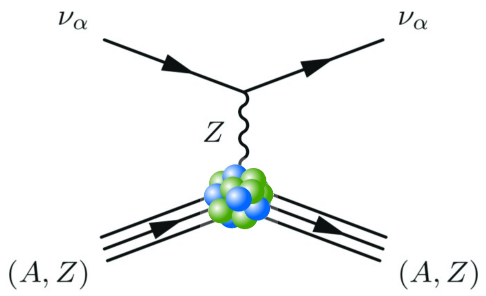


Overview on neutrino detection with CEvNS

Janina Hakenmüller

MARIETTA BLAU INSTITUTE FOR PARTICLE PHYSICS

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN
INSTITUT FÜR HOCHENERGIEPHYSIK

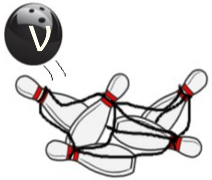
NNN2025, Sudbury, Ontario, Canada, 2nd of October, 2025

Coherent elastic neutrino nucleus scattering (CEνNS)

no coherence

Strike guaranteed!

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

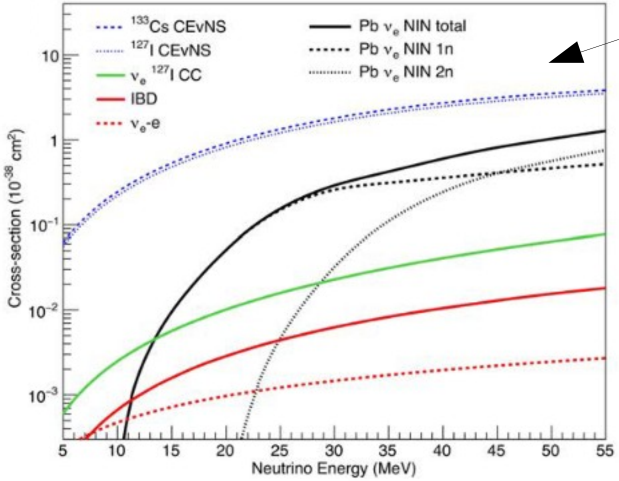
$$\frac{d\sigma}{d\Omega} = \frac{G_f^2}{16\pi^2}(N - (1 - 4\sin^2\theta_W)Z)^2 E_\nu^2 (1 + \cos\,\theta) F(Q^2)$$

neutrino energy

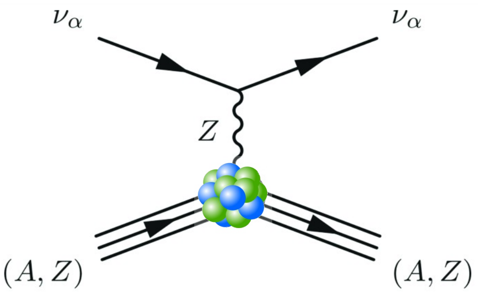
nucleus

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

CEvNS

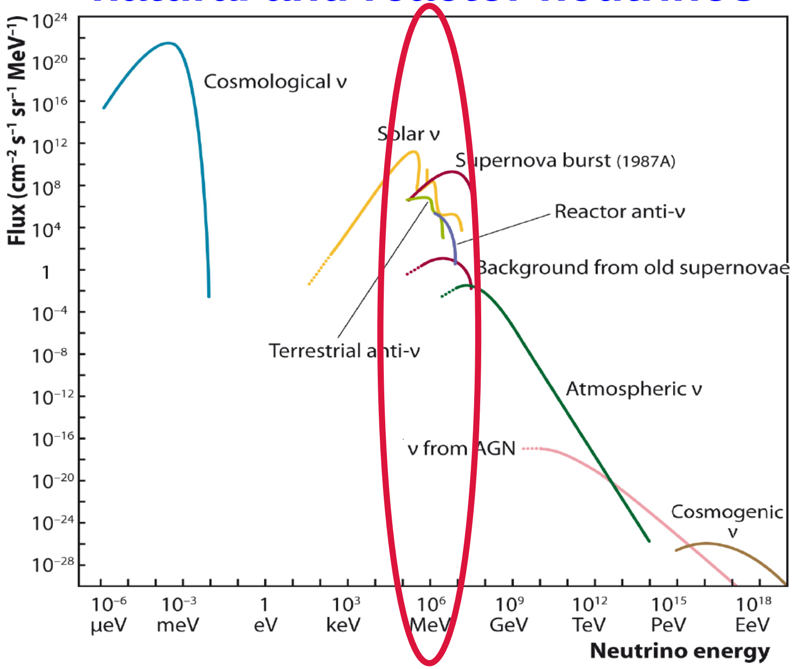


D. Akimov et al., Science 10.1126/science.aao0990, 2017



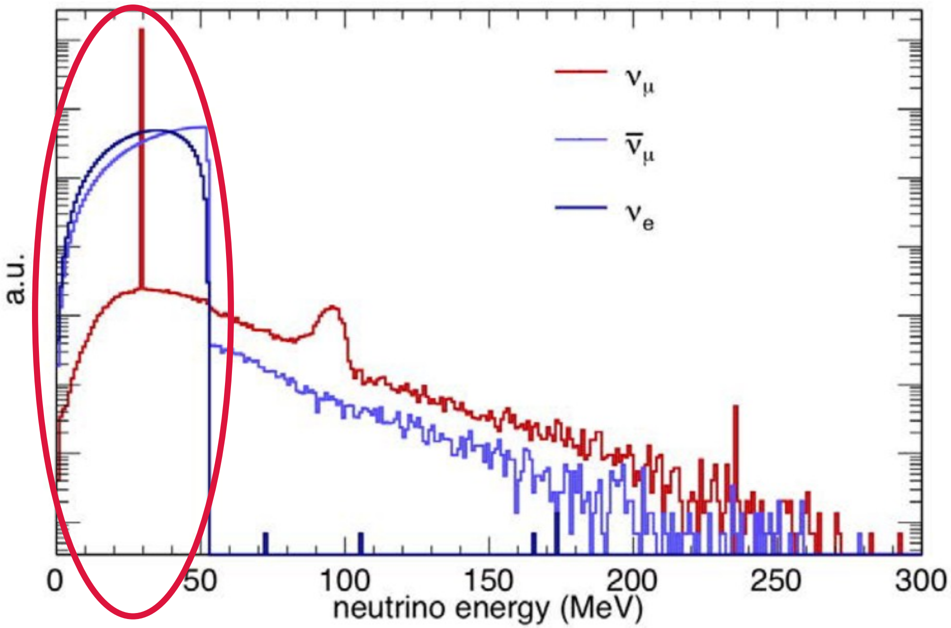
Neutrino sources for CEvNS

natural and reactor neutrinos



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

accelerator neutrinos

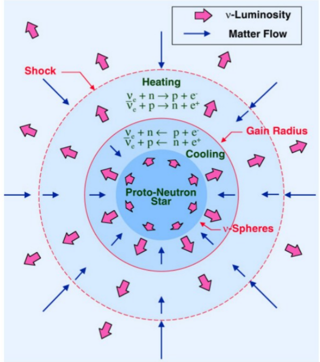


D. Akimov et al., Science 10.1126/science.aao0990, 2017

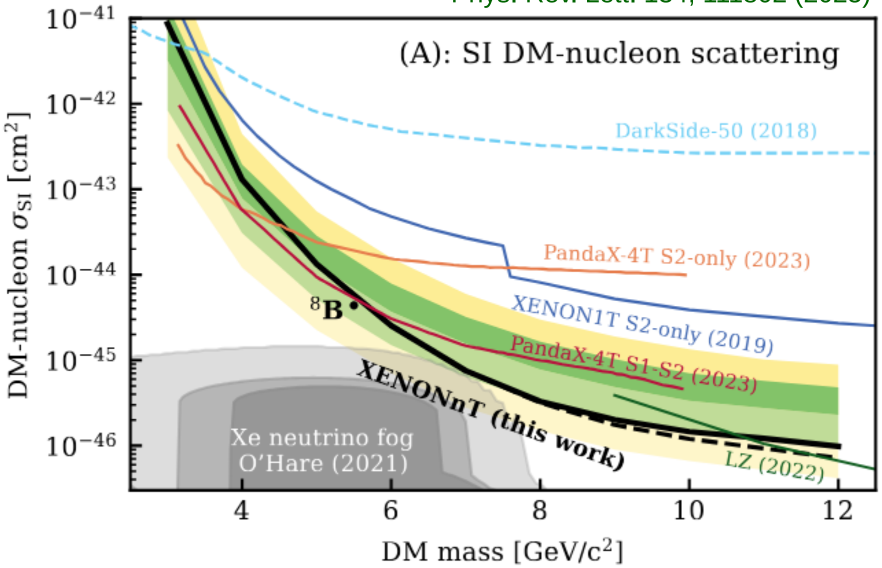
radioactive decay, solar neutrinos, nuclear reactor, supernovea, spallation source

Motivation

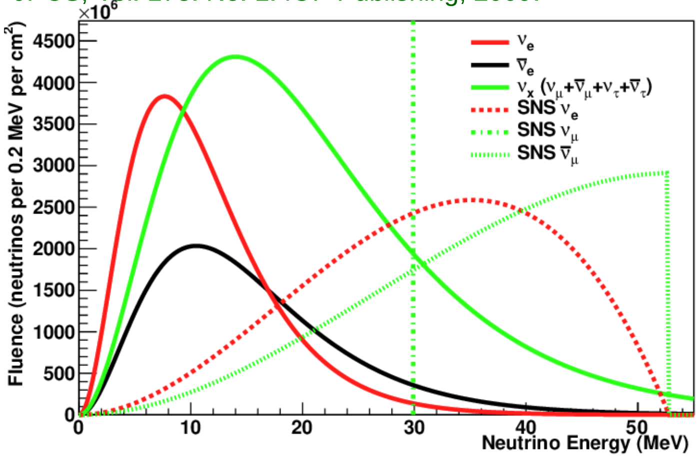
- stellar collapse:
  99% energy
  released in neutrinos
  → burst modeling
  → detect on Earth



Credit: TeraScale Supernova Initiative



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



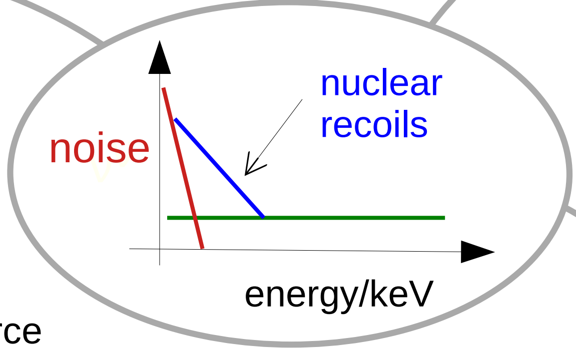
- "neutrino floor/fog" in dark matter experiments: signature like dark matter
  → same detector response
- nuclear safeguarding (non-proliferation), studies of the reactor spectrum below IBD threshold
- direct determination of neutron form factor

- Precision standard model test: N^2 behaviour of cross section, BSM physics

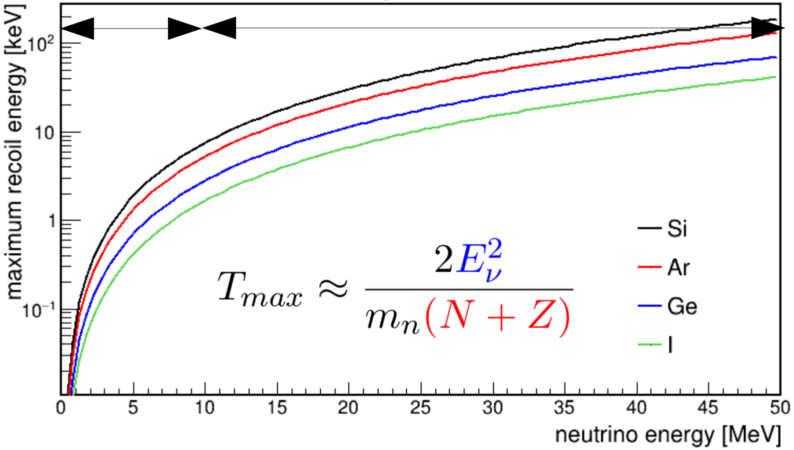
How to detect CEvNS

Detectors

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

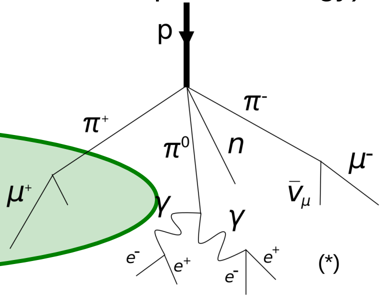


reactor spallation source



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

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

types of recoil energy depositions

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

CEvNS around the world

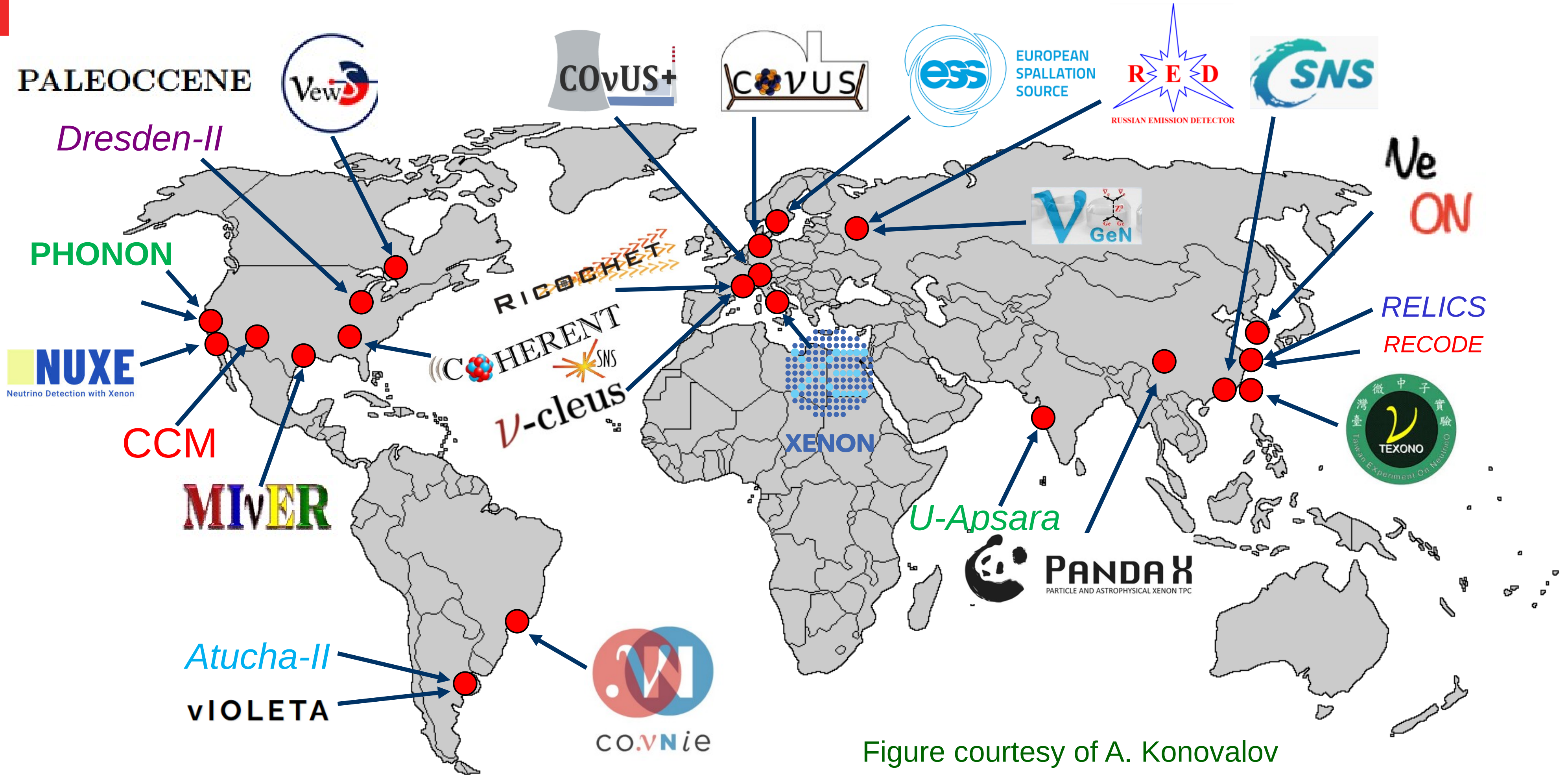
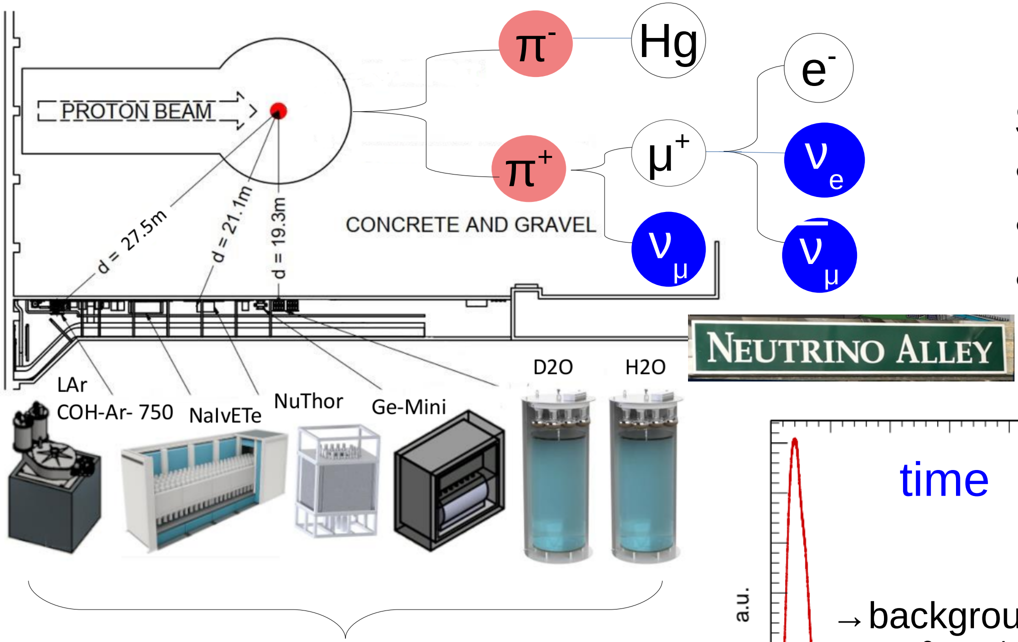


Figure courtesy of A. Konovalov

COHERENT experiment



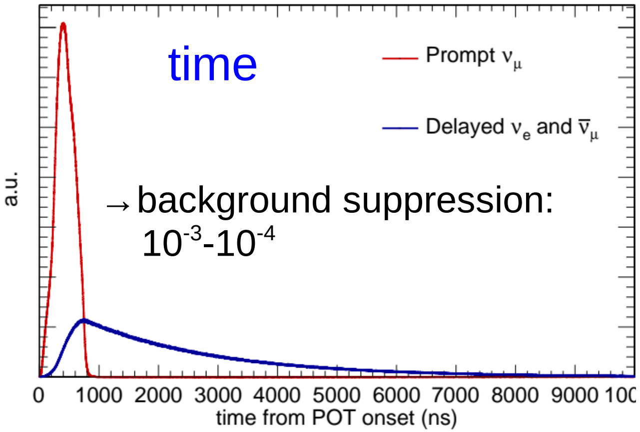
Spallation neutron source at Oak Ridge, US:

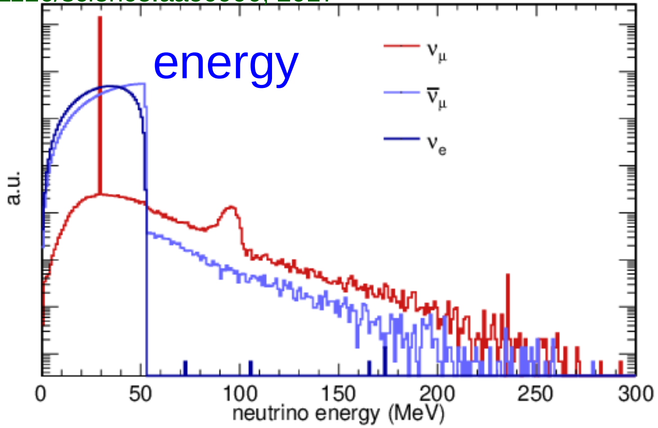
- Pion-decay at rest source
- pulsed beam with 60 Hz
- $\sim 10^{20}$ protons on target per d, up to 1.8 MeV beam power

multitude of detector technologies and target materials

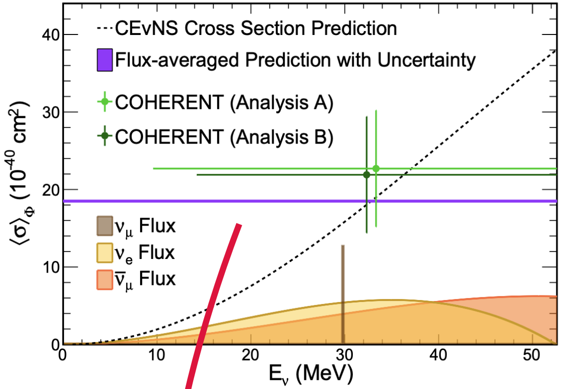
→ N^2 dependence of cross section

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

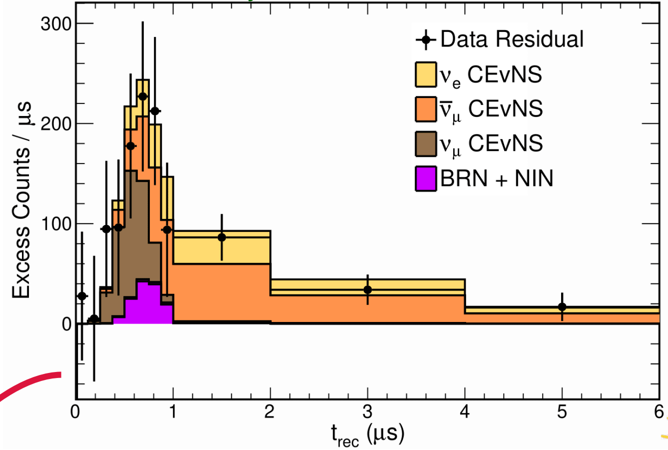




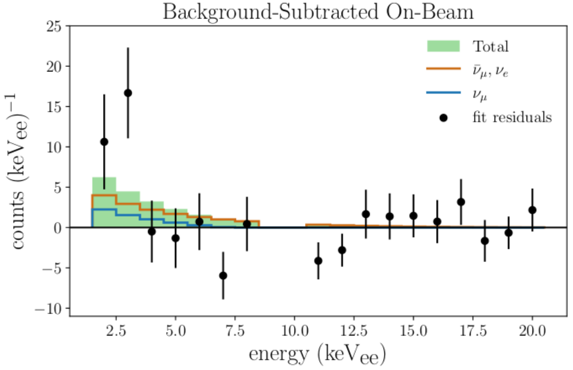
single phase LAr – light

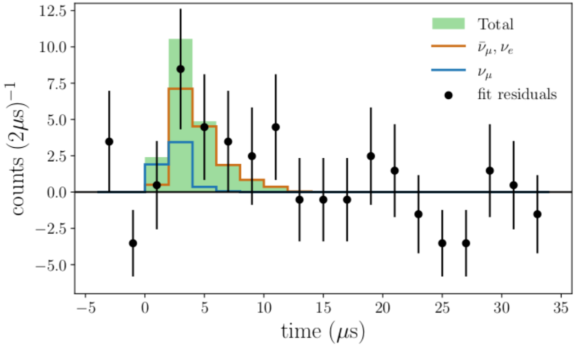


D. Akimov et al. Phys. Rev. Lett. 129, 081801,2022



Germanium Ge-Mini - ionization





Adamski, S., et al., Phys. Rev. Lett. 134, 231801

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

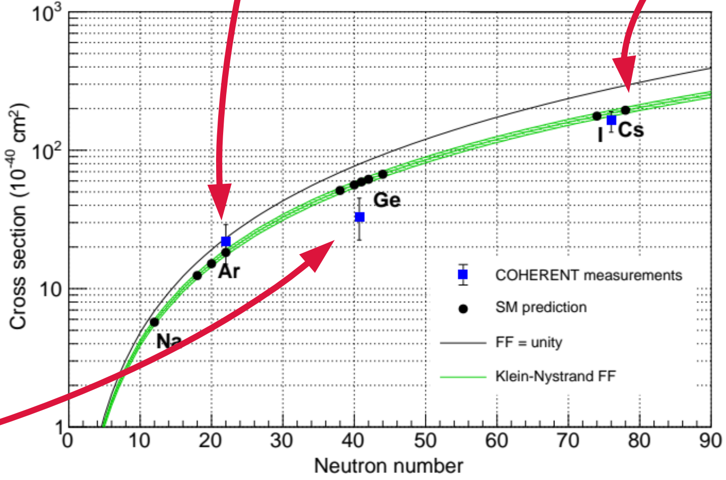


Figure courtesy of K. Scholberg

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

Future CEvNS

more mass

LAr

CENNS-10: 24 kg
3x more exposure
→ O(500 CEvNS)
CENNS-750: ~476 kg
→ O(5000 CEvNS), 500 charged-current

lower threshold

Ge-Mini

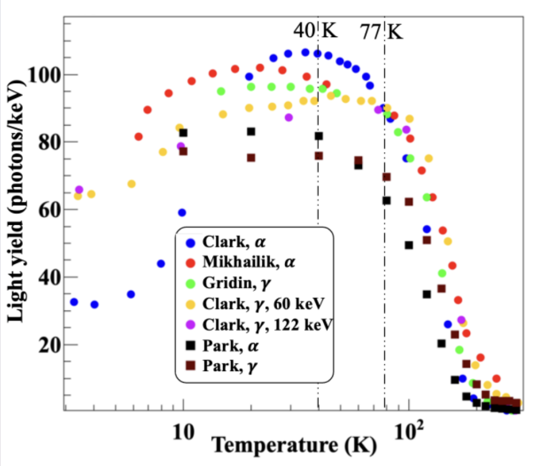
more exposure:
10.22 GWhkg → ~24 GWhkg
lower analysis threshold:
1.5 keV_{ee} → 0.5 keV_{ee}
(ML noise identification, timing reco)
PSD: Signal/background > 1

~120 neutrinos expected (>3x more to Campaign-2)
→ stay tuned!

lighter isotope:
Na, Ne

NaI

NaI scintillating crystals
NaIvE: charged-current on I
P. An, et al., PRL. 131, 221801 (2023)
NaIvETe: total mass 3.4t
(4 of 7 modules deployed)

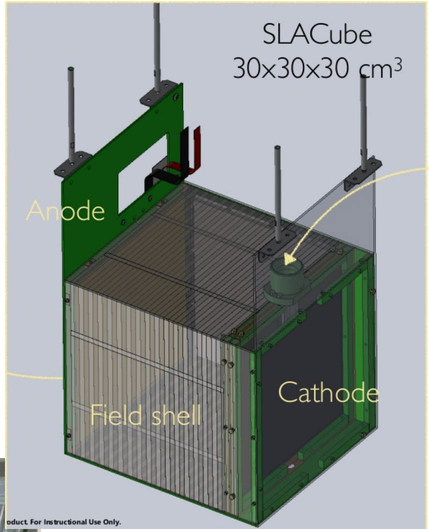


PHYS. REV. D 109, 092005 (2024)

CryoCsI

CsI threshold: 5 keV_{nr}
undoped CsI
at 40 K
→ 0.5 keV_{nr} in reach

Beyond CEvNS



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)

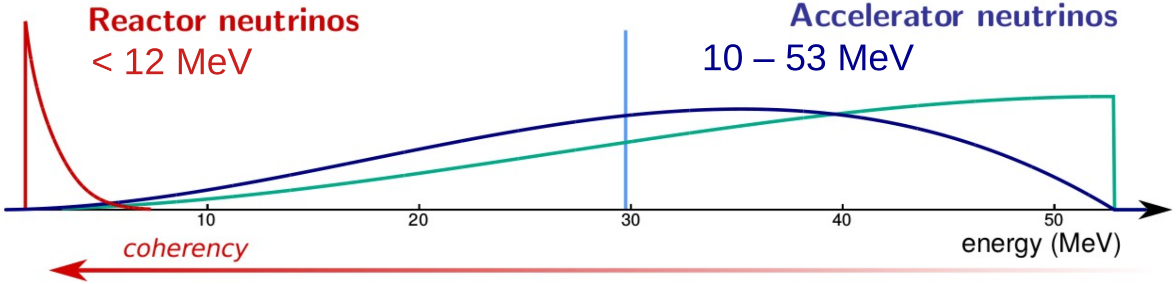
More physics:

- Charged-current interactions on I, Ar, O,...
- Nubes: Neutrino-induced neutrons on Pb
  P. An et al., Phys. Rev. D 108, 072001
- NuThor: neutrino-induced fission:
- Dark matter (SNS target = beam dump)
  D. Akimov et al .Phys. Rev. D 106 (2022), 052004 202
  D. Akimov et al. Phys.Rev.Lett. 130 (2023) 5, 051803
- Pixilated LAr TPC
- ...

+ beam power upgrade FTS to 2MeV ultimately, second target station

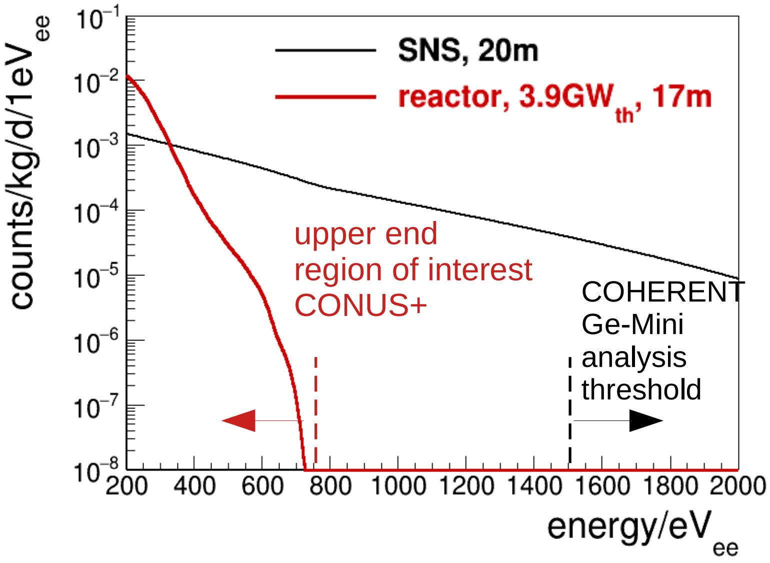
Reactor neutrino experiments

anti electron neutrinos from beta decays



muon, anti muon and electron neutrinos

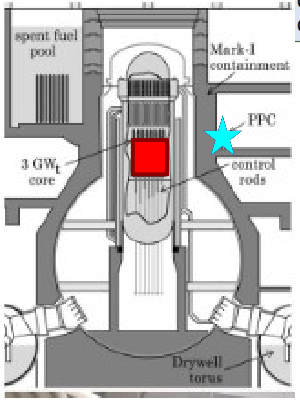
Figure courtesy of A. Bonhomme



	reactor	SNS
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) → bkg model	off-beam (10^{-2} - 10^{-4})*(10^{-3} - 10^{-4}) (shield)*(beam-corr.)

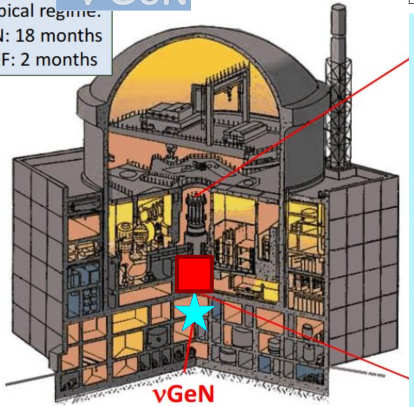
HPGe at reactor site

NCC-1701, USA
→ Sweden?



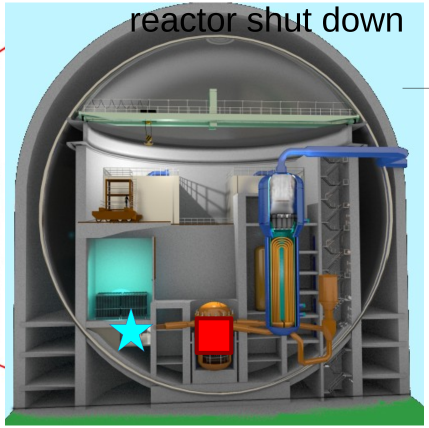
Russia

Typical regime:
ON: 18 months
OFF: 2 months

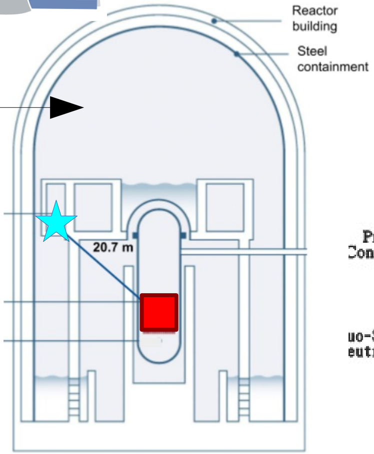


Germany

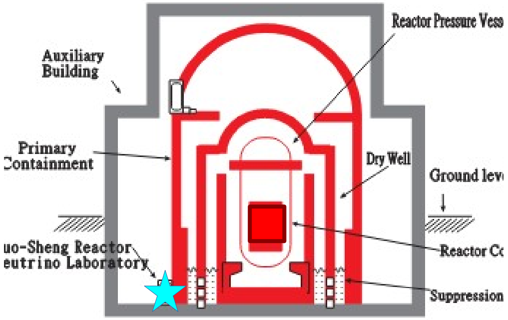
reactor shut down



Switzerland



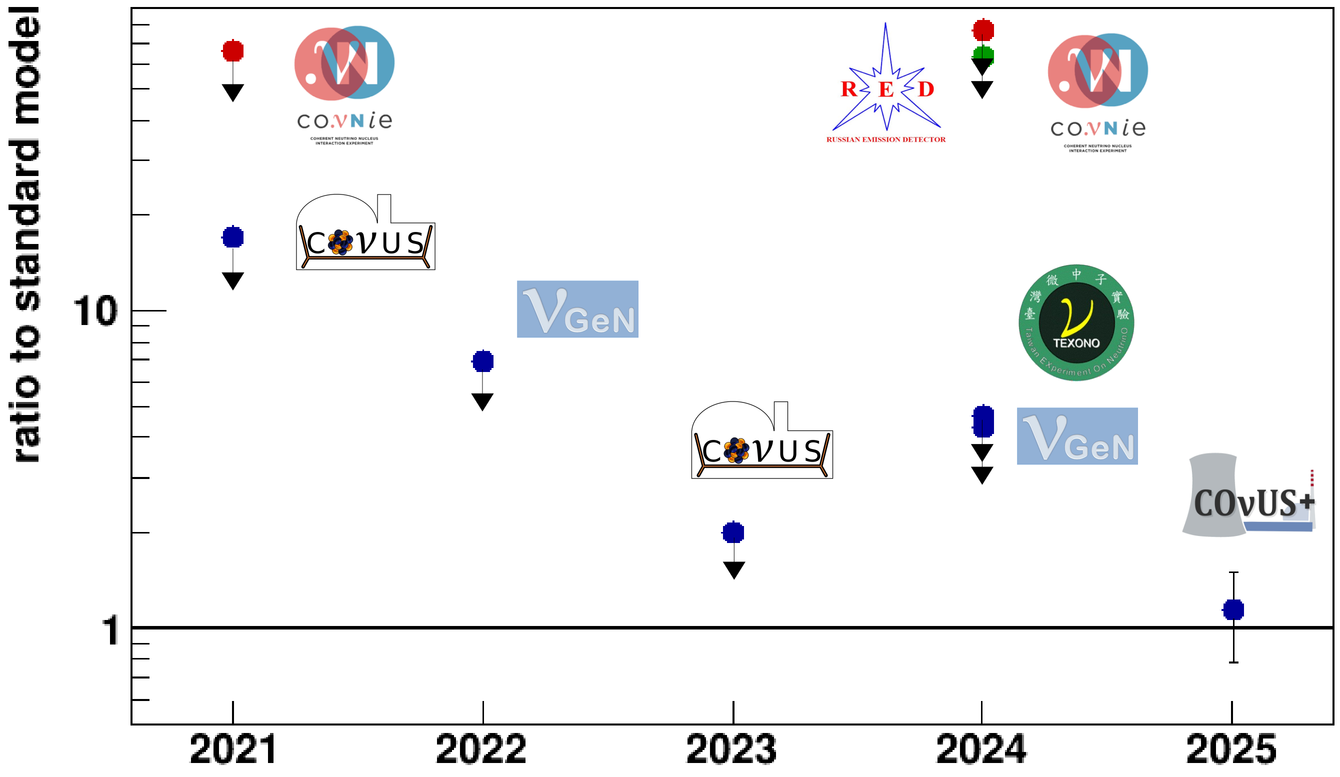
Taiwan
→ RECODE, China



reactor shut down

	dist. to core	**mass**	**threshold** (trigger eff.)	**bkg level ROI**
NCC-1701	10.4 m	2.4 kg	200 eVee (>0%)	~2000 ON, ~500 OFF cts/d/kg/keV
NuGen	11.1 m	1.4 kg	290 eVee (~85%)	~30 cts/d/kg/keV
CONUS **CONUS+**	17.1 m 20.7 m	4 kg 4 kg	210 eVee (>20%) ~160 eVee (>95%)	~20 cts/d/kg/keV ~80 ON, ~70 OFF cts/d/kg/keV
TEXONO RECODE	28 m ~25 m	2 kg tbd kg	200 eVee (~100%) Aim 160 eVee (tbd)	~50 cts/d/kg/keV tbd

Reactor experiment CEvNS results



Ge HPGe
Si CCDs
Xe two-phase

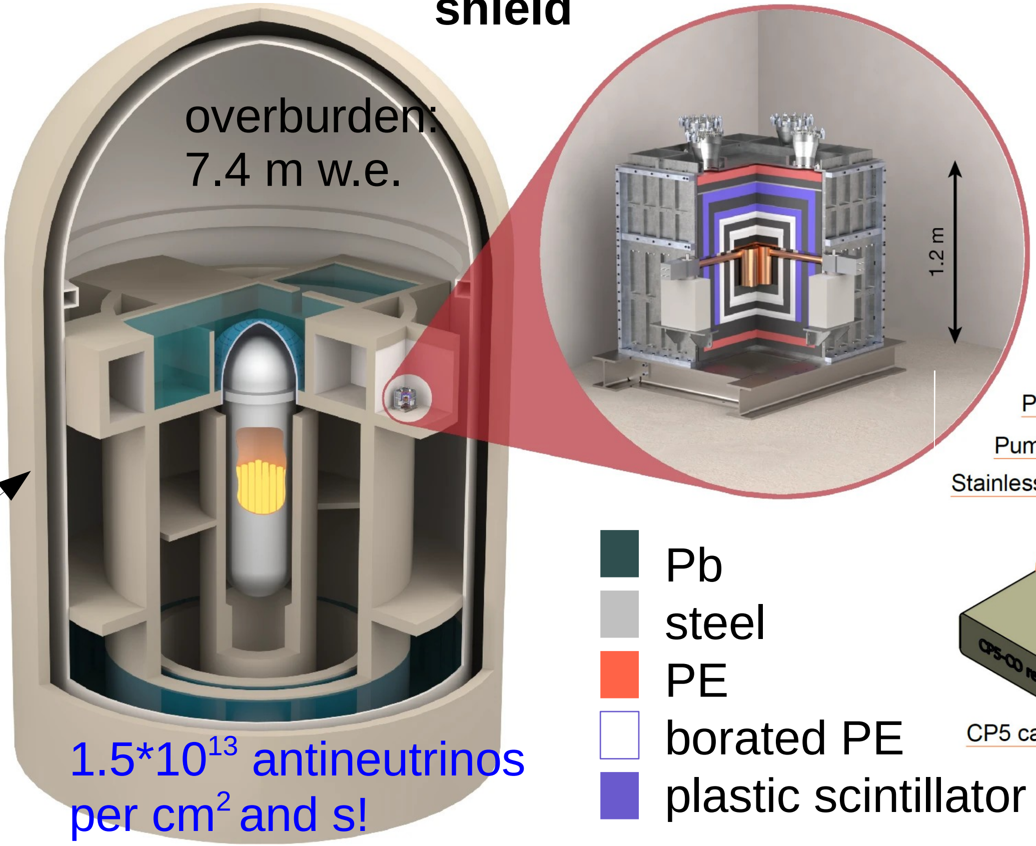
CONUS CONUS+ Max-Planck-Institut für Kernphysik Heidelberg Preussen Elektra Kernkraftwerk Leibstadt

reactor

CONUS: 2018-2022
Brokdorf reactor,
17.1 m to core

From 2023: CONUS+
Leibstadt reactor,
20.7 m to core

shield

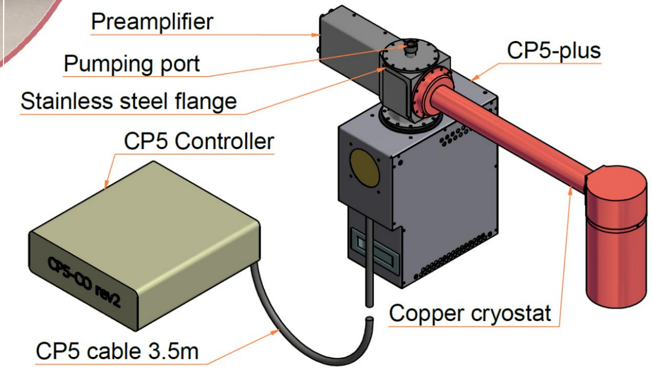


$1.5*10^{13}$ antineutrinos per cm^2 and s!

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

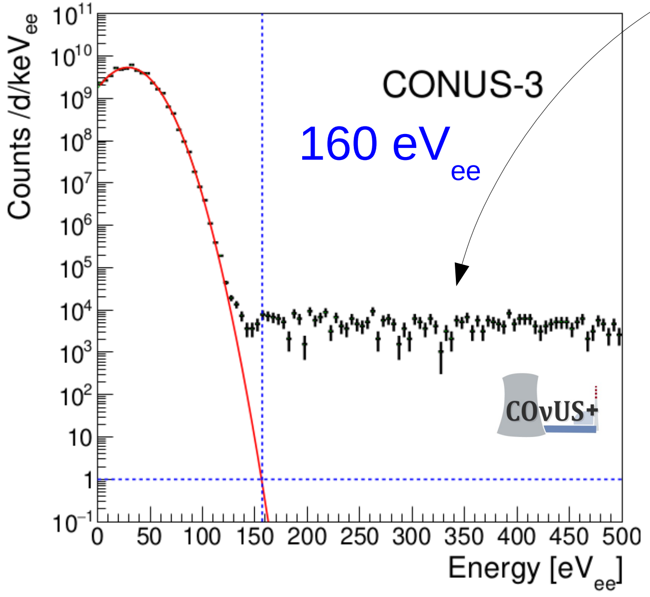
HPGe detectors

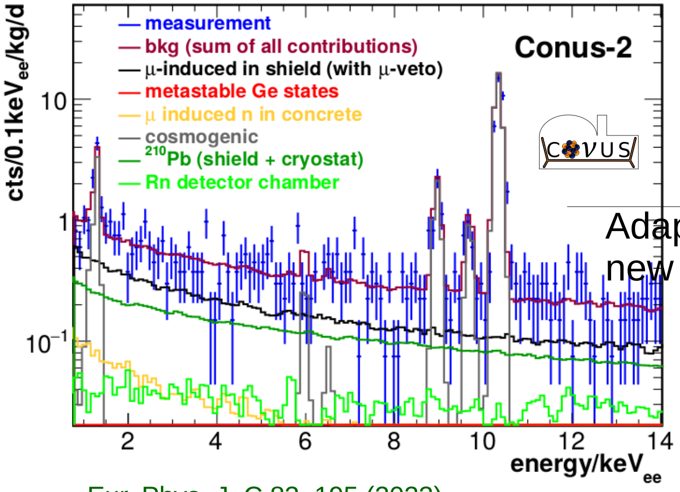
4 detectors in shield
1 kg active mass
threshold:
CONUS: 210 eV_{ee}
CONUS+: 160-180 eV_{ee}



CONUS+ background & detector performance

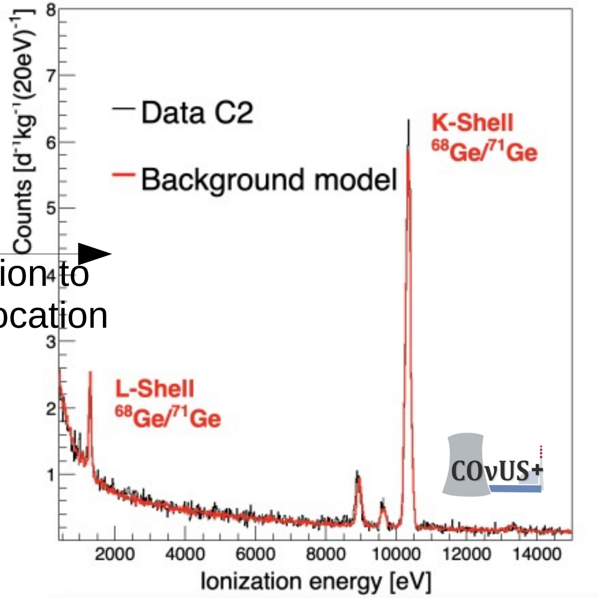
MC background model





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

Adaption to new location



Nature 643, 1229–1233 (2025)

Detector upgrade CONUS+:

Small point contact
→ lower capacity
→ improved noise resolution
→ lower threshold

Background model CONUS+:

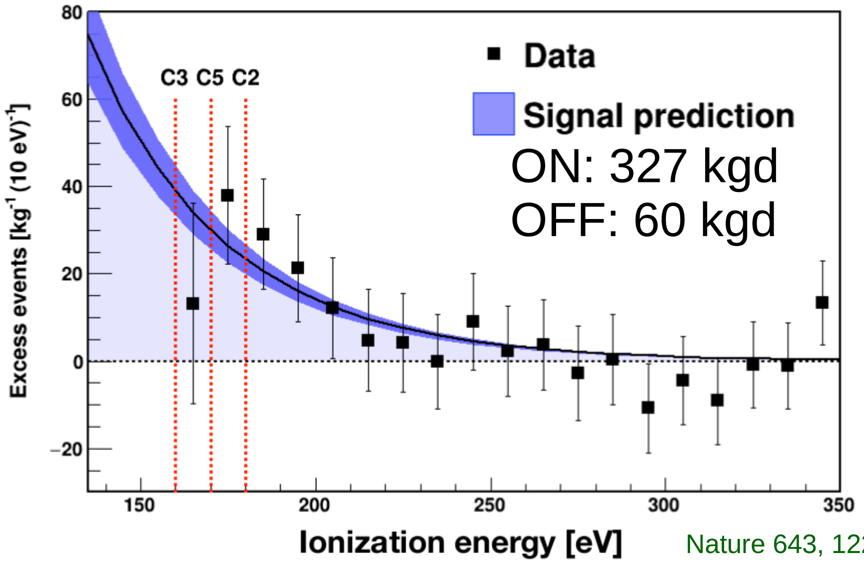
- dominant: cosmic ray-induced contributions (muon-induced neutrons, hadronic component)
- airborne radon
- Cosmic activation, material contaminations

First detection of CEvNS at reactor site

Simultaneous binned log likelihood fit of:

reactor OFF (→ bkg model) and reactor ON data (→ bkg model + CEvNS)

Figure: bkg model subtracted



Nature 643, 1229–1233 (2025)

Quenching:

detectable with HPGe

recoil → ionization energy + phonons

=> Lindhard theory (confirmed in)

Total active mass: (2.83+-0.02) kg
Signal events data: **395+-106**
Signal predicted: 347+-59

Ratio to SM: 1.14+-0.36

3.7 σ significance!

First detection of CEvNS at reactor side!

Upgrade since Nov. 2024: 1 kg → 2.4 kg detector mass,
more data collected including reactor OFF

Get all the (reactor) neutrinos!

O(1-10 kg-sized)

Ge

CONUS-100kg

RECODE

Si

Atucha-II

O(100 kg-sized)

NaI

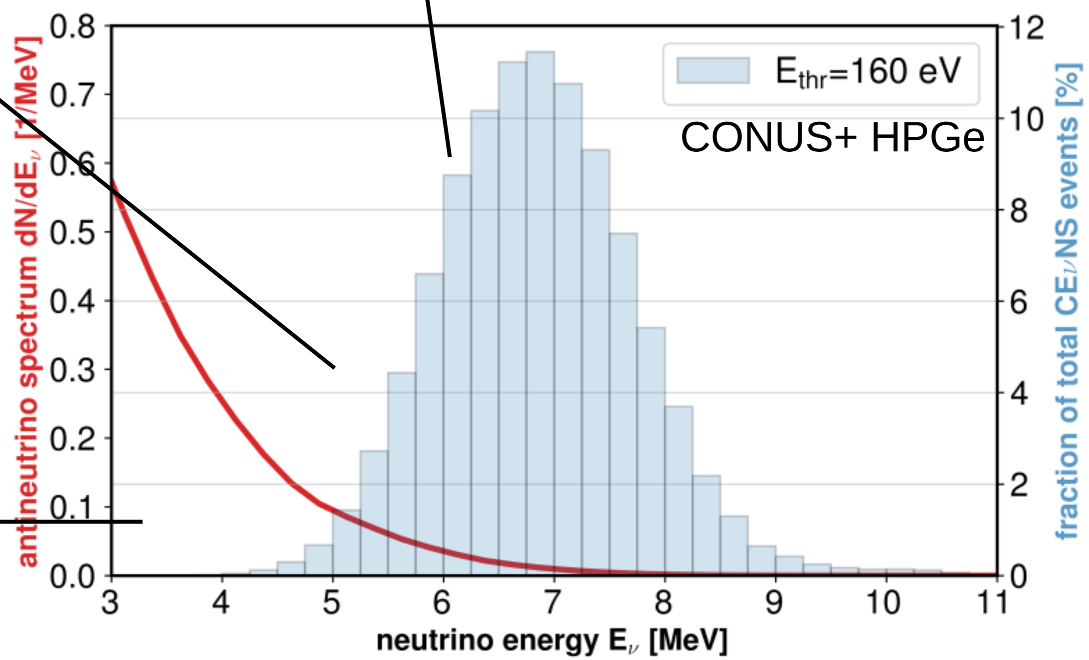
NUXE

Xe, Ar

O(gram-sized)

Ge, Zn

$CaWO_4$, Al_2O_3



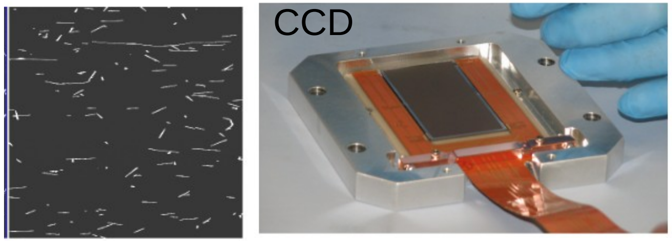
R&D:
- SBC
- Paleoccene (color centers)
- spherical prop. counters
...

Nature 643, 1229–1233 (2025)

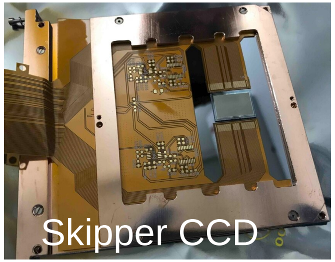
Si Charge coupled devices CCDs

imaging detector with pixelated readout

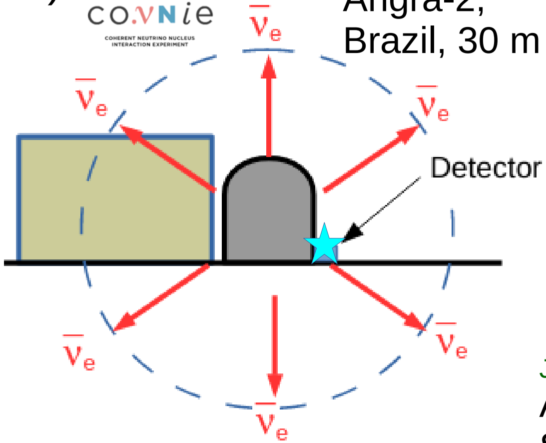
- cooled to ~130-140 K, low mass, slow readout O(10 min)
- lower threshold with skipper CCDs, similar limits
- CONNIE detector upgrade in August 2024
  → 32x more detector mass (8g total)



JINST 11 (2016) 07, P07024



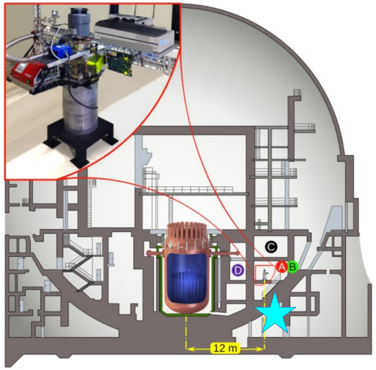
arXiv:2403.15976



Angra-2, Brazil, 30 m

2016 J. Phys.: Conf. Ser. 761 012057

Atucha-II experiment



J. High Energ. Phys. 2024, 155

Atucha-II, Brazil, 12 m Skipper CCDs

	ion. thr. eV_{ee}	**mass**	**Exposure** ON/OFF	**Limit**
CONUS+ (HPGe)	160-18	4 kg	327 kgd, 60 kgd	1.14+-0.36
CCDs (CONNIE)	50	8 x 6 g	1.2 kgd, 1.0 kgd	**SM x66**
Skipper CCDs (CONNIE)	**15**	2 x 0.25 g	14.9 gd, 3.5 gd	**SM x76**

JHEP 05 (2022) 017

arXiv:2403.15976

(current best limits Si, more exposure needed)

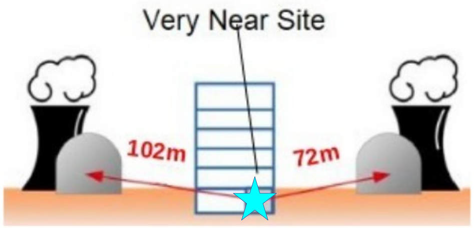
Bolometers/cryogenic calorimeters

recoil-incuded temperature change in gram-sized crystals

- cryogenic temperatures in mK range (large infrastructure)
- vibration migration important, low energy excess in heat channel

nucleus EXPERIMENT

crystals Al_2O_3, $CaWO_4$
+ transition edge sensor
~> threshold O(20 eV_{nr})

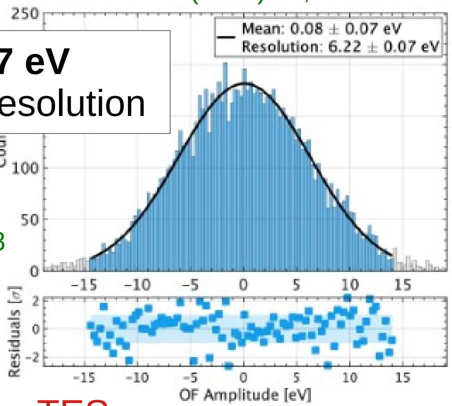


Commissioning
TU Munich: arXiv:2508.02488

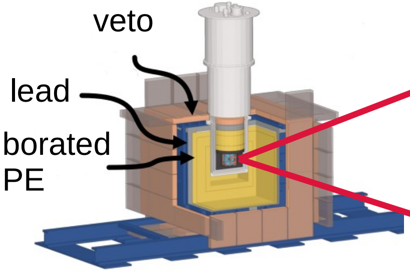
→ move ongoing
→ 2026: Commissioning at Chooz reactor, France

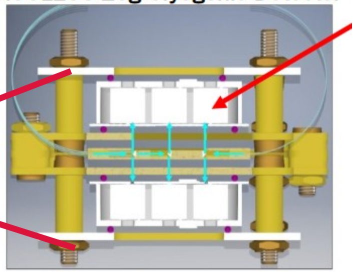
JINST 20 (2025) 05, P05022

6.22+-0.07 eV
baseline resolution

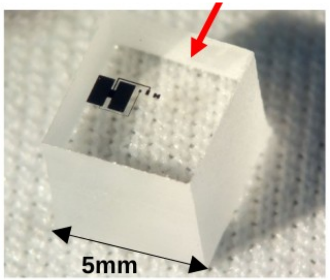


muon veto
lead
borated PE





TES



https://indico.cern.ch/event/1215362/contributions/5299993/

+ elaborate veto system

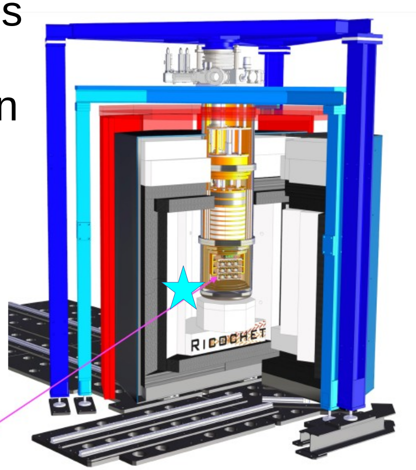
RICOCHET

CryoCube (Ge, ionization + heat)
42 g (18 detectors)
installed since July 2025,
start of physics run
- ionization: 30 eV_{ee} resolution
- heat: ~40 eV resolution
~> threshold O(100 eV_{nr})

both channels
→ particle discrimination

Q-Array (Zn, heat): R&D

research reactor 58 MW
ILL, France, 8.8 m

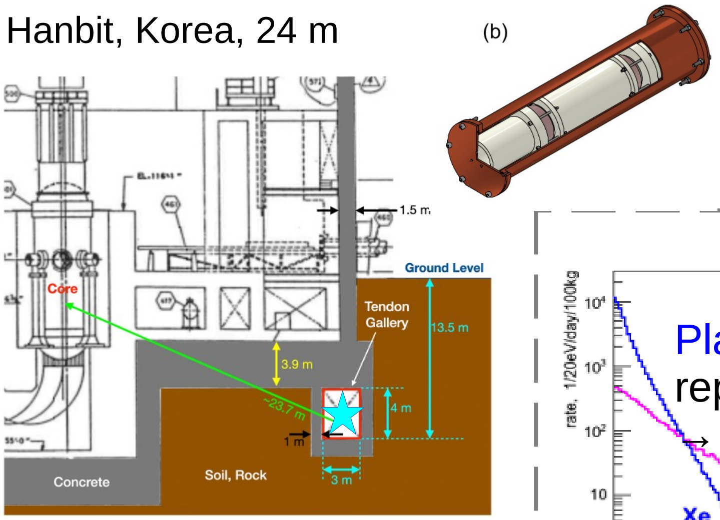


CryoCube

Scintillating crystals & Cryo noble liquids at reactors

6 NaI crystals with PMT readout (total 12.5 kg)

Hanbit, Korea, 24 m



Eur.Phys.J.C 83 (2023) 3, 226

reactor data since May 2021

aimed threshold:

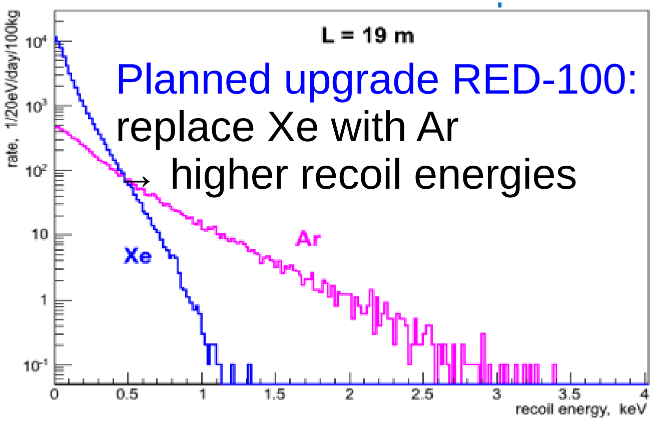
5 NPE → ~0.2 keV_{ee}

two-phase gas emission detectors

RED-100: 100 kg liquid Xe (fiducial volume)

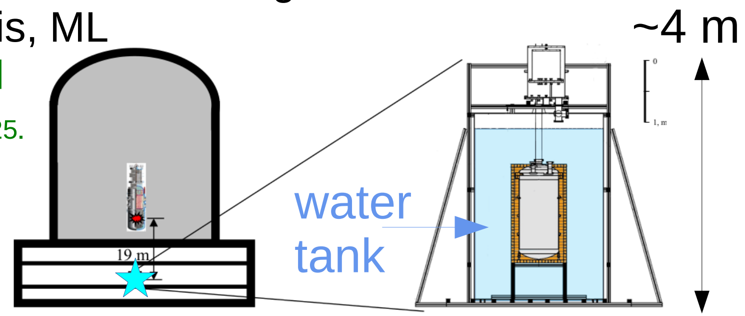
- threshold: 4. photoelectrons ↔ ~0.5 keV_{nr}
- below: huge single electron noise bkg
  → reduction in analysis, ML
  first result: **63-94x SM**

Physical Review D, 111(7):072012, 2025.



Planned upgrade RED-100:
replace Xe with Ar
→ higher recoil energies

Akimov D. Y., et al. JINST 17.11 (2022), T11011



KNPP, Russia, 19 m

https://indico.cern.ch/event/1215362/contributions/5300022/

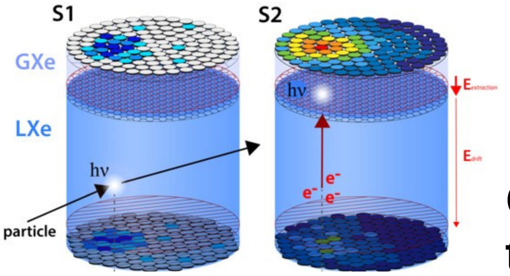
RELICS
REactor neutrino LIquid xenon Coherent elastic Scattering

(planned)

32 kg liquid Xe
Sanmen reactor, China,
outside containment,
at 25 m distance

First observation of solar CEvNS

two-phase liquid Xe TPCs
for dark matter detection



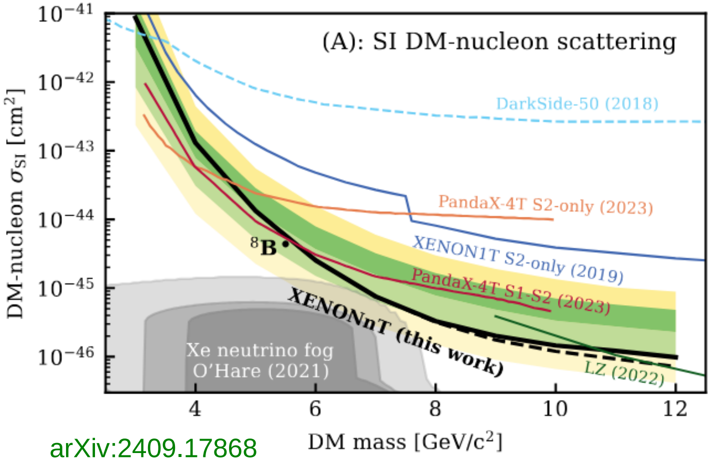
Universe 2021, 7(8), 313

	sensitive target	fiducial mass	overburden	drift field
XenonNT	5.9 t	~4 t	3600 m w.e.	23 V/m
PANDA-X	3.7 t	2.6 t	6700 m w.e.	~90 V/m

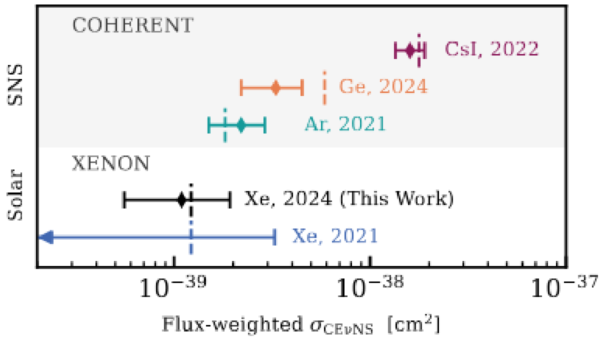
CEvNS with
tau neutrinos
(not available at
piDar or reactor)

small flux
O(10^{-6}) ^{8}B neutrinos
→ large detectors

no "OFF" data/no beam
correlation
→ deep underground



arXiv:2409.17868



Thresholds below 1 keV_{nr}!

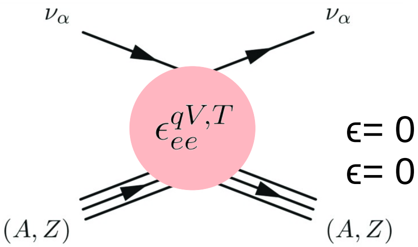
XenonNT: Phys. Rev. Lett. 133, 191002 (2024)
paired S1/S2: 37 events
Significance: 2.73 σ

PandaX: Phys. Rev. Lett. 133, 191001 (2024)
S2 only: 75+-28, paired: 3.5+-1.3
Significance: 2.64 σ

+ LUX-ZEPLIN analysis ongoing

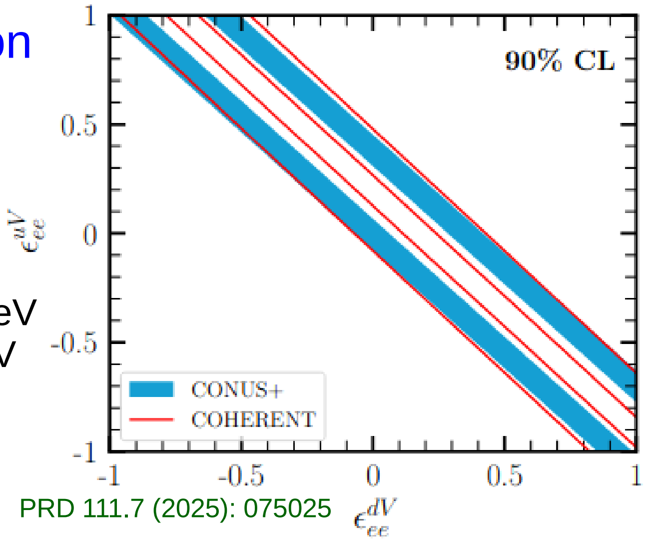
Beyond the standard model

- N² behaviour of cross section
- non-standard neutrino interactions (NSI)

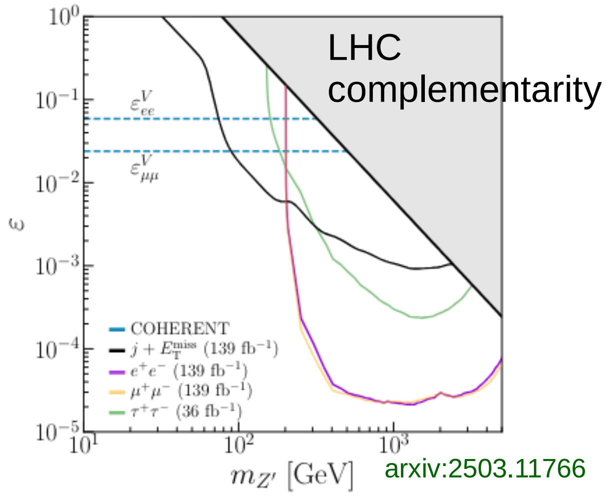


$$\epsilon \approx \frac{g_x^2}{g^2}\frac{M_W^2}{M_x^2}$$

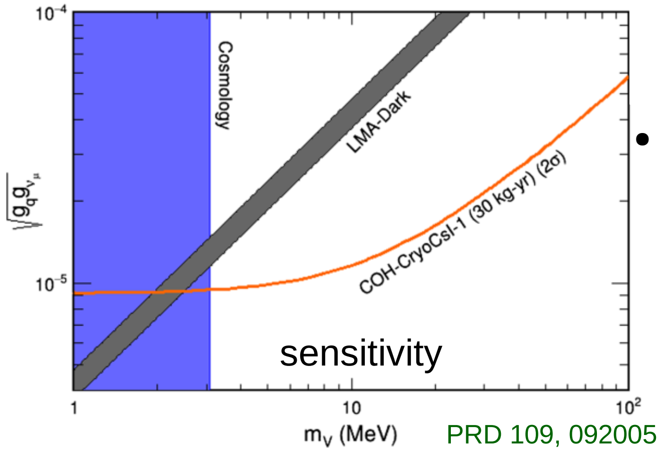
ϵ= 0.01 → 820 GeV
ϵ= 0.001 → 2.6 TeV



PRD 111.7 (2025): 075025



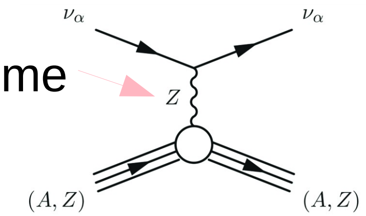
arxiv:2503.11766

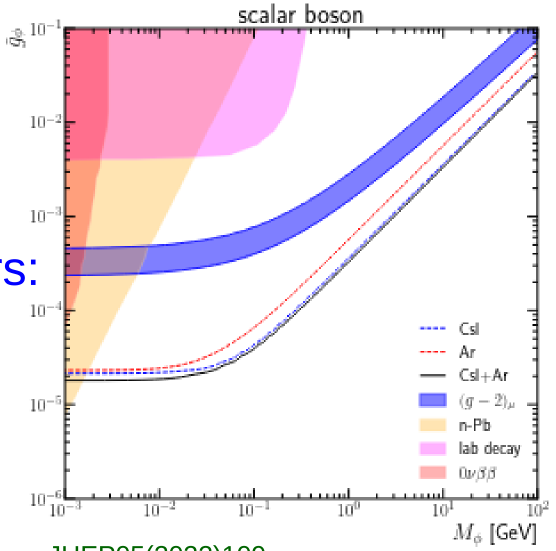


PRD 109, 092005 (2024)

- light scaler or vector mediators:

Z prime

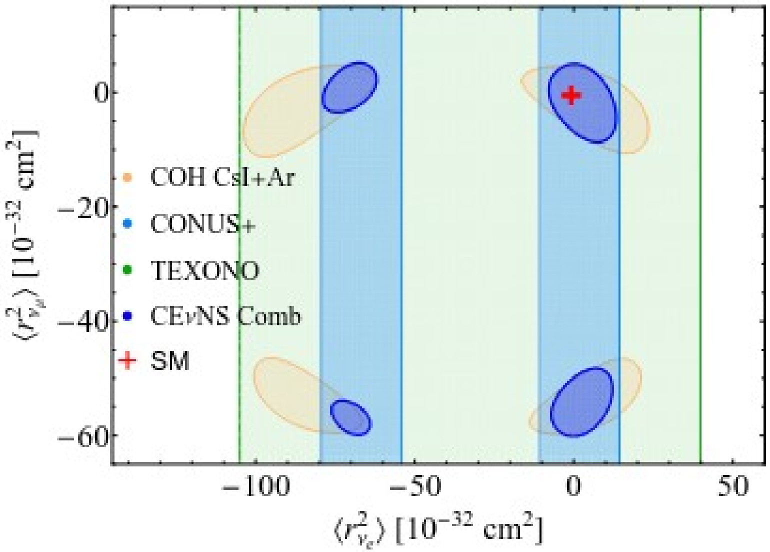




JHEP05(2022)109

Probing the standard model

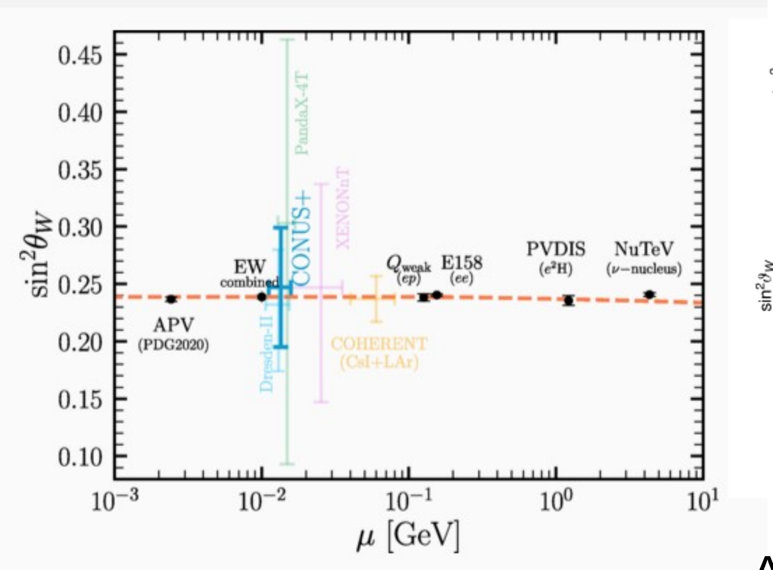
- Neutrino charge radius



Phys. Rev. D 110, 033005 (2024)

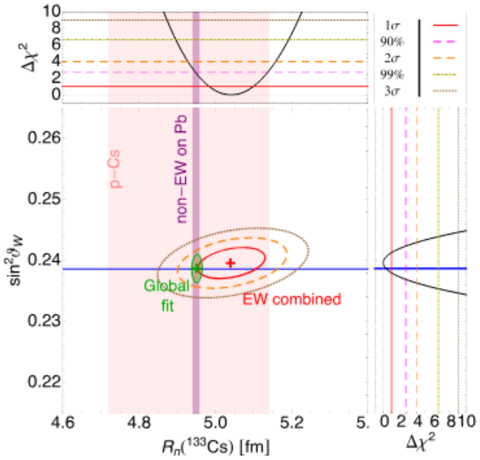
- Weinberg angle at low energies

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



PRD 111.7 (2025): 075025

disambiguity at spallation sources:

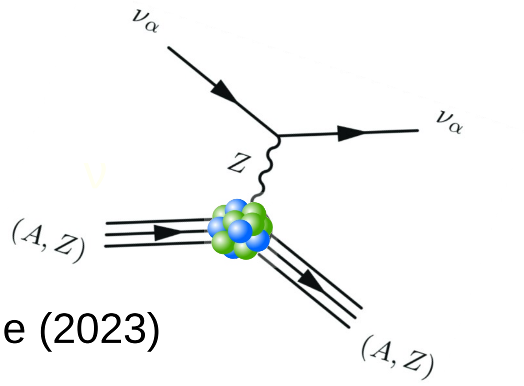


Phys. Rev. D 110, 033005 (2024)

→ APV data, reactor data

- magnetic moment and milli charge

Summary and outlook



CEvNS is fast growing field with many recent detections:

- **SNS pion decay-at-rest** (pulsed): COHERENT
  first detection of CEvNS in 2017 with CsI, followed by LAr (2021) and HPGe (2023)
- **Reactor** (lower energies): first detection in 2024 by CONUS+ with HPGe
  multitude of efforts with different technologies at reactors:
  CCDs (CONNIE,..), cryogenic bolometers (NUCLEUS, Ricochet), twophase TPCs (RED-100,..),…
- first evidence on CEvNS from **solar neutrinos** (XenonNT, PandaX)

→ bright future:
more exposure, lower thresholds, different isotopes
=> **many more CEvNS events** in the next few years

→ **precision test of the standard model with neutrinos**

Thank you for your attention!

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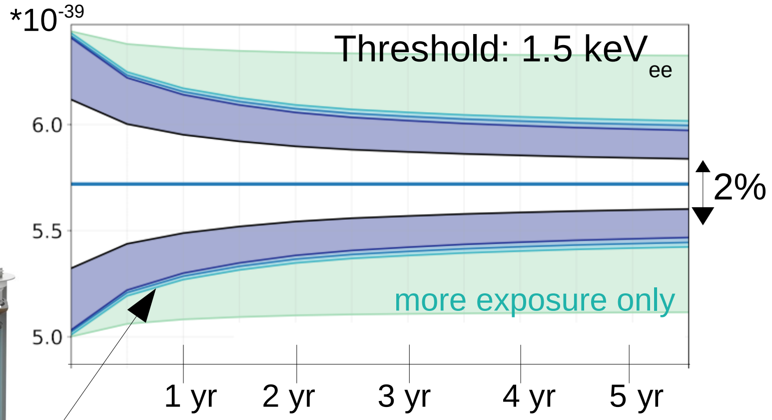
(figure by K. Scholberg)

BACK UP

Ge-Mini future

More data: Campaign-3
~two times more statistics collected

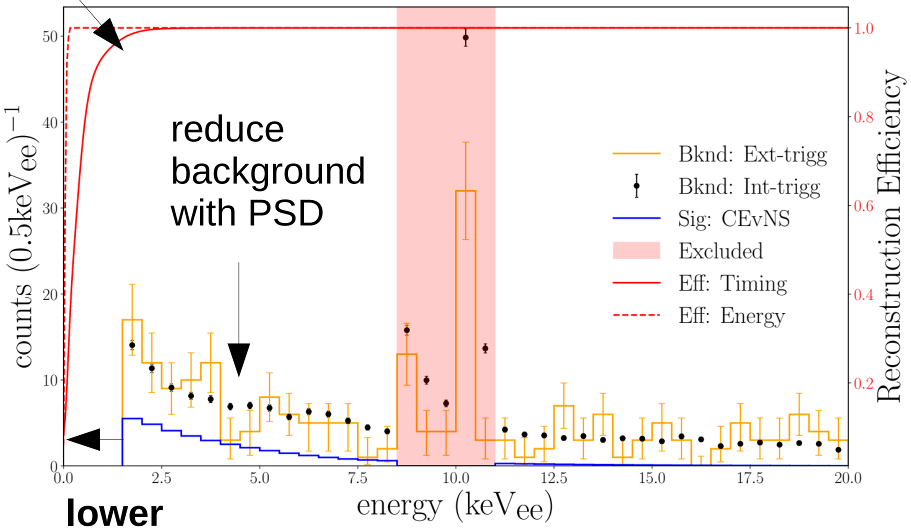


neutrino flux uncertainty reduction

Charged current deuteron scattering:
~10% → 2-3% (5 SNS years)

Improved analysis techniques:
→ thresholds <0.5 $\mathrm{keV_{ee}}$ in reach!
→ ~40 % more signal

improve timing reconstruction



reduce background with PSD

lower threshold

→ next result: ~120 CEvNS events expected!

Quenching

detectable with HPGe

recoil → ionization energy + phonons

Recent quenching measurements:

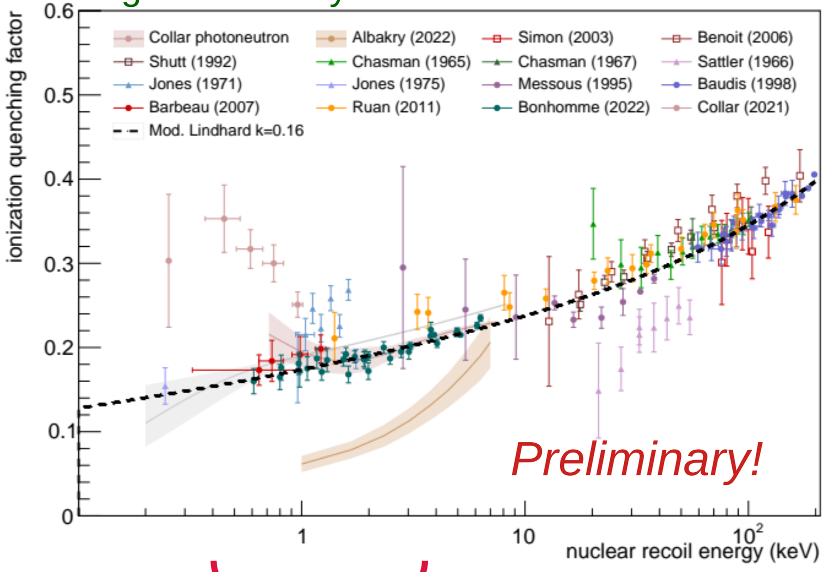
CONUS measurement
TUNL measurement
} compatible with Lindhard theory

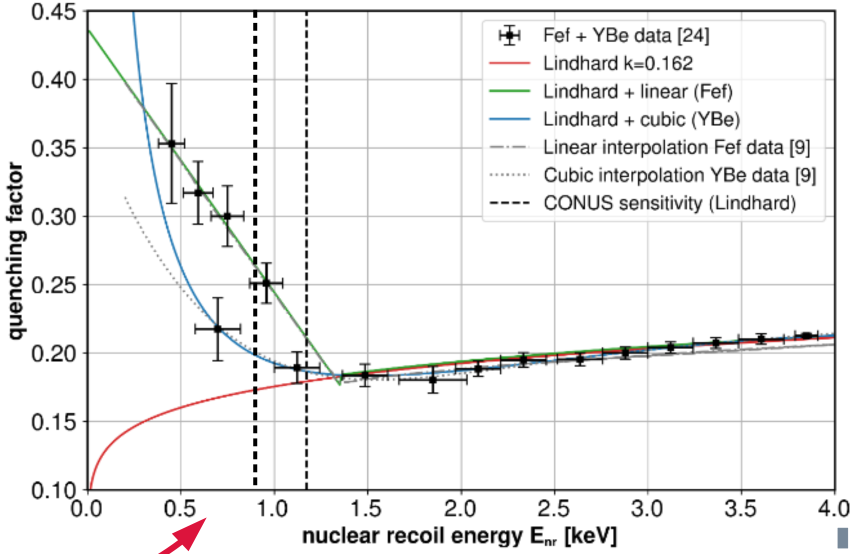
Collar measurements → increase

→ CONUS KKL Run-1

→ CONUS KBR Run-5

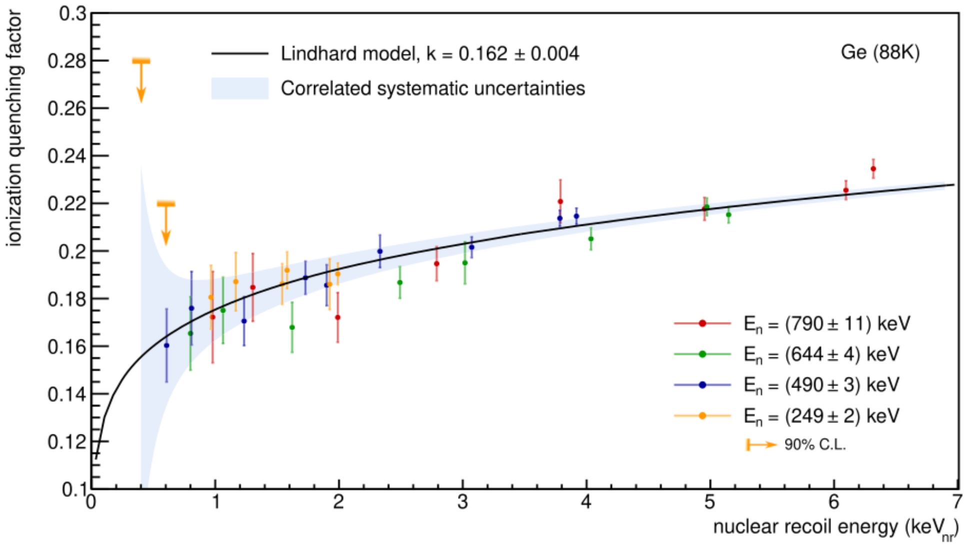
Figure courtesy of A. Bonhomme



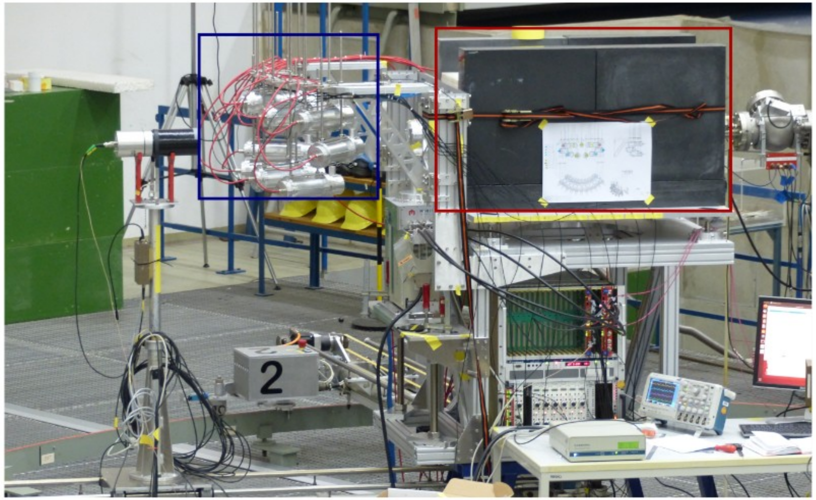


COHERENT
Ge-Mini
6.7 keV_{nr}

Quenching

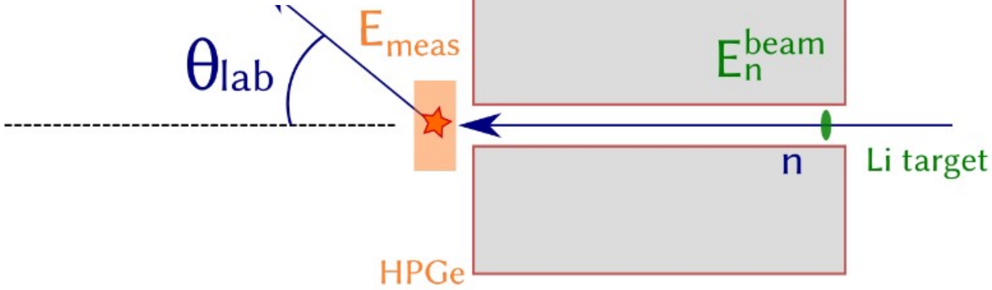


A. Bonhomme et al, EPJC, 82(9):815, 2022

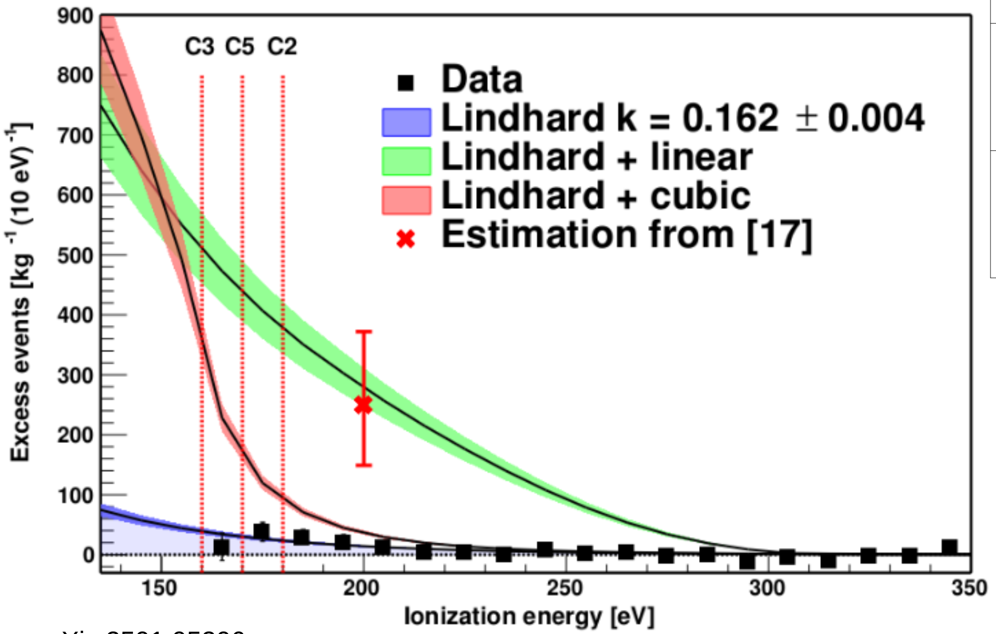


6mm thick
Ge crystal

coincidence detector



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

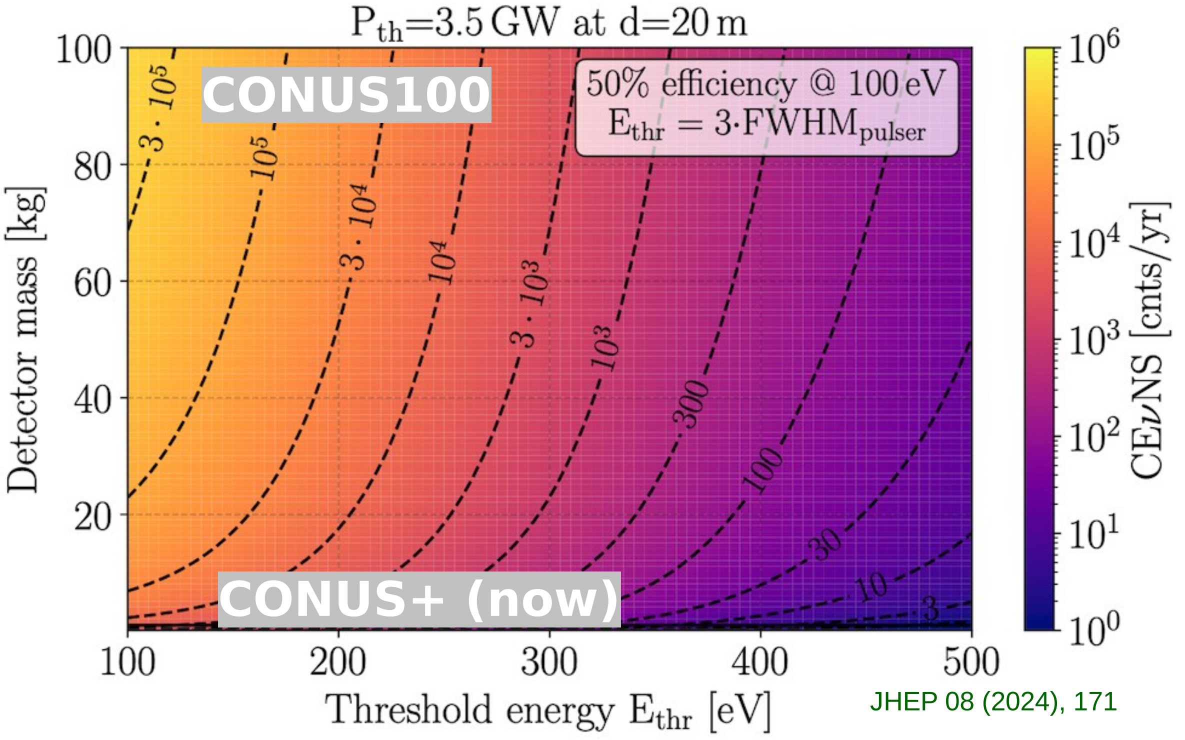
KKL Run-1 uncertainties:

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

Towards a precision CEvNS detection



JHEP 08 (2024), 171

much more mass → CONUS100