

First observation of reactor antineutrinos by coherent scattering with CONUS+

On behalf of the CONUS Collaboration

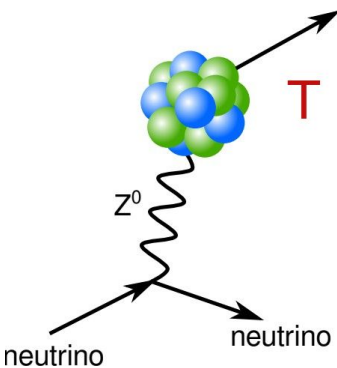


Edgar Sánchez García
(MPIK)



WIN 2025 (University of Sussex), June 2025

Coherent elastic neutrino nucleus scattering



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

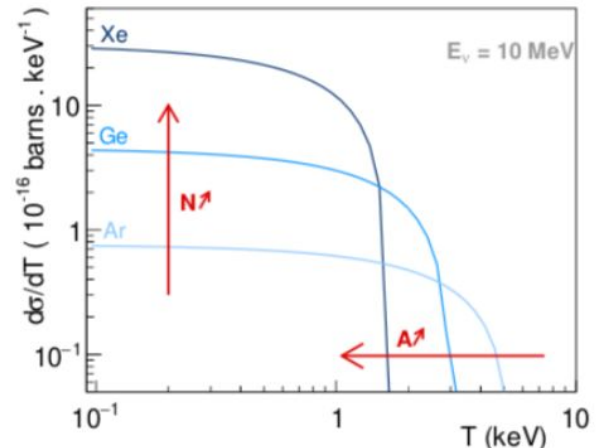
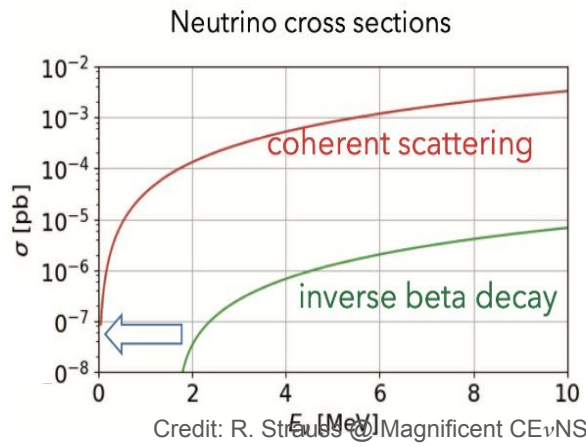
Low momentum transfer \rightarrow full coherence
 $E_\nu < 1/2R_A$ (in Ge ~ 20 MeV).

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

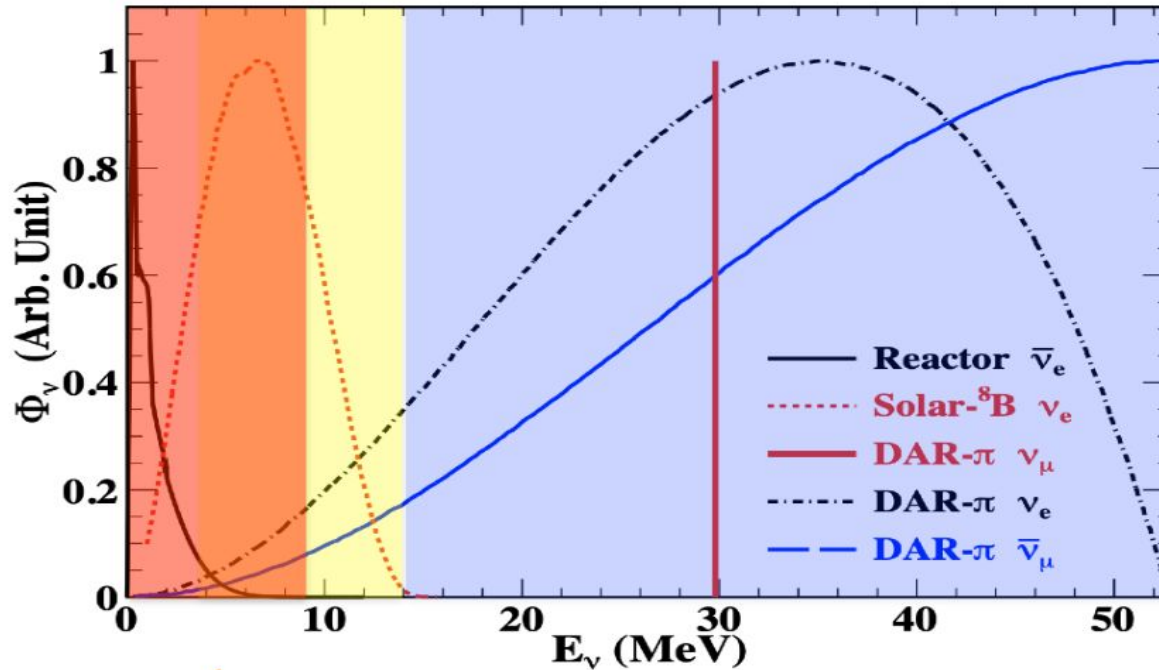
Experimental signature: low energy recoil of the nucleus:

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

The isotope selection is a push-pull situation.



Neutrinos sources



TEXONO, arXiv2502.20007

Coherence ←

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

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

$E_\nu \sim 0\text{-}10$ MeV (fully coherent $\rightarrow F \sim 1$).

ν from π -DAR. Different neutrino flavors.

$E_\nu \sim 20\text{-}50$ MeV ($F < 1$).

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

Complementary experiments

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

CONUS+ location: KKL power plant

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

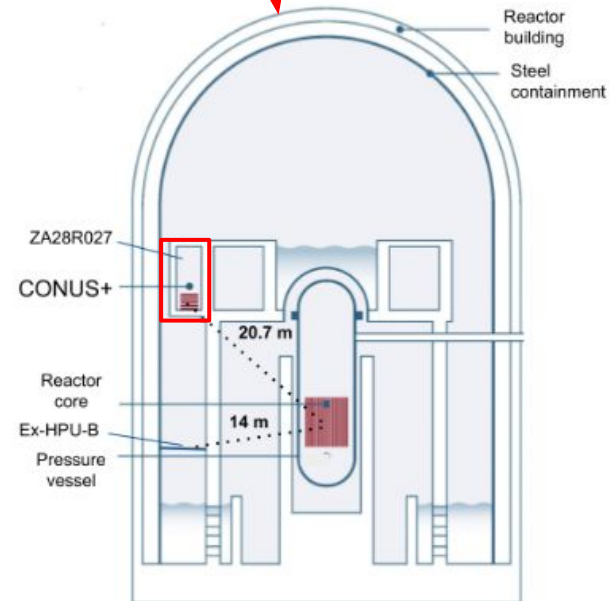
BWR with high duty-cycle: 1 month/year of reactor-off.

CONUS+ is placed inside the reactor building in the ZA28R027 room.

20.7 m from 3.6 GW reactor core → high antineutrino flux expected
 $1.45 \times 10^{13} \bar{\nu}_e \text{ s}^{-1} \text{ cm}^{-2}$

Concrete ZA28R027 room 0.35 m. Average overburden of 7.4 m w.e.

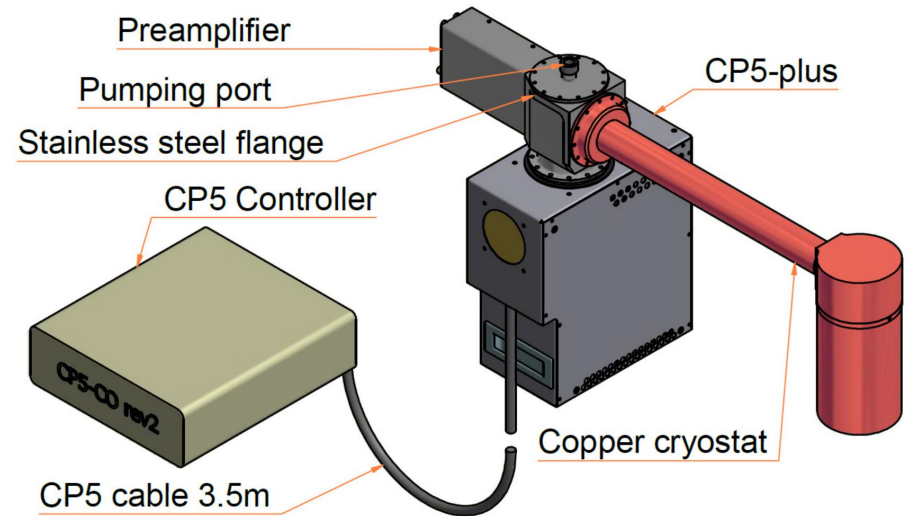
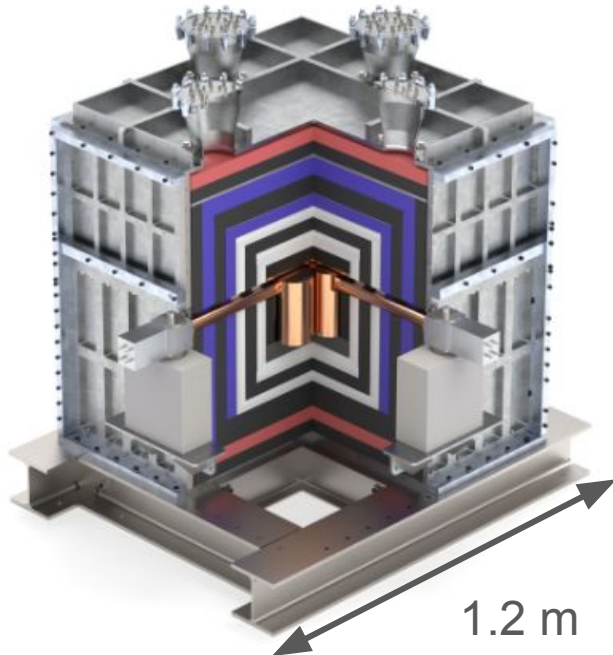
Reactor drywell head over room during reactor off. Increase overburden by 0.25 m w.e.



CONUS+ detector

4 p-type point contact HPGe:

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

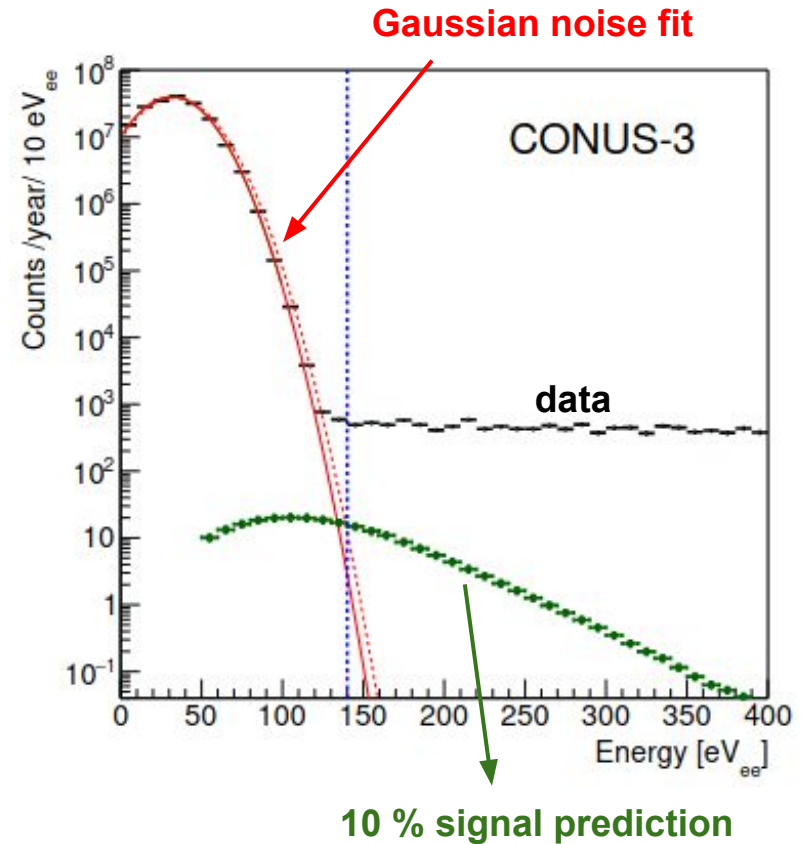
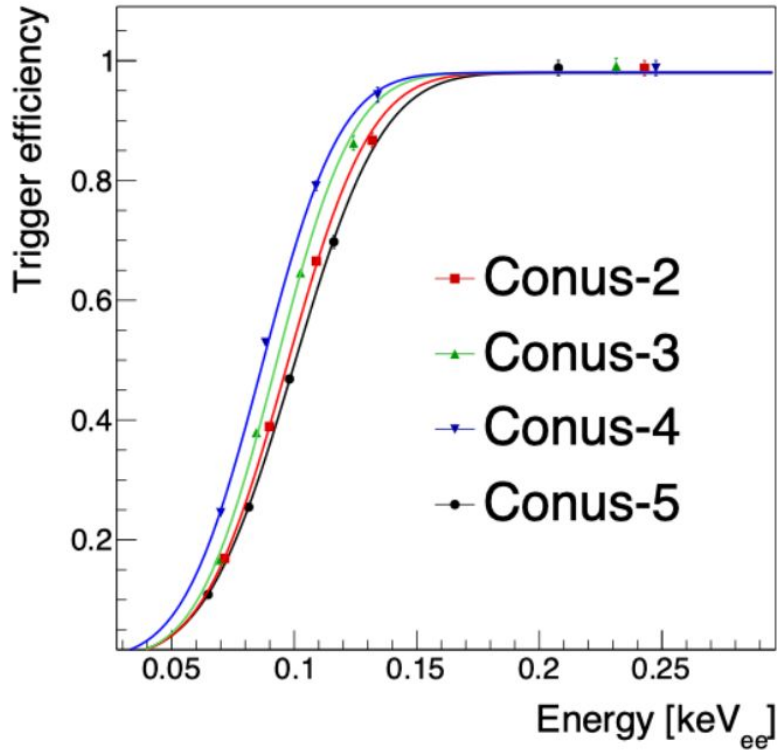


Active + passive shielding:

- 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

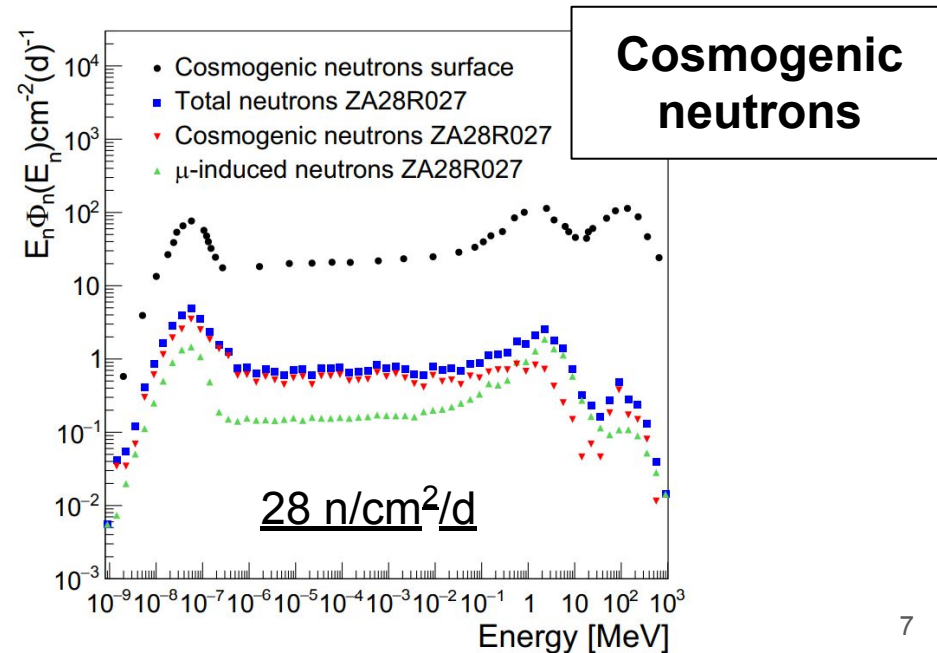
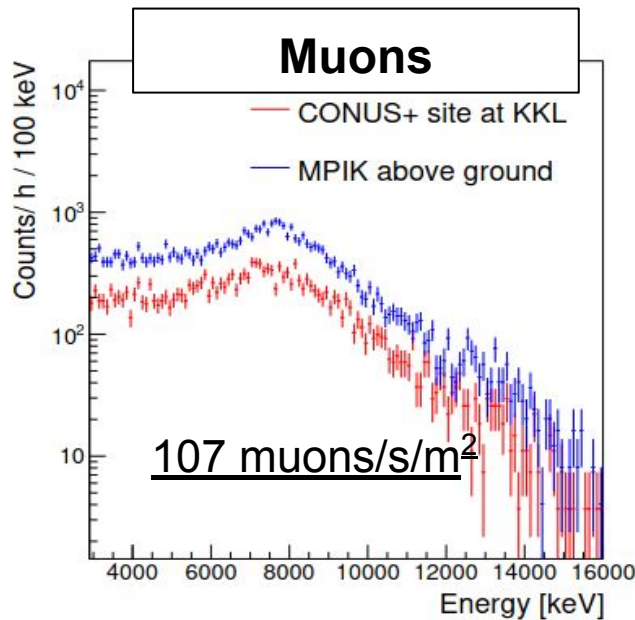
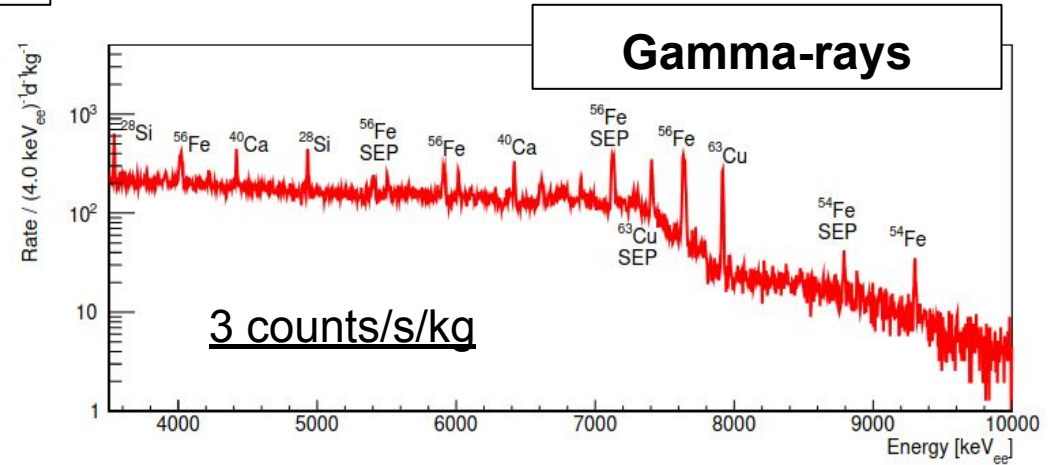
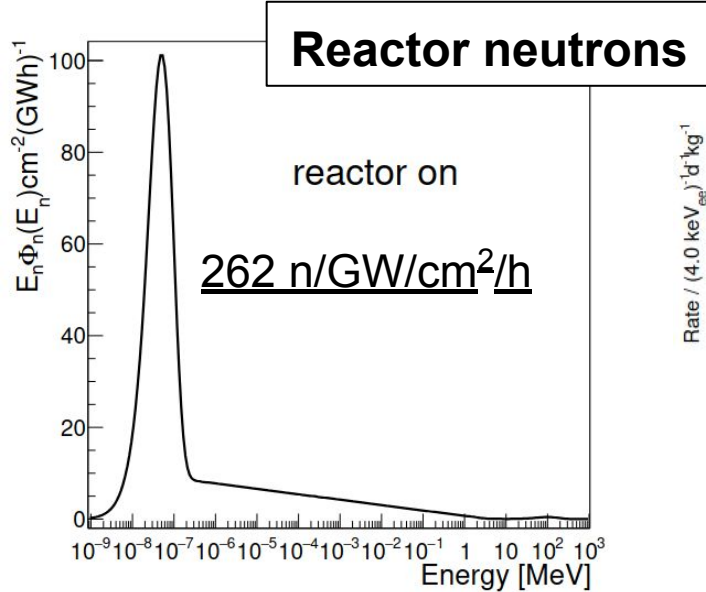


Energy threshold improved from 210 eV (CONUS) to ~160 eV!

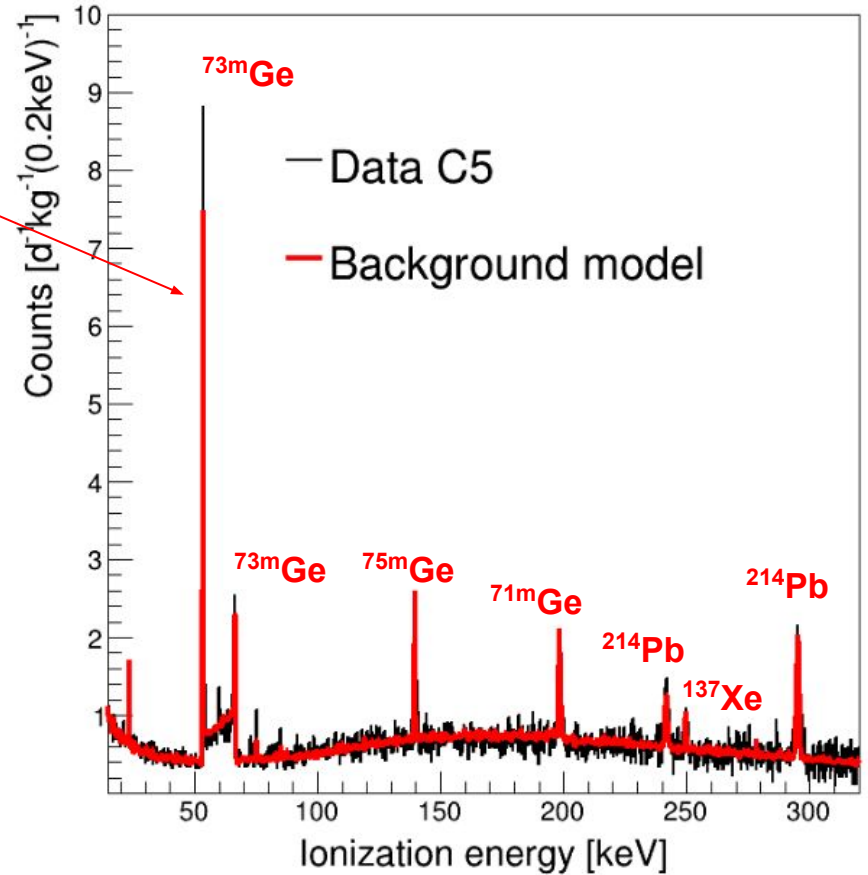
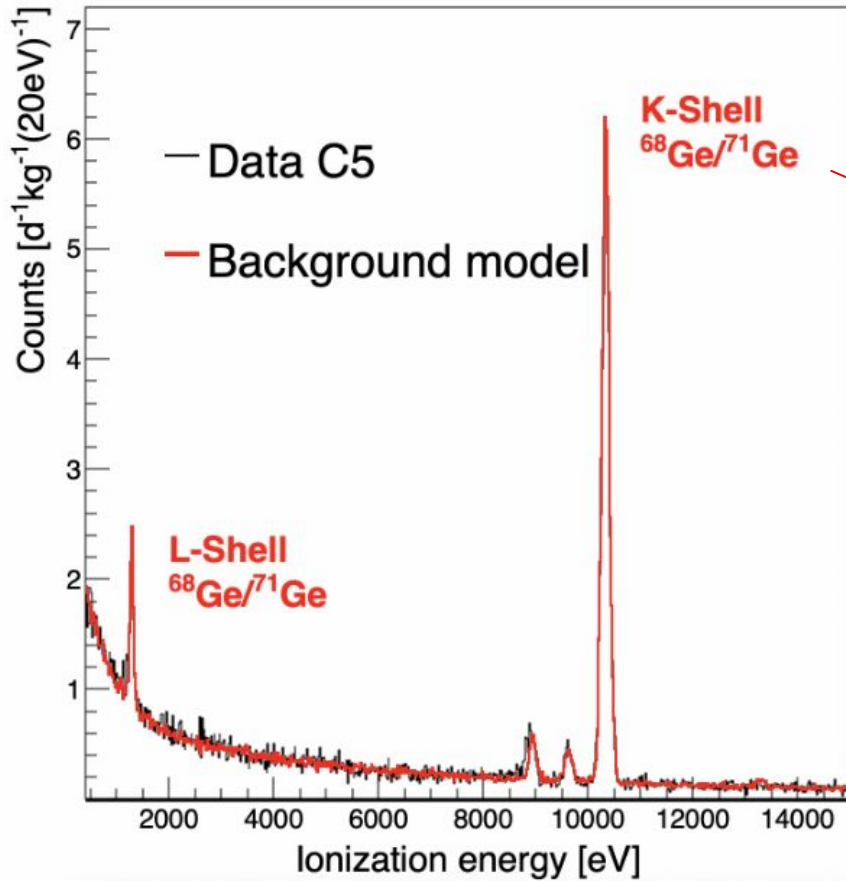
Trigger efficiency from 50% @300 eV to 50% @90 eV

Background characterization

CONUS, EPJC 85
(2025) 465



Full background model



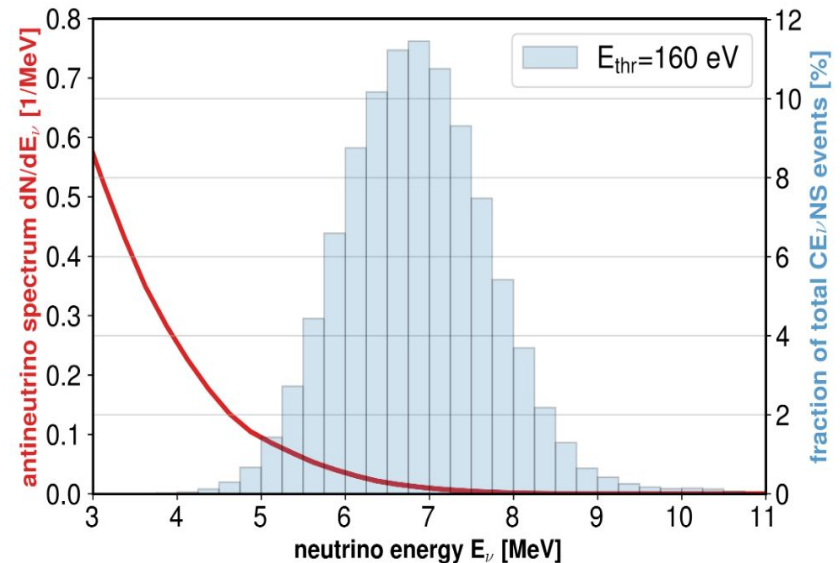
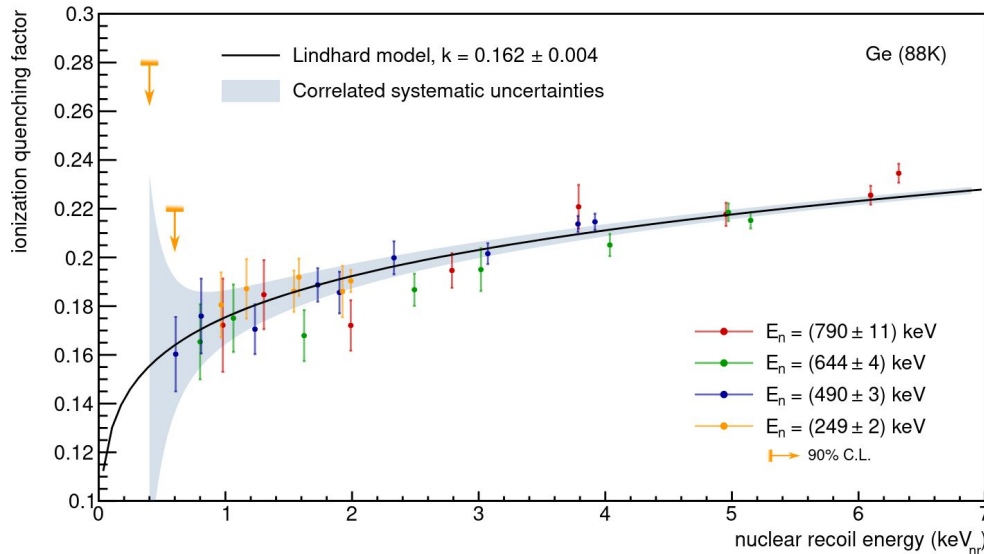
Full background understanding above $\text{CE}\nu\text{NS}$ energy region!!

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 $k=0.162\pm 0.004$.

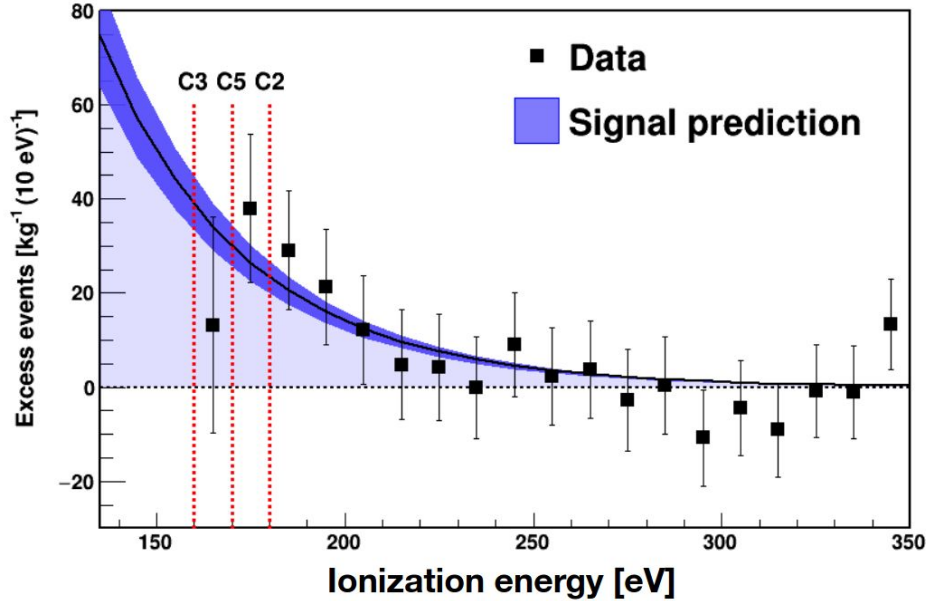
Considering an exposure of 327 kg d and the different energy thresholds, a $\text{CE}_{\nu\text{NS}}$ signal prediction of 347 ± 59 is estimated for Run-1.



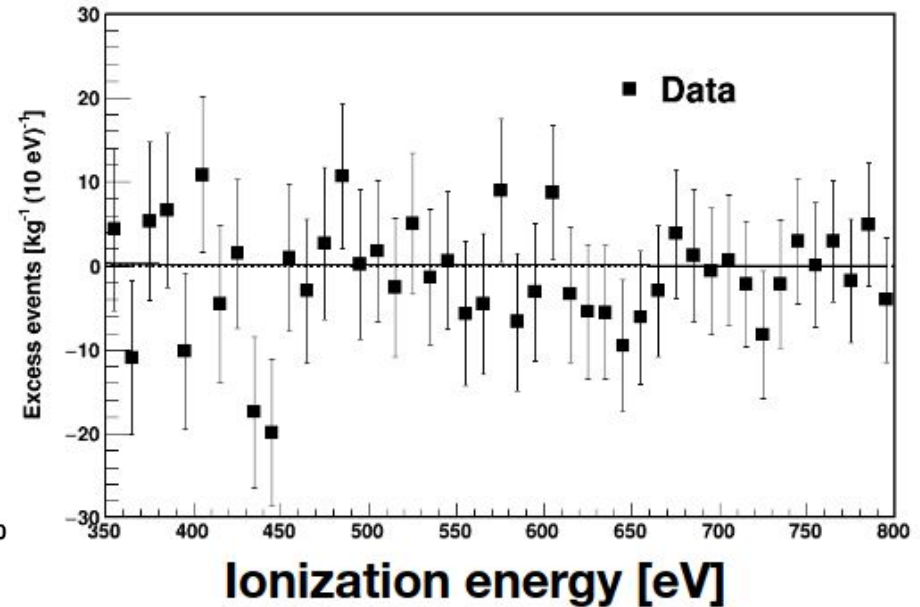
A. Bonhomme et al. , Eur.
Phys. J. C 82, 815 (2022)

First $CE_{\nu}NS$ 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

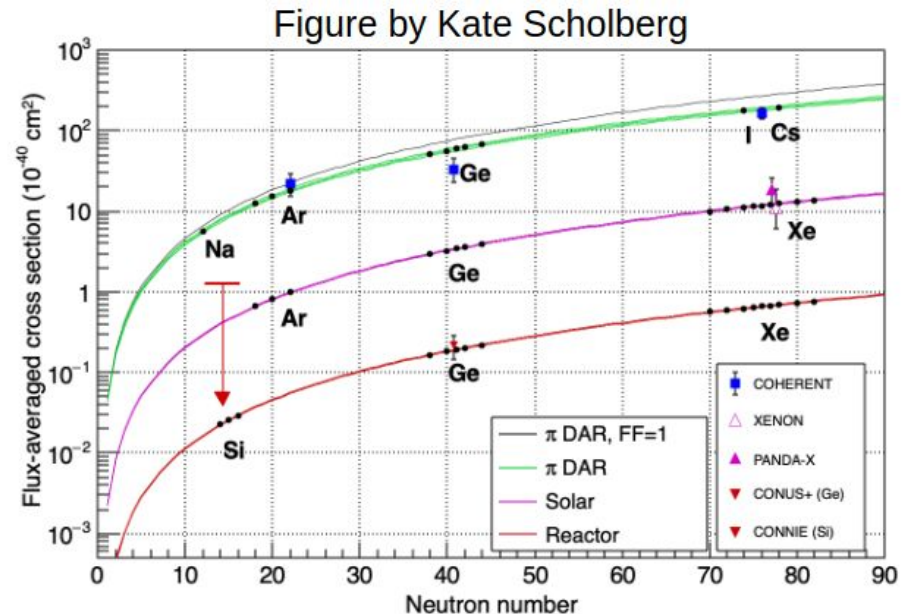
CONUS, arXiv 2501.05206 (2025)

Comparison other experiments

Source	Target	ν energy [MeV]	flux [$\text{cm}^{-2}\text{s}^{-1}$]	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	Xe	< 15	$5 \cdot 10^6$	11 ± 4	0.90 ± 0.45
Sun	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 $\text{CE}\nu\text{NS}$ channel (down to 4 MeV).

CONUS+ has accumulated the highest number of $\text{CE}\nu\text{NS}$ counts in one single isotope (low threshold + high flux).

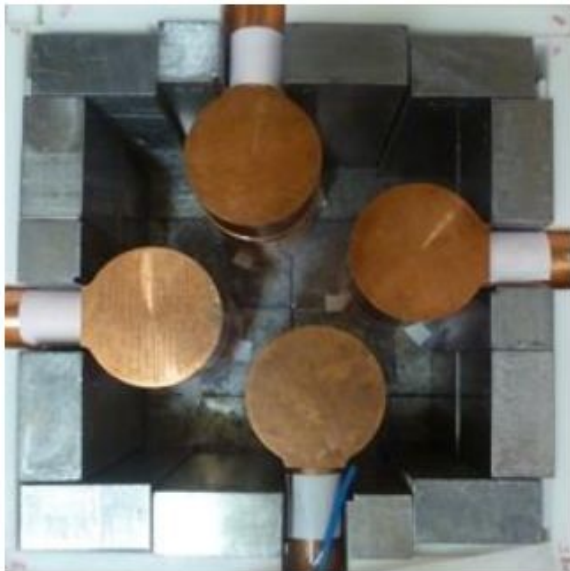
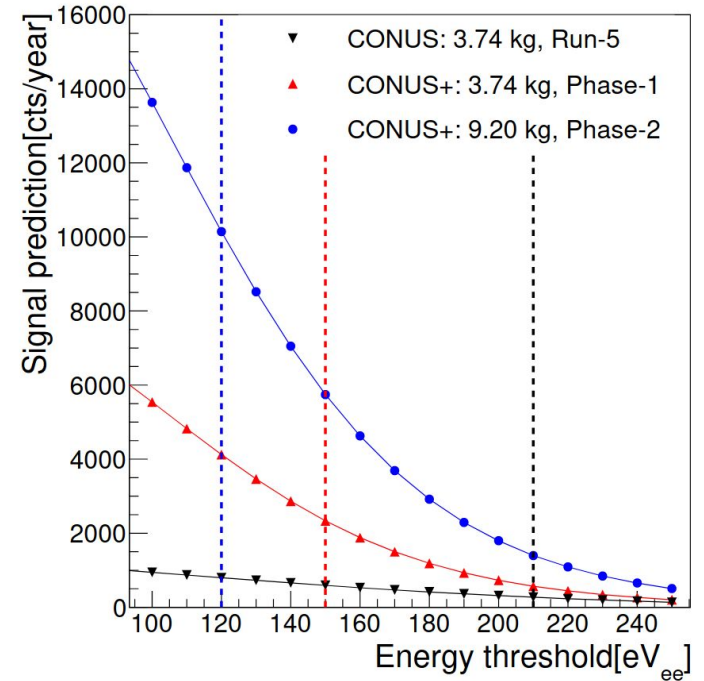


CONUS+ phase 2

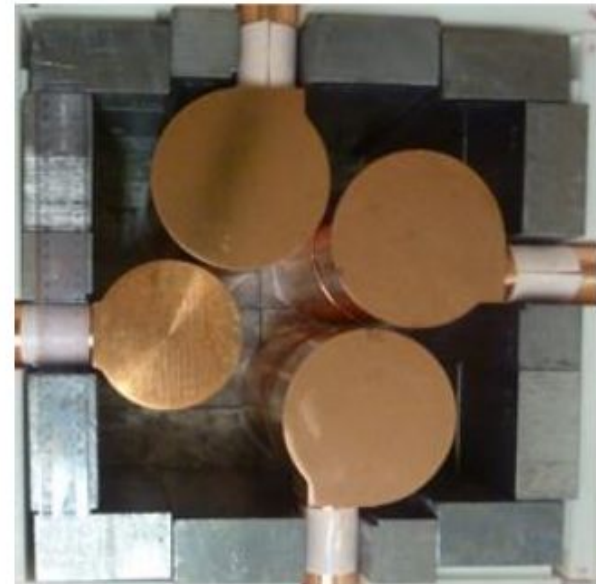
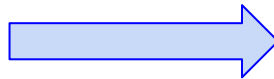
3 new 2.45 kg detectors → total mass 8.4 kg.

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

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



Nov 2024



Summary

- High cross-section of CE ν NS ==> compact neutrino detectors
- CONUS+: HPGe detectors at 20.7 m from reactor core
- Mainly cosmic background events: reactor power uncorrelated!
- First CE ν NS detection 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!

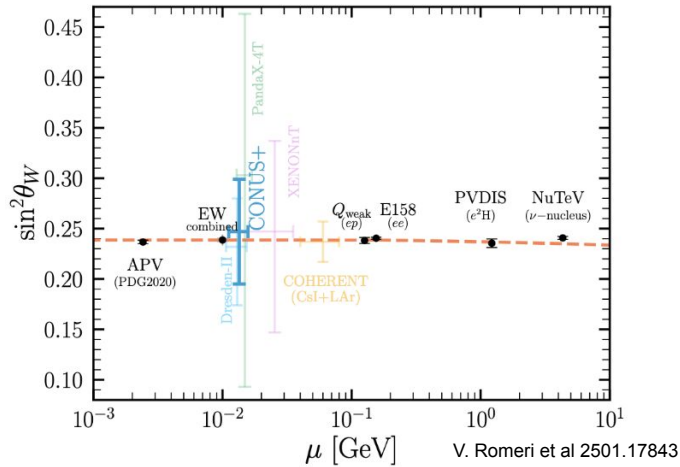
Thank you for your attention!



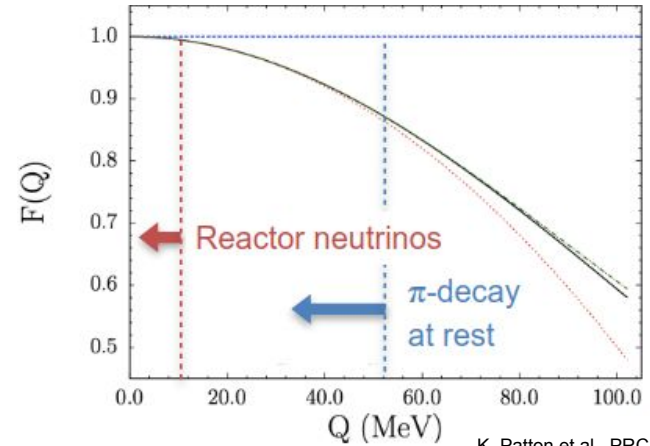
esanchez@mpi-hd.mpg.de

Physics potential

Electroweak precision tests

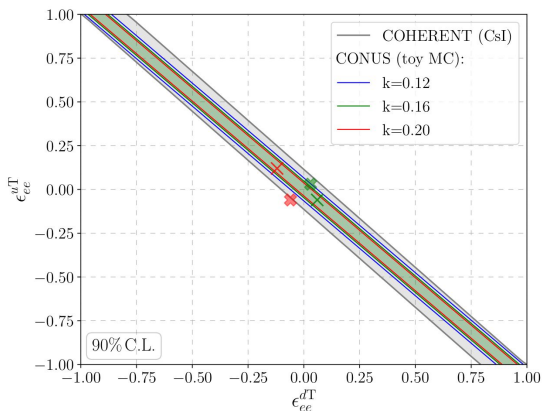


Nuclear physics

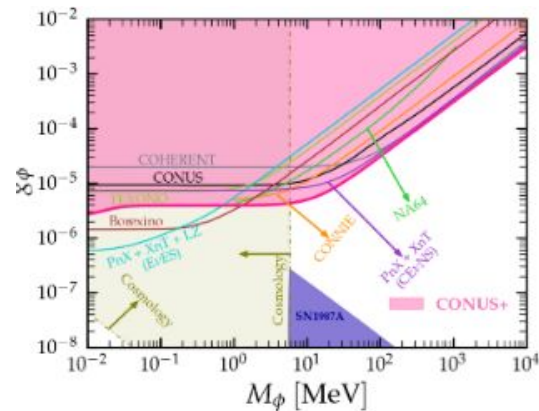


K. Patton et al., PRC 86, 024612 (2012)

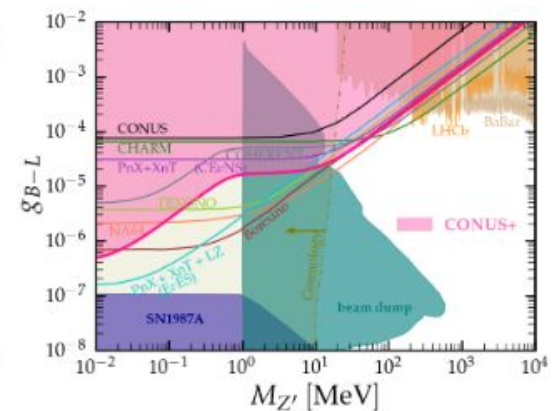
CONUS collaboration JHEP 85 (2022)



New neutrino interactions

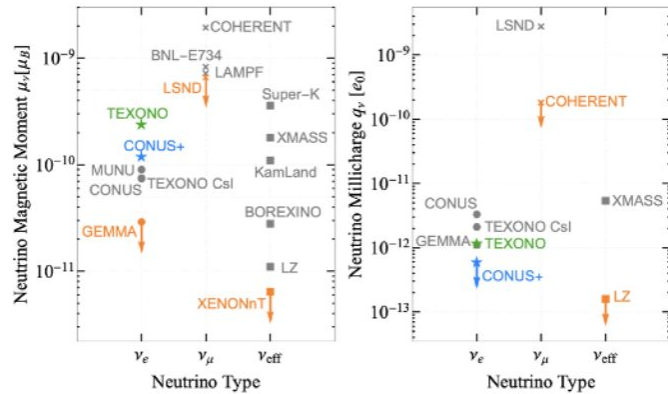


arXiv 2501.12441 (2025)



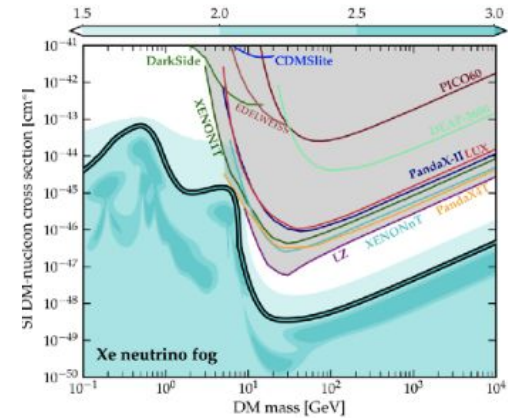
Physics potential

Neutrino electromagnetic properties



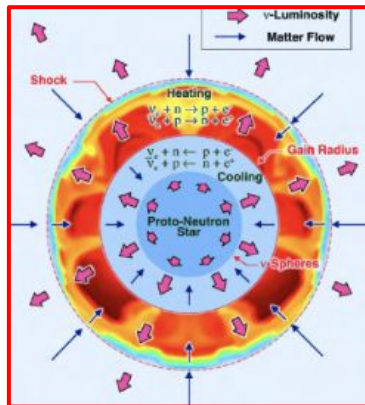
arXiv 2501.18550 (2025)

Dark Matter



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

Astrophysics



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

Daily life applications

Use as Nuclear Safeguard
(nonproliferation, storage monitor)

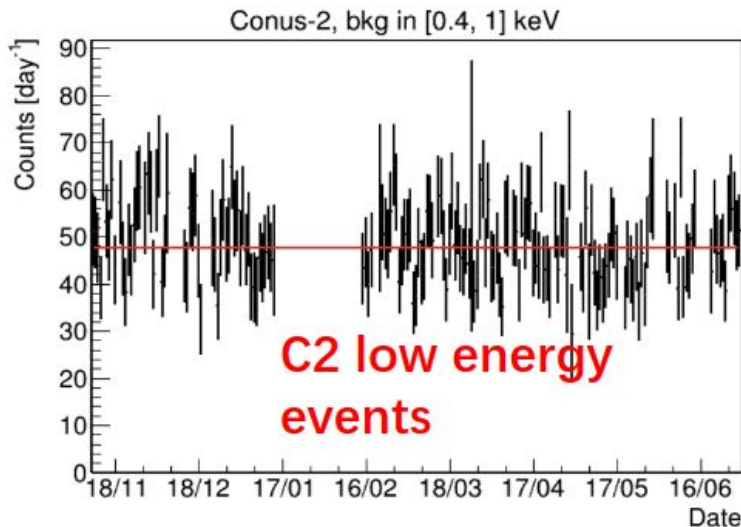


Stability during Run1

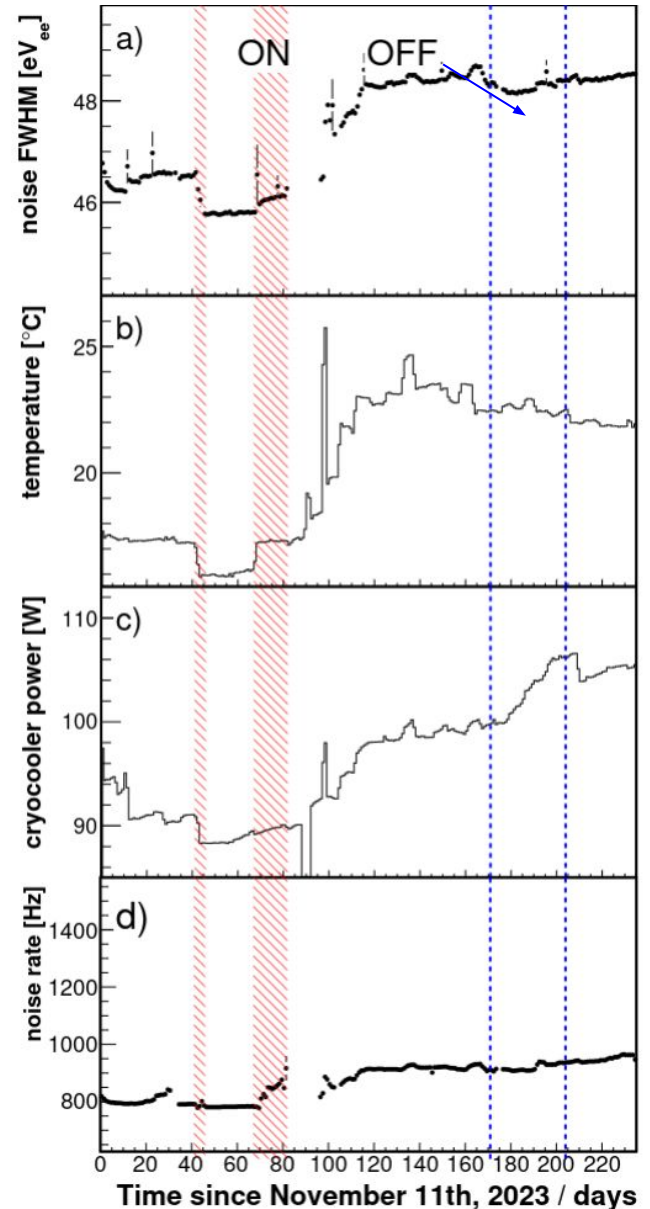
Good stability reached during the data taking.

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

Cryocooler 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 .

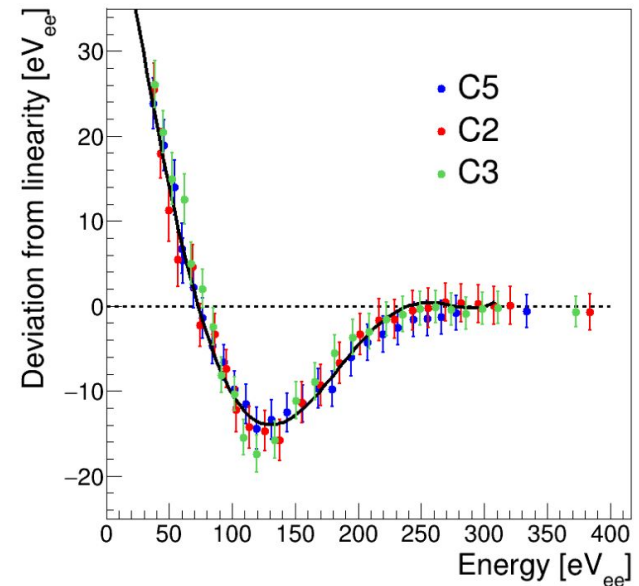
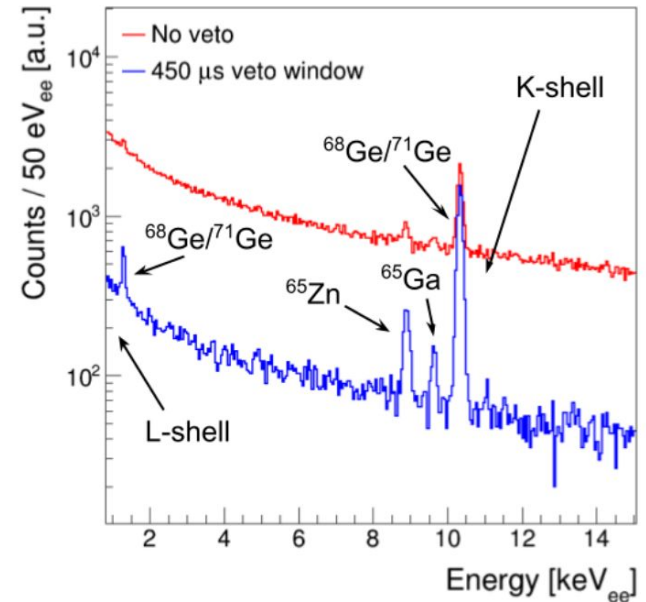
Irradiation with a ^{252}Cf source at the end of the physics run to increase statistics in these lines. Energy calibration uncertainty below 5 eV achieved.

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.

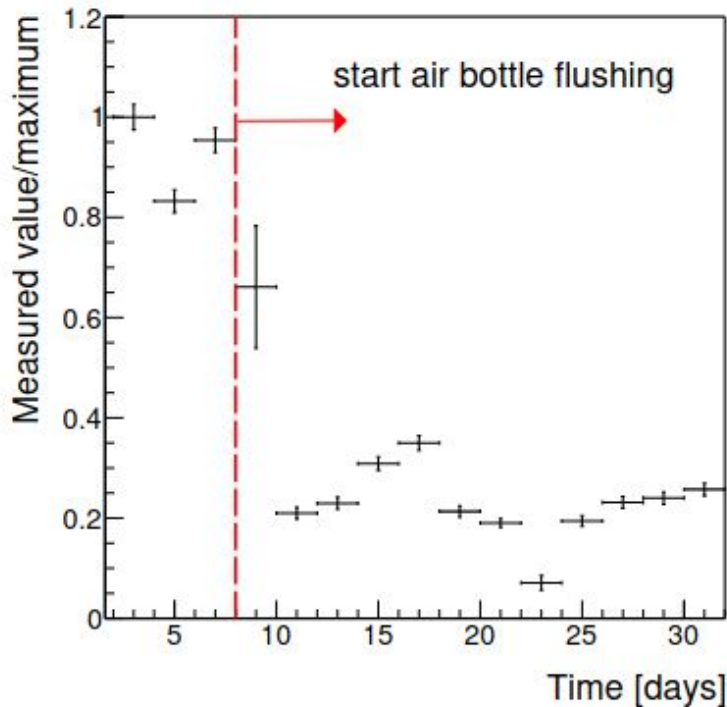
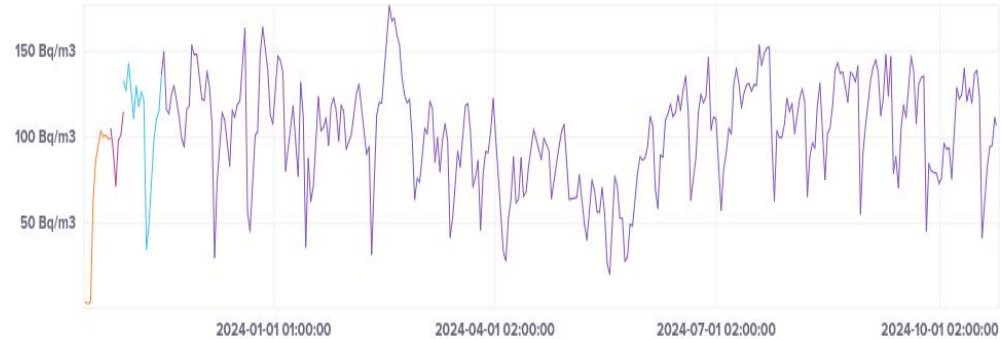
Estimated with pulser scan from 2 keV down to few eV. Maximum deviation from linearity 15 eV.



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/m³.

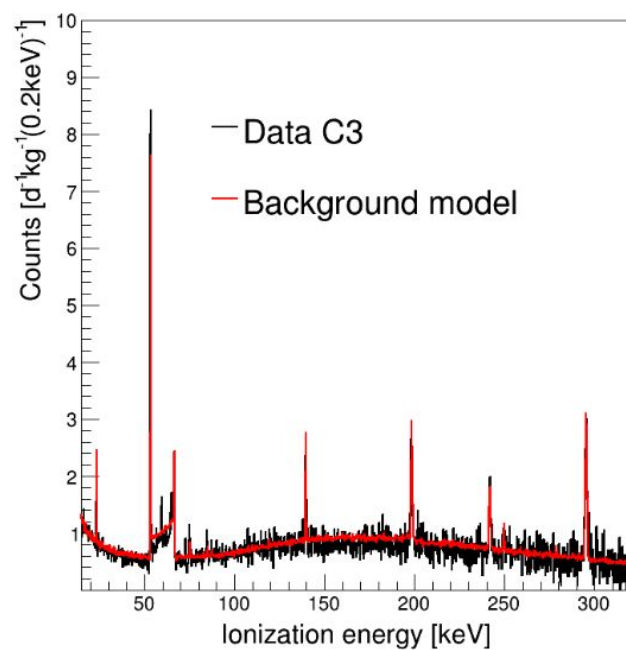
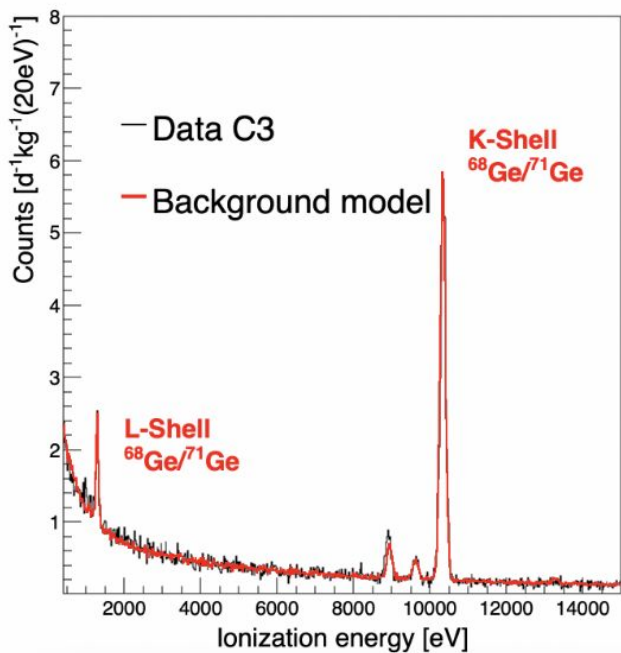
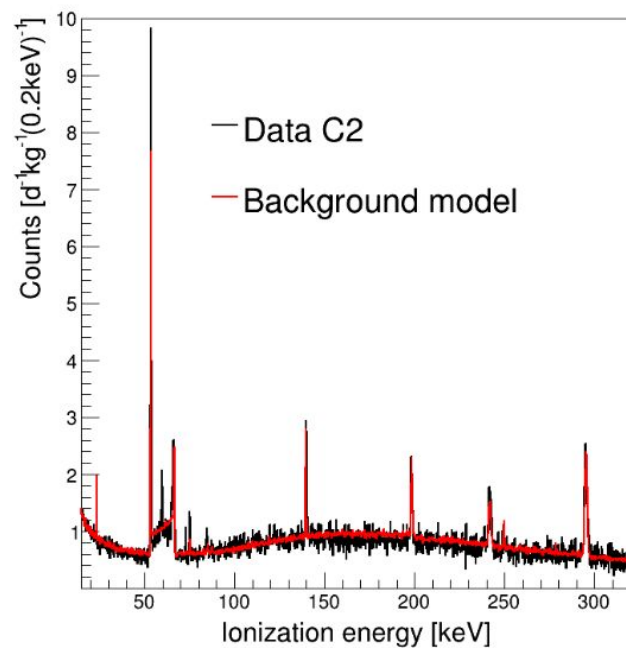
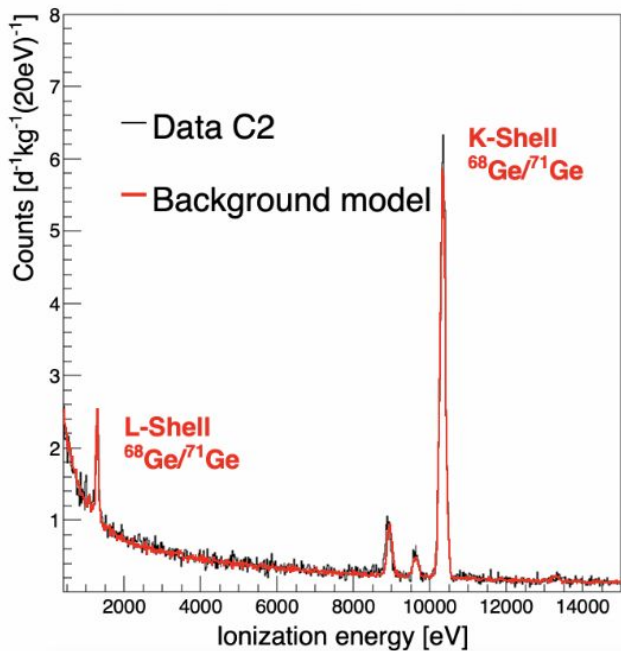
Flushing with bottles filled with air and stored for periods over 3 weeks.

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

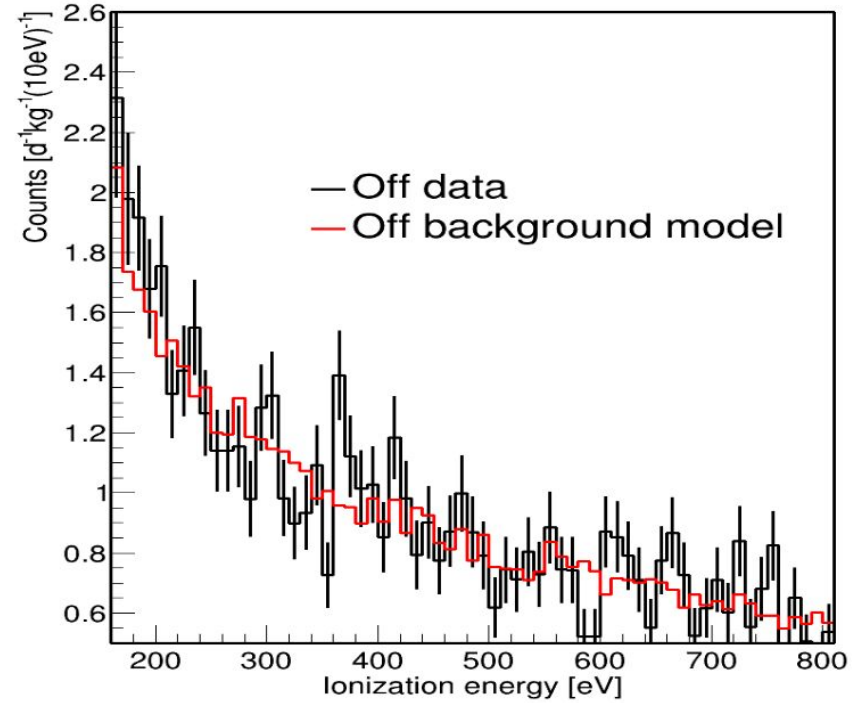
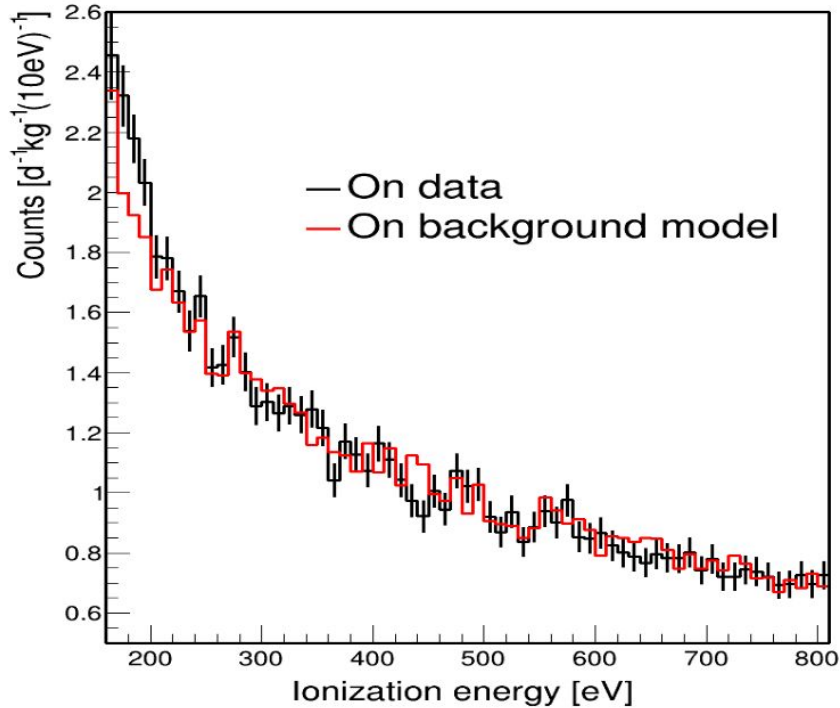
Background model decomposition

[0.4-1.0] keV _{ee}						
Detector	C5		C2		C3	
Reactor 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!!



Background model in $CE\nu NS$ region

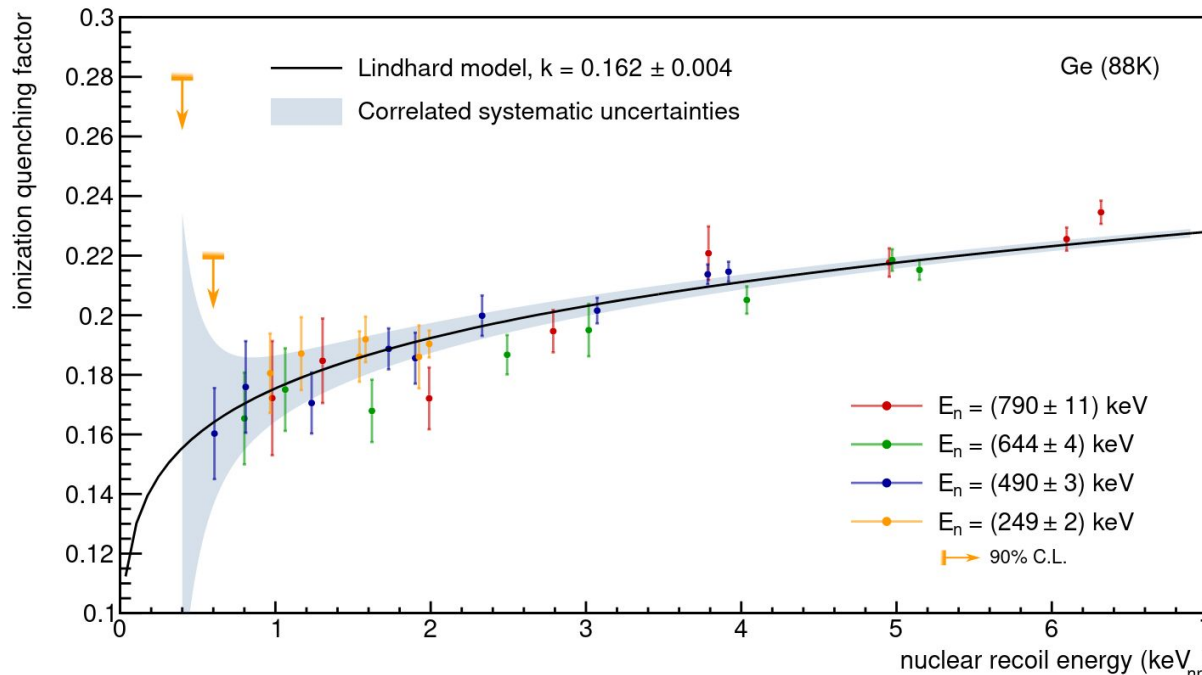
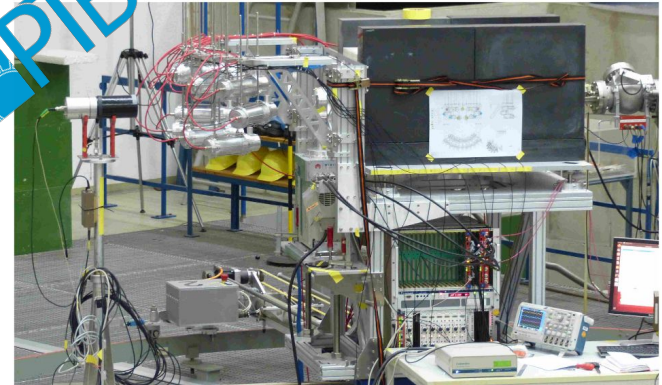
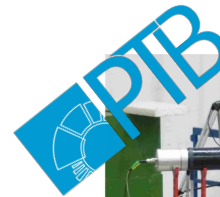


Quenching measurement

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).

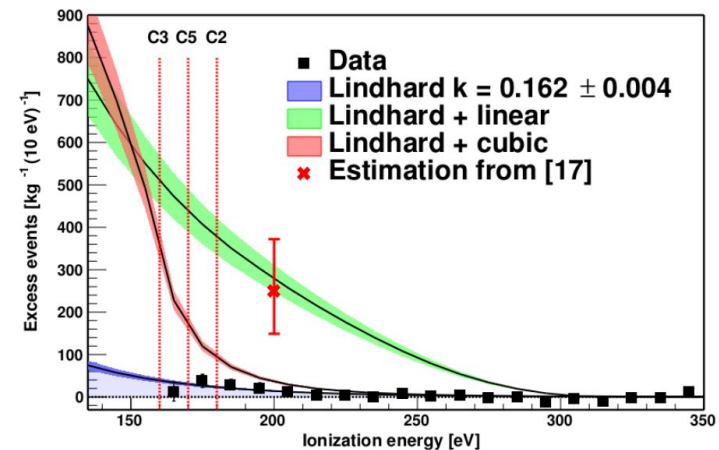
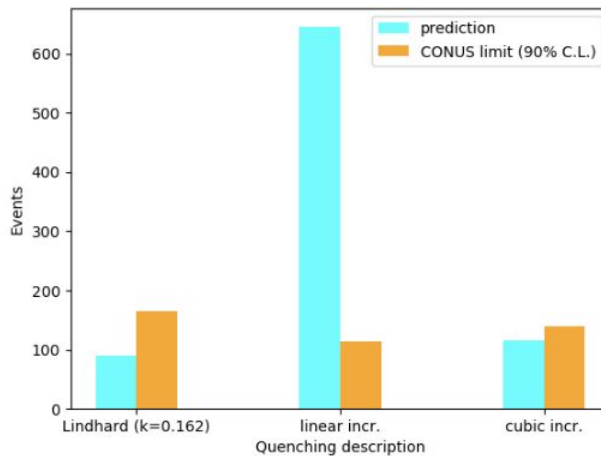
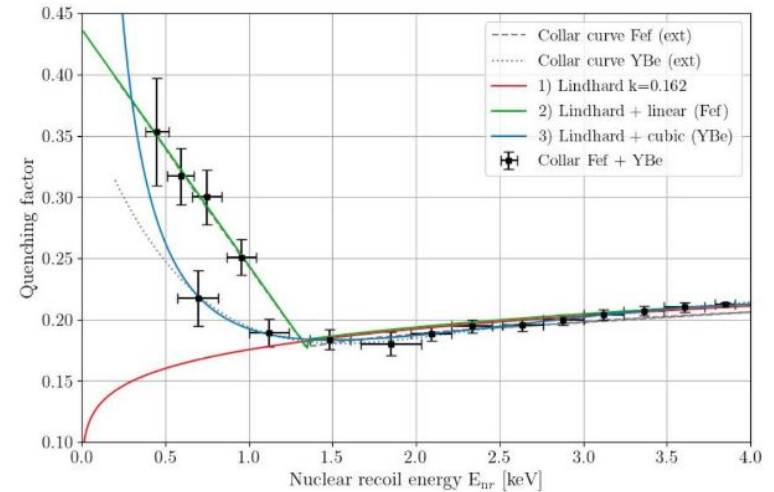
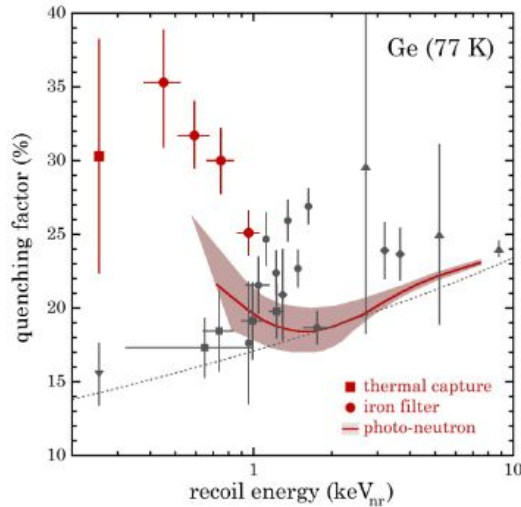
All relevant systematic uncertainties included: setup geometry, beam energy, detector response including energy scale non-linearities.



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

Comparison with other result – CONUS

- Constraints from CONNIE, TEXONO, vGen
- 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%

CE ν NS result uncertainties	
Uncertainty	Contribution
Likelihood fit	± 86
Fit method	± 7
Background model	± 40
Non-linearity implementation	± 47
All combined	± 106