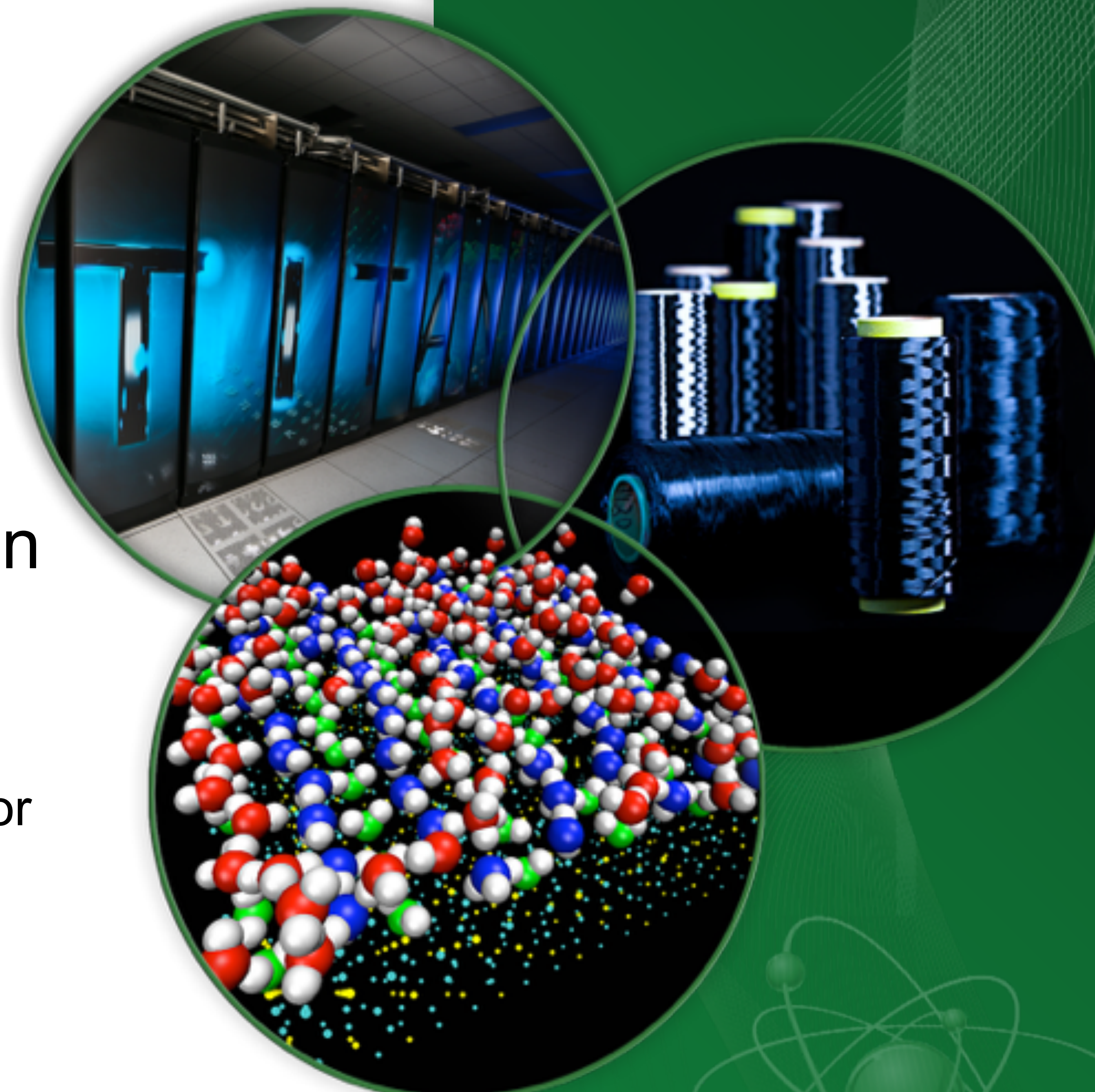
The COHERENT Experiment at the SNS



Jason Newby

for the COHERENT Collaboration

March 14, 2017

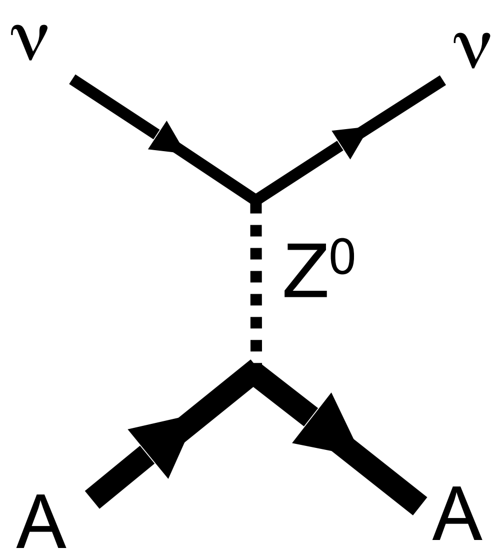
Precision Investigations of the Neutrino Sector Workshop, SLAC March 13-17

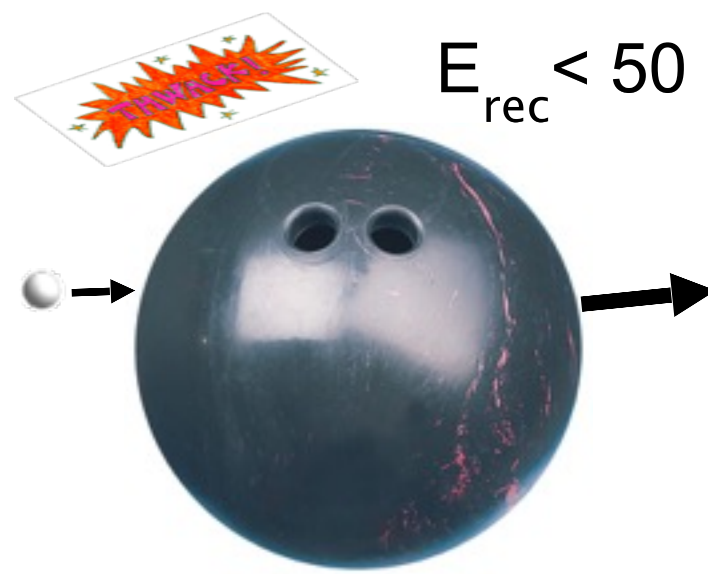
Precision Investigations of the NEUTRINO Sector
SLAC National Accelerator Laboratory, March 13-17, 2017

ORNL is managed by UT-Battelle
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





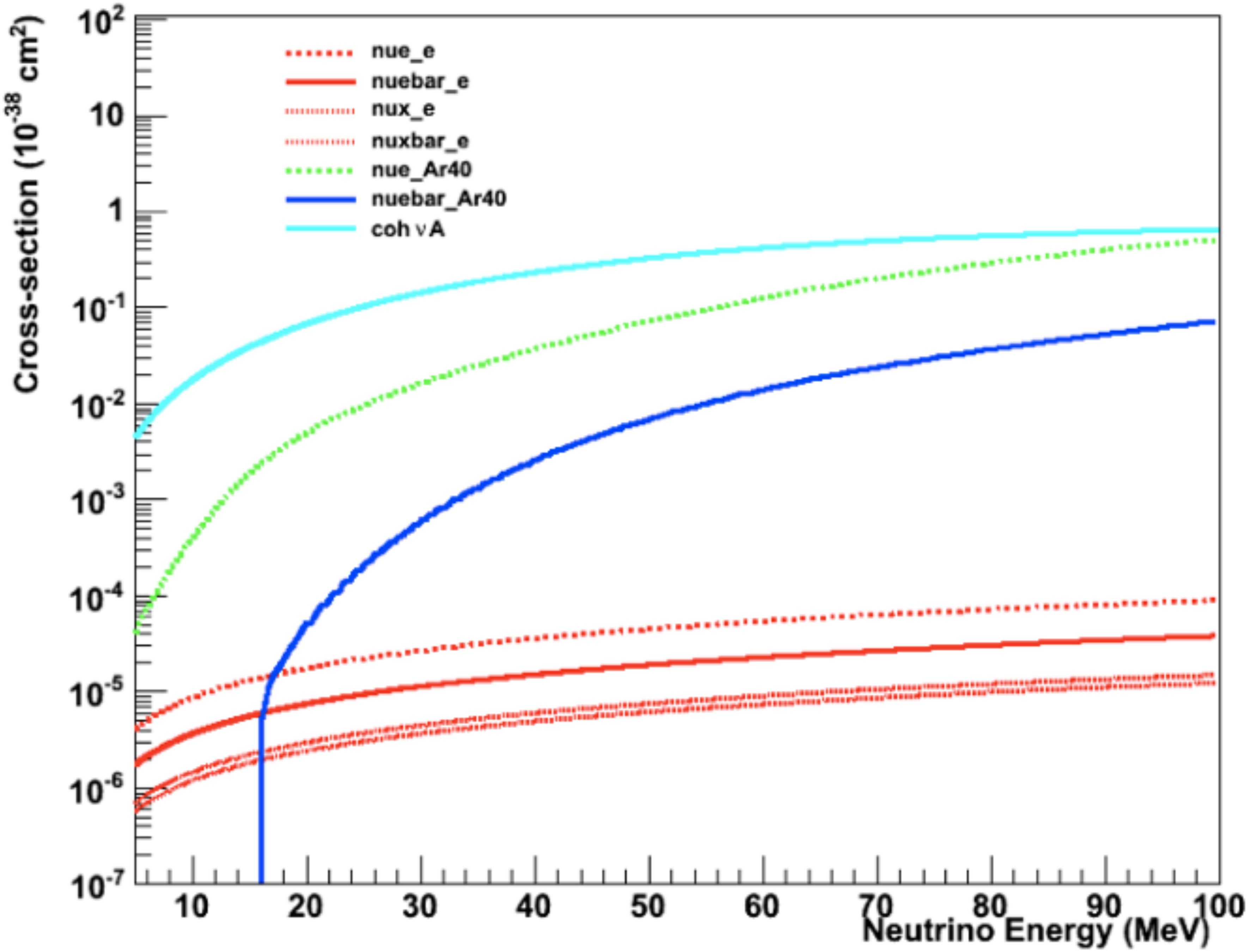
E_{rec}< 50 keV

CEvNS cross section is well calculable in the Standard Model

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

- Largest neutrino cross section but never observed!
  - ➡No neutrino source with compatible characteristics so far.
  - ➡Detectors are just now becoming sensitive to these small recoils.

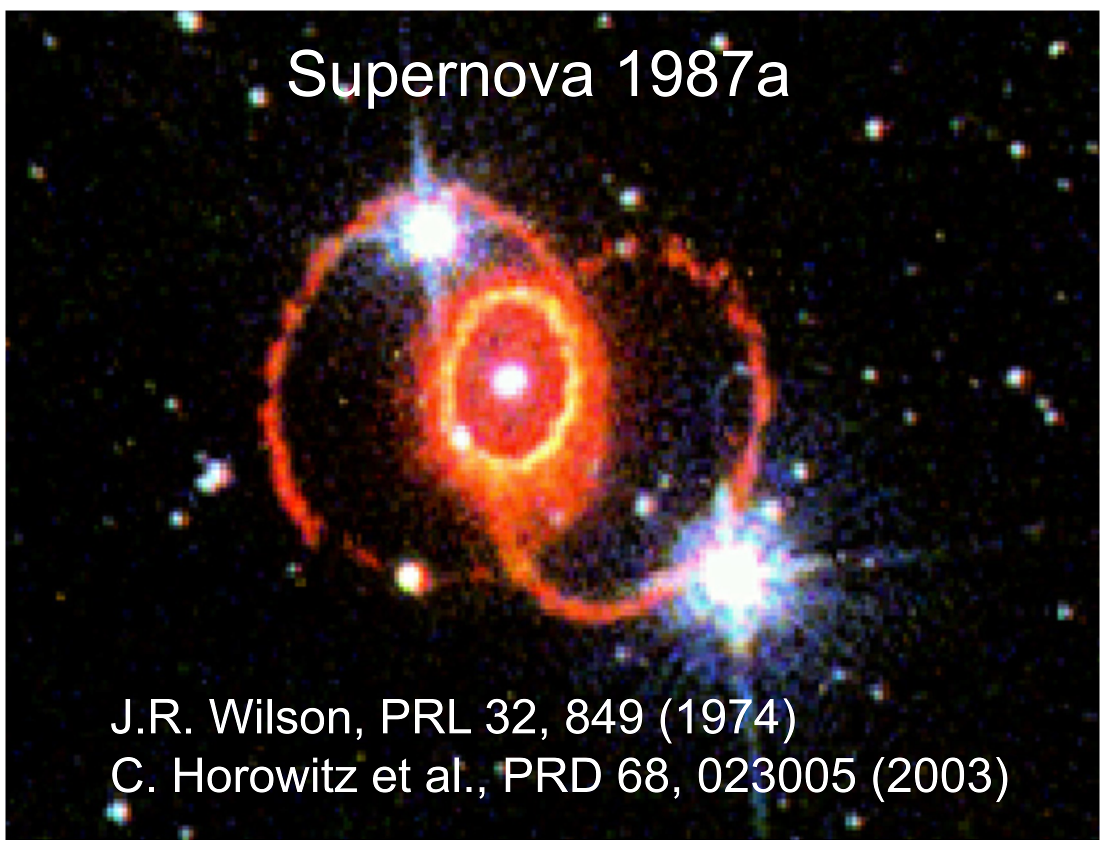
CEvNS cross-section is “large” for neutrinos



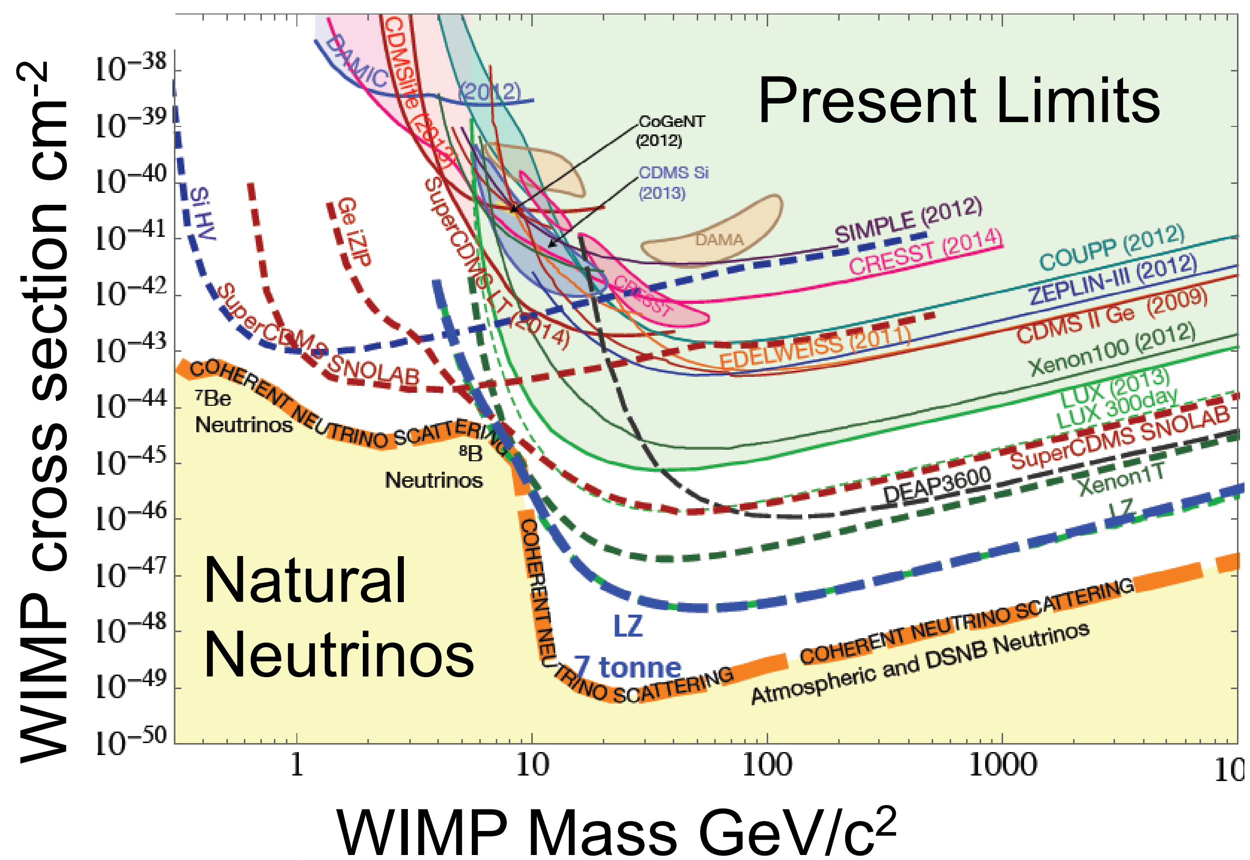
Why measure CEvNS?

- Test of the Standard Model: Predicted 42 years ago, but yet to be observed! D.Z. Freedman. Phys. Rev. D9, 1389 (1974).

Largest σ in supernovae dynamics.



Background for future DM searches.

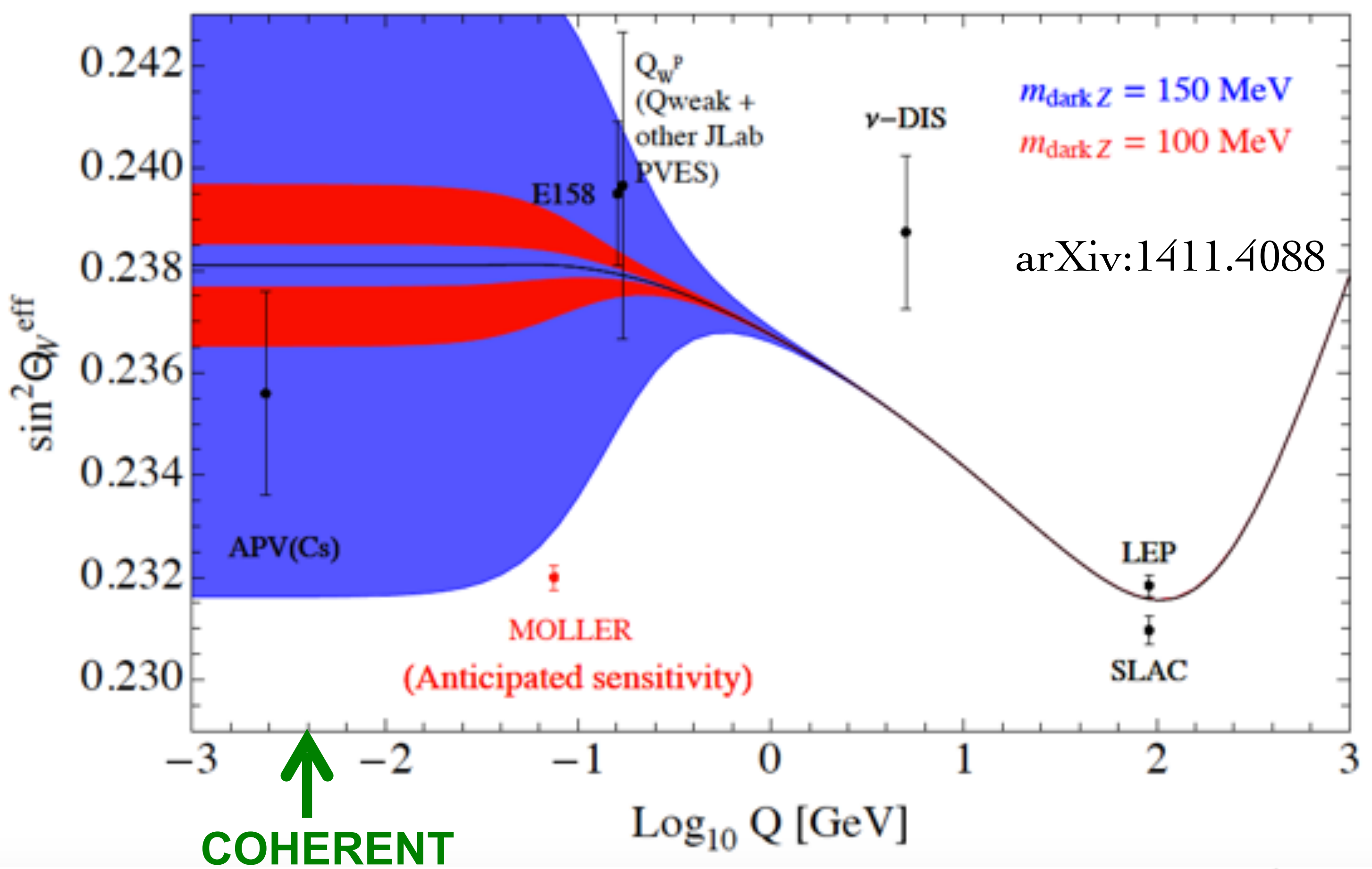


CEvNS and the Weinberg Angle

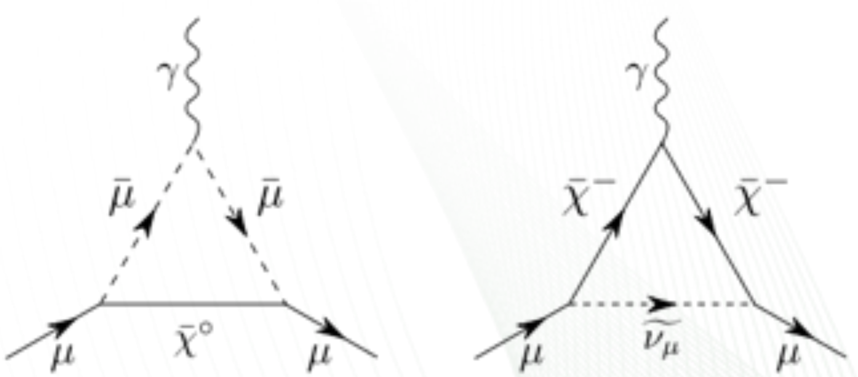
A precision test of the σ is a sensitive of test of new physics above the weak scale. Sensitivity to a hypothetical dark Z mediator, a possible explanation of the $(g\text{-}2)_\mu$ anomaly, can be reached with a 5% measurement.

$$\sigma_{coh} \sim \frac{G_f^2 E^2}{4\pi}(Z(4\ sin^2\theta_w - 1) + N)^2$$

Measurement with targets having different Z/N ratio is required.



Correction to g-2 for muon magnetic moment due to a light mediator



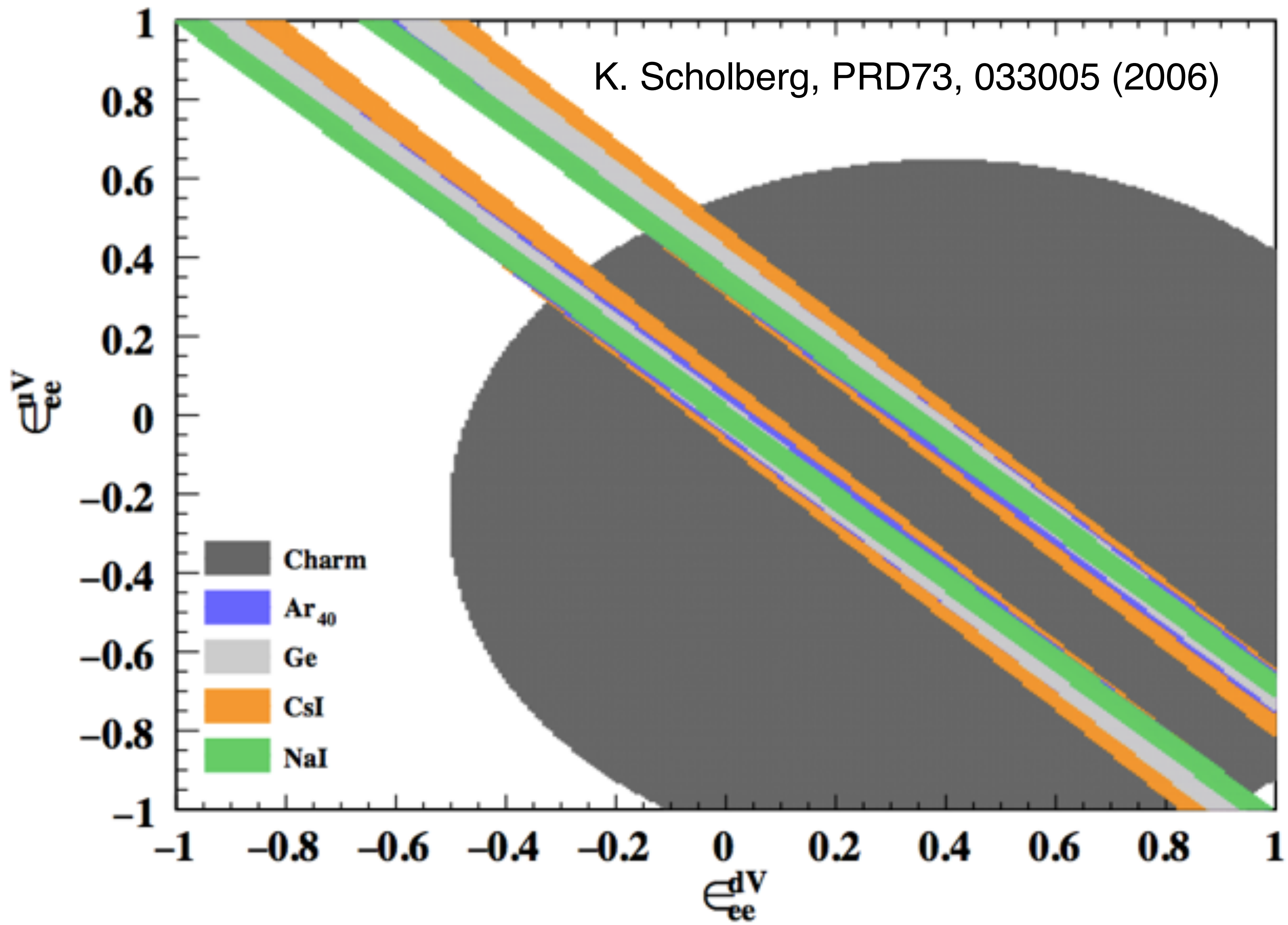
COHERENT

OAK RIDGE National Laboratory

Non-Standard Interactions of Neutrinos

new interaction **specific to ν's**

$$\mathcal{L}_{\nu H}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} [\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5)\nu_\beta] \times (\varepsilon_{\alpha\beta}^{qL}[\bar{q}\gamma_\mu(1-\gamma^5)q] + \varepsilon_{\alpha\beta}^{qR}[\bar{q}\gamma_\mu(1+\gamma^5)q])$$

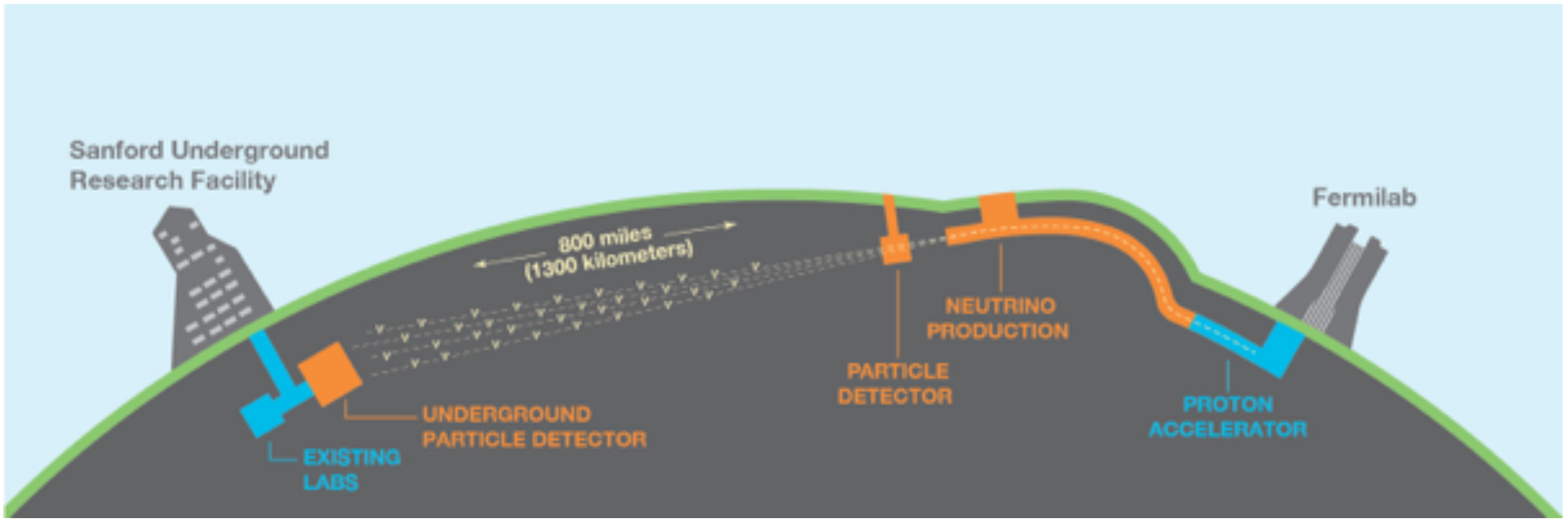


Can improve ~order of magnitude beyond CHARM limits with a first-generation experiment (for best sensitivity, want ***multiple targets***)

COHERENT SNS Spallation Neutron Source

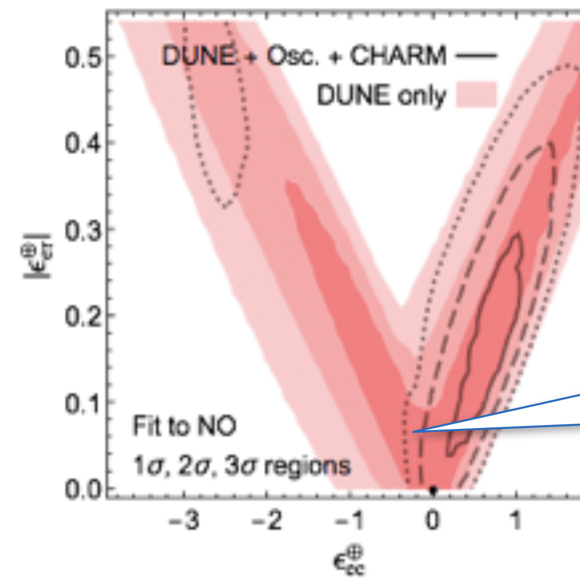
Oak Ridge National Laboratory

Non-Standard Interactions in DUNE



- Measuring the charge-parity (CP) violating phase CP
- Determining the neutrino mass ordering (the sign of Δm^2_{12})
- Precision tests of the three-flavor neutrino oscillation paradigm

FIG. 1: Results from a fit to simulated data for DUNE. We assume a true NO and no NSI, and perform a fit allowing for non-zero values of ϵ_{ee} and $\epsilon_{e\tau}$. In the upper panel we fit with the correct mass spectrum, while in the lower panel we adopt IO and exchange $\sin\theta_{12} \leftrightarrow \cos\theta_{12}$. The shaded regions correspond to DUNE alone, whereas the contour curves include the constraints from global oscillation data [7] and from the CHARM experiment [20] on the NC cross section. We marginalize over Δm^2_{31}, δ, θ_{23} and the complex phase of $\epsilon_{e\tau}$.

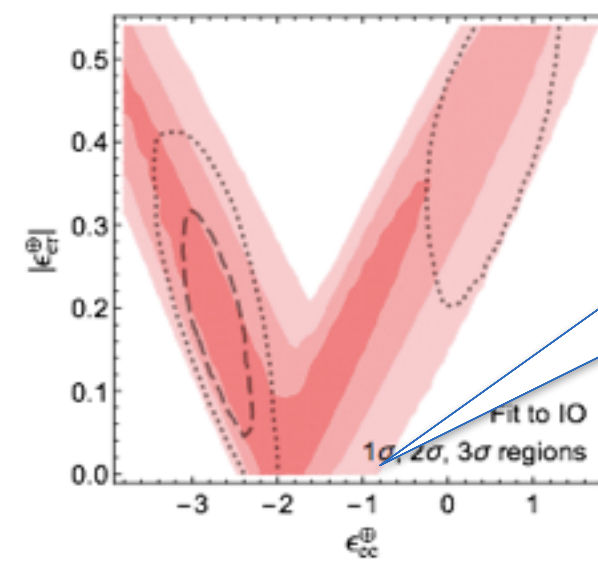


NO w/no NSI...

Generalized mass ordering degeneracy in neutrino oscillation experiments

Pilar Coloma[1] and Thomas Schwetz[2]

arXiv:1604.05772v1



...looks just like IO w/NSI

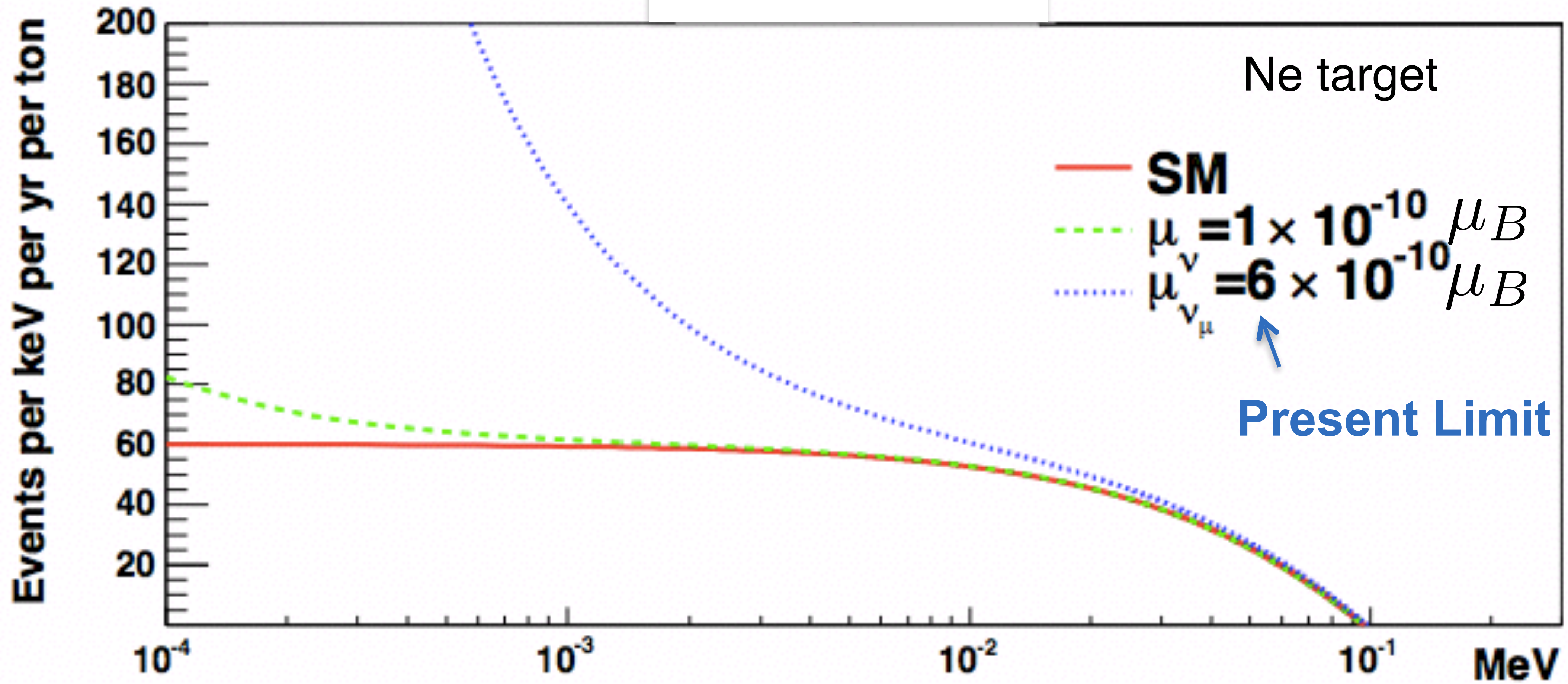
If you allow for NSI to exist, can't tell the neutrino mass ordering without constrains on NSI

See also Pilar Coloma et al. **Curtailing the Dark Side in Non-Standard Neutrino Interactions** arXiv:1701.04828

Neutrino Magnetic Moment

Signature is **distortion at low recoil energy E**

$$\frac{d\sigma}{dE} = \frac{\pi\alpha^2\mu_\nu^2 Z^2}{m_e^2}\left(\frac{1-E/k}{E} + \frac{E}{4k^2}\right)$$

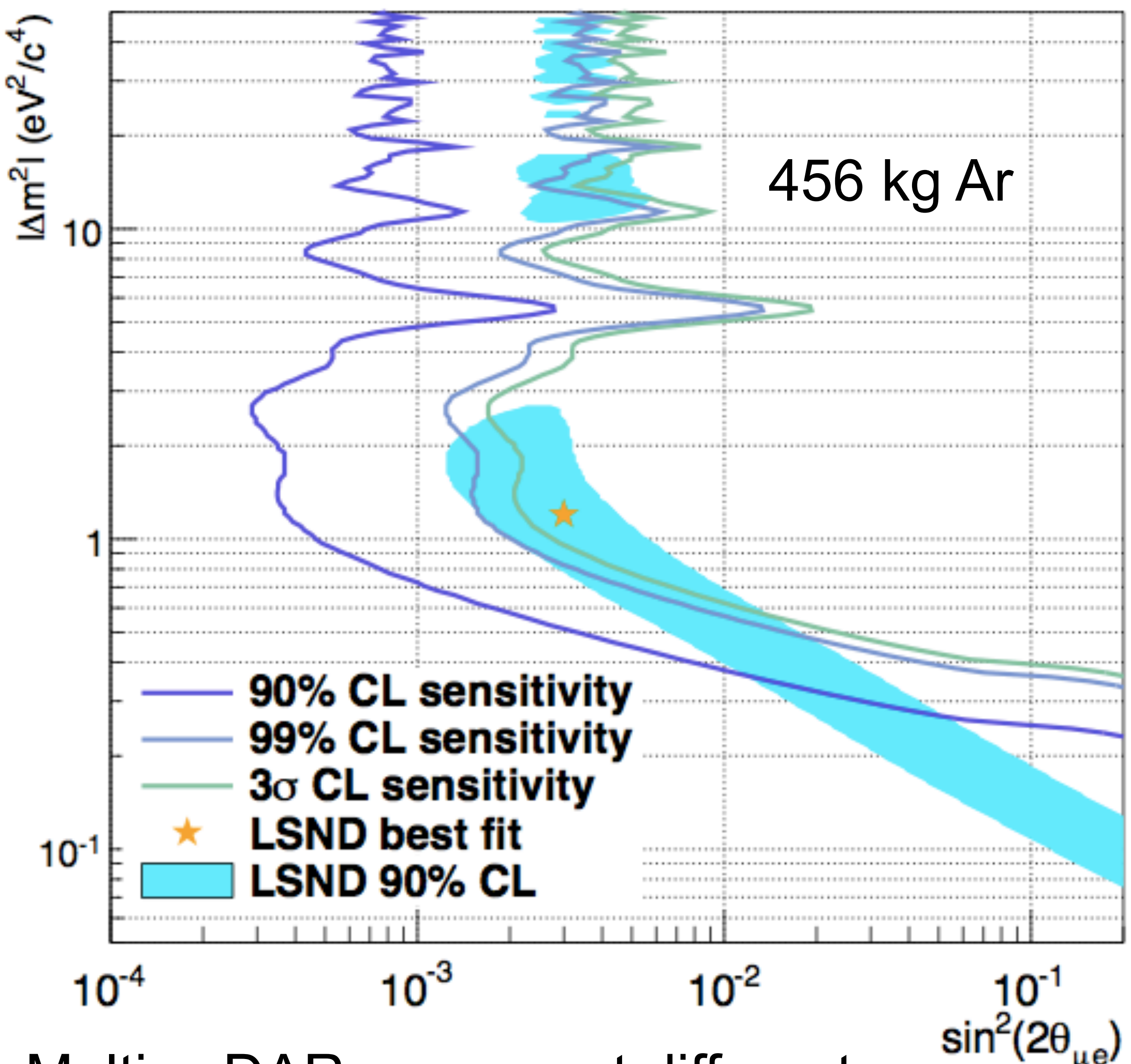


➔requires low energy threshold, well-understood quenching factors

See also Kosmas et al., arXiv:1505.03202

Oscillations to Sterile Neutrinos with CEvNS

Look for deficit and spectral distortion vs L,E



The development of a coherent neutrino scattering detection capability provides the most natural way to explore the sterile neutrino sector.

NC is flavor blind: A potential new tool!

A. Drukier & L. Stodolsky, PRD 30 (84) 2295

Multi-π DAR sources at different baselines (20 & 40 m)

A. J. Anderson et al., PRD 86 013004 (2012) arXiv:1201.3805

Nuclear physics with CEvNS

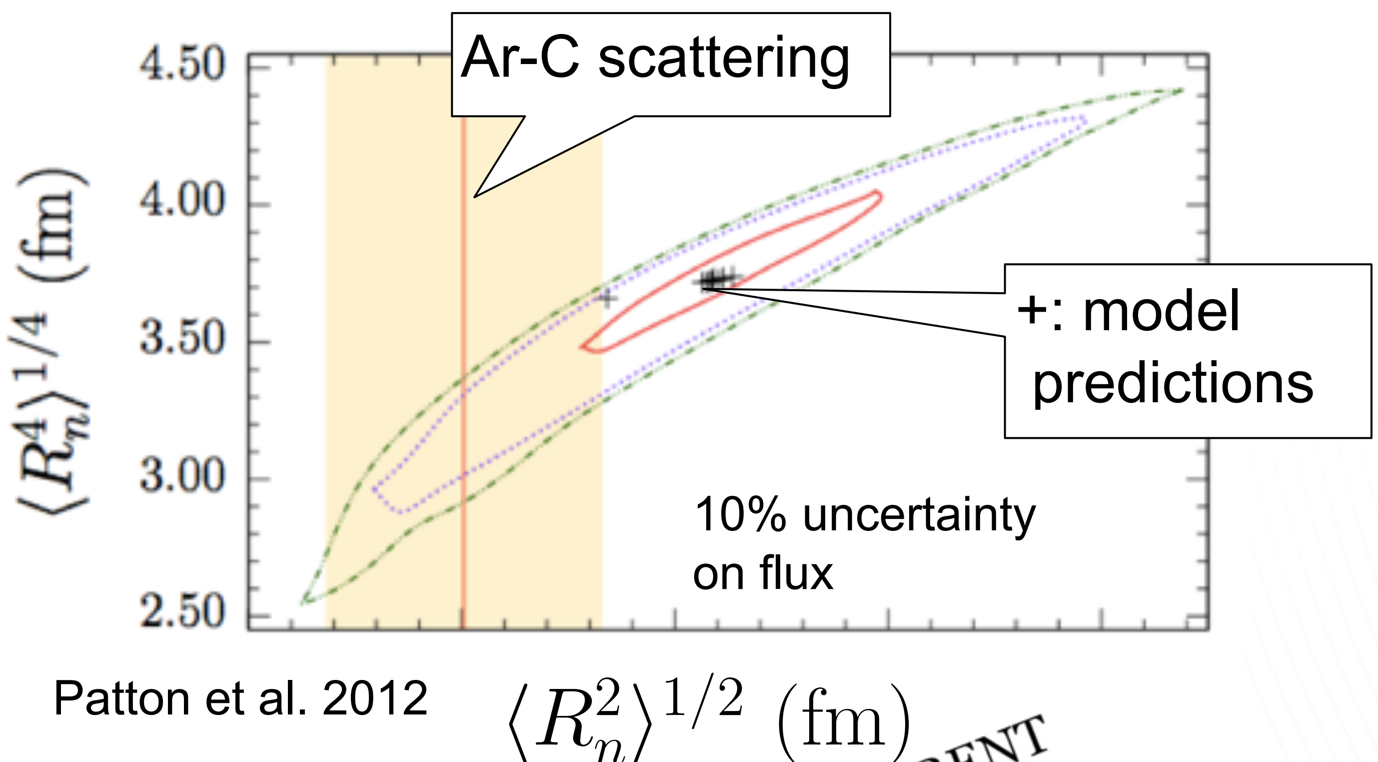
If systematics can be reduced to ~ few % level, we can start to explore nuclear form factors

P. S. Amanik and G. C. McLaughlin, J. Phys. G 36:015105
K. Patton et al., PRC86 (2012) 024612

$$\frac{d\sigma}{dT}(E,T) = \frac{G_F^2}{2\pi} M \left[2 - \frac{2T}{E} + \left(\frac{T}{E}\right)^2 - \frac{MT}{E^2}\right] \frac{Q_W^2}{4} F^2(Q^2)$$

Form factor: encodes information about nuclear (primarily neutron) distributions

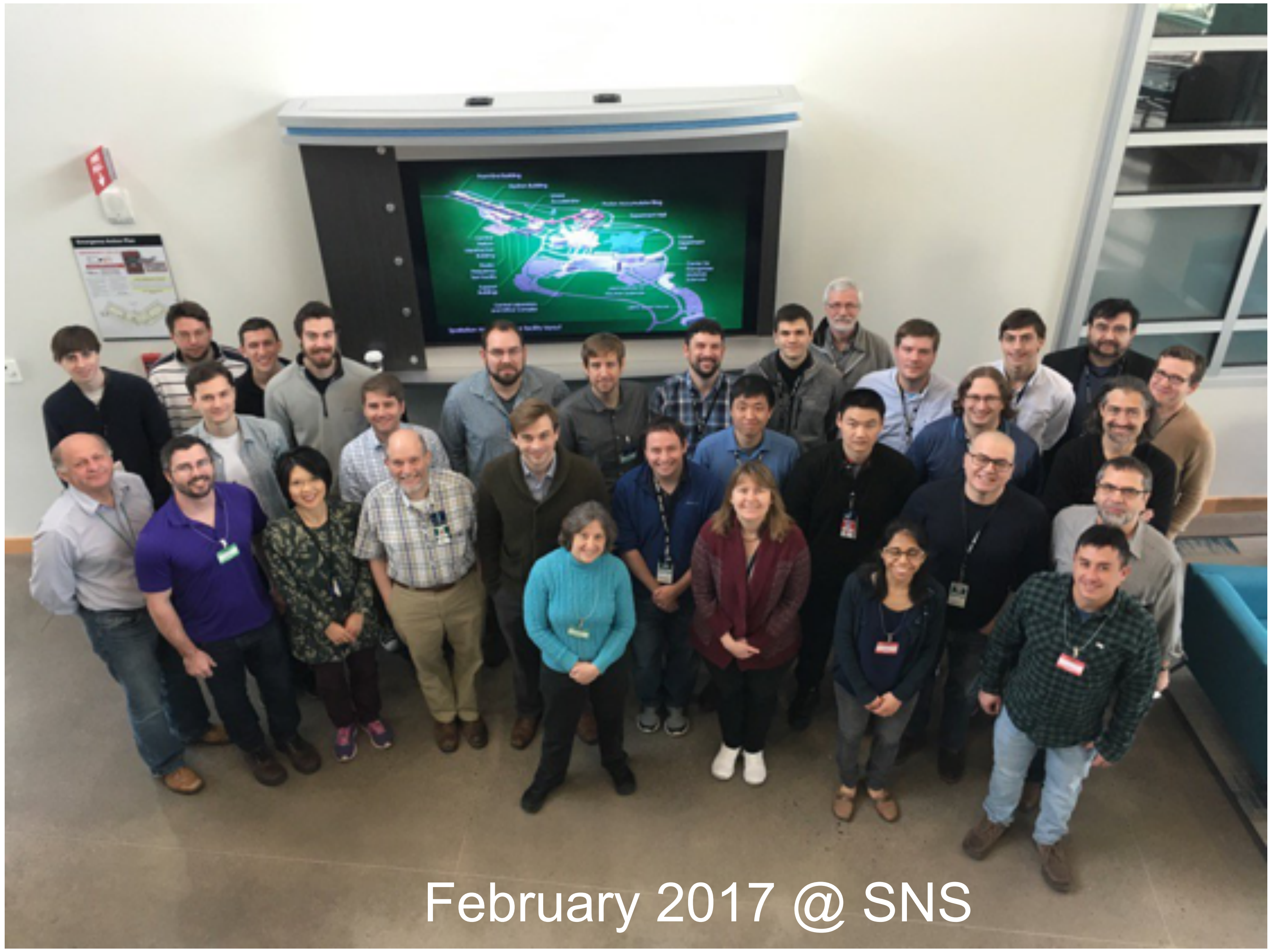
Fit recoil ***spectral shape*** to determine the $F(Q^2)$ moments (requires very good energy resolution,good systematics control)



Patton et al. 2012

Example: tonne-scale experiment

The COHERENT Collaboration



The primary goal of COHERENT is detection of CEvNS using the extremely clean, pulsed stopped-pion flux at SNS.

19 Institutions

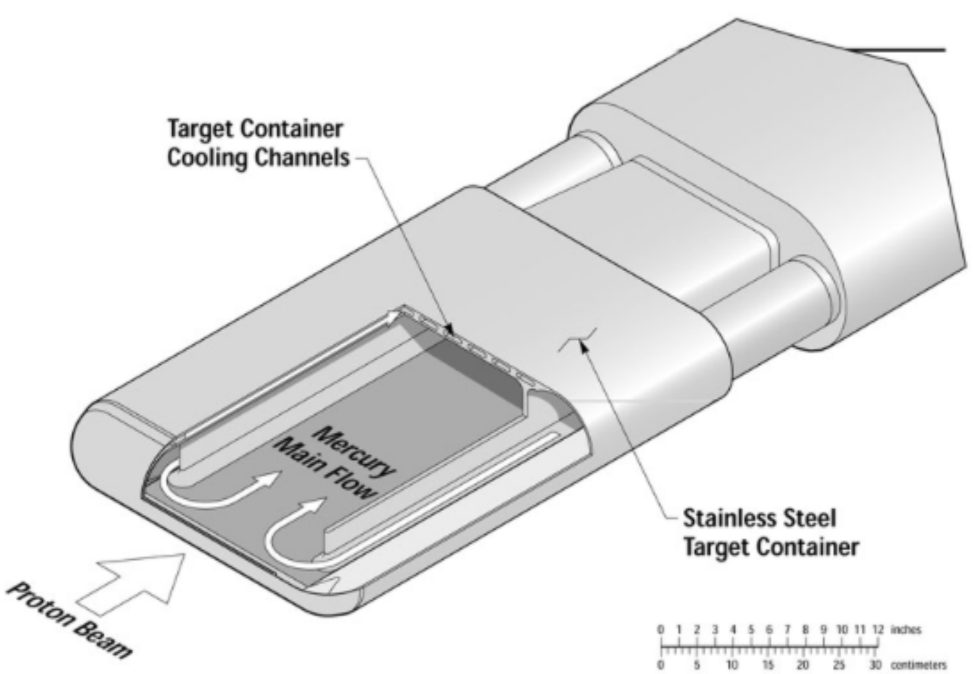
(USA, Russia, Canada, Korea)

https://sites.duke.edu/coherent/

arXiv:1509.08702

Spallation Neutron Source

Oak Ridge National Laboratory, TN

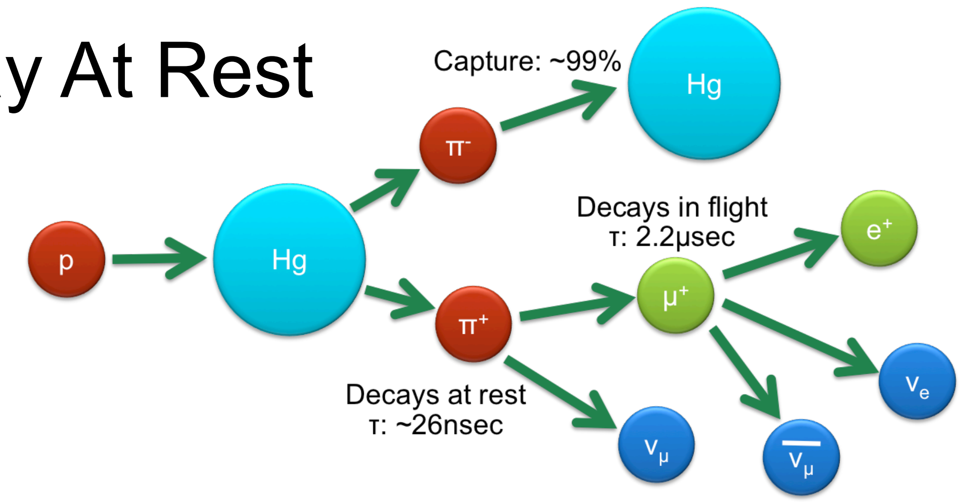


Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target
5000 hours/year

Neutrinos at the SNS

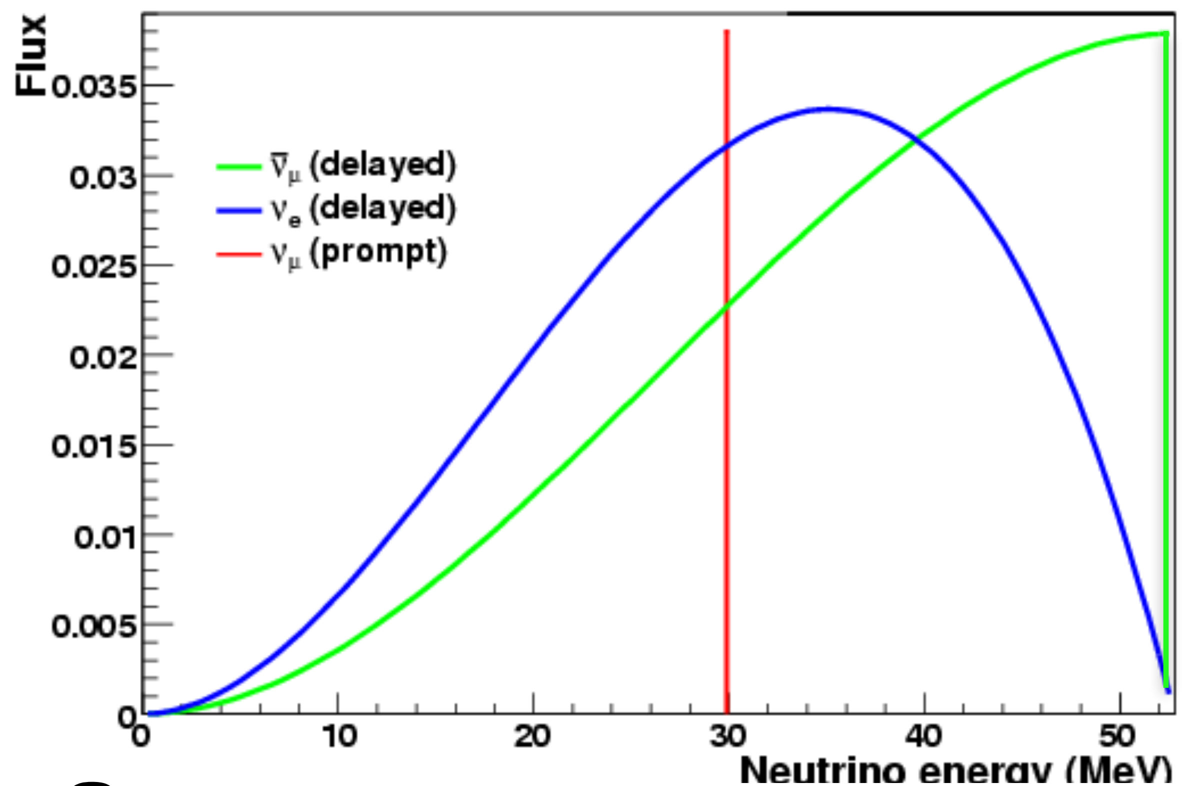
Neutrinos via

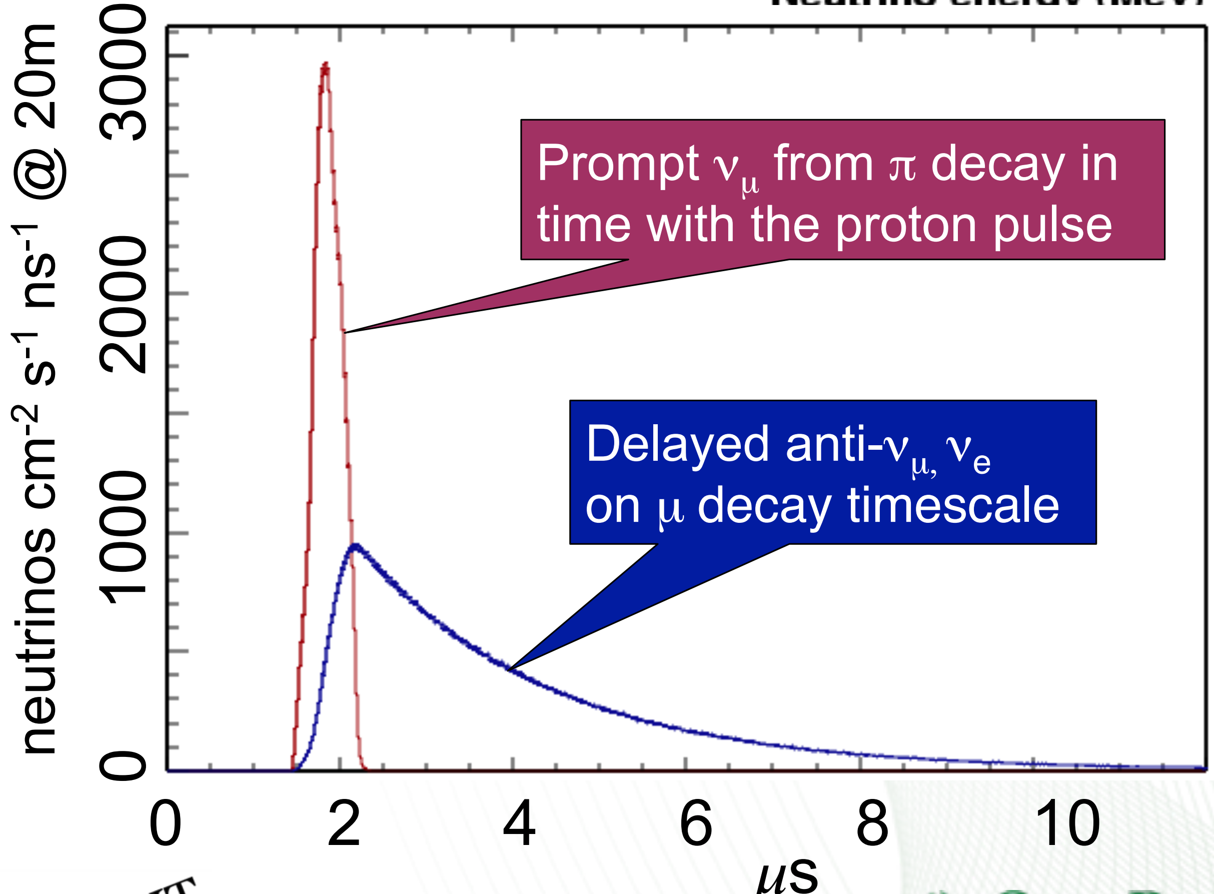
π Decay At Rest



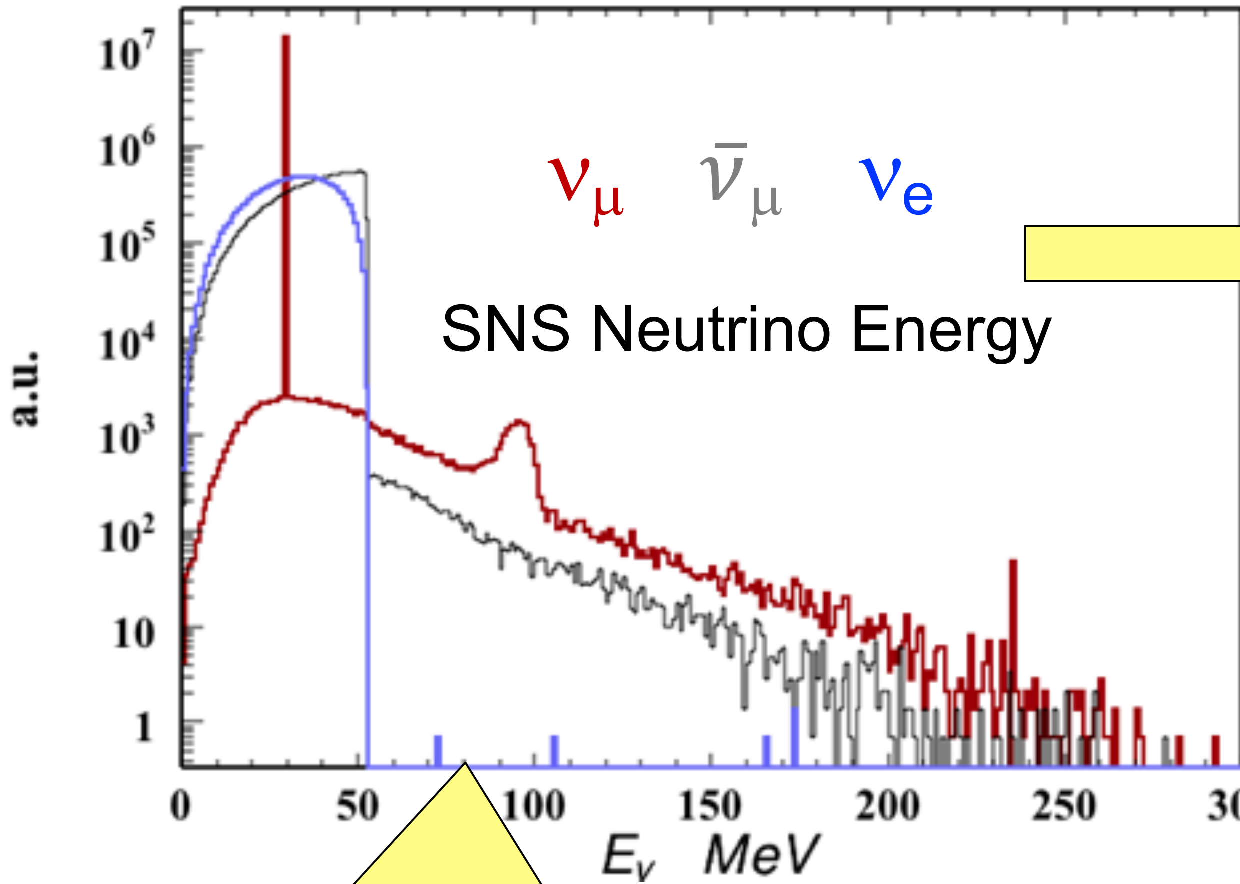
- High Intensity (10^7/s/cm^2 @ 20m)
- Ideal Neutrino Energy →Coherence
- Ideal Beam Energy
- Complete Stopping: Pointlike source
- Multiple Neutrino Flavors: ν_e, (anti)ν_μ
- Prompt & delayed neutrinos provide additional handle for systematic errors
- Ideal Time Structure (Short Pulses)

Background rejection factor ~few x 10^4

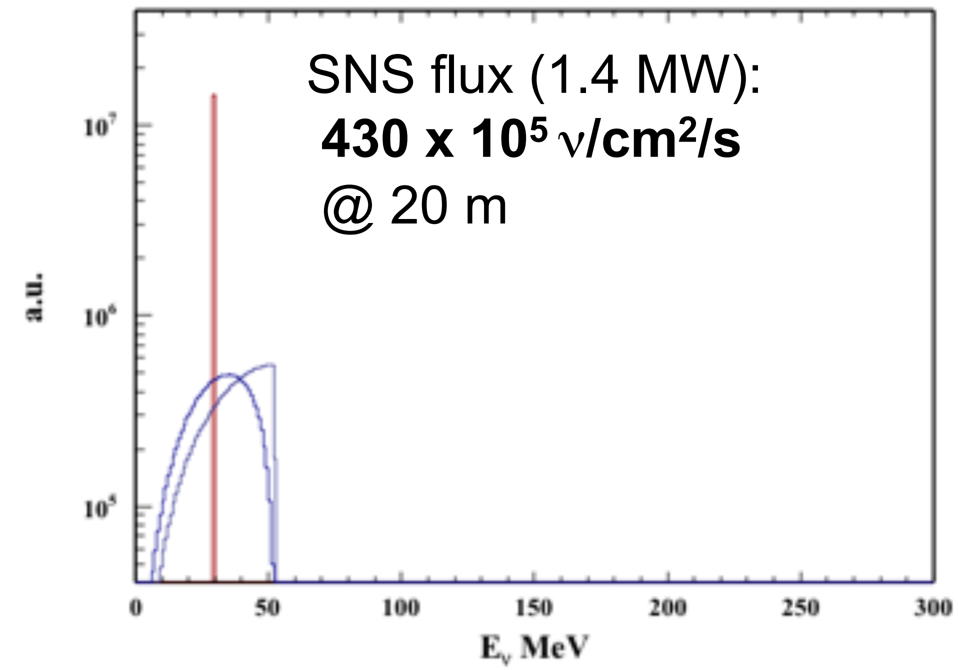


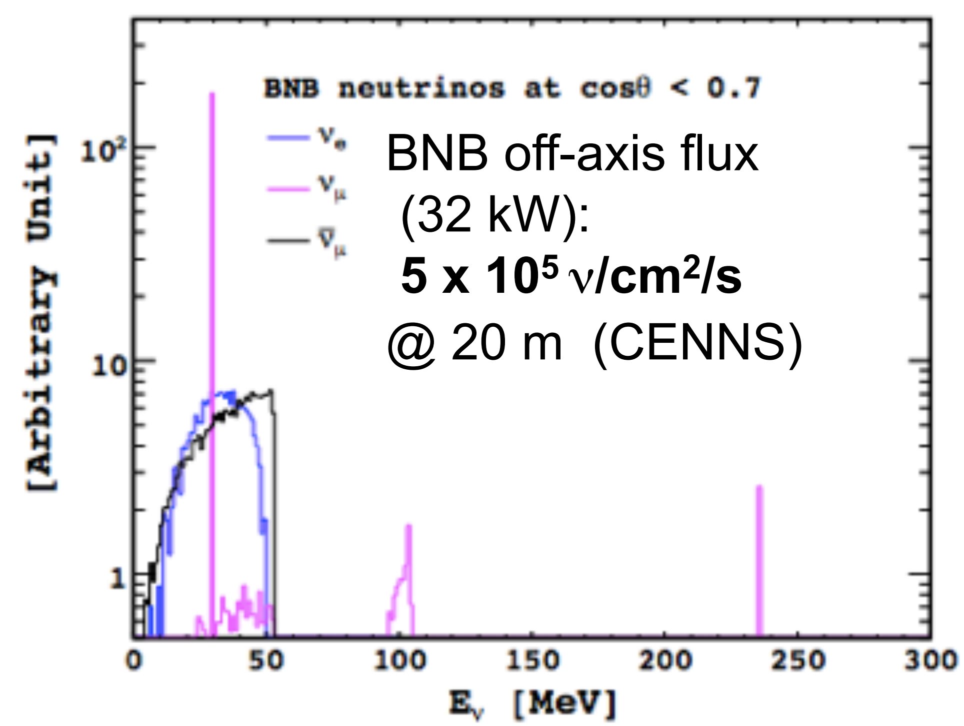


The SNS DAR neutrino flux is large and extremely clean



Note that contamination from
non π-decay at rest
(decay in flight, kaon decay, μ capture...)
is **down by several orders of magnitude**

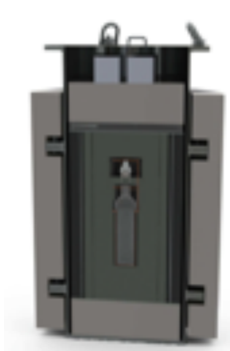




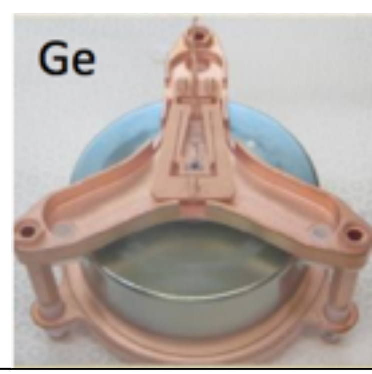
COHERENT Phase I Overview

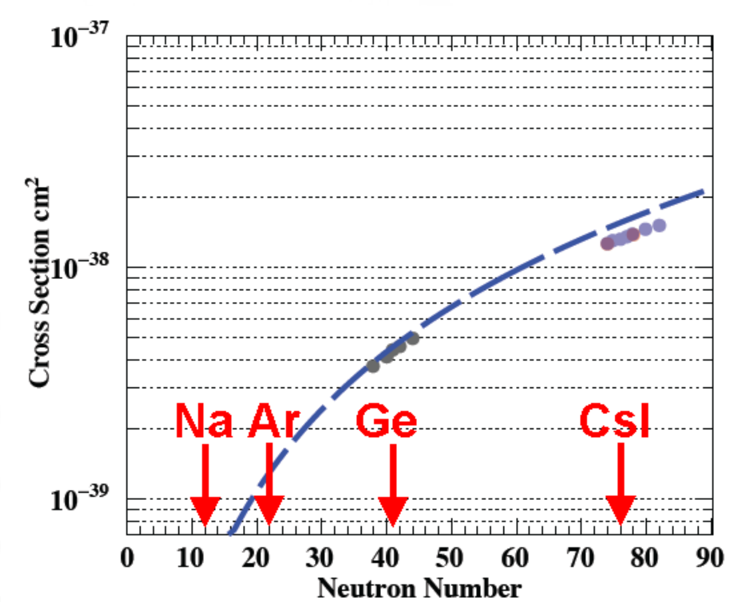
- Unambiguous first observation from the N^2-dependence of the CEvNS cross-section in multiple targets.

Nuclear Target	Technology	Mass (kg)	Target Distance (m)	Recoil threshold (keVr)	Data-taking start date; CEvNS detection goal
CsI[Na]	Scintillating Crystal	14	20	6.5	9/2015; 3σ in 2 yr 6 GW·hr Recorded
Ge	HPGe PPC	10	22	5	Install Spring 2017
LAr	Single-phase	28	29	20	Installed 12/2016
NaI[Tl]	Scintillating Crystal	185*/2000	28	13	*high-threshold deployment summer 2016



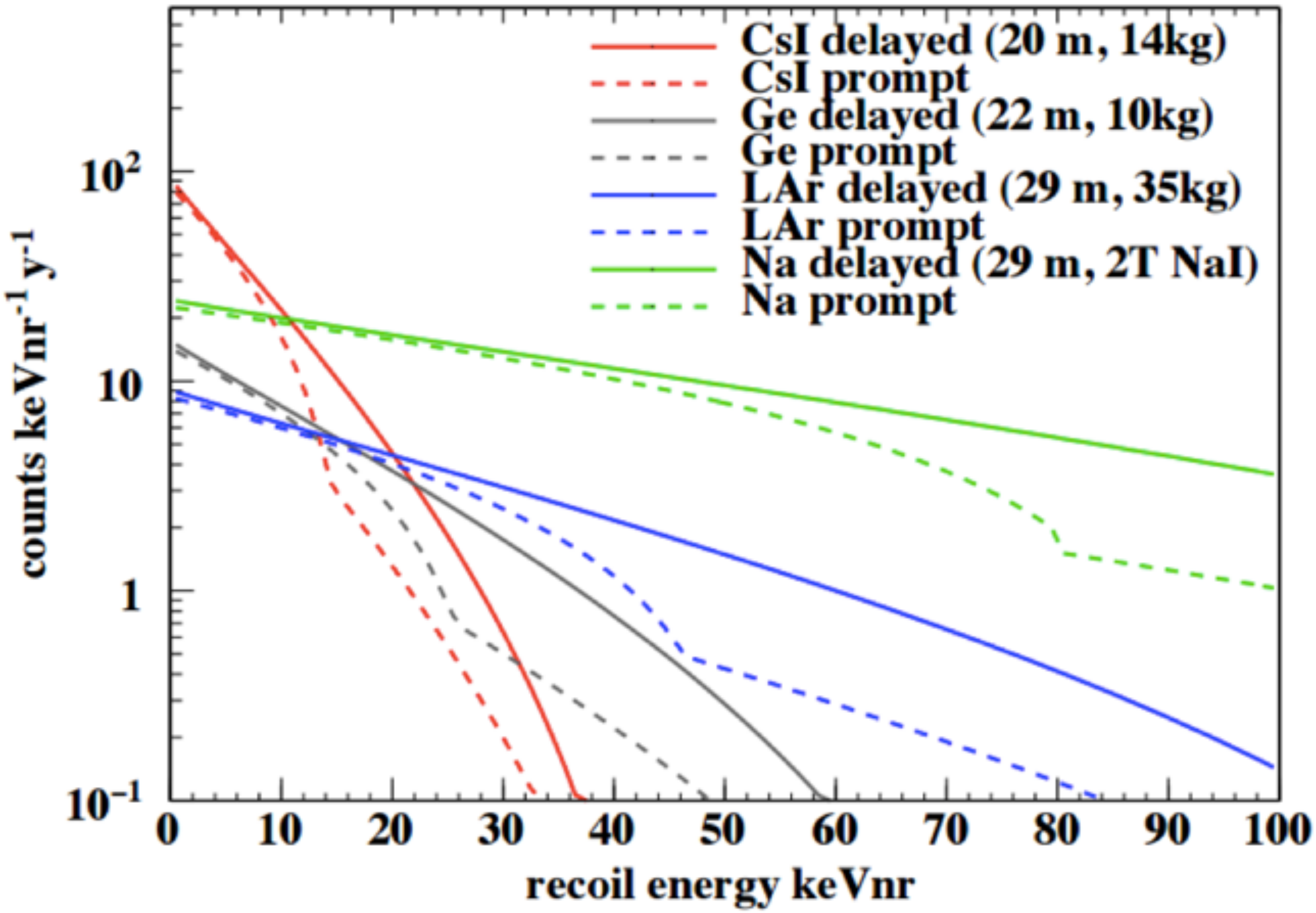
CsI(Na)





- 100's CEvNS detections expected per year
- Experimental Challenges
  - Backgrounds, Quenching Factors, Thresholds

COHERENT Phase I
Expected Recoil Signals



Prompt defined as first μs;
note some contamination from ν_e and ν_μ-bar

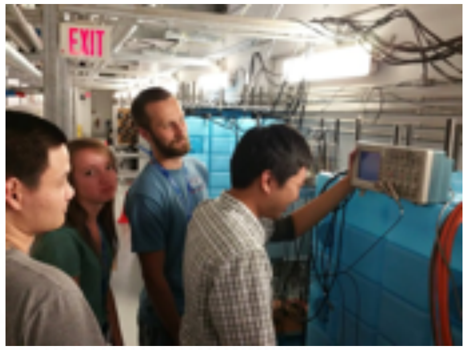
COHERENT Activities at the SNS

- June 2013 First proto-collaboration meeting @ SNS
- Aug 2013 Target Floor Background Measurements
- May 2014 Basement Background Measurements
- Sep 2014 Neutrino Induced Neutrons Measurements
- July 2015 First CEvNS Detector Installed (CsI 14kg)
- Aug 2015 SciBath Installed in the Basement
- Jan 2016 Pb Nube (NINs) Commissioned
- Sep 2016 NaI (185kg) High Threshold Operation
- Dec 2016 Liquid Argon Installed and Operating
- Feb 2017 Fe Nube NINs Installed

Scatter Camera

SciBath

CsI

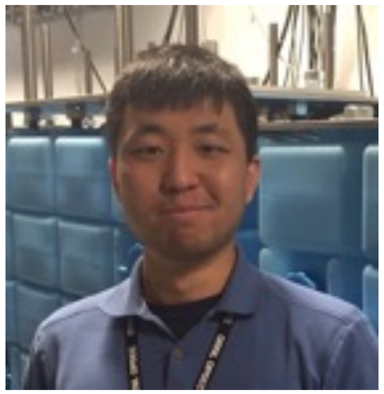


NaI

Much of this work accomplished by students and postdocs working at ORNL.

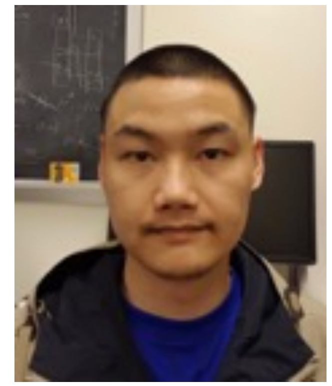
COHERENT Students and Postdocs Working @ SNS


Grayson Rich
Duke

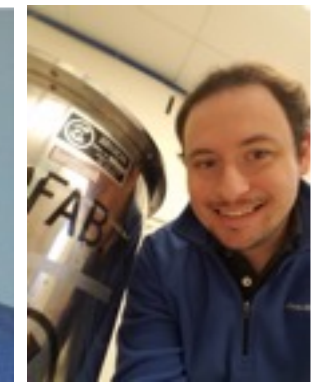

Ben Suh
ORNL


Justin Raybern
Duke


Sam Hedges
Duke

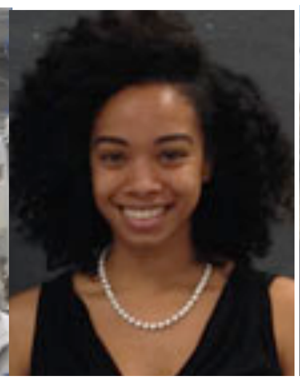

Long Li
DUKE

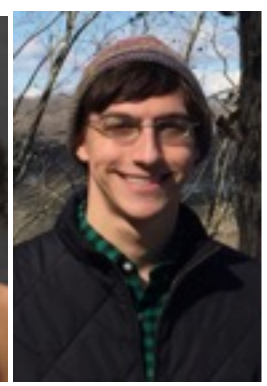

Brandon Becker
UT

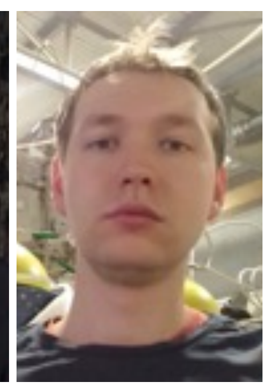

Jacob
Zettlemoyer IU


Conner Awe
Duke


Alexey
Kanovalov
MEPhI

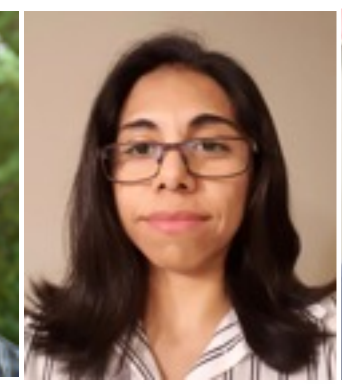

Katrina
Miller
Duke


Matt Heath
IU


Alex Kromov
MEPhI


Bjorn Scholz
U of Chicago


Gleb Sinev
Duke

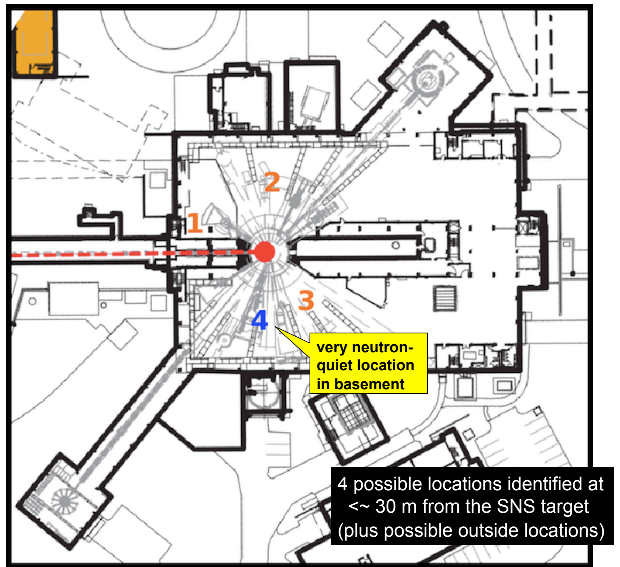

Mayra Cervantes
Duke (Postdoc)

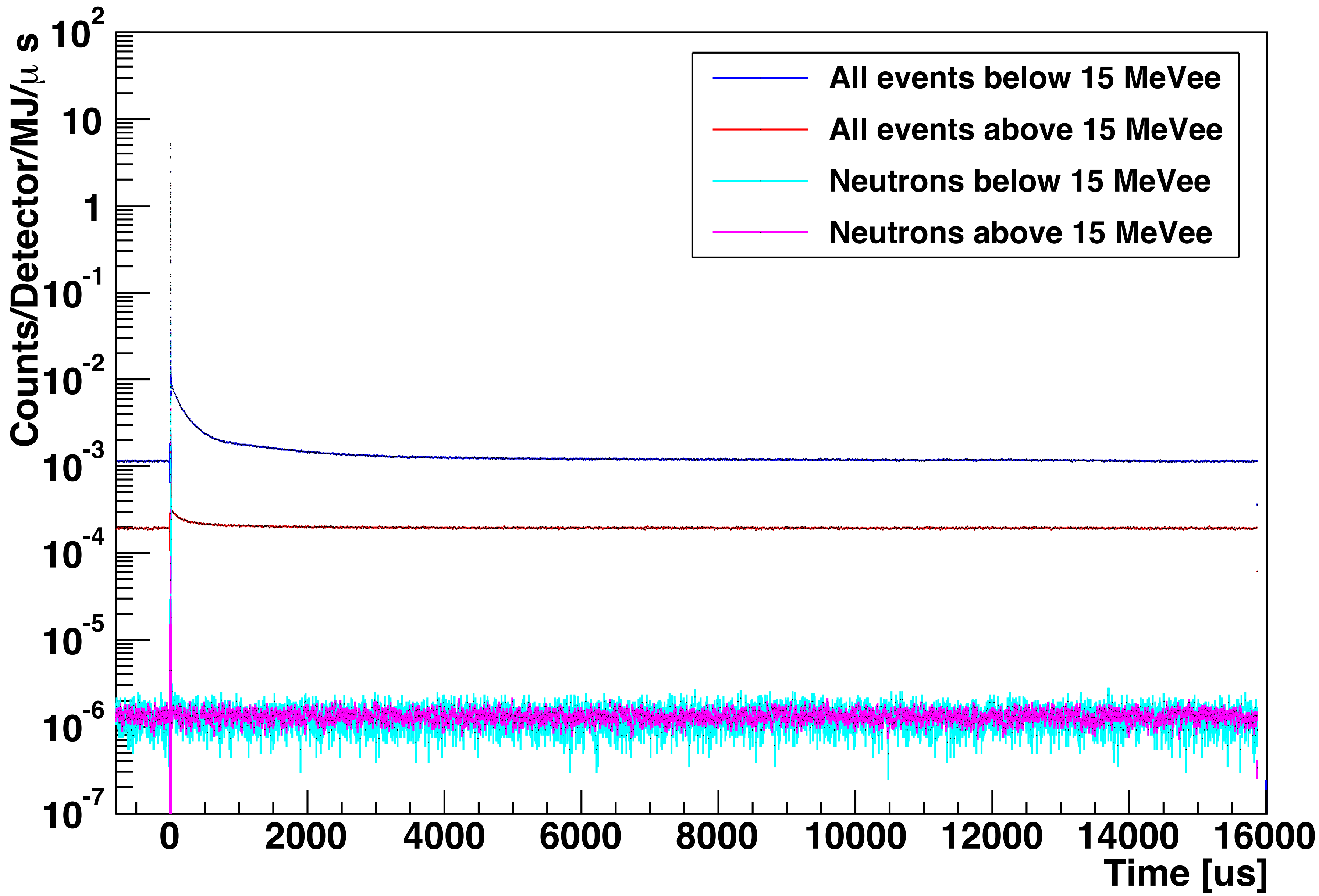

Ivan Tolstukhin
IU (Postdoc)


Josh Albert
IU (Postdoc)

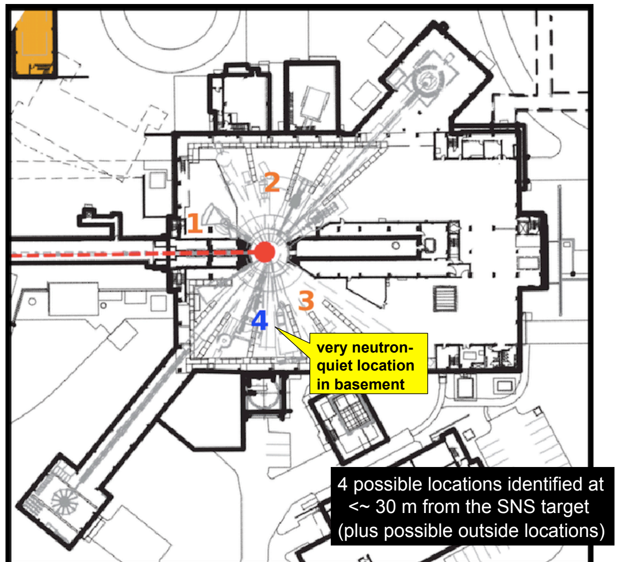
All above have worked at ORNL for multiple weeks or months and four will be resident for more than 1 year.

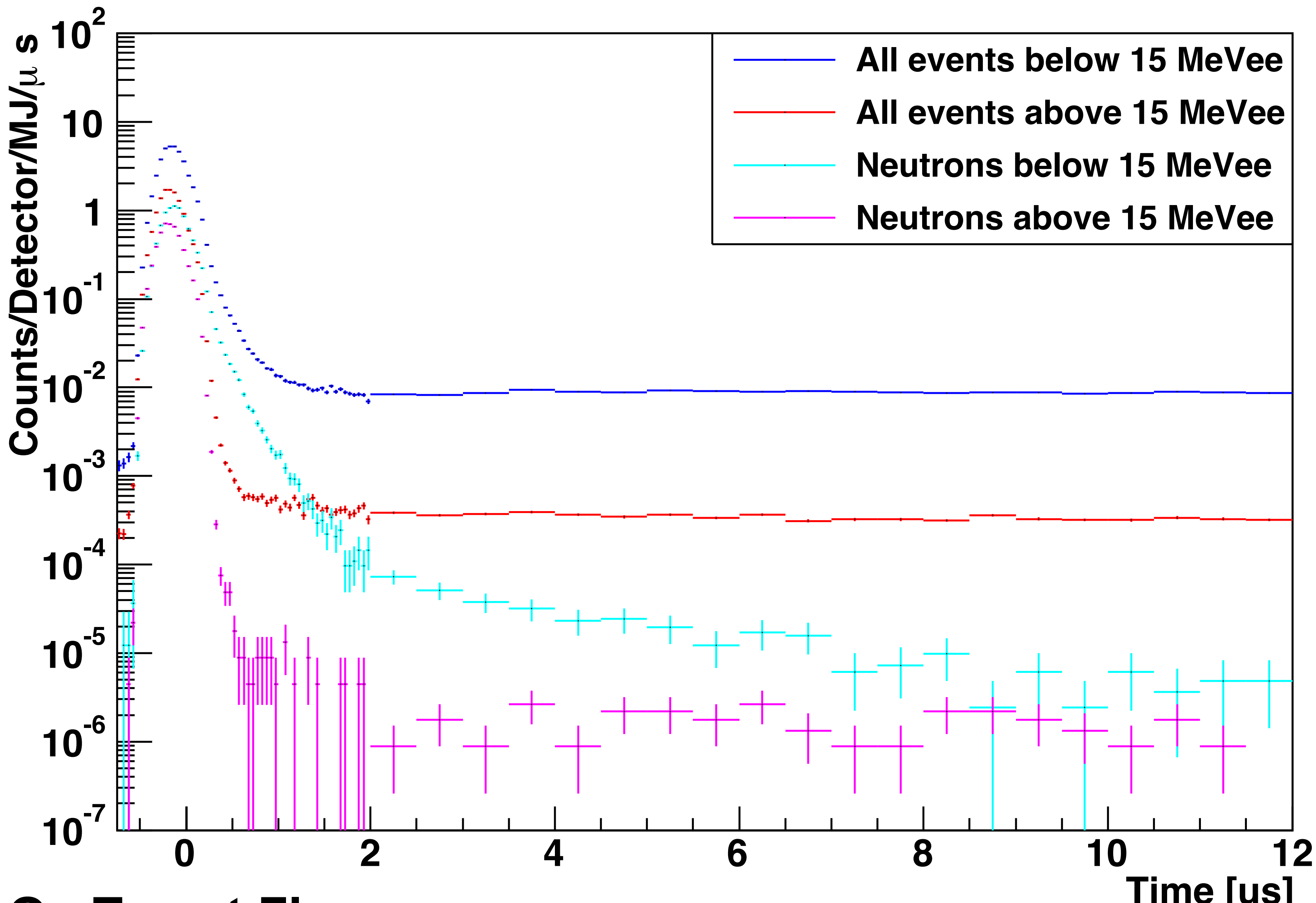
Initial Siting Backgrounds Measurements





Initial Siting Backgrounds Measurements



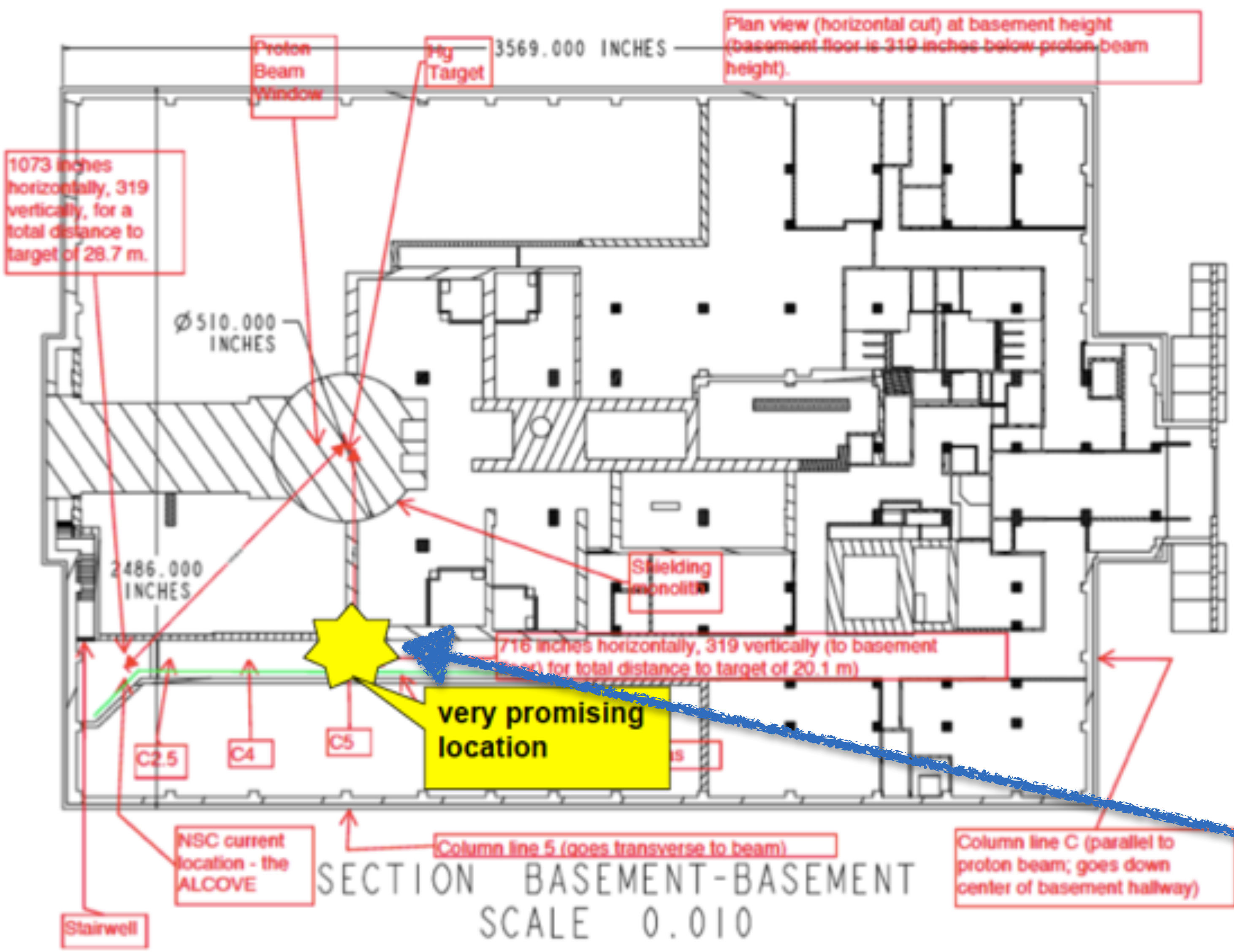


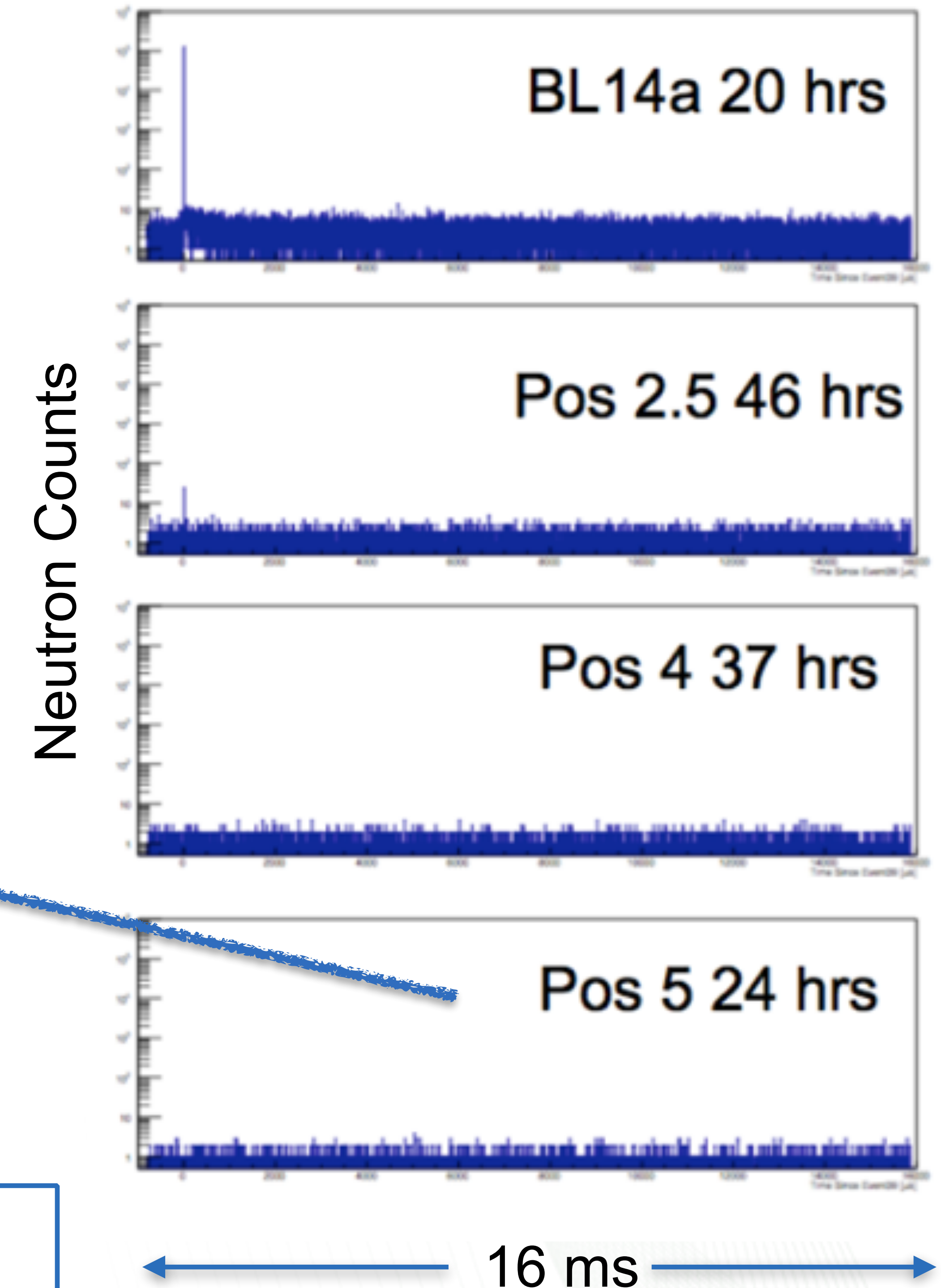
On Target Floor

Intense burst of fast neutrons 10^5 above nominal.

Most energetic neutrons limited to the prompt flash.

Explore an option in the SNS Basement

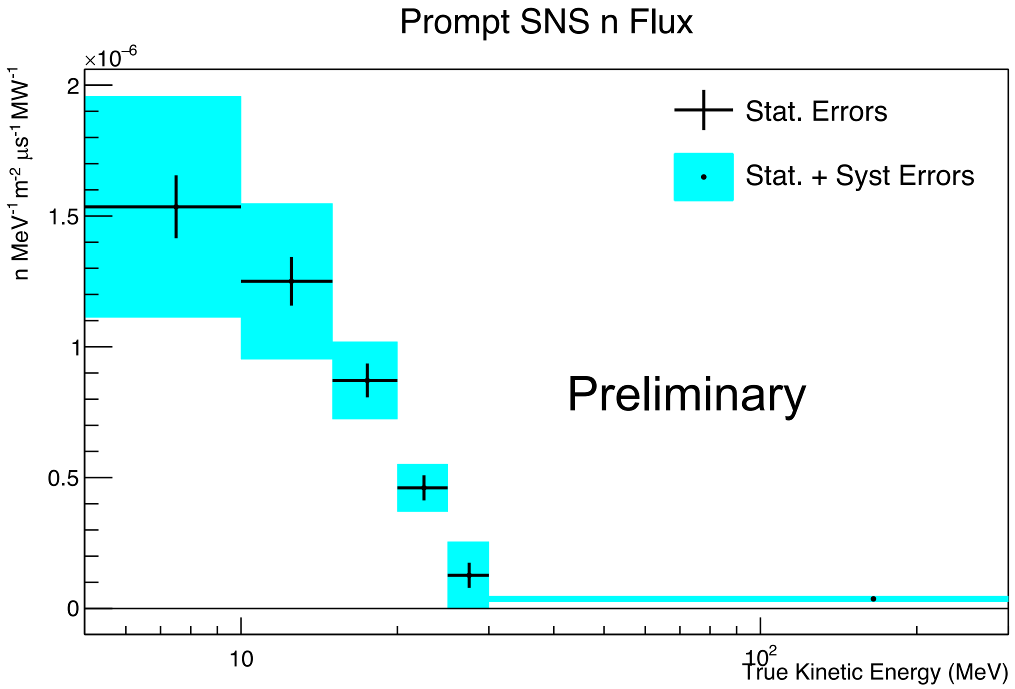




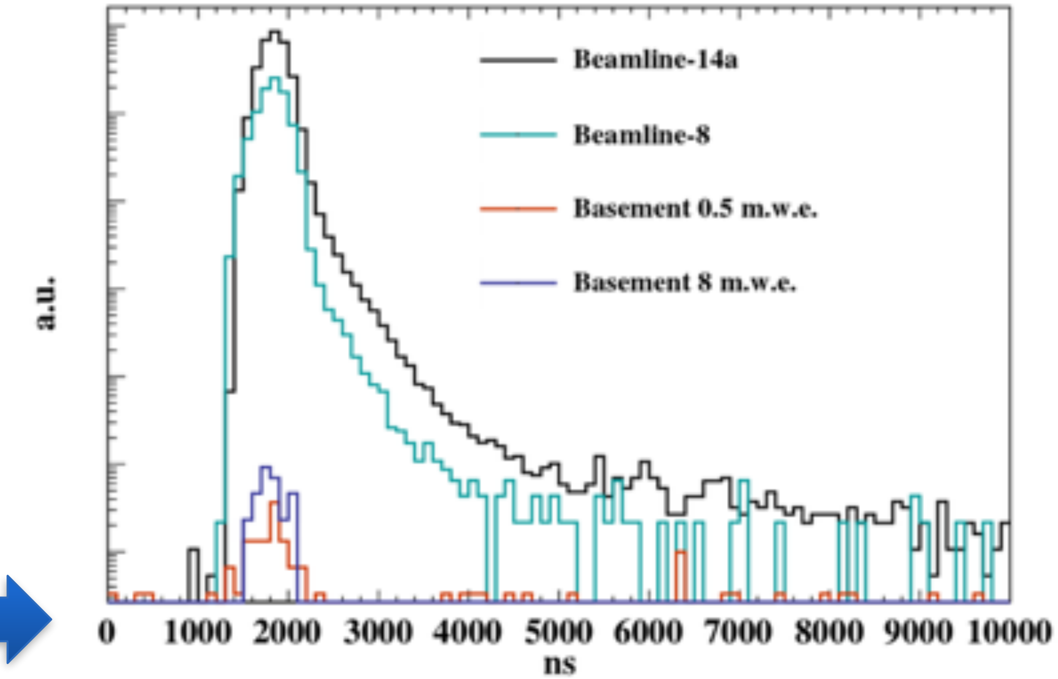
Pos 5 is location with very low neutron flux.

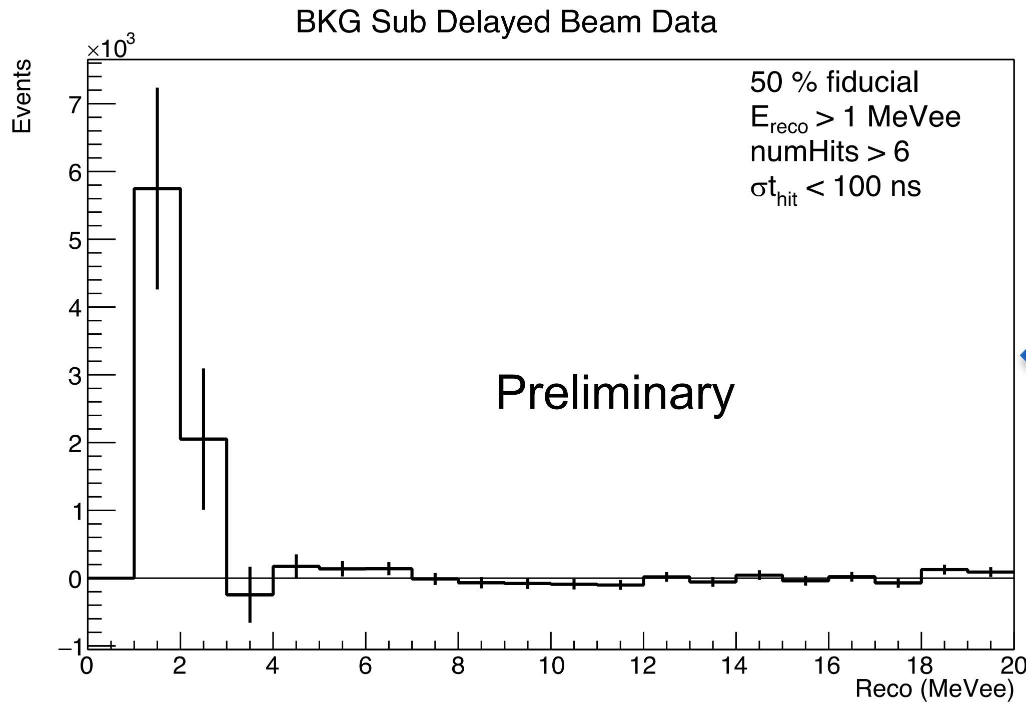
Basement corridor is now called Neutrino Alley

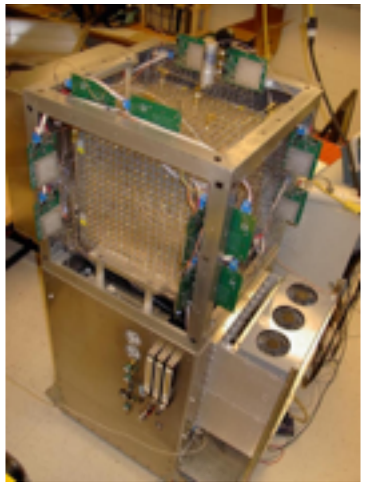
Measured Fast Neutron Spectra in Neutrino Alley



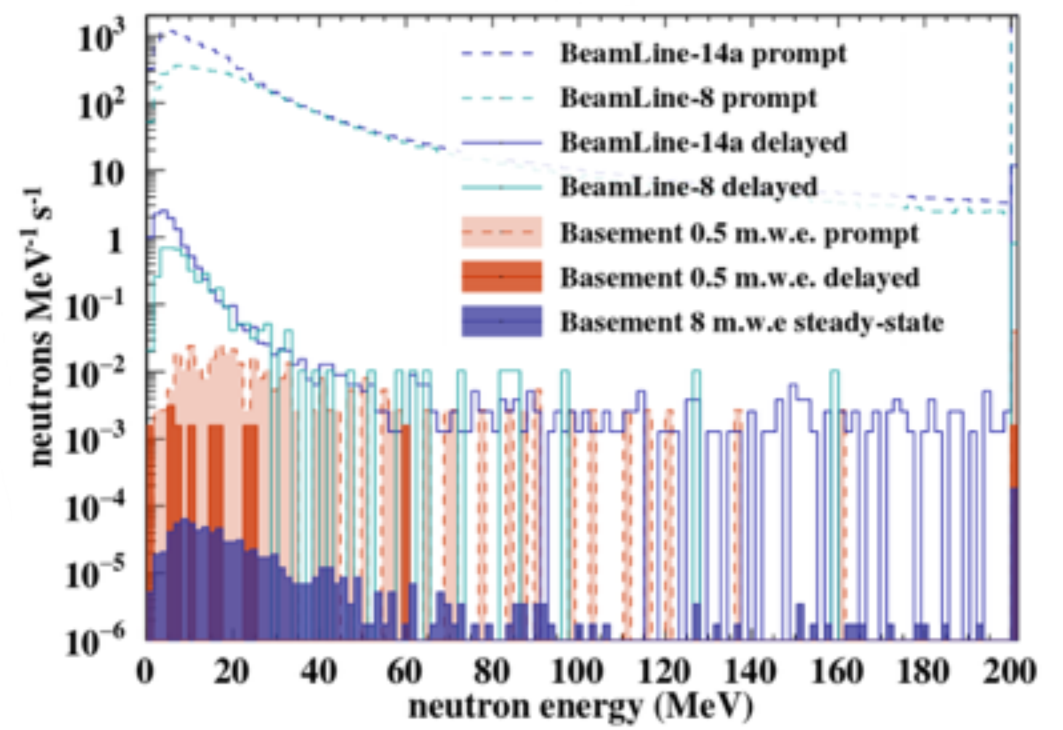
Sandia Scatter Camera



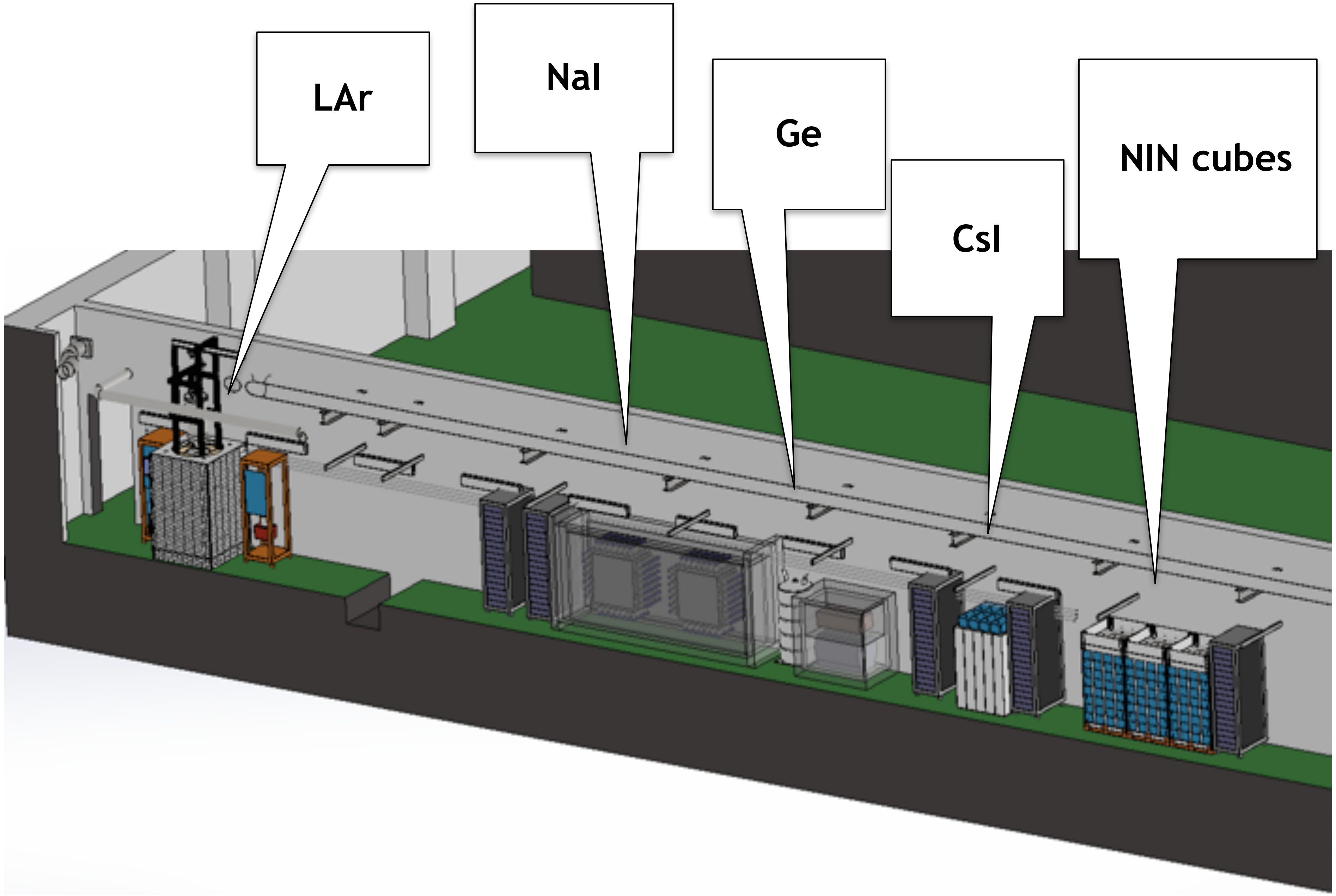




IU SciBath



Neutrino Alley at the SNS

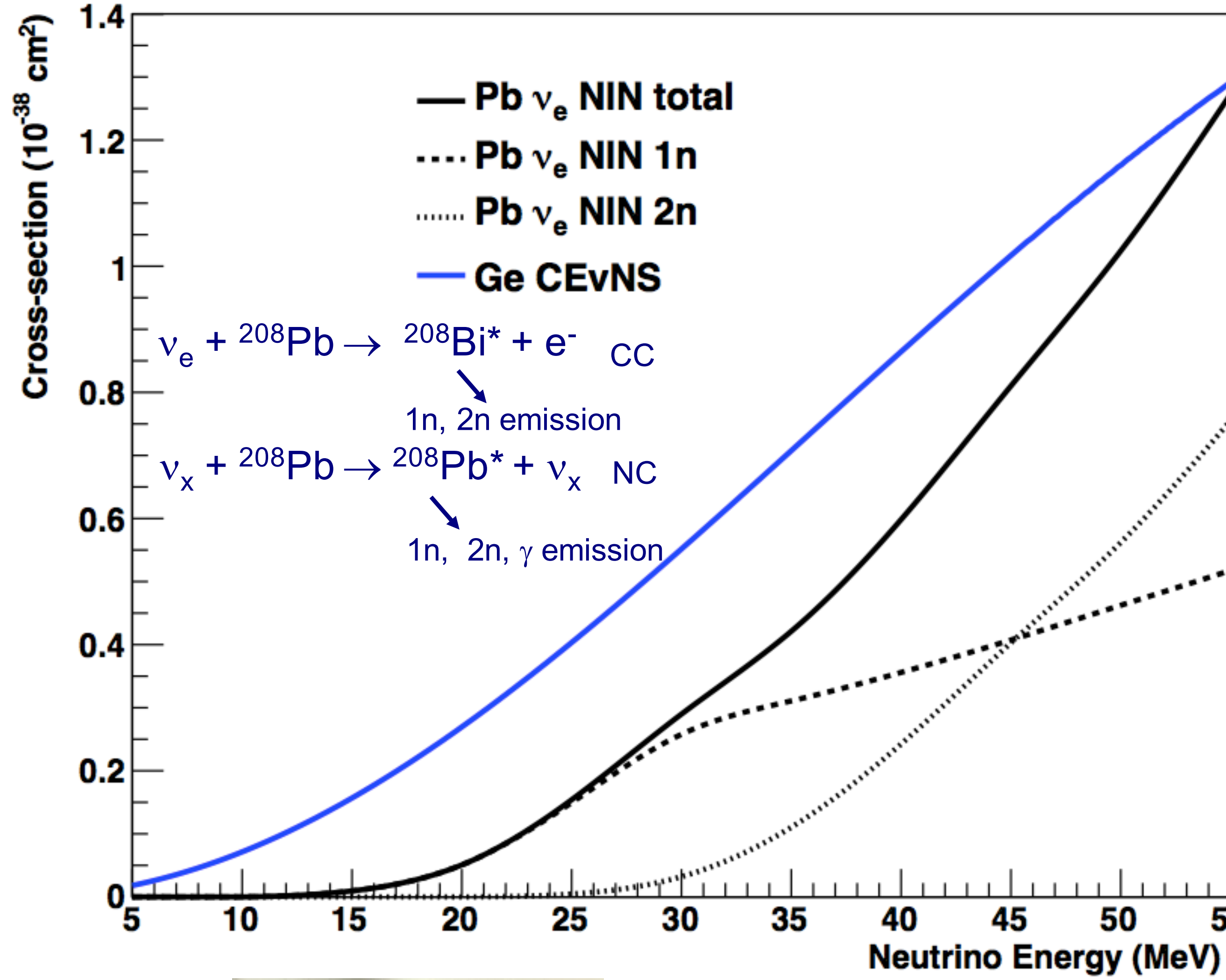


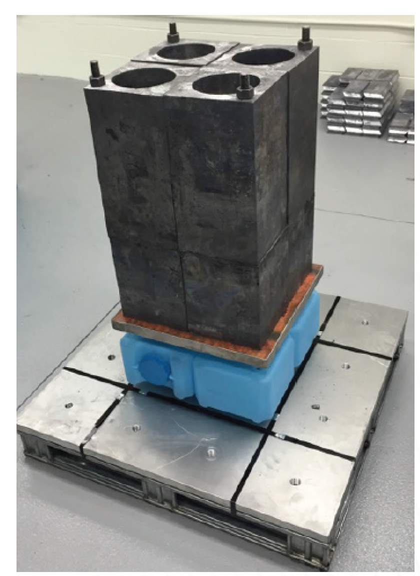
Basement location is far away from Neutron beam Lines.
Extra protection from cosmic rays (8 mwe).

First Step: Measure Neutrino Induced Neutrons

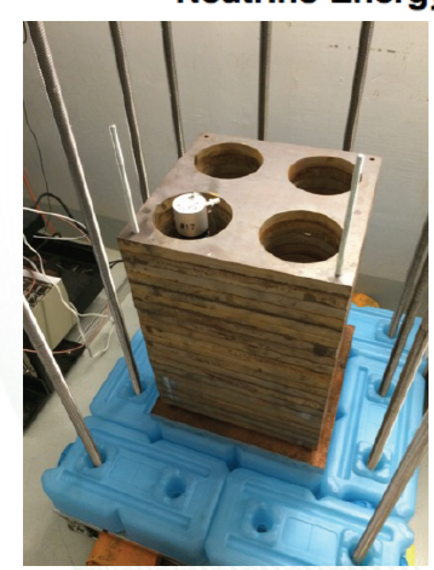
- Background for CEvNS measurement.
- Used by HALO experiment in the SNOlab, to watch for supernovae.

- First Neutrino Experiment at the SNS!
  - Never measured.
  - Liquid Scintillator detectors inside Lead, Poly, Cd, Water shield with muon veto. (U of Chicago)
  - Total of 175 days of “beam”
  - Did not seen anything above background … consistent with expectation.
  - This is a good news for us!
- Dedicated long term experiment now running with Pb (1ton) and Fe(700kg) targets. (Duke)





Pb (1ton)



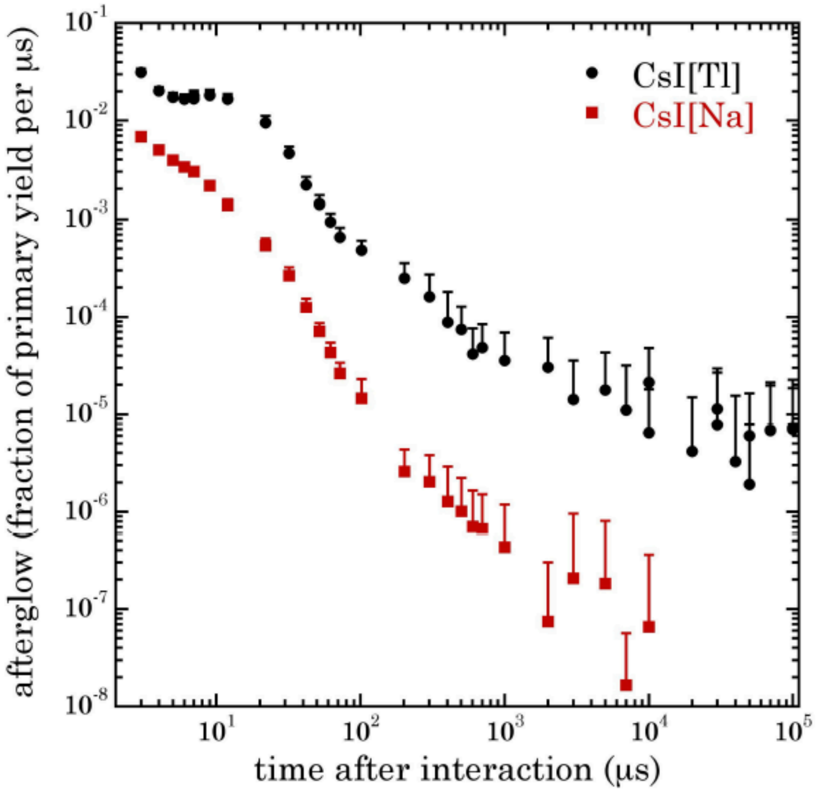
Fe (700 kg)

COHERENT SNS Spallation Neutron Source

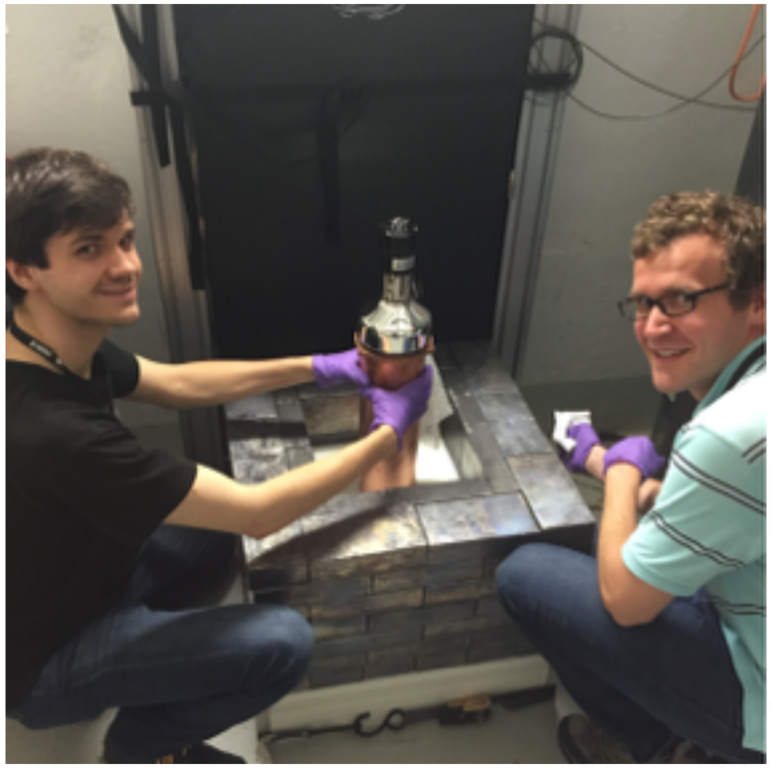
Oak Ridge National Laboratory

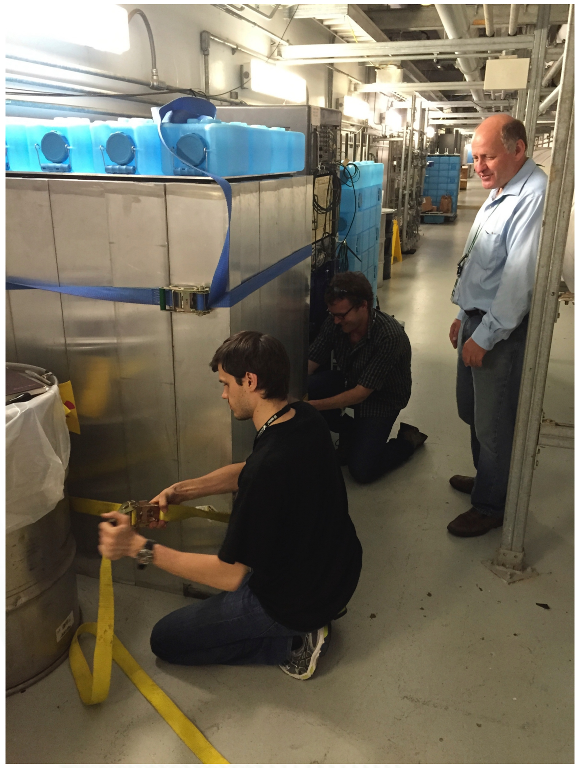
COHERENT CsI

- 14 kg CsI[Na] crystal
- Na doping reduces afterglow seen in more common Tl doping
- Commissioned at SNS in July 2015
- Shielding structure includes lead, water, and plastic
- Quenching factor measurements recently performed at TUNL
- Steady-state backgrounds at SNS installation site less than measurements taken at Chicago
- Neutrino-Induced-Neutrons reduced to ~4% of CEvNS including HDPE shielding
- SM:~100 CEvNS neutrinos on disk?
- Two blind analyses underway
  - Bjorn Scholz (U of Chicago)
  - Alexey Konovalov (MEPhI/ITEP)



J.I. Collar et al. Nucl.Instrum.Meth. A773 (2015) 56-65





6GW·h of data recorded, this is 1.4*10^{23} POT or 0.22 grams of protons

Liquid Argon Detector Installed and Operating

OAK RIDGE
National Laboratory

PO Box 2008
Oak Ridge, TN 37831-6492
(865) 566-1030 | johnsgd@ornl.gov

Date: December 2, 2016

Ref: NSCD-RAD-16-0007-R00

To: R. J. Newby, Nuclear Science and Engineering Directorate

c: K. W. Jones, SNS Operations Manager
H. R. Vogel, Neutron Sciences Directorate
B. L. Cross, SNS Instrument Operations Manager
M. B. Farrar, Nuclear Science and Engineering Directorate
D. J. Dean, Physics Division

From: G. D. Johns, SNS Operations Manager (Acting)

Subject: **Authorization for Coherent experiment including usage of liquid argon**

References:

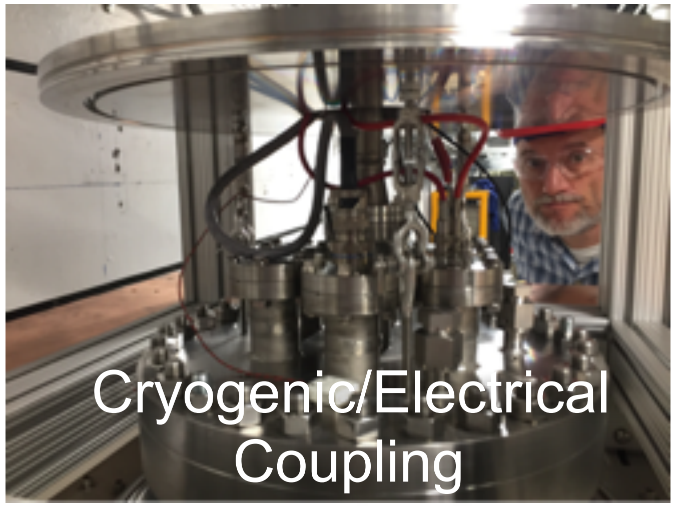
1. Memorandum SNS-NSCD-SC-MO-0022-R00, "ISSC Review of the Coherent Experiment" from G. Johns to K. Jones dated December 2, 2016.
2. SNS-OPM-6.U-7, "Coherent Experiment," Completed December 2, 2016.
3. SNS-NSCD-SC-RA-0018-R00, "ISSC Review of the Coherent Experiment," dated November 29, 2016.

SNS Operations Management has reviewed the outcome of the Coherent review as documented in SNS-NSCD-SC-RA-0018. The nine pre-start action items identified in the report have been closed and are documented on the IRR Sharepoint site.

SNS-OPM-6.U-7 for the Coherent Experiment has been approved.

I find that all necessary conditions have been met and I authorize use of liquid argon in the Coherent detector system and the start of their experimental program.

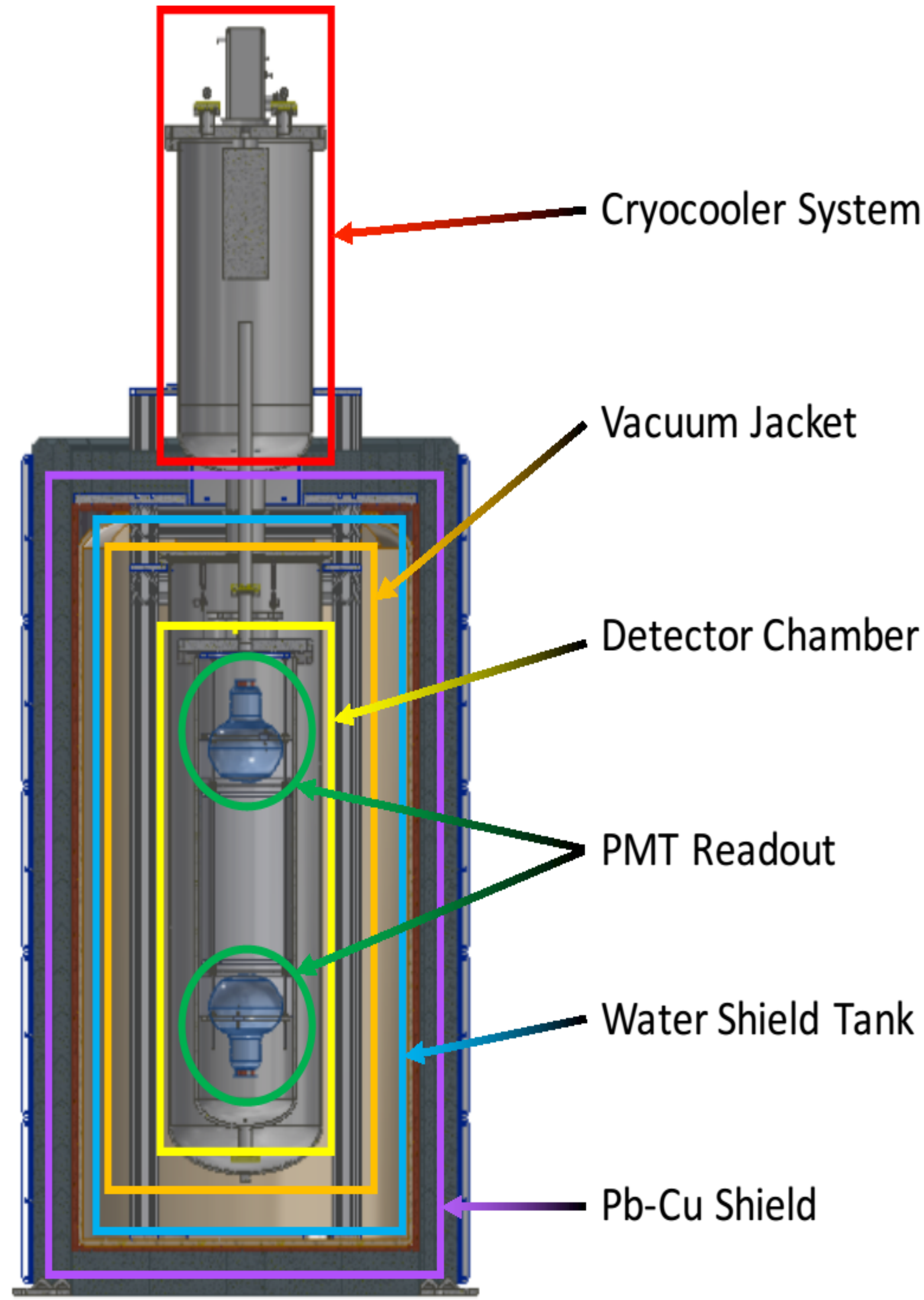
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY



- CENNS-10 detector on inter-lab loan from Fermilab
- First COHERENT detector reviewed and installed under formal agreement with SNS
- Repeatable process ... We know how to install additional instruments.

Liquid Argon Detector

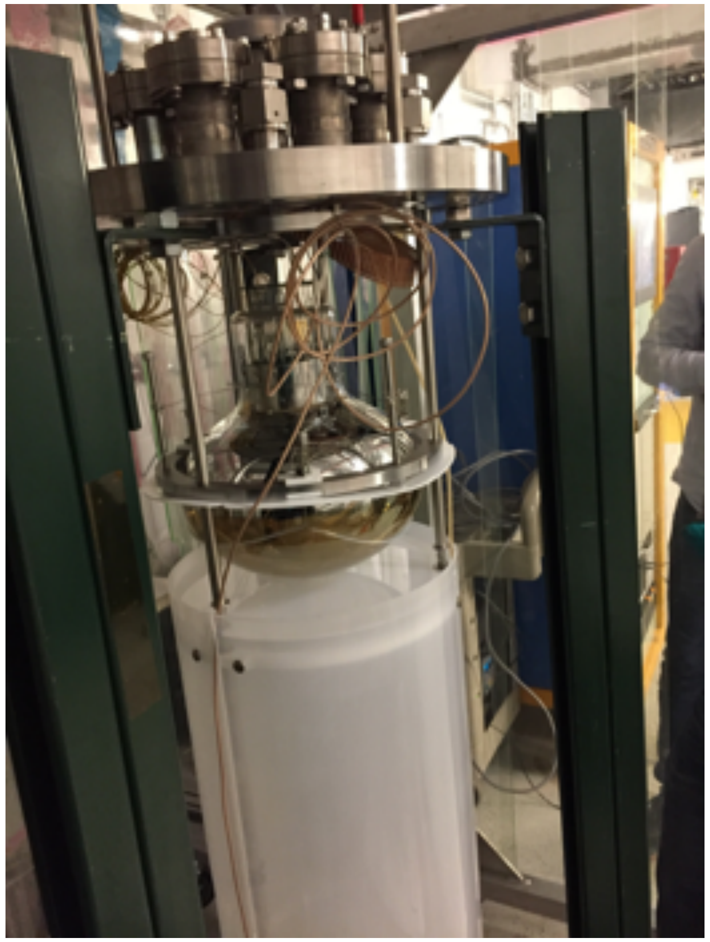
- Single phase liquid argon
  - ~30 kg fiducial volume
- 2×Hamamatsu R5912-02-MOD 8”PMTs
  - 8 “ borosilicate glass window
  - Standard bialkali photocathode (K_2CsSb)
  - 14 dynodes
  - QE: 18%@400 nm
- WLS - Tetraphenyl butadiene (TPB)
- Cryomech cryocooler – 90 Wt
  - PT90 single-stage pulse-tube cold head
  - compressor: CP950

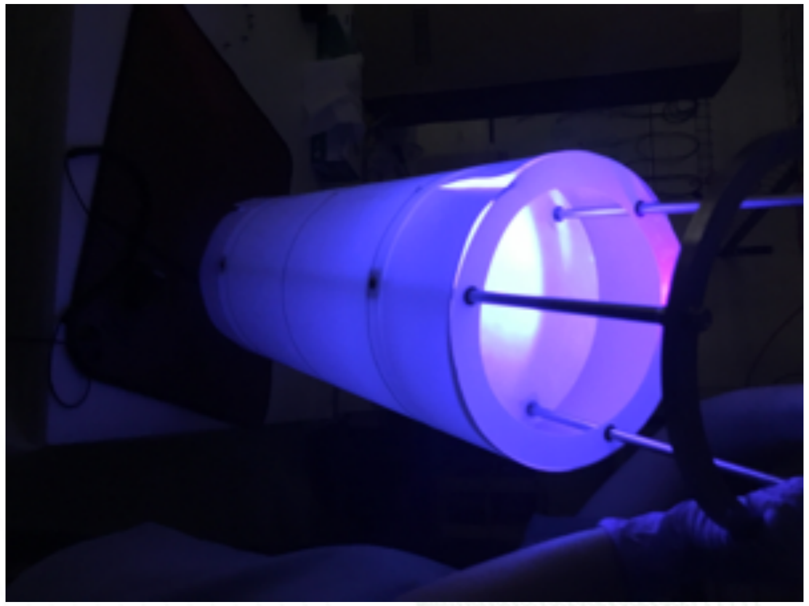


LAr Construction

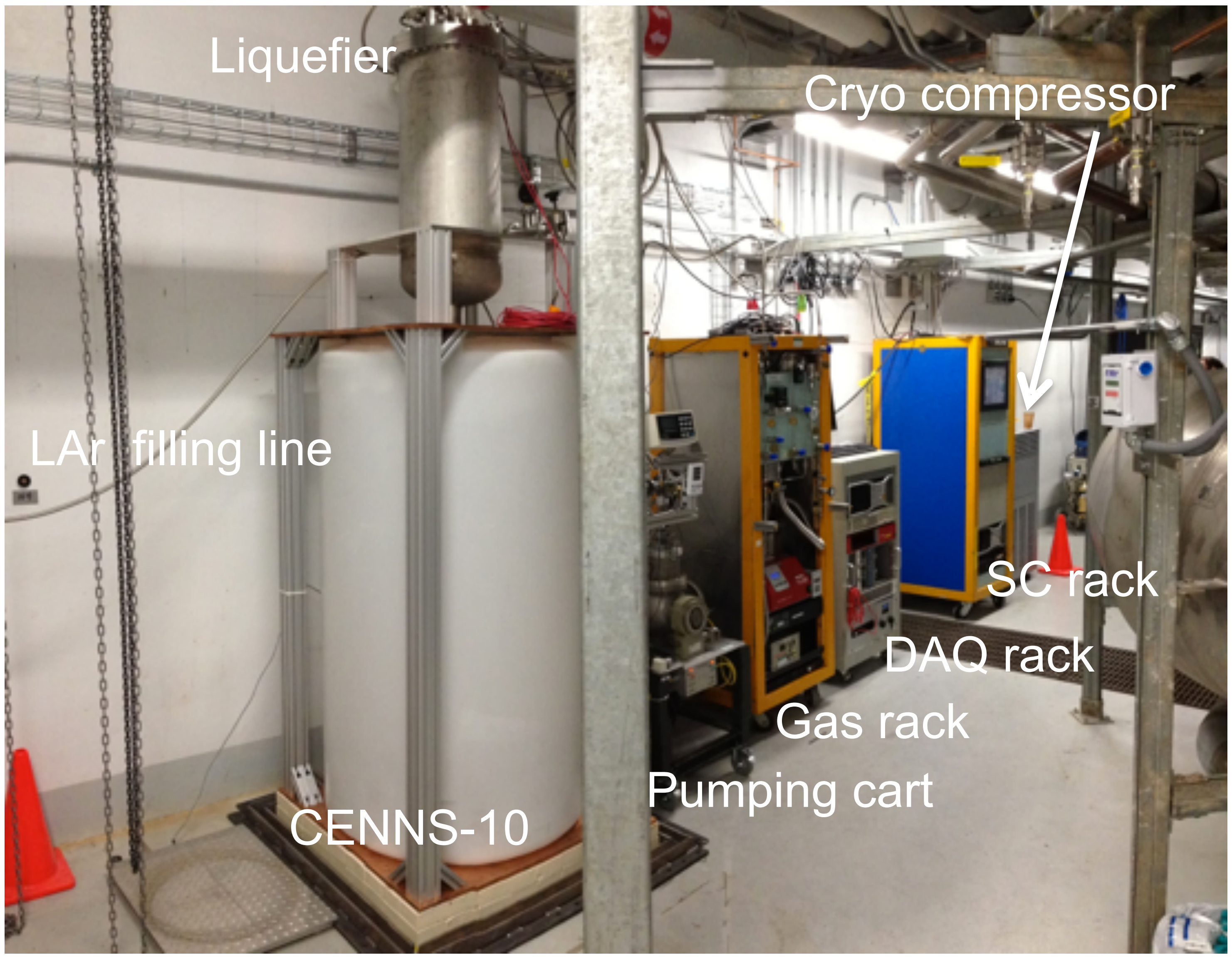
- Acrylic cylinders and discs coated by TPB
  - 3 x cylinder by airbrush
  - 2 x disk by evaporation at ORNL
- The thickness of the TPB is optimal ~ 0.2 mg/cm^2
- Teflon wrap

- Detector was assembled in clean room at the staging area of the SNS basement

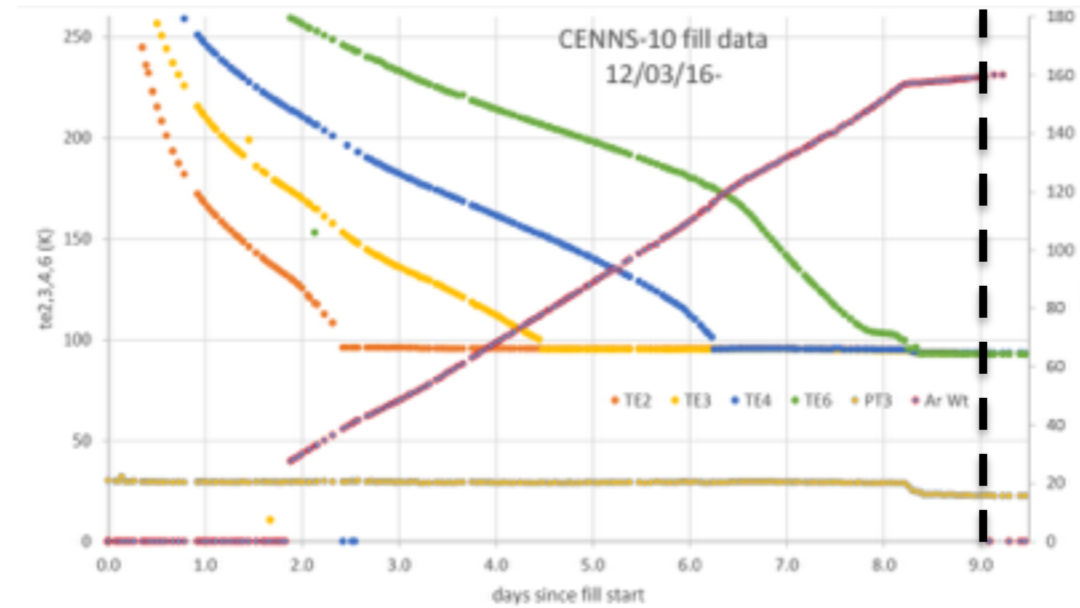





LAr in Neutrino Alley



Cooldown began morning of Dec 3



12/12/2016

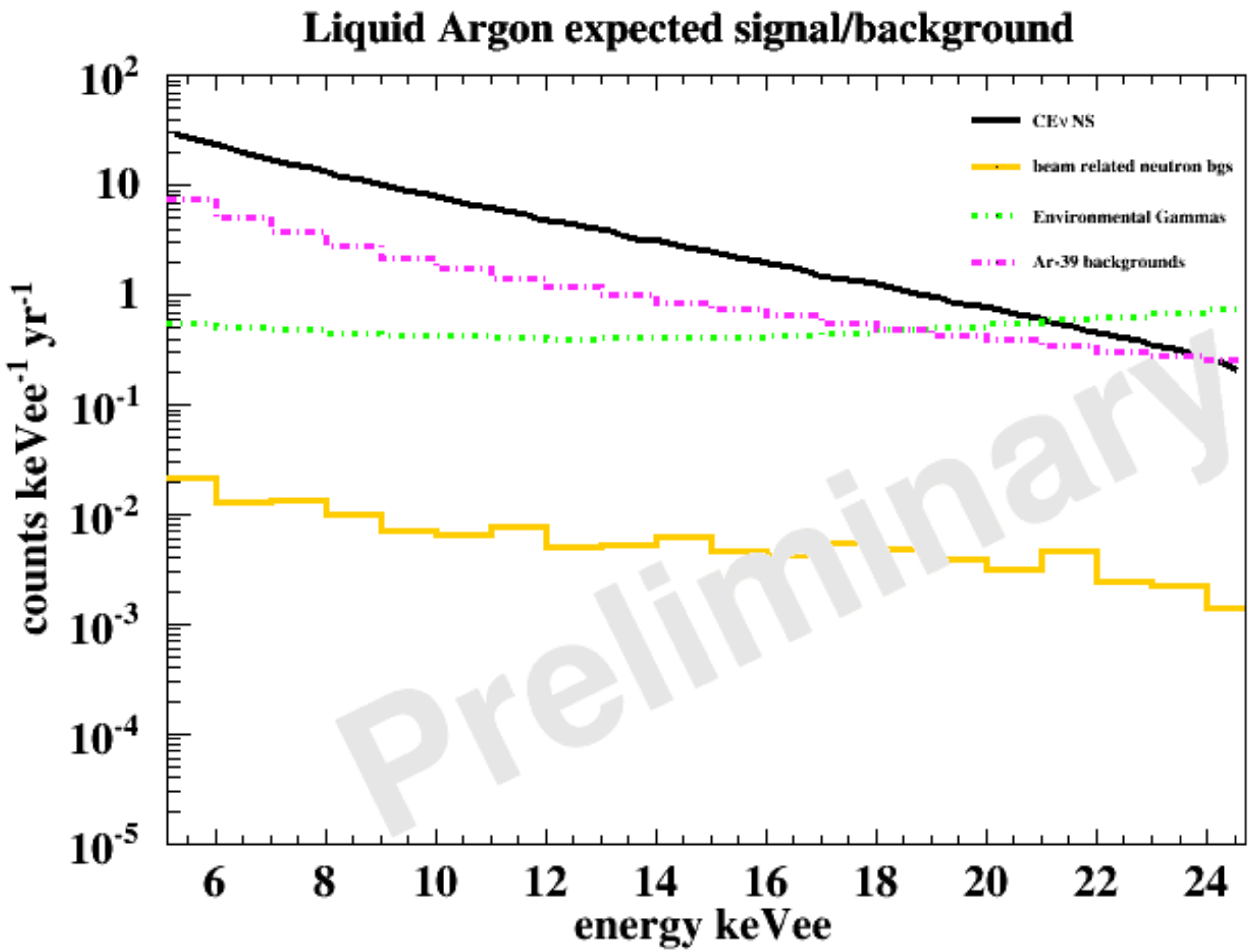
- ~ 9 days for filling
- 160 lbs LAr

1/2" Copper Shielding
Installed March 10

COHERENT SNS

Oak Ridge National Laboratory

LAr Projected Rates in Delayed Region

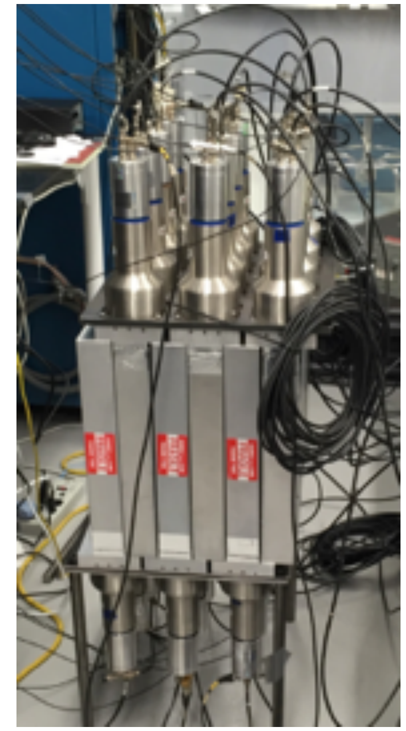


COHERENT NaI

- 100s of 7.7kg 2x4x16" NaI Detectors available
- 185 kg currently deployed with high thresholds
- Sensitive to Charged Current (CC)

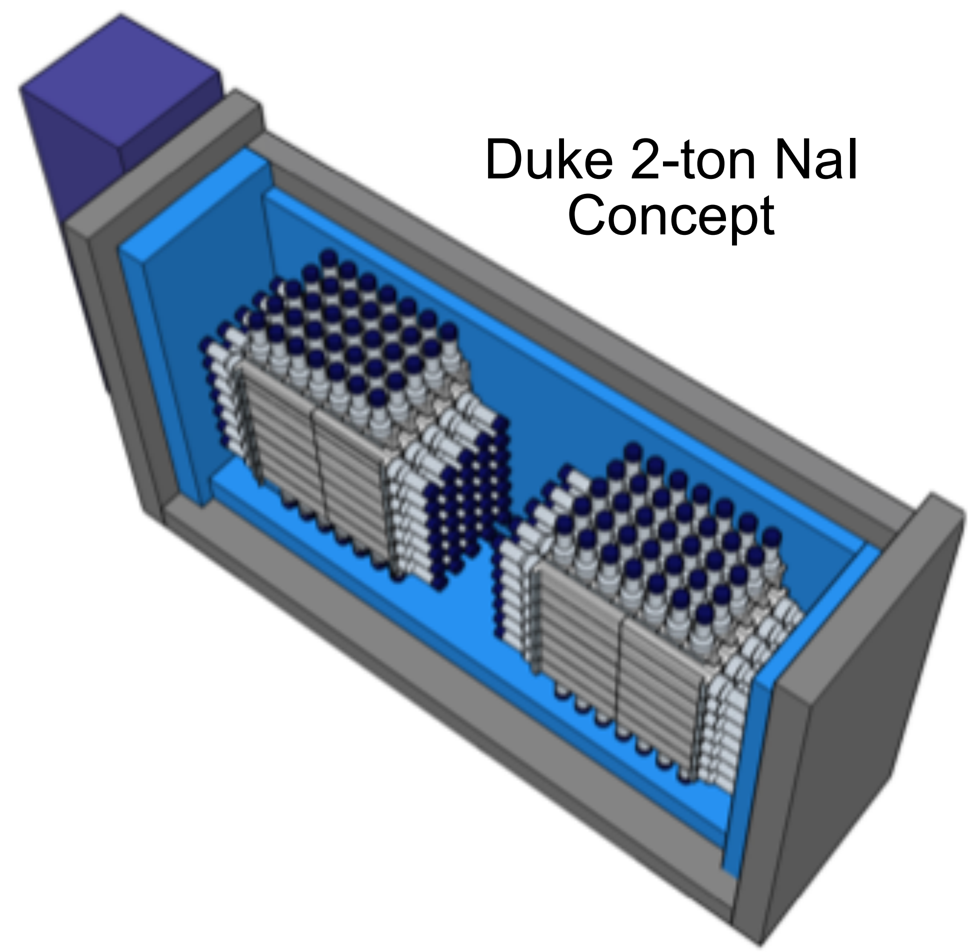
$$\nu_e +^{127}\mathrm{I} \rightarrow^{127}\mathrm{Xe} + \mathrm{e}^-$$

- Neutrino Interactions of CC on I & CEvNS on Na will be measured simultaneously
- Developing custom, active bases:
  - Dual Gain: 1pe – 50 MeV
  - Low cost: $50 per base

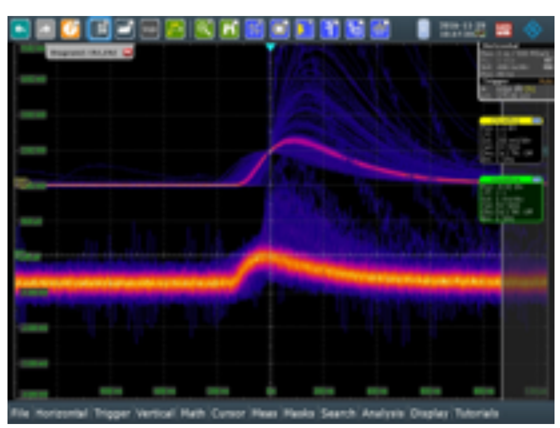


Duke Test Setup

NaI 185 kg @ SNS



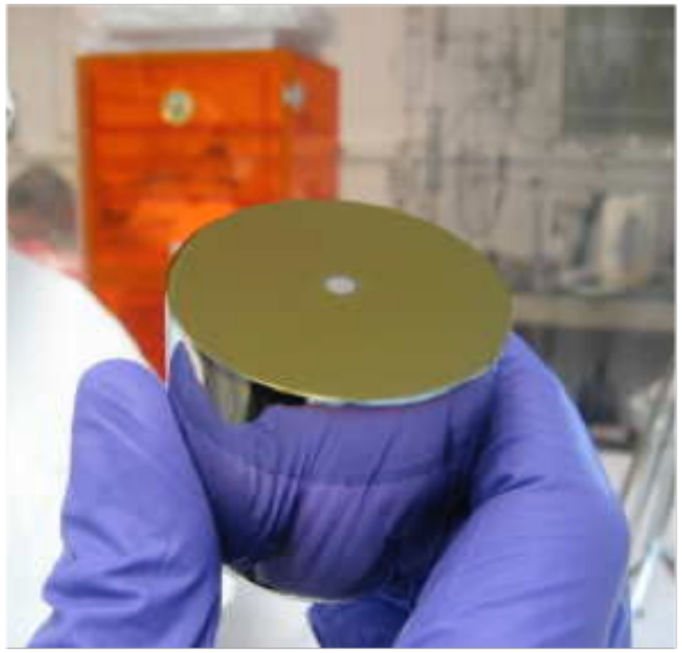
Duke 2-ton NaI Concept

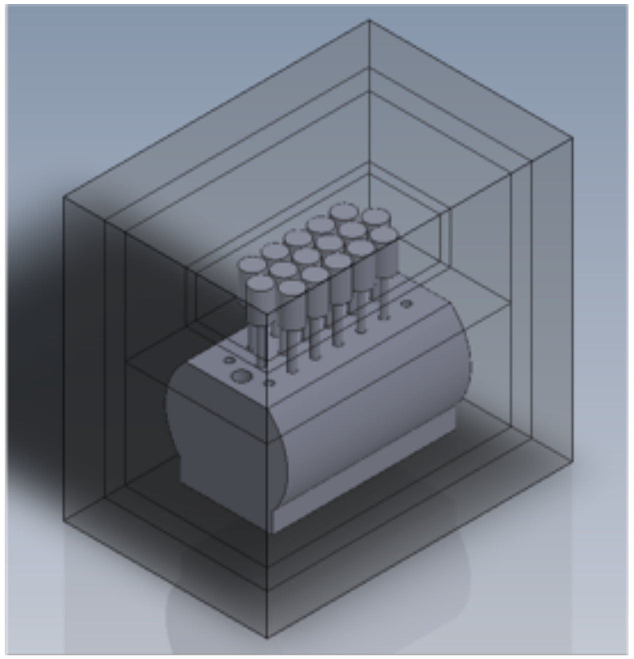


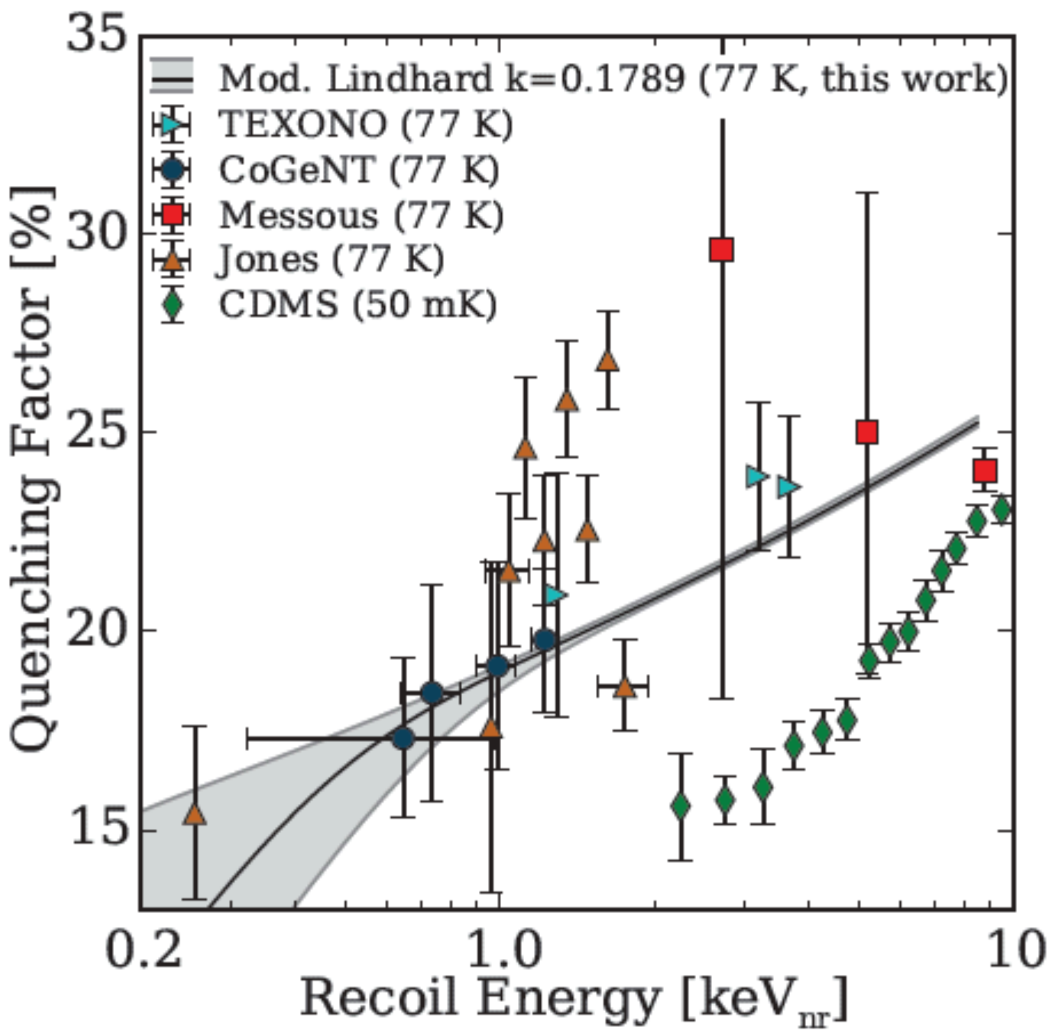
^{137}Cs: HV = 700V
~250 mV high gain
~750 uV in low gain

COHERENT HPGe

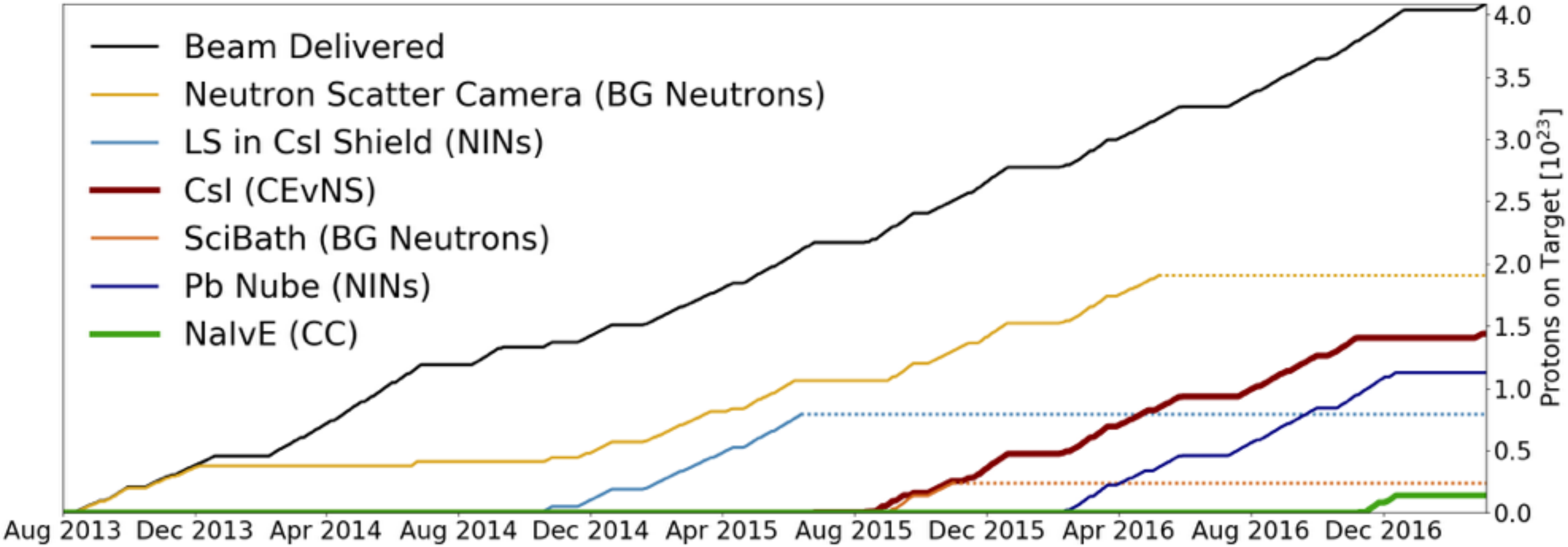
- Excellent energy resolution at low energies
- Well measured quenching factors
- First deployment: ~10 kg PPC detector array
- Common LN Dewar for 18 Detectors
- Repurpose on-hand Majorana Demonstrator/LANL ^{nat}Ge detectors
- Shielding structure of Lead, Copper, and Poly along with plastic scintillator muon veto
- Installation Spring 2017







Physics Data Collection Underway



COHERENT SNS SPALLATION NEUTRON SOURCE

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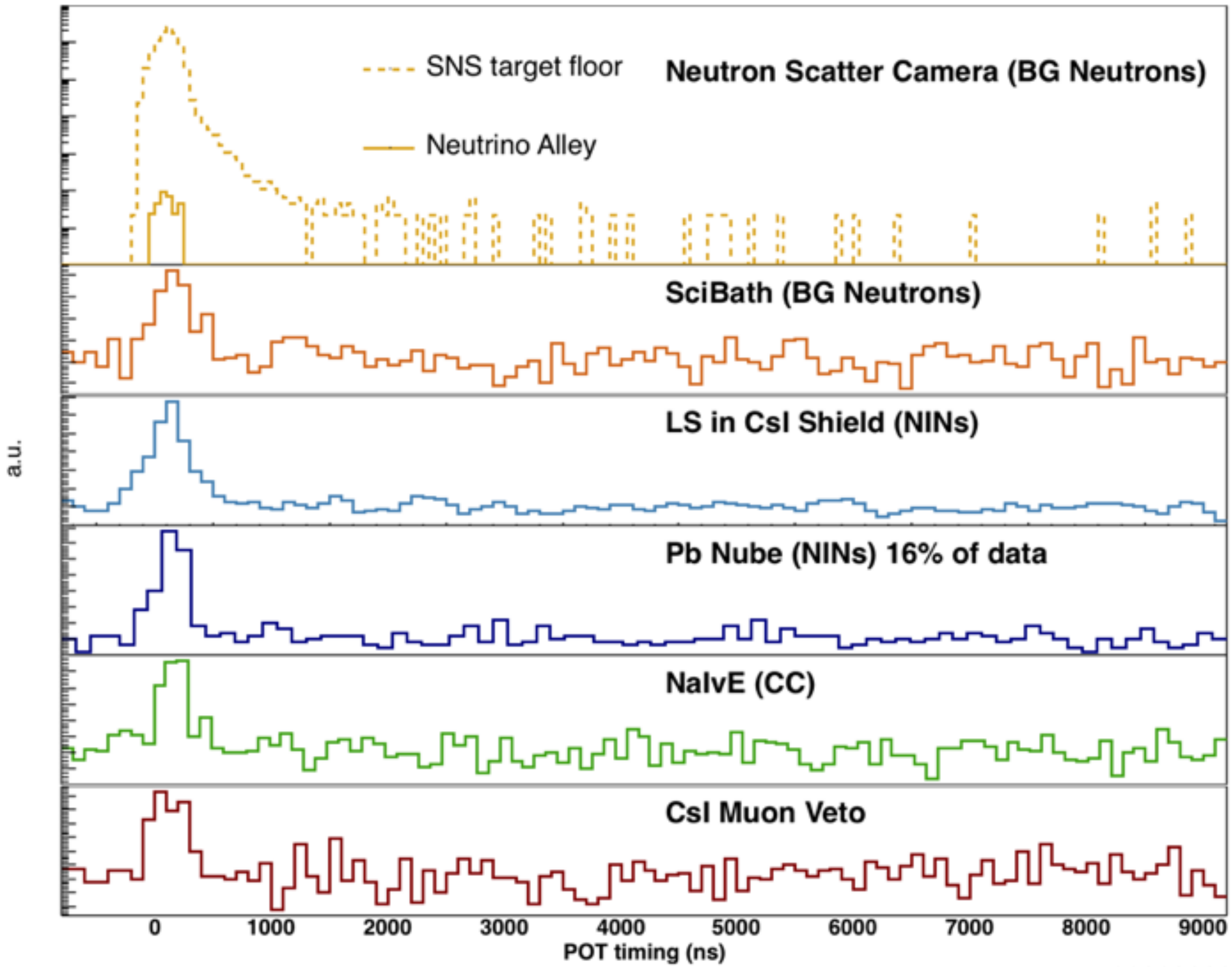
Beam is visible in all non-CEvNS channels

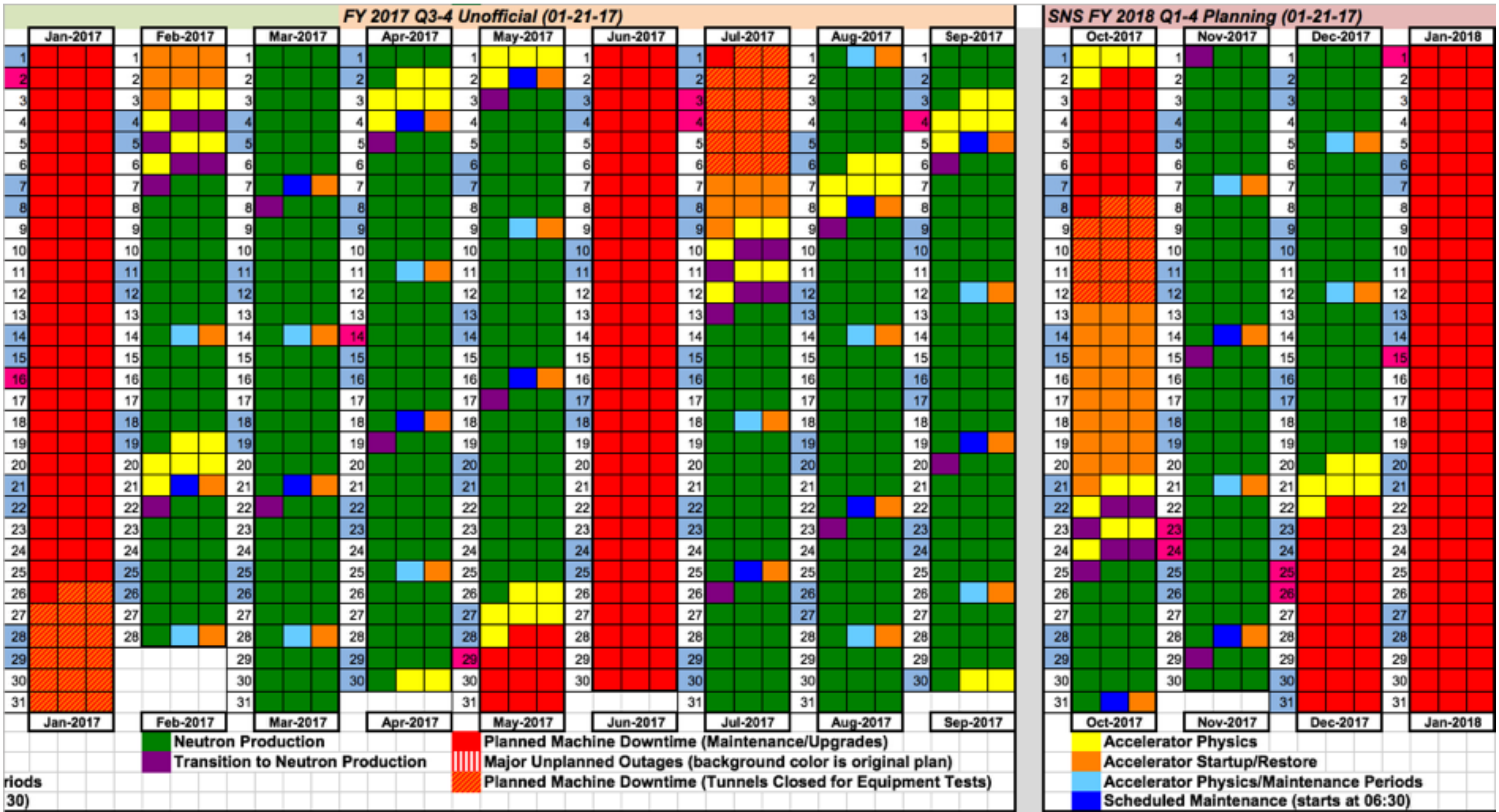


Beam timing is well understood in all instruments.

Non-CEvNS signals are all consistent with expectations!

SNS Beam Schedule

- 2100 hours @ 1 MW
- 2100 hours @ 1.2 MW
- 1500 hours @ 1.3 MW

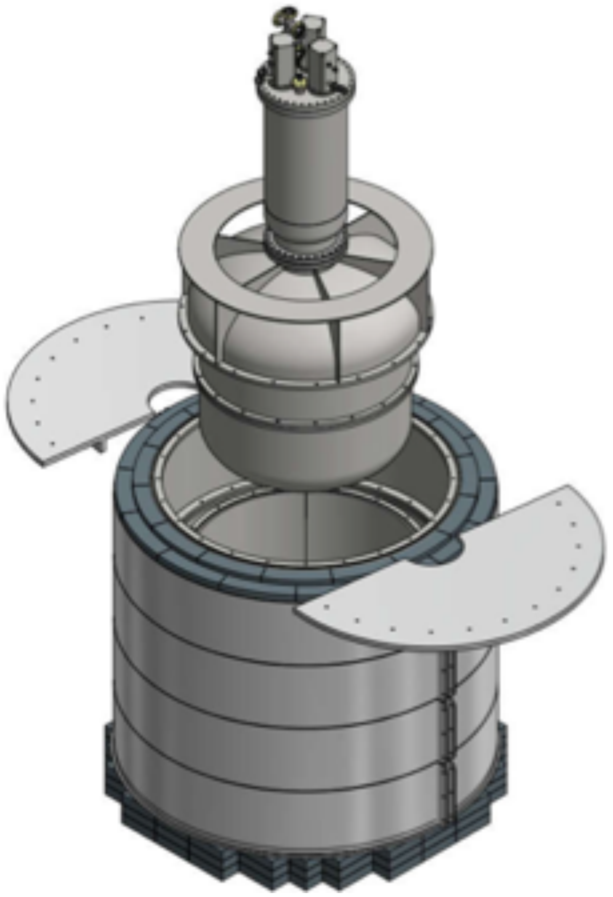


In the coming year…

- Record 6500 MW·hrs of Quality Physics Data
  - CsI, LAr, Fe-NINs, Pb-NINs, NaI-CC
- HPGe Deployment (NSCU lead)
  - Component testing underway at NSCU
  - Deployment at SNS Spring 2017
- Neutron Background Monitor Deployment (Sandia Lead)
- NaI 185 kg Upgrade (Duke lead)
  - Install muon veto with steel shielding
  - Dual Gain PMT Base Development
- LAr Light Collection Upgrade (IU/UT lead)

Beyond 2017 …

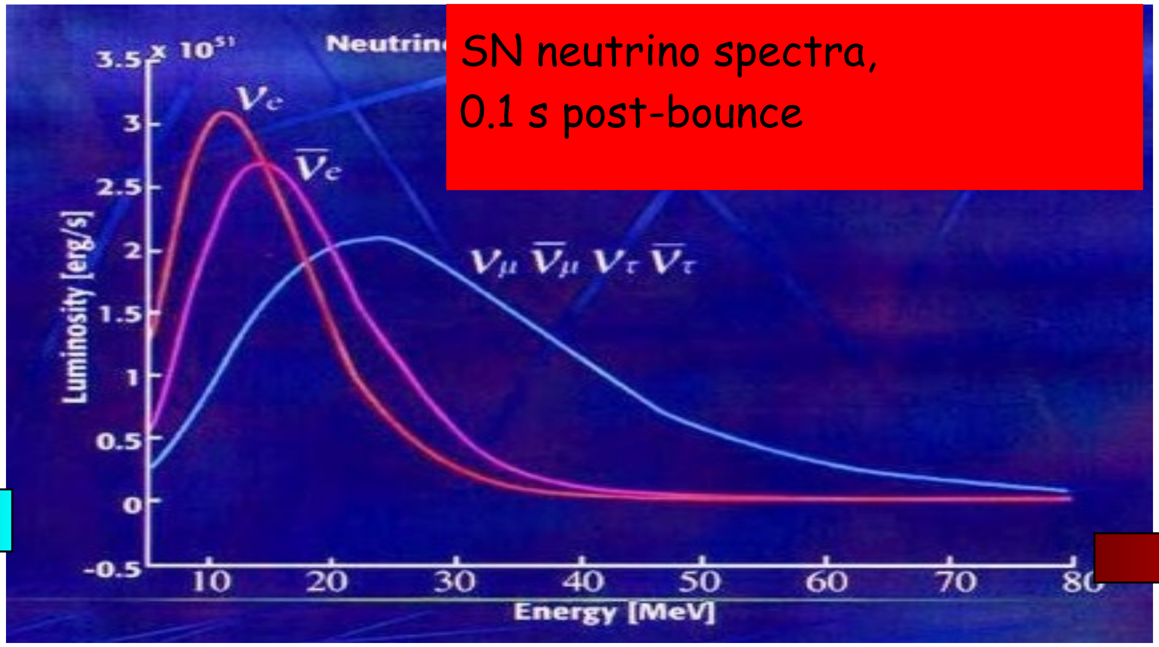
- Collect Quality Physics Data with full suite of Phase 1 Detectors
  - CEvNS: CsI, LAr, HPGe, NaI
  - CC NaI, Pb/Fe NINs
- Develop a strategy for deploying xenon and neon targets in neutrino alley to significantly increase the N^2 range and basement-deployable mass upgrades of phase 1 detectors.
- Feasibility and scoping studies of large mass CEvNS instrument at the SNS with sufficient measurement precision to limit non-standard interactions to break the DUNE mass-ordering ambiguity.



IU 1-ton LAr Concept

Core-collapse supernovae

- Destruction of massive star initiated by the Fe core collapse
  - 10^{53} ergs of energy released
  - 99% carried by neutrinos
  - A few happen every century in our Galaxy, but the last one observed was over 300 years ago
- Dominant contributor to Galactic nucleosynthesis
- Neutrinos and the weak interaction play a crucial role in the mechanism, which is not not well understood



Nuclear reactors
E_ν<10 MeV
Too cold

H.E. "accelerators"
E_ν>100 MeV
Too hot

COHERENT SNS

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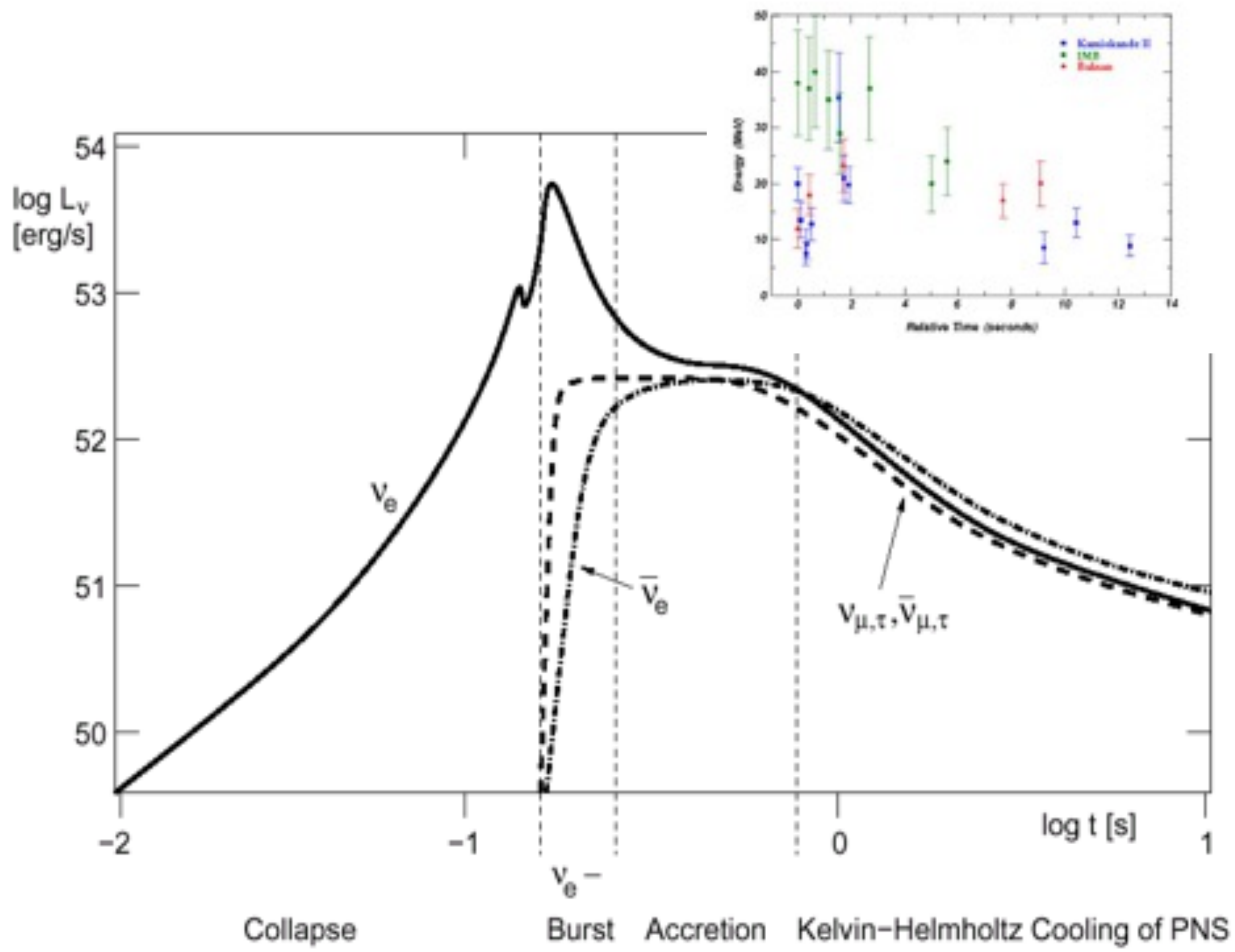
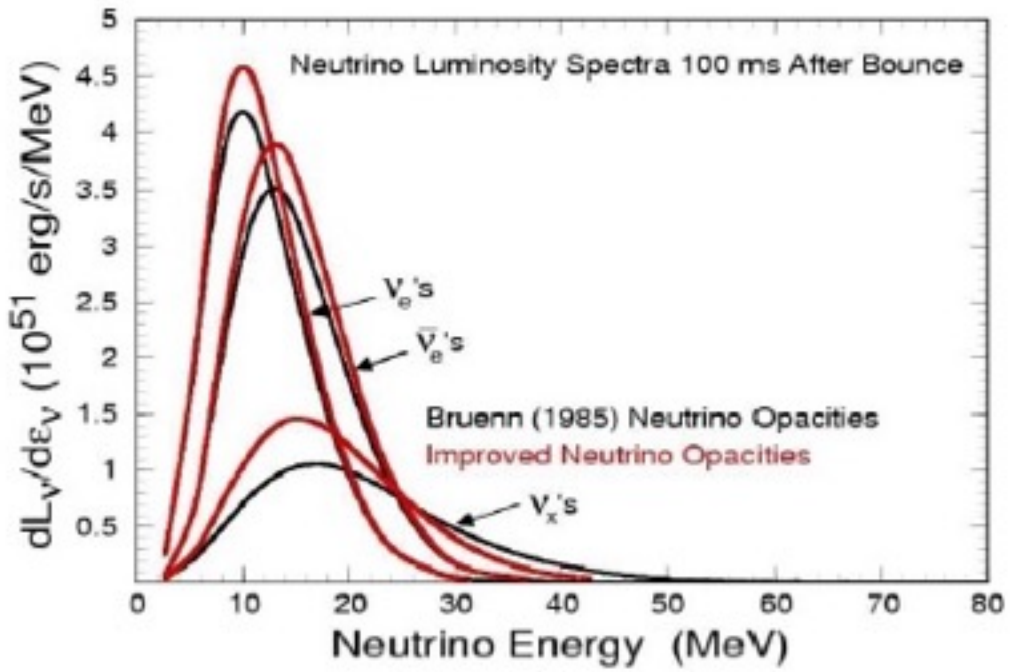
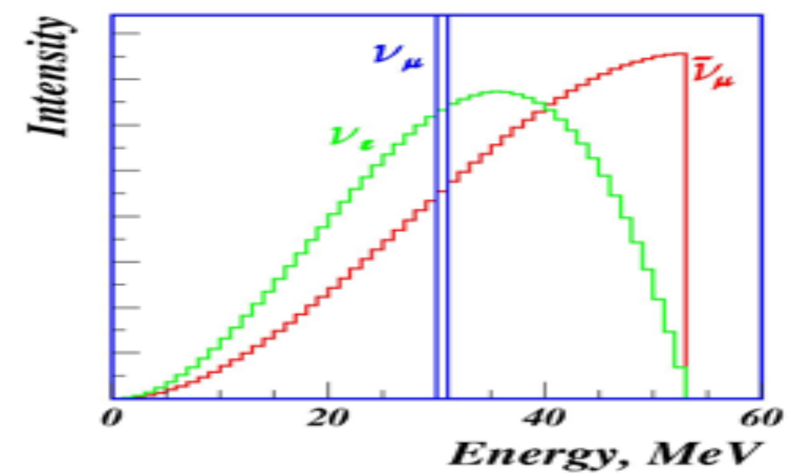
Supernova neutrino observations

- Measurement of the neutrino energy spectra and time distribution from a Galactic supernova would provide a wealth of information on the conditions in supernovae, neutrino oscillations, etc.







New generation of Large mass Dark matter experiments could be sensitive to the Galactic Supernovae.
Need to understand signal in detectors.
Low energy neutrino interactions have never been measured!!!

Summary

- The Spallation Neutron Source is an ideal πDAR source of neutrinos for CEvNS measurements and much more.
- ORNL has created a neutrino laboratory within the target facility for smaller proof-of-concept measurements. The SNS is a welcoming place for neutrino physicists.
- The COHERENT experiment is underway to make an unambiguous first observation of CEvNS with multiple targets.
- COHERENT is anticipating a rich neutrino physics program with precision measurements with ton scale detectors.

Acknowledgements

- We are grateful for logistical support and advice from SNS (a DOE Office of Science facility) and ORNL personnel. Much of the background measurement work was done using ORNL SEED funds, as well as Sandia Laboratories Directed Research and Development (LDRD) and NA-22 support. LAr detector deployment is supported by ORNL LDRD funds and the CENNS-10 detector is on loan from Fermilab. We thank Pacific Northwest National Laboratory colleagues and Triangle Universities Nuclear Laboratory for making resources for various detector components available. COHERENT collaborators are supported by the U.S. Department of Energy Office of Science, the National Science Foundation, NASA, and the Sloan Foundation.