# The COHERENT Collaboration: Initial Results and Present Status

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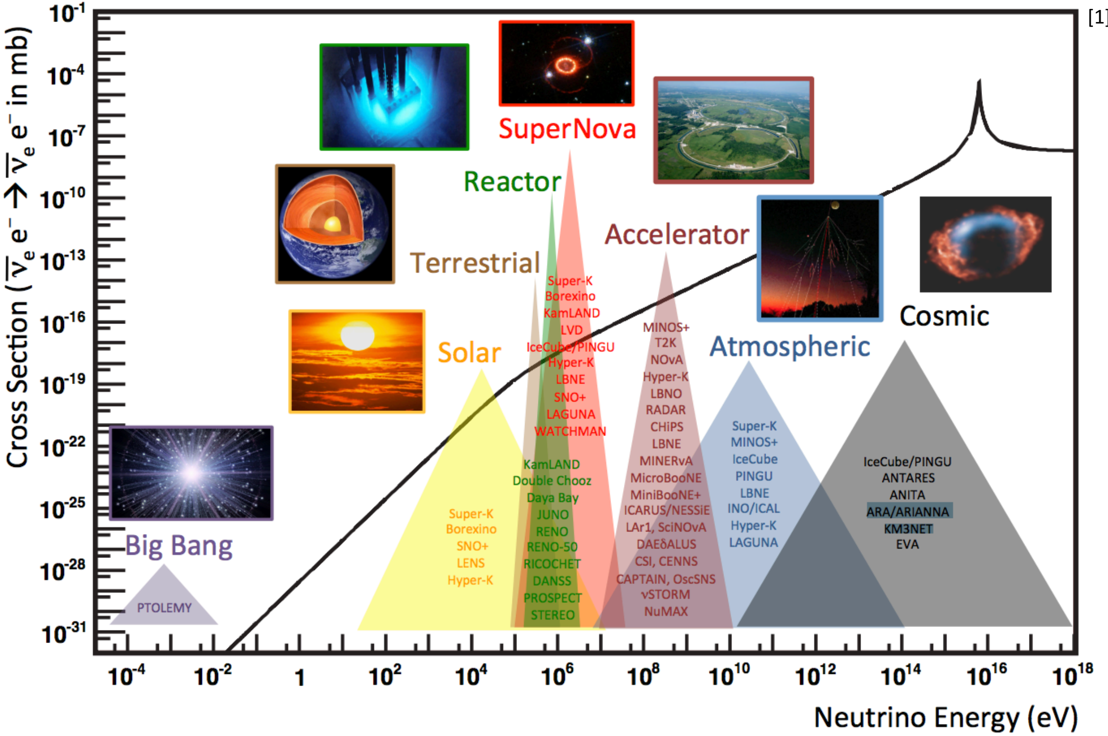
# Outline

- Motivation/overview of coherent elastic neutrino-nucleus scattering (CE$\nu$NS)
- The COHERENT collaboration
- Preliminary work
- Initial results with COHERENT's CsI[Na] detector
- COHERENT's other detectors

# Neutrino Sources




[1] A. de Gouvea, et. al, arXiv:1310.4340v1, 2013

# Coherent Elastic Neutrino-Nucleus Scattering (CE$\nu$NS)

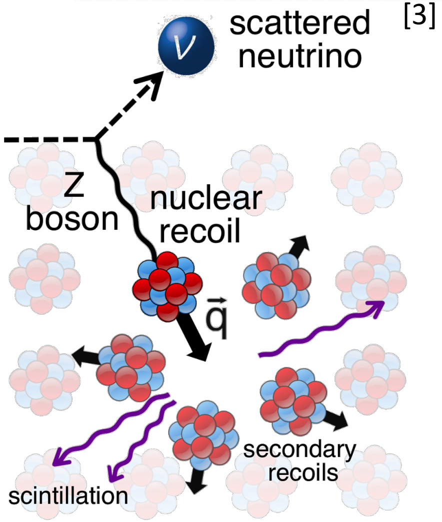
- Suggested by D. Freedman in 1974[2]
  - Neutrinos elastically scatter off of nucleus, nucleons recoil in phase
  - Leads to large enhancement in scattering cross section
- Cross section proportional to number of neutrons in nucleus squared ($N^2$)
- Coherence requires low momentum transfer, $\lesssim 50$ MeV
  - Identical nucleus in initial and final states

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

**Coherent effects of a weak neutral current**

Daniel Z. Freedman†
*National Accelerator Laboratory, Batavia, Illinois 60510*
*and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790*

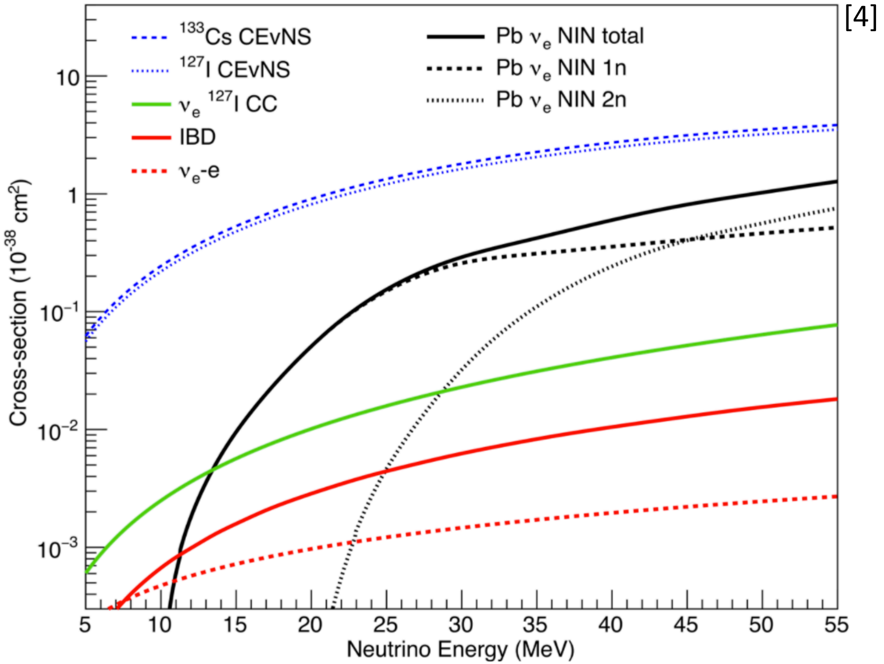
(Received 15 October 1973; revised manuscript received 19 November 1973)




[2] D. Freedman, Phys. Rev. D, **1** 5 (1974)
[3] D. Akimov, et. al,, Science (2018)

# Coherent Elastic Neutrino-Nucleus Scattering (CE$\nu$NS)

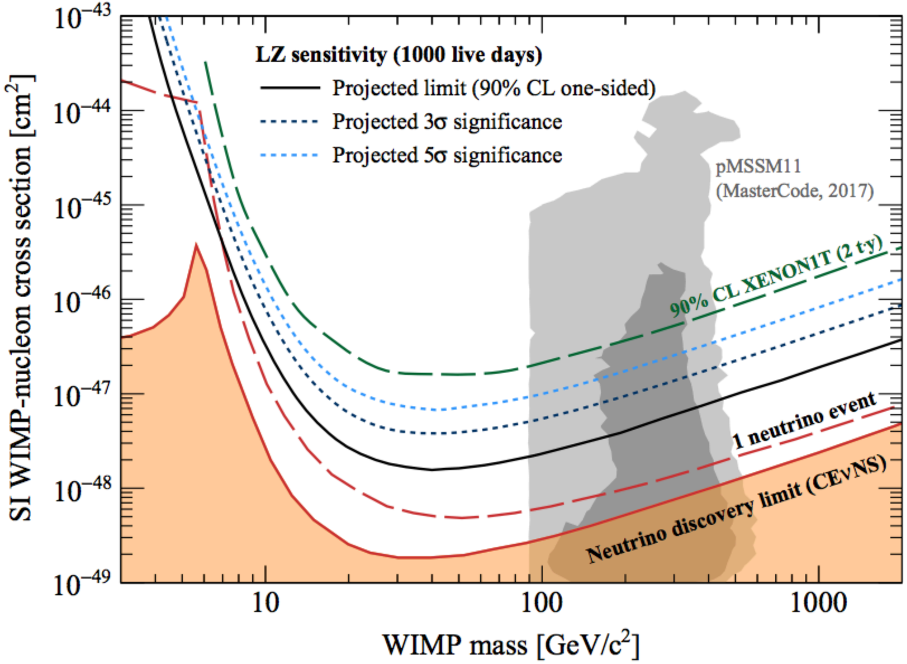
- Cross section can be orders of magnitude greater than other neutrino cross sections
- Cross section well predicted by standard model of electroweak interactions
  - Can test standard model, look for non-standard interactions
- Process important for:
  - WIMP search backgrounds
  - Supernova dynamics and detection
  - Applications for reactor monitoring




[4] D. Akimov, et. al, arXiv:1509.08702 (2015)

# CE$\nu$NS as a Background for Dark Matter Searches

- Neutrinos can produce similar nuclear recoils to WIMPs elastically scattering off nuclei
- CE$\nu$NS from atmospheric, supernova, and solar neutrinos can be a background for WIMP searches

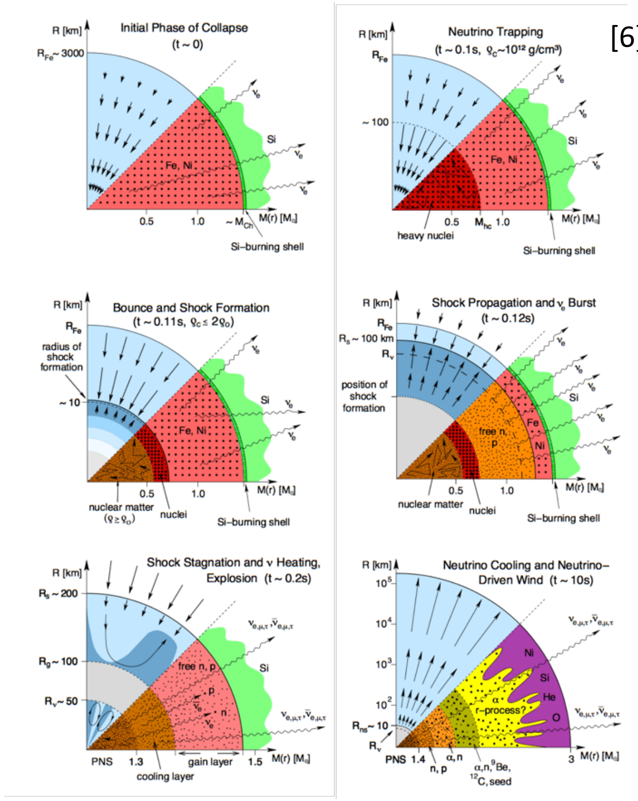



[5]

[5] D.S. Akerib, et. al, arXiv:1802.06039 (2018)

# CE$\nu$NS and Supernovae

- CE$\nu$NS affects supernova dynamics:
  - ~99% gravitational binding energy released in neutrinos
  - Most neutrinos low energy ($\lesssim$ 40 MeV), CE$\nu$NS largest cross section
  - At supernova densities, neutrino mean free path can be reduced to ~km
- CE$\nu$NS can also be used for detection of supernova neutrinos on earth
  - Responds to all neutrino flavors, complementary to other detection methods

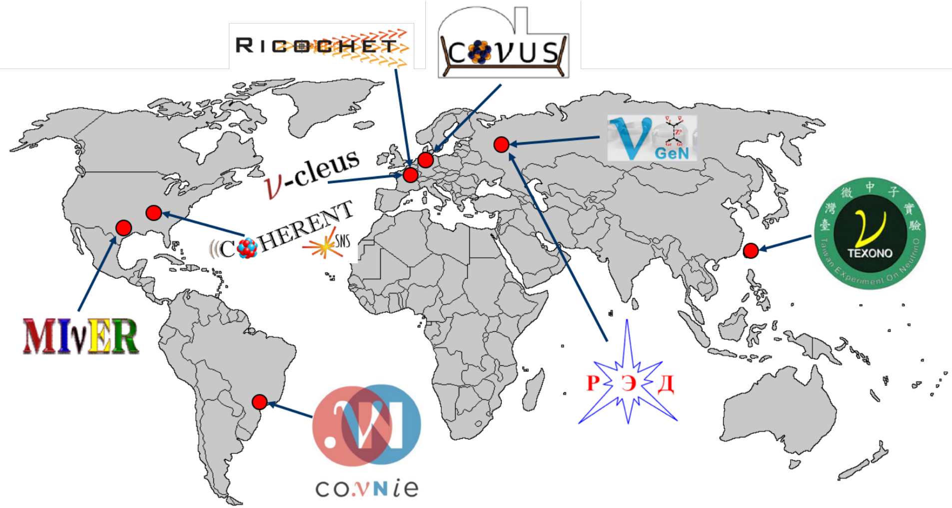



[6]

[6] H.-Th. Janka, et. al, arXiv:0612072 (2006)

# CE$\nu$NS and Reactor Monitoring

- Reactors emit large fluxes of neutrinos (~$10^{13}$ $\bar{\nu}_e$/cm$^2$/sec at 20m)
  - Low energies (< ~8 MeV)
  - Impossible to shield
- Non-intrusive way to monitor information about reactor such as on/off status, fissile content
- CEνNS can lead to smaller footprints, capabilities to monitor reactors from further distances
- Many current efforts at reactors

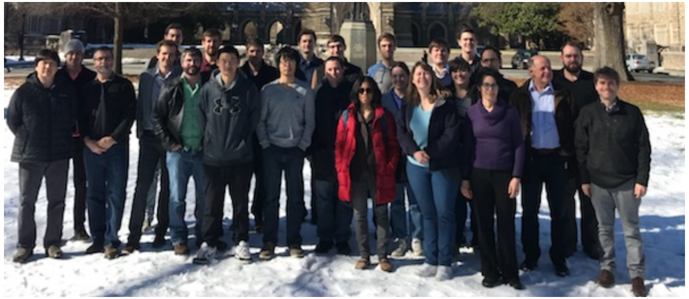


# Why is it difficult to detect CE$\nu$NS?

- While cross section for CE$\nu$NS is large, experimental signature (low energy nuclear recoil) difficult to observe
  - At stopped-pion sources, higher energy neutrinos give higher energy nuclear recoils
- Detector response to nuclear recoils must be understood (nuclear recoils quenched compared to electron recoils)
  - Measurements at Triangle Universities Nuclear Laboratory (TUNL)
- Need low backgrounds and thresholds
  - Benefit from advances in dark matter detection technology
- Need a strong neutrino source
  - Stopped-pion sources, reactors

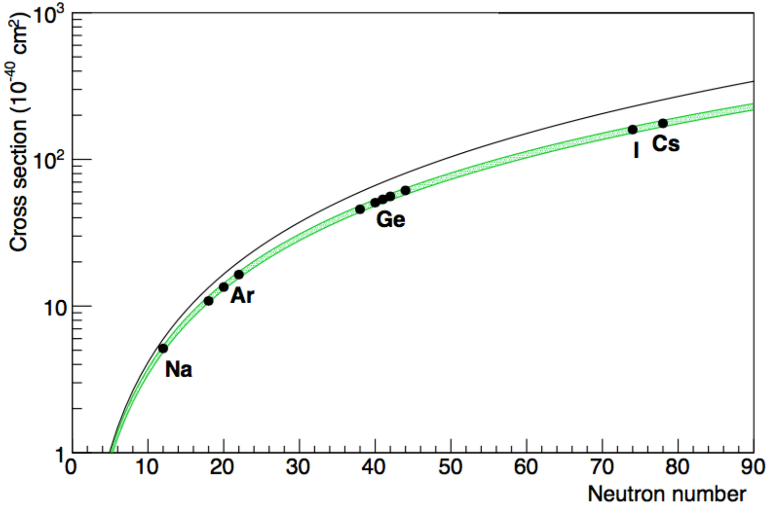
# The COHERENT Collaboration

- ~80 members from 18 institutions in 4 countries
- Combining individual experience and expertise
- Using neutrinos produced at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL), Tennessee



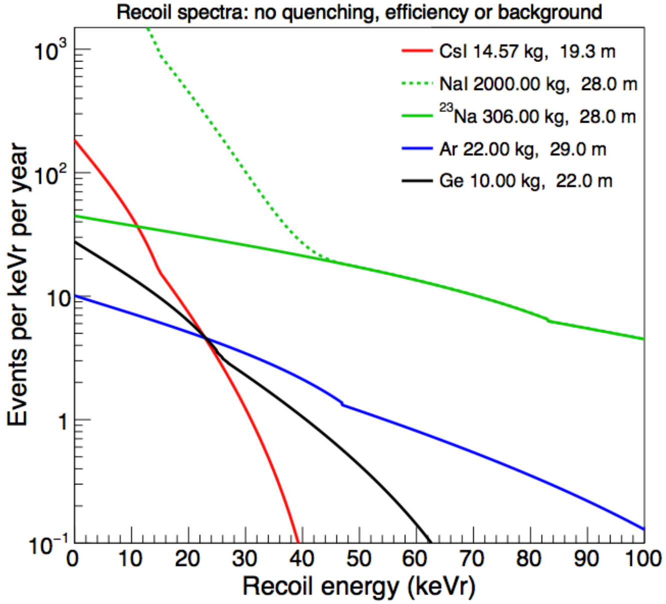
# The COHERENT Collaboration

- Test $N^2$ cross section scaling
- Using a variety of targets and detector technologies
  - CsI[Na] scintillator
  - Single-phase liquid Argon
  - P-type point contact Ge
  - Segmented NaI[Tl] scintillator
- Multiple targets allow cancellation of some systematic uncertainties



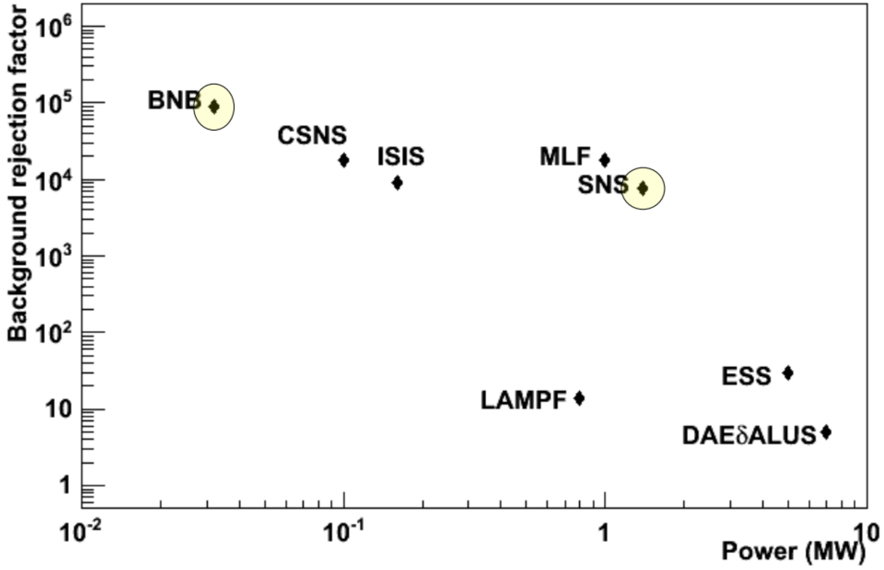
# COHERENT's Detectors

| Nucleus | Detector | Mass (kg) | Threshold (keVnr) | Start date |
|---|---|---|---|---|
| CsI | CsI[Na] scintillator | 14.57 | 6.5 | 9/2015 |
| Na | NaI[Tl] scintillator array | 185/2000+ | 13 | 7/2016 for 185 kg<br>2018 for 2000 kg |
| Ar | Single-phase liquid Argon | 22 | 20 | 12/2016 |
| Ge | P-type point contact Ge | 10 | 5 | 2018 |

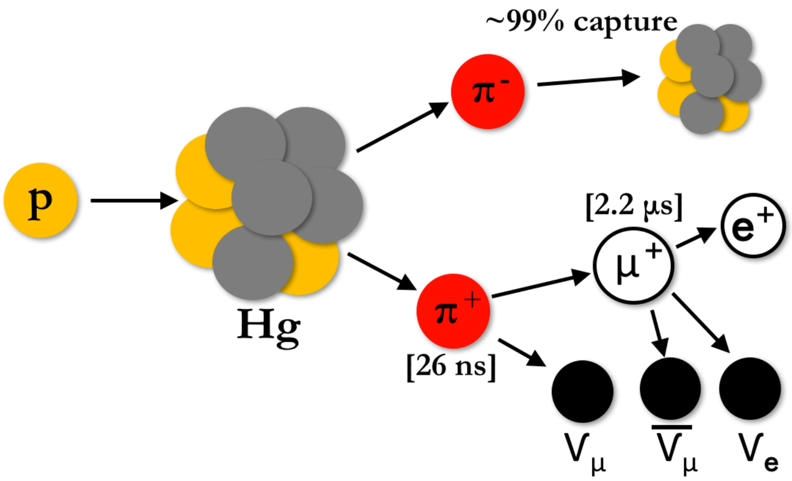


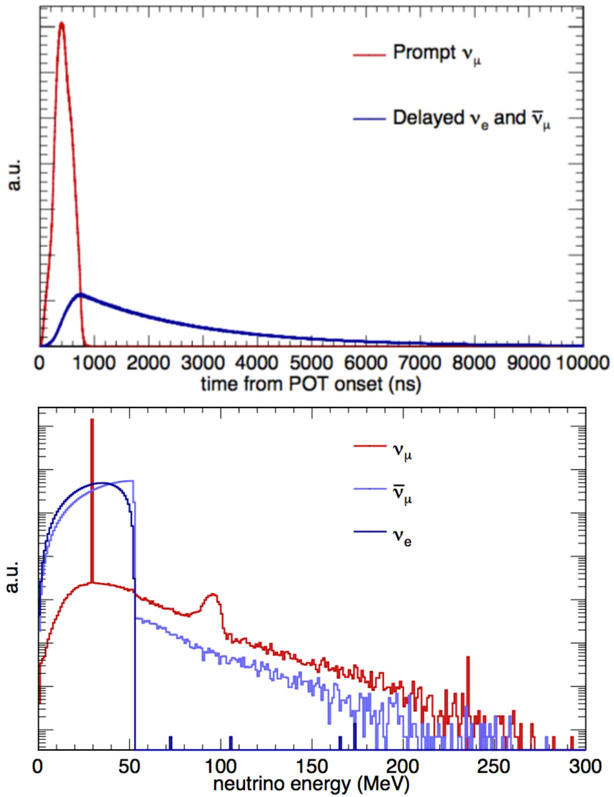
# Why the SNS?

- Higher energy neutrinos than at a reactor
  - Larger cross sections
  - Higher energy nuclear recoils
- SNS produces a pulsed proton beam
  - ~1μs pulses, 60Hz
  - Good understanding of steady state backgrounds
  - Reject backgrounds outside beam windows
- High intensity source with short pulse lengths



# Neutrino Production at the SNS



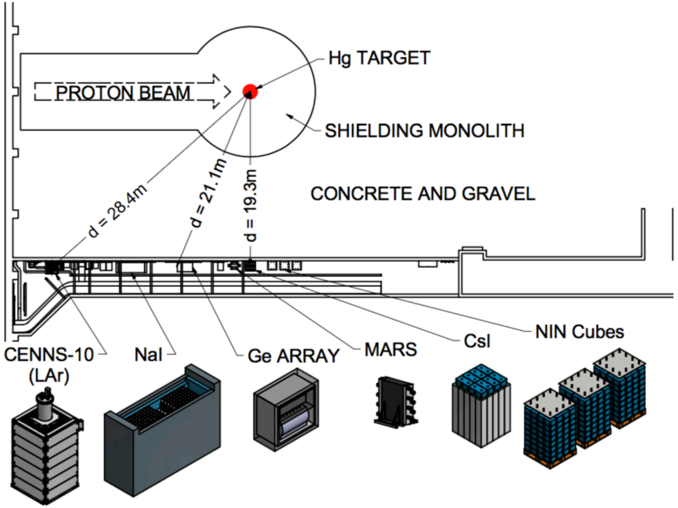



# Preliminary work

- Site selection at the SNS
- Beam-related neutrons backgrounds
- Neutrino-induced backgrounds
- Quenching factor measurements

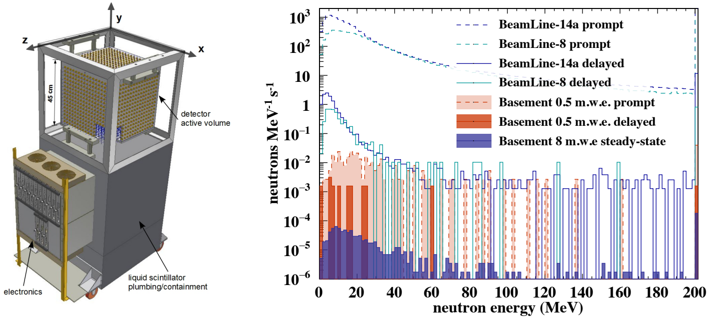
# Site Selection at the SNS

# Site Selection at the SNS

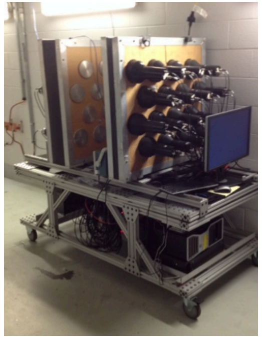



# Beam-related neutrons

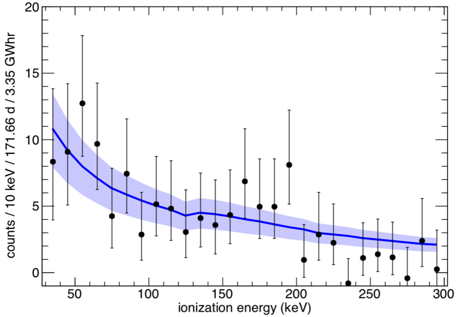
- SciBath detector



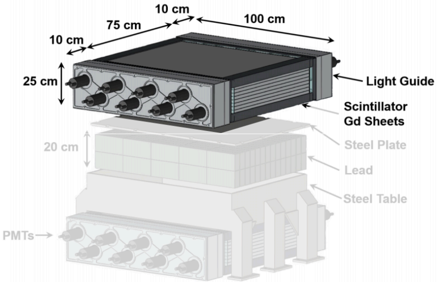

- Neutron scatter camera



- Eljen LS cell in CsI shielding




- Multiplicity and Recoil Spectrometer (MARS)



# Neutrino-Induced Neutrons

- Neutrinos can interact in shielding materials to produce excited nuclei that can de-excite through neutron emission
- Background for CE$\nu$NS
  - Neutrons will have timing structure of neutrinos
- Theoretical calculations showed lower cross section than CE$\nu$NS, but had never been measured
- Same mechanism HALO experiment will use to detect supernova neutrinos
- Primarily concerned with this cross section in common shielding materials (lead, iron), but other materials are also interesting

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

$$\Downarrow$$

$${}^{208-y}\mathrm{Bi} + x\gamma + yn$$

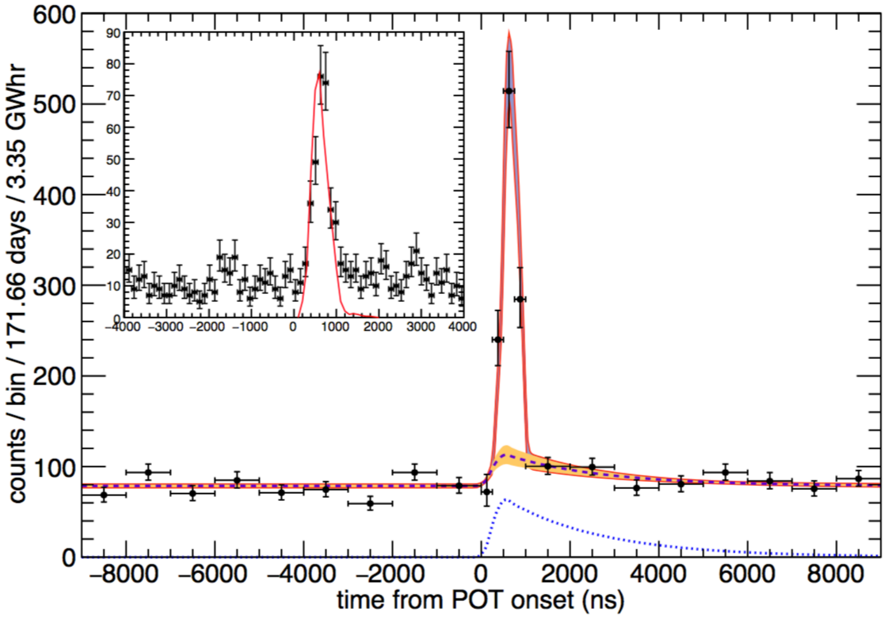
$$\nu_x + {}^{208}\mathrm{Pb} \rightarrow 208\mathrm{Pb}^* + \nu_x'$$

$$\Downarrow$$

$${}^{208-y}\mathrm{Pb} + x\gamma + yn$$

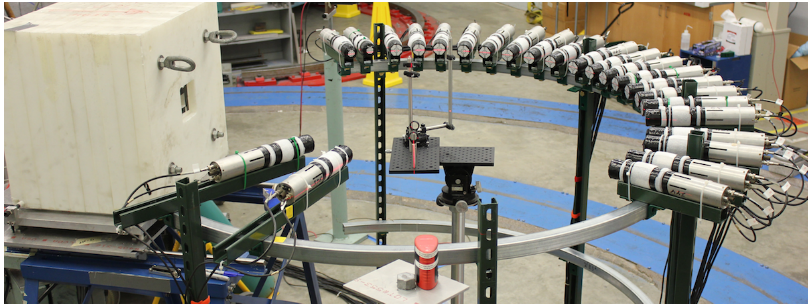
# Result: Neutrino-Induced Neutrons in Pb

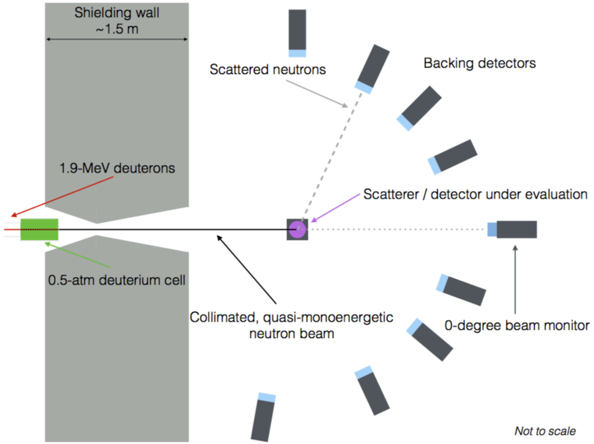
- From Eljen LS cell in CsI detector's shielding, got initial measurement of NIN cross section on Pb
  - Low exposure, done prior to deployment of CsI[Na] crystal
  - Added HDPE between lead and detector to reduce neutron backgrounds
- Cross section lower than expected
- Dedicated detectors deployed to the SNS to study this process



# Quenching Factor Measurements

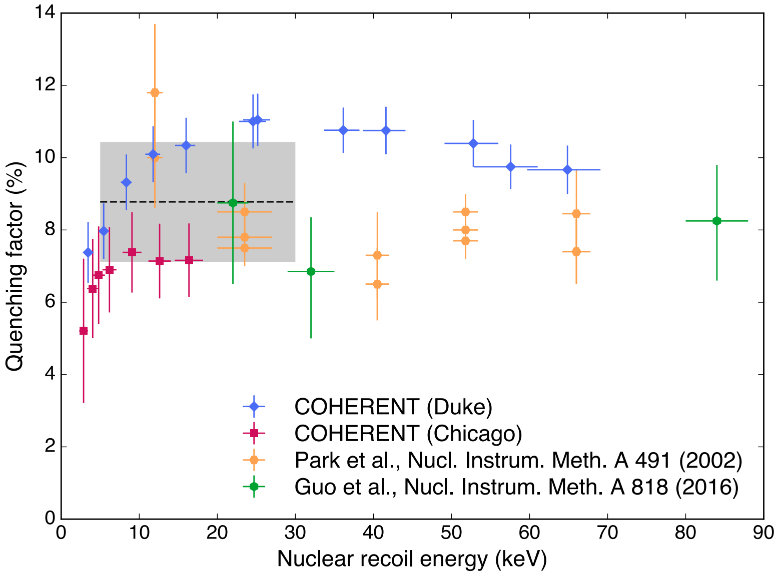
- Light output from nuclear recoils quenched compared to electron recoils of the same energy
- Previous measurements for CsI existed
  - Large uncertainties
  - Quenching factor may be energy dependent, need low-energy recoil data points
- Measurement campaign for COHERENT's targets (and other materials) at the Triangle Universities Nuclear Laboratory (TUNL)





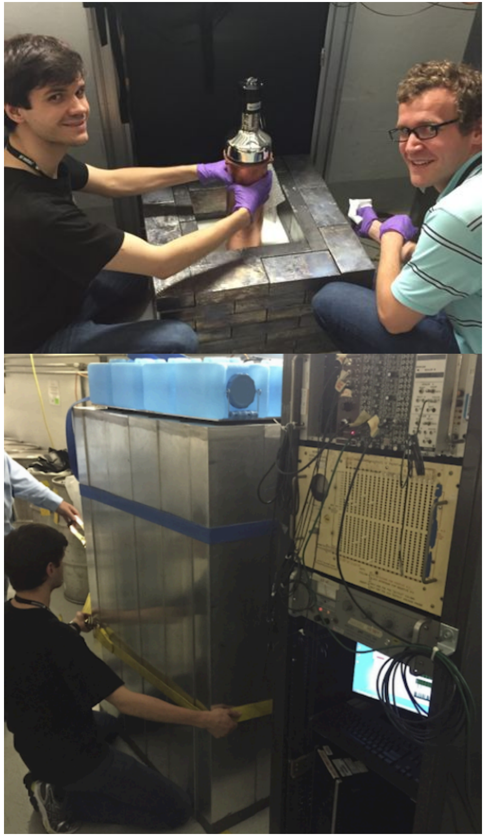
# Result: CsI[Na] Quenching factor

- Two measurements using same crystal/PMT, same facility/neutron source
- Different backing detectors and configurations
- Adopted a flat quenching factor of 8.78% ± 1.66%
- Working to resolve discrepancy between measurements



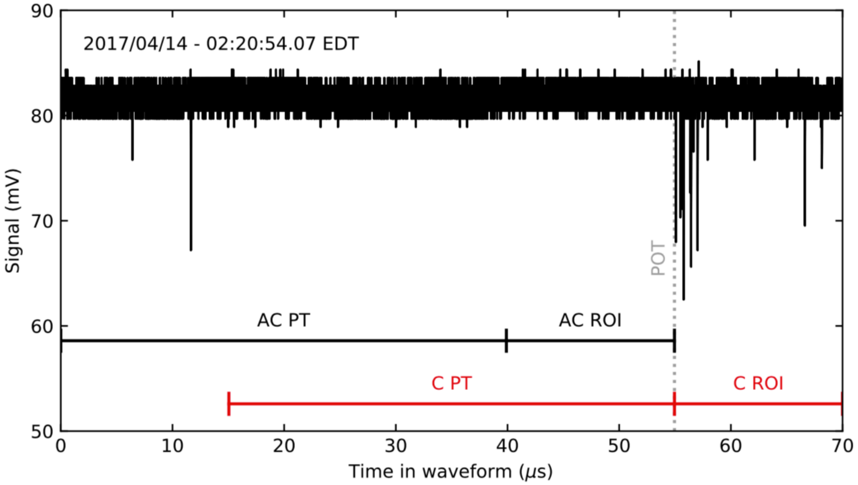
# CsI[Na] Detector

- 14.57kg CsI[Na] scintillator
- Operates at room temperature
- Crystal casing designed with low background components
- Shielding consists of water, lead, low-background lead, HDPE
- Doped with Na to reduce afterglow compared to CsI[Tl]
- Deployed in summer 2015

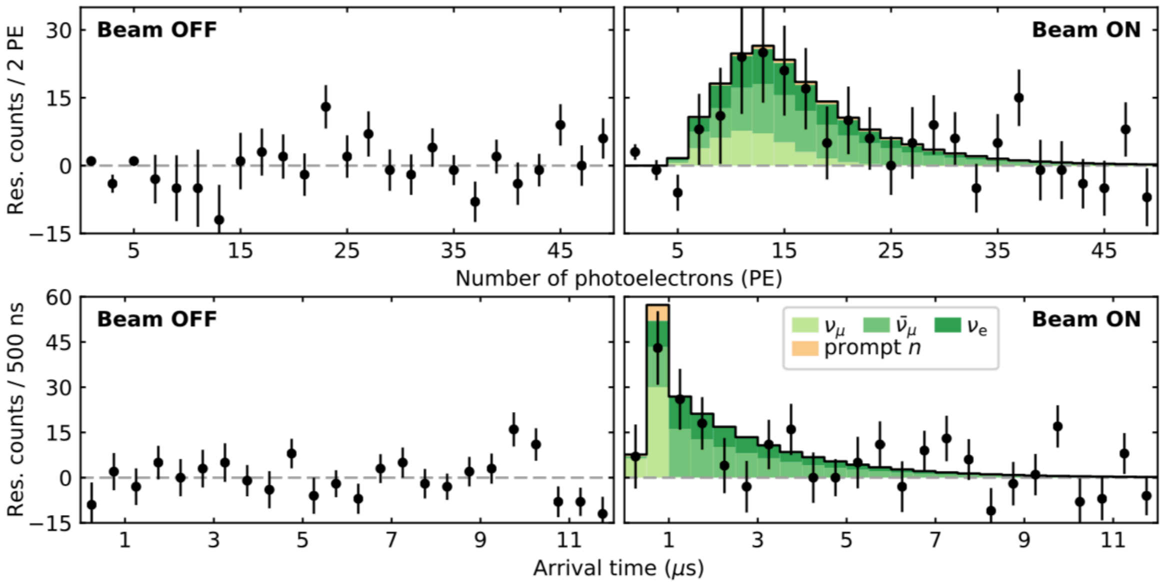


# CsI[Na] Analysis

- Triggers on SNS timing signal (60 Hz)
- 70 μs waveforms split into two regions:
  1. Anti-coincidence to understand steady-state backgrounds
  2. Coincidence for signal region
- Calibration done with $^{241}$Am and $^{133}$Ba sources
- Cuts on muon veto, afterglow pulses, high energy signals
- Independent analysis by U. Chicago and MEPhI
- $1.76 \times 10^{23}$ protons-on-target (~1/3 g)

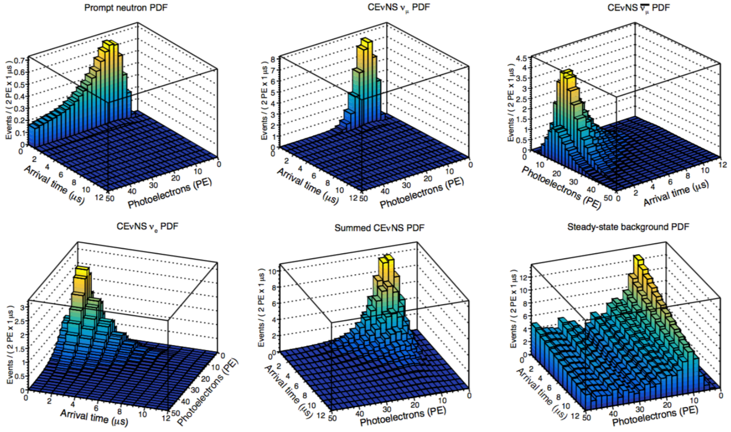


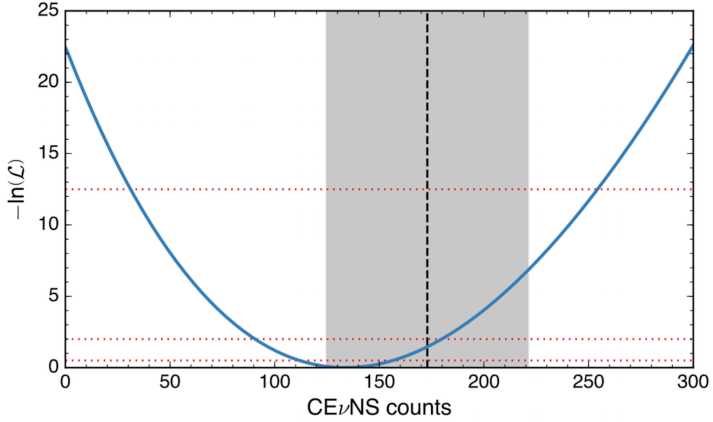
# CsI[Na] Result




# CsI[Na] Result

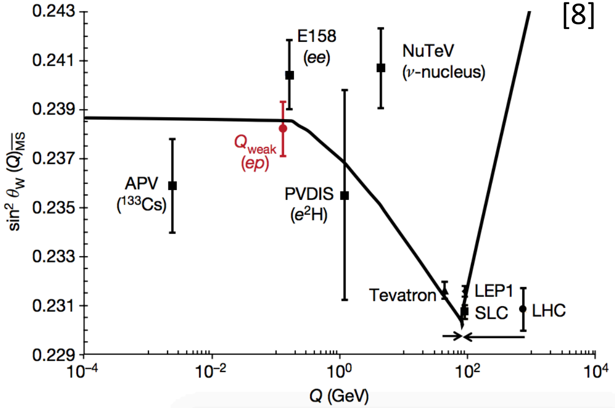
- 2D likelihood fit in energy, time shows a signal 6.7σ
- Consistent with Standard Model at 1σ level
- 134 ± 22 events observed, 173 ± 48 predicted in SM
- Lots of physics being done with the initial results!



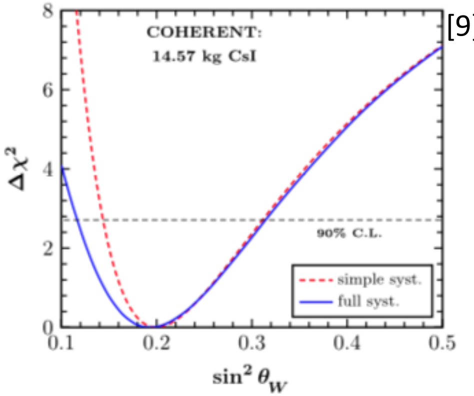



# Weak Mixing Angle

- Possible to measure the weak mixing angle at a low Q value (~40 MeV)
- Large uncertainties, but small detector, ~1 year of exposure
- Measuring CE$\nu$NS in multiple targets will reduce uncertainties




[8]




[9]

[8] The Jefferson Lab Qweak Collaboration, Nature **557** (2018)
[9] D.K. Papoulias and T.S. Kosmas, Phys. Rev. D **97** (2018)

# Neutron Distribution Functions

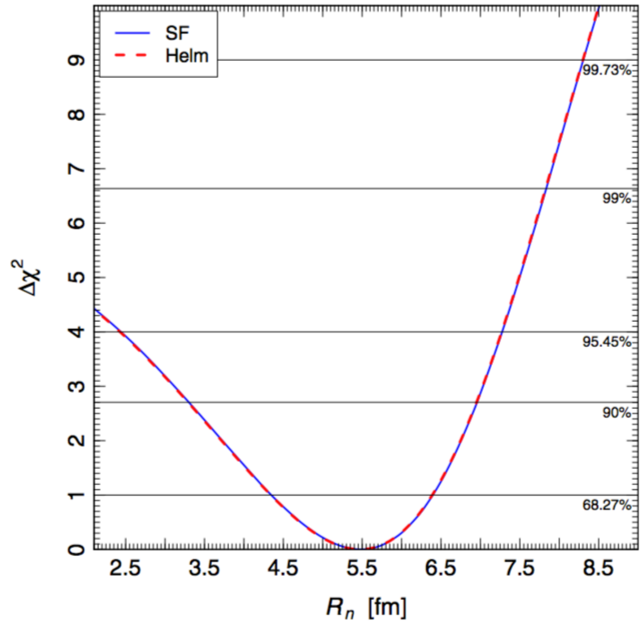
- Neutron RMS radius can be measured with neutrino-nucleus scattering

$$\mathrm{R_n} = 5.5^{+0.9}_{-1.1}\ \mathrm{fm}$$

- Neutron skin depth (difference between neutron and proton RMS radii)

$$\Delta\mathrm{R_{np}} \simeq 0.7^{+0.9}_{-1.1}\ \mathrm{fm}$$

- More exposure and reduced uncertainties can improve calculations

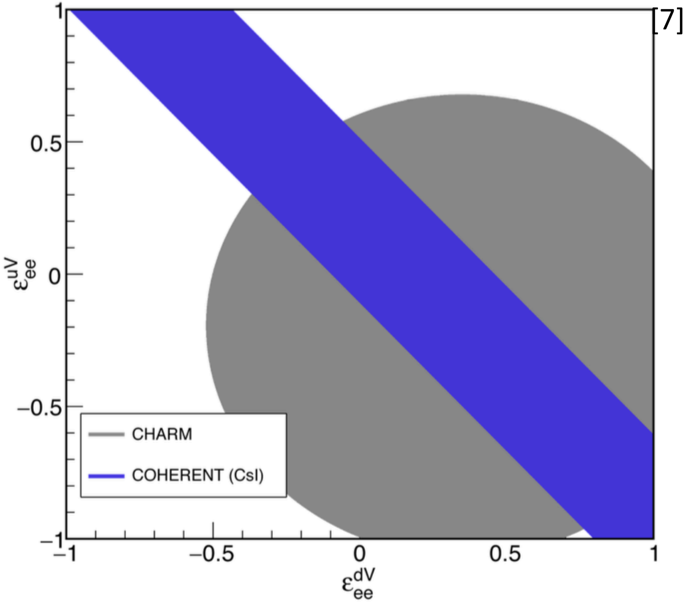



[10]

[10] M. Cadeddu, et. al, PRL **120** (2018)

# Non-Standard Interactions (NSI)

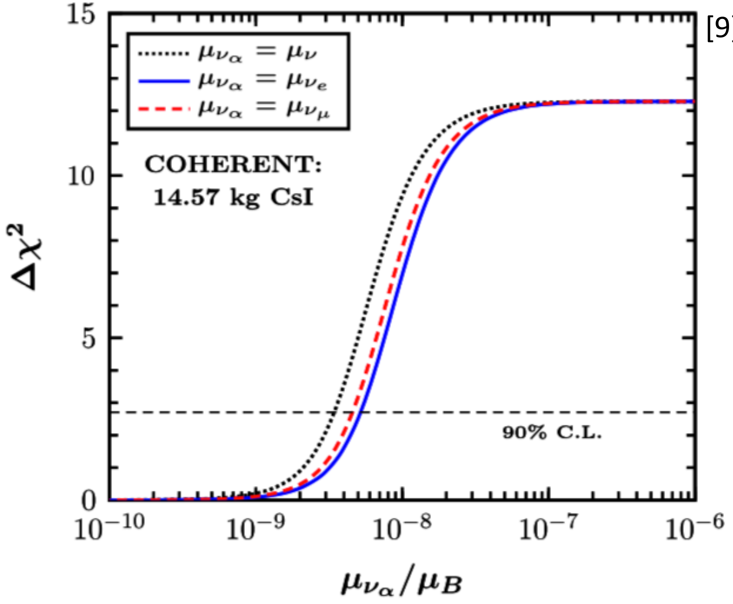
- Non-standard neutrino-quark interactions could affect neutrino mass ordering experiments, long-baseline neutrino oscillation experiments
- NSI can enhance or suppress CE$\nu$NS rate
- Measurement for different nuclei will further constraints




[7] D. Akimov, et. al, arXiv:1803.09183 (2018)

# Neutrino Magnetic Moment

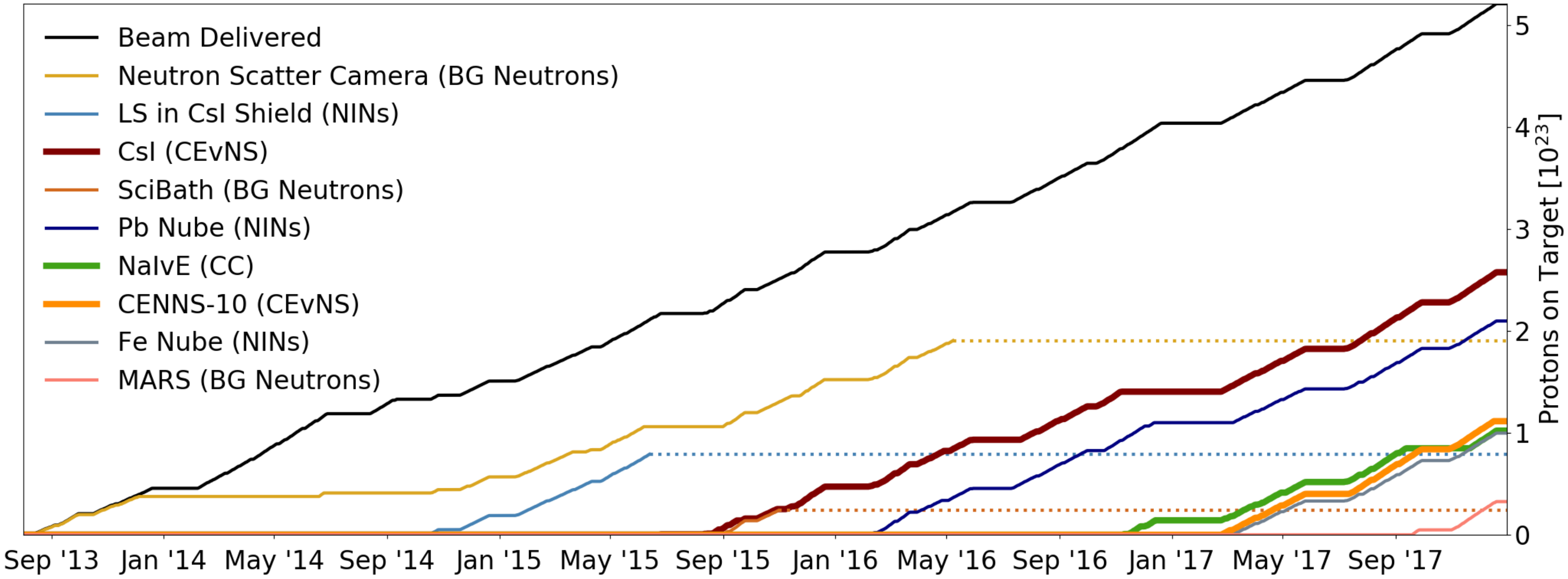
- Massive neutrinos may have EM properties (charge radius, magnetic moment)
- Signature would be an enhancement to the cross section, distorted spectrum
  - Proportional to $1/E_{recoil}$ at low energies
  - $Z^2$ coherence
- Low threshold, high resolution detectors will provide better constraints




[9]

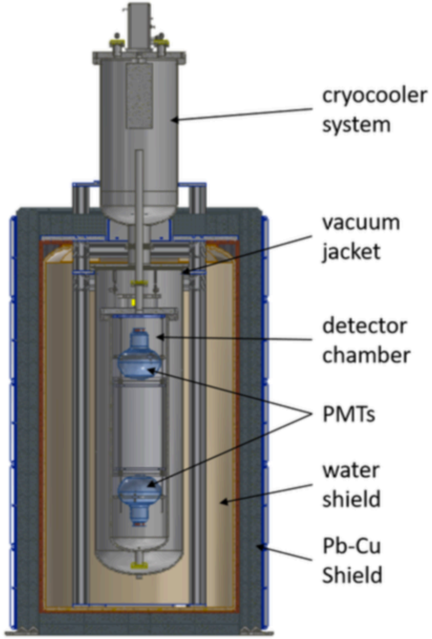
[9] D.K. Papoulias and T.S. Kosmas, Phys. Rev. D **97** (2018)

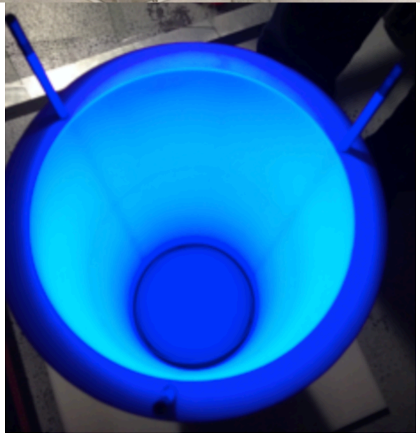
# COHERENT's Other Detectors



# Liquid Argon

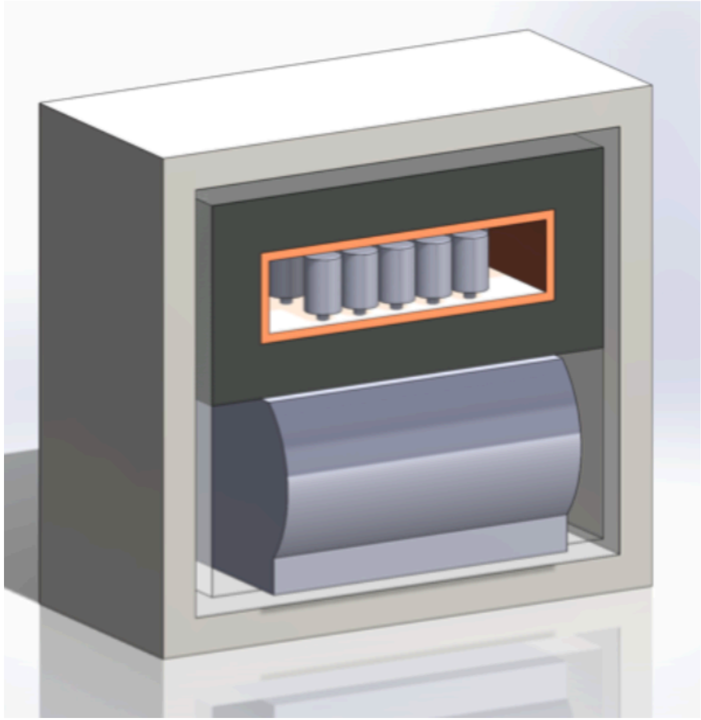
- Used CENNS-10 detector (from FermiLab)
- 22 kg fiducial volume, coated with wavelength-shifting paint
- Data collection started in Dec. 2016, full shielding in summer 2017



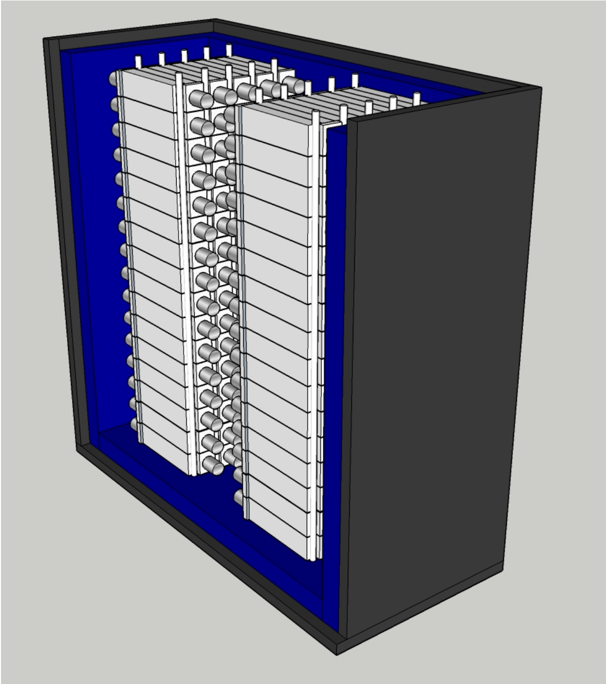
# Germanium

- Ge detectors offer low threshold, high resolution
- Testing existing Ge detectors for backgrounds
- Recent advances have led to detectors with very low noise, thresholds



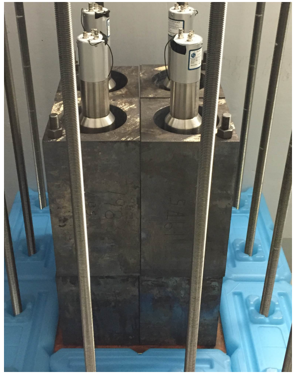
# NaI[Tl]

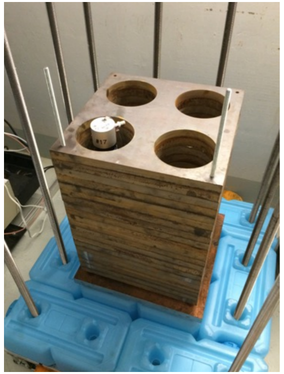
- Na is COHERENT's lightest nuclei
  - Smaller cross section, but higher energy nuclear recoils
- Collaboration has access to several tons of NaI[Tl] detectors left over from Advanced Spectroscopic Portal program
  - Crystals not designed to have low backgrounds, but can compensate with sufficient mass
- Nuclear recoils have large dE/dX—recoils limited to single crystal
  - Coincidence between neighboring detectors can be used to reduce backgrounds

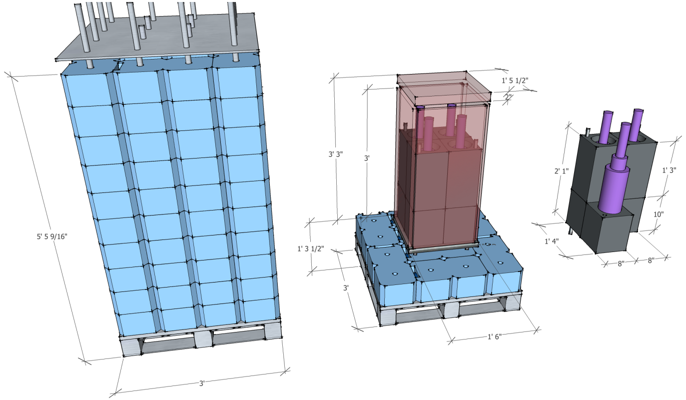


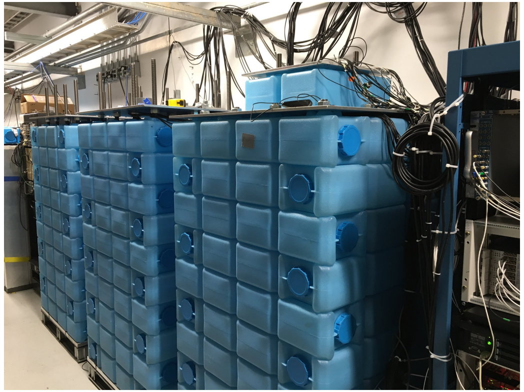
# Neutrino Cubes

- Palletized neutrino detectors with switchable targets (~700 kg Fe, 900 kg Pb)
- Large PSD capable liquid scintillators in targets
- Look for neutrons produced in CC and NC events from neutrinos with energy above the particle emission threshold
- Muon vetos, water shielding reduce backgrounds
- Pb neutrino cube deployed in fall 2015, Fe in winter 2017







# $^{127}$I Charged Current

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

- Haxton proposed $^{127}$I as solar, supernova neutrino detector in 1988
  - Measurement can test nuclear models, $g_A$ quenching with neutrinos
  - Very few neutrino-nucleus interactions measured at these energies
- Previous measurement[12] done at Los Alamos Meson Production Facility (LAMPF) using a radiochemical approach
  - Large uncertainties in cross section

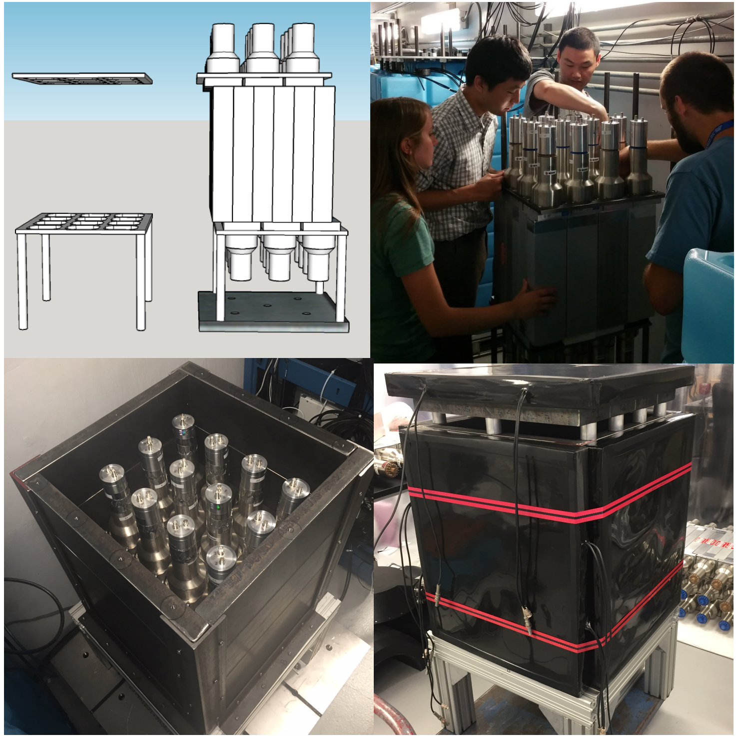
$$\sigma = 2.84 \pm 0.91\,(\mathrm{stat}) \pm 0.25\,(sys) \times 10^{-40}\ \mathrm{cm}^2$$

  - No information on energy dependence of cross section
  - Required $^{127}$Xe to be end state of reaction (particle emission threshold in $^{127}$Xe ~7.2 MeV, average neutrino energy at SNS close to 30 MeV)

[12] J. R. Distel, et. al, Phys. Rev. C 2003

# NaI$\nu$E Detector

- NaI$\nu$E (NaI $\nu$-Experiment) consists of twenty-four 7.7kg NaI[Tl] detectors at the SNS
- Dual purpose: make preliminary measurement of charged-current cross section on $^{127}$I, test backgrounds for CE$\nu$NS deployment for Na
- Operating since summer 2016, upgraded in fall 2017 to reduce backgrounds



# Dual-Gain Bases

- PMTs that came with NaI[Tl] detectors show saturation effects at high gains
- To simultaneously measure both channels, need to measure events between 3 keV and 60 MeV
- Dual-gain base designed with separate outputs
- Design tested, refined in 2016
- First production run of 16 bases recently completed

# Future Outlook

- Collaboration working to reduce systematics (flux, quenching factor) for CsI[Na] result, gather more statistics
- Beam recently resumed at SNS, operating at higher power
- Many detectors deployed, expecting results soon
- SNS is a unique neutrino source, interesting neutrino physics can be done with it

# Acknowledgements

CNEC Consortium for Nonproliferation Enabling Capabilities

KICP

NNSA National Nuclear Security Administration

NSF

U.S. DEPARTMENT OF ENERGY