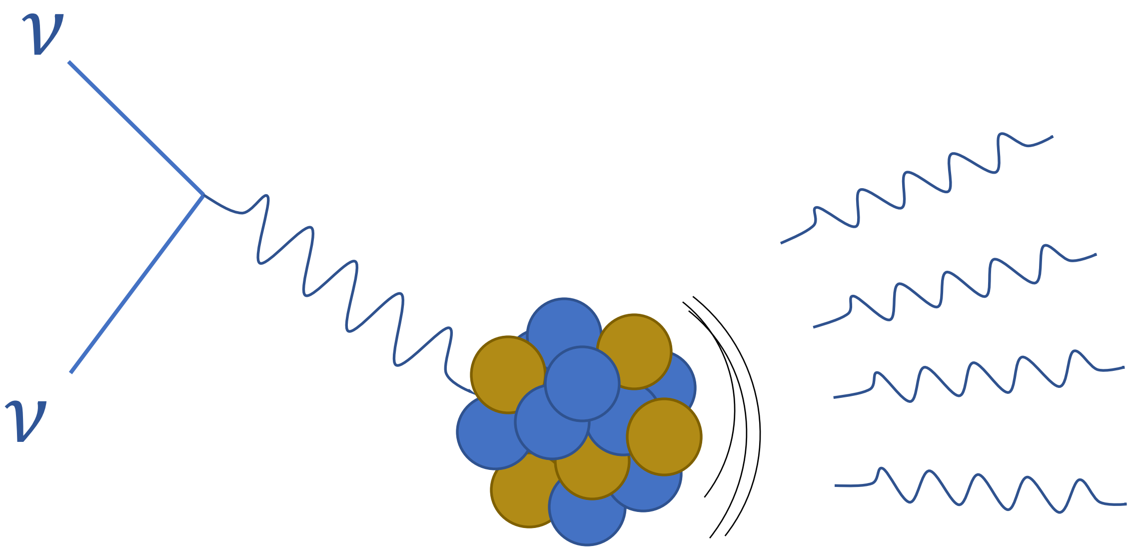
# Phenomenology of coherent elastic neutrino-nucleus scattering

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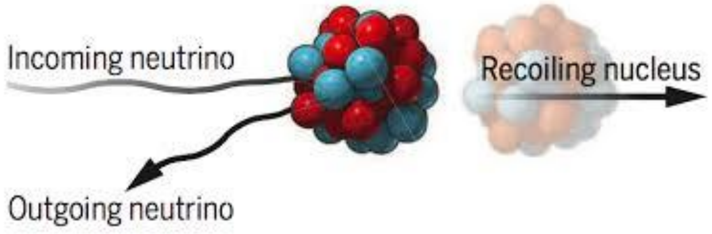
**Based on:** *Phys.Rev.D 111 (2025) 7, 7*

# Outline

- Coherent Elastic Neutrino Nucleus Scattering.
- What is new in CE$\nu$NS detection?
- Phenomenolgy of CE$\nu$NS with COHERENT and CONUS+.
- Future prospects.
- Conclusions.

# **C**oherent
# **E**lastic
# **ν**eutrino
# **N**ucleus
# **S**cattering




D. Z. Freedman, Phys. Rev. D 9 (1974)
COHERENT Collaboration, Science 357 (2017) 6356

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

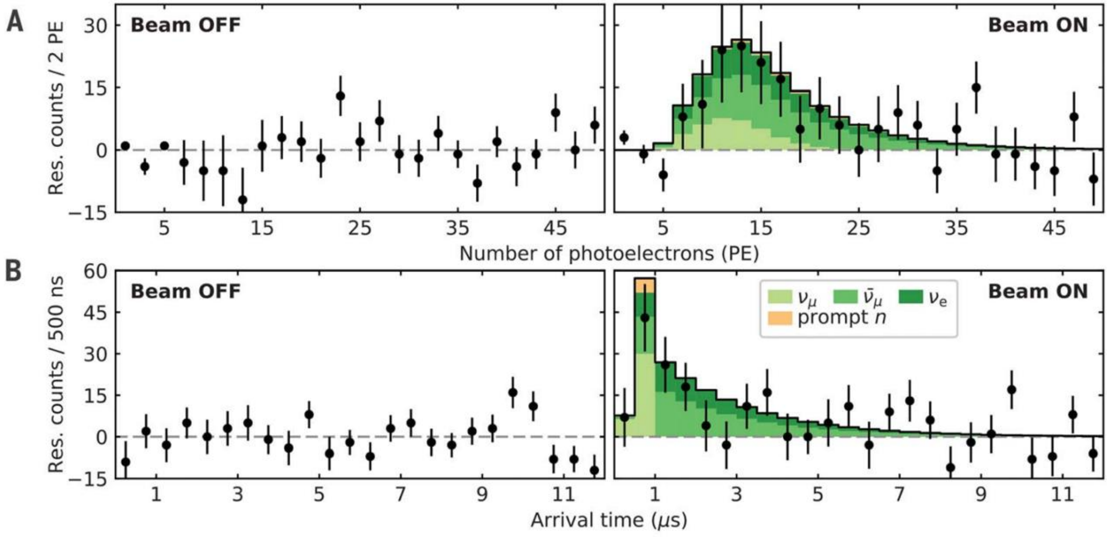
**Coherent effects of a weak neutral current**

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 $\nu + A \rightarrow \nu + A$ should have a sharp coherent forward peak just as $e + A \rightarrow e + A$ 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 $\nu + A \rightarrow \nu + A^*$ 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.

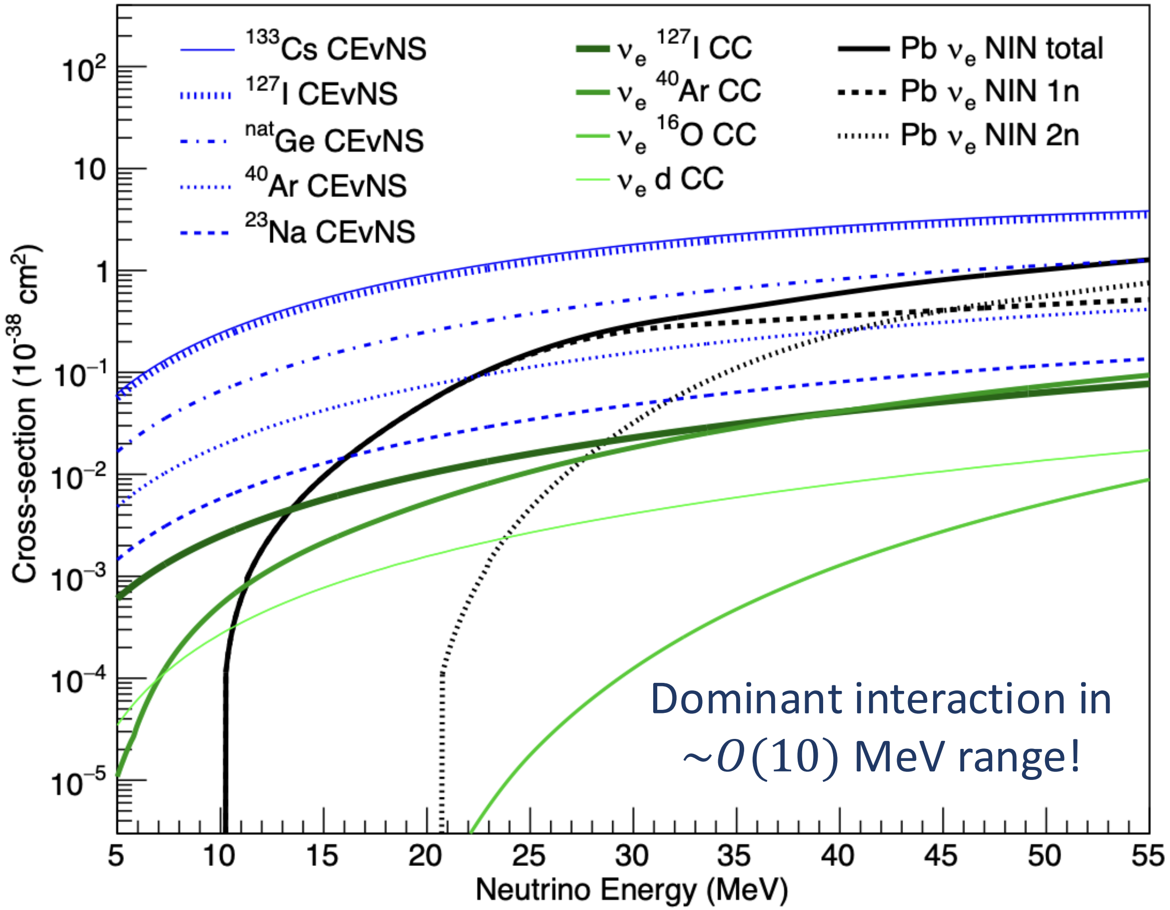
*51 years since first proposed by Freedman!*




*8 years since first detection by COHERENT!*

# CE$\nu$NS as a Standard Model prediction

A neutral current process




Diana Parno's Talk at Magnificent CEvNS 2024

The good news

- Large cross section.
- Small detectors needed.

$$\left.\frac{d\sigma_{\nu N}}{dE_{\rm nr}}\right|^{\rm SM}_{{\rm CE}\nu{\rm NS}} = \frac{G_F^2 m_N}{\pi} F_W^2(|\vec{q}|^2)\left(Q_V^{\rm SM}\right)^2\left(1 - \frac{m_N E_{\rm nr}}{2E_\nu^2}\right)$$

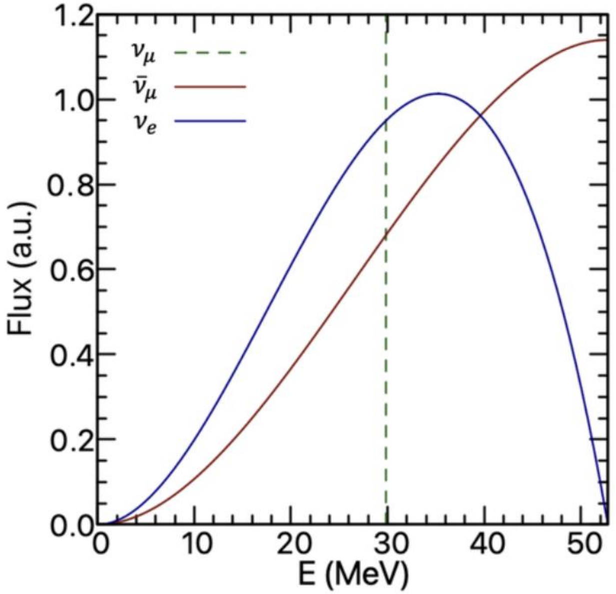
$$\left(Q_W^V\right)^2 = \left[Z F_Z(q^2)\, g_V^p + N F_N(q^2)\, g_V^n\right]^2$$

The not so good news

- Very low energy thresholds needed.

# CE$\nu$NS from different sources

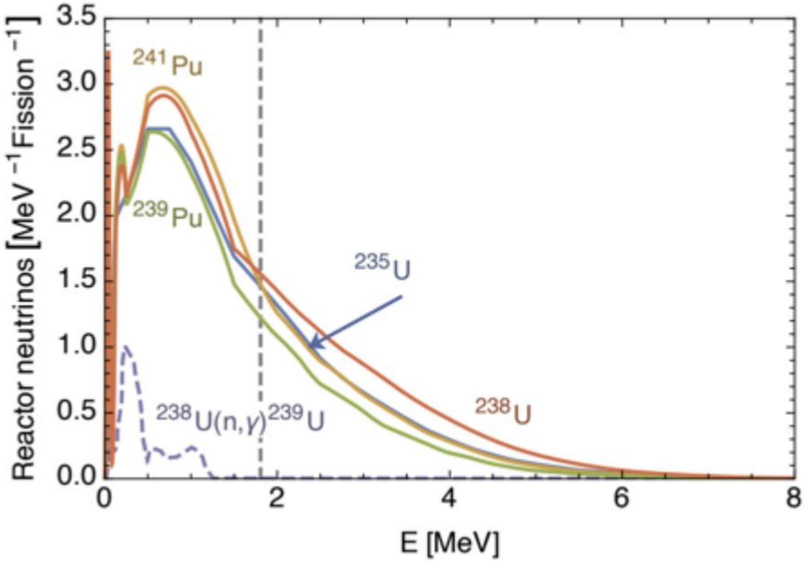
## Spallation Sources




- Pion decay at rest source.
- Well-known fluxes.

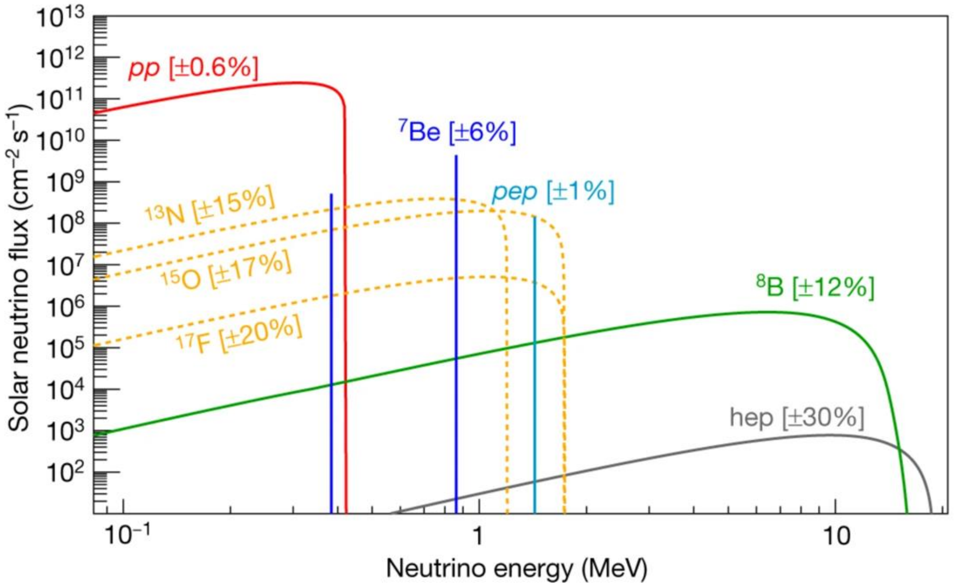
## Reactor Sources

- Neutrinos from nuclear decays.
- Huber-Muller model for E > 1.8 MeV.




Vitagliano, Tamborra, and Raffelt RevModPhys.92.045006

## Solar neutrinos




Vitagliano, Tamborra, and Raffelt RevModPhys.92.045006

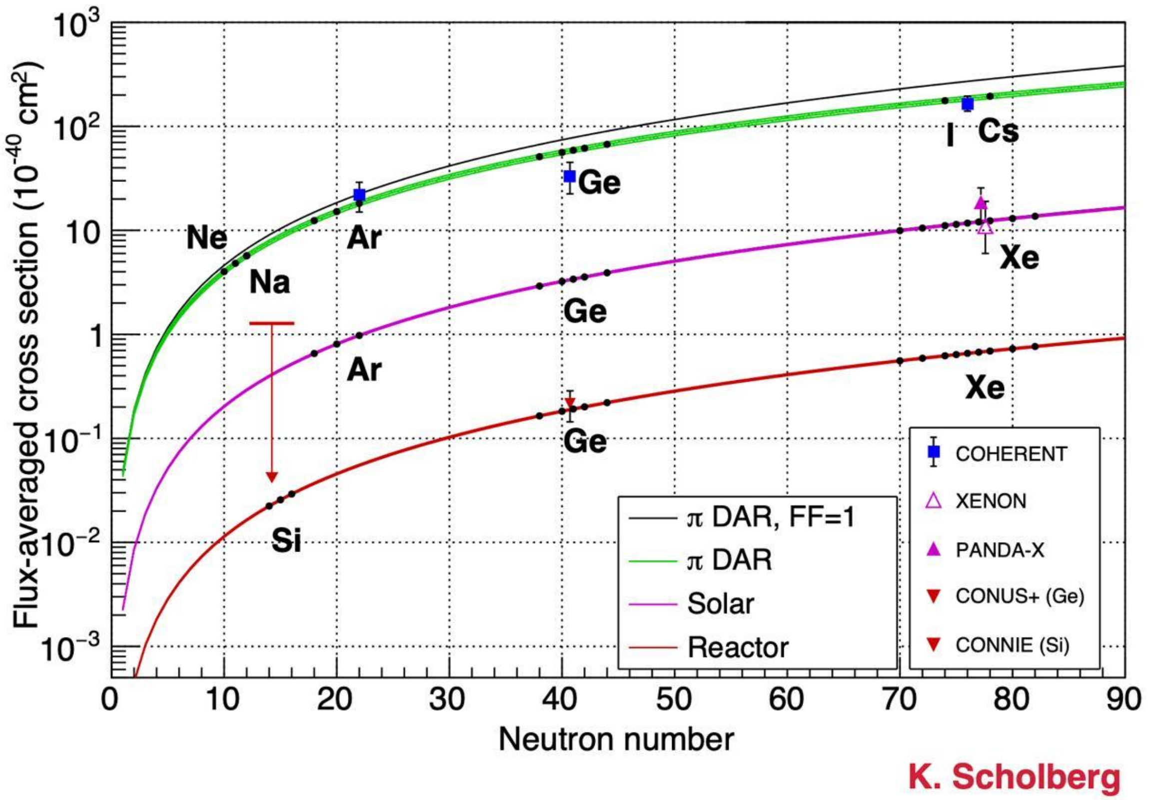
- Neutrinos from reactions within the sun.
- Currently sensitive to $^8$B flux.

# Different sources for CEνNS measurements

Current experiments and prospects.

| Source | Status 2023 | | Status 2025 | |
|---|---|---|---|---|
| Spallation Sources | ✓ Detected!<br>CsI (2017, 2021)<br>LAr (2020) | COHERENT SNS<br>Phys.Rev.Lett. 129 (2022) 8<br>Phys.Rev.Lett. 126 (2021) 1 | ✓ Detected!<br>Ge (2024) | COHERENT SNS<br>arXiv:2406.13806 |
| Reactor Experiments | ○ Detected?<br>Phys.Rev.Lett. 129 (2022) 21 | | ✓ Detected!<br>Ge (2024) | CONUS+<br>arXiv:2501.05206 |
| Solar Neutrinos | X Not detected | | ✓ Detected!<br>Xe (2024) | XENON PANDAX<br>Phys.Rev.Lett. 133 (2024) 19 |

# Summary of current measurements with different sources:



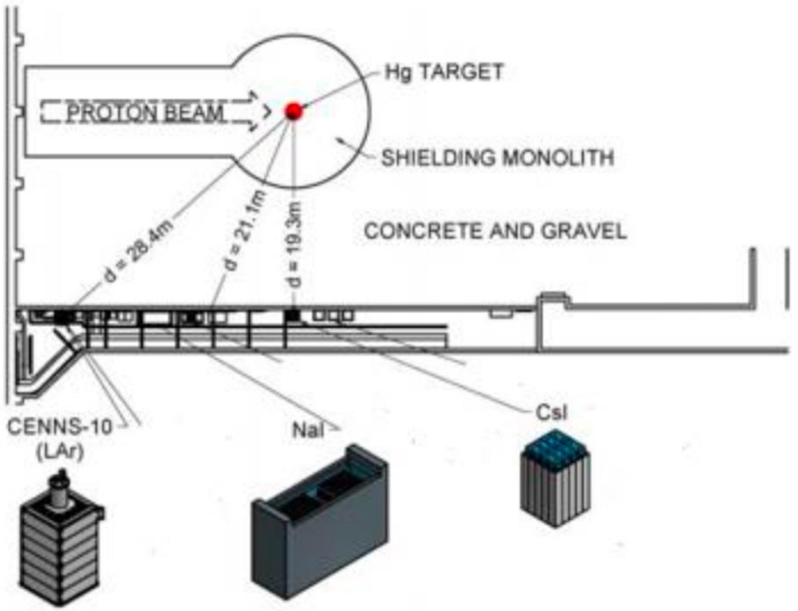

K. Scholberg talk at Magnificent CEvNS.

## Prospects for the near and far future run:

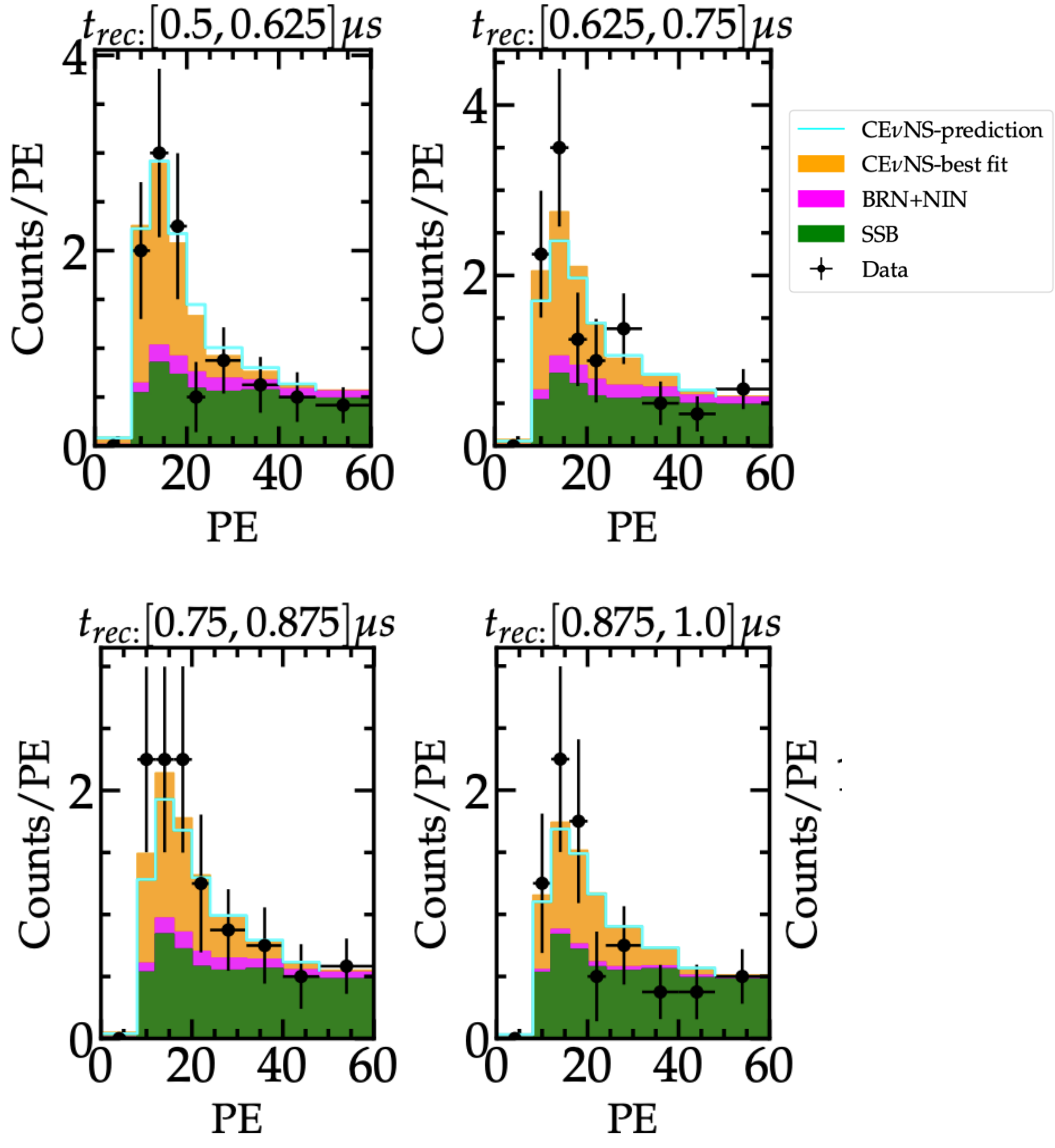
- COHERENT (NaI and LAr detectors)
- European Spallation Source
- CONUS+
- CONNIE (ICN-UNAM)
- NuGen
- Red-100
- NEON

Opportunity for phenomenological analyses!

# The COHERENT experiment



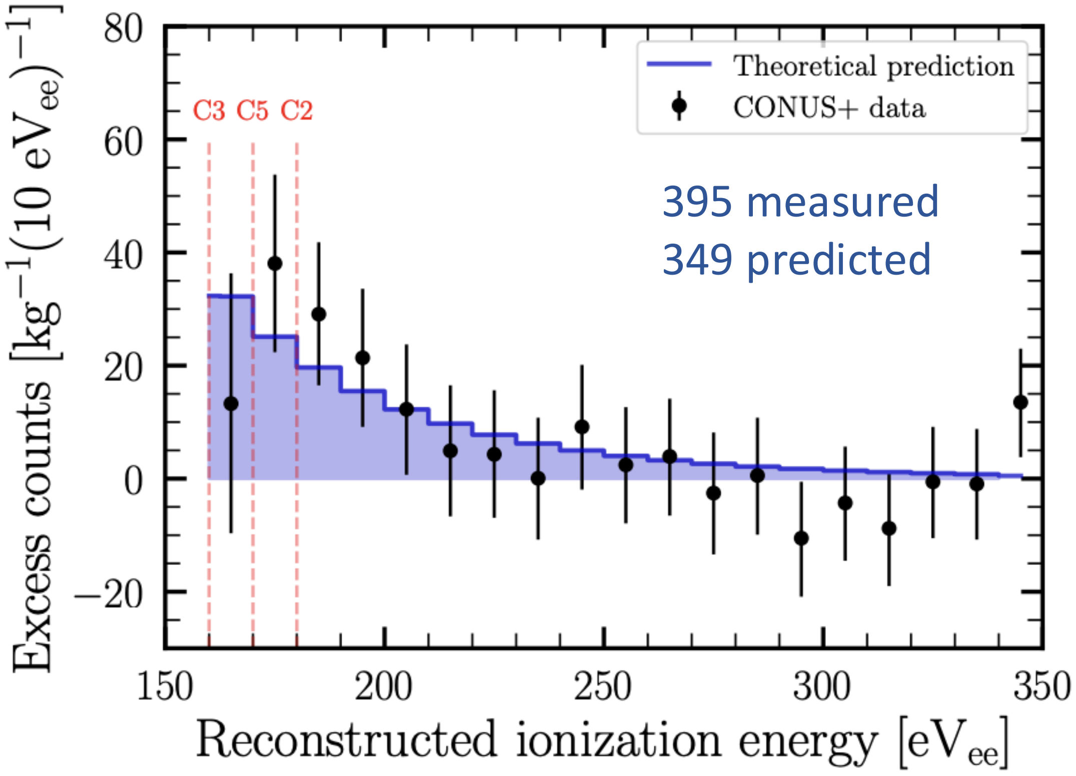

D. Akimov et al. Science, 357(6356) 1123–1126 (2017).




- Decay of muons and pions at rest
- Detector at 19 m (CsI) and 27 m (LAr) from source
- CsI detector of 14 kg and LAr detector of 24 kg.
- Order of $10^{23}$ POT.

De Romeri, Miranda, Papoulias, **GSG**, Tórtola, and Valle, JHEP 04 (2023) 035

# The CONUS+ Experiment




N. Ackerman, et all. arXiv:2501.05206

C. Buck talk at ICHEP 2024

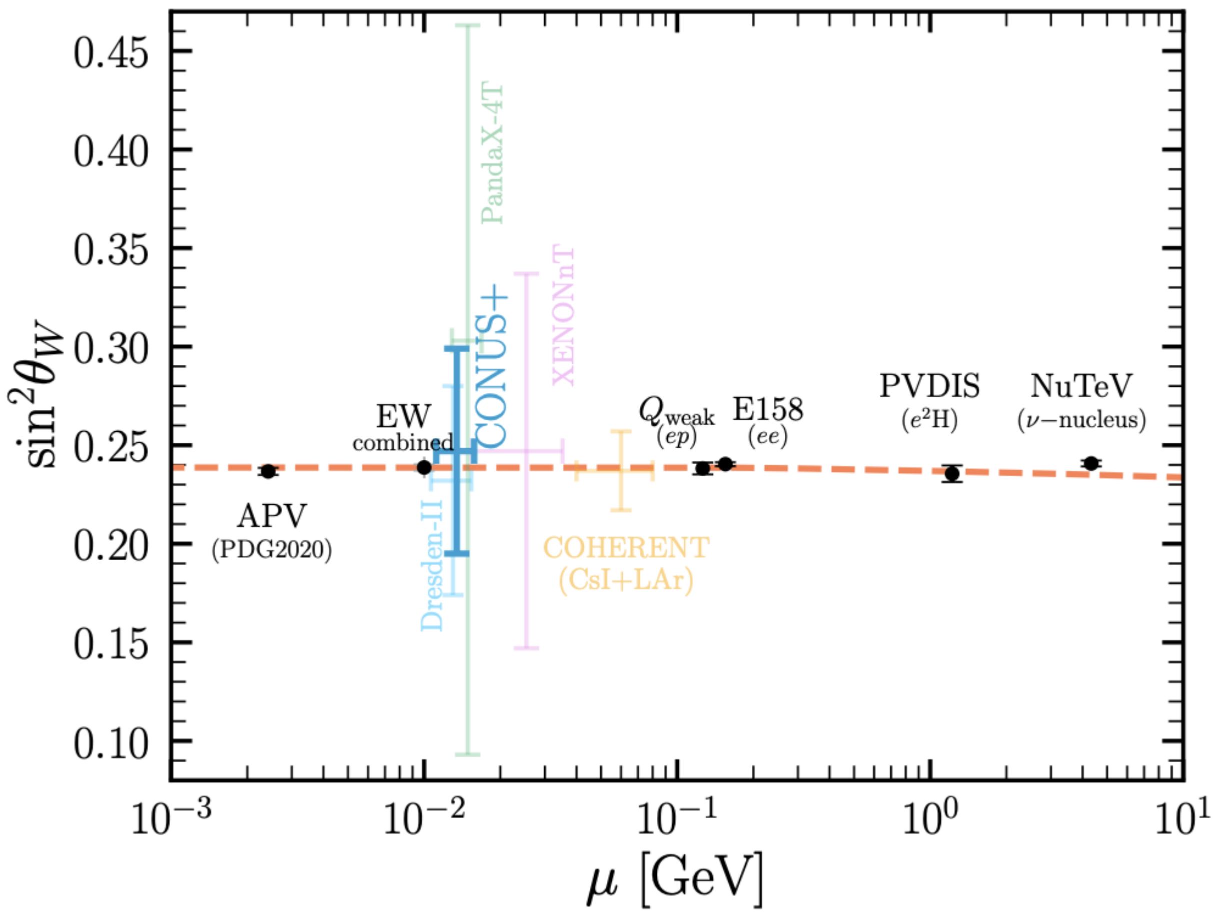
- Reactor neutrinos as a source
- Detector at 20.7m from the core
- 4 Ge detectors of ≈ 1 kg
- 119 days of operation

Need of a quenching factor to convert to nuclear recoil energy!

# Standard Model tests at low energies

## Weak mixing angle

$\theta_W$




De Romeri, Papoulias, **GSG** arXiv:2501.17843

- Compute the expected rate:

$$\left.\frac{\mathrm{d}R}{\mathrm{d}E_{\mathrm{ee}}^{\mathrm{reco}}}\right|_{\mathrm{CE}\nu\mathrm{NS}} = \mathcal{E}\int_{E_{\mathrm{er}}^{\min}}^{E_{\mathrm{er}}^{\max}} \mathrm{d}E_{\mathrm{er}}\, \mathcal{G}(E_{\mathrm{ee}}^{\mathrm{reco}}, E_{\mathrm{er}})\mathcal{F}(E_{\mathrm{er}}) \int_{E_{\nu}^{\min}}^{E_{\nu}^{\max}} \mathrm{d}E_{\nu}\, \frac{\mathrm{d}\phi}{\mathrm{d}E_{\nu}} \frac{\mathrm{d}\sigma_{\nu\mathcal{N}}}{\mathrm{d}E_{\mathrm{er}}}\right|$$

- Test against experimental data:

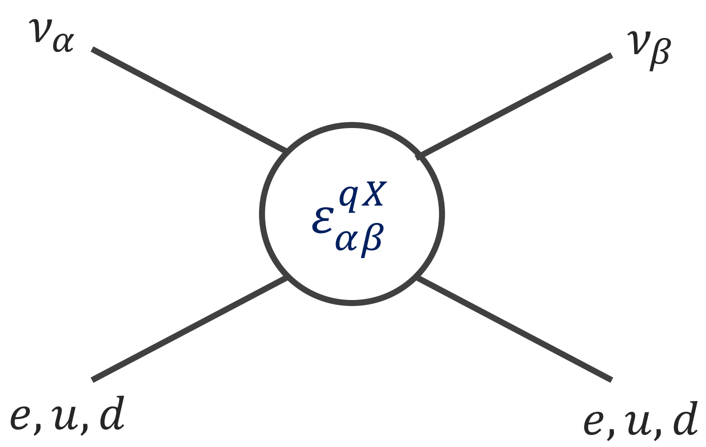
$$\chi^2(\vec{\beta}) = \sum_i \frac{\left[R_i^{\mathrm{exp}} - (1+\alpha)R_i^{\mathrm{th}}(\vec{\beta})\right]^2}{\sigma_i^2} + \left(\frac{\alpha}{\sigma_\alpha}\right)^2 ,$$

# Beyond the Standard Model physics

## Non-Standard Interactions

### The Model

Neutral current Lagrangian introduced to allow for non-universal and flavor changing interactions.




$\varepsilon_{ll}^{qX}$ non−universal

$\varepsilon_{ll'}^{qX}$ flavor changing

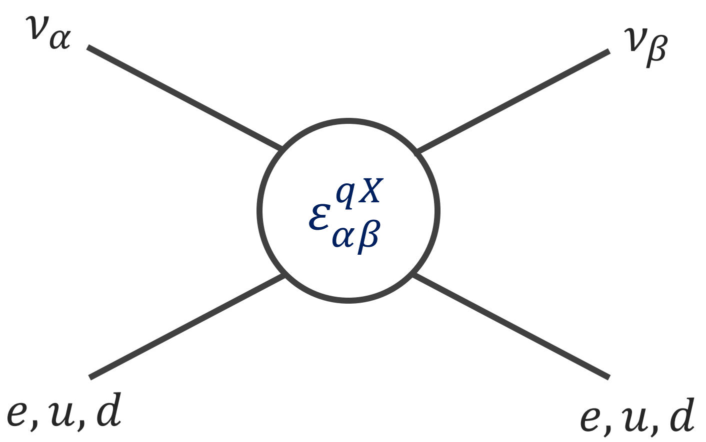
$$\mathcal{L}_{\rm NC}^{\rm NSI} = -2\sqrt{2}G_F \sum_{\ell,\ell'} \varepsilon_{\ell\ell'}^{fC} (\bar{\nu}_\ell \gamma^\mu P_L \nu_{\ell'})(\bar{f}\gamma_\mu P_C f)\,,$$

# Beyond the Standard Model physics

## Non-Standard Interactions

### The Model

Neutral current Lagrangian introduced to allow for non-universal and flavor changing interactions.

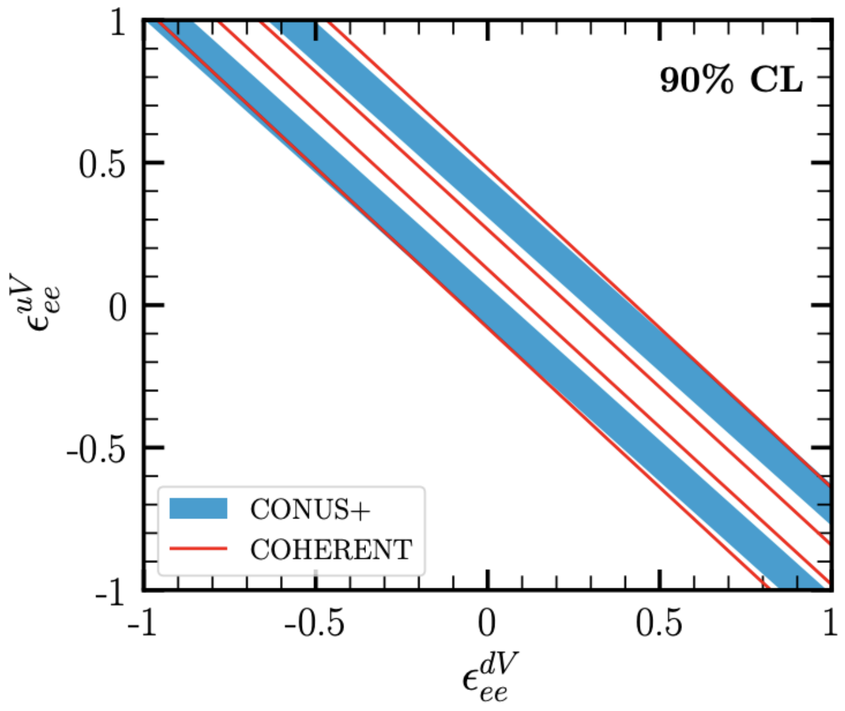



$$\left(Q_V^{\rm NSI}\right)^2 = \left[Z\left(g_V^p + 2\varepsilon_{\ell\ell}^{uV} + \varepsilon_{\ell\ell}^{dV}\right) + N\left(g_V^n + \varepsilon_{\ell\ell}^{uV} + 2\varepsilon_{\ell\ell}^{dV}\right)\right]^2$$

$$+ \sum_{\ell\neq\ell'} \left|Z\left(2\varepsilon_{\ell\ell'}^{uV} + \varepsilon_{\ell\ell'}^{dV}\right) + N\left(\varepsilon_{\ell\ell'}^{uV} + 2\varepsilon_{\ell\ell'}^{dV}\right)\right|^2 .$$

Barranco, Miranda, and Rashba JHEP 12 (2005) 021

### Non-Universal NSI




De Romeri, Papoulias, **GSG.** arXiv:2501.17843

# Beyond the Standard Model physics

## Non-Standard Interactions

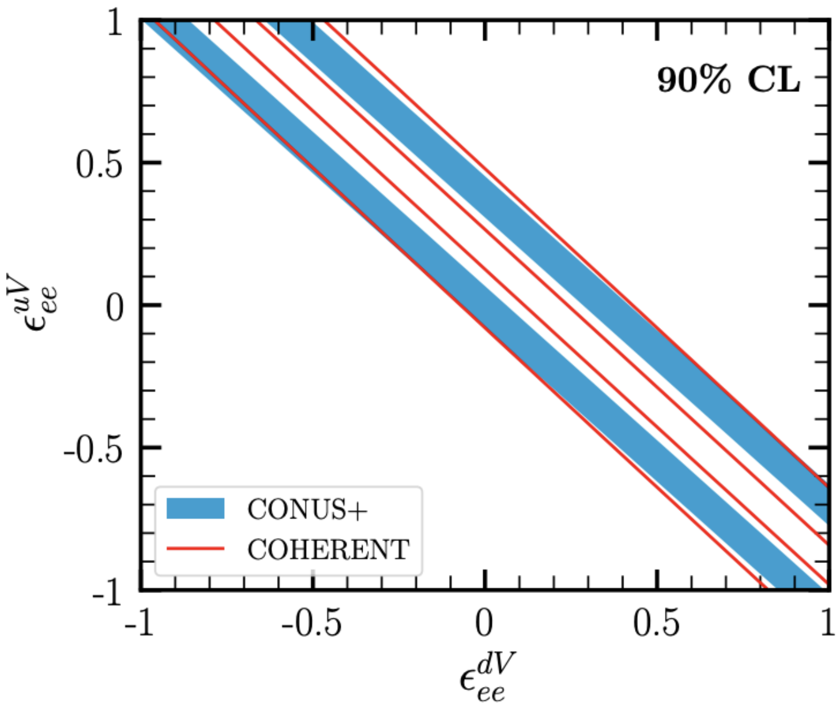
### The Model

| NSI | CONUS+ (This Work) | COHERENT (CsI+LAr) [89] |
|---|---|---|
| $\varepsilon_{ee}^{uV}$ | $[-0.037, 0.026] \cup [0.348, 0.411]$ | $[-0.024, 0.045] \cup [0.34, 0.43]$ |
| $\varepsilon_{ee}^{dV}$ | $[-0.034, 0.024] \cup [0.322, 0.380]$ | $[-0.027, 0.048] \cup [0.30, 0.39]$ |
| $\varepsilon_{e\mu}^{uV}$ | $[-0.123, 0.123]$ | $[-0.081, 0.081]$ |
| $\varepsilon_{e\mu}^{dV}$ | $[-0.114, 0.114]$ | $[-0.071, 0.071]$ |
| $\varepsilon_{e\tau}^{uV}$ | $[-0.123, 0.123]$ | $[-0.13, 0.13]$ |
| $\varepsilon_{e\tau}^{dV}$ | $[-0.114, 0.114]$ | $[-0.12, 0.12]$ |

- CONUS+ provides better bounds for $\varepsilon_{ee}^{qV}$
- COHERENT has better sensitivity to $\varepsilon_{e\mu}^{qV}, \varepsilon_{\mu\mu}^{qV}$.
- $\varepsilon_{\tau\tau}^{qV}$ only accessible through solar data!

D. Aristizabal, et all Phys.Rev.D 111 (2025) 5

### Non-Universal NSI

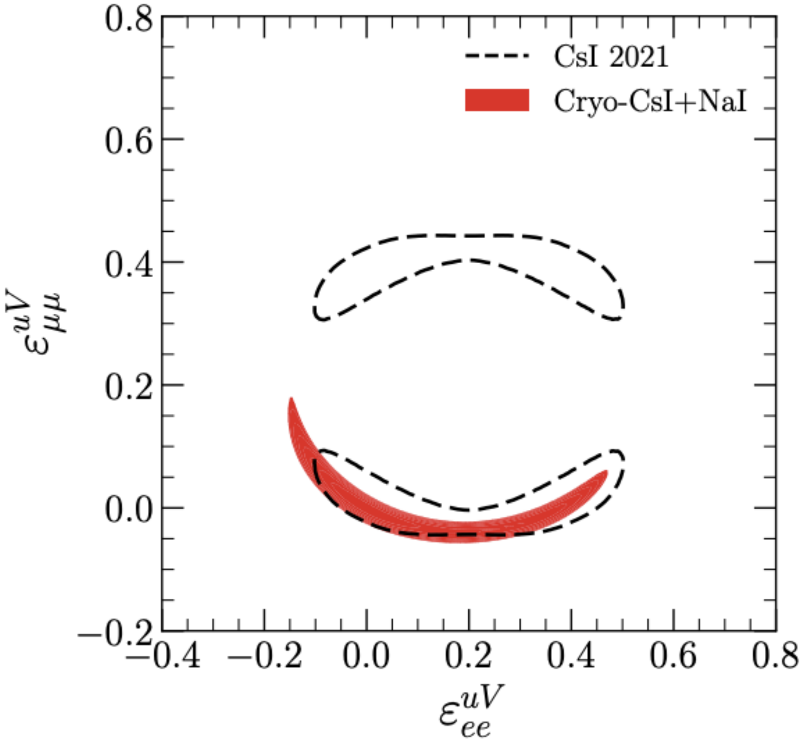


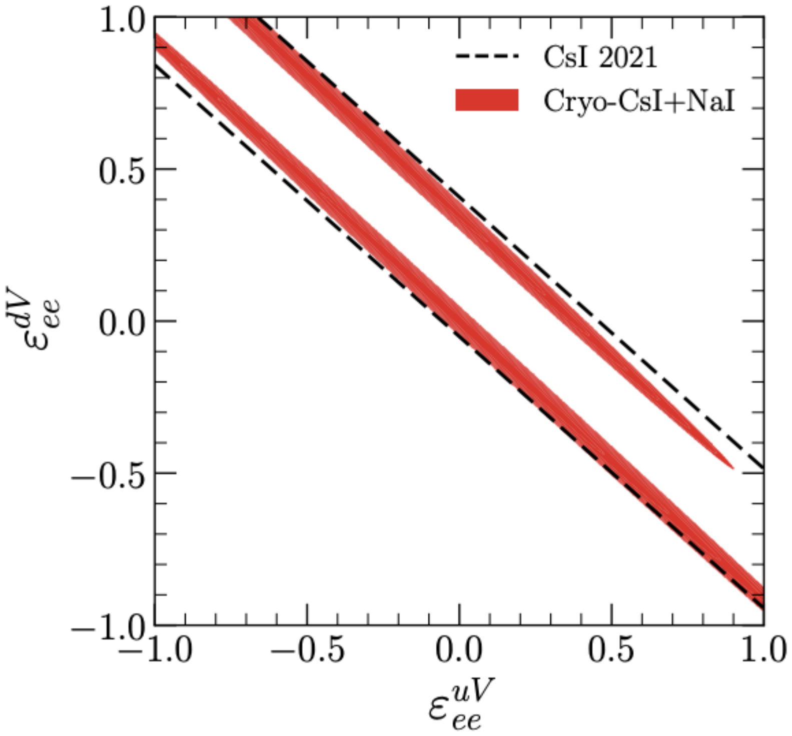

De Romeri, Papoulias, **GSG.** arXiv:2501.17843

# Beyond the Standard Model physics

## Non-Standard Interactions – COHERENT

- Future COHERENT detectors are expected to break degeneracies in the parameter space.




Chatterjee, Lavignac, Miranda, and **GSG**,
Phys.Rev.D 110 (2024) 9

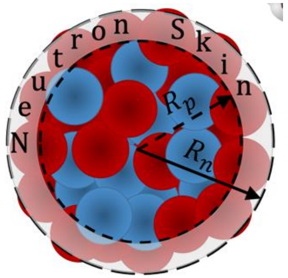
# Interplay between SM and new physics

## NSI and neutron rms radius – Current COHERENT – Future reactor

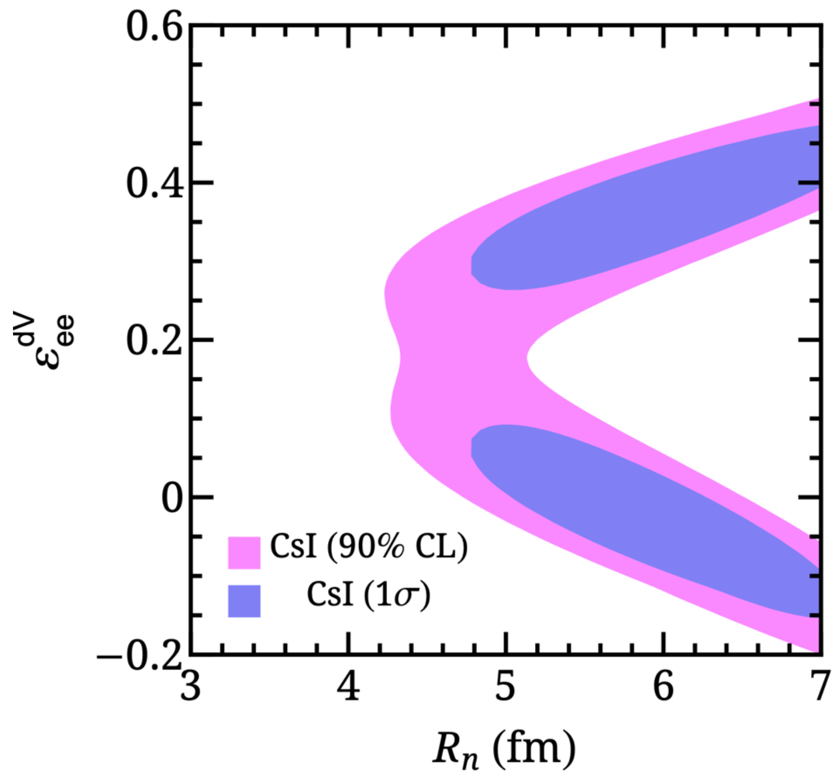
- Weak charge is sensitive to nuclear form factors.

$$\left(Q_W^V\right)^2 = \left[Z F_Z(q^2)\, g_V^p + N F_N(q^2)\, g_V^n\right]^2$$

Depends on neutron *rms* radius




Cadeddu's Talk at NuFact 2018




Rossi, **GSG**, and Tórtola Phys. Rev. D 109 (2024)

- We either do not know the nuclear structure or indeed have the presence of NSI.

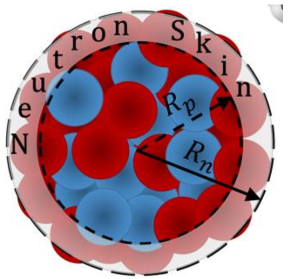
# Interplay between SM and new physics

## NSI and neutron rms radius – Current COHERENT – Future reactor

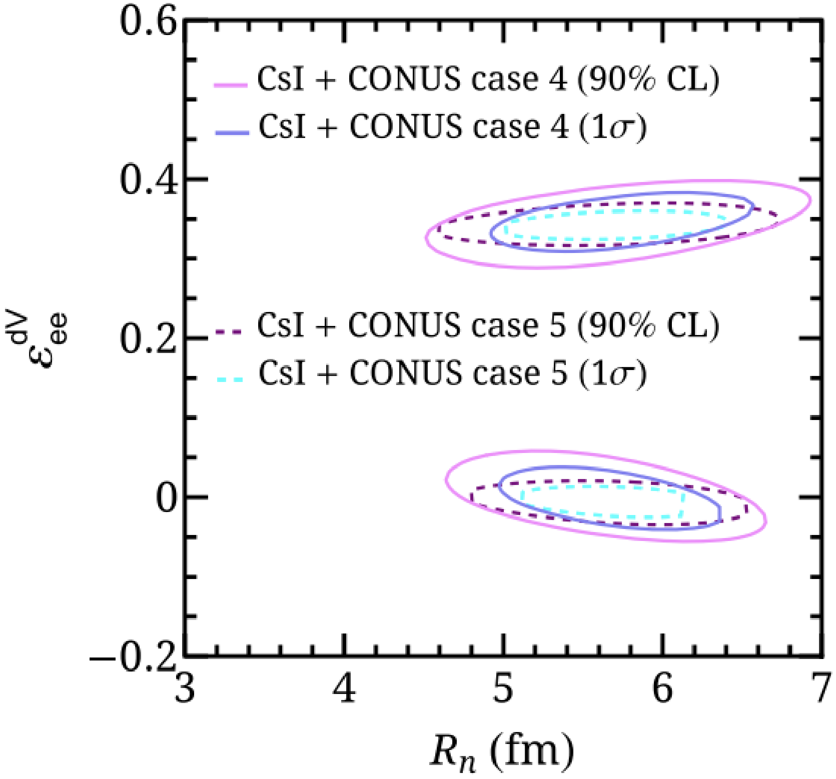
- Weak charge is sensitive to nuclear form factors.

$$(Q_W^V)^2 = \left[ZF_Z(q^2)\, g_V^p + NF_N(q^2)\, g_V^n\right]^2$$

Depends on neutron *rms* radius




Cadeddu's Talk at NuFact 2018




Rossi, **GSG**, and Tórtola Phys. Rev. D 109 (2024)

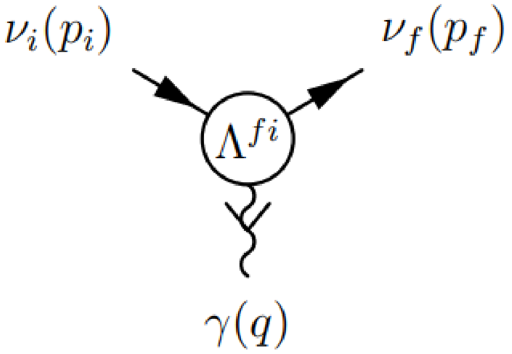
- Reactor neutrinos are not sensitive to the nuclear structure.

# Beyond the Standard Model physics

## Neutrino Magnetic Moment – CONUS+

### The Model

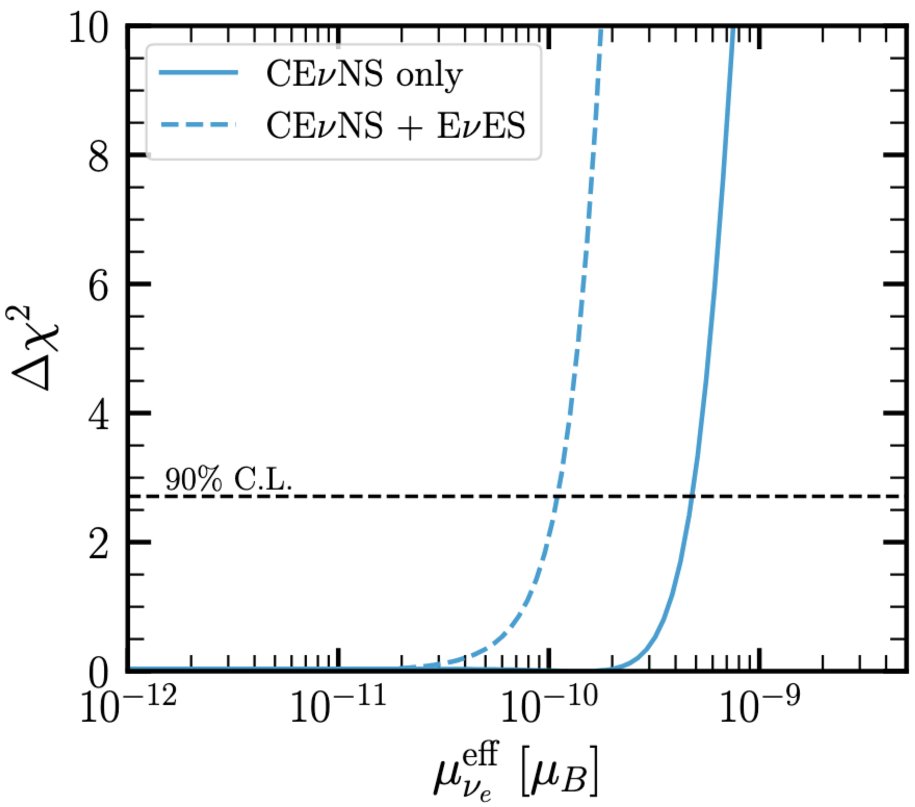
Massive neutrinos can induce a neutrino coupling to the photon at loop level




$$\mu^{\rm eff}_{\nu_\ell} = \sum_k \left| \sum_j U^*_{\ell k}\lambda_{jk}\right|^2 ,$$

$$\frac{d\sigma_{\nu\mathcal{N}}}{dT_\mathcal{N}}\bigg|^{\rm MM}_{\rm CE\nu NS} = \frac{\pi\alpha^2_{\rm EM}}{m_e^2}\left(\frac{1}{T_\mathcal{N}}-\frac{1}{E_\nu}\right) Z^2 F_W^2(|\mathbf{q}|^2)\left|\frac{\mu^{\rm eff}_{\nu_\ell}}{\mu_{\rm B}}\right|^2 ,$$

### Neutrino Magnetic Moment




De Romeri, Papoulias, **GSG.** arXiv:2501.17843

# Beyond the Standard Model physics

## Neutrino Magnetic Moment – CONUS+

### Other bounds

| Experiment | $\mu_{\nu_e}^{\text{eff}}$ ($10^{-11}$ $\mu_B$) | Process |
|---|---|---|
| CONUS+ | $\leq 11$ | CEνNS+EνES |
| COHERENT (CsI+LAr) | $\leq 360$ | CEνNS+EνES |
| DRESDEN-II | $\leq 19$ | CEνNS+EνES |
| XENONnT + PandaX-4T (combined) | $\leq 190$ | CEνNS |
| CONUS | $\leq 7.5$ | EνES |
| Borexino | $\leq 3.7$ | EνES |
| TEXONO | $\leq 7.4$ | EνES |
| GEMMA | $\leq 2.9$ | EνES |
| LZ | $\leq 1.4$ | EνES |
| XENONnT | $\leq 0.9$ | EνES |
| XENONnT+PandaX-4T+LZ (combined) | $\leq 1.03$ | EνES |

- A comparison with other limits should be done carefully.

Aristizabal, Miranda, Papoulias, **GSG.**
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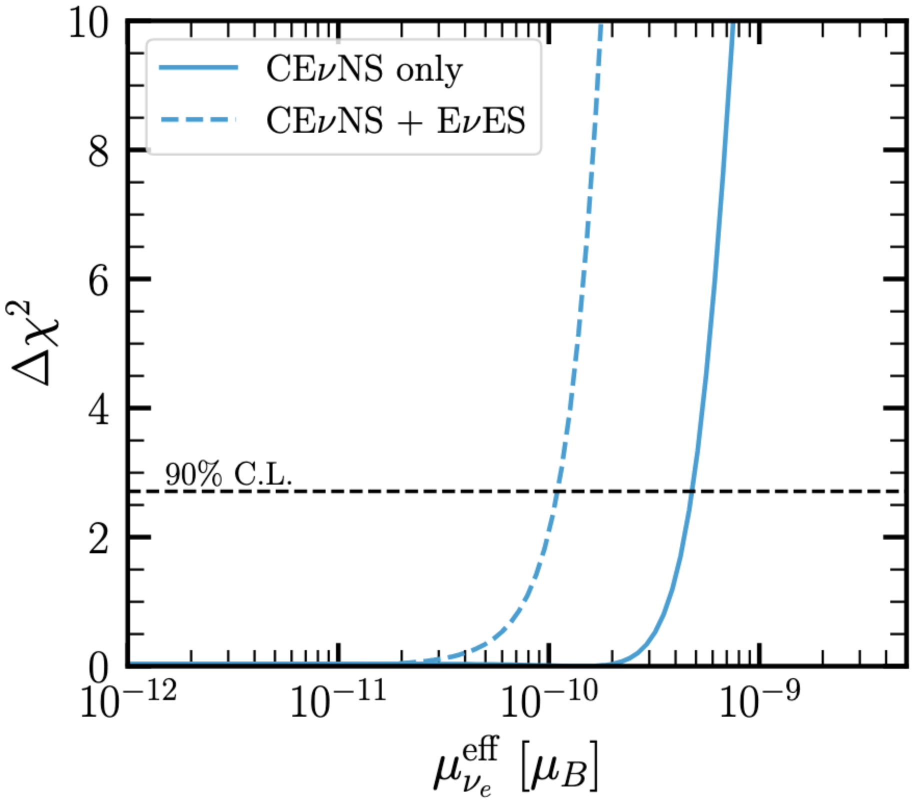
### Neutrino Magnetic Moment




De Romeri, Papoulias, **GSG.** arXiv:2501.17843

# Conclusions

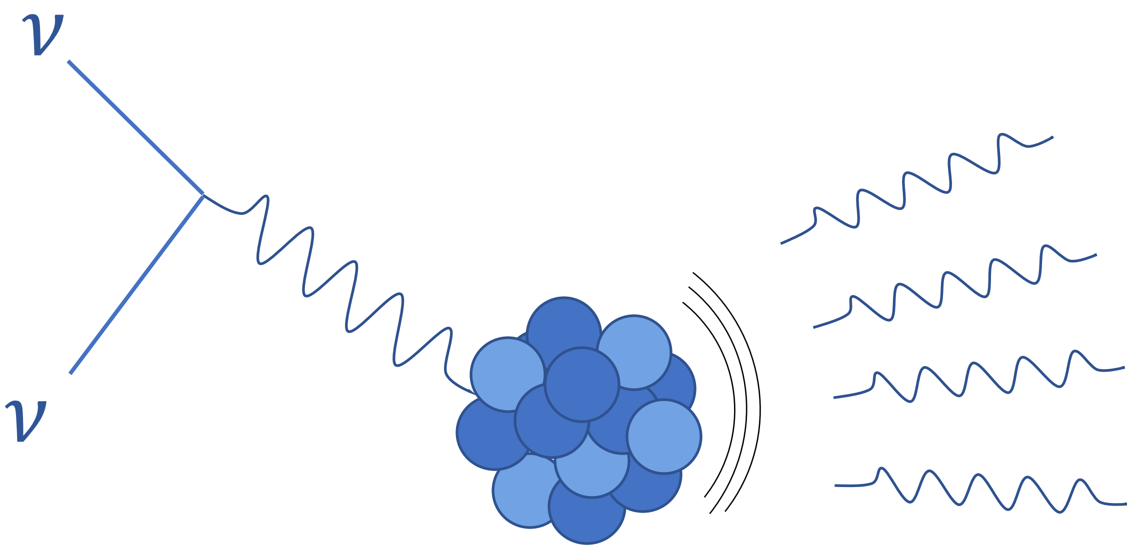
- CE$\boldsymbol{\nu}$NS is a powerful tool to perform tests of the SM.
- We can also use CE$\boldsymbol{\nu}$NS to constrain new physics scenarios such as NSI, magnetic moments and light mediators.
- Further experiments can enhance current bounds.
- Many different experiments are on their way to take more data.

# Conclusions

# Thank you!

- CE$\nu$NS is a powerful tool to perform tests of the SM.
- We can also use CE$\nu$NS to constrain new physics scenarios such as NSI, magnetic moments and light mediators.
- Further experiments can enhance current bounds.
- Many different experiments are on their way to take more data.

# Backup

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GENERALITAT VALENCIANA Conselleria d'Educació, Universitats i Ocupació
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

# Beyond the Standard Model physics

## Light Mediators – CONUS+

### The Model

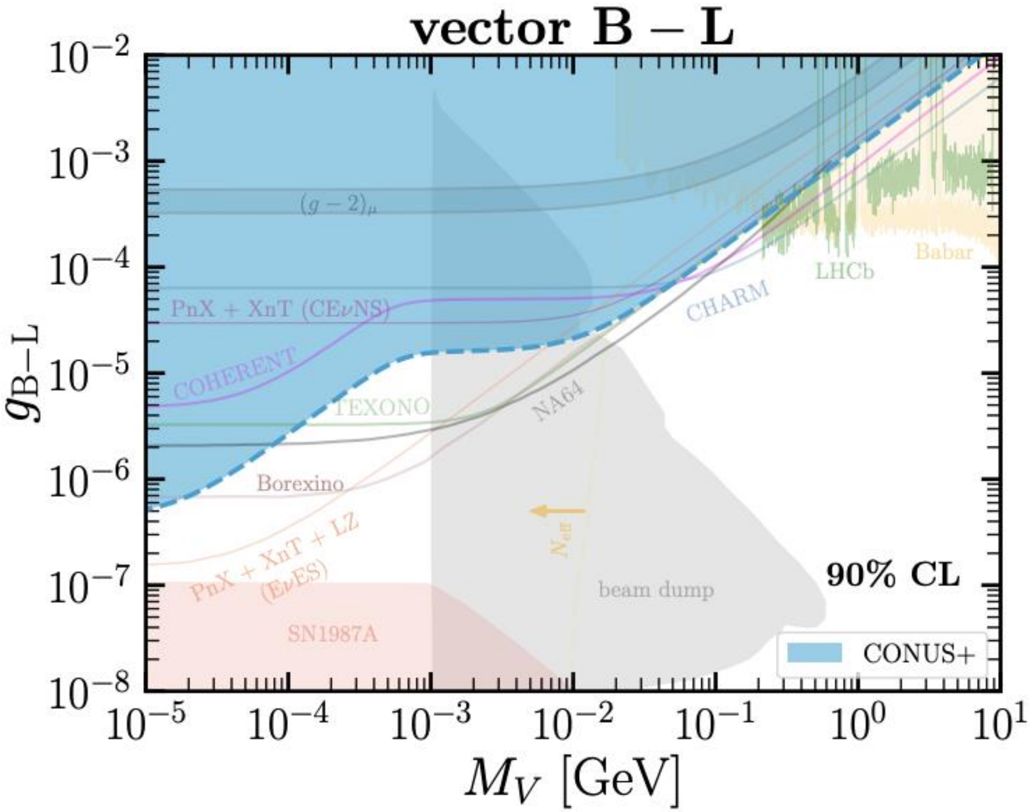
We promote GNI to the case where the interaction is driven by a light mediator compared to the energy scale.

$$\left.\frac{d\sigma_{\nu\mathcal{N}}}{dT_{\mathcal{N}}}\right|^{S}_{\mathrm{CE}\nu\mathrm{NS}} = \frac{m_{\mathcal{N}} \mathcal{Q}_S^2}{4\pi (m_S^2 + 2 m_{\mathcal{N}} T_{\mathcal{N}})^2} F_W^2(|\mathbf{q}|^2) \frac{m_{\mathcal{N}} T_{\mathcal{N}}}{E_\nu^2},$$

$$\left.\frac{d\sigma_{\nu\mathcal{N}}}{dT_{\mathcal{N}}}\right|^{V}_{\mathrm{CE}\nu\mathrm{NS}} = \left[1 + \kappa \frac{\mathcal{Q}_V}{\sqrt{2} G_F Q_V^{\mathrm{SM}} (m_V^2 + 2 m_{\mathcal{N}} T_{\mathcal{N}})}\right]^2 \left.\frac{d\sigma_{\nu\mathcal{N}}}{dT_{\mathcal{N}}}\right|^{\mathrm{SM}}_{\mathrm{CE}\nu\mathrm{NS}},$$

✓ Complementary results to other existing bounds.

### B - L scenario




De Romeri, Papoulias, **GSG.** arXiv:2501.17843