Physics Opportunities of Coherent Elastic neutrino-Nucleus Scattering Phenomenology

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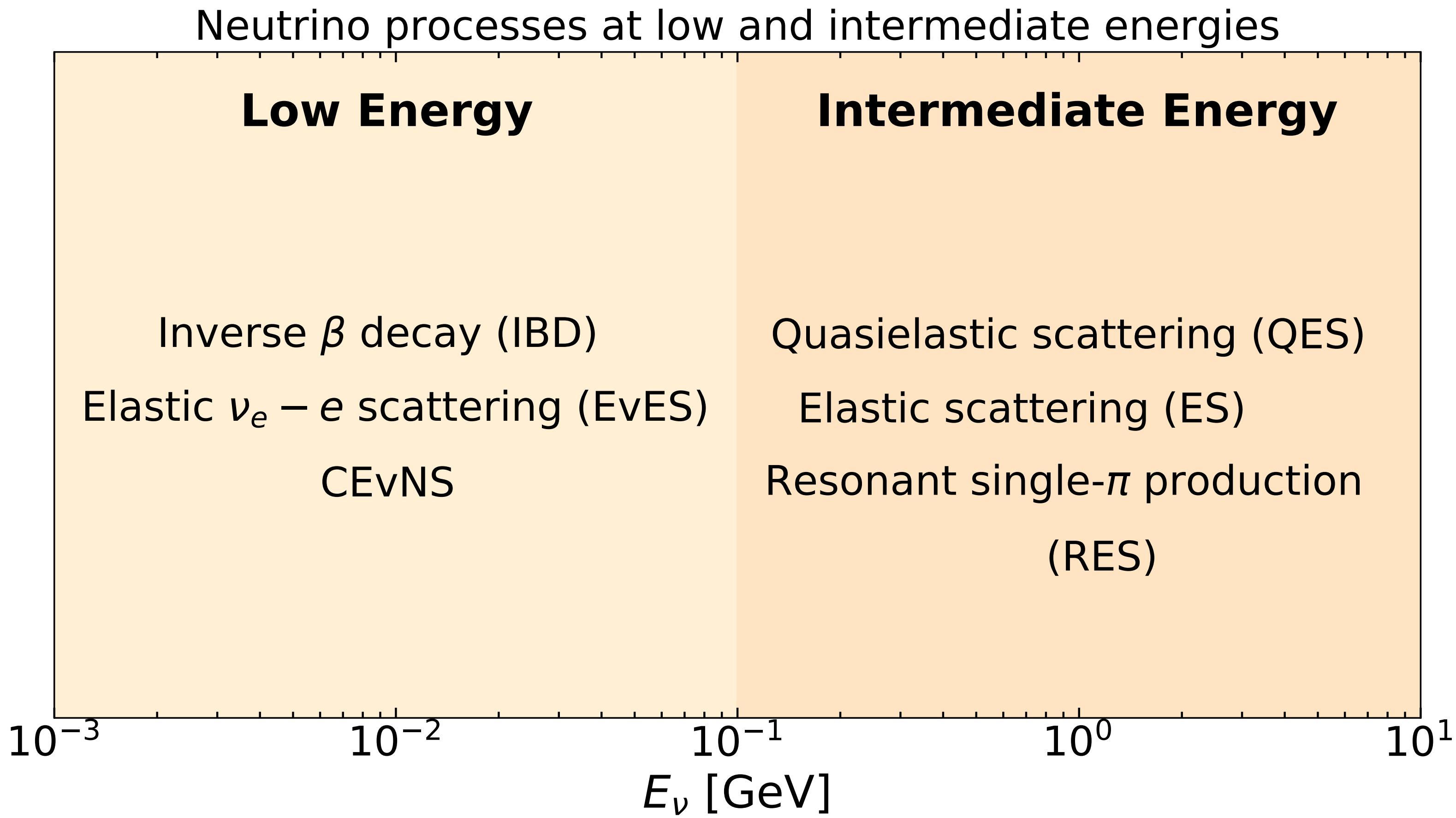
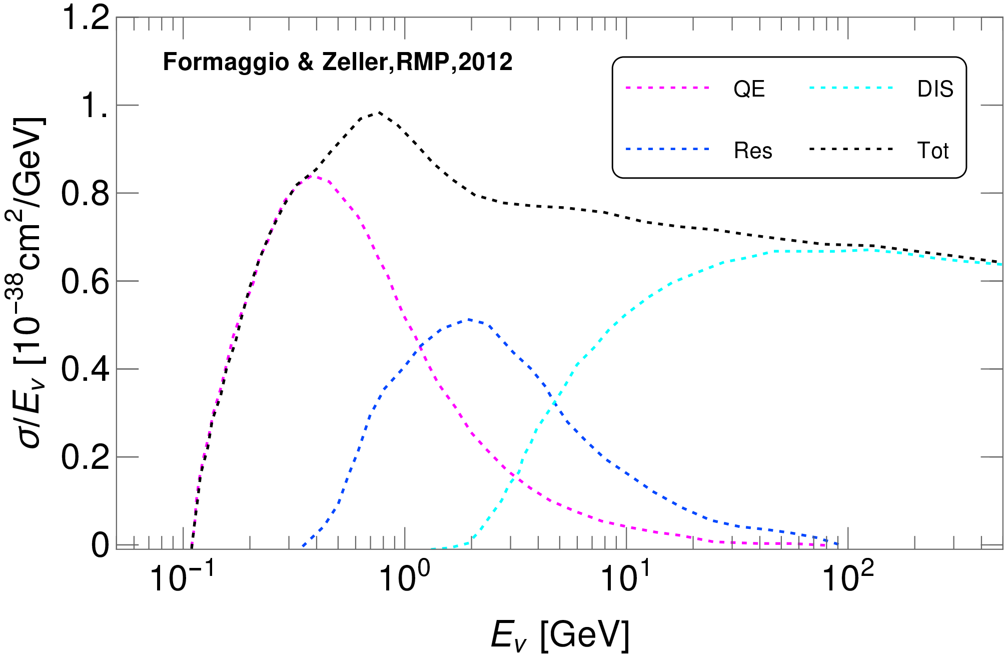
Why Coherent Elastic ν-nucleus Scattering (CEvNS)?

Neutrino processes at different energy scales



Intermediate regime

QES (CC)	ES (NC)		RES (NC & CC)
$\nu_\mu + n \to \mu^- + p$	$\nu + p \to \nu + p$	$\bar{\nu} + p \to \bar{\nu} + p$	$\nu_\mu N \to \mu^- N^* \to \mu^- \pi N'$
$\bar{\nu}_\mu + p \to \mu^+ + n$	$\nu + n \to \nu + n$	$\bar{\nu} + n \to \bar{\nu} + n$	$\nu_\mu N \to \nu_\mu N^* \to \nu_\mu \pi N'$



QES:	MINERvA, 2013 (FNAL)
	MINERvA, 2020
ES:	MiniBooNE, 2010 (FNAL)
RES:	K2K, 2008 (JPARC)
	T2K, 2017
	MINERvA, 2017

Theoretically calculations are challenging
Theoretical uncertainties are large!

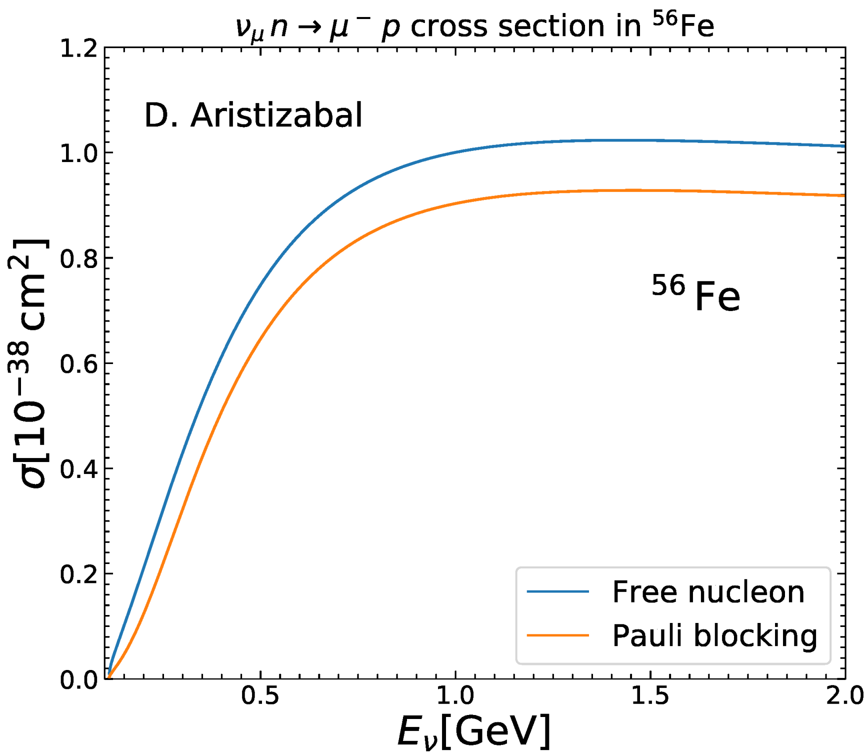
A few comments on theoretical uncertainties

Dominant effects

Pauli blocking: Final-state fermion states must be assured an unoccupied quantum state.

Fermi motion: Nucleons in the nuclear environment are not at rest.

Reinteractions: The recoiling nucleon can reinteract in the nuclear medium



Environmental effects are $\sim 20\% - 30\%$

Nuclear effects are relevant

Effects in MC generators:

`GENNIE` & `NuWro` Differences $\sim 10\%$

Low-energy regime

Inverse beta decay (IBD)

$$\overline{\nu}_e + p \to e^+ + n$$

Used in reactor neutrino detection. Daya Bay, 2015

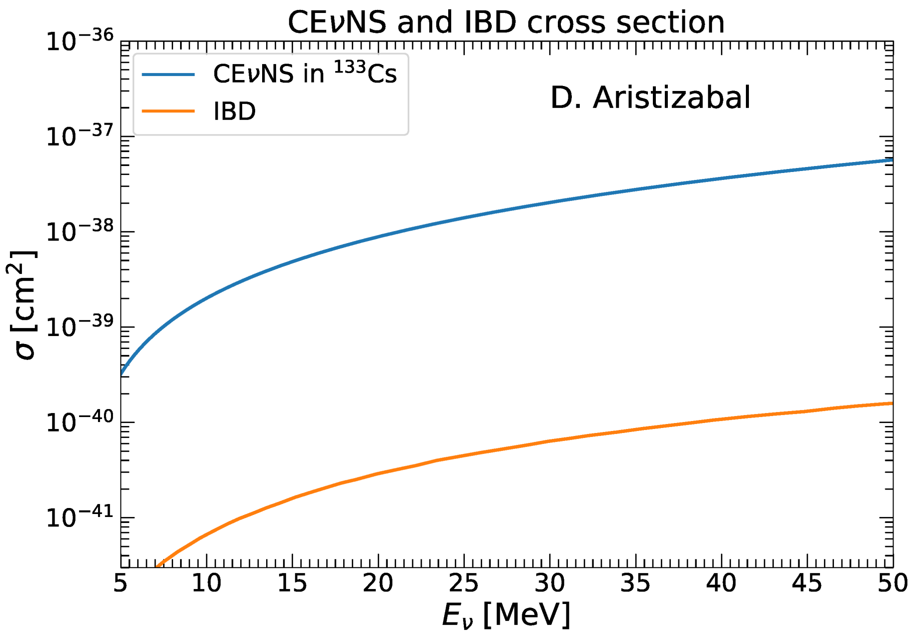
Uncertainties of $\sim 0.1\%$ (τ_n), PDG, 2023

CEvNS

$$\nu + (A, Z) \to \nu + (A, Z)$$

Measured at the SNS, 2017 (first ever)

Uncertainties of $\sim 1 - 5\%$ (rms of n^0 distribution)



Environmental effects are absent

Nuclear effects are subdominant

Clean processes!

In neutrino standards

CEvNS cross section is “huge”

CEvNS: Cross section, environments and measurements

CEνNS cross section

CEνNS occurs when the neutrino energy E_ν is such that nucleon amplitudes sum up coherently ⇒ cross section enhancement

$$\lambda \gtrsim R_N \;\Rightarrow\; q \lesssim 200\ \text{MeV}$$

$$E_R = q^2/2m_N \;\Rightarrow\; E_\nu \simeq \sqrt{E_R^{\text{max}} m_N/2}$$

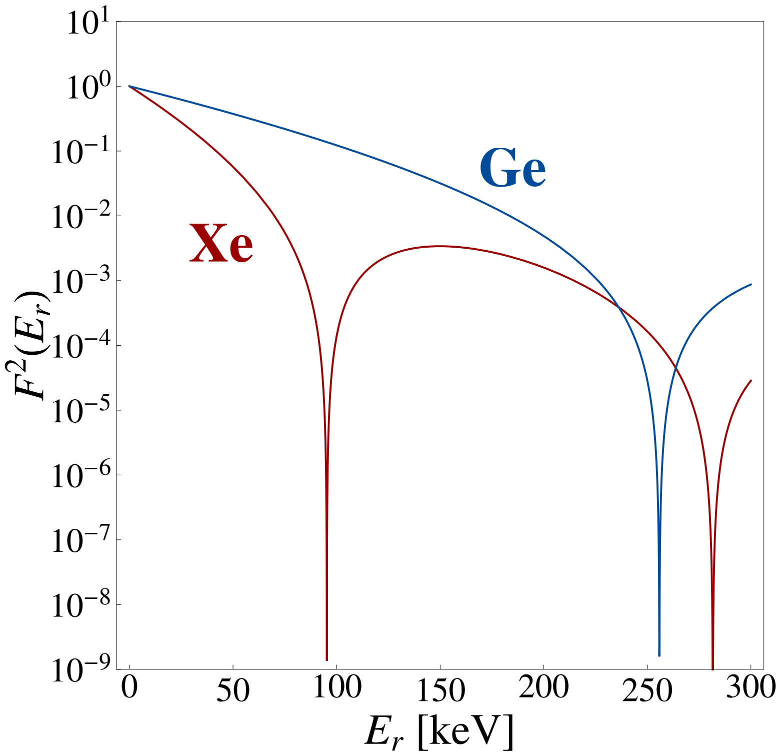
$$E_\nu \lesssim 200\ \text{MeV}$$

Freedman, 1974; Drukier & Stodolsky, 1984

$$\frac{d\sigma_\nu}{dE_R} = \frac{G_F^2}{4\pi} Q_{\text{W}}^2 m_N \left(1 - \frac{E_r m_N}{2E_\nu^2}\right) \underbrace{F_W^2(E_r)}_{\text{Form factor}}$$

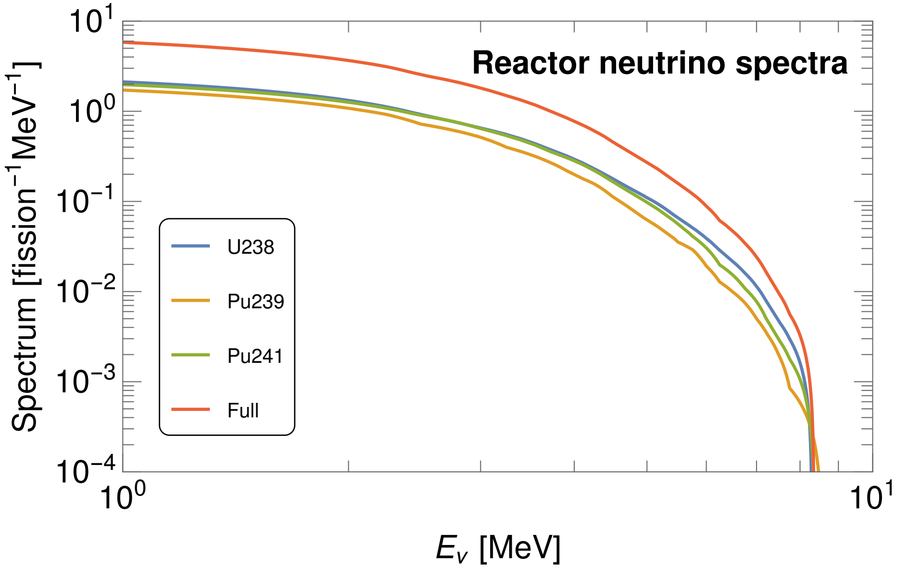
$$Q_{\text{W}}^2 = [N - (1 - s_W^2)Z]^2 \simeq N^2$$

Helm, 1956

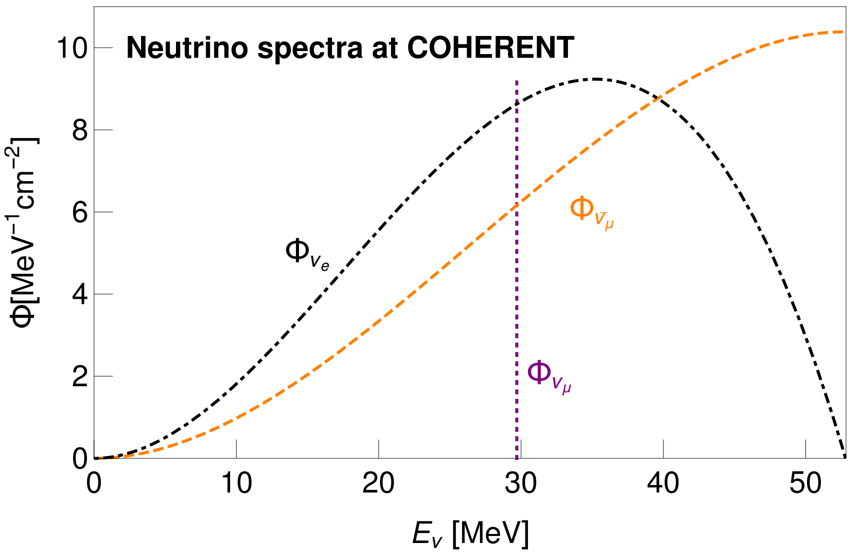


CEvNS environments

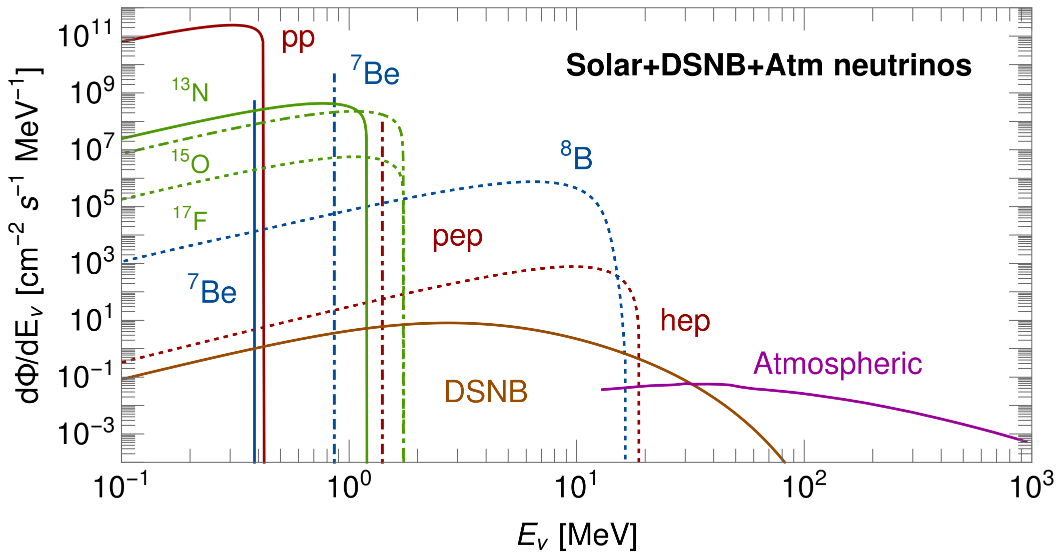
Reactor (CONUS, NUCLEUS, RICOCHET...)



Fixed target neutrinos (COHERENT)



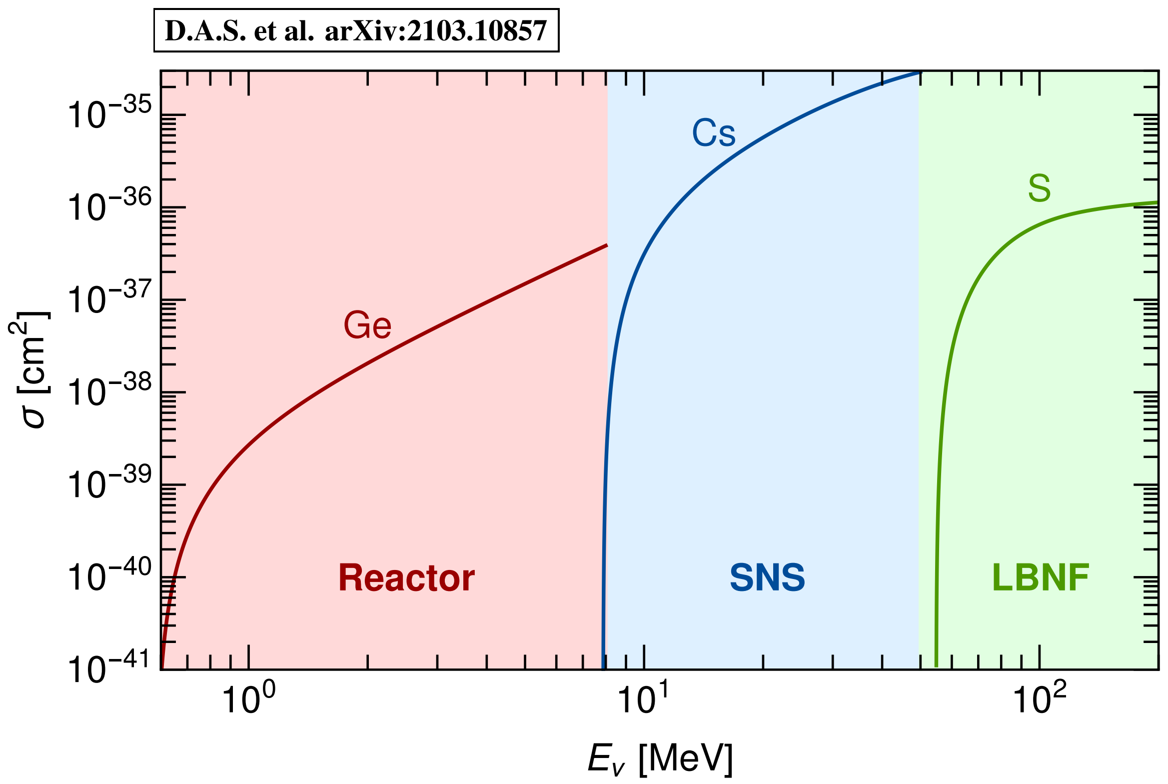
Solar+DSNB+Atm (DM detectors)



Neutrino sources and CEvNS "regimes"

Decay-in-flight neutrinos sources can as well be used

NuMI and LBNF



Entering the "high-energy" window requires a substantial amount of ν's in the low-enery tail

LBNF provides that!

Physics program (opportunities)

The combination of measurements from different sources

and different detectors define a rather rich physics program

CEvNS measurements

CONUS (Ge), CONNIE (Si), COHERENT (Ar, CsI, NaI)

νBDX-DRIFT (CS_2, CF_4, $C_8H_{20}Pb$), XLZD (LXe), Captain-Mills (LAr)

SM measurements

Measurements of $\sin^2\theta_W$ at a new energy scale

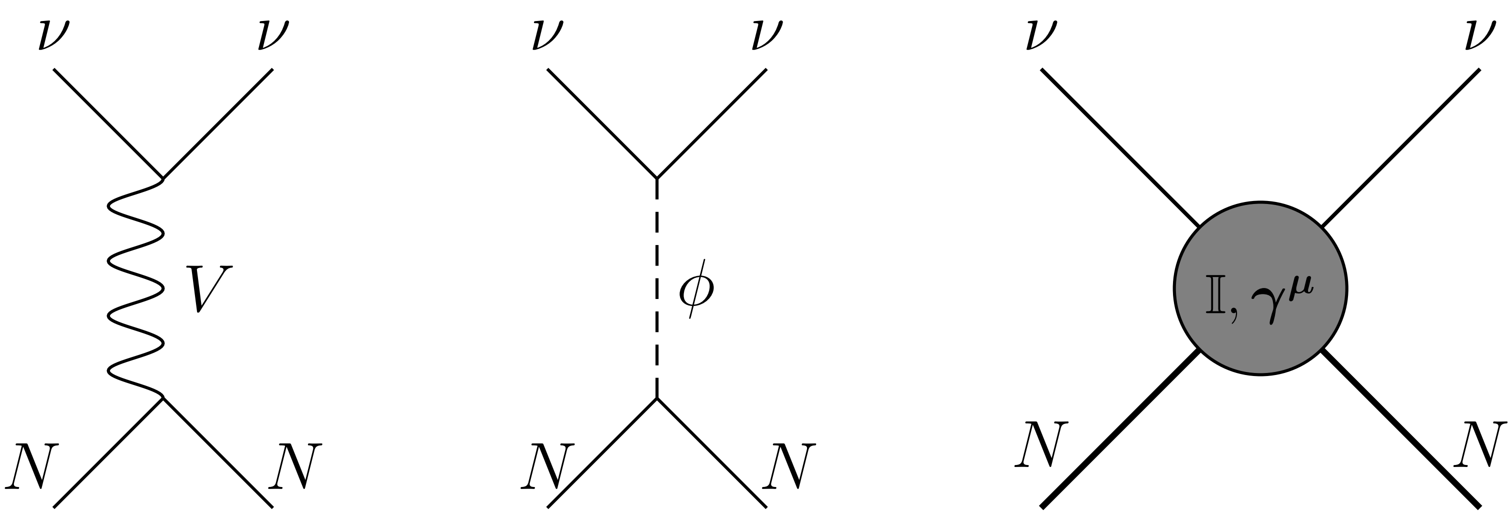
... Complementary to DUNE measurements in electron channel

Measurements of neutron distributions in e.g. Ge, C, S, F, Pb...

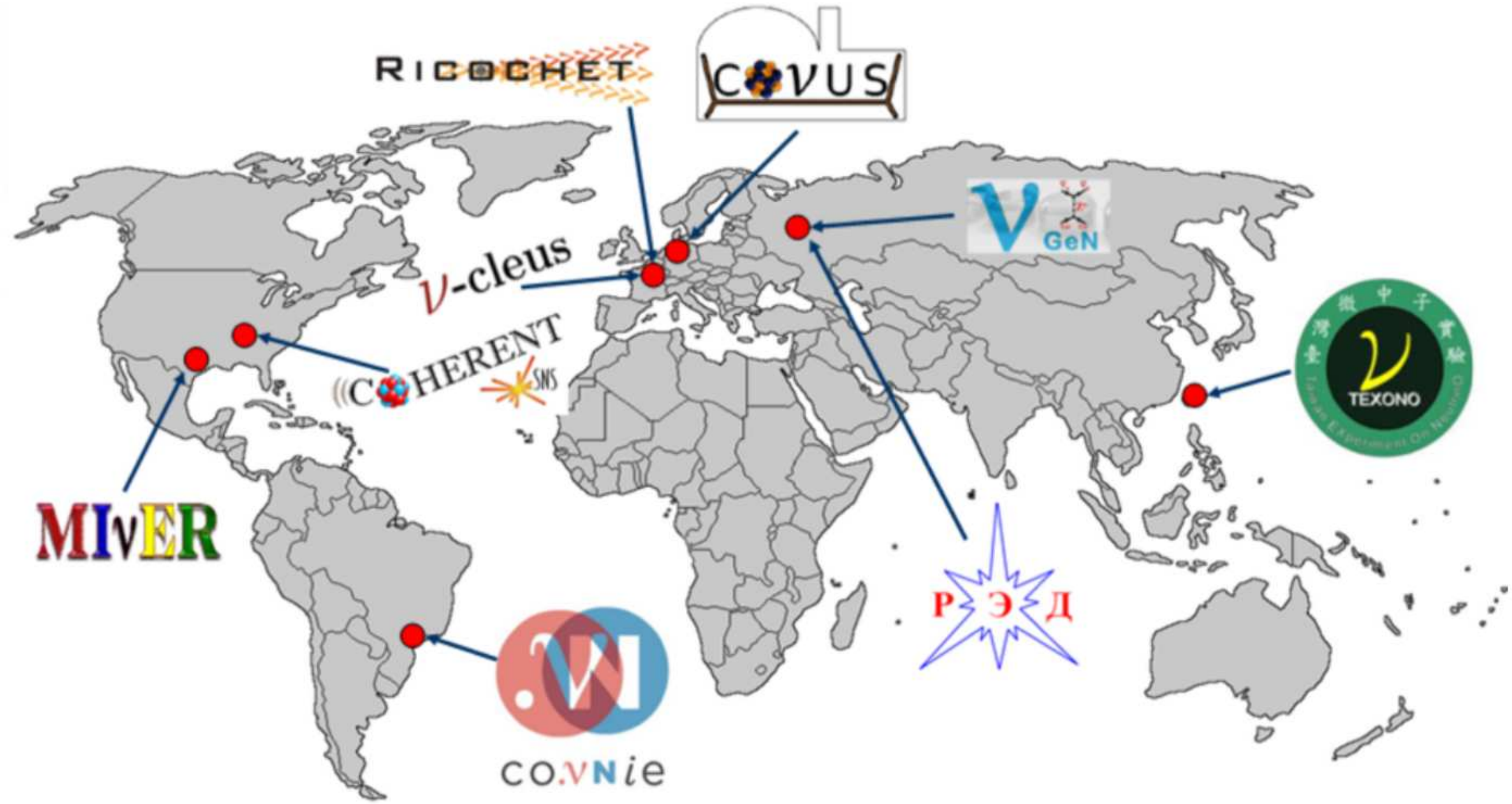
BSM searches

Neutrino NSI, NGI, Dark-neutrino interactions, dark sectors

Possible BSM scenarios



Ongoing projects worldwide



- Argentina vIOLETA (Neutrino Interaction Observation with a Low Energy Threshold Array)
- Mexico SBC (Scintillating Bubble Chamber)
- Belgium SoLid (Search for oscillations with Lithium 6 detector)
- South Korea NEON (Neutrino Elastic-scattering Observation experiment with NaI[Tl] crystal)

Measurements: COHERENT

Measurements with CsI (2017)

CEνNS observed by COHERENT more than 40 years after its prediction

Akimov et. al. 2017

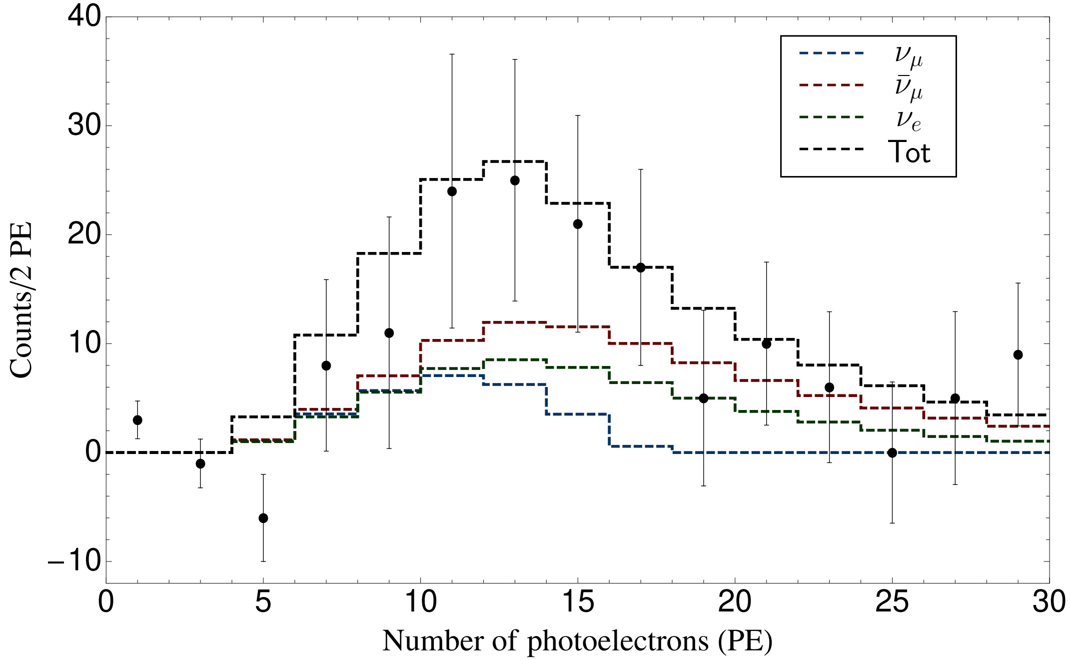
COHERENT uses neutrinos produced at the SNS

@ Oak Ridge National Laboratory in the collision p – Hg

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

Presence of CEνNS favored @ the 6.7σ level. Data consistent with SM @ the 1σ



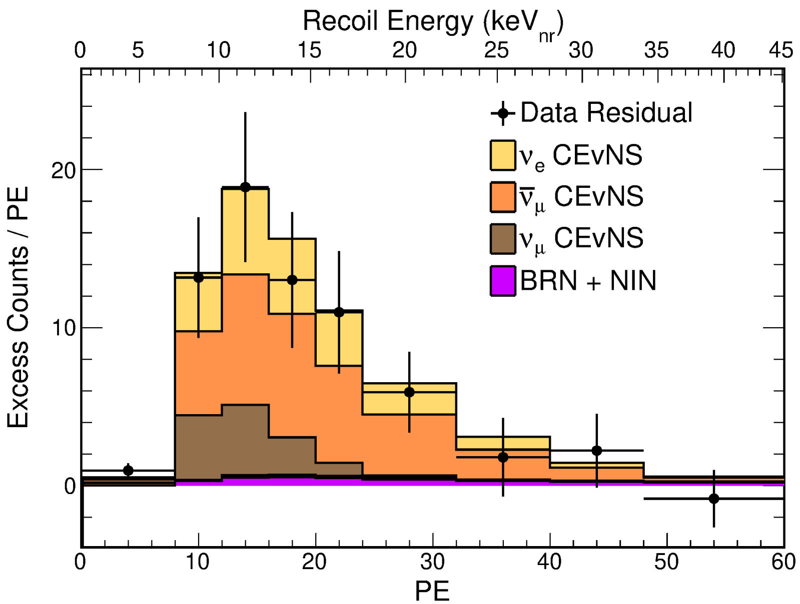
$$n_{\text{PE}} = 1.17\,(E_R/\text{keV})$$

Measured in LAr

CENNS-10 2003.10630

Ge expected in 2024

Updated CsI data (2021)

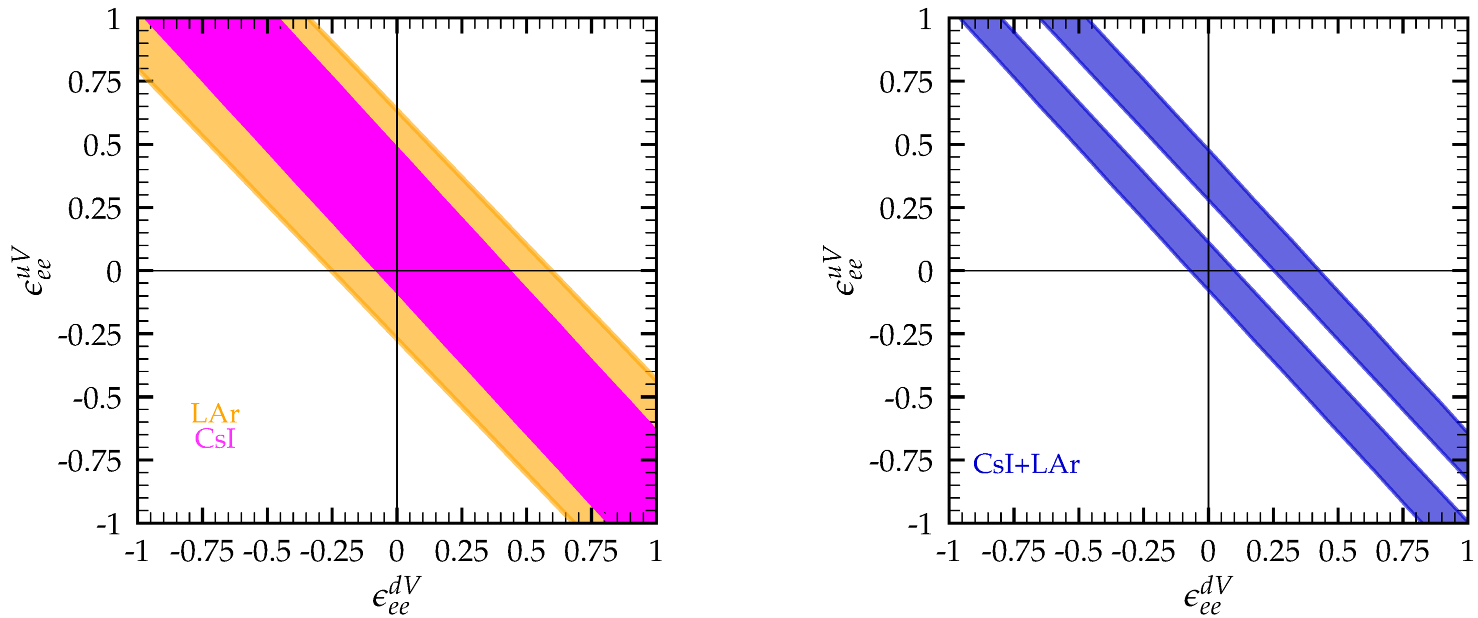


Larger data set (twice that of 2017)

$N_{\text{exp}} = 306 \pm 20$ ($N_{\text{th}} = 341 \pm 11$)

Smaller statistical uncertainties (Q_F)

De Romeri et al, 2211.11905



CEvNS physics with the νBDX-DRIFT detector

Project

➪ **Collaboration** started back in 2021: D.A.S. (USM), Bhaskar Dutta (TAMU)
Joshua Barrow (Minnesota), Doojin Kim (South Dakota)
Daniel Snowden-Ifft (Oxy College), Louis Strigari (TAMU)

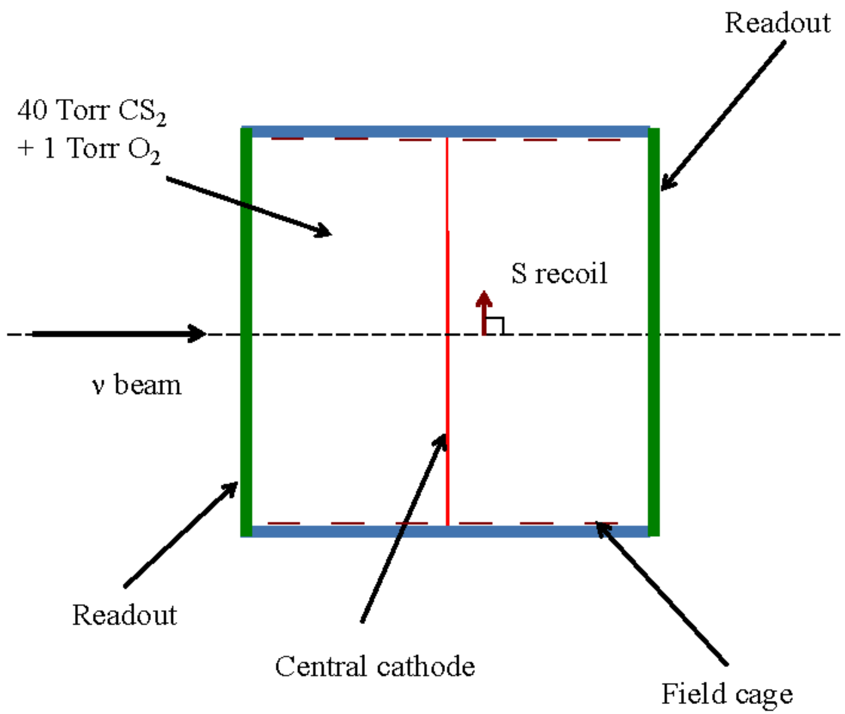
➪ **Goal**: CEvNS Physics and LDM searches with directional detectors

➪ **Strategy**: Use Fermilab neutrino beamlines (pion decay-in-flight)
Levarage on low-energy tail & abundant flux

Directional LDM signals & sensitivities: Work in progress
Neutron backgrounds at the MINOS hall: 2210.08612 [hep-ex] (PRD)
CEvNS measurements: 2103.10857 [hep-ph] (PRD)

νBDX-DRIFT: Basics

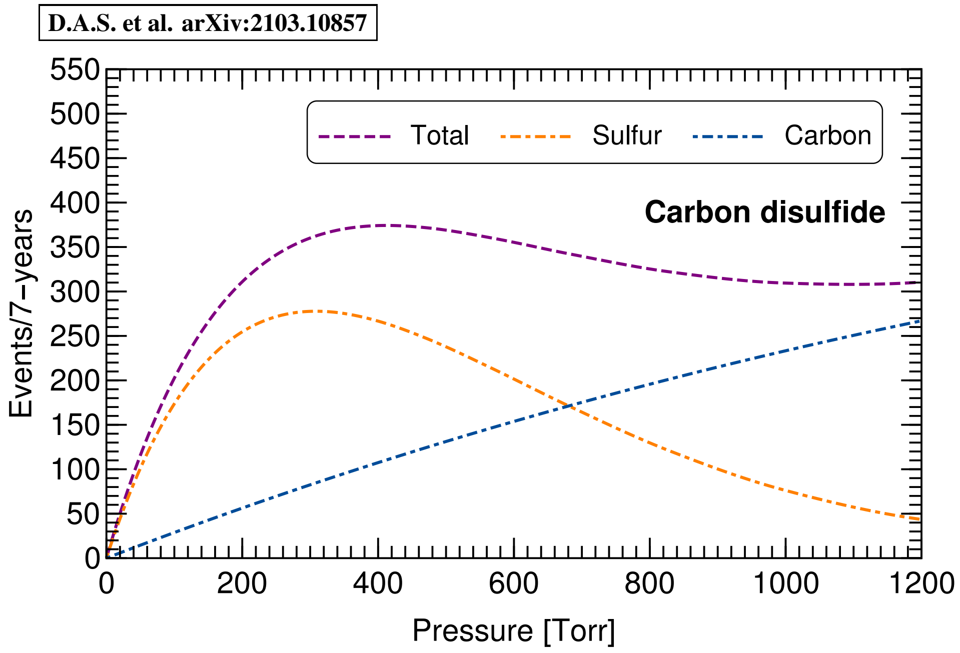
- Directional low pressure TPC detector
- Operates with CS_2 (other gases possible CF_4, $C_8H_{20}Pb$...)



- NRs mainly in sulfur induce ionization
- CS_2^- ions used to transport the ionization to the readout planes (MWPCs)

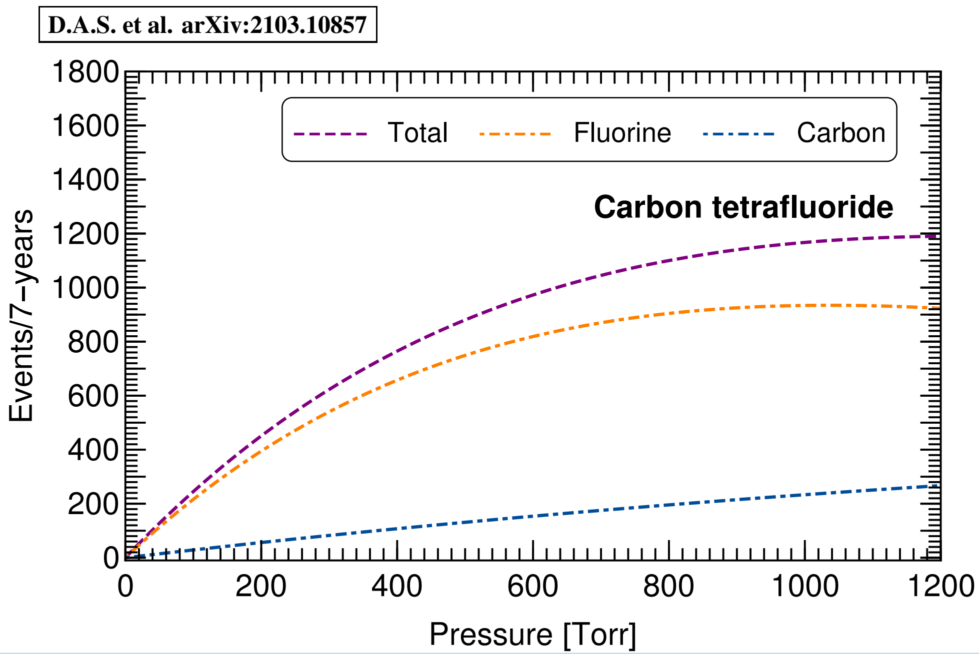
Multi-wire proportional chambers

Signals in CS_2 and CF_4



Signal peaks at 400 Torr

Expected signal: 370 events



100% filled with CF_4

Expected signal: 880 events

Measurements of R_n via CEvNS

$$F_W(q^2) = \frac{1}{Q_W}\left[Z\, g_V^p\, F_V^p(q^2) + (A-Z)\, g_V^n\, F_V^n(q^2)\right]$$

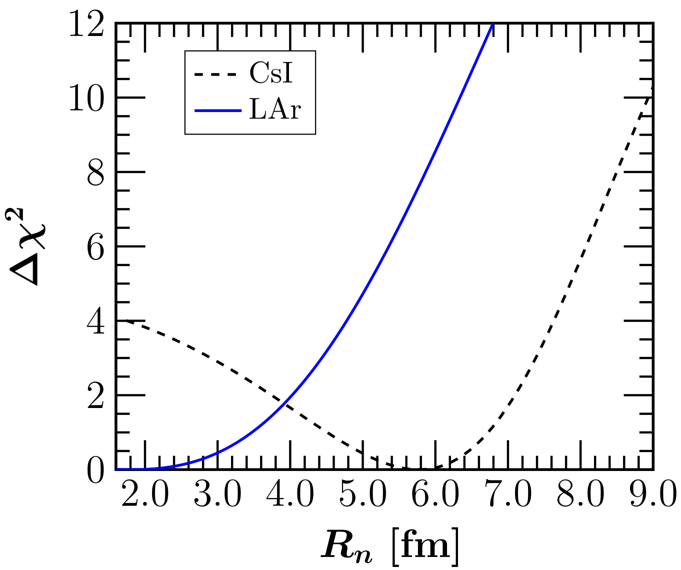
$\Rightarrow$ F_V^p: Depends on $R_p \Rightarrow$ known at 0.1% level ($e^- - N$ scattering)

$\Rightarrow$ F_V^n: Depends on $R_n \Rightarrow$ poorly known (hadron experiments)

$$N_{\text{CEvNS}} = N_{\text{CEvNS}}(R_n)$$

$$N_{\text{CEvNS}}^{\text{Exp}} \Rightarrow R_n$$

Miranda et al, JHEP 05 (2020)



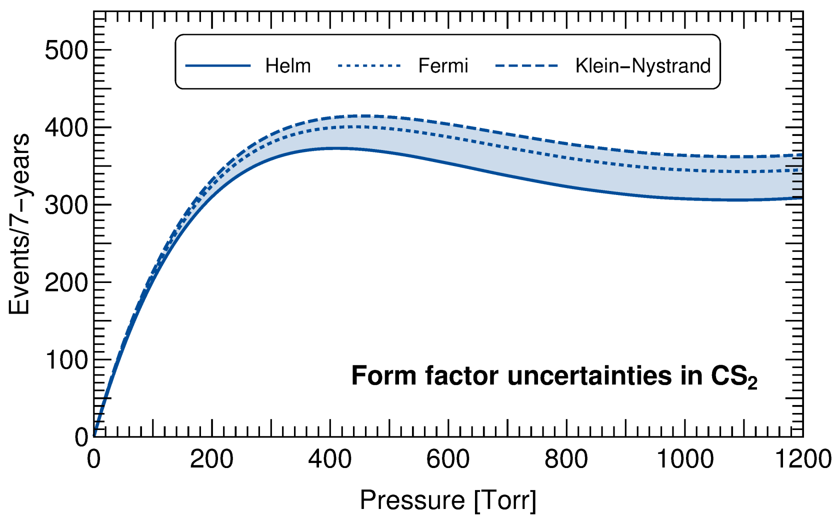
COHERENT 90% CL limits

CsI: $R_n^{\text{Cs}} = R_n^{\text{I}}$: $R_n \subset [3.4, 7.2]$ fm

Ar: $R_n < 4.33$ fm

Neutron density distributions: Results

D.A.S. et al. PRD, 104 (2021)

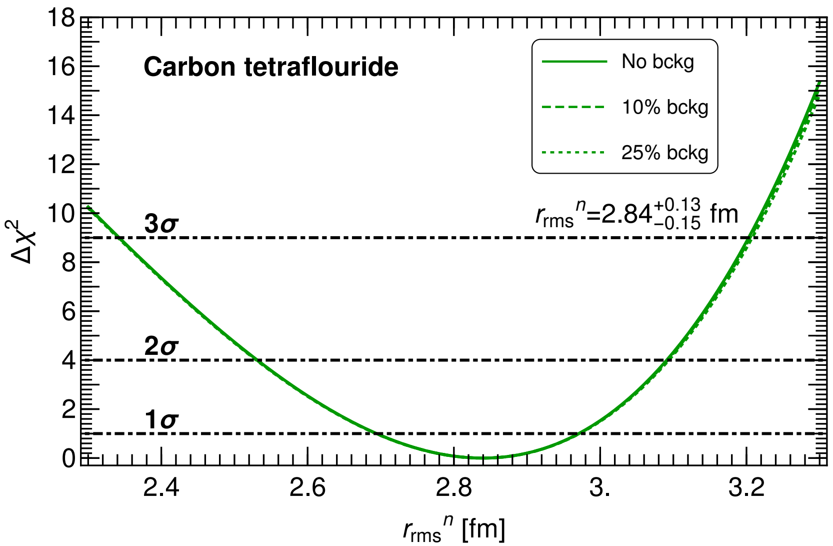


High-energy nature of the flux

⇒ Moderate dependence on the FF

⇒ Accounted for in signal uncertainty $\sim 10\%$

D.A.S. et al. PRD, 104 (2021)



Approximation: $r^n_{\text{rms}}|_{\text{C}} = r^n_{\text{rms}}|_{\text{F}}$

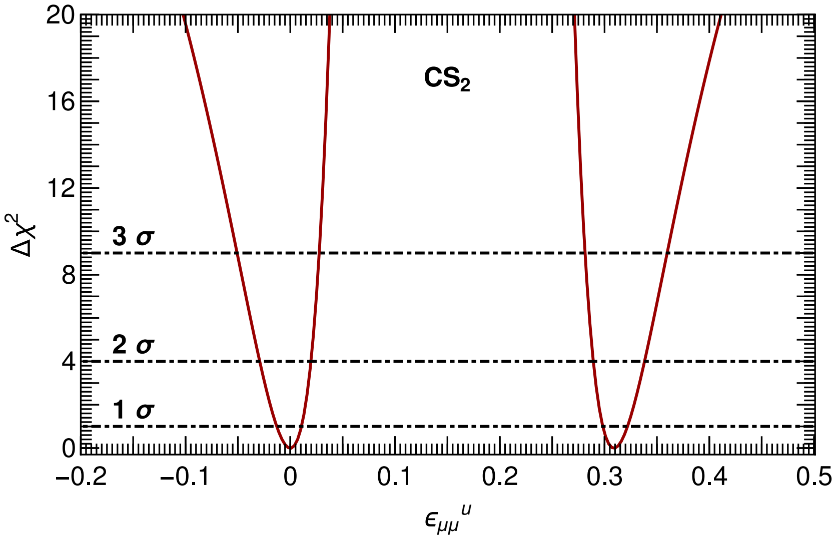
C and F determined with a 3% accuracy

Neutrino Nonstandard Interactions (NSI)

$$\mathcal{L}_{\text{NSI}} \sim G_F \bar{\nu}_a \gamma_\mu (1-\gamma_5)\nu_b \, q\gamma^\mu \epsilon^q_{ab} q$$

Initial state flavor, ν_μ: Only $\epsilon_{\mu b}$ parameters are testable

D.A.S. et al, PRD 104 (2021)



Region I: Deviations are small, $\epsilon^u_{\mu\mu} \to 0$

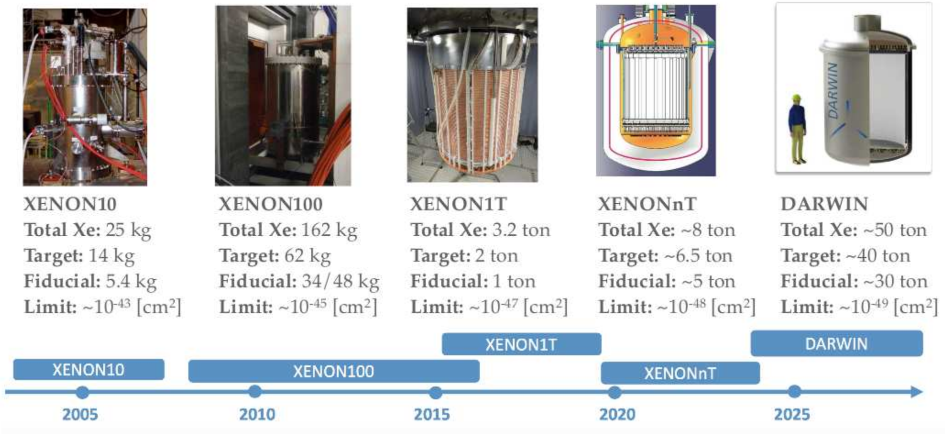
Region II: NSI exceeds SM by ~ 2

$\Rightarrow$ Destructive interference

νBDX-DRIFT CS_2 (7-years)		**COHERENT CsI** (1-year)	
$\epsilon^u_{\mu\mu}$	$[-0.013, 0.011] \oplus [0.30, 0.32]$	$\epsilon^u_{\mu\mu}$	$[-0.06, 0.03] \oplus [0.37, 0.44]$
$\epsilon^u_{e\mu}$	$[-0.064, 0.064]$	$\epsilon^u_{e\mu}$	$[-0.13, 0.13]$

The case of DM detectors: PandaX-4T & XENONnT

Multi-ton DM detectors



Lux-Zeplin (LZ) [G2 detector]

SURF, South Dakota, USA

Total: 10 ton of LXe

Fiducial: 5.6 ton of LXe

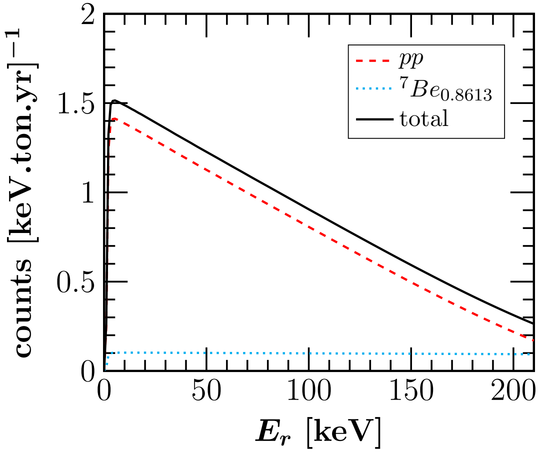
DM sensitivity: 10^{-48} cm^2

XLZD Consortium: 40-100 ton

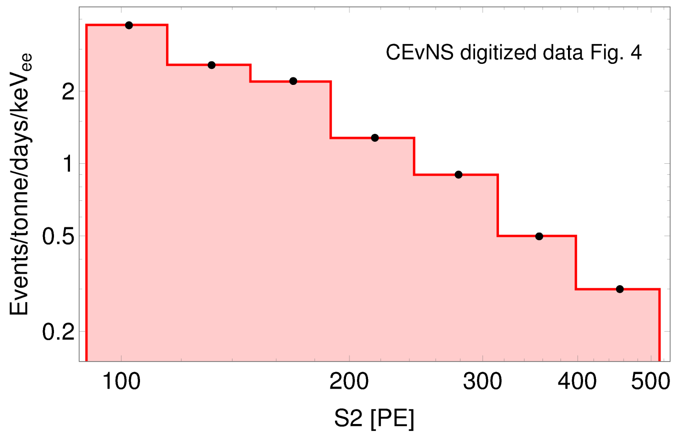
Neutrino-induced NR and ER will be abundant

in thrid generation DM detectors (XLZD)

D.A.S, De Romeri, Flores, Papoulias, 2006.12457

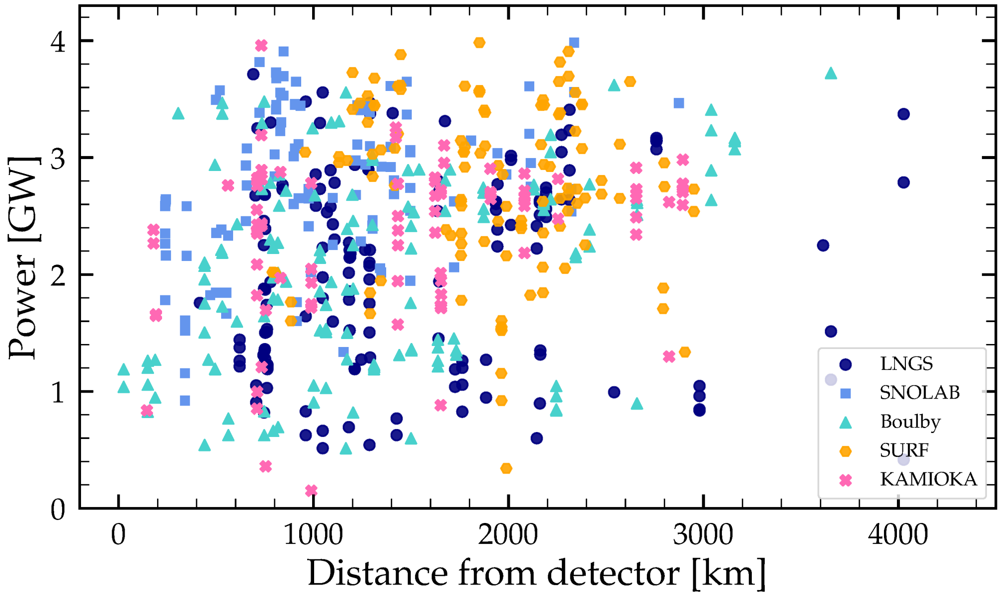


E. Aprile et. al, 1907.11485



Impact of reactor neutrinos

D.A.S. et al, 2402.06416

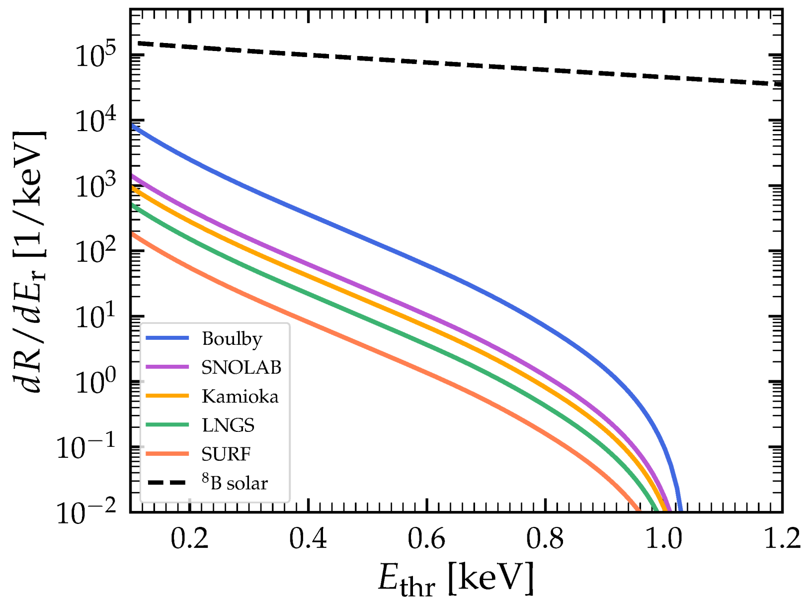


Reactor clusters $L \leq 1000$ km

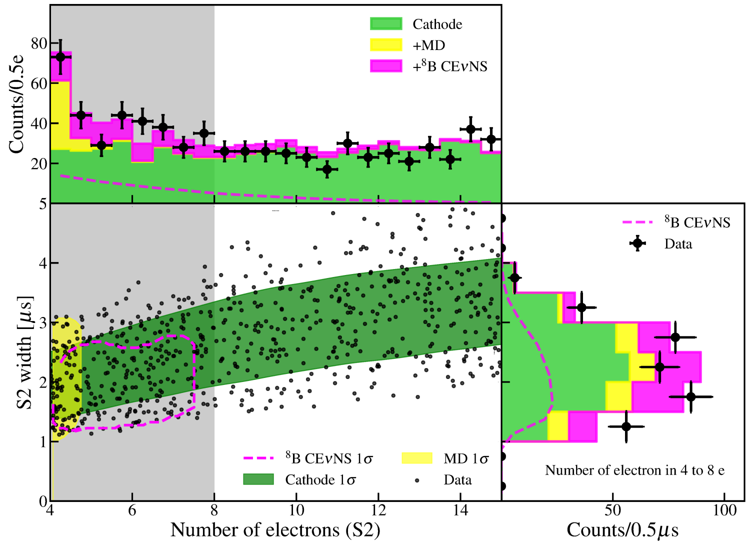
Boulby: Power+short baselines

Event rates sizable in all cases

Best location: SURF & LNGS



Actual measurements



PandaX-4T, arXiv:2407.10892

Paired scintillation+ionization signals (P)

Ionization-only signals (US2)

P signals: 3.5 ± 1.3 events

US2 signals: 75 ± 28 events

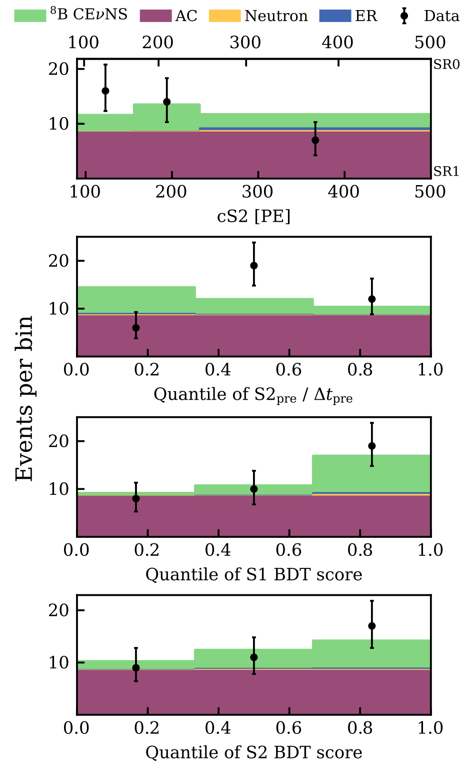
XENONnT, arXiv:2408.02877

Exposure: 3.5 tonne-year

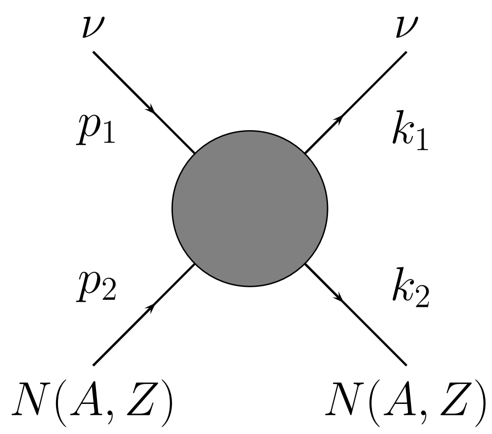
NR threshold at 0.5 keV

Signal: $11.9^{+4.5}_{-4.2}$ events

Background-only signal rejected at 2.73σ



What can you learn from these data?



Implications

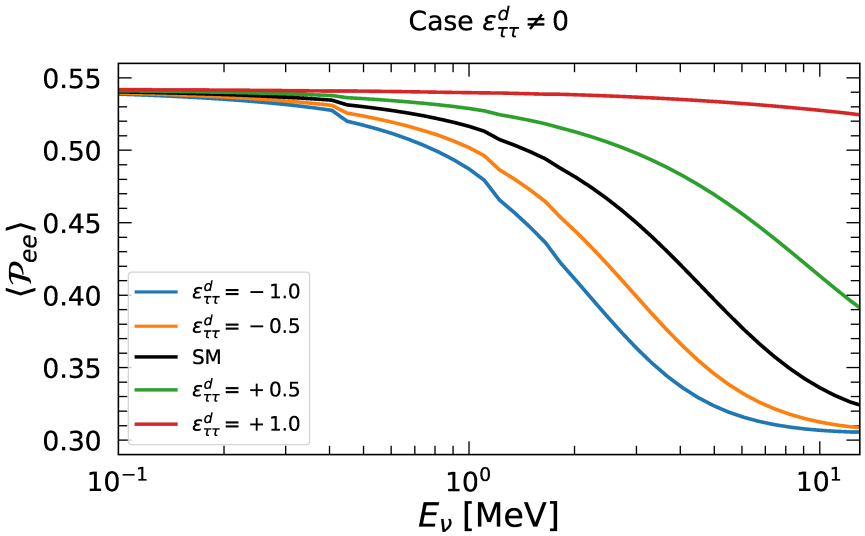
➠ Induce new matter potentials ⇒ Affects neutrino propagation in the SUN

Affects neutrino flavor conversion

➠ Modifies $\nu - q$ interactions ⇒ Affects the CEvNS cross section

Affects the detection process

Survival probability and event rate



Resonant conversion of matter states

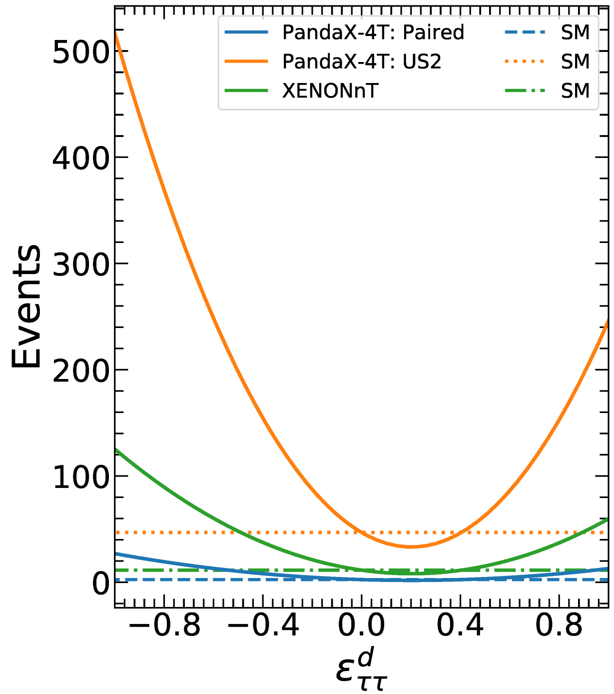
Positive effective couplings ⇒

farther from resonant region

Effects of the new couplings

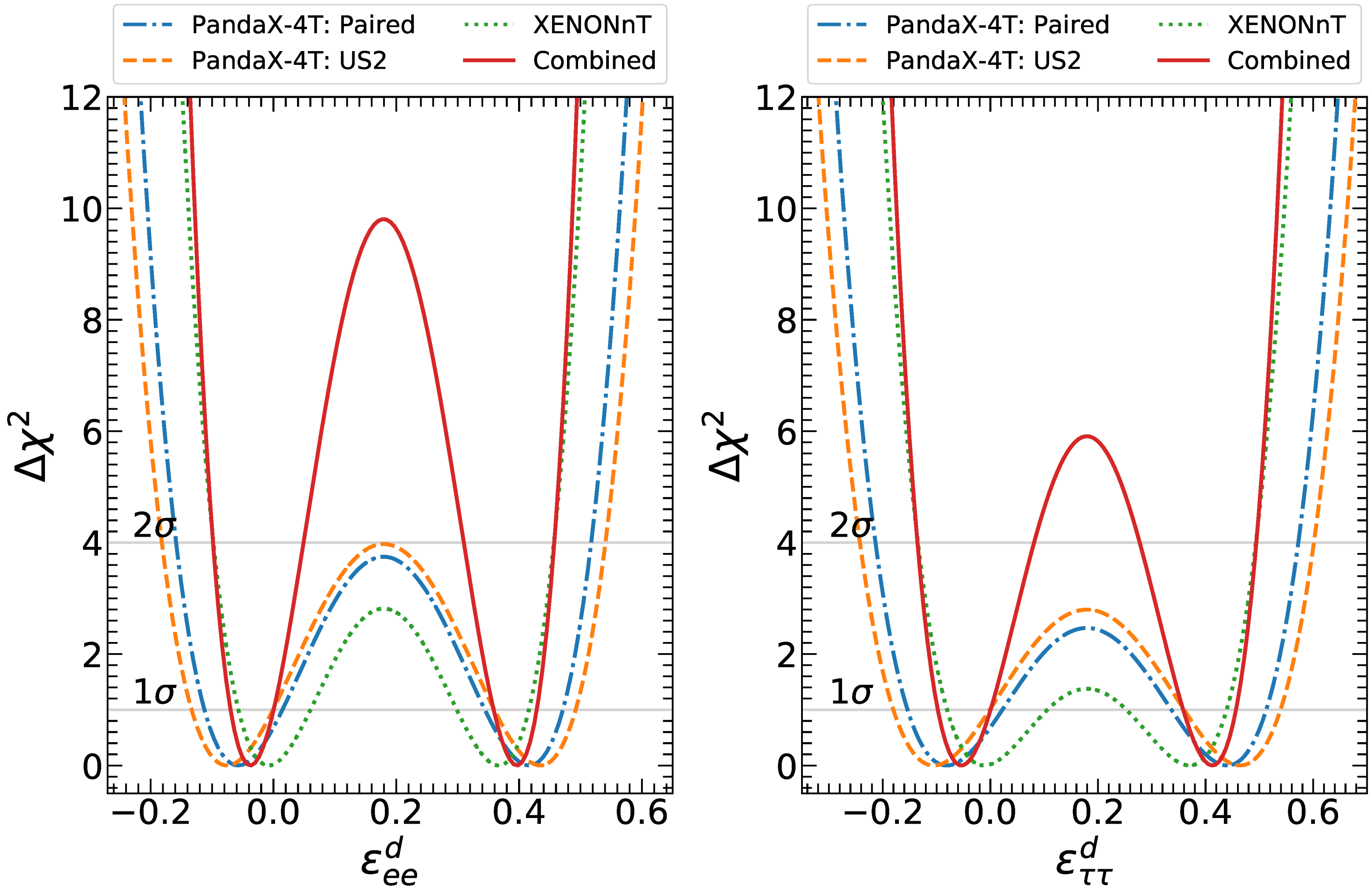
enhance/depletes the detection cross section

Event rate increases/decreases



Sensitivities

D.A.S. et al, 2409.02003



Sensitivities (exclusion limits) are competitive with COHERENT combined measurements!

Final remarks

Takeaways

✍ CEvNS measurements (facilities) offer a rich neutrino program agendas: ν-cleus, CONUS, CONNIE, COHERENT (SNS), NuMI & LBNF

✍ Directional detectors (νBDX-DRIFT) combined with a high-energy neutrino beam (e.g. LBNF) is suitable for CEvNS measurements in CS_2, CF_4, $C_8H_{20}Pb$...

✍ Directional detection improves background rejection
Other aspects of directionality yet to be explored: Identification of DM spin [?]

✍ Multi-ton DM detectors already observing neutrino-induced NRs
Still small statistics and sizable uncertainties... Improvements expected

✍ Into the future: Multi-ton DM detectors along with multi-ton detectors (LAr) at the STS
Measurements at the European Spallation Source... Delivering $\gtrsim 10^3$ events/year