Recent results from COHERENT's inelastic neutrino-nucleus scattering detectors

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June 27, 2023

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COHERENT SNS

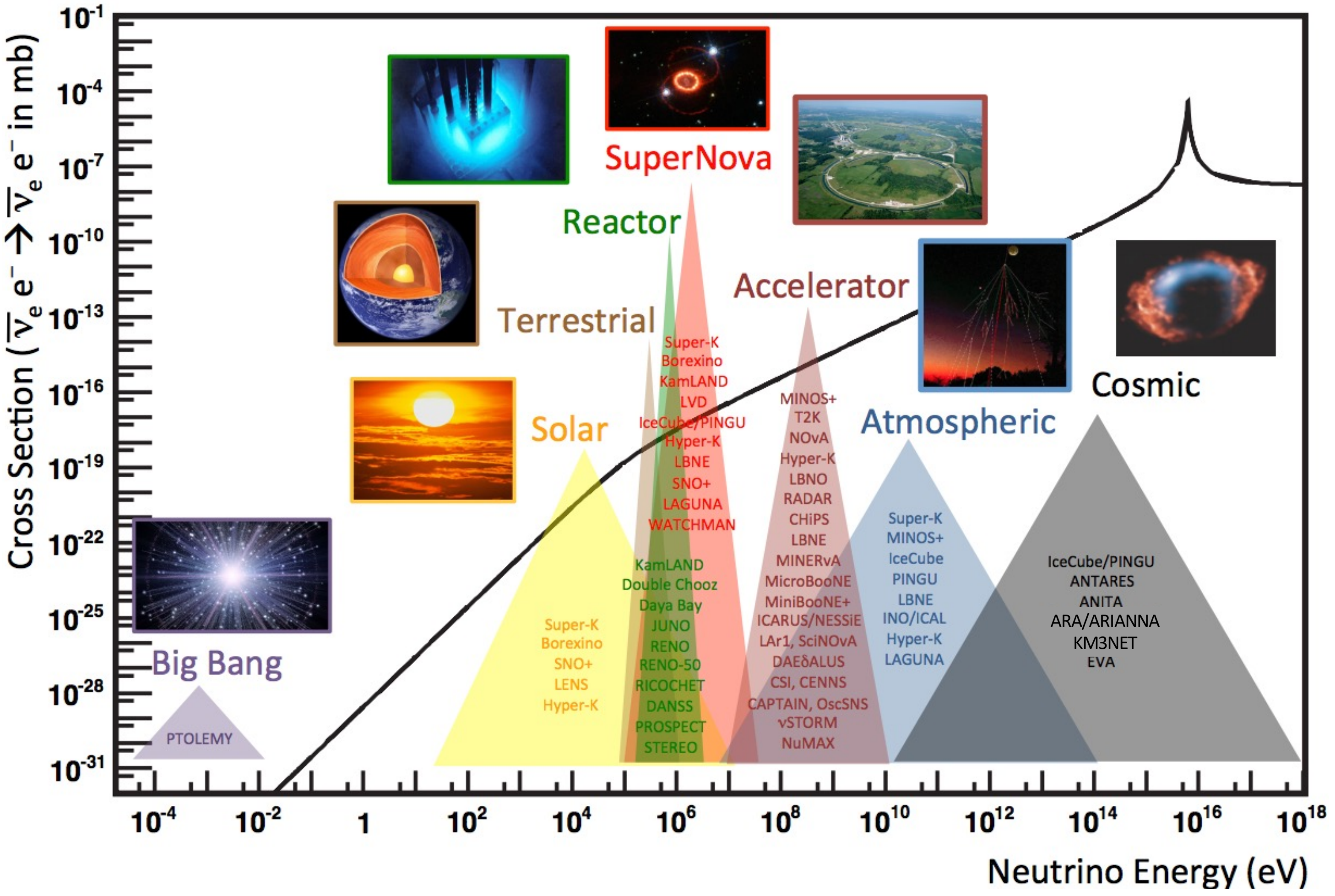
Outline

- Motivation
- The COHERENT collaboration & neutrino production at the SNS
- The COHERENT inelastic program:
  - Lead neutrino cube—neutrino-induced neutrons on lead
  - NaIvE-185 detector—inclusive electron-neutrino charged-current measurement on ^{127}I
  - Ongoing & future inelastic detectors

Motivation

Neutrino Sources

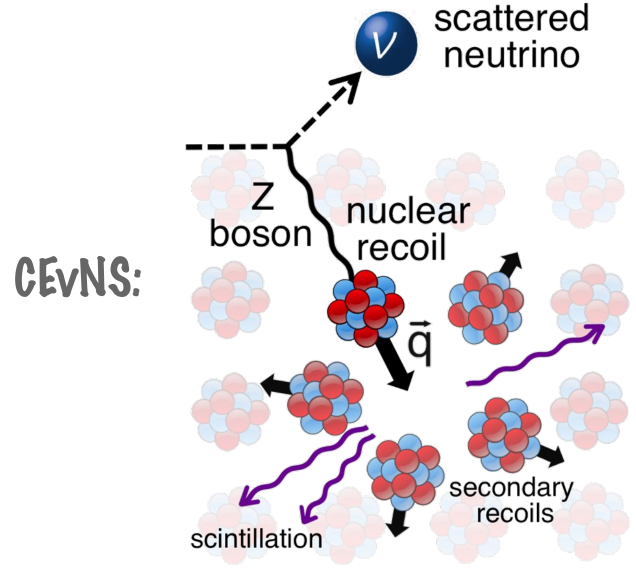
- Neutrinos produced across a large range of energies
- Many interesting sources produce exclusively low energy (<100 MeV) neutrinos
  - Neutrinos reveal key information about processes generating them
  - Sources can be used to study fundamental properties of neutrino
- Cross sections tend to scale with E^2, difficult to observe low energy neutrinos

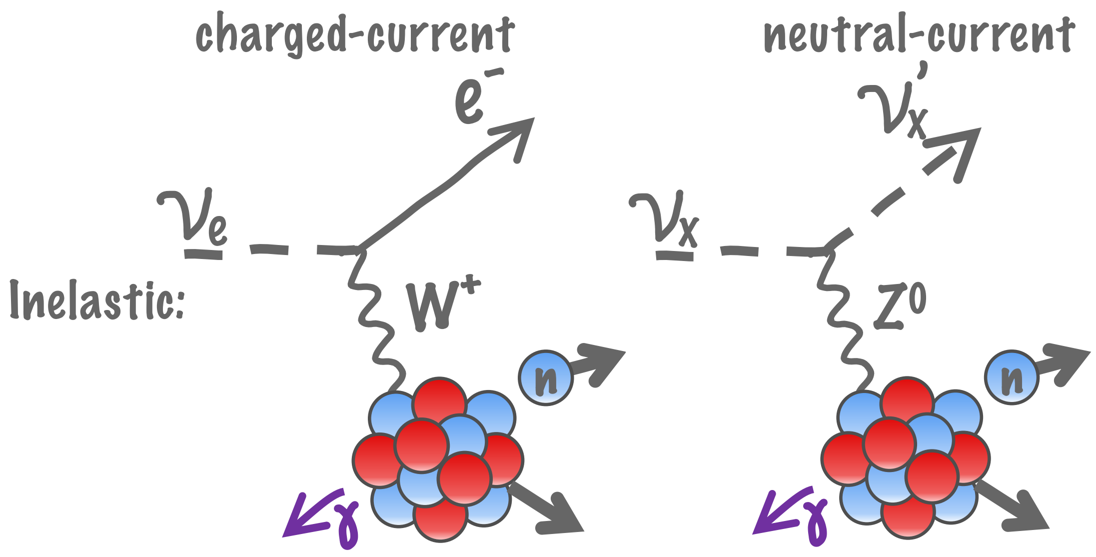


[A. de Gouvea, et al., arxiv:12104340 (2013)]
[J. A. Formaggio & G. P. Zeller, Rev. Mod. Phys **84** (2012)]

Low Energy Neutrino Detection

- Common methods for detecting low-energy neutrinos: inverse-beta decay, elastic neutrino-electron scattering
  - Typically large deployment of water, liquid scintillator
  - Unique signatures to help reject backgrounds
    - Neutron-positron coincidence for IBD, Cherenkov cone for neutrino-electron scattering
  - Interaction thresholds of 1.8 MeV for IBD, Cherenkov threshold for neutrino-electron scattering
- An alternate channel for studying low-energy neutrinos is neutrino-nucleus interactions
  - Can have larger cross sections, lower interaction thresholds, different detection signatures
  - Can build detectors based off of different detector technology, more dense scattering targets
- Few existing measurements of neutrino-nucleus interactions at these energies!





Existing Low-Energy Neutrino-Nucleus Measurements

List of <300 MeV neutrino-nucleus measurements with terrestrial sources

Isotope	Reaction Channel	Source	Experiment	Measurement (10^{-42} cm^2)	Theory (10^{-42} cm^2)
^{2}H	^{2}H(ν_e, e^-)pp	Stopped π/μ	LAMPF	52 ± 18(tot)	54 (IA) (Tatara *et al.*, 1990)
^{12}C	^{12}C$(\nu_e, e^-)^{12}$N$_{g.s.}$	Stopped π/μ	KARMEN	9.1 ± 0.5(stat) ± 0.8(sys)	9.4 [Multipole](Donnelly and Peccei, 1979)
		Stopped π/μ	E225	10.5 ± 1.0(stat) ± 1.0(sys)	9.2 [EPT] (Fukugita *et al.*, 1988).
		Stopped π/μ	LSND	8.9 ± 0.3(stat) ± 0.9(sys)	8.9 [CRPA] (Kolbe *et al.*, 1999b)
	^{12}C$(\nu_e, e^-)^{12}$N*	Stopped π/μ	KARMEN	5.1 ± 0.6(stat) ± 0.5(sys)	5.4-5.6 [CRPA] (Kolbe *et al.*, 1999b)
		Stopped π/μ	E225	3.6 ± 2.0(tot)	4.1 [Shell] (Hayes and S, 2000)
		Stopped π/μ	LSND	4.3 ± 0.4(stat) ± 0.6(sys)	
	^{12}C$(\nu_\mu, \nu_\mu)^{12}$C*	Stopped π/μ	KARMEN	3.2 ± 0.5(stat) ± 0.4(sys)	2.8 [CRPA] (Kolbe *et al.*, 1999b)
	^{12}C$(\nu, \nu)^{12}$C*	Stopped π/μ	KARMEN	10.5 ± 1.0(stat) ± 0.9(sys)	10.5 [CRPA] (Kolbe *et al.*, 1999b)
	^{12}C(ν_μ, μ^-)X	Decay in Flight	LSND	1060 ± 30(stat) ± 180(sys)	1750-1780 [CRPA] (Kolbe *et al.*, 1999b)
					1380 [Shell] (Hayes and S, 2000)
					1115 [Green's Function] (Meucci *et al.*, 2004)
	^{12}C$(\nu_\mu, \mu^-)^{12}$N$_{g.s.}$	Decay in Flight	LSND	56 ± 8(stat) ± 10(sys)	68-73 [CRPA] (Kolbe *et al.*, 1999b)
					56 [Shell] (Hayes and S, 2000)
^{56}Fe	^{56}Fe$(\nu_e, e^-)^{56}$Co	Stopped π/μ	KARMEN	256 ± 108(stat) ± 43(sys)	264 [Shell] (Kolbe *et al.*, 1999a)
^{71}Ga	^{71}Ga$(\nu_e, e^-)^{71}$Ge	^{51}Cr source	GALLEX, ave.	0.0054 ± 0.0009(tot)	0.0058 [Shell] (Haxton, 1998)
		^{51}Cr	SAGE	0.0055 ± 0.0007(tot)	
		^{37}Ar source	SAGE	0.0055 ± 0.0006(tot)	0.0070 [Shell] (Bahcall, 1997)
^{127}I	^{127}I$(\nu_e, e^-)^{127}$Xe	Stopped π/μ	LSND	284 ± 91(stat) ± 25(sys)	210-310 [Quasi-particle] (Engel *et al.*, 1994)

[J. A. Formaggio & G. P. Zeller, Rev. Mod. Phys **84** (2012)]

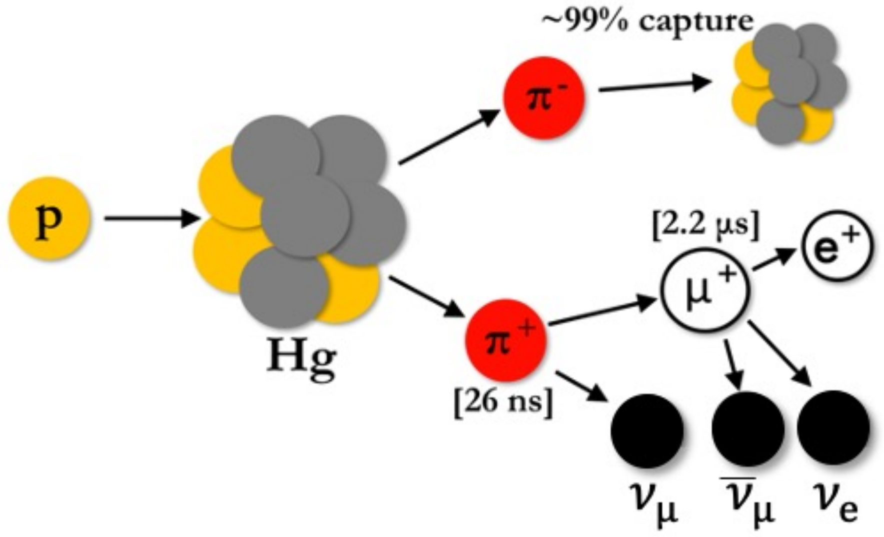
The COHERENT collaboration & neutrino production at the SNS

The COHERENT Collaboration

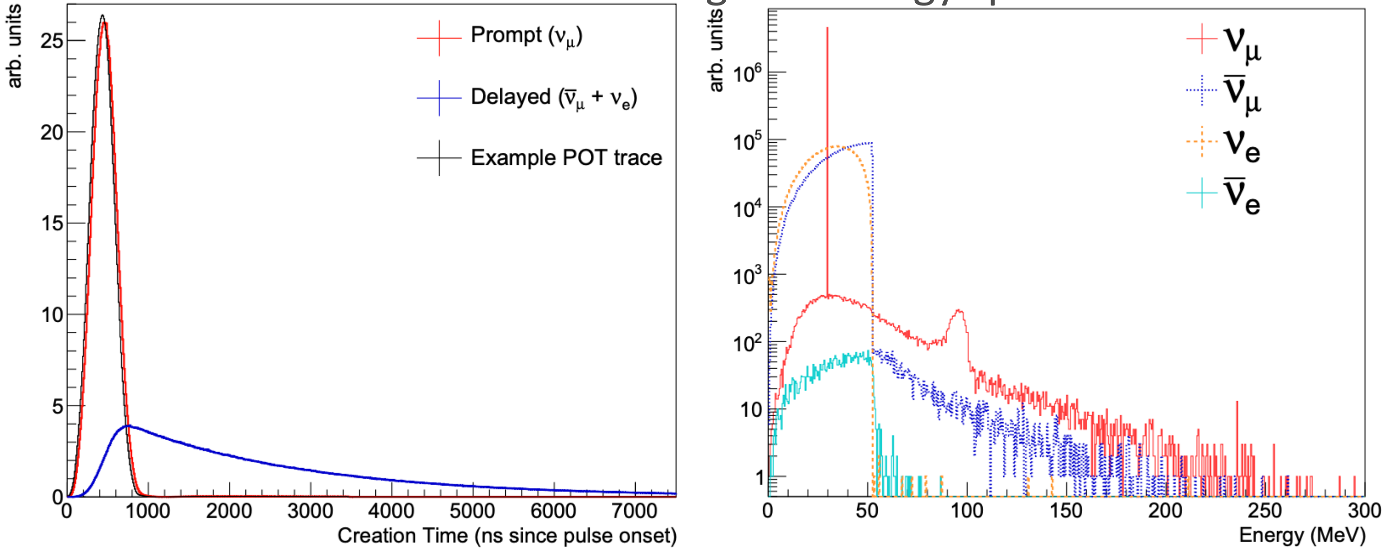
- ~80 members, 20 institutions
- Formed to observe CEvNS, study physics in multiple targets, including N^2 scaling of cross section
- Use neutrinos produced by the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL)
- Intense flux of low-energy pulsed neutrinos useful for studying inelastic neutrino-nucleus interactions as well

Neutrinos at the SNS

- 1 GeV protons strike Hg target at the SNS at 60Hz
  - 350ns FWHM of proton pulse
- Produces π^- and π^+ (and neutrons)
  - Neutrons are a background for our detectors, we refer to them as beam-related neutrons (**BRNs**)
- π^+decay in ~26ns, leading to prompt ν_μ (~30 MeV) and μ^+
- μ^+ decay with lifetime of 2.2μs, producing delayed ν_e and $\bar{\nu}_\mu$ (<53 MeV)
  - ν_μ roughly in time with beam, ν_e and $\bar{\nu}_\mu$ largely free from beam-related backgrounds



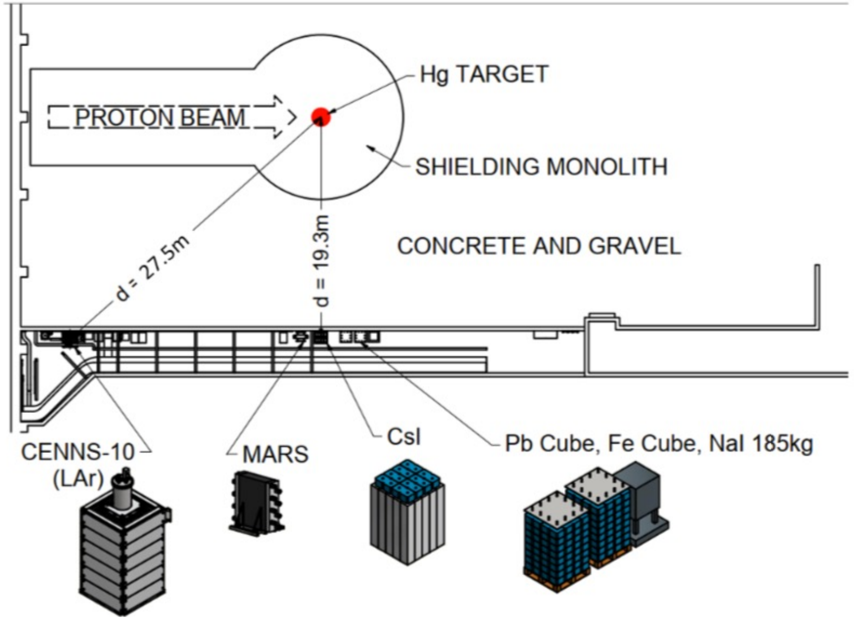
Simulated timing and energy spectra



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

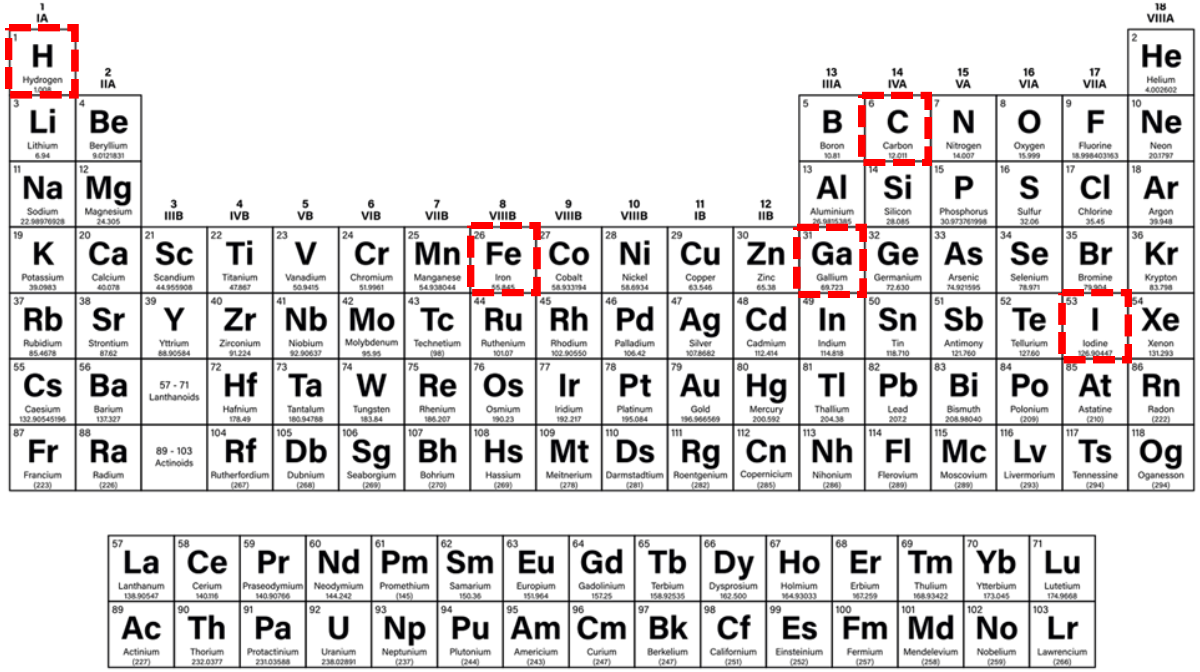
Neutrino Alley

- COHERENT's detectors in "Neutrino Alley" at the SNS
  - 25m long hallway, 20-30m from target
  - Not designed for neutrino detectors
  - Concrete and gravel reduce beam neutrons
- Dedicated detectors for measuring neutrons



Existing Low-Energy Neutrino-Nucleus Measurements

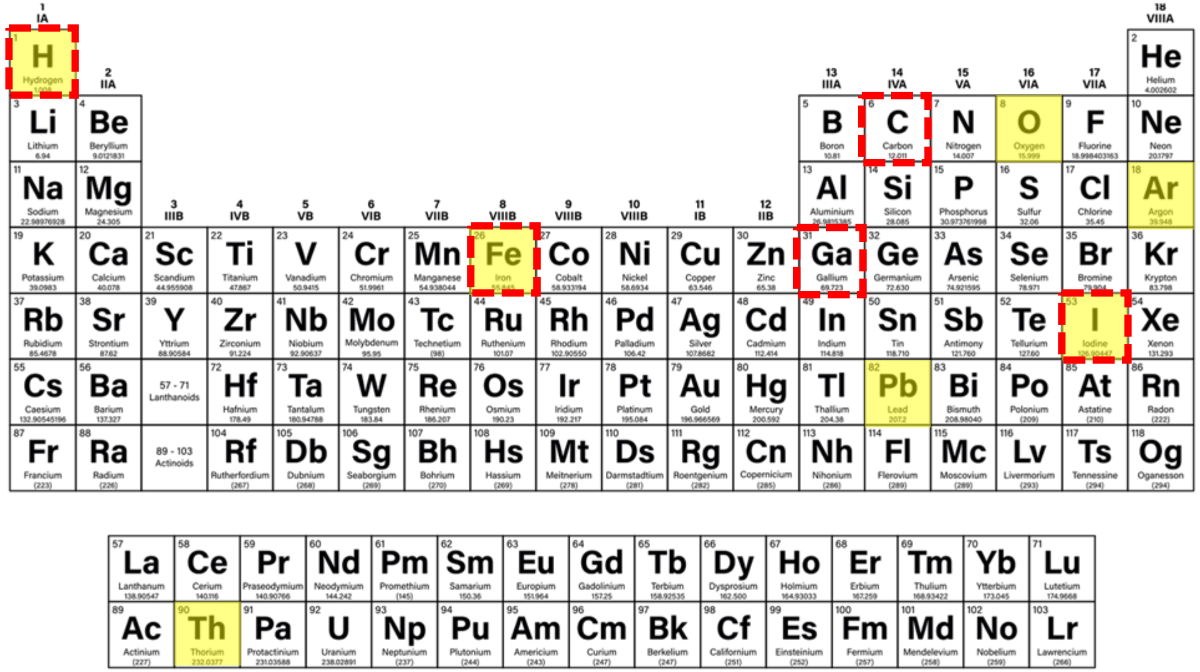
= existing measurements for low-energy (<300 MeV) neutrinos from terrestrial sources



COHERENT's Inelastic Detectors

= existing measurements for low-energy (<300 MeV) neutrinos from terrestrial sources

= COHERENT's current & planned detectors



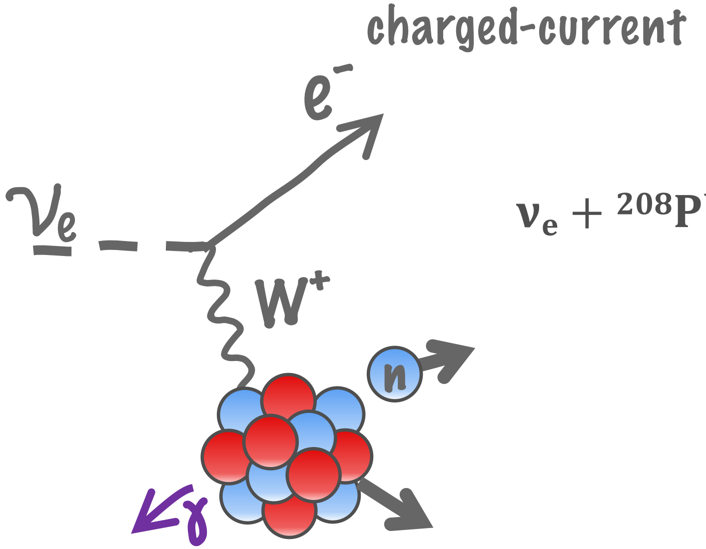
Name	Target	Channel	Deployment Date
Lead Neutrino Cube	Lead	$\mathrm{Pb}(\nu_e, e^- + xn)$	1/2016
Iron Neutrino Cube	Iron	$\mathrm{Fe}(\nu_e, e^- + xn)$	2/2017
Na$\mathrm{I}\nu$E (COH-NaI-185)	$^{127}\mathrm{I}$	$^{127}\mathrm{I}(\nu_e, e^- + x)$	6/2016
CENNS-10 (COH-Ar-10)	Argon	$\mathrm{Ar}(\nu_e, e^- + x)$	2017
νThor	Thorium	$\mathrm{Th}(\nu_e, e^- + x)$	2022
CENNS-750 (COH-Ar-750)	Argon	$\mathrm{Ar}(\nu_e, e^- + x)$	future
D_2O	$^2\mathrm{H/O}$	$^2\mathrm{H/O}(\nu_e, e^- + x)$	future

Results presented today!

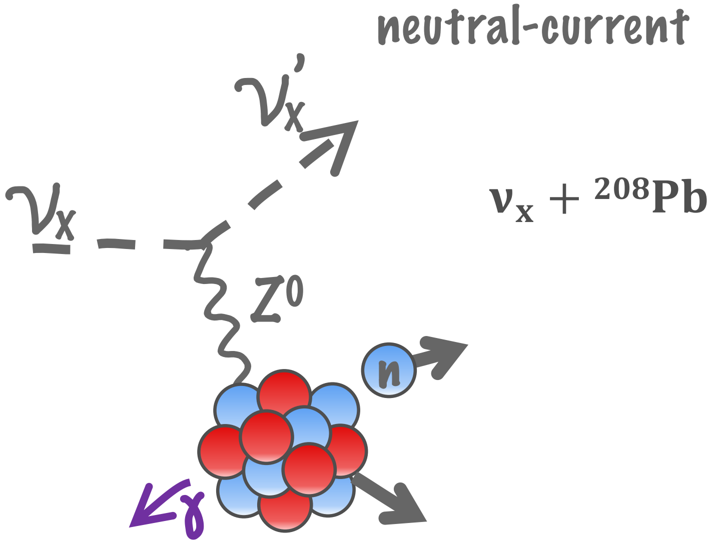
The Lead Neutrino Cube

Motivation for Measuring Neutrino-Induced Neutrons (NINs)

- Neutrino interactions in shielding (mostly lead) of COHERENT's detectors could present beam-related background
  - Neutrino interactions can generate excited nuclei that de-excite by emitting neutrons
  - Produced neutrons follow the timing distribution of the neutrinos, and can produce low energy nuclear recoils in detectors



$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{208}\mathrm{Bi}^* + e^-$$
$$\Downarrow$$
$${}^{208-y}\mathrm{Bi} + x\gamma + yn$$



$$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{208}\mathrm{Pb}^* + \nu_x'$$
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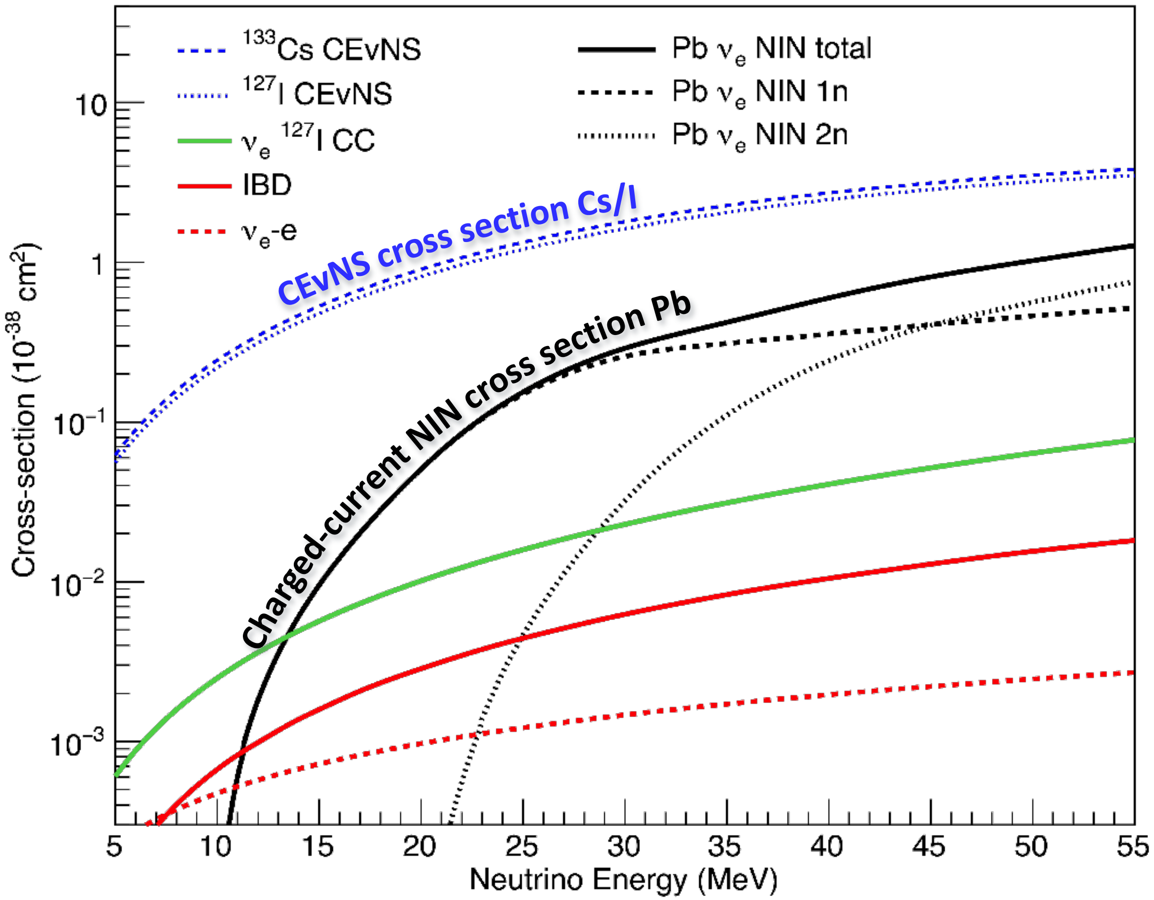
- Cross section expected to be lower than CEνNS, but previously unmeasured



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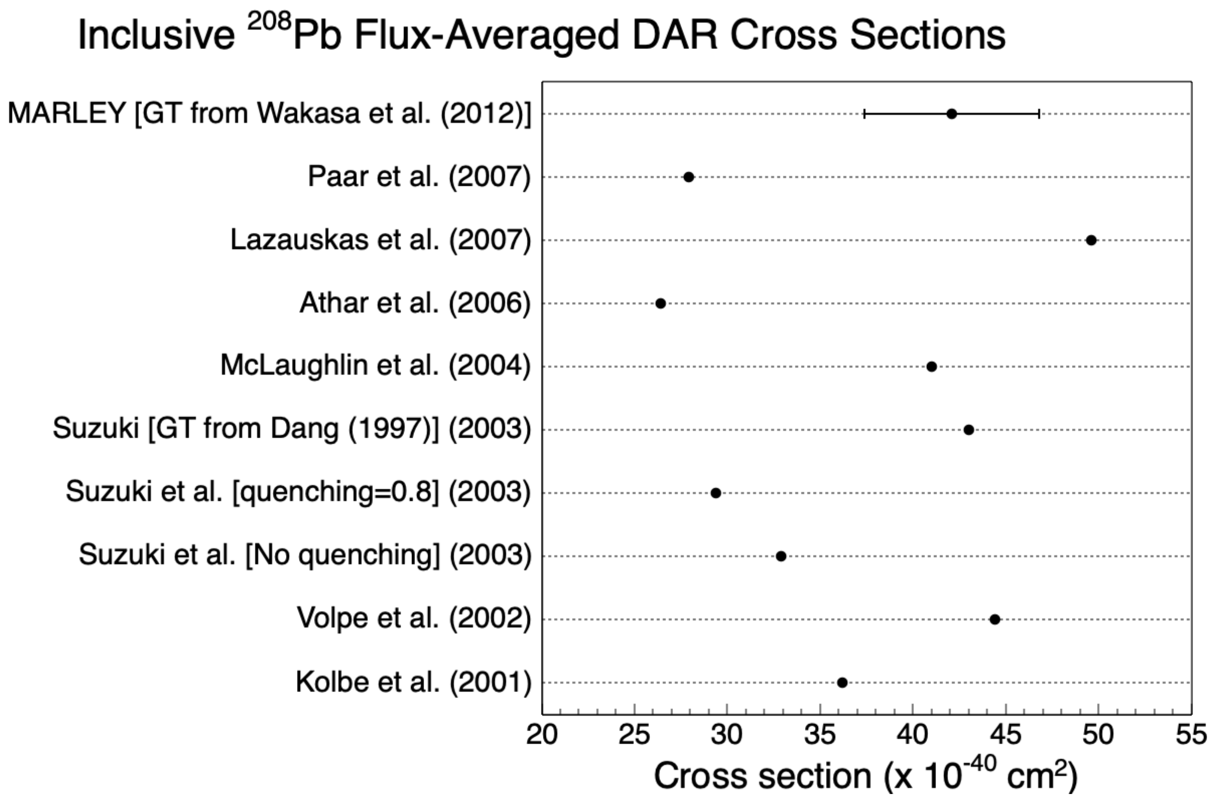

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- Cross section expected to be lower than CEνNS, but previously unmeasured
  - Variations in calculations
  - Much greater mass of shielding than CEνNS detectors themselves

CEνNS Target	**Shielding**
14.6 kg CsI[Na]	2,200 kg lead
24 kg liquid argon	11,000 kg lead
16 kg Ge	3,400 kg lead
2,425 kg NaI	17,000 kg iron and lead

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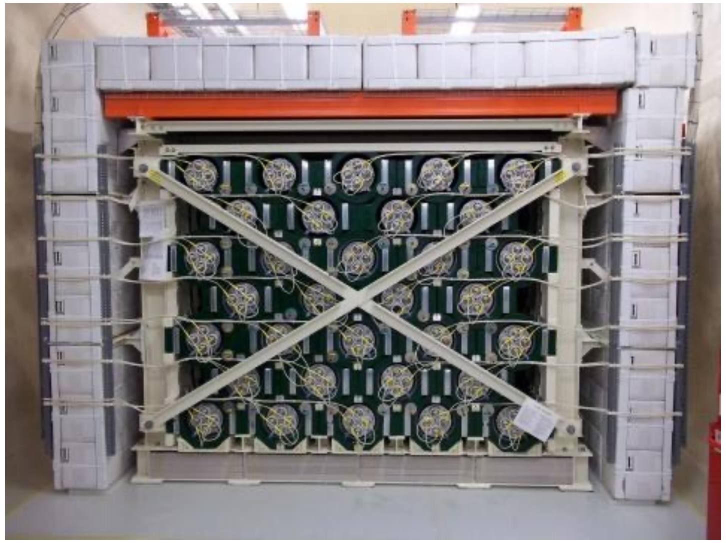
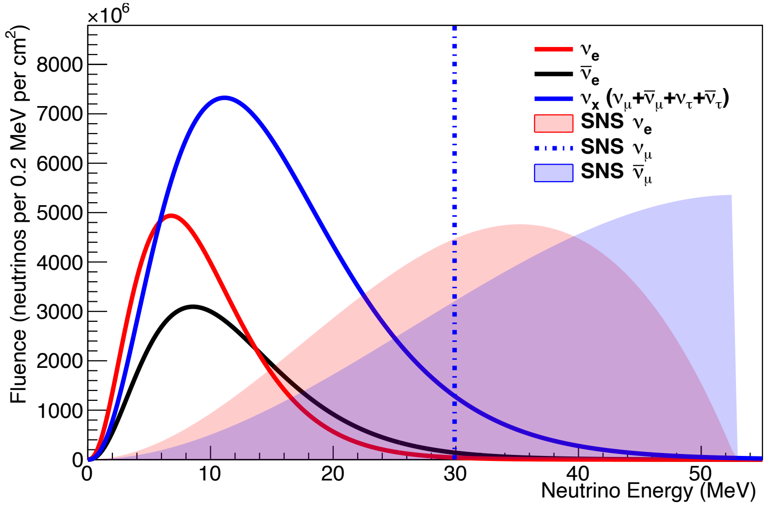
- Cross section expected to be lower than CEνNS, but previously unmeasured
  - Variations in calculations
  - Much greater mass of shielding than CEνNS detectors themselves
- Primary mechanism for HALO to detect supernova neutrinos



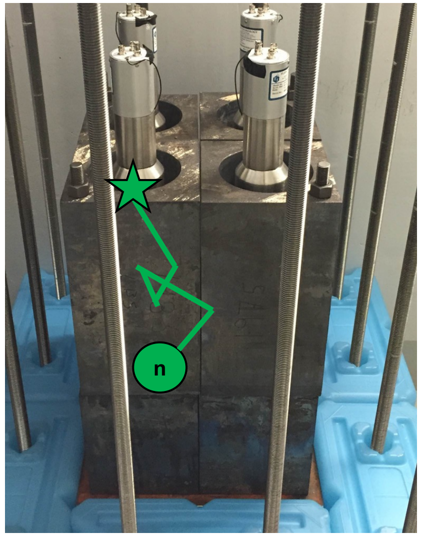
[https://www.triumf.ca/research-highlights/experimental-result/halo-operational-snolab]



[image courtesy of K. Scholberg]

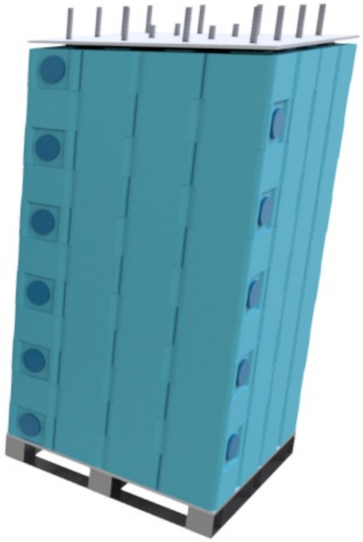
The Lead Neutrino Cube

- 900-kg lead target, cavities for liquid scintillator detectors
- NINs produced in lead have small but non-zero efficiency to make their way to LS cells, identified as neutrons using PSD
- Muon veto panels surround targets to reject muon-induced neutrons
- Water shielding reduces steady-state, beam-related neutrons
- Focus on delayed neutrino window, CC cross section expected to be larger than NC, free of prompt beam-related neutron (BRN) background



LS detectors
Pb target

Muon veto panels
Water shielding

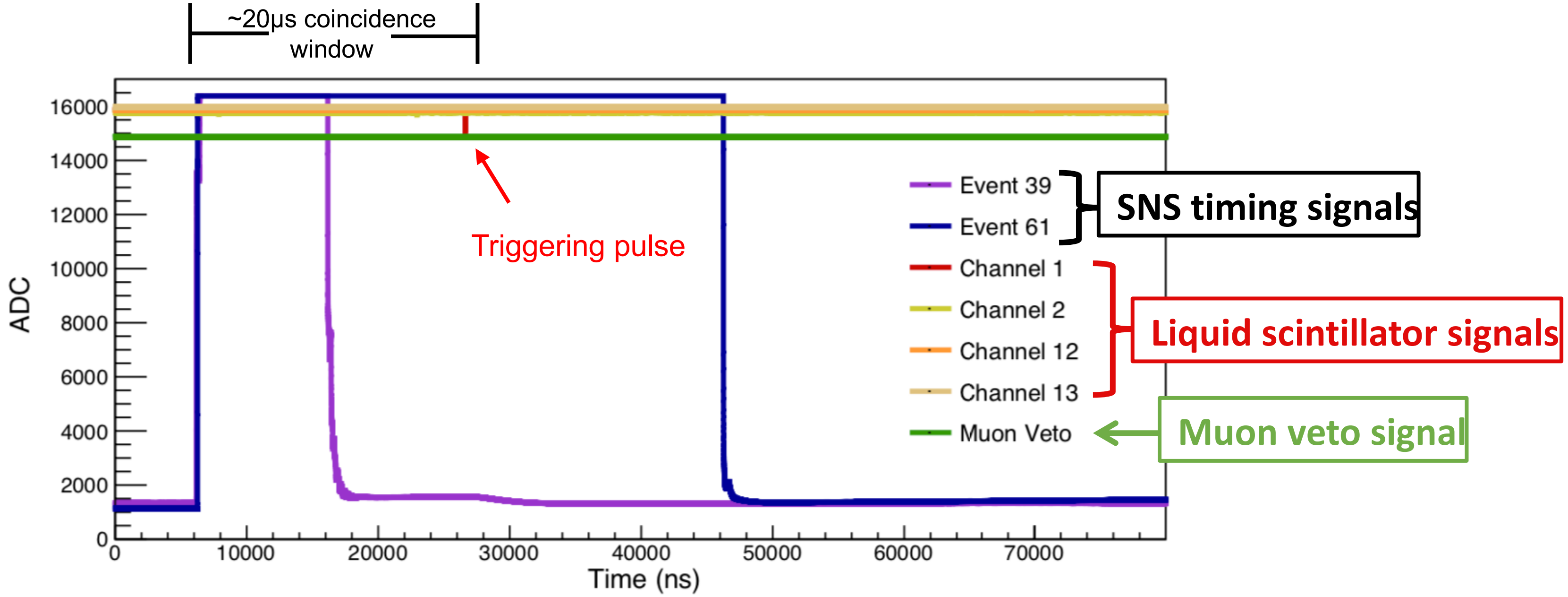


Detector Operation

- DAQ triggers on coincidences between SNS timing signals and liquid scintillator pulses in ~20μs window, record all channels when coincidence observed
- Find onset of LS pulses, integrate for 400ns to determine energy, integrate tail of pulse

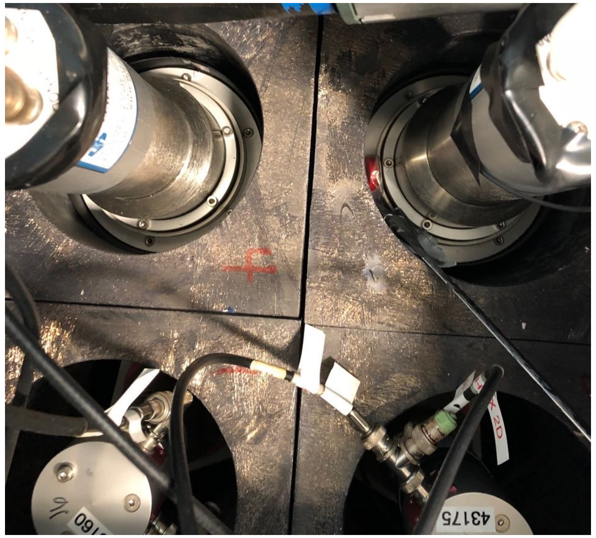
$$\mathrm{PSD} = \frac{\text{tail integral}}{\text{full integral}}$$

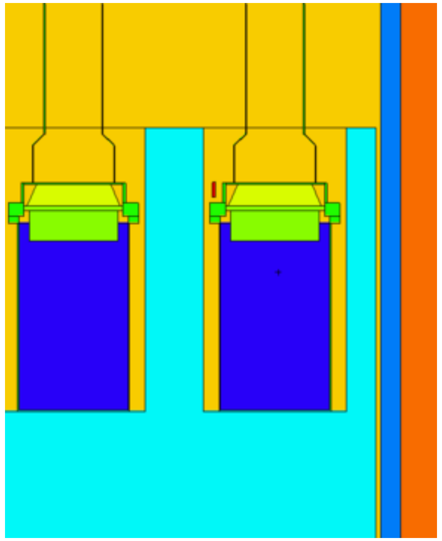
- Correlate liquid scintillator pulses with SNS timing signal, veto in software
- Events within a 14μs window around the SNS timing signal blinded
- Dedicated gamma calibrations to set energy scale of events, neutron calibrations to optimize PSD & develop cut



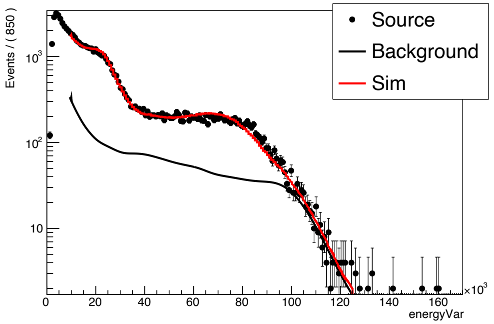
Gamma Calibrations

- Calibrated with gamma sources (^{60}Co, ^{22}Na, ^{137}Cs, ^{133}Ba) several times throughout lifetime
- Source and detector simulated in MCNP, fit to data allowing energy-resolution and ADC-to-keV calibration parameters to float

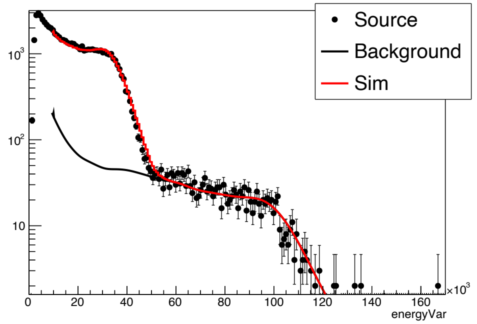




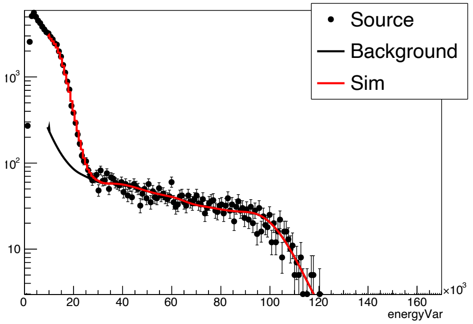
^{22}Na



^{137}Cs



^{133}Ba



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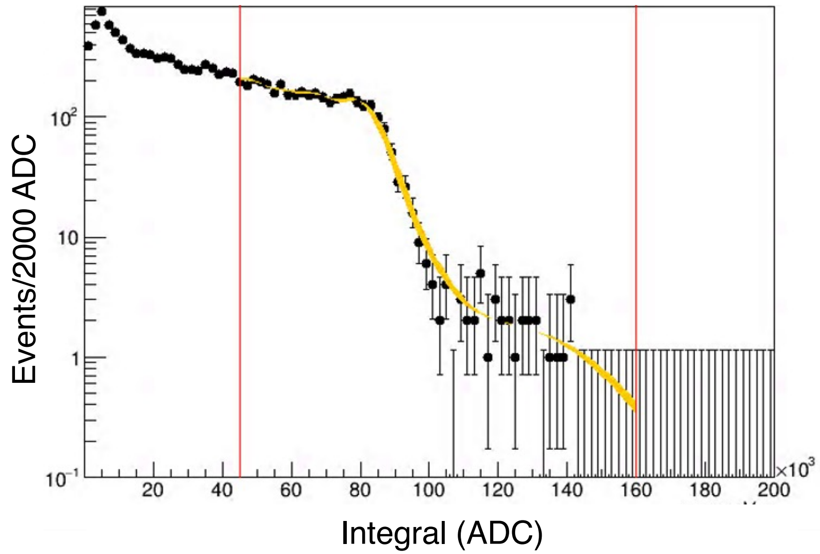
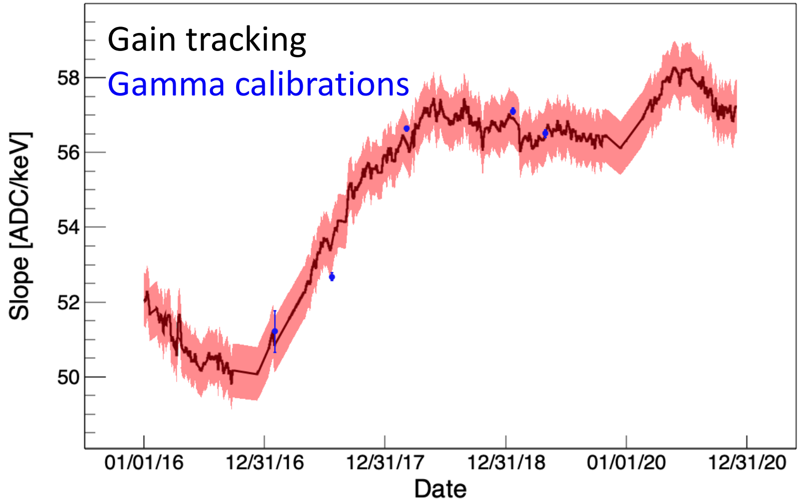
- Source and detector simulated in MCNP, fit to data allowing energy-resolution and ADC-to-keV calibration parameters to float
- Between calibrations, background spectrum fit (largely due to ^{40}K) to track gain on shorter time scales

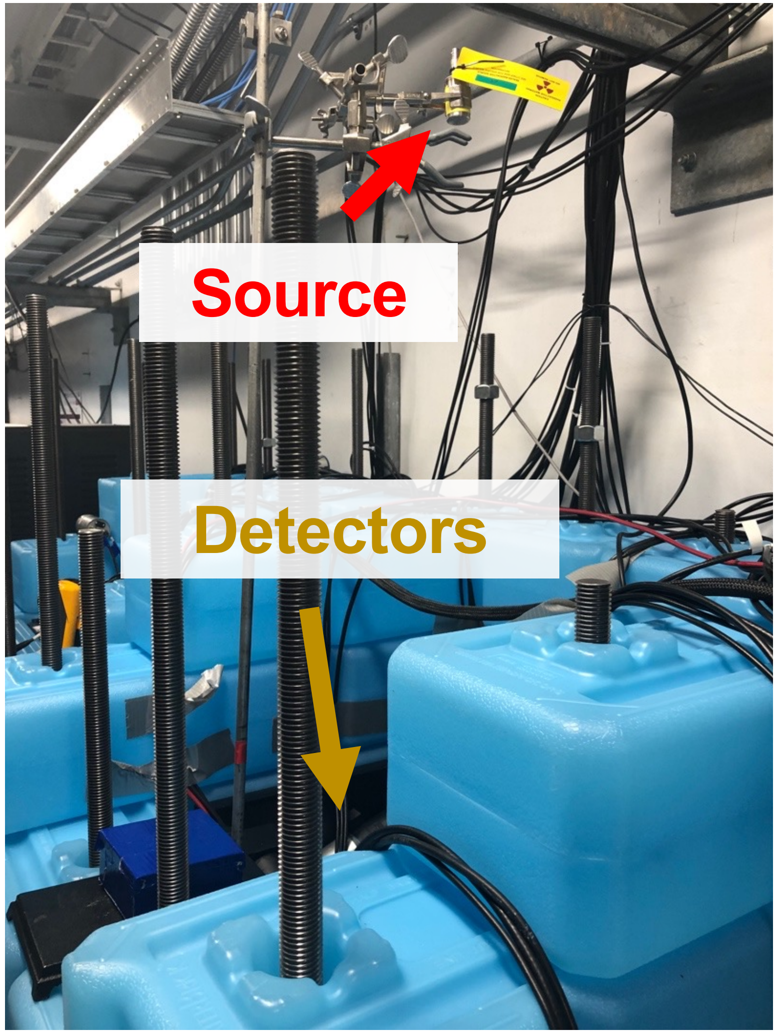


Gain changes over time



Neutron Calibrations

- *in-situ* run performed with time-tagged ^{252}Cf neutron source
- Time-tagged signal replaced SNS timing signal in DAQ, shielding removed to expose detectors to source, otherwise identical to running configuration



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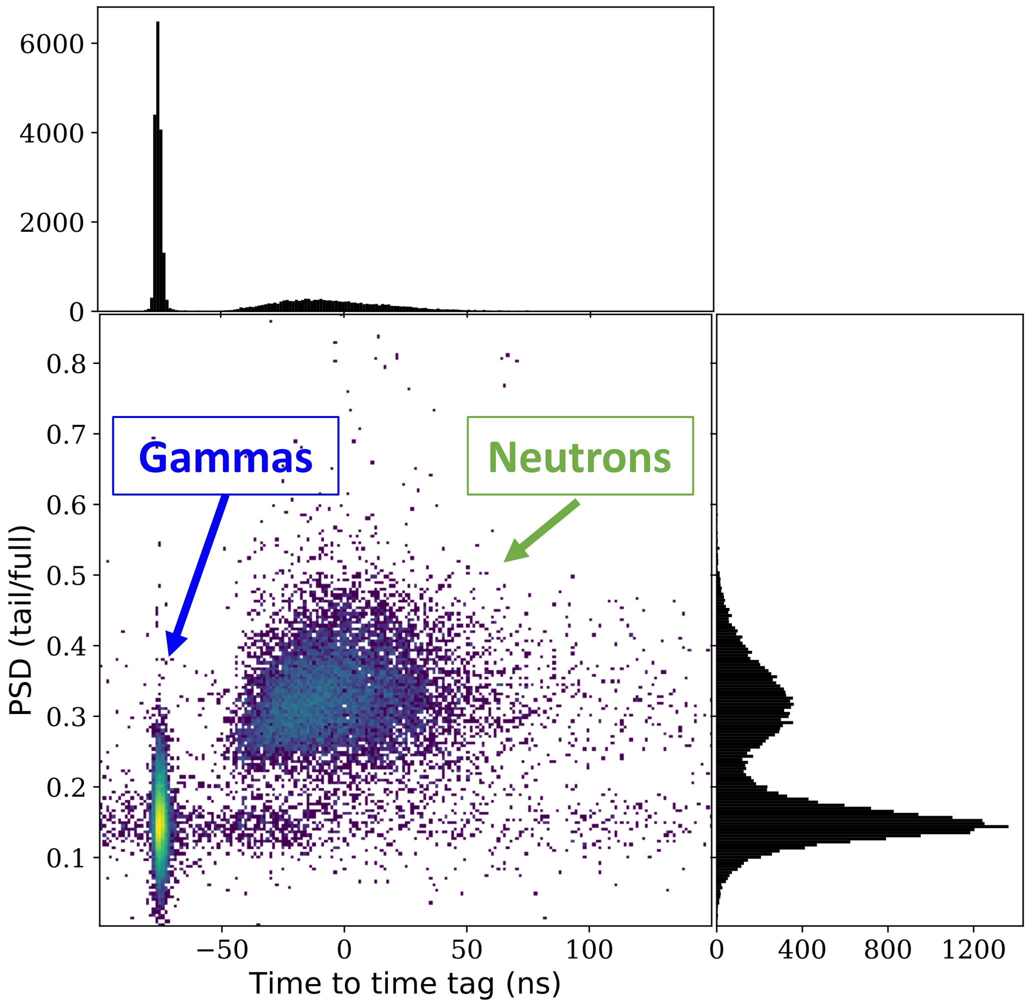

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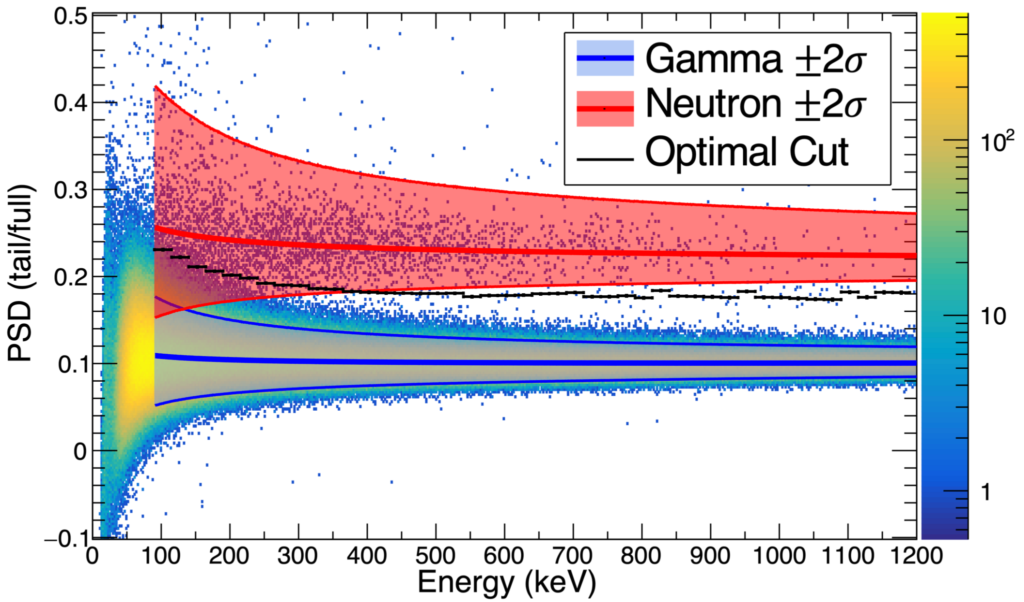
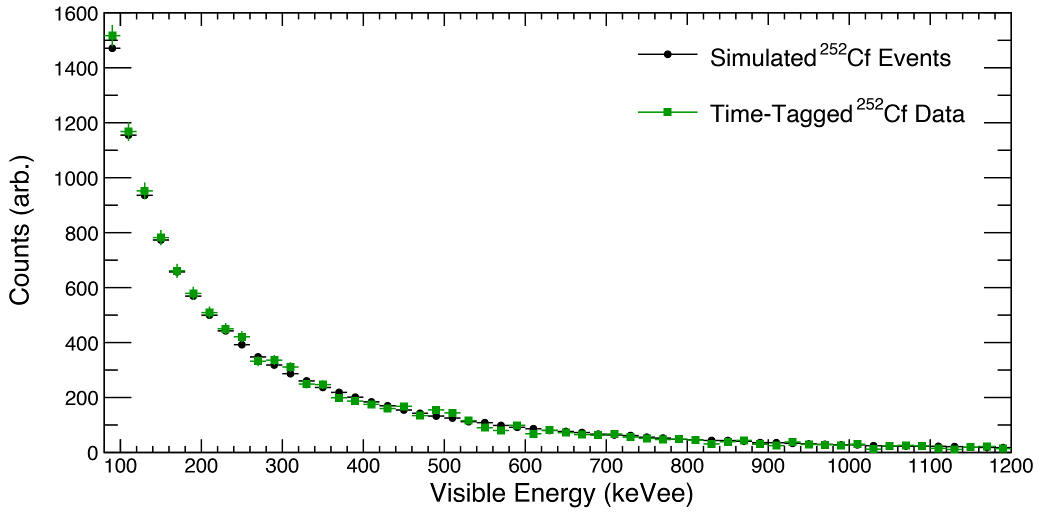
- Produced clean population of gammas, neutrons for understanding thresholds, optimizing PSD parameter
- Develop neutron PSD cut
- Compare data to simulation to ensure we understand energy response





MARLEY for ^{208}Pb

- Gamow-Teller strengths obtained from (p,n) measurement
  - Input B(GT⁻) and B(F) values into MARLEY along with electron neutrino DAR spectrum

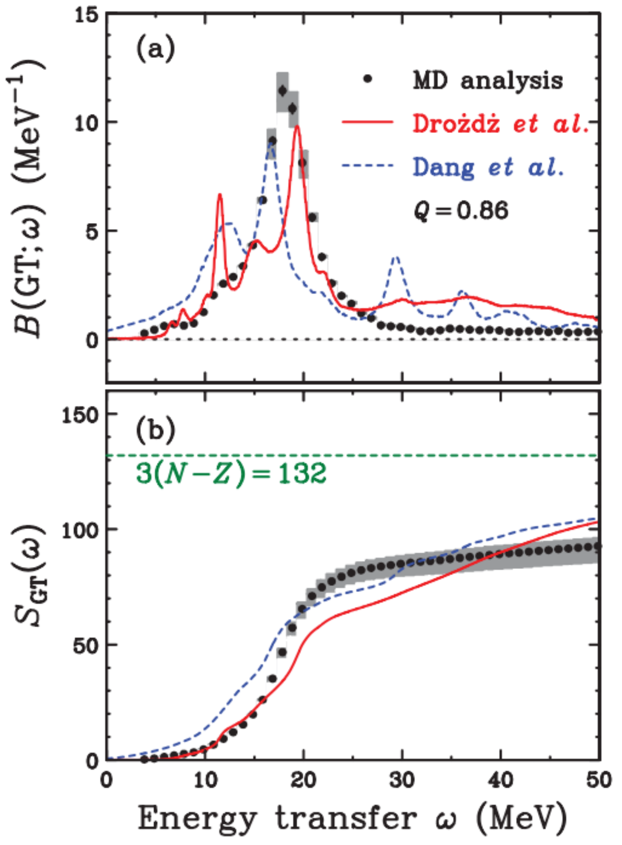
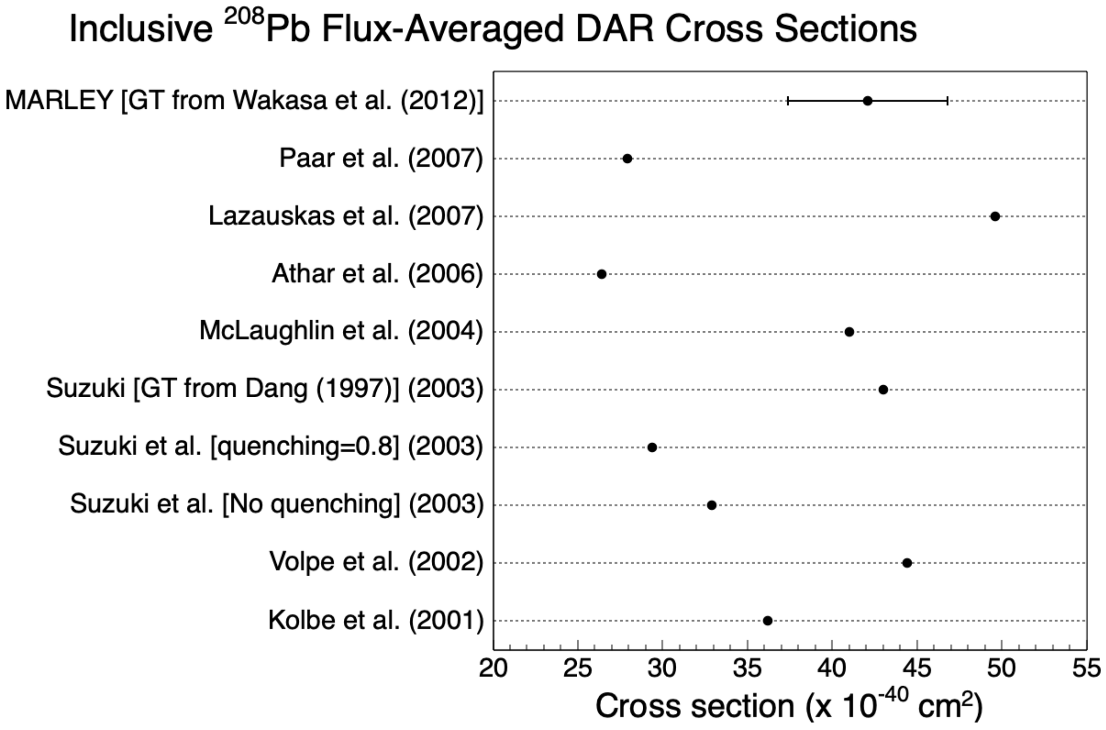


FIG. 16. (Color online) (a) The GT strength $B(\mathrm{GT};\omega)$ and (b) its integrated $S_{\mathrm{GT}}(\omega)$ distributions obtained by MD analysis of the ^{208}Pb(p,n) reaction. The bands represent the uncertainties arising from the selection of α in Eq. (18). The solid and dashed curves are 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 for ^{208}Pb

- Gamow-Teller strengths obtained from (p,n) measurement
  - Input B(GT^{-}) and B(F) values into MARLEY along with electron neutrino DAR spectrum
- MARLEY outputs cross sections, energies and multiplicities of emitted particles
  - Cross section for lead agrees well with existing theoretical calculations
  - Provides calculations for specific channels

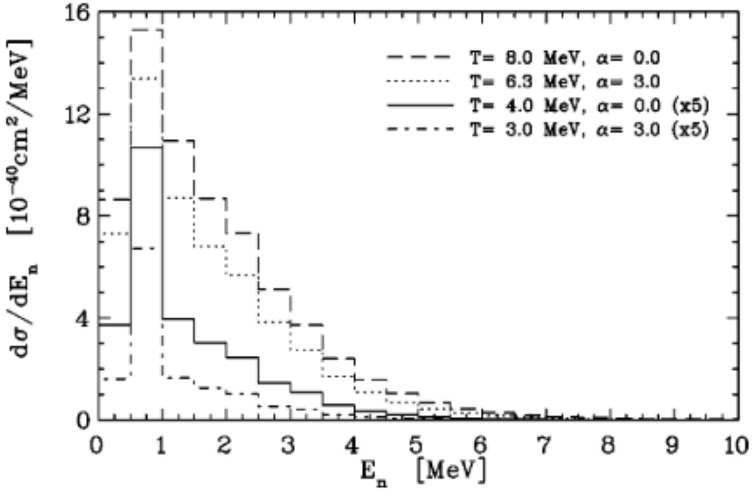


Channel	Cross section ($\times 10^{-40}$cm^2)
^{208}Pb(ν_e, X)	42.1
^{208}Pb$(\nu_e, e^- + n)^{207}$Bi	31.6
^{208}Pb$(\nu_e, e^- + 2n)^{206}$Bi	7.7
^{208}Pb$(\nu_e, e^- + 3n)^{205}$Bi	0.4

MARLEY for ^{208}Pb

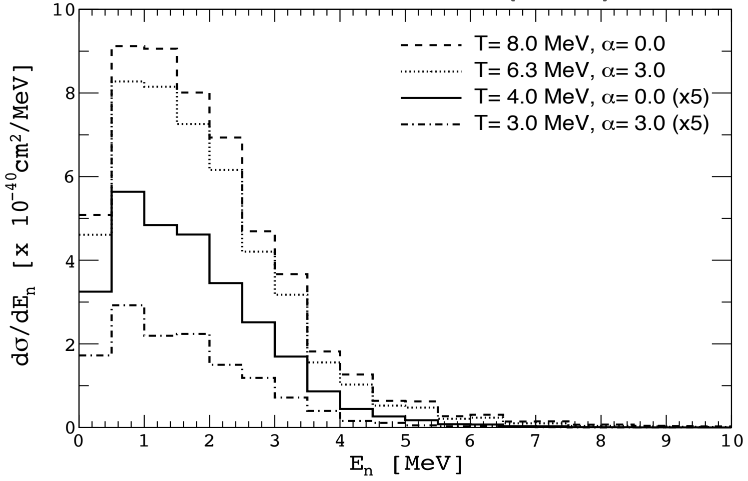
- Gamow-Teller strengths obtained from (p,n) measurement
  - Input B(GT⁻) and B(F) values into MARLEY along with electron neutrino DAR spectrum
- MARLEY outputs cross sections, energies and multiplicities of emitted particles
  - Cross section for lead agrees well with existing theoretical calculations
  - Provides calculations for specific channels
- Similar neutron energy spectrum as E. Kolbe & K. Langanke, Phys. Rev. C **64** (2001) for supernova neutrinos
  - No published neutron spectrum from DAR neutrinos w/o MARLEY

Kolbe & Langanke (2001)



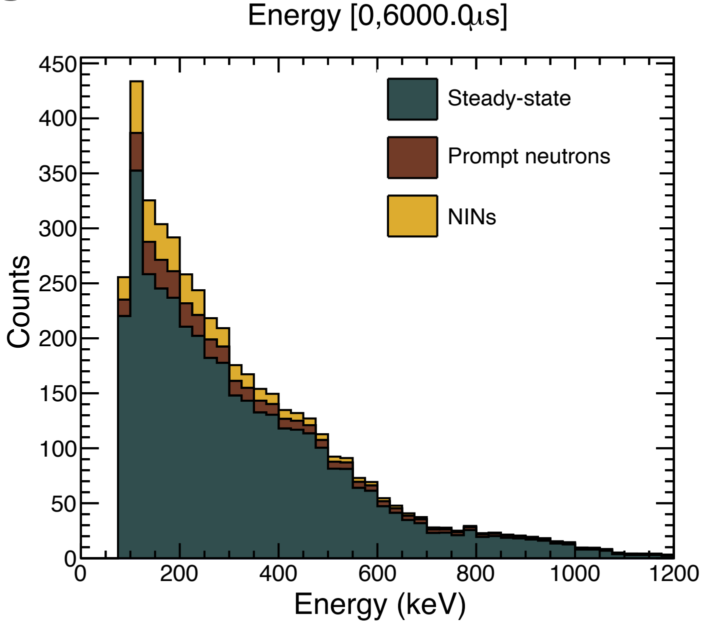
[E. Kolbe & K. Langanke, Phys. Rev. C **64** (2001)]

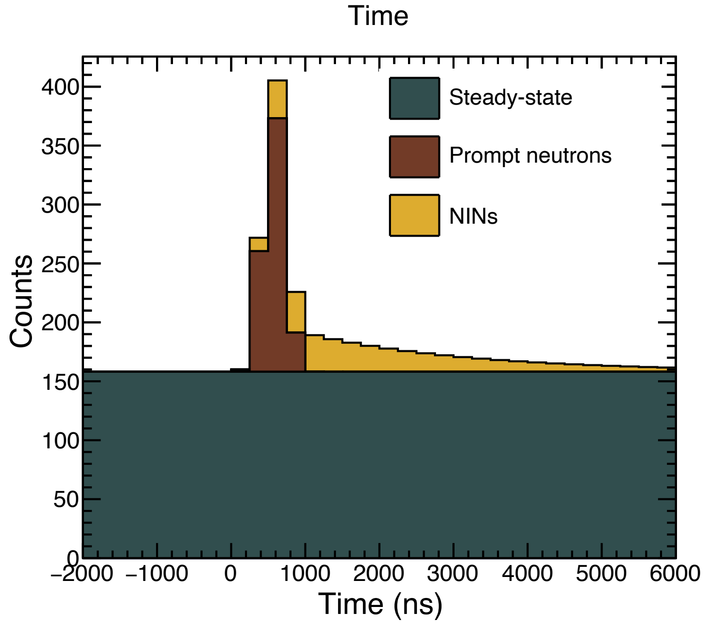
MARLEY + Wakasa B(GT⁻) data



Signal Predictions

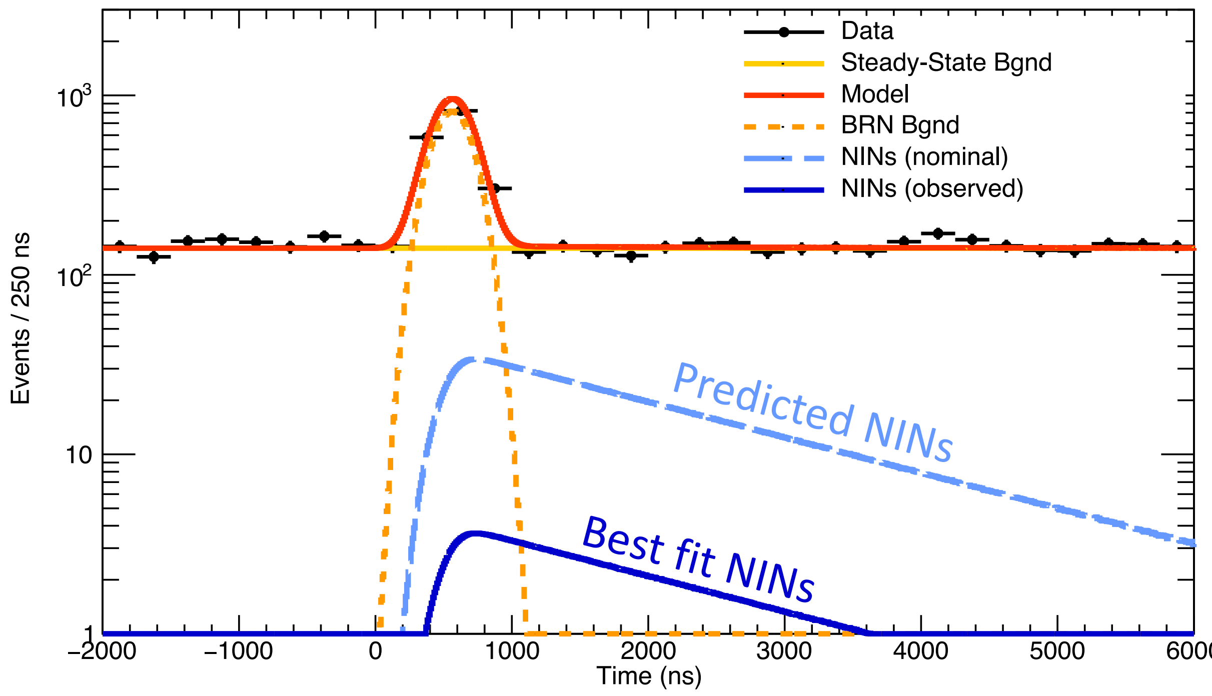
- Simulate signal in MCNP, GEANT4 to determine efficiency for NINs arriving in detector of 18.8%
- Apply measured trigger threshold, energy resolution, PSD cut, to arrive at an efficiency of detecting NINs of 3.3%
- One-dimensional (time-only) fit to data
- Expect 346 charged-current NIN events with cuts
  - Approx. 5σ significance with nominal cross section





Unblinded Results

- Best fit of 36^{+72}_{-36} events compared to expected 346 events
  - Cross section much lower than expected
  - See >4σ discrepancy with model
- Open questions:
  - Is neutron emission channel suppressed?
    - Study inclusive lead charged-current cross section
      - Can do within COHERENT, also external plans (arXiv:2205.11769)
    - Study NIN cross section with different target (Fe neutrino cube)
  - Are emitted neutrons lower in energy than predicted?
    - Study lead NIN cross section with capture-gated detector
  - Is the total cross section suppressed?
    - Can study in the NaIνE detector



The NaIνE-185 Detector

Motivation for Measuring ^{127}I CC Interactions

- Initial motivation from W. C. Haxton, Phys. Rev. Lett **60** (1988), proposing radiochemical experiment using ^{127}I for solar neutrino detection

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

  - Low threshold gives access to ^{7}Be solar neutrinos, larger cross section than for ^{37}Cl
  - Resulting ^{127}Xe has long half-life, use similar radiochemical technique as used for ^{37}Cl
- The cross section depends on g_A, weak axial-vector coupling constant
  - Suppression of g_A important for $0\nu\beta\beta$ experiments (nEXO, LEGEND, SNO+, CUPID), half-lives
  - Can potentially test quenching at momentum transfer not available through beta-decay experiments

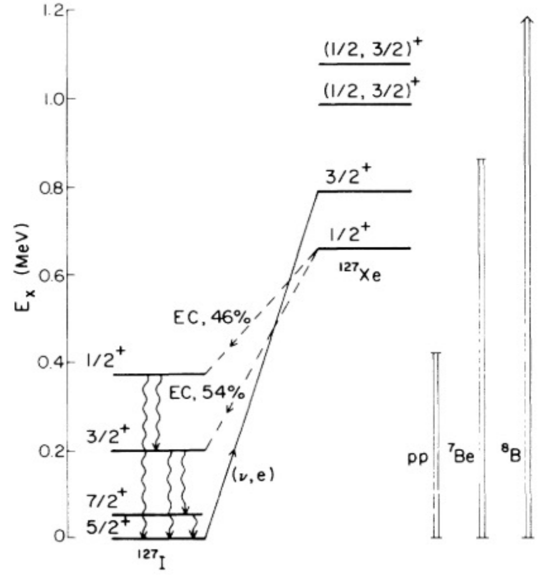


FIG. 1. Level scheme showing weak transitions between ^{127}I and ^{127}Xe.

[W. C. Haxton, Phys. Rev. Lett **60** (1988)]

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

[J. Engel, S. Pittel, & P. Vogel, Phys. Rev. C **50** (1994)]

Motivation for Measuring ^{127}I CC Interactions

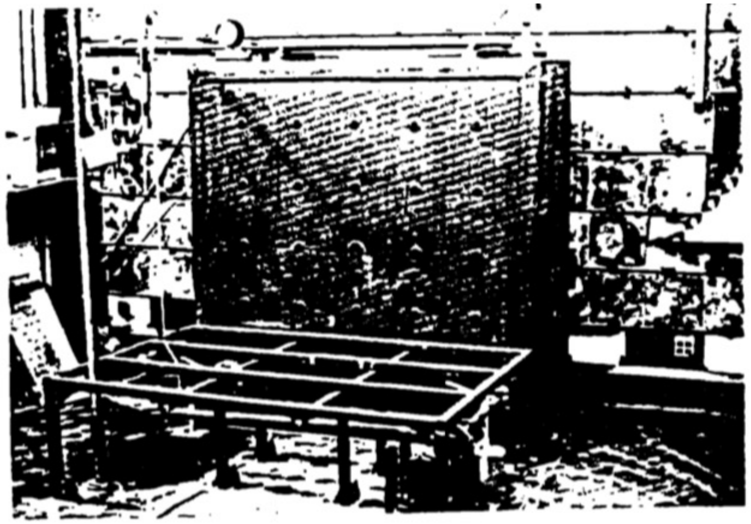
- Exclusive cross section to bound ^{127}Xe measured at LAMPF in the 1990s with radiochemical approach

$$\nu_e + {}^{127}\mathrm{I} \rightarrow e^- + {}^{127}\mathrm{Xe}_{\mathrm{bound}}$$

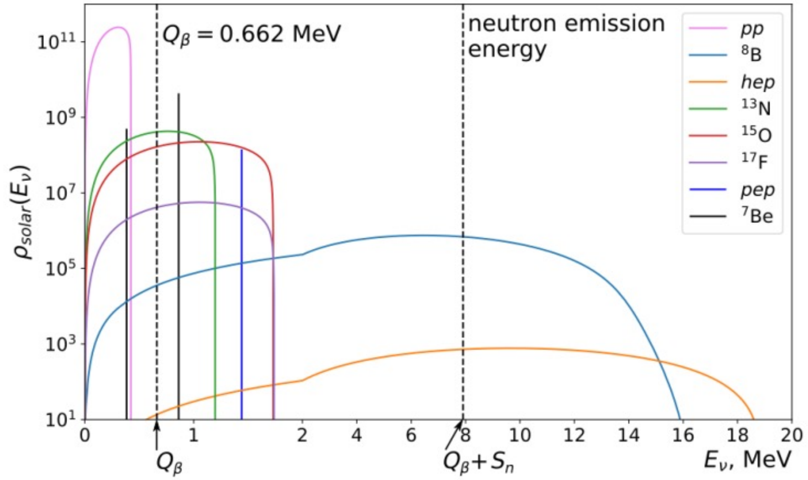
- Reported flux-averaged cross section of

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

  - Only measured cross section to bound states of ^{127}Xe—majority of neutrinos at DAR sources have energy above neutron emission threshold
- Suggested repetition with electronic NaI detector to measure energy-dependence of cross section
- Recently interest in looking at ^{126}Xe/^{127}Xe ratio for comparing ^{7}Be to ^{8}B/HEP neutrinos



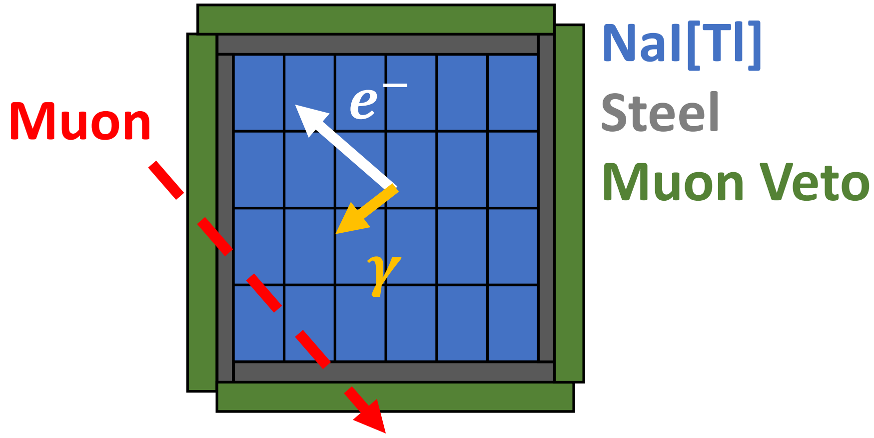
[B. T. Cleveland, et al., 23rd Int. Cosmic Ray Conf. **3** (1993)]

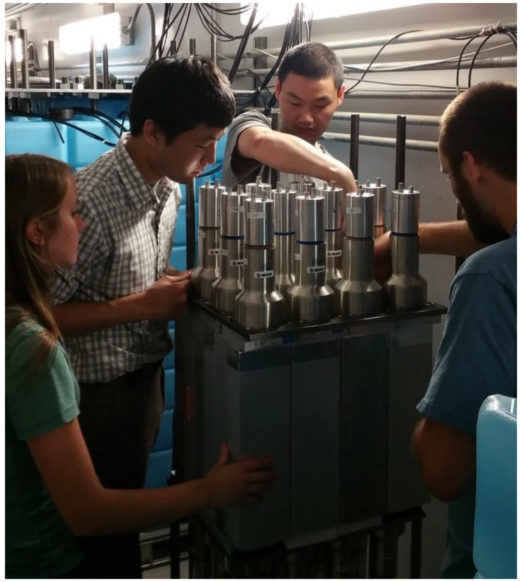


[Y. S. Lutostansky, et al., arXiv:2103.12325 (2021)]

NaIνE-185 Detector

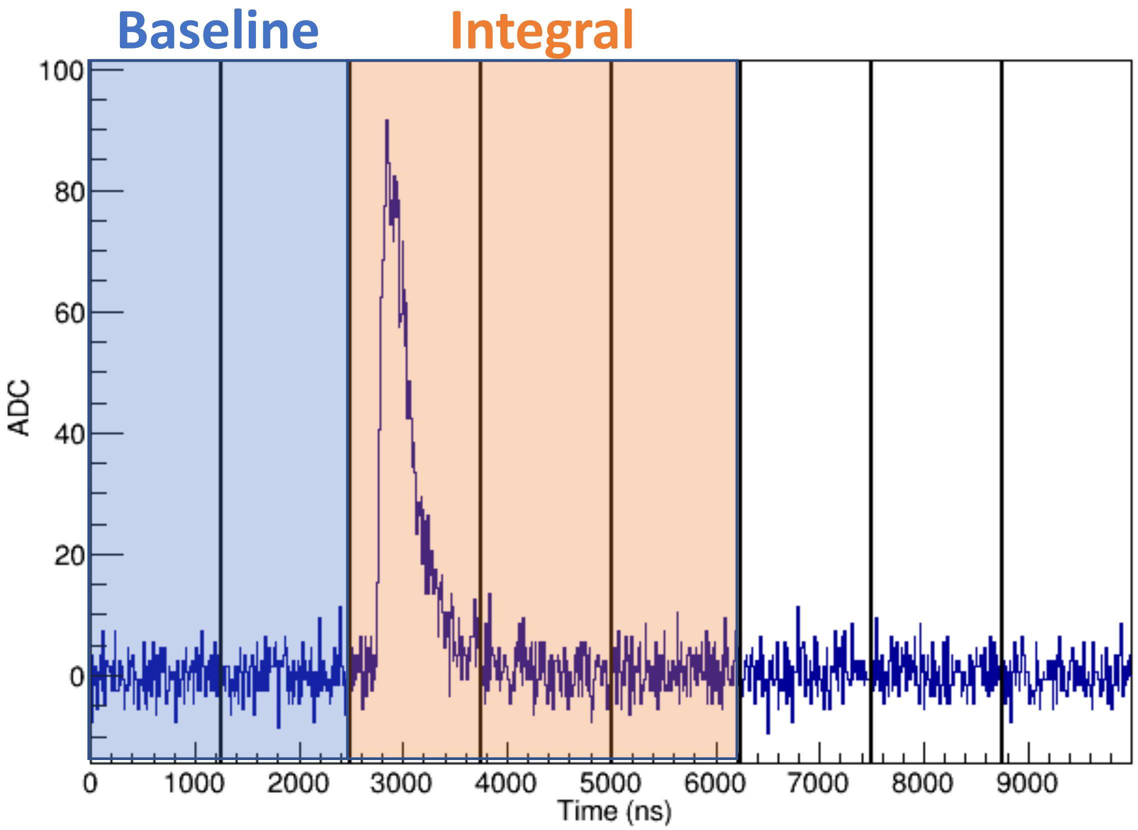
- NaI neutrino Experiment (**NaIνE**) designed to measure the inclusive charged-current cross section, energy-dependence
- Twenty-four 7.7-kg NaI[Tl] scintillator detectors (185-kg mass), deployed 2016
- Signal is “large-energy” (10-55 MeV) depositions in delayed neutrino window
- Muon veto panels to reduce cosmic muons
  - 1.5” steel between NaI and veto panels to avoid vetoing signal
- Detector also used as prototype for ton-scale NaI CEνNS detector





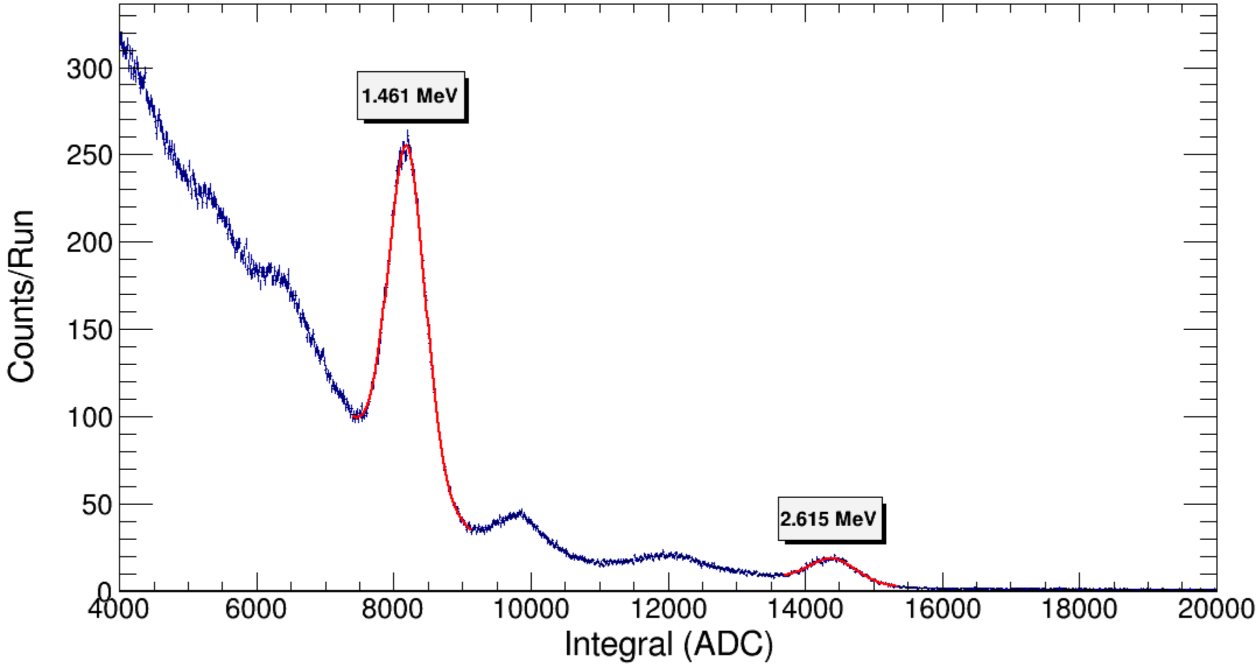
Data Acquisition System

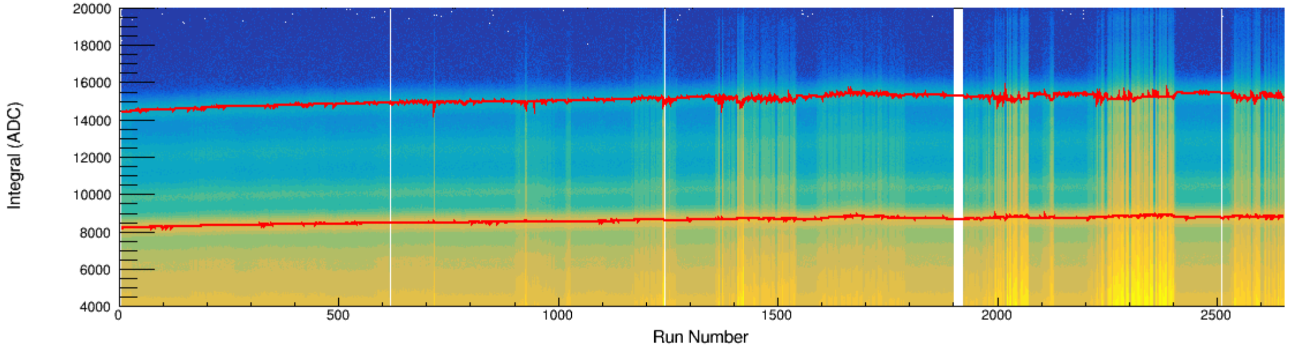
- Detector uses digitizer trigger to record scintillation in any NaI channel above a threshold (500-900 keV)
- Integrated PMT charge recorded in eight timing windows (accumulators) around the pulse to determine baseline, integral
- Muon veto panels, SNS timing pulses trigger independently, timing correlation done in software
  - Data within -2μs to +20μs of SNS timing signal blinded



Intrinsic Background Calibrations

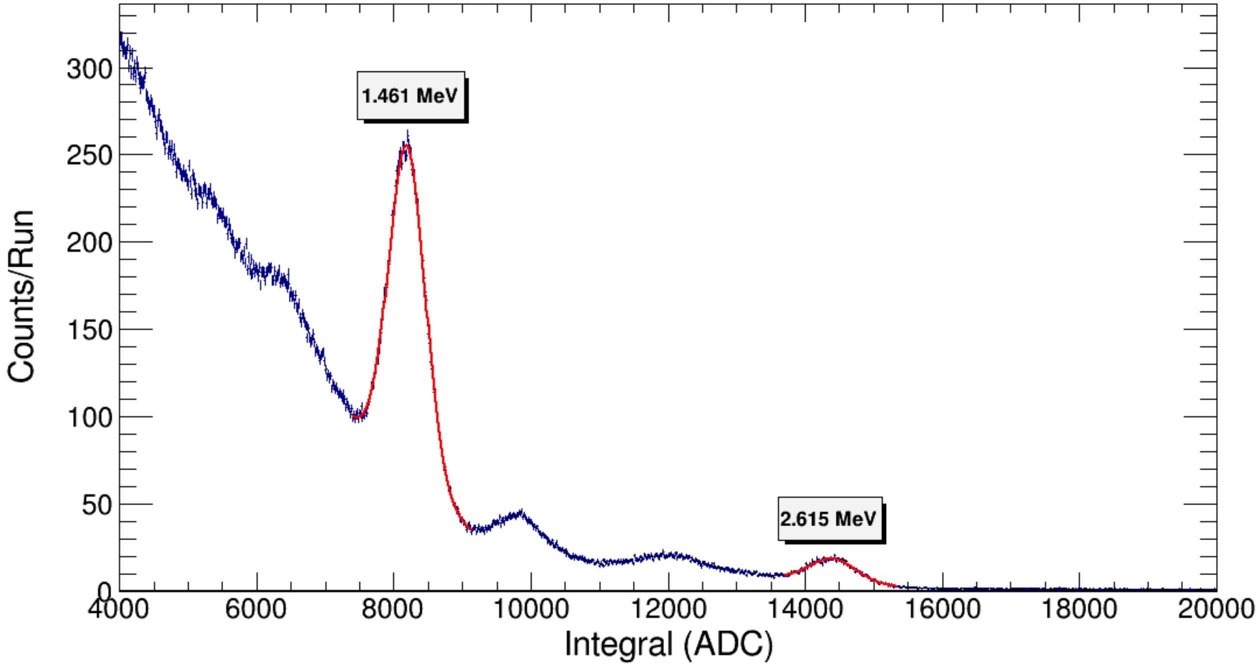
- Calibrate each NaI channel based on ^{40}K and ^{208}Tl intrinsic backgrounds
  - Track gain changes over time, measure energy resolution in crystals

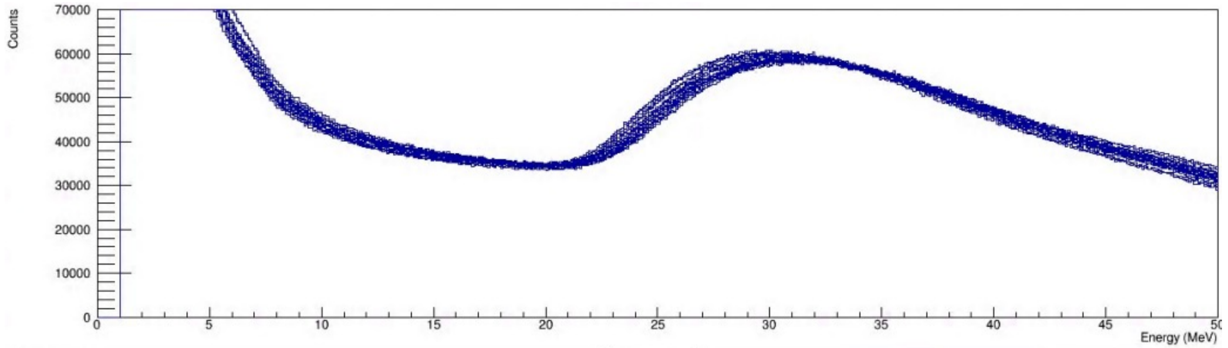


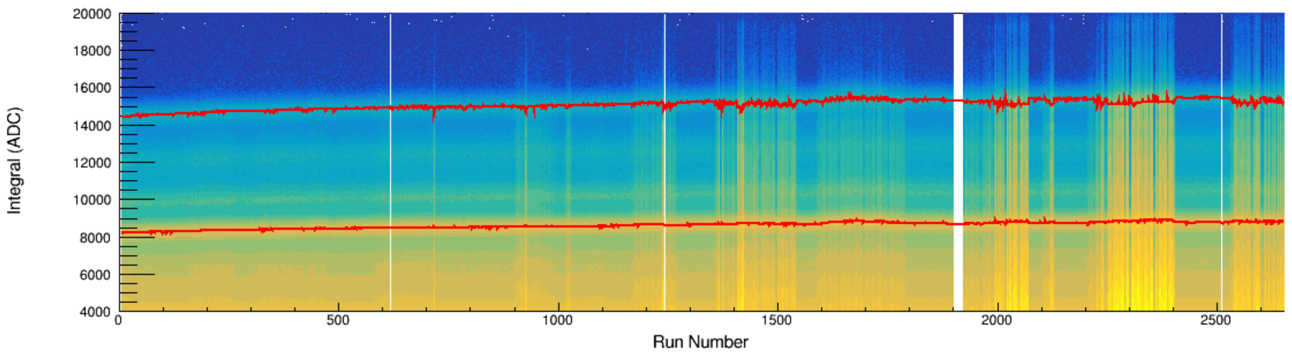


Intrinsic Background Calibrations

- Calibrate each NaI channel based on ^{40}K and ^{208}Tl intrinsic backgrounds
  - Track gain changes over time, measure energy resolution in crystals
- Extending calibration to higher-energies leads to small discrepancies in large energy background (muon) spectrum in each crystal

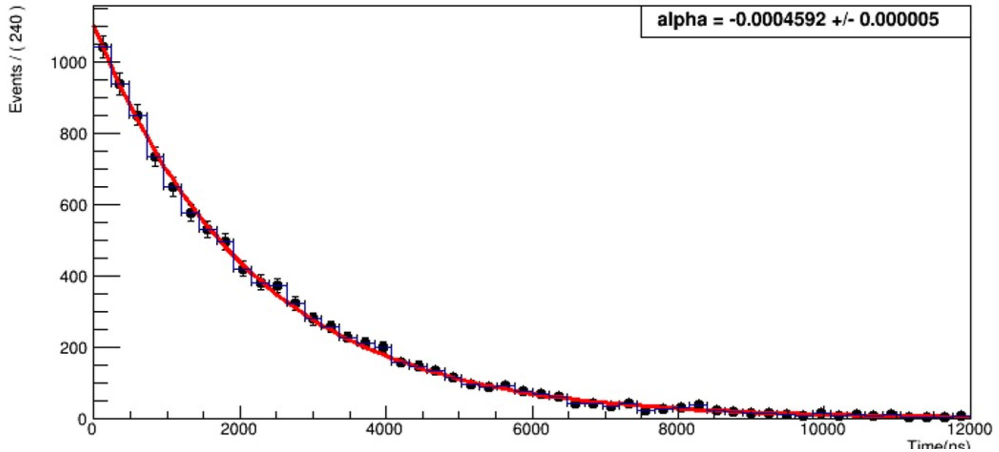


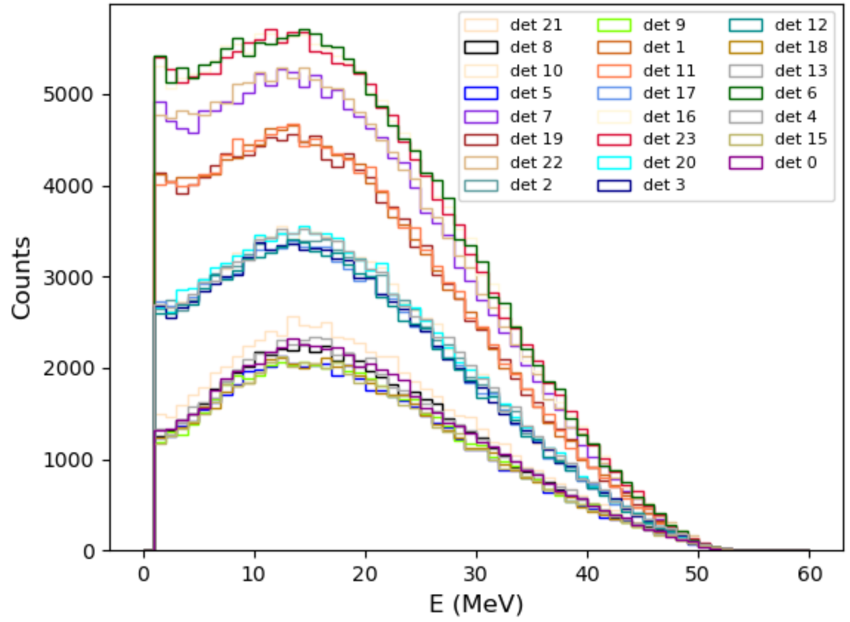




Michel Positron Correction

- Use Michel positrons to correct calibration
- Collect population of Michel events by looking for large energy depositions in crystals after a muon event (tagged with veto panels)
  - Fitting data gives anti-muon mean lifetime of $2.172 \pm 0.024 \mu s$
- Simulate positrons in GEANT4, matching data selection criteria
- Fit quadratic calibration function to data that preserves low energy calibrations





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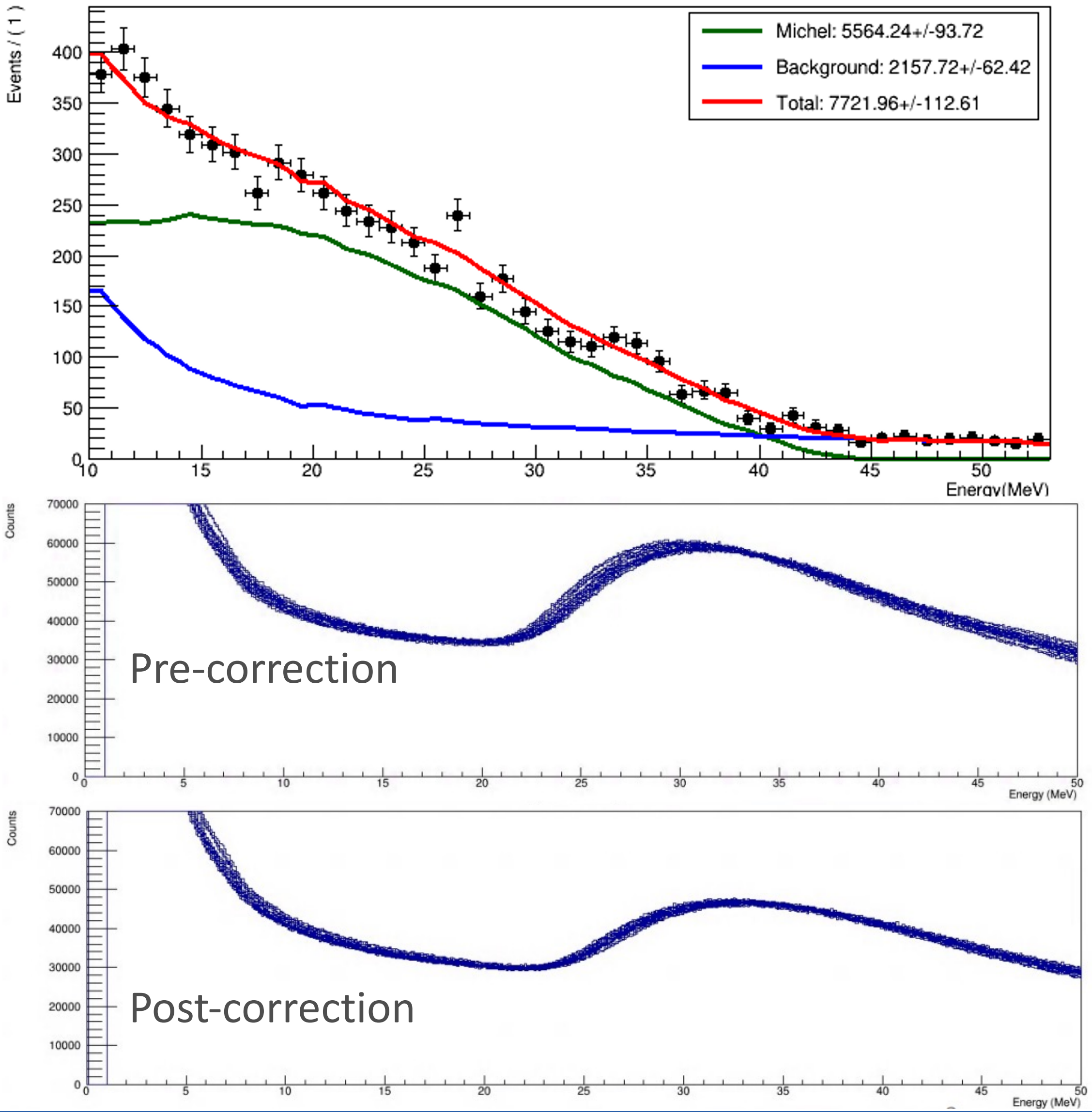
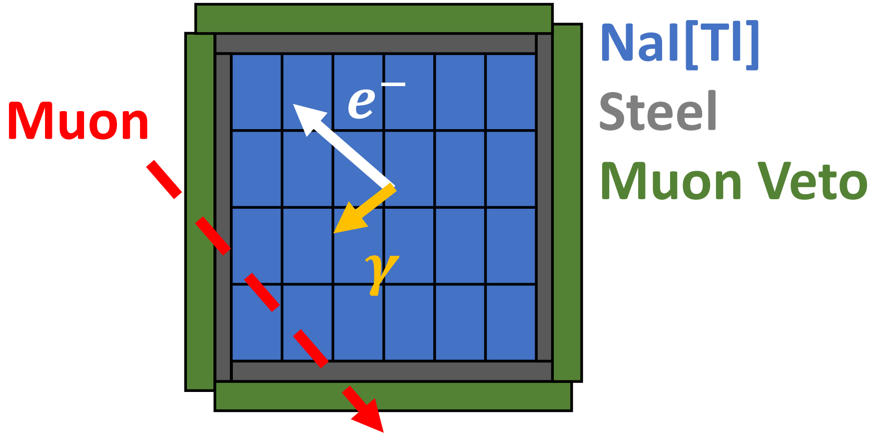
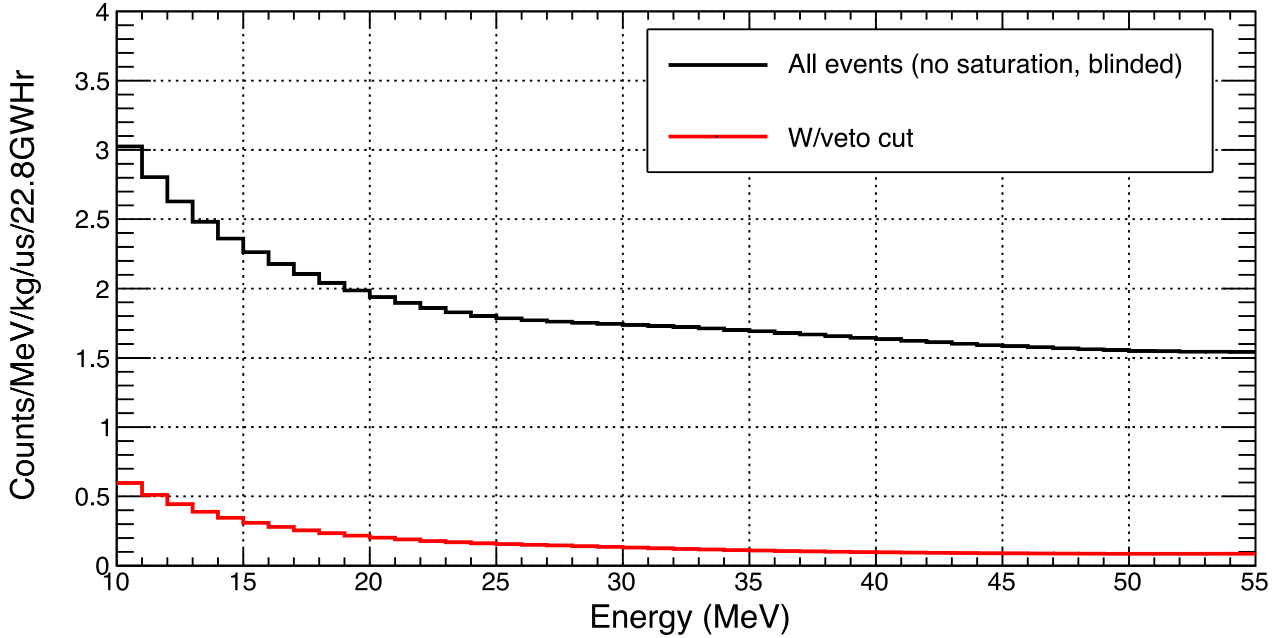


Muon Veto Cut

- Cosmic muons the largest source of backgrounds for charged-current signal
- Tag NaI events close in time to muon veto panel PMT events above threshold
  - 1.5" steel between NaI crystals and veto panels to avoid vetoing signal
  - Systematic incorporated into analysis to account for uncertainty in veto thresholds
- Veto rejects ~93% of cosmic muon backgrounds between 10-55 MeV
  - Additionally benefit from looking in a small (several microsecond) window around SNS timing signal to reduce backgrounds





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:

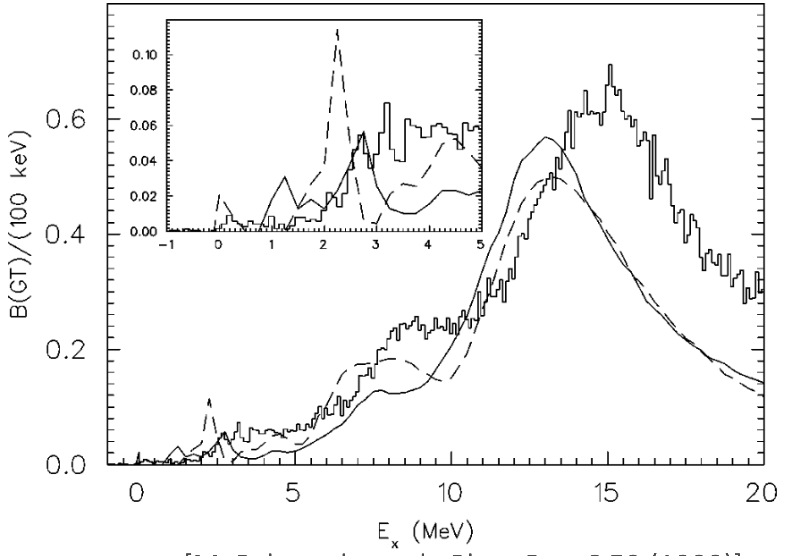
$$22.5^{+1.2}_{-6.5} \times 10^{-40}\ \mathrm{cm}^2$$

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

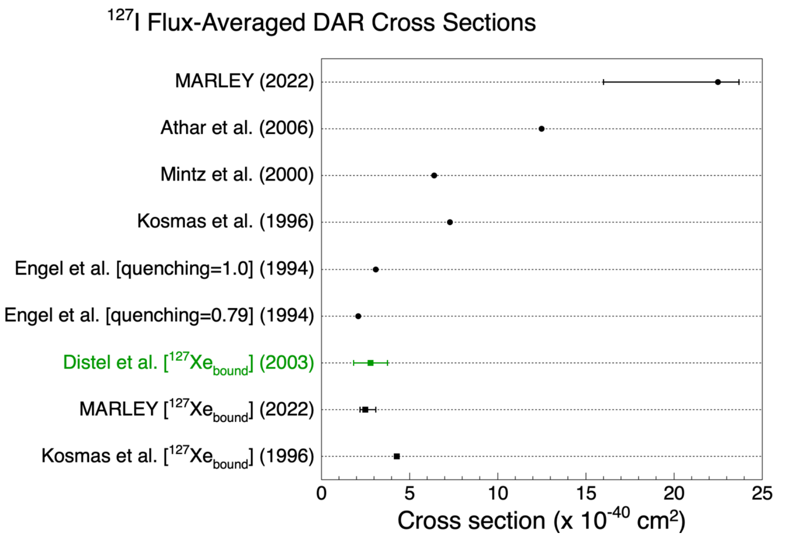
$$2.5^{+0.3}_{-0.6} \times 10^{-40}\ \mathrm{cm}^2$$

  - Good agreement with LAMPF measured value of

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

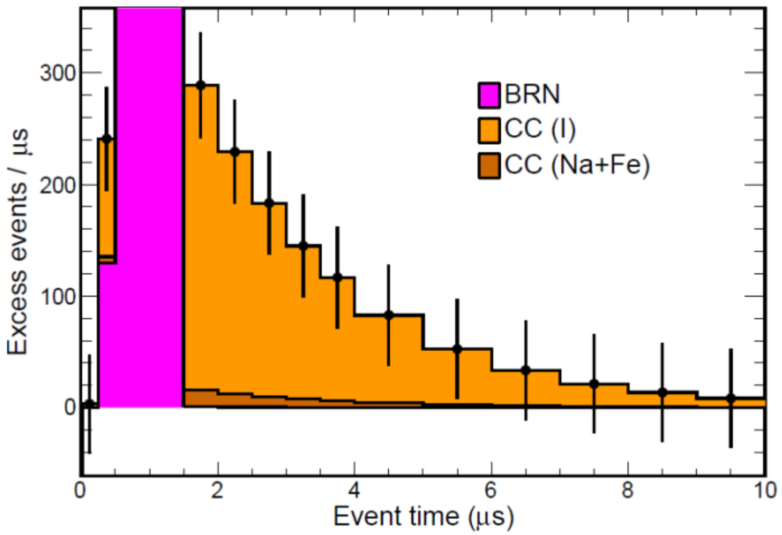


[M. Palarczyk, et al., Phys. Rev. C 59 (1999)]



Signal Predictions

- Simulate charged-current events in GEANT4, process matching analysis cuts to arrive at signal predictions
  - Restrict to 10-55 MeV where most of signal expected to reside
    - Above neutron capture energy on ^{23}Na and ^{127}I
  - Expect 1,320 CC events on ^{127}I
  - ~61 events from CC on sodium, iron shielding
- Three main results:
  - Inclusive cross-section: 1D fit in time
  - Spectrum of charged-current events: 1D fits in time in 5 MeV energy bins
  - 0n vs. ≥1n exclusive cross sections

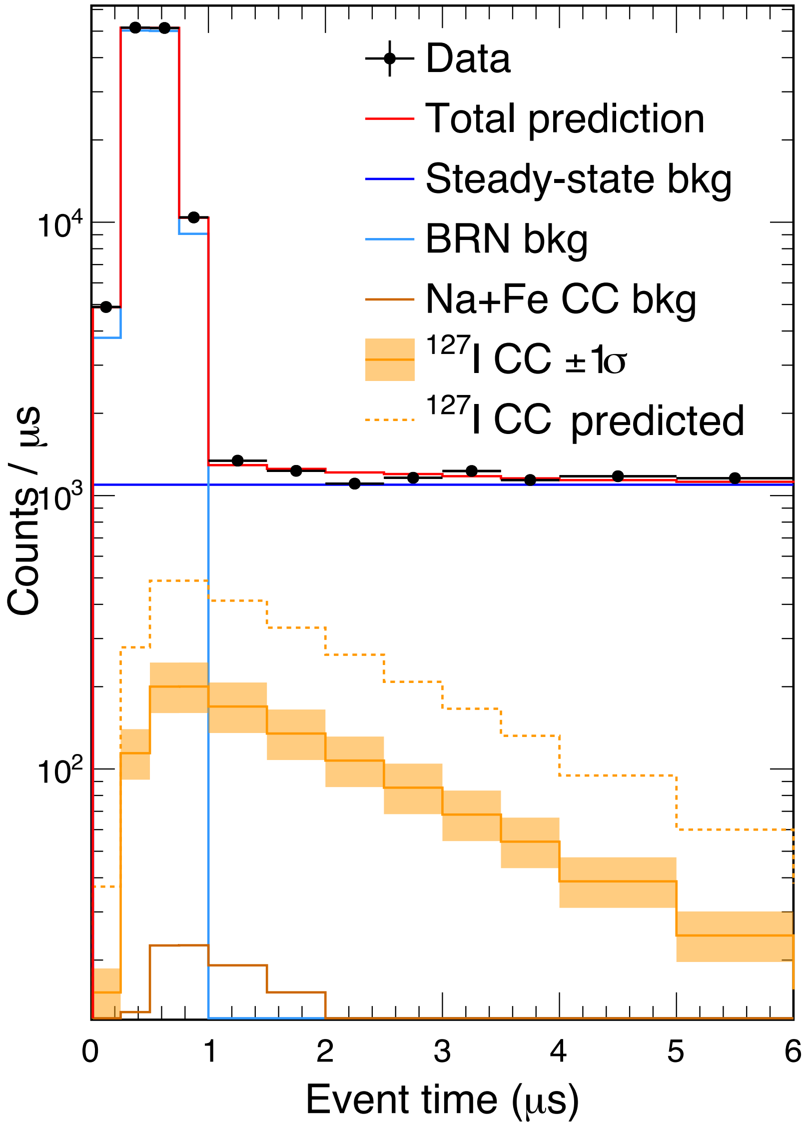


Results: Inclusive Cross Section

- Best fit gives 541^{+121}_{-108} events
  - 5.8σ evidence of CC events
  - χ^2 of 13.1, 12 d.o.f.
- Corresponds to cross section of

$$\mathbf{9.2^{+2.1}_{-1.8} \times 10^{-40}\ cm^2}$$

  - 40.9% theoretical cross section



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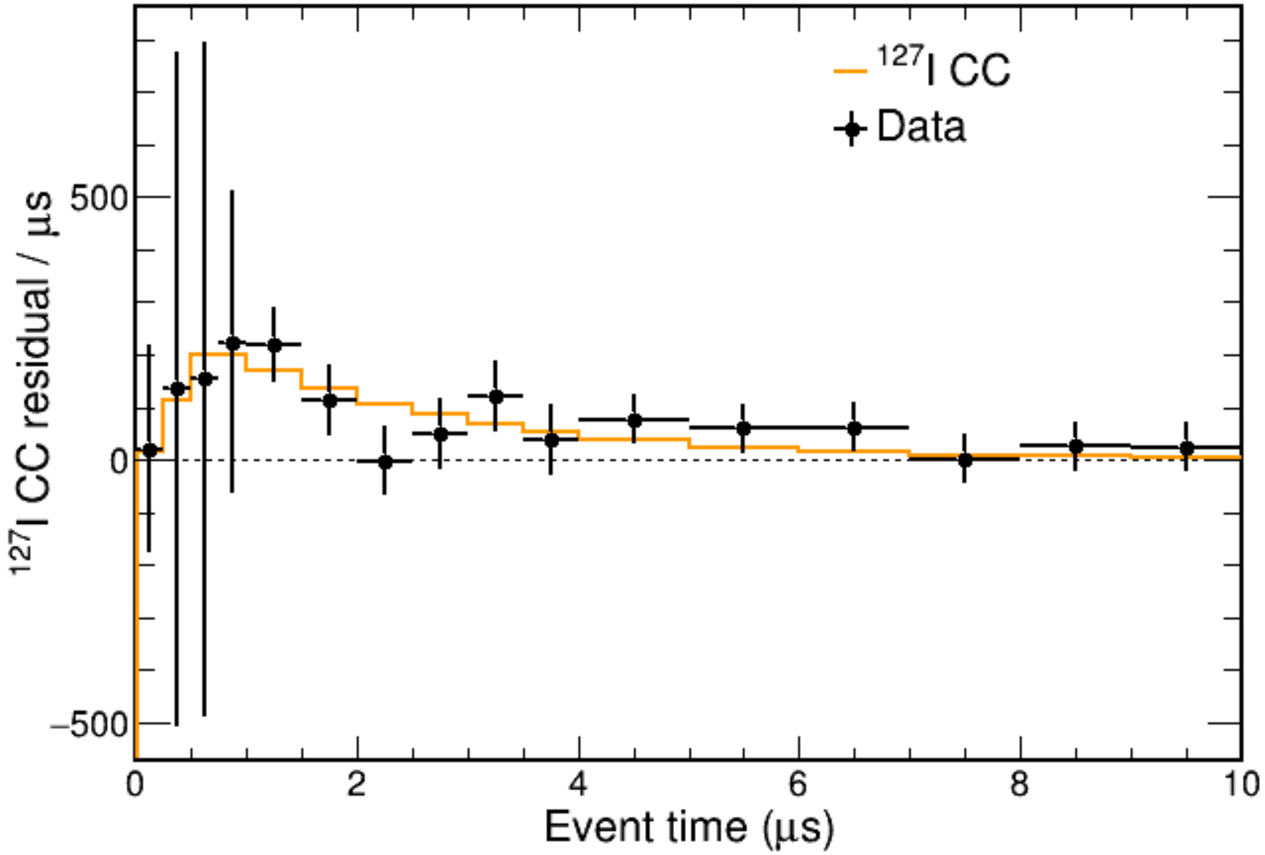
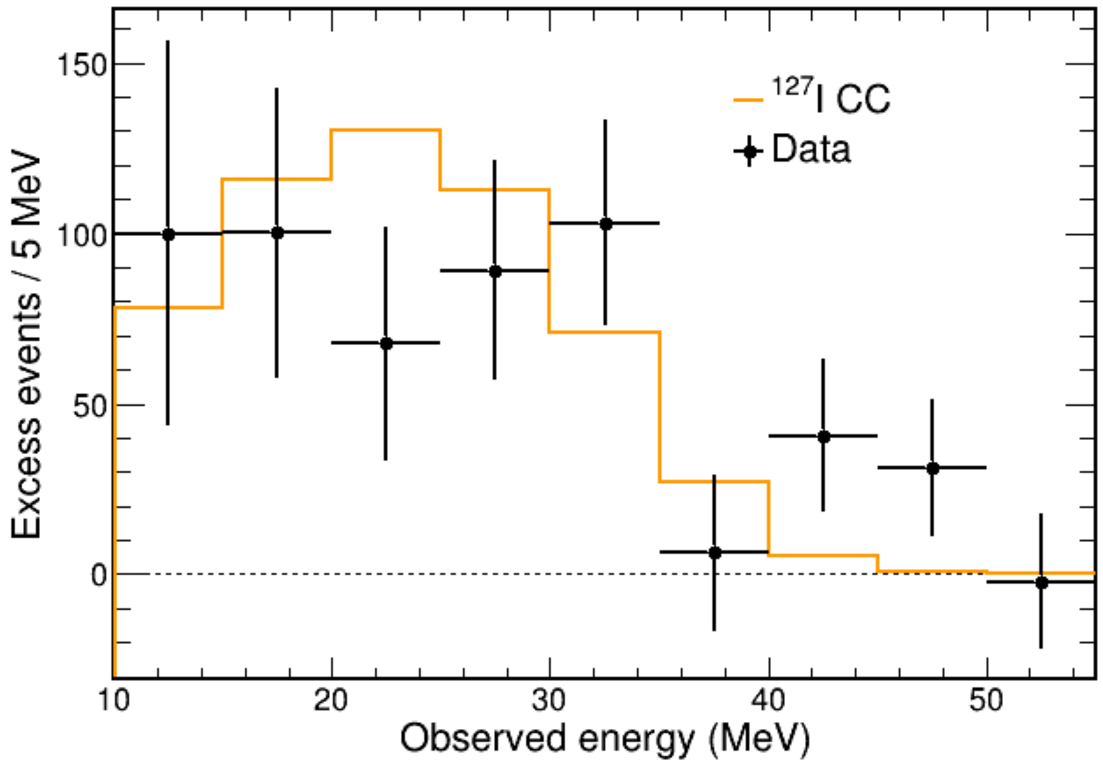
$$\mathbf{9.2^{+2.1}_{-1.8} \times 10^{-40}\ cm^2}$$

  - 40.9% theoretical cross section
- Subtract off steady-state, BRN backgrounds to form signal residuals for 1D timing fit across 10-55 MeV range



Results: ^{127}I Charged-Current Spectrum

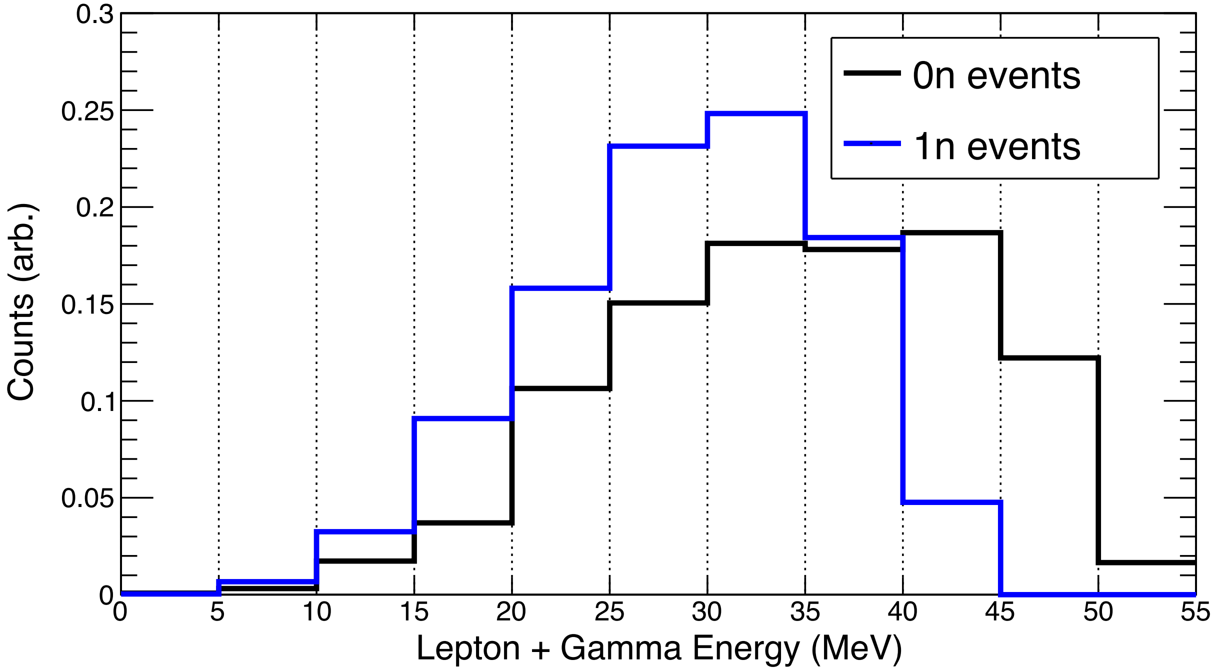
- Fit 1D timing spectrum in 5 MeV bins from 10-55 MeV to generate an energy spectrum
  - In each bin, independent fits to timing to estimate BRN and CC amplitudes
- Does not show great agreement with theoretical model, but two caveats
  - Large error bars on due to low statistics
  - Forbidden transitions not incorporated in predictions



Result: 0*n*/1*n* Cross Sections

- Different spectrum of visible energy (gammas + lepton) for events with neutron emission (1*n*) compared to those without (0*n*)
  - Threshold for 1*n* emission events is 7.9 MeV compared to 0*n* threshold of 0.7 MeV
  - Plot intended to demonstrate difference in spectral shape, amplitudes arbitrary

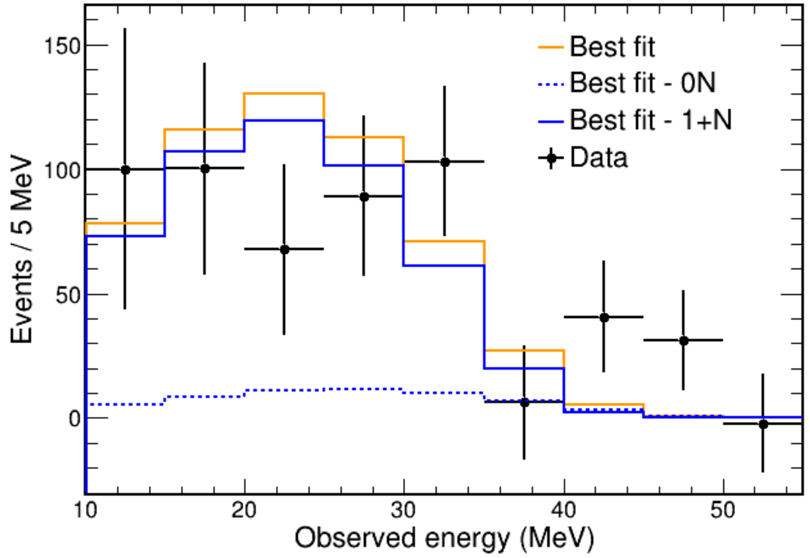
Sum energy of lepton + gamma from MARLEY (no detector effects)



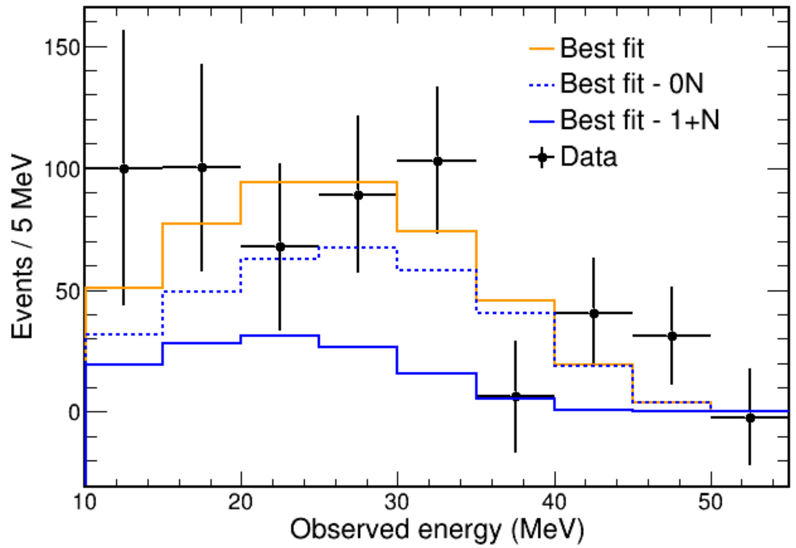
Result: 0*n*/1*n* Cross Sections

- After simulating events in detector geometry, 2D fit in energy and time allowing 0*n* and 1*n* amplitudes to float freely
- MARLEY predicts 10.6% events are 0*n*, data favors larger fraction (72.3%) of events are 0*n*
- 0*n* cross section: $\mathbf{5.2^{+3.4}_{-3.1} \times 10^{-40} cm^2}$
  - Compare to LAMPF measured value: $\mathbf{2.84 \pm 0.91(\mathit{stat}) \pm 0.25(\mathit{sys}) \times 10^{-40}\ cm^2}$
- 1*n* cross section: $\mathbf{2.4^{+3.3}_{-2.4} \times 10^{-40} cm^2}$

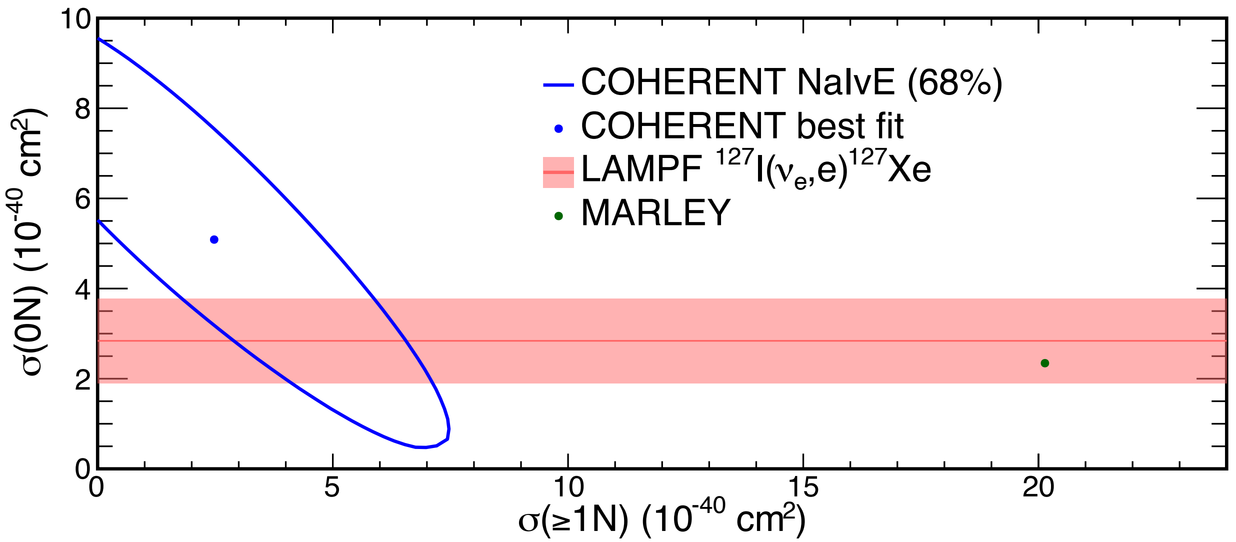
Nominal MARLEY prediction: 10.6% 0*n* events

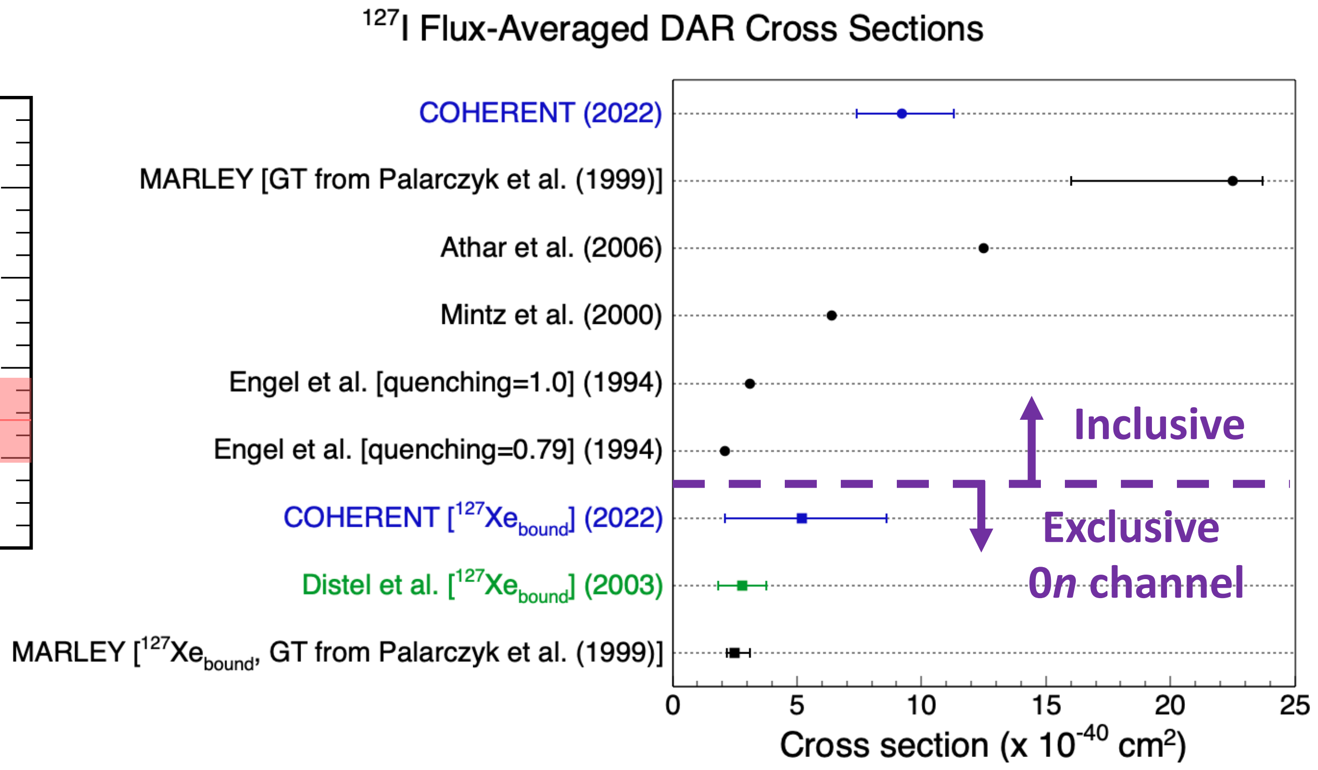


Best fit value: 72.3% 0*n* events



Comparison of Results

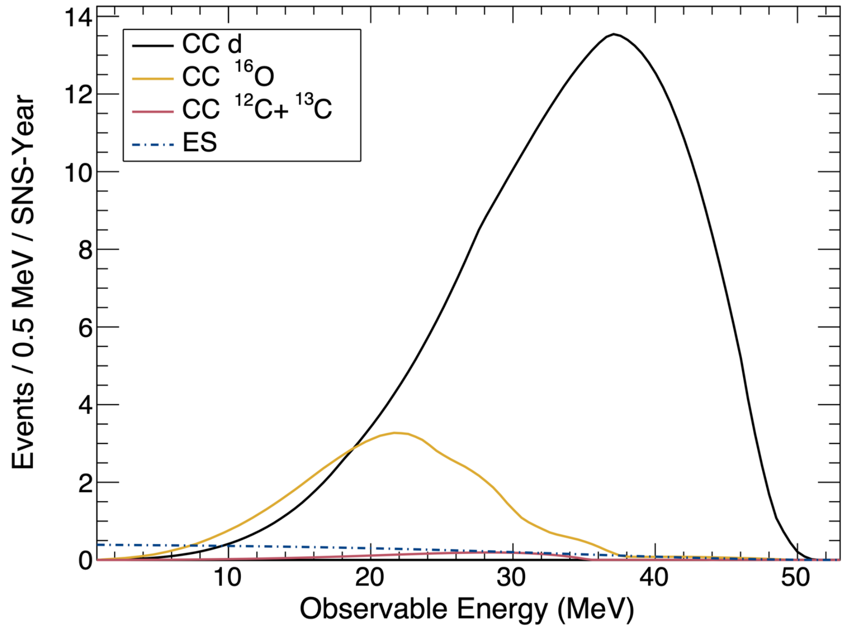




Future Inelastic Neutrino-Nucleus Measurements

D_2O for Flux Normalization

- Neutrino flux one of largest uncertainties for neutrino measurements at SNS, ~10%
  - ν_e CC cross section on ^2H calculated to within 2-3%
- Deploying 600-kg D_2O detector measure flux, reduce uncertainties
  - Signal comes from Cherenkov light from electron interacting in water
- May also be able to measure ^{16}O charged-current events
  - Potentially useful for understanding supernova neutrinos interacting via this channel in large water detectors



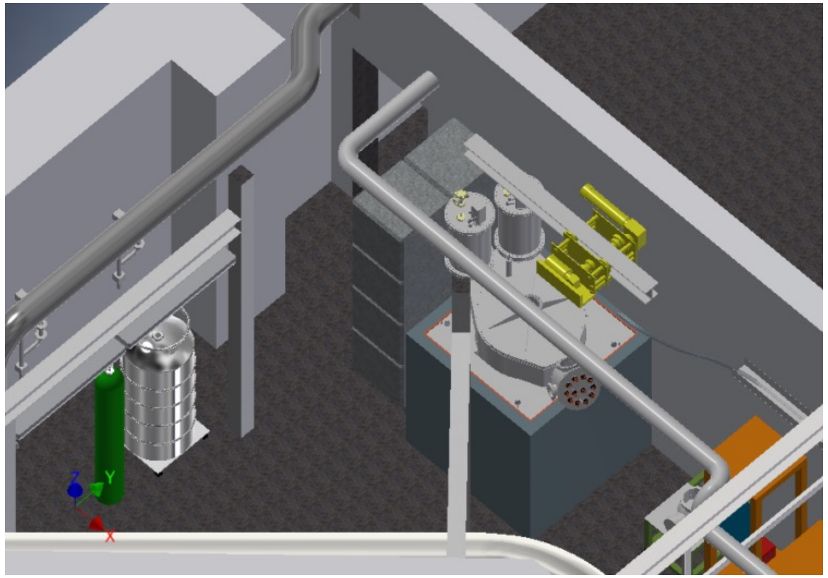
[arxiv:1910.00630.pdf]

CENNS-10/CENNS-750

- CENNS-10 single-phase liquid argon detector with 24-kg fiducial volume, deployed in 2016
  - Primary goal to measure CEνNS, data being studied to see what can be said about inelastic events on ^{40}Ar
- CENNS-750 upgrade in development, increase statistics and go after charged-current interactions on ^{40}Ar
  - Recent funding from Korea National Research Foundation (Jun 1, 2022)
  - Will study CEνNS, charged-current, and dark matter

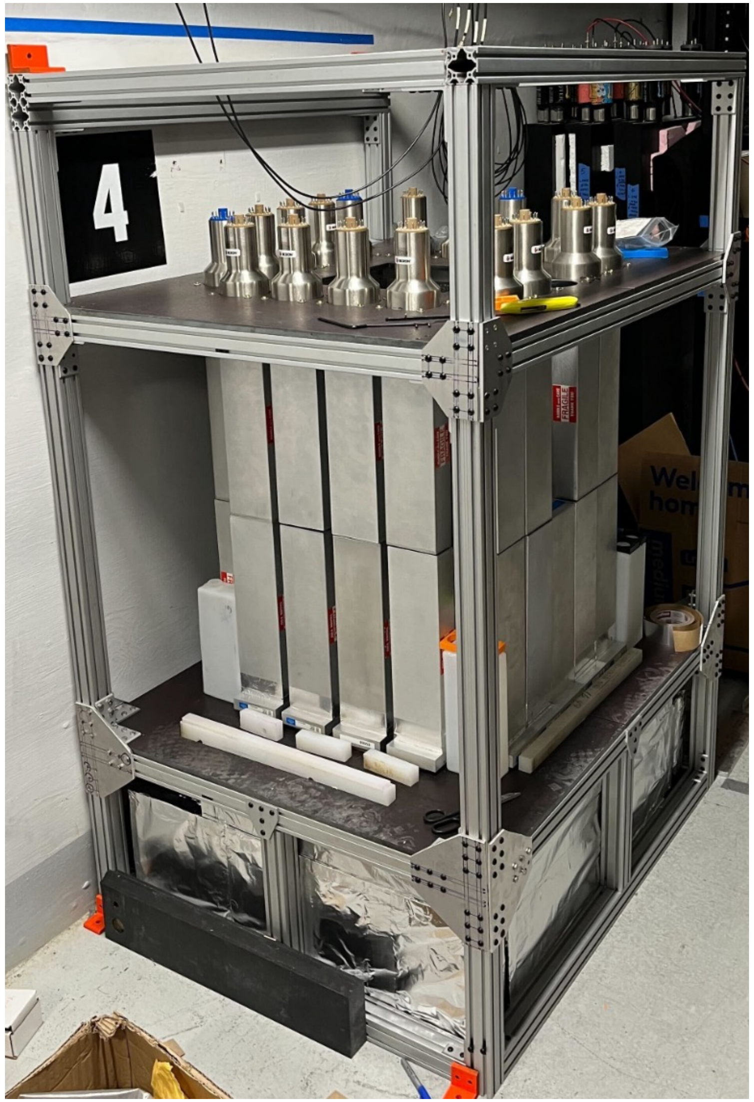
CENNS-10:

CENNS-750:



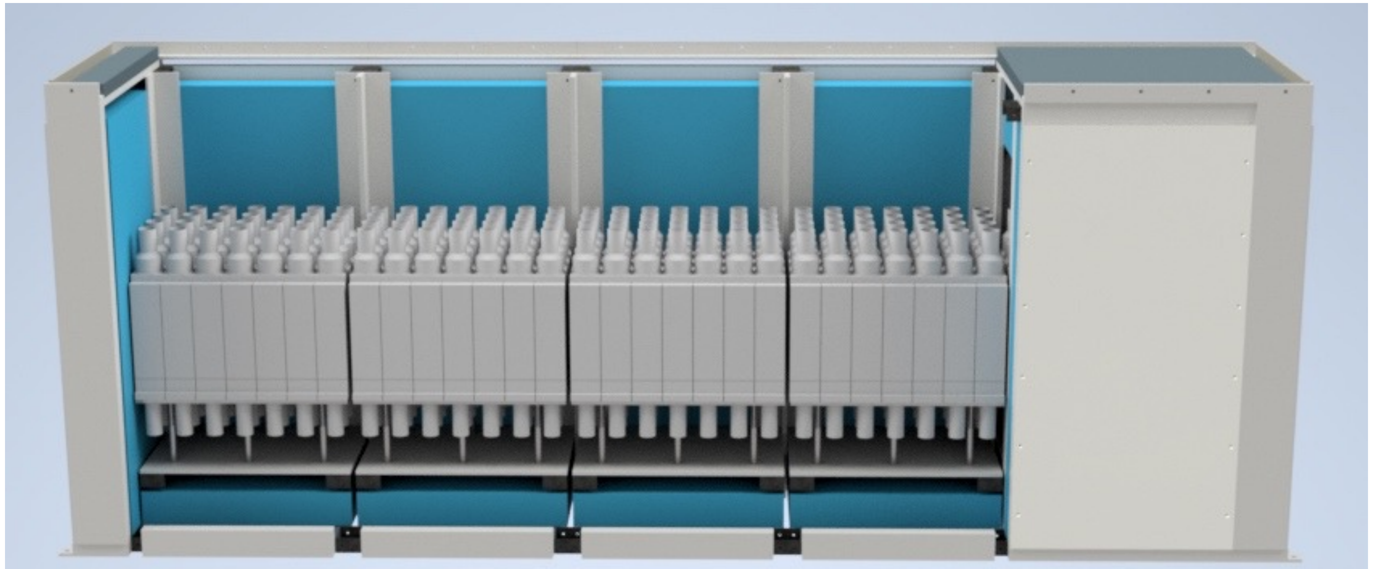
NuThor: Neutrino-Induced Fission

- Detector designed to study neutrino-induced fission, a long-theorized but never observed process
- Studies neutrino interactions on approx. 50kg ^{232}Th
- Looks for neutrons from neutrino-induced fission through capture of gadolinium-doped water
  - Gd-doped water bricks surrounded by NaI[Tl] scintillators
- Initial data collection has started!



NaIvETe

- NaI neutrino Experiment TonnE-scale (**NaIvETe**)
- Ton-scale version of NaIvE-185, consisting of 315 NaI detectors (2,425 kg)
- Main goal is to measure CEvNS on ^{23}Na
- Space left in design to implement muon veto panel to enable charged-current measurement
- Better gamma shielding, water shielding, and improved statistics from larger mass, may be able to go after CC on ^{23}Na/^{27}Al as well



Summary

- COHERENT has measured CEνNS on two targets
  - See good agreement with standard model, first measurements already producing physics results
  - More detectors coming online:
    - NaIvETe – Ton-scale NaI array (partially deployed)
    - Ge-mini – 16kg low-background germanium array (collecting first data)
    - CENNS-750 – larger version of CENNS-10 detector (in development)
- COHERENT has results from its first searches for inelastic neutrino-nucleus scattering
  - Both detectors see suppression in measured cross section compared to predicted results
  - Suite of new detectors coming online:
    - D_2O for reducing flux uncertainty, ^{16}O CC events (in development)
    - NuThor for neutrino-induced fission on ^{232}Th (collecting first data)
    - NaIvETe increase stats on ^{127}I CC, potentially $^{23}Na/^{27}Al$ CC as well (partially deployed)
    - CENNS-750 for ^{40}Ar (in development)

Acknowledgements

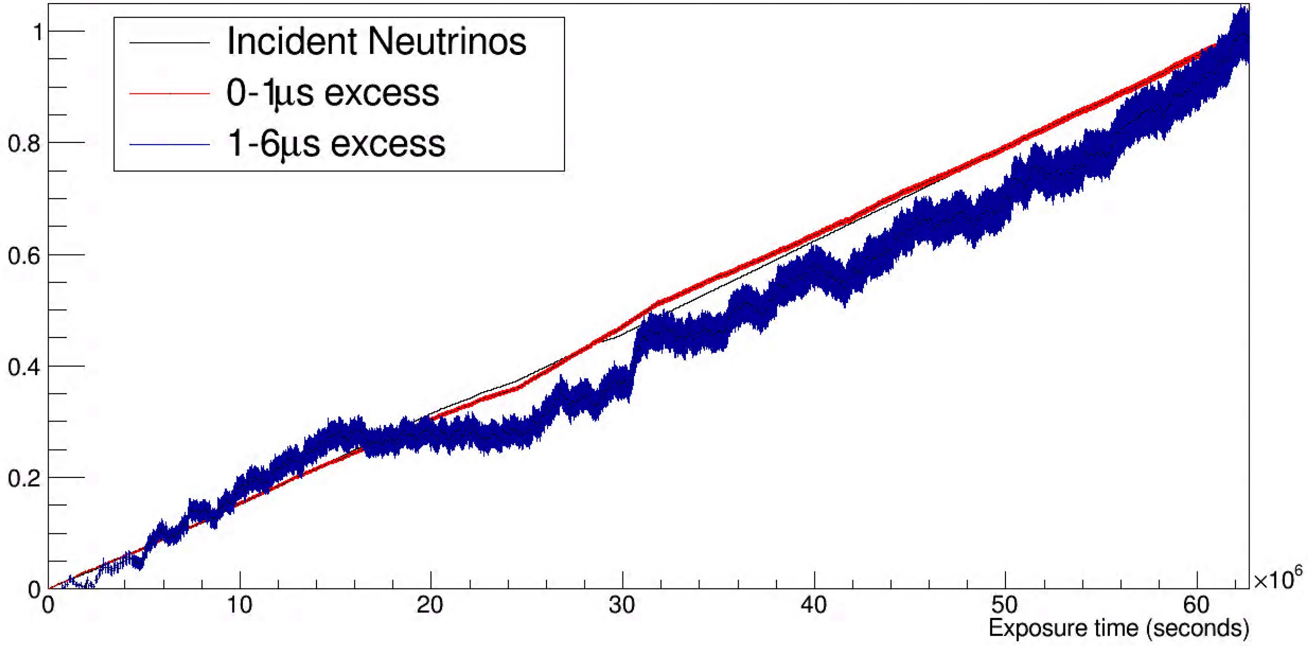
- This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Thank you for your attention!

Back-up

NaIvE: Post-Unblinding Checks

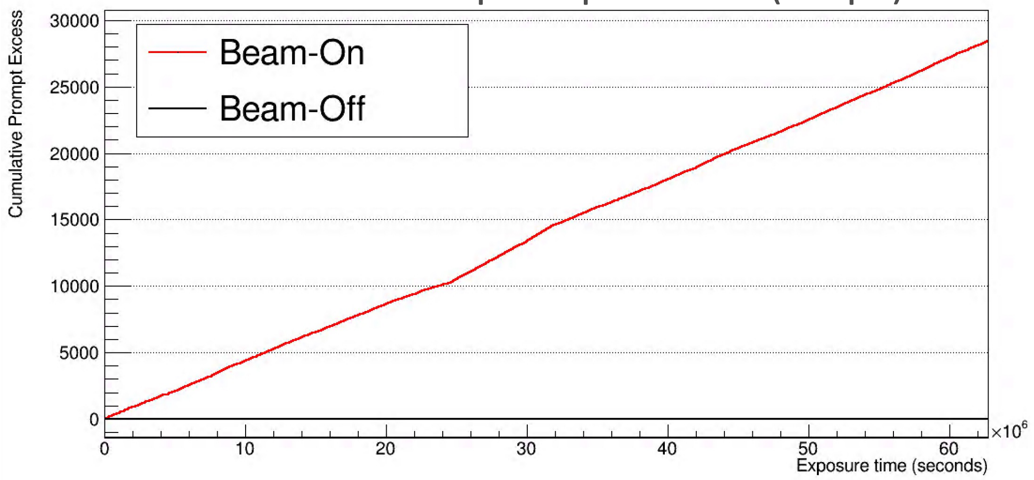
- K-S test shows good agreement between prompt and delayed excesses and delivered beam
  - With 1000 pseudo-experiments, K-S probabilities are 1.000 and 0.987 from prompt and delayed excesses



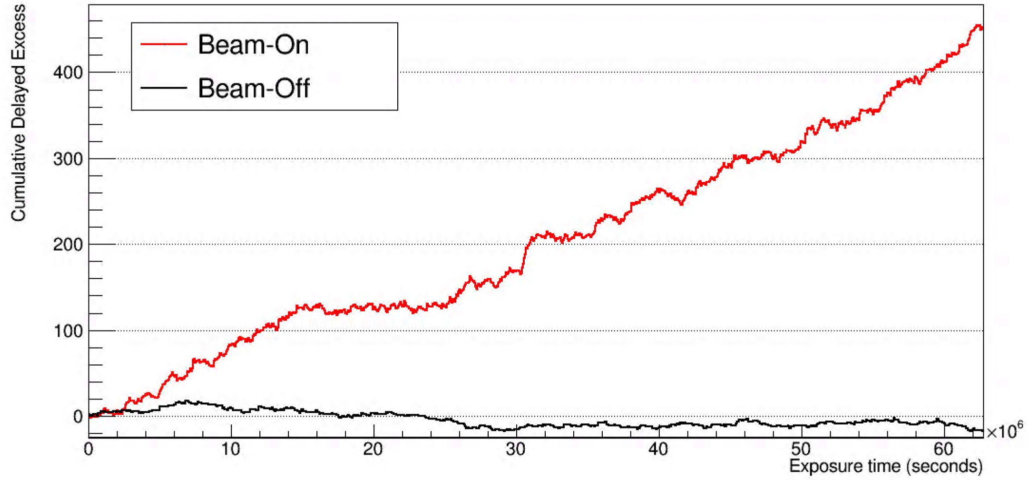
NaIvE: Post-Unblinding Checks

- K-S test shows good agreement between prompt and delayed excesses and delivered beam
  - With 1000 pseudo-experiments, K-S probabilities are 1.000 and 0.987 from prompt and delayed excesses
- No excess observed in prompt/delayed windows when beam not on target

Accumulated prompt excess (0-1μs)



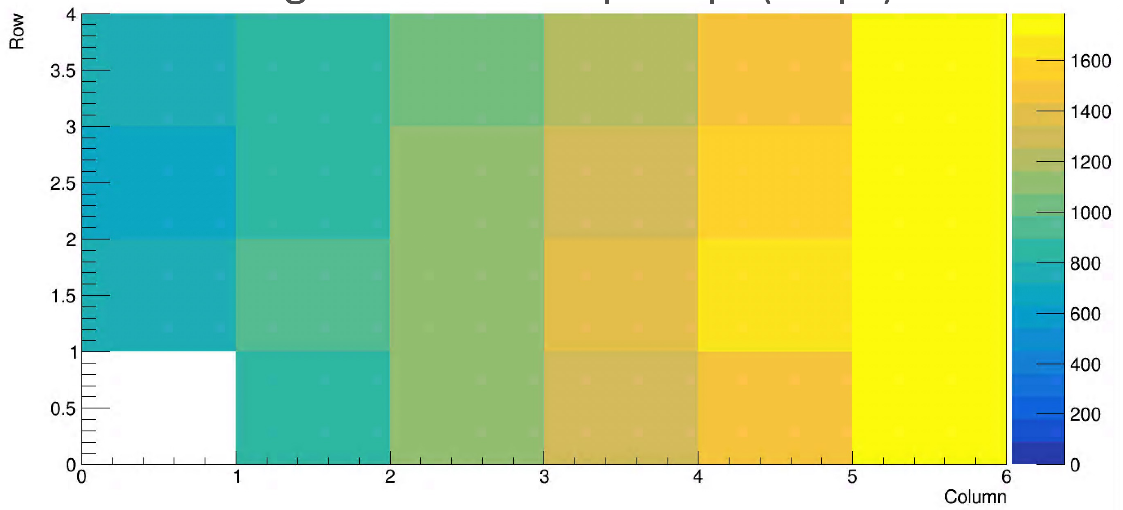
Accumulated delayed excess (1-6μs)



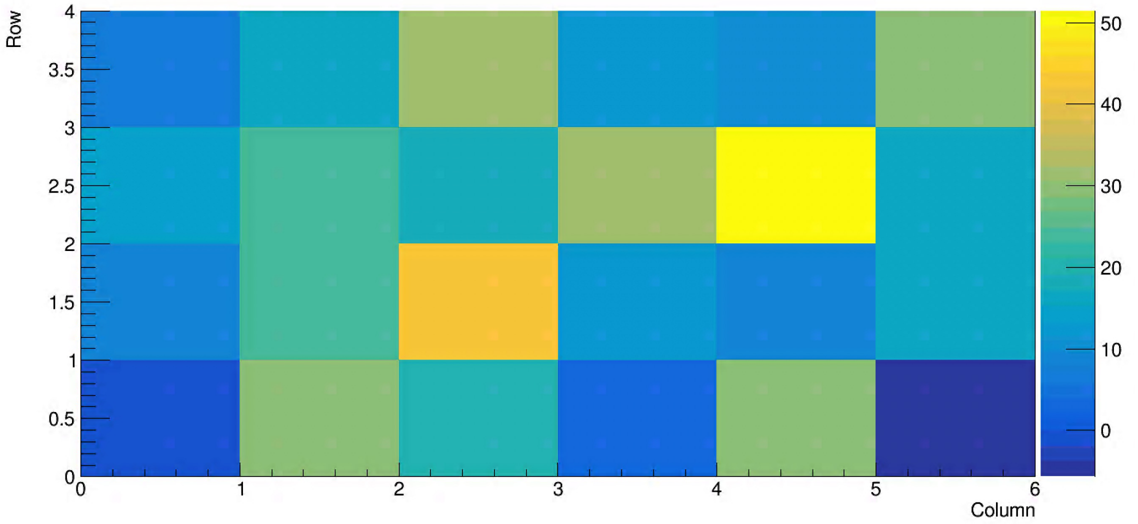
NaIvE: Post-Unblinding Checks

- K-S test shows good agreement between prompt and delayed excesses and delivered beam
  - With 1000 pseudo-experiments, K-S probabilities are 1.000 and 0.987 from prompt and delayed excesses
- No excess observed in prompt/delayed windows when beam not on target
- Some initial topology studies show neutrons incident on detector from side, do not see same pattern for delayed events
  - Helps understand BRN background for COHERENT's other detectors

Most energetic channel in prompt (1-6μs) window

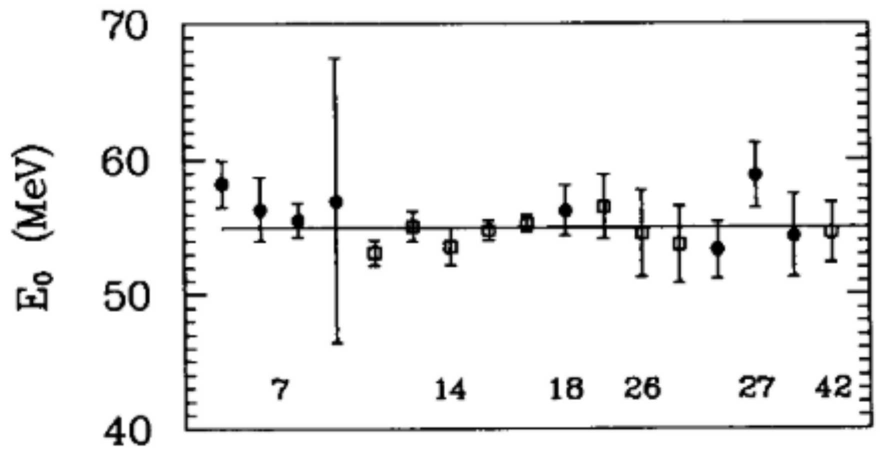


Most energetic channel in delayed (1-6μs) window



NaIvE: g_A quenching

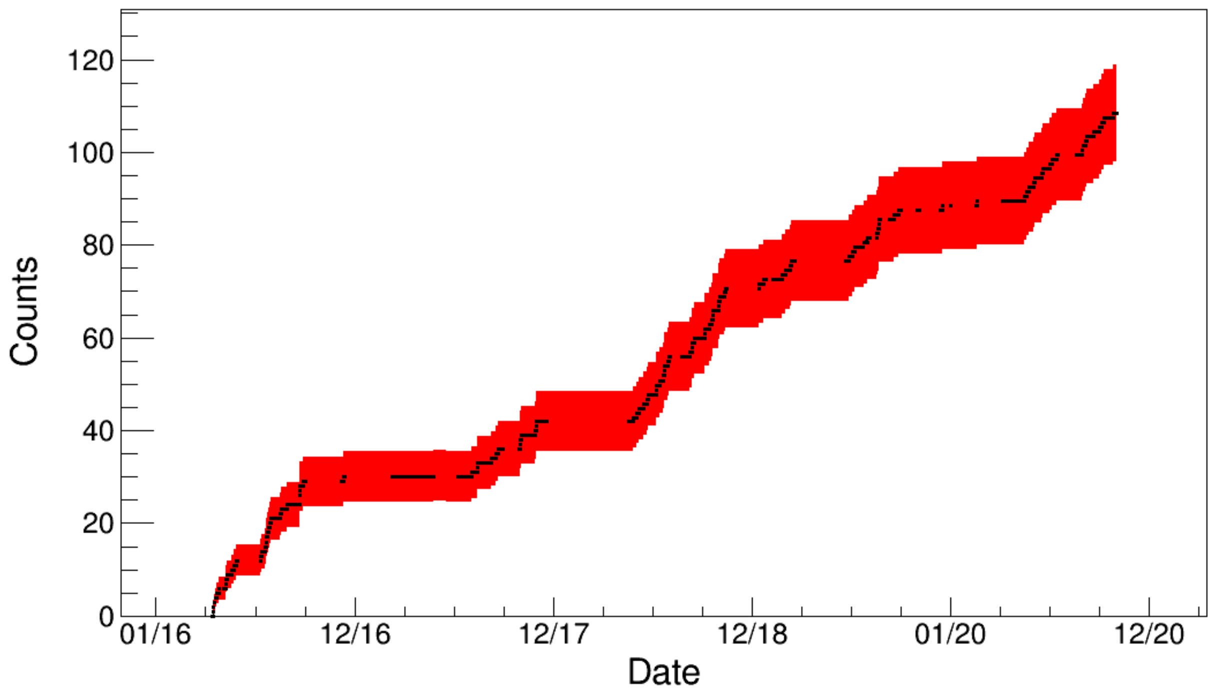
- Definition of matrix elements in (p,n) and weak interactions differs by g_A^2
- Cannot determine the value of g_A from cross section
  - Forbidden transitions not included in MARLEY
- Can set limit on maximum value of g_A, with large caveat:
  - Normalization for B(GT) in (p,n) charge-exchange measurements assumes a value for g_A=1.26, compares 0^o scattering cross sections with beta-decay half-lives
  - Heaviest element used in normalization has A=42
  - Incorrect normalization for strengths in (p,n) experiments would lead to incorrect value of g_A



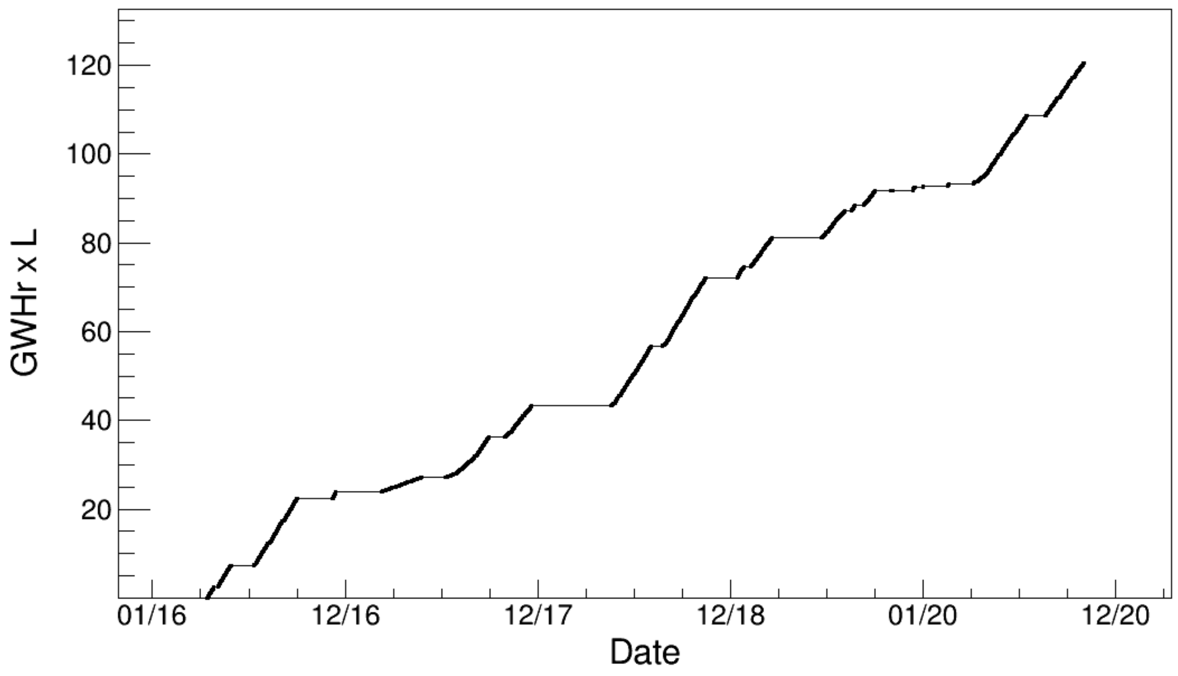
[T. Taddeucci, et al., Nuc. Phys. A 469 (1987)]

Lead Neutrino Cube: Prompt Signal vs. Beam Power

Prompt signal excess (BRNs)



Delivered beam power



Lead Neutrino Cube: Trigger Thresholds