New Results from a CEvNS Search with the CENNS-10 Liquid Argon Detector

Jacob Zettlemoyer, for the COHERENT Collaboration
Indiana University, Bloomington
Fermilab Joint Experimental-Theoretical Physics Seminar
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Overview

1. Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)
2. COHERENT at the Spallation Neutron Source and First observation of CEvNS on CsI target
3. CENNS-10 Detector and First detection of CEvNS on Ar target
4. Future COHERENT Liquid Argon (LAr) – Towards CENNS-750
5. Summary

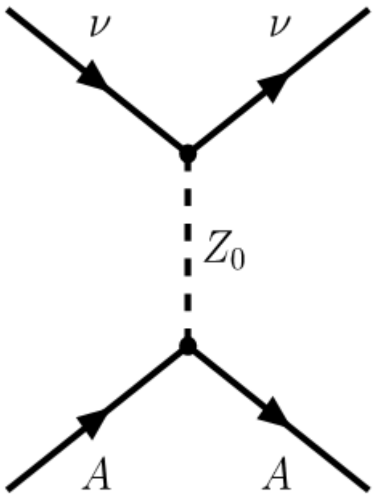
Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

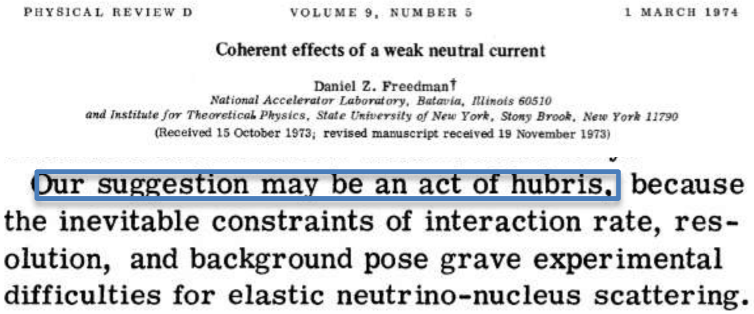
Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

- First mentioned by Freedman in 1974
- Neutrino interacts via neutral current with all nucleons in target nucleus
    - Initial and final states of the nucleus are identical
    - Neutral current, all flavors participate
- For large nuclei, E_ν < 50 MeV to meet coherence condition
- De Broglie wavelength for 50 MeV neutrino

$$\lambda = \frac{h}{p} = \frac{1200\ \mathrm{MeV\ fm}}{50\ \mathrm{MeV}} \sim 25\ \mathrm{fm}$$

- Compare to ~fm (10^{-15} m) nuclear radius




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)

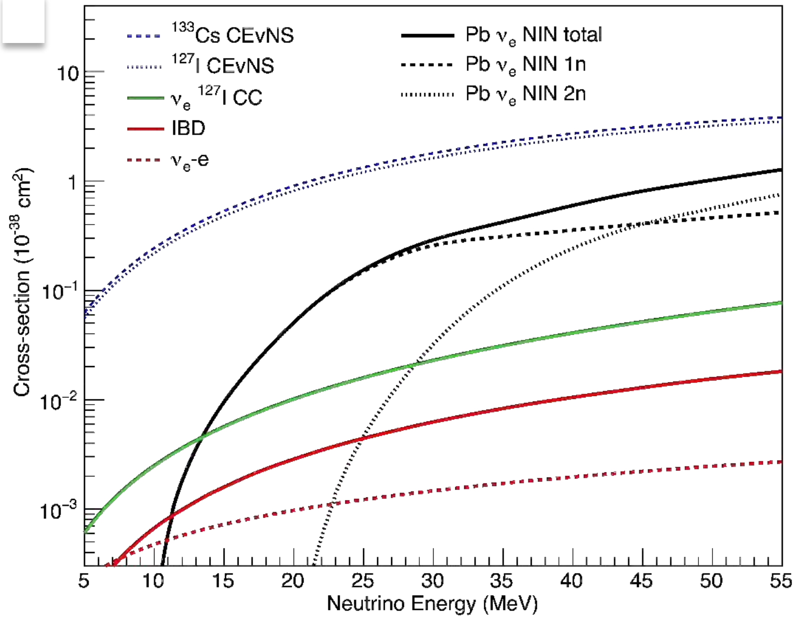
Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering.

D.Z. Freedman, Phys. Rev. D 9 (1974)
V.B. Kopeliovich and L.L. Frankfurt, ZhETF Pis. Red. 19 (1974)

CEvNS cross section

- CEvNS cross section is largest neutrino cross section (<100 MeV) on heavy nuclei
- Via coherence of recoil and near-zero weak charge of proton, cross section takes on distinct N^2 dependence
  - N is number of neutrons in target nucleus

$$\sigma \approx \frac{G_F^2 N^2}{4\pi} E_\nu^2$$



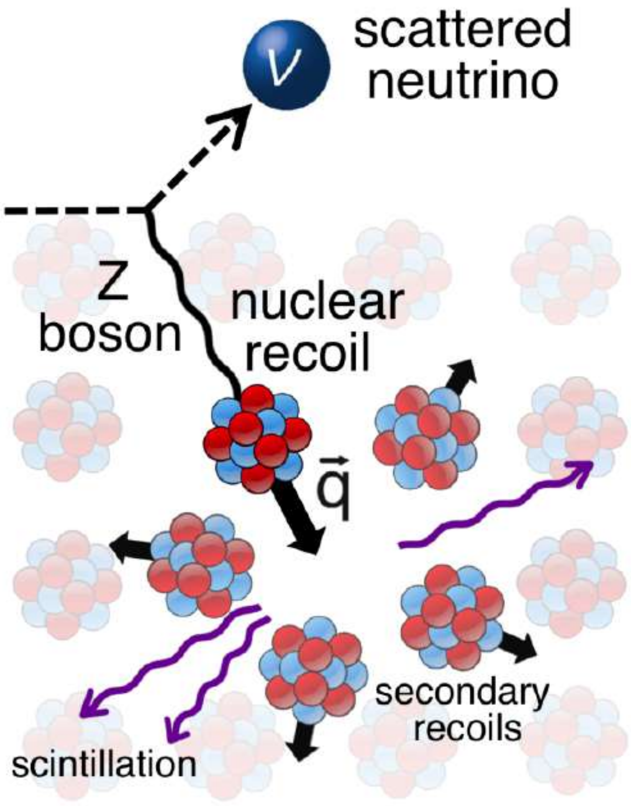
D. Akimov et al. (COHERENT). Science 357, 1123–1126 (2017)

Why is CEvNS hard to detect?

- Cross section is large for a weak-nuclear interaction
- Very-low energy nuclear recoils

$$E_r^{max} \simeq \frac{2E_\nu^2}{M} \simeq 50\,\mathrm{keV}$$ For 50 MeV neutrino

  - Detector needs low detection energy threshold!
- Background rejection paramount!

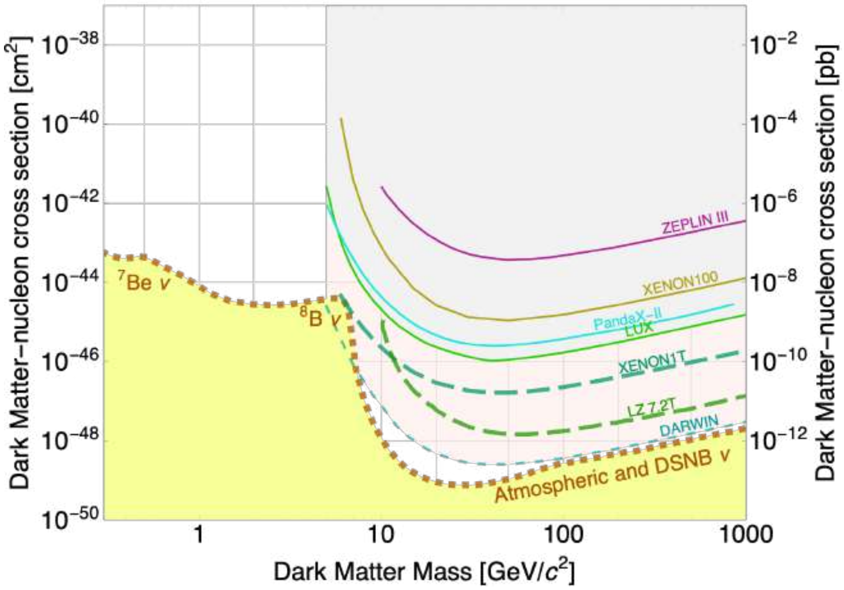


D. Akimov et al. (COHERENT). Science 357, 1123–1126 (2017)

Physics Implications

$$\frac{d\sigma}{dE} = \frac{G_F^2}{2\pi}[(1/2 - 2\sin^2\theta_w)Z - (1/2)N]^2(1 - \frac{ME}{2E_\nu^2})F(Q^2)^2$$

- Measurement of $\sin^2(\theta_W)$ at low momentum transfer
- Neutrino electromagnetic properties
- Physics Beyond the Standard Model
  - New mediators and non-standard interactions
  - Background to Dark Matter searches
  - Accelerator-Produced Dark Matter
- Reactor Monitoring
- Nuclear Structure
- Supernova Neutrino (SN) physics



http://cdms.berkeley.edu/limitplots/

Non-standard interactions (NSI)

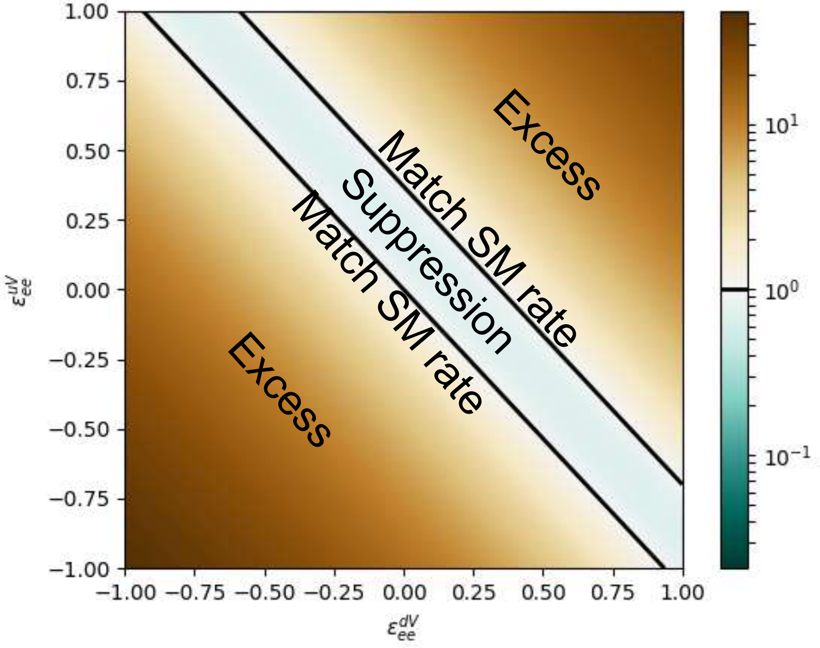
- Addition to SM Lagrangian

$$\mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \epsilon_{\alpha\beta}^{f,P} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P f)$$

$$Q_W^2 \to Q_{\text{NSI}}^2 = 4\left[N\left(-\frac{1}{2}+\epsilon_{ee}^{uV}+2\epsilon_{ee}^{dV}\right)+Z\left(\frac{1}{2}-2\sin^2\theta_W+2\epsilon_{ee}^{uV}+\epsilon_{ee}^{dV}\right)\right]^2 + 4\left[N(\epsilon_{e\tau}^{uV}+2\epsilon_{e\tau}^{dV})+Z(2\epsilon_{e\tau}^{uV}+\epsilon_{e\tau}^{dV})\right]^2 .$$

  - Modifies weak charge
  - NSI manifest as scaling of expected CEvNS cross section

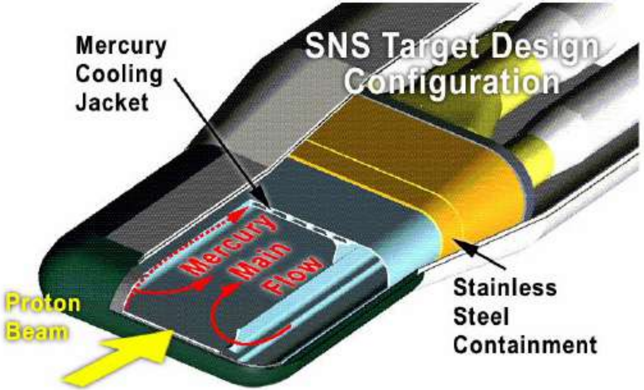
- CEvNS sensitive to both non-universal and flavor changing neutral currents



J. Barranco *et al.*, Phys. Rev. D 76 (2007)
J. Billard, J. Johnston, B. Kavanagh, arXiv:1805.01798

COHERENT at the Spallation Neutron Source and First observation of CEvNS on CsI target

The Spallation Neutron Source (SNS) at ORNL

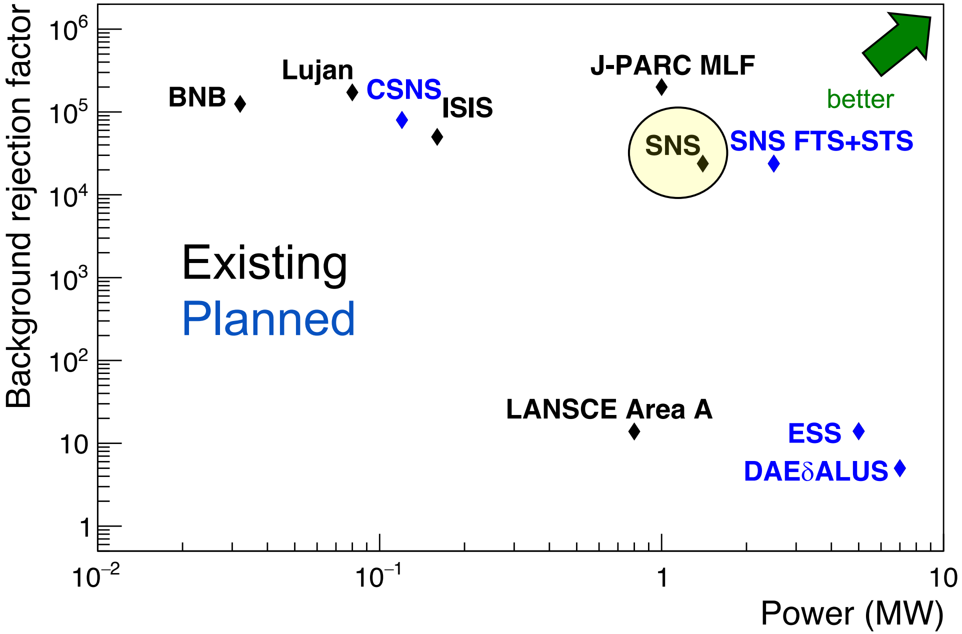


- Currently world's most powerful pulsed proton beam
  - Proton collisions with mercury create neutrons
    - AND neutrinos!

Images from neutrons.ornl.gov

Why SNS?

- Multiple accelerators around the world
  - SNS has best combination of
    - Beam power - 1.4 MW
    - Background rejection through 60 Hz, 350 ns FWHM pulsed beam



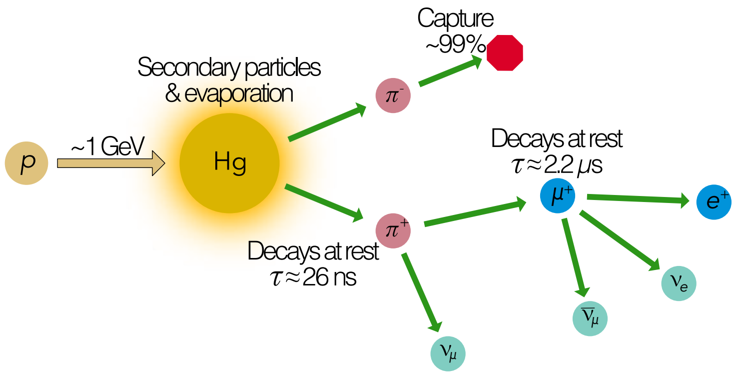
SNS as a Neutrino Source

- p-Hg interactions also produce pions at a rate of ~0.09 pions/proton in addition to neutrons
  - Pions then decay at rest and produce muon and neutrino ("prompt")
  - Muon decays at rest and produces two other neutrinos ("delayed")

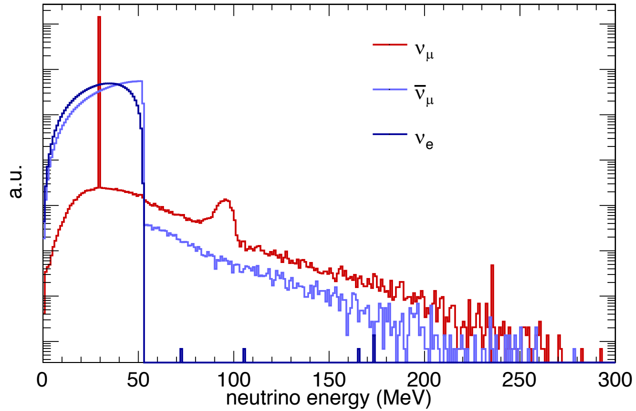
$\pi^+ \rightarrow \mu^+ + \nu_\mu$ Prompt 29.9 MeV ν_μ

$\mu^+ \rightarrow e^+ + \overline{\nu}_\mu + \nu_e$

Delayed, spectrum from 3-body decay



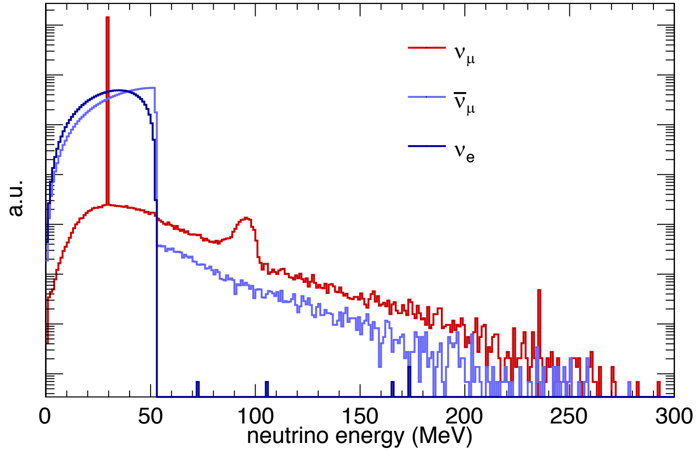
SNS neutrino spectrum

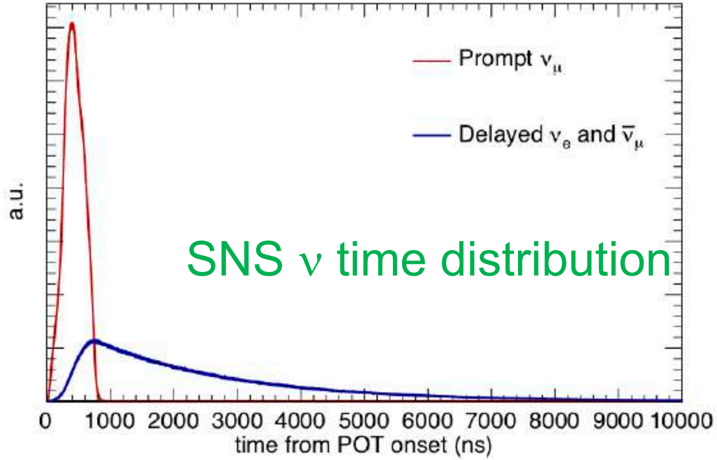


SNS as a Neutrino Source

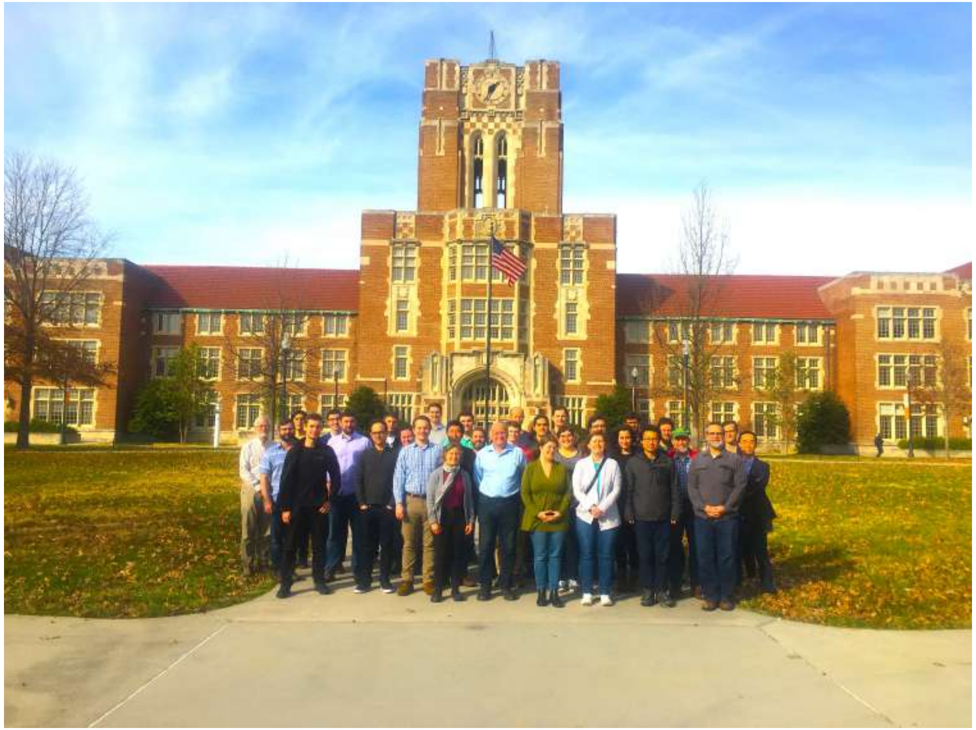
- Neutrino flux ~1 x 10^7 ν/flavor/cm^2/s at 20 m from target
- 1% decay in flight component
- ~2 x 10^{23} protons on target (POT)/year with routine operation at 1.4 MW!

SNS ν energy spectrum





The COHERENT Collaboration



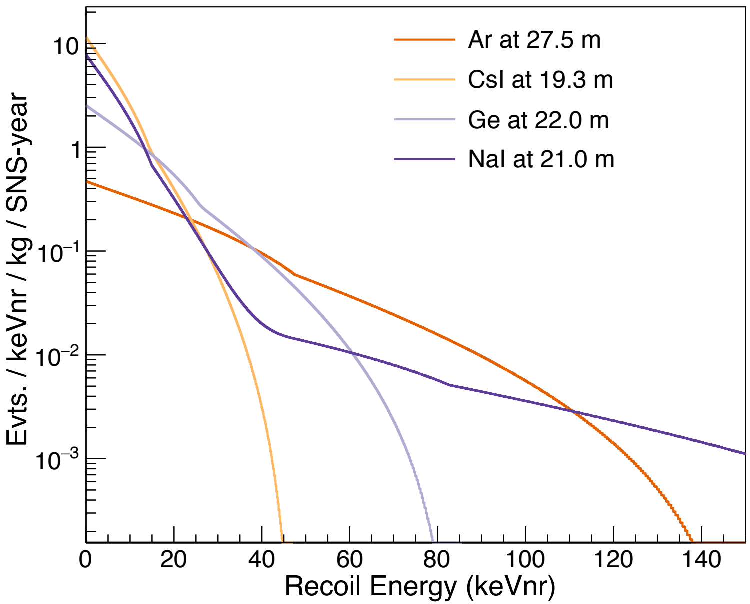
~80 members,
~20 institutions
4 countries

http://coherent.ornl.gov/

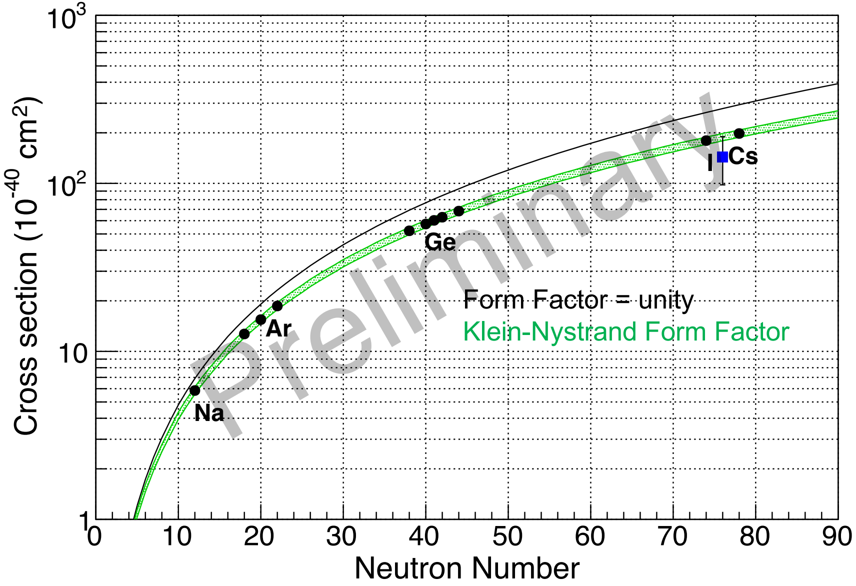
The COHERENT Collaboration

- First goal to observe CEvNS and measure N^2 dependence of CEvNS cross section via multiple targets

SM predicted CEvNS recoil spectra



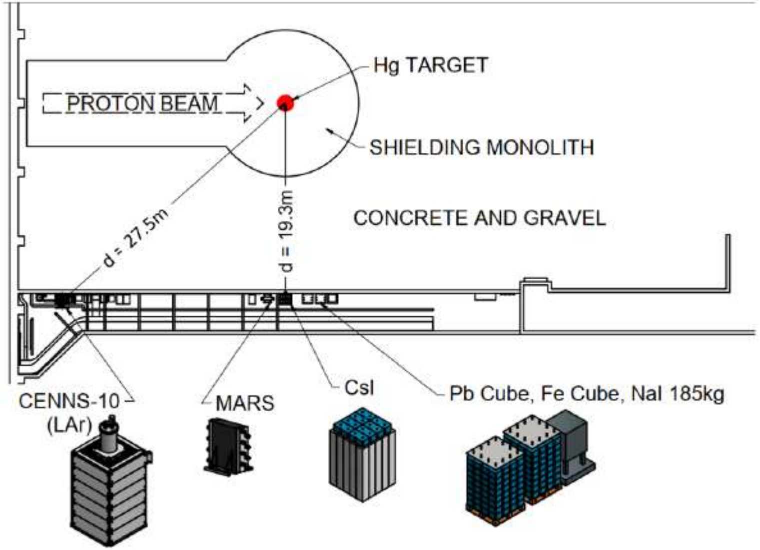
Total SM predicted CEvNS cross section vs *N*



S. R. Klein and J. Nystrand., Phys. Rev. C 60, 014903 (1999)

COHERENT at the SNS

- Location in basement of SNS target building ("Neutrino Alley")
  - 19-28 meters from Hg target
  - A lot of hard work went into this location by demonstrating low backgrounds

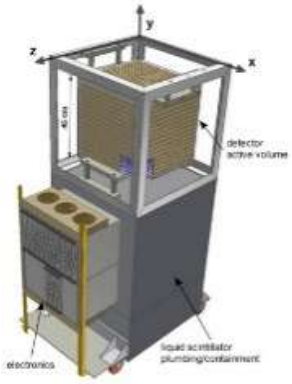


Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil Threshold (keVnr)
CsI[Na]	Scintillating crystal	14.6	19.3	6.5
Ge	HPGe PPC	16	20	2-2.5
LAr	Single-phase	24	27.5	20
NaI[Tl]	Scintillating crystal	185*/3338	28	13

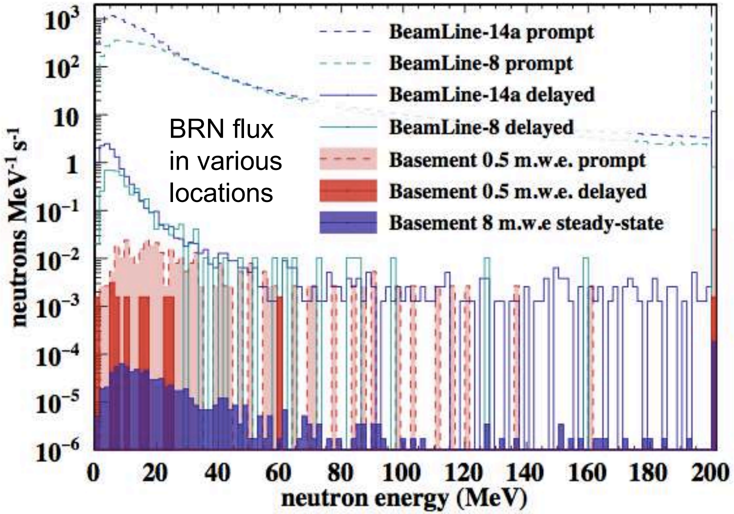
Neutron Background Measurements

- Neutrons produced by proton colliding with the target are problematic for CEvNS measurement (beam related neutrons)
  - Mimic CEvNS signal and are in time with the beam!
  - Neutrino Alley at 8 m.w.e overburden
    - 19-28 m steel+concrete shielding from target
  - Beam related neutron (BRN) background measured across hallway with several detectors
    - MARS – Sandia
    - Sandia “Neutron Scatter Camera”
    - IU SciBath detector - at CENNS-10 location
    - Many orders of magnitude lower in Neutrino Alley than in neutron scattering experiment beamlines

Sandia “Neutron Scatter Camera”



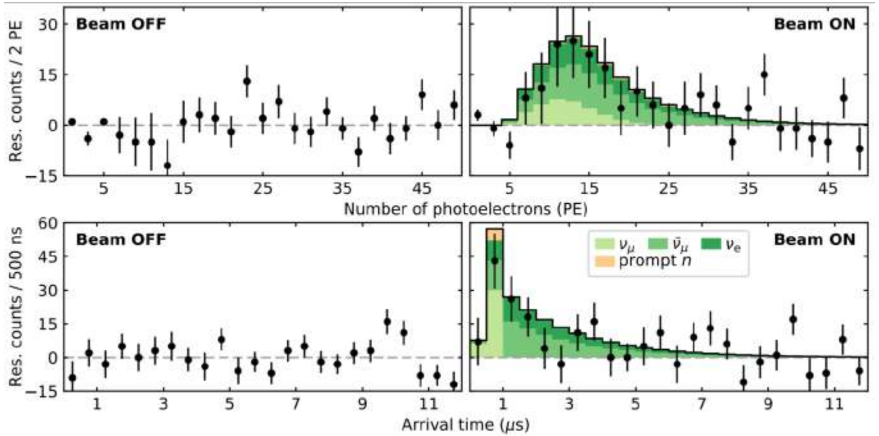
SciBath



Discovery of CEvNS

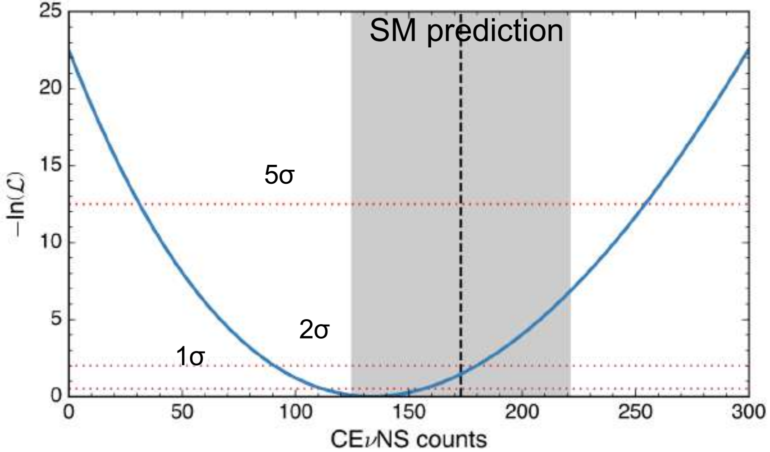
- 14.6 kg CsI crystal
- 2D (energy and time) Maximum Likelihood fit to data gives:
- 134 ± 22 CEvNS events
- Standard model predicts 173 ± 48 CEvNS events
- Null result rejected at 6.7σ
- New constraints on NSI
- More data available

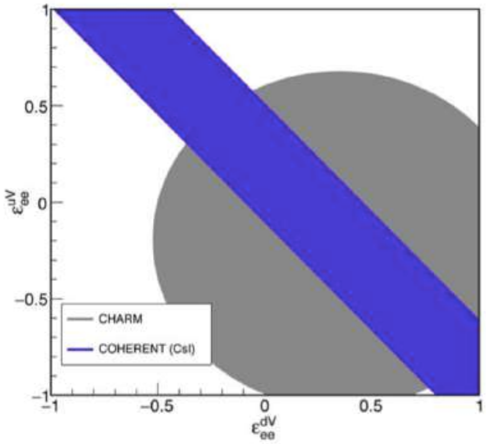
Energy



Time relative to beam pulse

10.1126/science.aao0990



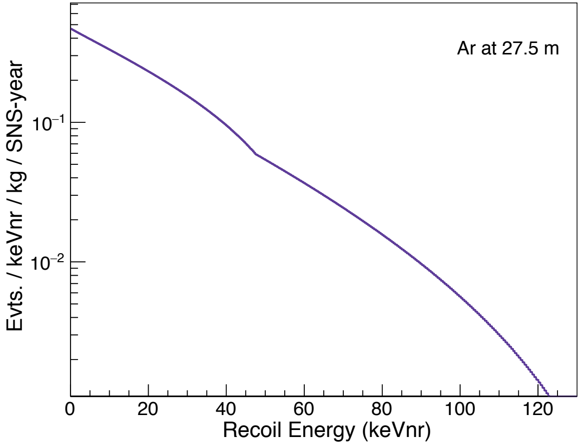


CENNS-10 Detector and First detection of CEvNS on Ar target

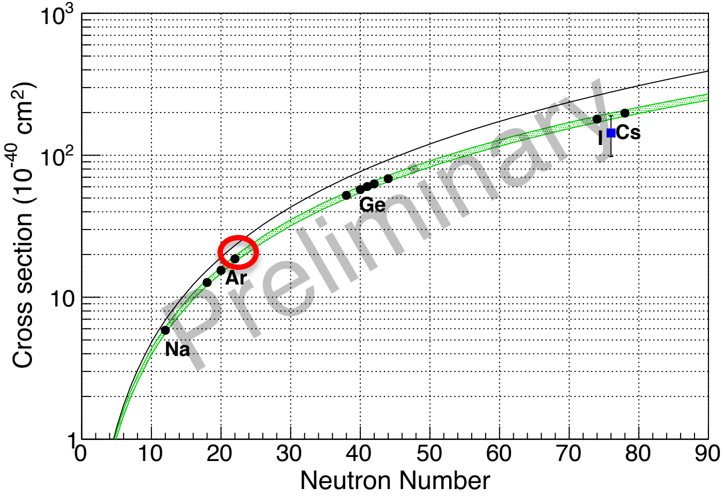
Liquid Argon (LAr) for CEvNS

- Low N nucleus for CEvNS measurement
  - Map out N^2 dependence of CEvNS cross section after CsI measurement
- Large scintillation yield of 40 photons/keVee
  - Scintillation light at 128 nm, need wavelength shifter
- Well-measured quenching factor
- Pulse shape discrimination (PSD)/Particle ID (PID) capabilities for nuclear/electron recoil separation
  - ~6 ns singlet light
  - ~1.6 μs triplet light
  - Electron recoil (ER) events mostly triplet light, Nuclear recoil (NR) events mostly singlet light

SM predicted CEvNS event rate vs. recoil energy

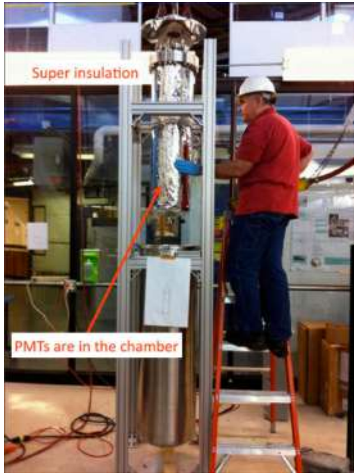


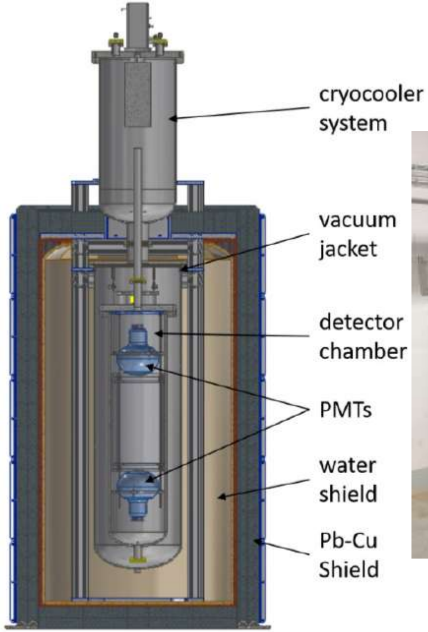
Total SM predicted CEvNS cross section vs *N*



The CENNS-10 Detector

- Originally built in 2012-2014 by J. Yoo et al. at Fermilab for CENNS effort at Fermilab
  - Thanks to A. Lathrop, R. Flores, R. Schmitt, R. Davila, D. Butler, and L. Harbacek for help on construction, design, and review!
- Moved to the SNS for use in COHERENT late 2016 after upgrades at IU and additional of substantial shielding and infrastructure at the SNS
- 24 kg fiducial volume
- 2x 8” Hamamatsu PMTs, 18% QE at 400 nm
- Tetraphenyl butadiene (TPB) coated side reflectors/PMTs
- 10 cm Pb/ 1.25 cm Cu/ 20 cm H_2O shielding
- Engineering Run (early 2017): high threshold, no lead shielding, blind analysis finished, published results (Phys. Rev. D100 (2019) no.11, 115020)
- First Production Run (July 2017-December 2018): improved threshold, blind analysis with two parallel groups finished, publication expected in very near future

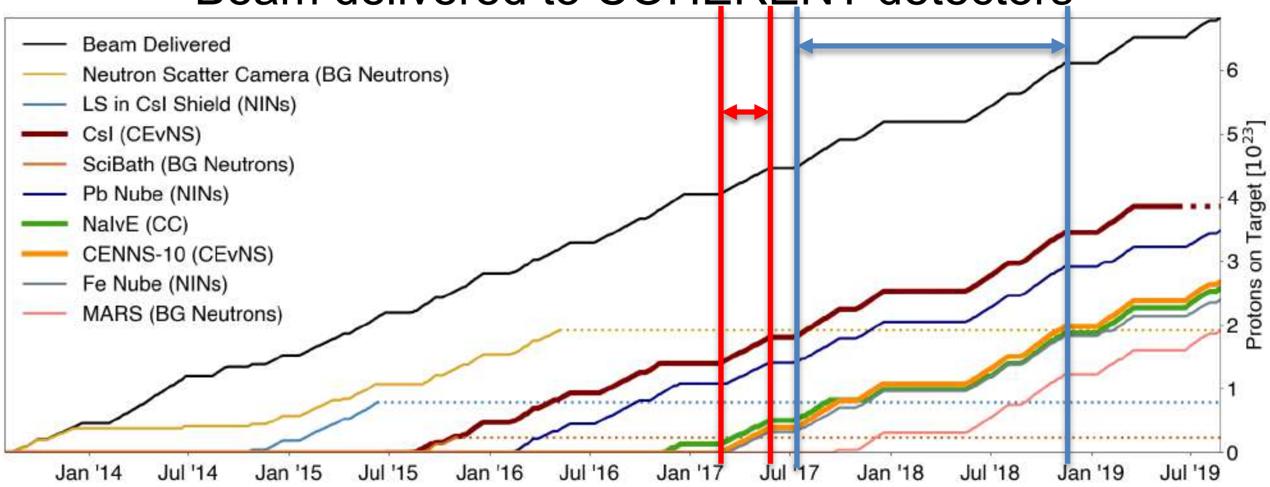




CENNS-10 Data Collection

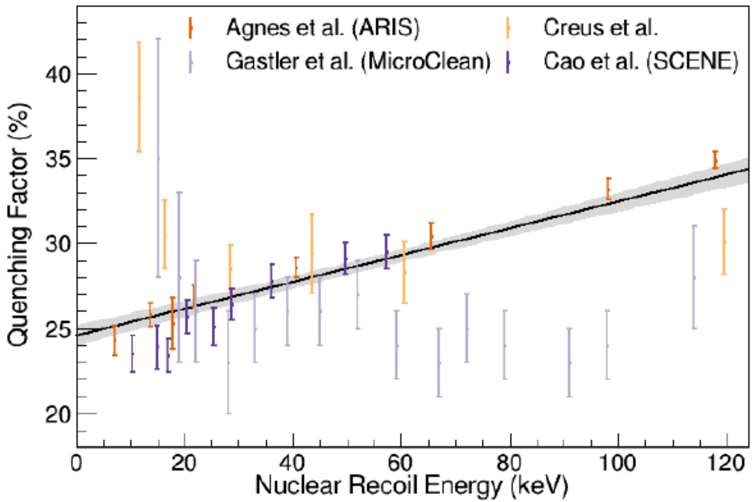
- Engineering Run of total 1.8 GWhr (~0.4 x 10^{23} POT) of integrated beam power from February-May 2017
- Data set considered for first physics result (First Production Run) reported here is total 6.1 GWhr (~1.4 x 10^{23} POT) of integrated beam power from July 2017-November 2018

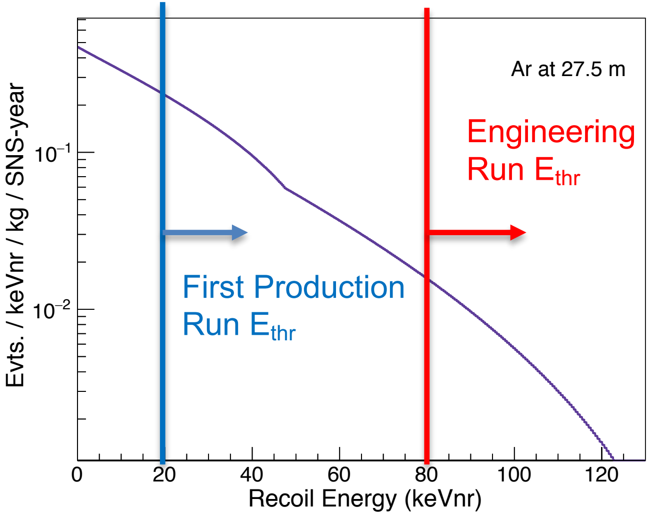
Beam delivered to COHERENT detectors



LAr Quenching Factor

- Measurement of ratio of measured energy deposited from a nuclear recoil to measured energy deposited by an electron recoil at known energy
- Multiple measurements of LAr quenching factor in CEvNS region of interest
- Linear model fit to literature data over recoil energy range of 0-125 keVnr
  - 2% average relative uncertainty on quenching factor value in region of interest (ROI) from 0-125 keVnr
- Provides conversion from keVnr (nr = 'nuclear recoil') to keVee (ee = 'electron equivalent')

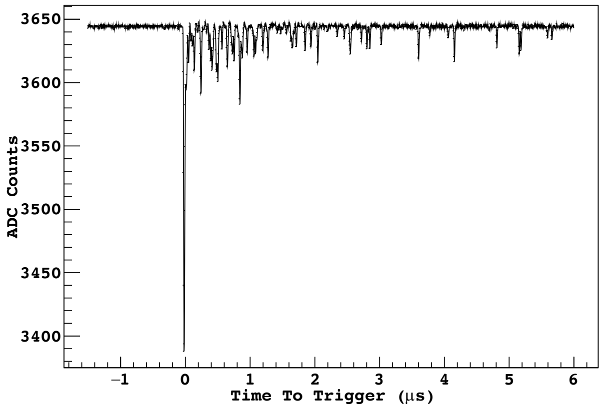




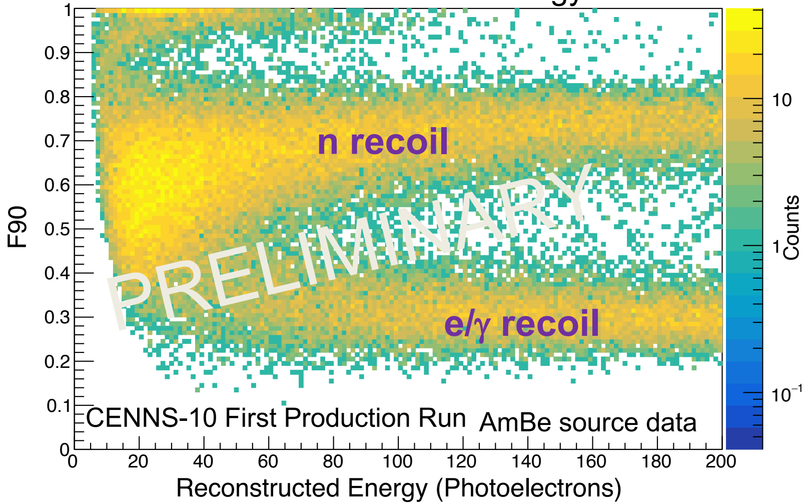
CENNS-10 Analysis Overview

- Read out 33 μs around each beam spill ("waveforms")
  - Apply pulse finding algorithm to find Ar interactions ("events")
- Characterize backgrounds
  - Measure and subtract beam-unrelated backgrounds with off-beam trigger
  - Measure beam-related neutrons (BRN) with no-water shielding runs
- Place cuts in energy, pulse shape discrimination (PSD, particle ID), and time
  - Define PSD variable "F90" = fraction of light detected in first 90 ns
- Analysis result from full 3D binned likelihood analysis in energy, F90, and time

Example waveform

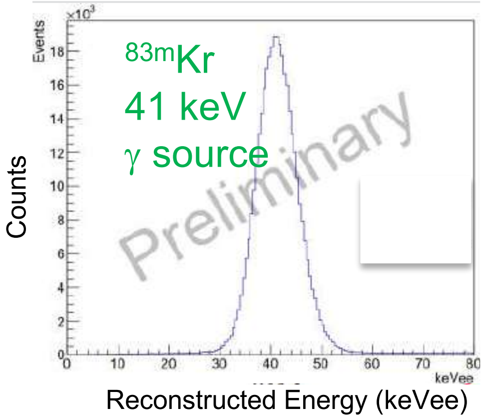


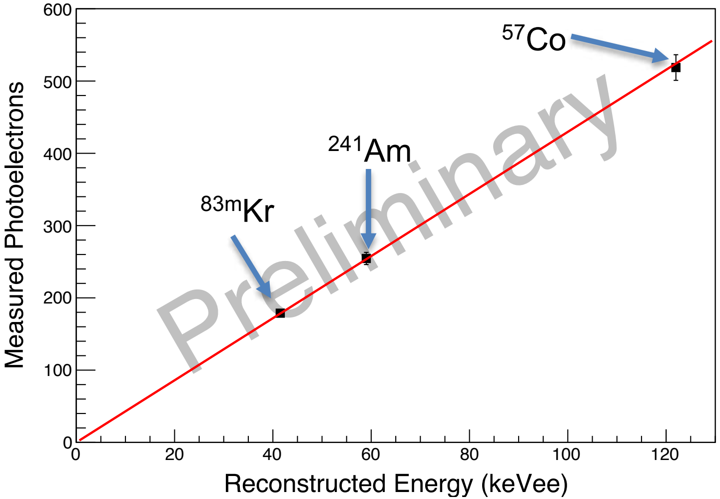
PSD vs reconstructed energy



CENNS-10 Calibration

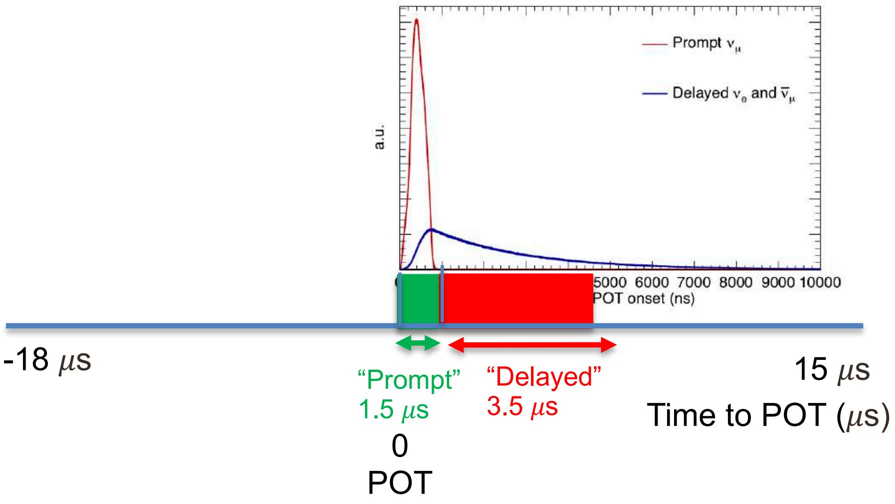
- Calibrate detector with variety of gamma sources
  - Measured light yield: 4.6 ± 0.4 photoelectrons/keVee
  - At ^{83m}Kr energy (41.5 keVee), mean reconstructed energy measured to 2%
    - 9.5% energy resolution at 41.5 keVee
- Calibrate detector nuclear recoil response using AmBe source





SNS Trigger Details

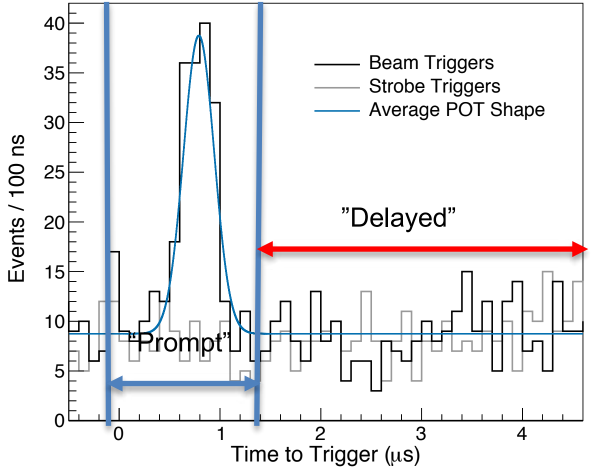
- SNS provides neutrinos in regions after protons on target (POT)
  - ”Prompt”: 0-1.5 μs after POT
  - “Delayed”: 1.5-5 μs after POT
- CEvNS neutrino signal in both prompt and delayed windows
- Beam-related neutron background measured only in prompt window
  - Delayed neutron measurements consistent with zero
- Identical off-beam trigger 14 ms after accelerator trigger
  - Measure beam-unrelated backgrounds in-situ



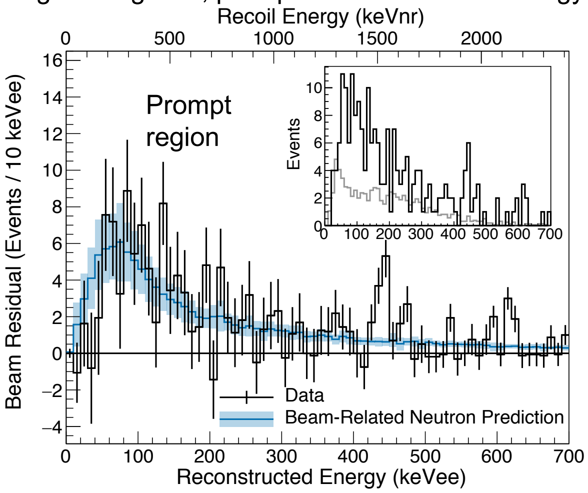
Neutron Background Characterization

- Data from Engineering Run, analysis of 1.8 GWhr of SNS beam data from February-May 2017
- TPB coated acrylic backed by Teflon reflector and TPB coated acrylic disk
- Threshold (80 keVnr) not low enough for sensitive CEvNS search
- Optimized cuts based on signal/noise
- Beam-related excess consistent with previous measurements/simulations
  - Delayed window excess consistent with zero due to high threshold and small beam sample
  - Use to constrain prompt beam-related neutron backgrounds for First Production Run
- Also, place limit on CEvNS cross section

Engineering Run, events vs time



Engineering Run, prompt beam excess vs energy



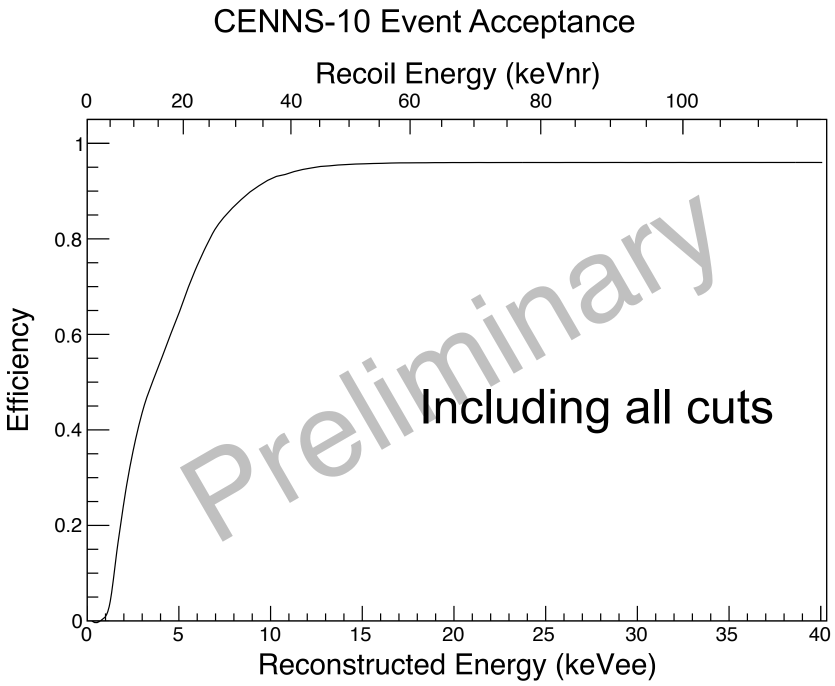
Engineering Run Results:
Phys. Rev. D100 (2019) no.11, 115020
M. R. Heath (IU PhD Thesis) (2019)
http://inspirehep.net/record/1744690?ln=en
PRD Editor's Suggestion

Parallel Blind Analyses

- Two groups performed independent analysis of CENNS-10 First Production Run
  - To lessen potential bias on result during analysis procedure
    - e.g. we know SM prediction
  - US-based and Moscow-based groups
  - SNS beam-on data were not seen until cuts finalized
  - No cut-values or results shared between groups before data opening
  - Will focus on US analysis in this talk

Event Selection

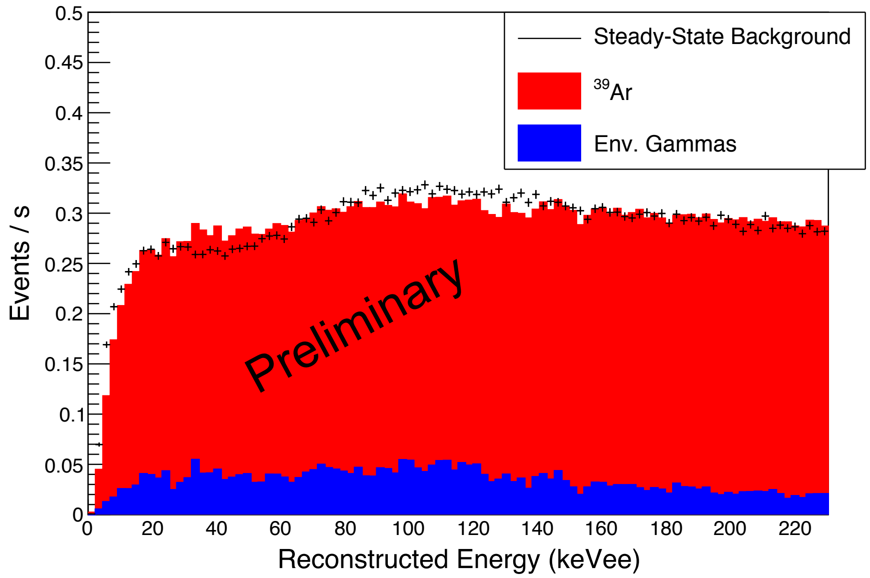
- Waveform/Event quality cuts
  - Baseline, Saturation, Pile-up
    - >96% of events pass
  - Candidate events
    - Threshold (>2 photoelectrons seen in both PMTs)
    - Apply energy, time, pulse shape discrimination (PSD) cuts



Beam-Unrelated Backgrounds

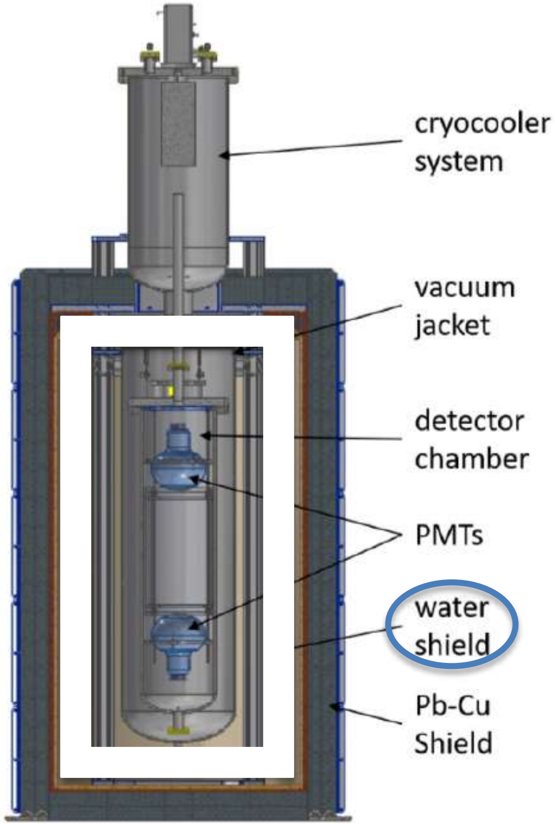
- Main beam-unrelated background is ^{39}Ar with full shielding
- Directly measured through off-beam triggers
- Large statistical errors remain after the background subtraction

CENNS-10 beam-unrelated background energy spectrum



Beam-Related Neutrons (BRN)

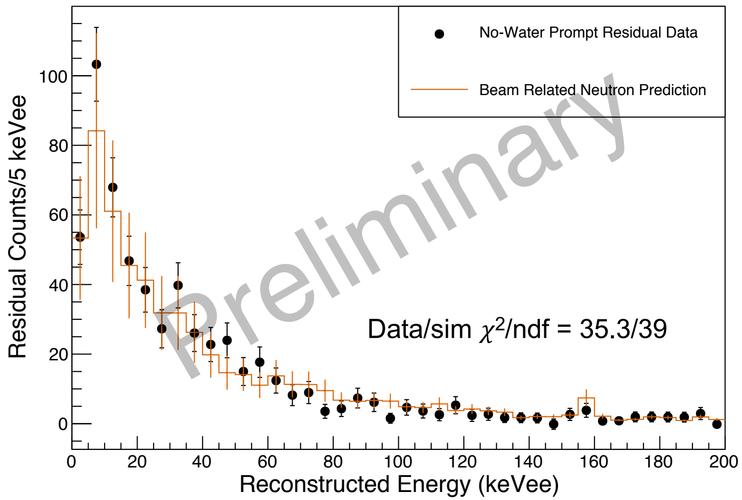
- Beam related neutron normalization from no-water shielding data
  - Remove 20 cm water shielding by emptying water tank
  - 0.54 GWhr integrated beam power of no-water shielding data
  - Predicted flux input to MC comes from external flux measurement at CENNS-10 location
    - Using IU built SciBath detector
- Scale MC for full-shielding with data/MC ratio from no-water
  - Only rely on MC to transport neutrons through water shield



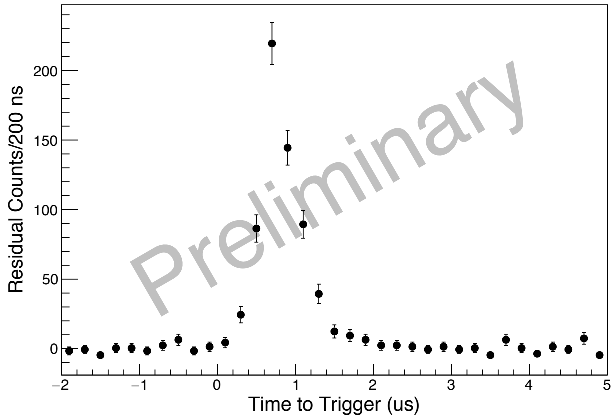
Beam-Related Neutrons (BRN)

- Compare beam-unrelated background subtracted excess in energy with MC prediction
  - Good energy shape agreement
- Normalization constraints come from measured Engineering Run rates
  - 30% prior uncertainty on the beam-related neutron normalization to reflect uncertainty in procedure
- Energy shape not sensitive to errors in quenching factor or flux shape
- Beam-related neutron predictions in time set by this measurement

No-water prompt beam excess vs reconstructed energy

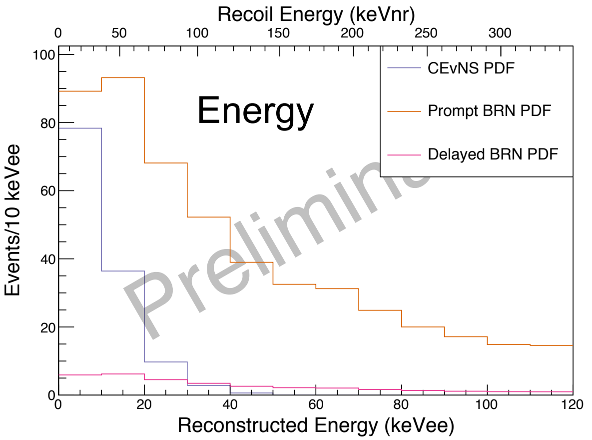


No-water beam excess vs time

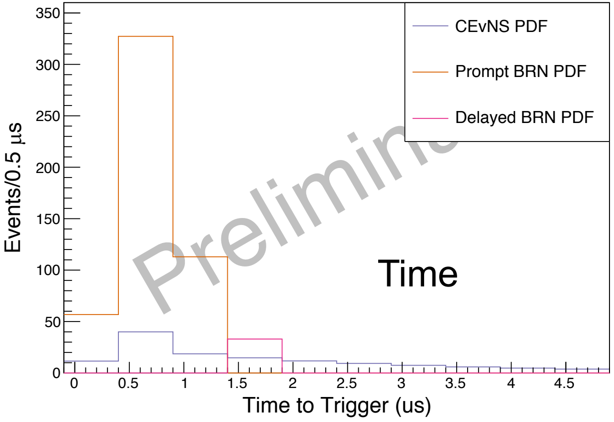


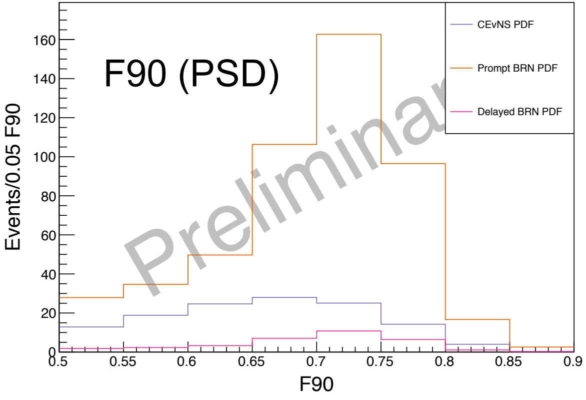
Predicted Event Distributions for Likelihood Analysis

- Perform 3D binned likelihood analysis in energy, F90, and time
- Waveform/event quality cuts
- 0-120 keVee energy range
- 0.5-0.9 F90 range
- -0.1-4.9 μs time to trigger range
- 960 total bins
- PDFs determined from CEvNS, beam-related neutron predictions
  - Beam-unrelated background determined from oversampling of data in off-beam window
  - Fit will further constrain background rates



Sample Prediction Projections in 1D





Sample Predictions

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

Systematic Errors

- For 3D likelihood analysis, need to further consider changes to energy, time, F90 spectra
  - Significant errors listed in lower table are those that change the PDF shape substantially
  - Additional systematics that effect the fit CEvNS rate are:
    - CEvNS: F90, timing profile
    - Beam-related neutrons: energy, timing profile

CEvNS Rate Measurement Systematic Errors	
Error Source	Total Event Uncertainty
Quenching Factor	1.0%
Energy Calibration	0.8%
Detector Model	2.2%
Prompt Light Fraction	7.8%
Fiducial Volume	2.5%
Event Acceptance	1.0%
Nuclear Form Factor	2.0%
SNS Predicted Neutrino Flux	10%
Total Error	13.4%

Additional Likelihood Fit Shape-Related Errors	
Error Source	Fit Event Uncertainty
CEvNS Prompt Light Fraction	4.5%
CEvNS Arrival Mean Time	2.7%
Beam Related Neutron Energy Shape	5.8%
Beam Related Neutron Arrival Time Mean	1.3%
Beam Related Neutron Arrival Time Width	3.1%
Total Error	8.5%

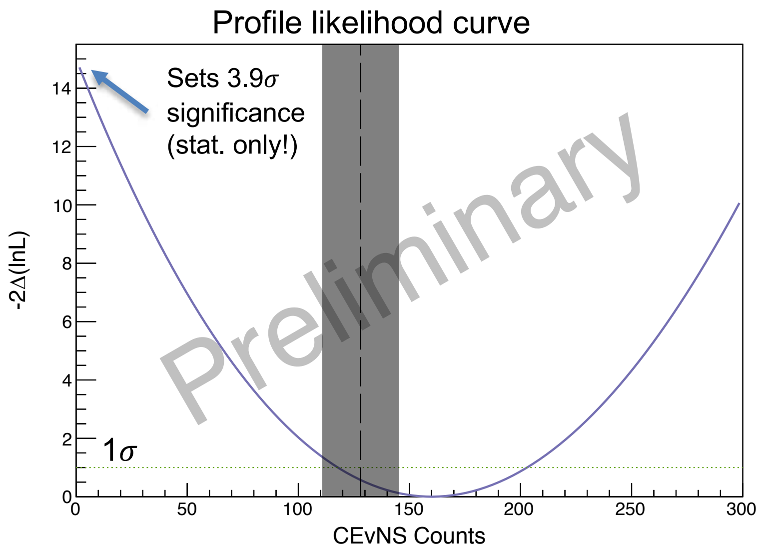
Then the data was opened!

Likelihood Fit Results

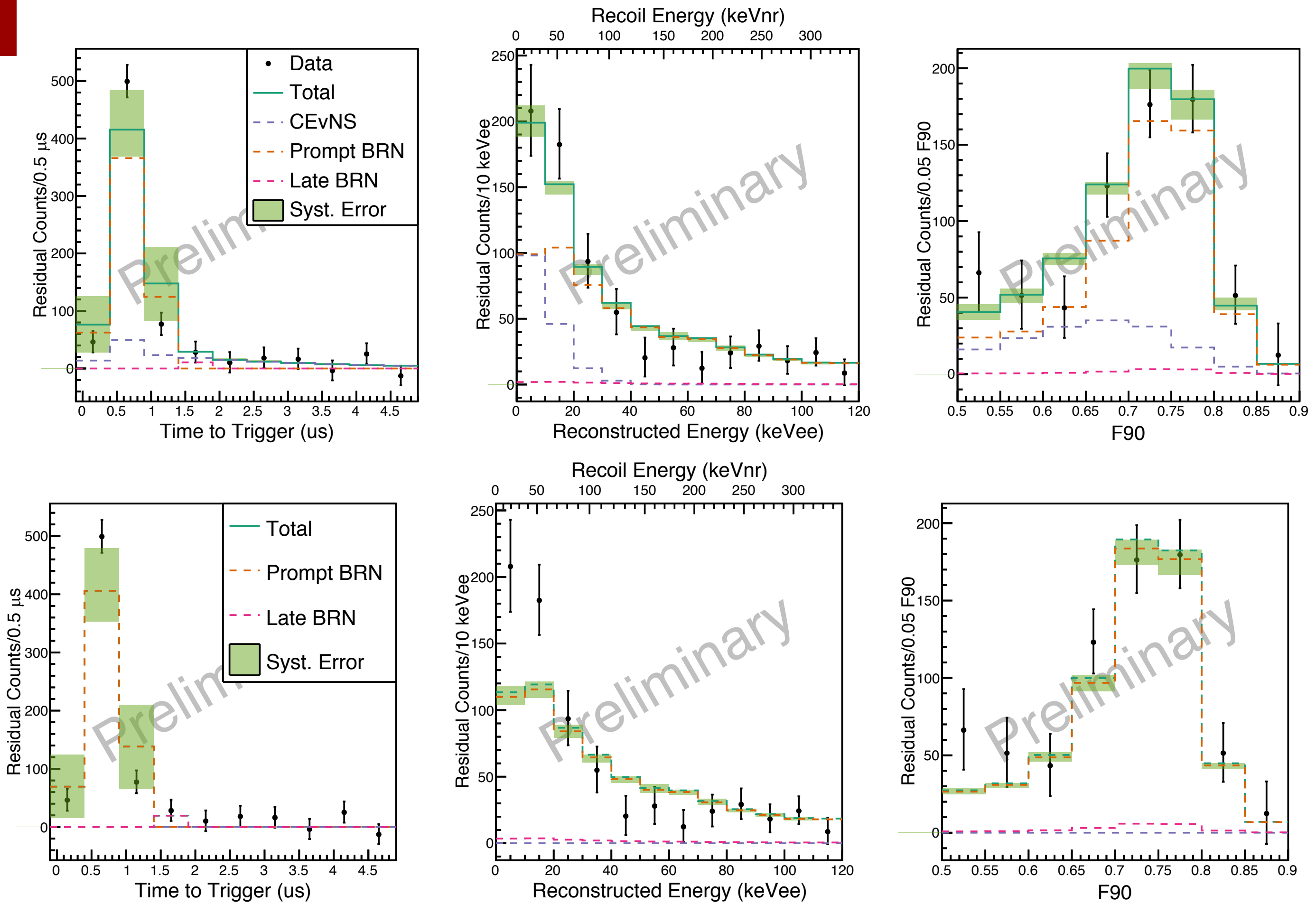
Predicted SM CEvNS	128 ± 17
Predicted Beam Related Neutrons	497 ± 160
Predicted Beam Unrelated Background	3154 ± 25
Predicted Late Beam Related Neutrons	33 ± 33

- 3D binned likelihood analysis in energy, F90, time space
  - Include both prompt and delayed time regions
- Best fit CEvNS counts of 159 ± 43 (stat.) ± 14 (syst.)
  - Result (stat. only) rejects null hypothesis at 3.9σ
  - Result (stat. + syst.) rejects null hypothesis at 3.5σ
  - Best fit result within 1σ of SM prediction
  - Wilks' Theorem checked with fake data

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



Spectra and Comparison with Null Hypothesis



Top Left: Prompt+delayed region, beam unrelated background subtracted projections of 3D likelihood fit

Bands are systematic errors calculated from 1 sigma excursions

Bottom Left: Same as above, null hypothesis fit (CEvNS = 0)

- Presence of CEvNS fits data well
- Recoil energy distribution results in poor fit without CEvNS

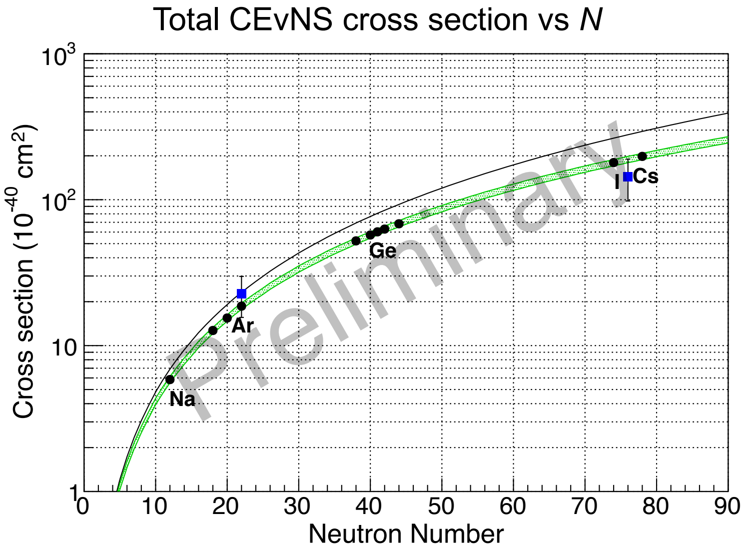
CEvNS Cross Section

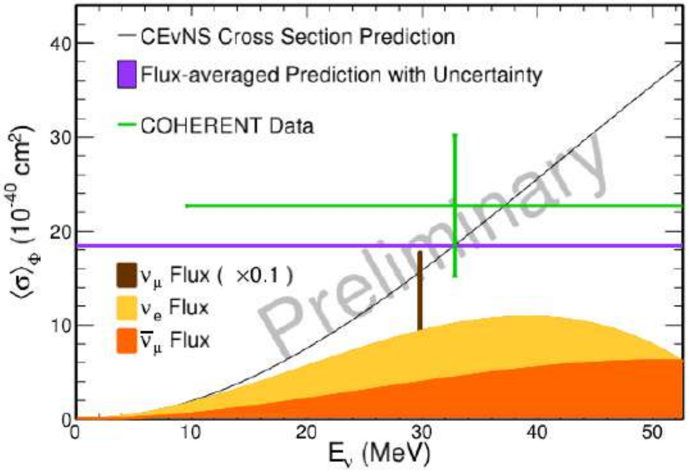
- Flux-averaged cross section
  - Compute using ratio of measured CEvNS events to predicted SM CEvNS events

$$\frac{N_{meas}}{N_{SM}} = 1.2 \pm 0.4$$

$$\sigma_{meas} = \frac{N_{meas}}{N_s \phi \epsilon} = (2.3 \pm 0.7) \times 10^{-39}\ cm^2$$

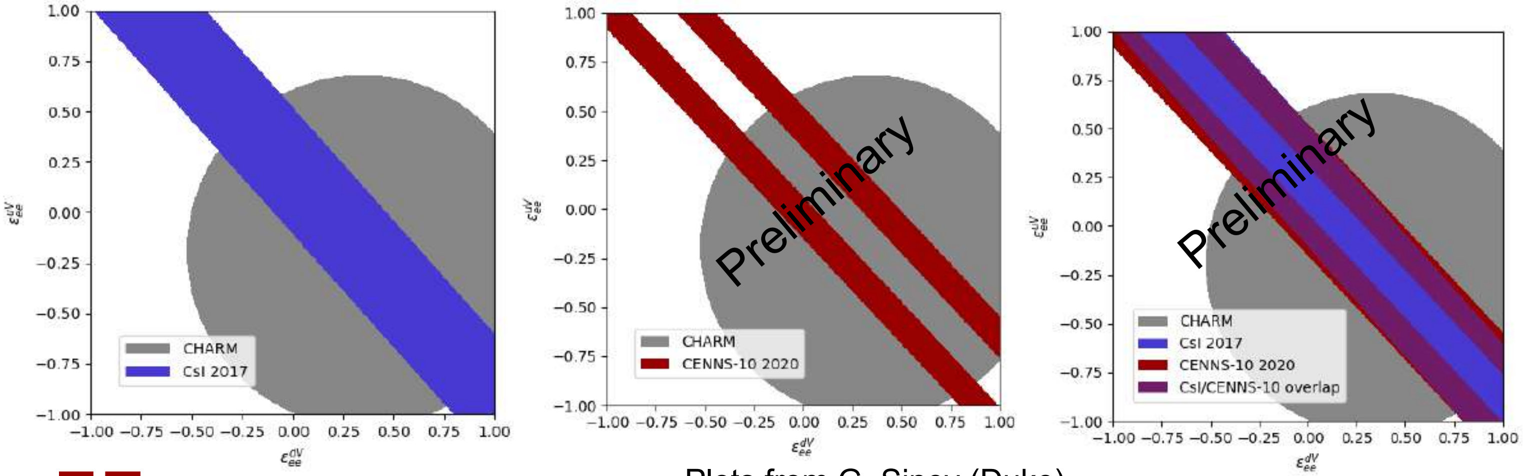
  - Error on σ_{meas} dominated by statistical error on N_{meas}
  - Additional systematics from fit systematics and on N_s, ϕ, ε via flux, fiducial volume, efficiency errors





Non-Standard Interactions (NSI)

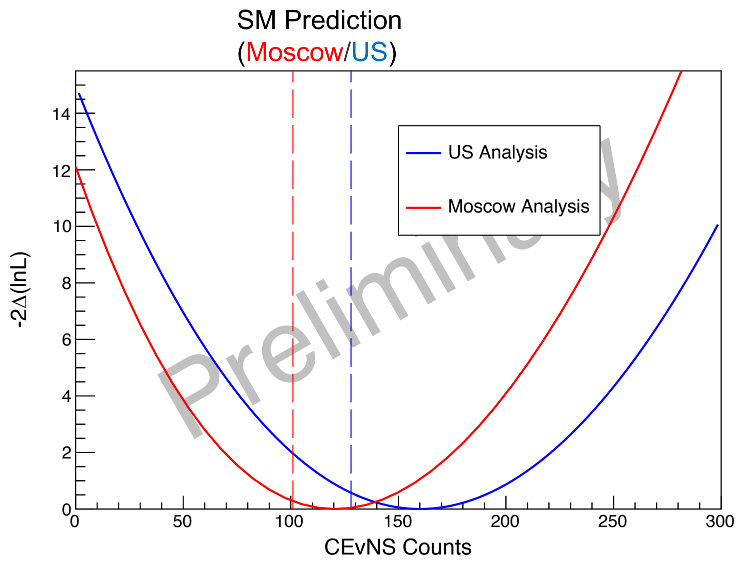
- Compute allowed regions in NSI parameter space
  - Specifically $\boldsymbol{\nu}_e$ flavor-preserving quark-vector coupling parameter space
    - Set all other $\boldsymbol{\varepsilon}$ = 0



Plots from G. Sinev (Duke)

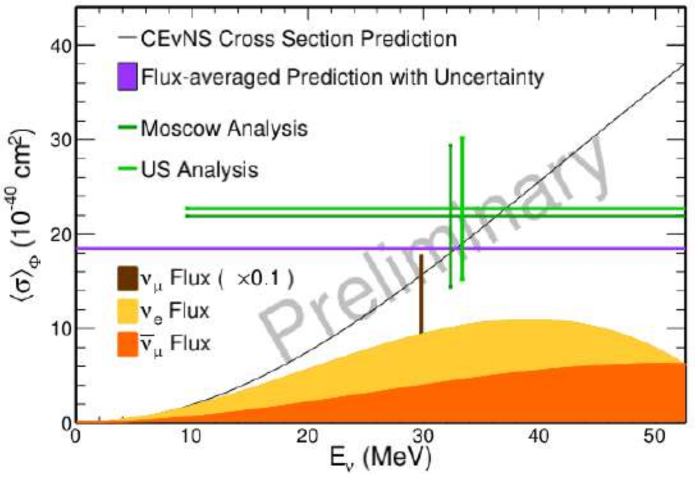
2-Analysis Comparison

- Moscow analysis
  - Similar 3D binned likelihood analysis performed
    - More strict selection cuts used in energy, F90
- Both analyses find significant excess of events within 1σ of SM prediction



Moscow analysis results

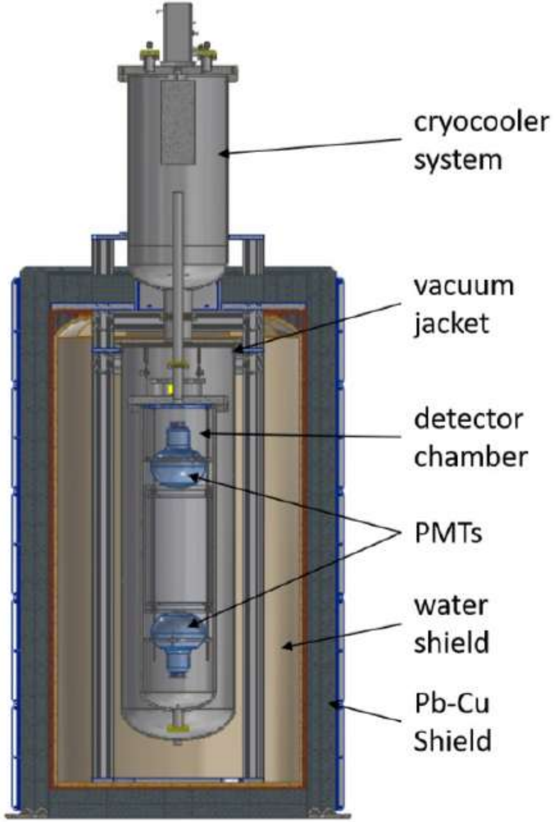
Predicted CEvNS	101 ± 12
Fit CEvNS	121 ± 36 (stat.) ± 15 (syst.)
2Δ(-lnL)	12.1
Null Rejection Significance	3.1σ (stat. + syst.)



Future COHERENT Liquid Argon – Towards CENNS-750

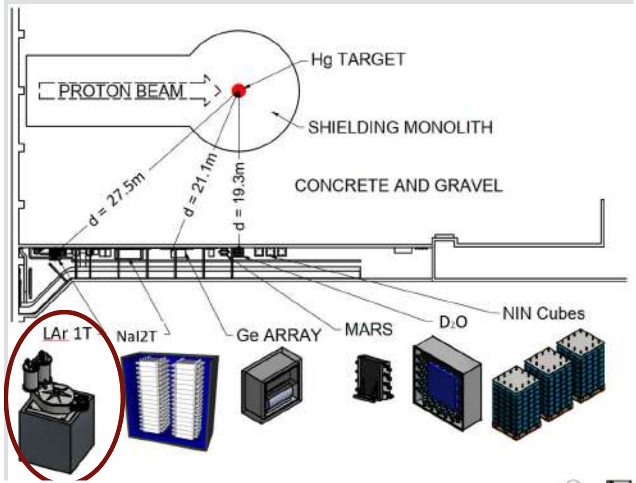
Future CENNS-10 Activities

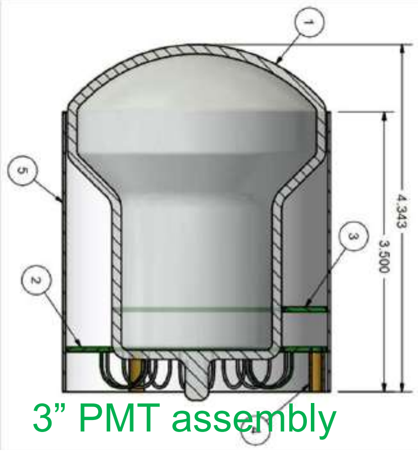
- Continuing physics data collection using CENNS-10
  - Additional >3 GWhr of data with additional neutron shielding installed
    - Need further neutron MC studies for analysis
- Possible considerations for CENNS-10 improvements
  - Possibility of acquiring underground Ar with lower ^{39}Ar content
  - Addition of further neutron shielding in current detector location
  - Move detector to previous CsI detector location for increased neutrino flux and lower neutron backgrounds
- R&D vessel to test Xe doping in LAr, photodetectors, wavelength shifters for ton-scale detector CENNS-750



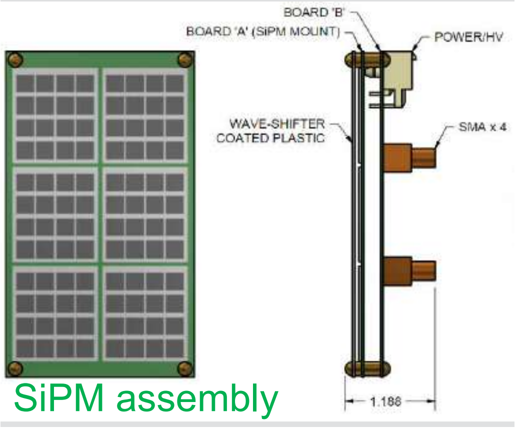
CENNS-750

- Single-phase LAr calorimeter, 610 kg fiducial mass
- Leverage successful operation of CENNS-10
    - Expect ~20 keVnr threshold in ~25x LAr volume, push for lower
- 3” PMTs or VUV/visible silicon photomultipliers (SiPMs)
    - Investigate optimal wavelength shifting scheme
    - Ongoing testing at IU/ORNL



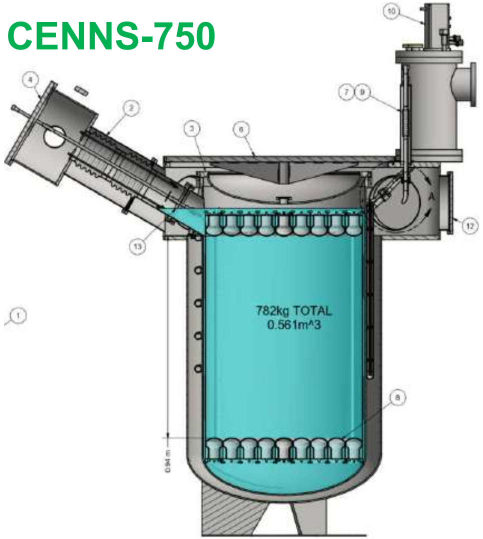


3” PMT assembly



SiPM assembly

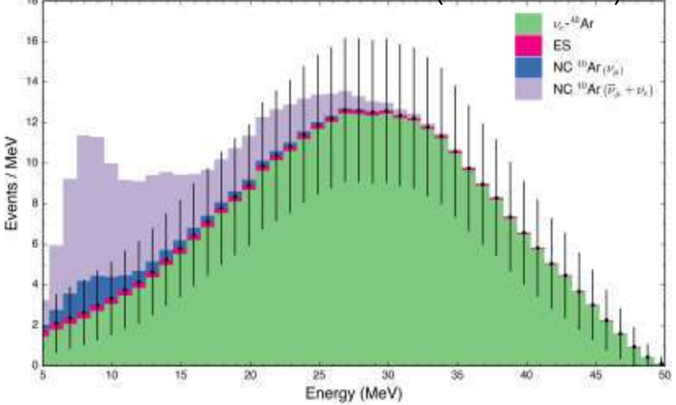
CENNS-750



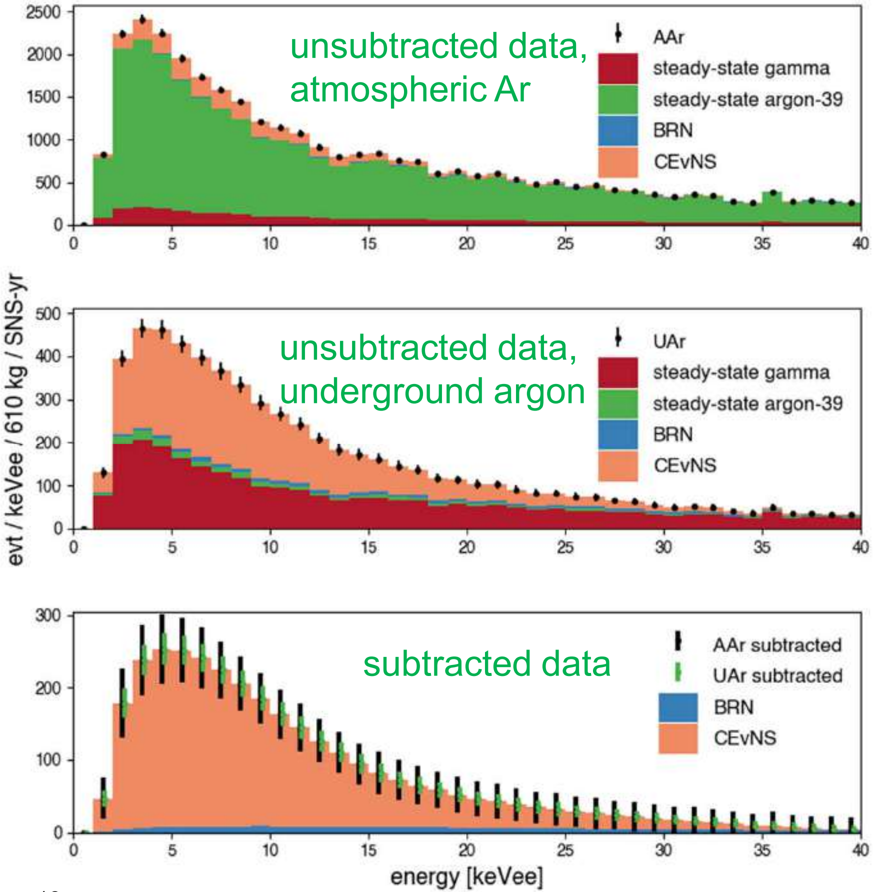
Precision Physics with CENNS-750

- ~3000 CEvNS events/SNS-year
- ~400 inelastic charged/neutral current (CC/NC) events/SNS-year
  - Important for DUNE low-energy physics program!

Estimated inelastic CC/NC (non-CEvNS) rates



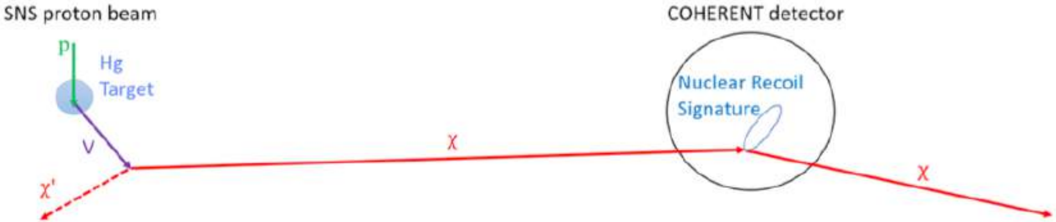
CEvNS/bkg predictions with CENNS-750

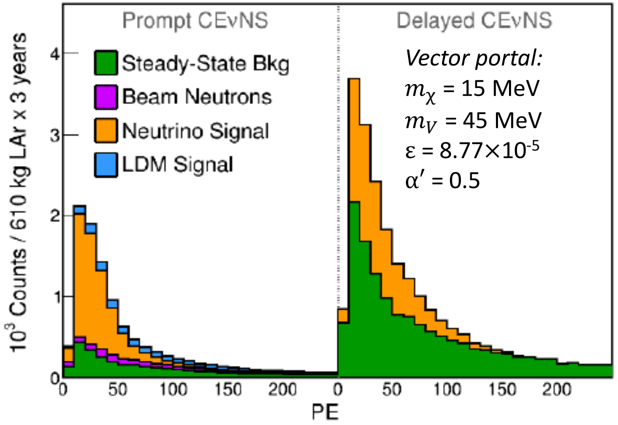


$\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K} \quad (\text{CC}) \qquad \nu + {}^{40}\text{Ar} \rightarrow \nu + {}^{40}\text{Ar} \quad (\text{NC})$

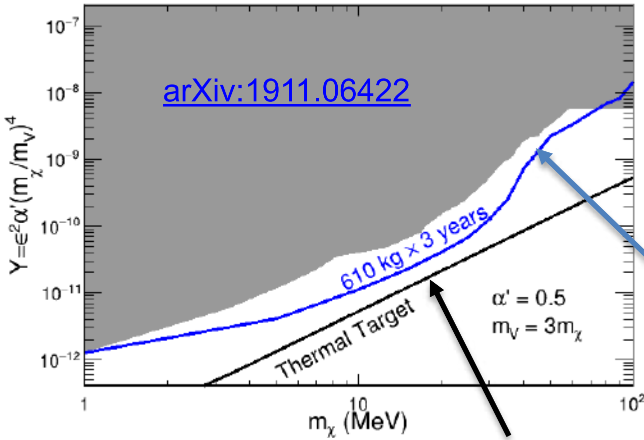
Precision Physics with CENNS-750

- CENNS-750 places strong limits on vector portal accelerator-produced light dark matter
  - Produced in p-Hg collisions at SNS
    - π^0 decay into dark matter
    - Interaction identical to CEvNS
  - Dark matter signal is excess over CEvNS signal
    - CEvNS is a background!
    - Understanding/reduction of beam-related neutrons important!





Plots from D. Pershey (Duke)



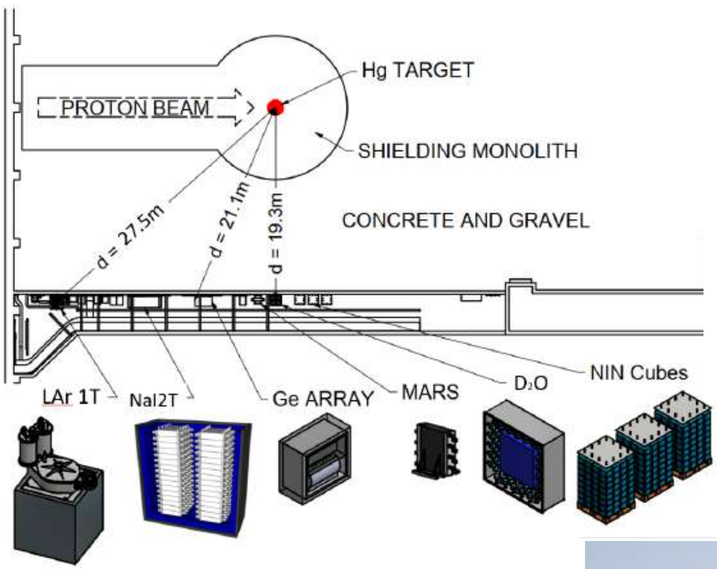
[arXiv:1911.06422](https://arxiv.org/abs/1911.06422)

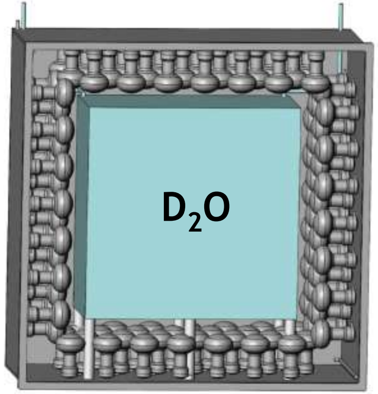
3 yrs of CENNS-750 at SNS

Relic density

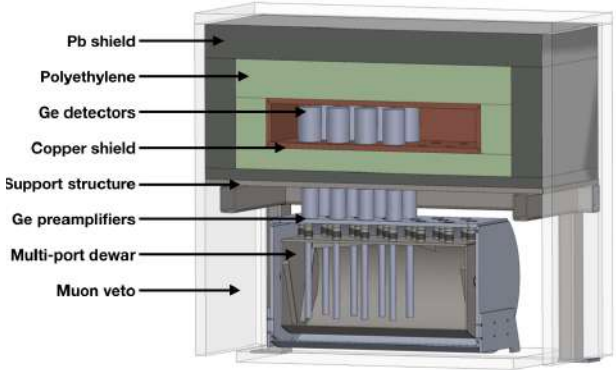
Other Future COHERENT Efforts

- 16 kg of HPGe detectors for CEvNS measurement
- Ton-scale NaI[Tl] detector array for simultaneous CEvNS/^{127}I charged current measurements
- Ton-scale D_2O Cherenkov detector to reduce neutrino flux uncertainty
  - ν_e-d charged current cross section theoretically known to 2-3%





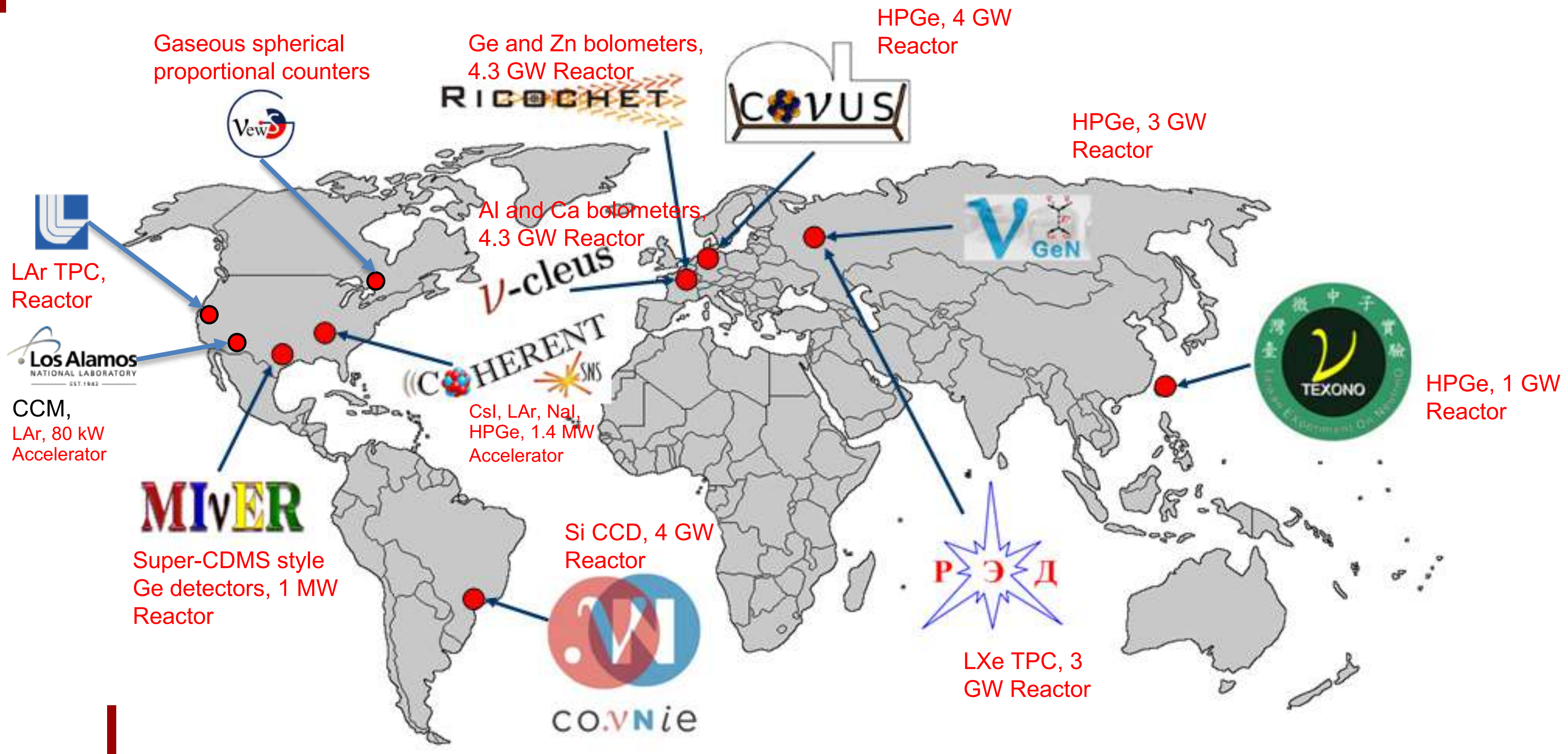
Ton-scale D_2O concept



COHERENT Ge conceptual design

Modular ton-scale NaI[Tl] concept

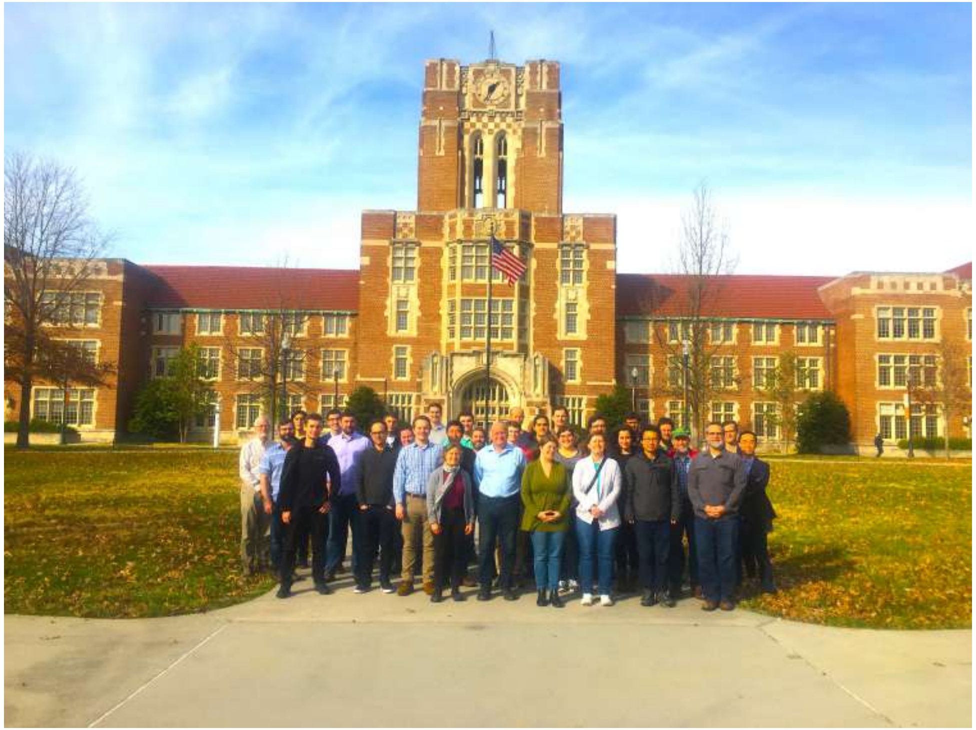
CEvNS Around the World



Summary

- CEvNS is a tool to access a host of fundamental physics topics
- The COHERENT experiment at the SNS has a rich program to measure CEvNS after first detection in 2017
- First low N measurement of CEvNS on ^{40}Ar with CENNS-10 detector
  - Thanks to Fermilab for the continued loan of the CENNS-10 detector!
  - 3.5σ observation of CEvNS in ^{40}Ar with first production data!
- COHERENT has a robust suite of future experiments, including Ge, NaI, and a ton-scale LAr detector CENNS-750

Thank you! Questions?



http://coherent.ornl.gov/

COHERENT

SNS SPALLATION NEUTRON SOURCE

Oak Ridge National Laboratory
Duke University
TUNL
Sandia National Laboratories
The University of Tennessee Knoxville
Los Alamos National Laboratory EST. 1943
NC State University
University of Washington
The University of Chicago
NM State
MEPhI
UF University of Florida The Foundation for The Gator Nation
KAIST
North Carolina Central University Founded 1910
Tufts University
Carnegie Mellon University
Laurentian University Université Laurentienne
University of South Dakota

U.S. Department of Energy Office of Science
NSF
KICP
NNSA National Nuclear Security Administration
CNEC