THE UNIVERSITY OF TENNESSEE KNOXVILLE

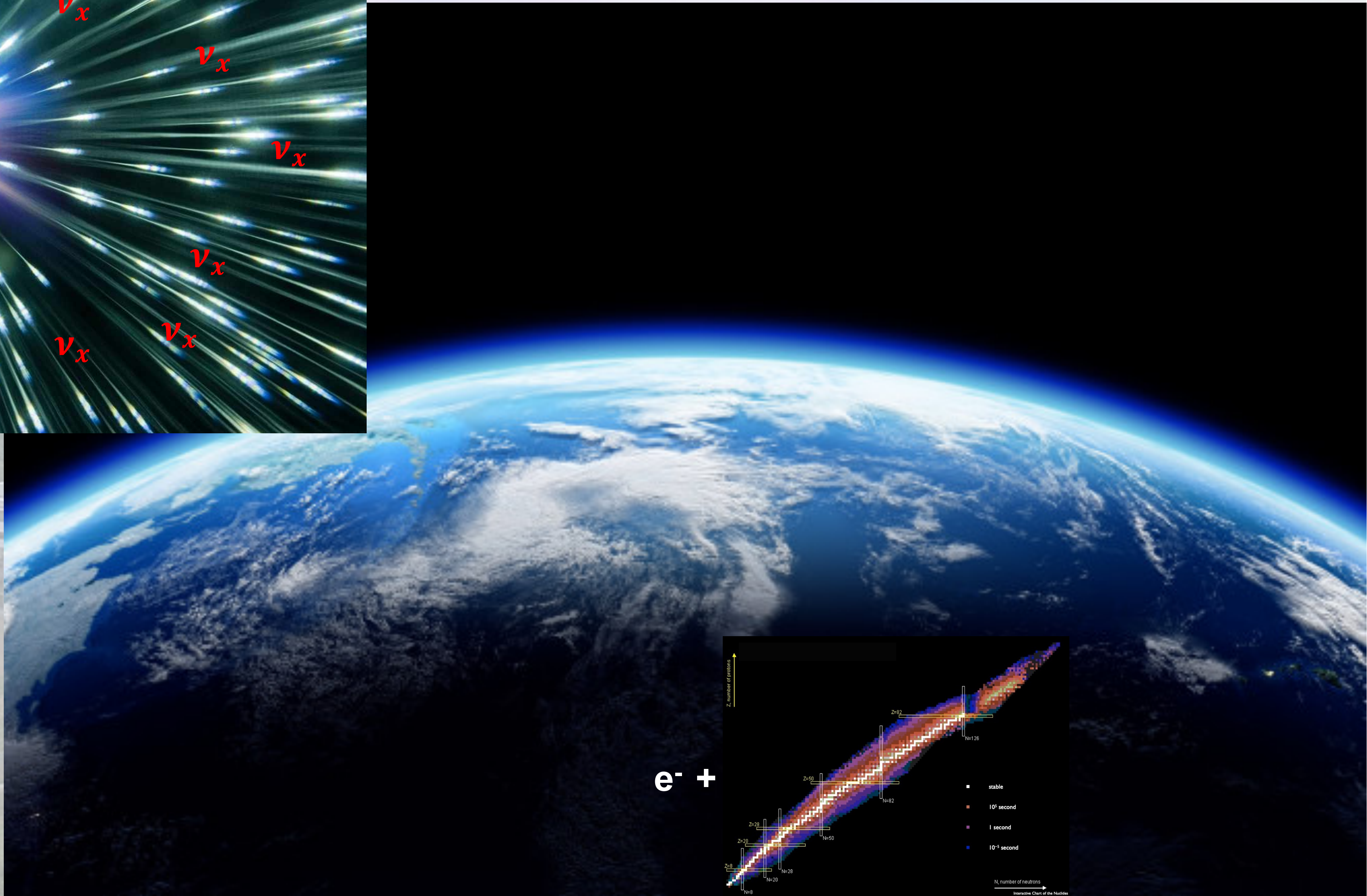
COHERENT SNS SPALLATION NEUTRON SOURCE

Measurements of cross-section with the COHERENT

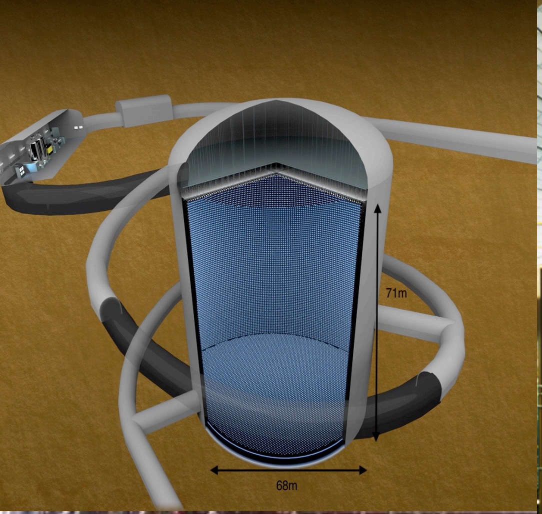
Yu. Efremenko UTK, ORNL

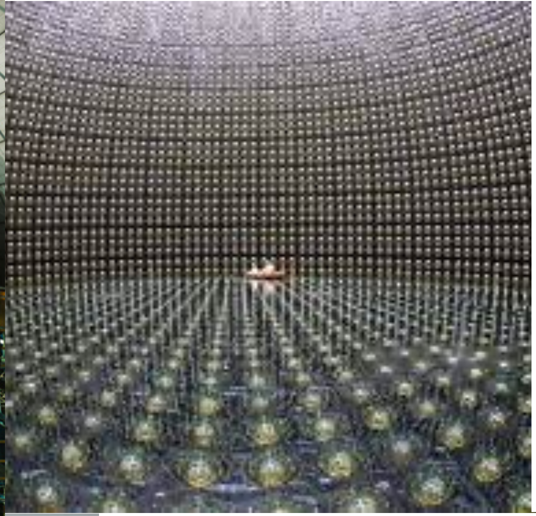
May 31, 2023, SNvD 2023@LNGS

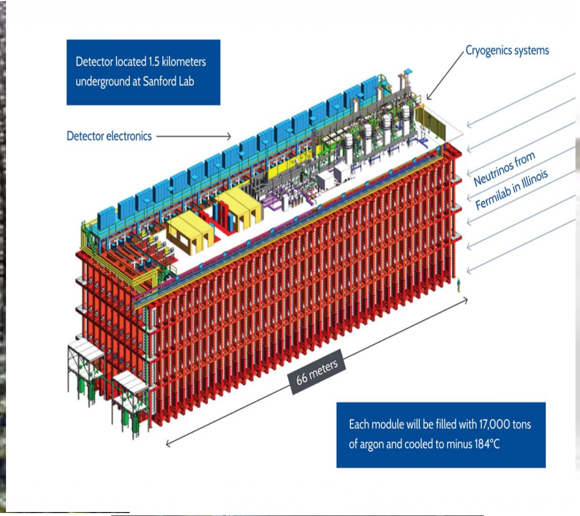
Multiple SN explosions in our galaxy already happens, so neutrinos are coming

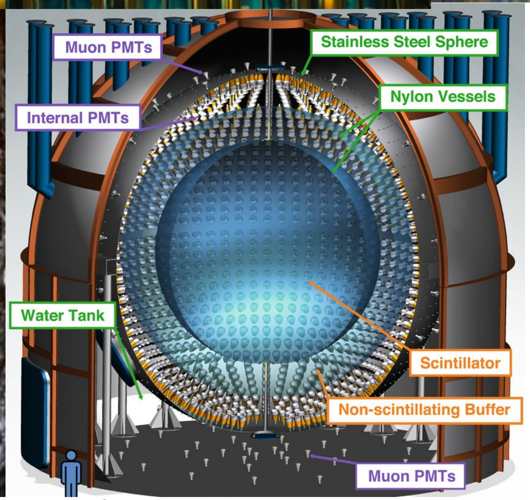


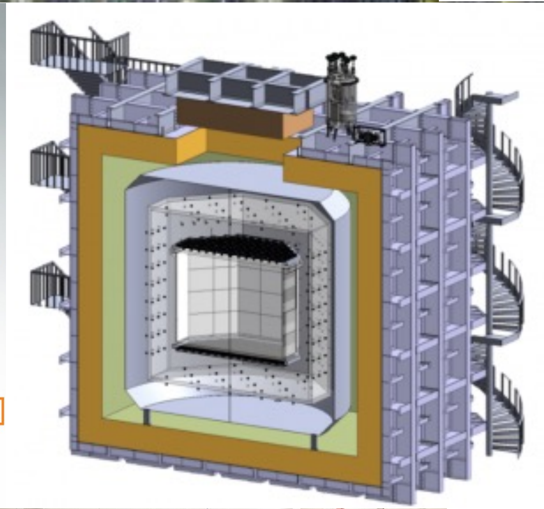
e^- +

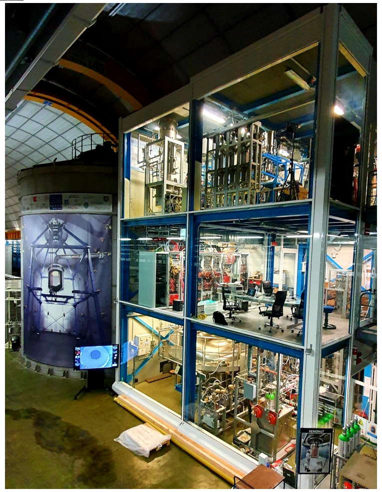

71m
68m

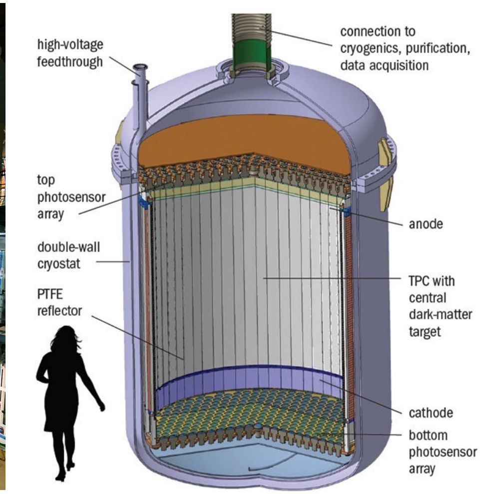


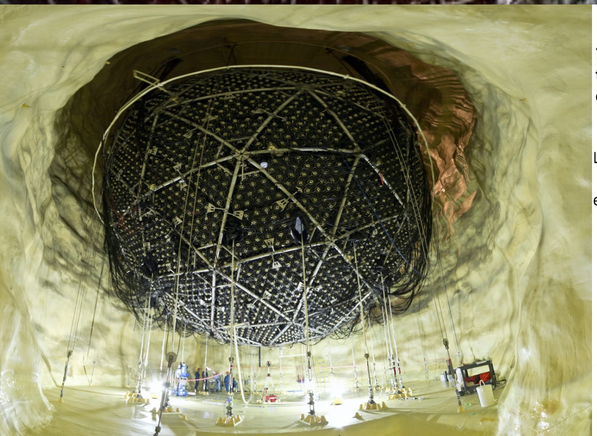

Detector located 1.5 kilometers underground at Sanford Lab
Cryogenics systems
Detector electronics
Neutrinos from Fermilab in Illinois
66 meters
Each module will be filled with 17,000 tons of argon and cooled to minus 184°C

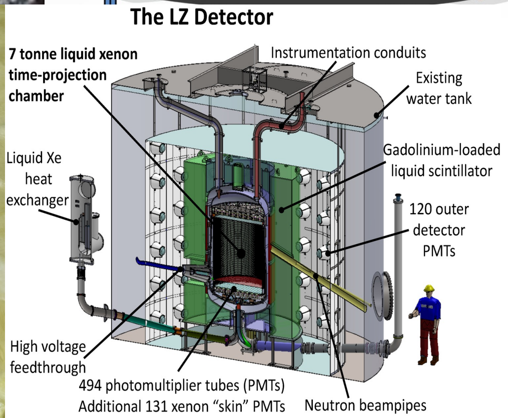

Muon PMTs
Stainless Steel Sphere
Nylon Vessels
Internal PMTs
Water Tank
Scintillator
Non-scintillating Buffer
Muon PMTs

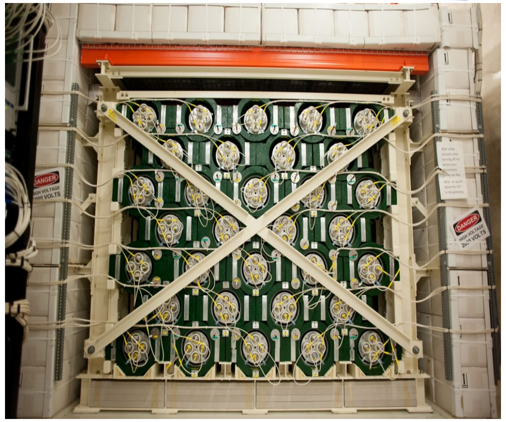


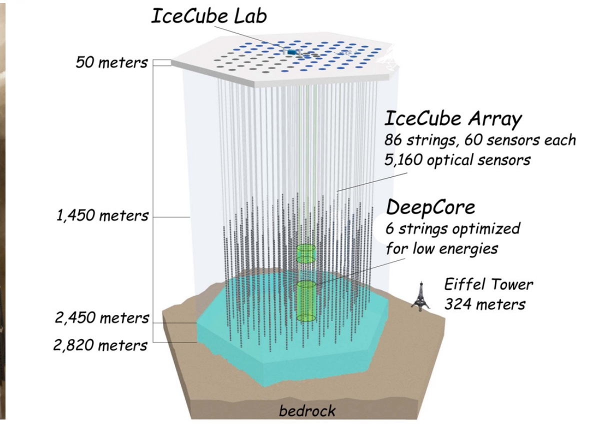


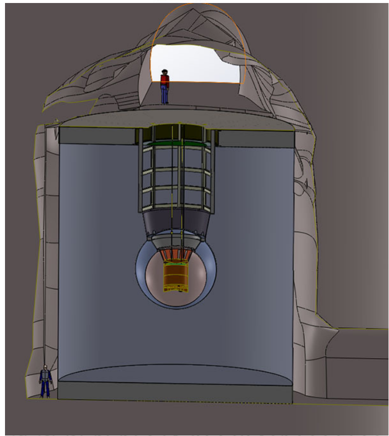

high-voltage feedthrough
connection to cryogenics, purification, data acquisition
top photosensor array
anode
double-wall cryostat
PTFE reflector
TPC with central dark-matter target
cathode
bottom photosensor array




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



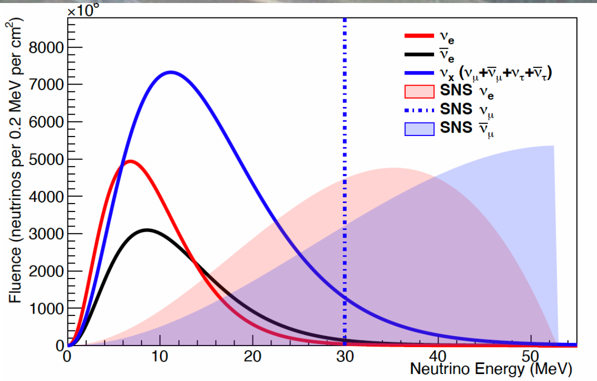
What Experimental Data do we have for Low Energy (<100 MeV) Neutrino Interactions on Nuclei?

Isotope	Reaction	Experiment
^{2}H	CC	E31 (LAMPF)
^{12}C	CC, NC	KARMEN (ISIS), LSND (LAMPF), E225 (LAMPF)
^{13}C	CC	KARMEN (ISIS)
^{56}Fe	CC	KARMEN (ISIS)
^{71}Ga	CC	GALEX (Gran Sasso), SAGE (Baksan)
^{127}I	CC	E-1213 (LAMPF), COHERENT 2023 (SNS)
^{208}Pb	CC+NC	COHERENT 2022 (SNS)

What Are Nuclear Targets for the Large Neutrino Detectors?

C, O, Ar, Xe, Pb

SNS at ORNL is the most powerful pulsed neutrino source and produce neutrinos with energy similar to ones from Super Nova



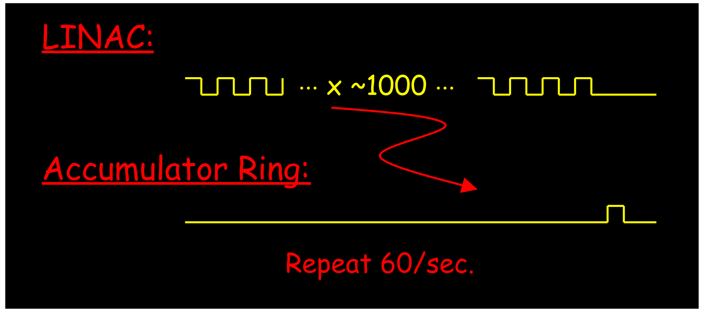
[image courtesy of K. Scholberg]

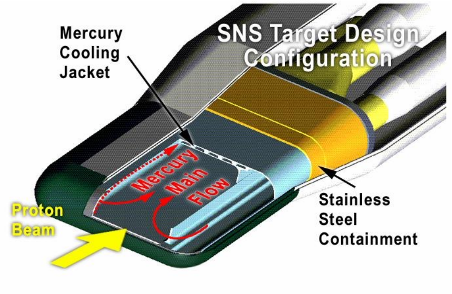
Nuclear power plants are too cold
Particle Accelerators are too hot

COHERENT Choose to Use Spallation Neutron Source (SNS)

- It is world most powerful pulsed neutrino source. Presently it delivers 8 · 10^{20} POT daily *~10% of protons produce 3 neutrino flavors*
- *1 GeV proton driver produce 1.55 MW*
- **Decay At Rest from pions and muons (DAR)** gives very well-defined neutrino spectra.

  For 99% of neutrinos $E_\nu < 53$ MeV
- 60 Hz proton pulses with duration of ~400 nsec each
- Fine duty factor let suppression of steady background by a factor of 2000.



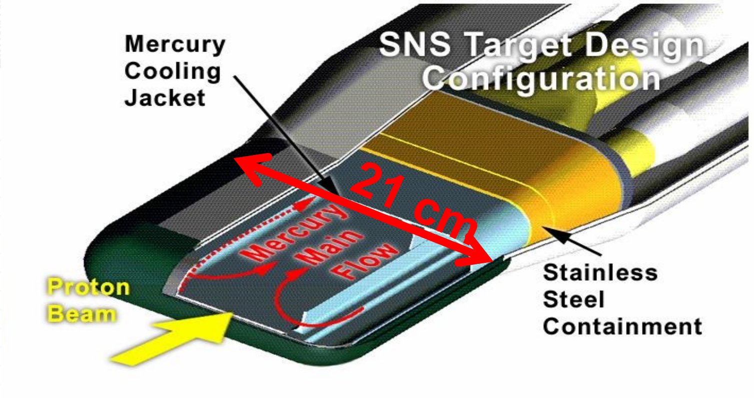


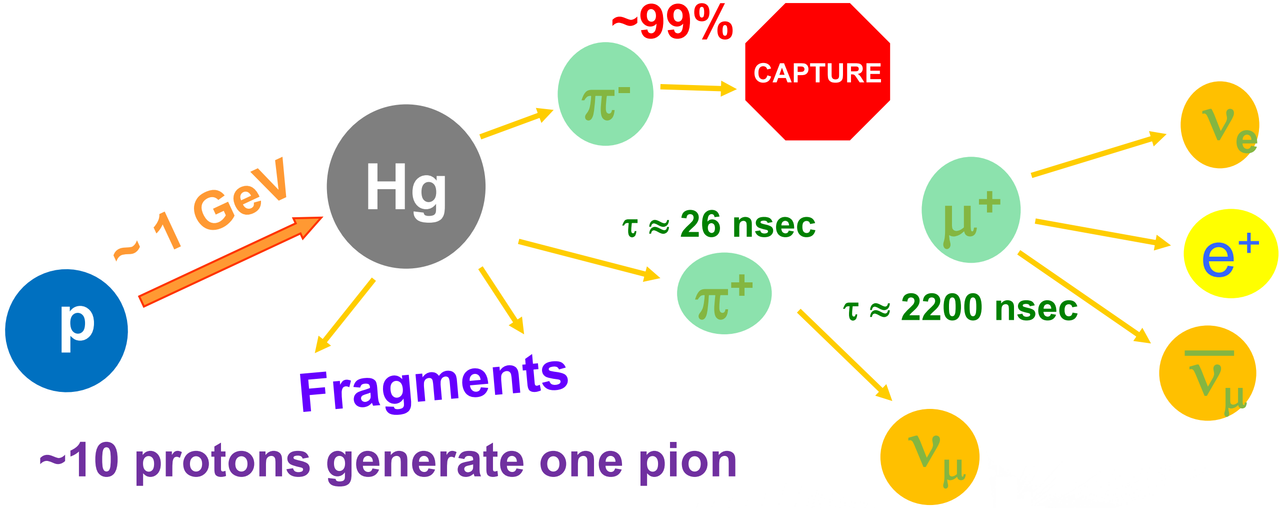
1.0 GeV

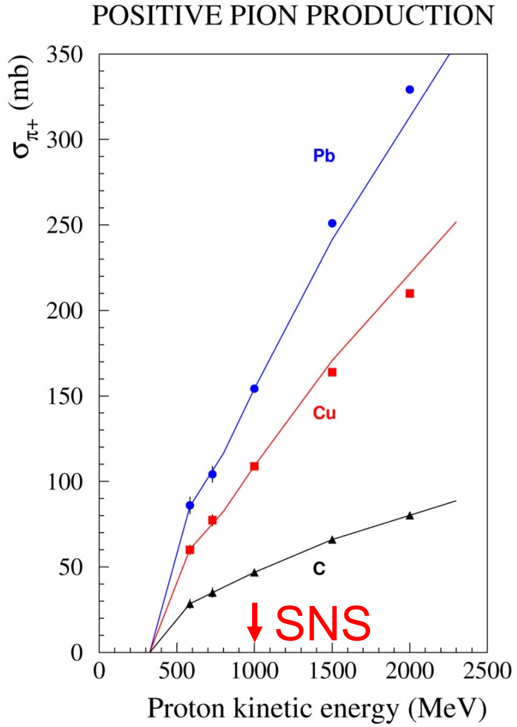
Compact Mercury Target (7 x 40 x 50 cm^3)

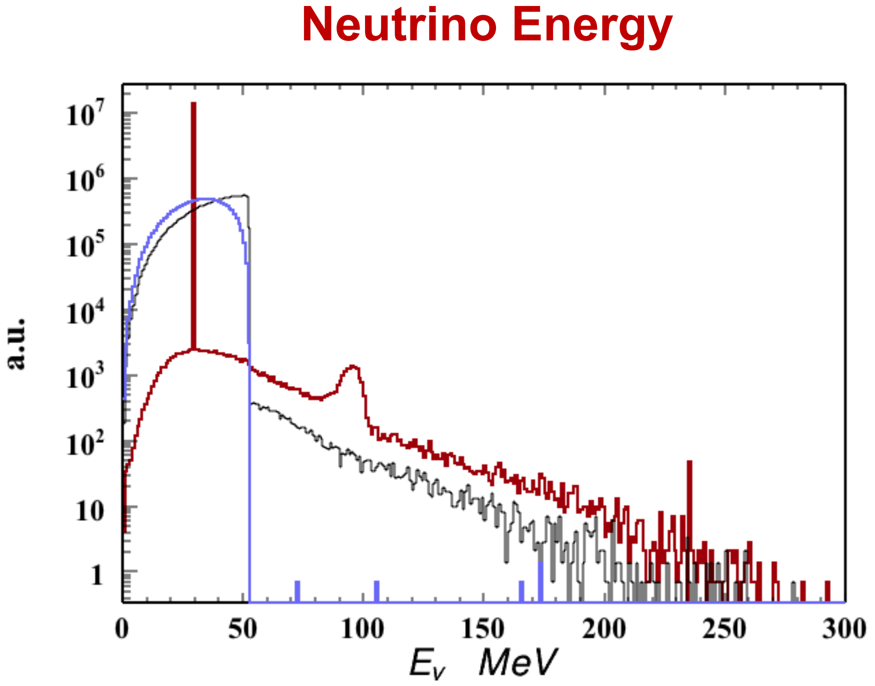
Oak Ridge National Laboratory

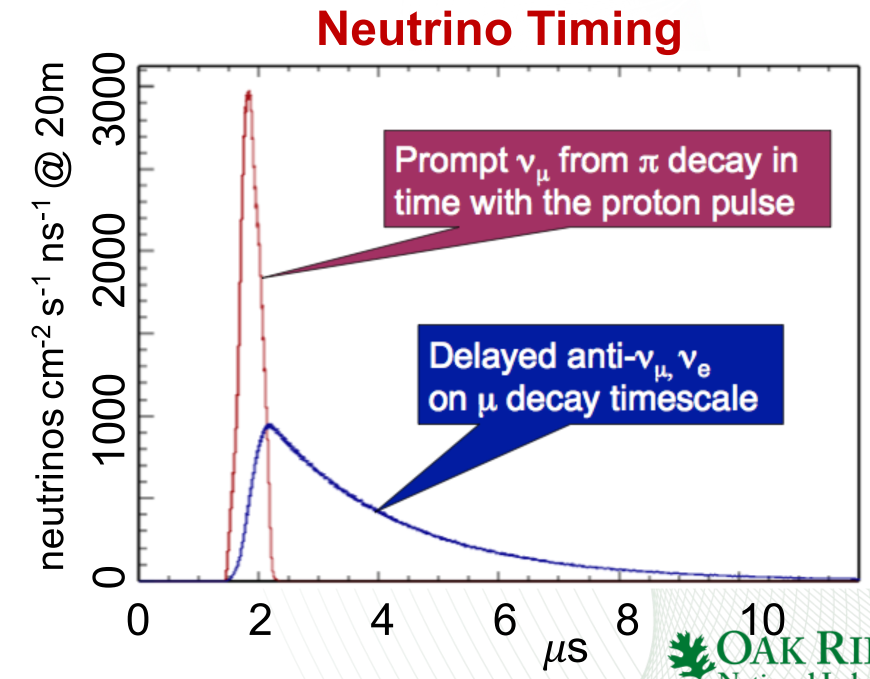
Neutrino Production at the SNS











OAK RIDGE National Laboratory

SNS is Optimized to Produce Neutrons

Experimentalists who are trying to put neutrino detector next to the world most powerful neutron source should recall:

Legend of Icarus

Daedalus, a mythical inventor, created wings made of feathers and wax to escape from Crete where he and his son, Icarus, were held captive by King Minos. Icarus, however, ignored his father's warnings and flew too close to the sun. His wings melted and he fell into the sea where he met his end

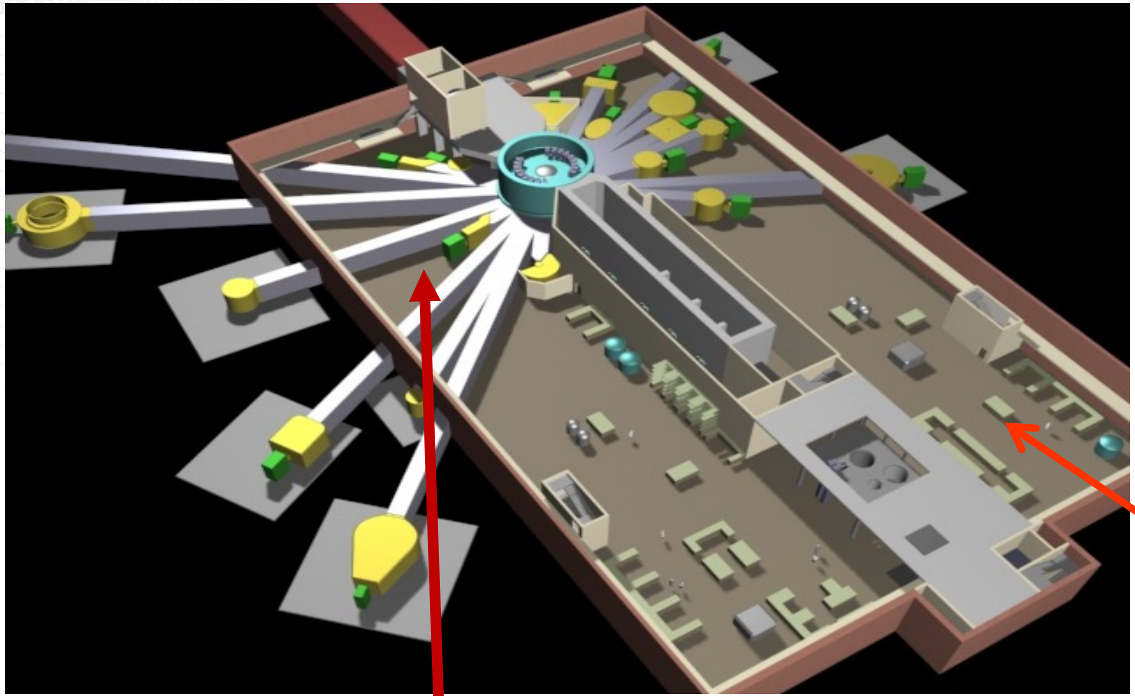
There are Multiple Sources of neutrons inside the Target building.

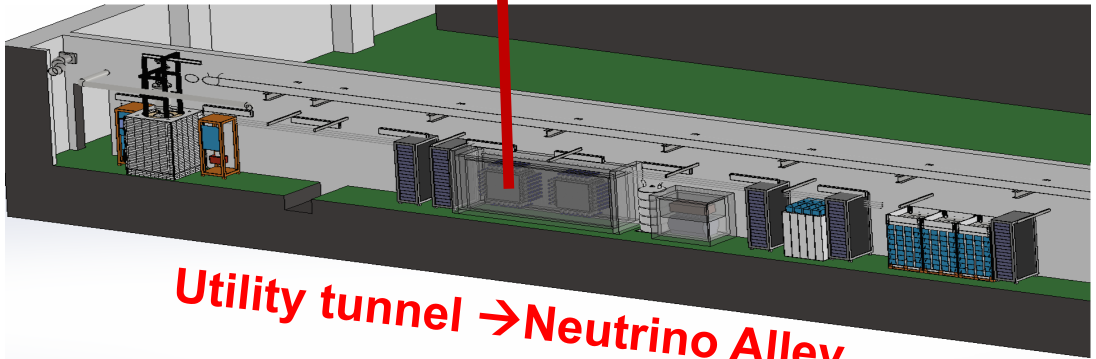
Intermediate Neutrons with energy more than 50 keV can produce nuclear recoils

Neutrons are our biggest worry as a background !

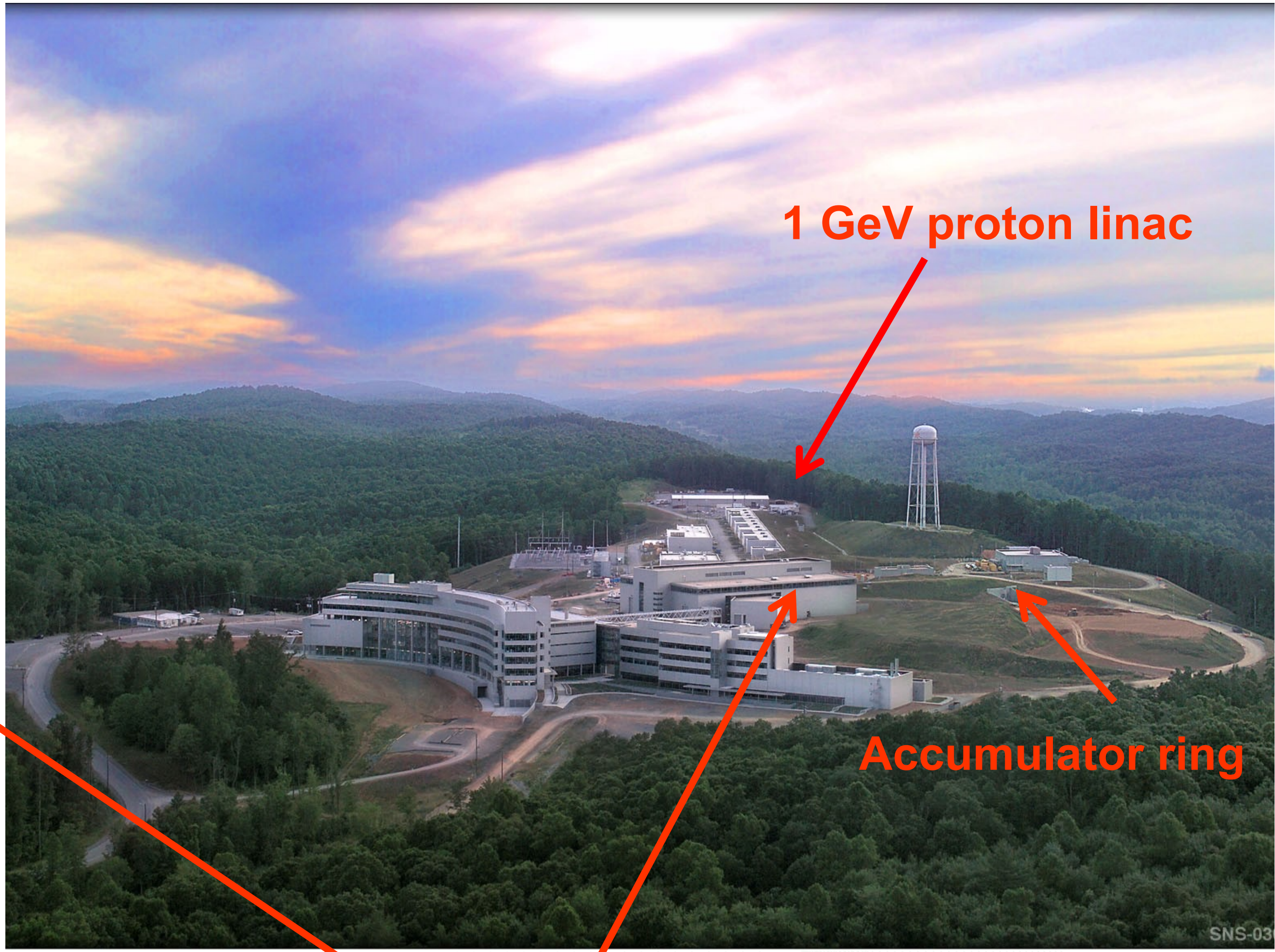
Neutrino Alley

After extensive BG studies, we find a well protected location





Utility tunnel →Neutrino Alley



Target Building

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

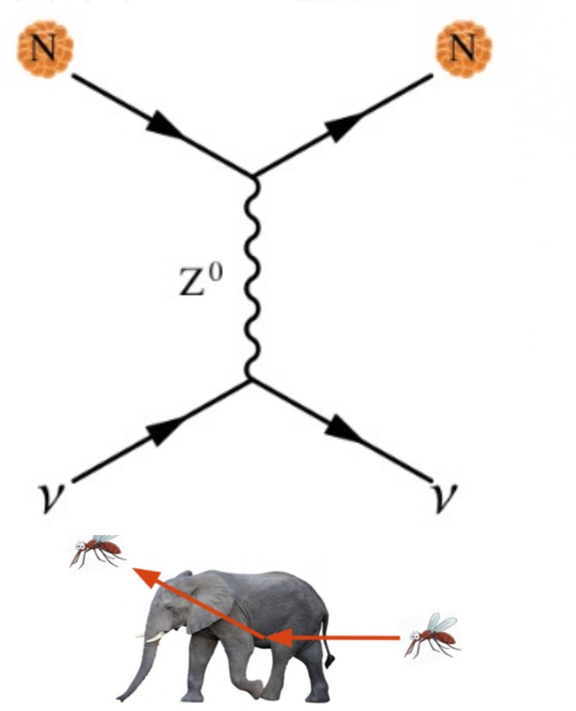
There are 10 M.W.E. from above

We have 1m*2m*25m of space !!!

Neutrino Alley
NEUTRINO ALLEY
HOT OFF GAS
CAUTION
WET FLOOR
Help | Terms
Matterport
Neutrino Alley
Charged-Current Inte
Previous Measurement
Neutrino Production at the SNS
Help | Terms
Matterport

Coherent Elastic neutrino-Nucleus Scattering (CEvNS)

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

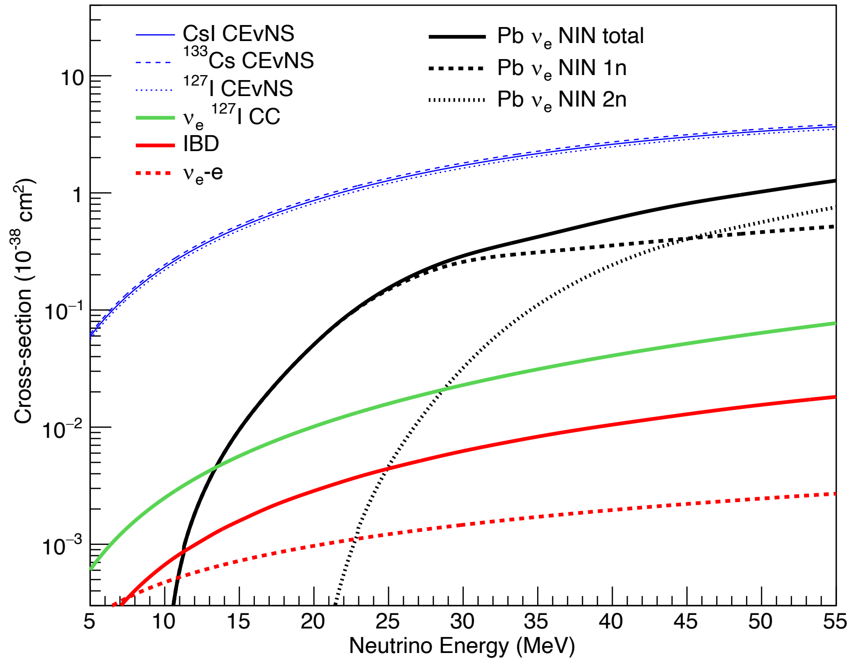


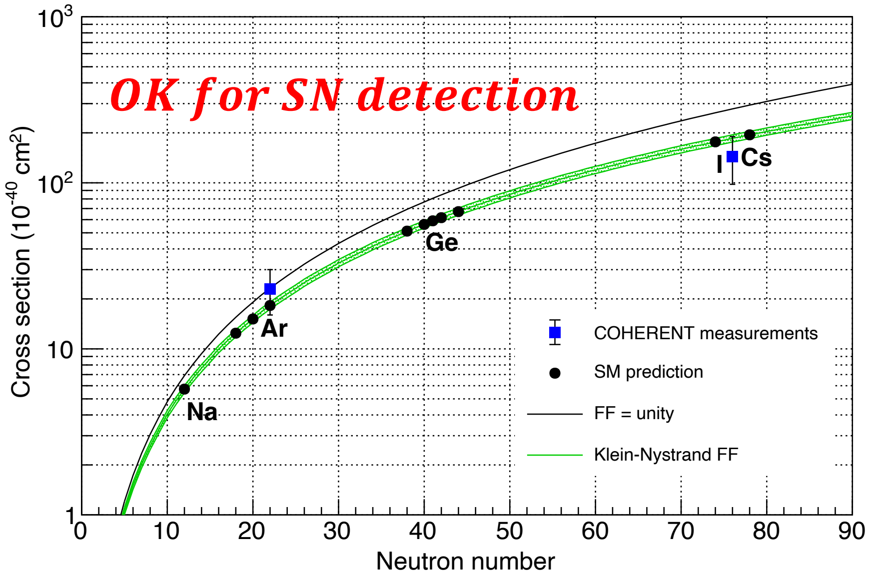
CEvNS cross-section is large, but very hard to detect

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.

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

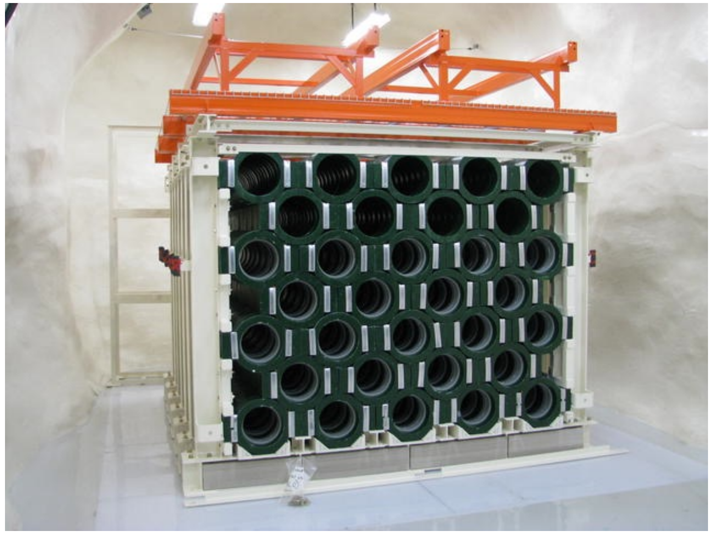




Look for Neutrino Induced Neutrons (NIN) on Lead
SN detector at SNOLAB and Background for CEvNS

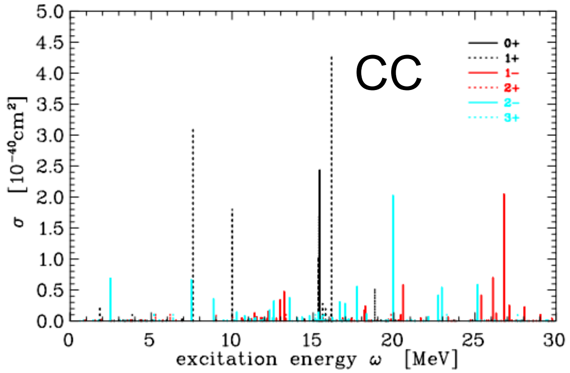
$$\nu_e + {}^{208}Pb \Rightarrow {}^{208}Bi^* + e^- \qquad (CC)$$
$$\Downarrow$$
$${}^{208-y}Bi + x\gamma + yn$$

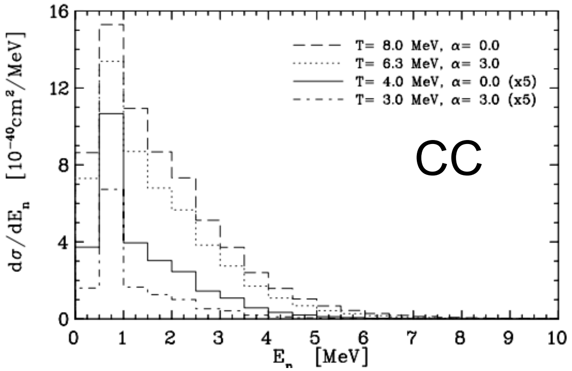
$$\nu_x + {}^{208}Pb \Rightarrow {}^{208}Pb^* + \nu_x' \qquad (NC)$$
$$\Downarrow$$
$${}^{208-y}Pb + x\gamma + yn.$$

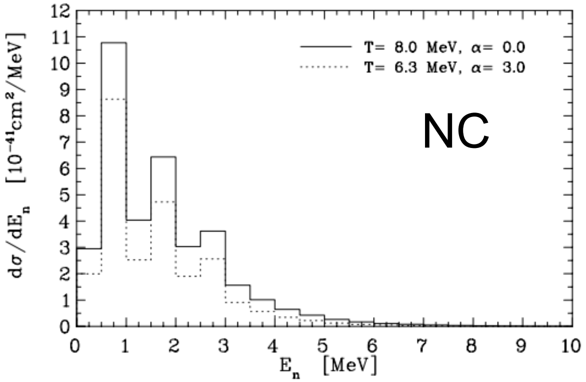


HALO at SNOlab

Kolbe & Langanke (2001)







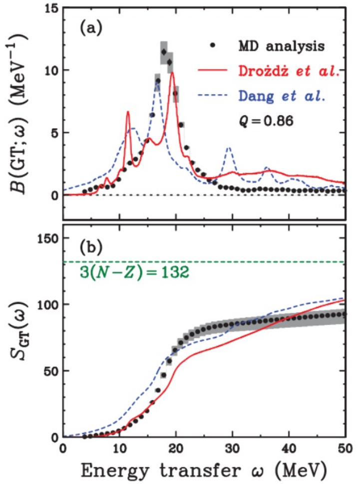
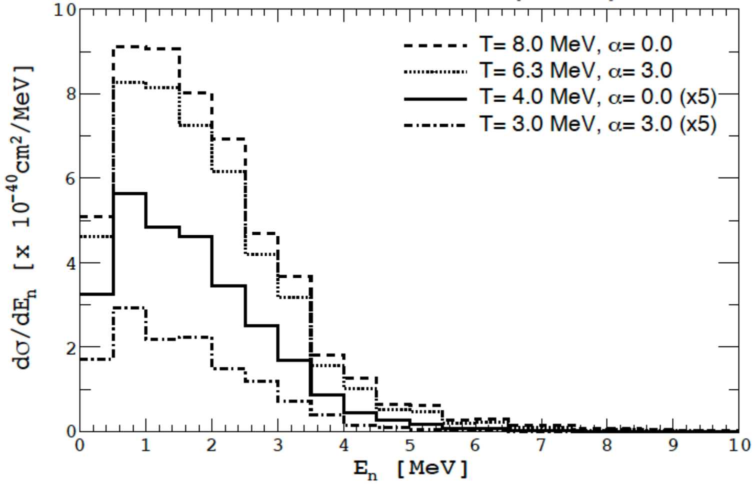


FIG. 16. (Color online) (a) The GT strength $B(\mathrm{GT};\omega)$ and (b) its integrated $S_{\mathrm{GT}}(\omega)$ distributions obtained by MD analysis of the $^{208}\mathrm{Pb}(p,n)$ reaction. The bands represent the uncertainties arising from the selection of α in Eq. (18). The solid and dashed curves are the theoretical predictions reported by Drożdż *et al.* [18] and Dang *et al.* [62], respectively, with a quenching factor $Q = 0.86$ [13].

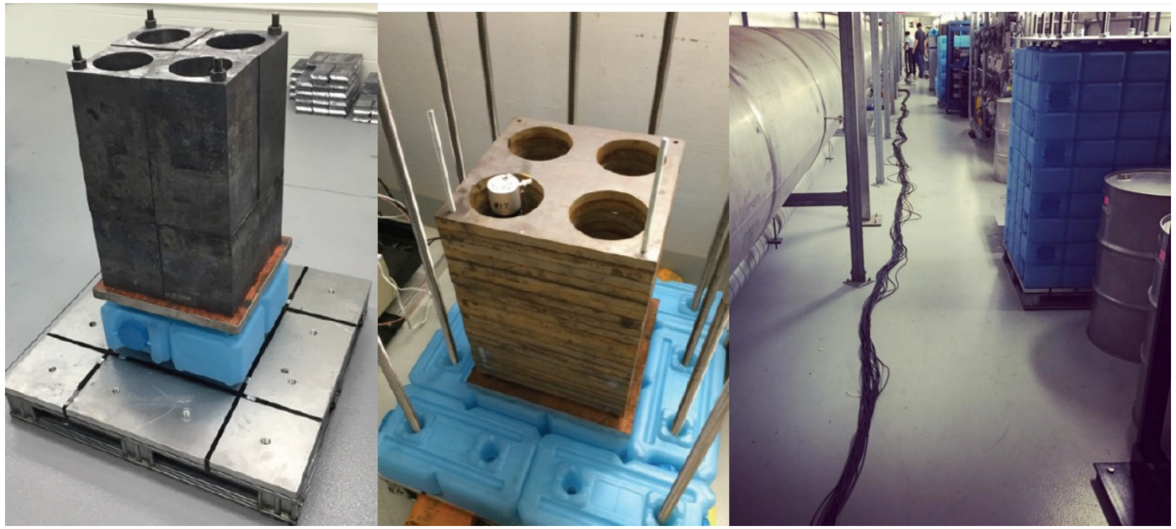
[T. Wakasa, et al., Phys Rev. C **85** (2012)]

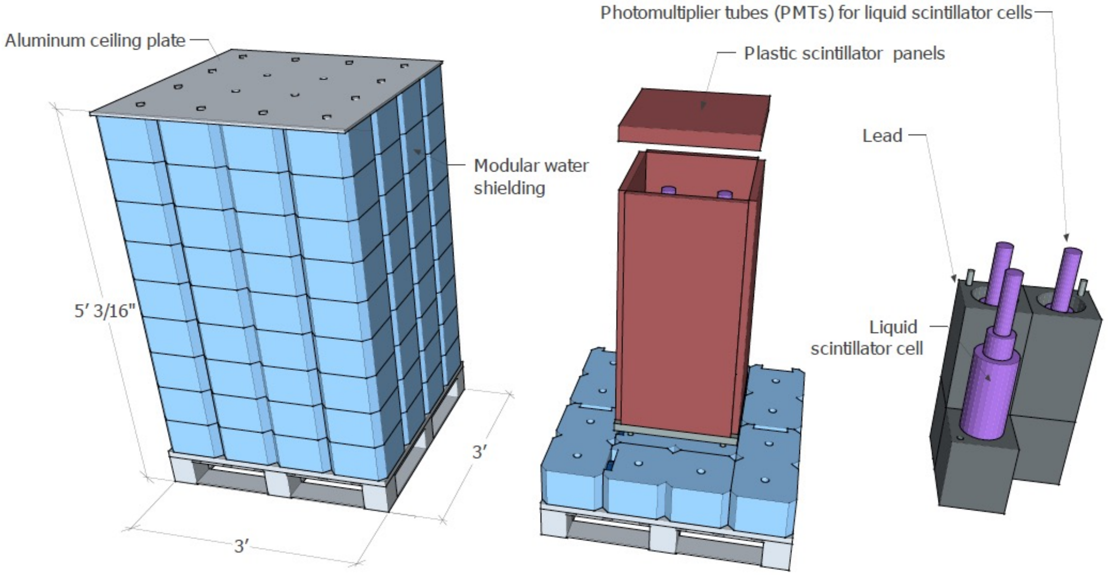
MARLEY + Wakasa B(GT$^-$) 2012

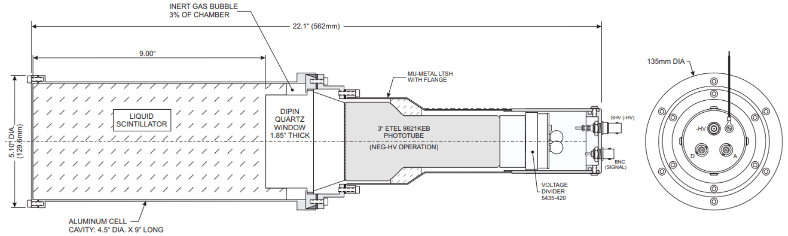


Neutrino-Induced Neutron Detectors (NUBES)

- 900 kg Pb and 700 kg Fe Neutrino Cube
- Low background lead cast with cavities for EJ-309 Liquid Scintillator Detectors
  - 1st run conf: 4x 2.4 L Cylinder (Eljen)
  - 2nd run conf: 2x 2.4 L Cylinder
  - 3rd 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
- Exterior water bricks for neutron moderation
- Deployed late 2015 and final data set up to August 2020
  - Flux weighted average distance of 18.88 m from target

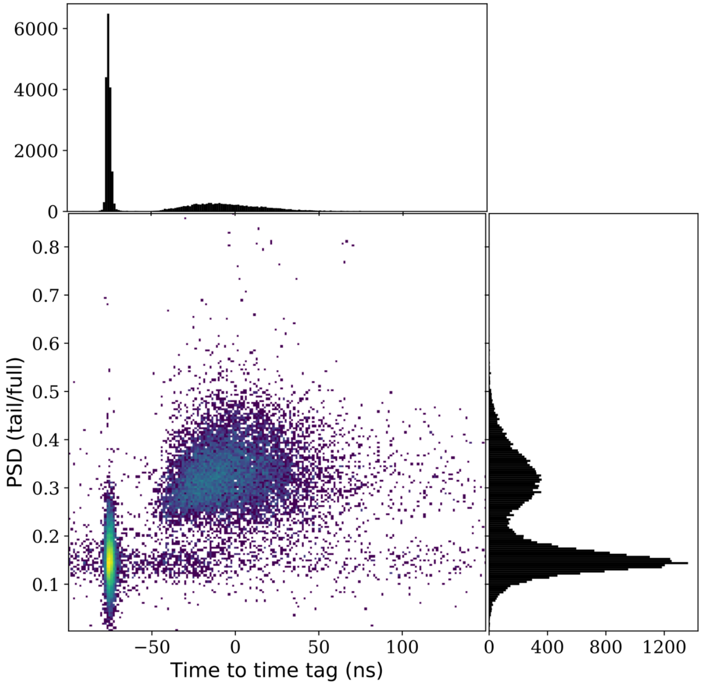


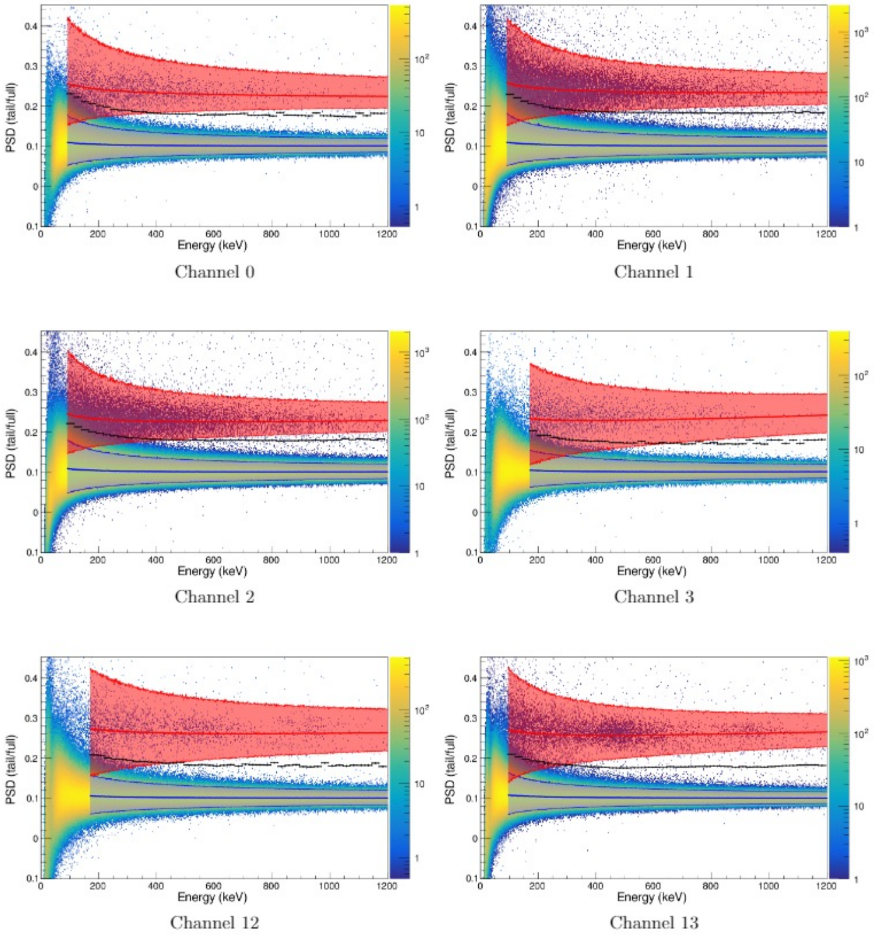




Detectors Calibration for Neutrons

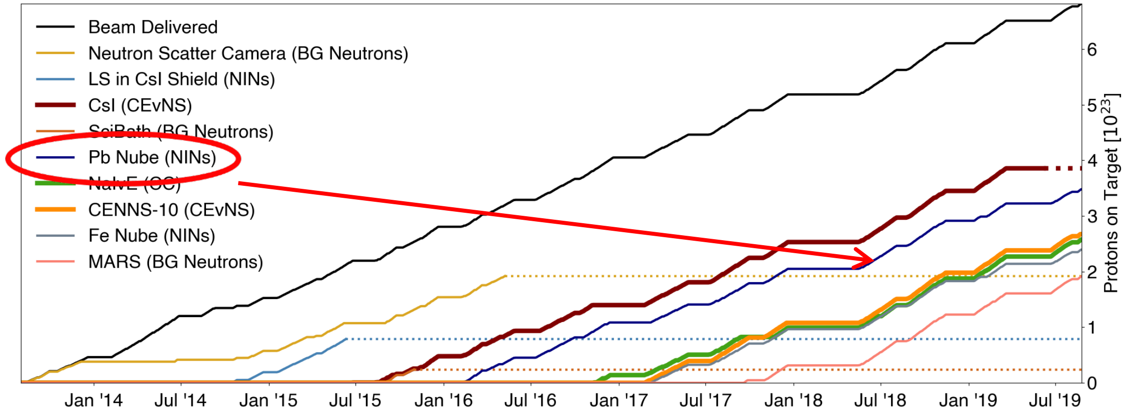
We used time-tagged ^{252}Cf neutron source (fission chamber)





NINs on Lead Results

e-Print: [2212.11295](2212.11295) [hep-ex]

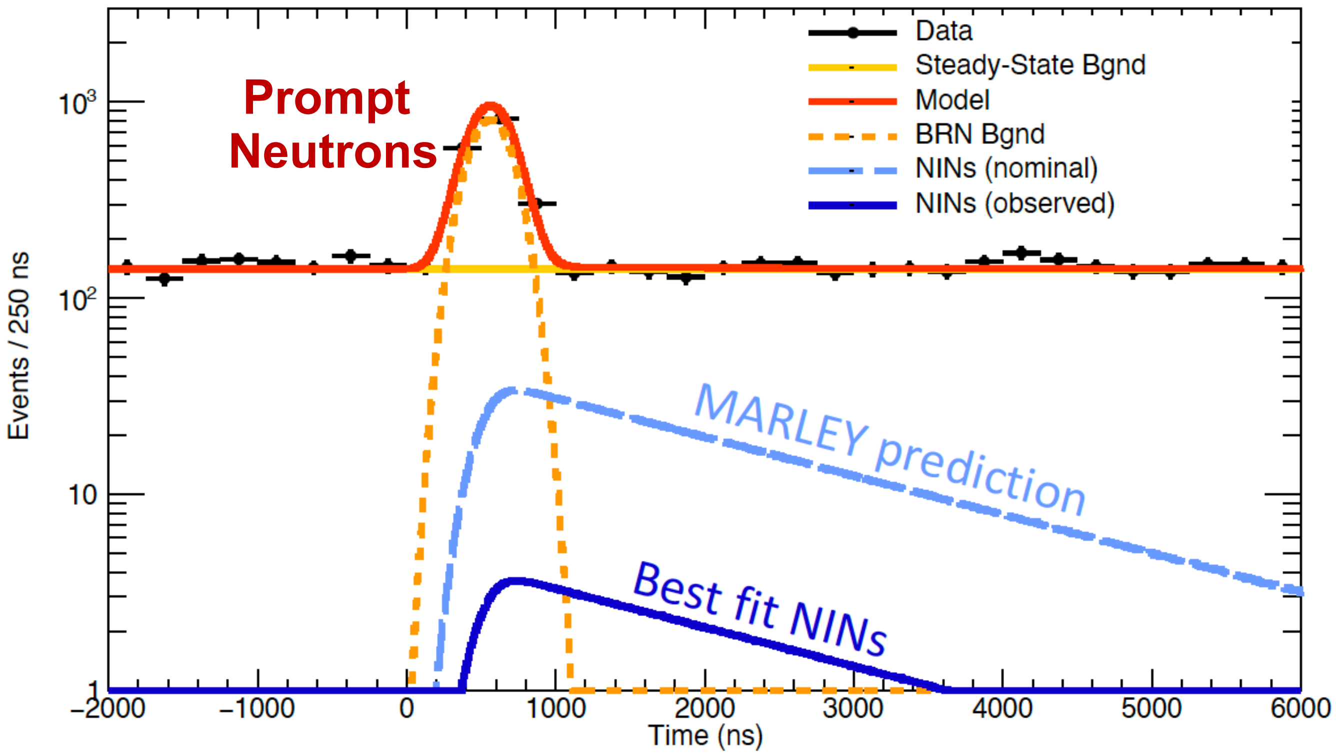


Statistics was accumulated for 5 years starting form January 2016

During that period SNS delivered ~$5 \cdot 10^{23}$ protons (0.8g) to the target.

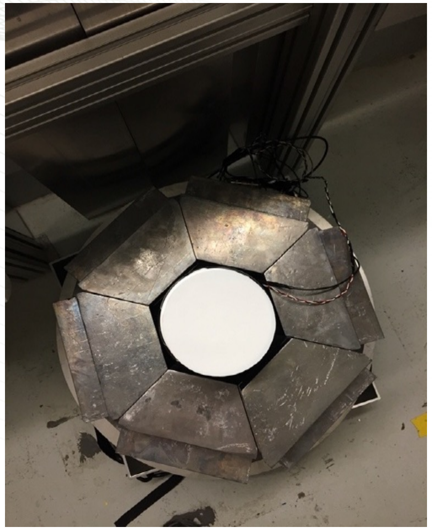
Expected number of events from MARLEY simulation: 346

Detected 36^{+72}_{-36}

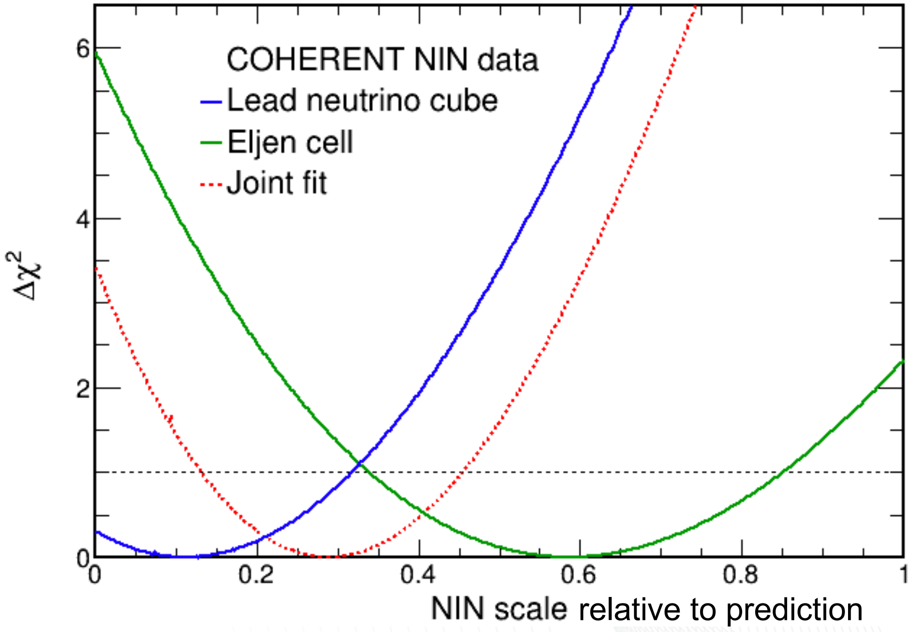


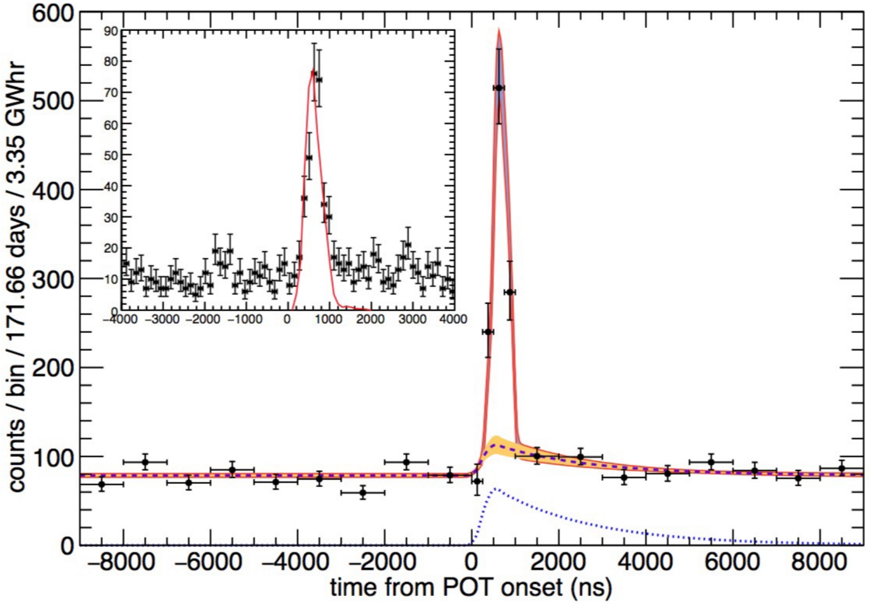
Compare with the Previous Measurements

(D. Akimov, et al., arXiV:2109.11049 (2021)



Single 1.5 Liter L.S. detector
2200 kg of Lead
~8·10^{22} protons on target (~ 6 times less POT)





Group in Japan (J-PARC) will follow up with similar measurement
(DaRveX: arXiv:2205.11769 hep-ex)

Neutrino Interaction with ^{127}I

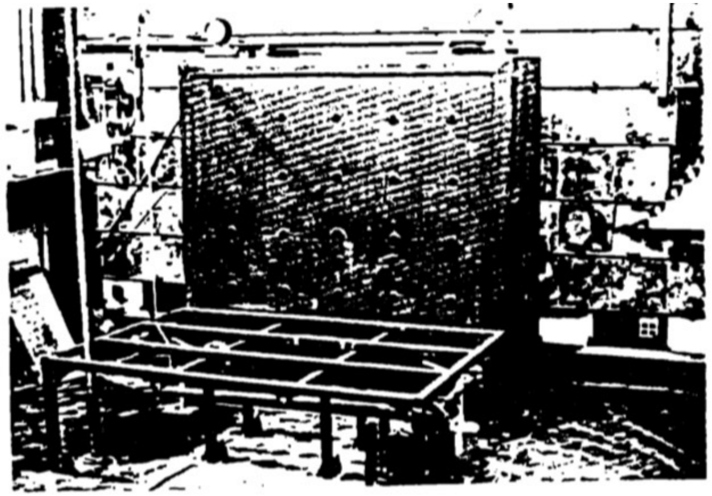
Proposed by Haxton in 1988 as a way to detect solar neutrinos using radiochemistry, similar to gallium experiment

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

Low threshold for this reaction 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



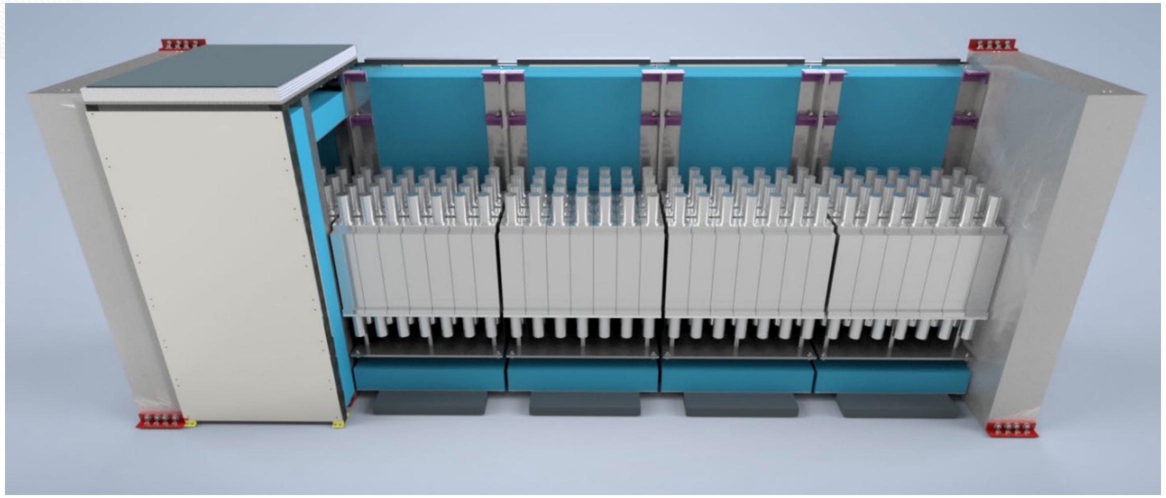
E-1213 LAMPF experiment

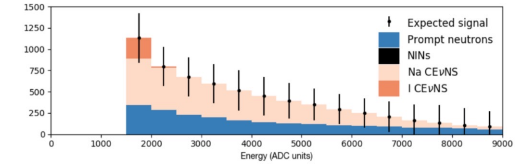
Due to the radiochemical approach measured only transition to the bound state of ^{127}Xe

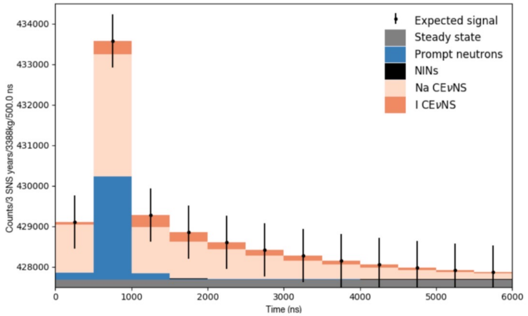
$$\boldsymbol{\sigma = 2.84 \pm 0.91\ stat \pm 0.25\ sys \times 10^{-40}\ \mathrm{cm}^2}$$

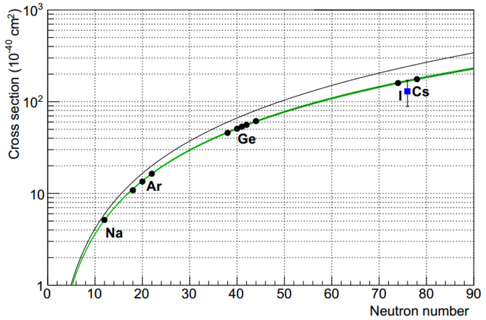
2.5-ton Array of NaI crystals (Na target for CEvNS)

- COH-NaIvETE: deployment in progress!







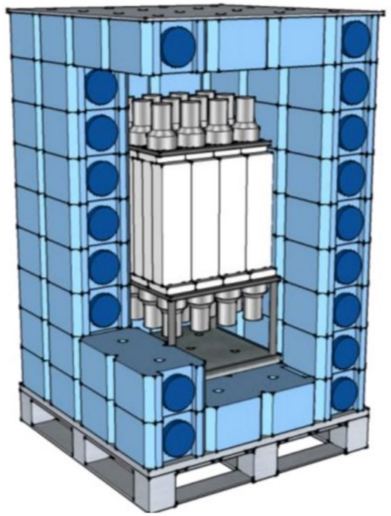


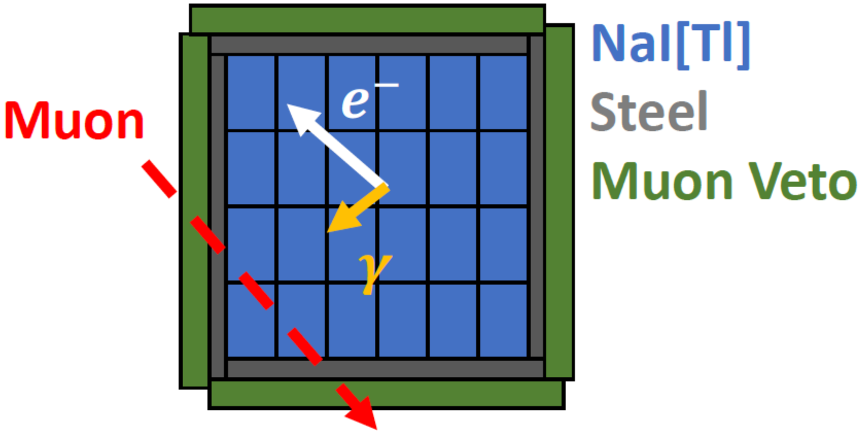
First section ~0.5 ton has been deployed last summer and taking data
Will look for both: CEvNS and CC

Pre-Deployment of NaI. CC on Iodine

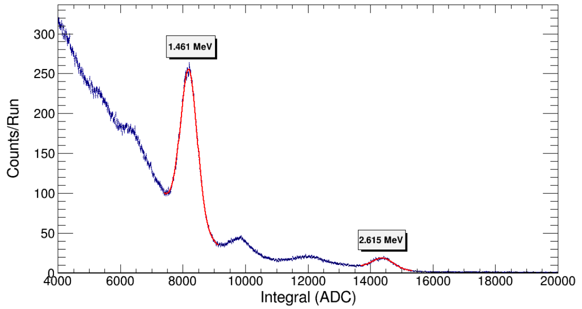
COH-NaIvE: Twenty-four 7.7 kg NaI crystals with total mass of 185 kg

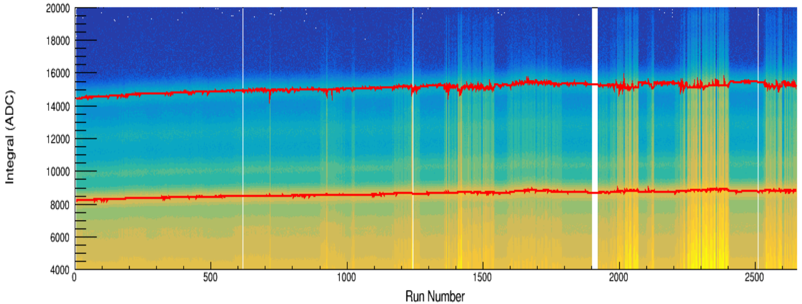
Deployed in 2016 and still taking data

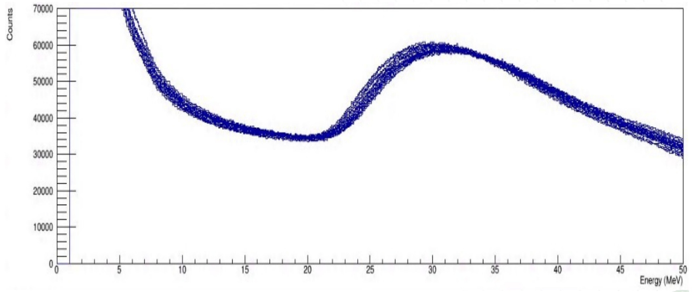


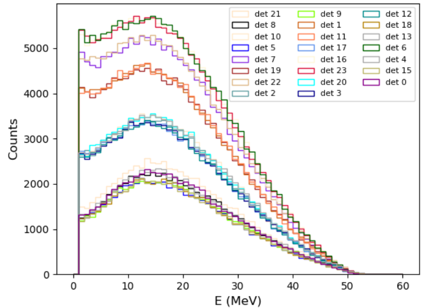



Internal constant calibration using ^{40}K and ^{208}Tl lines, Muons and Michel electrons









MARLEY predictions for ^{127}I

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

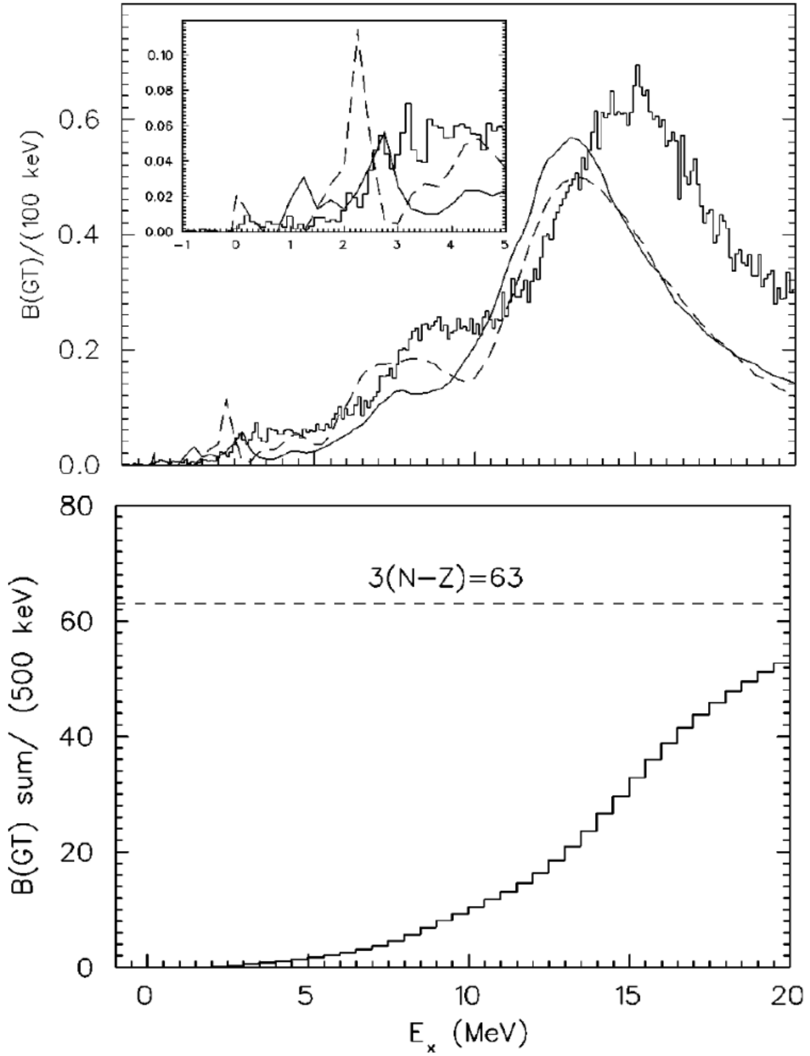
$$22.5^{+1.2}_{-6.5} \times 10^{-40}\ \mathrm{cm}^2$$

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

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

  - Good agreement with LAMPF measured value of

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



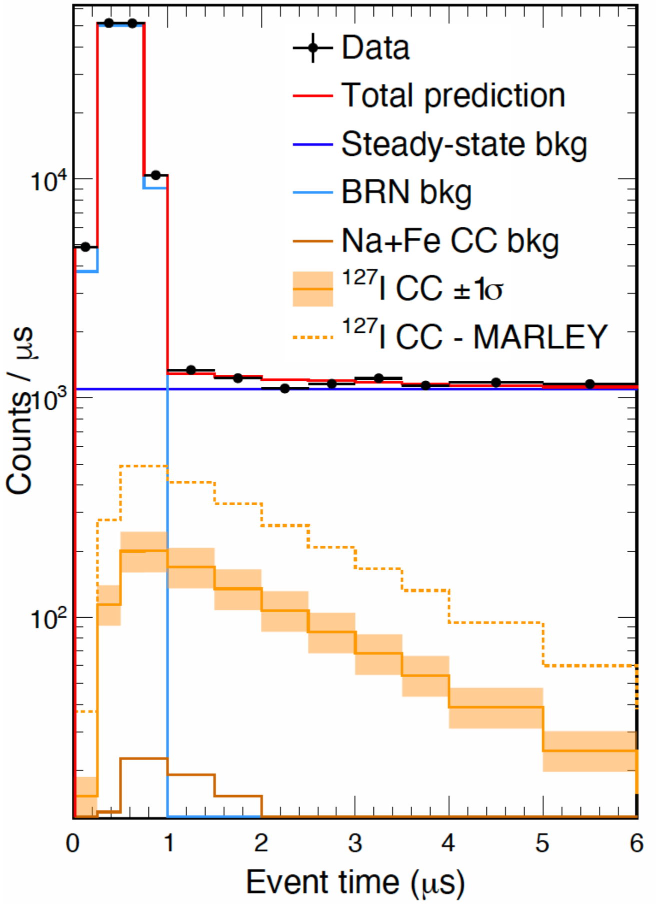
[M. Palarczyk, et al., Phys. Rev. C 59 (1999)]

Ph.D.

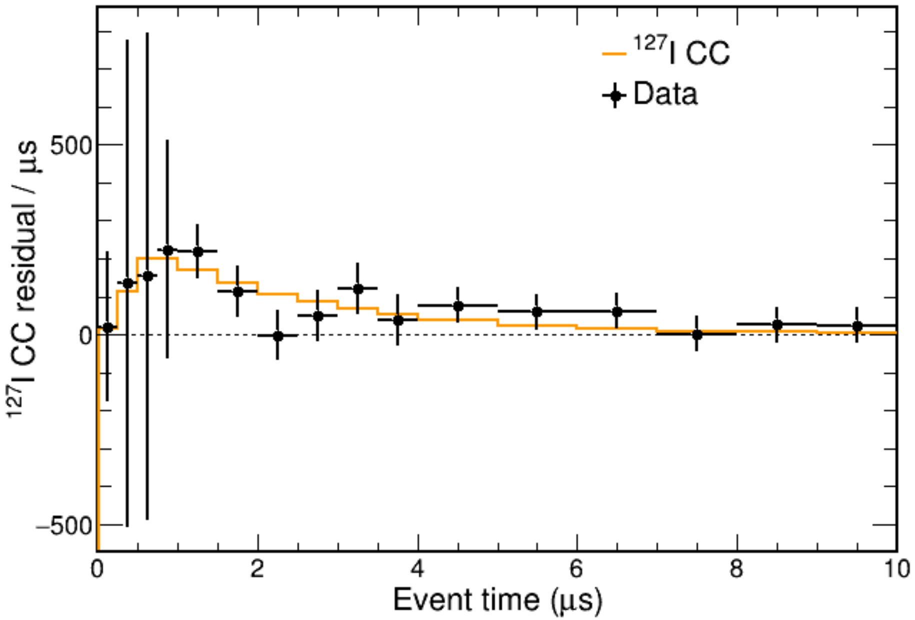
Iodine cross section results

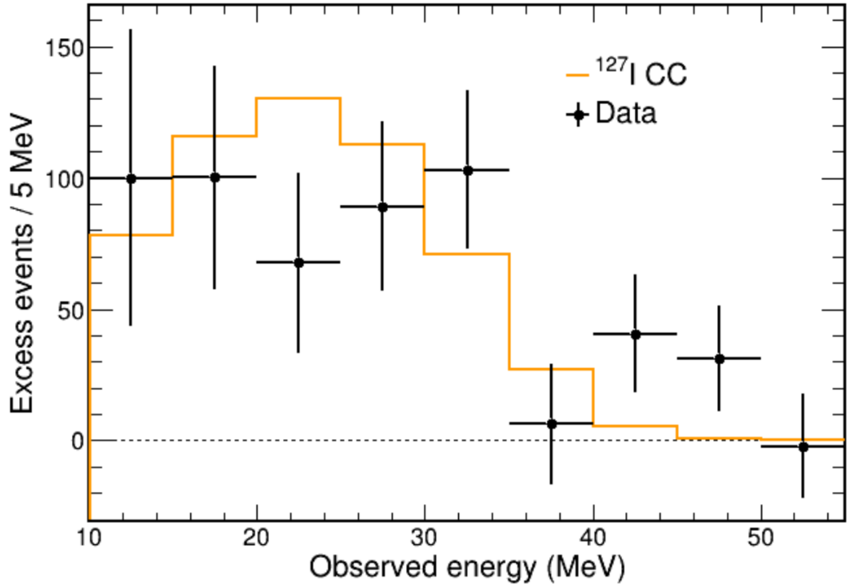
Best fit gives 541^{+121}_{-108} events or 5.8σ evidence of CC

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

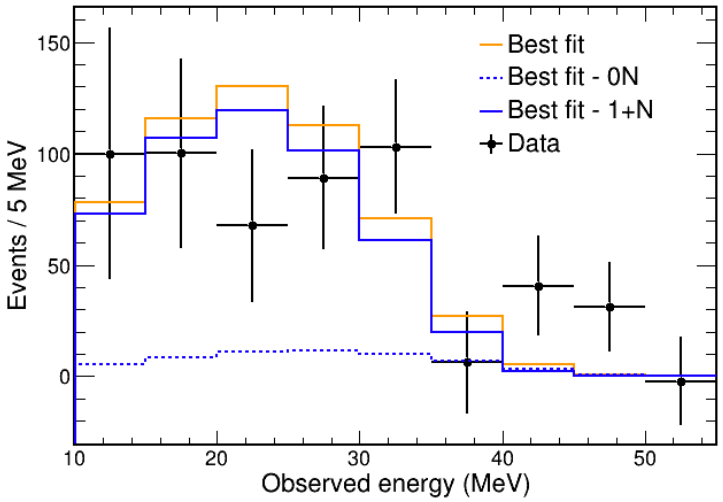




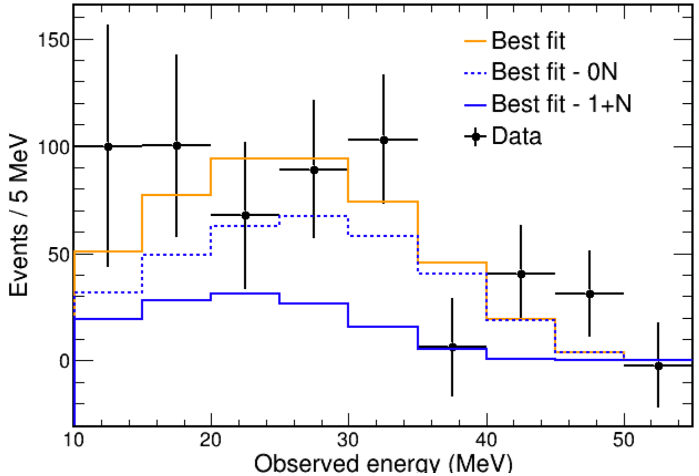
Zero or One+ Neutron Emission ?

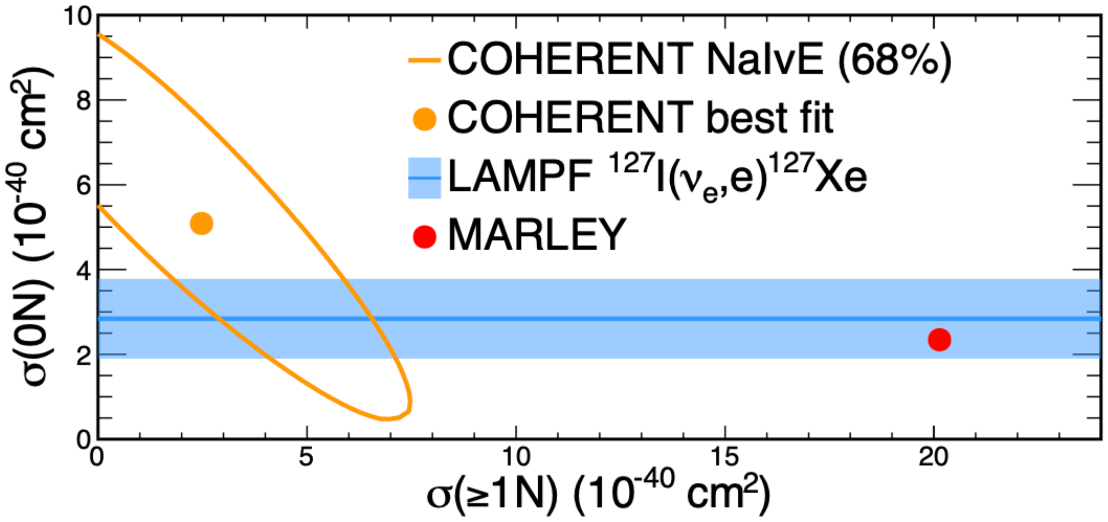
$$\nu_e + {}^{127}I \rightarrow e^- + {}^{127}Xe + ?*n$$

MARLEY prediction.
Ratio 0n to 1+n fixed



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





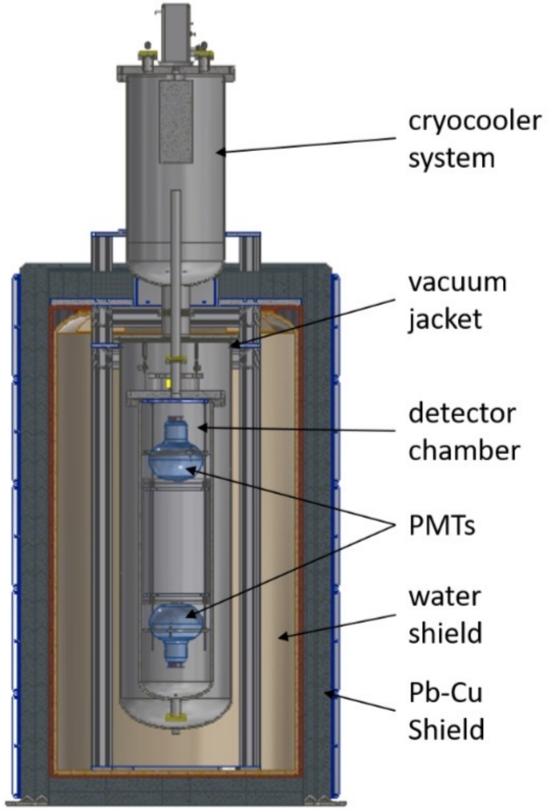
For zero neutron emission our result is in agreement with MARLEY and previous LAMPF data

Nonzero neutron emission is significantly suppressed

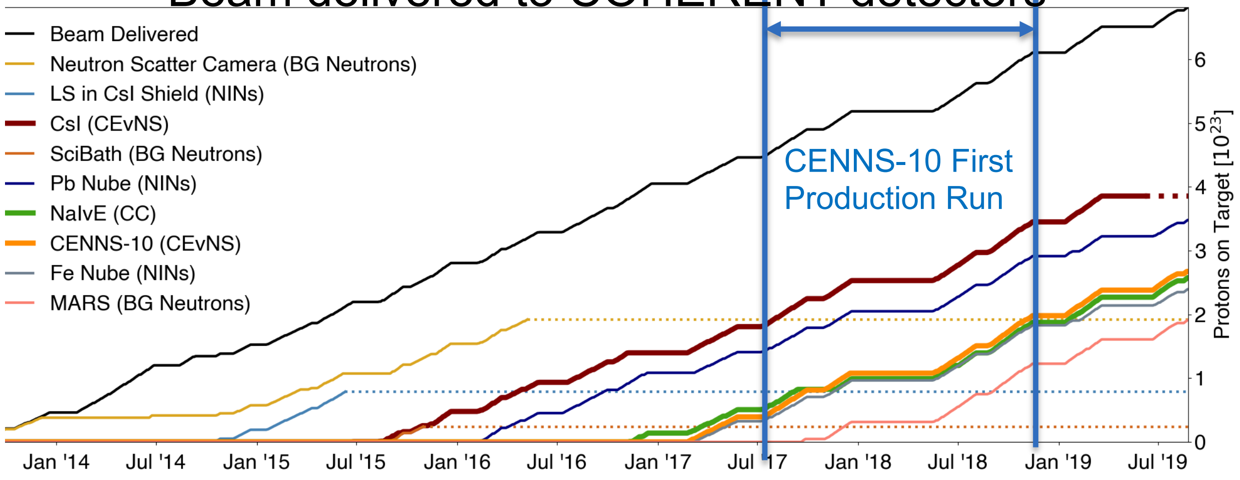
Result has been submitted for publication

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
- Tetraphenyl butadiene (TPB) coated side reflectors/PMTs
- Production Run starting July 2017.

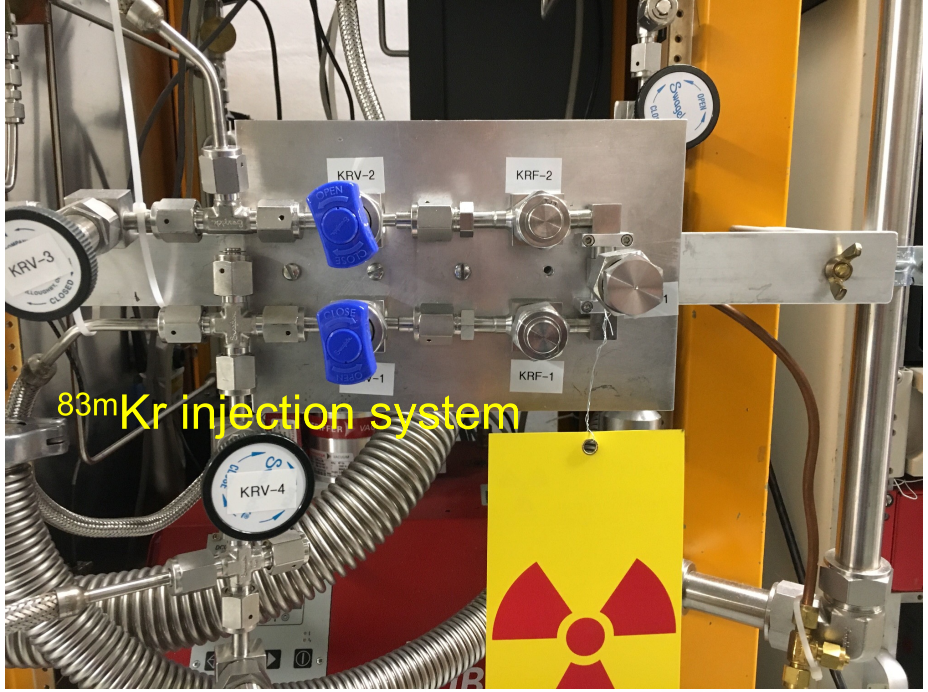


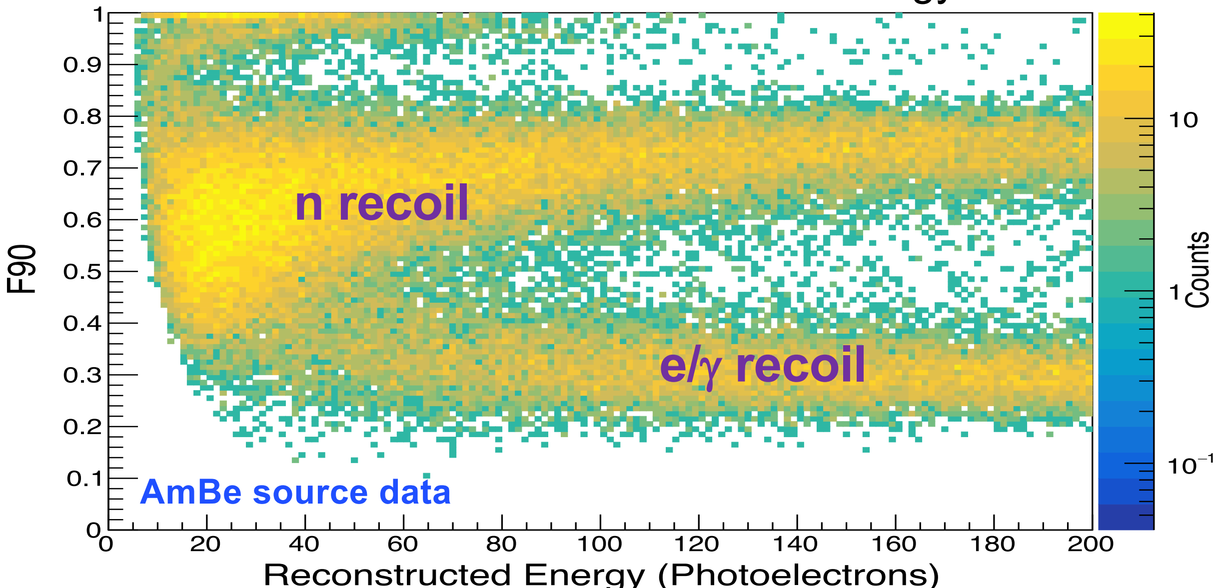
Beam delivered to COHERENT detectors

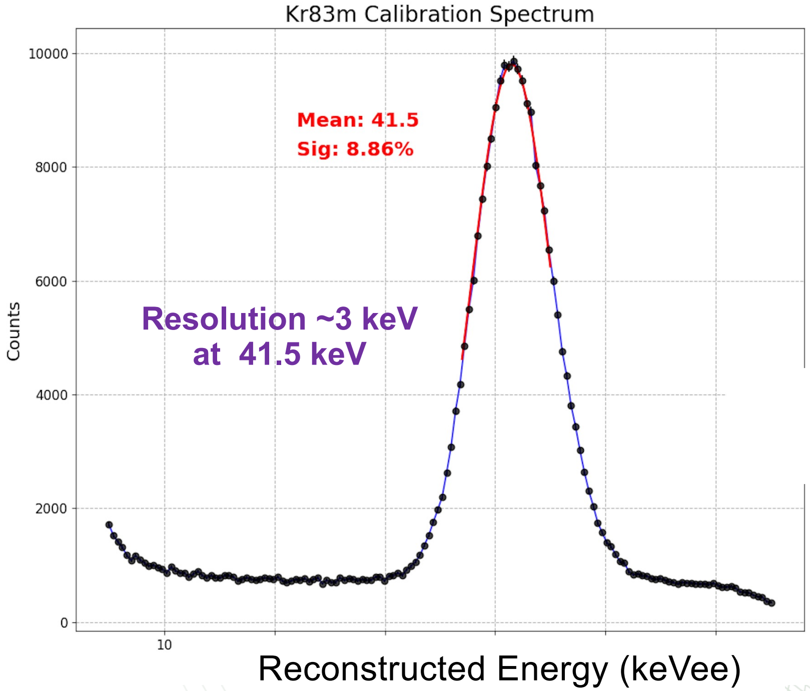


CENNS-10 Performance

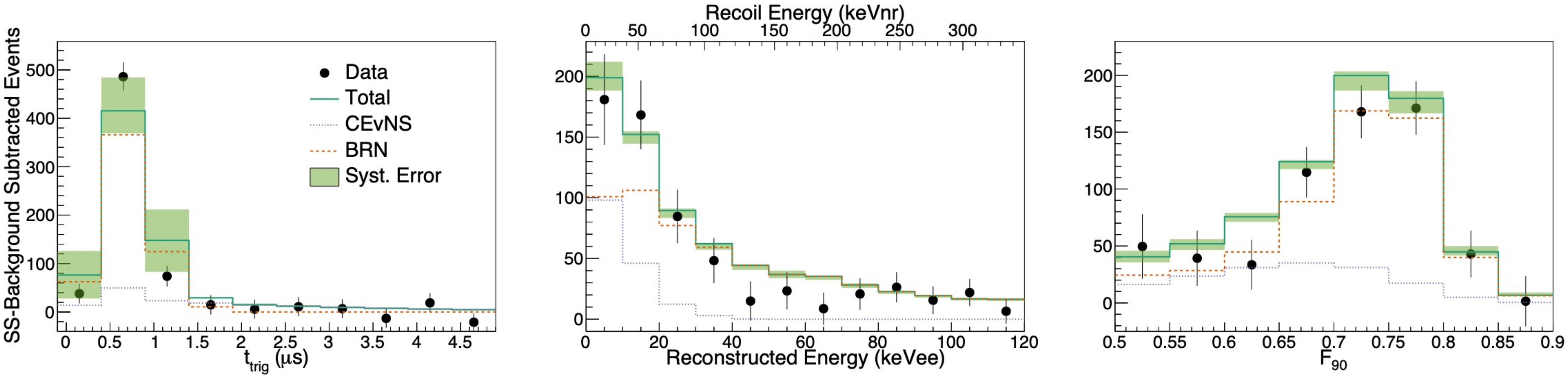
- Calibrate detector with variety of gamma sources
  - Measured light yield: 4.6 ± 0.4 photoelectrons/keVee
  - At ^{83m}Kr energy (41.5 keVee), mean reconstructed energy measured to 2%
    - 9.5% energy resolution at 41.5 keVee
- **Detector was optimized for CEvNS detection and signals are saturated for CC reaction**

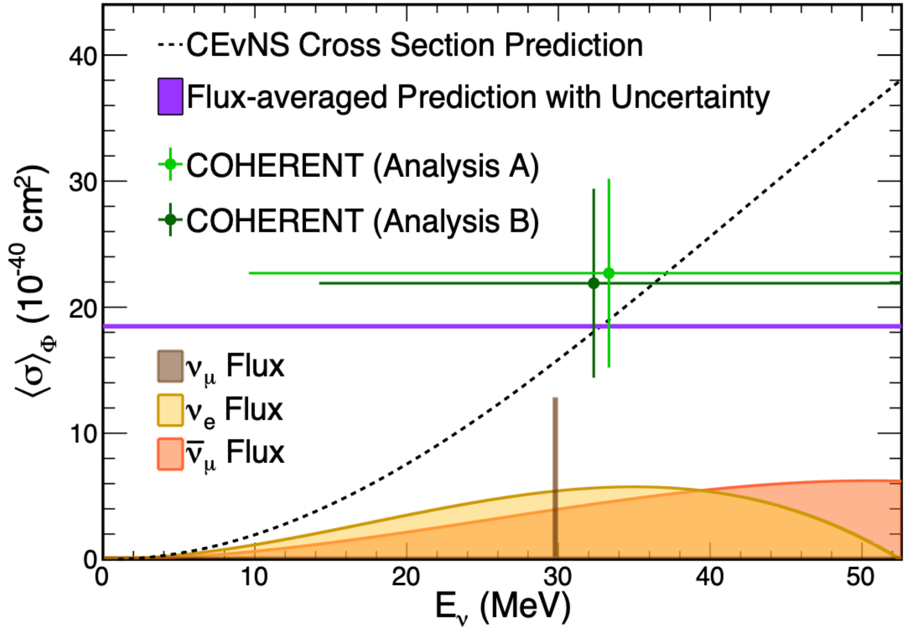






CEVNS detection on Argon





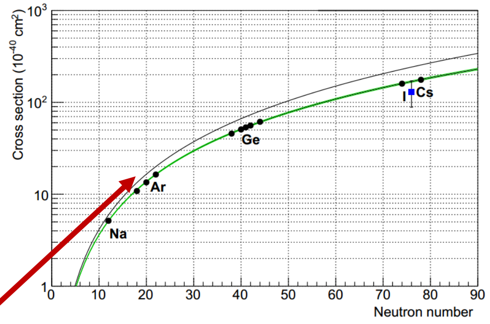
Two completely independent blind analyses are in an excellent agreement with each others

Predicted SM CEvNS	128 ± 17
Predicted Beam Related Neutrons	497 ± 160
Predicted Beam Unrelated Background	3154 ± 25
Predicted Late Beam Related Neutrons	33 ± 33

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.)

Future for LAr - 1 ton LAr detector

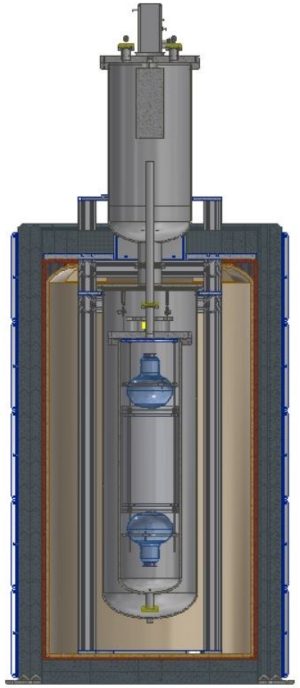
Need high statistics and low background measurements for CEvNS and good energy linearity for CC

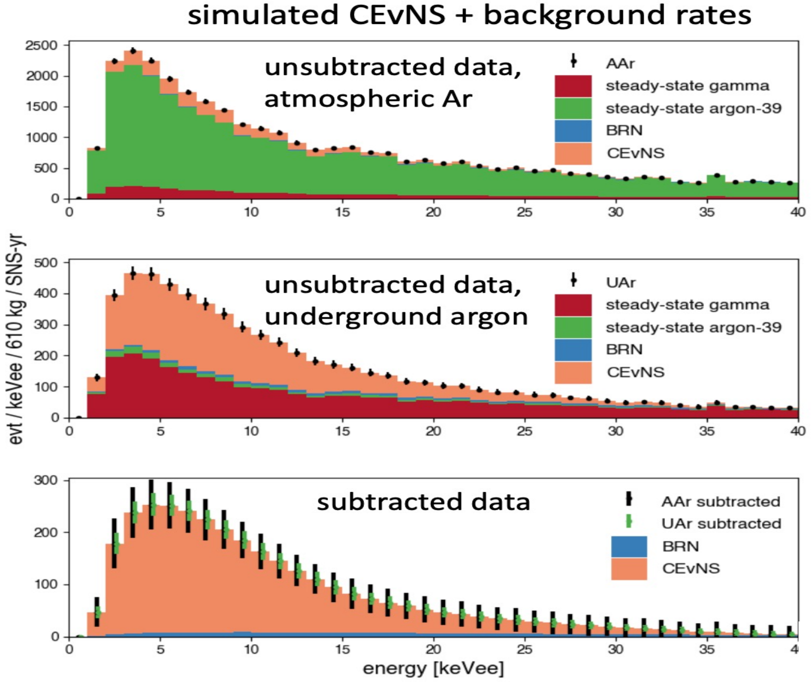


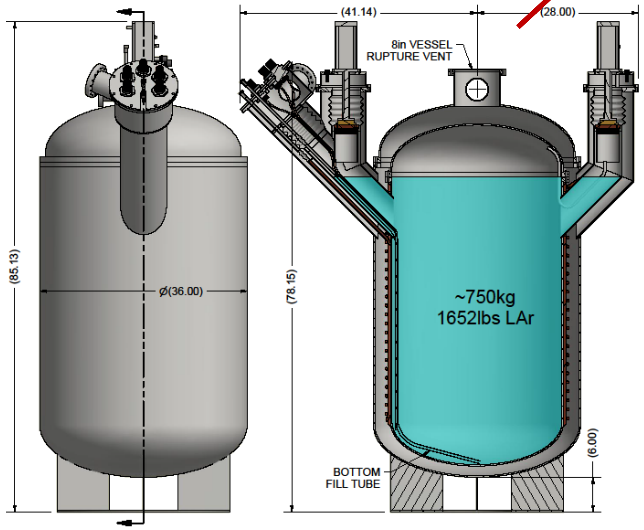
Transition from 22 kg to 1 ton LAr detector.

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

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

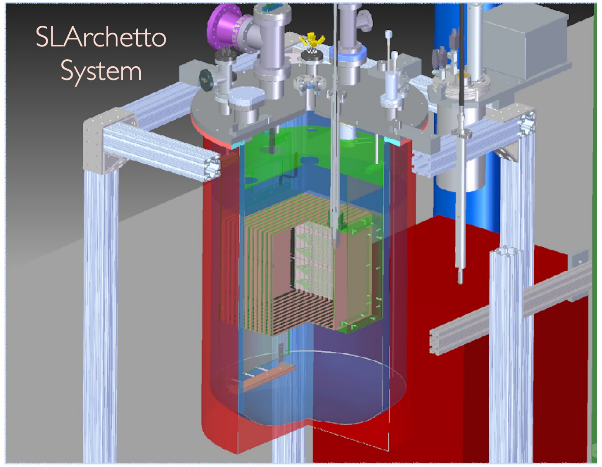






+

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

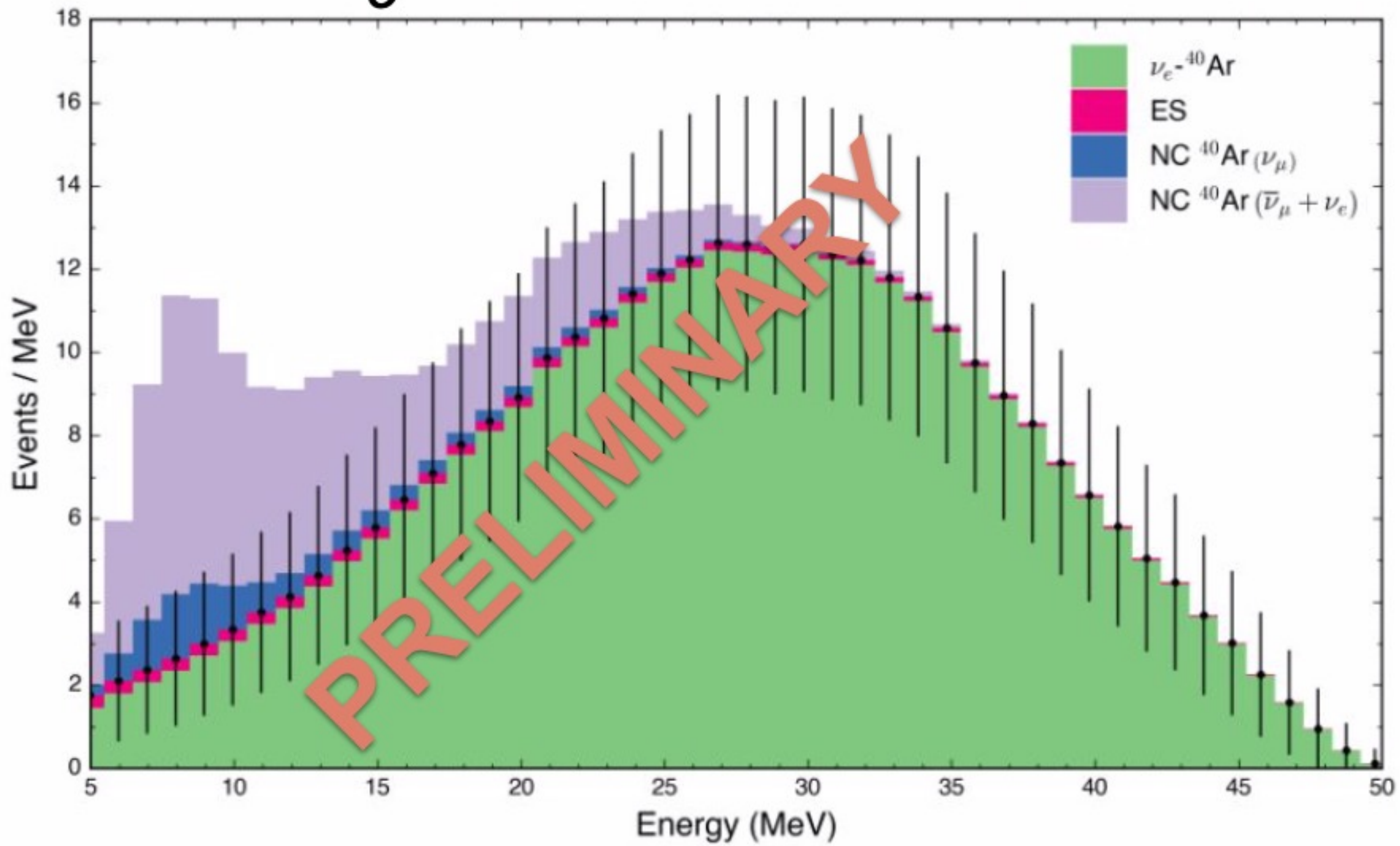


Detector is being build by our Korean collaborators. Deployment at the SNS soon

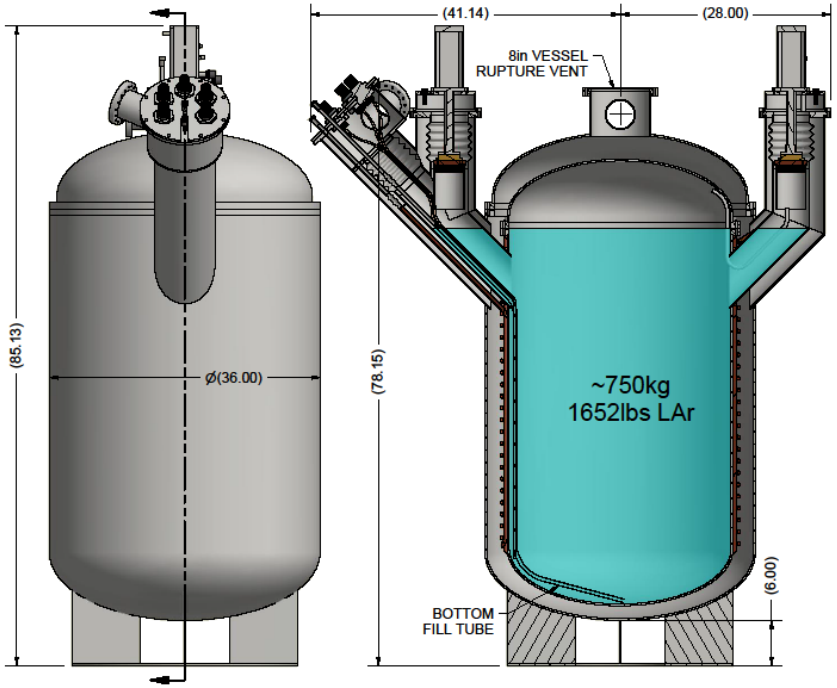
Oak Ridge National Laboratory

Expected signal CC on Argon

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$

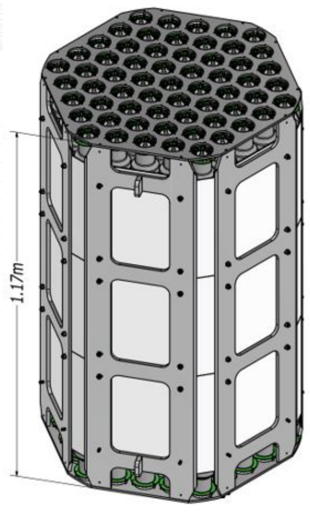


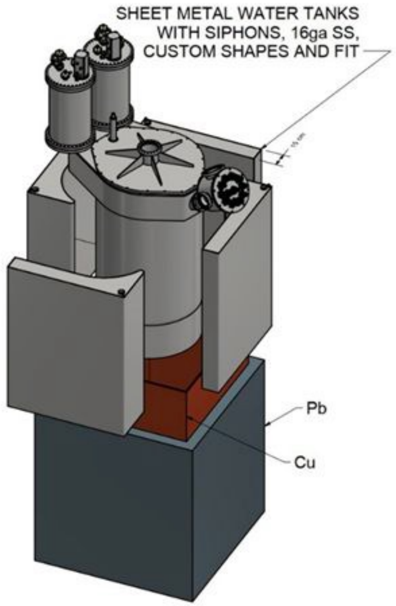
This is the channel to detect Supernovae Neutrino signal at LAr detectors

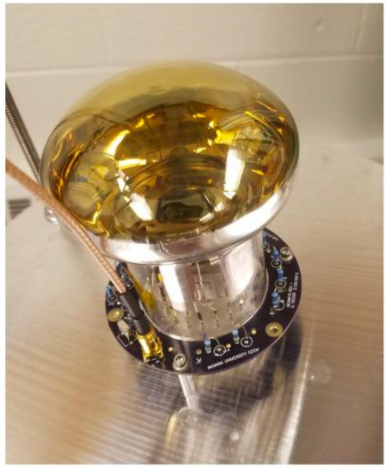


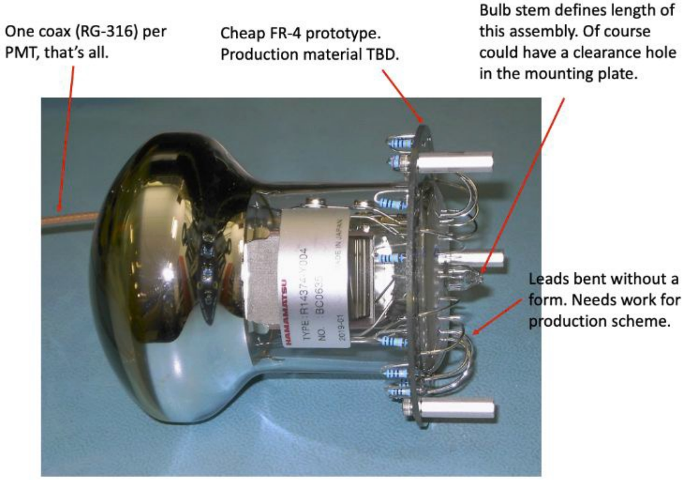
Some Details about Ar-750

2*61 Hamamatsu 3” PMTS





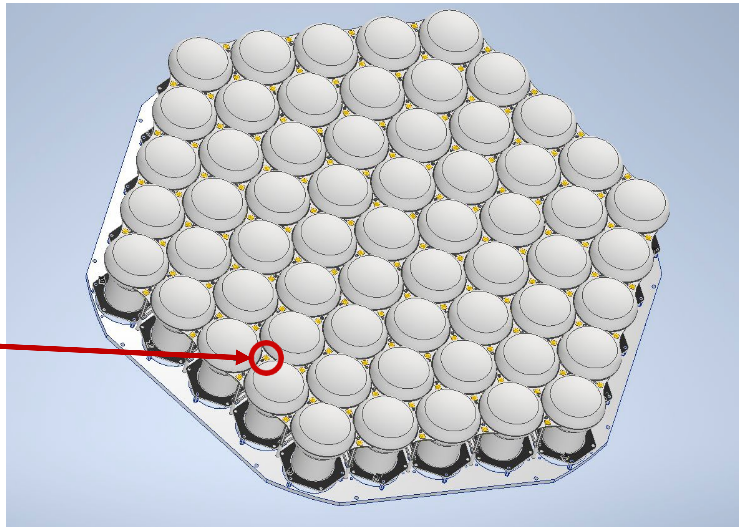




Detector is optimized for CEvNS

To have a good linearity for high energy evens there is proposal to install SiPMs in between PMTs

Detector is funded by Korean part of collaboration and is under construction



Concept of 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

For 1 t fiducial mass detector ~ thousand interactions per year

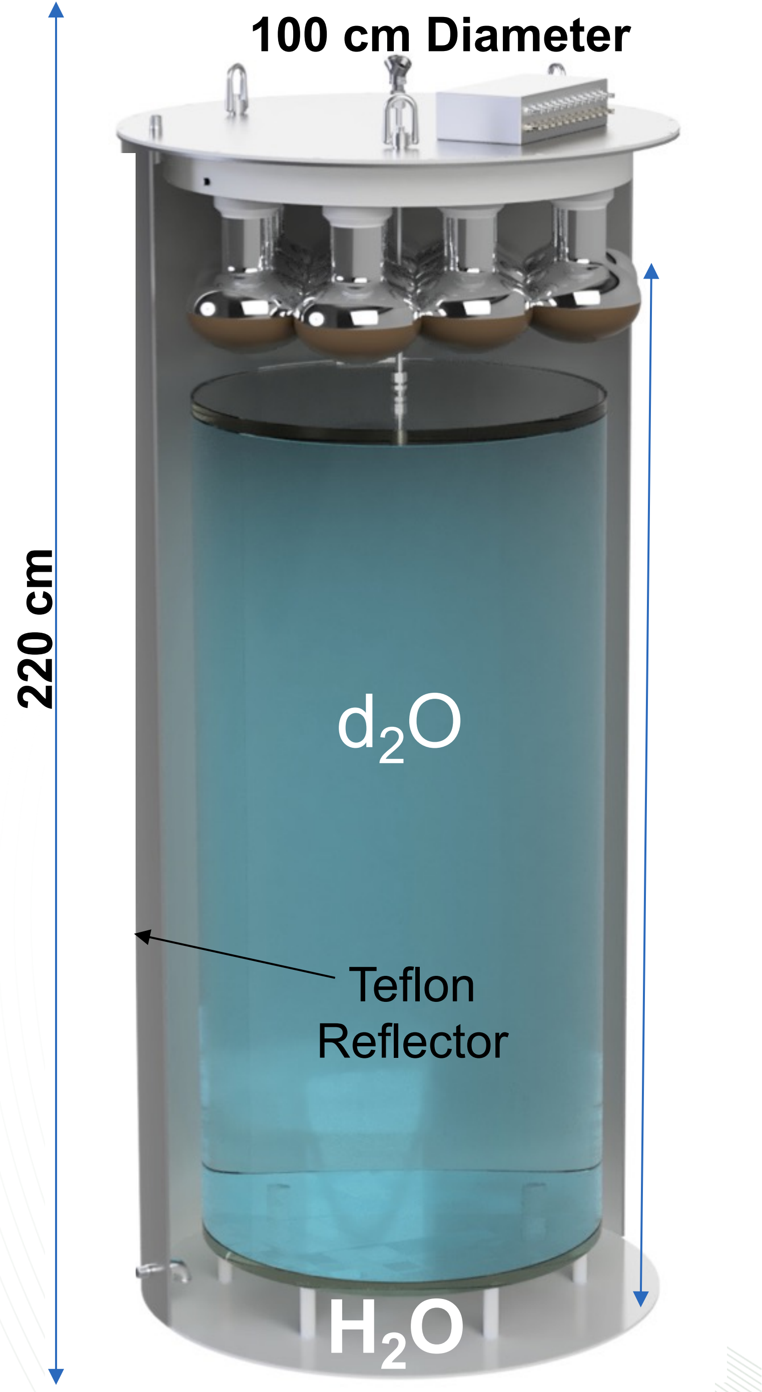
Detector calibration with
Michel Electrons from cosmic muons
(same energy range)

- Neutrino Alley space constraints for the D2O detector:
  - 1 m diameter x 2.3 m height
- Locations 20 meters from the target

Will do CC measurement on Oxygen for SN

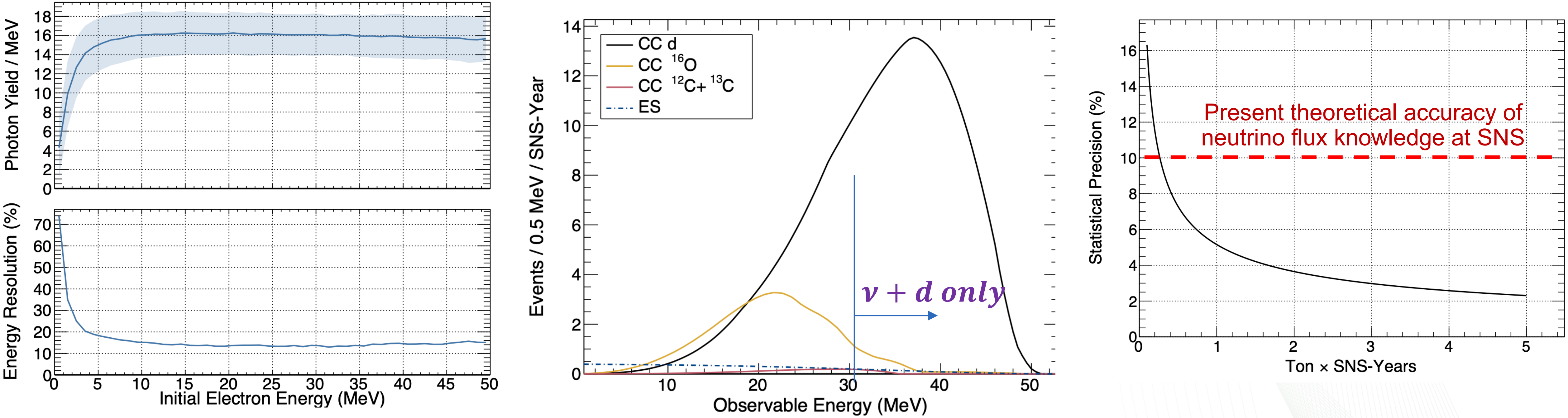
Specifications

- 0.8 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 to
- Lead Shielding
- Hermetic veto system



Predictions for d_2O detector response

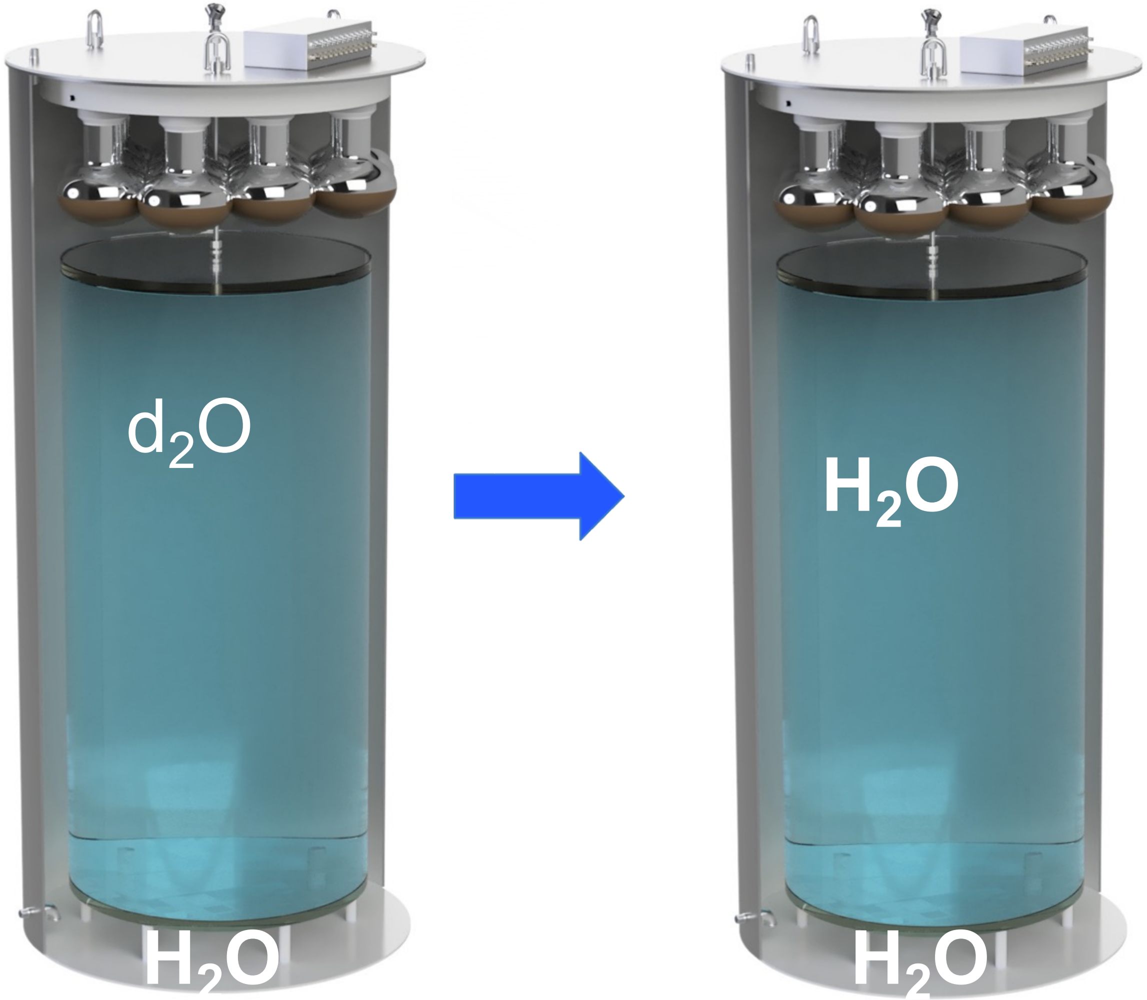
See JINST 16 (2021) 08, P08048

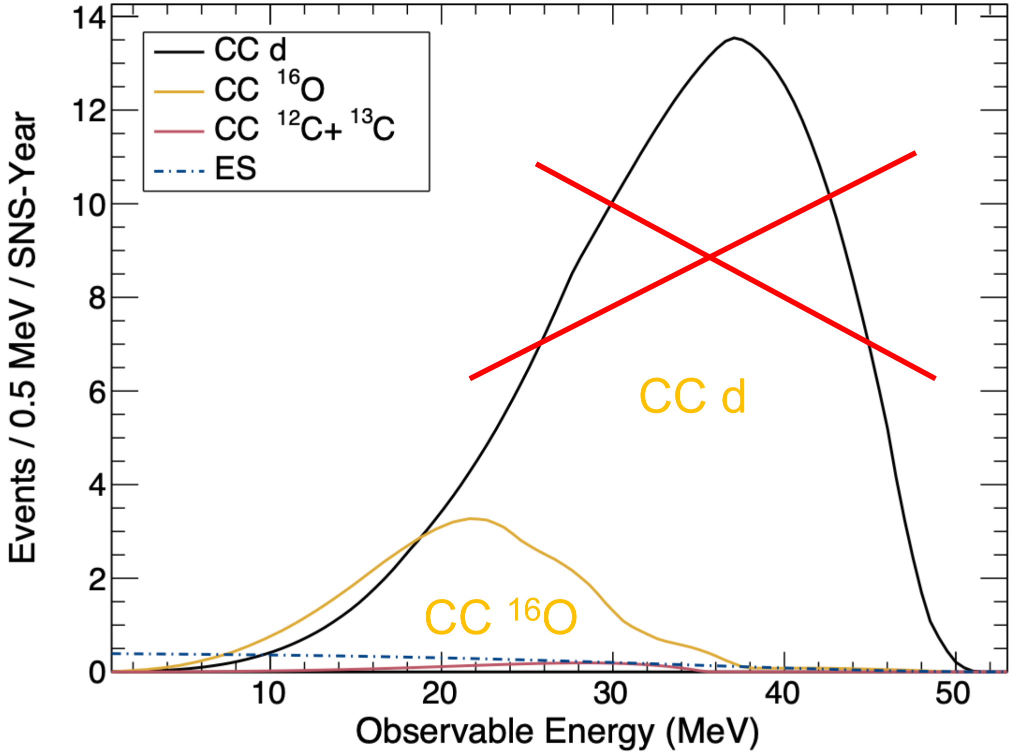


Detector will start to accumulate statistic this summer

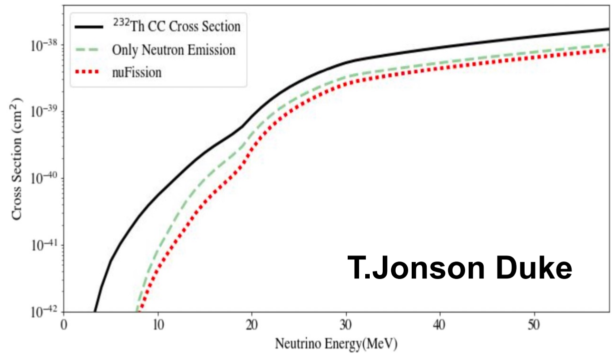
CC Detection on the Oxygen

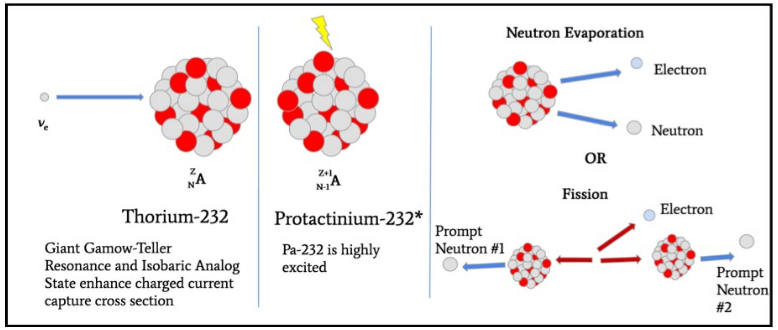
Two Identical modules. One without D2O





ν-Induced Fission: NuThor

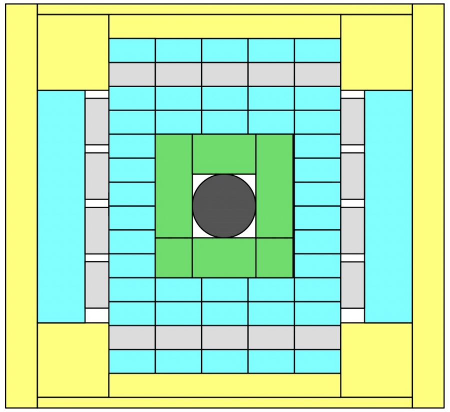


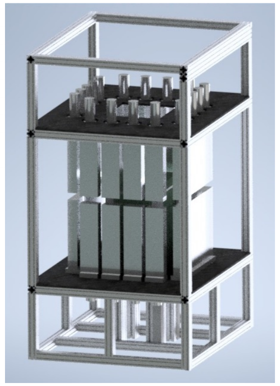


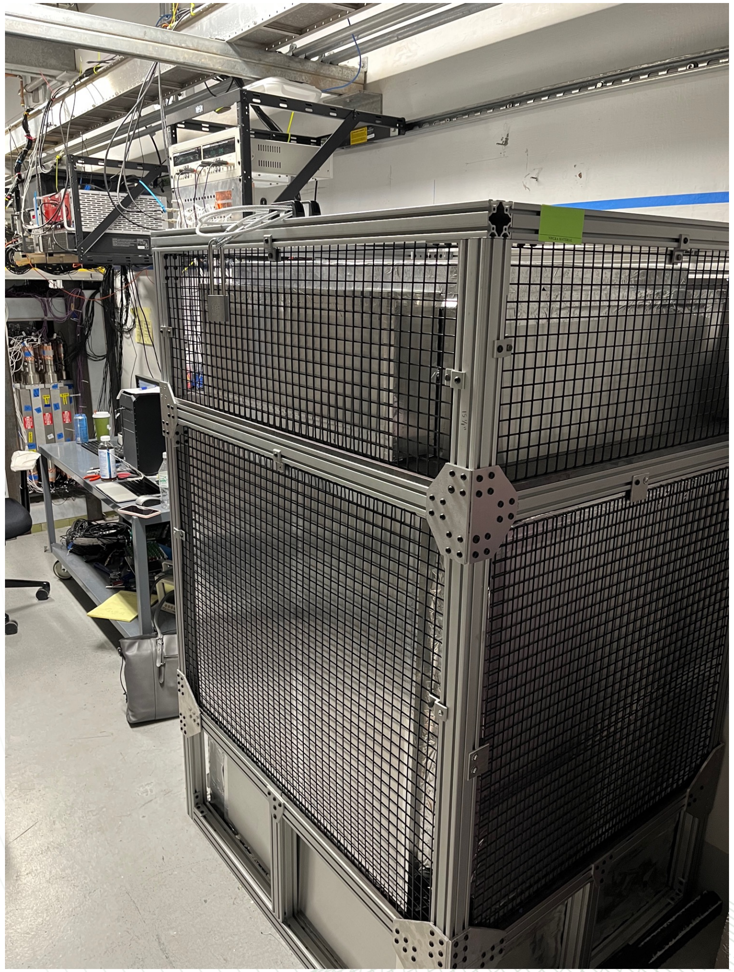
POSSIBLE METHOD OF MEASURING THE ELECTROMAGNETIC FORM FACTOR OF THE NEUTRINO

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)

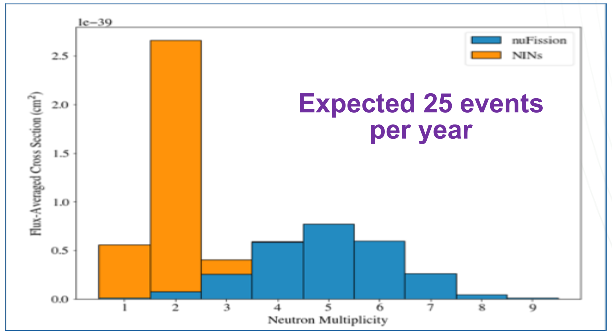
in [5]. In order to obtain on the basis of [6] information on the electromagnetic form factor of the neutrino, it is necessary to investigate the processes (1) and (5) that are optimal in the sense of the value of the cross section and the possibility of registration. From this point of view we consider 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.







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

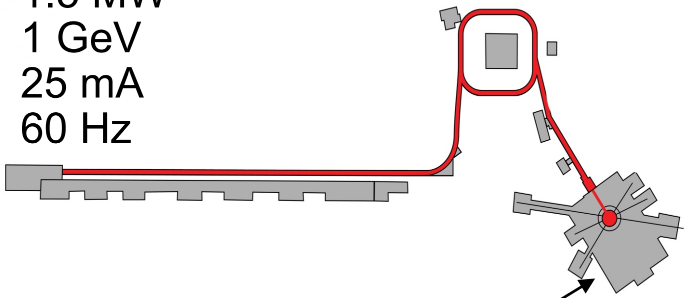


PPU and STS upgrades for SNS are coming

Today

- 900 users
- Materials at atomic resolution and fast dynamics

1.5 MW
1 GeV
25 mA
60 Hz

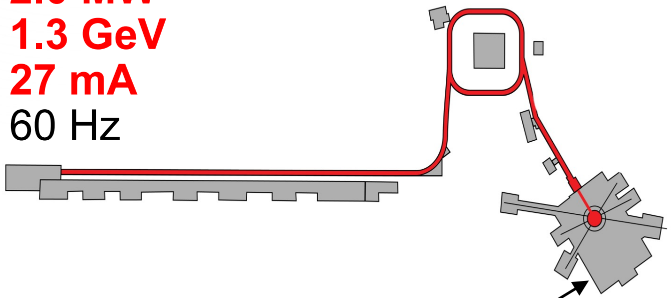


FTS
1.5 MW
60 Hz

2024 after PPU

- **1000+** users
- Enhanced capabilities

2.0 MW
1.3 GeV
27 mA
60 Hz



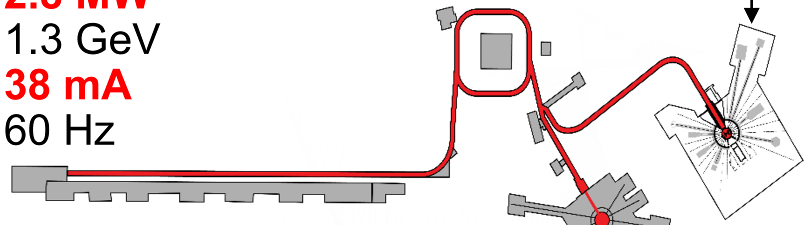
FTS
2 MW
60 Hz

2028 after STS

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

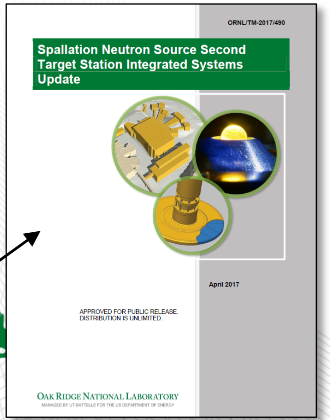
STS
0.7 MW
15 Hz

2.8 MW
1.3 GeV
38 mA
60 Hz



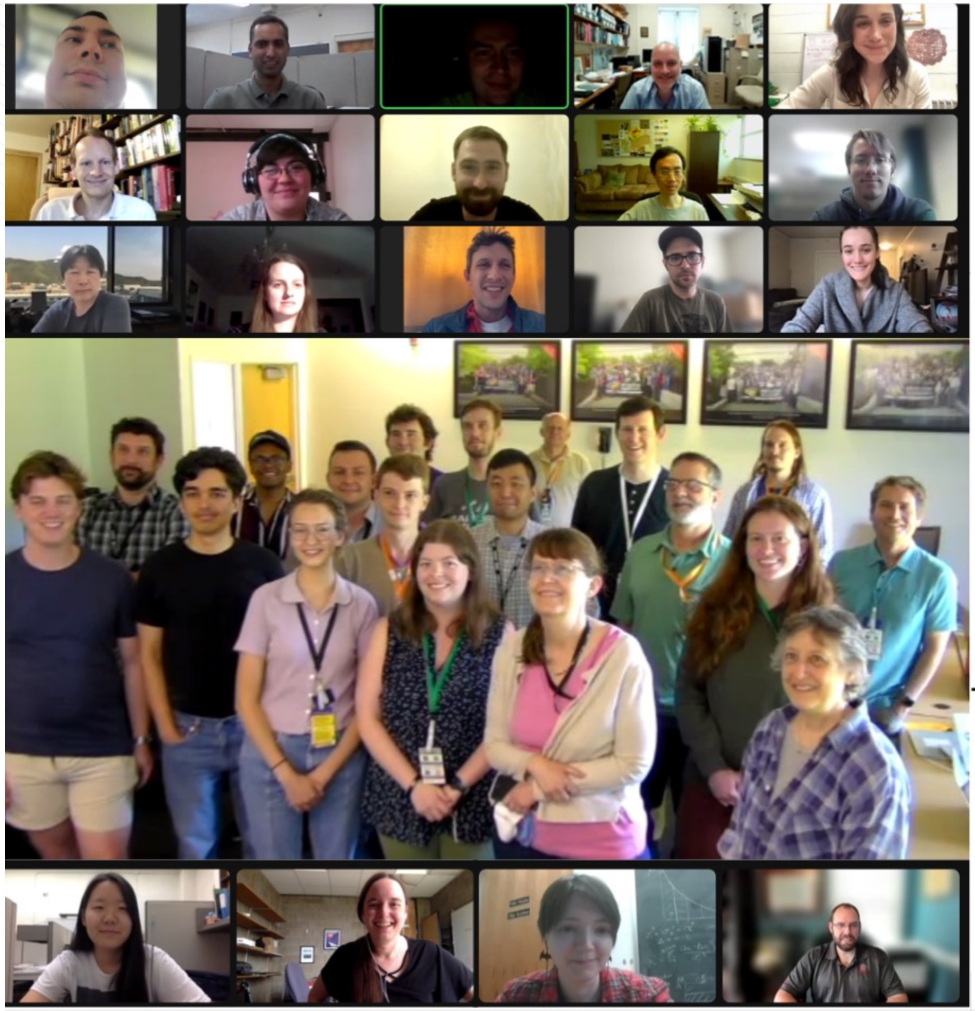
FTS
2 MW
45 pulses/sec

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

- ~85 people, 21 institutions, 4 countries, all fun



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 which is within 10% agreement with the standard model prediction. This is good enough for SN signal predictions via CEvNS in the wide range of targets

First results of CC reactions on iodine and lead measured reaction rates are significantly lower than theoretical predictions (neutron emission channels)

New measurements with high statistics on iodine will follow

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

Other future targets could be germanium, xenon and argon

CC part of COHERENT collaboration activity is critical for the interpretations of future SN neutrino signals