Recent progress in CEvNS theory

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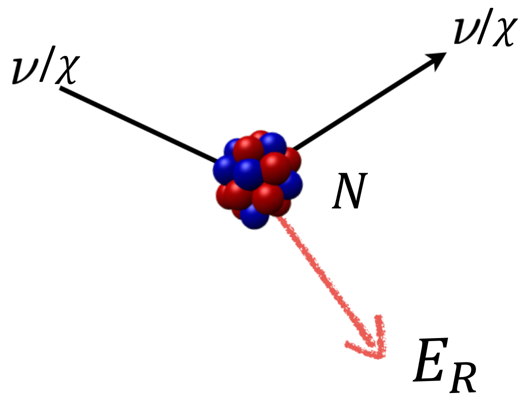
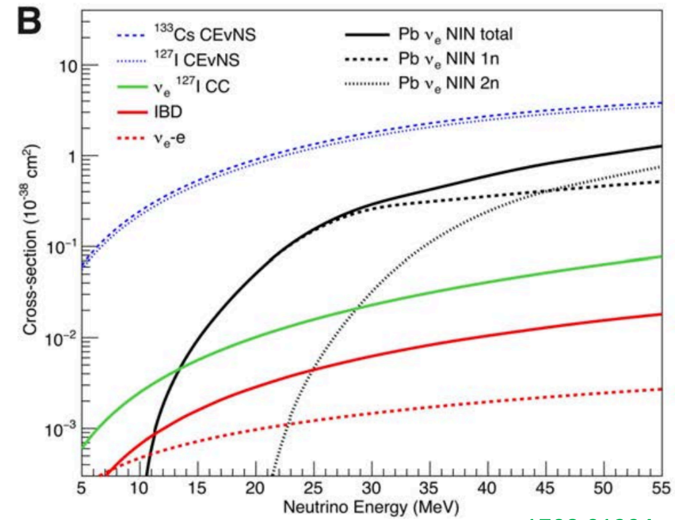
Outline

- Introduction to CEvNS
- Recent studies in CEvNS theory
  - ➢ Implications from recent CEvNS data
  - ➢ CEvNS as a probe of neutrino sources
  - ➢ Coherent scattering in new processes
- Summary

Coherent Elastic ν-Nucleus Scattering





1708.01294

Coherence condition: $qR \lesssim 1$, Momentum transfer $q = \sqrt{2ME_r}$

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

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

$F(q^2)$: nuclear form factor

$$Q_{\rm SM}^2 = (Zg_p^V + Ng_n^V)^2 \quad \begin{cases} g_p^V = \frac{1}{2} - 2\sin^2\theta_W \sim 0.03 \\ g_n^V = -0.5 \end{cases}$$

$\Longrightarrow$ $\sigma_{\rm SM} \propto N^2$

Route to the discovery of CEvNS

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.

PRL **100,** 021303 (2008) PHYSICAL REVIEW LETTERS week ending 18 JANUARY 2008

First Results from the XENON10 Dark Matter Experiment at the Gran Sasso National Laboratory

PRL **117,** 121303 (2016) PHYSICAL REVIEW LETTERS week ending 16 SEPTEMBER 2016

Dark Matter Results from First 98.7 Days of Data from the PandaX-II Experiment

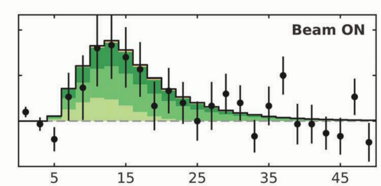
PHYSICAL REVIEW LETTERS **120,** 241301 (2018)

Limits on Light Weakly Interacting Massive Particles from the First 102.8 kg × day Data of the CDEX-10 Experiment

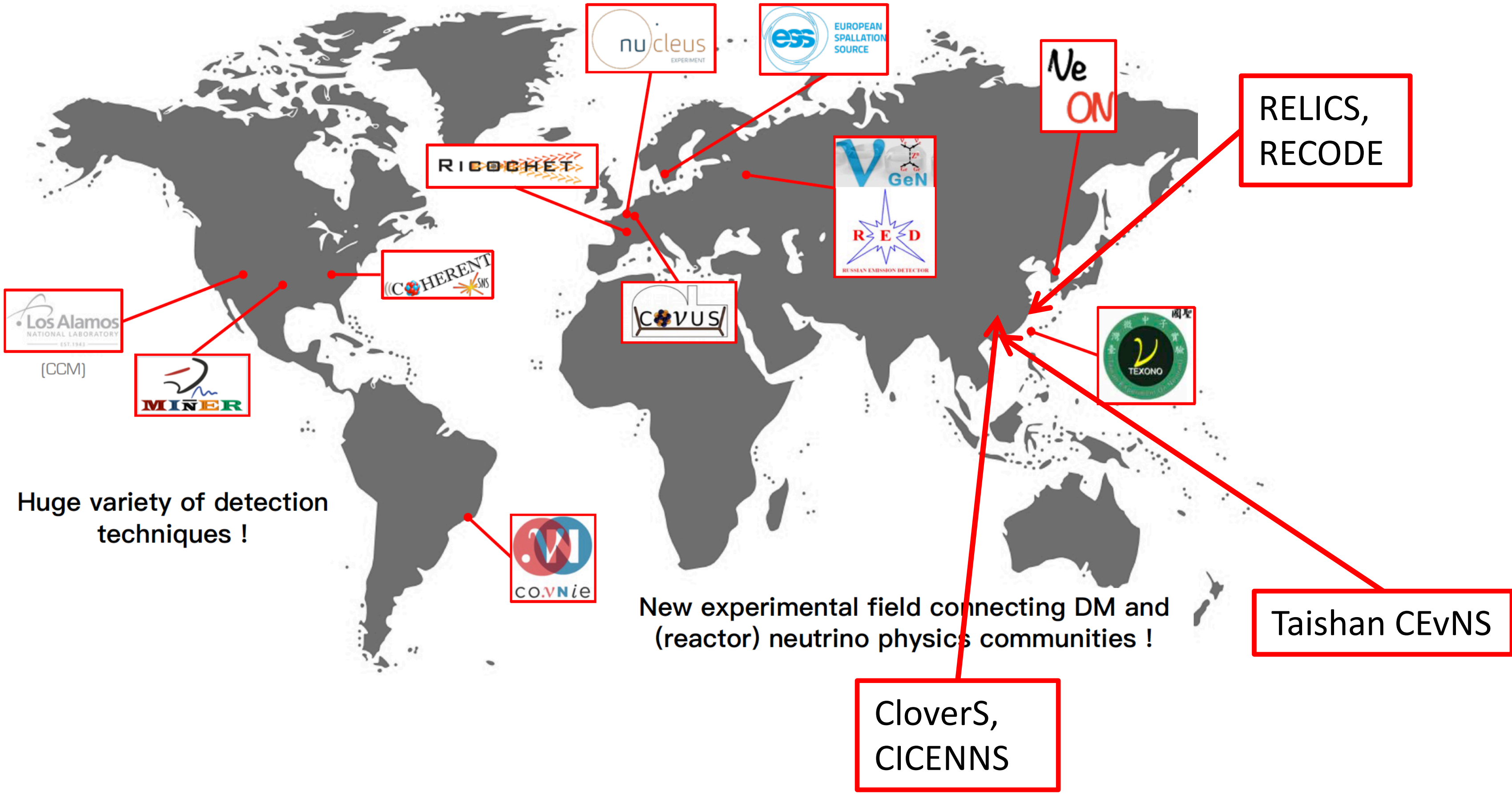
RESEARCH

NEUTRINO PHYSICS

Observation of coherent elastic neutrino-nucleus scattering



Global efforts



Adapted from M. VIVIER@Magnificent CEvNS 2020

Current measurements

- πDAR source @ SNS

  COHERENT first observed in 2017 at 6.7σ, improved in 2022 at 11.6σ with a CsI detector

  COHERENT, Science 357,1123 (2017)

  COHERENT, PRL 129 081801 (2022)

  Later confirmed in 2021 with LAr detector and in 2025 with Ge detector

  COHERENT, PRL 126, 012002 (2021)

  COHERENT, PRL 134, 231801 (2025)

- Reactor neutrino source

  Dresden-II see a strong preference in a Ge detector

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

  CONUS+ first observed at 3.7σ in a Ge detector

  CONUS+, Nature 643, 8074 (2025)

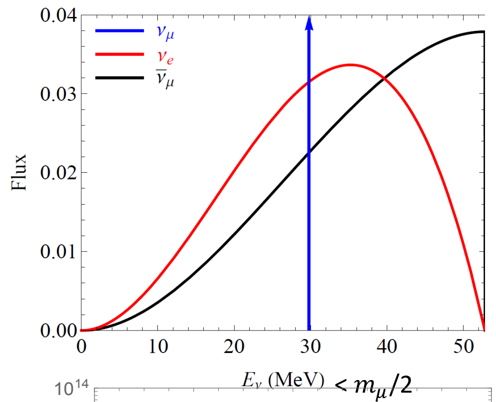
- Solar ^{8}B neutrino source

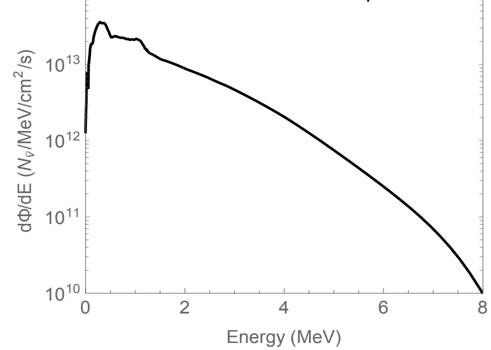
  PandaX-4T detected at 2.64σ in a LXe detector

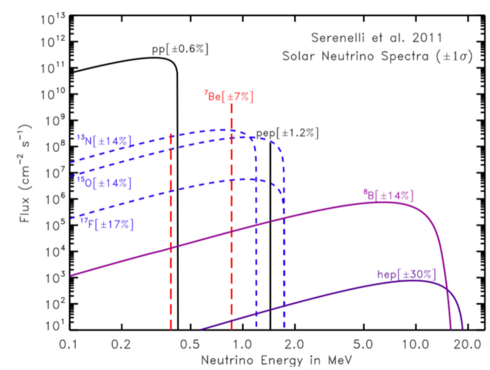
  PandaX, PRL 133, 191001 (2024)

  XENONnT detected at 2.73σ in a LXe detector

  XENON, PRL 133, 191002 (2024)

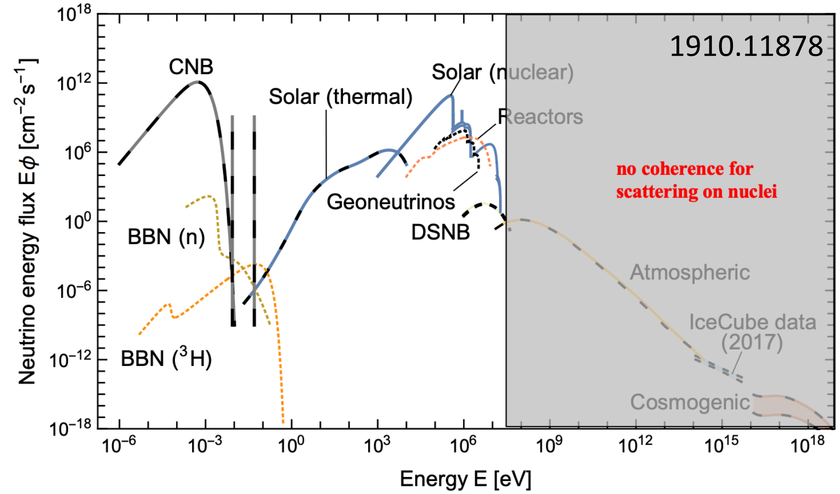


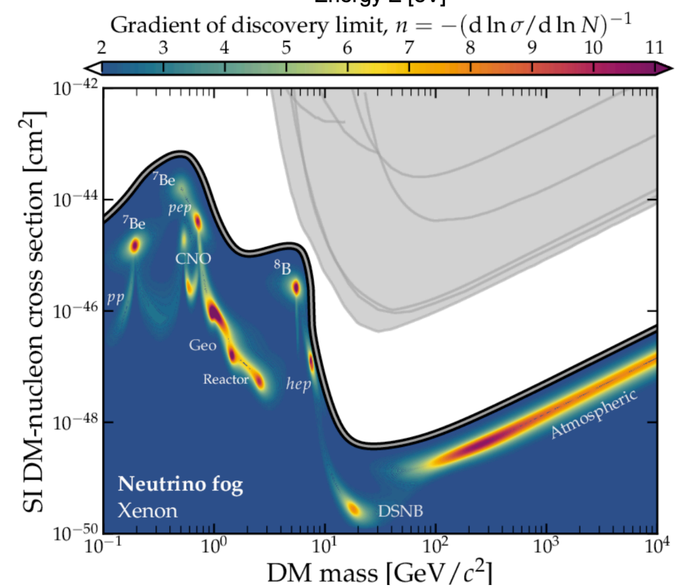




Physics potential of CEvNS

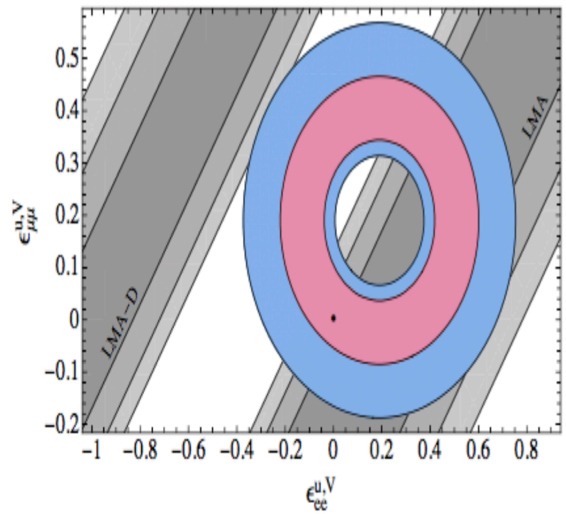
- **SM tests:** weak mixing angle, electroweak charges;
- **Neutrino properties:** neutrino magnetic moment, neutrino charge radius, radiative corrections;
- **New physics:** nonstandard interactions, light mediators, generalized interactions, light dark matter, sterile neutrinos;
- **Nuclear physics:**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





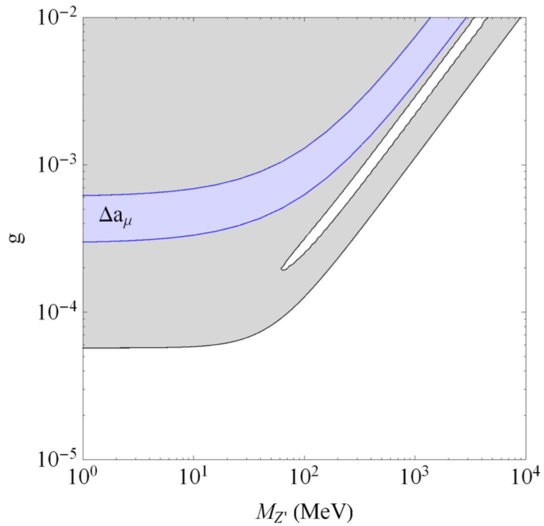
O'Hare, PRL [2109.03116]

Nonstandard interactions



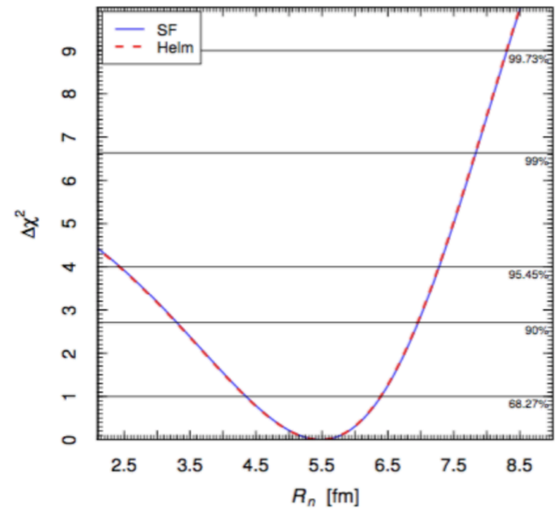
Coloma, et.al., PRD [1708.02899]

Light mediators



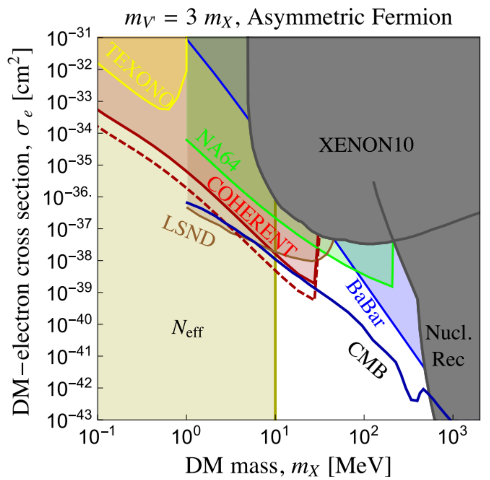
JL, Marfatia, PLB [1708.04255]

Neutron radius



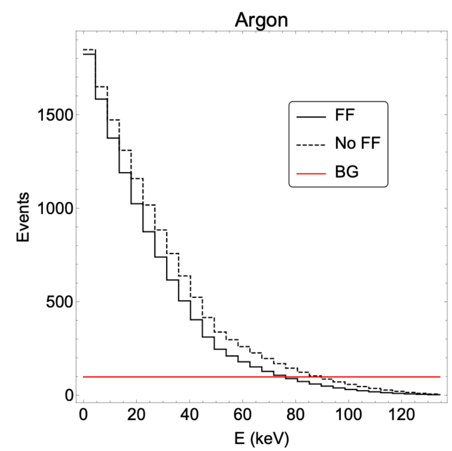
Cadeddu, Giunti, Li, Zhang PRL[1710.02730]

Photon Portal DM



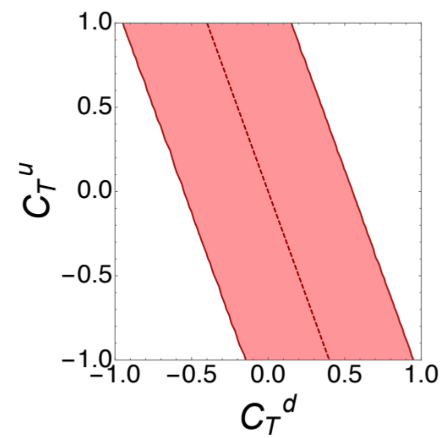
Ge, Shoemaker, PRD [1710.10889]

Nuclear form factor



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

Generalized Interactions



Aristizabal Sierra et.al., JHEP [1806.07424]

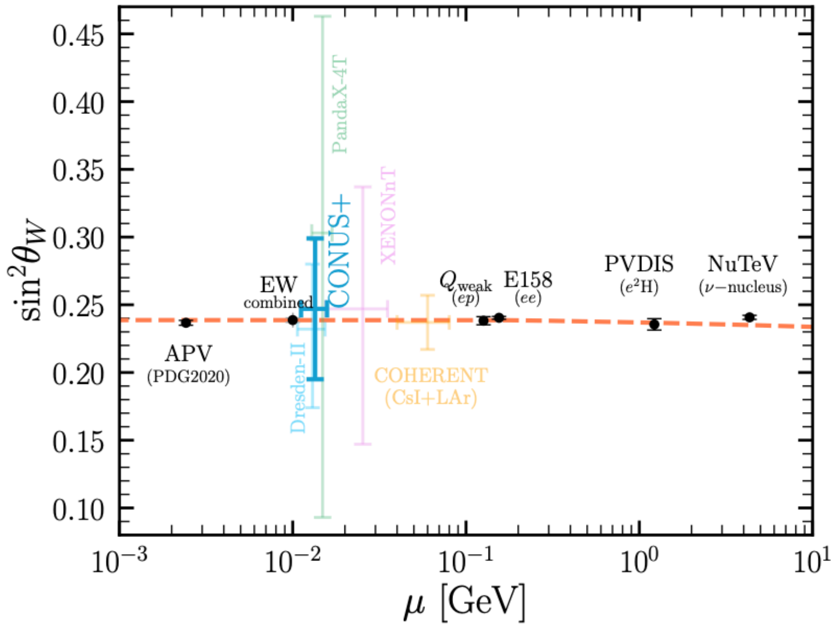
Recent studies in CEvNS theory

- Implications from recent CEvNS data
- CEvNS as a probe of neutrino sources
- Coherent scattering in new processes

SM tests: Weak mixing angle

$$\frac{d\sigma}{dE_N} = \frac{G_F^2}{4\pi} Q_W^2 m_N \left(1 - \frac{m_N E_N}{2E_\nu^2}\right) F^2(E_N)\,, \quad Q_W = N - Z(1 - 4\sin^2\theta_W)$$

- CEvNS provides low-Q^2 test of $\sin^2\theta_W$; complementary to atomic parity violation and electron scattering.



De Romeri, Papoulias, Sanchez Garcia, PRD [2501.17843]

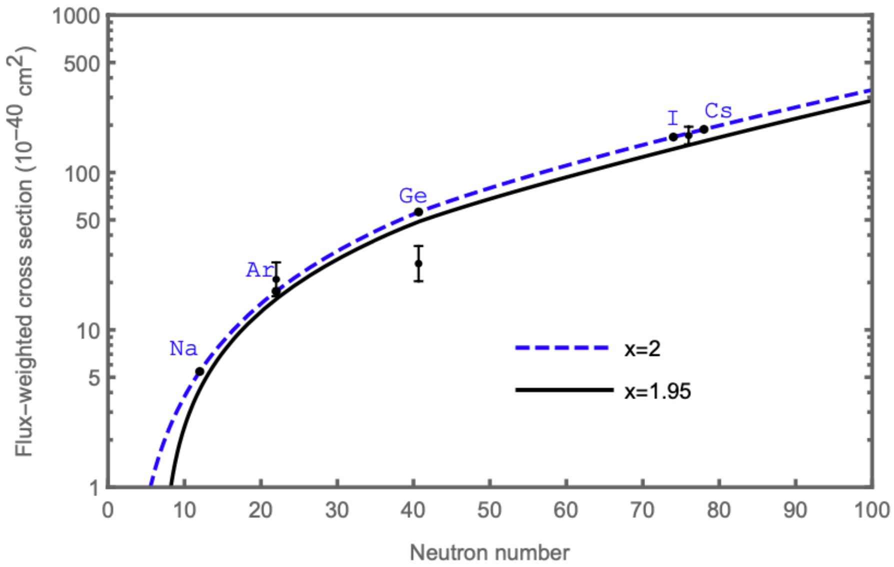
See also, Atzori Corona et.al., PRD [2501.18550]

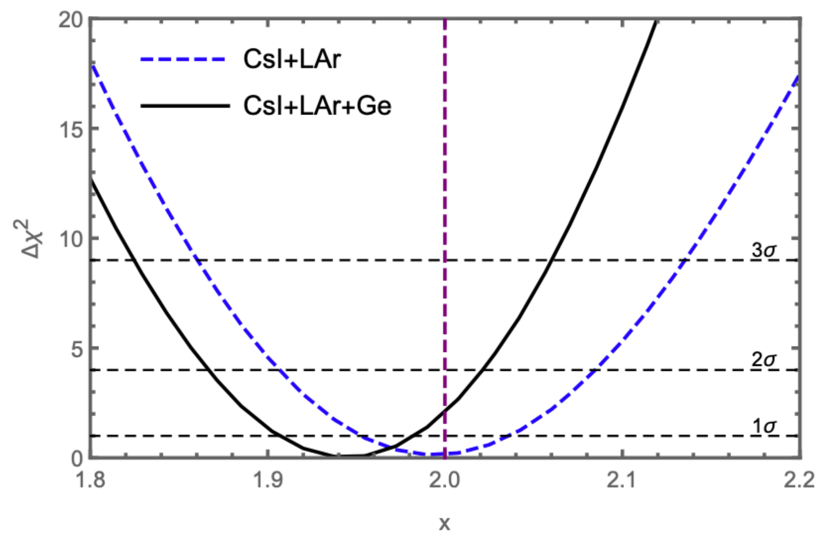
SM tests: N^2 dependence

$$Q^2_{\rm SM} = \left[N g_V^n F_N(q^2) + Z g_V^p F_Z(q^2)\right]^2$$

$$\Longrightarrow \quad Q^x_{\rm SM} = \left[N g_V^n F_N(q^2) + Z g_V^p F_Z(q^2)\right]^x$$

➢ Introduced parameter x: $x = 2 \to$ full coherence; $x = 1 \to$ total decoherence.





JL, Marfatia, Zhang, PRD [2408.06255]

See also, Kerman et.al., PRD [1603. 08786]

BSM constraints: ν magnetic moment

$$\frac{d\sigma^{\rm MM}_{\nu_\ell\text{-}\mathcal{N}}}{dT_{\rm nr}} = \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_{\rm nr}} - \frac{1}{E}\right) Z^2 F_Z^2(|\vec{q}|^2)\left|\frac{\mu_{\nu_\ell}}{\mu_{\rm B}}\right|^2 ,$$

- $\mu_\nu^{\rm eff}$ is an effective neutrino magnetic moment depending on the neutrino beam (SNS, reactor, solar, etc.)
- Sensitivity to $\mu_\nu^{\rm eff}$ is enhanced at low-energy recoil spectrum.

Experiment	$\mu_{\nu_e}^{\rm eff}$ $(10^{-11}\ \mu_B)$	**Process**	**Reference**
CONUS+	≤ 11	CEνNS+EνES	this work
COHERENT (CsI+LAr)	≤ 360	CEνNS+EνES	[90]
DRESDEN-II	≤ 19	CEνNS+EνES	[35]
XENONnT + PandaX-4T (combined)	≤ 190	CEνNS	[20]
CONUS	≤ 7.5	EνES	[43]
Borexino	≤ 3.7	EνES	[97]
TEXONO	≤ 7.4	EνES	[98]
GEMMA	≤ 2.9	EνES	[99]
LZ	≤ 1.4	EνES	[100]
XENONnT	≤ 0.9	EνES	[100]
XENONnT+PandaX-4T+LZ (combined)	≤ 1.03	EνES	[101]

De Romeri, Papoulias, Sanchez Garcia, PRD [2501.17843]

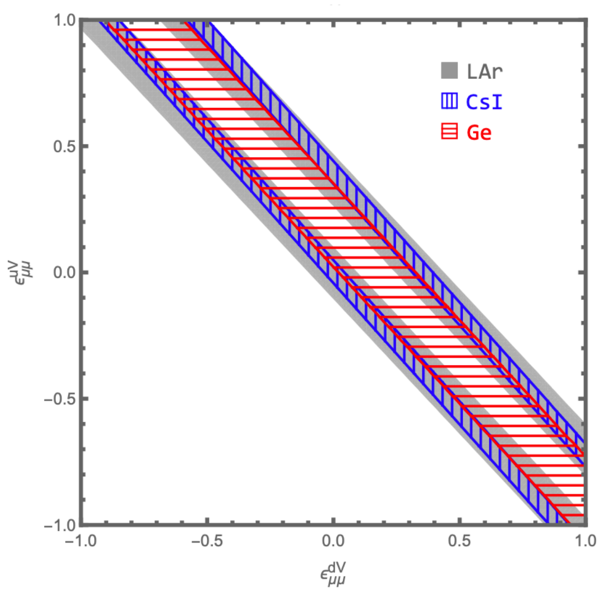
See also, Atzori Corona et.al., PRD [2501.18550]

BSM constraints: Nonstandard interactions

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

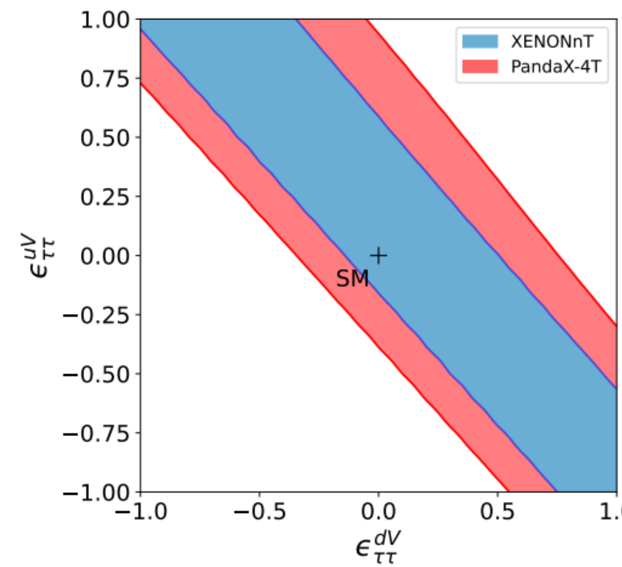
$$Q^2_{\rm NSI,\ell} = \left[\left(g_V^p + 2\varepsilon_{\ell\ell}^{uV} + \varepsilon_{\ell\ell}^{dV}\right) Z + \left(g_V^n + \varepsilon_{\ell\ell}^{uV} + 2\varepsilon_{\ell\ell}^{dV}\right) N\right]^2 + \sum_{\ell,\ell'} \left[\left(2\varepsilon_{\ell\ell'}^{uV} + \varepsilon_{\ell\ell'}^{dV}\right)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

- different materials have different slopes, combination will break degeneracies



JL, Marfatia, Zhang, PRD [2408.06255]

- DM DD experiments provide an new probe to τ-flavor NSI



Li, Song, Tang, Yu, PRD [2409.04703]

See also De Romeri, Papoulias, Sanchez Garcia, PRD [2501.17843]

BSM constraints: Generalized interactions

$$\mathcal{L}_{\rm NGI} = \frac{G_F}{\sqrt{2}} \sum_{\substack{a=S,P,V,A,T \\ q=u,d}} [\bar{\nu}\Gamma^a \nu]\ [\bar{q}\Gamma_a (C_a^q + i\gamma_5 D_a^q) q]\ , \quad \Gamma_a = \{\mathbb{I}, i\gamma_5, \gamma_\mu, \gamma_\mu\gamma_5, \sigma_{\mu\nu}\}$$

Lindner, Rodejohann, Xu, JHEP [1612.04150]

$$\left.\frac{d\sigma}{dE_{\rm nr}}\right|_{{\rm CE}\nu{\rm NS}}^{\rm NGI} = \frac{G_F^2 m_N}{4\pi} F_W^2(|\vec{q}|^2)\Big\{C_S^2 \frac{m_N E_{\rm nr}}{2E_\nu^2} + \left(C_V + 2Q_V^{\rm SM}\right)^2 \left(1 - \frac{m_N E_{\rm nr}}{2E_\nu^2} - \frac{E_{\rm nr}}{E_\nu}\right) + 8\,C_T^2 \left(1 - \frac{m_N E_{\rm nr}}{4E_\nu^2} - \frac{E_{\rm nr}}{E_\nu}\right) \pm \mathcal{R}\frac{E_{\rm nr}}{E_\nu}\Big\}.$$

Aristizabal Sierra et.al., JHEP [1806.07424];
Han, **JL**, Liu, Marfatia, JHEP [2004.13869];
Li, Ma, Schmidt, JHEP [2005.01543];
Flores,et.al.,PRD [2112.05103];
Majumda et. al., PRD [2112.03309];
De Romeri, et.al. JHEP [2211.11905], ...

- Earlier studies use the same spin-independent (SI) weak form factor for all GNI.
- Axial-vector and tensor operators induce spin-dependent (SD) contributions.
- The standard weak SI form factor → nuclear response functions

$$\left.\frac{\mathrm{d}\sigma_{\nu\mathcal{N}}}{\mathrm{d}T_\mathcal{N}}\right|^A (E_\nu, T_\mathcal{N}) = \frac{2m_\mathcal{N}}{2J+1} \frac{g_A^4}{(m_A^2 + 2m_\mathcal{N} T_\mathcal{N})^2} \left(2 + \frac{m_\mathcal{N} T_\mathcal{N}}{E_\nu^2} - \frac{2T_\mathcal{N}}{E_\nu}\right) \tilde{S}^\mathcal{T}(|\mathbf{q}|^2)\,,$$

$$\left.\frac{\mathrm{d}\sigma_{\nu\mathcal{N}}}{\mathrm{d}T_\mathcal{N}}\right|^T (E_\nu, T_\mathcal{N}) = \frac{m_\mathcal{N}}{2J+1} \frac{g_T^4}{(m_T^2 + 2m_\mathcal{N} T_\mathcal{N})^2} \times \left[\left(2 - \frac{m_\mathcal{N} T_\mathcal{N}}{E_\nu^2} - \frac{2T_\mathcal{N}}{E_\nu}\right) \tilde{S}^\mathcal{T}(|\mathbf{q}|^2) + \left(1 - \frac{T_\mathcal{N}}{E_\nu}\right) \tilde{S}^\mathcal{L}(|\mathbf{q}|^2)\right].$$

Altmannshofer, et.al., JHEP [1812.02778];
Hoferichter, et.al., JHEP [2007.08529];
Candela, et.al, JHEP [2404.12476];
De Romeri, et.al., JCAP [2411.11749];
Chattaraj, et.al., JHEP [2501.12443];

$\tilde{S}^L$, $\tilde{S}^T$ are spin structure functions to account for the longitudinal and transverse multipoles calculated by the nuclear shell model.

Tensor interactions: Coherence strikes back

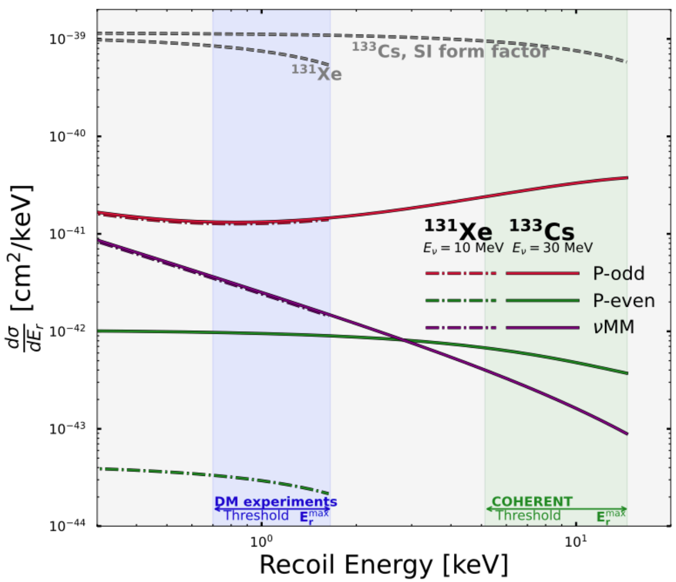
JL, Tang, Zhang, PRD [2502.10702]

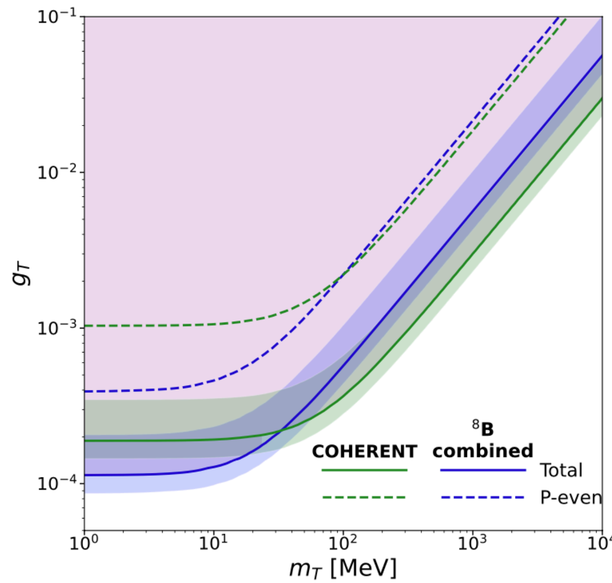
$$\mathcal{L}^T_{\rm eff} = \sum_{\mathfrak{q}=u,d}\sum_{\alpha=e,\mu,\tau} G^q_{T,\alpha}(\overline{\nu}_\alpha\sigma^{\mu\nu}\nu_\alpha)(\overline{\mathfrak{q}}\sigma_{\mu\nu}\mathfrak{q})$$

NR expansion ⇒

	$\mathcal{L}^1_{(0)}$	$\mathcal{L}^1_{(1)}$	$\mathcal{L}^2_{(0)}$
neutrino	$-2\overline{u}_{k'}\vec{\sigma}_{(0)}u_k$	$2\overline{u}_{k'}\vec{\sigma}_{(1)}u_k$	$-2\overline{u}_{k'}\vec{\sigma}_{(0)}u_k$
nucleon	$\frac{i\vec{q}1_N-\vec{P}\times\vec{\sigma}_N}{2m_N}G^{N,1}_T\rho$	$\vec{\sigma}_N G^{N,1}_T\rho$	$-\frac{i\vec{q}}{m_N}1_N G^{N,2}_T\rho$
parity	odd	even	odd

- Previous studies only consider nuclear response functions for P-even spin operator $\vec{\sigma}_N$, and the momentum suppressed P-odd operators are ignored due to $\frac{|q|}{m_N}\sim O(0.01)$.
- Momentum suppressed P-odd terms can be coherently enhanced, i.e., $\frac{A^2|\vec{q}|^2}{m_N^2\langle\mathbf{S}_N\rangle^2}\gtrsim\mathcal{O}(10)$





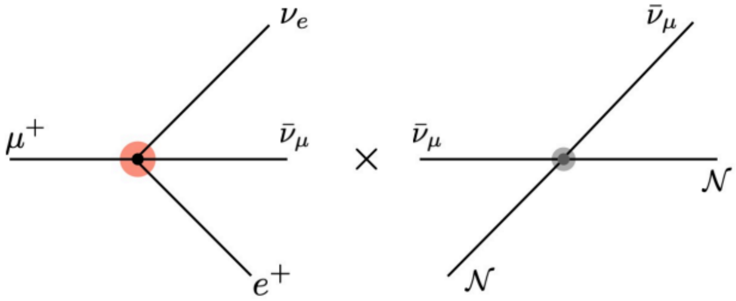
Recent studies in CEvNS theory

- Implications from recent CEvNS data
- CEvNS as a probe of neutrino sources
- Coherent scattering in new processes

CEvNS as a probe of muon decay

$\pi^+ \rightarrow \mu^+ \, \nu_\mu$ (prompt)

↳ $\mu^+ \rightarrow e^+ \, \bar{\nu}_\mu \, \nu_e$ (delayed)



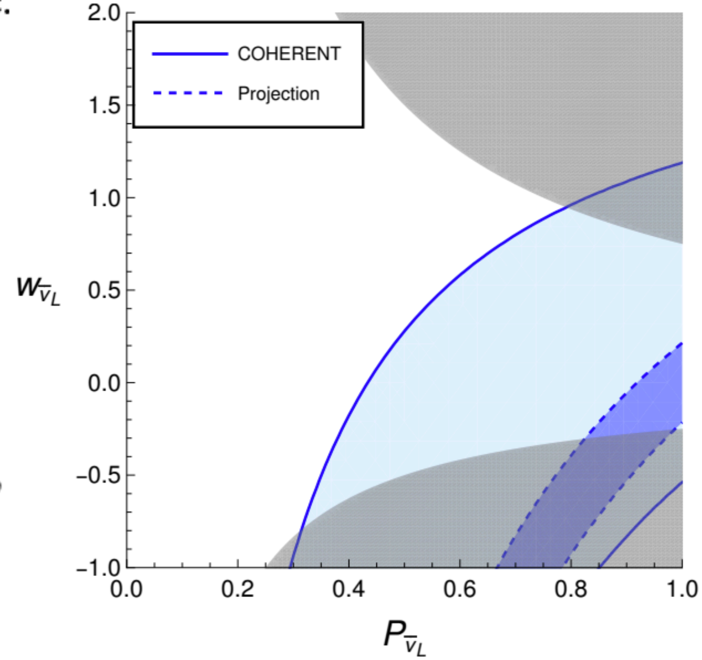
$$\mathcal{L} = -\frac{4G_F}{\sqrt{2}} \sum_{X,\eta,\epsilon} g^X_{\epsilon\eta} (\bar{e}_\epsilon \Gamma^X (\nu_e)_\rho)((\bar{\nu}_\mu)_\gamma \Gamma_X \mu_\eta) + h.c.$$

$$\frac{d\Gamma_{\bar{\nu}_H}}{dE_{\bar{\nu}}} = \frac{24\Gamma_\mu}{m_\mu} P_{\bar{\nu}_H} \left[y^2 \left(\frac{1}{2} - \frac{y}{3} \right) + \frac{8}{9} w_{\bar{\nu}_H} y^2 \left(\frac{3}{4} - y \right) \right],$$

- $P_{\nu H}$ and $\omega_{\nu H}$ are the analogue of the Michel parameters for the electron energy distribution.

$$P_{\bar{\nu}_L} = |g^V_{LL}|^2 + |g^V_{RL}|^2 + \frac{1}{4}|g^S_{RR}|^2 + \frac{1}{4}|g^S_{LR}|^2 + 3|g^T_{LR}|^2 \; ,$$

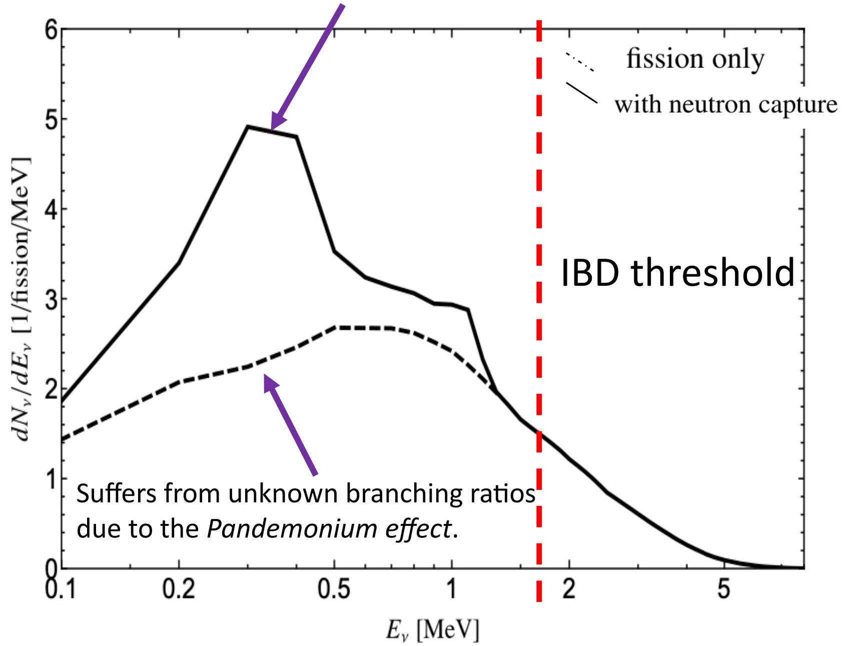
$$P_{\bar{\nu}_L} w_{\bar{\nu}_L} = \frac{3}{16} \left(|g^S_{RR}|^2 + |g^S_{LR}|^2 - 4|g^T_{LR}|^2 \right)$$



Bresi-Pla, et.al., PRL [2502.18175]

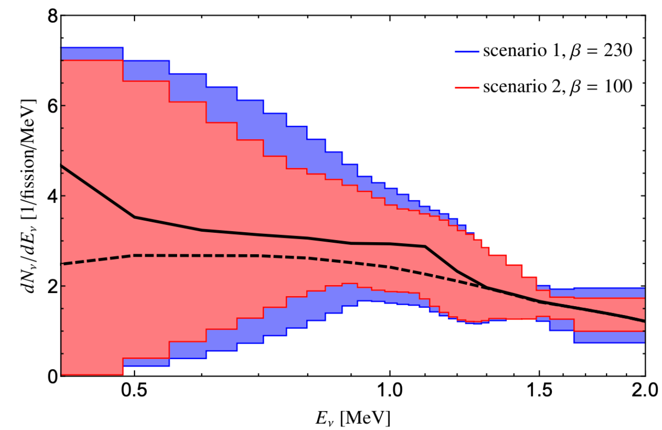
CEvNS as a probe of reactor flux

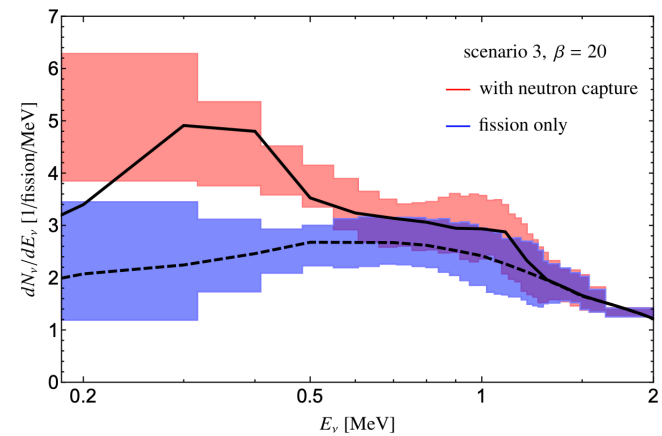
$$^{238}\mathrm{U} + \mathrm{n} \to {}^{239}\mathrm{U} \xrightarrow{\beta} {}^{239}\mathrm{Np} \xrightarrow{\beta} {}^{239}\mathrm{Pu}$$



- NUCLEUS and similar cryogenic detectors can reach extremely low threshold.
  - 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.

- CEvNS provides model-independent flux measurement below the IBD threshold.





JL, Liu, Marfatia, PRD [2302.10460]

Recent studies in CEvNS theory

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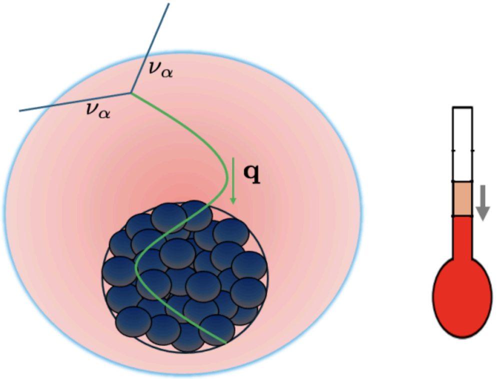
Coherent scattering of CvB with NS

$$\sigma_{\nu n} \simeq \frac{G_F^2}{\pi} E_\nu^2 \simeq (1.7 \times 10^{-58}\ \mathrm{cm}^2) \left(\frac{E_\nu}{0.1\ \mathrm{eV}}\right)^2 ,$$



- Due to the huge number density of neutrons in neutron star (NS), the cross section can be coherently enhanced by a factor of

$$N_C \simeq \frac{4}{3}\pi\lambda_\nu^3 n_n \simeq 3 \times 10^{30} \left(\frac{0.1\ \mathrm{eV}}{|\mathbf{q}|}\right)^3 \left(\frac{n_n}{4 \times 10^{38}\ \mathrm{cm}^{-3}}\right)$$

$$\frac{L_{C\nu B}}{L_\gamma} = \frac{3GM_{\rm NS} n_\nu}{4\sigma_{\rm SB} R_{\rm NS} T_{\rm NS}^3 v_{\rm rel}} \left(1 - \frac{2GM_{\rm NS}}{R_{\rm NS}}\right)^{-1} \simeq \sum_i 6 \times 10^{-10} \left(\frac{10^3\ \mathrm{K}}{T_{\rm NS}}\right)^3 \left(\frac{0.1\ \mathrm{eV}}{m_i}\right)^{1/2}$$

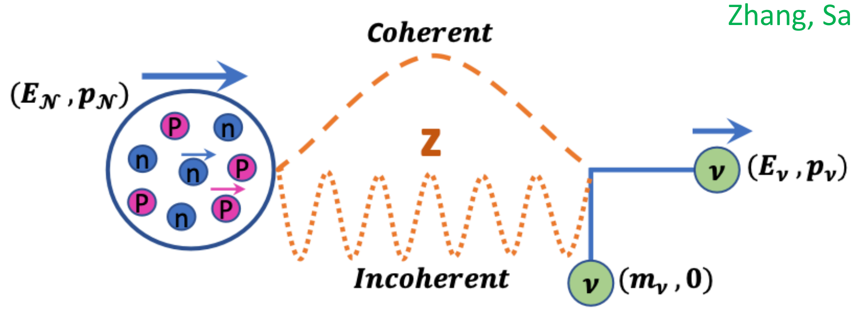
Das, Dev, Okawa, Soni, PRD[2408.01484]

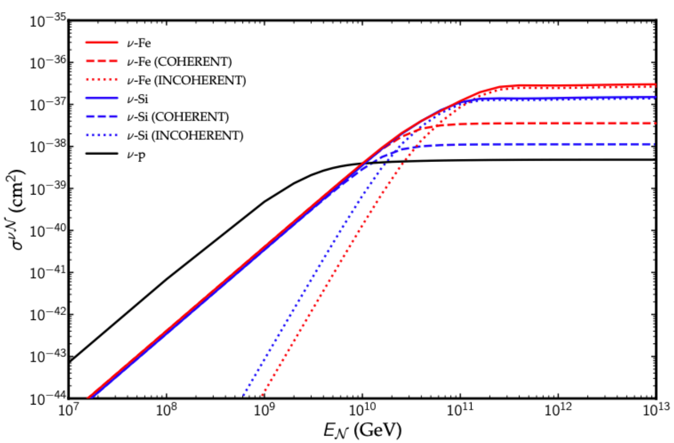
See also Chauhan, PRD[2408.01489]

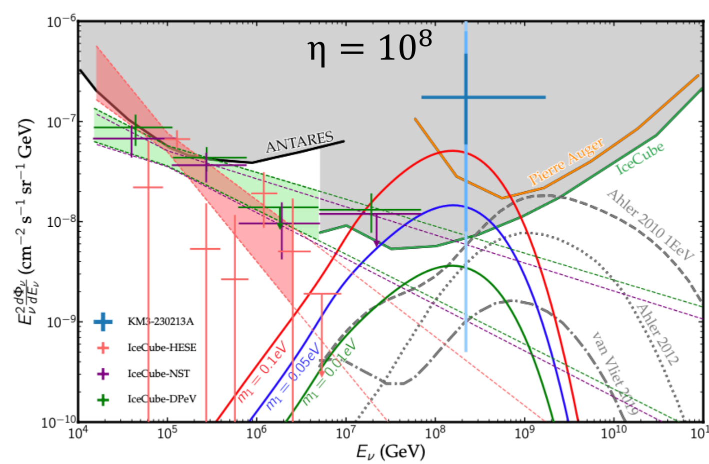
- The anomalous cooling can be observable if there exists a local CvB overdensity $\eta \gtrsim 10^9$, which is still allowed by laboratory constraints (10^{11}) at KATRIN.

Coherent scattering of CvB with CR

- Pierre Auger data suggests heavy nuclei dominate (>90%) at cosmic ray (CR) energy $\gtrsim 10$ EeV. Pierre Auger, JCAP [2211.02857]
- For iron CRs (~10 EeV) scattering on CvB (~ 0.1 eV), the relic neutrino energy is ~20 MeV in the nucleus rest frame, exactly within the CEvNS regime. Zhang, Sandrock, **JL**, Yue, [2505.04791]







Summary

- CEvNS opens a new window to test the SM and explore new physics.
- CEvNS at SNS has entered the precision era.
- New measurement from the DM and reactor experiments offer complementary approaches.
- CEvNS can be useful to probe neutrino sources, and coherent concepts can be extended into new environments.
- Both experimental and theoretical studies are undergoing rapid development, and new ideas are continually emerging in this field.

Stay tuned!

Thanks for your attention!