis of LZ (solid lines) and XENONnT (dashed lines) data.

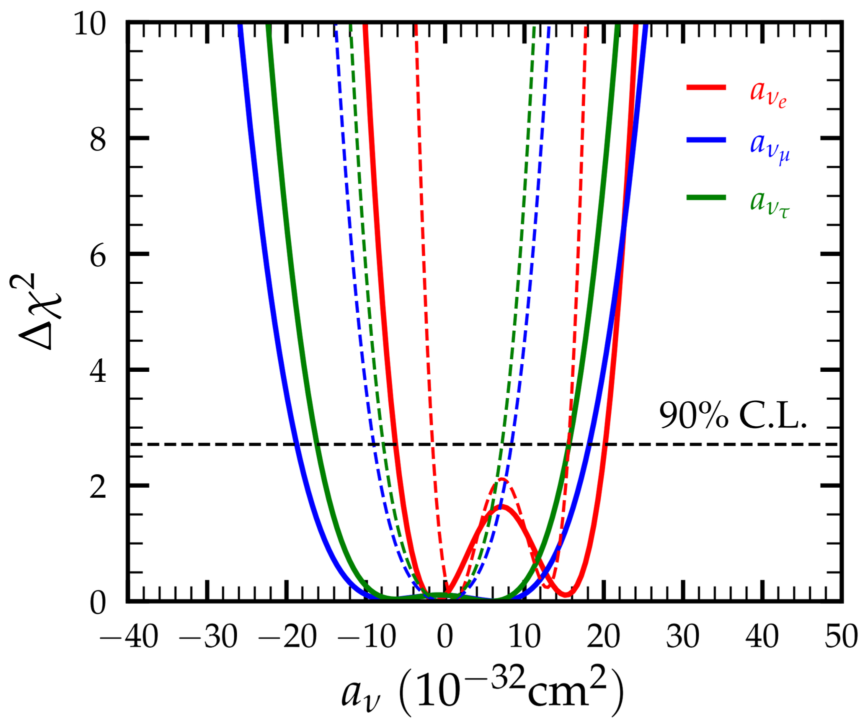


Fig.5 $\Delta\chi^2$ profiles of the flavor dependent anapole moment from the analysis of LZ (solid lines) and XENONnT (dashed lines) data.

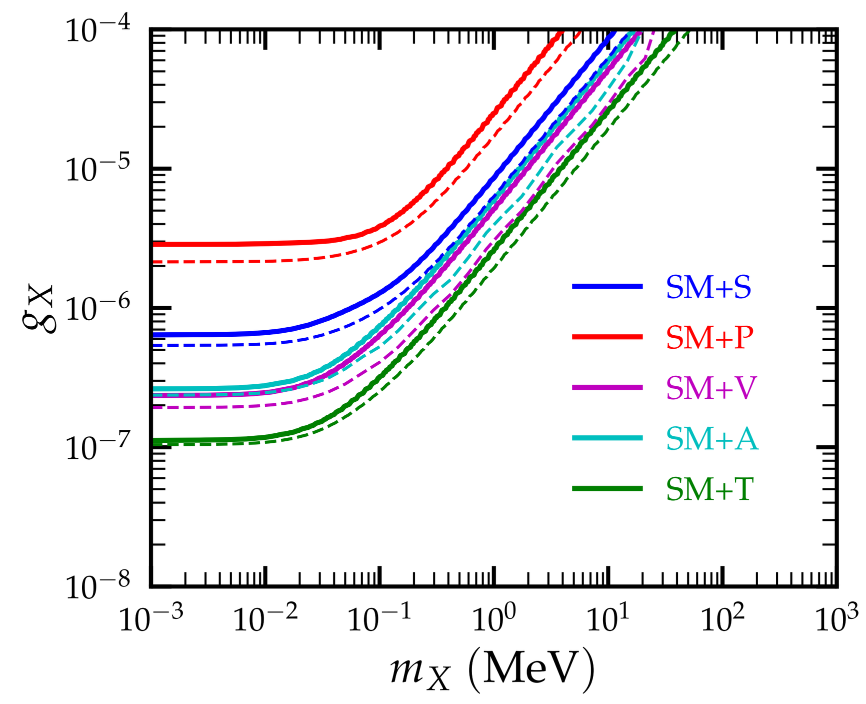


Fig.6 90% C.L. sensitivity in the NGI parameter space (g_X and m_X) corresponding to the various interaction channels $X = \{S, P, V, A, T\}$, from the analysis of LZ (solid lines) and XENONnT (dashed) lines.

Summary of the Results

- Our findings indicate that XENONnT places the most stringent upper limit on the neutrino millicharge ($\sim 10^{-13}e$) and magnetic moment ($\sim 10^{-12}\mu_B$). For these scenarios XENONnT results are competitive to LZ and improved by about one order of magnitude in comparison to existing constraints from Borexino and TEXONO experiments.
- The limits on neutrino charge radius and anapole moment extracted from these data, are subpar and in no way comparable with other electroweak processes.

Flavor	$\lvert\mu_\nu\rvert$ $[10^{-11}\mu_B]$	q_ν $[10^{-12}e]$	$\langle r_\nu^2\rangle$ $[10^{-32}\text{cm}^2]$
ν_e	$\le$ **1.4 (LZ)** $\le$ **0.9 (XENONnT)** ≤ 3.7 (Borexino) ≤ 7.4 (TEXONO) ≤ 2.9 (GEMMA)	**[−0.3, 0.6] (LZ)** **[−0.1, 0.6] (XENONnT)** ≤ 1 (Reactor) [−9.3, 9.5] (Dresden-II)	**[−121, 37.5] (LZ)** **[−93.4, 9.5] (XENONnT)** [−4.2, 6.6] (TEXONO) [−5.94, 8.28] (LSND) [-7.1,5] (COHERENT + Dresden-II)
ν_μ	$\le$ **2.3 (LZ)** $\le$ **1.5 (XENONnT)** ≤ 5 (Borexino)	**[−0.7, 0.7] (LZ)** **[−0.6, 0.6] (XENONnT)** ≤ 11 (XMASS-I)	**[−109, 112.3] (LZ)** **[−50.2, 54] (XENONnT)** [−1.2, 1.2] (CHARM-II) [-5.9,4.3] (COHERENT + Dresden-II)
ν_τ	$\le$ **2 (LZ)** $\le$ **1.3 (XENONnT)** ≤ 5.9 (Borexino)	**[−0.6, 0.6] (LZ)** **[−0.5, 0.5] (XENONnT)** ≤ 11 (XMASS-I)	**[−93.7, 97] (LZ)** **[−43, 46.8] (XENONnT)**

- The limits on NGIs from LZ or XENONnT are improved by a factor 5 compared to existing ones from Borexino.

References

1. **LZ** Collaboration, J. Aalbers *et al.*, "First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment," arXiv:2207.03764 [hep-ex]
2. **XENON** Collaboration, E. Aprile *et al.*, "Search for New Physics in Electronic Recoil Data from XENONnT," Phys. Rev. Lett. **129** (2022) no.16, 161805, arXiv:2207.11330 [hep-ex]
3. ShivaSankar. K. A., A. Majumdar, D. K. Papoulias, H. Prajapati and R. Srivastava, "First results of LZ and XENONnT: A comparative study of neutrino properties and light mediators," arXiv:2208.06415 [hep-ph]