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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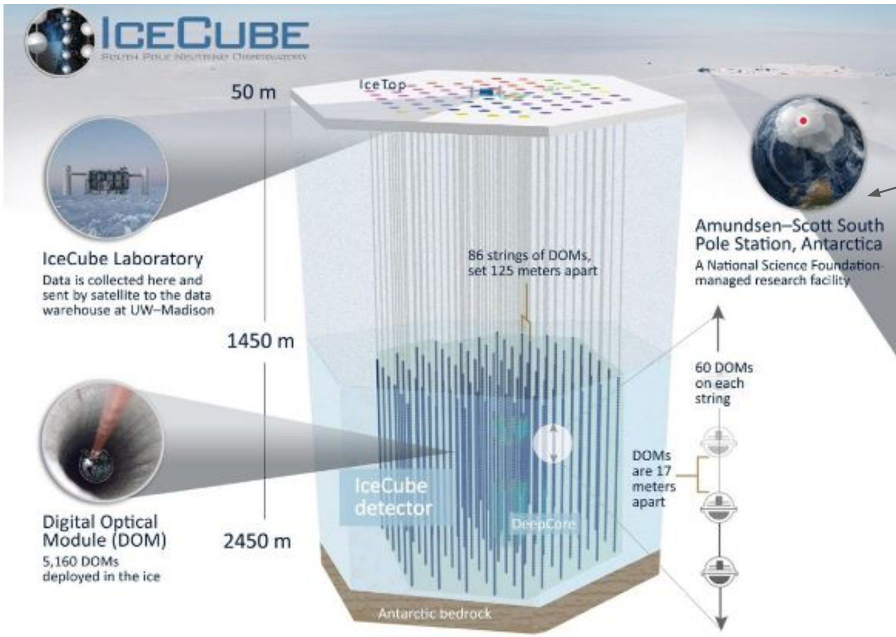
(MPIK)

3rd IAEA TM on Nuclear Data Needs for Antineutrino Spectra

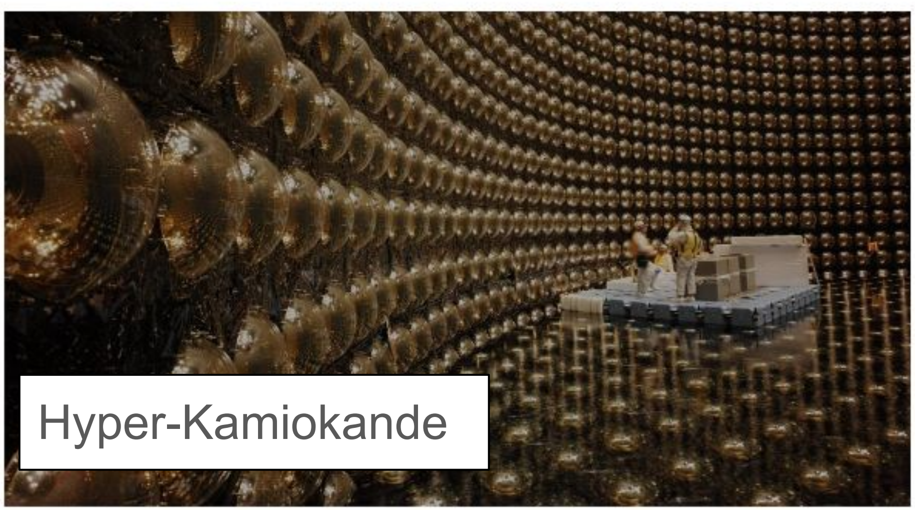
(Seoul National University), April 2025

Example neutrino experiments



Neutrino small cross-section → huge active volume

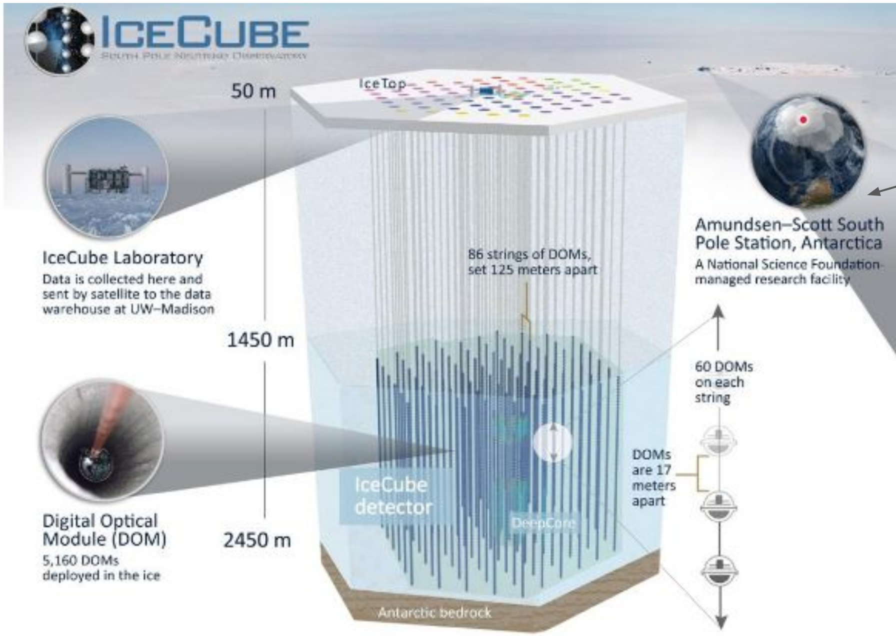
Size of 1 km^3



260 ktons of water

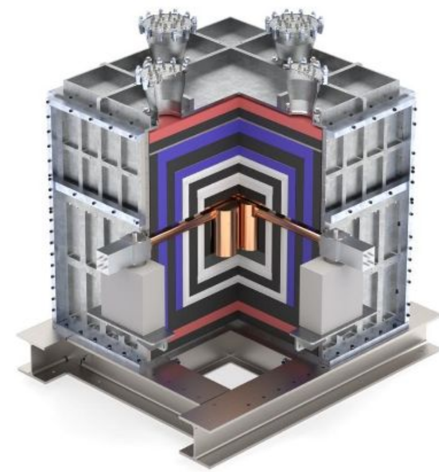
Example neutrino experiments

<u>Neutrino small cross-section → huge active volume</u>

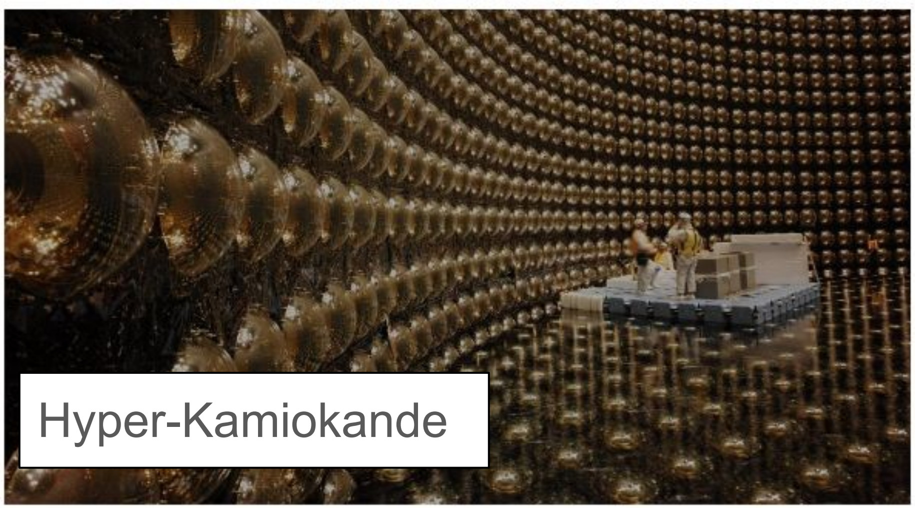


Size of 1 km^3

CONUS+



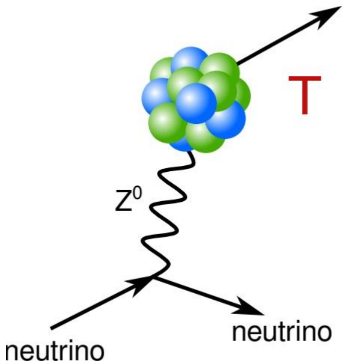
vs.



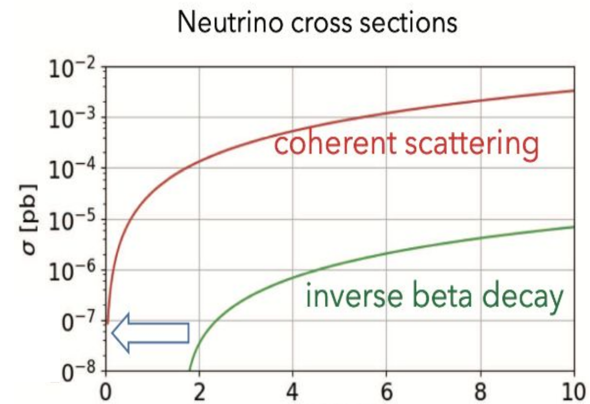
260 ktons of water

1 m^3, 4 kg active mass

Coherent elastic neutrino nucleus scattering



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



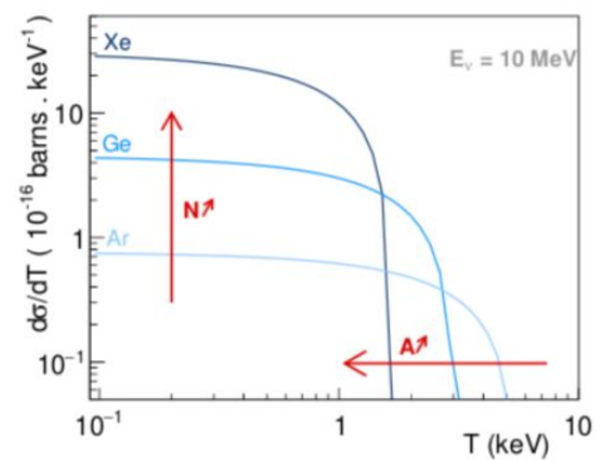
Credit: R. Strauss @ Magnificent CEνNS

Low momentum transfer → full coherence
E_ν< 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:

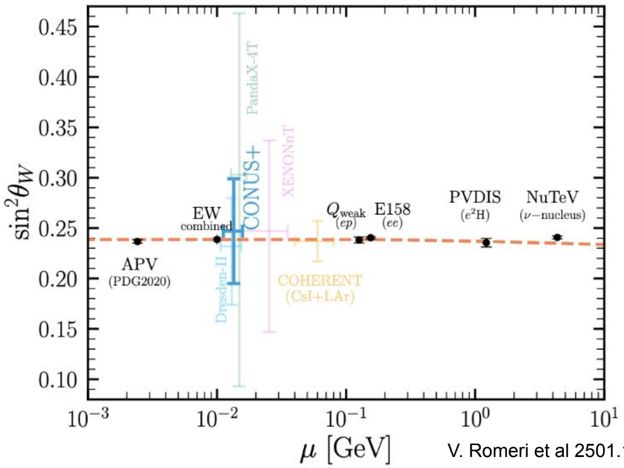
$$T_{Max} \approx \frac{2\,E_\nu^2}{m_n A}$$



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

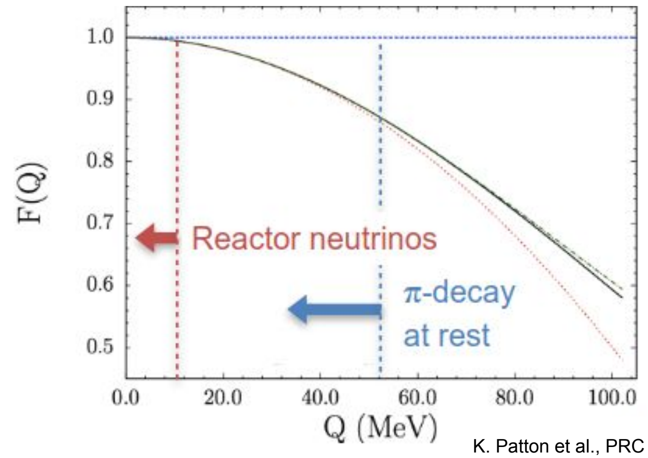
Physics potential

Electroweak precision tests



V. Romeri et al 2501.17843

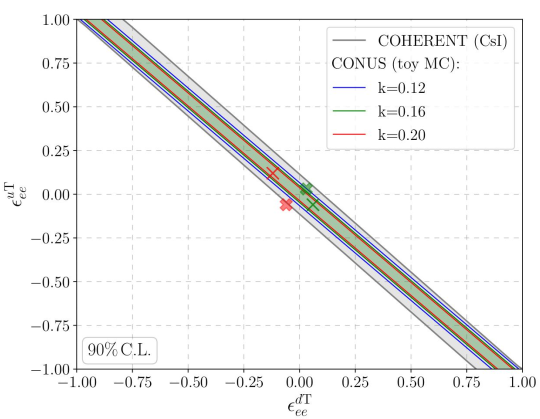
Nuclear physics

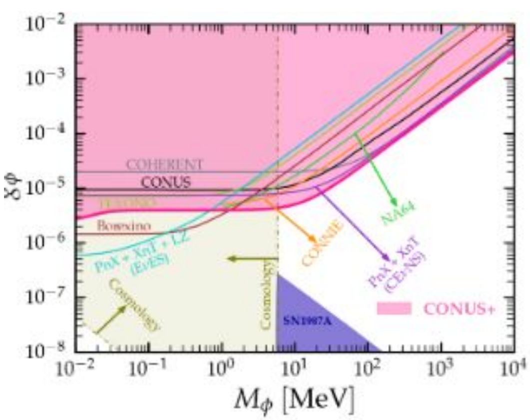


K. Patton et al., PRC 86, 024612 (2012)

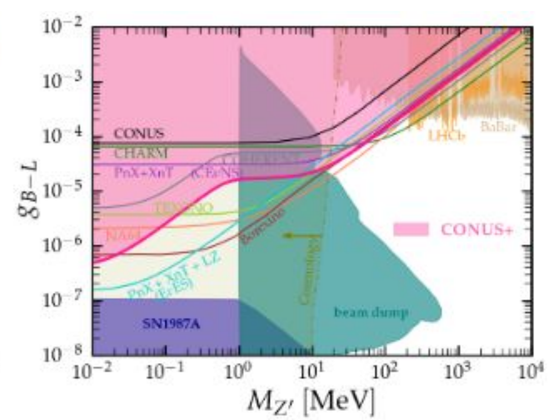
New neutrino interactions

CONUS collaboration JHEP 85 (2022)



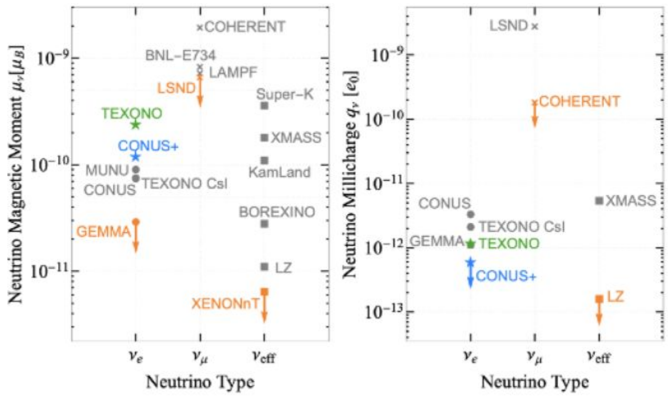


arXiv 2501.12441 (2025)



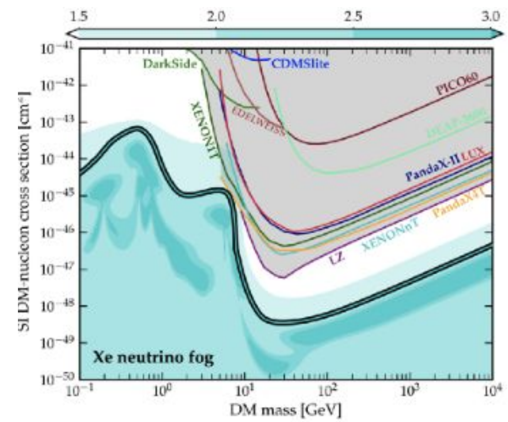
Physics potential

Neutrino electromagnetic properties



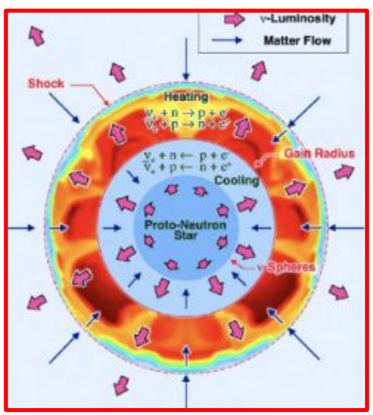
arXiv 2501.18550 (2025)

Dark Matter



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

Astrophysics

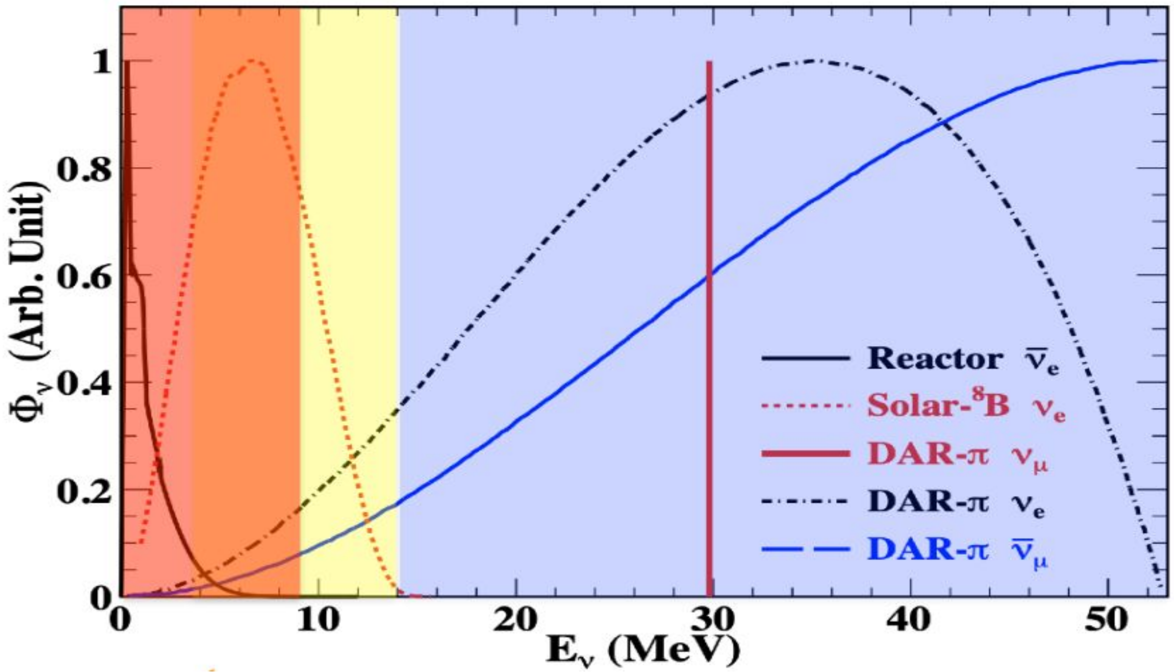


https://science.osti.gov/-/media/ascr/ascac/pdf/meetings/mar03/Mezzacappa.pdf

Daily life applications

Use as Nuclear Safeguard (nonproliferation, storage monitor)

Neutrinos sources



TEXONO, arXiv2502.20007

Coherence ←

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

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

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

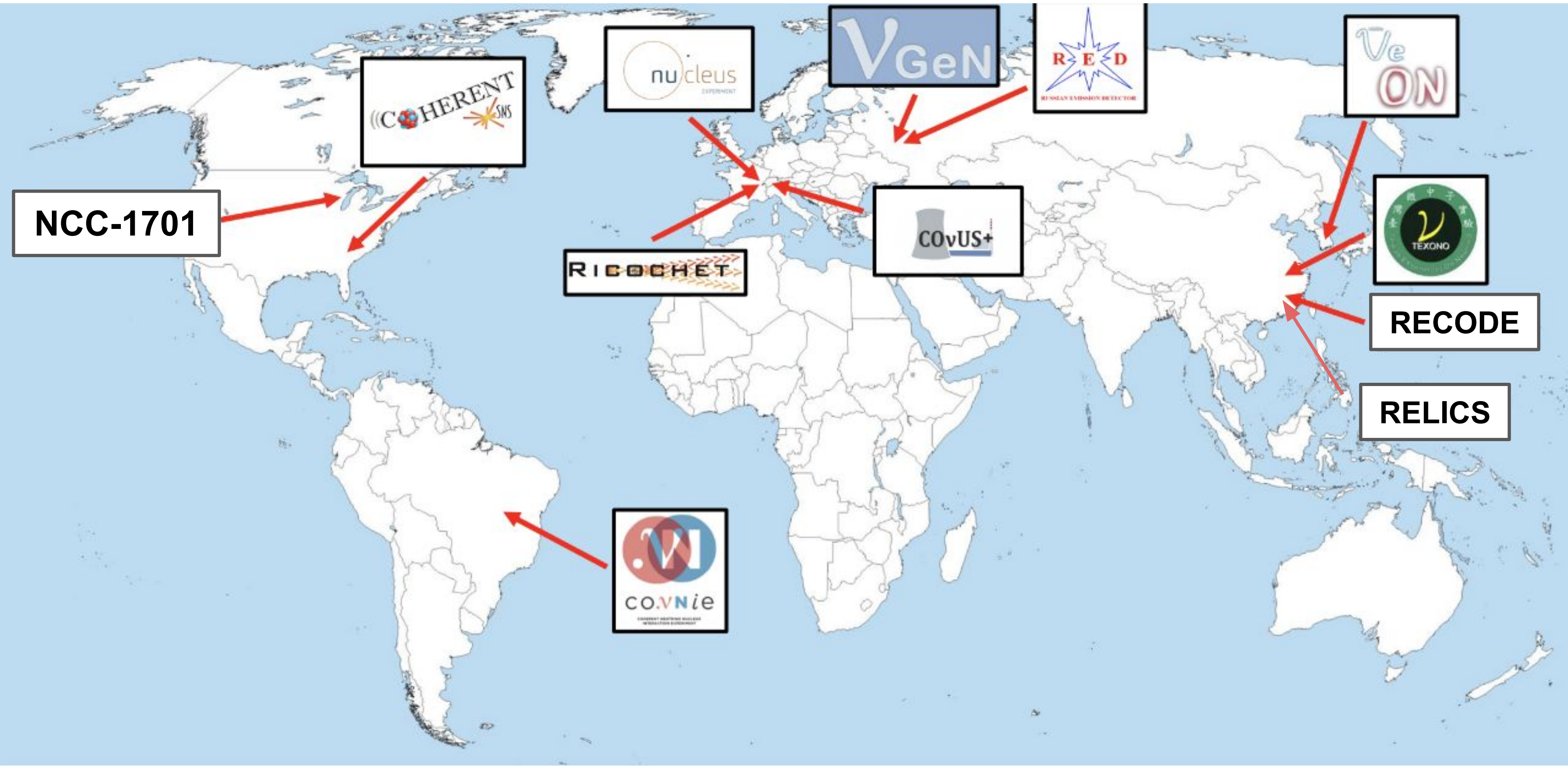
ν from π-DAR. Different neutrino flavors.

E_ν ~ 20-50 MeV (F < 1).

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

Complementary experiments

CEvNS 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, 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)

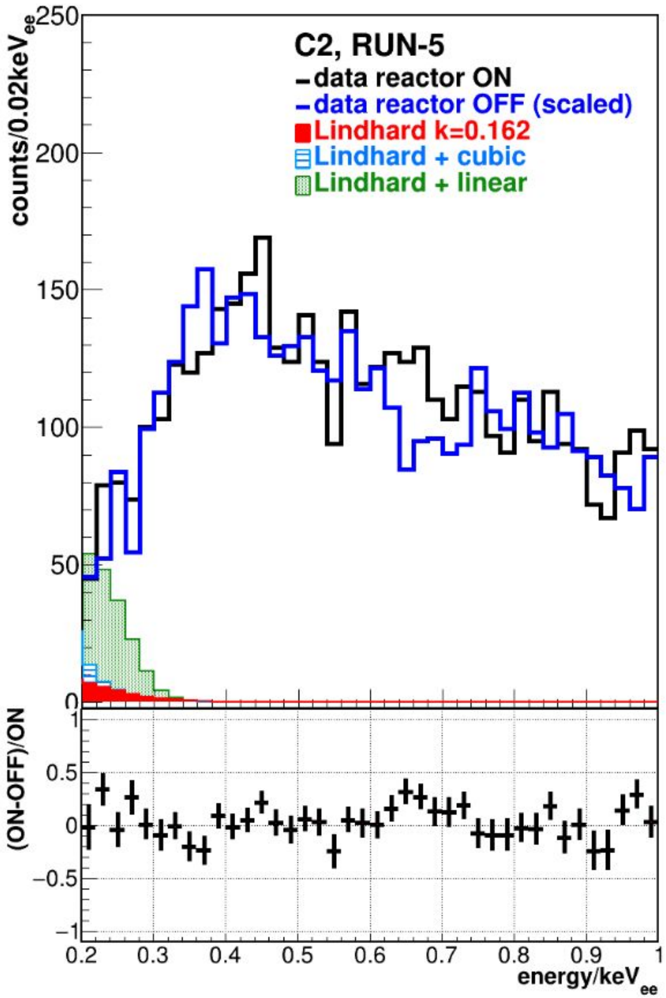
M. Rank, I. Stalder, J. Woenckhaus

Predecessor experiment: CONUS

CONUS detector operated in Brokdorf nuclear power plant (Germany) from 2018 to 2022.

No excess was found. Upper limit factor 1.5 above the SM prediction.

Brokdorf nuclear power plant stopped its operation at the end of 2021.



CONUS, PRL 133 (2024) 251802

CONUS+ location: KKL power plant

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

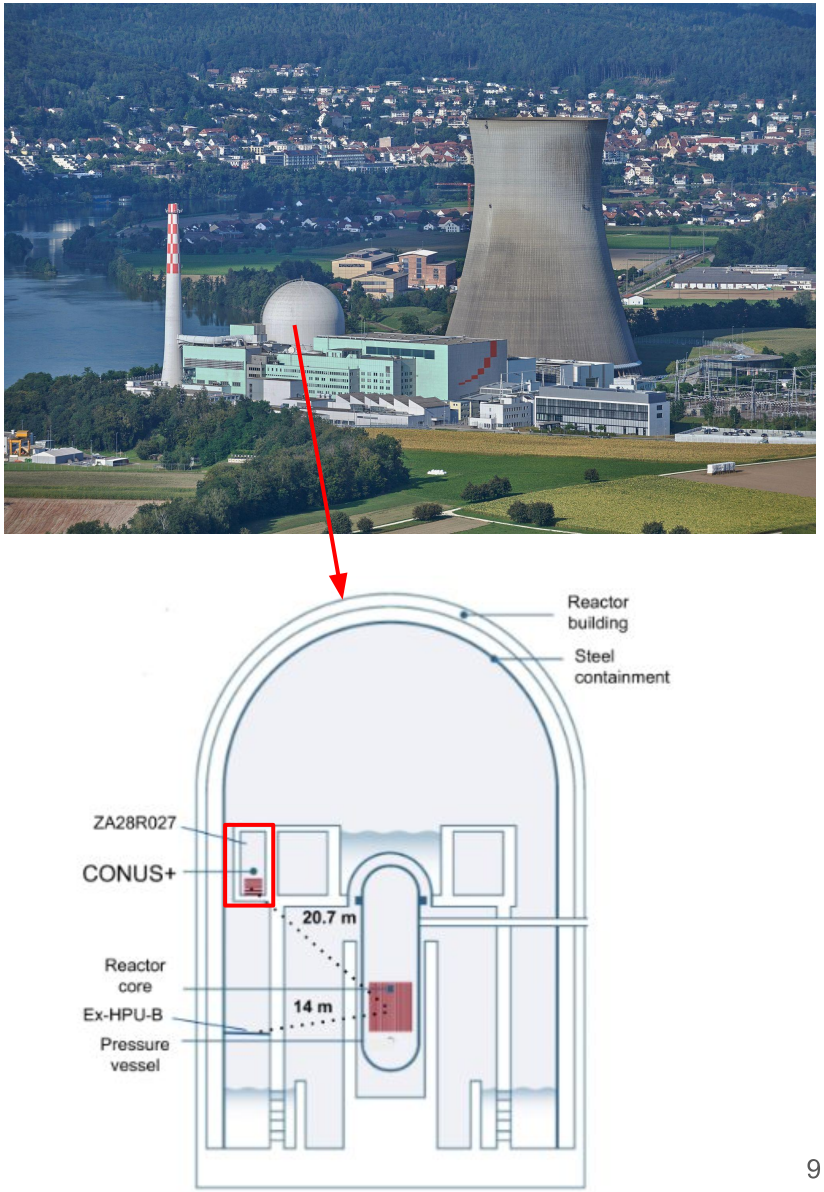
BWR with high duty-cycle: 1 month/year of reactor-off.

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

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

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+ experiment

CONUS, EPJC 84 (2024) 1265

Onion-like shield w/ active and passive layers (increasing radiopurity towards the center).

Small overburden →Two layers of muon veto with 18 independent plastic scintillators.

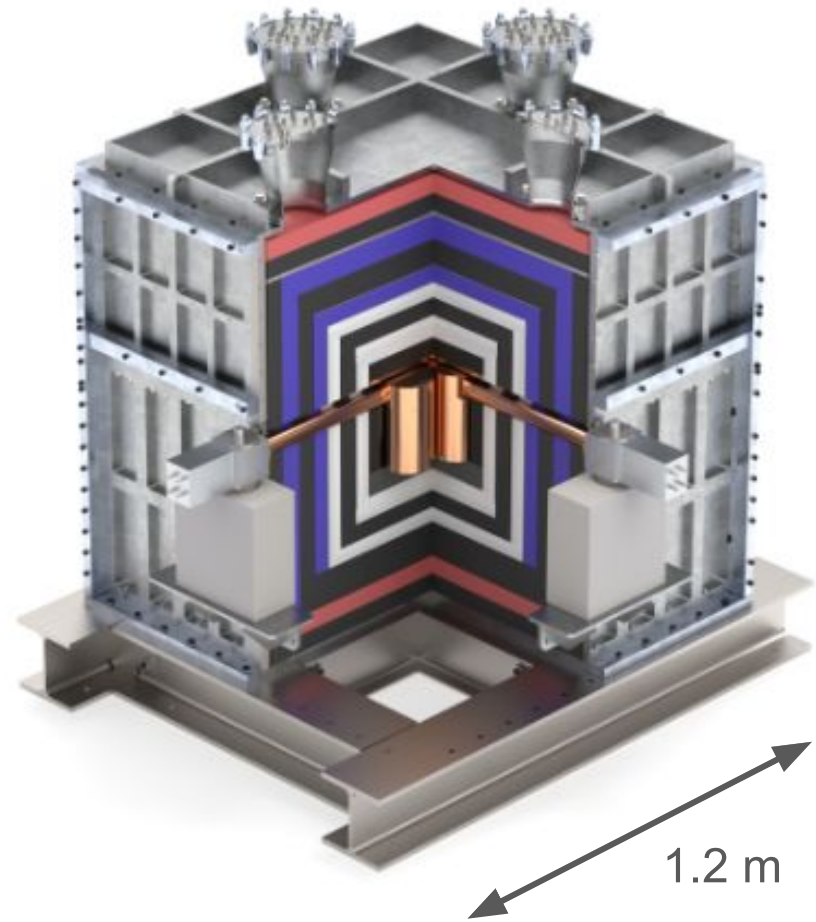
4 lead layers for ɣ suppression (20 cm).

Several PE and borated PE layers for neutron suppression.

Flushing of detector chamber with radon-free air.

Total detector weight < 10 tons.

<u>Total background reduction by 4 orders of magnitude!!</u>



CONUS+ HPGe detectors

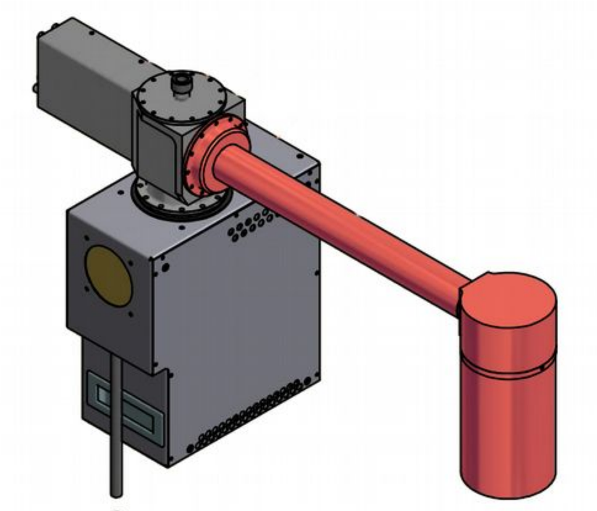
4 p-type point contact HPGe with total crystal/active mass: 4 kg /3.74kg as target.

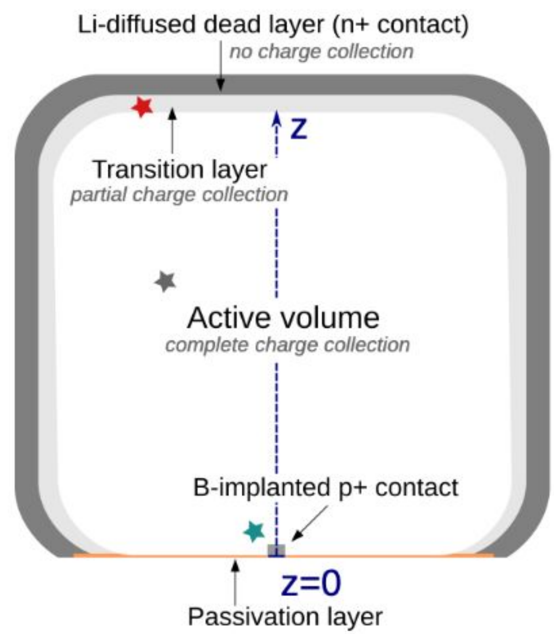
Ultra-radiopure materials.

Ge crystals refurbished from CONUS with reduced point-contact size and new front-end electronics.

Energy resolution and trigger efficiency improved. Energy threshold 160 eV achieved.

Liquid-cooling system to reduce vibration and mircrophonic noise.





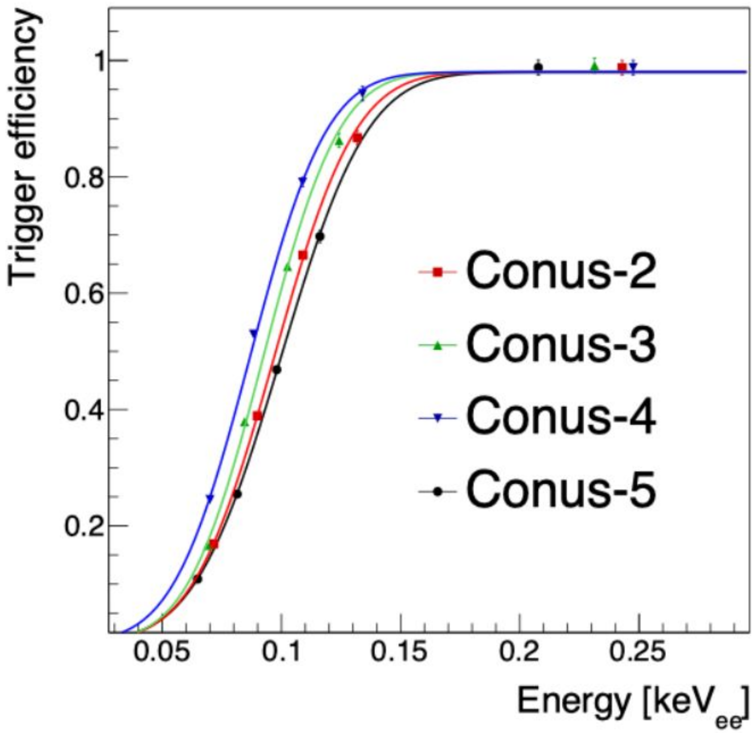
Trigger efficiency

Probability that a physics signal event in detected by the DAQ. Measured with signal generator.

Described by:

$$\varepsilon_{trig} = 0.5 \cdot \left(1 + \mathrm{erf}\left(\frac{E_{ee}/eV_{ee} - t_1}{t_2}\right)\right)$$

Stability of the t_1 and t_2 parameters at the eV level.



	C4 before refurb.	C4 after refurb.
100% down to	~500 eV_{ee}	~160 eV_{ee}
50% at	~300 eV_{ee}	~90 eV_{ee}
20% at	~210 eV_{ee}	~70 eV_{ee}

Energy resolution

The energy resolution is described by:

$$\sigma^2_{res} = F\, E_{dep}\, \epsilon + \sigma^2_{noise}$$

Fano factor

energy creation
electron-hole pair in Ge

related to the electronics

The other terms are negligible. The σ_{noise} is determined through the injection of pulses.

Additionally, determine with noise peak width and resolution extrapolation from physical lines. <u>All values agreed.</u>

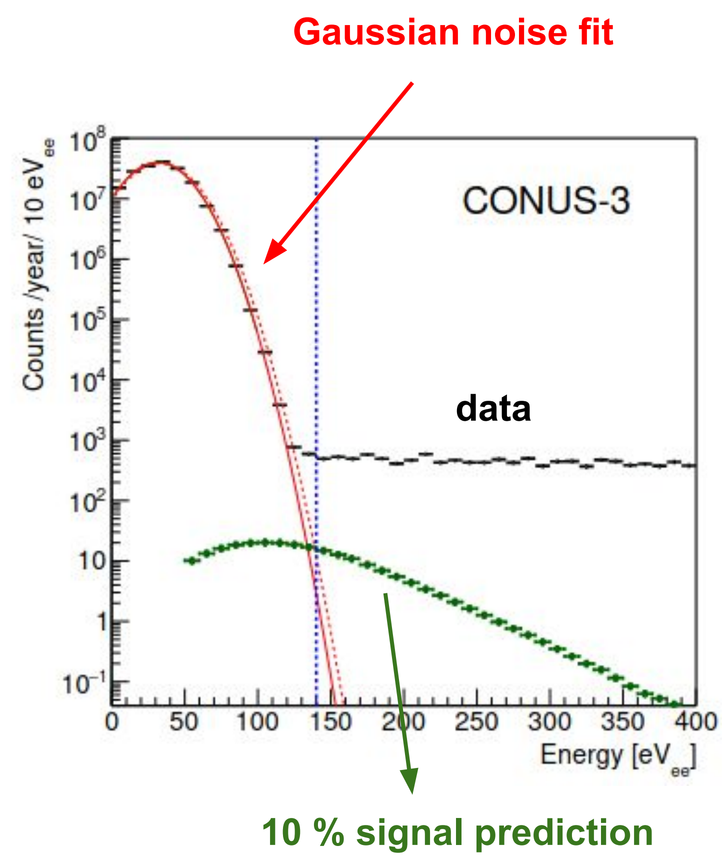
Detector	Pulser resolution FWHM before refub. [eV_{ee}]	Pulser resolution FWHM after refub. [eV_{ee}]
C5	85	47
C2	77	48
C3	64	47
C4	68	47

Energy threshold

Energy threshold defined independently for each detector. Two conditions:

- Trigger efficiency over 20% (down to 70 eV_{ee}).
- Noise peak contribution below 10% expected CEvNS signal.

Detector	Threshold [eV_{ee}]
C5	170
C2	180
C3	160
C4	–

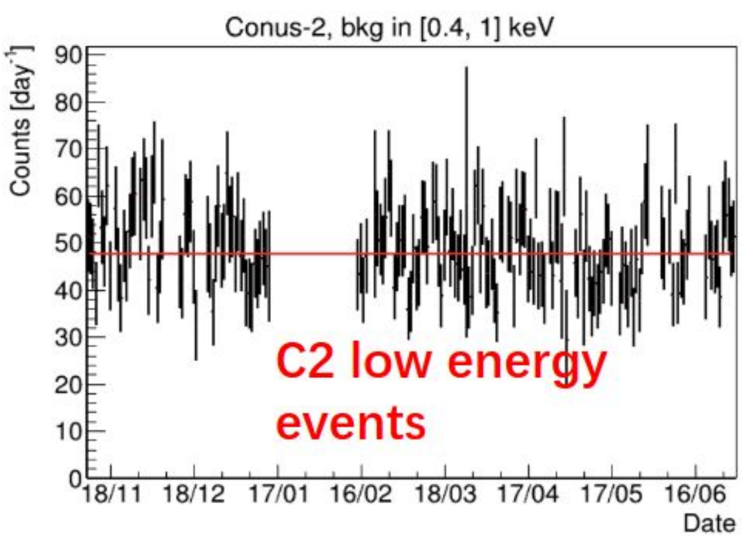


Stability during Run1

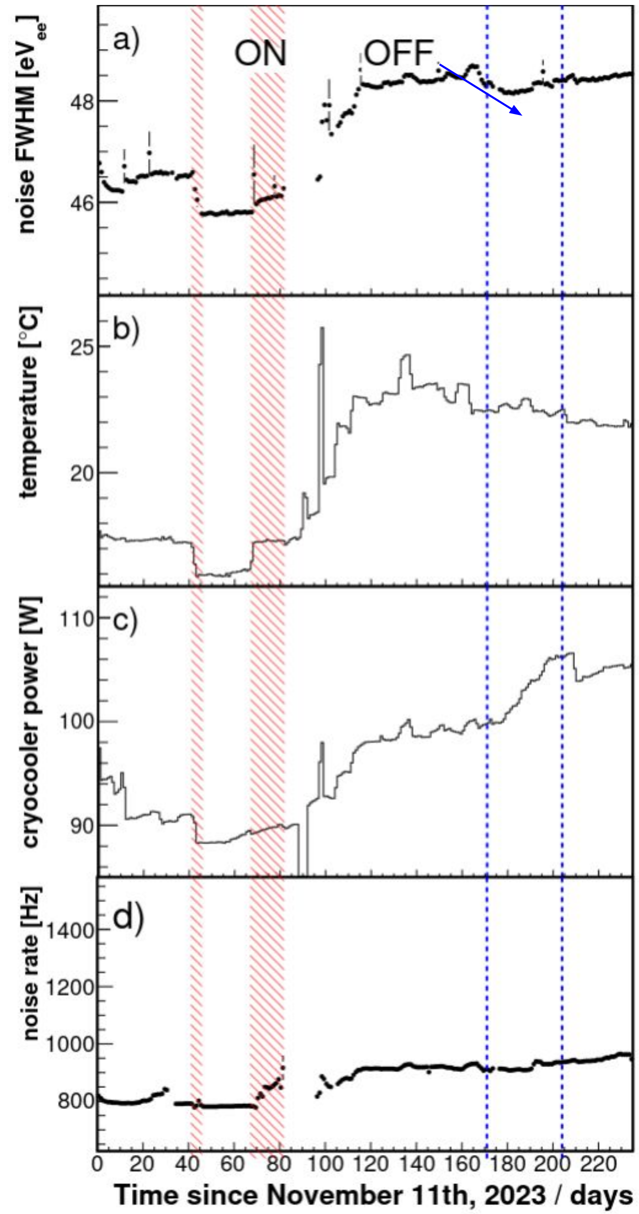
Good stability reached during the data taking.

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.

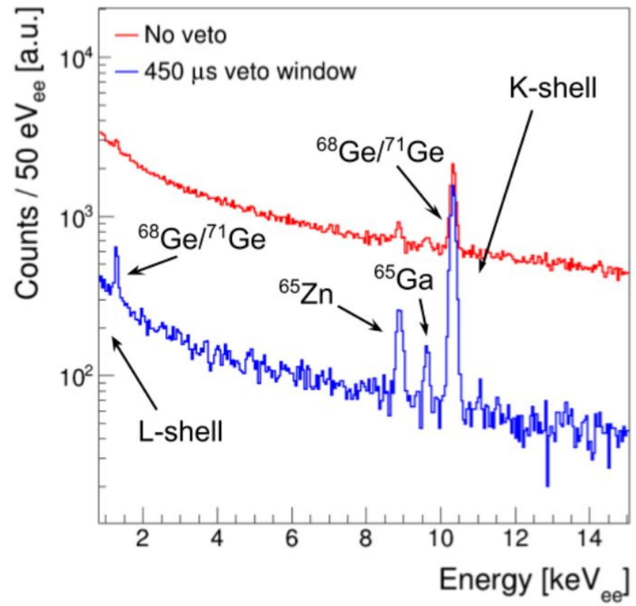
Irradiation with a ^{252}Cf source at the end of the physics run to increase statistics in these lines. Energy calibration uncertainty below 5 eV achieved.

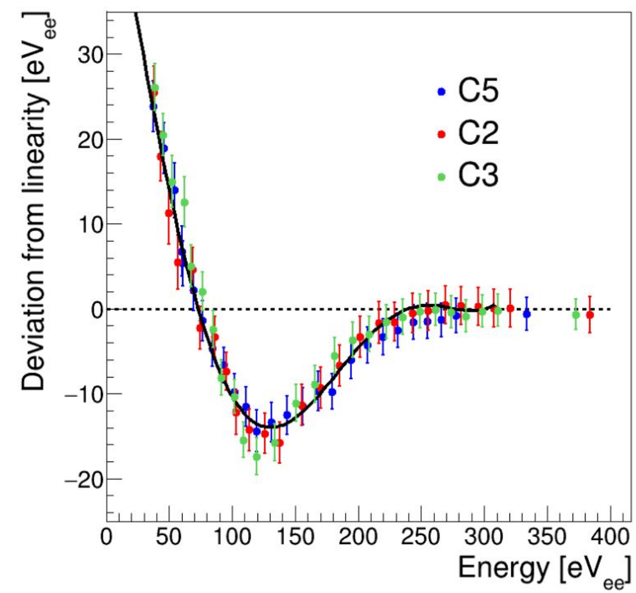
Energy calibration at high energy with ^{228}Th source and Ge metastable states.

Stability energy scale below 2% variations.

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

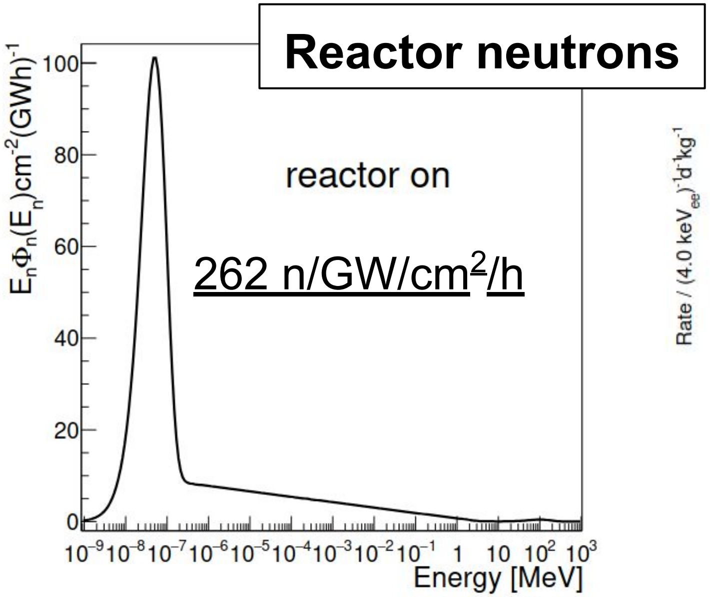
Estimated with pulser scan from 2 keV down to few eV. Maximum deviation from linearity 15 eV.

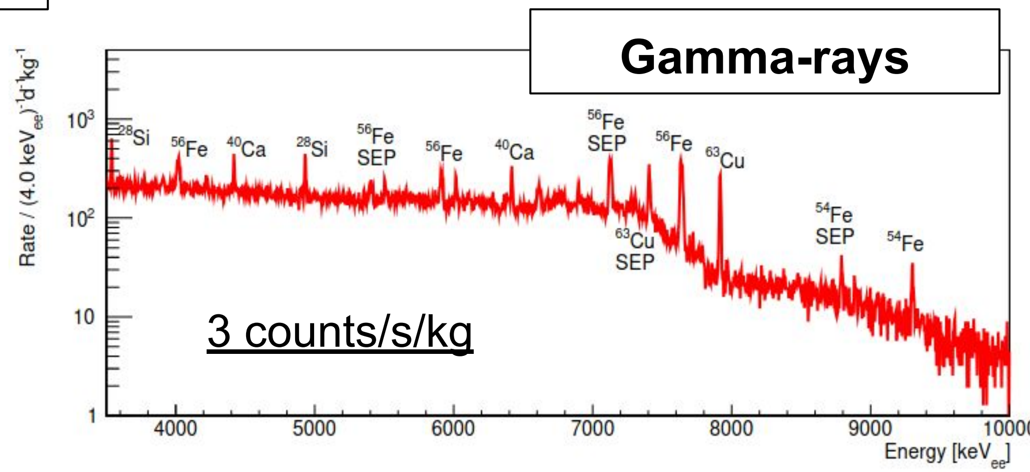


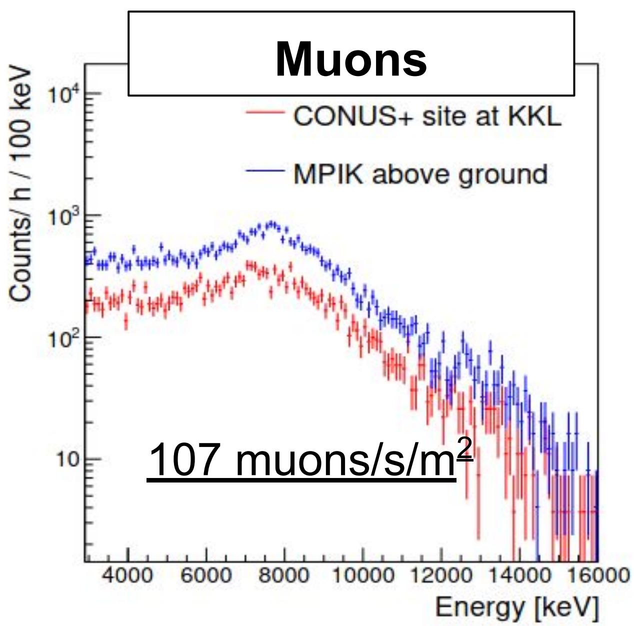


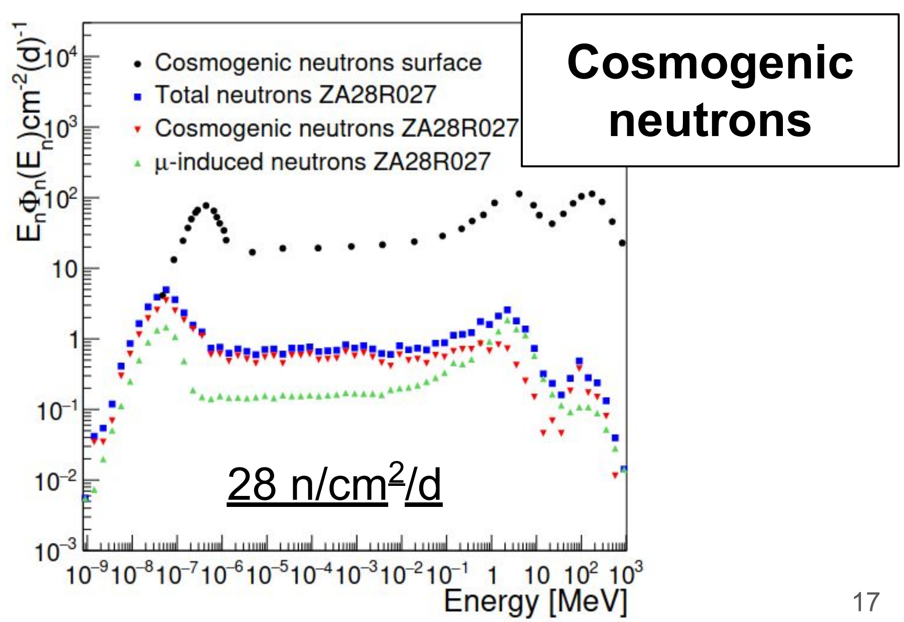
Background characterization

CONUS, arXiv 2412.13707 (2024)





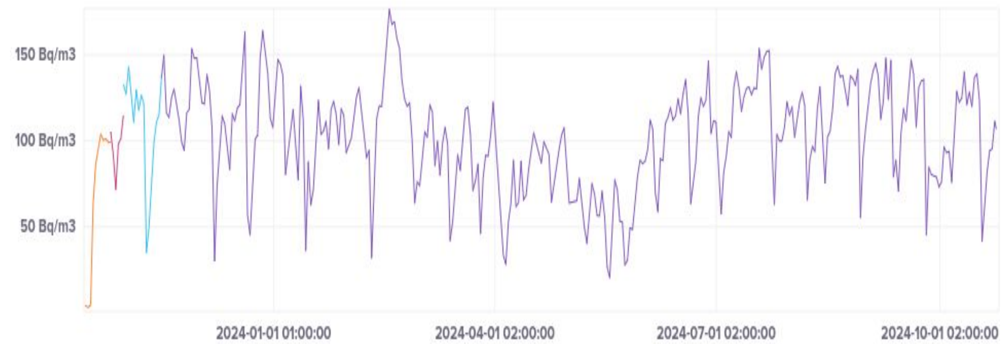


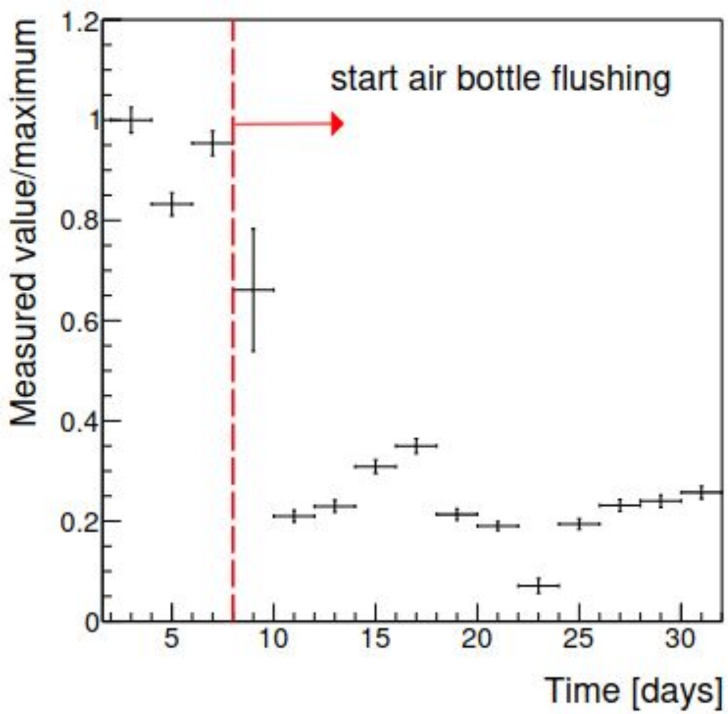


CONUS+ background: Radon

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

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



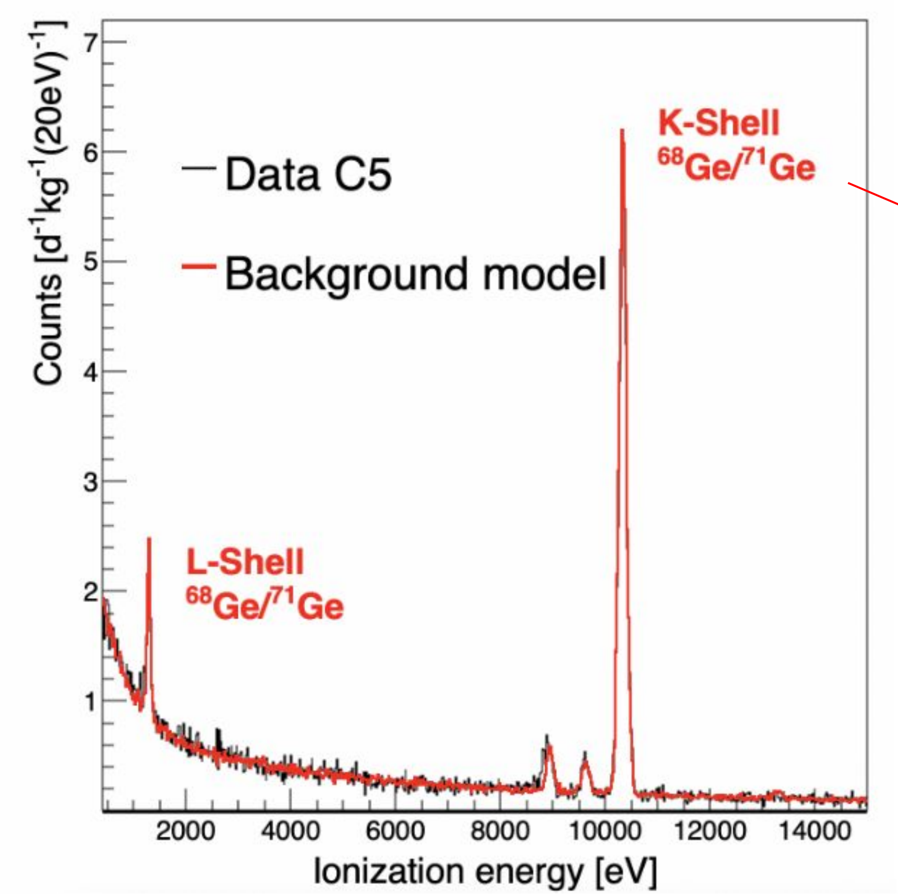


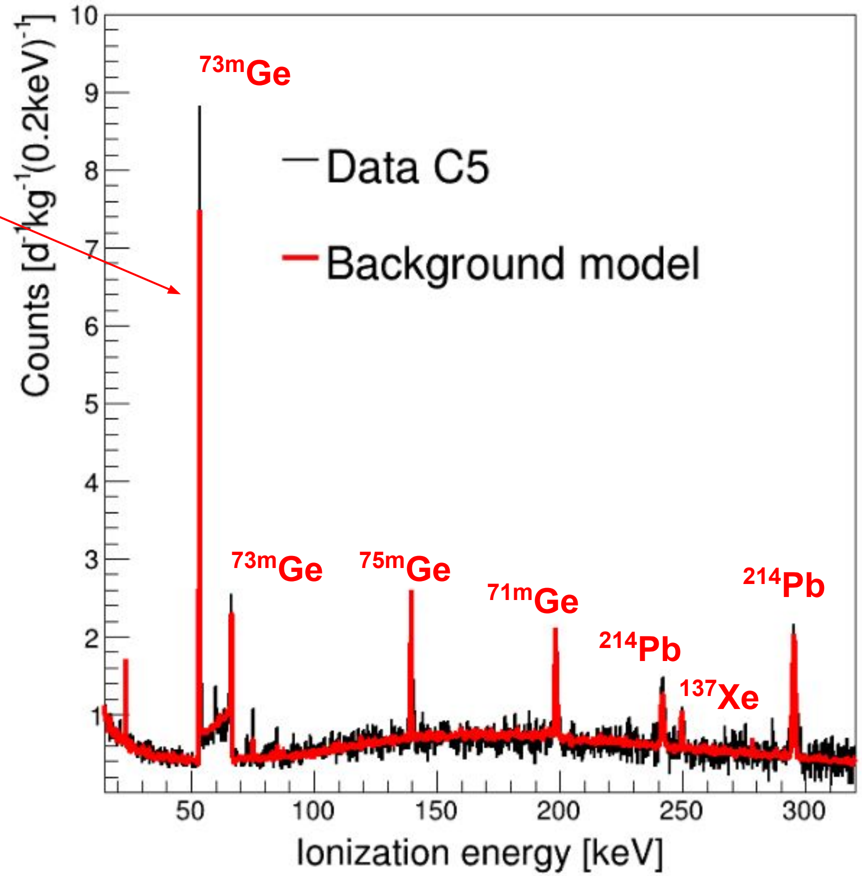
Radon concentration average value of [30,190] Bq/m^3.

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.

Full background model





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

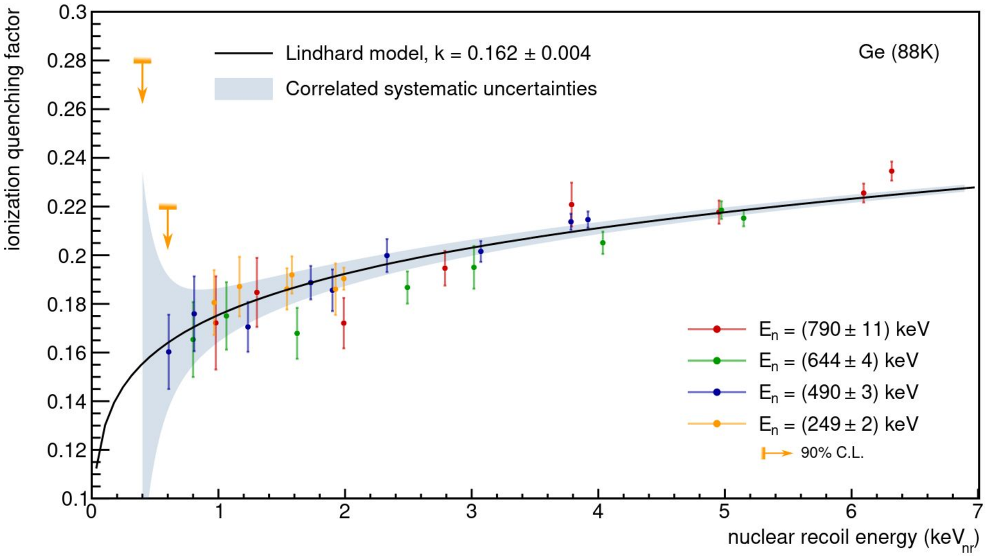
Full background understanding above CEνNS energy region!!

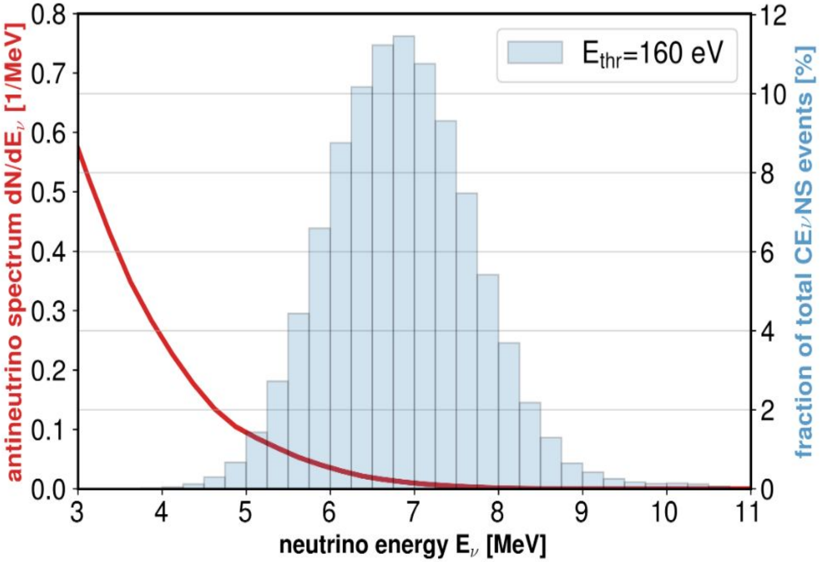
Signal prediction

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)

Likelihood analysis

Fit reactor ON/OFF spectrum on all 3 detectors simultaneously. Two independent analysis.

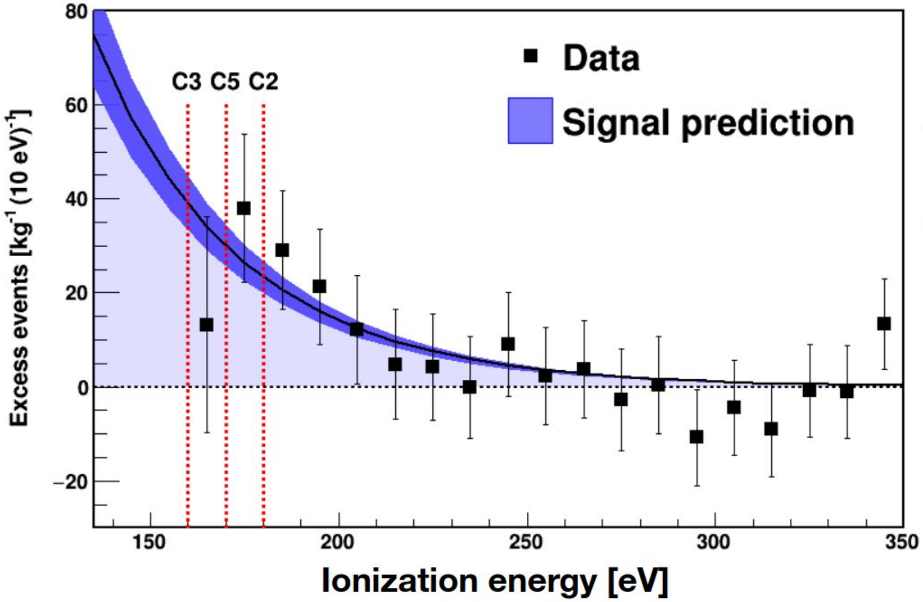
Inputs: Data, background model, predicted signal spectrum, trigger efficiency, detector resolution, active volume and neutrino flux at CONUS+ location

Region of interest from energy threshold (160-180 eV_{ee}) up to 800 eV_{ee}

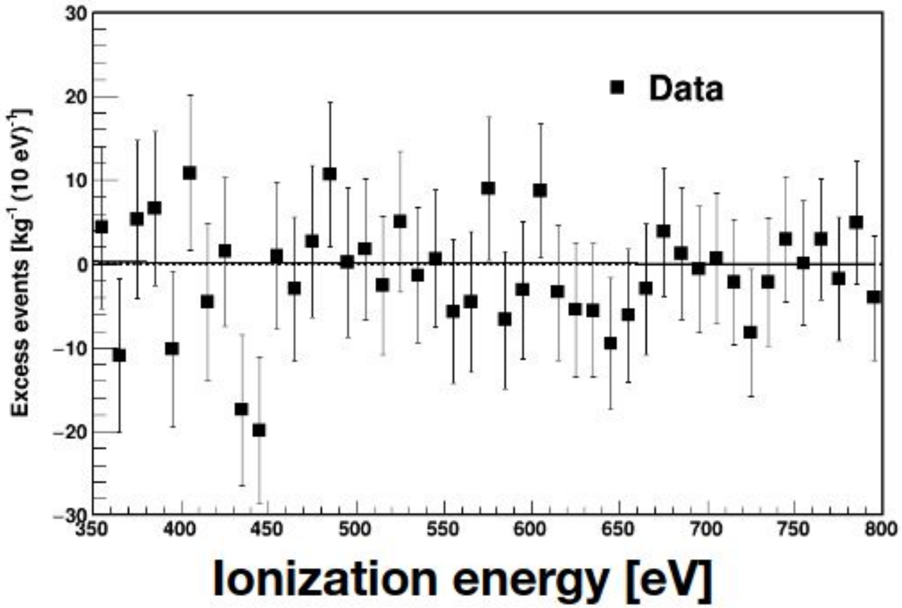
Parameter	Number of parameters per detector	Pull terms?
Signal strength s	1	No
Neutrino flux	1	Yes
Background scaling b	1	Yes
Trigger efficiency	2	Yes
Quenching uncertainty	4	Yes
Energy calibration uncertainty	1	Yes

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, arXiv 2501.05206 (2025)

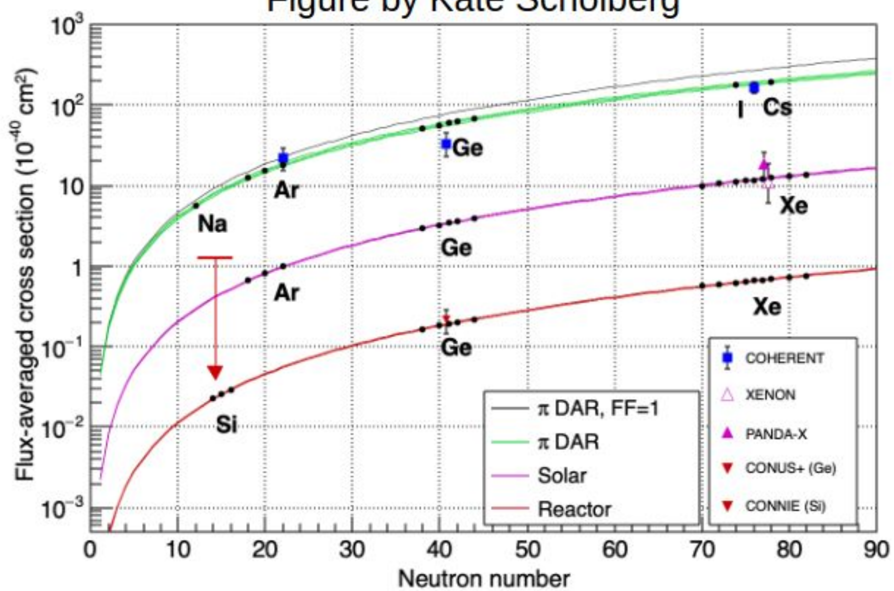
Comparison other experiments

Source	Target	ν energy [MeV]	flux [$\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	data	data/SM prediction
Accelerator [37]	Cs	$\sim 10-50$	$5{\cdot}10^7$	306 ± 20	0.90 ± 0.15
Accelerator [3]	Ar	$\sim 10-50$	$2{\cdot}10^7$	140 ± 40	1.22 ± 0.37
Accelerator [38]	Ge	$\sim 10-50$	$5{\cdot}10^7$	21 ± 7	0.59 ± 0.21
Sun [24]	Xe	< 15	$5{\cdot}10^6$	11 ± 4	0.90 ± 0.45
Sun [25]	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



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

Future (short term) plans

How can we improve our result?

Reduce uncertainty over energy scale and non-linearity effects:

- Measure M-shell from ^{71}Ge (X-rays at ~160 eV_{ee}). Currently working in neutron irradiation at MPIK.
- Optimize event reconstruction at low energies.

Reduce background and improve knowledge about it:

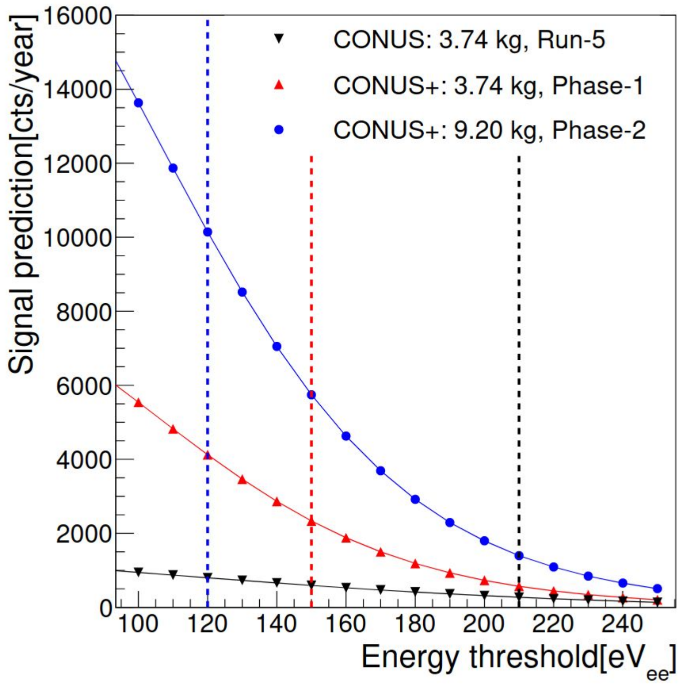
- Use pulse shape information to reject multi scattering and surface events.
- Additional measurements for environmental background conditions at KKL.

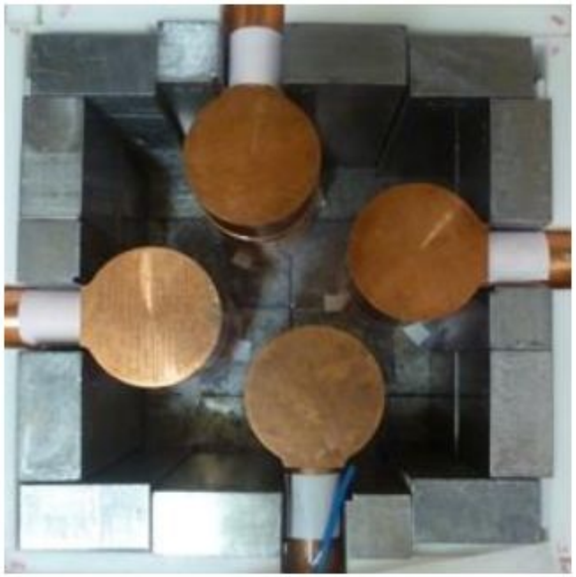
CONUS+ phase 2

3 new 2.45 kg detectors → total mass 8.4 kg.

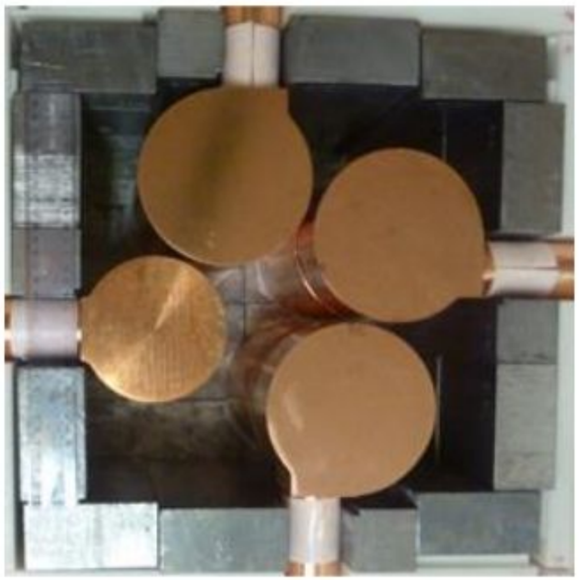
Threshold at least as low as in previous run.
Better background and improved stability.

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





Nov 2024



Summary

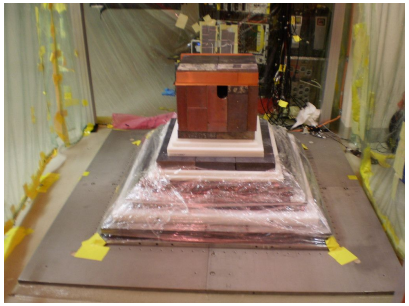
- High cross-section of CEvNS ==> compact neutrino detectors
- CONUS+: HPGe detectors at 20.7 m from reactor core
- Mainly cosmic background events: reactor power uncorrelated!
- First CEνNS detection at nuclear reactor (null hypothesis rejected at 3.7 sigma C.L.)
- Result consistent with theoretical models and predictions
- Run-2 with increased mass has started. Additional measurement to reduce systematic uncertainties under preparation.

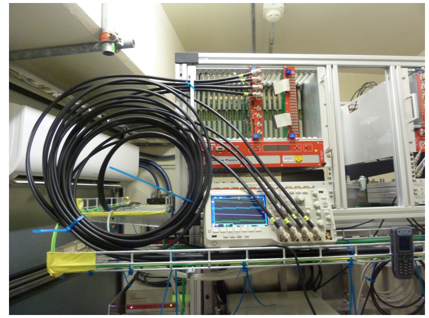
Thank you for your attention!

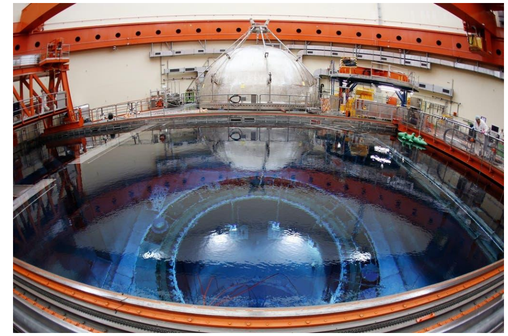
COνUS+

esanchez@mpi-hd.mpg.de

From CONUS to CONUS+







Dec.2022
KBR HPGE detector extraction and refurbishment

Apr.2023
KBR dismantling. KKL onsite preparation

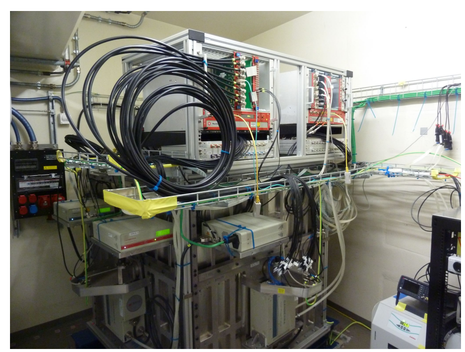
Jul.2023
Installation campaign at KKL

Sep.2023
Commissioning at KKL

Nov.2023
Start first physics run (Run1)

May.2024
First reactor-off data

Jan.2025
CEνNS result from Run1



First observation of reactor antineutrinos by coherent scattering

N. Ackermann[1], H. Bonet[1], A. Bonhomme[1,a], C. Buck[1], K. Fülber[2], J. Hakenmüller[1,b], J. Hempfling[1], G. Heusser[1], M. Lindner[1], W. Maneschg[1], K. Ni[1], M. Rank[3], T. Rink[1,c], E. Sánchez García[1], I. Stalder[3], H. Strecker[1], R. Wink[2], J. Woenckhaus[3,d]

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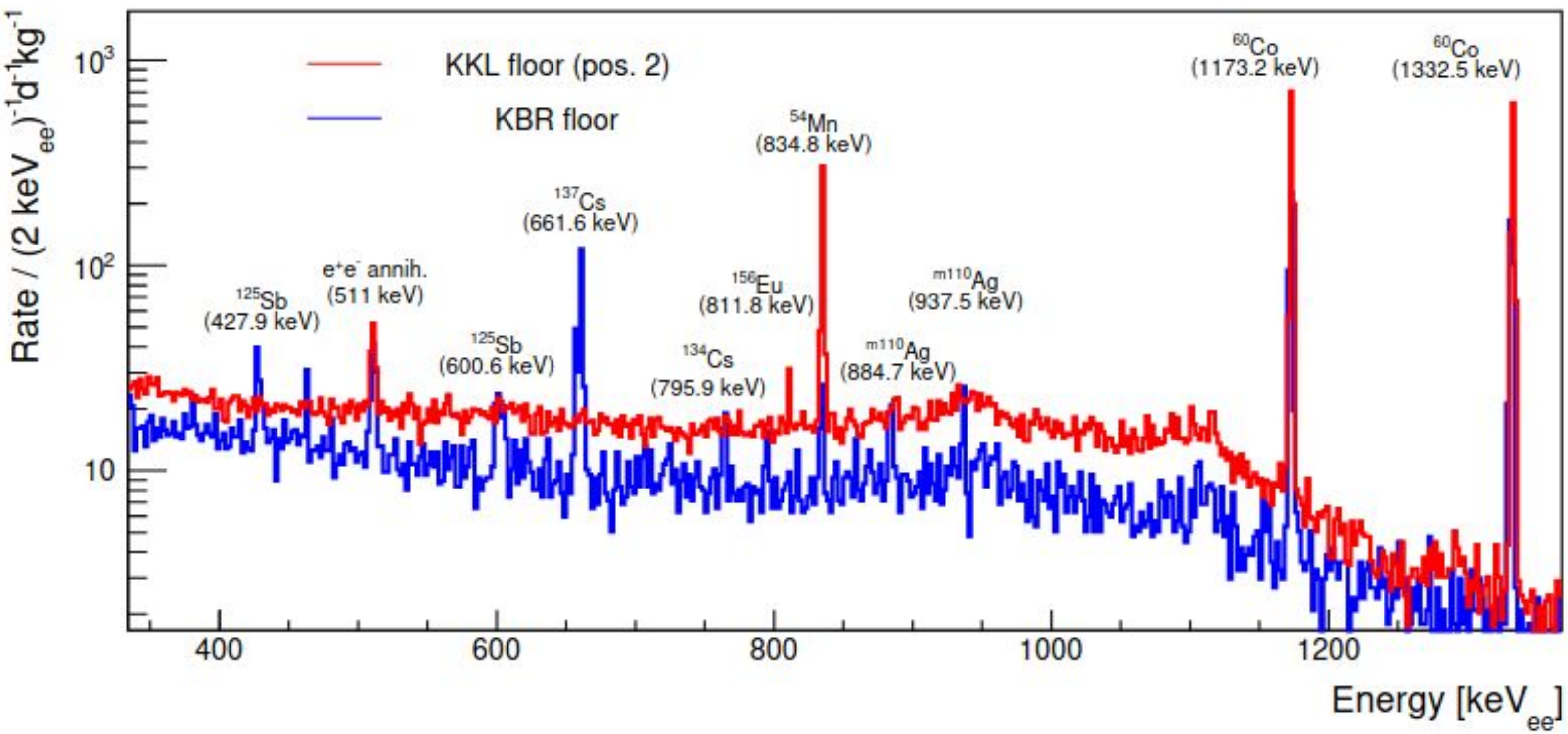
Abstract

Neutrinos are elementary particles that interact only very weakly with matter. Neutrino experiments are therefore usually big, with masses on the multi-ton scale. The thresholdless interaction of coherent elastic scattering of neutrinos on atomic nuclei leads to drastically enhanced interaction rates, that allows for much smaller detectors. The study of this process gives insights into physics beyond the Standard Model of particle physics. The CONUS+ experiment was designed to first detect elastic neutrino-nucleus scattering in the fully coherent regime with low-energy neutrinos produced in nuclear reactors. For this purpose, semiconductor detectors based on high-purity germanium crystals with extremely low energy threshold of 160−180 eV were developed. Here we show the first observation of a neutrino signal with a statistical significance of 3.7 sigma from the CONUS+ experiment, operated at the nuclear power plant in Leibstadt, Switzerland. In 119 days of reactor operation (395±106) neutrinos were measured compared to a predicted number from calculations assuming standard model physics of (347±59) events. The good agreement between data and prediction constrains

1

Surface contamination

- Larger surface contamination respect to KBR. e.g. ^{60}Co 300 vs 1200 cts/day/kg.
- Wipe test from “hot spot” will increase CONUS+ background by 5 times.
- <u>Strict cleaning protocols mandatory during installation.</u>

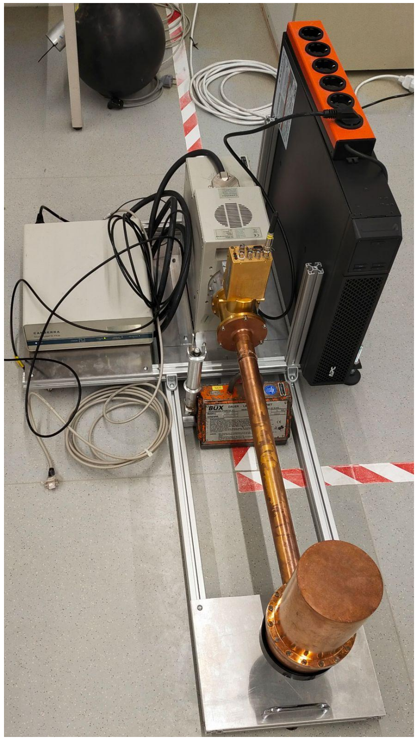


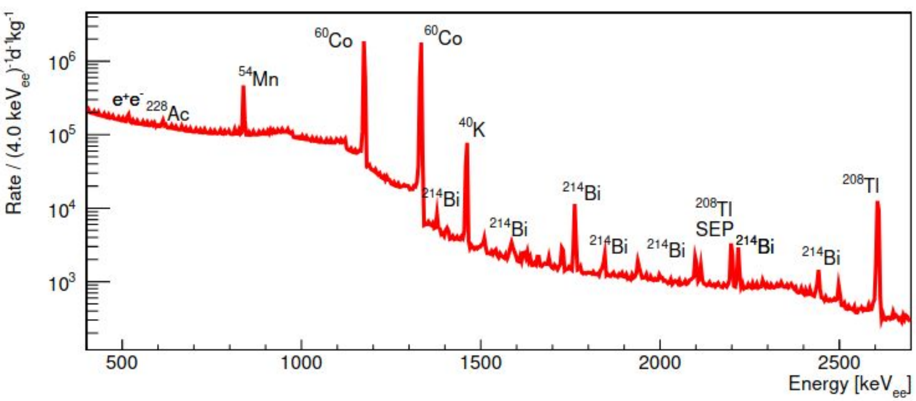
CONUS+ background: γ's

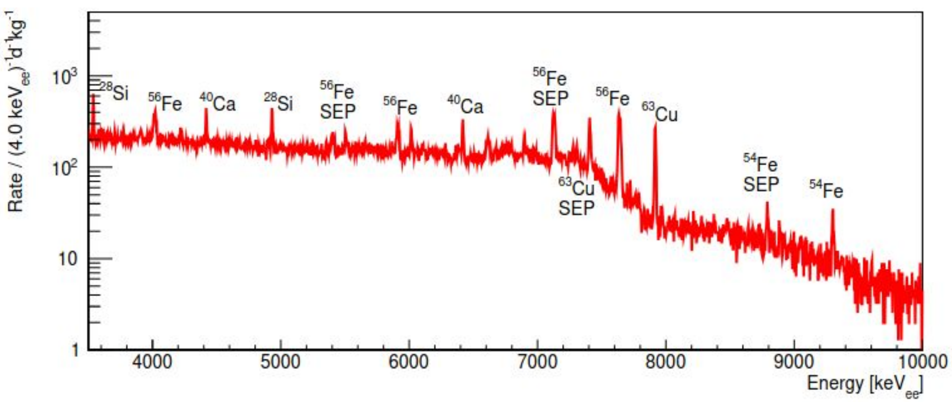
Ultra-low background p-type coaxial HPGe detector CONRAD (m =2.2 kg). Electrical cryocooling system.

Scan over different positions with measurement from few hours to one day.

High energy gamma contribution (>2.7 MeV) factor 25 smaller than at Brokdorf power plant. Stronger contribution of ^{60}Co lines.







CONUS+ background: γ's

- Lines produced by ^{16}N strongly reduced compared to KBR. Larger distance to reactor cooling system.

- Lines from ^{28}Si and ^{40}Ca visible at KKL. Portland cement with high content of these isotopes.

- Larger contribution from ^{56}Fe at KKL. Larger neutron fluence and more material.

- Larger contribution of ^{63}Cu from CONRAD cryostat. Larger neutron fluence at KKL.

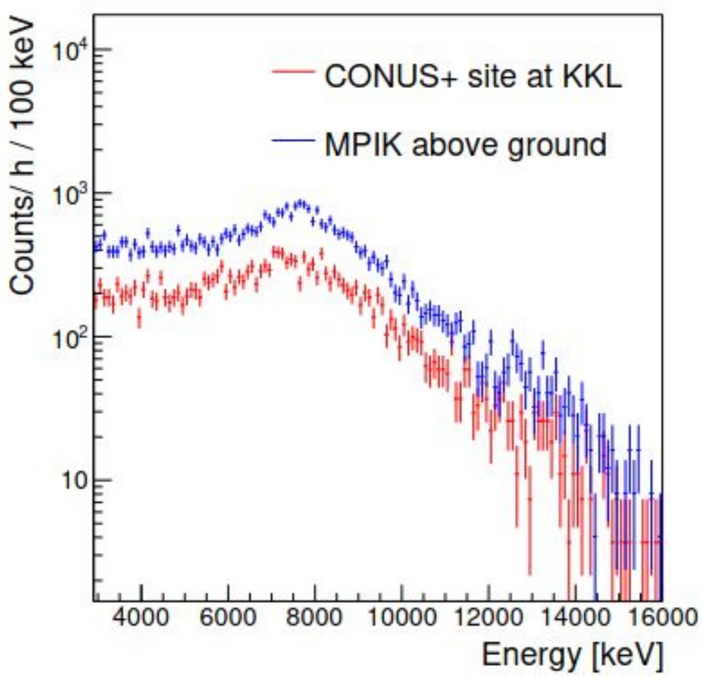
PC / Energy [keV_{ee}] /BR[%]	KKL: Ex-HPU-B	KKL: ZA28R027	KBR: ZA408
$^{54}Fe(n,\gamma)^{55}Fe$	(reactor structure)		
8787 SEP	573±45	18.5±1.5	5.1±0.8
8886 (18.6%)	98.1±7.7	not visible	not visible
9298 (100%)	707±56	19.7±1.6	5.9±0.9
$^{56}Fe(n,\gamma)^{57}Fe$	(reactor structure)		
4217 (23.3%)	1896±149	78.5±6.2	not visible
5920 (33.1%)	2504±190	95.1±7.5	not visible
6018 (34.1%)	2787±220	98.0±7.4	not visible
7120 SEP	6974±596*	285±23*	not visible
7135 SEP	double peak	double peak	double peak
7279 (20.7%)	1544±122	80.5±6.4	6.1±0.9
7631 (100%)	8717±735*	363±29*	72±11*
7646 (86.2%)	double peak	double peak	double peak
$^{63}Cu(n,\gamma)^{64}Cu$	(HPGe cryostat)		
7406 SEP	1992±157	228±18	14.3±2.1
7638 (48.9%)	995±79*	120±9*	8.3±1.2*
7916 (100%)	2034±161	245±19	15.6±2.3
$^{28}Si(n,\gamma)^{29}Si$	(concrete CONUS+ room)		
3539 (100%)	not visible	276±22	not visible
4934 (93.3%)	not visible	213±17	not visible
6380 (16.0%)	not visible	19.9±1.6	not visible
7199 (10.0%)	not visible	6.8±0.5	not visible
$^{40}Ca(n,\gamma)^{41}Ca$	(concrete CONUS+ room)		
4419 (19.3%)	not visible	105±8	not visible
6421 (49.15%)	not visible	181±14	not visible
^{16}N	(reactor cooling system)		
5617 SEP	7143±564	not visible	26301±3945
6128 (67%)	12652±998	not visible	44782±6774
7115 (4.9%)	2526±199	not visible	5314±797

CONUS+ background: Cosmic muons

Liquid scintillator cell filled with 120 ml of “Ultima Gold”. PMT for light detection.

Measurements at MPIK and KKL during off time for comparison.

Pulse shape discrimination cut to remove neutrons.



Energy cut at 3 MeV to avoid environmental radioactivity. Reactor OFF to avoid high energy ɣ contribution.

<u>Muon rate surface: 200±5 counts/s/m^2.</u>

<u>Muon rate ZA28R027: 107±3 counts/s/m^2.</u>

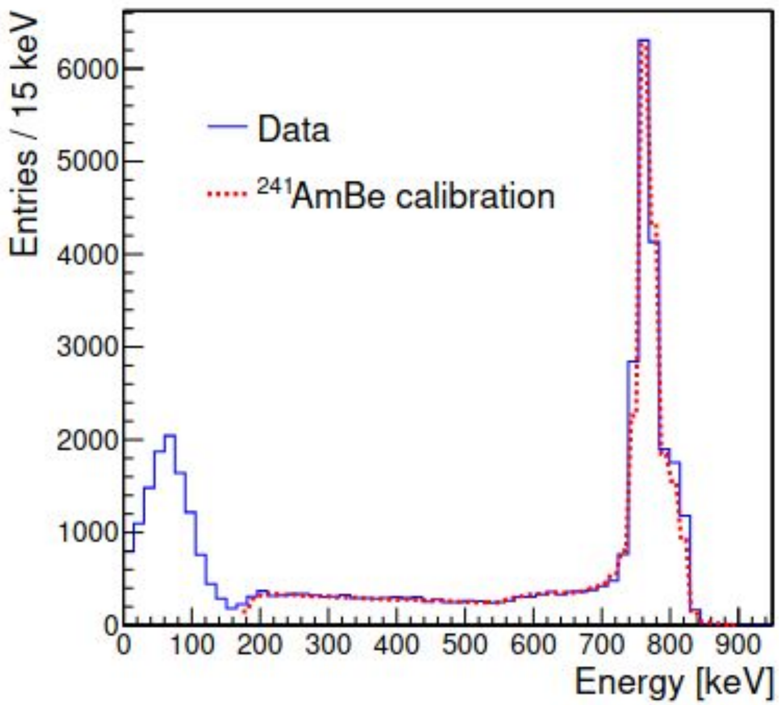
Reduction factor of 1.9 in KKL compared to surface → overburden 7.4 m w.e.

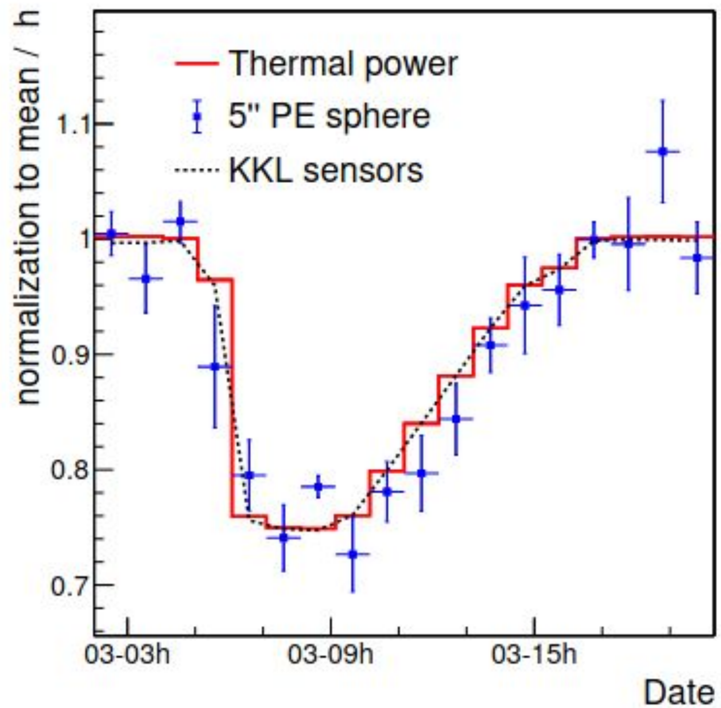
Impact reactor drywell head 0.25 m w.e.

CONUS+ background: Reactor neutrons

$$n + {}^3\text{He} \rightarrow {}^3\text{H} + p + Q, \quad \text{with } Q=764 \text{ keV}.$$

- Monitoring neutron rate with 5” PE sphere. Correlation with thermal power. Most neutrons in the room are produced by the reactor.





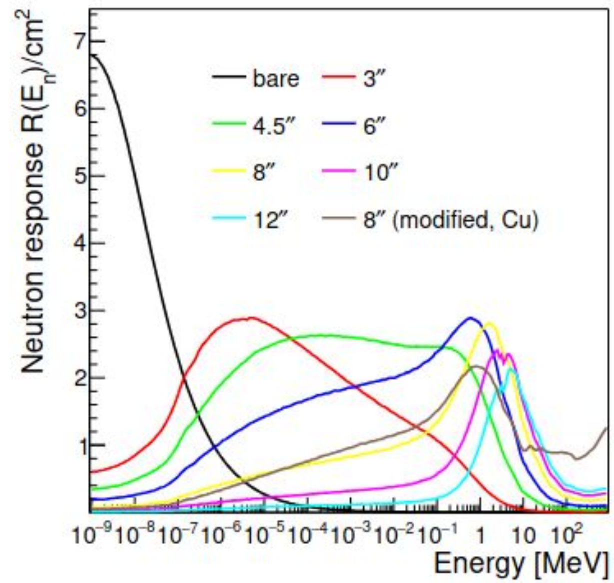
CONUS+ background: Reactor neutrons

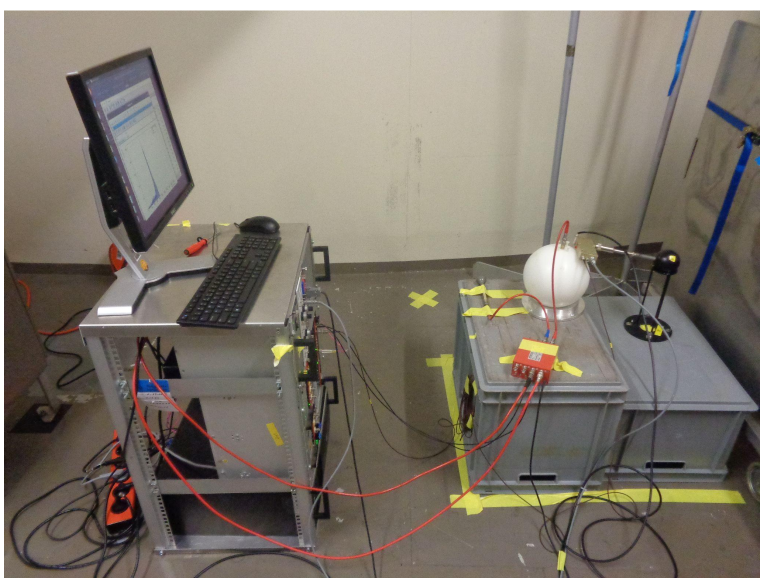
Neutron spectrometry with Bonner Sphere detectors in scientific cooperation with PSI.

Measurement in same position with 1 sphere at the time. Neutron flux stable within 3%.

80% of the neutrons have energies below 0.4 eV.
Total neutron flux 262 n/GW/cm^2/h.

<u>Simulations show a negligible impact!!</u>





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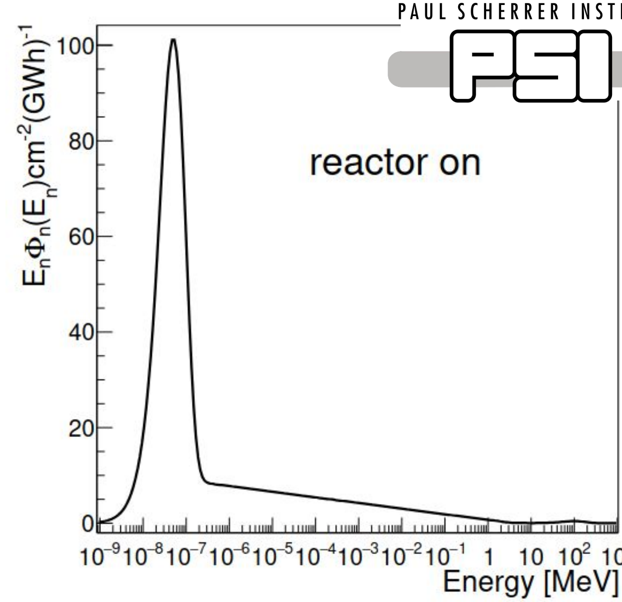
PSI



CONUS+ background: Cosmic neutrons

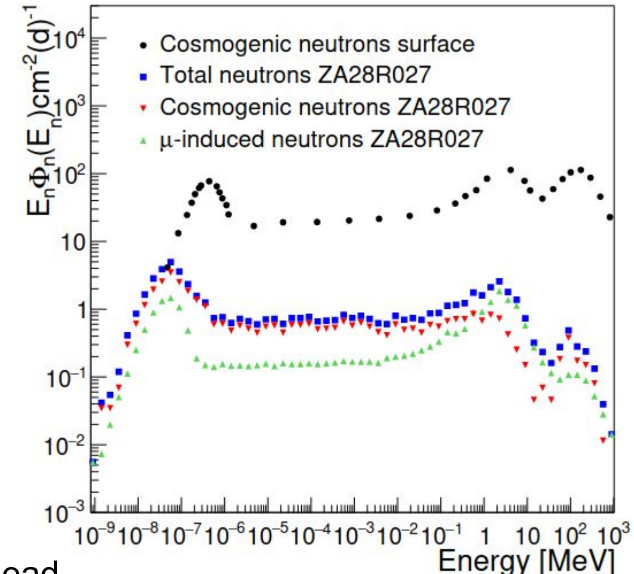
Measurement with BSS not conclusive.
Count rates 6 times larger than in KBR.

Alternative approach based on simulations.

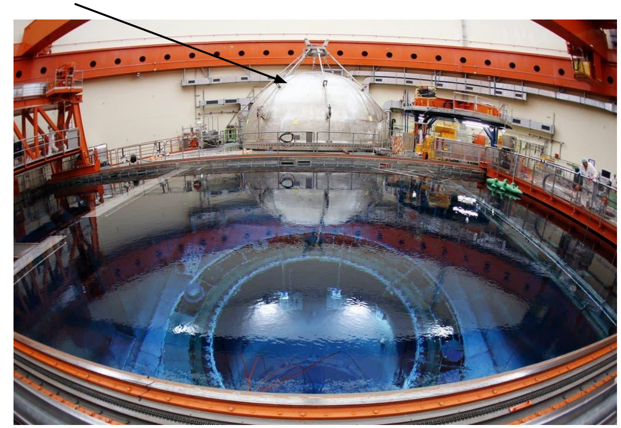
Initial neutron spectra from [1], neutron flux value considered 0.013 n/s/cm^2.

Rate variation for cascade neutrons with the reactor drywell head ~16%.

Muon-induced neutrons in concrete dominant in MeV region. Total neutron flux 28 n/cm^2/d



drywell head



[1] P. Goldhagen, J. M. Clem, J. W. Wilson, *Radiation Protection Dosimetry*, Volume 110, Issue 1-4, 1 August 2004, Pages 387–392, https://doi.org/10.1093/rpd/nch216

Data processing

Rejection of time periods with high radon level, noise rate and microphonics events.

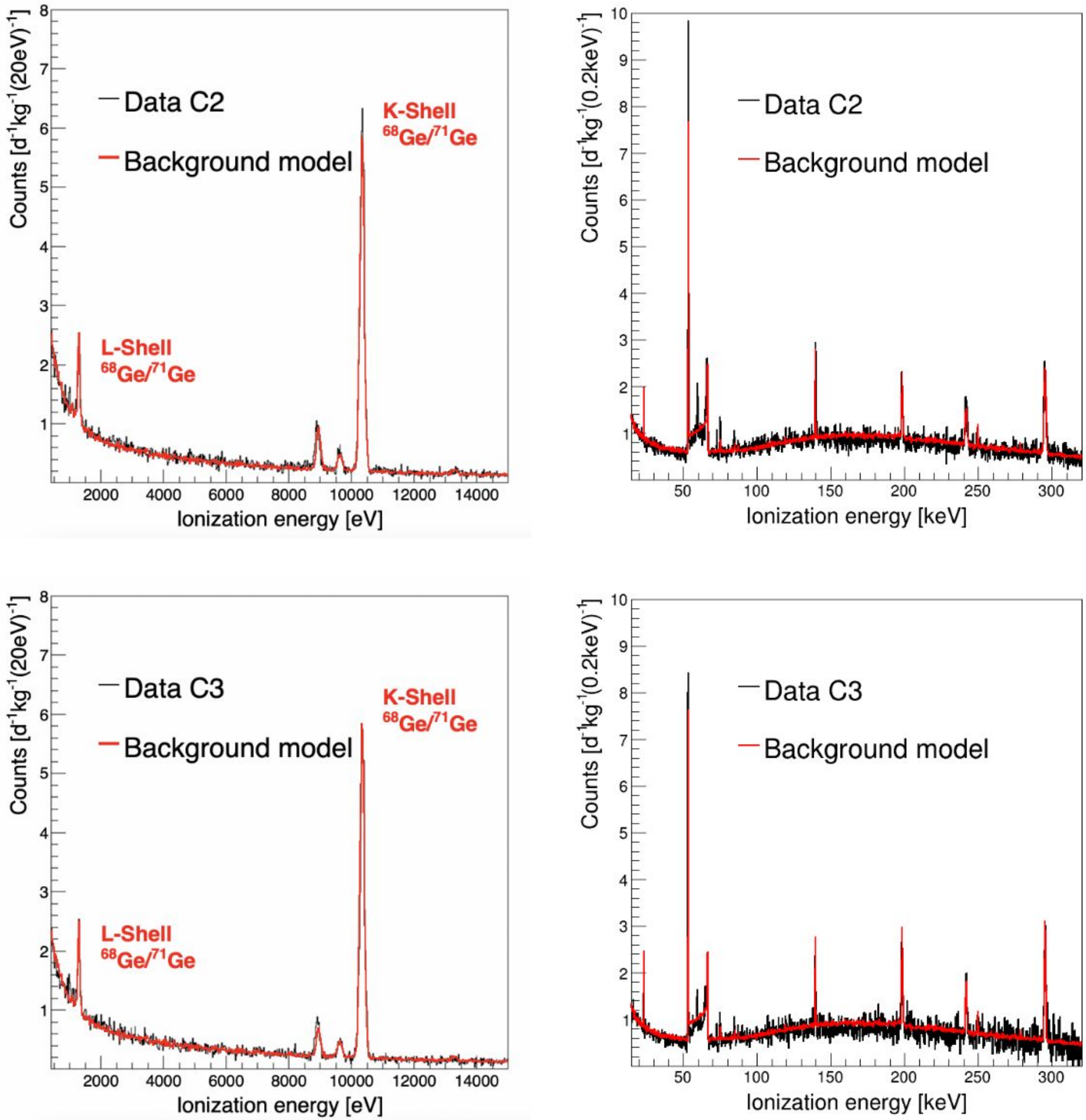
Selection cuts: muon veto anticoincidence, TRP anticoincidence, microphonics and detector anticoincidence.

Dead time dominated by muon veto and TRP cuts (11-13%).

DAQ deadtime below < 2%.

Exposure: 327 kg d reactor on and 60 kg d with reactor off. C4 detector excluded from analysis.

[0.4-1.0] keV_{ee}						
Detector	C5		C2		C3	
Rector period	On	Off	On	Off	On	Off
muon veto anti.	99.3%	99.3%	99.8%	99.8%	99.8%	99.8%
TRP anti.	35.9%	39.6%	43.4%	44.0%	43.9%	46.5%
TDD	0.1%	0.1%	0.2%	0.5%	0.2%	0.1%
neutron anti.	6.8%	6.6%	4.3%	4.8%	7.2%	6.8%
combined	99.6%	99.6%	99.9%	99.9%	99.9%	99.9%
[2-8] keV_{ee}						
Detector	C5		C2		C3	
Rector period	On	Off	On	Off	On	Off
muon veto anti.	98.9%	98.9%	98.6%	98.6%	98.7%	98.9%
TRP anti.	19.7%	25.0%	3.9%	5.5%	6.1%	6.7%
TDD	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
neutron anti.	6.5%	7.0%	4.3%	4.3%	6.7%	6.5%
combined	99.2%	99.2%	99.1%	99.1%	98.9%	99.1%



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]

Cosmogenic components - Muons

<u>Data without muon veto</u>: ca. 99% muons

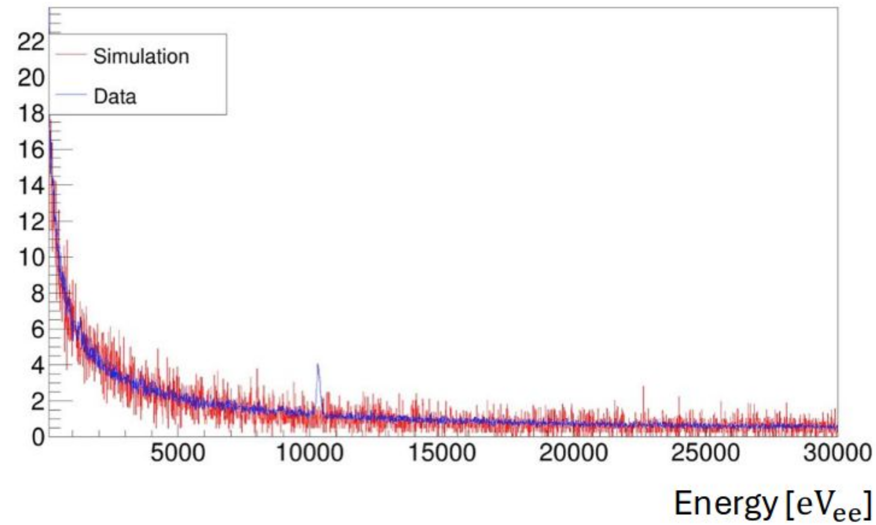
→ Use this to get "baseline" for muon simulations

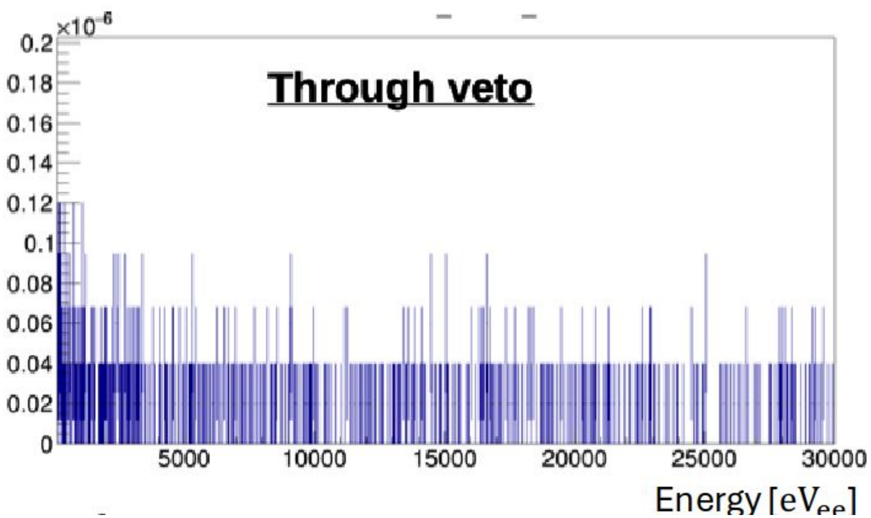
Muon flux in room: (53 +- 1) muons $s^{-1}cm^{-2}$

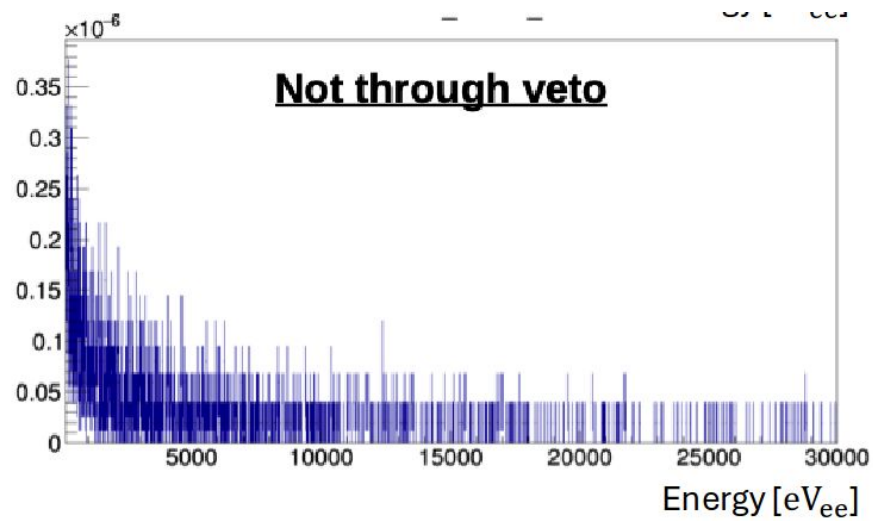
→ consistent with expected overburden

To this we apply a factor accounting for the muon veto efficiency

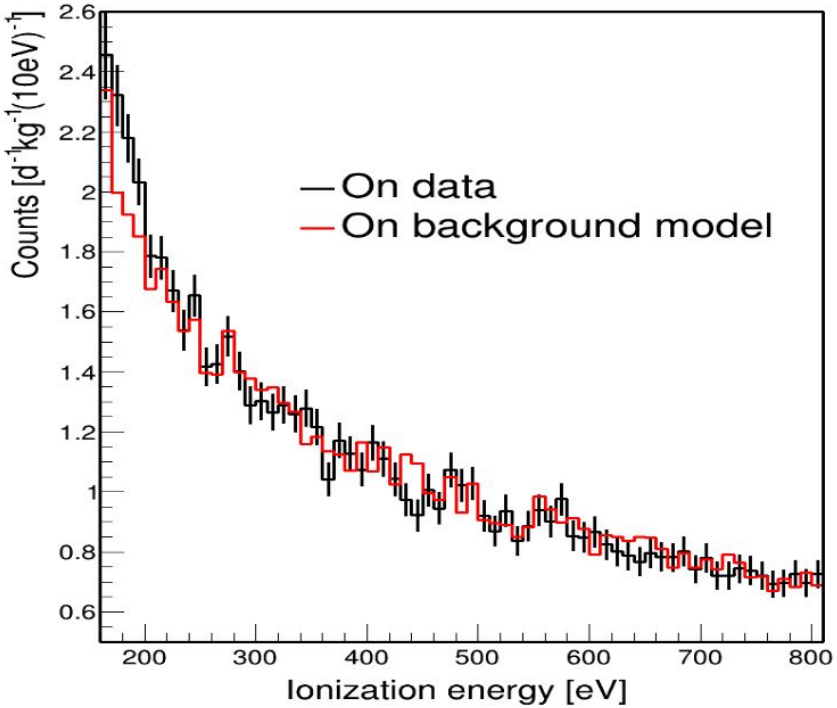
<u>Factor</u>:
99% at higher energies, but energy dependence at very low E

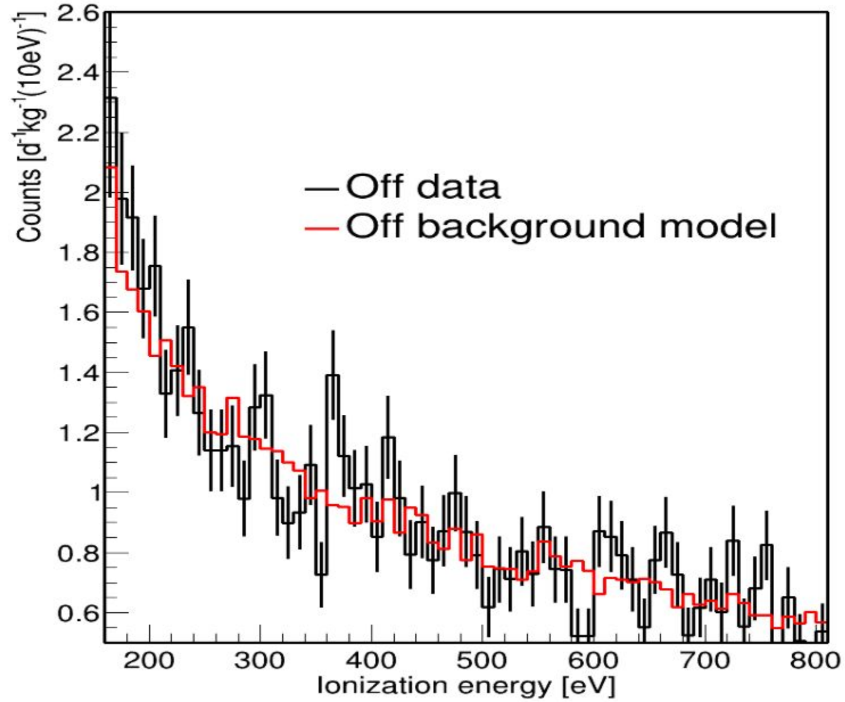






Background model in CEνNS region





Single detector fits

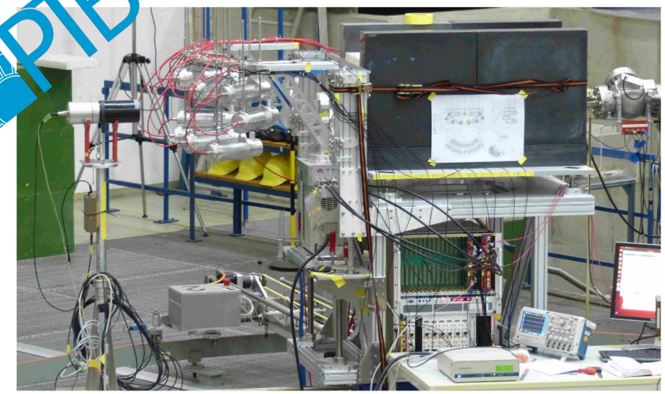
Detector	E_{th} [eV$_{ee}$]	mass [kg]	live time	Signal events data	Signal predicted	Ratio
C2	180	0.95 ± 0.01	117 days	69 ± 47	96 ± 16	0.72 ± 0.50
C3	160	0.94 ± 0.01	110 days	186 ± 66	135 ± 23	1.38 ± 0.54
C5	170	0.94 ± 0.01	119 days	117 ± 75	116 ± 20	1.01 ± 0.67
combined		2.83 ± 0.02		395 ± 106	347 ± 59	1.14 ± 0.36

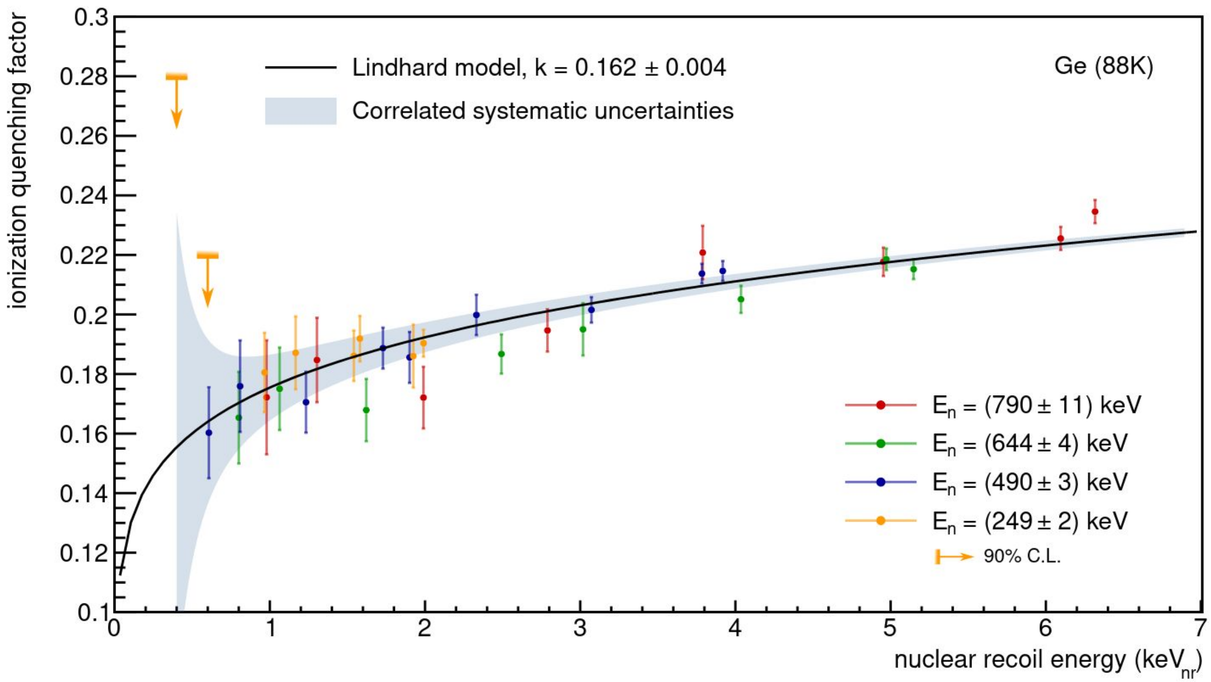
Quenching measurement

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: <u>k = 0.162 ± 0.004 (stat+syst).</u>

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