A Precision Neutrino Laboratory at the Spallation Neutron Source

Jason Newby

for the COHERENT Collaboration

Magnificent CEvNS Workshop

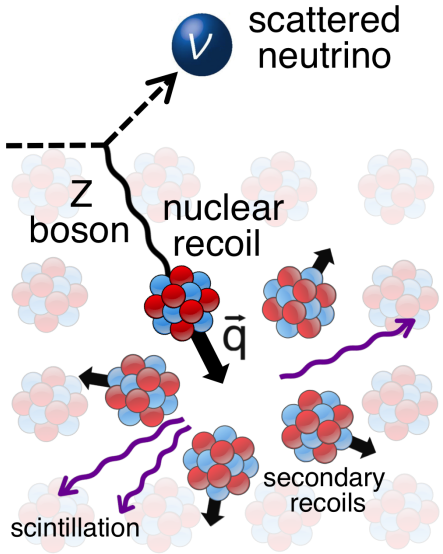
November 1-2, 2018

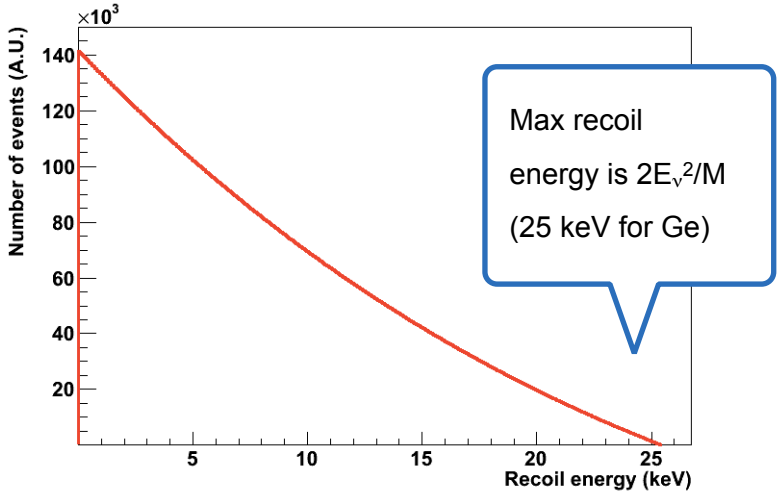
University of Chicago

ORNL is managed by UT-Battelle, LLC for the US Department of Energy

Coherent elastic neutrino-nucleus scattering (CEvNS)

A neutrino scatters on a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to E_ν ~ 50 MeV





- Predicted in 1974 by D. Freedman
- Interesting test of the standard model
  - Sensitive to **non-standard interactions**
  - Largest cross section in **supernovae** dynamics
  - Background for future **dark matter** experiments
  - Sensitive to nuclear physics, **neutron skin**

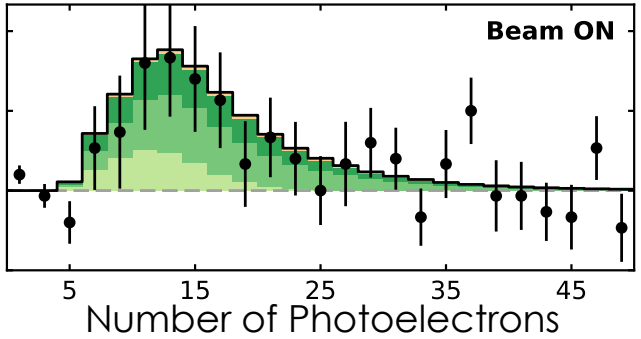
CEvNS cross section is well calculable in the Standard Model

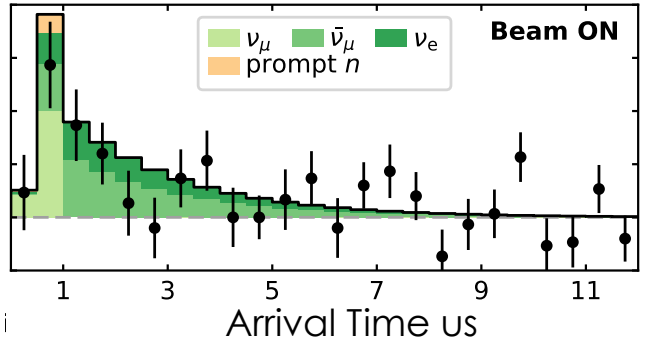
$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1+\cos\theta) \frac{(N-(1-4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$

CEvNS cross section is large! $\propto N^2$

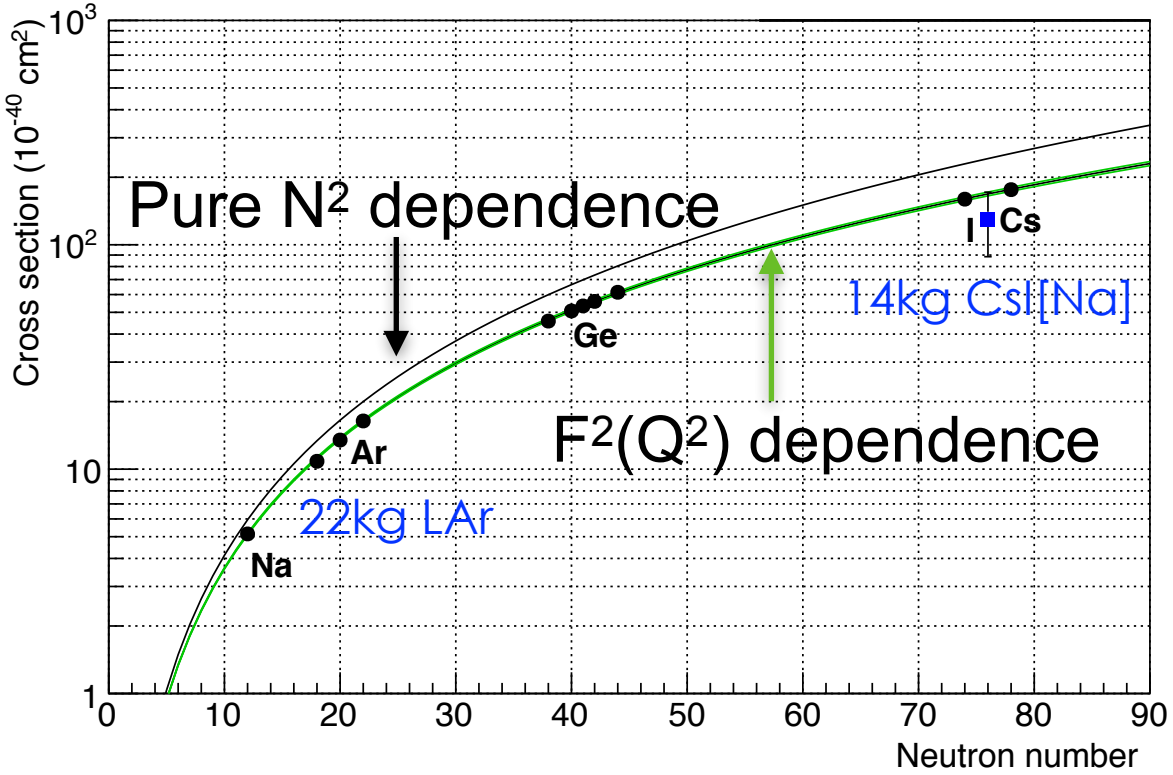
- Difficult to observe
  - Need a low threshold detector
  - Need an intense neutrino source

First Observation of CEvNS





Akimov et al. *Science* Vol 357, Issue 6356 15 September 2017

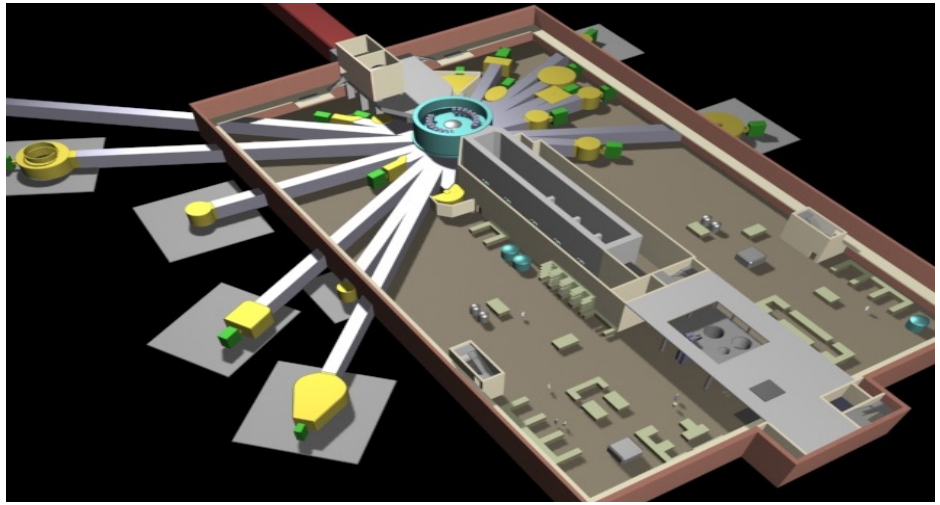


First light detectors deployed to measure neutron-squared dependence. (Na, Ge in 2019)

High precision measurements enable the full potential of CEvNS scientific impact.

Spallation Neutron Source User Program

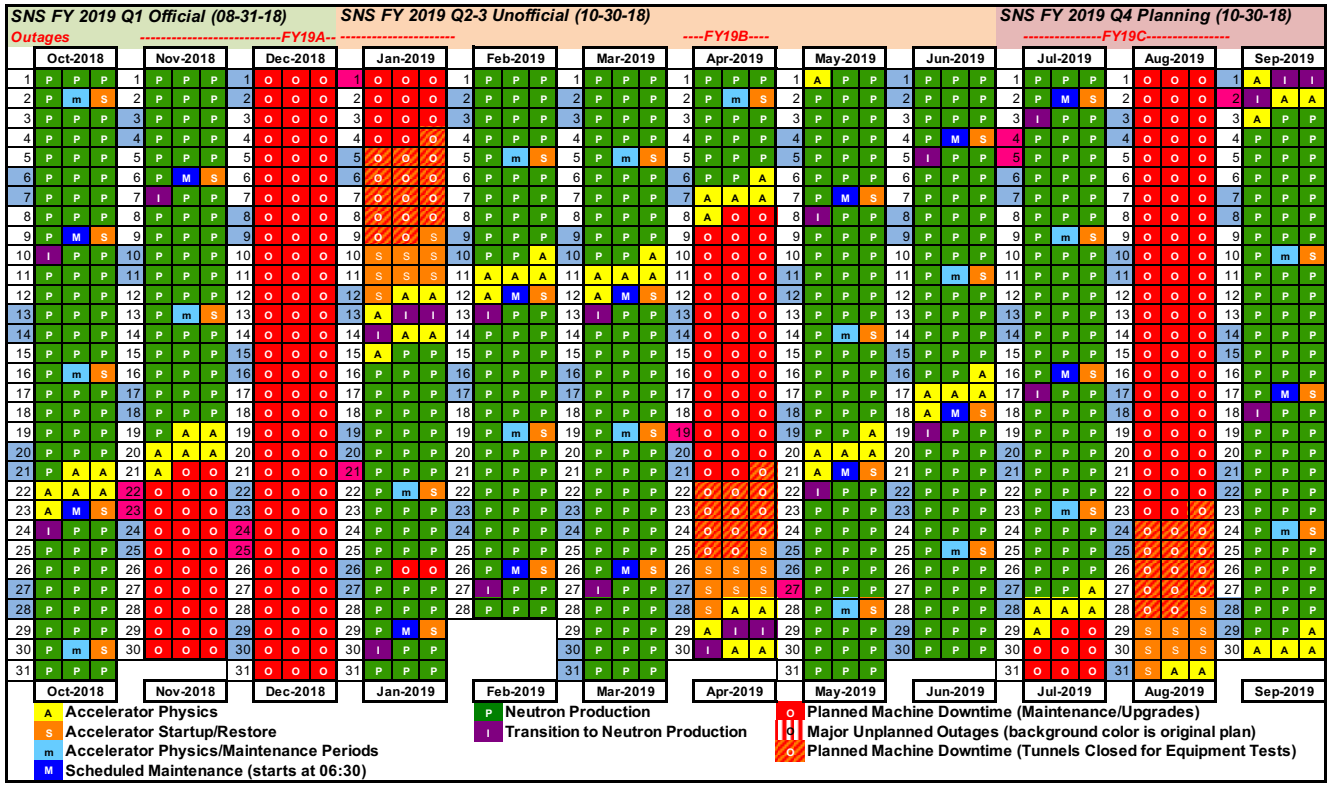
- 19 Neutron Beam-lines for Basic Energy Sciences missions
- 1 Fundamental Neutron Physics Beam-line for Office of Nuclear Physics missions
- 24/7 Operation with round-the-clock support staff, operations and user support
- Dedicated Instrument Scientist for each beam-line instrument
- Over 700 users in 2017 performing 1679 independent experiments.
- 1 Dedicated Laboratory for Neutrino Science

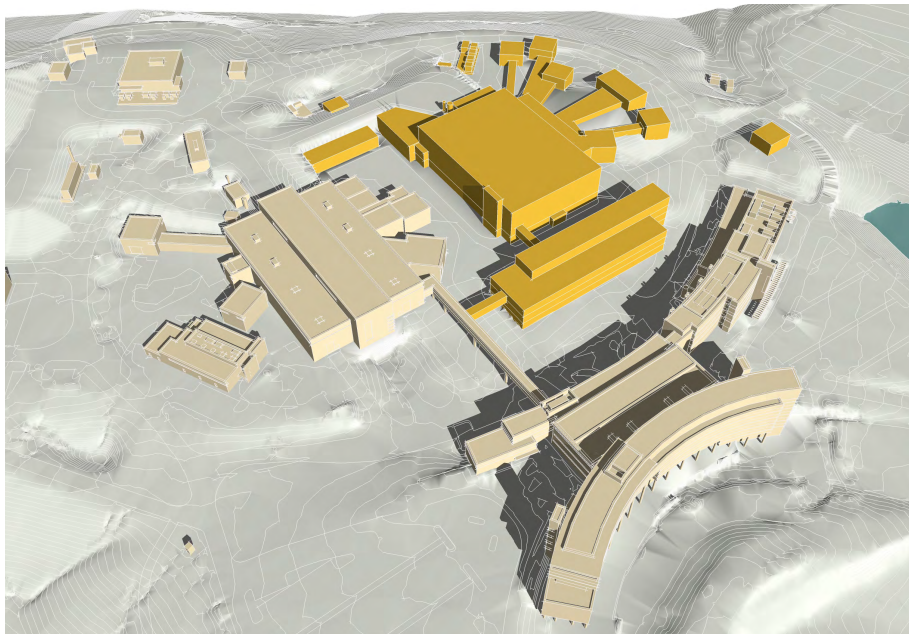


SNS Target Floor

SNS Scheduled Production Operation

- Goal is 5000 hours per year of neutron production
- Reliably scheduled beam uptime
- Recently completed Inner Reflector Plug replacement (first since 2007) during long shutdown
- Plan to operate at 1.4 MW indefinitely
- No long interruptions planned for next several years





- BES Approved Scientific Program for Second Target Station (STS) now under engineering design
- Planning for 2.4 MW on First Target and 800 kW on Second Target (tungsten)
- COHERENT discussing STS opportunities with SNS

Converting the service corridor into "Neutrino Alley"

- In 2015, ORNL approved LDRD to prepare service corridor as neutrino laboratory
- May 2016, CENNS-10 22 kg Argon selected for installation
- July 2016, CENNS-10 delivered
- Sept 2016, Electrical, Oxygen Monitoring, FixedBeam Hoist Installed
- Nov 2016, Instrument Readiness Review, Cryogenic Operations Begin
- June 2017, 11 ton Lead Shielding Approved and Installed

- 25 m^2 of equipment floor space
- Limited to 1 m depth (except in alcove)
- The fast neutron shielding provided by the SNS.
- Larger areas are available but Neutron Shielding not provided.

SNS Flux

SNS Hours per Year	5000
Pulses Per Second	60
Protons Per Pulse*	1.35×10^{14}
Pions Per POT* (KE_p=1010 MeV)	0.090
Neutrinos/cm^2/flavor/SNSYear @ 20m @1.3MW	2.51×10^{14}
Neutrinos/cm^2/flavor/SNSYear @ 20m @1.4MW	2.81×10^{14}

* Summer 2018 Run @ 1.3 MW, KE_p=1010 MeV, ChargePerPulse 2.16E-5

Proton Energy	**G4 π/p**
939.5	0.082
957	0.084
972	0.086
990	0.088
1010	0.090†

† Linear Extrapolation

- In Fall 2018, SNS transitioned from 1.3 to 1.4MW indefinitely
  - ➡Flux @ 20m 2.81×10^{14} neutrinos/cm^2/flavor/SNSYear
- SNS is a magnificent resource for neutrino physics
- How do we best leverage this opportunity?

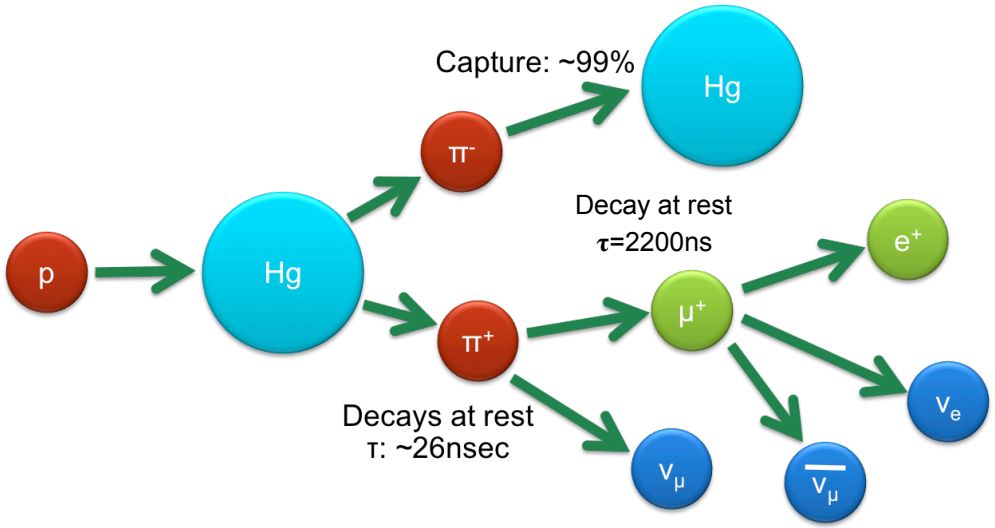
Systematic Uncertainties of the CEvNS observation

Uncertainties on CsI signal and background predictions	
Event selection (signal acceptance)	5%
Form Factor	5%
Neutrino Flux	10%
Quenching factor	25%
Total uncertainty on signal	**28%**

All uncertainties except neutrino flux are detector specific and could be much less for other technologies

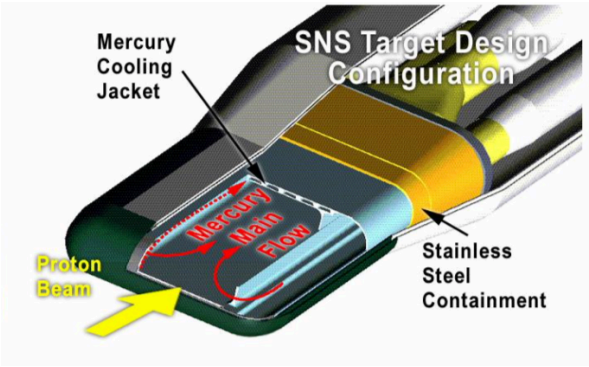
To unlock high precision CEvNS program, we need to calibrate SNS neutrino flux

SNS produces pions via π decay at rest



- Largest uncertainty is pion production from p+Hg
- 10% discrepancy between Bertini and LAHET calculations

Determining the SNS Neutrino Flux

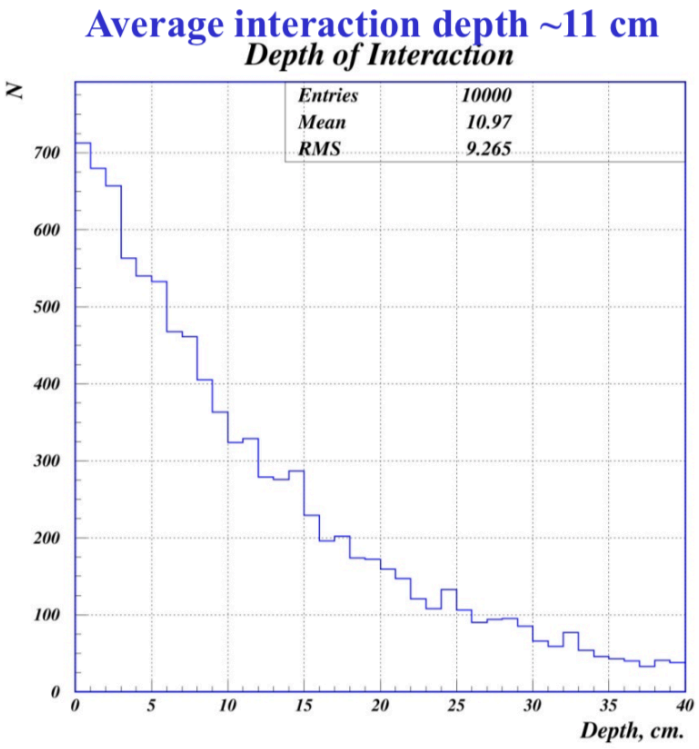


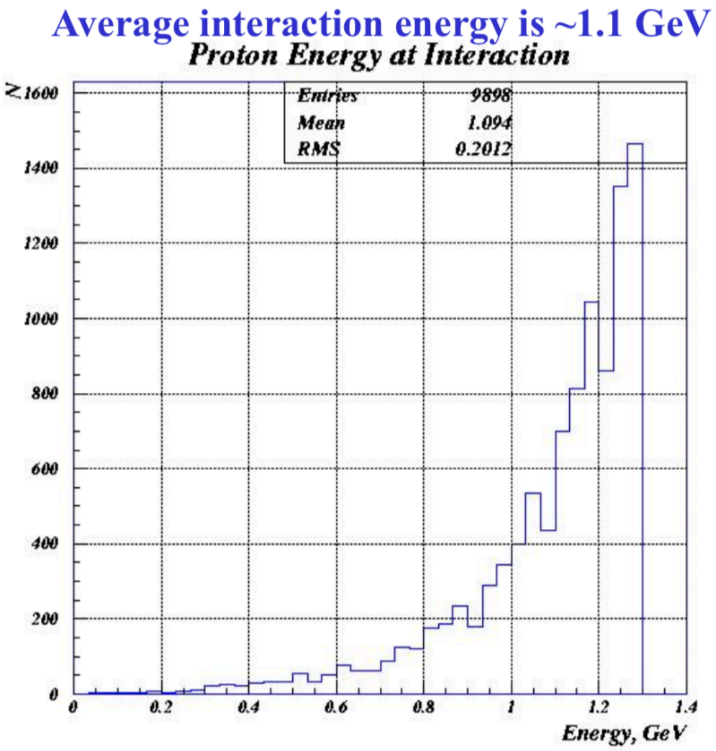
Source Parameters

- Proton Energy ~1 GeV
- 1.5×10^{23} POT per year
- **Thick Target**

Proton Energy	G4 π/p
939.5	0.082
957	0.084
972	0.086
990	0.088
1010	0.09

1.3 GeV proton energy





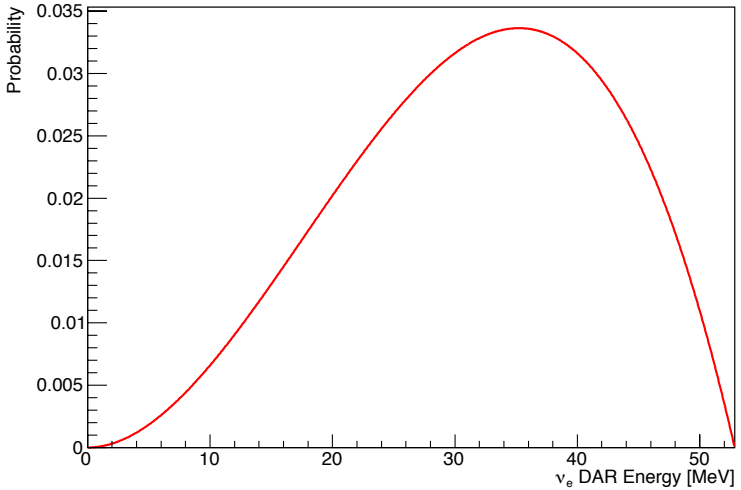
- Measure pion production to infer neutrino flux
  - Challenge: proton energy loss in target requires measurement over broad energy range, at all outgoing angles, and measurement of pion interaction in target
- Direct measurement of neutrinos with well calibrated process
  - Challenge: neutrino cross sections are low

Direct Measurement of Neutrino Flux with Heavy Water

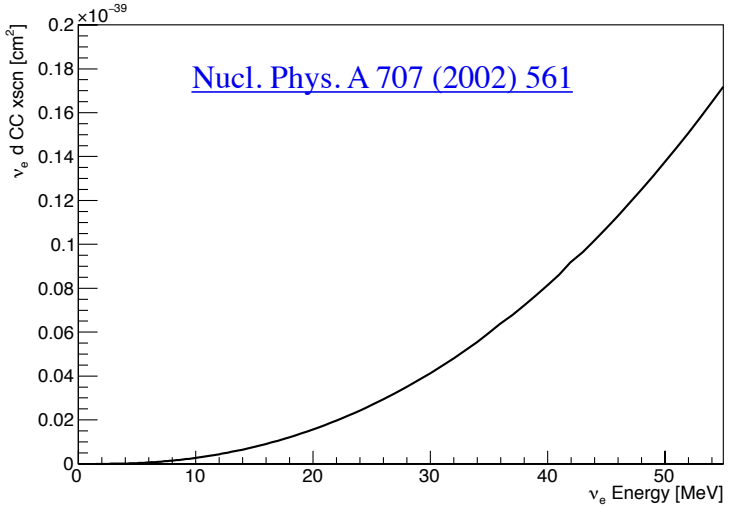
- Charged current ν_e-d cross section known to about 2-3%.

S.Nakamura et. al. Nucl.Phys. A721(2003) 549

$$\nu_e + d \rightarrow p + p + e^-$$ 5.5×10^{-41} cm^2



×



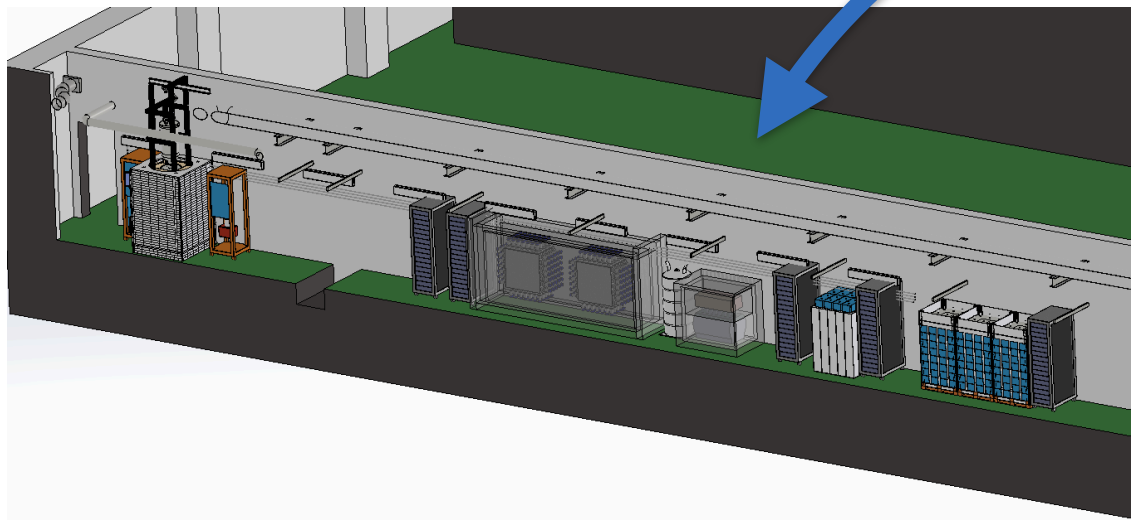
930 CC interactions per ton per SNS-year

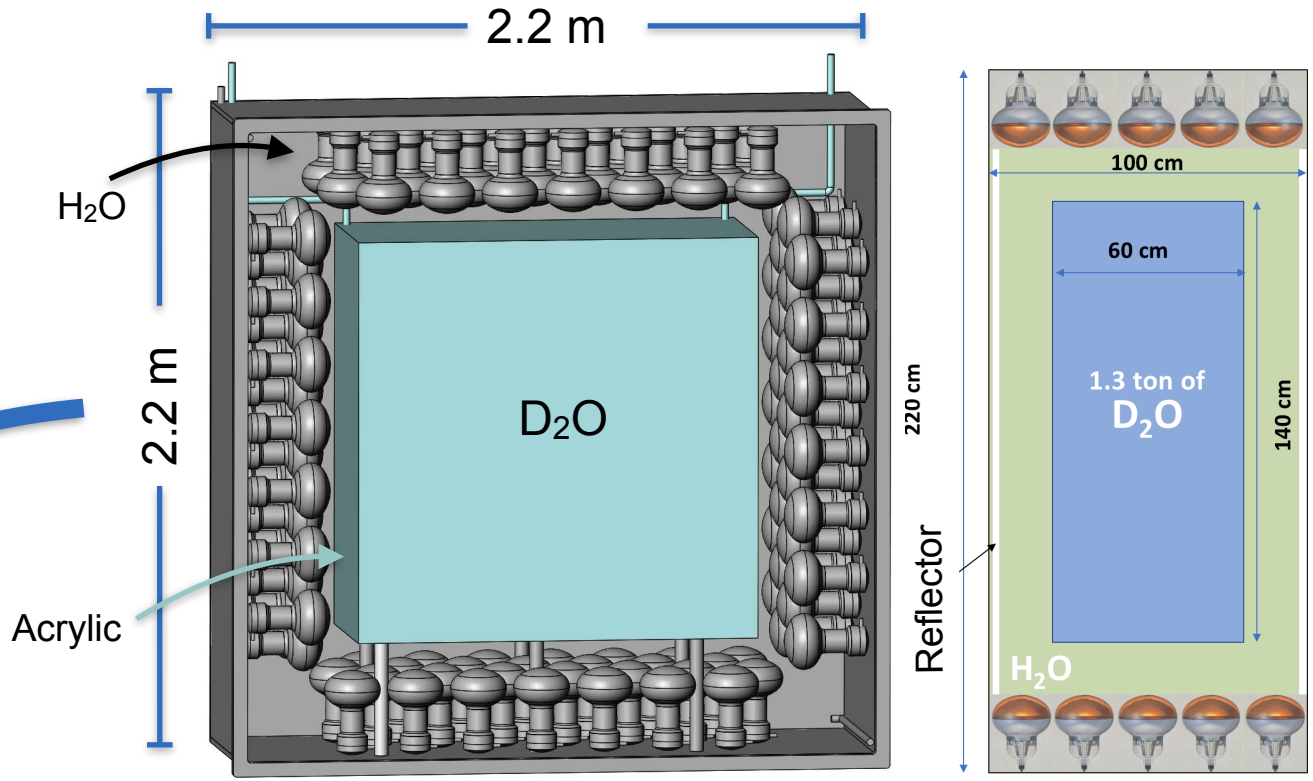
5000 hrs/yr @ 1.4 MW
0.09 ν_e per proton

1-ton Heavy Water Detector at the SNS

- Neutrino Alley space constraints:
  1m depth x 2.3m height x 3m width
- Locations 20-29 meters from target
- Neutron shielding supplied by SNS

Neutrino Alley



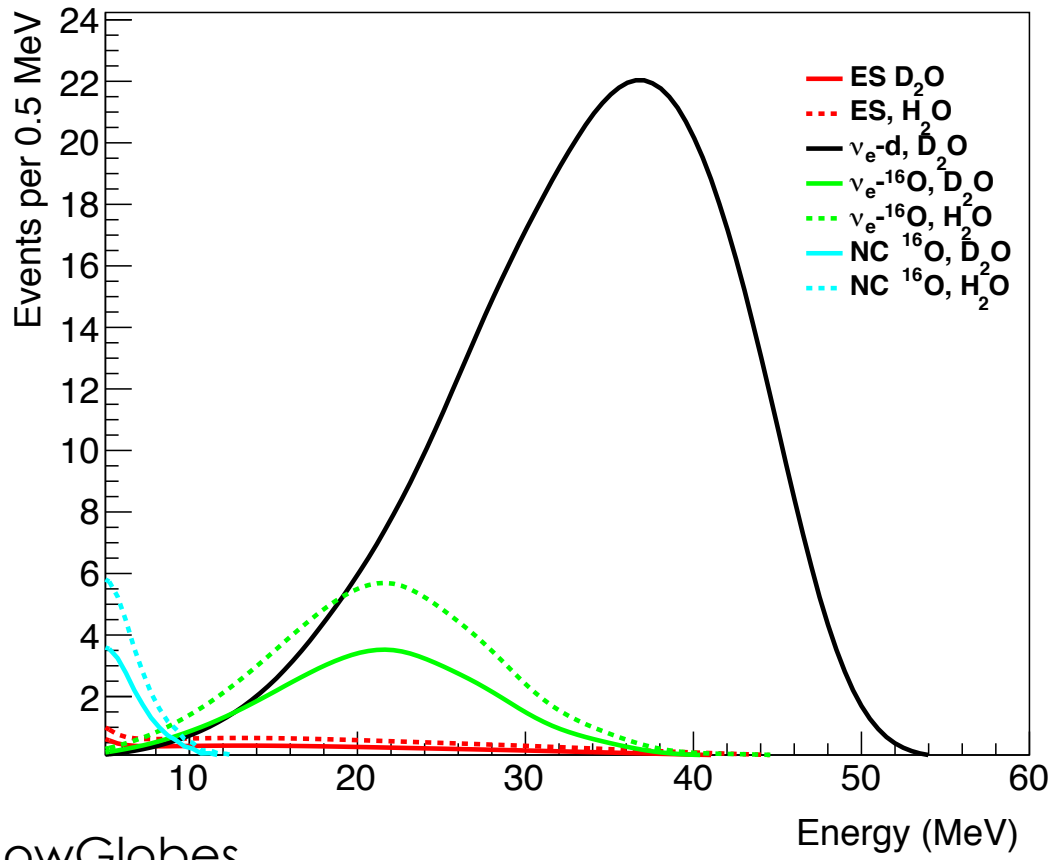


Darryl Dowling, ORNL

- 1.3 tons D_2O within acrylic inner vessel
- H_2O "tail catcher" for high energy e^-
- Outer light water vessel contains PMTs, PMT support structure, and optical reflector.
- Outer steel vessel to support shielding and veto

Dominant Beam Related Backgrounds?

- Updated SnowGlobes tool indicates largest beam related background is charged current on oxygen
- With a nominal 10cm tail catcher, 1.3 tons of D_2O requires 1.8 tons of H_2O which produces Cherenkov too.
- Full detector response model needed for accurate optimization.



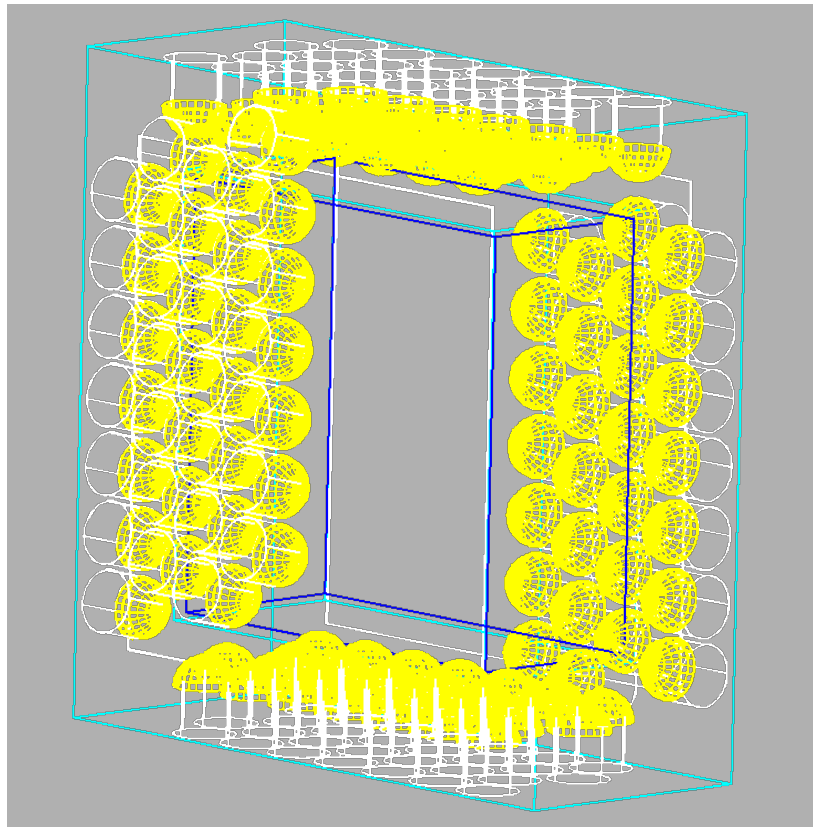
SnowGlobes

SNS flux weighted ν_e-d CC xscn by Jes Koros
SNS flux weighted ν_e-O CC xscn by Kate Scholberg

W. C. Haxton. Phys. Rev. C **37**, 2660

How much light water is optimal?

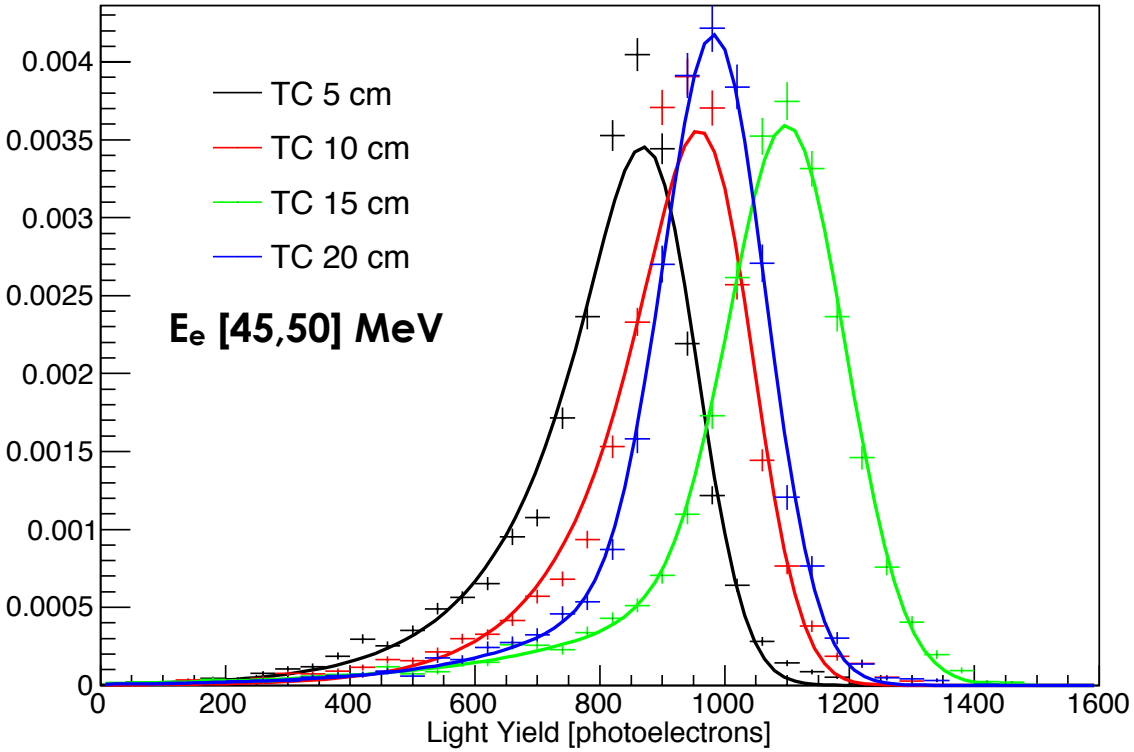
- G4 Simulation
  - 1.3 tons of D_2O (60×140×140 cm)
  - 1 inch acrylic tank
  - Light water gap to reflector/PMT {5,10,15,20} cm
  - 8 Inch Bialkali (25% peak QE) PMT on four sides
  - 0.25 Inch Teflon reflector on 2 sides
  - No reflector between PMTs

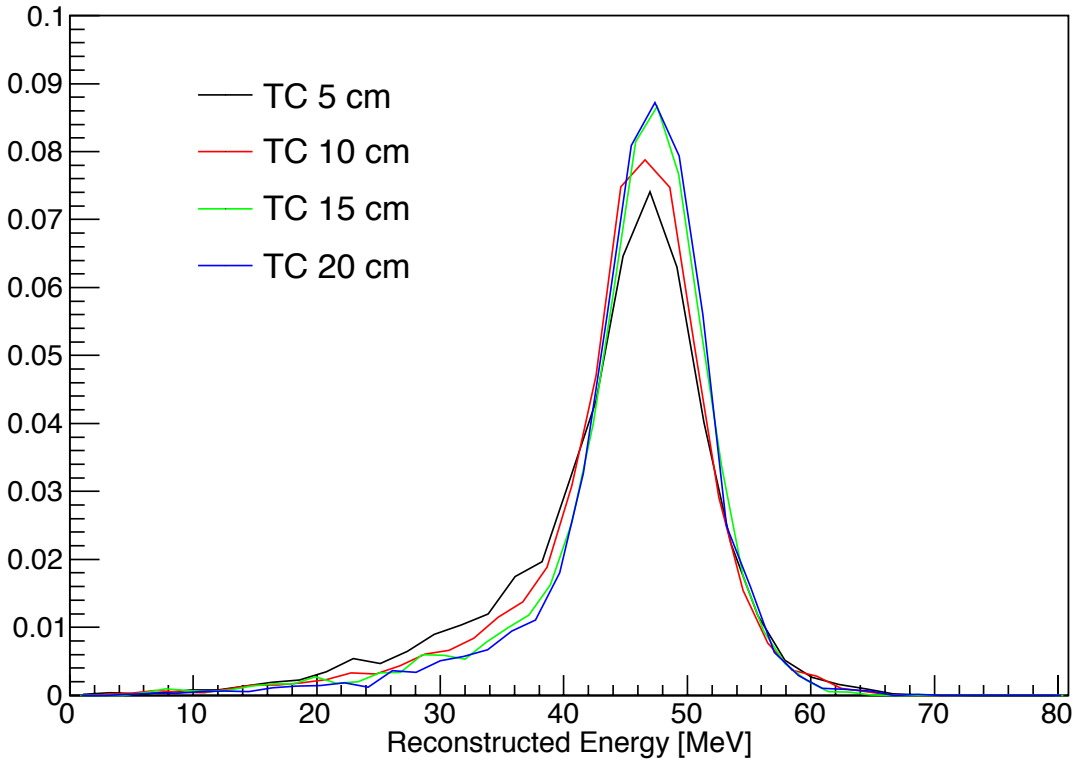


Geant4 Model
Matthew Blackston

- 160 PMTs for H_2O Thickness of 15,20 cm
- 112 PMTs for H_2O Thickness of 5,10 cm

Energy Resolution Degrades slightly with less H_2O

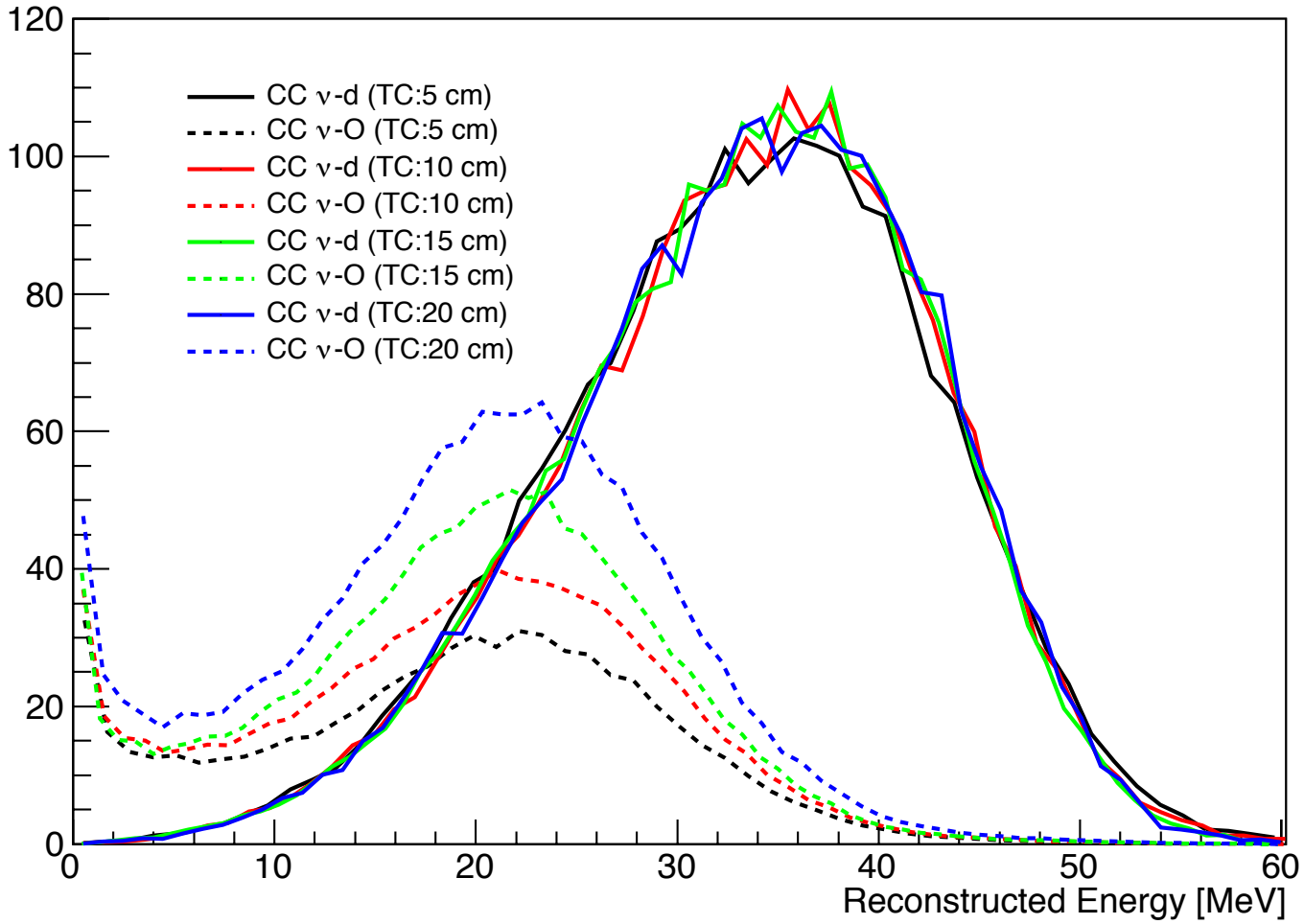




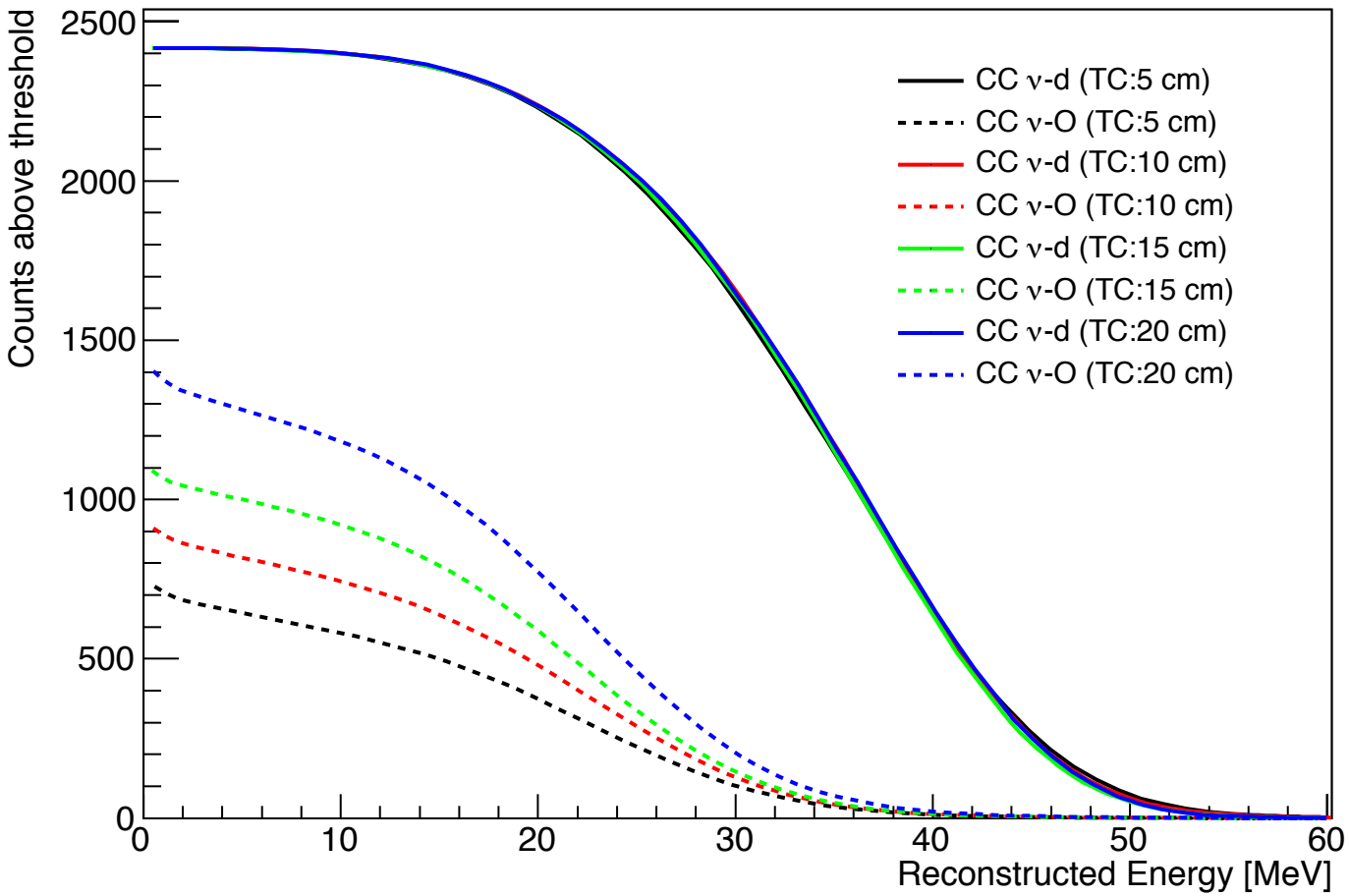
- 200k electron recoils thrown for each "tail catcher" (TC) thickness
- E dependent QE applied at PMT
- About 20 PE per MeV, 18% resolution at 50 MeV

With thicker H_2O layer, more recoil electrons at the edges range out and deposit full energy.

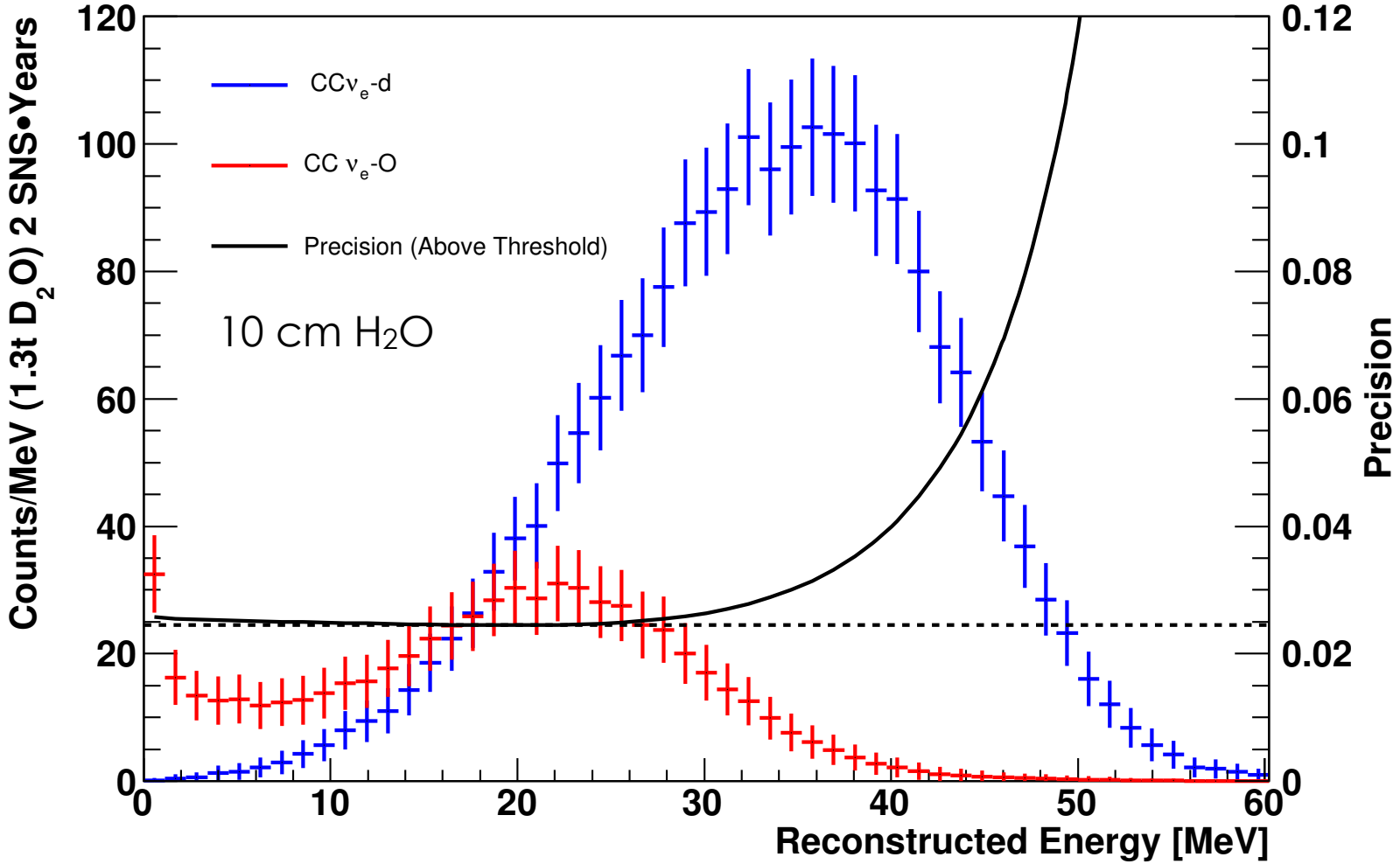
Flux Weighted Distributions for 2 SNS Years @ 1.4 MW

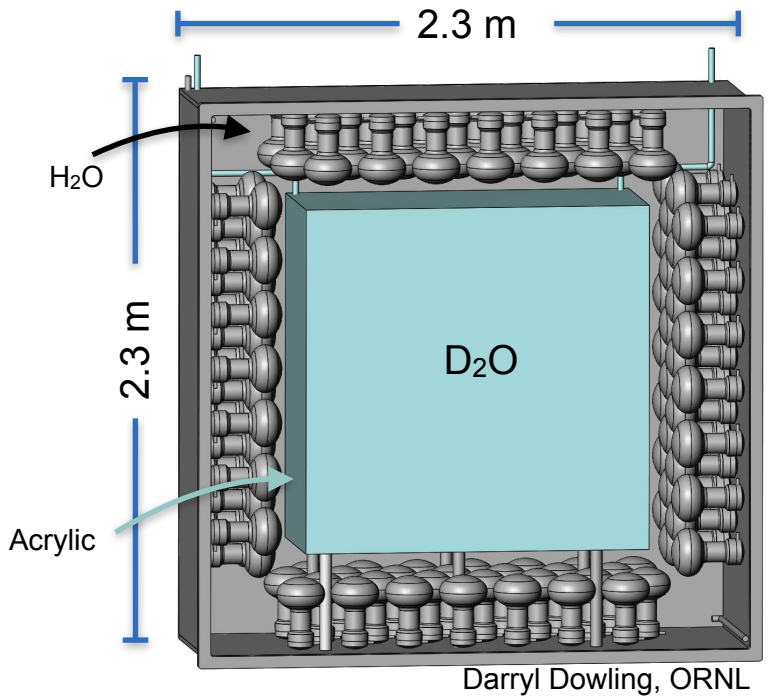


Integrated Counts above threshold



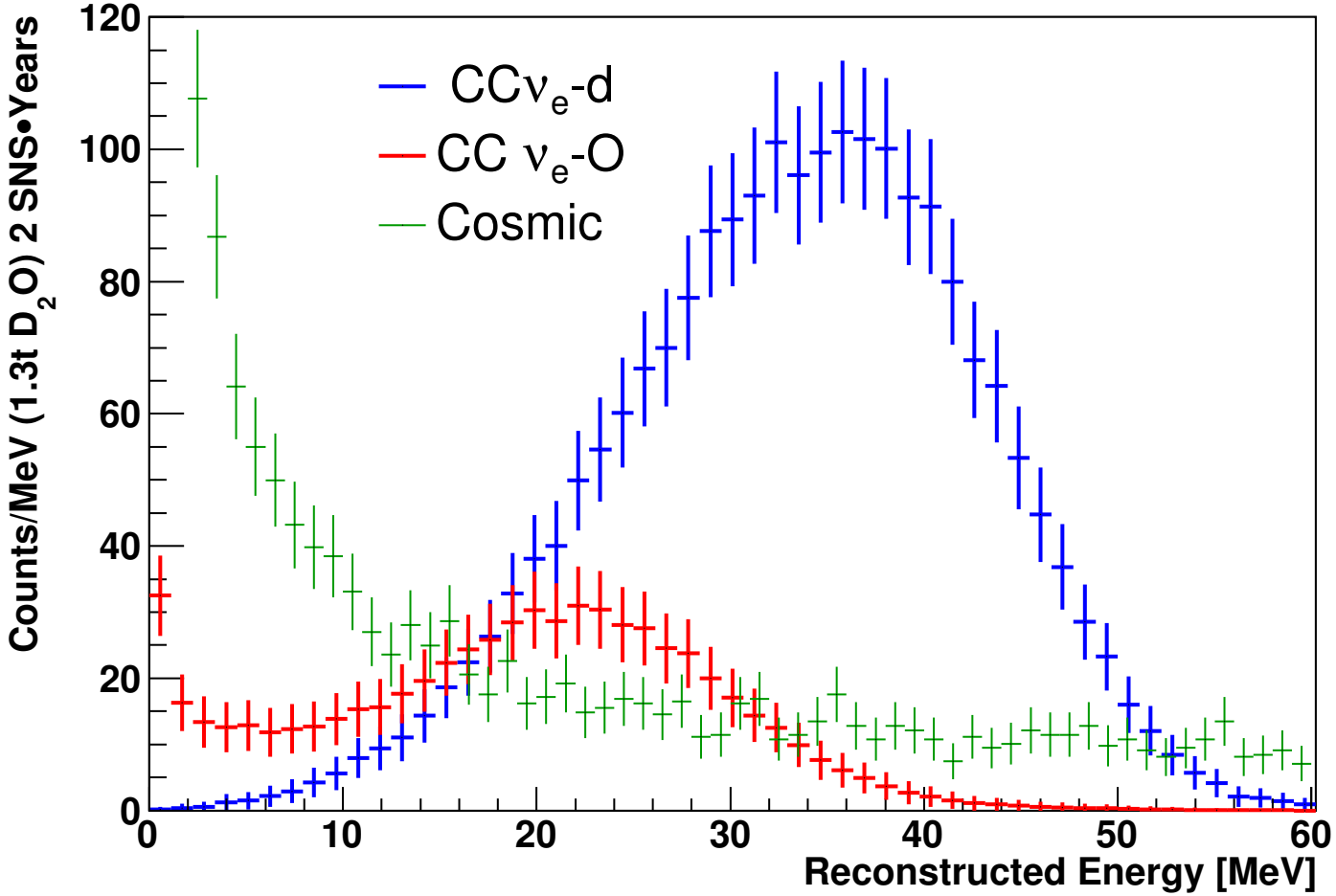
Measurement Precision with 2 SNS years at 1.4 MW





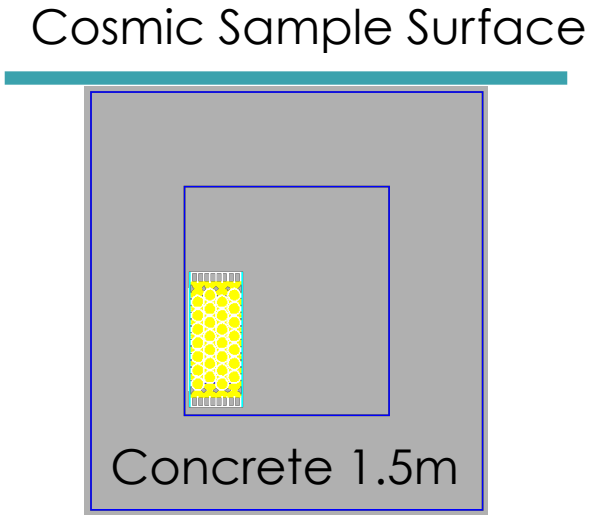
- 1.3 tons D_2O within acrylic inner vessel
- 10 cm H_2O "tail catcher" for high energy e^-
- 112 8" bialkali photomultipliers

Cosmic Backgrounds



Majorana Demonstrator Cosmic Panels 99.8% with 2 1-inch layers of plastic
NIM. A758 (2014) 91-96 (2014)

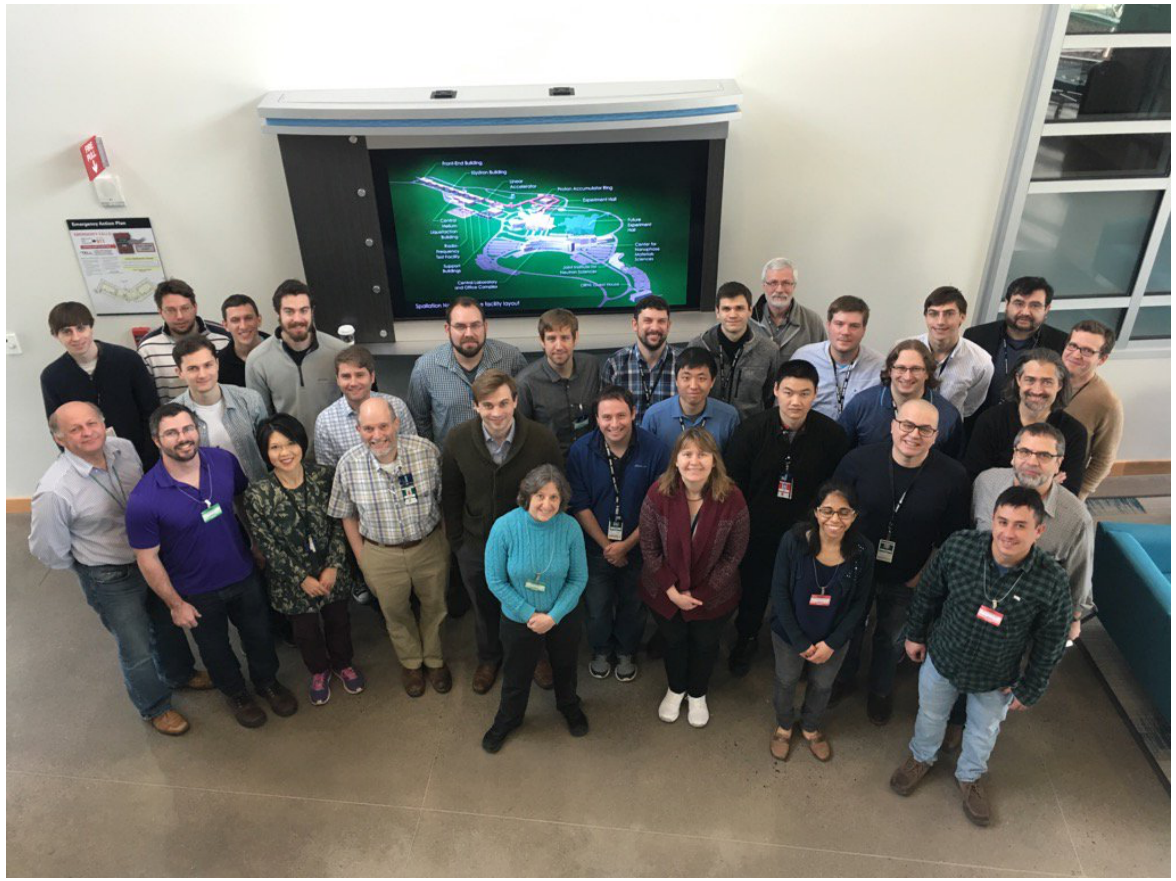
- Geant4 simulation using LLNL CRY package
- Neutrino Alley simulated as 1.5 m concrete ceiling, wall, and floor.
- 10×10 m surface sampled for 35 seconds scaled to 2 SNS years with 5μs beam coincidence window.
- Assuming 99.9% cosmic veto efficiency



Summary

- The Spallation Neutron Source is currently the cleanest, most intense stopped pion neutrino source with stable operation planned for decades.
- Precision neutrino flux measurement unlocks the full potential of a CEvNS program at the Spallation Neutron Source.
- Precision neutrino flux measurement is feasible with a ton-scale heavy water detector in Neutrino Alley.
- Replacement of D_2O with H_2O for CC neutrino interactions for SN neutrinos with Oxygen.

COHERENT Collaboration



https://coherent.ornl.gov arXiv:1509.08702