COHERENT Elastic Neutrino-Nucleus Scattering at the SNS

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Aspen 2019 Winter Conference - March 29, 2019

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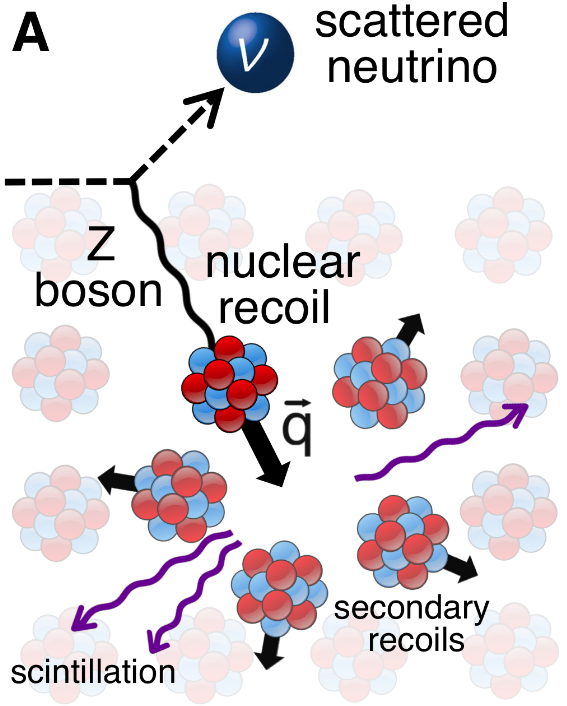
Photo: Rocky Maloney

Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

- Over 40 years ago, Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) was predicted as a consequence of the neutral weak current.
  D. Z. Freedman, PRD 9 (5) 1974

- Neutrino scatters coherently off all Nucleons → cross-section enhancement: $\sigma \propto$ **N²**
- Initial and final states must be identical: Neutral Current elastic scattering
- Only observable: nuclear recoil
- Nucleons must recoil in phase →low momentum transfer qR <1 → *very* low energy recoil



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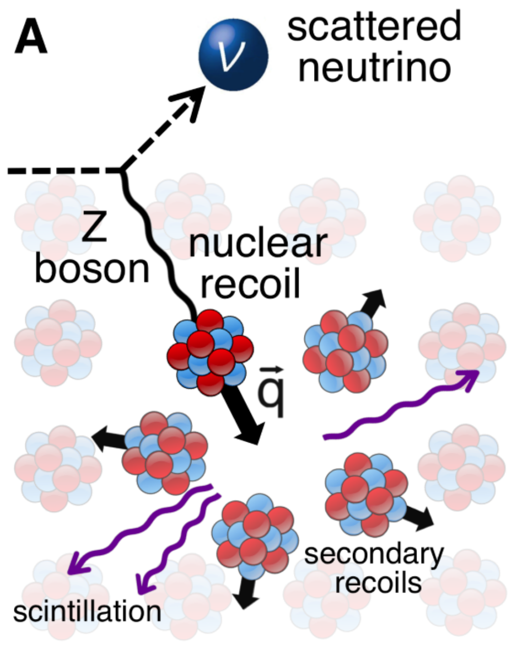
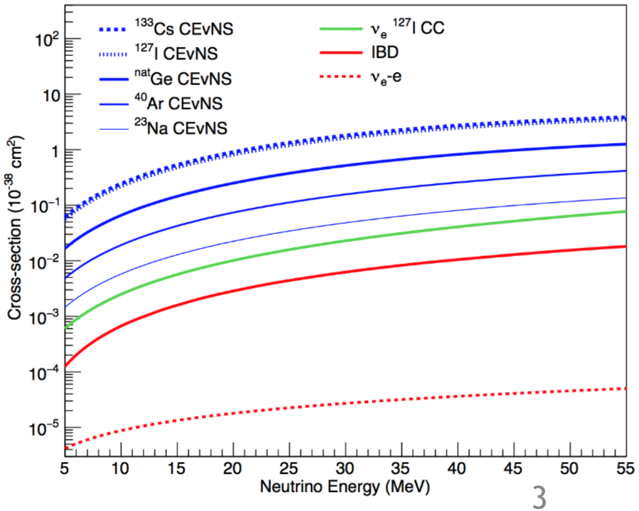


$$\frac{d\sigma}{dT}_{coh} = \frac{G_F^2 M}{2\pi}\left[(G_V+G_A)^2+(G_V-G_A)^2\left(1-\frac{T}{E_\nu}\right)^2-(G_V^2-G_A^2)\frac{MT}{E_\nu^2}\right]$$

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

$$G_V = (g_V^p Z + g_V^n N)F_{\mathrm{nucl}}^V(Q^2)$$
$$G_A = (g_A^p(Z_+ - Z_-) + g_A^n(N_+ - N_-))F_{\mathrm{nucl}}^A(Q^2)$$

$$g_V^p = \rho_{\nu N}^{NC}\left(\frac{1}{2}-2\hat{\kappa}_{\nu N}\sin^2\theta_W\right)+2\lambda^{uL}+2\lambda^{uR}+\lambda^{dL}+\lambda^{dR}$$
$$g_V^n = -\frac{1}{2}\rho_{\nu N}^{NC}+\lambda^{uL}+\lambda^{uR}+2\lambda^{dL}+2\lambda^{dR},$$



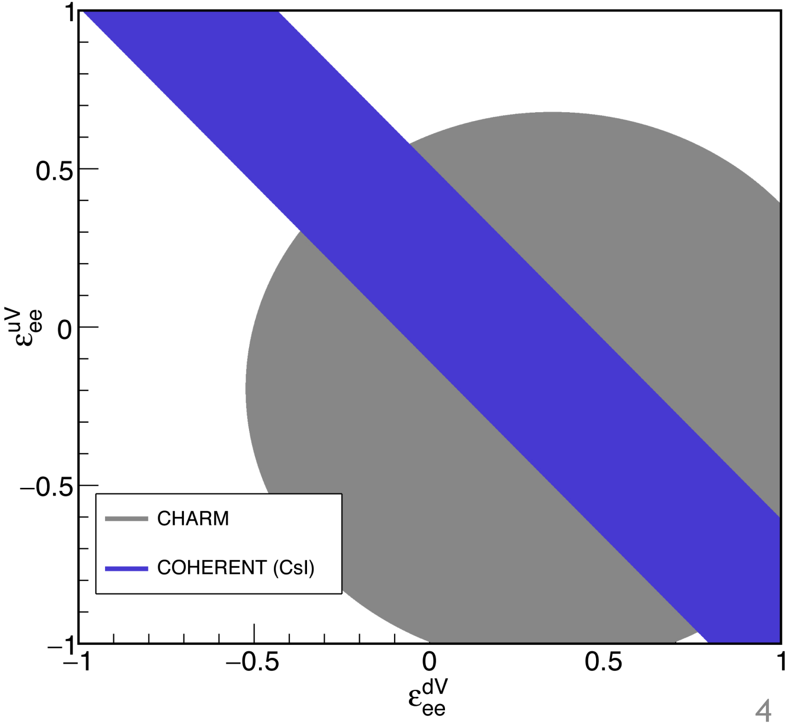
Well-understood CEvNS Standard Model cross section enables probes of new Physics!

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

$$G_V = ((g_V^p + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV})\, Z + (g_V^n + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV}\ )N)\ F_{\rm nucl}^V(Q^2)$$

Non-Standard Neutrino Interactions

- ‘ϵ’s represent new neutral current couplings, here flavor-preserving, non-universal.
- Arise from new mediators - Z’
- Constraints from CEvNS produce diagonal bands, angle determined by N:Z ratio



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CEvNS Physics

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

Nuclear Form Factors

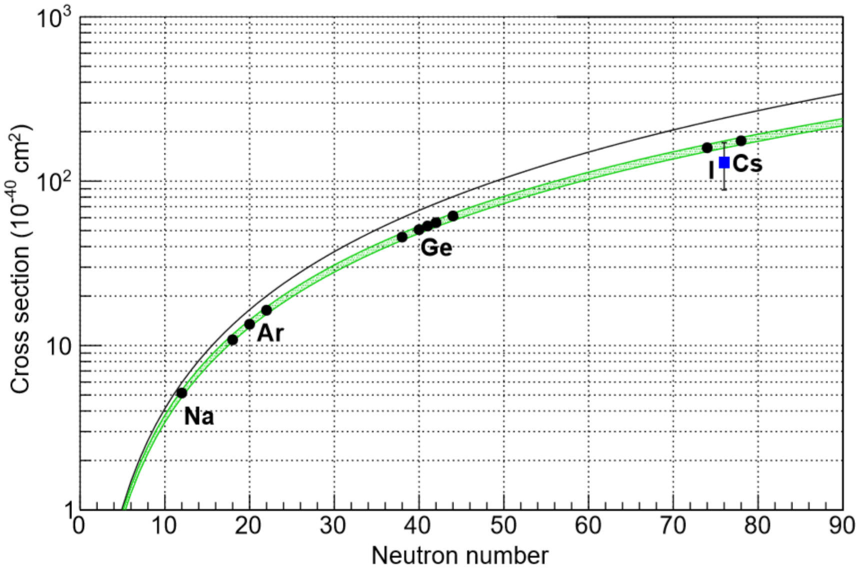
- Inferable through precision measurements

Sterile Neutrino Searches

- NC signal modulation with distance implies oscillations to steriles.

Weak Mixing Angle

- Measurements featuring targets with differing Z/N ratios
- Sensitive probe of SM physics



— Form Factor = 1

— Assumed Form-Factor

CEvNS Physics

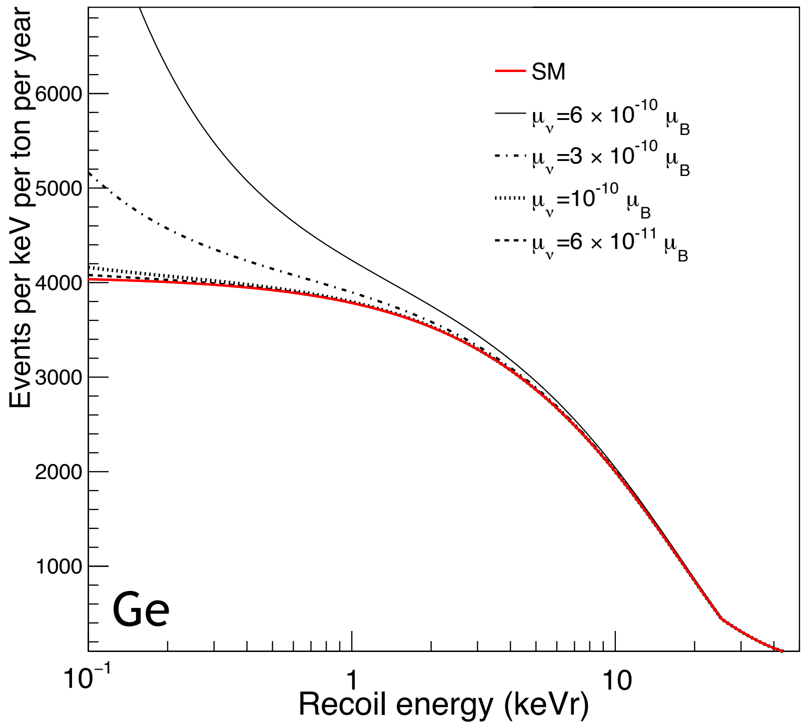
$$\frac{d\sigma}{dT}_{coh} = \frac{G_f^2 M}{2\pi} G_V^2 \left[1 + \left(1 - \frac{T}{E_\nu}\right)^2 - \frac{MT}{E_\nu^2}\right]$$

$$\left(\frac{d\sigma}{dT}\right)_{\rm EM} = \frac{\pi \alpha_{\rm em}^2 {\mu_{eff}}^2 Z^2}{m_e^2} \left(\frac{1 - T/E_\nu}{T}\right) F_Z^2(q^2)$$

Kosmas, Miranda, Papoulias, Tórtola, Valle: arXiv:1505.03202

Neutrino Magnetic Moment

- Dirac neutrino masses predict a NMM: $\mu_\nu \leq 10^{-19}\ \mu_B\ (m_\nu/1\text{eV})$
- Upper limits from
  - Cosmology: $\mu_\nu \leq \sim 10^{-12}\ \mu_B$
  - Borexino / Reactors: $\mu_\nu \leq 3\text{x}10^{-11}\ \mu_B$



K. Scholberg

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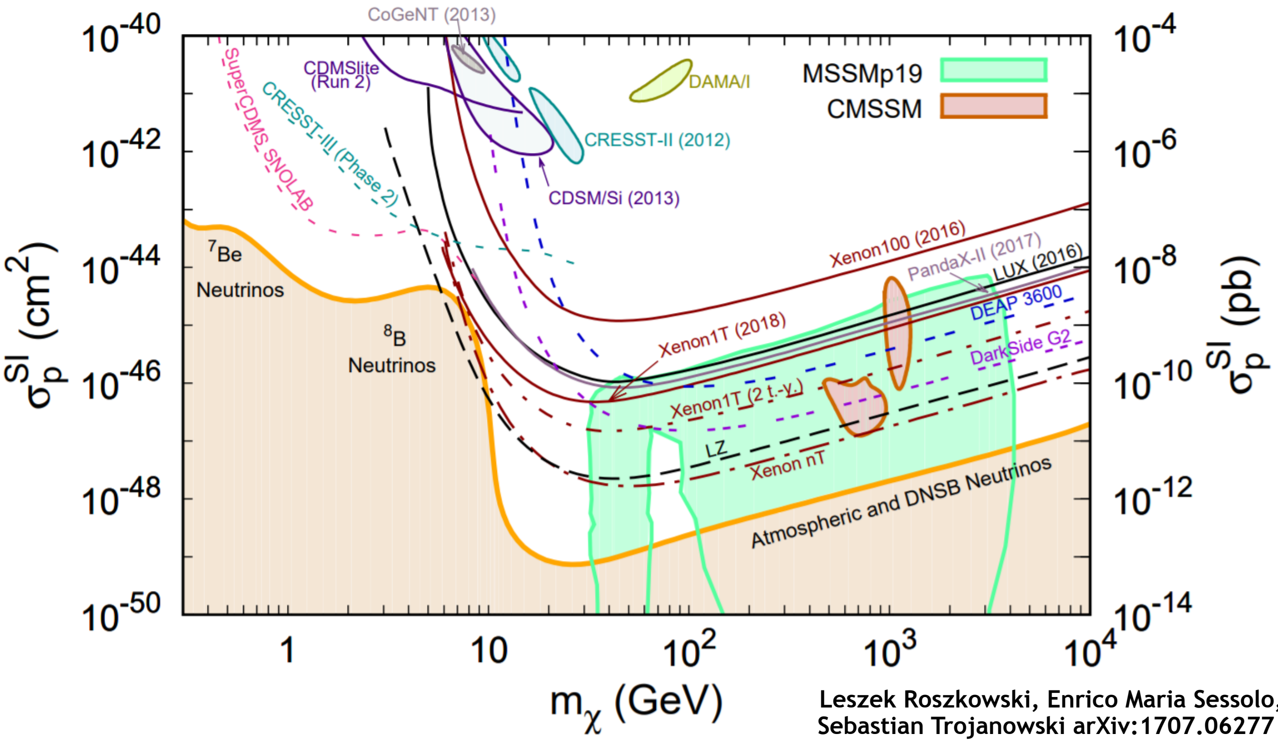
Irreducible Background for Direct Detection Dark Matter Experiments



Leszek Roszkowski, Enrico Maria Sessolo, Sebastian Trojanowski arXiv:1707.06277

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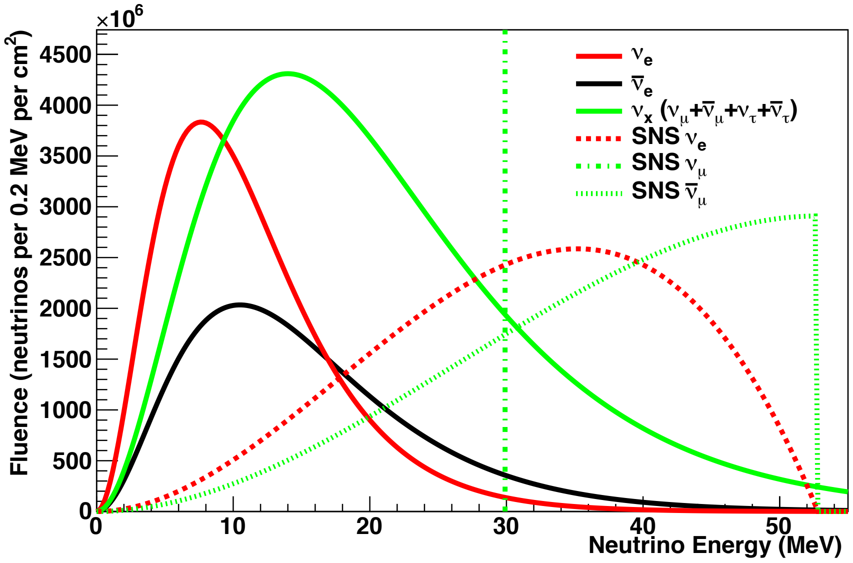
Dominant Cross Section at Supernova Energies



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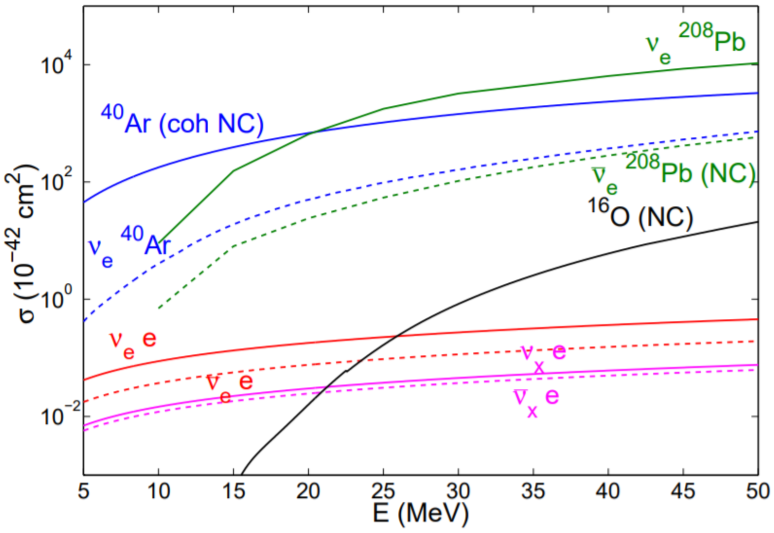

Irene Tamborra, Bernhard Müller, Lorenz Hüdepohl, Hans-Thomas Janka, and Georg Raffelt Phys. Rev. D 86, 125031 (2012)

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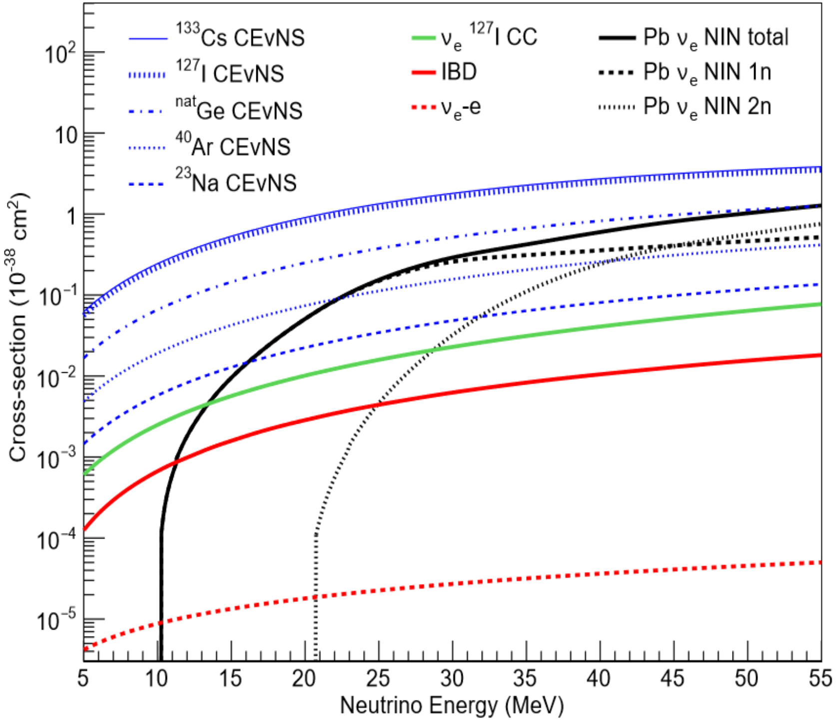
Detecting CEvNS

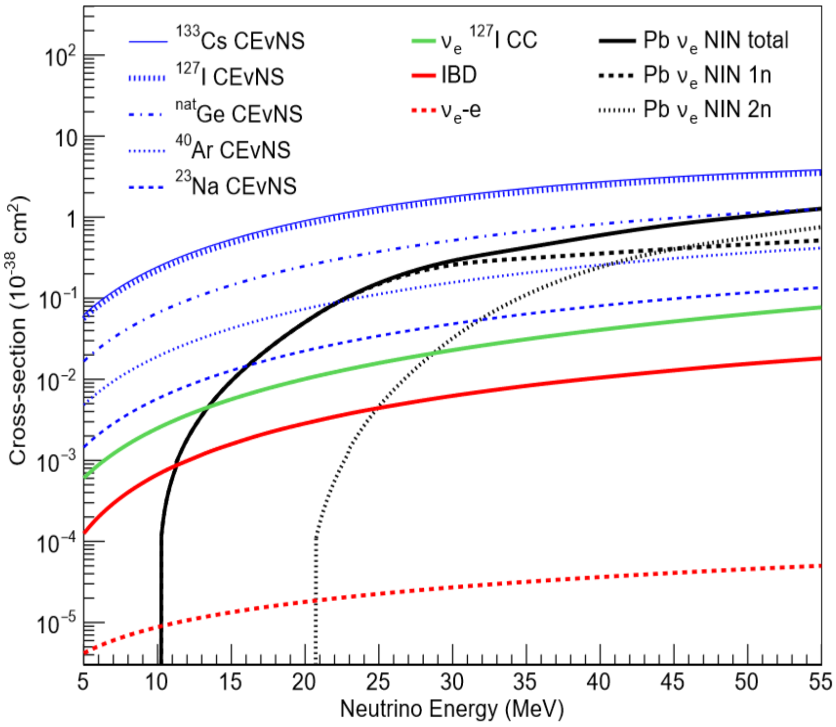


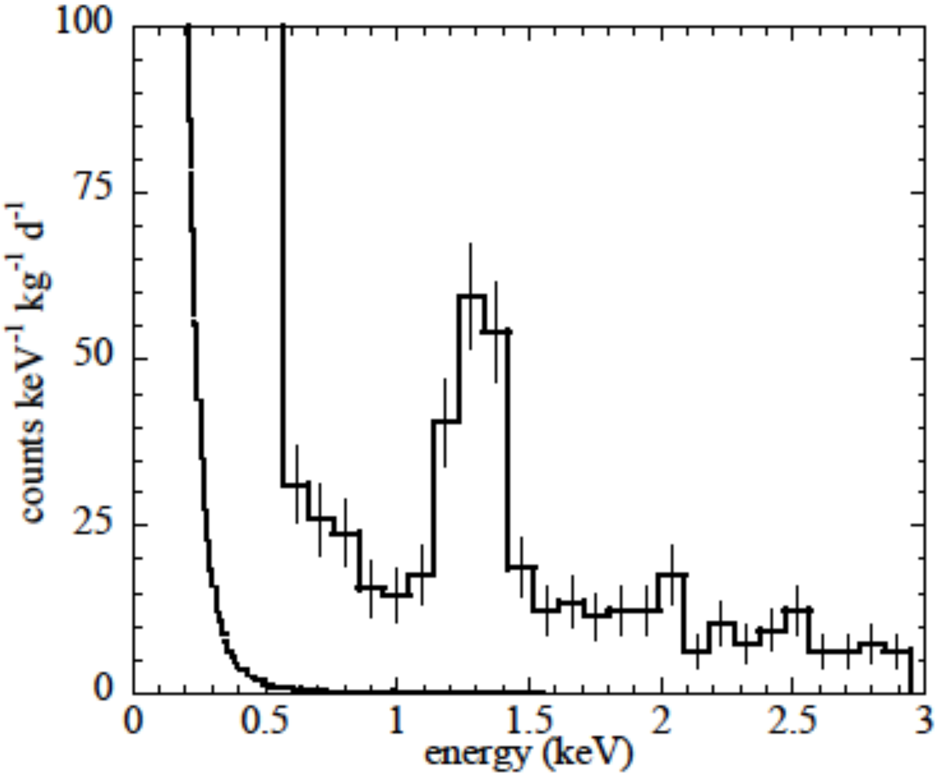
Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering.

- D. Freedman

- Signal: low-energy nuclear recoil
- Cross-section proportional to N^2
- Heavier nuclei will have higher event rate, but lower energy recoils.
- Any detector will need a low threshold and low backgrounds OR ability to discriminate nuclear recoils from other events.

Detecting CEvNS





P. Barbeau, PhD Dissertation, U. Chicago 2009

The Spallation Neutron Source

- Neutron production facility for materials science, life science, physics research.
- Neutrons are produced by the spallation of Hg nuclei by protons.
- 1 GeV protons are delivered to the Hg target at 60 Hz in 400 ns FWHM bunches.
- Latest production runs have achieved 1.4 MW power!

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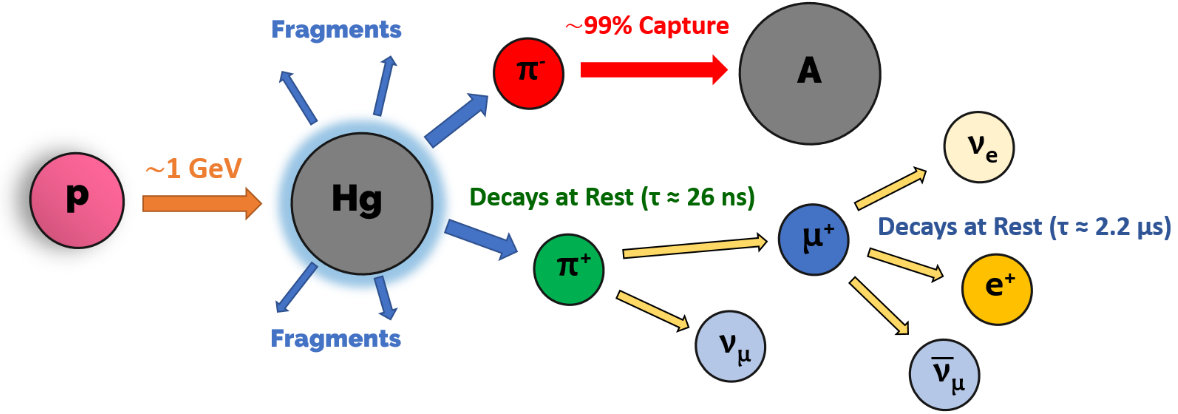
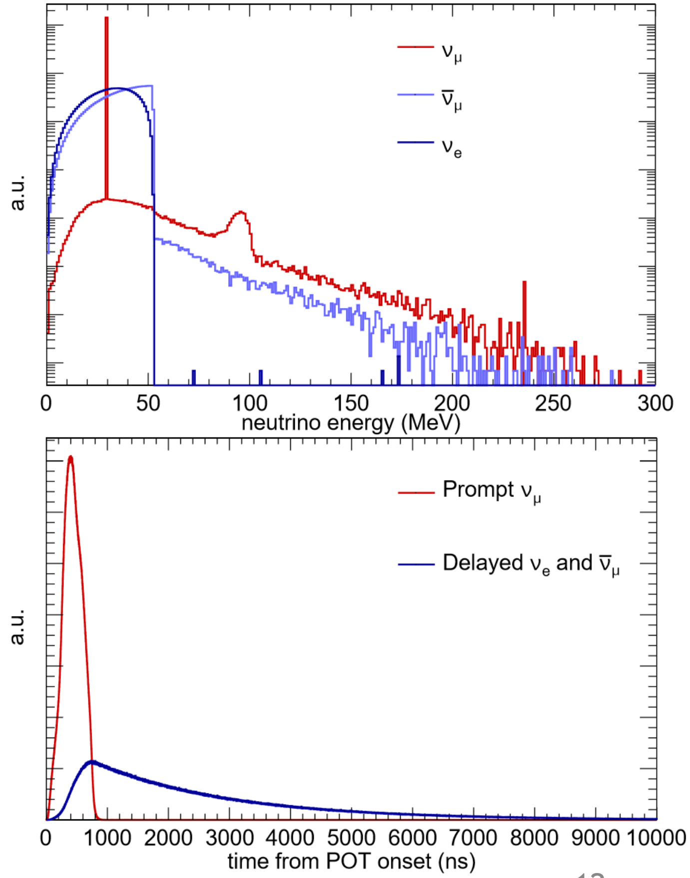
Neutrino Production at the SNS





- Total ν flux approximately 4.3×10^{7} ν cm^{-2} s^{-1} at 20 m
- Well understood energy spectrum (>99% DAR)
- Beam timing & duty cycle (60Hz, <800ns POT) allow for powerful reduction of steady-state backgrounds (~4×10^{-4})

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NNSA National Nuclear Security Administration

KICP

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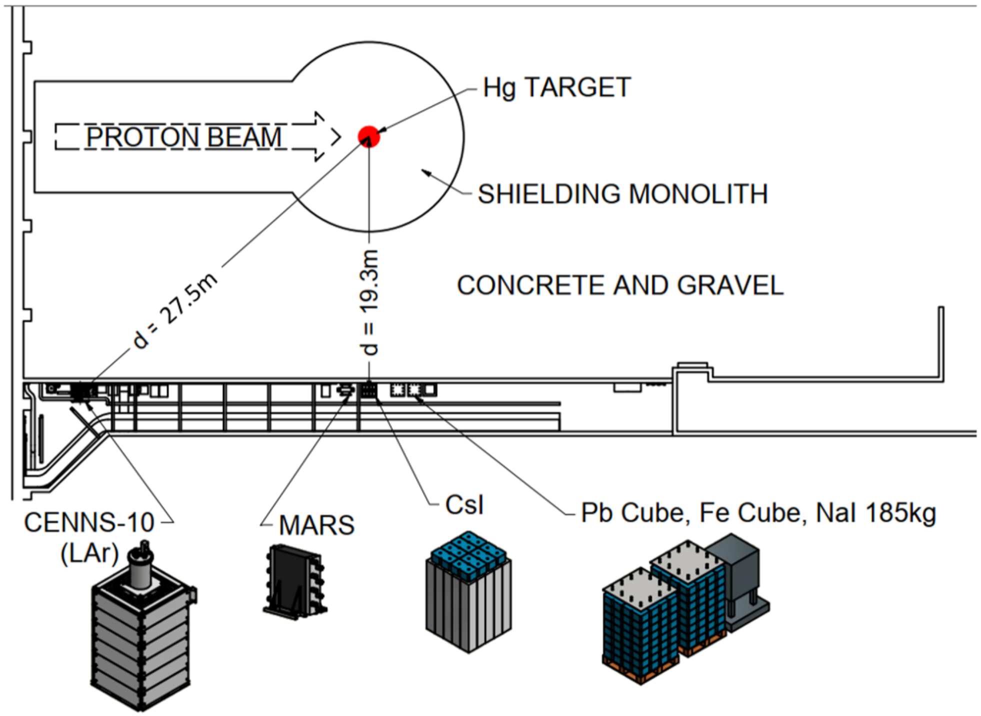
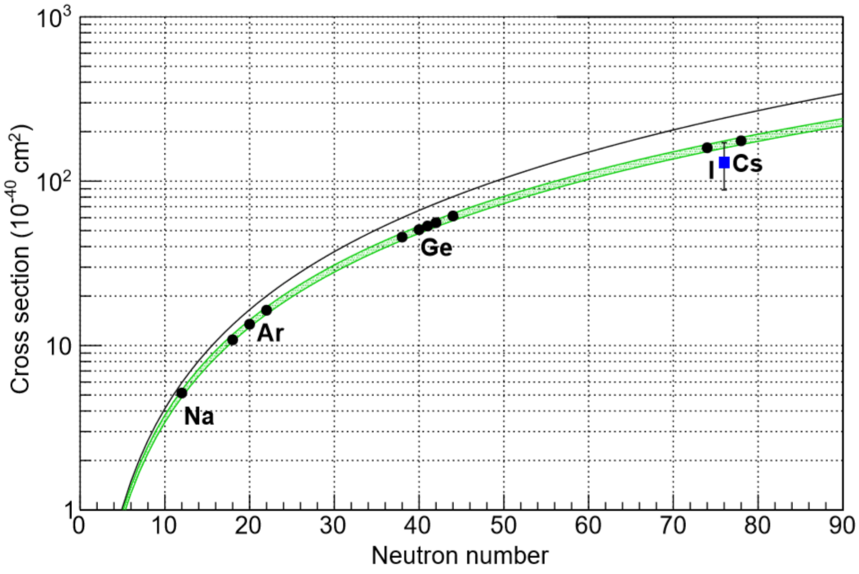
COHERENT Multi-Target Program - Phase I





Form Factor = 1

Assumed Form-Factor

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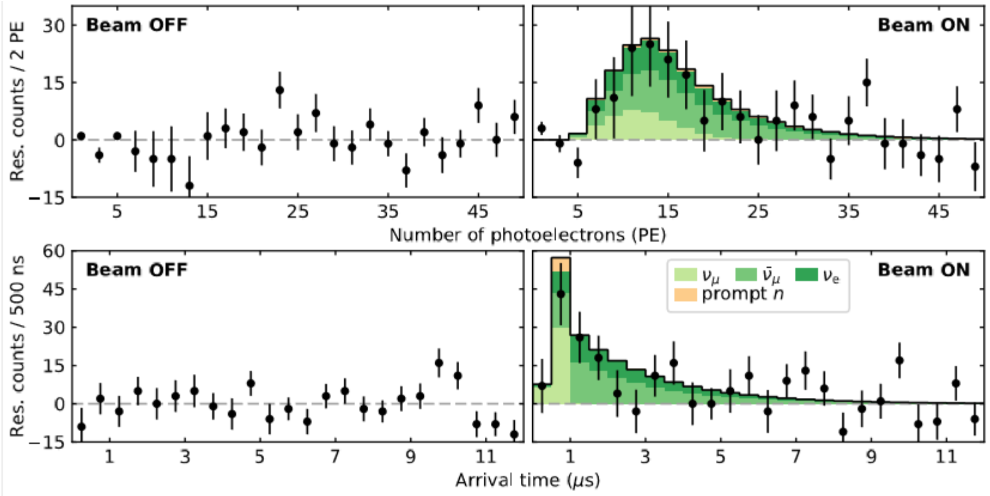
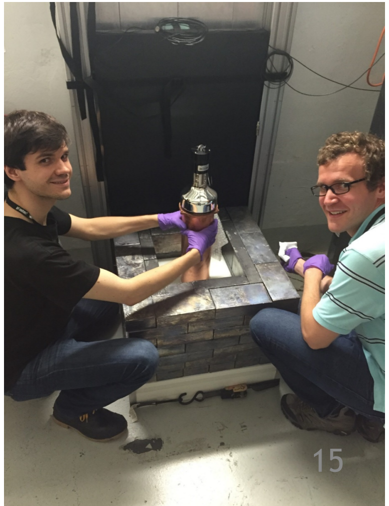
First Observation of CEvNS

D. Akimov et al., Science 10.1126/science.aao0990 (2017).

- Observation of CEvNS in 14.6 kg CsI[Na] detector!
- 6.7σ significance with likelihood fit
- Best fit of 134±22 Signal Events within 1σ of SM Prediction: 173±48
- Uncertainties due to nuclear quenching, neutrino flux, nuclear form factor, etc.
- Beam OFF Data: 153.5 days; Beam ON Data: 308.1 Days (7.48 GWhr)





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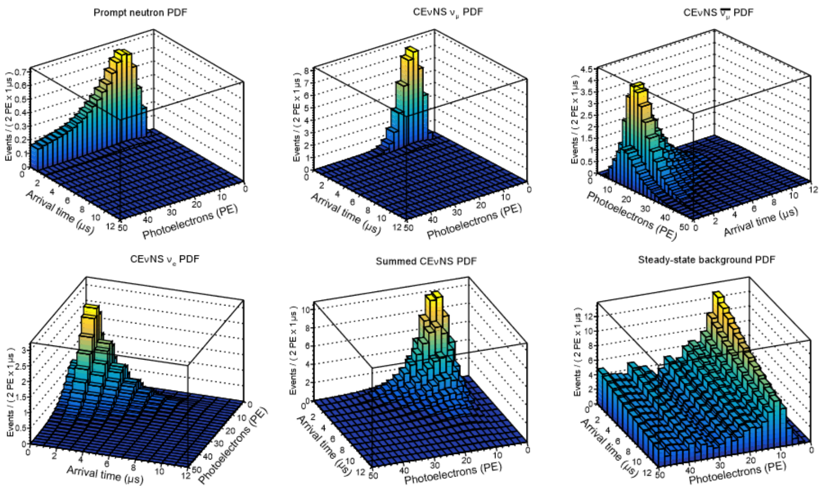

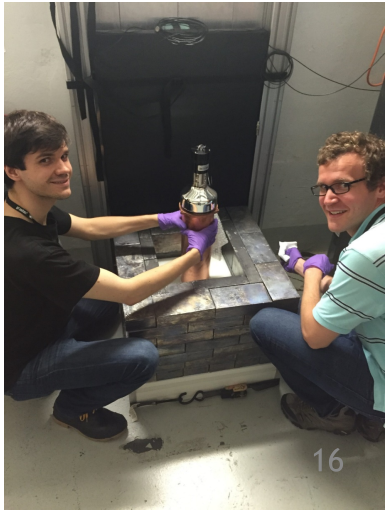

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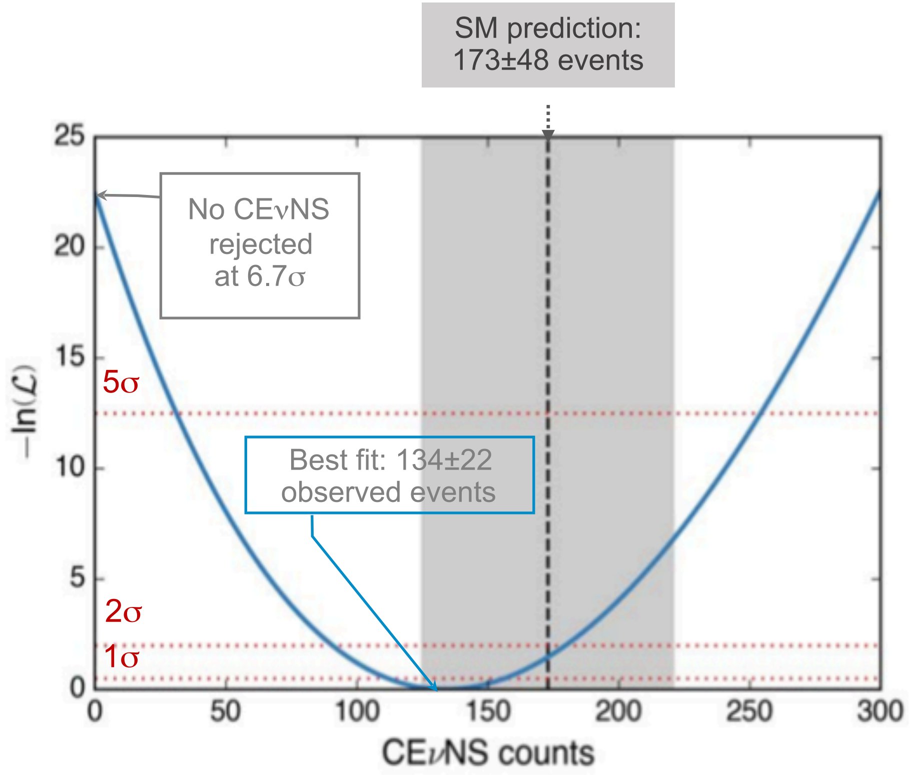


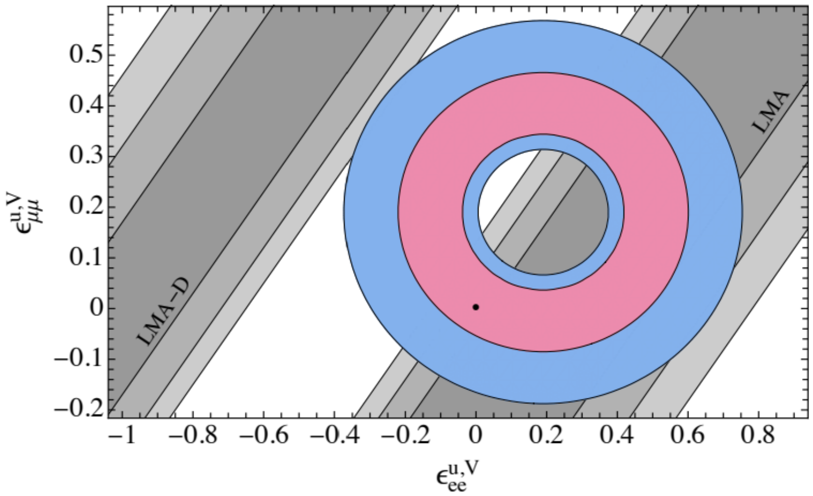
- CsI detector still acquiring data; will soon be decommissioned.
- Have since doubled POT data (14 GWhr).
- Uncertainty in this result is dominated by current quenching factor determination; new QF analysis will reduce this considerably.

Dominant systematic uncertainties on predicted rates

Quenching factor	25%
ν flux	10%
Nuc. form factor	5%
Analysis acceptance	5%

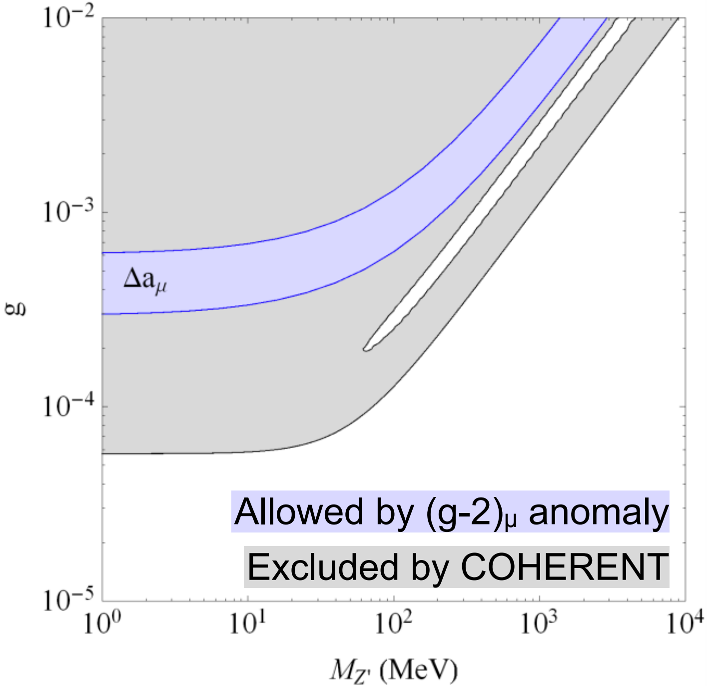
CsI Impact

Current result already rules out (in combination with neutrino oscillation data) the Large Mixing Angle “Dark” solution.

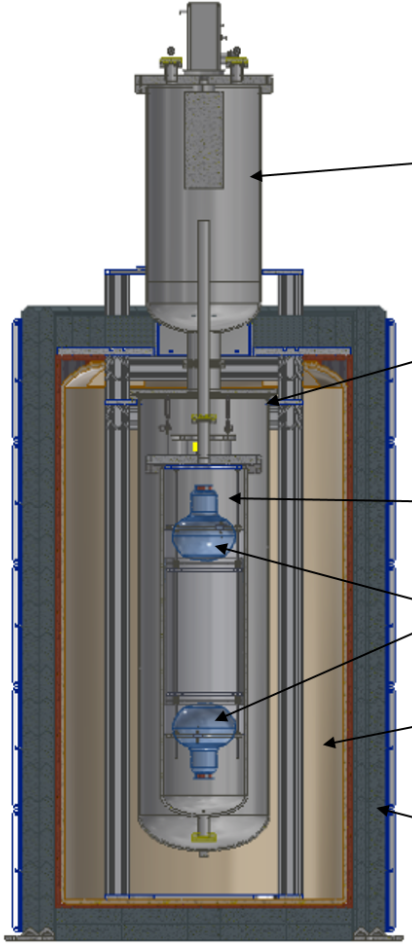


Coloma et al, arXiv:1708.02899v1

Finds tension (at 2 sigma) with a light-mass Z’ dark mediator that can explain the $(g-2)_\mu$ anomaly.

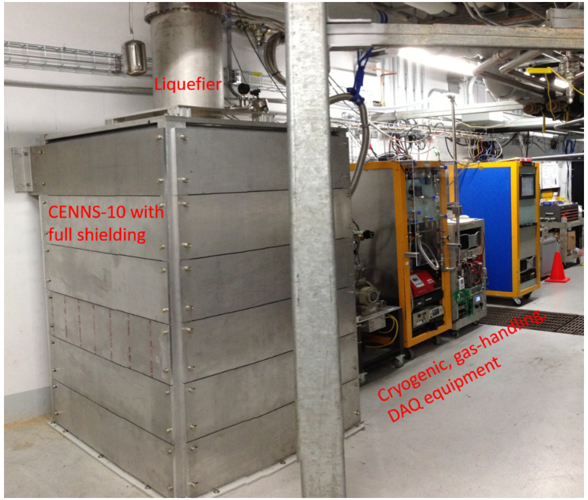


Liao and Marfatia, arXiv:1708.04255v1



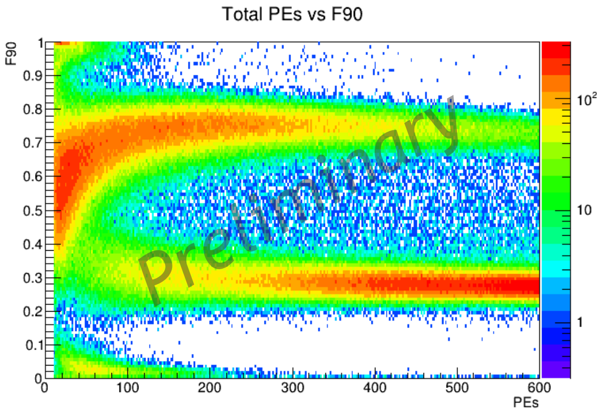
CENNS-10

- Single-phase liquid Ar scintillation detector
- Located 28 m from SNS target: 2x10^7 ν/s
- Engineering Run: Dec 2016 -> May 2017
- June 2017 upgrade
- Production Run: August 2017 -> Present

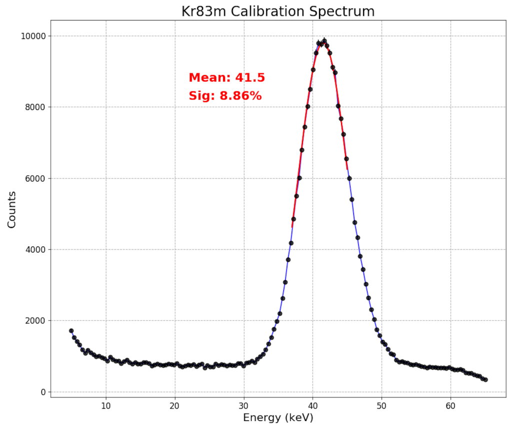


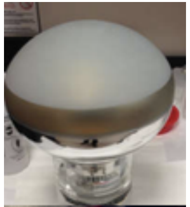
CENNS-10 Upgrade

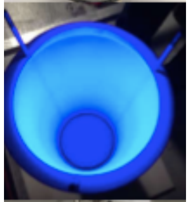
- 8” PMTs were swapped with PMTs directly coated with TPB; acrylic cylinder replaced with set of 3 TPB coated Teflon cylinders (22.4-kg fiducial volume).
- Post-upgrade light yield in the range of 4-5 pe/ keVee; threshold reduced to 20 keVnr.
- Complete layer of Pb shielding added to reduce environmental gamma backgrounds.
- ^{83m}Kr calibration source loop added to grant ability for in situ energy calibration at lower energies.
- Analysis of 6.5 GWhr of data in the upgraded detector underway; will soon be opening the box!



AmBe Calibration







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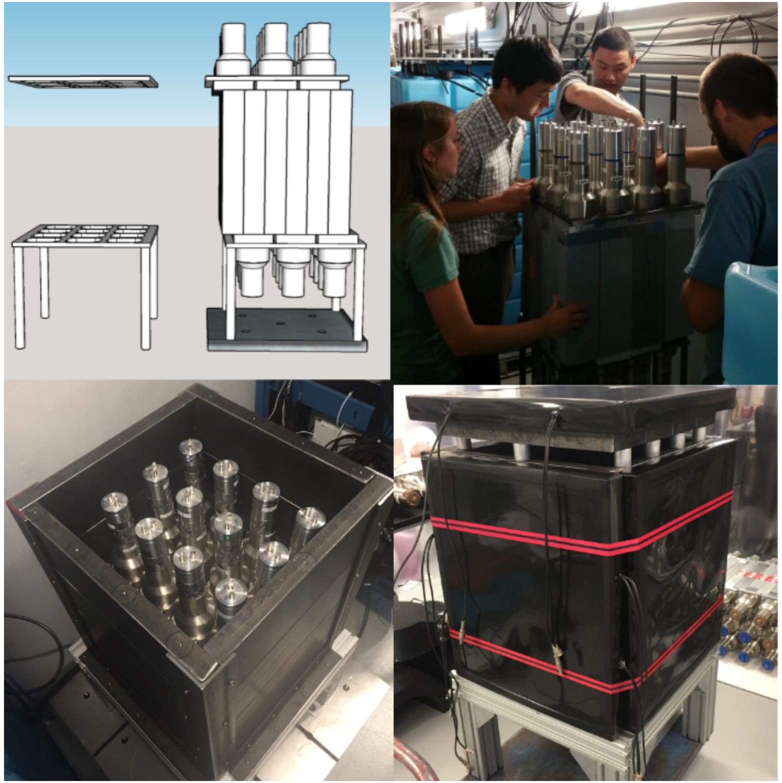
NaIvE Prototype



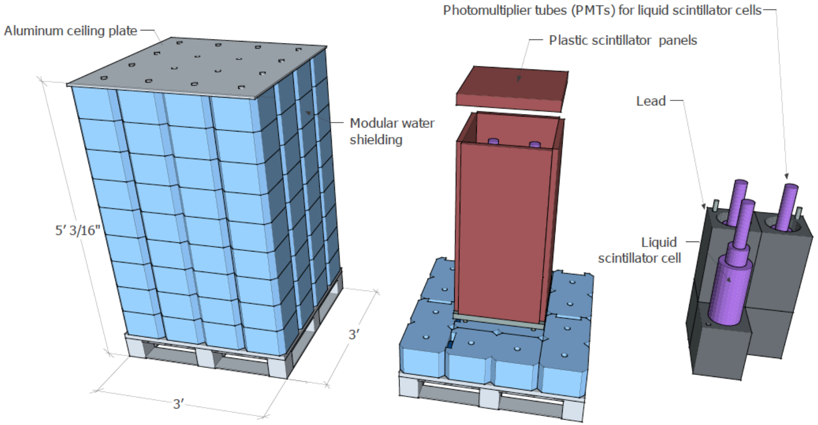
- Several tons of NaI[Tl] detectors available for use after closing of Spectroscopic Portal program (DHS).
- Crystals are NOT designed with low-background or threshold
- NaIvE prototype: 185kg in 24 modules
- Purpose:
    - Measurement of CC cross-section on ^{127}I
    - Testing of backgrounds for ton-scale deployment optimized for CEvNS
- New dual-gain PMT bases being developed at ORNL to allow for both low energy nuclear recoils and high energy CC signals to be observed

Neutrino-Induced Neutrons (NINs)

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

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

- Neutrinos can interact in shielding materials to produce energetic neutrons.
- These neutrons can induce nuclear recoils in the detectors mimicking the CEvNS signal!
- Cross-section poorly constrained, and a potential important background for COHERENT.
- Set of Neutrino Cube detectors (NUBES) seek to observe this process and constrain the potential contribution to CEvNS signal.
- ***Detection mechanism for the HALO supernova observatory.***



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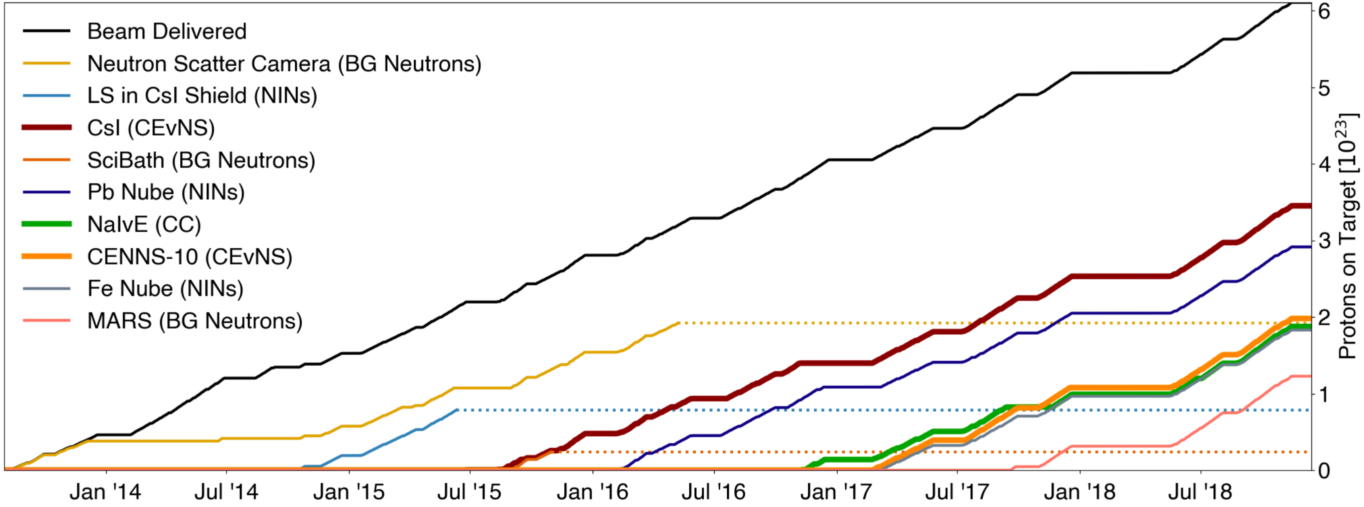
Data Collected - Future Plans



- Several detector systems have begun or finished data taking and characterization of location backgrounds is complete.
- What's next? Bigger detectors and additional targets! Higher statistics and low backgrounds are essential.
- Data from current LAr and NaI detectors essential for informing large-scale detector design.

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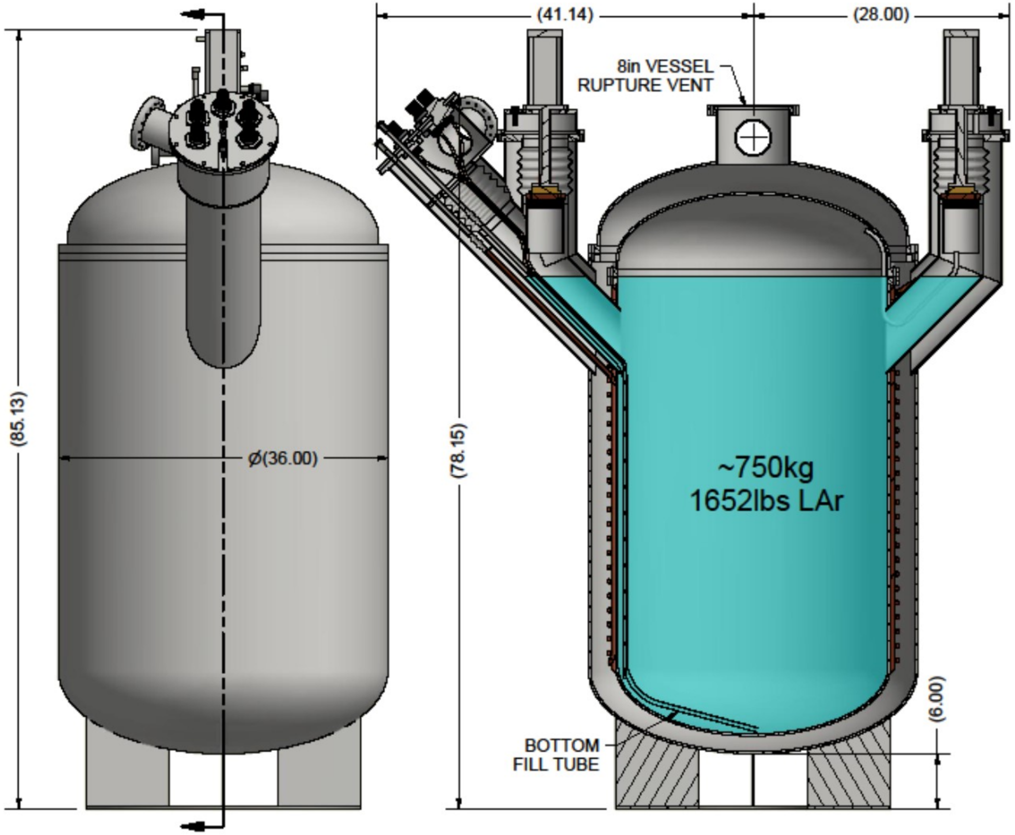
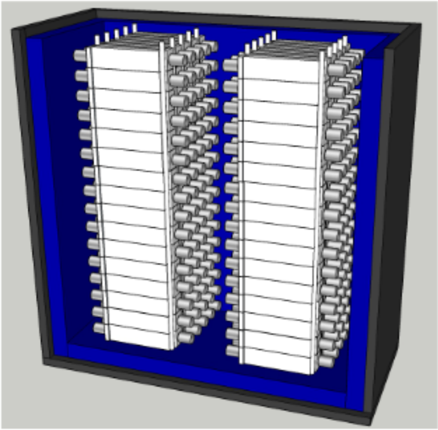
CENNS-750

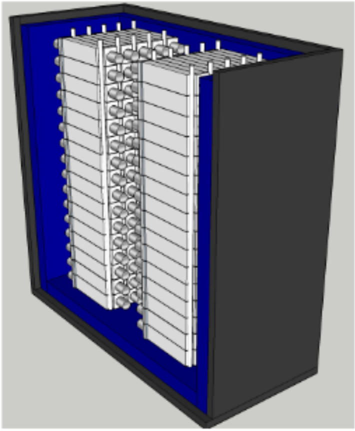
- Preliminary design for LAr detector featuring ~612 kg fiducial volume ready.
- Light collection technology under review: PMTs or SiPMs
- Will fit in Neutrino Alley!
- Expected CEvNS rate: 3000 events per SNS year
- Ar form factor nearly unity; precise measurement made easier without this uncertainty
- Analysis of opportunity – Measurement of CC ν on Ar cross-section (DUNE)

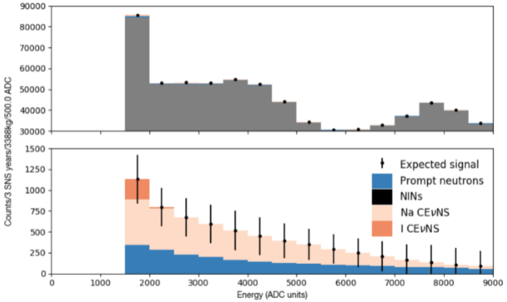


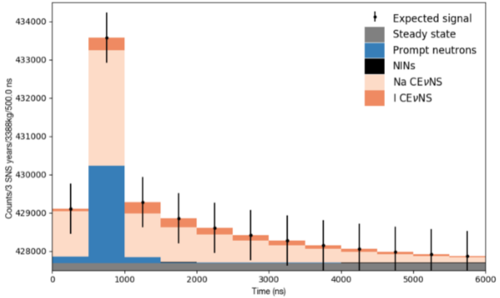
Ton-Scale NaI Array

- Designs for ton-scale (3.38 tons) NaI array:
  - Two stacks with 144-160 detectors each
  - Single continuous array
- PMT Testing, backgrounds, detector quality for each detector element needed.
- Plan for new quenching factor measurements to minimize uncertainty and resolve conflict in existing data.
- Physics targets:
  - CEvNS on ^{23}Na
  - ν_e CC on ^{127}I









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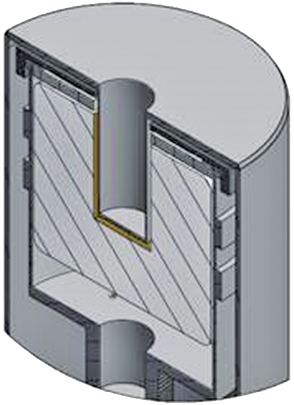
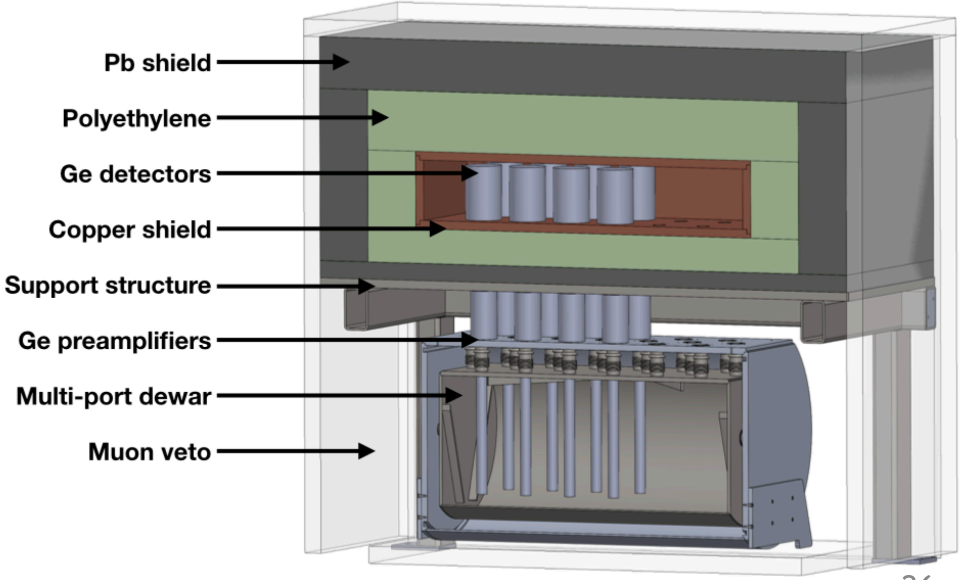
PPC Germanium Array



- P-Type Point Contact Ge detectors well-suited to precision CEvNS measurements
    - Excellent energy resolution
    - Low thresholds: <1 keVnr
    - Intermediate N
- Best-understood systematics; energy spectrum faithful to recoil spectrum.
- 16-kg array of PPC Ge detectors placed in compact shielding using multi-port dewar that has already been procured.
- Expectation of 500-600 CEvNS events per year of SNS operation. Predicted signal-to-background ratio of 3.5



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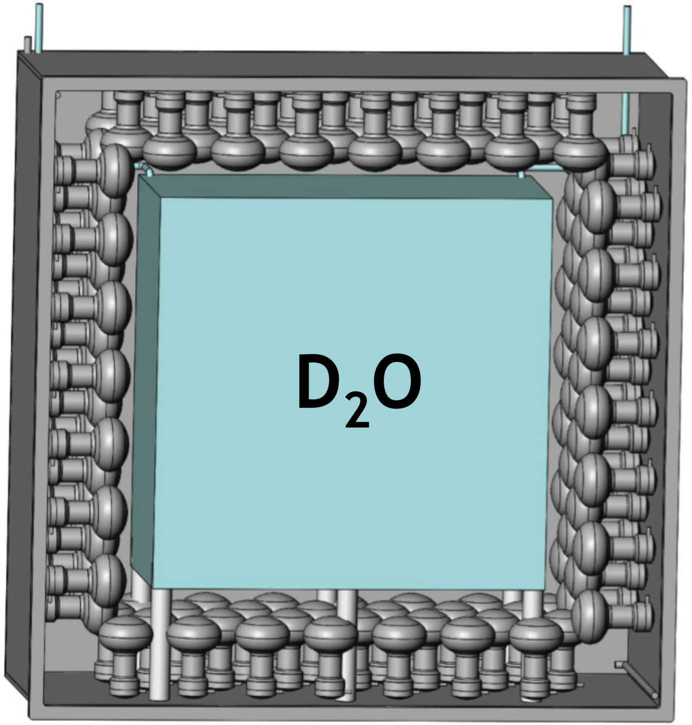
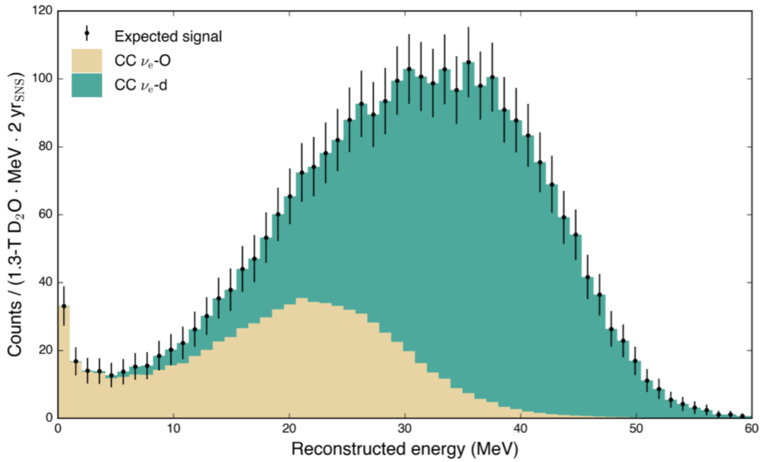
Heavy Water Detector





- Precise measurement of CEvNS will require reduction in systematic uncertainties:
  - Signal Efficiency
  - Quenching Factors
  - Nuclear Form Factor
  - **Neutrino Flux (10%)**
- CC cross-section on deuterium known with approx. 2% accuracy. Motivates the construction of a ton-scale heavy water Cherenkov detector to normalize SNS neutrino flux.

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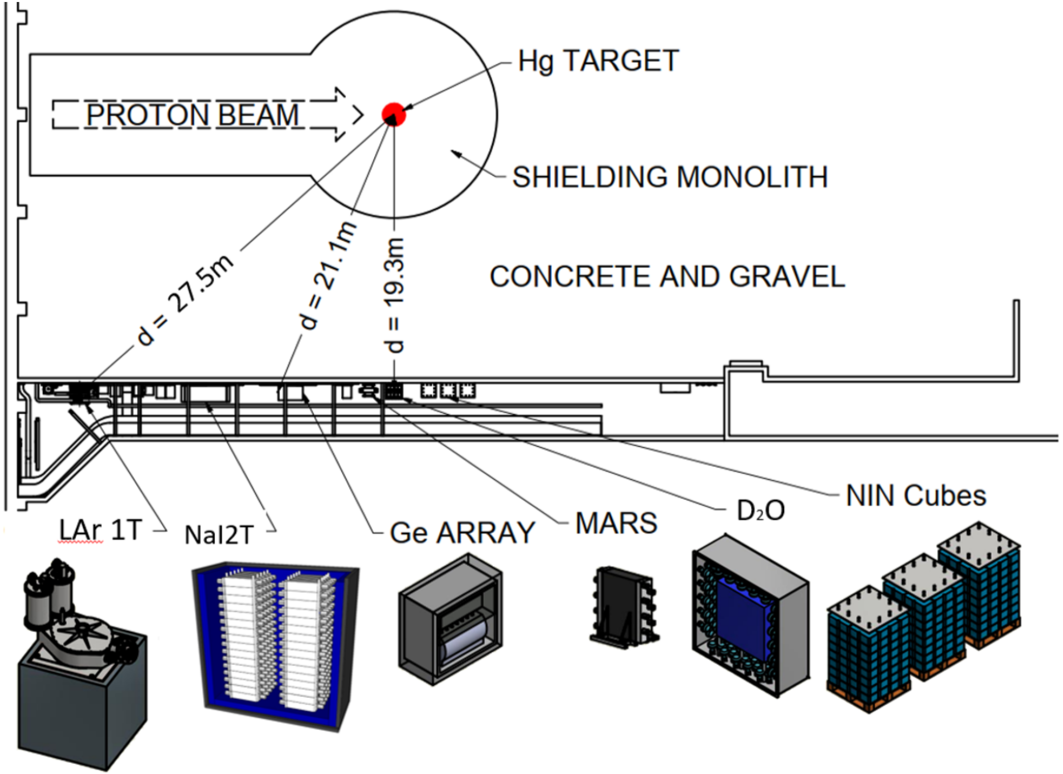
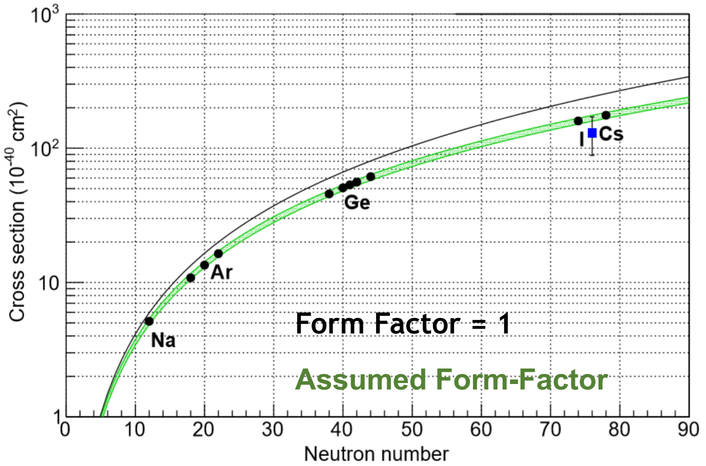
An Evolving Neutrino Alley

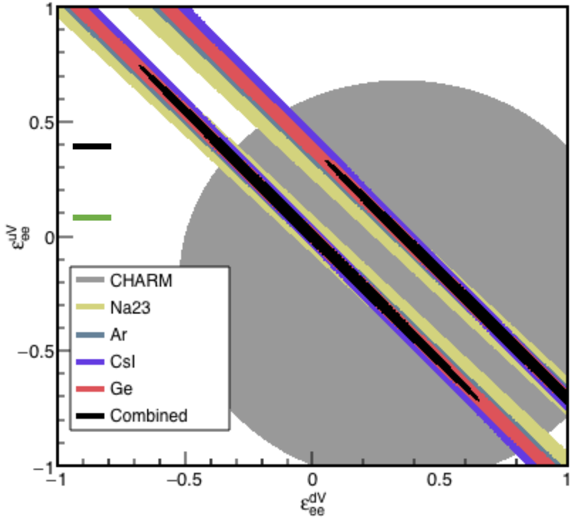


NC STATE UNIVERSITY

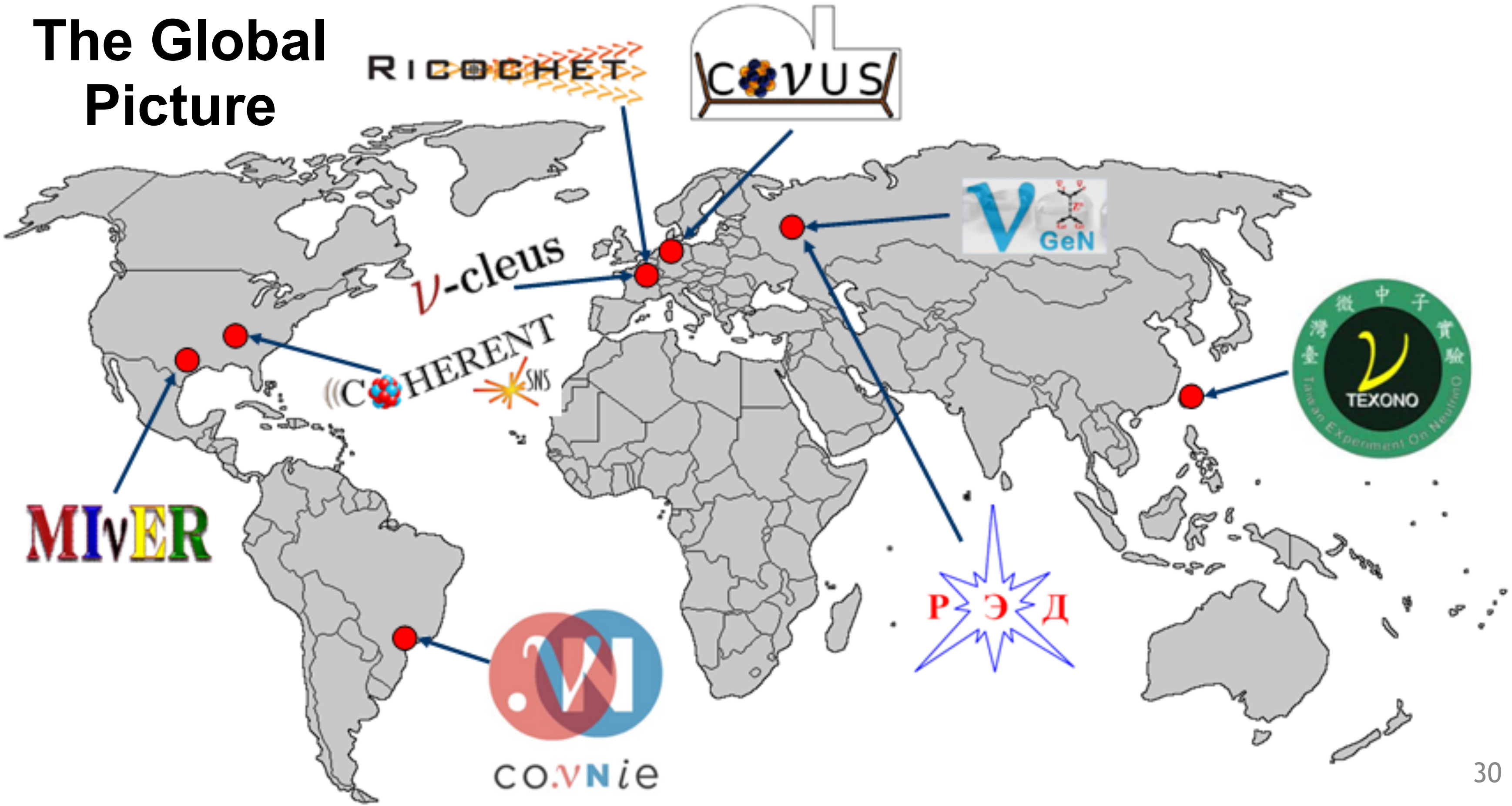
Future CEvNS Physics

- Proposed detector suite allows for precise measurement of CEvNS cross-section and recoil spectrum for several targets.
- Implications for wide range of neutrino, nuclear, and BSM physics:
  - Test of N^2 dependence
  - Measurements of nuclear form factors without strong force perturbations.
  - Deviations due to Non-Standard Interactions
  - Neutrino CC cross-section measurements on ^{127}I, and Ar
  - Sterile neutrino measurements with near and far detectors
  - Neutrino magnetic moments





The Global Picture



Summary

- Using a CsI detector, the COHERENT collaboration has made the first observation of coherent elastic neutrino-nucleus scattering (CEvNS), a long-predicted Standard Model interaction.
- Several detectors are in place taking data at the SNS with first observations on other targets soon to come.
- Success of initial experiments is motivating and informing the design of new large-scale additions to neutrino alley which will allow for precision measurement of the CEvNS process.
- Additionally, the results from the next generation of detectors promise rich physics potential with respect to searches for physics beyond the Standard Model (NSI, sterile neutrinos, dark matter).