Recent results from the CONUS experiment

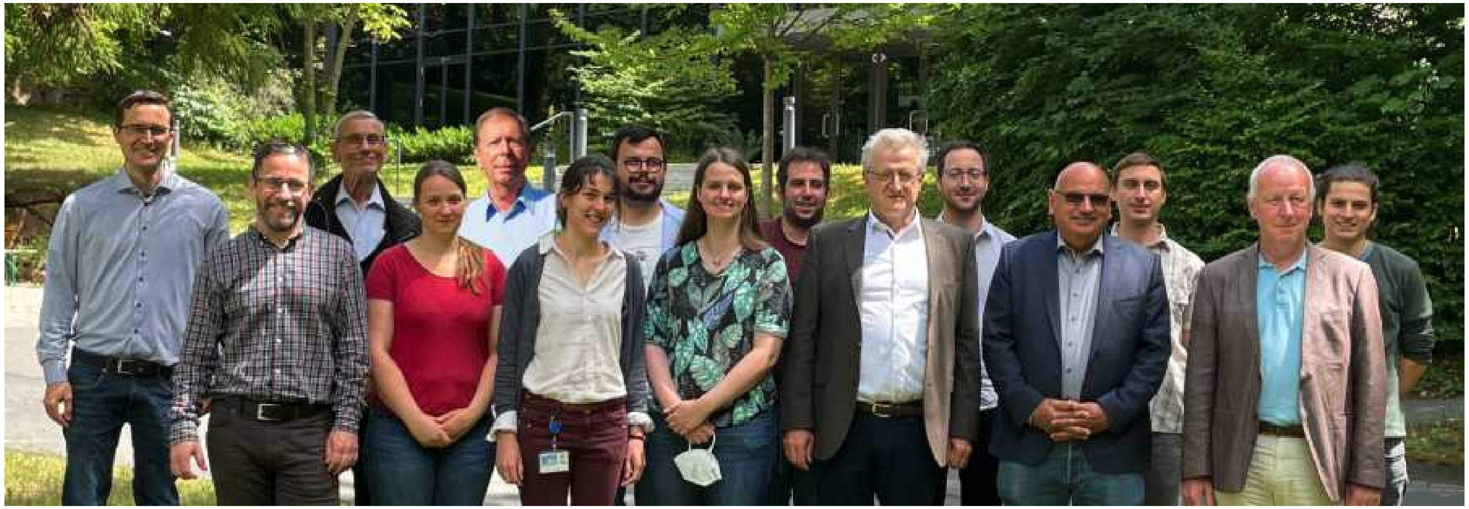
Max-Planck-Institut
für Kernphysik
Heidelberg

Werner Maneschg

- on behalf of the CONUS collaboration -

Magnificent CEvNS workshop – March 22-24, 2023

The CONUS collaboration



Collaboration:

Max-Planck-Institut für Kernphysik (MPIK), Heidelberg:
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Former collaborators: T. Schierhuber, E. Van der Meeren, J. Henrichs, T. Hugle
Preussen Elektra GmbH, Kernkraftwerk Brokdorf (KBR), Brokdorf: K. Fülber, R. Wink

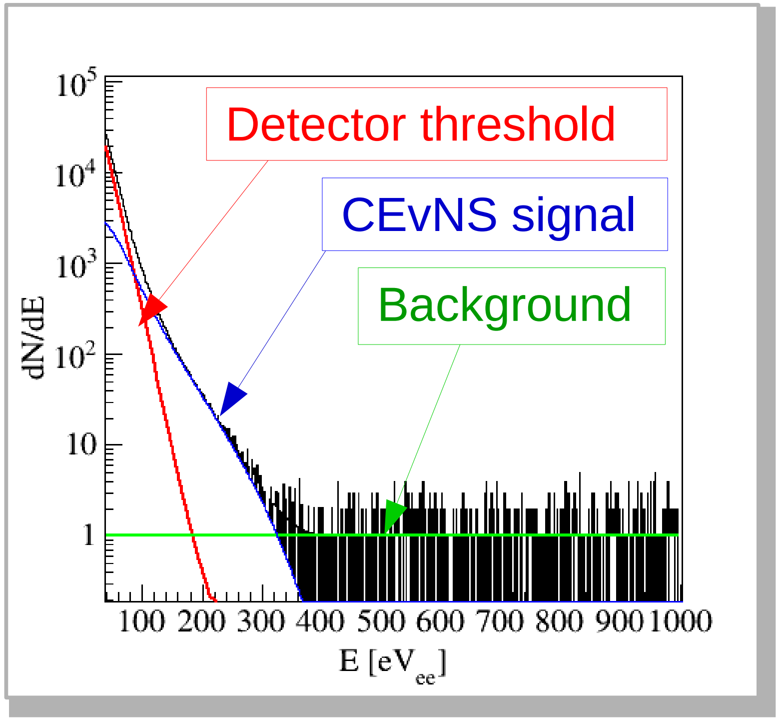
Scientific cooperation:

Physikalisch-Technische Bundesanstalt (PTB), Braunschweig:
R. Nolte, E. Pirovano, M. Reginatto, M. Zboril, A. Zimbal

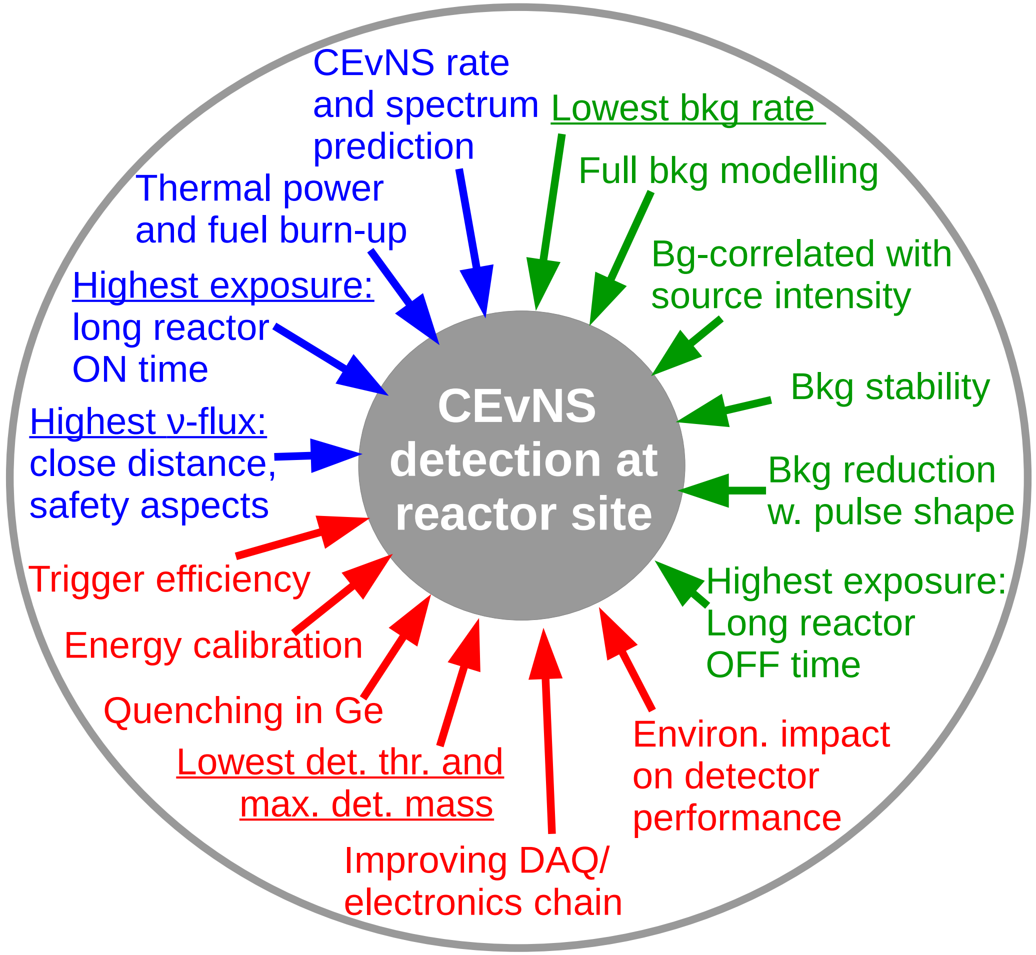
CONUS: introduction

Challenges: in general and in specific

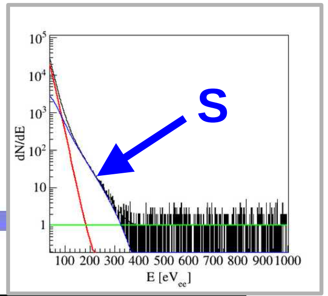
Optimisation of 3 parameters:



Realistic simulation for Ge with k=0.20



CONUS experimental site

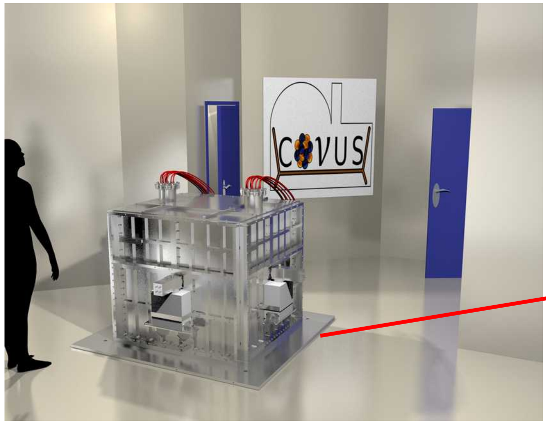


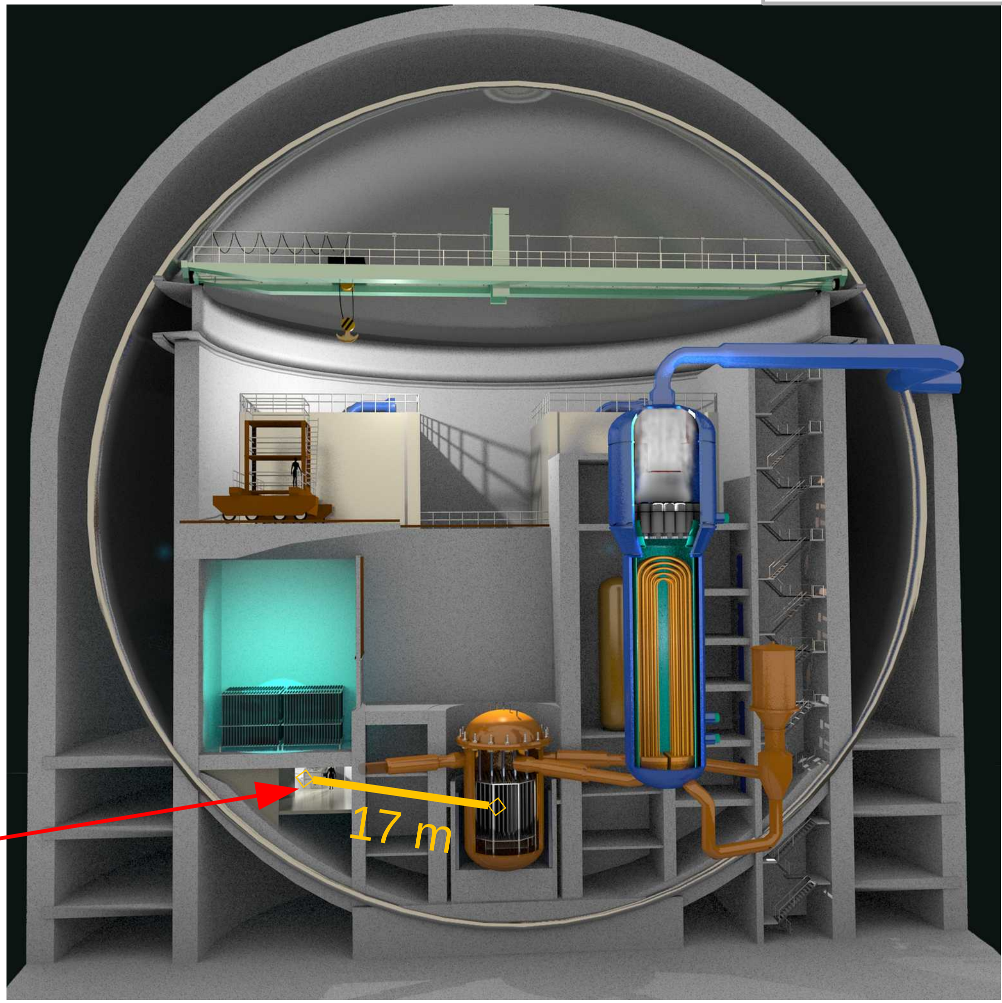
Brokdorf reactor (KBR):

- pressurized light water reactor
- 193 fuel assemblies, total 100 tons
- thermal power: 3.9 GW
- high duty cycle (1 month OFF/a)
- operation: 10/1986 – 12/2021
- Conus: access to reactor physics data

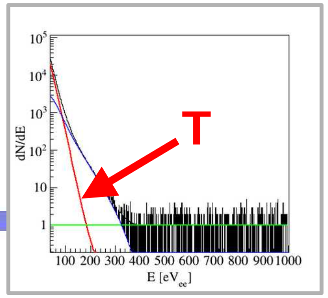
Experimental site for CONUS:

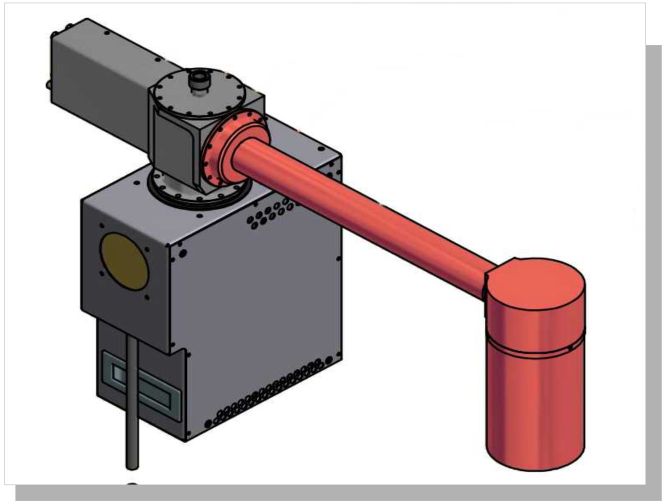
- beneath fuel cooling pool:
  10-45 m w.e., 24 m w.e. on average
- distance to reactor core center: 17 m
  → $\Phi = 2.3 \times 10^{13}\ \bar{\nu}/s/cm^2$





CONUS Ge detectors





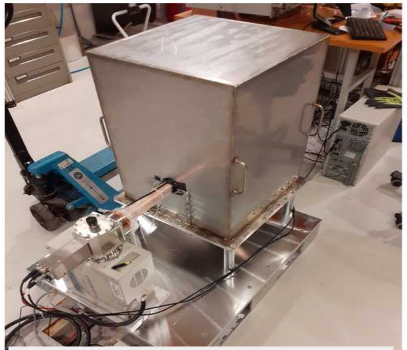
CONUS-1 to -4 (C1-C4):

- point-contact high purity Ge detectors
- active mass: 3.72 kg
- energy threshold: ~200 eV$_{ee}$
- electrical PT cryocoolers
- very low bkg components
- long cryostat arms
- pulse shape bkg discrimination (PSD) at sub-keV$_{ee}$
- operated as ionisation det. at ~85 K: quenching effect

} R&D between MPI-K and Mirion-France

CONUS-5:

- same spec's as C1-C4
- used for tests:
  - environment extremes
  - mobile setup at KBR
  - PSD technique
- R&D: improve detector performance

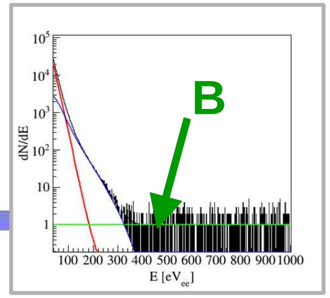


1/R² test at KBR

CONRAD (CONus RADiation):

- p-type semi-coaxial HPGe
- active mass: 2.2 kg
- electrical PT cryocooler
- used for characterisation:
  - bkg inside CONUS shield
  - gamma-ray bkg at KBR

CONUS shield in a nutshell

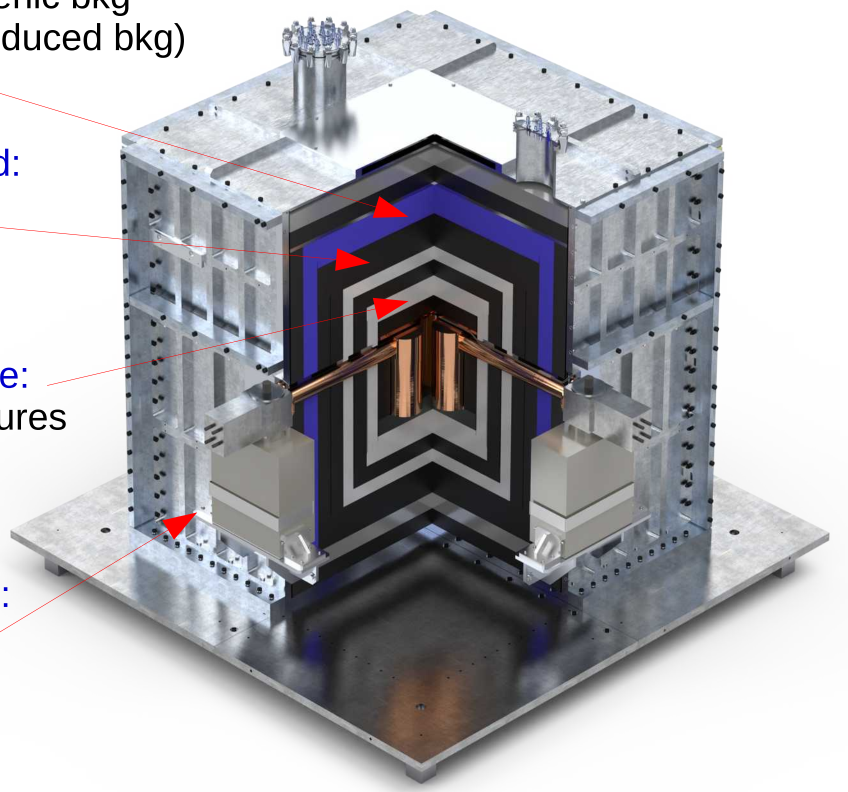


Active muon veto system:
suppresses cosmogenic bkg
(muons and muon-induced bkg)

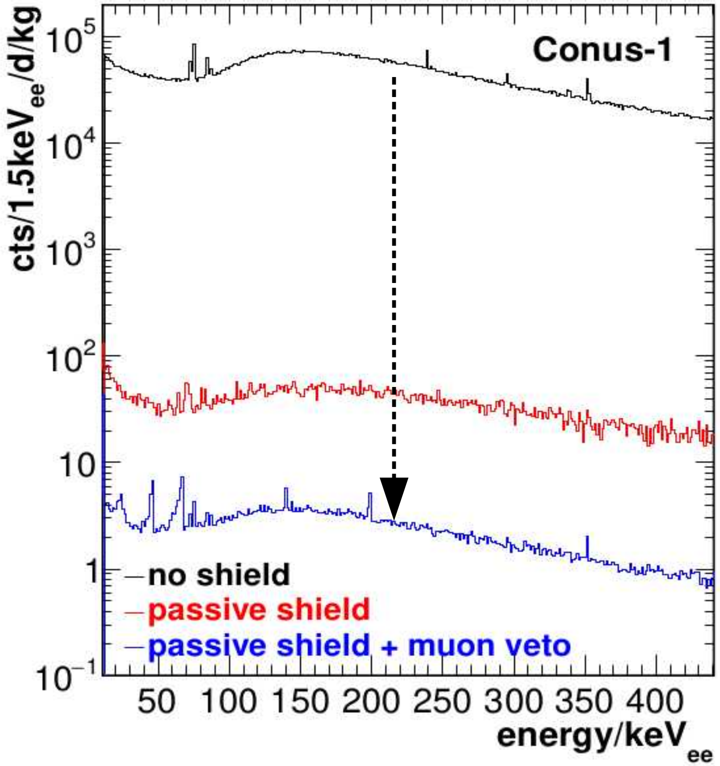
25 cm radiopure lead:
suppresses external
gamma-radiation

Borated Polyethylene:
moderates and captures
neutrons

Stainless steel cage:
fullfills earthquake
safety requirements



Overall background suppression
via **passive** and **active** shield

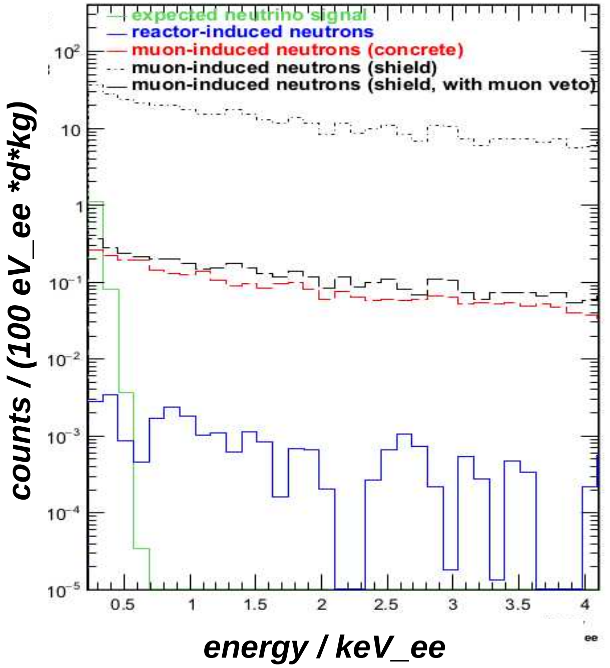


- based on long-lasting experience at MPI-K
- highly compact: volume: 1.65 m³; mass: 11 tons

- total bkg suppression (w/o PSD): >10^4 x
- remaining bkg rate in ROI: O(10) cts/d/kg
  i.e. (0.3,1.0) keV_ee

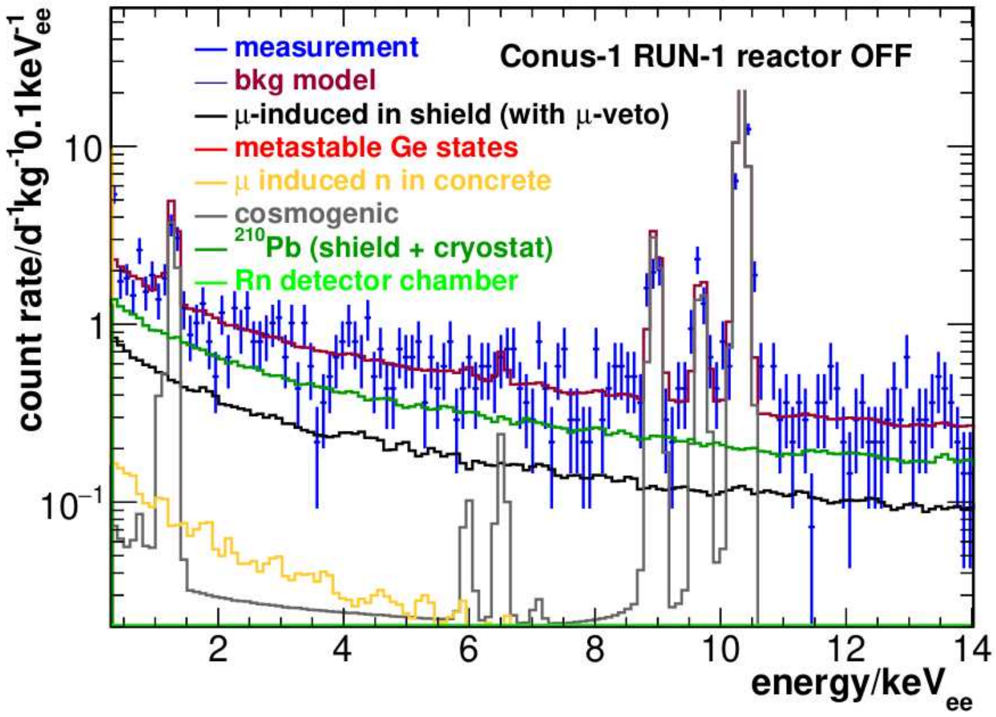
CONUS: residual background at KBR

Investigate neutrons as potential reactor thermal power correlated background



- n-field highly thermalized (>80%) and inhomogeneous at CONUS site
- reactor-induced neutrons
  → reduced by 10^{20} at CONUS site
  → negligible in CONUS shield (0.02 cts/d/kg/keV)

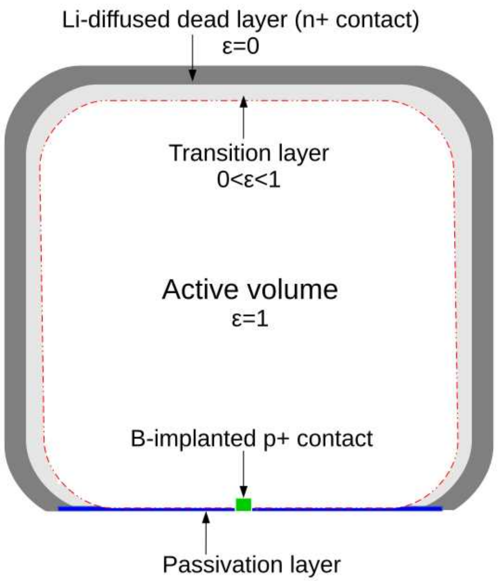
Reproduce background via validated Monte-Carlo simulation

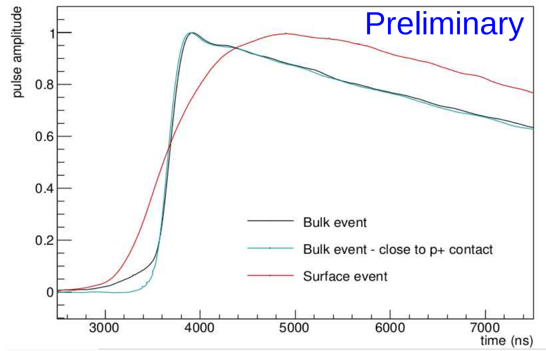


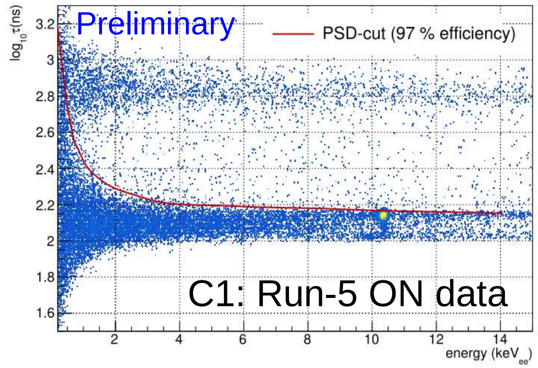
- full bkg decomposition in (0.3-440) keV_ee
  → first time for Ge at shallow depth reactor site
  → input for Likelihood spectral analyses

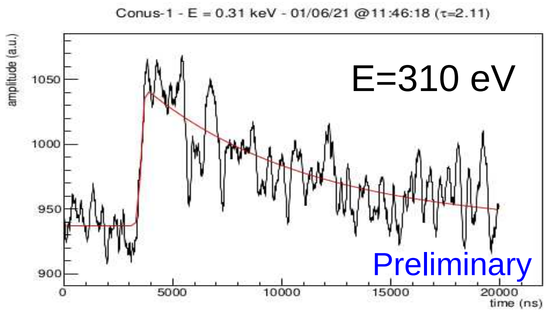
CONUS: further background reduction

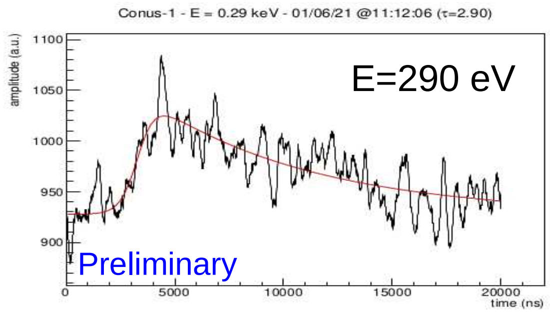
Pulse shape background discrimination









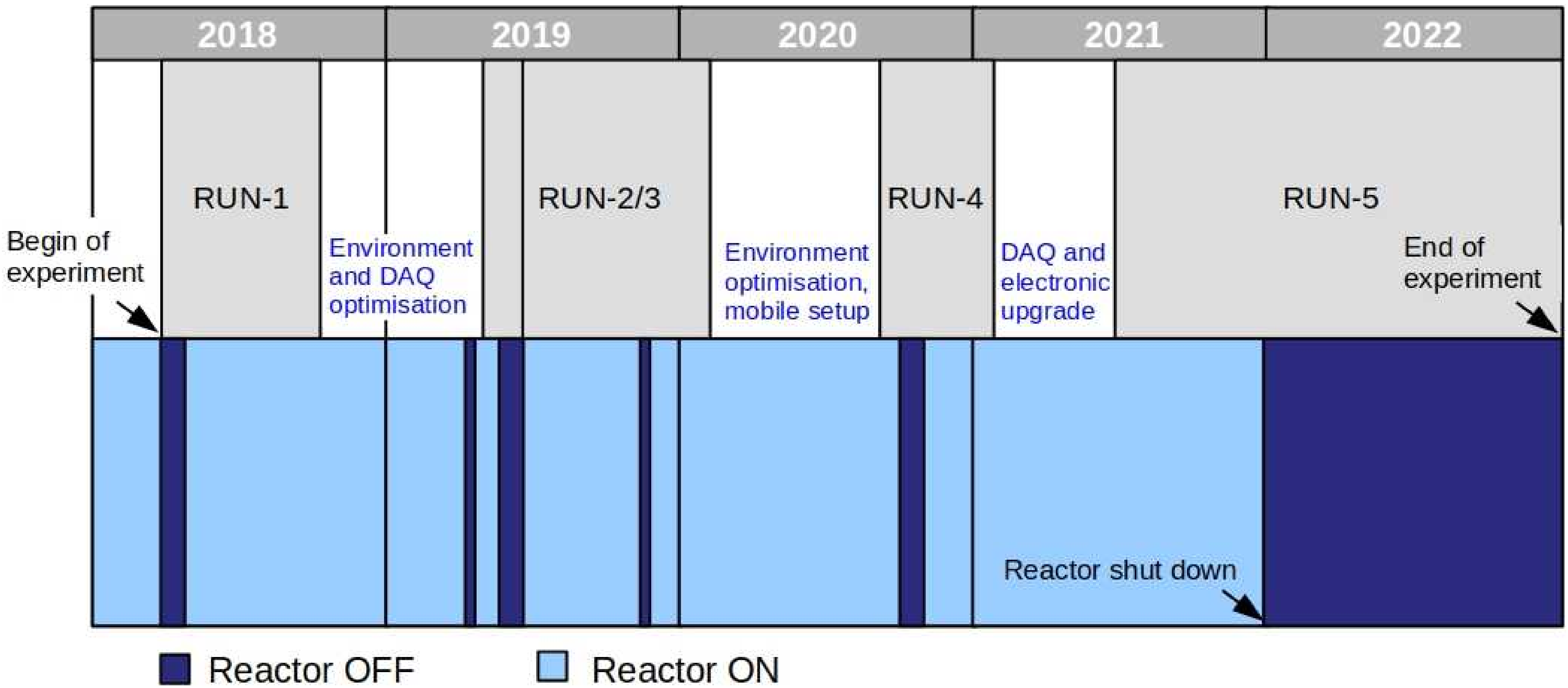


Energy deposition in:

1. transition layer:
   → slower risetime
   → *'surface events'*
2. active volume
   → faster risetime
   → *'bulk events'*

- pulse shape discrimination of slow pulses down to ~200 eV possible
- slow pulses rejection in CONUS det's: ~20% background reduction
- publication in preparation

CONUS: data collection & reactor operation



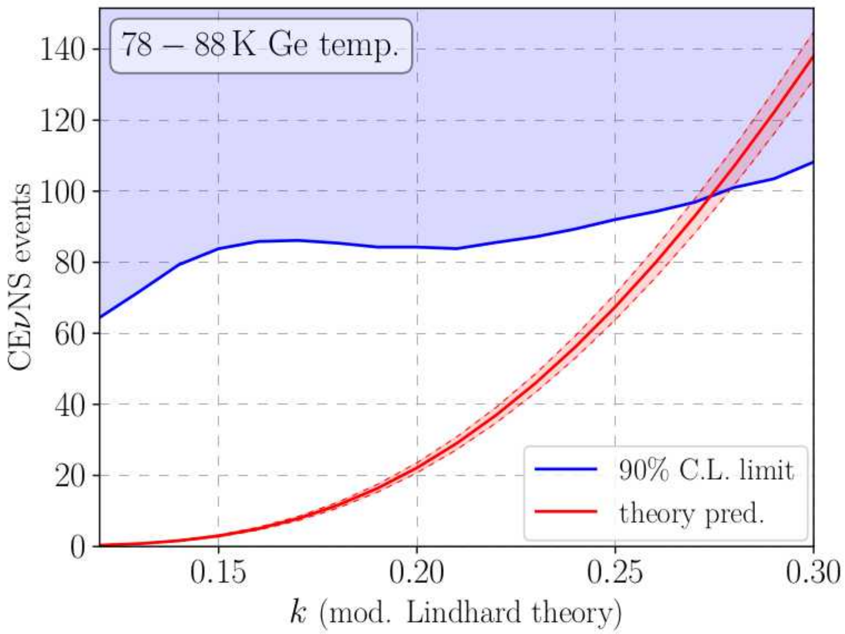
CONUS: RUN-1/-2: SM physics

Applied method:

- binned likelihood ratio test
- **simultaneous fit** of ON/OFF spectra and all runs & detectors
- **background** for OFF description:
  - Use MC model
  - Free normalization
  - Noise: approx. with exp. function
- **systematics:** beside quenching all included via Gaussian pull terms;
- scan over signal parameter as function of k-parameter: (at that time, CONUS quenching result not yet available)

1st CONUS CEvNS spectral fit result

ON: 59 kg*d OFF: 249 kg*d

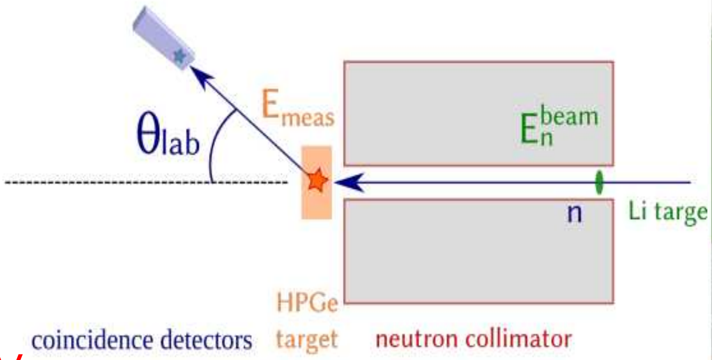


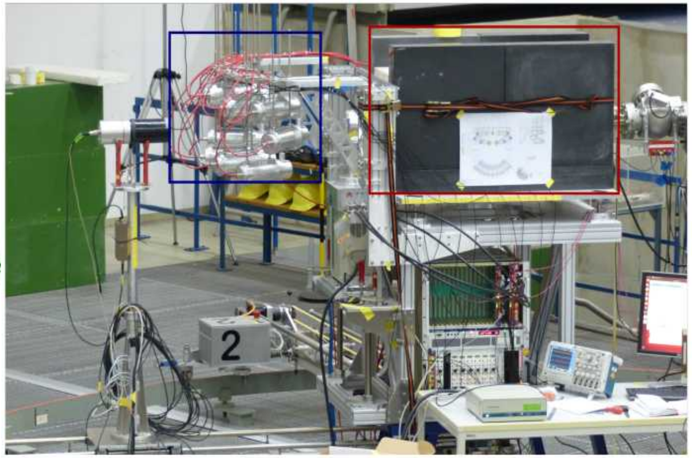
Result: quenching factor k >0.27 disfavored by CONUS data alone

CONUS: Ge quenching measurement

Measurement at PTB:

Method:
- purely kinematics
  → model-independent
- triple time coincidence
- angles 18-45°
  (1° precision)
- monoenergetic neutron beam:
  energies 250 - 800 keV
  → nuclear recoils: (0.4, 6.3) keV

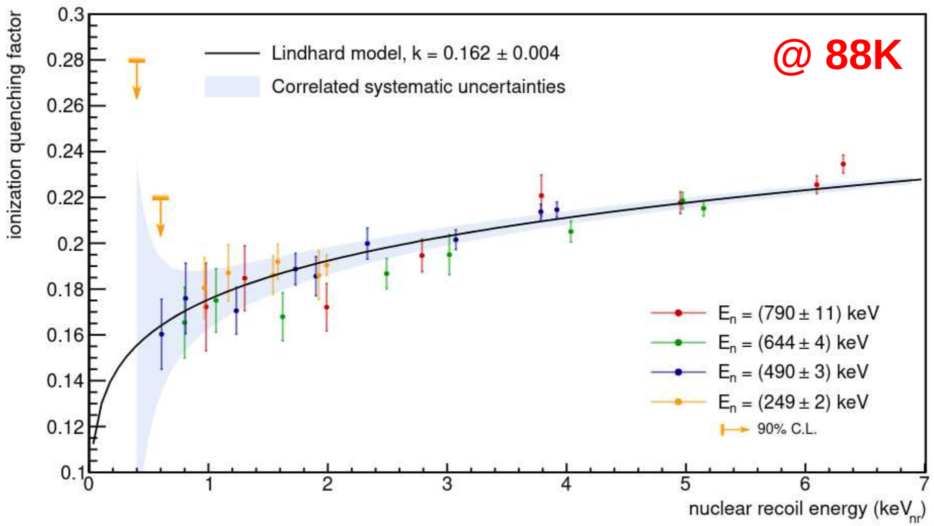




Main result:

k=0.162+-0.004 (stat.+syst.)

→ precision at +-2.5% !
→ confirm validity of Lindhard theory !
→ CEvNS detection even more challenging



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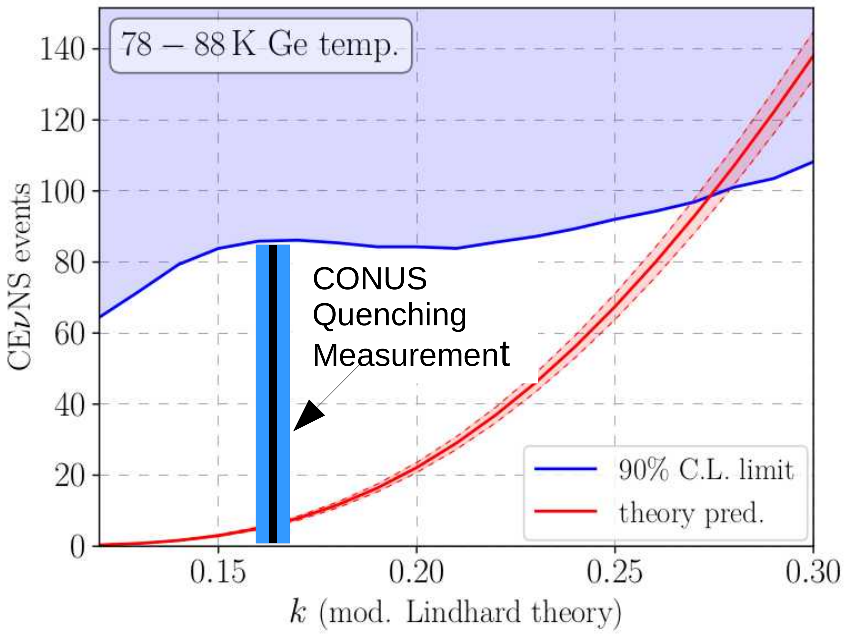


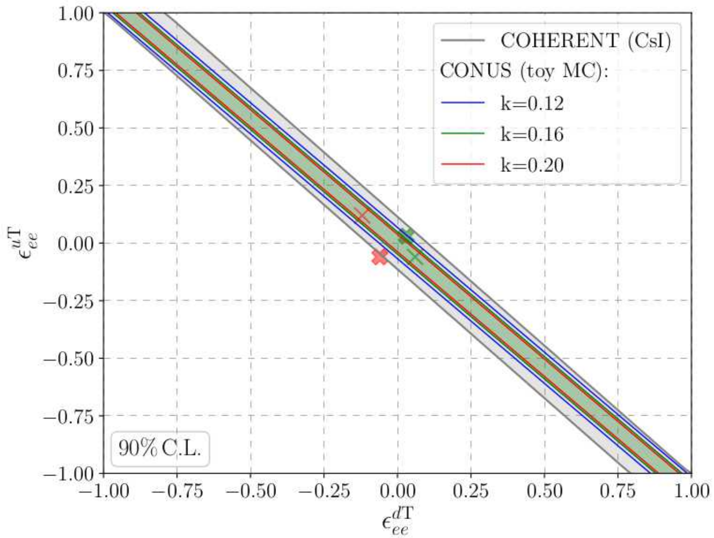
Result: quenching factor k >0.27 disfavored by CONUS data alone
With our quenching factor k=0.162:
→ **CEvNS limit:** <0.4 cts/d/kg (90% C.L.) → Limit is still ~17x above SM prediction

CONUS RUN-1/-2: BSM physics

Light mediators (e.g. Z') and NSIs

ON: (209-649) kg*d   OFF: (38-94) kg*d

Example: Tensor-type NSI

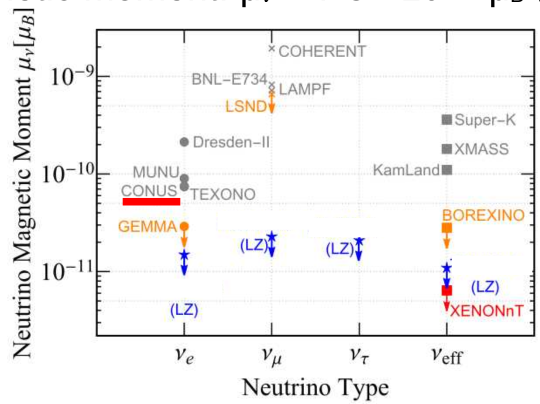


- kinematic cut-off largely above SM CEvNS
- degeneracy of couplings ϵ can be broken by using different isotopes
- since $\epsilon \approx \frac{M_W^2}{M_{NSI}^2}$ → new exchange boson mass >360 GeV; with ε=0.01 → TeV (LHC)

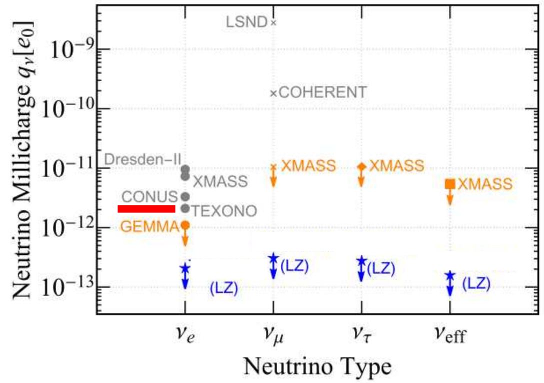
Electromagnetic properties of neutrinos

ON: 689 kg*d   OFF: 131 kg*d

Magnetic moment: $\mu_\nu < 7.5 \cdot 10^{-11}\ \mu_B$ (90% C.L.)



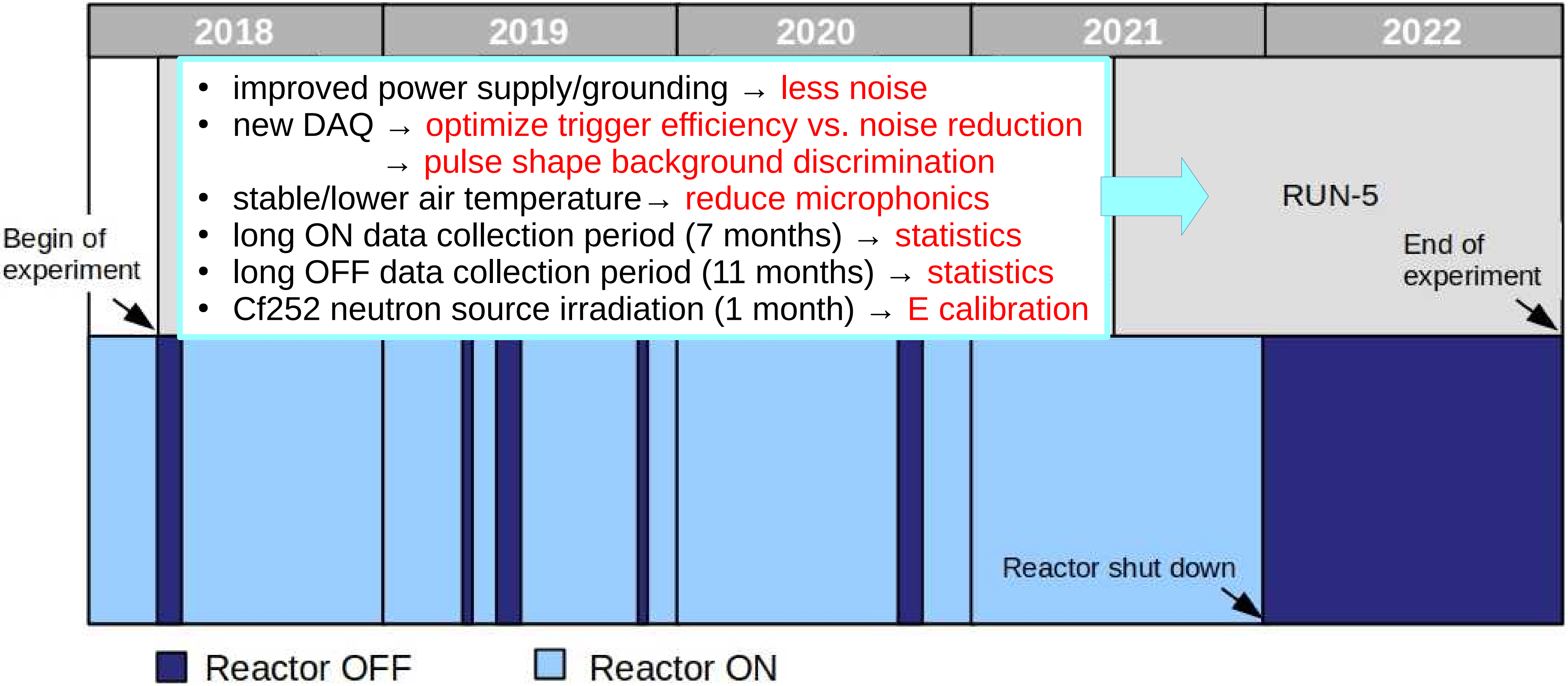
Millicharge: $|q_\nu| < 3.3 \cdot 10^{-12}\ e_0$ (90% C.L.)



Figures from: Phys. Rev. D 107, 053001 (2023)

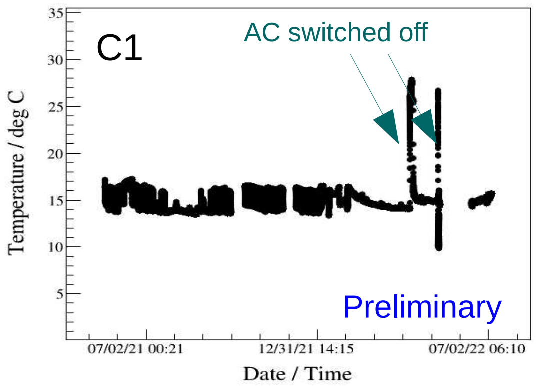
CONUS: RUN-5 data collection

- improved power supply/grounding → less noise
- new DAQ → optimize trigger efficiency vs. noise reduction
  → pulse shape background discrimination
- stable/lower air temperature → reduce microphonics
- long ON data collection period (7 months) → statistics
- long OFF data collection period (11 months) → statistics
- Cf252 neutron source irradiation (1 month) → E calibration

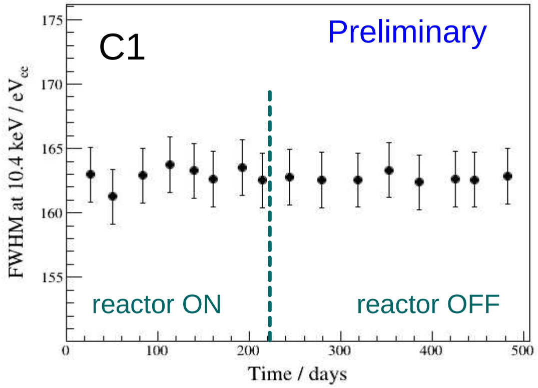


CONUS: RUN-5 stability

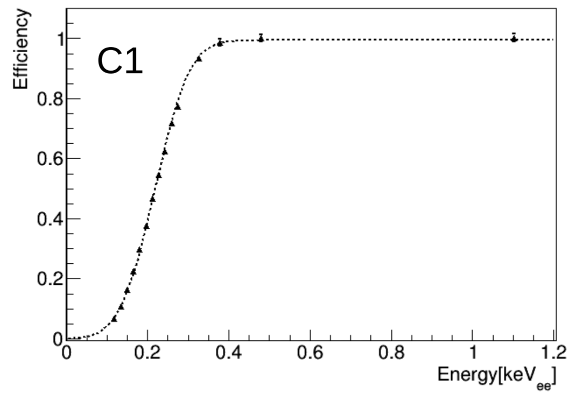
Room temperature



Peak pos. of 10.4 keV line

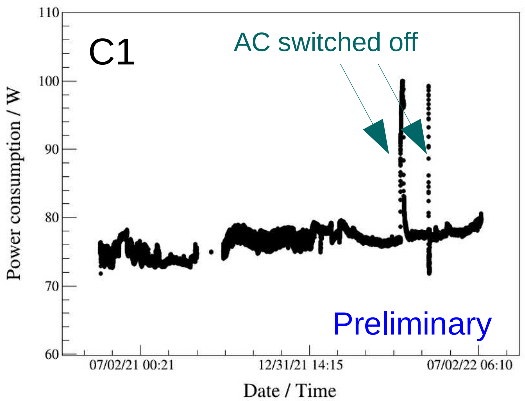


Trigger efficiency curve

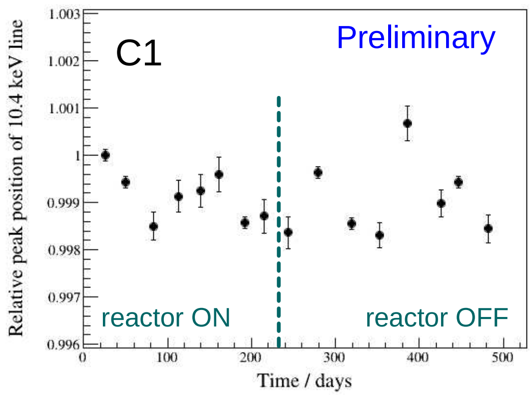


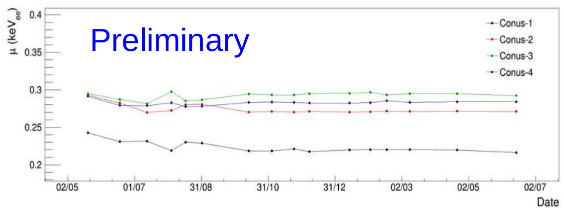
Analytical description: 0.5*[1+erf((x-μ)/σ))]

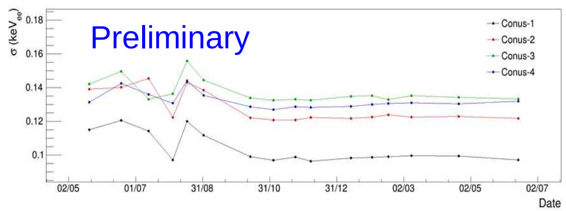
Power consumption



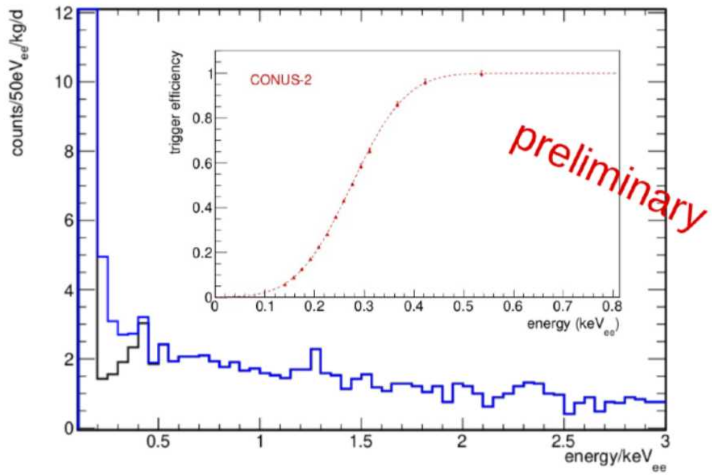
FWHM of 10.4 keV line







CONUS: RUN-5 SM physics

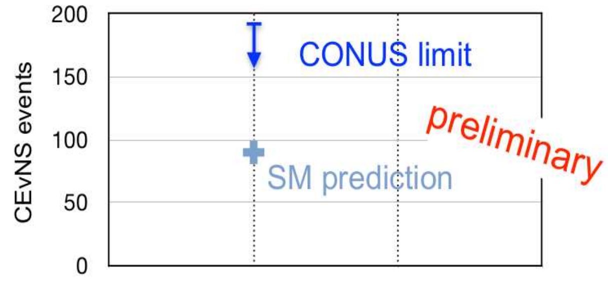


Detector	ON kg*d	OFF kg*d	ROI lower threshold / eV
C1	151	43	220
C2	154	138	210
C4	153	112	220
Total	**458**	**293**	

ROI upper threshold: 1 keV

Preliminary results:

- so far, statistical likelihood ratio test
- all Conus detectors do not find a signal
- combined limit (90% C.L.): factor ~2 above predicted CEvNS based on Lindhard quenching with k=0.162
- further slight improvements expected (PSD, additional statistics,…)



Comparison with other experiments

Reactor CEvNS experiments:

- so far, constraints from νGen, CONNIE, ...
- strong signal preference with NCC-1701 at Dresden-II reactor:

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

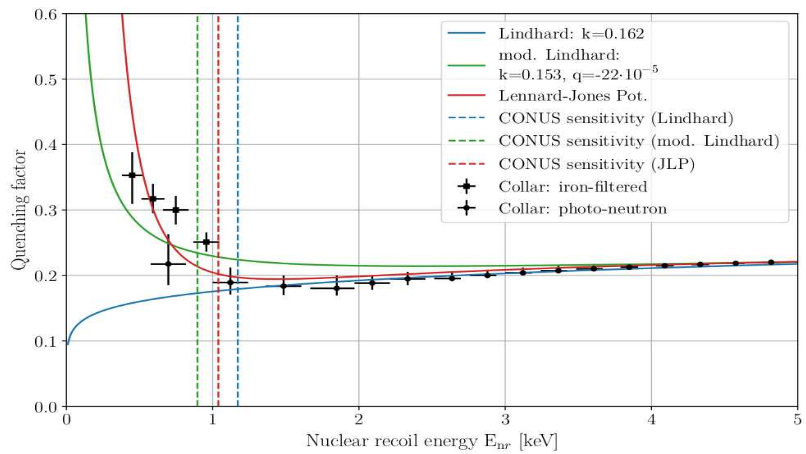
The 96.4 day exposure of a 3 kg ultralow noise germanium detector to the high flux of antineutrinos from a power nuclear reactor is described. A very strong preference ($p < 1.2 \times 10^{-3}$) for the presence of a coherent elastic neutrino-nucleus scattering (CEνNS) component in the data is found, 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.

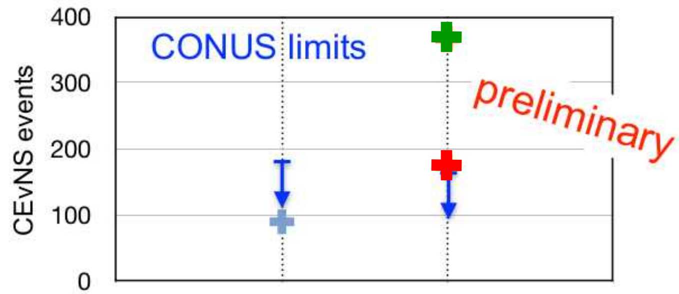
Abstract of Phys. Rev. D 103, 122003 (2021)

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.

↔ tension with CONUS quenching

Test NCC-1701 signal with CONUS data





green/**red** cross:
2 parametrisations of Lindhard+Migdal like measured in Phys. Rev. D 103, 122003 (2021)

blue cross:
Lindhard, k=0.162
CONUS meas.

↔ tension with CONUS reactor ON/OFF data

CONUS: Summary

- Background / stability / systematics:
  - challenging environment, support from nuclear power plant (NPP) Brokdorf essential
  - consideration of all relevant systematics and stability issues
  - extensive background studies, specifically of neutrons!
  - first full background decomposition in Ge at reactor site
  - pulse shape background discrimination method working at sub-keV
  - precision quenching measurement with PTB: validity of Lindhard theory confirmed

- Data collection and physics results:
  - 5 years of successful detector operation 2018-2022
  - strong constraints on CEvNS: 90% C.L. limit is **factor ~2 above SM prediction**
  - constraints on BSM models and electromagnetic neutrino properties
  - complementary to other CEvNS experiments (diff. energy regimes/neutrino sources/isotopes)

- Outlook:
  - reactor shut down in Dec '21:
  - unique situation for long reactor-OFF measurement
  - 'natural end' of CONUS experiment, but
  - successor experiment CONUS+ in new location at NPP Leibstadt in preparation
    → See talk by ***Edgar Sanchez-Garcia on Friday 9:00 a.m.***

Thank you for your attention!

SPARE

CONUS: literature

HPGe detectors:

- Characteristics and performance — CONUS, Eur. Phys. J. C (2021) 81:267
- Quenching measurement in Ge — CONUS+PTB, Eur. Phys. J. C 82, 815 (2022)

Background:

- Reactor-correlated bkg — CONUS+PTB, Eur. Phys. J. C (2019) 79:699
- Bkg model: full decomposition — CONUS, Eur. Phys. J. C 83 (2023) 3, 195

CEvNS search:

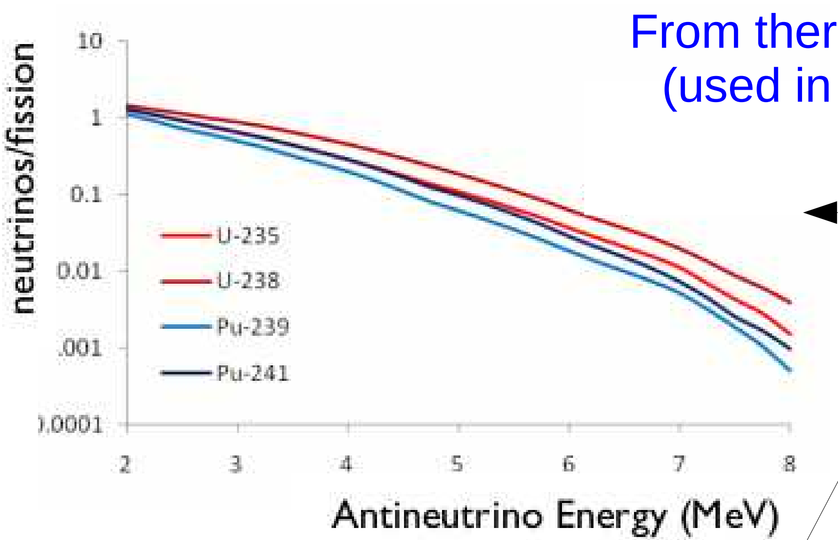
- Constraints on CEvNS from reactor neutrinos (Run-1 and -2) — CONUS, Phys. Rev. Lett. 126 (2021) 041804

Beyond Standard Model:

- Limits on NSIs and light mediators — CONUS, J. High Energ. Phys. 2022, 85 (2022)
- Limits on electromagnetic properties of neutrinos — CONUS, Eur. Phys. J. C 82, 813 (2022)

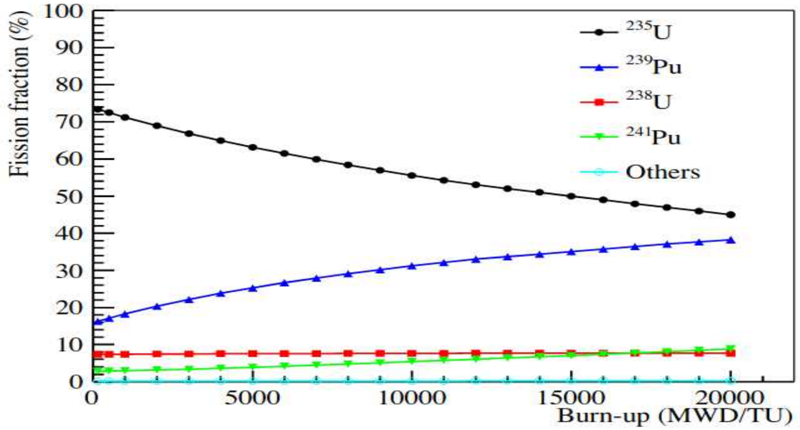
+ a few more publication in preparation

CONUS: CEvNS signal calculation

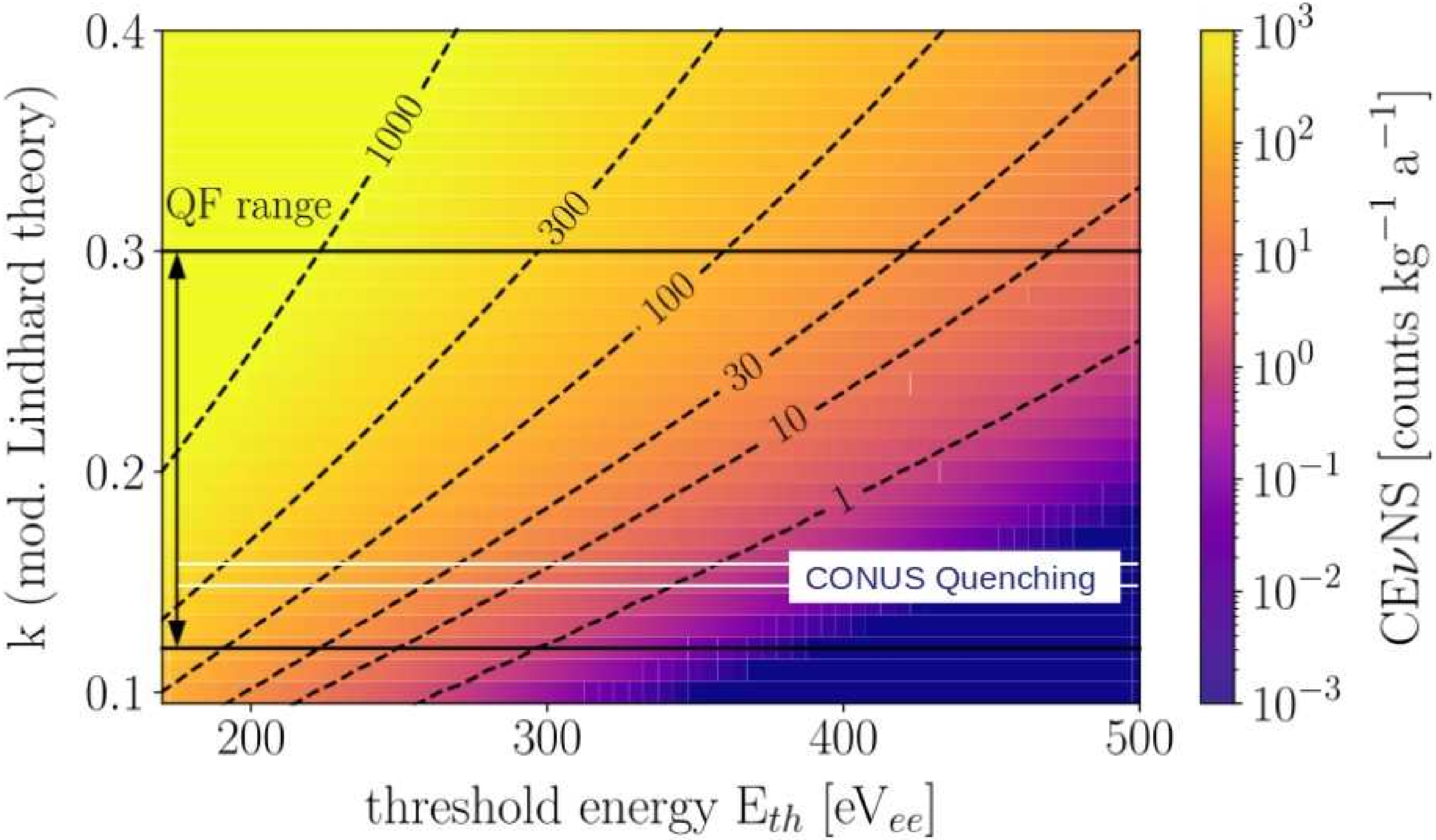


From thermal power to signal expectation
(used in current RUN-5 analysis 2023)

- **thermal power and reactor geometry** from KBR with ca. 200 MeV/fission, 7.2 nu's/fission:
- **fission fractions evolution** from PreussenElektra
- **reactor neutrino spectra:**
  - **<1.8 MeV:** Summation spectra of Estienne & Fallot (2019)
  - **(1.8-7) MeV:**
    - Daya Bay 2021: unfolded IBD spectra of U235, (Pu239+ Pu241), total
    - Pu241 from Huber (+-15% uncorr.), U238 from
    - Müller (+-10% uncorr.)
  - **>7 MeV:** Daya Bay 2022:
    - measurement of combined high energy spectrum 2022



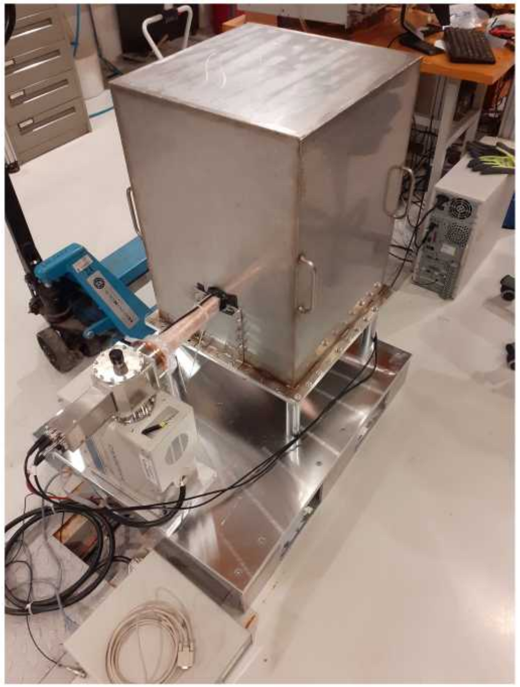
CONUS: signal projection



CONUS: multiple use of C5

Example: Prototyping a mobile neutrino detector

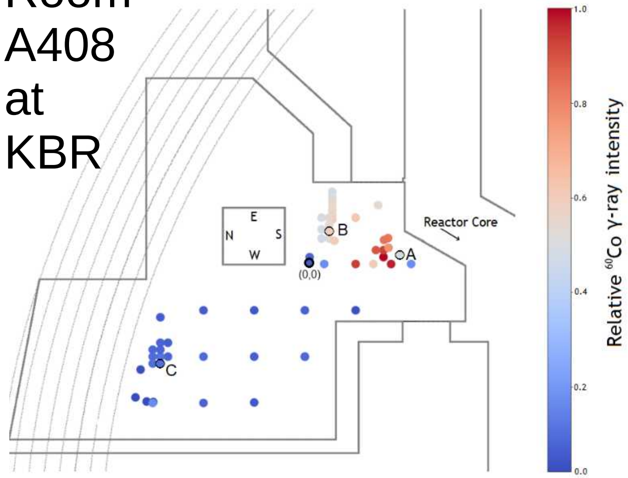
Mobile shield

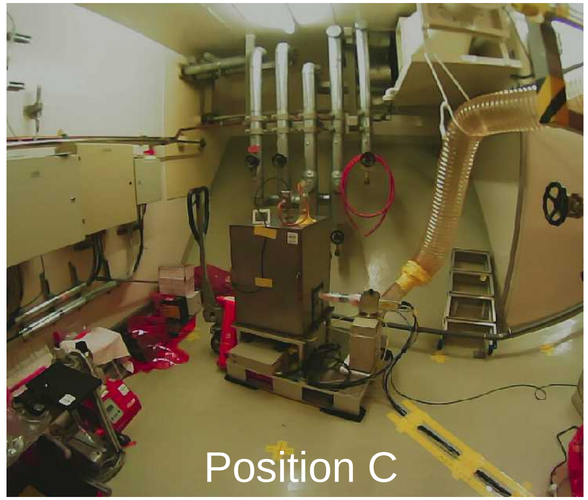


- 1 ton of lead (15 cm in each dir.)
- Rn mitigation via air flushing
- no (borated) PE
- no muon veto

Measurement campaign in August 2020

Room A408 at KBR





Pos	Distance to core / m	Exp. flux intensity
A	15.1	1
B	16.3	0.86
C	18.7	0.65

- **1/R²** behavior can be "distorted" by many effects
- **require** bkg characterisation in every position
- **require** better shield

CONUS: multiple use of CONRAD

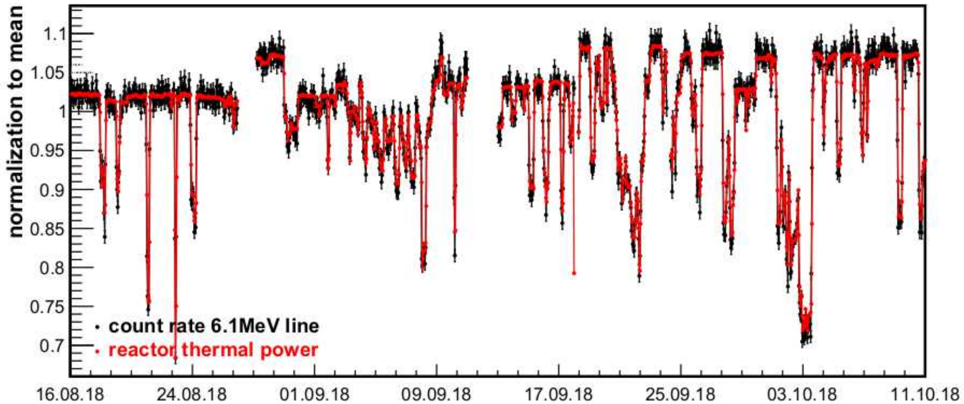
The CONus RADiation detector

Passive / active shield characterisation in low level laboratory @ MPIK

- CONRAD alone in CONUS shield:
  → comparison with GIOVE
  (both ULB and similar diode mass, same overburden, only 2 m distant)
- CONRAD with CONUS detectors:
  → Intrinsic bg of CONUS detectors

Mapping of gamma-ray background at CONUS site

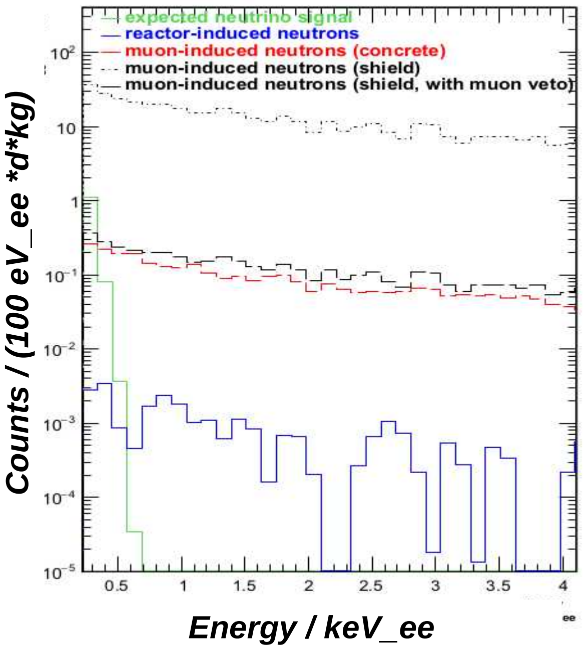
- 6.1 MeV gammas from N-16 decays, from 0-16(n,p)N-16 in the primary loop
- Cs-137, Co-60 contamination on floors
- MC: CONUS shield effective enough, especially for N16



CONUS: critical background components

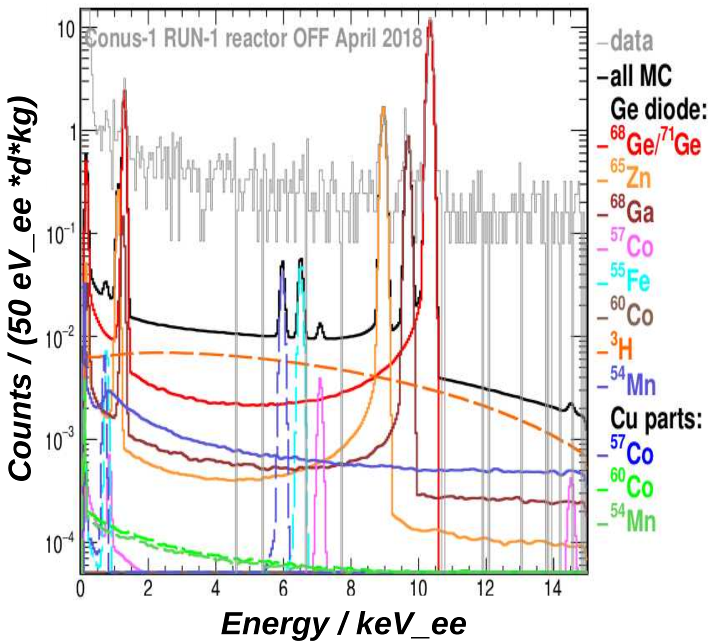
Neutrons from reactor

Most critical for an ON-OFF comparison



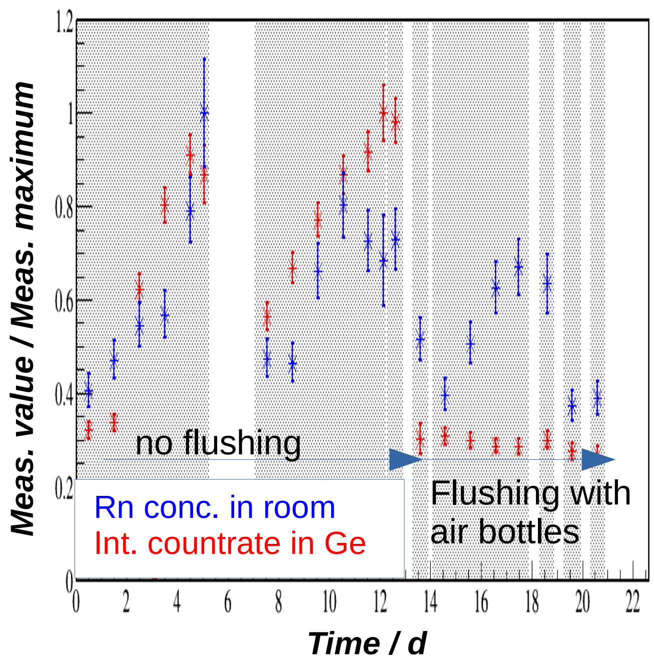
- n-field highly thermalized (>80%) and inhomogeneous at CONUS site
- reactor-induced neutrons
  → reduced by 10^{20} at CONUS site
  → negligible within CONUS shield

Cosmogenic radioisotopes



- cosmic activation in Ge and Cu at Earth surface fully tracked
- time-dependent bkg: MC predicts small contr. to ROI MC model able to apply correction

Air-borne Radon



- Radon conc.: (175+-35) Bq/m³
- boil-off nitrogen not allowed
- solution: Breathing air bottles 4 x 6.8 l bottles (á 300 bar) last 1 week to flush detector chamber