# Probing neutrino and nuclear physics with CEvNS

廖佳军

中山大学

第一届中微子散射：理论、实验、唯象研讨会

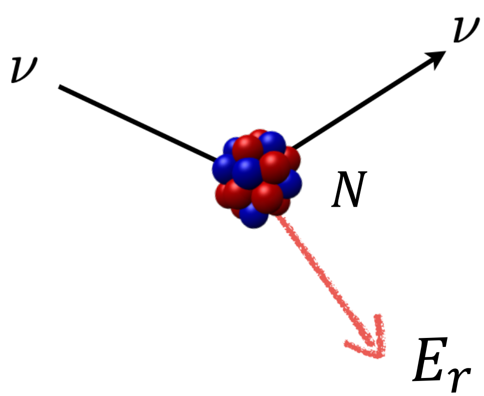
杭州，5/19/2024

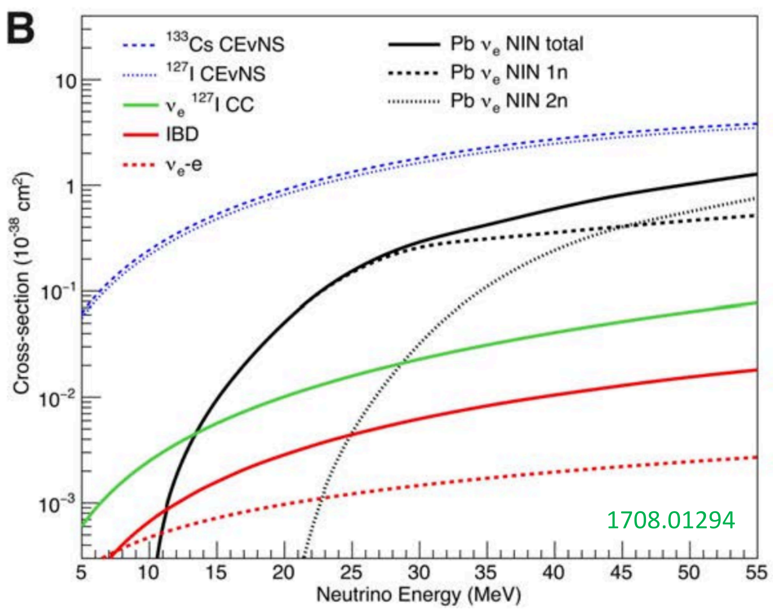
# Outline

- Introduction to CEvNS
- CEvNS as probe of neutrino physics
- CEvNS as probe of nuclear physics
- Summary

# Introduction to CEvNS

# Coherent Elastic $\nu$-Nucleus Scattering




$$\frac{d\sigma}{dE_r} = \frac{G_F^2 m_N}{4\pi}\left(1 - \frac{E_r m_N}{2E_\nu^2}\right) Q_{SM}^2 F(q^2)^2$$

SM weak charge: $Q_{SM}^2 = \left(Z g_p^V + N g_n^V\right)^2$

$$g_p^V = \frac{1}{2} - 2\sin^2\theta_W \sim 0.03$$

$$g_n^V = -0.5$$

$\Rightarrow$ $\sigma_{SM} \propto N^2$

Moment transfer $\longrightarrow$ $q = \sqrt{2ME_r} \lesssim 1/R$ $\longleftarrow$ Nuclear radius

Satisfied for $E_\nu < 50$ MeV, Nuclear recoil energy $E_r \leq \frac{2E_\nu^2}{M+2E_\nu} \sim O(10)$ keV

# From neutrino to DM

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.

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

## Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky
*Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany*
(Received 21 November 1983)

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true "neutrino observatory." The recoil energy which must be detected is very small ($10$—$10^3$ eV), however. We examine a

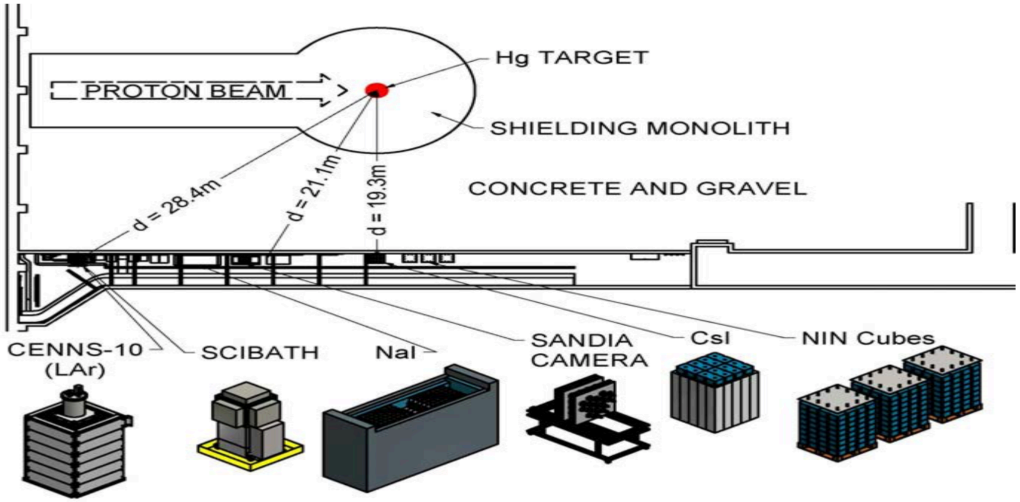
PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

## Detectability of certain dark-matter candidates

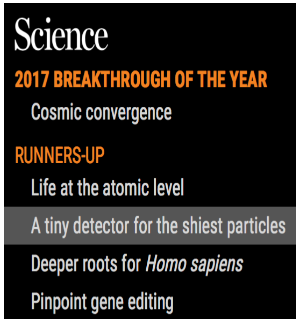
Mark W. Goodman and Edward Witten
*Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544*
(Received 7 January 1985)

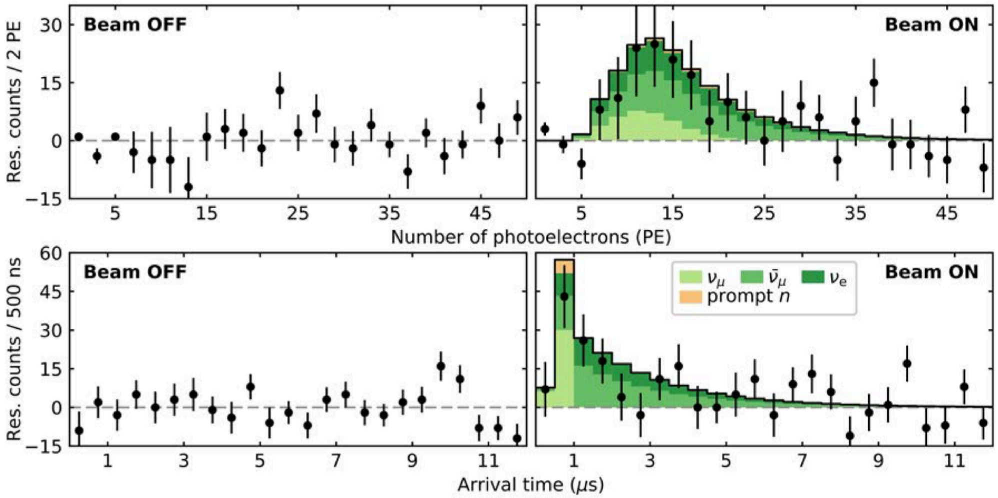
We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1$—$10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1$—$10^2$ GeV; or strongly interacting particles of masses $1$—$10^{13}$ GeV.

# COHERENT







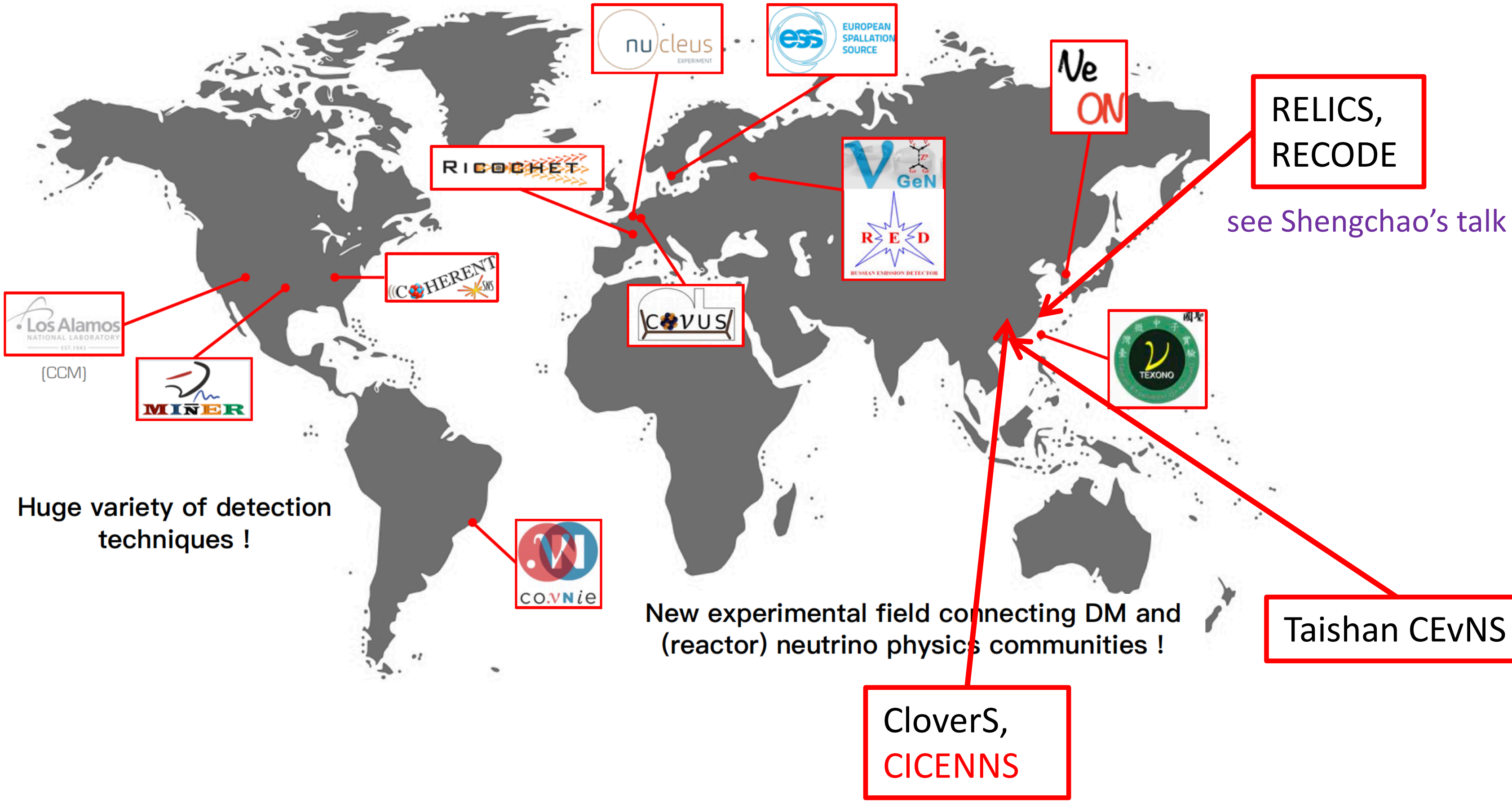

$134 \pm 22$ observed

$173 \pm 48$ predicted in SM

6.7σ CL evidence for CEvNS

COHERENT Collaboration, Science [1708.01294]

# Global efforts



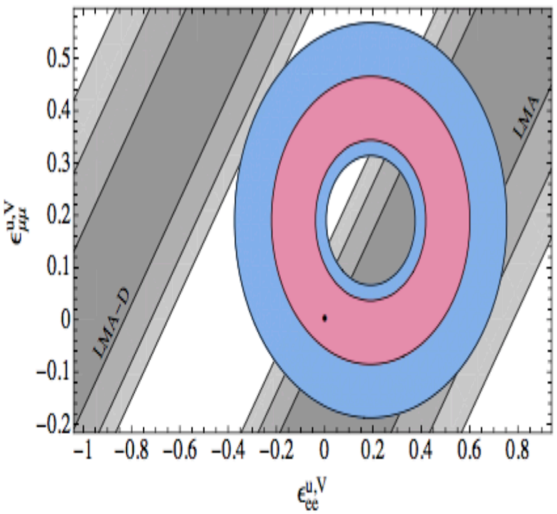

Modified from Matthieu VIVIER@Magnificent CEvNS workshop 2020

# Physics potential

- **EW precision tests:** weak mixing angle, electroweak charges;
- **Neutrino physics:** neutrino magnetic moment, charge radius, sterile neutrinos,
- **New interactions:** nonstandard interactions, light mediators, generalized interactions; light dark matter;
- **Nuclear Physics:** neutron radius, quenching factor, reactor neutrino flux;
- **Astroparticle physics:** supernova, solar, atmospheric neutrinos, DSNB;…

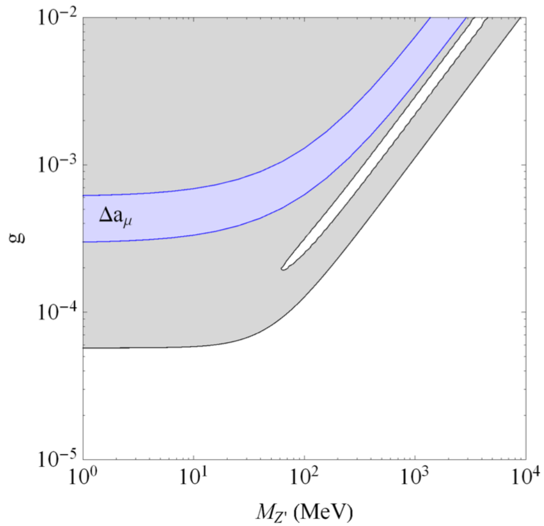

E. Lisi, Neutrino 2018

## Nonstandard interactions



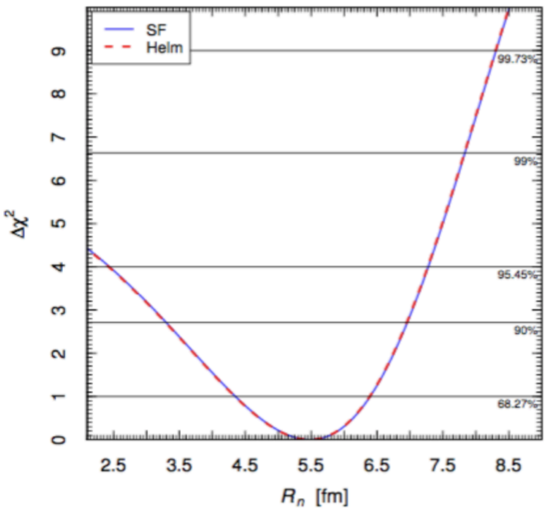

Coloma, et.al., PRD [1708.02899 ]

## Light mediators



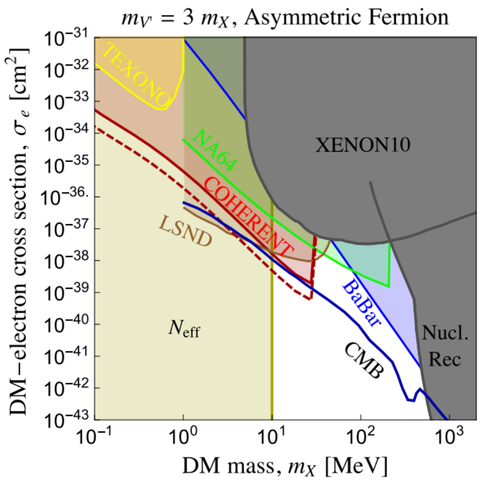

**JL**, Marfatia, PLB [1708.04255]

## Neutron radius



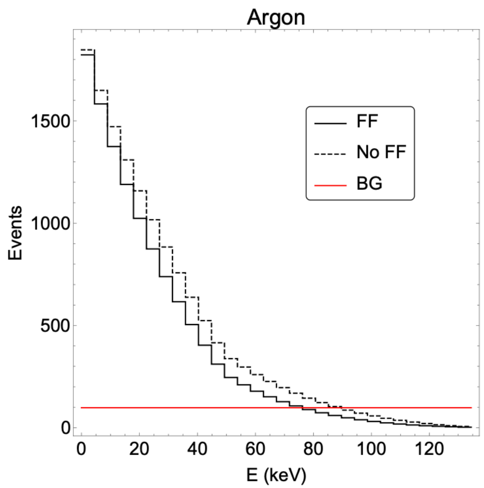

Cadeddu, Giunti, Li, Zhang PRL[1710.02730]

## Photon Portal DM



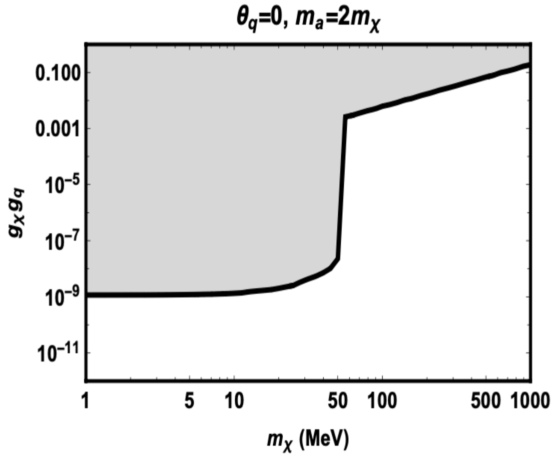

Ge, Shoemaker, PRD [1710.10889 ]

## Nuclear form factor




Ciuffoli, Evslin, Fu, Tang , PRD [1801.02166 ]

## DM Loop contribution




Li, **JL**, JHEP [2008.00743]

# Current data

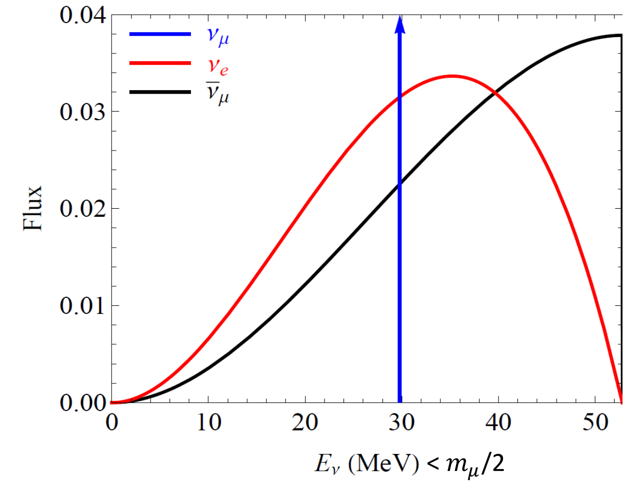
## ❖ $\pi$DAR source @ SNS

COHERENT first observed CE$\nu$NS in 2017 at the 6.7σ CL with a CsI detector

COHERENT, Science 357,1123 (2017);
COHERENT, PRL 129, 081801 (2022)

Later confirmed in 2020 at more than 3σ CL with LAr detector

COHERENT, PRL 126, 012002 (2021)




## ❖ Reactor neutrino source

CONNIE uses a Si detector with 0.1 $\mathrm{keV}_{ee}$ threshold

CONNIE, PRD 100, 092005 (2019)

CONUS uses a Ge detector with 0.3 $\mathrm{keV}_{ee}$ threshold

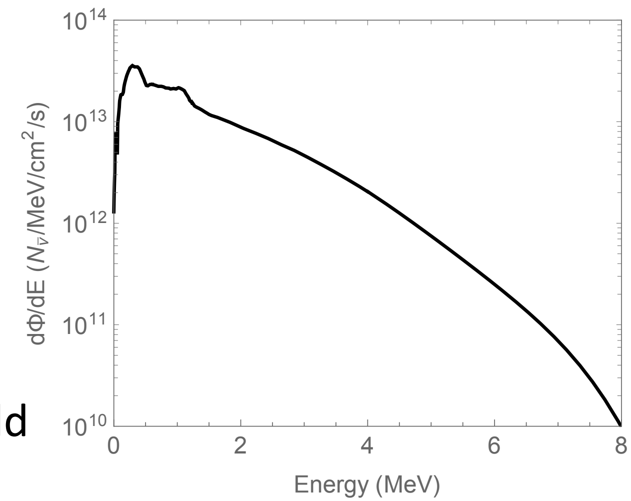
CONNIE, PRL 126, 041804 (2021)

**$\nu$**GeN uses a Ge detector with 0.3 $\mathrm{keV}_{ee}$ threshold

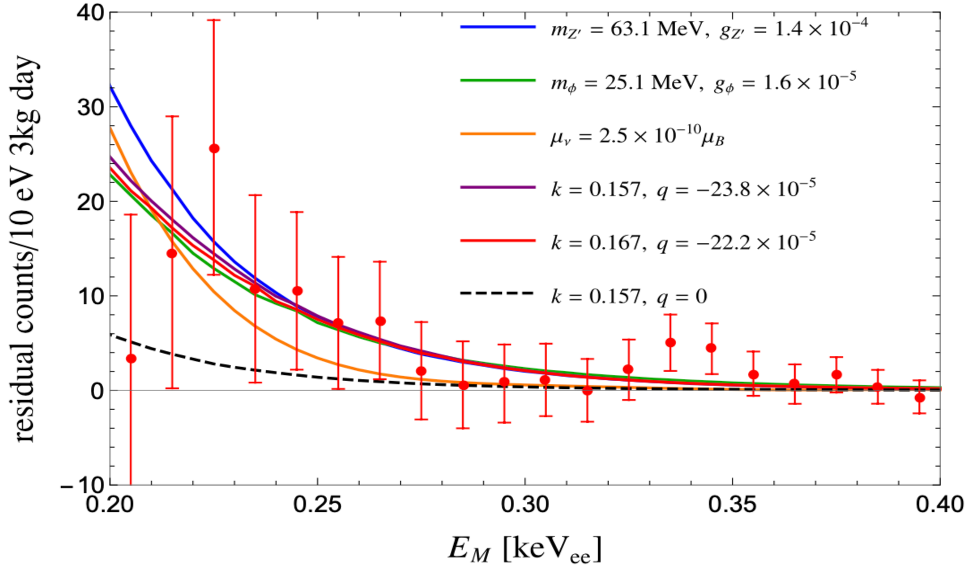
**$\nu$**GeN, PRD 106, L051101 (2022)

Dresden-II uses a Ge detector with 0.2 $\mathrm{keV}_{ee}$ threshold

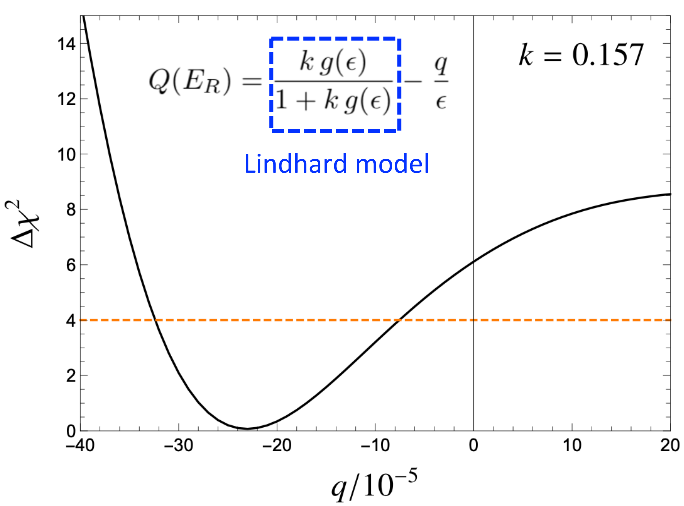
Colaresi at al. , PRL 129, 211802 (2022)

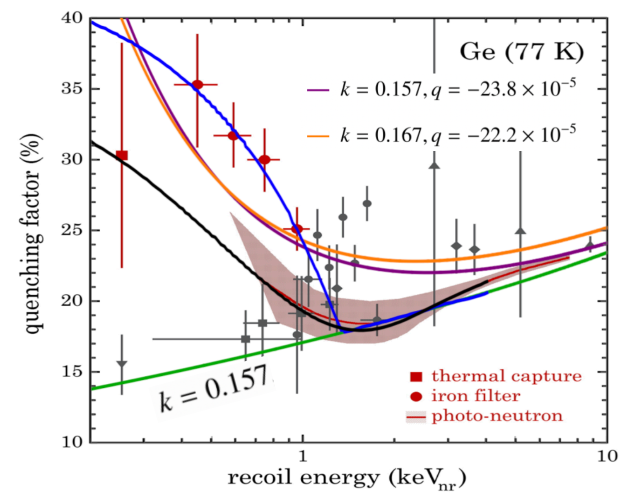


# Quenching factor ambiguity




**JL**, Liu, Marfatia, PRD 106, L031702 (2022) [arXiv: 2202.10622]




Collar, et al, PRD 103, 122003 (2021）

# CEvNS as a probe of neutrino physics

# Test of neutrino mass models

$$\mathbf{A_1}: \begin{pmatrix} 0 & 0 & \times \\ 0 & \times & \times \\ \times & \times & \times \end{pmatrix}, \quad \mathbf{B_1}: \begin{pmatrix} \times & \times & 0 \\ \times & 0 & \times \\ 0 & \times & \times \end{pmatrix}, \quad \mathbf{B_2}: \begin{pmatrix} \times & 0 & \times \\ 0 & \times & \times \\ \times & \times & 0 \end{pmatrix},$$

$$\mathbf{A_2}: \begin{pmatrix} 0 & \times & 0 \\ \times & \times & \times \\ 0 & \times & \times \end{pmatrix}; \quad \mathbf{B_3}: \begin{pmatrix} \times & 0 & \times \\ 0 & 0 & \times \\ \times & \times & \times \end{pmatrix}, \quad \mathbf{B_4}: \begin{pmatrix} \times & \times & 0 \\ \times & \times & \times \\ 0 & \times & 0 \end{pmatrix}; \quad \mathbf{C}: \begin{pmatrix} \times & \times & \times \\ \times & 0 & \times \\ \times & \times & 0 \end{pmatrix};$$

Frampton, Glashow, Marfatia, PLB[0201008]; Xing, PLB[0201151]; Fritzsch, Xing, Zhou, JHEP [1108.4543]

$$-\mathcal{L}_Y^\nu = y_{ij}^D \overline{l_i}_L \tilde{H} \nu_{Rj} + \frac{1}{2} M_{ij} \overline{\nu_{Ri}^C} \nu_{Rj} + \frac{1}{2} y_{ij,m}^M \overline{\nu_{Ri}^C} \nu_{Rj} \Phi_m + h.c. \; ,$$

The most general anomaly-free U(1)' model satisfy

$$3(Q'_1 + Q'_2 + Q'_3) + Q'_e + Q'_\mu + Q'_\tau = 0$$

Kownacki, Ma, Pollard, Zakeri, PLB[1611.05017] ]

To avoid FCNC in the quark sector

$$B - \sum_\alpha x_\alpha L_\alpha \quad \text{with} \quad \sum_\alpha x_\alpha = 3$$

Take $B - L_e - 3L_\mu + L_\tau$ for example

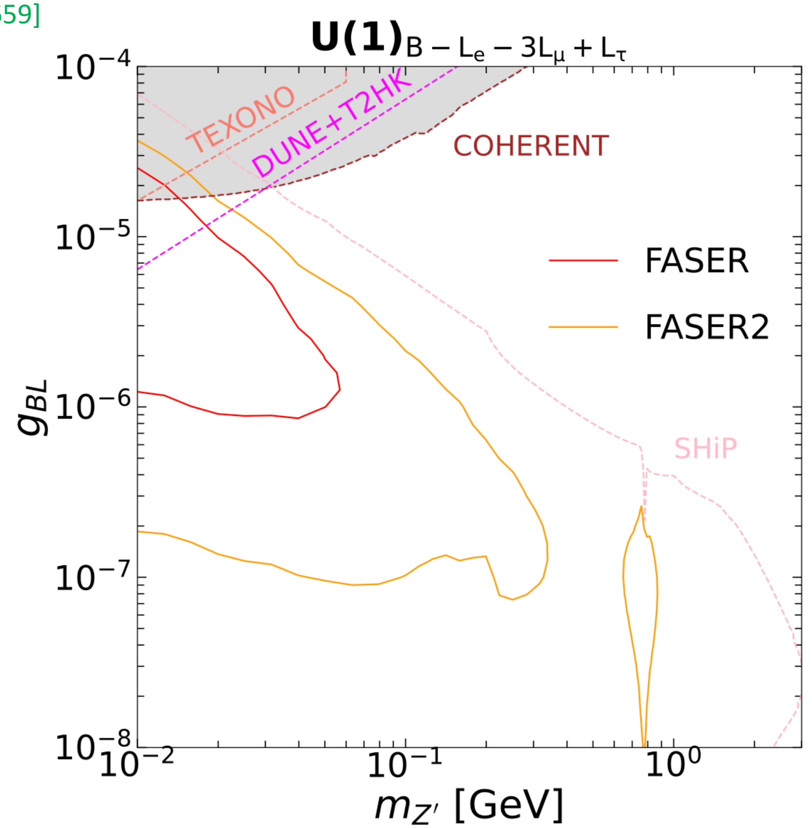
Araki, Heeck and Kubo, JHEP [1203.4951];
**JL**, Marfatia, Whisnant, PRD [1306.4659]

$$Y'(\overline{\nu_{Ri}^C}\nu_{Rj}) = \begin{bmatrix} -2 & -4 & 0 \\ \cdot & -6 & -2 \\ \cdot & \cdot & 2 \end{bmatrix}$$ choose $|Y'(\Phi_m)| = 2$

$$M_R = M_{B-L_e-3L_\mu+L_\tau} \begin{bmatrix} 0 & 0 & \times \\ \cdot & 0 & 0 \\ \cdot & \cdot & 0 \end{bmatrix} + \langle \Phi_m \rangle \begin{bmatrix} \times & 0 & 0 \\ \cdot & 0 & \times \\ \cdot & \cdot & \times \end{bmatrix}$$

$$\sim \begin{bmatrix} \times & 0 & \times \\ \cdot & 0 & \times \\ \cdot & \cdot & \times \end{bmatrix}$$

$$m_\nu = -M_D M_R^{-1} M_D^T \sim \begin{bmatrix} \times & \times & 0 \\ \cdot & \times & \times \\ \cdot & \cdot & 0 \end{bmatrix} \qquad (B_4)$$



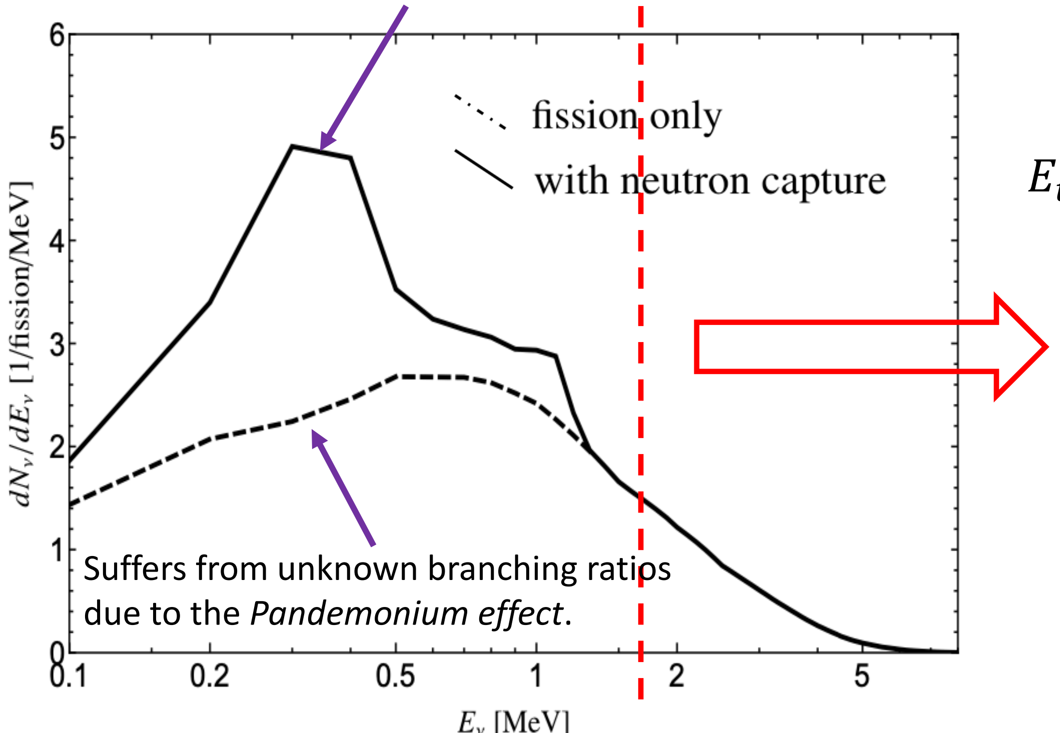

Felkl, Li, **JL**, Schmidt, JHEP [2306.09569]

# Reactor neutrino flux

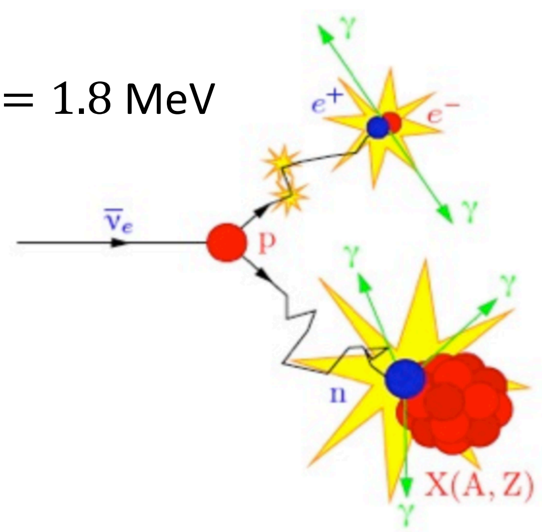
| Channels | Fractional Compositions by Mass (%) | Relative Rates per Fission | Neutrino Yield per Event | Neutrino Yield per Fission |
|---|---|---|---|---|
| $^{235}$U Fission | 1.5 | 0.55 | 6.14 | 3.4 |
| $^{238}$U Fission | 98.0 | 0.07 | 7.08 | 0.5 |
| $^{239}$Pu Fission | 0.4 | 0.32 | 5.58 | 1.8 |
| $^{241}$Pu Fission | <0.1 | 0.06 | 6.42 | 0.4 |
| $^{238}$U (n,$\gamma$) $^{239}$U | – | 0.60 | 2.00 | 1.2 |

TEXONO, hep-ex/0605006

$$^{238}\mathrm{U} + \mathrm{n} \rightarrow {}^{239}\mathrm{U} \xrightarrow{\beta} {}^{239}\mathrm{Np} \xrightarrow{\beta} {}^{239}\mathrm{Pu}$$




$E_{th} = 1.8$ MeV




Inverse beta decay

# NUCLEUS experiment

- NUCLEUS uses cryogenic detectors and has achieved a 20 eV threshold using a 0.5 g prototype made from $Al_2O_3$.

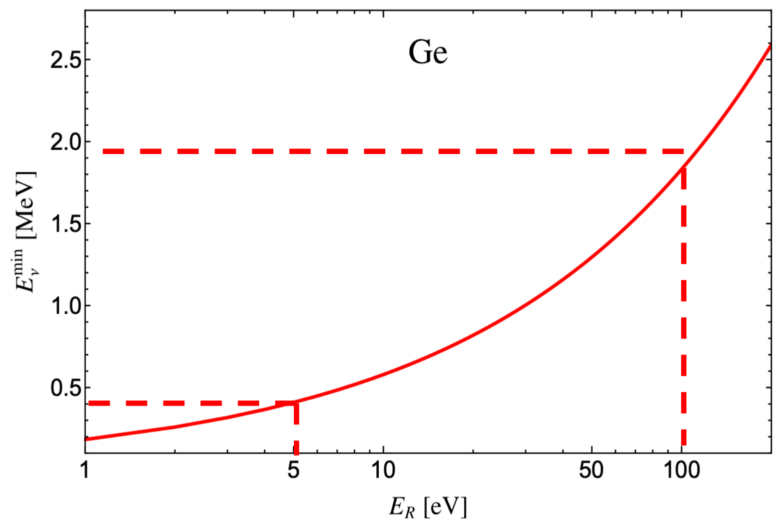
EPJC 77, 506 (2017) [1704.04320]

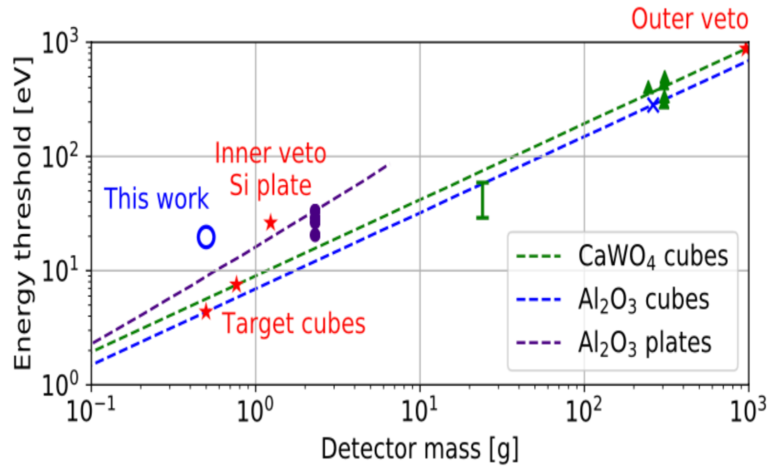
- A total 10 g mass of $CaWO_4$ and $Al_2O_3$ crystals, and 1 kg of Ge is planned.

- NUCLEUS-1kg is expected to have a background below 100 ckkd and an ultra low energy threshold of 5 eV.

EPJC 79, 1018 (2019) [1905.10258]

JL, Liu, Marfatia, PRD[2302.10460]



# Normal unfolding

CEvNS spectrum:

$$\mu_j = R_{ji}\nu_i + h_j + b_j$$

Response matrix

$$R_{ji} \equiv \frac{tN_T P}{4\pi \tilde{d}_{\rm eff}^2 \epsilon} \int_{E_R^j}^{E_R^{j+1}} dE_R \int_{E_\nu^i}^{E_\nu^{i+1}} dE_\nu \frac{d\sigma}{dE_R}$$

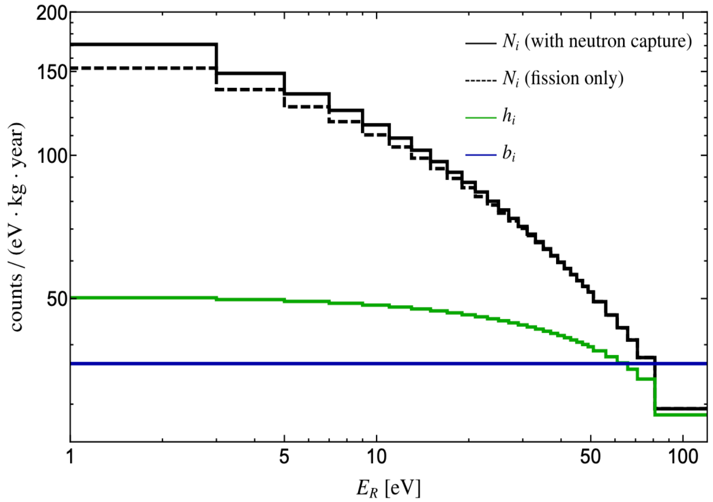
Neutrino flux:

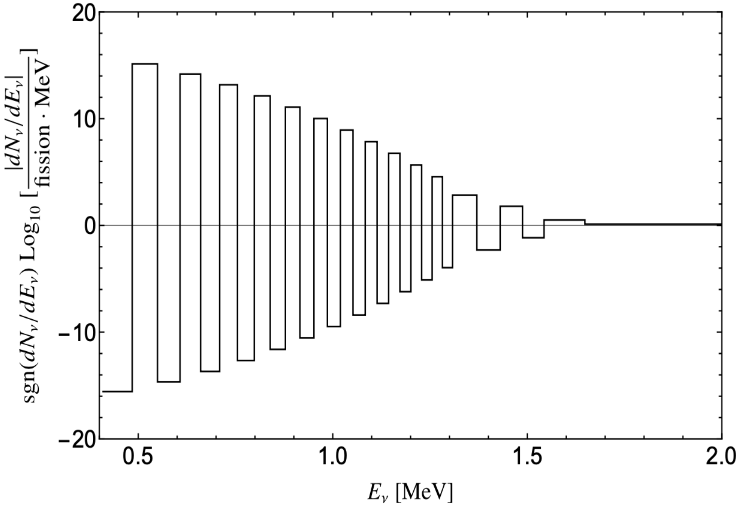
$$\boldsymbol{\nu} = \boldsymbol{R}^{-1}(\boldsymbol{\mu} - \boldsymbol{h} - \boldsymbol{b})$$

Statistical fluctuations in observed spectrum

$$n_i = \text{Poisson}(N_i + b_i)$$

Equal to minimize: $\chi^2(\boldsymbol{\nu}) = \sum_{i=1}^{m} \frac{(\mu_i(\boldsymbol{\nu}) - n_i)^2}{n_i}$




**JL**, Liu, Marfatia, PRD[2302.10460]

# Regularized unfolding

Tikhonov regularization: $$\varphi(\boldsymbol{\nu}) = \chi^2(\boldsymbol{\nu}) + \beta S(\boldsymbol{\nu})$$

$$S(\boldsymbol{\nu}) = \sum_{i=1}^{m-2} (-\nu_i + 2\nu_{i+1} - \nu_{i+2})^2 = G_{ij}\nu_i\nu_j$$

- The neutrino flux is obtained by minimizing the regularized function ϕ

$$\frac{\partial\varphi(\boldsymbol{\nu})}{\partial\nu_i} = D_{ij}\nu_j - K_j = 0\,, \quad i = 1, 2, \ldots m$$

Estimated neutrino flux: $$\hat{\boldsymbol{\nu}} = \boldsymbol{D}^{-1}\boldsymbol{K}$$

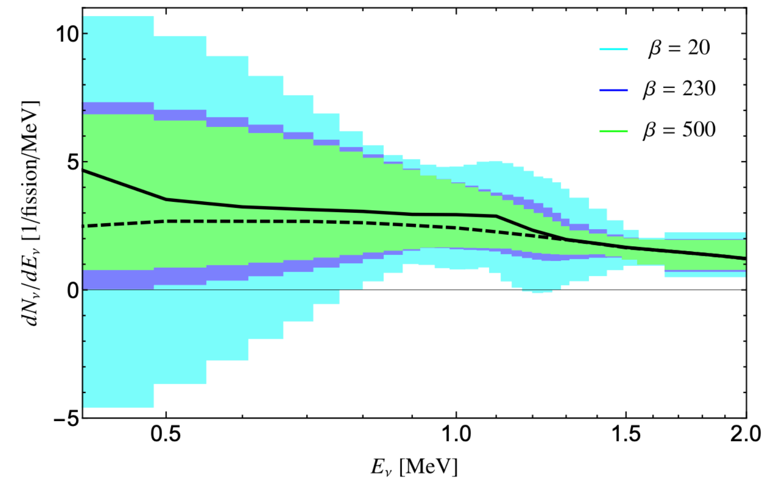
Estimated CEvNS spectrum: $$\hat{\boldsymbol{\mu}}(\beta, \boldsymbol{n}) = \boldsymbol{R}\hat{\boldsymbol{\nu}}(\beta, \boldsymbol{n}) + \boldsymbol{h} + \boldsymbol{b}$$

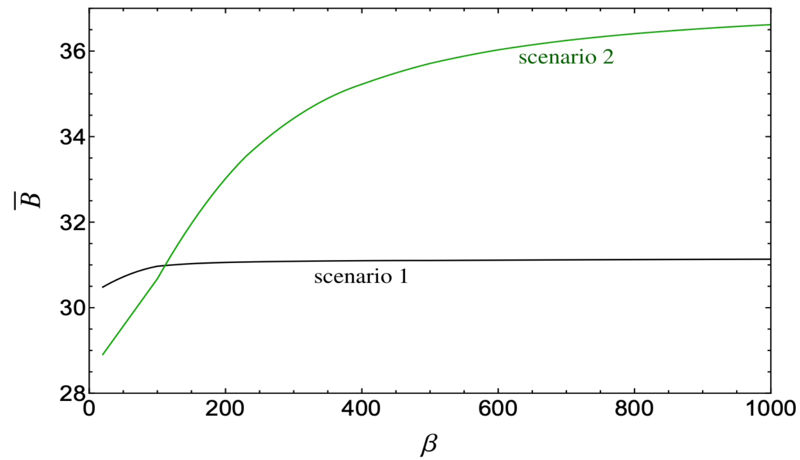
Bias: $$B = \sum_{i=1}^{m} \frac{\hat{b}_i^2}{W_{ii}} \qquad \hat{b}_i = \sum_j^m C_{ij}(\hat{\mu}_j - n_j)$$

Covariance matrix: $$\boldsymbol{W} = (\boldsymbol{CRC} - \boldsymbol{C})\boldsymbol{V}(\boldsymbol{CRC} - \boldsymbol{C})^T, \quad C_{ij} \equiv \frac{\partial\hat{\nu}_i}{\partial n_j}$$

# β selection criterion

- A large β suppresses the variance, but allows an increased bias.
- The physical criterion: we choose the smallest value of β that yields a positive definite flux at all energies.
- Average bias $\bar{B}$ plateaus at a value that is not much larger than the number of bins *m.*
- Consistent with the strategy for selecting β that lowers β until $B \sim m$

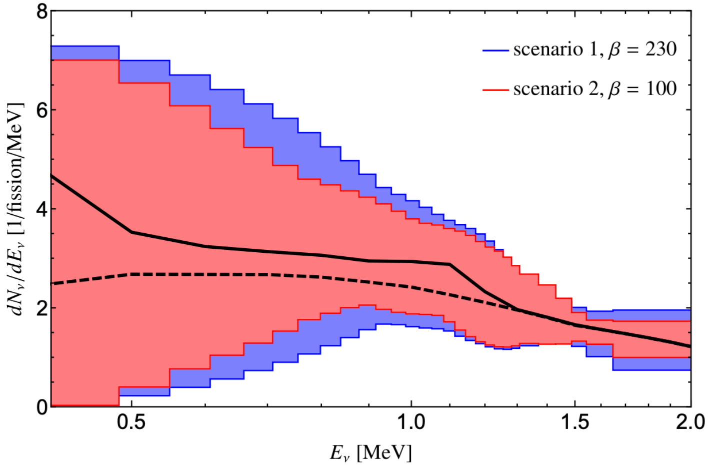



JL, Liu, Marfatia, PRD[2302.10460]

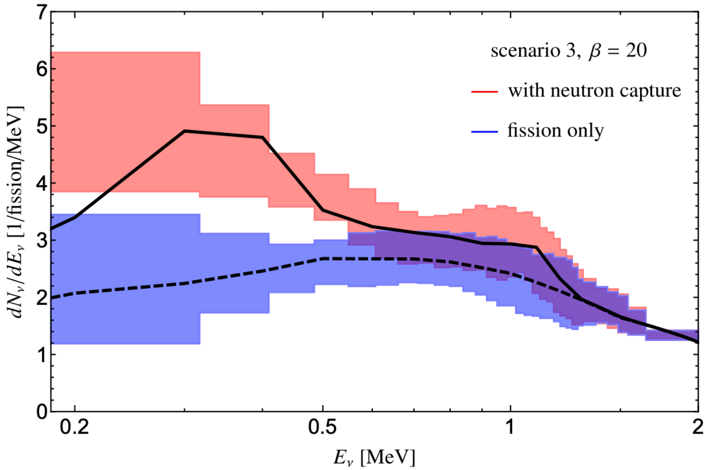
# Simulation results

- scenario 1: $t = 1$ kg · year, bkg = 100 counts/(keV · kg · day), $E_{R,\mathrm{thr}} = 5$ eV.
- scenario 2: $t = 3$ kg · year, bkg = 1 count/(keV · kg · day), $E_{R,\mathrm{thr}} = 5$ eV.
- scenario 3: $t = 300$ kg · year, bkg = 1 count/(keV · kg · day), $E_{R,\mathrm{thr}} = 1$ eV.




➢ For scenario 1 and 2, a meaningful upper bound can be placed on the low energy flux.

➢ For scenario 3, β=20 can separate the neutron capture component, but the physical criterion allows a smaller β, and the uncertainty bands will have considerable overlap.




JL, Liu, Marfatia, PRD[2302.10460]

# CEvNS as a probe of nuclear physics

# Form factor parametrization

$$F(q^2) = \int e^{i\vec{q}\cdot\vec{r}} \rho(r)\, d^3\vec{r}\,.$$

- Helm R. H. Helm, Phys. Rev. 104, 1466 (1956)

$$\rho_H(r) = \frac{3}{4\pi R_0^3} \int f_G(r-r')\theta(R_0 - |r'|) d^3\vec{r'}$$

$$F_{\rm H}(q^2) = 3\frac{j_1(qR_0)}{qR_0} e^{-q^2 s^2/2}\,, \qquad \langle r^2 \rangle_{\rm H} = \frac{3}{5}R_0^2 + 3s^2$$

- Symmetrized Fermi distribution D. W. L. Sprung and J. Martorell, Journal of Physics A30, 6525 (1997)

$$F_{\rm SF}(q^2) = \frac{3}{qc}\left[\frac{\sin(qc)}{(qc)^2}\left(\frac{\pi q a}{\tanh(\pi q a)}\right) - \frac{\cos(qc)}{qc}\right]\left(\frac{\pi q a}{\sinh(\pi q a)}\right)\frac{1}{1+(\pi a/c)^2}$$

$$\langle r^2 \rangle_{\rm SF} = \frac{3}{5}c^2 + \frac{7}{5}(\pi a)^2$$

- Klein-Nystrand S. Klein and J. Nystrand, Phys. Rev. C60, 014903 (1999),

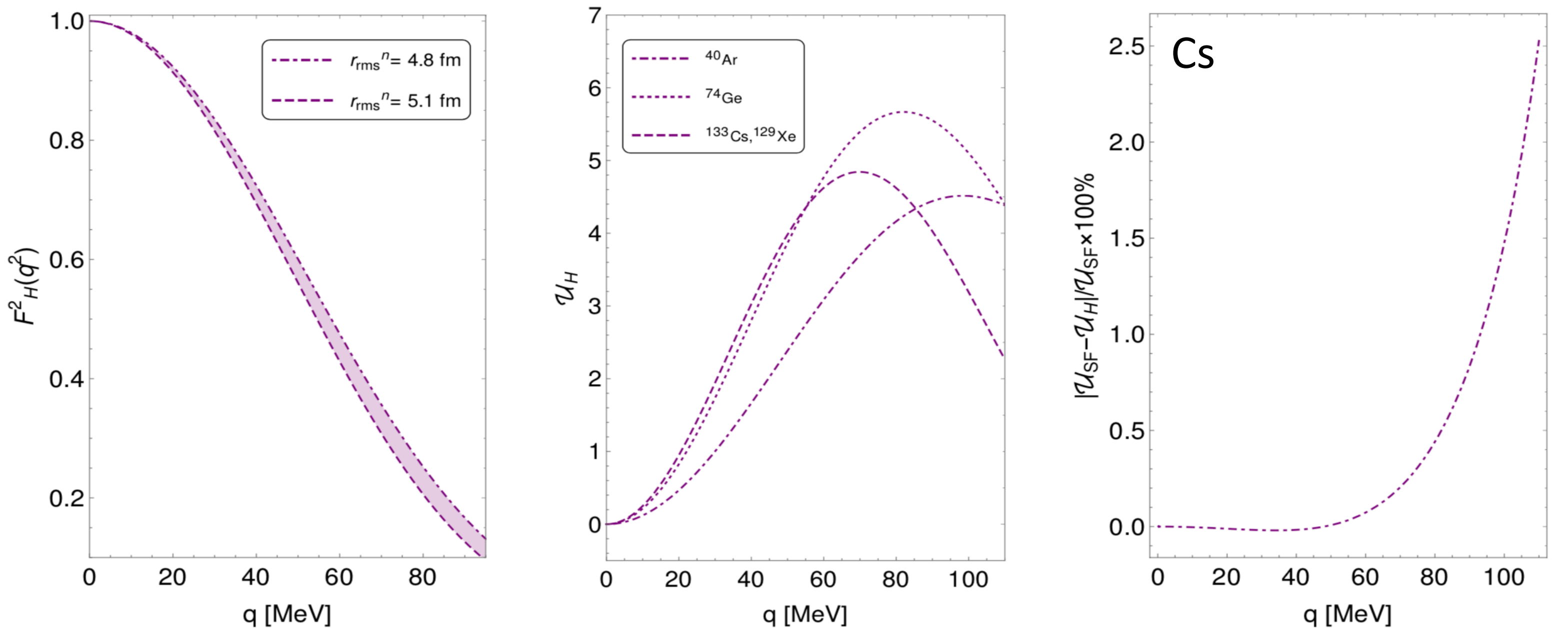
$$F_{\rm KN}(q^2) = 3\frac{j_1(qR_A)}{qR_A}\frac{1}{1+q^2 a_k^2}\,. \qquad \langle r^2 \rangle_{\rm KN} = \frac{3}{5}R_A^2 + 6a_k^2$$

# Form factor uncertainties

- Neutron rms radius are poorly known. Neutron skin: $\Delta r_{np} = r^n_{\rm rms} - r^p_{\rm rms}$

$$\Delta r_{np}(^{208}\mathrm{Pb}) = 0.33^{+0.16}_{-0.18}\ \mathrm{fm}$$

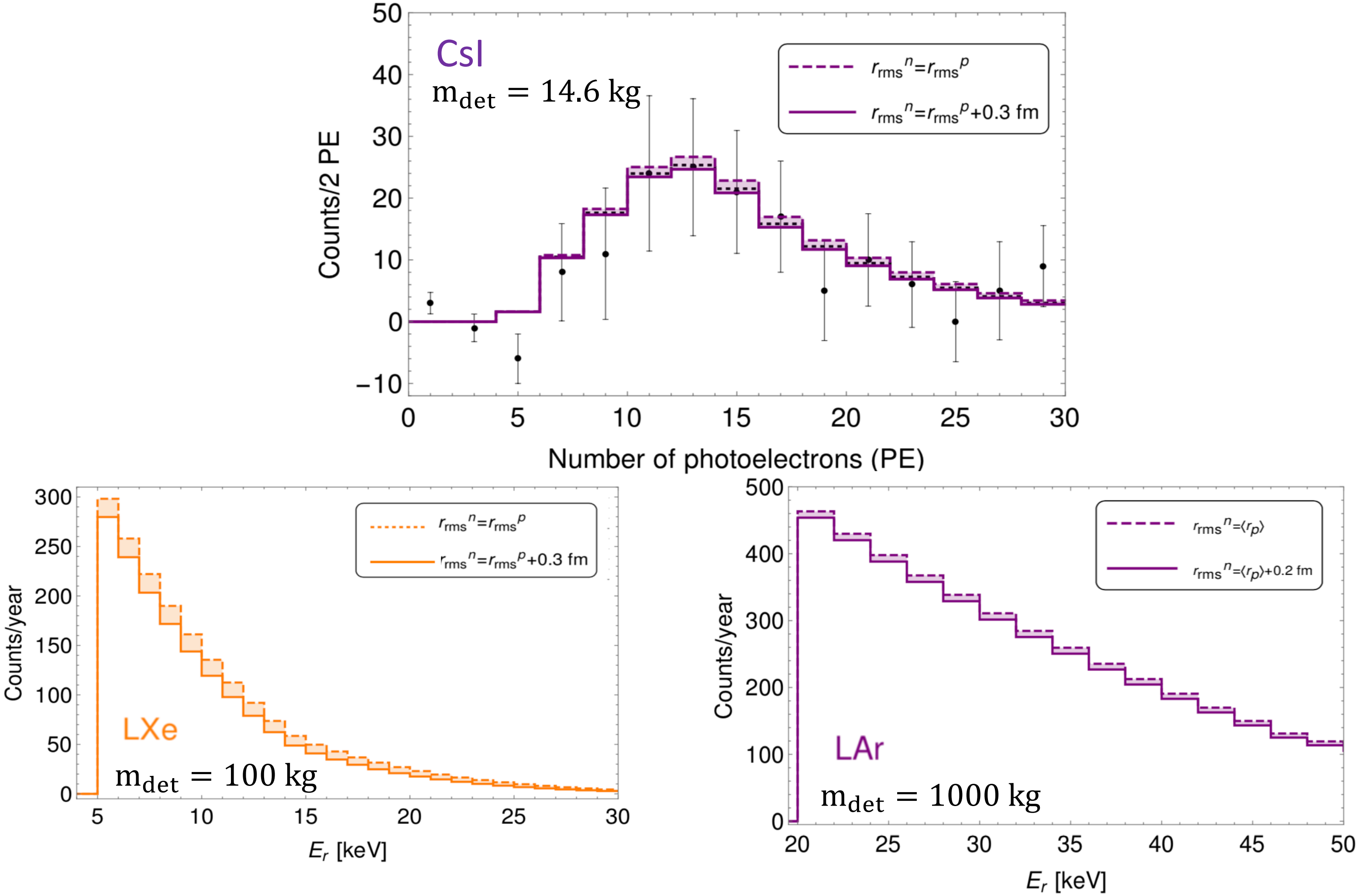
PREX experiment, Phys. Rev. Lett. 108, 112502 (2012)




Aristizabal Sierra, **JL,** Marfatia, JHEP [1902.07398 ]

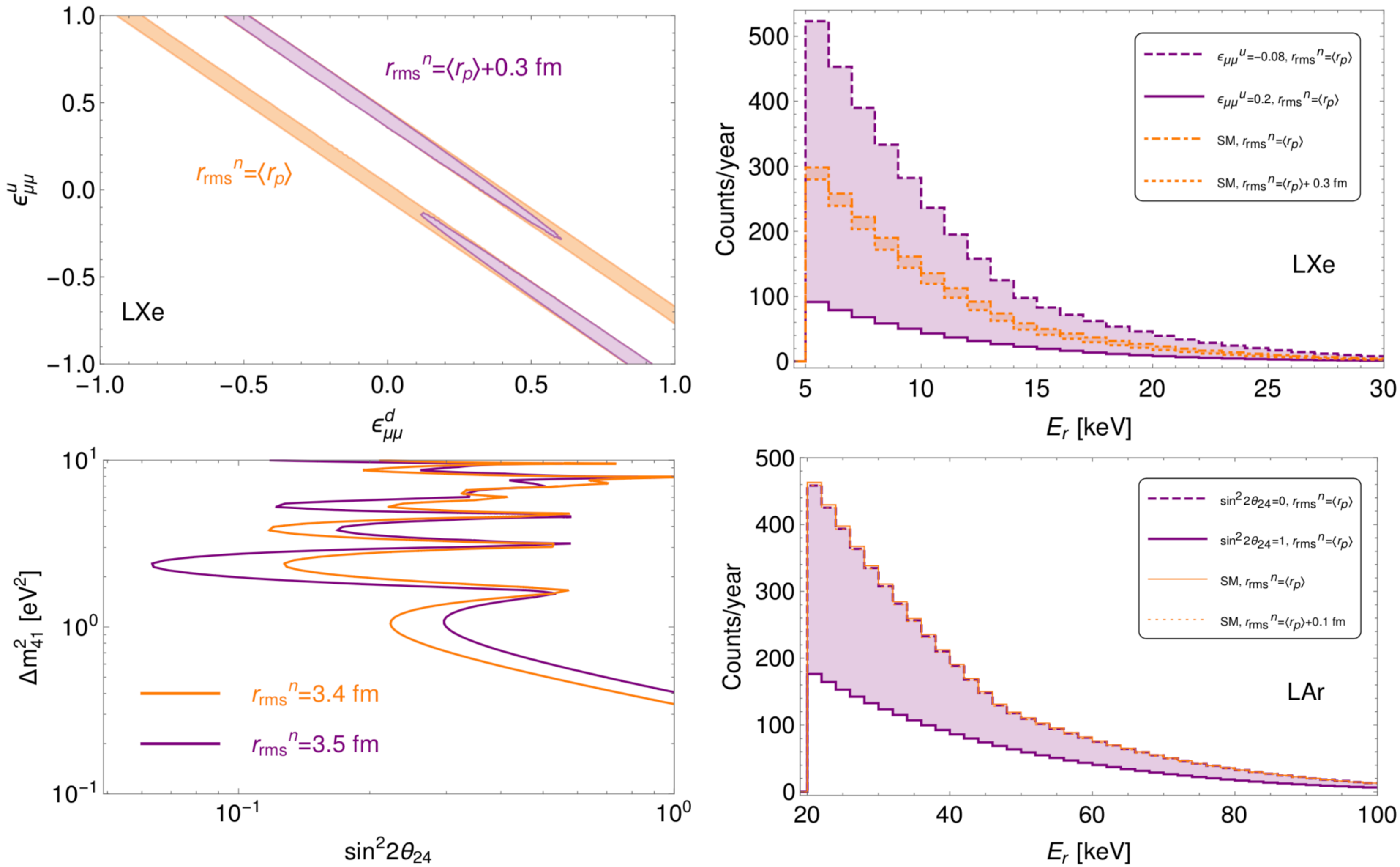
- FF uncertainties are relevant for $q \gtrsim 20$ MeV
- Percentage uncertainties reach maximum at $q \approx 65$ MeV
- Size of the uncertainties do not depend on the FF parameterization chosen

# Impact on spectrum




Aristizabal Sierra, **JL,** Marfatia, JHEP [1902.07398 ]

# Impact on New physics search




Aristizabal Sierra, **JL,** Marfatia, JHEP [1902.07398 ]

# Nuclear quadrupole deformation

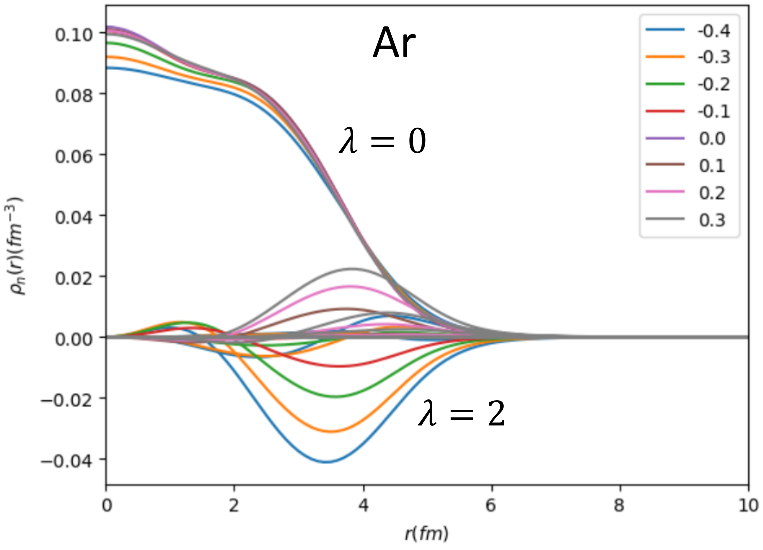
$$\rho(\mathbf{R}) = 2\sum_i v_i^2 \left|\Phi_i(\mathbf{R})\right|^2 ,$$

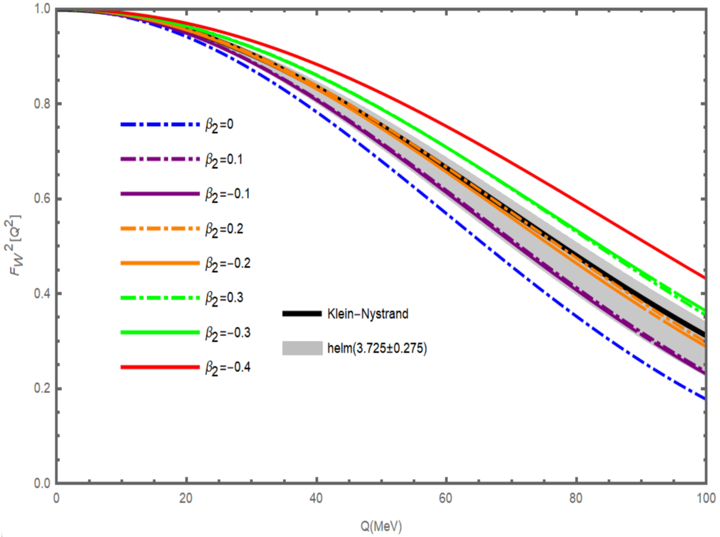
J. Meng et al. Prog. Part. Nucl. Phys. 57, 470 (2006); S. G. Zhou et al., Phys. Rev. C 82, 011301(R) (2010); Sarriguren, PRC [2402.08304]

$$\beta_2 = \sqrt{\frac{\pi}{5}} \frac{Q_0}{A < R^2 >} ,$$

$$Q_0 = \sqrt{16\pi/5} \int \rho(\mathbf{R}) R^2 Y_{20}(\Omega_R) d\mathbf{R} ,$$

$$\langle R^2 \rangle = \frac{\int R^2 \rho(\mathbf{R}) d\mathbf{R}}{\int \rho(\mathbf{R}) d\mathbf{R}}$$

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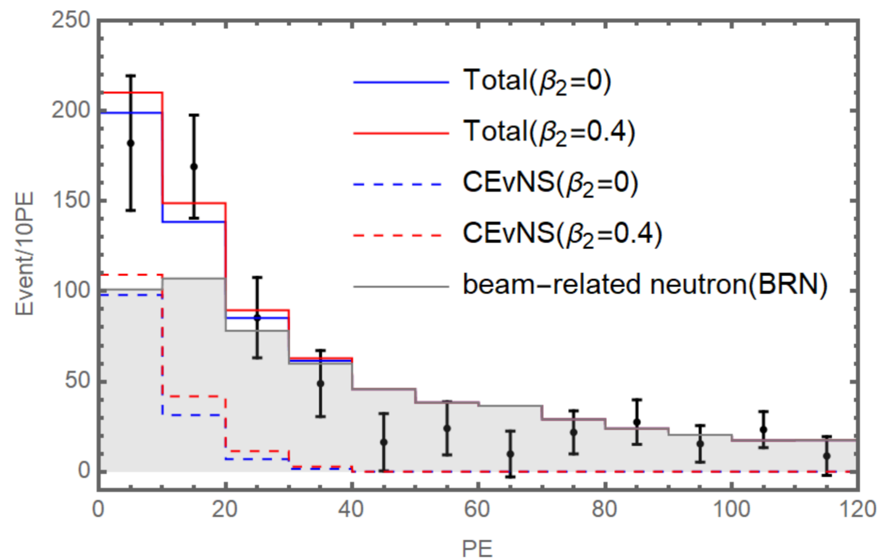
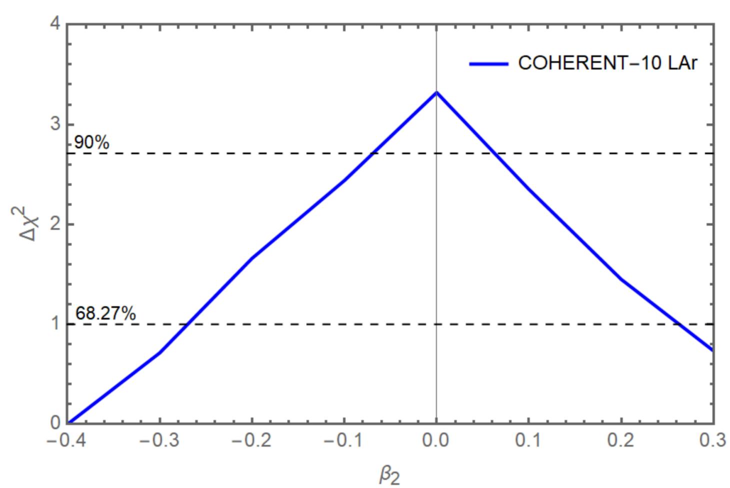
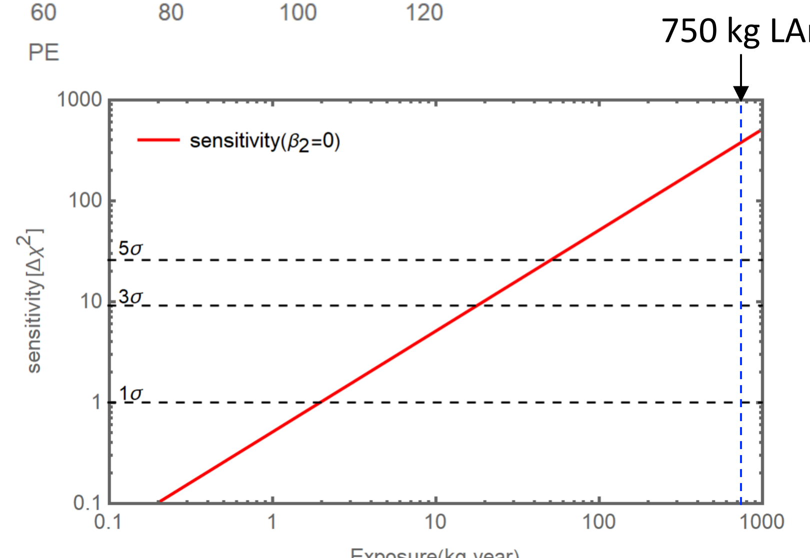
# Sensitivity at COHERENT

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# Summary

- CEvNS open a new window to probe the neutrino and nuclear physics at the low energy frontier.
- A CEvNS experiment with a O(10) eV threshold has the potential to detect the low energy reactor neutrino flux below IBD threshold.
- New physics searches are strongly affected by nuclear form factor uncertainties.
- COHERENT experiment has the potential to probe nuclear quadrupole deformation.

*Thanks!*