COHERENT Experiment

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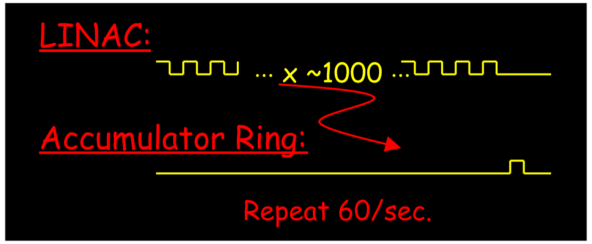
February 20th 2024,
International Symposium on Neutrino Physics and Beyond
Hong Kong

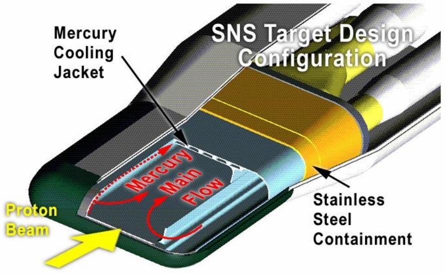
Test of the Standard model with CEvNS

Measurement on Neutrino Nucleus CC Cross Sections at Low Energy

COHERENT Experiment is Based at SNS (ORNL)

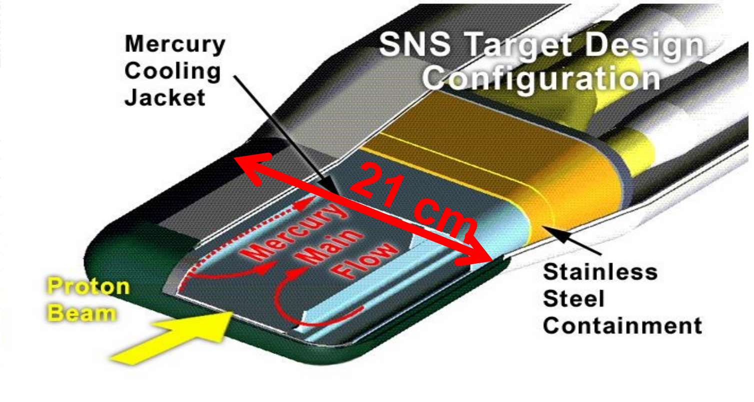
- *1 GeV, 1.7 MW proton beam*
- It is the world's most powerful pulsed neutrino source. Presently it delivers 9.2 · 10^{20} POT daily *~10% of protons produce 3 neutrino flavors*
- Neutrino energies at SNS are ideal to study CEvNS and low energy neutrino interactions
- *For 99% of neutrinos $E_{\nu} < 53$ MeV*
- Decay At Rest from pions and muons (DAR) gives very well-defined neutrino spectra
- 60 Hz, ~400 nsec beam spils let suppression of steady background by a factor of 2000.
- *It is like being at 1000 m.w.e underground*

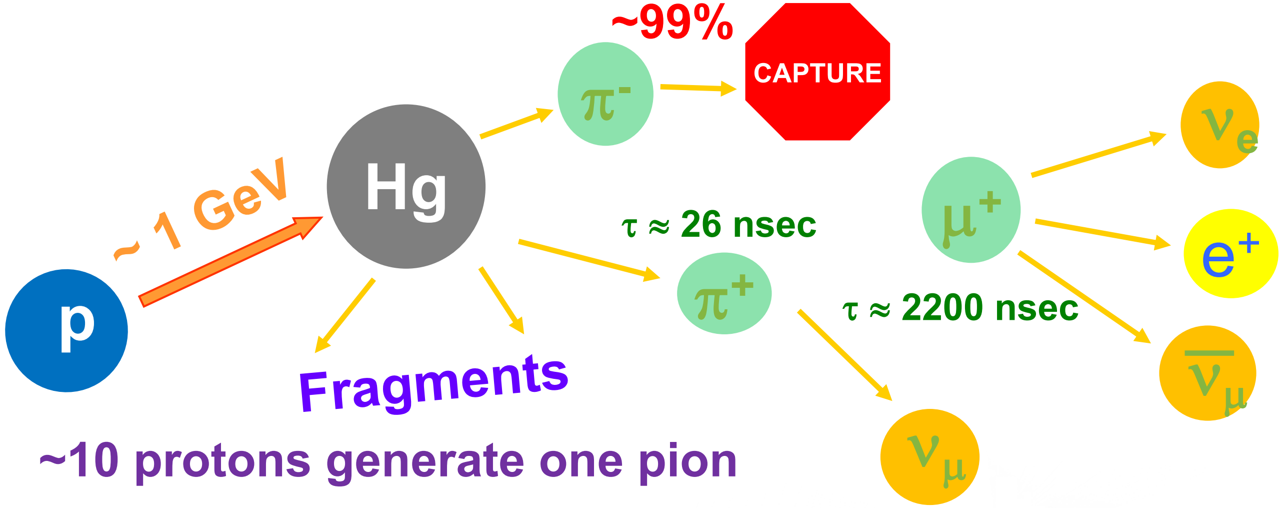


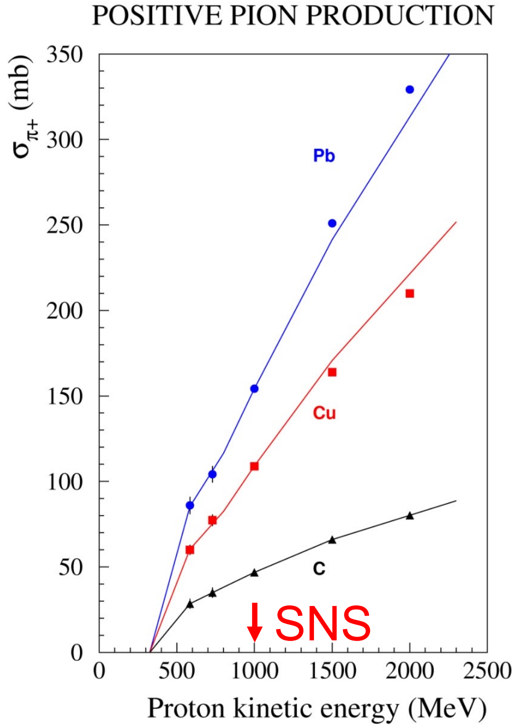


Compact Mercury Target
(7 x 40 x 50 cm^3)

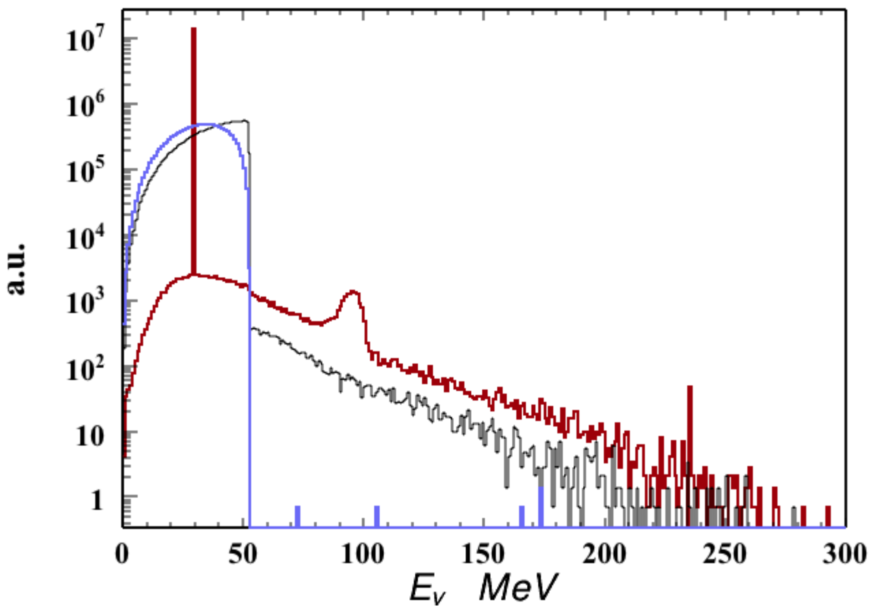
Neutrino Production at the SNS



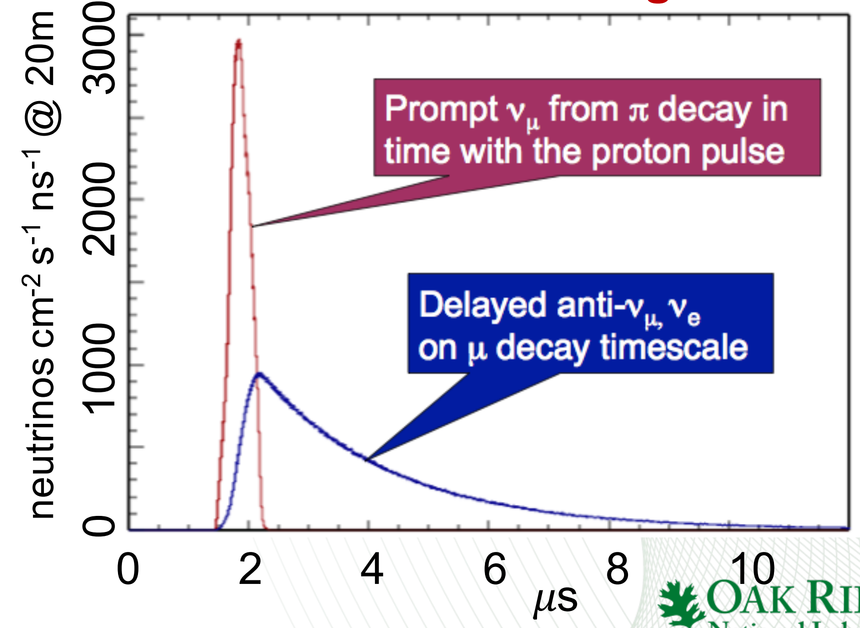




Neutrino Energy



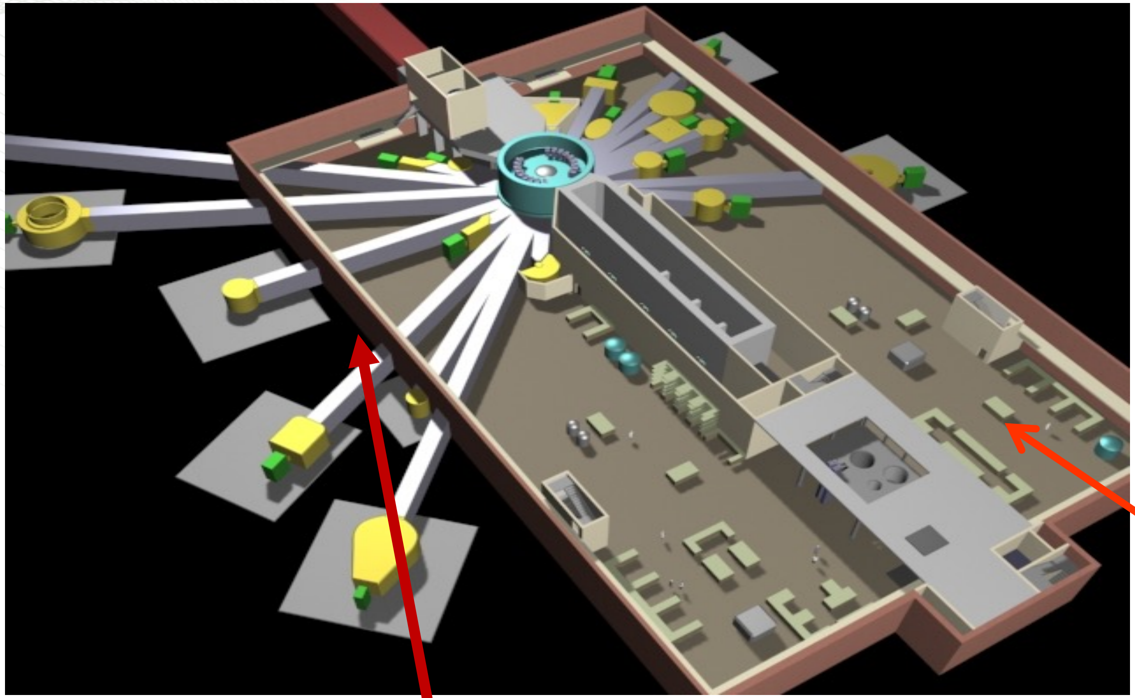
Neutrino Timing

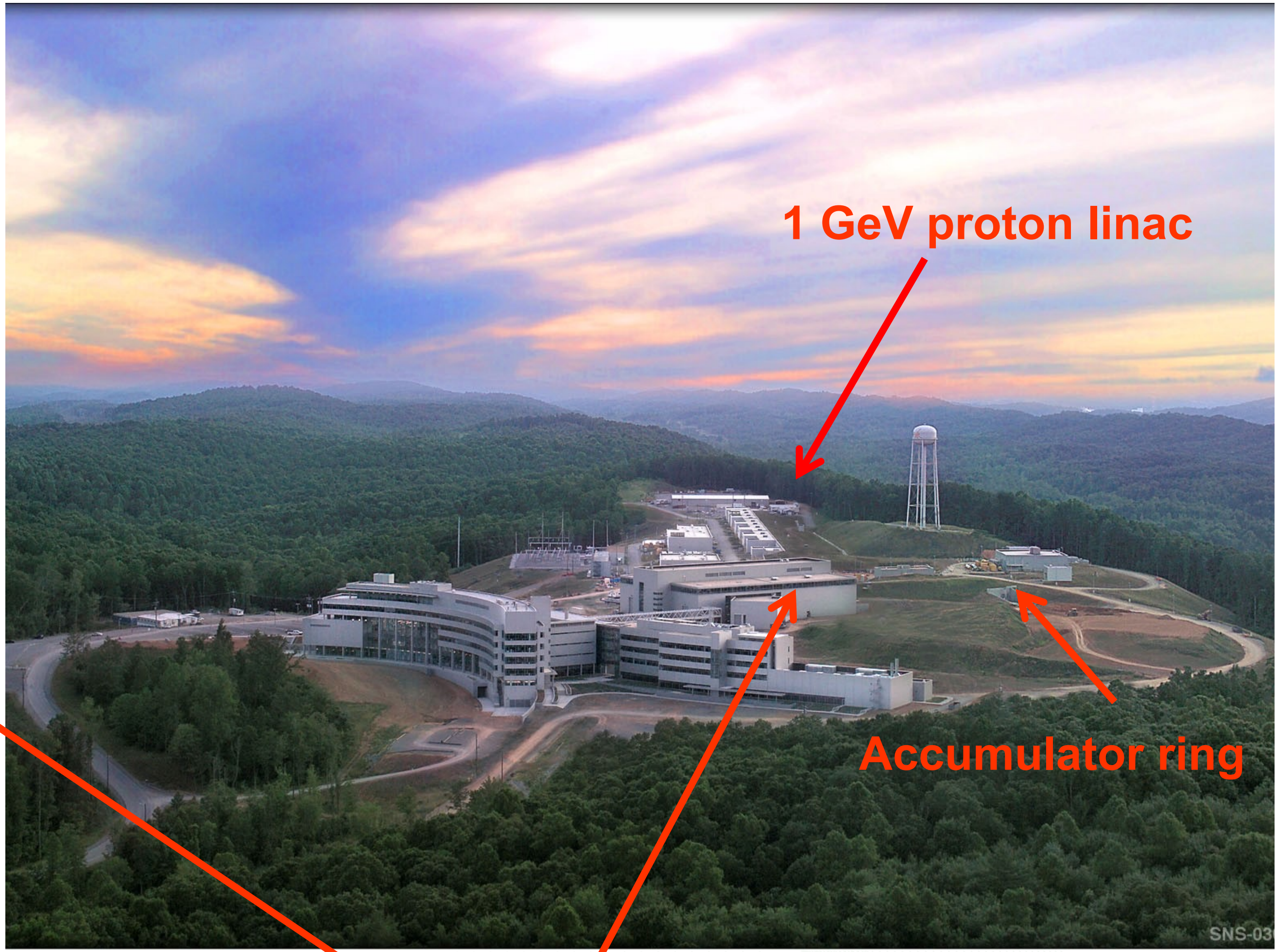


OAK RIDGE National Laboratory

Neutrino Alley

After extensive BG studies, we find a well protected location





Target Building

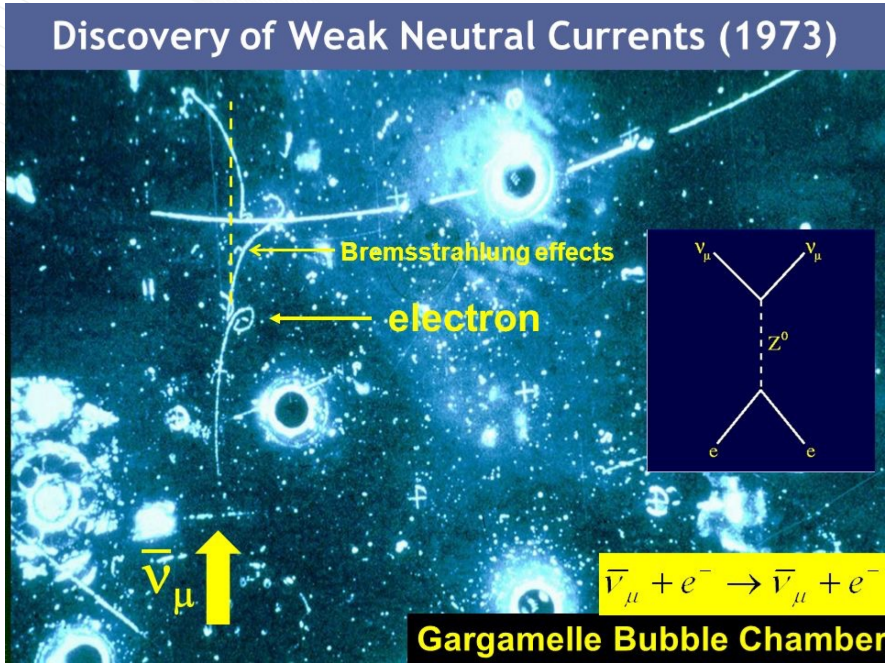
It is 20-30 meters from the target. Space between the target and the alley is filled with steel, gravel and concrete

There are 10 M.W.E. from above

We have 1m · 2m · 25m of good space !!!

Coherent Elastic neutrino Nucleus Scattering

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



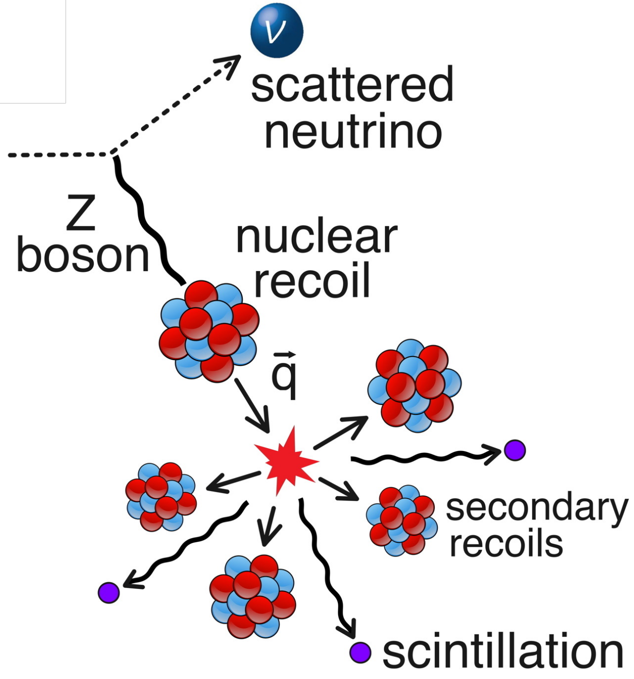
D.Z. Freedman PRD 9 (1974)

Submitted Oct 15, 1973

V.B.Kopeliovich & L.L.Frankfurt

JETP Lett. 19 (1974)

Submitted Jan 7, 1974



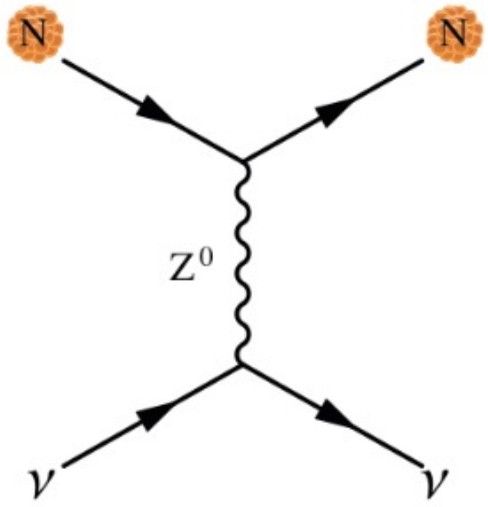
$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1 + \cos\theta) \frac{(N - (1 - 4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$

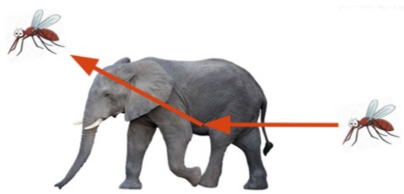
CEvNS cross section is well calculated in the Standard Model

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.

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

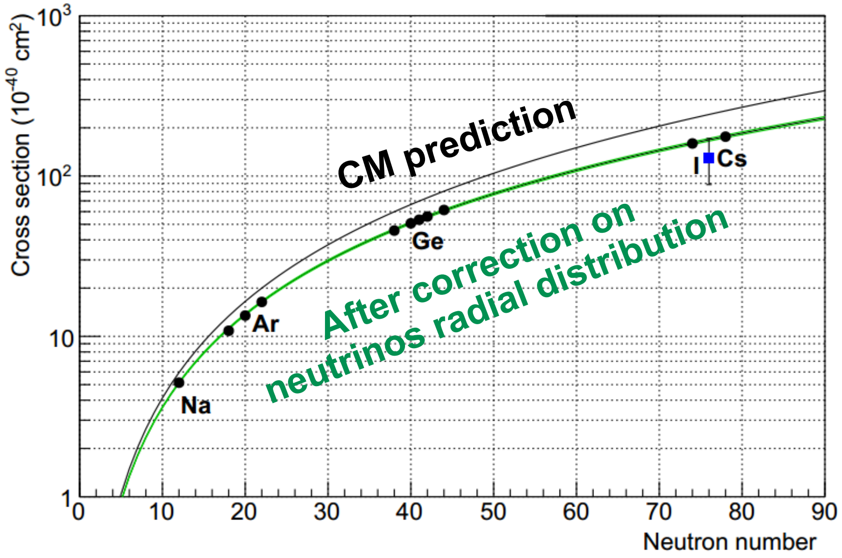


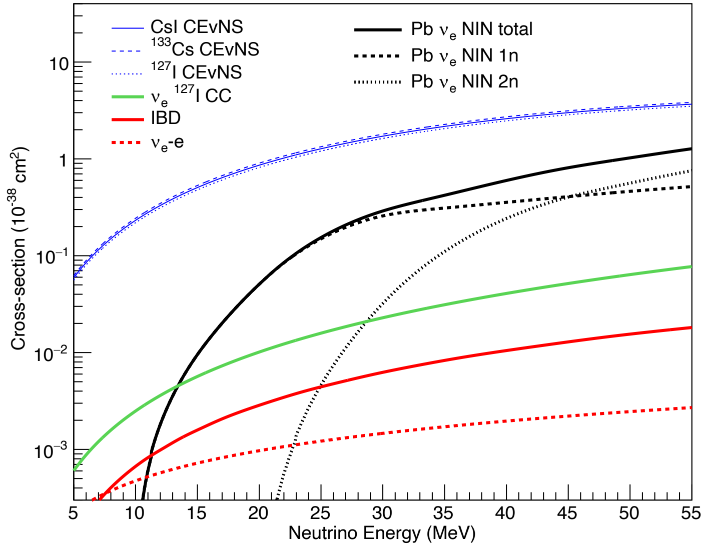


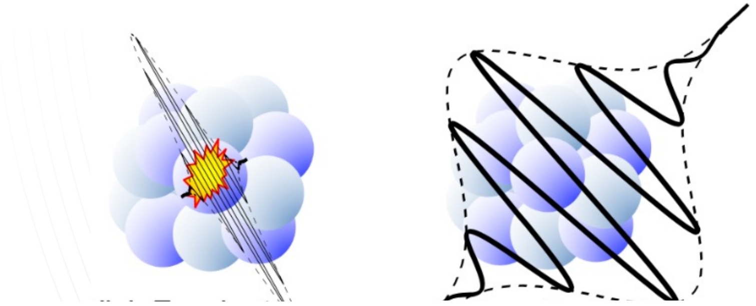
CEvNS cross-section is large, but very hard to detect

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.





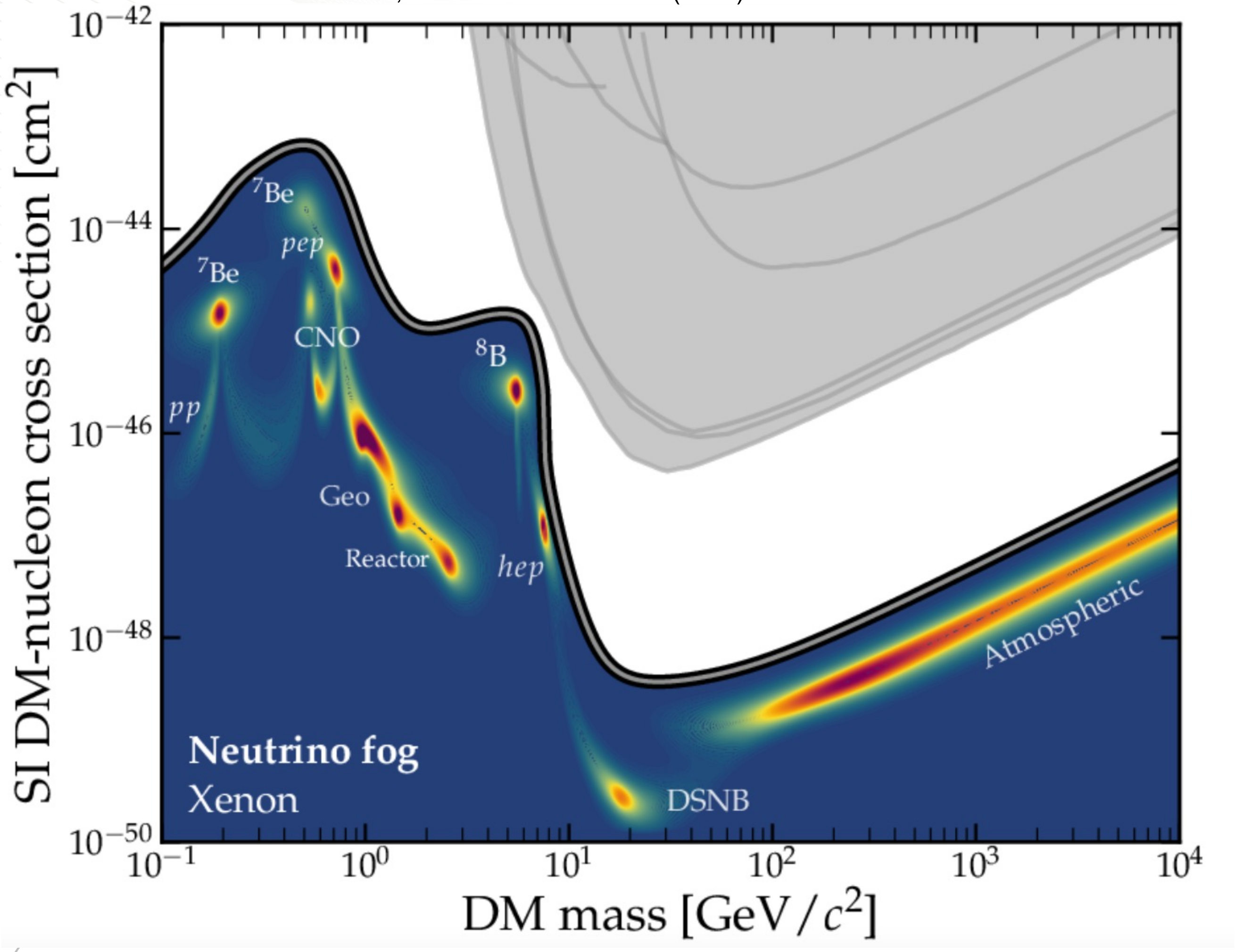


High Q = short de Broglie wavelength

Low Q = long de Broglie wavelength

CEvNS is the Neutrino "Fog" for DM experiments

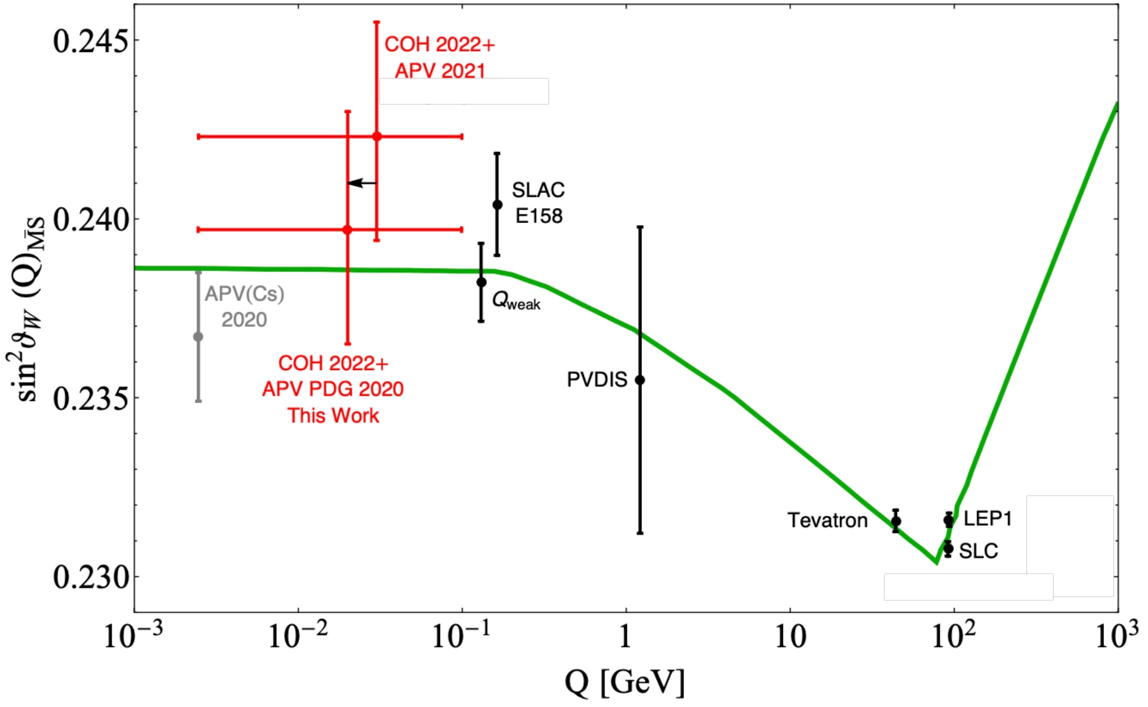
O'Hare, Ciaran AJ. PRL 127.25 (2021): 251802



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



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

new interaction specific to ν's

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

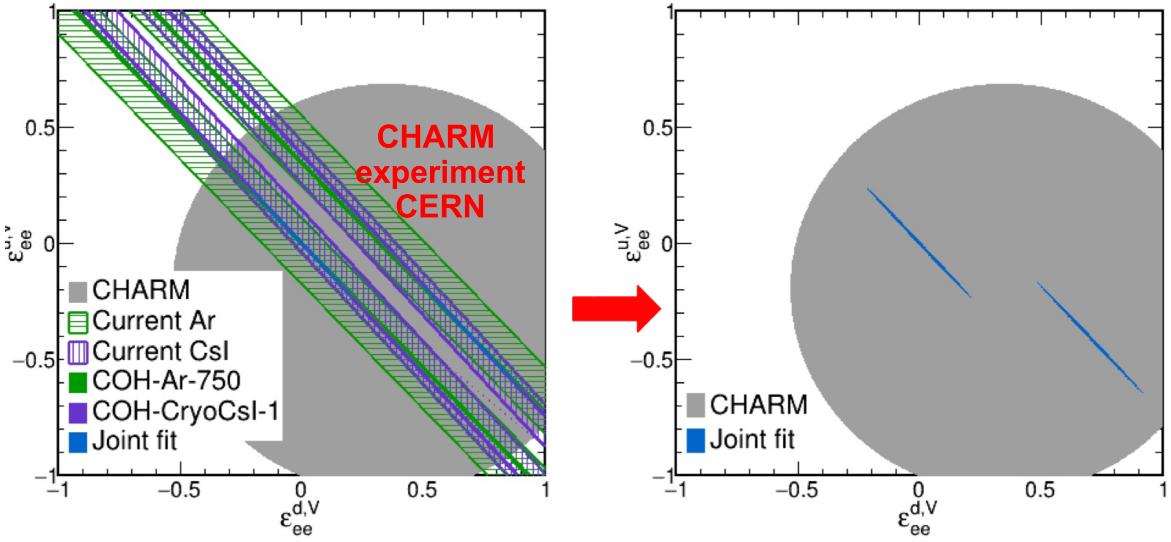
J. H J. High Energy Phys. 03(2003) 011

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
$-0.008 < \varepsilon_{\mu\mu}^{dR} < 0.015$	
$\lvert\varepsilon_{e\mu}^{uP}\rvert < 7.7 \times 10^{-4}$	$\mu \to e$ conversion on nuclei
$\lvert\varepsilon_{e\mu}^{dP}\rvert < 7.7 \times 10^{-4}$	$\mu \to e$ 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

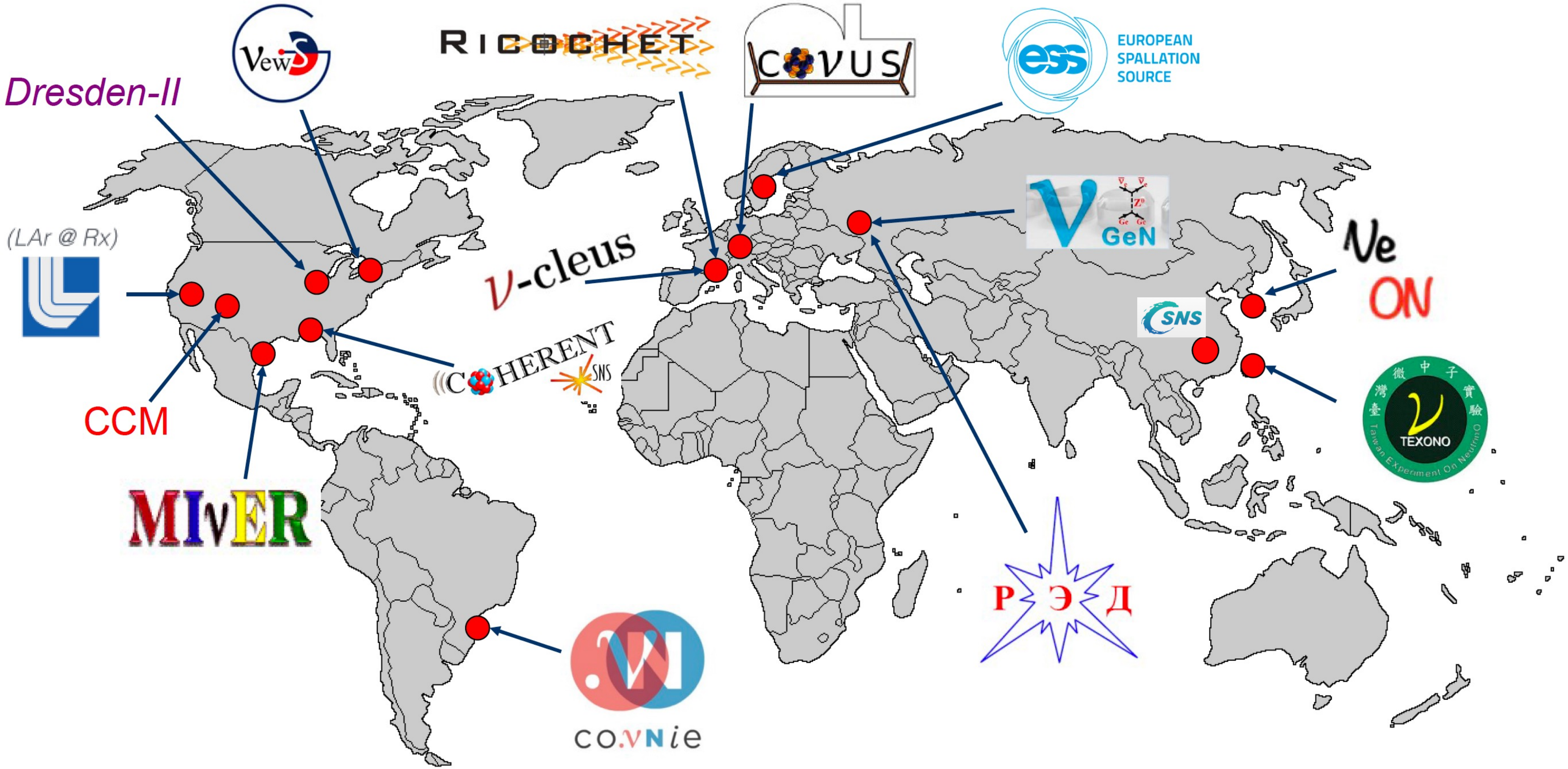
Non-Standard ν Interactions (Supersymmetry, neutrino mass models) can impact the cross-section differently for different nuclei

arXiv:2204.04575 [hep=ex]

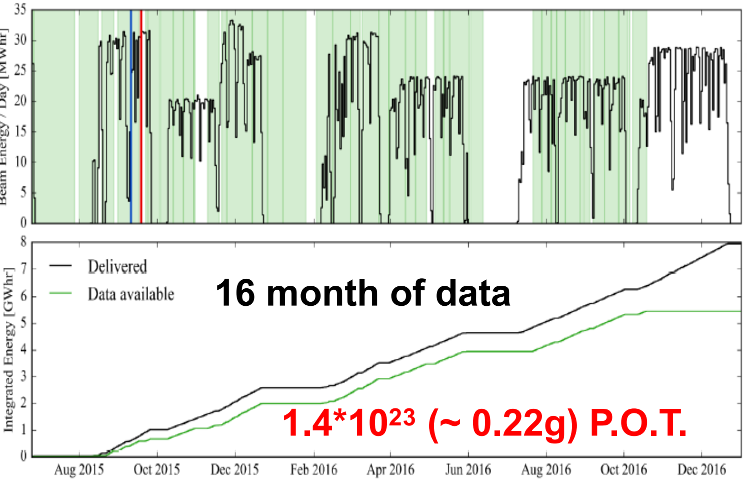


There are many collaborations around the world looking for CEvNS

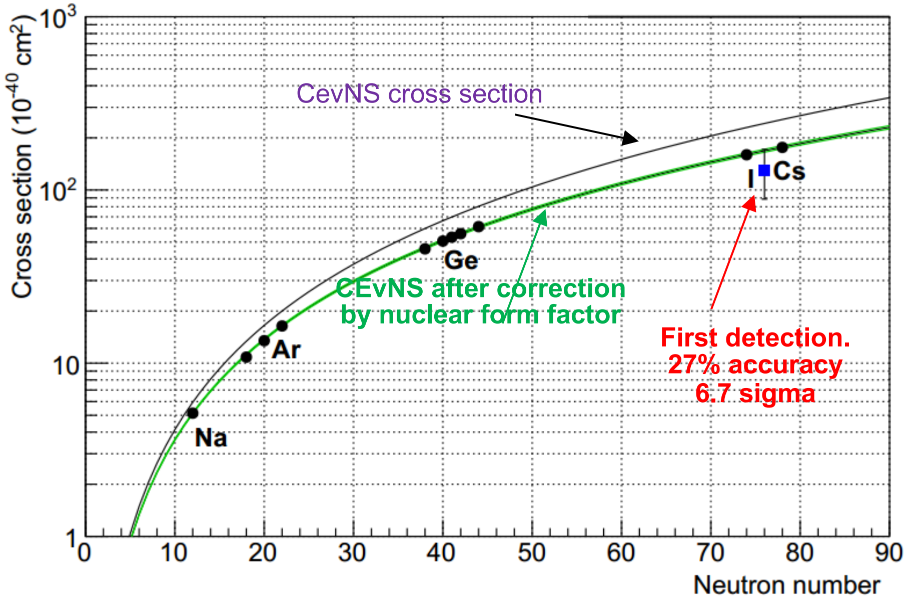
All except COHERENT, CCM, and CSNS are using neutrinos from nuclear reactors



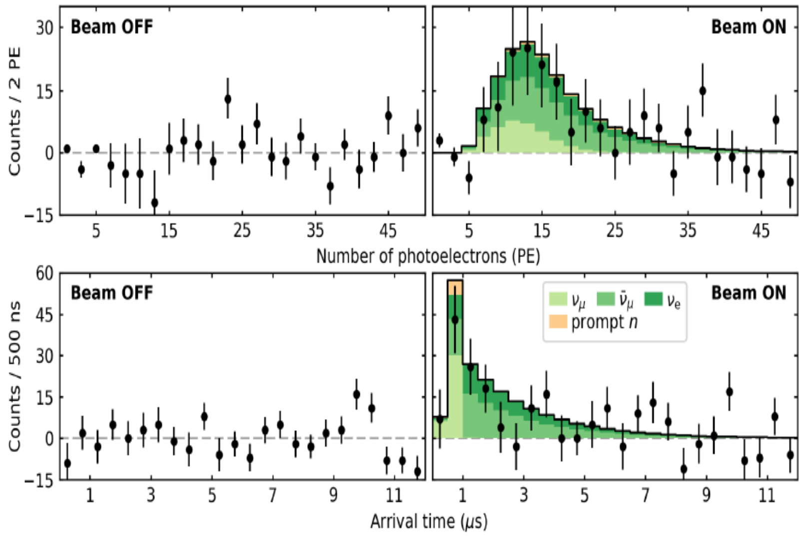
First Detection of CEvNS with 14 kg CsI detector



CsI first result



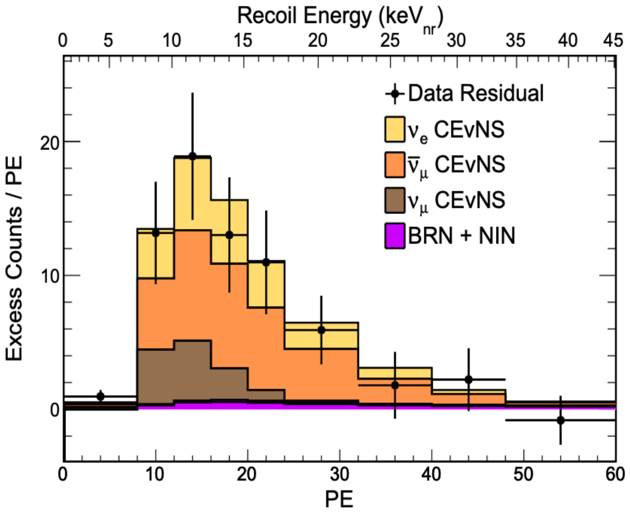
6.7 sigma effect
Cross section accuracy 27%

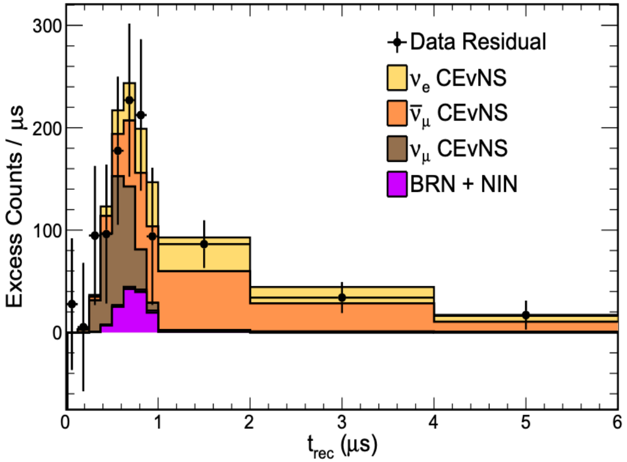


After 2.5 times more statistic and better quenching measurements

11.6 sigma effect
Cross section accuracy 16%

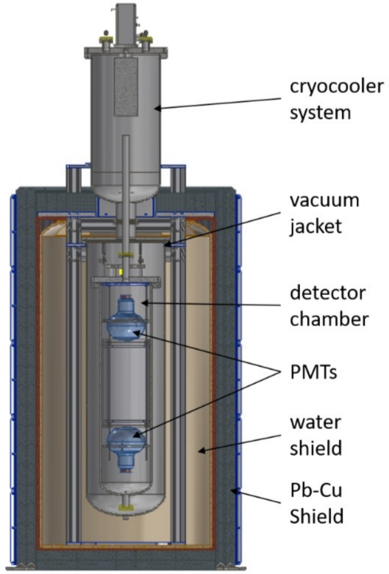
*COHERENT, [PRL **129** (2022) 081801]*



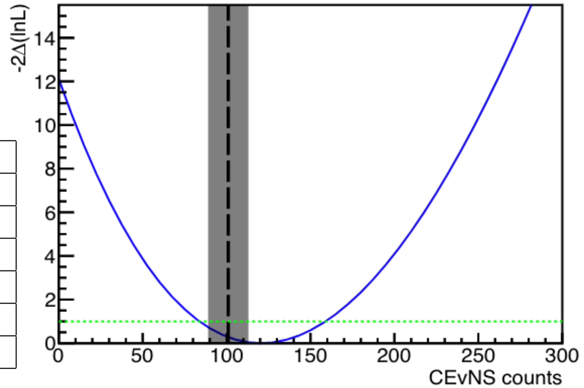


Lq. Argon Detector (CENNS-10)

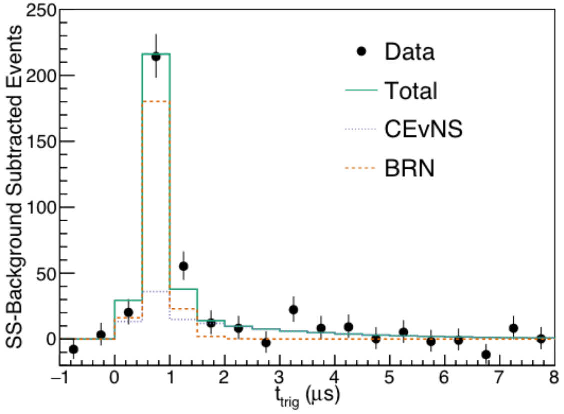
- Originally built in 2012-2014 by J. Yoo et al. at Fermilab for CEvNS effort at Fermilab
- Moved to the SNS for use in COHERENT late 2016 after upgrades at IU. Rebuild in 2017 at ORNL with new PMTs and TPB coating sputtered in vacuum. L.Y. increased by a factor of 10.
- 10 cm Pb/ 1.25 cm Cu/ 20 cm H_2O shielding
- 24 kg fiducial volume
- 2 x 8” Hamamatsu PMTs, 18% QE at 400 nm
- Production Run starting July 2017.
- Decommissioned last week. New 750 kg detector is coming soon.

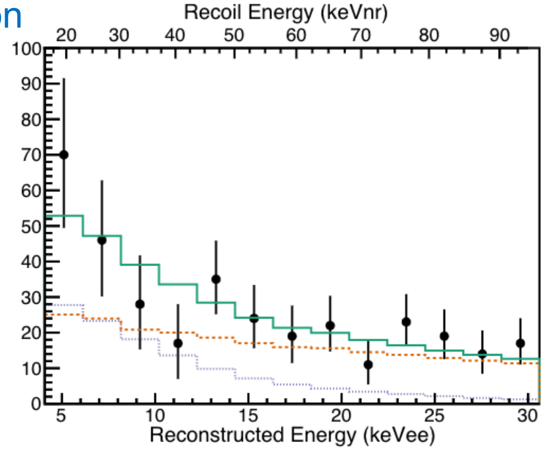


Data Events	3752
Fit CEvNS	159 ± 43 (stat.) ± 14 (syst.)
Fit Beam Related Neutrons	553 ± 34
Fit Beam Unrelated Background	3131 ± 23
Fit Late Beam Related Neutrons	10 ± 11
2Δ(-lnL)	15.0
Null Rejection Significance	3.5σ (stat. + syst.)



First result. Update is coming soon

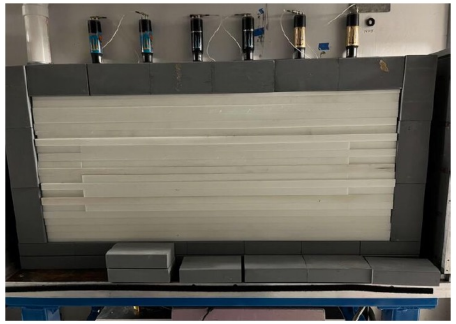


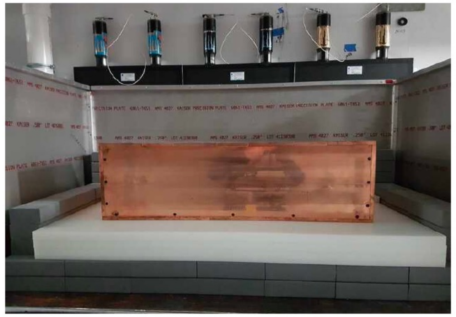


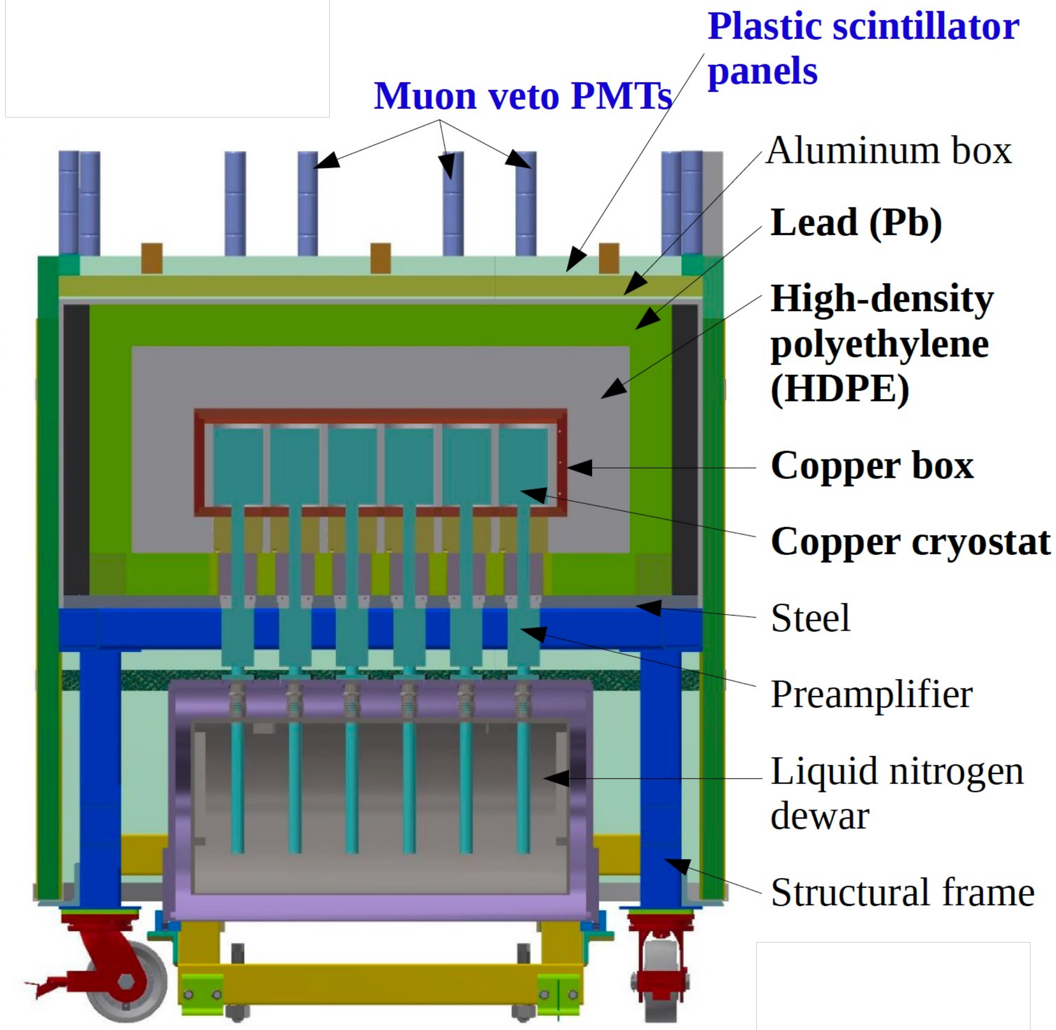
Phys.Rev.Lett. 126 (2021) 1, 012002

New deployment Last Summer → Ge array

Ge-Mini

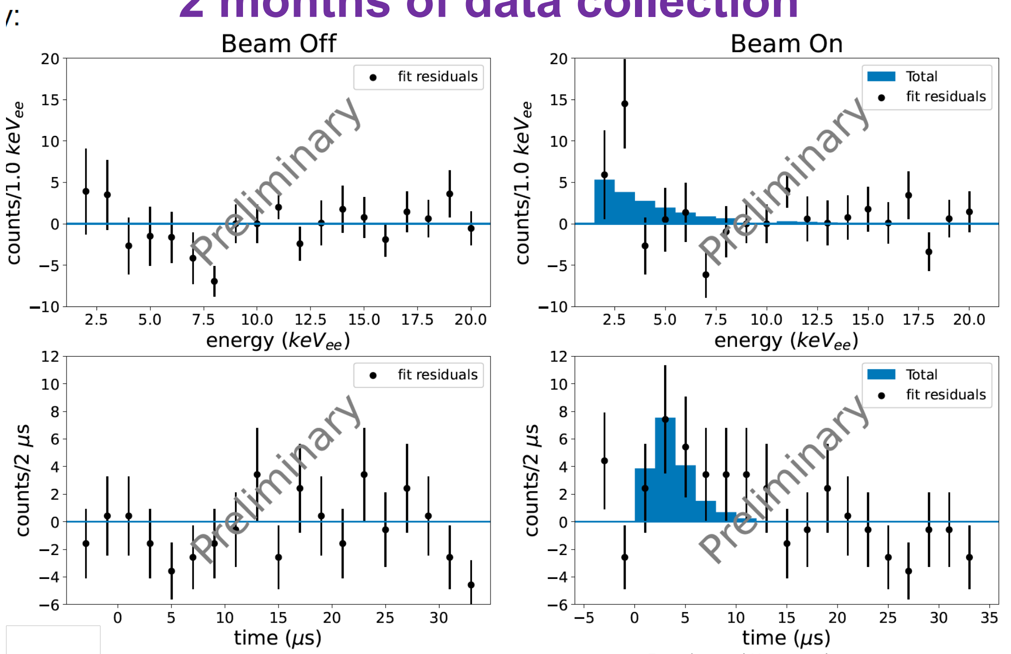


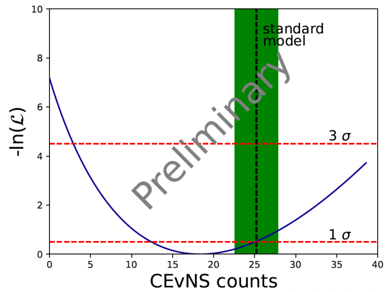


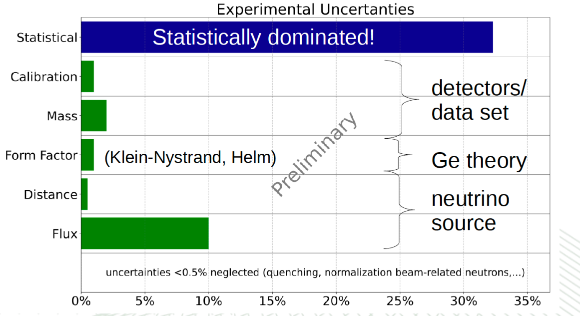


Eight high-Purity Germanium diodes ~2.2 kg each
Inverted (semi) coaxial ICPC
transistor reset preamp (TRP)
110-150 eV FWHM pulser resolution/noise

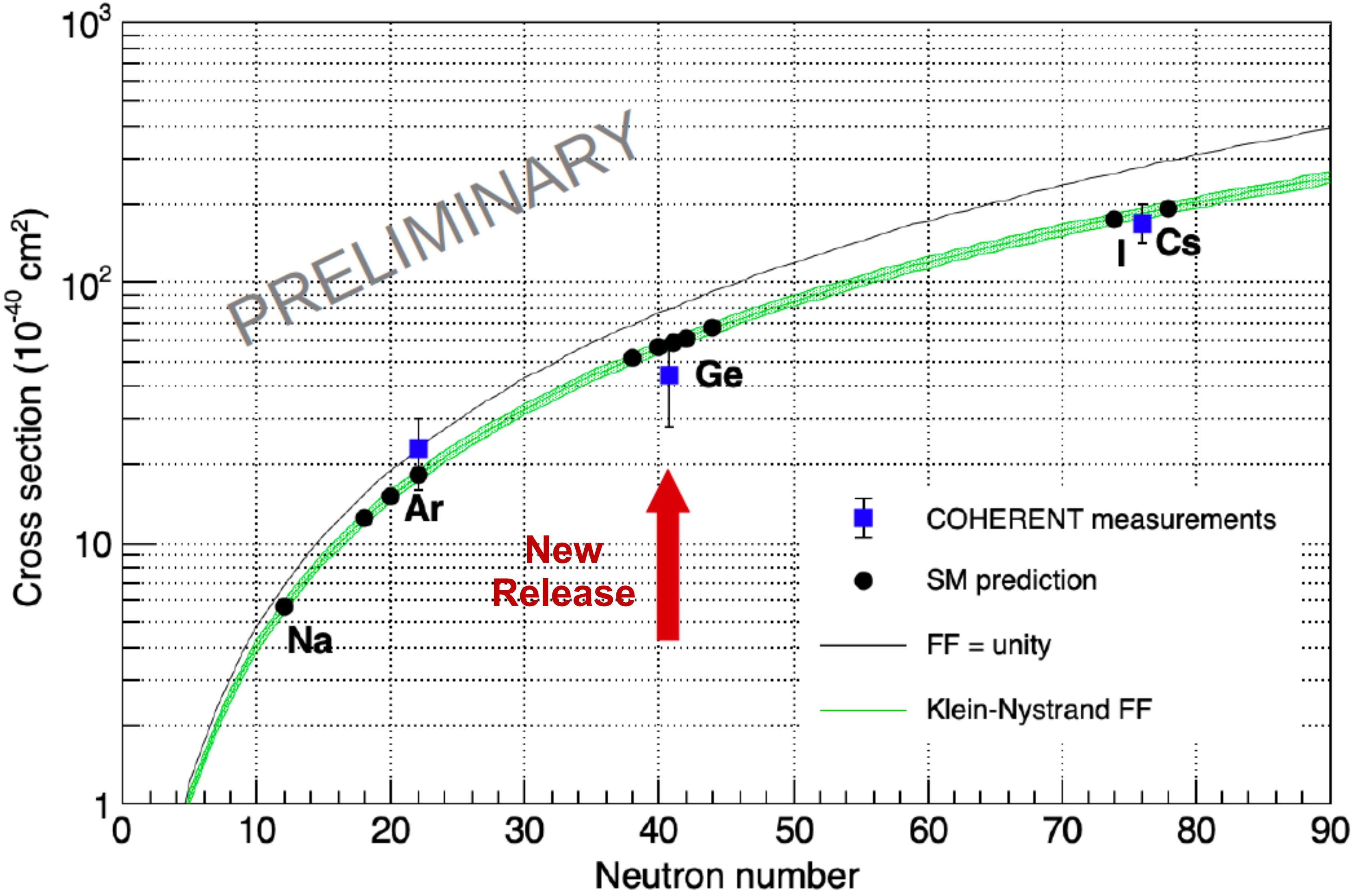
2 months of data collection







Collaboration Published Detection of CEvNS on Three Targets



All three individual results agree with the Standard Model within one sigma

However, accuracy is limited so far

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

Heavy Water Detector to Measure Neutrino Flux and CC on oxygen

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.

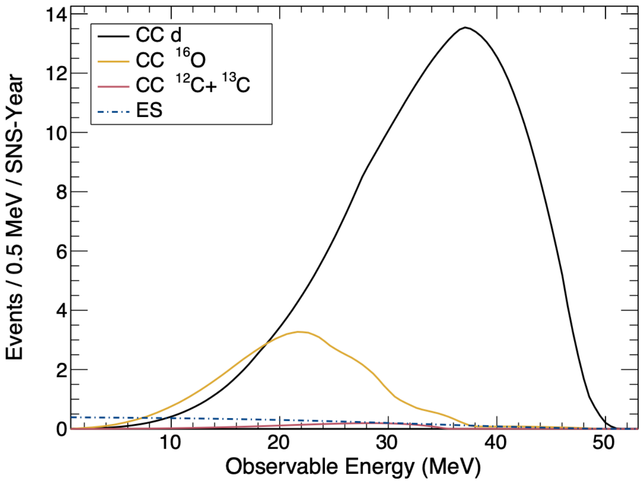
Second Module will be with H_2O only

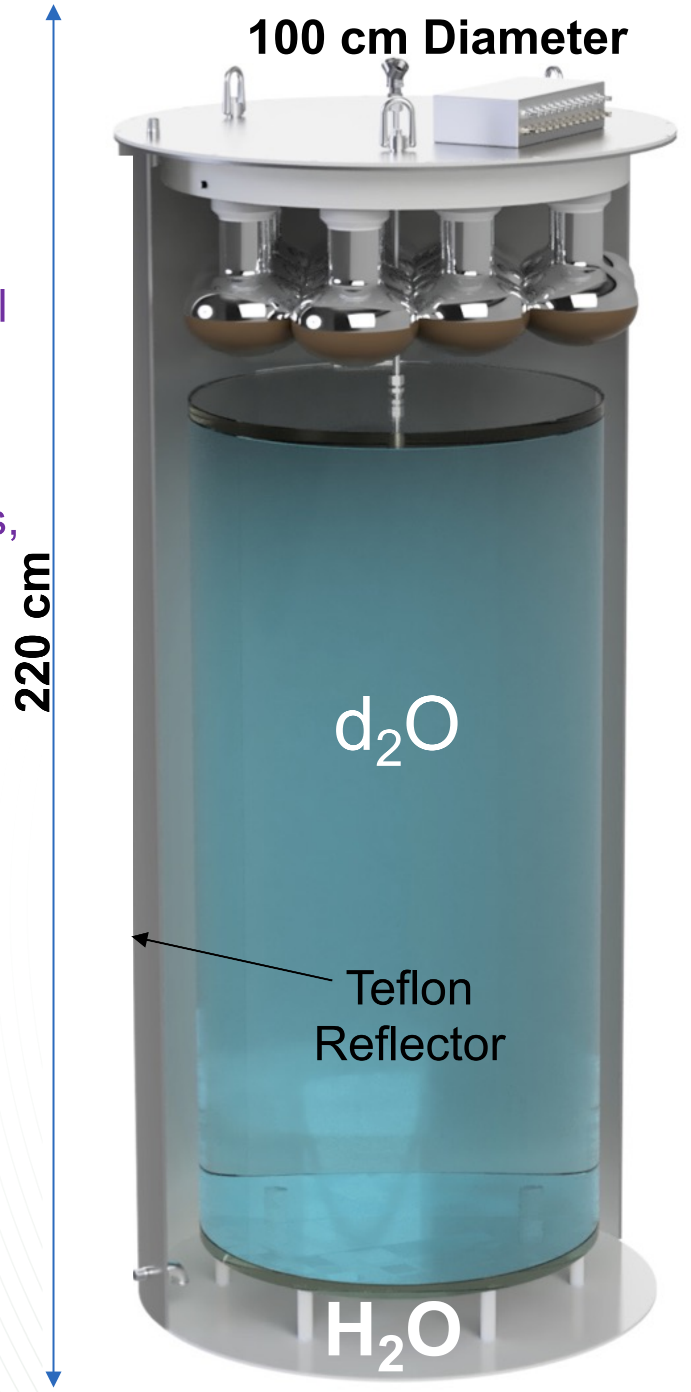
First d_2O module commissioned in July 2023

Specifications

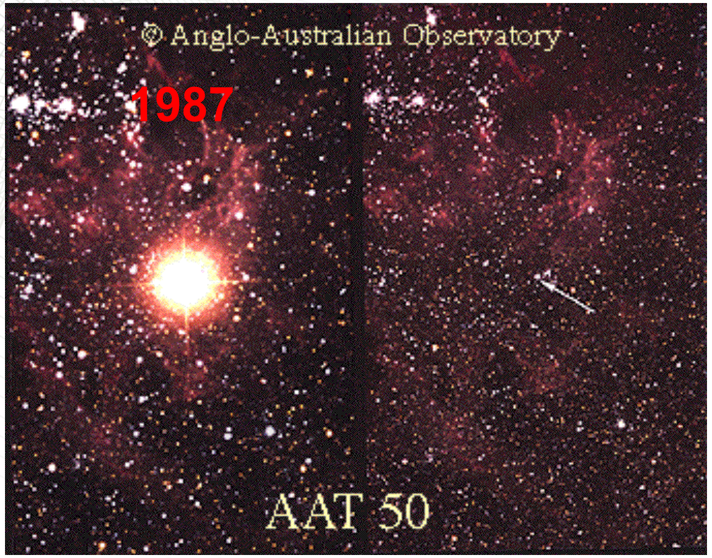
- 0.6 tons D_2O within acrylic inner vessel
- Water Cherenkov Calorimetry
- H_2O “tail catcher” for high energy e^-
- Outer light water vessel contains PMTs, PMT support structure, and optical reflector.
- Outer steel vessel
- Lead Shielding
- Hermetic veto system

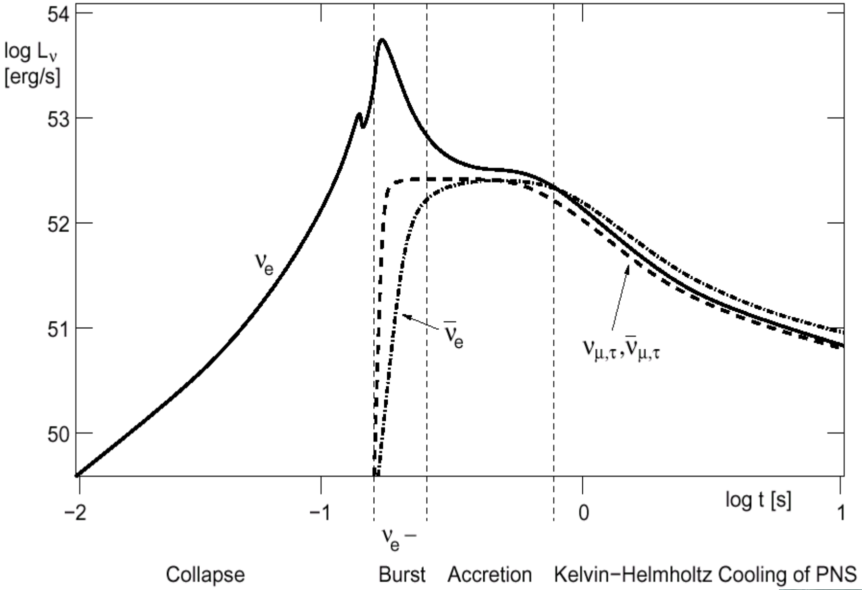
JINST 16 (2021) 08, 08

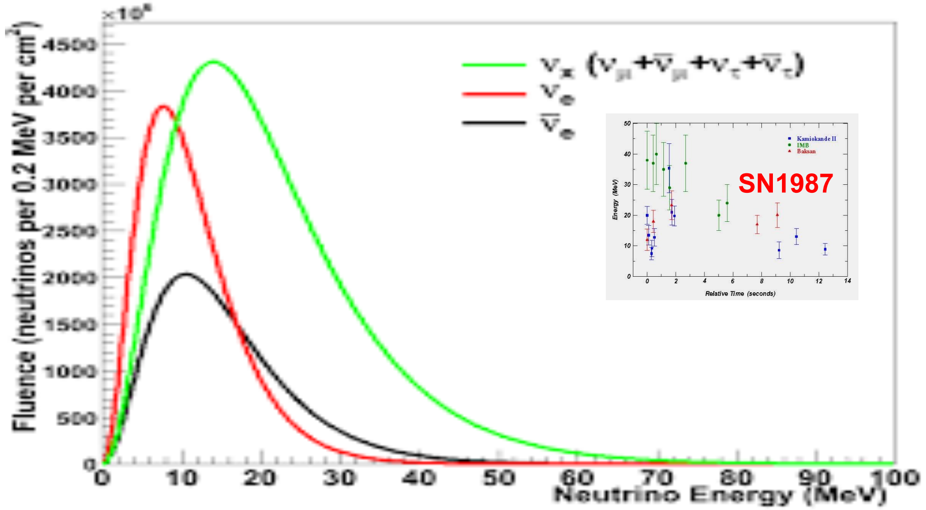




Core Collapse Supernovae





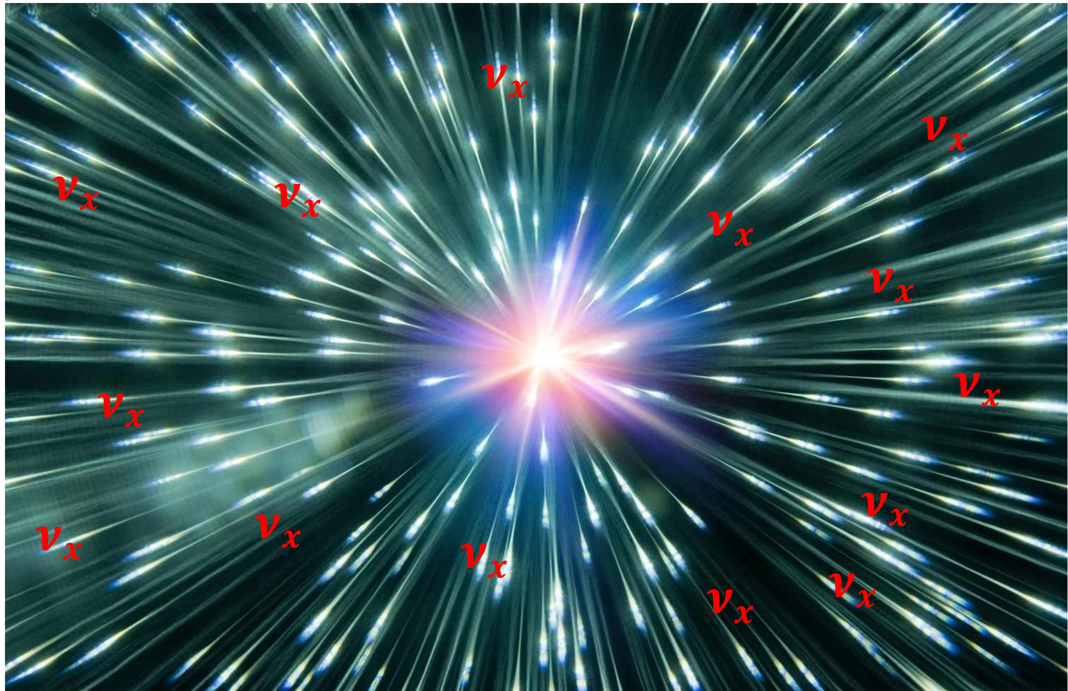


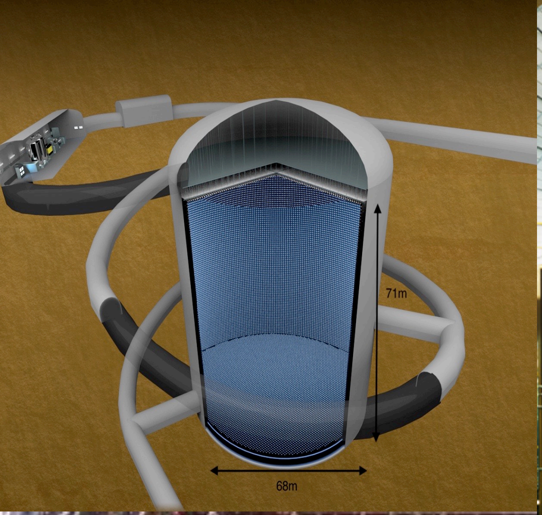
Physics of SN explosion is very rich
99% of explosion energy is emitted by Neutrinos
SN explosion is one of the sources of heavy elements in the universe

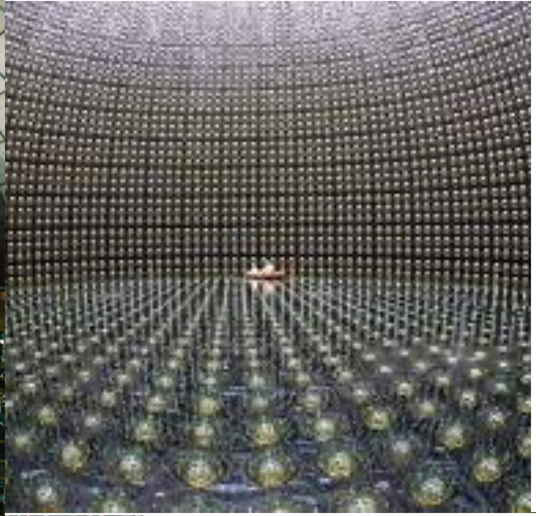
See Prof. Meng-Ru Wu talk

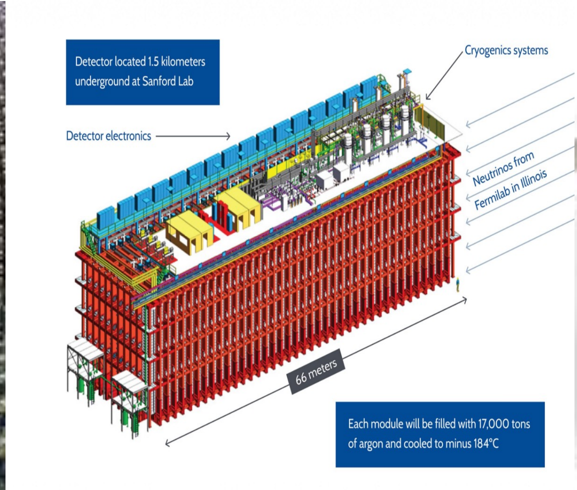
Are we ready for the next galactic SN?

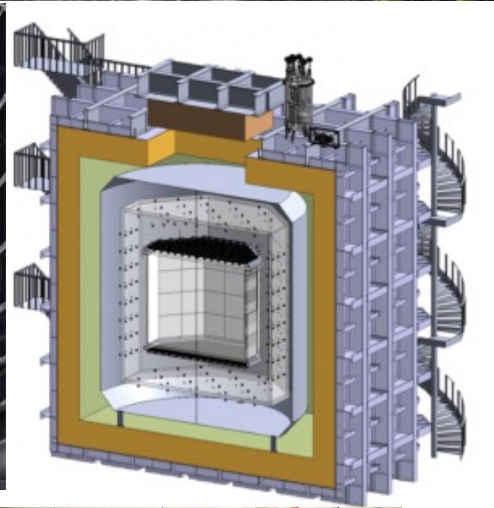
The answer is: not really.
We measured neutrino CC on carbon only at SN neutrino energy range

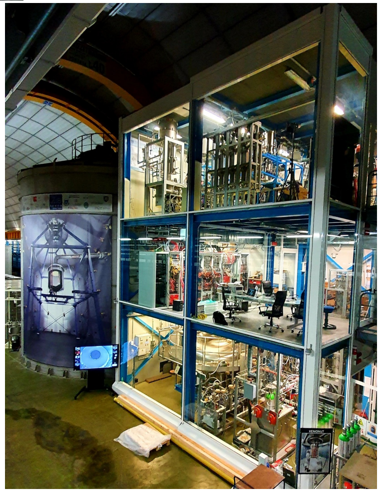


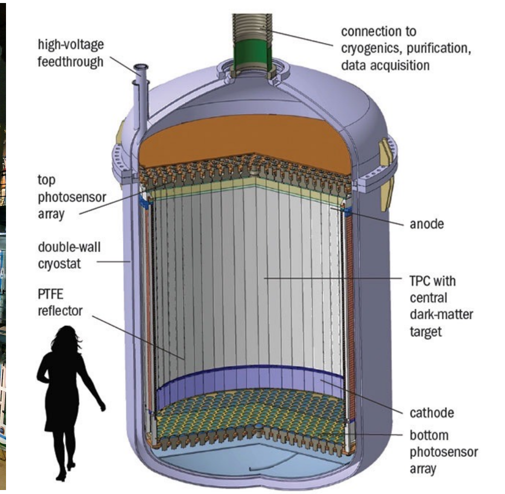

71m
68m

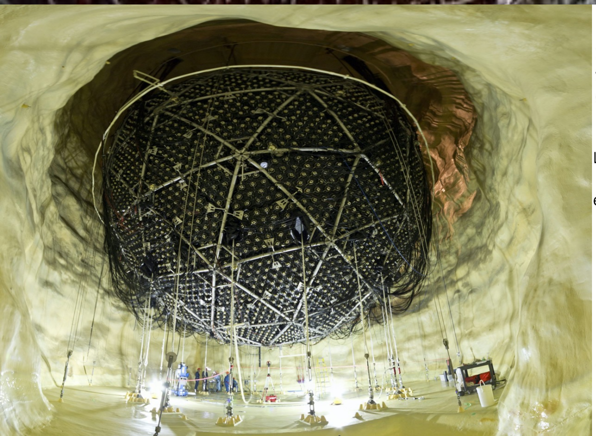


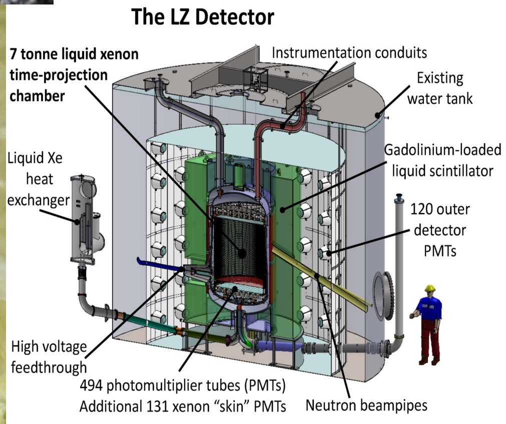

Detector located 1.5 kilometers underground at Sanford Lab
Cryogenics systems
Detector electronics
Neutrinos from Fermilab in Illinois
66 meters
Each module will be filled with 17,000 tons of argon and cooled to minus 184°C

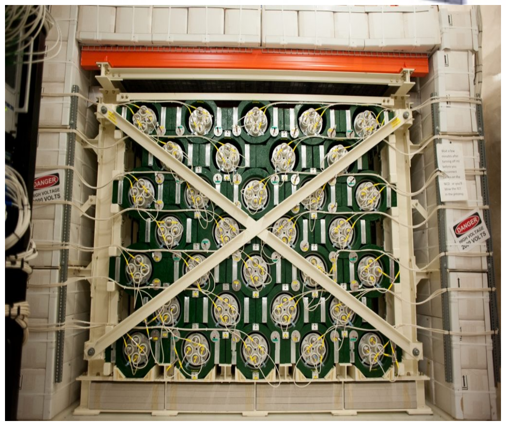


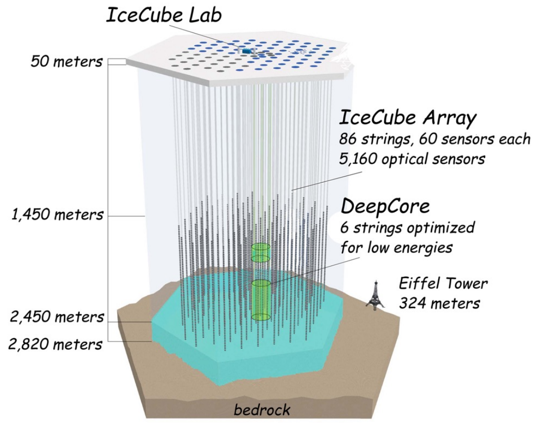


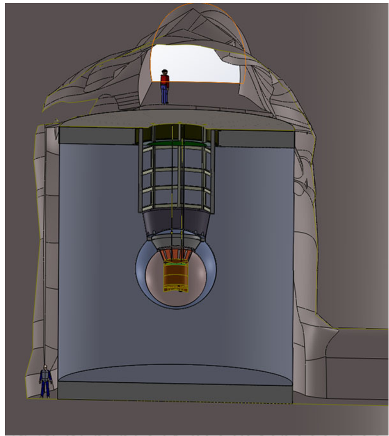

high-voltage feedthrough
connection to cryogenics, purification, data acquisition
top photosensor array
anode
double-wall cryostat
TPC with central dark-matter target
PTFE reflector
cathode
bottom photosensor array




The LZ Detector
7 tonne liquid xenon time-projection chamber
Instrumentation conduits
Existing water tank
Liquid Xe heat exchanger
Gadolinium-loaded liquid scintillator
120 outer detector PMTs
High voltage feedthrough
494 photomultiplier tubes (PMTs)
Additional 131 xenon "skin" PMTs
Neutron beampipes




IceCube Lab
50 meters
IceCube Array
86 strings, 60 sensors each
5,160 optical sensors
1,450 meters
DeepCore
6 strings optimized for low energies
Eiffel Tower
324 meters
2,450 meters
2,820 meters
bedrock

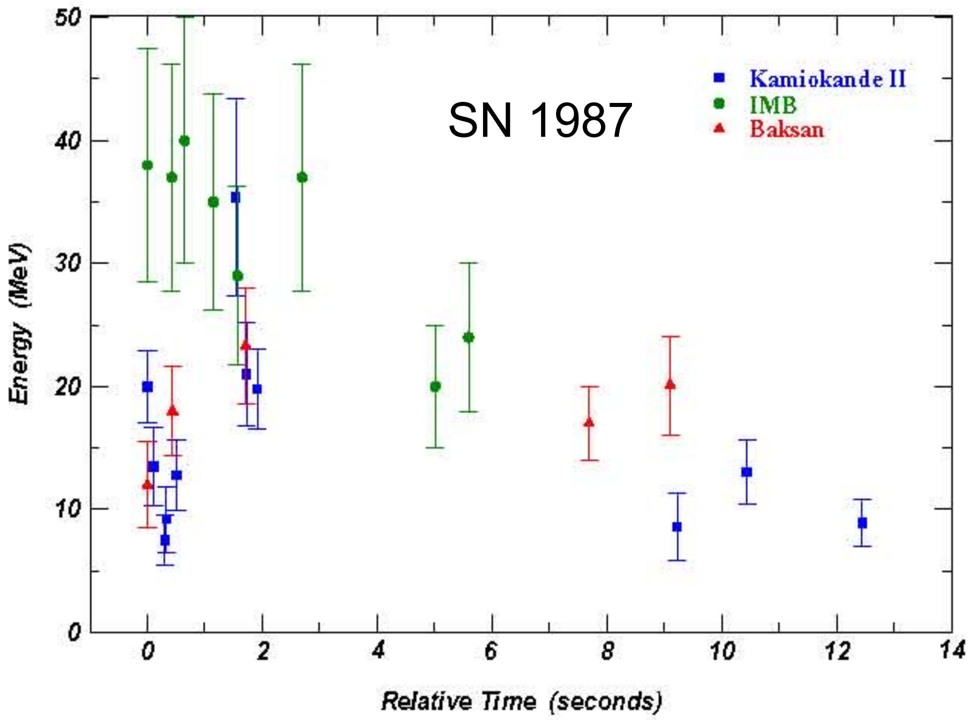


Neutrino Nucleus Inelastic Interactions at the COHERENT

It is motivated by unique similarities between SNS and SN neutrinos energy range

Aimed to measure target relevant to the large neutrino detectors of the present and the future

Help to build neutrino nucleus Interactions generators capable to make accurate predictions at low neutrino energy range <100 MeV



For SN-20XX we will have many more detectors
They will be much bigger and more sophisticated
It will be more variety of targets

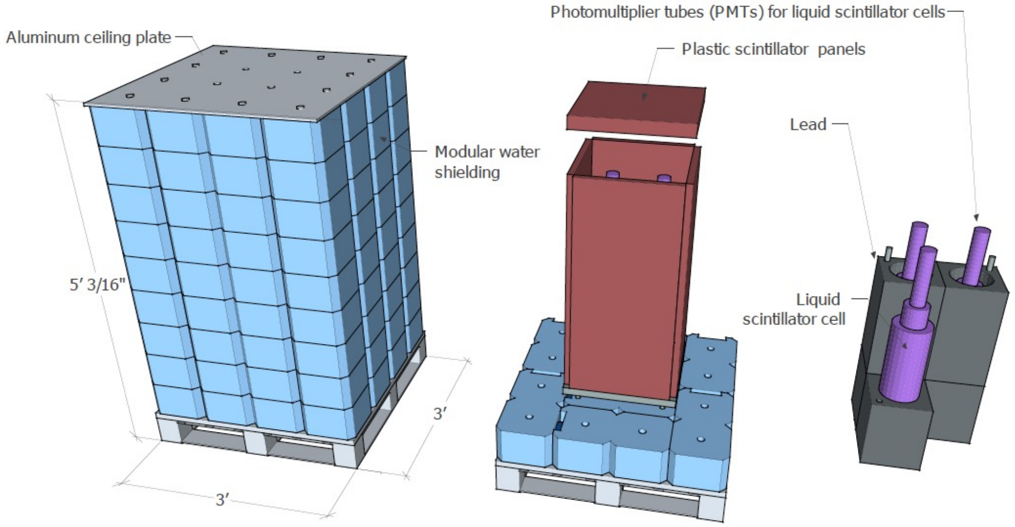
Collaborations will be in a rush how to make a proper interpretation of detected signals

Our short list of interest: lead, iodine, argon, oxygen, xenon

OAK RIDGE National Laboratory

Neutrino-Induced Neutron Detectors (NUBES) Motivated by HALO SNOLAB experiment

- 900 kg Pb
- Low background lead cast with cavities for EJ-309 Liquid Scintillator Detectors
    - 1^{st} run conf: 4x 2.4 L Cylinder (Eljen)
    - 2^{nd} run conf: 2x 2.4 L Cylinder
    - 3^{rd} run conf. 2x 2.4 L Cylinder an 2x 1.4 L Hex (ORNL)
- 2” Plastic Scintillator Muon Veto Panels on Top and Sides each with 2 PMTs
- Water bricks for moderation of external neutrons
- Flux weighted average distance of 18.88 m from target

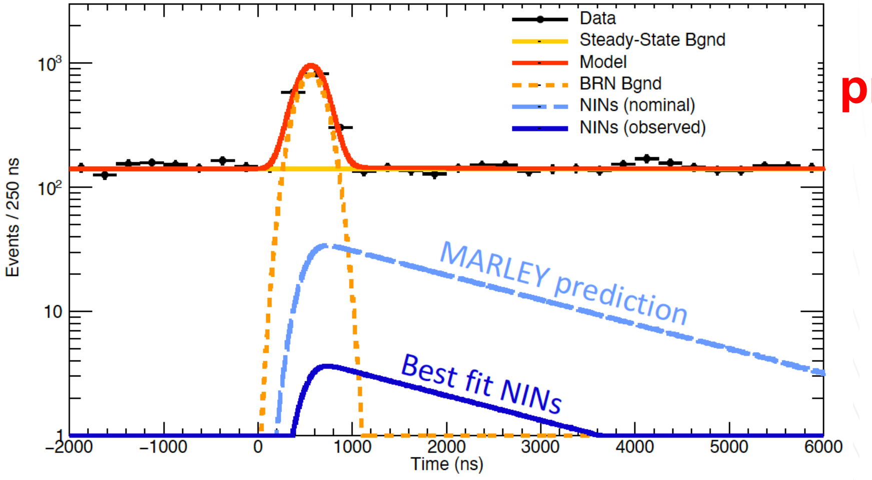


Statistics was accumulated for 5 years starting form January 2016

During that period SNS delivered ~$5\cdot10^{23}$ protons (0.8g) to the target.

Predicted cross section from from MARLEY: $42.1\cdot10^{-40}$ cm^2

Measured: $12.2^{+7.2}_{-6.7}\cdot10^{-40}$ cm^2



Phys.Rev.D 108 (2023) 7, 072001

Disagreement with prediction by a factor of 3!!!

Group in Japan is following up with a similar measurement at J-PARC

DaRveX: arXiv:2205.11769 hep-ex

Neutrino Interaction with ^{127}I

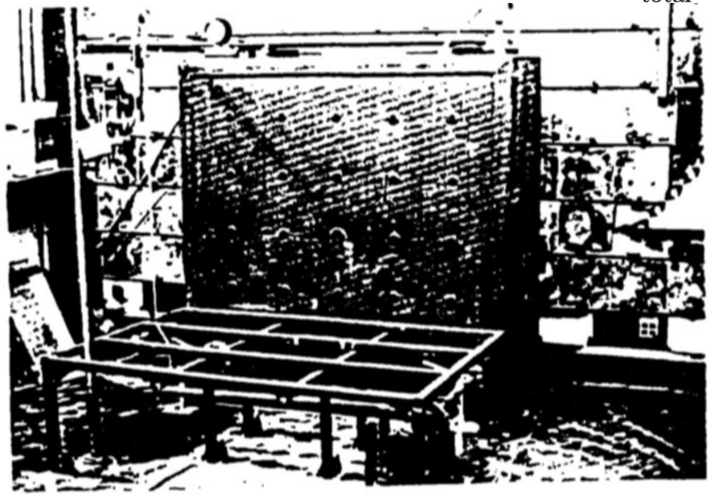
Proposed by Haxton in 1988 as a way to detect solar neutrinos using radiochemistry, similar to gallium experiment

$$\nu_e + {}^{127}I \rightarrow e^- + {}^{127}Xe^*$$

Low threshold for this reaction (125 keV) gave access to the ^{7}Be solar neutrinos

[J. Engel, S. Pittel, & P. Vogel, Phys. Rev. C 50 (1994)]:Cross section depends of g_A

J^π	$g_A = -1.0$	$g_A = -1.26$
0^+	0.096	0.096
0^-	0.00001	0.00002
1^+	1.017	1.528
1^-	0.006	0.008
2^+	0.155	0.213
2^-	0.693	1.055
3^+	0.149	0.171
3^-	0.017	0.025
total	2.098	3.096



E-1213 LAMPF experiment

Due to the radiochemical approach measured only transition to the bound state of ^{127}Xe

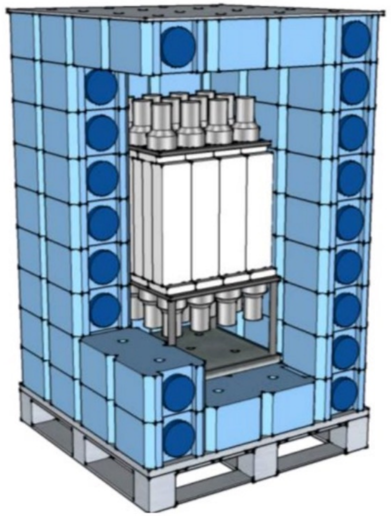
$\boldsymbol{\sigma = 2.84 \pm 0.91\ stat \pm 0.25\ sys \times 10^{-40}\ \mathrm{cm}^2}$

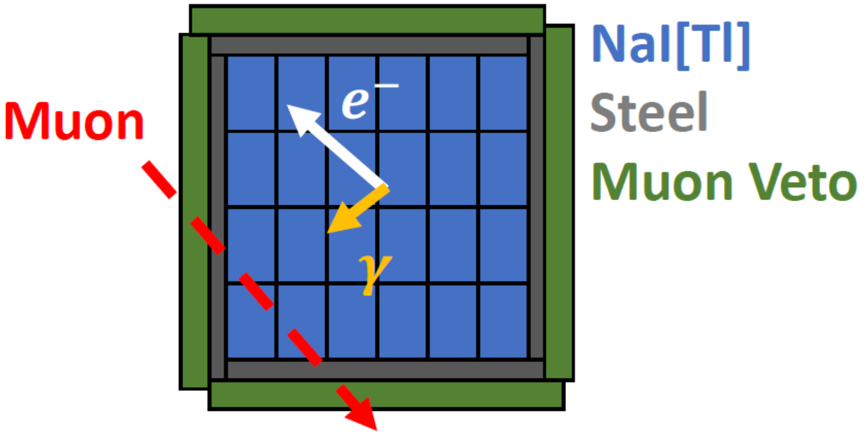
OAK RIDGE National Laboratory

First Deployment for NaI CC at SNS

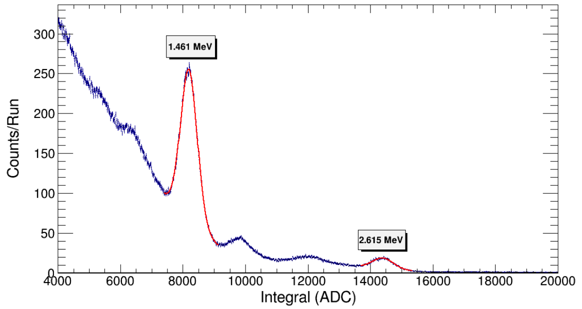
COH-NaIvE: Twenty-four 7.7 kg NaI crystals with the total mass of 185 kg

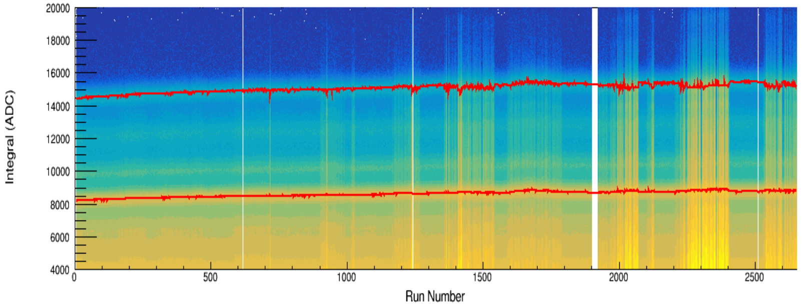
Deployed in 2016 and still taking data

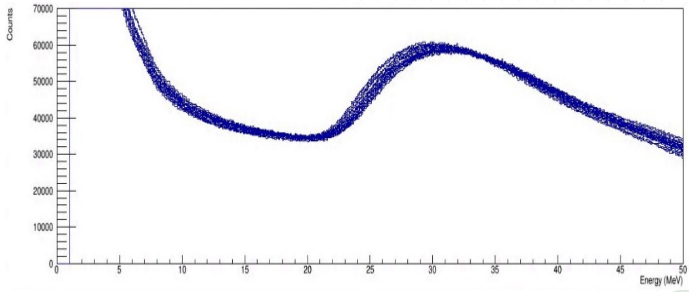


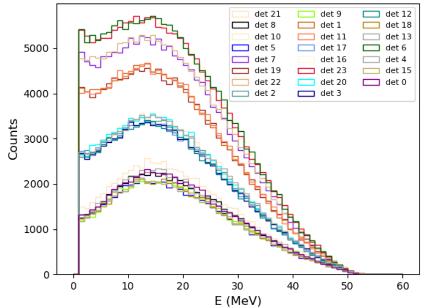



Internal constant calibration using ^{40}K and ^{208}Tl lines, Muons and Michel electrons









Cross section Predictions for ^{127}I from MARLEY

- MARLEY used for ^{127}I charged-current predictions along with (p,n) charge-exchange data
- MARLEY's inclusive cross section for DAR neutrinos:

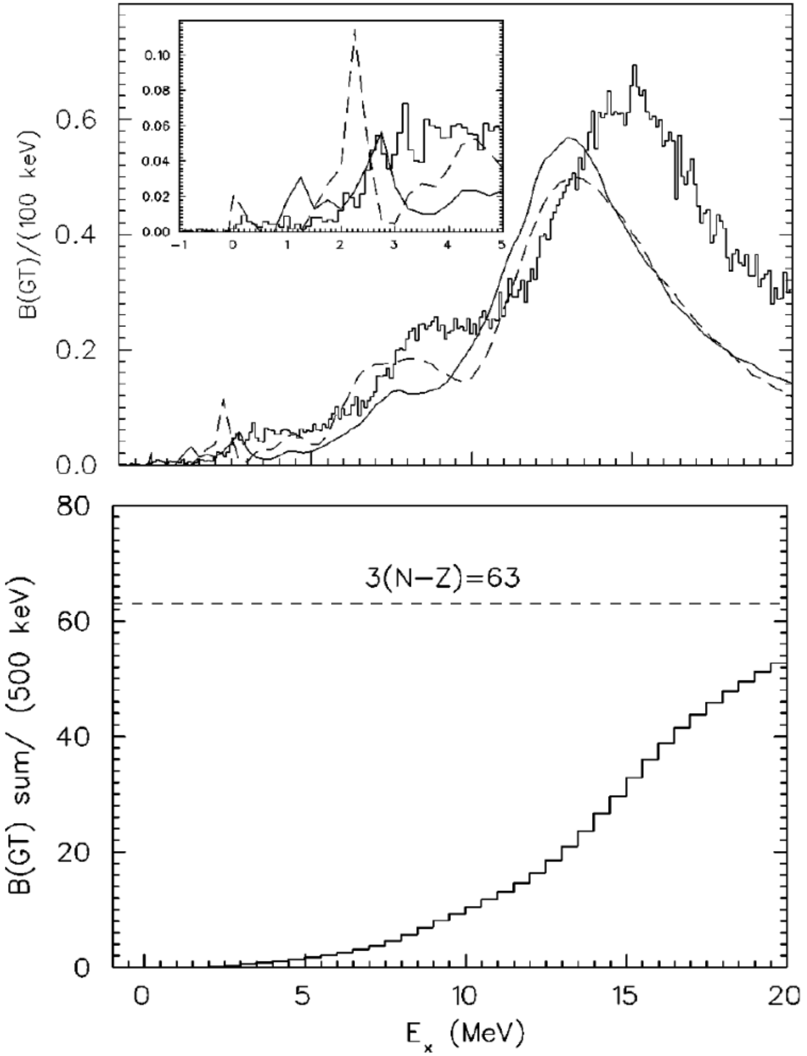
$$22.5^{+1.2}_{-6.5} \times 10^{-40}\ \mathrm{cm}^2$$

  - Uncertainty from B(GT$^-$) normalization uncertainty
- Cross section for exclusive channel to $^{127}Xe_{bound}$:

$$2.5^{+0.3}_{-0.6} \times 10^{-40}\ \mathrm{cm}^2$$

  - Good agreement with LAMPF measured value of

$$2.84 \pm 0.91(stat) \pm 0.25(sys) \times 10^{-40}\ \mathrm{cm}^2$$



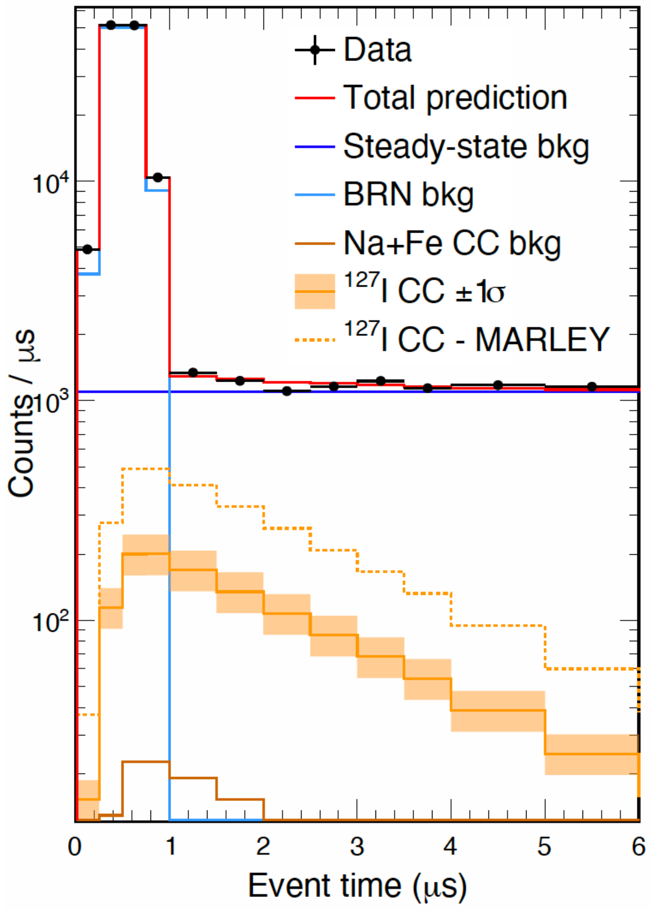
[M. Palarczyk, et al., Phys. Rev. C 59 (1999)]

Ph.D. Dissertation by Samuel Hedges, LLNL

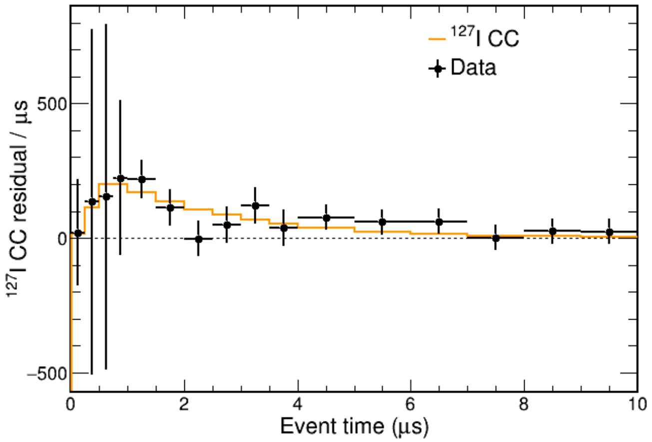
Iodine cross section results

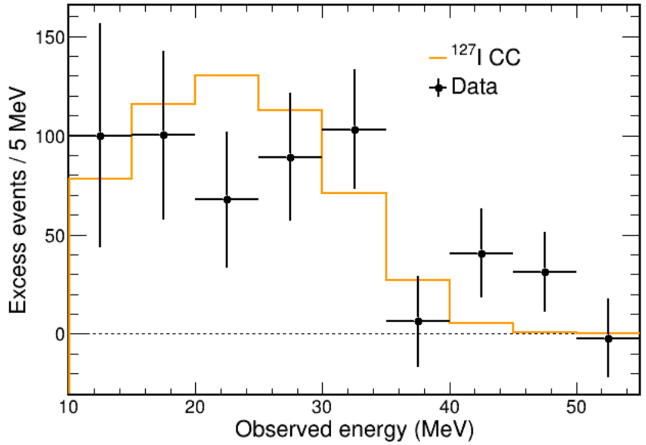
Best fit gives 541^{+121}_{-108} events or 5.8σ evidence of CC

Corresponds to cross section of $9.2^{+2.1}_{-1.8} * 10^{-40}$ cm² or 40% of MARLEY prediction



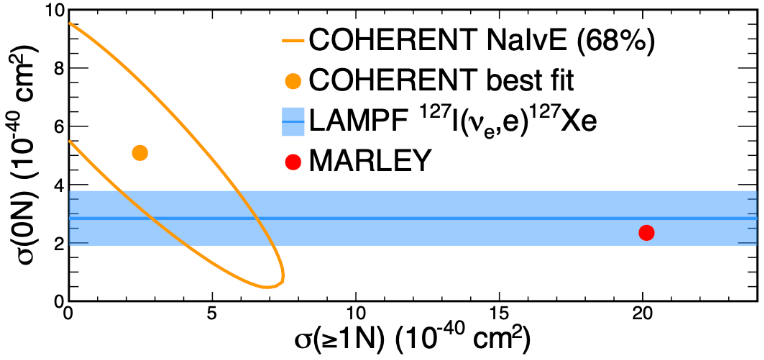
Subtracted steady state and BRN backgrounds





Zero neutrons or many neutrons?

Big overprediction toward neutron emission channels !!!

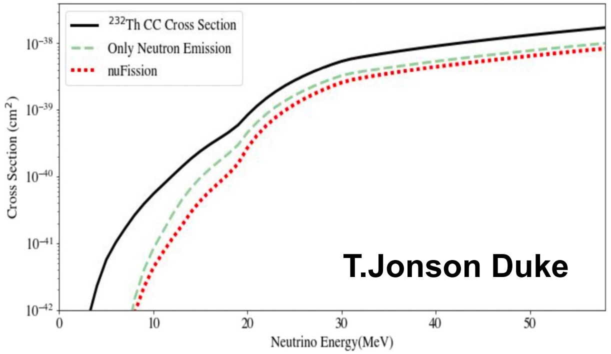


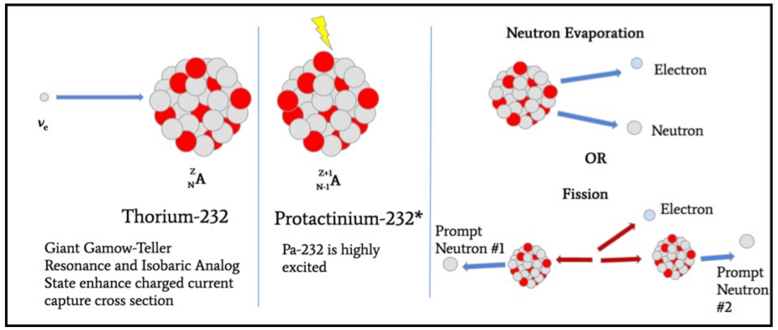
Phys.Rev.Lett. 131 (2023) 22, 221801

OAK RIDGE National Laboratory

ν-Induced Fission: NuThor

Experiment proposed designed and build by graduate student Tyler Johnson

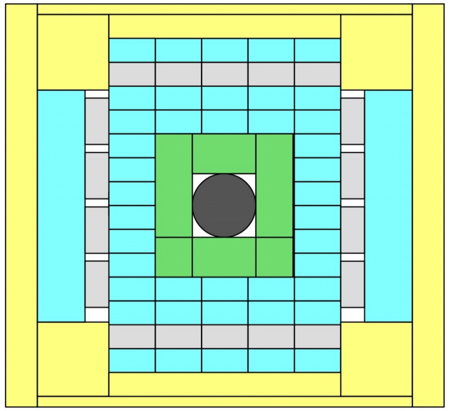


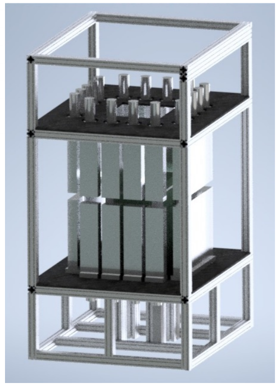


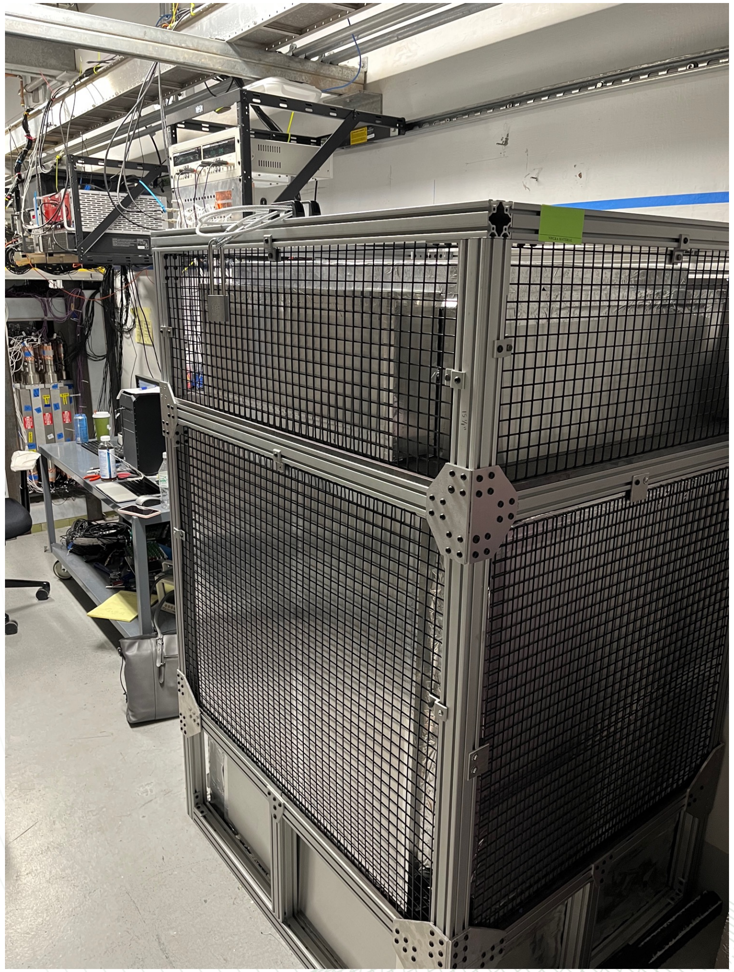
POSSIBLE METHOD OF MEASURING THE ELECTROMAGNETIC FORM FACTOR OF THE NEUTRINO

V.I. Andryushin, S.M. Bilen'kii, and S.S. Gershtein
Joint Institute for Nuclear Research
Submitted 8 April 1971
ZhETF Pis. Red. 13, No. 10, 573 - 576 (20 May 1971)

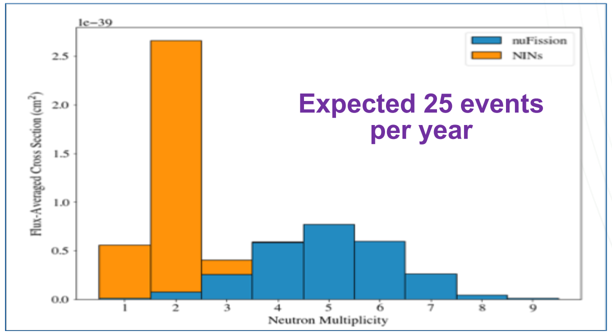
in [5]. In order to obtain on the basis of [6] information on the electromagnetic form factor of the neutrino, it is necessary to investigate the processes (1) and (5) that are optimal in the sense of the value of the cross section and the possibility of registration. From this point of view we consider it to be highly promising to study the scattering of the neutrino in the region of the giant resonance[1] and the investigation of the nuclear-fission process due to scattering of neutrinos of medium energy[2]. Intense fluxes of such neutrinos can be obtained with "meson factory" type of accelerators.







- Process Predicted in 1971, but never been observed
- NuThor has been deployed last summer with
  - 52 kg ^{232}Th
  - Lead and Poly shielding
  - Gd-loaded water blocks to capture neutrons
  - NaI detectors to detect gammas from neutron capture

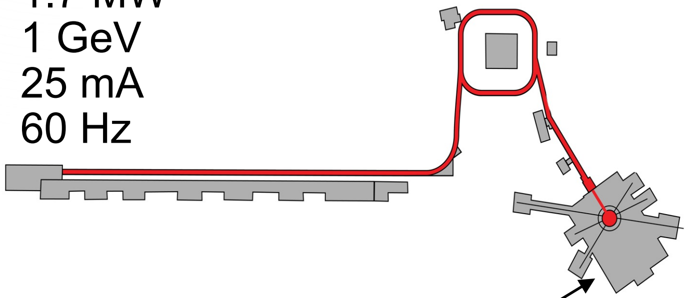


PPU and STS upgrades for SNS are coming

Today

- 900 users
- Materials at atomic resolution and fast dynamics

1.7 MW
1 GeV
25 mA
60 Hz

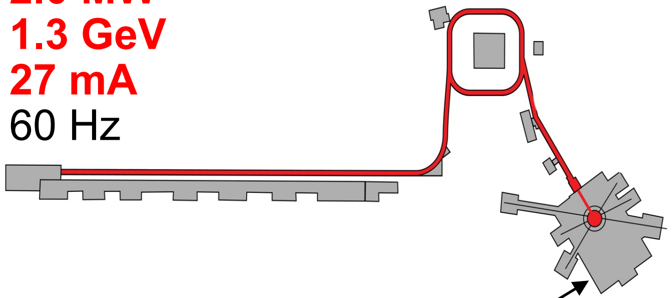


FTS
1.7 MW
60 Hz

2024 after PPU

- **1000+** users
- Enhanced capabilities

2.0 MW
1.3 GeV
27 mA
60 Hz



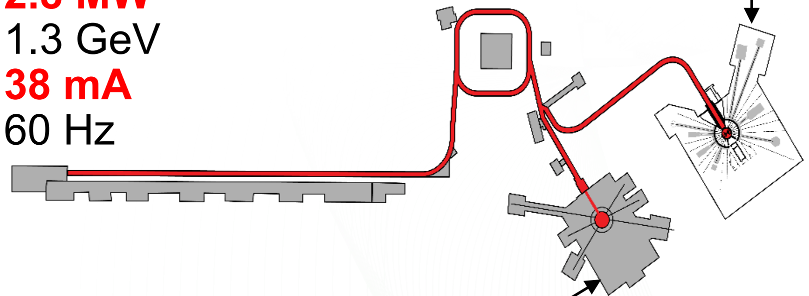
FTS
2 MW
60 Hz

2028 after STS

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

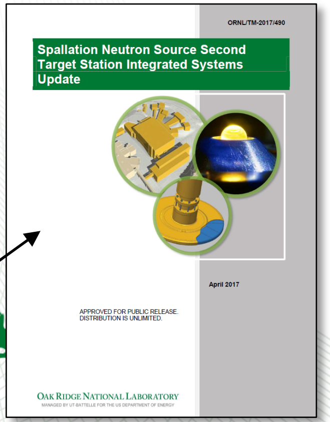
STS
0.7 MW
15 Hz

2.8 MW
1.3 GeV
38 mA
60 Hz



FTS
2 MW
45 pulses/sec

The choice of 15 Hz and 0.7 MW resulted from a detailed analysis of STS design (reviewed by a panel of experts in 2017) and optimizes performance of STS without impacting performance of FTS



The COHERENT Collaboration

Summary

COHERENT collaboration using SNS produced neutrinos to study CEvNS and neutrino interaction on nuclei relevant to the SN energy range

Collaboration uses multiple detectors at the same time

We detected CEvNS on CsI and Ar and Ge which is within 10% agreement with the standard model prediction.
More accurate measurements will follow !!!!

First results of CC reactions on iodine and lead measured reaction rates are significantly lower than theoretical predictions

New measurements with high statistics on iodine will follow

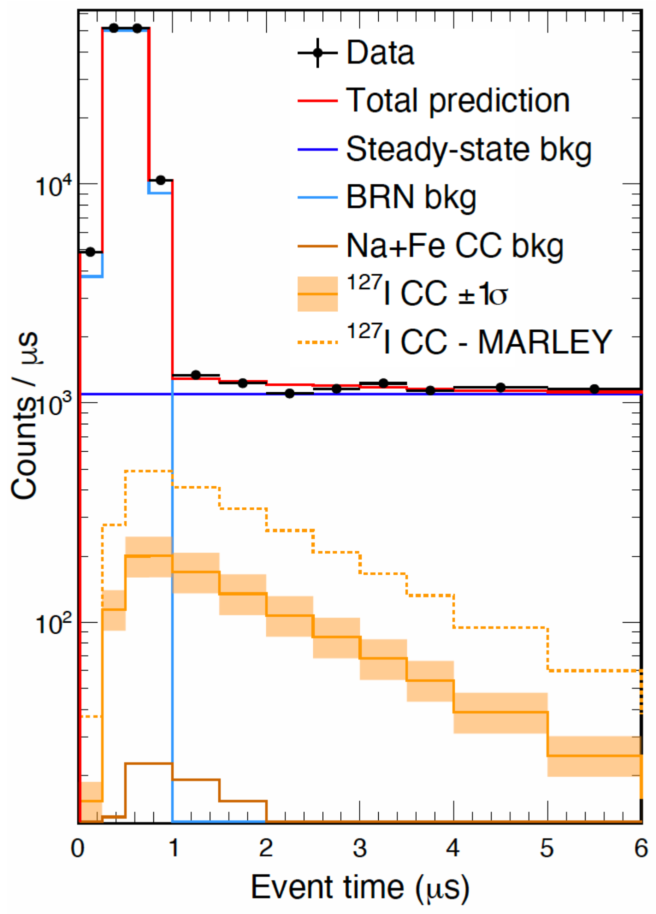
Other nuclei to be studied in a near future for CC are oxygen, argon, thorium

Potential future targets could be germanium, xenon and neon

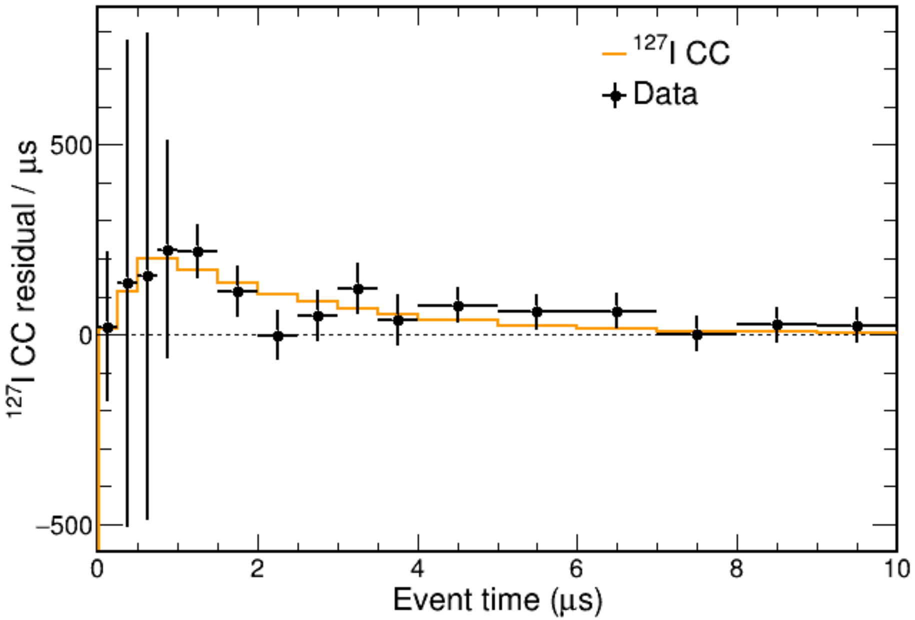
Iodine cross section results

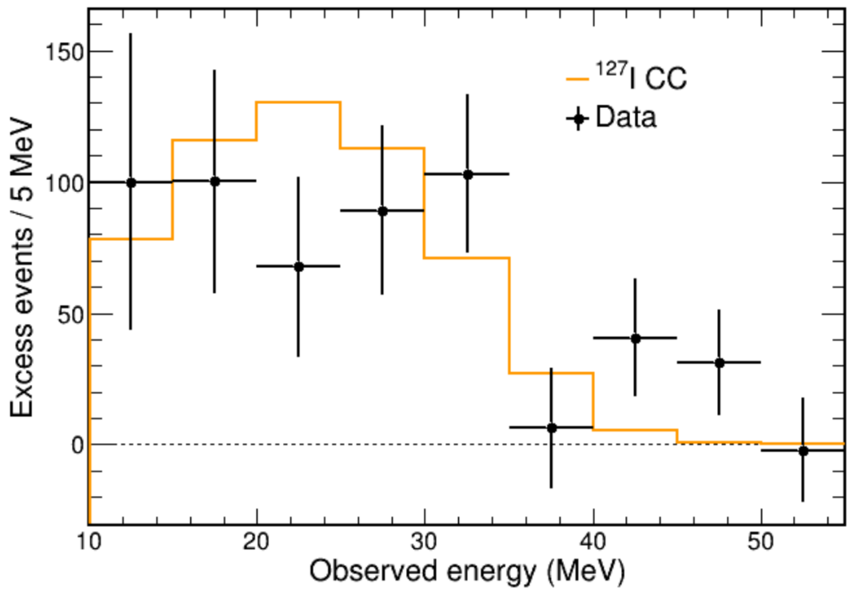
Best fit gives 541^{+121}_{-108} events or 5.8σ evidence of CC

Corresponds to cross section of $9.2^{+2.1}_{-1.8}$ * 10^{-40} cm^2 or 40% of MARLEY prediction



Subtracted steady state and BRN backgrounds

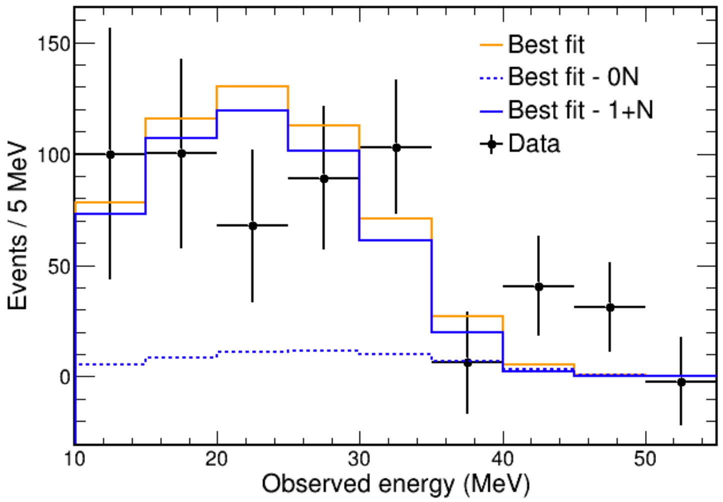




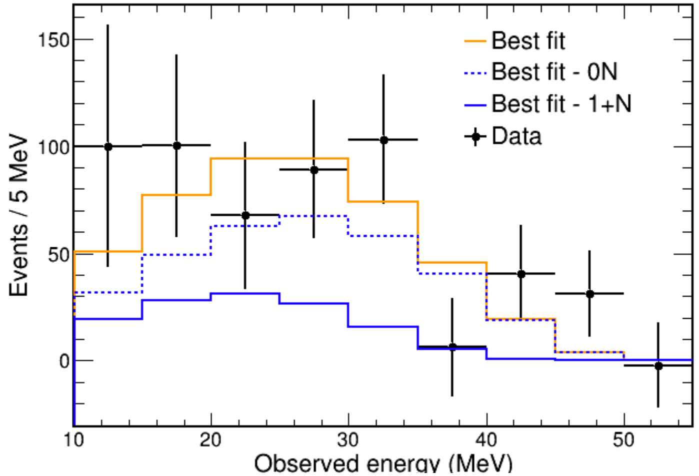
Zero or One+ Neutron Emission ?

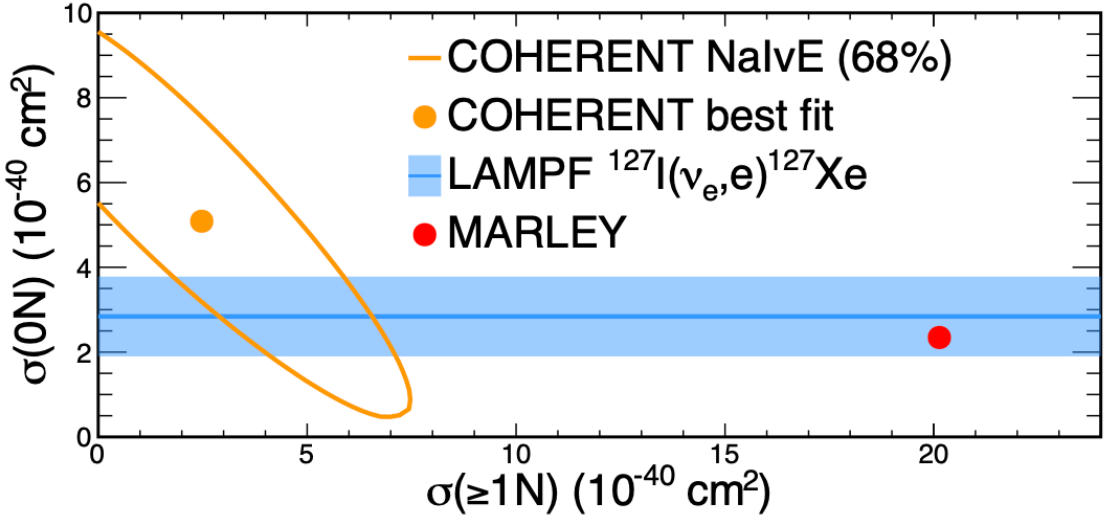
$$\nu_e + {}^{127}I \rightarrow e^- + {}^{127}Xe + ? * \text{n}$$

MARLEY prediction.
Ratio 0n to 1+n fixed



Data fit if to let ratio of zero to 1+n to float





For zero neutron emission our result is in agreement with MARLEY and previous LAMPF data

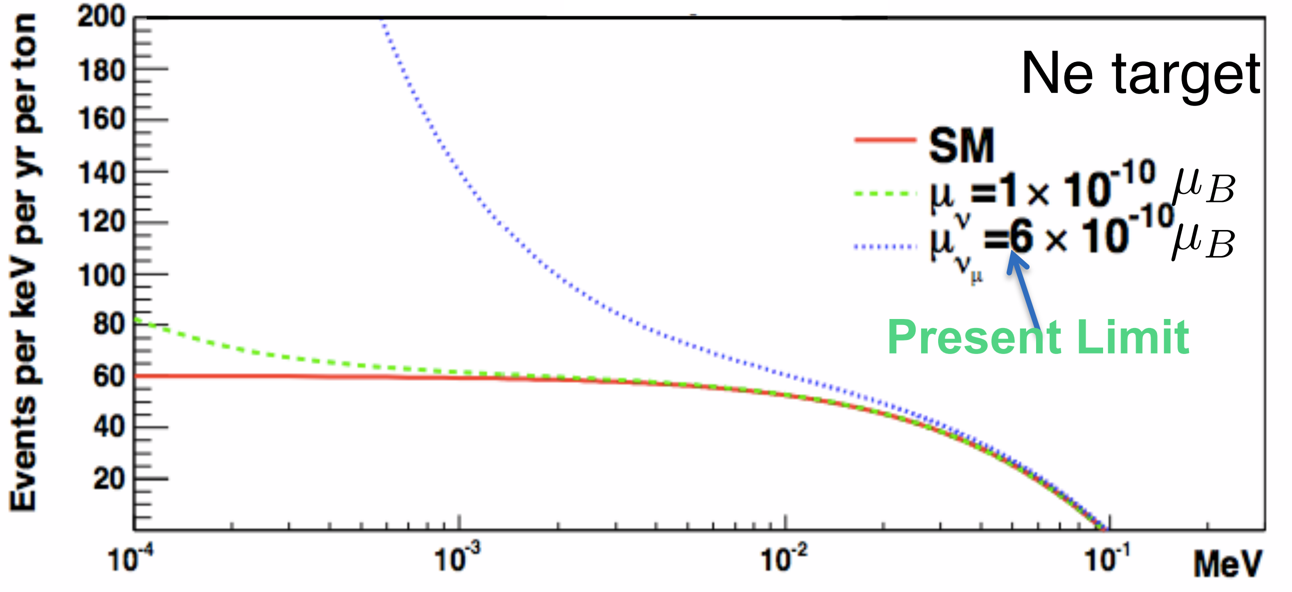
Nonzero neutron emission is significantly suppressed

e-Print: 2305.19594 [nucl-ex]

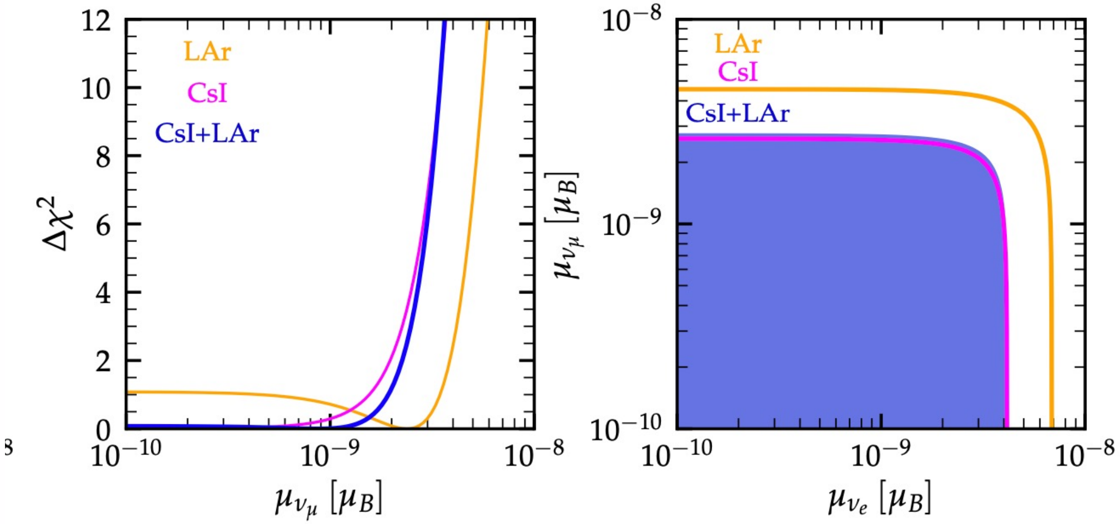
Search For Neutrino Magnetic Moment via CEvNS

Signature is distortion at low recoil energy E

$$\frac{d\sigma}{dE} = \frac{\pi\alpha^2\mu_\nu^2 Z^2}{m_e^2}\left(\frac{1-E/k}{E} + \frac{E}{4k^2}\right)$$

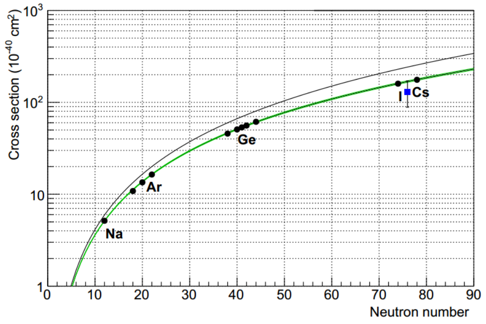


arXiv:2211..11905v1 [hep=ph]



See also Kosmas et al., arXiv:1505.03202

Future for LAr - 1 ton LAr detector

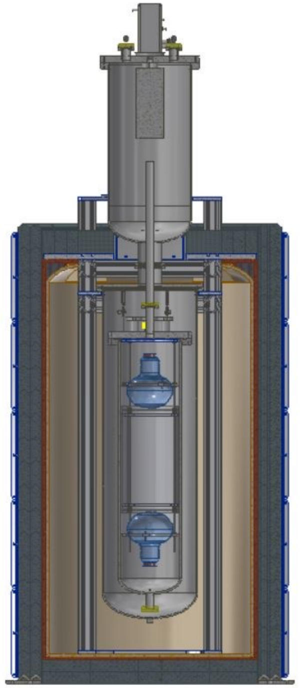


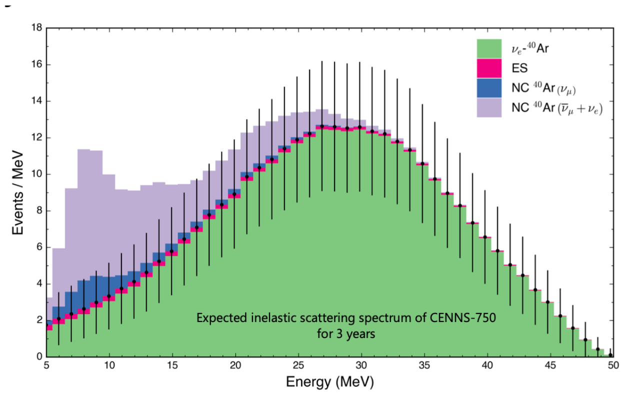
Need high statistics and low background measurements for CEvNS and good energy linearity for CC

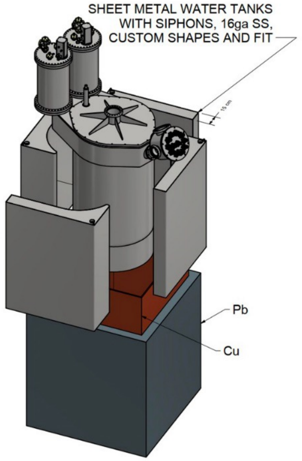
Transition from 22 kg to 1 ton LAr detector.

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

Will see 3kt of CEvNS events per year + 400 CC

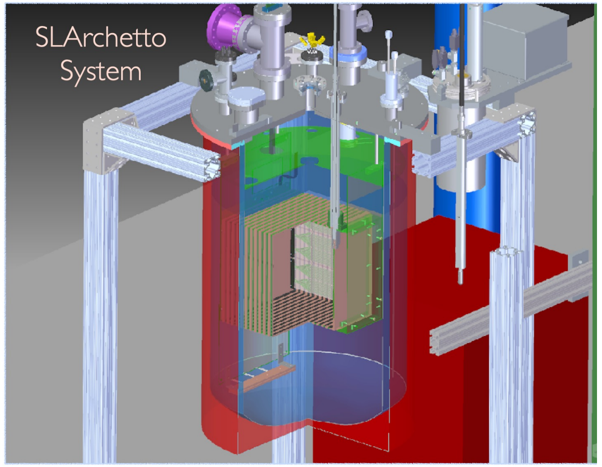






+

R&D on compact TPC SLAC (Yun-Tse-Tsai)



Detector is being build by our Korean collaborators at SNU

OAK RIDGE National Laboratory