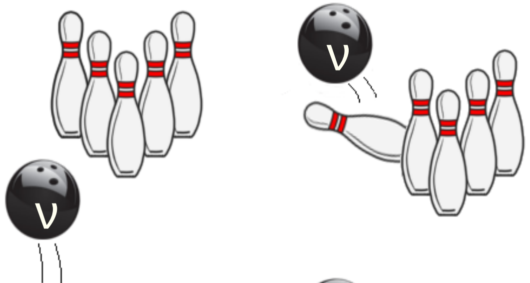
Recent results of the CONUS experiment

Janina Hakenmüller
(for the CONUS collaboration)

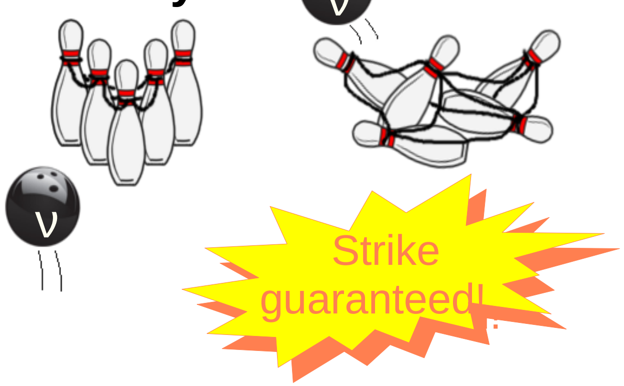
PASCOS 2023, University of California, Irvine, 26th of June 2023

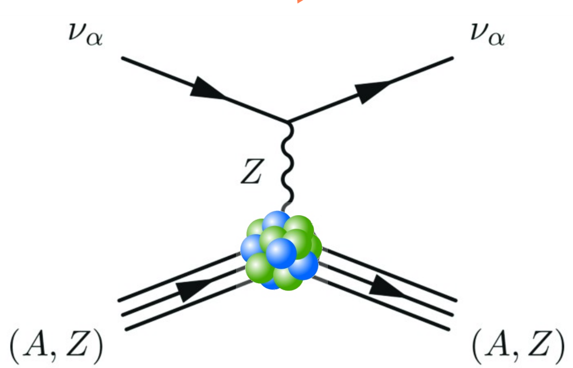
Coherent elastic neutrino nucleus scattering (CEvNS)

no coherence



coherency





- standard model interaction, flavor blind, no energy threshold
- predicted in 1974: D.Z. Freedmann, Phys. Rev. 9 (1974) 5
- first detected in 2017: COHERENT experiment
  → CsI detectors at pion decay-at-rest source
- detection at nuclear reactor (lower energies) still pending
- cross section **large** compared to other neutrino interactions (e.g inverse beta decay)

neutrino energy

$$\frac{d\sigma}{d\Omega} = \frac{G_f^2}{16\pi^2}(N-(1-4sin^2\theta_W)Z)^2 E_\nu^2 (1+cos\ \theta)F(Q^2)$$

nucleus

nuclear form factor
$F(Q^2) \rightarrow 1$ for $Q^2 \rightarrow 0$

coherency condition:
λ(mom. Transfer Q) > size of atom
=> σ ~ (#scatter targets)^2
=> upper limit on neutrino energy:

$$E_\nu \leq \frac{1}{2R_A} \approx \frac{197}{2.5\sqrt[3]{A}}\ (\text{MeV})$$ => E_{max}≤50 MeV (for mean A)

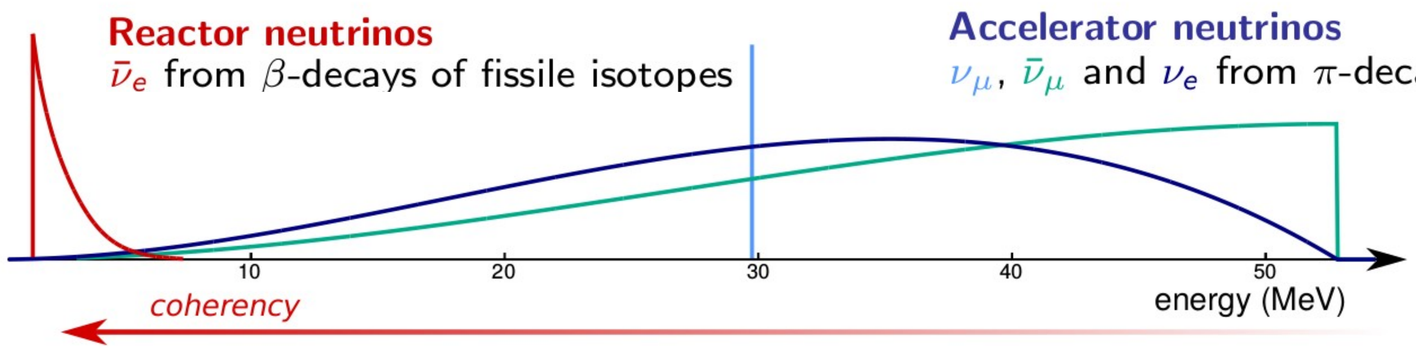
R_A=radius, A= mass number

Detecting CEνNS

Coherency condition: E_{max}≤50 MeV

=> $\sigma \propto N^2 E_\nu^2$ large cross section => small detector (kg sized!)

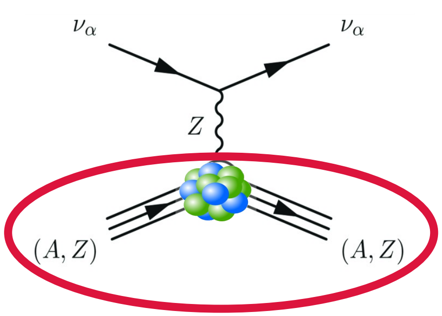
nuclear form factor ~1



nuclear form factor <1

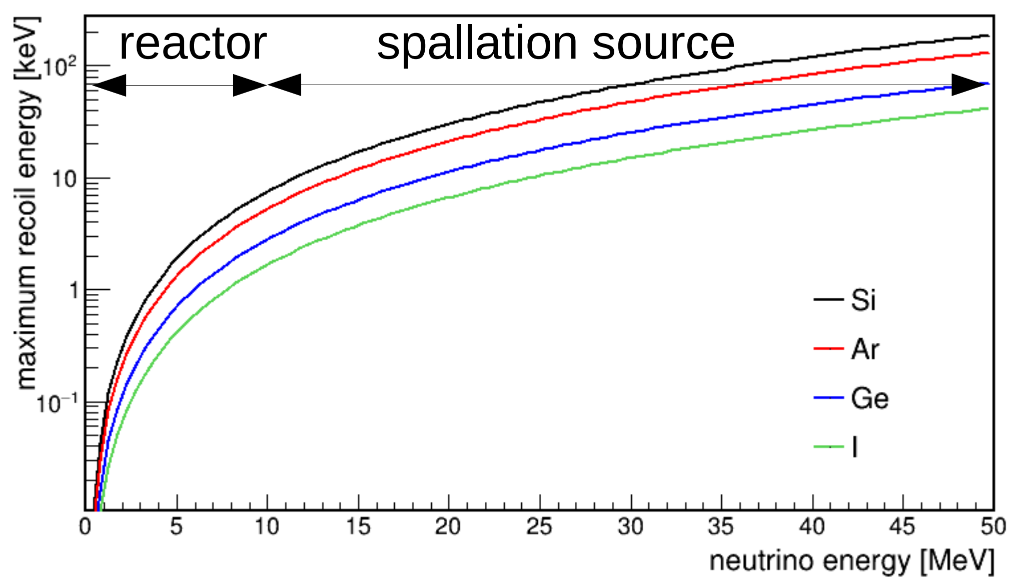
Figure courtesy of A. Bonhomme

Detection parameter:
recoil of target nucleus



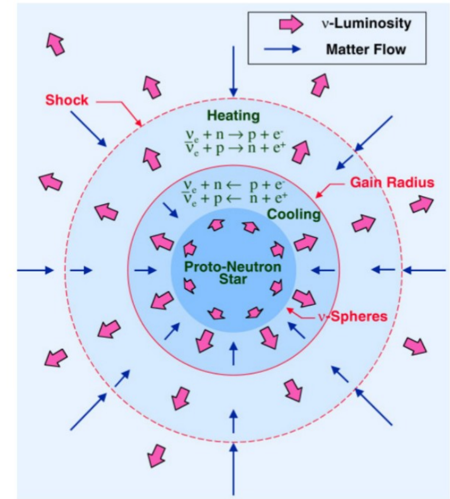
$$T_{max} \approx \frac{2E_\nu^2}{m_n(N+Z)}$$

→ push-pull situation



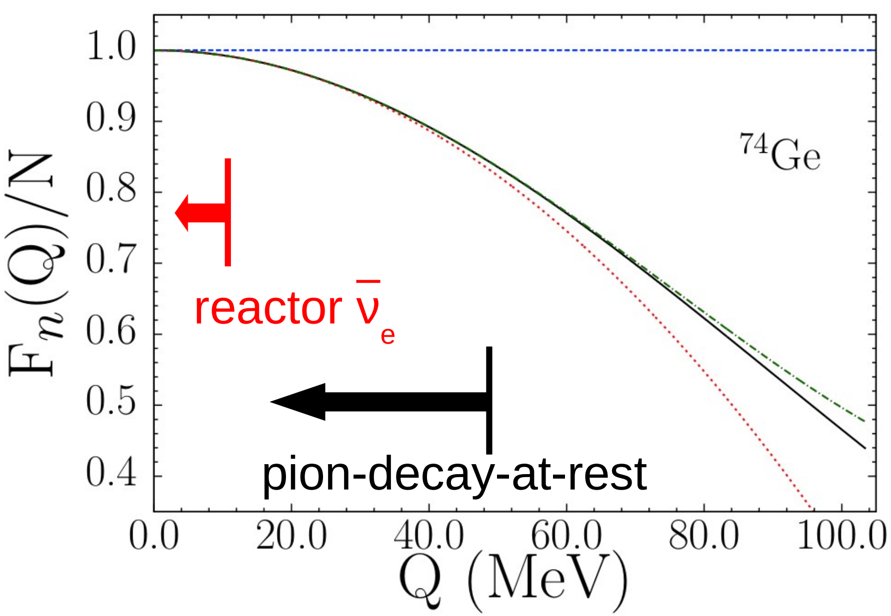
Motivation

- stellar collapse: 99% energy release in neutrinos
- “neutrino floor/fog” in dark matter experiments: signature like dark matter → same detector response
- Weinberg angle at low energies $\frac{d\sigma}{d\Omega} \propto (N-(1-4sin^2\theta_W)Z)^2$

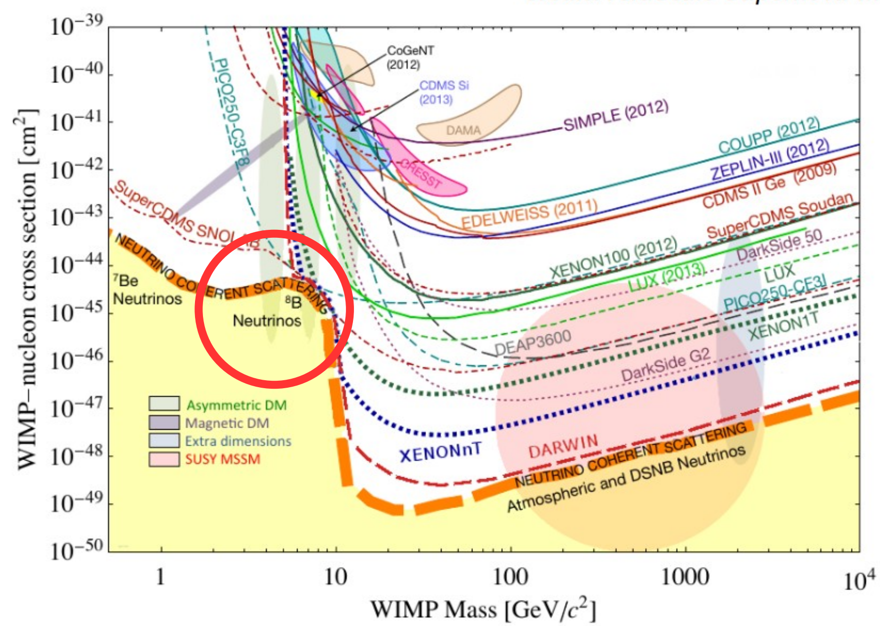


Credit: TeraScale Supernova Initiative

nuclear form factor



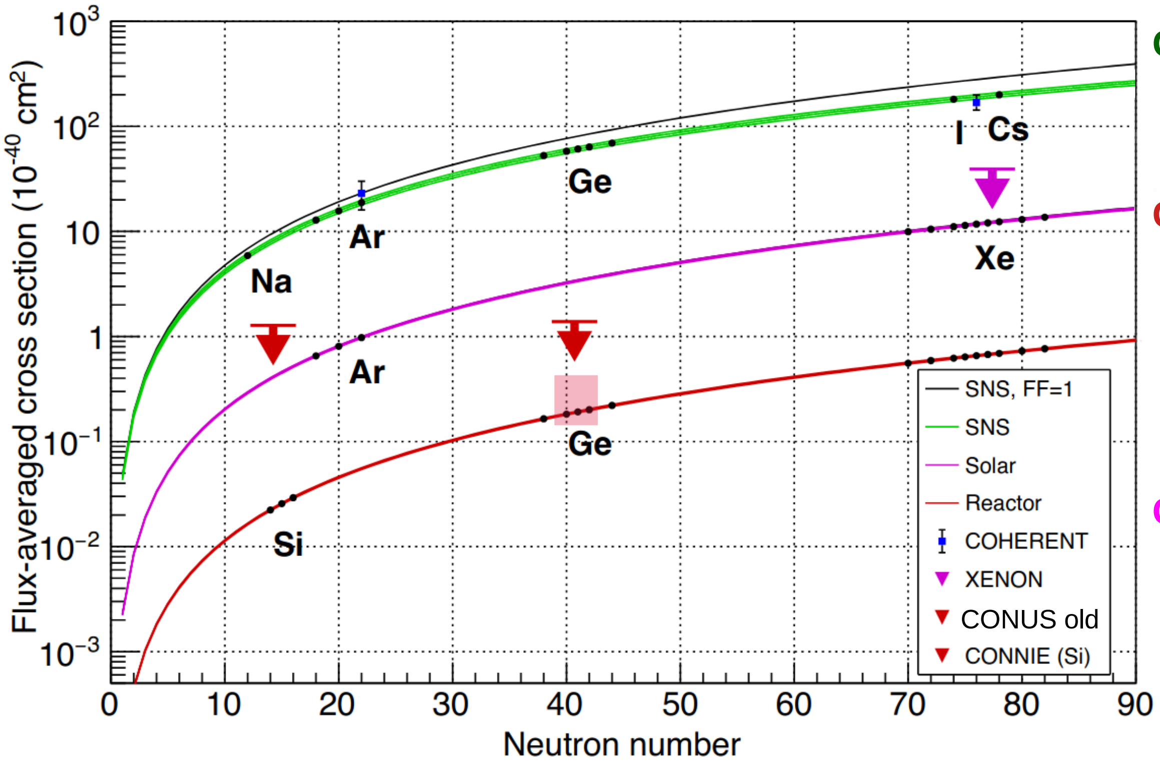
K. Patton et al., Phys. Rev. C 86 (2012) 0246



Baudis, Laura, Physics of the Dark Universe 4 (2014): 50-59.

- neutron form factor $F(Q^2)$
- non-standard neutrino interactions (NSI)
- nuclear safe guarding (non-proliferation)

N^2 dependence



plot by Kate Scholberg, PANIC 2021 conference

CEνNS at accelerators:

PRL129, 081801 (COHERENT, CsI, > 11σ)
PRL126 012002 (COHERENT, Ar, > 3σ)

CEνNS at reactors:

J. High Energ.Phys. (CONNIE, Si, constraint)
PRL126 **(2020)** 041804 (**CONUS**, Ge, constraint)
PRL129 (2022) 211802 (Colaresi et al., Ge, evidence)
→ highly quenching model dependent
PRD 106 L051101 (2022) (NuGen, Ge, constraint)

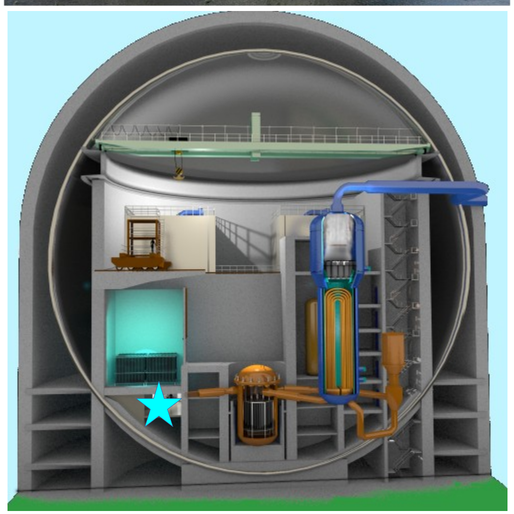
CEνNS with solar neutrinos:

PRL126 091301 (Xenon1t, Xe, constraint)

Any deviation from N^2 behavior would immediately give hints on BSM physics!

CONUS experiment

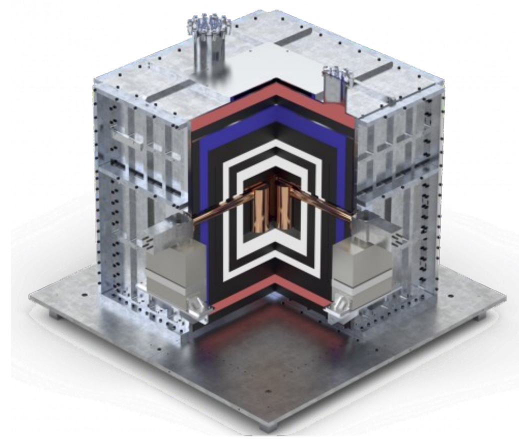
Neutrino source:

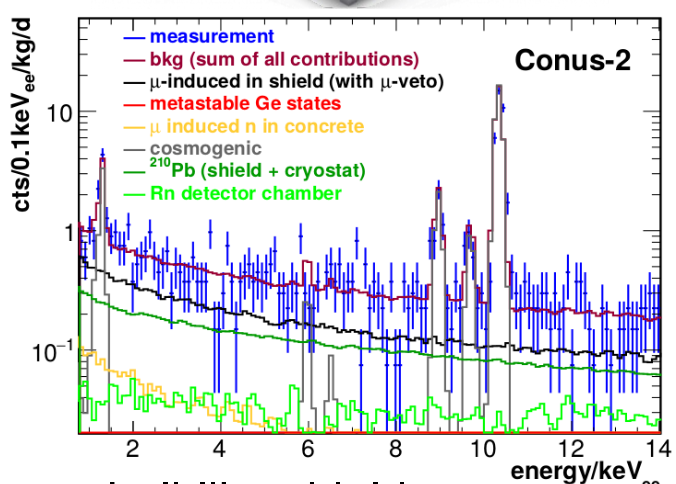


commercial nuclear power plant Brokdorf, Germany, 3.9GW, distance to core: 17m
=> $2*10^{13}\ \bar{\nu}/cm^{-2}s^{-1}$

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

Background suppression:

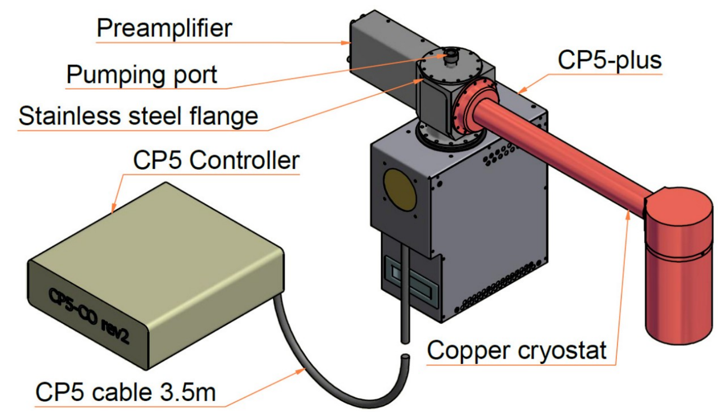




shell-like shield
with active muon veto
=> ~10cts/d/kg in $[0.5,1]keV_{ee}$

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

Detectors with low energy threshold:

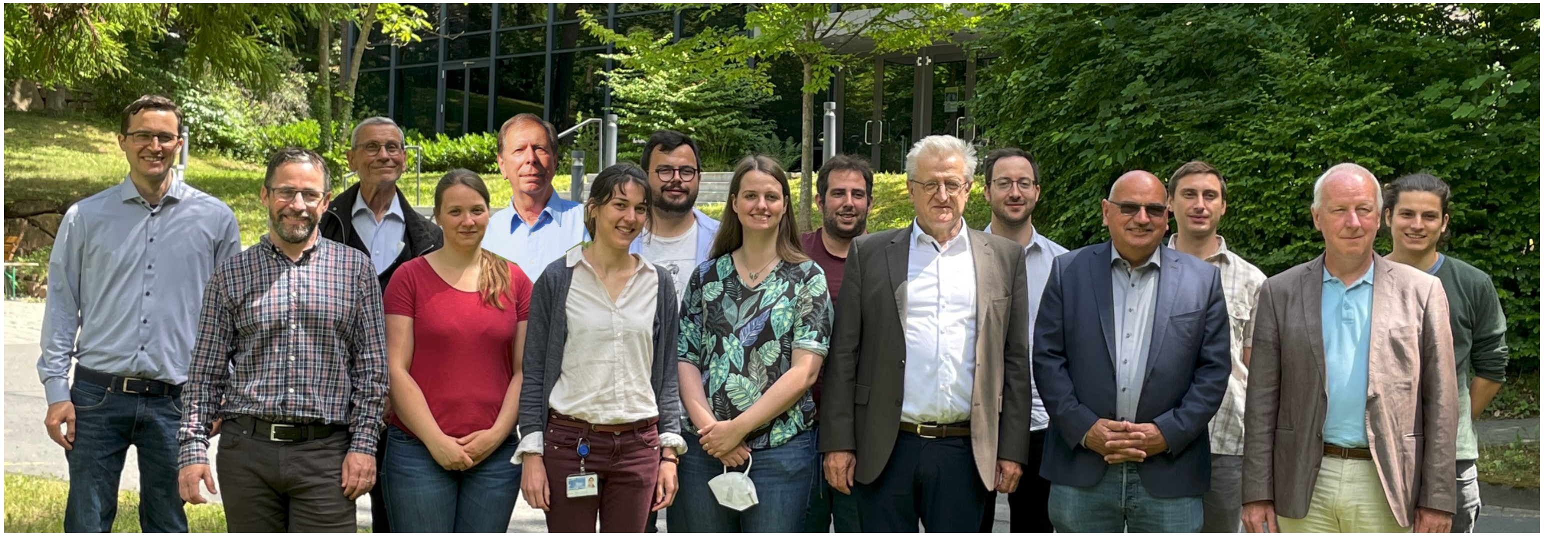


4 x high-purity point-contact Germanium spectrometer,

- 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 collaboration



Collaboration:

Max-Planck-Institut für Kernphysik (MPIK), Heidelberg:
N. Ackermann, S. Armbruster, H. Bonet, A. Bonhomme, C. Buck, J. Hakenmüller, J. Hempfling, G. Heusser, M. Lindner, W. Maneschg, K. Ni, T. Rink, E. Sanchez-Garcia, J. Stauber, H. Strecker

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

Preussen Elektra GmbH, Kernkraftwerk Brokdorf (KBR), Brokdorf:
K. Fülber, R. Wink

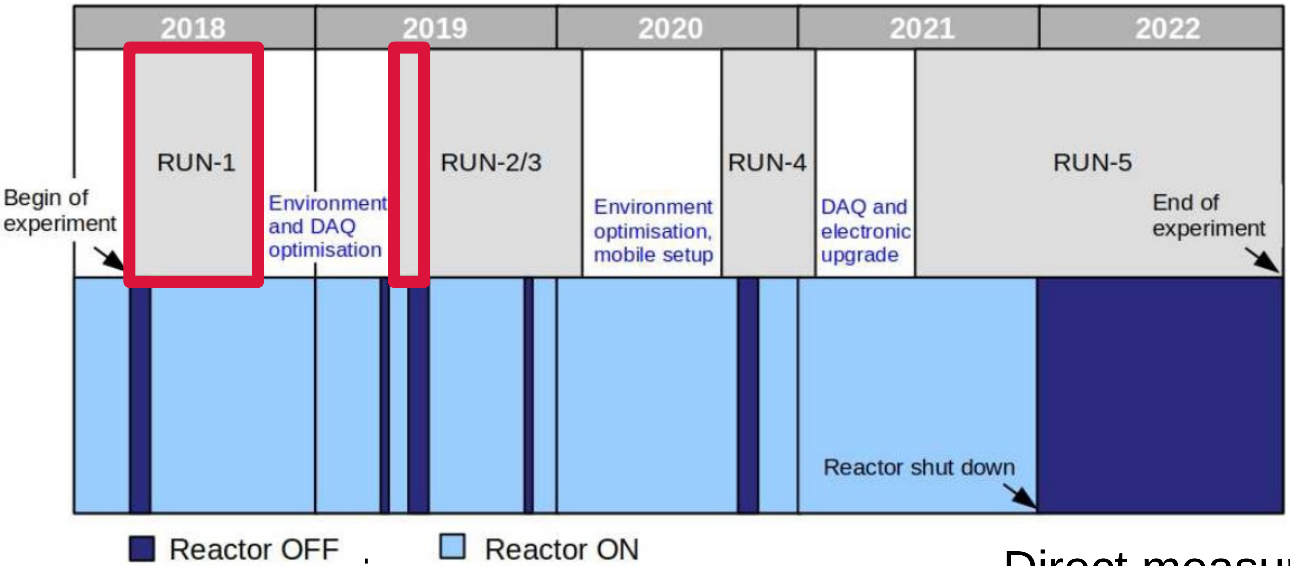
Scientific cooperation:

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

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

Preussen Elektra

Run-1/Run-2 CONUS results

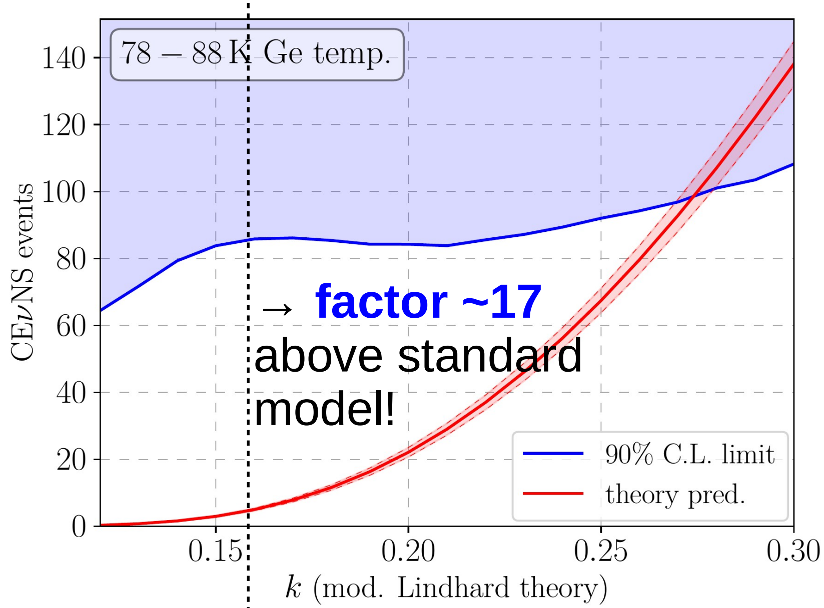


Extensive cuts of exposure due to:

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

→ exposure: 248.7 kgd ON, 58.8 kgd OFF

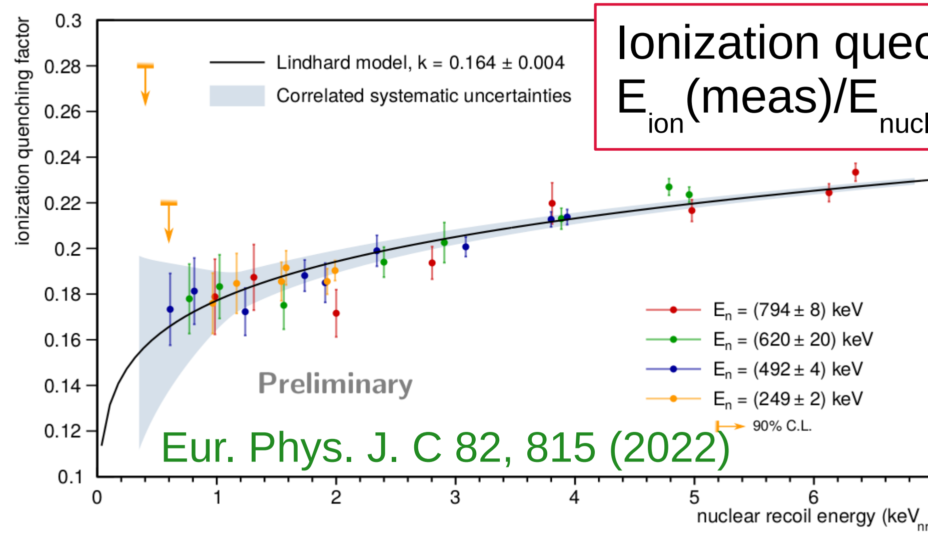
→ energy threshold: >296eV$_{ee}$



Phys. Rev. Lett. 126, 041804

Direct measurement of ionization quenching factor **after** Run-1/Run-2 analysis (results 2022):

k=0.162+-0.004 compatible with Lindhard

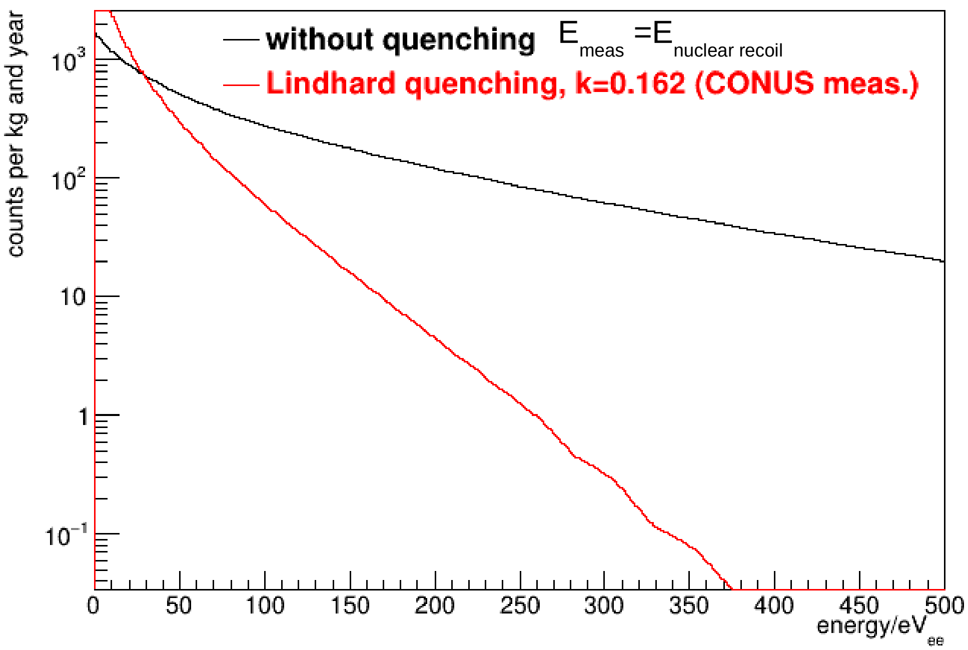


Ionization queching: E$_{ion}$(meas)/E$_{nuclear\ recoil}$

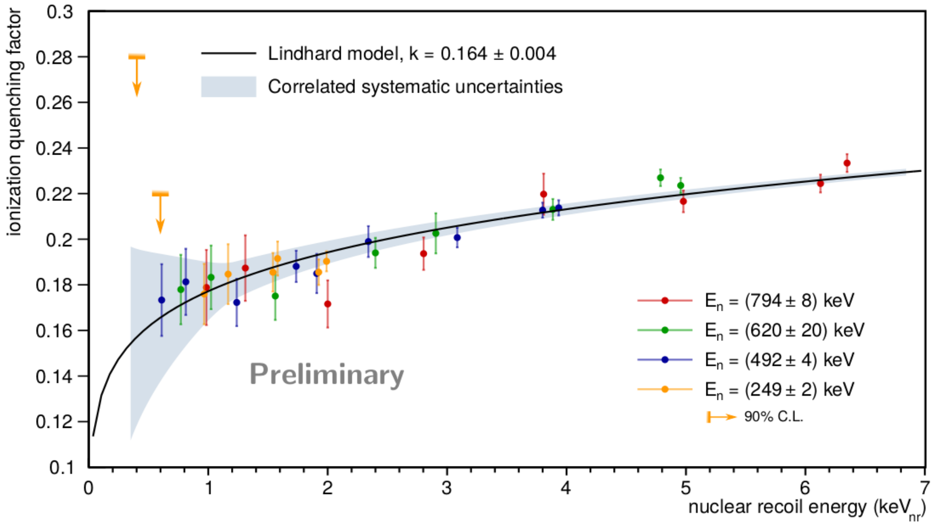
Eur. Phys. J. C 82, 815 (2022)

Signal expectation in Ge

Signal expectation:



CONUS quenching factor measurement:



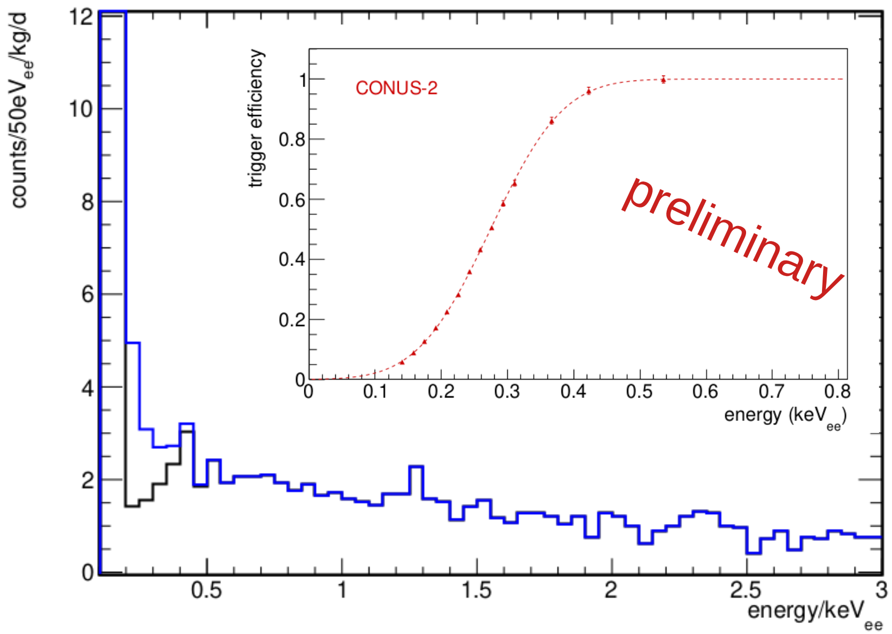
Eur. Phys. J. C 82, 815 (2022)

Quenching:

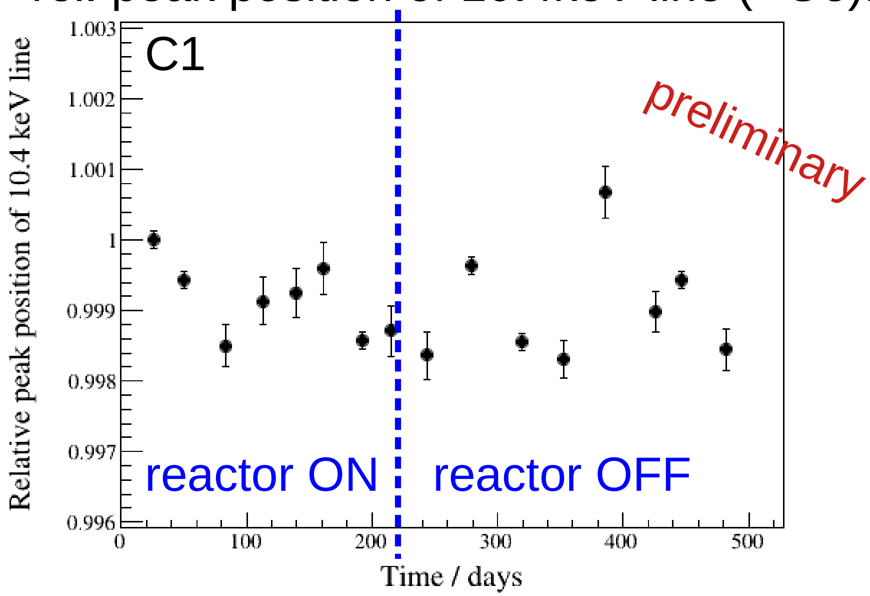
- Quenching factor: $Q=E(meas)/E_{nuclear\ recoil}$
  e.g. HPGe: 1keV recoil → ~20% ionization (read-out), ~80% phonons (not read-out)

=> often not (yet) well known at low recoil energies for CEνNS
=> major uncertainty, quenching measurement highly important!

Run-5 upgrade

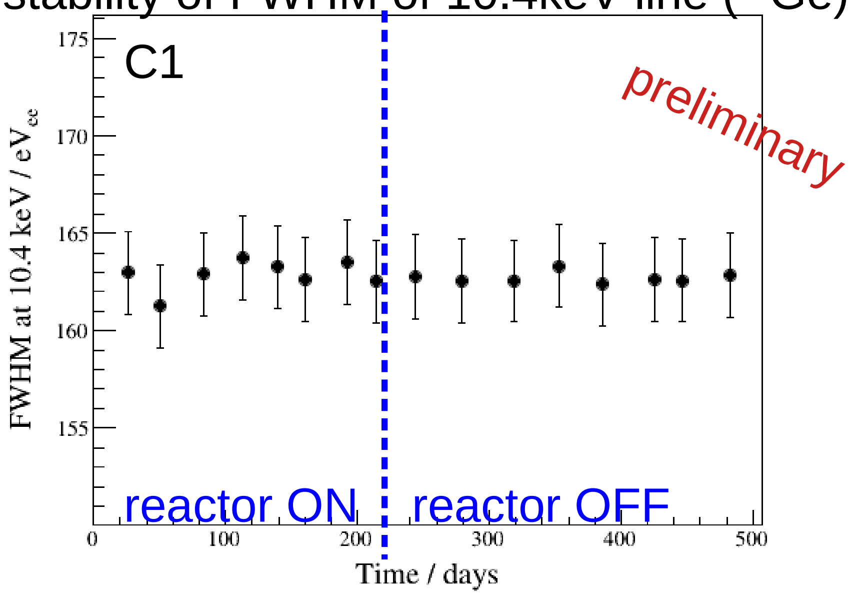


rel. peak position of 10.4keV line (^{71}Ge):



- improved power supply/grounding
  → less noise
- new DAQ → optimize trigger efficiency vs. noise reduction, pulse shape discrimination
- stable/lower air temperature
  → reduce microphonics
- long OFF data collection period, long ON data collection period
  → statistics
- Cf252 neutron source irradiation
  → energy calibration

stability of FWHM of 10.4keV line (^{71}Ge):



Likelihood analysis

<u>Binned likelihood fit:</u> combined fit of all detectors and runs
- Poisson distribution in each bin
- simultaneous fit of reactor ON and OFF data

active mass (determined from radioactive source measurements)

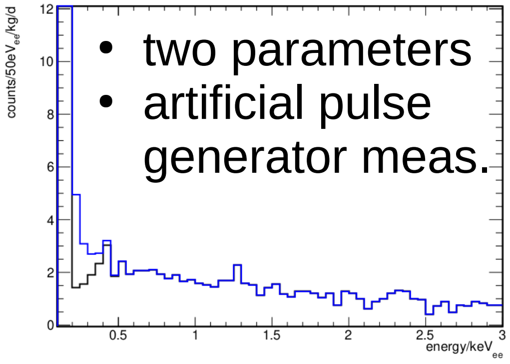
energy scale calibration

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

scan over signal parameter

background description

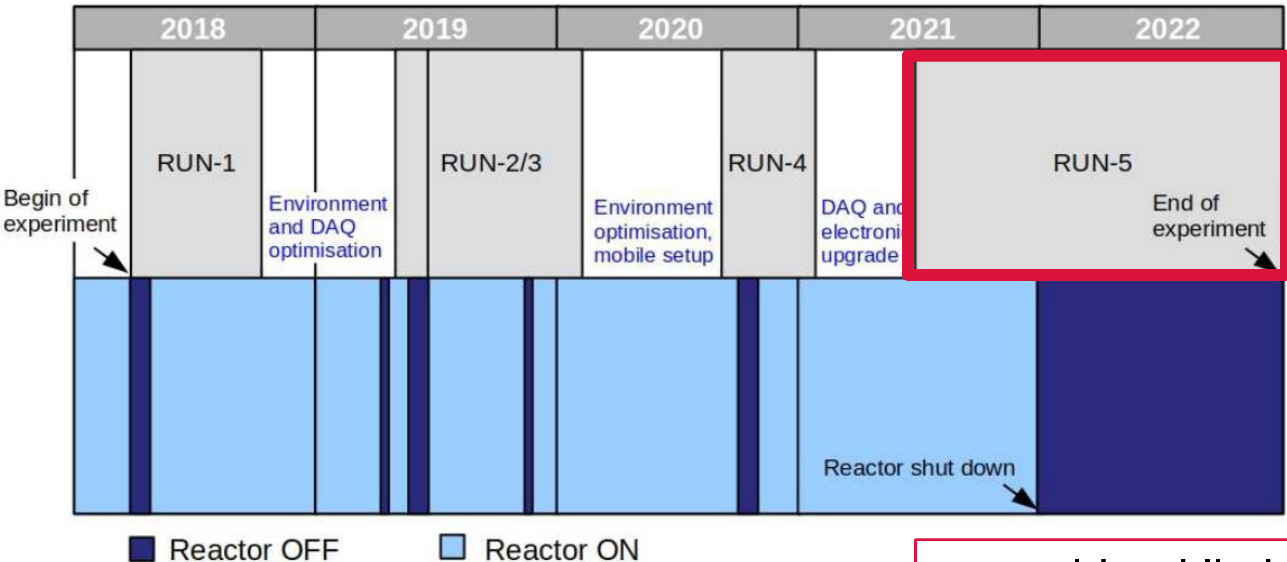
trigger efficiency: (reduction within region of interest)



quenching (CONUS quenching factor measurement)

reactor:
distance to reactor core
thermal power
fission fractions

CONUS Run-5 results



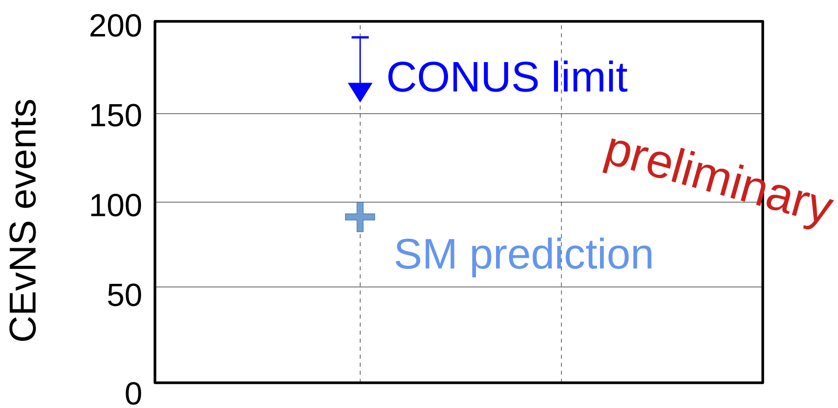
Energy thresholds (above significant noise contribution):

C1: 220 eV_{ee}

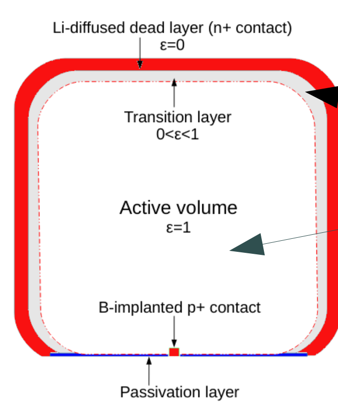
C2: 210 eV_{ee}

C4: 210 eV_{ee}

Run-5 exposure:
458 kgd ON, 293 kgd OFF



- combined limit (90% C.L.): **factor ~2** above predicted (Lindhard quenching with k=0.162)
- further slight improvements expected from background suppression by pulse shape discrimination (PSD)



PSD:

- remove events created in transition layer
- keep bulk events

=> bkg reduction by ~20%

→ publication in preparation

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:

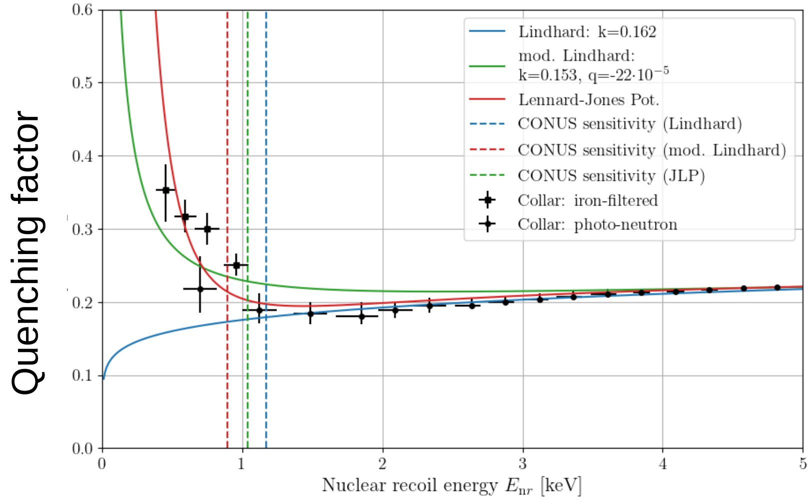
Abstract of Phys. Rev. Lett. 129, 211802 (2022)

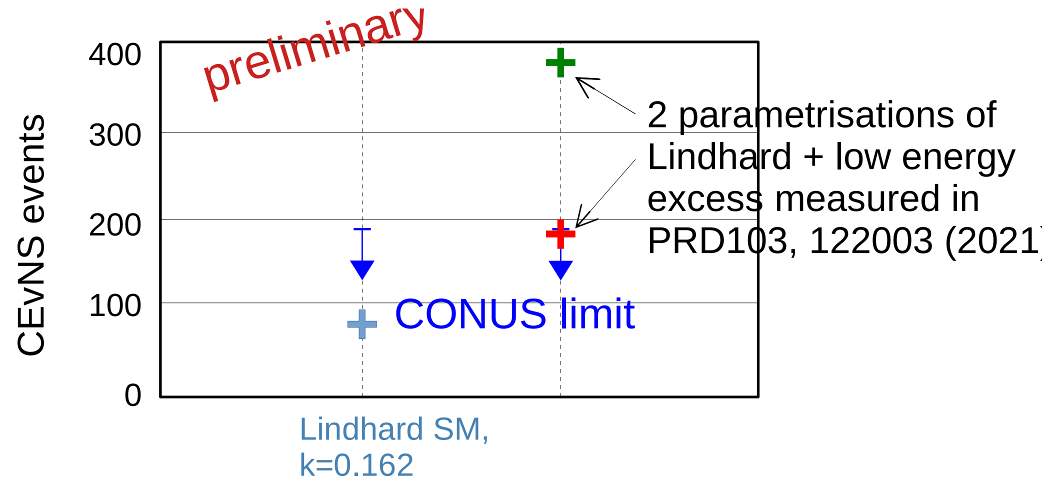
The 96.4 day exposure of a 3 kg ultralow noise germanium detector to the high flux of antineutrinos from a power nuclear reactor is described. A very strong preference ($p < 1.2 \times 10^{-3}$) for the presence of a coherent elastic neutrino-nucleus scattering (CEνNS) component in the data is found, 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 NCC-1701 signal with CONUS data:

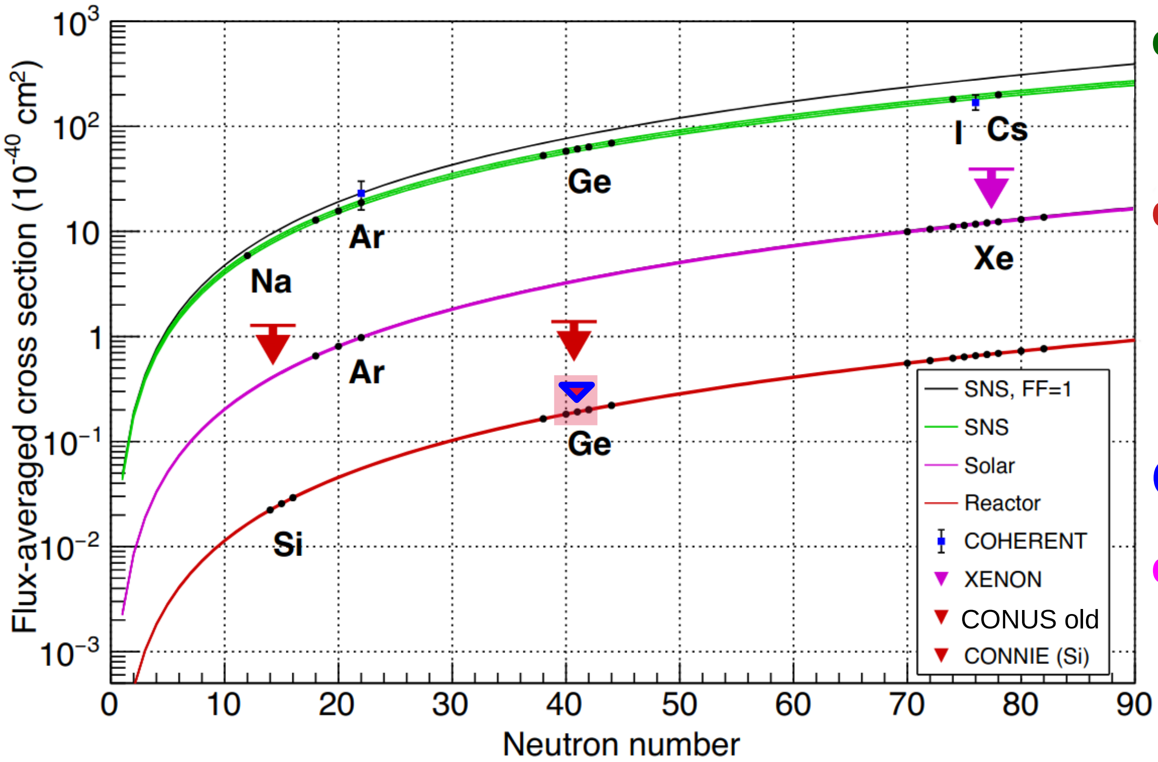




↔ tension with CONUS quenching factor measurement

↔ tension with CONUS reactor ON/OFF data

CONUS new result



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CONUS new result (preliminary)!

CEνNS with solar neutrinos:

PRL126 091301 (Xenon1t, Xe, constraint)

Summary & Outlook

Coherent elastic neutrino nucleus scattering (CEνNS):

→ coherency condition fulfilled (<50MeV) (spallation source, nuclear reactor,...)

→ neutrino interacts with all nucleons in nucleus, enhancement of cross section (~N^2)

Standard model: neutrino floor, Super Nova explosions, Weinberg angle, non-profilation,…

Beyond: setting limits NSIs, light mediators, NMM, dark matter, sterile neutrinos,...

=> detecting CEνNS = detecting a tiny recoil

CONUS: nuclear recoil in Ge <0.5keV_{ee}

- 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, lower energy threshold due to new trigger algorithm
  → preliminary limit **about factor of two above standard model**
- coming soon: final analysis including pulse shape discrimination
- CONUS+ in Switzerland → site characterization and commissioning ongoing

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CONUS

Thank you for your attention!

BACKUP

Environmental stability