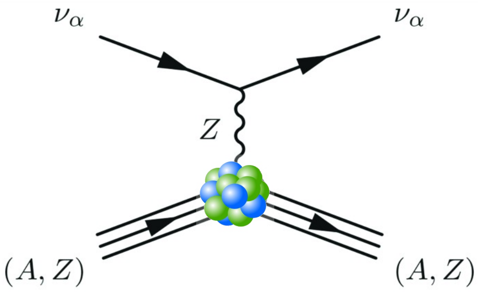


Overview on coherent elastic neutrino nucleus scattering & successful first detections

Dr. Janina Hakenmüller

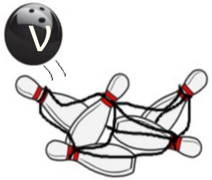
Duke University

DPG Frühjahrstagung, Göttingen, 02.04.2025

Coherent elastic neutrino nucleus scattering (CEνNS)

no coherence

coherence



coherence condition:

λ(mom. transfer Q) > size of atom

=> σ ~ (#scatter targets)^2

→ upper limit on neutrino energy:

E_{max}≤50 MeV (for medium A)

- standard model interaction, flavor blind, no energy threshold
- predicted in 1974: D.Z. Freedmann Phys. Rev. 9 (1974) 5

neutrino energy

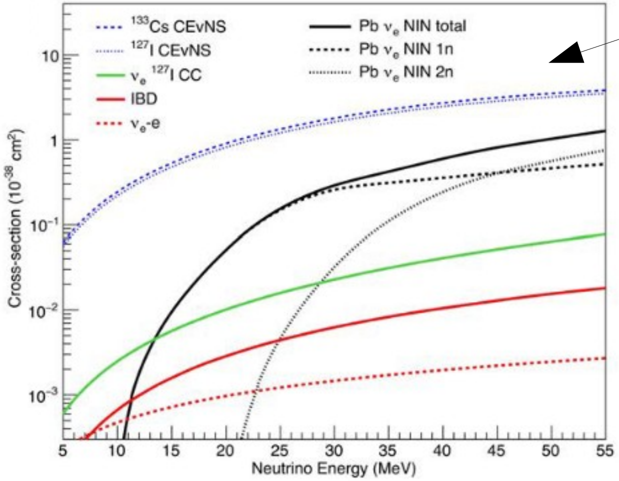
$$\frac{d\sigma}{d\Omega} = \frac{G_f^2}{16\pi^2}(N-(1-4\sin^2\theta_W)Z)^2 E_\nu^2 (1+\cos\,\theta) F(Q^2)$$

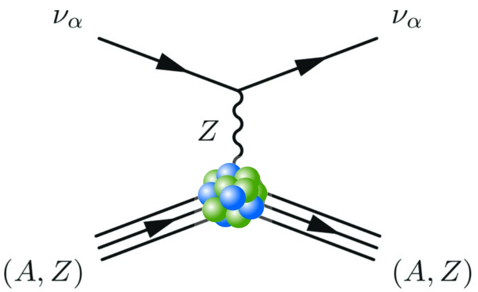
nucleus

nuclear form factor

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

CEvNS





D. Akimov et al., Science 10.1126/science.aao0990, 2017

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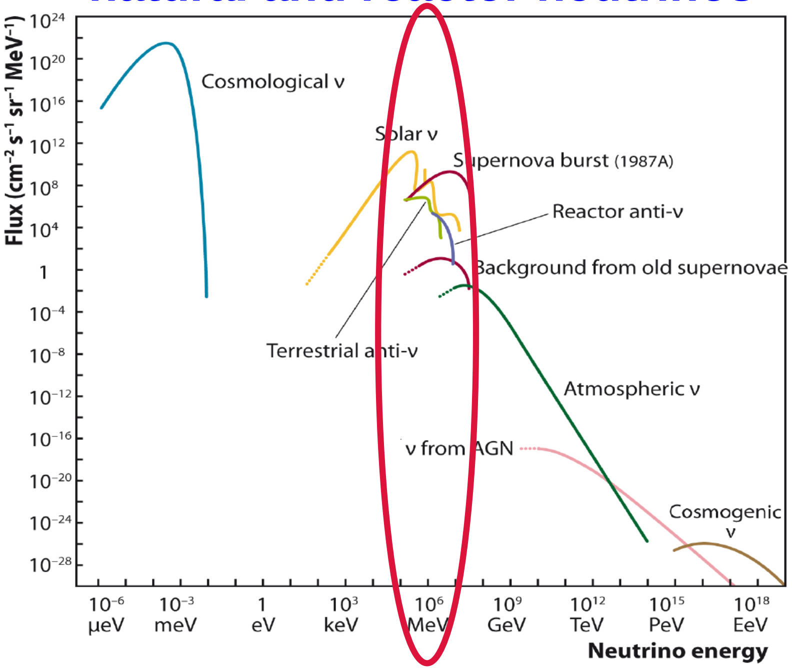
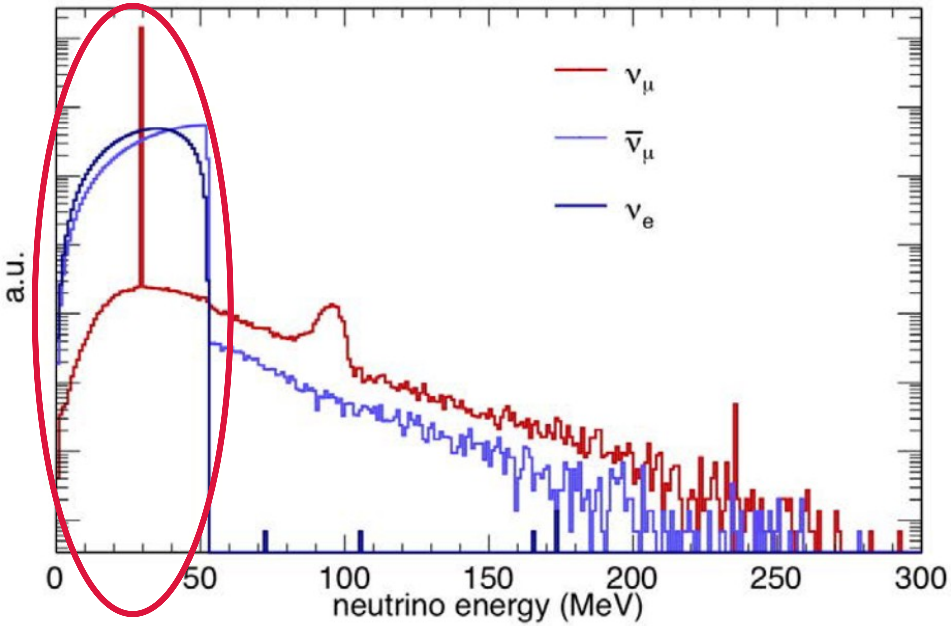
Neutrino sources for CEvNS

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.aao0990, 2017

radioactive decay, solar neutrinos, supernovea, nuclear reactor, spallation source

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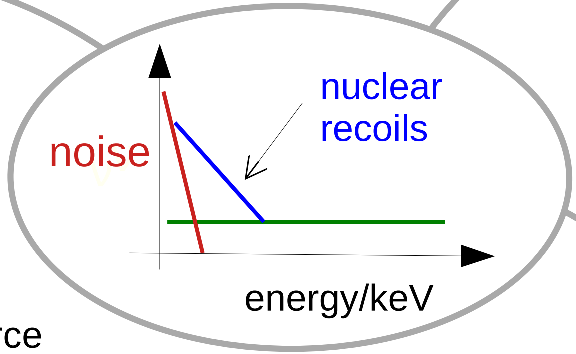
How to detect CEvNS

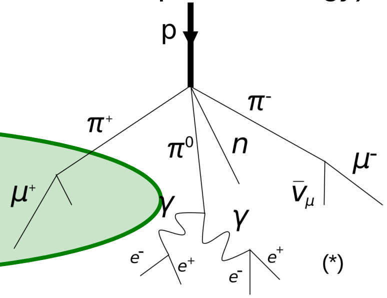
Detectors

coherence
→ large cross section
→ **kg-sized detectors** and below

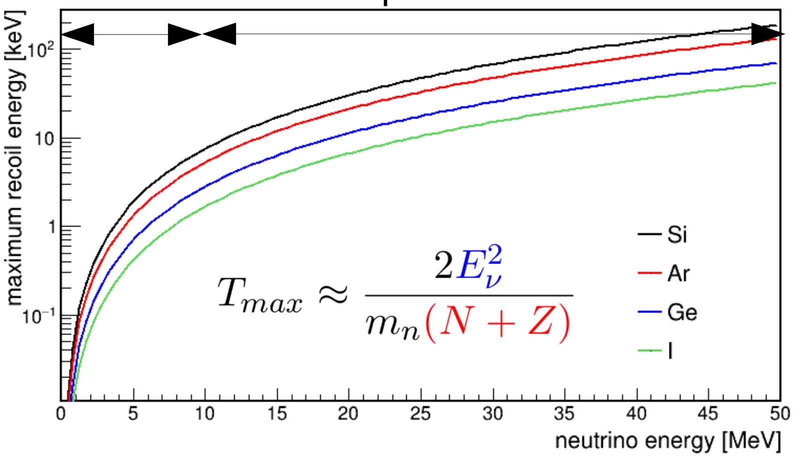


Neutrino source

close to strong neutrino source:
nuclear reactor: $O(10^{20})$ per s per GW
spallation source: $O(10^{15})$ per s
(1.4MeV, 1GeV proton energy)

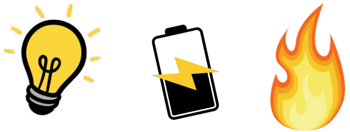


Background



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

signature:
recoil of nucleus
→ **low energy threshold**

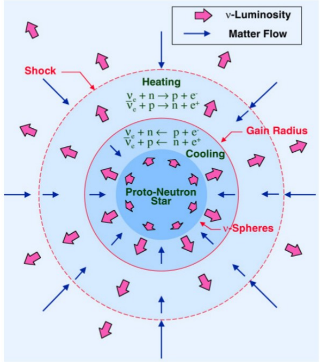


neutrino sources at Earth's surface + source = neutron source
→ site background characterization
→ shield, background measurements

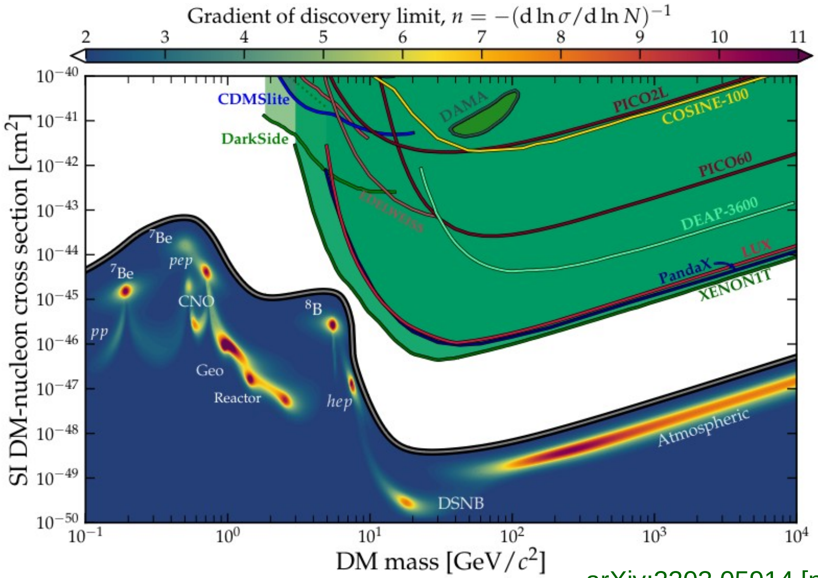
(*) https://en.wikipedia.org/wiki/Cosmic_ray#/media/File:Atmospheric_Collision.svg

Motivation

- stellar collapse:
  99% energy
  released in neutrinos
  → burst modeling
  → detect on Earth

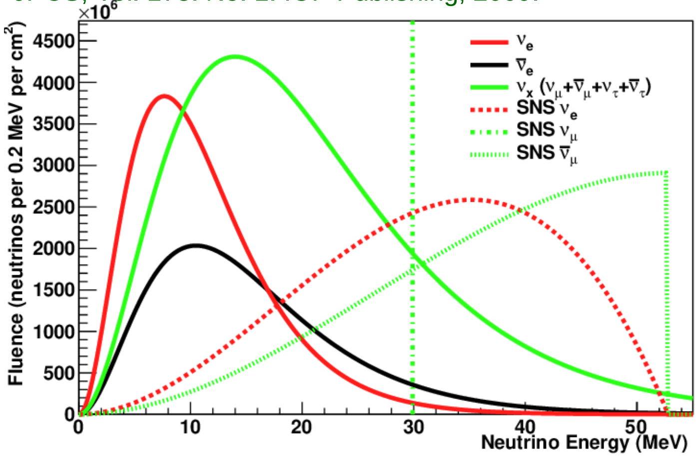


Credit: TeraScale Supernova Initiative

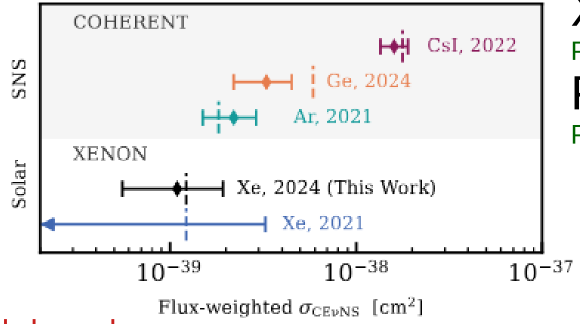


arXiv:2203.05914 [physics.ins-det]

Efremenko, Yu, and William Raphael Hix.
JPCS, Vol. 173. No. 1. IOP Publishing, 2009.



- "neutrino floor/fog" in dark matter experiments: signature like dark matter
  → same detector response



XenonNT 2.7 σ
Phys. Rev. Lett. 133, 191002 (2024)
PandaX 2.6 σ
Phys. Rev. Lett. 133, 191001 (2024)

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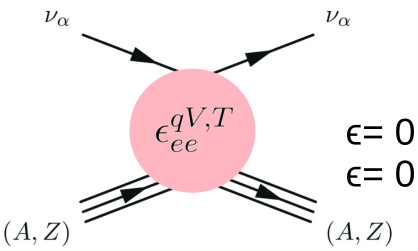
Motivation

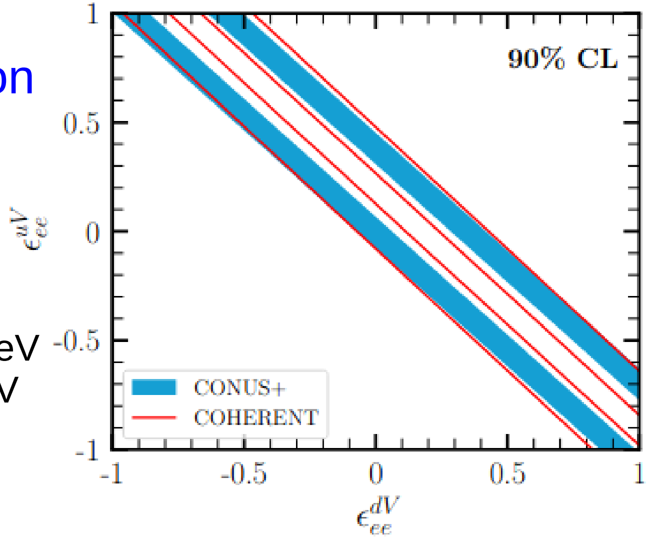
- N^2 behaviour of cross section
- non-standard neutrino interactions (NSI)

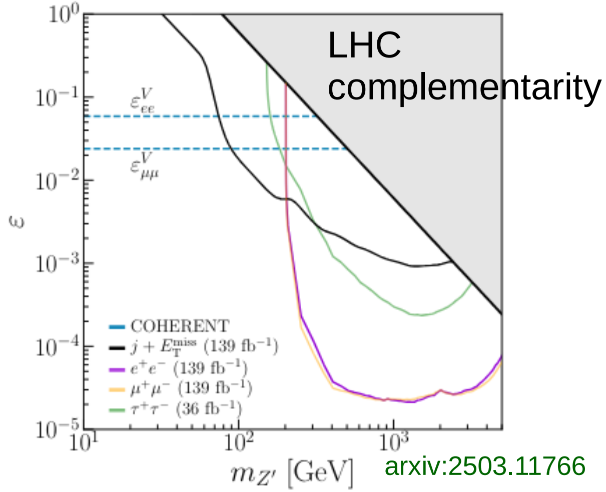


$$\epsilon \approx \frac{g_x^2}{g^2}\frac{M_W^2}{M_x^2}$$

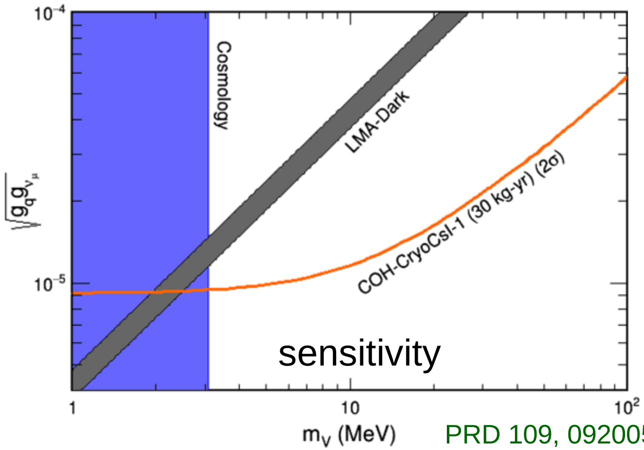
ϵ= 0.01 → 820 GeV
ϵ= 0.001 → 2.6 TeV

arXiv:2501.17843





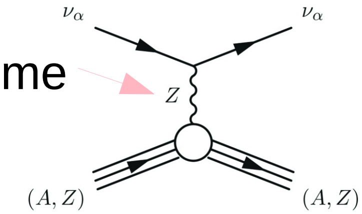
arxiv:2503.11766

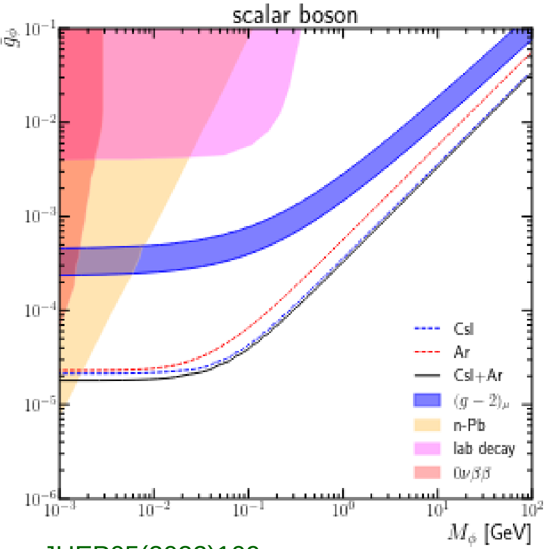


PRD 109, 092005 (2024)

- light scaler or vector mediators:

Z prime





JHEP05(2022)109

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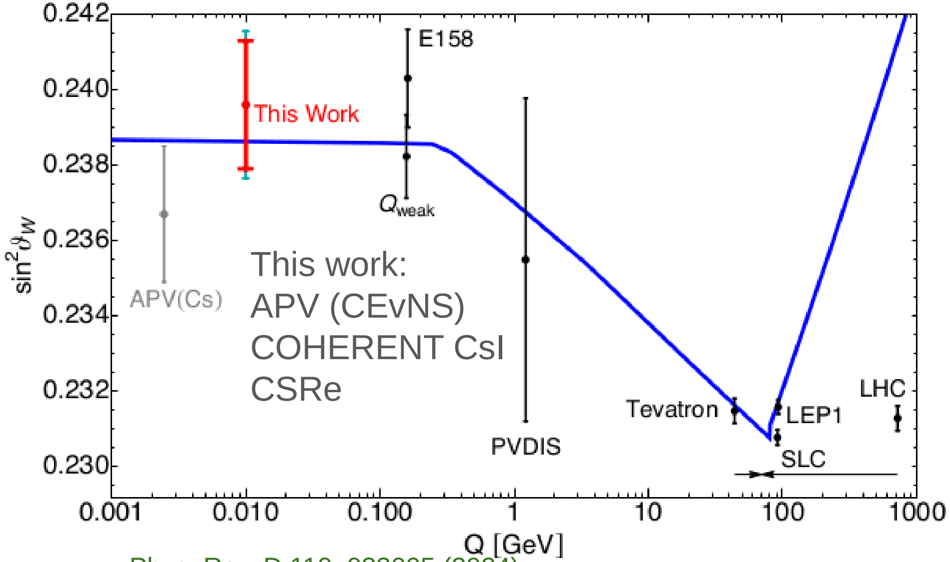
Beyond the standard model

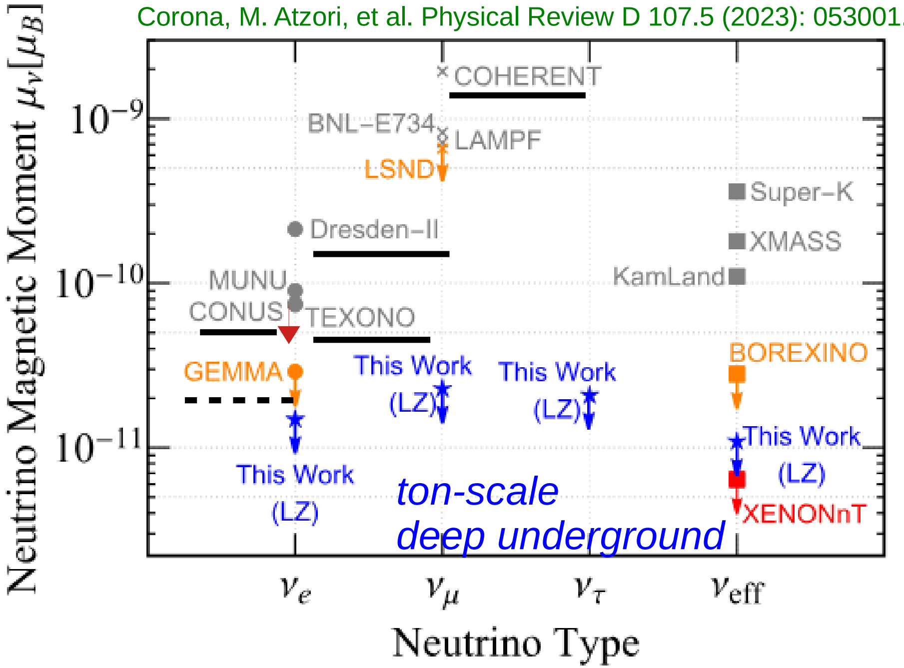
- Weinberg angle at low energies

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



Phys. Rev. D 110, 033005 (2024)

Corona, M. Atzori, et al. Physical Review D 107.5 (2023): 053001.



- magnetic moment and milli charge
- nuclear safeguarding (non-proliferation)

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CEvNS around the world

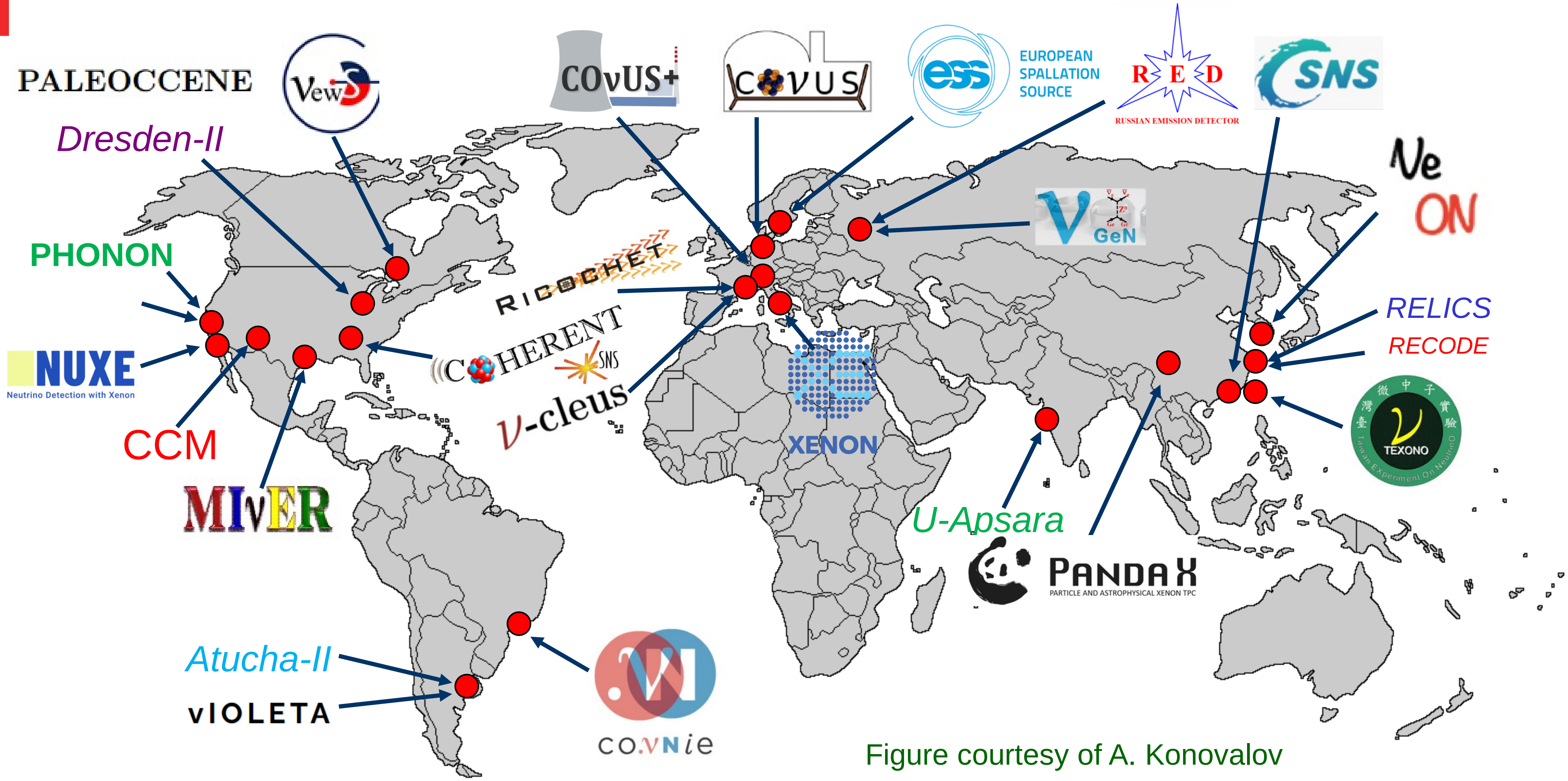

Figure courtesy of A. Konovalov

COHERENT SNS

Oak Ridge National Laboratory
Duke University
TUNL Triangle Universities Nuclear Laboratory
서울대학교 Seoul National University
Los Alamos National Laboratory EST. 1943
Laurentian University Université Laurentienne
岡山大学 Okayama University
NC State University
The University of Tennessee Knoxville
NC Central University
Chinese Academy of Sciences
ICRR Institute for Cosmic Ray Research University of Tokyo
Sandia National Laboratories
Carnegie Mellon University
University of South Dakota
東京大学
Tufts University
Canadian Nuclear Laboratories
Laboratoires Nucléaires Canadiens
UF University of Florida
Kyoto University
University of Hawai'i
Concord University
SLAC National Accelerator Laboratory
Virginia Tech
Washington & Jefferson College
Florida State University 1851
MEPhI

Consortium for Monitoring, Technology, and Verification
NSF
NRF 한국연구재단 National Research Foundation of Korea
NNSA National Nuclear Security Administration
U.S. Department of Energy
Office of Science

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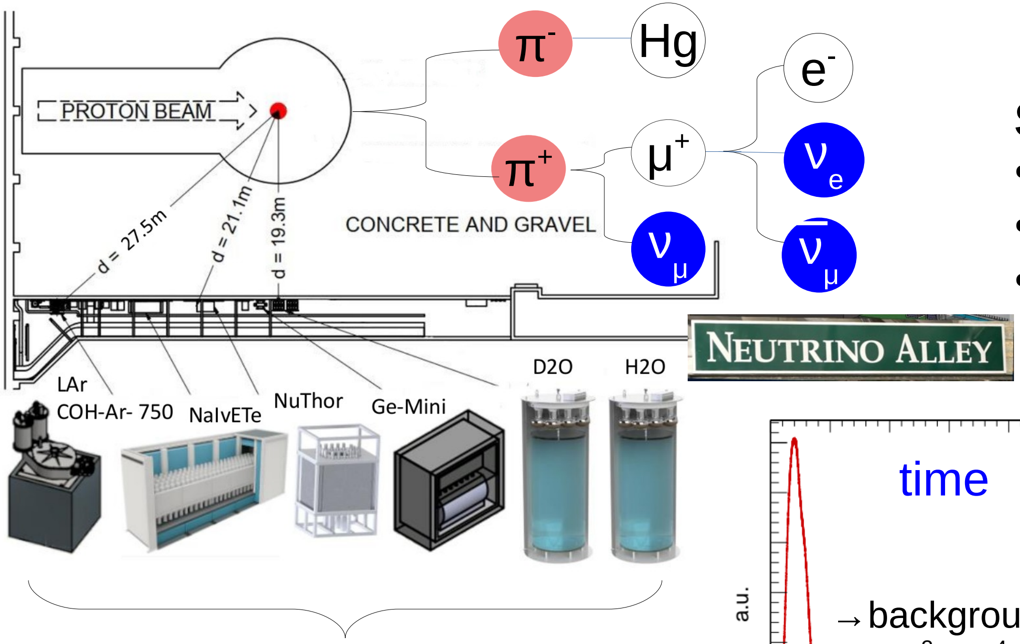
COHERENT experiment

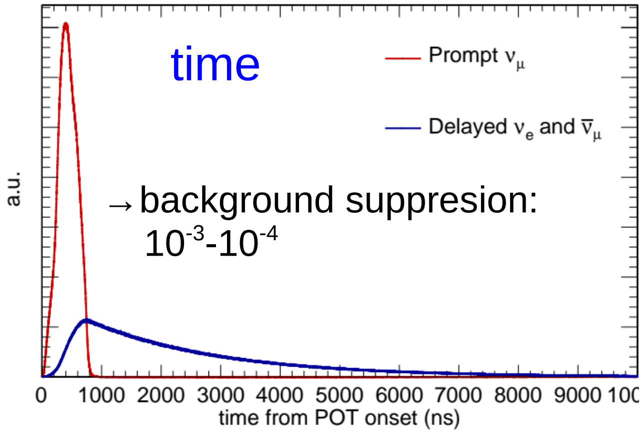


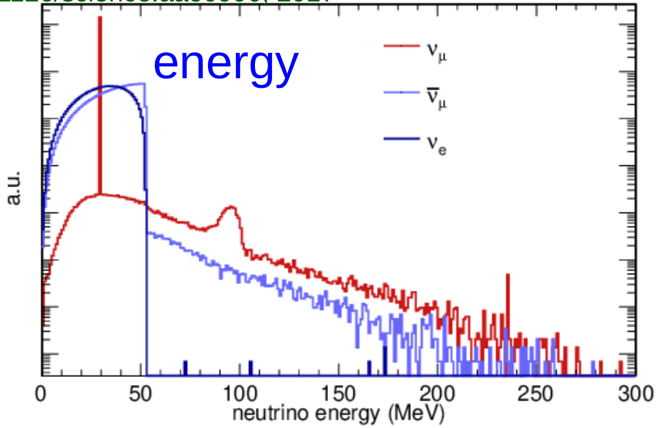
multitude of detector technologies and target materials
→ N^2 dependence of cross section

Spallation neutron source at Oak Ridge, US:

- Pion-decay at rest source
- pulsed beam with 60 Hz
- ~10^{20} protons on target per d, up to 1.7 MeV thermal power

D. Akimov et al., Science 10.1126/science.aao0990, 2017





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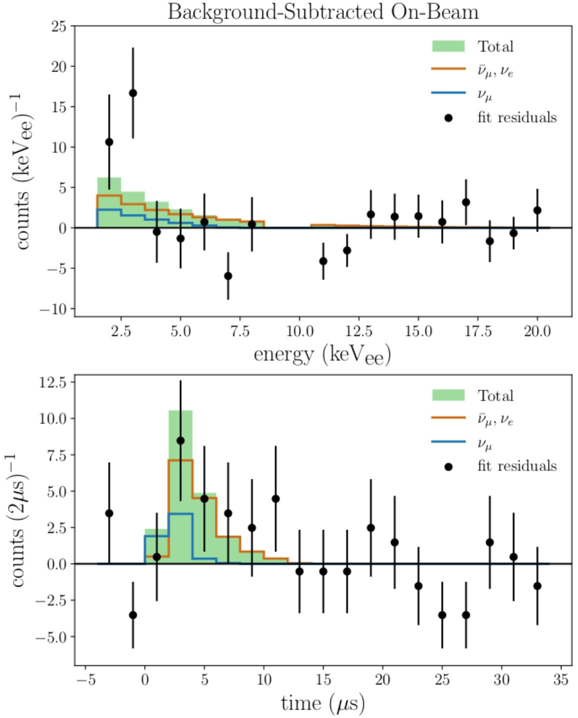
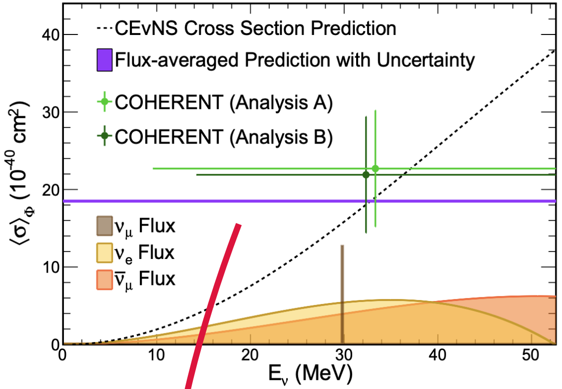
COHERENT

Germanium Ge-Mini - ionization



Adamski, S., et al., arXiv:2406.13806 (2024).

single phase LAr – light



D. Akimov et al. Phys. Rev. Lett. 126, 012002, 2021

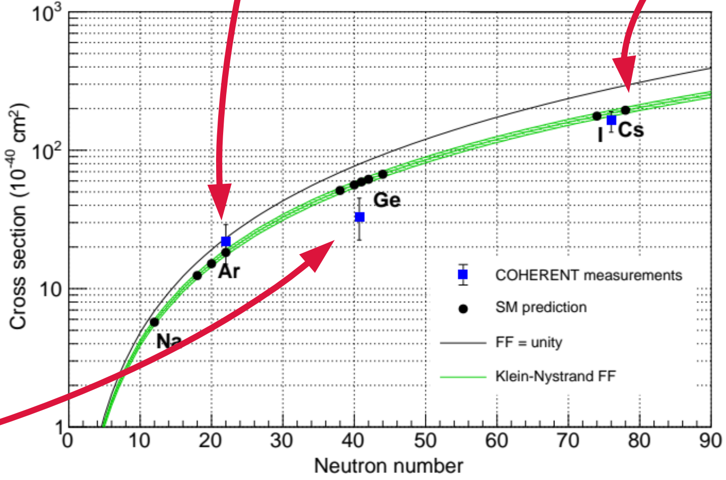
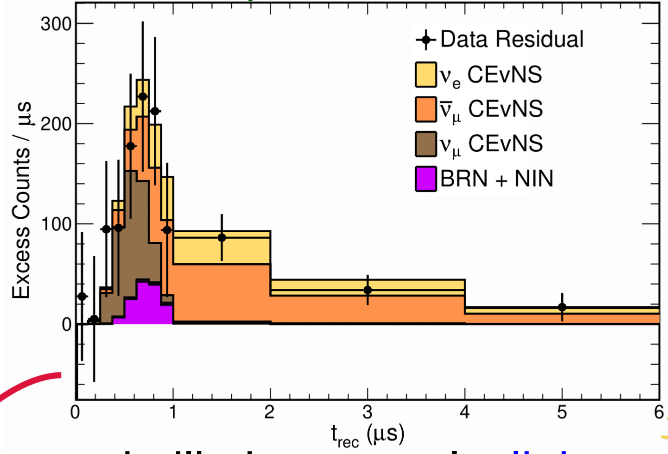


Figure courtesy of K. Scholberg

D. Akimov et al. Phys. Rev. Lett. 129, 081801,2022



scintillating crystals light

COHERENT CsI: **First ever** observation of CEvNS in a detector!

D. Akimov et al., Science 10.1126/science .aao0990, 2017

CsI (final): 11.6 σ

LAr (1st data set): 3.5 σ

Ge (1st data set): 3.9 σ

Towards a precision CEvNS detection

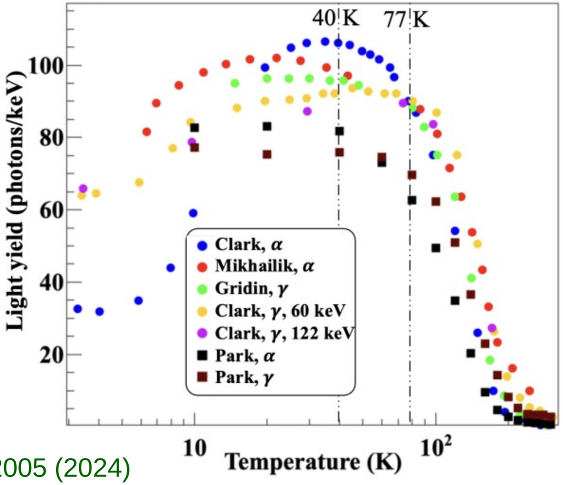
	threshold/ keV_{nr}	mass/kg	Significance
CsI	5	14.6	11.6 σ
LAr	20	24	3.5 σ
Ge	6.7	11.1	3.9 σ

COH-Ar-750

increase fiducial mass:
24 kg → 476 kg
→ ~5000 CEvNS
~500 charged-current
(per SNS year)

CryoCsI

undoped CsI at 40 K
→ 0.5 keV_{nr} in reach

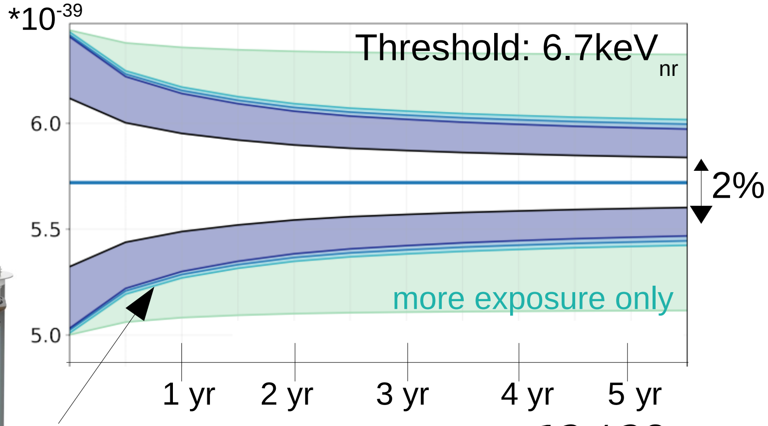


PHYS. REV. D 109, 092005 (2024)

Ge-Mini

- more exposure
- lower threshold in analysis to <2.5 keV_{nr}

D2O



neutrino flux uncertainty reduction

Dr. J. Hakenmüller, Duke University, janina.hakenmuller@duke.edu

CEvNS and beyond

D_2O at neutrino alley:

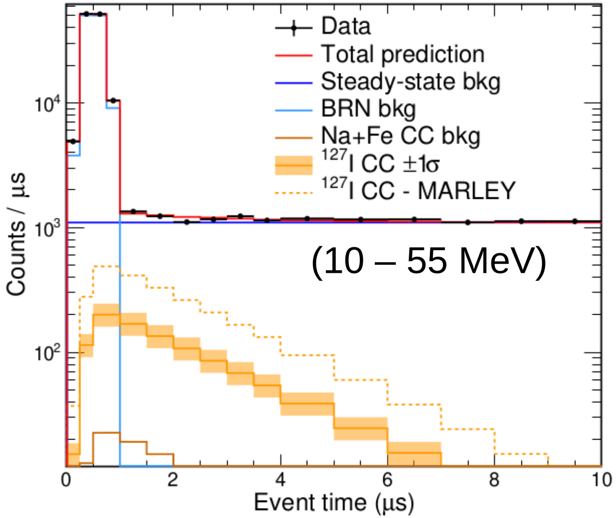
- Cherenkov heavy water: charged-current deuteron scattering → well known cross section
- neutrino flux uncertainty reduction: ~10% → 2-3% (5 SNS years)

Inelastics and charged-current:

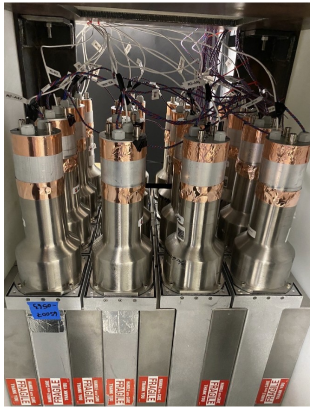
→ region of interest: several MeV and above

- NaIvE, Neutrino Cubes, NuThor, more isotopes and statistics to come!

NaIvE: 5.8σ charged-current on iodine (41% of MARLEY prediction)



P. An, et al., PRL. 131, 221801 (2023)



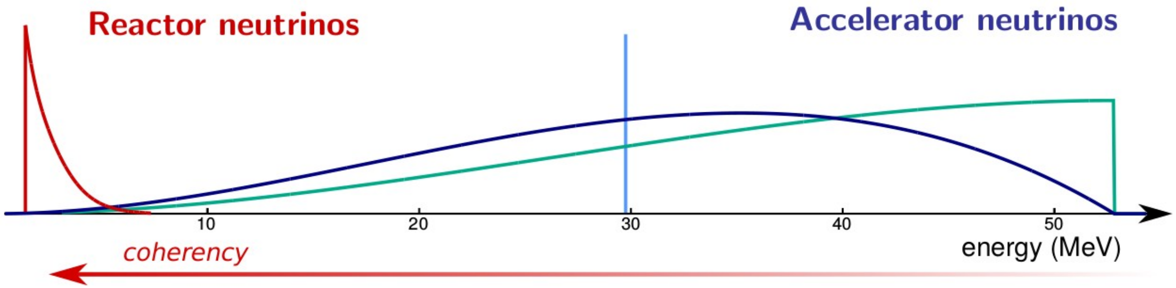
CEvnS on lighter isotopes: Na, Ne

NaIvETe: NaI scintillating crystals → total mass 3.4t, 1.46t deployed (3 modules)

NEON: reuse CENNS-10 cryostat

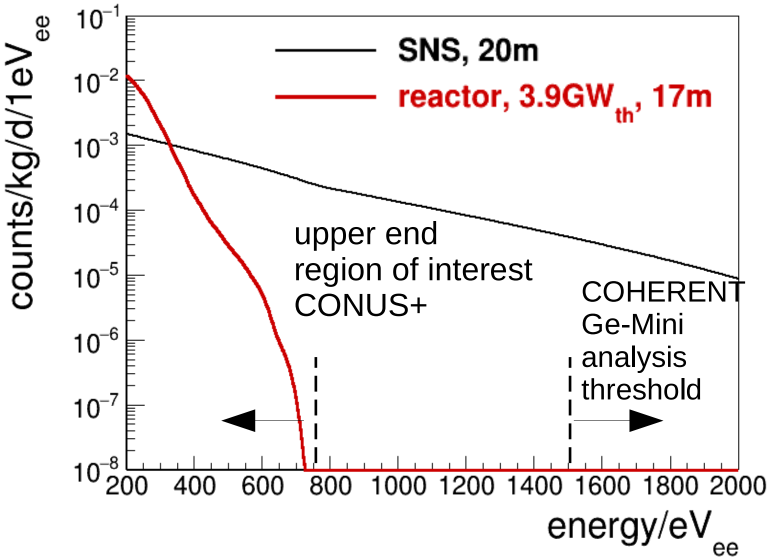
Reactor neutrino experiments

anti electron neutrinos from beta decays



muon, anti muon and electron neutrinos

Figure courtesy of A. Bonhomme



	reactor	SNS
energy	< 12 MeV	10 – 53 MeV
form factor	~1	<1
flux	$O(10^{20})$ per s per GW	$O(10^{15})$ per s (1.4MeV, 1GeV proton energy)
background supression	outages $10^{-2} - 10^{-4}$ (shield)	off-beam $(10^{-2} - 10^{-4})*(10^{-3} - 10^{-4})$ (shield)*(beam-corr.)

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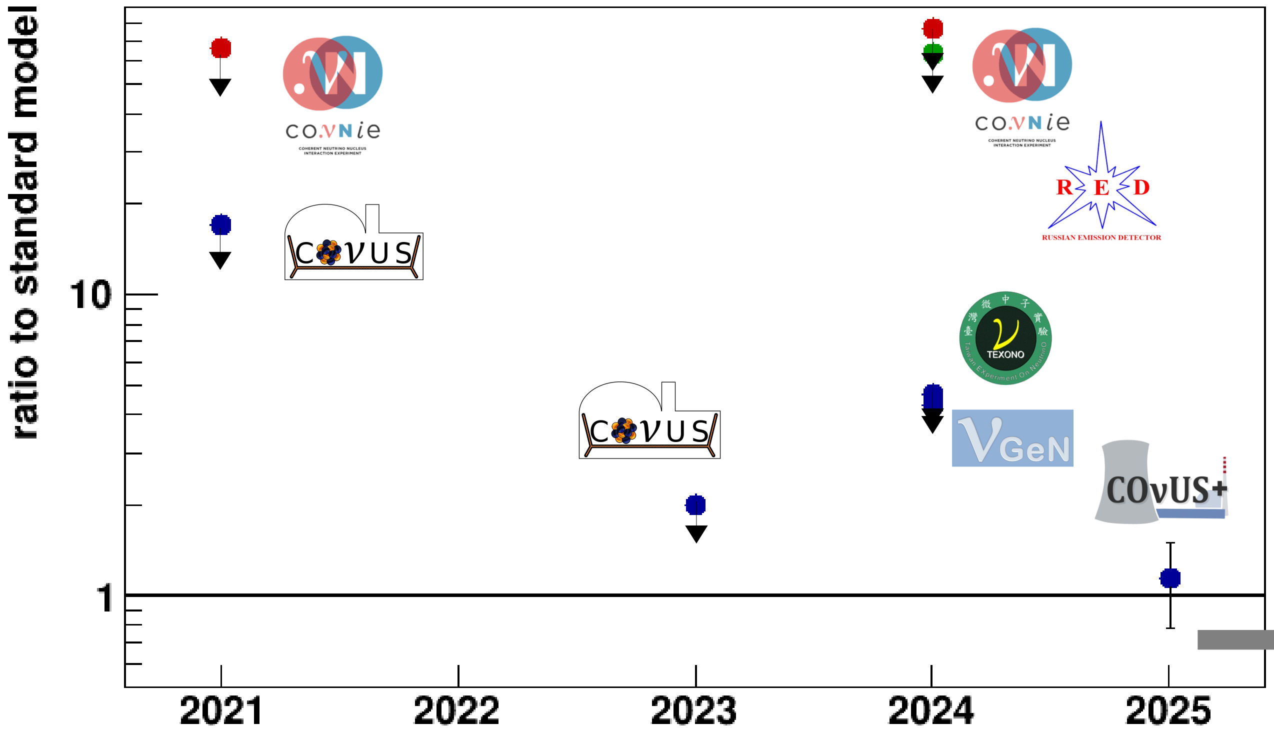
Reactor experiment CEvNS results



Ge HPGe
Si CCDs
Xe two-phase

NUCLEUS
EXPERIMENT
cryogenic bolometers

Atucha-II

RICOCHET

CONUS-100

RECODE/ RELICS

νeON
scintillation light

Dr. J. Hakenmüller, Duke University, janina.hakenmuller@duke.edu

CONUS

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

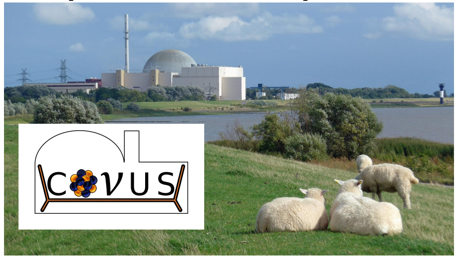
PreussenElektra

KKL Kernkraftwerk Leibstadt

CONUS+

CONUS/CONUS+

Brokdorf reactor KBR (2018-2022):



(*)

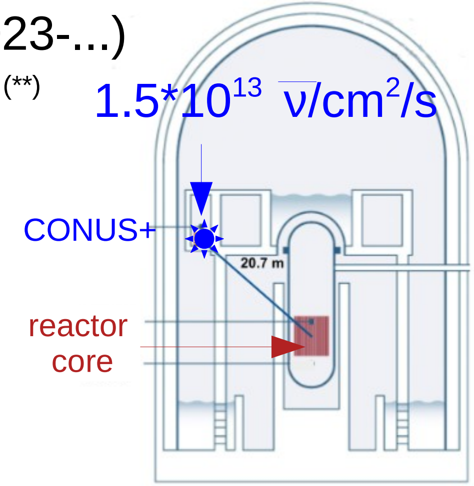
light-water reactor,
max. **3.9 GW, 17** m to core

Leibstadt reactor KKL (2023-...)

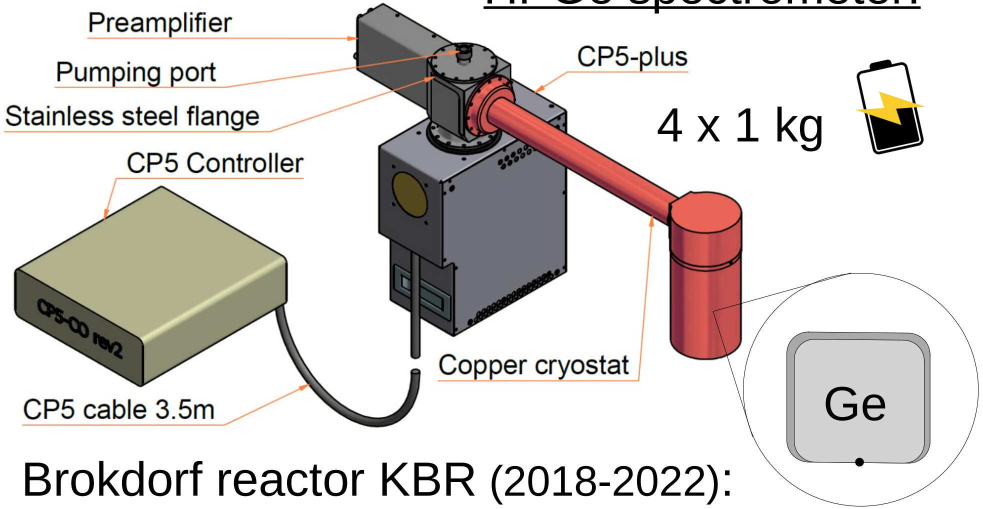
(**)

boiling water reactor,
max. **3.6 GW, 20.7 m** to core

$1.5 \cdot 10^{13}$ $\bar{\nu}/cm^2/s$



HPGe spectrometer:



4 x 1 kg

Brokdorf reactor KBR (2018-2022):

- Pulser resolution: 60-75 eV_{ee}
- Final run: x 2 SM with 210 eV_{ee} threshold

Leibstadt reactor KKL (2023-….):

- detector upgrade

→ pulser resolution: 50 eV_{ee}

→ energy threshold: 160-180 eV_{ee}

(*)https://www.deutschlandfunk.de/vor-dem-aus-umstrittenes-akw-brokdorf-geht-fuer-immer-vom-netz-dlf-eff16a7e-100.html
(**)https://de.wikipedia.org/wiki/Kernkraftwerk_Leibstadt#/media/Datei:AKW_Leibstadt1.jpg

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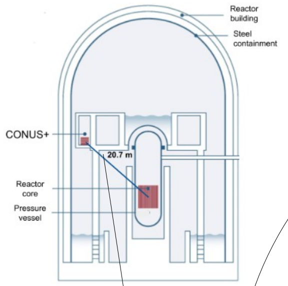
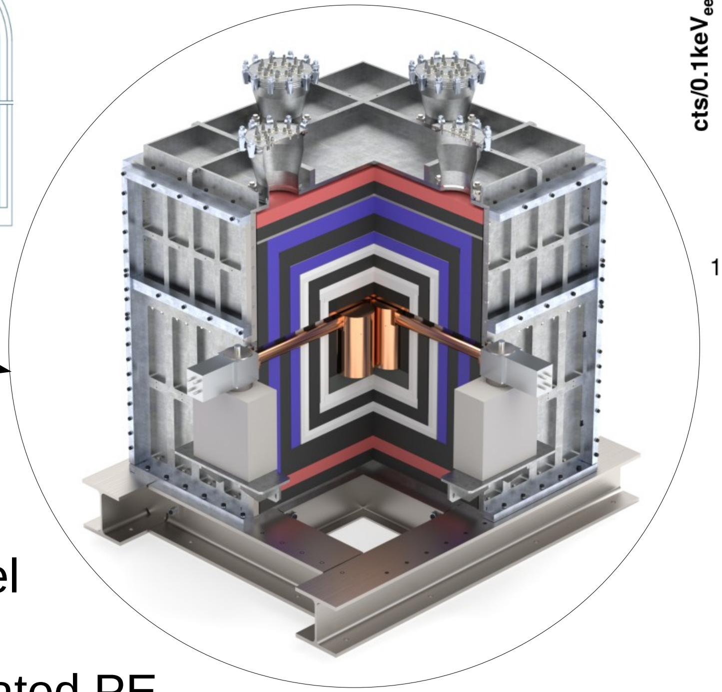
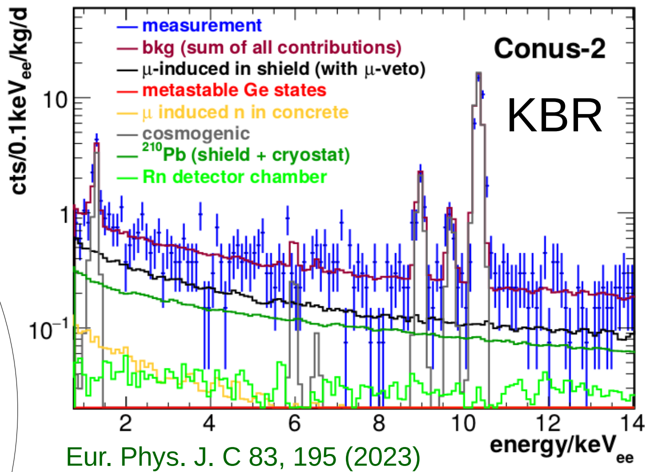
CONUS+ background & shield



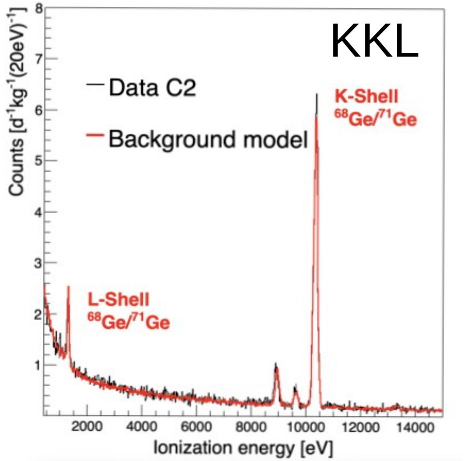


- Pb
- steel
- PE
- borated PE
- plastic scintillator



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

arXiv:2501.05206

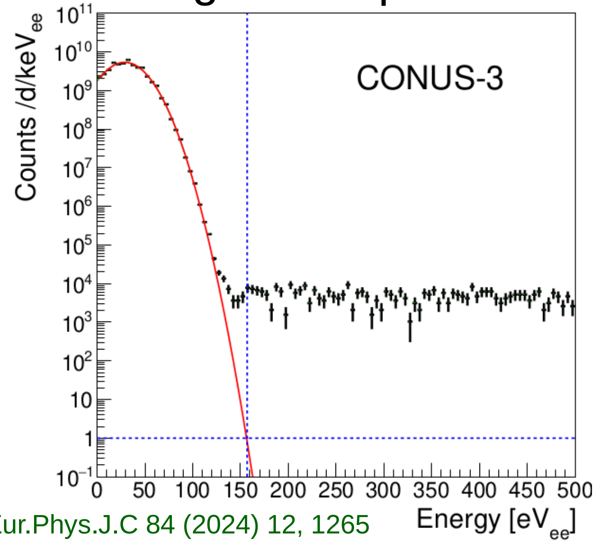


Background model: KKL based on KBR

- cosmic ray induced backgrounds: ~70-95%
- radioactive material contaminations, airborne radon
- reactor-correlated background negligible (dedicated measurement campaign arXiv:2412.13707)

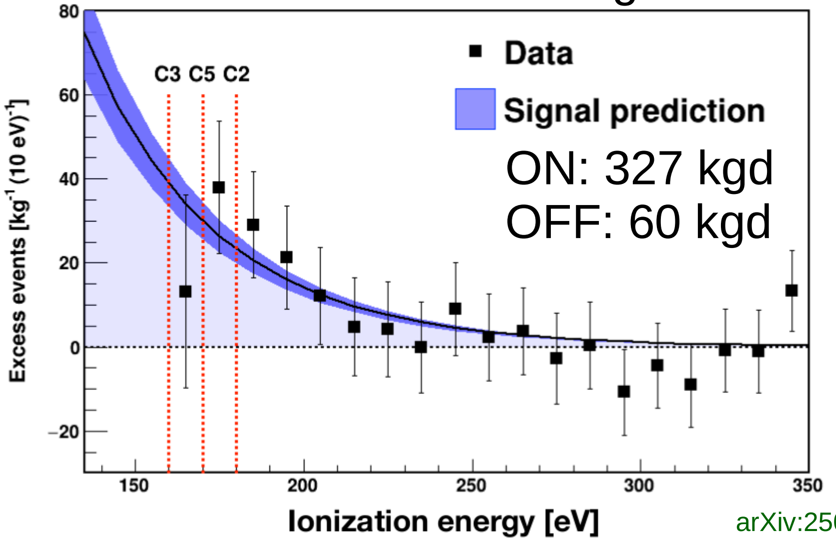
First detection of CEvNS at reactor site

Background spectrum



Eur.Phys.J.C 84 (2024) 12, 1265

after subtraction of background model



arXiv:2501.05206

Nov 2023: start reactor ON, May 2024: first reactor OFF
Total active mass: (2.83+-0.02) kg
Signal events data: **395+-106**
Signal predicted: 347+-59

ratio: 1.14+-0.36

3.7 σ significance!

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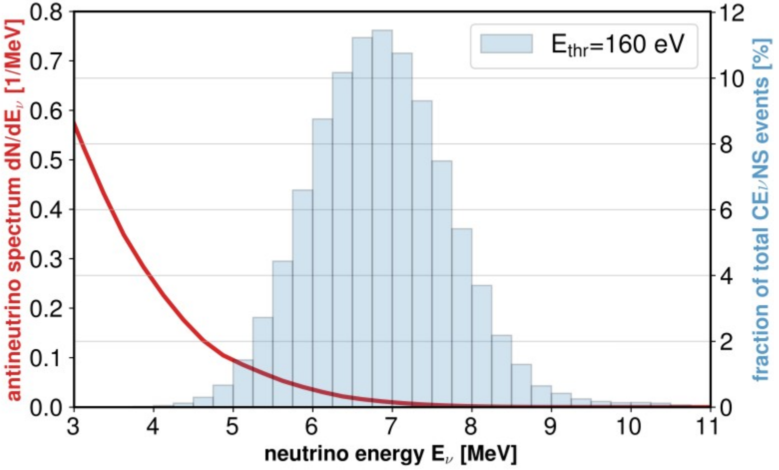
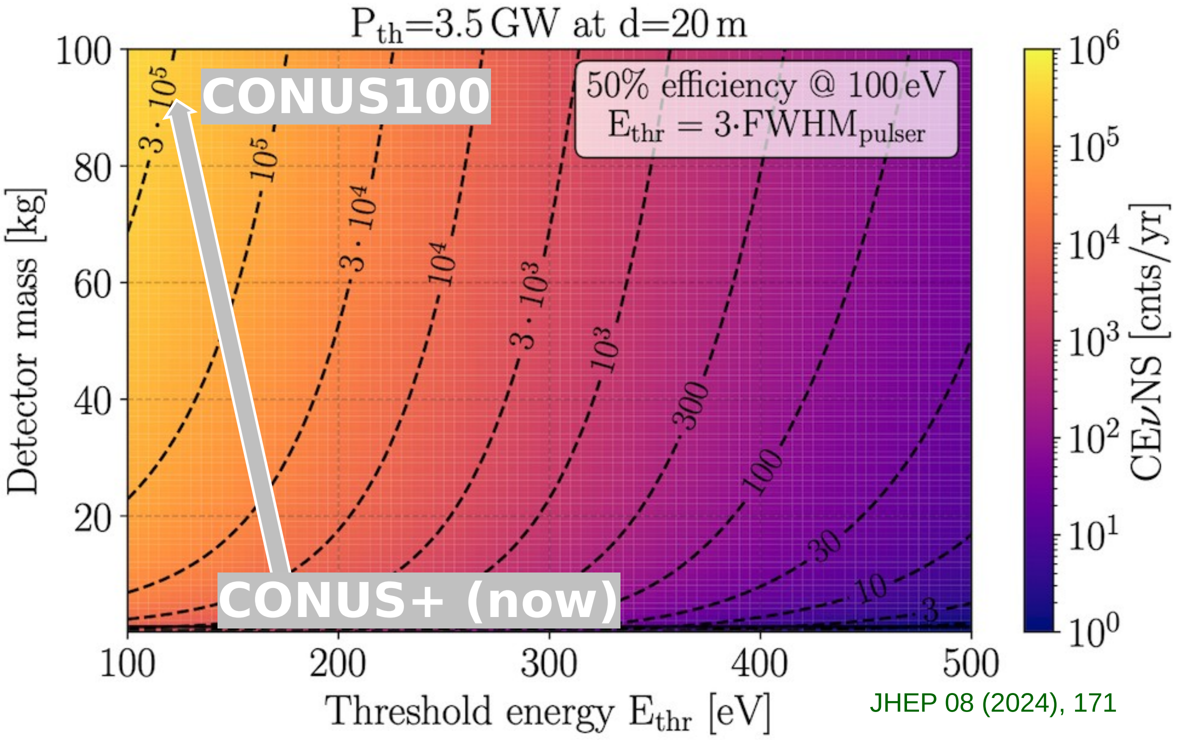
Towards a precision CEvNS detection

Get all the neutrinos!

arXiv:2501.05206





JHEP 08 (2024), 171

- more exposure already collected
- more mass with inverted coaxial detectors (2.4 kg), detector swap Nov. 2024

much more mass → CONUS100

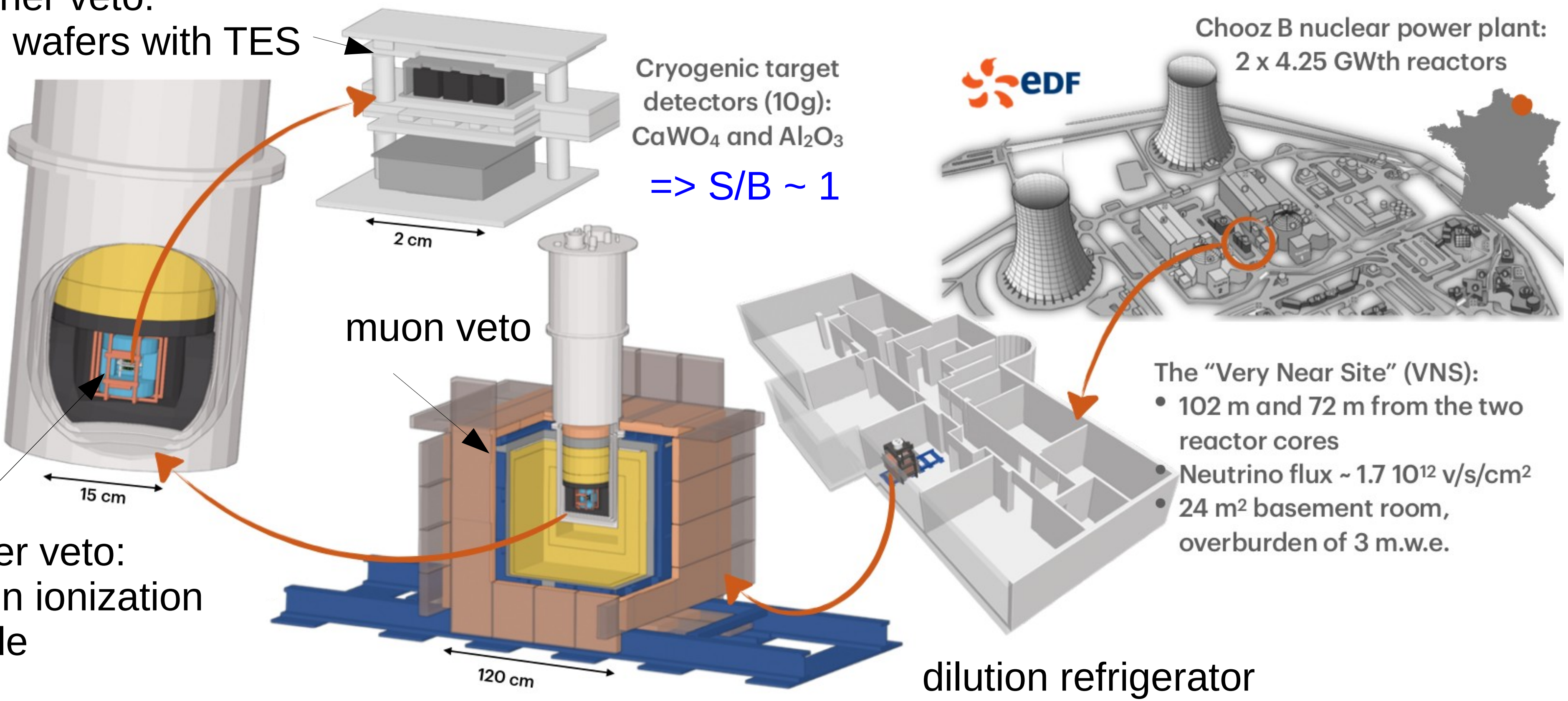
nucleus
EXPERIMENT

Munich, April 2024

NUCLEUS

Adapted from E. Bossio, Magnificent CEvNS workshop Valencia, https://indico.global/event/6083/timetable/#20240612.detailed

Inner veto:
Si wafers with TES



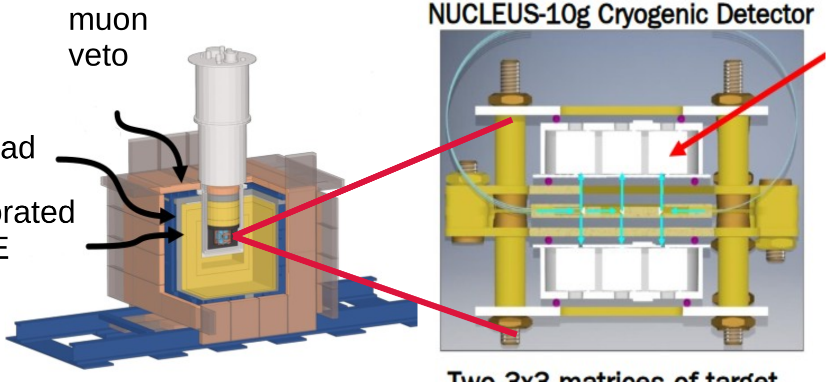
=> S/B ~ 1

muon veto

Outer veto:
Ge in ionization mode

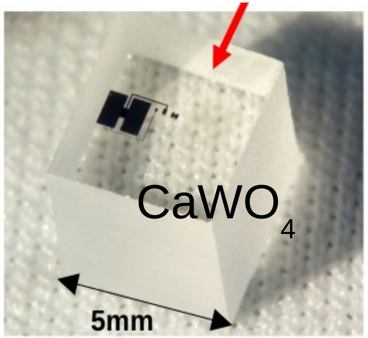
dilution refrigerator
at <7 mK temperatures

NUCLEUS



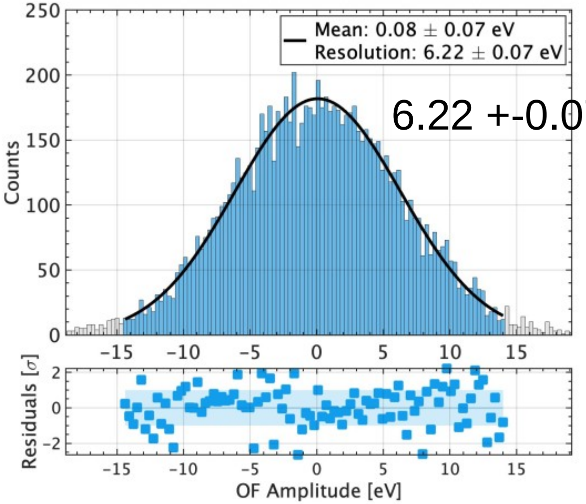
Two 3x3 matrices of target detectors

Transition-edge sensor (TES)



+ squid readout

Baseline resolution at TU Munich:



2501.04471 [physics.ins-det]

https://indico.global/event/1271/contributions/26671/

Target energy threshold: O(10 eV_{nr}) with gram-scale mass

→ lowest target threshold of all CEvNS experiments with no quenching loss

→ understanding of low energy heat channel excess in progress

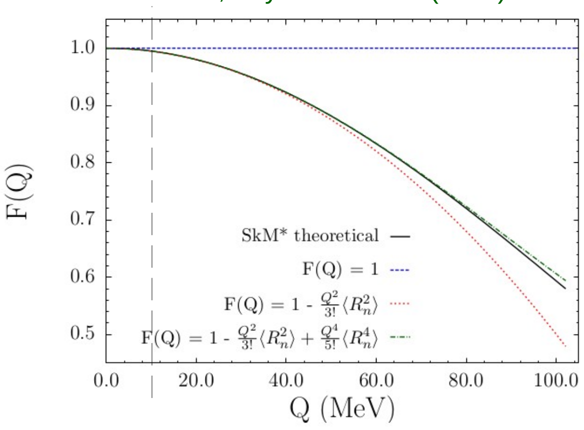
Status: commissioning at TU Munich and at reactor site

physics data taking end of this year → longterm scale to 10 kg

Summary

form factor effects

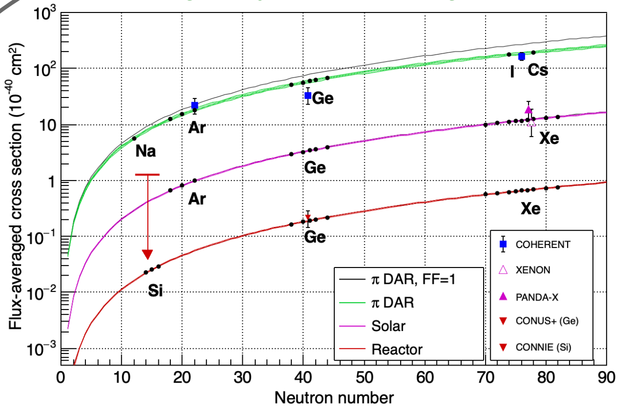
K. Patton et al., Phys. Rev. C 86 (2012) 0246

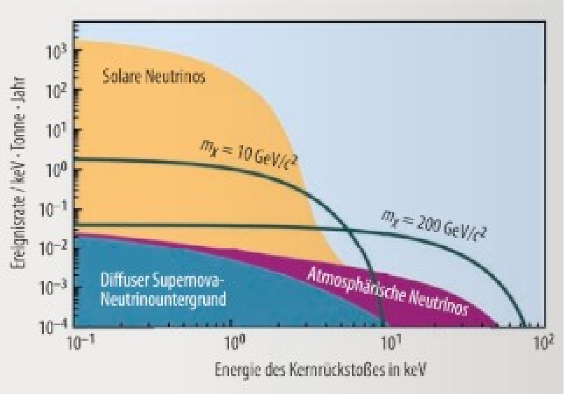


kg-mass detectors

spallation source (SNS)

Figure by Kate Scholberg





Physik Journal 2024/03

reactor

kg-mass detectors

N^2 dependence

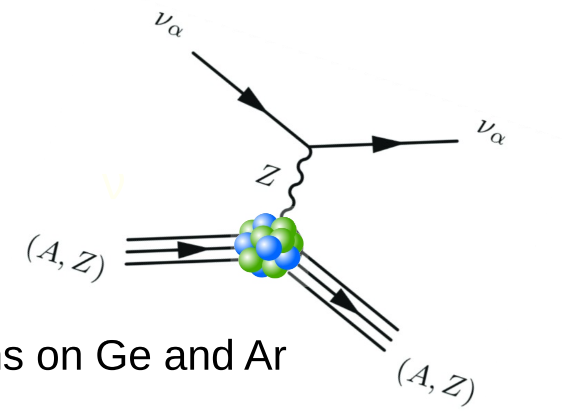
solar

ton-scale detectors

(almost) fully coherent

Dr. J. Hakenmüller, Duke University, janina.hakenmuller@duke.edu

Summary and outlook



CEvNS=neutrino interacts with the nucleus as a whole, N2 enhancement

- first observation 2017 at SNS on CsI by **COHERENT**, two more detections on Ge and Ar
  → more exposure, more mass, lower thresholds, lighter isotopes
- at lower energies at reactor: first detection in 2024 by **CONUS+** with HPGE
  → more exposure, more mass
- at very low energies: **NUCLEUS** aiming at 10 eV threshold with cryogenic bolometers
  → currently commissioning at reactor site

=> from **O(10 - 100) CEvNS** events to **O(10 000)** and more CEvNS events!

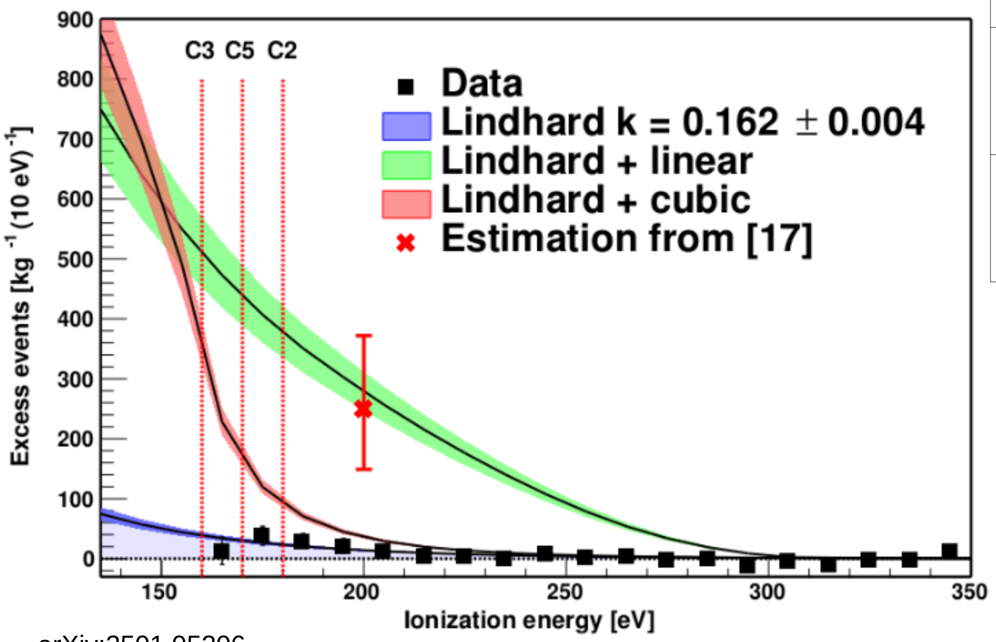
=> A precision detection of CEvNS in the few percent level is in reach!
Lots of interesting physics: supernova, neutrino fog/floor, nuclear form factor, Weinberg angle, NSI, light mediators, magnetic moment,….

ν ν ν ν ν ν Thank you for your attention! ν ν ν ν ν ν ν ν ν ν ν ν

BACK UP

Dr. J. Hakenmüller, Duke University, janina.hakenmuller@duke.edu

First detection of CEvNS at reactor site



arXiv:2501.05206

	Threshold	Bkg/$d^{-1}kg^{-1}keV^{-1}$
CONUS+	160-180 eV_{ee} (>90% trigg. efficiency)	ON: ~70-80 OFF: ~60-75
Dresden-II	200 eV_{ee} (0% trigg. efficiency)	ON: ~2000 OFF: ~500

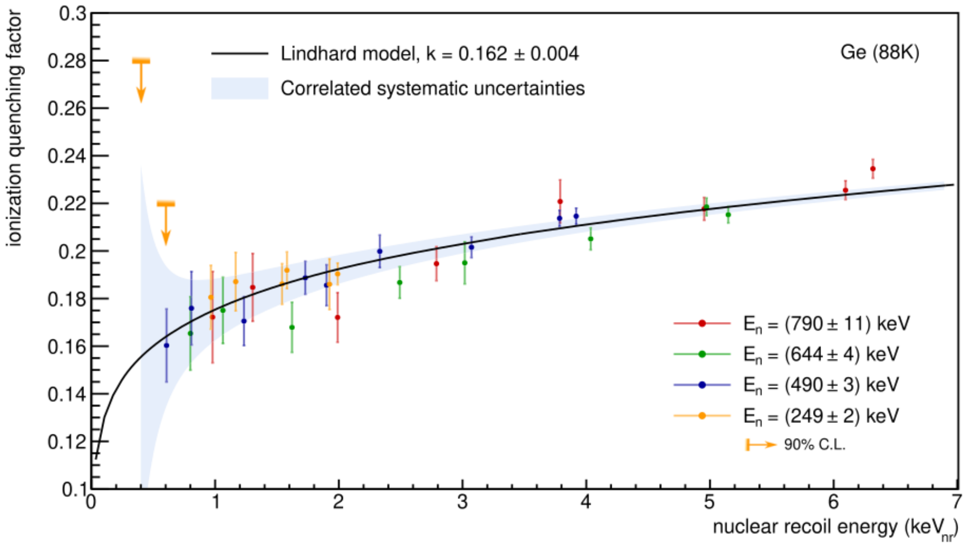
KKL Run-1 uncertainties:

Prediction uncertainties	
Uncertainty	Contribution
Energy threshold	14.1%
Quenching Ge	7.3%
Reactor neutrino flux	4.6%
Cross-section	3.2%
Active mass Ge	1.1%
Trigger efficiency	0.7%
All combined	17%

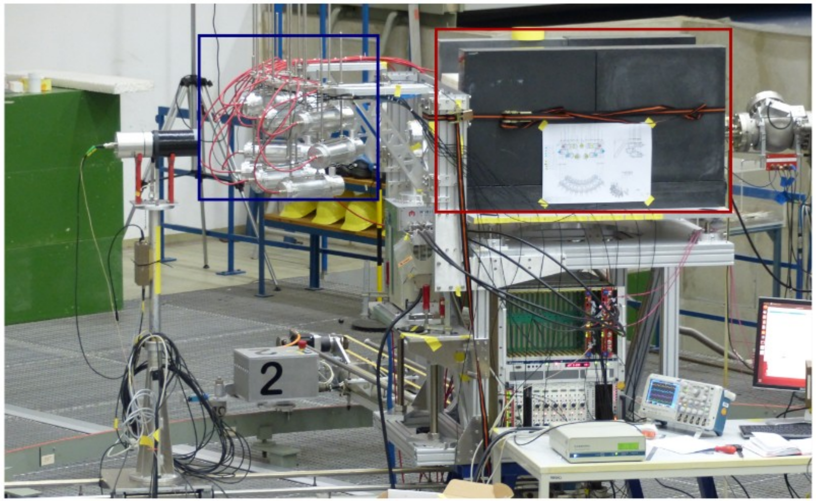
→ Cf source calibration

→ strong tension to claim of CEvNS detection at Dresden-II reactor

Quenching



A. Bonhomme et al, EPJC, 82(9):815, 2022



coincidence detector

6mm thick
Ge crystal