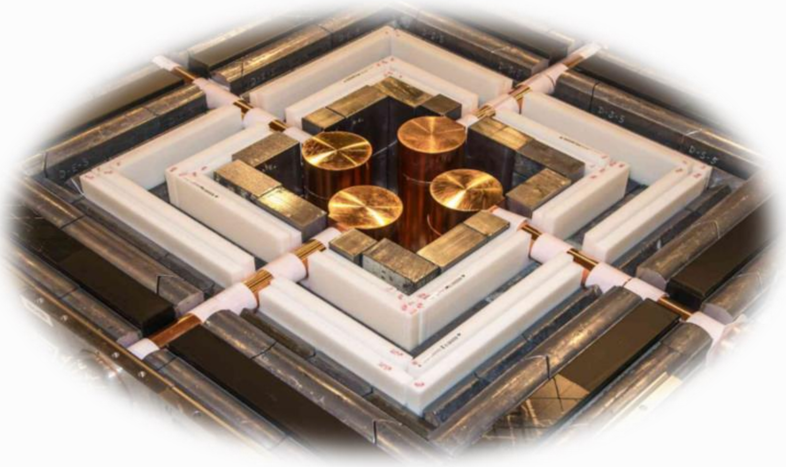
CONUS experiment: recent results and prospects for reactor CEvNS research

Kaixiang Ni – On behalf of the CONUS collaboration



MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

CONUS

CONUS+

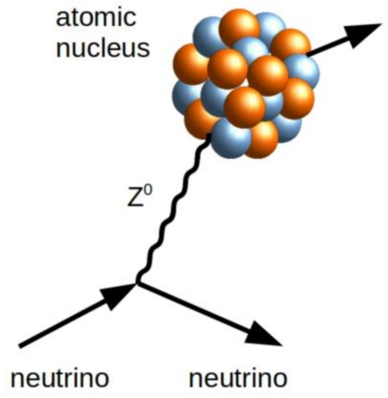
NuPhys2023: Prospects in Neutrino Physics King's College London, Dec. 2023

Coherent elastic neutrino nucleus scattering (CEνNS)

"Coherent": neutrino interacts with the nucleus as a whole

- Standard model predicted: *D. Freedman, PRD 9 1389 (1974)*
- Relatively large cross section: ~10^{-16} barn
- Low energy scale: several keV of recoil energy

$$\frac{d\sigma}{d\mathrm{T}} = \frac{G_f^2}{4\pi}\left(N - \left(1 - 4\sin^2\theta_w\right)Z\right)^2 F^2(q^2)M\left(1 - \frac{MT}{2E_v^2}\right)$$

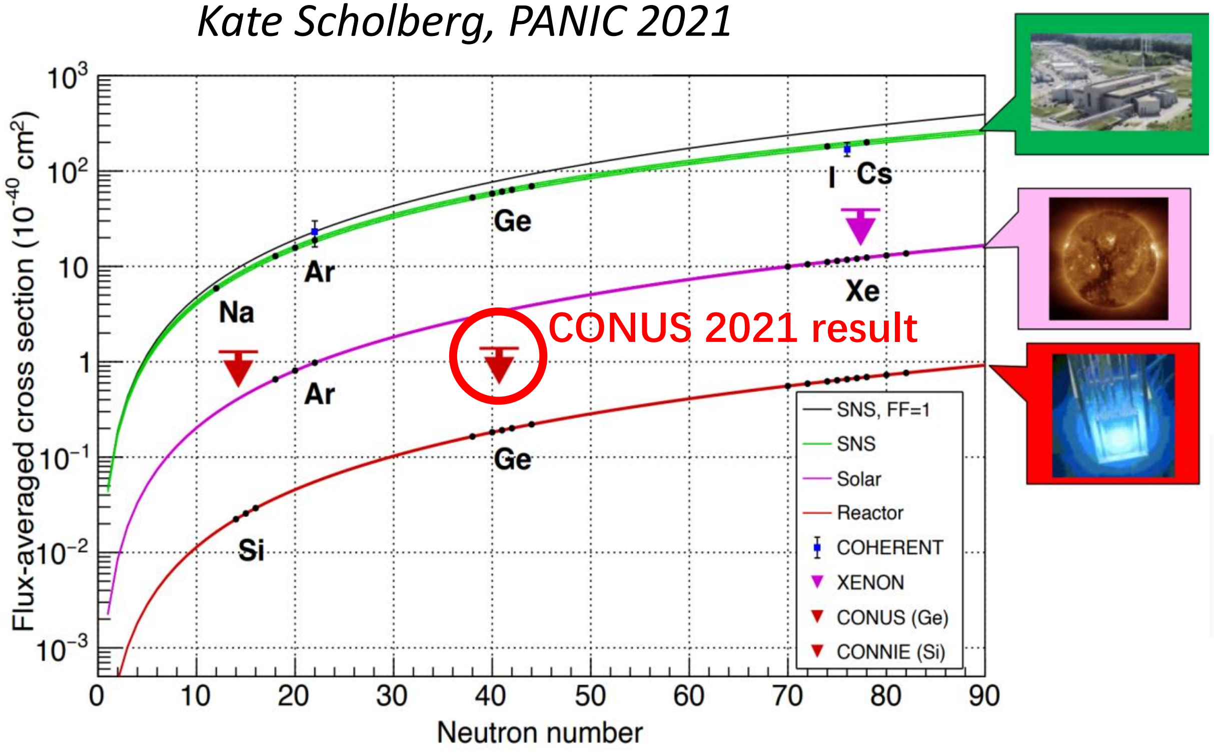


Detection of CEvNS by COHERENT!
Science 357 (2017) 6356, 1123-1126

- ✓ Verification of Standard model (e.g. Weinberg angle) at low energy
- ✓ BSM searches for new neutrino interactions: magnet moments, millicharged, etc.
- ✓ Insight of nuclear structure (nuclear matrix, etc.)
- ✓ Supernova neutrinos, "neutrino floor" in dark matter search

Neutrino sources

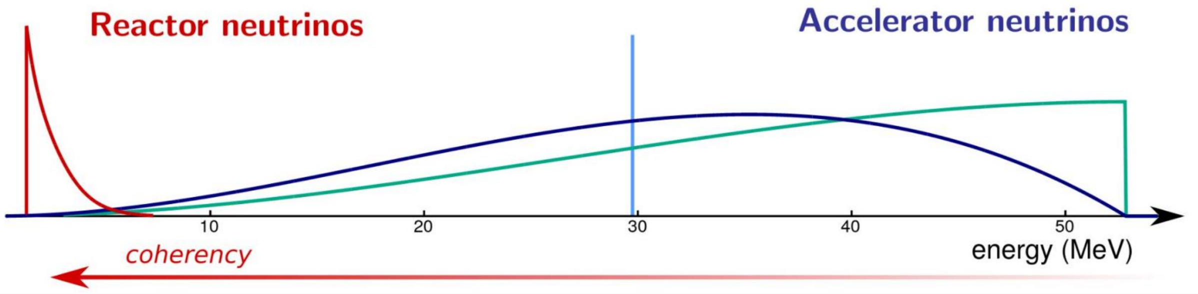
Kate Scholberg, PANIC 2021



- Accelerator ν:
  - Different neutrino flavors
  - E_ν ~ 20-50 MeV (F < 1), less coherency
  - Pulsed flux, higher S/N ratio

Detected by COHERENT!
PRL 126 012002 (2021)
PRL 129 081801 (2022)

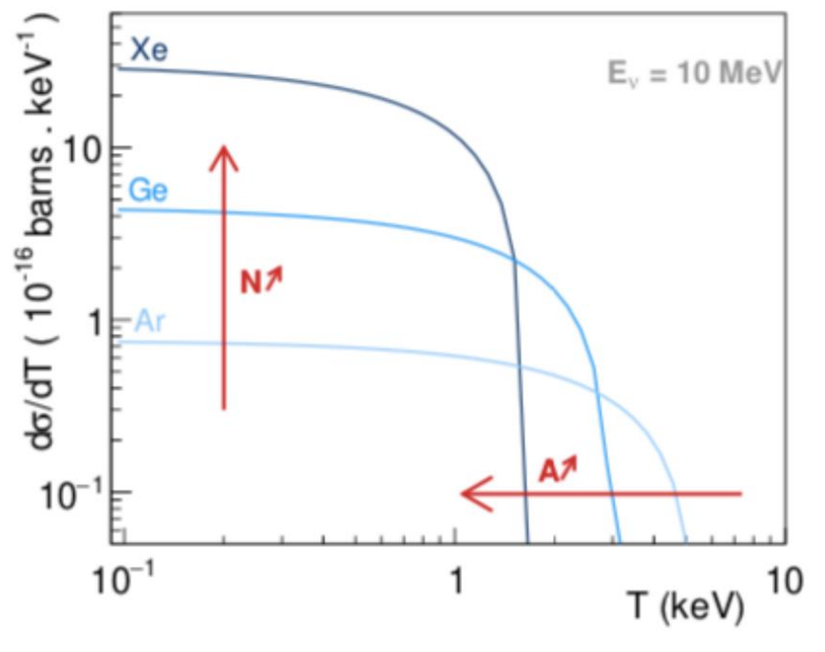
- Solar ν (^8B ν):
  - By-product of dark matter experiments
  - No on-off comparison
- Reactor ν
  - Inside **fully coherent** regime
  - **Complementary** to the accelerator experiments



Reactor experiments worldwide

reactor	CONUS	Brokdorf: 3.9 GW	17 m	4 MeV	Ge	4 kg
	CONUS+	Leibstadt: 3.6 GW	21 m	4 MeV	Ge	4 kg (upgraded)
	νGEN^{O}	Kalinin: 3.1 GW	11-12 m	4 MeV	Ge	1.4 kg→6 kg
	RED-100^{O}	Kalinin: 3.1 GW	19 m	4 MeV	Xe	160 kg
	NCC-1701^{T}	Dresden-II: 3 GW	10.4 m	4 MeV	Ge	3 kg
	NCC-1701^{P}	Ringhals: 3.6 GW	23 m	4 MeV	Ge	3 kg (upgraded)
	RECODE^{P}	Sanmen: 3.4 GW	25 m	4 MeV	Ge	2x5 kg
	RELICS^{P}	Sanmen: 3.4 GW	25 m	4 MeV	Xe	30 kg
	N.N.^{P}	Taishan: 4.6 GW	35 m	4 MeV	Ar	100 kg
	CONNIE^{O}	Angra: 3.9 GW	30 m	4 MeV	Si	50 g
	NEON^{O}	Hanbit: 2.8 GW	24 m	4 MeV	NaI	15 kg
	TEXONO^{O}	Kuosh.: 2.9 GW	25 m	4 MeV	Ge	1-2 kg
	MINER^{P}	TAMU: 1 MW	2-3 m	4 MeV	Ge/Si	1 kg
	Richochet A^{P}	MIT R: 5.5 MW	4 m	4 MeV	Ge, Zn	5 kg, 5 kg
	Richochet B^{P}	ILL: 58 MW	8.8 m	4 MeV	Ge	1 kg
	Basket^{R}	Chooz: 8.6 GW	70-400 m	4 MeV	Li2WO4	
	ν-CLEUS^{P}	Chooz: 8.6 GW	70-100 m	4 MeV	$CaWO_4$, Al_2O_3	1 g→10 kg, 1 g→10 kg

O/T: operational/terminated, P: in preparation, R= R&D



Choose of target materials:

- Larger atomic number: higher cross section, but larger quenching and lower threshold
- Technologies applied to detect energy at sub-keV level
- Target mass as kg scale is enough to see CEvNS.

The CONUS/CONUS+ collaboration

Max-Planck-Institut für Kernphysik (MPIK), Heidelberg: N. Ackermann, S. Armbruster, A. Bonhomme, H. Bonet, C. Buck, J. Hakenmüller, J. Hempfling, G. Heusser, M. Lindner, W. Maneschg, K. Ni, T. Rink, E. Sanchez-Garcia, H. Strecker
Former collaborators: T. Schierhuber, E. Van der Meeren, J. Henrichs, T. Hugle, J. Stauber
Preussen Elektra GmbH, Kernkraftwerk Brokdorf (KBR), Brokdorf: K. Fülber, R. Wink
Kernkraftwerk Leibstadt AG (KKL), Leibstadt: J. Wönckhaus, M. Rank

Scientific cooperations with:

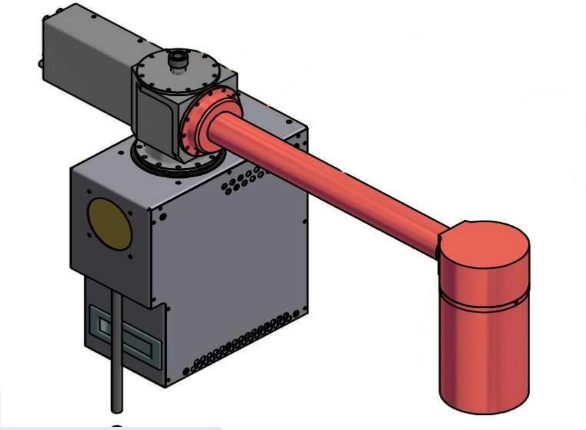
Physikalisch-Technische Bundesanstalt (PTB), Braunschweig: R. Nolte, E. Pirovano, M. Reginatto, M. Zboril, A. Zimbal
Paul-Scherrer-Institut (PSI), Villigen: E. Hohmann, R. Gaalev

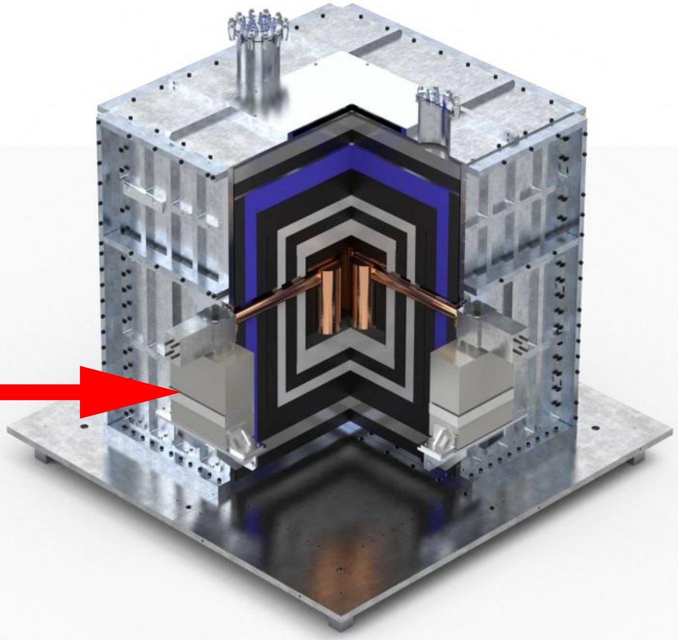
CONUS @ KBR

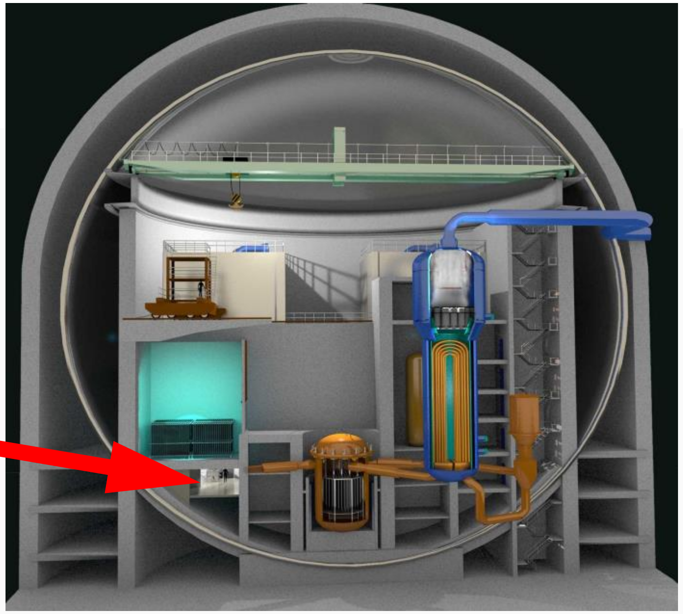
Detector:
- Point-contact high purity Germanium crystal
- Electrical cryo-cooled
- Energy threshold: 200-300eV
- Four 1-kg modules, in array

Shield:
- Lead + Polyethylene + active muon veto scintillators
- Volume: 1.65m^3, mass: 11 tons
- Total bkg suppression: >10^{4} x

Experiment site:
- 3.9GW thermal power
- 17m distance to the reactor core, 2.3 x 10^{13} ν/s/cm^2
- 24m w.e. overburden

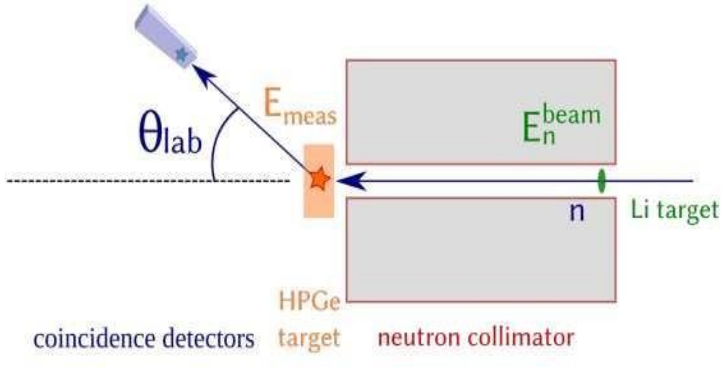


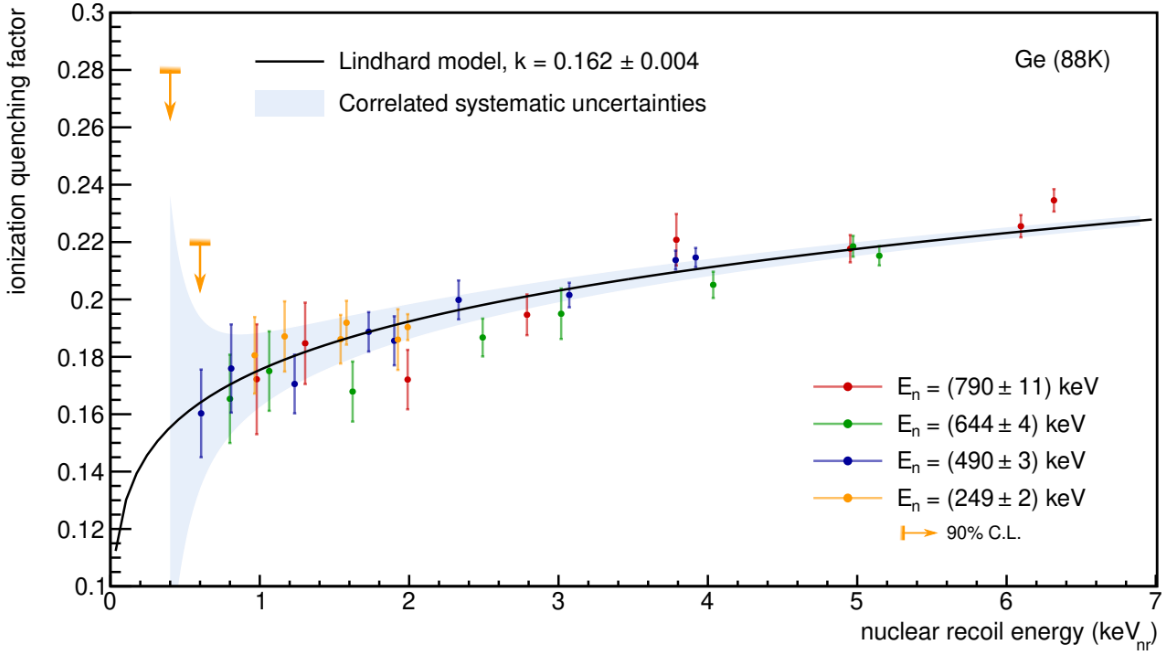


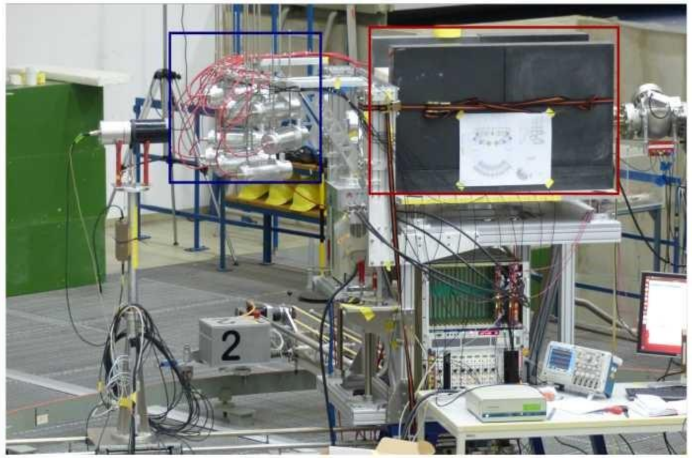


Quenching measurement

- Only part of the nuclear recoil energy could turn into detectable signal
  → **quenching**
- Most commonly used model: Lindhard model, with unknown parameter k
- Auxiliary measurement done with neutron beams at PTB, Germany
- k=0.162+-0.004 (stat.+syst.)



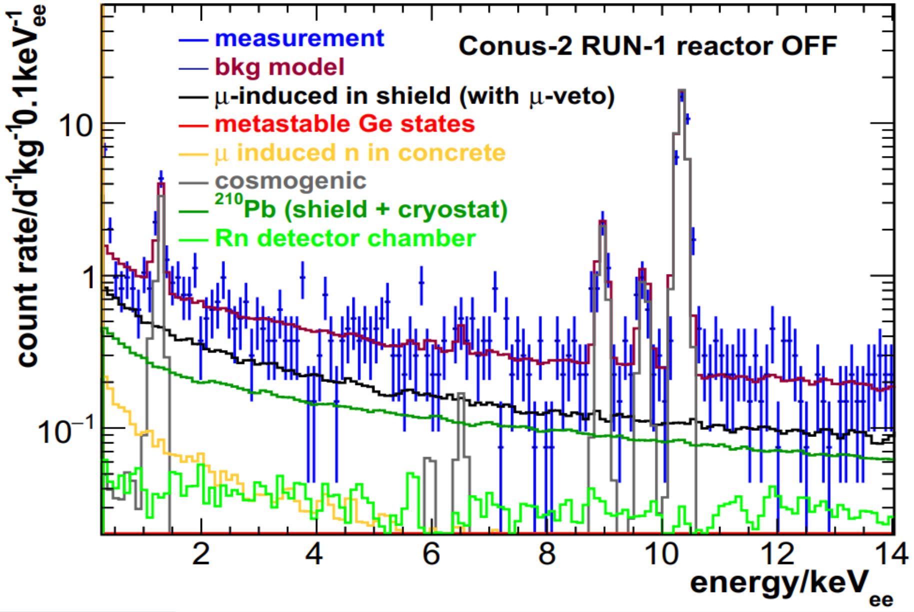


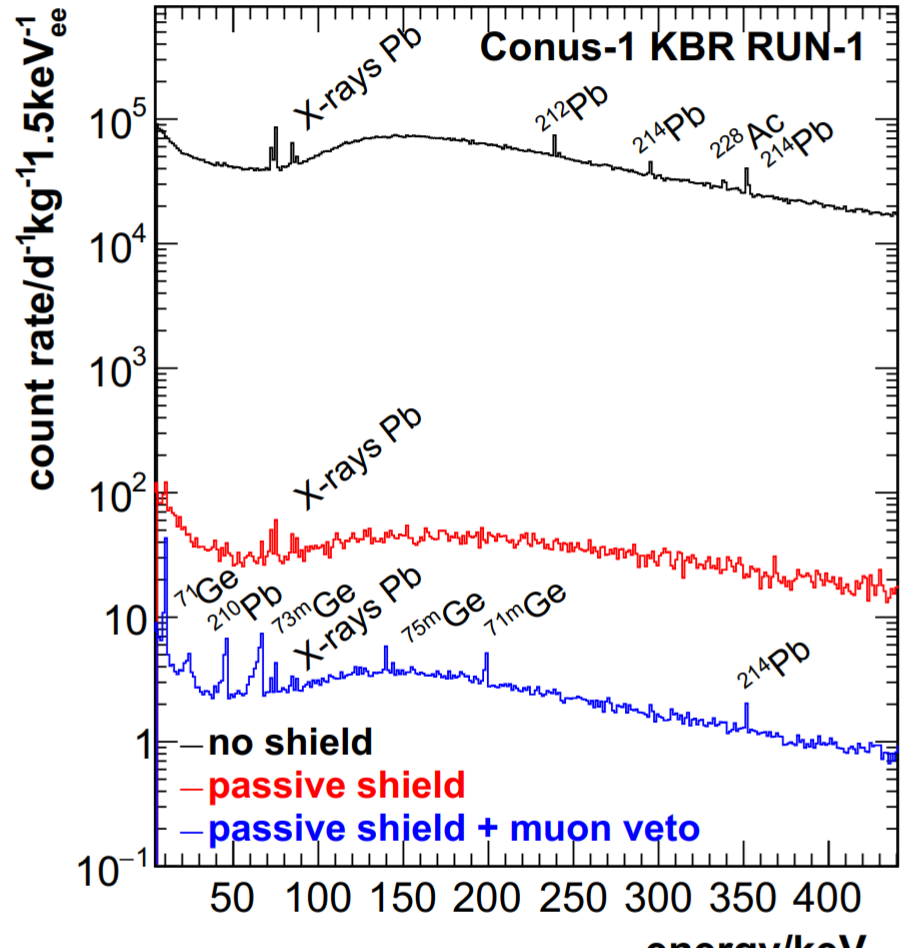


Eur. Phys. J. C ***82****, 815 (2022)*

Background estimation

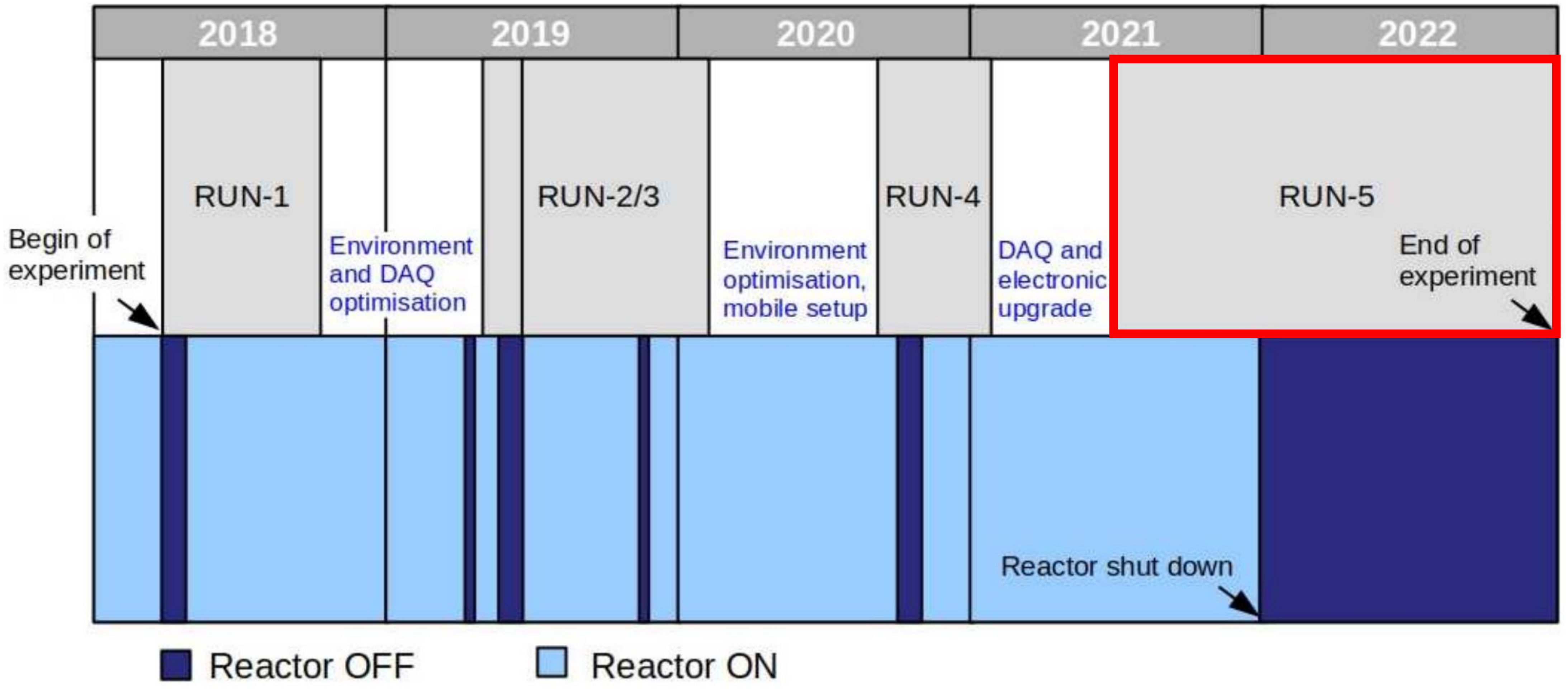
- Suppression factor by shield: >10^4
- Remaining bkg rate in ROI: O(10) cts/d/kg
- Bkg is dominated by muon-induced events and ^{210}Pb events
    - Reactor neutron/activation negligible



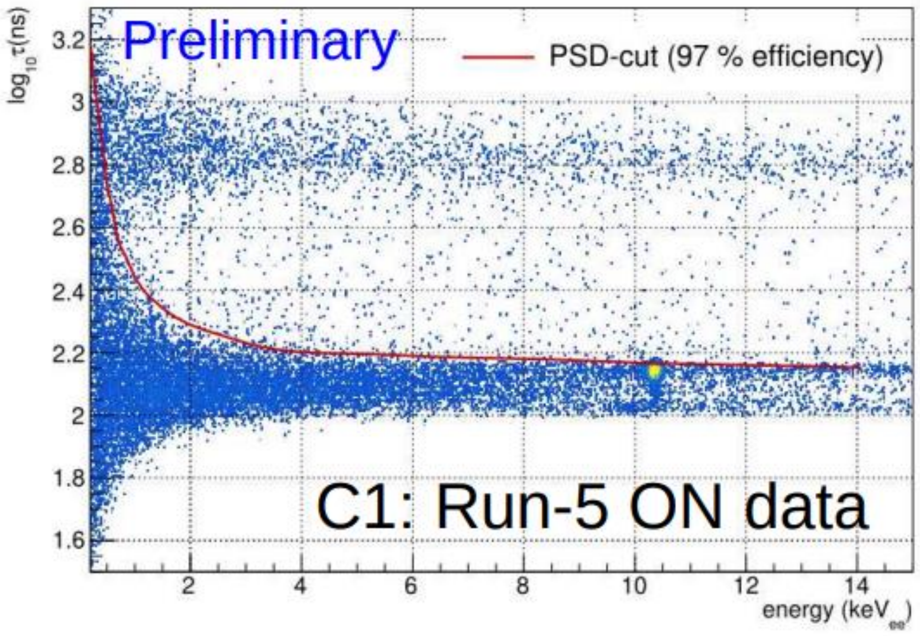


Eur. Phys. J. C ***83****, 195 (2023)*

Runs

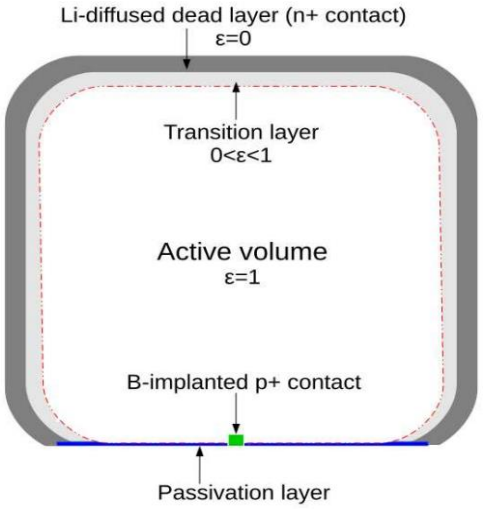

2018
2019
2020
2021
2022
RUN-1
RUN-2/3
RUN-4
RUN-5
Begin of experiment
Environment and DAQ optimisation
Environment optimisation, mobile setup
DAQ and electronic upgrade
End of experiment
Reactor shut down
Reactor OFF
Reactor ON

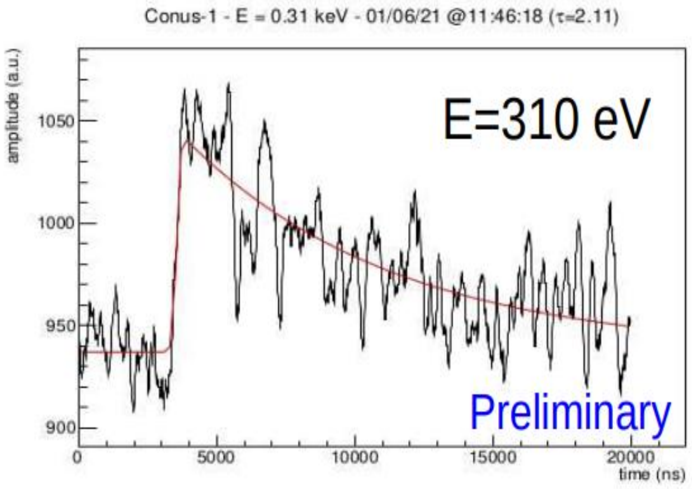
Run 5 with Pulse Shape Discrimination (PSD)



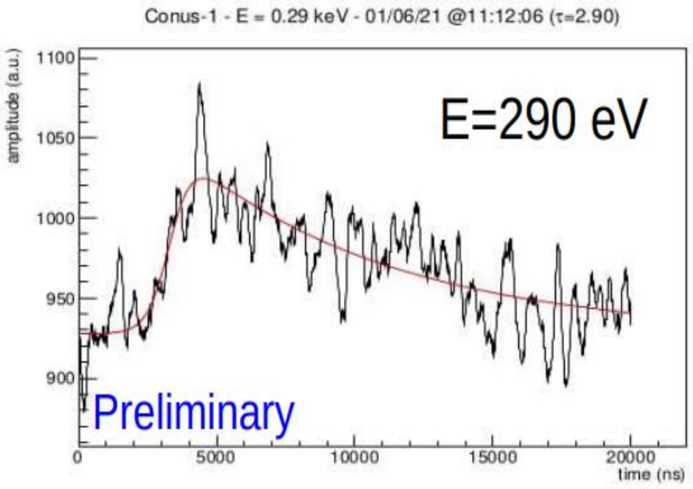
Efficiency: remove ~50% of the surface events at ~300eV with >90% bulk event acceptance

- Energy deposition near the transition layer contributes to a slow signal
- Removing slow pulses could reduce surface background, while losing a little effective mass





Normal (fast) pulse



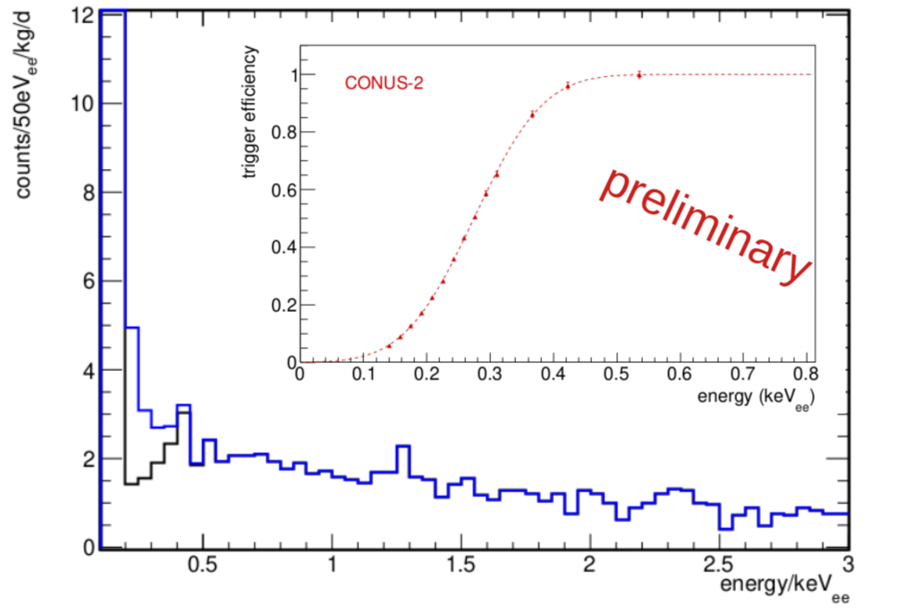
Slow pulse (transition edge)

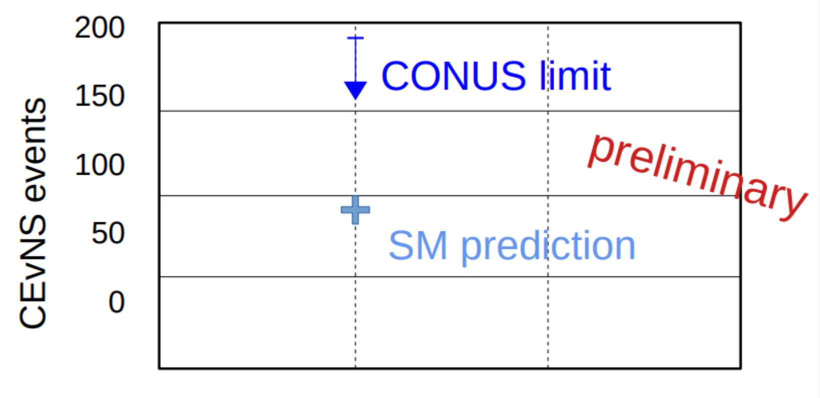
New limits from Run5

- Upper limit: factor ~2 above SM prediction
- Strongest limit on reactor CEνNS count rate! (Assuming Lindhard quenching)
- Publication in preparation

Detector	Exposure (ON/OFF, kg-d)	Threshold (eV)	Anticipated Signals (k=0.16)	Likelihood fit
C1	142/40	210	42	<59
C2	146/130	210	26	<75
C4	139/102	210	24	<90
Total	426/272		92	<163

preliminary





Comparison with other experiments

Current results from reactor CEvNS experiments:

- constraints from νGen, CONNIE,…
- strong signal preference with NCC-1701 at Dresden-II reactor US:

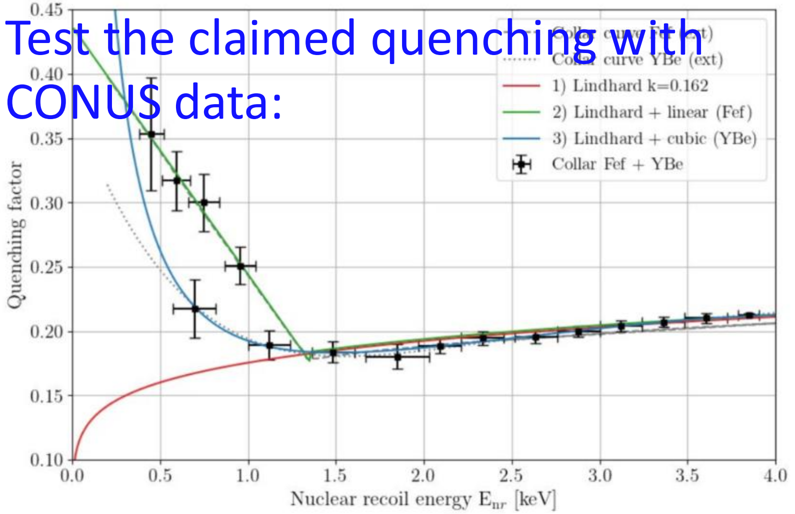
Abstract of Phys. Rev. Lett. 129, 211802 (2022)

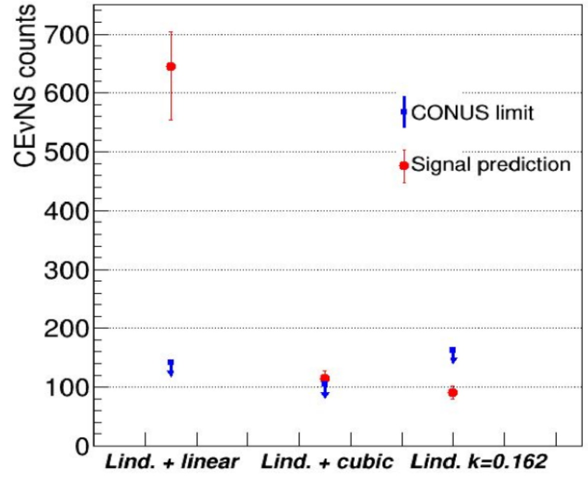
The 96.4 day exposure of a 3 kg ultralow noise germanium detector to the high flux of antineutrinos from a power nuclear reactor is described. A very strong preference ($p < 1.2 \times 10^{-3}$) for the presence of a coherent elastic neutrino-nucleus scattering (CEνNS) component in the data is found, when compared to a background-only model. No such effect is visible in 25 days of operation during reactor outages. The best-fit CEνNS signal is in good agreement with expectations based on a recent characterization of germanium response to sub-keV nuclear recoils. Deviations of order 60% from the standard model CEνNS prediction can be excluded using present data. Standing uncertainties in models of germanium quenching factor, neutrino energy spectrum, and background are examined.

Abstract of Phys. Rev. D 103, 122003 (2021)

Germanium is the detector material of choice in many rare-event searches looking for low-energy nuclear recoils induced by dark matter particles or neutrinos. We perform a systematic exploration of its quenching factor for sub-keV nuclear recoils, using multiple techniques: photoneutron sources, recoils from gamma-emission following thermal neutron capture, and a monochromatic filtered neutron beam. Our results point to a marked deviation from the predictions of the Lindhard model in this mostly unexplored energy range. We comment on the compatibility of our data with low-energy processes such as the Migdal effect, and on the impact of our measurements on upcoming searches.

Test the claimed quenching with CONUS data:

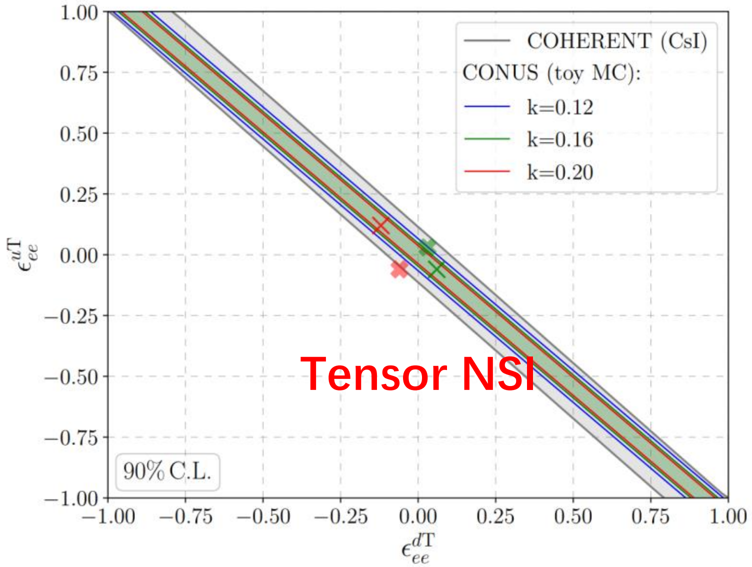


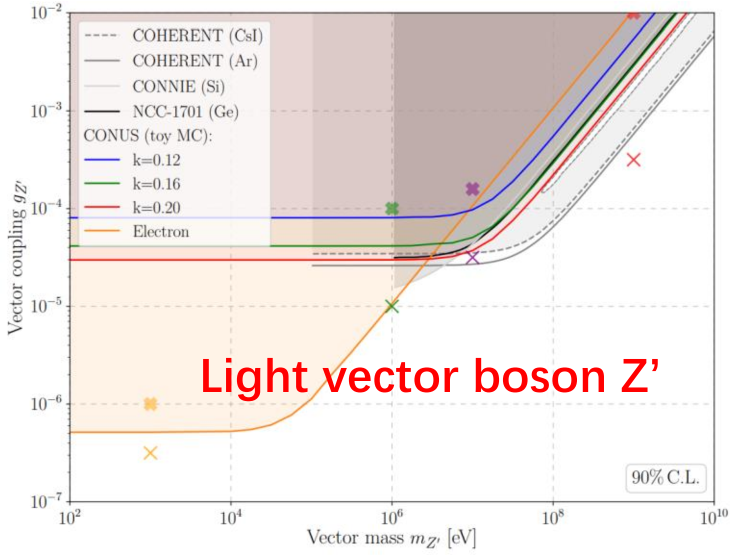


"A signal should have been seen in the CONUS data, in case the excess reported in the left article is from CEvNS or BSM."

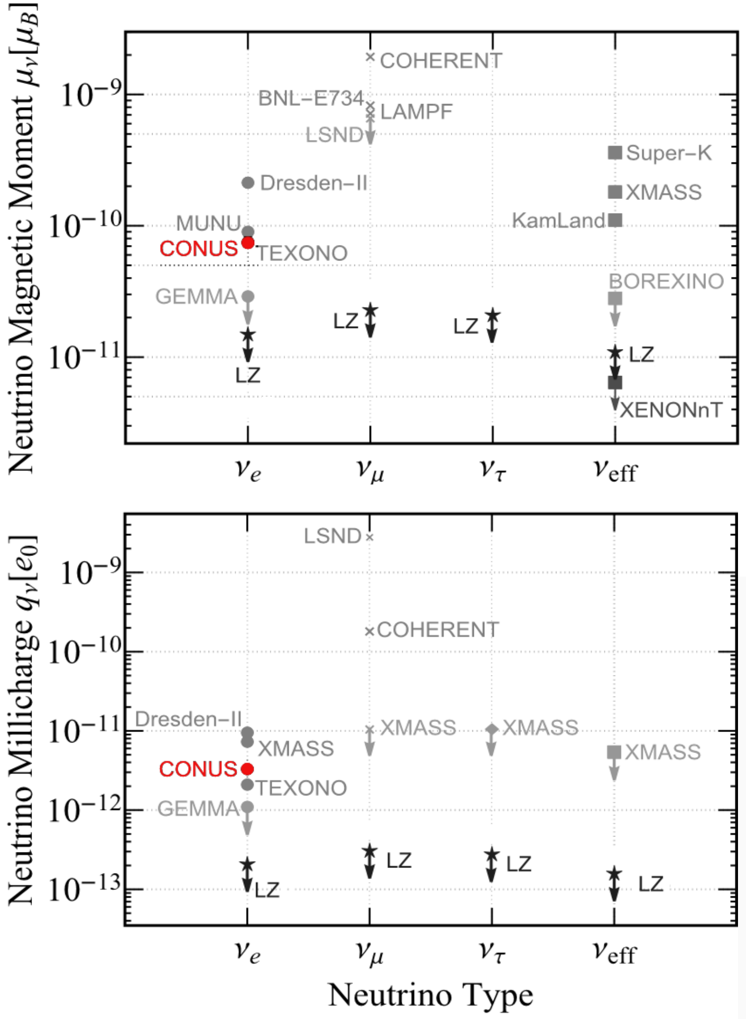
BSM results

Tensor/Vector NSI (non-standard interactions): limits the coupling parameter space
Light vector boson: limits the mass-coupling parameter space
Neutrino millicharged: $|q_\nu| < 3.3 \times 10^{-12}\ e_0$
Neutrino magnetic moment: $\mu_\nu < 7.5 \times 10^{-11}\ \mu_B$





JHEP 05 (2022) 085



Phys. Rev. D 107, 053001 (2023)

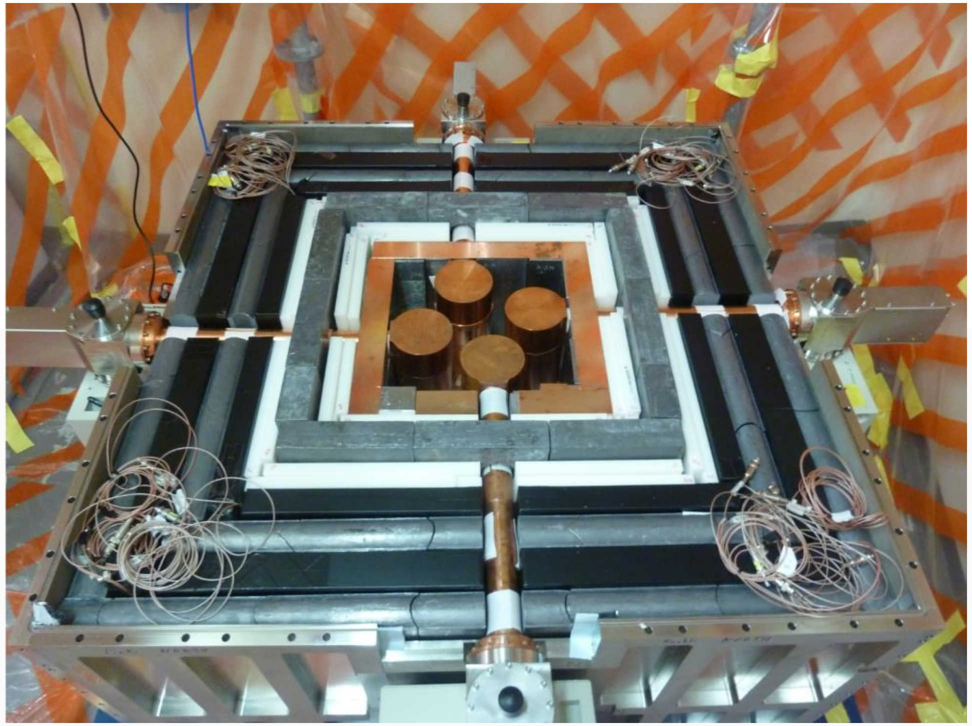
From CONUS to CONUS+

- Nuclear power plants in Germany are shut-down…
- Our new home: Kernkraftwerk Leibstadt (KKL), Switzerland
  - Experiment hall: ~21m from 3.6 GW reactor core, 1.45 x 10^{13} ν/s/cm^2
  - New environmental background characterized, large differences observed

Parameter	Method	CONUS+ vs. CONUS
Gamma-radiation (>3 MeV)	Low bg. Ge spectr. CONRAD	25x smaller
Cosmic muon flux	Liquid scintillator cells	2.2x larger (critical)
Neutron spectrometry	Bonner Spheres from MPIK + PSI	30x larger (still subdominant)
Temperture, Radon conc	diff. sensors	similar

Upgraded experiment

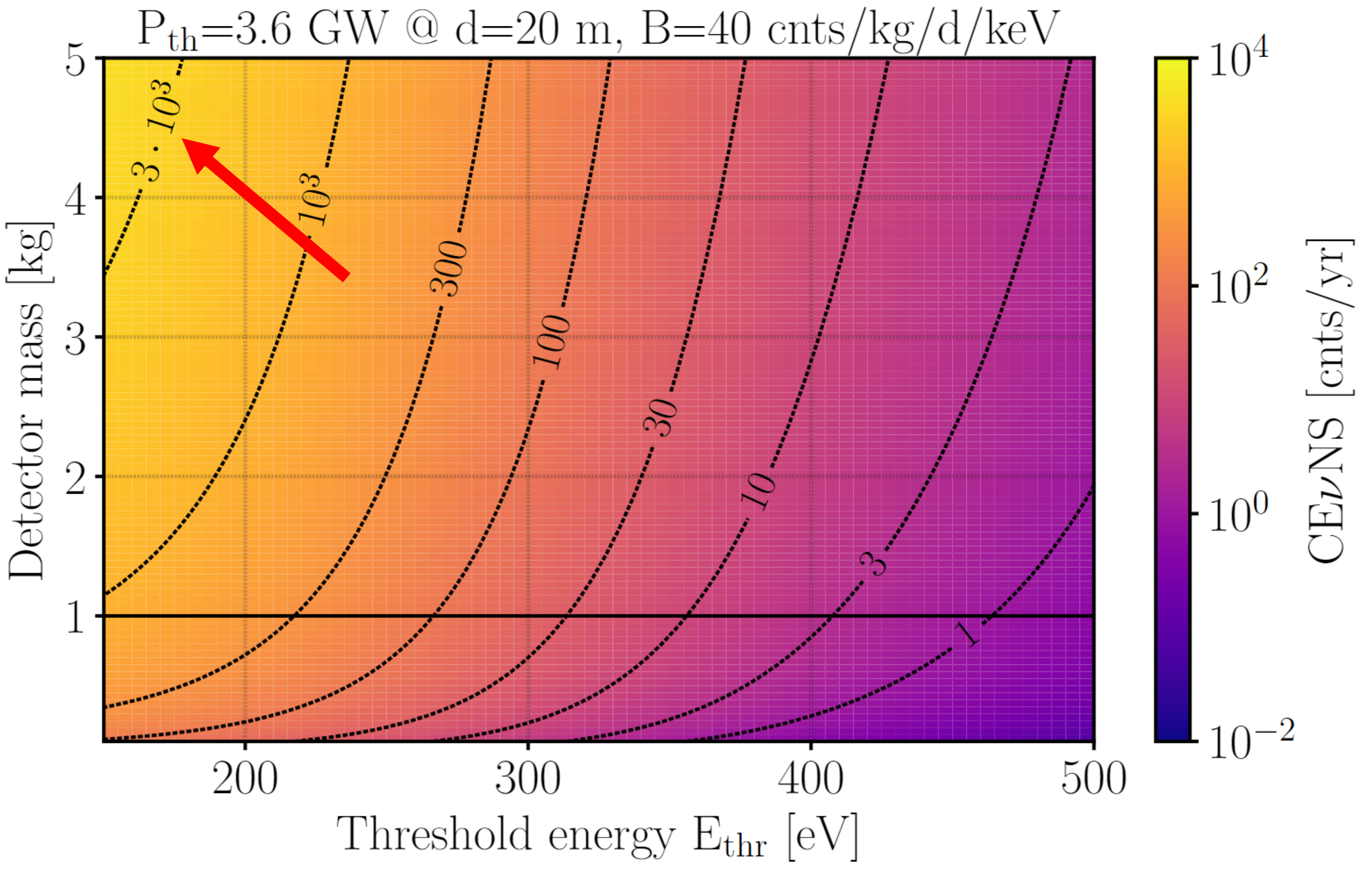
- **Ge detector refurbishment:**
  - Reduced point-contact size
  - Higher trigger efficiency ASIC
  - Water-cooled system to reduce vibration and microphonic noise
- **2nd muon veto**
  - Higher coverage, less gamma interference
  - Independent trigger on each scintillator, coincidence available
- **Real-time remote control**
- **NOW ongoing physical data taking!**



Future prospects

For CONUS+, a threshold down to <200eV will hopefully provide >10^3 CEνNS events per year!

Global pursuit of reactor CEνNS detection has just begun, aiming for higher detector mass and lower threshold.



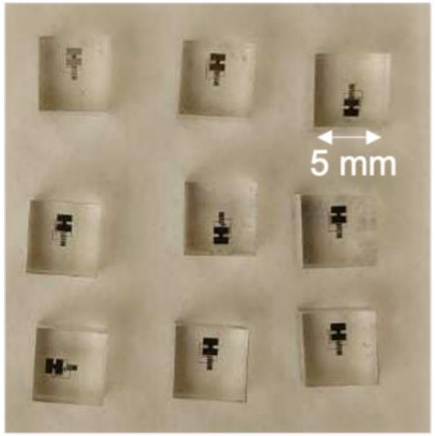
Towards lower threshold

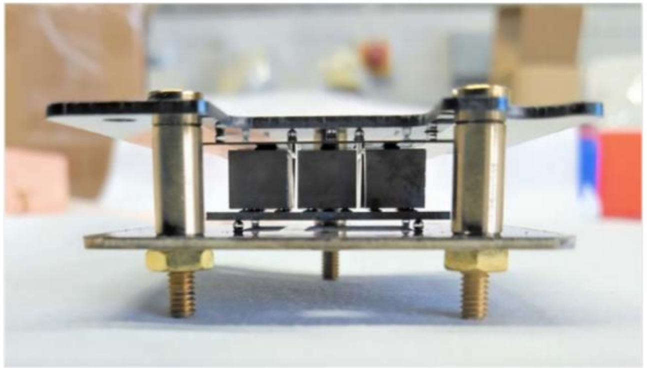
With new detection technology!

NUCLEUS: transition edge sensors(TES) ***J.Low Temp.Phys.*** **199 (2019) 1-2, 433-440**

- Energy threshold: O(10 eV)
- Target material: $Al_2O_3/CaWO_4$
- Target mass: 10g, second phase up to 1kg

→ Reach 5σ in less than 40 days with background rate of 100 counts/(keV·kg·day)



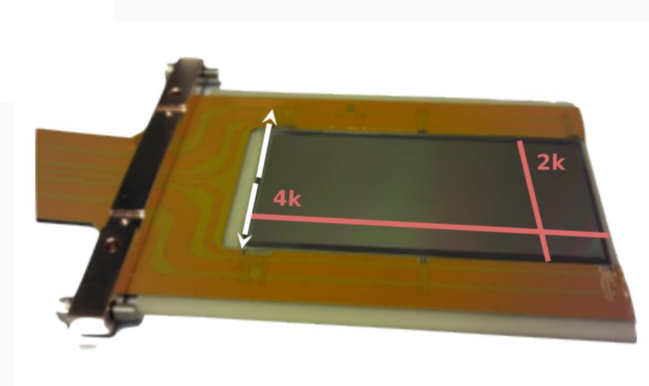


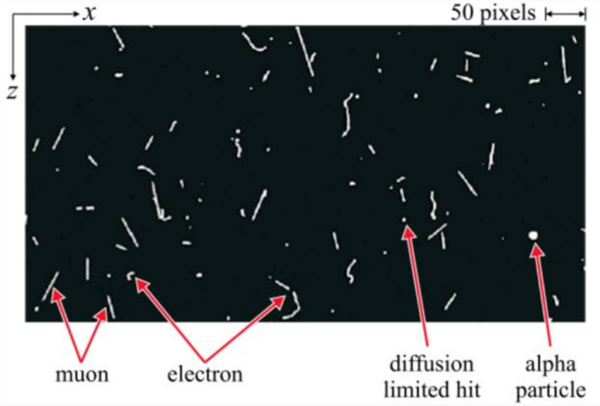
CONNIE: CCD ***J.Phys.Conf.Ser.*** **761 (2016) 1, 012057**

- Energy threshold: 50eV
- Target material: Si
- Target mass: 50g

→ Additional tracking ability

→ Reached limit: <551 counts/keV/kg/day, 39 times larger than the standard model expectation





Towards larger target mass

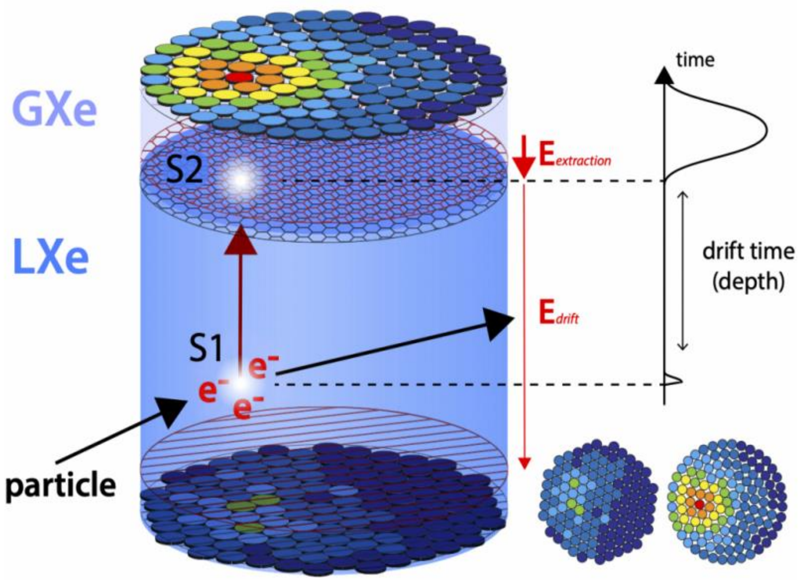
At O(100)kg level, ordinary crystals may not be available. The alternative is to use noble liquid detectors.

- Well developed technique thanks to the dark matter community
- Happens both scintillation/ionization, helps to discriminate electron/nuclear recoils
- Delayed single electron signal might be the dominant background

Experiments:

- Currently running: RED-100.
- More proposals/R&Ds came out recently: RELICS, NUXE, etc.

Signal prediction of a xenon TPC with 30kg-yr exposure @ 10^{13} ν/s/cm^2 flux: >5000

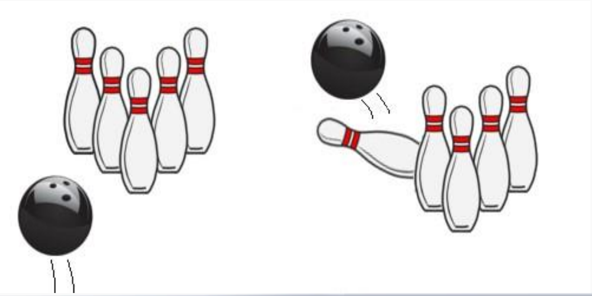


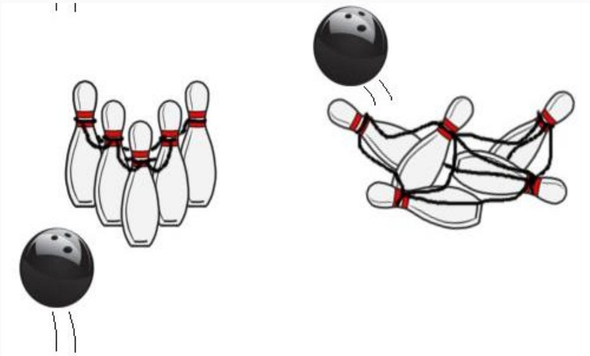
the two-phase (LXe/GXe) time projection chamber (TPC), XENON Collaboration

Also stay tuned to solar neutrino CEvNS detection by the dark matter experiments (PandaX-4T, LZ, XENONnT)!

Summary

- Reactor CEvNS is a validation for SM neutrino interaction at low energy limit, but is still not observed.
- The CONUS experiment was running in KBR to detect CEvNS until the end of 2022. Analysis of the full data set is completed and the preliminary result shows that ***we are at the edge of making discovery.***
- The next phase of the experiment, CONUS+, is moved to KKL with improved Ge detector performance and adaptions to the new background composition.
- There is a global effort to search for CEvNS where various detection technologies beside HPGe are being developed. We are glad to see a more and more active CEvNS community!

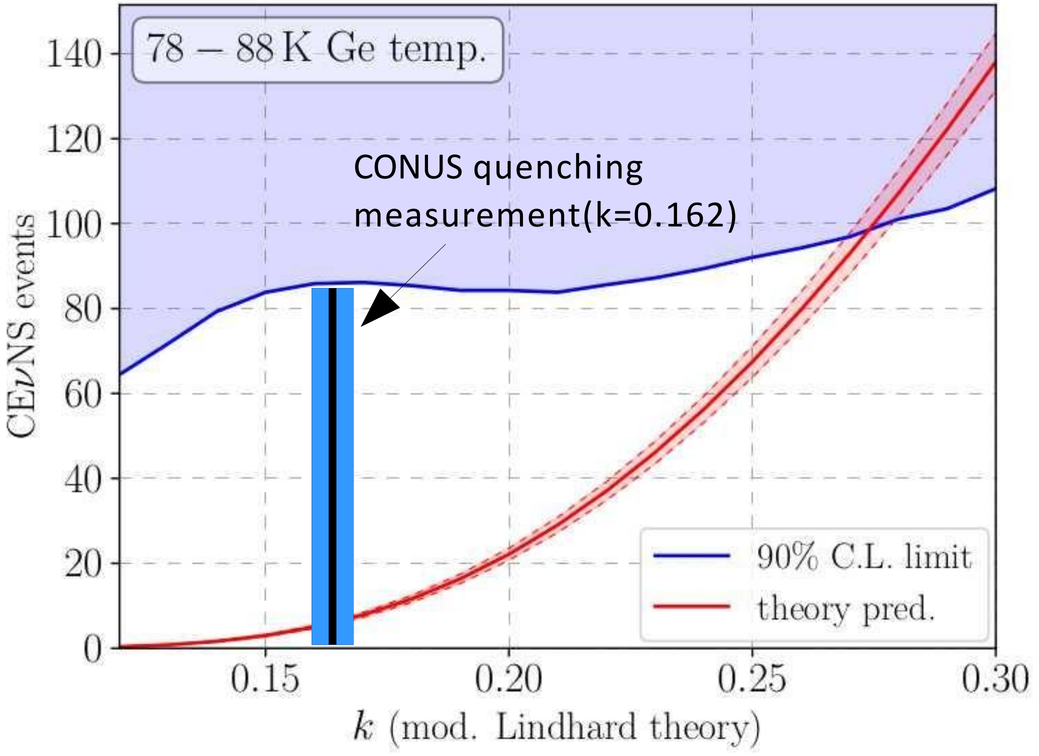


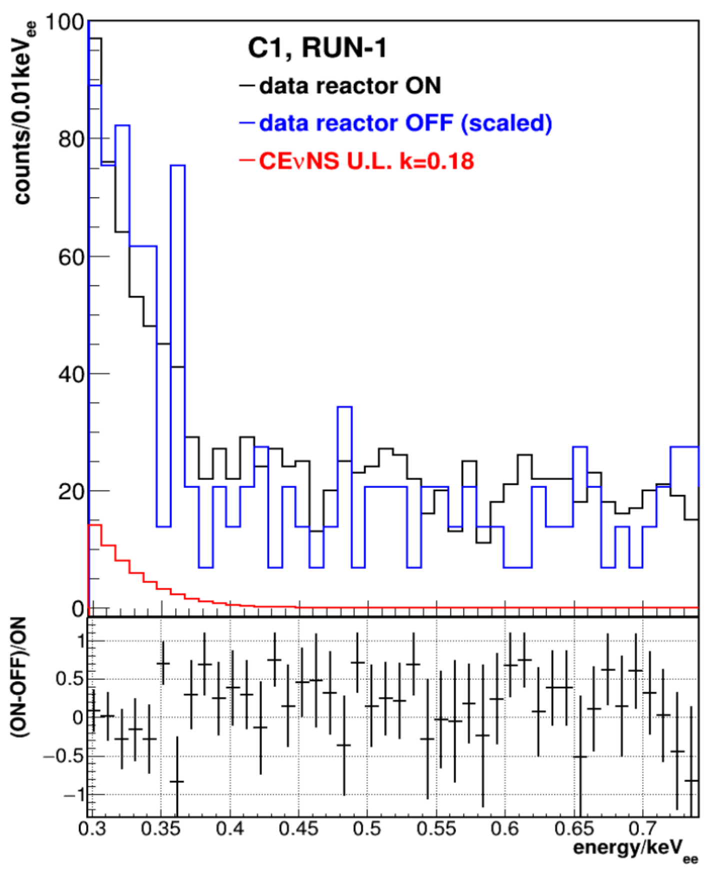


THANKS

Backup

Results (Run1/Run2)





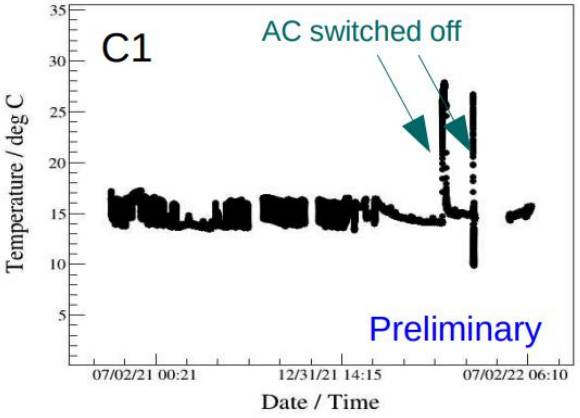
<85 events are detected
Upper limit is still factor 17 higher than SM!

- Data: 248.7kg-d ON, 58.8kg-d OFF
- Threshold: ~300eV
- Binned Likelihood:
  - Simultaneously fit ON/OFF data
  - Poisson distribution in each bin

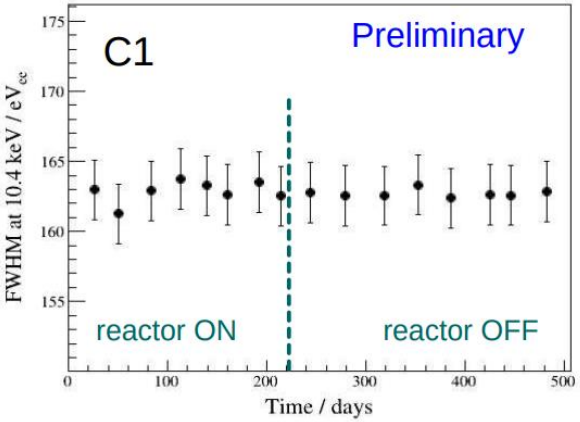
Phys.Rev.Lett. 126 (2021) 4, 041804

Run stability (Run5)

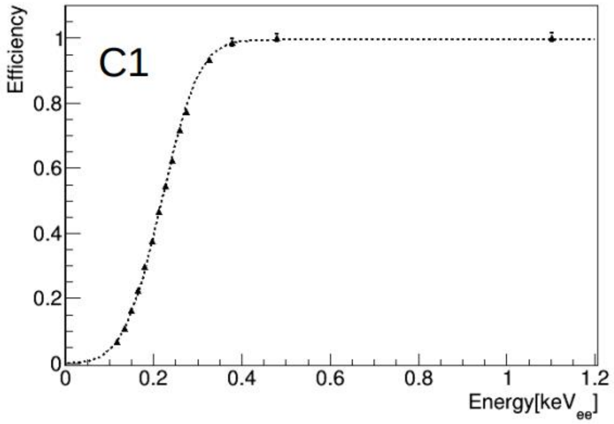
Room temperature



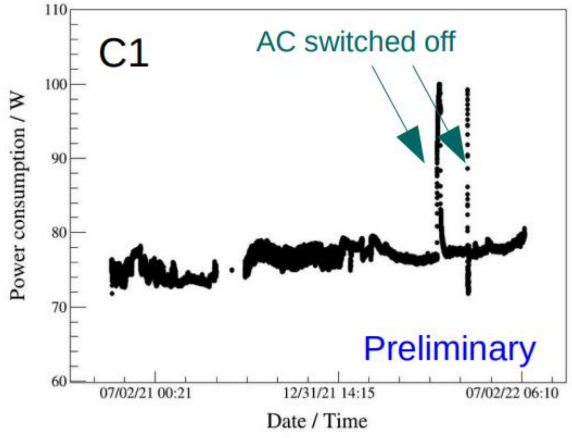
Peak pos. of 10.4 keV line



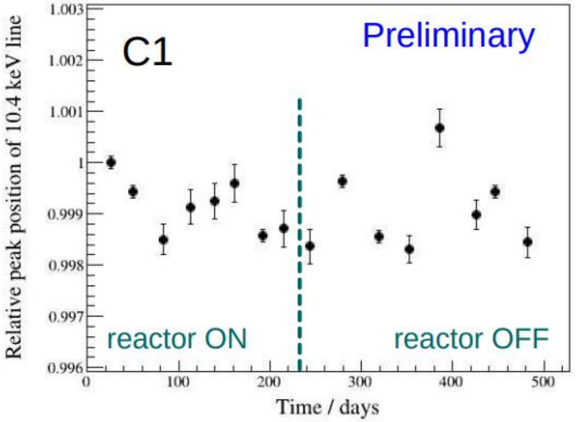
Trigger efficiency curve



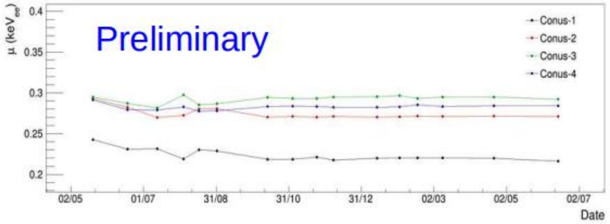
Power consumption

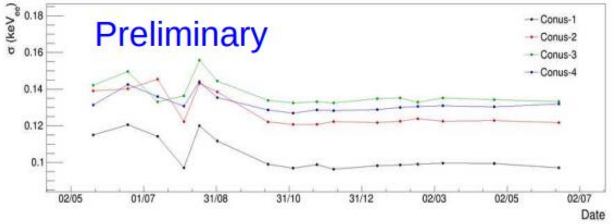


FWHM of 10.4 keV line



Analytical description: 0.5*[1+erf((x-μ)/σ))]





Reactor correlated neutron

- **Neutron spectrometry with NEMUS detectors by PTB**

→ Highly thermalized (>80%) and correlated with reactor thermal power

- **Muon induced neutron takes the major role in CONUS background, instead of reactor neutron**