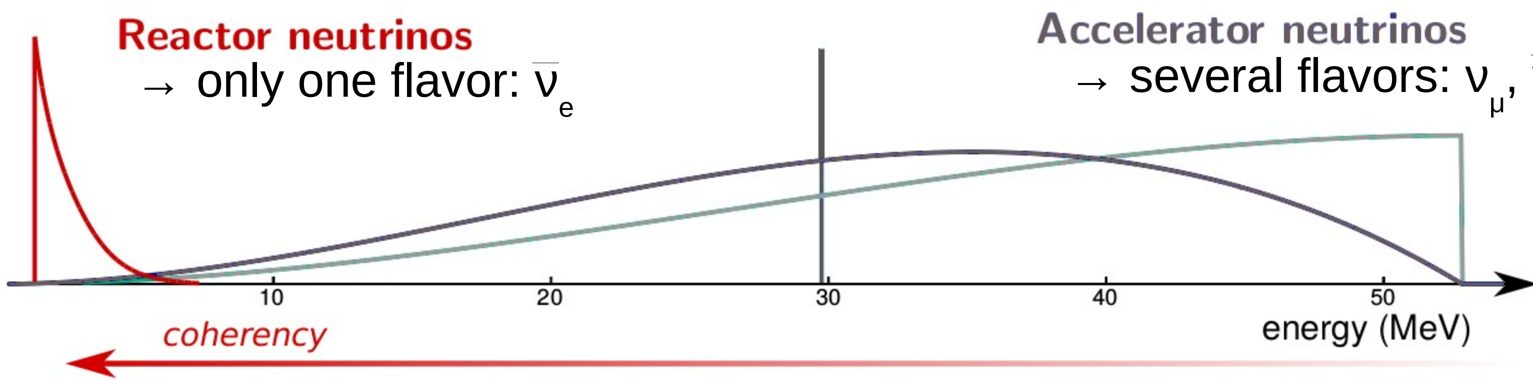
Latest results from CONUS

Janina Hakenmüller (for the CONUS collaboration)

12th June 2024, Magnificent CEvNS workshop,University of Valencia

CEvNS at reactor site

Figure courtesy of A. Bonhomme

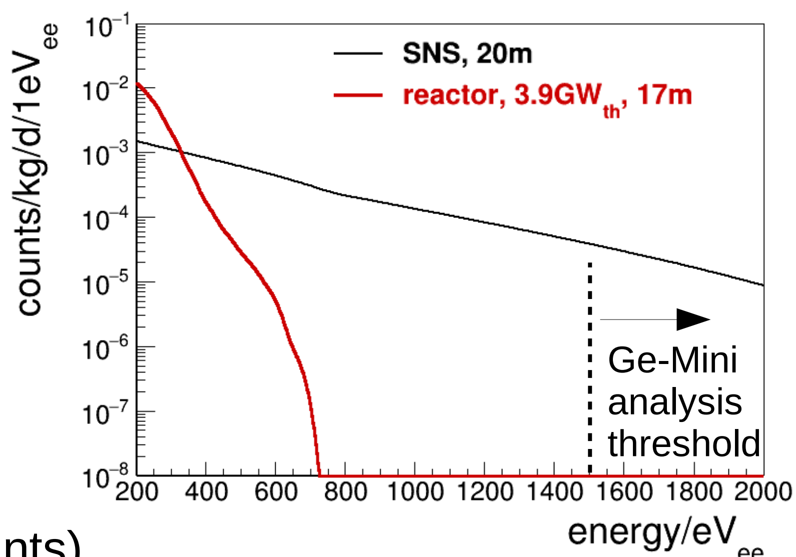


energy ≤10 MeV
- tiny recoil
- nuclear form factor ~1

higher **flux** for
GW thermal power:
e.g. 1.5×10^{13} $cm^{-2}s^{-1}$
at 20 m for 3.6 GW

backgrounds:
shield (shallow depth):
suppression up to $O(10^4)$
OFF data during outage
(limited at commercial plants)

Signal expectation in high-purity Germanium spectrometers:



energy 10-50 MeV
- recoil at higher energies
- nuclear form factor <1

lower **flux**:
e.g. 4.7×10^{7} $cm^{-2}s^{-1}$ at 20 m
for 1.4 MW (SNS)

backgrounds:
shield (shallow depth):
suppression up to $O(10^4)$
pulsed beam:
additional factor of 10^3-10^4
comparable ON and
OFF statistics

CONUS collaboration

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

Preussen Elektra

Kernkraftwerk Leibstadt

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Former collaborators: T. Schierhuber, E. Van der Meeren, J. Henrichs, T. Hugle, J. Stauber

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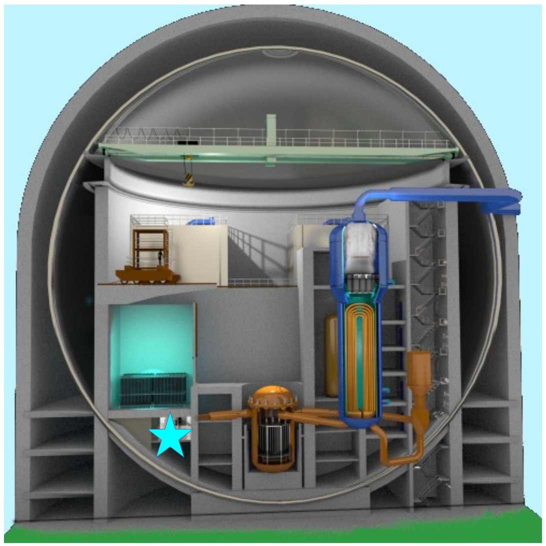
Paul-Scherrer-Institut (PSI), Villigen:
E. Hohmann

PTB

PAUL SCHERRER INSTITUT PSI

CONUS experiment – reactor & detectors

Neutrino source: (2018-2022)



commercial nuclear power plant Brokdorf, Germany
- maximum thermal power: 3.9 GW
- distance to core: 17.1 m

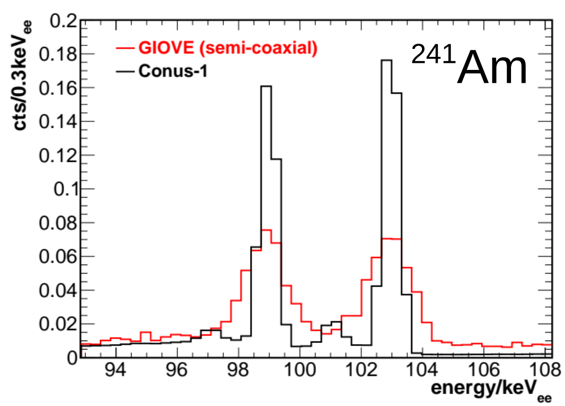
} $2 \cdot 10^{13}\ \bar{\nu}/cm^2s$

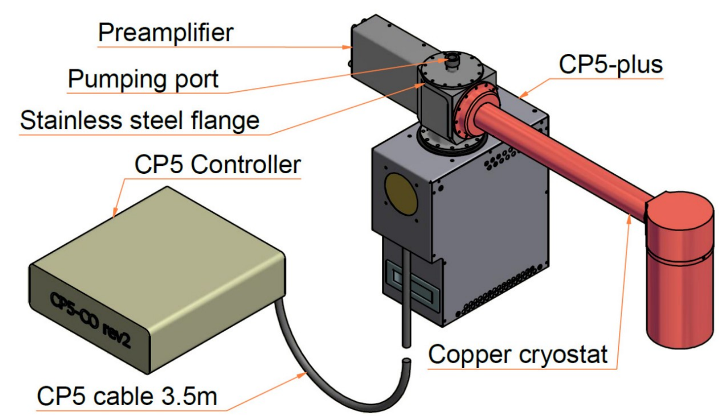
Eur. Phys. J. C (2019) 79:699

Detectors with low energy threshold:

4 x high-purity point-contact Germanium spectrometer:
- crystal / active mass: total: 4.0kg / 3.74kg
- pulser resolution $<80eV_{ee}$
  energy threshold $\leq 250eV_{ee}$
- electrical cryocooler
- screening for radiopurity

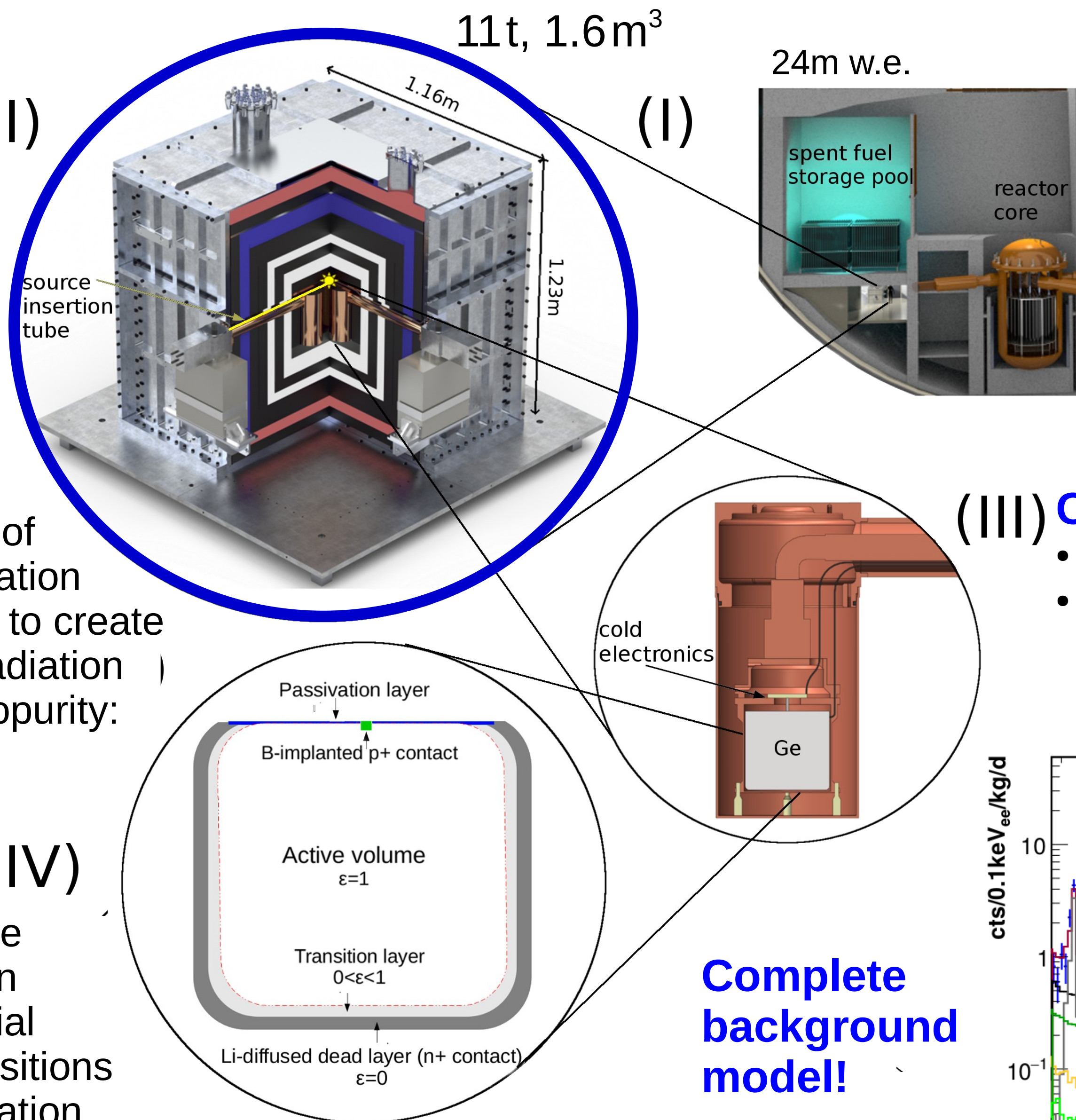
Eur. Phys. J. C 81, 267 (2021)





CONUS experiment - backgrounds

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



Location:

- overburden to shield muons
- potential reactor-correlated background: neutrons, gamma-rays → site characterization

Shield:

- suppression of external radiation
- target for μ's to create secondary radiation
- intrinsic radiopurity: Pb layers

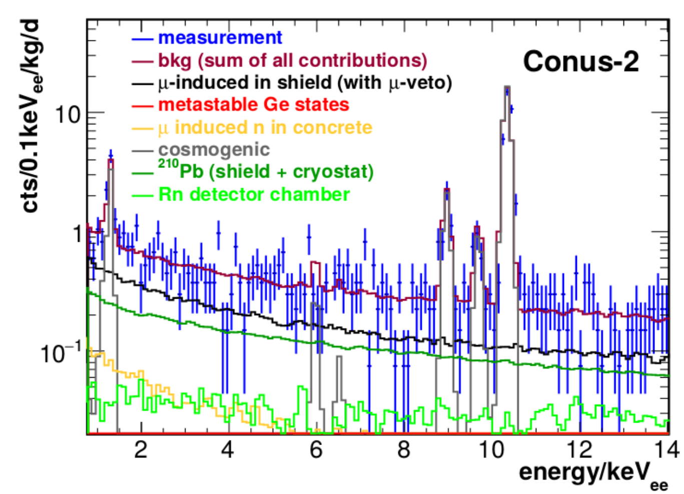
Cryostat:

- ^{210}Pb related to soldering
- cosmic activation of Cu

Diode:

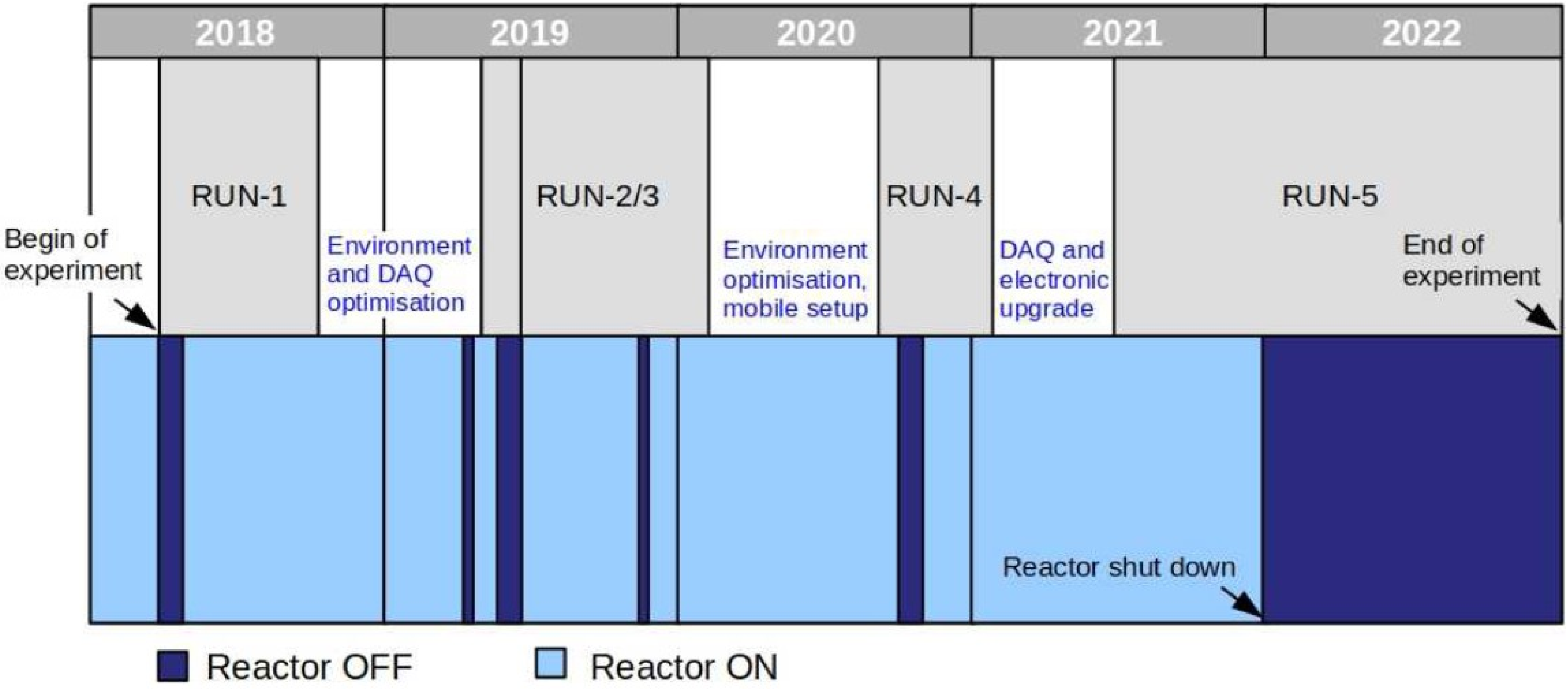
- active volume and transition layer → partial energy depositions
- cosmic activation of Ge

Complete background model!



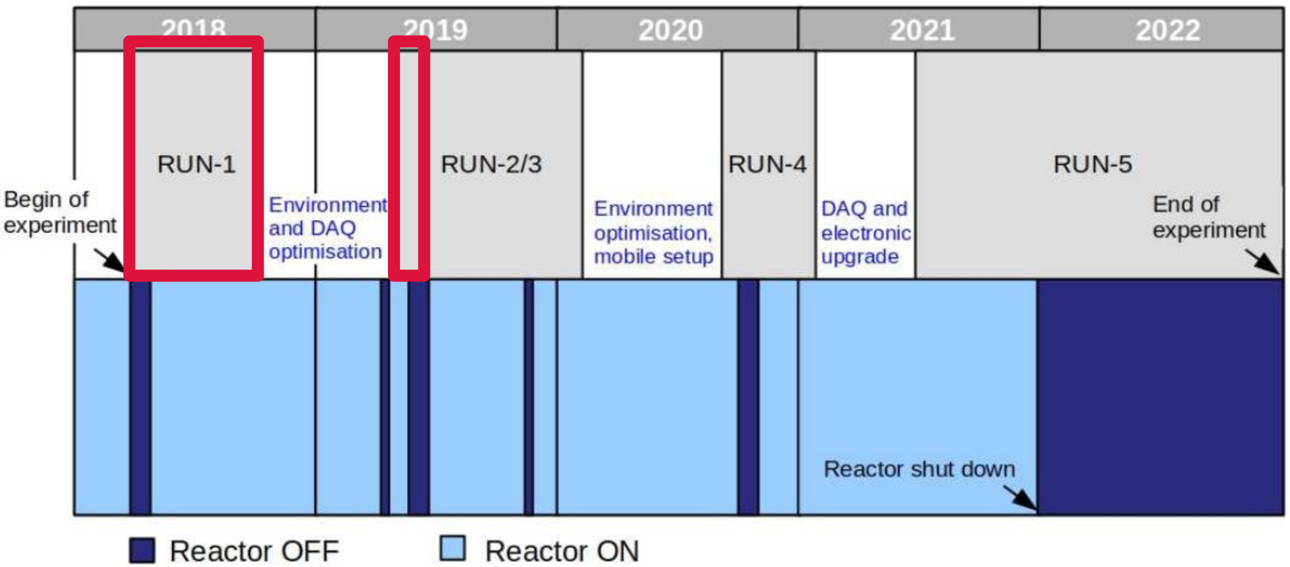
=> ~10cts/d/kg in [0.5,1]keV$_{ee}$

Data collection and operation



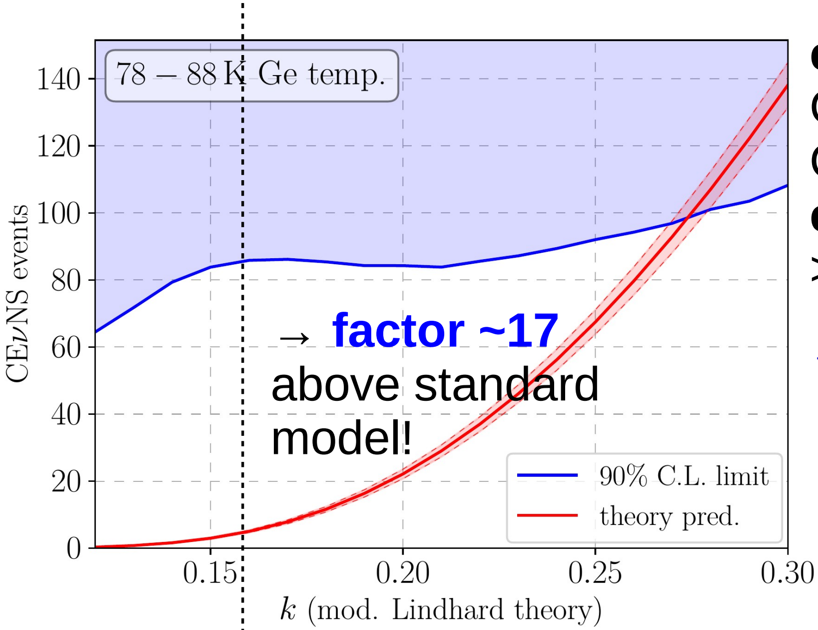
Run-1/Run-2 CONUS results

Phys. Rev. Lett. 126, 041804



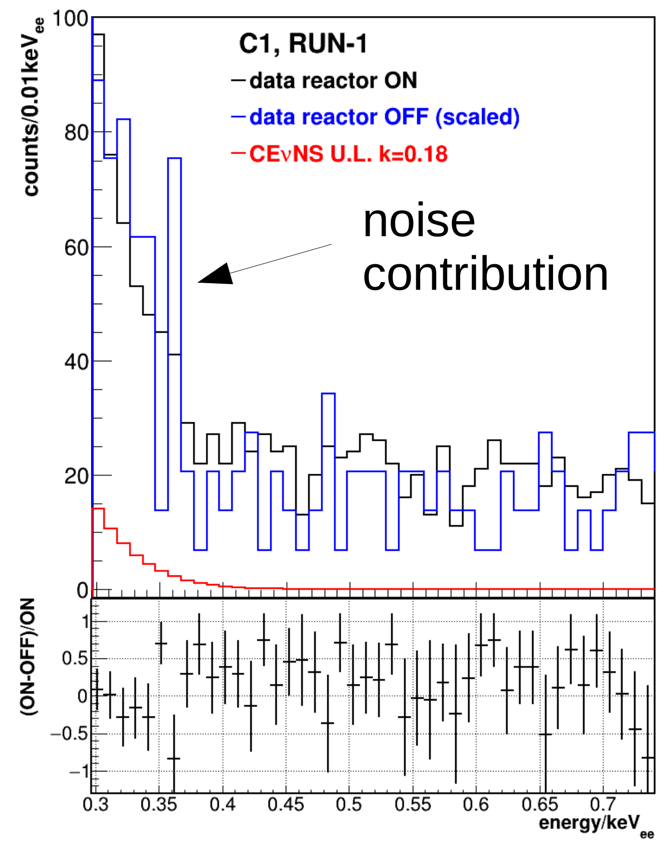
Extensive cuts of exposure:

- increased noise (related to fluctuating room temperature)
- time difference between events



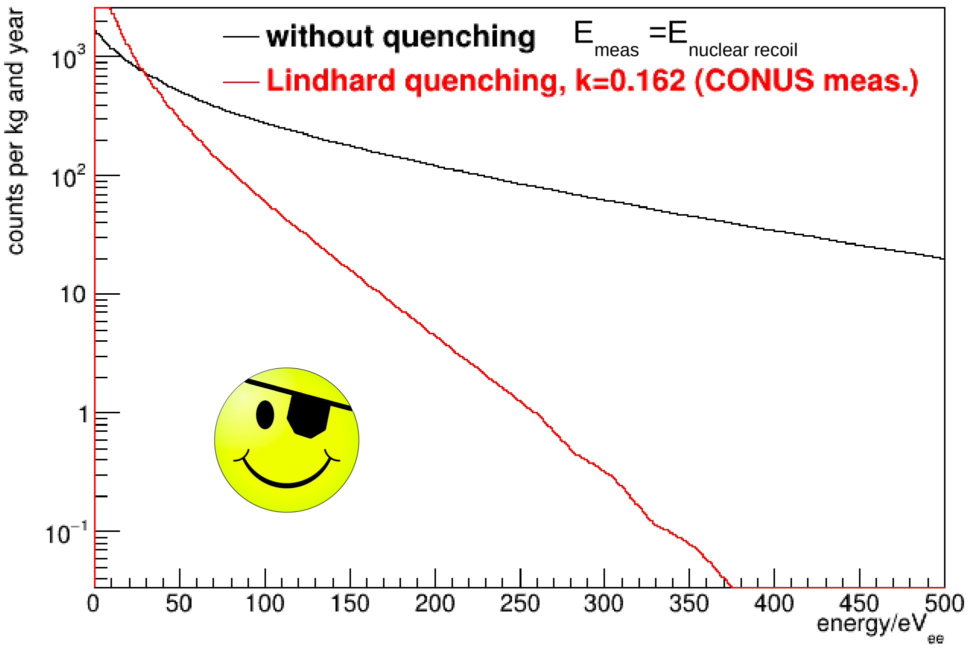
exposure:
ON: 248.7 kgd
OFF: 58.8 kgd
energy threshold:
>296eV$_{ee}$

→ **result: upper limit**
k = 0.16:
<0.4 cts/d/kg (90% C.L.)
k > 0.27 and
above disfavored

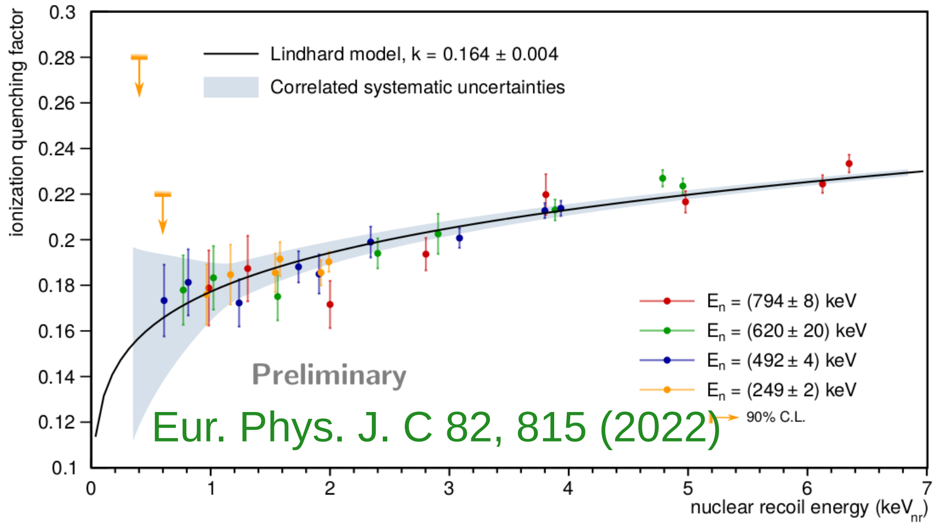


Quenching in Ge

Signal expectation:



Direct measurement of ionization quenching **after** Run-1/Run-2 analysis (results 2022):
k=0.162+-0.004 compatible with Lindhard

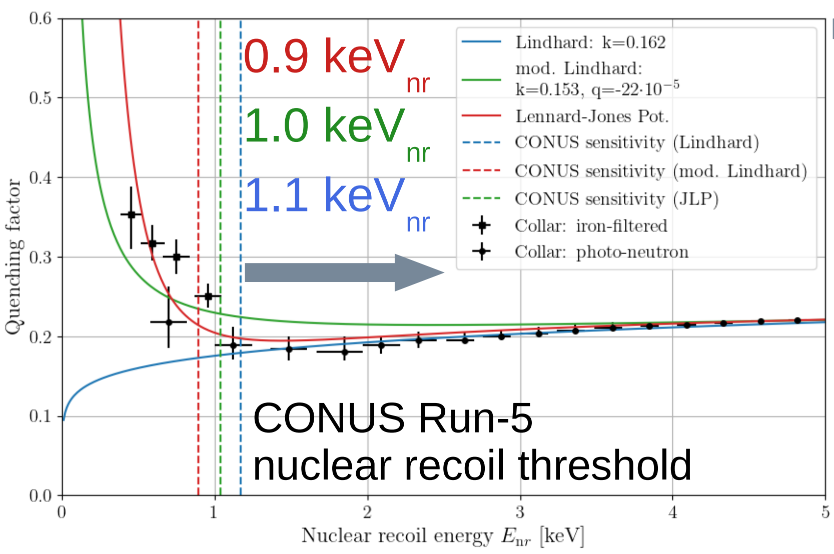


Quenching: *detectable with HPGe*

recoil → ionization energy + phonons

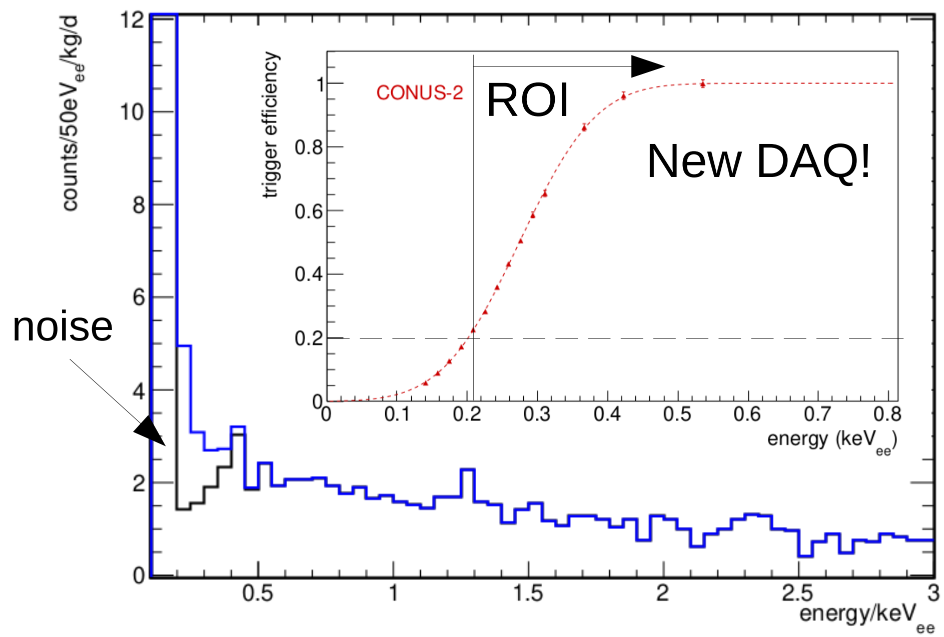
=> often not (yet) well known
at low recoil energies for CEνNS

=> quenching measurement highly important



SNS
Ge-Mini

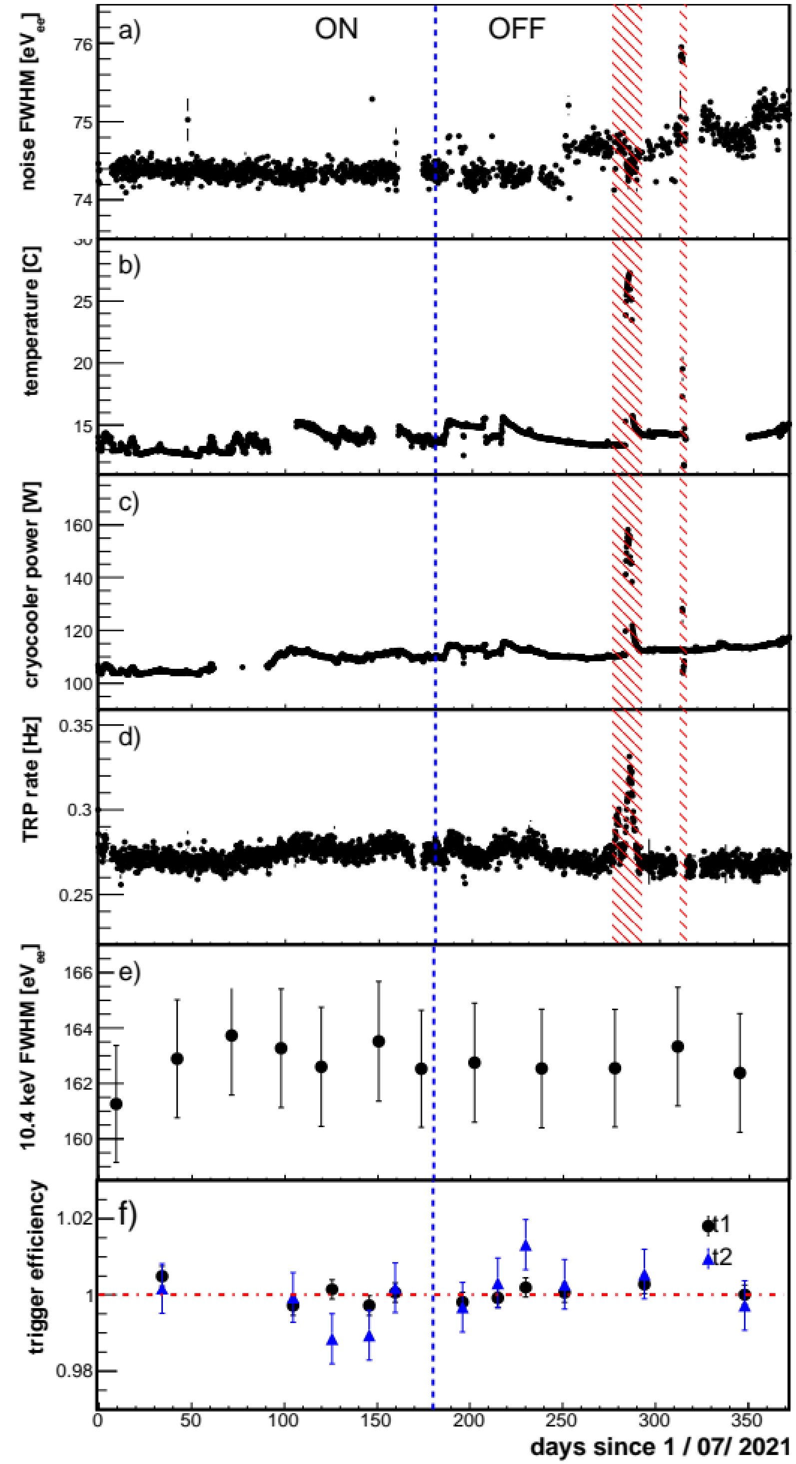
Run-5 upgrades



→ optimize trigger efficiency vs. noise reduction + pulse shape discrimination

- lower noise: improved power supply/grounding, stable/lower air temperature
- more exposure, especially OFF

	Run-1/Run-2	Run-5
ON/kg*d	248.7	426
OFF/kg*d	58.8	272
threshold/eV$_{ee}$	296-348	210



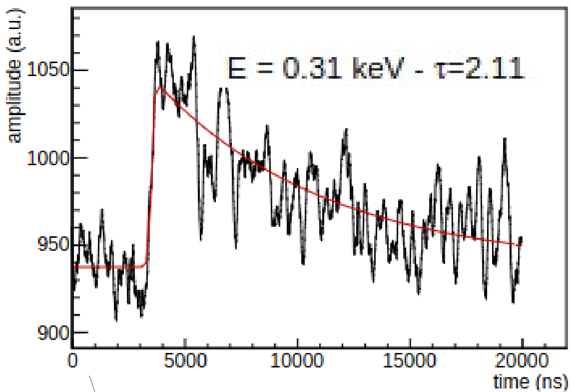
less & more stable noise

higher stability

less & more stable noise

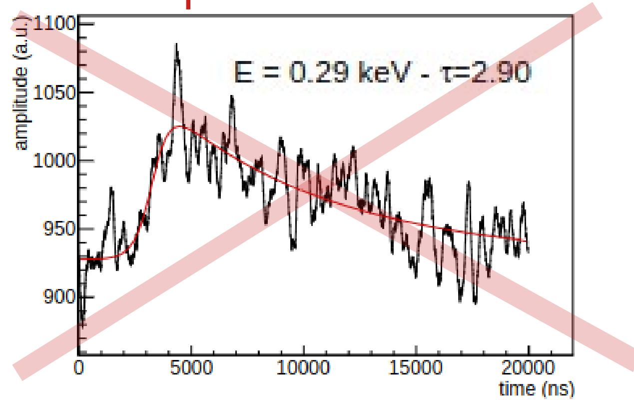
Pulse-shape discrimination

Eur. Phys. J. C (2024) 84: 139



(c)

slow pulse



(d)

<u>Fit of all pulses:</u>

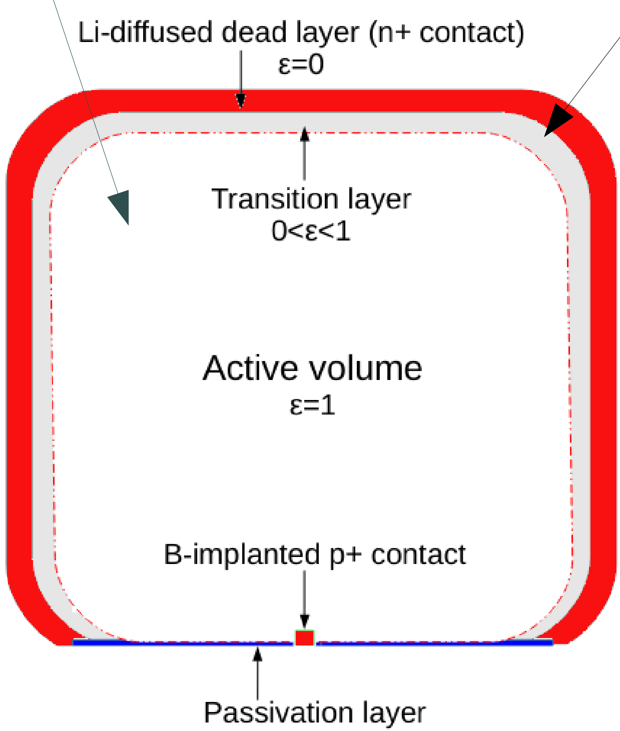
fit parameter τ describes rise

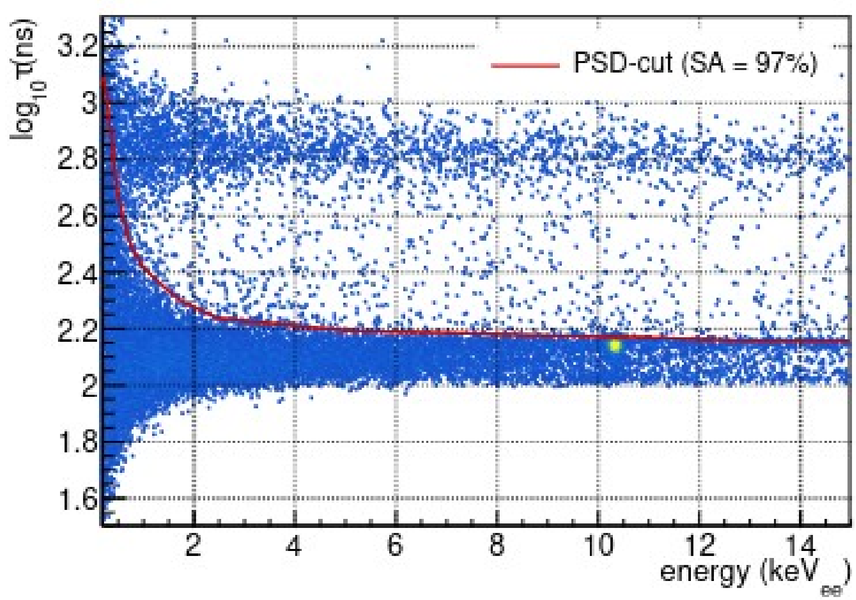
→ cut on value of τ

Signal acceptance: 97%

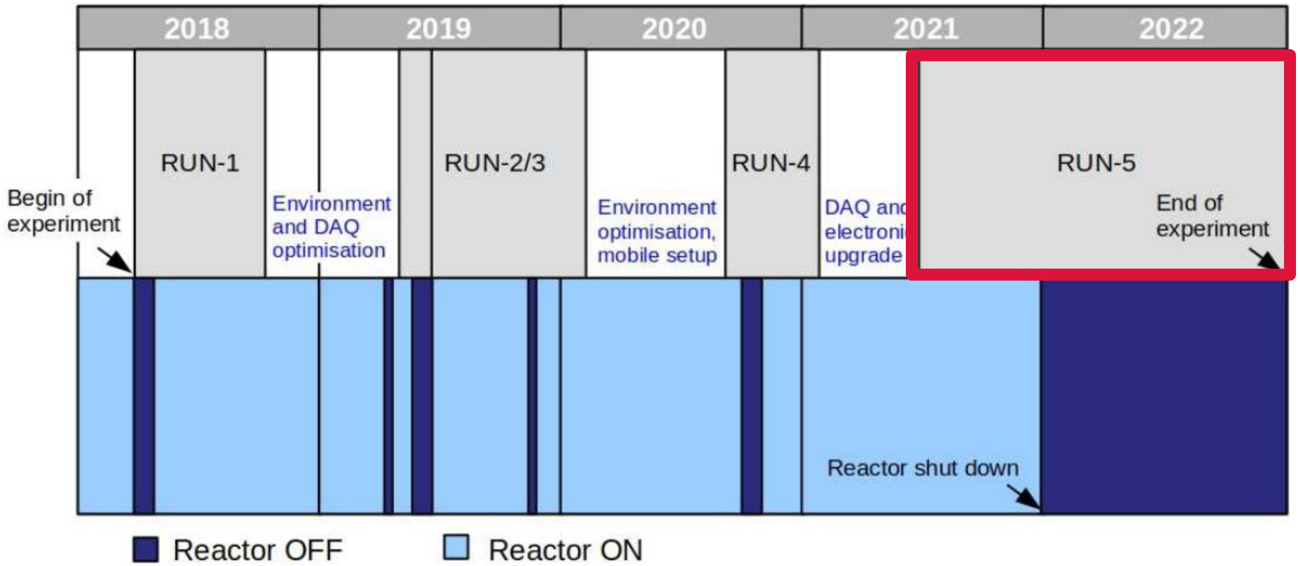
→ Slow pulse rejection in $[0.21,1]\mathrm{keV}_{ee}$: ~57%

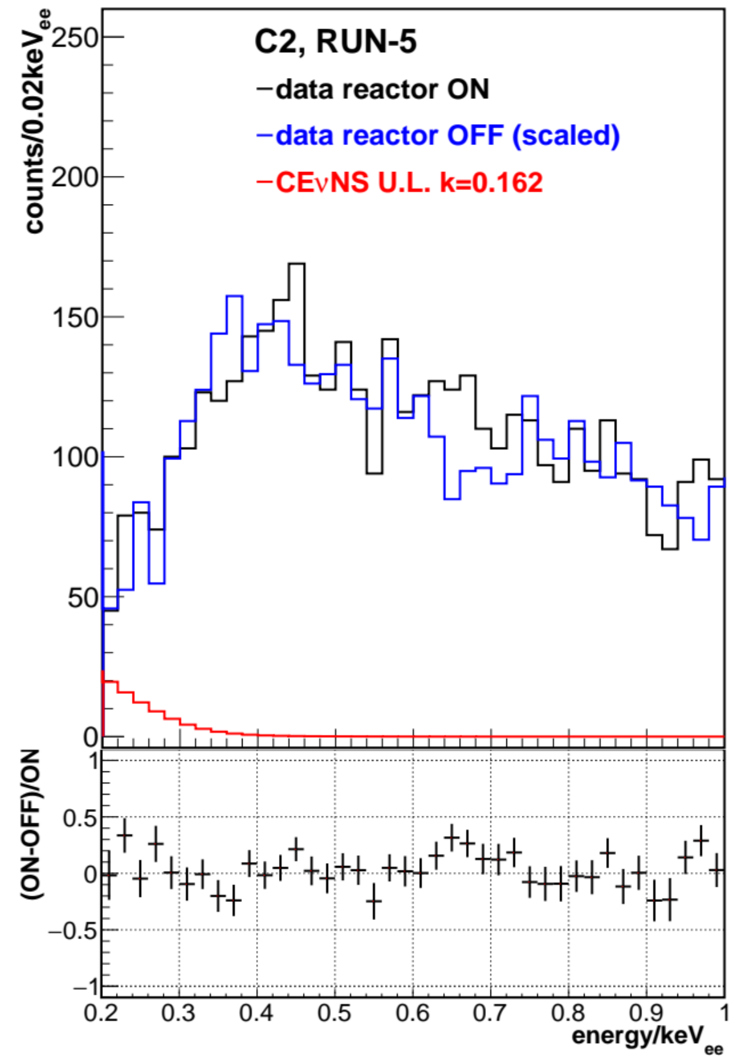
→ Background reduction in $[0.21,1]\mathrm{keV}_{ee}$: 5-10%





CONUS Run-5 results





	Run-1/Run-2	Run-5
ON/kg*d	248.7	426
OFF/kg*d	58.8	272
threshold/eV$_{ee}$	296-348	210
Limit (k=0.162)	factor 17 > SM	factor 2 > SM

signal prediction: 92+-10,
upper limit: <163 (90% C.L.)

arXiv:2308.12105

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)

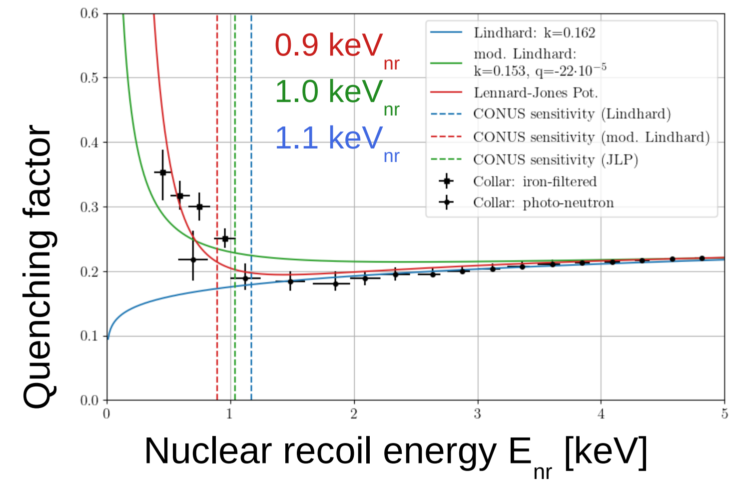
The 96.4 day exposure of a 3 kg ultralow noise germanium detector to the high flux of antineutrinos from a power nuclear reactor is described. A very strong preference ($p < 1.2 \times 10^{-3}$) for the presence of a coherent elastic neutrino-nucleus scattering (CEνNS) component in the data is found,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

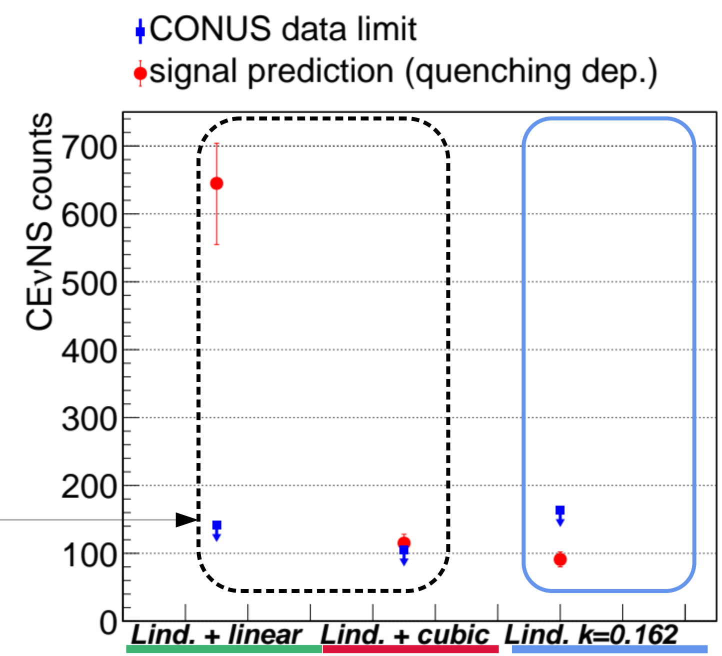
Abstract of Phys. Rev. D 103, 122003 (2021)

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.

↔ tension with CONUS quenching factor measurement

Test NCC-1701 signal with CONUS data:

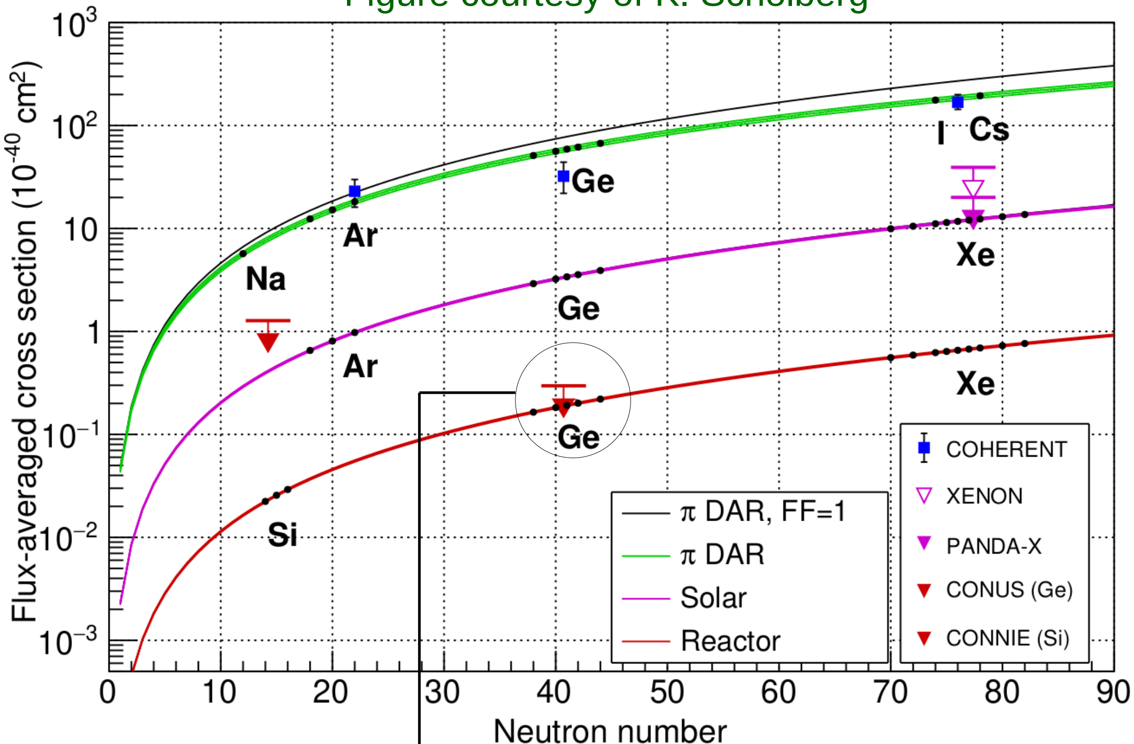




CONUS quenching meas./ Lindhard

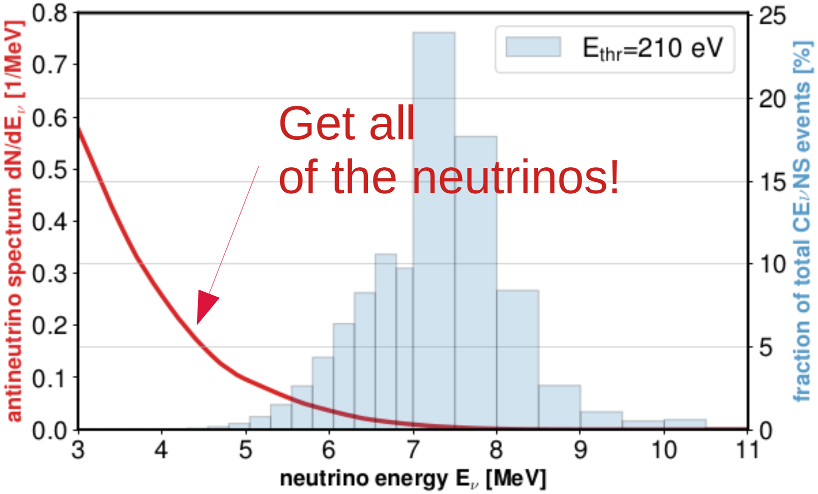
CONUS new result

Figure courtesy of K. Scholberg



Close the gap!

CONUS Run-5
accessible reactor spectrum:



3.6GW reactor Leibstadt, Switzerland
detector upgrade → lower threshold!

Talk by Kaixuan Ni on 13th of June

Summary & Outlook

CONUS: reactor experiment at Brokdorf nuclear power plant, Germany
→ 5 years of successful operation, end of data taking with Run-5 end of 2022

- main upgrades during Run-5:
  - improved environmental control → more stable and lower noise
  - lower energy threshold due to new trigger algorithm → 210 eV_{ee}!
  - more exposure due to long off period
  - Background reduction with pulse shape discrimination
- results
  - RUN-1: factor of 17 above standard model
  - RUN-5: **factor of 2** above standard model (arXiv:2308.12105)
- updated magnetic moment and milli charge results with full exposure on the way
- CONUS+ in Switzerland → even lower energy threshold!

Thank you for your attention!

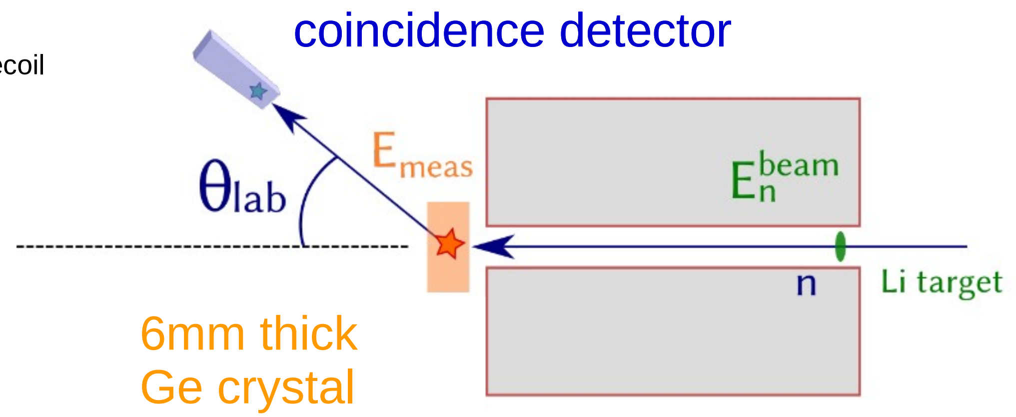
Max-Planck-Institut für Kernphysik Heidelberg

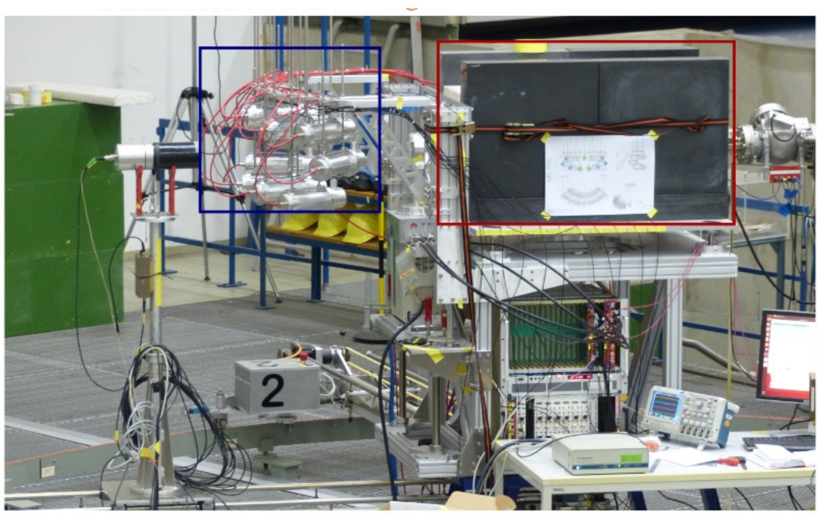
CONUS

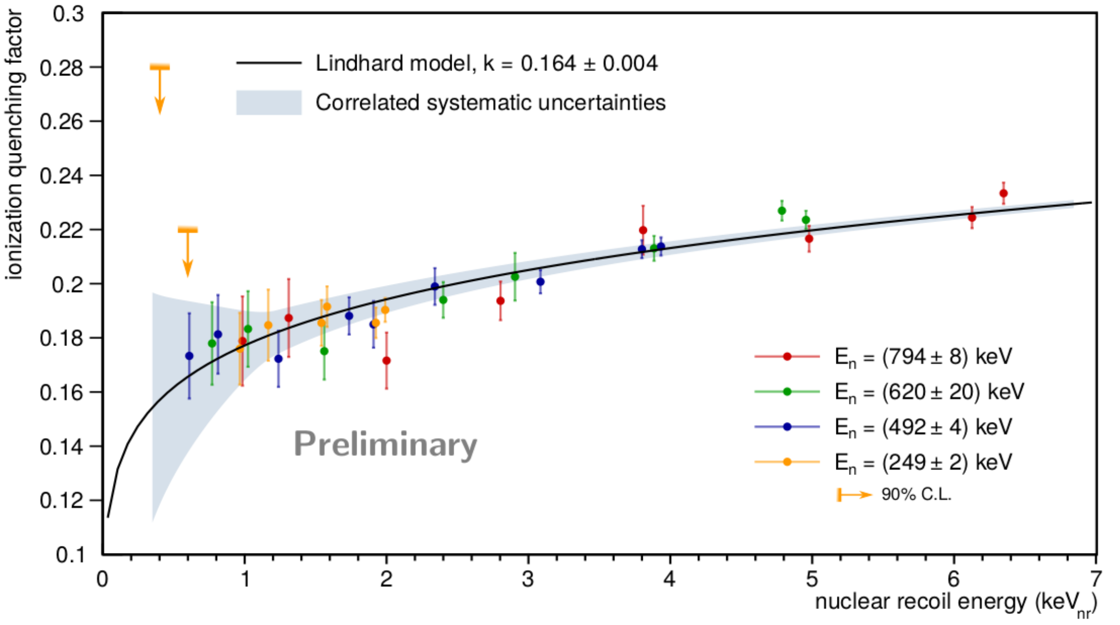
BACKUP

Quenching factor measurement

- Ionization queching: $Q=E_{ion}(meas)/E_{nuclear\ recoil}$
- direct measurement at collimated neutron beam at PTB Braunschweig
- scan over recoil energies $[0.4,7]keV_{nr}$
- data compatible with Lindhard model for: **k = 0.162±0.004 (stat+syst)**







Likelihood analysis

Binned likelihood fit: combined fit of all detectors and runs

- Poisson distribution in each bin
- simultaneous fit of reactor ON and OFF data

$$\mathcal{L} = \Sigma \mathcal{L}(ON)\mathcal{L}(OFF)$$
$$= \Sigma \mathcal{L}(\mathbf{s} + b; \theta_{trig}, \theta_{actvol}, \Delta E, \theta_{rea}, \theta_{quench})\mathcal{L}(b; \theta_{trig}, \Delta E, \theta_{calib}) + \text{pull terms}$$

scan over signal parameter

background description

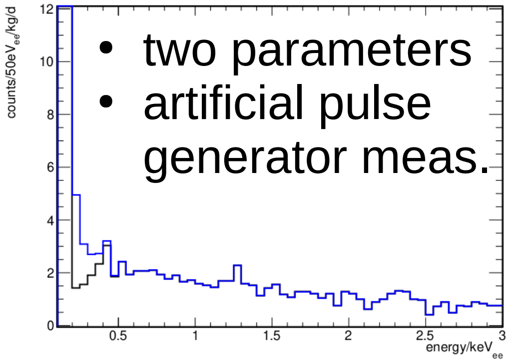
trigger efficiency: (reduction within region of interest)

active mass (determined from radioactive source measurements)

energy scale calibration

reactor: distance to reactor core thermal power fission fractions

quenching (CONUS quenching factor measurement)



Energy scale stability

rel. peak position of 10.4keV line (^{71}Ge):