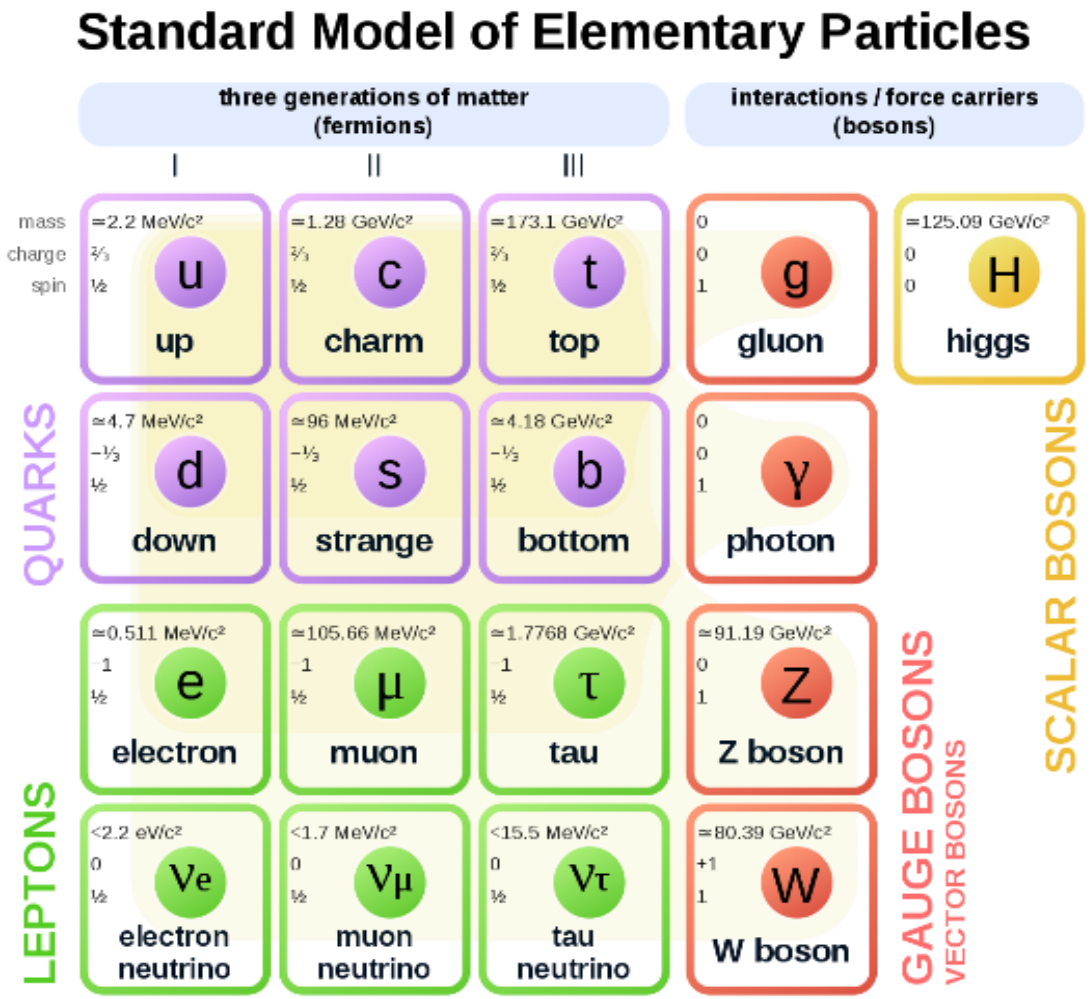
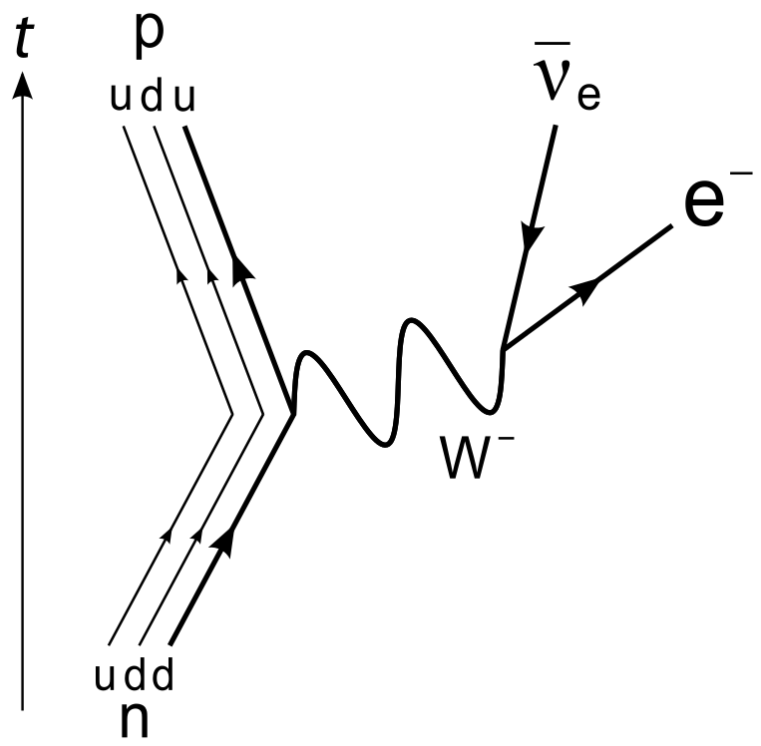
First Detection of Coherent Elastic Neutrino-Nucleus Scattering on Argon

Jacob Daughhetee

BNL Physics Seminar
May 19th, 2020

Neutrinos

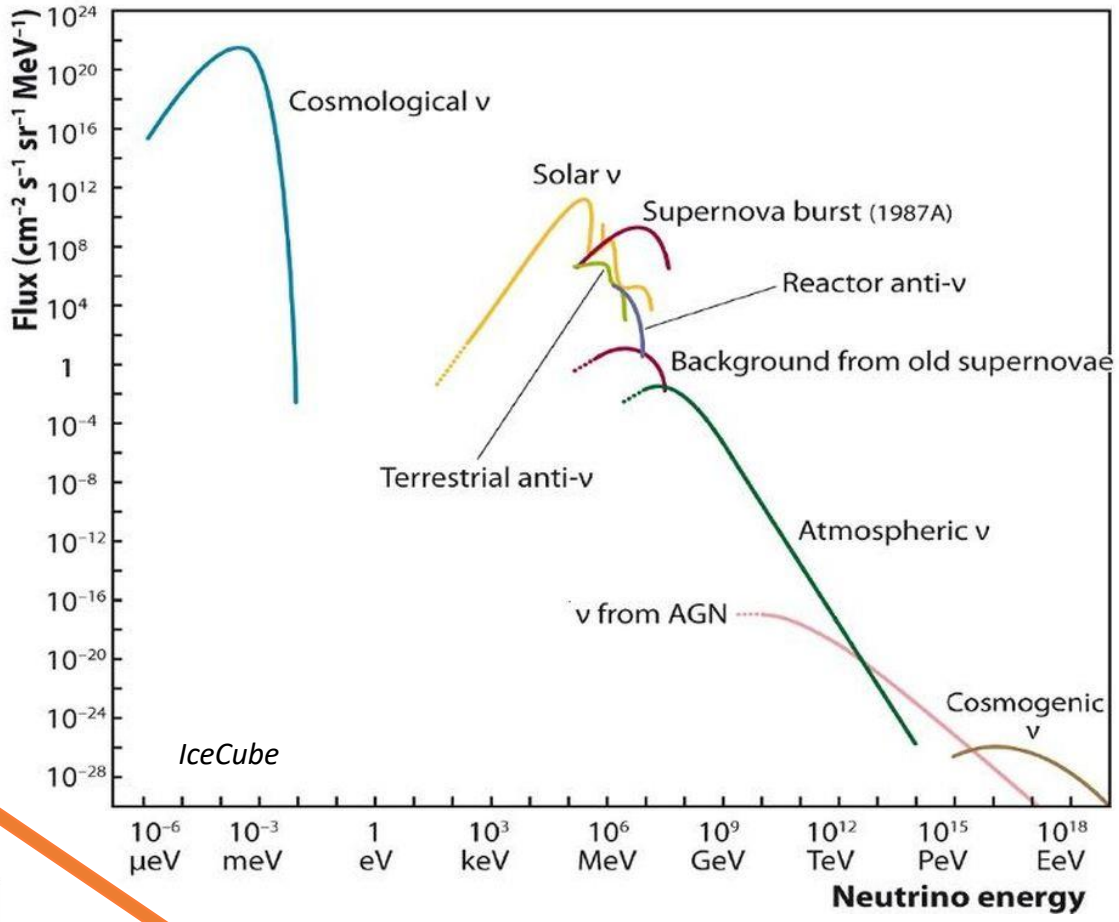


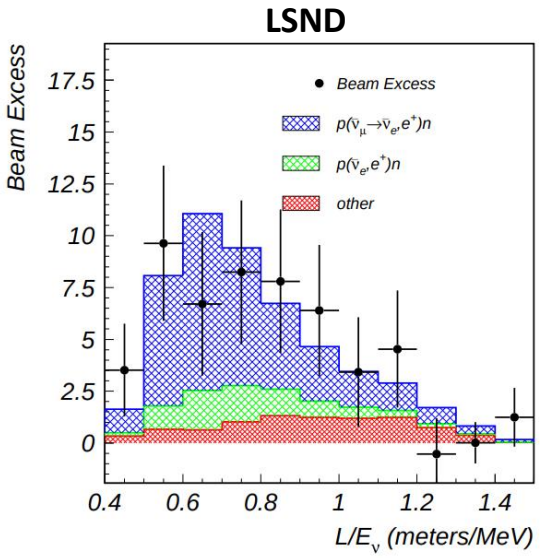


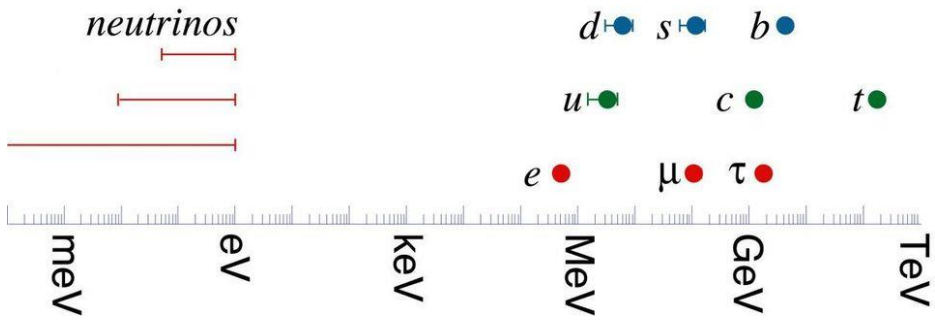
- Existence hypothesized to explain missing energy in beta decay (1930).
- Lightest of Standard Model fermions (m_ν < 1 eV)
- Interact through the weak force and gravity only.
- Cross sections are very small!

Neutrinos

- Abundantly produced in the Universe!
- Peculiar fit in the Standard Model:
  - Anomalously small mass scale
  - Large mixing-angle oscillations
  - Potential additional ‘sterile’ flavors…



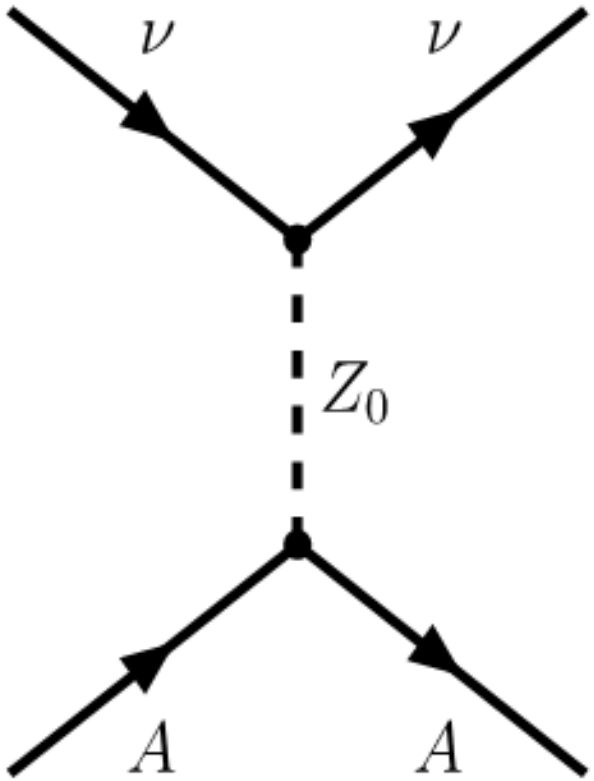




Hitoshi Murayama

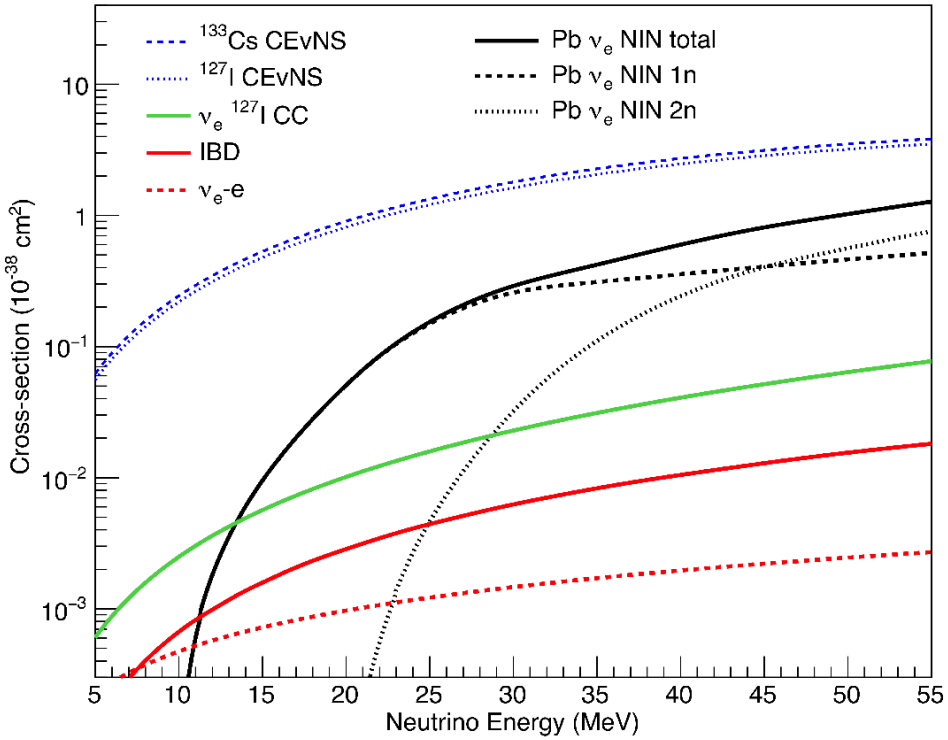
Neutrino physics has been full of unexpected results; precision measurements and Standard Model tests are warranted!

Coherent Elastic Neutrino-Nucleus Scattering



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

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



- 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 CEνNS

CEνNS Physics

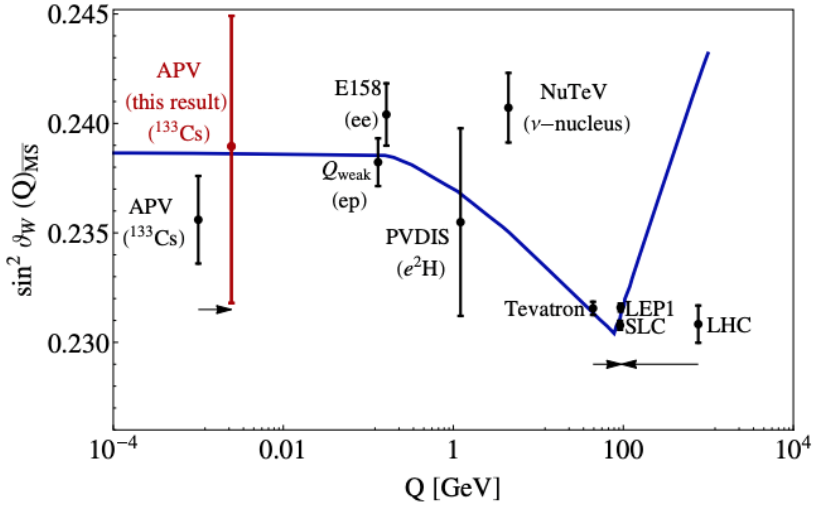
$$\sigma_{tot} = \frac{G_F^2 E_\nu^2}{4\pi}\left[Z\left(1-4\sin^2\theta_W\right)-N\right]^2 F^2(Q^2)$$

Nuclear Form Factors

- Unknown to a few %
- Potentially inferable through high-precision measurements.

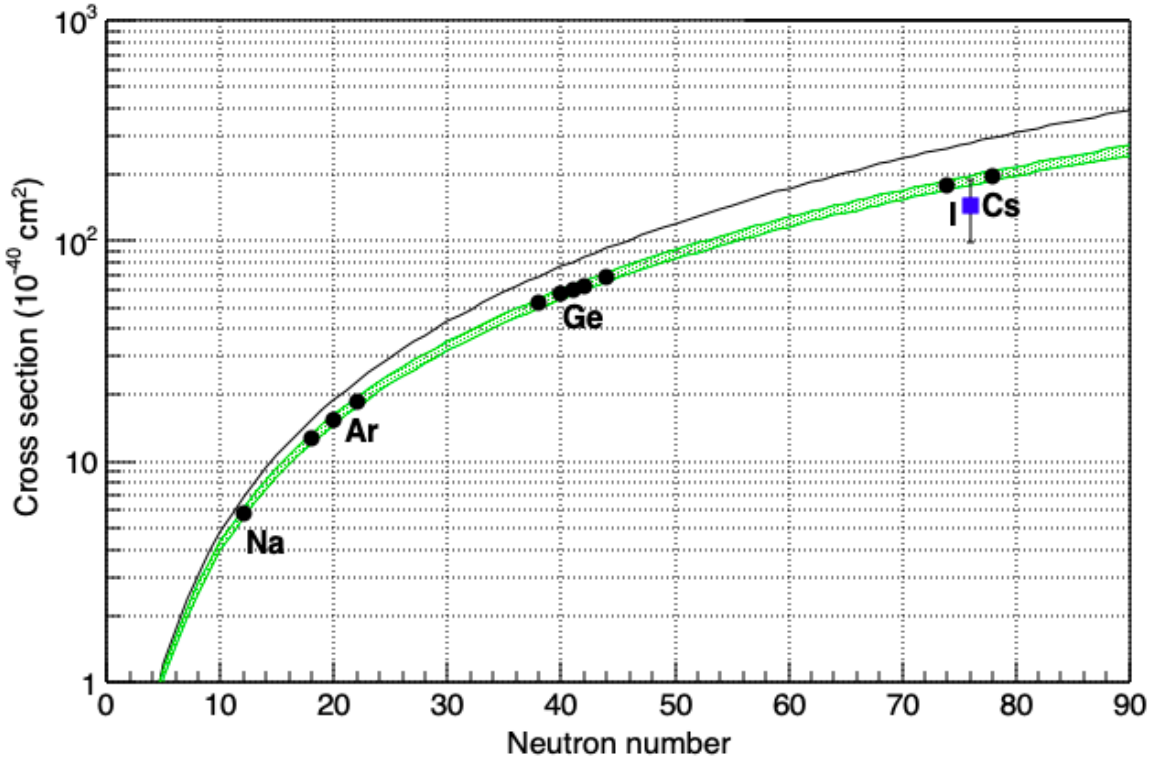
Weak Mixing Angle

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

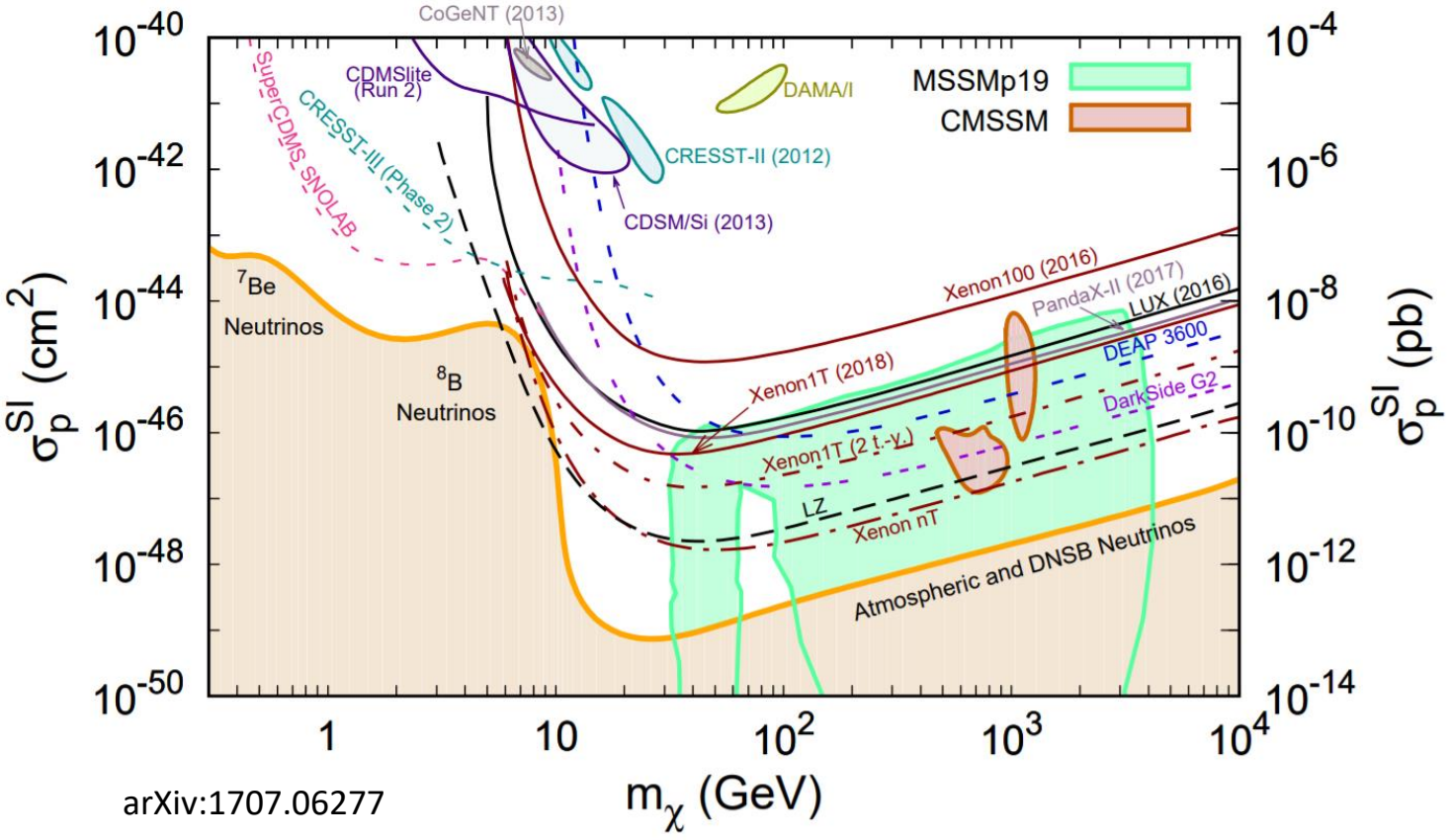


M. Cadeddu and F. Dordei, Phys. Rev. D 99 033010 (2019)

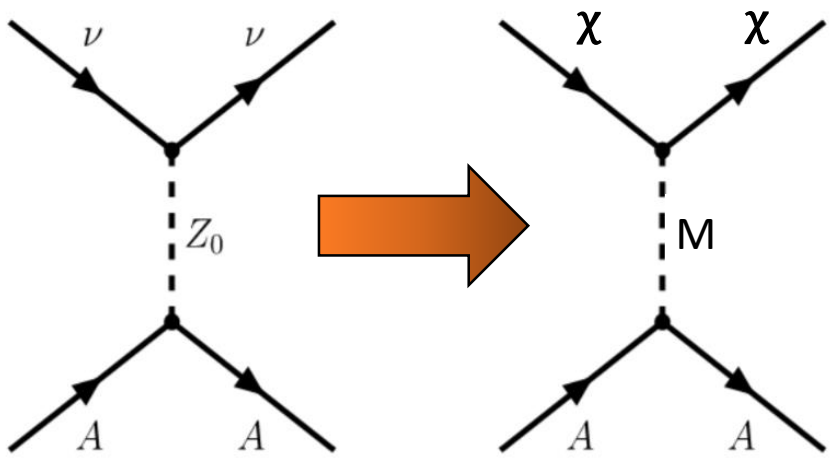
Neutron Number Dependence



CEνNS Physics – Dark Matter



arXiv:1707.06277

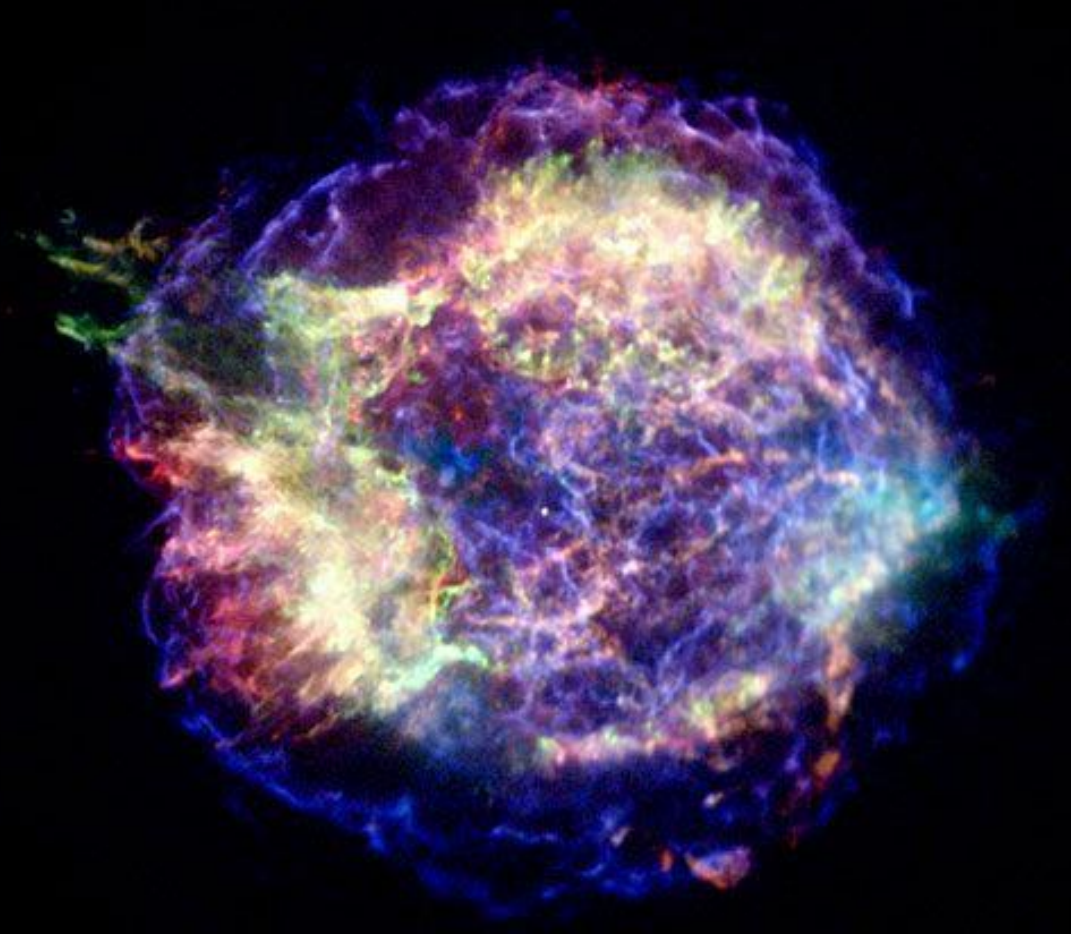


CEνNS

WIMP-Scatter

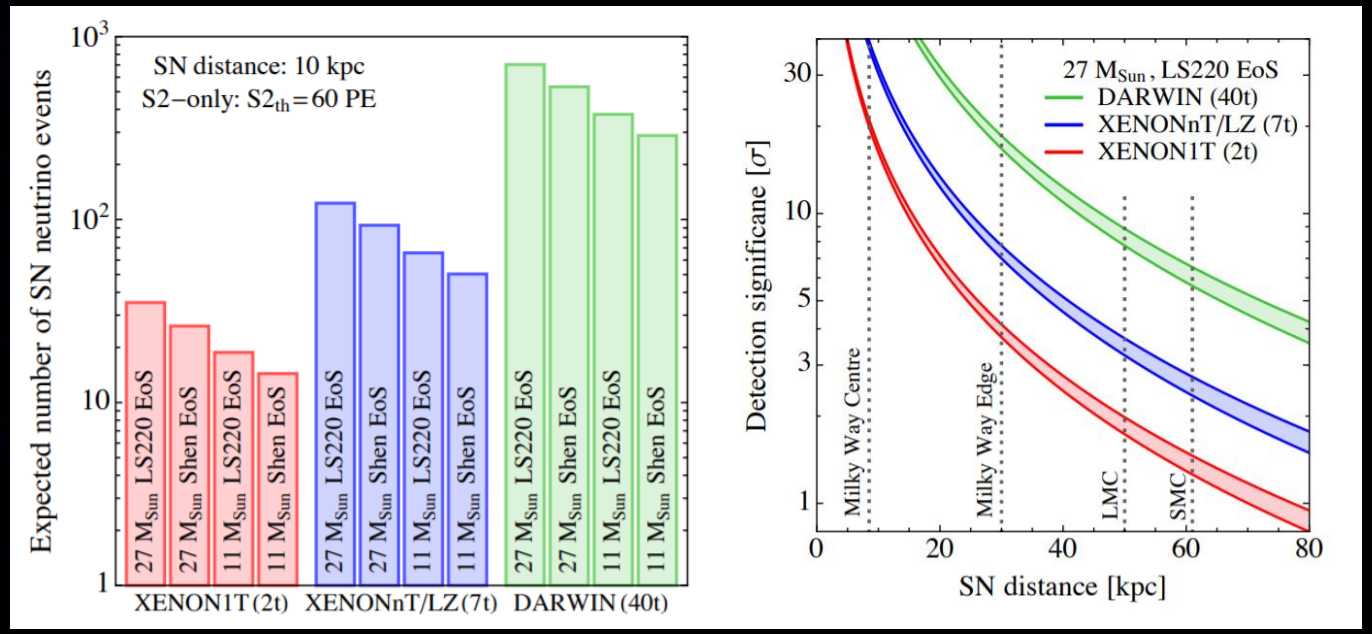
Near-Irreducible Background for Direct Detection Dark Matter Experiments

CEνNS Physics – Supernovae



Supernova Dynamics

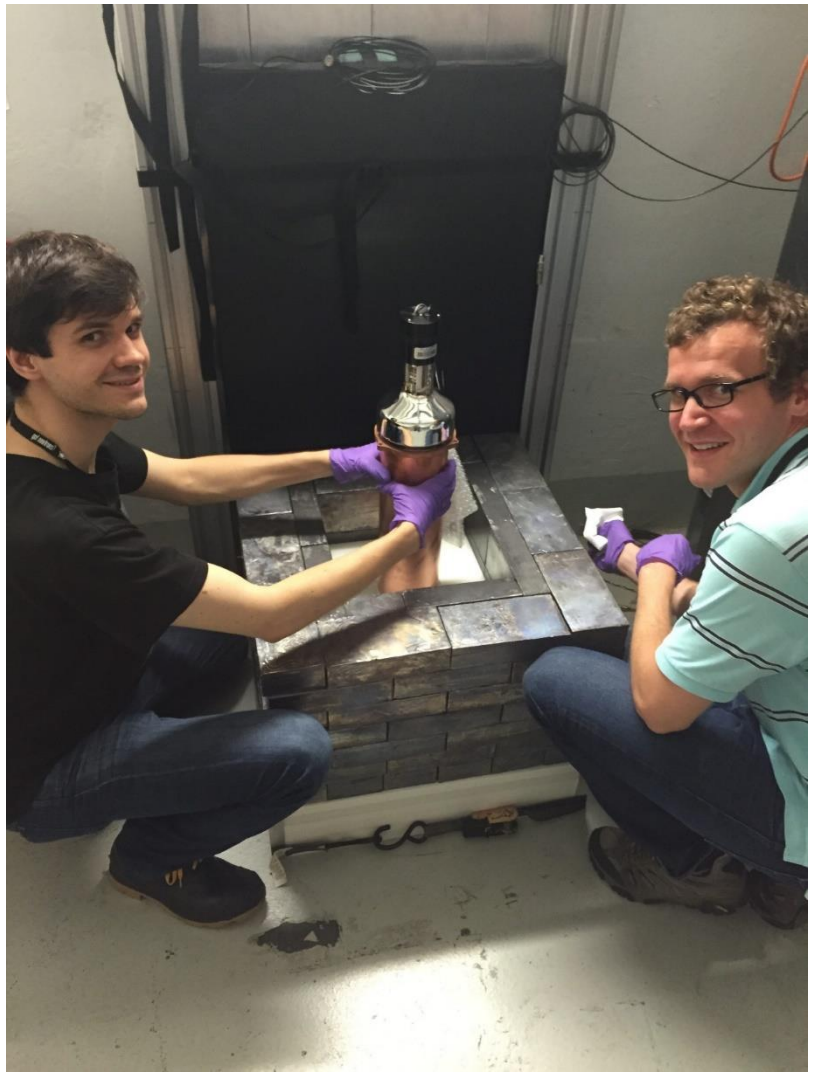
Supernova Detection via CEνNS Liquid Xe



Lang et. al - Phys. Rev. D 94 (2016) no.10, 103009

Detector Miniaturization

Increased X-section -> Smaller Sizes



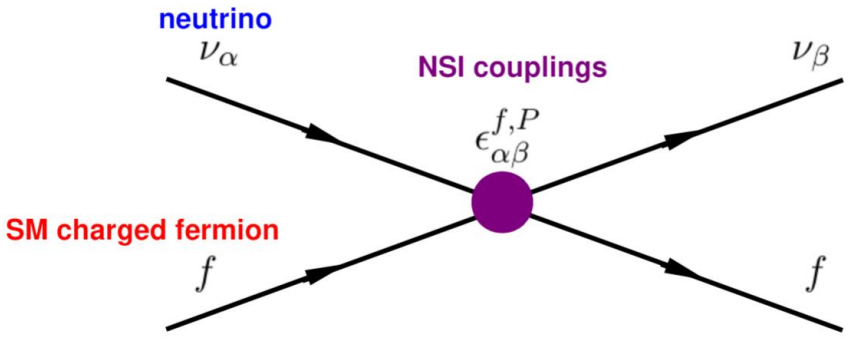
COHERENT CsI[Na] – 14.6 kg

- Detectors sensitive to CEνNS can have smaller masses and therefore increased portability.
- Potentially useful for monitoring of reactor activity and enforcing non-proliferation.

Non-Standard Interactions

Potential Non-SM Vector Interactions

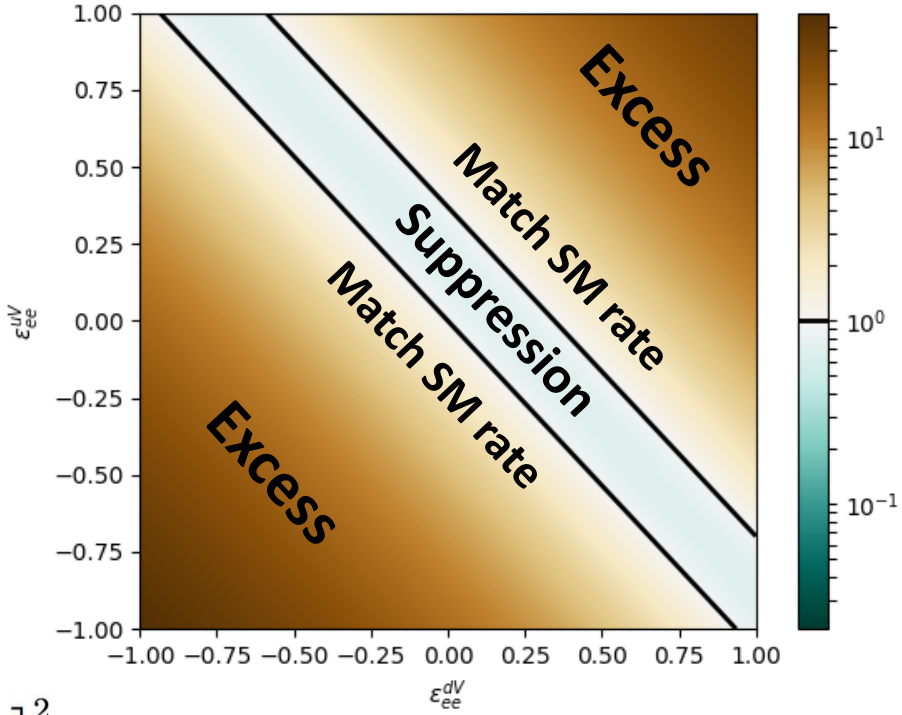
$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \epsilon^{f,P}_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P f)$$



Assuming heavy NSI mediators

Modified Cross Section

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



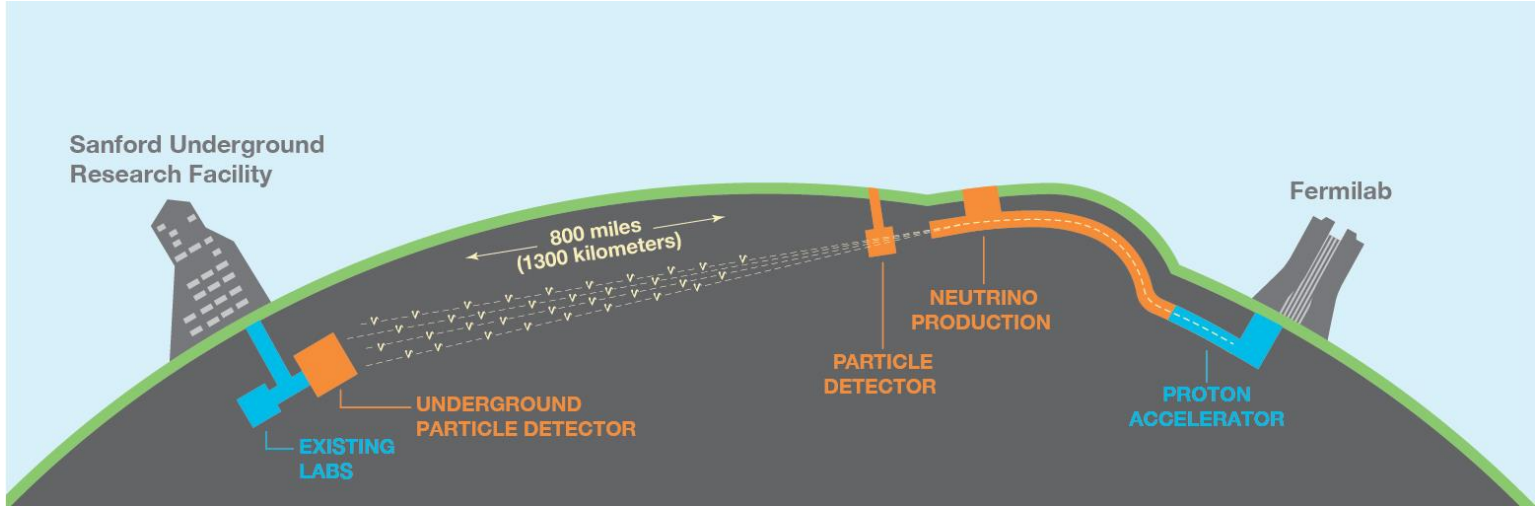
J. Barranco *et al*. Phys Rev D **76** (2007)
J. Billard, J. Johnston, B. Kavanagh. arXiv:1805.01798

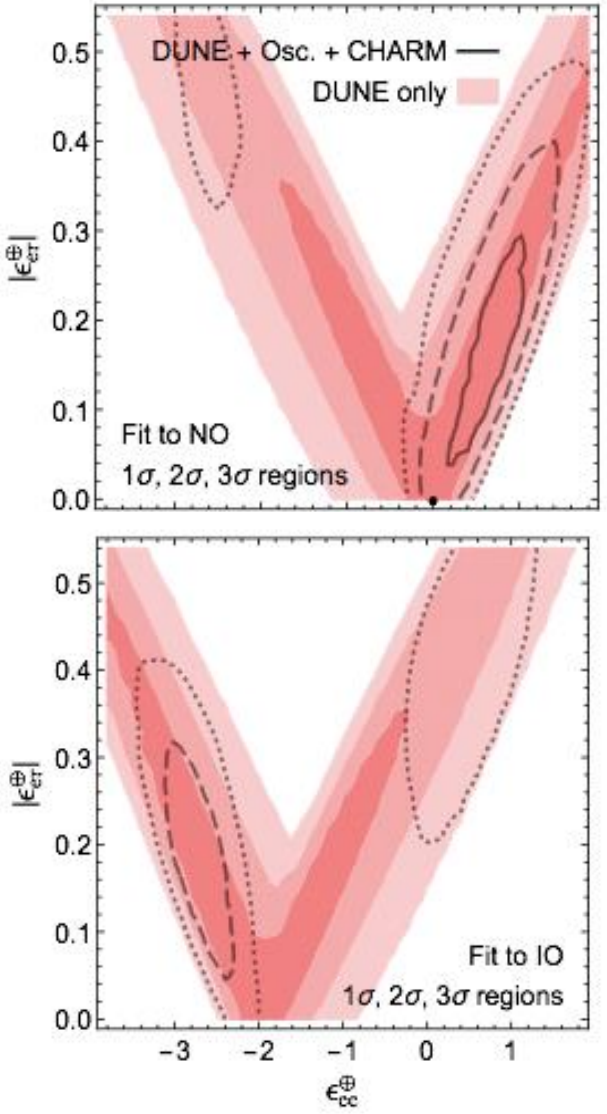
Presence of these interactions can lead to suppression or enhancement of CEvNS rate w.r.t. Standard Model.

Non-Standard Interactions

Generalized mass ordering degeneracy in neutrino oscillation experiments

Pilar Coloma[1] and Thomas Schwetz[2]

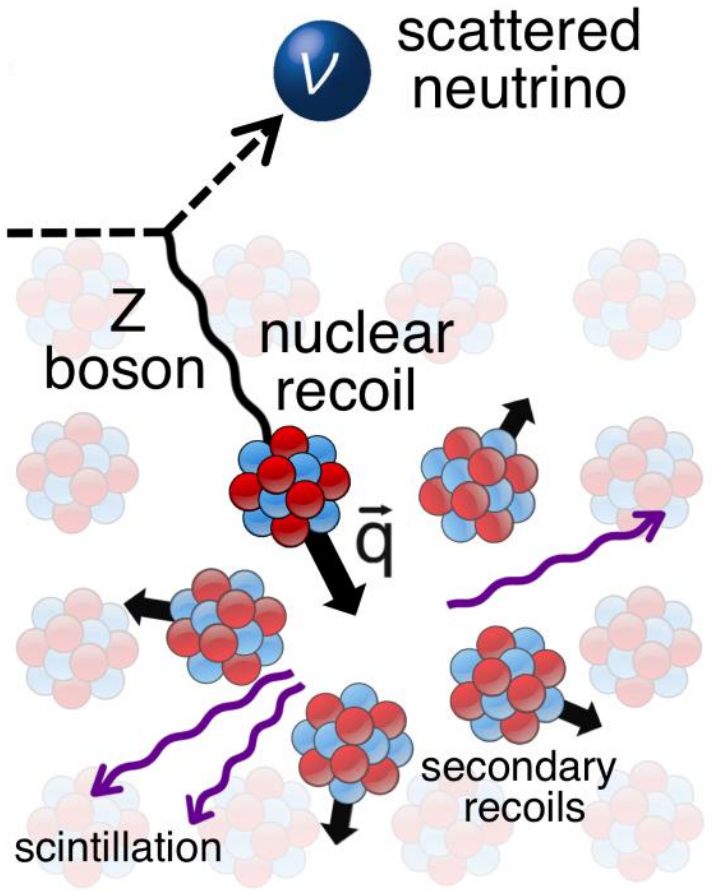


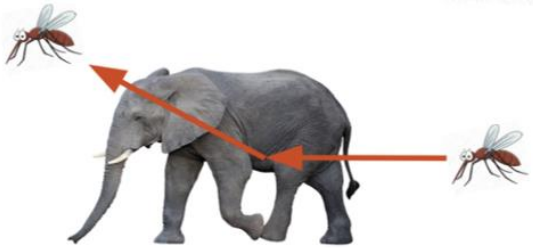


Long-baseline neutrino program seeks to precisely measure oscillation parameters, CP-violation, neutrino mass ordering (NMO).

Constraining these interactions is essential for interpretation of oscillation results!

Detecting CEνNS





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.

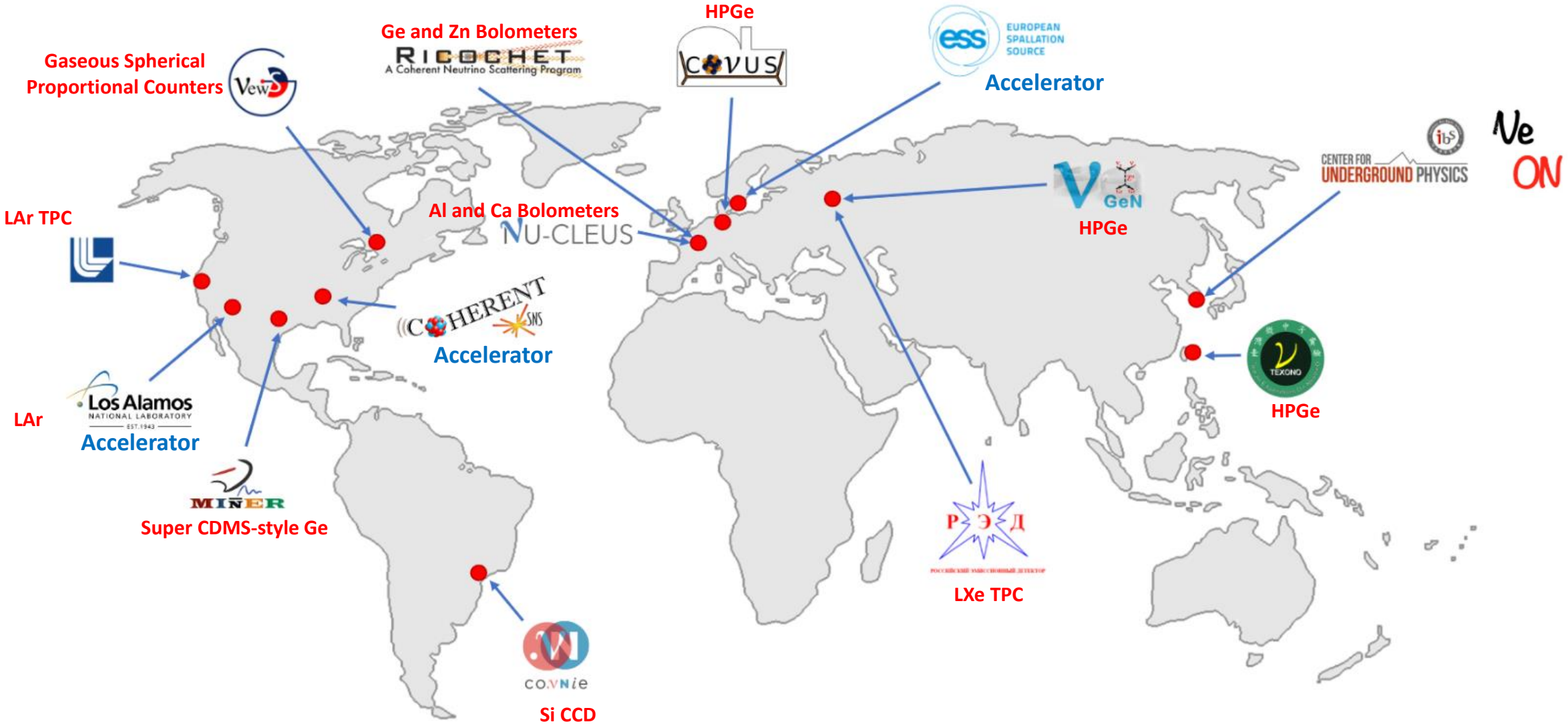
D.Z. Freedman, Phys. Rev. D 9 (1974)
V.B. Kopeliovich and L.L. Frankfurt, ZhETF Pis. Red. 19 (1974)

Cross section may be high, but the signal is in the form of a low-energy nuclear recoil!

Detection requirements:

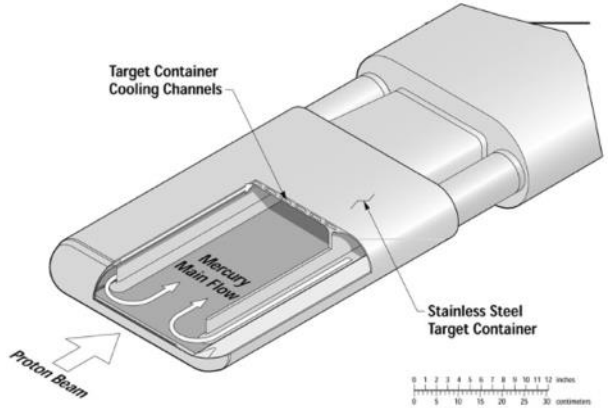
- **Excellent background rejection**
- **Low E-threshold**

CEνNS Efforts



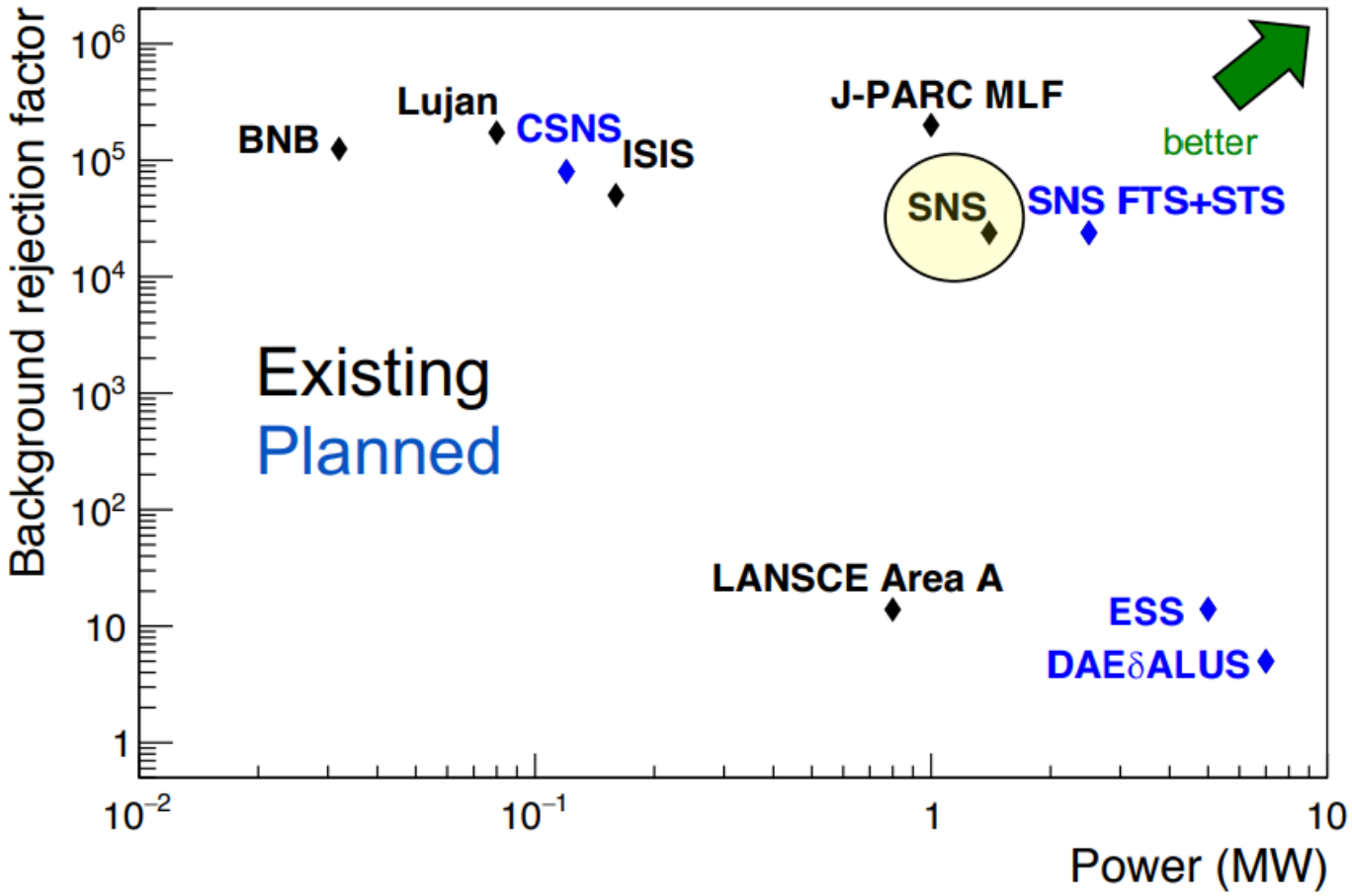
COHERENT at the Spallation Neutron Source

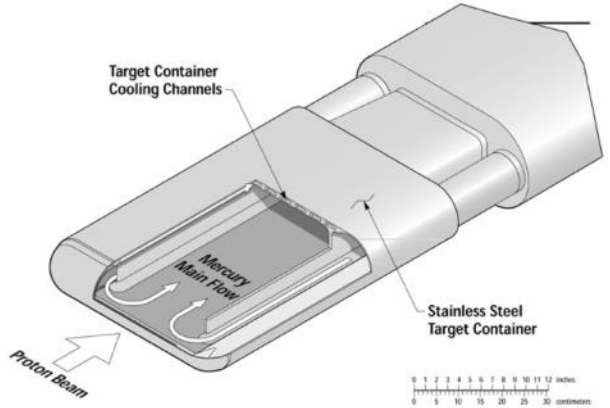
The Spallation Neutron Source



- Primary objective of the Spallation Neutron Source (SNS) is the production of a large flux of neutrons for myriad physics, biology, and materials science studies.
- Neutrons are produced by the spallation of Hg nuclei during bombardment from accelerated protons.
- ~1 GeV protons are delivered to the Hg target at 60 Hz in 400 ns FWHM bunches.
- Current production runs at 1.4 MW power; power upgrade and second target station in the future.

The Spallation Neutron Source





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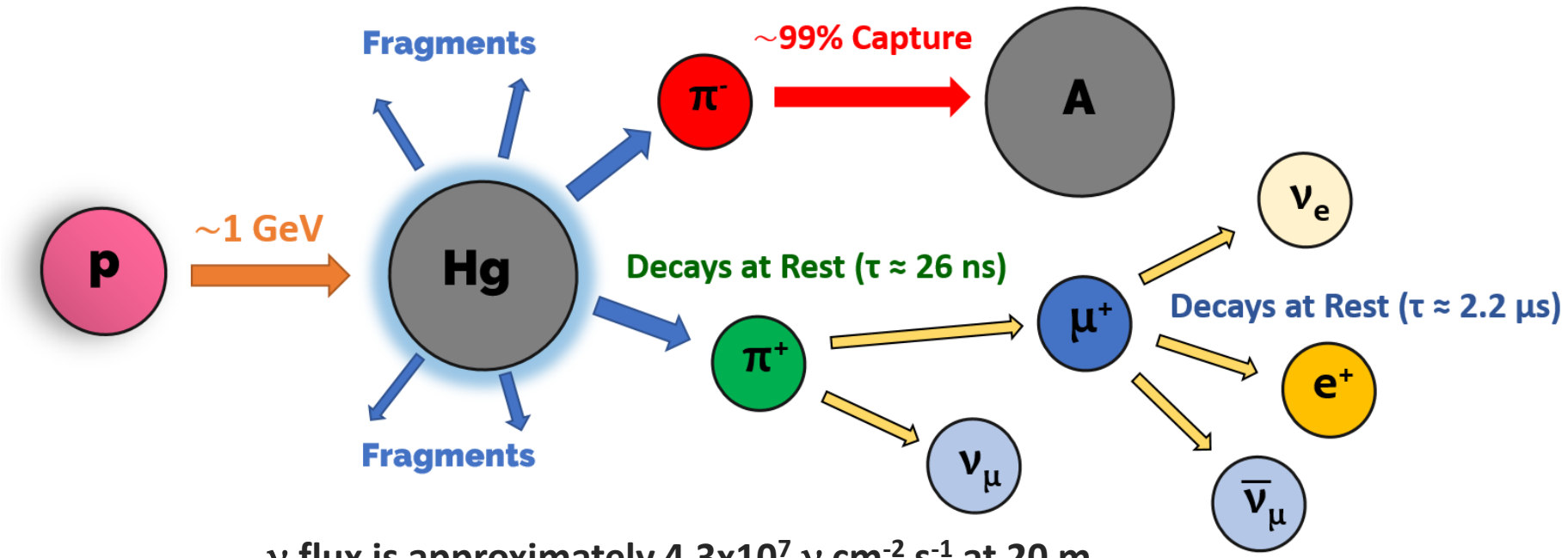
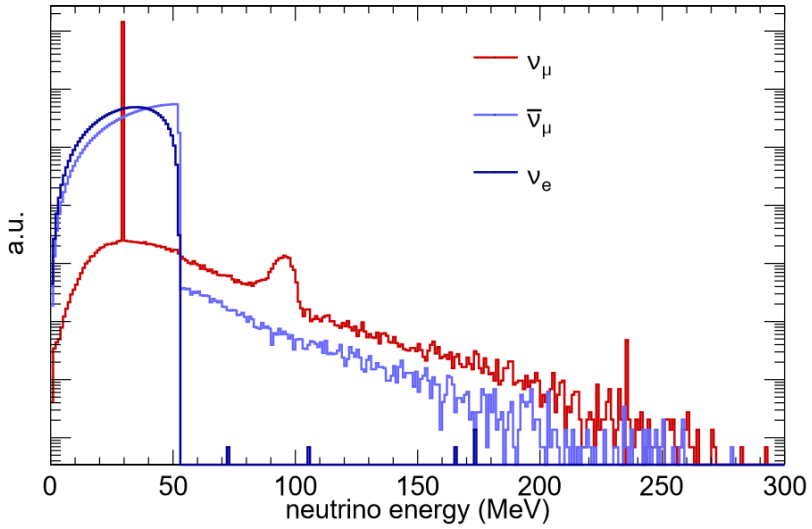
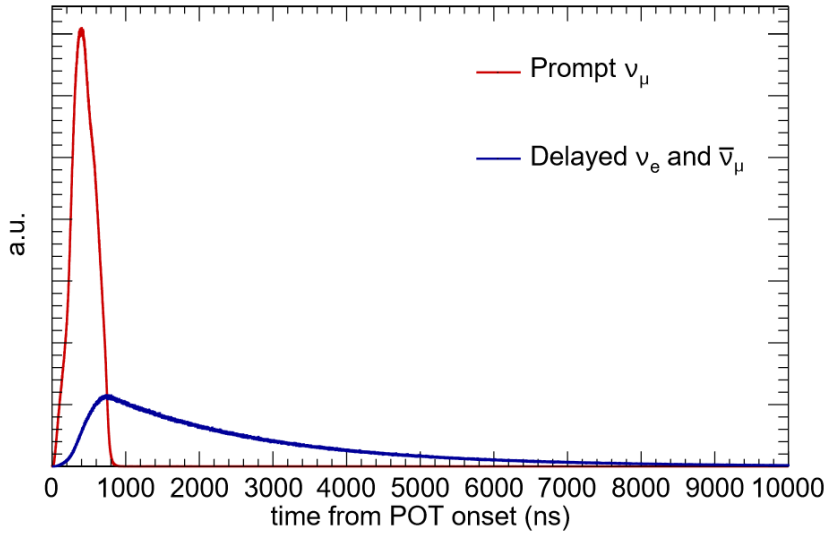
SNS as a Neutrino Source

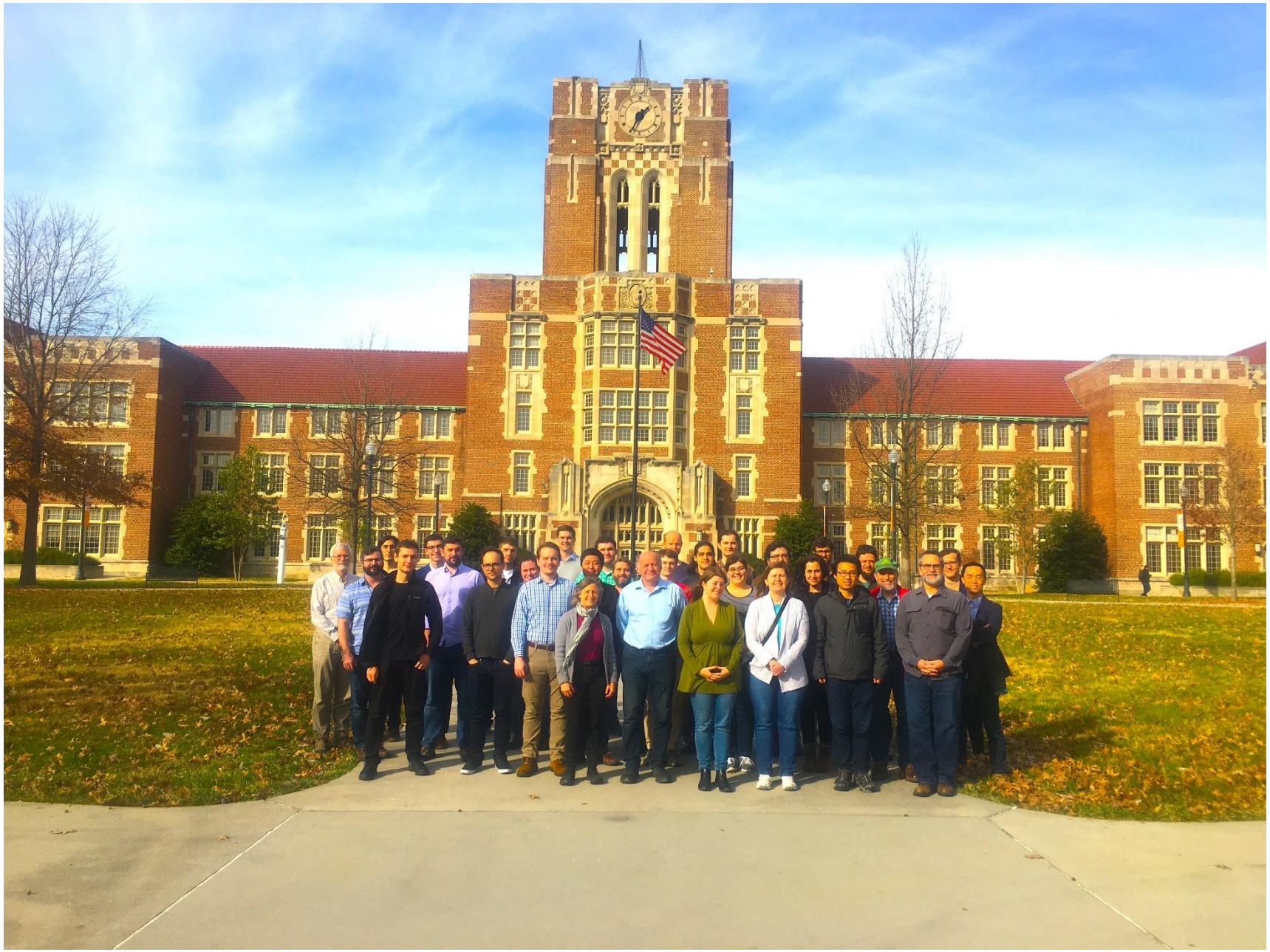


ν flux is approximately 4.3×10^{7} ν cm^{-2} s^{-1} at 20 m





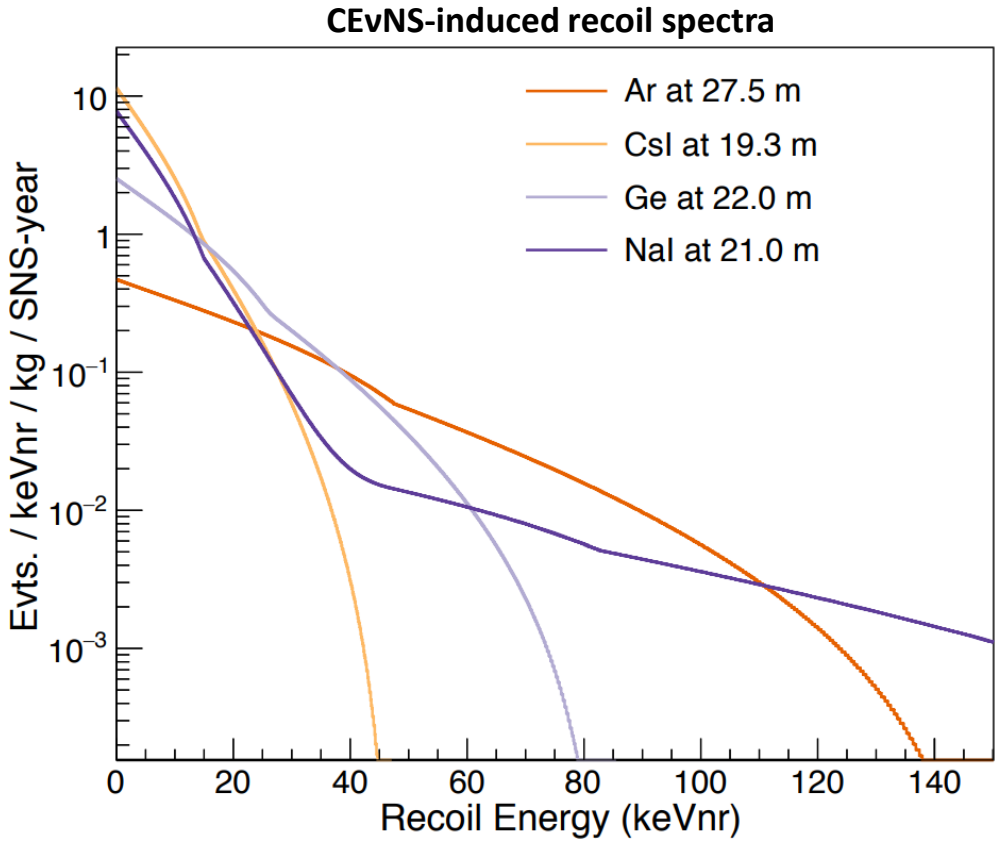
The COHERENT Collaboration

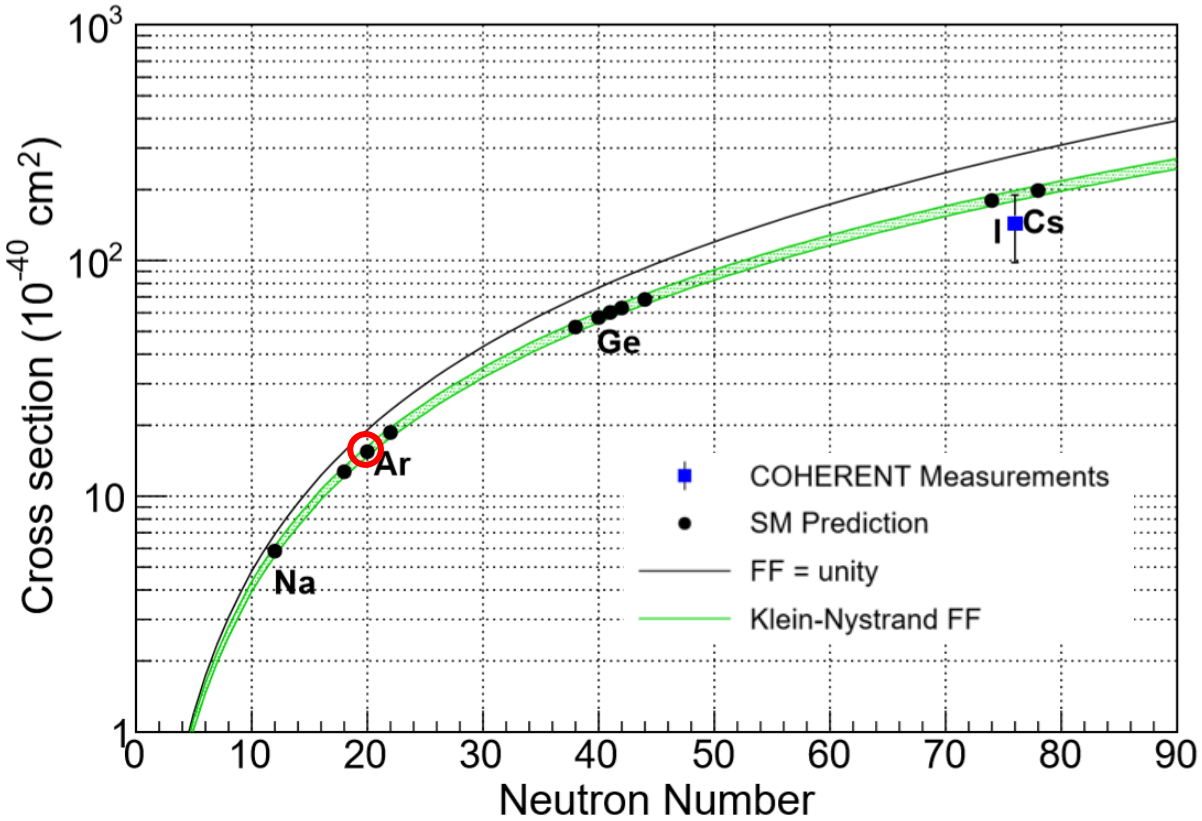


Oak Ridge National Laboratory
Duke University
TUNL
Sandia National Laboratories
The University of Tennessee Knoxville
Los Alamos National Laboratory EST. 1943
NC State University
University of Washington
The University of Chicago
NM State
MEPhI
UF University of Florida — The Foundation for The Gator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

COHERENT Program

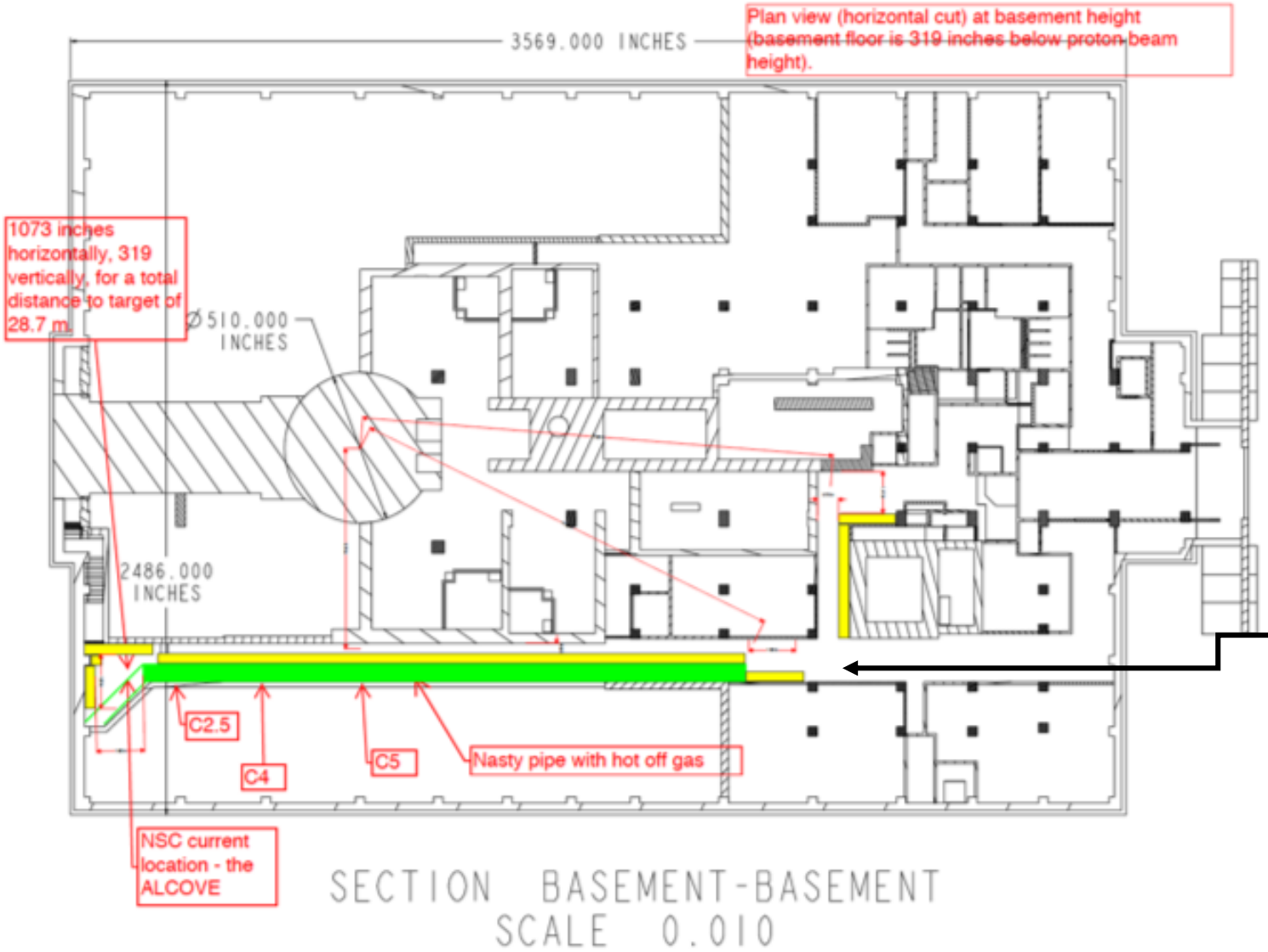
Multi-target program to measure CEvNS cross section over wide range of *N*

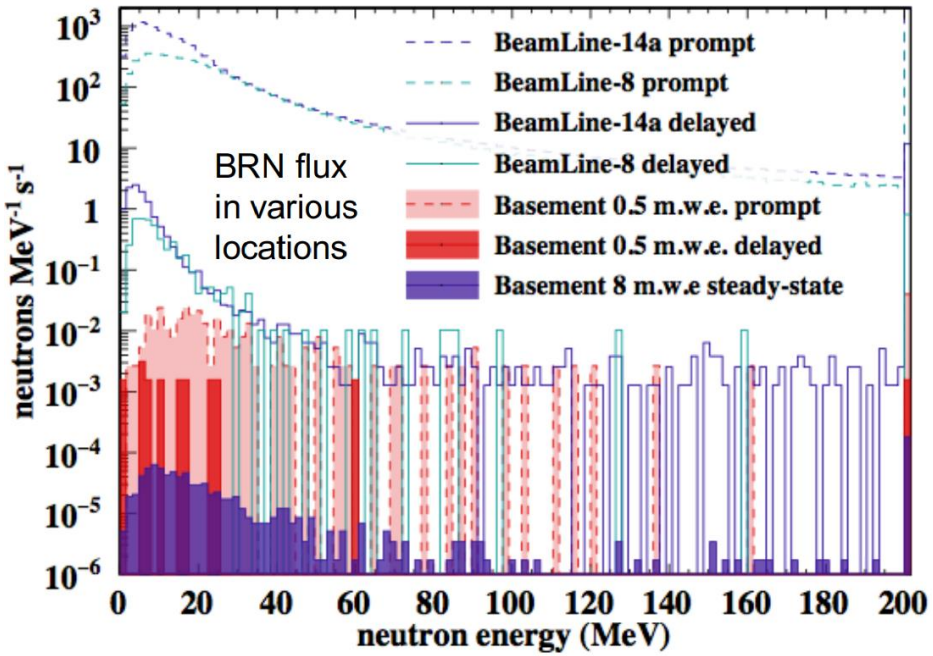




Staged approach: ***Observation -> Precision***

Deployment at the SNS



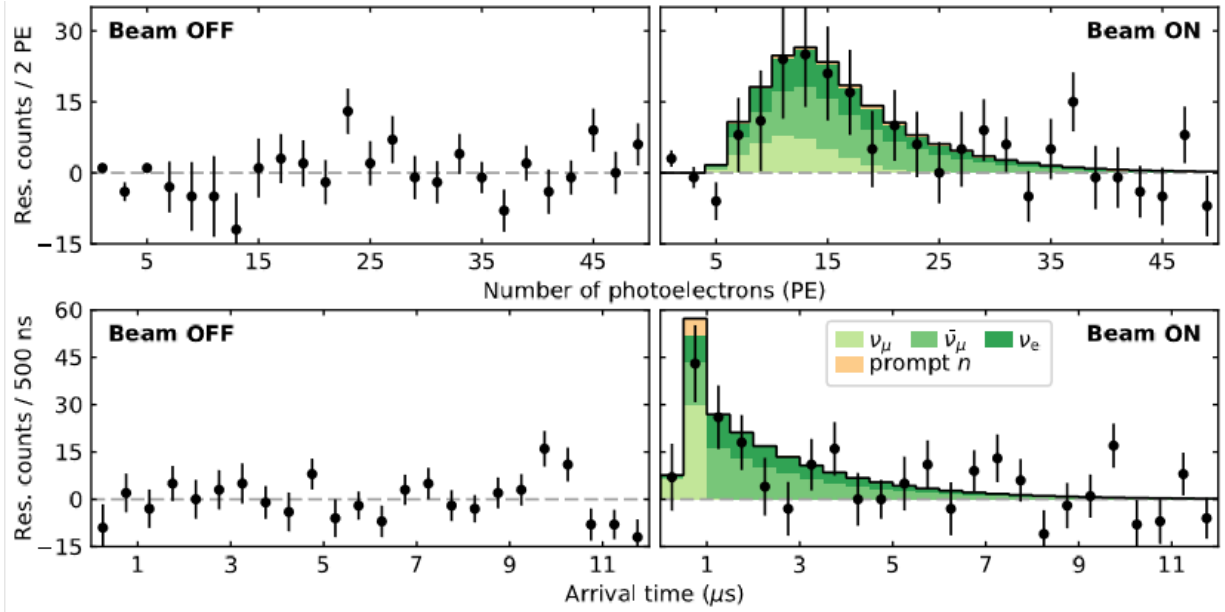


Neutrino Alley

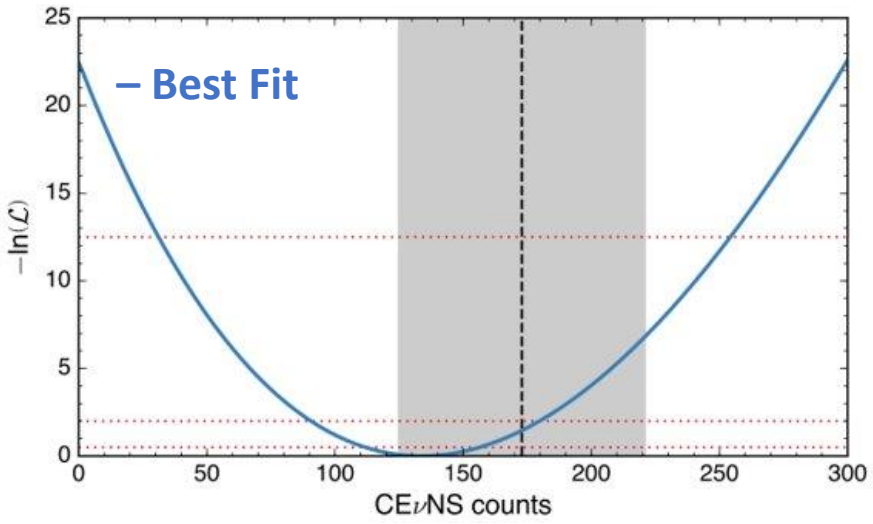
10.1126/science.aao0990

First Light with CsI

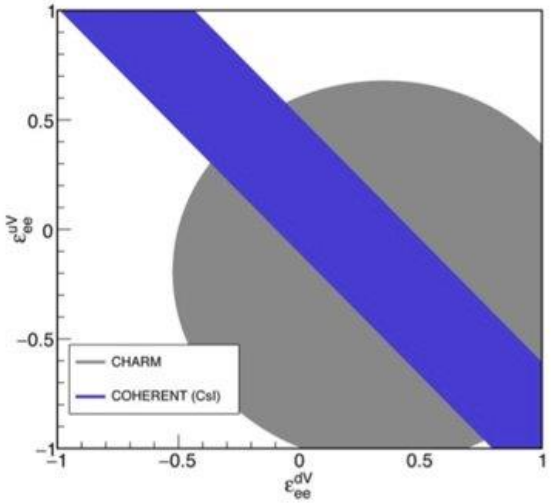
- Observation of CEνNS in 14.6 kg CsI[Na] detector!
- 6.7σ significance with likelihood fit
- Best fit of 134±22 Signal Events within 1σ of SM Prediction: 173±48
- Uncertainties due to nuclear quenching, neutrino flux, nuclear form factor, etc.
- Beam OFF Data: 153.5 days ; Beam ON Data: 308.1 Days (7.48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



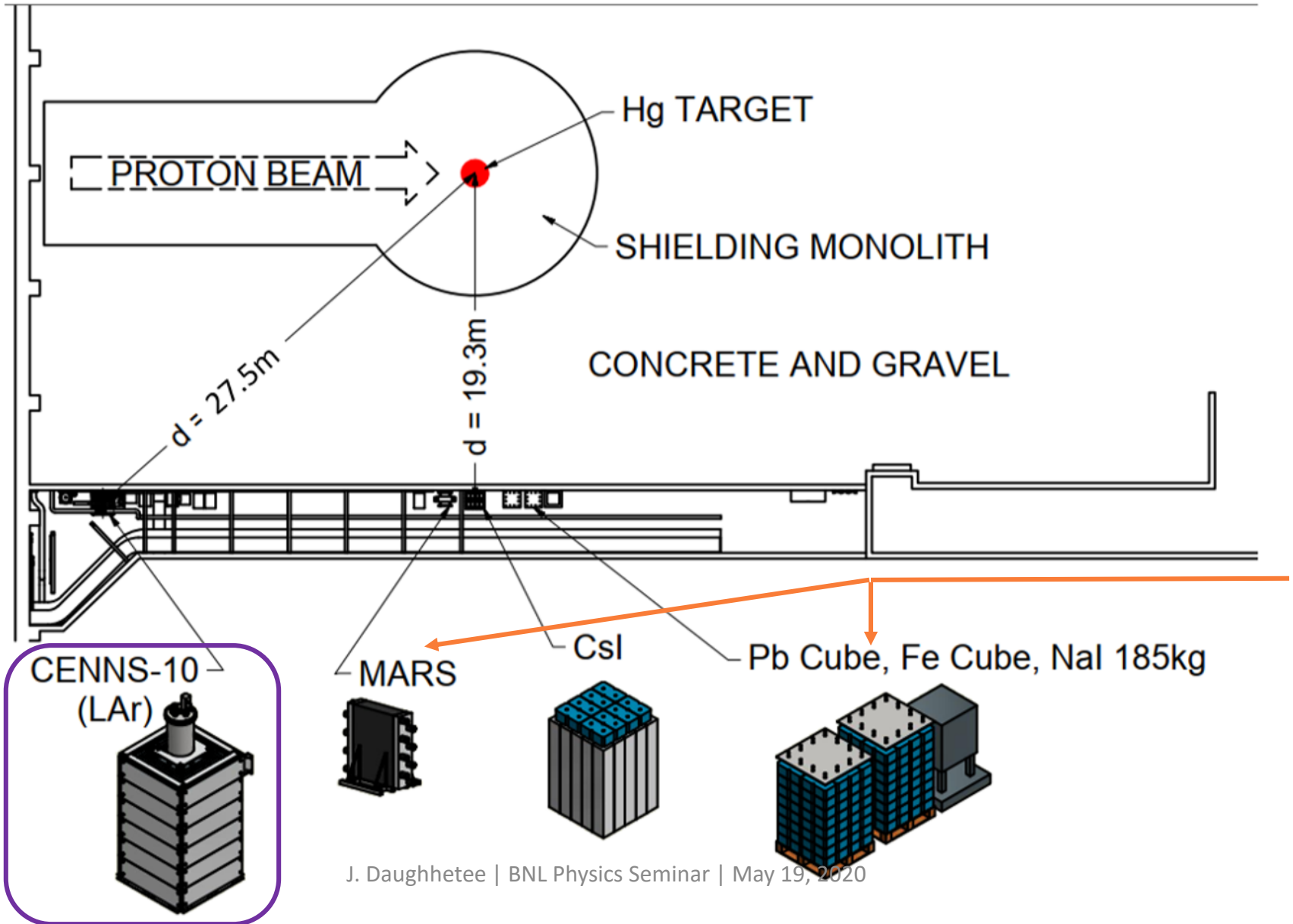
SM Prediction



NSI Constraints



COHERENT Current Operations



Data Analysis Underway

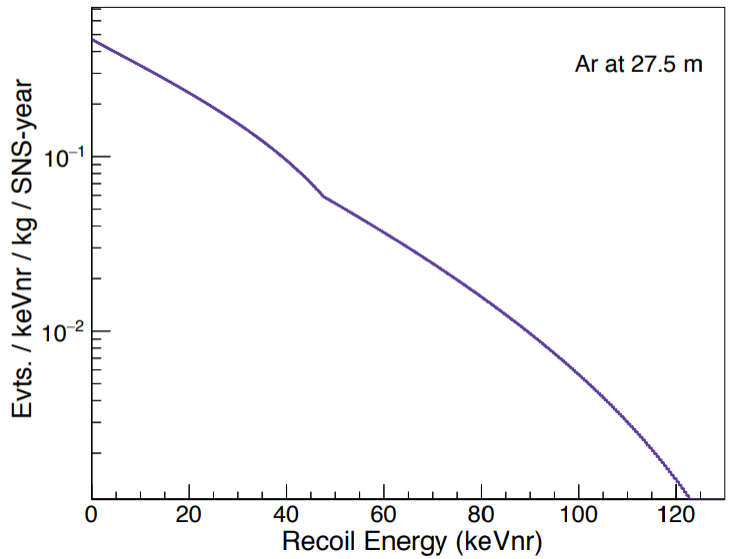
Subject of This Talk!

The CENNS-10 Argon Detector

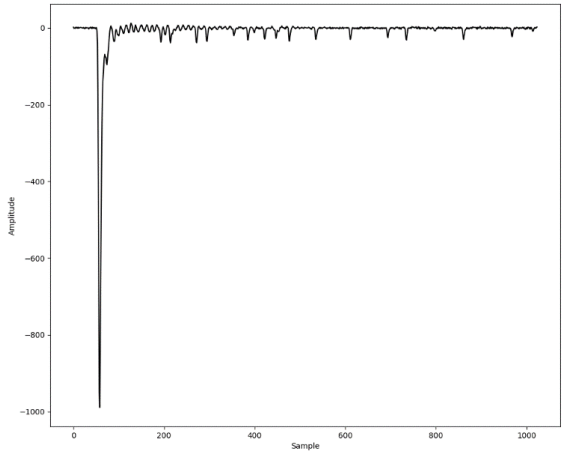
Liquid Ar for CEvNS

- Bright scintillator (40 photons/keVee)
- Well-known nuclear quenching factor
- Emission timescales:
  - 6 ns (singlet)
  - 1.6 µs (triplet)
- Electron recoils (ER) and nuclear recoils (NR) yield different ratio in exited state populations -> **Pulse Shape Discrimination** (PSD)
- Scintillation light wavelength: **128 nm** (requires wavelength shifting)
- Benefit of using liquid noble gas – **Scalability**

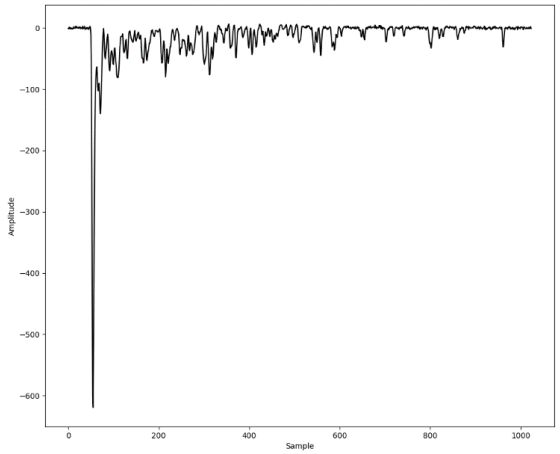
SM predicted CEvNS event rate vs. recoil energy



Nuclear Recoil

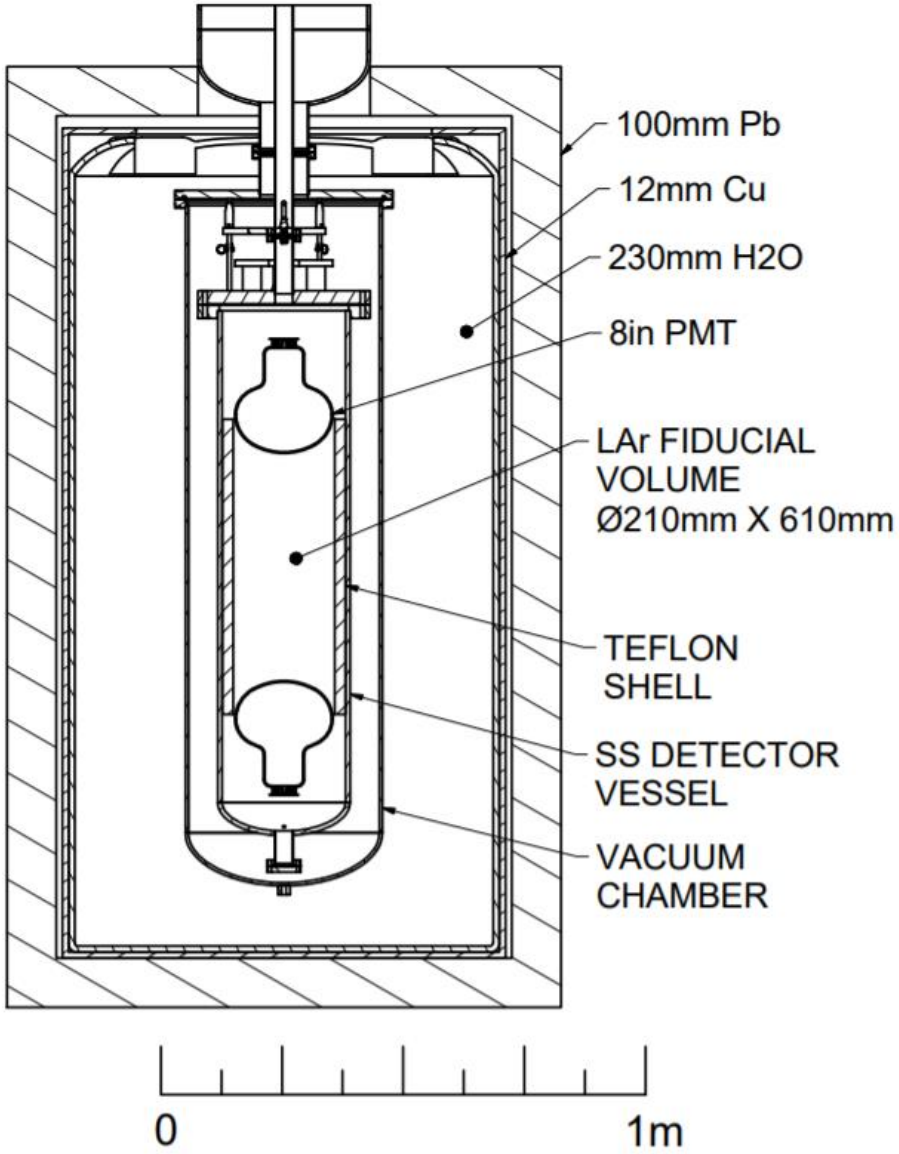


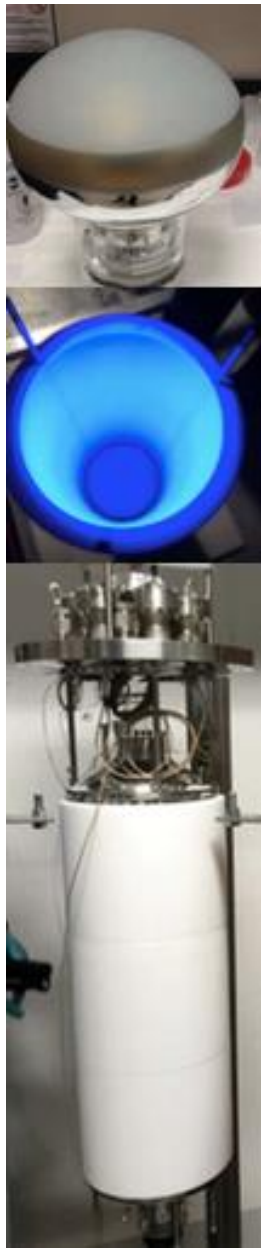
e^- / γ



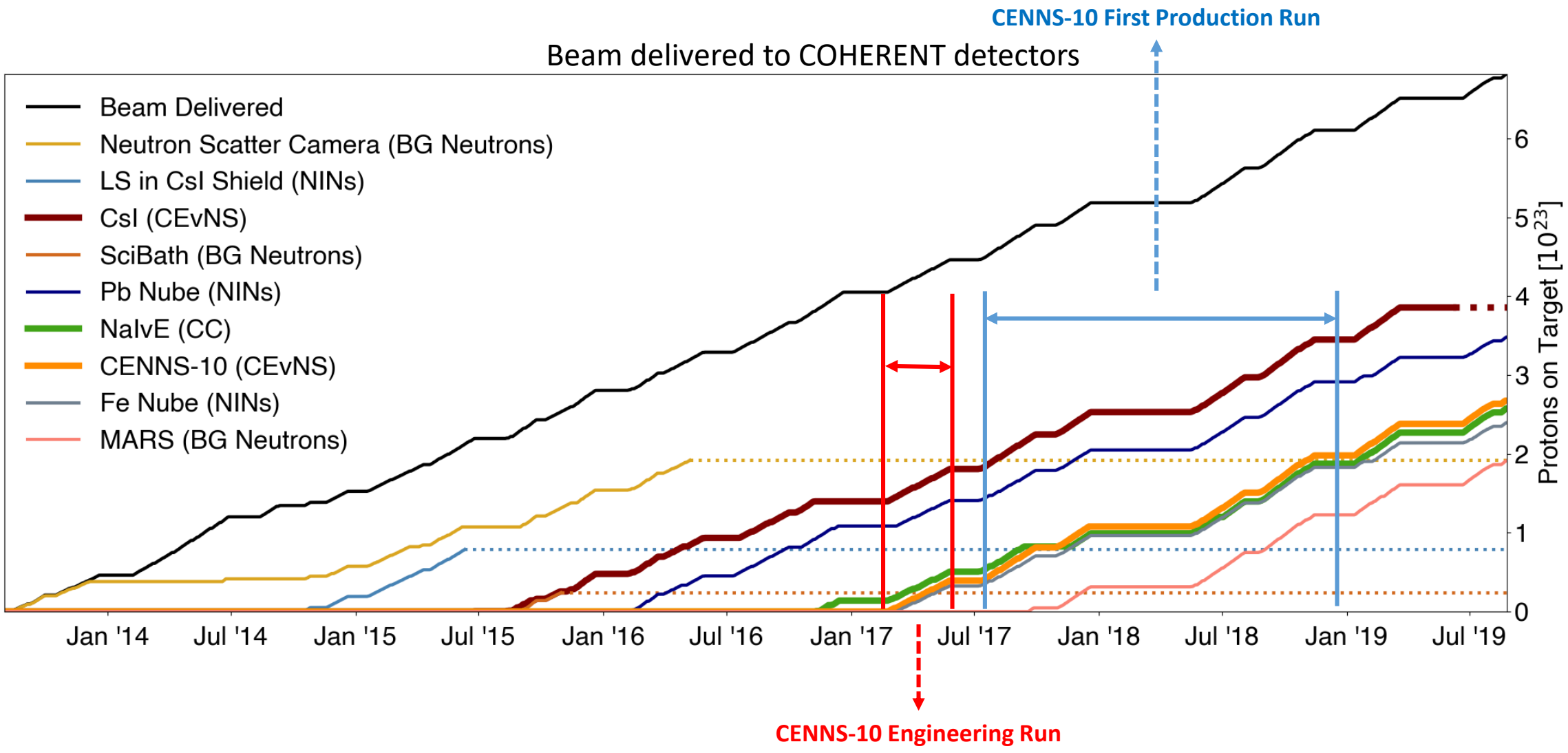
CENNS-10

- Loaned from J. Yoo *et al* from Fermilab.
- Single-phase liquid Ar scintillation detector located 28 m from SNS target (~2 x 10^7 ν / s)
- **Engineering Run:** Dec 2016 -> May 2017
  - 80 keVnr threshold
  - No Pb shielding
  - Analysis Results -> Phys. Rev. D100 (2019) no. 11, 115020
- **First Production Run:** July 2017 -> December 2018
  - Dramatically improved light yield results in lower threshold (20 keVnr)
  - 2x 8” Hamamatsu PMTs with 18% eff @ 400 nm
  - Tetraphenyl butadiene (TPB) wavelength shifter coating Teflon walls and PMT glass.
  - 24 kg fiducial volume.



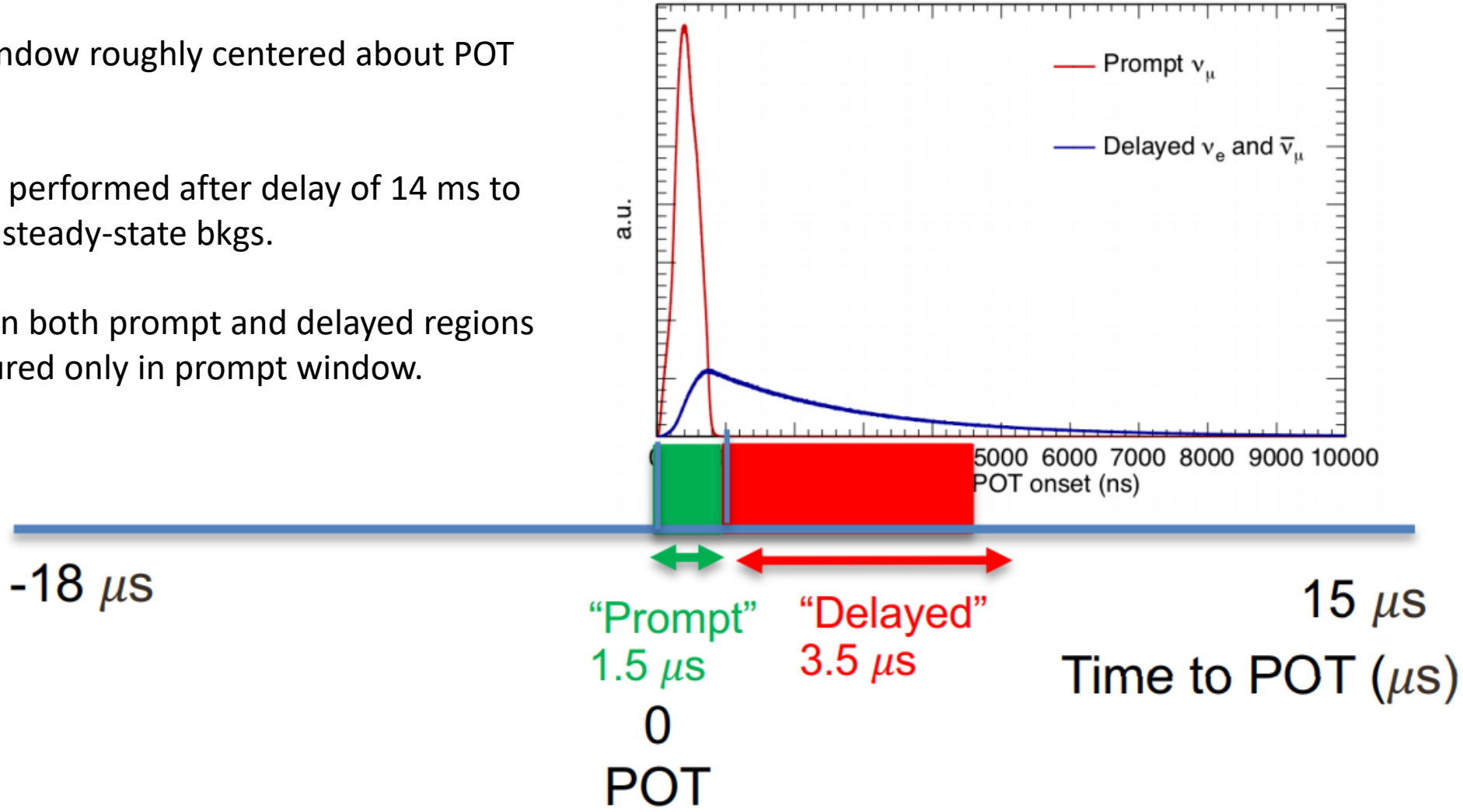


Data Collection



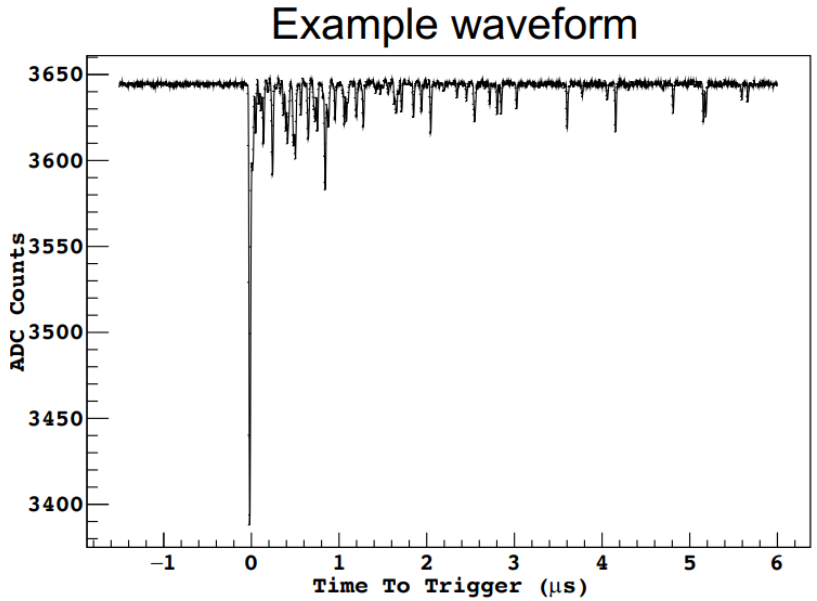
Triggering

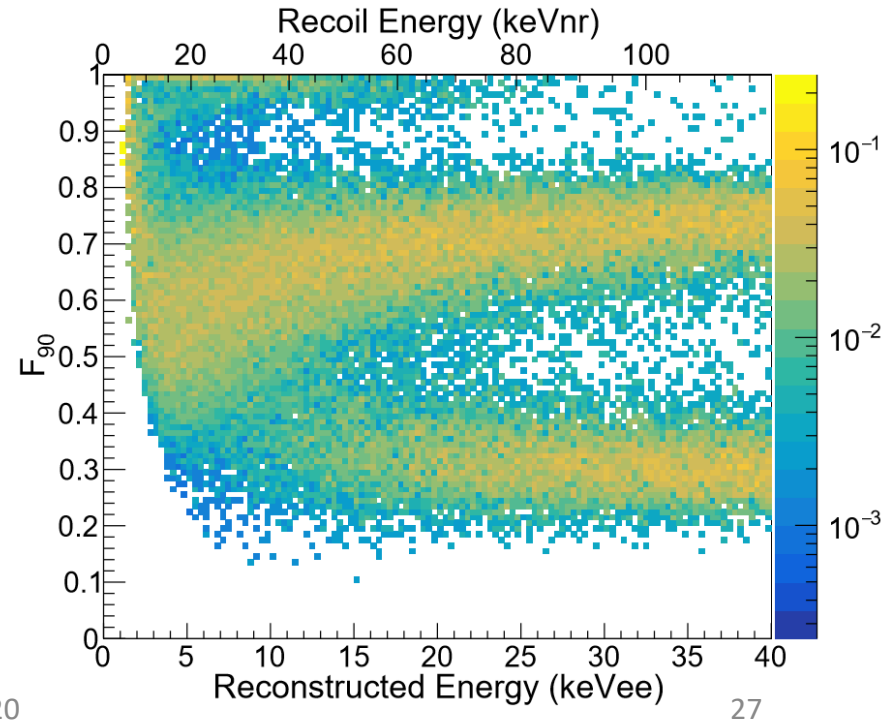
- 33 µs readout window roughly centered about POT time.
- Identical readout performed after delay of 14 ms to directly measure steady-state bkgs.
- CEvNS expected in both prompt and delayed regions while BRN measured only in prompt window.



Data Selection / Analysis Steps

- Pulse finding algorithm applied to triggered waveforms.
- Requirement of 2 photons in first 90ns on both PMTs.
- Pulse-shape discrimination variable “F90” is computed:
  (Integral of WF in first 90 ns / Total WF Integral)
- Steady-state background characterized with anti-coincident data (delayed trigger).
- Beam-related neutrons (BRN) measured with dedicated ‘neutron’ runs which lack water shielding.
- Cuts on energy, F90, and time established prior to box-opening.
- 3D Likelihood fit applied to final dataset .
- **Two separate analyses performed, this talk details US analysis!**





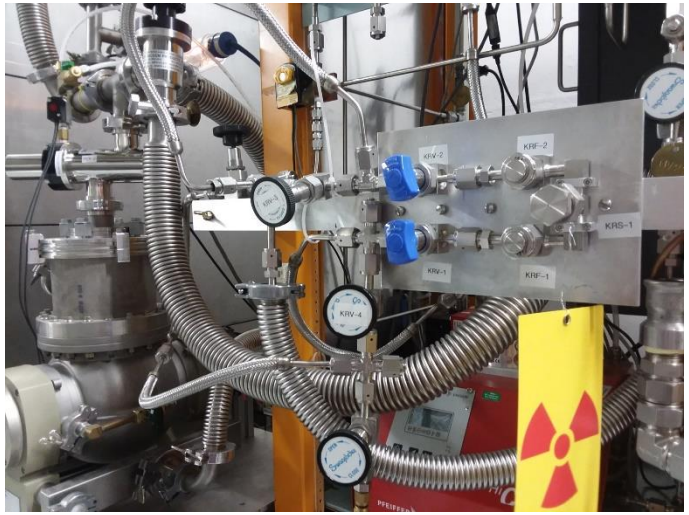
Energy Calibrations

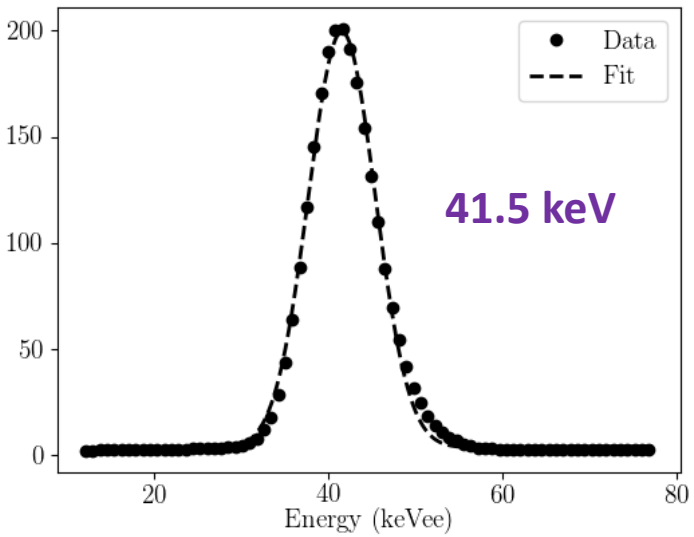
- Calibrations performed using multiple gamma sources (^{57}Co, ^{241}Am, ^{83m}Kr).
- Observed light yield: 4.6 $\pm$ 0.4 p.e./keVee
- 9.5% resolution at 41.5 keVee
- Linearity of detector response over energy range of interest.
- Provides ADC -> keVee conversion. (ee – electron equivalent)

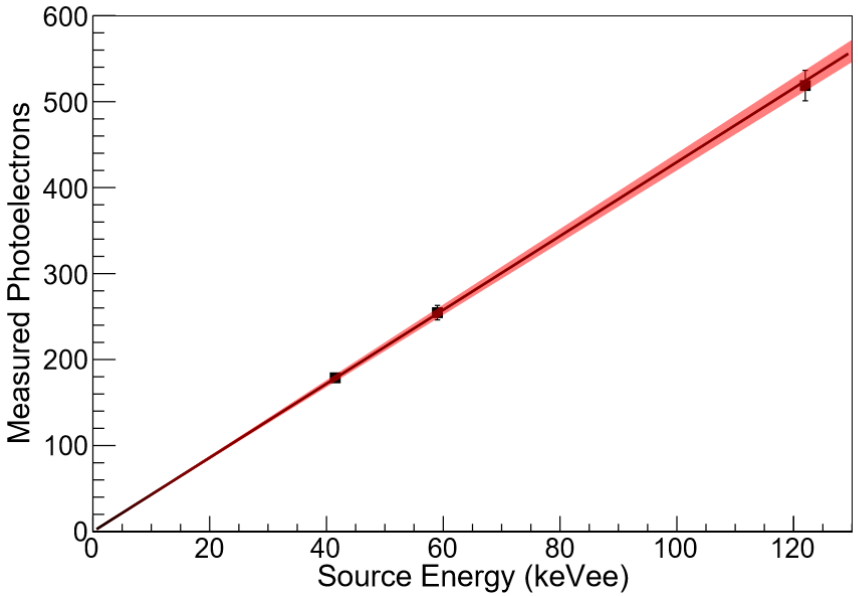
Neutron Calibrations

- **AmBe** – Used to measure NR response in detector and model CEvNS signal.
- **DT Generator** – Used to confirm veracity of external neutron simulations

^{83m}Kr Calibration

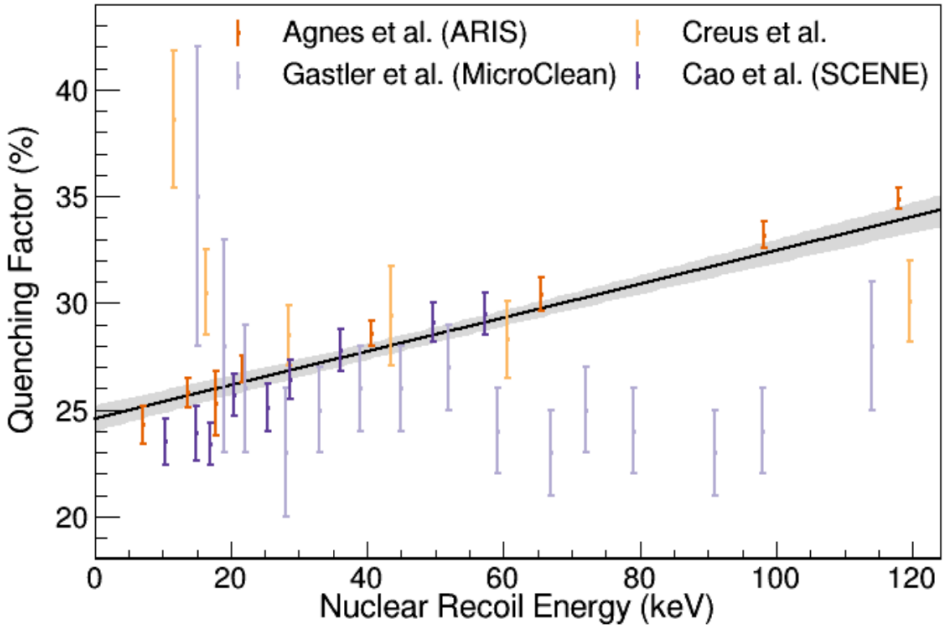


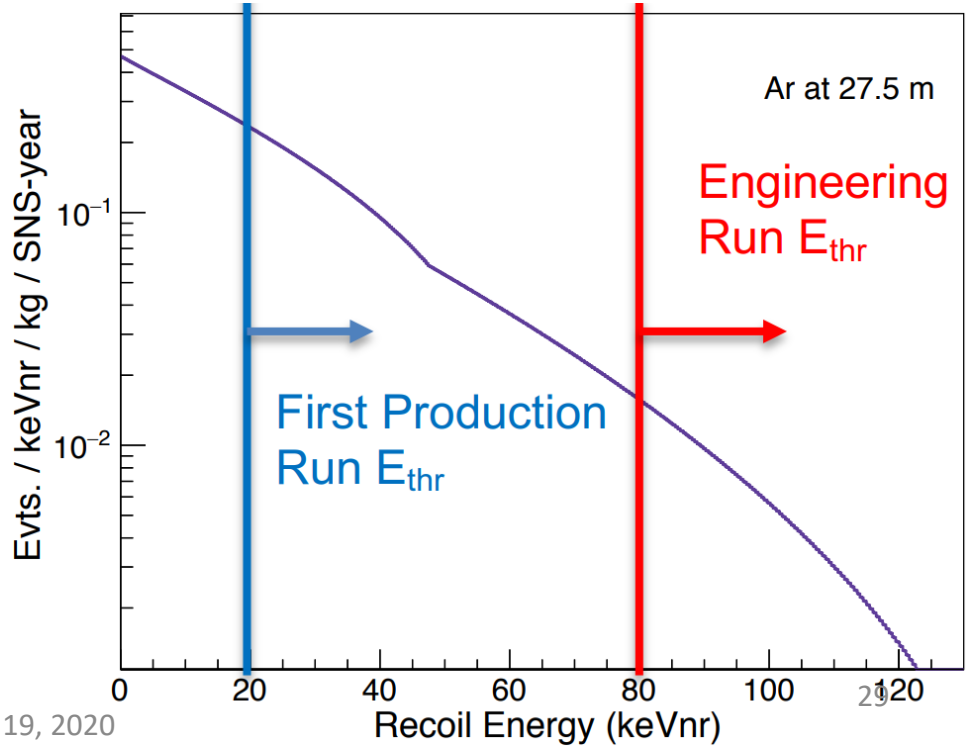




LAr Quenching Factor

- Defined as ratio of measured NR energy to observed ER of known energy.
- Several measurement for noble gases due to use in dark matter experiments, etc.
- Global analysis performed with linear energy dependence.
- Approximately 2% uncertainty in the CEvNS analysis energy ROI.
- Provides keVnr -> keVee conversion. (nr – nuclear recoil)

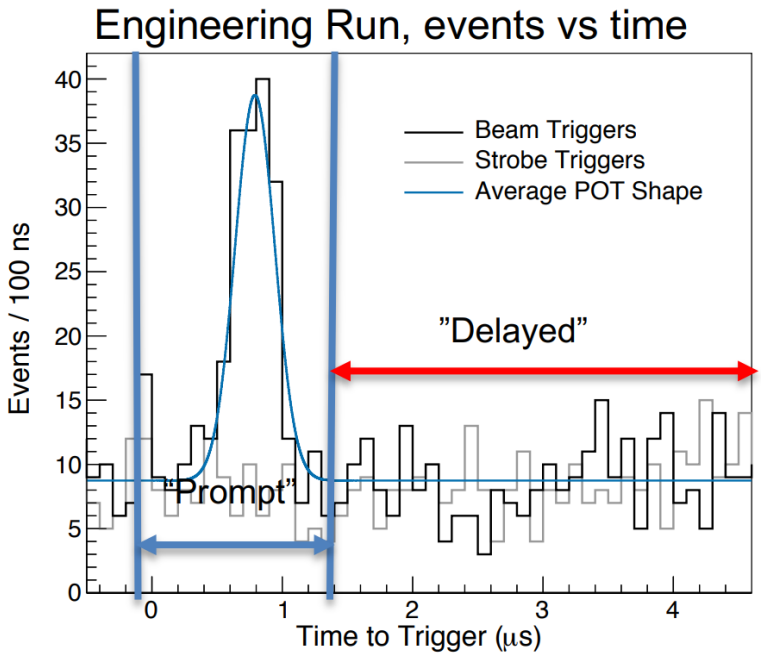


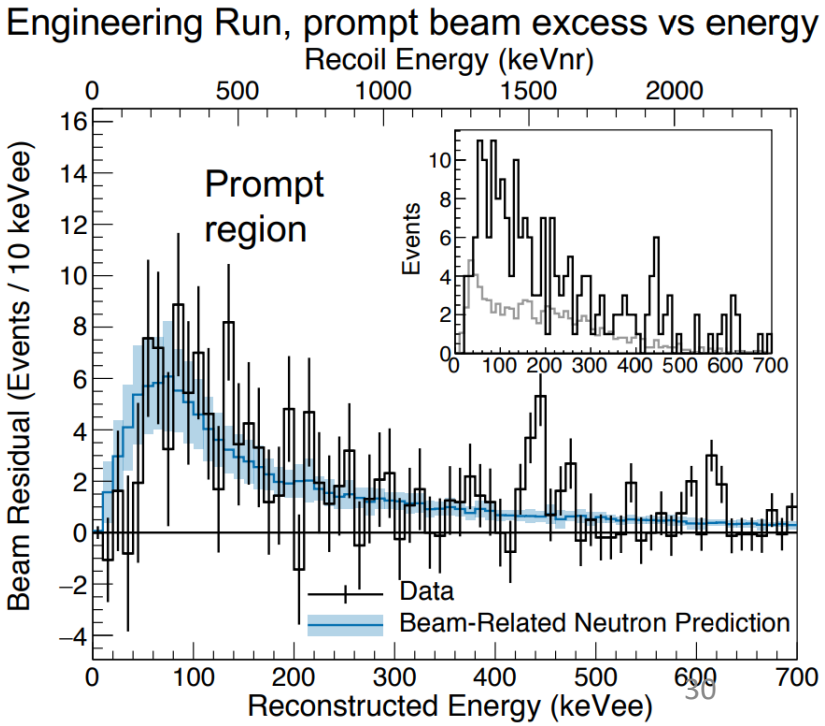


Beam-Related Neutrons

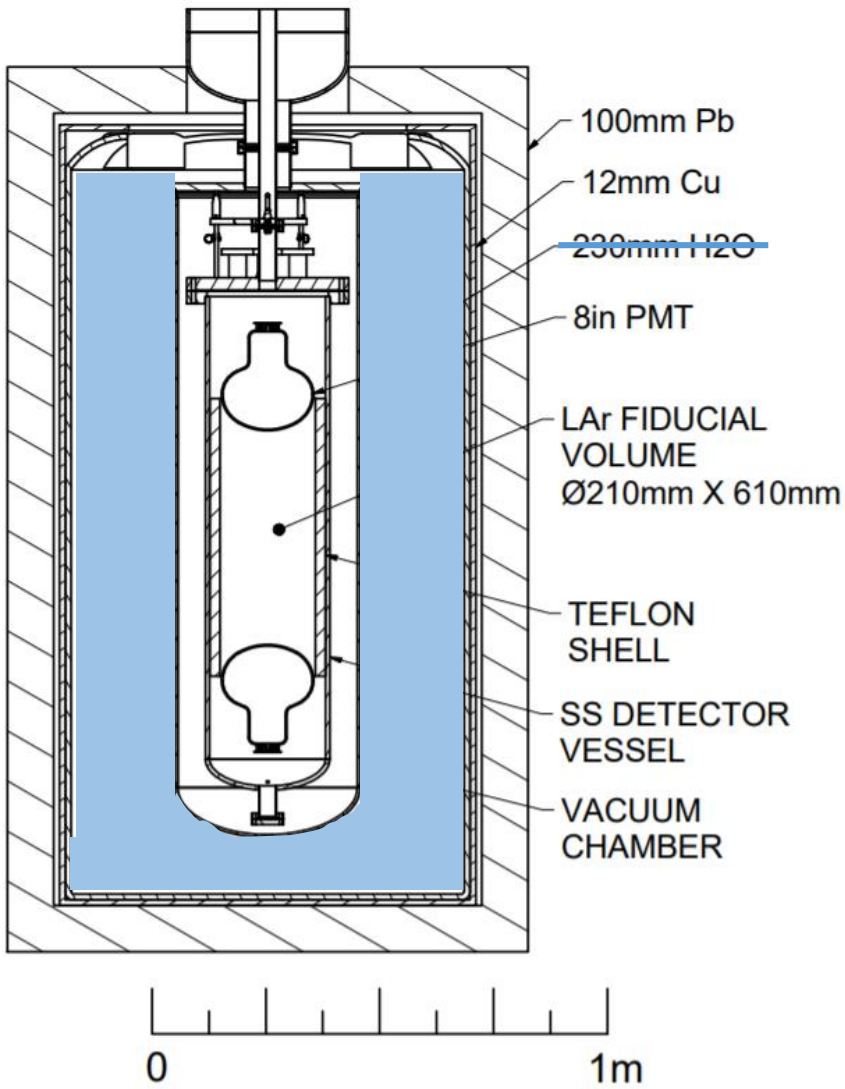
- Total of 1.8 GWhr of data taken during CENNS-10 'Engineering' run.
- Lower light yield -> 80 keVnr threshold ; not sensitive to CEvNS
- Analysis of this data does allow for characterization of BRN:
  - No 'delayed' BRNs observed.
  - Measurement of BRNs in prompt window used to inform/verify GEANT4 simulation and confirm previous measurements with dedicated neutron detectors.

M.R. Heath PhD thesis (IU 2019)
Phys. Rev. D **11** 115020 (2019)



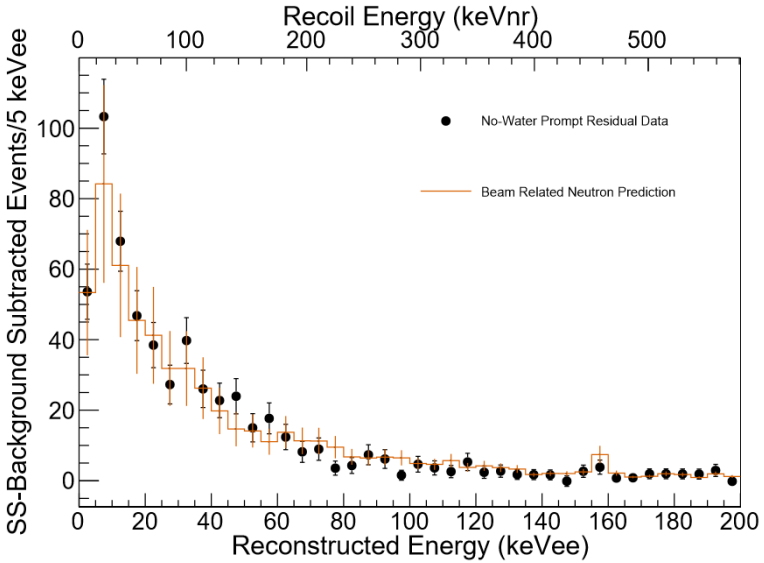


Beam-Related Neutrons



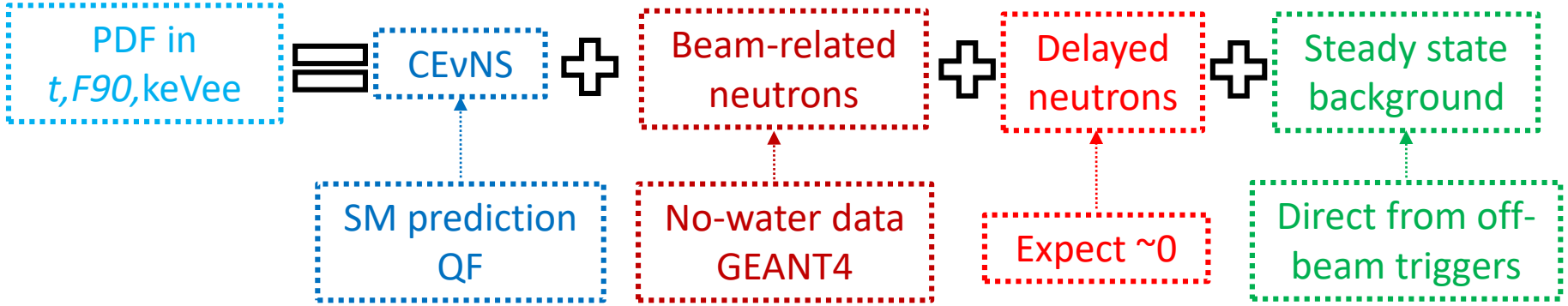
BRN increase by an order of magnitude with tank drained.

- Multiple data taking periods without water shielding (0.54 GWhr of integrated beam power).
- These "neutron" runs are used to tune GEANT4 simulation.
- Optimized simulation is used in turn to predict rate of BRN events in unblinded data.
- Uncertainty envelope for prediction includes simulation uncertainties.
- Scaled simulation is directly informed by the data.

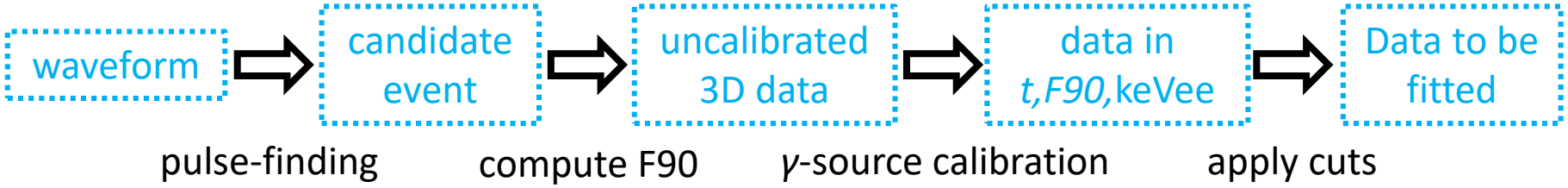


Analysis Overview

Predictions

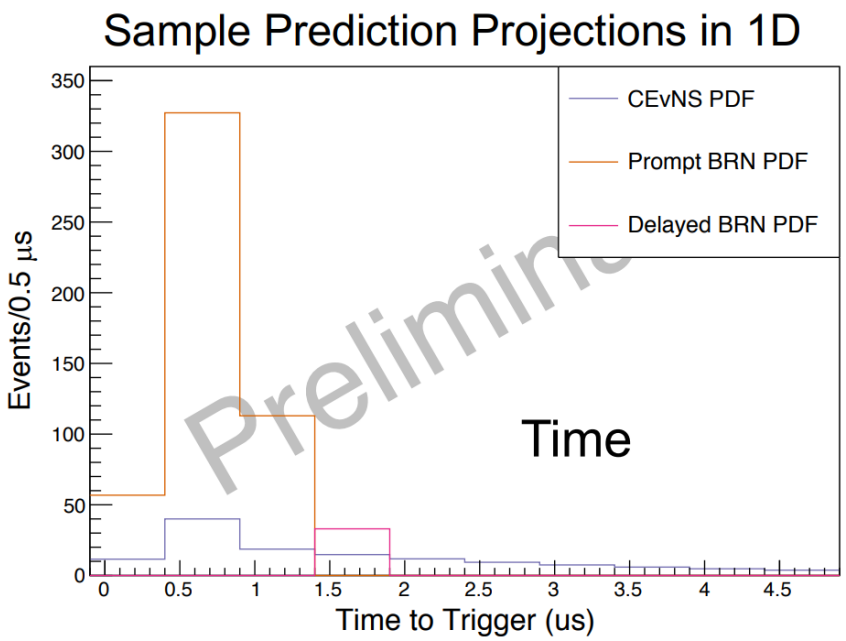


Data



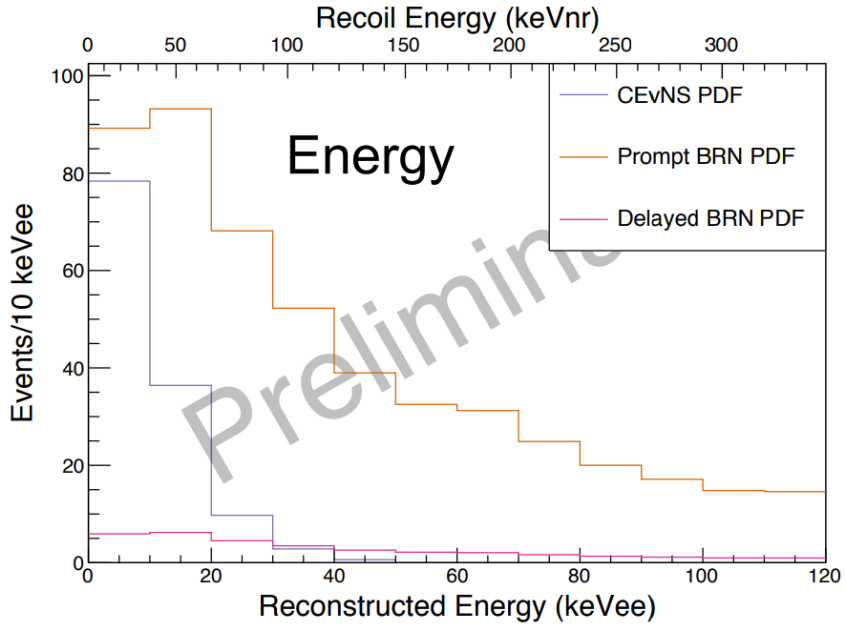
Shape and Rate Predictions

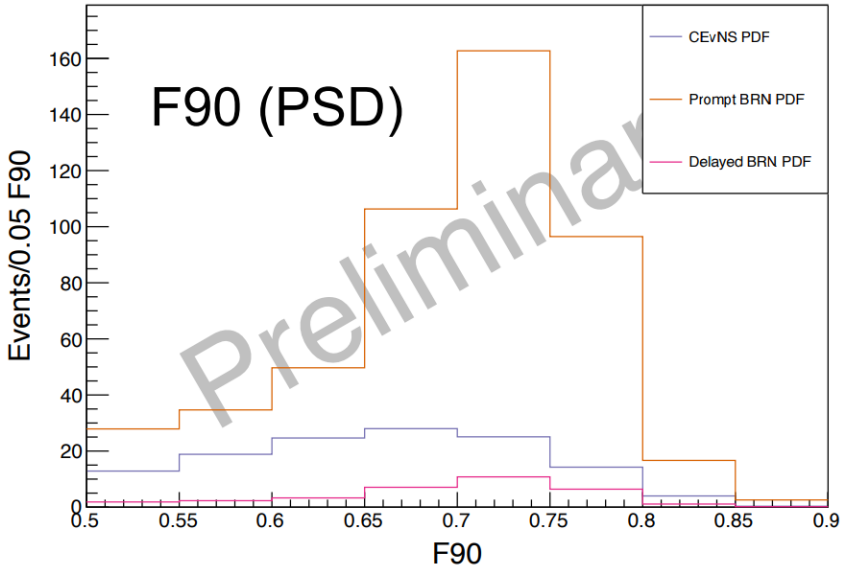
- 3D binned likelihood fit in energy, F90, and time.
- Waveform / event quality cuts.
- Analysis Cuts:
  - Energy -> 0-120 keVee
  - F90 -> 0.5-0.9
  - Time -> -0.1-4.9 µs



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 Uncertainties

Largest Systematics

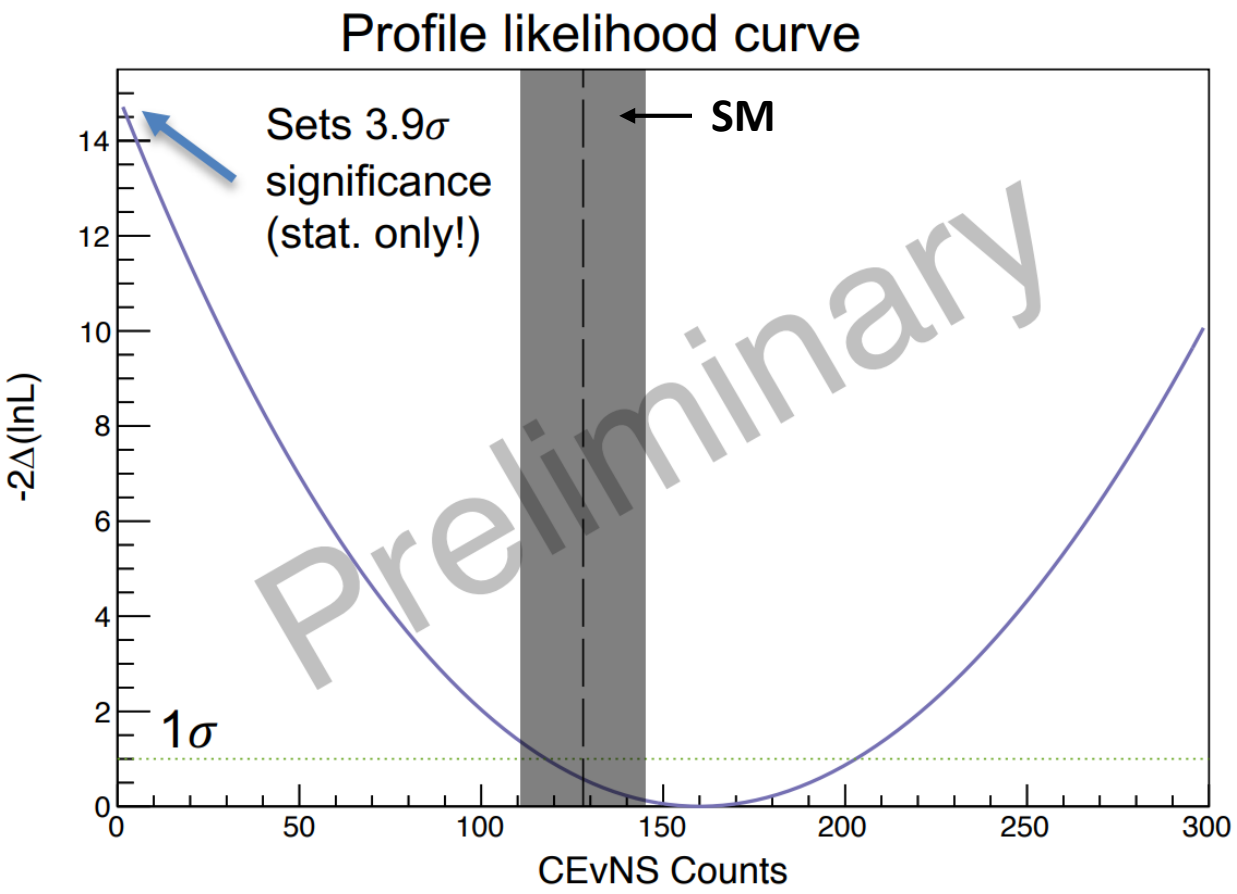
CEvNS Rate Measurement Systematic Errors	
Error Source	Total Event Uncertainty
Quenching Factor	1.0%
Energy Calibration	0.8%
Detector Model	2.2%
Prompt Light Fraction	7.8%
Fiducial Volume	2.5%
Event Acceptance	1.0%
Nuclear Form Factor	2.0%
SNS Predicted Neutrino Flux	10%
Total Error	13.4%

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%

- Potential changes to predictions are examined with extensive MC simulations and pseud-datasets.
- Systematics sorted into two classes:
  - Top - Change in SM predicted rate
  - Bottom - Change in 3D pdf shape (*E, F90, t*)

Unboxing…

Fit Results



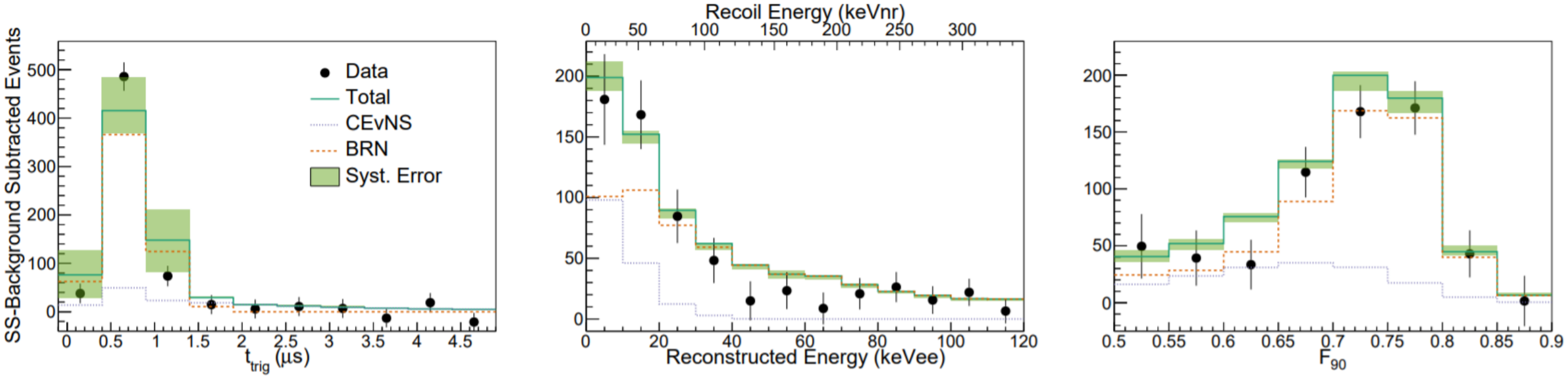
Predicted SM CEvNS	128 ± 17
Predicted Beam Related Neutrons	497 ± 160
Predicted Beam Unrelated Background	3154 ± 25
Predicted Late Beam Related Neutrons	33 ± 33

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
2Δ(-lnL)	15.0
Null Rejection Significance	3.5σ (stat. + syst.)

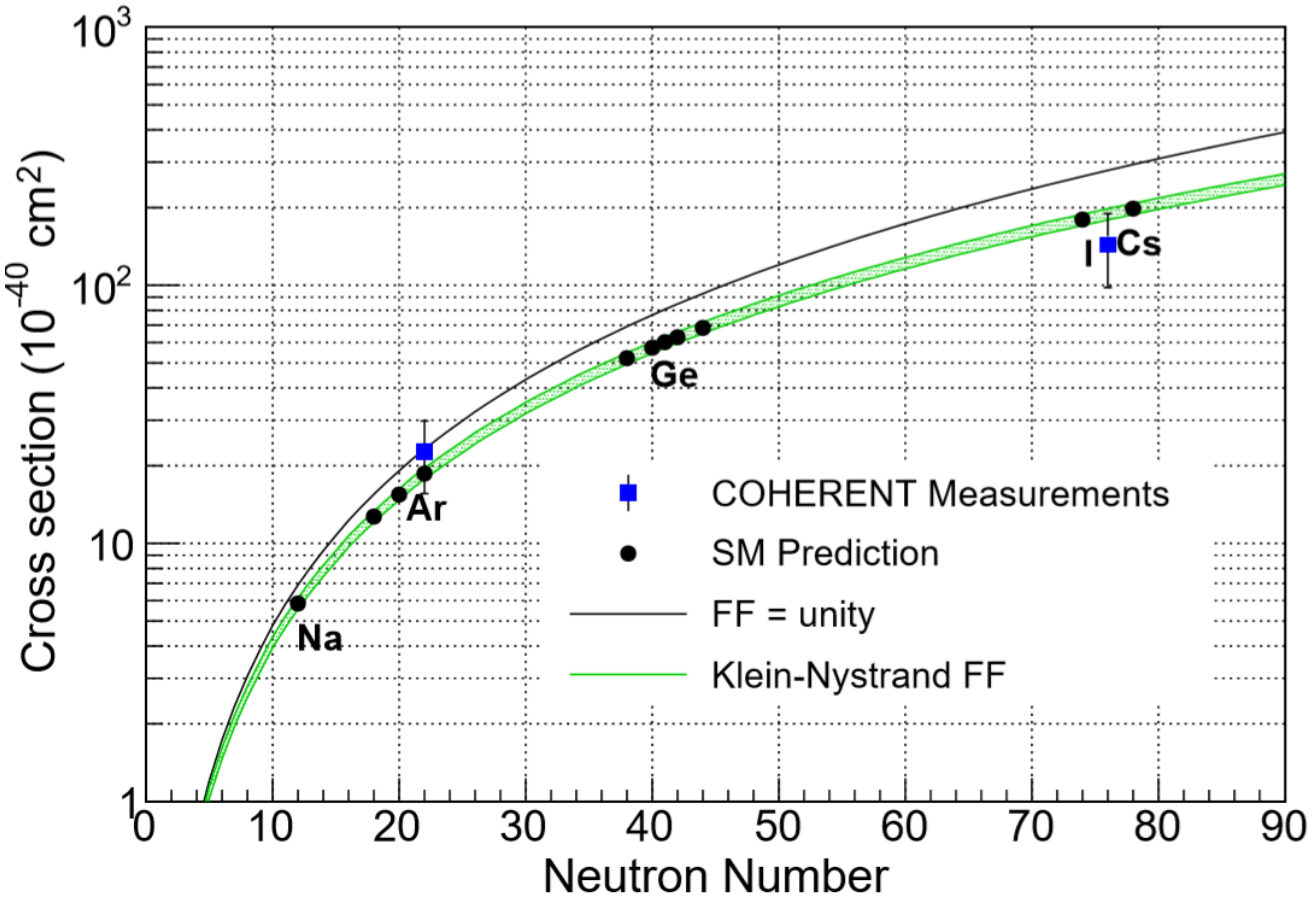
- Best fit for N CEvNS is 159 ± 43 (stat) ± 14 (syst)
- Null hypothesis rejected at 3.9σ (stat only)
- Null hypothesis rejected at **3.5σ** (stat+syst)
- Validity of Wilks' theorem checked with pseudo-data.
- **Result within 1-σ of SM prediction.**

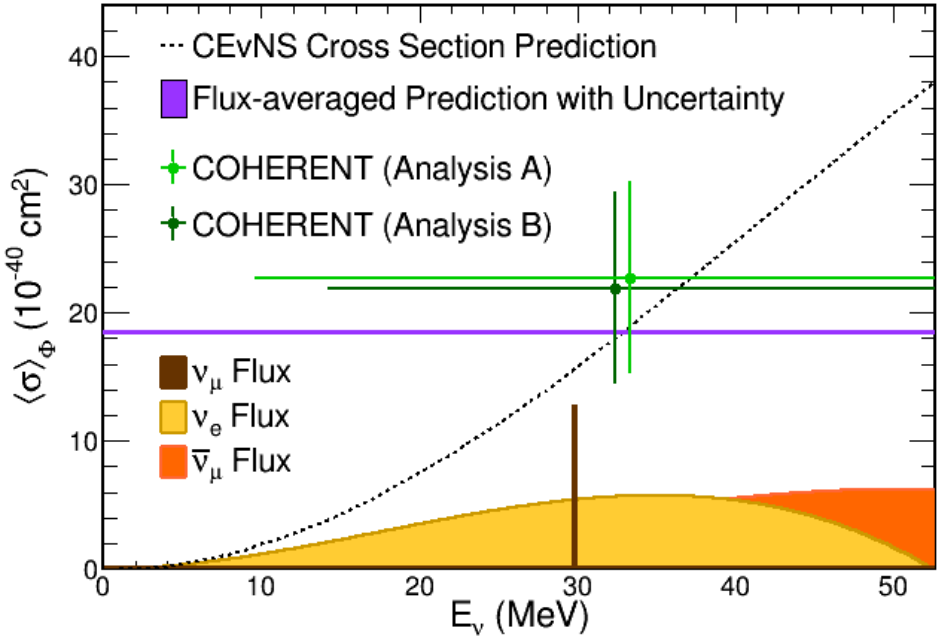
Fit Projections

Best Fit 1-D Projections



CEνNS Cross Section





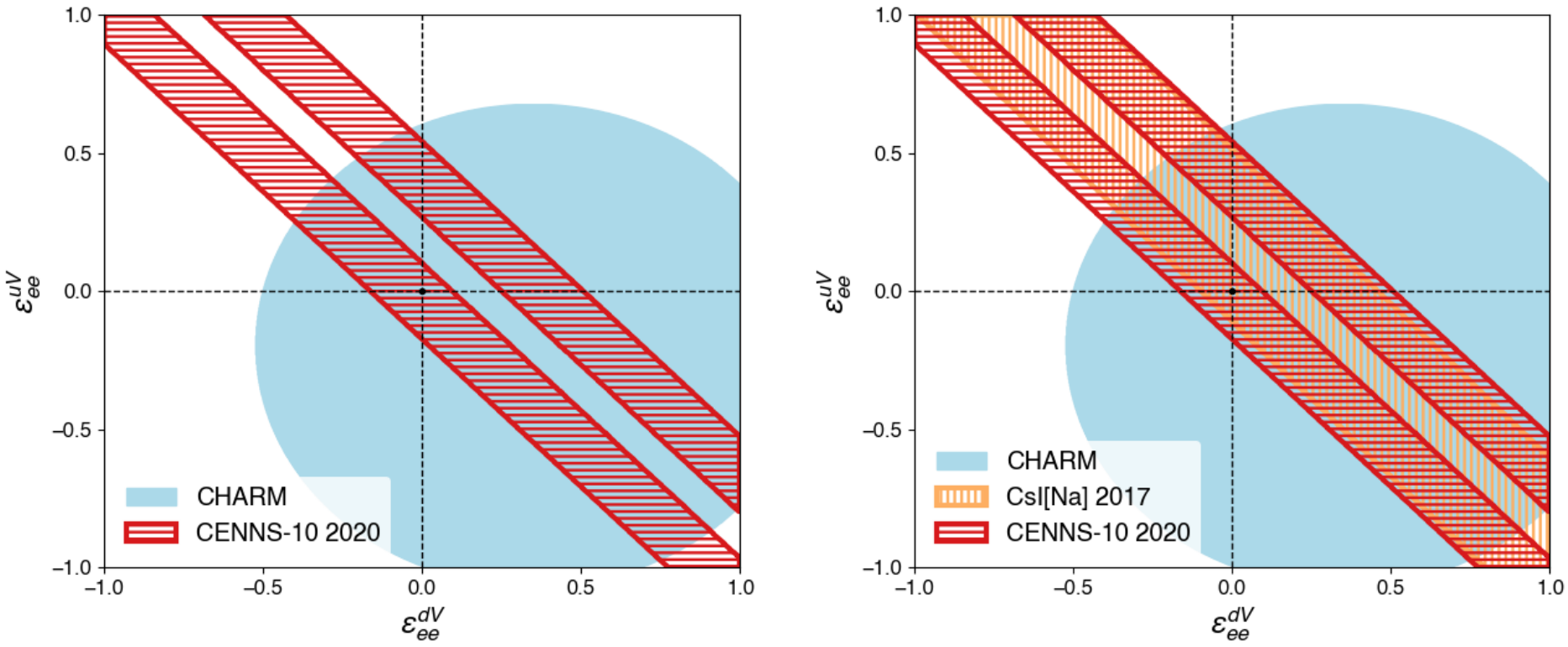
- Combine best fit CEvNS counts with flux, fid. volume, efficiency uncertainties.

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

- Obtain flux-averaged cross section:

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

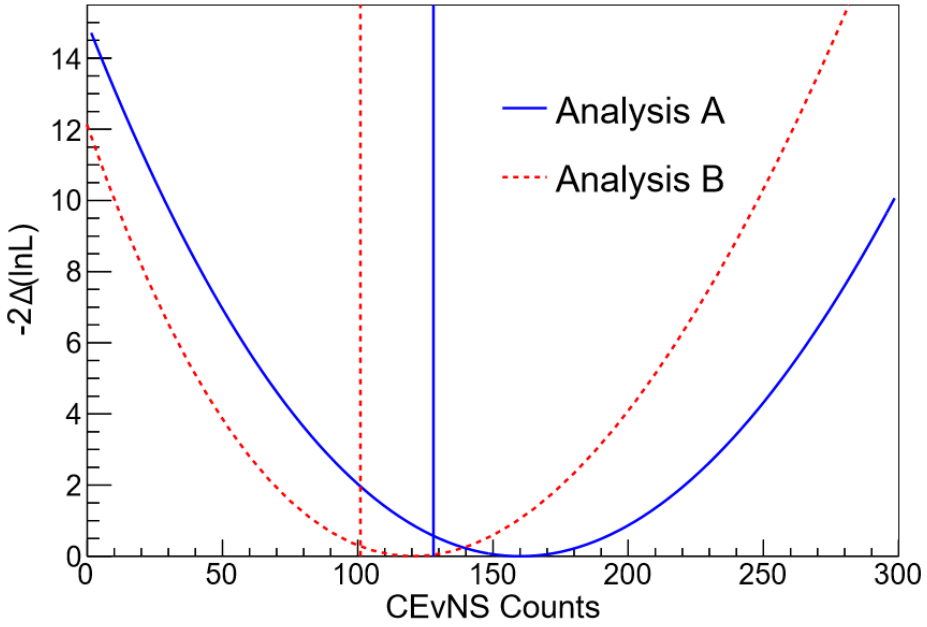
Constraints on Non-Std Interactions



- Assume non-zero electron flavor-diagonal vectorlike NSI (all other ε set to 0).
- Fit results used to compute allowed regions in parameter space.

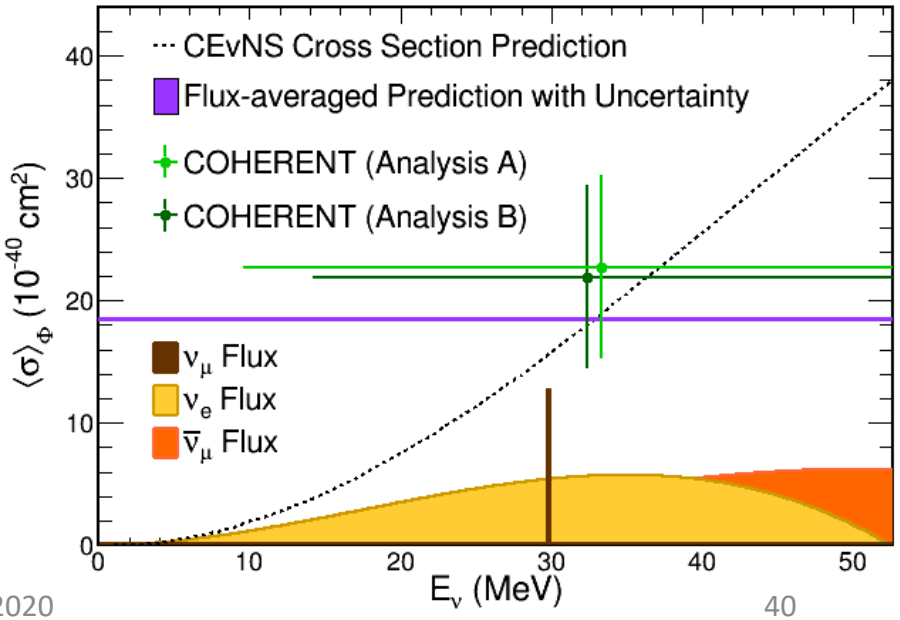
Parallel Analysis Comparison

- Separate blind analysis performed by Russian collaborators.
- Independent reconstruction software and stricter cuts for analysis level dataset.
- Results consistent with US analysis.



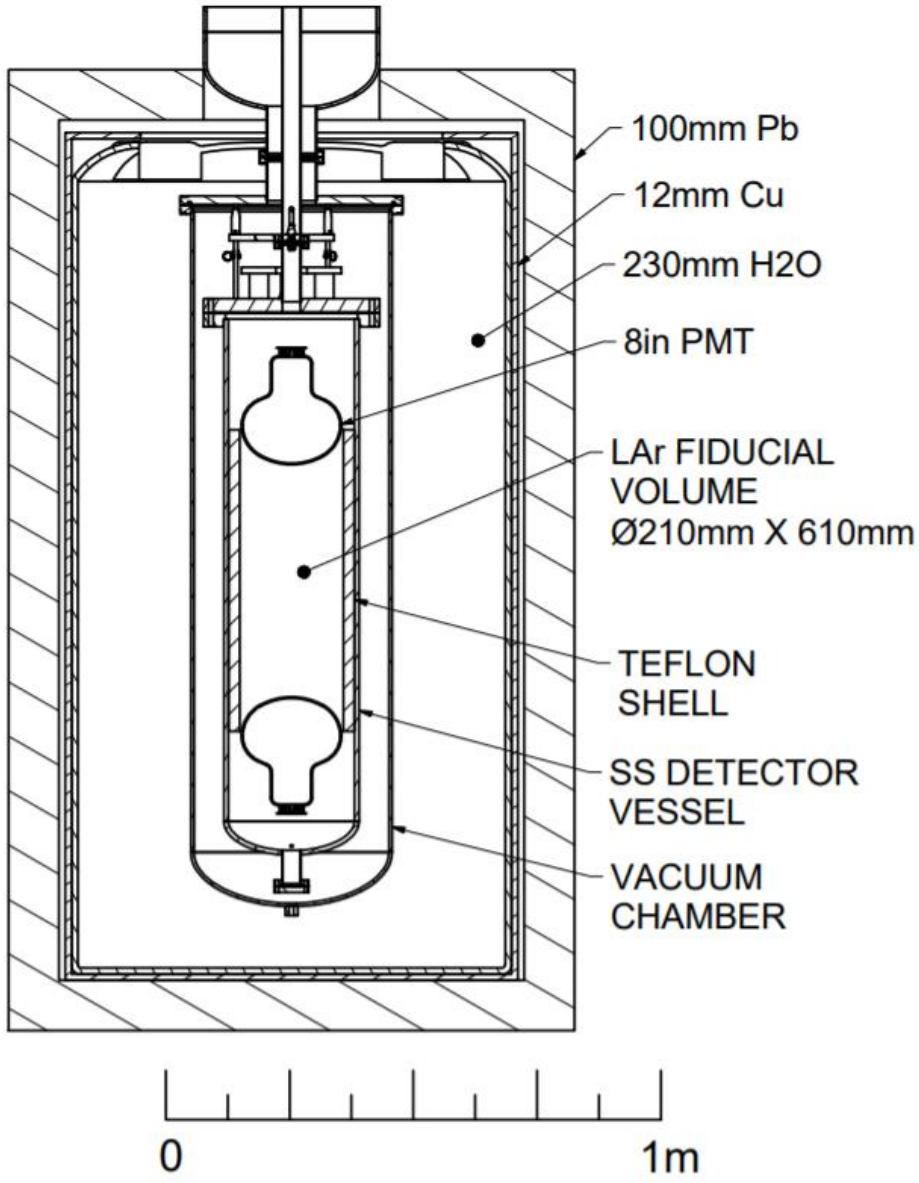
Moscow analysis results

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



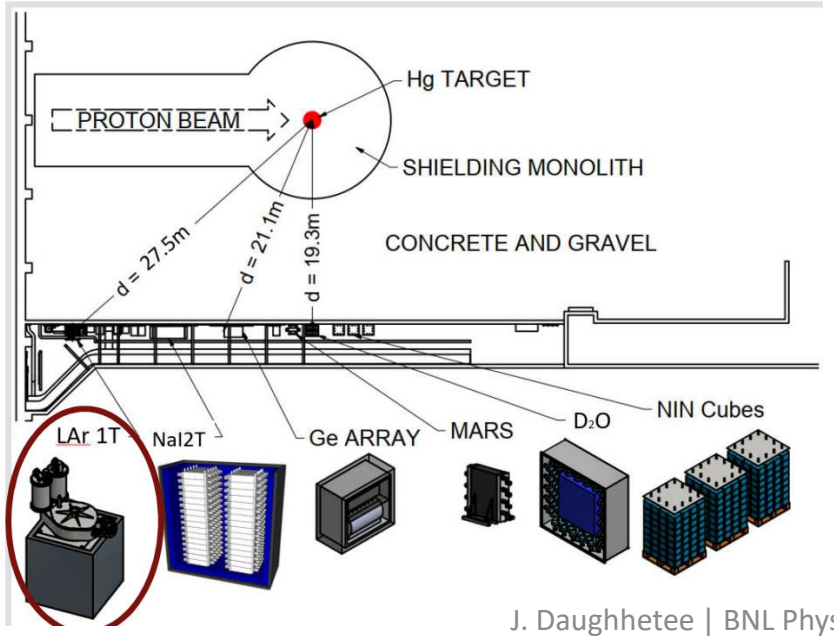
Future of CENNS-10

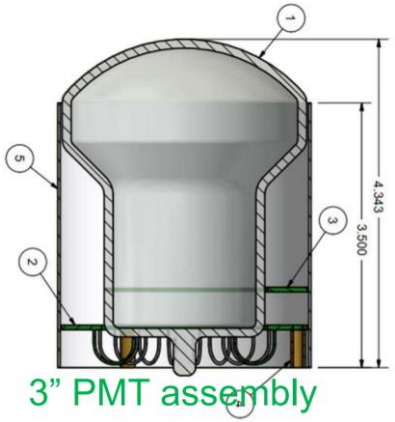
- Additional data to be analyzed (3 GWhr and counting) with potential improvements in neutron shielding, analysis methods, and understanding of systematics.
- Potential modifications / testing:
  - Move detector to vacated CsI location (lower *n* bkg, higher ν flux)
  - Additional neutron shielding in current location.
  - Reduced steady-state bkg with underground Ar.
  - Xe-doping for increased light output.
  - Test photo-detection schemes for planned ton-scale detector.
  - Test wavelength shifting schemes.



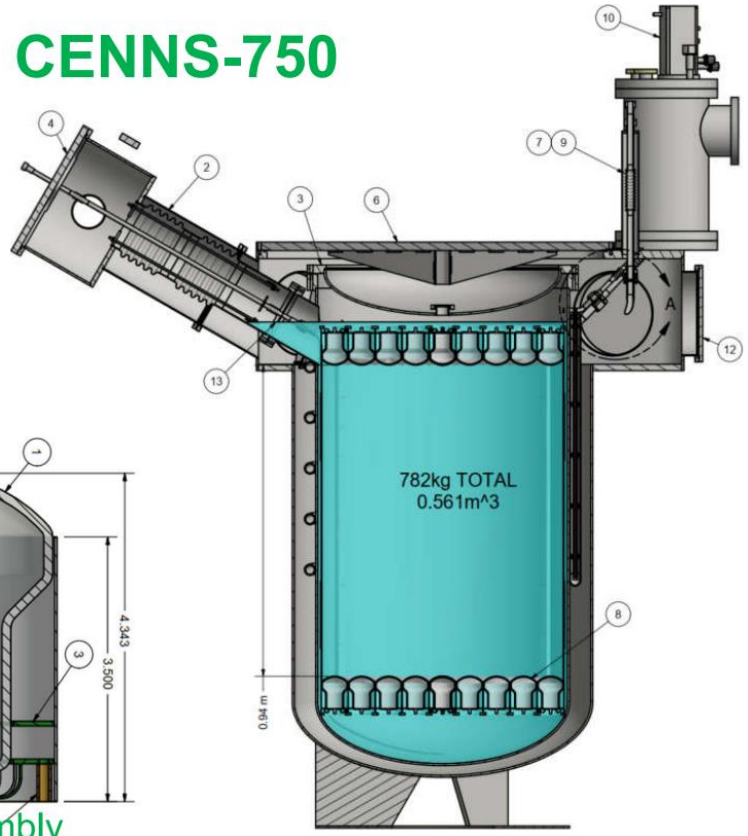
CENNS-750

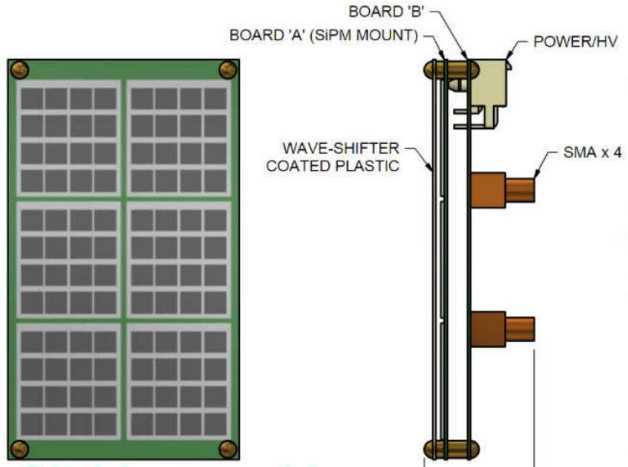
- Scaled up single-phase LAr detector featuring 610 kg fiducial mass.
- Photon detection system designed to maintain or exceed 20 keVnr threshold.
- Will fit in existing CENNS-10 location.
- Two possible configurations (SiPMs or 3” PMTS)
- Ongoing R&D at IU, ORNL, and Tufts.





3” PMT assembly



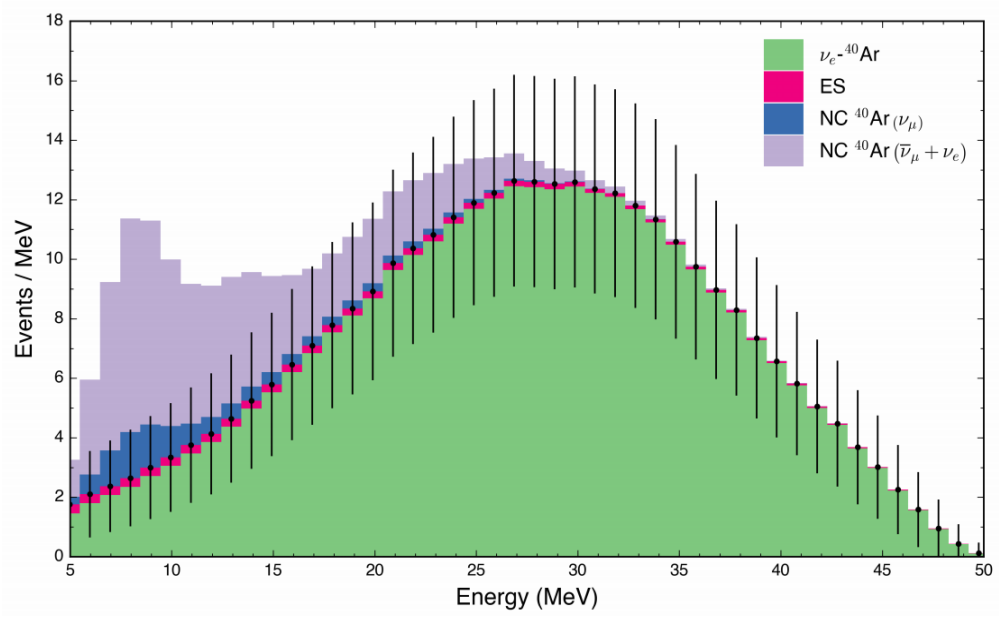


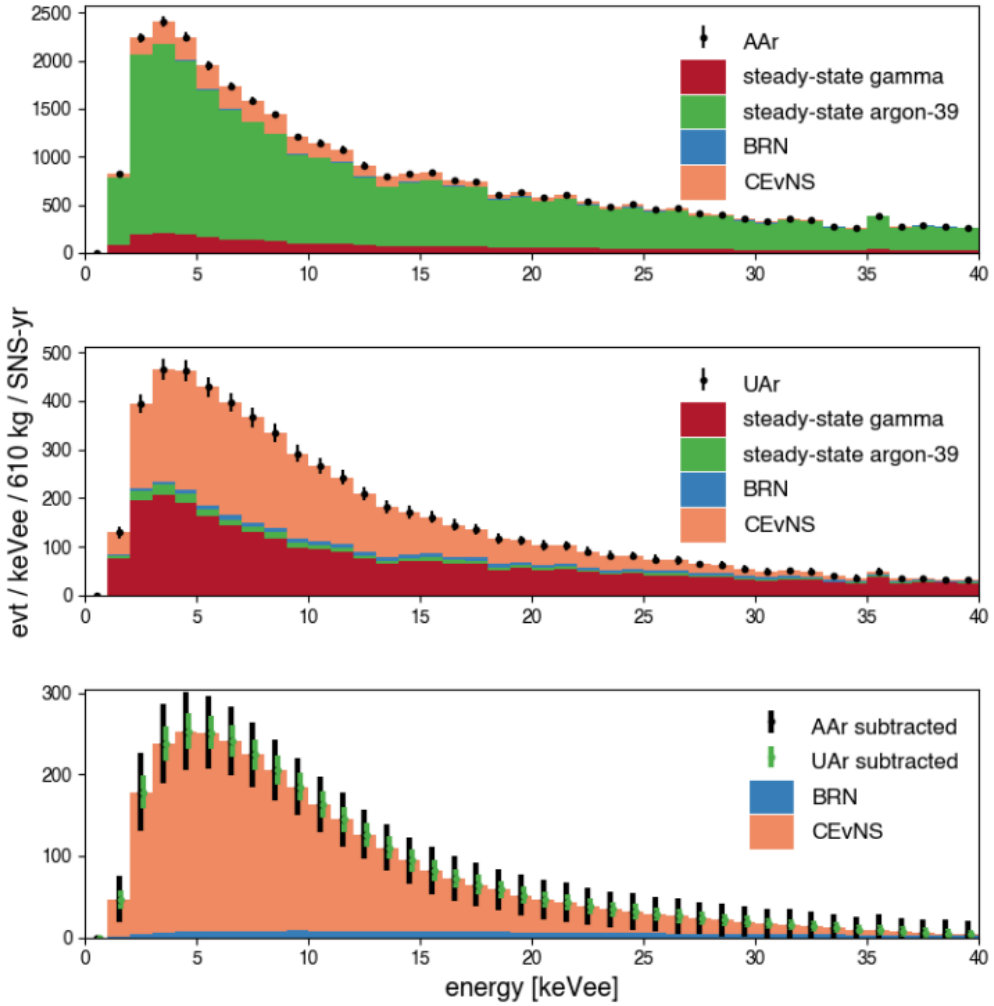
SiPM assembly

Precision Physics with CENNS-750

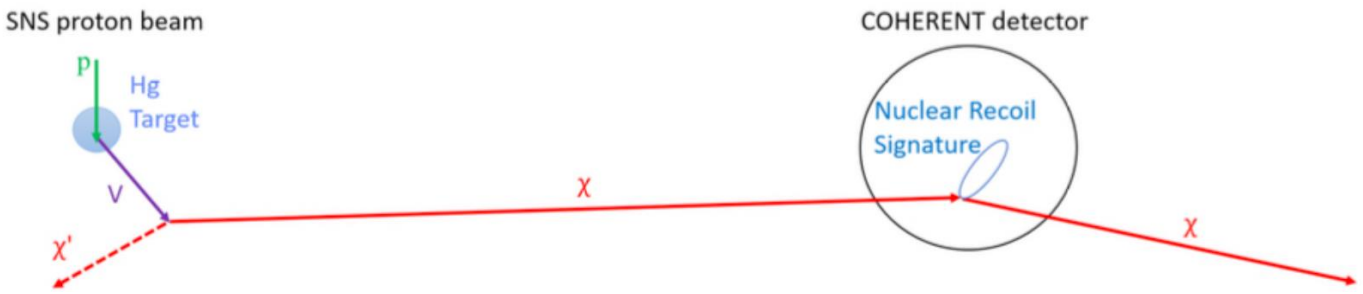
- Signal expectation of ~3000 CEvNS per SNS-year
- Approx. 400 inelastic CC and NC events per SNS-year

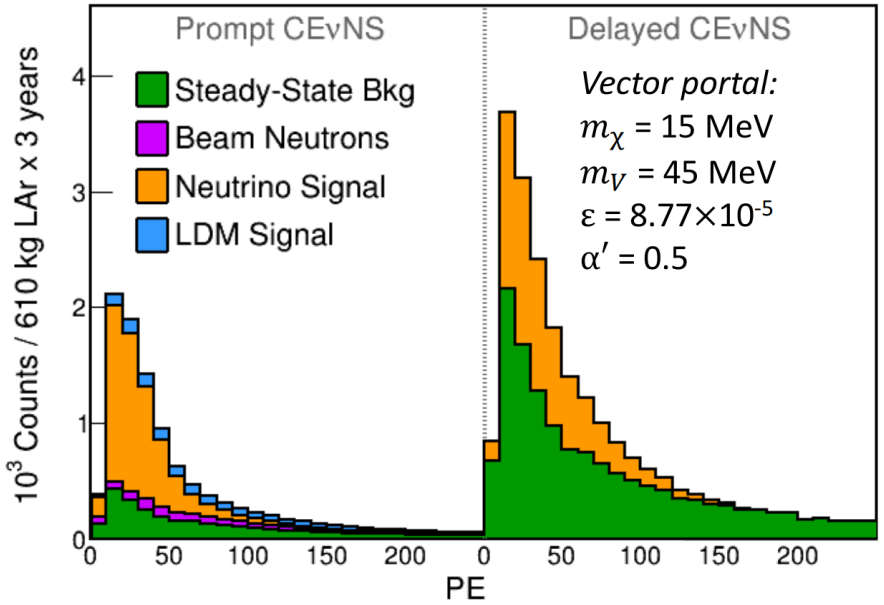
Important measurement for DUNE!



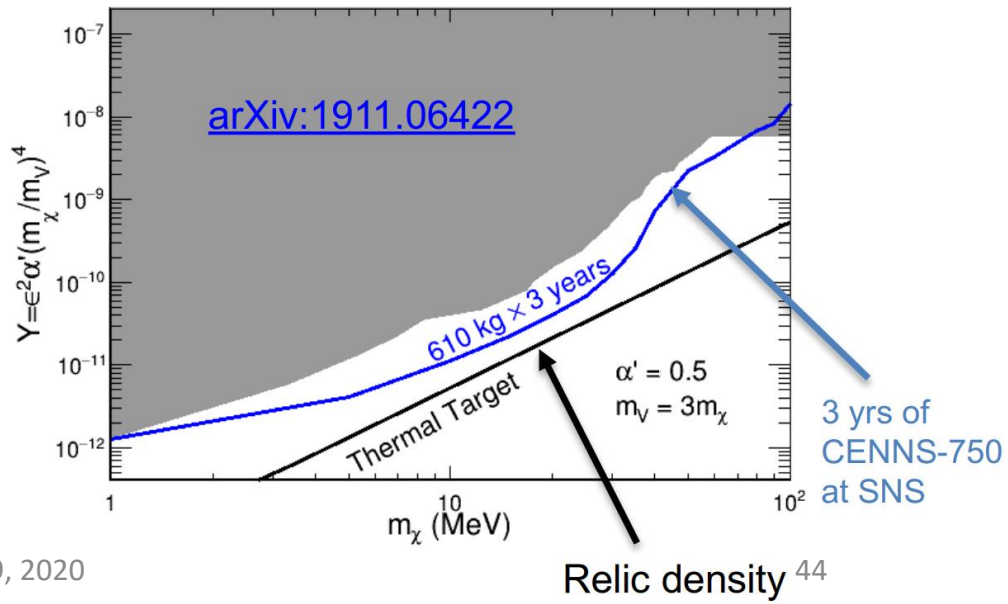


Accelerator-Produced Dark Matter

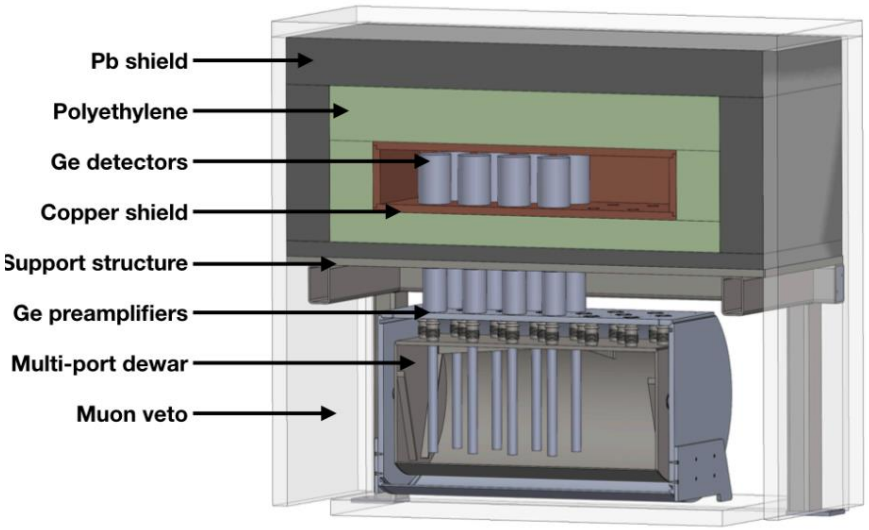




- Potential for vector portal DM via neutral pions produced at the target.
- Signal Expectation:
  - NR events with beam timing profile
  - Recoil spectrum depends on mediator and DM mass.
- Improved understanding and mitigation of beam-related neutrons improves sensitivity.



Future COHERENT Efforts

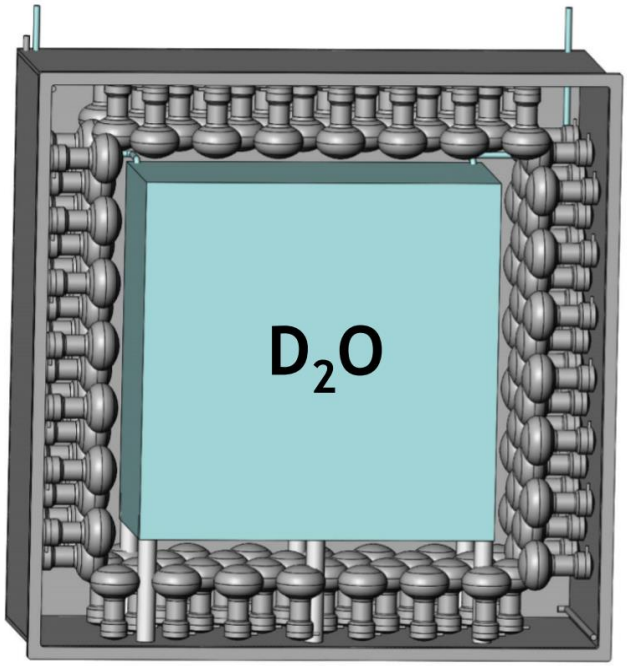


HPGe Array

16 kg array for measuring CEvNS on Ge. Low threshold and high Signal-to-Bkg ratio.

Modular NaI[Tl] Array

Ton-scale array to measure CEvNS on ^{23}Na and CC on ^{127}I cross sections.



Heavy Water Cerenkov

Use known ν_e – d cross section (2-3%) to constrain ν–flux normalization at SNS

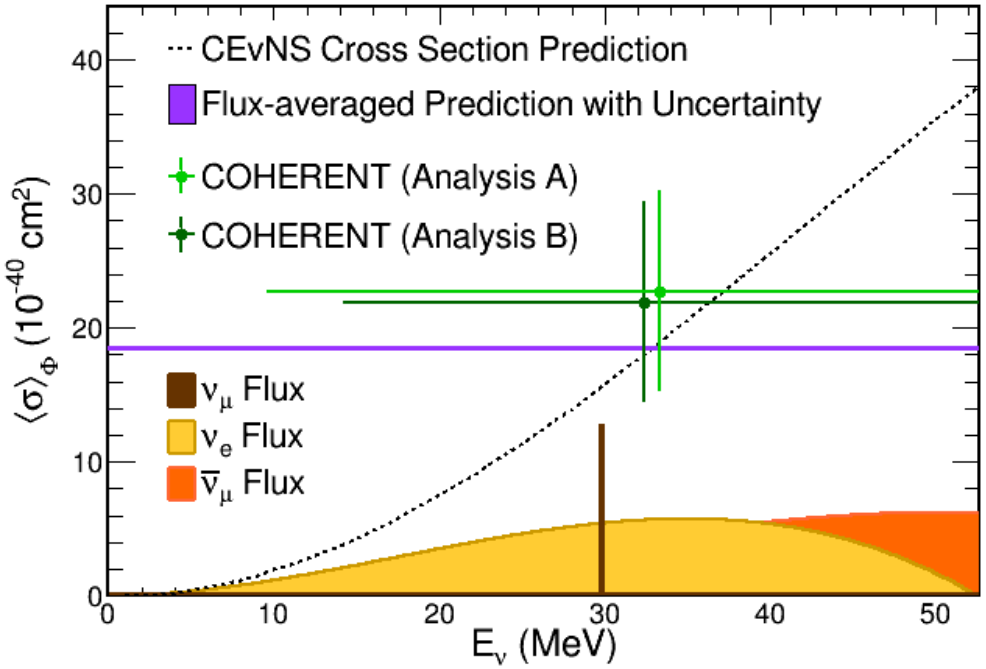
Summary and Outlook

- CEvNS measurements offer rich physics potential:
  - **Standard Model Tests**
  - **Neutrino Electromagnetic Properties**
  - **Nuclear Physics**
  - **Supernova Dynamics (Detection?)**

- COHERENT aims to build upon first observation results in multiple isotopes and make precision measurements of this process.

- Results of CENNS-10 analysis are the first measurement of CEvNS on Ar and lowest *N* measurement to date.

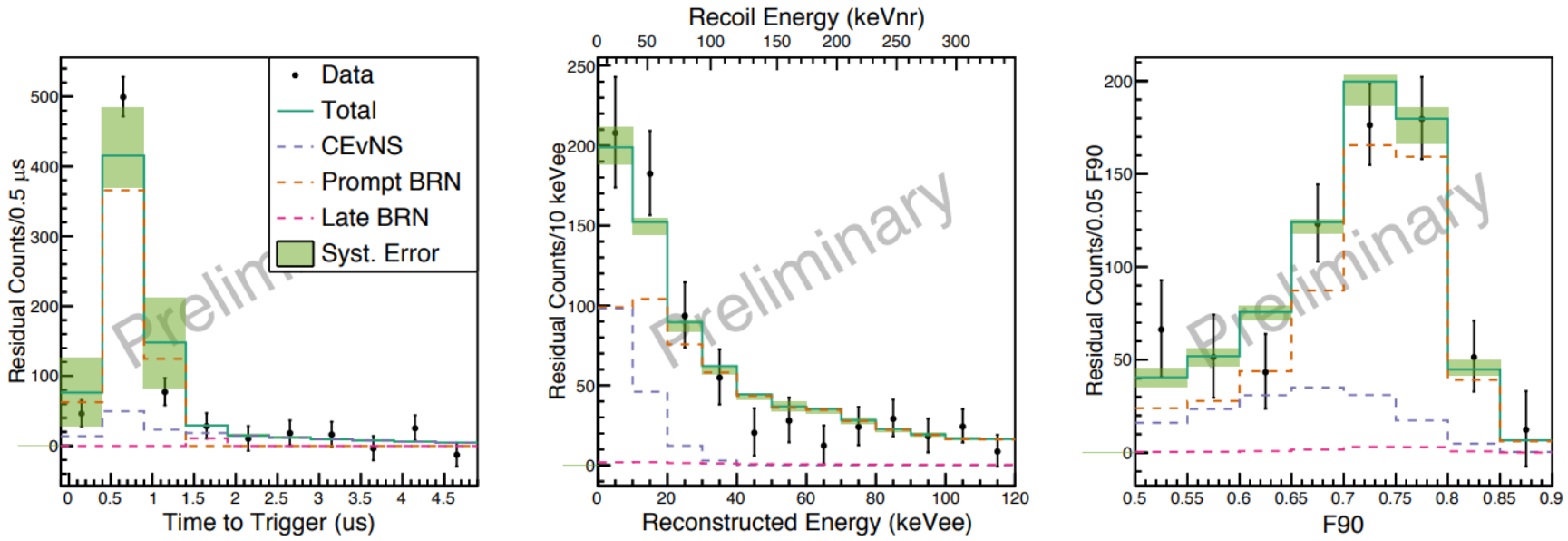
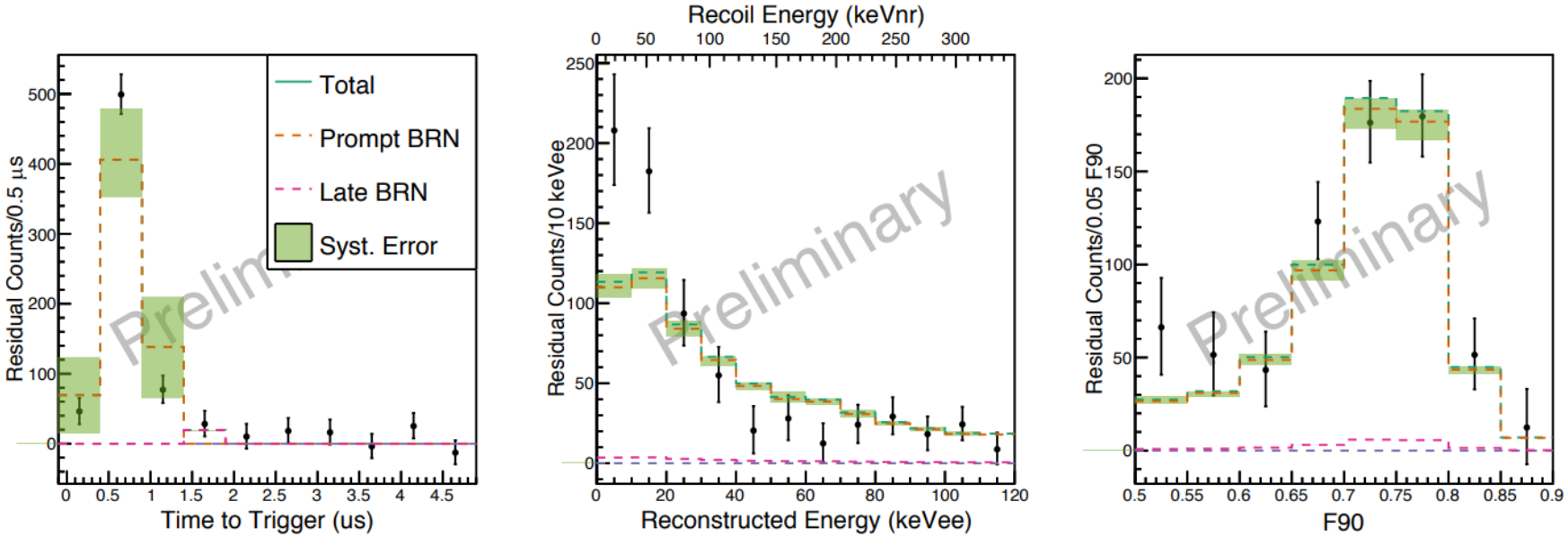
- Forthcoming results with Ge, NaI, and Ar will map out the expected *N*-dependence of this process.



Auxiliary Slides

Fit Projections

Best Fit 1-D Projections



Best Fit 1-D Projections with CEvNS = 0