A. Konovalov (LPI RAS, MEPhI)

Review of CEvNS measurements

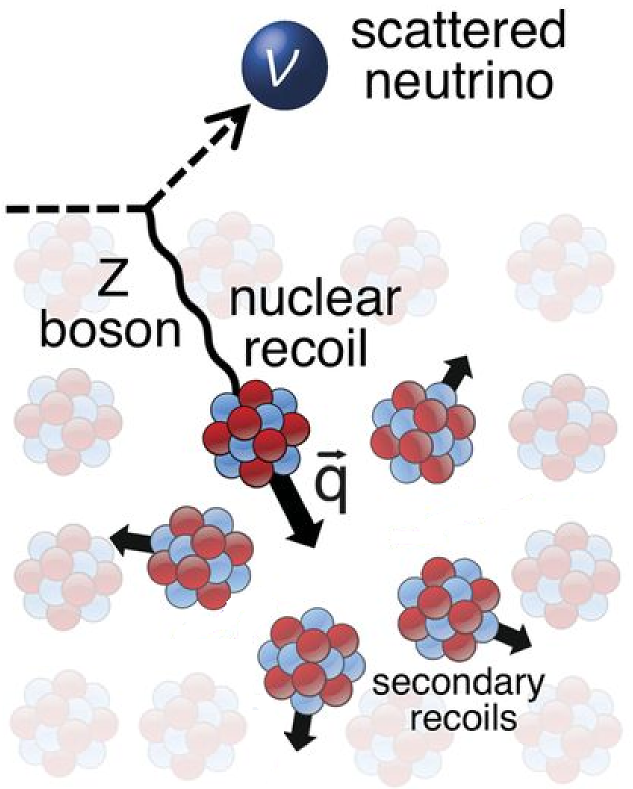
Supported by Ministry of Science and Higher Education of Russia, project FSWU-2023-0073

Moscow, MSU *August 22 2025*

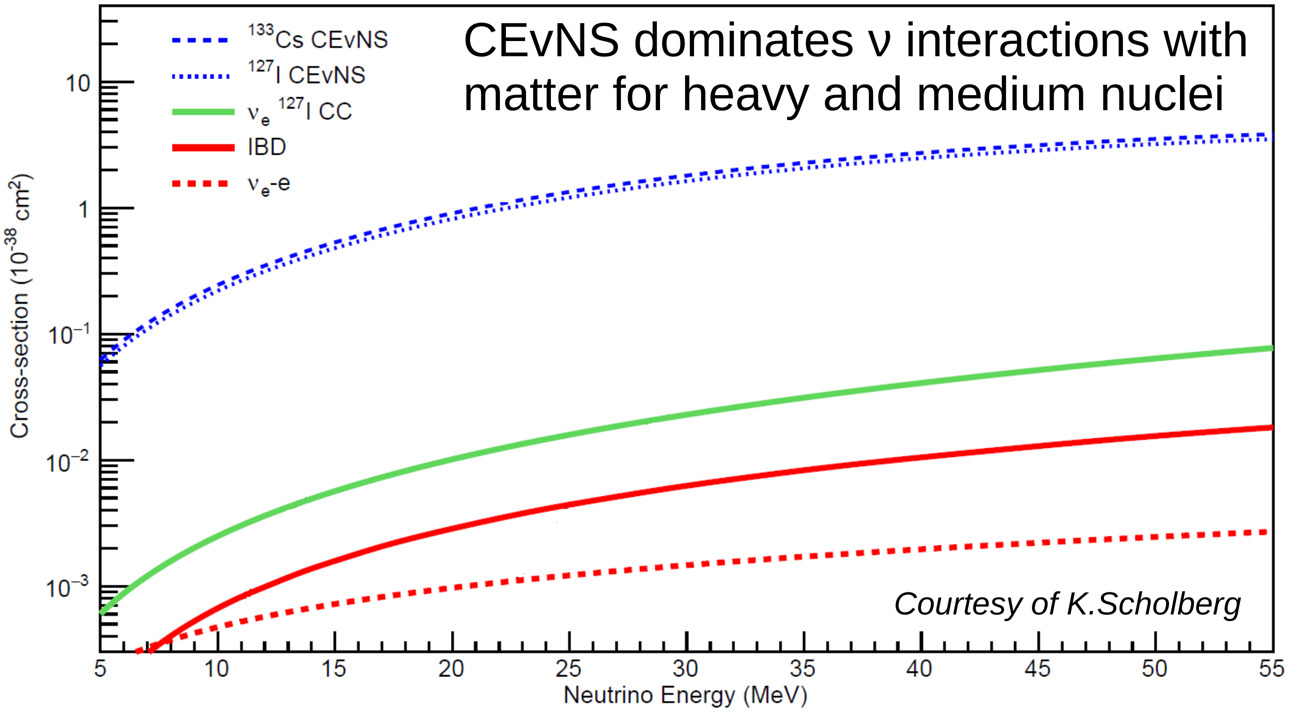
CEvNS — coherent elastic neutrino-nucleus scattering

«Coherent effect of a weak neutral current», D. Freedman, PRD v.9, iss.5 (1974)

«Isotopic and chiral structure of neutral current», V.Kopeliovich, L. Frankfurt, ZhETF. Pis. Red., v.19 n.4 (1974)



$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{4\pi}\left([1 - 4\sin^2\theta_W]Z - N\right)^2\left[1 - \frac{T}{T_{max}}\right]F_{nucl}^2(q^2)$$



Energy of nuclear recoils

Despite a large cross-section was detected 43 years after the prediction (COHERENT)

$$T_{max} = 2E_\nu^2/(M + 2E_\nu)$$

«Observation of Coherent Elastic Neutrino-Nucleus Scattering», Science 357 6356 (2017)

The largest experimental challenge – low energy of nuclear recoils (NR)

Nucleus	T_{max}, keV (E_ν =5 MeV)	T_{max}, keV (E_ν =30 MeV)
^{12}C	4.44	159.0
^{23}Na	2.32	83.2
^{40}Ar	1.33	47.9
^{74}Ge	0.72	25.9
^{133}Cs	0.40	14.4

1.5 keV NR in Ge -> 0.27 keV_{ee} ionization

10 keV NR in CsI-> 0.85 keV_{ee} scintillation

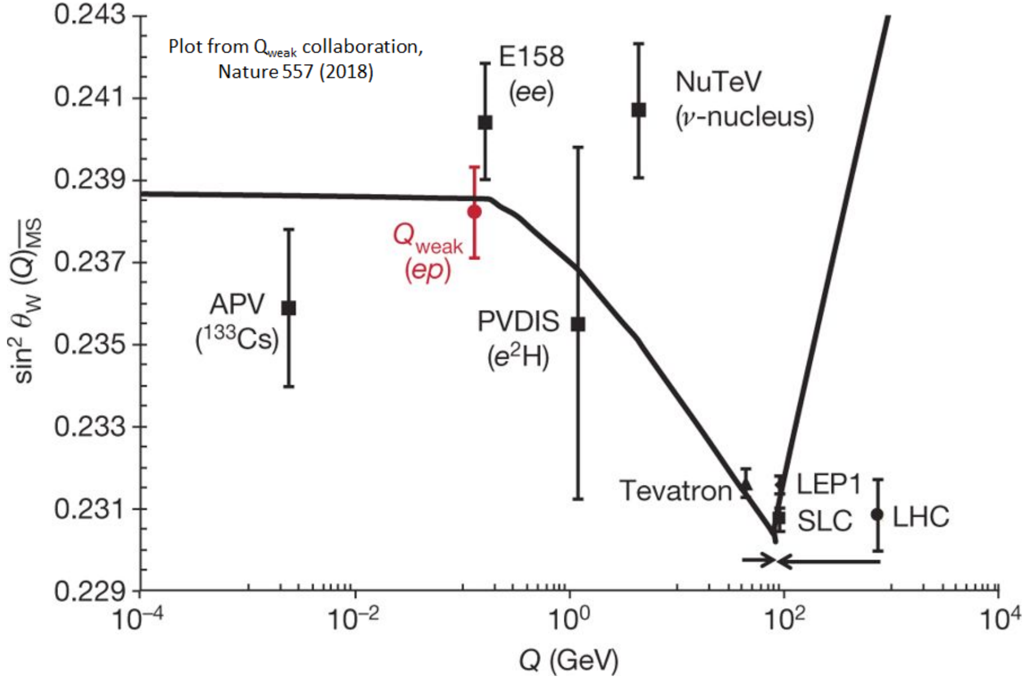
Only a fraction of NR energy can be detected, the ionization and scintillation response to NR is quenched relative to electron recoils

Motivation

Search for New physics

BSM $\nu_{(e)}$-q interactions via neutral current (e.g. Z')

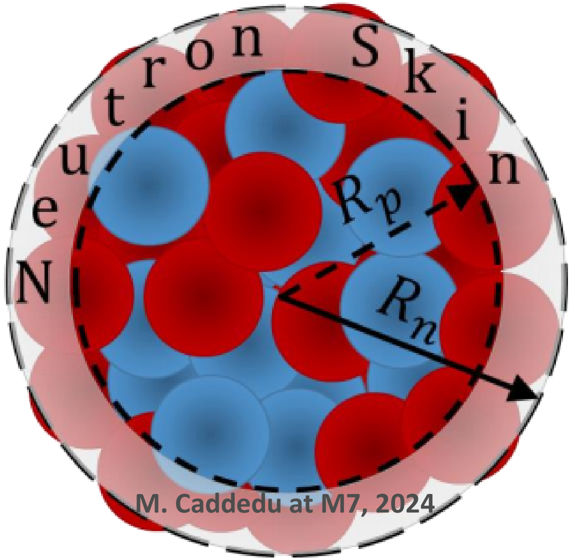
K. Scholberg, PRD 73 033005 (2006)   P. Coloma, T. Schwetz, PRD 94 055005 (2016)



SM test via $\sin^2\theta$ running   L. M. Krauss, Phys. Lett. B 269 407 (1991)

Nuclear structure

$F^V_{\rm nucl}(Q^2)$ shows strength of interference



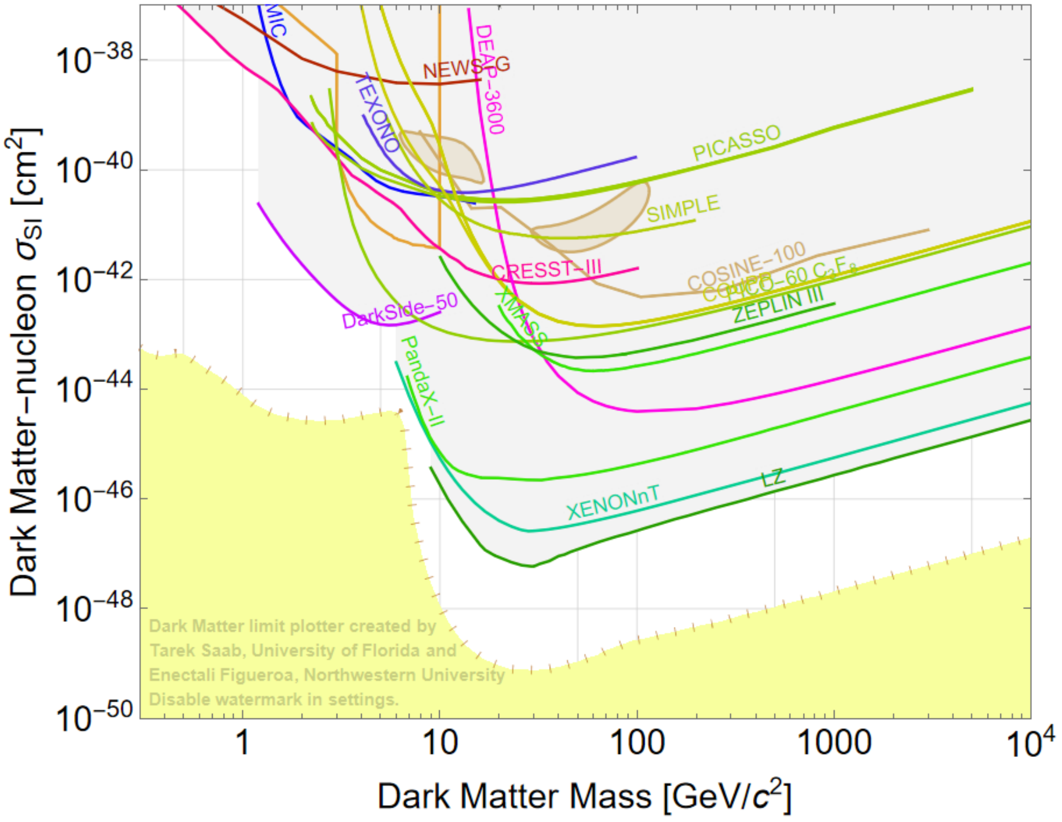
CEvNS probes the distribution of neutrons free of 'strong" uncertainties

K. Patton et al., PRC 86, 024216 (2012)

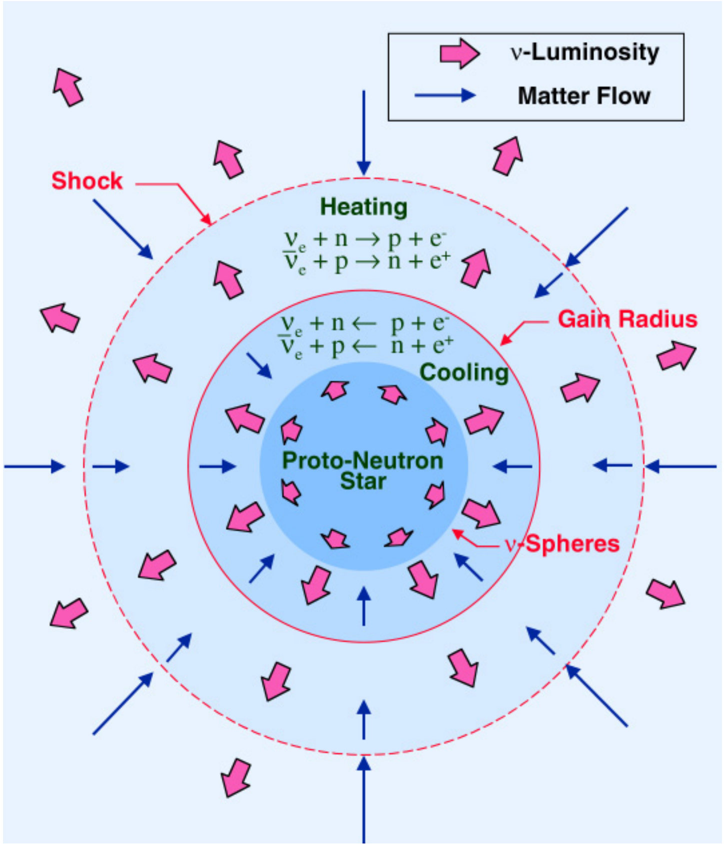
Motivation

In WIMP searches

J. Billard et al., PRD 89 (2014)



In supernova dynamics

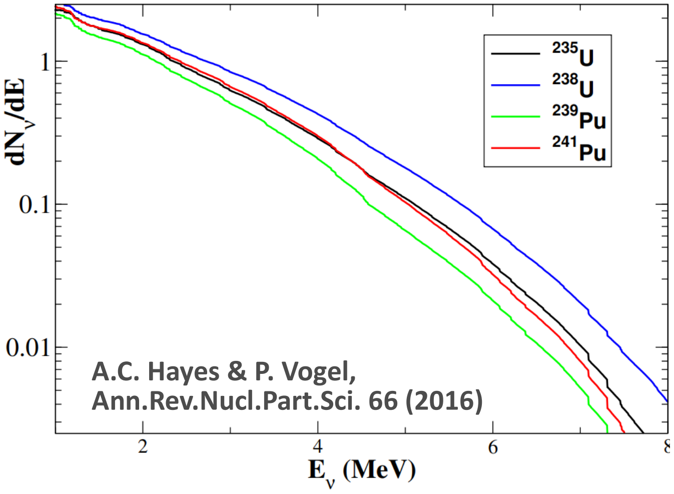


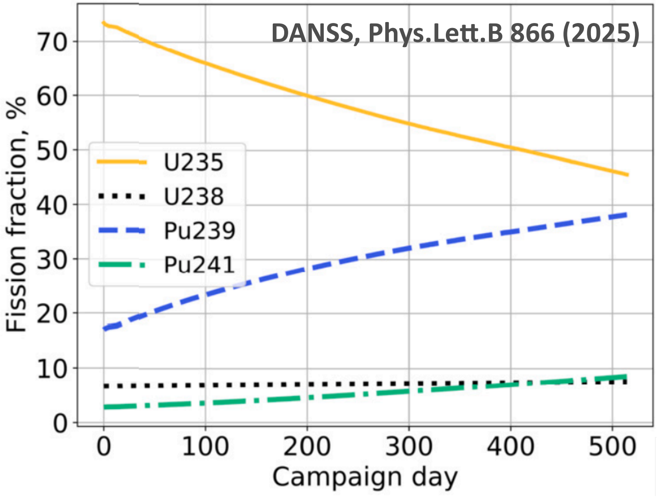
J.R. Wilson, PRL 34 113 (1974) D.N. Schramm, W.D. Arnett, PRL 34, 113 (1975)

Application: reactor monitoring

Antineutrino spectra of reactor fuel components

A.C. Hayes & P. Vogel, Ann.Rev.Nucl.Part.Sci. 66 (2016)





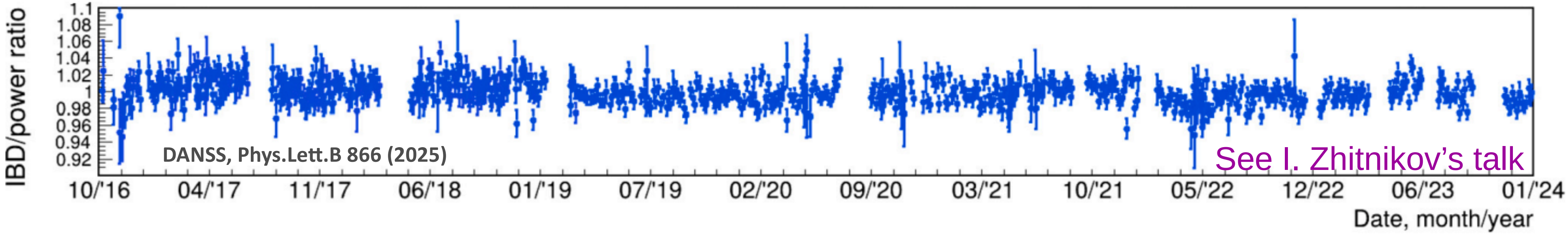
Large cross-section

Y. Kim, Nucl. Eng. Tech. 48, 285 (2016)

Compact detector

Fuel evolution via count rate

Competition from IBD experiments M. Bowen & P. Huber, PRD 102 (2020)

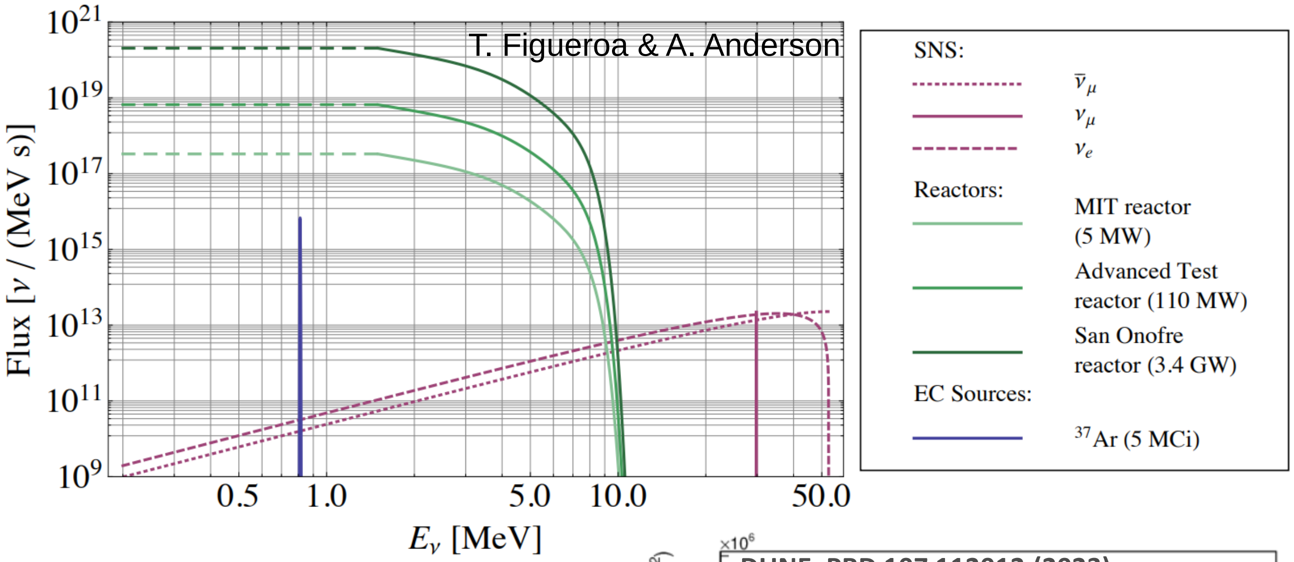


See I. Zhitnikov's talk

Neutrino sources to study CEvNS

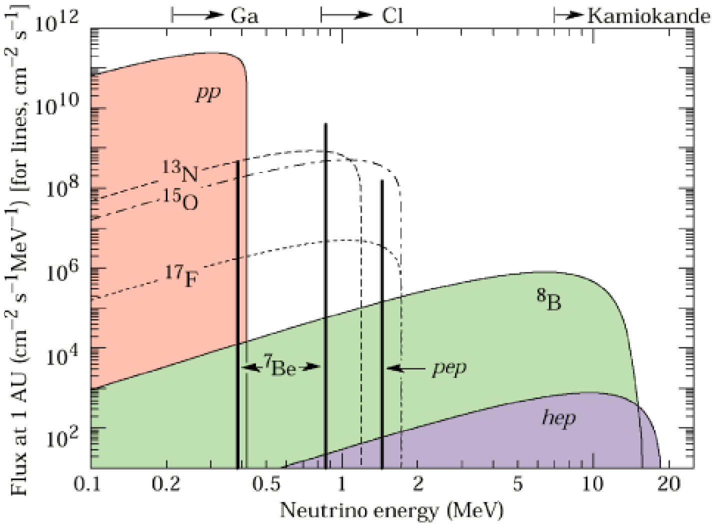
Anthropogenic

- Reactors
- Accelerators (π DAR)
- Radionuclides

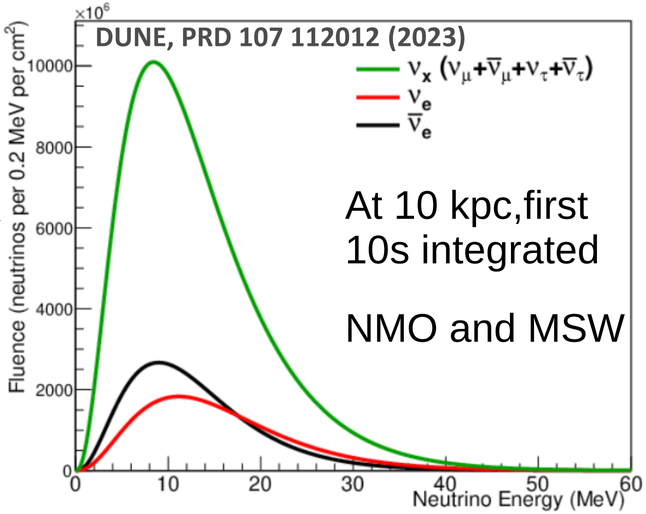


Astrophysical

- Sun
- Supernovae



Benefit of overburden in underground laboratories



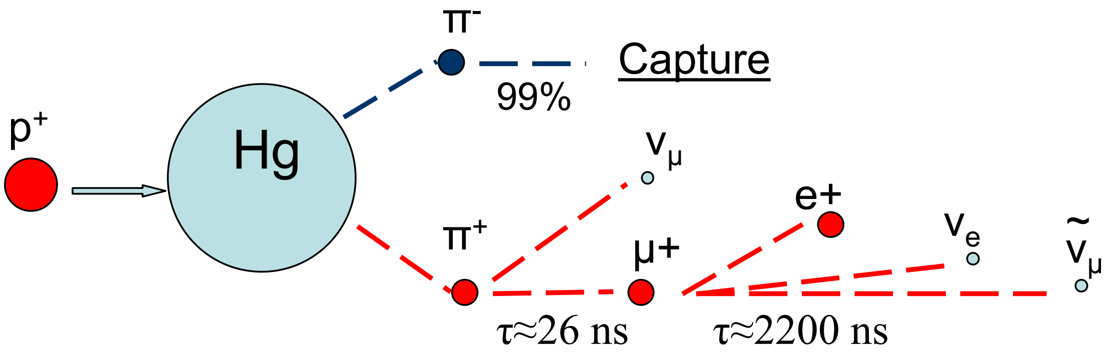
At 10 kpc, first 10s integrated

NMO and MSW

Spallation neutron source (SNS) at ORNL

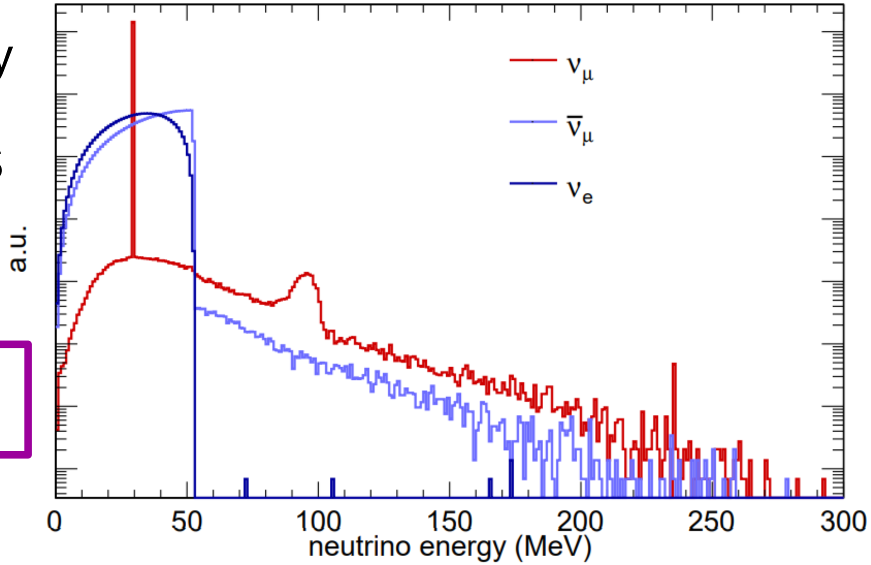
Bunches of ~1 GeV protons on the Hg target with 60 Hz frequency, ~350 ns FWHM bunch

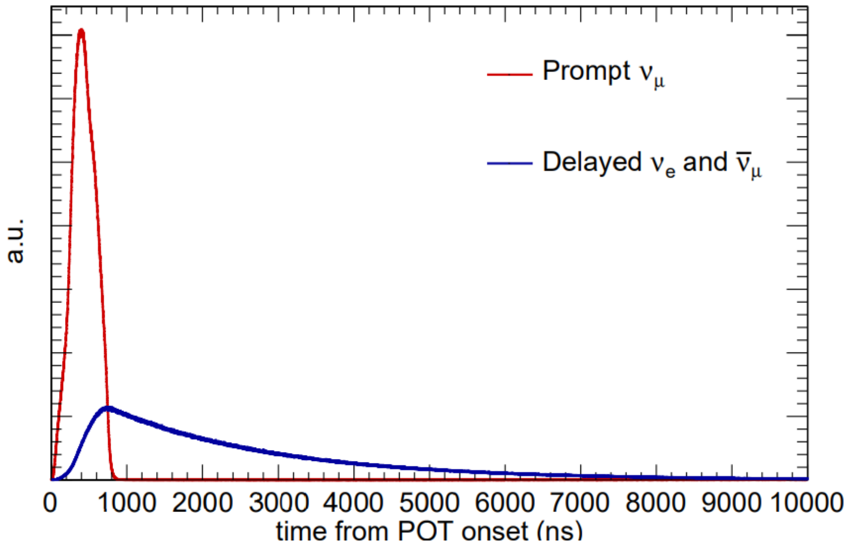
Total neutrino flux of $4.3 \cdot 10^{7}$ $cm^{-2}s^{-1}$ at 20m



Neutrino energy and timing suit well for CEvNS search

COHERENT, PRD 106, 032003 (2022)





Detectors in “Neutrino alley” – the target building basement, 8 mwe above, 20 m of materials to the target

COHERENT: results

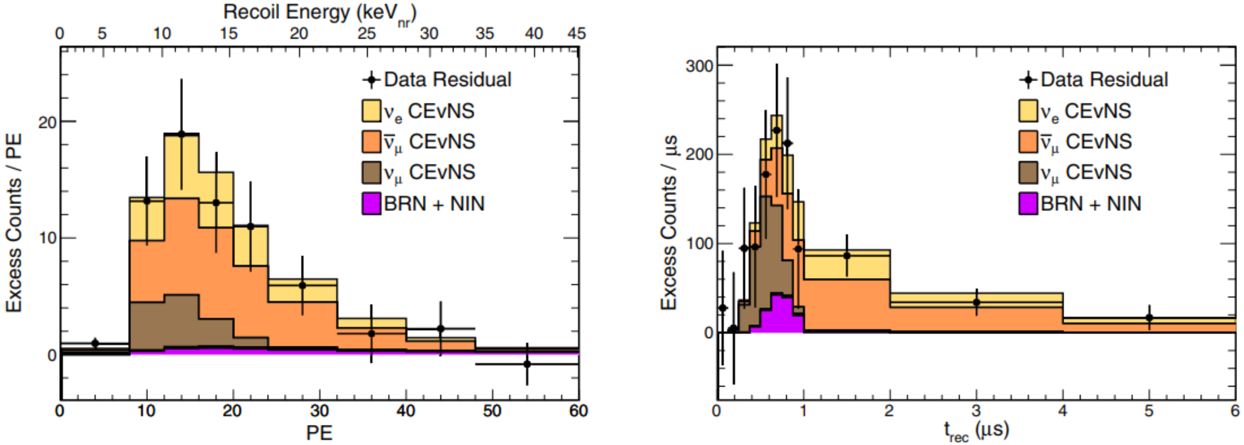
CsI[Na], 14.6 kg

2015-2017: 6.7σ | $\sigma_{meas}/\sigma_{SM} = 0.77 \pm 0.25$

Science vol. 357 iss. 6456 (2017)

2015-2019: 11.6σ | $\sigma_{meas}/\sigma_{SM} = 0.87^{+0.16}_{-0.13}$

PRL vol. 129 081801 (2022)

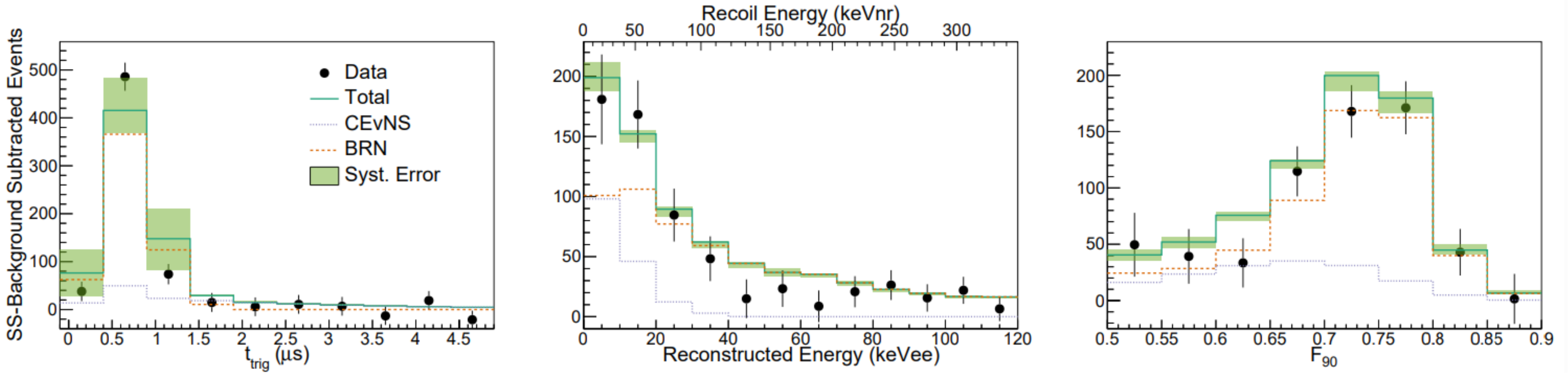


LAr, 24 kg (CENNS-10)

2017-2018: ~3σ

$\sigma_{meas}/\sigma_{SM} = 1.28 \pm 0.39$

PRL vol. 126 012002 (2021)



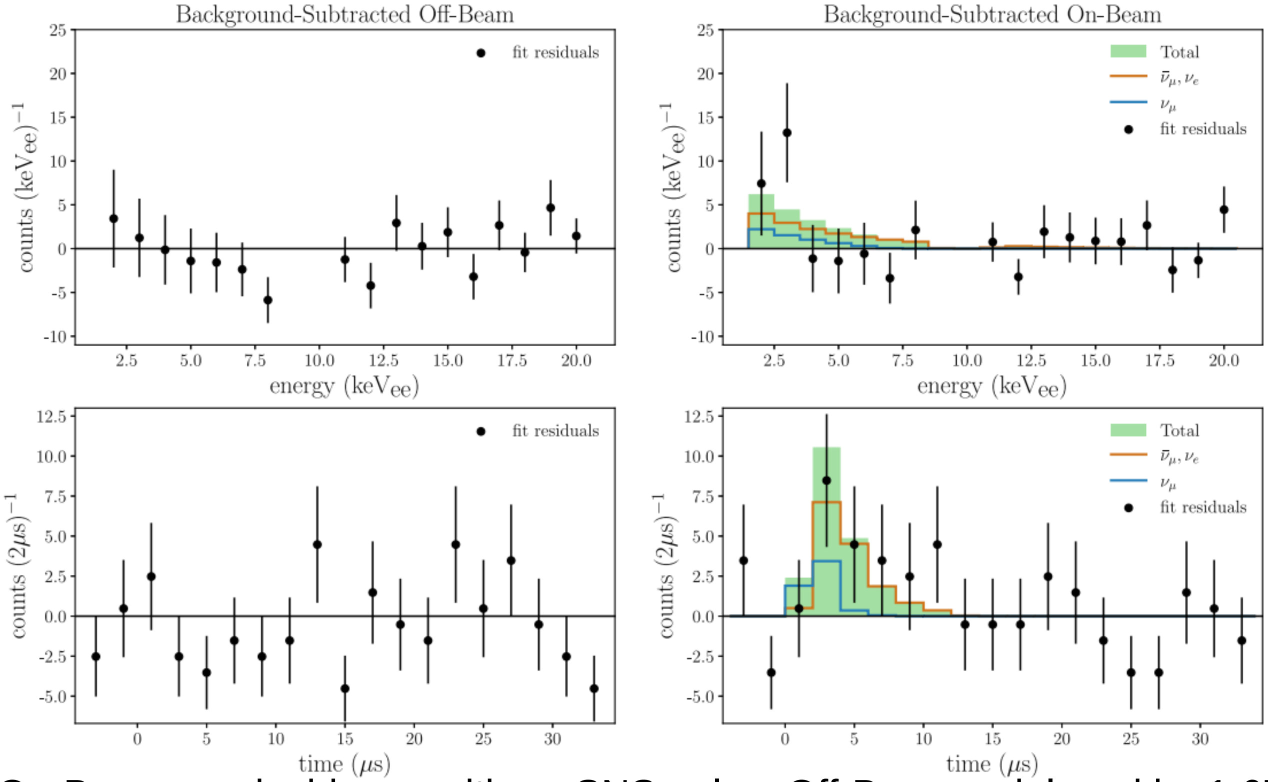
Soon: full statistics of 2017-2021, ~5σ null-rejection expected

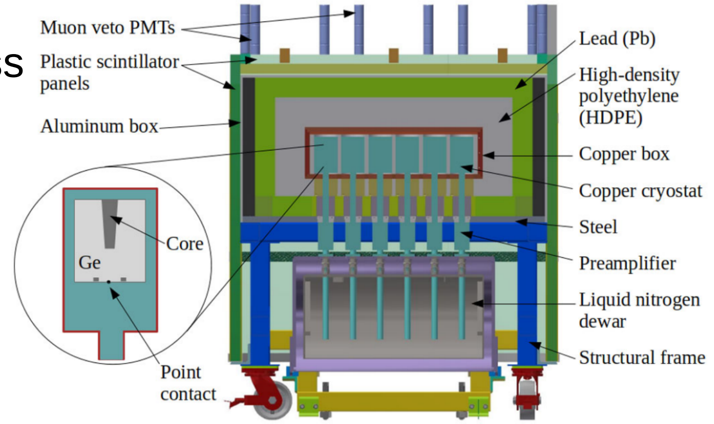
COHERENT: GeMini

Array of 8 HPGe ICPC detectors, 2.2 kg each

Data of June-August 2023 with 5 stable detectors, 10.7 kg active mass

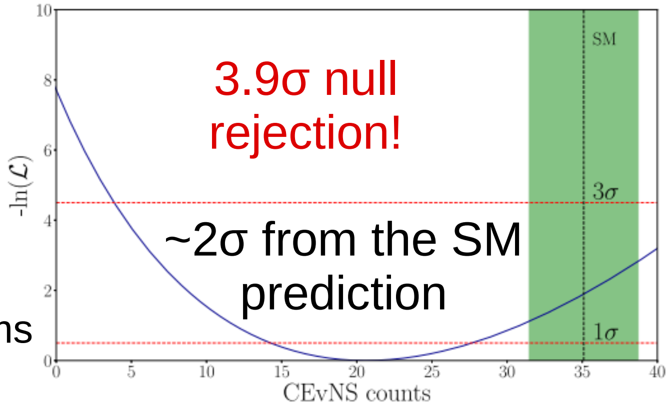
Signal to BG is 1:1, ~1 BG counts/day in array for the SNS trigger





$\sigma_{meas}/\sigma_{SM} = 0.59^{+0.21}_{-0.19}$

PRL 134, 231801 (2025)



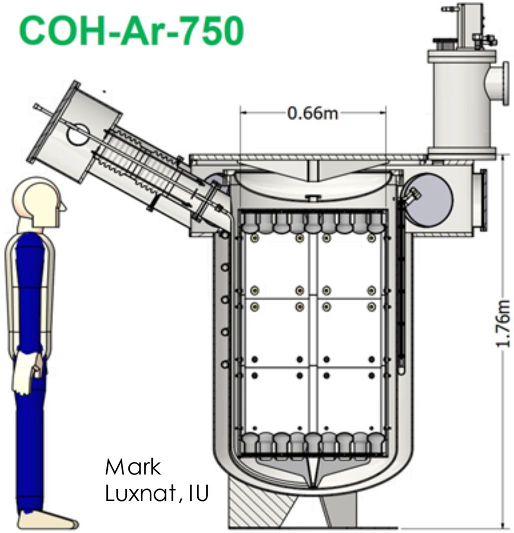
On-Beam – coincidence with an SNS pulse, Off-Beam – delayed by 1.67 ms

BG model from the self-triggered data to increase statistical power

COHERENT: CEvNS plans

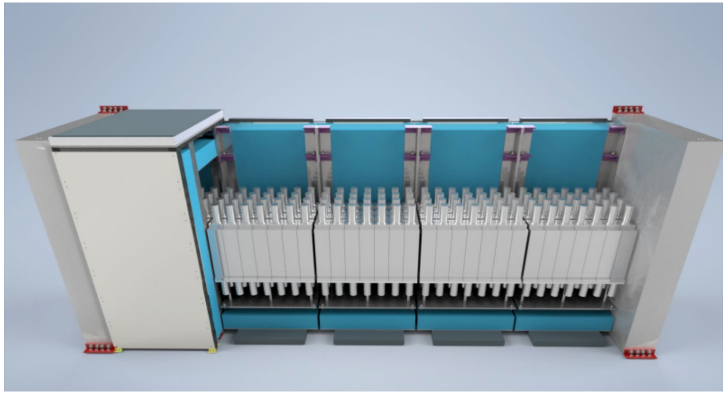
CENNS-750

LAr: 750 kg total (610 kg fid.)
~3000 CEvNS/year,
Expected signal to BG of ~1/30
TPB for WL shifting, 122 PMTs



Detector tests in the lab,
2026 – in Neutrino alley

NaIvETe



1 NaI[Tl] crystal = 7.7 kg,
1 module = 63 crystals,
5 to 7 modules planned
(2.4 -> 3.4 T of NaI)

4 mod. deployed, tests *in situ*

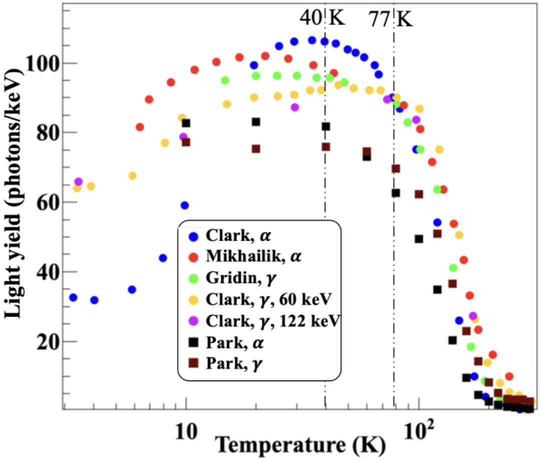
Cryogenic CsI

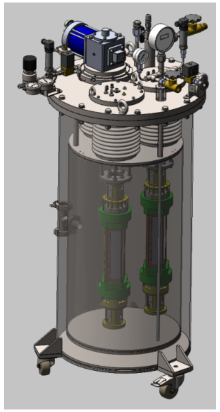
~2026 deployment in Neutrino alley:
10 kg@77K, PMTs, 29 PE/keV

R&D: @40K, SIPMs readout

QF@77K: O(14%), soon for 40K

PRD 109 9, 092005 (2024)

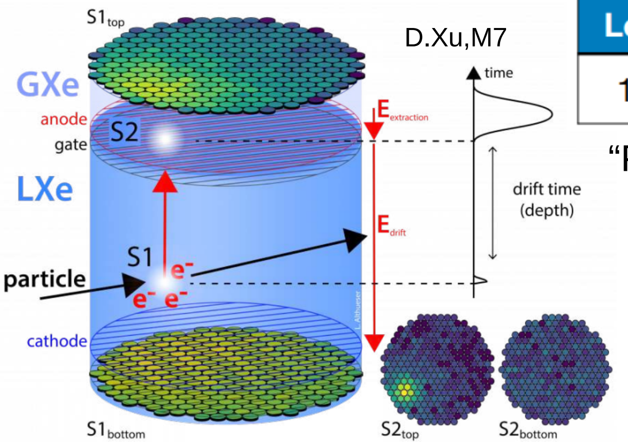




SNS neutrino flux to be verified by the ~600 kg D_2O Cherenkov detector (deployed), down to 5% in 2 years

"Solar" results

XENONnT



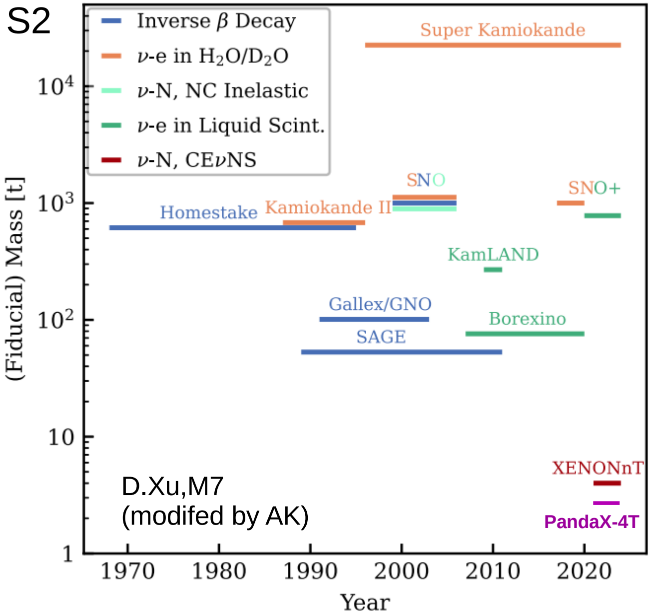
Drift Length	Diameter	Sensitive Target	Fiducial Mass	Drift Field
1.5 m	1.32 m	5.9 tonne	~4 tonne	23 V/cm

"Paired" events: 2-3 PMTs for S1, 120-500 PE of S2

	Expected	Fit
Total Background	26.4 ± 1.4	26.3
^{8}B	11.9 ± 4.5	10.7
Observed	37	

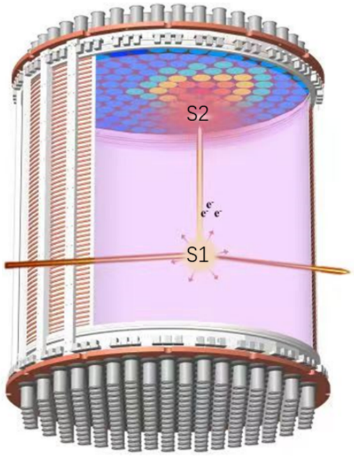
Exposure: ~3.5 t·y, 2.73σ null-rejection

PRL 133, 191002 (2024)



PandaX-4T

NIM A 1077 170548 (2025)



Drift Length	Diameter	Sensitive Target	Fiducial Mass	Drift Field
1.2 m	1.2 m	3.7 tonne	2.6 tonne	~90 V/cm

Combination of S2-only and "paired" events

Best-fit	paired	s2only
B8 number	3.5±1.3	75±28
P-value	0.004	
significance	2.64σ	

PRL 133, 191001 (2024)

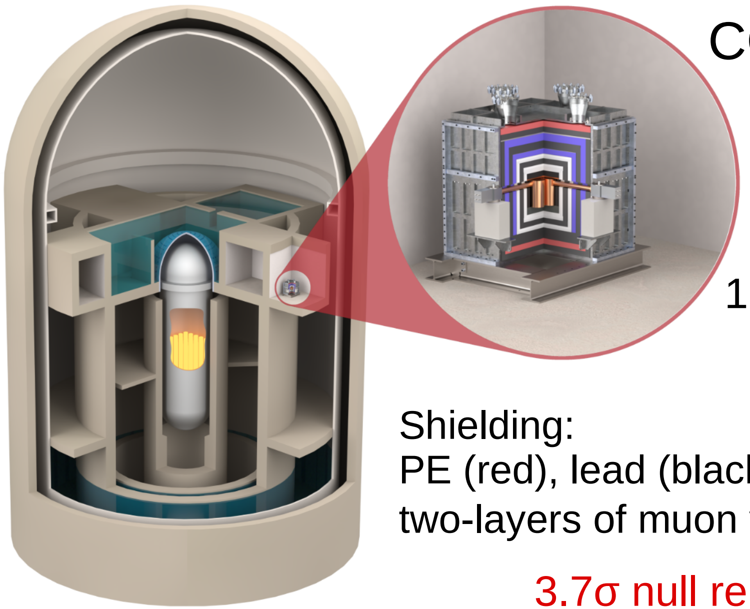
Probably soon: results from LZ (7 tonne active LXe)

Reactors: CONUS+

Nature v.643, 1229–1233 (2025)

Predecessor: CONUS at Brokdorf NPP, 4 HPGe,
3.7 kg tot. mass, E_{th}≈210 eV, 2024: limit of 1.6 times above SM

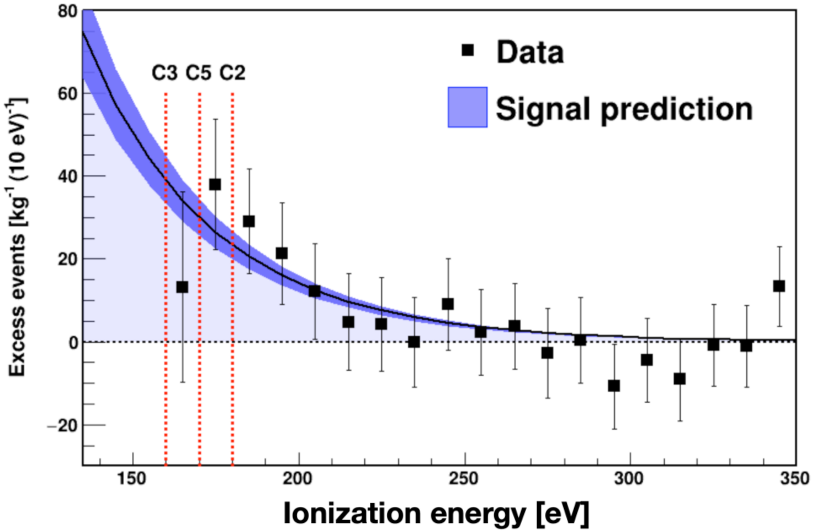
Analysis approach: comparison of ON spectrum with data driven BG model.



CONUS+ at Leibstadt

3.6 GW reactor
7.4 m w.e. overburden

1.5×10^{13} ν/cm²/s at 20.7 m

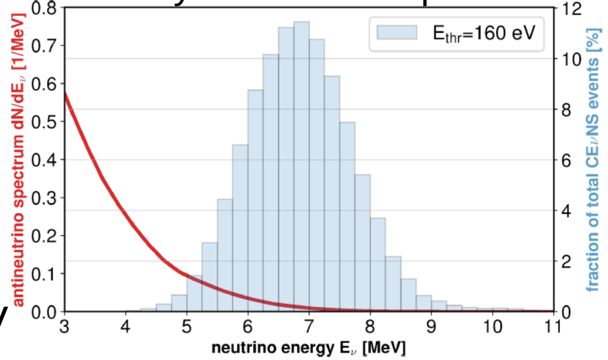


Shielding:
PE (red), lead (black) and B-doped PE (white), two-layers of muon veto panels (blue)

3.7σ null rejection!

Detector	E_{th} [eV_{ee}]	mass (kg)	live time	signal data	prediction	ratio
C2	180	0.95 ± 0.01	117.1 days	69 ± 47	96 ± 16	0.72 ± 0.50
C3	160	0.94 ± 0.01	109.9 days	186 ± 66	135 ± 23	1.38 ± 0.54
C5	170	0.94 ± 0.01	119.5 days	117 ± 75	116 ± 20	1.01 ± 0.67
combined		2.83 ± 0.02		395 ± 106	347 ± 59	1.14 ± 0.36

Sensitivity to reactor ν spectrum



Now new 2.4 kg HPGe, plans for a O(100 kg) HPGe array and E_{th} ~100 eV

Germanium tension

Dresden-II claim

PRL 129, 211802 (2022)

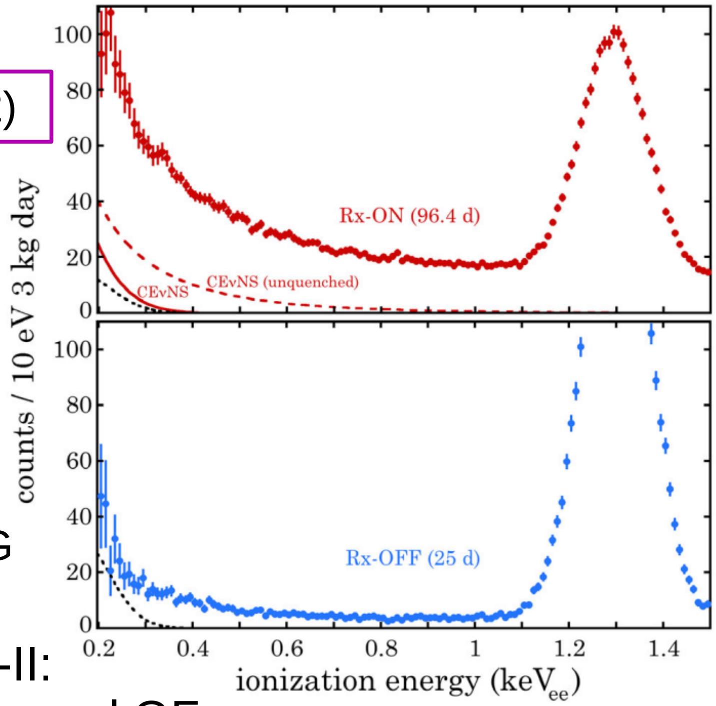
Close to reactor: 10.4 m

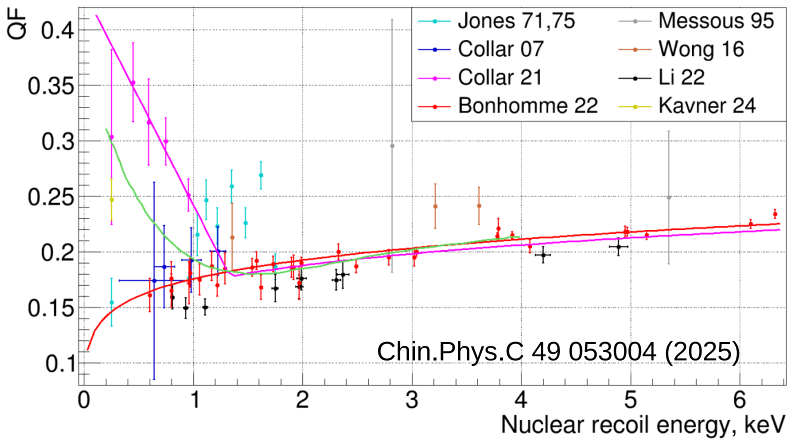
4.8×10^{13} ν/cm^2/s

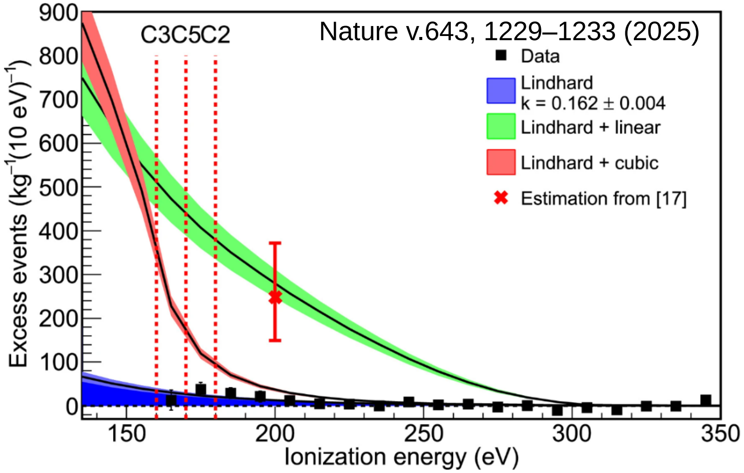
Almost no overburden

Shielding change between ON and OFF

Reactor-correlated n BG







CONUS+ vs. Dresden-II:

1. Discrepancy in measured QF
2. Discrepancy in observed rate at a reactor

COHERENT at SNS (GeMini): 1.95σ off SM prediction,

not affected by the QF problem: E_{th}≈1.5 keV$_{ee}$≈6.7 keV$_{nr}$

“No choice of quenching factor can bring these three data sets into mutual agreement...” (arXiv:2502.12308)

Other Ge experiments: TEXONO, νGeN (see D.Medvedev’s talk), RECODE and RICOCHET

Other reactor experiments

RICOCHET

ILL research reactor (58 MW)

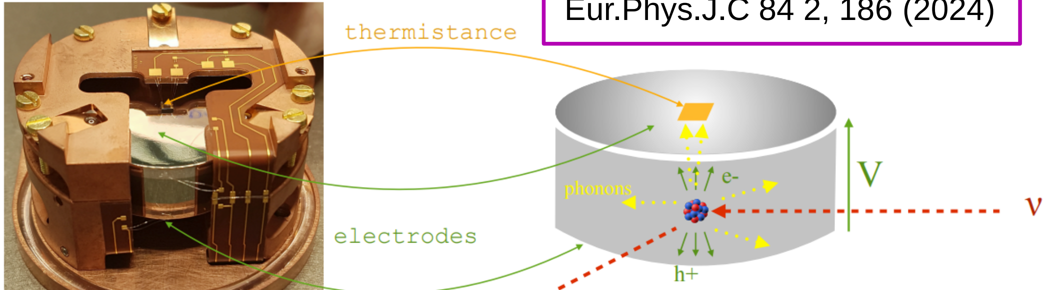
15 m w.e. overburden

3 ON cycles/year, 2 months each

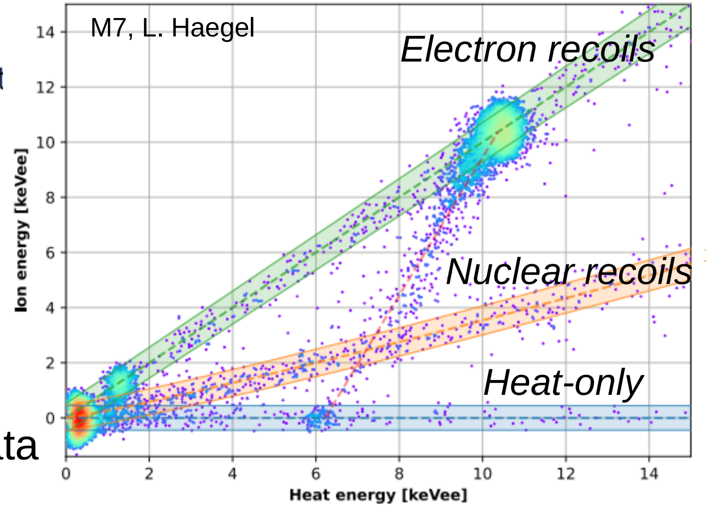
Cryocubes (18 detectors)

- 42-g semiconductor Germanium target
- simultaneous detection of ionisation and heat

Eur.Phys.J.C 84 2, 186 (2024)



~50 eV E_{th} expected, taking data



NUCLEUS

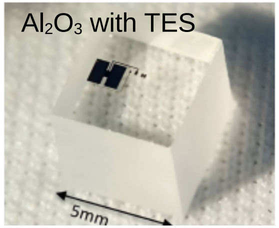
"Very near site"@Chooz-B: 72/102 m from cores

1.7×10^{12} ν/cm²/s

~3 m w.e. overburden

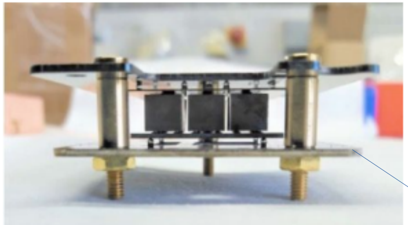
Detectors: Al_2O_3 and $CaWO_4$ bolometers with TES

❖ **NUCLEUS-1g**



~20 eV threshold achieved in lab

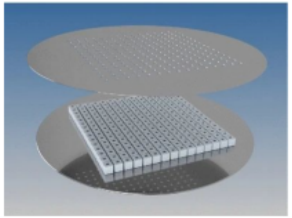
❖ **NUCLEUS-10g**



Si wafers with TES detectors as holders for target crystals

Ge crystals as an active veto, 4π coverage

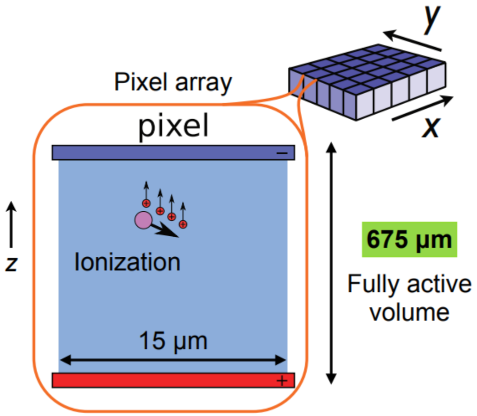
❖ **NUCLEUS-100g**

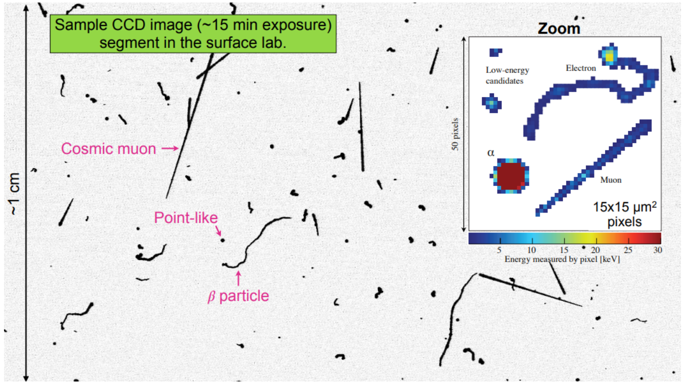


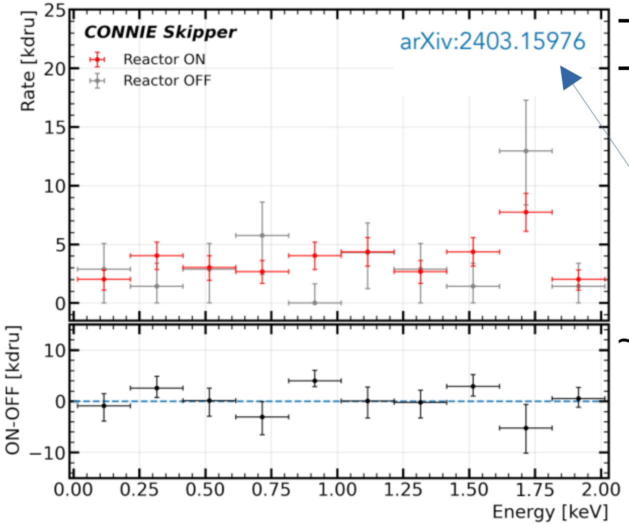
Detector relocation to Chooz ongoing

Other reactor experiments

CONNIE – CCD-based, Angra NPP (Brazil)







- Slow sequential pixel readout
- Low active mass (gram-scale)

Energy threshold of 15 eV!

CEvNS limits at ~70xSM level

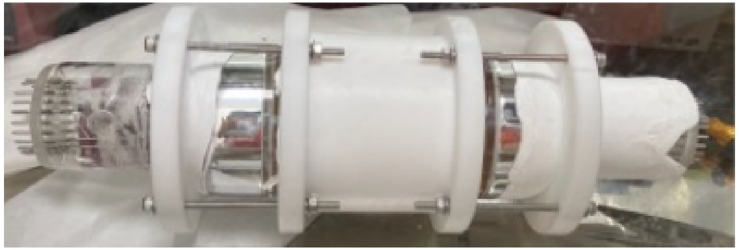
JHEP 05 017 (2022)

~10g multi-CCD module deployed

Good limits on milliQ particles: PRL 134, 071801 (2025)

NEON – NaI[Tl] at Hanbit NPP (S. Korea)

Six crystals, total mass of 16.7 kg
Light yield of ~24 PE/keV



Taking data since April 2022.
Large dataset: ~600 days ON and 200 (OFF)

0.6 keV (15 PE) threshold achieved, need 0.2 keV and 10x BG reduction (large afterglow)

Good limits on ALPs

PRL 134, 201002 (2025)

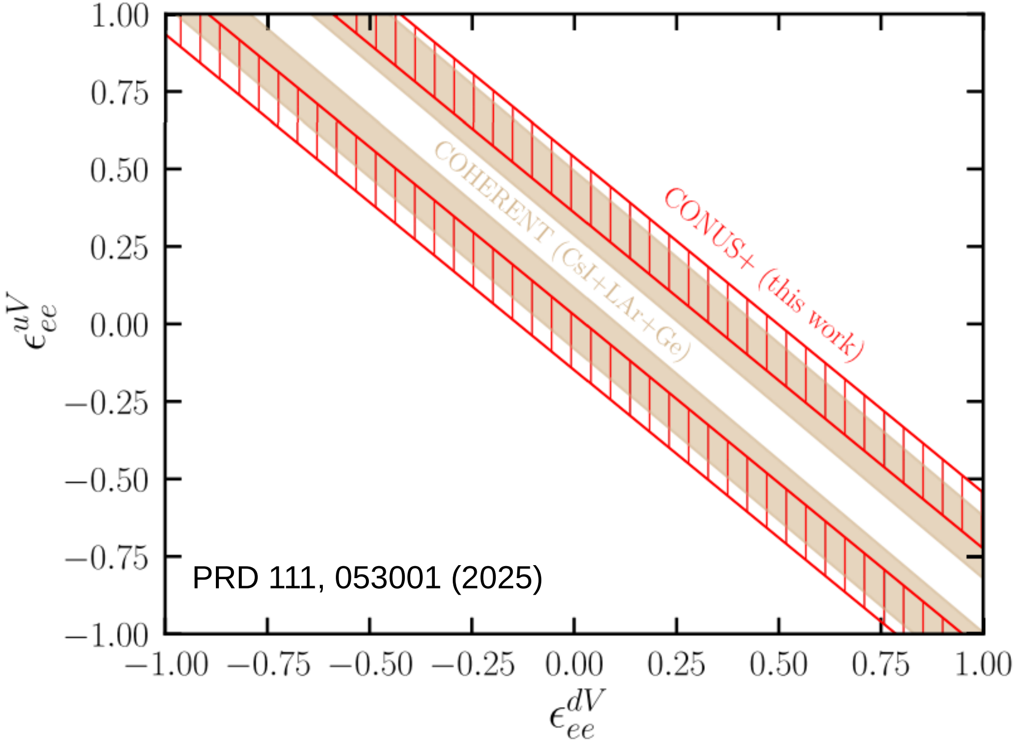
Two-phase Xe, see talks by A. Shakirov and J. Yang

NSI limits

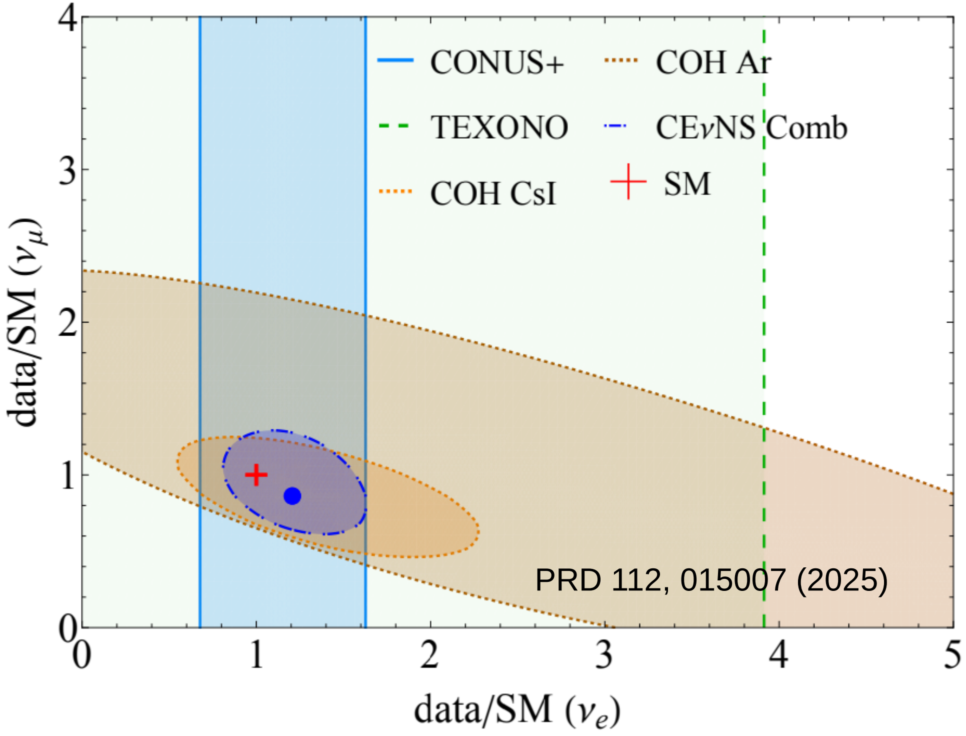
$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi} \left\{ (G_V + G_A)^2 + (G_V - G_A)^2 \left(1 - \frac{T}{E_\nu}\right)^2 - \left(G_V^2 - G_A^2\right) \frac{MT}{E_\nu^2} \right\}$$

$$G_V = \left[\left(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}\right) Z + \left(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV}\right) N\right] F_{nucl}^V(Q^2)$$

Testing previously only loosely constrained (CHARM) parameter space of ν-q NSI



PRD 111, 053001 (2025)



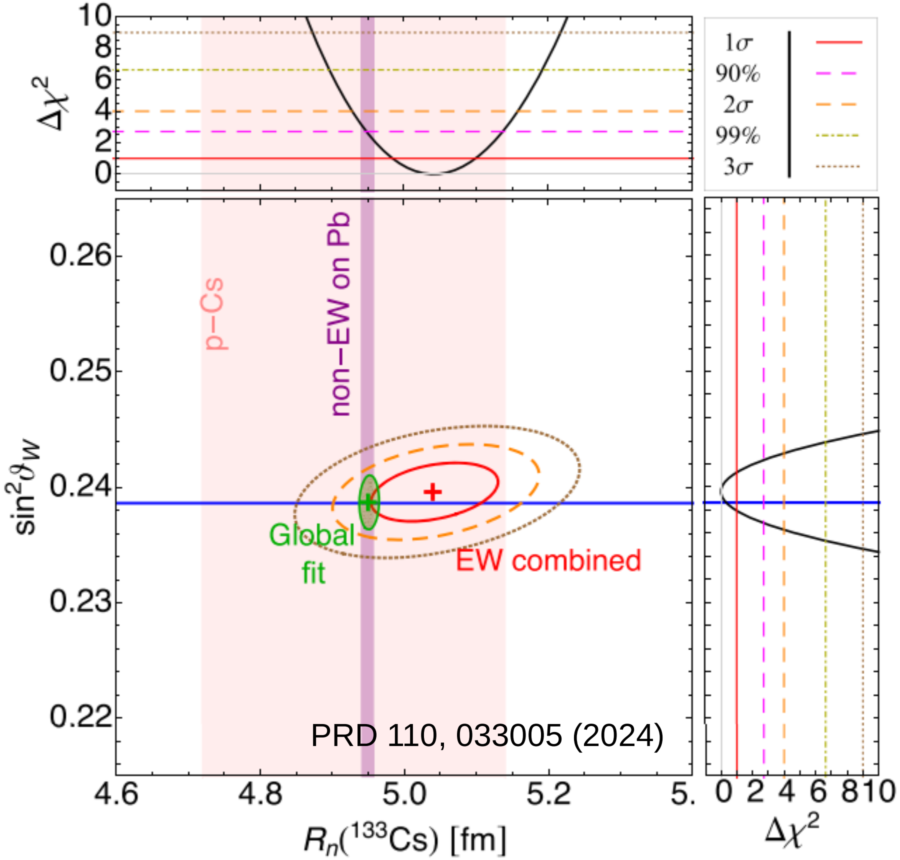
PRD 112, 015007 (2025)

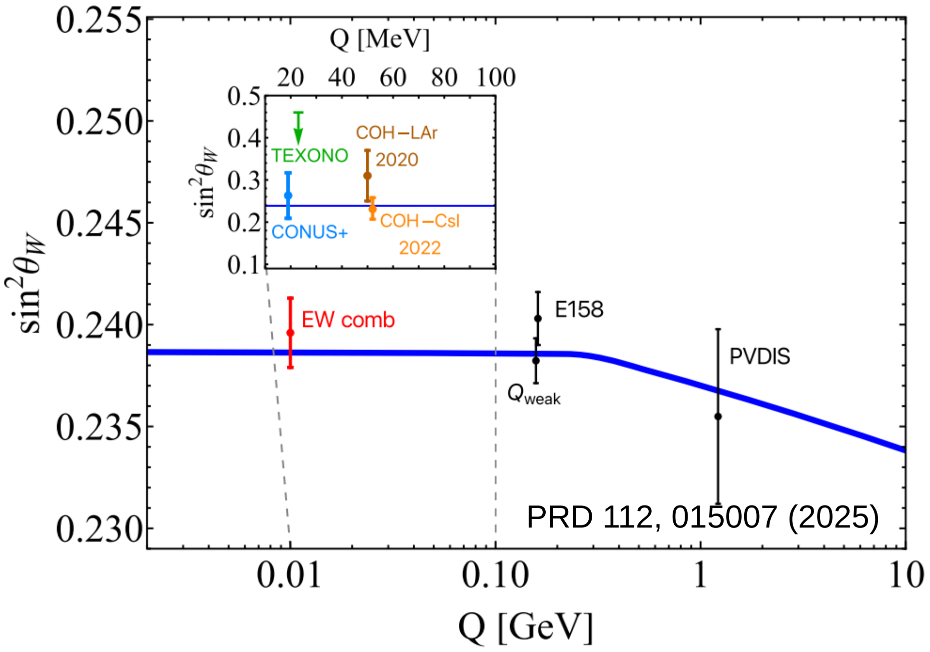
Nuclear FF and electroweak mixing angle

At πDAR: entanglement between $F_N(Q^2)$ and $\sin^2\theta_W$, reactor CEvNS is free of this uncertainty

Approach: $F_N(Q^2)$ from CEvNS -> (input) Cs APV => EW-only $\sin^2\theta_W$

PRD 110, 033005 (2024)

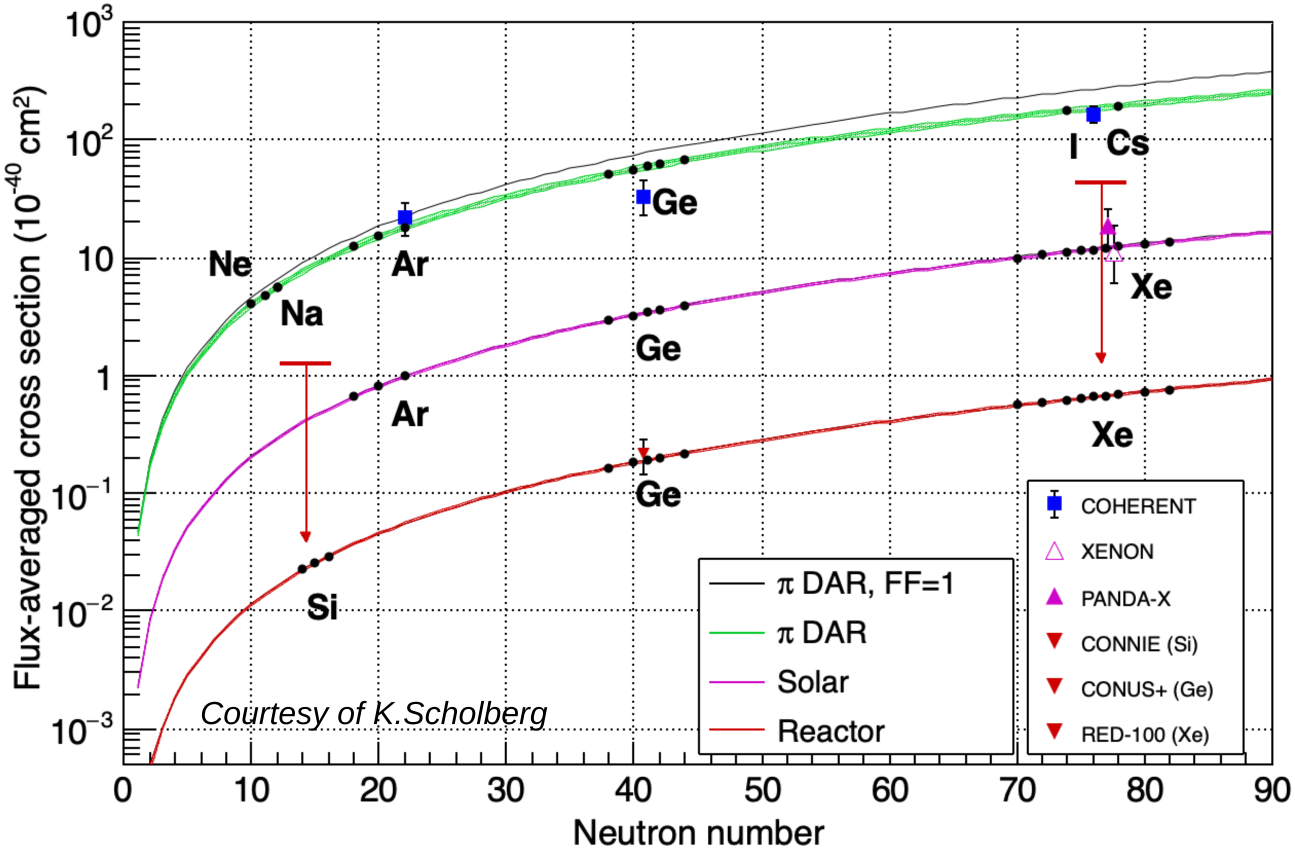




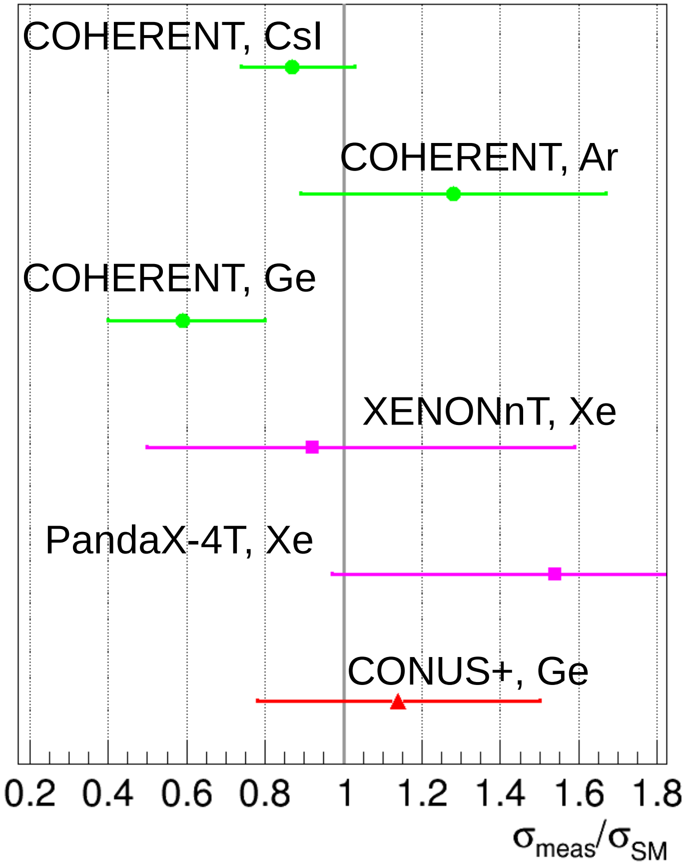
	$\sin^2\vartheta_W$	$R_n(^{133}Cs)$(fm)
APV(Cs) + COH + CSRe	$0.2396^{+0.0020}_{-0.0019}$	5.04 ± 0.19
EW combined	0.2396 ± 0.0017	5.04 ± 0.06
Global fit	0.2387 ± 0.0016	4.952 ± 0.009

Summary of results

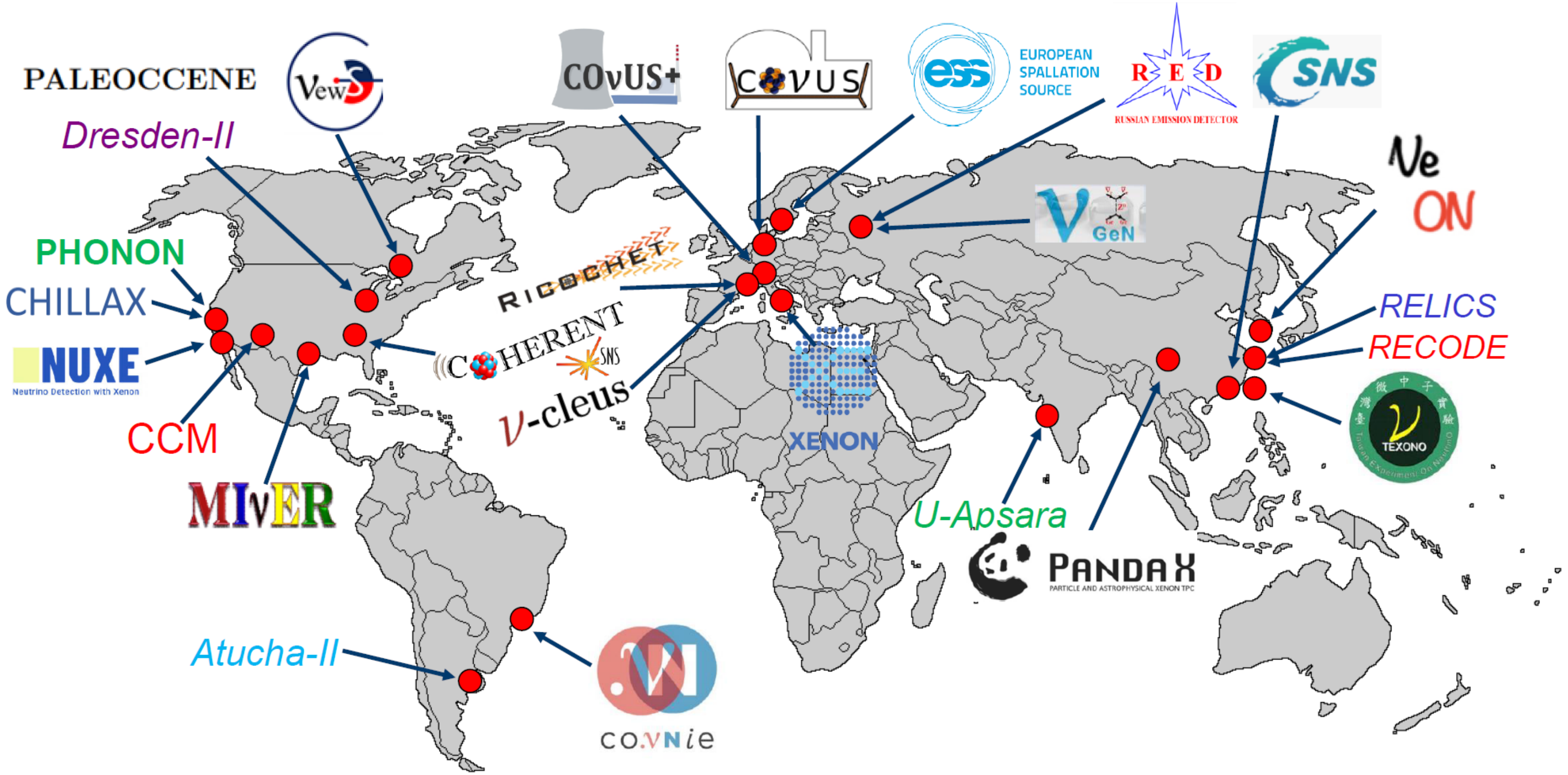
Best results for source/target



Ratio to SM



Worldwide effort



SATURNE – a project to detect CEνAS (ν-atom), see the talk by K.Kouzakov

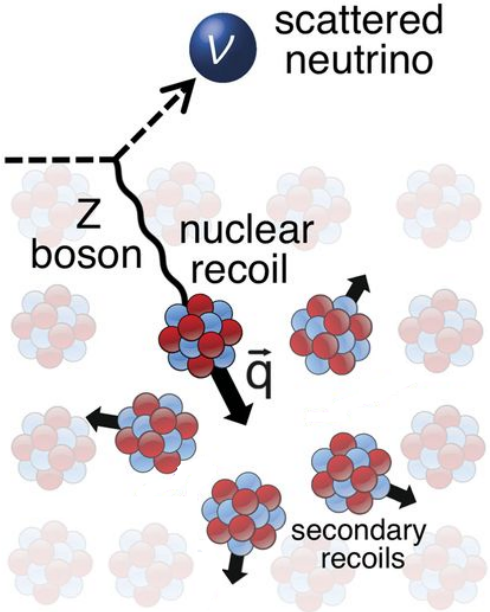
Int.J.Mod.Phys.E 33 11, 2441011 (2024)

Conclusion

CEvNS is a rapidly developing field of research relevant for ν-q NSI, nuclear form-factors and $\sin^2\theta_W$

From “first light” experiments to precision measurements

Large detector workshop of CEvNS experiments, pushing the experimetnal technique to the limit at low overburden

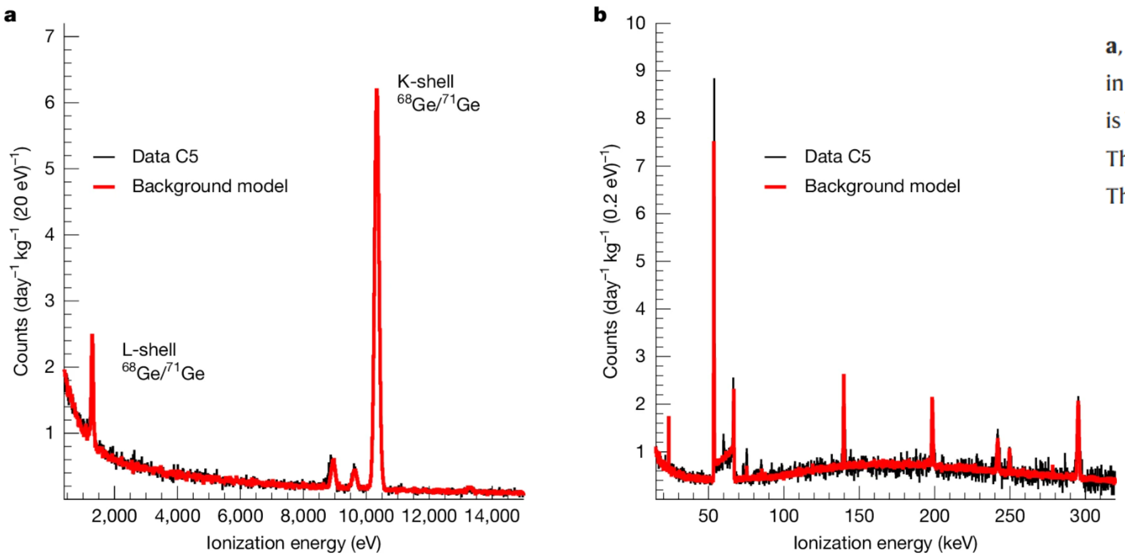


CEvNS adjacent physics:

millicharged particles, ν EM properties, ν CC reactions

Thank you for your attention!

Backup: CONUS+ BG model and uncertainties



a, The plot shows the background spectrum from 0.4 keV, directly above the ionization energy range in which the neutrino signal is expected. The data (black line) are shown for the reactor on period and is based on the measurement of the detector with the lowest background in the CONUS+ analysis (C5). These data are compared with the background model (red line) and found to be in good agreement. **b**, The high-energy channel up to a few hundred keV is shown.

Details in:
1. Nature v.643, 1229–1233 (2025)
2. Eur.Phys.J.C 85 4, 465 (2025)
3. M.Lindner’s Magnificent CEvNS talk

Component	Contribution ON [counts/d/kg]	Contribution OFF [counts/d/kg]
Muons	15.2 +- 0.3	15.1 +- 0.3
Neutrons	21.6 +- 3.1	17.7 +- 2.5
Muon-induced neutrons in overburden	2.2 +- 0.1	1.8 +- 0.1
Cu cosmogenics	0.1 +- 0.05	0.1 – 0.05
Pb210 in cryostat	< 0.1	< 0.1
Pb210 in shield	0.1 +- 0.02	0.1 +- 0.02
Ge cosmogenics	0.2 +- 0.02	0.2 +- 0.02
Metastable Ge states	0.1 +- 0.01	0.1 +- 0.01
Radon	1.9 +- 0.1	0.3 +- 0.1
Kr85	< 0.1	< 0.1
H3	1.3 +- 0.2	0.5 +- 0.2
Xe135	0.1 +- 0.01	< 0.1
Total	42.9 +- 3.1 (DATA = 43.5 +- 1.1)	35.8 +- 2.5 (DATA = 33.4 +- 1.8)

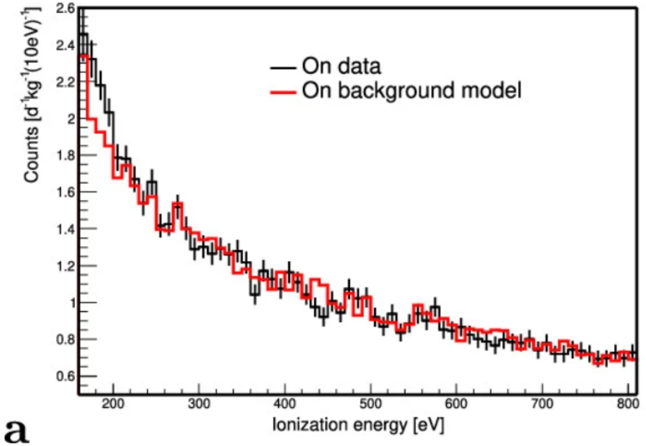
Prediction uncertainties

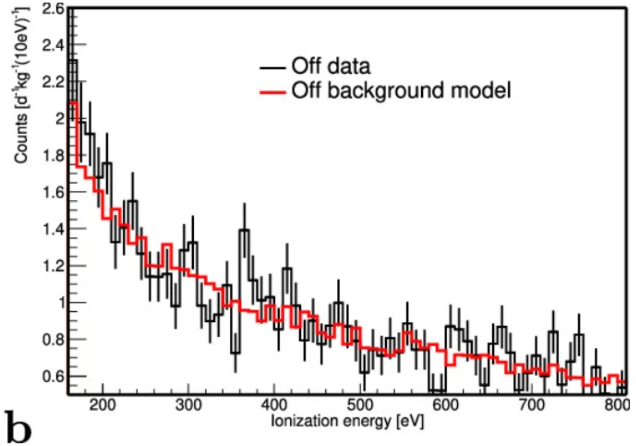
Uncertainty	Contribution
Energy threshold	14.1%
Quenching Ge	7.3%
Reactor neutrino flux	4.6%
Cross-section	3.2%
Active mass Ge	1.1%
Trigger efficiency	0.7%
All combined	17%

CEνNS result uncertainties

Uncertainty	Contribution
Likelihood fit	$\pm$ 86
Fit method	$\pm$ 7
Background model	$\pm$ 40
Non-linearity implementation	$\pm$ 47
All combined	$\pm$ 106

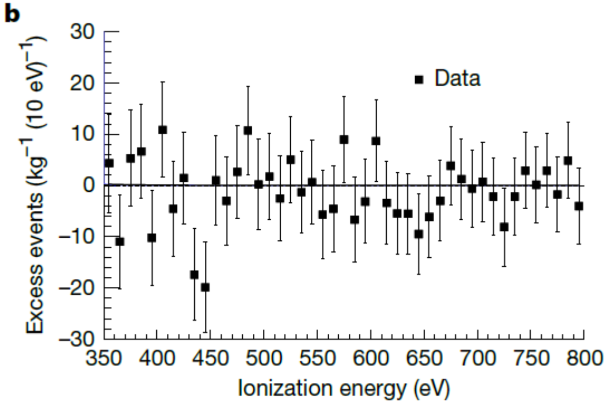
Backup: CONUS+ BG model

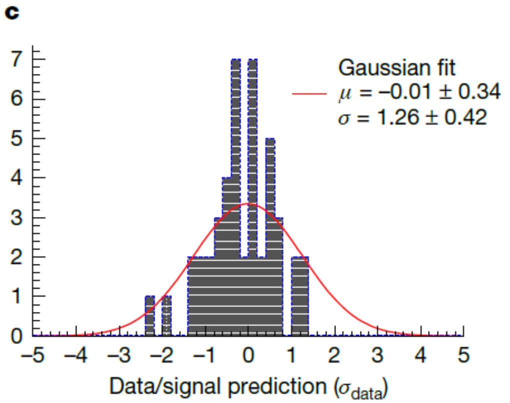




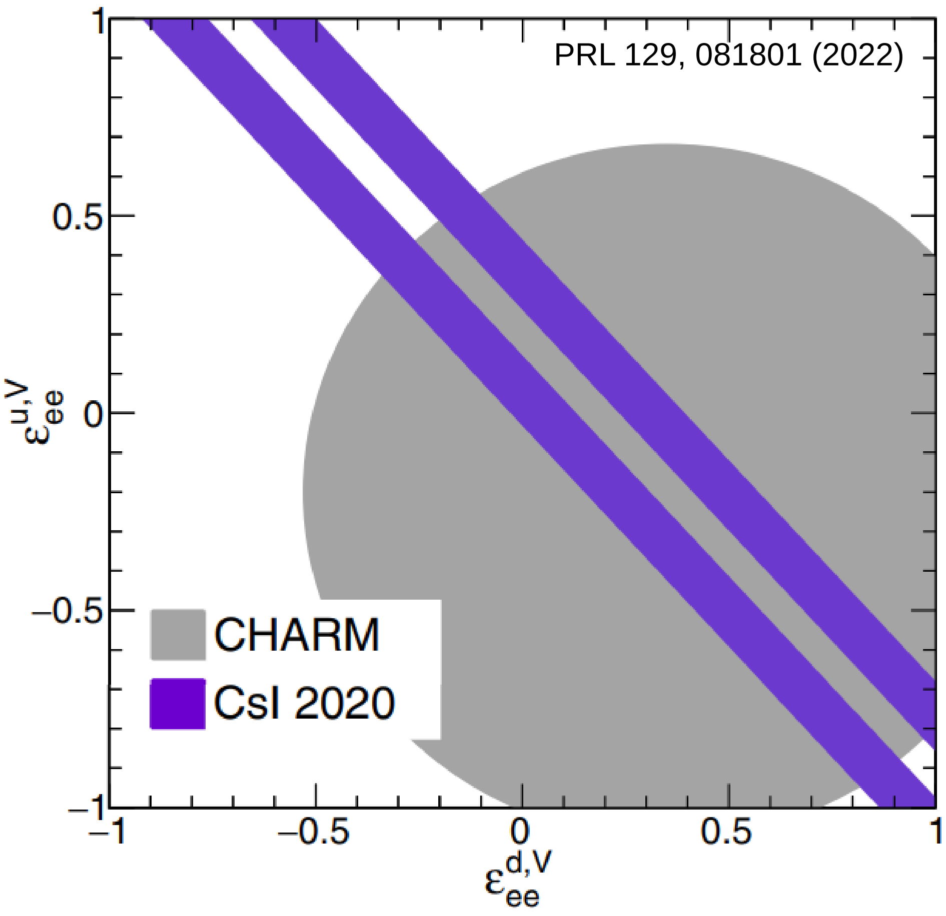
a, **b**, Off count rates normalized to 1 kg day in comparison to the corresponding background models are shown in the region of interest. The signal excess in the reactor on data is seen at low energies below 250 eV_{ee}. The vertical bars represent the statistical uncertainties of the data in each 10 eV_{ee} bin at a 68% CL (1σ). Statistical fluctuations are significantly higher in the off than in the on data due to the shorter period of data collection. Due to the slightly different detector thresholds only one detector (C3) contributes to the lowest bin, the second includes two detectors (C3 and C5) and bins above 180 eV_{ee} are based on the summed spectra of of all three detectors. The difference between the two reactor on curves is shown in Fig. 3.

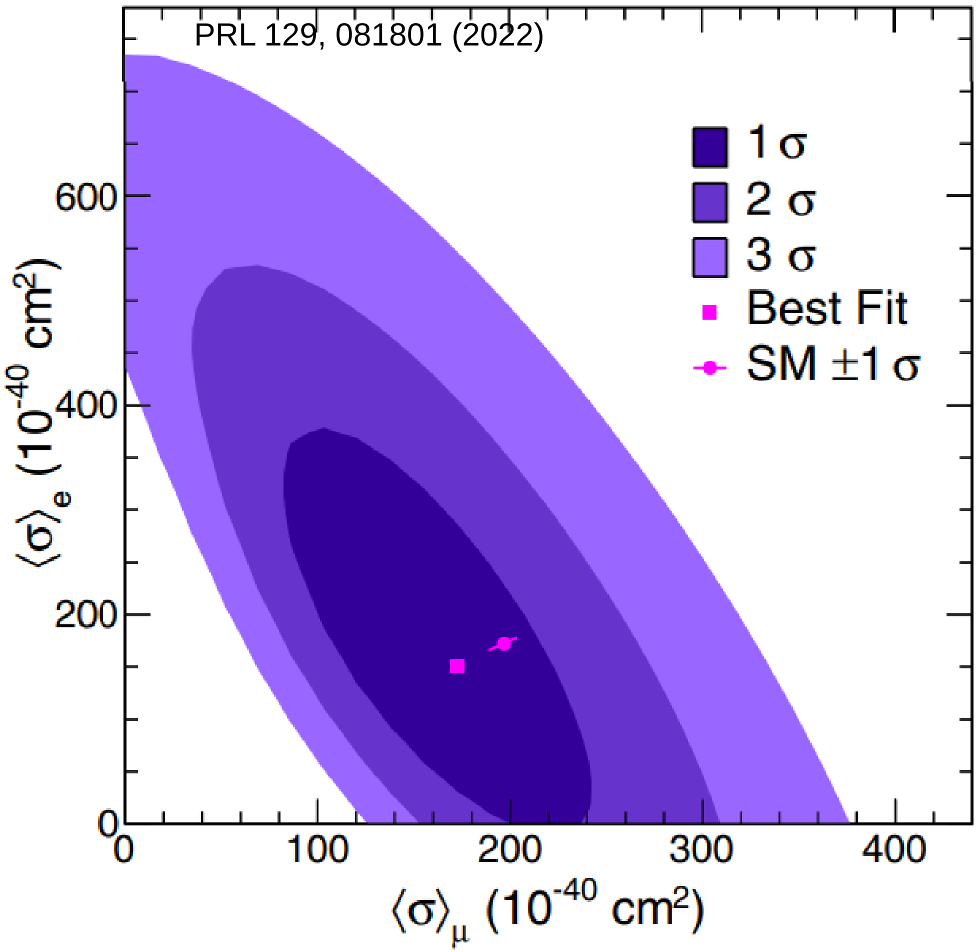
b, This graph shows the good agreement between the data and the background model above the signal region from 350 eV to 800 eV. **c**, This histogram shows the spread of the data points around the background model for the same energy interval as in **b**.



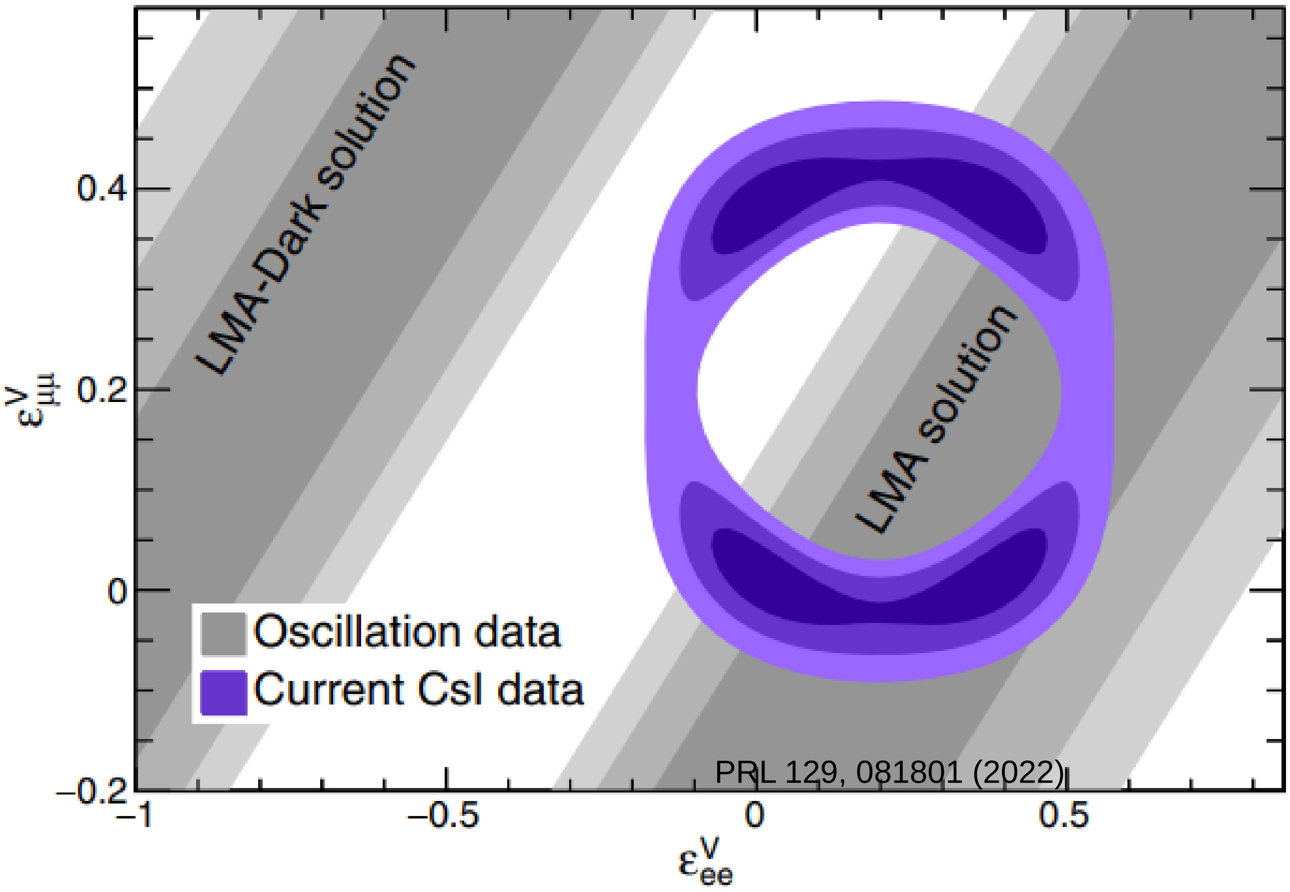


NSI limits examples: CsI[Na]





NSI limits examples: LMA-dark



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