First observation of reactor antineutrinos by coherent scattering with CONUS+

On behalf of the CONUS Collaboration

Max-Planck-Institut für Kernphysik Heidelberg

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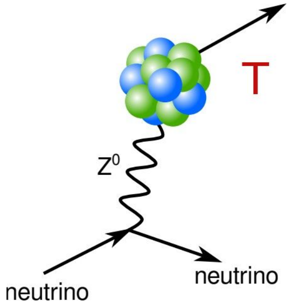
(MPIK)

CONUS+

PATRAS 2025 (IAC Tenerife, Spain), September 2025

Coherent elastic neutrino nucleus scattering



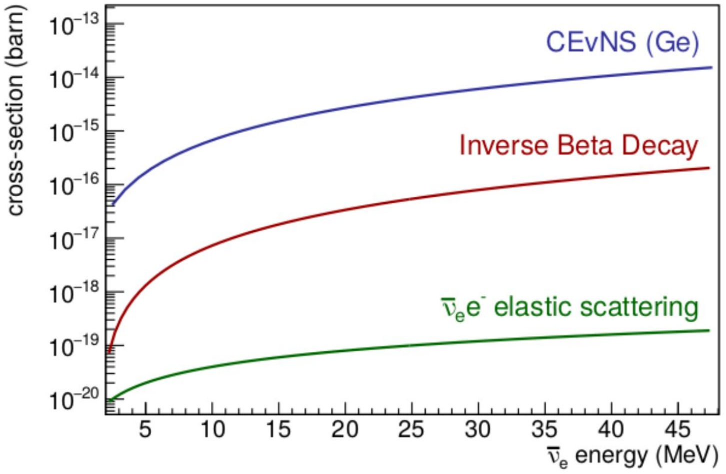
$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi}\underbrace{\left[\mathrm{N} - \left(1 - 4\sin^2\theta_W\right)\mathrm{Z}\right]^2}_{\theta_W \sim 0.238 \rightarrow N^2} M\left(1 - \frac{MT}{2E_\nu^2}\right)\overbrace{F^2(q^2)}^{F^2 \rightarrow 1}$$

Full coherence for $E_\nu < 1/2R_A$ (in Ge ~20 MeV).

CEvNS cross section is “large”. Small, potentially mobile neutrino detectors feasible. All flavors, no reaction threshold.

Experimental signature is a low energy nuclear recoil:

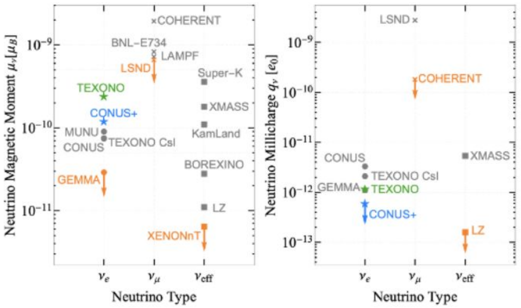
$$T_{Max} \approx \frac{2\,E_\nu^2}{m_n A}$$



<u>The isotope selection is a push-pull situation.</u>

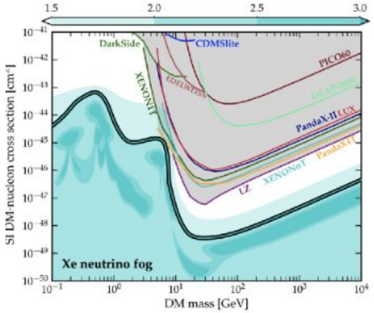
Possible CEνNS applications

BSM physics



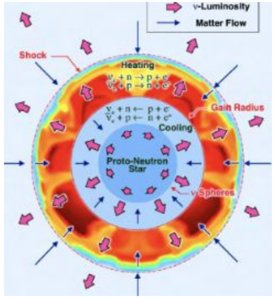
Phys. Rev. D 112, 015007 (2025)

Dark Matter



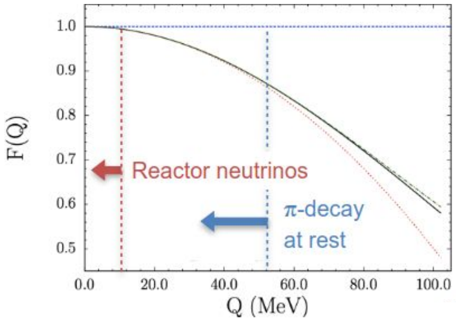
J .Tang et al., PRD 108, 062004 (2023)

Astrophysics



https://science.osti.gov/-/media/ascr/ascac/pdf/meetings/mar03/Mezzacappa.pdf

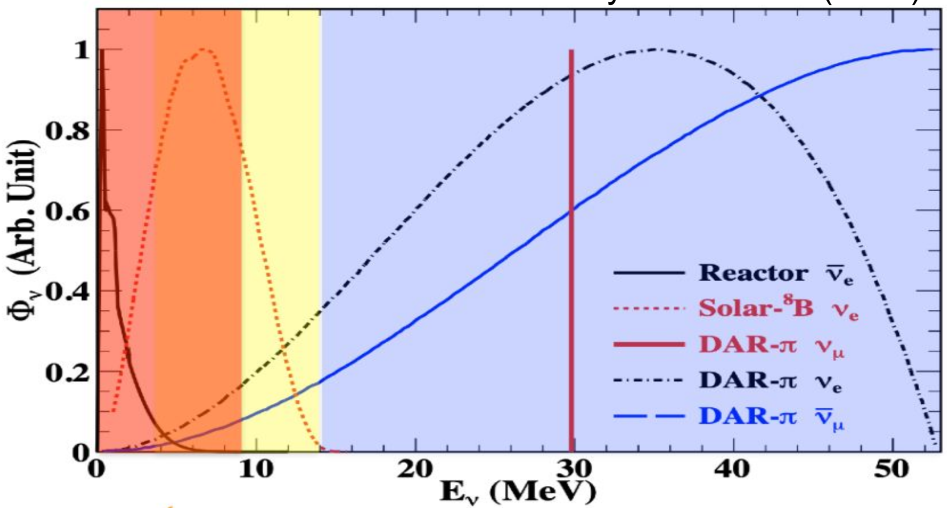
Nuclear physics



K. Patton et al., PRC 86, 024612 (2012)

Neutrinos sources

Phys.Rev.D 103 (2021) 9, 092002



Coherence ←

$\overline{\nu}_e$ from β-decays of fissile isotopes.

Pure flux of $\overline{\nu}_e$.

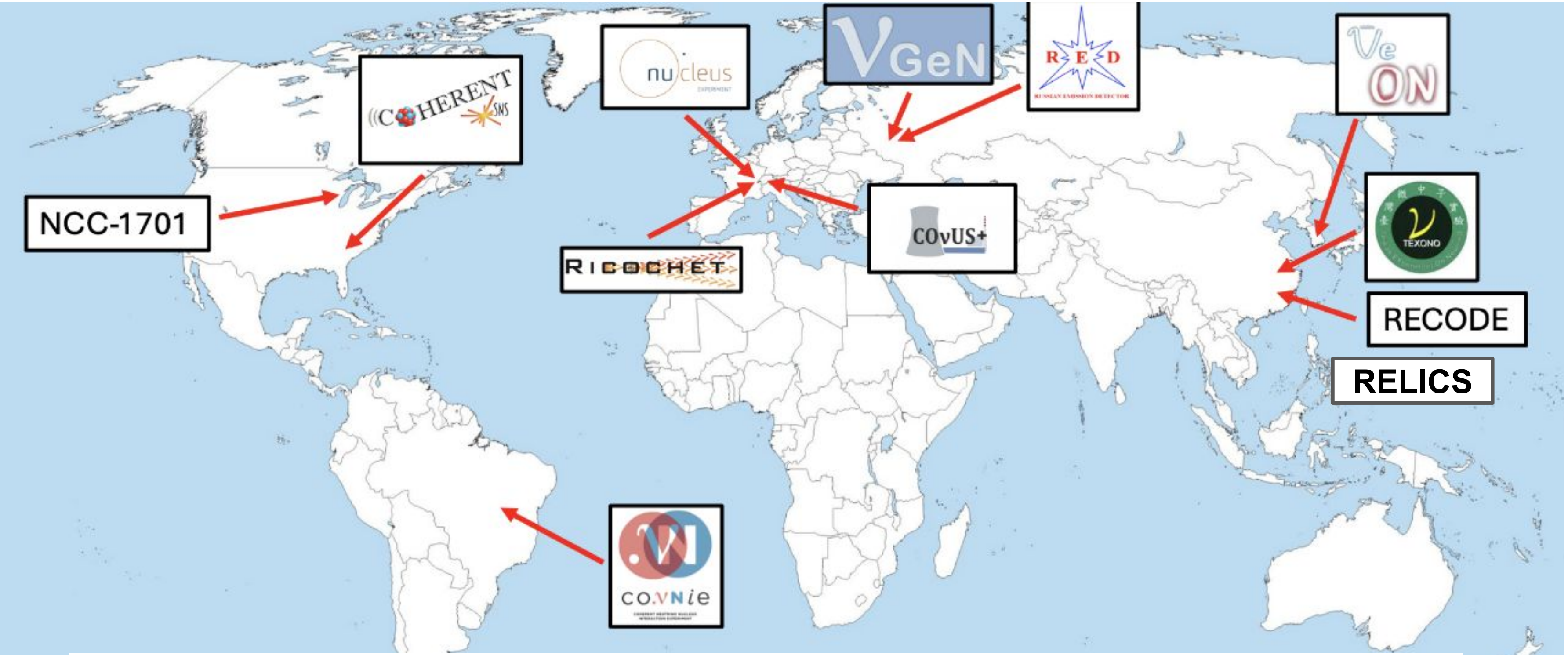
E_ν ~ 0-10 MeV (fully coherent → F ~ 1).

ν from π-DAR. Different neutrino flavors.

E_ν ~ 20-50 MeV (F < 1).

Observation with CsI[Na] in 2017, with Ar in 2020 and with Ge in 2024.

CEvNS detection worldwide



Larger effort worldwide to measure CEνNS with reactor antineutrinos!!

The CONUS collaboration

Max Planck Institut für Kernphysik (MPIK)

N. Ackermann, H. Bonet, C. Buck, J . Hakenmüller, J. Hempfling, G. Heusser, M. Lindner, W. Maneschg, S. Mertens, K. Ni, T. Rink, E. Sanchez Garcia and H. Strecker

Preussen Elektra GmbH, Kernkraftwerk Brokdorf (KBR)

K. Fülber and R. Wink

Leibstadt AG , Kernkraftwerk Leibstadt (KKL)

M. Rank, I. Stalder, J. Woenckhaus

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

Preussen Elektra

Kernkraftwerk Leibstadt

CONUS+ location: KKL power plant

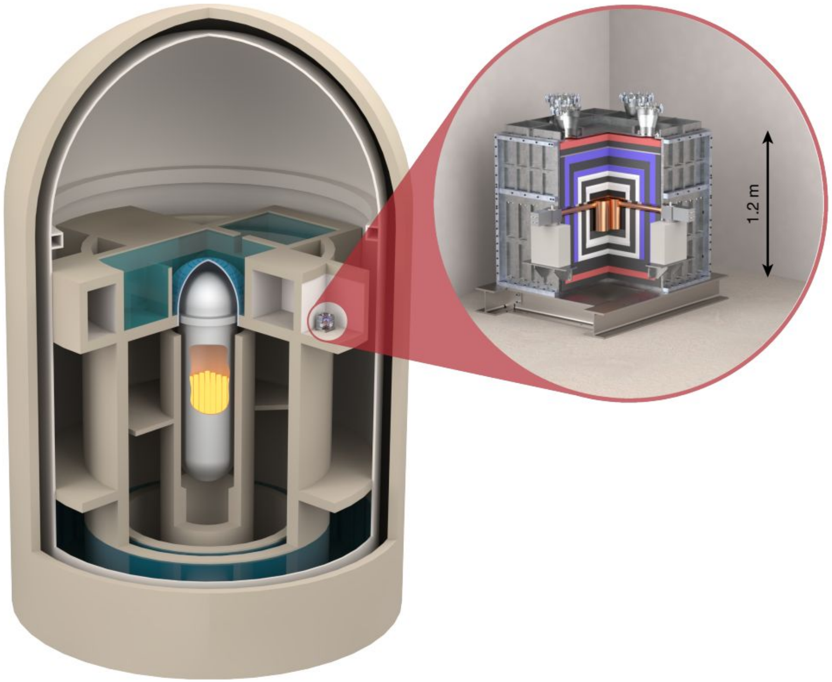
CONUS+ experiment is operating at the KKL power plant (Leibstadt, Switzerland) since November 2023.

BWR with high duty-cycle, about 1 month/year of reactor-off.

CONUS+ is placed inside the reactor building.

20.7 m from 3.6 GW reactor core. This corresponds to a high antineutrino flux of about 1.45 x 10^{13} $\bar{\nu}_e$ $s^{-1}cm^{-2}$

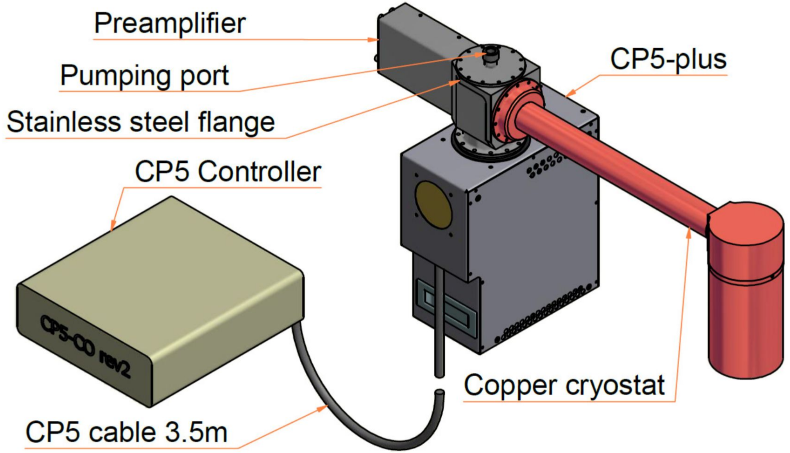
Average overburden of 7.4 m w.e.

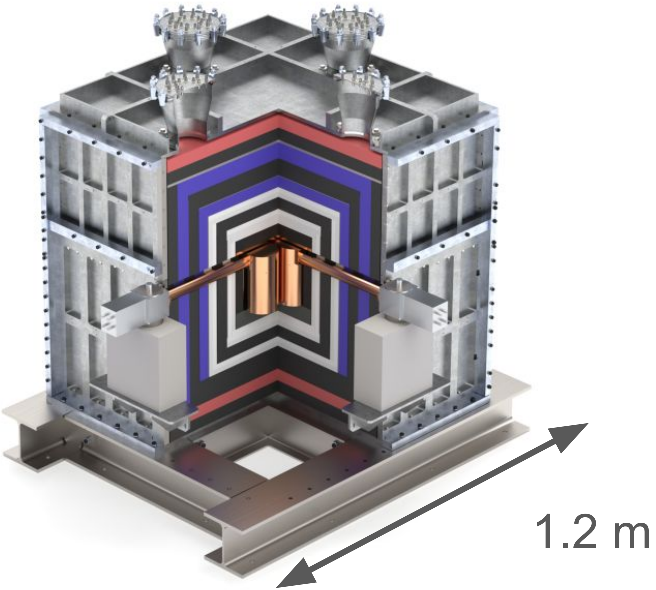


CONUS+ detector

4 p-type point contact HPGe:

- Total crystal/active mass: 4 kg /3.74kg.
- Pulser resolution (FWHM) ~50eVee.
- New liquid cooling system for cryocooler



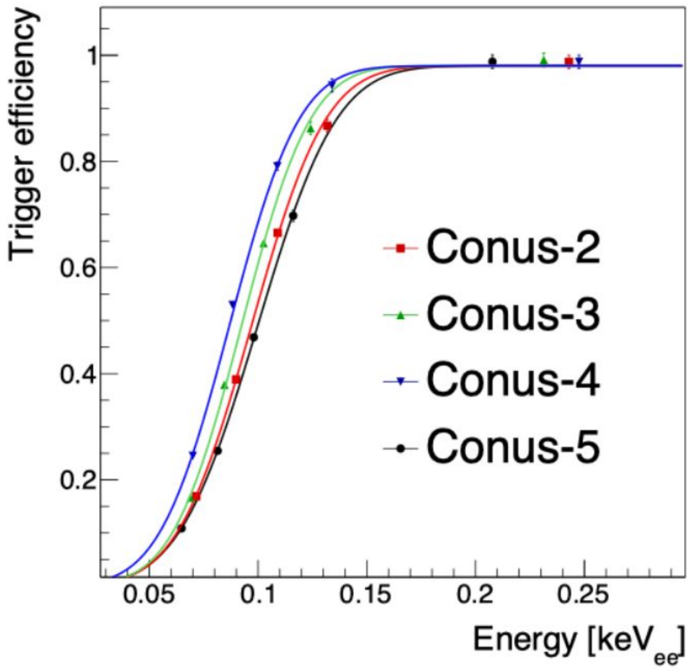


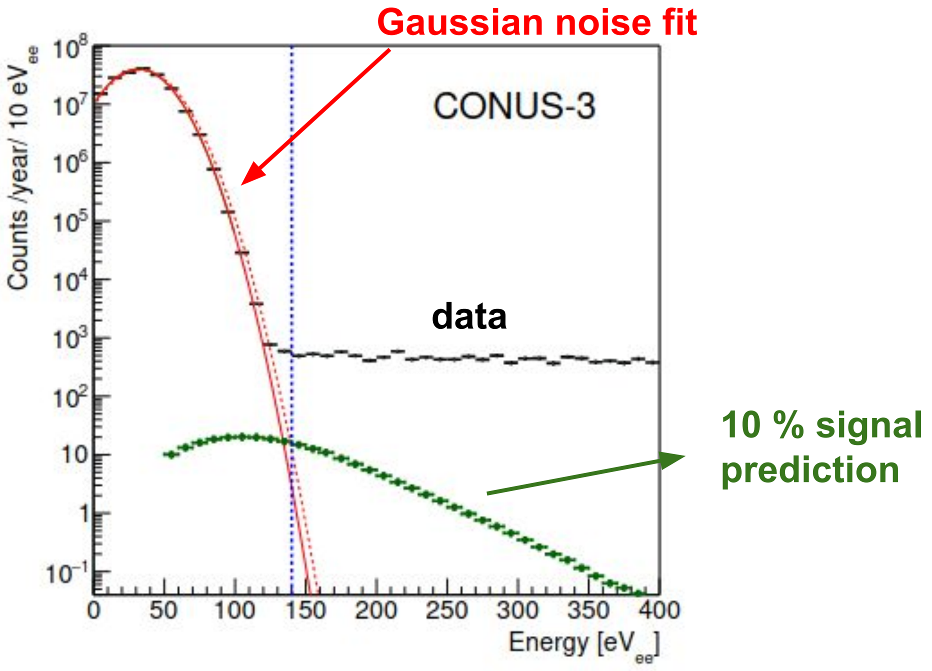
Active + passive shielding:

- Low ^{210}Pb lead.
- Borated and pure PE.
- Active μ-veto (plastic scintillator).
- Flushing against airborne radon.

HPGe detector upgrade

CONUS, EPJC 84 (2024) 1265





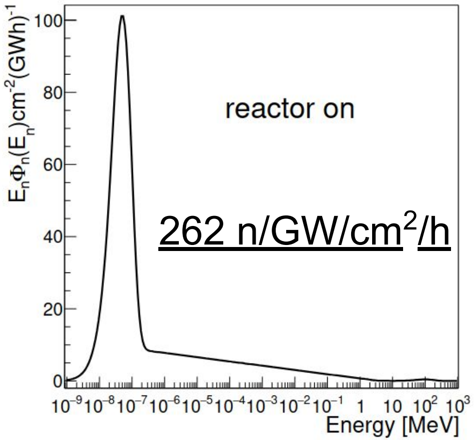
Energy threshold improved from 210 eV (CONUS) to ~160 eV!

Trigger efficiency from 50% @300 eV to 50% @100 eV

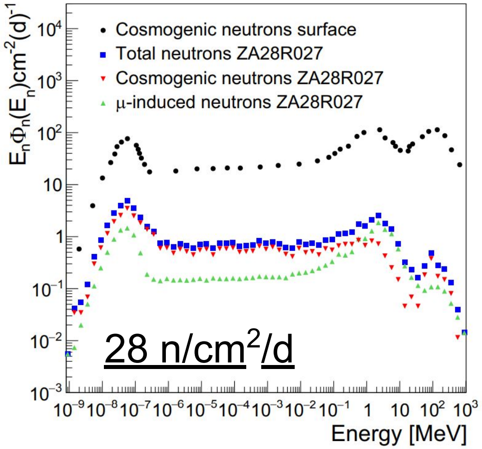
Background characterization

CONUS, EPJC 85 (2025) 465

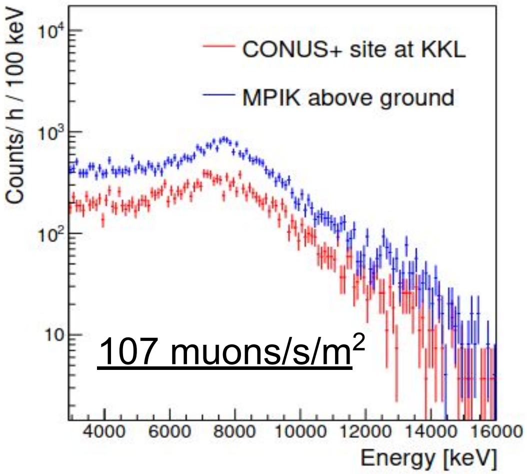
Reactor neutrons



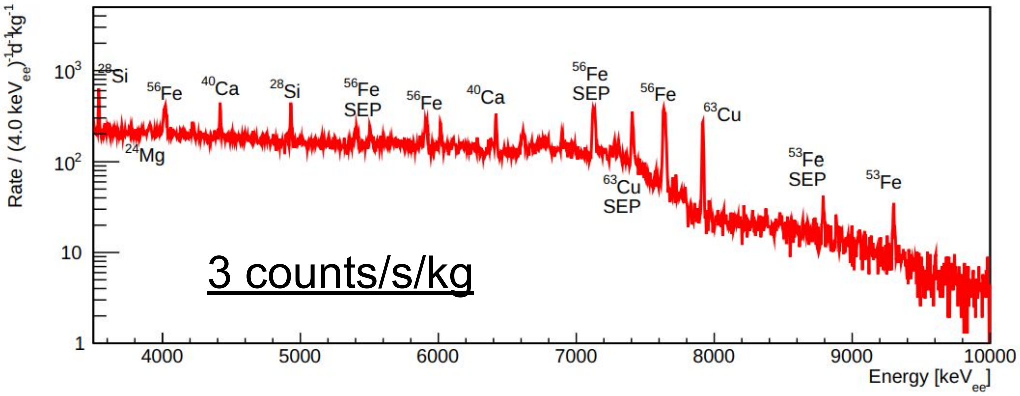
Cosmogenic neutrons



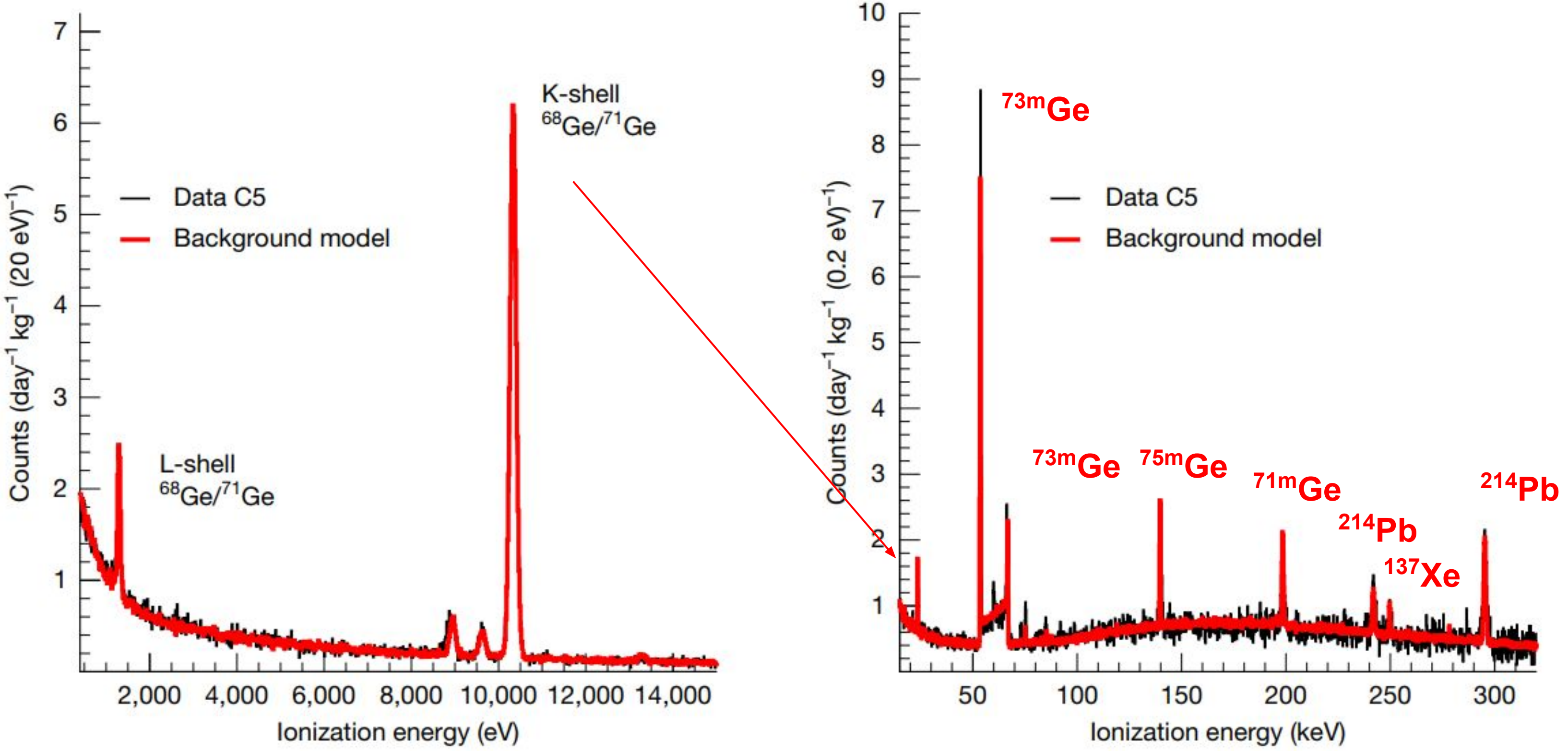
Muons



Gamma-rays



Full background model



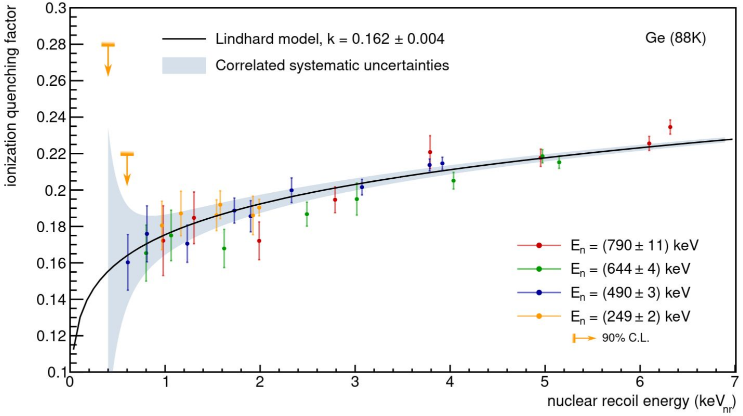
Full background understanding above CEνNS energy region!!

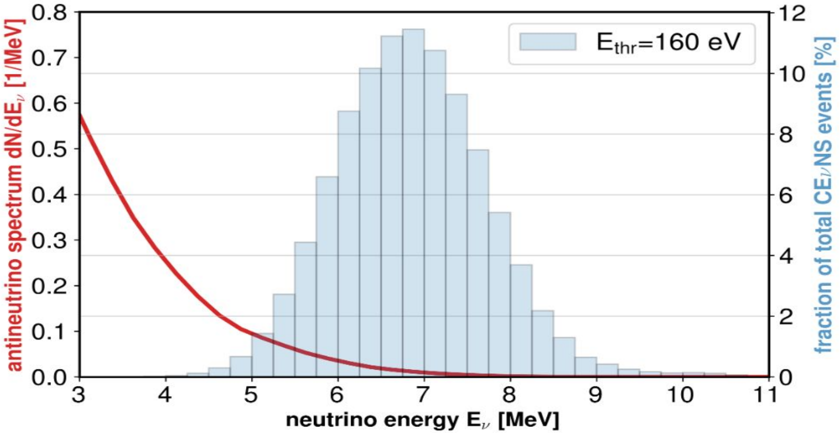
Signal prediction

Signal prediction based on DayaBay measured spectra including neutrinos over 8 MeV. Summation method for neutrinos below 1.8 MeV.

Lindhard quenching factor with k=0.162±0.004.

Considering an exposure of 327 kg d and the different energy thresholds, a CEνNS signal prediction of 347±59 is estimated for Run-1.

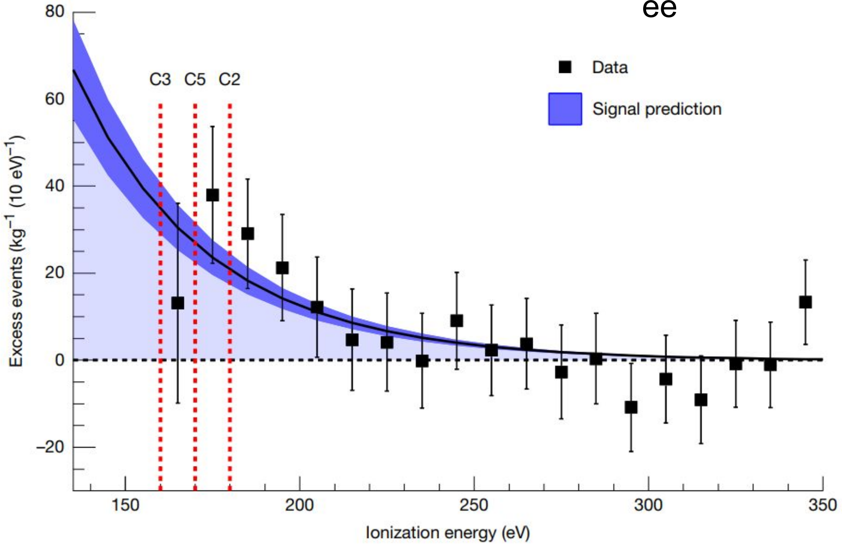




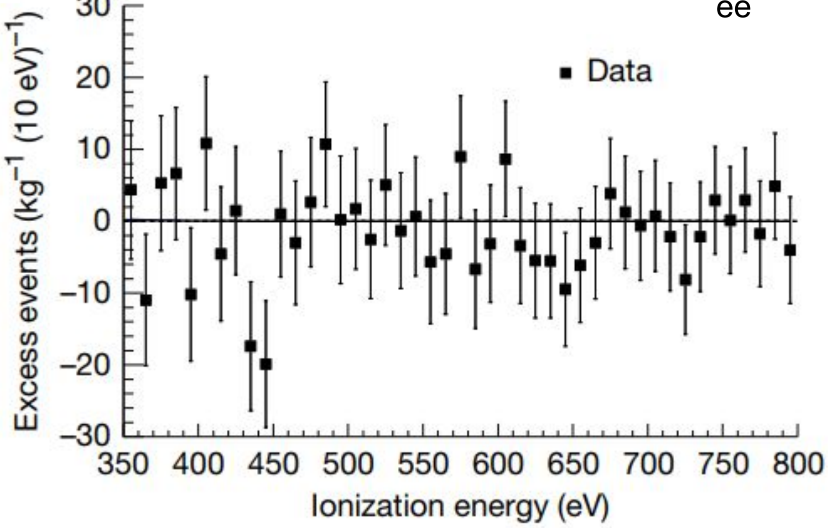
A. Bonhomme et al. , Eur. Phys. J. C 82, 815 (2022)

First CEνNS detection at reactor

Excess below 350 eV_{ee} !!



No excess above 350 eV_{ee} !!



Exposure: 327 (kg d) reactor on and 60 (kg d) reactor off

Signal events from combined fit 395±106

Data/SM prediction: 1.14±0.36

CONUS, Nature 643,(2025)

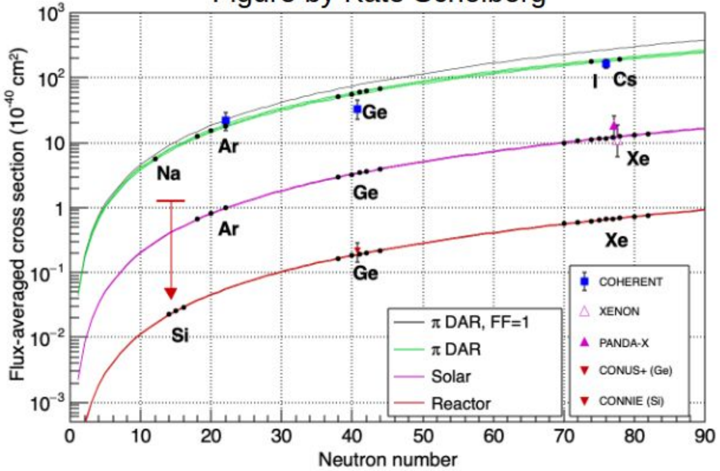
Comparison other experiments

Source	Target	ν energy [MeV]	flux [$cm^{-2}s^{-1}$]	data	data/SM prediction
Accelerator	Cs	$\sim 10-50$	$5{\cdot}10^7$	306 ± 20	0.90 ± 0.15
Accelerator	Ar	$\sim 10-50$	$2{\cdot}10^7$	140 ± 40	1.22 ± 0.37
Accelerator	Ge	$\sim 10-50$	$5{\cdot}10^7$	21 ± 7	0.59 ± 0.21
Sun (XENONnT)	Xe	< 15	$5{\cdot}10^6$	11 ± 4	0.90 ± 0.45
Sun (PandaX-4T)	Xe	< 15	$5{\cdot}10^6$	4 ± 1	1.25 ± 0.52
Reactor	Ge	< 10	$1.5{\cdot}10^{13}$	395 ± 106	1.14 ± 0.36

CONUS+ has detected the lowest energy neutrinos via the CEνNS channel (down to 4 MeV).

CONUS+ has accumulated the highest number of CEνNS counts in one single isotope (low threshold + high flux).

Figure by Kate Scholberg

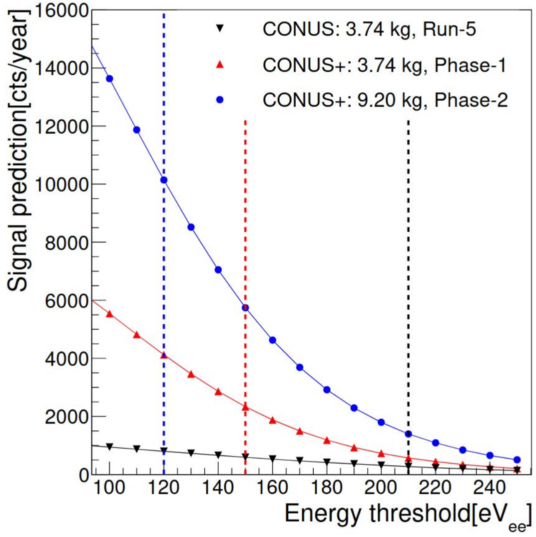


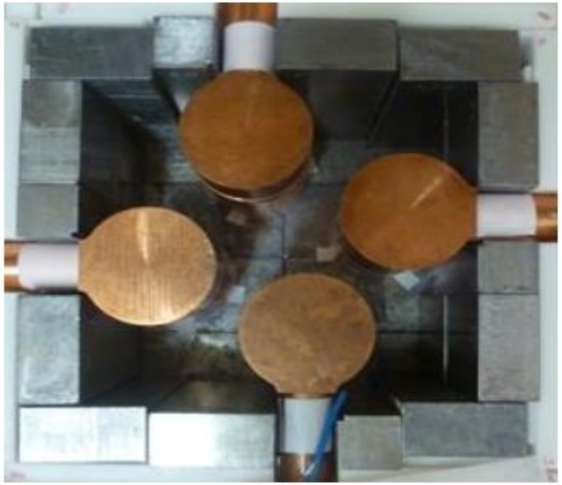
CONUS+ phase 2

3 new 2.45 kg detectors → total mass 8.4 kg.

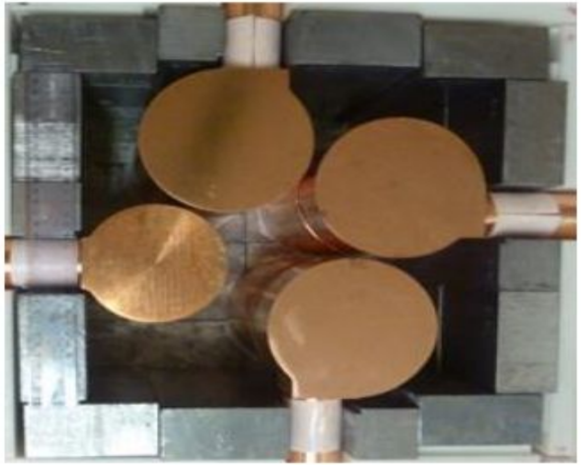
Threshold at least as low as in previous run. Better background and improved stability.

<u>Probed feasibility of scaling technology to larger Ge diodes → upscaling to O(100 kg) possible (>10^5 ev/year)</u>





Nov 2024 →



Summary

- High cross-section of CEvNS ==> compact neutrino detectors
- CONUS+: HPGe detectors at 20.7 m from reactor core
- Mainly cosmic background events: reactor power uncorrelated!
- First CEvNSdetection at nuclear reactor (null hypothesis rejected at 3.7 sigma C.L.)
- Result consistent with theoretical models and predictions
- CONUS+ phase 2 with increased mass has started. Physics data taking ongoing. Stay tuned for more results!

Thank you for your attention!

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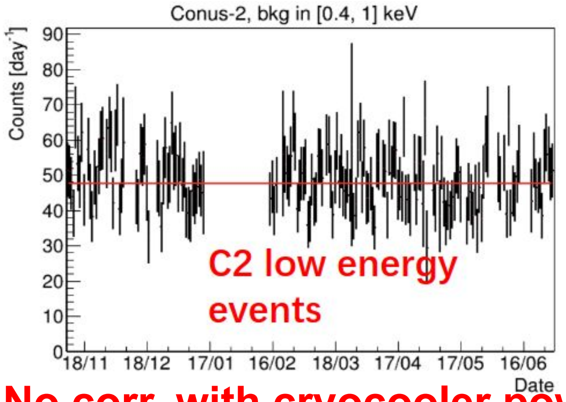
Stability during Run1

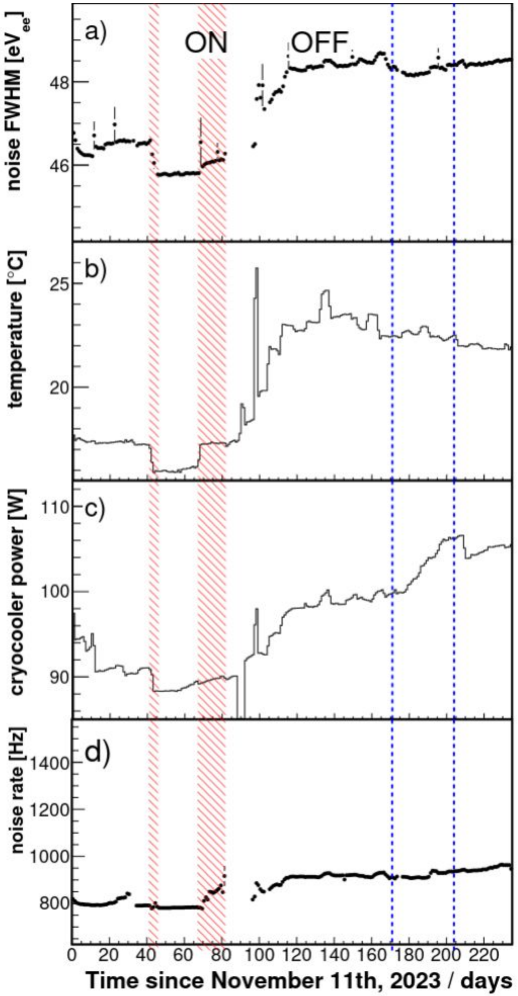
Good stability reached during the data taking.

Cryocooler-noise correlation strongly reduced with liquid-cooling system respect to CONUS.

Crycooler power variation due to problem with coolant liquid. However, no impact of microphonics events in ROI.



No corr. with cryocooler power!



Energy reconstruction

Energy calibration with X-rays from binding energies of the K and L shells from ^{71}Ge.

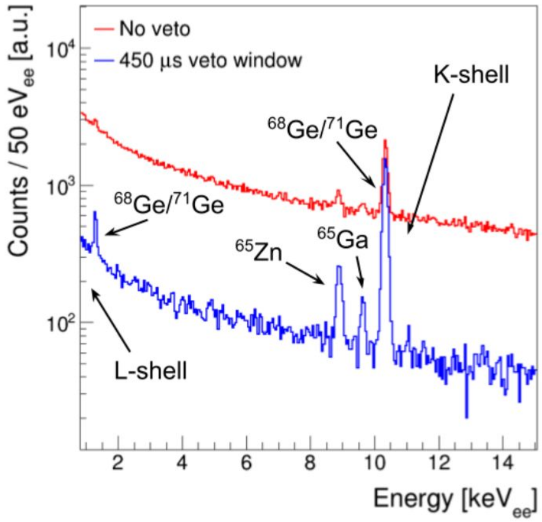
Irradiation with a ^{252}Cf source at the end of the physics run to increase statistics in these lines. Energy calibration uncertainty below 5 eV achieved.

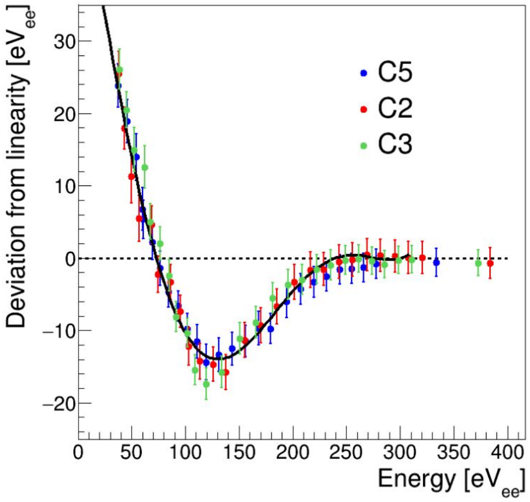
Energy calibration at high energy with ^{228}Th source and Ge metastable states.

Stability energy scale below 2% variations.

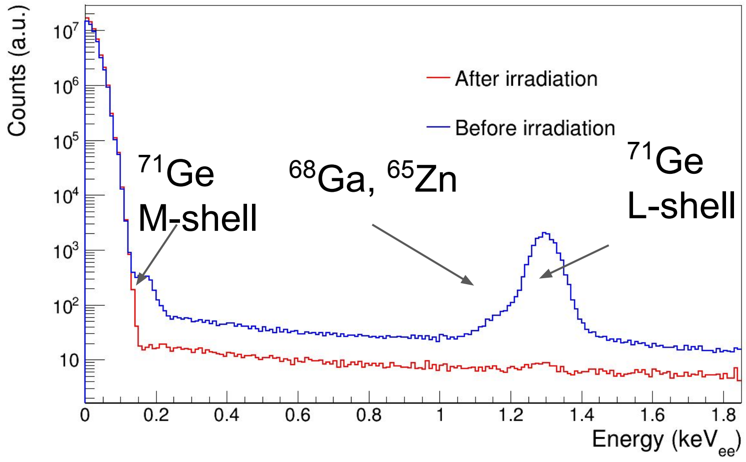
Non-linearity at low energies due to DAQ energy reconstruction limitations and lost of trigger efficiency.

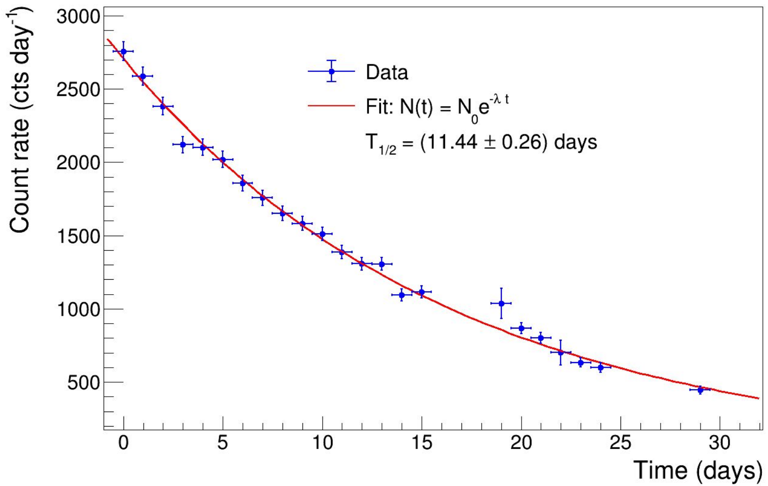
Estimated with pulser scan from 2 keV down to few eV. Maximum deviation from linearity 15 eV.

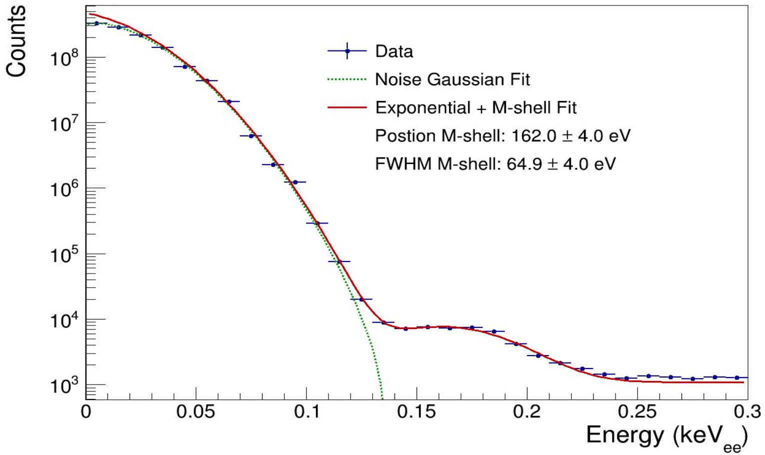




Determination of ^{71}Ge M-shell







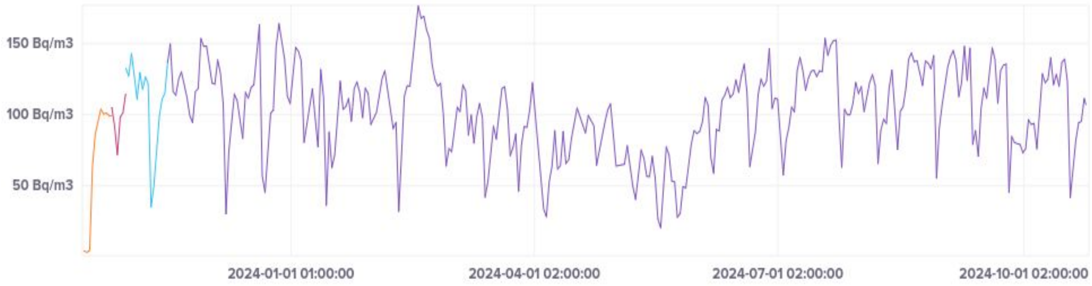
Measured position for M-shell X-ray line 162±4 eV. Literature 158.1±0.5 (nuDat3) and 162±2 (CDMS).

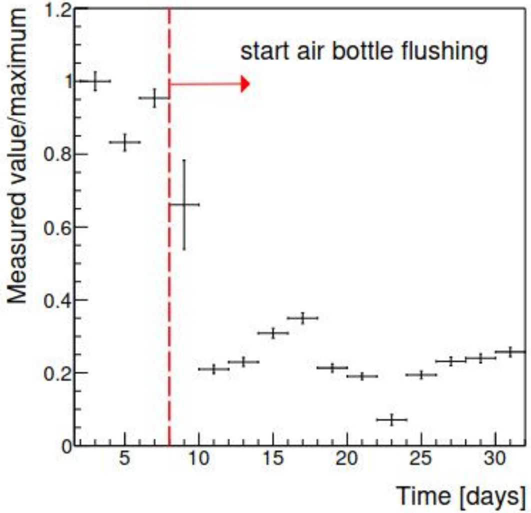
Ratio to M/K shells 0.021±0.002. Literature 0.027±0.01.

CONUS+ background: Radon

Radon can diffuse into the detector chamber and produce some background.

Monitoring of the radon level in the room during one year.





Radon concentration average value of [30,190] Bq/m^3.

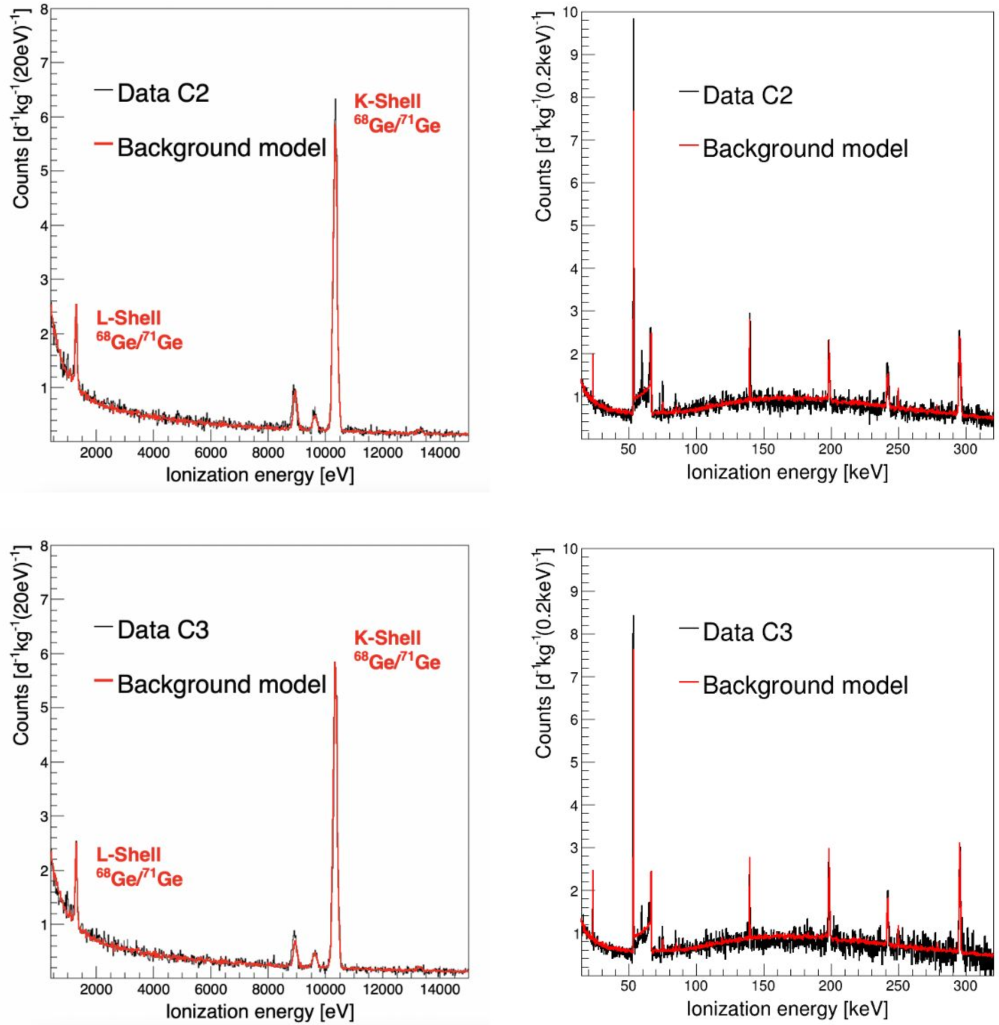
Flushing with bottles filled with air and stored for periods over 3 weeks.

Background reduction in [100-400] keV range by factor 5. Radon lines (242, 295 and 352 keV) strongly suppressed.

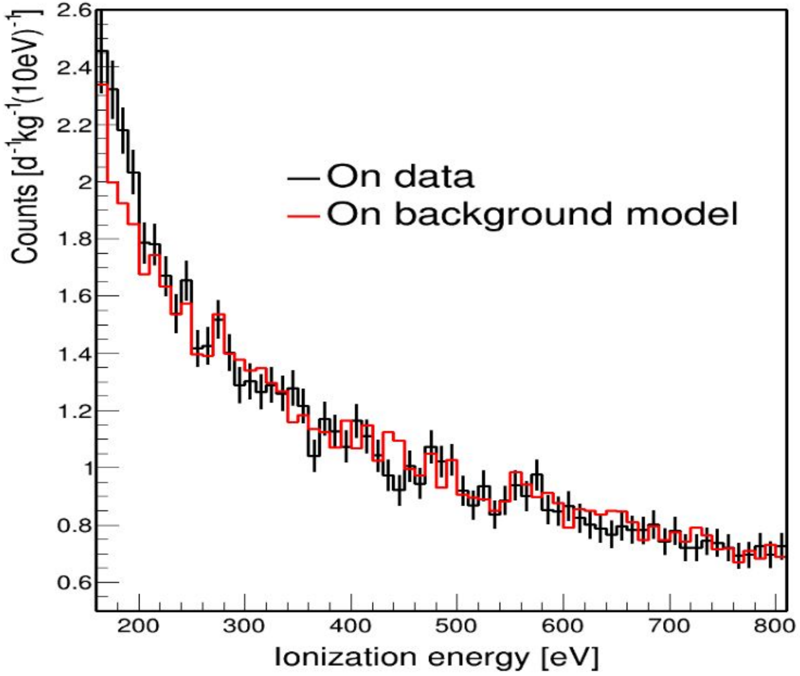
Background model decomposition

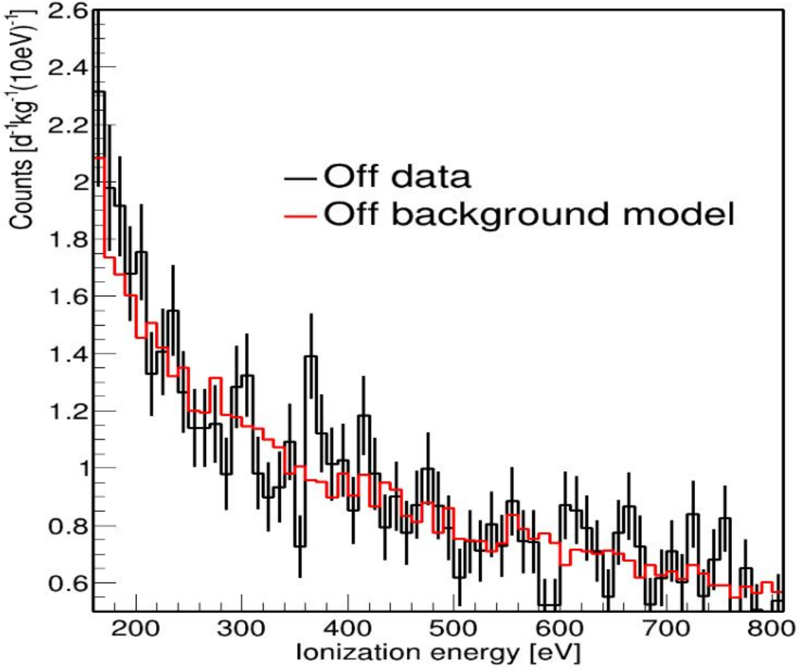
[0.4-1.0] keV_{ee}						
Detector	C5		C2		C3	
Rector period	On	Off	On	Off	On	Off
Cosmogenic neutrons	21.6 ± 3.1	17.7 ± 2.5	21.6 ± 3.1	17.7 ± 2.5	21.6 ± 3.1	17.7 ± 2.5
Cosmogenic muons	17.4 ± 0.3	16.9 ± 0.3	17.4 ± 0.3	16.9 ± 0.3	17.4 ± 0.3	16.9 ± 0.3
Radon	1.9 ± 0.1	0.3 ± 0.1	2.8 ± 0.1	0.7 ± 0.1	2.6 ± 0.1	0.7 ± 0.1
Other	2.0 ± 0.2	1.2 ± 0.2	6.4 ± 0.5	5.6 ± 0.5	5.6 ± 0.5	4.8 ± 0.5
Leakage test component	-	-	3.0 ± 0.5	3.0 ± 0.5	0.8 ± 0.2	0.8 ± 0.2
Total (Model)	42.9 ± 3.1	35.8 ± 2.5	52.3 ± 3.3	45.1 ± 2.7	49.3 ± 3.1	42.2 ± 2.7
Total (Data)	43.5 ± 1.1	33.4 ± 1.8	50.7 ± 1.2	45.3 ± 1.3	48.8 ± 1.2	42.5 ± 2.0

Full background understanding above CEνNS energy region!!


Data C2
Background model
K-Shell
68Ge/71Ge
L-Shell
68Ge/71Ge
Counts [d-1kg-1(20eV)-1]
Ionization energy [eV]
Data C2
Background model
Counts [d-1kg-1(0.2keV)-1]
Ionization energy [keV]
Data C3
Background model
K-Shell
68Ge/71Ge
L-Shell
68Ge/71Ge
Counts [d-1kg-1(20eV)-1]
Ionization energy [eV]
Data C3
Background model
Counts [d-1kg-1(0.2keV)-1]
Ionization energy [keV]

Background model in CEνNS region

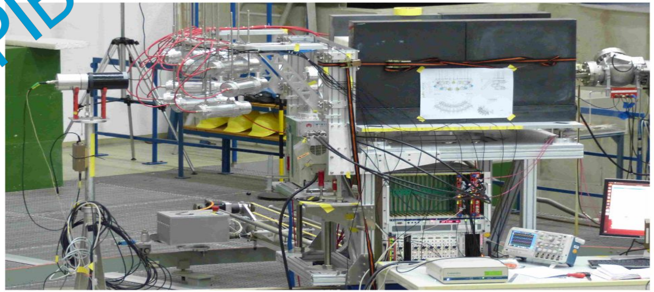


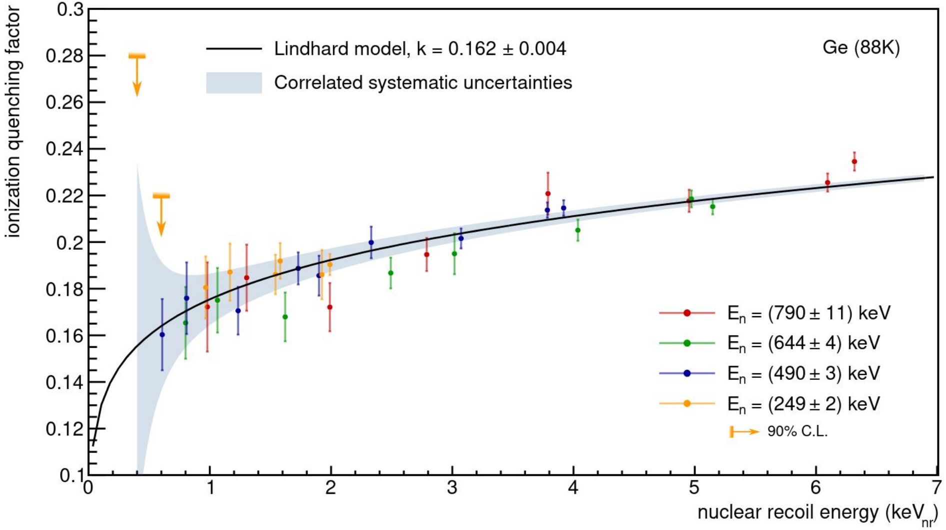


Quenching measurement

A. Bonhomme et al. , Eur. Phys. J. C 82, 815 (2022)

CONUS and PTB collaboration for a direct, model-independent (purely kinematics) measurement using neutrons (nuclear recoils).

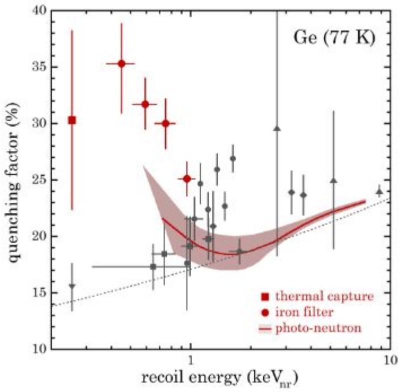


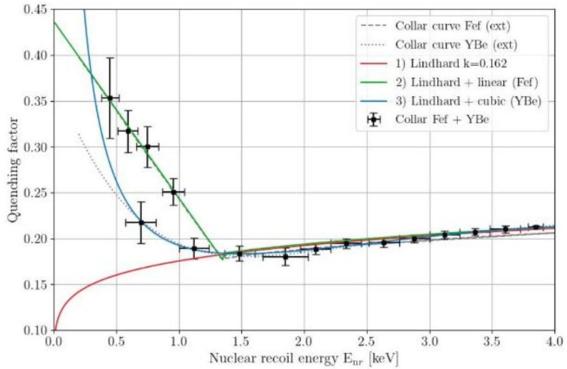


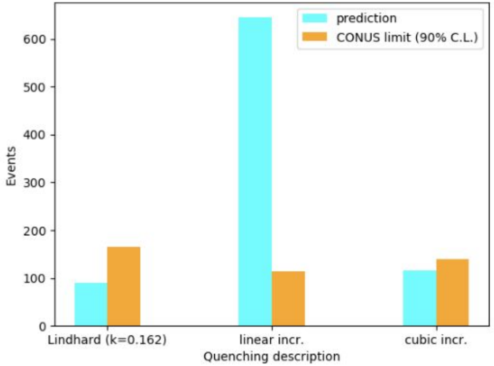
Data compatible with Lindhard theory down to sub-keV: k = 0.162 ± 0.004 (stat+syst).

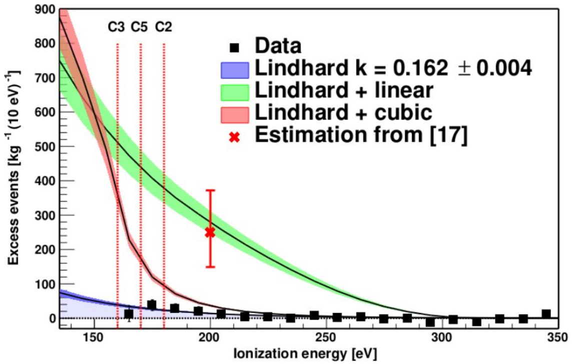
Comparison with other result – CONUS

- Constraints from CONNIE, TEXONO, νGen
- Colaresi et al, PRL 129, 211802 (2022)
  - "…very strong preference… for the presence of … CEvNS …"
  - Signal prefers low energy excess of quenching factor as compared to Lindhard quenching to be consistent with SM









Uncertainty overview

Dominant uncertainty over signal prediction energy scale.

Likelihood fit uncertainty dominated by statistics. Second dominant term uncertainty energy scale over non-linearity.

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