Physics opportunities of CEvNS experiments

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νBDX-DRIFT collaboration:

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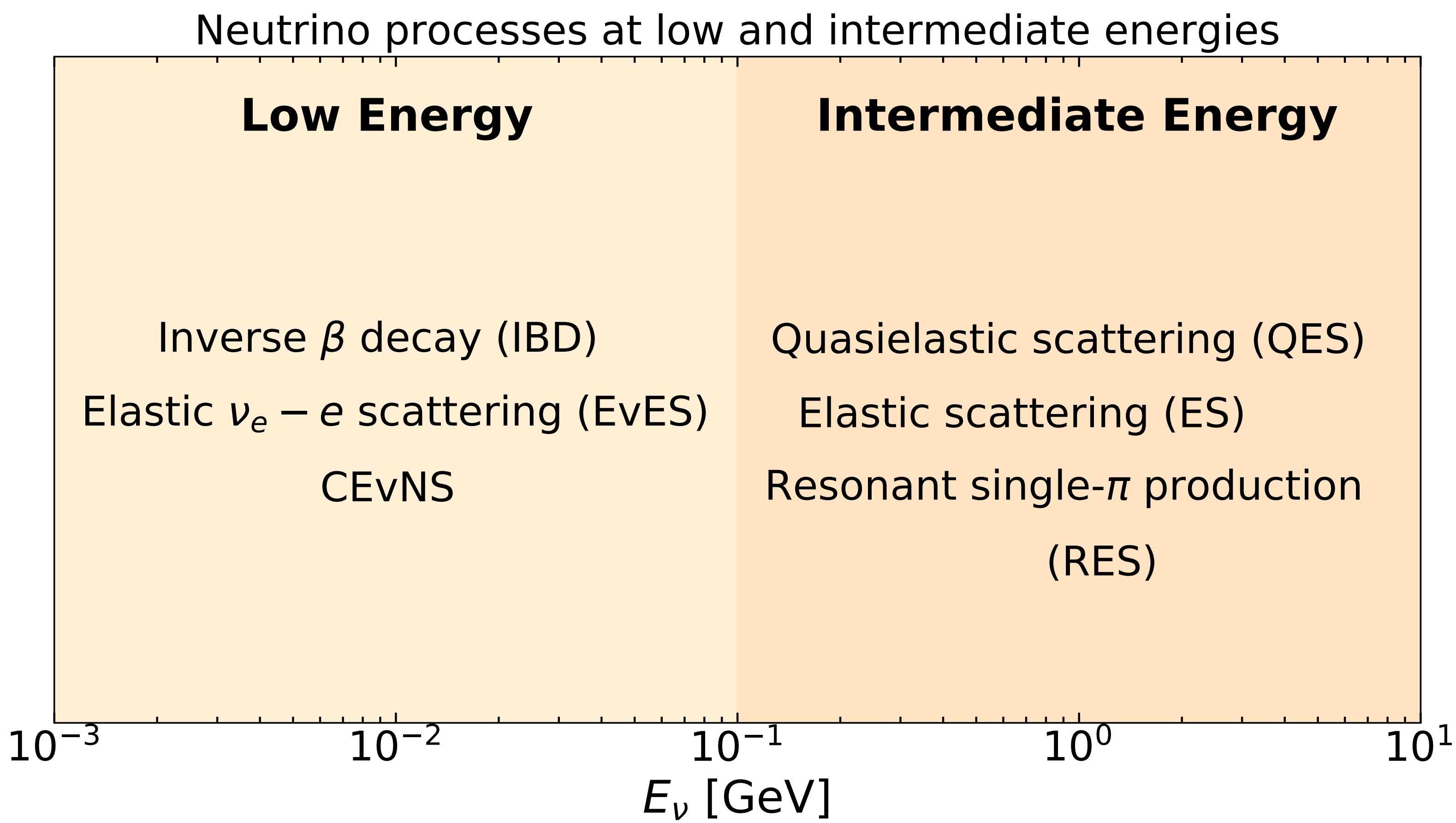
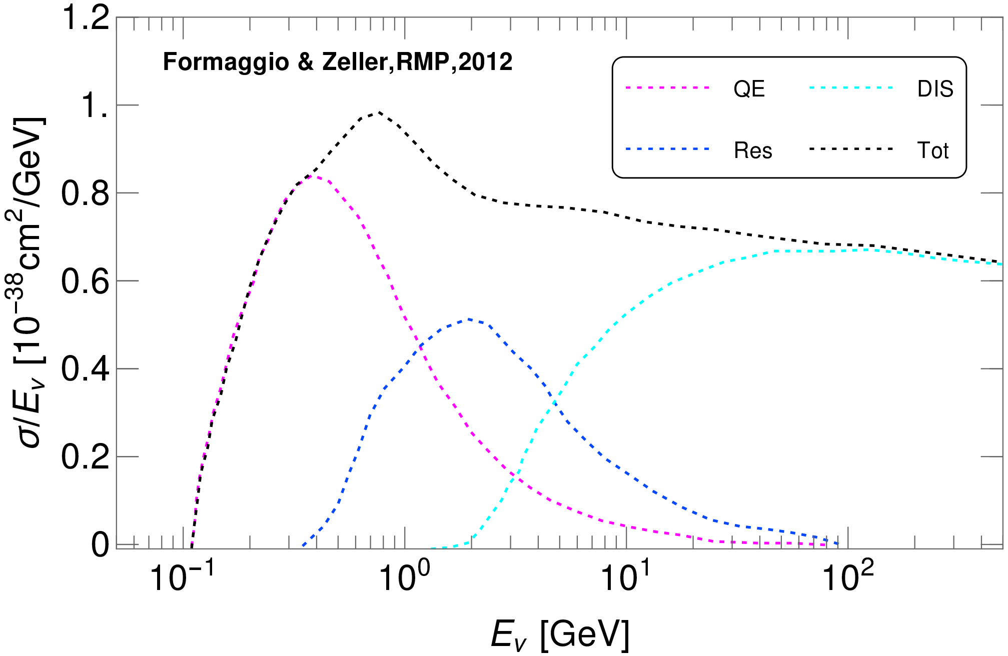
Why Coherent Elastic ν-nucleus Scattering (CEvNS)?

Neutrino processes at different energy scales



Intermediate regime

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



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!

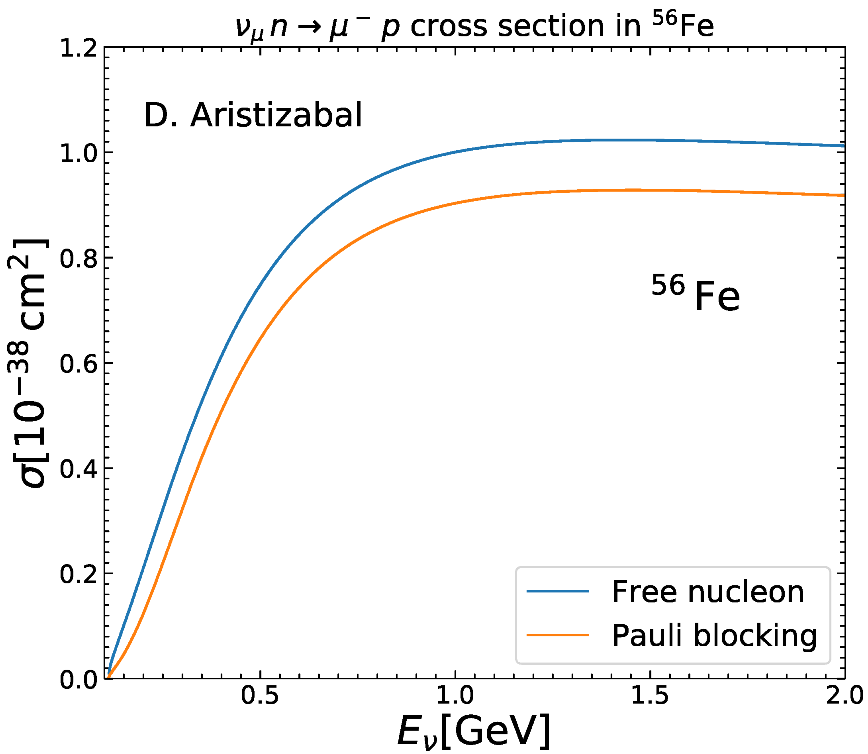
A few comments on theoretical uncertainties

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 $\sim 30\% - 20\%$

Nuclear effects are relevant

Effects in MC generators:

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

Low-energy regime

Inverse beta decay (IBD)

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

Used in reactor neutrino detection. Daya Bay, 2015

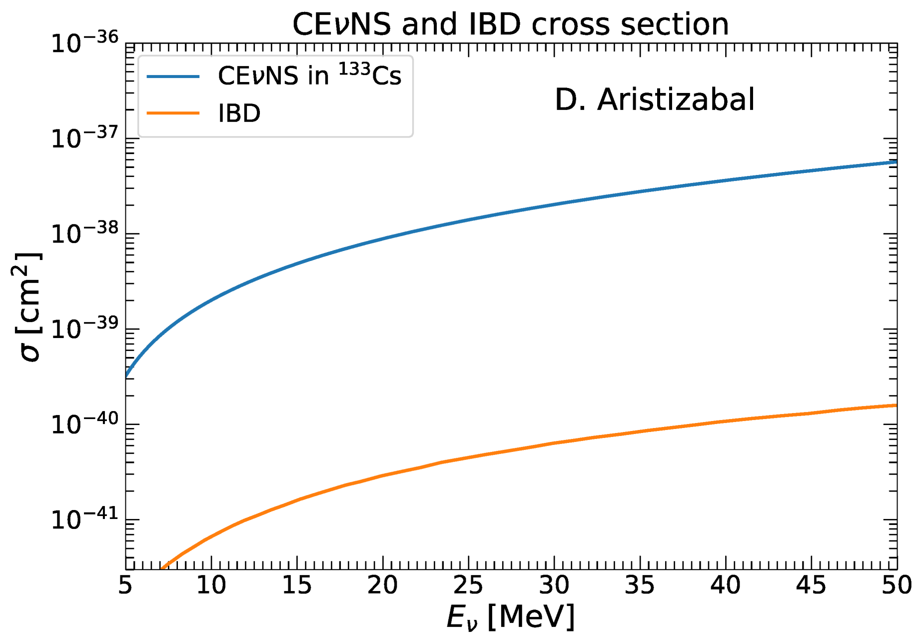
Uncertainties of $\sim 1\%$ (τ_n)

CEvNS

$$\boxed{\nu + (A, Z) \to \nu + (A, Z)}$$

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 occurs when the neutrino energy E_ν is such that nucleon amplitudes sum up coherently $\Rightarrow$ cross section enhancement

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

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

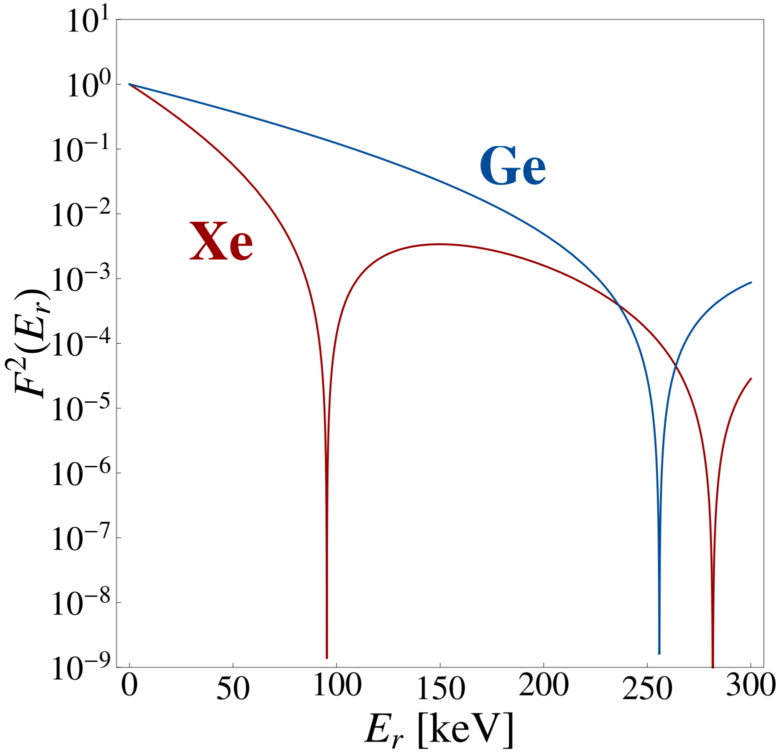
$$E_\nu \lesssim 200 \text{ MeV}$$

Freedman, 1974; Drukier & Stodolsky, 1984

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

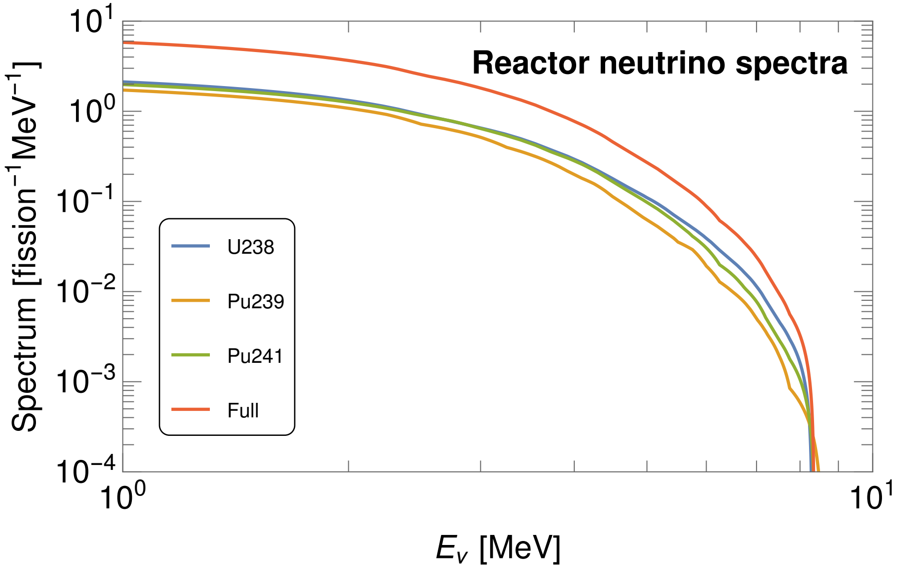
$$Q_{\text{W}}^2 = [N - (1 - s_W^2)Z]^2 \simeq N^2$$

Helm, 1956

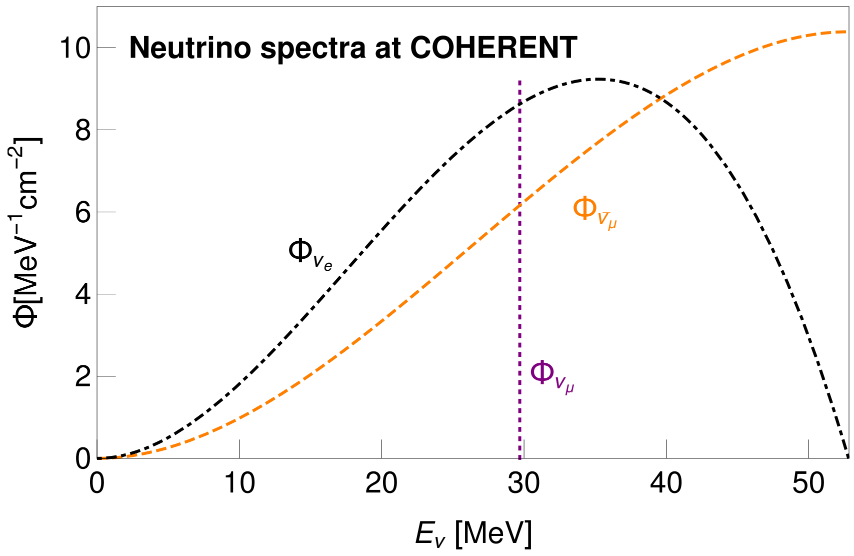


CEvNS environments

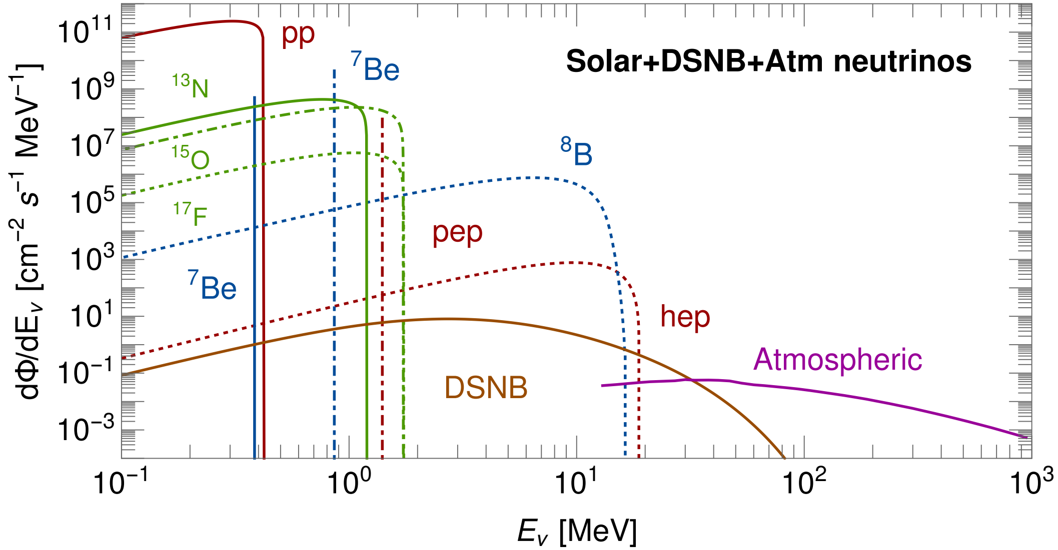
Reactor (CONUS, NUCLEUS, RICOCHET...)



Fixed target neutrinos (COHERENT)



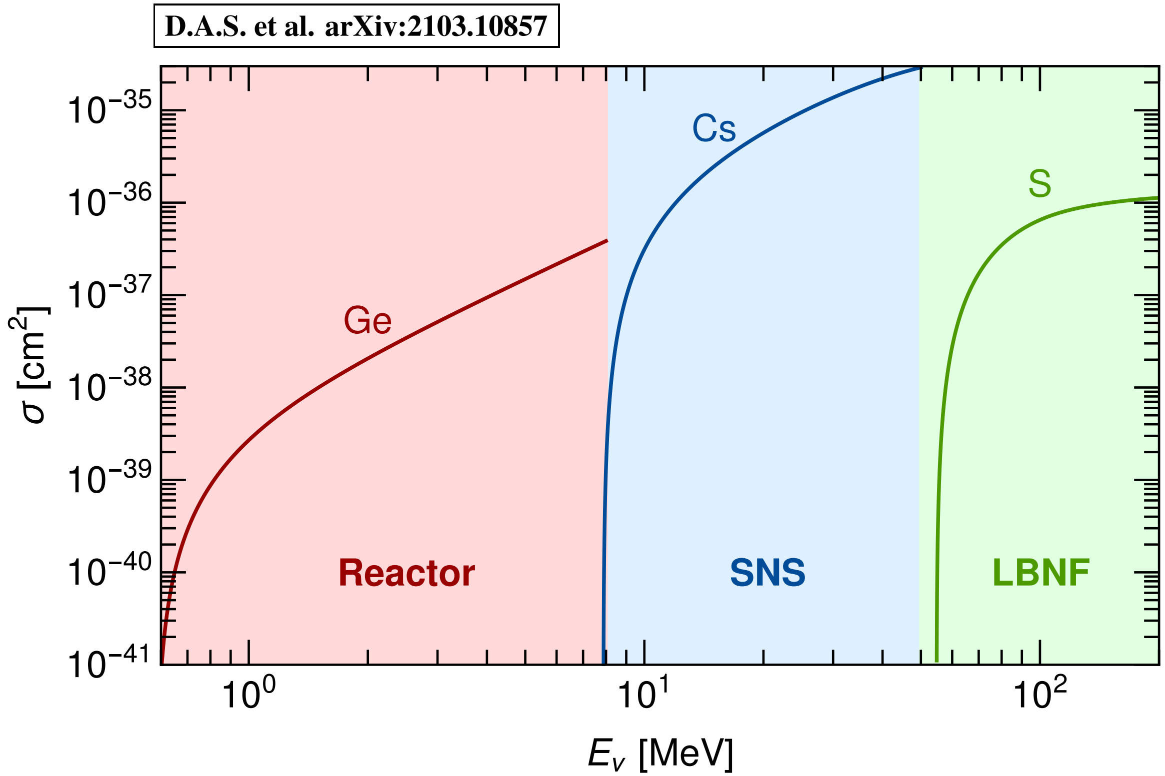
Solar+DSNB+Atm (DM detectors)



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!

Measurements

CEνNS observed by COHERENT more than 40 years after its prediction

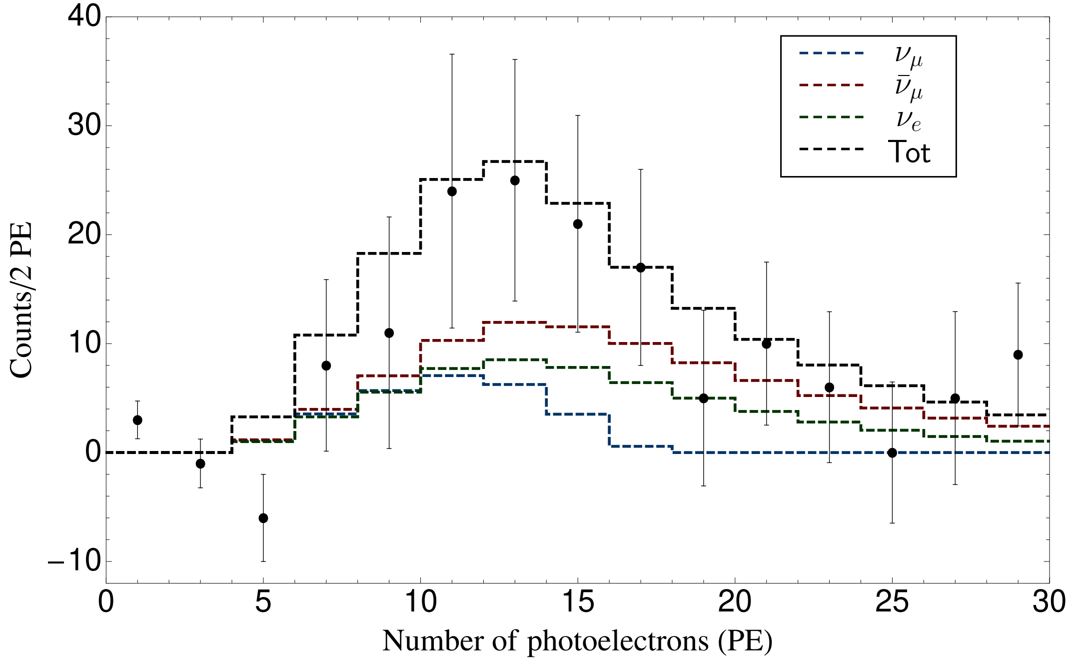
Akimov et. al. 2017

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



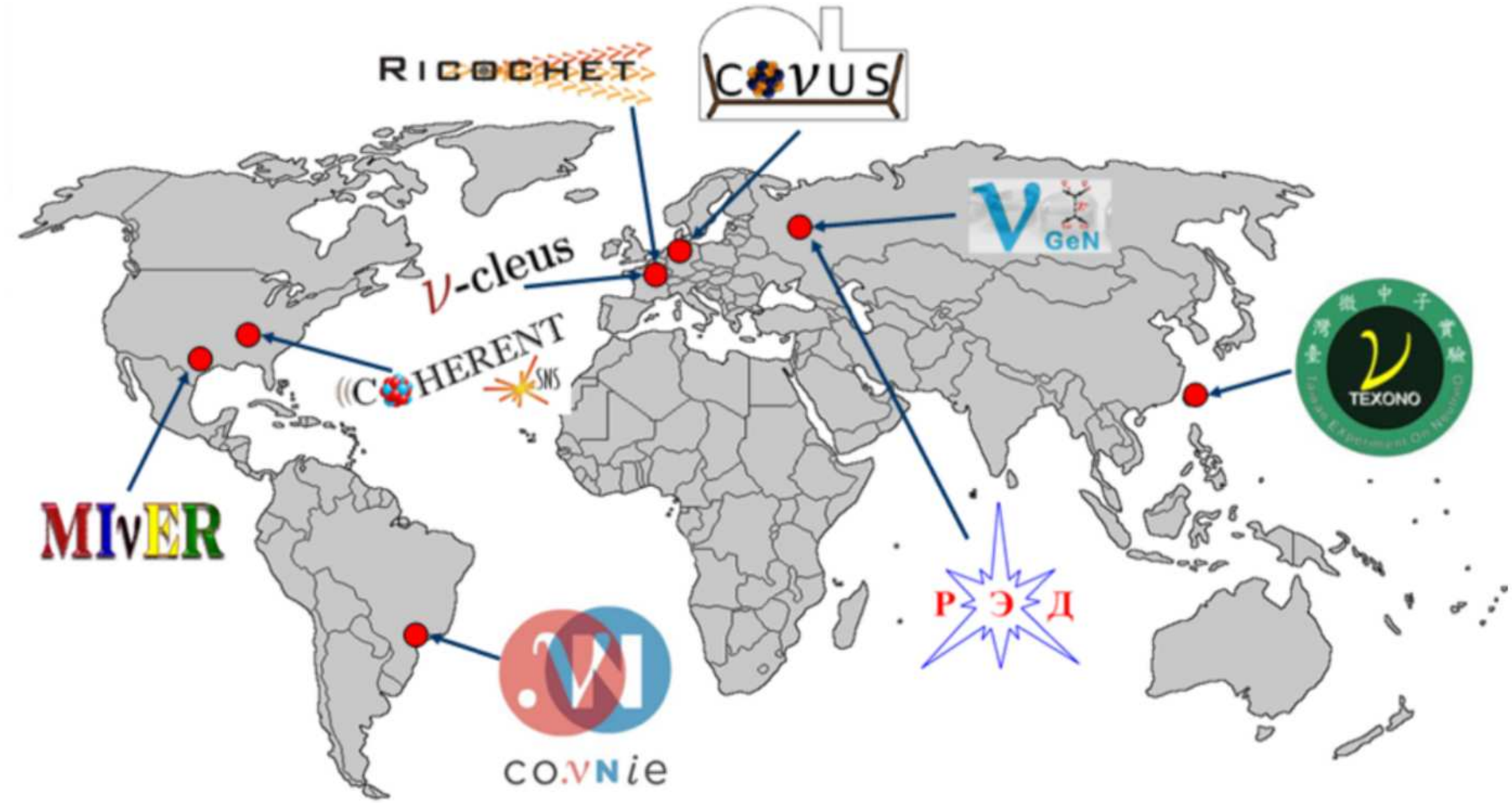
$$n_{\mathrm{PE}} = 1.17\,(E_R/\mathrm{keV})$$

Measured in LAr

CENNS-10 2003.10630

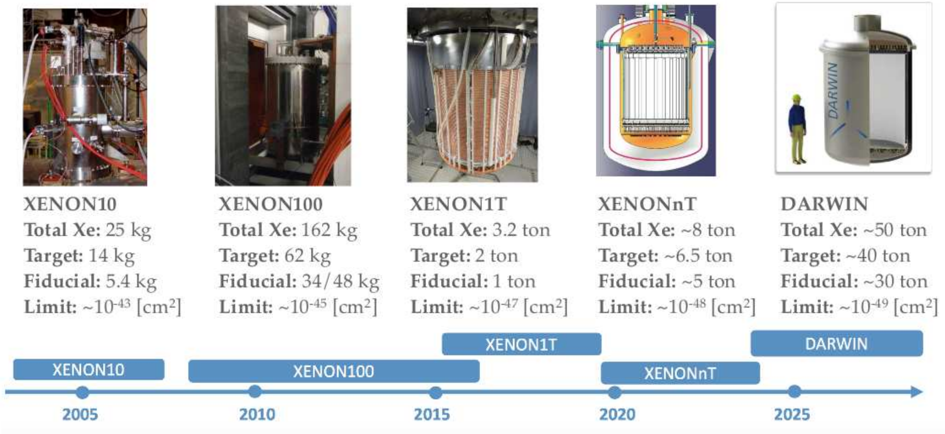
Ge expected in 2024

Ongoing projects worldwide



- Argentina — νIOLETA (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)

Multi-ton DM detectors



Lux-Zeplin (LZ) [G2 detector]

SURF, South Dakota, USA

Total: 10 ton of LXe

Fiducial: 5.6 ton of LXe

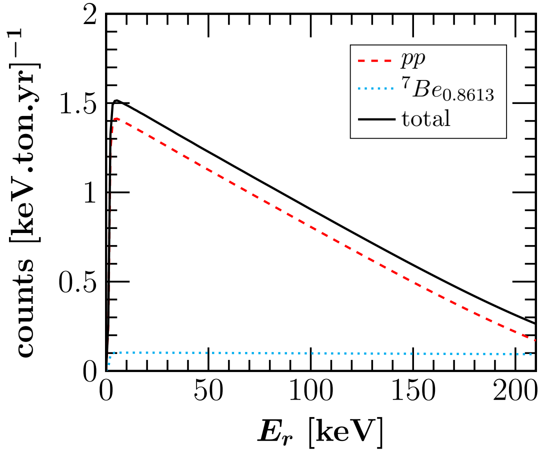
DM sensitivity: 10^{-48} cm^2

XLZD Consortium: 40-100 ton

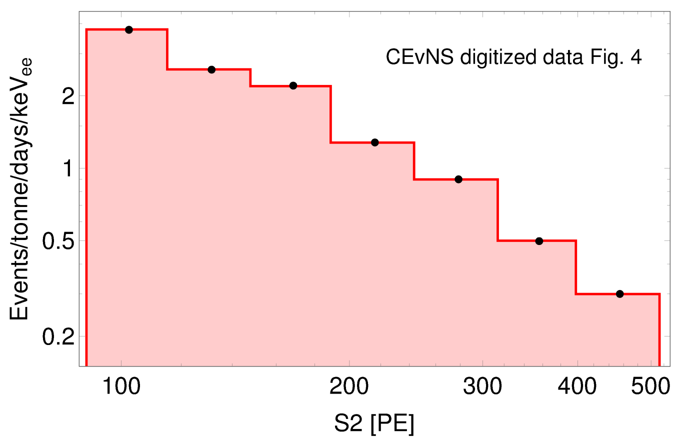
Neutrino-induced NR and ER will be abundant

in thrid generation DM detectors (XLZD)

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



E. Aprile et. al, 1907.11485



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...

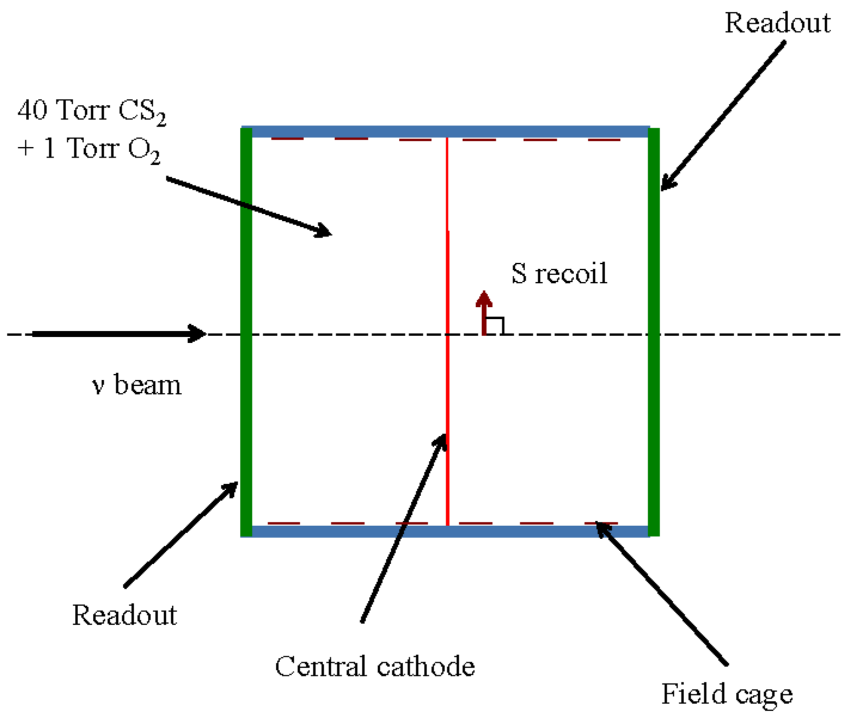
BSM searches

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

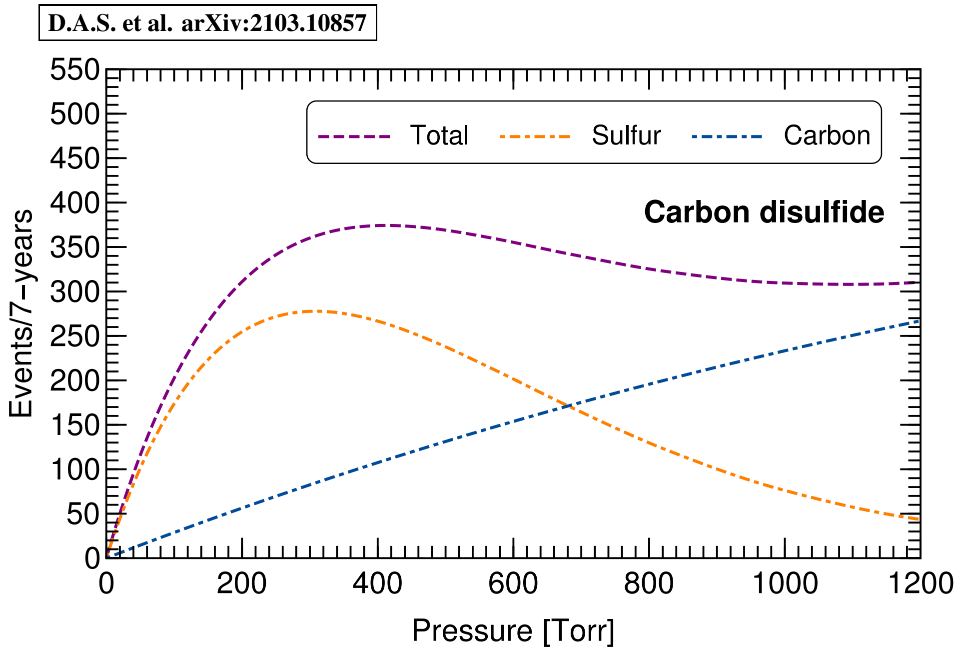
CEvNS physics with the νBDX-DRIFT detector

νBDX-DRIFT: Basics

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

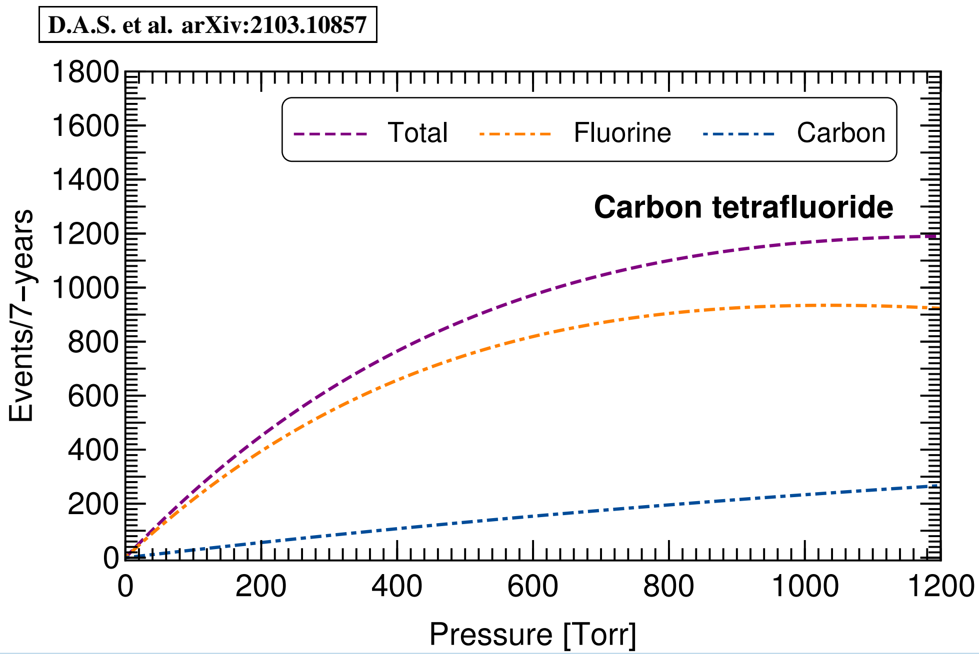


- NRs mainly in sulfur induce ionization
- CS_2^- ions used to transport the ionization to the readout planes (MWPCs)



Signal peaks at 400 Torr

Expected signal: 370 events



100% filled with CF_4

Expected signal: 880 events

Measurements of R_n via CEvNS

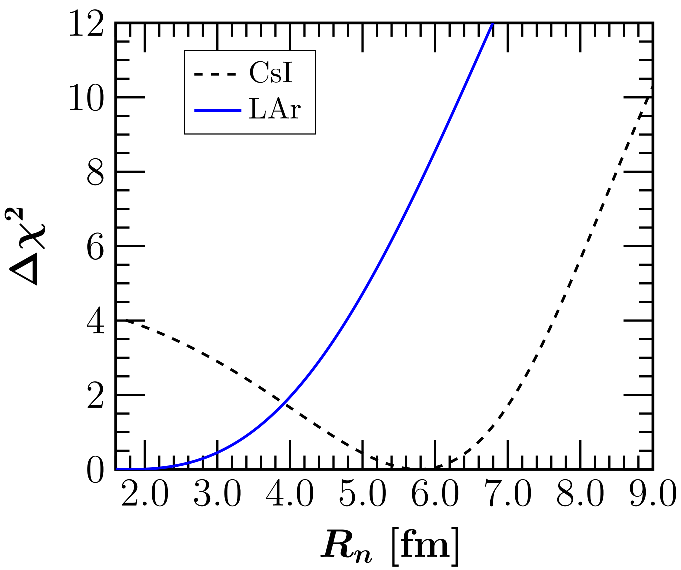
$$\boxed{F_W(q^2) = \frac{1}{Q_W}\left[Z\, g_V^p\, F_V^p(q^2) + (A-Z)\, g_V^n\, F_V^n(q^2)\right]}$$

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

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

$$\boxed{N_{\text{CEvNS}} = N_{\text{CEvNS}}(R_n)} \qquad \boxed{N_{\text{CEvNS}}^{\text{Exp}} \Rightarrow R_n}$$

Miranda et al, JHEP 05 (2020)



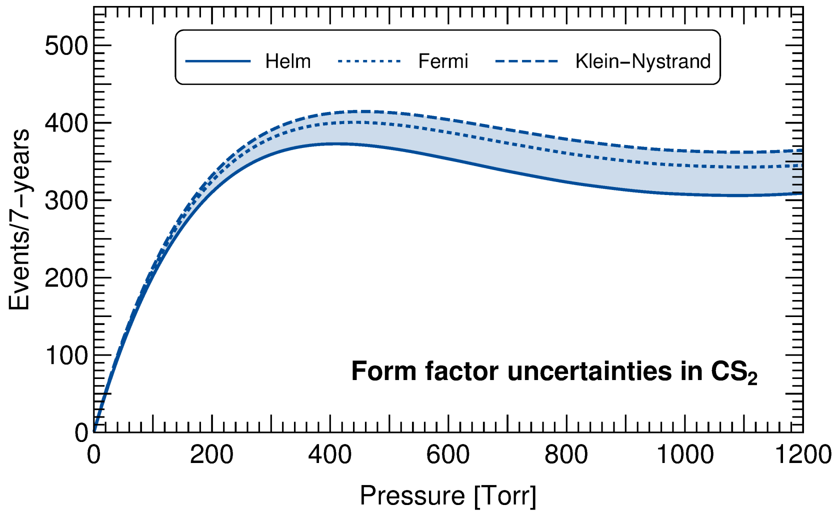
COHERENT 90% CL limits

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)

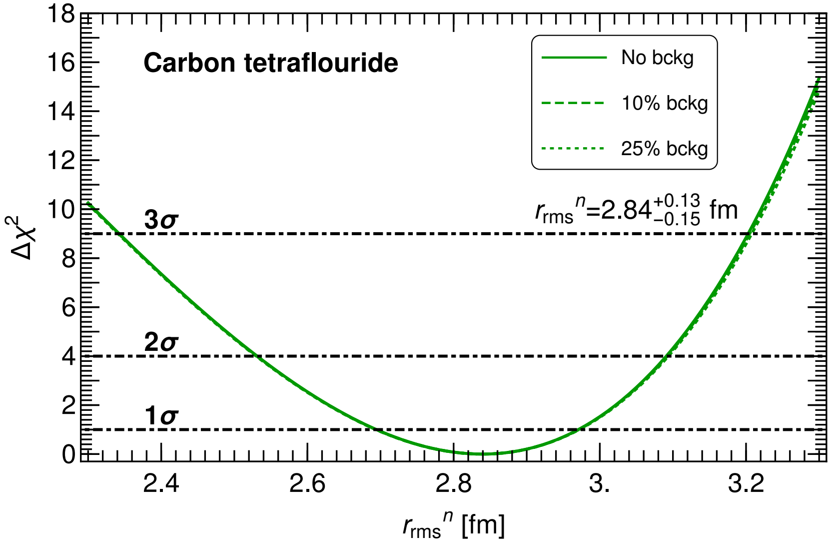


High-energy nature of the flux

$\Rightarrow$ Moderate dependence on the FF

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

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



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

C and F determined with a 3% accuracy

Measurements of the WMA via CEvNS

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

$$\boxed{g_V^p = 1/2 - 2\sin^2\theta_W}$$

$\Rightarrow$ Measurements of CEvNS are done at $q \ll \Lambda_{\text{EW}}$

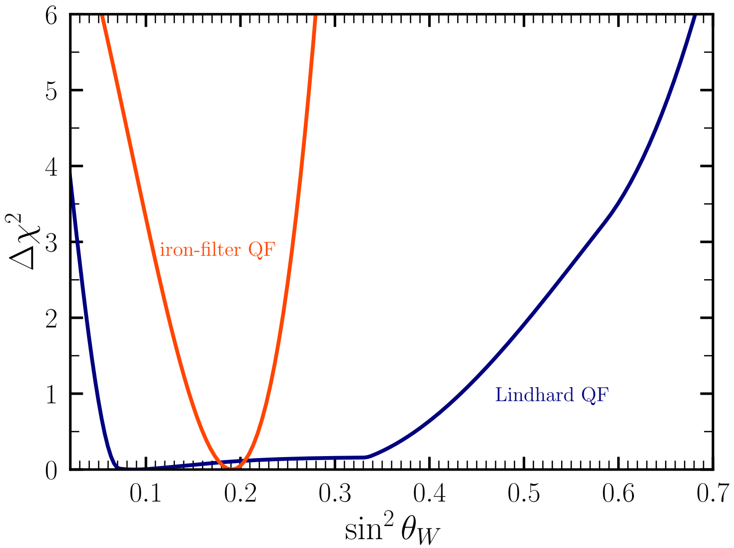
$\Rightarrow$ Done using CsI and LAr COHERENT data, recently using Dresden-II data

D.A.S, De Romeri, Papoulias, 2203.02414

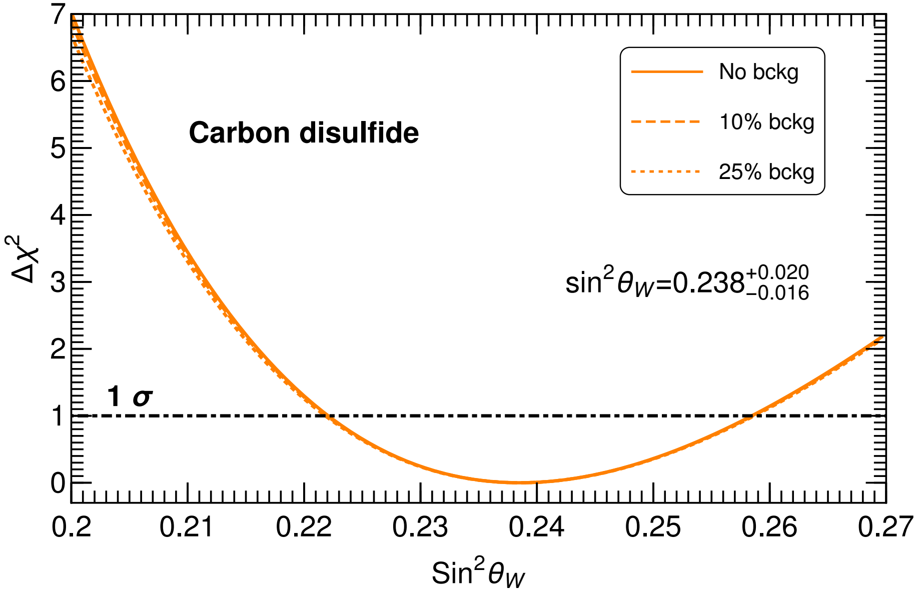
ML QF: $s_W^2 = 0.086^{+0.347}_{-0.038}\,(1\sigma)$

Iron-filter QF: $s_W^2 = 0.191^{+0.039}_{-0.045}\,(1\sigma)$

COHERENT LAr: $s_W^2 = 0.258^{+0.048}_{-0.050}$ (90%CL)



Weak mixing angle at νBDX-DRIFT



CS_2: $\sin^2\theta_W = 0.238^{+0.020}_{-0.016}$

CF_4: $\sin^2\theta_W = 0.238^{+0.021}_{-0.017}$

$\sim 8\%$ level in NR channel

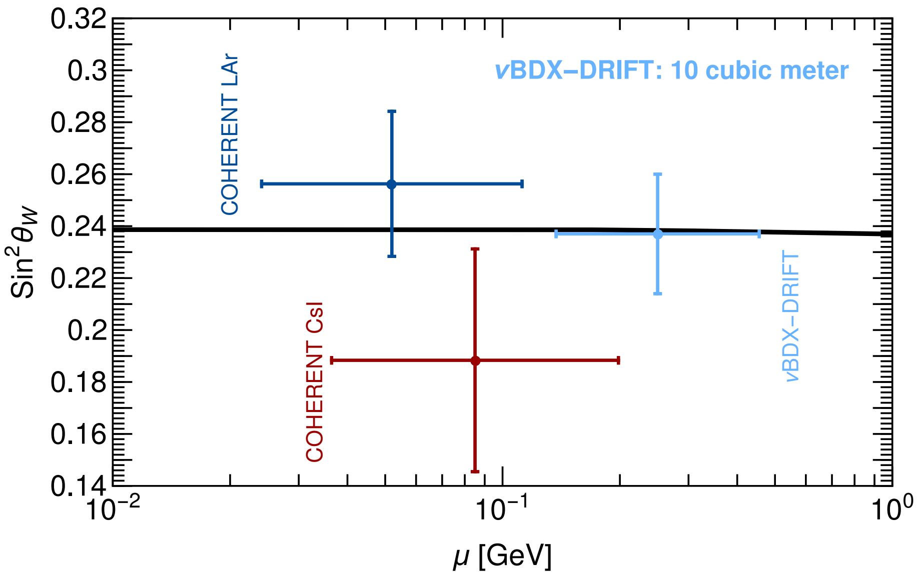
DUNE in e-channel 3%

How this compares with COHERENT?

CsI: $q \subset [35, 68]$ MeV

CsI: $q \subset [38, 78]$ MeV

νBDX-DRIFT: $q \subset [78, 397]$ MeV

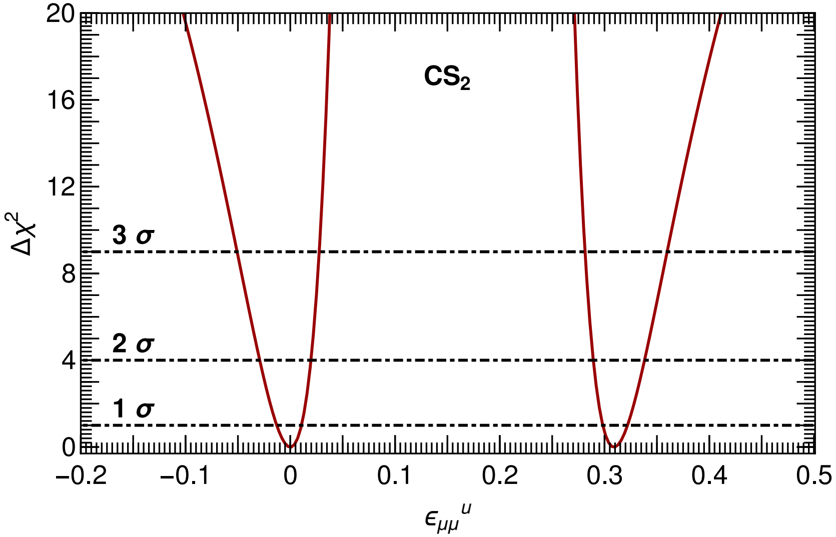


Neutrino Nonstandard Interactions (NSI)

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

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

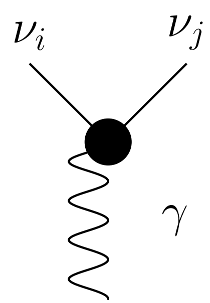
$\Rightarrow$ Destructive interference

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

Neutrino EM properties in G3 DM detectors

Neutrino EM current

$$\boxed{\text{Parametrization and model-independent results derived by Kayser PRD 26, 1982 (1662) and Nieves PRD, 26, 1982 (3152)}}$$



$$\boxed{\langle \nu_i | j_\mu | \nu_j \rangle = f_Q(q^2)_{ij}\gamma_\mu + f_A(q^2)_{ij}(q^2\gamma_\mu - q_\mu \not{q}) + i\sigma_{\mu\nu}q^\nu[f_M(q^2)_{ij} - i f_E(q^2)_{ij}\gamma_5]}$$

⇒ Diagonal EM FFs ($q^2 \to 0$): $f_Q \to Q_\nu$ $f_A \to a_\nu$ $f_M \to \mu_\nu$ $f_E \to \epsilon_\nu$

⇒ Diagonal EM FFs: $\underbrace{f_E(q^2)_{ii} = 0 \text{ (CP conserved)}}_{\text{Dirac } \nu}$ $\underbrace{f_A(q^2)_{ii} \neq 0}_{\text{Majorana } \nu}$

⇒ Off-diagonal EM FFs: Non-zero for ν_D and ν_M ⇒Transitions

Constraints I

These couplings contribute to a variety of processes

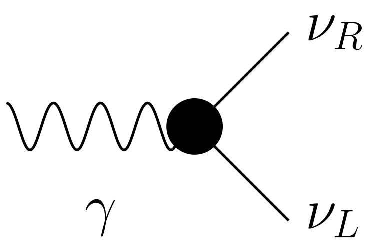
The most widely considered: μ_ν

Astrophysical bounds

Raffelt, Phys. Rep. 198 (1990)

Spin-flip scattering in SN

ν's are trapped by EW int

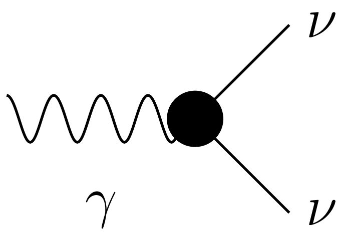


$\mu_\nu \lesssim 3 \times 10^{-12} \mu_B$

Arceo et. al, arXiv:1910.10568

Globular cluster stars

$\omega^2 + |\vec{k}|^2 \geq 0$



$\mu_\nu \lesssim 2.2 \times 10^{-12} \mu_B$

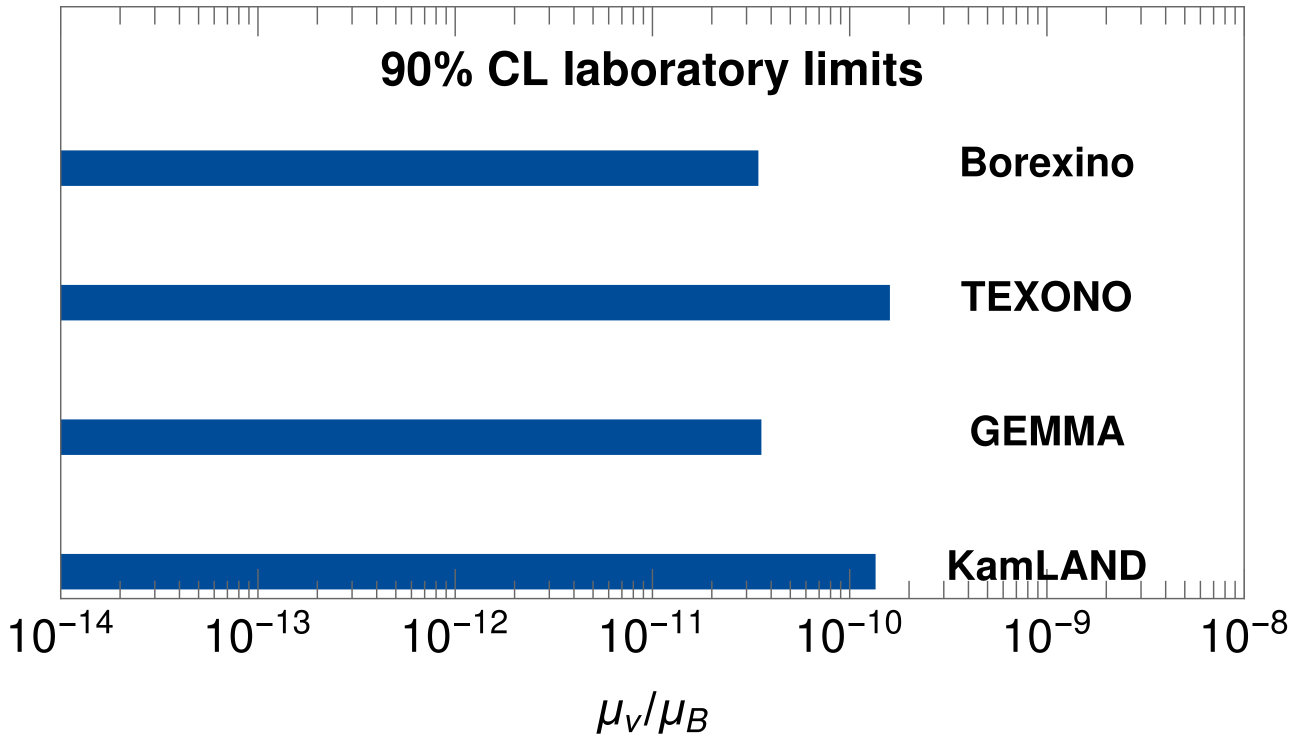
My view/understanding:

These bounds should be understood as order of magnitude estimations

Constraints II

Laboratory limits

More robust than astrophysical bounds. Follow from $\nu - e$ scattering using solar and reactor neutrino fluxes



μ_ν contribution to CEvNS (NR) event rates

Vogel & Engel, PRD, 39 (1989)

$$\frac{d\sigma_{\nu-N}}{dE_r} = \pi\alpha Z^2 \frac{\mu_{\text{eff}}^2}{m_e^2}\left(\frac{E_\nu - E_r}{E_\nu E_r}\right) F^2(E_r)$$

Spectral distortions, particularly relevant at low recoil energies

μ_ν contribution to $\nu - e$ (ER) event rates

Vogel & Engel, PRD, 39 (1989)

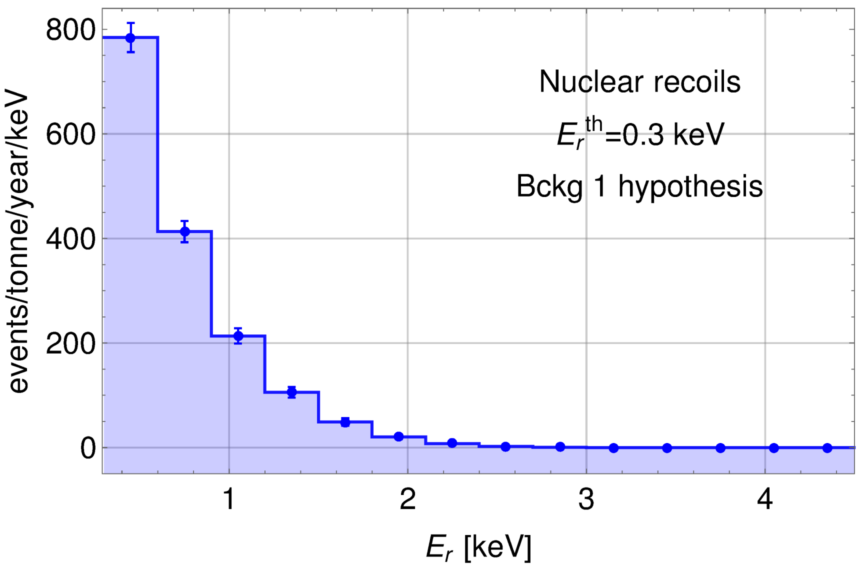
$$\frac{d\sigma_{\nu-e}}{dE_r} = \pi\alpha \frac{\mu_{\text{eff}}^2}{m_e^2}\left(\frac{E_\nu - E_r}{E_\nu E_r}\right)$$

Same spectral features

A detector sensitive to both allows an interplay between ER and NR measurements

Expectations at a 1-ton detector (XENON1T)

Ideal detector: 100% acceptance, no Gaussian smearing



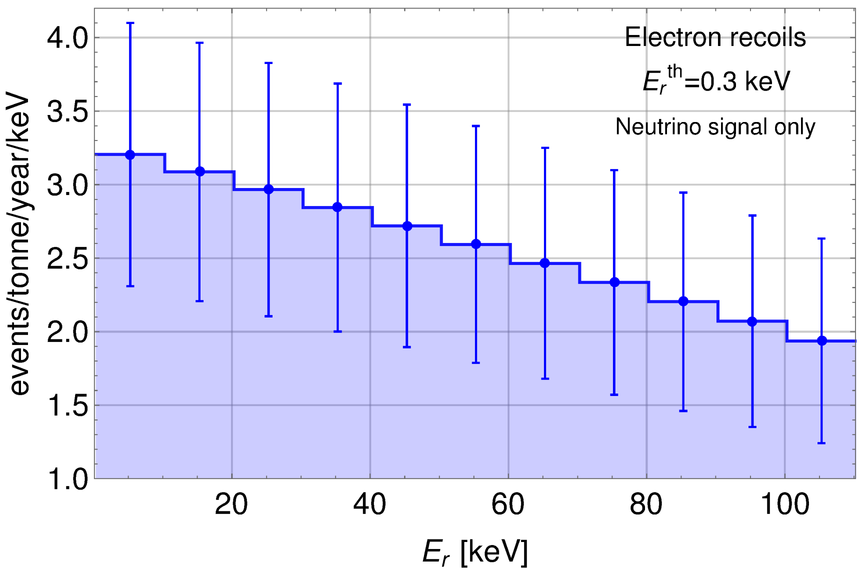
Signal dominated by ^{8}B

Rather sensitive to E_r thresholds

Signal dominated by pp

subdominant ^{7}Be (0.8 MeV)

less sensitive to E_r thresholds



Sensitivities: procedure

✍ Generate *toy experiments* assuming SM signals

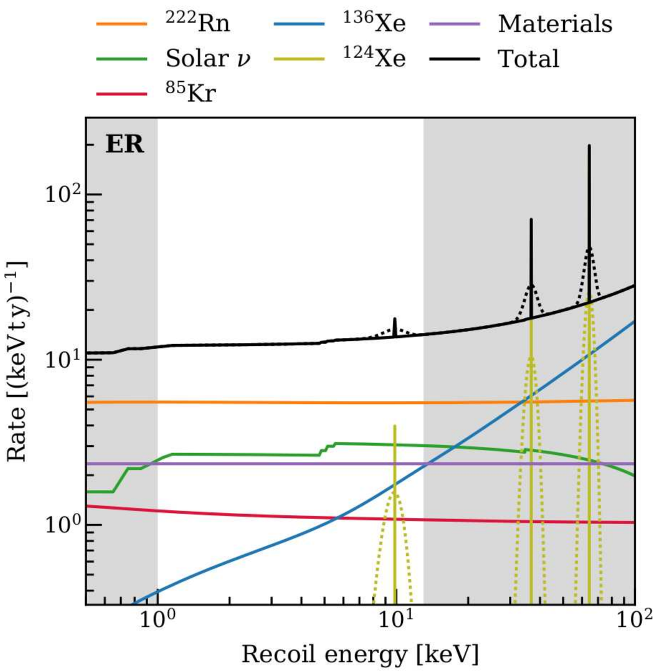
✍ For CEvNS assume two background hypotheses + two thresholds

✔ 25% and 68% of the signal rate & 1 keV and 0.3 keV

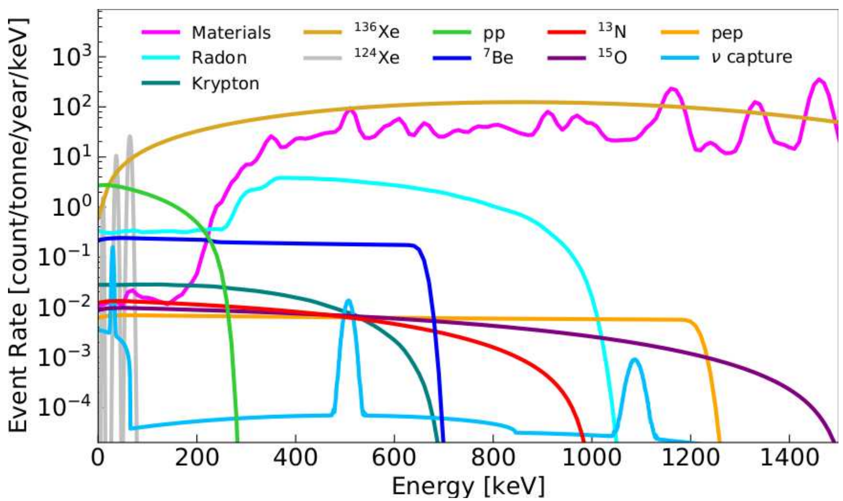
✍ For $\nu - e$ scattering use predicted background

✔ material radioactivity, $\beta\beta$ of ^{136}Xe...

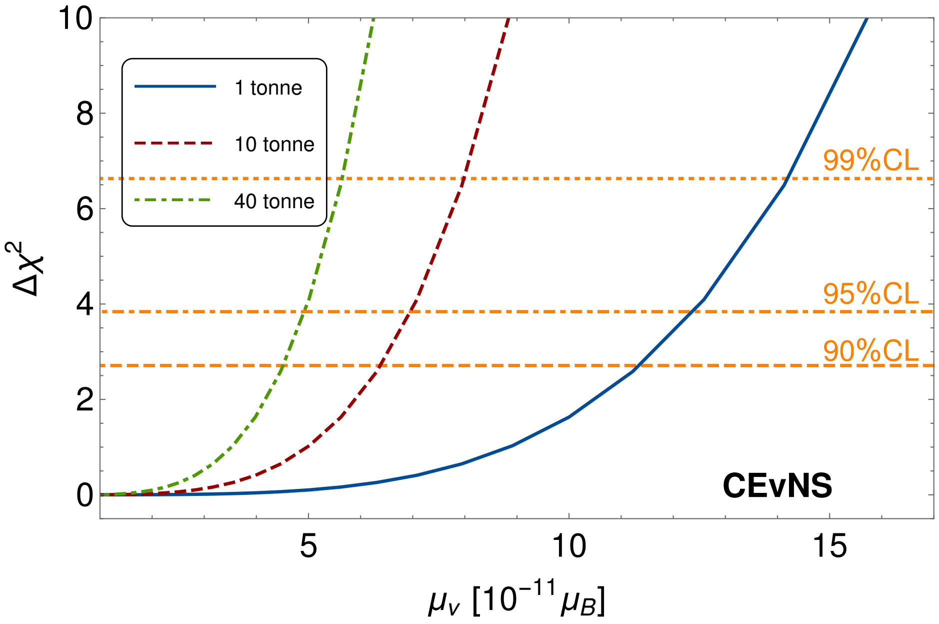
XENONnT, 2007.08796



DARWIN, 2006.03114



Nuclear recoils

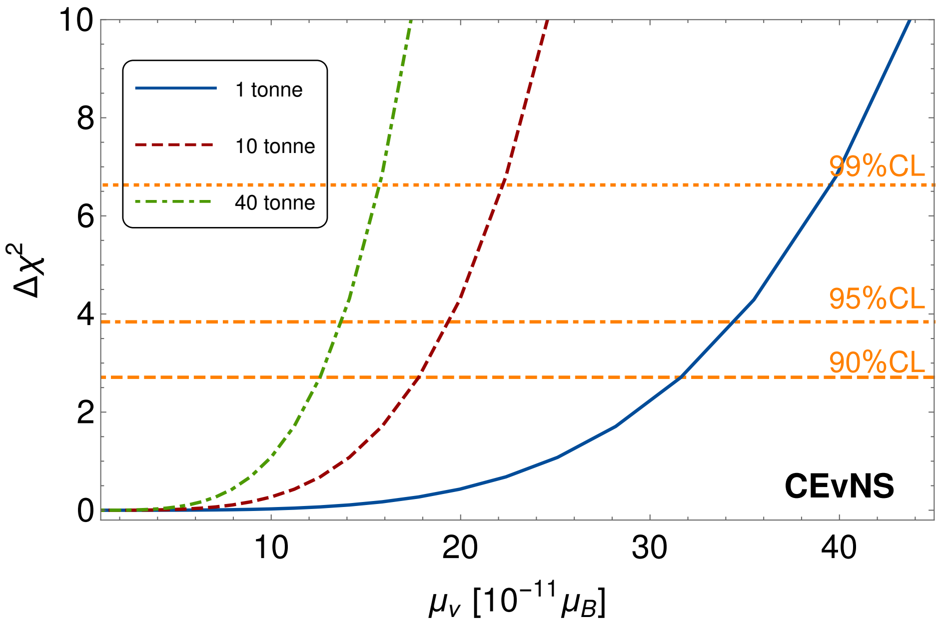


Best sensitivities found for

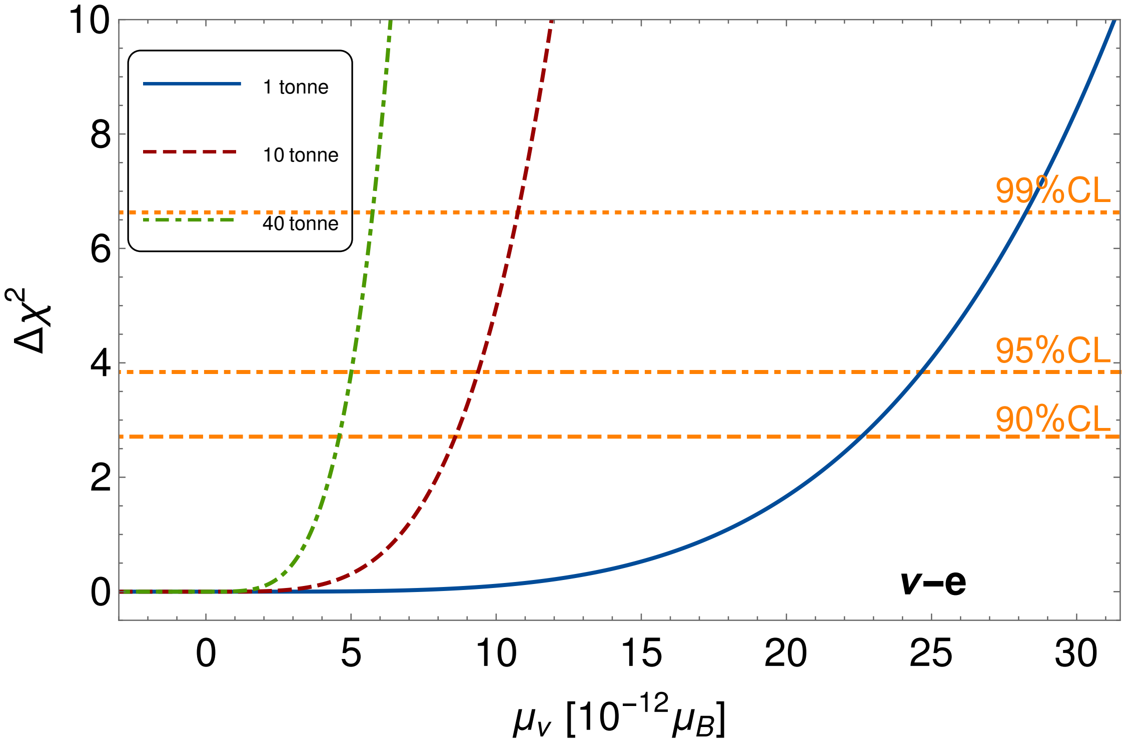
$E_r = 0.3$ keV and Bckg-2 hypothesis

Worse sensitivities found for

$E_r = 1$ keV and Bckg-1 hypothesis



Electron recoils



Sensitivities enter the region not constrained by astrophysical arguments... Region where some TeV-related new physics predicts $\mu_\nu \neq 0$

Final remarks

Conclusions

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

✍ 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 [?]

✍ SM measurements include: Weak mixing angle at $\langle Q \rangle \simeq 0.01 - 0.1$ GeV
neutron density distributions of e.g. C, F, S, Pb with sensitivities of order 3-8%

✍ BSM searches include: Neutrino NSI, NGI and light vector and scalar mediators, sterile ν's
Sensitivities for NSI: $\mathcal{O} \sim 10^{-2}$ couplings can be tested

✍ An agenda for light DM searches (MeV) is defined as well

$$\pi^0 \to \gamma + \gamma_{\text{Dark}} \to \gamma + \text{DM} + \text{DM}$$

Work in progress

Thanks!