CEvNS as a probe of new physics

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中山大学

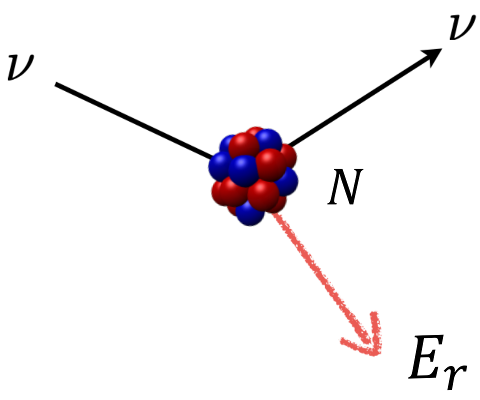
第三届地下和空间粒子物理与宇宙物理前沿问题研讨会
西昌，5/8/2024

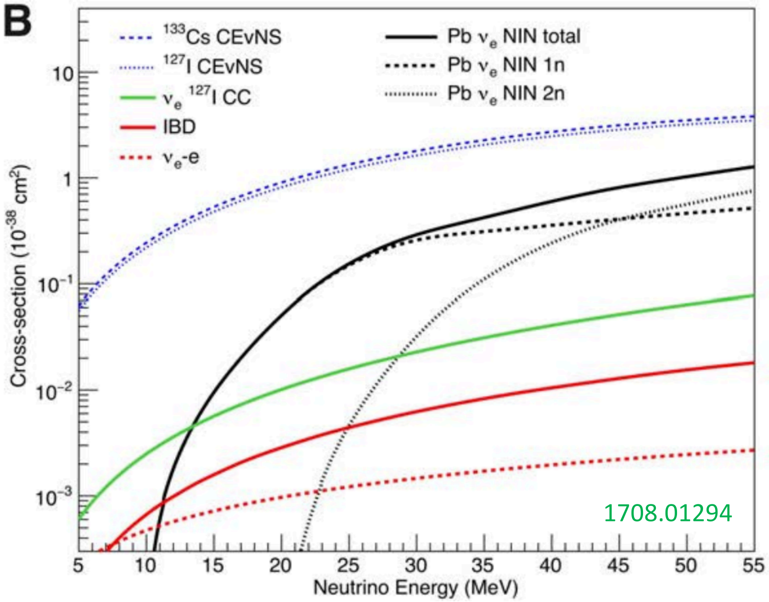
Outline

- Introduction to CEvNS
- Quenching factor measurement
- Low energy reactor neutrino flux
- Sensitivities at CICENNS
- Summary

Introduction to CEνNS

Coherent Elastic ν-Nucleus Scattering





1708.01294

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

SM weak charge: $Q_{\rm SM}^2 = \left(Zg_p^V + Ng_n^V\right)^2$

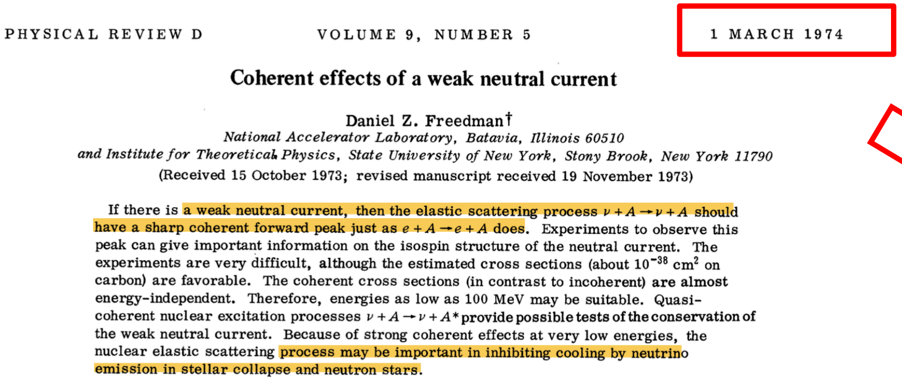
$$g_p^V = \frac{1}{2} - 2\sin^2\theta_W \; \sim 0.03 \qquad \Longrightarrow \qquad \sigma_{\rm SM} \propto N^2$$

$$g_n^V = -0.5$$

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

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

From neutrino to DM

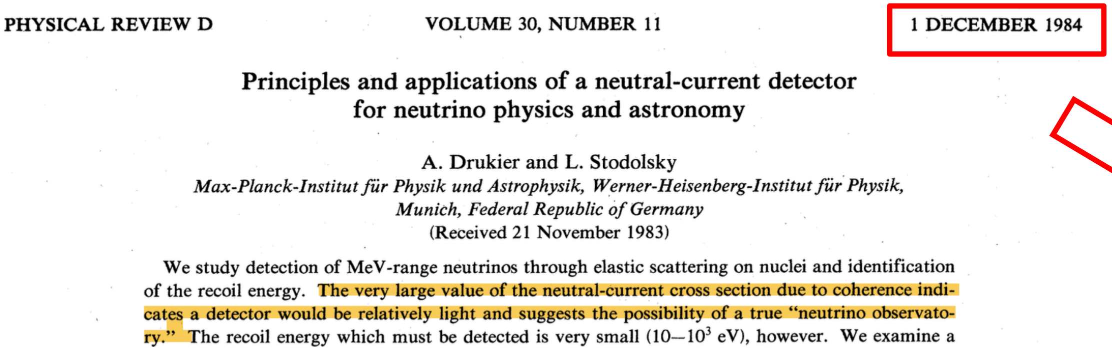


PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

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 $\nu + A \rightarrow \nu + A$ 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.

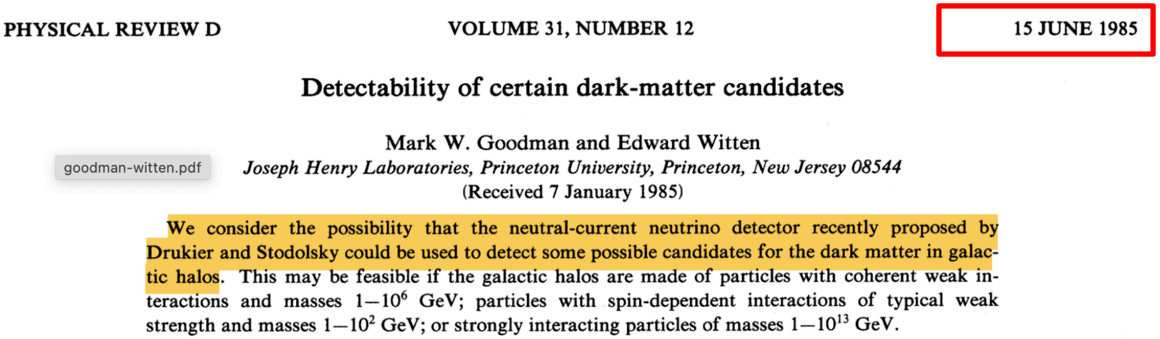


PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

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

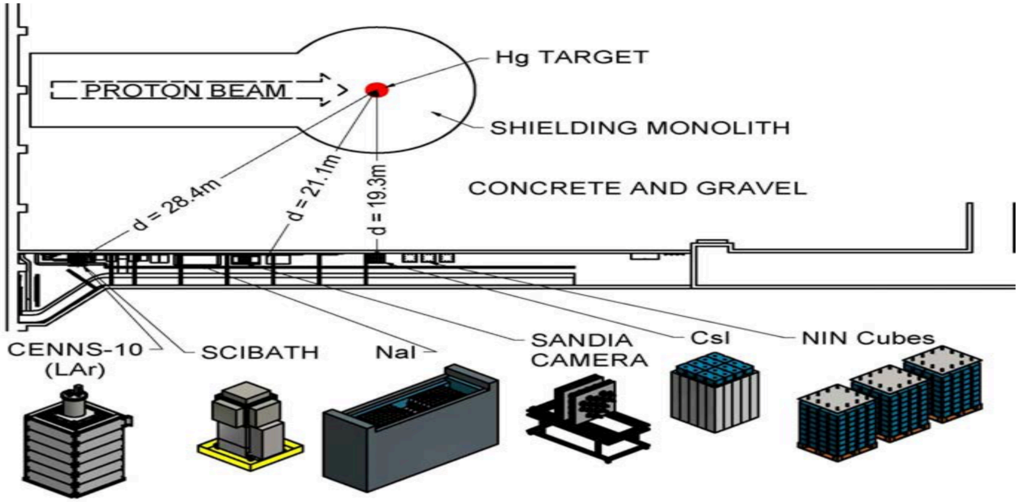
Detectability of certain dark-matter candidates

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

goodman-witten.pdf

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.

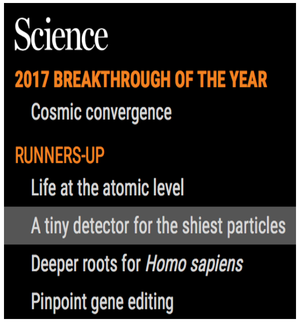
COHERENT



Science

SPOTTING A GHOST

A compact detector spies neutrinos scattering from nuclei



Science

2017 BREAKTHROUGH OF THE YEAR

Cosmic convergence

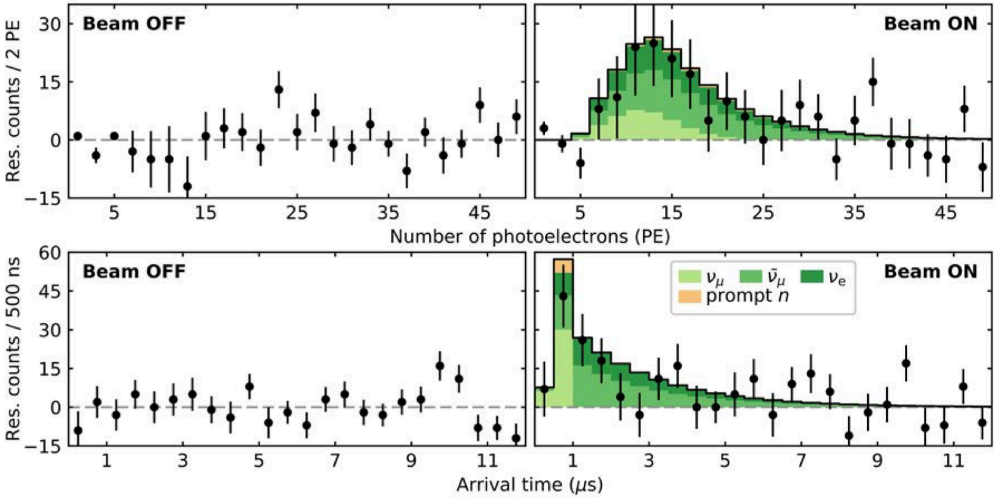
RUNNERS-UP

Life at the atomic level

A tiny detector for the shiest particles

Deeper roots for *Homo sapiens*

Pinpoint gene editing



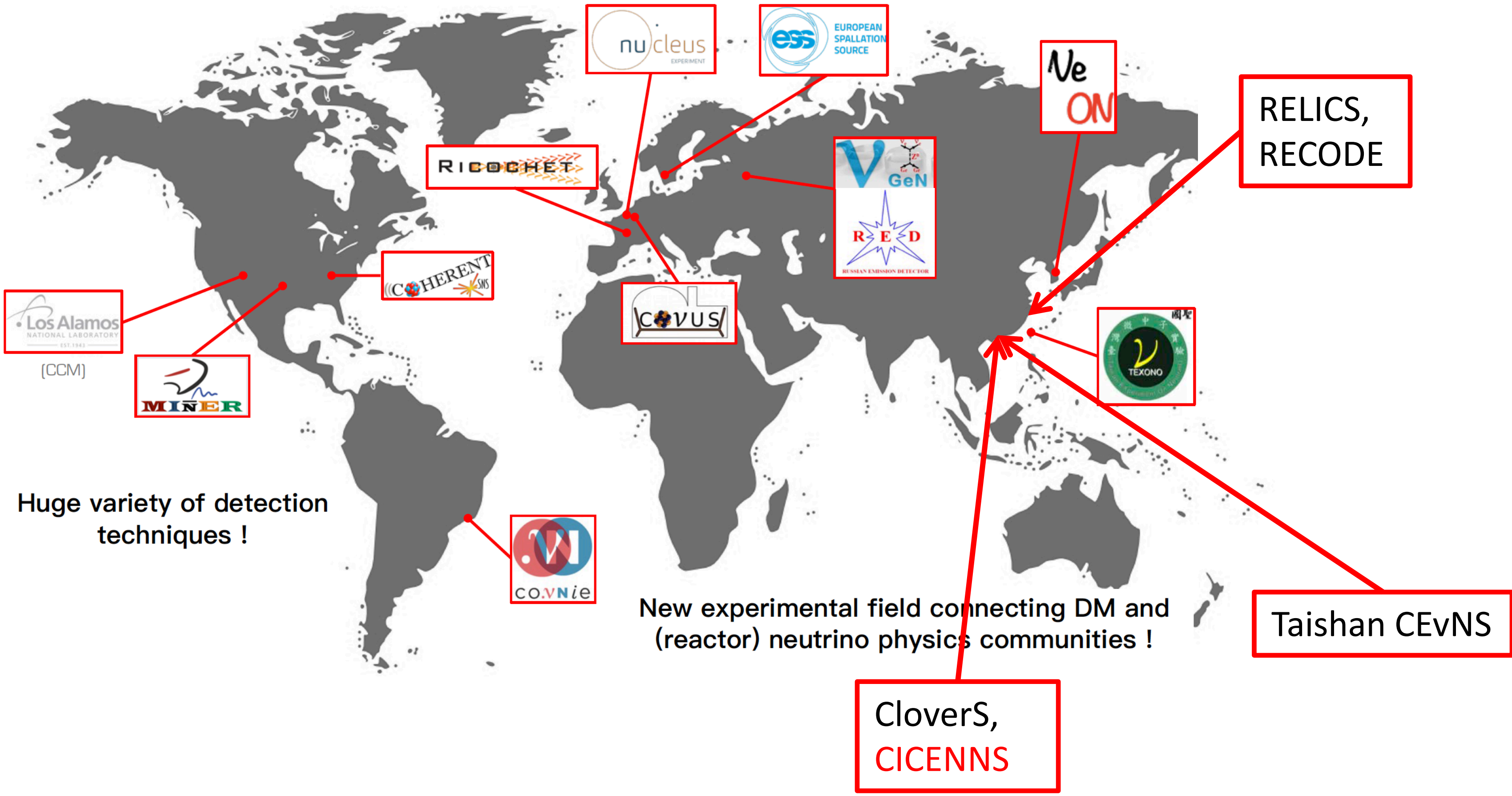
COHERENT Collaboration, Science [1708.01294]

134 ± 22 observed

173 ± 48 predicted in SM

6.7σ CL evidence for CEvNS

Global efforts



RELICS,
RECODE

Taishan CEvNS

CloverS,
CICENNS

Huge variety of detection techniques !

New experimental field connecting DM and (reactor) neutrino physics communities !

Modified from Matthieu VIVIER@Magnificent CEvNS workshop 2020

Current data

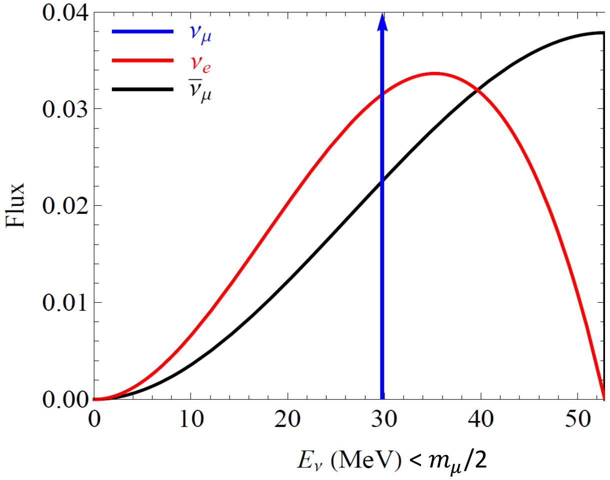
❖ πDAR source @ SNS

COHERENT first observed CEνNS in 2017 at the 6.7σ CL with a CsI detector

COHERENT, Science 357,1123 (2017)

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 keV$_{ee}$ threshold

CONNIE, PRD 100, 092005 (2019)

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

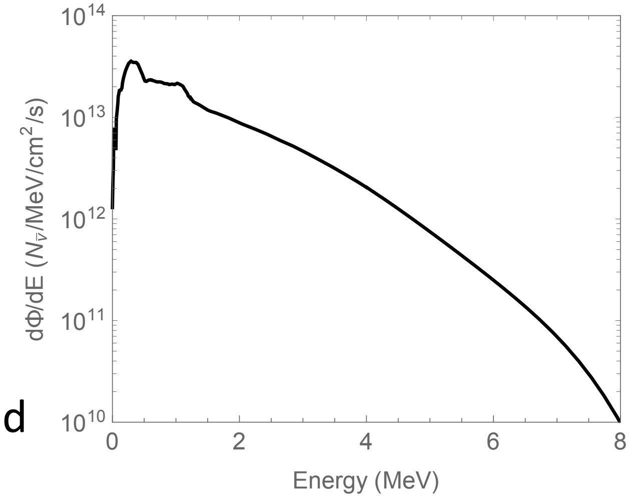
CONNIE, PRL 126, 041804 (2021)

***ν*GeN** uses a Ge detector with 0.3 keV$_{ee}$ threshold

***ν*GeN**, PRD 106, L051101 (2022)

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

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

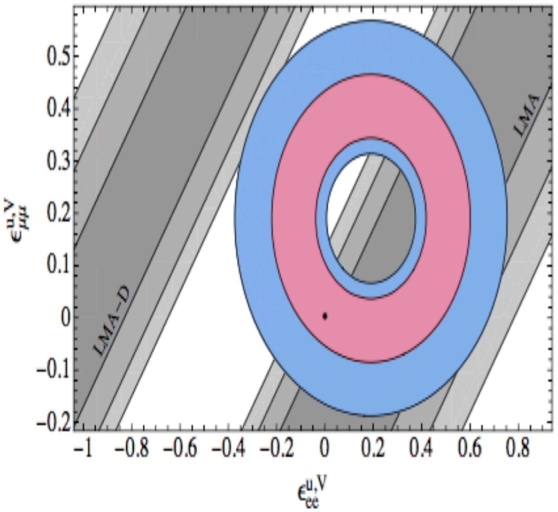


Physics potential

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

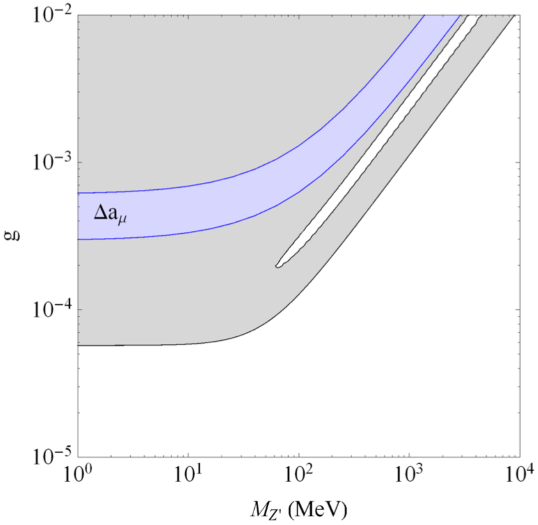
E. Lisi, Neutrino 2018

Nonstandard interactions



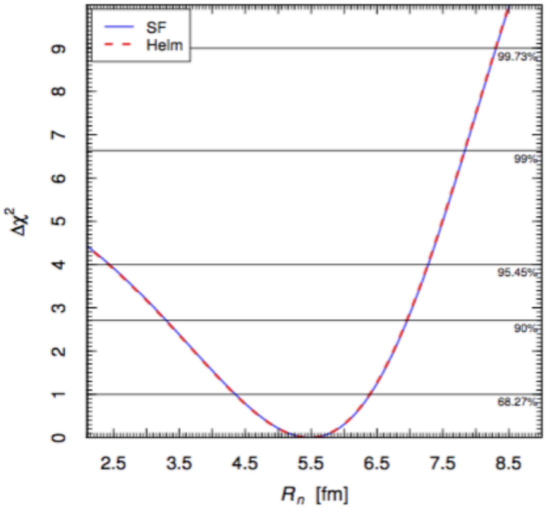
Coloma, et.al., PRD [1708.02899]

Light mediators



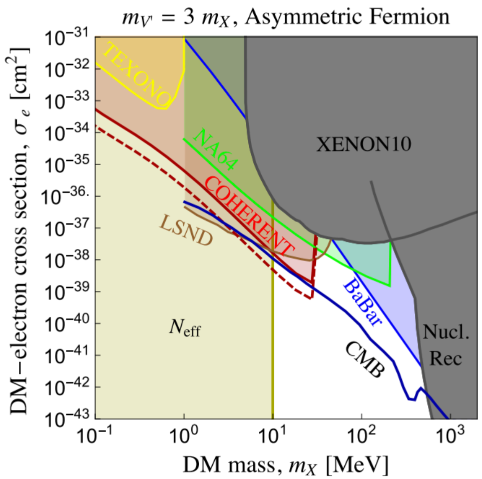
JL, Marfatia, PLB [1708.04255]

Neutron radius



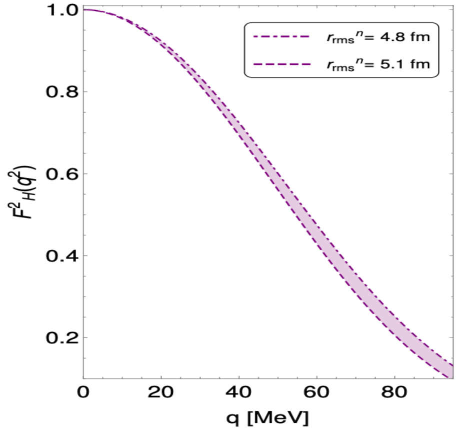
Cadeddu, Giunti, Li, Zhang PRL[1710.02730]

Photon Portal DM



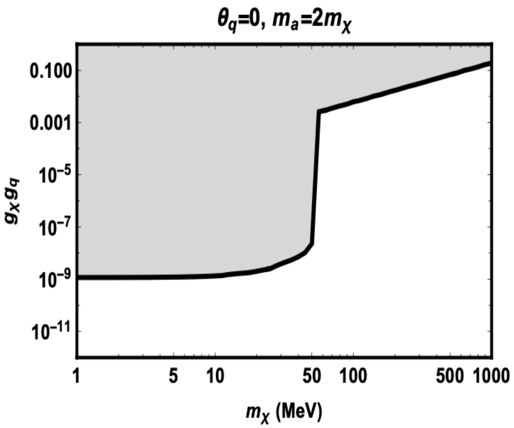
Ge, Shoemaker, PRD [1710.10889]

Nuclear form factor



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

Loop corrections



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

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]

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

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

$B - \sum_\alpha x_\alpha L_\alpha$ with $\sum_\alpha x_\alpha = 3$

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

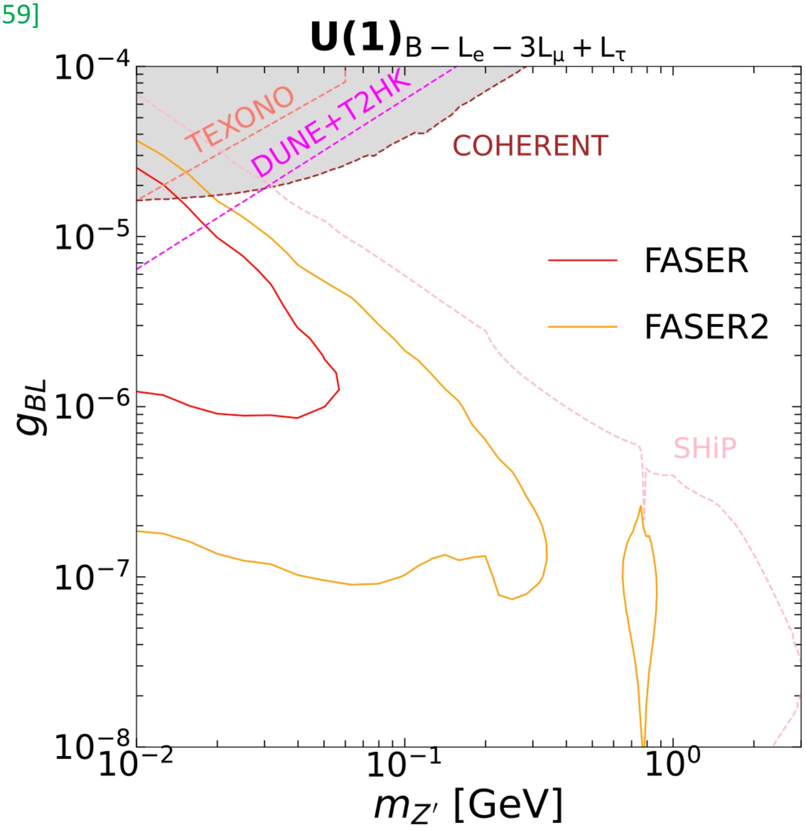
Araki, Heeck and Kubo, JHEP [1203.4951];
JL, Marfatia, Whisnant, PRD [1306.4659]

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

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

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

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



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

Quenching factor measurement

CEνNS spectrum

- Differential cross section

$$\frac{d\sigma_{SM}}{dE_R} = \frac{G_F^2 M}{4\pi} q_W^2 \left(1 - \frac{M E_R}{2E_\nu^2}\right) F^2(\mathfrak{q})$$

- Event spectrum

$$\frac{dR}{dE_R} = N_T \int \frac{d\Phi}{dE_\nu} \frac{d\sigma}{dE_R} dE_\nu$$

Only a small portion of nuclear recoiling energy E_R will go into electronic ionization energy E_I , which is measured.

Quenching factor (QF): $Q \equiv E_I / E_R$

$$\frac{dE_R}{dE_I}$$

- Measured number of events:

$$N_i = t \int_{E_I^i}^{E_I^{i+1}} \eta \frac{dR}{dE_R} \left(\frac{1}{Q} - \frac{E_I}{Q} \frac{dQ}{dE_I}\right) dE_I$$

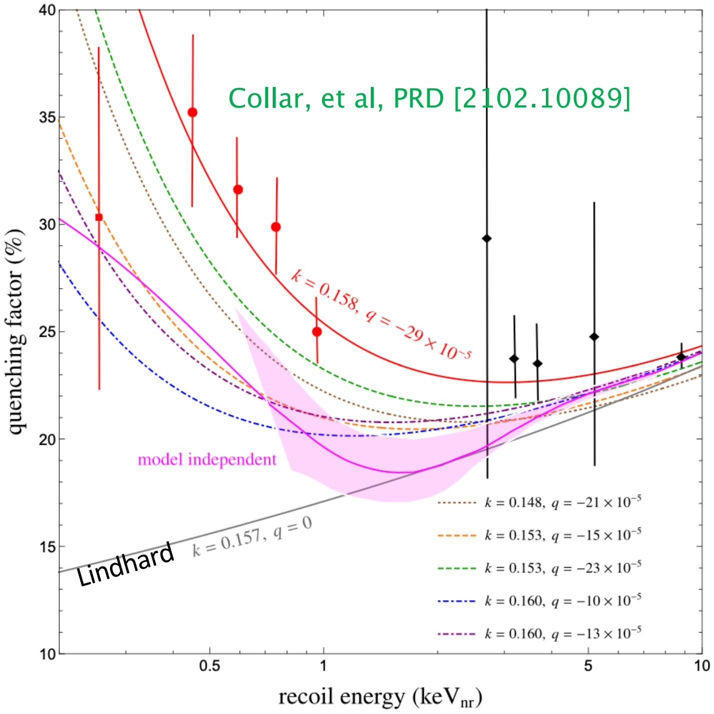
Modified quenching factor

Lindhard model

$$Q(E_R) = \boxed{\frac{k\,g(\epsilon)}{1+k\,g(\epsilon)}} - \frac{q}{\epsilon}$$

Sorensen, PRD [1412.3028]

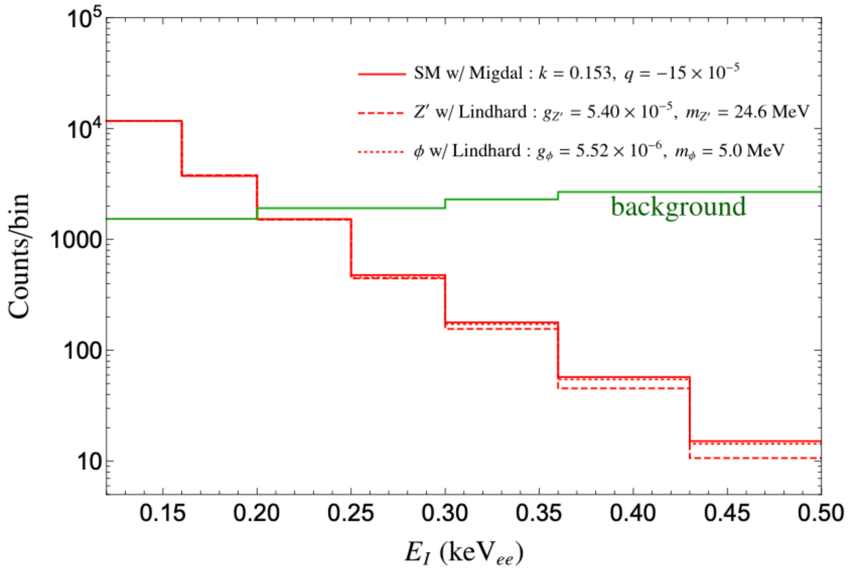
- A larger k value leads to a larger fraction of total energy going into electron.
- A positive q value allows a sharp cutoff in the energy given to electrons.
- A negative q value allows an enhancement in the energy given to electrons.



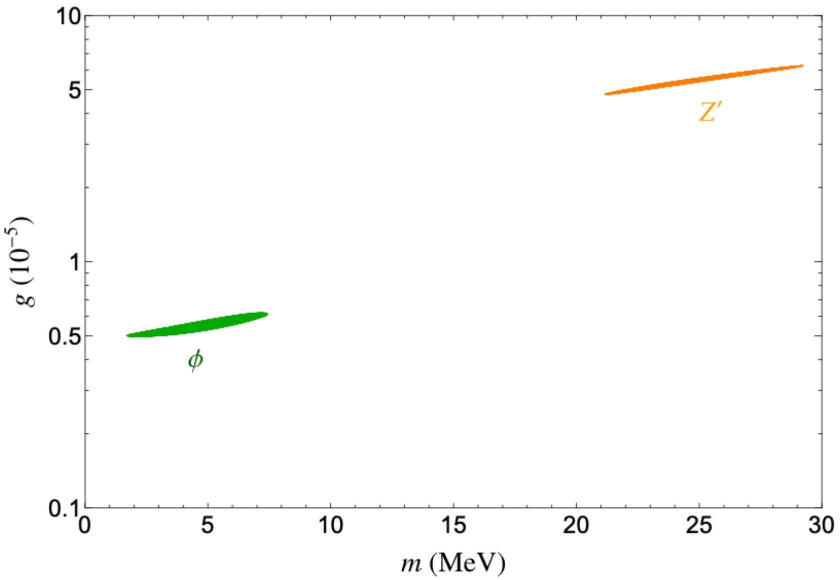
Collar, et al, PRD [2102.10089]

JL, Liu, Marfatia, PRD [2104.01811]

Mimic the signal of new physics



$P = 3.9$ GW $\quad d = 20$ m $\quad t = 7$ kg·year



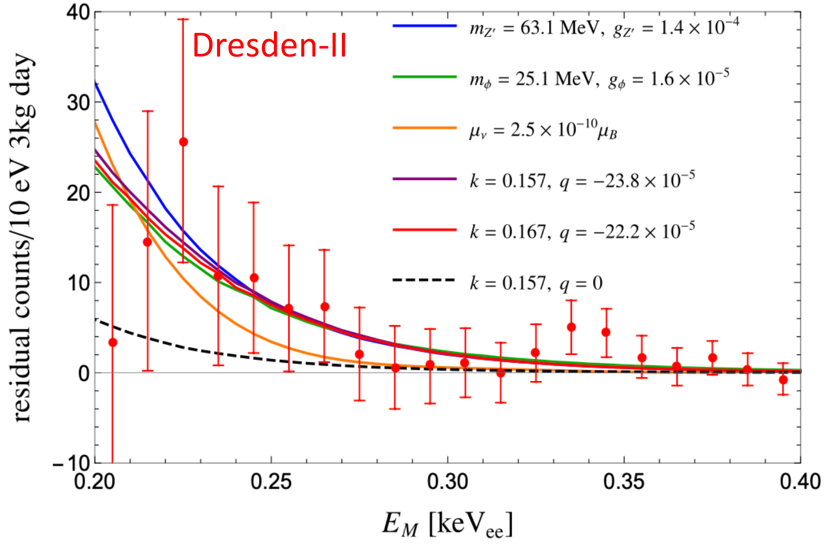
$k = 0.153$ and $q = -15 \times 10^{-5}$

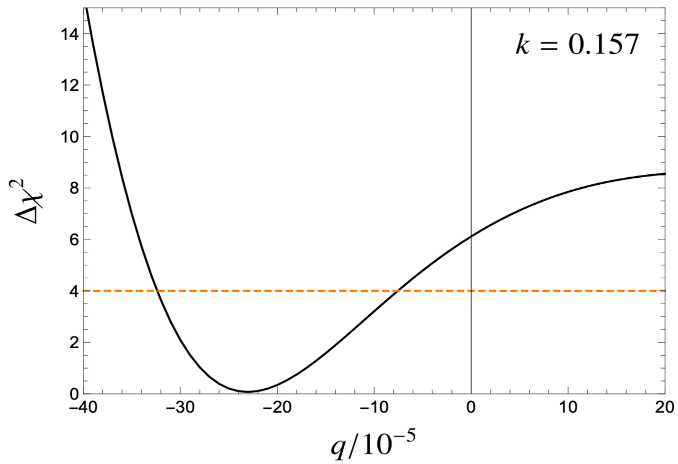
JL, Liu, Marfatia, PRD [2104.01811]

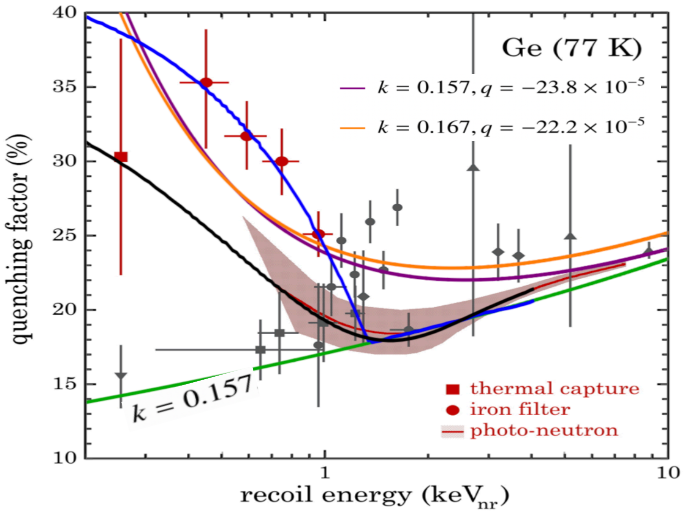
- Both the light Z′ and scalar cases with the standard Lindhard QF can fit the SM spectrum with the modified Lindhard QF.

- This will lead to confusion in determining the nature of new physics.

Indirect measurement of QF



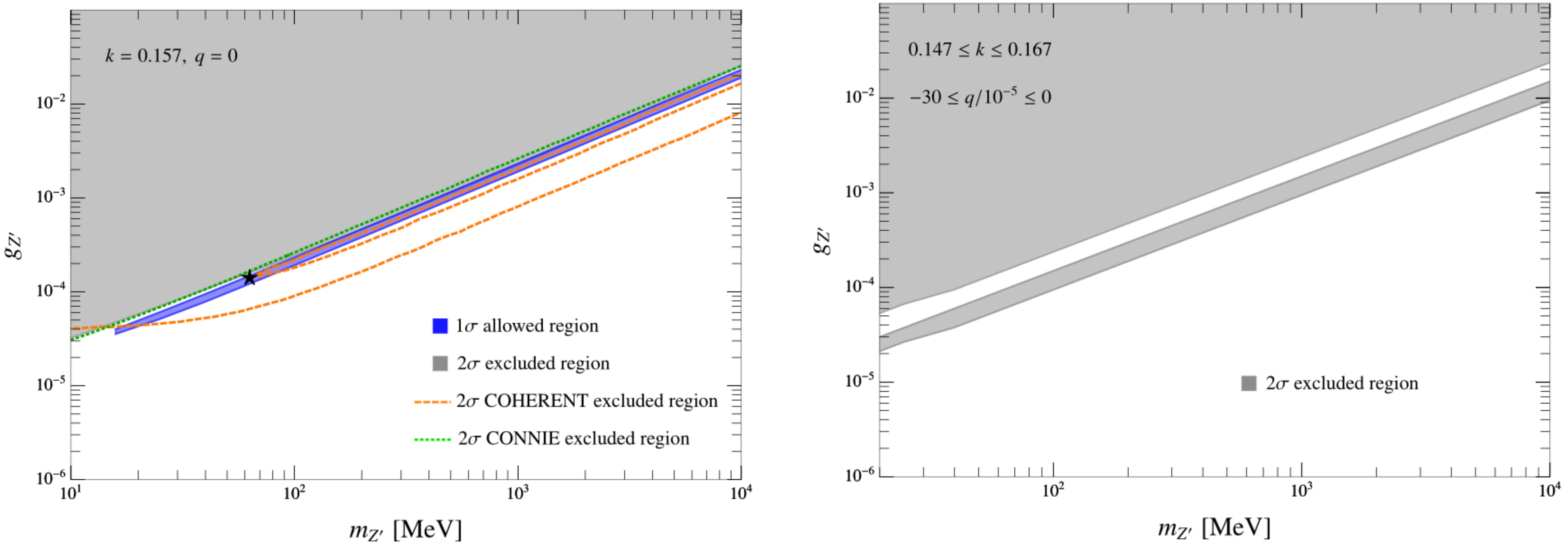




- A negative value of q is preferred by the Dresden data at 2.5σ in SM.
- This best-fit point is consistent with direct QF measurements using neutron source.

JL, Liu, Marfatia, PRD [2202.10622]

Constraints on new physics



JL, Liu, Marfatia, PRD [2202.10622]

- Left panel assuming the standard Lindhard QF is valid. A mild preference for the new physics if the Lindhard QF is assumed.

- Right panel marginalizing over the (k,q) of the modified Lindhard QF. Constraints are qualitatively affected by the QF model.

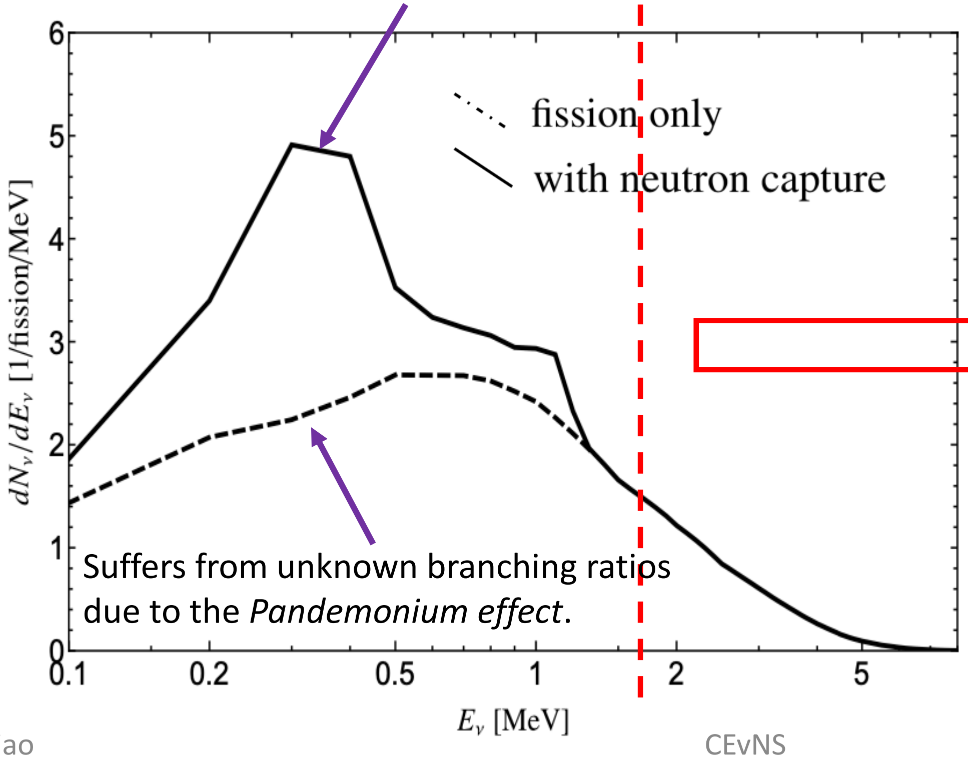
Low energy reactor neutrino flux

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,γ) ^{239}U	–	0.60	2.00	1.2

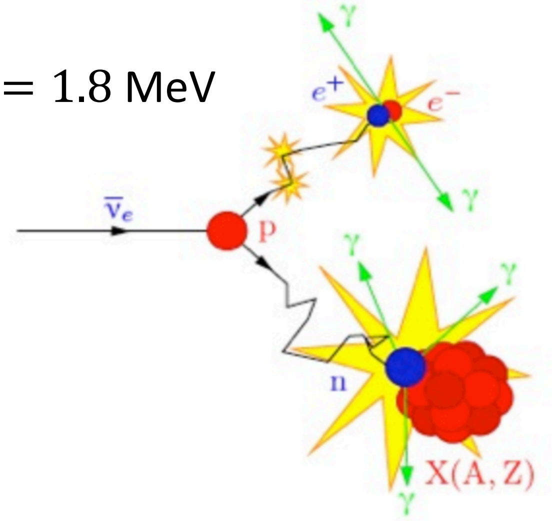
TEXONO, hep-ex/0605006

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



Suffers from unknown branching ratios due to the *Pandemonium effect*.

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.

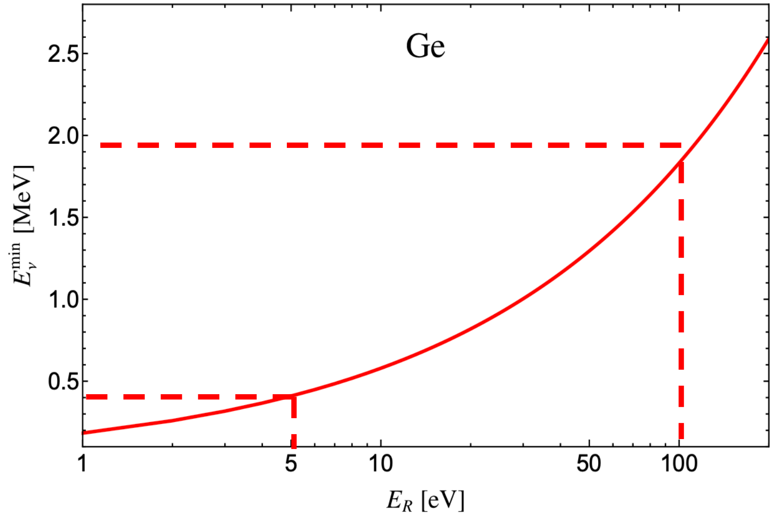
EPJC 77, 506 (2017) [1704.04320]

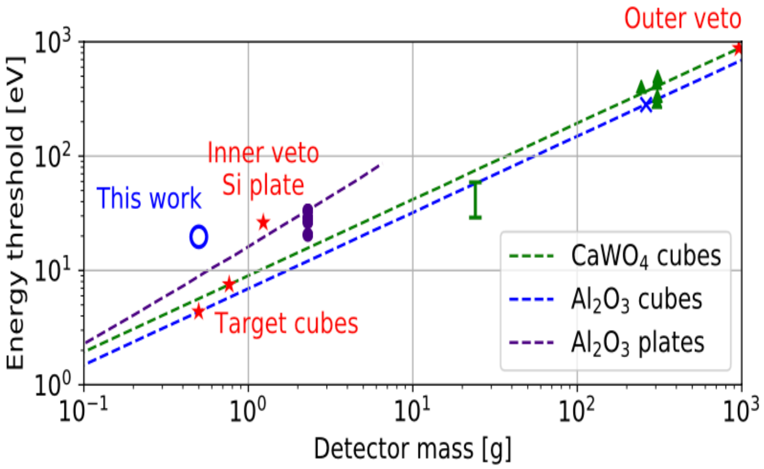
- A total 10 g mass of $CaWO_4$ and Al_2O_3 crystals, and 1 kg of Ge is planned.

- 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

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

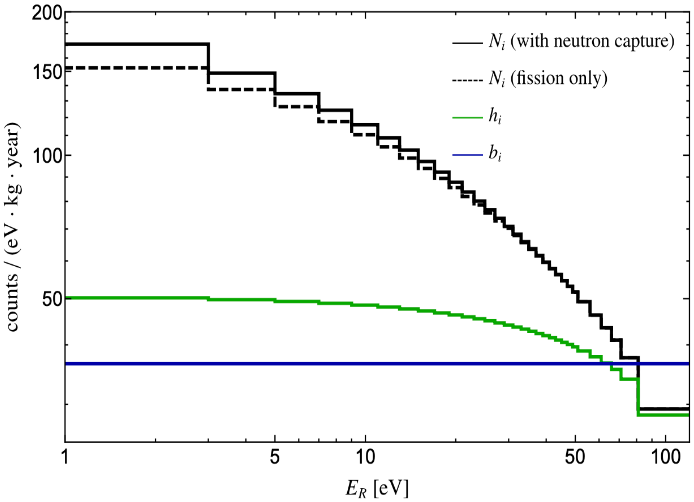
Neutrino flux:

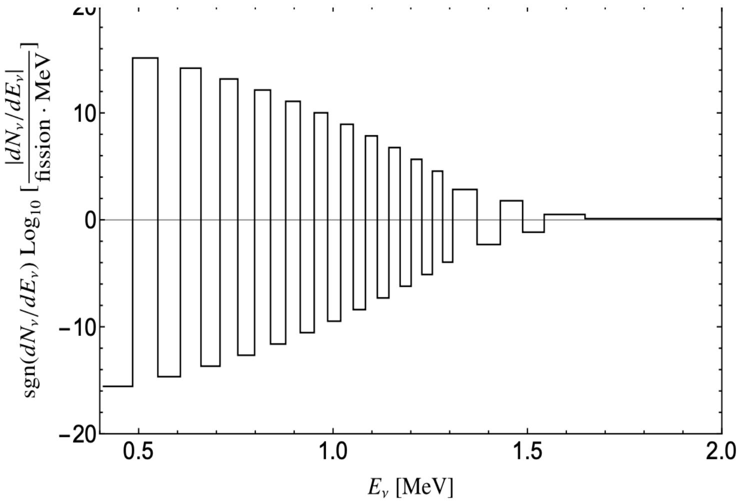
$$\boldsymbol{\nu} = \boldsymbol{R}^{-1}(\boldsymbol{\mu} - \boldsymbol{h} - \boldsymbol{b})$$

Statistical fluctuations in observed spectrum

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

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

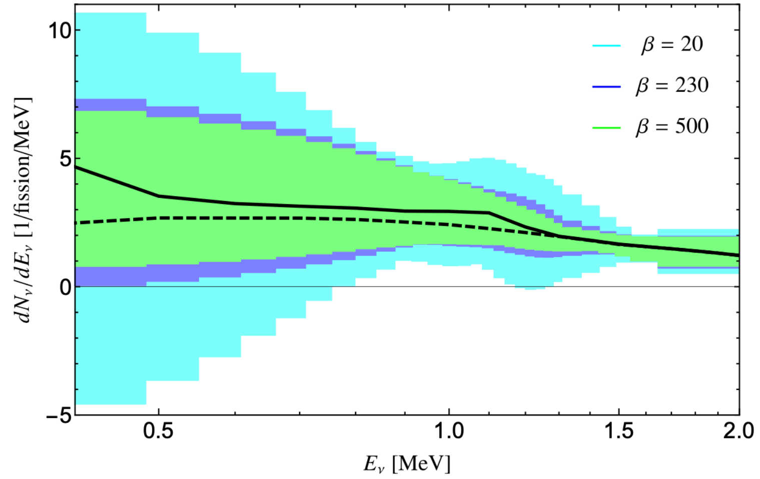
β selection criterion

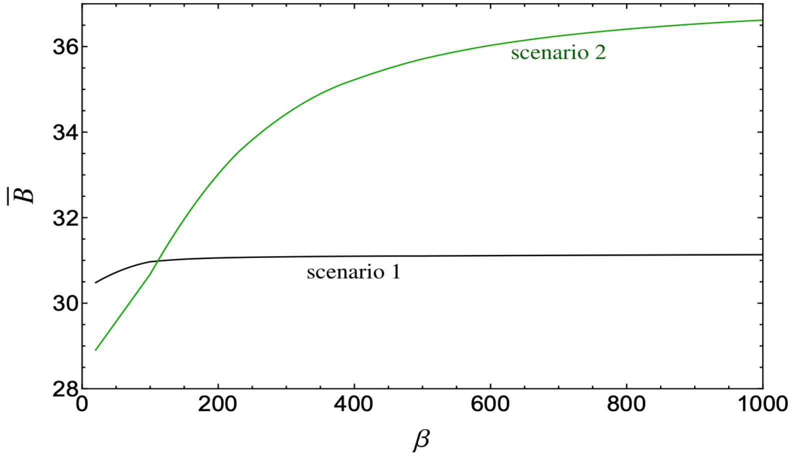
- A large β suppresses the variance, but allows an increased bias.

- 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]

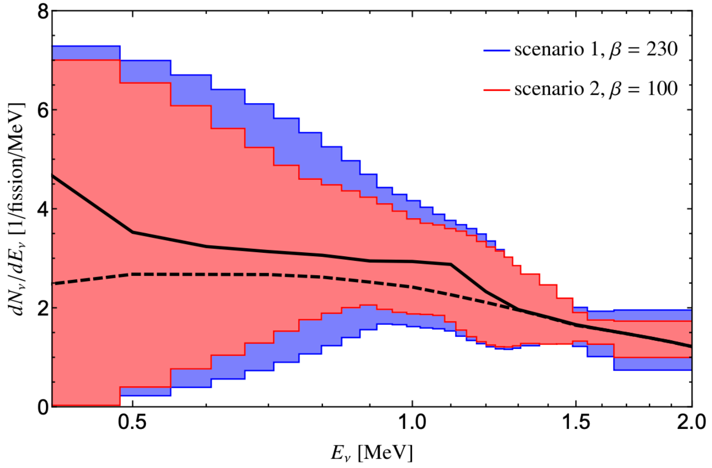
Simulation results

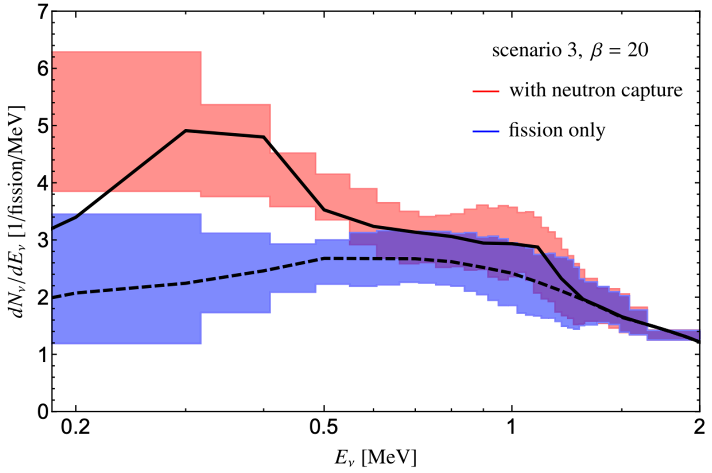
- scenario 1: $t = 1\ \mathrm{kg} \cdot \mathrm{year}$, $\mathrm{bkg} = 100\ \mathrm{counts}/(\mathrm{keV} \cdot \mathrm{kg} \cdot \mathrm{day})$, $E_{R,\mathrm{thr}} = 5\ \mathrm{eV}$.
- scenario 2: $t = 3\ \mathrm{kg} \cdot \mathrm{year}$, $\mathrm{bkg} = 1\ \mathrm{count}/(\mathrm{keV} \cdot \mathrm{kg}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

➢ 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.

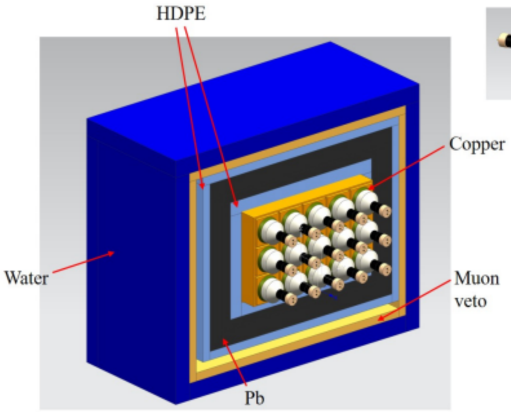
JL, Liu, Marfatia, PRD[2302.10460]

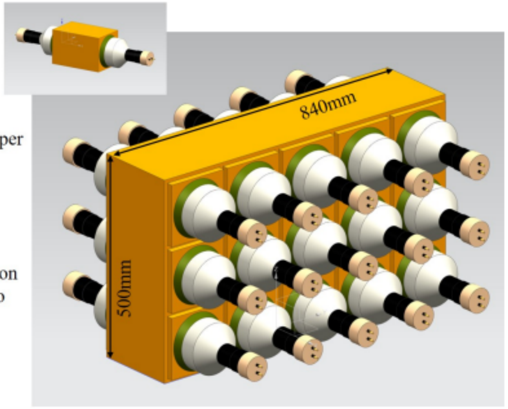


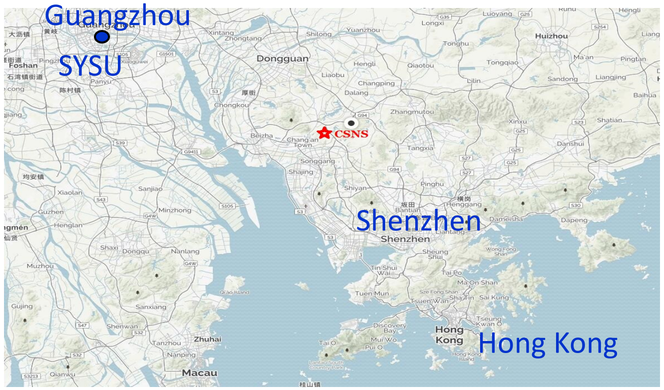


Sensitivities at CICENNS

CICENNS

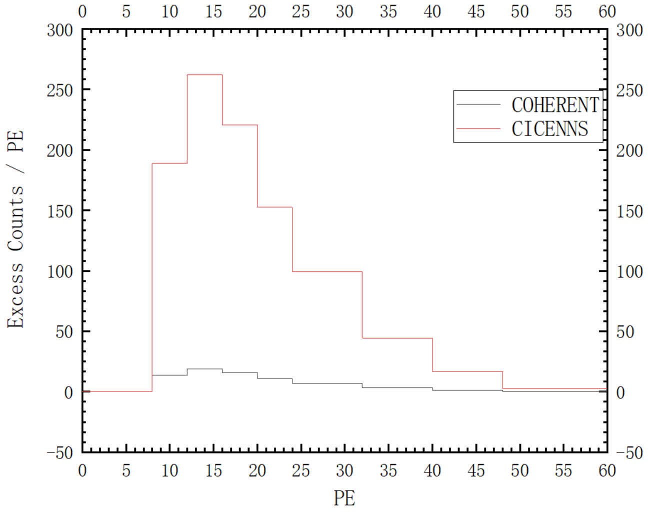




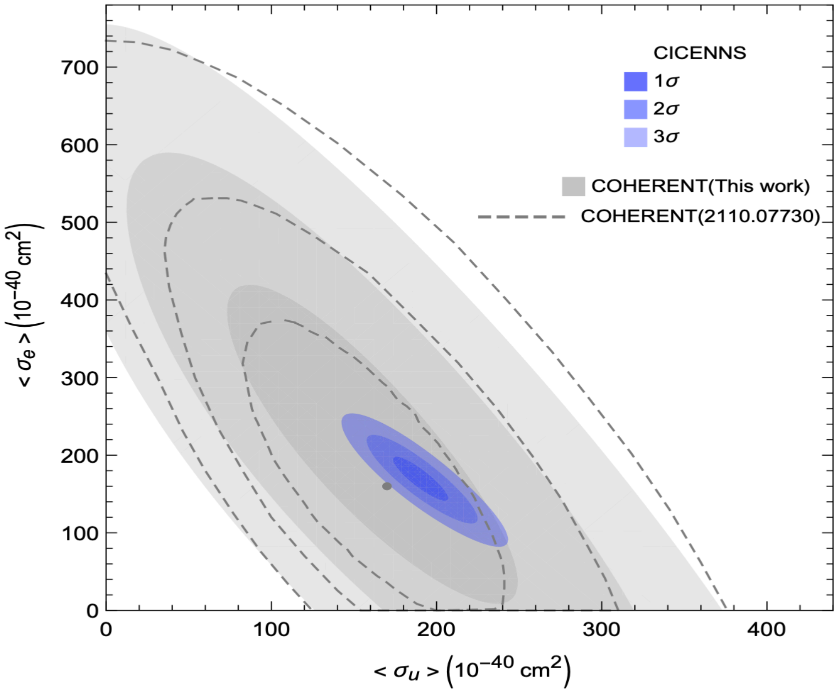


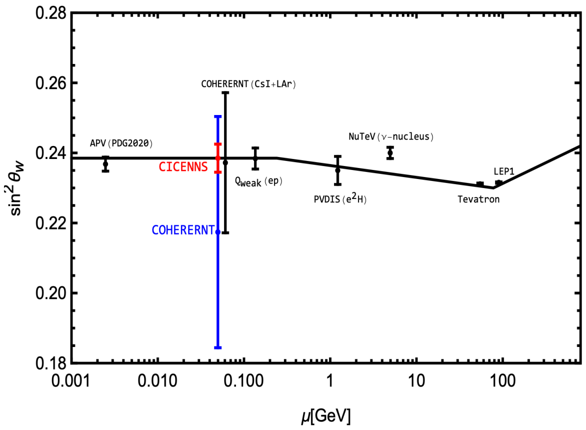
Also see Xiao’s talks

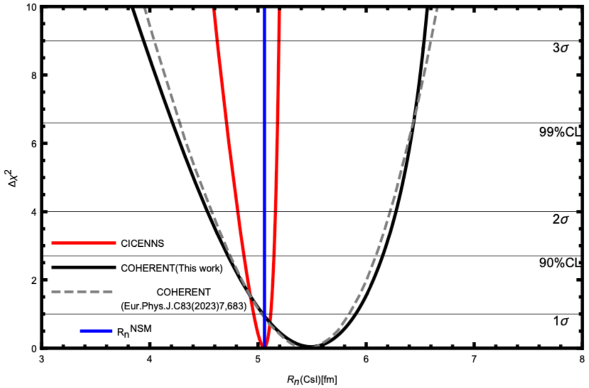
	COHERENT	CICENNS
Detector mass	14.6 kg	300 kg
Detector distance	19.3 m	10.5m
Neutrino flux $(cm^{-2}s^{-1})$	4.7×10^7	2.0×10^7
Events per year	306	~2500



SM measurements

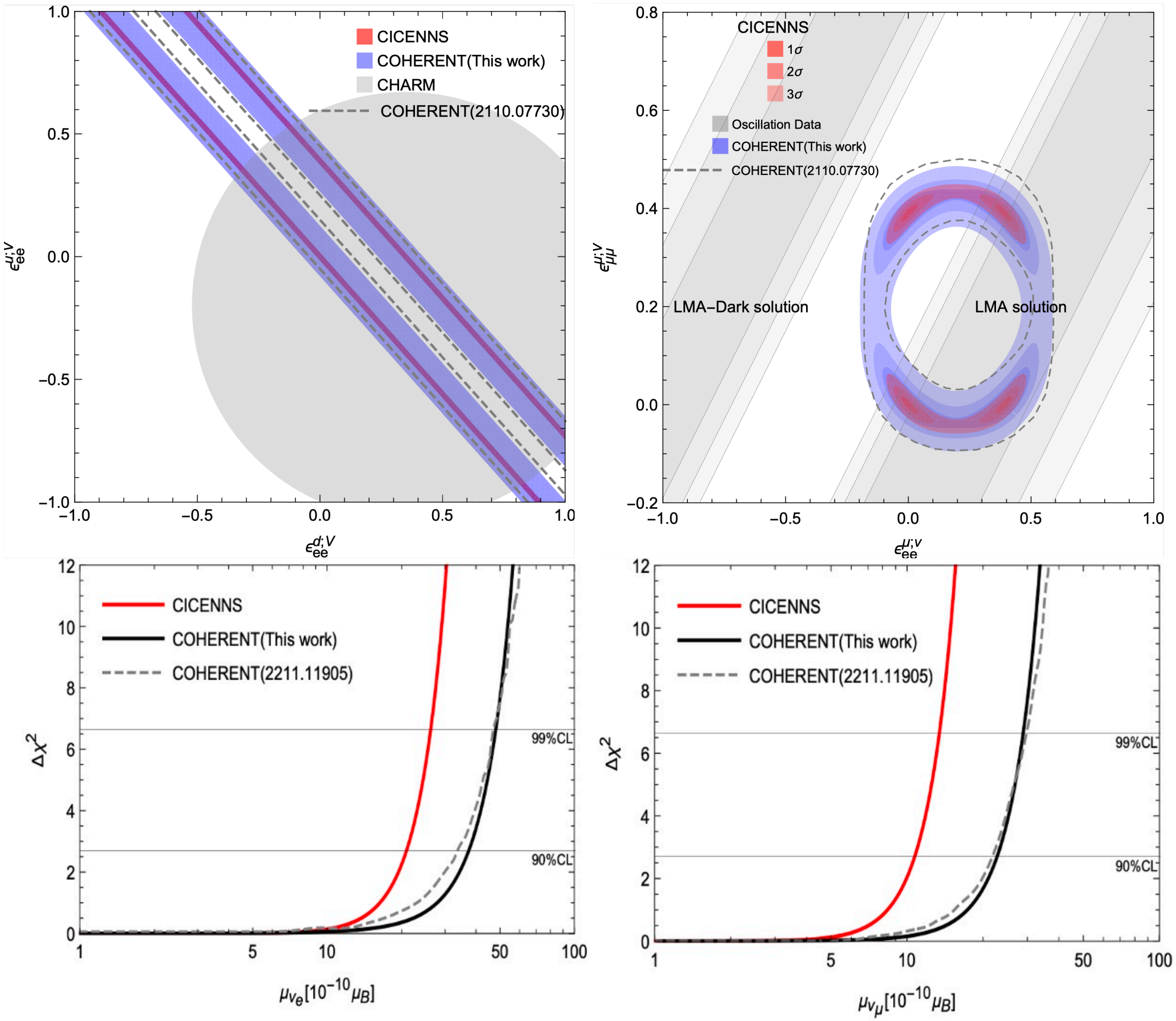






- Current uncertainty of the measured CEvNS cross section is ~16% while that of the SM prediction is 4.8%.
- The 300 kg CICENNS detector will reduce the uncertainty to roughly 6.5%.

New physics


CICENNS
COHERENT(This work)
CHARM
COHERENT(2110.07730)
$\epsilon_{ee}^{u;V}$
$\epsilon_{ee}^{d;V}$
1.0
0.5
0.0
−0.5
−1.0
CICENNS
1σ
2σ
3σ
Oscillation Data
COHERENT(This work)
COHERENT(2110.07730)
LMA−Dark solution
LMA solution
$\epsilon_{\mu\mu}^{u;V}$
$\epsilon_{ee}^{u;V}$
0.8
0.6
0.4
0.2
0.0
−0.2
CICENNS
COHERENT(This work)
COHERENT(2211.11905)
99%CL
90%CL
$\Delta\chi^2$
$\mu_{\nu_e}[10^{-10}\mu_B]$
$\mu_{\nu_\mu}[10^{-10}\mu_B]$
12
10
8
6
4
2
0
1
5
10
50
100

Summary

- CEvNS can be used as a new tool to probe the neutrino and nuclear physics at the low energy region.
- CEvNS can provide as an independent measurement of the quenching factor that is not well understood at the ultra-low energy threshold.
- A CEvNS experiment with a O(10) eV threshold has the potential to detect the low energy reactor neutrino flux below IBD threshold.
- A 300kg CICENNS detector will be built at CSNS to do a precision measurement of CEvNS.

Thanks!