Neutrinos: ORNL
PROSPECT, COHERENT AND NEW INITIATIVES

DOE High Energy Physics Review

September 6, 2018

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J. Newby, Y. Efremenko

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

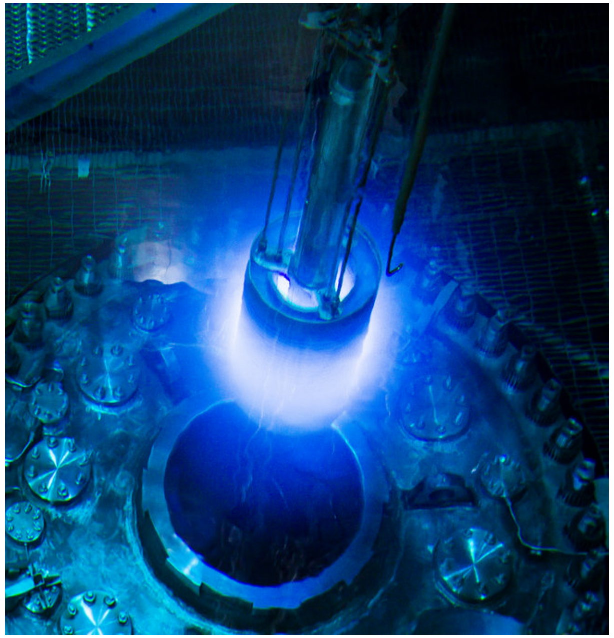
Outline

- ORNL HEP Opportunities
- The Group
- Projects
  - PROSPECT
  - COHERENT
  - New Initiatives
- Accomplishments
- Future Plans
- Summary

ORNL's Opportunities: World Class *Neutrino* Sources

Spallation Neutron Source: SNS

- Pulsed neutron source
- 1 GeV protons on Hg target
- 1.4 MW beam power
- 2nd target station

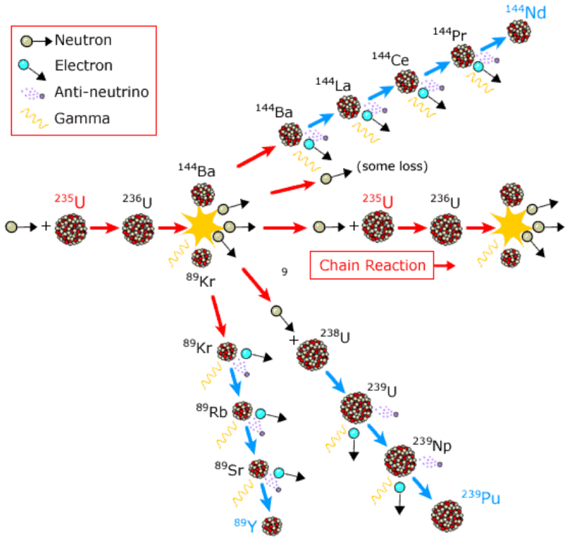


High Flux Isotope Reactor: HFIR

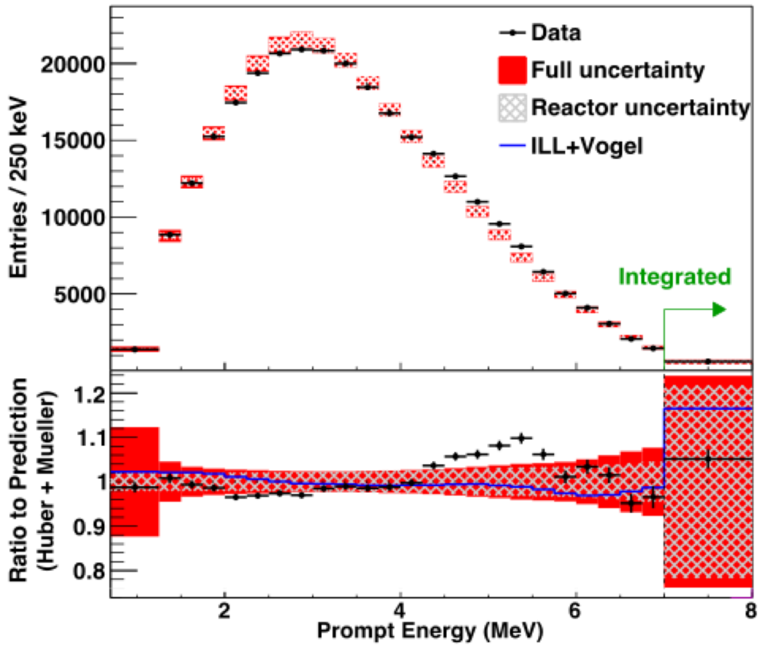
- 85 MW research reactor
- Compact core
- Highly-enriched uranium fuel

Neutrino flux origin and spectra

HFIR Fission

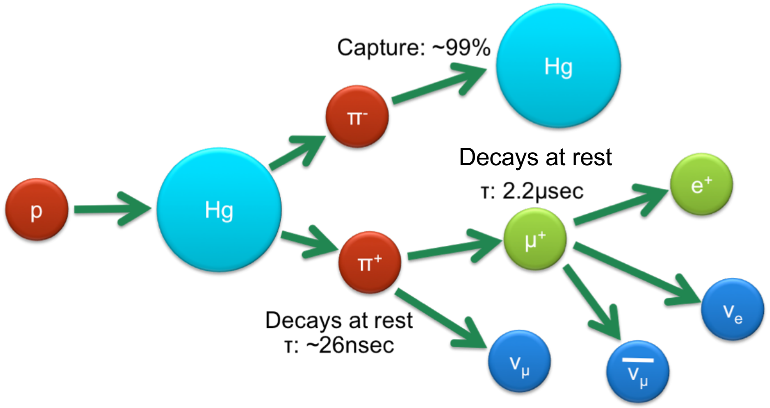


Beta decay fission fragments ($\overline{\nu}_e$)

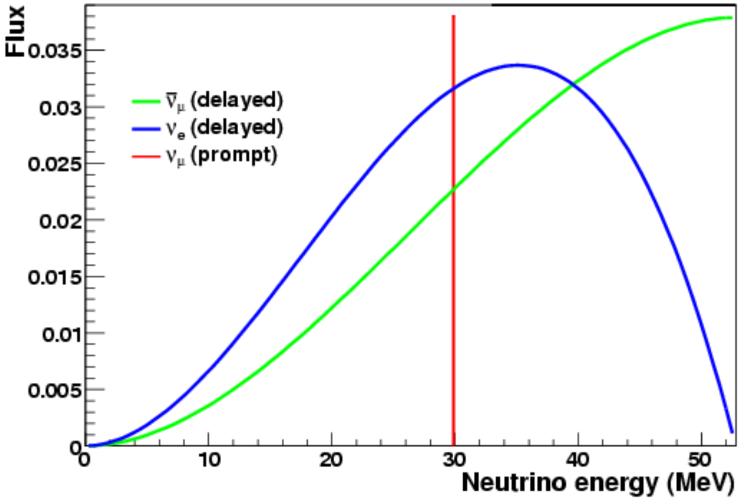


Huge flux
Few MeV
No timing structure

SNS Spallation



Pion-decay-at-rest neutrino source



Large Flux
Few tens-of-MeV,
Sharply-pulsed timing
Background rejection

Other ORNL Resources:

The Oak Ridge Leadership Computing Facility

- World class expertise in scientific computing
- Computing and data analysis resources
- Summit Supercomputer - World's Fastest

Physics Division

- Computer Cluster
- Laboratory Space
- High-bay area
- Office and Meeting Space for Visitors
- No-cost dormitories (JINPA)

Computational Sciences Activities Related to HEP

- Pilot Programs on Quantum Information:

PI Name:	
Raph Posser (led by Wisconsin)	Quantum-enhanced detection of dark matter and neutrinos
Travis Humble (with JHU)	Particle Track Recognition …
Travis Humble (with FNAL)	HEP Machine Learning and Optimization

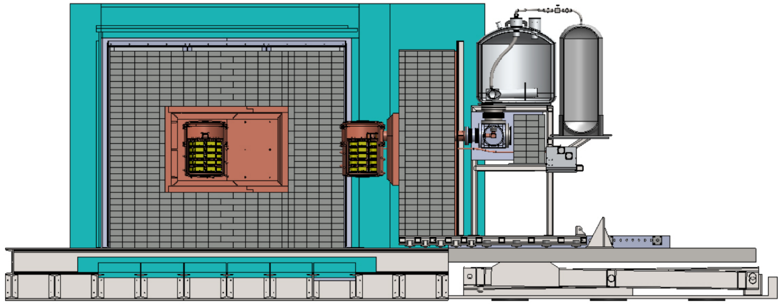
- Multi-lab whitepaper to DOE/HEP on future HEP software needs

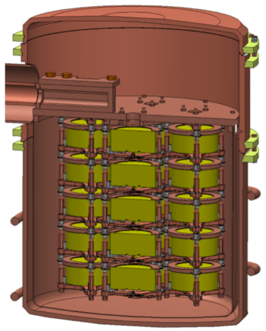
ORNL Physics Division will host a Workshop on mid-November 2018

Jack C. Wells, Director of Science, Oak Ridge Leadership Computing Facility

Current ORNL interests on neutrino physics

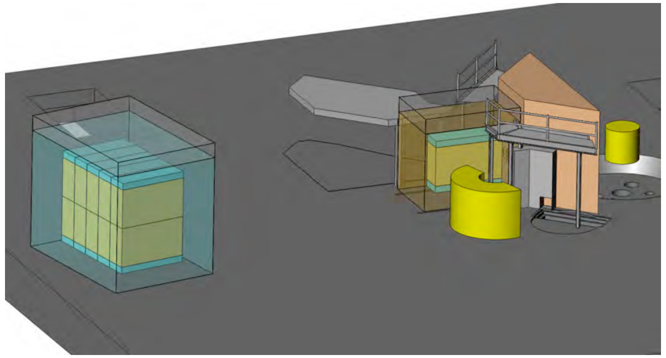
The **MAJORANA DEMONSTRATOR** (MJD)**-** A ^{76}Ge 0νββ experiment at SURF



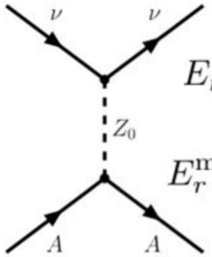


LEGEND 200/ LEGEND 1000- towards 1 tonne ^{76}Ge experiment

PROSPECT- A Precision Reactor Neutrino Oscillation and Spectrum Experiment at the 85MW HFIR



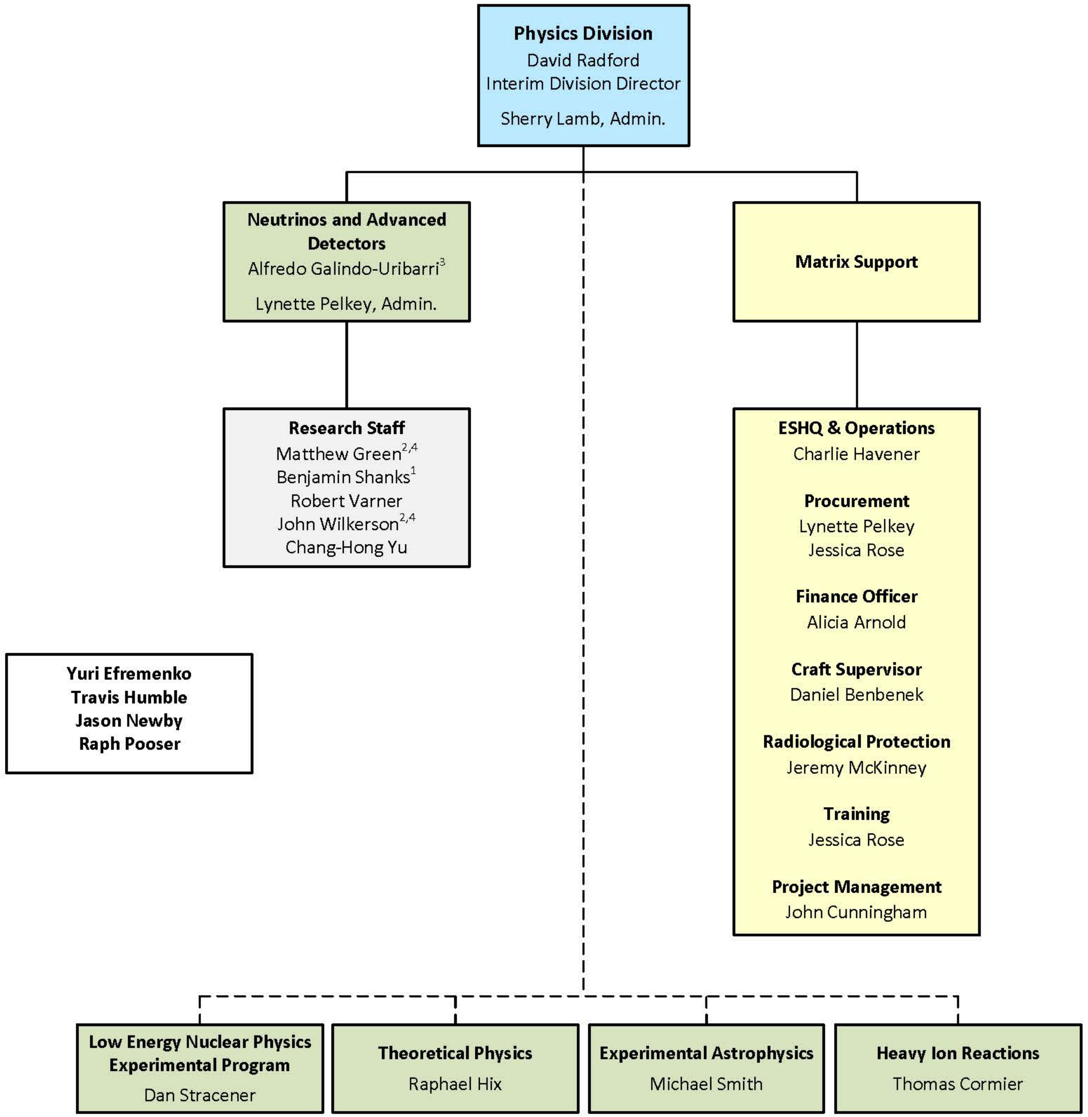
COHERENT- Coherent elastic neutrino-nucleus scattering using the neutrino emissions from the SNS spallation source at ORNL



$$E_\nu \lesssim \frac{hc}{R_N} \cong 50 \text{ MeV}$$

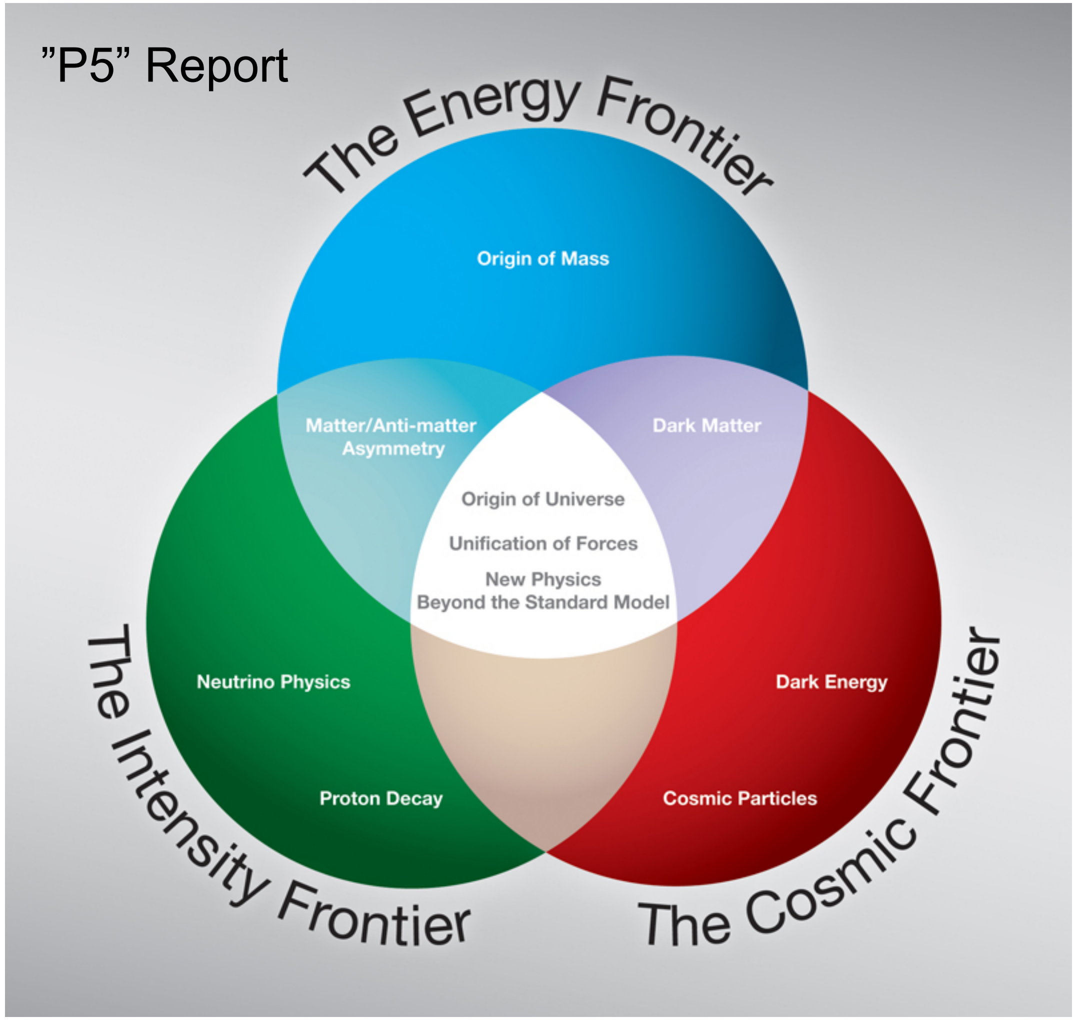
$$E_r^{\max} \simeq \frac{2E_\nu^2}{M} \simeq 50 \text{ keV}$$

- The Group
- Projects
  - Majorana Demonstrator
  - LEGEND
- R&D Accomplishments
  - Majorana Demonstrator
  - LEGEND
- Research Plan
- Summary



1 – Post-doc
2 – Adjunct Staff
3 – Interim
4 – ORNL/Core University Joint Faculty Appointment

Physics Goals



Particle Physics Project Prioritization Panel

- Pursuing a broad research program in nuclear, particle, and astrophysics
- emphasis on weak interactions and fundamental interactions.

The research program of the Physics Division includes:

- studies of neutrino oscillation
- neutrino properties
- neutrinoless double beta decay.

The initial success of this program is enabling the discussion of new ideas for future collaborations.

People

Research Staff

- D. Radford (Acting Division Director)
- A. Galindo-Uribarri (Acting Group Leader)
- P. Mueller
- R. Varner
- M. Febbraro (FY2018 hire; LDRD)
- J. Newby (Nuclear Sci. & Eng.)
- R. Pooser (Computational Sciences)
- T. Humble (Director Quantum Computing Institute)
- J. Wells (Director Science NCCS)

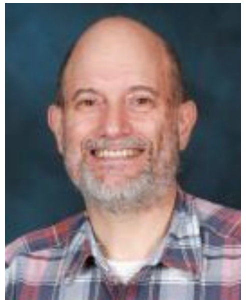
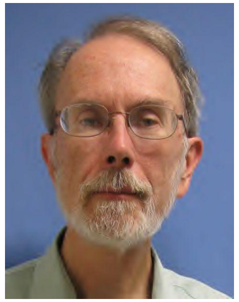
Joint Faculty

- Yu. Efremenko (UTK)
- M. Green (NCSU / TUNL) (Wigner Fellow 2013 - 2015)

PostDocs

- J. Matta









Background and Expertise

- Senior research staff come from backgrounds in nuclear structure and reactions physics
  - Extensive experience with Ge detector technologies, scintillators, particle detectors
  - Joined PROSPECT and COHERENT in 2012
- Hardware: Detector systems, vacuum, data acquisition, low-background shielding, …
- Software: Data acquisition, data analysis, deep learning, …
- Project management
- Scintillator chemistry and synthesis

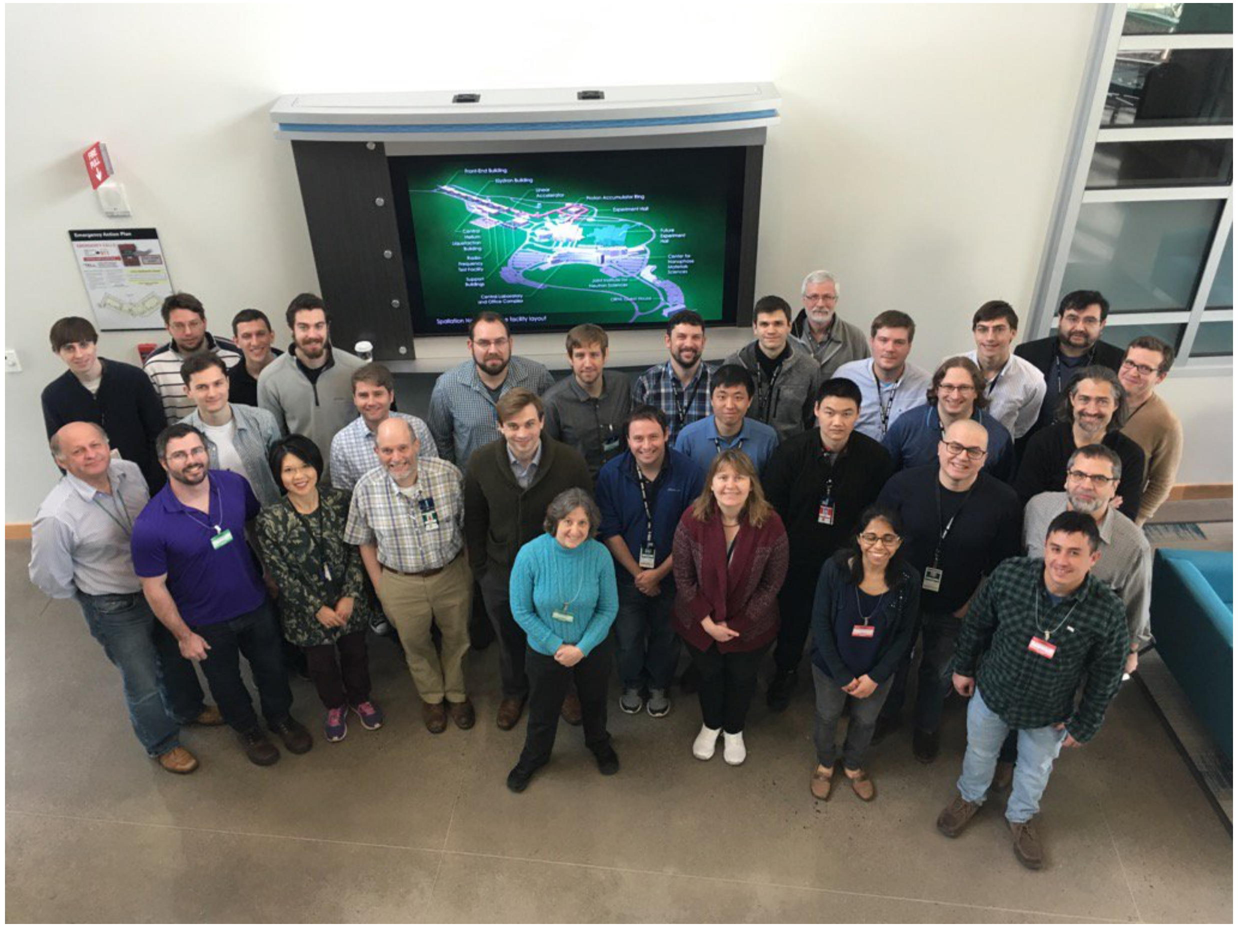
PROSPECT Collaboration

BROOKHAVEN NATIONAL LABORATORY
NIST
LE MOYNE COLLEGE
Lawrence Livermore National Laboratory
OAK RIDGE National Laboratory
Drexel
Yale

Supported by: U.S. DEPARTMENT OF ENERGY | Office of Science
HEISING-SIMONS FOUNDATION

COHERENT Collaboration

COHERENT SNS SPALLATION NEUTRON SOURCE



- Carnegie Mellon University
- The University of Chicago
- Duke University
- UF University of Florida
- KAIST
- Laurentian University Université Laurentienne
- Los Alamos National Laboratory EST. 1943
- MEPhI National Research Nuclear University · Moscow Engineering Physics Institute
- North Carolina Central University Founded 1910
- NC State University
- NM State University
- Oak Ridge National Laboratory
- Sandia National Laboratories
- The University of Tennessee Knoxville
- TUNL
- University of Washington

PROSPECT and COHERENT train high quality young scientists

- Blaine Heffron, Physics Graduate Student from University of Tennessee, Knoxville, M.Sc. 2017: “Characterization of Reactor Background Radiation at HFIR for the PROSPECT Experiment” represents the FIRST thesis of the PROSPECT
- Brennan Hackett, Physics Graduate Student from Surrey, UK, M. Phys. 2017: “DANG and the Background Characterisation of HFIR for PROSPECT”, SECOND thesis of PROSPECT
- Jack Boyle, Physics Graduate Student from Surrey, UK, M. Phys. 2018: “Characterising the Effects of Ambient Magnetic Fields on Photomultiplier Tubes and Monitoring Muon Flux for PROSPECT”, THIRD thesis of PROSPECT
- Bjorn Scholz, Physics Graduate Student from U. of Chicago, Ph.D. 2017: “First Observation of Coherent Elastic Neutrino-Nucleus Scattering”, FIRST thesis of COHERENT
- Grayson Rich, Physics Graduate Student from Duke University, Ph.D. 2017: “Measurement of Low-Energy Nuclear-Recoil Quenching Factors in CsI[Na] and Statistical Analysis of the First Observation of Coherent, Elastic Neutrino-Nucleus Scattering”, SECOND thesis of COHERENT

Students and Postdocs that worked in PROSPECT

Ran
Chu
UTK

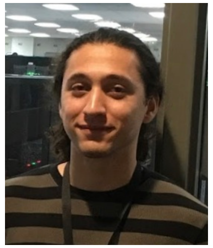
Brennan
Hackett
UTK

Elisa
Romero
UTK

Rosa Luz
Peinado
Sonora

James
Matta
ORNL

Brandon
White
ORNL

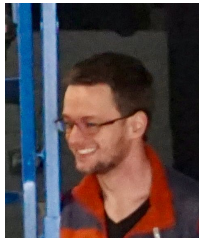


Alex
Guirado
Sonora

Alan
Garcia
UTEP

Diego
Vargas
Wesleylan

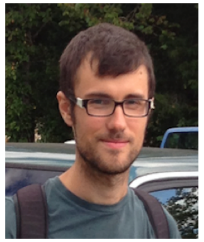
Ivan
Corona
UAEM



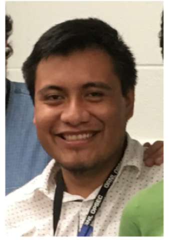
Corey
Gilbert
UTK

Xiaobin
Lu
UTK

Cristian
Baldenegro
Sonora

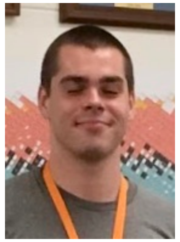


Blaine
Heffron
UTK



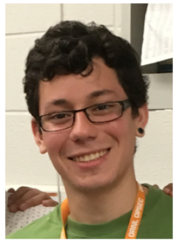
Noel
Cruz
UNAM

Jack
Boyle
Surrey



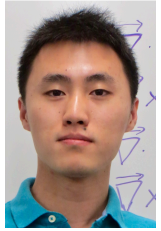
Travis
Stockinger
UTK

Biswas
Sharma
UTK



Felix
Pastrana
Colombia

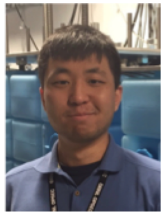
David
Murphy
UCD



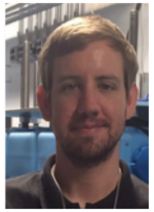
Shiyu
Fan
UTK

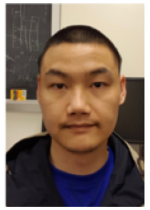
+ 28 more from collaboration institutions

Students and Postdocs that worked in COHERENT


Ben Suh
IU

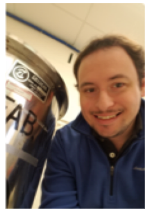

Justin Raybern
Duke


Sam Hedges
Duke


Long Li
Duke

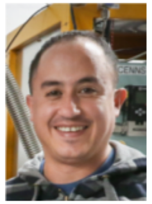

Alexander Kumpan,
MEPhI


Brandon Becker
UTK


Jacob Zettlemoyer
IU

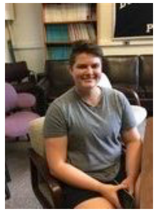

Connor Awe
Duke


Katrina Miller
Duke


Hector Moreno
UNM


Dmitry Rudik
MEPhI

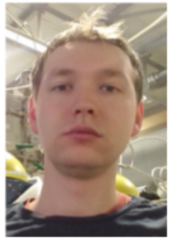

Rebecca Rall
CMU


Jes Koros
Duke


Alexander Kavner
Chicago

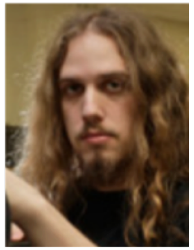

Alexey Konovalov
MEPhI


Matt Heath
IU


Alex Khromov
MEPhI


Gleb Sinev
Duke


Erin Conley
Duke


Dan Salvat
UW
(Postdoc)

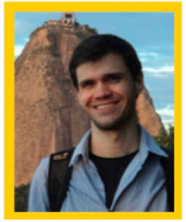

Jacob Daughhetee
UTK
(Postdoc)


Mayra Cervantes
Duke
(Postdoc)


Ivan Tolstukhin
IU
(Postdoc)


Josh Albert
IU
(Postdoc)

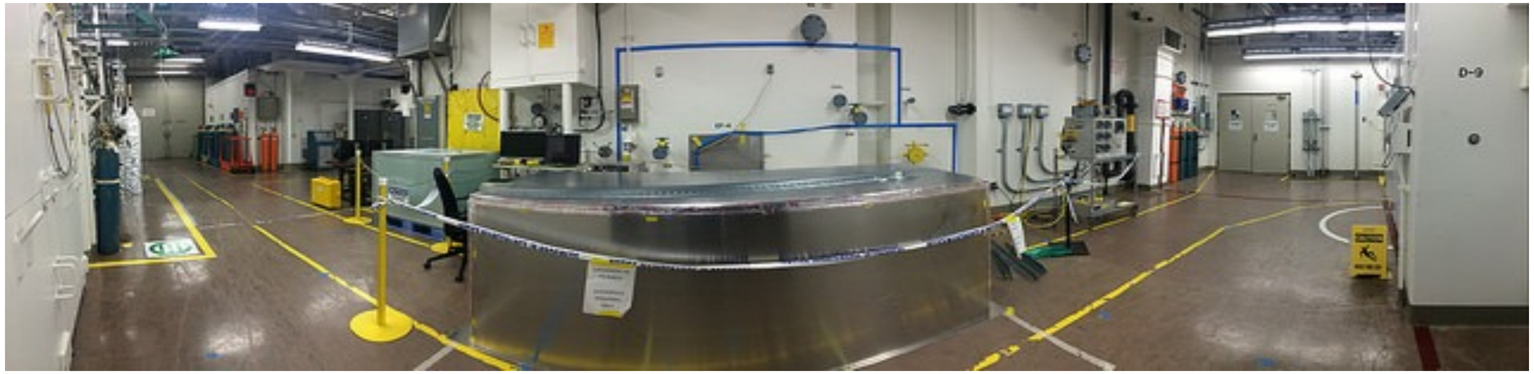
First two PhD dissertations completed


Bjorn Scholz
U of Chicago

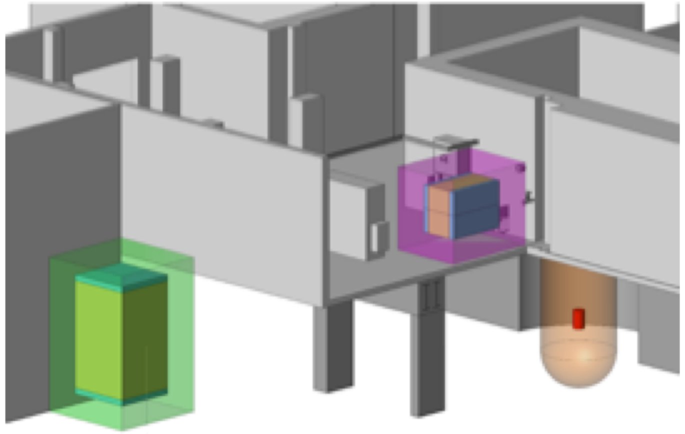

Grayson Rich
Duke

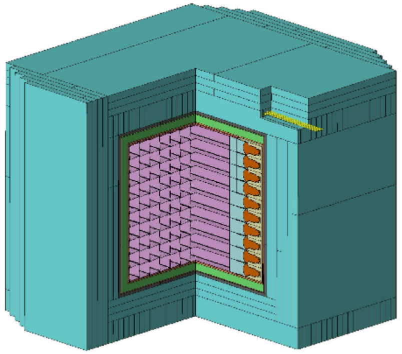
ORNL provides strong support for Neutrino Program

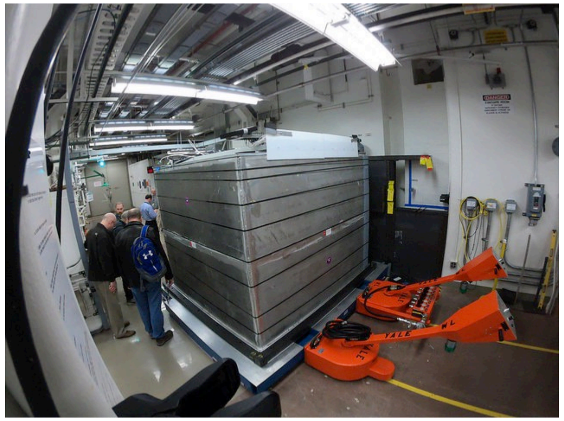
PROSPECT Collaboration with ORNL personnel at HFIR



A Precision Oscillation and Spectrum Experiment







PROSPECT Complete

PROSPECT is a reactor neutrino experiment at very short baselines to make a precision measurement of the flux and energy spectrum of antineutrinos emitted from nuclear reactors. PROSPECT will search for the oscillation signature of sterile neutrinos. The measurements of PROSPECT will test our understanding of the Standard Model of Particle Physics, deepen our understanding of nuclear processes in a reactor, and help develop technology for the remote monitoring of nuclear reactors for safeguard and non-proliferation. ORNL had key roles on the installation and commissioning.

Funding sources:

DOE Office of Science, Office of High Energy Physics

Heising-Simons Foundation

Resources:

Physics Division, HFIR

OAK RIDGE National Laboratory

ORNL - PROSPECT

- ORNL group has provided strong support for PROSPECT, significant contributions to the experiment, infrastructure, on-site logistics, safety, and supervision of students.
- Excellent training ground for young scientists (first 3 thesis).
- Key roles in the installation and commissioning of PROSPECT.
- Increase our participation in the antineutrino spectrum analysis effort, and to provide laboratory support to improve the overall performance (e.g. shielding hot spots, magnetometers for residual field monitoring, etc.)
- Key role in operations, data taking, calibrations, shift coordination, etc.
- Continue background studies in surface neutrino detector
- Measure and understand the ^{235}U reactor antineutrino spectrum

Detector Installation

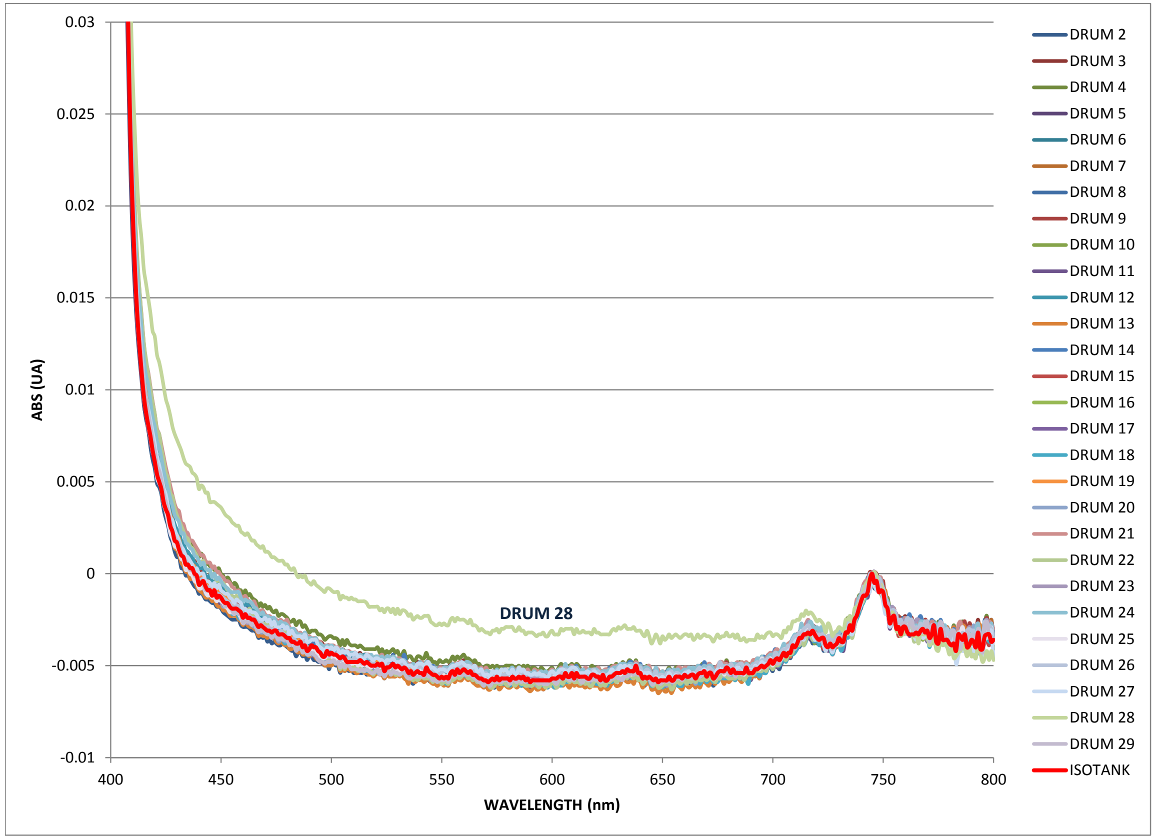
Temperature control and thermal shielding

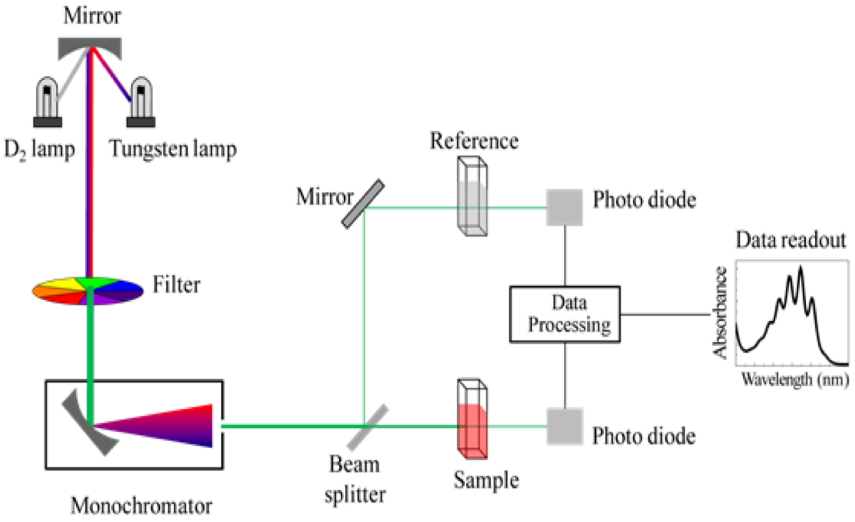
Moving ISOtank from PD to HFIR

Coordination with Yale

6LiLS QA/QC

UV-Vis spectra of individual LiLS drum samples compared with the ISO-tank sample





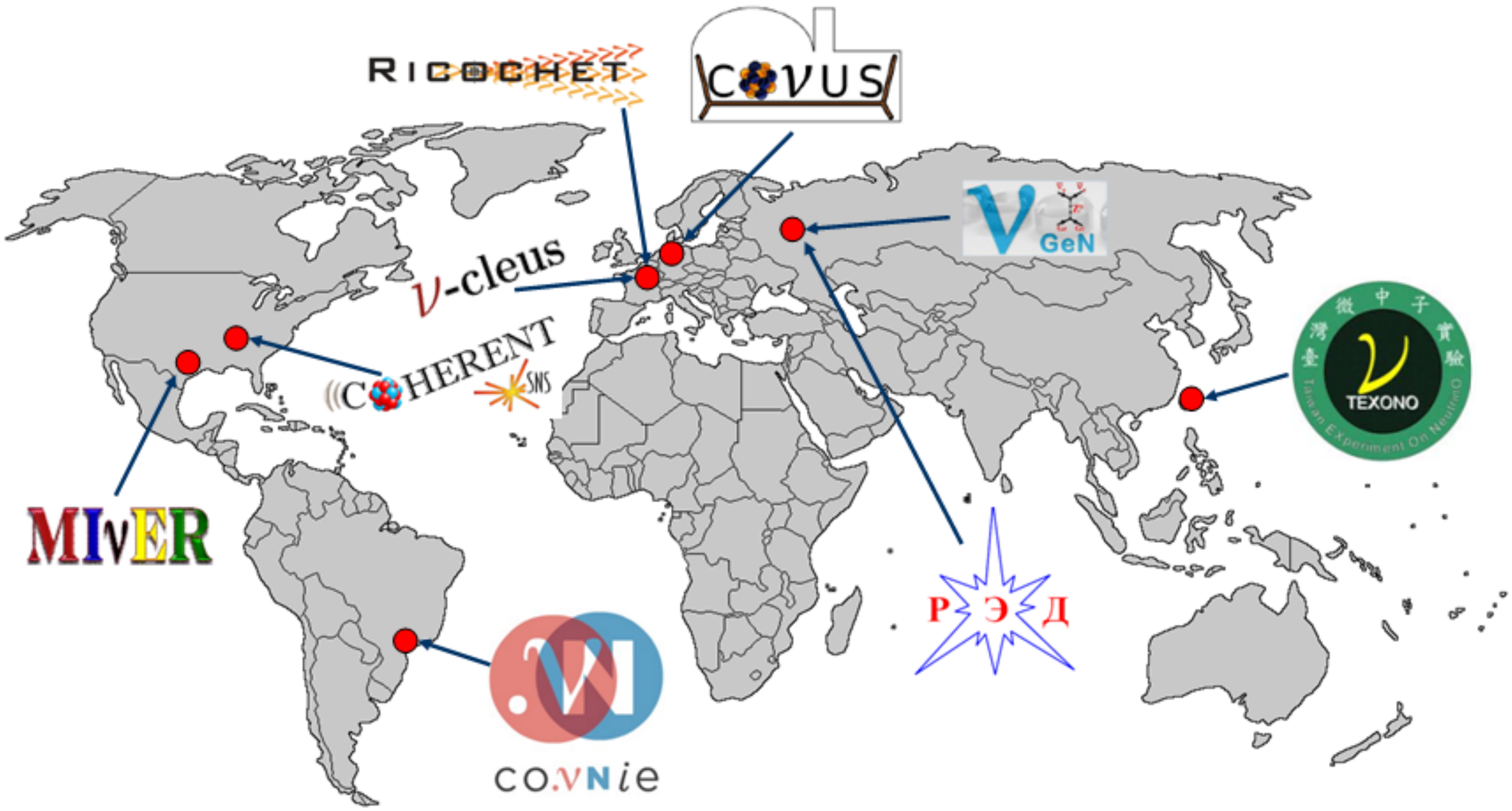
OAK RIDGE National Laboratory

Immediate Goals for PROSPECT

- Reactor-model independent search for sterile neutrinos at the eV-scale
- Measure and understand the ^{235}U reactor antineutrino spectrum

- Started taking data since March 2018
- Detected neutrinos from HFIR
- ✓ First oscillation analysis (submitted to PRL) – complete
- First spectrum analysis in progress
- Updated oscillation + spectrum results
- Joint analysis with other experiments
- Backgrounds in surface neutrino detectors

World Wide Efforts to Detect CEvNS



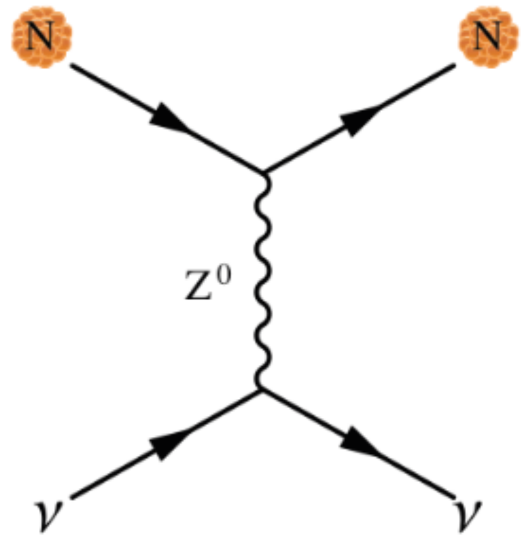
SNS as a neutrino source

- World most powerful pulsed neutrino source; 7 ▪ 10^{20} POT daily
  ~9% of protons produce 3 neutrinos
- Neutrino energies ideal to study CEvNS and Supernovae related neutrino cross sections.
  For most of neutrinos E_{ν}< 53 MeV
- Decay At Rest from pions and muons (DAR) gives very well defined neutrino spectra
- Fine duty factor let suppression of steady background by a factor of 2000.
  ~ 1000 m.w.e underground
- Neutrinos, space, and utilities are provided

Coherent Elastic neutrino-Nucleus Scattering (CEvNS)

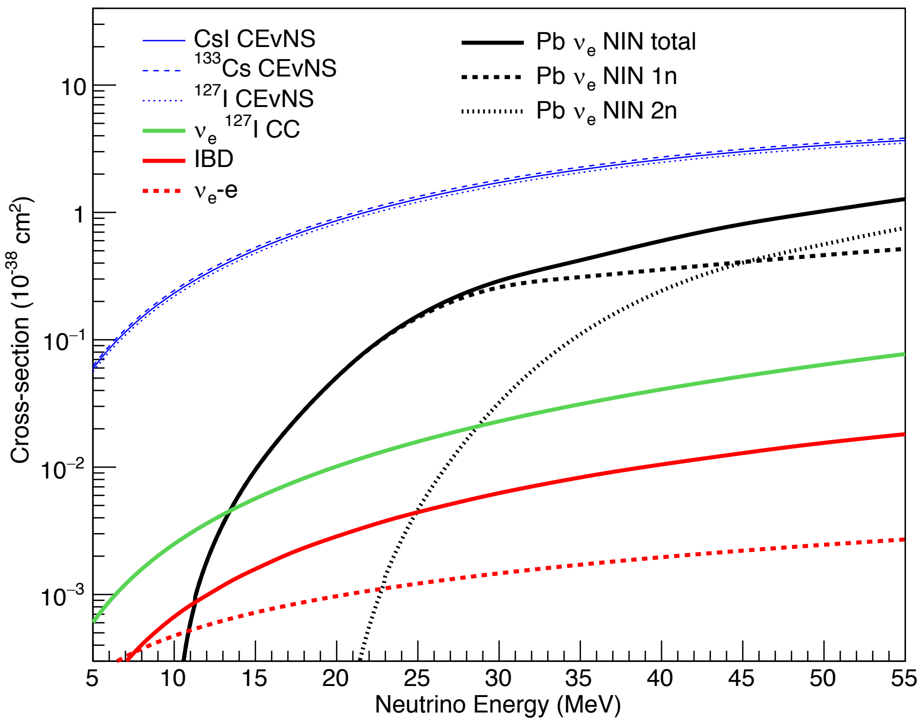
A neutrino scatters on a nucleus via exchange of a Z, and the nucleus recoils as a whole;

coherent up to E_ν~ 50 MeV



D.Z. Freedman PRD 9 (1974)
Submitted Oct 15, 1973

V.B.Kopeliovich & L.L.Frankfurt
JETP Lett. 19 (1974)
Submitted Jan 7, 1974



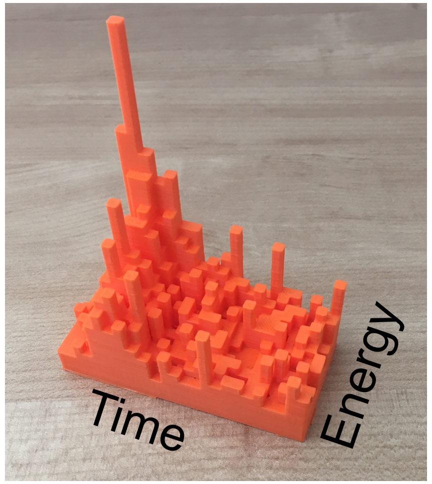
CEvNS cross-section is large!

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

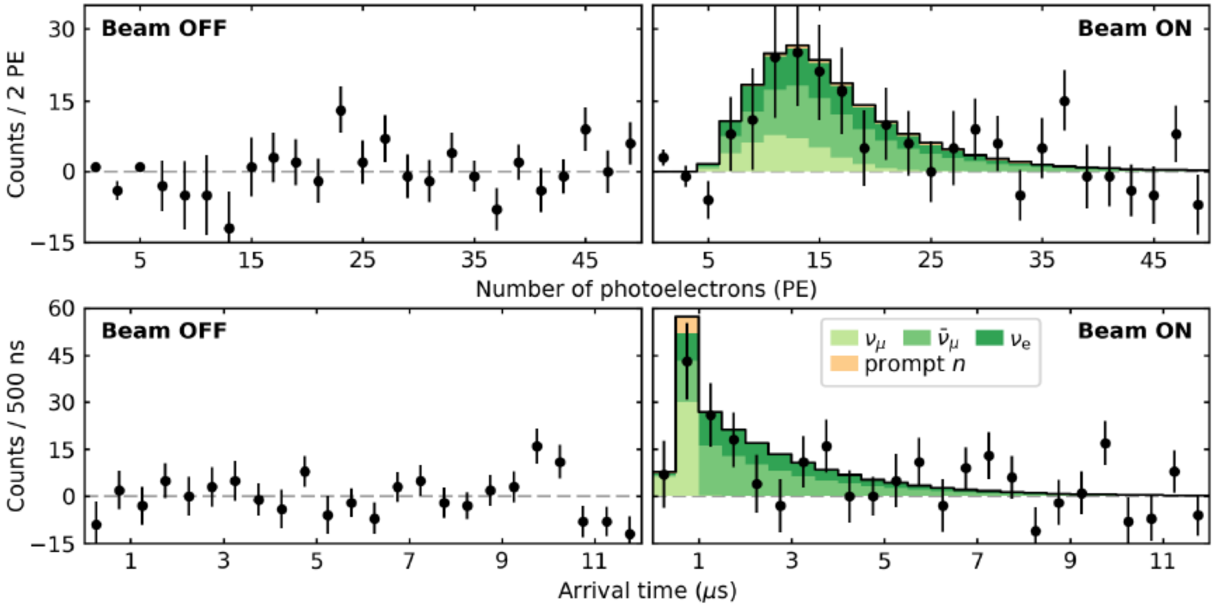
CEvNS cross section is well calculated in the Standard Model

First Detection of CEvNS

Hand held neutrino detector

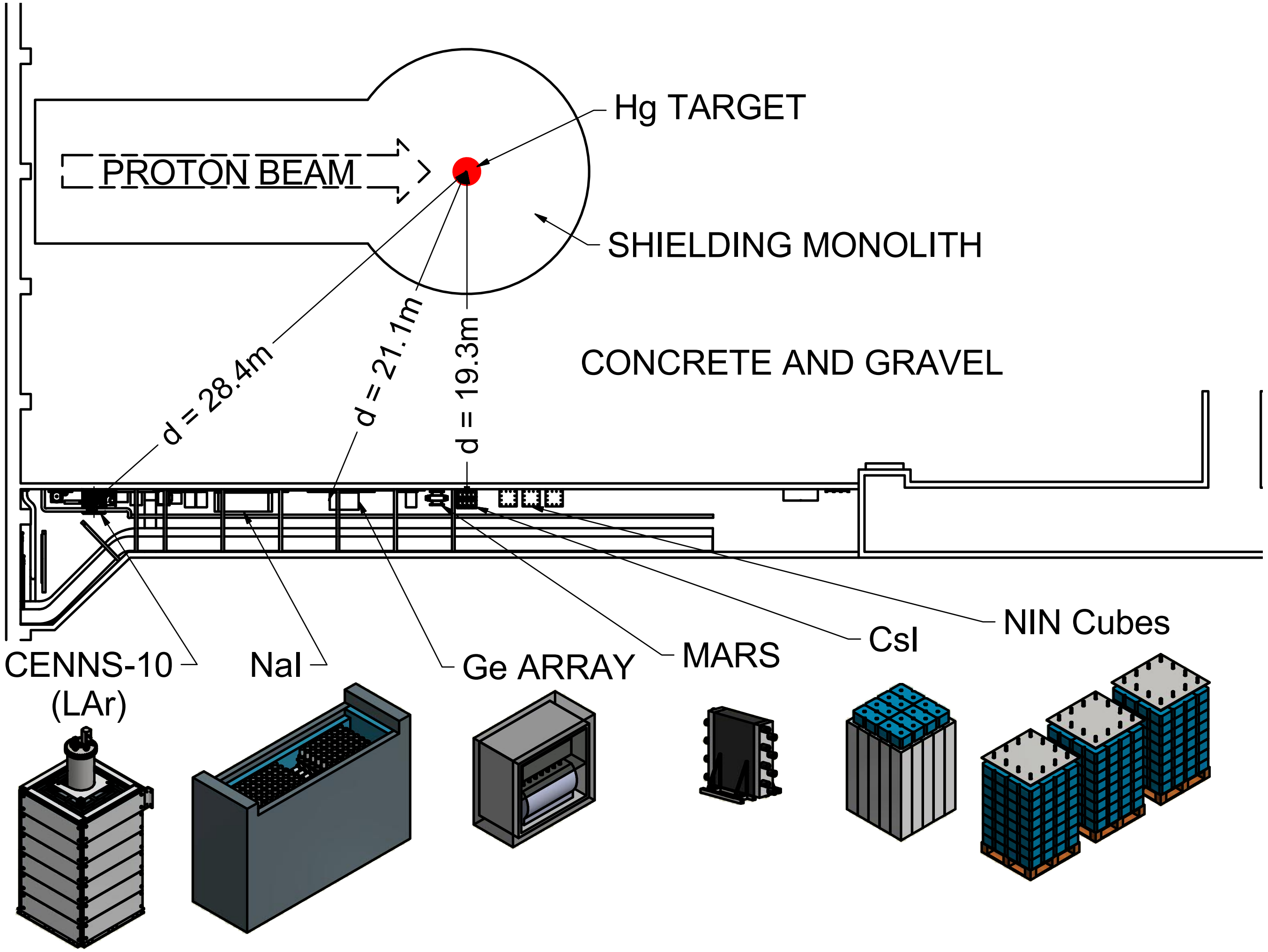


16 Month of data



Ongoing Activities in “Neutrino Alley”

“Neutrino Alley” at SNS basement with protection from SNS produced neutrons and hadronic component of cosmic rays.



Taking data with 22 kg LAr detector. Advanced analysis stage.

Taking data with 185 kg NaI detectors.

Study of neutron backgrounds. MARS commissioning and calibration.

Taking data with CsI(Na).

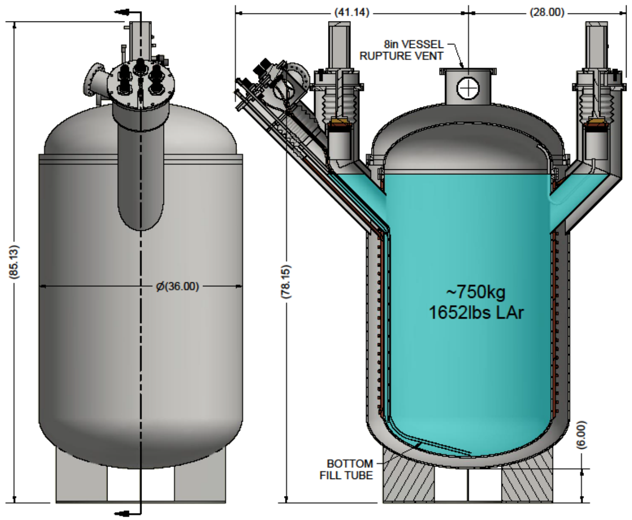
Study of ν Induced Neutrons on Pb and Fe. upgrade using PROSPECT LiLS

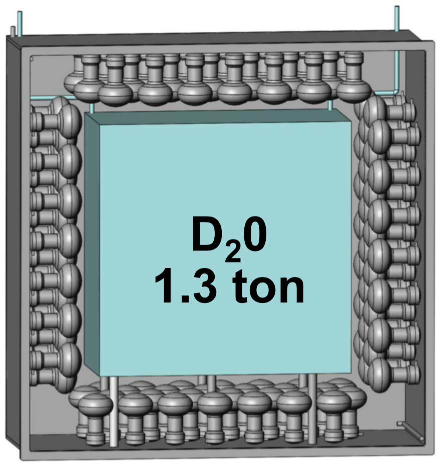
Immediate Goal for COHERENT

- Test of the Standard Model prediction of proportionality of the CEvNS cross section to neutron number squared.
  - 10 kg germanium (Ge) detector
  - 2.0 tonne sodium iodide (NaI) detector
  - 1.0 tonne liquid argon (LAr) detector
  - 1.3 tonne heavy water (D2O) detector

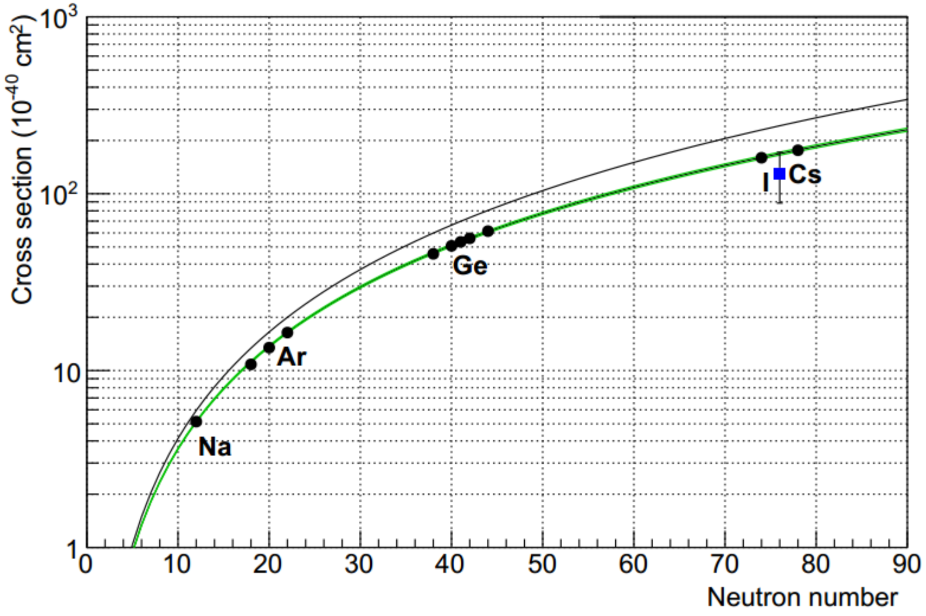
Ge, NaI, LAr: Measure CEvNS

D2O: Calibrate neutrino flux





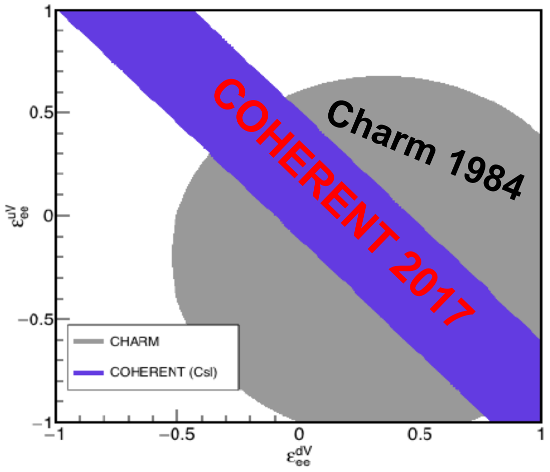
Future Physics for COHERENT



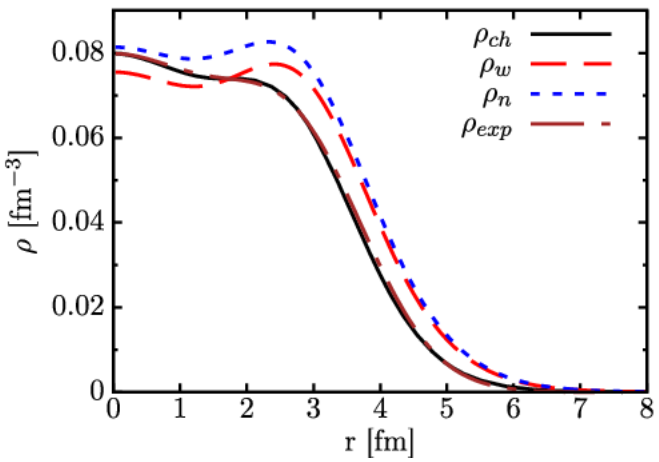
We need large detectors with various targets to untangle effects of nuclear form factors

Large statistics with accurate measurements of recoil spectra:

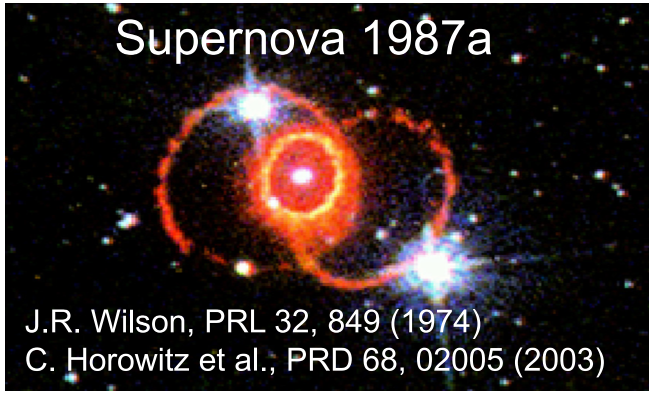
Non-Standard ν Interactions: Test of the SM, DM



Nuclear Physics
Form Factors, Axial Currents



Supernovae Cross Sections and E_W Measurements



COHERENT Director's Review – August 15-16, 2018

COMMITTEE:

- Baha Balantekin - Wisconsin-Madison
- Jonathan Link - Virginia Tech
- Gail McLaughlin - North Carolina State
- Hamish Robertson – U. of Washington

"The SNS provides a source of decay-at-rest neutrinos that is unique in the world, in its intensity and time structure."

"Extraordinarily important and long-sought achievement, the detection of coherent neutrino scattering from a nucleus."

"Great example of the wisdom of P5's Recommendation 4, to "Maintain a program of projects of all scales, from the largest international projects to mid- and small-scale projects."

"A compelling and unique scientific program at SNS. The experimental …could lead into further new physics in a cost effective way."

High Visibility PROSPECT and COHERENT- Publications and Conferences

- Observation of coherent elastic neutrino-nucleus scattering, D. Akimov et al. Science, August 3, 2017, (82 citations)
- First search for short-baseline neutrino oscillations at HFIR with PROSPECT, J. Ashenfelter et al., arXiv:1806.02784v3 [hep-ex], submitted to PRL
- The PROSPECT Reactor Antineutrino Experiment, J. Ashenfelter et al., submitted to Nuclear Instruments and Methods August 2, 2018
- Performance of a segmented 6Li-loaded liquid scintillator detector for the PROSPECT experiment, J. Ashenfelter et al 2018 JINST 13 P06023
- Participation on Major Conferences and Workshops (Neurinos 2018, INT181a, Eclipse, Hawaii APS/JPS, …)

Summary – New Opportunities of Neutrino Physics at ORNL

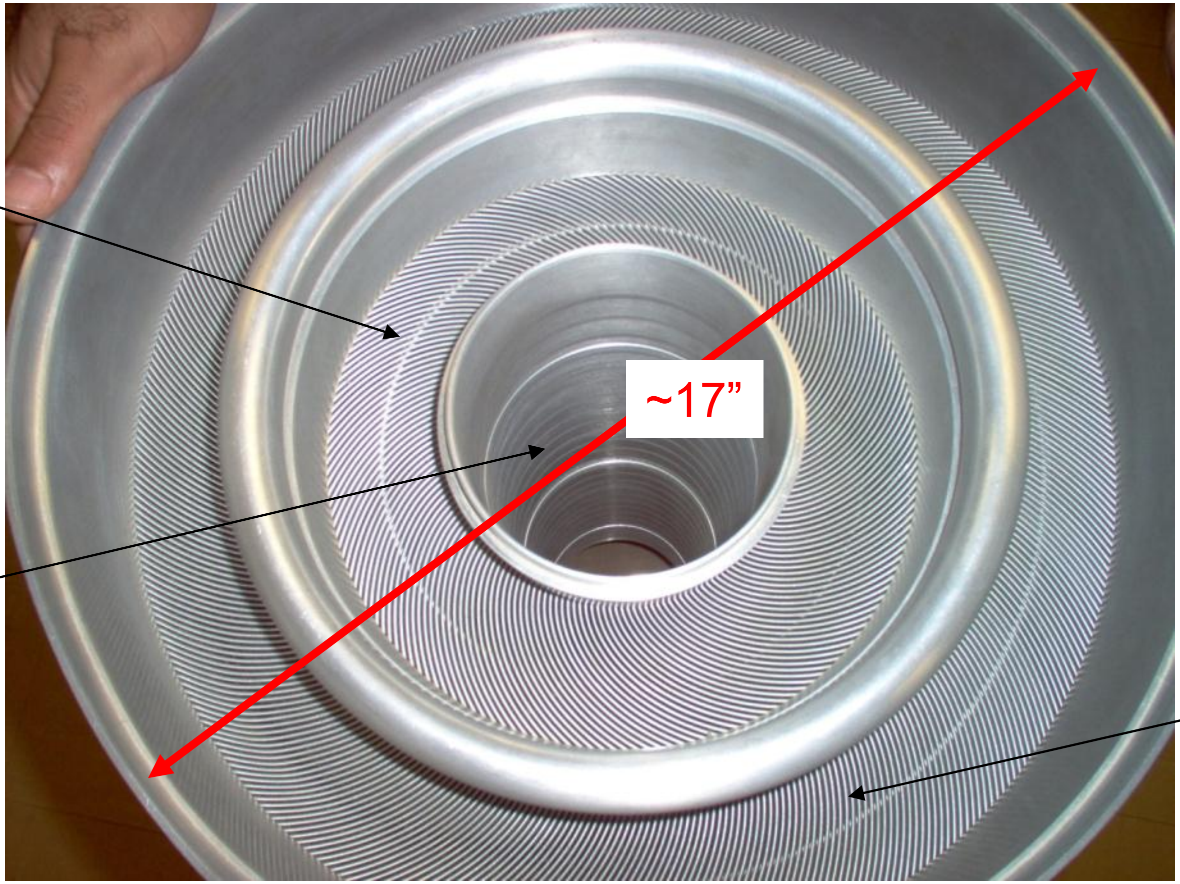
- World class resources: HFIR, SNS and Leadership Computing Facility
- Strong group with deep expertise in projects, detectors, and experimental techniques
- Unique cost-effective scientific program with 2 shallow-depth experiments
- Collaborations involve more than 130 scientists from 30 institutions
- Excellent training ground - More than 75 students and postdocs have been involved
- Strong support from ORNL Physical Sciences Directorate, HFIR and SNS
- PROSPECT successfully completed and taking data (Reactor_on – Reactor_off)
- First observation of CEvNS
- First results published in high-profile publications (Science, PRL)
- Have an effective research plan to build on that success

Backup Slides

HFIR a Research Reactor operating at 85 MW as an intense point-like source of neutrinos

171 Fuel Plates

Flux Trap Region



369 Fuel Plates

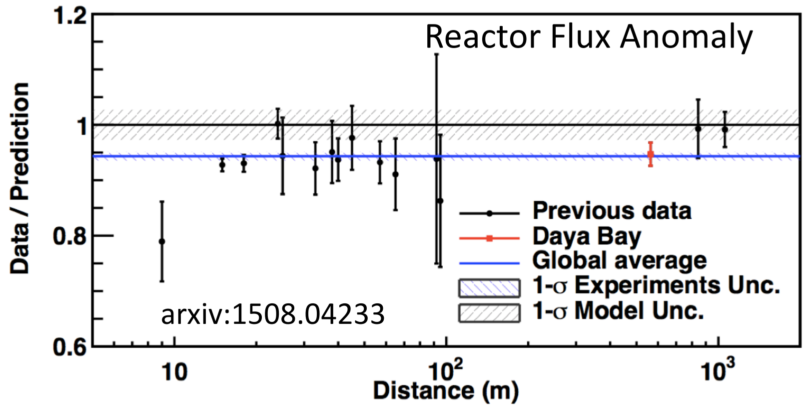
Compact core of HEU fuel

448 cycles X 540 fuel plates = 241,920 fuel plates without a failure.

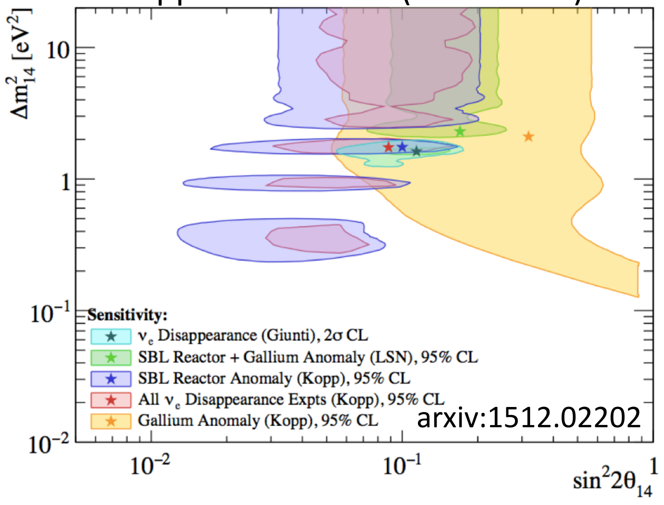
Excellent design and quality control by the fabricator.

PROSPECT Motivation

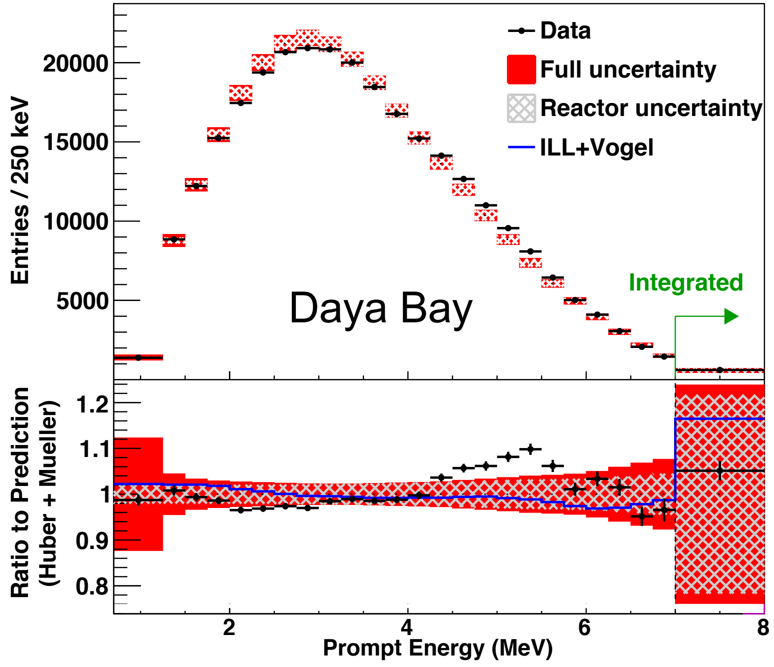
Directly test the hypothesis of a new oscillation with Δm2 ~ 1 eV^2, i.e. oscillation length of few meters



Allowed regions for ν_e disappearance data (3+1 model)



Provide new tests of reactor models by making precision measurements of novel reactor spectra, ^{235}U fuel



OAK RIDGE National Laboratory

Synergetic activities within ORNL PD

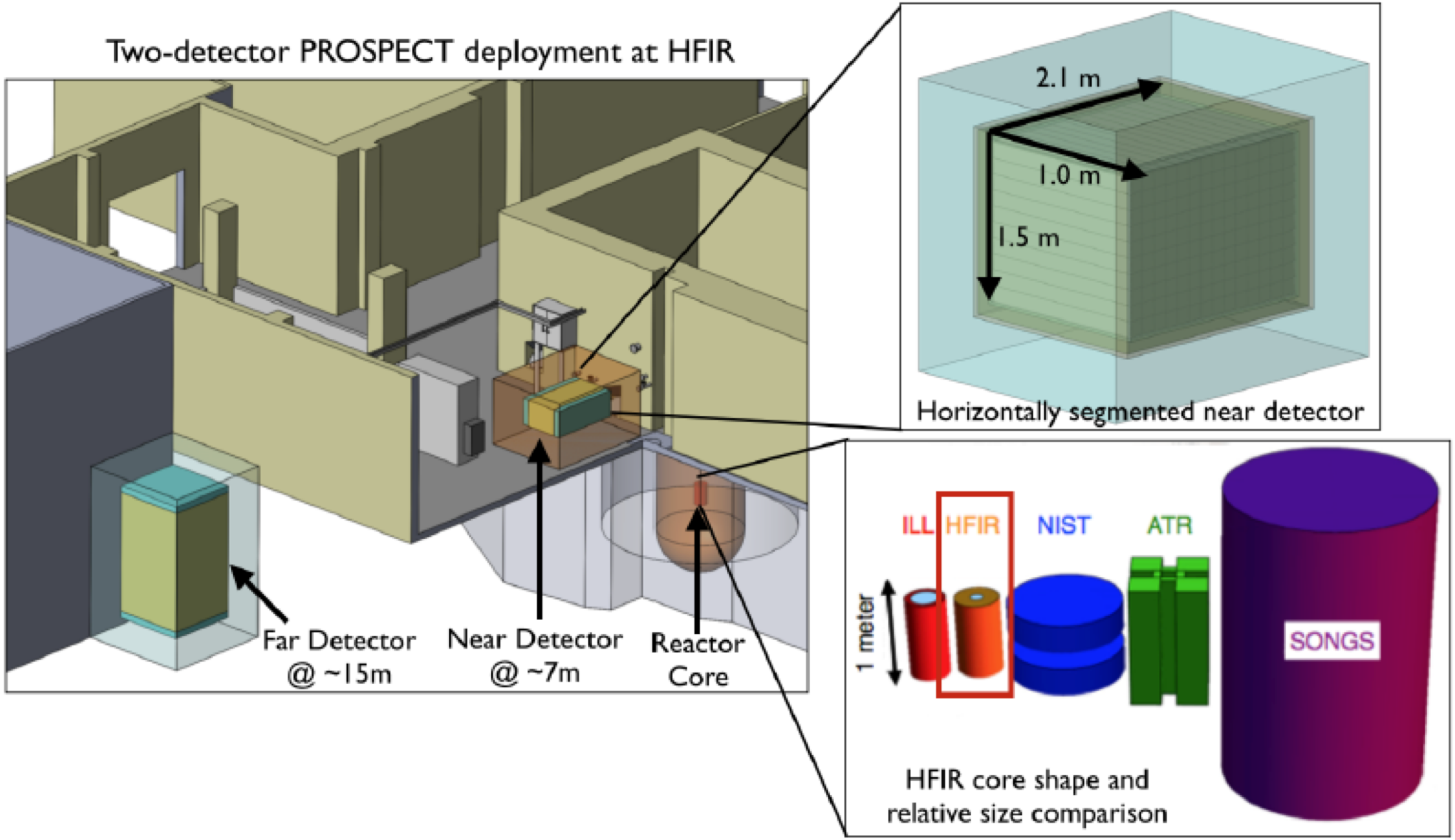
Low Background Materials and Ultrasensitive analytical techniques

Accelerator Mass Spectrometry
Resonant Ionization Laser Spectroscopy in Actinides
Nuclear Activation Analysis

Total Absorption Spectrometry

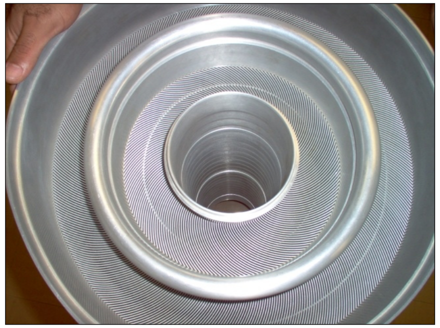
Beta decay of fission fragments

PROSPECT - concept

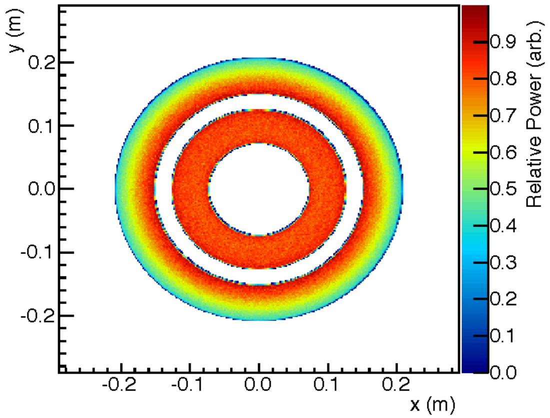


Experimental site: High Flux Isotope Reactor @ORNL

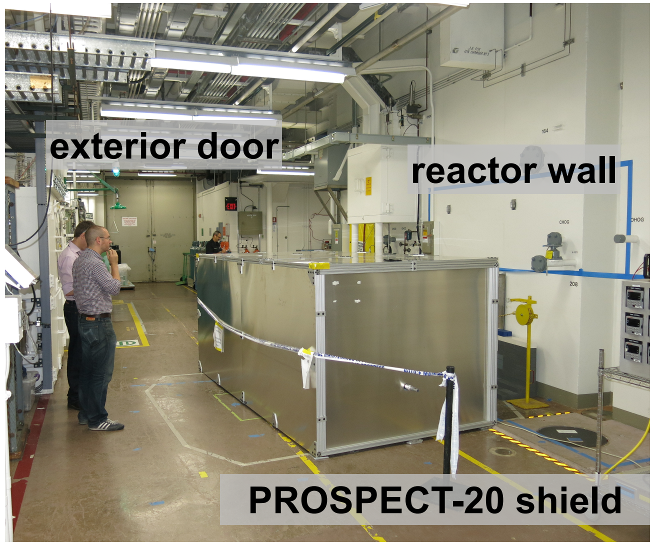
Compact Reactor Core

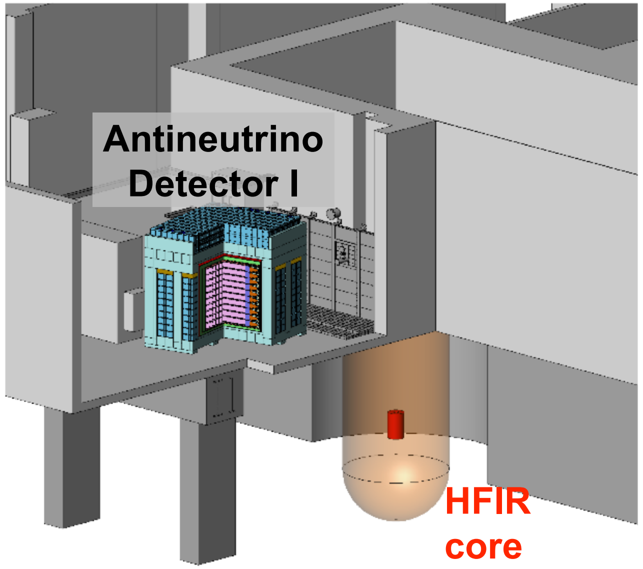


Power: 85 MW
Fuel: HEU (^{235}U)
Core shape: cylindrical
Size: h=0.5m r=0.2m
Duty-cycle: 41%



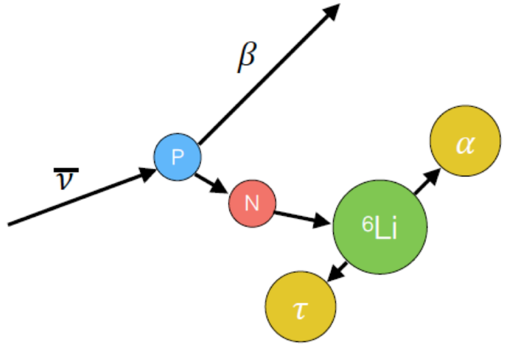
- Established on-site operation
- User facility, easy 24/7 access
- Exterior access at grade
- Full utility access, incl. internet





Event Detection in PROSPECT

Event Identification



Prompt signal: 1-10 MeV positron from inverse beta decay (IBD)

Delay signal: ~0.5 MeV signal from neutron capture on ^{6}Li

40μs delayed n capture

inverse beta decay (IBD)
γ-like prompt, n-like delay

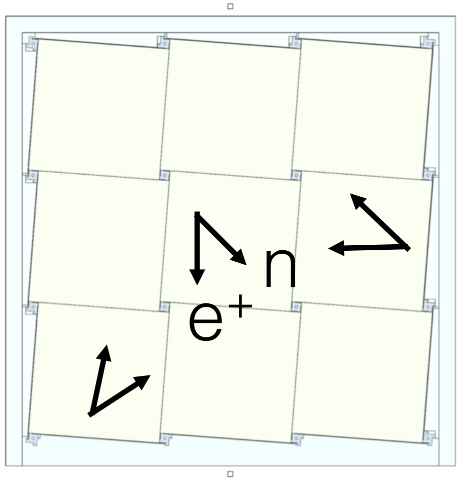
fast neutron background
recoil-like prompt, capture-like delay
capture-like prompt, capture-like delay

accidental gamma background
γ-like prompt, γ-like delay

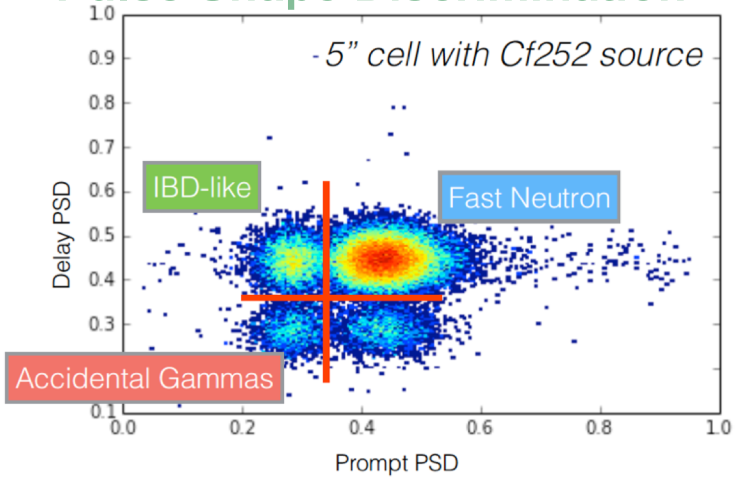
Background reduction is key challenge

Background reduction through **detector design & fiducialization**

IBD event in segmented ^{6}LiLS detector



Pulse Shape Discrimination

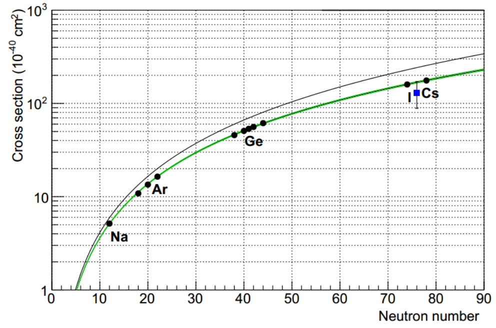


OAK RIDGE National Laboratory

COHERENT Collaboration Steps

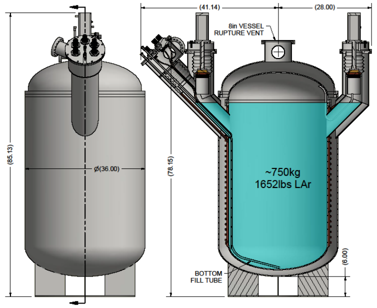
Present: First Light

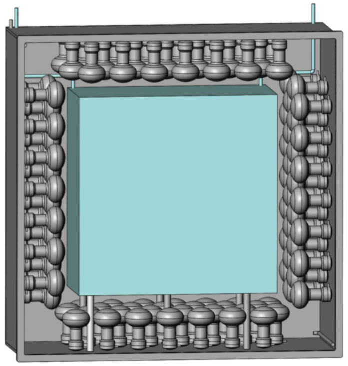
- Detect CEvNS
- Measure CEvNS for heavy and light nuclei
- Detect NINs

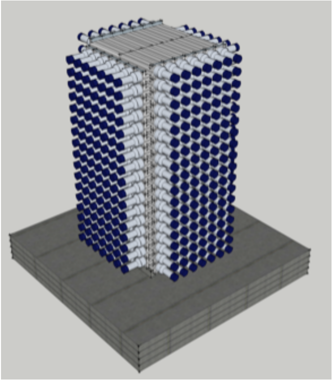


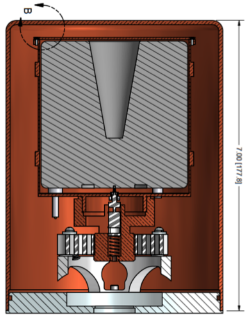
Next Step: New Deployments

- Deploy low threshold Ge detectors
- Calibrate SNS neutrino flux
- High precision CEvNS studies. Look for physics beyond SM.
- Measure neutrino CC to support Supernovae physics, and Weak interaction physics



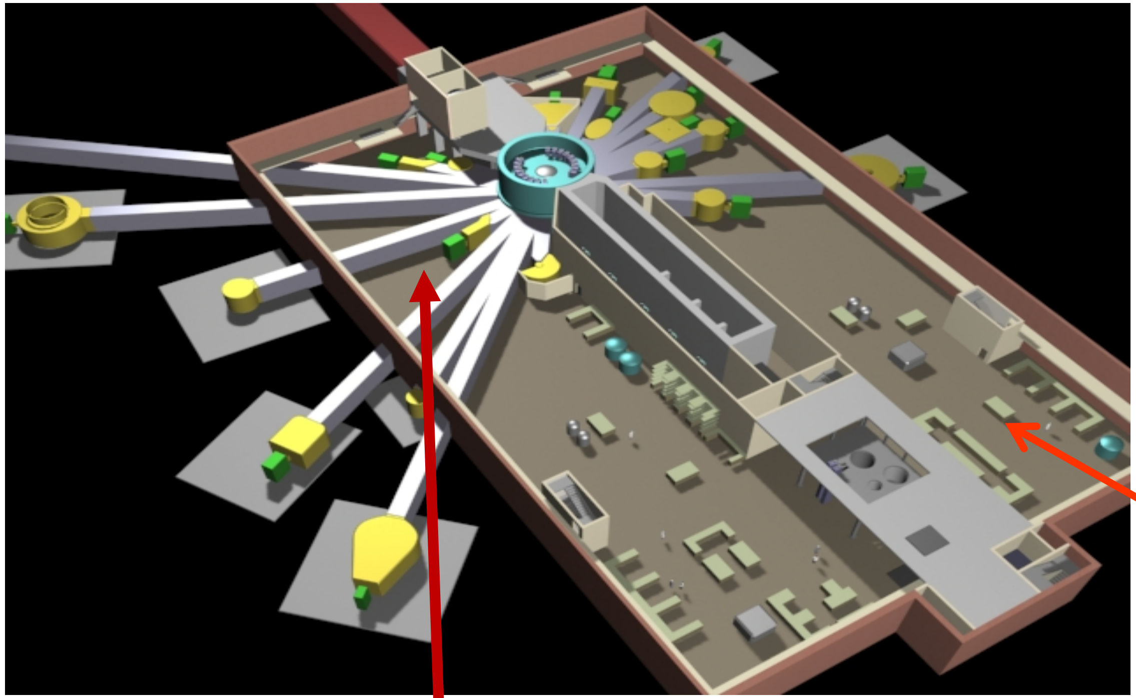


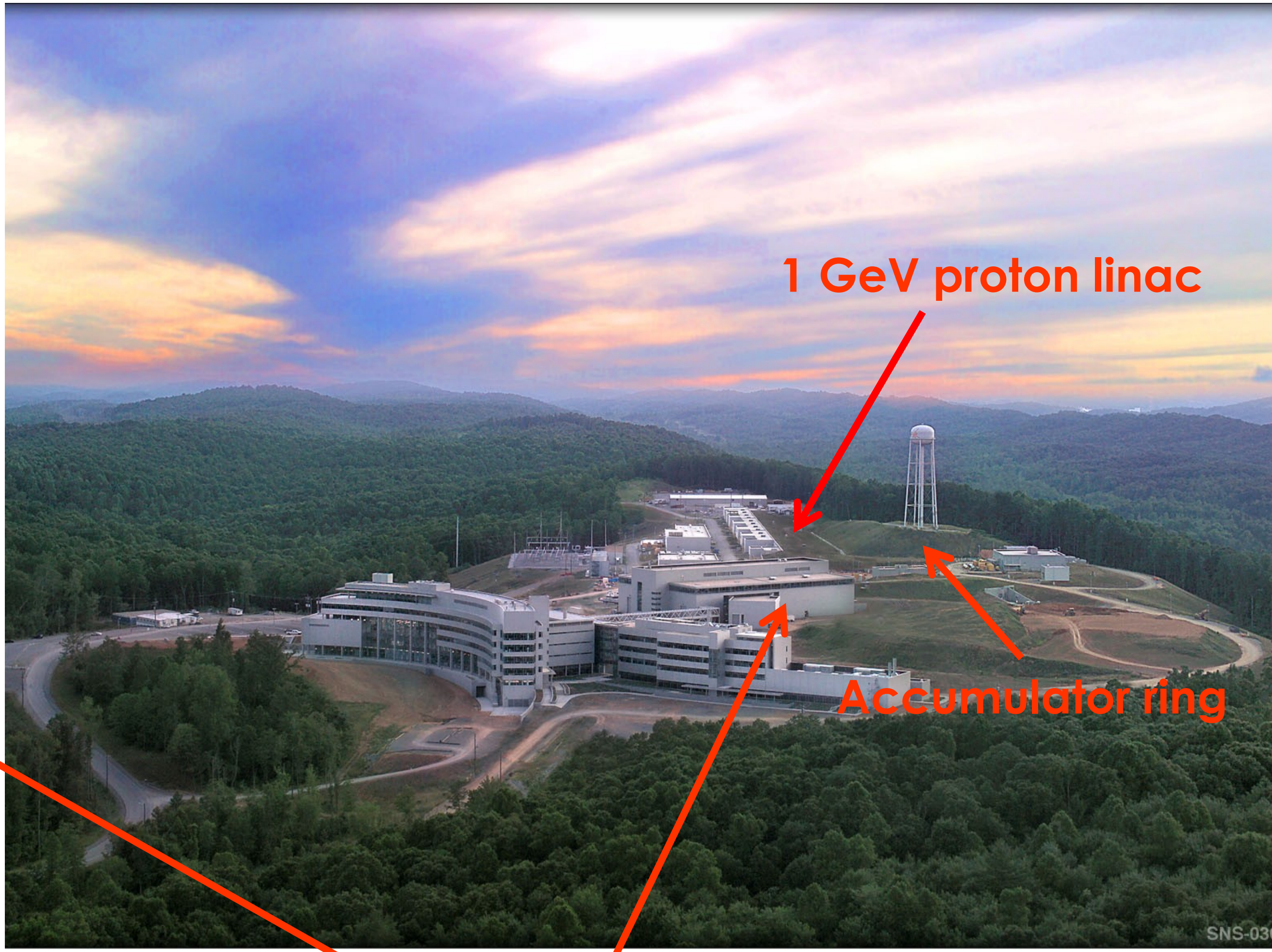


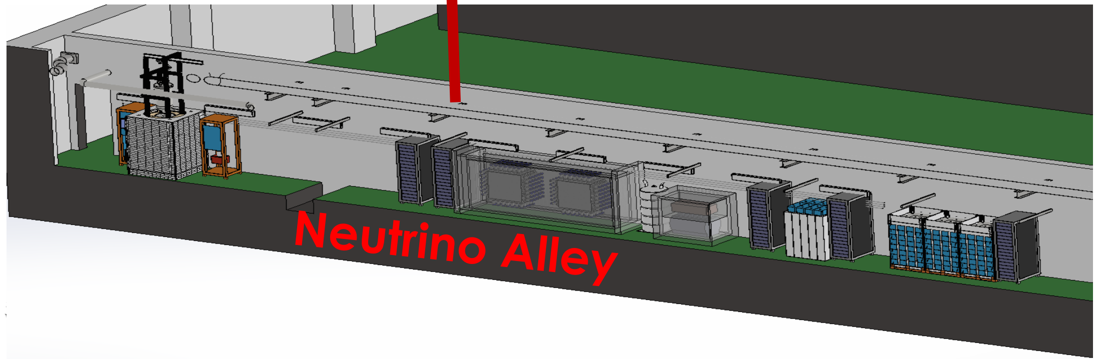


Neutrino Alley Location

After extensive BG program study we find a well protected location







Target Building

Alley is 20-30 meters from the target.
Space between target and alley is filled with steel, gravel and concrete

There are extra 10 MWE from above

COHERENT SNS SPALLATION NEUTRON SOURCE

Future Activities – SNS calibration

Presently we assume that neutrino flux at SNS is known within 10%

Cross sections of neutrino interaction with Deuterium are known with 2-3% accuracy

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

Prompt NC ν_μ +d → 1.8×10^{-41} cm^2
Delayed NC $\nu_{e\mu\text{-bar}}$+ d → 6.0×10^{-41} cm^2
Delayed CC ν_e + d → 5.5×10^{-41} cm^2

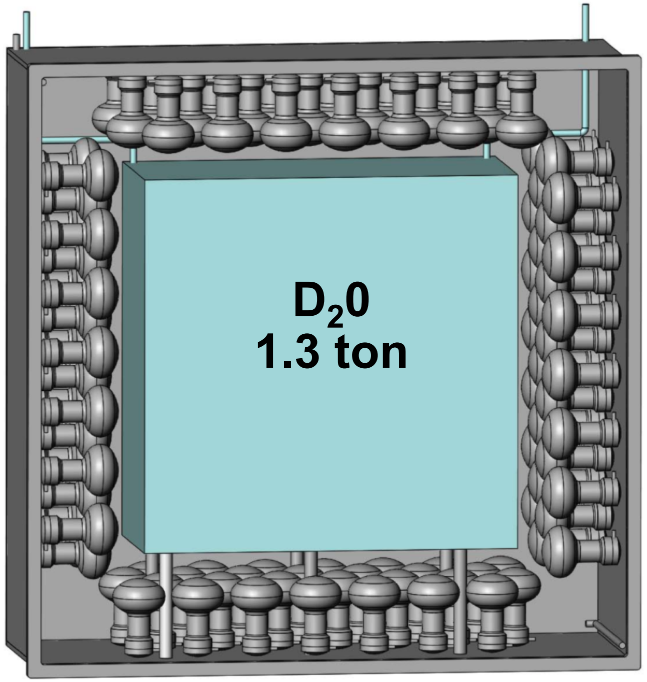
For 1 t fiducial mass detector ~ thousand interactions per year

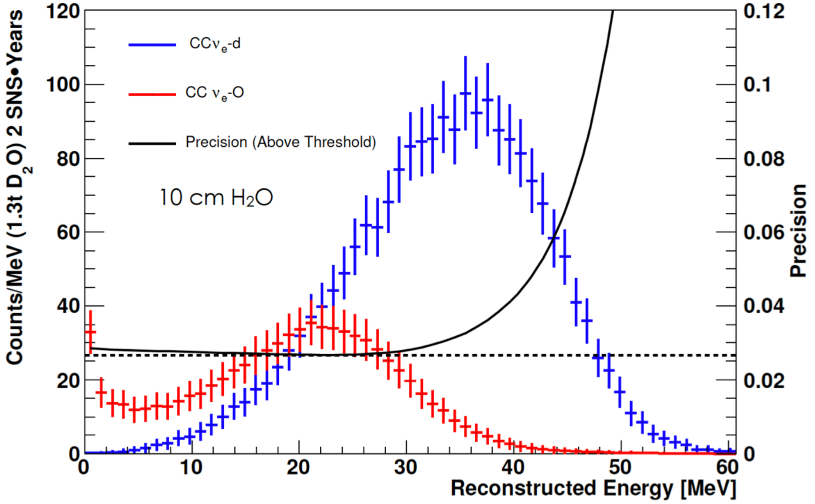
Detector calibration with Michel Electrons (same energy range)

Well defined D_2O mass constrained by acrylic tank

10 cm of light water tail catcher

Outer dimensions 2.3 * 2.3 * 1.0 m^3

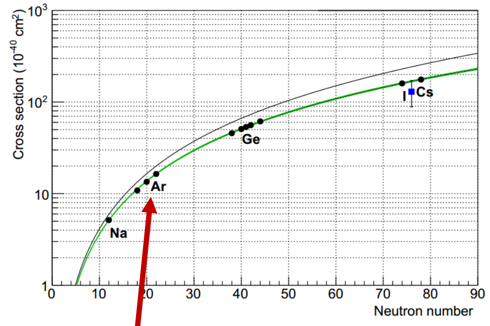


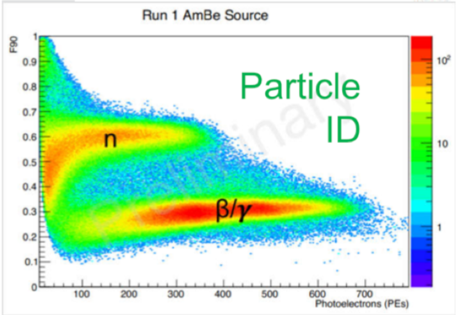


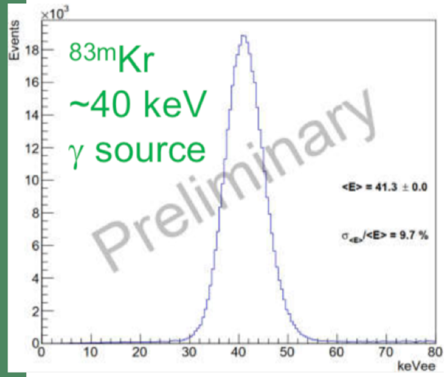
SNS calibration and CC measurements on Oxygen

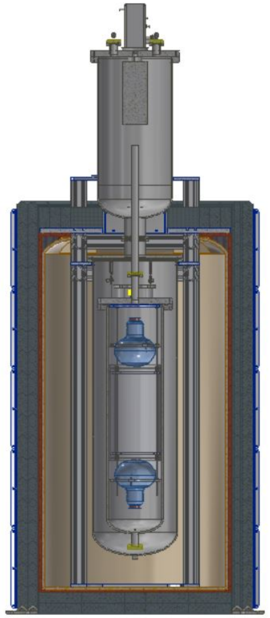
Future Activities - 1 ton LAr detector

Need high statistics low background measurements of CEvNS









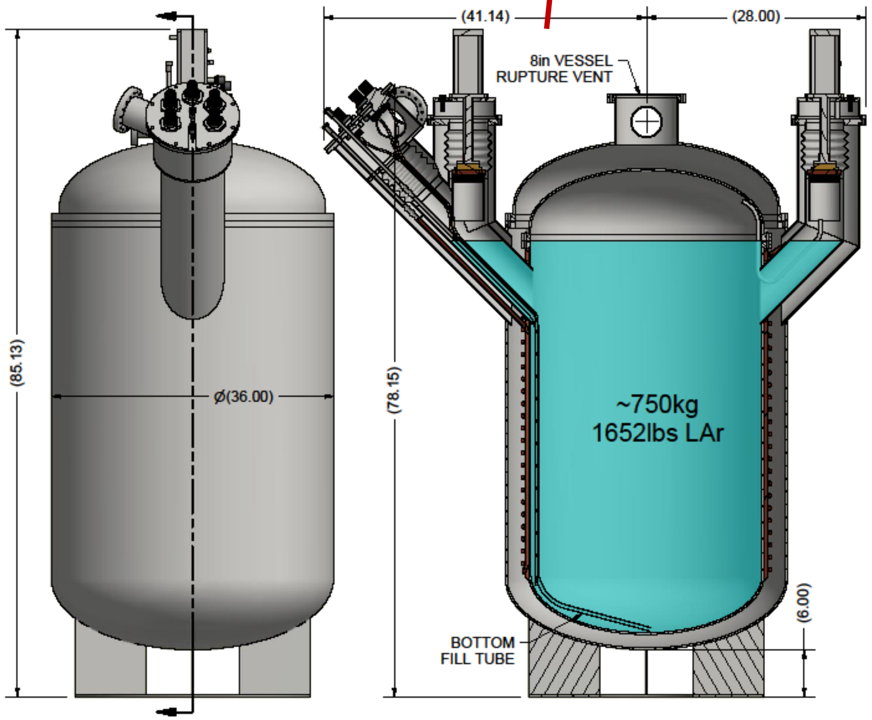
Transition from 22 kg to 1 ton LAr detector.

Can fit at the same place where presently 22 kg detector is sitting

Will reuse part of existing infrastructure

Potentially use depleted Argon; piggyback on DarkSide investments

Will see thousands of CEvNS events per year + CC



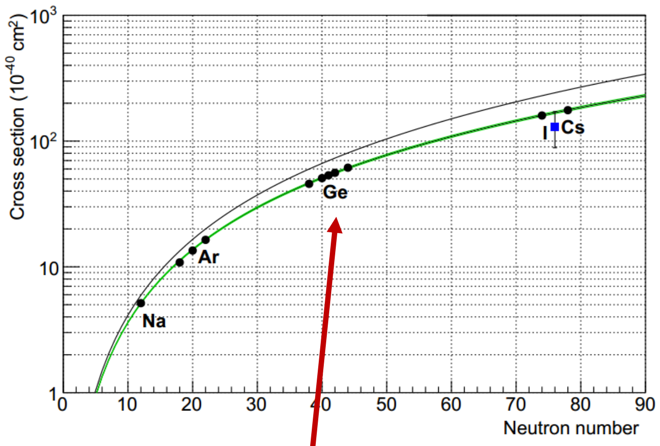
New Germanium Target for COHERENT

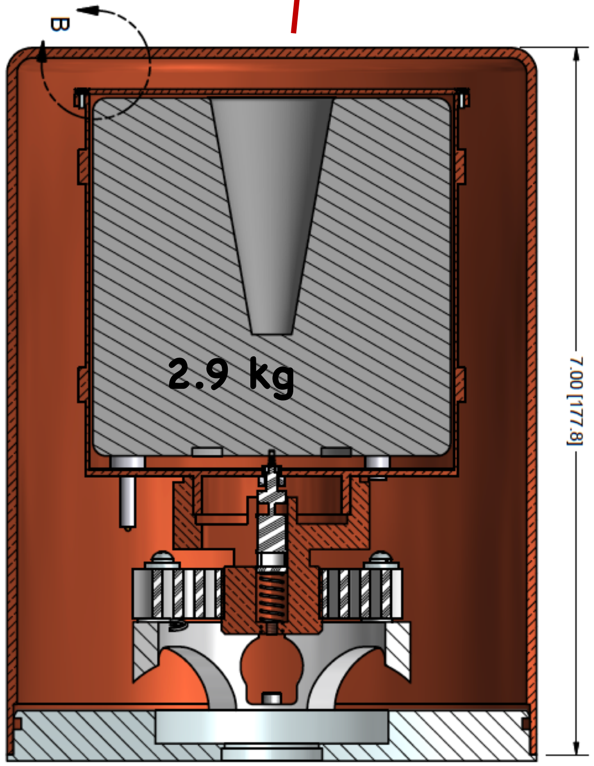
- Use state-of-the-art PPC Ge technology to perform a *precision* measurement of CEnNS. **>800 events/yr from 10 kg** array, with signal/background of ~15 (this was ~1/4 for CsI[Na] first COHERENT result).

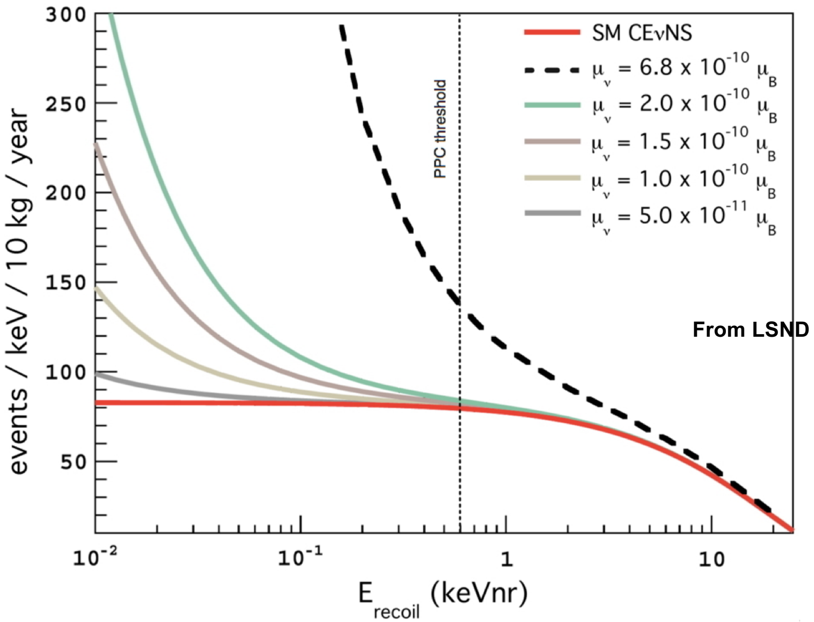
- Demonstrated analysis **threshold of 120eVee/600eVnr** (>70% SA, no false positives) allows measurement of full CEnNS recoil spectrum. Accompanying ongoing effort in quenching factor characterization.

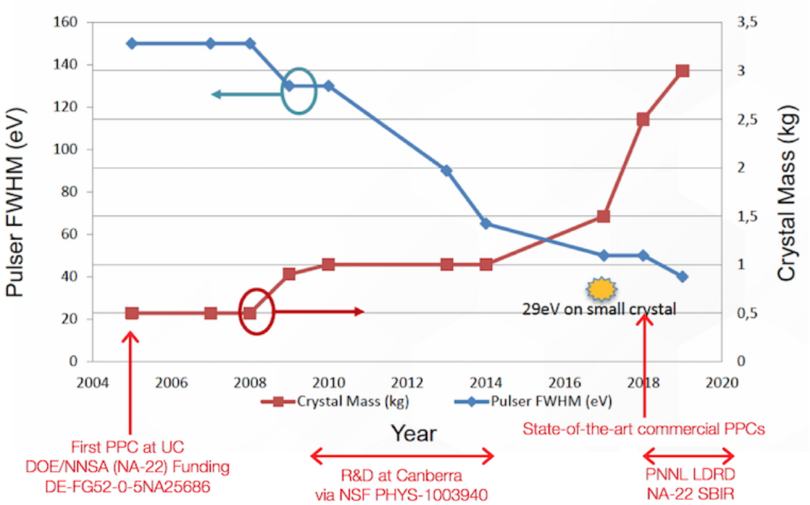
- Improved sensitivity to n electromagnetic properties, non-standard n interactions, MiniBooNE/LSND anomaly (steriles), DM models…

- **Two first detectors (6 kg) funded at University of Chicago through DARPA and NSF**. Shield will be designed to accommodate additional two units. **Support from ORNL/NSCU on shield design and installation is necessary**. Demonstration of threshold and background in 2018. **Start of data-taking at SNS during first quarter of 2019.**

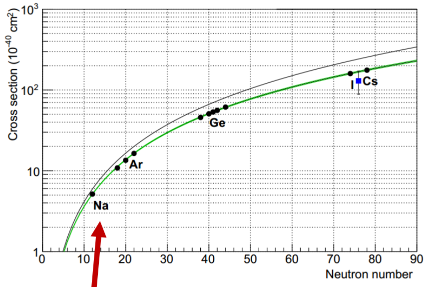








Future Activities - 2t NaI detectors array

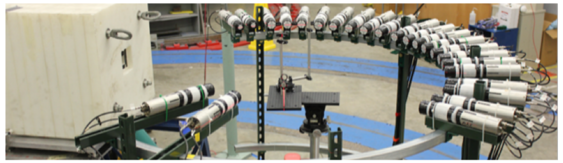


Transition from 185 kg to 2 ton array of NaI detectors

Detectors are available

Need dual gain bases (prototypes has been build)

Program to measure Quenching Factors is ongoing at TUNL



Need electronics and HV; some funds are secure

Potential to detect both CEvNS and CC reactions