Measuring reactor neutrinos with CEvNS

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In collaboration w/ Hongkai Liu and Danny Marfatia

arXiv: 2104.01811, Phys. Rev. D 104, 015005 (2021)
arXiv: 2202.10622, Phys. Rev. D 106, L031702 (2022)
arXiv:2302.10460

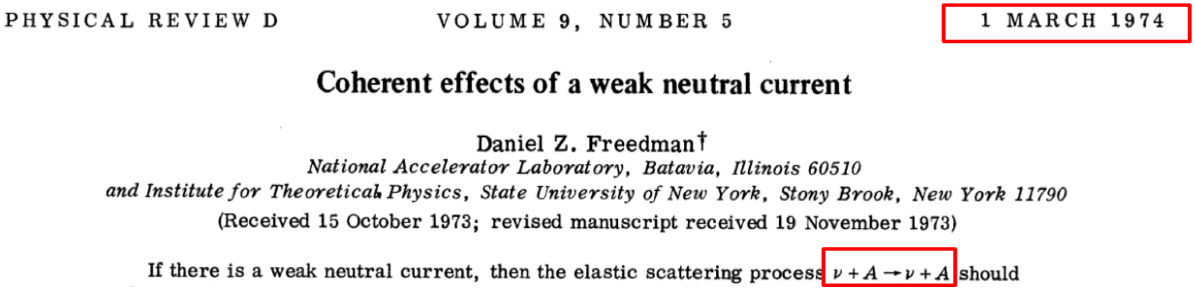
The 29th International Workshops on
Weak Interactions and Neutrinos
Zhuhai, 7/7/2023

Outline

- CEvNS with reactor neutrinos
- Indirect measurement of quenching factor
- Reactor neutrino flux below IBD
- Summary

CEνNS with reactor neutrinos

Coherent Elastic ν-Nucleus Scattering

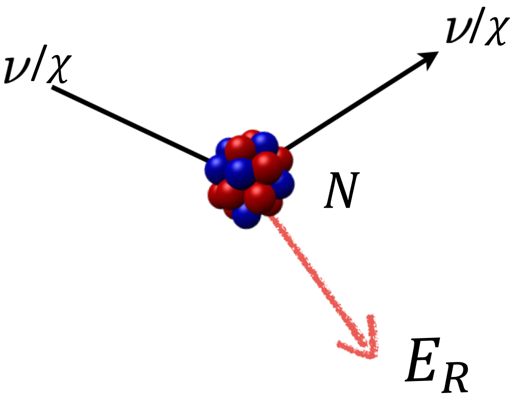


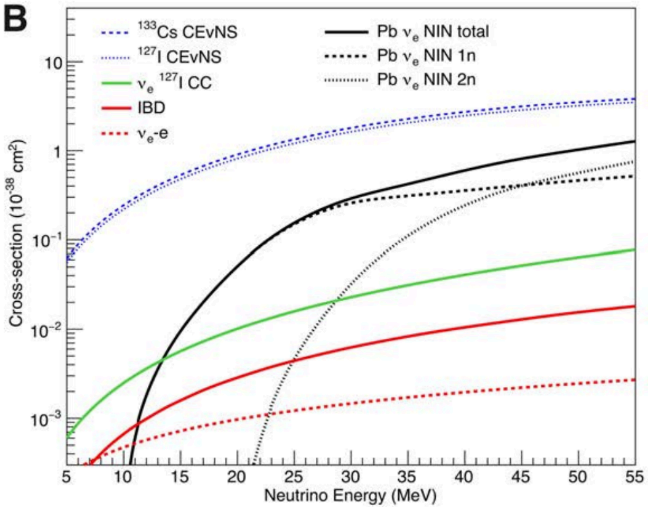
PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

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





COHERENT, Science 357,1123 (2017)

Moment transfer ⟶ $q \lesssim 1/R$ ⟵ Nuclear radius

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

DM direct detection experiments ⟹ detection thresholds of 10 keV

CEνNS experiments

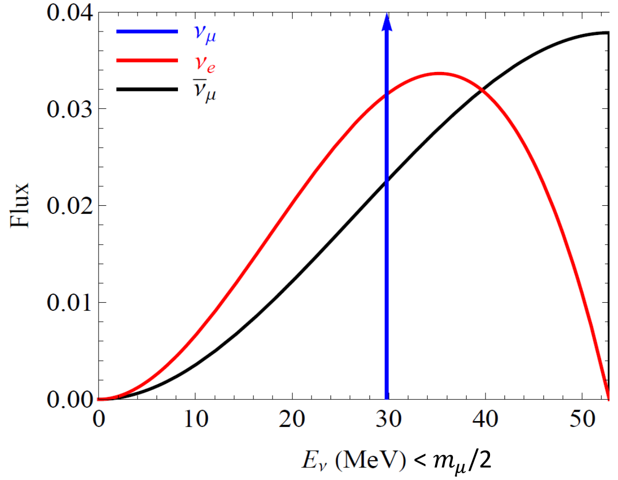
- πDAR source @ SNS

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

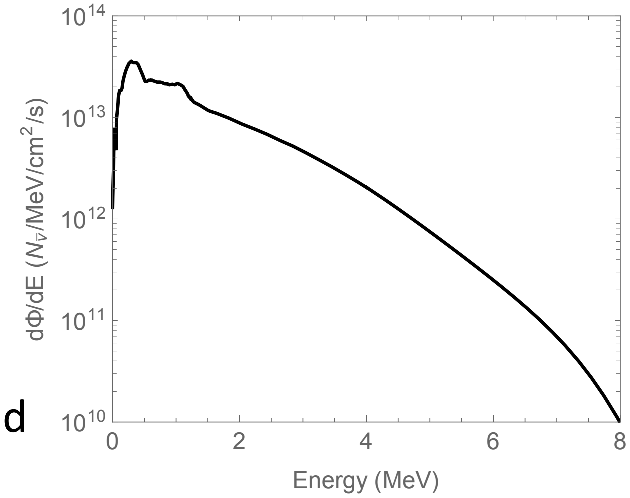
CONNIE, PRL 126, 041804 (2021)

νGeN uses a Ge detector with 0.3 keV_{ee} threshold

νGeN, PRD 106, L051101 (2022)

Dresden-II uses a Ge detector with 0.2 keV_{ee} threshold

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



CEνNS spectrum

- Differential cross section

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

- 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:

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

Lindhard Model

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

where $g(\epsilon) = 3\,\epsilon^{0.15} + 0.7\,\epsilon^{0.6} + \epsilon$

Lindhard el al, Mat. Fys. Medd.
Dan. Vid. Selsk. 33 10 (1963)

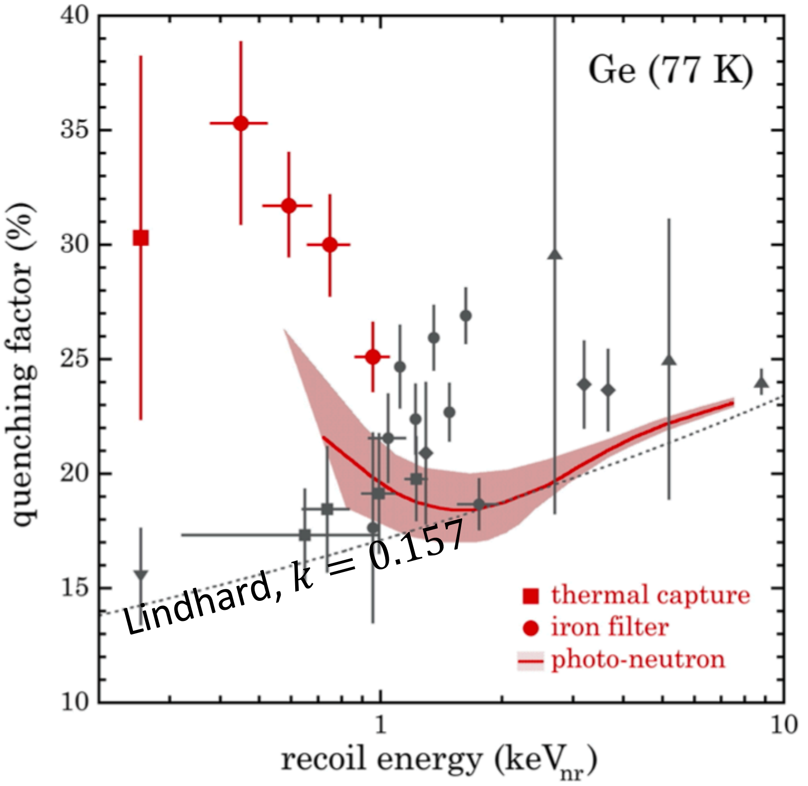
dimensionless reduced energy:

$$\epsilon = 11.5Z^{-\frac{7}{3}}\left(\frac{E_R}{\mathrm{keV_{nr}}}\right)$$

the slope of electronic stopping power

$$k = 0.1333Z^{\frac{2}{3}}A^{-\frac{1}{2}}$$

A larger k value leads to larger fraction of total energy going into electron.



Collar, et al, PRD 103, 122003 (2021）

Modified Lindhard Model

Key approximations made in Lindhard model：

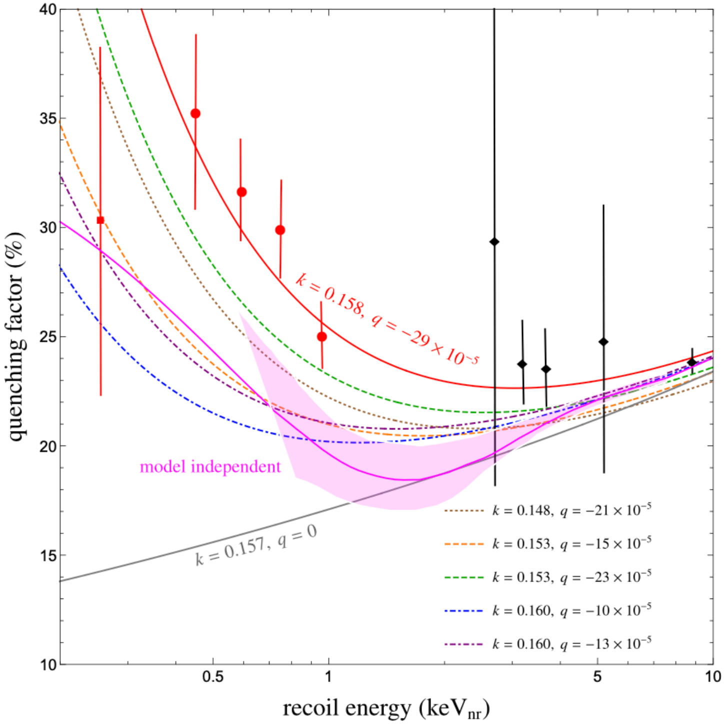
- Atomic binding energy of electrons is negligible.
- Energy transfers to electrons are small wrt energy transfers to atoms.

Sorensen, PRD 91, 083509 (2015) [arXiv: 1412.3028]

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

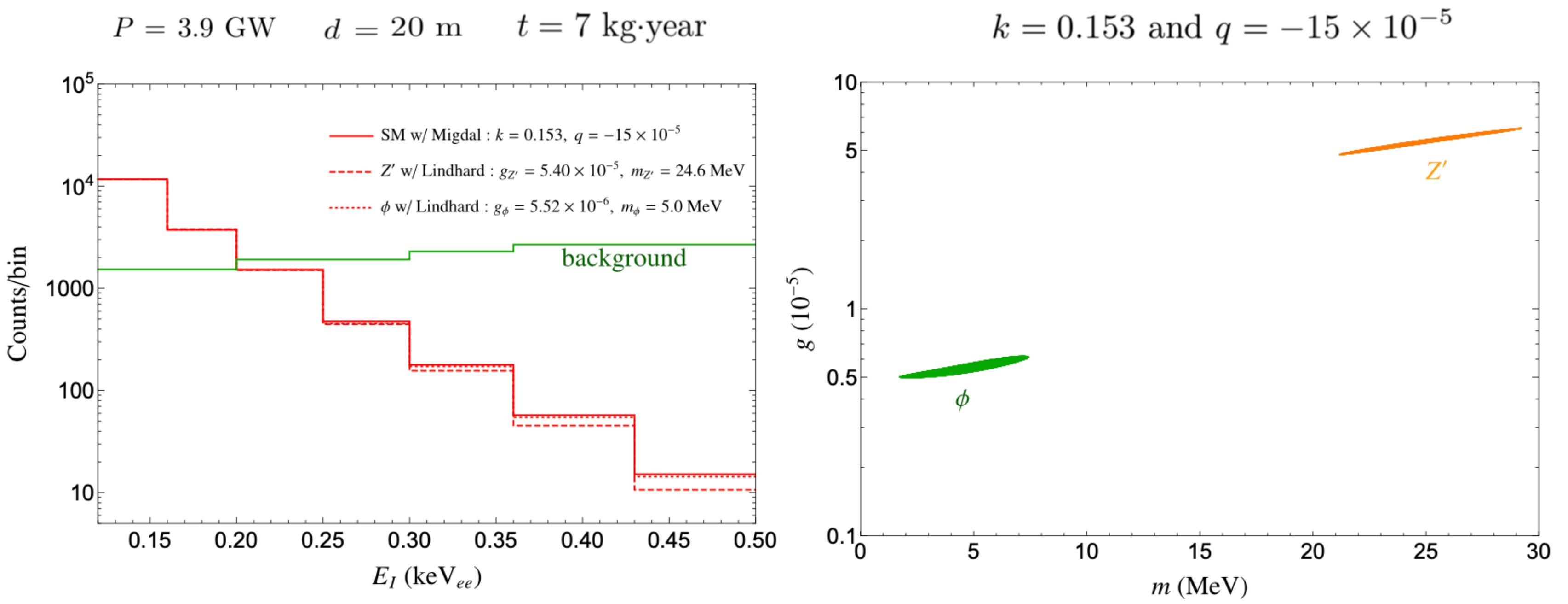
Lindhard model

- 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.



JL, Liu, Marfatia, PRD 104, 015005 (2021)

Mimic the signal of new physics

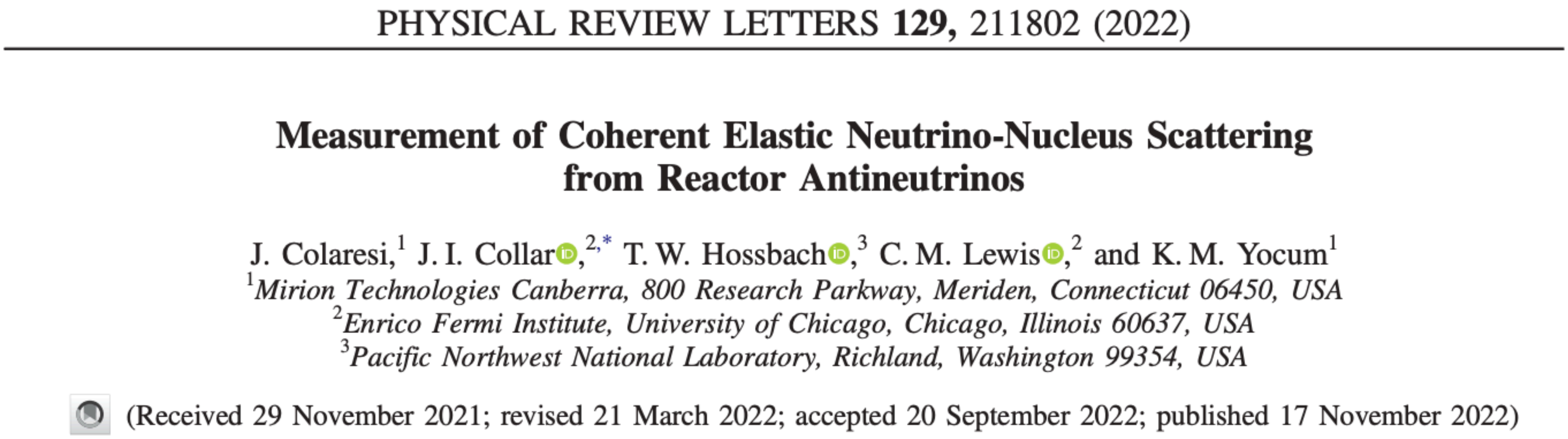


JL, Liu, Marfatia, PRD 104, 015005 (2021)

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

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

Indirect measurement of quenching factor



PHYSICAL REVIEW LETTERS **129,** 211802 (2022)

Measurement of Coherent Elastic Neutrino-Nucleus Scattering from Reactor Antineutrinos

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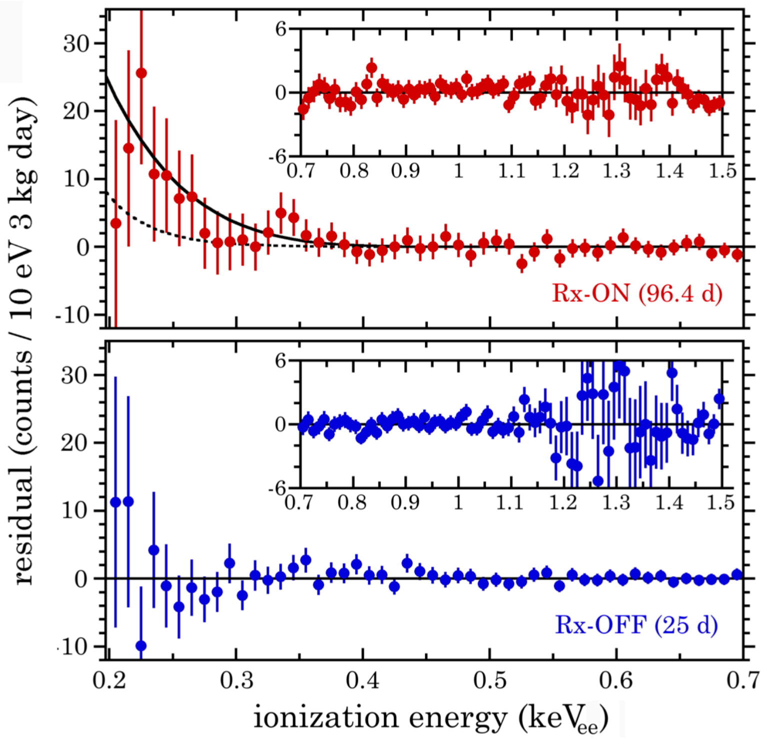
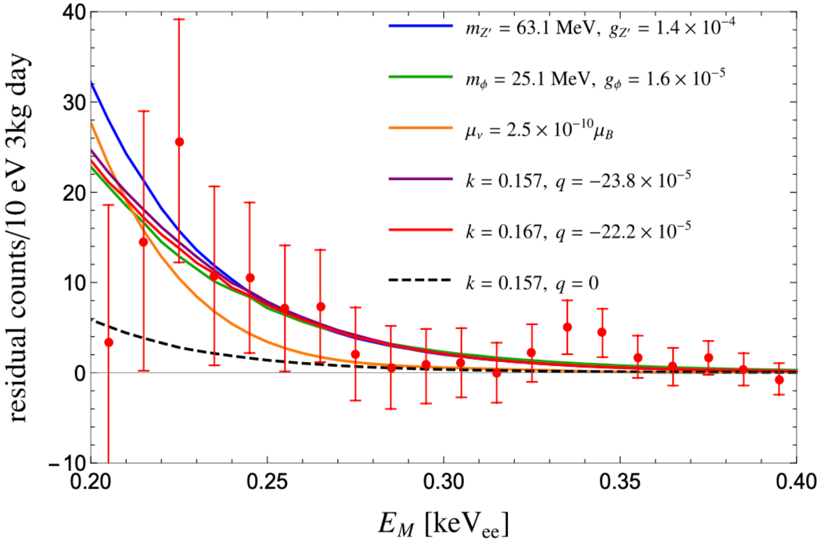
(Received 29 November 2021; revised 21 March 2022; accepted 20 September 2022; published 17 November 2022)

- Dotted line corresponds to the SM CEvNS prediction with the Lindhard model QF.
- Solid line shows the SM CEvNS prediction using their new measurement of QF.
- A very strong preference ($p < 1.2 \times 10^{-3}$) for the presence of CEvNS.
- Caveats: Incomplete background model may be employed.

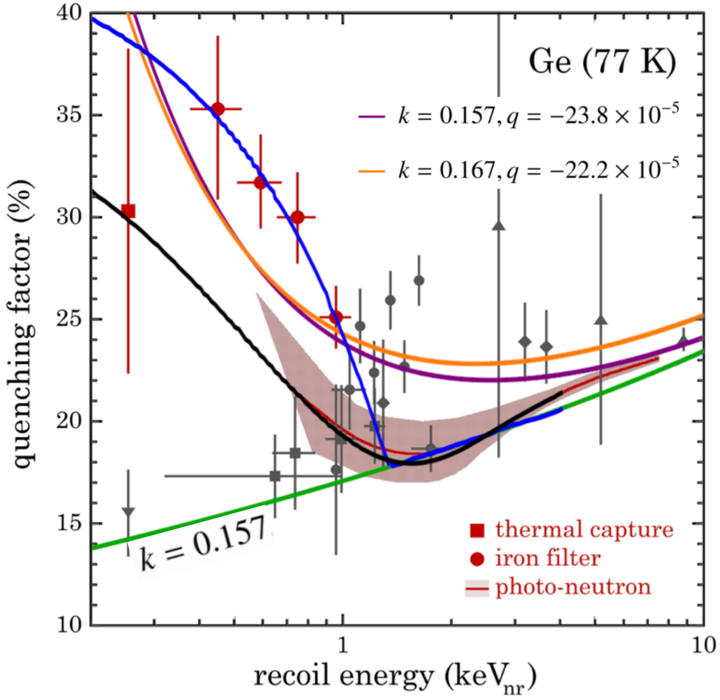


Indirect measurement of QF



- A negative value of q is preferred by the Dresden data at 2.5σ in SM.

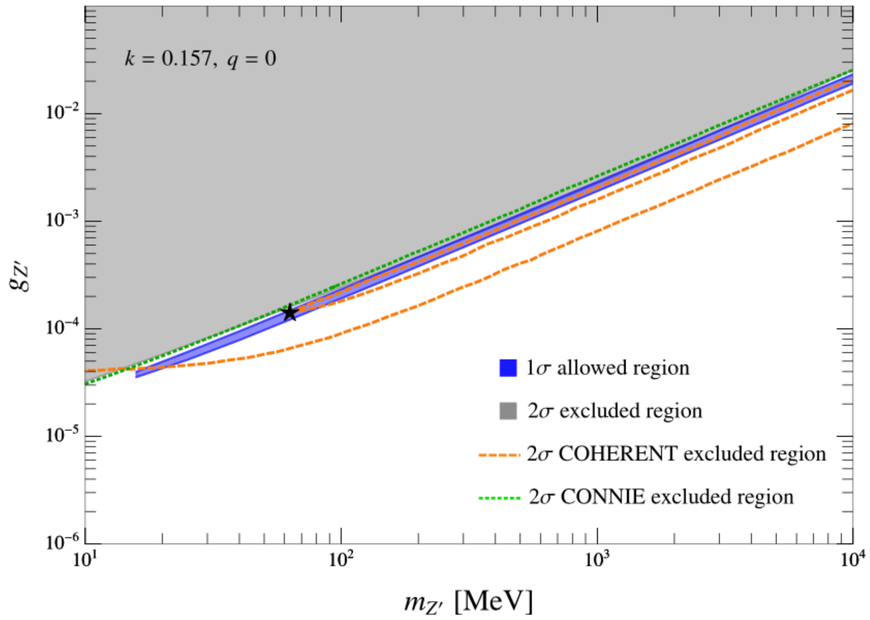
- This best-fit point is consistent with direct QF measurements using neutron source.

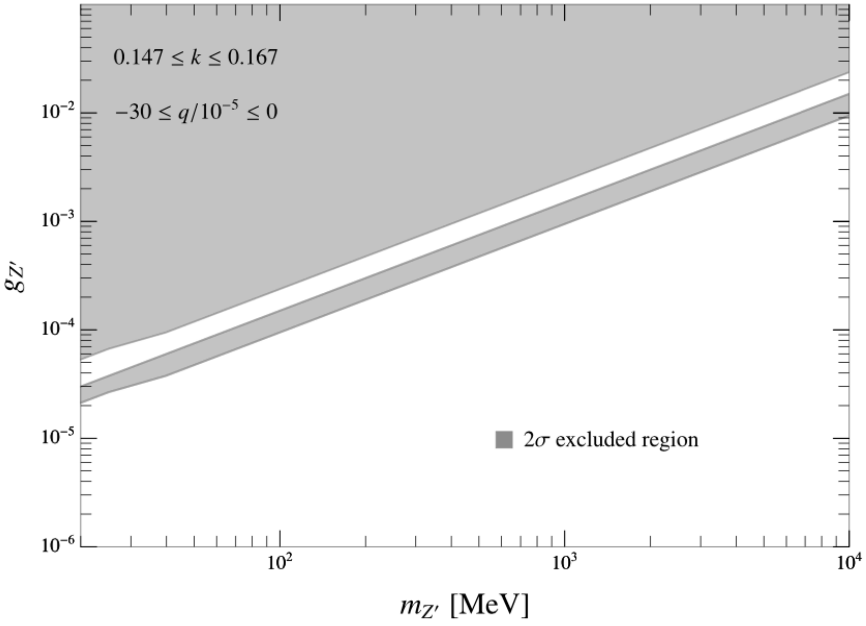


Blue (black) line are based on the data from the direct iron filter (photo-neutron) measurement.

JL, Liu, Marfatia, PRD 106, L031702 (2022)

Constraints on new physics





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

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

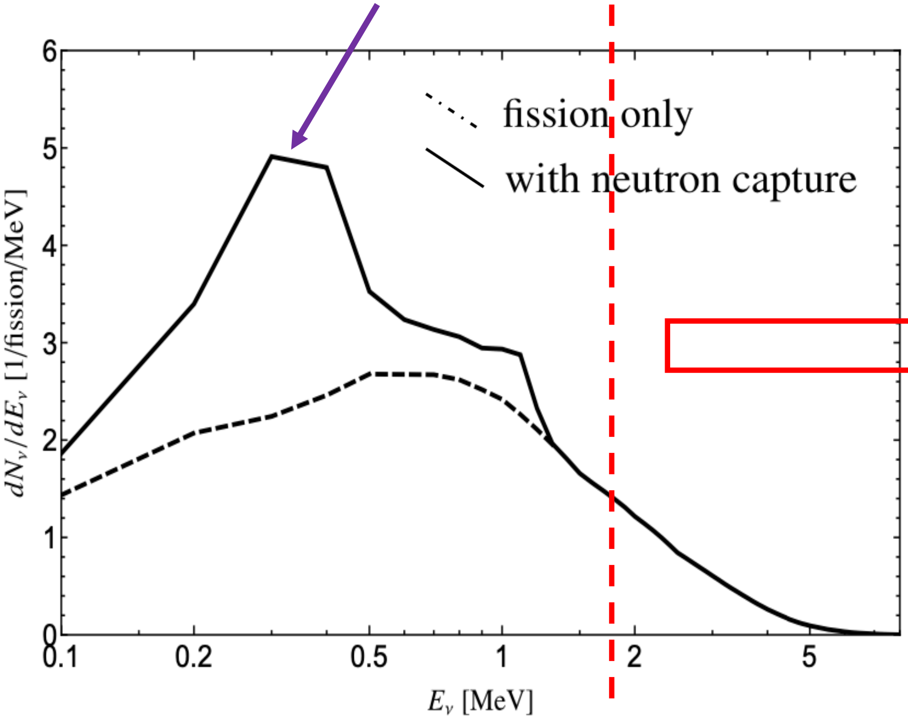
Measure reactor neutrinos below IBD

Reactor neutrino flux

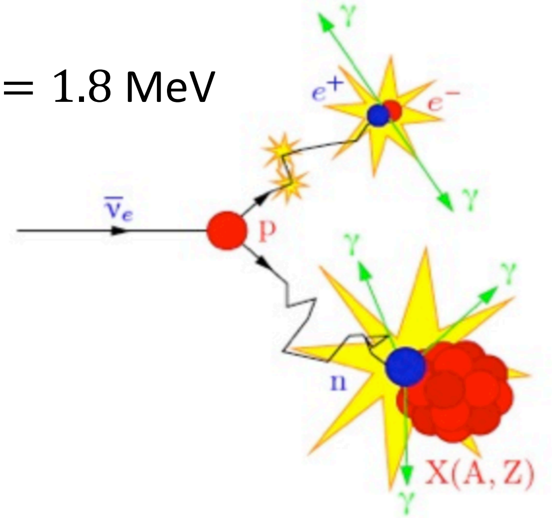
TEXONO, hep-ex/0605006

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

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



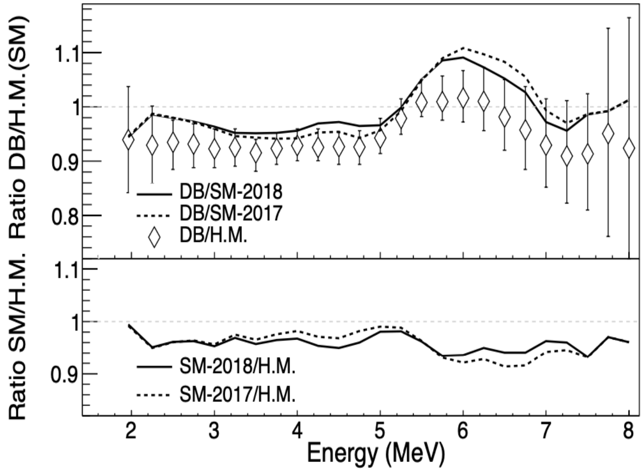
E_{th} = 1.8 MeV



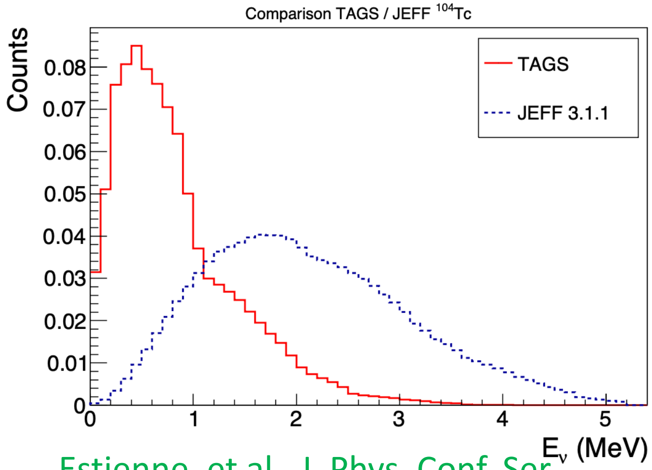
Theoretical predictions

- **Conversion method:**
  Huber-muller model, only allows an estimate of the reactor neutrino spectrum between 2−8 MeV. It does not predict the 5 MeV bump.

- **Summation method:**
  sum over all contributions of fission products from the nuclear data libraries, suffered from unknown branching ratios due to the Pandemonium effect.



Estienne, et al., PRL 123, 022502 (2019)

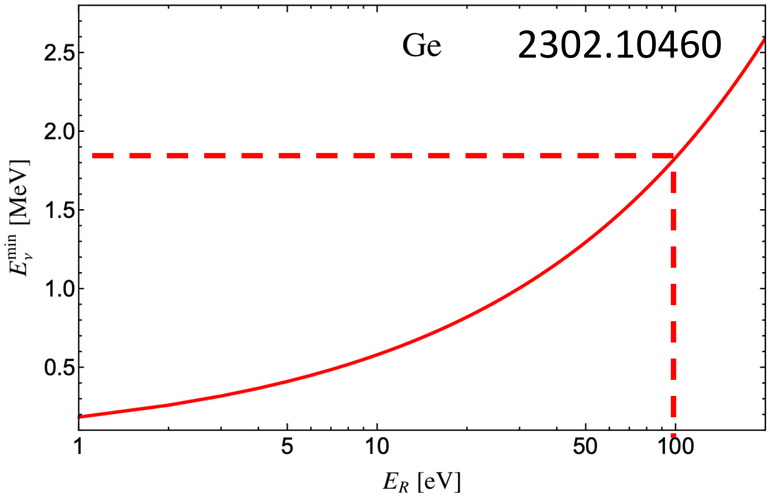


Estienne, et al., J. Phys. Conf. Ser. 1643, 012022 (2020).

NUCLEUS experiment

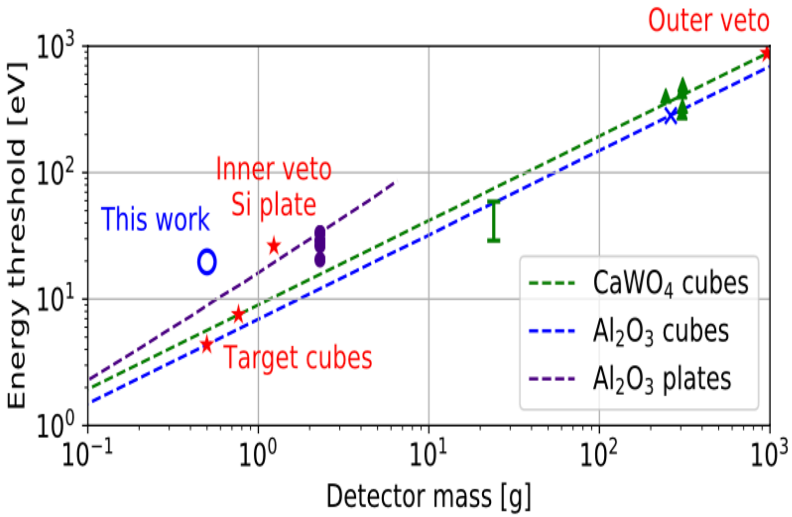
- NUCLEUS uses cryogenic calorimeters to measure the temperature rise and has achieved a 20 eV threshold using a 0.5 g prototype made from Al_2O_3.

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 ultralow energy threshold of 5 eV.

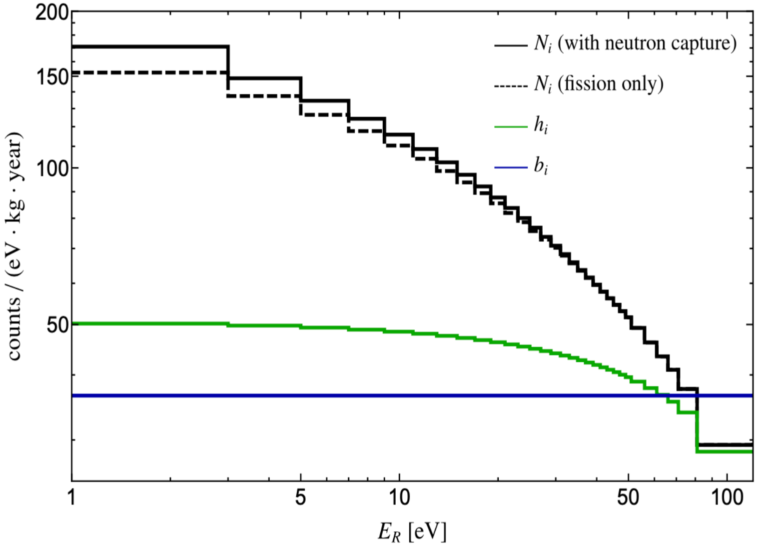
EPJC 79, 1018 (2019) [1905.10258]



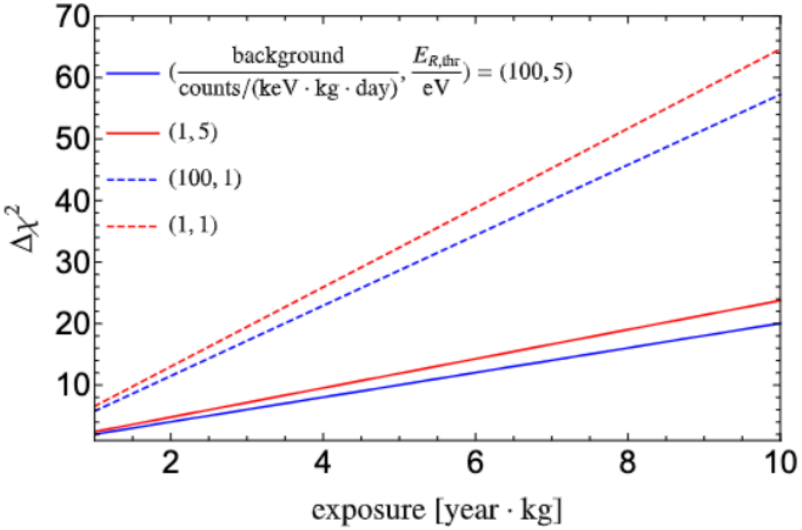
NUCLEUS spectrum

$$N_j = N_T t \int_{E_R^j}^{E_R^{j+1}} dE_R \int dE_\nu \frac{d\Phi}{dE_\nu} \frac{d\sigma}{dE_R} \,.$$

$$h_j \equiv \frac{t N_T P}{4\pi d_{\rm eff}^2 \tilde{\epsilon}} \int_{E_R^j}^{E_R^{j+1}} dE_R \int_{E_\nu > 2.0~\mathrm{MeV}}^{\infty} \frac{dN_\nu}{dE_\nu} dE_\nu \frac{d\sigma}{dE_R}$$



- High energy neutrino flux (E_ν > 2 MeV) has a negligible contribution to the low-energy CEvNS spectrum.
- The existence of neutron capture component can be established at 3σ with 5 year·kg exposure.



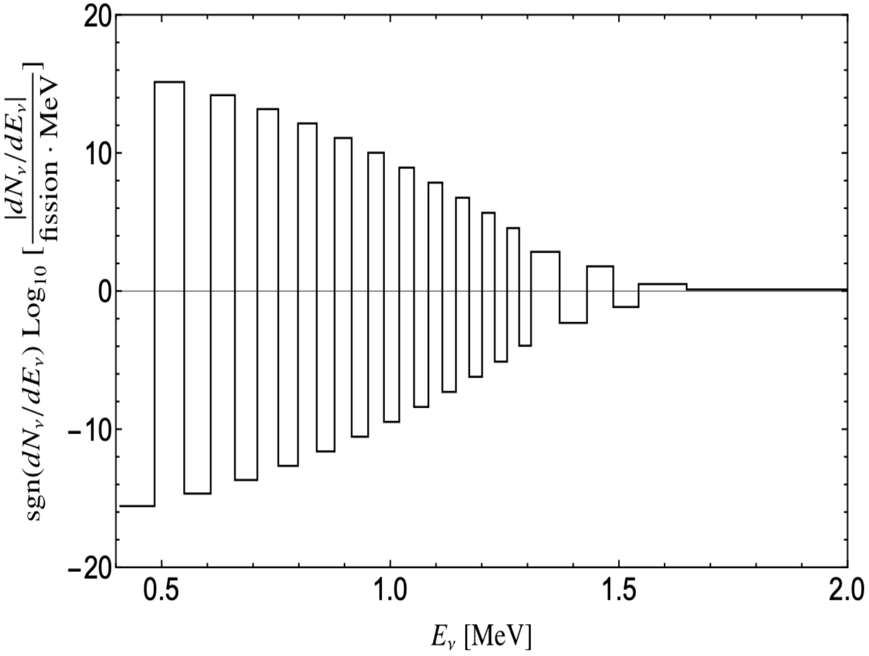
Normal unfolding

CEvNS spectrum:

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

Response matrix

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



Neutrino flux:

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

Statistical fluctuations in observed spectrum

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

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

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

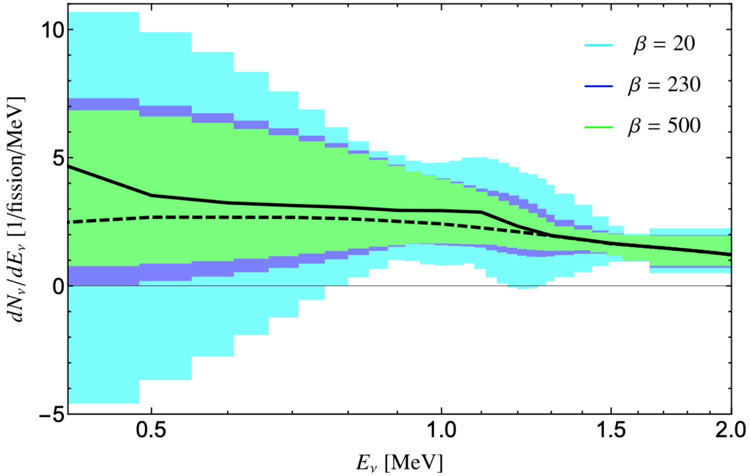
β selection criterion

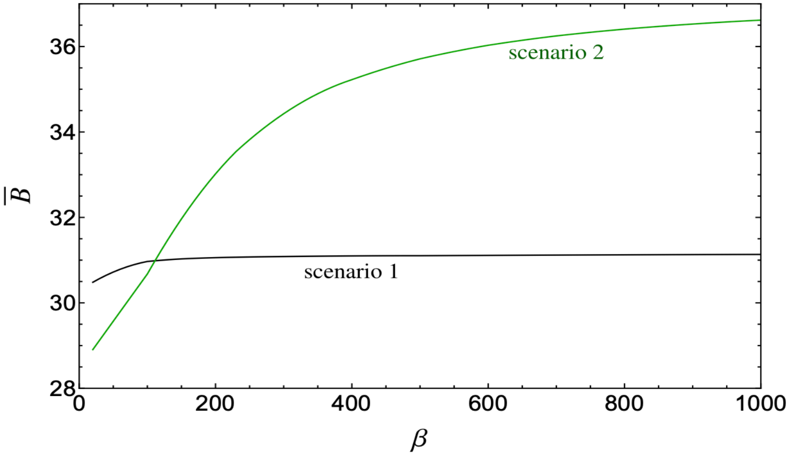
- A large β suppresses the variance, but allows an increased bias.

- The physical criterion: we choose the smallest value of β that yields a positive definite flux at all energies.

- Average bias $\overline{B}$ plateaus at a value that is not much larger than the number of bins *m.*

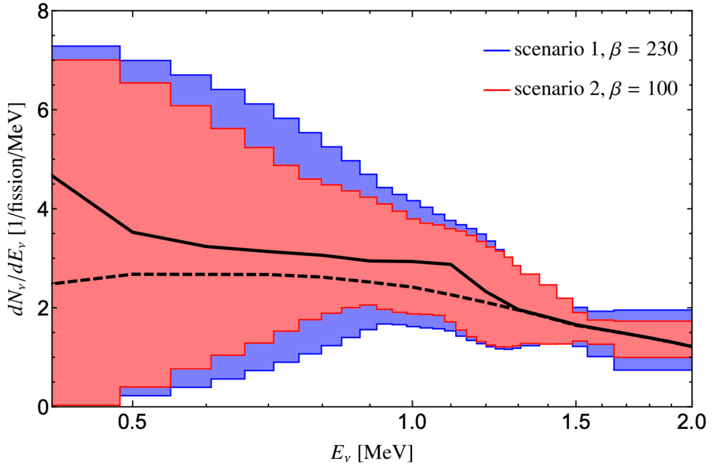
- Consistent with a strategy for selecting β that lowers β until $B \sim m$





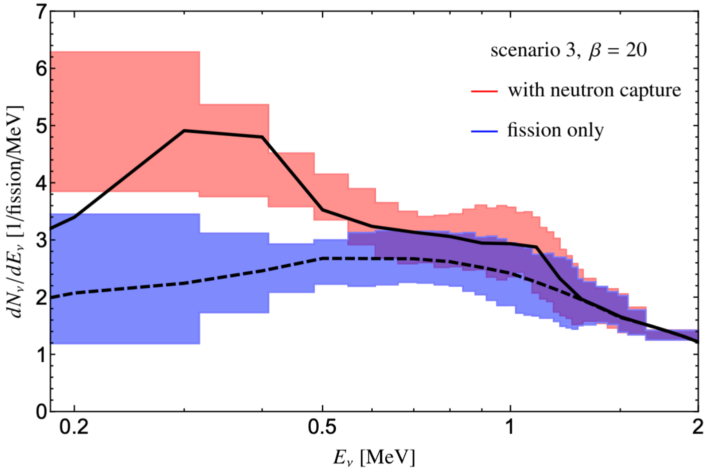
Results

- scenario 1: $t = 1$ kg $\cdot$ year, bkg $= 100$ counts/(keV $\cdot$ kg $\cdot$ day), $E_{R,\mathrm{thr}} = 5$ eV.
- scenario 2: $t = 3$ kg $\cdot$ year, bkg $= 1$ count/(keV $\cdot$ kg $\cdot$ day), $E_{R,\mathrm{thr}} = 5$ eV.
- scenario 3: $t = 300$ kg $\cdot$ year, bkg $= 1$ count/(keV $\cdot$ kg $\cdot$ 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, in which case the uncertainty bands will have considerable overlap.



Summary

- Recent direct measurements of Ge quenching factor indicates a departure from the standard Lindhard model at low energies.
- Modification of quenching factor can mimic the signal of new physics.
- CEvNS experiments can provide an independent measurement of quenching factor if there is no new physics at present.
- Majority of reactor neutrino flux has not been measured, and an ultra-low threshold CEvNS experiment like NUCLEUS has the potential to probe the reactor neutrino flux below IBD.

Thanks!

Backup slides

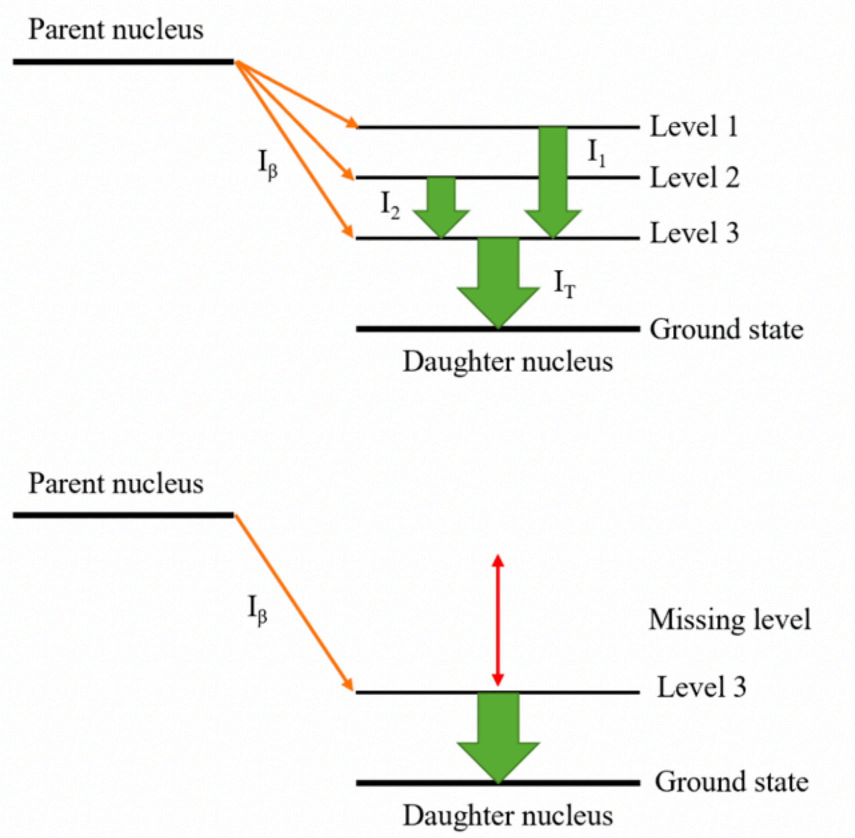
Pandemonium effect

- Limited efficiency of detecting gamma-rays from the de-excitation of high energy nuclear levels

- Leads to an underestimate of some beta branching fractions in the beta decay into the high energy levels of daughter nuclei.

  J. C. Hardy et al., Phys. Lett. B 71, 307 (1977).

- Can be corrected by Total Absorption Gamma-ray Spectroscopy (TAGS) technique.



Ang, Li and Prasad, 2112.12250