

## Coherent elastic neutrino nucleus scattering: experimental efforts at SNS and reactor-site

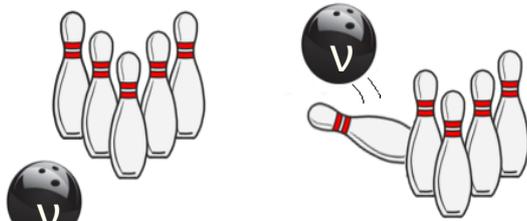
Janina Hakenmüller, Duke University



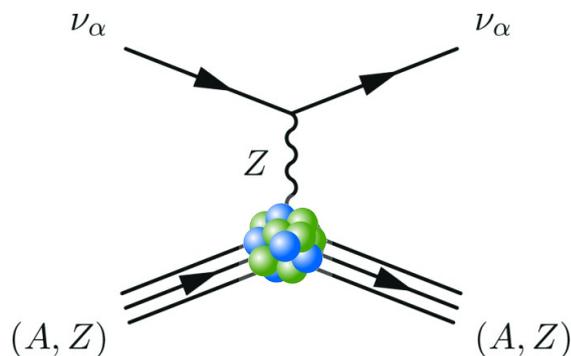
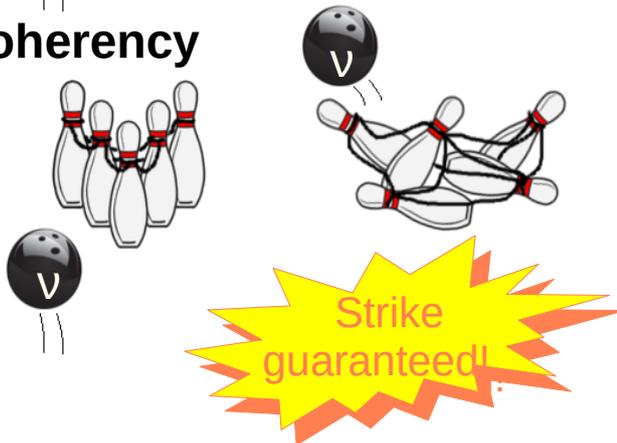
The Mitchell Conference on Collider, Dark Matter, and Neutrino Physics 2023, Texas A&M University, 19th of May

# 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)

$$\frac{d\sigma}{d\Omega} = \frac{G_f^2}{16\pi^2} \underbrace{(N - (1 - 4\sin^2\theta_W)Z)^2}_{\text{nucleus}} \underbrace{E_\nu^2}_{\text{neutrino energy}} (1 + \cos\theta) \underbrace{F(Q^2)}_{\text{nuclear form factor}}$$

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

**coherency condition:**

$\lambda(\text{mom. Transfer } Q) > \text{size of atom}$

$\Rightarrow \sigma \sim (\#\text{scatter targets})^2$

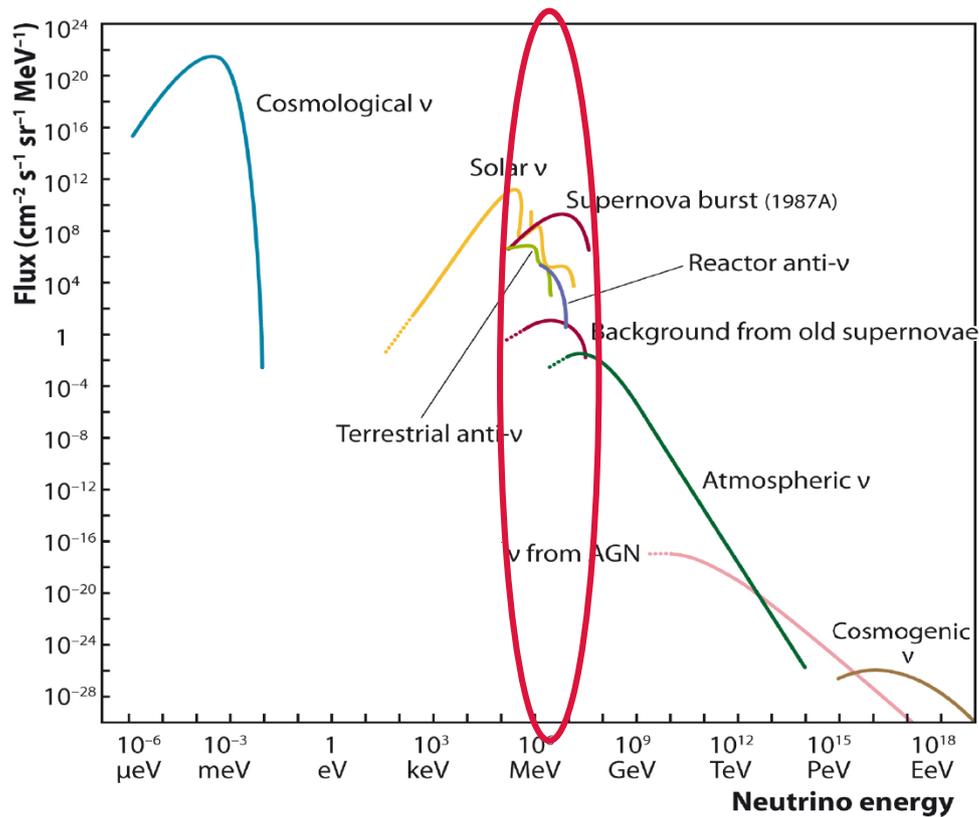
$\Rightarrow$  upper limit on neutrino energy:

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

$R_A$  = radius,  $A$  = mass number

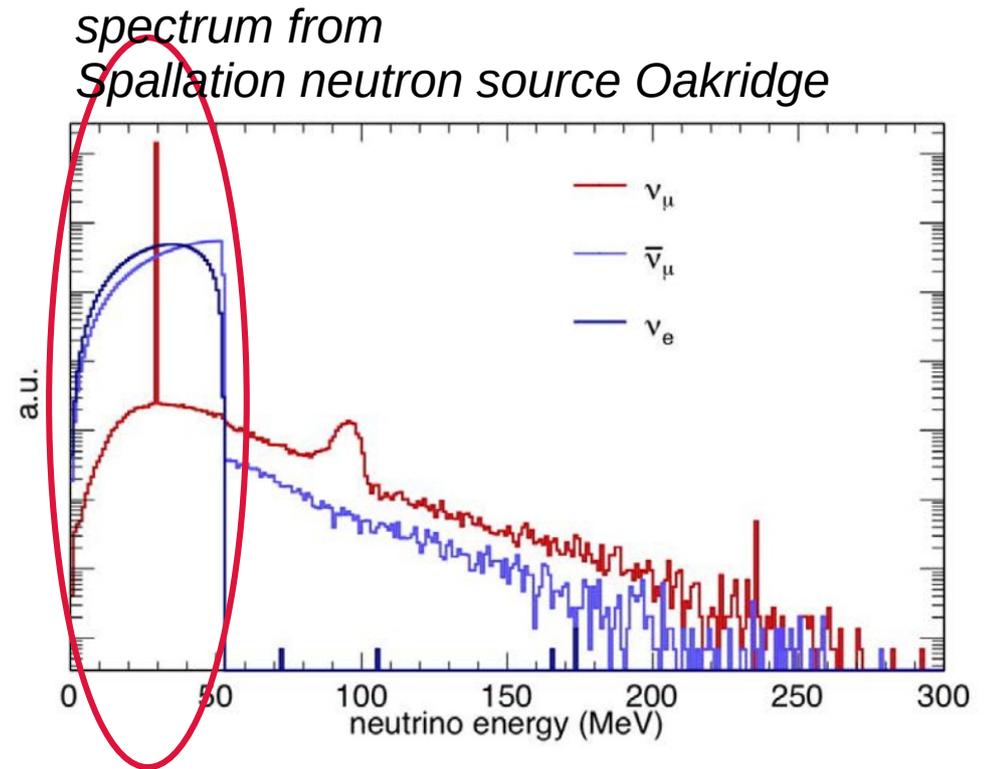
# Neutrino sources

## natural and reactor neutrinos



Katz, Ulrich F., and Ch Spiering.  
Progress in Particle and Nuclear Physics 67.3 (2012): 651-704.

## accelerator neutrinos



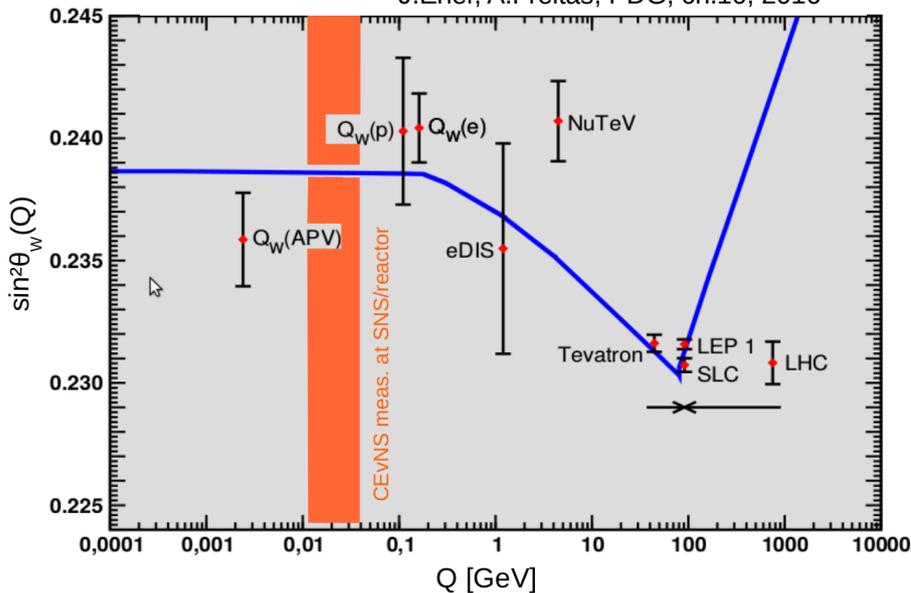
D. Akimov et al., Science 10.1126/science.aa0990, 2017

# Motivation

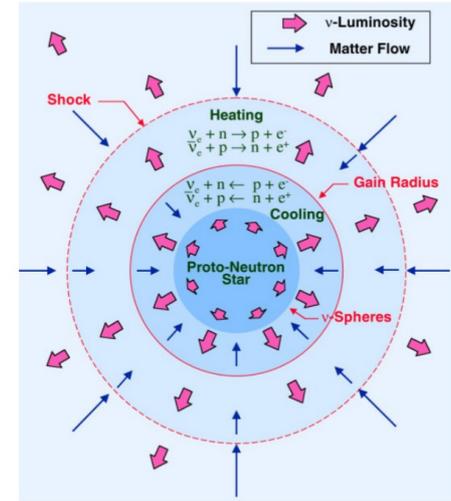
- **stellar collapse**: 99% energy release in neutrinos
- “**neutrino floor/fog**” in dark matter experiments: signature like dark matter → same detector response
- **Weinberg angle** at low energies

$$\frac{d\sigma}{d\Omega} \propto (N - (1 - 4\sin^2\theta_W)Z)^2$$

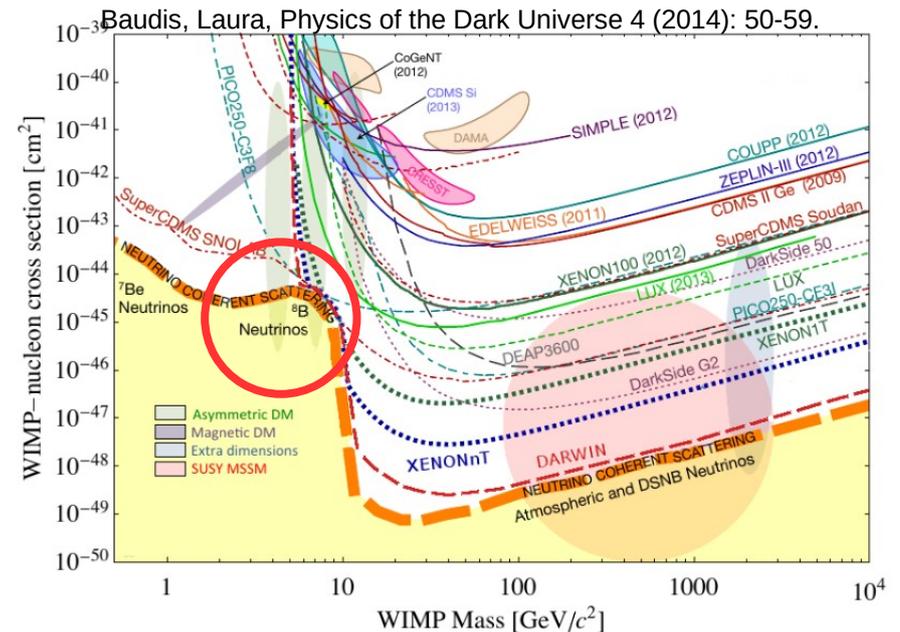
J.Erler, A.Freitas, PDG, ch.10, 2016



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



Credit: TeraScale Supernova Initiative



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

# Detecting CEvNS

Coherency condition:

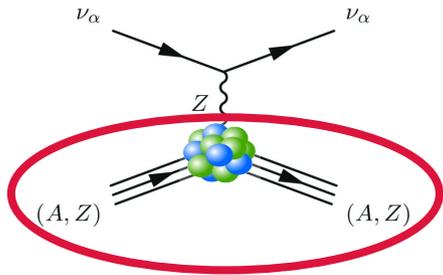
$$E_\nu \leq \frac{1}{2R_A} \approx \frac{197}{2.5\sqrt[3]{A}} \text{ (MeV)}$$

$E_{\text{max}} \leq 50 \text{ MeV (for mean A)}$

 $\Rightarrow \sigma \propto N^2 E_\nu^2$

large cross section => small detector (kg sized!)

Detection parameter: recoil of target nucleus



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

→ push-pull situation

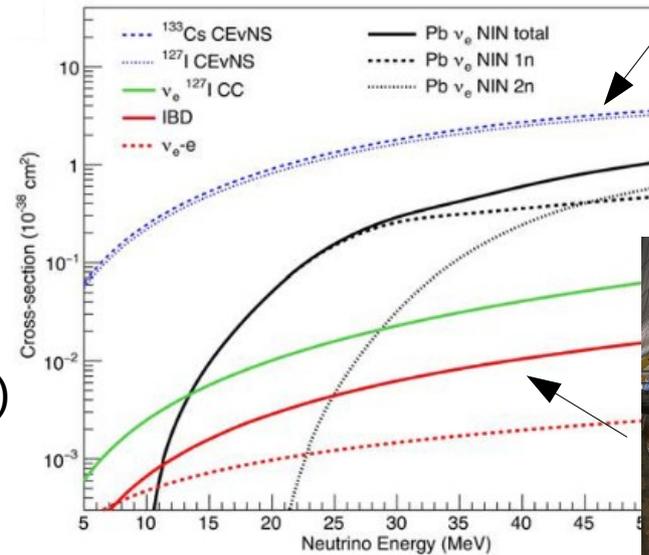
Maximum recoil energy:

| $T_{\text{max}}$         | Ge     | I      | Pb     |
|--------------------------|--------|--------|--------|
| $E_\nu = 10 \text{ MeV}$ | 2.8keV | 4.0keV | 2.6keV |
| $E_\nu = 30 \text{ MeV}$ | 25keV  | 36keV  | 23keV  |

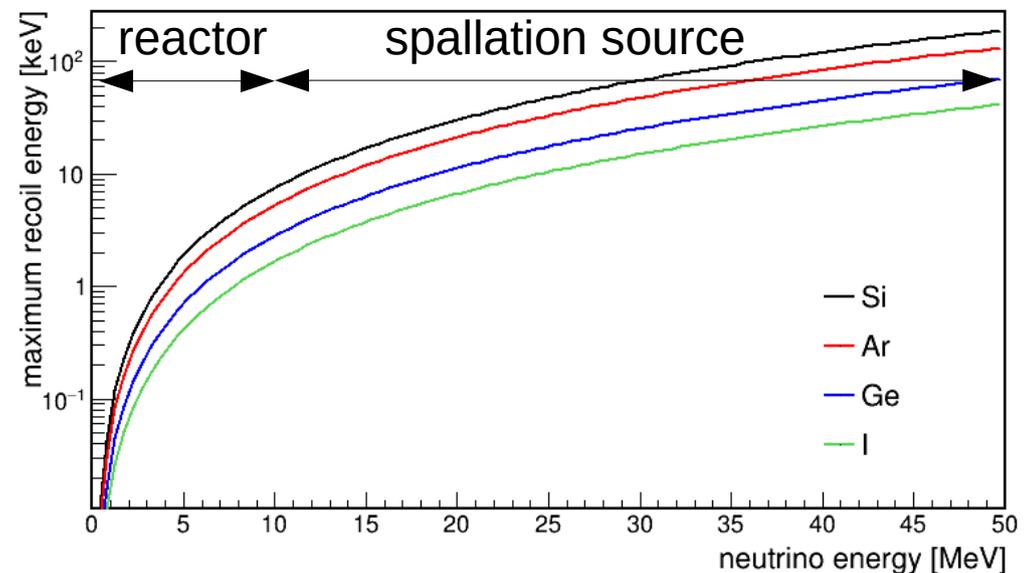
COHERENT  
Csl



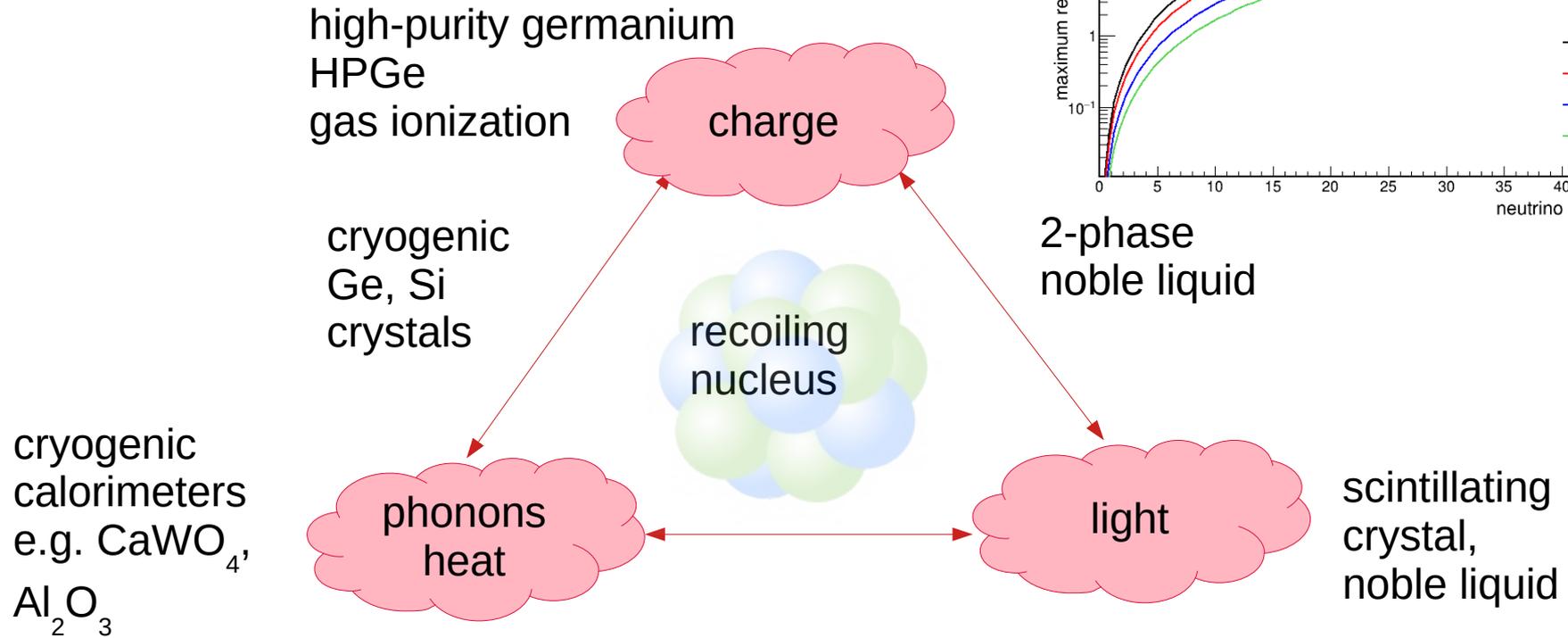
D. Akimov et al., Science 10.1126/science.aa00990, 2017



BOREXINO



# Detectors for CEνNS



## Quenching:

Quenching factor:  $Q = E(\text{meas}) / E_{\text{nuclear recoil}}$

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 measurements!

# COHERENT experiment



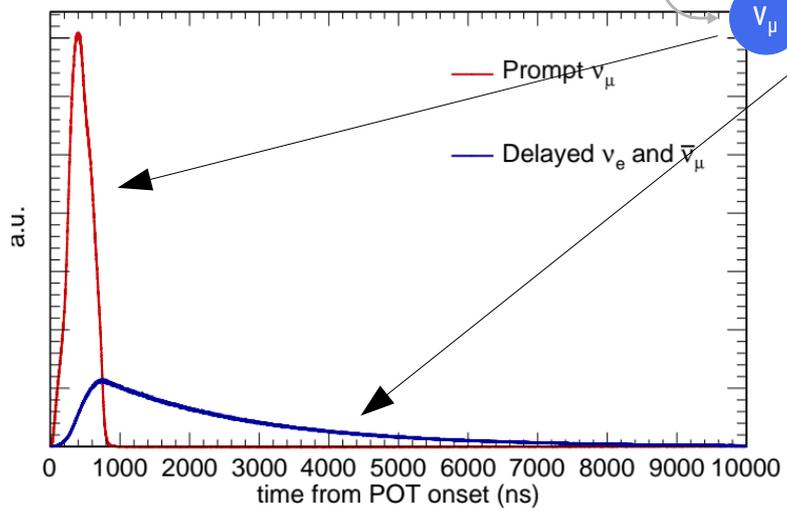
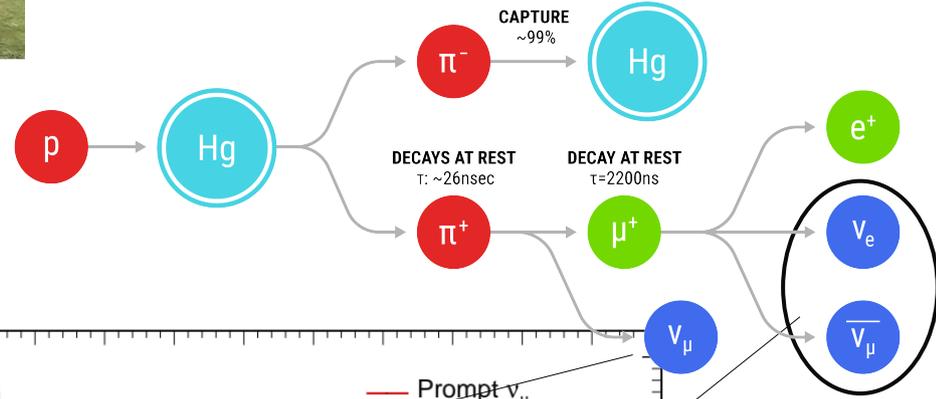
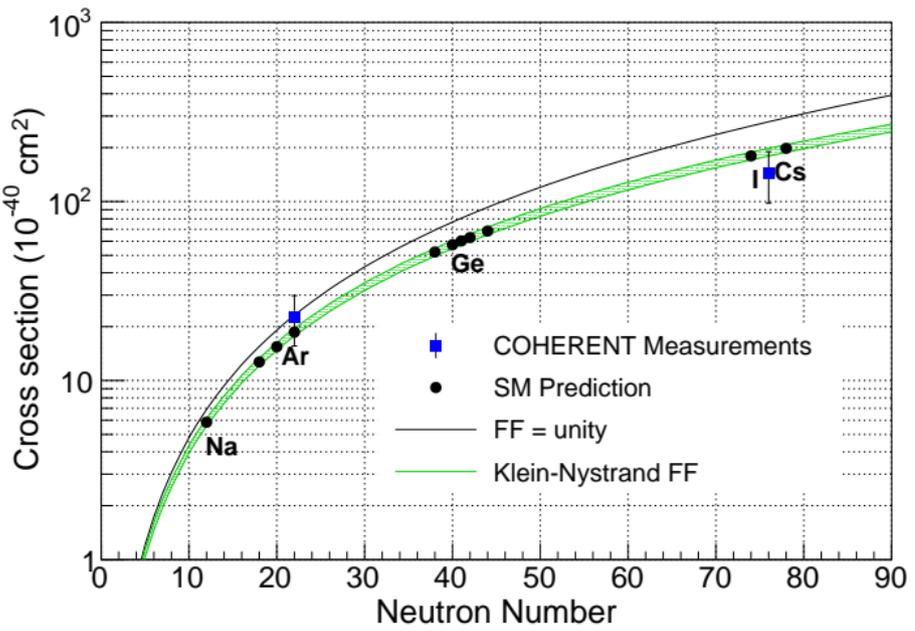
Neutrino Alley at Spallation Neutron Source at Oakridge, USA



## Pulsed proton beam with 60Hz:

- Pion decay at rest
- 1.4MW power,  $\sim 10^{20}$  protons on target/d  
 $\rightarrow 4.3 \cdot 10^7 \text{ cm}^{-2} \text{ s}^{-1}$  at 20 m
- background rejection factor by beam time structure

several types of detectors  $\rightarrow N^2$  dependence



# The COHERENT collaboration



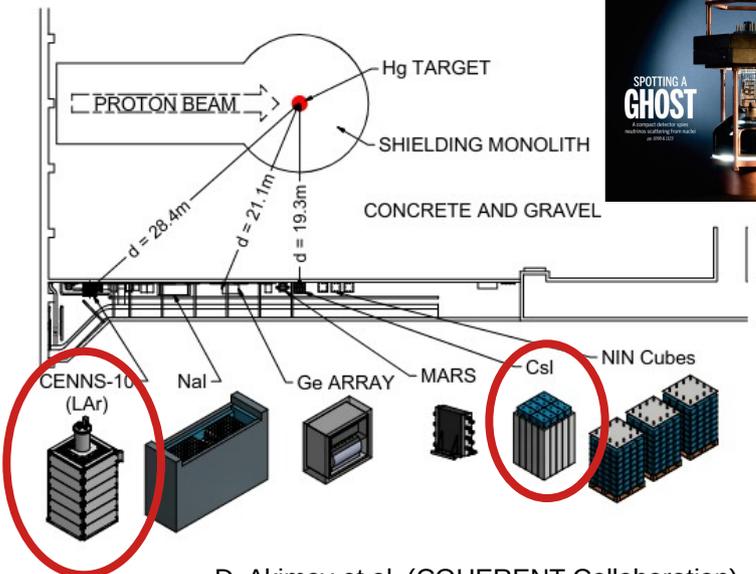
|  |                                    |  |   |
|--|------------------------------------|--|---|
| Canadian Nuclear Laboratories<br>Laboratoires Nucléaires Canadiens | Carnegie Mellon University         | Duke UNIVERSITY                                  | UF UNIVERSITY of FLORIDA                    |
|  |                                    | Laurentian University<br>Université Laurentienne | Los Alamos NATIONAL LABORATORY<br>EST. 1943 |
|  | NC Central UNIVERSITY              | NC STATE UNIVERSITY                              | OAK RIDGE National Laboratory               |
| Sandia National Laboratories                                       | 서울대학교<br>SEOUL NATIONAL UNIVERSITY | SLAC NATIONAL ACCELERATOR LABORATORY             | UNIVERSITY OF SOUTH DAKOTA                  |
| THE UNIVERSITY of TENNESSEE<br>KNOXVILLE                           | Tufts UNIVERSITY                   | TUNL<br>TRIANGLE UNIVERSITIES NUCLEAR LABORATORY | VT VIRGINIA TECH                            |
| W UNIVERSITY of WASHINGTON   | WASHINGTON & JEFFERSON COLLEGE     |  |   |



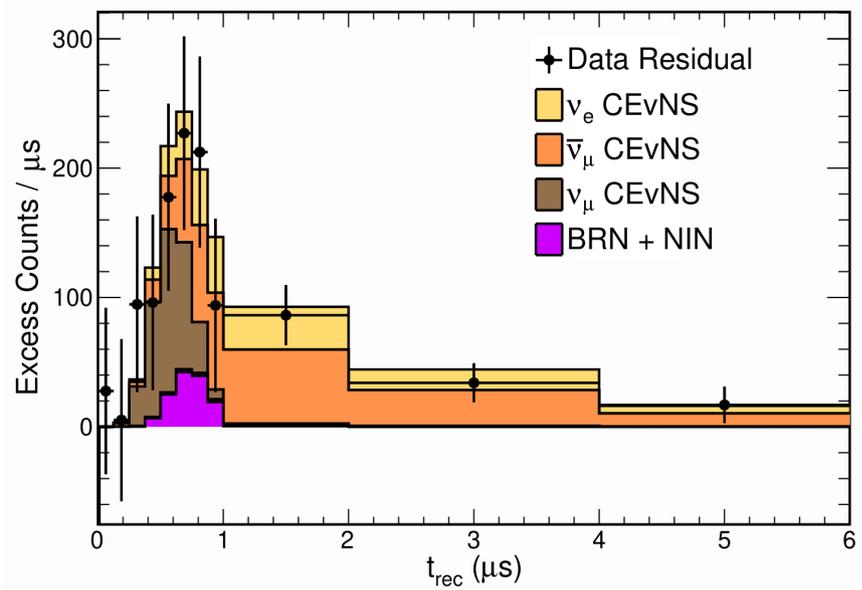
U.S. DEPARTMENT OF ENERGY

Office of Science

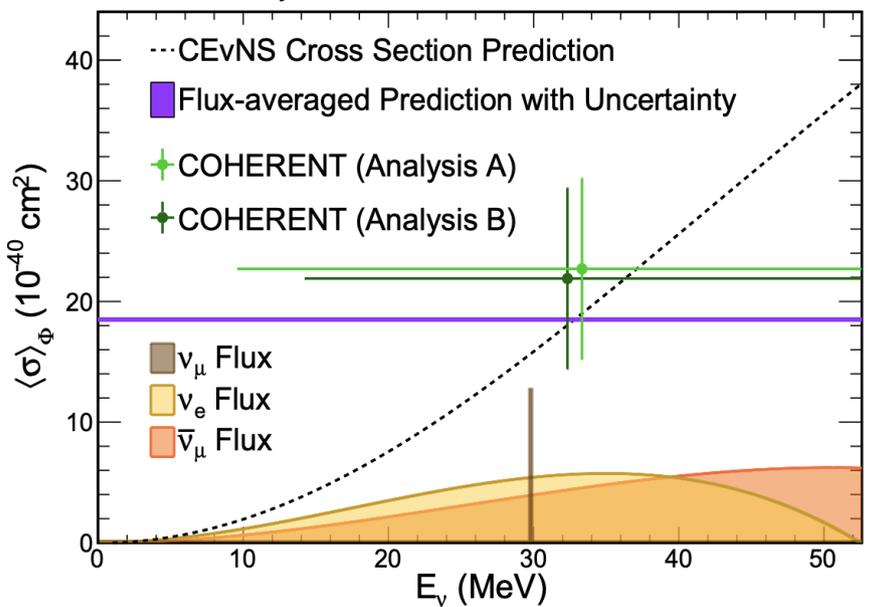
# COHERENT experiment



D. Akimov et al. (COHERENT Collaboration)  
Phys. Rev. Lett. 126, 012002, 2017



D. Akimov et al. (COHERENT Collaboration)  
Phys. Rev. Lett. 129, 081801, 2022



## CsI scintillatin crystal:

### 2017 - first observation of CEvNS

- 6.7 $\sigma$  discovery, 1 $\sigma$  consistent with standard model
- mass: 14.6kg, energy threshold: 5keV nuclear recoil
- 2021: +3yr of data, new quenching factor meas.
  - 11.6 $\sigma$  significance

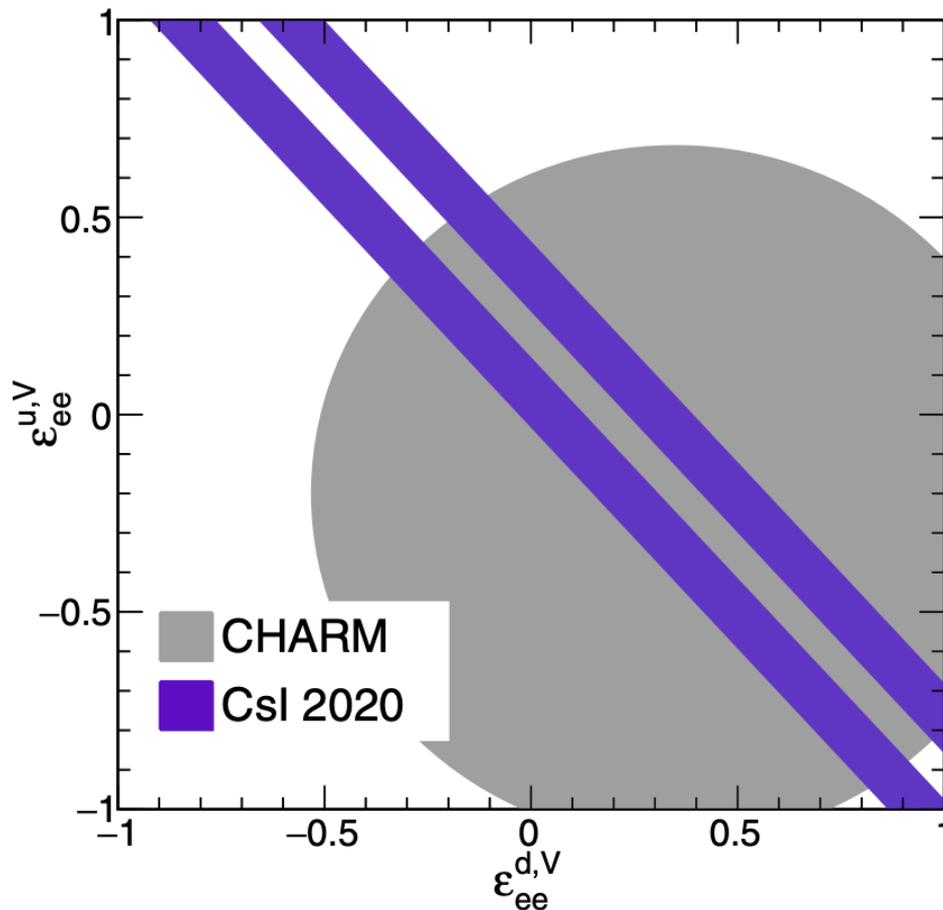
### Single phase Liquid Argon (CENNS-10): observation of CEvNS 2021

- 3.5 $\sigma$  significance, consistent with standard model
- mass: 24kg, energy threshold: 20keV nuclear recoil

# Beyond standard model

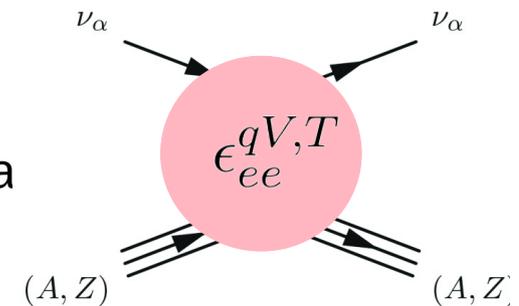
→ excess or deficit in comparison to standard model

One example:



Phys.Rev.Let. 129, 081801 (2022)

effective field  
theory approa



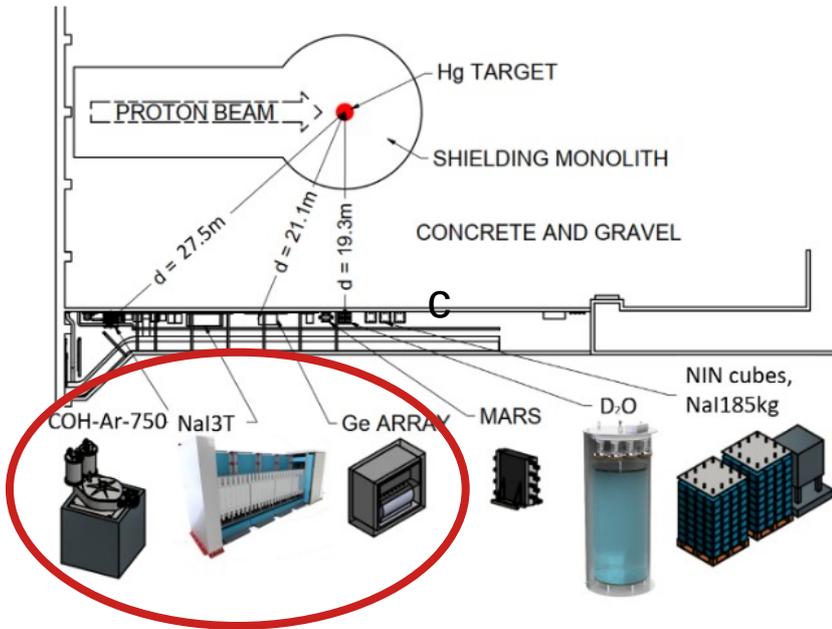
There are also:

- light mediators
- accelerator-based dark matter searches
- (anomalous) neutrino magnetic moment
- sterile neutrinos
- ...

# COHERENT: ongoing and future



NalvETe → CEvNS on Na



lighter nuclei

Ge-Mini → CEvNS on Ge

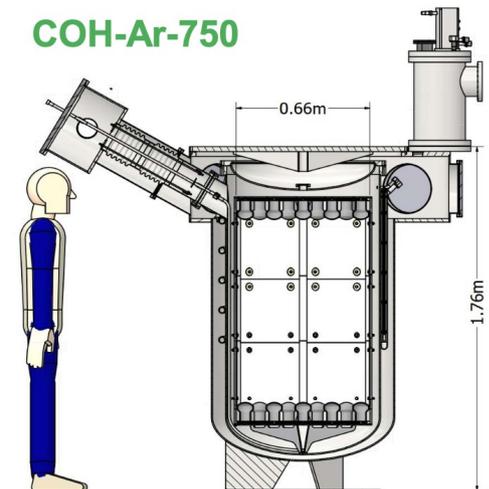
lower threshold



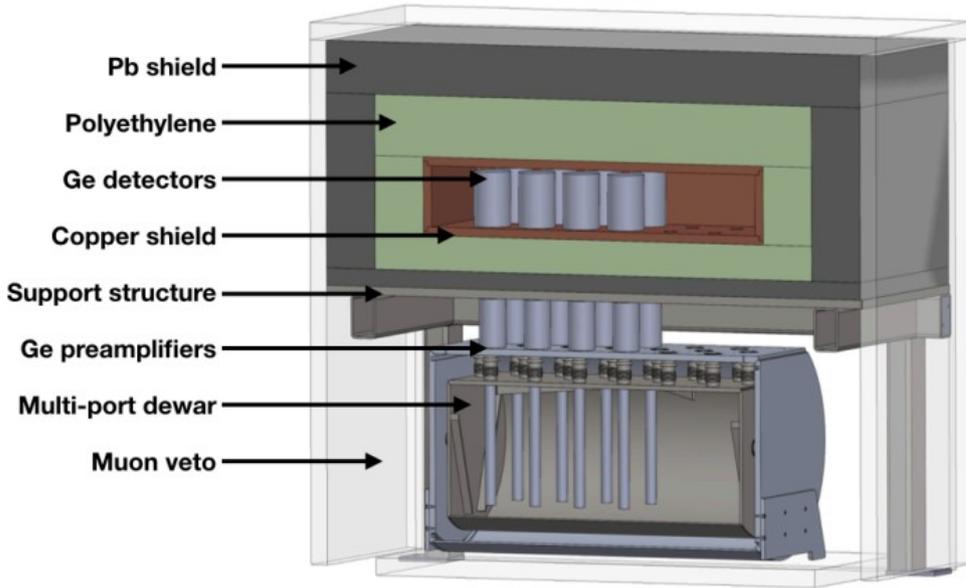
more mass

COH-Ar-750:  
750kg of LAr

COH-Ar-750

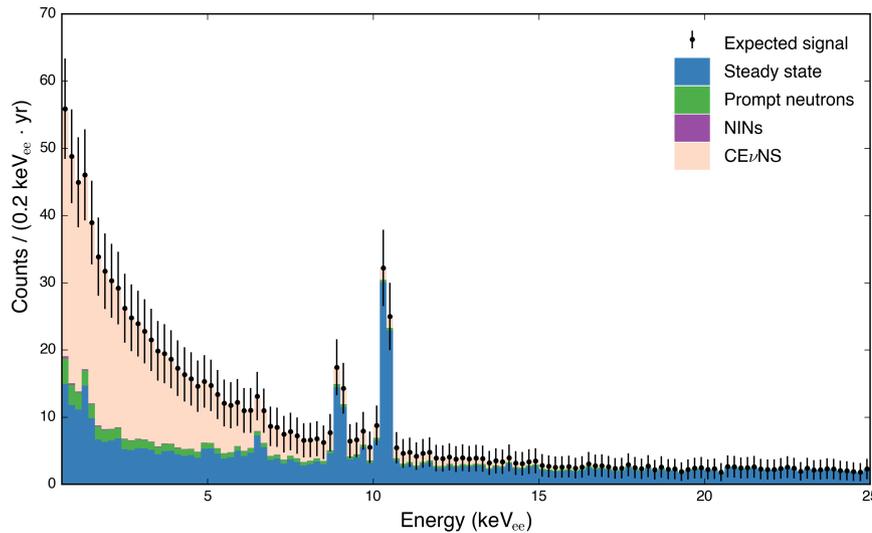


# COHERENT: Ge-Mini

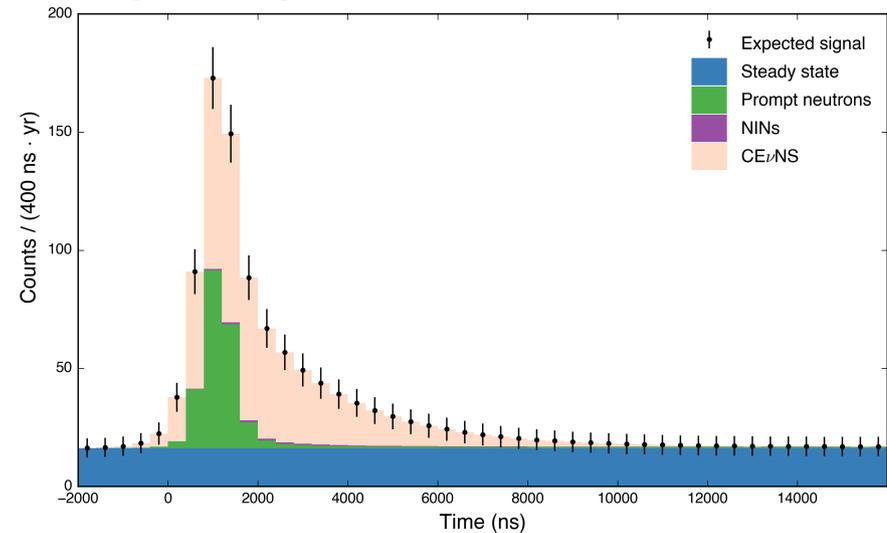


- mass: max 18 kg
- energy resolution:  $<150 \text{ eV}_{ee}$  FWHM  
 → energy threshold:  $<500 \text{ eV}_{ee}$  ( $2\text{-}2.5 \text{ keV}_{nr}$ )
- quenching factor well understood

Signal expectation in energy



Signal expectation in time



# Neutrino sources: $\pi$ DAR vs reactor

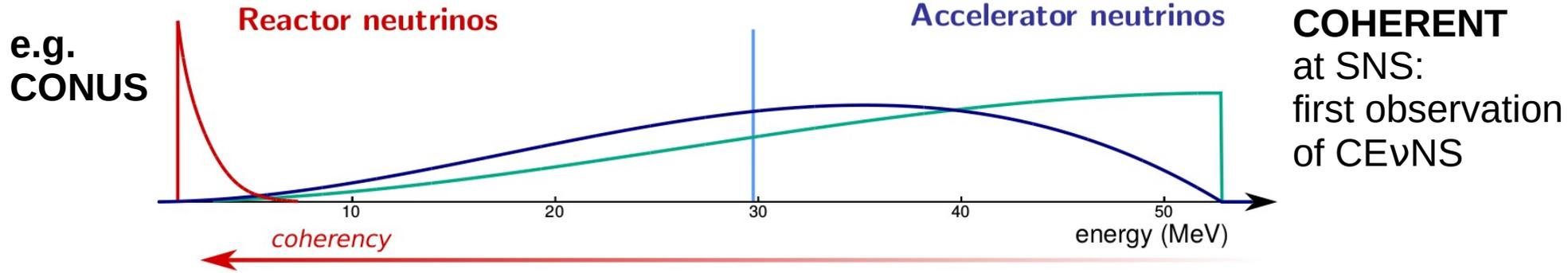
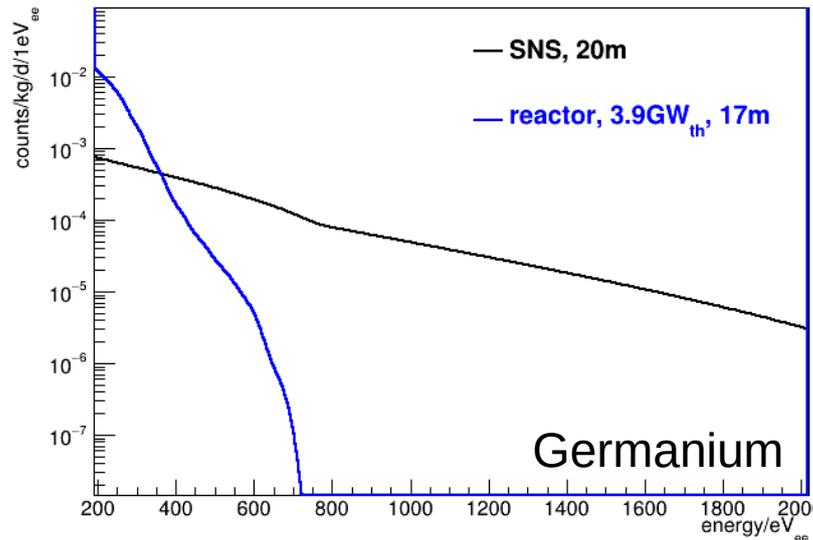


Figure by A. Bonhomme

$\bar{\nu}_e$  from  $\beta$ -decays of fissile isotopes

$\nu_\mu, \bar{\nu}_\mu$  and  $\nu_e$  from  $\pi$ -decay at rest

- higher flux for GW power
- energy <10MeV
  - tiny recoil
  - nuclear form factor  $\sim 1$
- background suppression:
  - shield (shallow depth)
  - OFF data during outage (usually limited statistics)

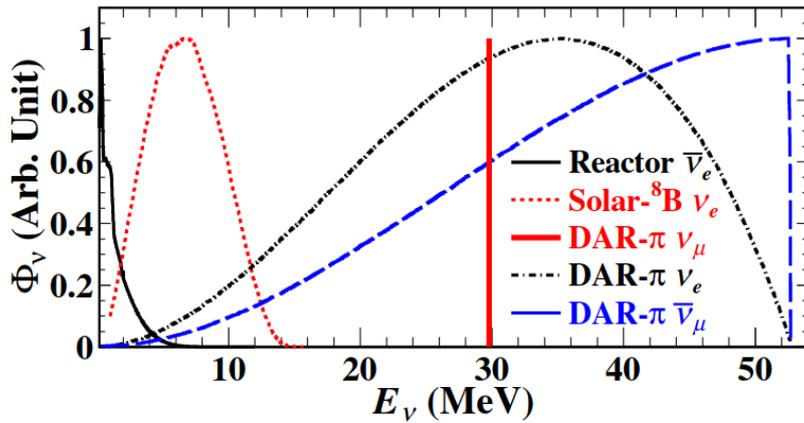


- lower flux
- energy 20-50MeV
  - recoil at higher energies
  - nuclear form factor <1
- Background:
  - shield (shallow depth)
  - pulsed beam: factor of  $10^{-3}$ - $10^{-4}$
  - comparable ON and OFF statistics

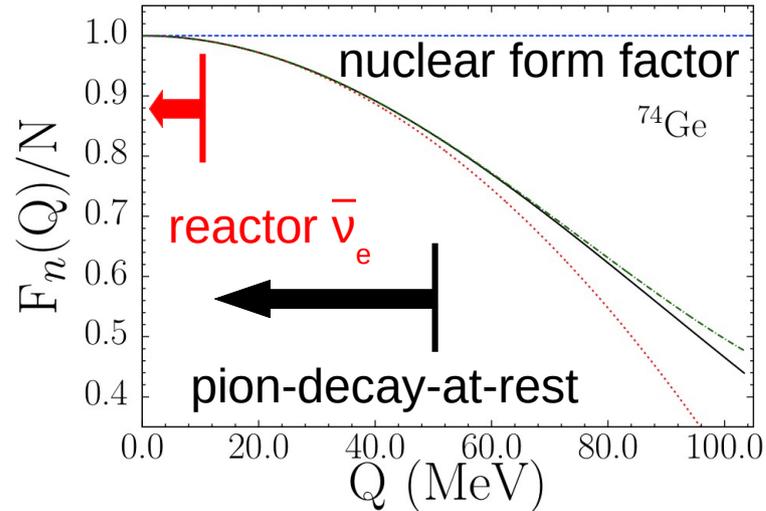
# Towards lower neutrino energies

From pion-decay at rest neutrinos to reactor anti neutrinos:

← coherency

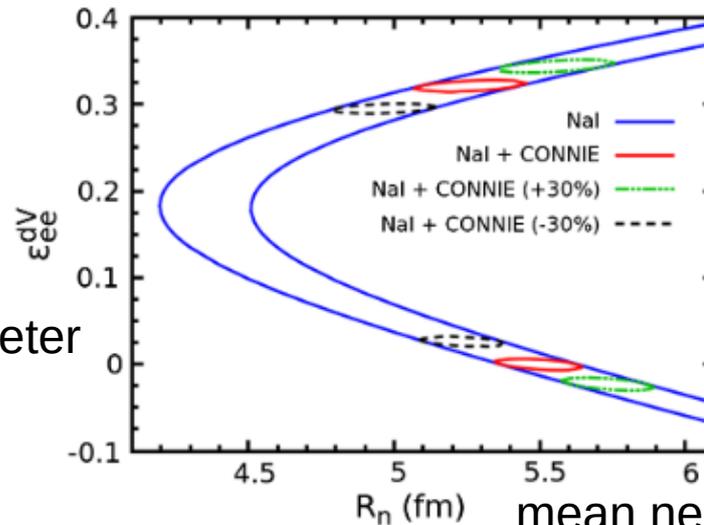


Phys.Rev.D 103 (2021) 9, 092002



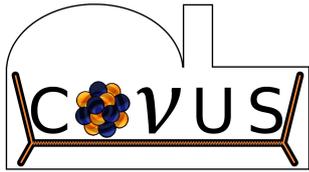
K. Patton et al., Phys. Rev. C 86 (2012) 0246

NSI parameter

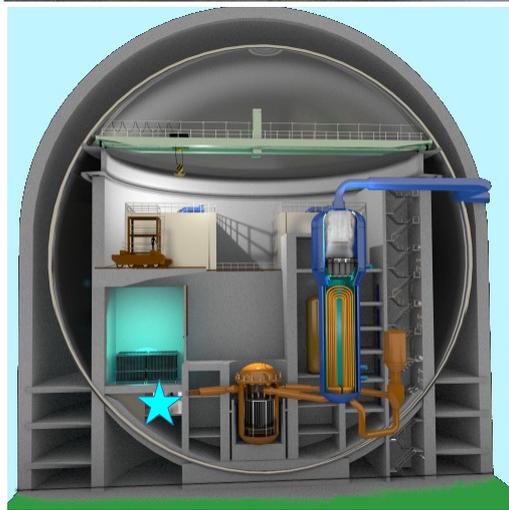


Phys.Rev.D 101, 035012 (2020)

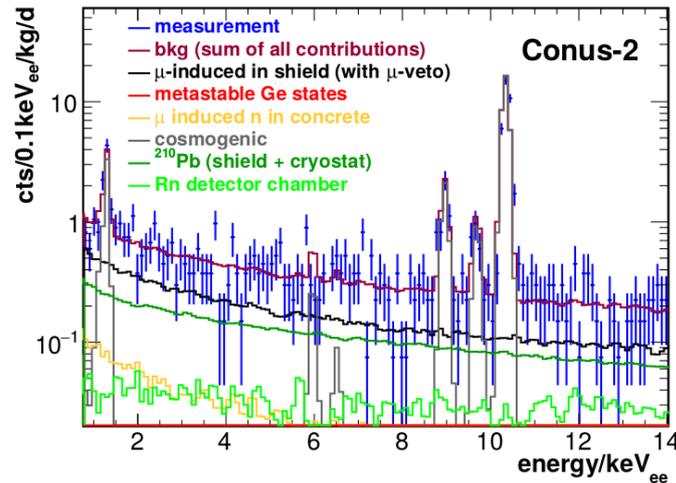
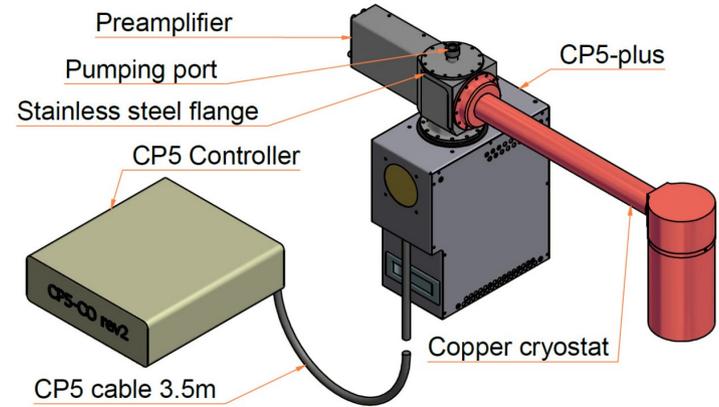
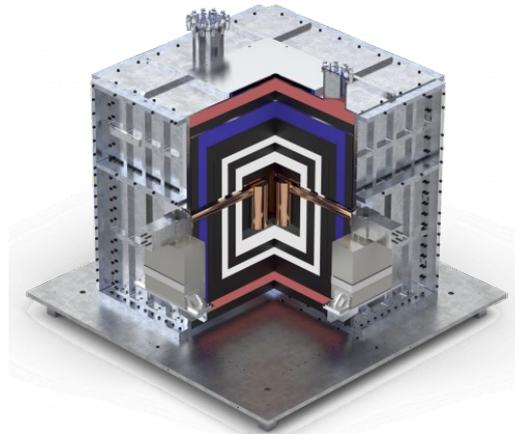
complementary approaches: neutron form factor, limits on BSM models,...



# experiment



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



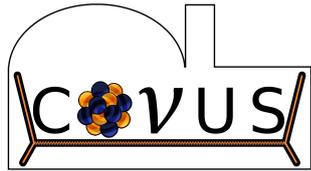
**Background:** shell-like shield  
 with active muon veto  
 $\Rightarrow \sim 10 \text{cts/d/kg}$  in  $[0.5, 1] \text{keV}_{ee}$

**Detectors:** 4 x high-purity point-contact Germanium spectrometer,

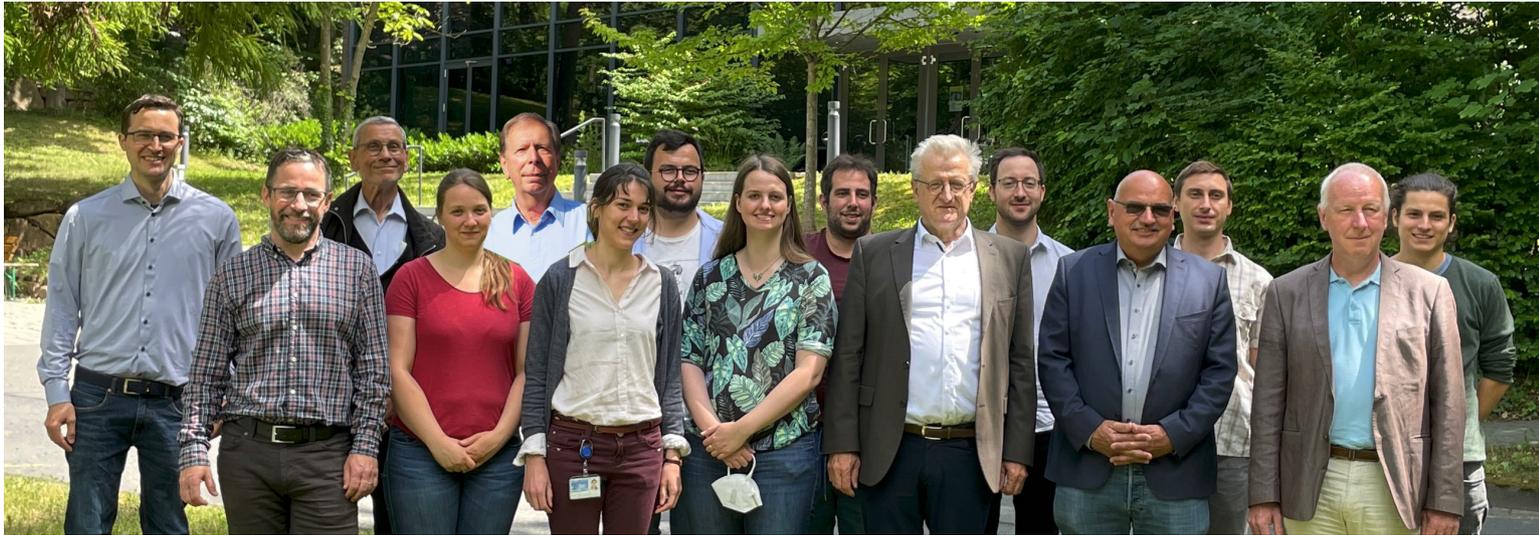
- crystal / active mass:  
total: 4.0kg / 3.74kg
- pulser resolution  $< 80 \text{eV}_{ee}$   
energy threshold  $\leq 250 \text{eV}_{ee}$
- Electrical cryocooler
- screening for radiopurity

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

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



# 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. Hügler

### Preussen Elektra GmbH, Kernkraftwerk Brokdorf (KBR), Brokdorf:

K. Fülber, R. Wink

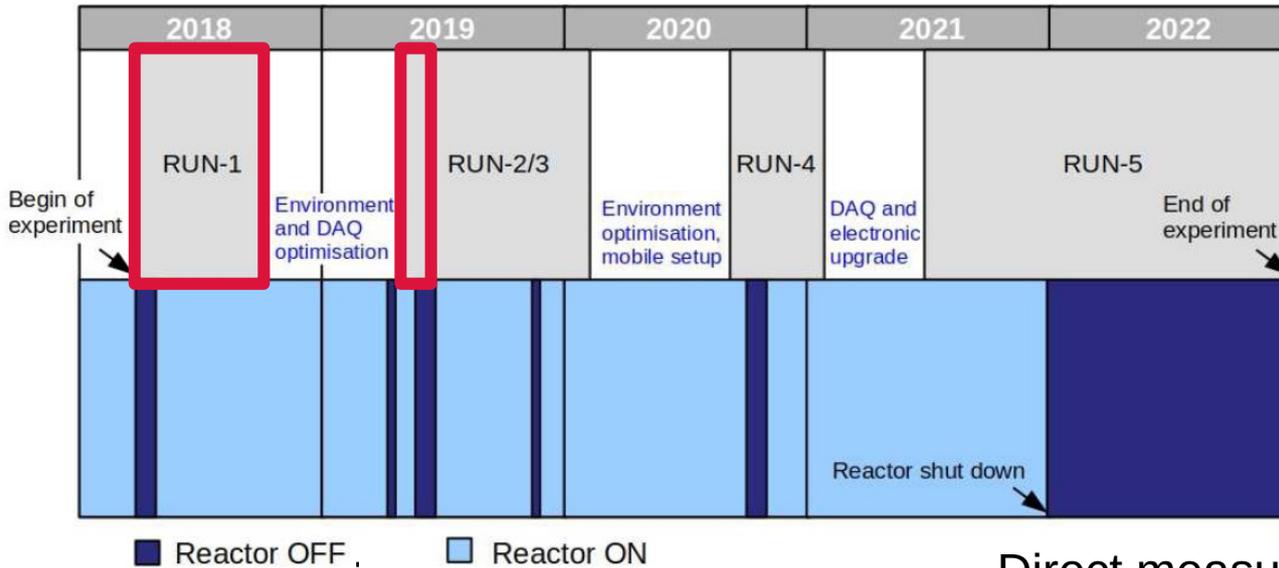
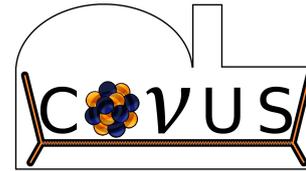
### Scientific cooperation:

### Physikalisch-Technische Bundesanstalt (PTB), Braunschweig:

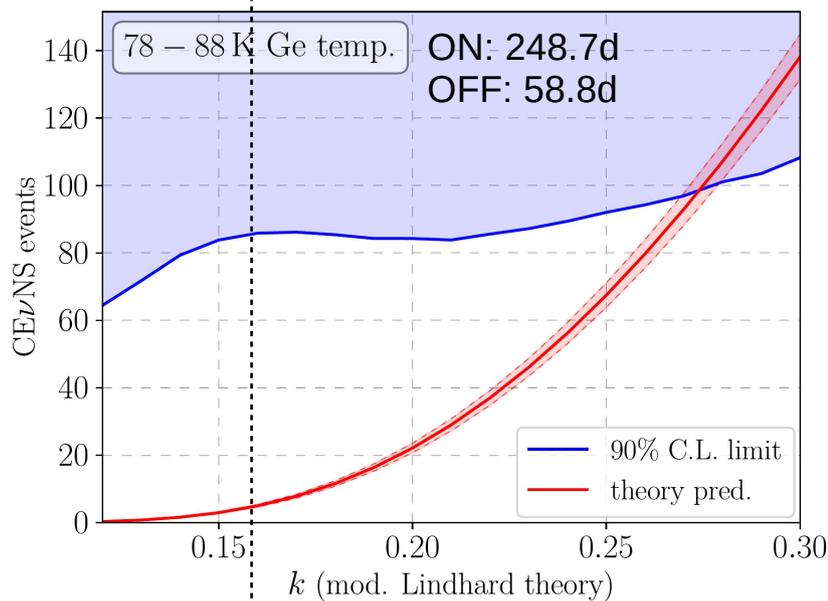
R. Nolte, E. Pirovano, M. Reginatto, M. Zboril, A. Zimbal



# Run-1/Run-2 results

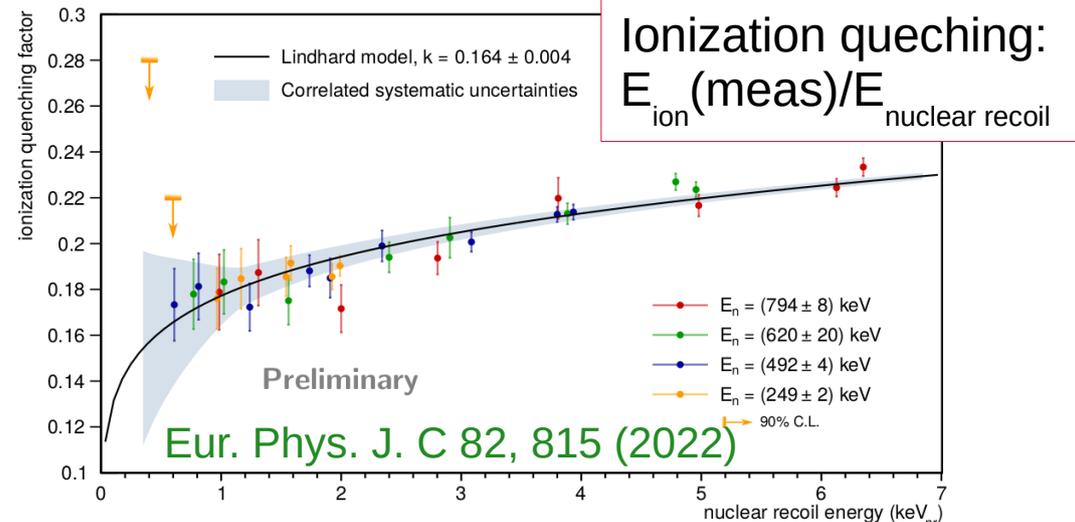


- cuts on increased noise and time difference between events
- combined fit of runs and detectors in binned log likelihood analysis including systematics
- MC background model
- min. energy threshold:  $296\text{eV}_{ee}$

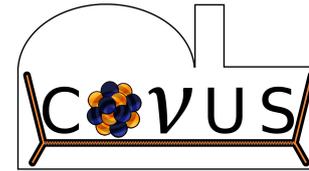


Phys. Rev. Lett. 126, 041804

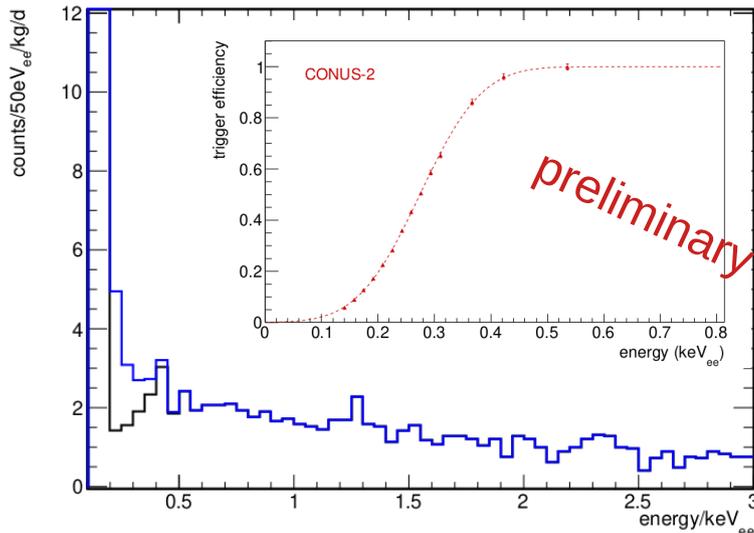
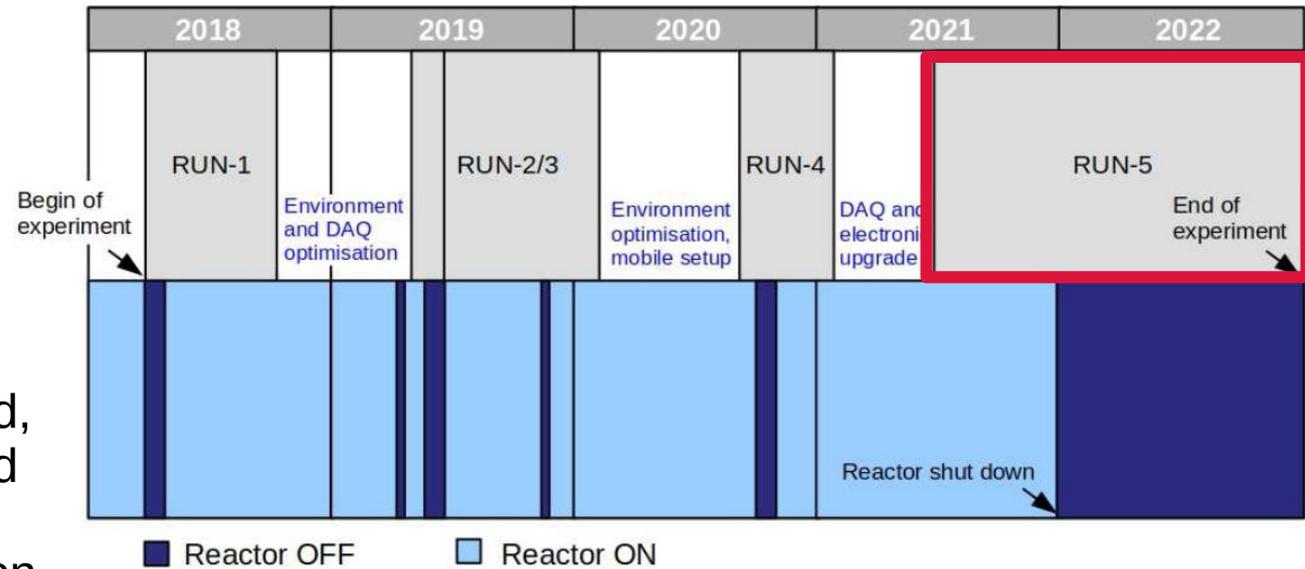
Direct measurement of ionization quenching factor **after** Run-1/Run-2 analysis (results 2022):  $k=0.162\pm 0.004$  compatible with Lindhard



# Run-5 results

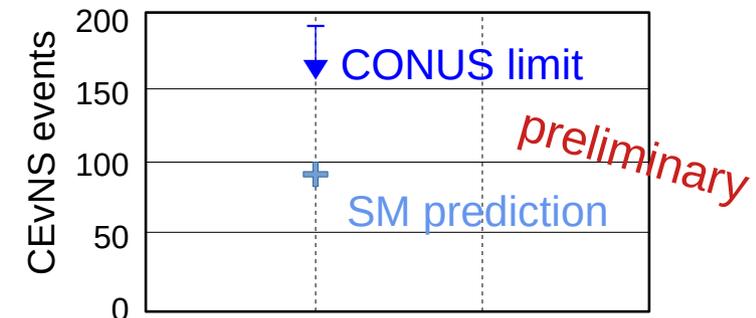


- Improved power supply/grounding → less noise
- new DAQ → optimize trigger efficiency vs. noise reduction, pulse shape discrimination
- stable/lower air temperature → reduce microphonics
- long OFF data collection period, long OFF data collection period → statistics
- Cf252 neutron source irradiation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



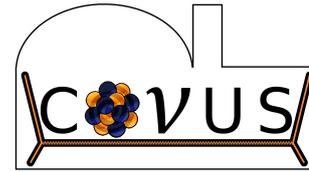
Energy thresholds:  
 C1: 220 eV<sub>ee</sub>  
 C2: 210 eV<sub>ee</sub>  
 C4: 210 eV<sub>ee</sub>

Total exposure: 458d ON, 293d OFF



- combined limit (90% C.L.): **factor ~2** above predicted (Lindhard quenching with  $k=0.162$ )
- further slight improvements expected (PSD, additional statistics,...)

# Comparison with other experiments



## Current results from reactor CEvNS experiments:

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

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

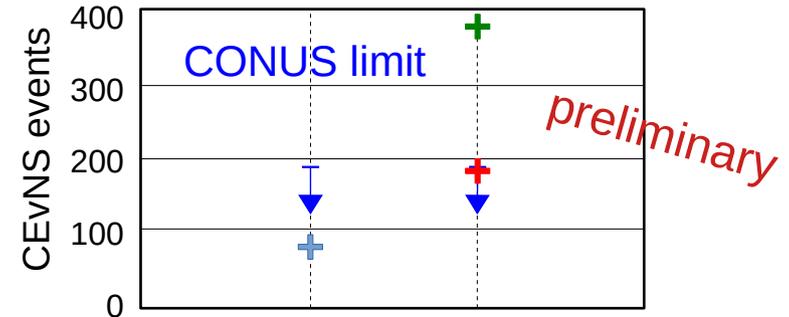
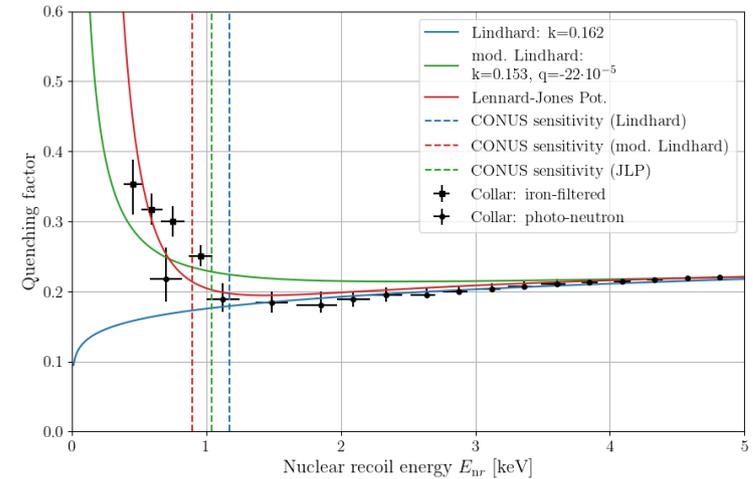
The 96.4 day exposure of a 3 kg ultralow noise germanium detector to the high flux of antineutrinos from a power nuclear reactor is described. A very strong preference ( $p < 1.2 \times 10^{-3}$ ) for the presence of a coherent elastic neutrino-nucleus scattering (CEvNS) component in the data is found, when compared to a background-only model. No such effect is visible in 25 days of operation during reactor outages. The best-fit CEvNS 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 CEvNS 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:



Green, red crosses: 2 parametrisations of Lindhard + Migdal like measured in Phys. Rev. D 103, 122003 (2021)  
 Blue cross: Lindhard,  $k=0.162$  (CONUS quenching measurement)

↔ tension with CONUS reactor ON/OFF data

# Summary & Outlook

## CEvNS:

- coherency condition fulfilled ( $<50\text{MeV}$ ) (spallation source, nuclear reactor,...)
- neutrino interacts with all nucleons in nucleus, enhancement of cross section ( $\sim N^2$ )

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

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

=> detecting CEvNS = detecting a tiny recoil

**COHERENT at SNS:** nuclear recoil in Ge  $<\sim 20\text{keV}_{ee}$

- detection 2017 with CsI (first ever)
- detection 2021 with LAr
- upcoming: Ge-Mini, NalveTE, CohAr750, D<sub>2</sub>O,  
power upgrade of SNS, second target station,...

**CONUS at KBR:** nuclear recoil in Ge  $<\sim 0.5\text{keV}_{ee}$

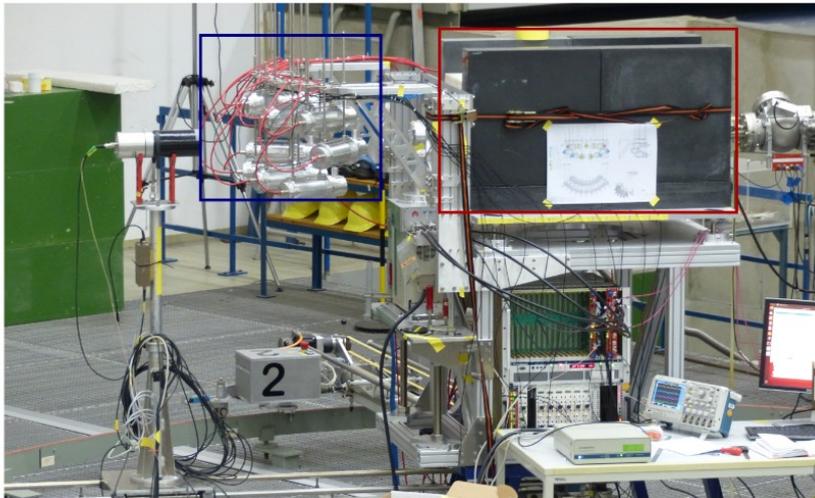
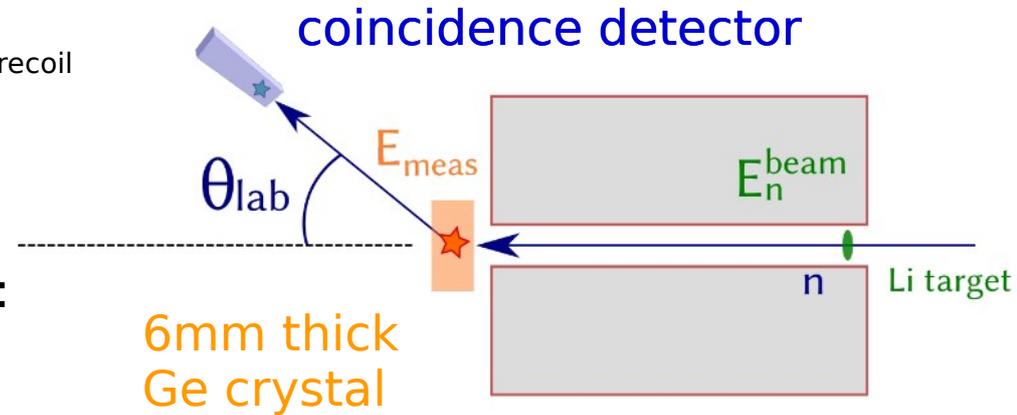
- reactor experiment at Brokdorf nuclear power plant, Germany, 5 years of succesful operaton
- preliminary limit for Run-5 data about factor of two above standard model
- CONUS++ in Switzerland

Thank you for your attention!

BACKUP

# Ge quenching factor measurement for CONUS at PTB

- Ionization quenching:  $Q = E_{\text{ion}}(\text{meas}) / E_{\text{nuclear recoil}}$
- direct measurement at collimated neutron beam at PTB Braunschweig
- scan over recoil energies [0.4, 7] keV<sub>nr</sub>
- data compatible with Lindhard model for:  **$k = 0.164 \pm 0.004$  (stat+syst)**



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