COHERENT: Recent Results and Future Prospects

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University of Tennessee
Underground Nuclear and Particle Symposium
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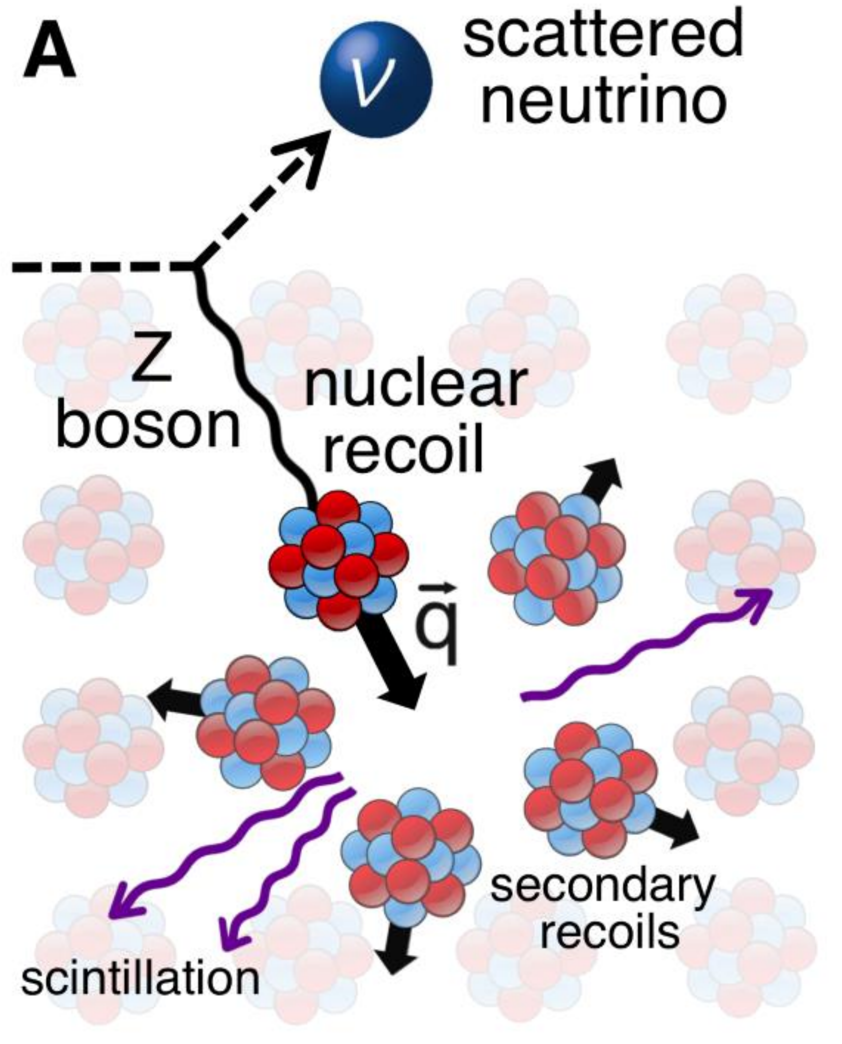
Coherent Elastic Neutrino-Nucleus Scattering



$$\frac{d\sigma}{dT_A} = \frac{G_F^2}{4\pi} m_A \left[Z\left(1-4\sin^2\theta_W\right)-N\right]^2 \left[1-m_A\frac{T_A}{2E_\nu^2}\right] F^2(Q^2)$$

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

m_A – nucleus mass

T_A – kinetic energy of recoil nucleus

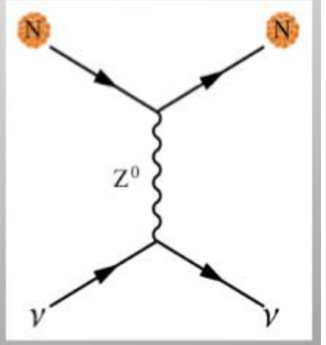
E_ν – neutrino energy

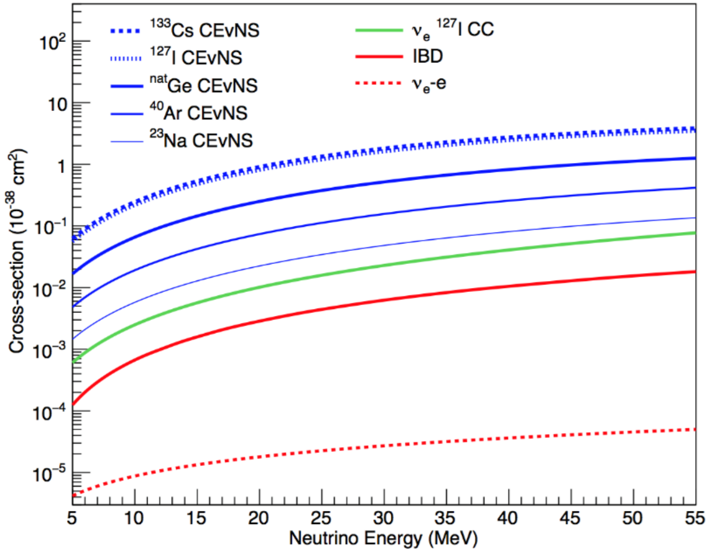
Z – nucleus charge

N – number of neutrons in the nucleus

F is nucleus form factor

$E_\nu < 50 MeV$





- Clean prediction from the Standard Model – D. Freedman 1974
- Cross-section increases with energy as long as coherence condition is satisfied ($q \leq \sim R^{-1}$)
- Largest of all SM neutrino cross-sections at 1-100 MeV scale
- NC mediated: all flavors of neutrino can scatter via CEvNS

CEνNS Physics

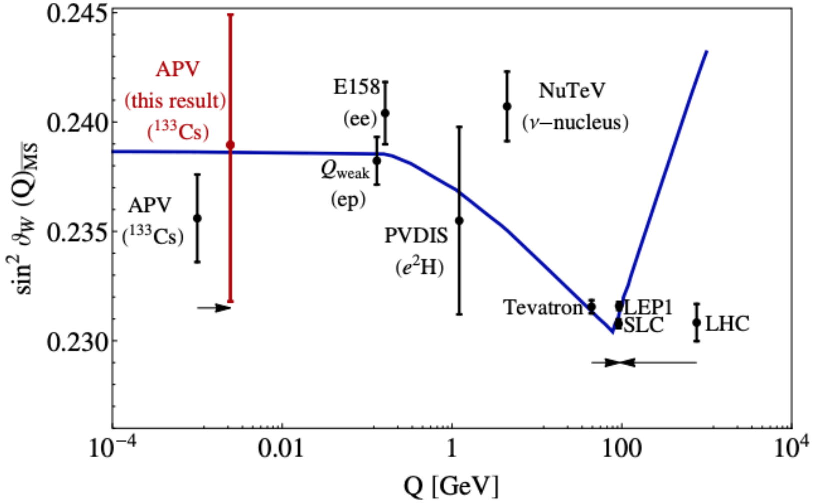
$$\sigma_{tot} = \frac{G_F^2 E_\nu^2}{4\pi}\left[Z\left(1-4\sin^2\theta_W\right)-N\right]^2 F^2(Q^2)$$

Nuclear Form Factors

- Inferable through precision measurements

Weak Mixing Angle

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



M. Cadeddu and F. Dordei, Phys. Rev. D 99 033010 (2019)

Non-Standard Interactions

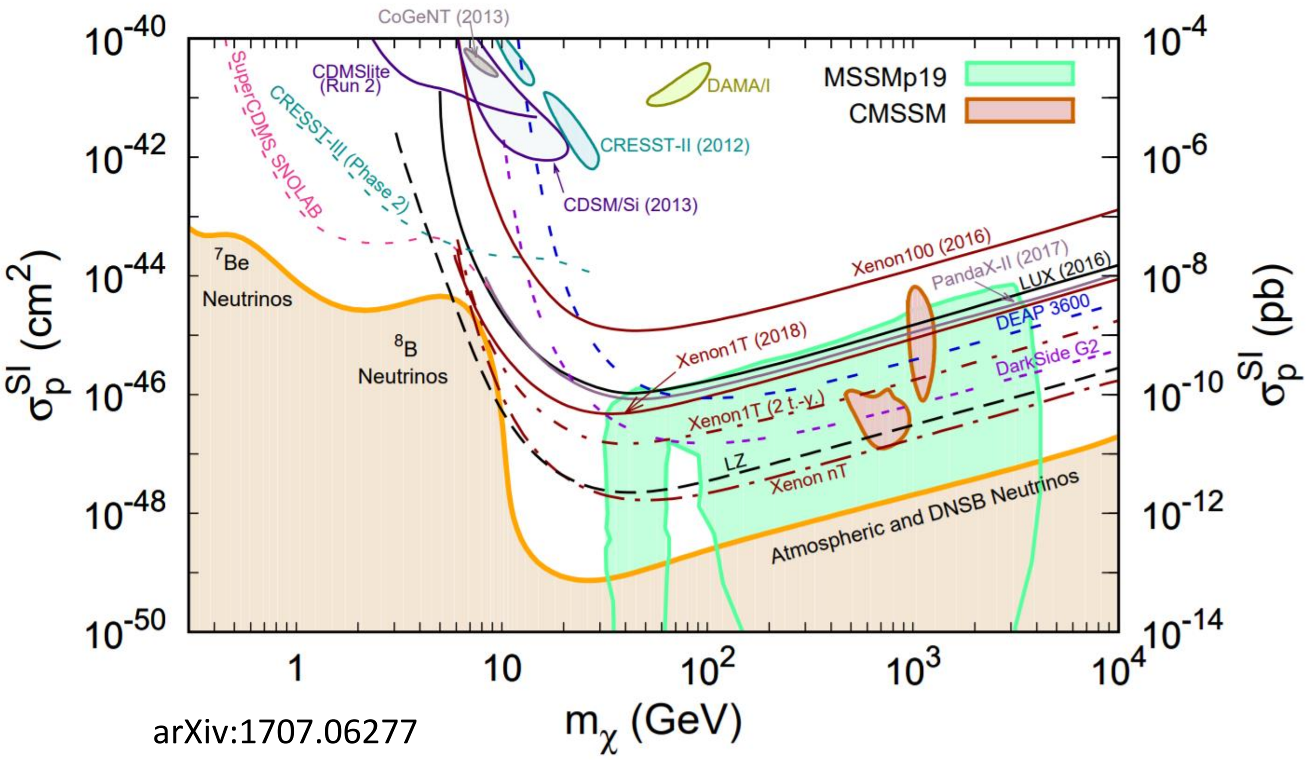
- Potentially mediated via heavy particles
- Constraints on NSI necessary for neutrino mass ordering (NMO) determinations
- Can manifest as suppression or enhancement CEνNS rate

Sterile Searches

- CEνNS interaction for all neutrino flavors
- Disappearance due to oscillation into sterile ν

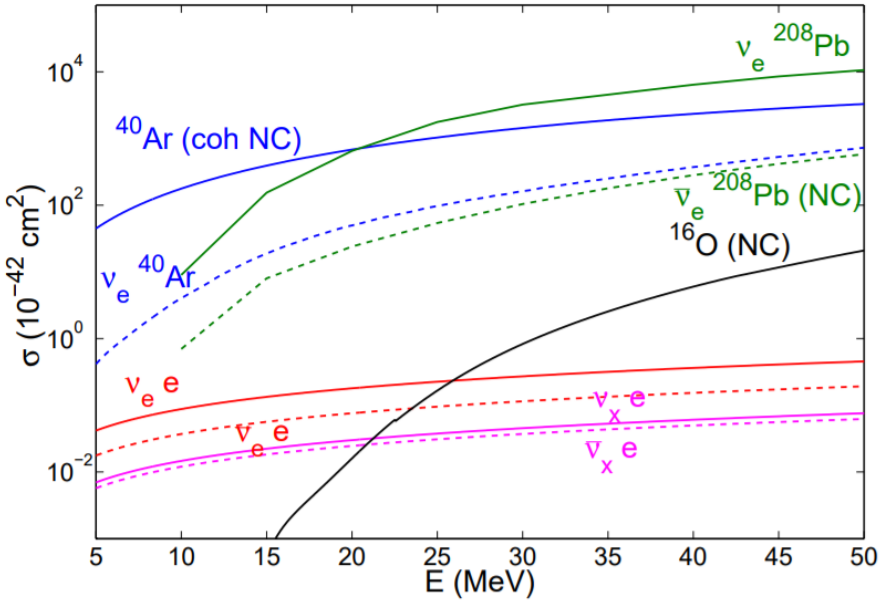
CEνNS Physics

Irreducible Background for Direct Detection Dark Matter Experiments



arXiv:1707.06277

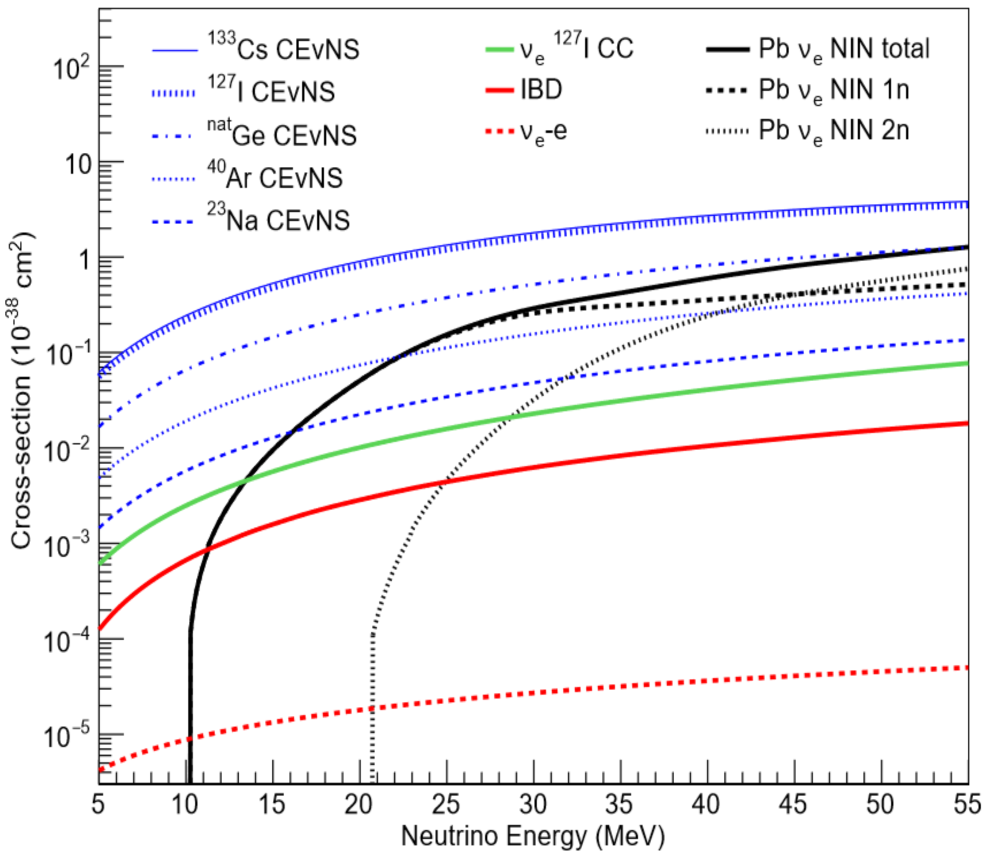
Supernova Physics



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

Monitoring

Detecting CEνNS



> 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 "Coherent effects of a weak neutral current" 1974

- Signal will be a low-energy recoil of target nucleus; improvements to WIMP detector technologies make this feasible!
- Cross-section should exhibit a N^2 – dependence. Higher N nuclei will have higher rate of interactions (but lower energy recoils…)
- Max Ar recoil from SNS neutrinos is about 100 keV (50 MeV incident neutrino)
- Any detector will need a low threshold and low backgrounds OR ability to discriminate nuclear recoils from other events.

The Spallation Neutron Source

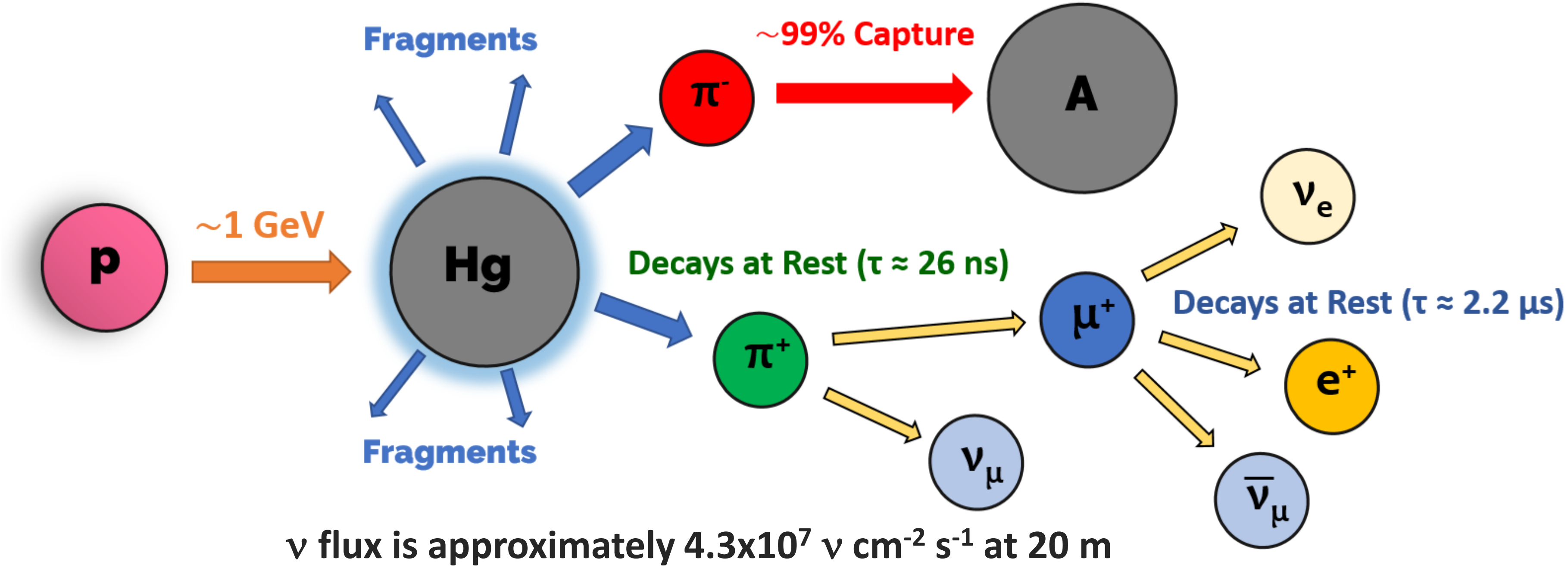
- The primary objective of the Spallation Neutron Source (SNS) is the production of a large flux of neutrons for myriad physics studies.

- Neutrons are produced by the spallation of Hg nuclei during bombardment from accelerated protons.

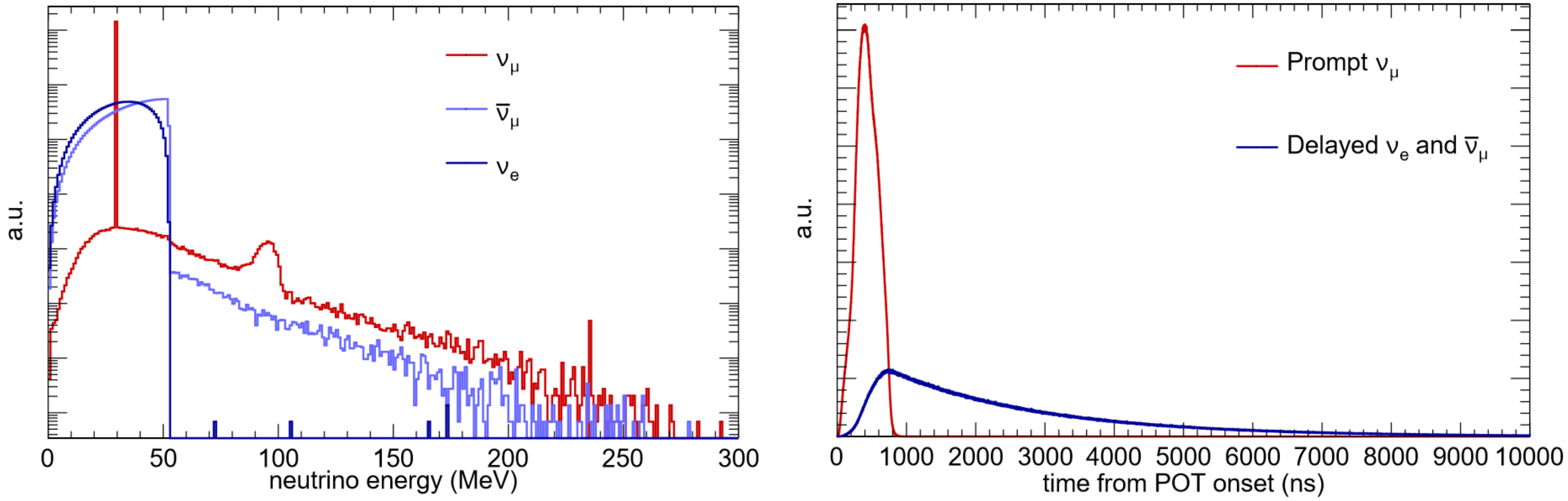
- $\sim$1 GeV protons are delivered to the Hg target at 60 Hz in 400 ns FWHM bunches.

- Latest production runs have achieved 1.4 MW power!

The Spallation Neutrino Source

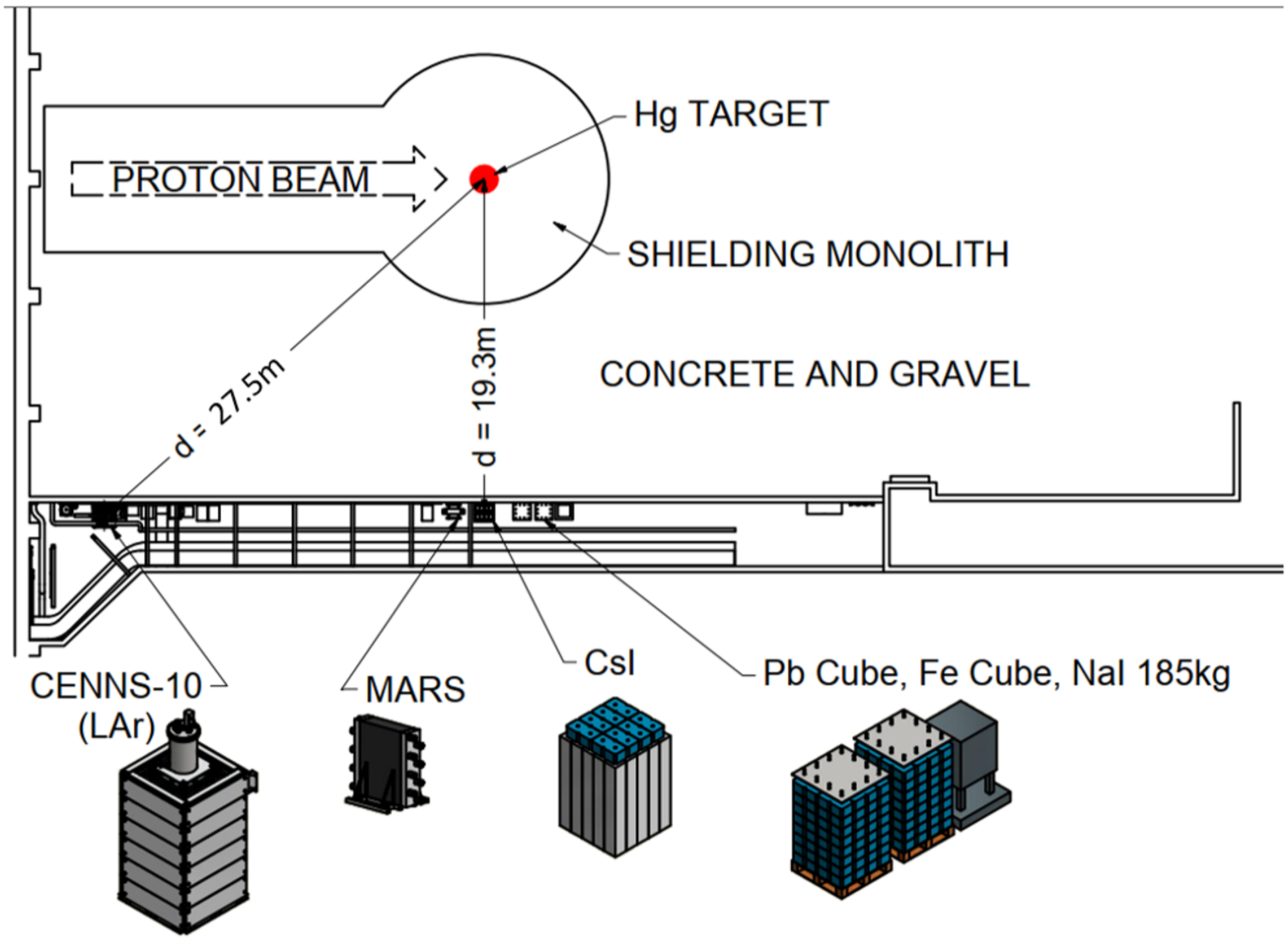


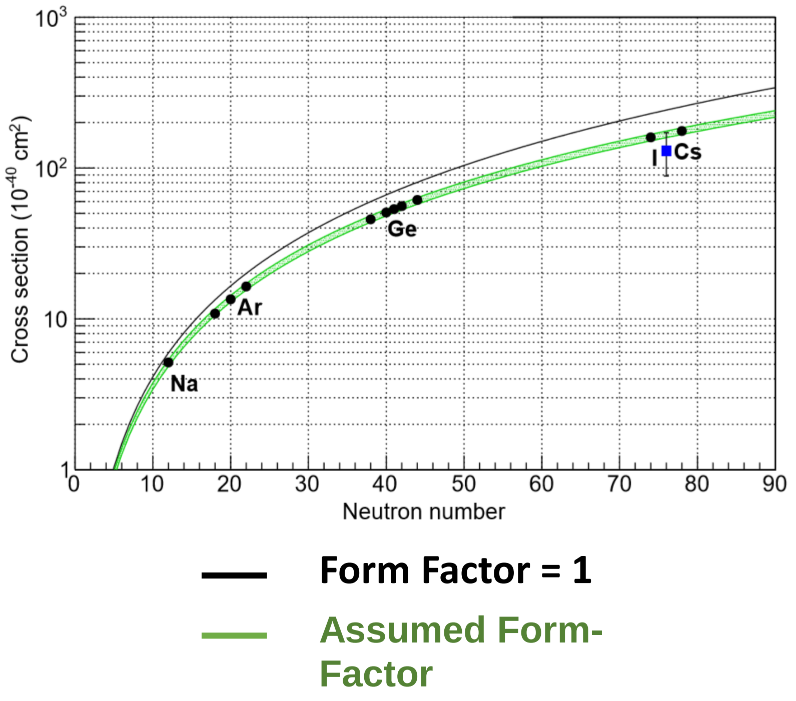
ν flux is approximately 4.3×10^{7} ν cm^{-2} s^{-1} at 20 m

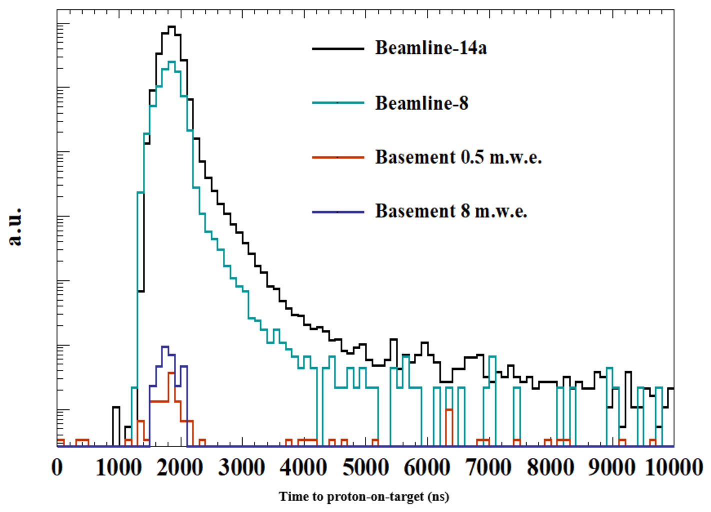


The COHERENT Collaboration

COHERENT Multi-target Program

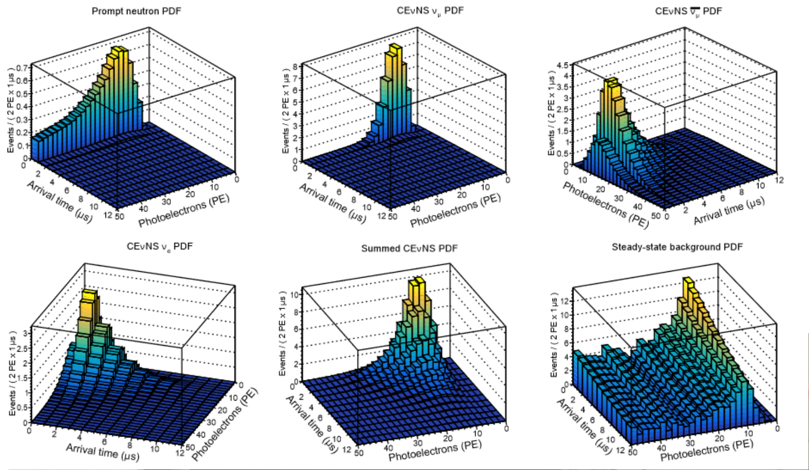


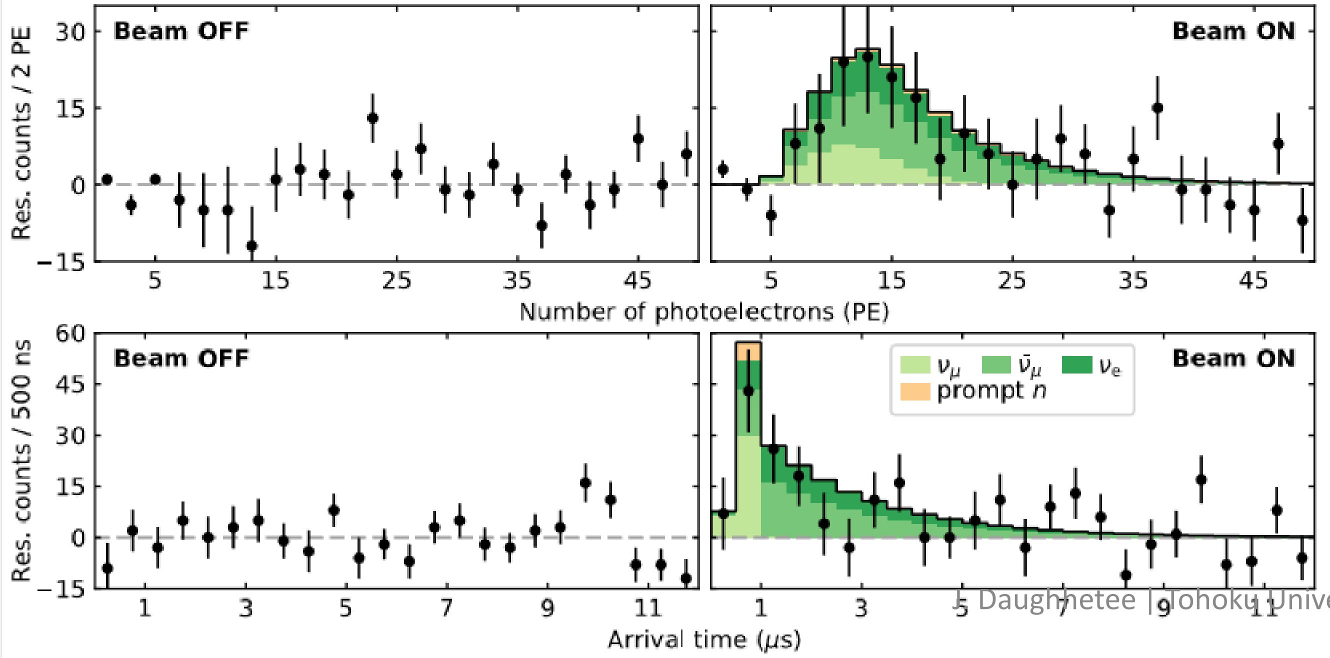


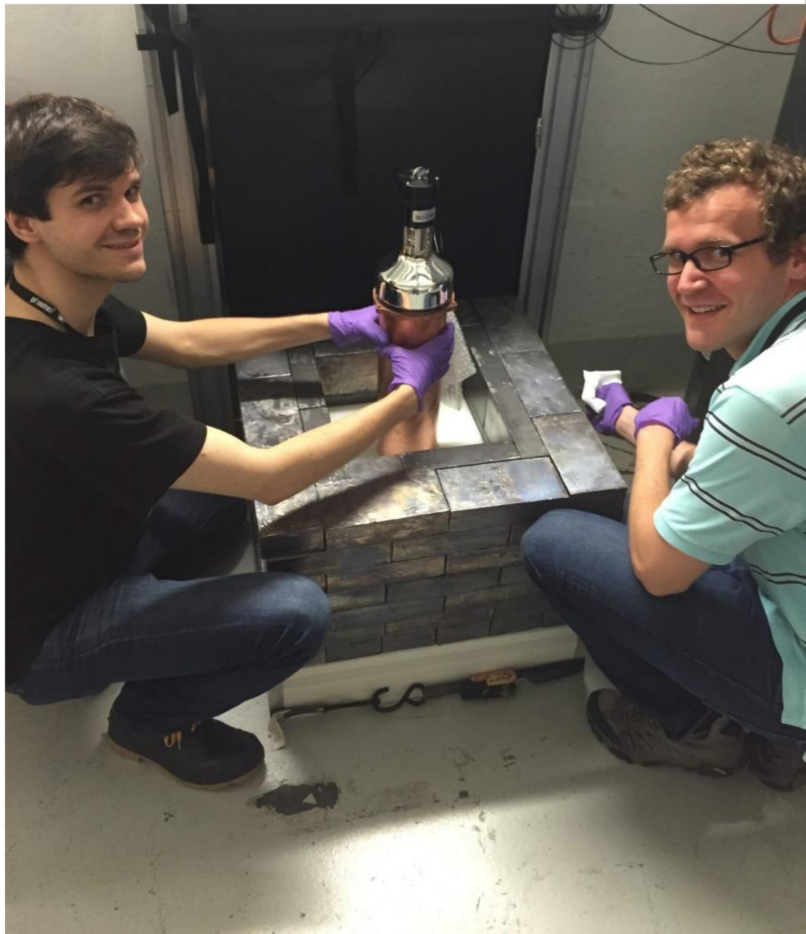


First Observation of CEνNS

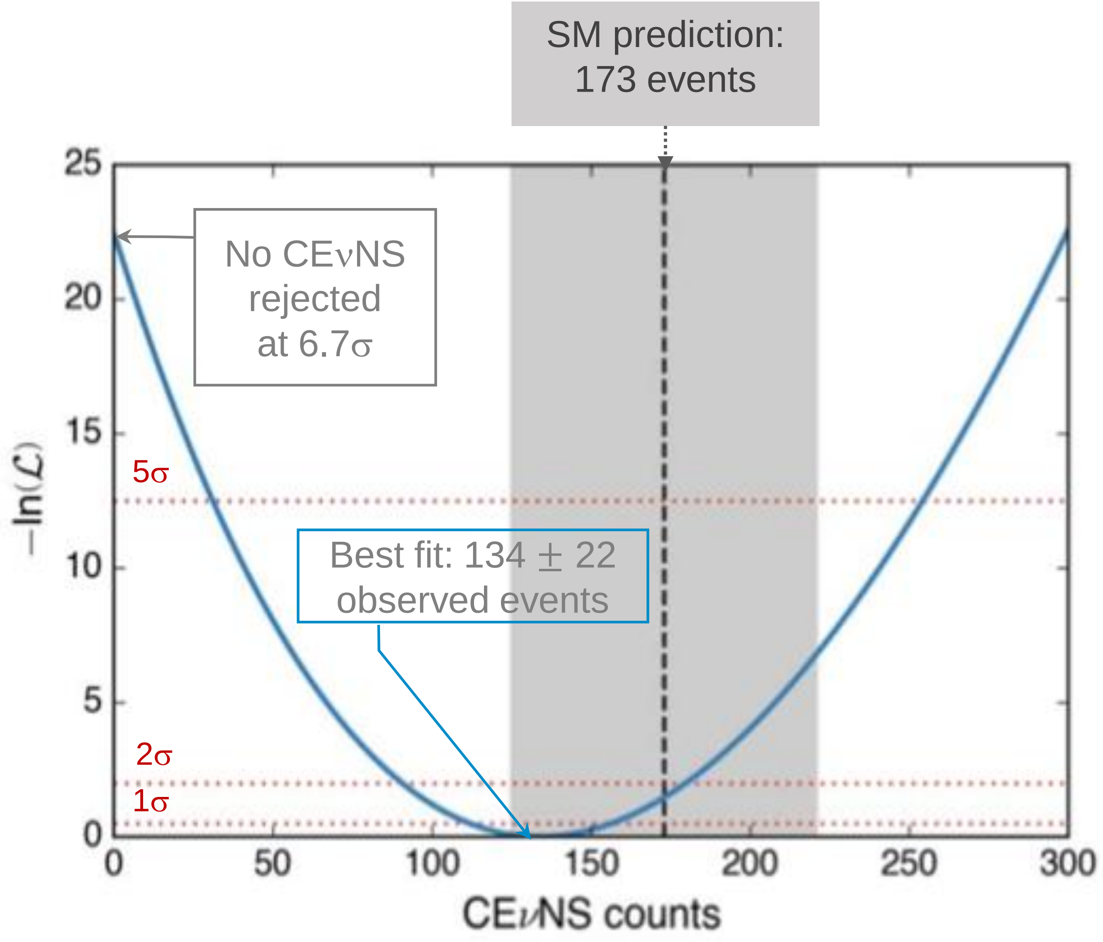
- Observation of CEνNS in 14.6 kg CsI[Na] detector!
- 6.7σ significance with likelihood fit
- Best fit of 134±22 Signal Events within 1σ of SM Prediction: 173±48
- Uncertainties due to nuclear quenching, neutrino flux, nuclear form factor, etc.
- Beam OFF Data: 153.5 days ; Beam ON Data: 308.1 Days (7.48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







First Observation of CEvNS



- CsI detector still acquiring data; will soon be decommissioned.
- Dataset available for analysis now features approximately twice the amount of POT data (~14 GWhr).
- Uncertainty in this result is dominated by current quenching factor determination; new QF analysis will reduce this considerably.

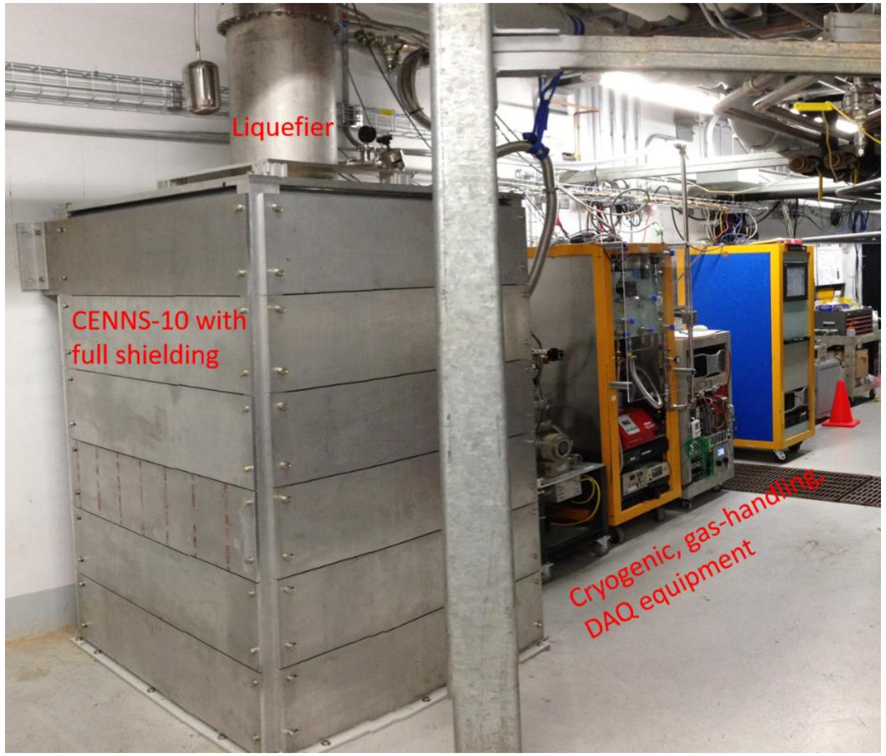
Dominant systematic uncertainties on predicted rates

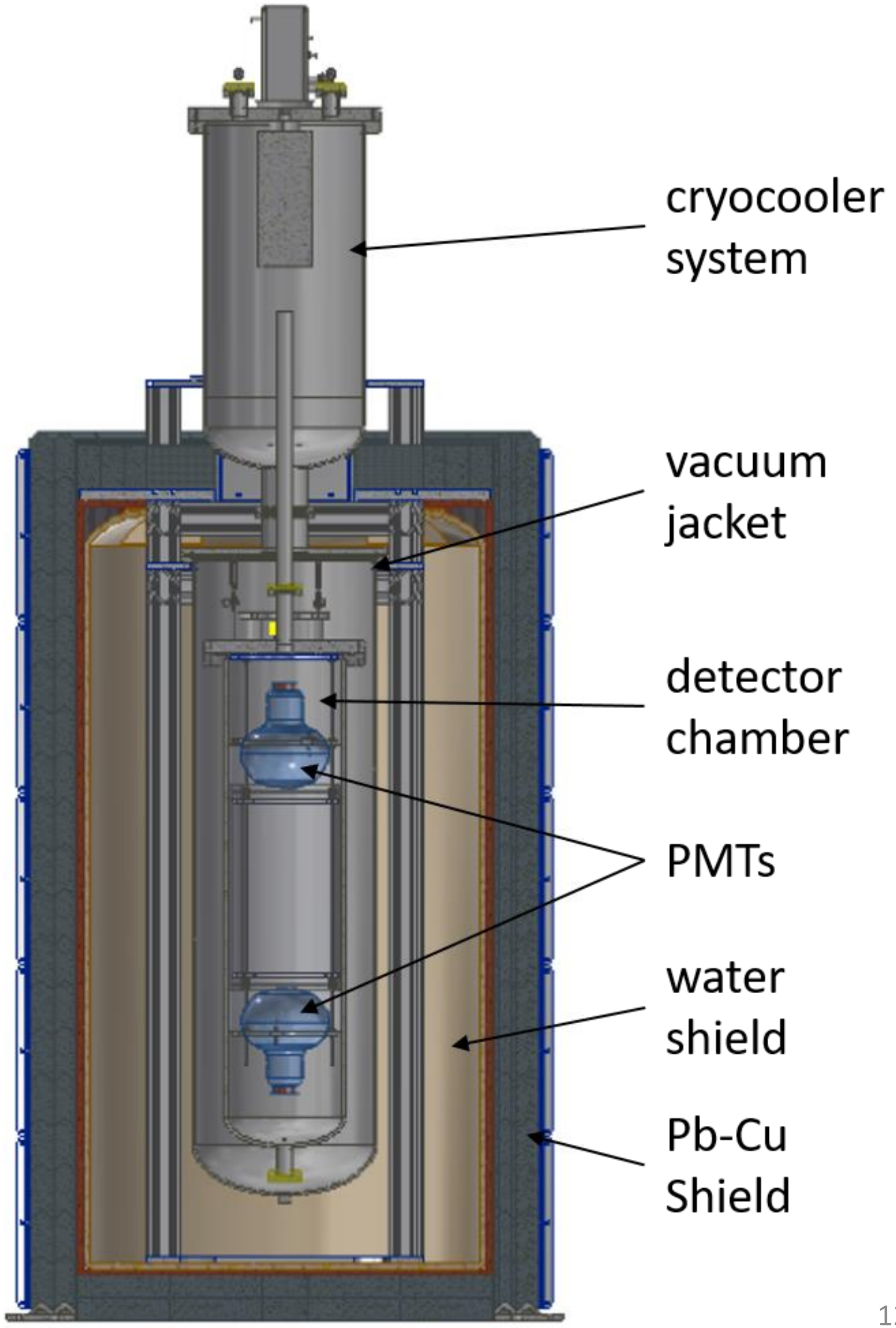
Quenching factor	25%
ν flux	10%
Nuc. form factor	5%
Analysis acceptance	5%

CENNS-10

- Single-phase liquid Ar scintillation detector located 28 m from SNS target (~2 x 10^7 ν / s)

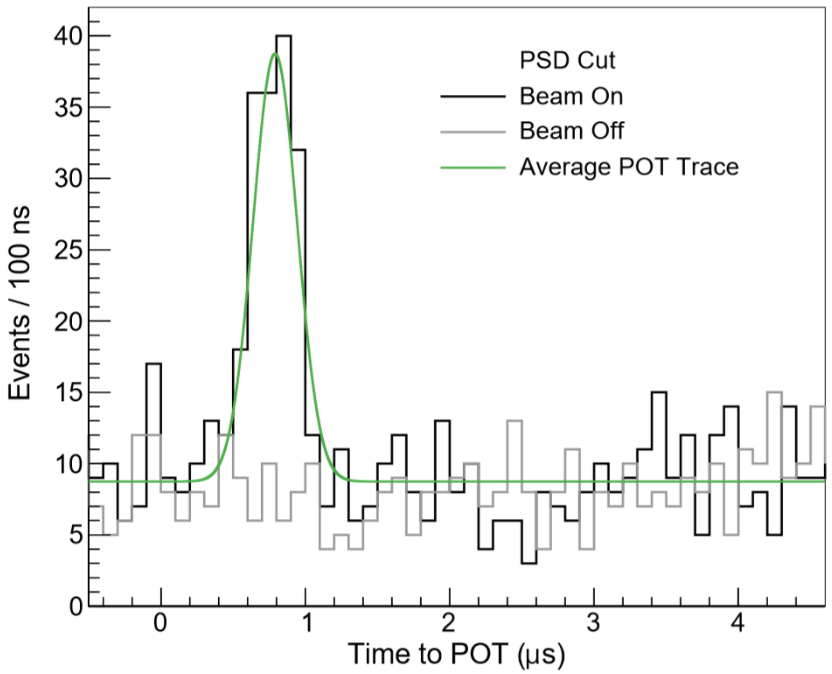
- Collecting data from December 2016 to present
  - Engineering Run: Dec 2016 -> May 2017
  - Production Run: August 2017 -> Present



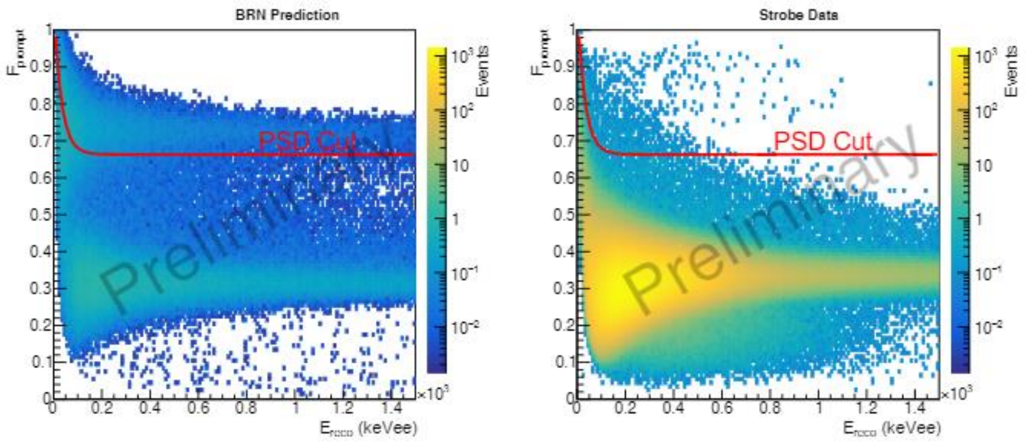


CENNS-10 Engineering Run

- Detector specs:
  - 29 kg fiducial volume
  - 8” PMTs located on top and bottom of volume
  - Acrylic cylinder defining volume coated with tetraphenyl butadiene (TPB) as a wavelength shifter for VUV light
  - Acrylic disks coated with TPB to shift VUV before hitting PMTs
- Initial data helps constrain neutron flux and neutron induced event rate at CENNS-10 location
- Light yield is approximately 0.5 pe/keVee
- Small CEvNS expectation due to high threshold (80 keVnr).

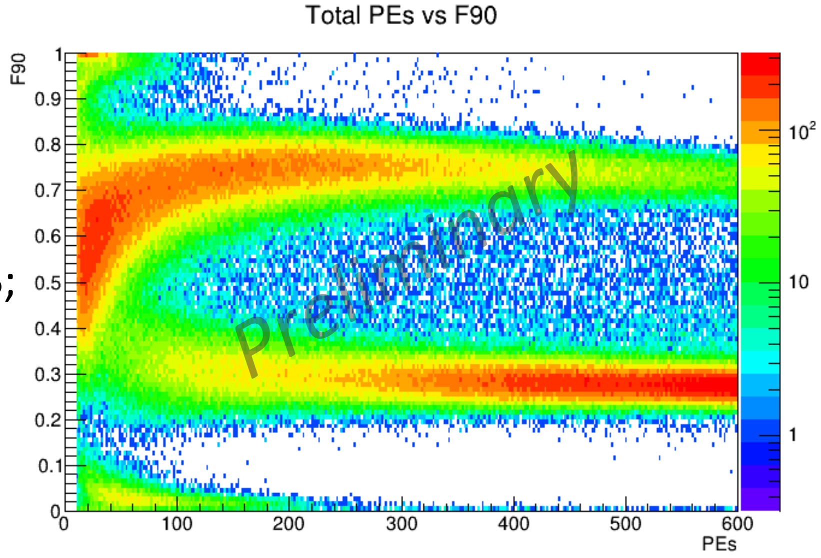


Beam-related neutrons in CENNS-10

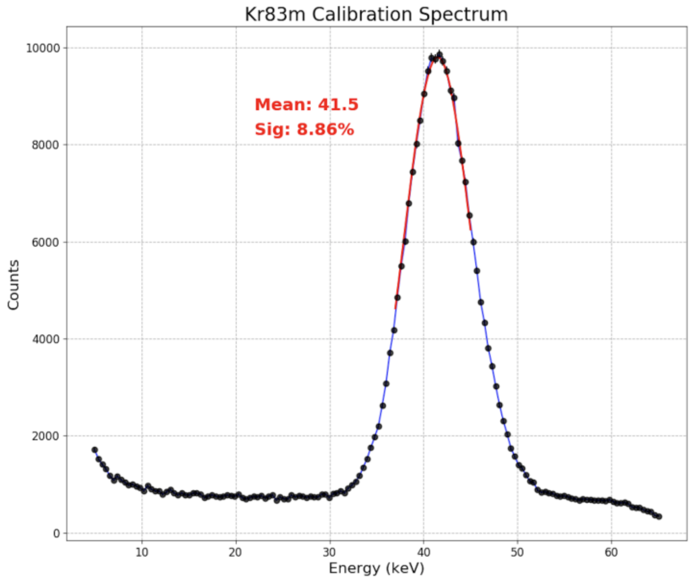


CENNS-10 Upgrade

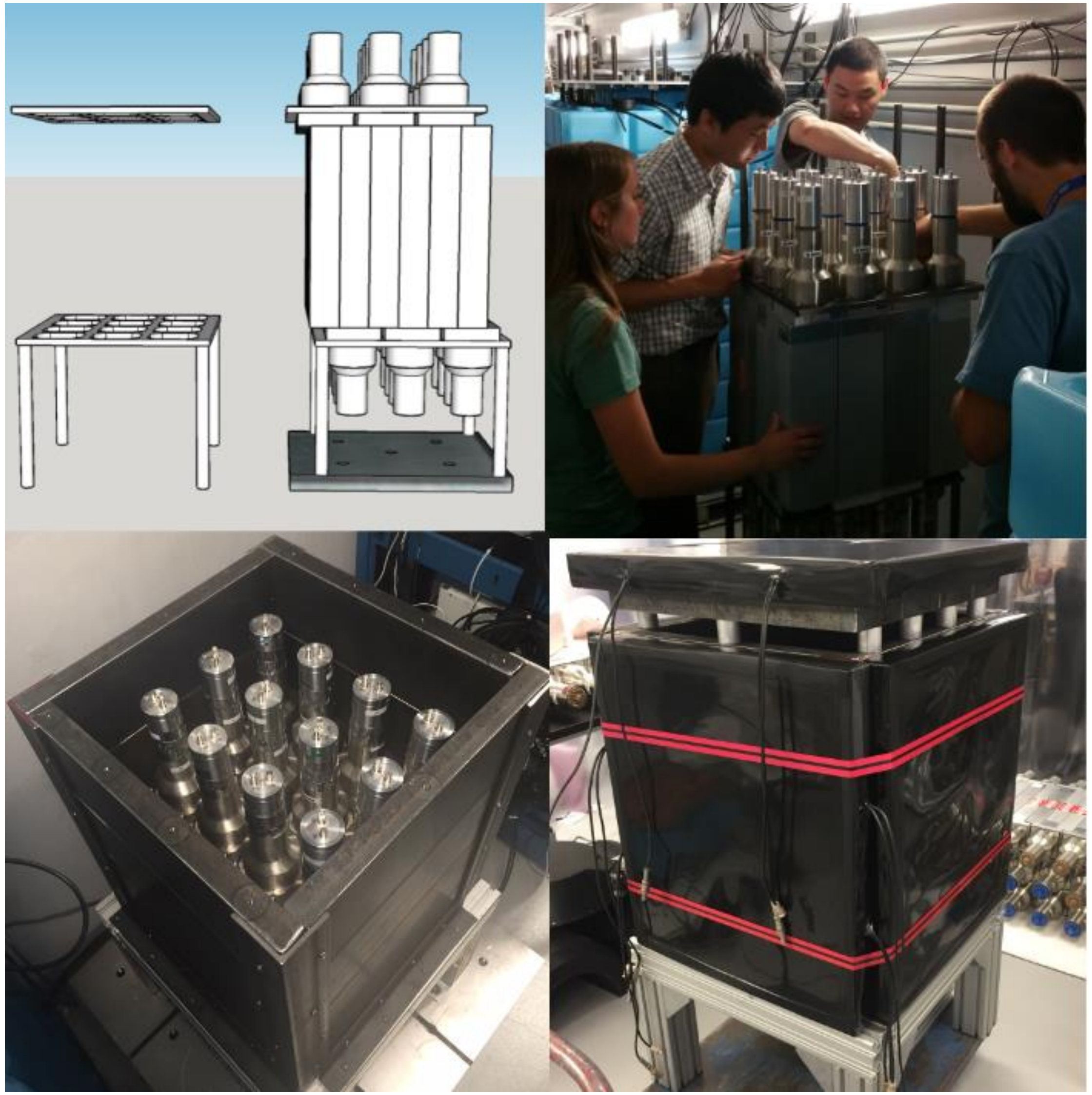
- 8” PMTs were swapped with PMTs directly coated with TPB; acrylic cylinder replaced with set of 3 TPB coated Teflon cylinders (22.4 kg fiducial volume).
- Post-upgrade light yield in the range of 4-5 pe/keVee; threshold reduced to ~ 20 keVnr.
- Complete layer of Pb shielding added to reduce environmental 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



NaIνE Prototype



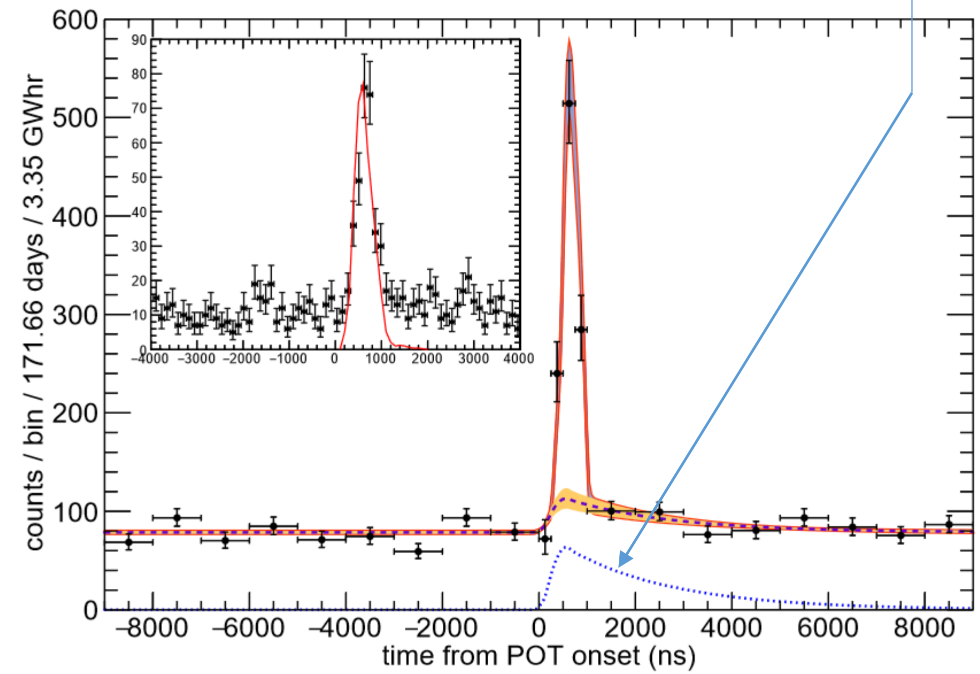
- Several tons of NaI[Tl] detectors available for use after closing of Spectroscopic Portal program (DHS).
- Detectors are 7.7 kg and are equipped with a Burle 10-stage PMT
- Crystals are NOT designed with low-background or threshold
- NaIνE prototype consists of 24 of these detectors
- Purpose:
  - 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)

- 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 is poorly constrained and process has yet to be observed, but this is a potential important background for COHERENT experiments.
- Set of Neutrino Cube detectors (NUBES) seek to observe this process and constrain the potential contribution to CEvNS signal.
- NINs is also the detection mechanism for the HALO supernova observatory.

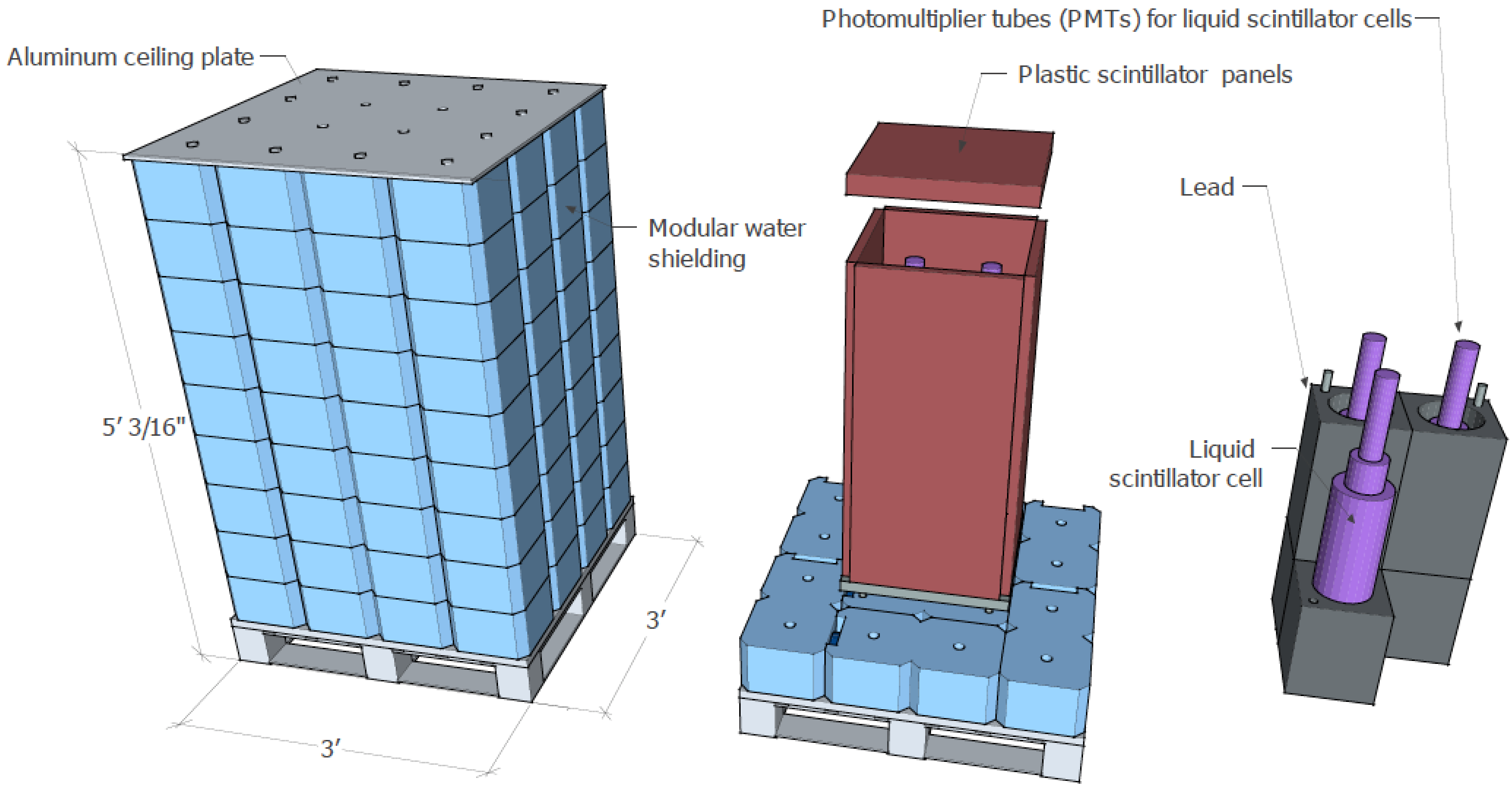
$$\nu_e +^{208} Pb \Rightarrow {}^{208}Bi^* + e^- \quad (CC)$$
$$\Downarrow$$
$$^{208-y}Bi + x\gamma + yn$$

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

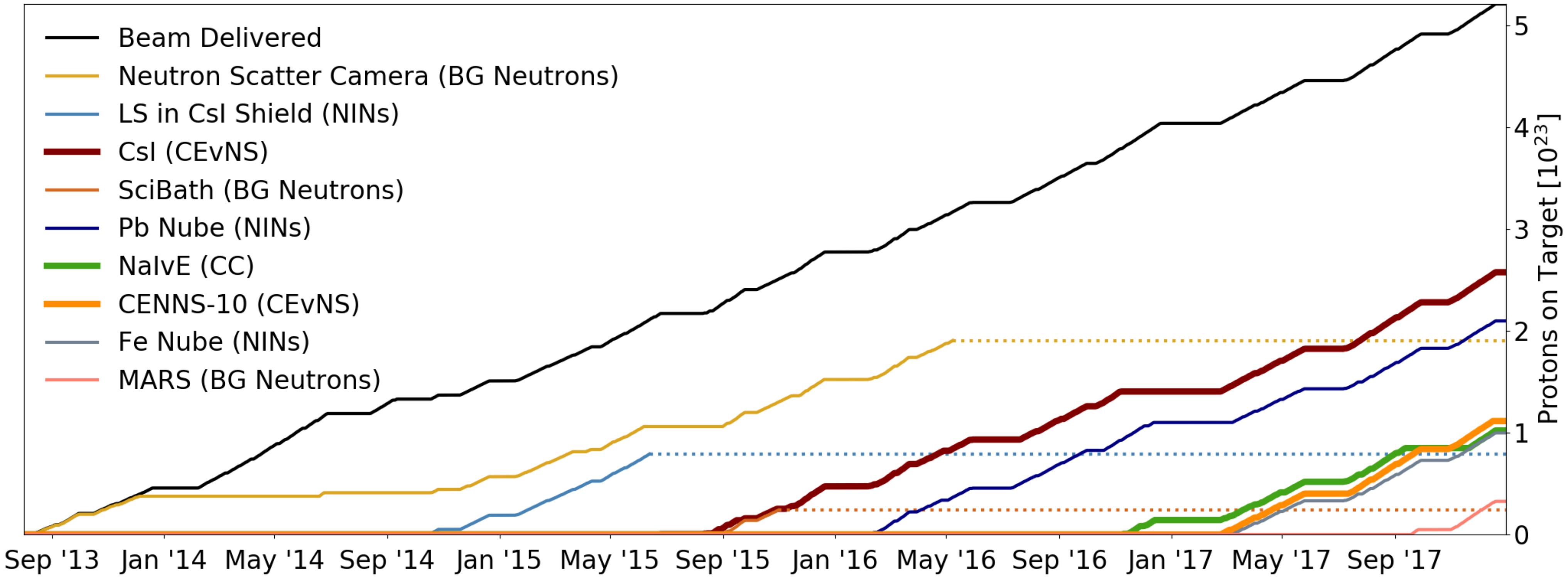


LS Cell in CsI Shielding

Neutrino Cubes (NUBES)



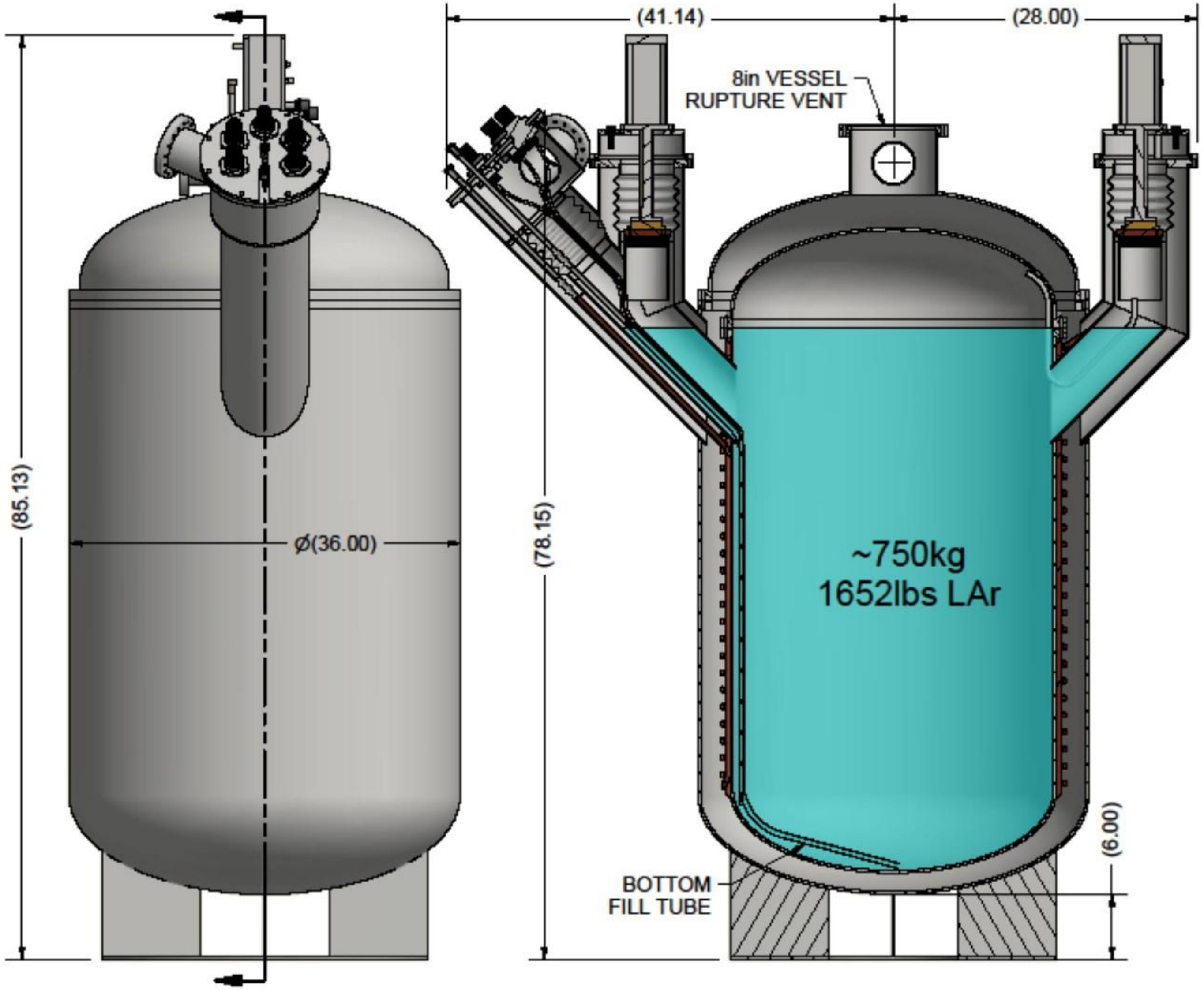
Data Collected – Future Plans



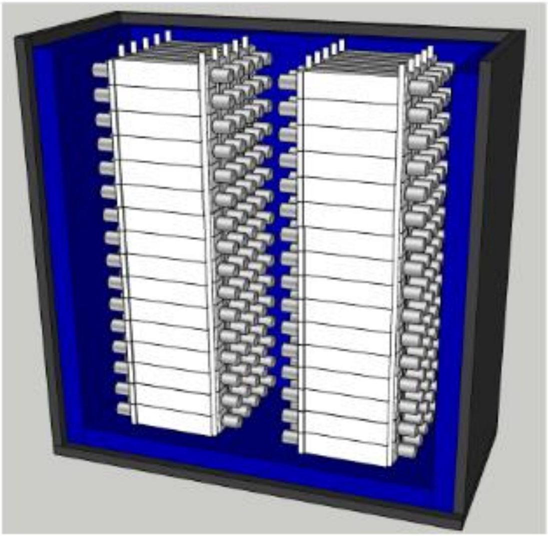
- Several detector systems have begun or finished data taking and characterization of location backgrounds is complete.
- What's next? Bigger detectors and additional targets! Higher statistics and low backgrounds are essential.
- Data from current LAr and NaI detectors essential for informing large-scale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

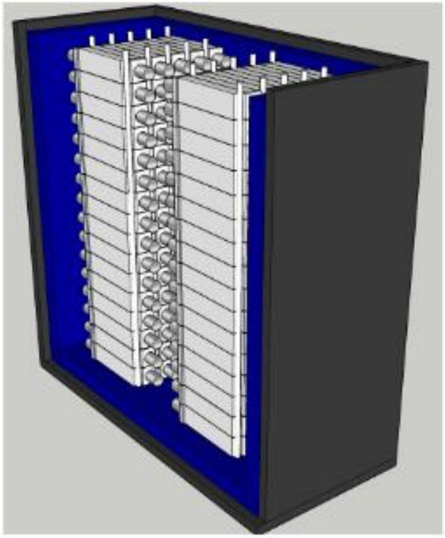
CENNS-750

- Preliminary design for Liq Ar detector featuring approx. 612 kg fiducial volume ready.
- Light collection technology under review: PMTs or SiPMs
- Will fit in Neutrino Alley! Footprint not dramatically larger than CENNS-10…
- 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; import for DUNE

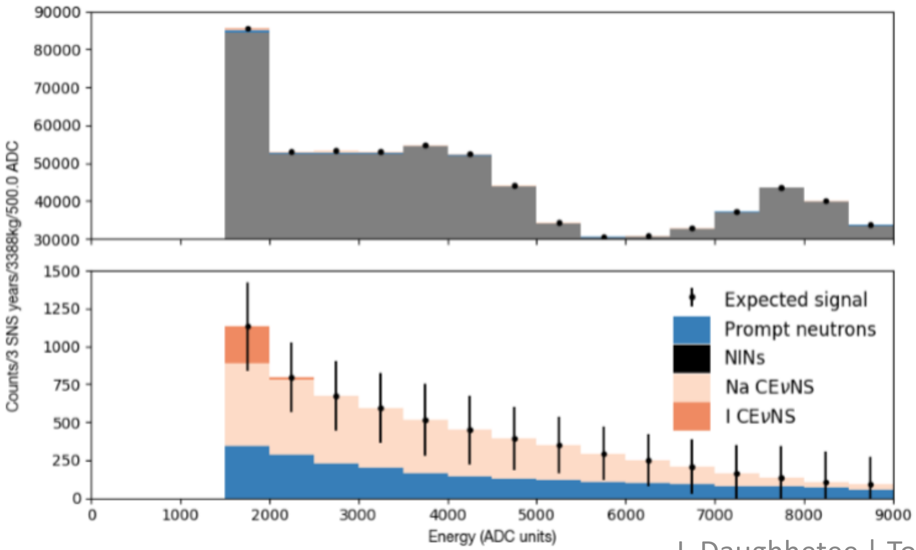


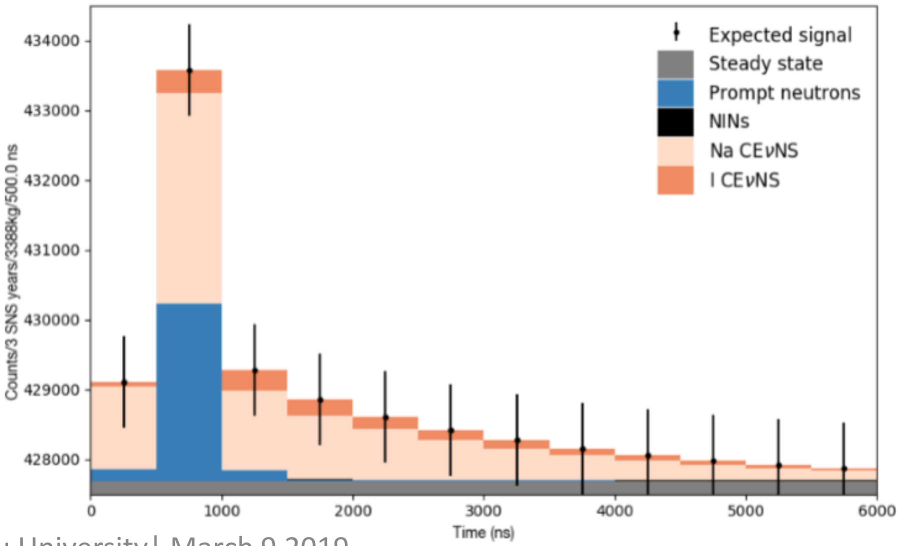
Ton-Scale NaI Array



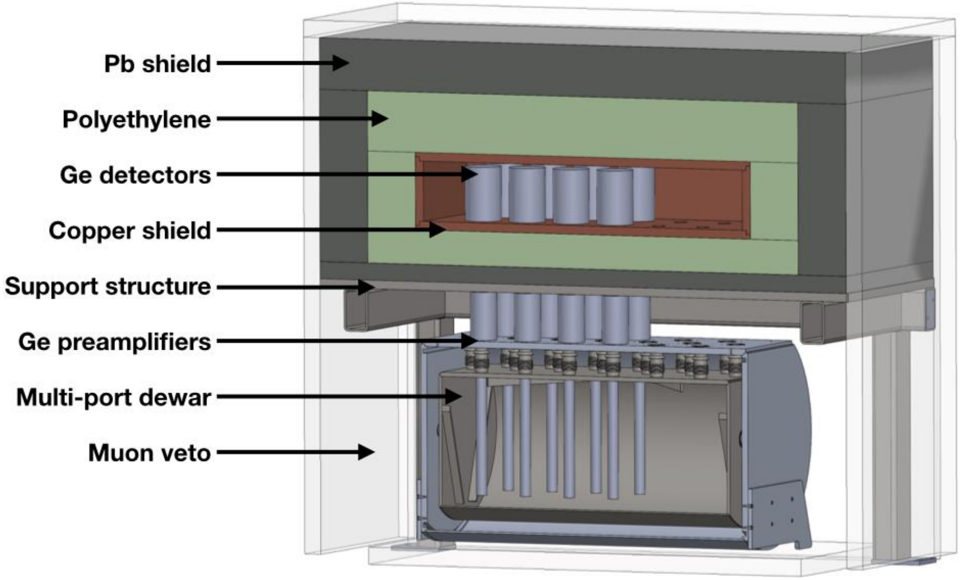


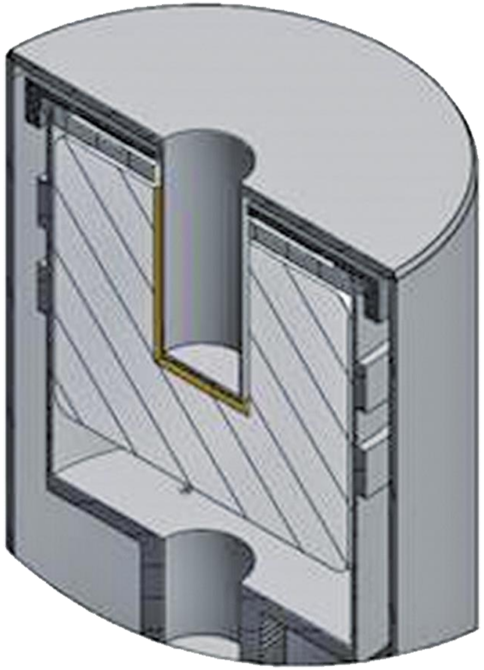
- Designs for ton-scale (3.38 tons) NaI array:
  - Two stacks with 144-160 detectors each
  - Single continuous array
- PMT Testing, backgrounds, detector quality for each detector element needed.
- Plan for new quenching factor measurements to minimize uncertainty and resolve conflict in existing data.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

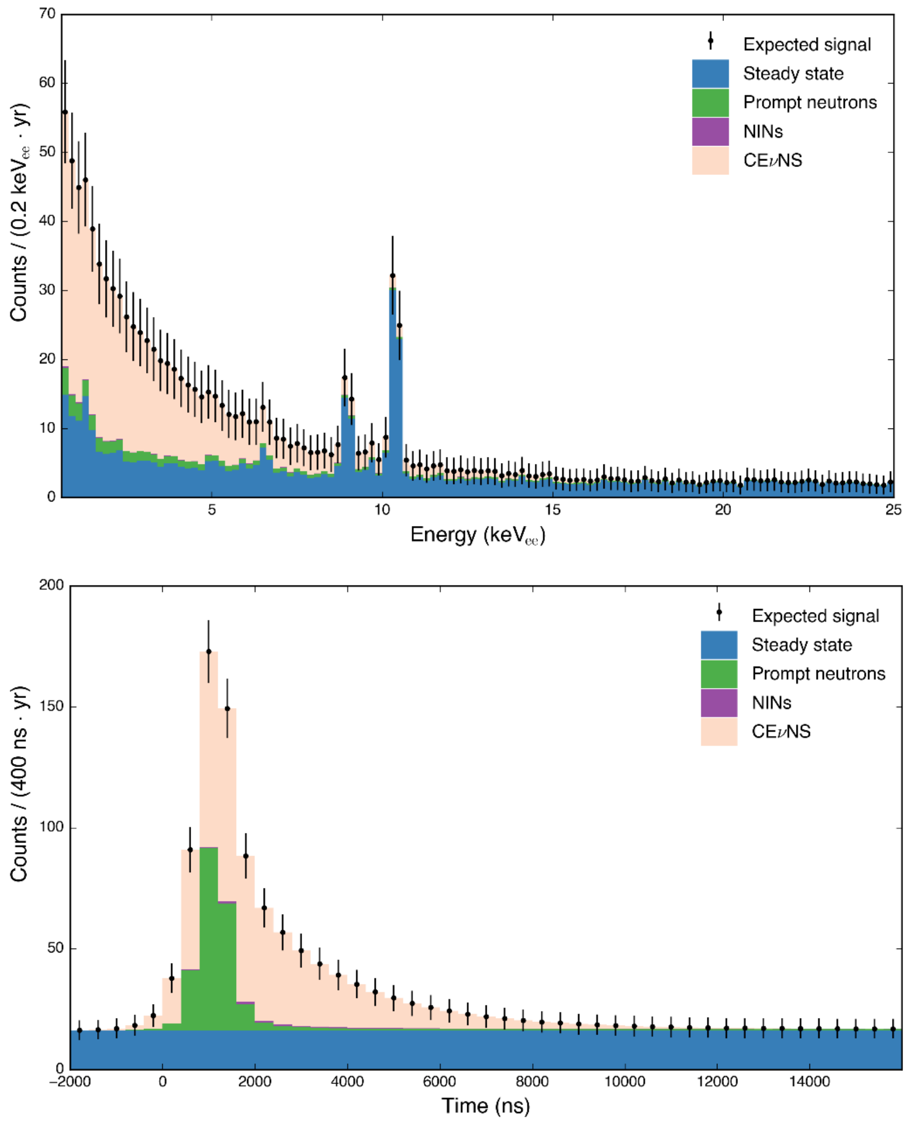




Ge Detector Array



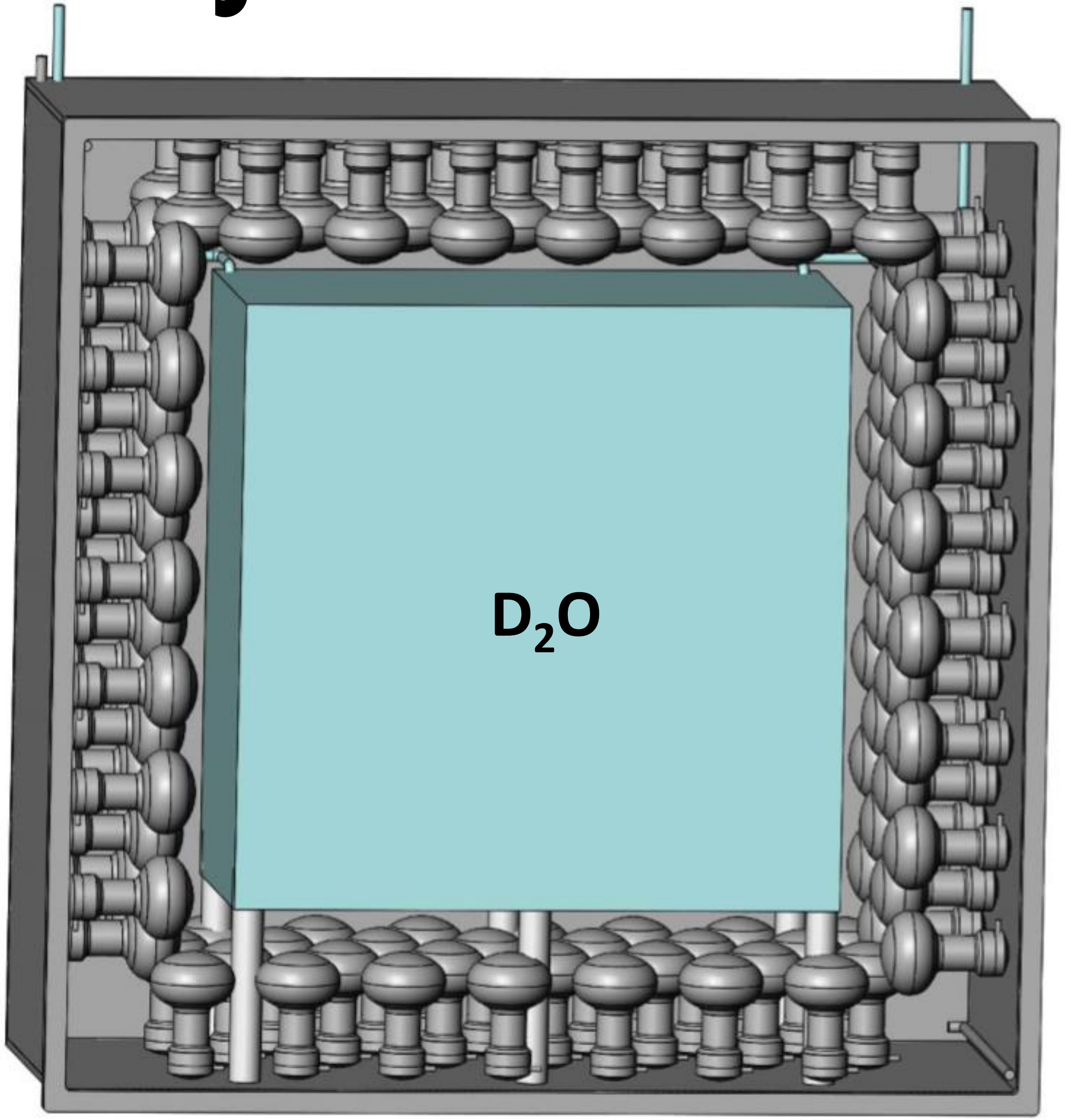




The expected CEvNS signal in a 14.4kg PPC germanium detector array in 1 year of SNS operation.

- 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 in defined ROI with a predicted signal-to-background ratio of 3.5 per year of SNS operation.
- Improved sensitivity for BSM physics: ν electromagnetic properties , non-standard interactions, sterile oscillations, DM, etc.

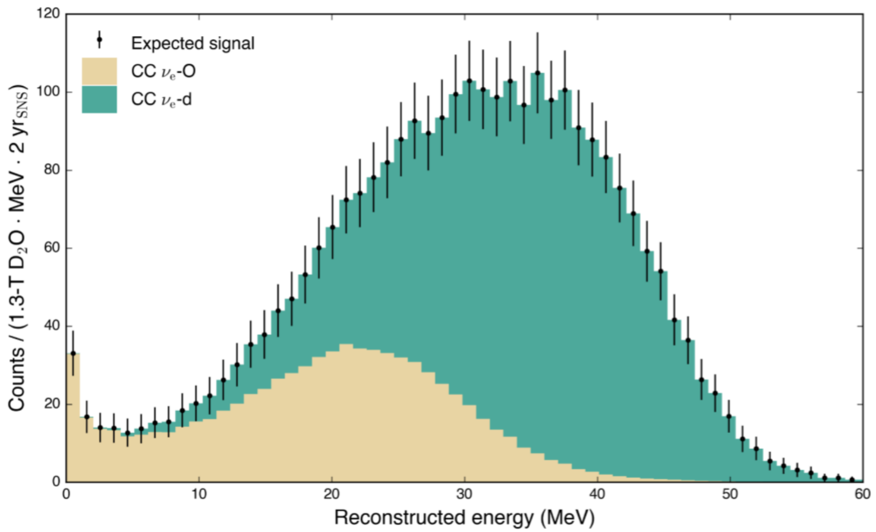
Heavy Water Detector



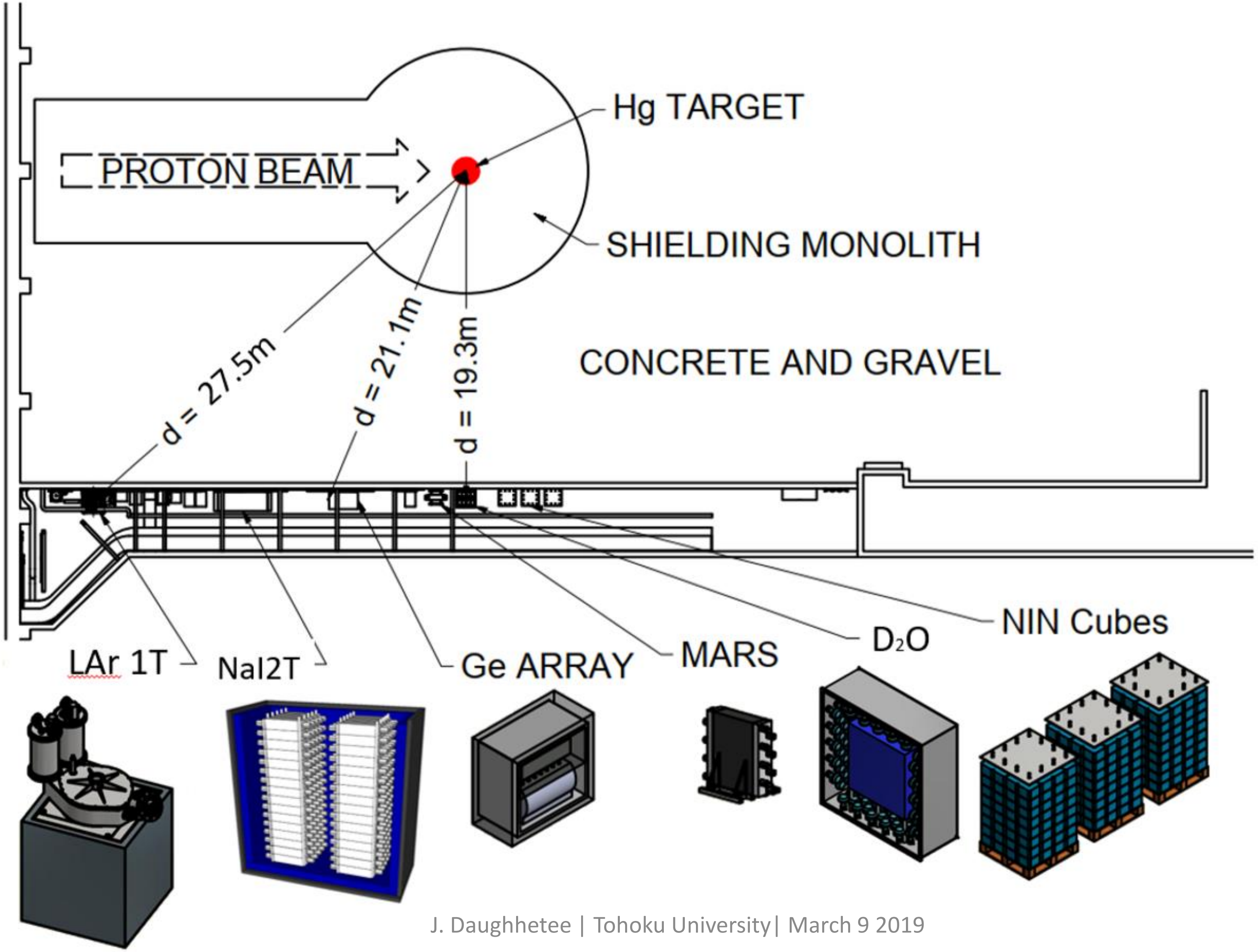
Precise measurement of CEvNS will require reduction in systematic uncertainties:

- 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.



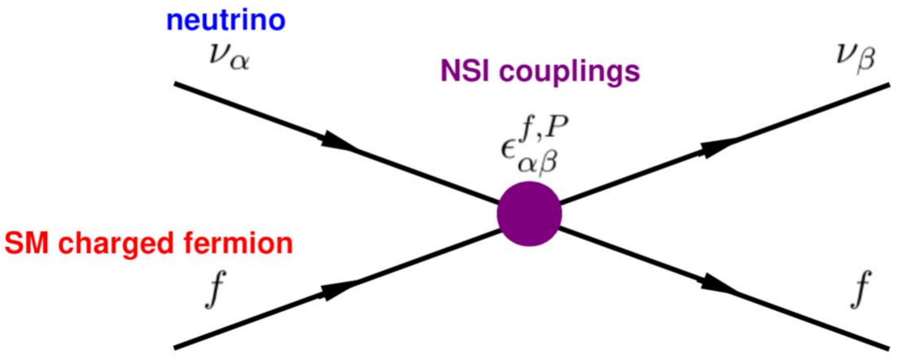
Making Room for the Future



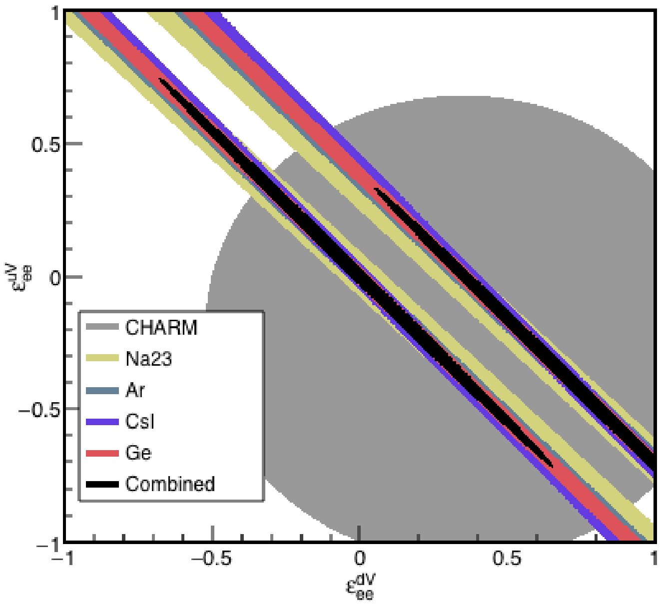
Future Program Physics Reach

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

- 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 X-section measurements on O and Ar
  - Sterile neutrino measurements with near and far detectors
  - Neutrino magnetic moment



Assuming heavy NSI mediators



NSI Searches

Summary

- Using a CsI detector, the COHERENT collaboration has made the first observation of coherent elastic neutrino-nucleus scattering (CEνNS), 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 CEνNS 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).

- Thank you for your attention and stay tuned!