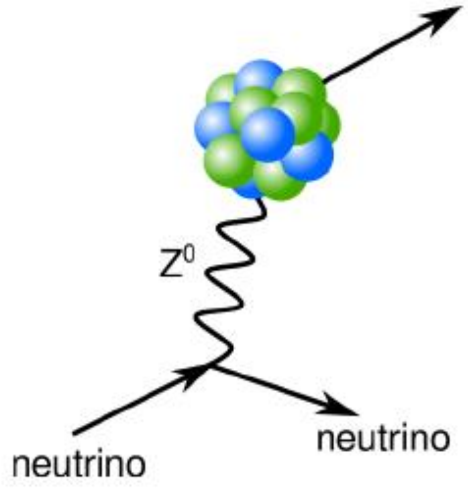
Nicola Ackermann on behalf of the
CONUS+ collaboration

First observation of reactor antineutrinos by coherent scattering with CONUS+

COνUS+

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK
HEIDELBERG

Coherent elastic neutrino nucleus scattering



Fermi constant

Weinberg angle

Form factor

$$\frac{d\sigma(E_\nu,T)}{dT} \simeq \frac{G_F^2}{4\pi}\left[N-\underbrace{\left(1-4\sin^2(\theta_W)\right)}_{\approx 0} Z\right]^2 F^2(q^2)\, M\left(1-\frac{MT}{2E_\nu^2}\right)$$

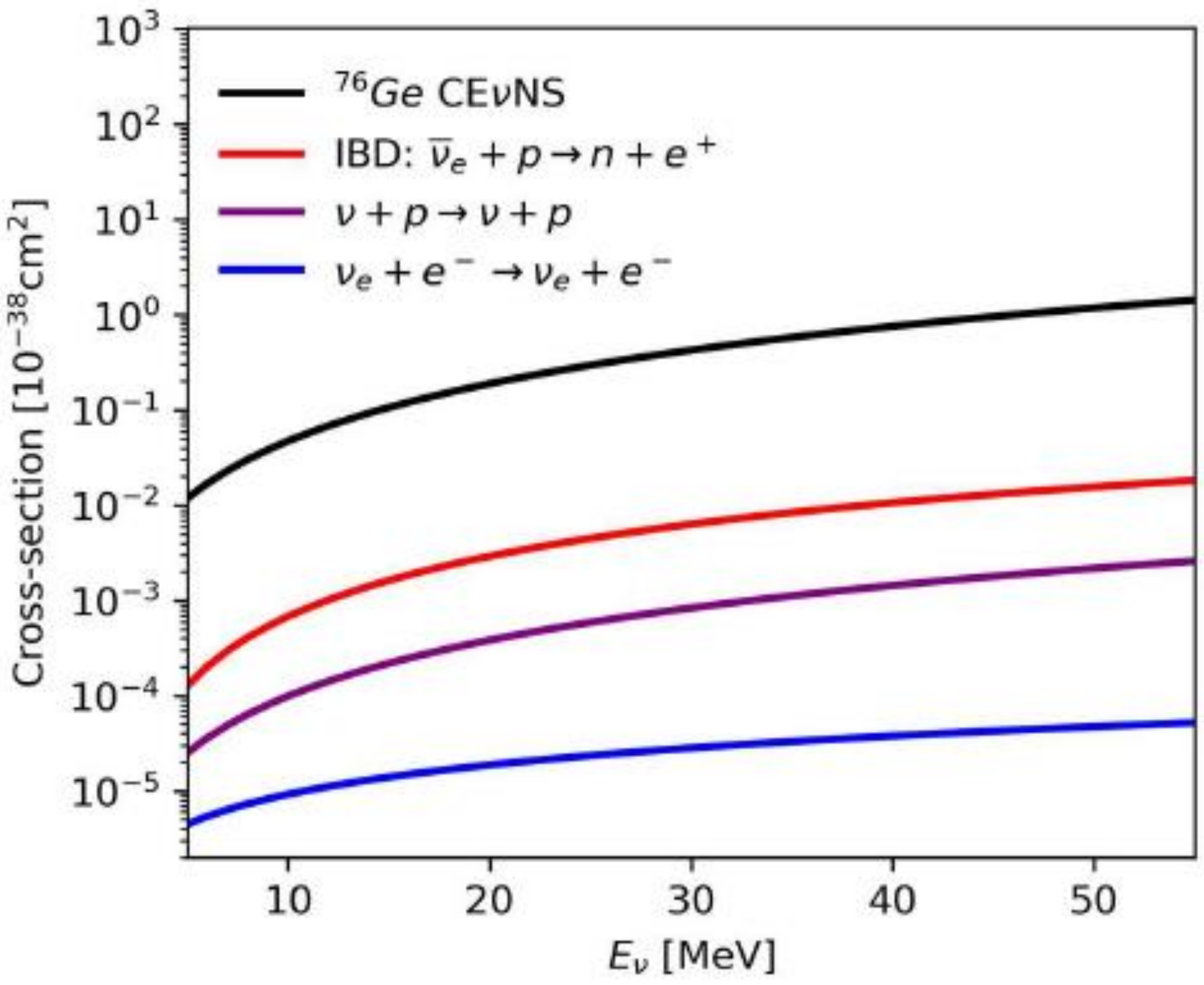
Neutron number

Proton number

Kinematics term

- First predicted by D.Z Freedman in 1974
- First measured by COHERENT in 2017: CsI detector at pion-decay-at-rest soruce
- Measurement at nuclear power plant (was) still pending!

Comparison to other channels



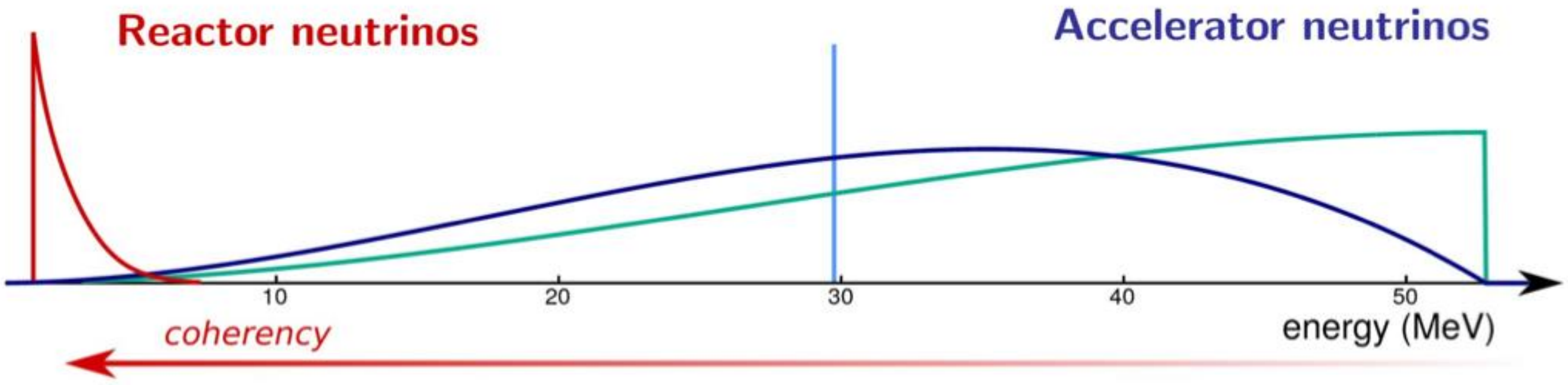
CEvNS cross section is large!
(For neutrino standards)

For Germanium:
$N = 41 \rightarrow N^2 = 1681$

→ ~ 3 orders of magnitude bigger than for IBD!

→ Allows much smaller neutrino detectors

Artificial neutrino sources



Reactors

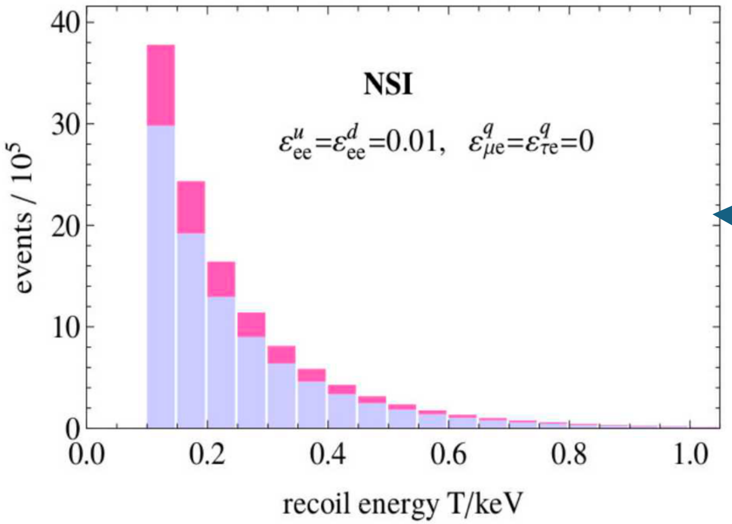
- Neutrinos from fission products
- Only $\overline{\nu_e}$
- Energies of < 10 MeV (fully coherent)
- First measurement with CONUS+

Complementary experiments!

Accelerators

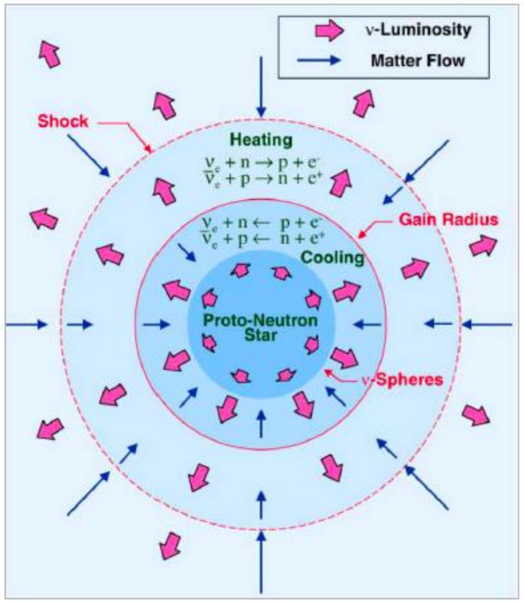
- Neutrinos from π-DAR
- Different flavors: ν_e, ν_μ and $\overline{\nu_\mu}$
- Energies of ~ 20 – 50 MeV
  → Partially coherent
- **First CEvNS observation**:
  COHERENT in 2017 using CsI [Na]

Physics potential of CEvNS

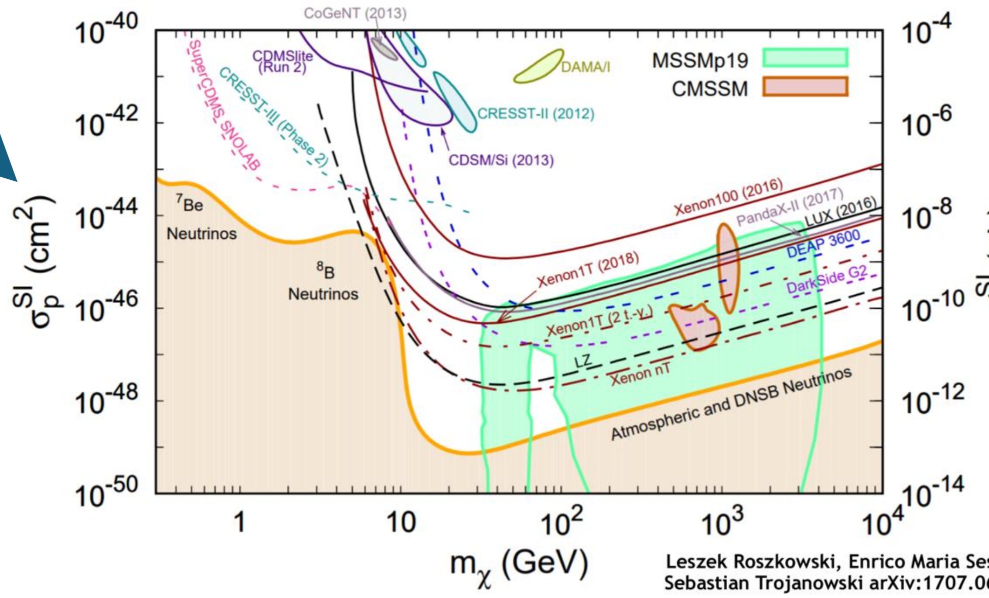


Measurement of BSM physics

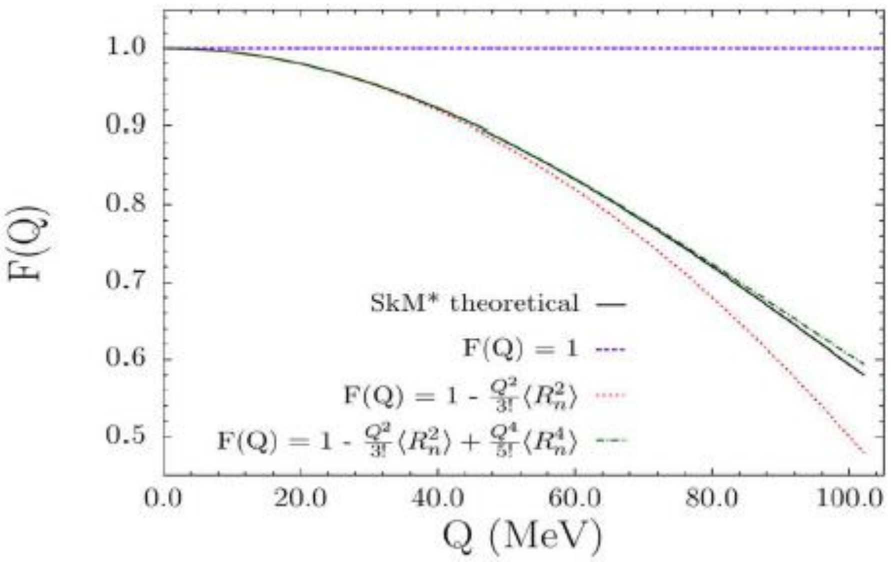
Supernova modelling and detection



Neutrino floor/fog in DM experiments



Leszek Roszkowski, Enrico Maria Sessolo, Sebastian Trojanowski arXiv:1707.06277



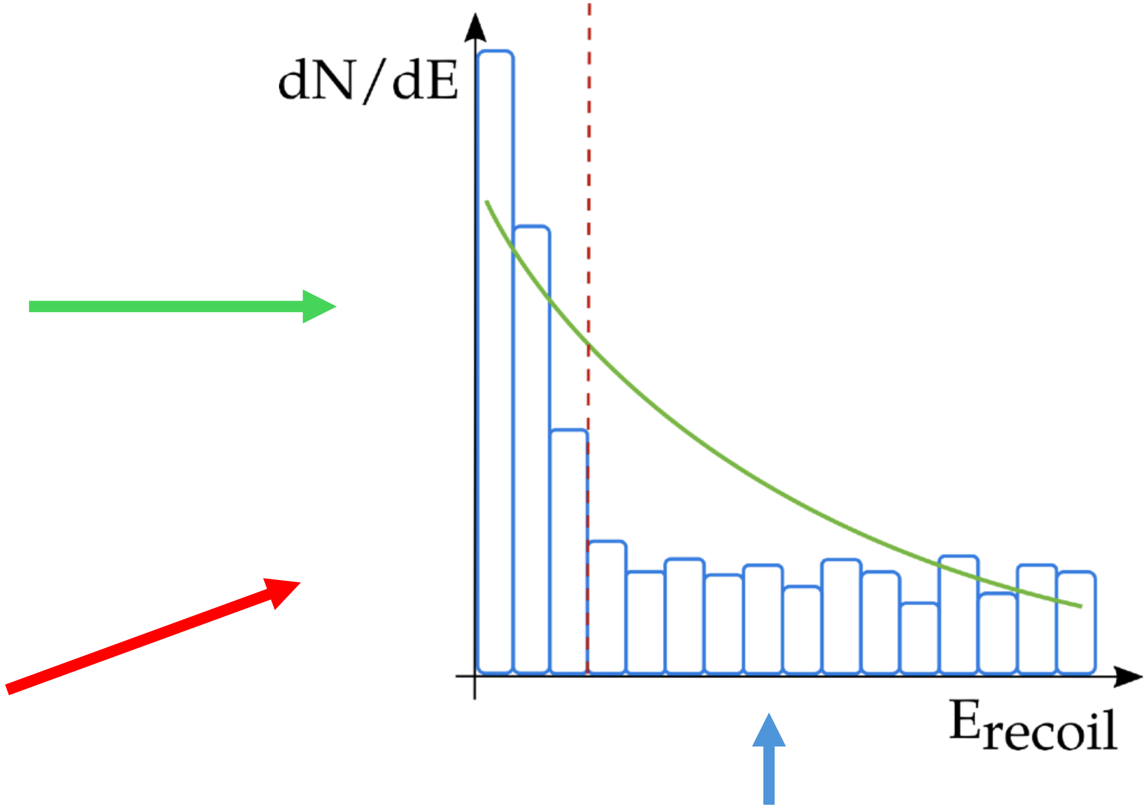
Measurement of nuclear form factors

The CONUS+ experiment

arXiv:2407.11912

N. Ackermann, H. Bonet,
C. Buck, J. Hakenmüller, J. Hempfling,
G. Heusser, M. Lindner, W. Maneschg,
K. Ni, T. Rink, E. Sanchez Garcia,
H. Strecker
Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany
K. Fülber, R. Wink
PreussenElektra GmbH, Kernkraftwerk Brokdorf (KBR), Germany
M. Rank, I. Stalder, J. Woenckhaus
Kernkraftwerk Leibstadt AG (KKL), Switzerland

Our approach



High signal strength

- High neutrino flux
  (i.e. proximity to source)
- Optimal choice of target isotope

Very low threshold

- Signal is expected to be < 1 keV (at reactor site) due to quenching
- Optimise noise edge
- Optimise trigger efficiency

Very low background

- Combination of active and passive shielding
- Choose extremly radiopure materials

The CONUS+ location

- Nuclear power plant KKL in Leibstadt, Switzerland (3.6 GW, operational 11 months per year)

- 20.7 m distance from reactor core
  → **neutrino flux: $1.45 * 10^{13}\ \overline{\nu_e}\ s^{-1}\ cm^{-2}$**

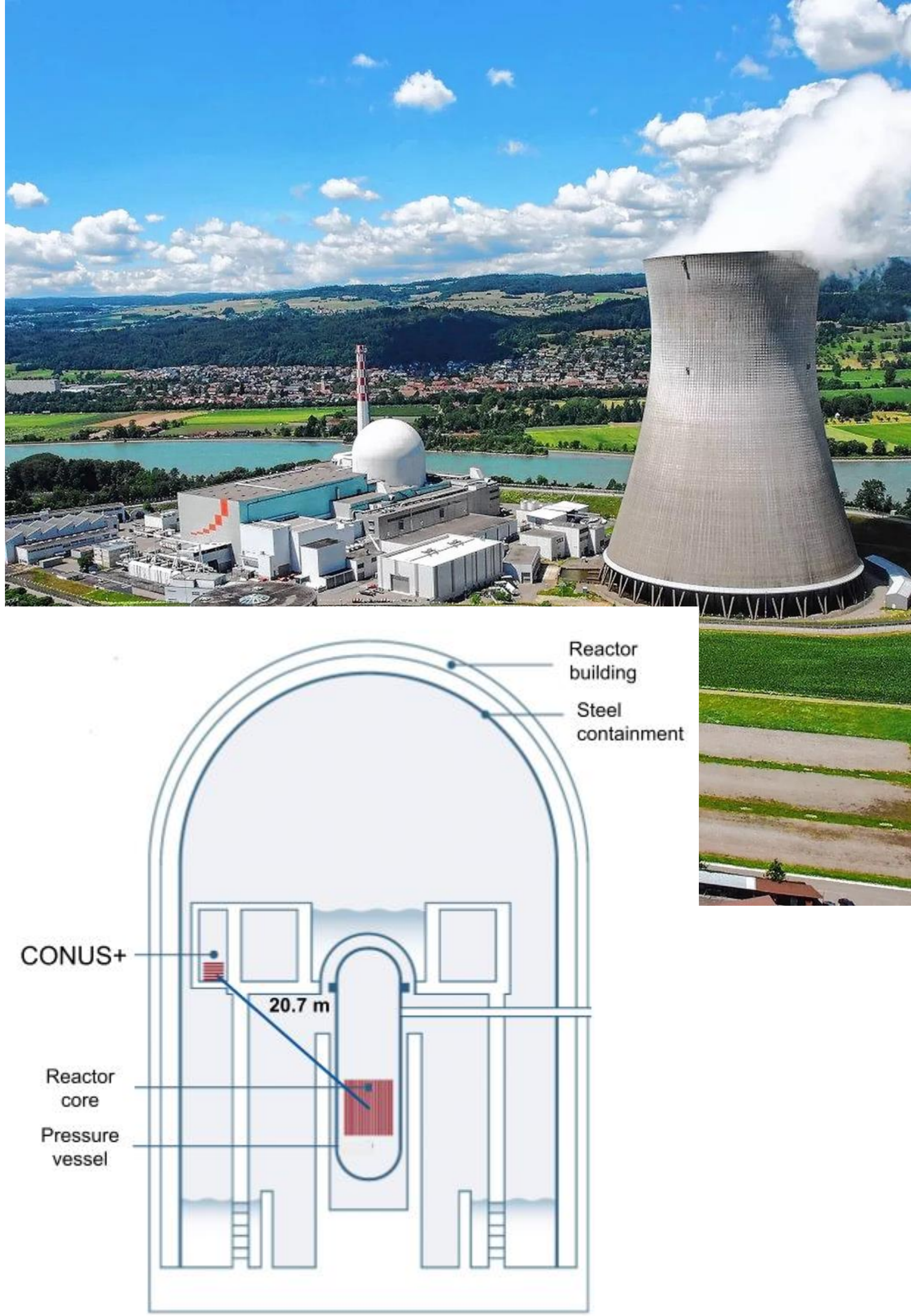
- Direct network connection to MPIK

- **Overburden: 7 – 8 m w.e.**

- Reactor building made from 1.2 m reinforced concrete and 3.8 cm steel containment structure

- 0.35 m thick ceiling in the room

- **In reactor outage**:
  drywell head placed above our room
  → additional overburden of 3.8 cm steel



CONUS+ shield

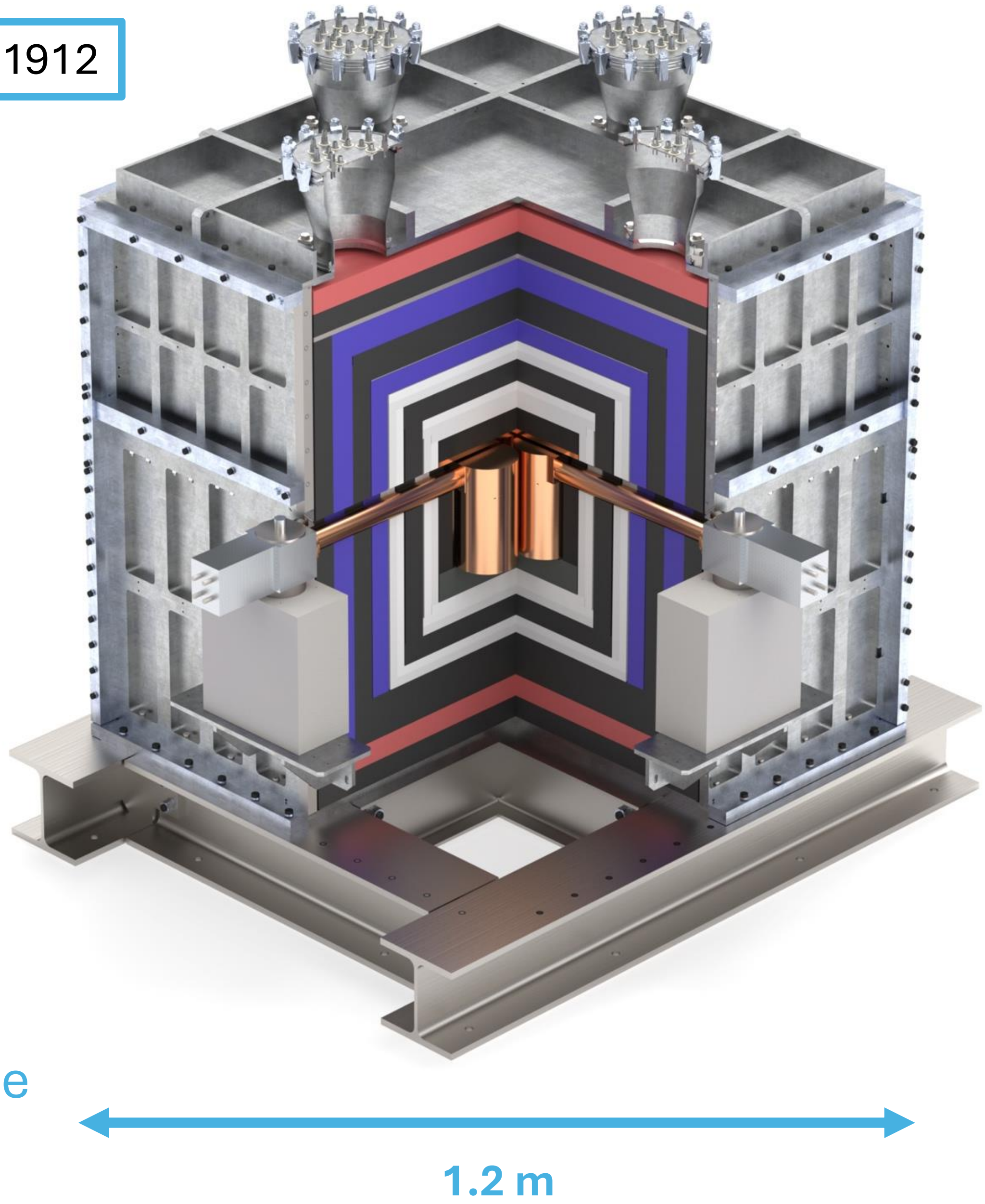
arXiv:2407.11912

- 10 tons in total
- Onion-like shield w/ active and passive layers (increasing radiopurity towards the center)

- Two layers of muon veto: one inner and one outer
  → to account for higher muon flux compared to CONUS

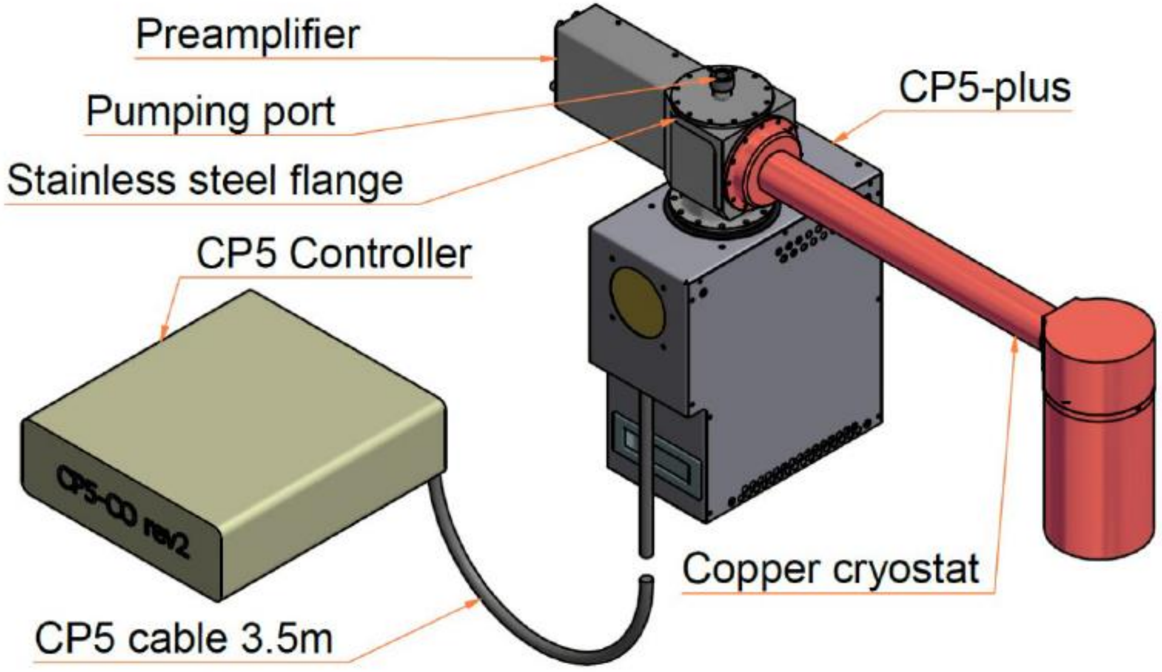
- Several lead layers for gamma suppression
- Several PE (and borated PE) layers for neutron suppression
- Flushing of detector chamber with radon-free air

→ Total background reduction by 4 orders of magnitude



CONUS+ Ge detectors

- 4 point-contact high purity Ge detectors
(C5, C2, C3 & C4, + C1 at MPIK)
- Crystal/active mass: 4.0 kg / 3.74 kg
- Low energy threshold: ~ 160 eV
- Electrically cryocooled
(No liquid nitrogen allowed in power plant)
- Ultra radiopure materials
- Long cryostat arms
- Produced in cooperation with Mirion Lingolsheim



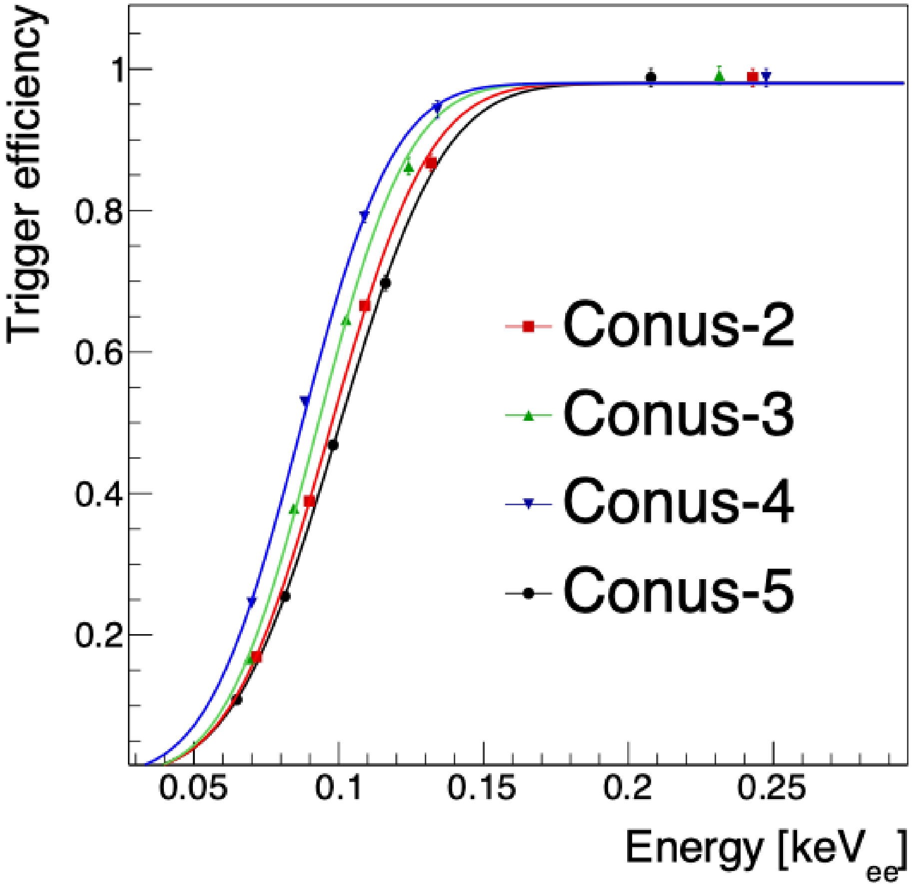
Upgrades after CONUS:

ASIC electronics & reduction of point contact size
→ significant improvement in resolution, trigger efficiency and threshold

Improved heat dissipation from electric cooler (fans → water cooling)
→ Less microphonics

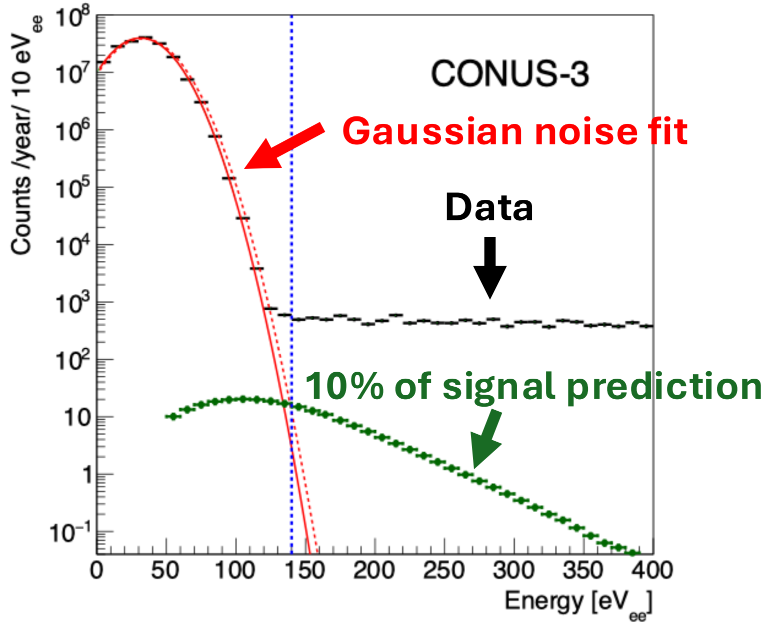
Detector performance

Detector	Pulser resolution (FWHM) [$\mathrm{eV_{ee}}$]	100% trigegr efficiency down to	Threshold [$\mathrm{eV_{ee}}$]
C5	48 +- 1	~ 170 $\mathrm{eV_{ee}}$	170
C2	47 +- 1	~ 160 $\mathrm{eV_{ee}}$	180
C3	47 +- 1	~ 150 $\mathrm{eV_{ee}}$	160
C4	47 +- 1	~ 150 $\mathrm{eV_{ee}}$	-

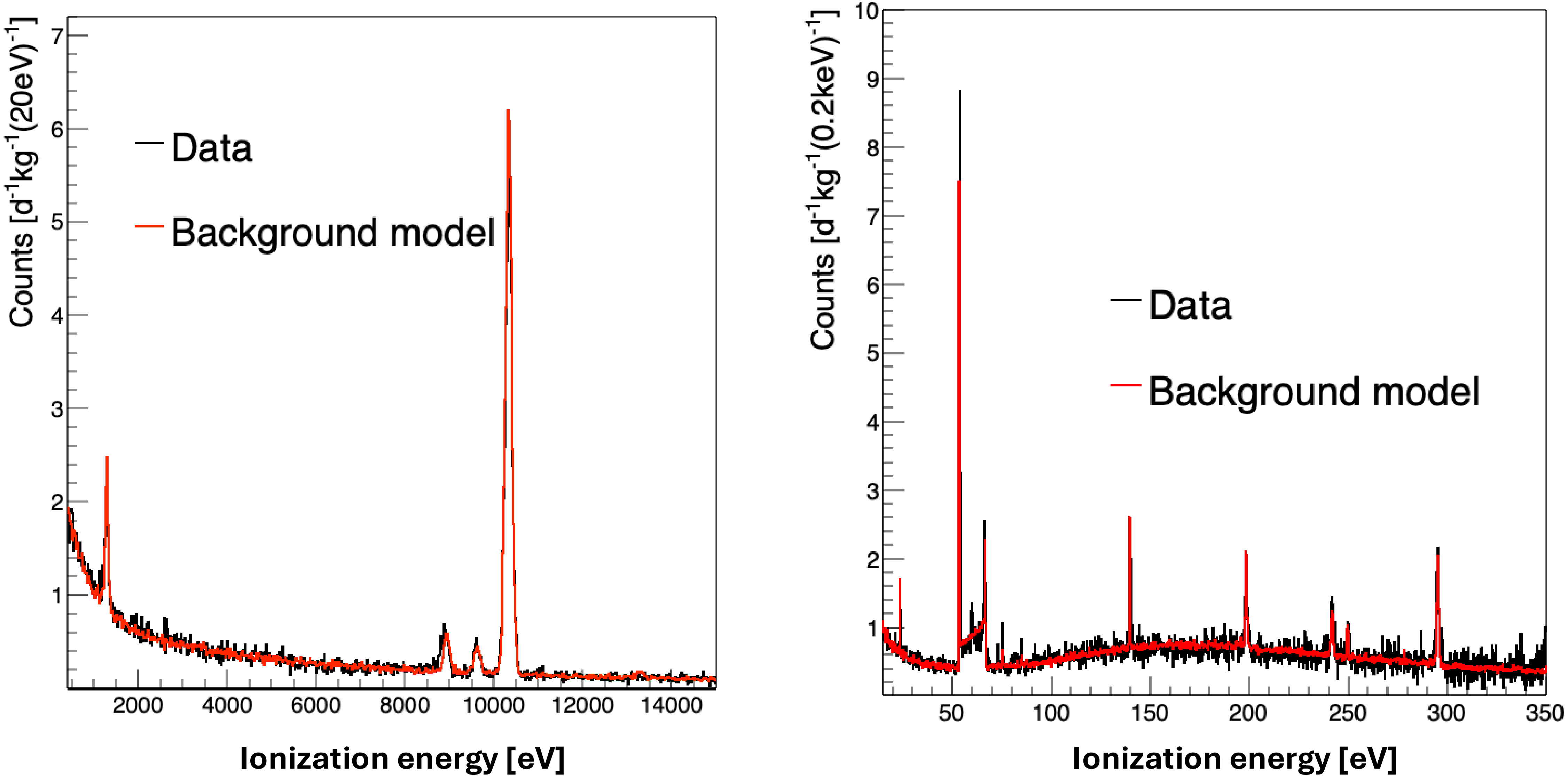


Threshold definition:

Noise contribution
(fitted with Gaussian)
<=
10% of expected CEvNS signal



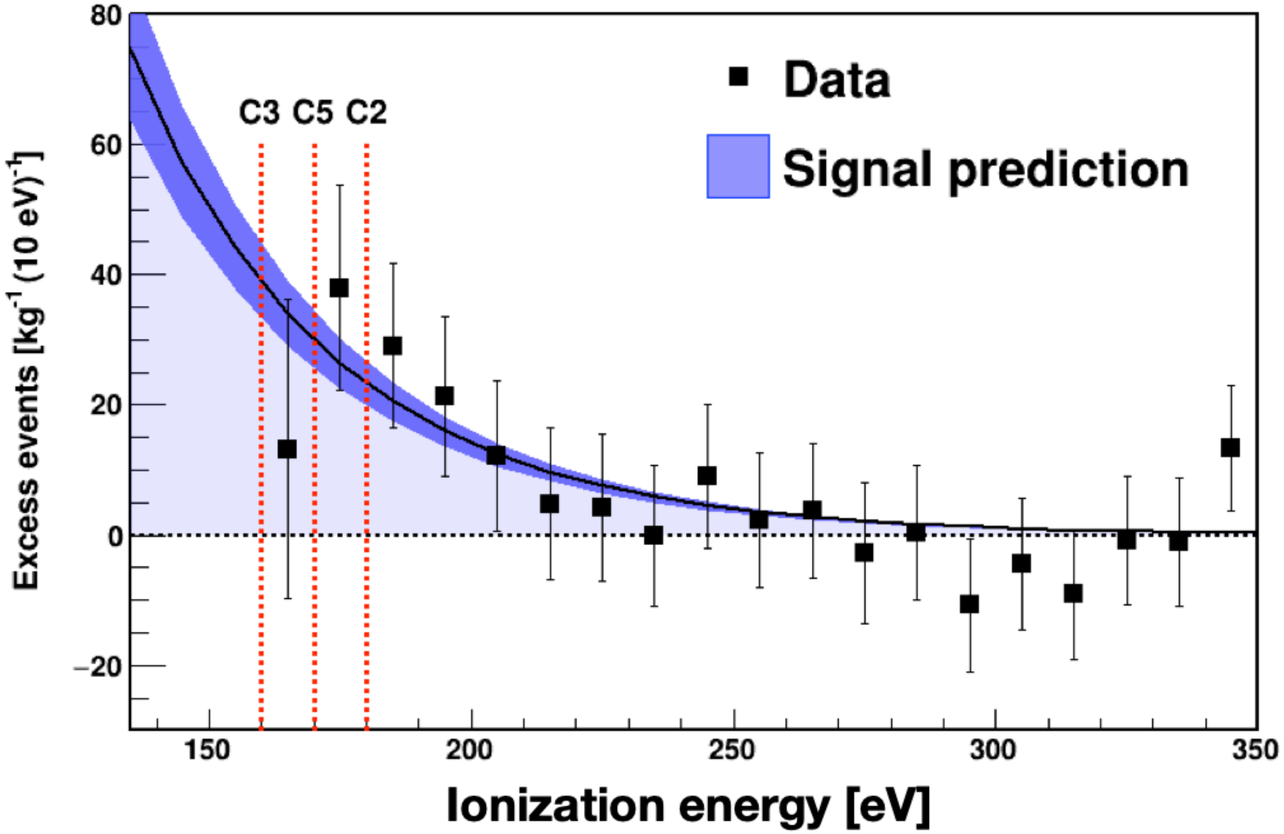
Full decomposition of background achieved!



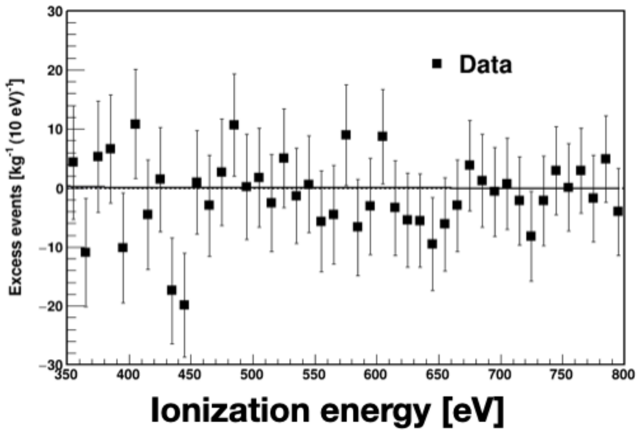
The CONUS+ result

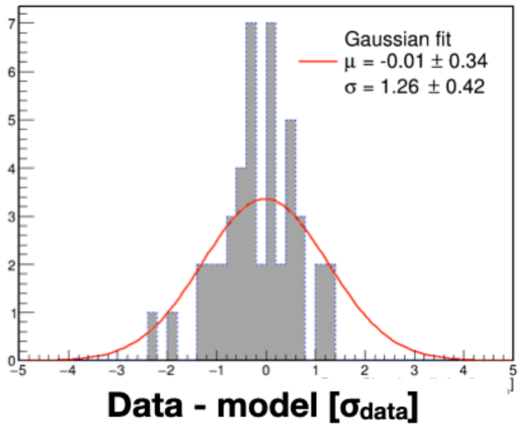
Excess in data over background model below 350 eV

Consistent with signal prediction



No excess above 350 eV





Result of likelihood fit

Detector	Threshold [eV_ee]	CEvNS counts in data	SM prediction
C5	170	117 +- 57	116 +- 20
C2	180	69 +- 47	96 +- 16
C3	160	186 +- 66	135 +- 23

Result of single detector fits

Number of CEvNS counts in combined fit = 395 +- 106 counts

Combined result includes systematics not included in single detector fits

arXiv:2501.05206

→Rejection of null hypothesis at 3.7 sigma C.L.

→ Consistent with SM prediction (345 +- 34 counts) within 0.5 sigma C.L.

First detection of CEvNS by reactor antineutrinos

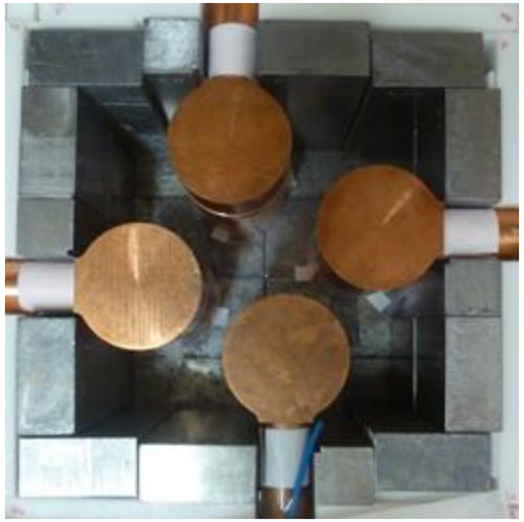
Summary

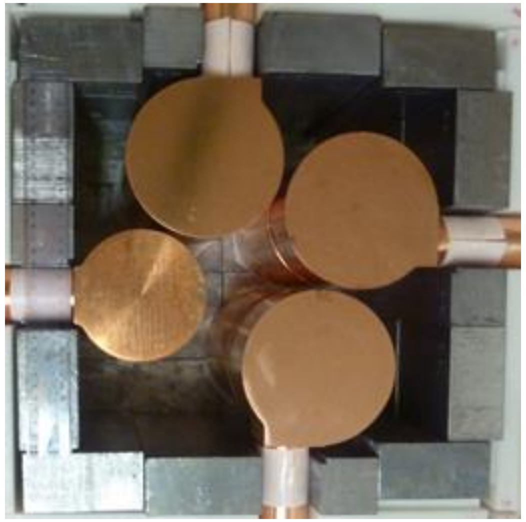
- CONUS concluded in 2022 at KBR → successful move to KKL in Switzerland

- Start of physics data taking in Nov. 2023
  - **New location**: less overburden → adaptations on shield and bkg. Model
  - **Detector upgrade**: improvement in energy resolution and trigger efficiency
  - Direct conenction to experiment possible → remote control of data acquisition

- First detection of CEvNS at reactor site:
  - Total exposure: 327 kg d ON, 60 kg d OFF
  - Observed: 395 +- 106 neutrinos (SM: 347 +- 95)
  - Rejection of null hypothesis: 3.7 sigma

CONUS+ outlook - Detector upgrade and future analysis





- Exchange three 1 kg detectors with new 2.4 kg PPC Ge detectors:
  C9, C7 and C6 (installed 11/24, taking data)
  Crystal mass: 4 kg → 8.2 kg
- Better cryocooler stability with new coolant
- Slight background improvement in new detectors
- Thresholds at least as low as in previous detectors

Data set expected to be doubled and significant improvement of result expected to be reached!

Upcoming analysis of current data set:

- PSD cut to be studied
- BSM analysis coming in the near future

CONUS+ technology established → Upscaling to 100 kg possible:
500,000 evts/5 y → precision measurement of CEvNS

BACKUP

Consequences of cross section

$$\sigma \sim N^2 E_\nu^2$$

Maximize E_ν

BUT: Coherency condition!

$$E_\nu \leq \frac{1}{2R_A} \approx \frac{197}{2.5\sqrt[3]{A}}\ [\text{MeV}] \approx 20\ \text{MeV (Ge76)}$$

→ Partially vs fully coherent experiment

→ Complementary!

Maximize N

BUT: Maximum recoil energy

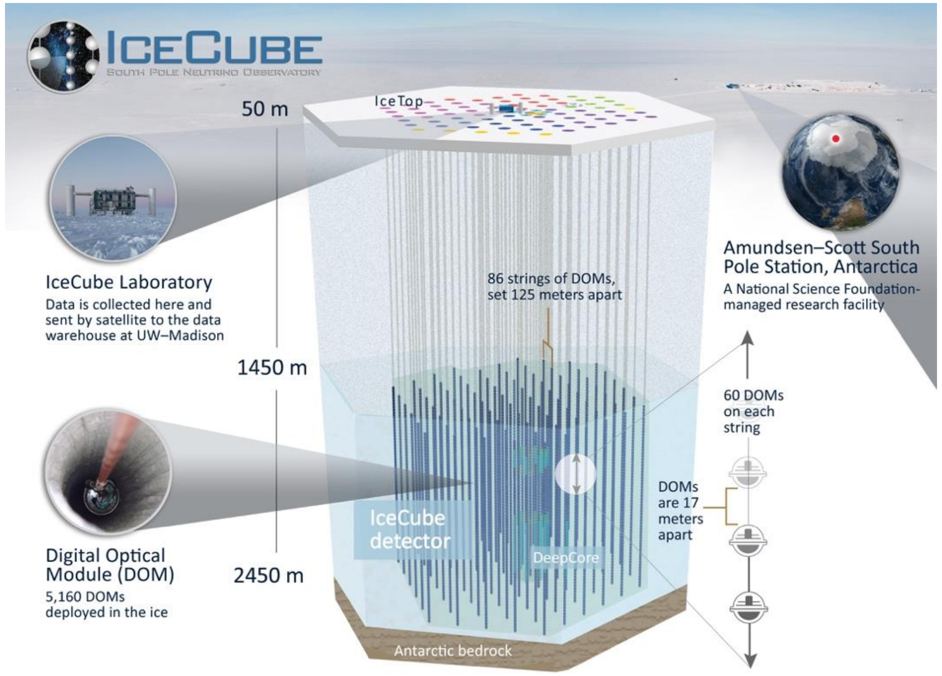
$$E_{rec}^{max} = \frac{2 \cdot E_\nu^2}{m_n \cdot A + 2 \cdot E_\nu} \approx \frac{2 \cdot E_\nu^2}{m_n \cdot A}$$

Higher recoil energy → Higher energy signals

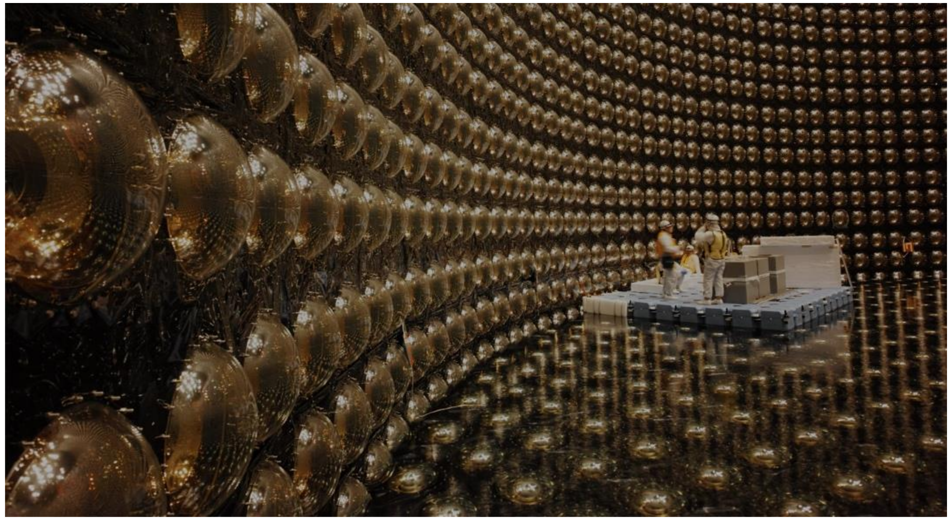
→ Easier to measure

→ Push-Pull situation when selecting target isotope

Typical neutrino experiments: Large target mass due to low cross sections

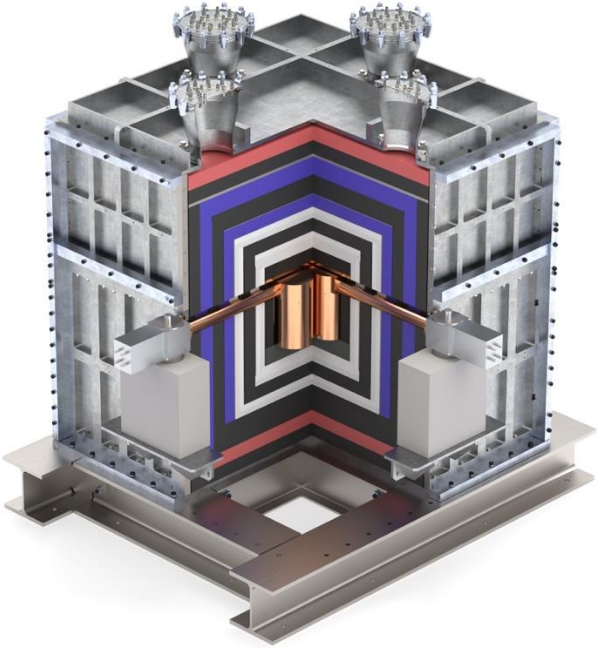


Size of 1 km^3



50,000 tons of water

VS.



<u>CONUS+:</u>

Size ~ 2 m^3

Active volume ~ 4 kg

→ Possible due to CEvNS channel!

The final CONUS result

Predecessor of CONUS+

Data collection from 2018 – 2022
at KBR power plant (Brokdorf, Germany)

Detector	Signal prediction	Likelihood fit constraint (90% CL)
C1	41 +- 8	< 47
C2	26 +- 5	< 67
C4	23 +- 5	< 79
All	91 +- 10	< 143

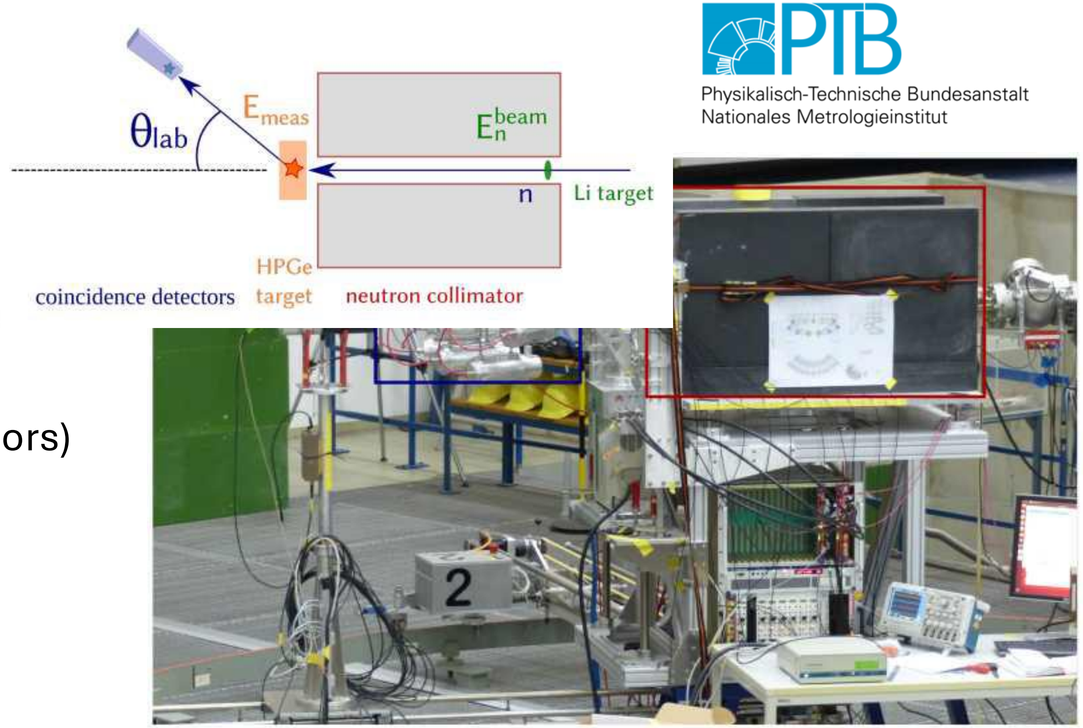
→ Factor ~ 1.6 (90% C.L.) above SM prediction

KBR was shut down permanently in 2021
→ Search for a new location

Phys. Rev. Lett. **133**, 251802 (2024)

Quenching of CEvNS signal

Physikalisch-Technische Bundesanstalt
Nationales Metrologieinstitut



CEvNS interaction in Germanium → recoil of Ge nuclei

BUT: The observable of the CEvNS process is only the part of the energy that turns into ionisation of atoms in the Ge crystal lattice
(Other part goes into phonons/heat → not measurable by our detectors)

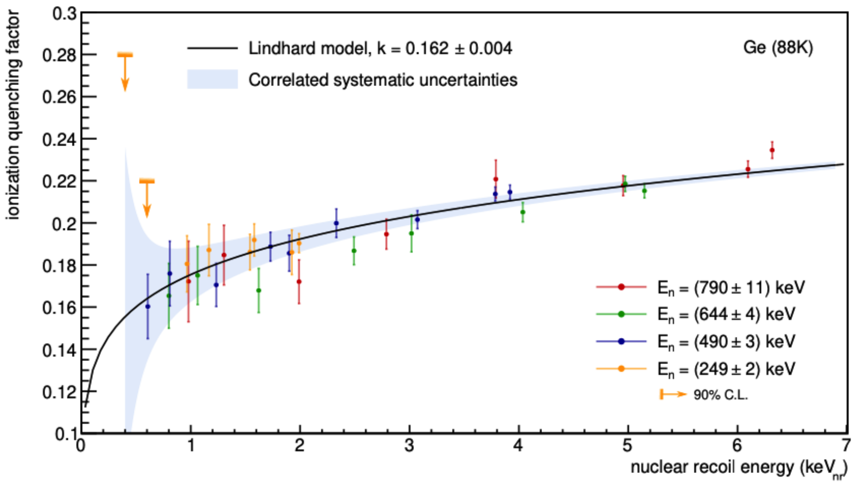
$$\text{Quenching factor} = \frac{E_{ion}}{E_{rec}}$$

Energy dependent!

Knowledge of quenching factor is crucial for the signal prediction!

→ Very important systematic, but previously very large uncertainties for E_{rec} < 10 keV

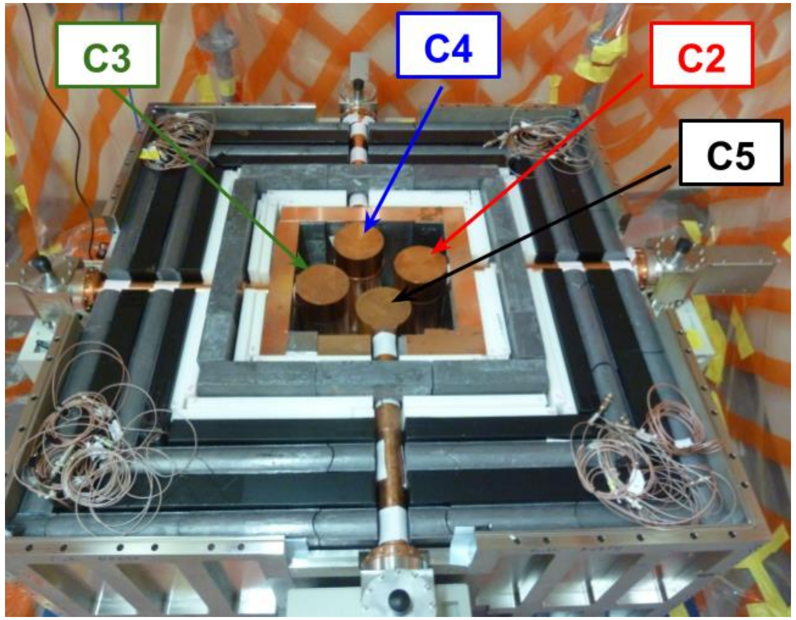
→ Dedicated quenching measurement by CONUS



Result consistent with Lindhard theory with k = 0.162 +- 0.004

Eur. Phys. J. C 82, 815 (2022)

Installation of CONUS+



Dec 2022
CONUS in KBR completed. Ge refurbishment

Apr 2023
KBR dismantling. KKL on site preparations

Jul 2023
Detector tests at MPIK. Final installation campaign

Aug 2023
Commissioning

Nov 2023
First physics run started

May 2024
First reactor off data produced

Nov 2024
Detector swap

Full Background model (C5, [400 – 1000] $\mathrm{eV_{ee}}$)

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)

Background Model C2

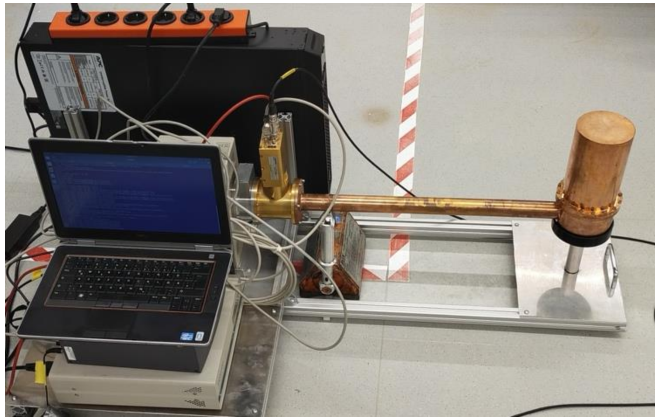
Component	Contribution ON [counts/d/kg]	Contribution OFF [counts/d/kg]
Muons	16.5 +- 0.3	16.4 +- 0.3
Neutrons	21.6 +- 3.1	17.7 +- 2.5
Muon-induced neutrons in overburden	2.2 +- 0.1	1.8 +- 0.1
Cu cosmogenics	4.4 +- 0.4	4.4 +– 0.4
Pb210 in cryostat	< 0.1	< 0.1
Pb210 in shield	0.1 +- 0.02	0.1 +- 0.02
Ge cosmogenics	0.2 +- 0.02	0.2 +- 0.02
Metastable Ge states	0.1 +- 0.01	0.1 +- 0.01
Radon	2.8 +- 0.1	0.7 +- 0.1
Kr85	< 0.1	< 0.1
H3	1.3 +- 0.2	0.5 +- 0.2
Xe135	0.1 +- 0.01	< 0.1
Leakage component	3.0 +- 0.5	3.0 +- 0.5
Total	52.3 +- 3.3 (DATA = 50.7 +- 1.2)	45.1 +- 2.7 (DATA = 45.3 +- 1.3)

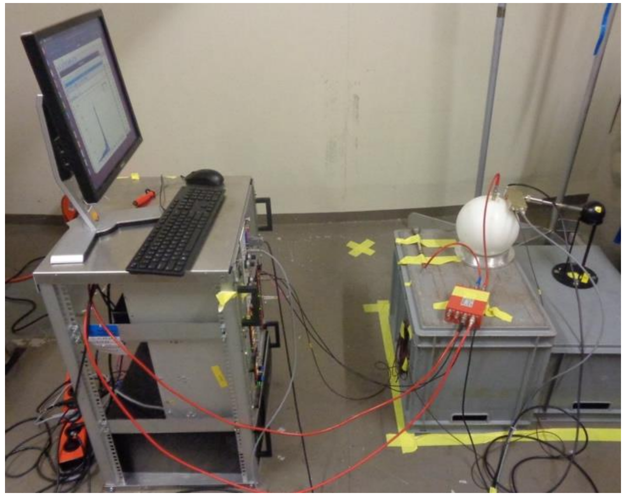
Background Model C3

Component	Contribution ON [counts/d/kg]	Contribution OFF [counts/d/kg]
Muons	16.5 +- 0.3	16.4 +- 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	3.6 +- 0.4	3.6 +– 0.4
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	2.6 +- 0.1	0.7 +- 0.1
Kr85	< 0.1	< 0.1
H3	1.3 +- 0.2	0.5 +- 0.2
Xe135	0.1 +- 0.01	< 0.1
Leakage component	0.8 +- 0.2	0.8 +- 3.1
Total	49.3 +- 3.1 (DATA = 48.8 +- 1.2)	42.2 +- 2.7 (DATA = 42.5 +- 2.0)

Background characterization of location

Done in preparation for move to Leibstadt



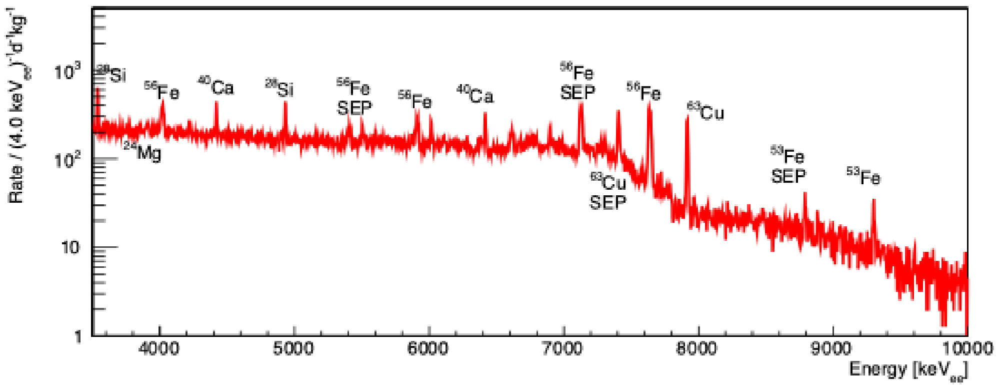


- Gamma measurement with HPGe detector (CONRAD)
- Neutron measurement with Bonner Sphere Array
- Environmental parameters (Radon, temperature ...)
- Cosmic muons with liquid scintillator
- Wipe tests to measure surface contamination
- Vibrations with piezoelectric sensors

arXiv:2412.13707

Background characterisation: Results

Gammas

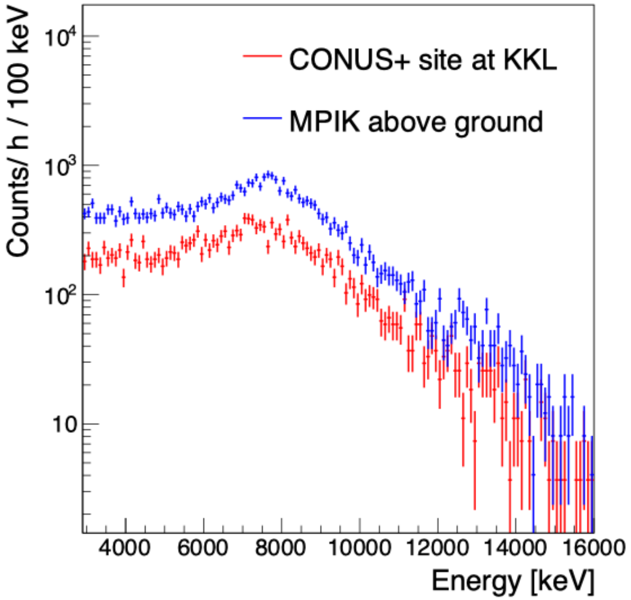


Muons

Muon rate in CONUS+ room:
(107 +- 3) counts/s/m^2

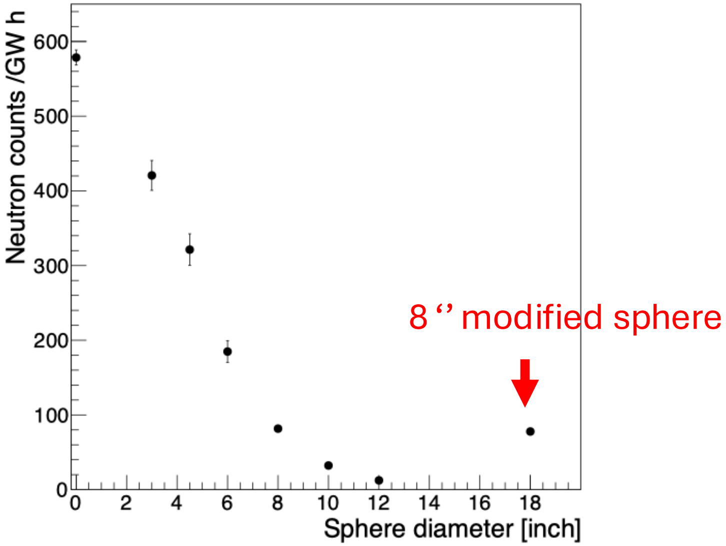
→ factor 1.9 reduction compared to outside

→ 7.4 m w.e. overburden



Neutrons

Energy region	$\phi\ (cm^{-2}\ (GW\ h)^{-1})$
Thermal	172.1 +- 16.3
intermediate	91.6 +- 6.3
Fast + cascade	1.0 +- 0.8
Total	264.7 +- 13.2

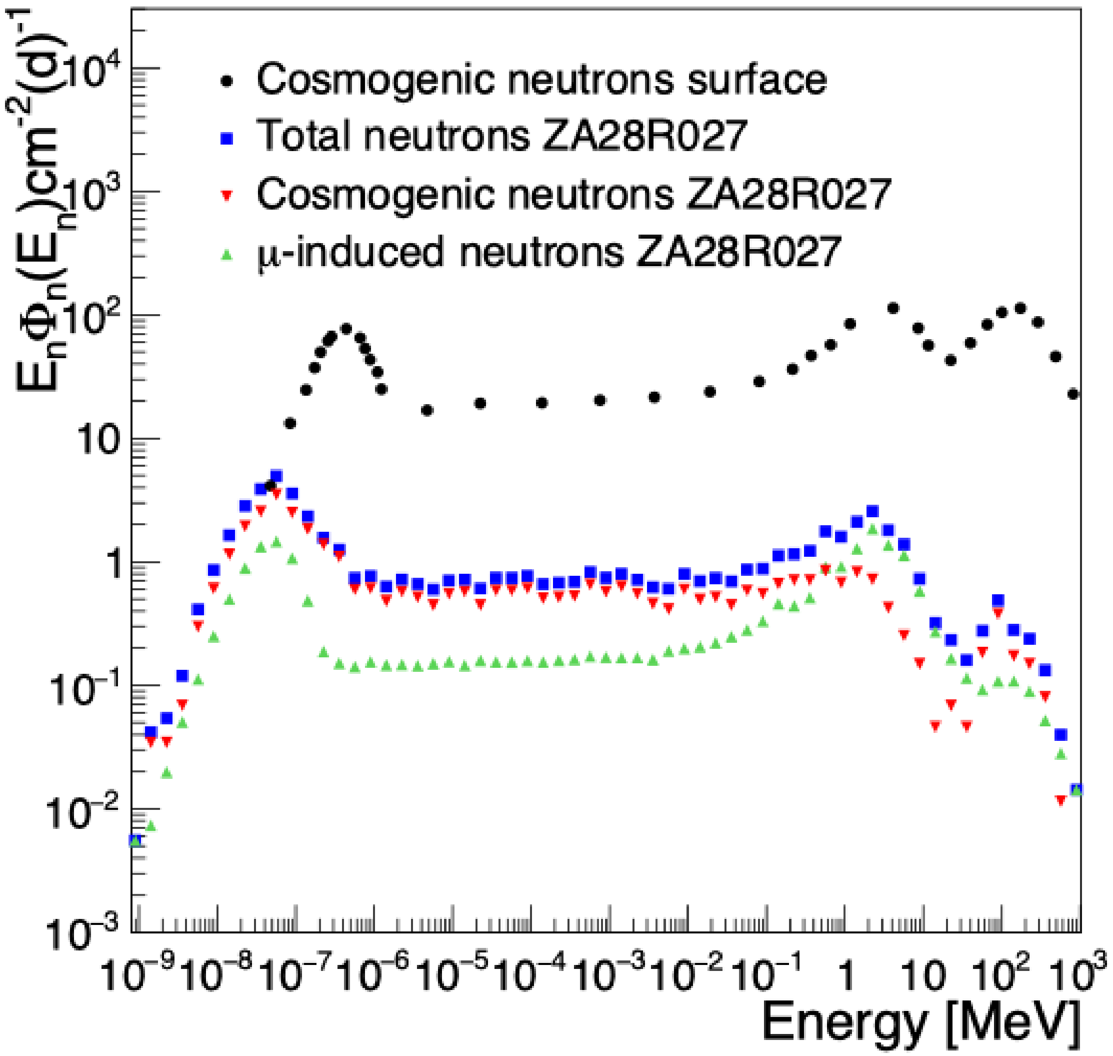


Cosmic neutrons

- Typical cascade peak at 100 MeV
- Not very well distinguishable from reactor neutrons due to very low flux and degeneracy in response functions of Bonner spheres
- Had to be simulated with model of reactor building and neutron flux from literature
- Result: 0.9 +- 0.2 neutrons/d/cm^2 in [20, 1000] keV

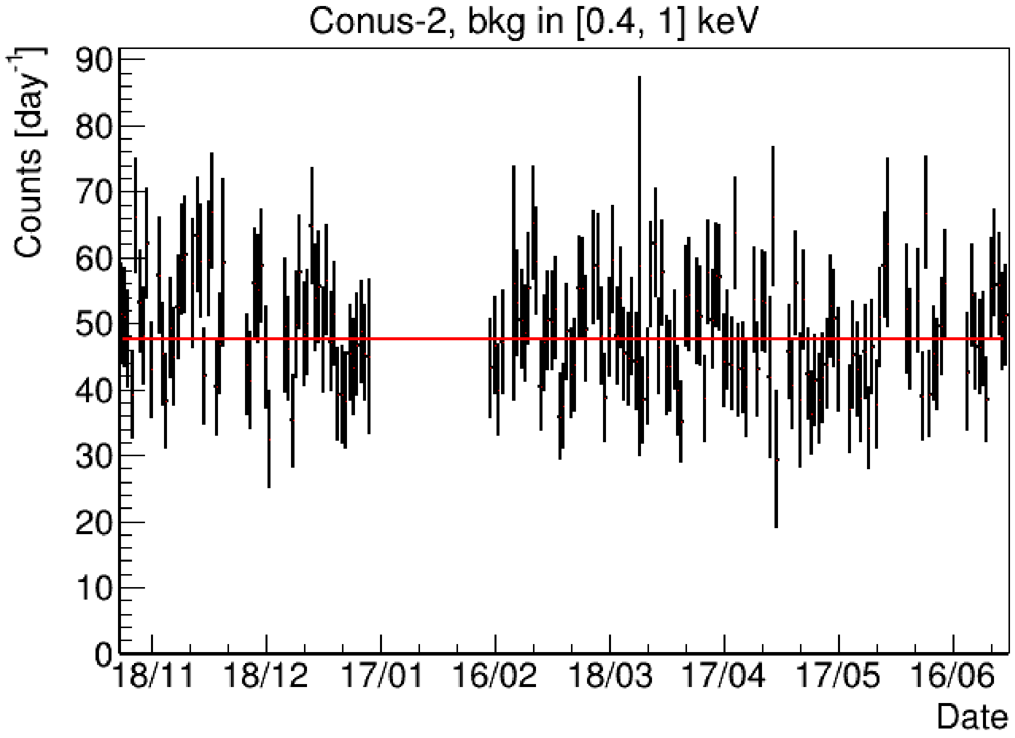
→ Small flux but not completely suppressed by overburden

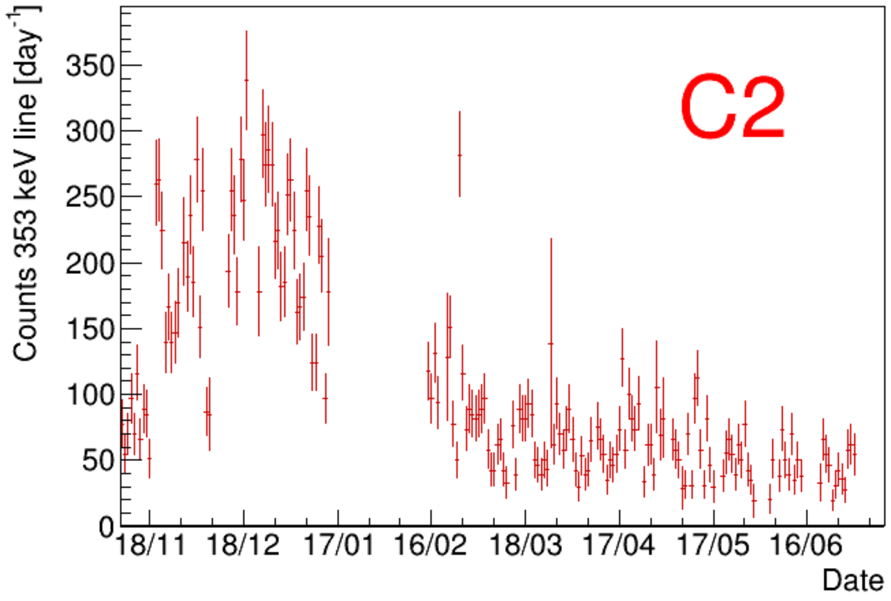
→ Important impact on CONUS+ background model



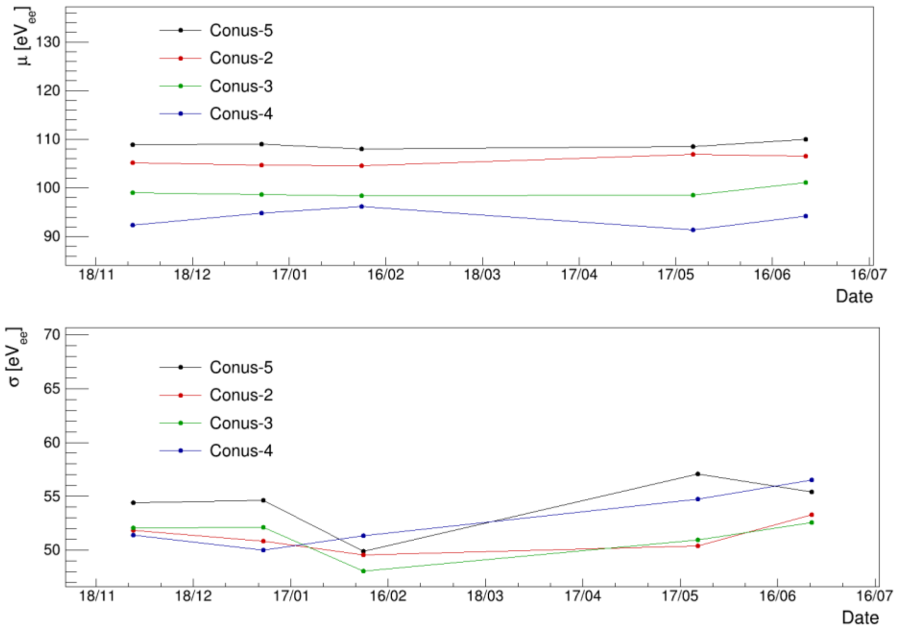
Data stability

Excellent data stability reached during the whole run!





Rate in radon line (C2)



Trigger efficiency parameters

Data processing

Overview of applied cuts

1. Rejection of time periods:

- High radon level (no flushing)
- High noise rate (due to grounding problems → exclusion of C4)
- Instabilities in noise peak
- Periods with more microphonic events
- Period of reactor shutting off/turning on

2. Applied cuts to data

- Muon veto anticoincidence cut with time window of 450 μs
- TRP cut: remove events immediately after pre-amplifier reset (window: 500 – 2000 μs)
- Microphonic cut
- Anticoincidence cut between detectors

Induced dead times

- Muon veto dead time = veto rate * time window
- TRP dead time = TRP rate * time window
  → cuts are correlated: overall dead time = 11%-13%

- DAQ dead time: lost events during saturation and trigger holdoff
  → dead time < 2%

Overall live time during Run 1:

ON: 119 d OFF: 19 d

Detector upgrades compared to CONUS

Refurbished crystals after dismanteling in KBR:

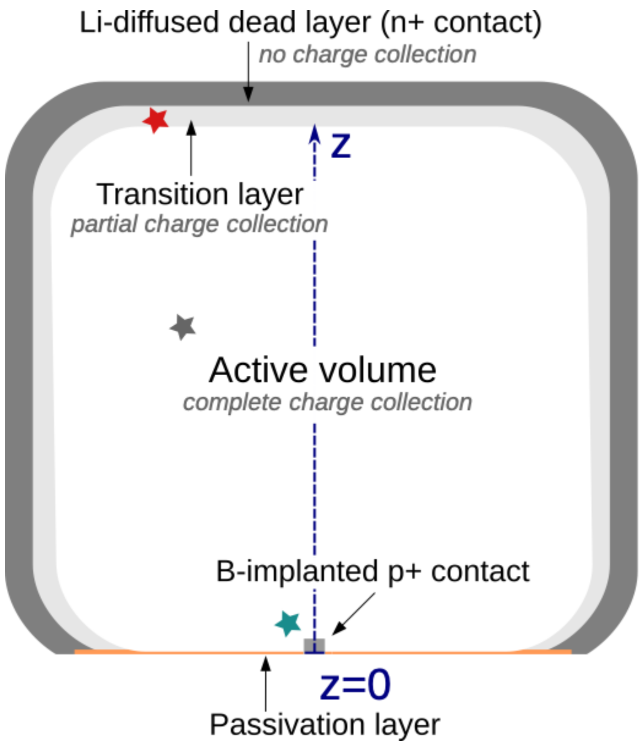
- ASIC based electronics

  → Improve trigger efficiency at low energies

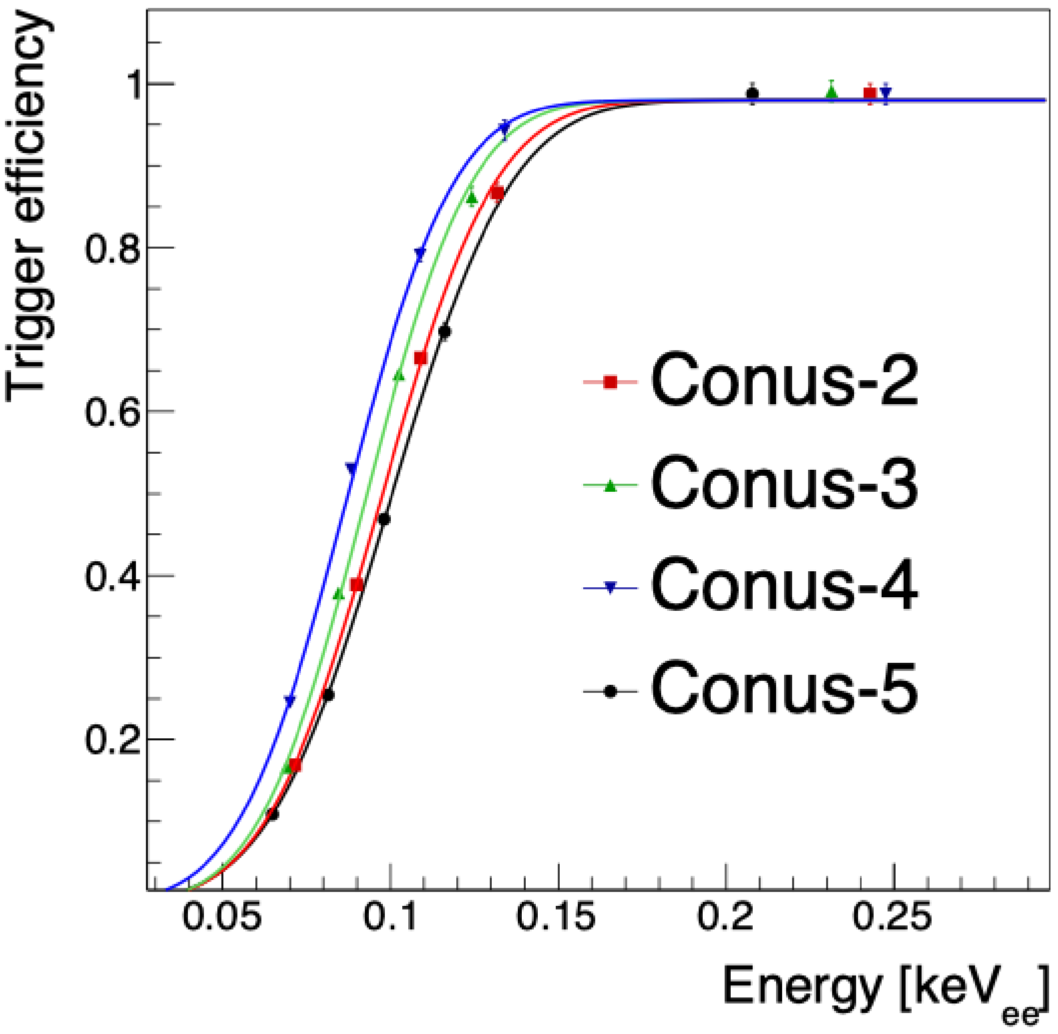
- Large reduction of point contact size and use of bonding techniques for contacting

  → Reduction of electronic noise

→ Substantial improvement of trigger efficiency curve as well as energy resolution and noise edge



Trigger efficiency

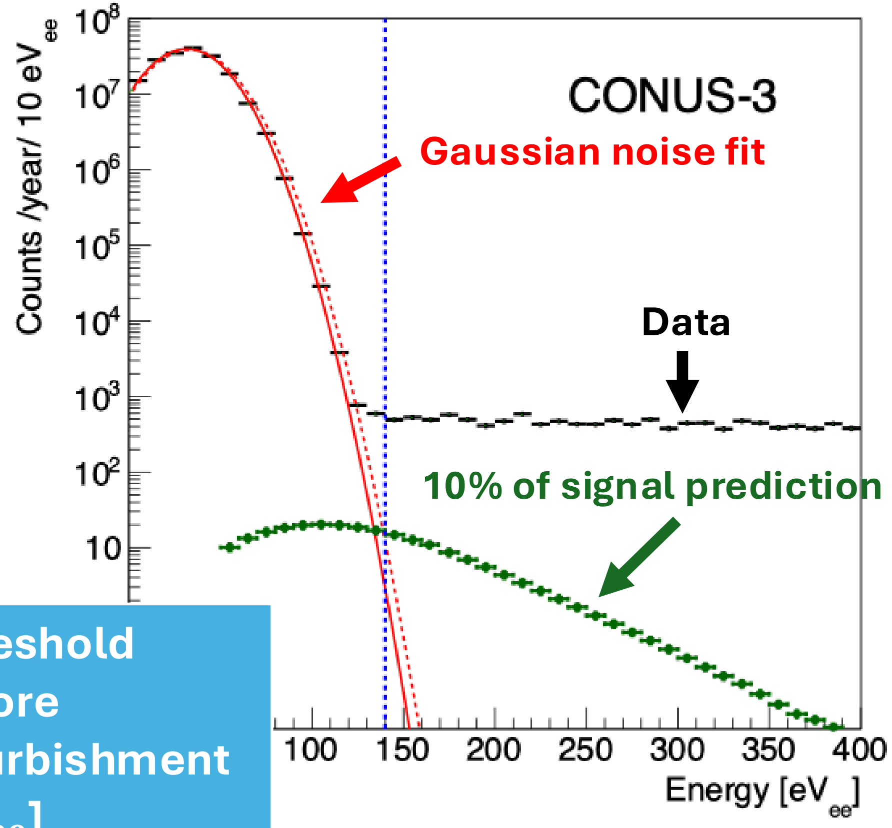


Gives the "probability" that a physics signal of a certain energy is recognized in the detectors

	C4 before refurbishment	**C4 after refurbishment**
100 % down to	~ 500 $\mathrm{eV_{ee}}$	~ 150 $\mathrm{eV_{ee}}$
50 % at	~ 300 $\mathrm{eV_{ee}}$	~ 85 $\mathrm{eV_{ee}}$
20 % at	~ 200 $\mathrm{eV_{ee}}$	~ 65 $\mathrm{eV_{ee}}$

Achieved with CAEN DAQ system

Detector resolution & threshold



Threshold definition:

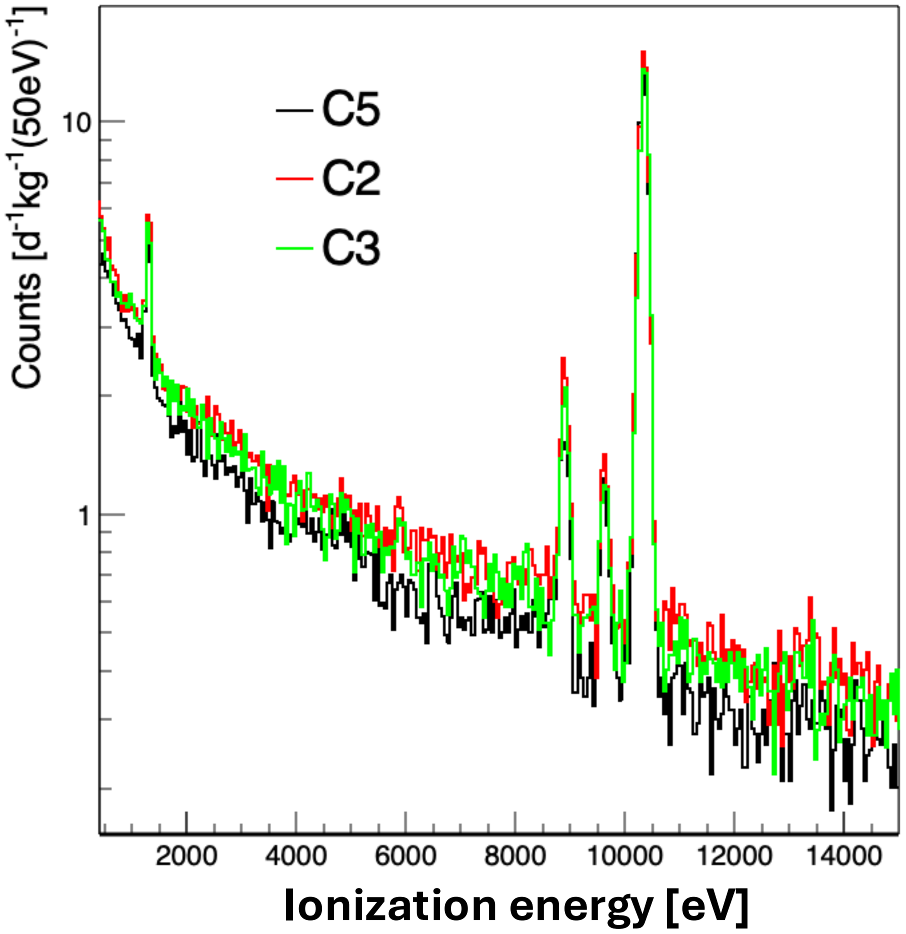
Noise contribution (fitted with Gaussian)
<=
10% of expected CEvNS signal

Detector	Pulser resolution after refurbishment (FWHM) [$\mathrm{eV_{ee}}$]	Pulser resolution before refurbishment (FWHM) [$\mathrm{eV_{ee}}$]	Threshold after refurbishment [$\mathrm{eV_{ee}}$]	Threshold before refurbishment [$\mathrm{eV_{ee}}$]
C5	48 +- 1		170	-
C2	47 +- 1	73 +- 1	180	210
C3	47 +- 1	74 +- 1	160	230
C4	47 +- 1	77 +- 1	-	210

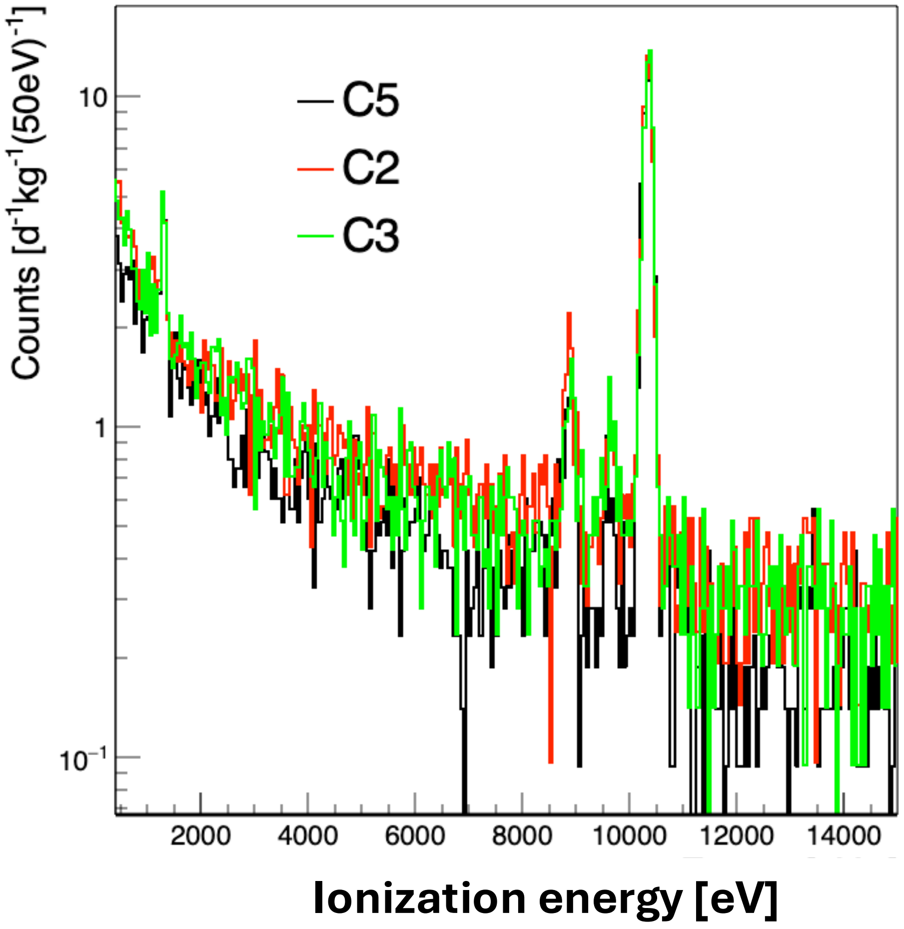
Non-linearity in energy reconstruction of up to ~ 10 eV at very low energies
→ considered in threshold definition

First look at data (0.4 – 15 keV)

Reactor ON



Reactor OFF



Background model

- Full decomposition of background achieved

  → Use of material screening, Monte Carlo simulations and measurements (fully consistent)

- Based on ~ 20 years of experience collected at MPIK

- <u>**Components to investigate**</u>:

From cosmic rays
Very important at shallow depths

Cosmogenic components

Muons and neutrons

Natural radioactivity

External to shield and internal (Radon)

Artificial components

Reactor neutrons, surface contaminations, inert gases (Xe, Kr, H3)

Cosmogenic components - Muons

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

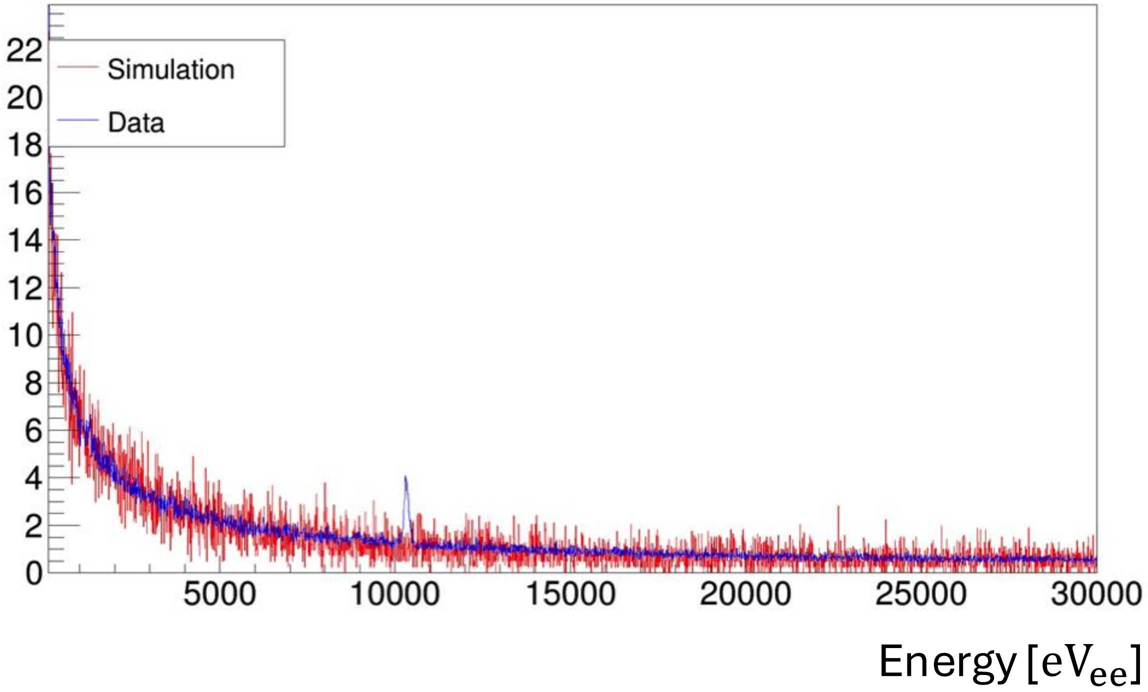
→ Use this to get ”baseline” for muon simulations

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

Factor:
99% at higher energies, but energy dependence at very low E

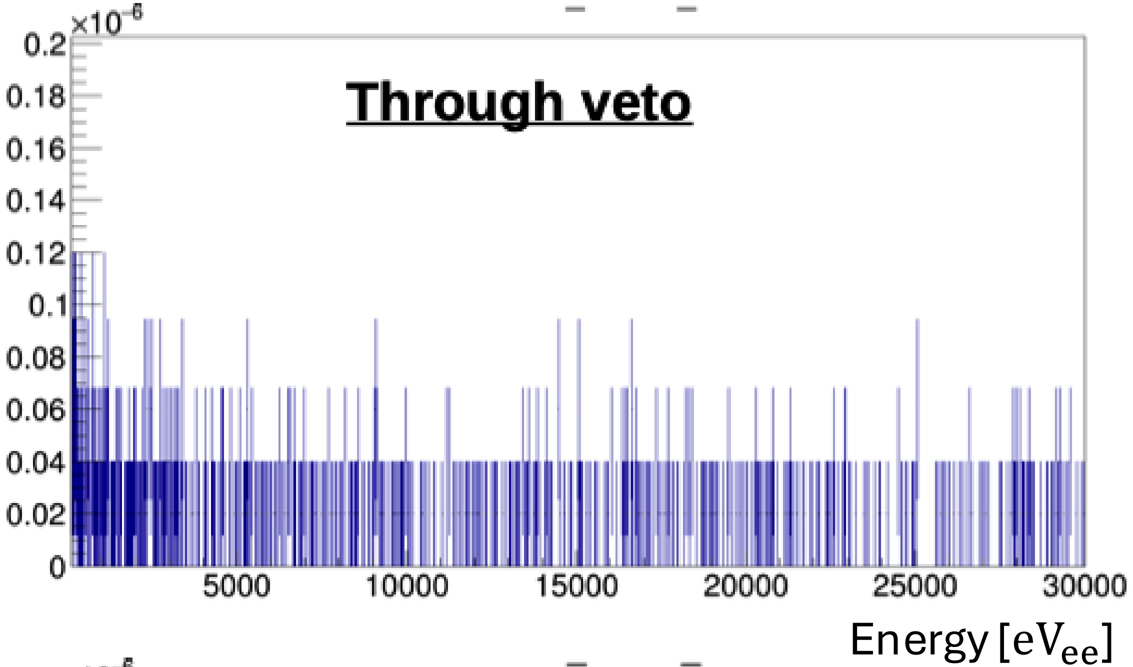


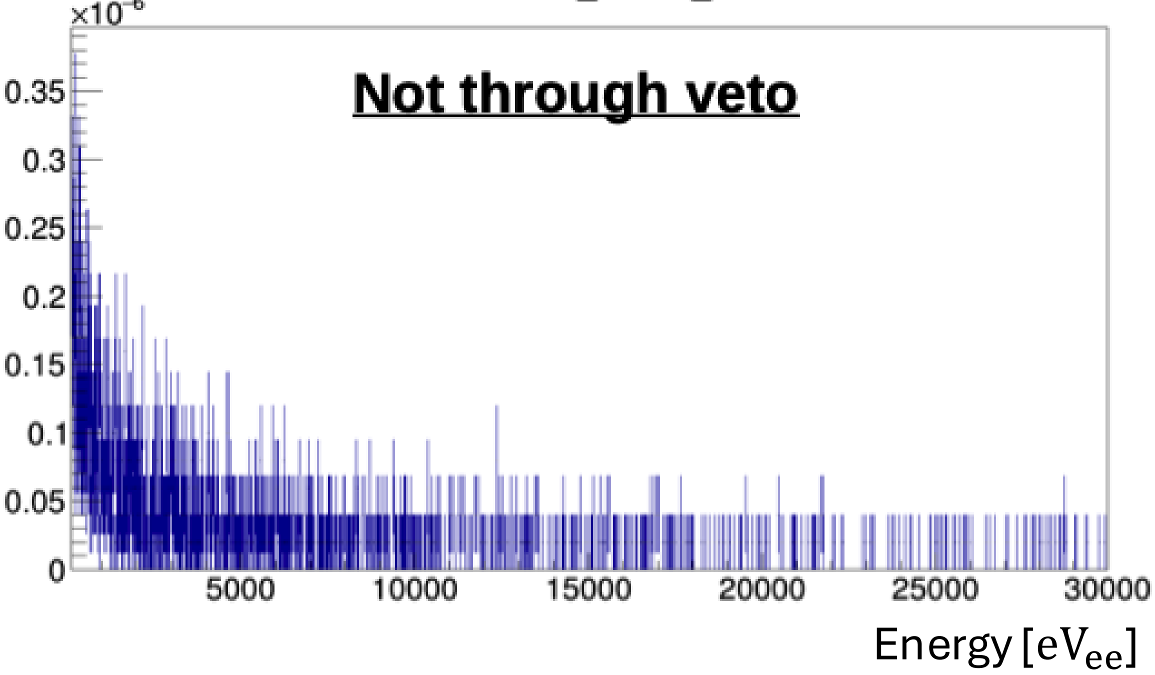
Muon tagging inefficiency at very low E

Simulations show that at very low E (< 400 eV) 80% of muon-induced signals in the crystals come from muons that don’t cross any muon veto plate!

This induces “inefficiency” in the muon veto system because not all of these events will be tagged by the veto!

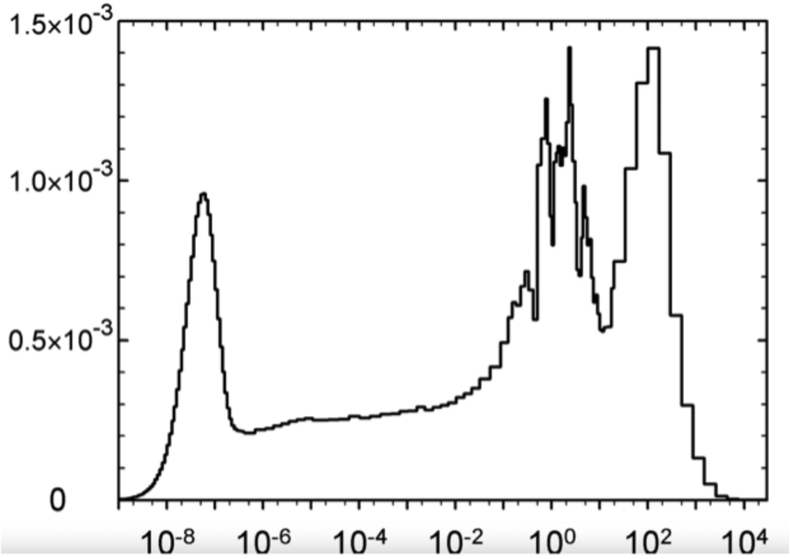
→ Efficiency at low E modeled with polynomial (i.e. 97% < 400 eV)



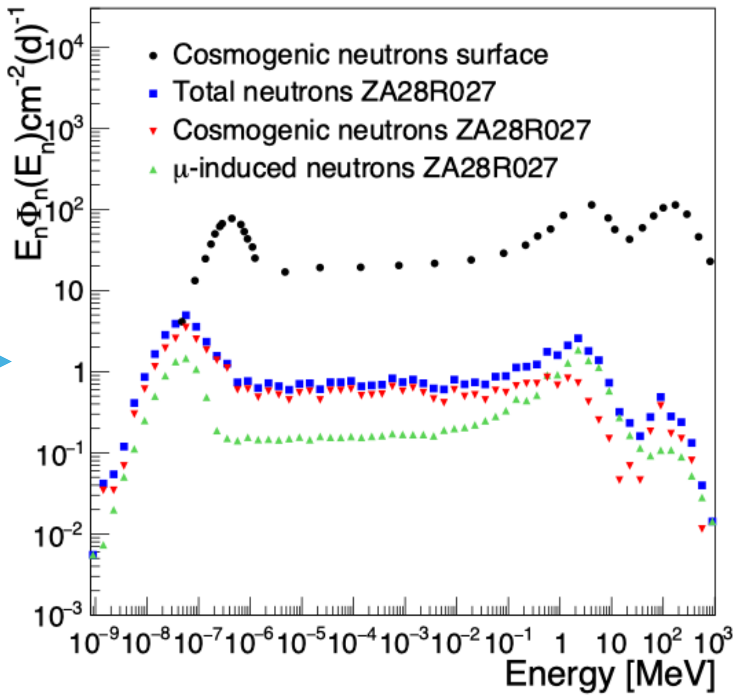


Cosmogenic components – Neutrons

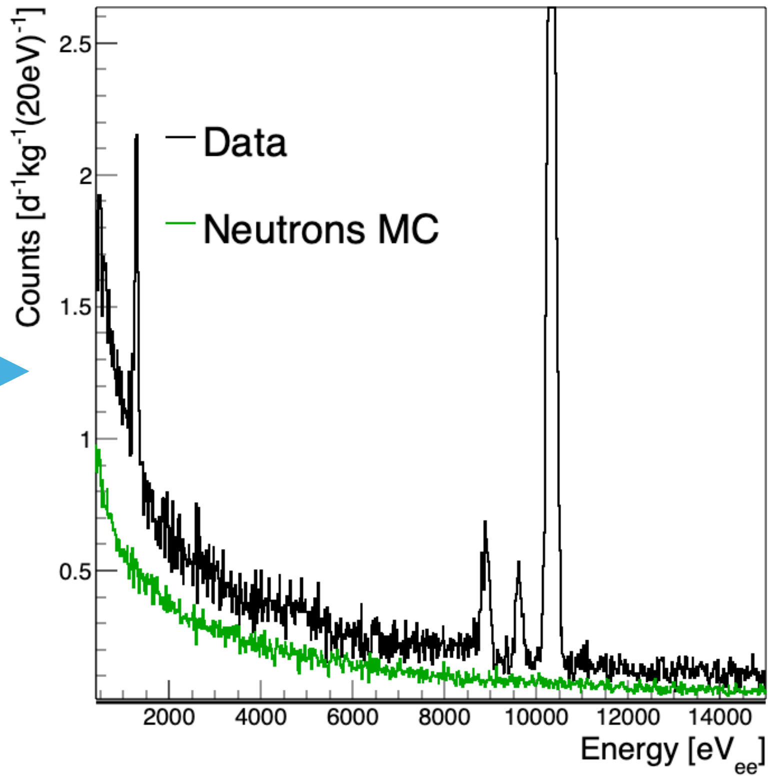
Initial cosmic neutron spectrum with 0.014 neutrons/s/cm^2



→ Cosmic neutrons in room: 0.9 +- 0.2 neutrons/d/cm^2



→ 21.6 +- 3.1 counts/d/kg in [0.4 – 1 $\mathrm{keV}_{\mathrm{ee}}$] (50.3 +- 7.2 % of C5 background)



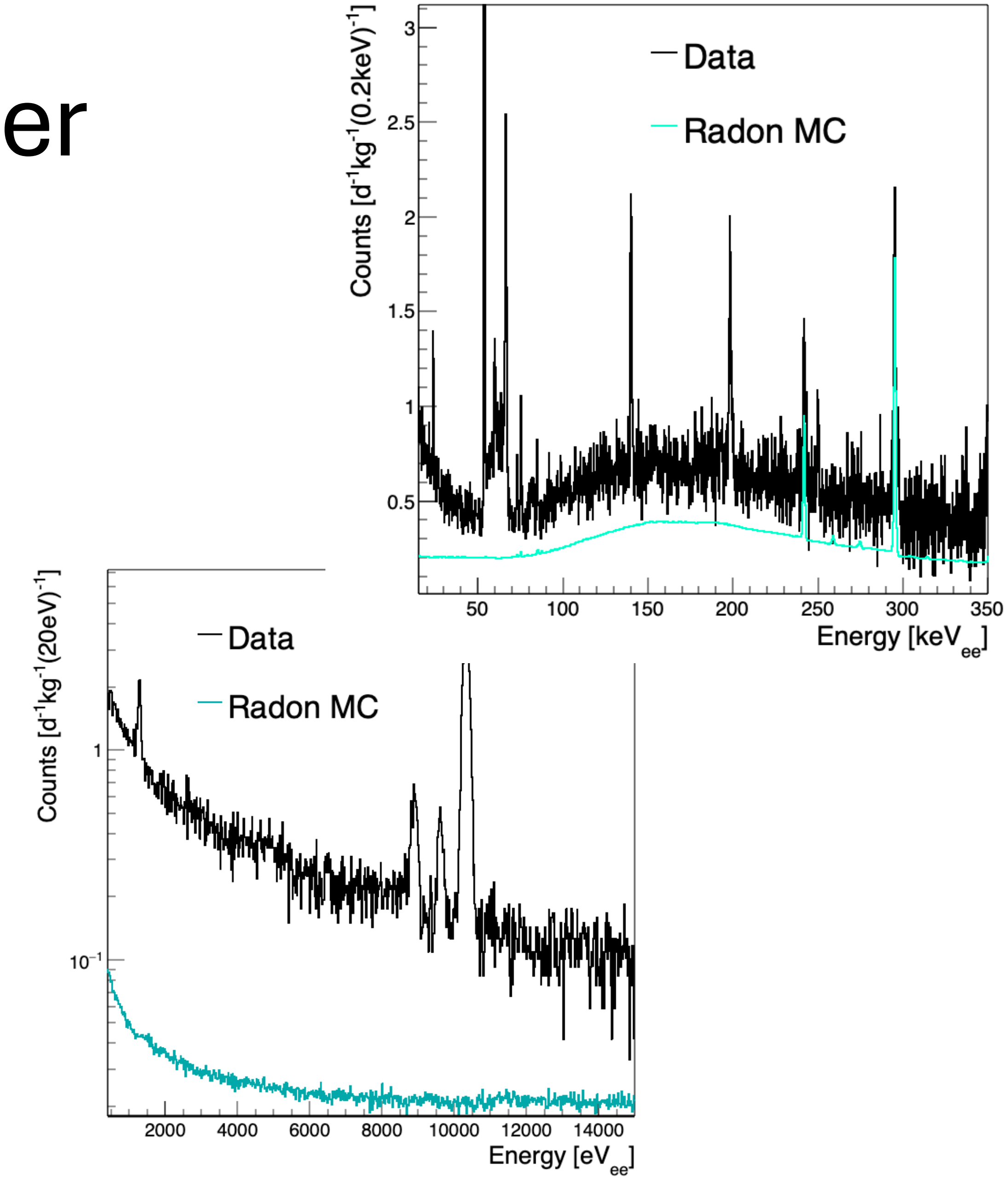
Radon in detector chamber

Stability plots show:

Radon greatly reduced by flushing, but lines still visible

→ High impact in [100,400] keV

→ Small impact in ROI



Experimental differences in ON vs OFF times

2 key differences:

1. Placement of drywell lid above room in OFF

→ 19% reduction in cosmic neutron flux in room

→ 3% reduction of muon flux

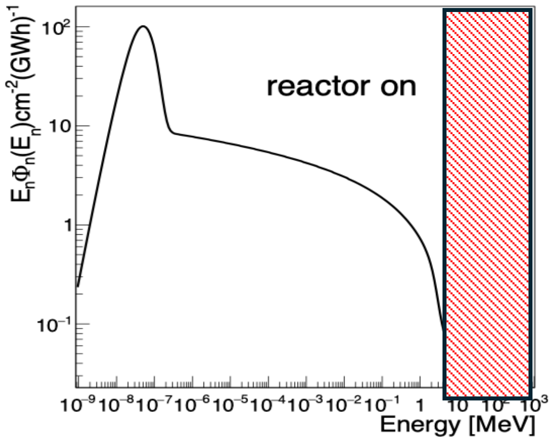
2. Better radon flushing in OFF

→ ca. factor 7 reduction of radon contribution in OFF

→ also reduction of inert gases in detector chamber

Reactor correlated backgrounds:

Neutrons:



Impact < 1% of background in all energy regions

No evidence of ^{16}N, small impact of inert gases from reactor

All effects considered in the Bkg model

Comparison to other CEvNS results

Experiment	Target	Source	Neutrino energy	Flux $[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	Data [counts]	Data/ SM prediction	Significance of null hypothesis rejection
COHERENT	Cs	Accelerator	10 – 50 MeV	$5 * 10^7$	306^{+20}_{-20}	$0.90^{+0.14}_{-0.14}$	$11.6\,\sigma$
COHERENT	Ar	Accelerator	10 – 50 MeV	$5 * 10^7$	140^{+40}_{-40}	$1.22^{+0.49}_{-0.49}$	$3.5\,\sigma$
COHERENT	Ge	Accelerator	10 – 50 MeV	$5 * 10^7$	21^{+7}_{-6}	$0.59^{+0.26}_{-0.24}$	$3.9\,\sigma$
XENONnT	Xe	Sun ($^8\mathrm{B}$)	< 15 MeV	$5 * 10^6$	11^{+4}_{-2}	$0.90^{+0.65}_{-0.67}$	$2.73\,\sigma$
PandaX-4T	Xe	Sun ($^8\mathrm{B}$)	< 15 MeV	$5 * 10^6$	4^{+1}_{-1}	$1.25^{+0.69}_{-0.69}$	$2.64\,\sigma$
CONUS+	Ge	Reactor	< 10 MeV	$1.5 * 10^{13}$	395^{+106}_{-106}	1.14^{+036}_{-036}	$3.7\,\sigma$

→ **CONUS+ has detected the lowest energy neutrinos via the CEvNS channel (down to 4 MeV)**

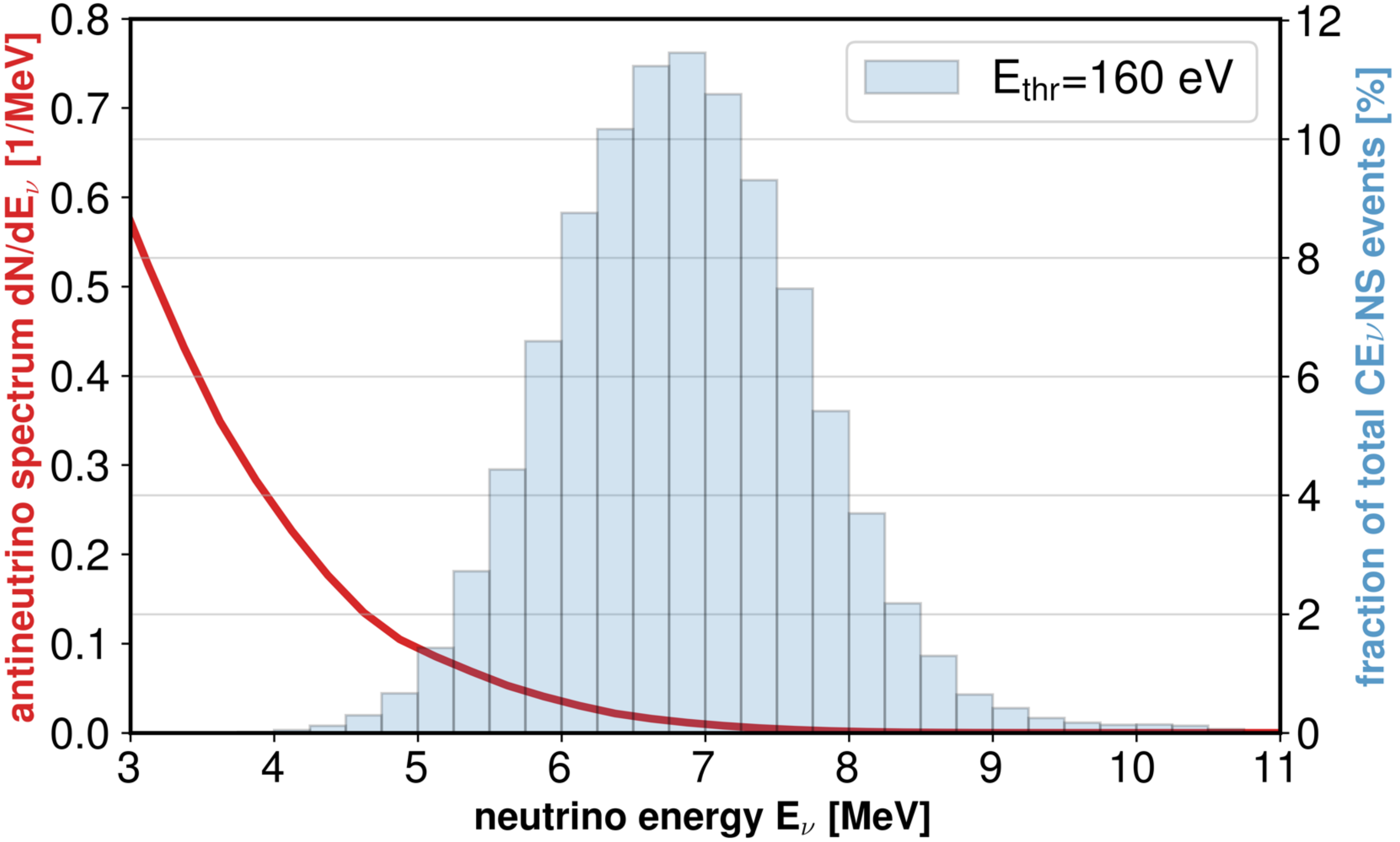
→ **CONUS+ has accumulated the highest number of CEvNS counts in one single isotope (low threshold + high flux)**

Likelihood analysis

- Fit both reactor ON and OFF spectrum
- **Inputs**: Data (including live time and dead times), background model, predicted signal spectrum, measured trigger efficiency values, measured detector resolution, active volumes, neutrino flux at CONUS+ location

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

Signal prediction

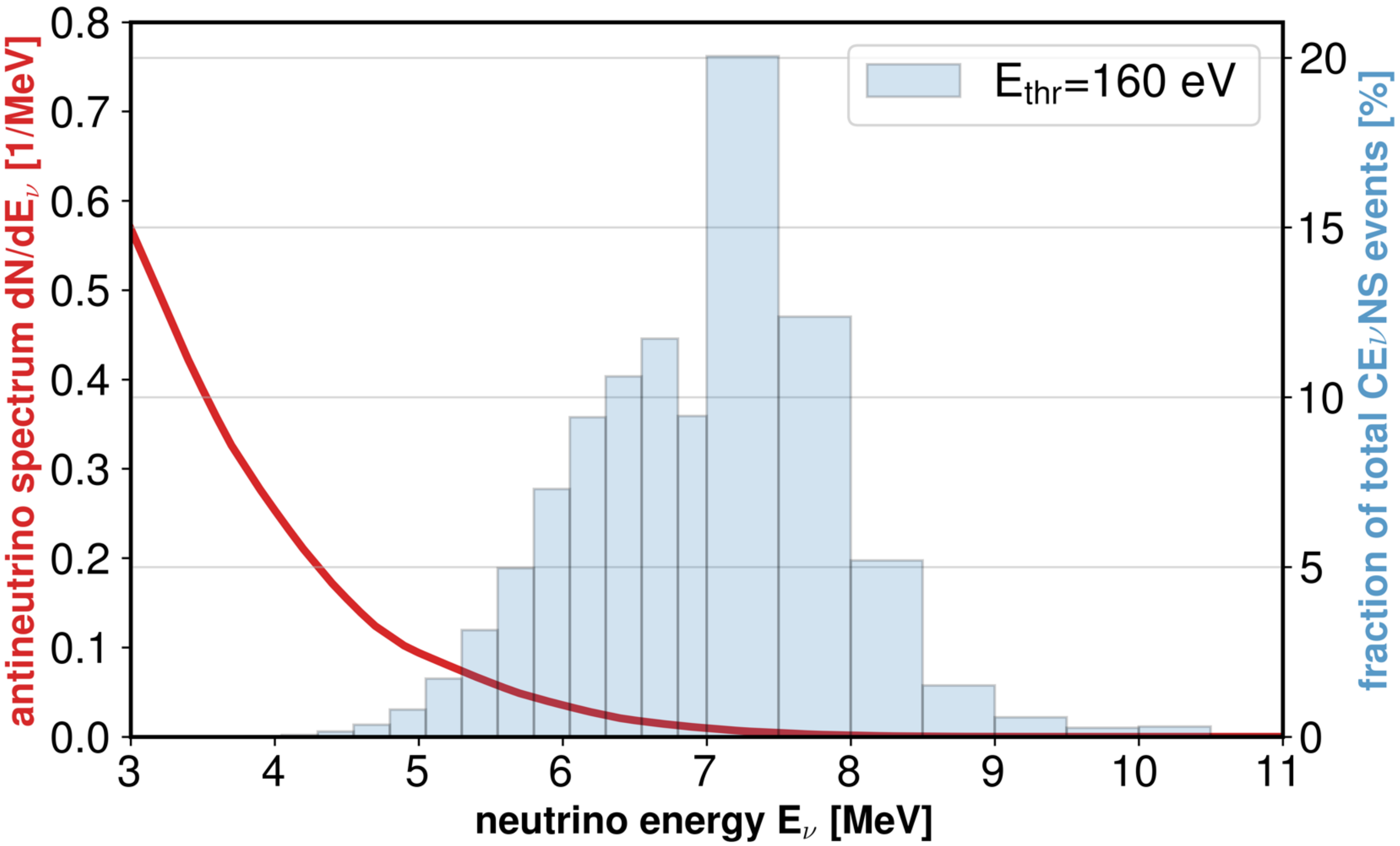


Data driven spectrum based on method proposed by the Daya Bay collaboration, including neutrino energies below threshold

Detector	Threshold [eV_{ee}]	Predictetd CEvNS counts
C5	170	116 (+20/-18)
C2	180	96 (+16/-14)
C3	160	135 (+23/-20)
COMBINED	-	345 (+34/-30)

Due to very low detector thresholds → increased impact of smaller neutrino energies

Signal prediction



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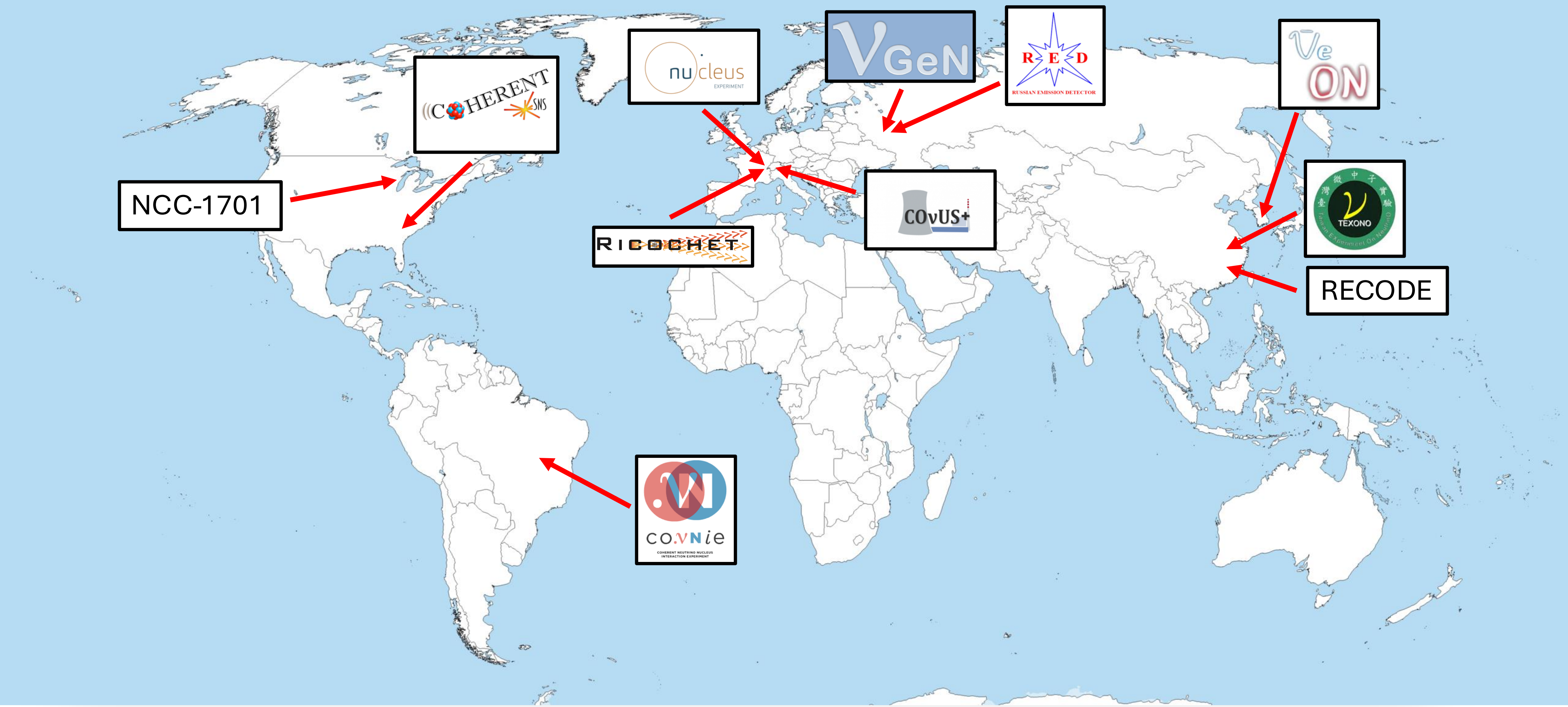
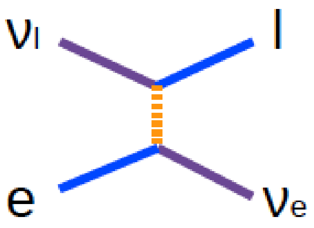
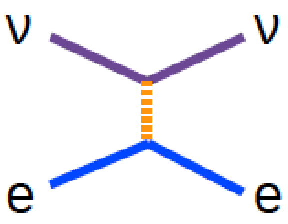


Many attempts to measure CEvNS worldwide!
Only COHERENT experiment successful up to now (w/ accelerator source)

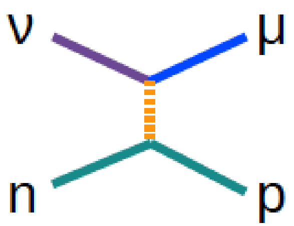
Neutrino interactions in the Standard Model



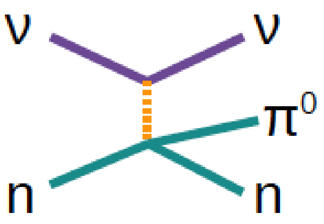
Inverese beta decay



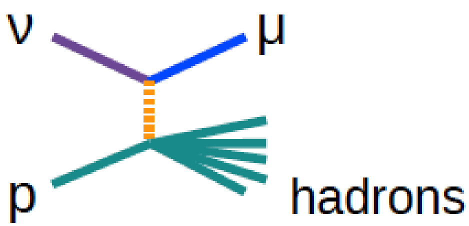
Elastic neutrino electron scattering



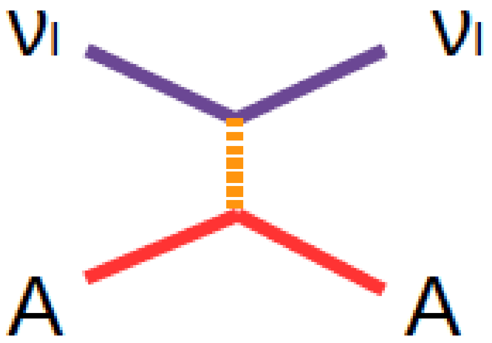
(Quasi-) elastic neutrino nucleon scattering



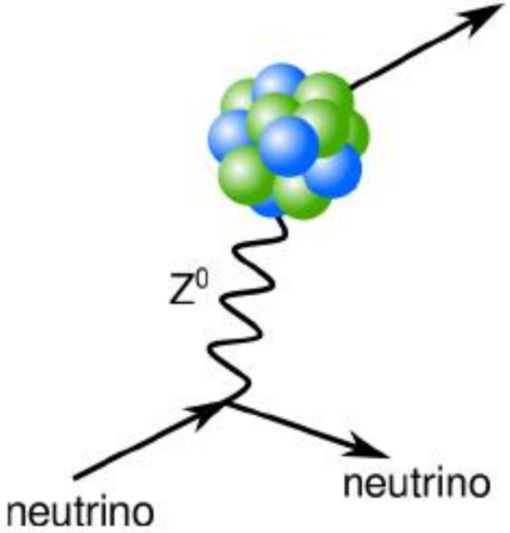
Nucleon excitation + resonance production



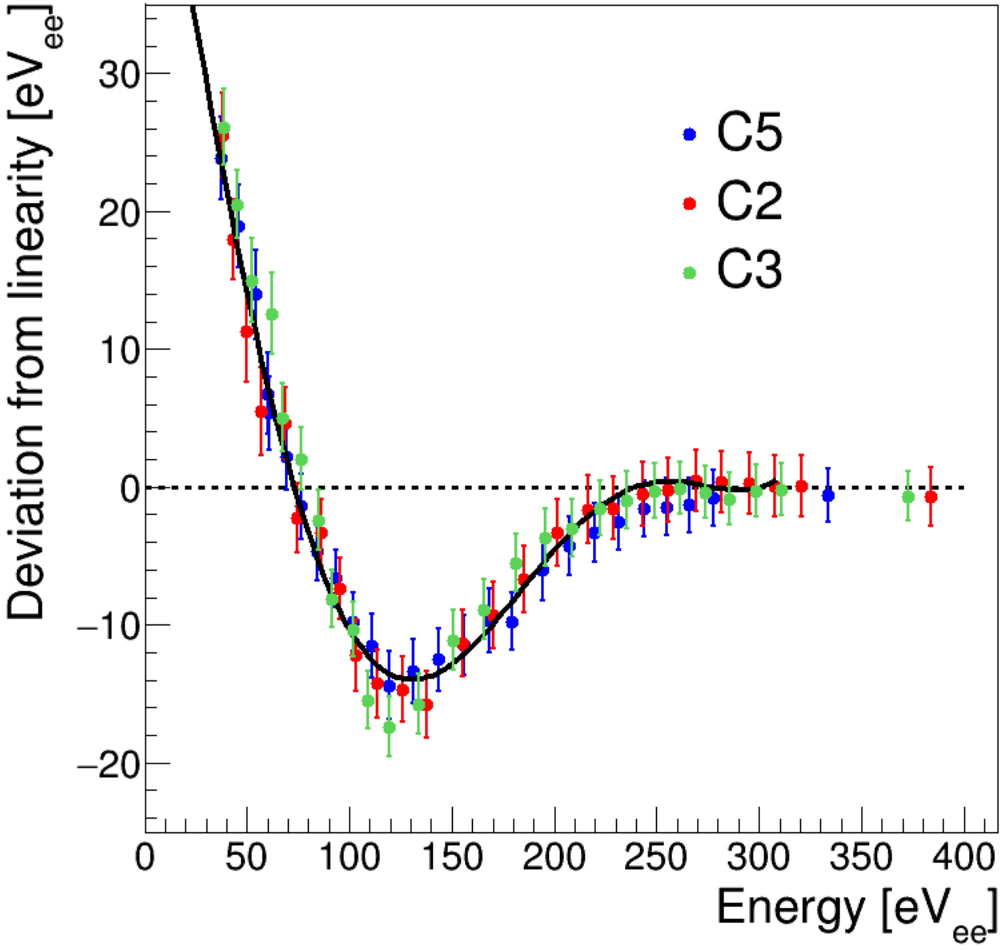
Deep inelastic scattering + jet production



Coherent **E**lastic
Neutrino
Nucleus
Scattering

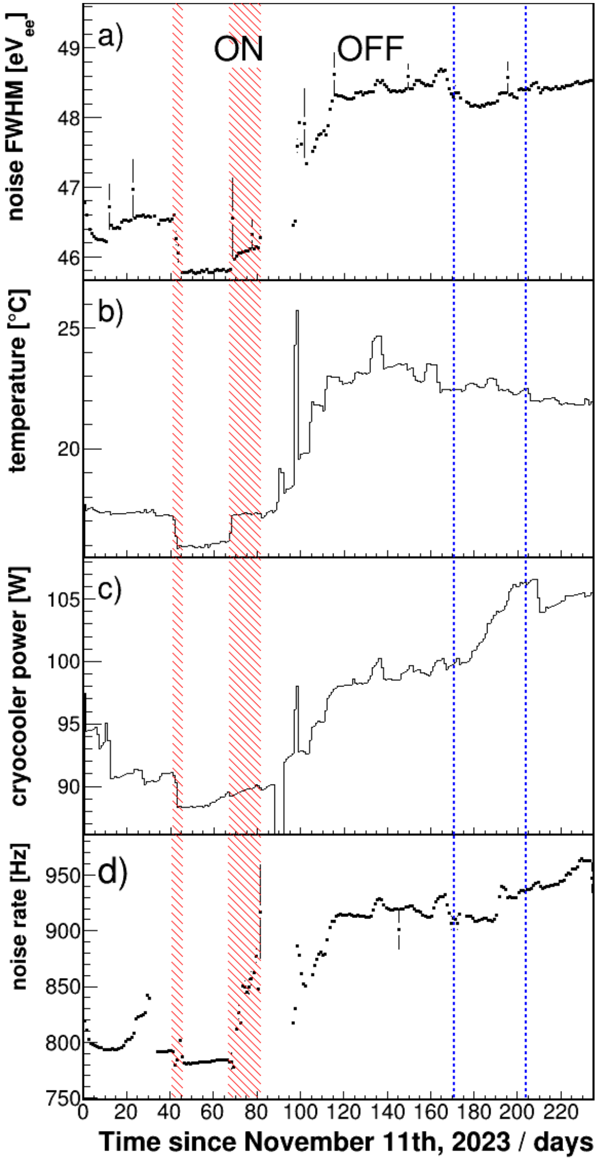


Non-linearity in energy calibration

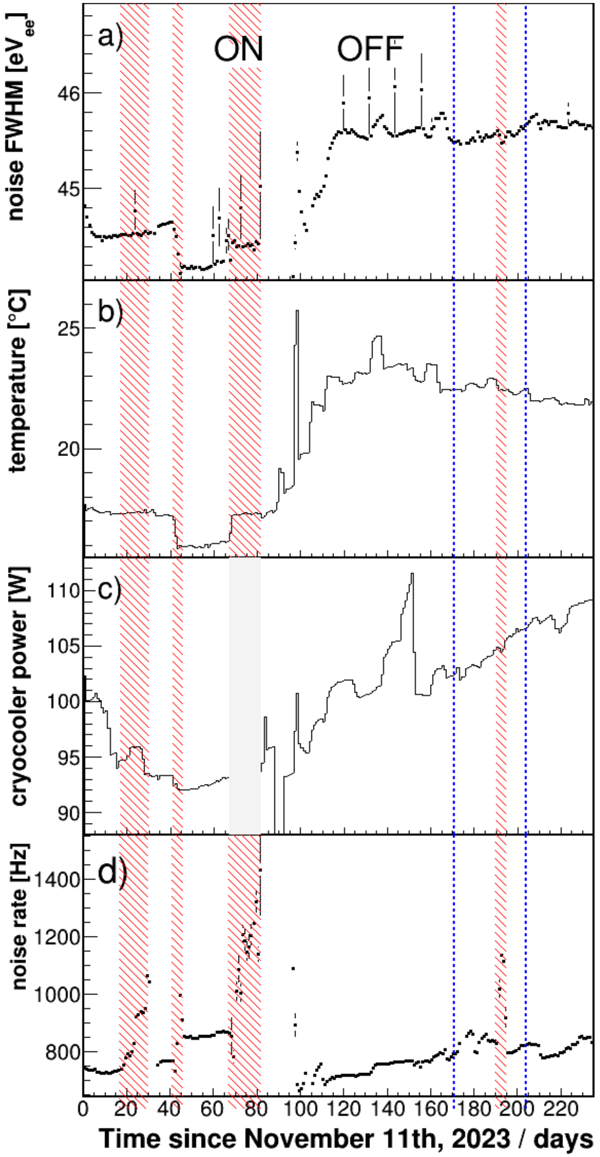


Data stability in CONUS+ Run1

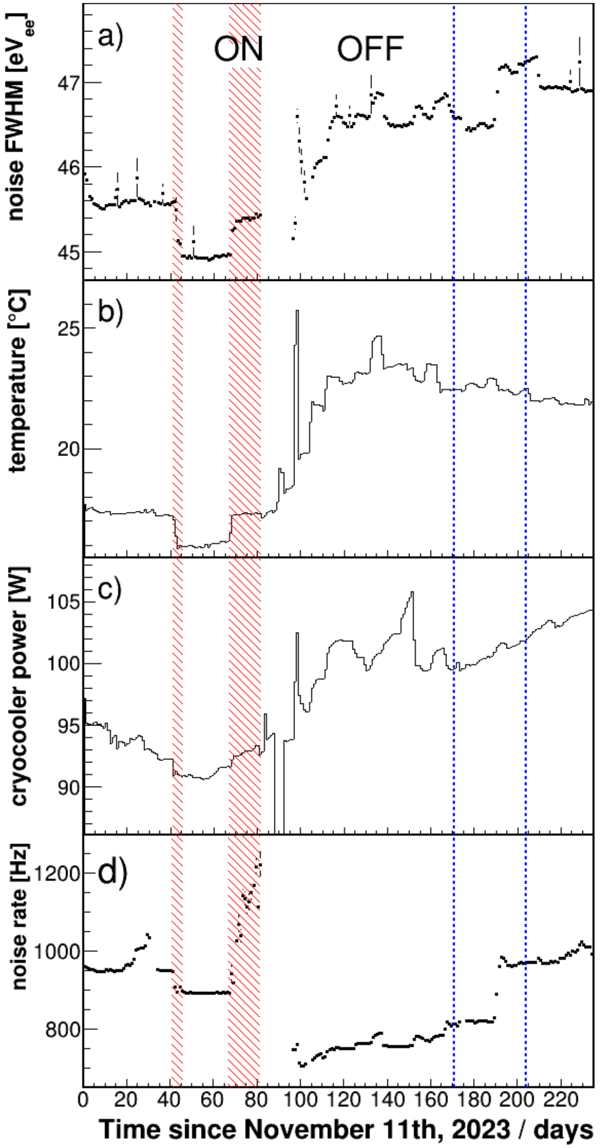
C2



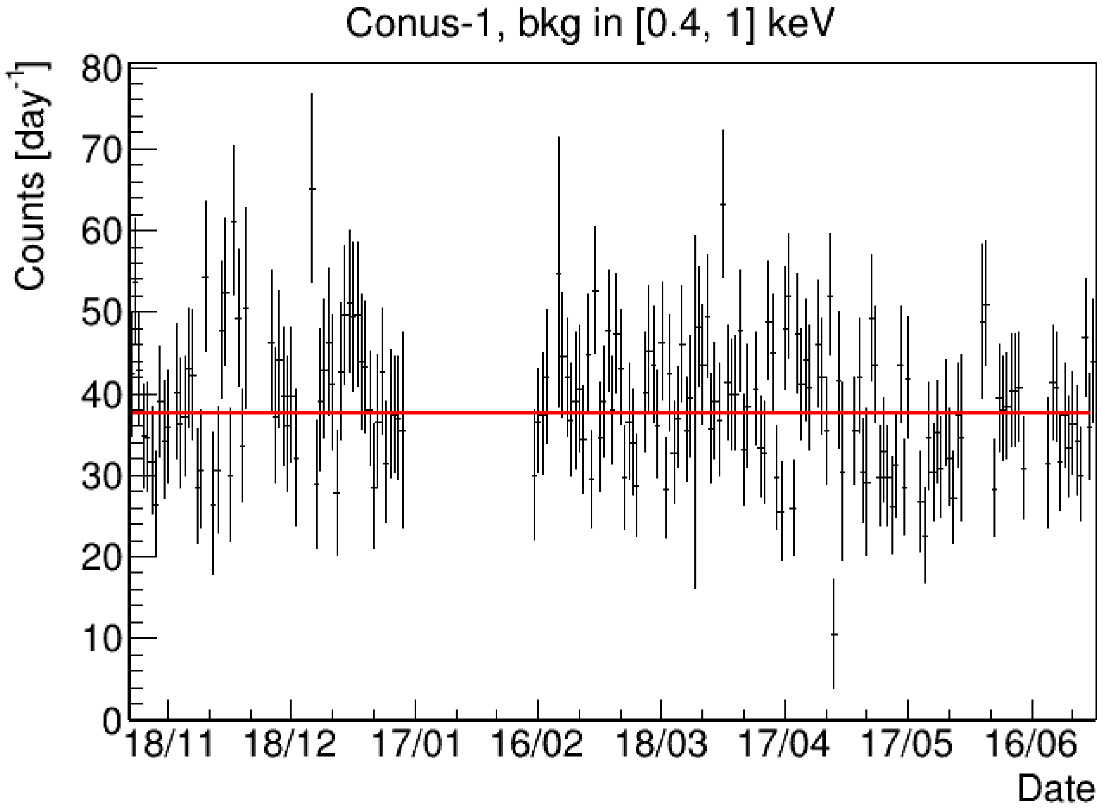
C3



C5

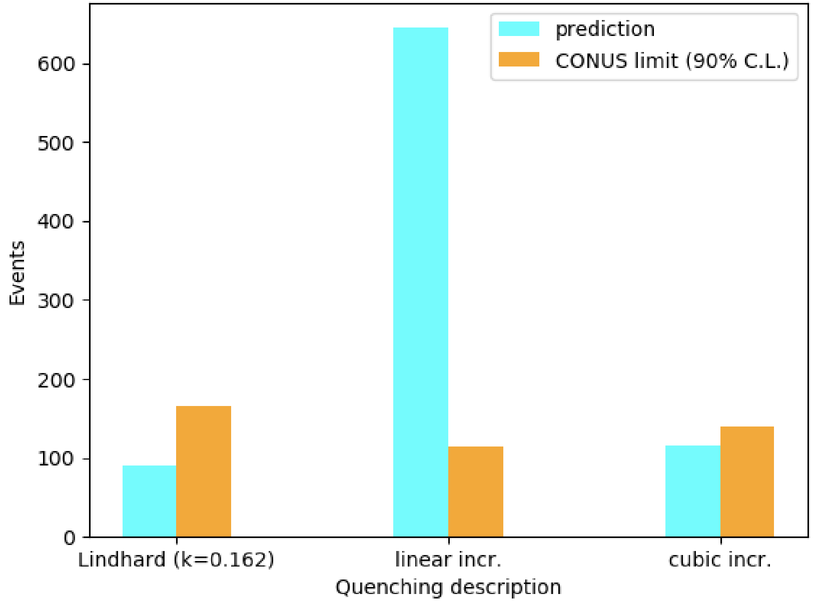


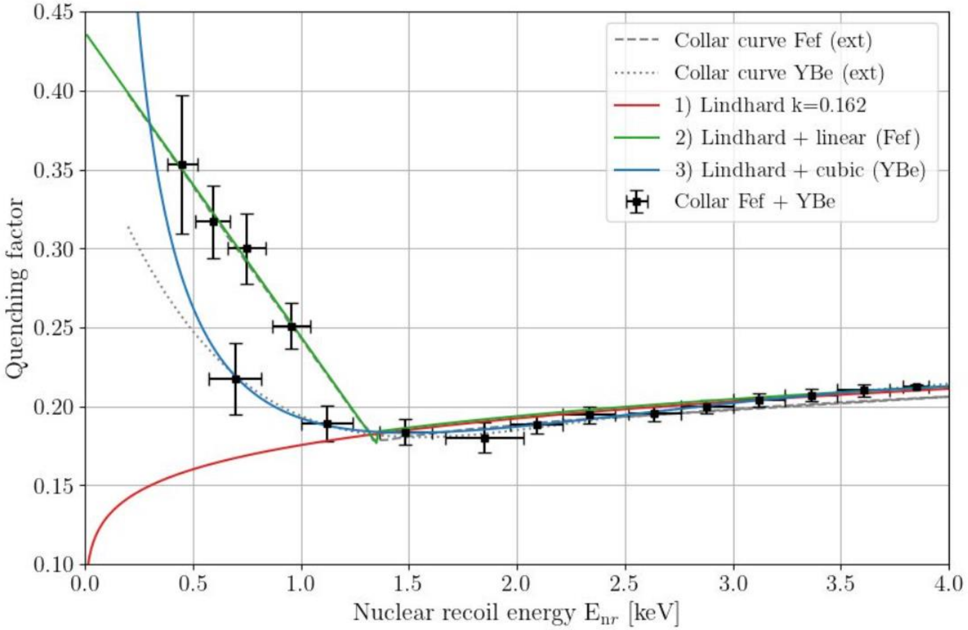
More stability plots



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





Comparison with other results – CONUS+