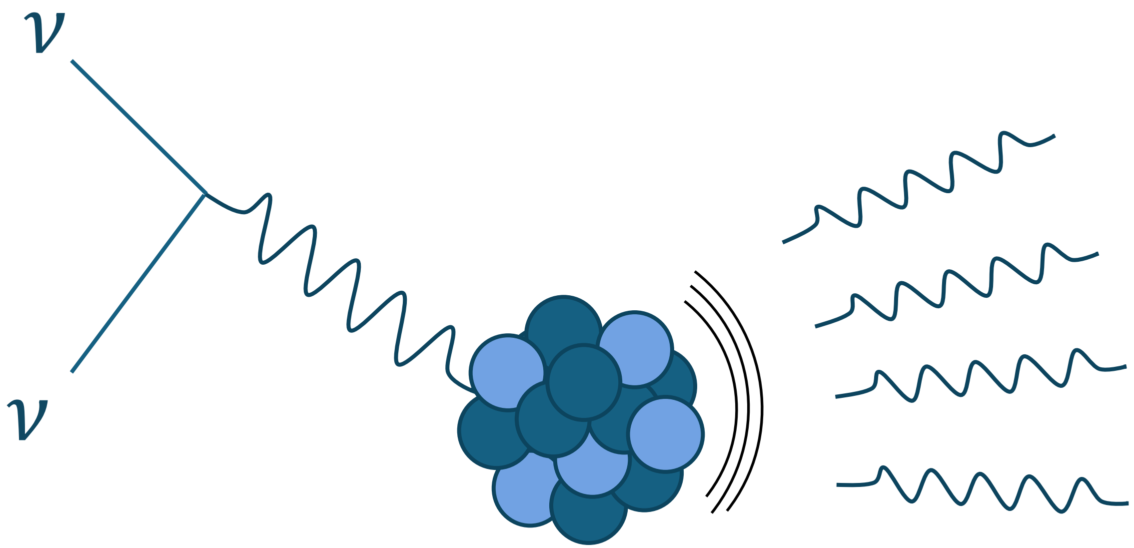
Beyond the Standard Model physics at spallation neutron sources



Gonzalo Sánchez García

Facultad de Ciencias (UNAM)

RADPyC, June 17, 2026

g.sanchez@ciencias.unam.mx

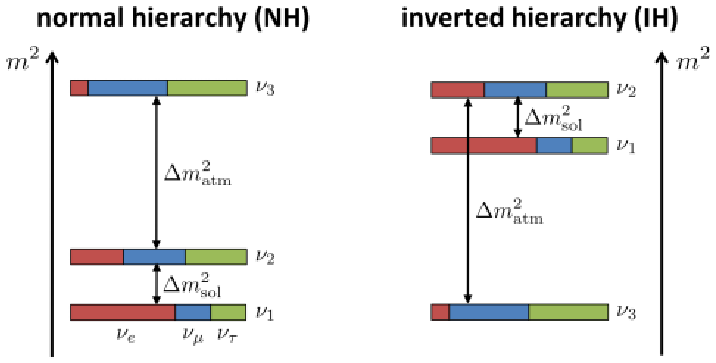
Outline

- Neutrinos within the Standard Model
- Spallation Neutron Sources
- Phenomenology of neutrinos at low energies
- Dark Matter searches in neutrino intended experiments
- Conclusions

Open questions in particle physics

Neutrino Physics

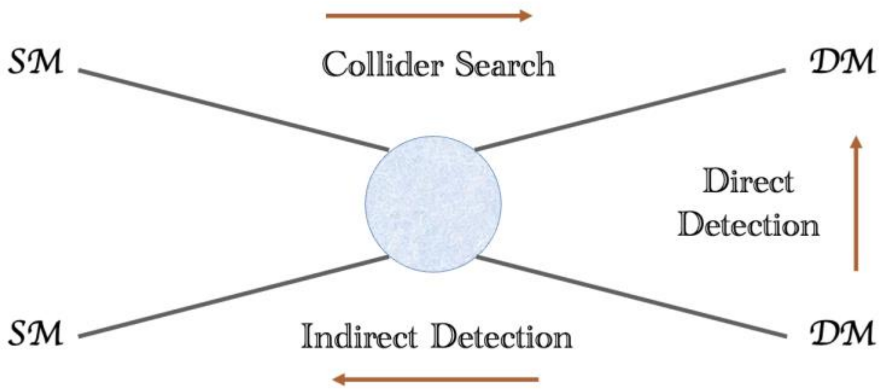
- ❑ Dirac vs Majorana particles.
- ❑ Origin and scale of neutrino mass.
- ❑ θ_{23} octant and δ phase value.



Credit: stereo-experiment.org

Dark matter

- ❑ What is it?
- ❑ How can we detect it?
- ❑ Most matter in the universe has a non-barionic nature.



Credit: G. Sánchez García

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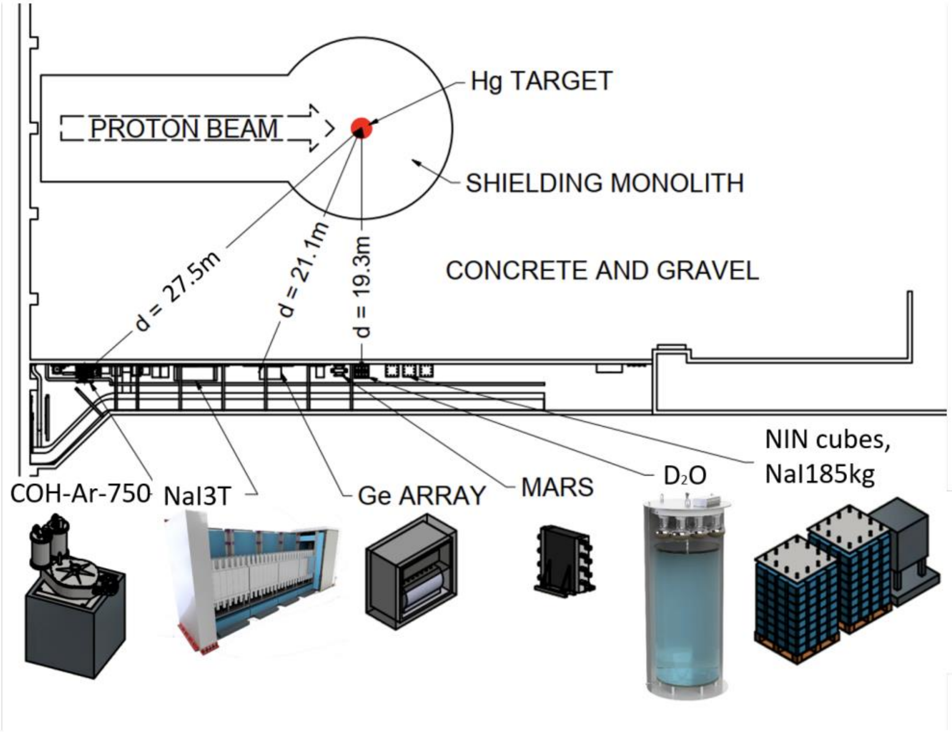
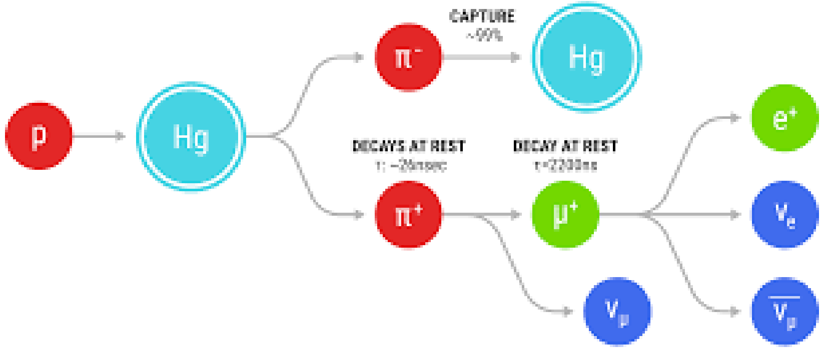
Spallation Neutron Source

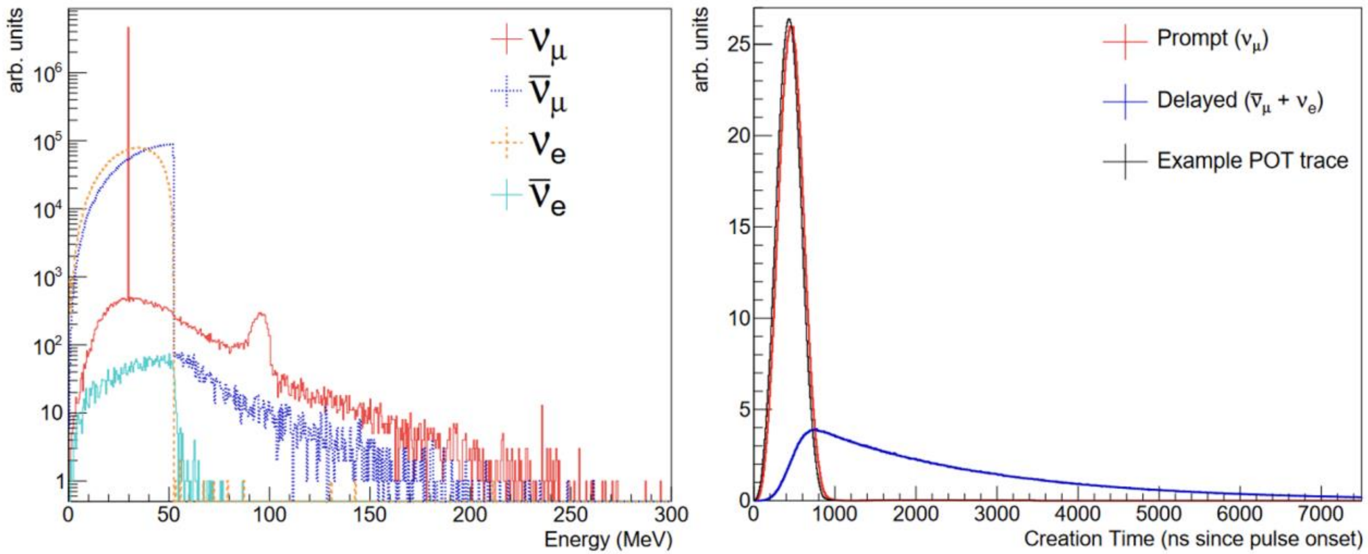
High energy proton beam



D. Akimov, et al, arXiv: 2204.04575



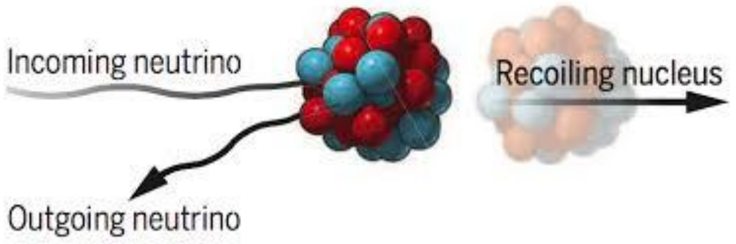
Neutrino production at the SNS



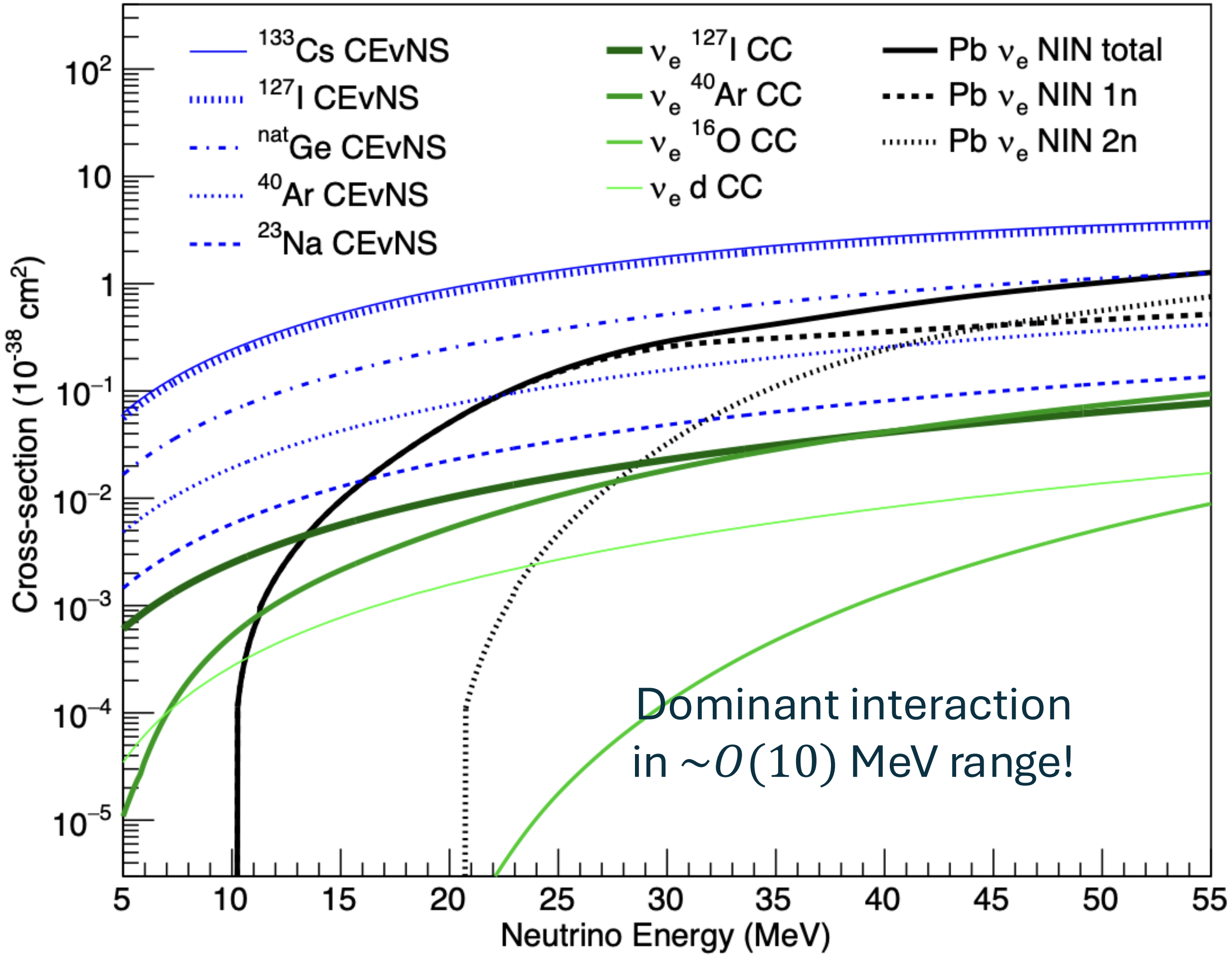
D. Akimov, et al, arXiv: 2204.04575

Neutrino Phenomenolgy at SNS

Coherent Elastic νeutrino Nucleus Scattering

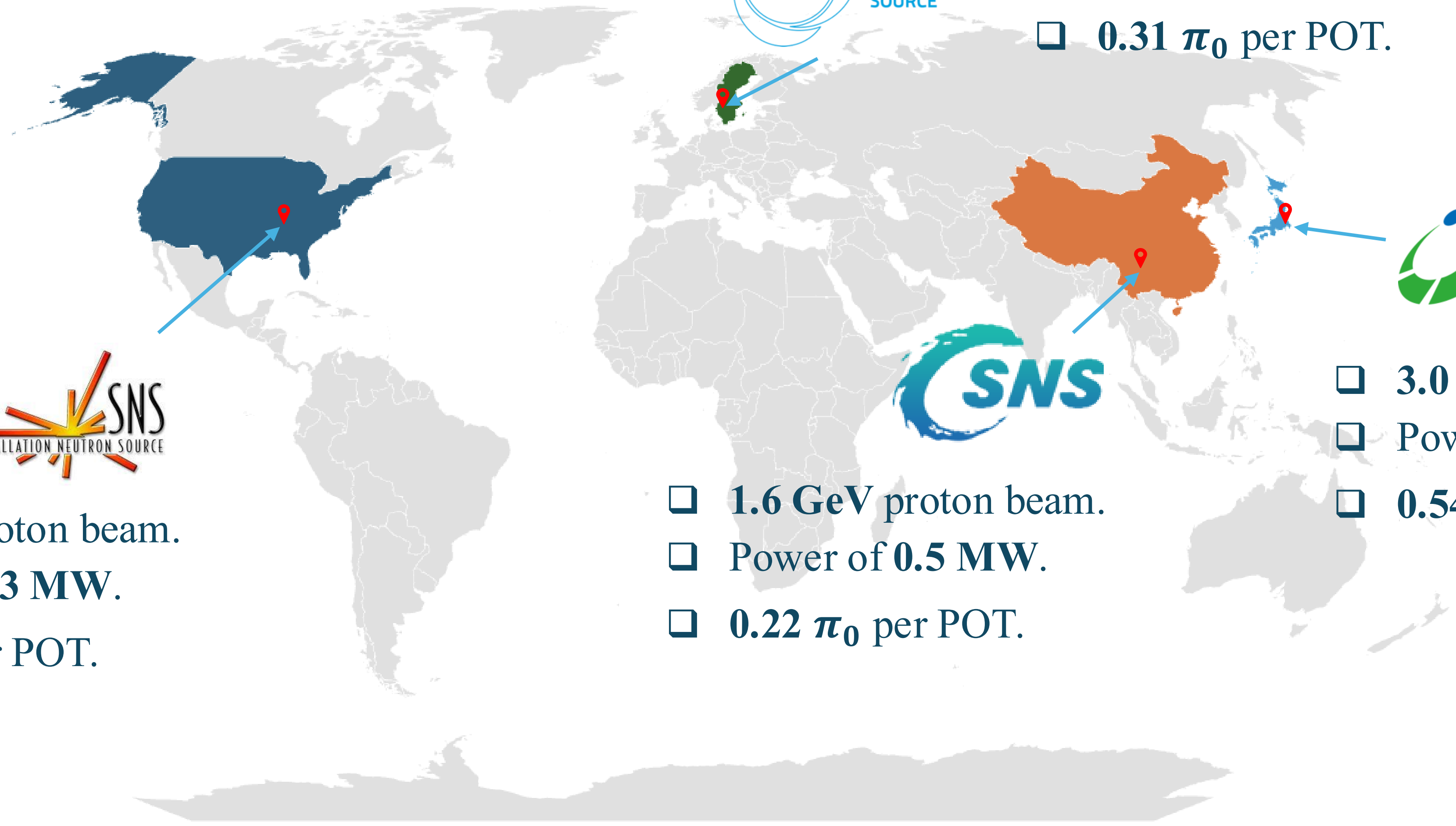


$$\left.\frac{d\sigma_{\nu\mathcal{N}}}{dE_{\rm nr}}\right|^{\rm SM}_{\rm CE\nu NS} = \frac{G_F^2 m_N}{\pi} F_W^2(|\vec{q}|^2)\left(Q_V^{\rm SM}\right)^2\left(1 - \frac{m_N E_{\rm nr}}{2E_\nu^2}\right)$$



Dominant interaction in $\sim\mathcal{O}(10)$ MeV range!

Spallation Neutron Sources around the world



European Spallation Source (ESS)

- ❑ **2.0 GeV** proton beam.
- ❑ Power of **5 MW**.
- ❑ **0.31** π_0 per POT.

SNS – Spallation Neutron Source

- ❑ **1.3 GeV** proton beam.
- ❑ Power of **1.3 MW**.
- ❑ **0.07** π_0 per POT.

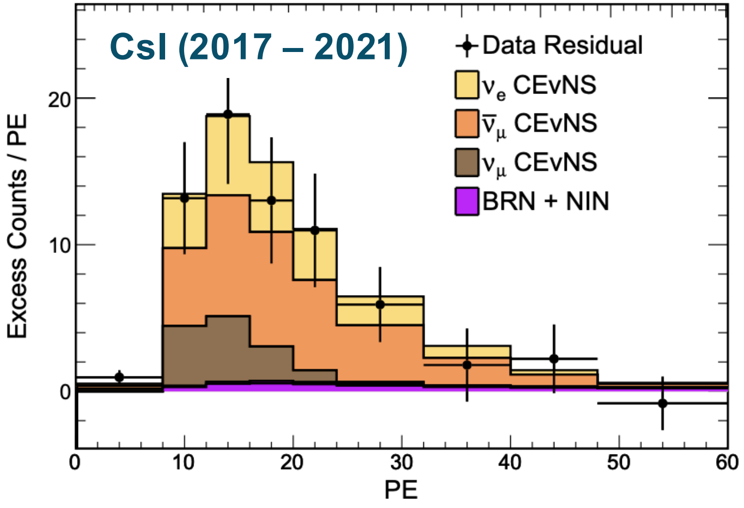
SNS

- ❑ **1.6 GeV** proton beam.
- ❑ Power of **0.5 MW**.
- ❑ **0.22** π_0 per POT.

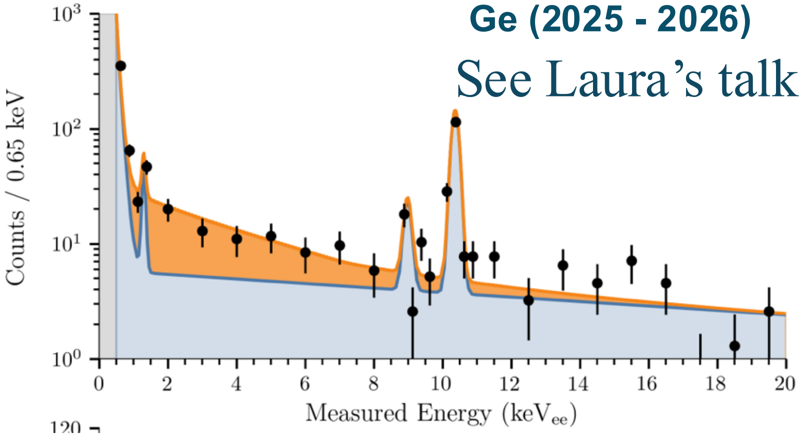
J-PARC

- ❑ **3.0 GeV** proton beam.
- ❑ Power of **1.3 MW**.
- ❑ **0.54** π_0 per POT.

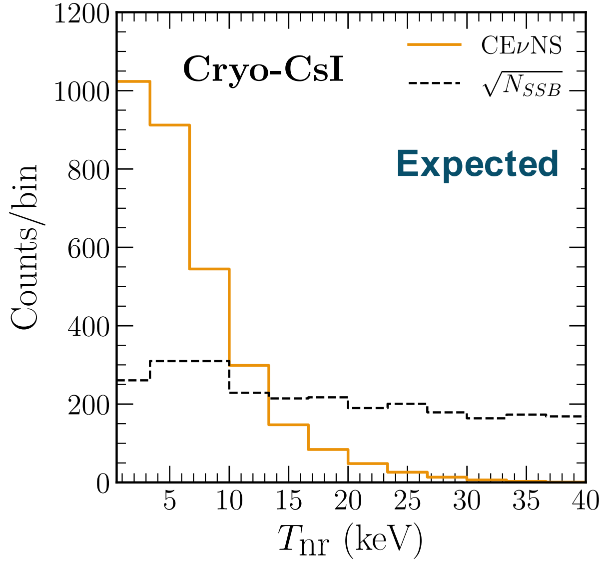
Spallation Neutron Source



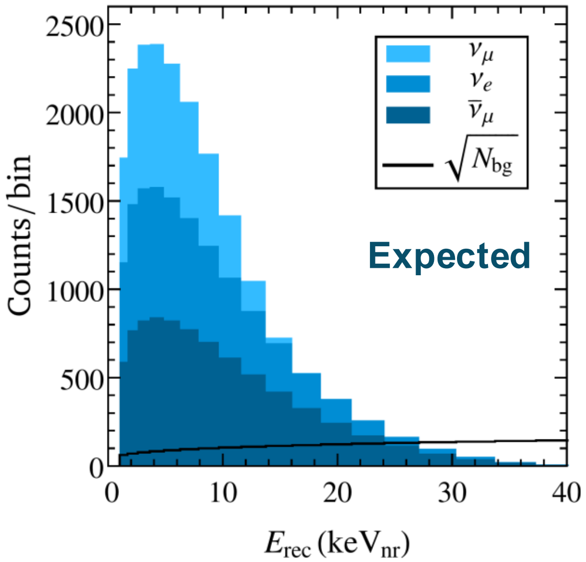
COHERENT Collaboration, Phys.Rev.Lett. 129 (2022)

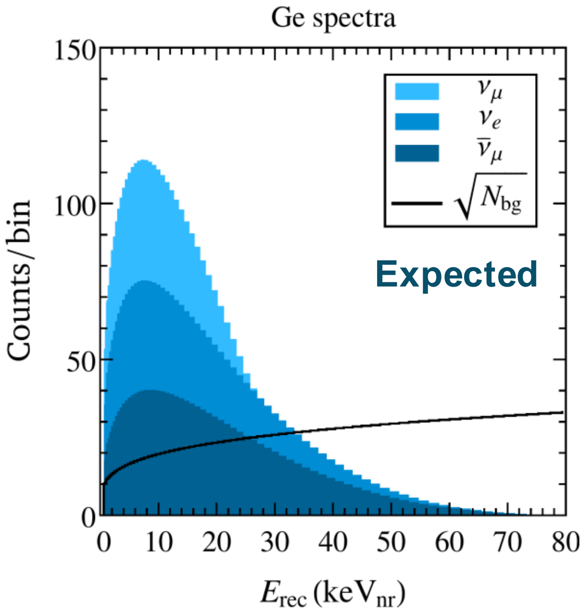


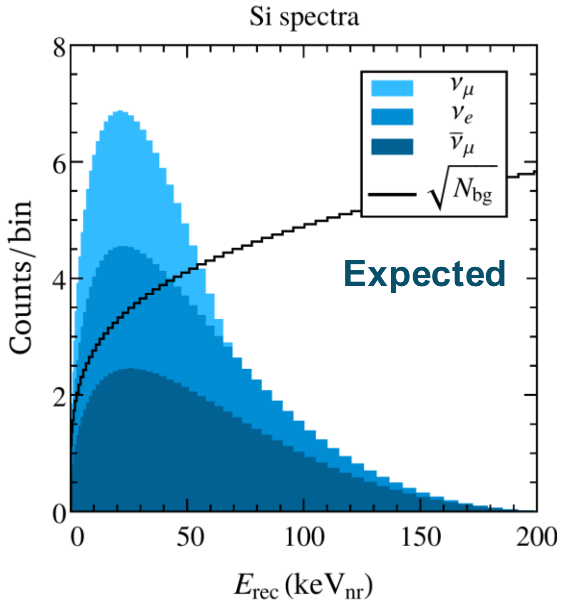
COHERENT Collaboration, arXiv:2602.15652



European Spallation Source







Baxter et all, JHEP 02 (2020) 123

Neutrino phenomenology at SNS

- Generalized Neutrino Interactions (GNI)

Scalar

Pseudo-scalar

$$\mathcal{L}_{\text{GNI}}^{eps} = -\frac{G_F}{\sqrt{2}} \Big\{ \varepsilon_{\alpha\beta}^{qS} \big(\overline{\nu}_\alpha (1-\gamma^5)\nu_\beta\big)\big(\overline{q}q\big) + \varepsilon_{\alpha\beta}^{qP} \big(\overline{\nu}_\alpha (1-\gamma^5)\nu_\beta\big)\big(\overline{q}\gamma^5 q\big)$$
$$+ \tilde{\varepsilon}_{\alpha\beta}^{qS} \big(\overline{\nu}_\alpha (1+\gamma^5)\nu_\beta\big)\big(\overline{q}q\big) + \tilde{\varepsilon}_{\alpha\beta}^{qP} \big(\overline{\nu}_\alpha (1+\gamma^5)\nu_\beta\big)\big(\overline{q}\gamma^5 q\big)$$
$$+ \varepsilon_{\alpha\beta}^{qV} \big(\overline{\nu}_\alpha \gamma^\mu (1-\gamma^5)\nu_\beta\big)\big(\overline{q}\gamma^\mu q\big) + \varepsilon_{\alpha\beta}^{qA} \big(\overline{\nu}_\alpha \gamma^\mu (1-\gamma^5)\nu_\beta\big)\big(\overline{q}\gamma^\mu\gamma^5 q\big)$$
$$+ \tilde{\varepsilon}_{\alpha\beta}^{qV} \big(\overline{\nu}_\alpha \gamma^\mu (1+\gamma^5)\nu_\beta\big)\big(\overline{q}\gamma^\mu q\big) + \tilde{\varepsilon}_{\alpha\beta}^{qA} \big(\overline{\nu}_\alpha \gamma^\mu (1+\gamma^5)\nu_\beta\big)\big(\overline{q}\gamma^\mu\gamma^5 q\big)$$
$$+ \varepsilon_{\alpha\beta}^{qT} \big(\overline{\nu}_\alpha \sigma^{\mu\nu} (1-\gamma^5)\nu_\beta\big)\big(\overline{q}\sigma_{\mu\nu}(1-\gamma^5) q\big)$$
$$+ \tilde{\varepsilon}_{\alpha\beta}^{qT} \big(\overline{\nu}_\alpha \sigma^{\mu\nu} (1+\gamma^5)\nu_\beta\big)\big(\overline{q}\sigma_{\mu\nu}(1+\gamma^5) q\big) \Big\},$$

Vector (SM structure)

Axial

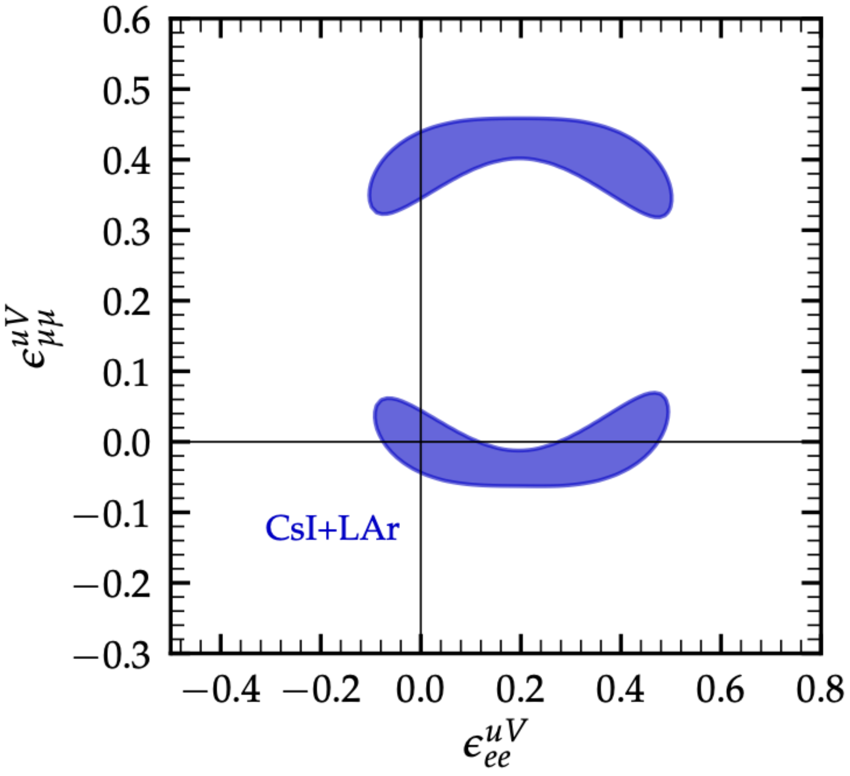
Tensor

Cross section sensitive to GNI parameters

Non-standard Interactions

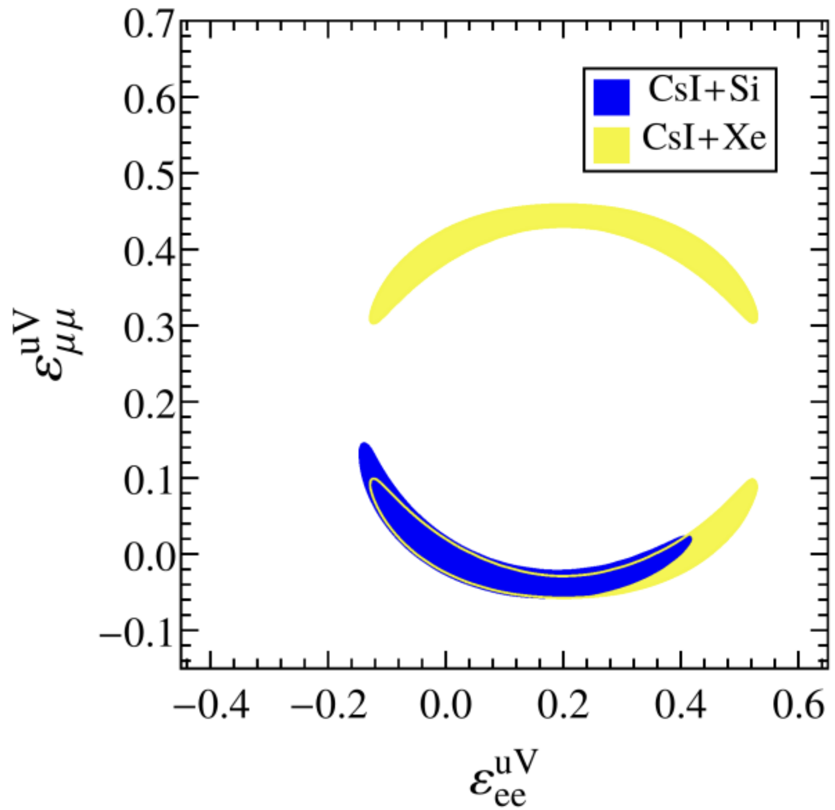
$$\left(Q_{W,\alpha}^{V}\right)^2 = \left[Z\left(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}\right) + N\left(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV}\right)\right]^2 + \sum_{\beta\neq\alpha}\left|Z\left(2\varepsilon_{\alpha\beta}^{uV} + \varepsilon_{\alpha\beta}^{dV}\right) + N\left(\varepsilon_{\alpha\beta}^{uV} + 2\varepsilon_{\alpha\beta}^{dV}\right)\right|^2 .$$

Current COHERENT



V. De Romeri, **GSG**, et al, JHEP 04 (2023) 035

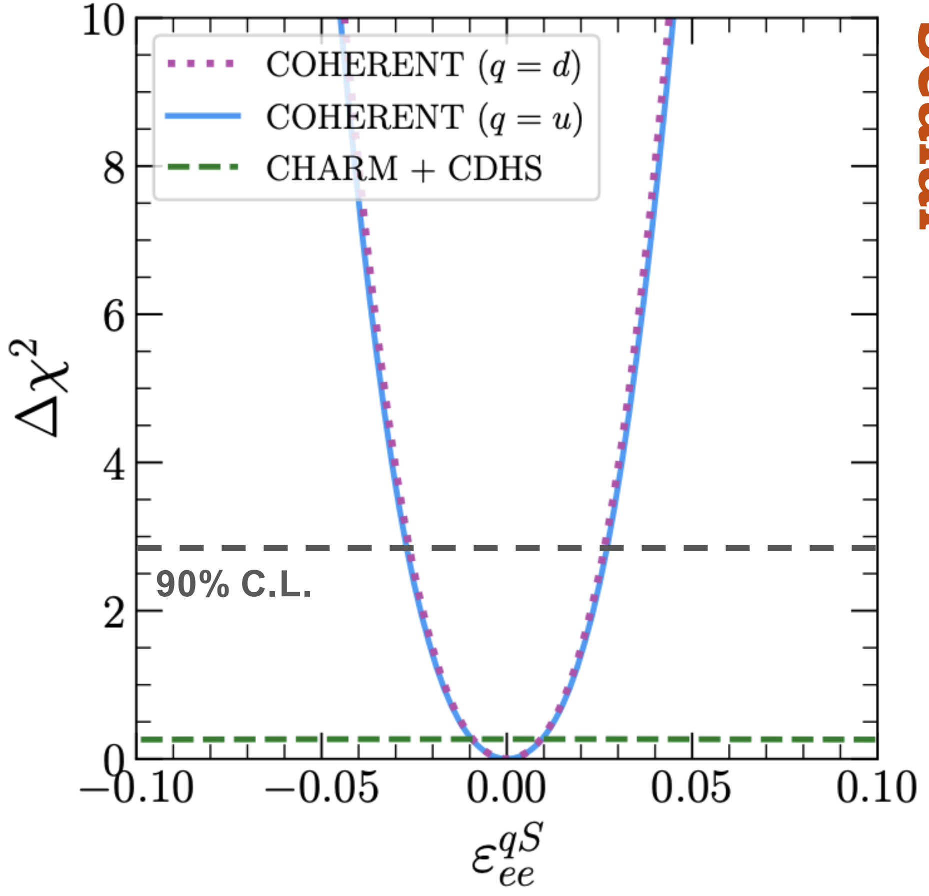
Projected ESS



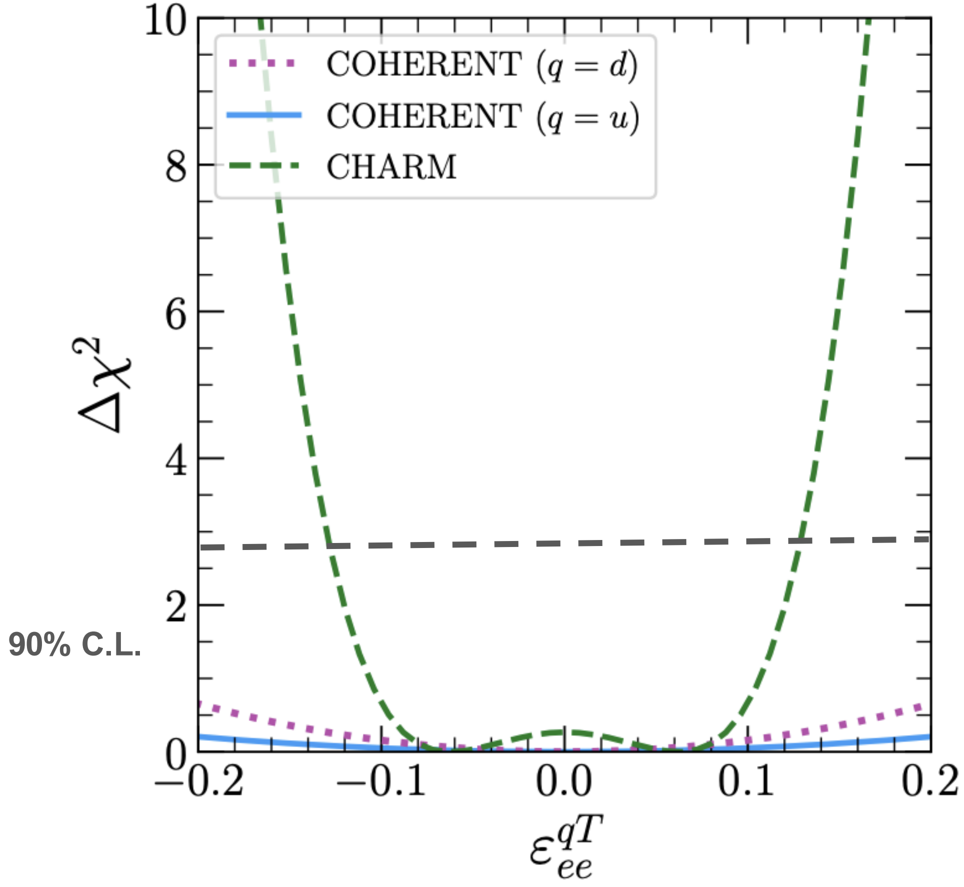
S. Chatterjee, **GSG**, et al, Phys.Rev.D 107 (2023) 5

Generalized Neutrino Interactions

Complementarity with other neutrino experiments like CHARM



Scalar

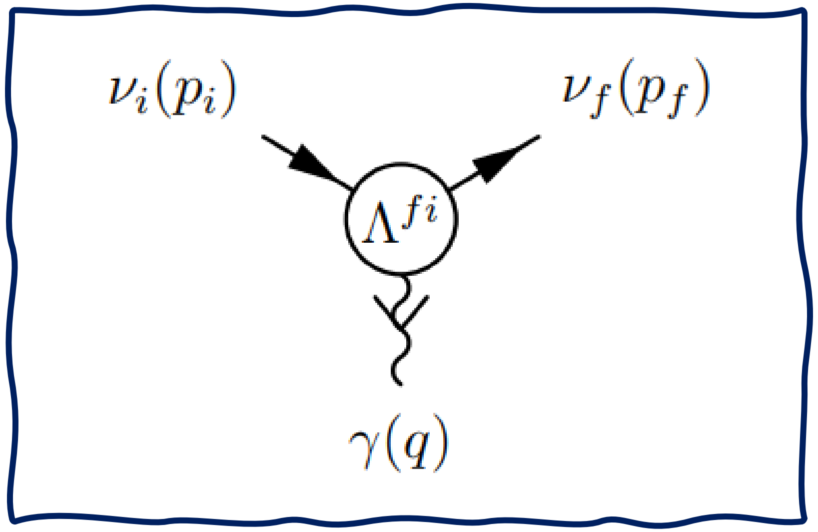


Tensor

L. J. Flores, **GSG**, et al, Phys.Rev.D 113 (2026) 9,

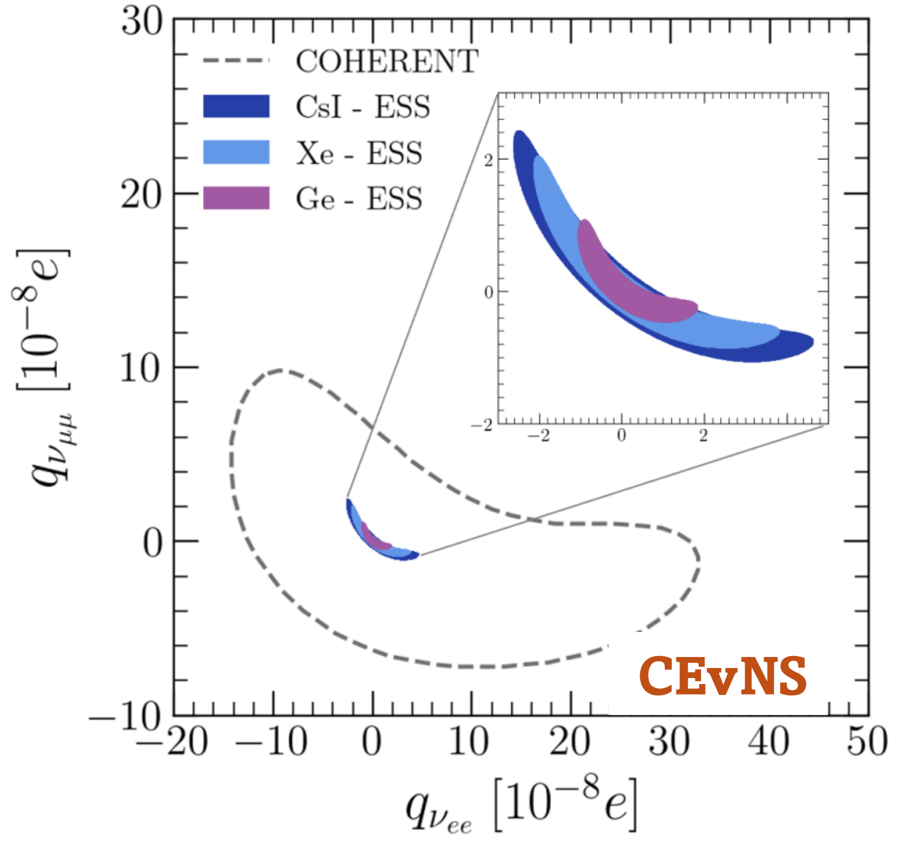
Electromagnetic properties of neutrinos

Massive neutrinos can couple to photons at loop level.



* The structure of the operator depends on mass nature (Dirac vs Majorana).

- Sensitivity to neutrino millicharges.



A. Parada, and **GSG**, Phys.Rev.D 111 (2025) 3

Dark Matter searches at SNS

$\phi \equiv$ Scalar DM.

$A' \equiv$ Dark photon.

Generic dark photon scenario from extra U´(1) symmetry.

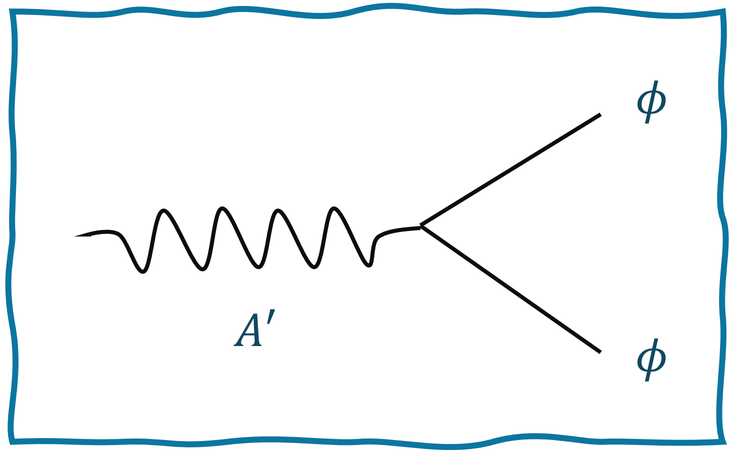
$$\mathcal{L}^{\epsilon}_{A'} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{\epsilon'}{2}F'_{\mu\nu}B^{\mu\nu} - g' j^{Y}_{\mu} B^{\mu} - g_D j'_{\mu} A'^{\mu} + \frac{1}{2}m^2_{A'}A'_{\mu}A'^{\mu} ,$$

$$j'_{\mu} = \phi^* \partial_{\mu}\phi - \phi\partial_{\mu}\phi^*$$

Field redefinition and rotation to the mass eigenstate basis.

$$\mathcal{L}^{\mathrm{M}}_{A'} \supset -\cos\theta_W \, \epsilon' \, e \, j^{\mu}_{\mathrm{EM}} \, A'_{\mu} + g_D j'_{\mu} \, A'^{\mu}$$

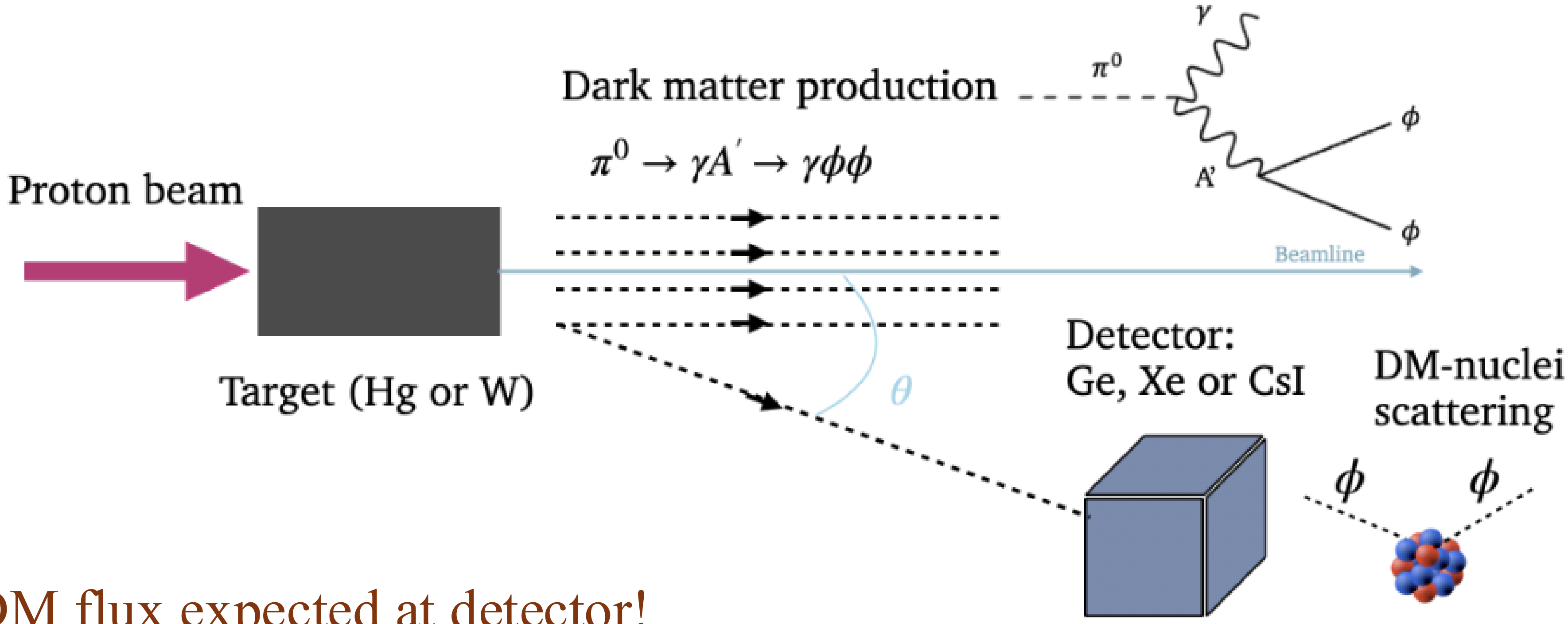
A' production through pion decay



Decay of A' into DM pairs.

Production mechanism at Spallation Sources

- SM picture implies pion decay to two photons
- BSM allows for production of dark photons.

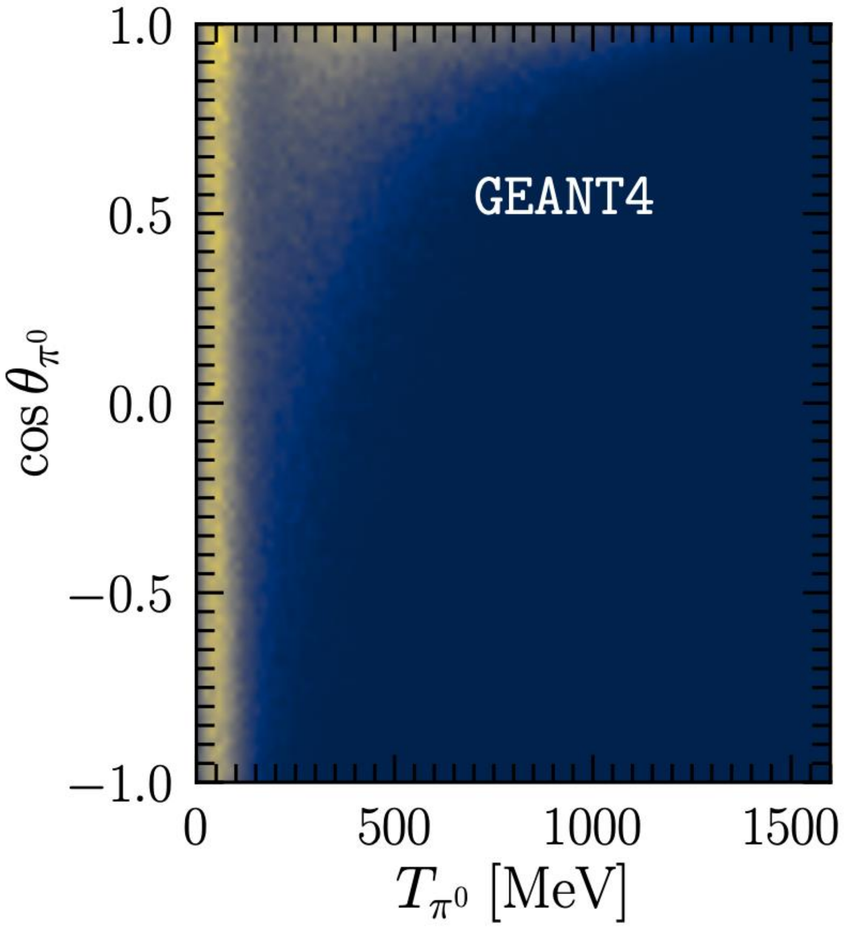


DM flux expected at detector!

Credit: V. De Romeri

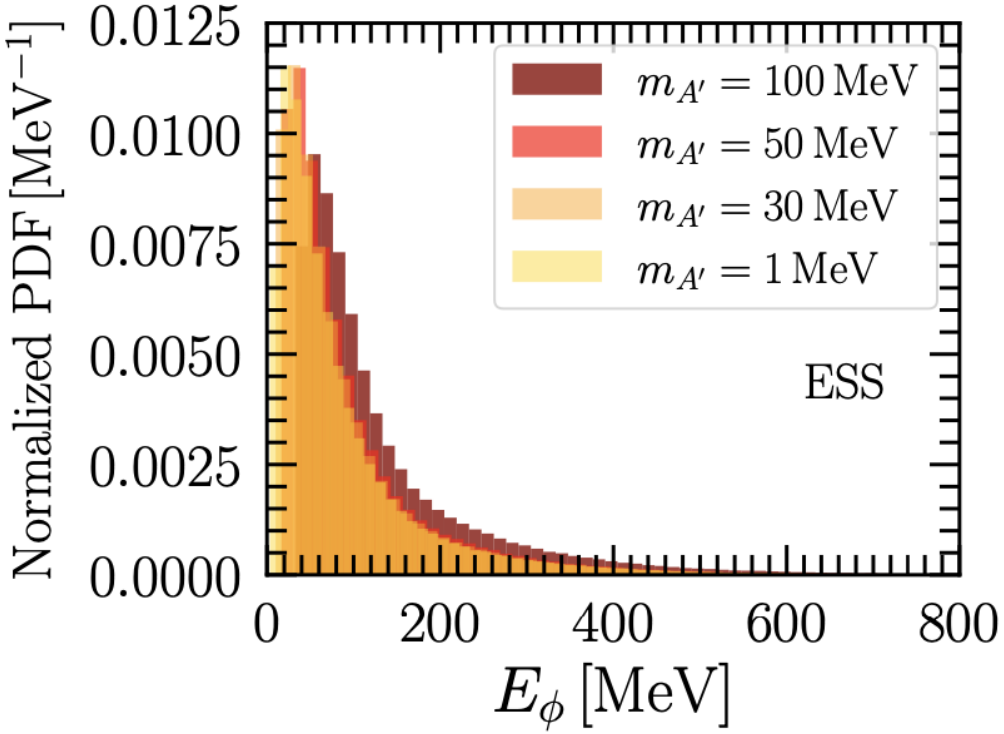
Determination of the pion flux

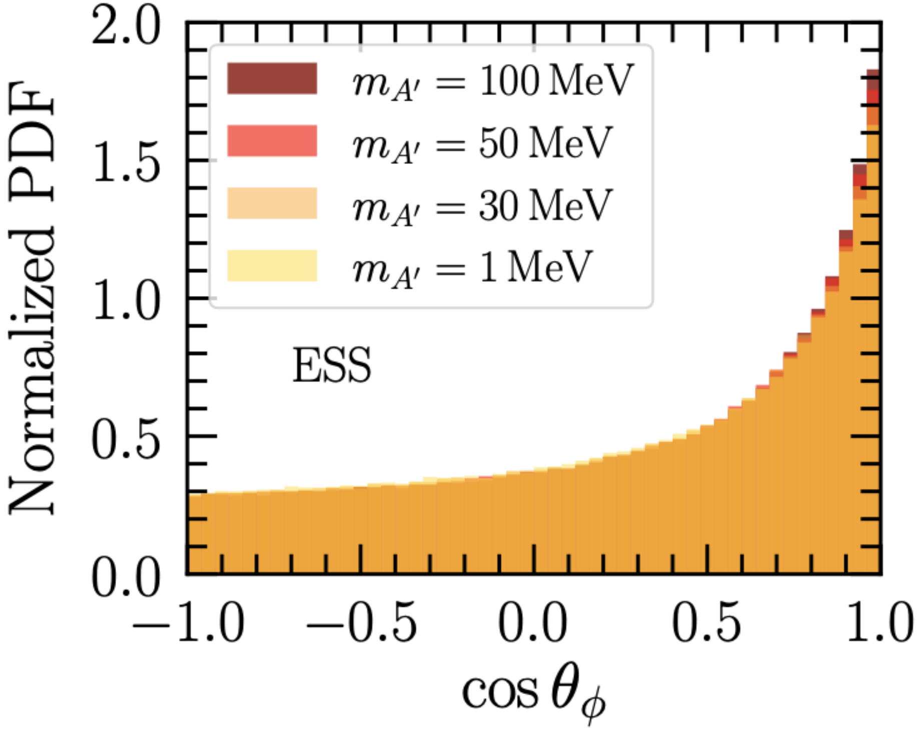
- We use Geant4 simulations.
- Primary and secondary processes taken into account.
- Negligible contribution from eta mesons.
- Agreement with COHERENT collaboration model.



D. Aristizabal Sierra, **GSG,** et al, arXiv:2603.02132

Dark matter flux from pion decay





$$\left.\frac{\mathrm{d}N^\phi}{\mathrm{d}X}\right|^{\mathrm{prod}} = N^{\mathrm{POT}} \times c_{\pi^0} \times 2\,\mathcal{B}(\pi^0 \to \gamma + \phi + \phi^*) \times \left.\frac{\mathrm{d}N^\phi}{\mathrm{d}X}\right|^{\mathrm{norm}=1}$$

D. Aristizabal Sierra, **GSG,** et al, arXiv:2603.02132

Accepted for publication in JHEP

Expected DM signal compared to CEvNS

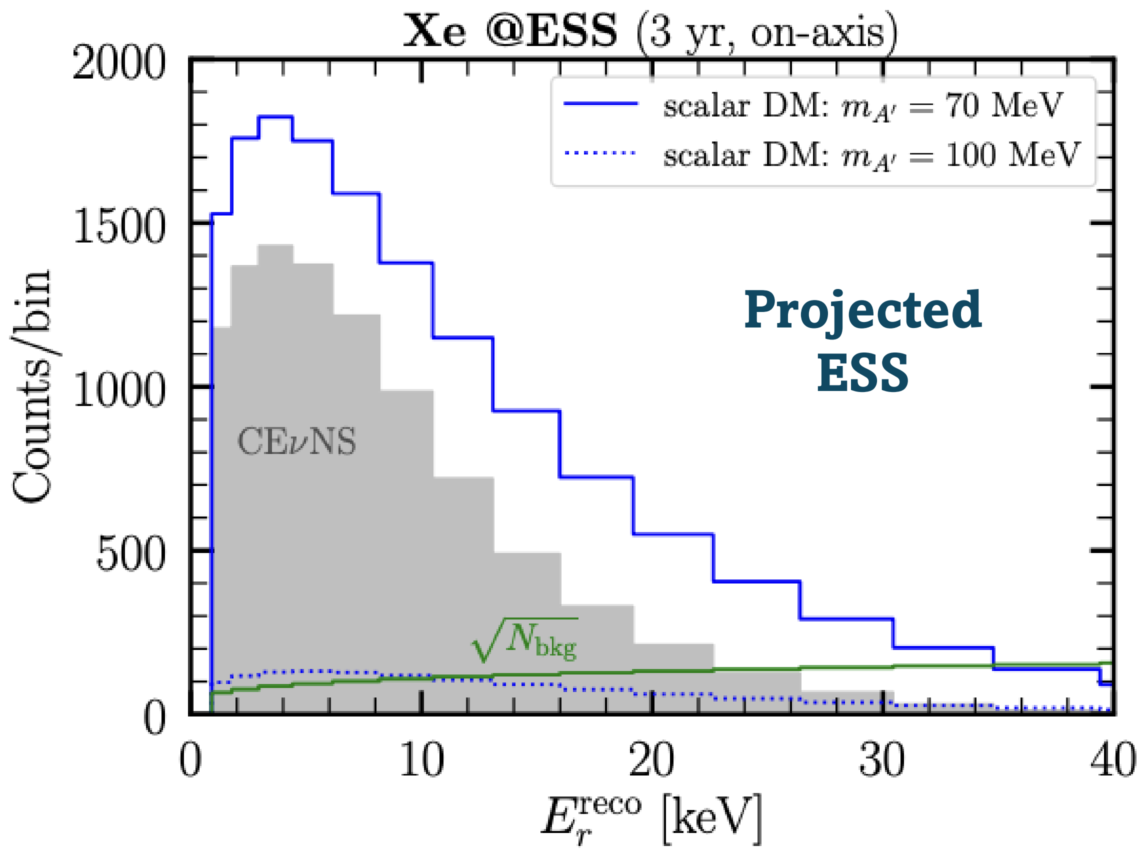
- Total DM production rate.

$$\frac{\mathrm{d}N}{\mathrm{d}E_r} = t_{\mathrm{run}} n_A \langle \ell \rangle \int_{E_\phi^{\mathrm{min}}}^{E_\phi^{\mathrm{max}}} \mathrm{d}E_\phi \left. \frac{\mathrm{d}N^\phi}{\mathrm{d}E_\phi} \right|^{\mathrm{det}} \frac{\mathrm{d}\sigma_{\phi\mathcal{N}}}{\mathrm{d}E_r} ,$$

Cross section proportional to Z^2.

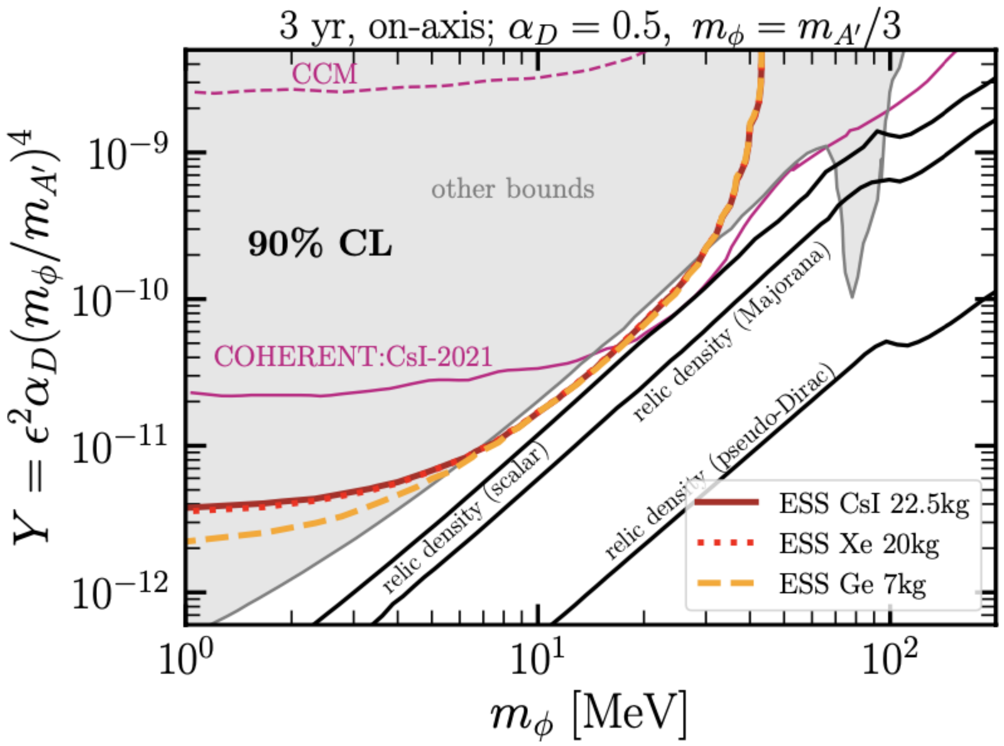
- Total DM arriving to the detector.

$$\left. \frac{\mathrm{d}N^\phi}{\mathrm{d}E_\phi} \right|^{\mathrm{det}} = \left(\frac{N^\phi_{\mathrm{cut}}}{N^\phi_{\mathrm{prod}}} \right) \left(\frac{\Delta\varphi}{2\pi} \right) \left. \frac{\mathrm{d}N^\phi}{\mathrm{d}E_\phi} \right|^{\mathrm{prod}} .$$

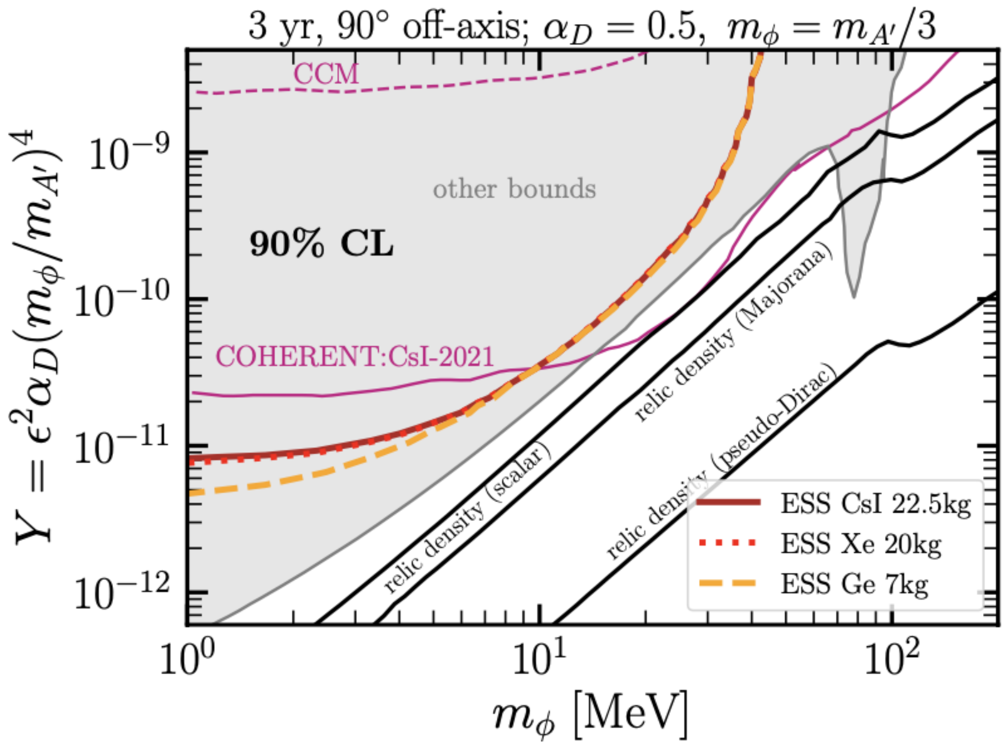


D. Aristizabal Sierra, **GSG,** et al, arXiv:2603.02132

Expected sensitivity at the ESS.



On-Axis

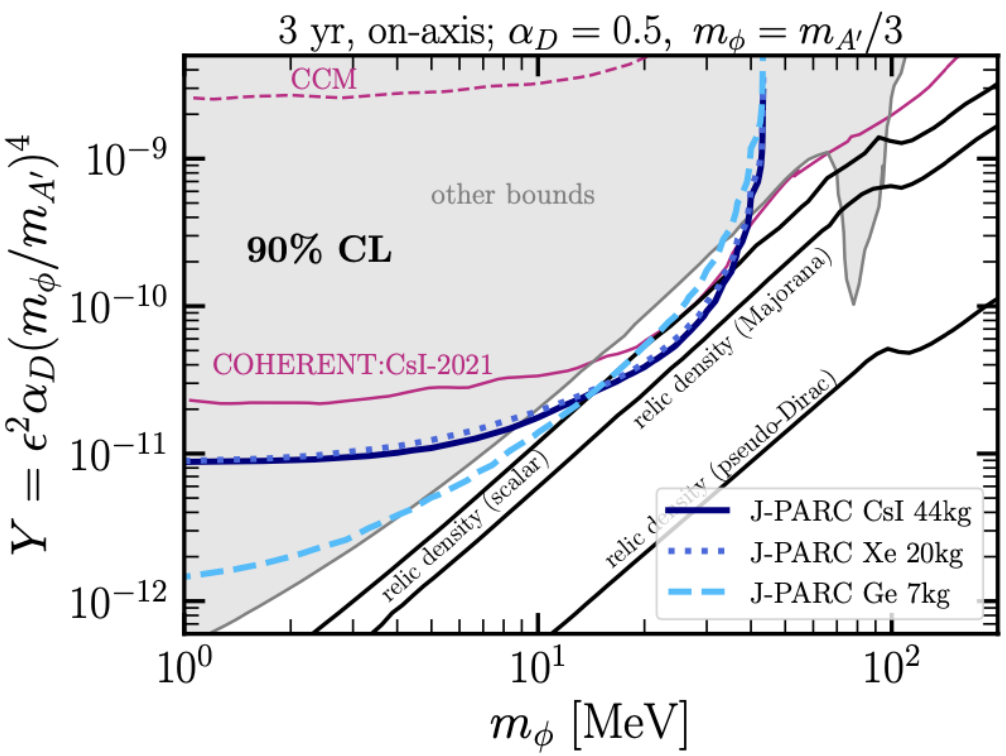


Off-Axis

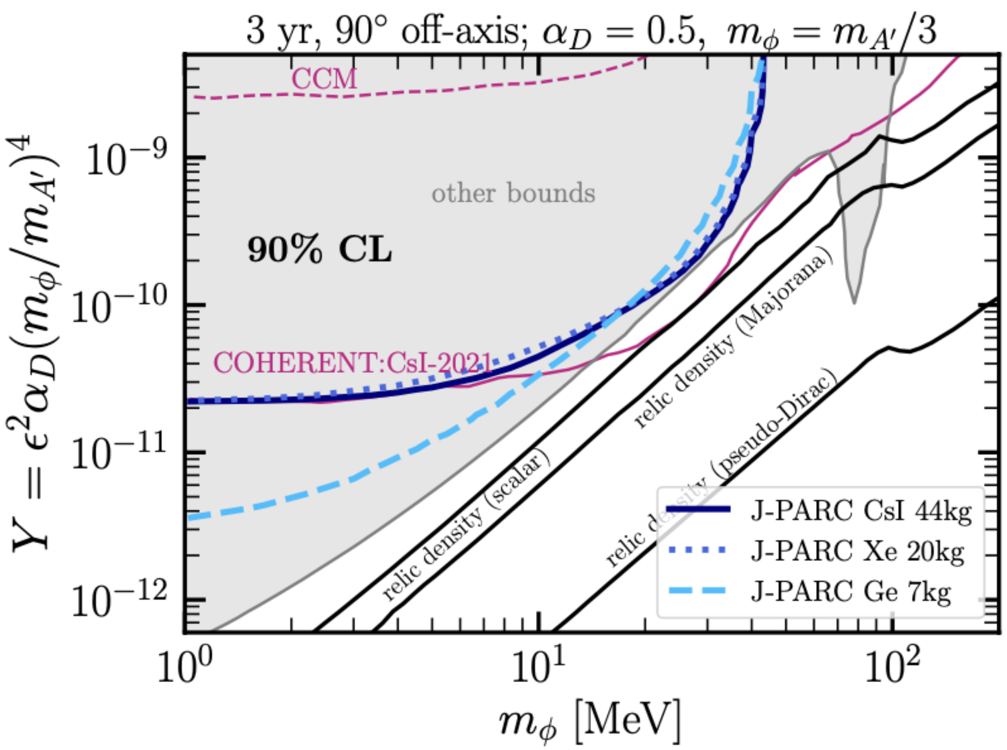
EUROPEAN SPALLATION SOURCE

D. Aristizabal Sierra, **GSG,** et al, arXiv:2603.02132
Accepted for publication in JHEP

Expected sensitivity at J-PARC.



On-Axis



Off-Axis

D. Aristizabal Sierra, **GSG,** et al, arXiv:2603.02132

Accepted for publication in JHEP

Conclusions:

- We can test neutrino properties at fixed target low energy experiments.
- Enhanced sensitivity to NSI, GNI and EM properties.
- We can also study DM properties at neutrino intended experiments.
- Spallation Sources currently play a significant role in the search of physics beyond the SM.

Conclusions:

- We can test neutrino properties at fixed target low energy experiments.
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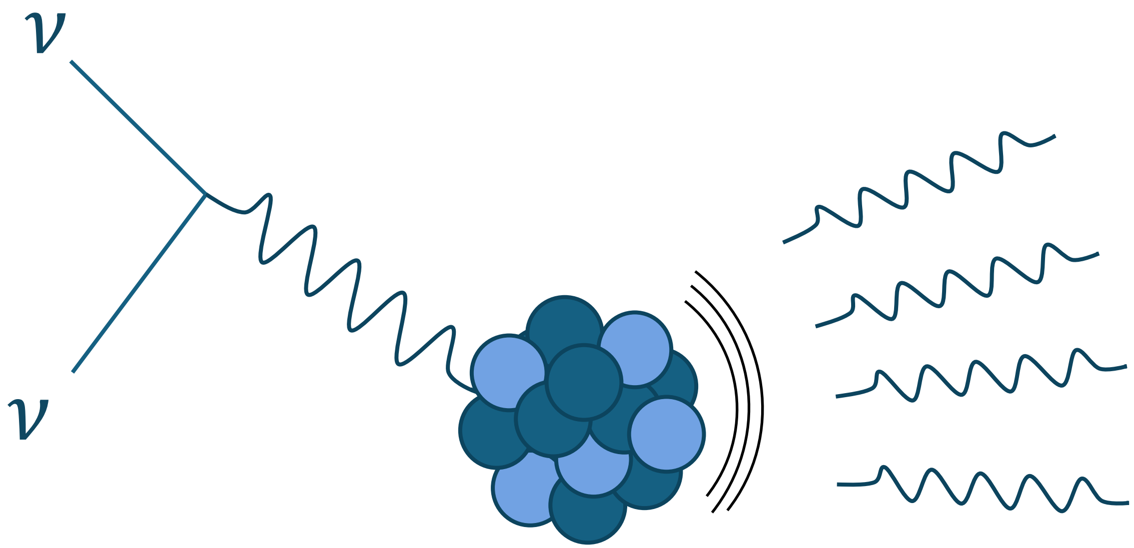
- Spallation Sources currently play a significant role in the search of physics beyond the SM.

Thank you!

Backup



Analysis

Minimization of the function χ^2

$$\chi^2_{\mathrm{CsI}}\Big|_{\mathrm{CE}\nu\mathrm{NS(+ES)}} = 2\sum_{i=1}^{9}\sum_{j=1}^{11}\left[N_{\mathrm{th}}^{\mathrm{CsI}} - N_{ij}^{\mathrm{exp}} + N_{ij}^{\mathrm{exp}}\ln\left(\frac{N_{ij}^{\mathrm{exp}}}{N_{\mathrm{th}}^{\mathrm{CsI}}}\right)\right] + \sum_{k=0}^{4(5)}\left(\frac{\alpha_k}{\sigma_k}\right)^2 .$$

Predicted events

$$N_{i,n}^{\mathrm{CE}\nu\mathrm{NS},\mathcal{N}} = N_{\mathrm{target}}\int_{E_{\mathrm{nr}}^{i}}^{E_{\mathrm{nr}}^{i+1}} dE_{\mathrm{nr}}\,\epsilon_E(E_{\mathrm{nr}})\int_0^{E_{\mathrm{nr}}^{\prime\max}} dE'_{\mathrm{nr}}\,P(E_{\mathrm{nr}},E'_{\mathrm{nr}})\times$$
$$\int_{E_\nu^{\min}(E'_{\mathrm{nr}})}^{E_\nu^{\max}} dE_\nu\,\frac{dN_n}{dE_\nu}(E_\nu)\,\frac{d\sigma_{\nu_\ell\mathcal{N}}}{dE'_{\mathrm{nr}}}\Big|_{\mathrm{CE}\nu\mathrm{NS}}(E_\nu,E'_{\mathrm{nr}}),$$

CEvNS experiments around the world

SNS

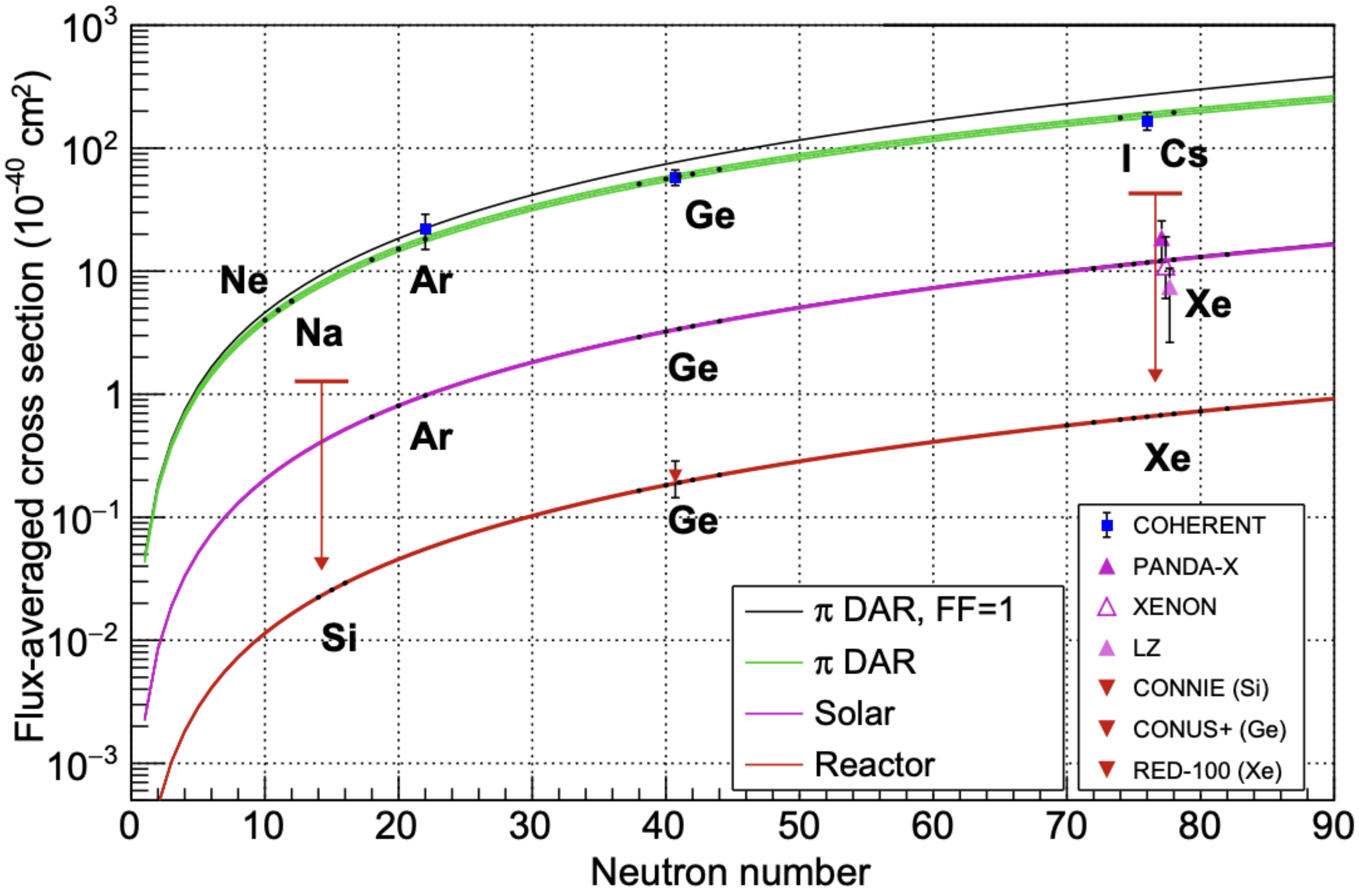
- ❑ Hasta 52 MeV.

Solar neutrinos

- ❑ Hasta 15 MeV.

Reactors

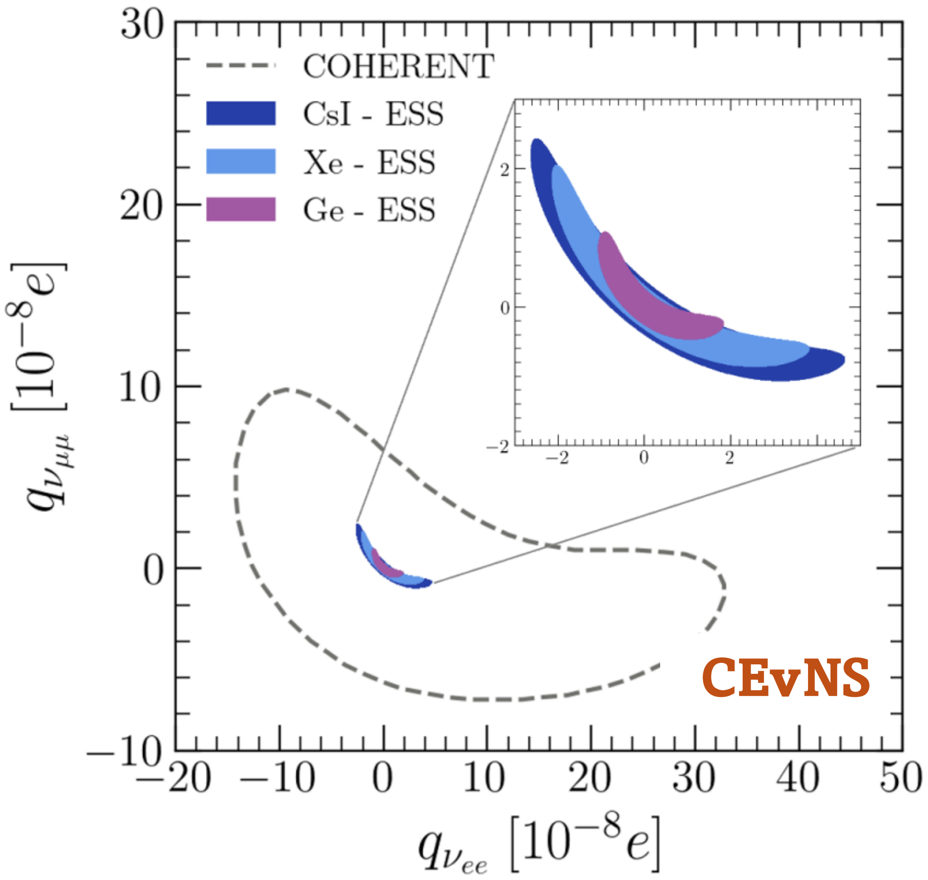
- ❑ Hasta 10 MeV.



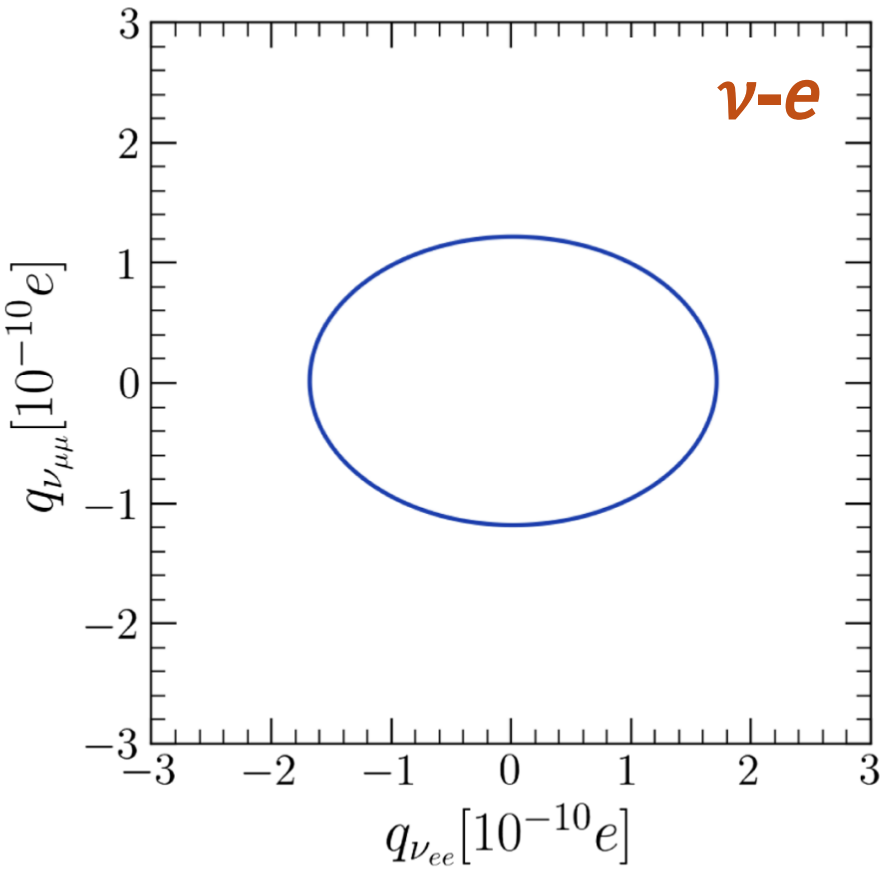
M. Adhikari et al, arXiv: 2602.15652

Sensitivity to neutrino millicharges

Parameter space consistent with experimental measurement



A. Parada and **GSG,** Phys.Rev.D 111 (2025) 3



A. Parada and **GSG,** Phys.Rev.D 111 (2025) 3