First look to the CONUS+ data

On behalf of the CONUS Collaboration

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

Edgar Sánchez García
(MPIK)

COνUS+

Applied Antineutrino Physics (Aachen), October 2024

KKL nuclear 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 GWt reactor core → high antineutrino flux expected 1.45 x 10^{13} $\bar{\nu}_e$ $s^{-1}cm^{-2}$
- Reactor dome 1.2 m steel reinforced concrete + 3.8 cm steel containment structure.
- Concrete ZA28R027 room 0.35 m. Average overburden between 7-8 m w.e.

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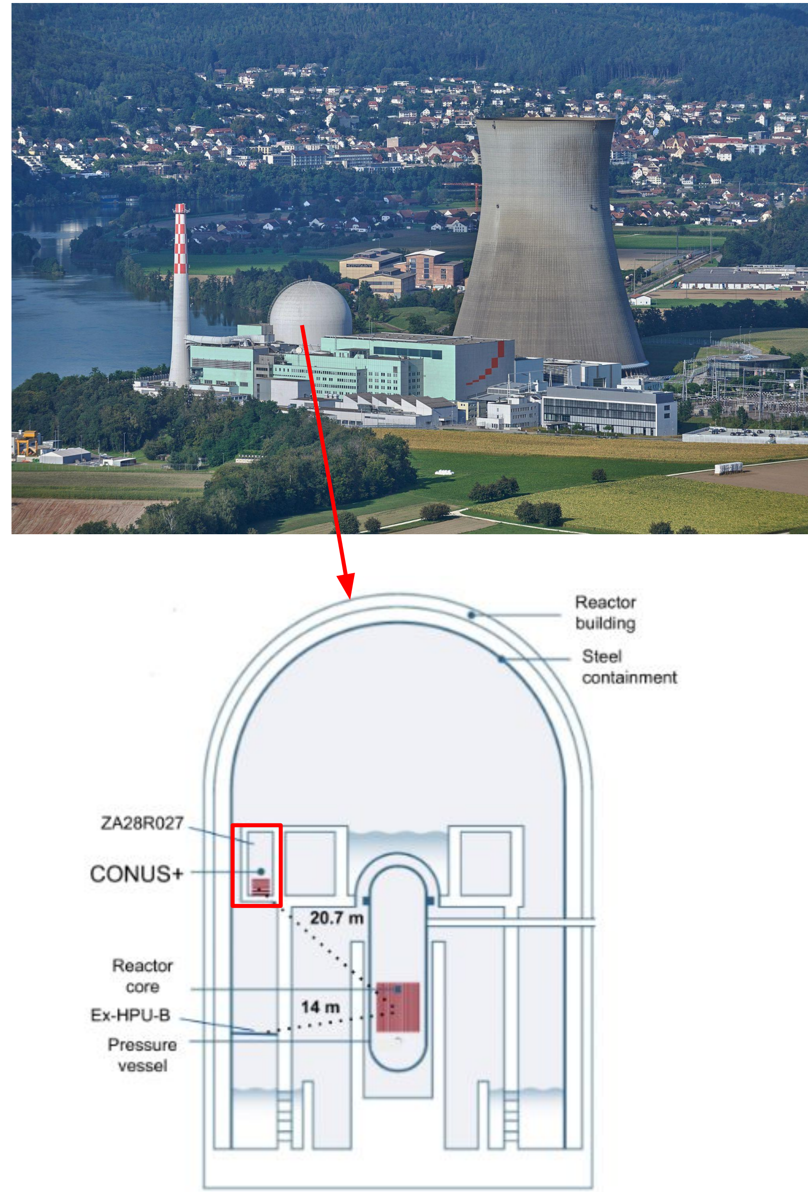
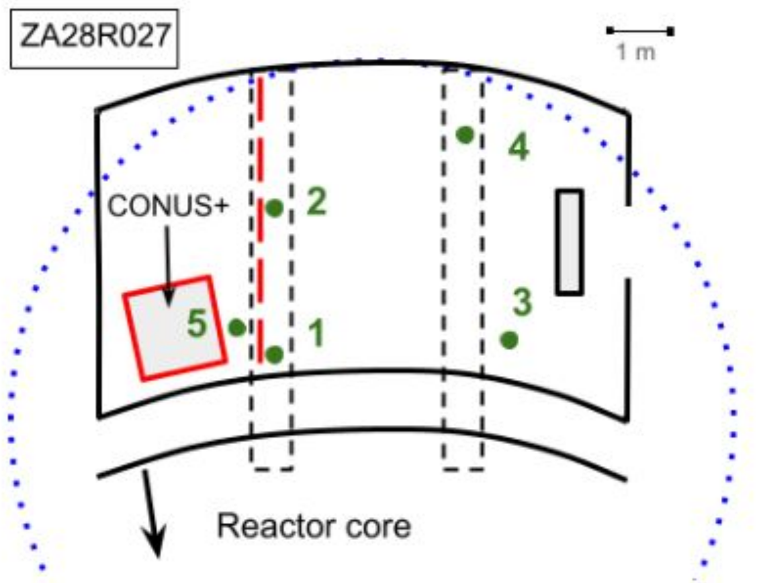
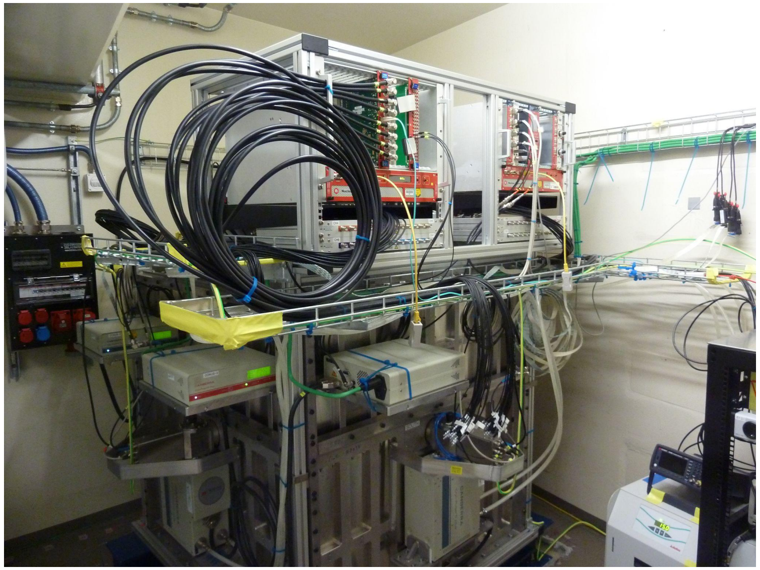


CONUS+ location: ZA28R027 room

- Isolated area for CONUS+ with metallic wall. Temperature in room kept stable with AC system.
- Direct network connection to MPIK. <u>Monitoring in real time possible!</u>
- Reactor drywell head over room during reactor off. Thickness 3.8 cm steel → overburden variation 0.25 m w.e.





Background characterization campaign

Extensive background characterization campaign between 2022-2023 at different positions:

- ɣ measurements with HPGe detector.
- Neutron measurements with Bonner Sphere array system.
- Environmental parameters (radon, temperature …).
- Cosmic muons with liquid scintillator.
- Vibrations with piezoelectric sensors.
- Surface contamination with wipe tests + low background Ge spectrometers.

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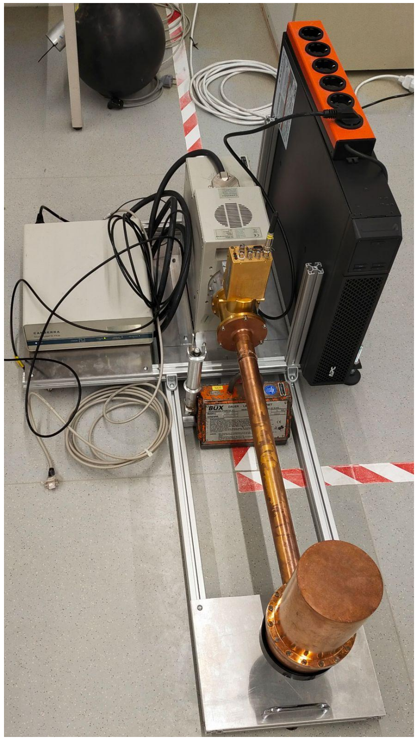
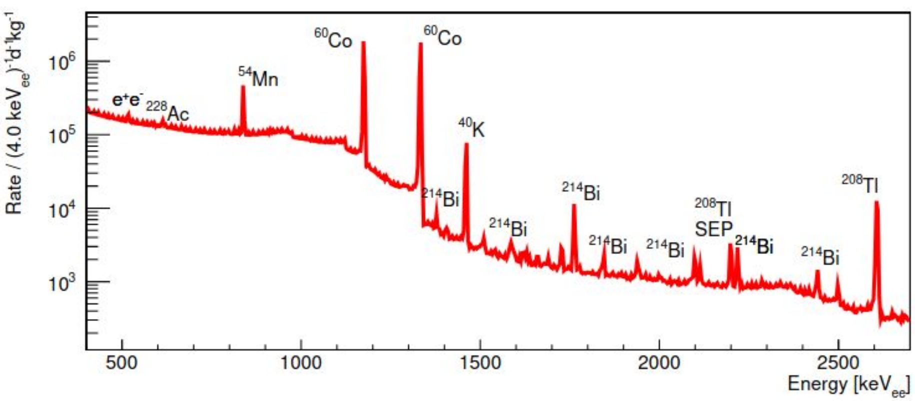
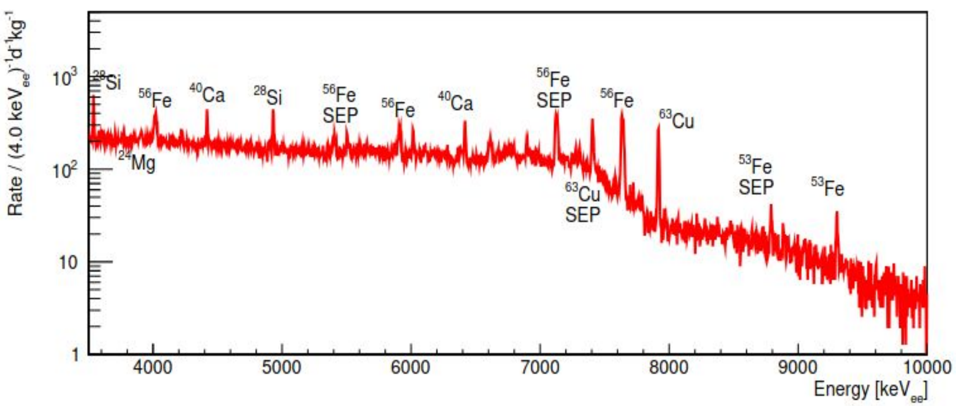
Publication in preparation!!

CONUS+ background: ɣ’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.

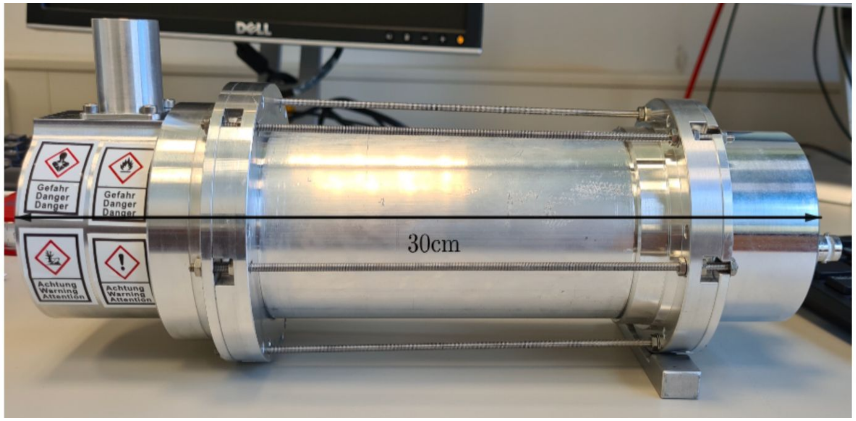


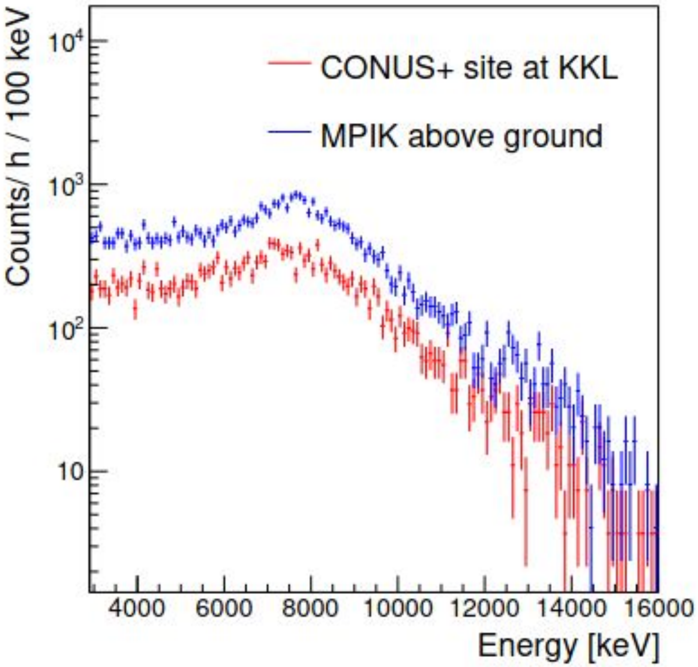




CONUS+ background: Cosmic muons

- Liquid scintillator cell filled with 120 ml of "Ultima Gold". PMT for light detection.
- Measurements at MPIK and KKL during off time for comparison.
- Quality cuts applied: saturation, pile-up.
- Pulse shape discrimination cut to remove neutrons.

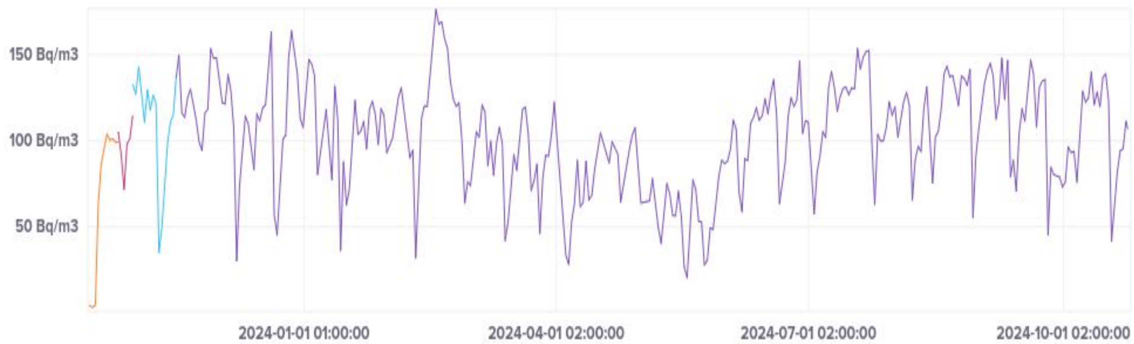


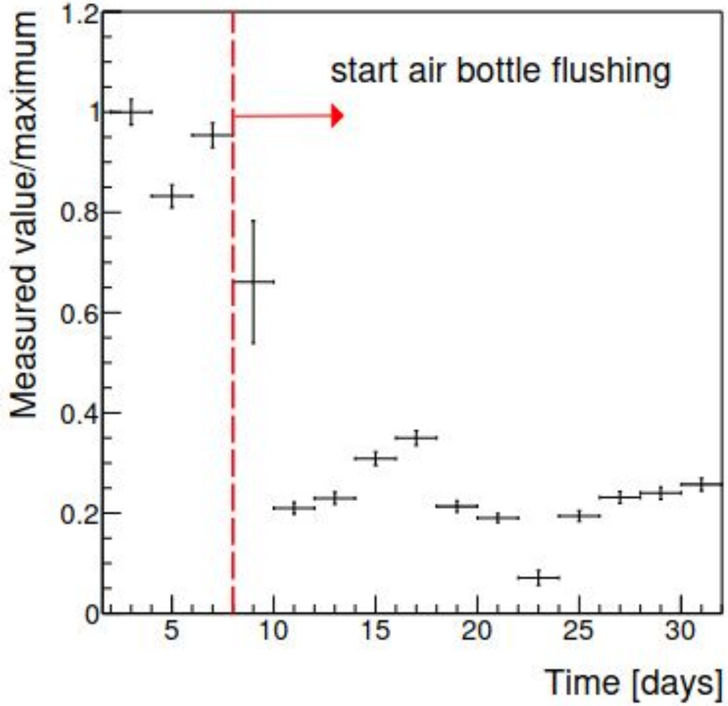


- Energy cut at 3 MeV to avoid environmental radioactivity. Reactor OFF to avoid high energy ɣ contribution.
- <u>Muon rate surface: 200±5 counts/s/m^2.</u>
- <u>Muon rate ZA28R027: 107±3 counts/s/m^2.</u>
- Reduction factor of 1.9 in KKL compared to surface → overburden 7.4 m w.e.
- Muon rate factor 2.4 larger than at KBR. Overburden at KBR 24 m w.e.
- Impact reactor drywell head 0.25 m w.e.

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 110 Bq/m^3. Significant fluctuations.
- 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.

CONUS+ background: Reactor neutrons

- Neutron spectrometry with Bonner Sphere detectors in scientific cooperation with PSI.
- Monitoring neutron rate with 5” PE sphere. Correlation with thermal power. Most neutrons in the room are produced by the reactor.
- Same configuration of spheres as in KBR for direct comparison giving a sensitivity from 10^{-9} to 10^{3} MeV

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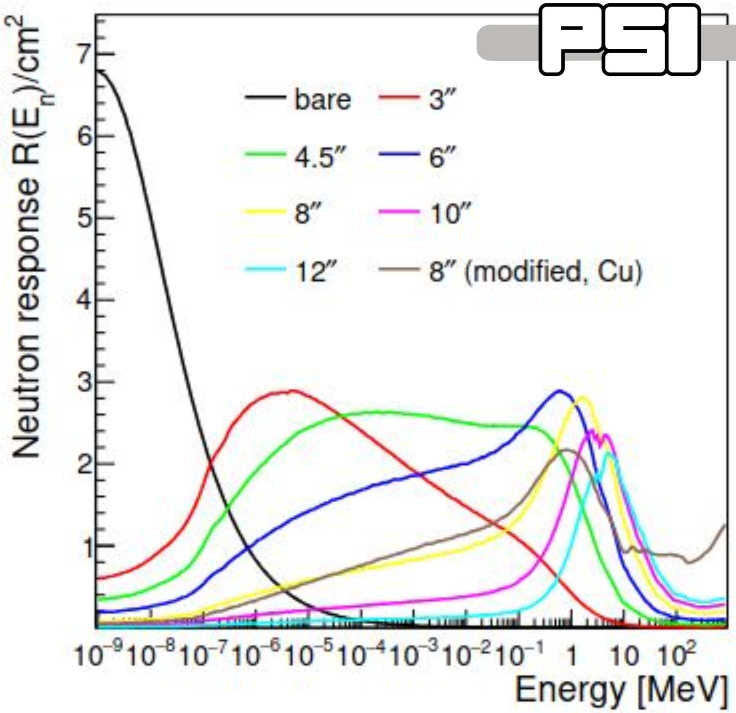
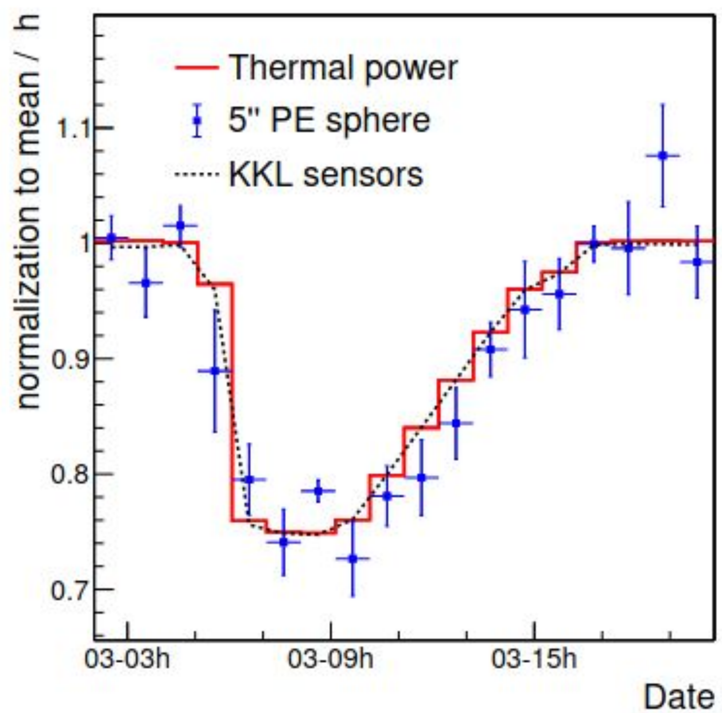




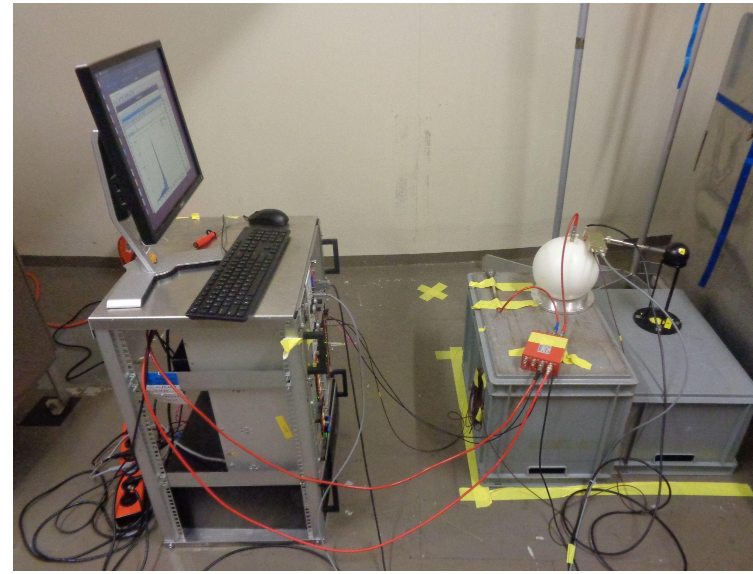
CONUS+ background: Reactor neutrons

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

- Unfolded spectra in lethargy representation during reactor on. 80% of the neutrons have energies below 0.4 eV.

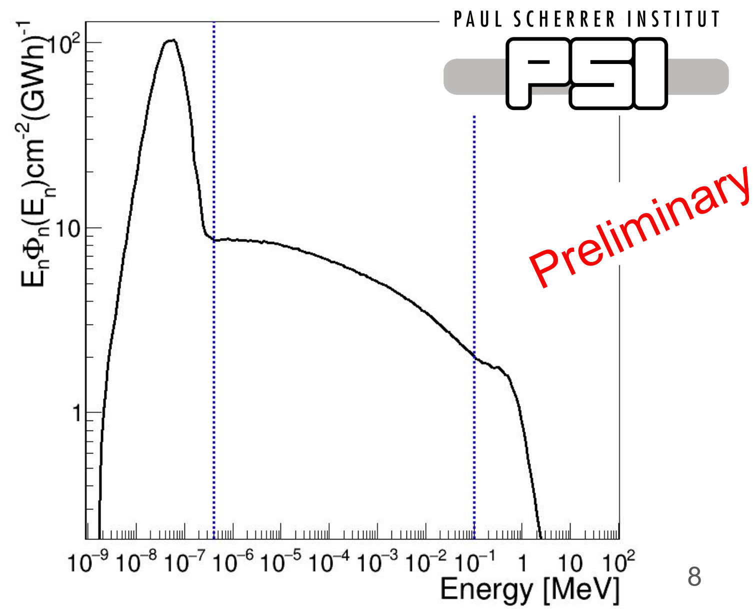
- Total neutron flux 284 n/GW/cm^2/h → 37 times larger than in KBR.

- <u>However, simulations show a negligible impact!!</u>



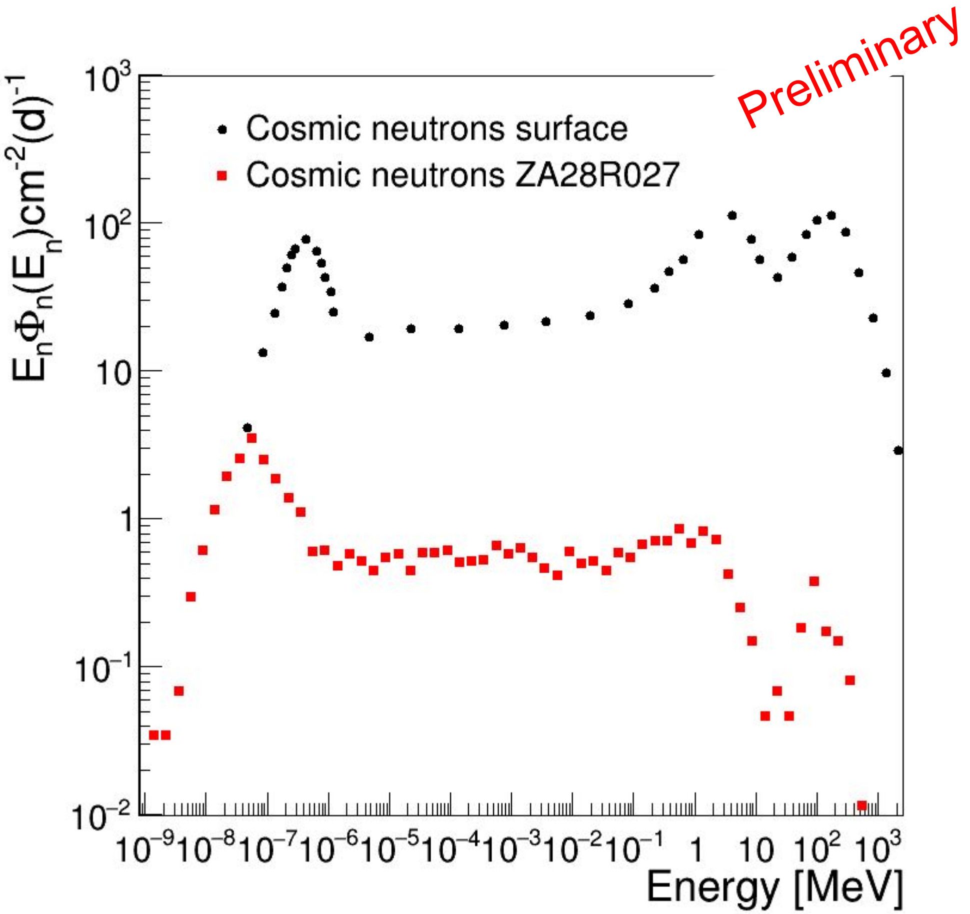
Preliminary

Energy region	ϕ [cm^{-2} (GWh)$^{-1}$]
Thermal (<0.4 eV)	206
Intermediate (>0.4 eV && < 0.1 MeV)	74
Fast (>0.1 MeV && < 19.4 MeV)	4
Total	284



CONUS+ background: Cosmic neutrons

- Measurement with BSS not conclusive. Count rates 6 times larger than in KBR.
- Alternative approach based on simulations.
- <u>Initial neutron spectra from [1], neutron flux value considered 0.013 n/s/cm^2.</u>
- Neutrons propagated over reactor building. Neutrons suppressed almost two orders of magnitude, but still large impact over the CONUS+ background.
- <u>Rate variation for cascade neutrons with the reactor drywell head ~16%.</u>
- Muon-induced neutrons in concrete yet not included in this simulation.



[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

CONUS+ modifications

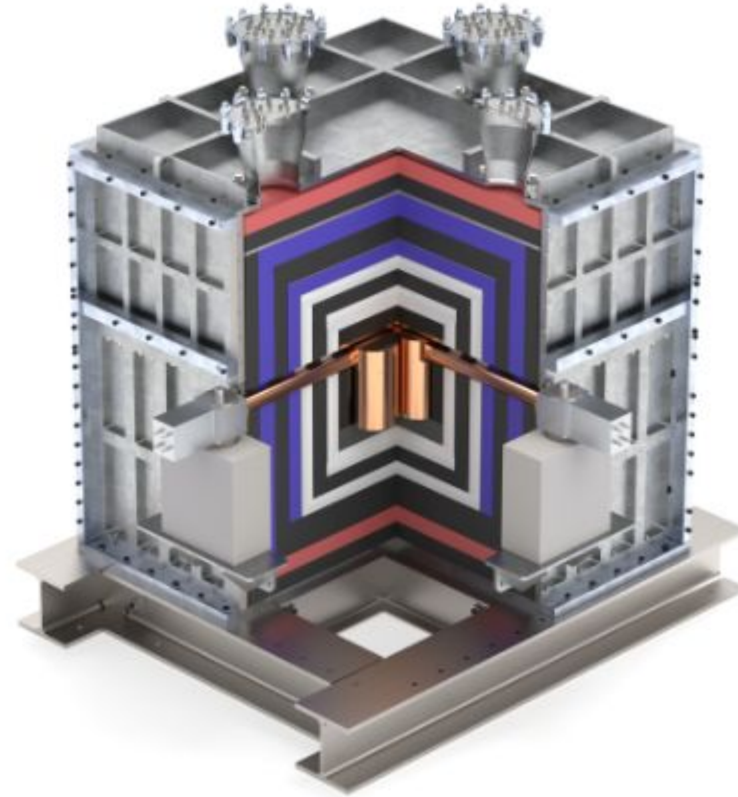
- 4 refurbished p-type point contact HPGe with total crystal/active mass: 4 kg /3.74kg as target. Better trigger efficiency and threshold.

- Active + passive shielding: low ^{210}Pb lead, borated and pure PE and 2 active μ-vetos (plastic scintillator).

- <u>Less ɣ's and more muons → Third lead layer replaced by additional second muon veto.</u>

- Apply muon veto offline. New DAQ for veto system. Energy deposited stored for each PMT.

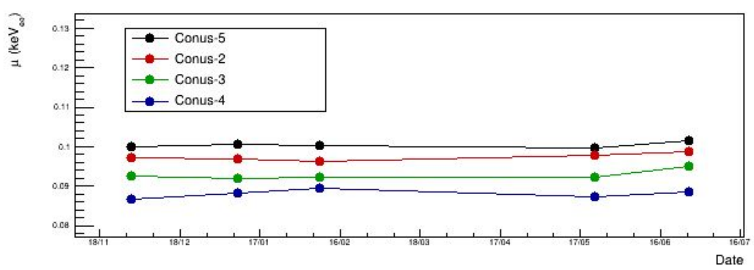
- New stainless steel frame to meet KKL earthquake safety requirements.

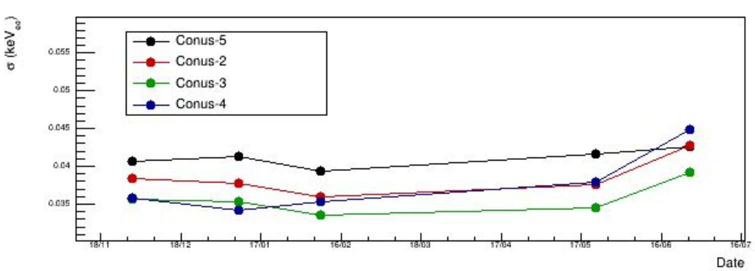


CONUS Collaboration,
arXiv:2407.11912

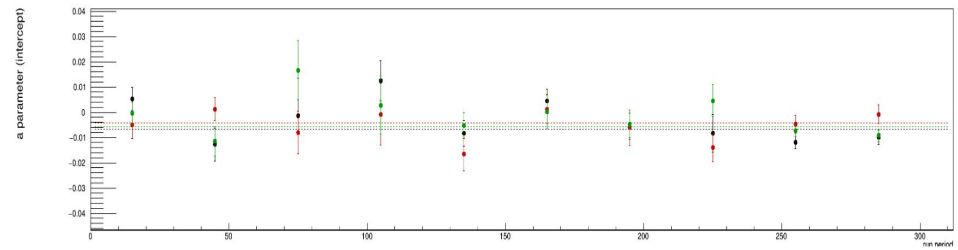
Stability during first year @KKL

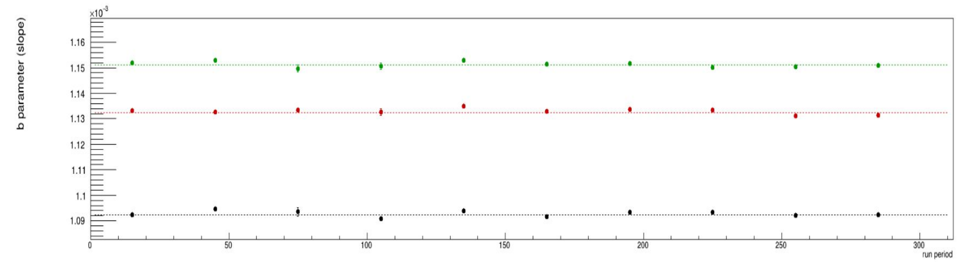
Trigger efficiency parameters



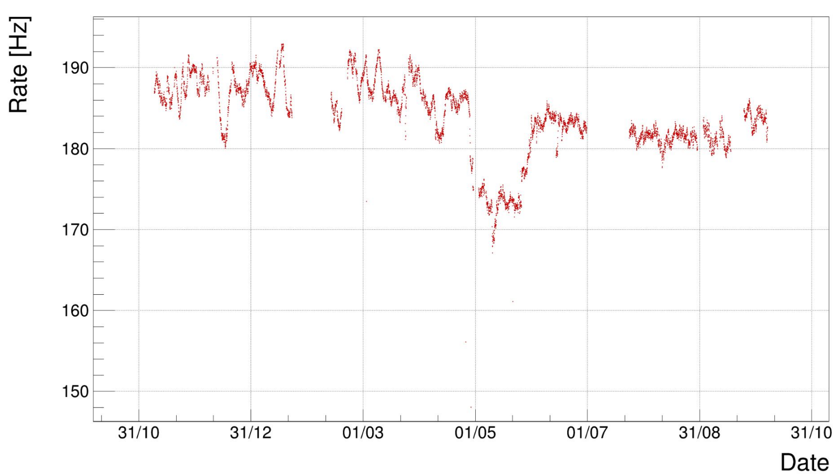


Energy calibration





μ-veto rate



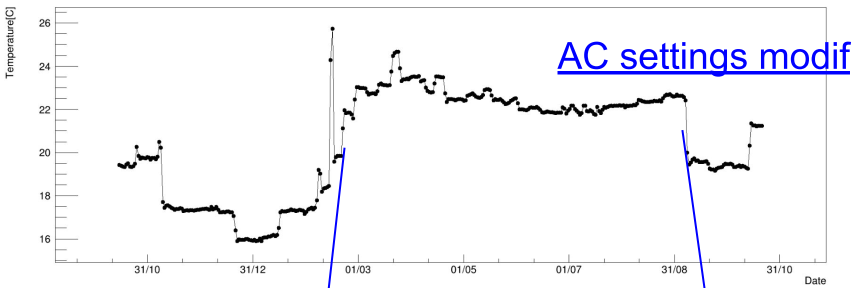
Seasonal variation veto rate. Anticorrelation with temperature (-0.13% /C) and pressure (-0.1% /mbar).

Variation during reactor off. Two effects:

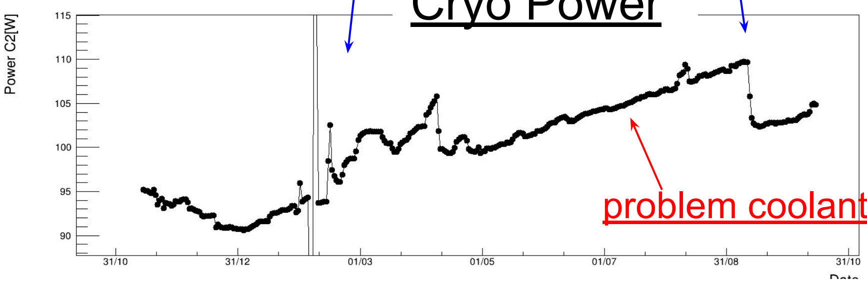
- Reactor correlated high energy ɣ's from neutron capture.
- Reactor drywell head over room.

Stability during first year @KKL

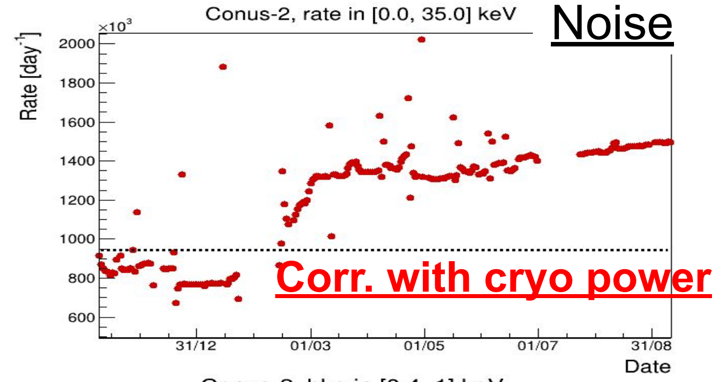
Temperature room



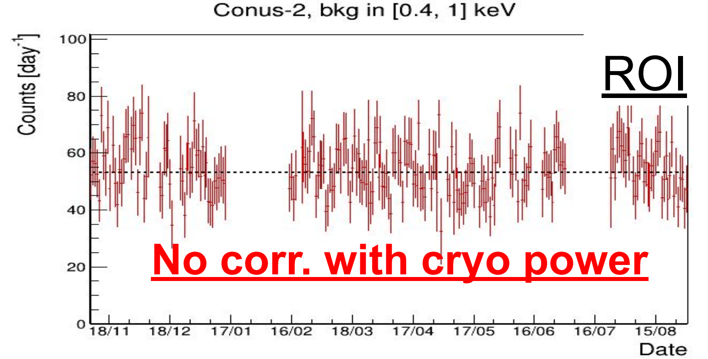
Cryo Power



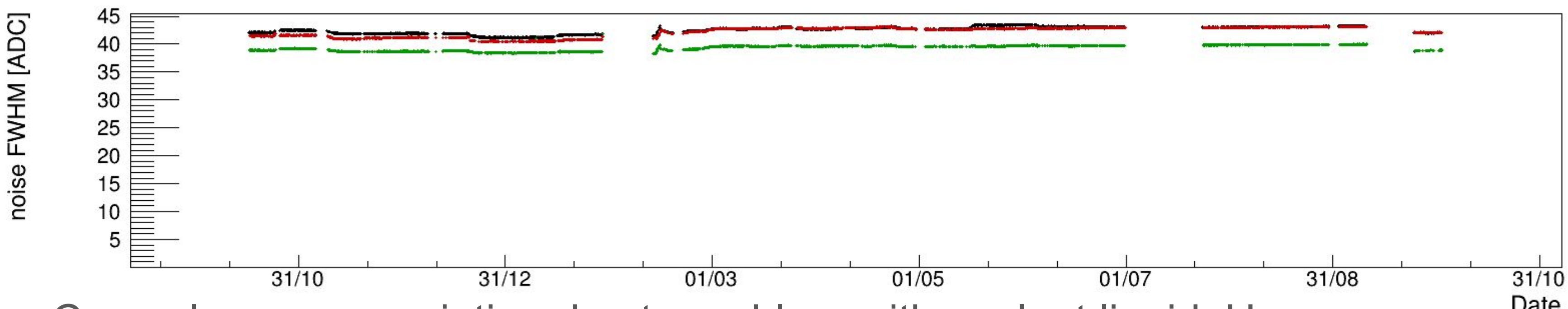
Noise



ROI



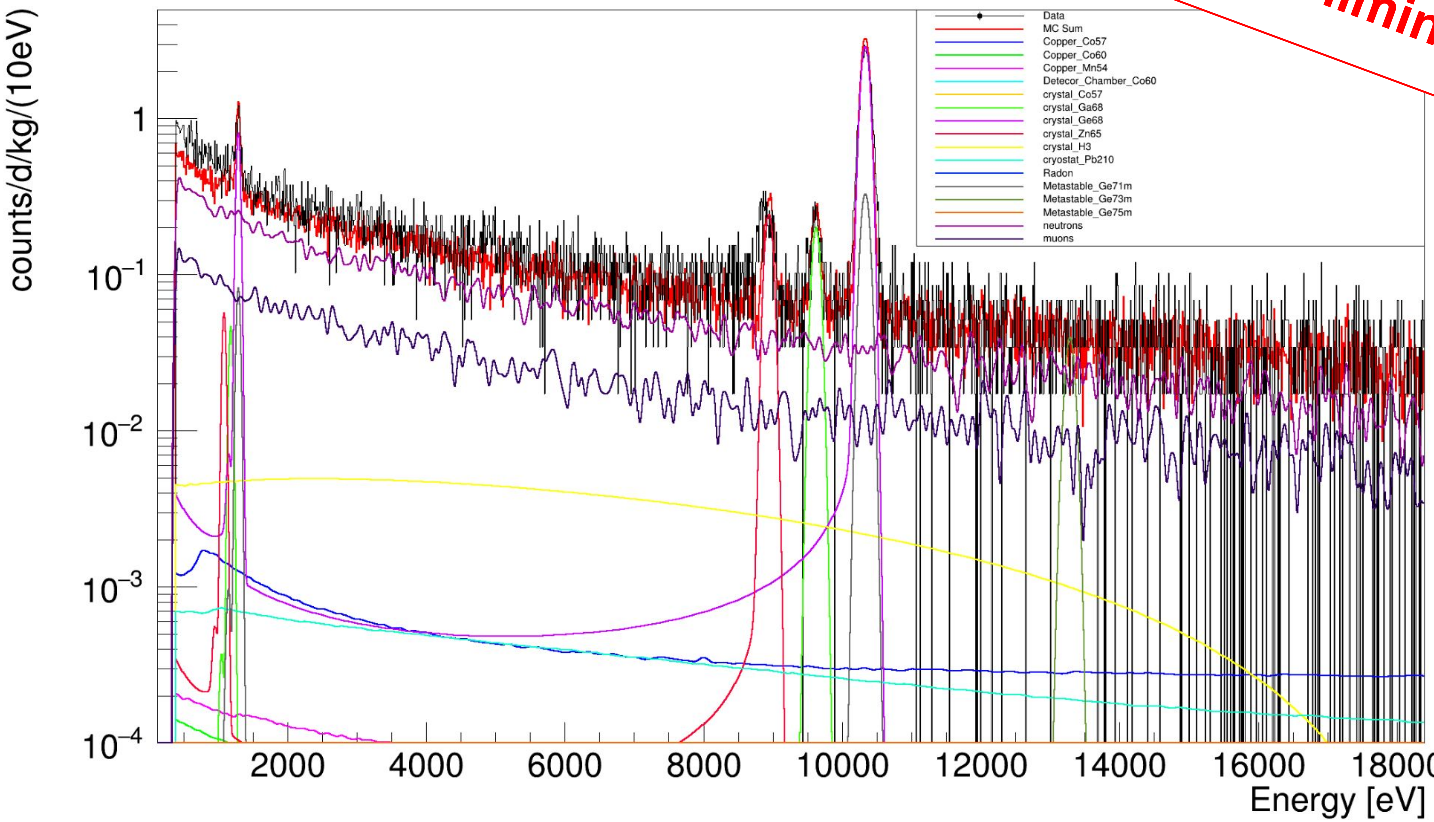
Resolution noise peak



Crycooler power variation due to problem with coolant liquid. However, no impact of microphonics events in ROI. Good stability in run-1!!

Background model

preliminary



Preliminary background rate in [0.4-1.0] keV region 35-45 cts/day (detector dependent).

Reactor neutrons negligible. ^{210}Pb strongly suppressed.

Dominant component from cosmic rays (muon-induced + cosmogenic neutrons). Still missing background at low energy.

Threshold determination

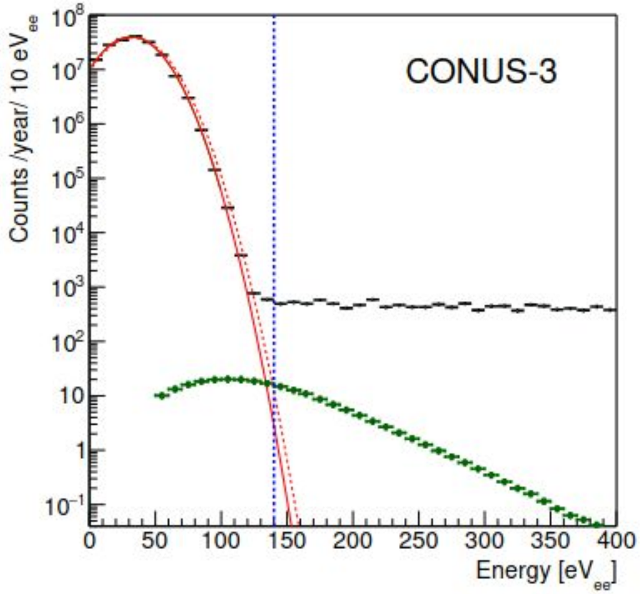
Energy threshold defined independently for each detector. Two conditions:

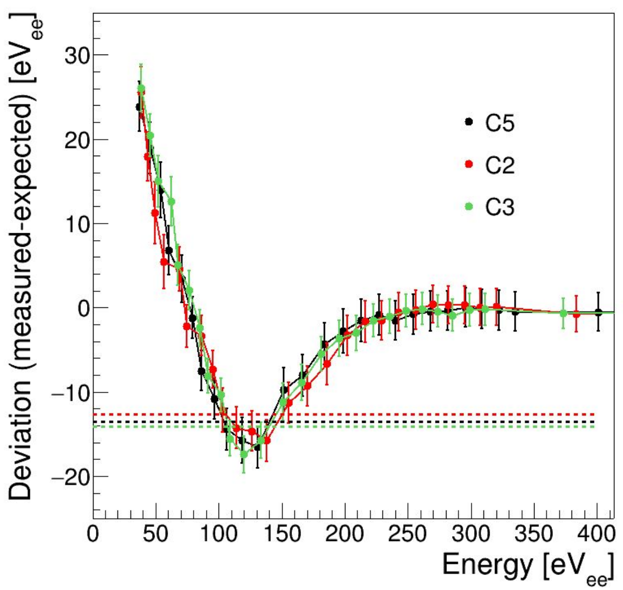
- Trigger efficiency over 20% (down to 70 eV_{ee}).
- Noise peak contribution below 10% expected CEvNS signal.

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.

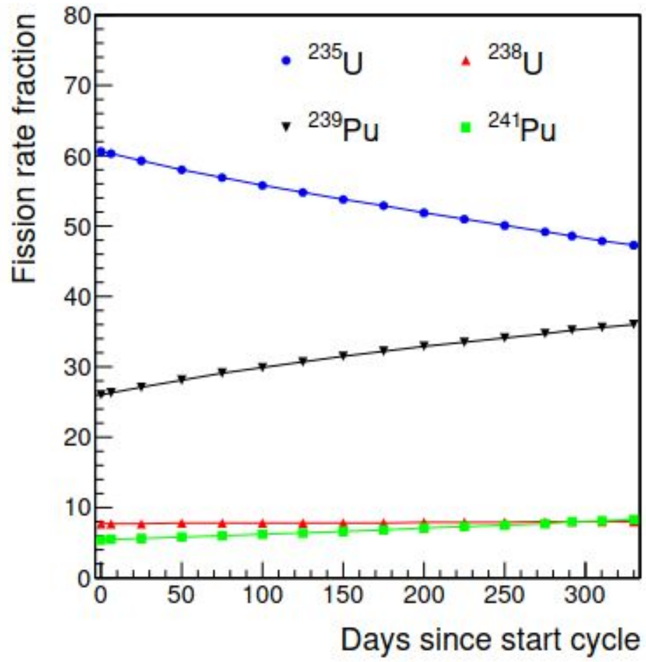
<u>Energy threshold for after non-linearity correction 150-160 eV_{ee} !!!</u>

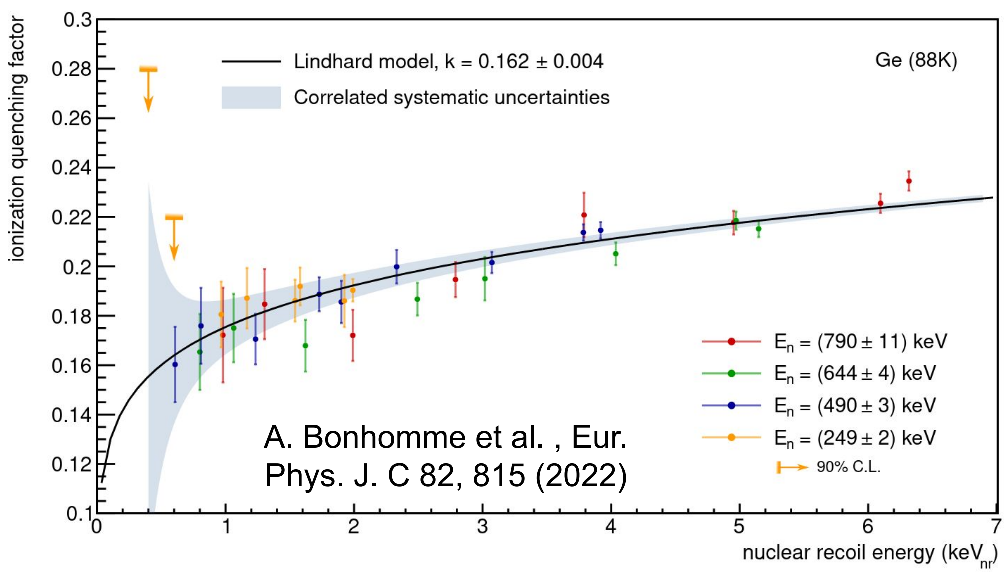


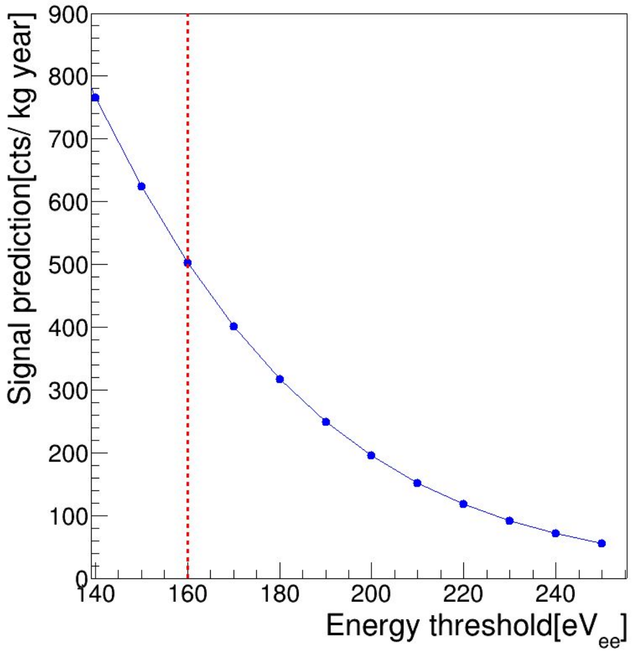


CEvNS signal

- Evolution most relevant actinides during typical reactor cycle at KKL.
- Average trigger efficiency during run-1 considered for each detector.
- Lindhard quenching factor with k=0.162.
- <u>With 160 eV_{ee} energy threshold, 500 events expected in 1 year kg.</u>







Summary

- Large differences in the background conditions compare to KBR: smaller overburden, less high energy ɣ-rays and more neutrons. Modifications to CONUS+ shield.

- Background dominated by muon-induced and cosmic neutrons. Background rate in [0.4-1] keV region ~2 times larger than in CONUS.

- First year of operation with the CONUS+ detector. Stable environmental and detector conditions.

- Energy threshold at KKL 150-160 eV_{ee}. Expected CEvNS signal with 1 year kg of data → > 500 events.

Stay tuned for new results!!

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)

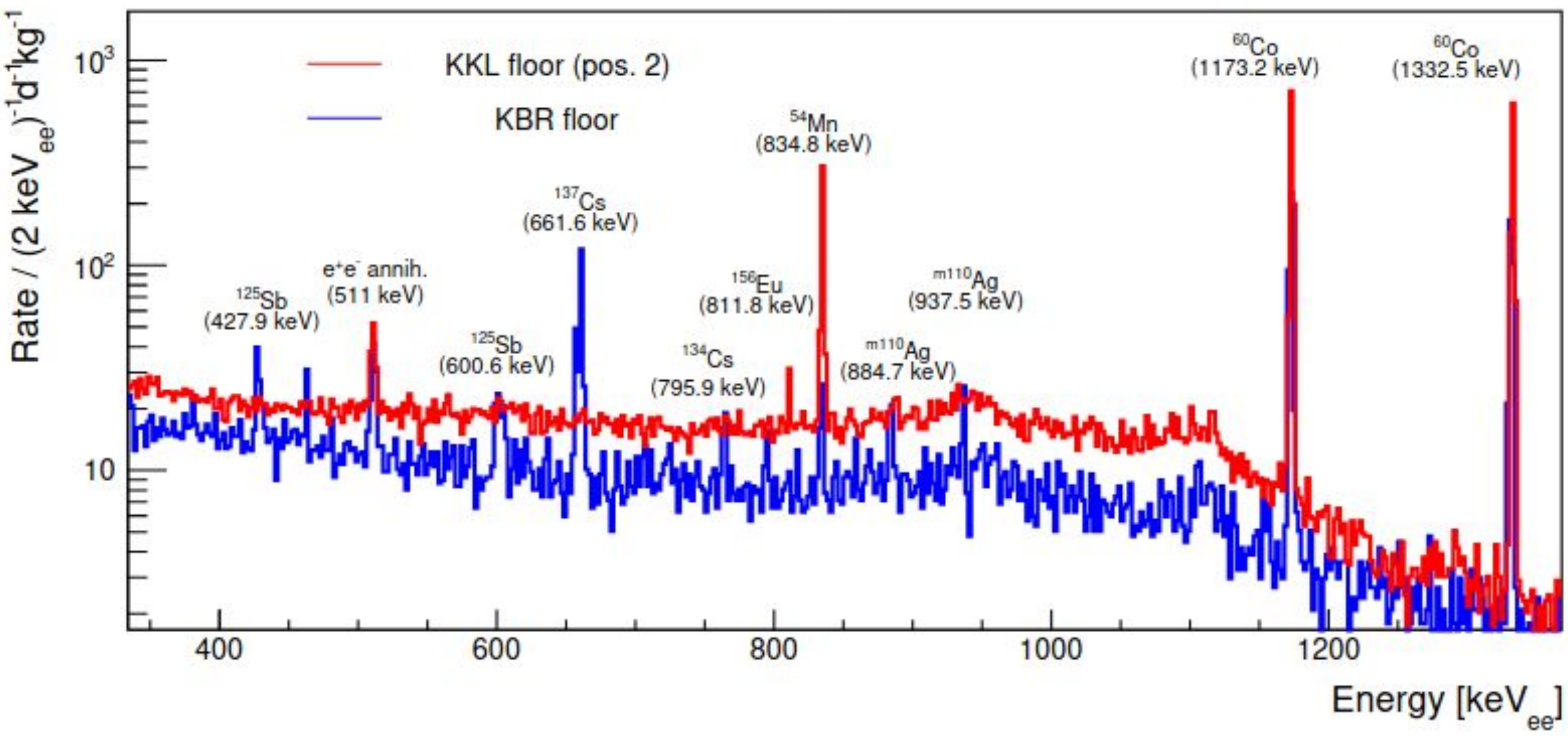
M. Rank, I. Stalder, J. Woenckhaus

Thank you for your attention

COvUS+

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.
- Strict cleaning protocols mandatory during installation.



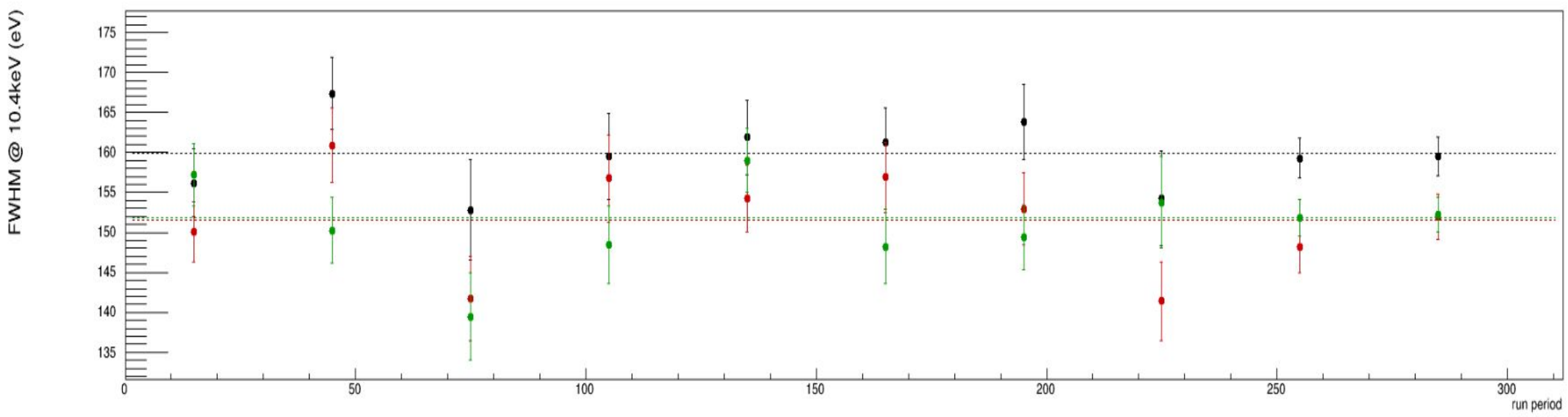
CONUS+ background: γ's

- 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.

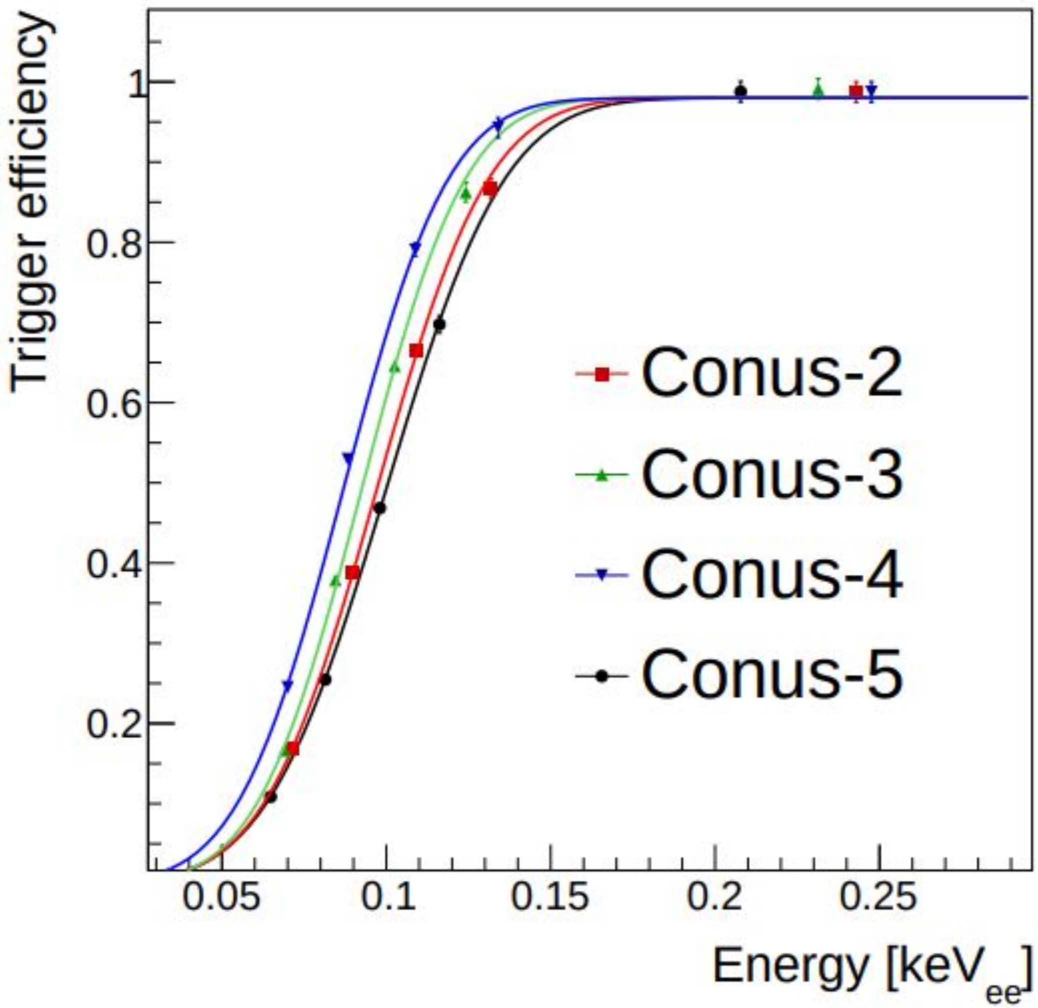
PC / Energy [keV] /BR[%]	KKL: Ex-HPU-B	KKL: ZA28R027	KBR: ZA408
$^{53}Fe(n,\gamma)^{54}Fe$	(reactor structure)		
8787 SEP	573±45	18.5±1.5	9.6±0.6
9298 (100%)	707±56	19.7±1.6	11.3±0.5
$^{56}Fe(n,\gamma)^{57}Fe$	(reactor structure)		
4217 (23.0%)	1896±149	78.5±6.2	not visible
5920 (33.8%)	2504±190	95.1±7.5	not visible
6018 (34.8%)	2787±220	98.0±7.4	not visible
7120 SEP	6974±596*	285±23*	not visible
7135 SEP	double peak	double peak	double peak
7278 (20.7%)	1544±122	80.5±6.4	11.5±1.1
7631 (100%)	8717±735*	363±29*	137±4*
7646 (86.2%)	double peak	double peak	double peak
$^{63}Cu(n,\gamma)^{64}Cu$	(HPGe cryostat)		
7406 SEP	1992±157	228±18	27.2±1.3
7638 (48.9%)	995±79*	120±9*	15.7±1.6*
7916 (100%)	2034±161	245±19	29.7±1.0
$^{28}Si(n,\gamma)^{29}Si$	(concrete CONUS+ room)		
3539 (100%)	not visible	276±22	not visible
4934 (93.3%)	not visible	213±17	not visible
6379 (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)		
4418 (17.1%)	not visible	105±8	not visible
6419 (43.5%)	not visible	181±14	not visible
$^{16}O(n,p\gamma)^{16}N$	(reactor cooling system)		
5617 SEP	7143±564	not visible	49972±575
6128 (67%)	12652±998	not visible	85086±979
7115 (4.9%)	2526±199	not visible	10097±116

Stability during first year @KKL

Resolution 10.4 keV line



Trigger efficiency @KKL



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

Energy spectra @KKL

- Veto window 450 µs. Conservative approach as in CONUS. Dead-time ~12%
- Background rejection with new veto system 99% in the [0.4-1] keV region.
- After veto, X-ray lines induced by cosmogenic events in Ge visible. Energy calibration with K and L shells and propagated to low energies. ^{252}Cf irradiation to improve energy calibration uncertainty <5 eV.