Coherent Neutrino Scattering

PIC2018

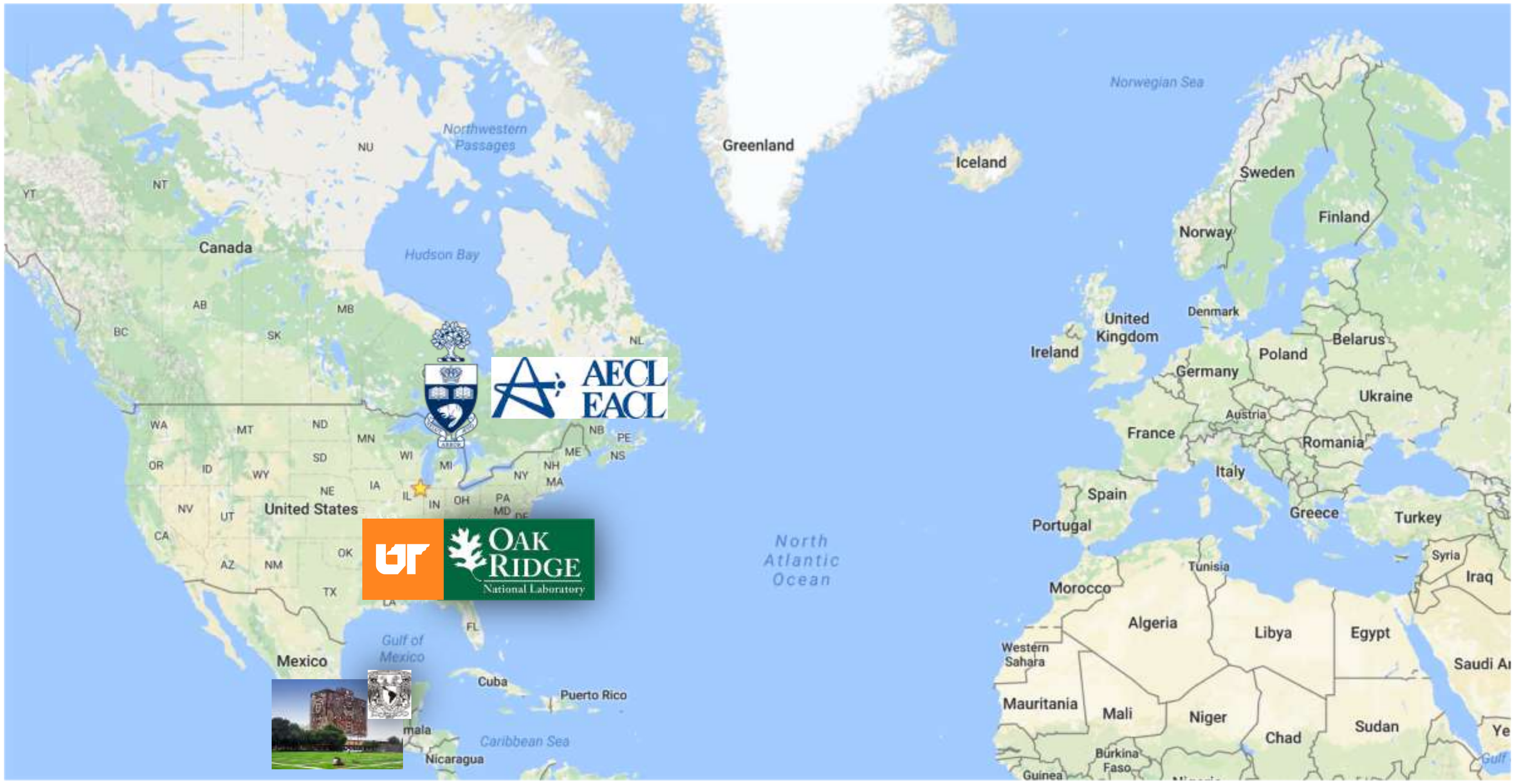
September 12, 2018

Bogota

A. Galindo-Uribarri

COHERENT collaboration

About me:



Northwestern Passages
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Norwegian Sea
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Caribbean Sea
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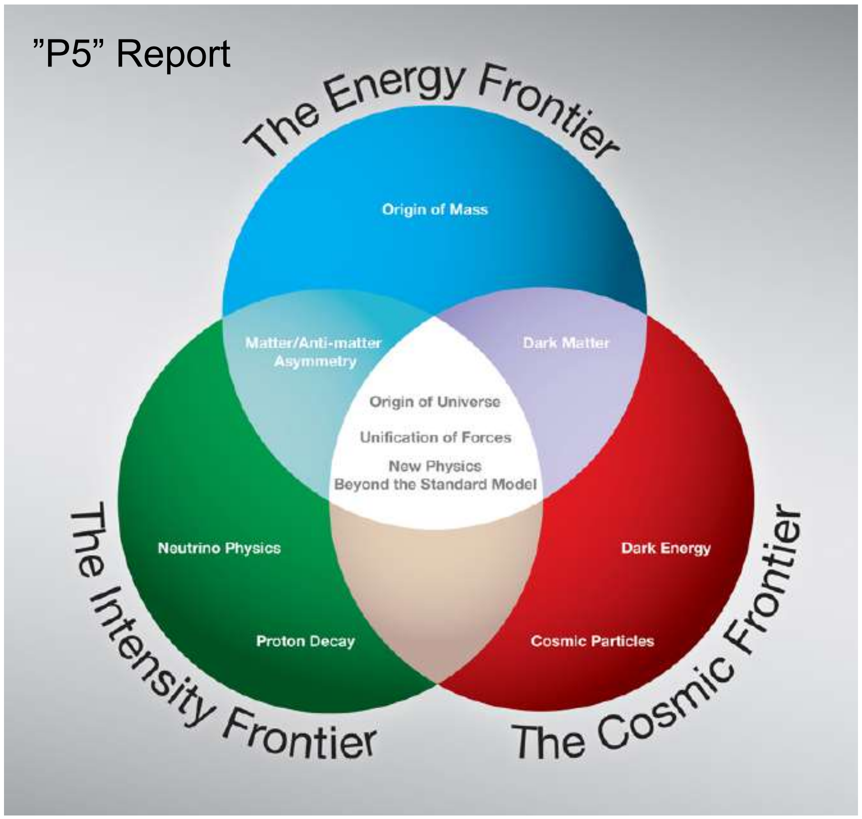
Oak Ridge National Laboratory

Outline

- ORNL Neutrino Opportunities
- Projects
  - PROSPECT
  - COHERENT
  - New Initiatives
- Accomplishments
- Future Plans
- Summary

Physics Goals



Particle Physics Project Prioritization Panel

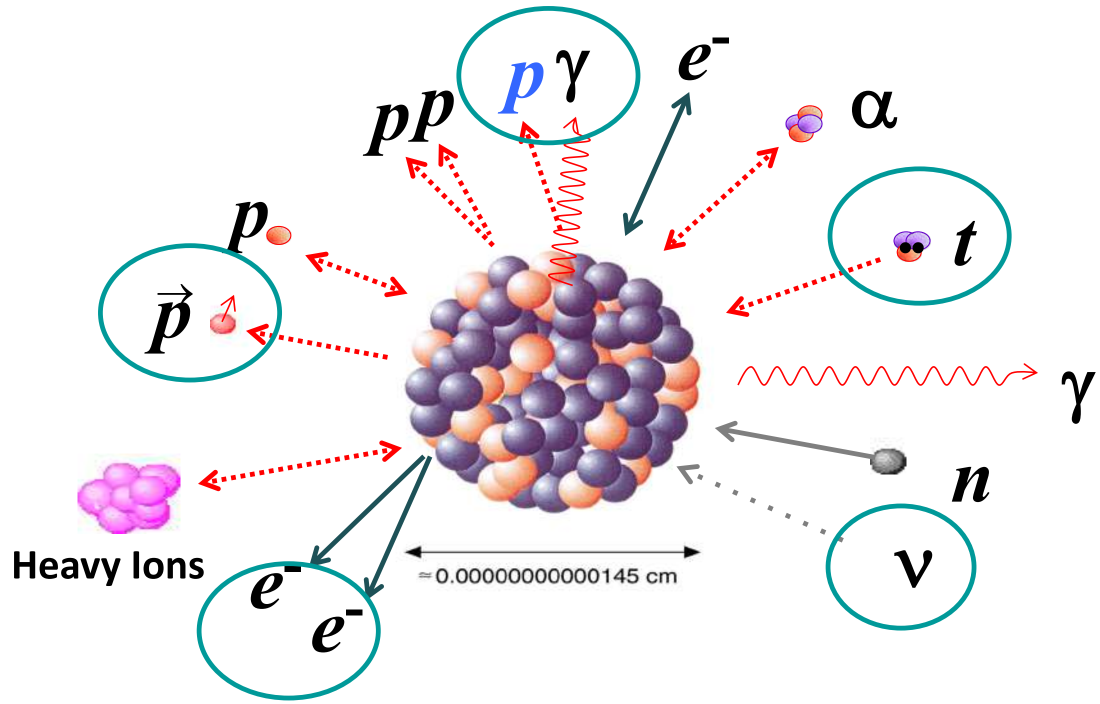
- Pursuing a broad research program in nuclear, particle, and astrophysics
- emphasis on weak interactions and fundamental interactions.

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.

Selective and complementary probes for subatomic physics



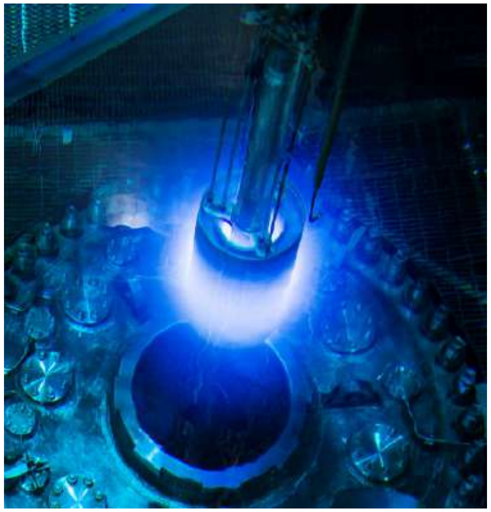
Neutrino Sources and Detectors

- Low Energy Neutrino Sources
  - Reactors (Fission)
  - Accelerators (Spallation; DAR)
- Detectors
  - CsI
  - LAr
  - NaI
  - Ge
  - D2O

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
- 2^{nd} target station



High Flux Isotope Reactor: HFIR

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

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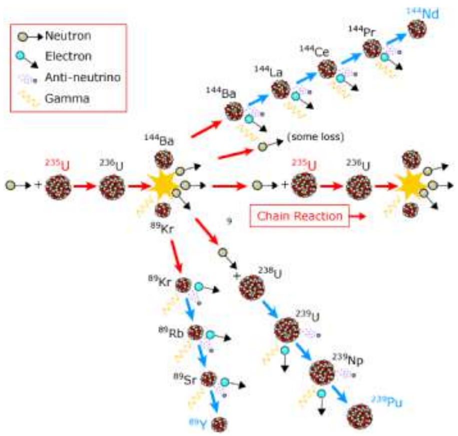
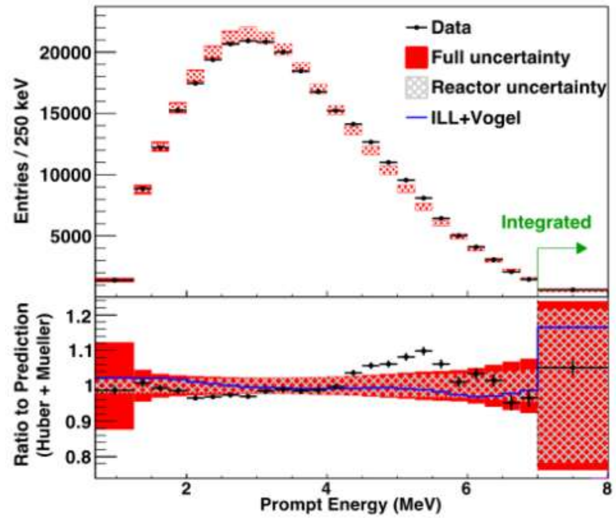
Neutrino flux origin and spectra

HFIR
Fission

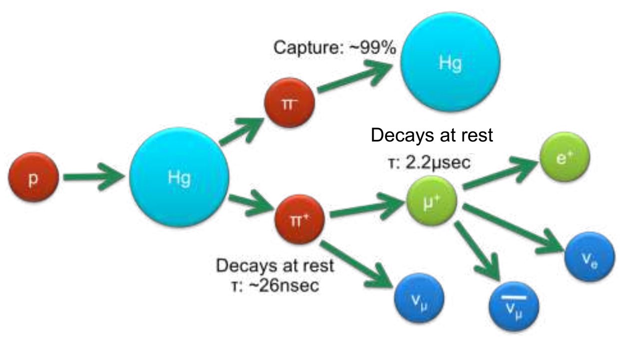


Beta decay fission fragments ($\overline{\nu_e}$)

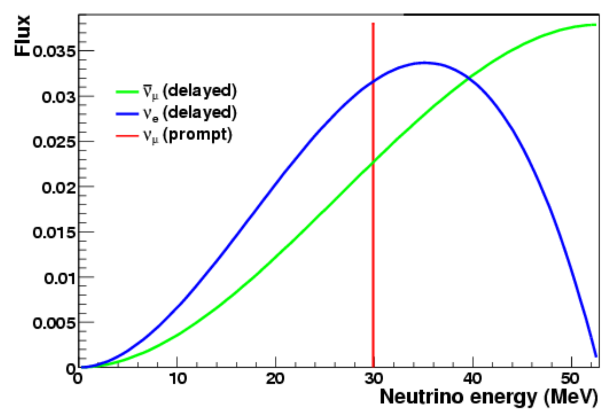


Huge flux
Few MeV
No timing structure

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

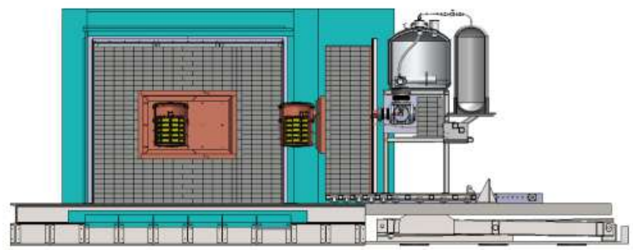
Physics Division

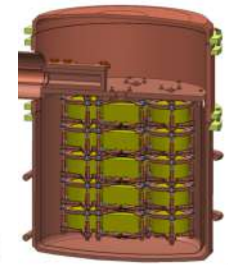
- Computer Cluster
- Laboratory Space
- High-bay area
- Office and Meeting Space for Visitors
- No-cost dormitories (JINPA)

National Laboratory

Current ORNL interests on neutrino physics

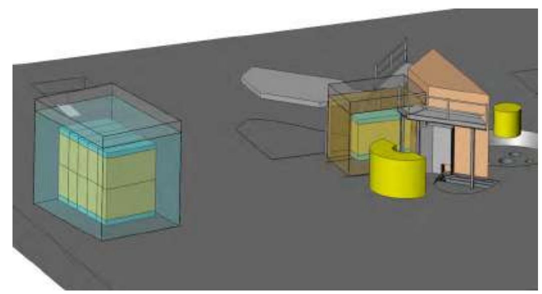
The **MAJORANA DEMONSTRATOR** (MJD)**-** A ^{76}Ge $0\nu\beta\beta$ experiment at SURF



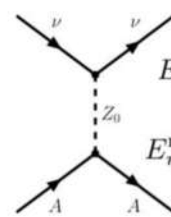


LEGEND 200/ LEGEND 1000-
towards 1 tonne ^{76}Ge experiment

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



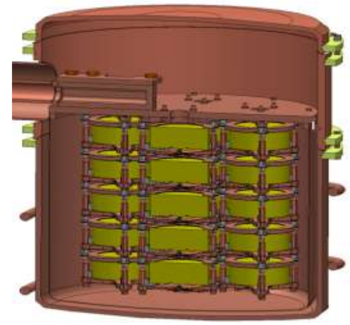
COHERENT- Coherent elastic neutrino-nucleus scattering using the neutrino emissions from the SNS spallation source at ORNL

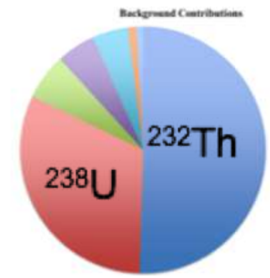


$$E_\nu \lesssim \frac{hc}{R_N} \cong 50 \text{ MeV}$$

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

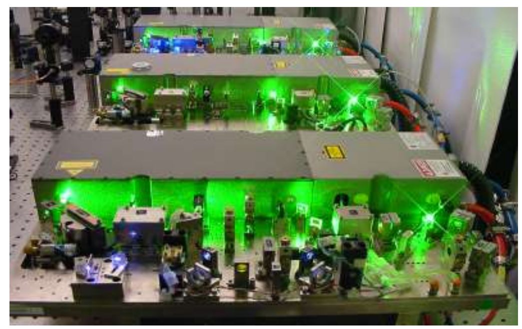
Synergetic activities within ORNL PD





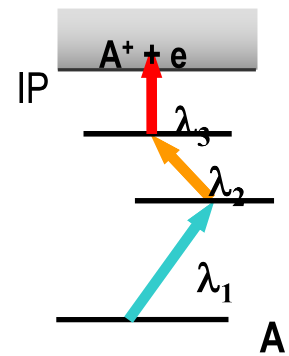
Rad Chem Laboratory

Calibration sources



Ultra-pure materials and powerful analytical techniques:

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

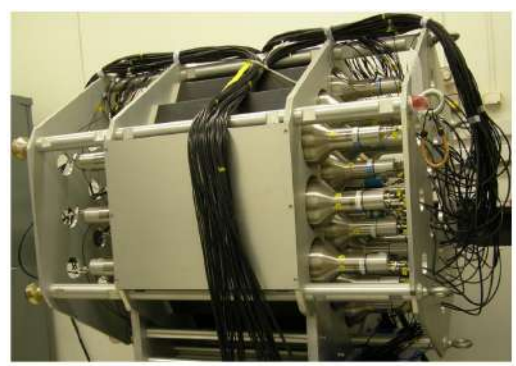


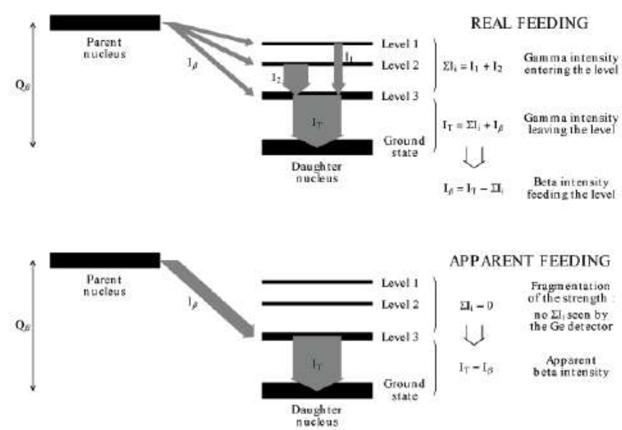
Overall ionization efficiency of **8.7%** for U, **40%** for Th and **51%** for Pu by RIS

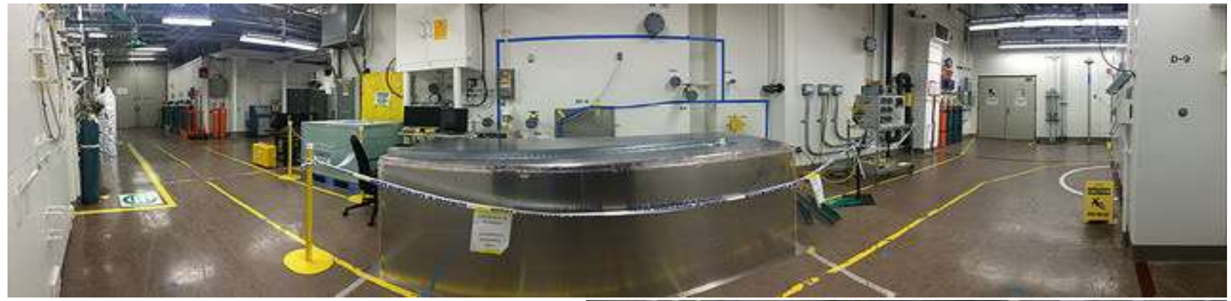
Total Absorption Spectrometry

Beta decay of fission fragments

"Pandemonium Effect"

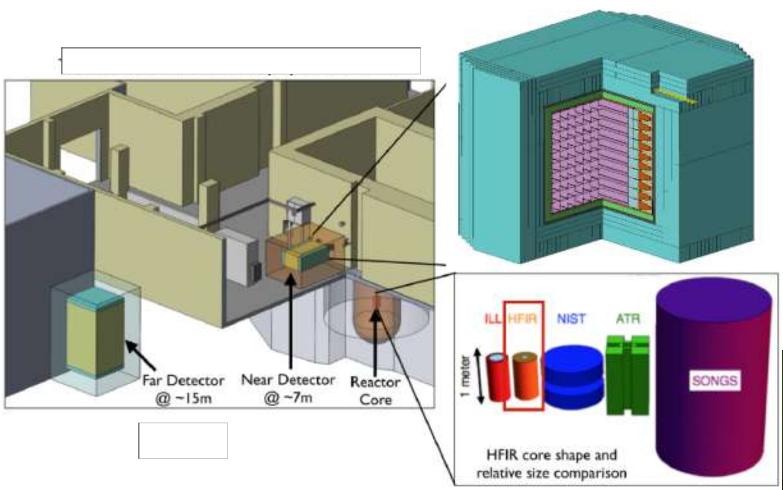


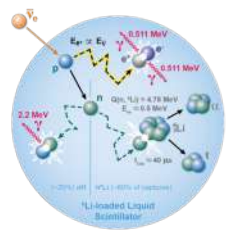


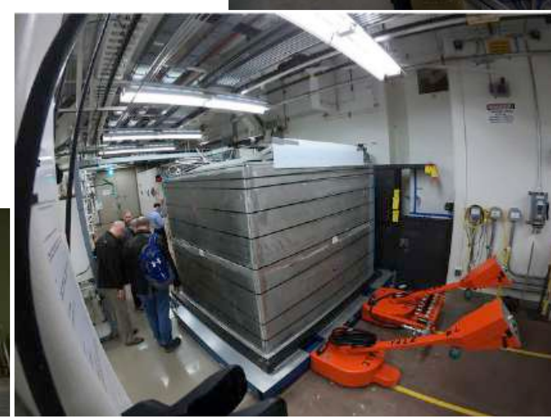


PROSPECT

A Precision Oscillation and Spectrum Experiment







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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

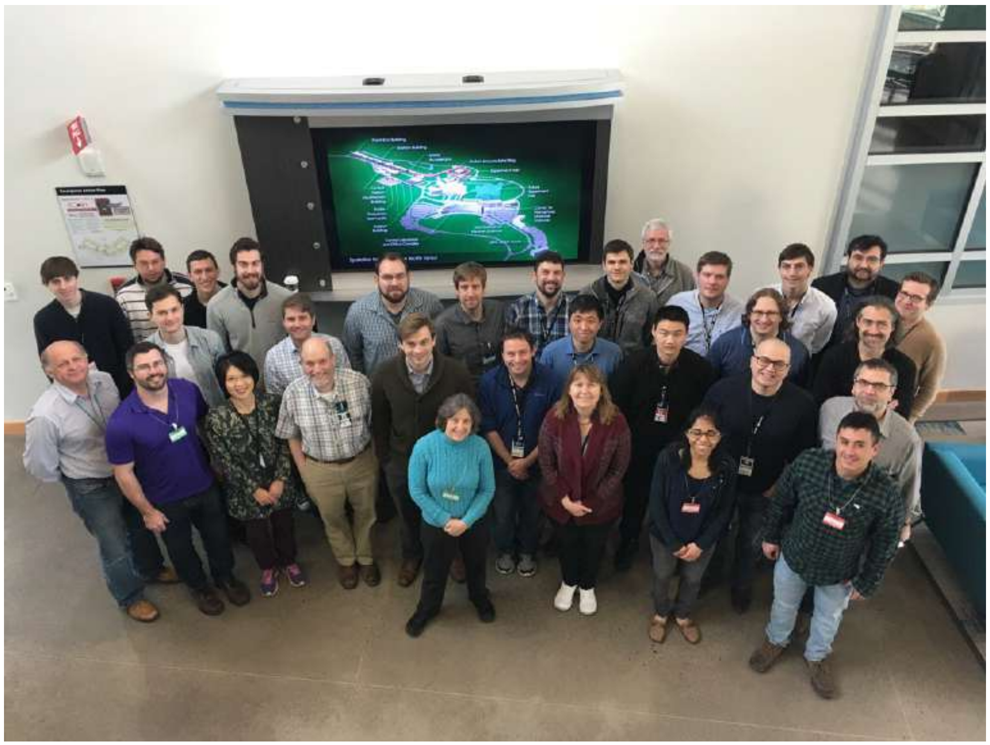
Immediate Goals for PROSPECT

- 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

COHERENT Collaboration

COHERENT SNS SPALLATION NEUTRON SOURCE



Carnegie Mellon University
THE UNIVERSITY OF CHICAGO
Duke UNIVERSITY
UF UNIVERSITY of FLORIDA
KAIST
LaurentianUniversity UniversitéLaurentienne
Los Alamos NATIONAL LABORATORY EST. 1943
MEPhI
NORTH CAROLINA CENTRAL UNIVERSITY FOUNDED 1910
NC STATE UNIVERSITY
NM STATE UNIVERSITY
OAK RIDGE National Laboratory
Sandia National Laboratories
THE UNIVERSITY of TENNESSEE UT KNOXVILLE
TUNL
W UNIVERSITY of WASHINGTON

COHERENT

The COHERENT collaboration aims to make the first successful measurement of Coherent Elastic Neutrino-Nucleus Scattering (CEvNS), a process predicted in the Standard Model.

Furthermore, it is to be done with multiple detector technologies to test the predicted N^2 dependence of the cross-section.

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

$\alpha\ N^2$

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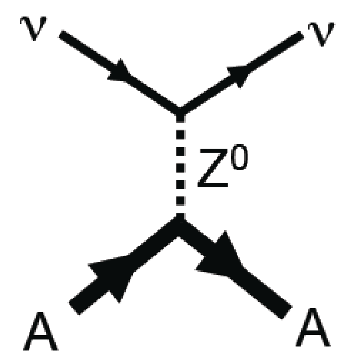
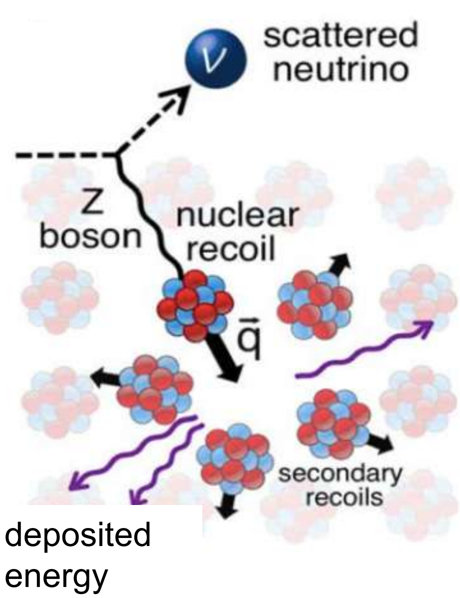
What is Coherent Elastic Neutrino-Nucleus Scattering?

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

$$\nu + A \rightarrow \nu + A$$





Initial and final states must be identical
- neutral current elastic scattering

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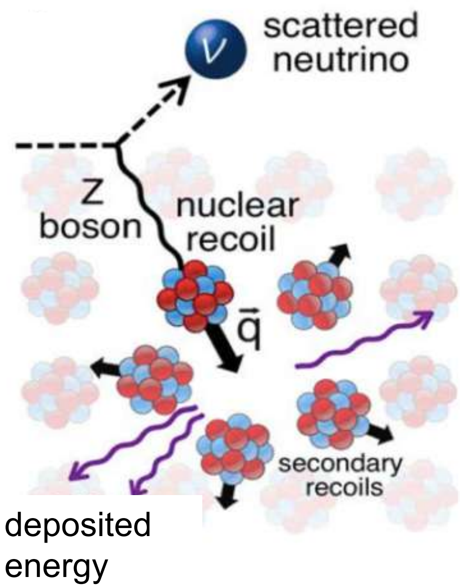


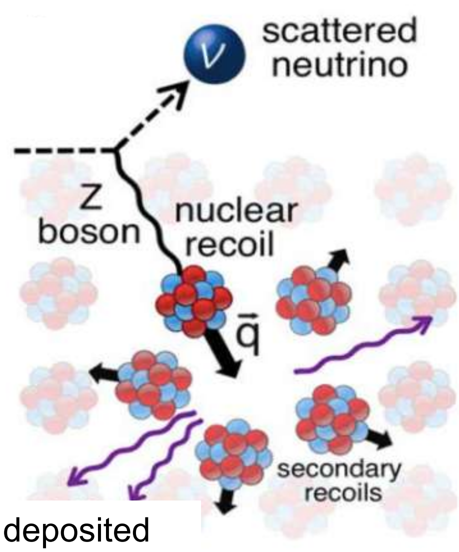
Neutrino scatters coherently off all nucleons - creates enhancement of the reaction cross section (probability of interaction)

Well understood Standard Model calculation - differential cross section with respect to T, the nuclear recoil energy, dependence on neutron number

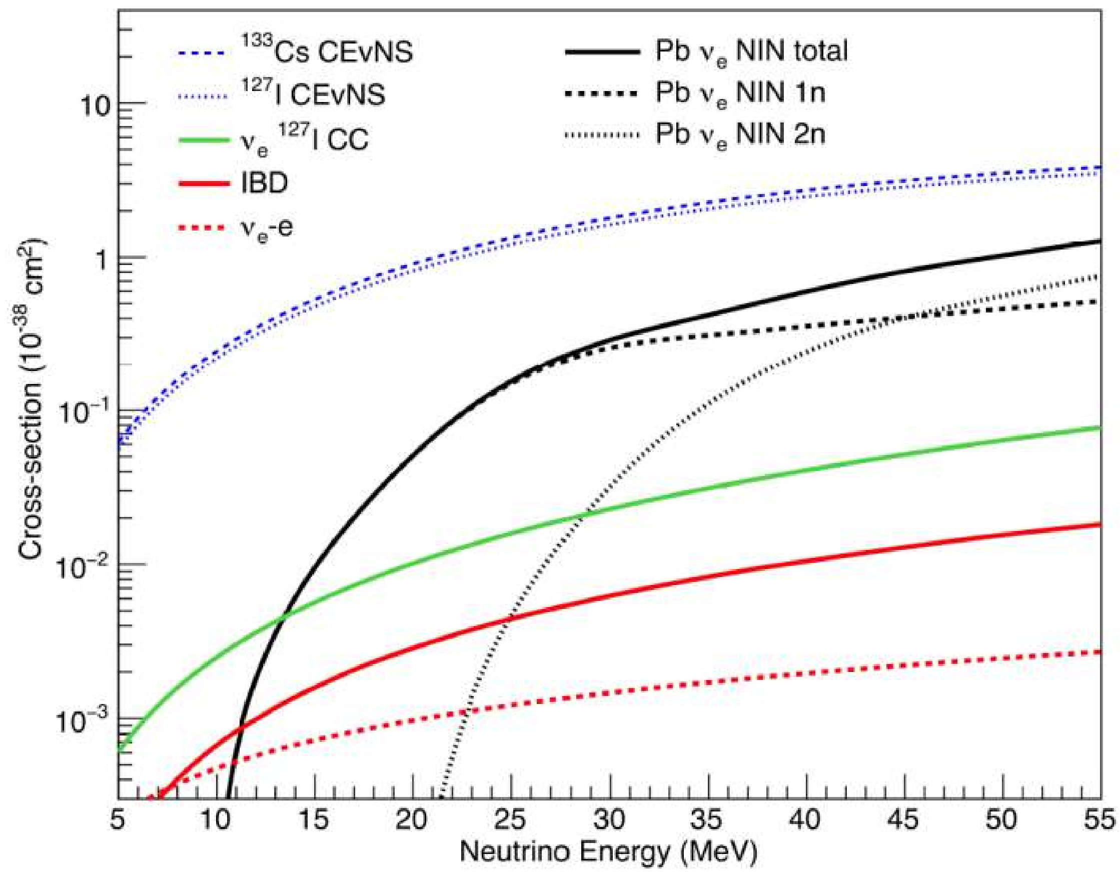
$$\frac{d\sigma}{dT} \propto N^2$$

What is Coherent Elastic Neutrino-Nucleus Scattering?

Cross Section Enhancement



deposited energy



What is Coherent Elastic Neutrino-Nucleus Scattering?

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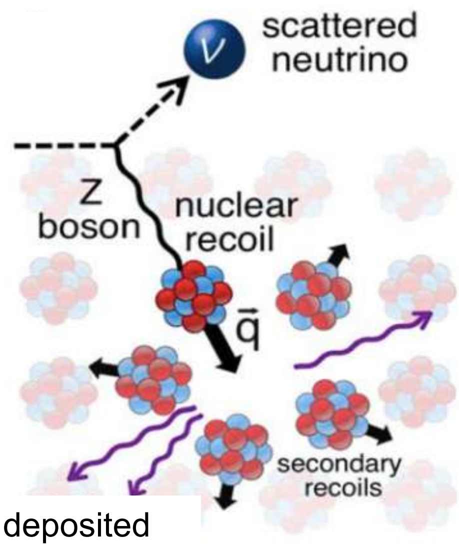

deposited energy

Nucleons must recoil in phase
→ low momentum transfer $qR < 1$
→ very low energy nuclear recoil

Experimental signature - less than about 50 keV of energy deposited from nuclear recoil (Very Difficult)

Perspective

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

CEvNS first proposed in 1974. Why being measured now?

Better detector technology - based on years of Dark Matter experiment development
WIMP dark matter detectors developed over the last ~decade
are sensitive to ~ keV to 10's of keV recoils

Stronger neutrino sources - access to close proximity

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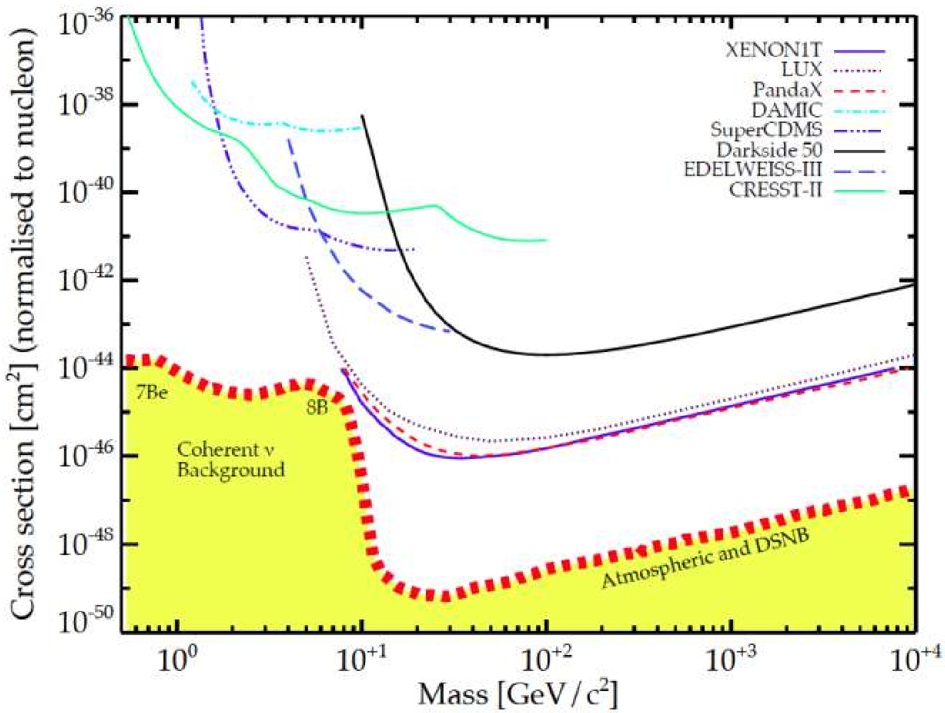
Physics Motivation - “Neutrino Floor”

Dark Matter Experiments

Important background for
10-ton direct searches
- “Neutrino Floor”

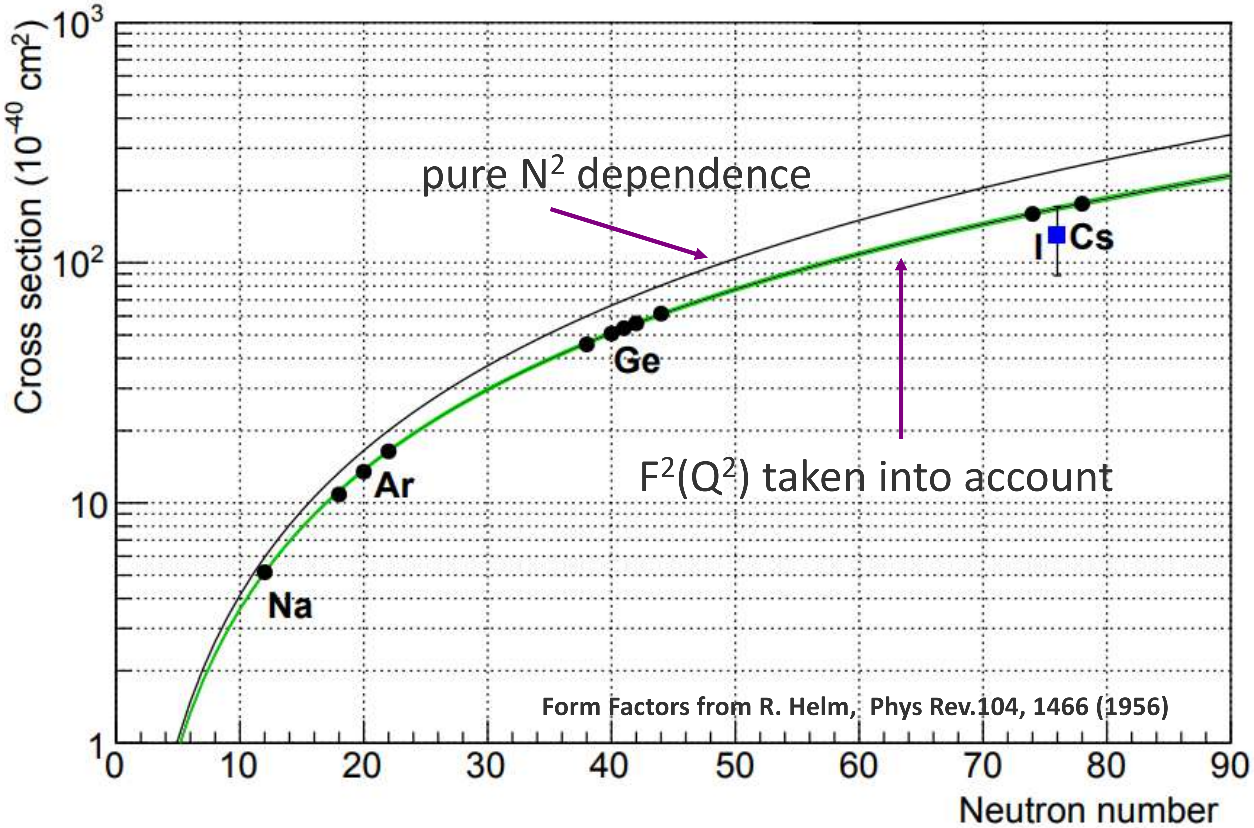


J. Billard, E. Figueroa-Feliciano, L. Strigari
arXiv:1307.5458v2 (2013)

Physics Motivation - Neutron Distribution Functions

K. Patton et al., PRC 86, 024216 (2012)

$$\frac{d\sigma}{d\Omega} \propto (\underline{N} - (1 - 4\sin^2\theta_W)Z)^2 \underline{F^2(Q^2)}$$

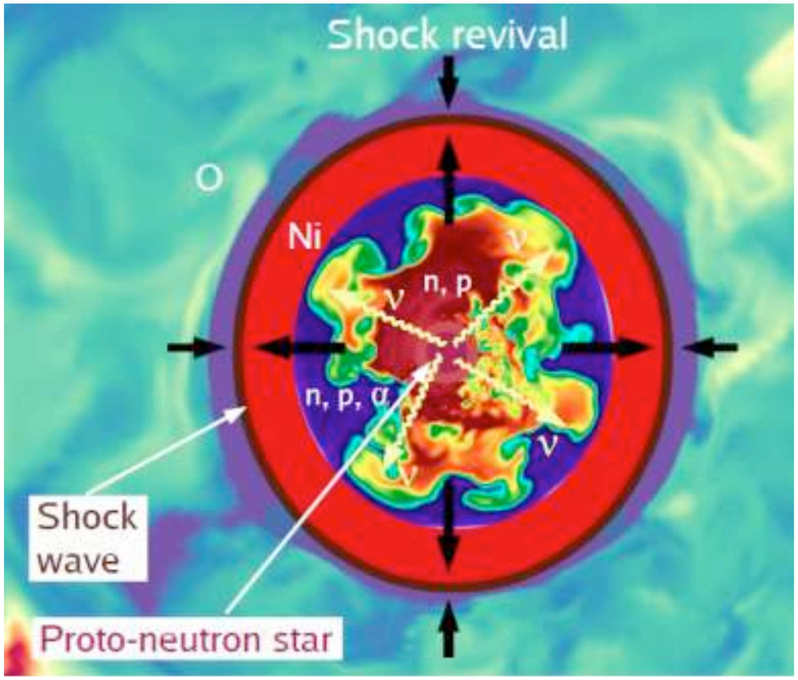


Physics Motivation - Supernova Explosions

In core collapse Supernova explosion the neutrinos carry away about 99% of the released energy ~10^{53} ergs

E_ν ~ 10 MeV

Neutrinos provide energy to stalled shock wave to start re-expansion
CEvNS rates may help reinvigorate stalled shock waves
J.R. Wilson, PRL 32 (74) 849



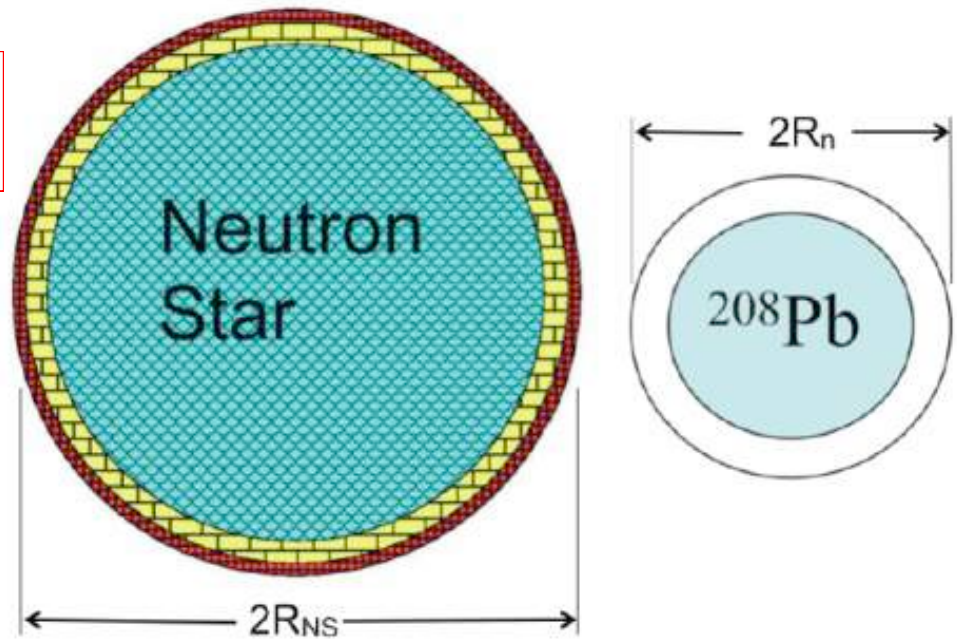
Irene Tamborra NuEclipse, 2017
Review paper: Mirizzi, Tamborra et al. (2016)

Physics Motivation - Neutron Skin Depth

The loss of coherence in CEvNS measures the neutron distribution.

Pressure of neutron matter
- neutrons push outward in nuclei
- radius of neutron star depends on P

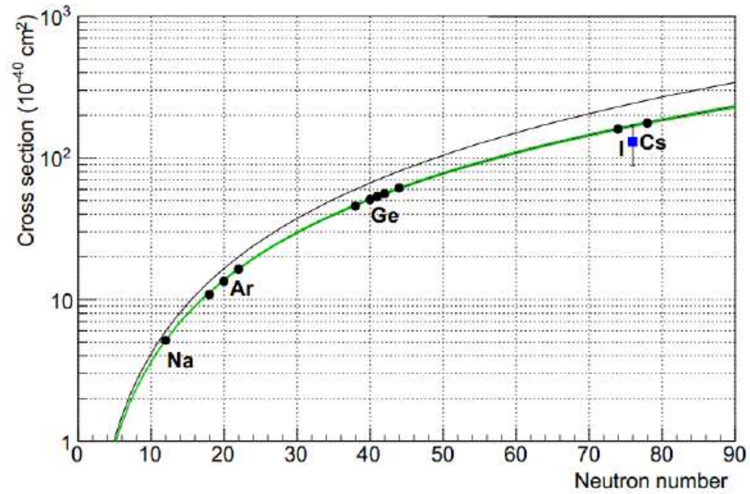
Measurement of nuclear weak radius has implications for neutron stars



Neutron star is 18 orders of magnitude larger than Pb nucleus but has same neutrons, strong interactions, and equation of state.

Chuck Horowitz, NuEclipse Workshop 2017

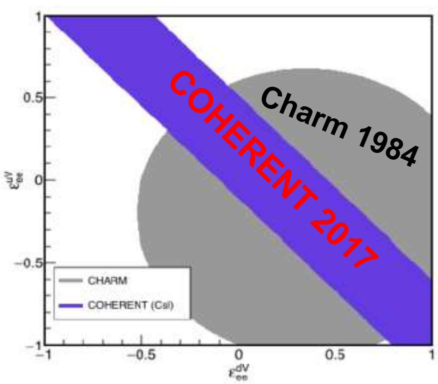
Future Physics for COHERENT



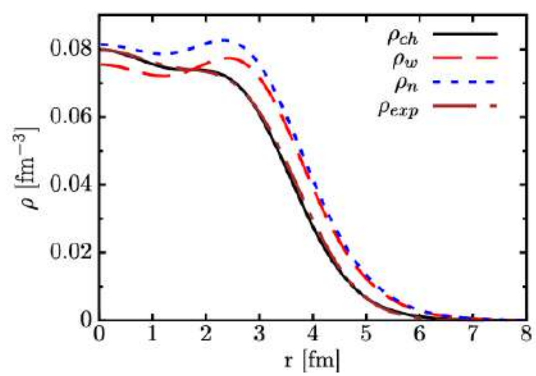
We need large detectors with various targets
to untangle effects of nuclear form factors

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

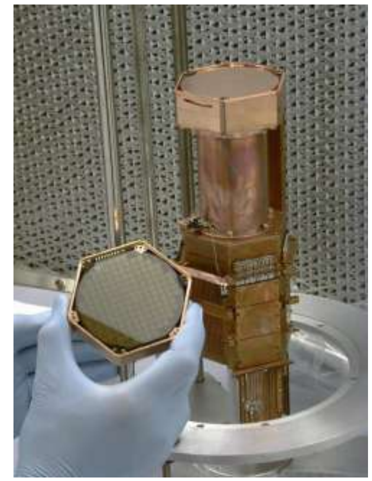
CEvNS - Dark Matter - CEvNS: cryo-bolometers

New type of Bolometer detector proposed in 1984 by Drukier and Stodolsky and 1985 by Blas Cabrerra, Lawrence Kraus and Frank Wilczek PRL 55,25 (1985)

Reactors and Spallation Sources proposed as sources

Precursor to CDMS and CRESST Dark Matter searches

CEvNS - Dark Matter - CEvNS: cryo-bolometers



Mitchell Institute Neutrino Experiment (MINER)

Ge semi-conductor technology with phonon amplification
low-threshold (<100 eV), sensitivity to CEvNS
2 m proximity to reactor core with moveable core (Texas)
- test short baseline oscillation

10 kg detector material - sensitivity to CEvNS in 1 month

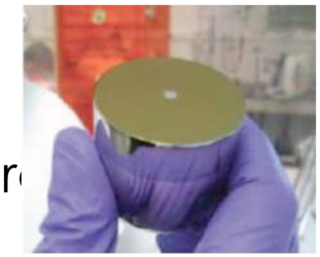
RICOCHET

Ge+Zn semi-conductor technology; use Zn for time profile analysis
low-threshold (~100 eV), sensitivity to CEvNS
355 m/467 m to two reactor 4.6 GW core - Double Chooz lab, France

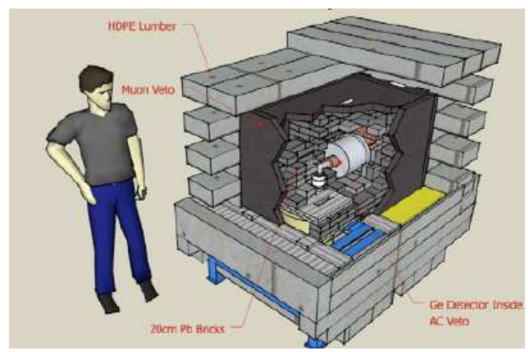
CEvNS - Dark Matter - CEvNS: HPGe

University of Chicago Group

P.S. Barbeau, J.L. Collar, O. Tench JCAP 2007 (09):009



CoGeNT - located at San Onofre Reactor, ~ 25 m from the cor
ultimately foiled by residual electronic noise
~ 600 eV threshold



PPC Ge detectors - now used in Dark Matter and 0nbb experiments

CEvNS - Dark Matter - CEvNS: HPGe

nGeN located ~10-12 m from Russian Reactor
350 eV threshold, 1.6 kg

COnUS located 17 m from 4 GW German Reactor
4 kg Ge

TEXONO located 17 m from 4 GW Taiwan Reactor
1 kg Ge, ~300eV threshold

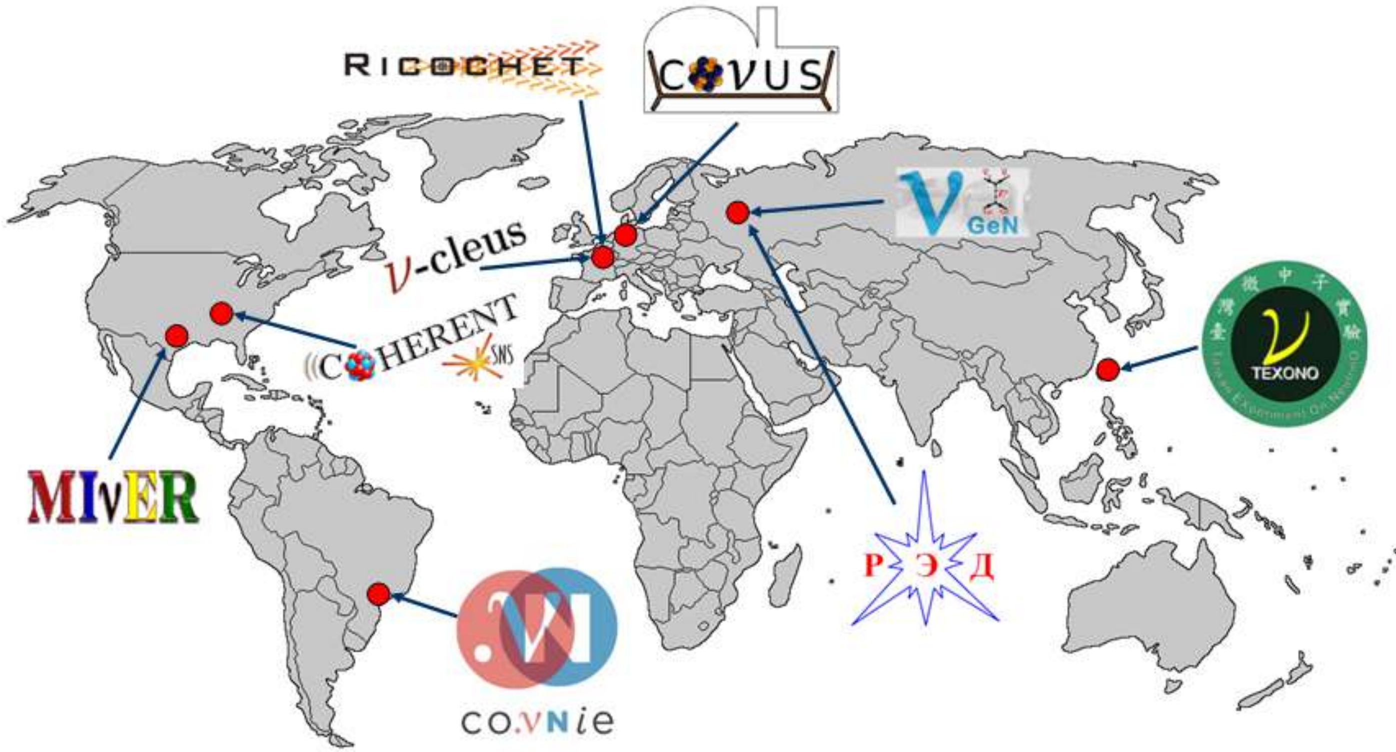
Very Productive Detector Technology Development

- HPGe detectors
- Cryogenic bolometers
- Two-phase noble elements
- Charge-coupled devices (CCD)
- Conventional scintillators (CsI, NaI, LAr)

REACTORS

DAR

World Wide Efforts to Detect CEvNS



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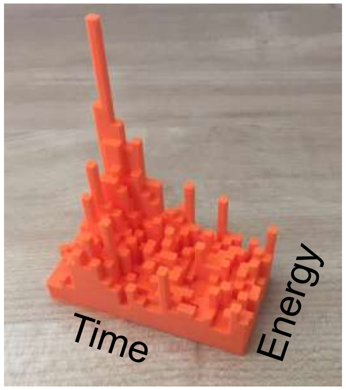
SNS as a neutrino source

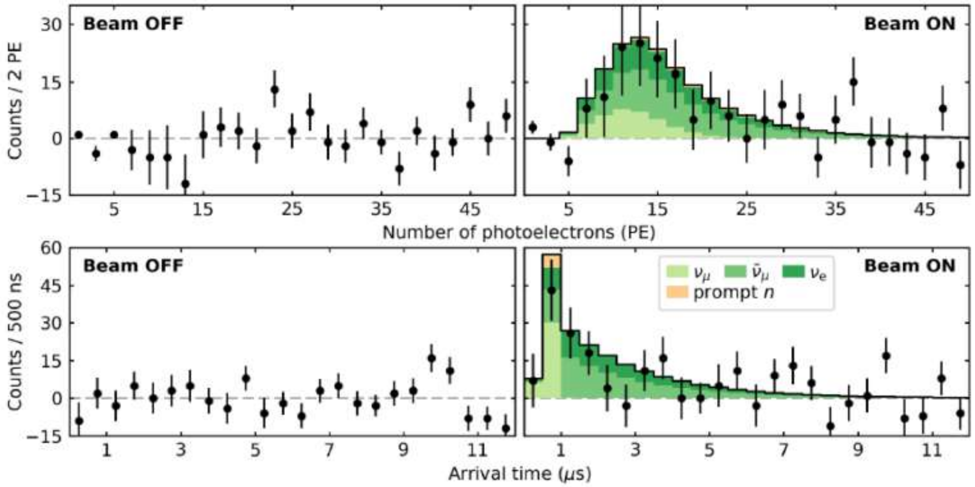
- World most powerful pulsed neutrino source; 7 · 10^{20} POT daily
  ~9% of protons produce 3 neutrinos
- Neutrino energies ideal to study CEvNS and Supernovae related neutrino cross sections.
  For most of neutrinos $E_\nu < 53$ MeV
- Decay At Rest from pions and muons (DAR) gives very well defined neutrino spectra.
- π+ have a mean free path of 5 cm in Hg - most will come to rest before decaying
- Fine duty factor let suppression of steady background by a factor of 2000.
  ~ 1000 m.w.e underground
- Neutrinos, space, and utilities are provided

First Detection of CEvNS

Hand held neutrino detector



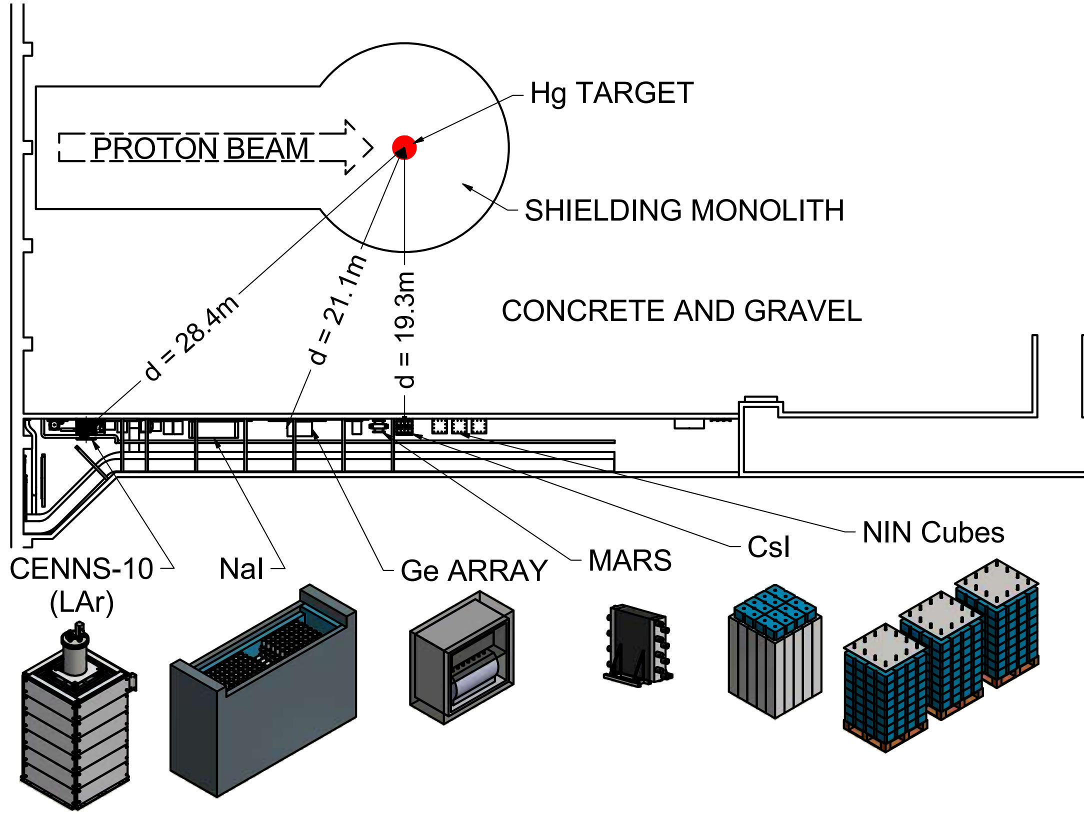
16 Month of data



Ongoing Activities in “Neutrino Alley”

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

Multiple auxiliary detectors have been deployed for an extensive background measurement campaign including environmental gammas, neutrons, beam-related backgrounds, and



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

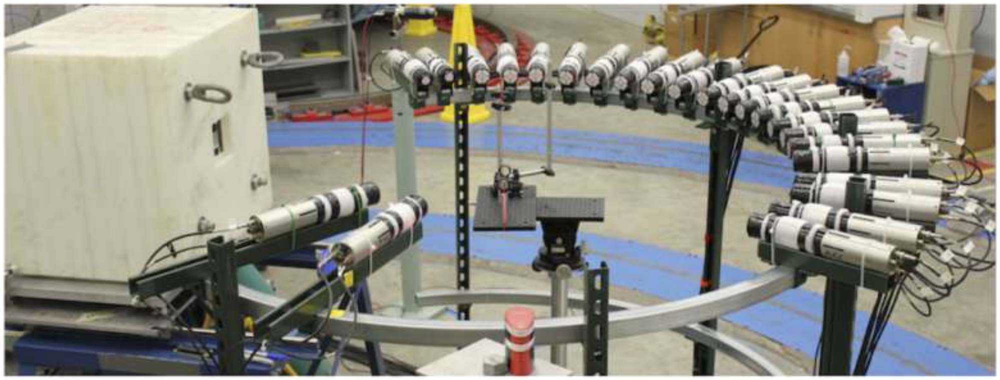
Calibration - Quenching Factor Measurements

The Quenching Factor provides the fraction of of light yield from nuclear recoils compared to light yield of electron recoil of similar energy

Only a fraction of the energy from the nuclear recoil measureable channels.

This fraction must be measured - quite carefully.

TUNL Facility to measure QF in various detector materials



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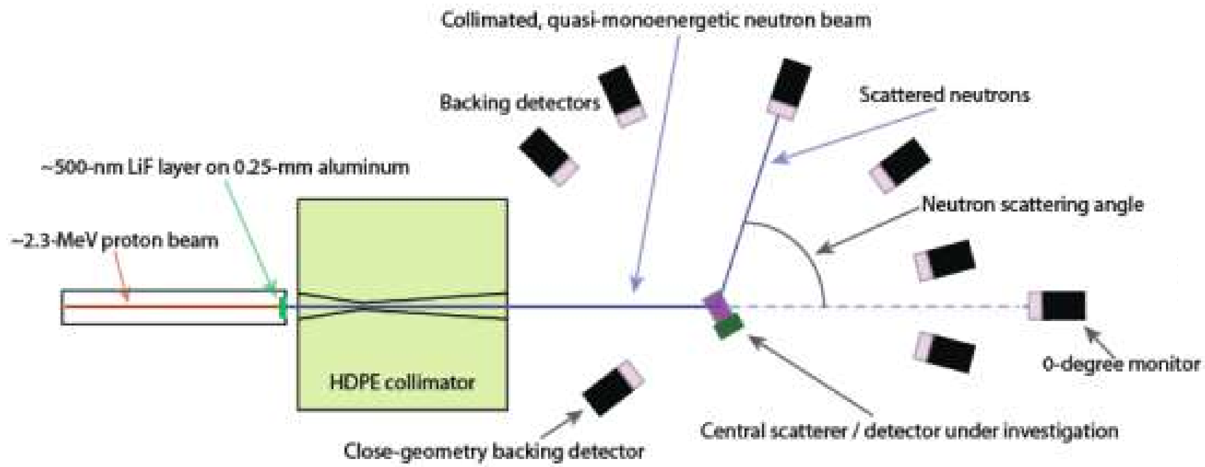
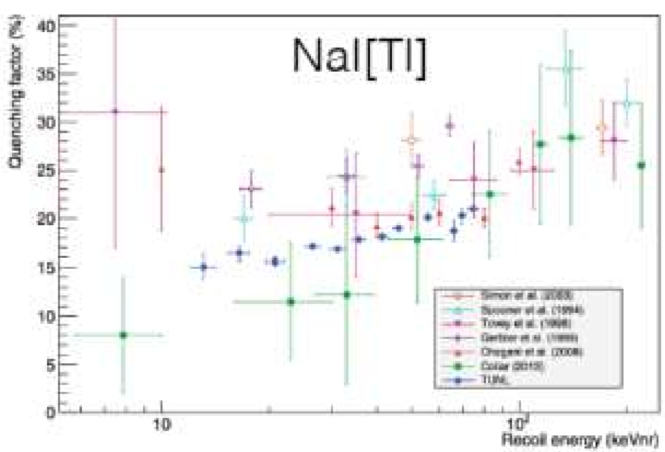
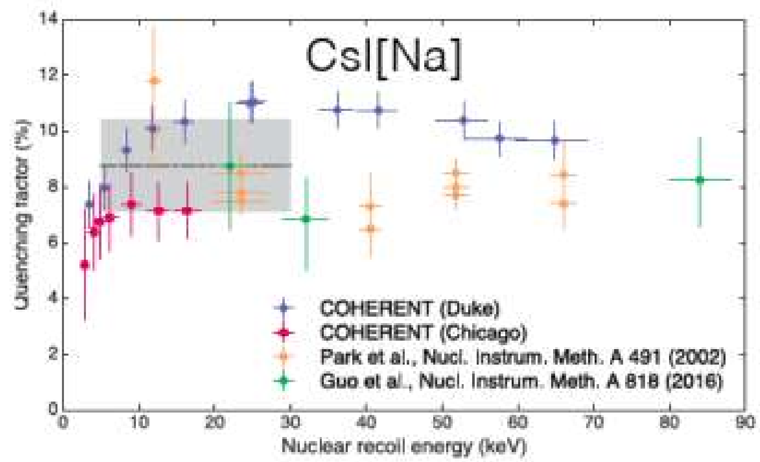
TUNL QF Measurements





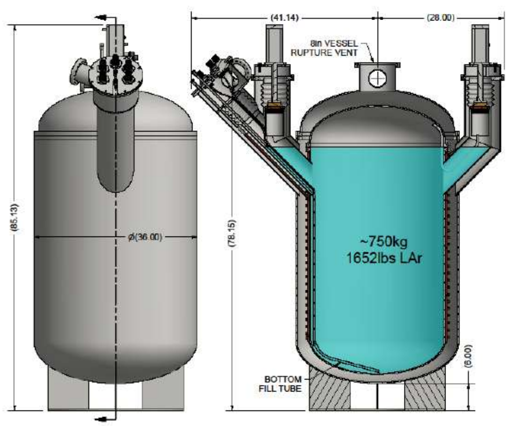


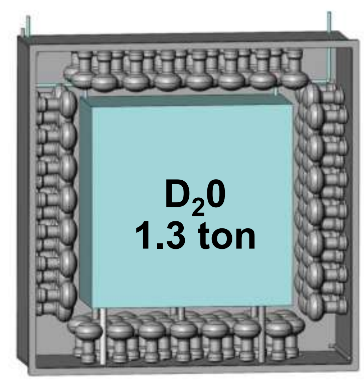
Immediate Goal for COHERENT

- 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

Measure **CEvNS** (Ge, NaI, LAr)

Calibrate neutrino flux (D2O)





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Neutrino-Induced Neutrons (NINs)

- Neutrino interacts with nucleus, raising the nucleus to an excited state.
- Excited nucleus decays via particle emission (p, n, α, γ)
- Charged-Current

  $\nu_e + {}_{Z}X_{N} \rightarrow e^- + {}_{Z+1}X^*_{N-1}$
- Neutral Current

  $\nu_x + {}_{Z}X_{N} \rightarrow \nu_x + {}_{Z}X^*_{N}$
- Large uncertainty in cross-section
- Interesting physics case on its own!

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."

COHERENT train high quality young scientists

- 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

Bjorn Scholz
U of Chicago

Grayson Rich
Duke

Enrico Fermi Fellow and KICP Fellow at University of Chicago

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

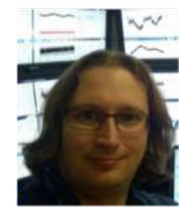
Erin
Conley
Duke

Dan
Salvat
UW
(Postdoc)

Jacob
Daughhetee
UTK
(Postdoc)

Mayra
Cervantes
Duke
(Postdoc)

Ivan
Tolstukhin
IU
(Postdoc)



Josh
Albert
IU
(Postdoc)

Summary – New Opportunities of Neutrino Physics at ORNL

- World wide effort to study CEvNS
- World class resources at ORNL: HFIR, SNS and Leadership Computing Facility
- Strong group with deep expertise in projects, detectors, and experimental techniques
- Unique scientific program with 2 shallow-depth experiments (PROSPECT and COHERENT)
- Together both collaborations involve more than 130 scientists from 30 institutions
- Excellent training ground - More than 75 students and postdocs have been involved
- First observation of CEvNS at ORNL (Science, 2017)
- Have an effective research plan to build on that success
- Deployment of new detector target systems for N^2 dependence of CEvNS cross section
- Push limits of thresholds, background and noise reduction - detector capability
- CEvNS measurements with high sensitivity to constrain physics

Quality of Colombian students

Shell Oil Chairman's Award

JUAN PABLO URREGO-BLANCO, PH.D.
Petrophysical Engineer
Shell Exploration & Production
Shell Oil Company

Ph.D., physics, University Of Tennessee, Knoxville; B.S., Physics, Universidad Nacional De Colombia (Bogotá, Colombia)

NPD - EPS 2015-2017 PhD Prize

RONALD GARCIA RUIZ, PH.D.
lead scientist COLLAPS experiment; CERN Fellow

Ph.D., physics, University Of Louvain, Belgium; M.Sc. UNAM, Mexico; B.S., Internship University Of Tennessee, Knoxville; Physics, Universidad Nacional De Colombia (Bogotá, Colombia)

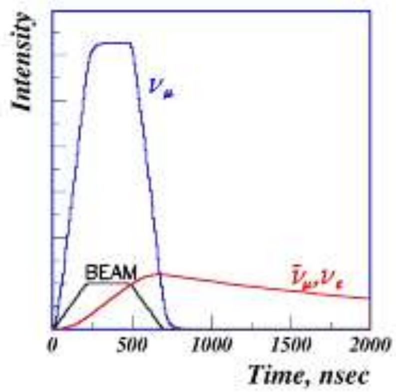
THANK YOU!

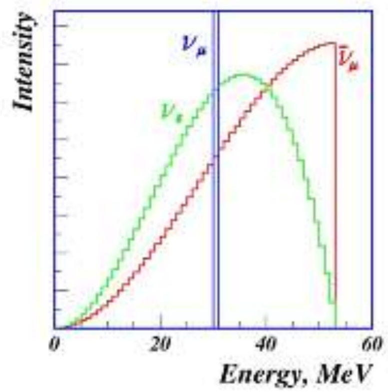
Backup Slides

Neutrino Production at SNS

- About 0.08 π^+ are produced per proton

- π^+ have a mean free path of 5 cm in Hg - most will come to rest before decaying





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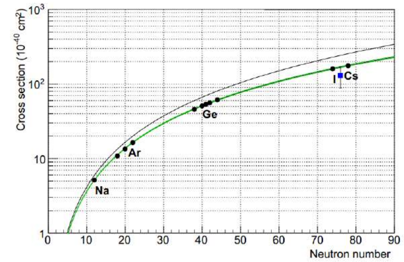
COHERENT Collaboration Steps

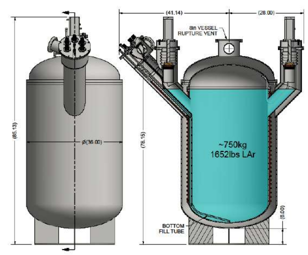
Present: First Light

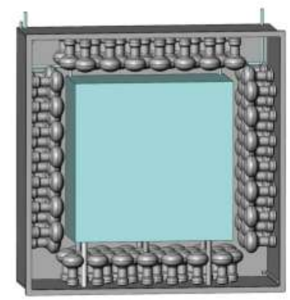
- Detect CEvNS
- Measure CEvNS for heavy and light nuclei
- Detect NINs

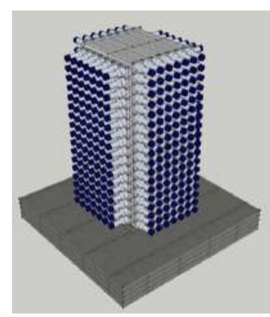


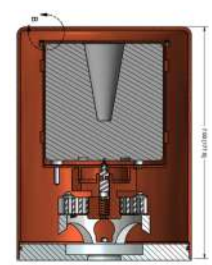
Next Step: New Deployments

- 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



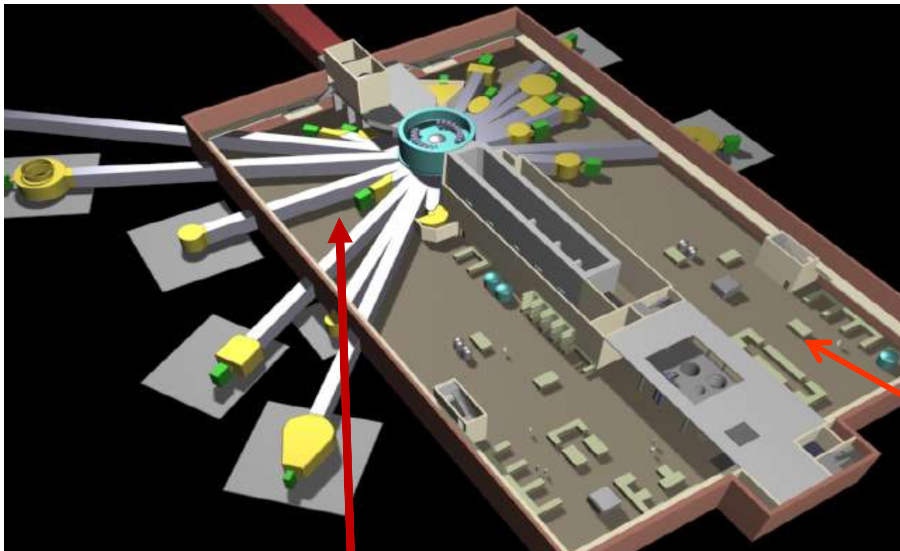


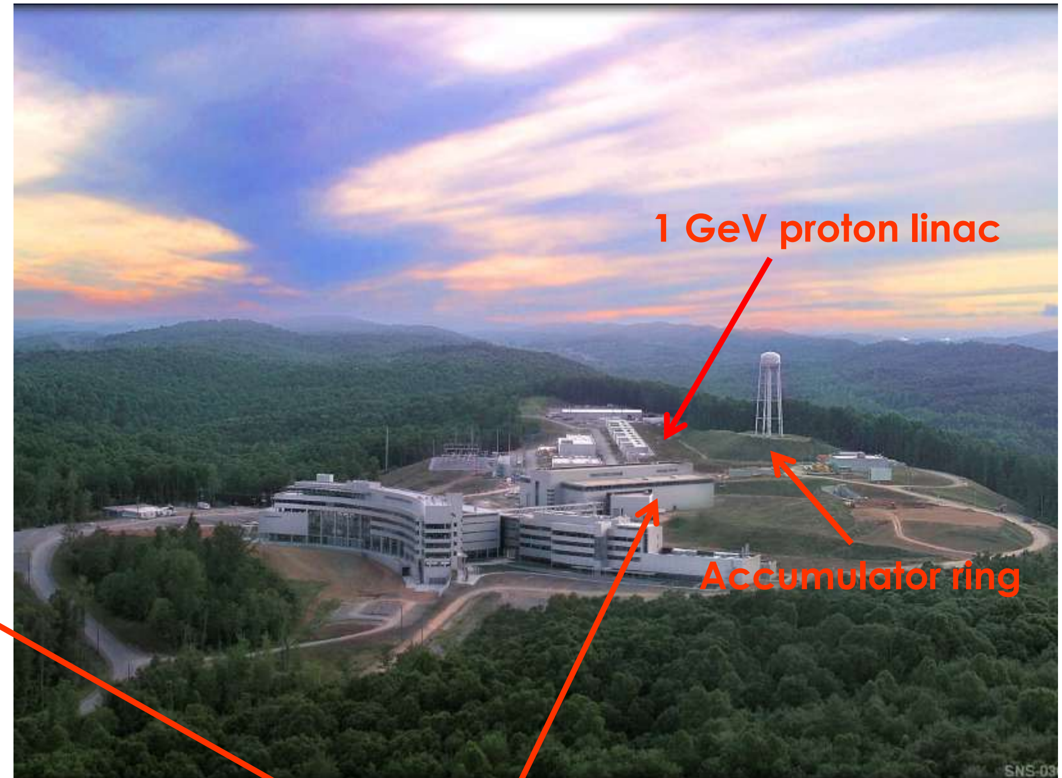




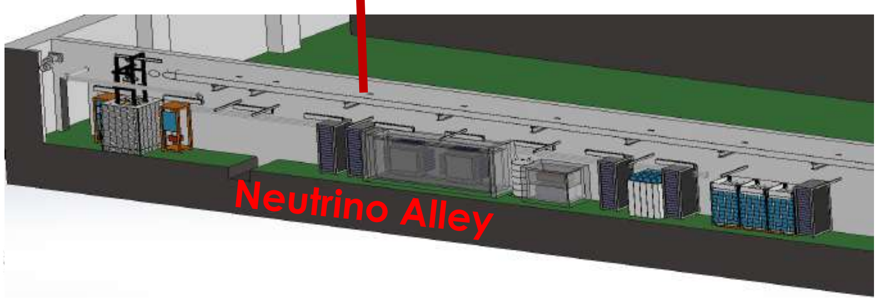
Neutrino Alley Location

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

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

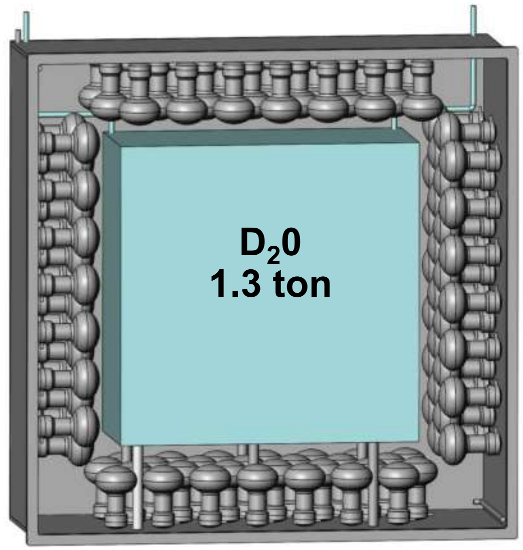
For 1 t fiducial mass detector ~ thousand interactions per year

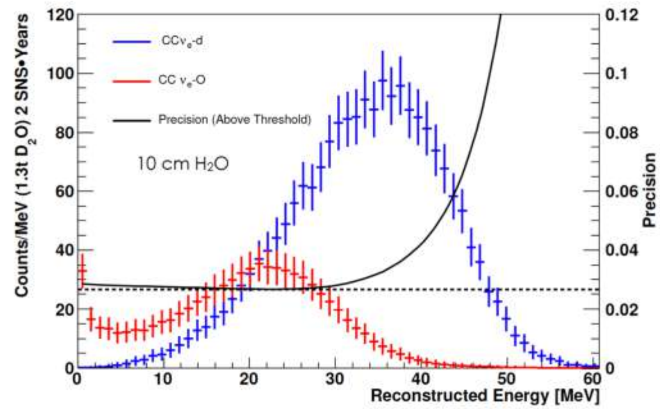
Detector calibration with Michel Electrons (same energy range)

Well defined D_2O mass constrained by acrylic tank

10 cm of light water tail catcher

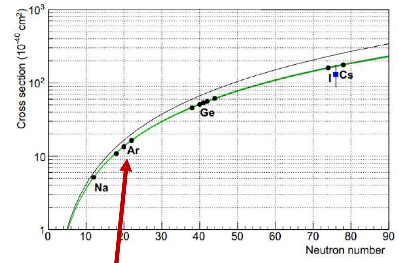
Outer dimensions 2.3 * 2.3 * 1.0 m^3



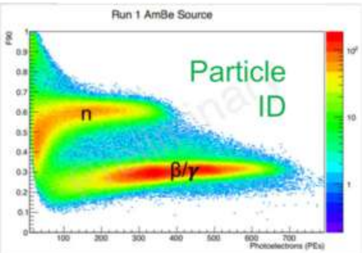


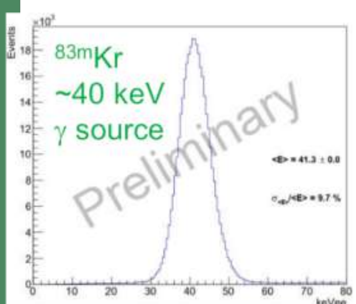
SNS calibration and CC measurements on Oxygen

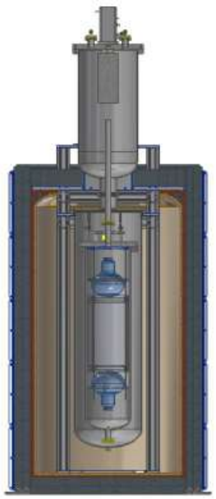
Future Activities - 1 ton LAr detector



Need high statistics low background measurements of CEvNS







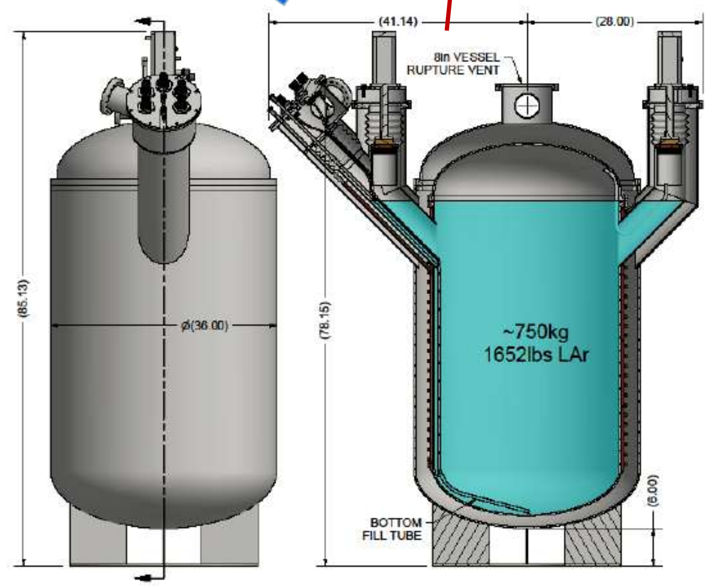
Transition from 22 kg to 1 ton LAr detector.

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



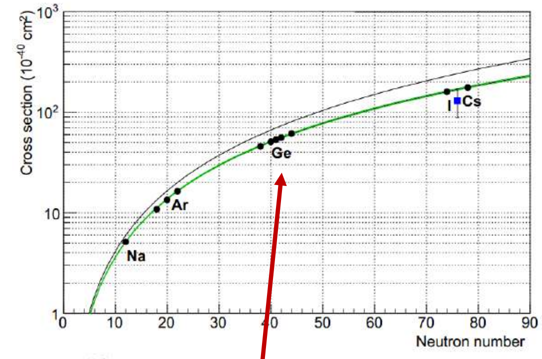
New Germanium Target for COHERENT

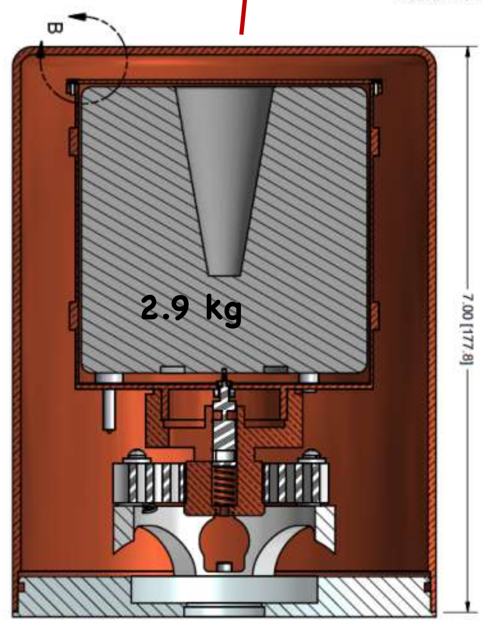
• Use state-of-the-art PPC Ge technology to perform a *precision* measurement of CEnNS. **>800 events/yr from 10 kg** array, with signal/background of ~15 (this was ~1/4 for CsI[Na] first COHERENT result).

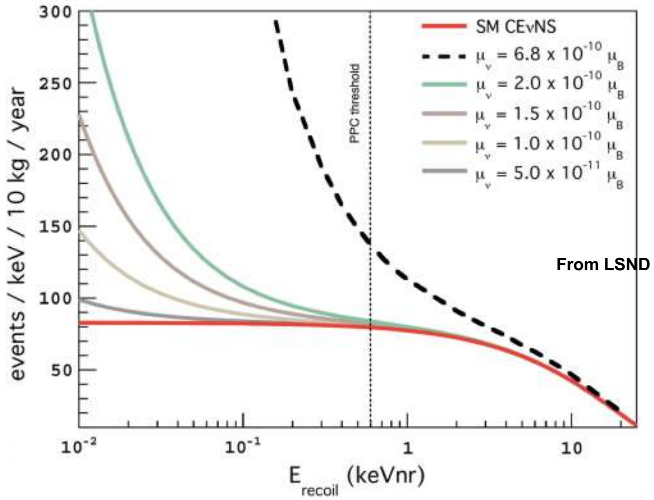
• Demonstrated analysis **threshold of 120eVee/600eVnr** (>70% SA, no false positives) allows measurement of full CEnNS recoil spectrum. Accompanying ongoing effort in quenching factor characterization.

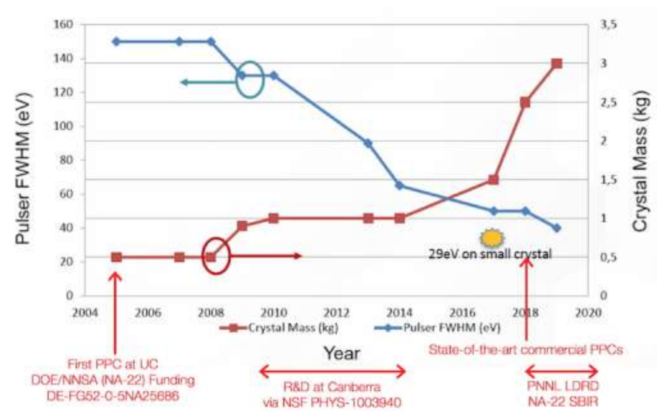
• Improved sensitivity to n electromagnetic properties, non-standard n interactions, MiniBooNE/LSND anomaly (steriles), DM models…

• **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.**

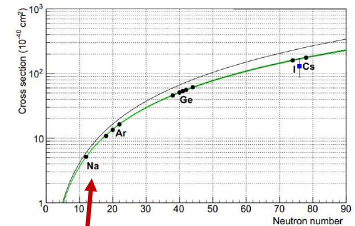








Future Activities - 2t NaI detectors array



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