# Studying neutrino properties with dark matter direct detection detectors

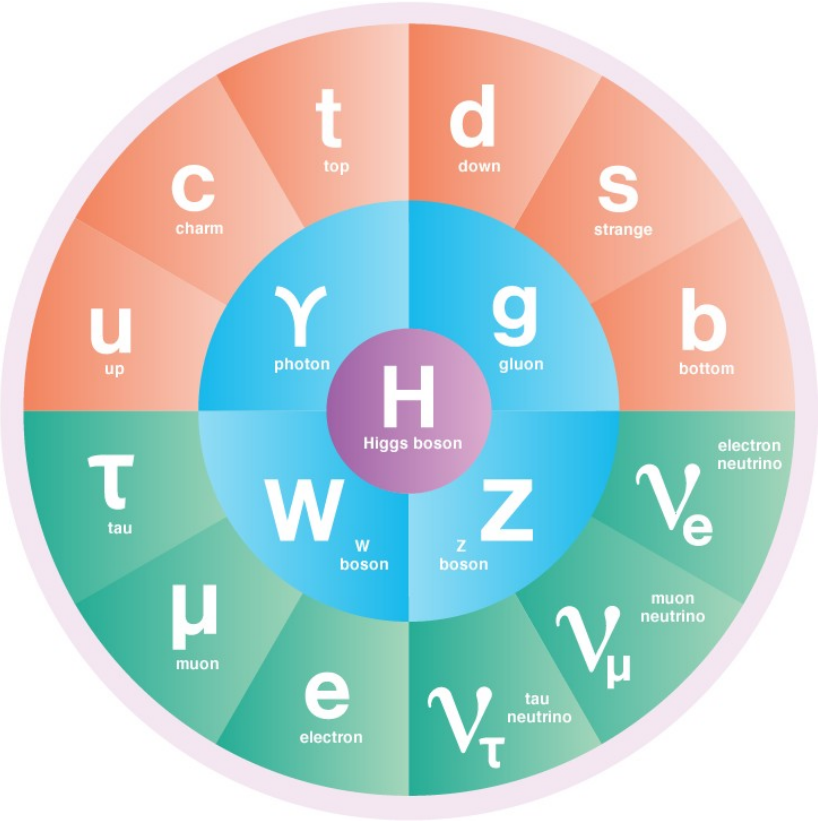
**Christoph Andreas Ternes**

Dark World to Swampland: the 9th IBS-IFT Workshop

November 6th 2024

INFN
LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

# Standard model neutrinos

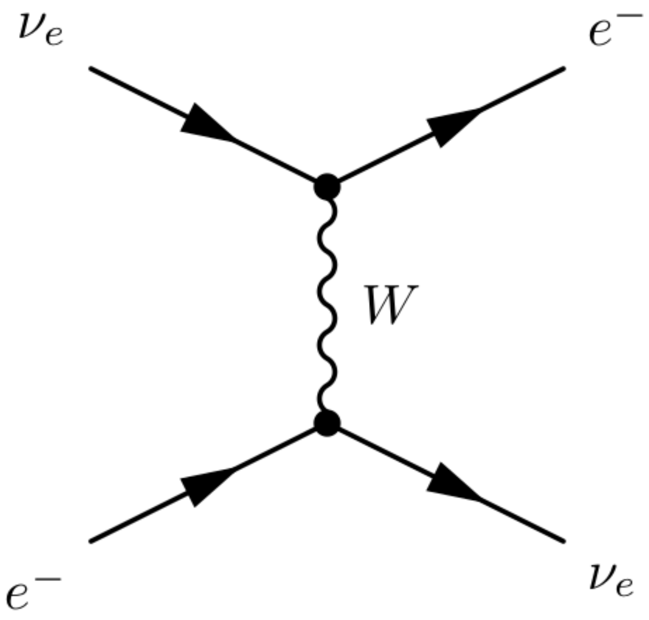


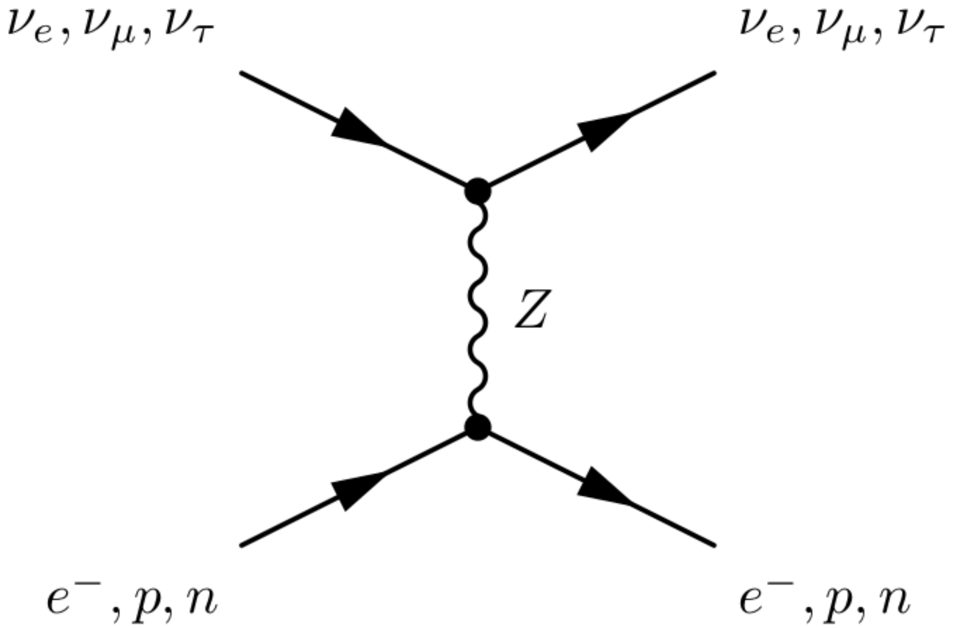
Neutrinos were predicted to explain the continuity of beta-spectra in 1930

Each charged lepton has a flavor neutrinos associated to them

Neutrinos belong to SU(2) doublets and are massless and neutral

# Standard model neutrinos

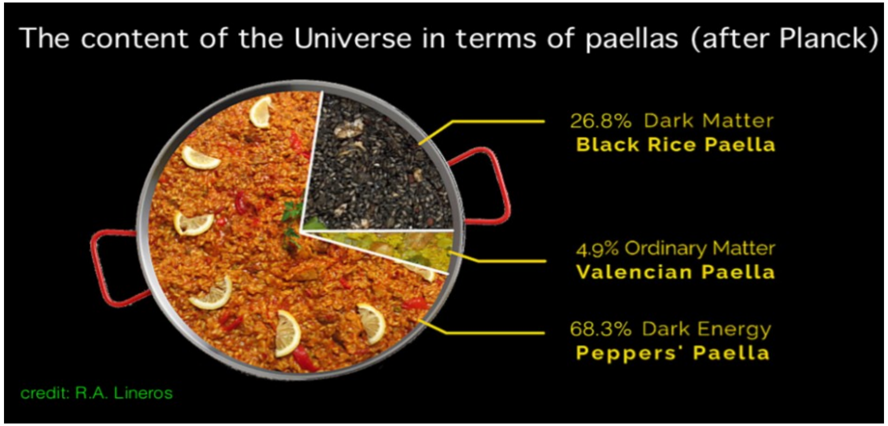




Neutrinos interact via exchange of W and Z bosons

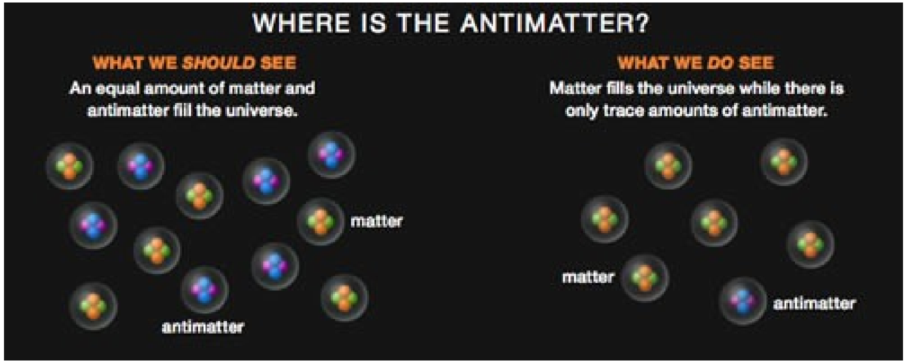
# We need physics beyond the standard model

What are dark matter and dark energy?


The content of the Universe in terms of paellas (after Planck)

credit: R.A. Lineros

Baryon asymmetry of the universe?


WHERE IS THE ANTIMATTER?

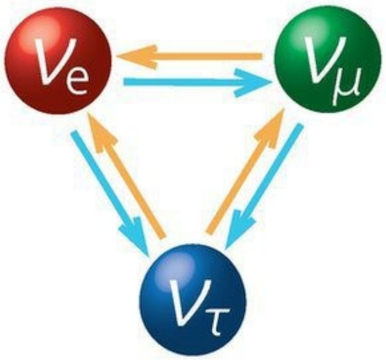
WHAT WE *SHOULD* SEE

An equal amount of matter and antimatter fill the universe.

WHAT WE *DO* SEE

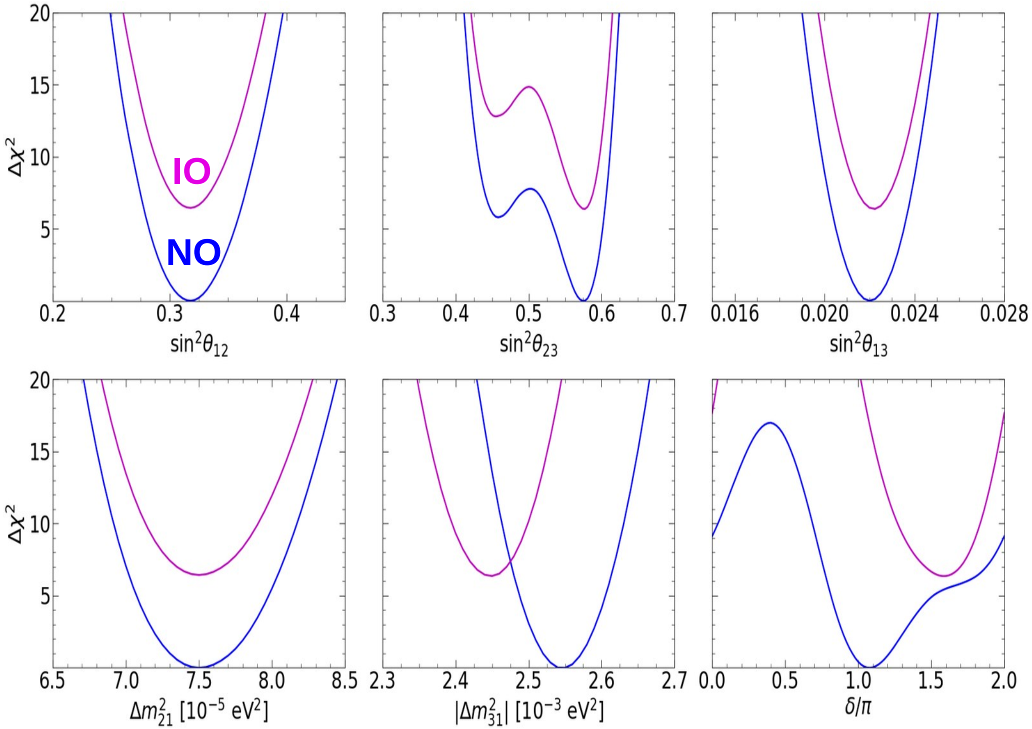
Matter fills the universe while there is only trace amounts of antimatter.

Neutrino oscillations?



# Neutrino oscillations

Valencia - Global Fit, 2006.11237, JHEP 2021

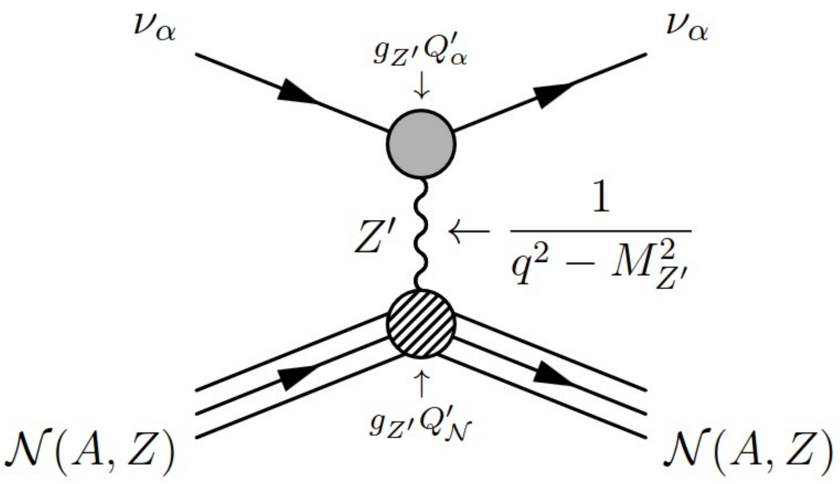


| parameter | best fit $\pm\ 1\sigma$ | $2\sigma$ range | $3\sigma$ range |
|---|---|---|---|
| $\Delta m^2_{21}[10^{-5}\mathrm{eV}^2]$ | $7.50^{+0.22}_{-0.20}$ | 7.12–7.93 | 6.94–8.14 |
| $\lvert\Delta m^2_{31}\rvert[10^{-3}\mathrm{eV}^2]$ (NO) | $2.55^{+0.02}_{-0.03}$ | 2.49–2.60 | 2.47–2.63 |
| $\lvert\Delta m^2_{31}\rvert[10^{-3}\mathrm{eV}^2]$ (IO) | $2.45^{+0.02}_{-0.03}$ | 2.39–2.50 | 2.37–2.53 |
| $\sin^2\theta_{12}/10^{-1}$ | $3.18 \pm 0.16$ | 2.86–3.52 | 2.71–3.69 |
| $\sin^2\theta_{23}/10^{-1}$ (NO) | $5.74 \pm 0.14$ | 5.41–5.99 | 4.34–6.10 |
| $\sin^2\theta_{23}/10^{-1}$ (IO) | $5.78^{+0.10}_{-0.17}$ | 5.41–5.98 | 4.33–6.08 |
| $\sin^2\theta_{13}/10^{-2}$ (NO) | $2.200^{+0.069}_{-0.062}$ | 2.069–2.337 | 2.000–2.405 |
| $\sin^2\theta_{13}/10^{-2}$ (IO) | $2.225^{+0.064}_{-0.070}$ | 2.086–2.356 | 2.018–2.424 |
| $\delta/\pi$ (NO) | $1.08^{+0.13}_{-0.12}$ | 0.84–1.42 | 0.71–1.99 |
| $\delta/\pi$ (IO) | $1.58^{+0.15}_{-0.16}$ | 1.26–1.85 | 1.11–1.96 |

See also:
Bari - 2107.00532, PRD 2021

See also:
NuFit - 2410.05380

# Light mediators



Some extensions of the Standard Model have new gauge bosons

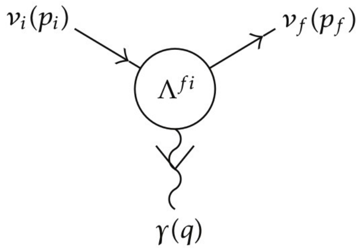
Depending on the model the charges can be different for each lepton family

$$\mathcal{L}_{Z'} = g_{Z'} Z'_\mu \left( Q^f_{Z'} \bar{f} \gamma^\mu f + \sum_\alpha Q^{\nu_\alpha}_{Z'} \bar{\nu}_{\alpha,L} \gamma^\mu \nu_{\alpha,L} \right) + \frac{1}{2} m^2_{Z'} Z'^\mu Z'_\mu$$

See Langacker, 0801.1345, Rev. Mod. Phys 2009

# Neutrino electromagnetic interactions

$$\mathcal{H}_{\text{em}}^{(\nu)} = j_\lambda^{(\nu)} A^\lambda = \sum_{j,k=1}^{3} \overline{\nu}_j \Lambda_\lambda^{jk} \nu_k A^\lambda$$



In some extensions of the Standard Model neutrinos acquire also electromagnetic properties through quantum loops effects

$$\Lambda_\lambda(q) = \left(\gamma_\lambda - \frac{q_\lambda \not{q}}{q^2}\right)\left[f_Q(q^2) + f_A(q^2) q^2 \gamma^5\right] - i\sigma_{\lambda\rho} q^\rho \left[f_M(q^2) + i f_E(q^2)\gamma^5\right]$$

**Neutrino charge and charge radius**

**Anapole**

**Magnetic and electric moments**

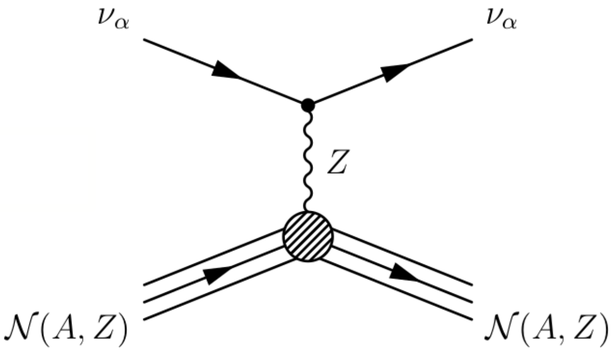
See Broggini, Giunti, Studenikin, 1207.3980, Adv.HEP 2012
Kouzakov, Studenikin, 1703.00401, PRD 2017

# Experimental data

We will use data from several experiments to bound new physics scenarios

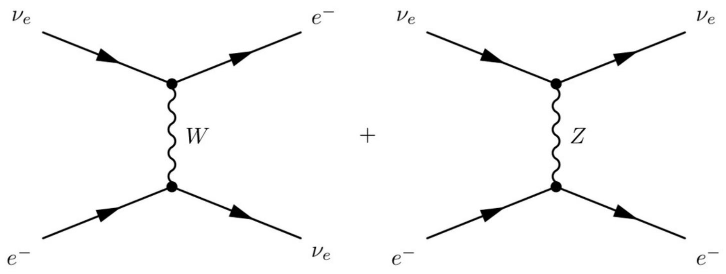
We use CEvNS data from

- COHERENT (CsI and Ar data)
- DRESDEN-II



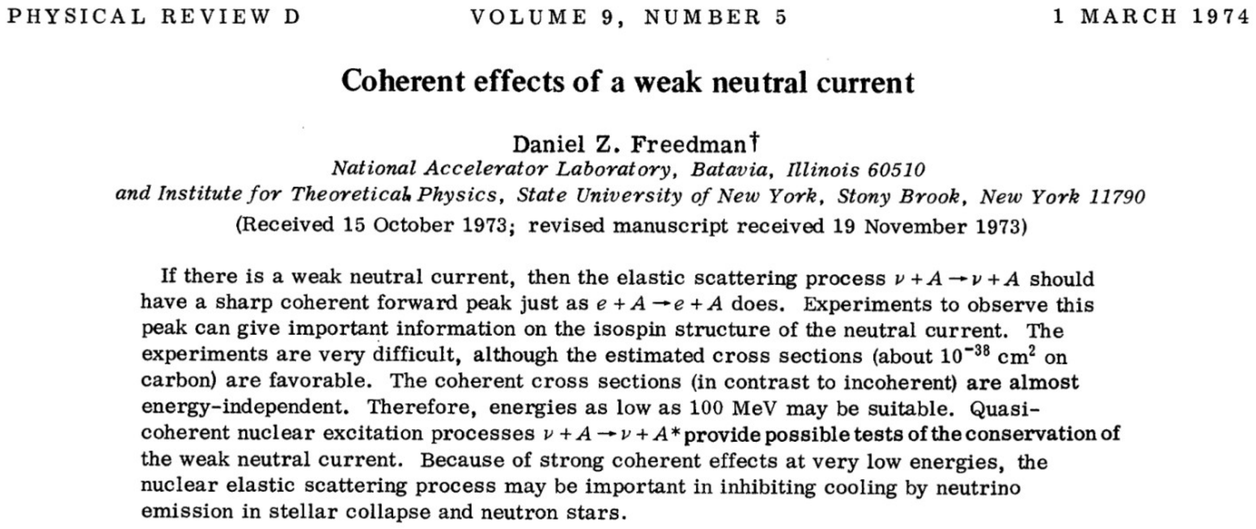
We use EvES data from

- PandaX-4T
- LUX-ZEPLIN
- XENONnT
- DARWIN (sensitivity)



# Coherent elastic neutrino nucleus scattering

## CEvNS was predicted in 1974!

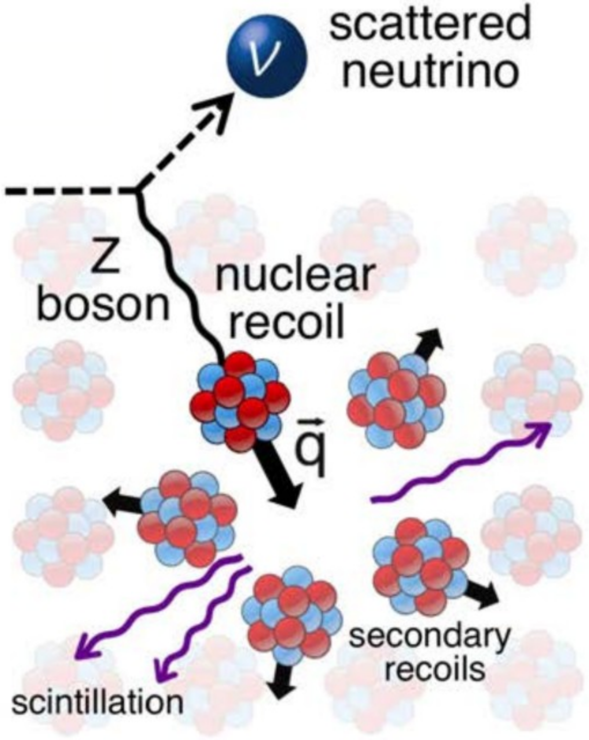


PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

### 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)

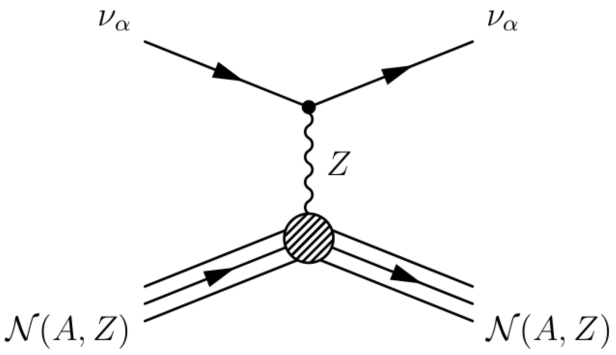
If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are 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.



# Coherent elastic neutrino nucleus scattering

In the standard model we have

$$\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT_{\rm nr}}(E,T_{\rm nr}) = \frac{G_{\rm F}^2 M}{\pi}\left(1-\frac{MT_{\rm nr}}{2E^2}\right)(Q^V_{\ell,\rm SM})^2$$



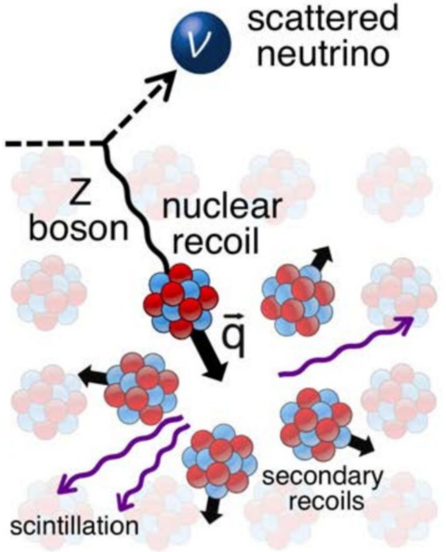
with the weak charge

$$Q^V_{\ell,\rm SM} = \left[g_V^p\,(\nu_\ell)\,Z F_Z(|\vec{q}|^2) + g_V^n N F_N(|\vec{q}|^2)\right]$$

$$g_V^p(\nu_e) = 0.0401, \qquad g_V^p(\nu_\mu) = 0.0318, \qquad g_V^n = -0.5094$$

The cross section scales with the neutron number squared

The form factors describe the loss of coherence for large momentum transfer



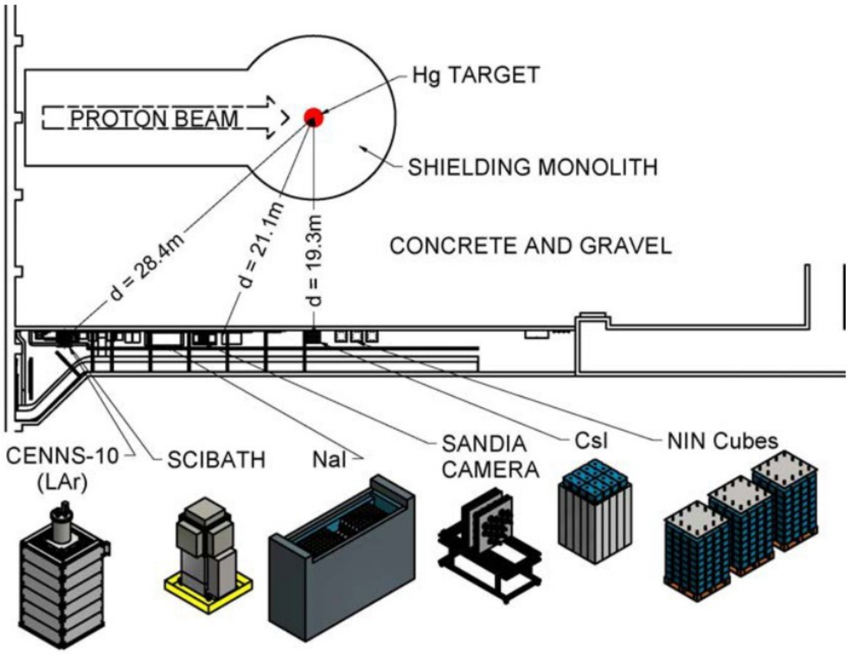
# COHERENT

Observed in 2017 in the COHERENT experiment!

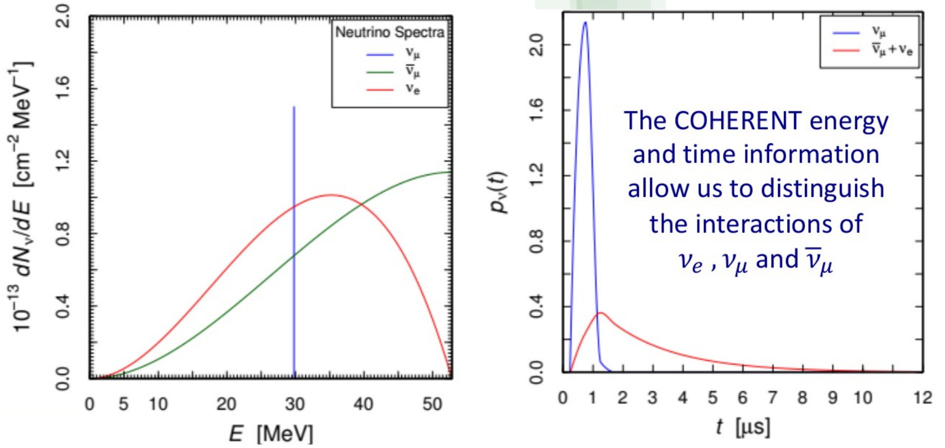
COHERENT uses neutrinos from the decay of

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$



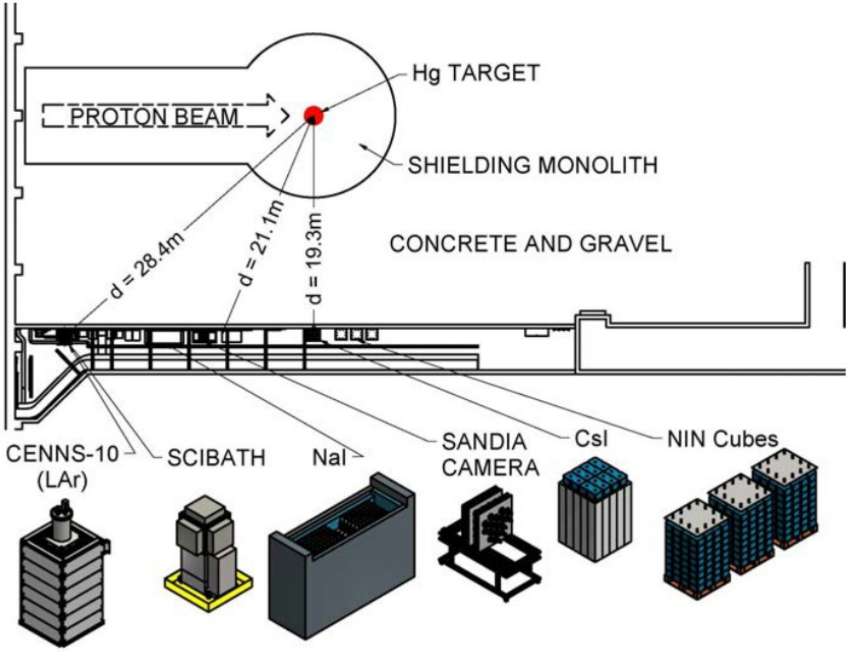
COHERENT, 1708.01294, Science 2017

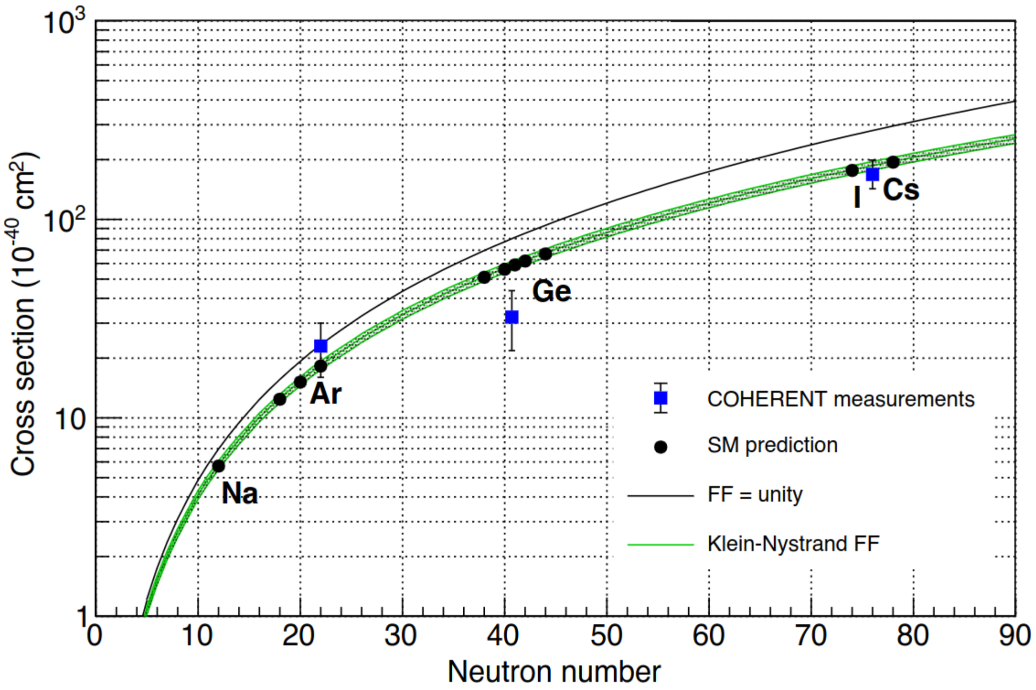


The COHERENT energy and time information allow us to distinguish the interactions of $\nu_e$ , $\nu_\mu$ and $\bar{\nu}_\mu$

Cadeddu et al, 1810.05606, PRD 2018

# COHERENT

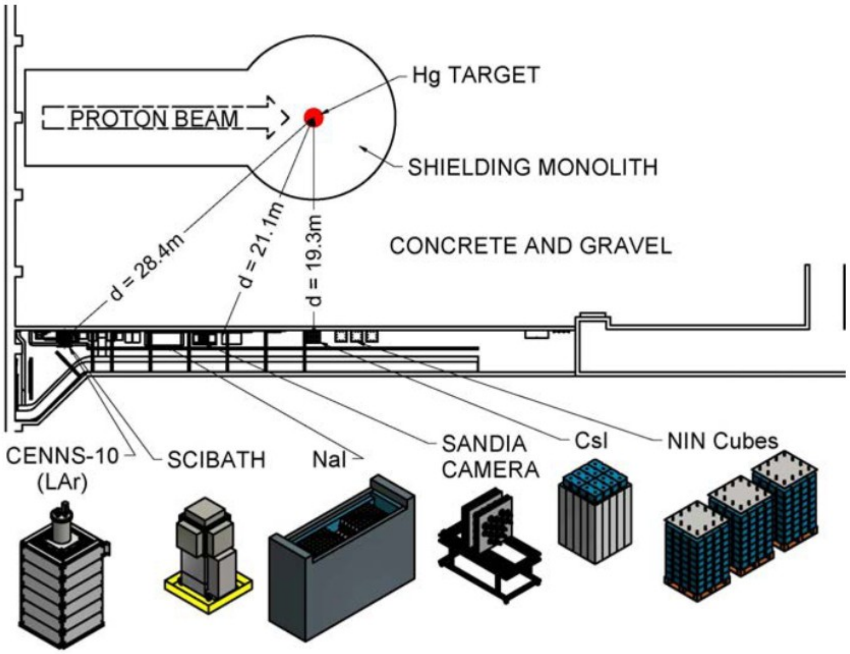




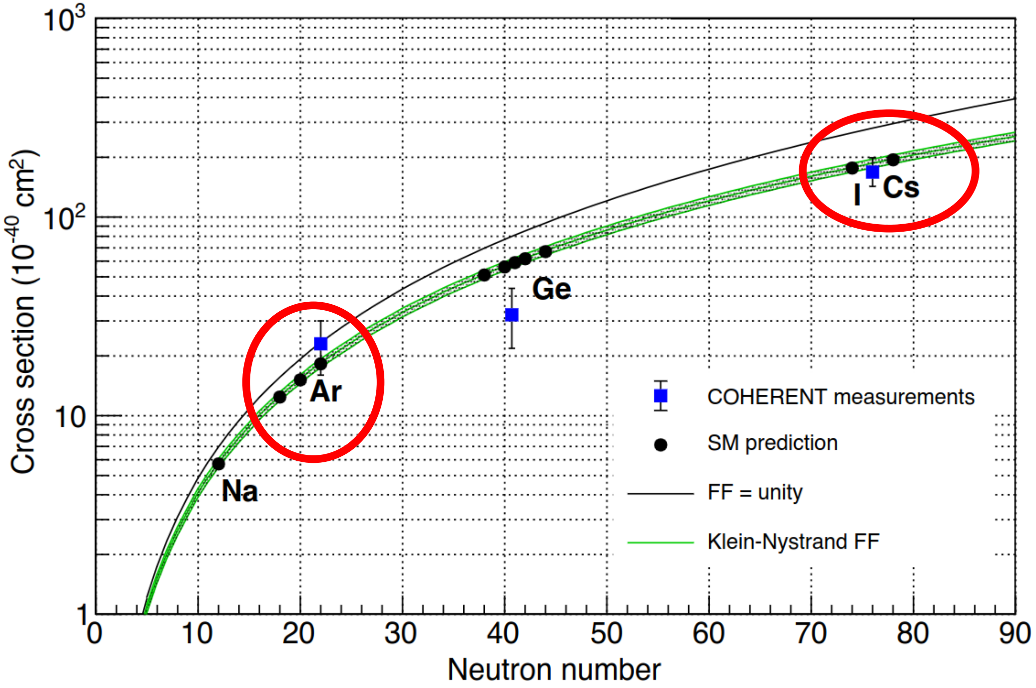
COHERENT, 1708.01294, Science 2017

Mathew Green @ Neutrino-2024

# COHERENT



COHERENT, 1708.01294, Science 2017



Mathew Green @ Neutrino-2024

# COHERENT

Data included

CEvNS on CsI scintillating crystal

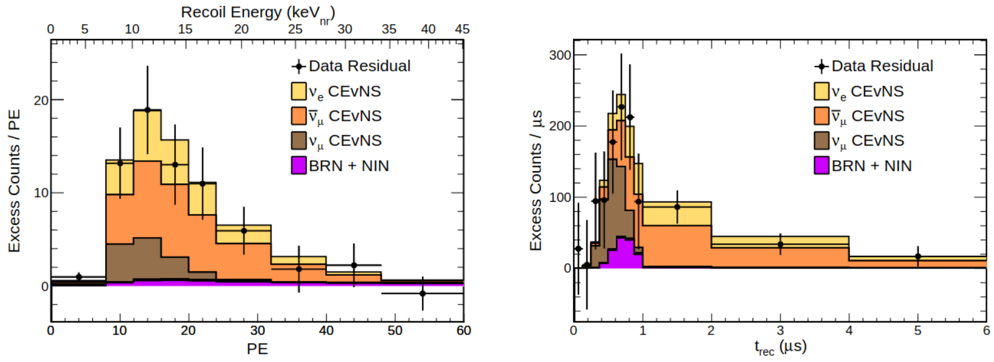
$306 \pm 20$ events, $> 11\sigma$

consistent with SM

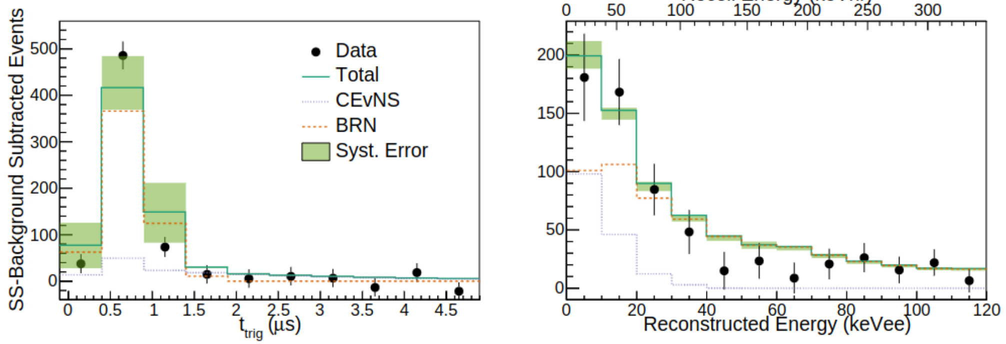
Data included

CEvNS on liquid argon

Still collecting data, more data expected to come soon



COHERENT, 2110.07730, PRL 2022

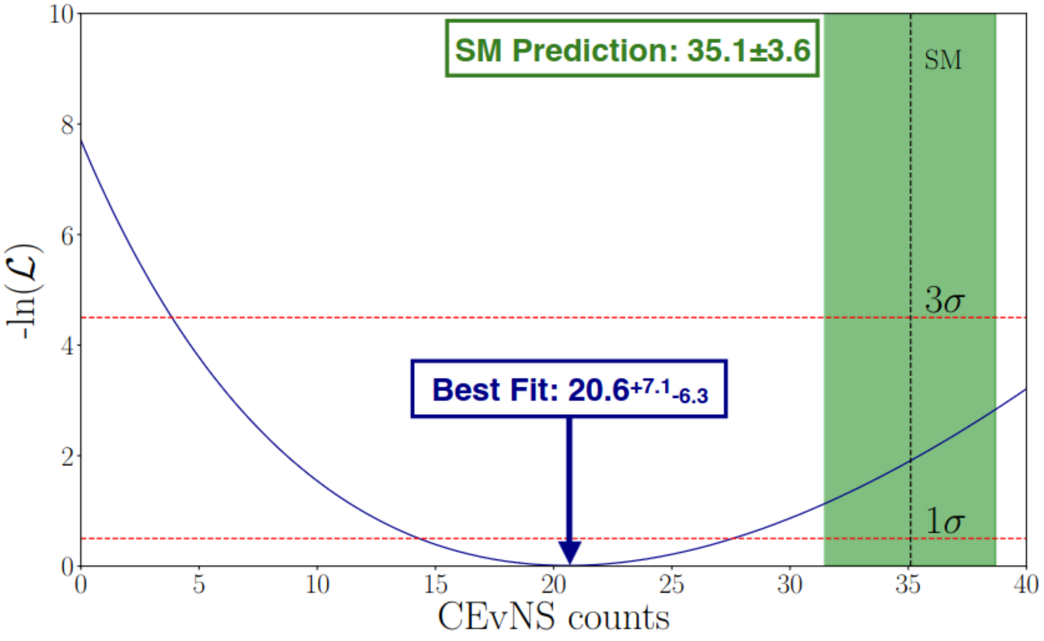


COHERENT, 2003.10630, PRL 2021

# COHERENT

New results were presented at the Magnificent CEvNS workshop in Valencia this year!

These data are not included in the analyses discussed today



**2D Unbinned Extended Likelihood Fit:**

- Null Hypothesis rejected at 3.9σ
- Reduced $\chi^2$: 1.84 (p=0.40)
- 1.8σ separation from SM prediction

See:
COHERENT, 2406.13806

# COHERENT

Calculation is more complicated

$$N_i^{\mathrm{CE}\nu\mathrm{NS}} = N(\mathcal{N}) \int_{T_{\mathrm{nr}}^{i}}^{T_{\mathrm{nr}}^{i+1}} dT_{\mathrm{nr}} A(T_{\mathrm{nr}}) \int_0^{T_{\mathrm{nr}}^{\prime\mathrm{max}}} dT'_{\mathrm{nr}} R(T_{\mathrm{nr}}, T'_{\mathrm{nr}}) \int_{E_{\min}(T'_{\mathrm{nr}})}^{E_{\max}} dE \sum_{\nu=\nu_e,\nu_\mu,\bar{\nu}_\mu} \frac{dN_\nu}{dE}(E) \frac{d\sigma_{\nu-\mathcal{N}}}{dT_{\mathrm{nr}}}(E, T'_{\mathrm{nr}})$$

Detector effects (resolution, efficiency, quenching) must be taken into account when calculating the expected number of events

In the statistical analysis we must consider several sources of background and associated systematic uncertainties

$$\chi^2_{\mathrm{CsI}} = 2 \sum_{i=1}^{9} \sum_{j=1}^{11} \left[ \sum_{z=1}^{4} (1+\eta_z) N_{ij}^{z} - N_{ij}^{\mathrm{exp}} + N_{ij}^{\mathrm{exp}} \ln \left( \frac{N_{ij}^{\mathrm{exp}}}{\sum_{z=1}^{4} (1+\eta_z) N_{ij}^{z}} \right) \right] + \sum_{z=1}^{4} \left( \frac{\eta_z}{\sigma_z} \right)^2$$

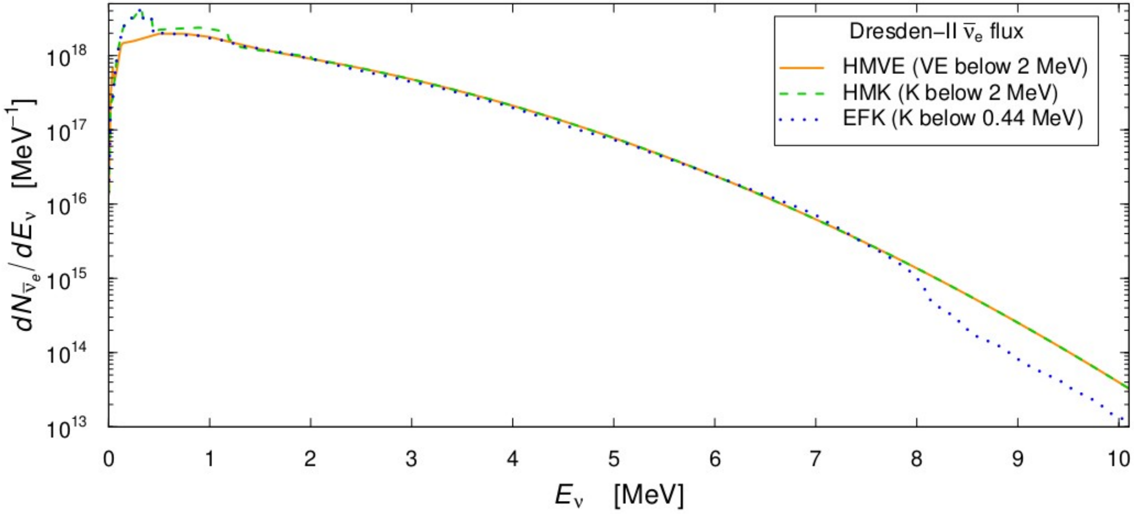
Atzori Corona et al, 2202.11002, JHEP 2022
Atzori Corona et al, 2205.09484, JHEP 2022

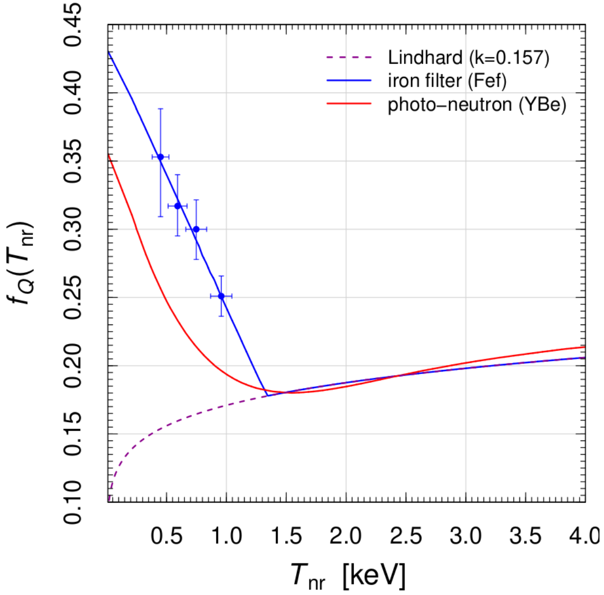
# DRESDEN-II

CEvNS using (anti)neutrinos from a nuclear reactor

Depends on the reactor flux model under consideration

Depends on the exact form of the quenching factor



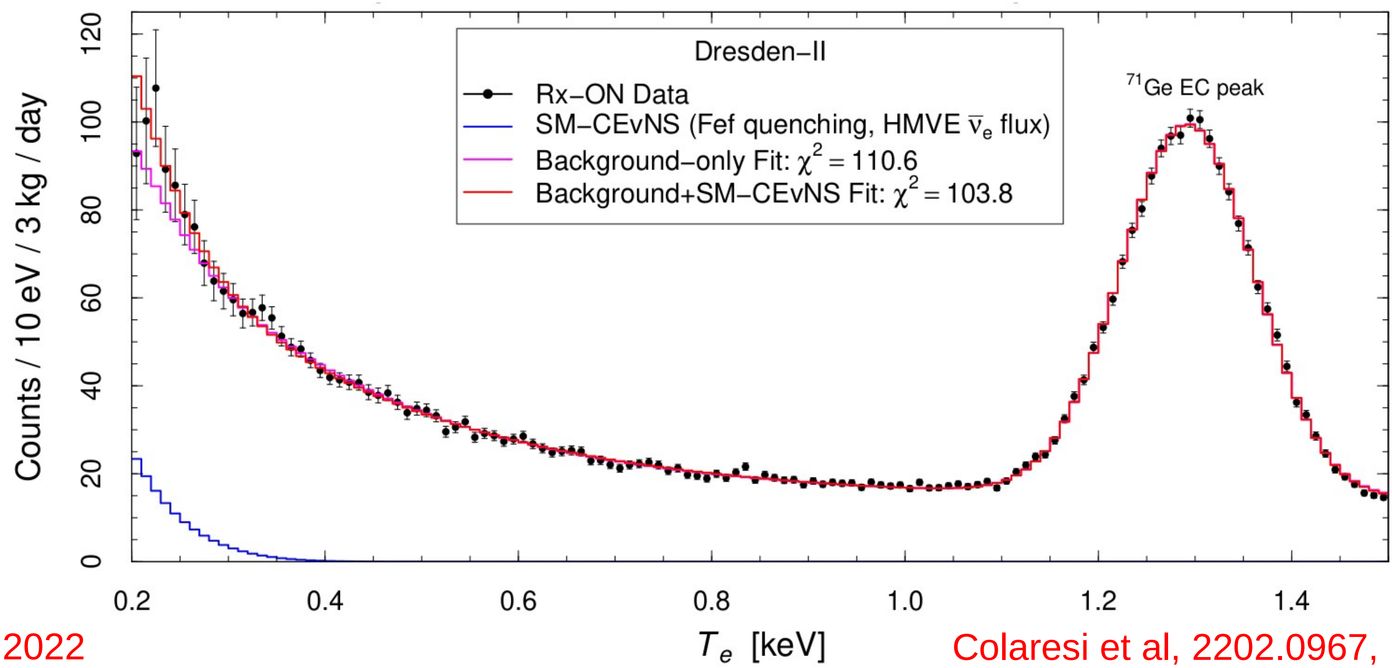


Giunti @ Neutrino 2022

Atzori Corona et al, 2205.09484, JHEP 2022

# DRESDEN-II

Rather CEvNS “indication” than measurement

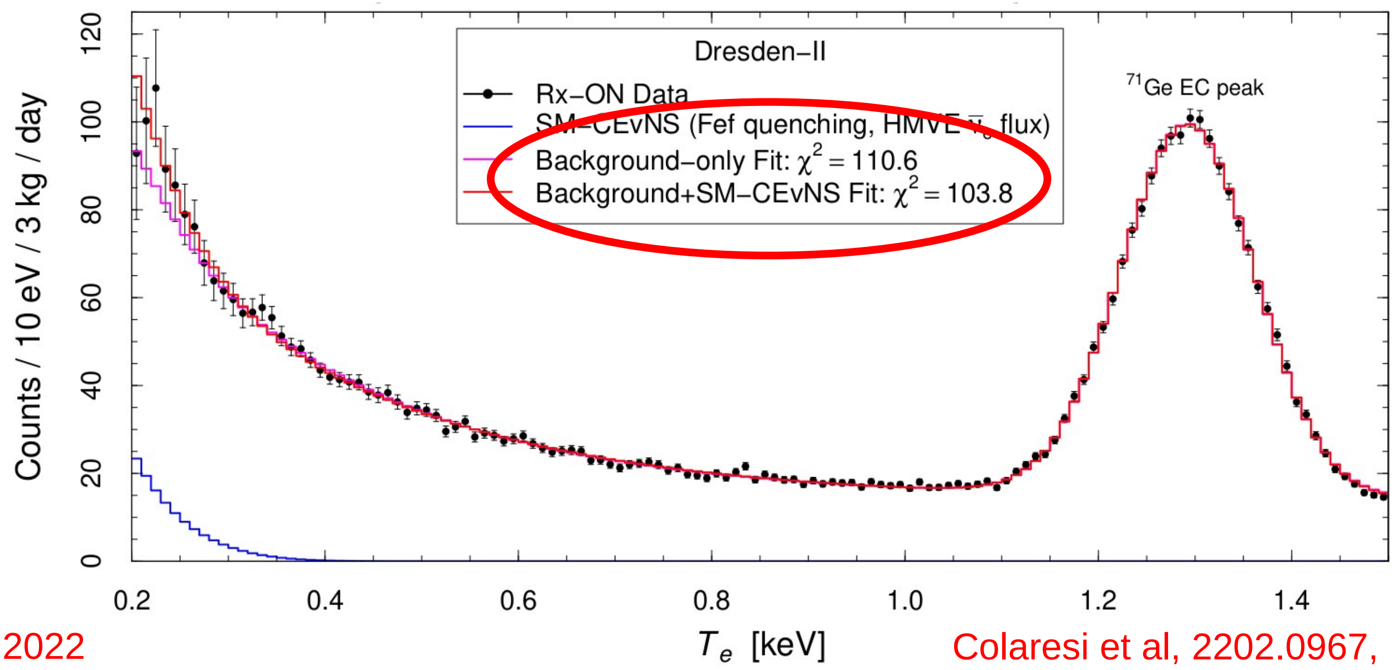


Giunti @ Neutrino 2022

Colaresi et al, 2202.0967, PRL 2022

# DRESDEN-II

## Rather CEvNS “indication” than measurement



Giunti @ Neutrino 2022

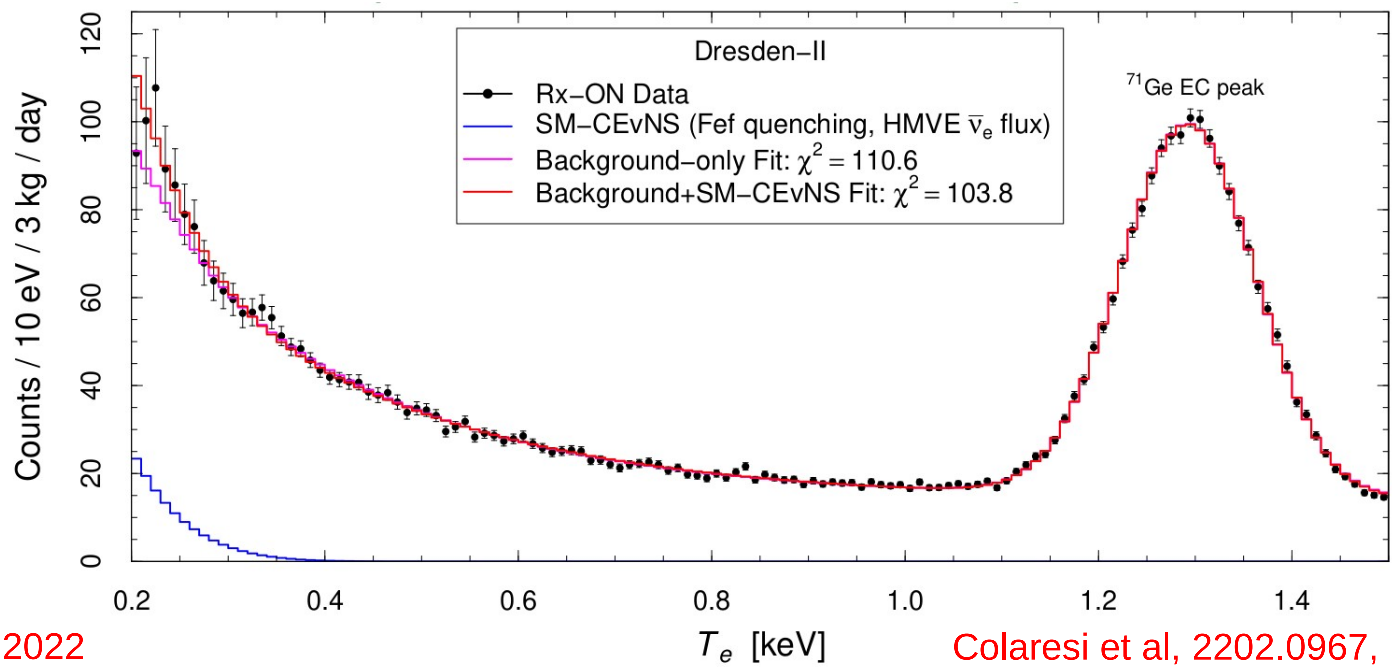
Colaresi et al, 2202.0967, PRL 2022

# DRESDEN-II

Rather CEvNS “indication” than measurement

Can still be used to bound new physics models

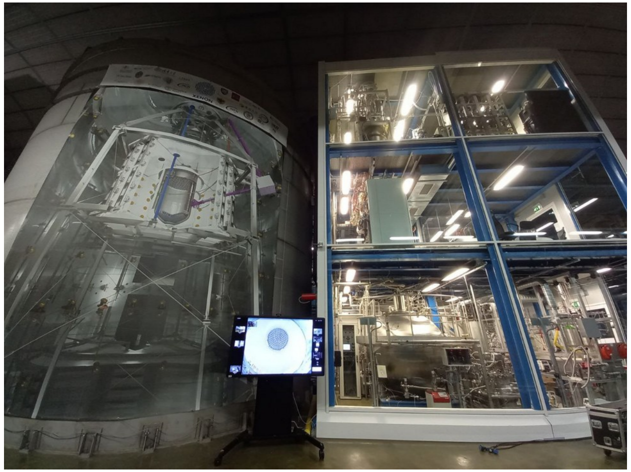
Very low energy threshold



Giunti @ Neutrino 2022

Colaresi et al, 2202.0967, PRL 2022

# Dark matter direct detection experiments



We will use data from several DMDD experiments

- PandaX-4T (China)
- LUX-ZEPLIN (USA)
- XENONnT (Gran Sasso)
- DARWIN (next generation experiment)

The original purpose of these experiments is to observe recoils induced by WIMP interactions

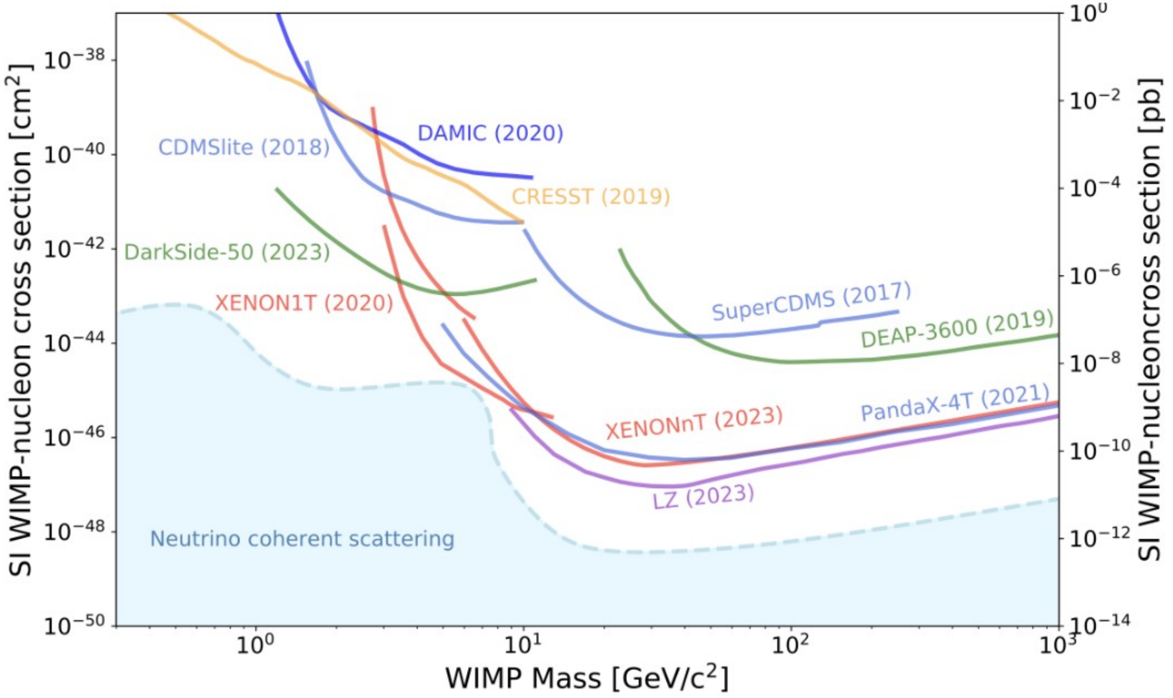
Solar neutrinos constitute an irreducible background for these experiments

These experiments can be used to measure nuclear and electron recoils!

# Dark matter direct detection experiments

Direct detection experiments put stringent bounds on the WIMP parameter space

[Baudis & Profumo, PDG 2023]



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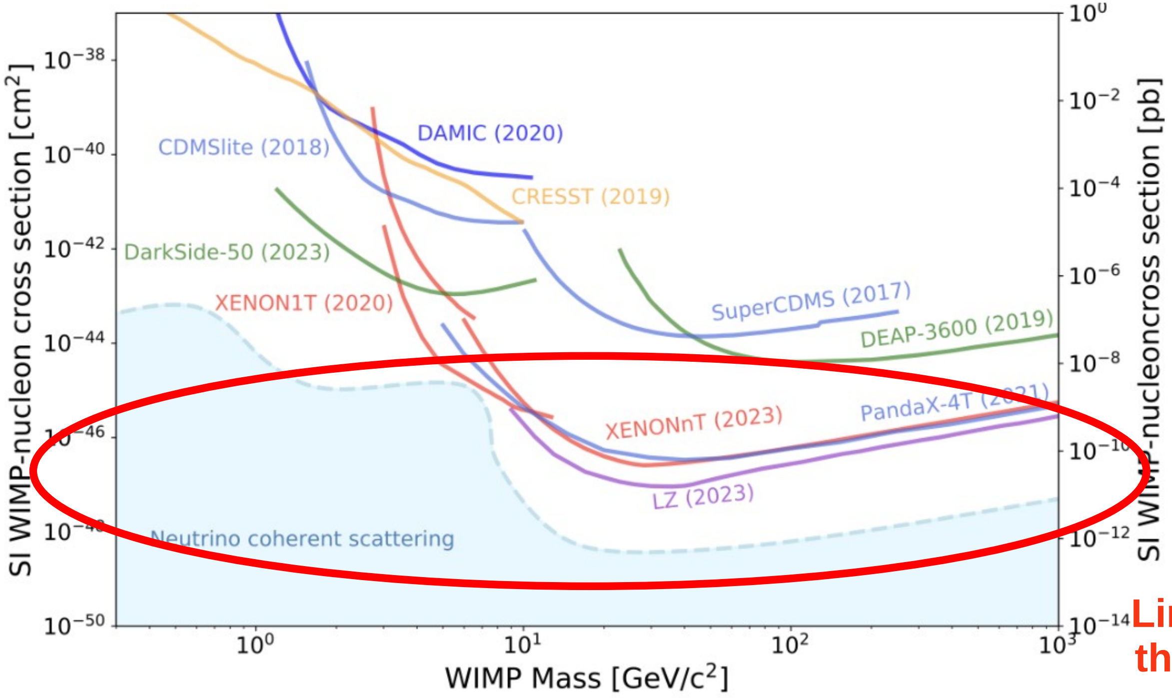
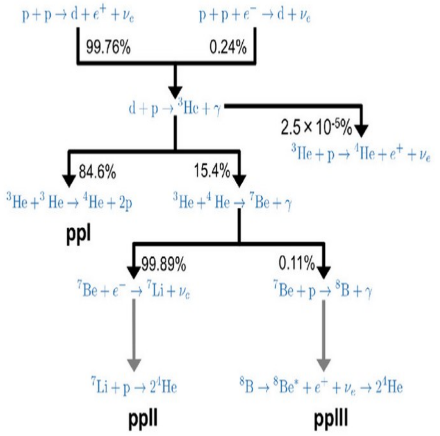
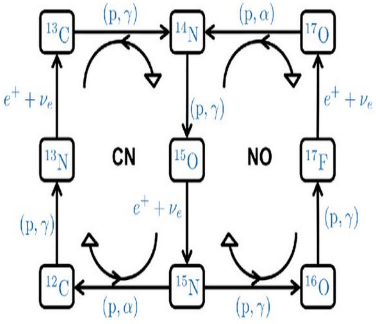


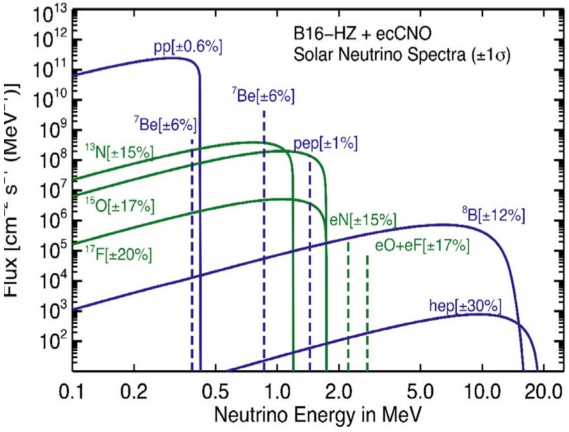
**Limits are getting close to the so-called neutrino fog**

# Dark matter direct detection experiments

Solar neutrinos oscillate and arrive at a detector on Earth as a mixture of $\nu_e$ , $\nu_\mu$ , and $\nu_\tau$ , whose fluxes are given by





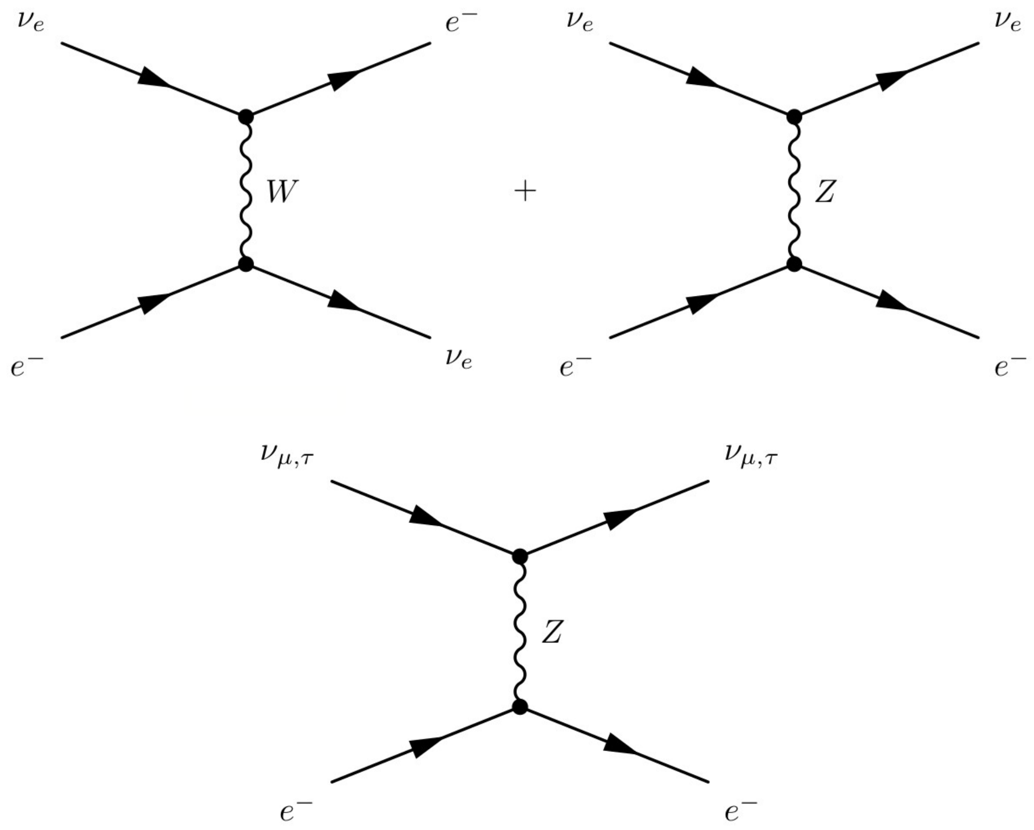


| Flux | B16-HZ | B16-LZ |
|---|---|---|
| $\Phi(pp)$ | 5.98 (1 ± 0.006) | 6.03 (1 ± 0.005) |
| $\Phi(pep)$ | 1.44 (1 ± 0.01) | 1.46 (1 ± 0.009) |
| $\Phi(hep)$ | 7.98 (1 ± 0.30) | 8.25 (1 ± 0.30) |
| $\Phi({}^7Be)$ | 4.93 (1 ± 0.06) | 4.50 (1 ± 0.06) |
| $\Phi({}^8B)$ | 5.46 (1 ± 0.12) | 4.50 (1 ± 0.12) |
| $\Phi({}^{13}N)$ | 2.78 (1 ± 0.15) | 2.04 (1 ± 0.14) |
| $\Phi({}^{15}O)$ | 2.05 (1 ± 0.17) | 1.44 (1 ± 0.16) |
| $\Phi({}^{17}F)$ | 5.29 (1 ± 0.20) | 3.26 (1 ± 0.18) |
| $\Phi(eN)$ | 2.20 (1 ± 0.15) | 1.61 (1 ± 0.14) |
| $\Phi(eO)$ | 0.81 (1 ± 0.17) | 0.57 (1 ± 0.16) |
| $\Phi(eF)$ | 3.11 (1 ± 0.20) | 1.91 (1 ± 0.18) |

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

Villante, Serenelli, 2101.03077, Frontiers 2021

# Elastic neutrino electron scattering



# Elastic neutrino electron scattering

In the standard model we have

$$\frac{d\sigma^{\mathrm{SM}}_{\nu_\ell-\mathrm{Xe}}}{dT_\mathrm{e}}(E_\nu,T_\mathrm{e}) = Z^{\mathrm{Xe}}_{\mathrm{eff}}(T_e)\,\frac{G_\mathrm{F}^2 m_e}{2\pi}\left[\left(g_V^{\nu_\ell}+g_A^{\nu_\ell}\right)^2+\left(g_V^{\nu_\ell}-g_A^{\nu_\ell}\right)^2\left(1-\frac{T_e}{E_\nu}\right)^2-\left((g_V^{\nu_\ell})^2-(g_A^{\nu_\ell})^2\right)\frac{m_e T_e}{E_\nu^2}\right]$$

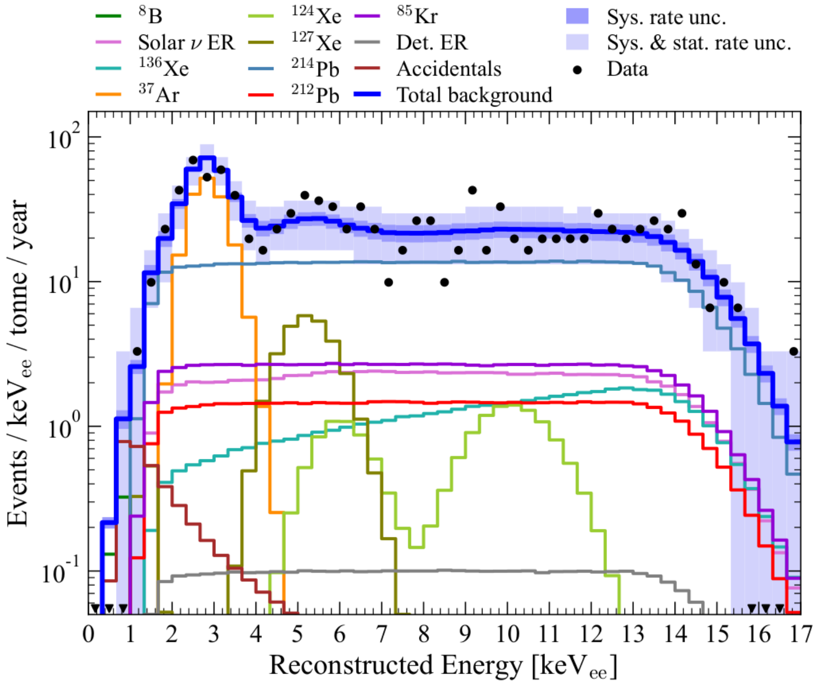
with the couplings

$$\begin{aligned} g_V^{\nu_e} &= 2\sin^2\vartheta_W + 1/2, & g_A^{\nu_e} &= 1/2,\\ g_V^{\nu_{\mu,\tau}} &= 2\sin^2\vartheta_W - 1/2, & g_A^{\nu_{\mu,\tau}} &= -1/2, \end{aligned}$$

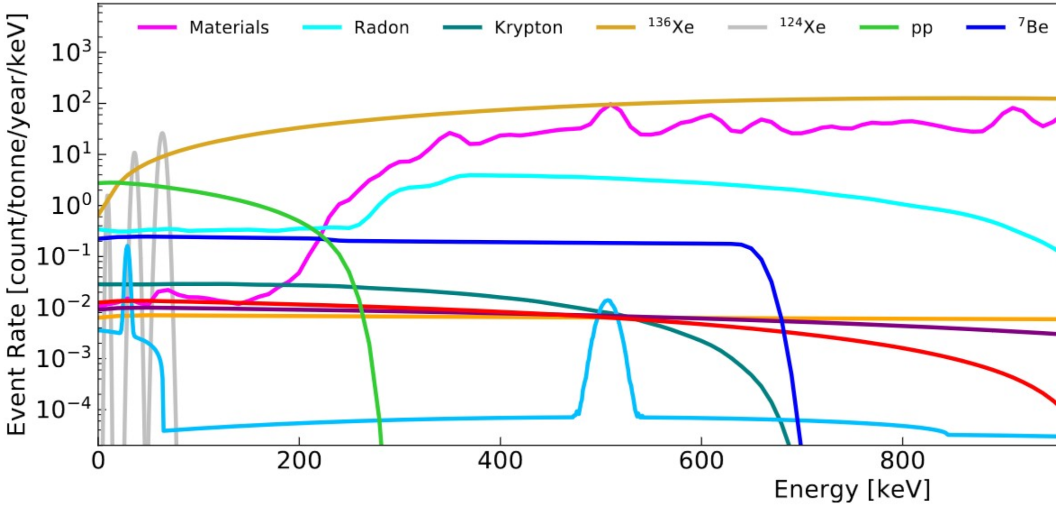
The first factor quantifies the effective number of electrons which can be ionized for a given recoil energy

# Dark matter direct detection experiments

Solar neutrinos EνES constitutes a subdominating (dominating) background component in current (future) experiment

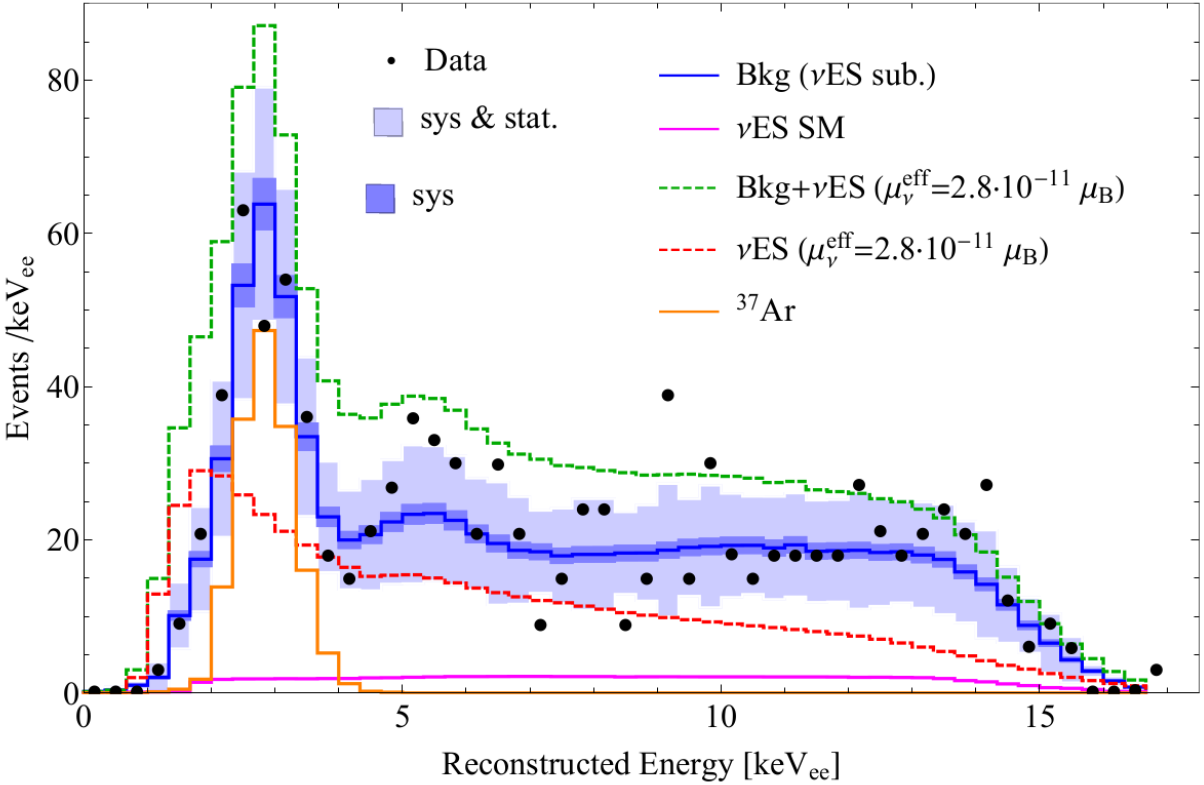


LZ, 2211.17120, PRD 2023



DARWIN, 2006.03114, EPJC 2020

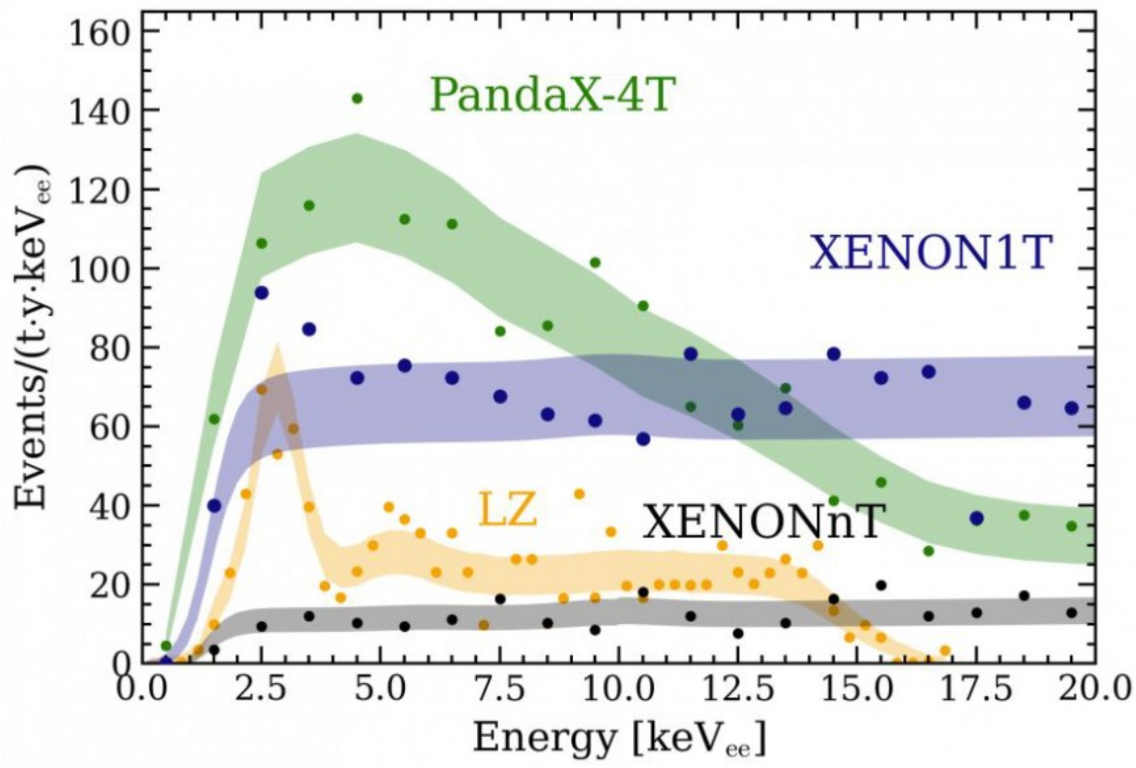
# Dark matter direct detection experiments



Even though the EvES rate is very small in the SM, new physics can dramatically increase the cross section

Atzori Corona et al, 2207.05036, PRD 2023

# Dark matter direct detection experiments



XENONnT has the lowest background rate

We can expect the strongest constraints on new physics from XENONnT data

PandaX-4T, 2206.02339, PRL 2022
LZ, 2207.03764, PRL 2023
XENON, 2207.11330, PRL 2022

Angelino @ Neurino Telescopes 2022

# Dark matter direct detection experiments

Again all background components with systematical uncertainties must be taken into account

$$R_k^X = R_k^{E\nu ES} + \sum_i R_k^i \qquad R_k^{E\nu ES} = N \int_{T_e^k}^{T_e^{k+1}} dT_e \int_0^\infty dT_e' \, R(T_e, T_e') \, A(T_e') \sum_{i=pp,^7\mathrm{Be}} \int_{E_\nu^{\mathrm{min}}}^{E_{\nu,i}^{\mathrm{max}}} dE_\nu \sum_\ell \Phi_{\nu_\ell}^i(E_\nu) \, \frac{d\sigma_{\nu_\ell}}{dT_e'}$$

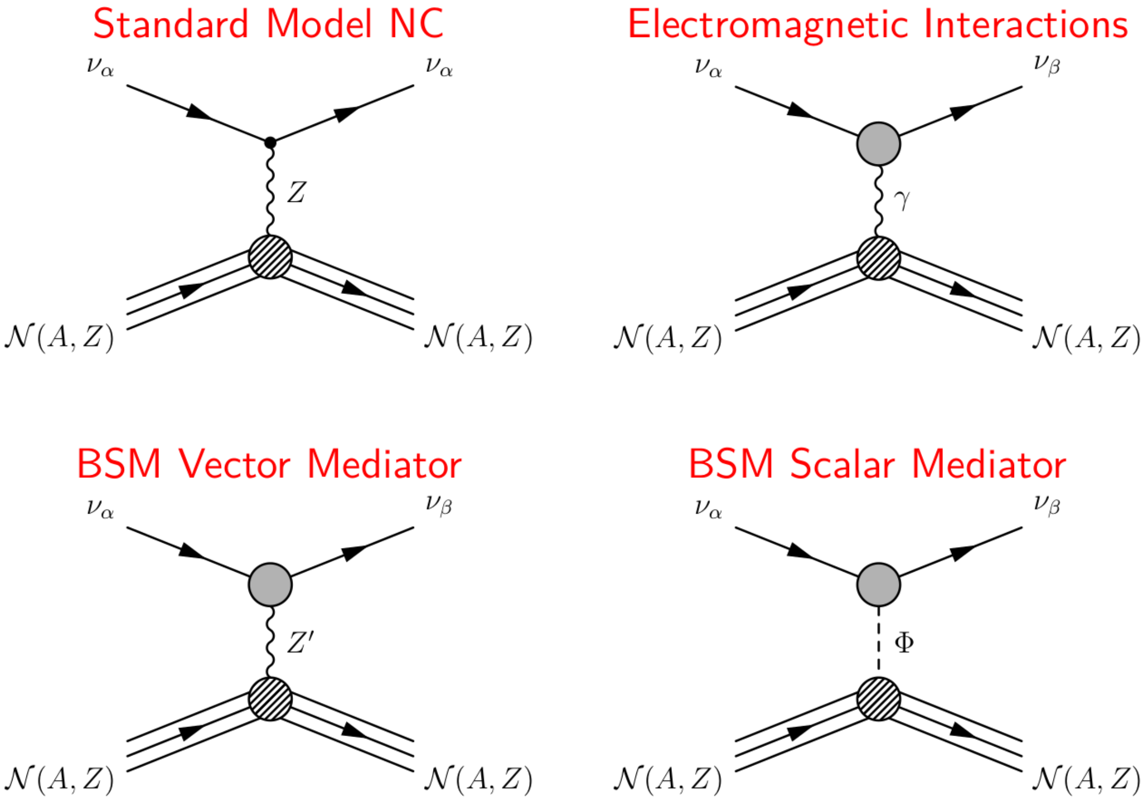
$$\chi_X^2 = \min_{\vec{\alpha},\vec{\beta}} \left\{ 2 \left( \sum_k R_k^X - D_k^X + D_k^X \, \log D_k^X / R_k^X \right) + \sum_i (\alpha_i/\sigma_{\alpha_i})^2 + \sum_i (\beta_i/\sigma_{\beta_i})^2 \right\}$$

We also perform a combined analysis of all DMDD experiments considering possible correlations among systematic uncertainties

Giunti, Ternes, 2309.17380, PRD 2023

# Possible new physics contributions

The process can be altered by many BSM scenarios



Giunti @ Neutrino 2022

# New light mediators

Some extensions of the Standard Model have new gauge bosons with different interaction with neutrinos, we consider two scenarios

New vector interactions motivated by flavor models

Depending on the model the charges can be different for each lepton family

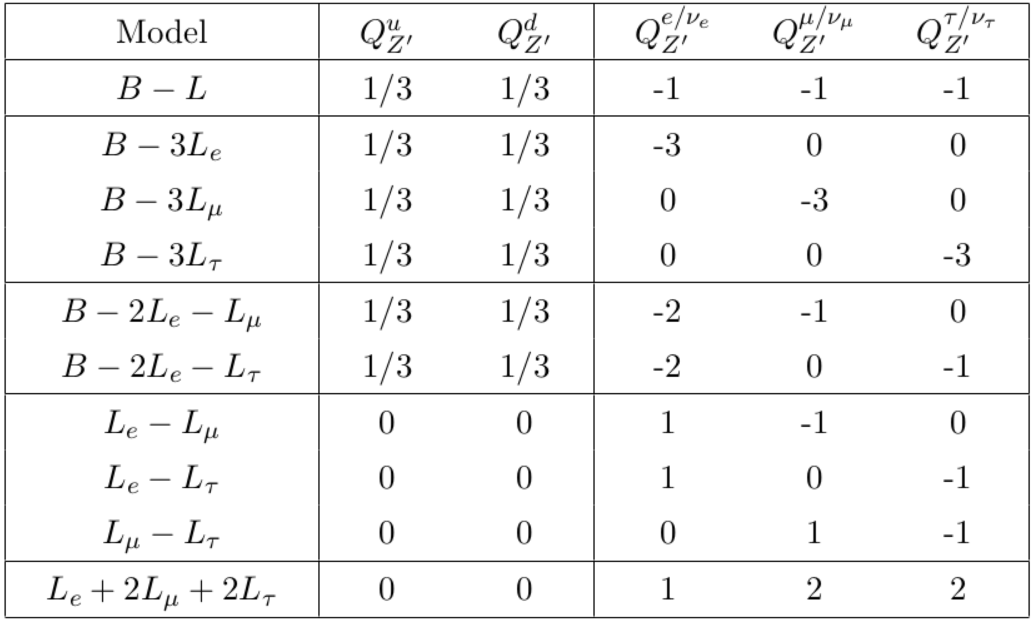
$$\mathcal{L}_{Z'} = g_{Z'} Z'_\mu \left( Q^f_{Z'} \bar{f} \gamma^\mu f + \sum_\alpha Q^{\nu_\alpha}_{Z'} \bar{\nu}_{\alpha,L} \gamma^\mu \nu_{\alpha,L} \right) + \frac{1}{2} m^2_{Z'} Z'^\mu Z'_\mu$$

General new neutrino interactions

$$\mathscr{L}^{\mathrm{NGI}}_{\mathrm{NC}} \supset \frac{G_F}{\sqrt{2}} \sum_{\substack{a=(S,P,V,A,T),\\ \ell=e,\mu,\tau}} C_a \left(\bar{\nu}_\ell \Gamma^a P_L \nu_\ell\right) \left(\bar{N} \Gamma_a N\right)$$

See Langacker, 0801.1345, Rev. Mod. Phys 2009

# Light vector mediators



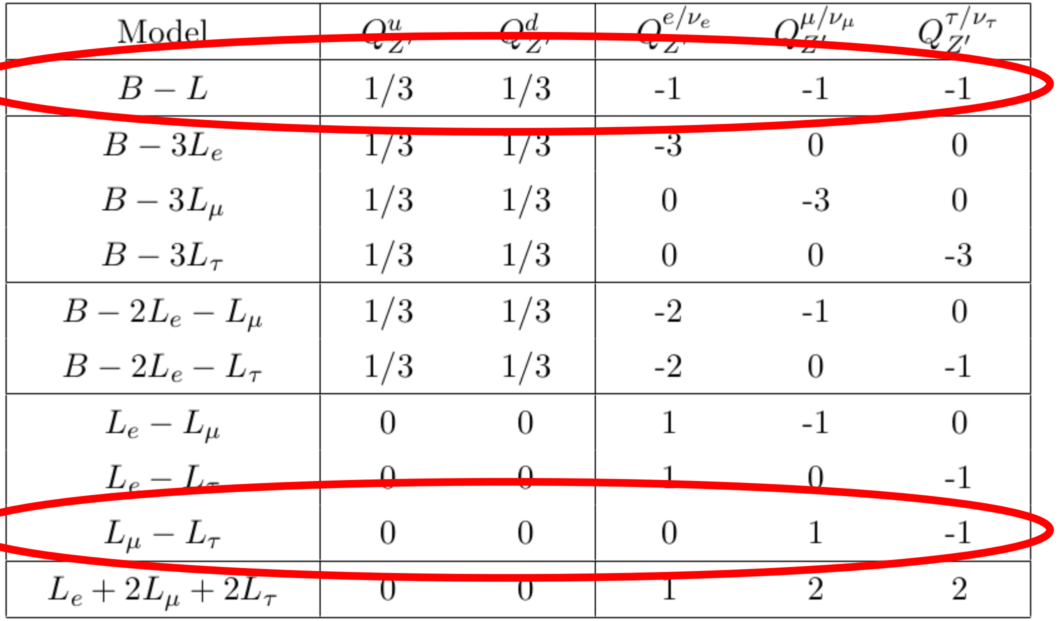
| Model | $Q^u_{Z'}$ | $Q^d_{Z'}$ | $Q^{e/\nu_e}_{Z'}$ | $Q^{\mu/\nu_\mu}_{Z'}$ | $Q^{\tau/\nu_\tau}_{Z'}$ |
|---|---|---|---|---|---|
| $B-L$ | 1/3 | 1/3 | -1 | -1 | -1 |
| $B-3L_e$ | 1/3 | 1/3 | -3 | 0 | 0 |
| $B-3L_\mu$ | 1/3 | 1/3 | 0 | -3 | 0 |
| $B-3L_\tau$ | 1/3 | 1/3 | 0 | 0 | -3 |
| $B-2L_e-L_\mu$ | 1/3 | 1/3 | -2 | -1 | 0 |
| $B-2L_e-L_\tau$ | 1/3 | 1/3 | -2 | 0 | -1 |
| $L_e-L_\mu$ | 0 | 0 | 1 | -1 | 0 |
| $L_e-L_\tau$ | 0 | 0 | 1 | 0 | -1 |
| $L_\mu-L_\tau$ | 0 | 0 | 0 | 1 | -1 |
| $L_e+2L_\mu+2L_\tau$ | 0 | 0 | 1 | 2 | 2 |

We consider U(1)’ models that are anomaly-free if the SM is extended with three right-handed neutrinos

Possible explanation for neutrino masses and mixings

Atzori Corona et al, 2202.11002, JHEP 2022
De Romeri, Papoulias, Ternes, 2402.05506, JHEP 2024

# Light vector mediators



| Model | $Q^u_{Z'}$ | $Q^d_{Z'}$ | $Q^{e/\nu_e}_{Z'}$ | $Q^{\mu/\nu_\mu}_{Z'}$ | $Q^{\tau/\nu_\tau}_{Z'}$ |
|---|---|---|---|---|---|
| $B-L$ | 1/3 | 1/3 | -1 | -1 | -1 |
| $B-3L_e$ | 1/3 | 1/3 | -3 | 0 | 0 |
| $B-3L_\mu$ | 1/3 | 1/3 | 0 | -3 | 0 |
| $B-3L_\tau$ | 1/3 | 1/3 | 0 | 0 | -3 |
| $B-2L_e-L_\mu$ | 1/3 | 1/3 | -2 | -1 | 0 |
| $B-2L_e-L_\tau$ | 1/3 | 1/3 | -2 | 0 | -1 |
| $L_e-L_\mu$ | 0 | 0 | 1 | -1 | 0 |
| $L_e-L_\tau$ | 0 | 0 | 1 | 0 | -1 |
| $L_\mu-L_\tau$ | 0 | 0 | 0 | 1 | -1 |
| $L_e+2L_\mu+2L_\tau$ | 0 | 0 | 1 | 2 | 2 |

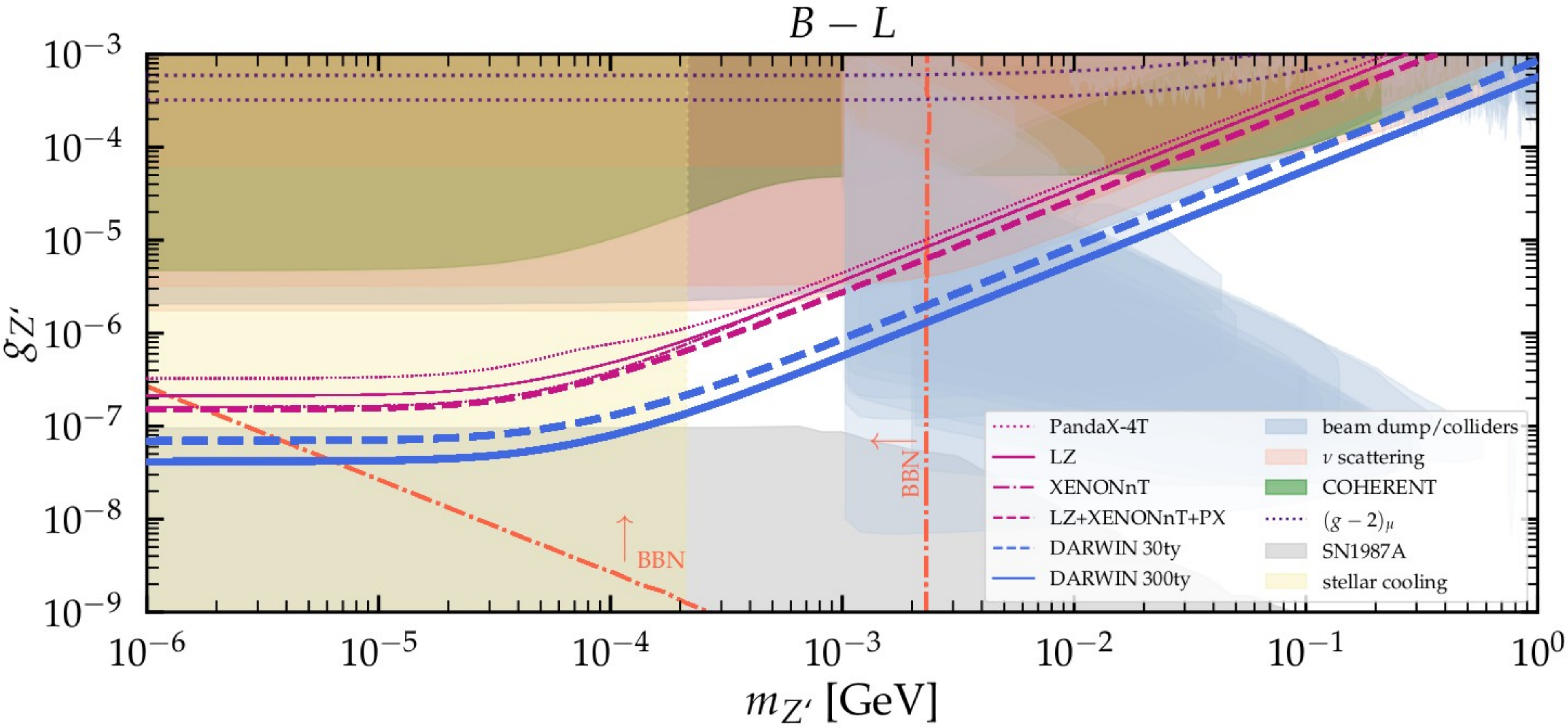
We consider U(1)’ models that are anomaly-free if the SM is extended with three right-handed neutrinos

Possible explanation for neutrino masses and mixings

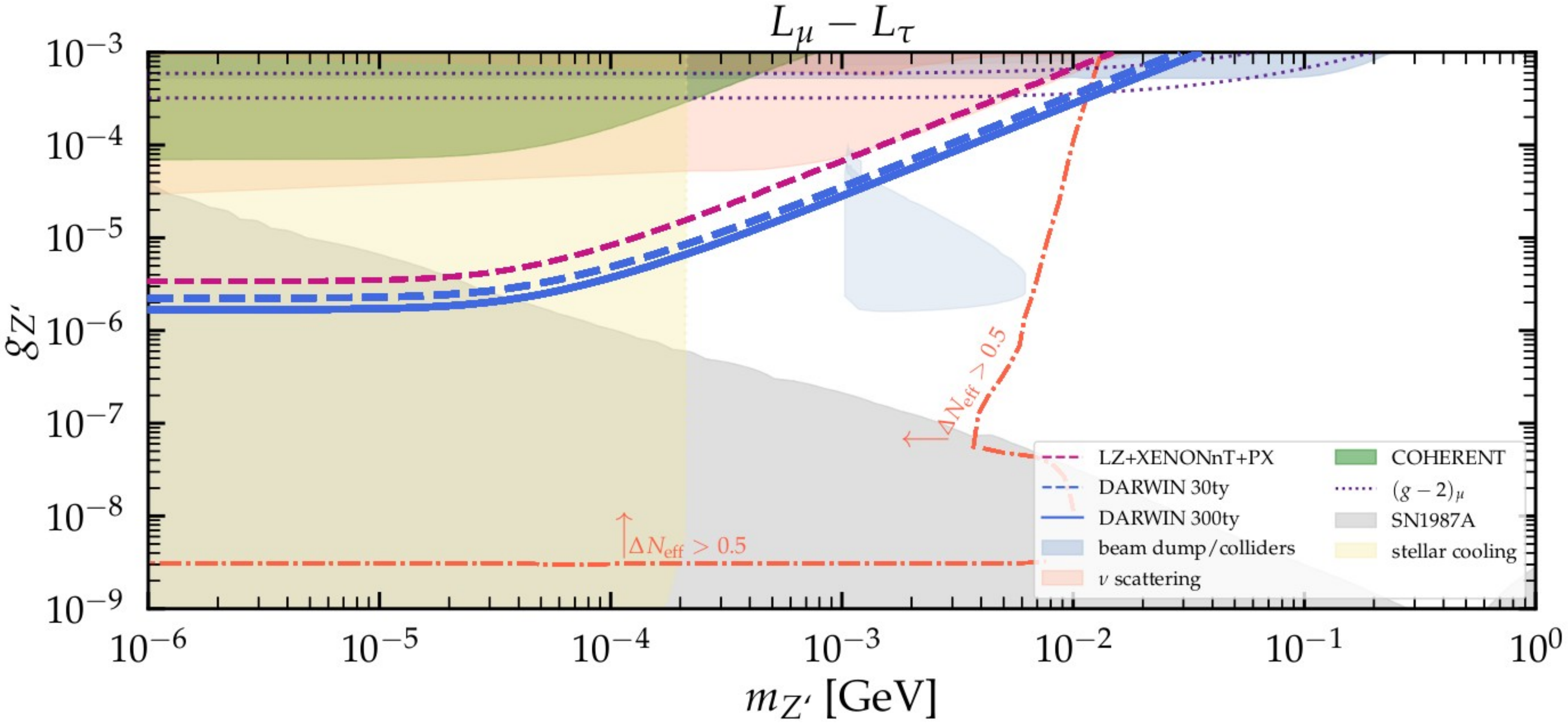
$$g_V \to g_V^{\mathrm{SM}} + \frac{(g_{Z'})^2 Q^e_{Z'} Q^{\nu_\alpha}_{Z'}}{\sqrt{2}G_F(2m_eT_e + m^2_{Z'})}$$

$$g_V \to g_V^{\mathrm{SM}} - \frac{\sqrt{2}\alpha_{\mathrm{em}} g^2_{Z'}(\delta_{\alpha\mu} - \delta_{\alpha\tau})}{\pi G_F(2m_eT_e + m^2_V)}\epsilon_{\tau\mu}(|\vec{q}|)$$

Atzori Corona et al, 2202.11002, JHEP 2022
De Romeri, Papoulias, Ternes, 2402.05506, JHEP 2024



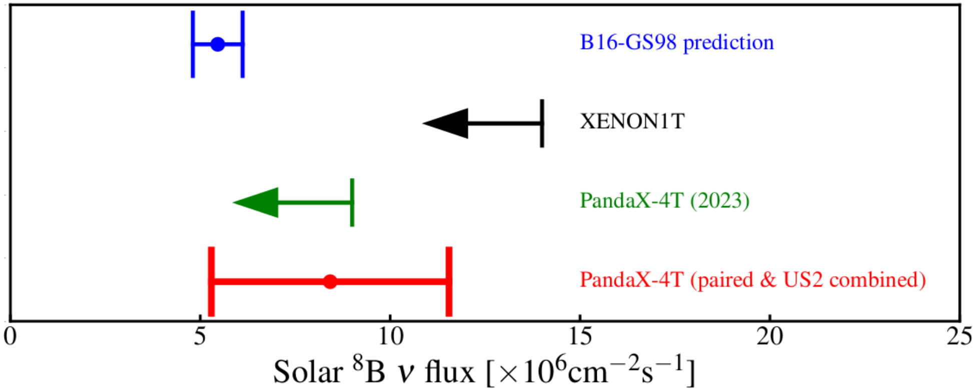
Atzori Corona et al, 2202.11002, JHEP 2022
De Romeri et al, 2211.11905, JHEP 2023
De Romeri, Papoulias, Ternes, 2402.05506, JHEP 2024



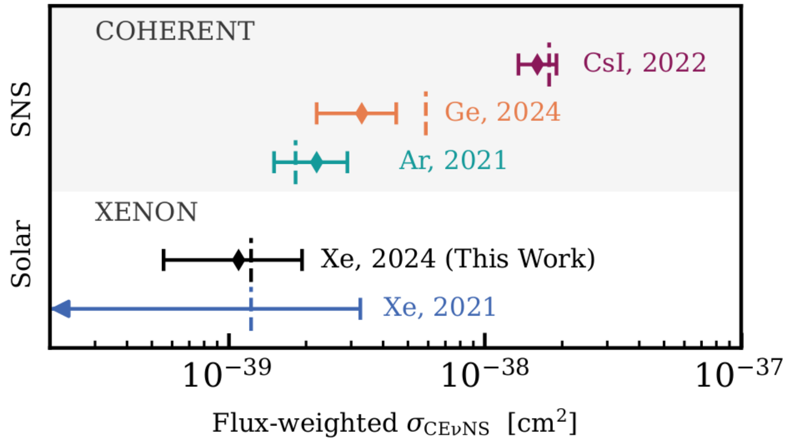
De Romeri et al, 2211.11905, JHEP 2023
De Romeri, Papoulias, Ternes, 2402.05506, JHEP 2024

# Into the neutrino fog

Panda coll.,2407.10892



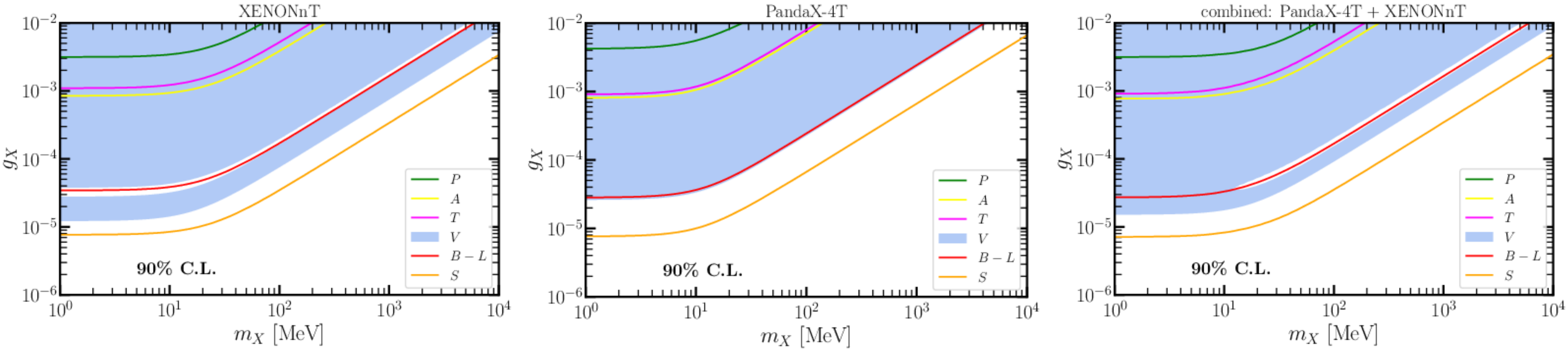
XENON coll., 2408.02877



First indication of CEvNS from solar neutrinos at PandaX-4T and XENONnT!

# Into the neutrino fog

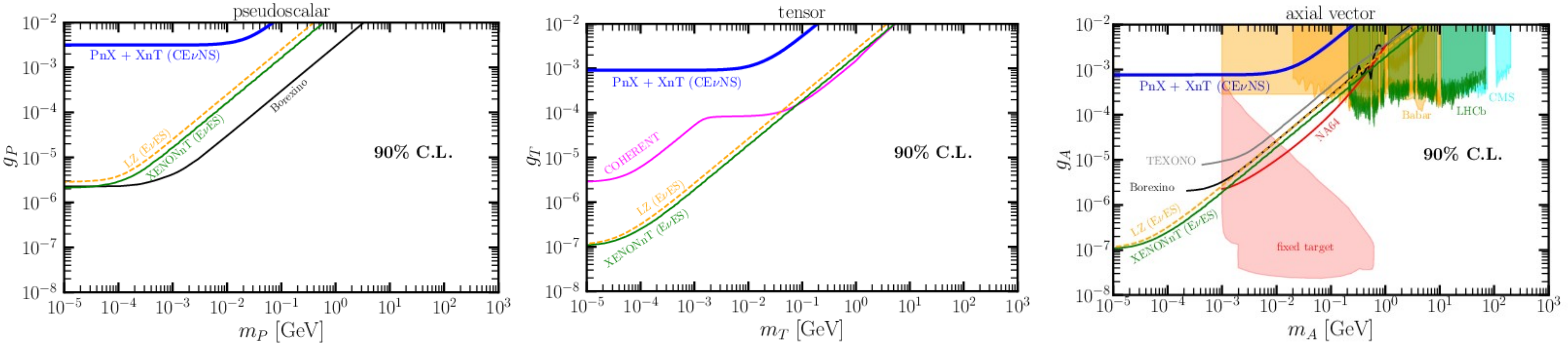
De Romeri, Papoulias, Ternes, PRELIMINARY



Data can be used to look for different new interactions of neutrinos!

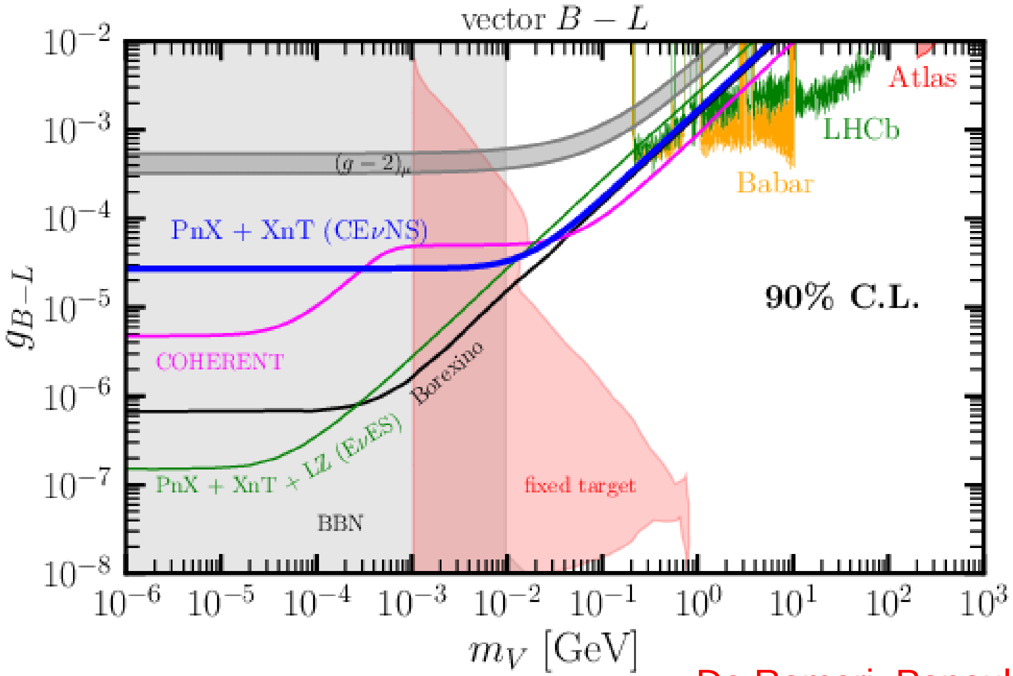
# Into the neutrino fog

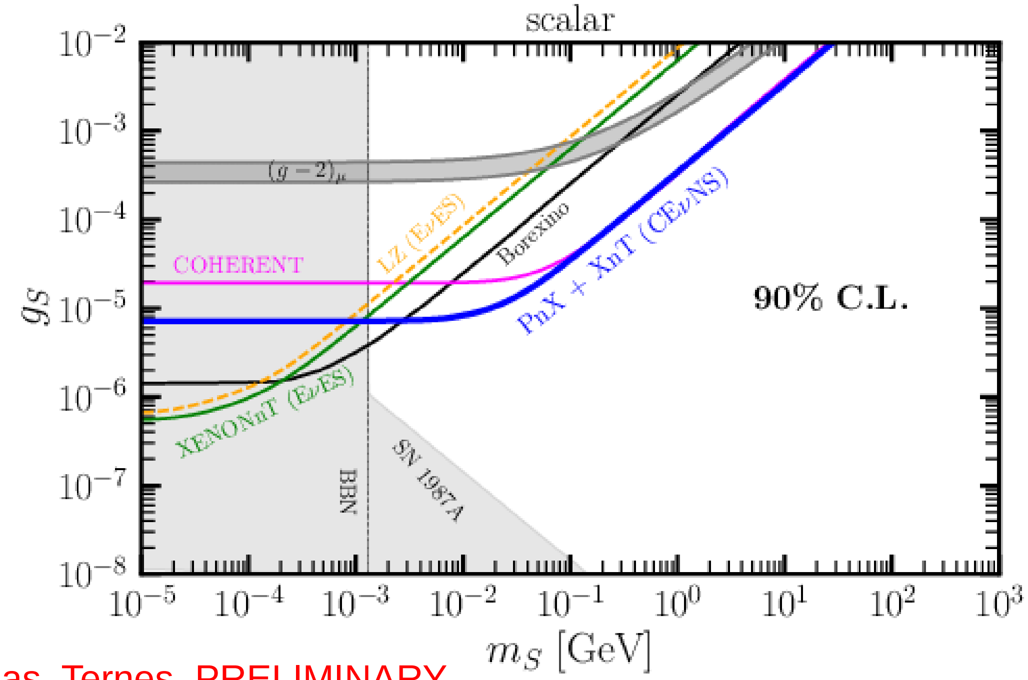
De Romeri, Papoulias, Ternes, PRELIMINARY



Weak bounds for pseudoscalar, tensor, or axial interactions.

# Into the neutrino fog



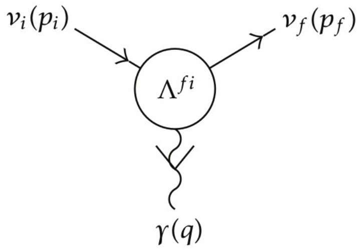


De Romeri, Papoulias, Ternes, PRELIMINARY

For vector (B-L) and scalar mediators we obtain already interesting bounds with current limited data!

# Neutrino electromagnetic interactions

$$\mathcal{H}_{\mathrm{em}}^{(\nu)} = j_\lambda^{(\nu)} A^\lambda = \sum_{j,k=1}^{3} \overline{\nu}_j \Lambda_\lambda^{jk} \nu_k A^\lambda$$



In some extensions of the Standard Model neutrinos acquire also electromagnetic properties through quantum loops effects

$$\Lambda_\lambda(q) = \left(\gamma_\lambda - \frac{q_\lambda \not{q}}{q^2}\right)\left[f_Q(q^2) + f_A(q^2)q^2\gamma^5\right] - i\sigma_{\lambda\rho}q^\rho\left[f_M(q^2) + i f_E(q^2)\gamma^5\right]$$

**Neutrino charge** **Anapole** **Magnetic and electric moments**

See Broggini, Giunti, Studenikin, 1207.3980, Adv.HEP 2012
Kouzakov, Studenikin, 1703.00401, PRD 2017

# Neutrino magnetic moments

In the minimal extended SM the magnetic moment is strongly suppressed by the small size of the neutrino mass

$$\mu_\nu = \frac{3\,e\,G_F}{8\sqrt{2}\,\pi^2} m_\nu \simeq 3.2 \times 10^{-19} \left(\frac{m_\nu}{\mathrm{eV}}\right) \mu_B$$

However, more complex models allow for larger magnetic moments, e.g. in left-right symmetric models

$$\mu_{\nu_l} = \frac{eG_F}{2\sqrt{2}\pi^2}\left[m_l\left(1 - \frac{m_{W_1}^2}{m_{W_2}^2}\right)\sin 2\xi + \frac{3}{4} m_{\nu_l}\left(1 + \frac{m_{W_1}^2}{m_{W_2}^2}\right)\right]$$

See Broggini, Giunti, Studenikin, 1207.3980, Adv.HEP 2012

# Neutrino magnetic moments

Neutrino magnetic and electric dipoles contribute to CEvNS and EvES

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

Vogel, Engel, PRD 1989

$$\frac{d\sigma^{\mathrm{MM}}_{\nu_\ell\text{-}\mathcal{N}}}{dT_{\mathrm{nr}}}(E,T_{\mathrm{nr}}) = \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_{\mathrm{nr}}}-\frac{1}{E}\right)Z^2F_Z^2(|\vec{q}|^2)\left|\frac{\mu_{\nu_\ell}}{\mu_{\mathrm{B}}}\right|^2 \qquad \frac{d\sigma^{\mathrm{ES,\ MM}}_{\nu_\ell\text{-}\mathcal{A}}}{dT_{\mathrm{e}}}(E,T_{\mathrm{e}}) = Z^{\mathcal{A}}_{\mathrm{eff}}(T_{\mathrm{e}})\frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_{\mathrm{e}}}-\frac{1}{E}\right)\left|\frac{\mu_{\nu_\ell}}{\mu_{\mathrm{B}}}\right|^2$$

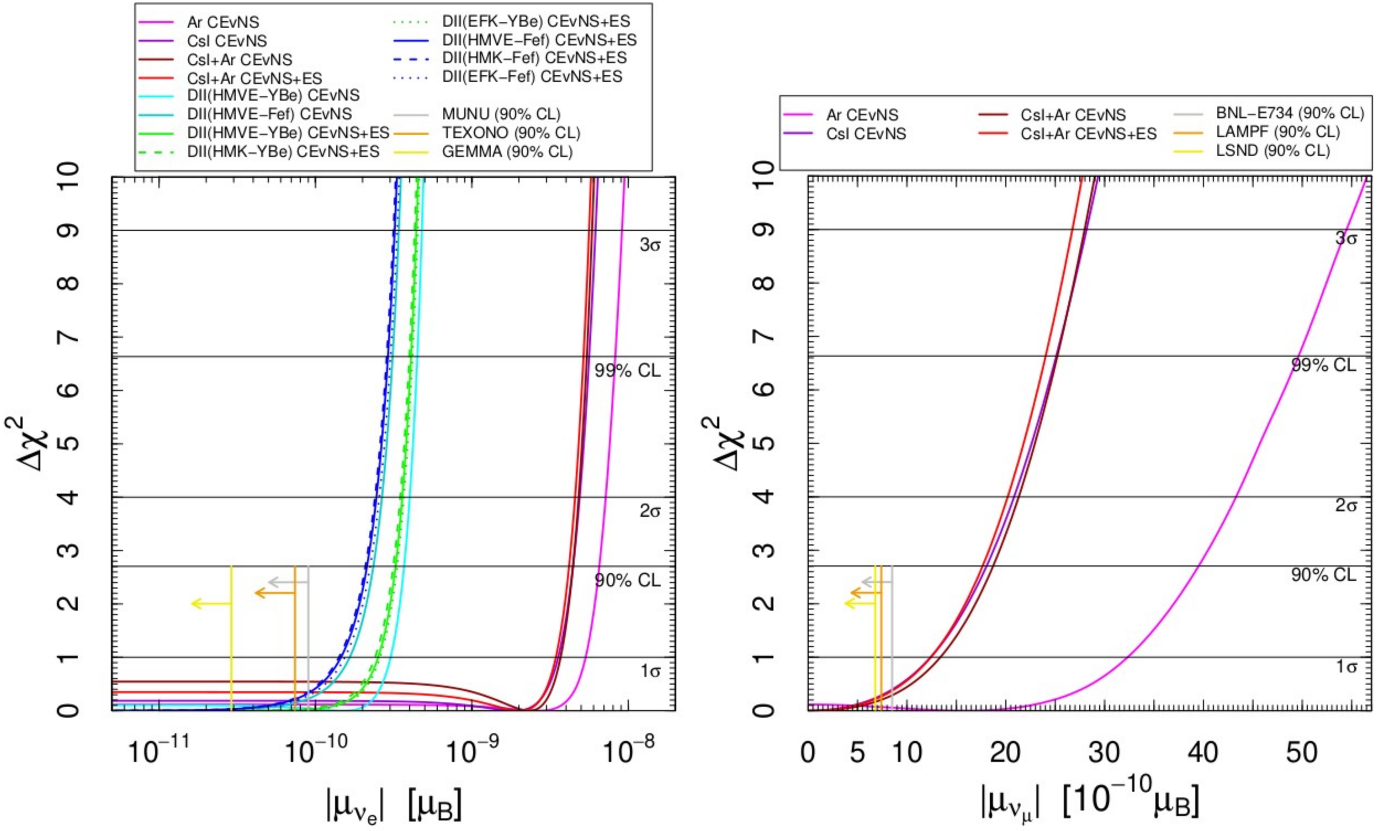
Care has to be taken when comparing bounds, the effective moment for solar neutrinos is not the same as for COHERENT

$$\lim_{L\to 0}|\mu_{\nu_l}(L,E))|^2 \to \sum_{l'}\left|\sum_{j,k}U^*_{lk}U_{l'j}(\mu_\nu)_{jk}\right|^2$$

$$\mu_\nu^2(\nu_\alpha,L,E) = \sum_j\left|\sum_k U^*_{\alpha k}e^{-im_k^2L/2E}(\mu_{jk}-i\epsilon_{jk})\right|^2 .$$

$$\lim_{L\to\infty}|\mu_{\nu_l}(L,E))|^2 \to \sum_{j,k}|U_{lk}|^2|(\mu_\nu)_{jk}|^2$$

# Neutrino magnetic moments

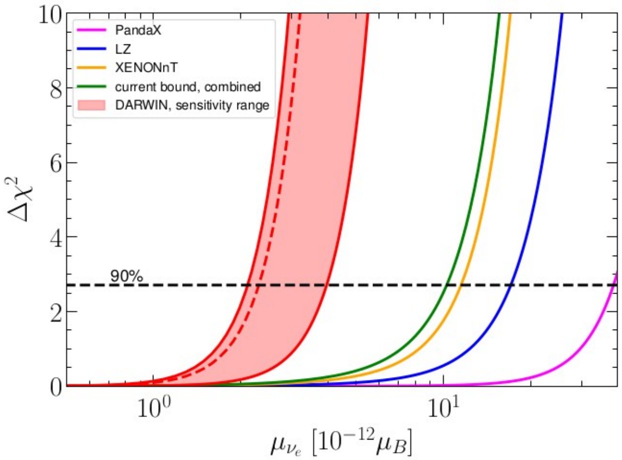


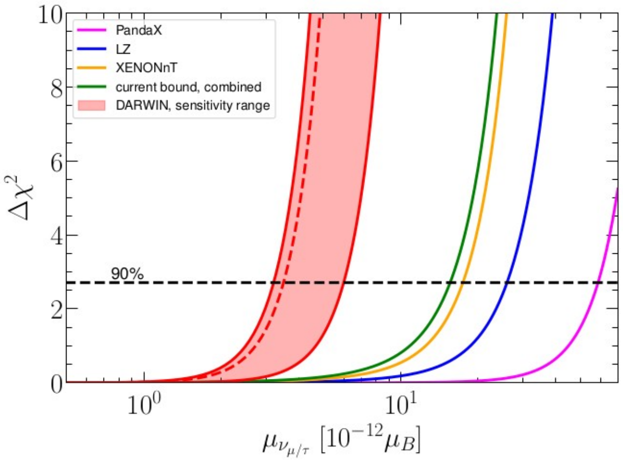
COHERENT and DRESDEN-II can be used to place bounds on the electron an muon sector

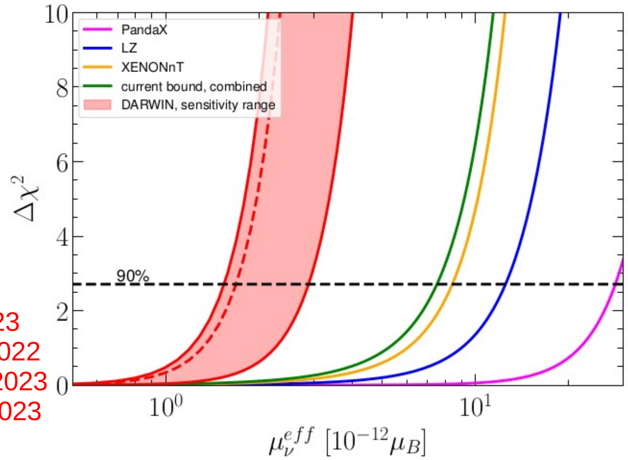
CEvNS bounds are not yet competitive with bounds from other probes

Atzori Corona et al, 2205.09484, JHEP 2022
See also: De Romeri et al, 2211.11905, JHEP 2023

# Neutrino magnetic moments







DMDD can be used to place bounds also on the tau sector

These are the strongest laboratory bounds on neutrino magnetic moments

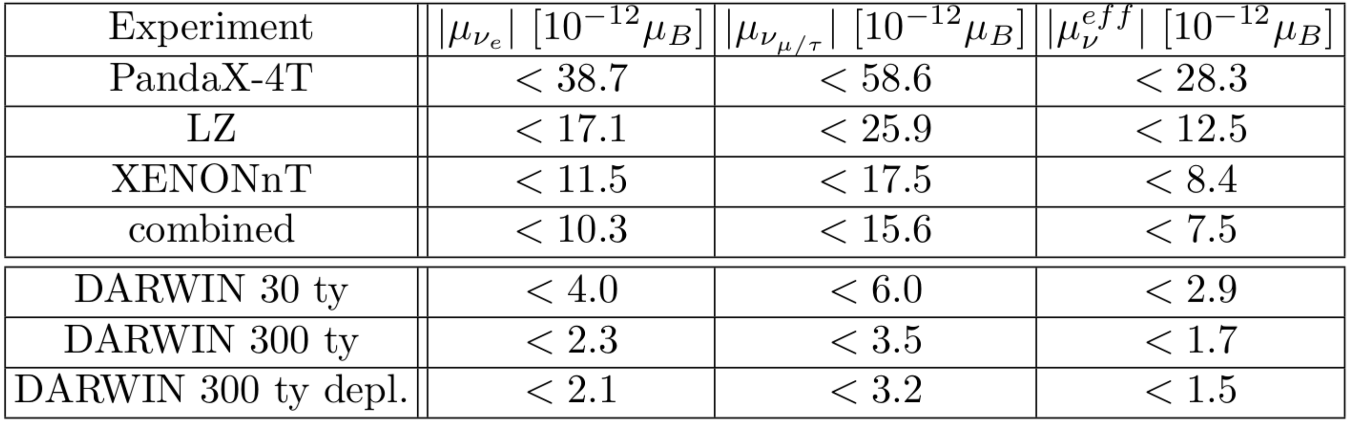
DARWIN will improve these bounds by up to a factor of 5

Giunti, Ternes, 2309.17380, PRD 2023
See also: XENON, 2207.11330, PRL 2022
Atzori Corona et al, 2207.05036, PRD 2023
ShivaSankar, et al, 2208.06415, PLB 2023

# Neutrino magnetic moments

Giunti, Ternes, 2309.17380, PRD 2023

$(\Delta\chi^2 = 2.71)$



| Experiment | $\lvert\mu_{\nu_e}\rvert\ [10^{-12}\mu_B]$ | $\lvert\mu_{\nu_{\mu/\tau}}\rvert\ [10^{-12}\mu_B]$ | $\lvert\mu_\nu^{eff}\rvert\ [10^{-12}\mu_B]$ |
|---|---|---|---|
| PandaX-4T | $< 38.7$ | $< 58.6$ | $< 28.3$ |
| LZ | $< 17.1$ | $< 25.9$ | $< 12.5$ |
| XENONnT | $< 11.5$ | $< 17.5$ | $< 8.4$ |
| combined | $< 10.3$ | $< 15.6$ | $< 7.5$ |
| DARWIN 30 ty | $< 4.0$ | $< 6.0$ | $< 2.9$ |
| DARWIN 300 ty | $< 2.3$ | $< 3.5$ | $< 1.7$ |
| DARWIN 300 ty depl. | $< 2.1$ | $< 3.2$ | $< 1.5$ |

DMDD bounds are stronger than BOREXINO bounds:

$$\Delta\chi^2 = 1.64 \quad \mu_{\nu_e} < 3.7 \times 10^{-11}\mu_B\,, \qquad \mu_{\nu_\mu} < 5.0 \times 10^{-11}\mu_B\,, \qquad \mu_{\nu_\tau} < 5.9 \times 10^{-11}\mu_B$$

DARWIN would become competitive with astrophysical observations

$$\mu_\nu < 1.5 \times 10^{-12}\mu_{\mathrm{B}}\ (95\%\ \mathrm{CL})$$

Coloma et al, 2204.03011, JHEP 2022

Capozzi, Raffelt, 2007.03694, PRD 2020

# Neutrino millicharges

In some BSM theories neutrinos may acquire small electric charges

The cross section receives extra contributions which add coherently (diagonal charges) and incoherently (non-diagonal charges) to the SM cross section

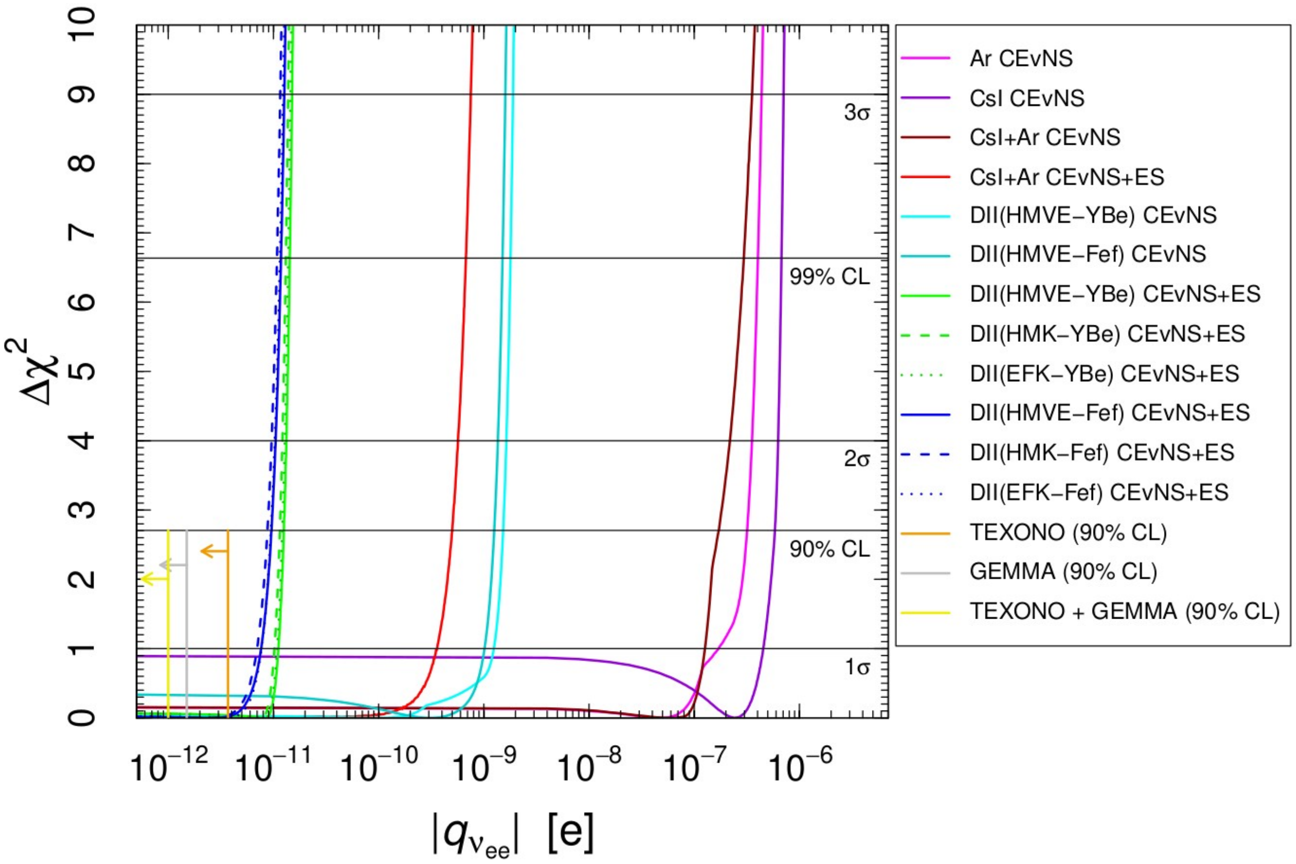
$$\frac{d\sigma^{\mathrm{SM+EC}}_{\nu_\ell-\mathrm{Xe}}}{dT_{\mathrm{e}}} = \left(\frac{d\sigma^{\mathrm{SM+EC}}_{\nu_\ell-\mathrm{Xe}}}{dT_{\mathrm{e}}}\right)_{q_{\nu_\ell}} + \sum_{\ell'\neq\ell}\left(\frac{d\sigma^{\mathrm{EC}}_{\nu_\ell-\mathrm{Xe}}}{dT_{\mathrm{e}}}\right)_{q_{\nu_{\ell\ell'}}}$$

$$g_{\mathrm{V}}^{\nu_\ell} \to g_{\mathrm{V}}^{\nu_\ell} - \frac{\sqrt{2}\pi\alpha}{G_{\mathrm{F}} m_e T_e}\, q_{\nu_\ell}$$

$$\left(\frac{d\sigma^{\mathrm{EC}}_{\nu_\ell-\mathrm{Xe}}}{dT_{\mathrm{e}}}\right)_{q_{\nu_{\ell\ell'}}} = Z_{\mathrm{eff}}^{\mathrm{Xe}}(T_e)\,\frac{\pi\alpha^2}{m_e T_{\mathrm{e}}^2}\left[1+\left(1-\frac{T_{\mathrm{e}}}{E_\nu}\right)^2-\frac{m_e T_{\mathrm{e}}}{E_\nu^2}\right]|q_{\nu_{\ell\ell'}}|^2$$

Kouzakov, Studenikin, 1703.00401, PRD 2017

# Neutrino millicharges

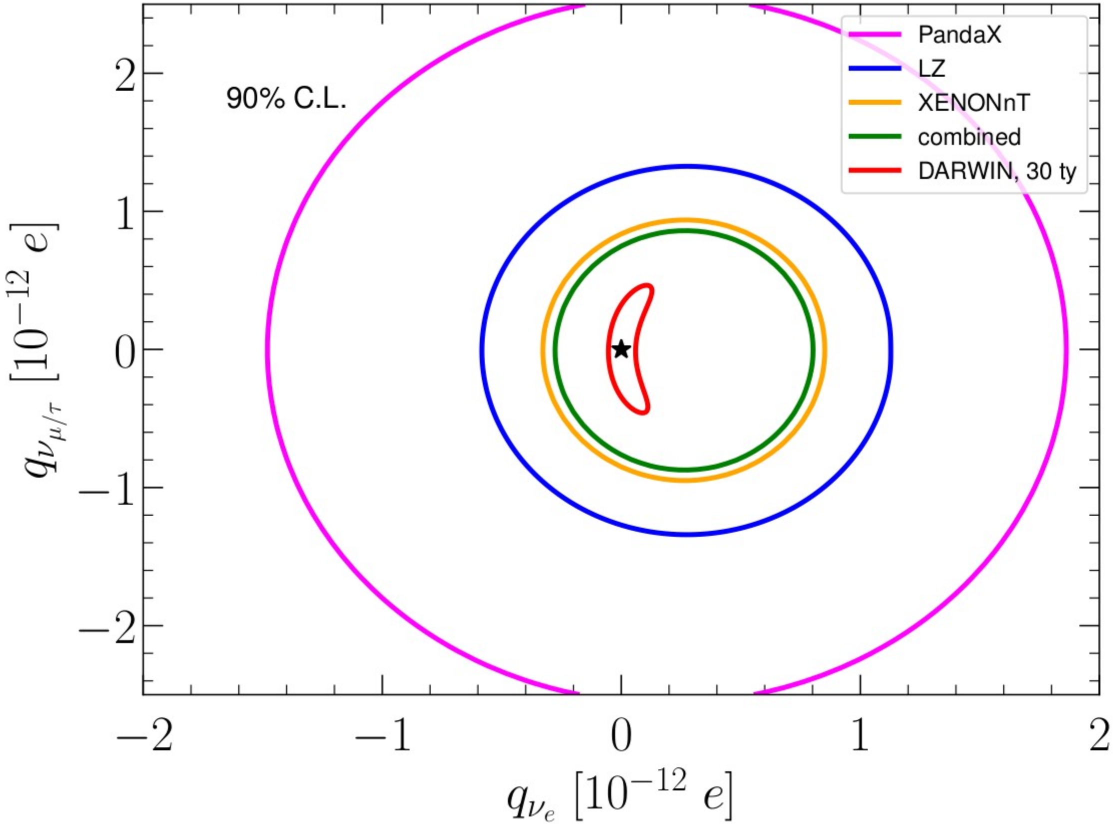


As previously, bounds from CEvNS experiments are not yet competitive with bounds from other experiments

(Similar strength for other charges)

Atzori Corona et al, 2205.09484, JHEP 2022

# Neutrino millicharges

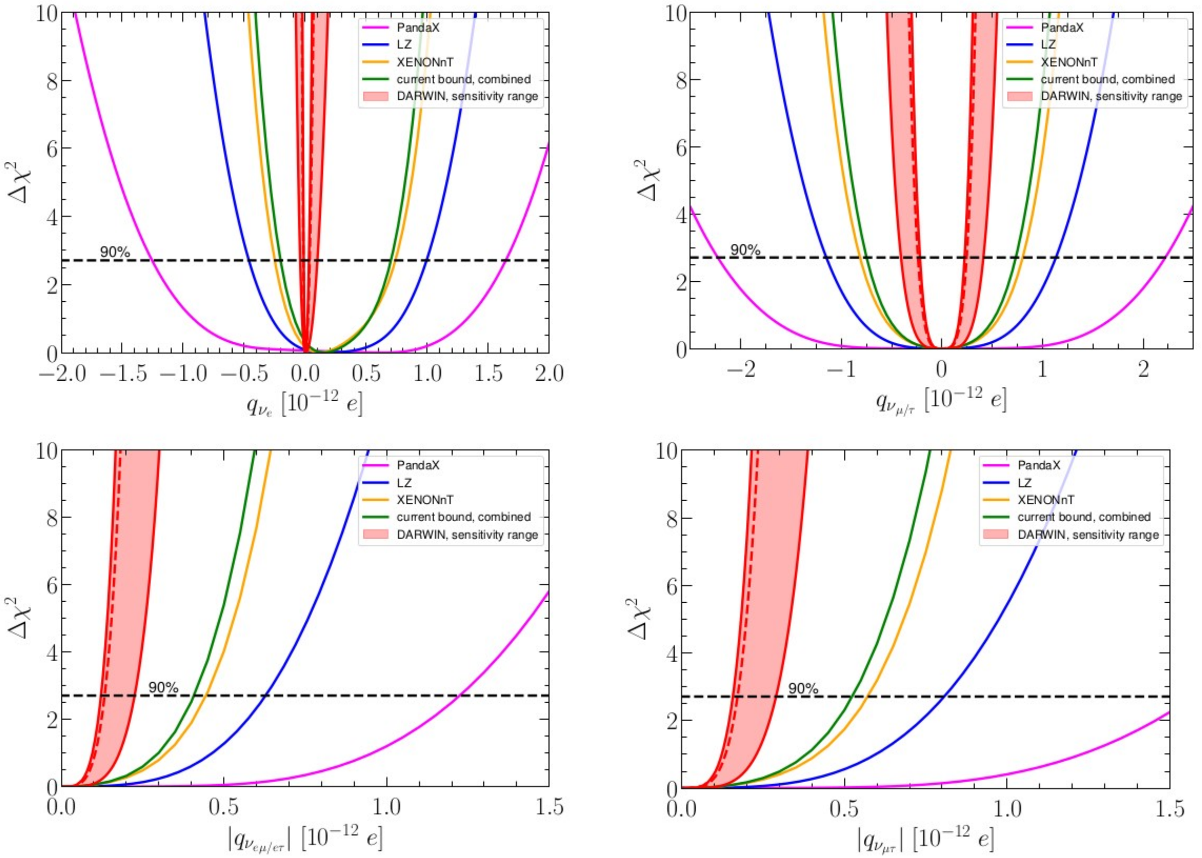


We obtain very strong bounds from DMDD experiments

Cancellations among parameters can occur and must be taken into account when deriving bounds

Giunti, Ternes, 2309.17380, PRD 2023

# Neutrino millicharges



We obtain very strong bounds from DMDD experiments

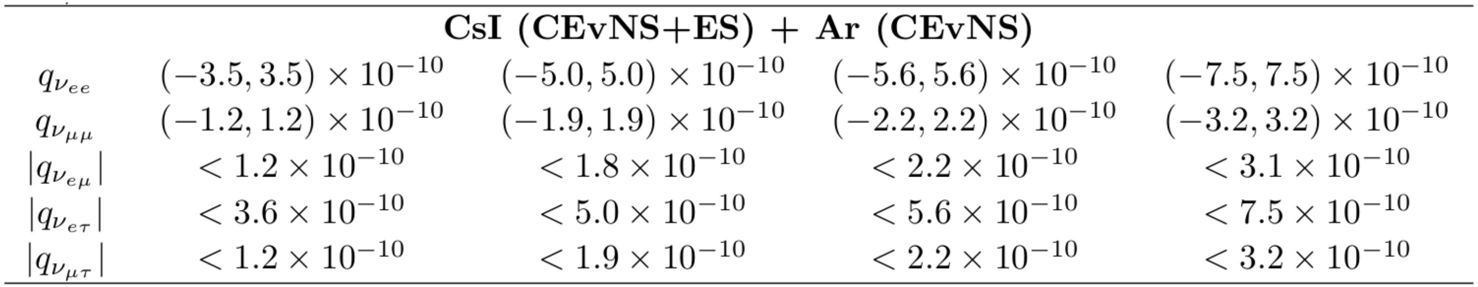
Cancellations among parameters can occur and must be taken into account when deriving bounds

Bounds can be significantly improved by DARWIN

Giunti, Ternes, 2309.17380, PRD 2023

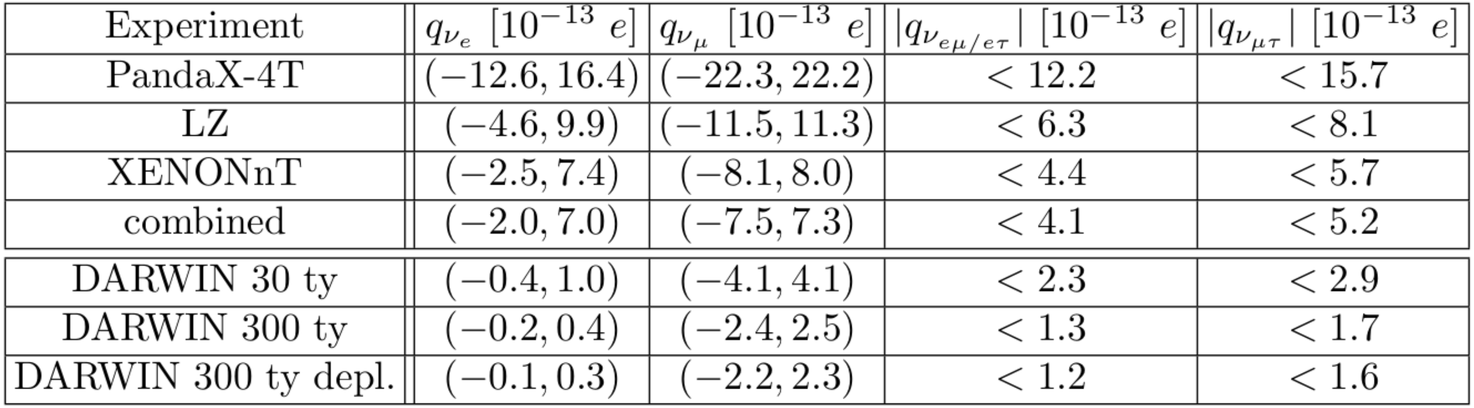
# Neutrino millicharges

DMDD bounds are around 3 orders of magnitude more stringent than COHERENT bounds



**CsI (CEvNS+ES) + Ar (CEvNS)**

| | | | | |
|---|---|---|---|---|
| $q_{\nu_{ee}}$ | $(-3.5, 3.5) \times 10^{-10}$ | $(-5.0, 5.0) \times 10^{-10}$ | $(-5.6, 5.6) \times 10^{-10}$ | $(-7.5, 7.5) \times 10^{-10}$ |
| $q_{\nu_{\mu\mu}}$ | $(-1.2, 1.2) \times 10^{-10}$ | $(-1.9, 1.9) \times 10^{-10}$ | $(-2.2, 2.2) \times 10^{-10}$ | $(-3.2, 3.2) \times 10^{-10}$ |
| $\lvert q_{\nu_{e\mu}} \rvert$ | $< 1.2 \times 10^{-10}$ | $< 1.8 \times 10^{-10}$ | $< 2.2 \times 10^{-10}$ | $< 3.1 \times 10^{-10}$ |
| $\lvert q_{\nu_{e\tau}} \rvert$ | $< 3.6 \times 10^{-10}$ | $< 5.0 \times 10^{-10}$ | $< 5.6 \times 10^{-10}$ | $< 7.5 \times 10^{-10}$ |
| $\lvert q_{\nu_{\mu\tau}} \rvert$ | $< 1.2 \times 10^{-10}$ | $< 1.9 \times 10^{-10}$ | $< 2.2 \times 10^{-10}$ | $< 3.2 \times 10^{-10}$ |

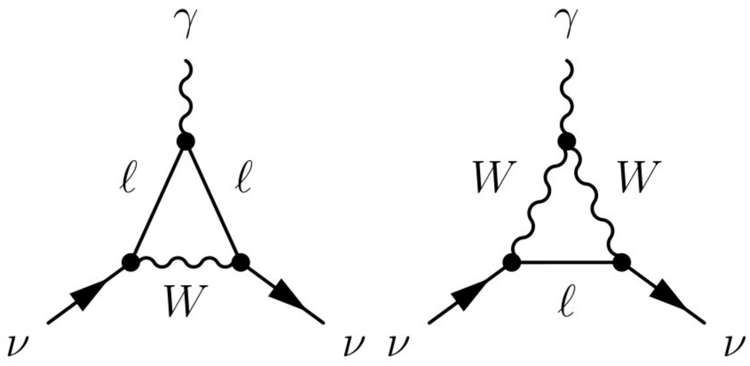


| Experiment | $q_{\nu_e}$ $[10^{-13}\ e]$ | $q_{\nu_\mu}$ $[10^{-13}\ e]$ | $\lvert q_{\nu_{e\mu/e\tau}} \rvert$ $[10^{-13}\ e]$ | $\lvert q_{\nu_{\mu\tau}} \rvert$ $[10^{-13}\ e]$ |
|---|---|---|---|---|
| PandaX-4T | $(-12.6, 16.4)$ | $(-22.3, 22.2)$ | $< 12.2$ | $< 15.7$ |
| LZ | $(-4.6, 9.9)$ | $(-11.5, 11.3)$ | $< 6.3$ | $< 8.1$ |
| XENONnT | $(-2.5, 7.4)$ | $(-8.1, 8.0)$ | $< 4.4$ | $< 5.7$ |
| combined | $(-2.0, 7.0)$ | $(-7.5, 7.3)$ | $< 4.1$ | $< 5.2$ |
| DARWIN 30 ty | $(-0.4, 1.0)$ | $(-4.1, 4.1)$ | $< 2.3$ | $< 2.9$ |
| DARWIN 300 ty | $(-0.2, 0.4)$ | $(-2.4, 2.5)$ | $< 1.3$ | $< 1.7$ |
| DARWIN 300 ty depl. | $(-0.1, 0.3)$ | $(-2.2, 2.3)$ | $< 1.2$ | $< 1.6$ |

# Neutrino charge radii

In the Standard Model neutrinos are neutral and there are no electromagnetic interactions at the tree-level

Radiative corrections generate an effective electromagnetic interaction vertex



$$\langle r^2_{\nu_\ell} \rangle_{\mathrm{SM}} = -\frac{G_{\mathrm{F}}}{2\sqrt{2}\pi^2}\left[3 - 2\ln\left(\frac{m^2_\ell}{m^2_W}\right)\right]$$

$$\langle r^2_{\nu_e} \rangle_{\mathrm{SM}} = -0.83 \times 10^{-32}\,\mathrm{cm}^2,$$
$$\langle r^2_{\nu_\mu} \rangle_{\mathrm{SM}} = -0.48 \times 10^{-32}\,\mathrm{cm}^2,$$
$$\langle r^2_{\nu_\tau} \rangle_{\mathrm{SM}} = -0.30 \times 10^{-32}\,\mathrm{cm}^2.$$

Bernabeu, et al, hep-ph/0210055 , NPB 2004

# Neutrino charge radii

The cross section receives extra contributions which add coherently (diagonal charge radii) and incoherently (non-diagonal charge radii) to the SM cross section

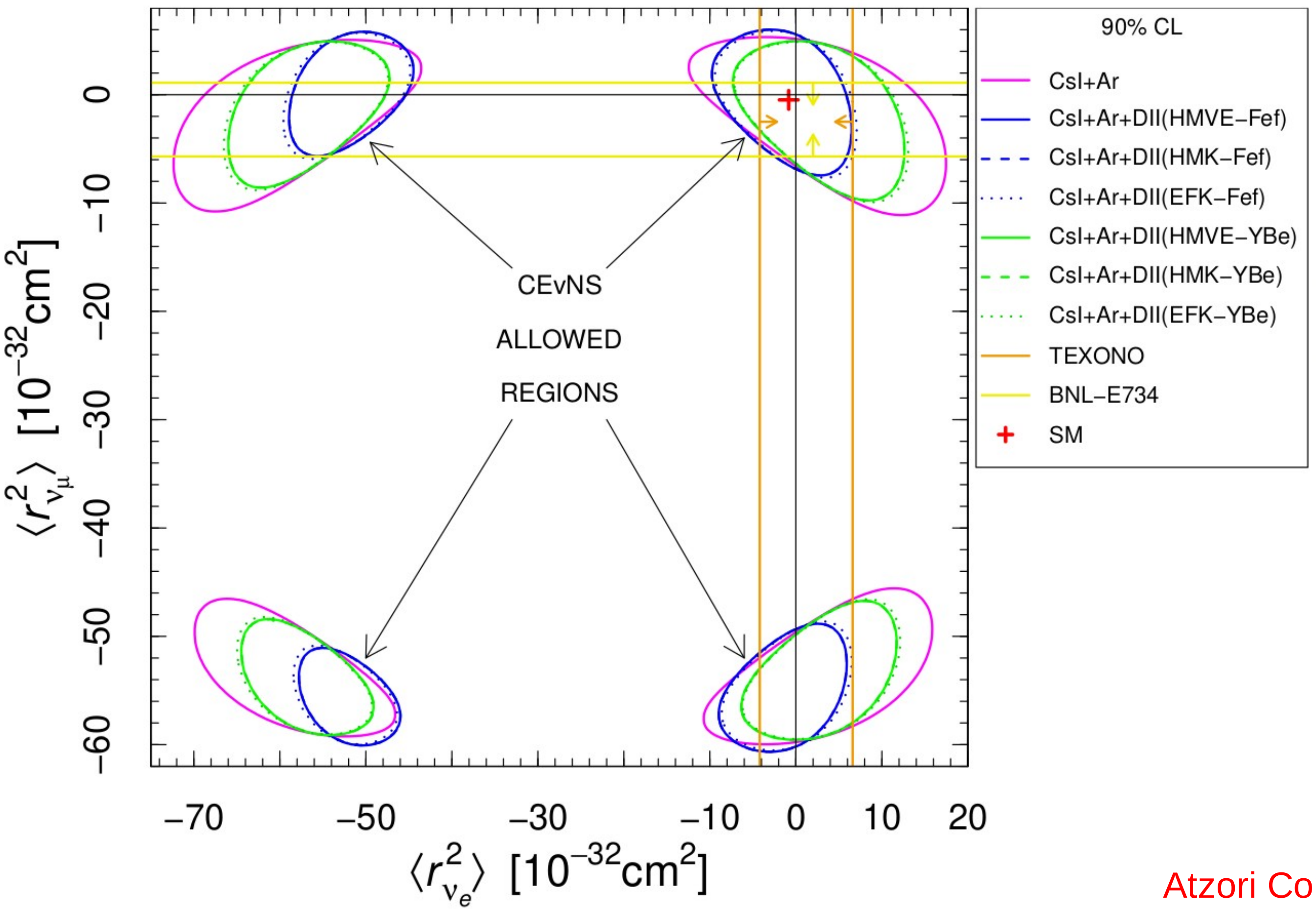
$$\frac{d\sigma^{\mathrm{SM+CR}}_{\nu_\ell-\mathrm{Xe}}}{dT_\mathrm{e}} = \left(\frac{d\sigma^{\mathrm{SM+CR}}_{\nu_\ell-\mathrm{Xe}}}{dT_\mathrm{e}}\right)_{\langle r^2_{\nu_\ell}\rangle} + \sum_{\ell'\neq\ell}\left(\frac{d\sigma^{\mathrm{CR}}_{\nu_\ell-\mathrm{Xe}}}{dT_\mathrm{e}}\right)_{\langle r^2_{\nu_{\ell\ell'}}\rangle}$$

$$g_V^{\nu_\ell} \to g_V^{\nu_\ell} + \frac{\sqrt{2}\pi\alpha}{3G_\mathrm{F}}\langle r^2_{\nu_{\ell\ell'}}\rangle$$

$$\left(\frac{d\sigma^{\mathrm{CR}}_{\nu_\ell-\mathrm{Xe}}}{dT_\mathrm{e}}\right)_{\langle r^2_{\nu_{\ell\ell'}}\rangle} = Z^{A}_{\mathrm{eff}}(T_e)\,\frac{\pi\alpha^2 m_e}{9}\left[1+\left(1-\frac{T_e}{E_\nu}\right)^2-\frac{m_e T_e}{E_\nu^2}\right]|\langle r^2_{\nu_{\ell\ell'}}\rangle|^2$$

Kouzakov, Studenikin, 1703.00401, PRD 2017

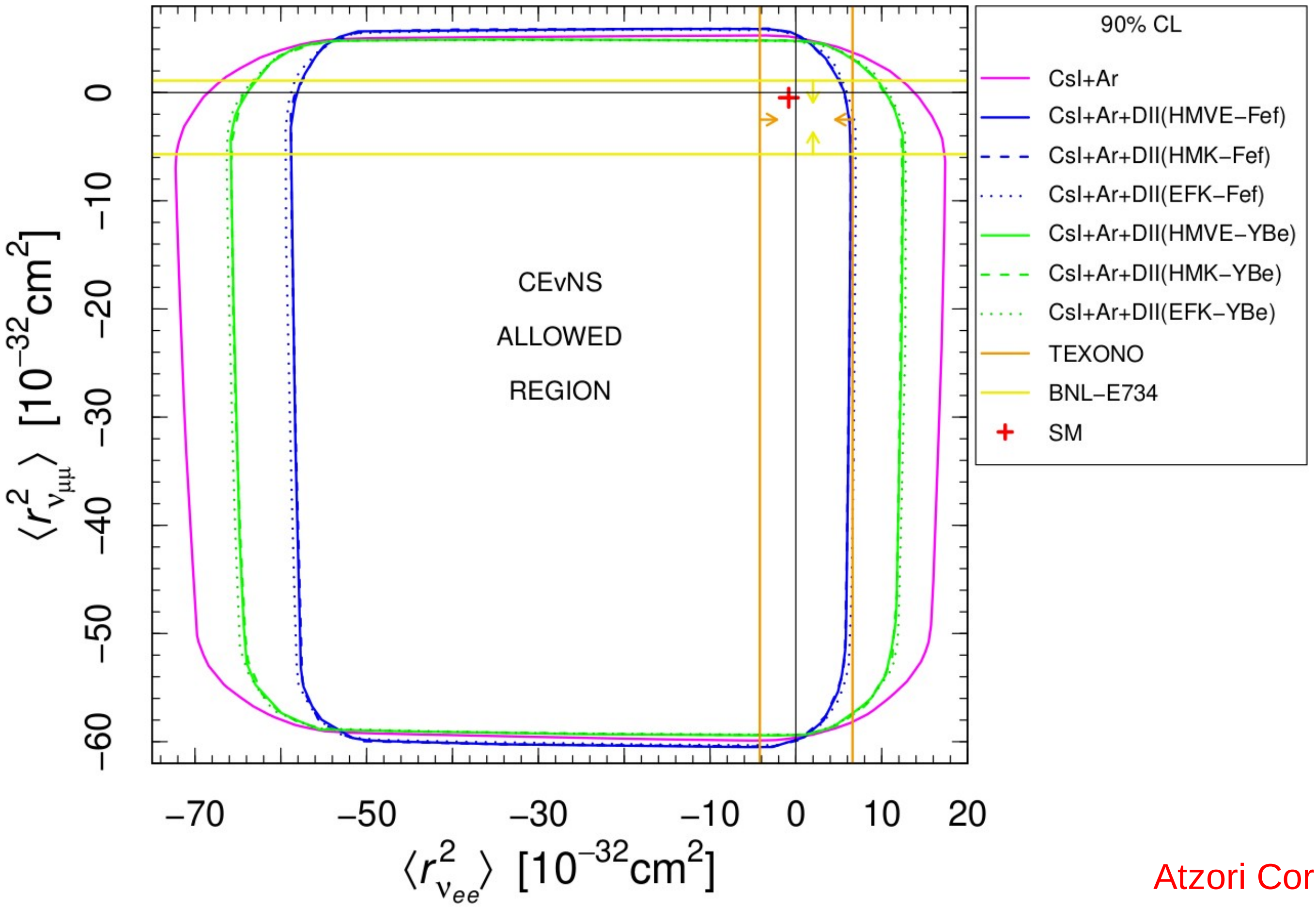
# Neutrino charge radii



When allowing only for diagonal elements four separate regions are allowed

Atzori Corona et al, 2205.09484, JHEP 2022

# Neutrino charge radii



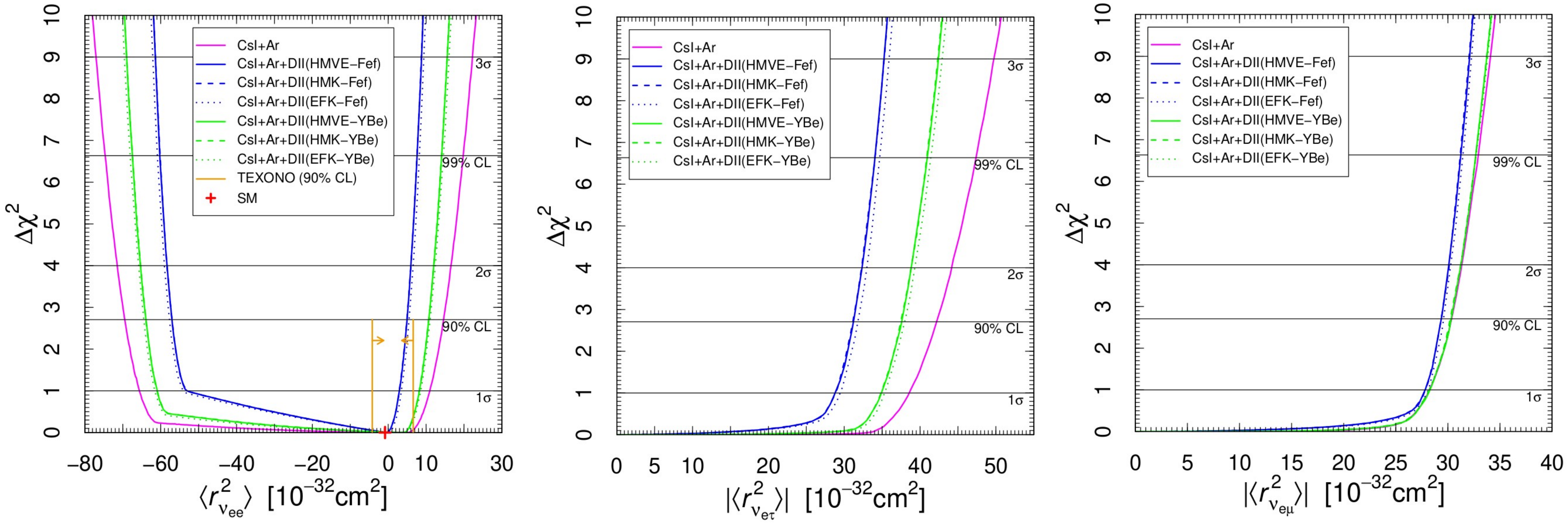
When allowing only for diagonal elements four separate regions are allowed

When marginalizing over the non-diagonal parameters the whole interior region remains allowed

Atzori Corona et al, 2205.09484, JHEP 2022

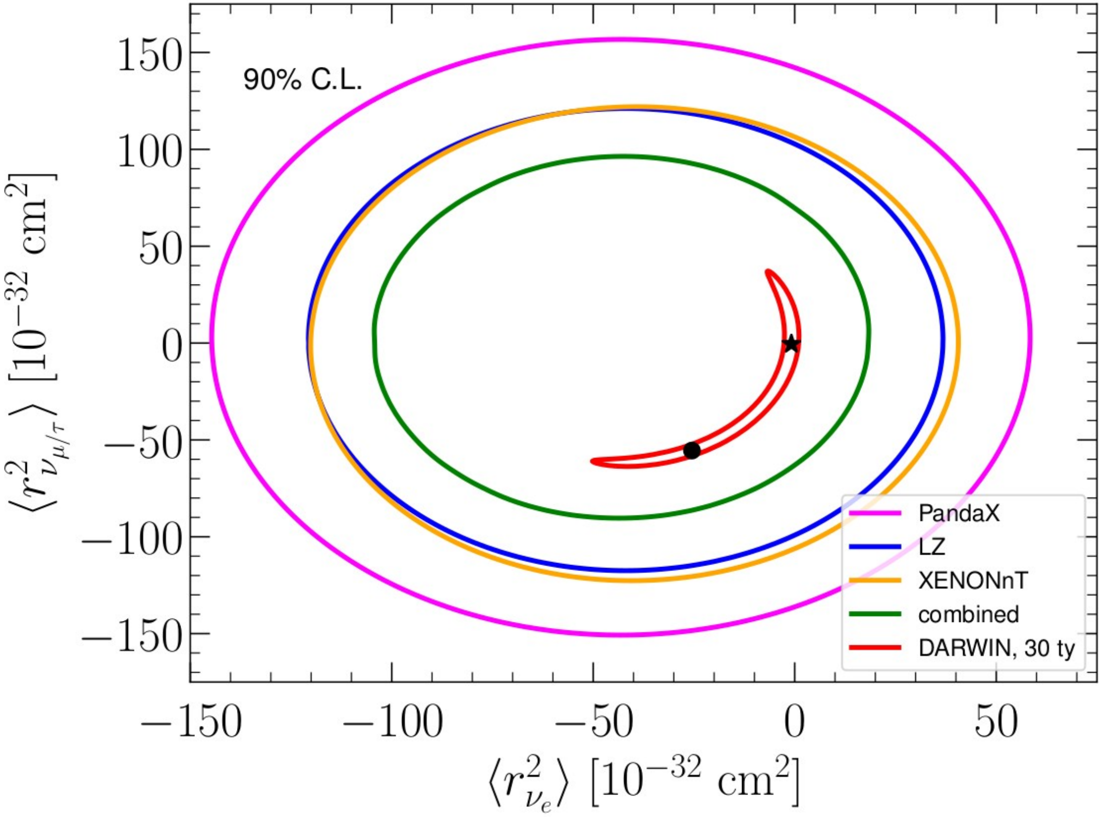
# Neutrino charge radii

## Leading bounds on transition charge radii



Atzori Corona et al, 2205.09484, JHEP 2022

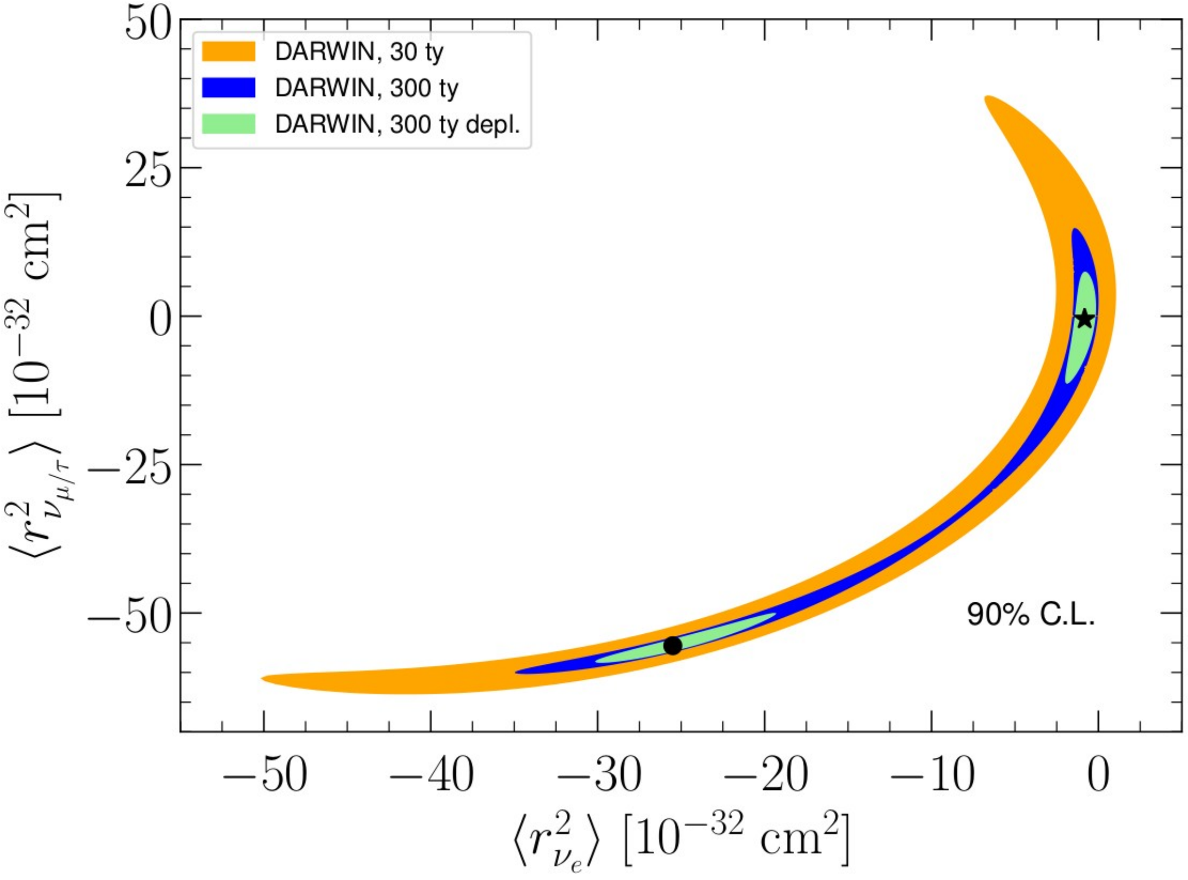
# Neutrino charge radii



This time current DMDD experiments are not competitive with CEvNS experiments

Giunti, Ternes, 2309.17380, PRD 2023

# Neutrino charge radii



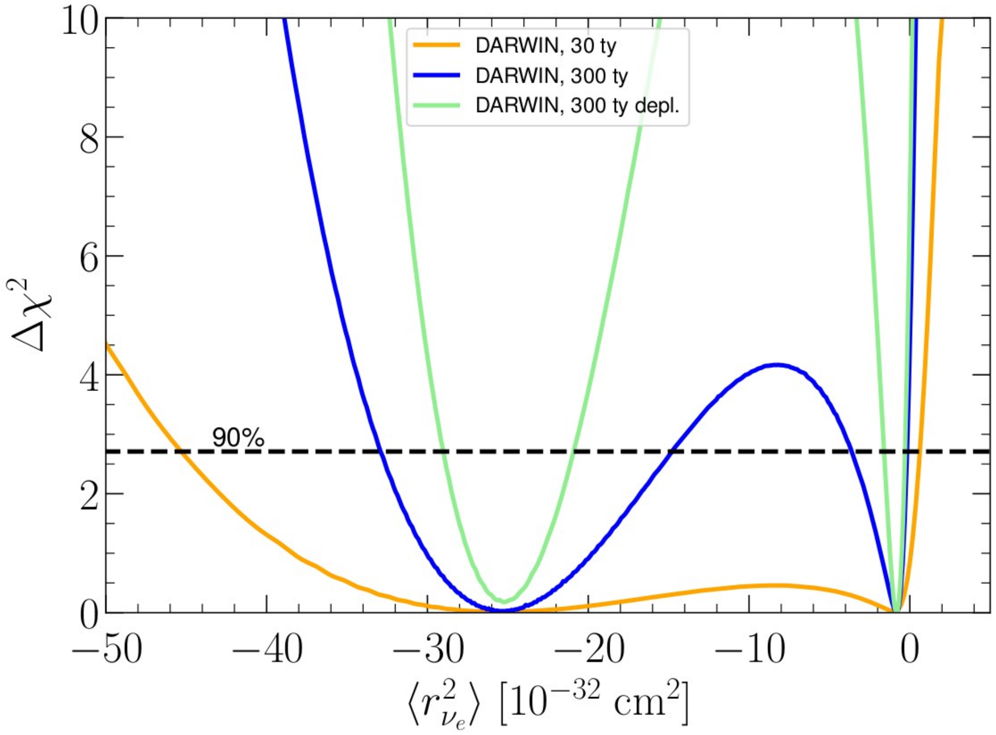
This time current DMDD experiments are not competitive with CEvNS experiments

Situation will dramatically improve with DARWIN

Giunti, Ternes, 2309.17380, PRD 2023

# Neutrino charge radii

Giunti, Ternes, 2309.17380, PRD 2023



$$\langle r^2_{\nu_e} \rangle \in (-45.3, 0.6) \times 10^{-32}\ \text{cm}^2,\ \text{DARWIN 30 ty}\,,$$

$$\langle r^2_{\nu_e} \rangle \in \{(-32.9, -14.8)\ \&\ (-3.6, -0.2)\} \times 10^{-32}\ \text{cm}^2,\ \text{DARWIN 300 ty}\,,$$

$$\langle r^2_{\nu_e} \rangle \in \{(-29.1, -20.7)\ \&\ (-1.6, -0.3)\} \times 10^{-32}\ \text{cm}^2,\ \text{DARWIN 300 ty, depleted}$$

This time current DMDD experiments are not competitive with CEvNS experiments

Situation will dramatically improve with DARWIN

DARWIN could provide the first ever measurement of one of the charge radii

# Conclusions

Neutrino scattering experiments provide powerful tools for SM tests and BSM searches

Currently EvES provides stronger bounds on most light mediator models, on the (effective) neutrino magnetic moments and neutrino electric charges than CEvNS

Charge radii are better constrained using CEvNS data

DARWIN could provide the first measurement of one of the charge radii


Thanks!
electron-neutrino
muon neutrino
tau-neutrino