Latest Results from COHERENT

Samuel Hedges

Lawrence Livermore National Laboratory

The COHERENT Collaboration

- COHERENT formed to measure coherent elastic neutrino-nucleus scattering (CEνNS)

- Approx. 80 members from 20 institutions

- Detectors located at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL)
  - Stopped-pion neutrino source, produces intense pulsed low energy neutrinos
  - SNS useful for studying CEνNS and other neutrino interactions, searches for accelerator-produced dark matter

Neutrino Alley

- COHERENT's detectors in "Neutrino Alley"
  - 20-30m from target, 25m long
  - Not designed for neutrino detectors
  - Concrete and gravel reduce beam neutrons
- Dedicated detectors for measuring neutron backgrounds
- For studying neutrino interactions, benefit from timing structure of neutrinos produced at the SNS
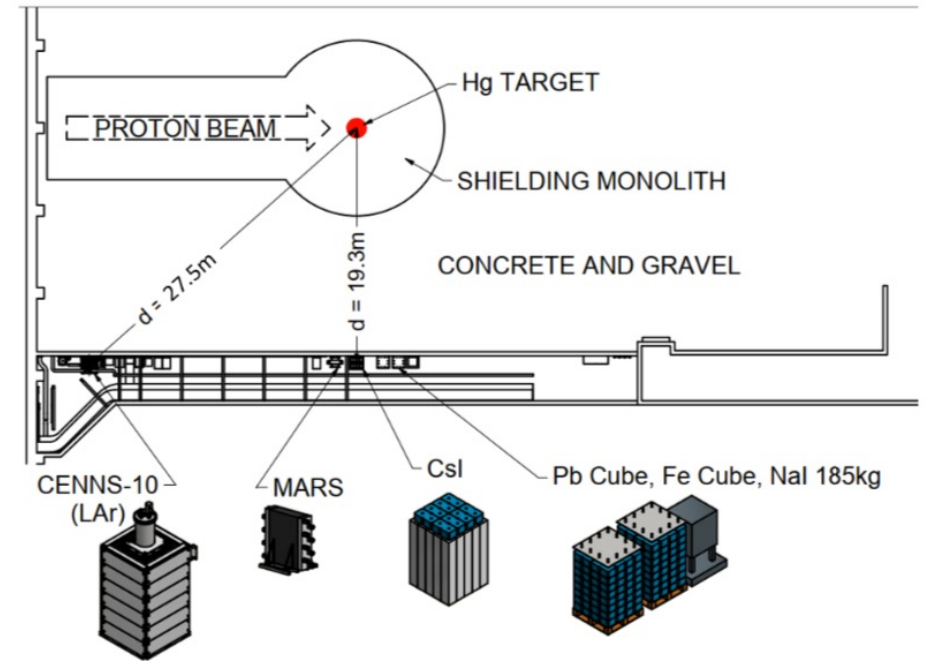
Neutrino Production at the SNS

- 1 GeV protons strike Hg target at the SNS at 60Hz, 350ns FWHM of proton pulse
- Produces π^- and π^+ (and neutrons)
  - π^+ decays at rest w/half-life of 26ns, producing ν_μ (prompt, 29.9 MeV)
  - μ^+ decays at rest w/half-life of 2.2µs, producing ν_e, and $\bar{\nu}_\mu$ (delayed, energy up to ~53 MeV)
- Currently operating at 1.4MW, future upgrade planned to 2.8MW
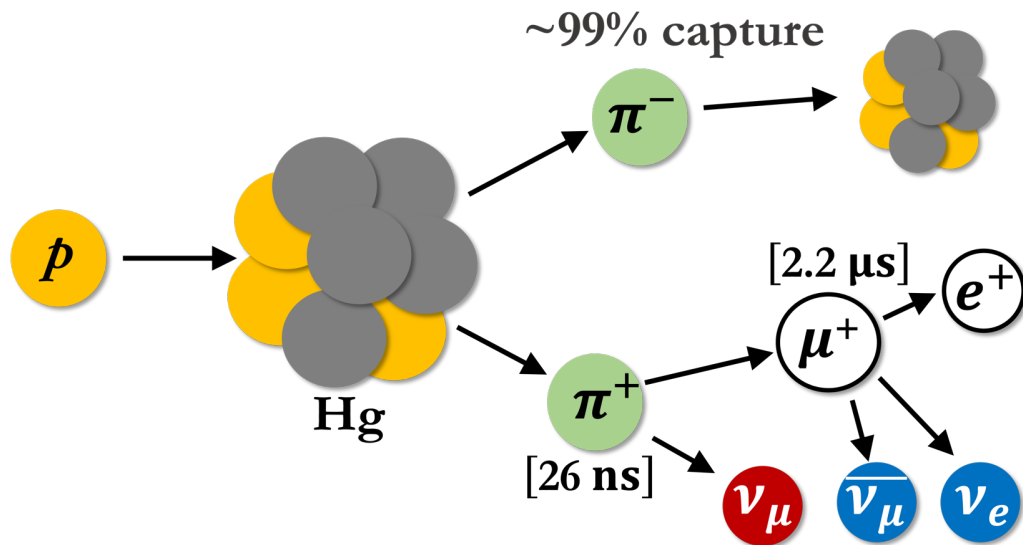
Simulated timing/energy of neutrinos at the SNS
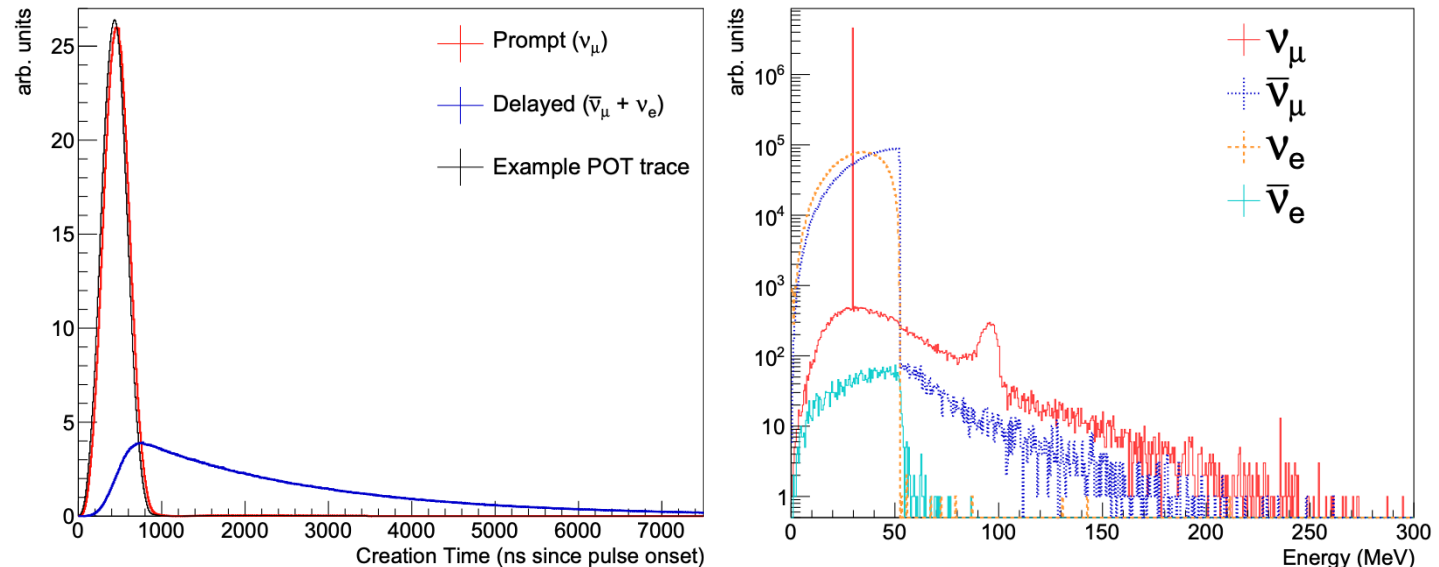
[D. Akimov, et al., arXiV:2109.11049 (2021)]

Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)

- Standard Model, neutral-current process

- Independently formulated by Freedman, Kopeliovich and Frankfurt in 1974

- Neutrino interacts with nucleus as a whole, nucleons recoil in phase
  - Requires same initial and final state—only signature is a low energy nuclear recoil
  - Requires momentum transfer comparable to size of nucleus

$$qR \leq 1$$

- Coherence leads to large enhancement in scattering cross section, $\propto N^2$

$$\frac{d\sigma}{d(\cos\theta)} = \frac{G^2}{8\pi}[Z(4\sin^2\theta_W - 1) + N]^2 E^2(1 + \cos\theta)$$

  - Potentially orders of magnitude greater than other low energy neutrino-nucleus cross sections!

scattered neutrino
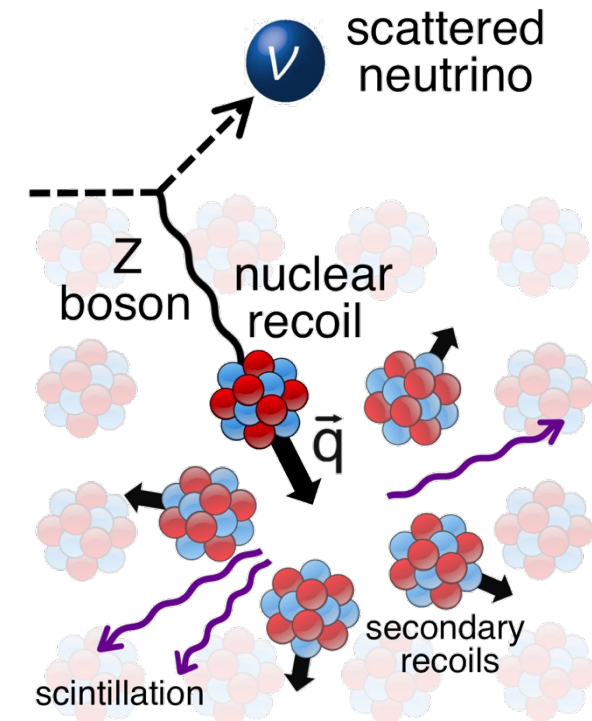
ν

Z boson

nuclear recoil

$\vec{q}$

secondary recoils

scintillation

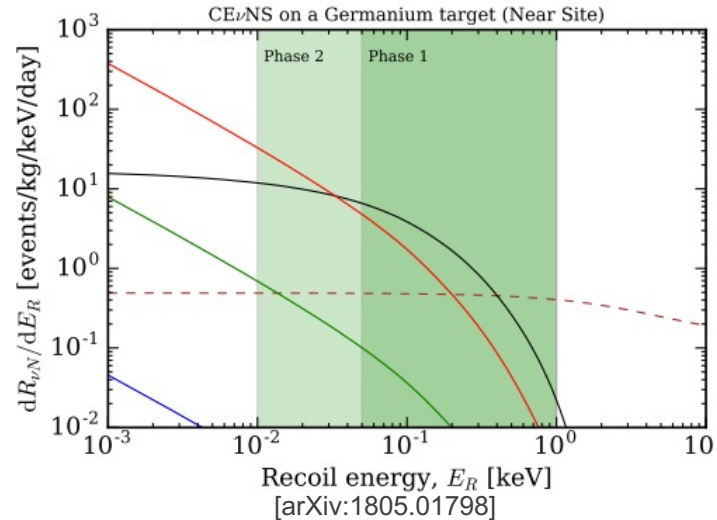[D. Akimov, et al., Science **357** (2017)]
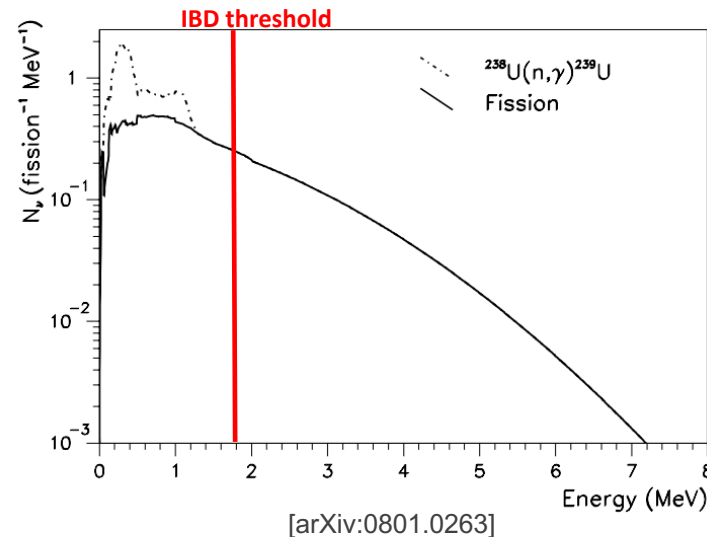
Some Applications of CEνNS

Process predicted in standard model, can search for new physics

- Anomalously large neutrino magnetic moments
- Non-standard neutrino-quark interactions
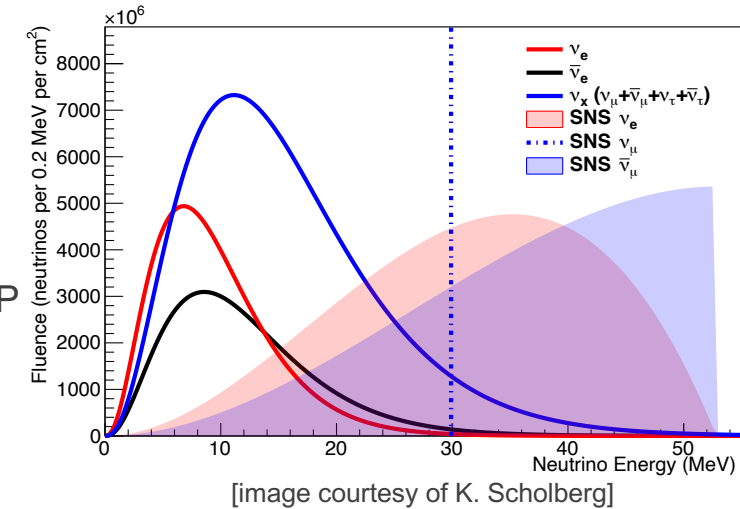- Sterile neutrinos

[arXiv:1805.01798]

Supernova neutrino detection

- Large cross section, sensitive to all ν
- Can observe in large low-threshold detectors (WIMP detectors)

[image courtesy of K. Scholberg]

Detecting reactor neutrinos

- Reactor monitoring
- Access to neutrinos below the IBD threshold (^{238}U neutrinos)

[arXiv:0801.0263]

Dark matter

- CEνNS from solar and DSNB neutrinos a background for WIMP searches

[arXiv:1802.06039]
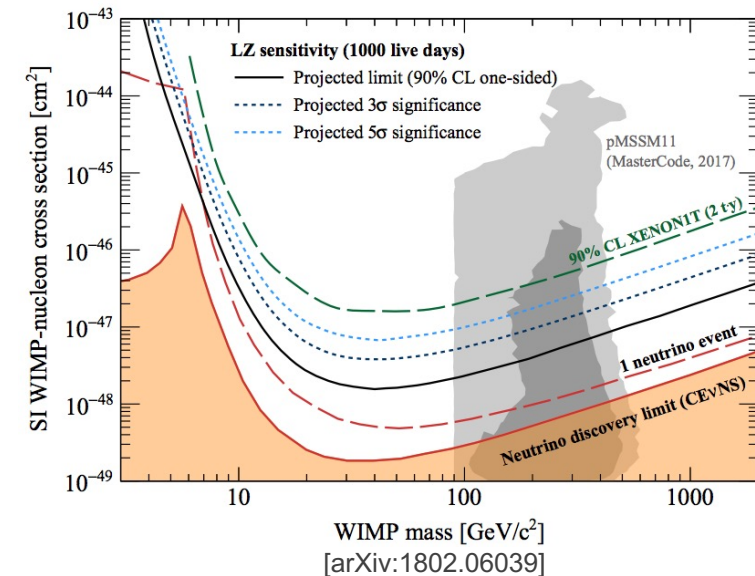
Difficulty in Observing CEνNS

- Predicted in 1974, eluded detection for more than 40 years

- Main experimental difficulties:
  - Only signature is a low energy (~keV) nuclear recoil, quenched
  - Low energy backgrounds can be formidable—benefit from work developing low-background detectors
  - Need an intense source—reactors, stopped-pion sources

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.

[D. Freedman, Phys. Rev. D **9** (1974)]

COHERENT's CEνNS Detectors
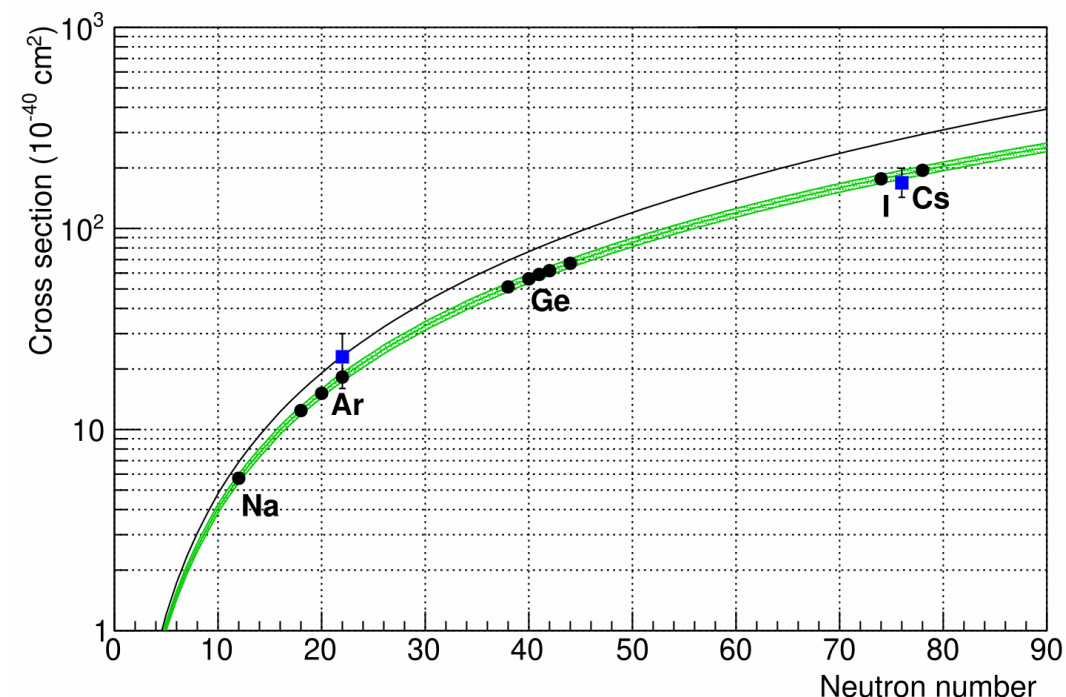
Target	Technology	Mass (kg)	Threshold (keV$_{nr}$)	Date
CsI	CsI[Na] scintillator	14.6	6.5	6/2015
Ar	Single-phase liquid argon	24	20	12/2016
Na	NaI[Tl] scintillator array	185/2,425	13	2016/2022
Ge	p-type point contact Ge	16	3	2022

Non-Elastic Neutrino-Nucleus Scattering

- Mediated by a $W^{\pm}$ (charged-current) or Z^0 (neutral-current) boson
  - Unlike CEvNS, these interactions result in emission of one or more particles (leptons, gammas, neutrons, …)
- Cross sections, thresholds, emitted particles depend on properties of the interacting nucleus
  - Calculations can be complex
  - Can study nuclear physics with neutrinos!

Charged-current scattering   Neutral-current scattering
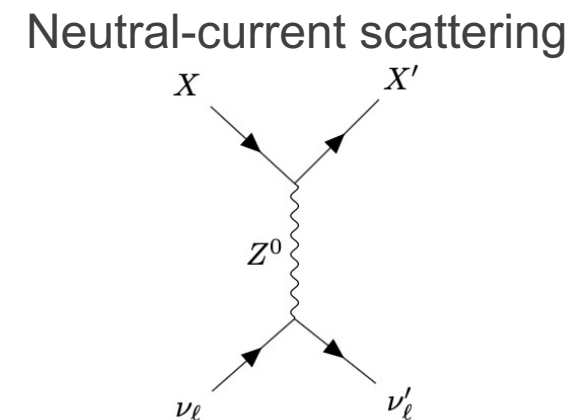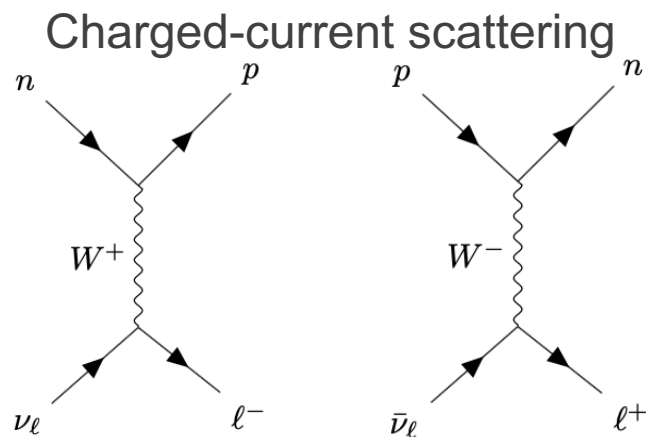
Only Measured for Five Nuclei*

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)]

*Table slightly out of date

COHERENT's Non-Elastic ν-A Detectors

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

On to the Results…

- Latest results:
  - Latest CEνNS results—CsI[Na] full data set
  - Neutrino-Induced Neutrons on Pb results
  - Accelerator-produced dark matter—not in this talk!
    - Sub-GeV dark matter: arXiv:2110.11453
    - Leptophobic dark matter: arXiv:2205.12414
- Upcoming:
  - Data collecting for NaIνE-185 charged-current analysis, updated CENNS-10 CEνNS analysis
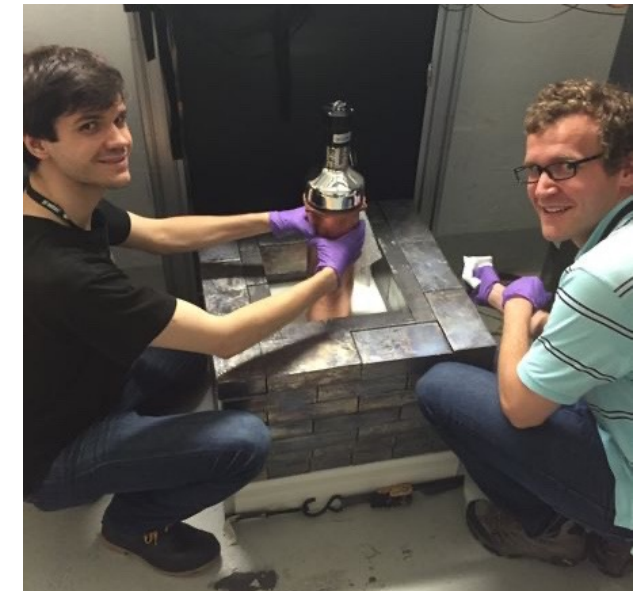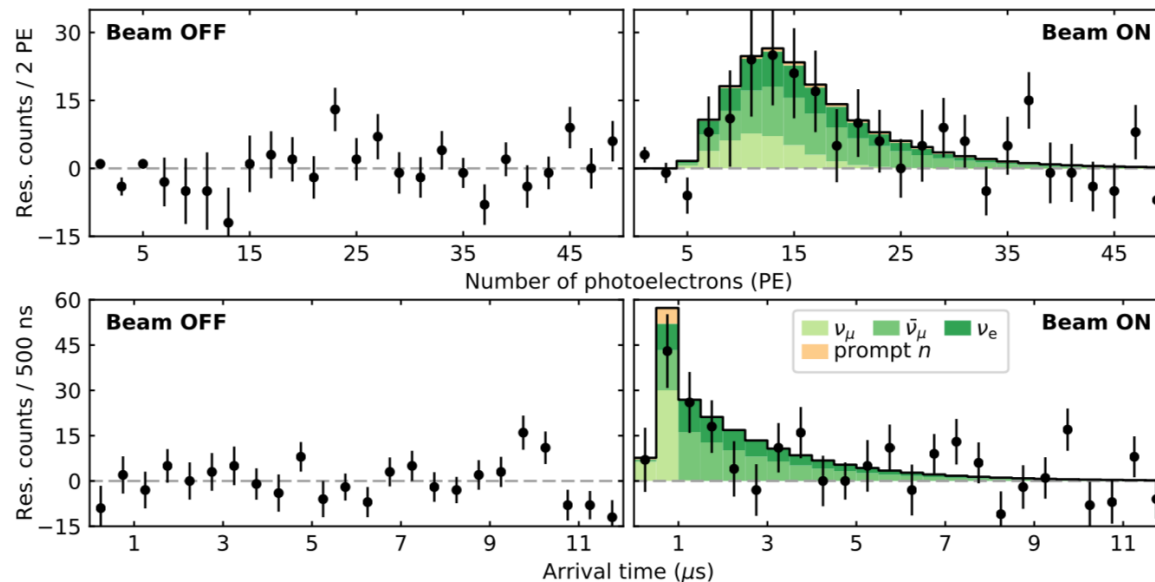 - Future deployments of GeMini, NaIνETe, NuThor, D_2O, CENNS-750

Updated CsI[Na] CEvNS Results

CsI[Na] Detector—Initial Result

- 14.6-kg CsI[Na] scintillator surrounded with lead, HDPE, water shielding

- Deployed in 2015, made first observation of CEνNS in 2017
  - Exposure of 1.76 x 10^{23} protons-on-target (~1/3 g)
  - Reject null-hypothesis (no-CEνNS) at 6.7σ

- Largest uncertainties nuclear recoil quenching factor, neutrino flux
- Detector continued collecting data for two more years…
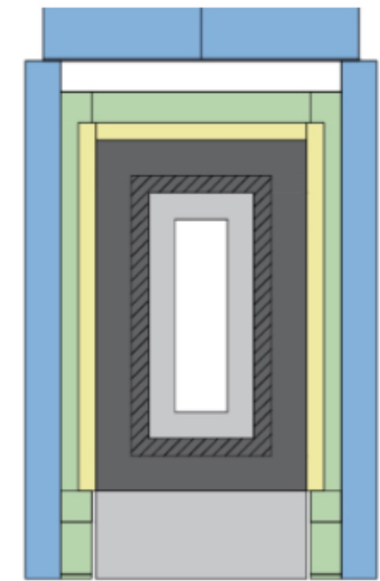
| Layer	HDPE*	Low backg. lead	Lead	Muon veto	Water
Thickness	3"	2"	4"	2"	4"
Colour					

Updated CsI[Na] Quenching Factor

- For initial analysis, adopted energy-independent quenching factor with large uncertainties due to discrepancies in existing measurements
- Followed up with additional measurements, independent analysis of existing COHERENT QF data sets, global fit to data
- Uncertainty reduced from 25%→4%, no longer dominant uncertainty

QF adopted for initial observation
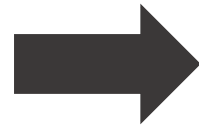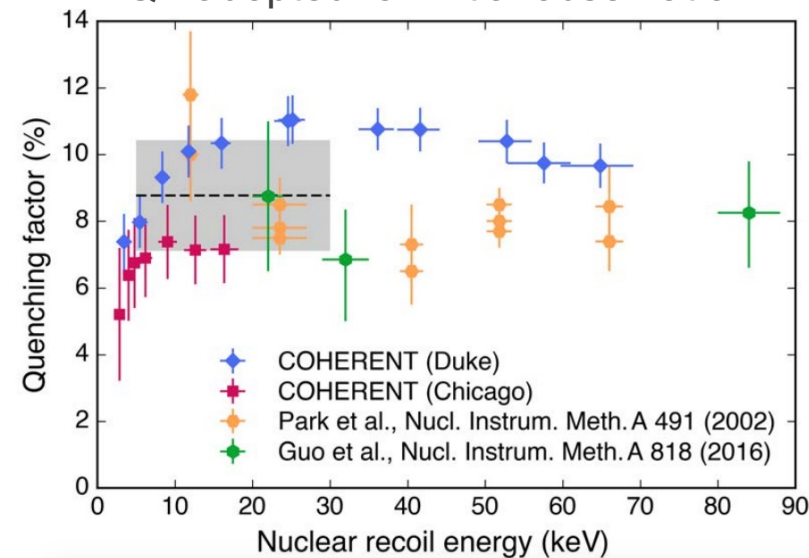
Updated CsI[Na] QF
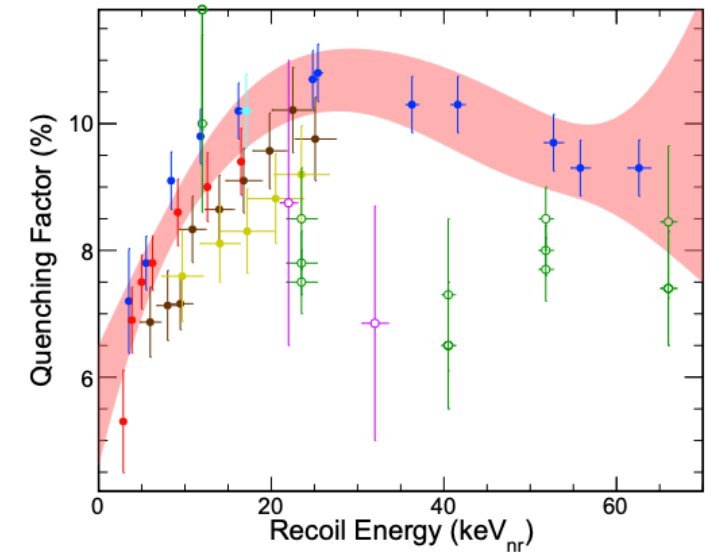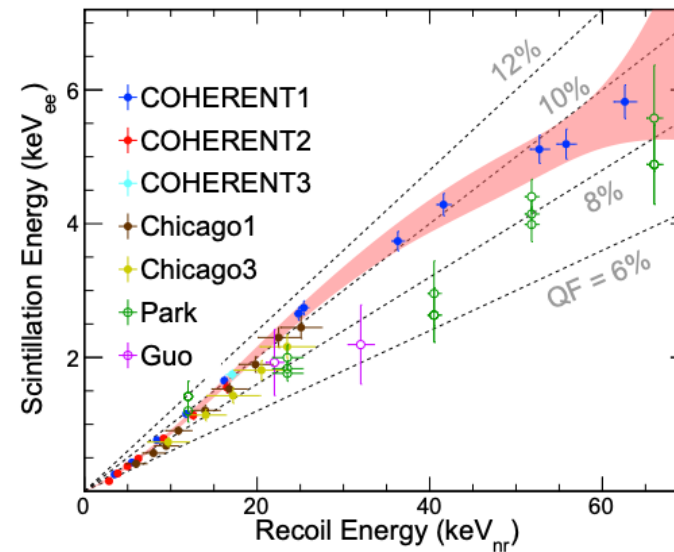
CsI[Na] Detector—Full Dataset

- Detector operation ceased in summer 2019
- Full exposure of 3.2×10^{23} POT (1.8x more, ~0.54g)
- With full data set:
  - Data disfavor null hypothesis at 11.6σ
  - See 1σ agreement with SM CEνNS prediction
  - Largest source of uncertainty is neutrino flux, ~10%
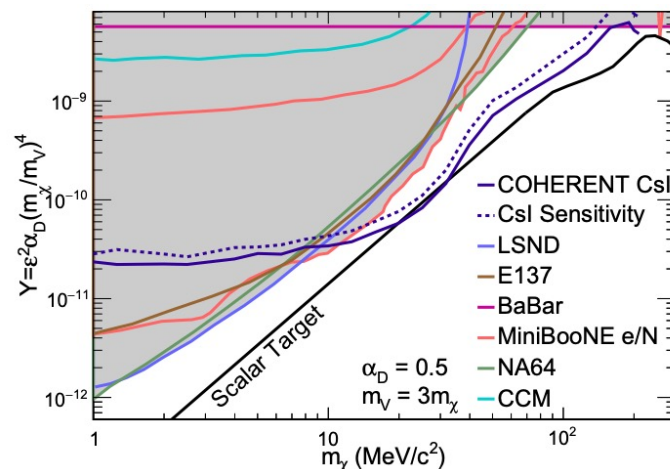- Enough statistics to separate out neutrino flavor in fit, measure cross sections for different neutrino flavors
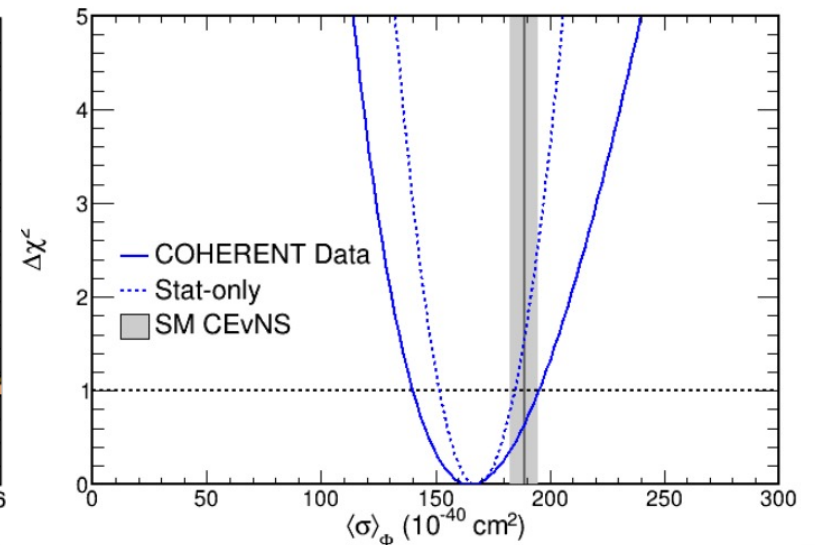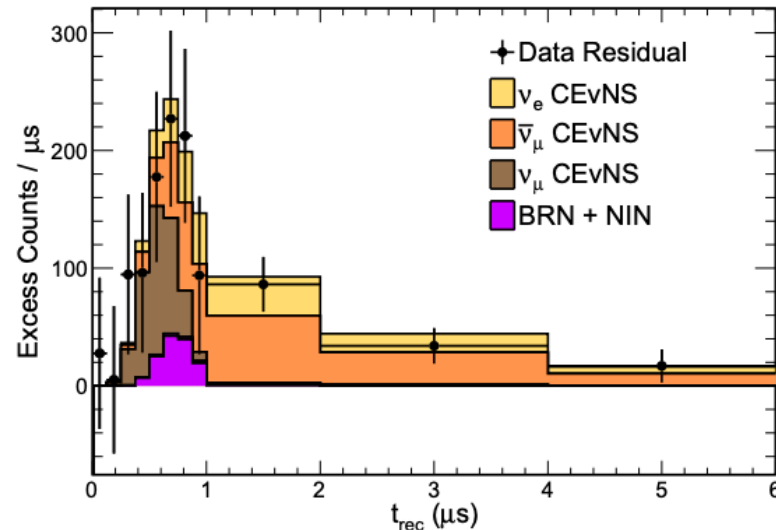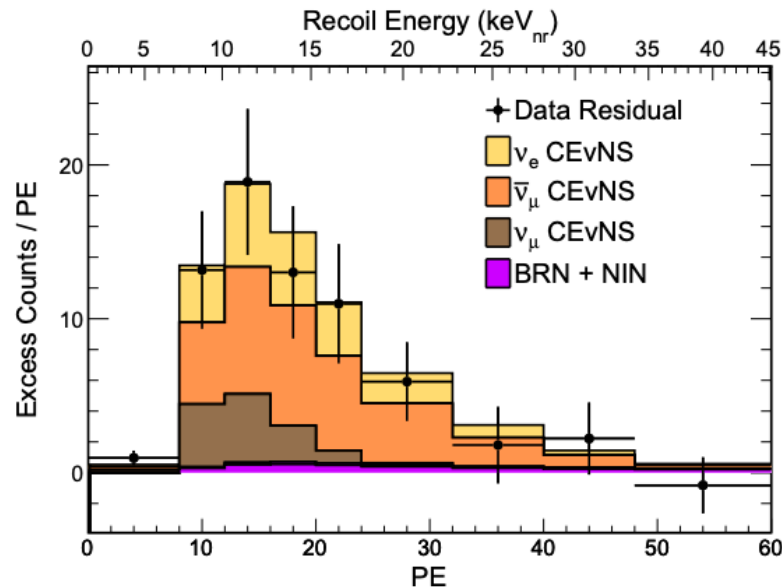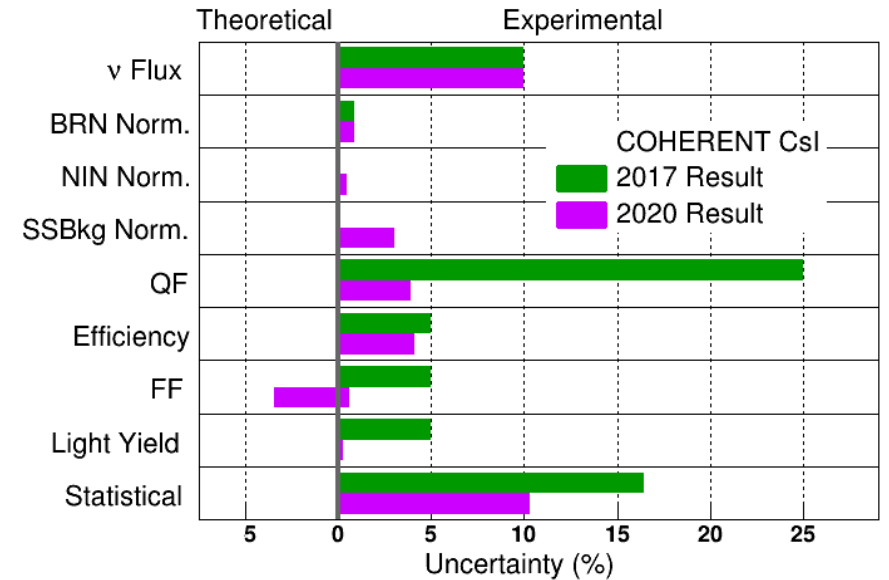
Applications of Physics Results!
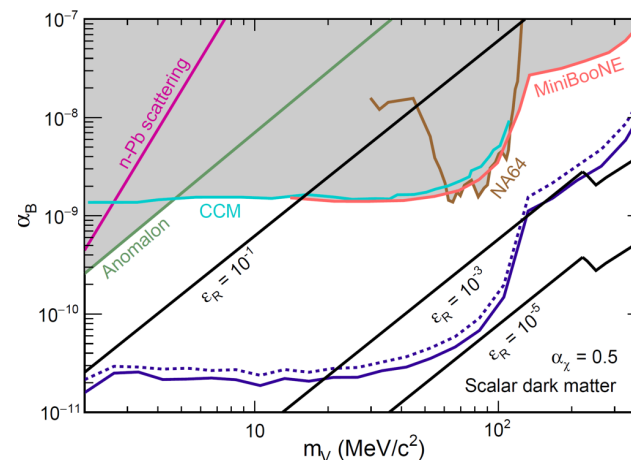
Neutrino magnetic moments
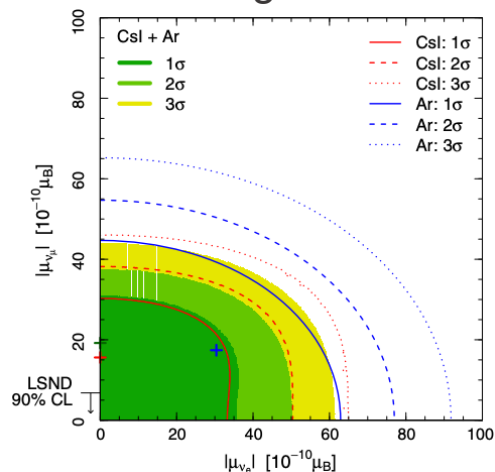
[arXiv:2005.01645]
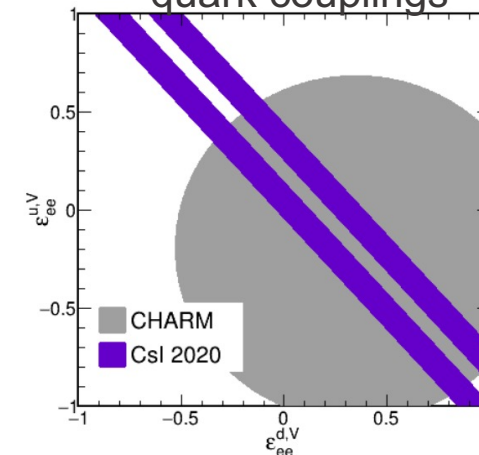
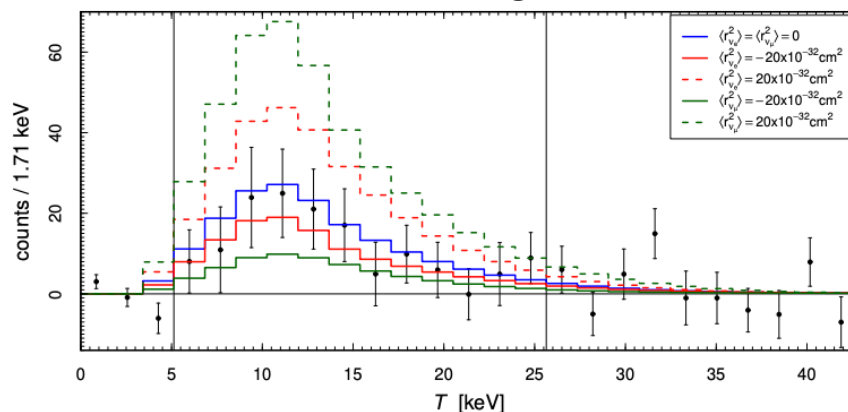## Accelerator-produced DM

[arXiv:2110.11453]

[arXiv 2205.12414]

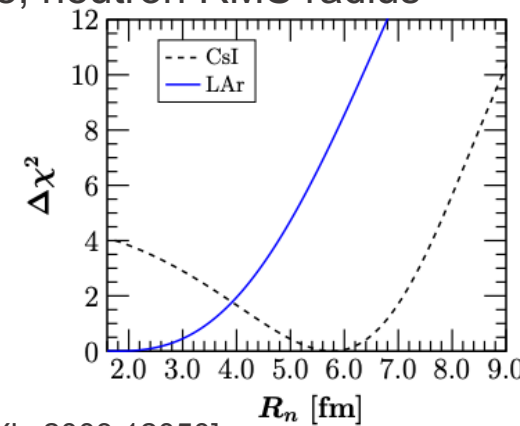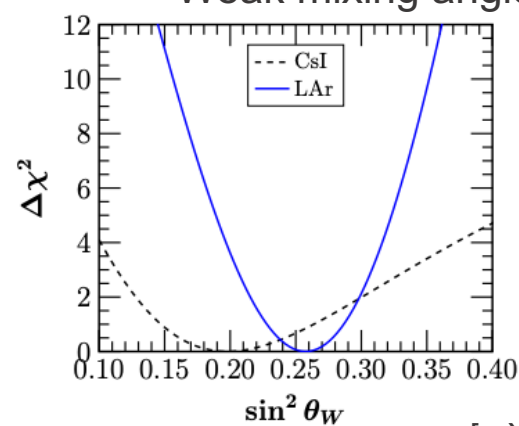## Non-standard neutrino-quark couplings

[arXiv:2110.07730]

Neutrino charge radius

[arXiv:1810.05606]

## Weak mixing angle, neutron RMS radius

[arXiv:2003.12050]

# Results from COHERENT's Lead Neutrino-Induced Neutron (NIN) Detector

Neutrino-Induced Neutrons (NINs) on Lead
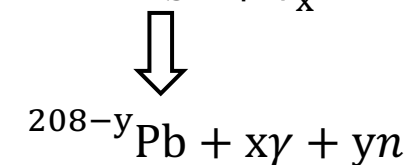
- Charged- and neutral-current neutrino interactions can form a CEνNS background
  - Excite lead nuclei above particle emission threshold, de-excite by emitting neutrons
  - NINs follow timing of neutrinos, can create low energy nuclear recoils
  - Cross sections expected to be low, but unmeasured, large amounts of shielding used
    - 2,200-kg lead shielding around 14.6-kg CsI detector
- Also useful for HALO experiment, detecting supernova ν_e through neutron capture of NINs
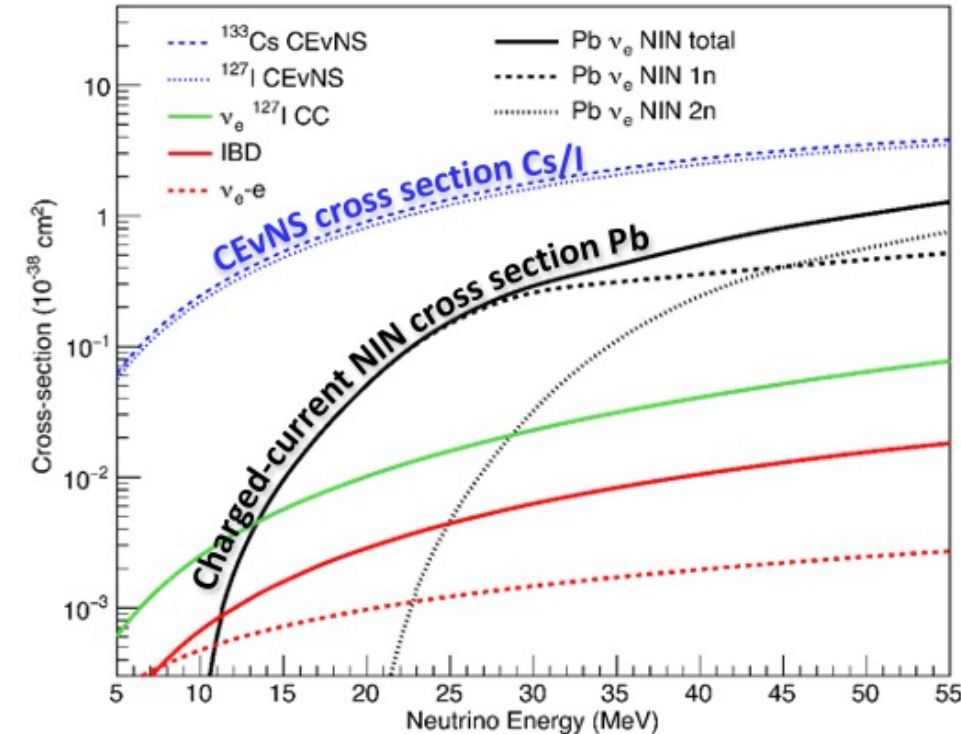
Charged-current interaction on lead

$$\nu_e + {}^{208}\text{Pb} \rightarrow {}^{208}\text{Bi}^* + e^-$$

$$\Downarrow$$

$${}^{208-y}\text{Bi} + x\gamma + yn$$
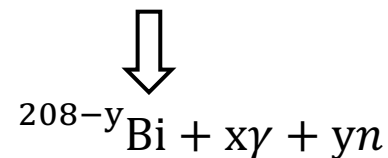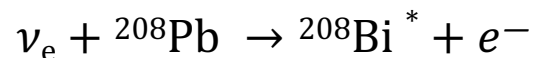
Neutral-current interaction on lead

$$\nu_x + {}^{208}\text{Pb} \rightarrow {}^{208}\text{Pb}^* + \nu_x'$$

$$\Downarrow$$

$${}^{208-y}\text{Pb} + x\gamma + yn$$
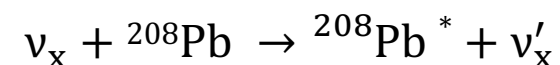
Initial Deployment—Eljen Cell Detector

- Prior to CsI[Na] operation, deployed two 1.5L LS cells inside CsI[Na] shielding
 - 2,200 kg of Pb shielding 20m from target
  - Exposure of 171.7 days (3.35 GWhr)—10.05 GWHr · liters
  - Threshold of 30 keVee
- Reported cross section 35% lower than expected, 2.9σ significance
- W/additional HDPE, NINs lower than CEνNS predictions by a factor of 47!
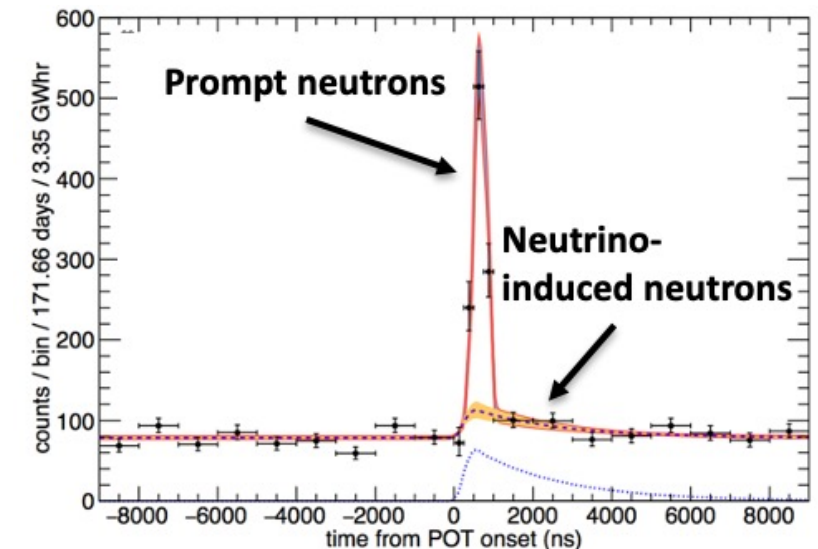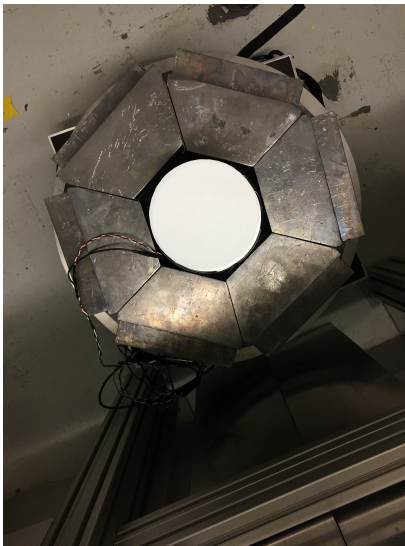
A Dedicated Detector—The Neutrino Cubes

- Lead Neutrino Cube deployed in 2015, collected data through 2021
- ~900kg lead target, with cavities for four large LS
- NINs produced by neutrino interactions in lead (primarily charged-current), have some small efficiency to make their way to our detectors
- Lead surrounded by muon vetoes to reject muon-induced neutrons, water bricks to reduce environmental and beam neutron backgrounds

Water bricks

Muon veto panels

Lead target
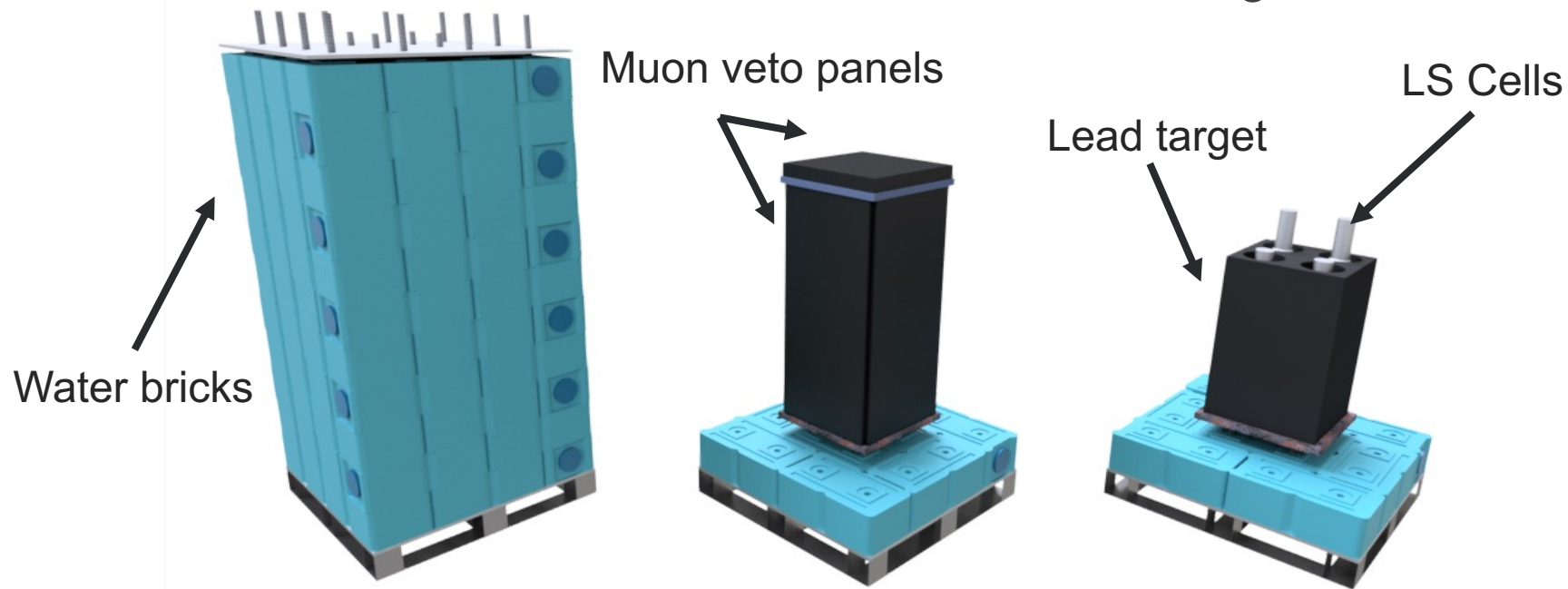
LS Cells

Neutrino Cube Analysis

- Trigger on coincidence between LS cells and SNS beam
  - Record timing, integral, PSD, veto status
- Collected nearly six years of data—127 GWHr · liters
- Dedicated gamma calibrations
- Use ^{40}K background from PMT to track gain changes
- Used time-tagged ^{252}Cf source to determine trigger efficiencies, optimize PSD cut

^{137}Cs — Source, Background, Sim — Counts vs Integral (ADC)

^{22}Na — Source, Background, Sim — Counts vs Integral (ADC)

PSD (tail/full) vs Time to time tag (ns)
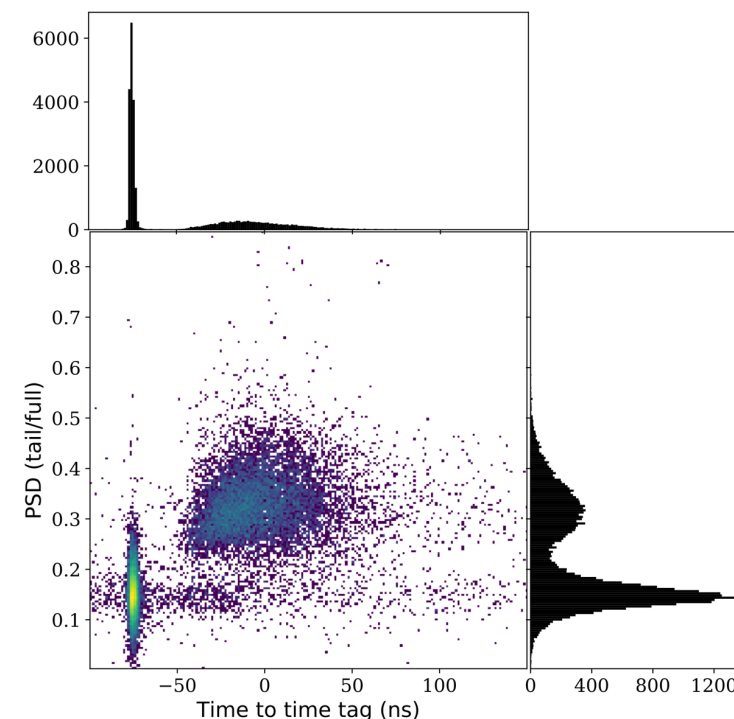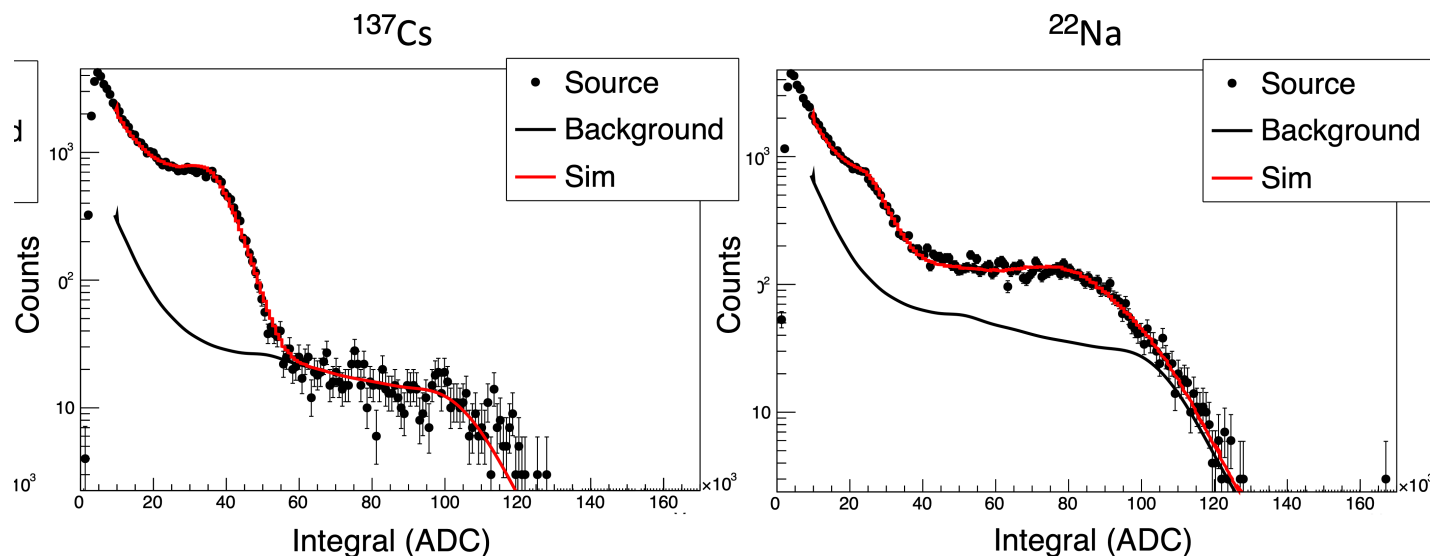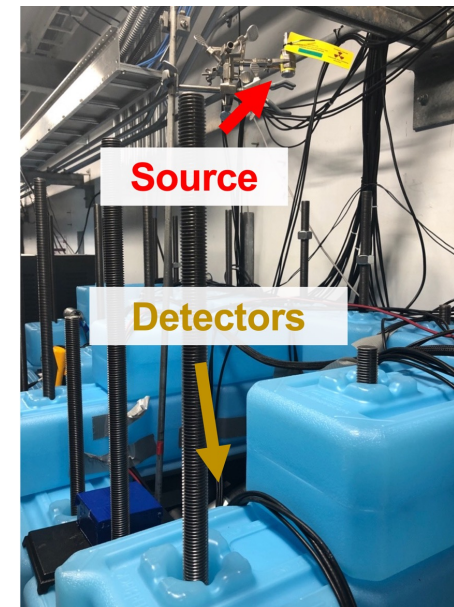
PSD Cut
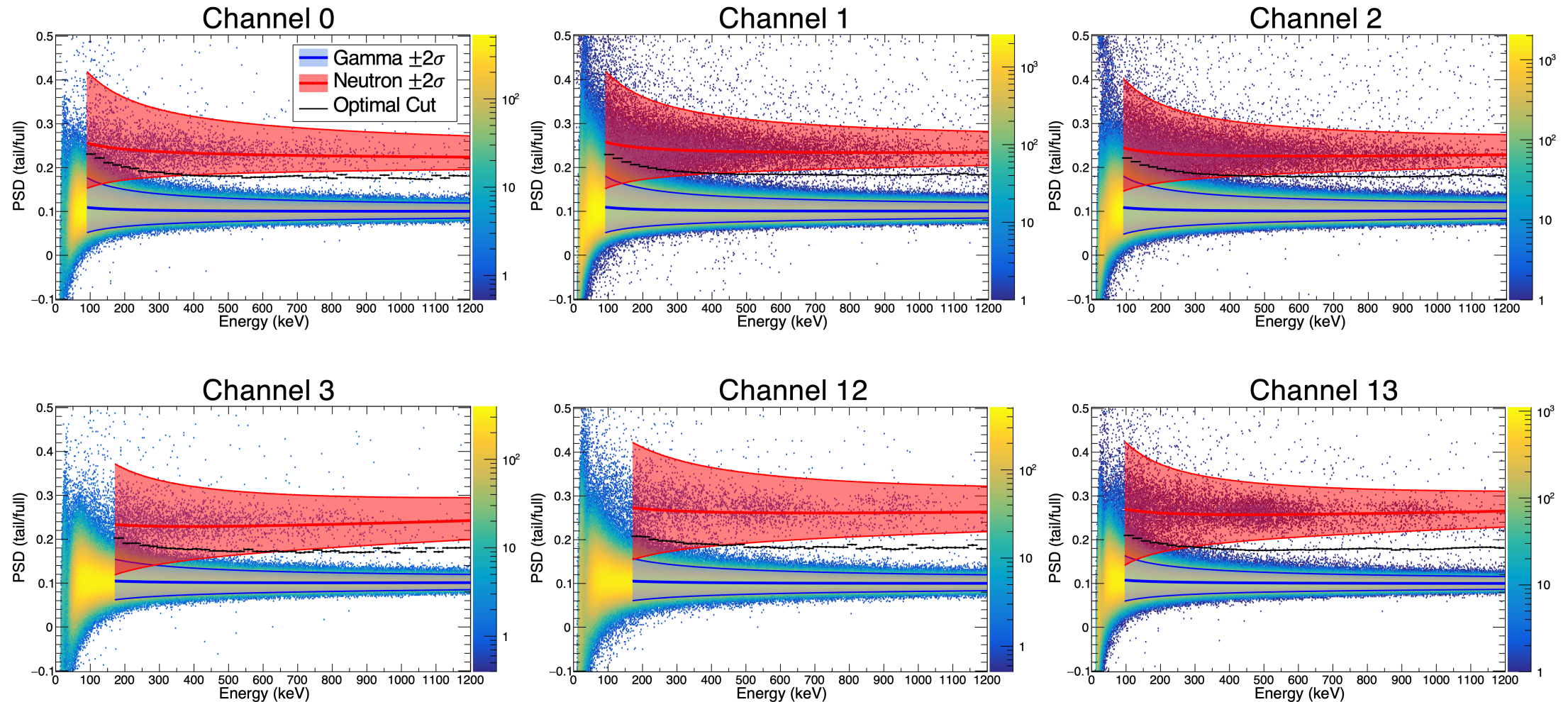
Signal Prediction

- Used MARLEY to generate signal predictions for non-elastic neutrino-nucleus interactions at the SNS

- **M**odel of **A**rgon **R**eaction **L**ow **E**nergy **Y**ields [arXiv:2101.11867]—originally designed for ^{40}Ar, but used with other nuclei

- Handles allowed components of neutrino-nucleus reactions at low energies

$$\frac{d\sigma}{d\cos\theta_\ell} = \frac{G_F^2 |U_{ud}|^2}{2\pi} F_C \left[\frac{E_i E_f}{s}\right] E_\ell |\vec{p}_\ell| \left[(1 + \beta_\ell \cos\theta_\ell) B(F_-) + \left(1 - \frac{1}{3}\beta_\ell \cos\theta_\ell\right) B(GT_-)\right]$$

  - Good approximation, but forbidden transitions play larger role at higher energies

- Inputs are Gamow-Teller strength distributions

MARLEY with Lead

- B(GT) distributions can be measured by high-energy small-angle (p,n) charge-exchange measurements
- MARLEY predicts cross sections & de-excitations, energies of emitted particles
- Can calculate predictions specific for decay-at-rest neutrinos
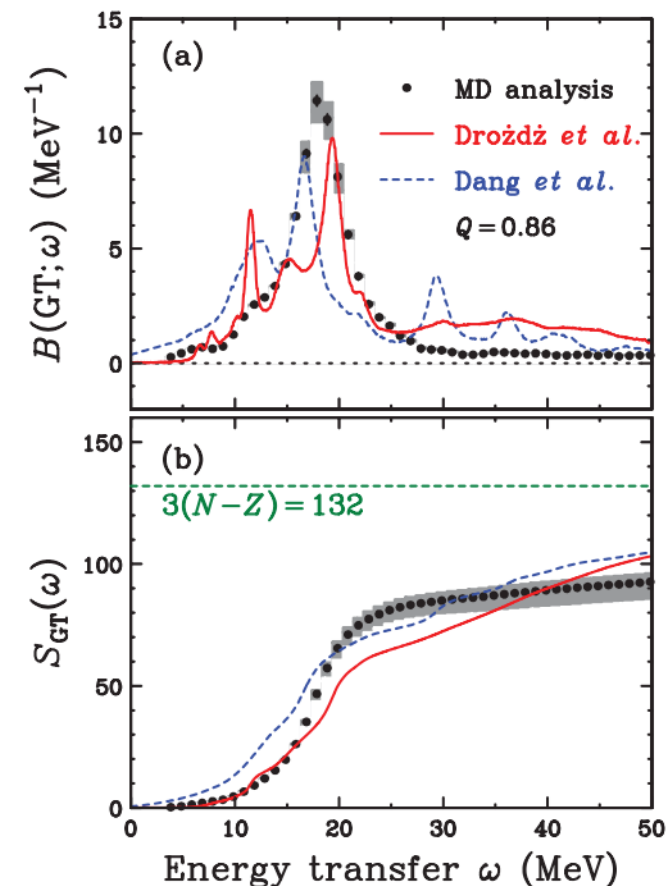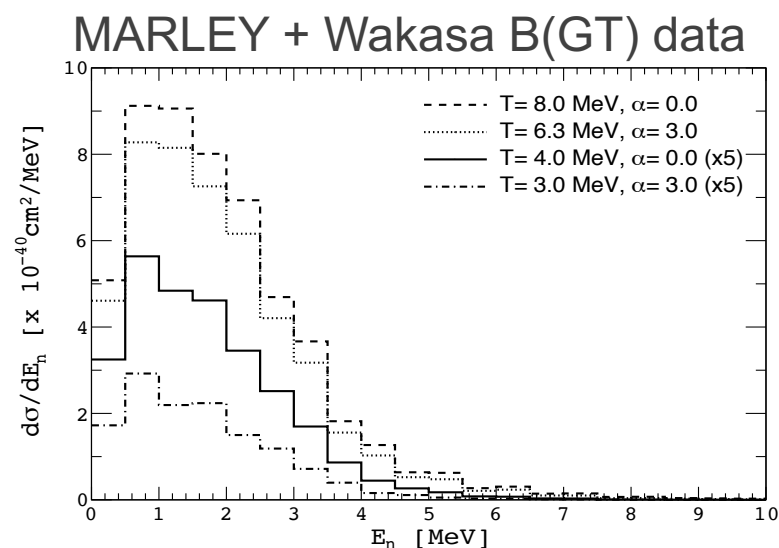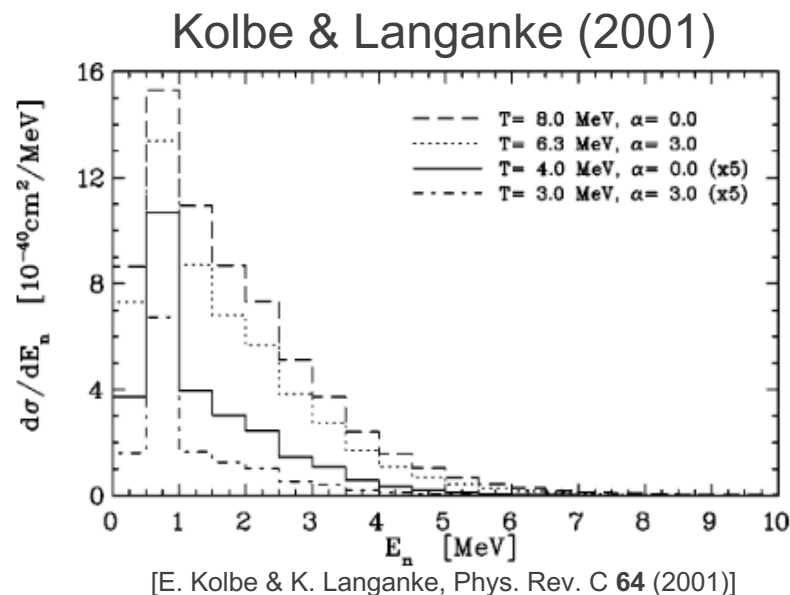- Simulate MARLEY events in GEANT4

Kolbe & Langanke (2001)

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

MARLEY + Wakasa B(GT) data

FIG. 16. (Color online) (a) The GT strength $B(GT; \omega)$ and (b) its integrated $S_{GT}(\omega)$ 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)]

Preparing to Unblind

Reaction Channel	$\bar{\sigma}$ ($\times 10^{-40}$ cm^2)	Reference
^{208}Pb(ν_e, e^-)X	36.23	Kolbe, et al. (2001) [129]
	44.39	Volpe, et al. (2002) [151]
	43.0	Suzuki, et al. (2003) [152]
	29.5	Suzuki, et al. (2003) [152]
	32	Suzuki, et al. (2003) [152]
	41	McLaughlin (2004) [153]
	26.43	Athar, et al. (2006) [154]
	49.6	Lazauskas, et al. (2007) [155]
	26.43-36.20	Paar, et al. (2008) [156]
	42.1	MARLEY, B(GT) from [157]
^{208}Pb$(\nu_e, e^-n)^{207}$Bi	32.9	Kolbe, et al. (2001) [129]
	23.5	McLaughlin (2004) [153]
	31.6	MARLEY, B(GT) from [157]
^{208}Pb$(\nu_e, e^-2n)^{206}$Bi	13.5	McLaughlin (2004) [153]
	7.73	MARLEY, B(GT) from [157]
^{208}Pb$(\nu_e, e^-3n)^{205}$Bi	0.4	MARLEY, B(GT) from [157]

Signal Prediction
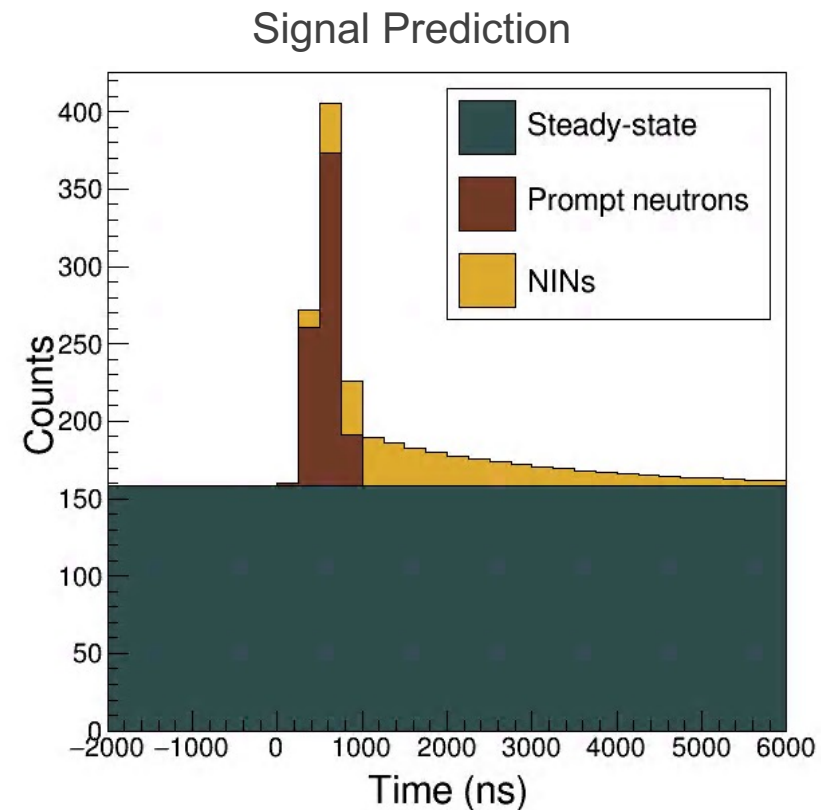
Quantity	Expected
Steady-state backgrounds	20,794
Prompt neutrons	1,684
NINs	346
Prompt neutron shift (ns)	0
NIN shift (ns)	0
Additional BRN (ns)	

Unblinded Results

- Best fit of 37^{+69}_{-37} NIN events, inconsistent with MARLEY prediction at $>4\sigma$

- Updated analysis of Eljen-cell decreases significance from 2.9σ to 2.3σ

- Combining results from both yield cross section suppressed by factor of $0.29^{+0.16}_{-0.15}$

| Quantity	Expected	Fit
Steady-state backgrounds	20,794	$20,821^{+165}_{-150}$
Prompt neutrons	1,684	$1,295^{+44}_{-48}$
NINs	346	37^{+69}_{-37}
Prompt neutron shift (ns)	0^{+71}_{-71}	-13^{+8}_{-8}
NIN shift (ns)	0^{+38}_{-38}	0^{+38}_{-44}
Additional BRN smearing (ns)		79^{+11}_{-11}
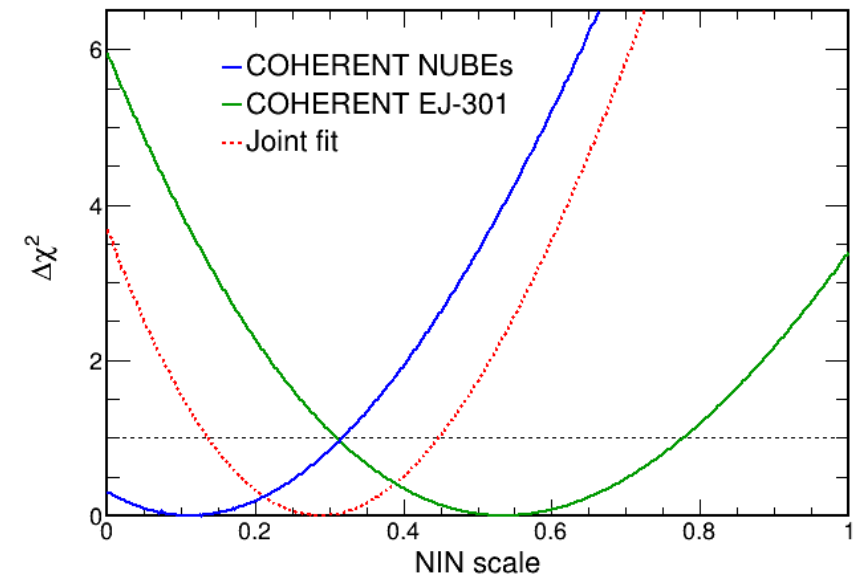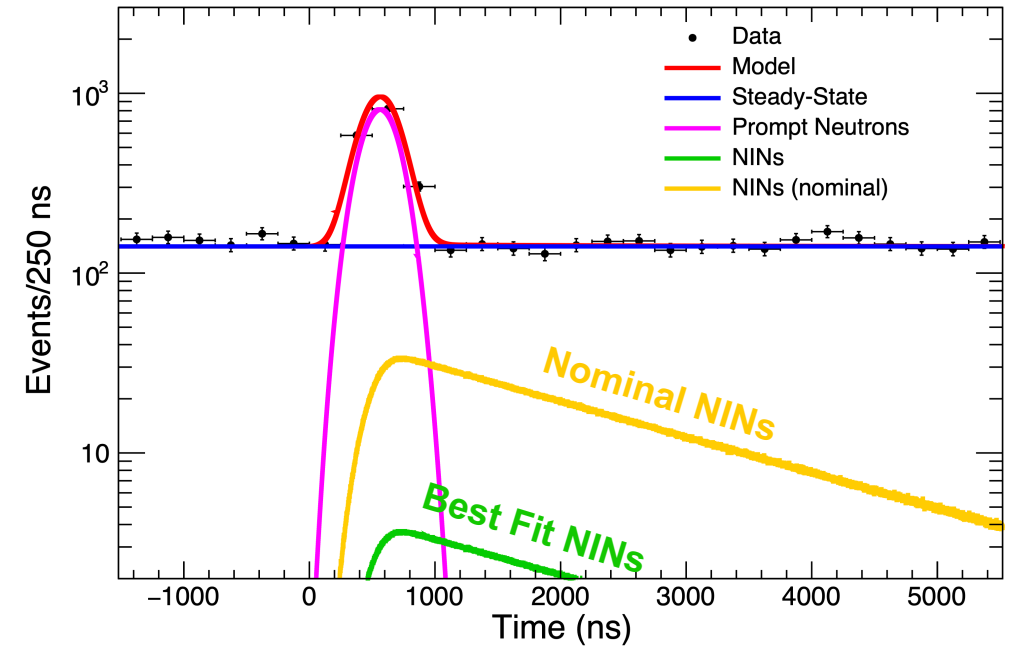
Unblinded Results

- Cross checks
  - Good agreement between MCNP and GEANT4 efficiencies
  - Lead purity spec'd at >99.99%, density measurement consistent
  - Detector sensitive to neutrons throughout its life, prompt beam neutrons track beam power over time
- Future work:
  - Is the inclusive cross section suppressed?
    - Inclusive cross section measurement with lead, both within COHERENT and external (DaRveX – arXiv:2205.11769)
    - Inclusive measurement with another nuclei (^{127}I)
  - Are emitted neutrons lower in energy than predicted?
    - Capture-gated measurement would test this, useful for HALO
  - NIN cross section measurement with another target?
    - Iron neutrino cube deployed ran from 2017-2021, lower predicted cross section

Upcoming Physics

NaIνE-185/NaIνETe

NaIνE-185 (NaI Neutrino Experiment)

- Studying inclusive charged-current electron neutrino cross section on ^{127}I
- ^{127}I a potential target for solar neutrino detection
- By measuring electromagnetic energy deposition, may be able to test nuclear models including gA quenching at ~30 MeV momentum transfer
- Collecting data since 2016

$$\nu_e + {}^{127}\text{I} \rightarrow e^- + {}^{127}\text{Xe}^*$$
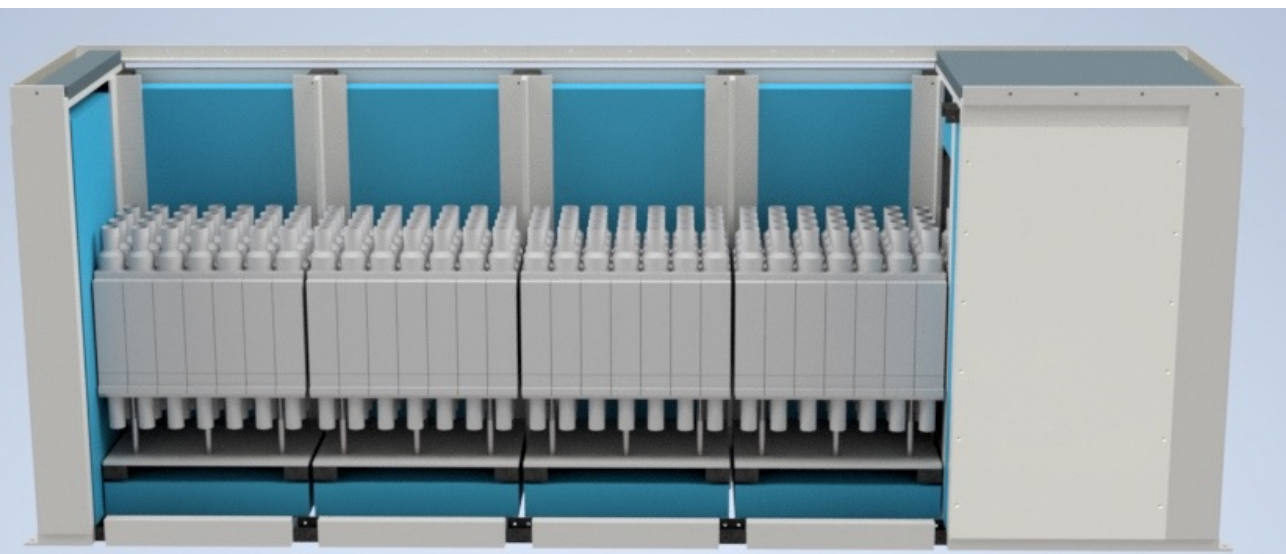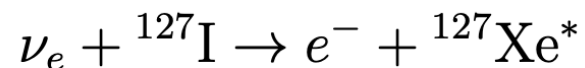
NaIνETe (NaI Neutrino Experiment TonnE-scale)

- Measure ^{23}Na CEνNS, COHERENT's lightest target
- Unpaired proton in ^{23}Na gives potential to measure axial-vector contributions to CEνNS cross section
- Take advantage of detector segmentation to reject backgrounds spanning multiple crystals
- Module one (of five) current deployed
- Full deployment of 2,425.5-kg

CENNS-10/CENNS-750

- Modified CENNS-10 detector loaned from Fermilab
- Single-phase, 24-kg fiducial volume, container sides and PMT window coated with TPB
- Initial results from 2017-2019 data, more in the can
  - Full PDF fit favors presence of signal at 3.1-3.5σ
  - 1σ agreement w/standard model
- CENNS-750 upgrade in development
  - Recent funding from Korea National Research Foundation (Jun 1, 2022)
 - Will study CEνNS, charged-current, and dark matter
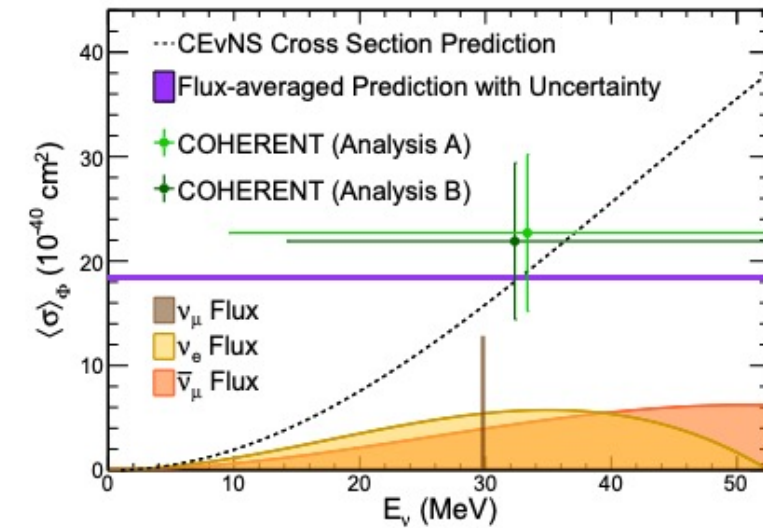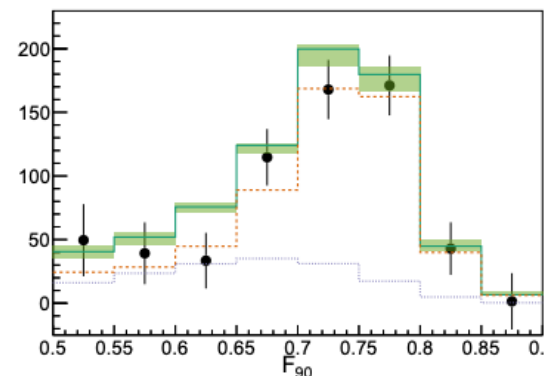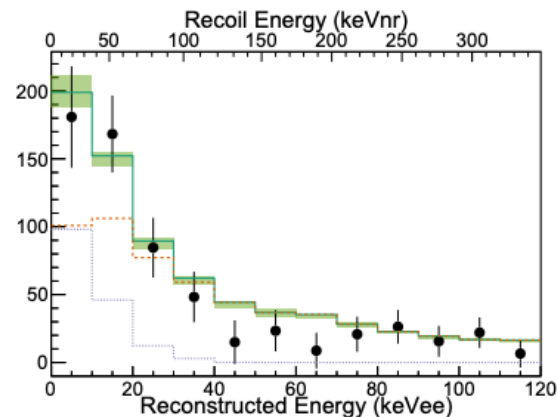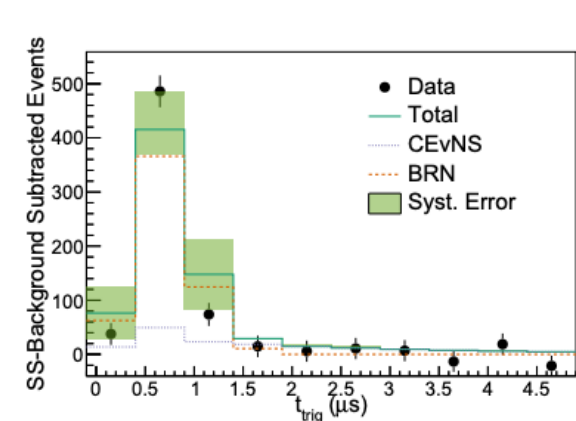
GeMini

- Plan to deploy eight ~2kg p-type point contact Ge detectors
  - Good energy resolution
  - Threshold of ~3keVnr
  - Low-background targets, cryostat
- Detector characterization, deployment under way
- Expect 500-600 CEνNS events/year
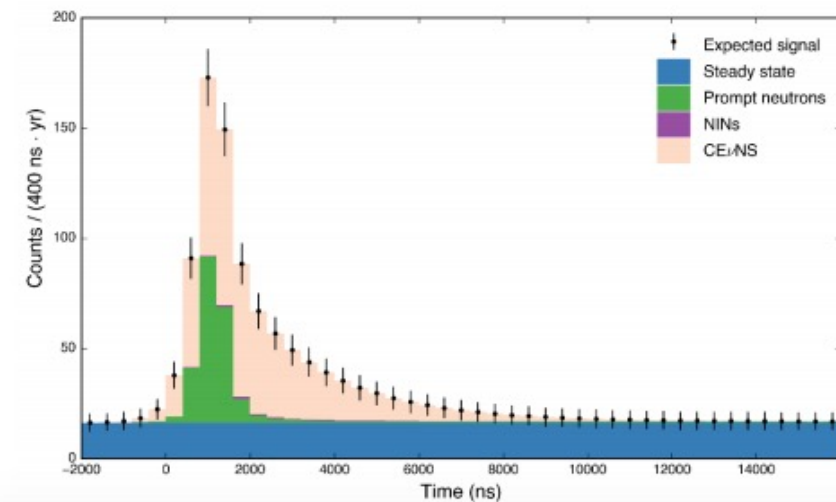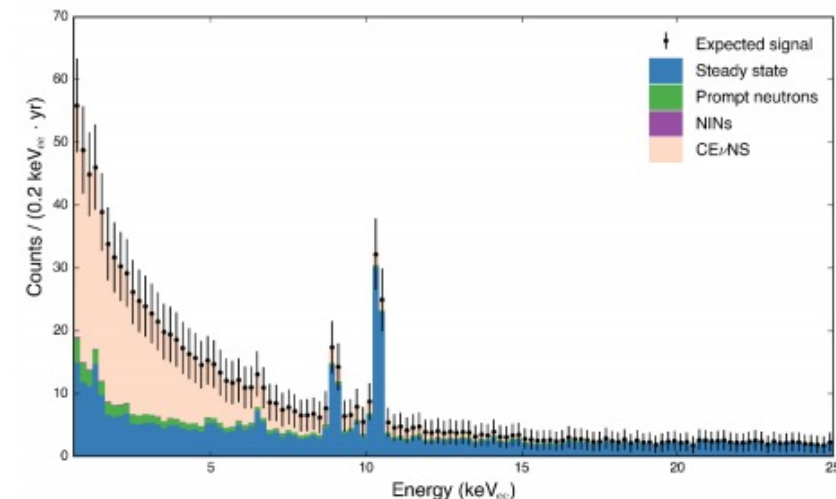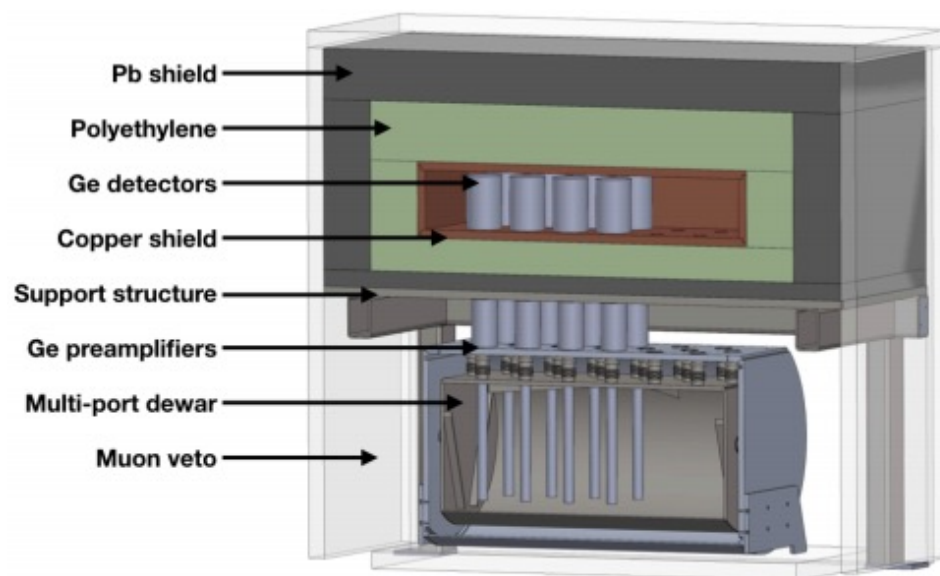
D$_2$O

- Large source of uncertainty (~10%) in CEνNS cross sections from neutrino flux

- Planning to deploy 600-kg D$_2$O detector to reduce uncertainty

- Electron neutrino charged-current cross section on deuterium known to 2-3%

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

- May also be able to measure electron neutrino charged-current cross section on oxygen
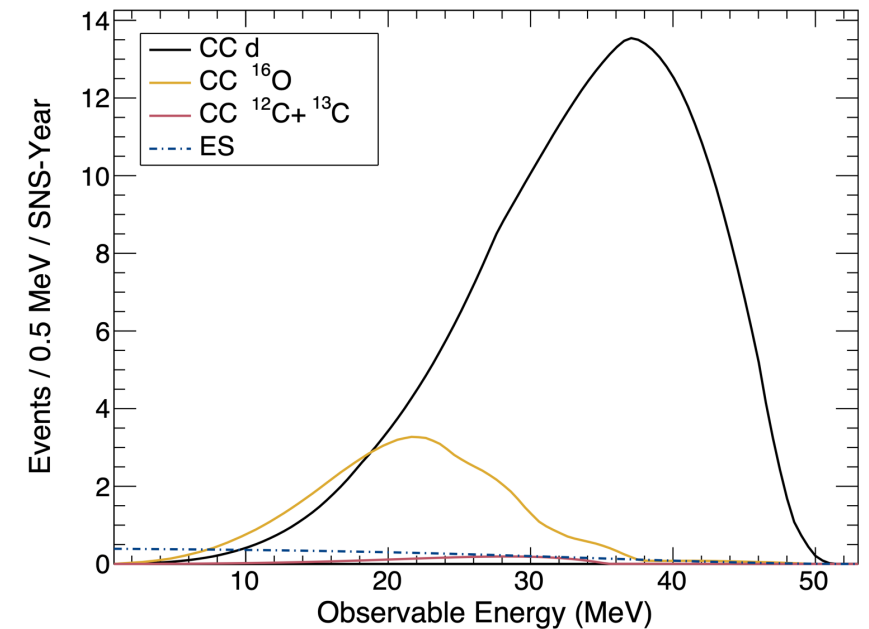
[arxiv:1910.00630.pdf]

NuThor

- Detector designed to study neutrino-induced fission, a long-theorized but never observed process

- Looks for neutrino-induced fission neutrons capturing on gadolinium-doped water

- First beam-data being collected now!

Summary

- COHERENT's updated CsI[Na] CEνNS result reduces systematic and statistical uncertainties, increases physics reach
  - Benefit from improved quenching factor measurements, analysis, and more beam power
- Lead neutrino cube confirms previously observed suppression of electron neutrino charged-current cross section on lead
  - Origin unknown, results from NaIνE and other detectors may shed light
- Analysis of NaIνE, full CENNS-10 data set in the works
- Many new detectors deployed this summer!
- Future SNS upgrade will double beam power through second-target station, potential for neutrino physics being studied

Acknowledgements

What DALL-E thinks neutrino-nucleus scattering looks like
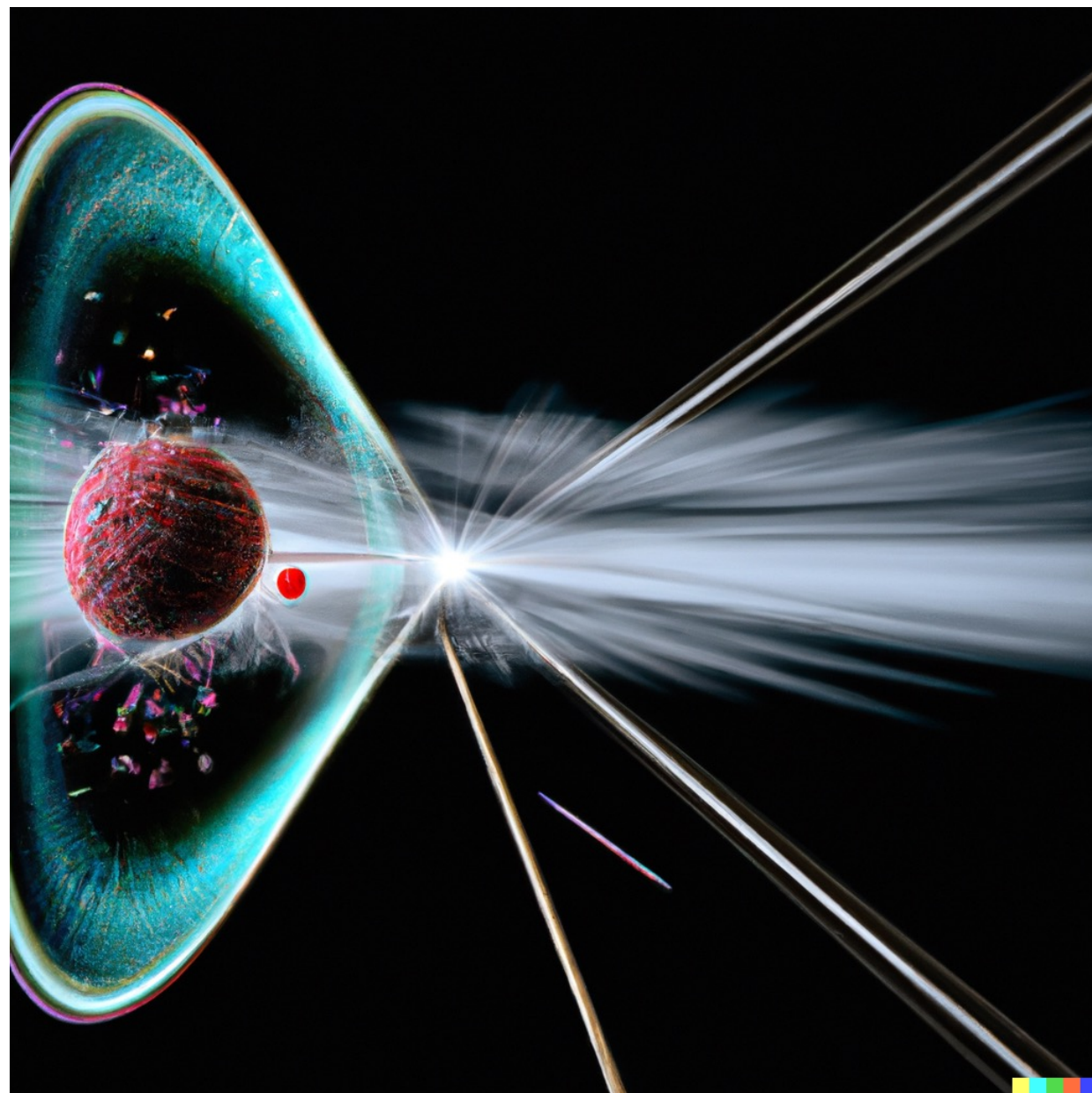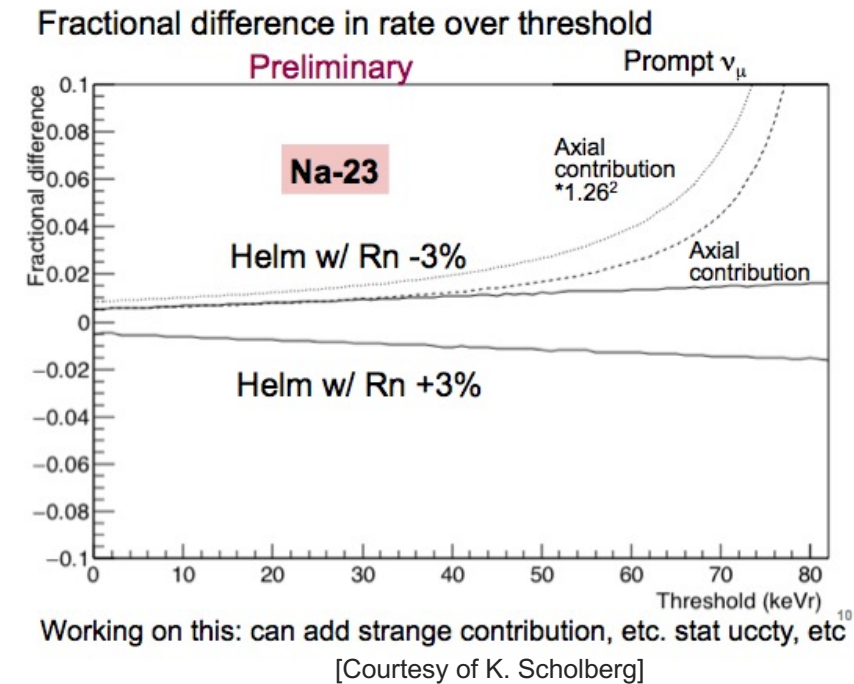
Back-up

Back-up: "Full" CEvNS Cross Section

- "Full" CEνNS cross-section:

$$\frac{d\sigma}{dT}_{coh} = \frac{G_F^2 M}{2\pi} \left[(G_V + G_A)^2 + (G_V - G_A)^2 \left(1 - \frac{T}{E_\nu}\right)^2 - (G_V^2 - G_A^2)\frac{MT}{E_\nu^2} \right]$$

$$G_V = (g_V^p Z + g_V^n N)F_{nucl}^V(Q^2)$$

$$G_A = (g_A^p(Z_+ - Z_-) + g_A^n(N_+ - N_-))F_{nucl}^A(Q^2),$$

- For non-even-even nuclei, additional axial-vector terms from strange quark and weak magnetism couplings

Fractional difference in rate over threshold

Working on this: can add strange contribution, etc. stat uccty, etc

[Courtesy of K. Scholberg]
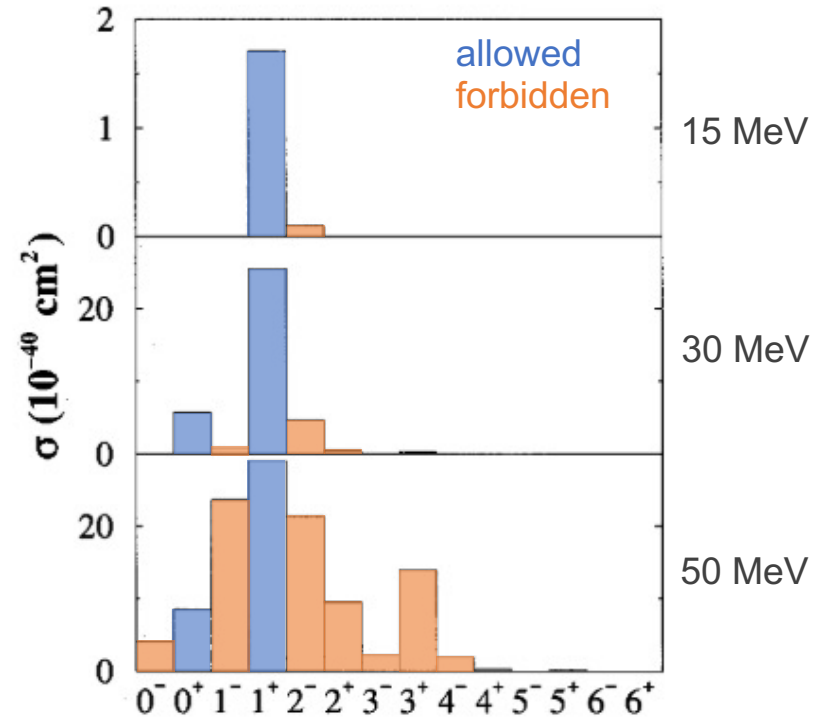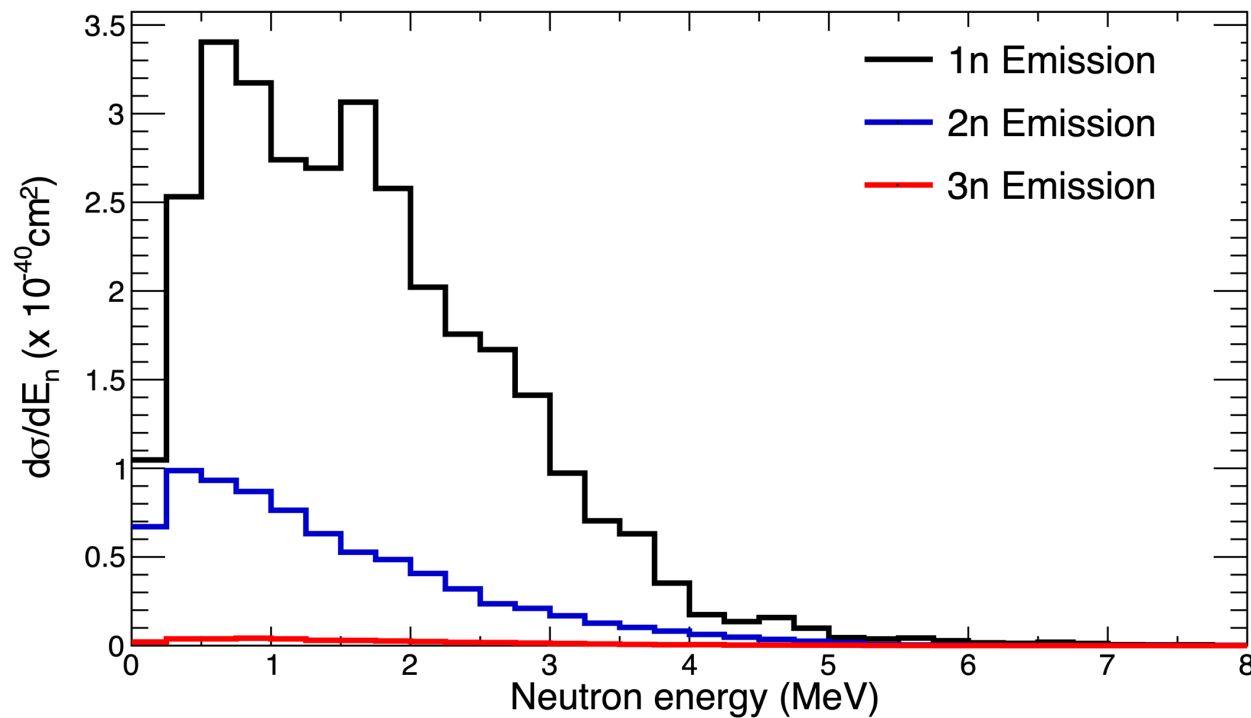
Back-up: Forbidden transitions in ^{208}Pb at the SNS

FIG. 3. Contribution of the different multipolarities to the differential ^{208}Pb$(\nu_e, e^-)^{208}$Bi cross section (10^{-40} cm^2) of Fig. 1 for $E_{\nu_e} = 15$ MeV (up), 30 MeV (middle), 50 MeV (bottom).
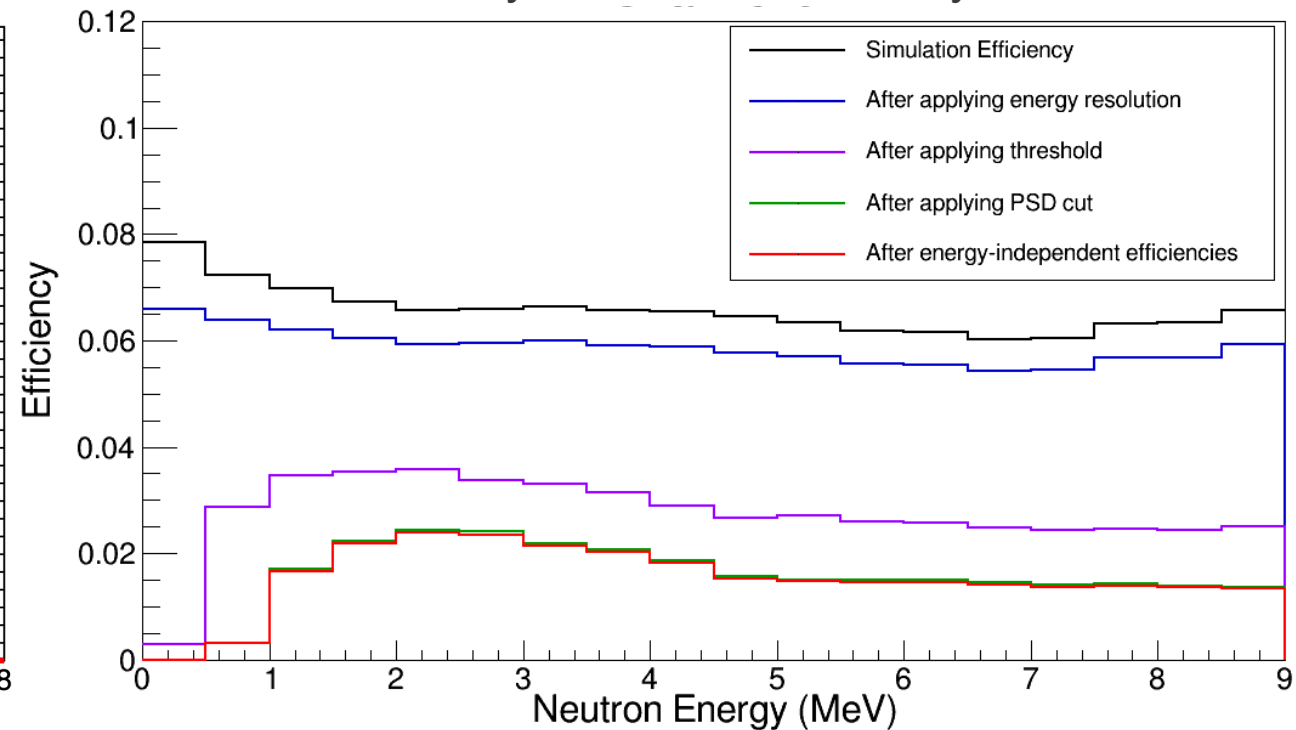
[C. Volpe, et al., Phys. Rev. C **65** (2002)]

Back-up: Pb Neutrino Cube Efficiency
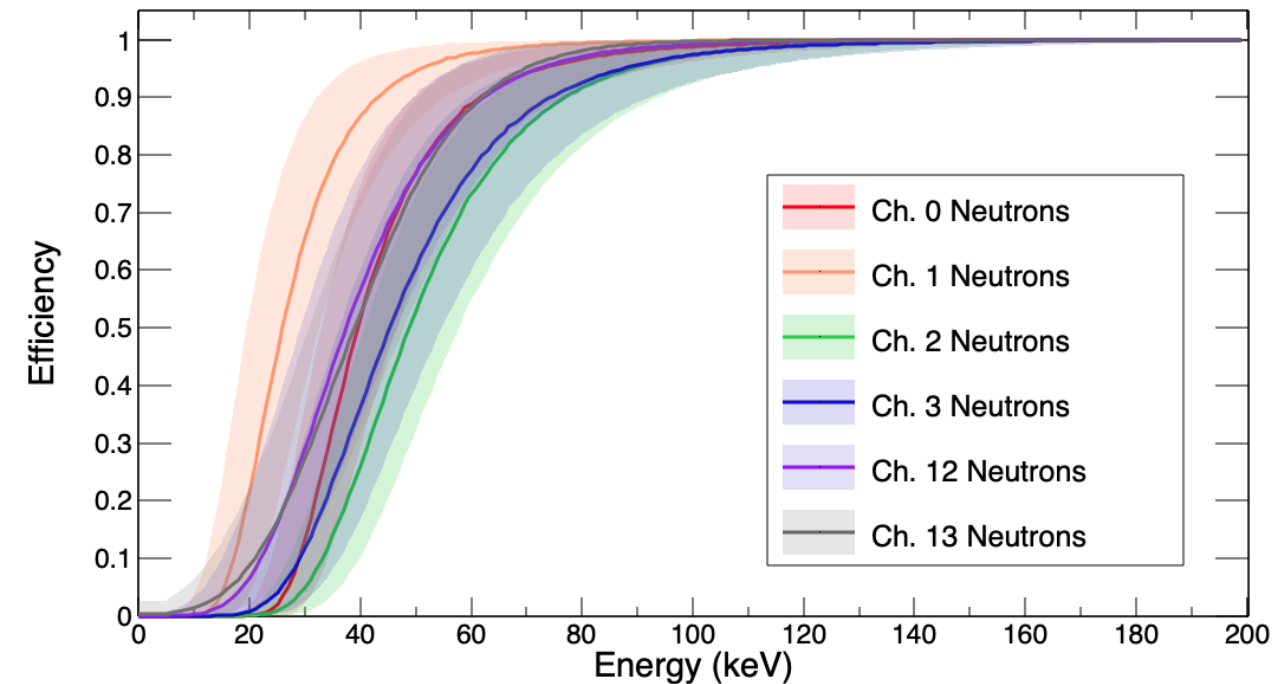
MARLEY Neutron Spectrum

4-Cyl Detection Efficiency

Back-up: Pb Neutrino Cube Thresholds