CEvNS Neutrino Experiments

Yu. Efremenko UTK, ORNL

September 19th 2024

NuFact 2024

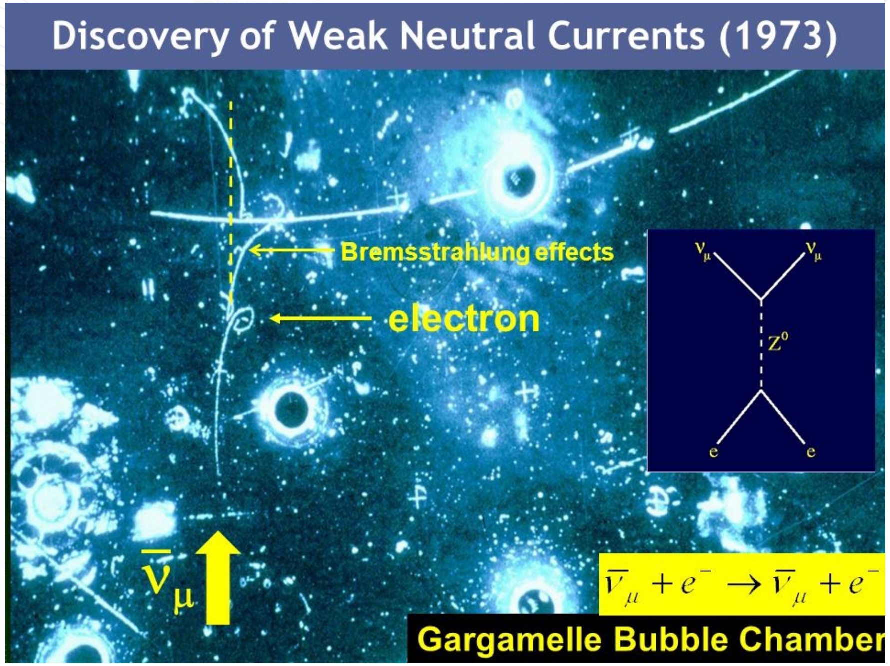
THE UNIVERSITY OF TENNESSEE KNOXVILLE

OAK RIDGE National Laboratory

Number of the slides about detectors are stolen from M-CEvNS workshops

Coherent Elastic neutrino Nucleus Scattering (CEvNS)

A neutrino scatters on a nucleus via exchange of a Z, and the nucleus recoils as a whole;



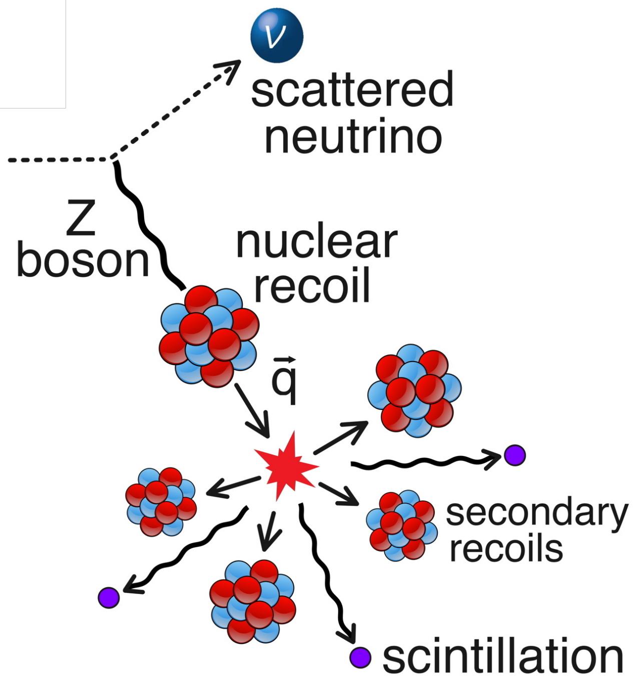
D.Z. Freedman PRD 9 (1974)

Submitted Oct 15, 1973

V.B.Kopeliovich & L.L.Frankfurt

JETP Lett. 19 (1974)

Submitted Jan 7, 1974

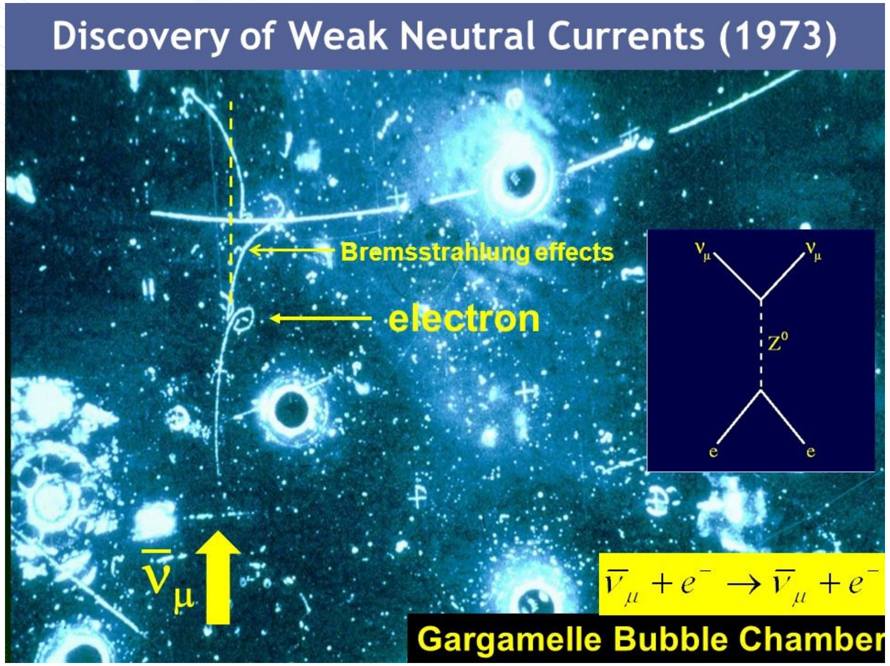


$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1 + \cos\theta) \frac{(N - (1 - 4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$

CEvNS cross section is predicted by the Standard Model

Coherent Elastic neutrino Nucleus Scattering (CEvNS)

A neutrino scatters on a nucleus via exchange of a Z, and the nucleus recoils as a whole;



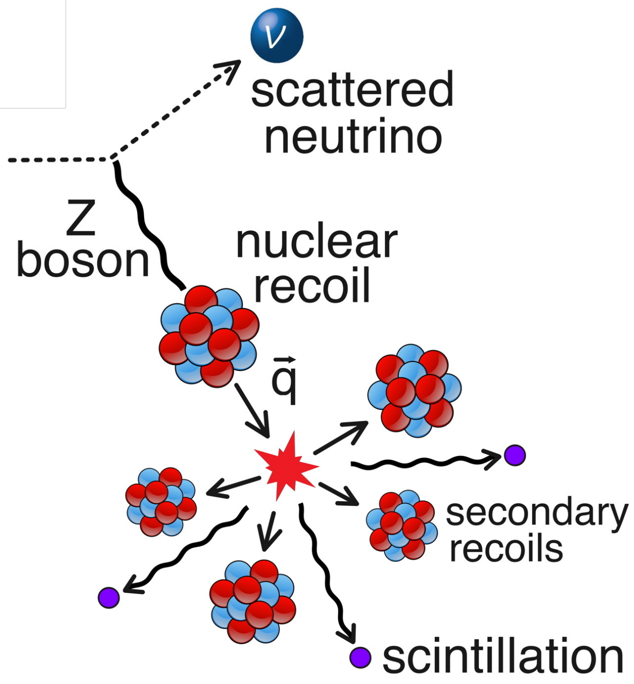
D.Z. Freedman PRD 9 (1974)

Submitted Oct 15, 1973

V.B.Kopeliovich & L.L.Frankfurt

JETP Lett. 19 (1974)

Submitted Jan 7, 1974



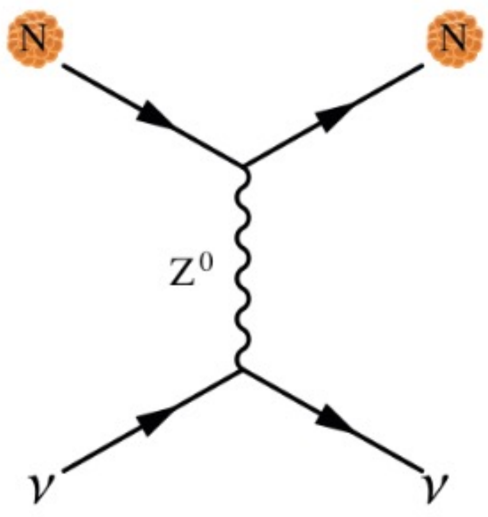
$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2}k^2(1+\cos\theta)\frac{(N-(1-4\sin^2\theta_W)Z)^2}{4}F^2(Q^2) \quad \propto N^2$$

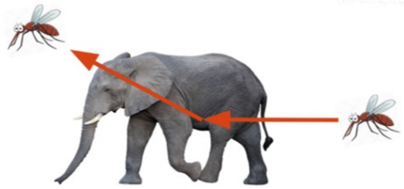
~0

CEvNS cross section is predicted by the Standard Model

Coherent Elastic neutrino-Nucleus Scattering

A neutrino scatters on a nucleus via exchange of a Z, and the nucleus recoils as a whole, produce tiny recoils.

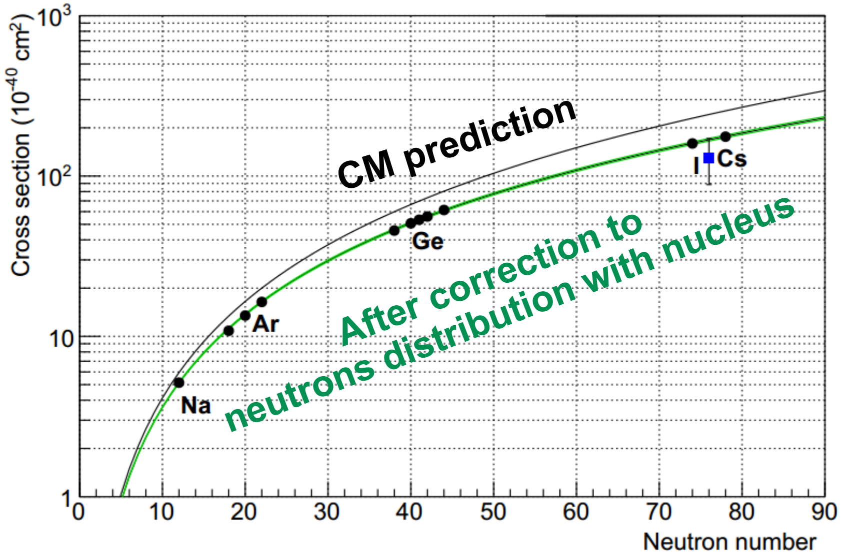


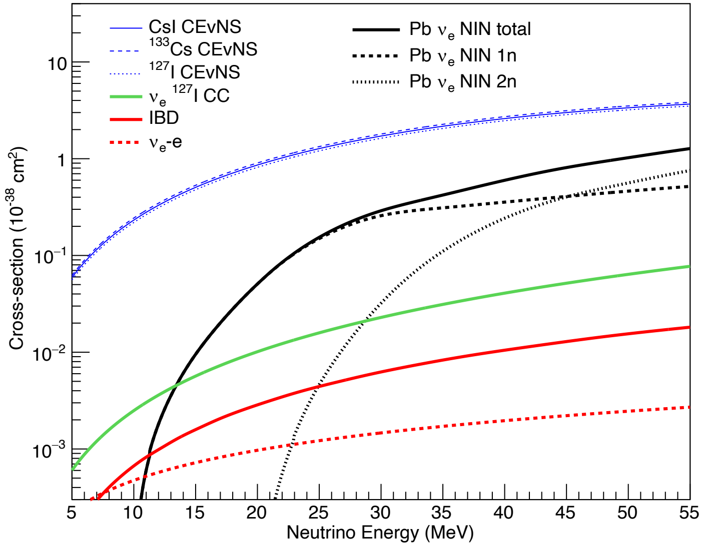


CEvNS cross-section is large, but very hard to detect

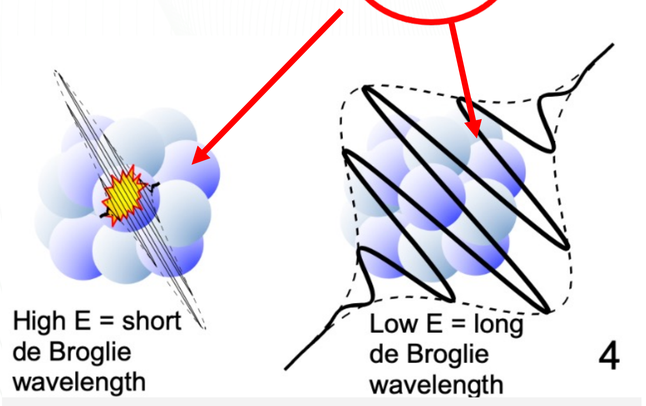
D.Z. Freedman PRD 9 (1974)

Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering.





$$\sigma=\frac{G_F^2 E_\nu^2}{4\pi}[Z(1-4\sin^2\theta_W)-N]^2 F^2(Q^2)$$

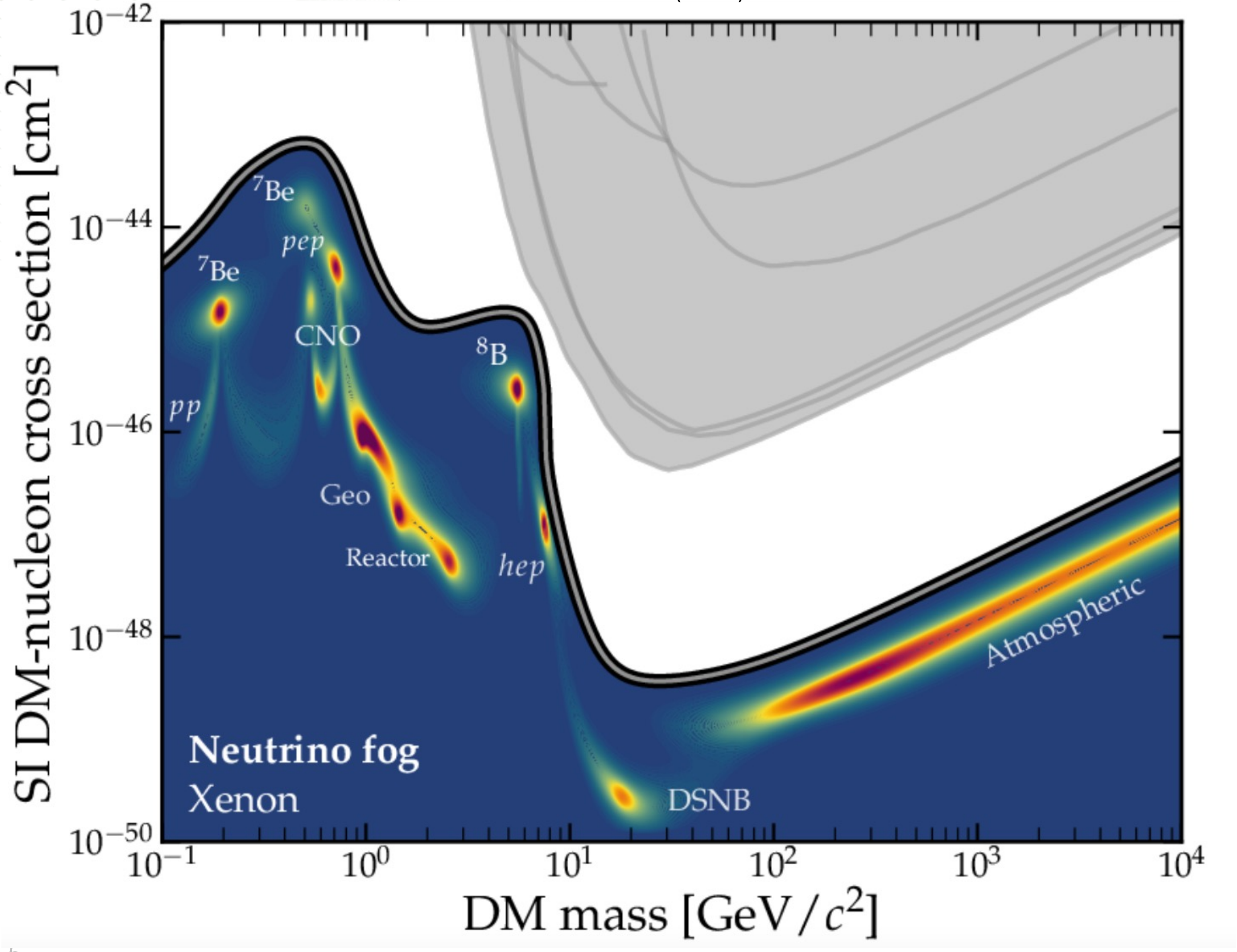


High Q = short de Broglie wavelength

Low Q = long de Broglie wavelength

CEvNS is the Neutrino "Fog" for WIMP DM experiments

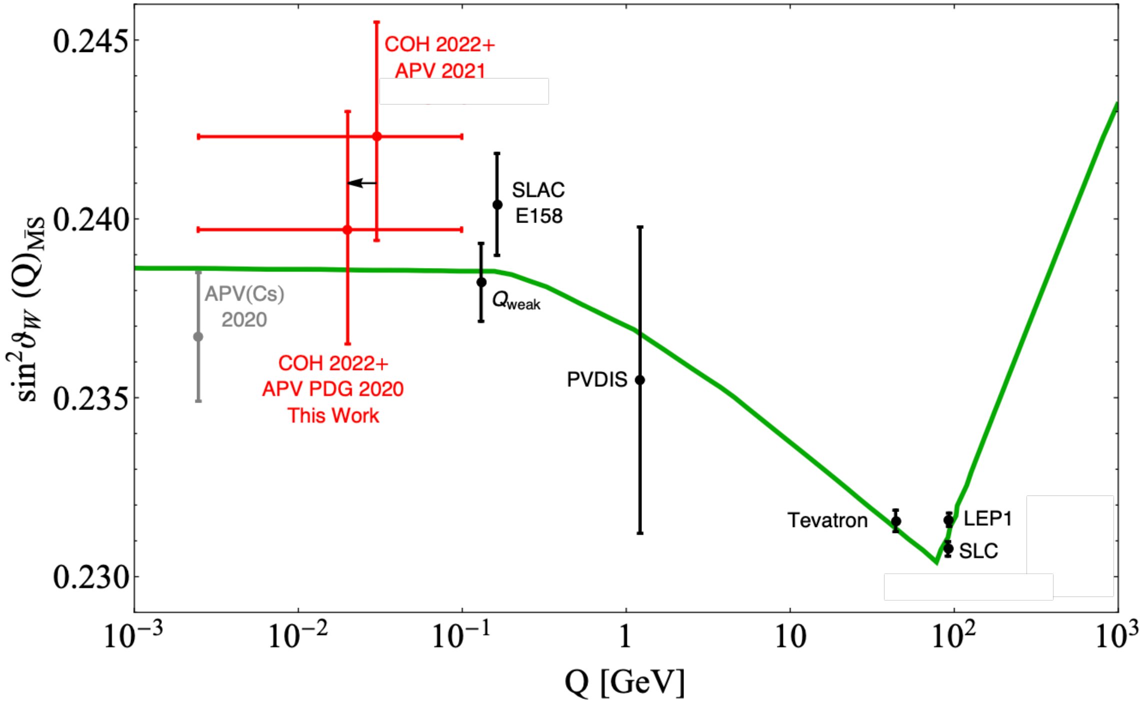
O'Hare, Ciaran AJ. PRL 127.25 (2021): 251802



CEvNS is a new way to measure Electro-Weak angle at Low Q

$$\sigma_{tot} = \frac{G_F^2 E_\nu^2}{4\pi}\left[Z\left(1-4\sin^2\theta_W\right)-N\right]^2 F^2(Q^2)$$

Cadeddu, M., F.Dordei, and C.Giunti, Europhysics Letters 143.2 (2—3): 34001



CEvNS is a Probe of Non-Standard Neutrino Interactions (NSI)

new interaction specific to ν's

$$\mathcal{L}_{\nu H}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} [\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5)\nu_\beta] \times (\varepsilon_{\alpha\beta}^{qL}[\bar{q}\gamma_\mu(1-\gamma^5)q] + \varepsilon_{\alpha\beta}^{qR}[\bar{q}\gamma_\mu(1+\gamma^5)q])$$

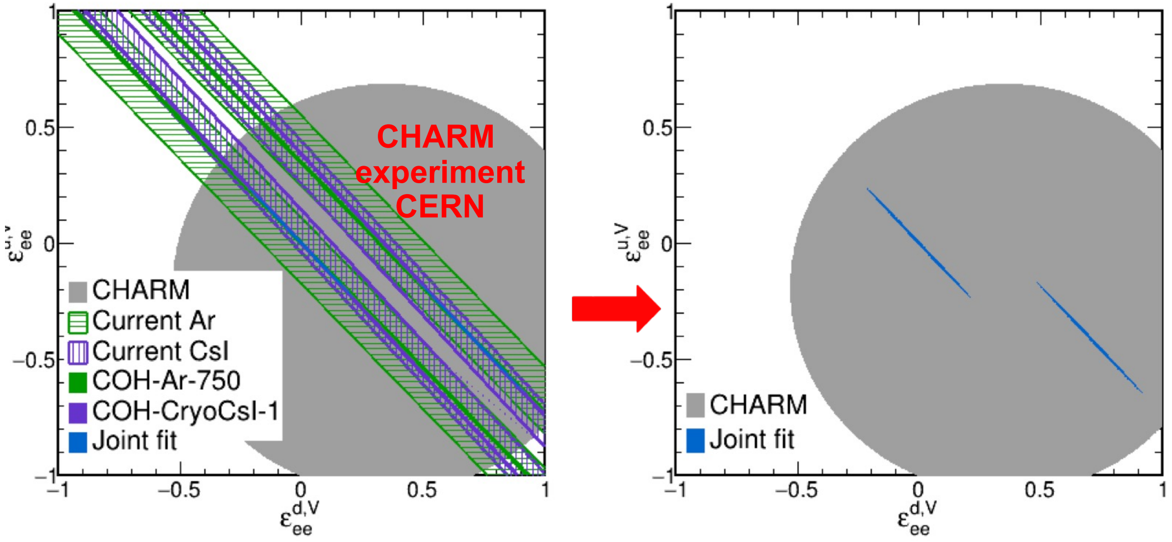
J. H J. High Energy Phys. 03(2003) 011

TABLE I. Constraints on NSI parameters, from Ref. [35].

NSI parameter limit	Source
$-1 < \varepsilon_{ee}^{uL} < 0.3$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$-0.4 < \varepsilon_{ee}^{uR} < 0.7$	
$-0.3 < \varepsilon_{ee}^{dL} < 0.3$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$-0.6 < \varepsilon_{ee}^{dR} < 0.5$	
$\lvert\varepsilon_{\mu\mu}^{uL}\rvert < 0.003$	NuTeV νN, $\bar{\nu} N$ scattering
$-0.008 < \varepsilon_{\mu\mu}^{uR} < 0.003$	
$\lvert\varepsilon_{\mu\mu}^{dL}\rvert < 0.003$	NuTeV νN, $\bar{\nu} N$ scattering
$-0.008 < \varepsilon_{\mu\mu}^{dR} < 0.015$	
$\lvert\varepsilon_{e\mu}^{uP}\rvert < 7.7 \times 10^{-4}$	$\mu \rightarrow e$ conversion on nuclei
$\lvert\varepsilon_{e\mu}^{dP}\rvert < 7.7 \times 10^{-4}$	$\mu \rightarrow e$ conversion on nuclei
$\lvert\varepsilon_{e\tau}^{uP}\rvert < 0.5$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$\lvert\varepsilon_{e\tau}^{dP}\rvert < 0.5$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$\lvert\varepsilon_{\mu\tau}^{uP}\rvert < 0.05$	NuTeV νN, $\bar{\nu} N$ scattering
$\lvert\varepsilon_{\mu\tau}^{dP}\rvert < 0.05$	NuTeV νN, $\bar{\nu} N$ scattering

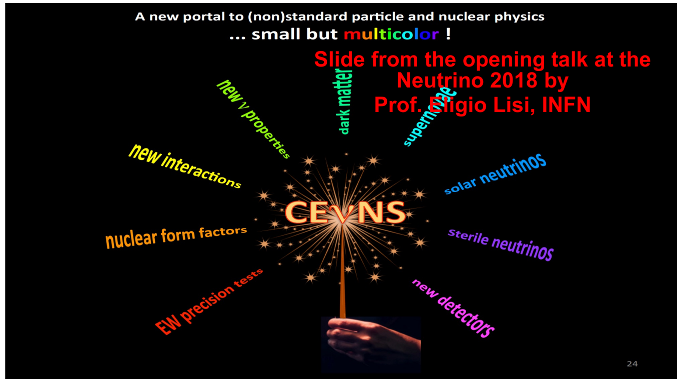
Non-Standard ν Interactions (Supersymmetry, neutrino mass models) can impact the cross-section differently for different nuclei

arXiv:2204.04575 [hep=ex]

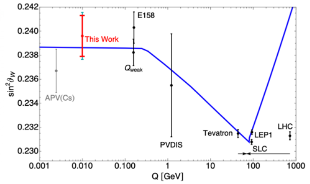


CEvNS as a Tool

Some randomly selected theoretical publications

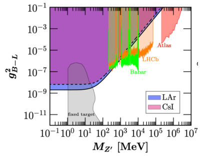


- **EW precision tests**



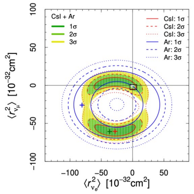
arXiv:2405.09416 (hep-ph)

- **New Neutrino Interactions**



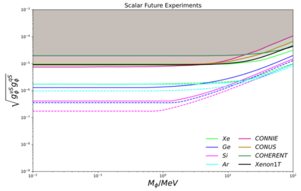
arXiv:2003.12050 (hep-ph)

- **Neutrino Properties (Neutrino charge radius)**



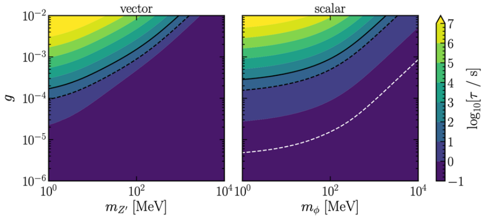
arXiv:2005.01645 (hep-ph)

- **Solar Neutrinos**



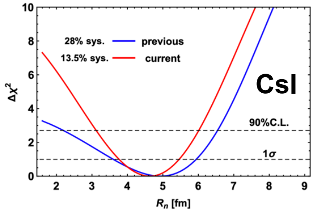
arXiv:2201.05015 (hep-ph)

- **Supernovae neutrino**



arXiv:2010.14545 (hep-ph)

- **Nuclear Physics**

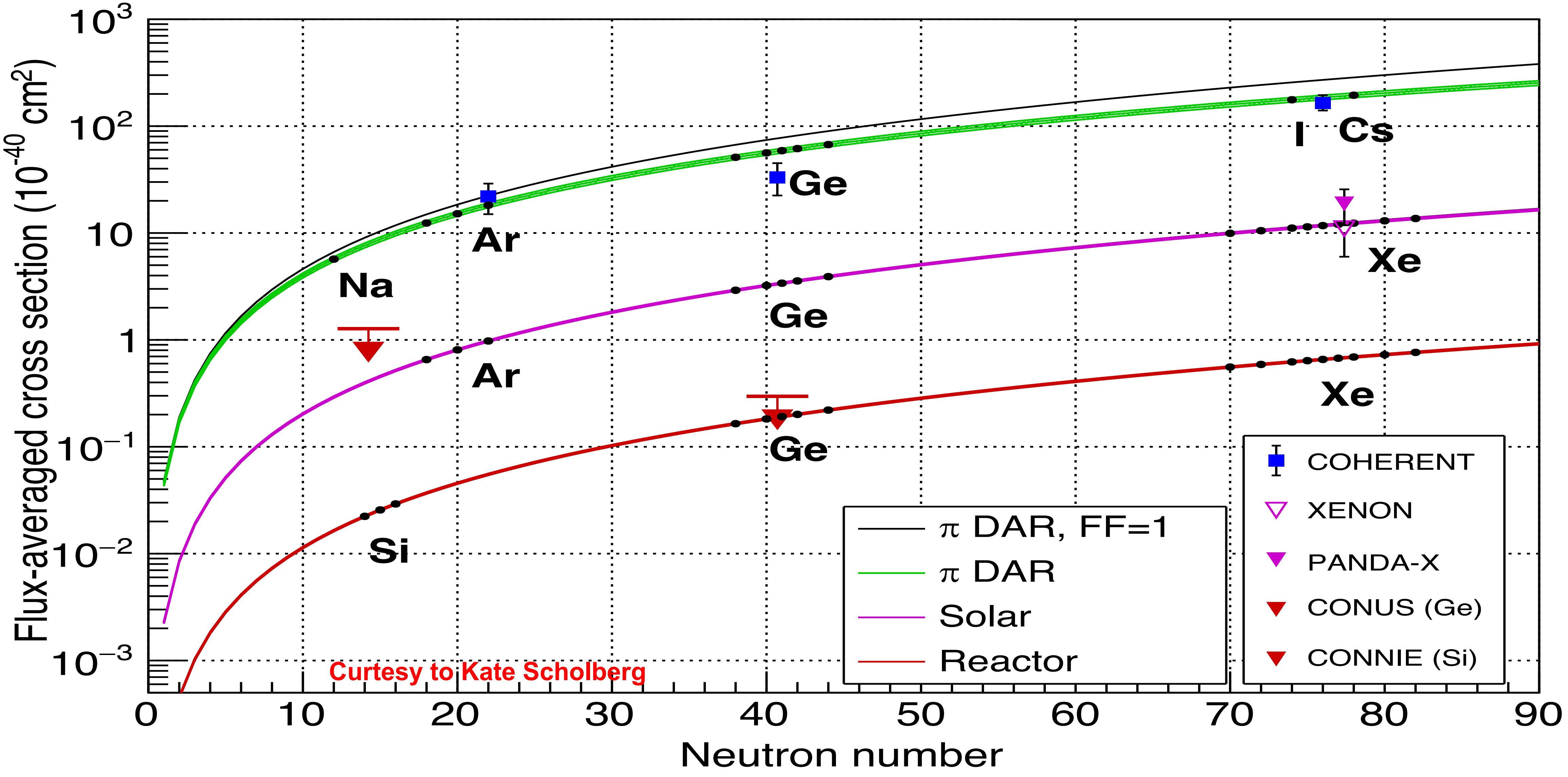


arXiv:1907.12444 (hep-ph)

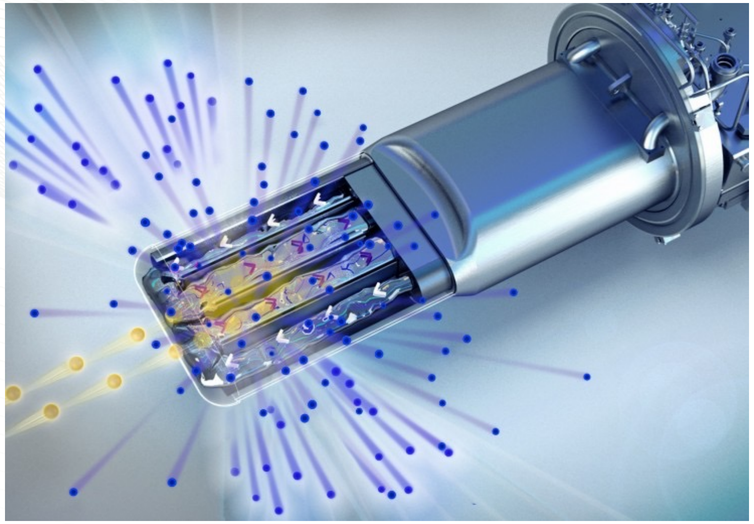
- **Light Dark Matte.**

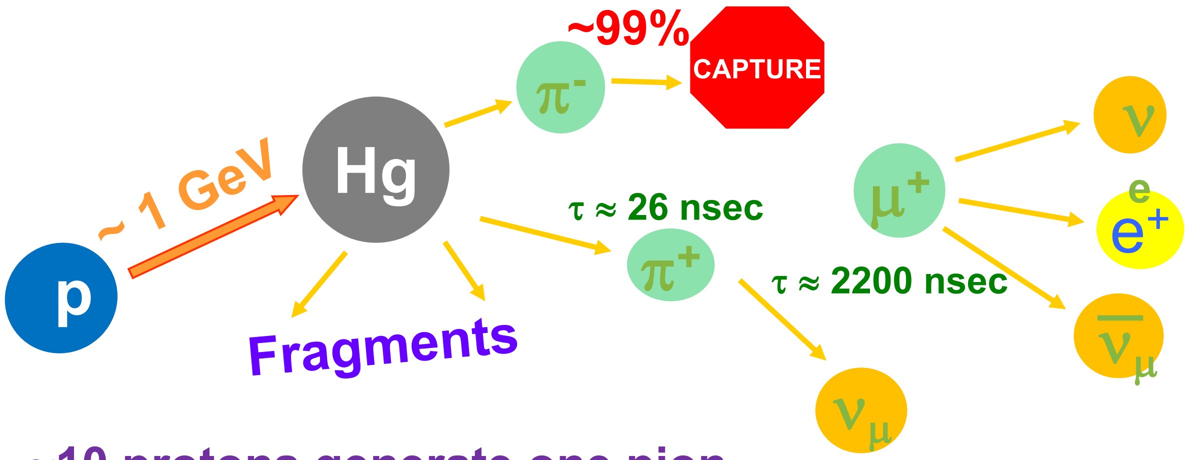
~300 publications with 15 000 citations during the last 7 years (mostly from theory folks).

CEvNS from various sources



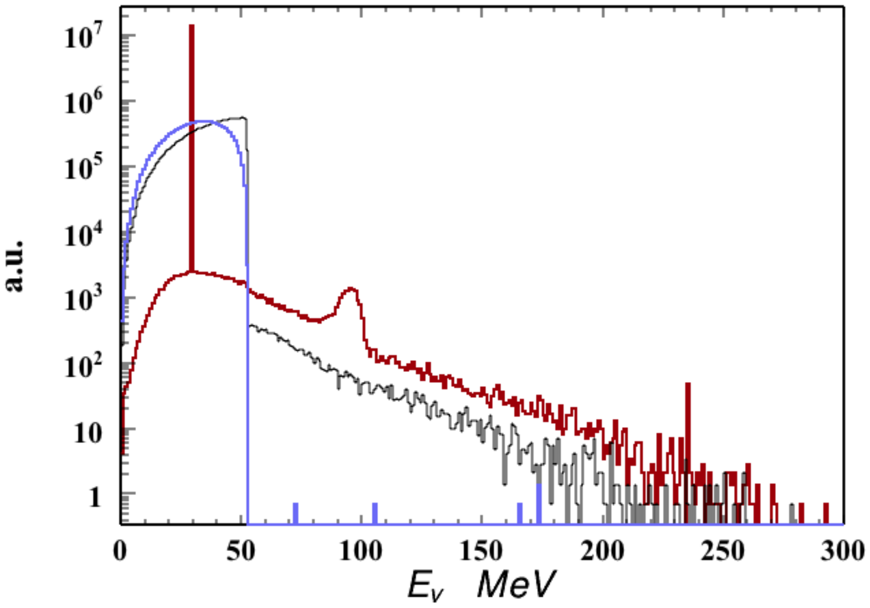
Neutrino Production at a Stop Pion Facility



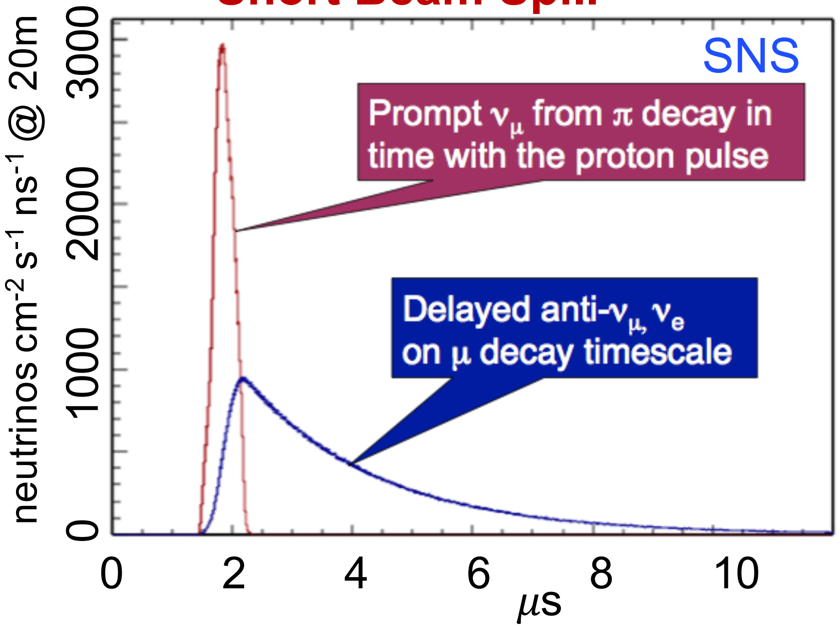


~10 protons generate one pion

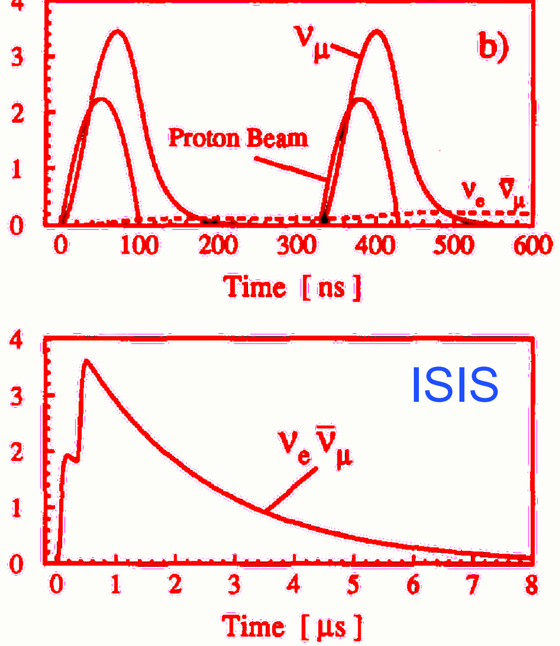
Neutrino Energy



Neutrino Timing for a Short Beam Spill



Neutrino Timing for a Two Short Beam Spills



Stop Pion Facilities

Facility	Beam Energy, GeV	Beam Power, MW	Beam Timing	Comments
CSNS	1.6	0.14 -> 0.5	0.5 usec, 25 Hz	CICENNS 2025, CEvNS
ISIS	0.8	0.16	Two 0.1 usec, 50 Hz	Decommissioned KARMEN
Lujan	0.8	0.08	0.3 usec, 20 Hz	Capitan Mills: CEvNS & D.M.
J-PARKS	3.0	0.85 -> 1.3	Two 0.1 usec, 25 Hz	**JSNS2:Oscillations, DaRveX: C.C.**
SNS	1.3	1.7 -> 2.8	0.3 usec, 60 Hz	COHERENT: CEvNS, D.M. C.C.
ESS	2.0 GeV	0 -> 5 MW	2860 usec, 14 Hz	nuESS (2027), CEvNS

Coherent Capitan Mills (CCM) Lujan (LANL)

Detector

2.58 m in diameter and 2.25 m high, LAr purification system to remove impurities

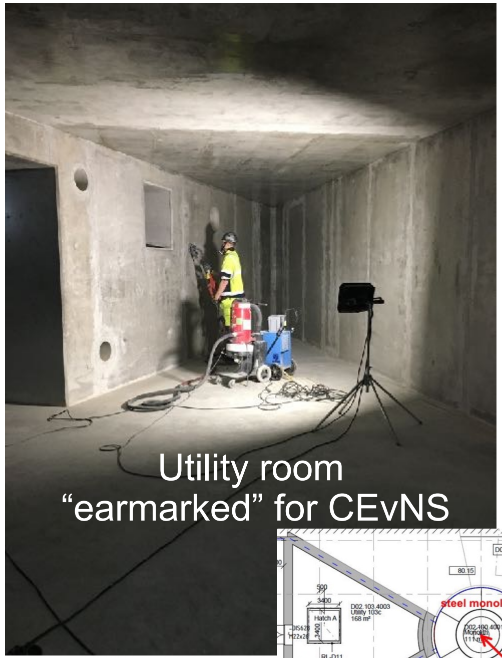
200 8” TPB coated PMTs ~ 50% photo coverage, 5 ton fiducial volume, 3 t active veto region

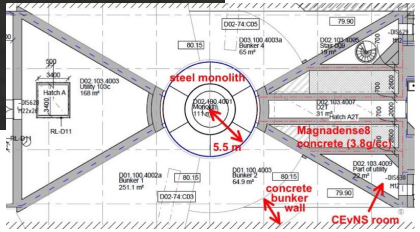
Detector is located 23 m from the target

Latest publication at: *Phys.Rev.D* 107 (2023) 9, 095036 “Prospects for detecting axionlike particles at the Coherent CAPTAIN-Mills experiment” Does CEvNS is still in agenda?

ESS → CEvNS program

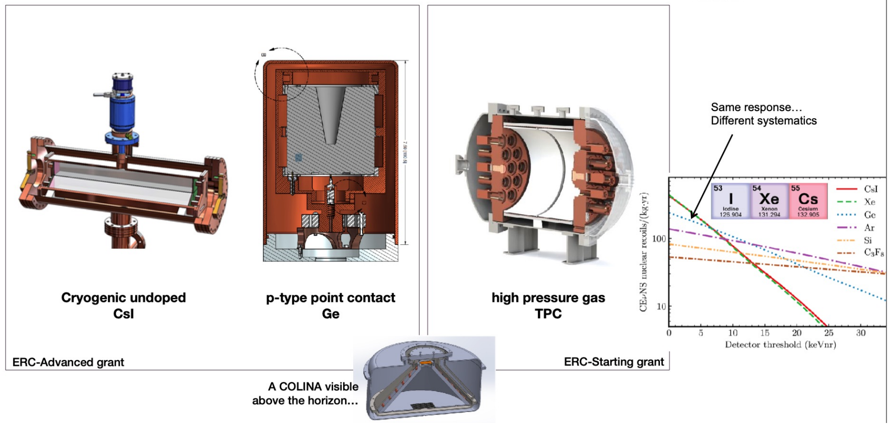
- Accelerator is at the initial stage of commissioning.
- First Beam expected in 2027
- Beam Energy 2 GeV and goal for the beam power is 5 MW
- Long beam spill, duty factor of 25.



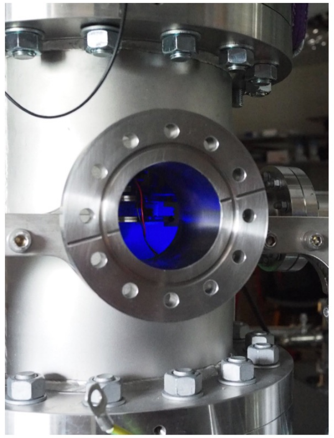


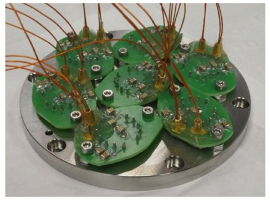
Active R&D for perspective technologies.
Challenge is to discriminate from Beam Relate Neutrons and steady state backgrounds.

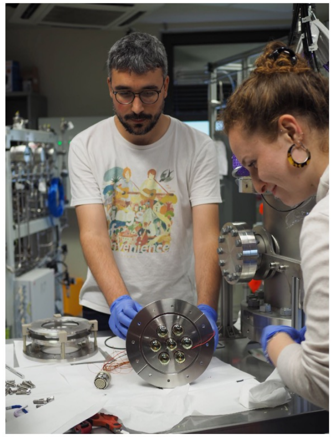
Funded detectors (thus far)



The Gaseous Prototype (GaP) Assembly

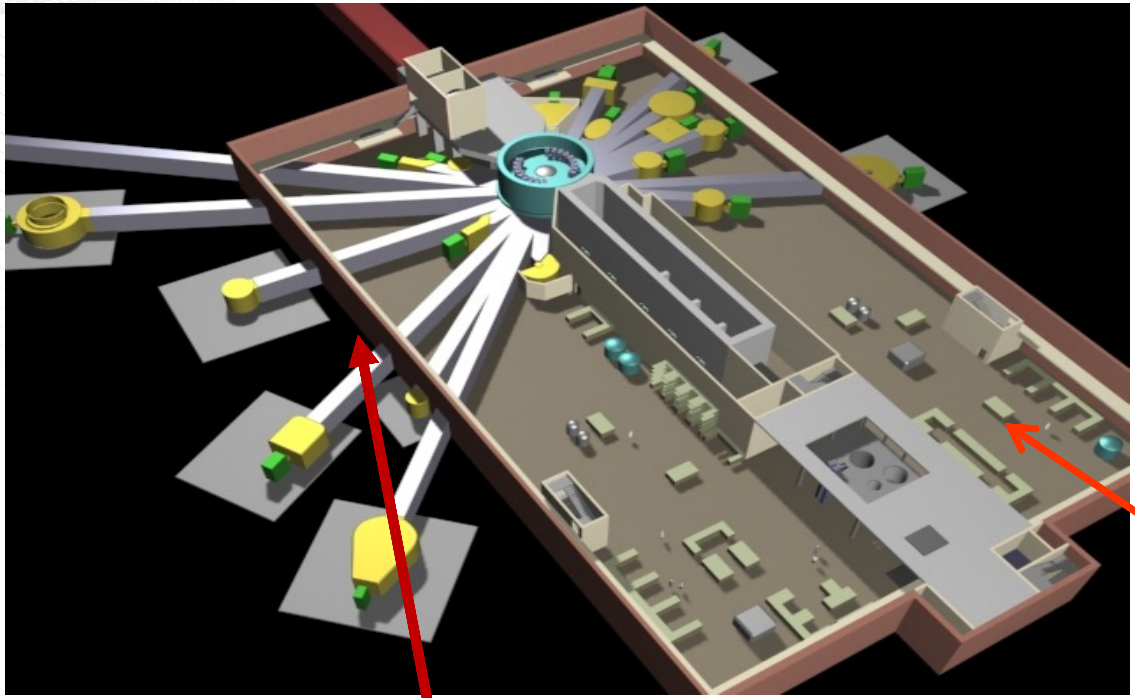




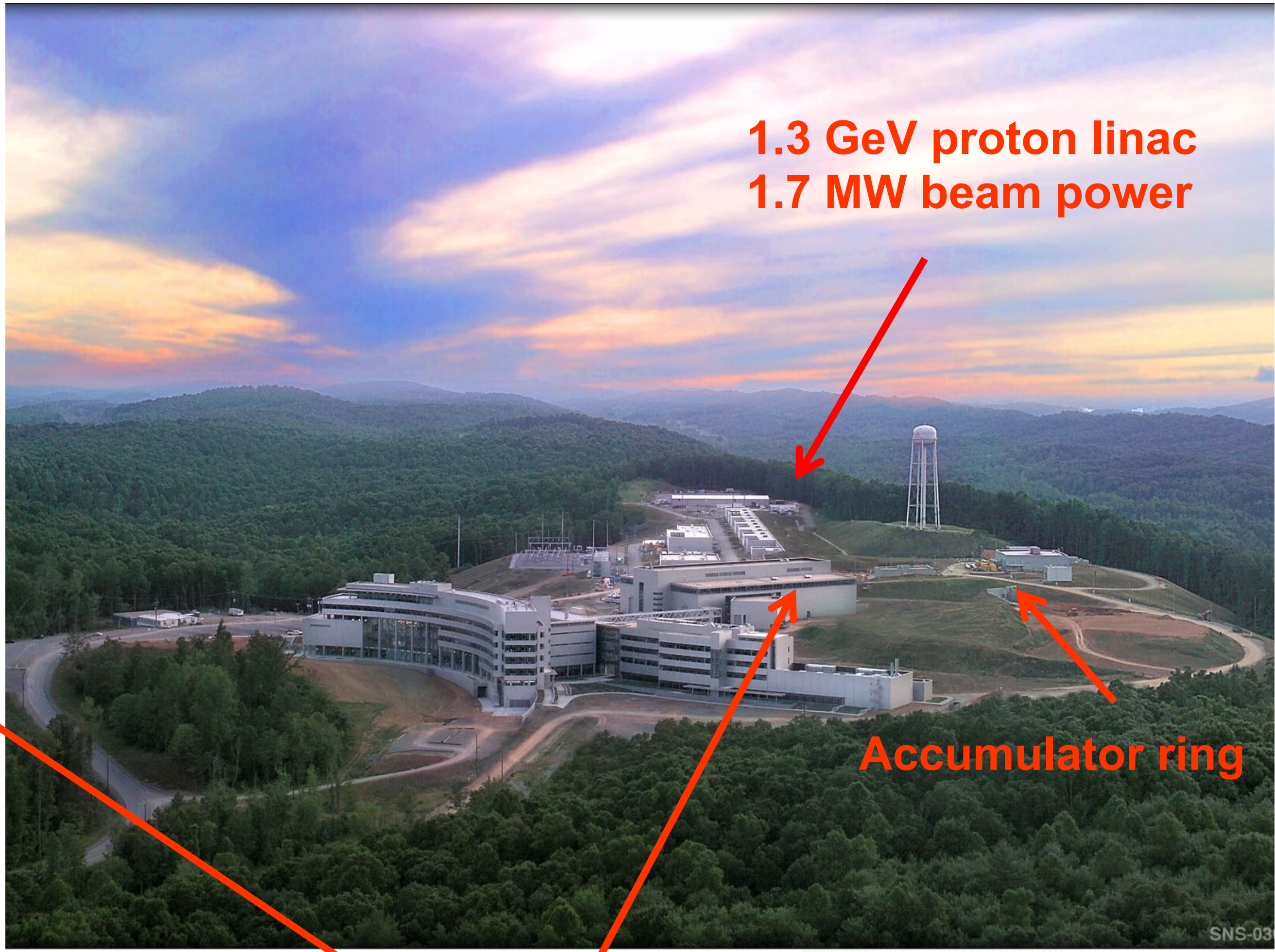


Neutrino Alley at the SNS

After extensive BG studies, we find a well protected location



Collaboration has 1m · 2m · 25m of good shielded space !!!

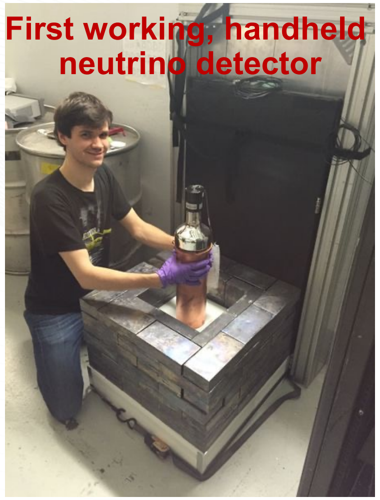


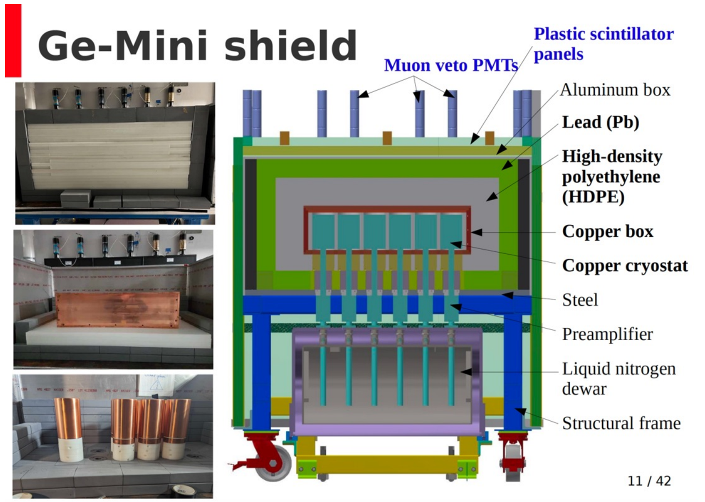
Target Building

It is 20-30 meters from the target. Space between the target and the alley is filled with steel, gravel and concrete

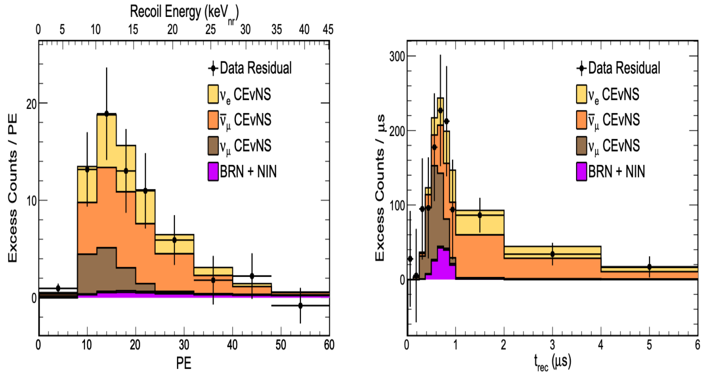
There are 10 M.W.E. from above

Detection of CEvNS at the SNS by the COHERENT





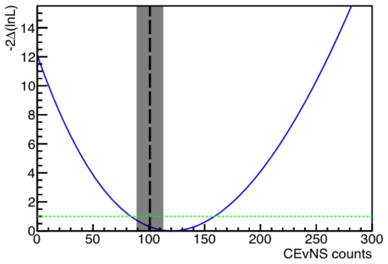
11.6 sigma effect
Cross section accuracy 16%
14 kg, CsI crystal

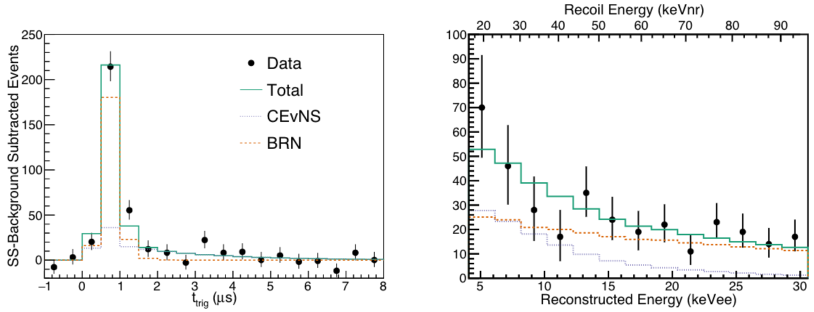


COHERENT, PRL 129 (2022) 081801

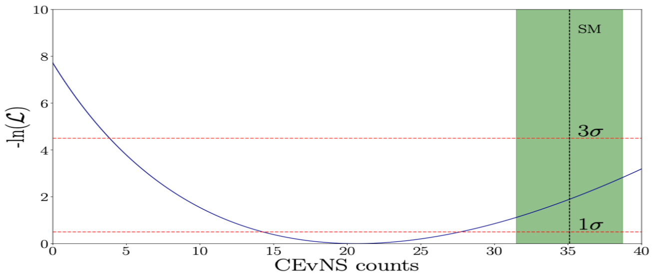
CENNS-10 LAr detector
10 cm Pb + 1.25 cm Cu
+ 20 cm H_2O shielding

24 kg fiducial volume
2 x 8” Hamamatsu PMTs,
18% QE at 400 nm

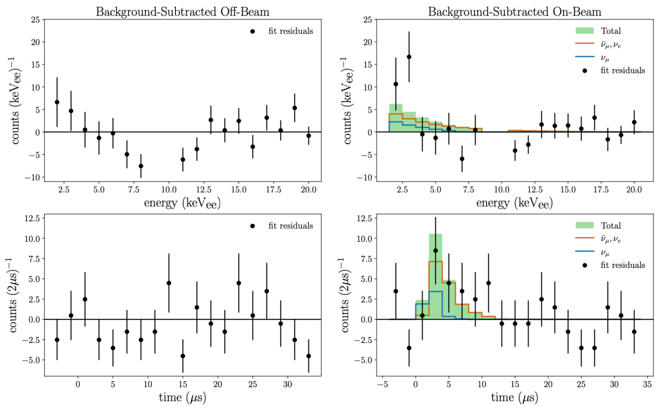




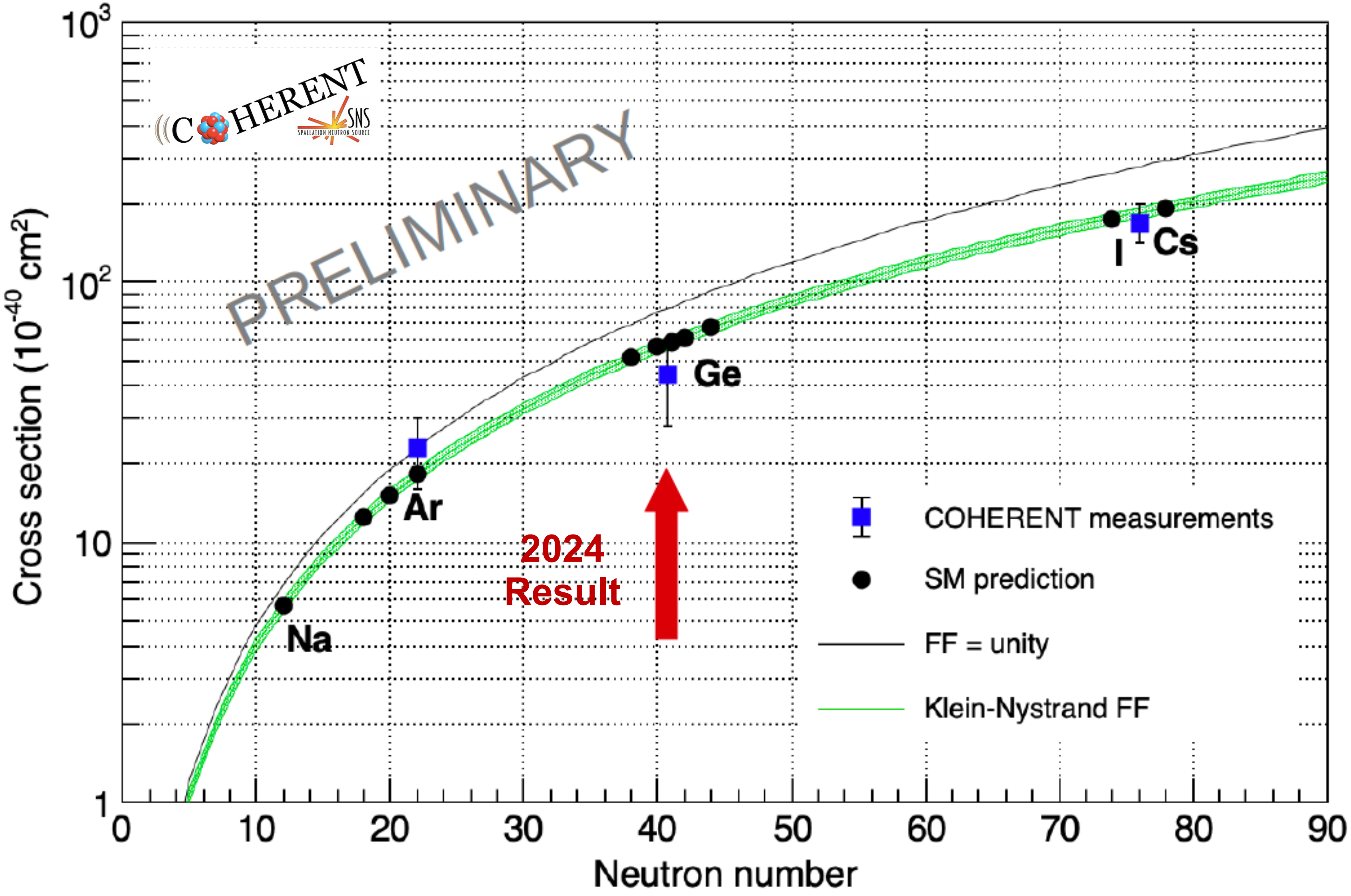
***Phys.Rev.Lett.* 126 (2021) 1, 012002**



arXiv:2406.13806



COHERENT Published Detection of CEvNS on Three Targets



All three individual results are in agreement with the Standard Model within one sigma

However, accuracy is limited so far

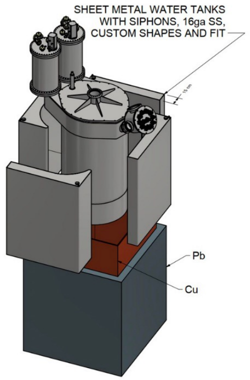
Dominant source of uncertainty is the knowledge of the Neutrino Flux at the SNS
We believe it is calculatable within 10% accuracy. Phys. Rev. D, 106(3):032003, 2022, 2109.11049.

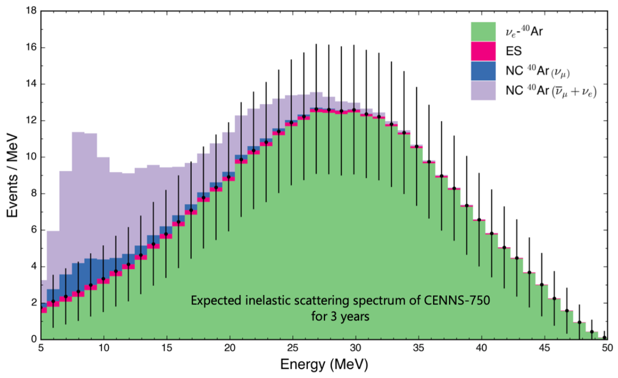
Near Future at the SNS

Transition from 22 kg to 750 kg LAr detector.

Can fit at the same place where presently CENSS-10 is

Expect to see 3k CEvNS events per year

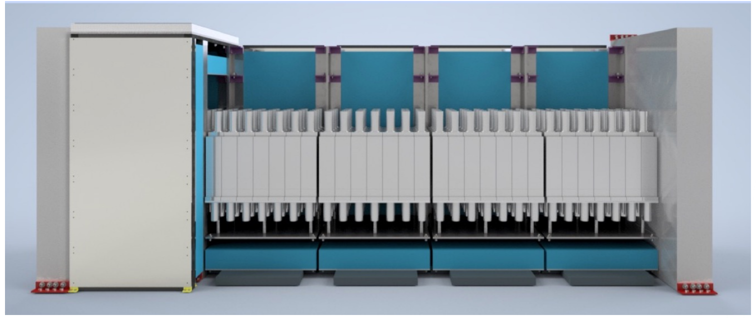


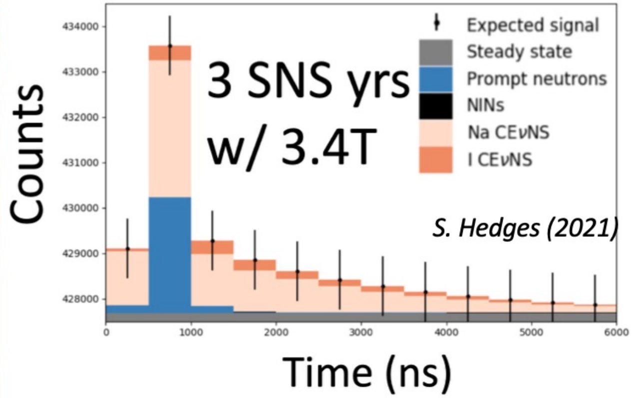


Cryostat for Detector is being build by Korean collaborators at SNU

NaIvETe - Sodium Iodide neutrino Experiment Tonne scale

Up to 3400kg of NaI detectors
7.7kg NaI crystals
- Dual gain bases: CEvNS + CC
- Baseline: ~21-24 m



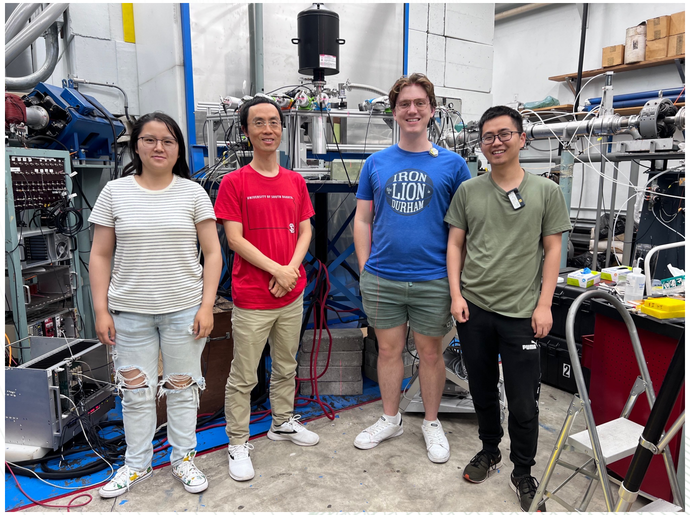


Cryo-CsI

10 kg undoped CsI at ~40K
SiPM readout x2 PDE relative to PMT.

Lover threshold then original CsI result. x2.5 times light yield.
Baseline: T.B.D.

Presently Quenching measurements at 40K at TUNL



Heavy Water Detector to Normalize Neutrino Flux at the SNS

S.Nakamura et. al. Nucl.Phys. A721(2003) 549

Prompt NC ν_μ +d → 1.8*10^{-41} cm^2
Delayed NC $\nu_{e\mu\text{-bar}}$+ d →6.0*10^{-41} cm^2
Delayed CC ν_e + d → 5.5*10^{-41} cm^2

Detector calibration with
Michel Electrons from cosmic muons
(same energy range)

Neutrino Alley space constraints for the D2O detector are:

– 1 m diameter x 2.3 m height

- Locations 20 meters from the SNS target

Will do CC measurement on Oxygen for SN.

Second Module will be with H_2O only

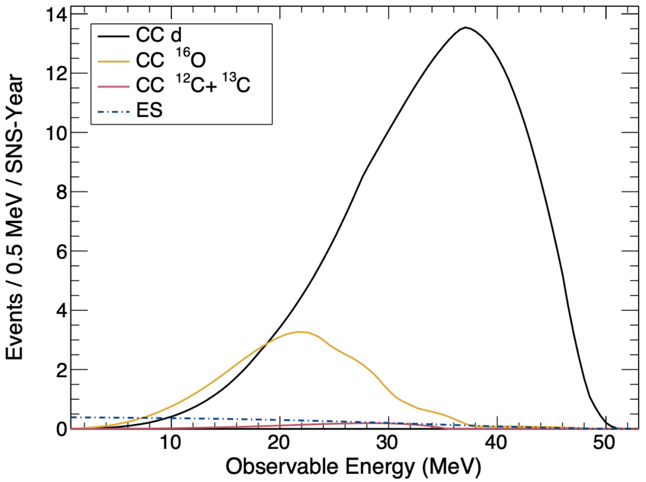
Detector commissioned in July 2023
Presently taking data
expect to record 4 neutrinos per day.

$$\nu_e + d \rightarrow p + p + e^-$$

Specifications

- 0.6 tons D_2O within acrylic inner vessel
- Water Cherenkov Calorimetry
- H_2O "tail catcher" for high energy e^-
- Outer light water vessel contains PMTs, PMT support structure, and optical reflector.
- Outer steel vessel
- Lead Shielding
- Hermetic veto system

JINST 16 (2021) 08, 08

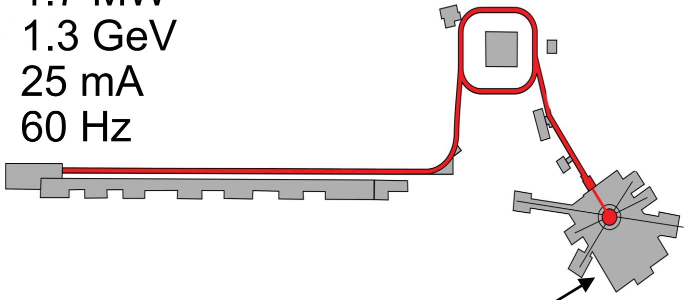


Upgrades for SNS are coming

Today

- 900 users
- Materials at atomic resolution and fast dynamics

1.7 MW
1.3 GeV
25 mA
60 Hz

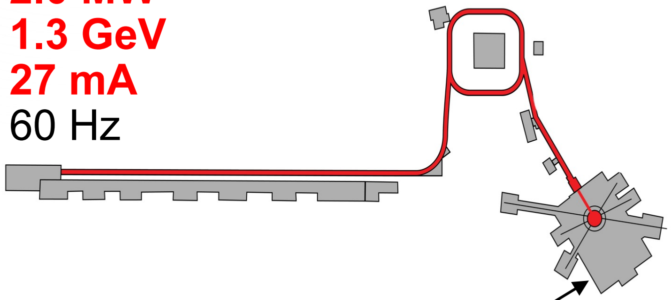


FTS
1.7 MW
60 Hz

2025 after PPU

- **1000+** users
- Enhanced capabilities

2.0 MW
1.3 GeV
27 mA
60 Hz



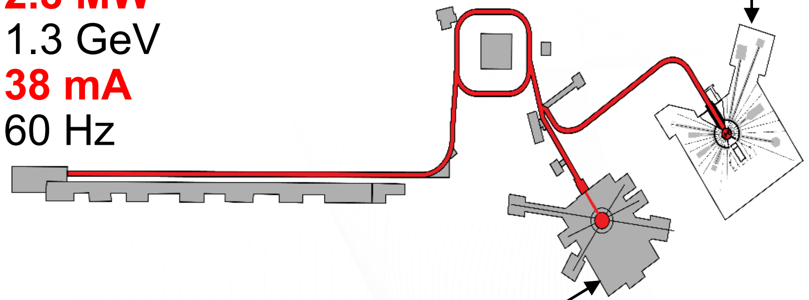
FTS
2 MW
60 Hz

2029 after STS

- **2000+** users
- Hierarchical materials, time-resolution and small samples

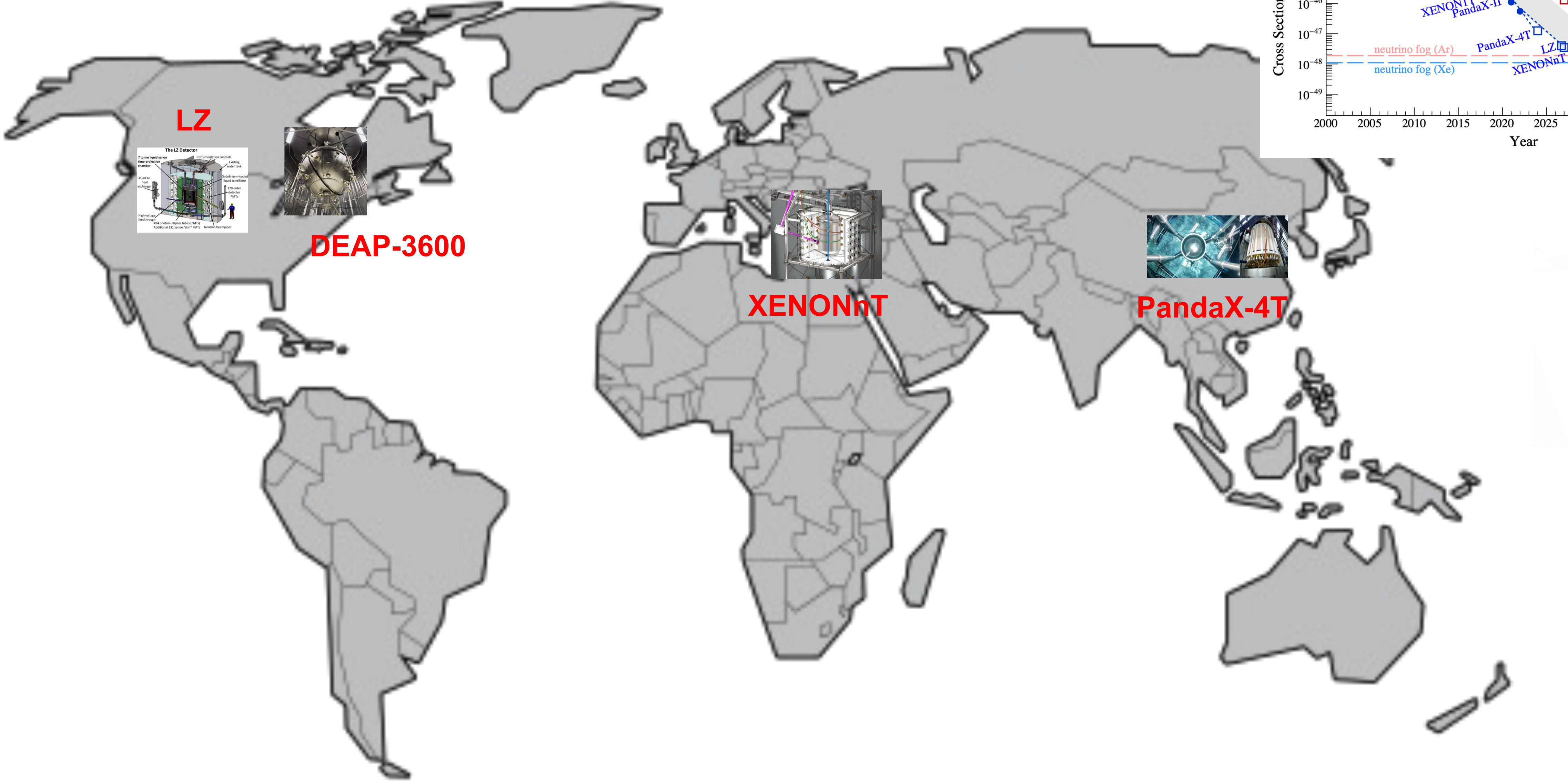
STS
0.7 MW
15 Hz

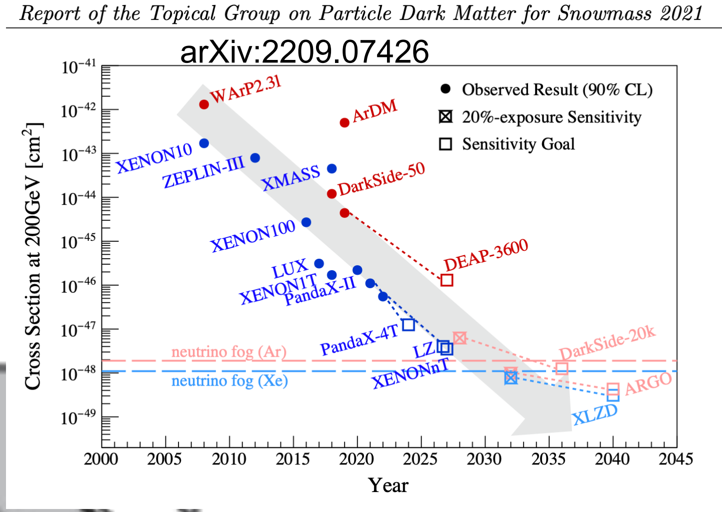
2.8 MW
1.3 GeV
38 mA
60 Hz



FTS
2 MW
45 pulses/sec

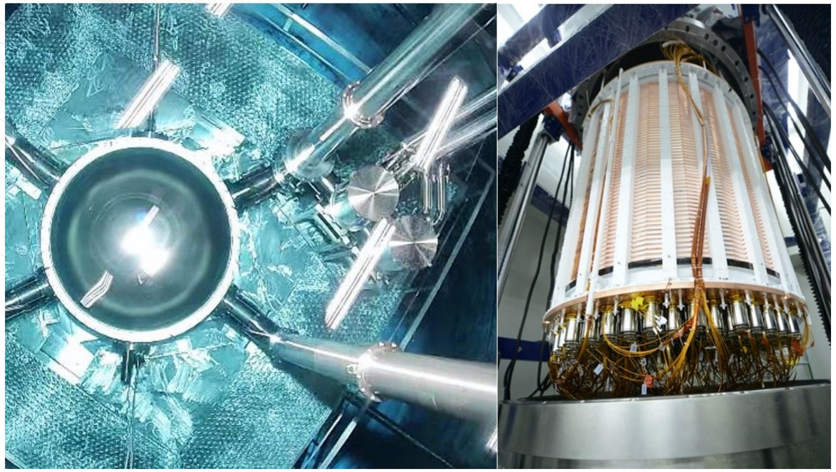
Solar Neutrino Detection via CEvNS by a large *WIMP Detectors*





2024 Break Through
Detection of solar ^{8}B neutrinos via CEvNS

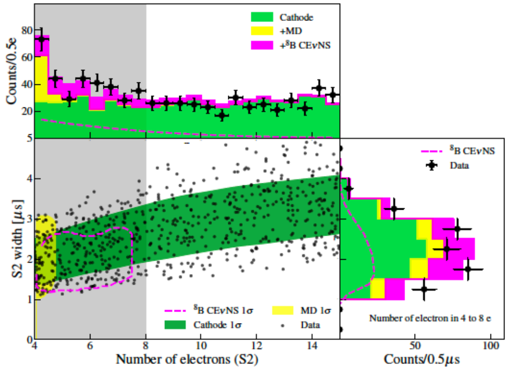
PandaX-4T(China)



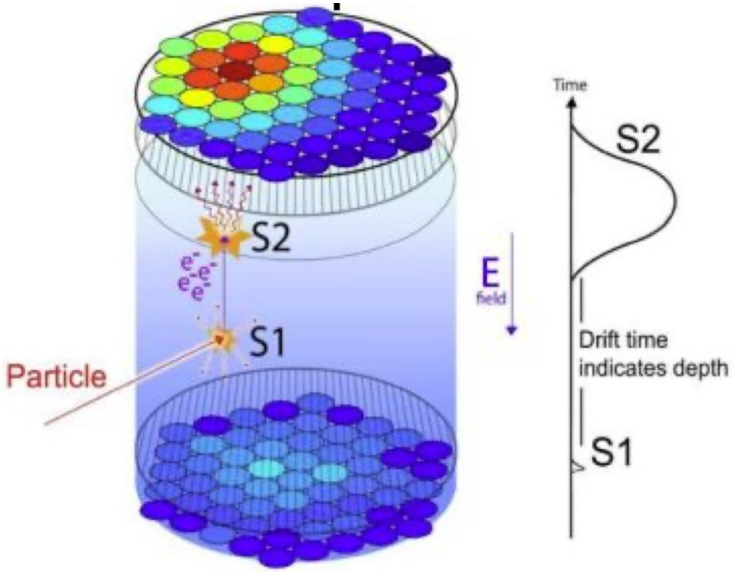
368 3” PMT’s, 2.29 t · y, ~2.5t fiducial
Analysis is mostly on S2 signal with Threshold 4 e^-
6720 MWE underground

Signal 75+/-28
Measured flux $(8.4\pm3.1)\cdot10^6$ cm^2 sec^{-1}

arXiv:2407.10892



Both experiments are 2 phase LZe detectors

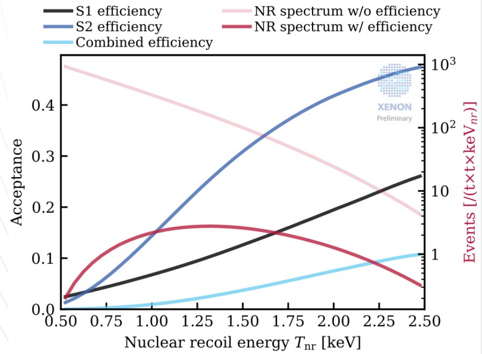


XENON nT(Italy)

494 3” PMT’s, 3.51 tonne year,
Threshold 2 phe S1 120 Phe (7e-) S2
3400 MWE underground

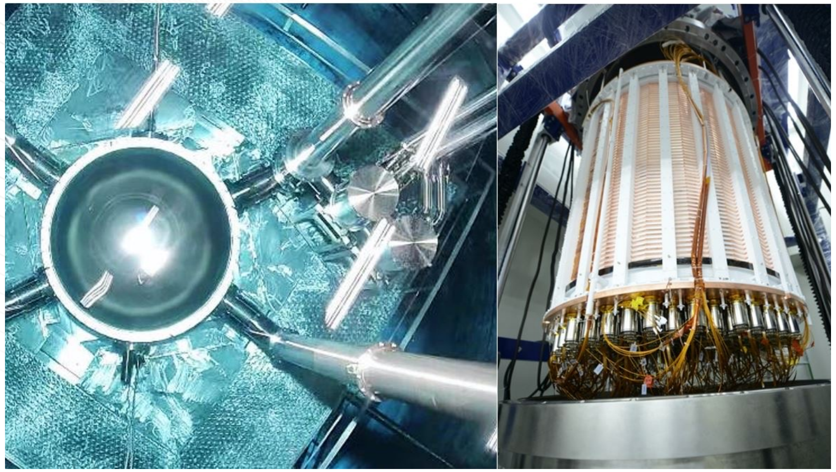
Signal 10.7+3.7-4.2
Measured flux $(4.7^{+3.6}_{-2.4})\cdot10^6$ cm^2 sec^{-1}

arXiv:2408.02877v1



2024 Break Through
Detection of solar ^{8}B neutrinos via CEvNS

PandaX-4T(China)

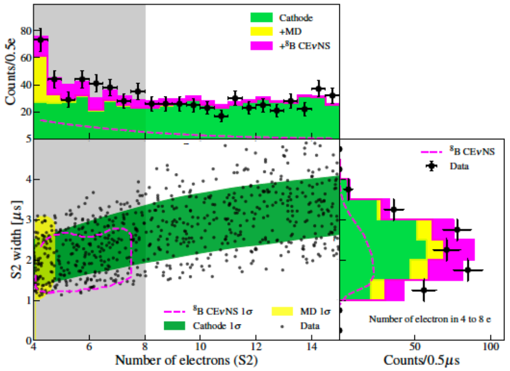


368 3" PMT's, 2.29 t · y, ~2.5t fiducial
Analysis is mostly on S2 signal with Threshold 4 e^-

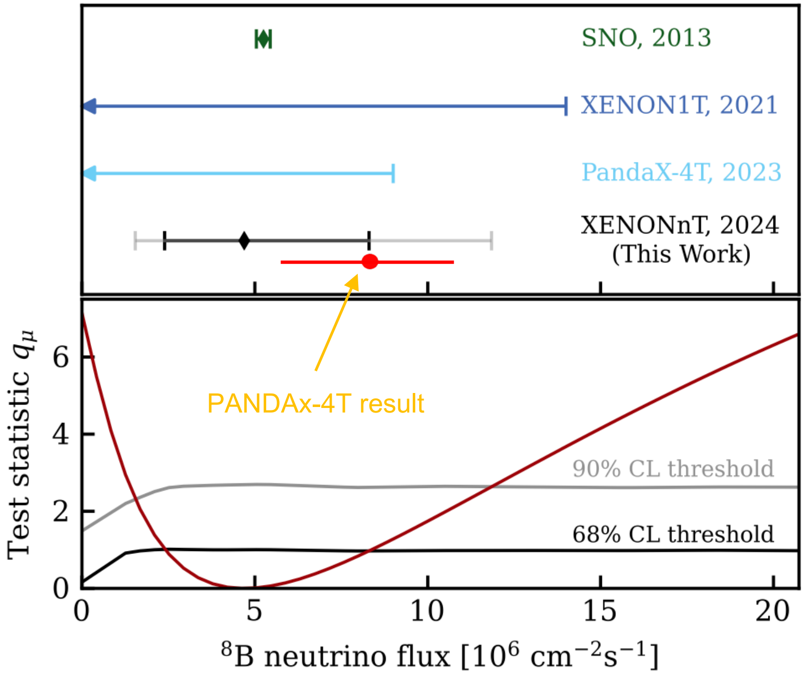
Signal 75+/-28

Measured flux $(8.4\pm3.1)\cdot 10^6$ cm^2 sec^{-1}

arXiv:2407.10892



arXiv:2408.02877v1

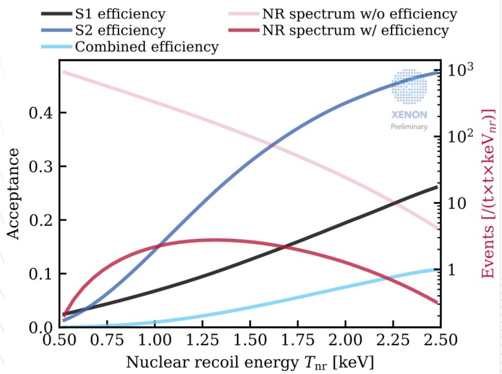


XENON nT(Italy)

494 3" PMT's, 3.51 tonne year, ?tones fiducial
Threshold 2 phe S1 120 Phe (7e-) S2

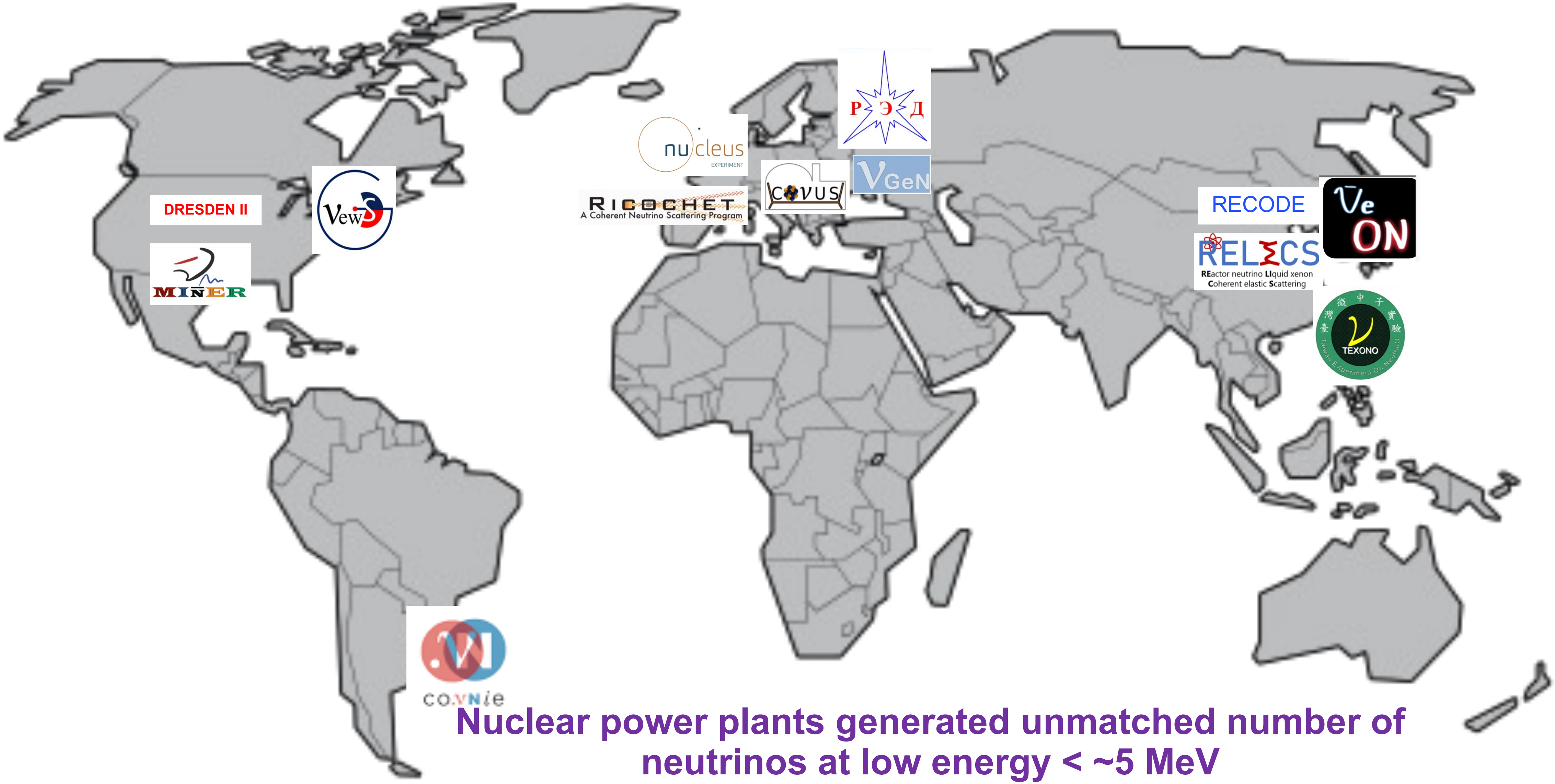
Signal 10.7+3.7-4.2

Measured flux $(4.7^{+3.6}_{-2.4})\cdot 10^6$ cm^2 sec^{-1}



SNO: $(5.25^{+0.11}_{-0.12}(sys)\pm 0.16(stat.))\cdot 10^6\ cm^{-2}s^{-1}$

Nuclear Reactors and CEvNS

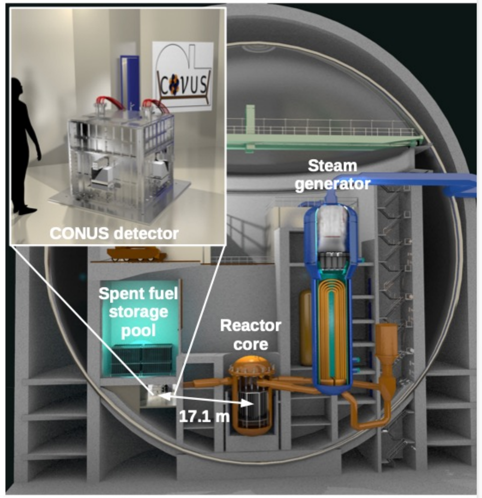


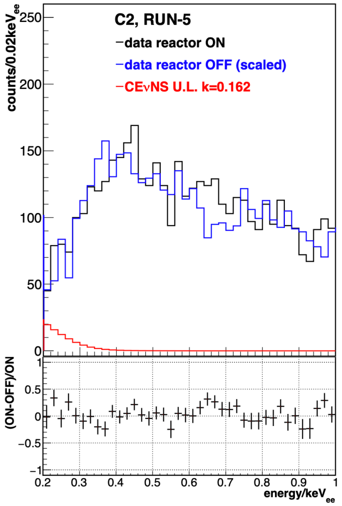
Nuclear power plants generated unmatched number of neutrinos at low energy < ~5 MeV

Germanium Based Experiments

CONUS
Four 1kg Ge detectors Brokdorf, Germany, 3.9 GW_{th} 17 m
Threshold 210 eV_{ee}

Data 2018-2022





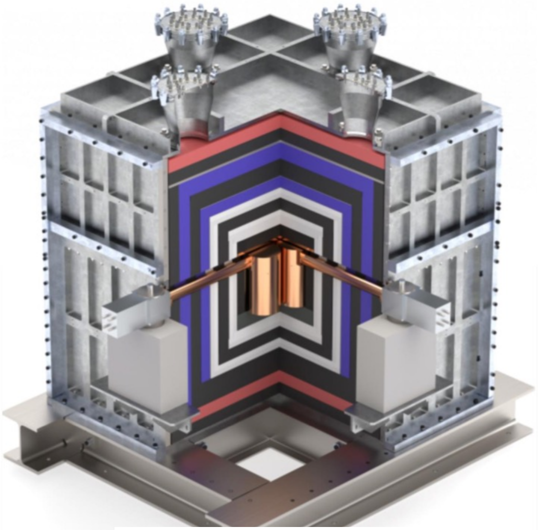
arXiv:2308.12105

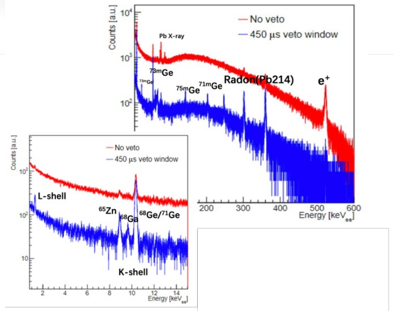
	Run-1/Run-2	Run-5
ON/kg*d	248.7	426
OFF/kg*d	58.8	272
threshold/eV_{ee}	296-348	210
Limit (k=0.162)	factor 17 > SM	factor 2 > SM

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

CONUS+
Four 1kg Ge detectors Leibstadt, Switzerland
3.6 GW_{th} 20.7 m
Threshold 150 eV_{ee}

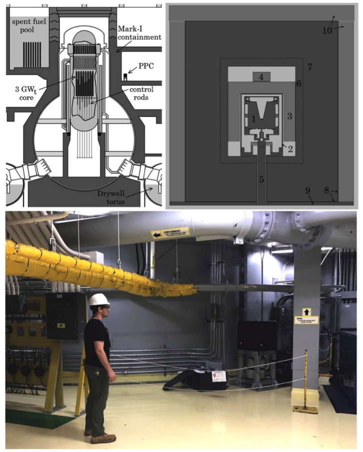
In operation since 2023
Two muon veto layers
Smoller size of point contact





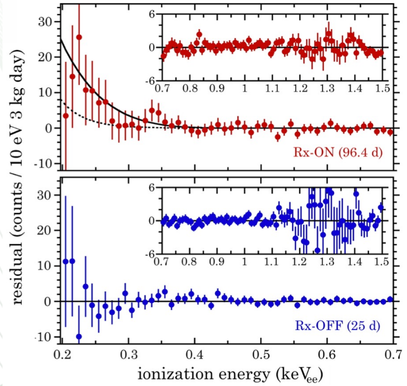
DRESDEN II
2.9kg Ge detector DRESDEN II(USA)
2.96 GW_{th} 8 m
Threshold 150 eV_{ee}

In operation during ~3.5 months in 2021



arXiv:2202.09672

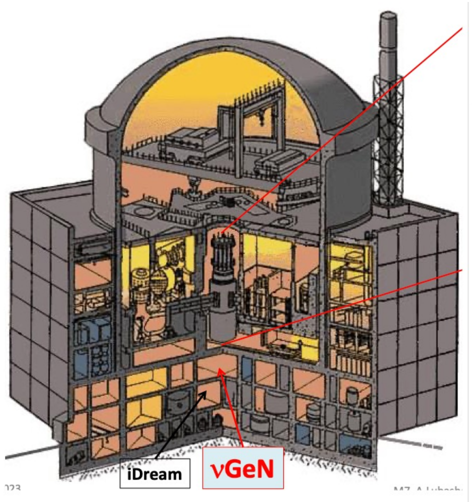
"very strong" preference for the presence of CEvNS



Germanium Based Experiments

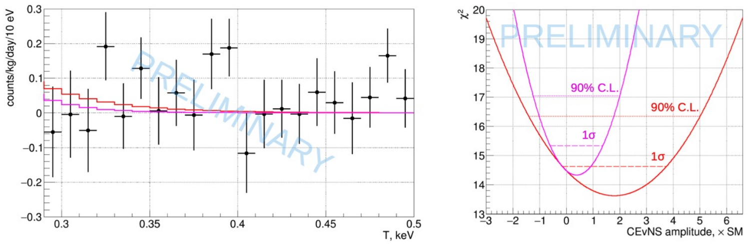
νGEN
1.5kg Ge detector Kalinin (Russia)
3.1 GW_{th} 11-12.5 m
Threshold 200 eV_{ee}

Data 2022-2023



Phys.Part.Nucl.Lett. **21 (2024) 4, 680-682**

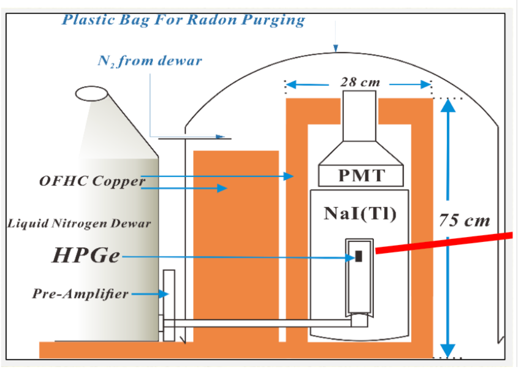
Lindhard K=0.162
Mod Lindhard k=0.157

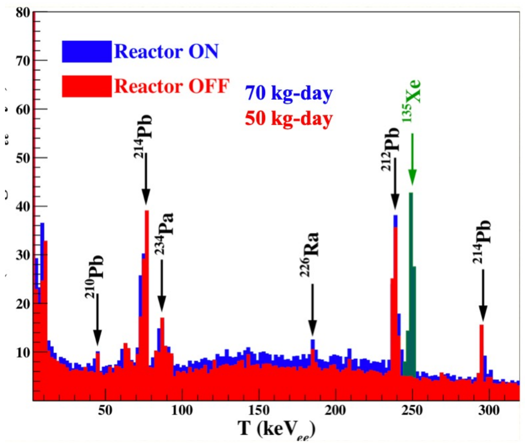


QF	Prediction, ev./kg/day	Sensitivity, ×SM	68% expectation for a 90% C.L. limit, ×SM	Best fit, ×SM	90% C.L. limit
CONUS	0.159	4.1	2.3-6.0	1.80	5.0
Dresden	0.278	2.6	1.6-3.6	0.38	2.0

TEXONO
1.43kg Ge detector Kuo-Sheng
(Korea) 2.9 GW_{th} 28 m
Threshold 200 eV_{ee}

Data since 2003
Preliminary limit at 4.2 SM

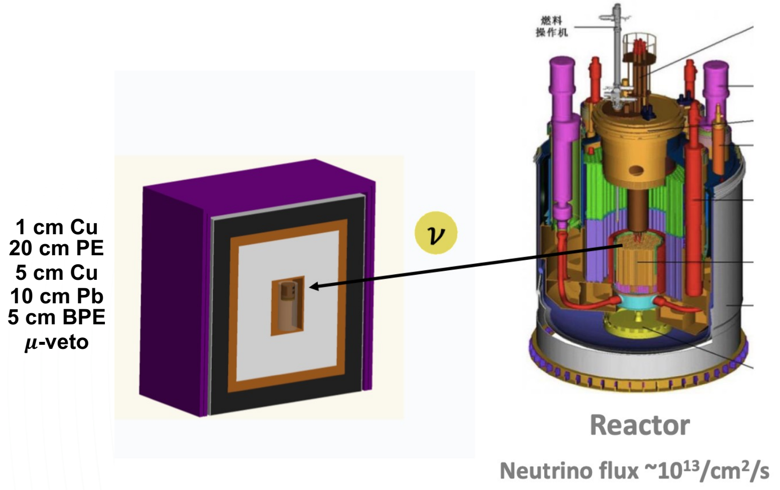




Considering new reactor
site (Sanmen) at 11m, Tr 150 eV_{ee}

RECODE
Two arrays with five 1kg Ge detectors
each, Sanmen 3.4 GW_{th} Power plant, 11,
22 m
Threshold 160 eV_{ee}

Starting in 2025



Schedule

2023	2024	2025	2026
✓ On site environmental background measurement/estimation ✓ Design, production, and processing of various subsystems	✓ Subsystem independent testing ✓ Joint testing work	✓ Transport to NPP, installation, testing ✓ First physics run	✓ Second physics run ✓ Data analysis

Subsystems testing @CJPL and ground, Sanmen Laboratory preparation

Physics Run (FS, NS, VNS) @Sanmen NPP

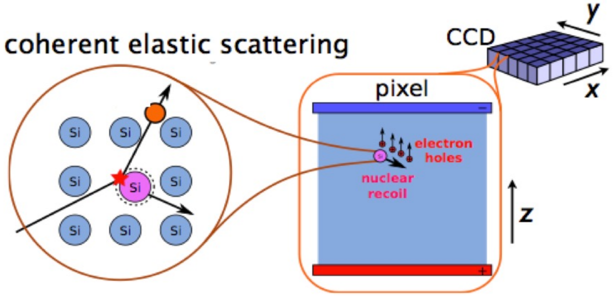
National Laboratory

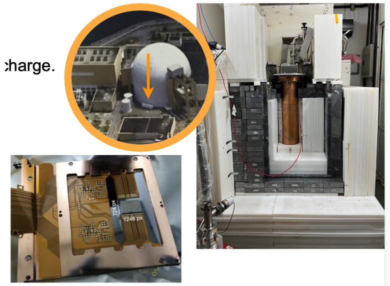
Other Technologies, Small Detectors

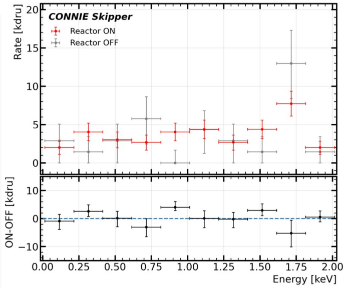
CONNIE

0.5 g of CCD sensors Angra (Brazil)
3.96 GW_{th} 30 m
Threshold 15 eV_{ee}

Data 2021-2023

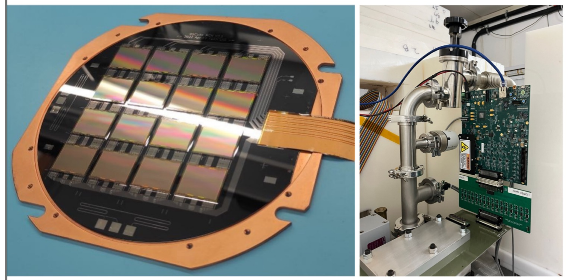






arXiv: 2403.15976

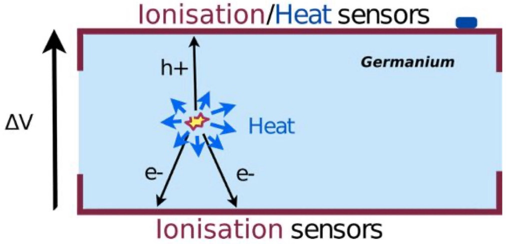
16 g of CCD starting from 2024

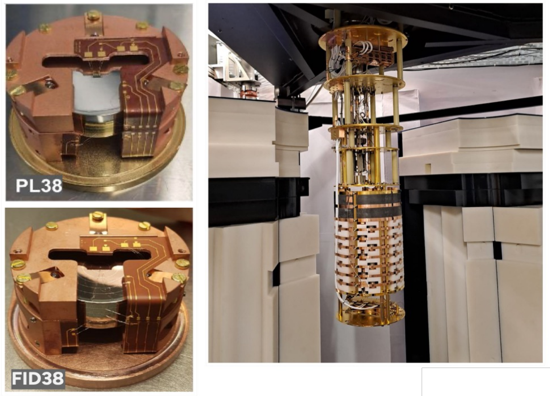


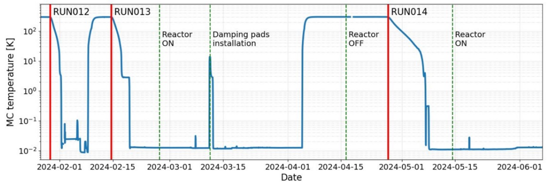
Ricoshet

0.68 kg Ge CryoCube with
Ionization and Heat redout
ILL (France) 58 MW_{th} 8.8 m
Threshold 160 eV_{ee}

Data starting from 2024







RUN012: Validation of cryogenics (8.6 mK)

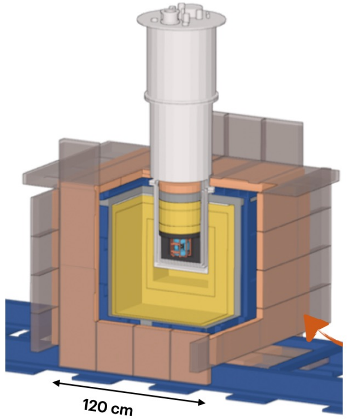
RUN013: Detector performance assessment (ON/OFF) and vibration mitigation

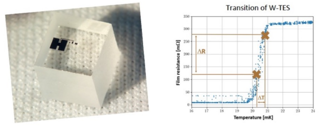
RUN014: Background characterization with full shielding

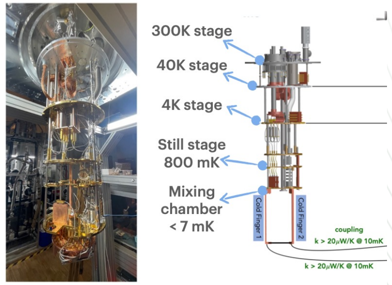
NUCLEUS

10 g cryogenic $CaWO_4$detector
with TES (transition Edge
sensor) readout.
Chooze(France) two Cores 2.4
GW_{th} each 77, 102 m
Threshold 20 eV_{ee}

Starting 2025



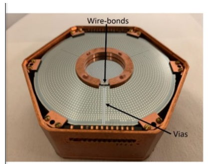


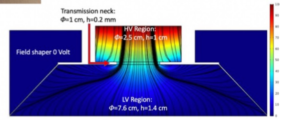


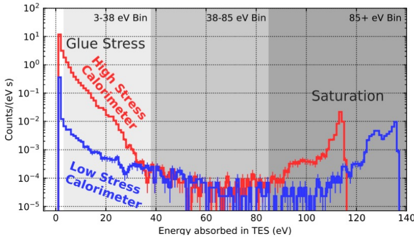
MINER

Super CDMS technology
Si, Ge, Al_2O_3 detectors
Threshold 100 eV_{ee}

Location and time TBD



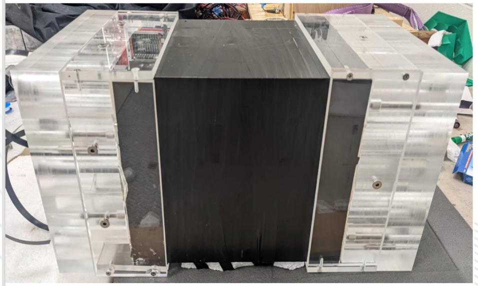




iZIP Detector with ionization and phonon sensors for ER/NR discrimination (>keV)

First SNOLAB Ge iZIP (fabricated at TAMU)

https://arxiv.org/pdf/1610.00006.pdf

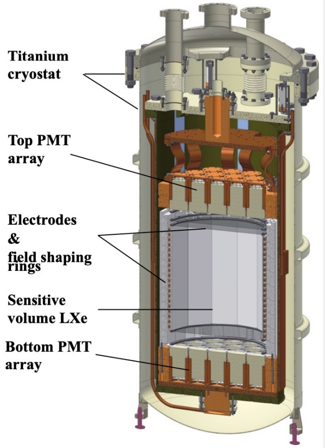


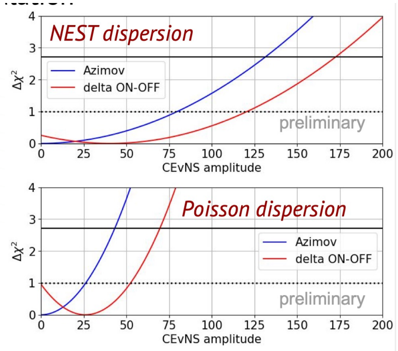
Other Technologies, Large Detectors

RED-100

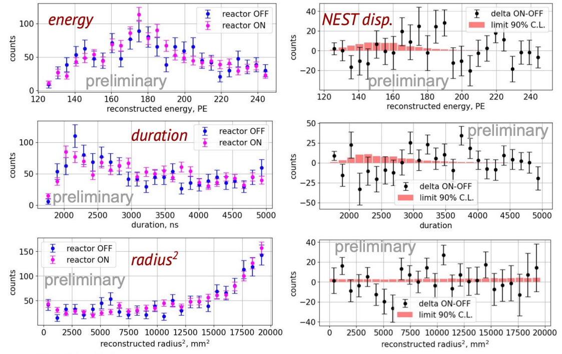
200 kg LXe two phase detector
26 3” PMTs
Kalinin (Russia) 3.1 GW_{th} 19 m distance
Threshold 4,5 e^-

Data 2021-2023





arXiv:2311.00870



RELICS

50 kg LXe two phase detector
Submerged in a water tank
64 2 by 2 cm^2 PMTs
Sanmen(China) 3.4 GW_{th},
22 m distance,
threshold 1 keV_{ne}

Deployment ???

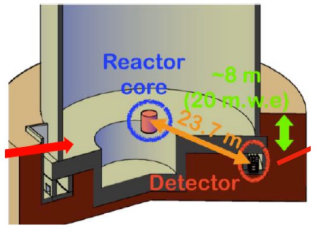
arXiv: 2405.05554

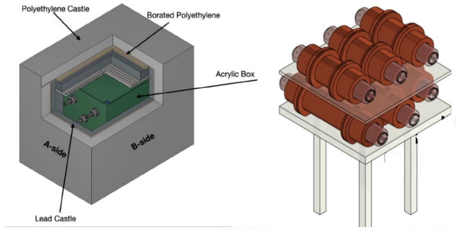
NEON

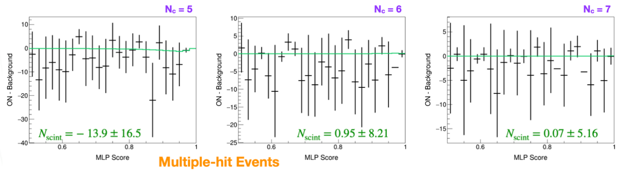
16.7 NaI[Tl] detectors

Hanbit-6 (Korea) 2.8 GW_{th}
23.7 m distance
Threshold 200 eV_{ee}

Data starting from 2022







Study on CEvNS observation

- Too high event rate due to phosphorescence
- Study on event selection to reduce noise events
- Single-hit events of full dataset will be used soon.

Considering to switch to LAr

There are Many Other very Nice Ideas and Developments

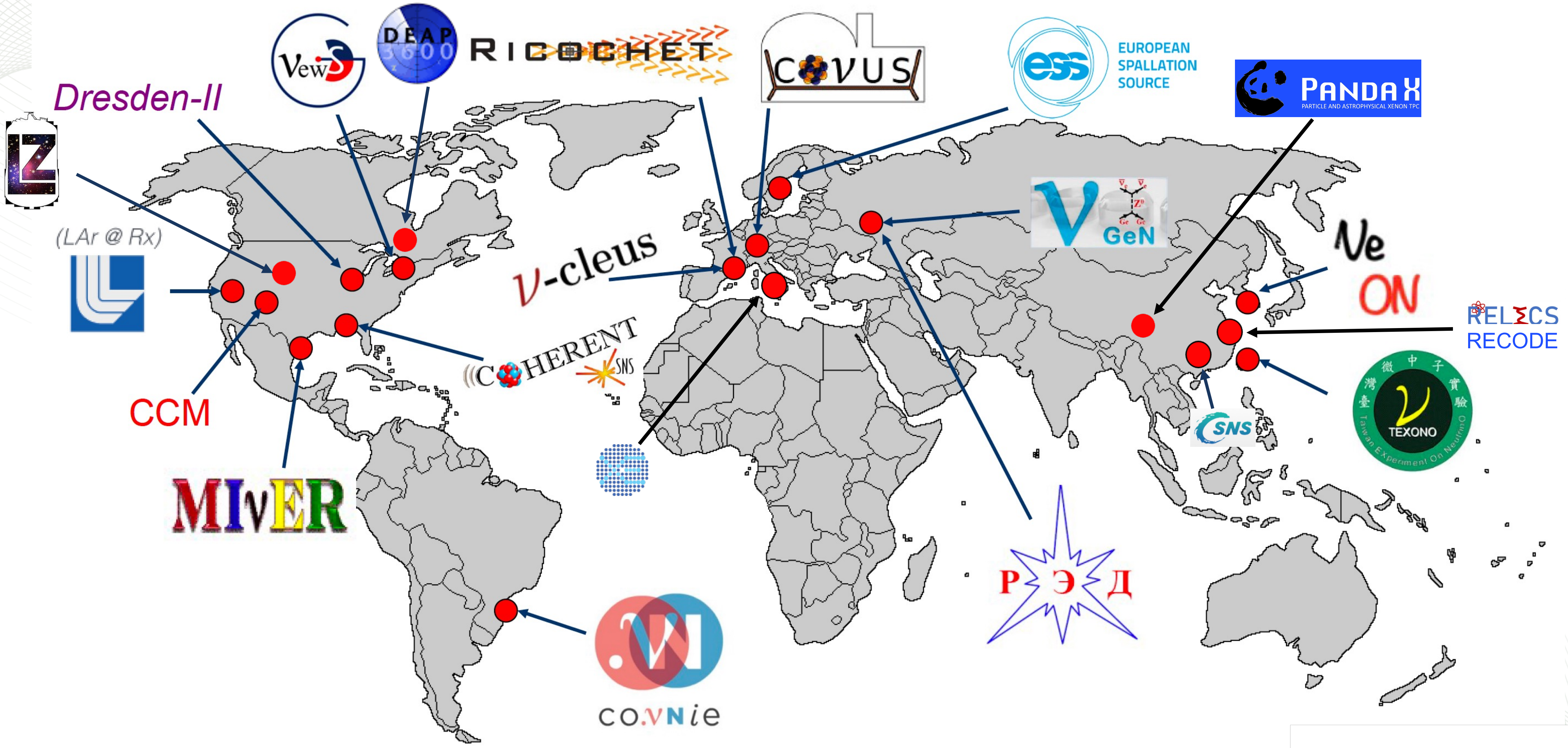
Many are Not Covered in This Talk
(Sorry, just not enough time)

I did want to have a generic illustration for all those initiatives but failed to came out with a good one.

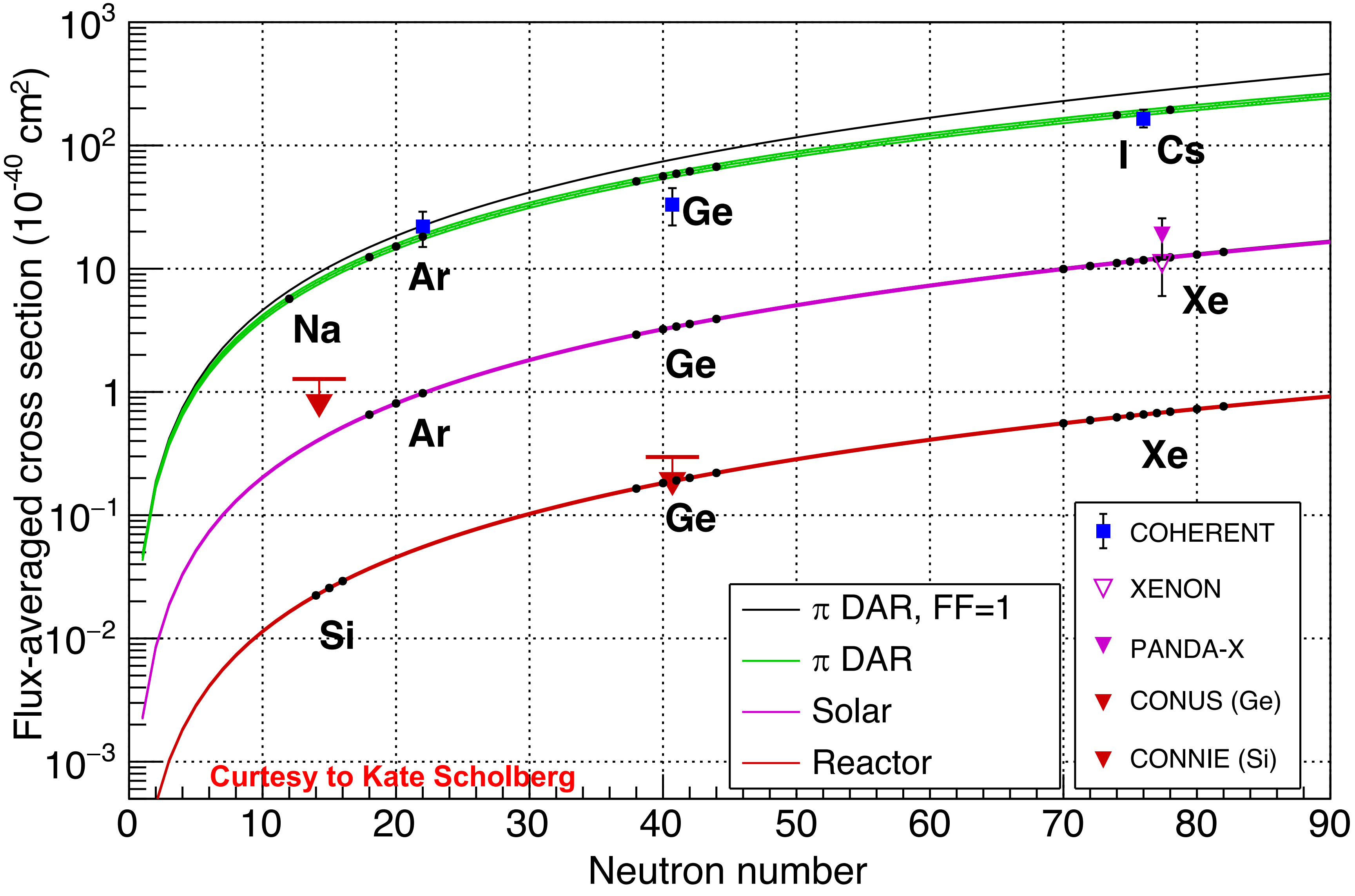
So, I asked I.A. to help me to draw multiple reactor neutrino detection technologies

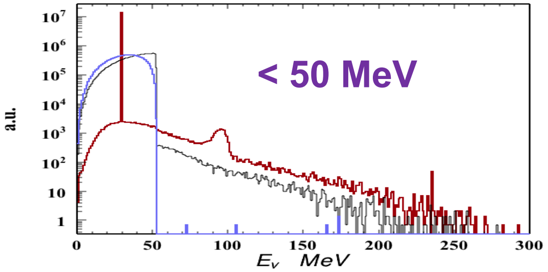
At this point, our field shouldn't worry about A.I. competition in detectors design.
At least not yet…

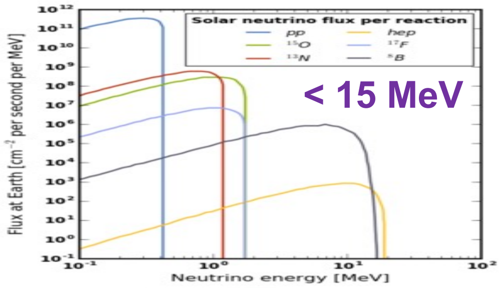
There are many activities around the world looking for CEvNS

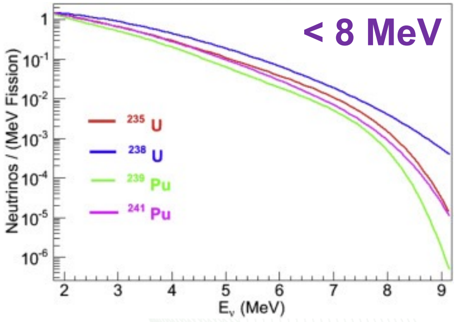


Almost Conclusion









Conclusion

CEVNs is the new tool to study neutrinos and The Standard Model

First results created waterfall of theoretical interpretations

CEvNS detection become worldwide efforts with multiple detector technologies

Community unitize DAR, Sun and Nuclear rectors at neutrino sources

This field become fertile ground for development of new low background and low threshold neutrino detectors

Next step is precision studies of CEvNS with high statistics and low systematics

Dawn of Magnificent CEvNS