Oak Ridge National Laboratory

The COHERENT Neutrino Experiment at the Spallation Neutron Source

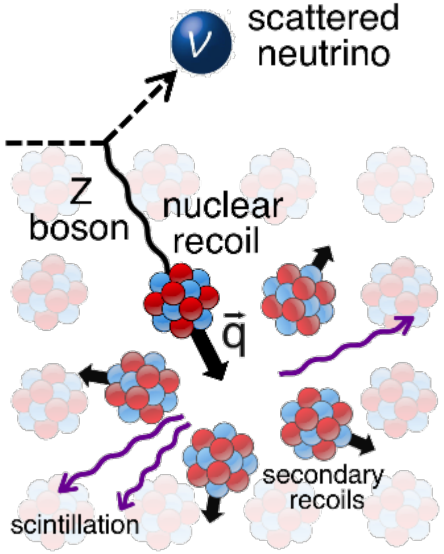
Jason Newby

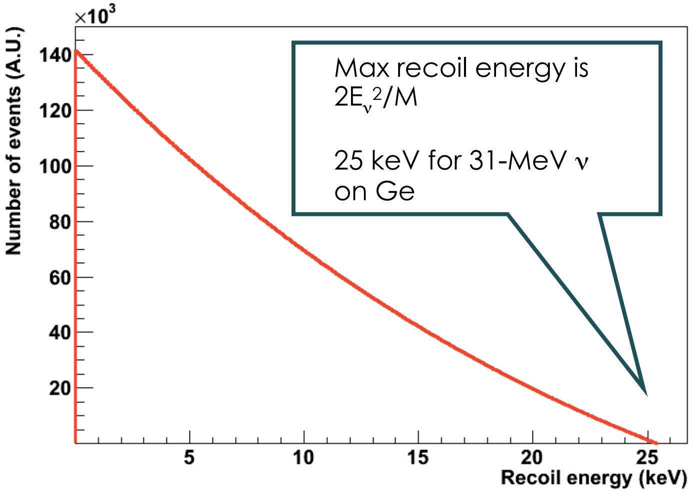
For the COHERENT Collaboration

Applied Antineutrino Physics Workshop 2023
York, UK Sept 18-21

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





CEvNS cross section is well calculable in the Standard Model

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

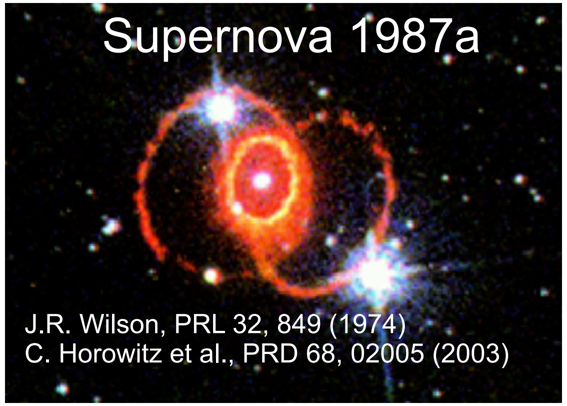
CEvNS cross section is large! $\propto N^2$

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

- "act of hubris" - D. Freedman
  - Need a low threshold detector
  - Need an intense neutrino source

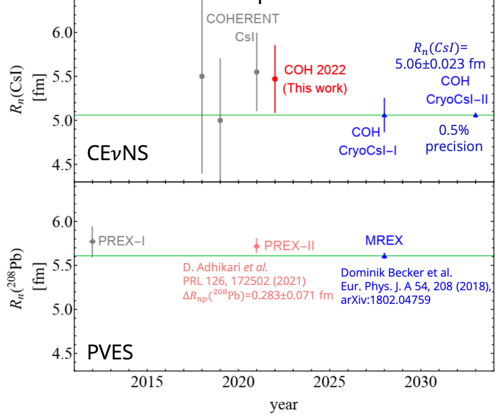
Broad Impact of π-DAR CEvNS Studies

Largest σ in Supernovae dynamics

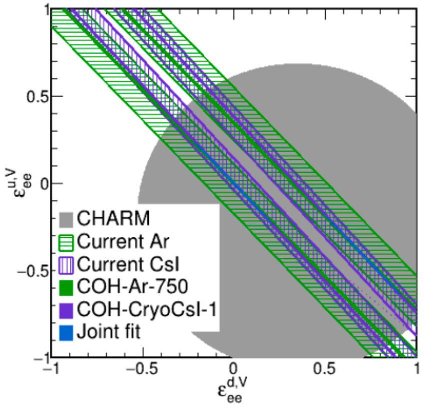


Nuclear Form Factors

Matteo Cadeddu presentation M7s '23

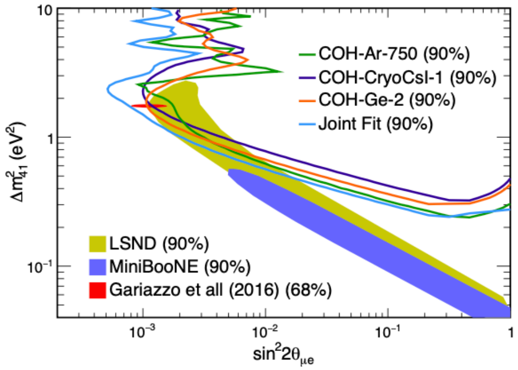


Non-Standard Interactions



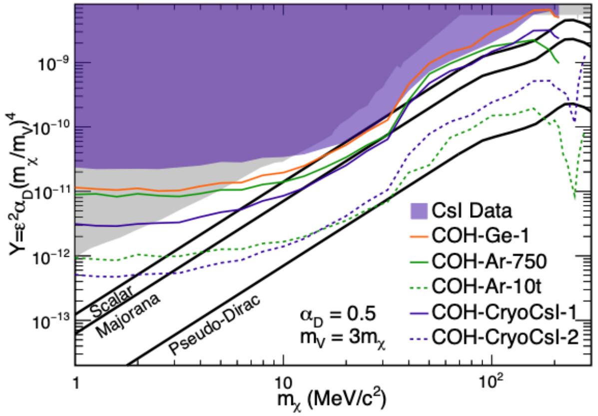
COHERENT Snowmass whitepaper 2022

Sterile Searches



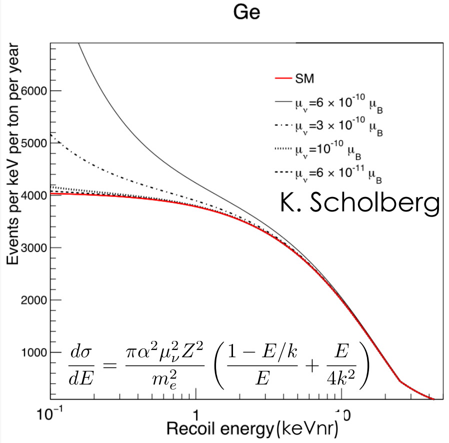
COHERENT Snowmass whitepaper 2022

Accelerator DM searches



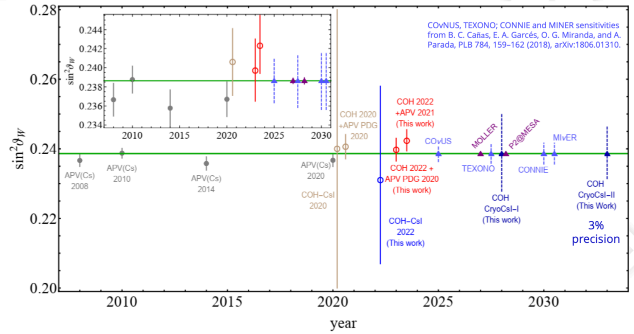
COHERENT Snowmass whitepaper 2022

Neutrino Magnetic Moment



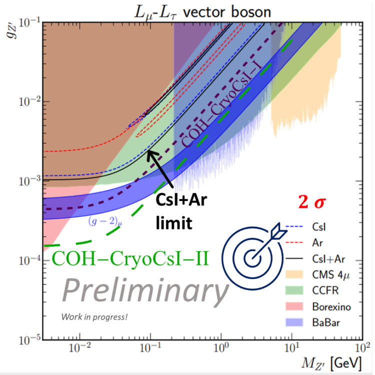
See also Kosmas et al., arXiv:1505.03202

Weak Mixing Angle



Matteo Cadeddu presentation M7s '23

BSM light mediator searches



Mattia Attori Corona presentation M7s '23

arXiv:2204.04575v1

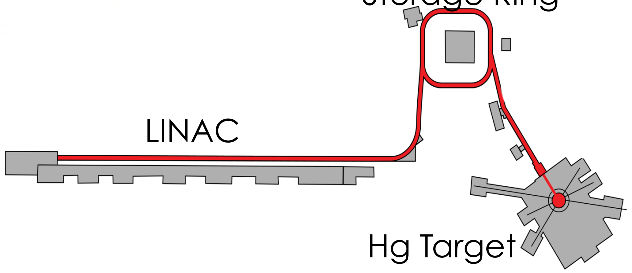
COHERENT Collaboration

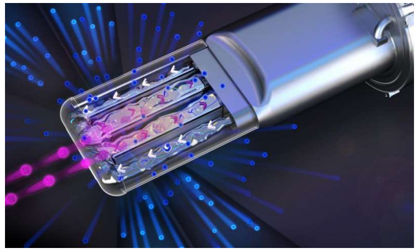
- ~80 members, 22 institutions
- Formed in 2013 to observe CEvNS in multiple nuclear targets to measure N^2-scaling of cross section
- Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL) is also a perfect source of neutrinos.
- Intense flux of low-energy pulsed neutrinos also useful for studying inelastic neutrino-nucleus interactions
- Intense proton pulses also useful for dark sector searches

COHERENT Collaboration Mtg May 2023

Carnegie Mellon University
Duke University
UF University of Florida
Laurentian University Université Laurentienne
Los Alamos National Laboratory EST. 1943
MEPhI
NC Central University
NC State University
Oak Ridge National Laboratory
Sandia National Laboratories
서 울 대 학 교 Seoul National University
SLAC National Accelerator Laboratory
University of South Dakota
The University of Tennessee Knoxville
Tufts University
TUNL Triangle Universities Nuclear Laboratory
Virginia Tech
University of Washington
Washington & Jefferson College
Florida State University 1851

Spallation Neutron Source at ORNL

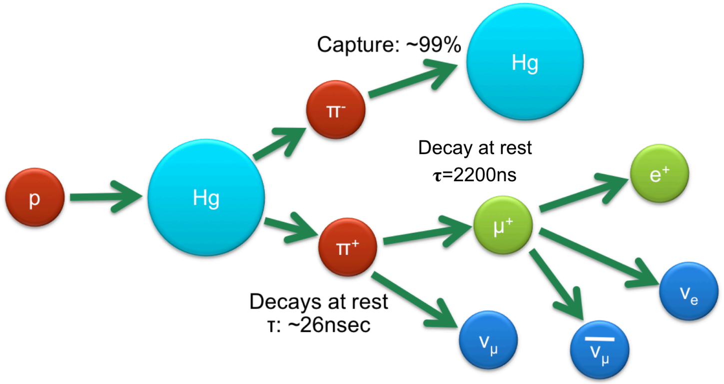




"Jet-flow" Target

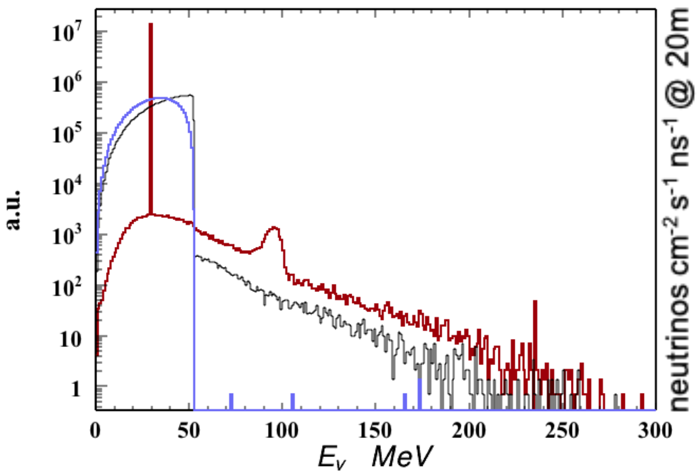
- Superconducting H- LINAC: 1 GeV @ **1.7MW** @ 60 Hz
- Storage Ring: 1200 pulses, 1μs Period, 350ns FWHM
- Liquid Mercury Target: circulates 20 tons with He gas injection to mitigate cavitation
- Operation ~5000 hours per year

Neutrinos via Pion Decay-at-Rest

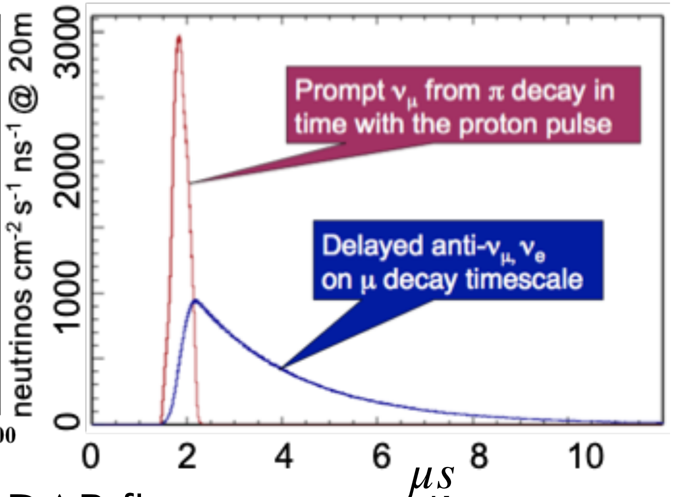


3×10^{14} ν/cm^2/flavor/SNSYear @ 20m

Neutrino Energy



Neutrino Timing

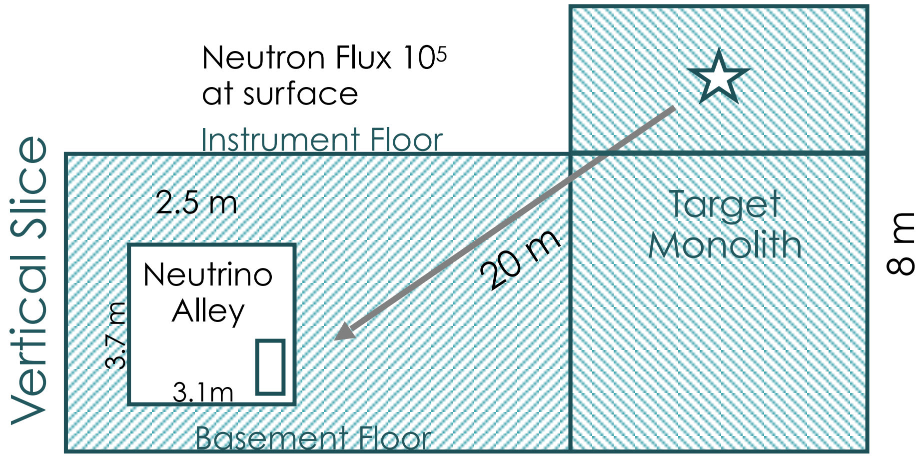


- SNS timing preserves DAR flavor separation
- Mono-energetic ν_μ separated from ν_e, $\bar{\nu}_\mu$

What are the required ingredients?

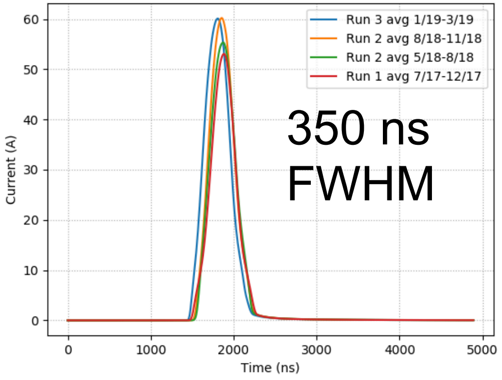
Low Noise Detectors and Low Background Materials from DM and $0\nu\beta\beta$ Detector R&D

Neutrino Alley is well-shielded from beam related backgrounds



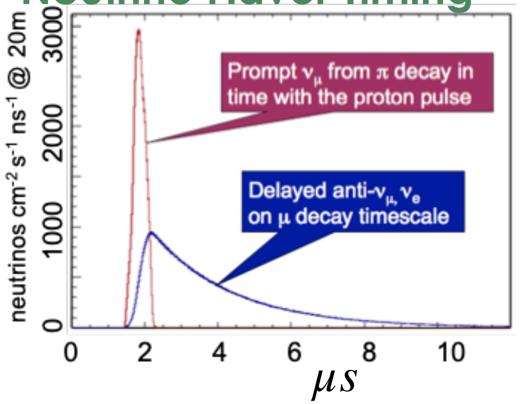
Pulsed Timing Structure of Neutrinos

Measured Proton Pulse

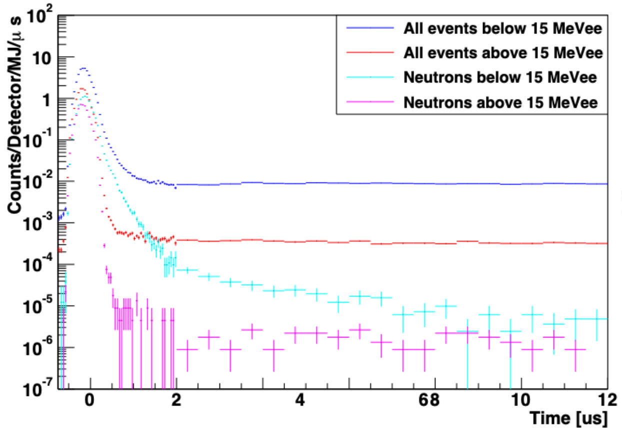


Lara Blokland, UTK

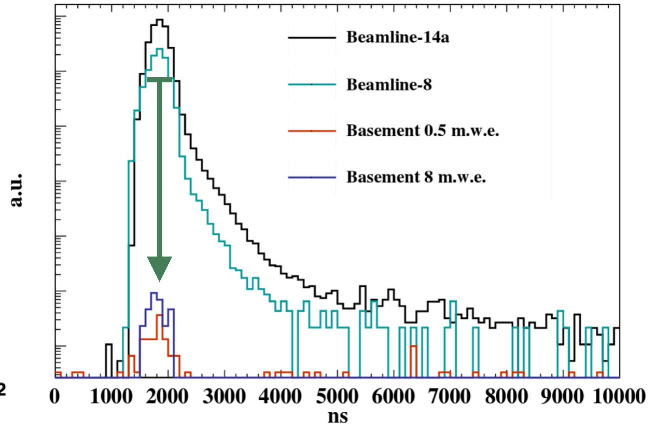
Neutrino Flavor Timing



SNS Instrument Floor

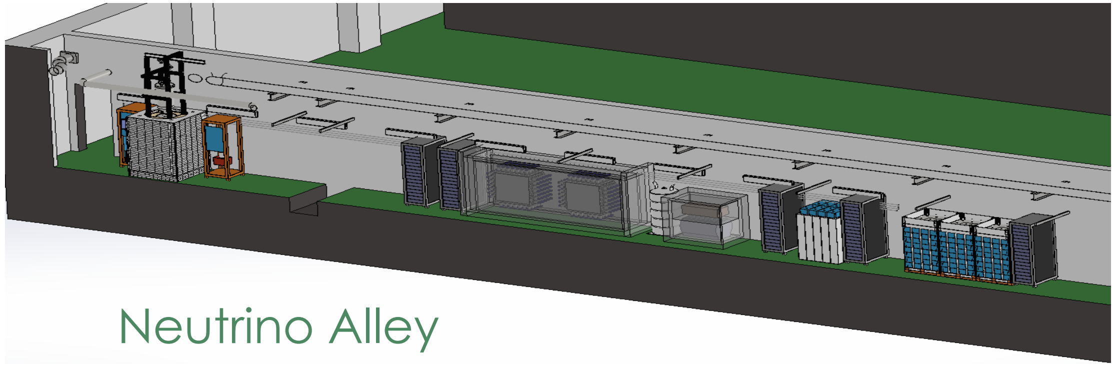


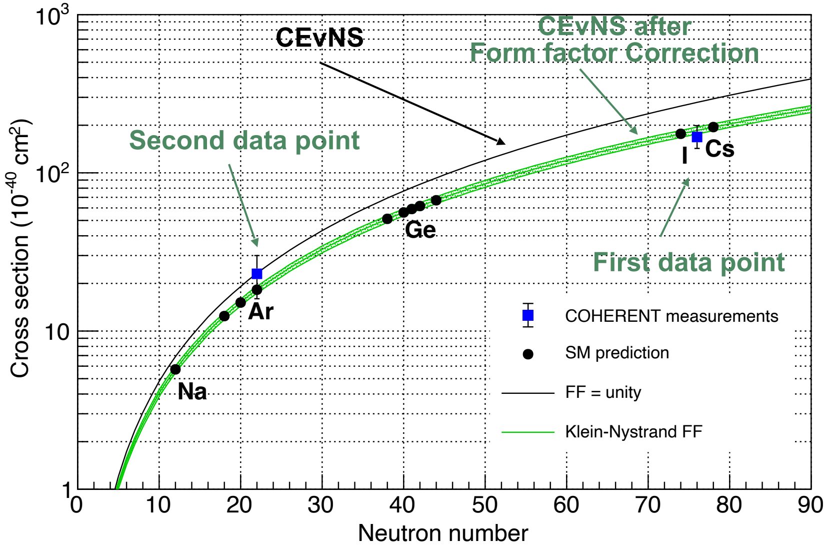
Basement Shielding



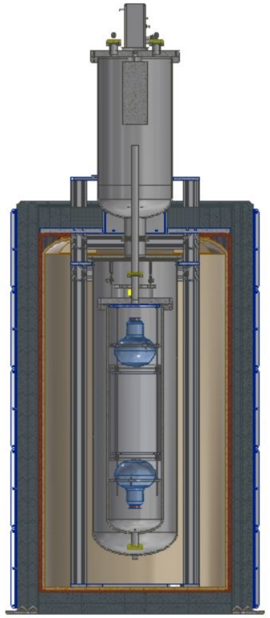
- Factor 3000 suppression in steady state bkgs
- Precise measurement of steady state bkgs
- Constrains systematics on beam-related bkgs.
- Enables flavor dependent analyses
- Enables prompt searches for exotic particles

COHERENT "First Light" CEvNS Program





Complete the mapping of N^2 Dependence



Designed by Jonghee Yoo, SNU

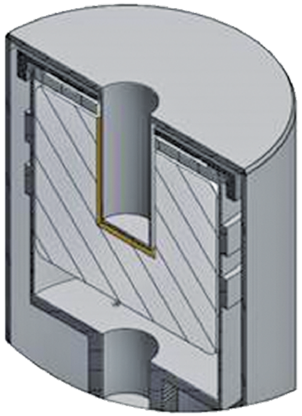
Argon

- 24 kg Fiducial Mass
- Single Phase
- Kr^{83m} Calibrations
- 4.5 p.e. per keVee
- 20 keVnr threshold
- ~5σ data in-hand
- Final analysis underway

Designed by Sam Hedges
Duke (LLNL)

Sodium (NaI)

- *Lightest-Nucleus*
- 3.4 ton NaI Array
- 3σ CEvNS/yr
- Installation 2022



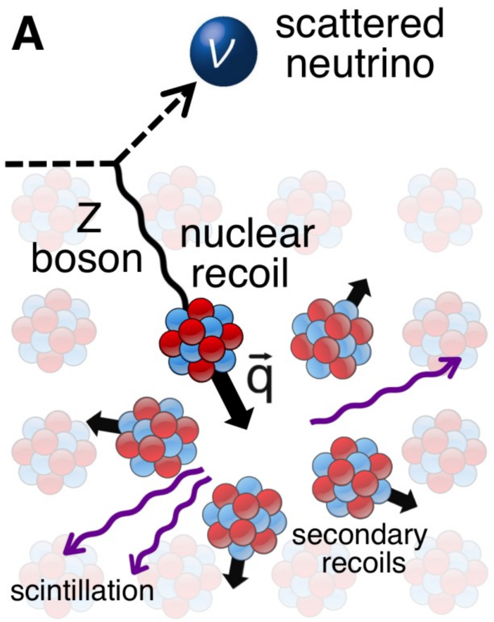
Germanium

- *Lowest Threshold*
- 16 kg HPGe Array
- 500-600 CEvNS/yr
- Installation 2022
- Funded NSF-MRI

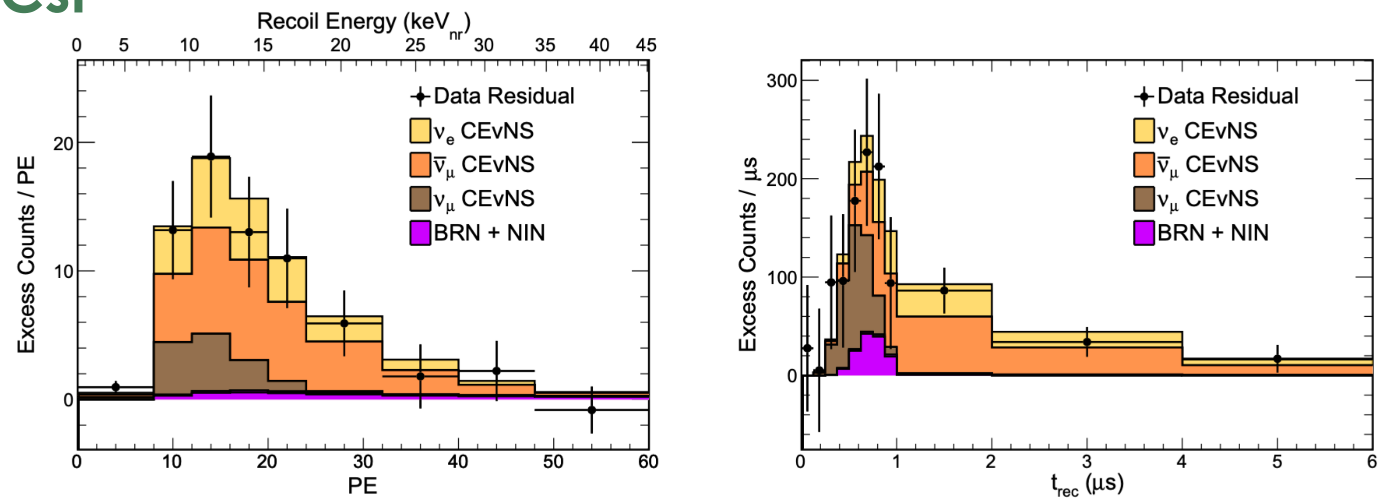
Led by Matt Green, NCSU

Multiple Targets key feature of COHERENT Experiment

CEvNS on two targets, a third very soon …

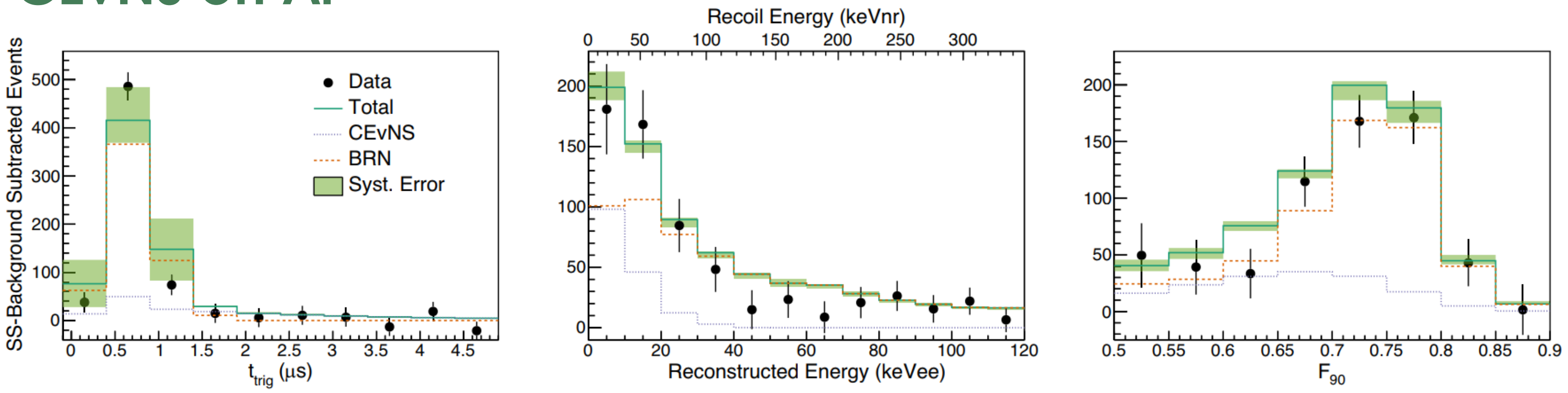


CEvNS on CsI



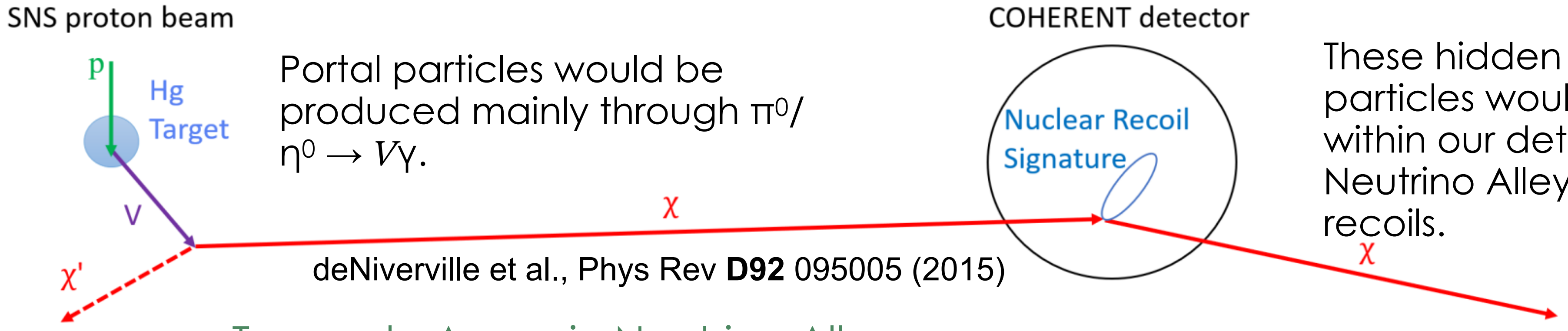
*COHERENT, PRL **129** (2022) 081801*

CEvNS on Ar



*COHERENT, PRL **126** 012002 (2021)*

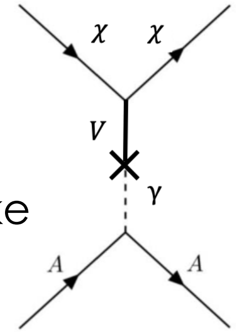
Accelerator-produced Dark Matter at the SNS



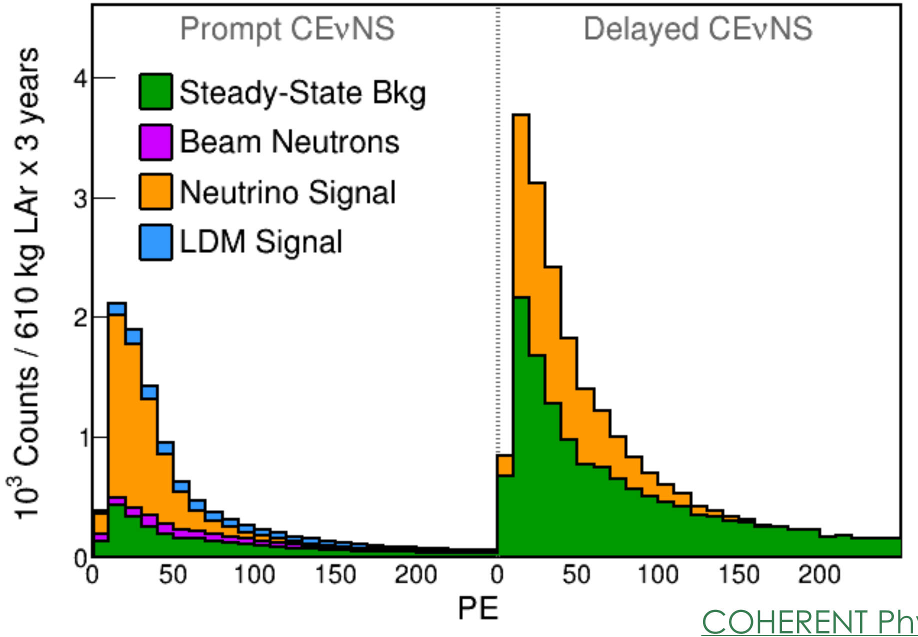
Portal particles would be produced mainly through π⁰/ η⁰ → $V\gamma$.

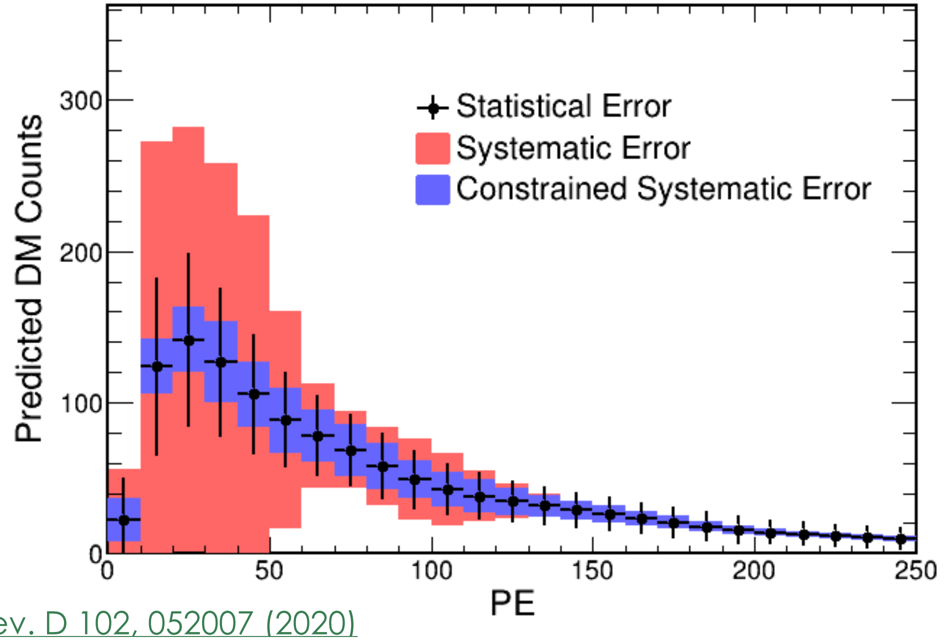
deNiverville et al., Phys Rev **D92** 095005 (2015)

These hidden sector particles would interact within our detectors in Neutrino Alley in CEvNS-like recoils.



Ton-scale Argon in Neutrino Alley





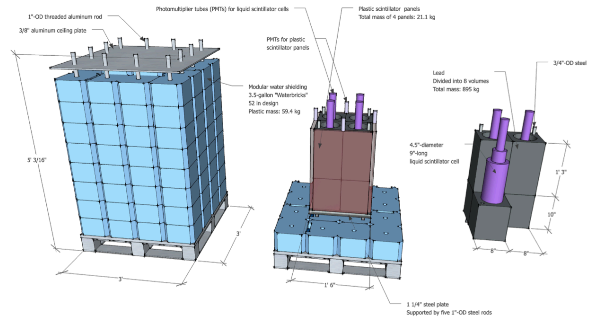
[COHERENT Phys. Rev. D 102, 052007 (2020)]
[COHERENT Phys. Rev. Lett. 130, 051803 (2023)]

The ability to measure delayed CEvNS is key to control systematics of prompt CEvNS "background".

Inelastic Interactions and Physics Background Detectors Supporting the CEvNS Program

Neutrino Induced Neutron Detectors
Pb & Fe Nubes

$$\nu_e + {}^{208}Pb \rightarrow {}^{208}Bi^* + e^- \quad \text{(CC)}$$
$$\hookrightarrow {}^{208-y}Bi + x\gamma + yn$$
$$\nu_x + {}^{208}Pb \rightarrow {}^{208}Pb^* + \nu'_x \quad \text{(NC)}$$
$$\hookrightarrow {}^{208-y}Pb + x\gamma + yn$$



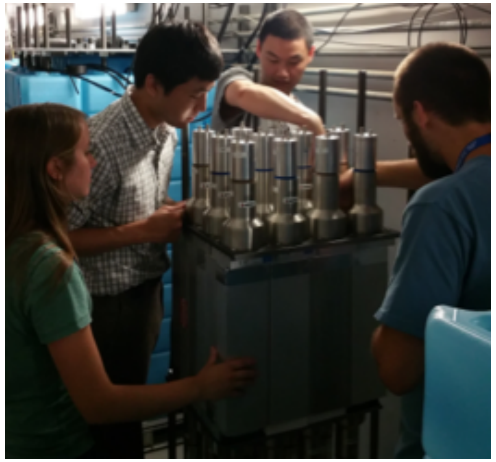
Designed by TUNL/Duke University
Installed in Neutrino Alley in 2014

arXiv:2212.11295

Fermilab W&C
Sam Hedges

NaIvE
Inelastic Interactions

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



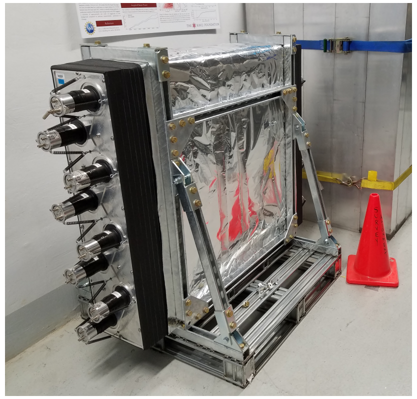
Designed by TUNL/Duke
Installed in Neutrino Alley

arXiv:2305.19594

NuThor
Neutrino Induced Fissions
52 kgs thorium metal

Designed by TUNL/Duke
Installed in Neutrino Alley

MARS
Fast Neutron Backgrounds

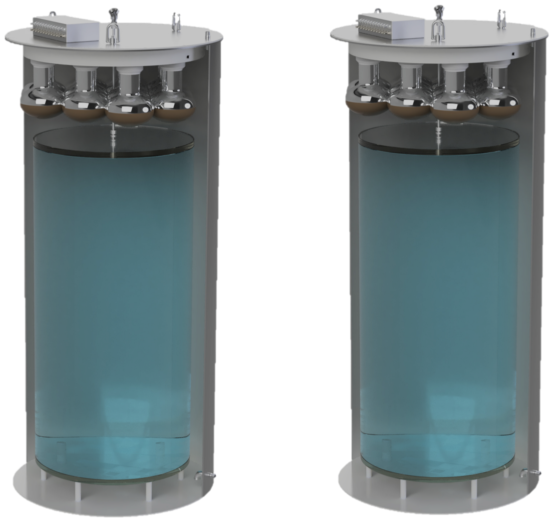


Assembled at Sandia
Installed in Neutrino Alley
in June 2017

COHERENT, 2022 JINST 17 P03021

COHERENT Precision Program now underway

Precise Flux Normalization



Module 1 Module 2

UTK/CMU/VT/ORNL

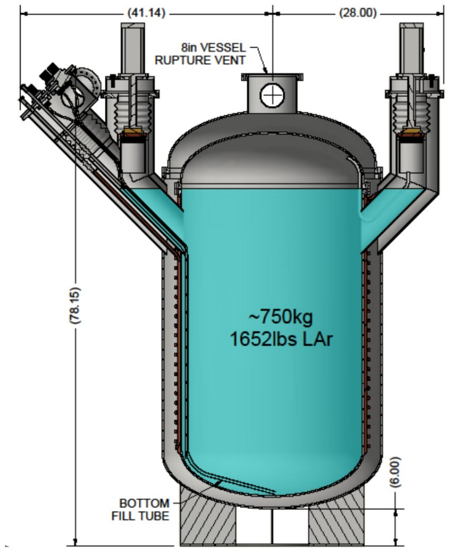
- Deuteron Charged Current
  $\nu_e + d \rightarrow p + p + e^-$
- 2-3% Theoretical Uncertainty*
- Calorimetry: no Ring Imaging
- 2.5% Statistical in 2 yrs
- Module 1 now operating

COHERENT 2021 JINST 16 P08048

US-Japan Workshop on Measurements for Supernova Neutrino Detection, ORNL Mar 2023

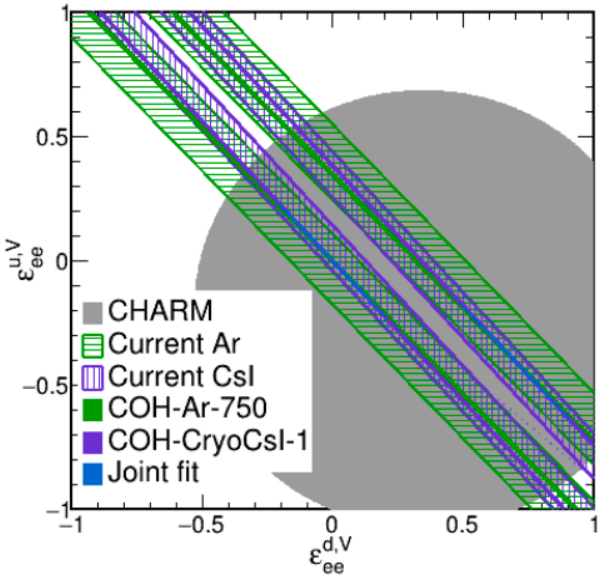
*S.Nakamura et. al. Nucl.Phys. A721(2003) 549

High Statistics CEvNS

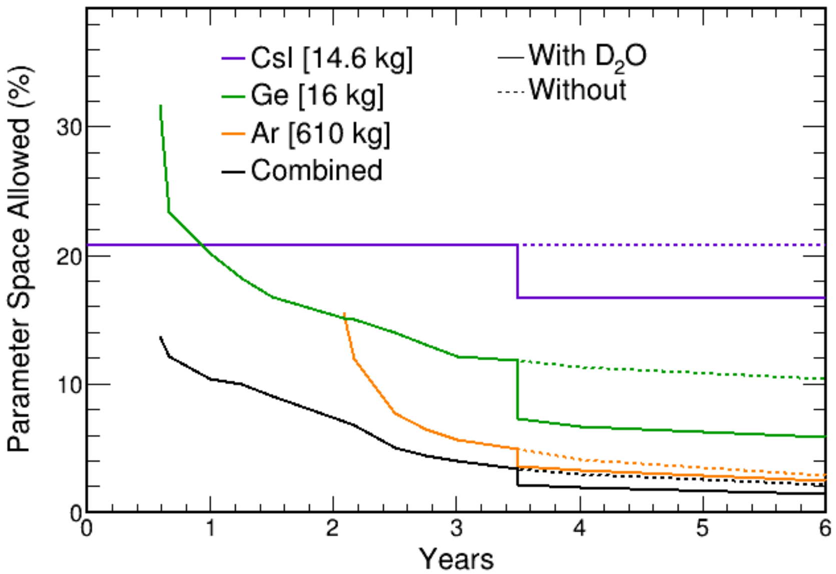


Walt Fox, IU

- 750kg LAr
- Single phase
- Light Collection Options
  - 3” PMT TPB
  - SiPM, Xenon Doping, …
- ~3000 CEvNS/yr
- Fabrication underway @ Seoul and IU

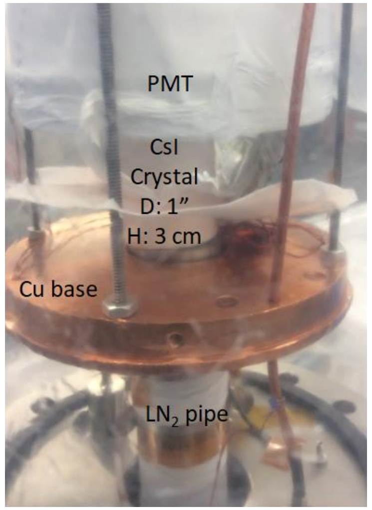


Significantly Improve NSI Constraints



Future Detectors for Neutrino Alley

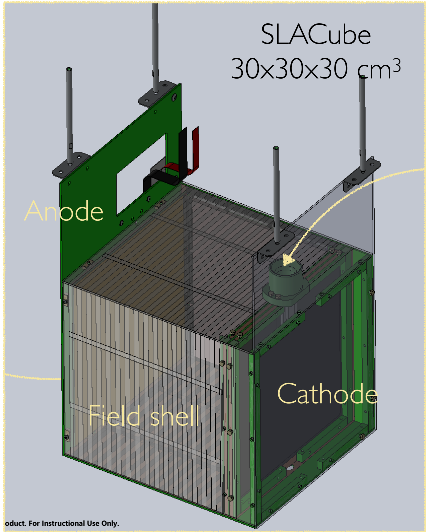
Cryogenic Scintillating Crystals



COH-CryoCsI Jing Liu, SD

- Undoped CsI
- Maximal Light Yield, Minimal Afterglow at 77K
- Well matched for SiPM readout
- ~0.4 keVnr thresholds possible
- 10kg and 750kg concepts

Time Projection Chambers



Yun-Tse Tsai, SLAC

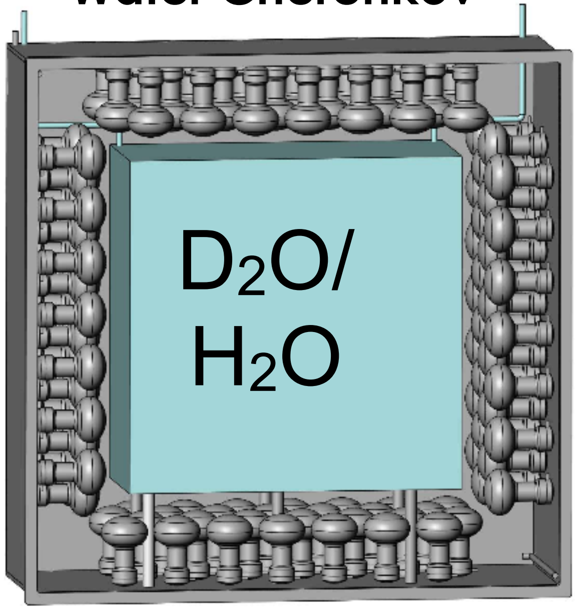
SLACube

- Compact LAr TPC Design
- LArPix Readout
- nu_e Charged Current

Gas TPC

- CEvNS recoil direction

Fully Instrumented Water Cherenkov



Performance Optimized Detector

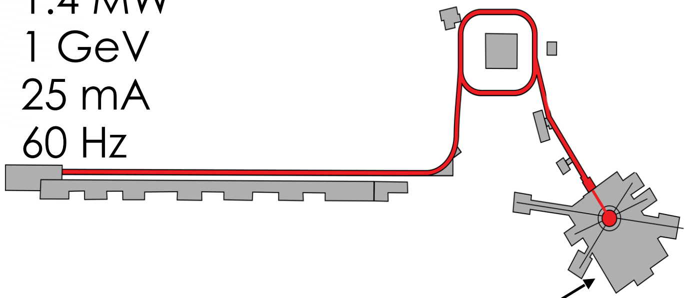
- High Light Collection
- Ring Reconstruction
- Directional Information
- ν_e CC differential cross section
- Fully characterize interaction response for supernova detection

PPU and STS upgrades will ensure SNS remains the world's brightest accelerator-based neutron source

Today

- 900 users
- Materials at atomic resolution and fast dynamics

1.4 MW
1 GeV
25 mA
60 Hz

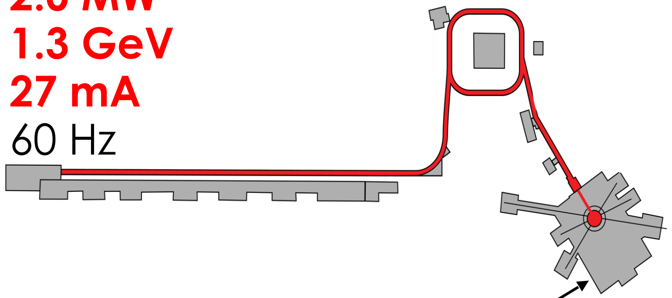


FTS
1.4 MW
60 Hz

2024 after PPU

- **1000+** users
- Enhanced capabilities

2.0 MW
1.3 GeV
27 mA
60 Hz



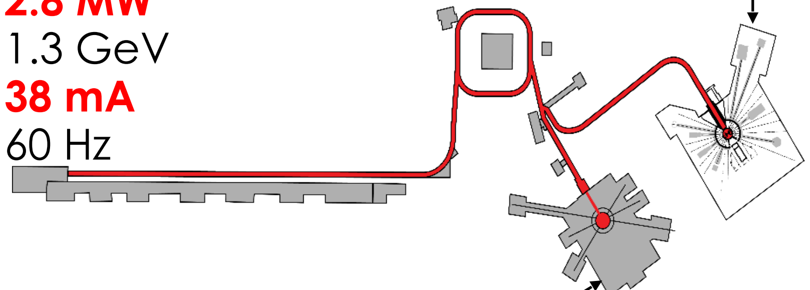
FTS
2 MW
60 Hz

2032 after STS

- **2000+** users
- Hierarchical materials, time-resolution and small samples

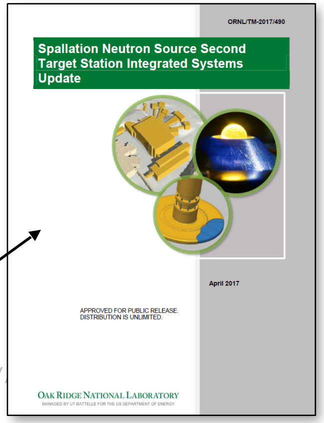
STS
0.7 MW
15 Hz

2.8 MW
1.3 GeV
38 mA
60 Hz



FTS
2 MW
45 pulses/sec

The choice of 15 Hz and 0.7 MW resulted from a detailed analysis of STS design (reviewed by a panel of experts in 2017) and optimizes performance of STS without impacting performance of FTS



ORNL LDRD to expand capability of HFIR/SNS for particle physics

Precision CEvNS with LAr

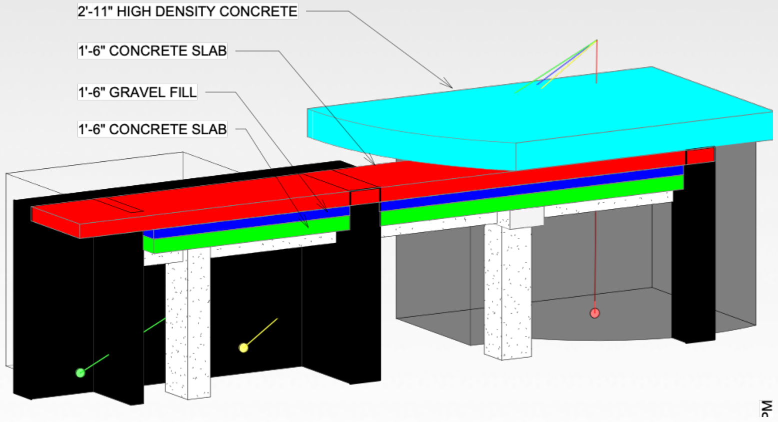
- Preparations for 2024 deployment of 750kg Liquid Argon Detector funded through Seoul National University
- ORNL leading the wavelength shifting coating of PMTs and Teflon panels developed for CENNS-10.

SCGSR Awardee Jacob Zettlemoyer (IU) led data analysis and worked with ORNL's Mike Febbraro on coatings, to shift argon light to visible wavelengths to boost detection

- Large panels and PMT count require larger coating apparatus at production scale.

Expanded FTS Footprint

- SNS First Target Station (FTS) will ramp to 2 MW in 2025, 1.7MW 2023
- SNS Engineering and Operations identified additional 4 candidate spaces with facility integrated shielding for neutrino experiments.



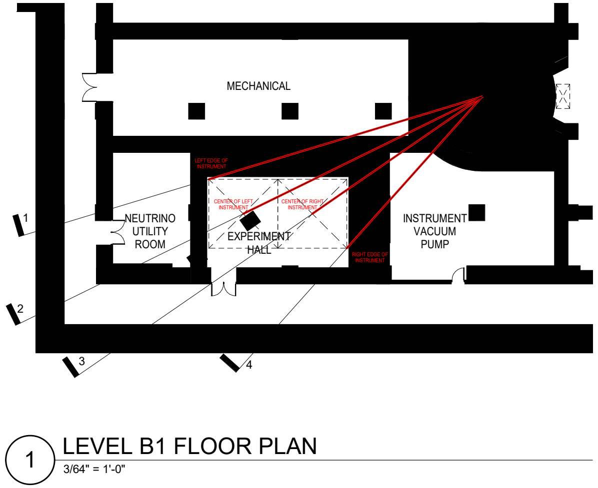
- Backgrounds measurements underway to establish feasibility

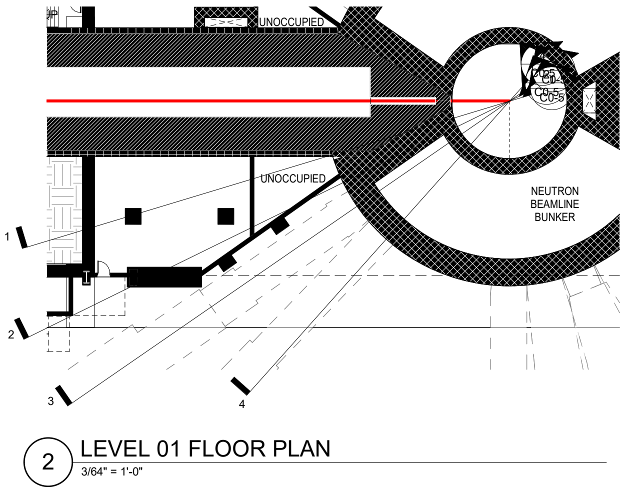
PROSPECT II and beyond

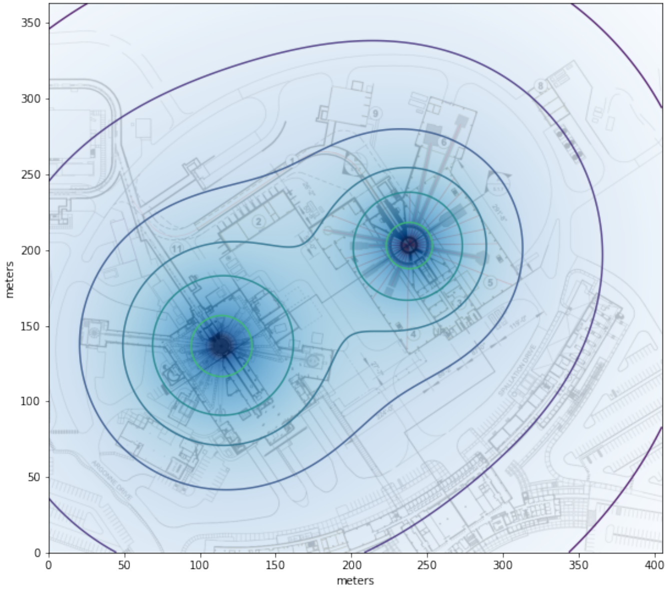
- ORNL mechanical engineers worked with collaboration to develop interface and requirements document for PROSPECT II liquid scintillator vessel.
- ORNL fabrication engineer led distribution of request-for-bid packages and worked with responding vendors for separate engineering and fabrication phases.
- HFIR engineering and operations evaluating options for facility integrated shielding for future neutrino programs such as reactor CEvNS: unlimited shielding mass tied to monolith, volumetric constraints.

Second Target Station Opportunities

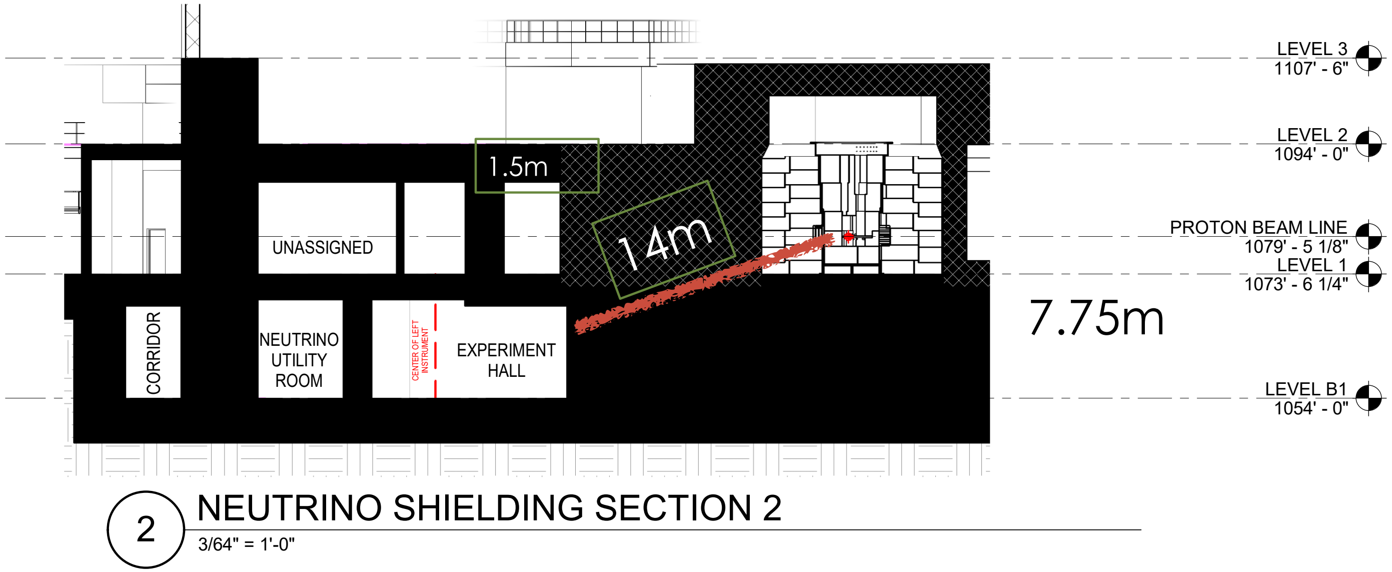
- Neutrino Laboratory now approved for STS Project Preliminary Design
- Basement location offers facility integrated neutron shielding for 2 10-ton scale detectors and adjacent utility room







Dueling Neutrinos Sources
K. Scholberg



Conclusions

- COHERENT succeeded in its primary goal to observe CEvNS: first on CsI in 2017 followed by Ar in 2019.
- COHERENT is well on its way to complete is secondary goal to map out the nuclear size dependance of the CEvNS cross section with new installations of Ge and NaI.
- The precision CEvNS program is now underway with ton-scale D2O and LAr in 2024.
- COHERENT has developed a broad multi-channel low energy neutrino program to take advantage of SNS facility upgrades and advances in instrumentation into the next decade.

Acknowledgements

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Backup Slides

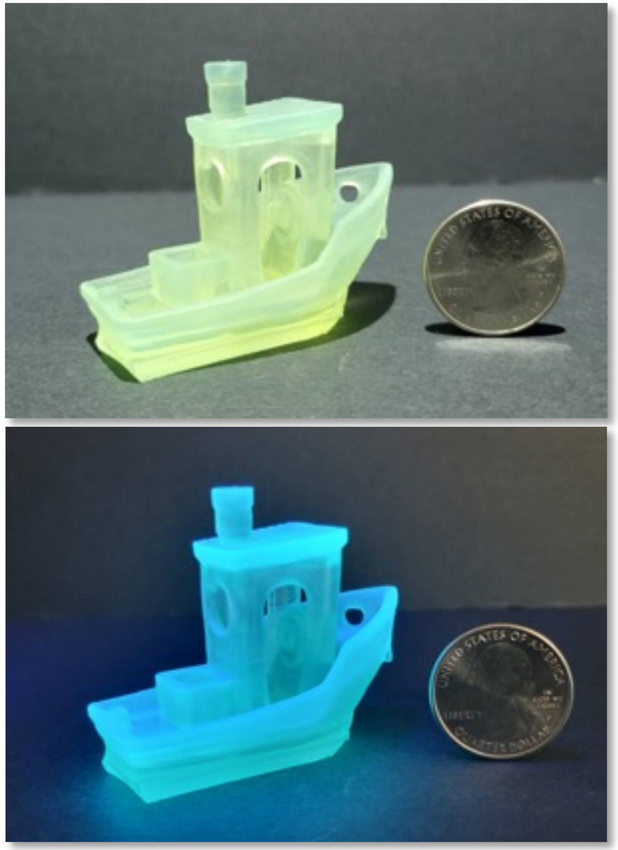
3D Printed Scintillator Activities

Additive manufacturing of wavelength shifters and low-background materials

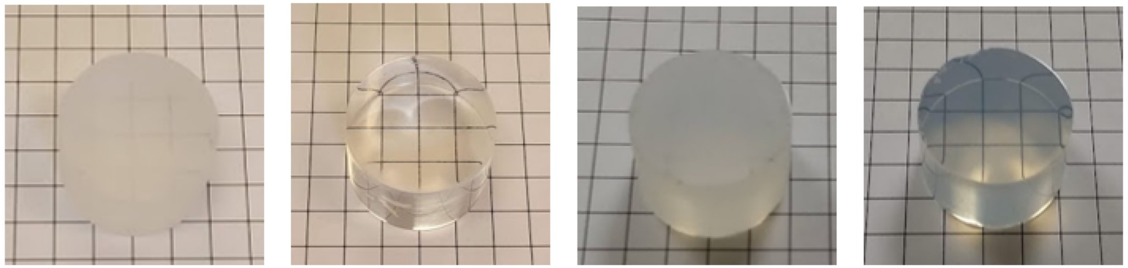
- World-leading spatial resolution for light-based 3D printing
- Developed multiple 3D printable formulations
  - Wavelength shifters, scintillators, potential low-background materials
- Developed a pulsed VUV light source for testing of wavelength shifters and photosensors and cryogenic VUV testing platform
  - Wavelength range: 58 – 3200 nm
  - Temperature range: 5 – 500 K

•Recently achieved the **3D printing of fast light-cured plastic scintillators, achieving a final stable, clear and hard plastic, achieving 83% light yield.**

•Publication in *J. Nucl. Eng.* **2023**, *4*(1), 241-257; https://doi.org/10.3390/jne4010019

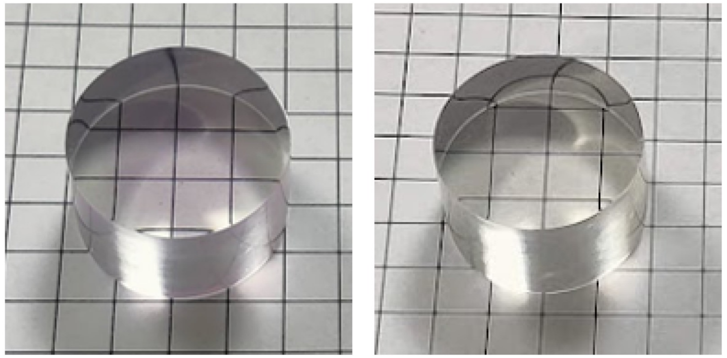


3D Printed "benchy" in wavelength shifting material



(a) (b) (c) (d)

We identified methods to mitigate PPO leaching and get rid of hazy surface effects

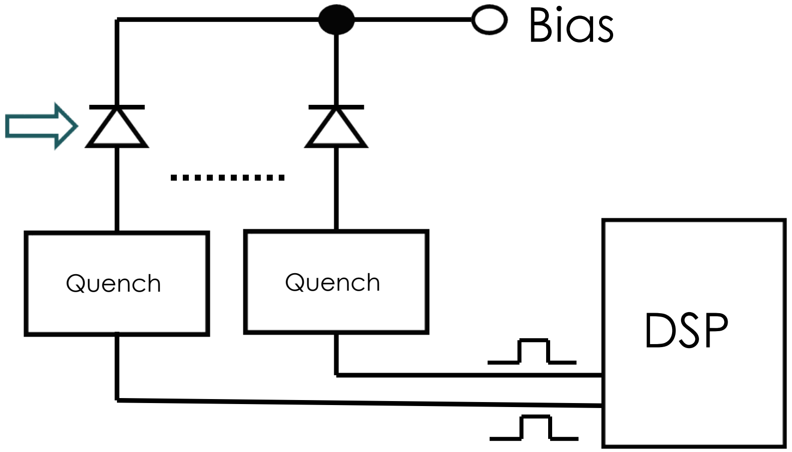


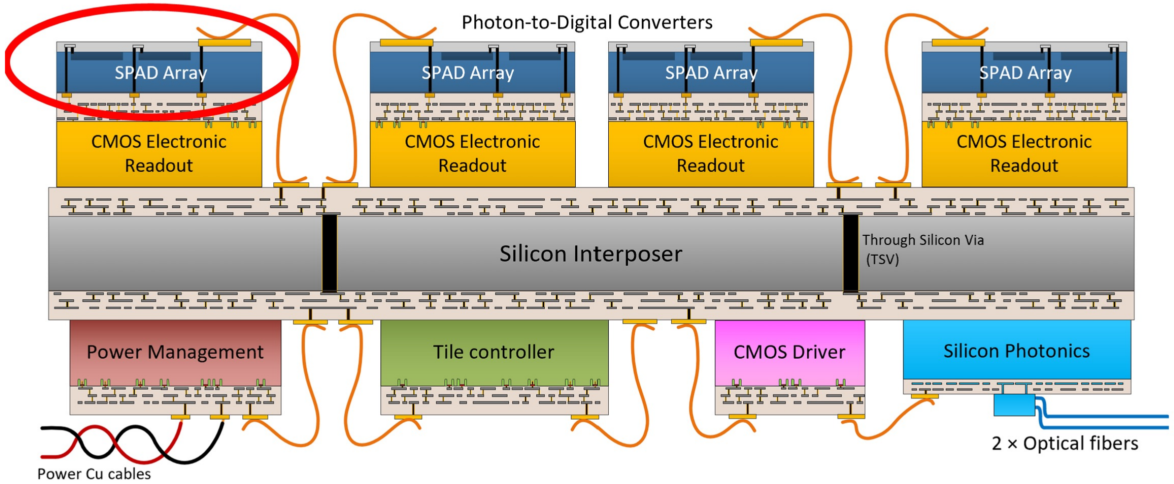
(a) (b)

Purpling of material controlled and disappear after curing

Photon-to-Digital Converters (PDCs)

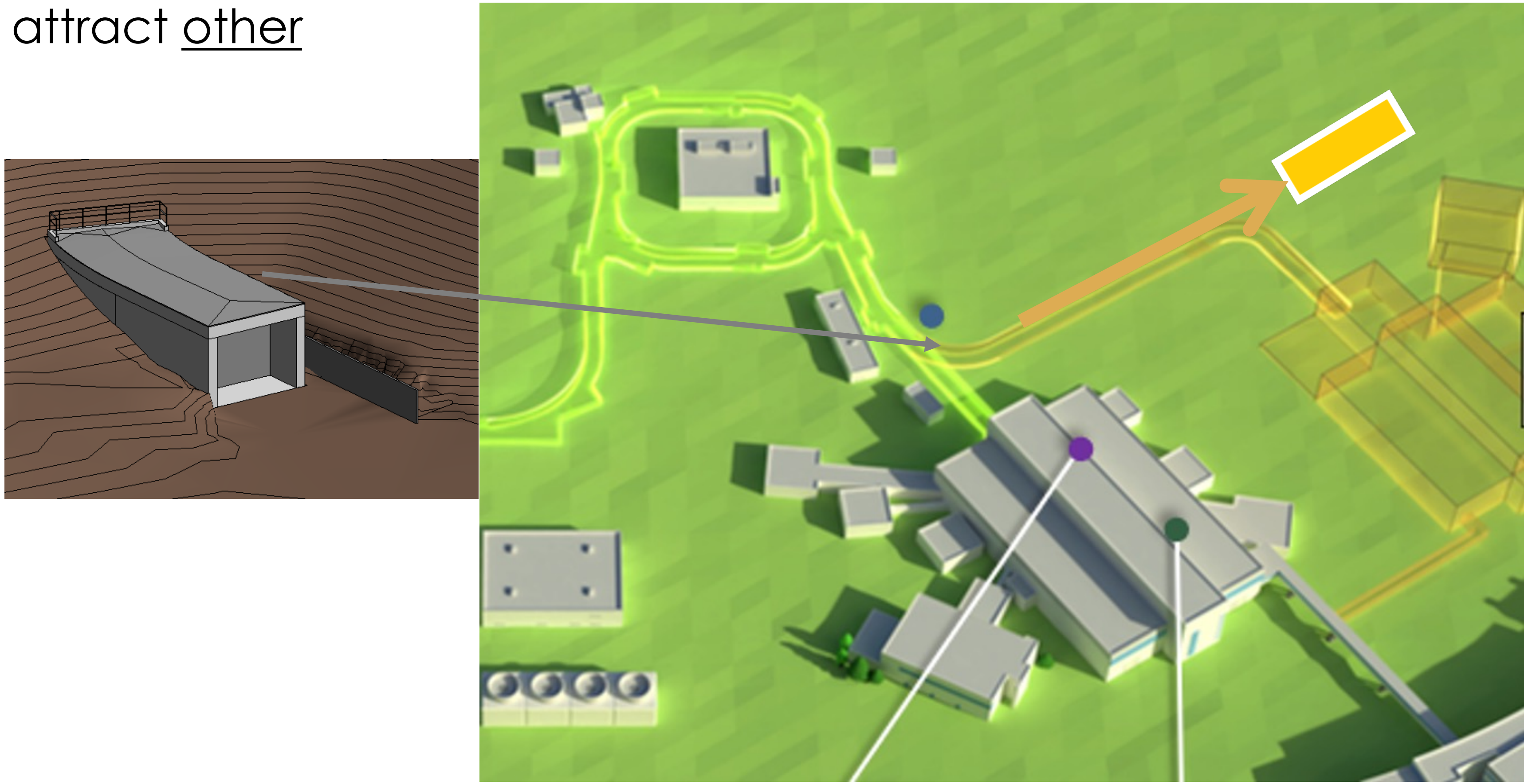
- ORNL/University of Sherbrooke(Canada) collaboration to develop Single SPAD level integrated PDC using deep sub-micron CMOS technology and 3D/Vertical integration
  - Increased circuit density allows to implement full 2D SPAD readout array with large fill factor
  - 3D integration of the SPAD tiles to readout electronics will yield to better Fill Factor, increasing efficiency
  - ORNL's new investment in equipment for Microelectronics in synergy with efforts on assembling more integrated Photodetection Module
  - Dialogue with Fermilab on 3D integration technology





Idea: Use the SNS 'excess' power early

- SNS will operate at 2 MW in 2026 and can ramp up to 2.8 MW in 2027-28
- The tunnel stub is part of PPU and will be completed in 2024
- STS present early project completion is mid to late 2030's
- **Advancing the construction of the STS beamline can make the extra power available for use before the STS is completed**
- It will advance STS and grow support outside the neutron community
- It leverages capability to attract <u>other funding sources</u>



Radiation Detection with Single Crystal Lithium Salicylate

Jason Newby
Lawrence Livermore National Laboratory

2009 MRS Spring Meeting

LLNL-PRES-412190

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Lithium component offers significant advantages in flexibility and sensitivity.

Why Lithium?

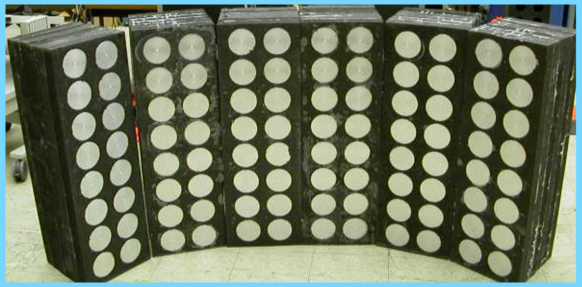
- Thermal Neutron Detection
- Sensitivity Fast Neutrons E_n<200keV : 1-3 barns results in 1% level intrinsic efficiencies
- Clean α,t Signal compared to Gadolinium (multiple-γ's), Boron (lower light yield, +γ)

Previous Work

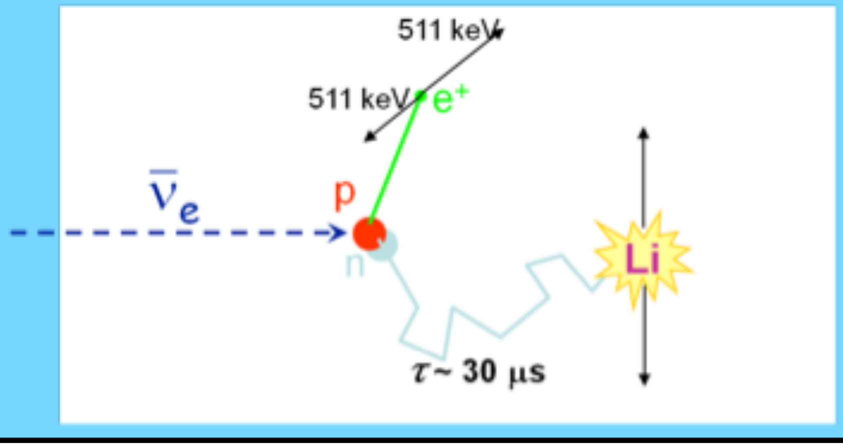
Greenwood and Chellew NIM 165 (1979)129-131 first examined small crystals (10μm) of Lithium Salicylate $LiC_6H_5O_3$
Demonstrated pulse-shape discrimination of $^6Li(n,\alpha)t$ process from a γ-Compton process.

Applications

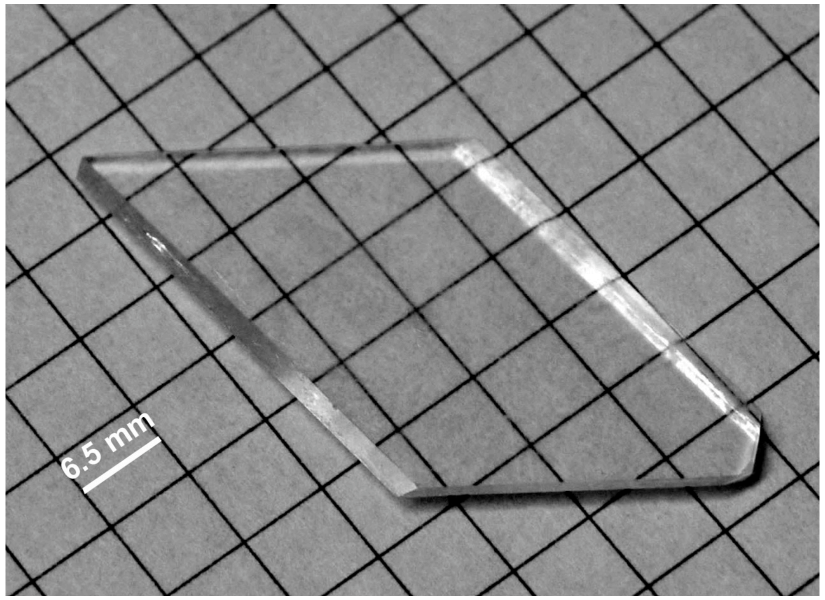
- All-In-One Radiation Detection γ, Fast-n, Slow-n Detection (^3He Substitute)
- Fission Neutron Spectra measurements via Time-of-flight

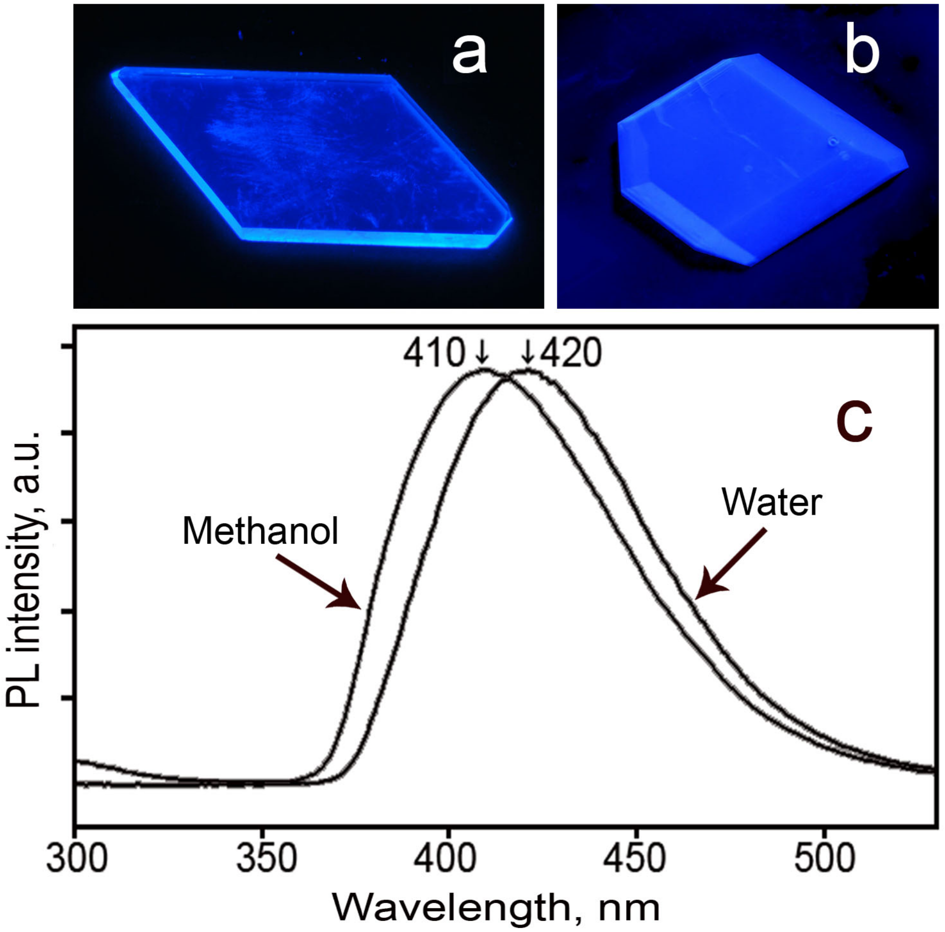


- Antineutrino Detection N.S. Bowden *et al.* NIMA 572 (2007) 985-998



Large Single Crystal Li-Salicylate Successfully Grown

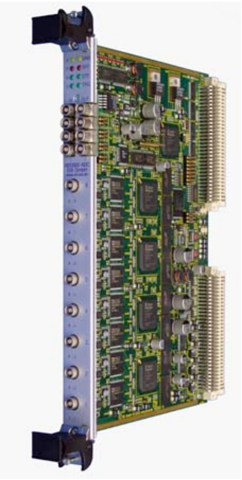


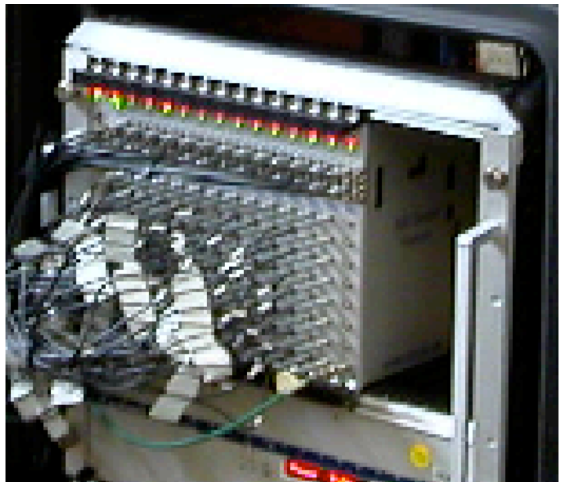


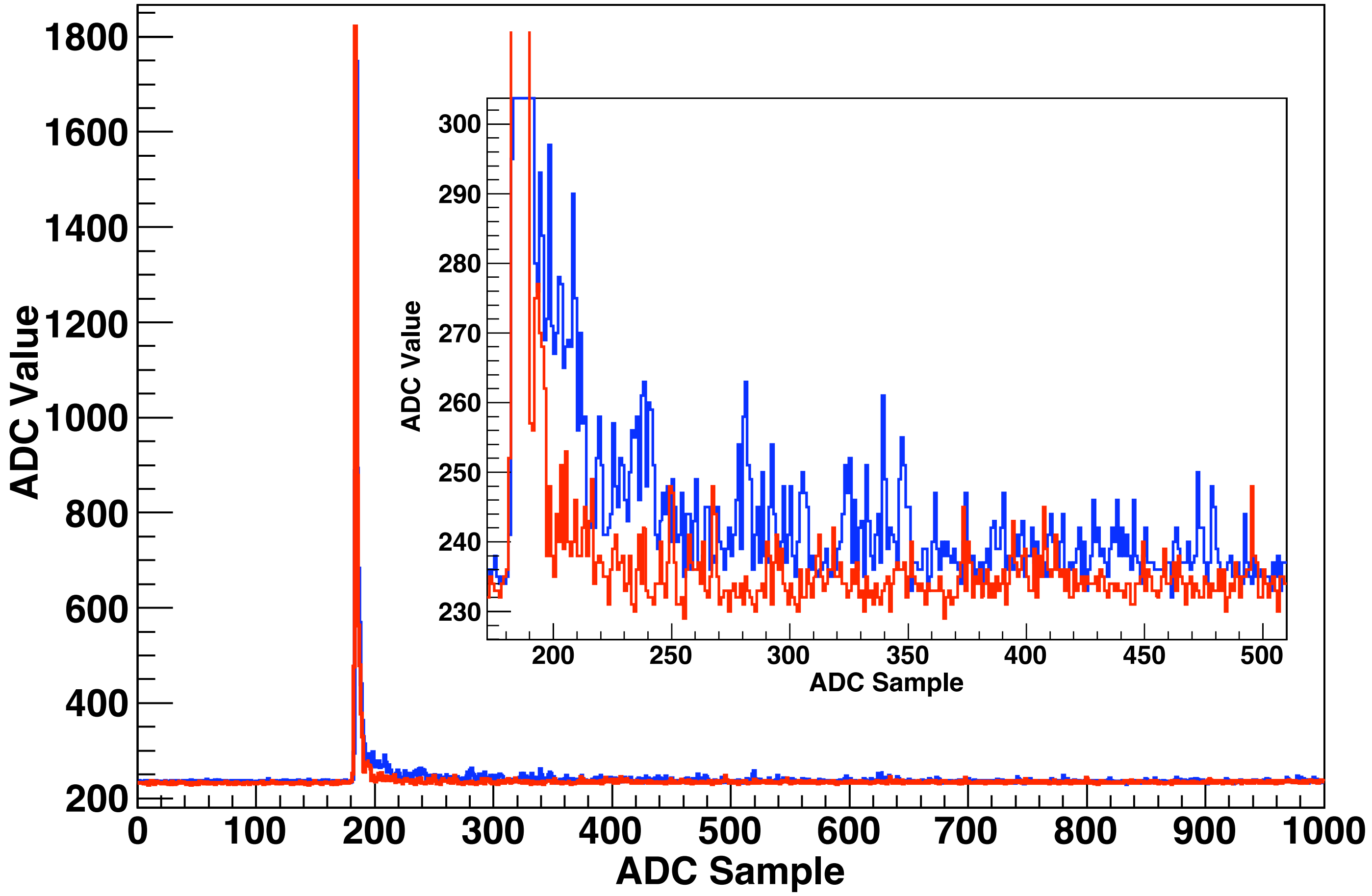
- Large cm size crystal grown from water (and methanol) at 1 mm/day growth.
- Both crystaline polymorphs exhibit similar pulse-shape discrimination.
- However, surface of methanol grown crystal visually degraded outside solution.
- Pulse-shape performance will be presented only on crystal grown from water.

Full Waveform Digitization enables automated exploration.

- Struck SIS3320 12bit 200MS/s Waveform Digitizer
  - 12 bit resolution enables analysis of lower yield delayed light
  - 5μs waveforms archived for offline analysis
- Hamamatsu PMT R6231U
  - Super-bialkalai photo cathode
  - Rise-time 5 ns well matched to digitizer
  - Low dark current
  - Lower after-pulse noise than faster PMT's

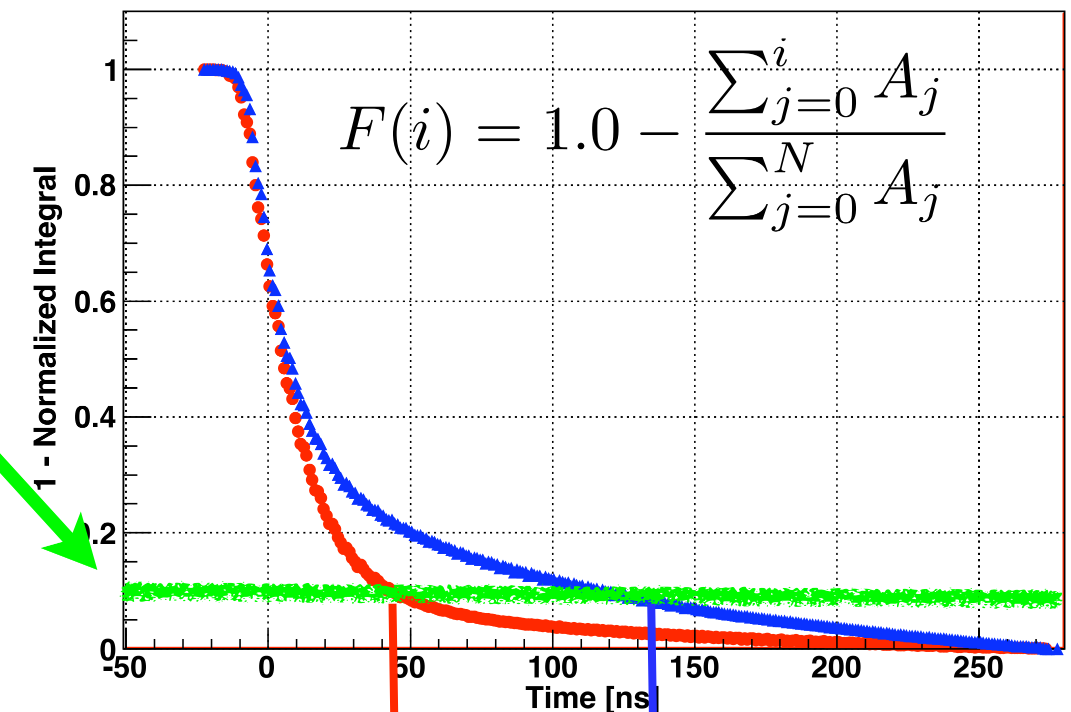


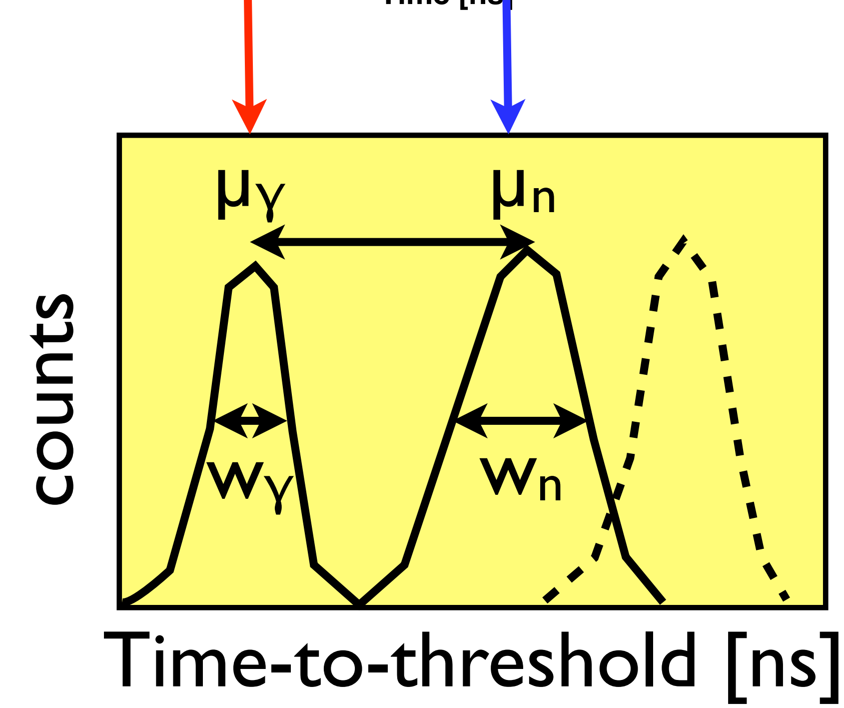


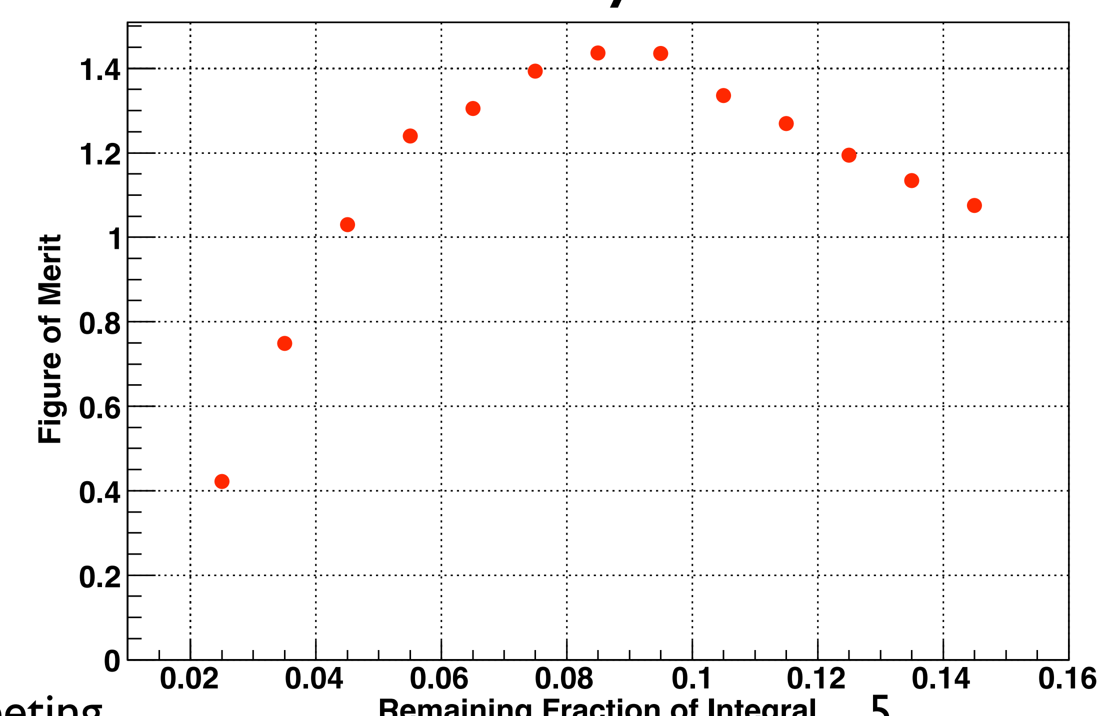


Digital Waveform Pulse Shape Analysis

- Time relative to quadratic fit of peak
- PSD parameter is time to ~90% of pulse integral
- Figure of merit is PSD separation divided by sum of widths: $\mu_n - \mu_\gamma / w_n + w_\gamma$
- Time-to-threshold is optimized to maximize FOM for each crystal

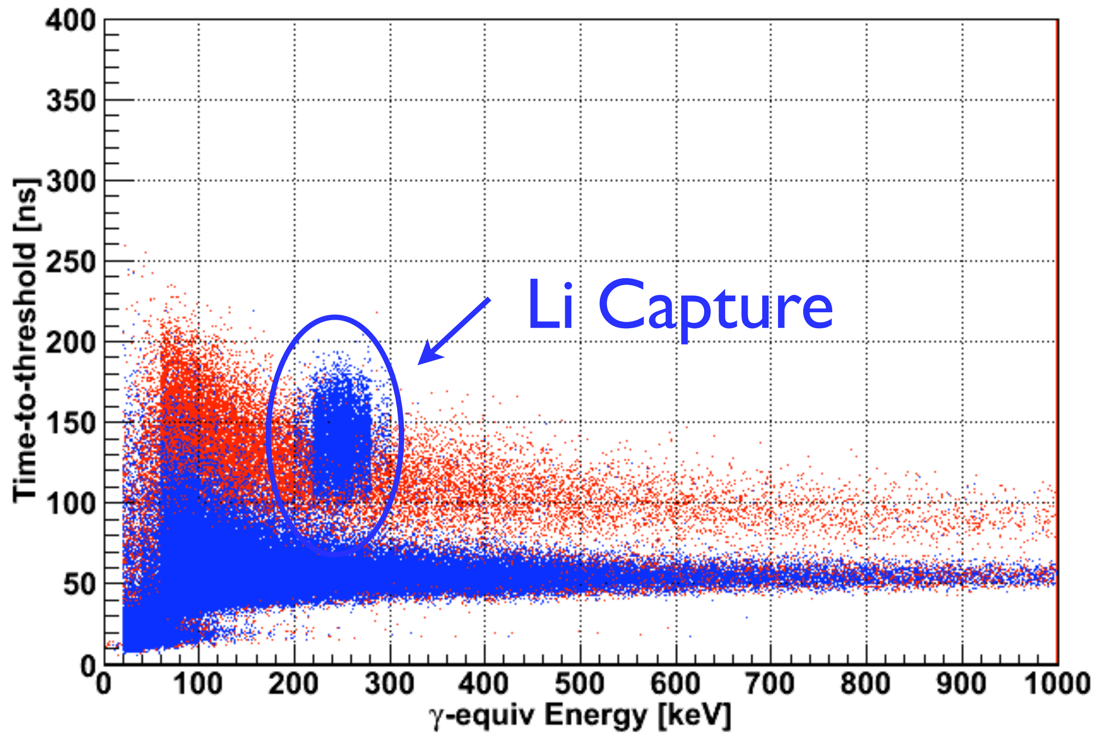


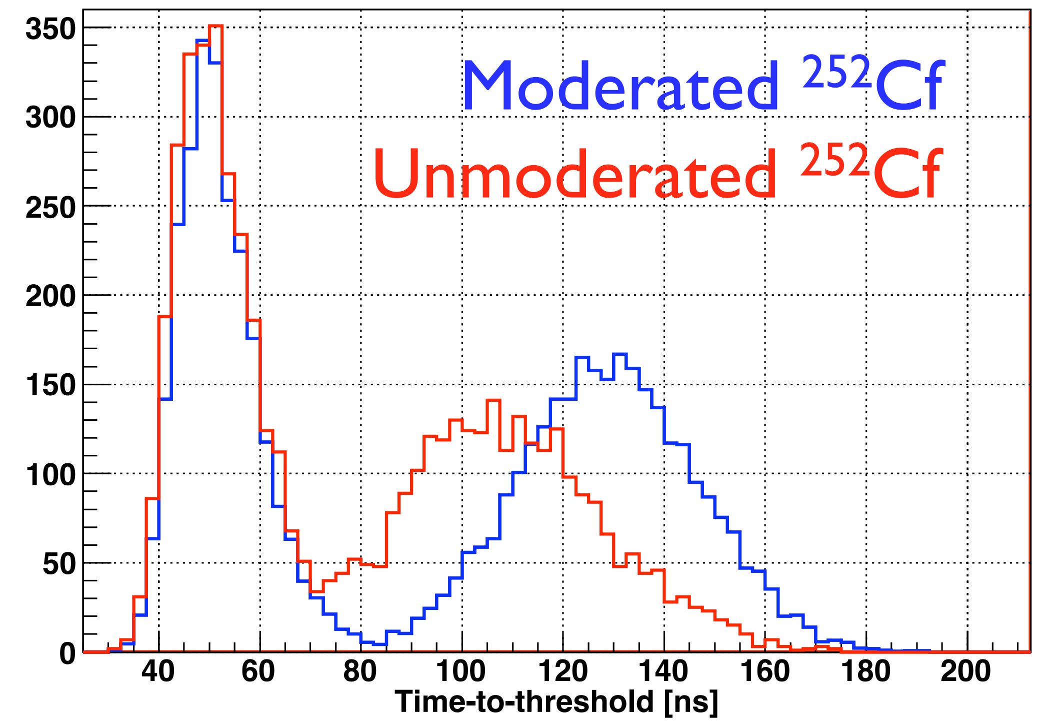


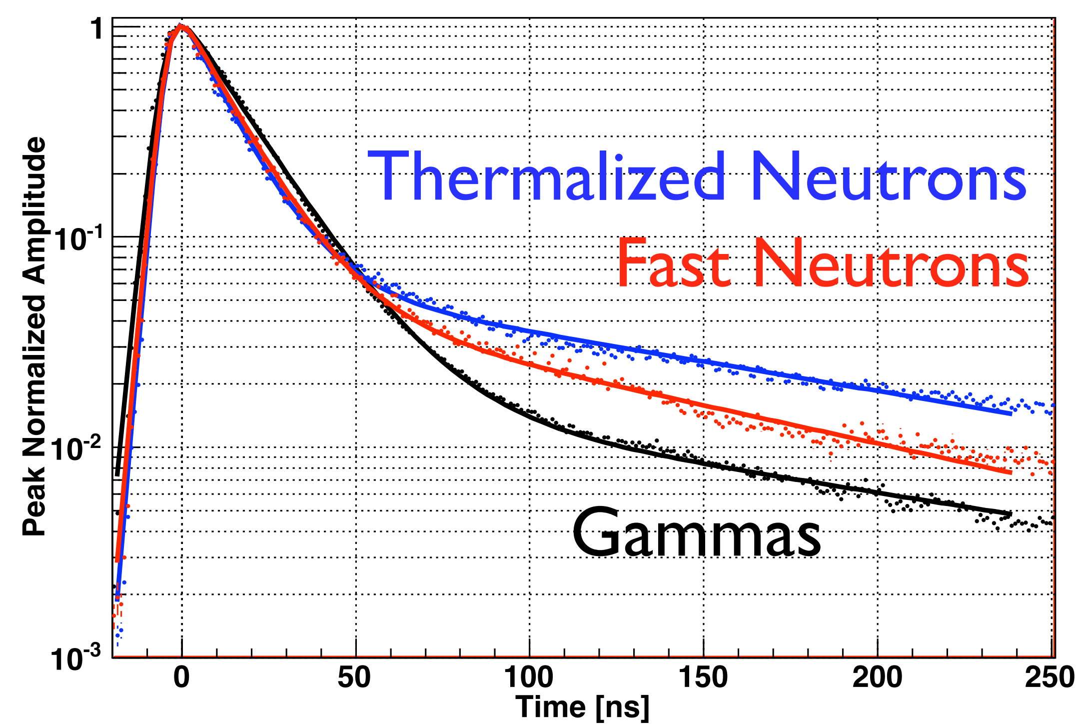


Single Crystal LiSal shows promising Fast/Slow Neutron Separation

^{252}Cf with/without 4"Moderator

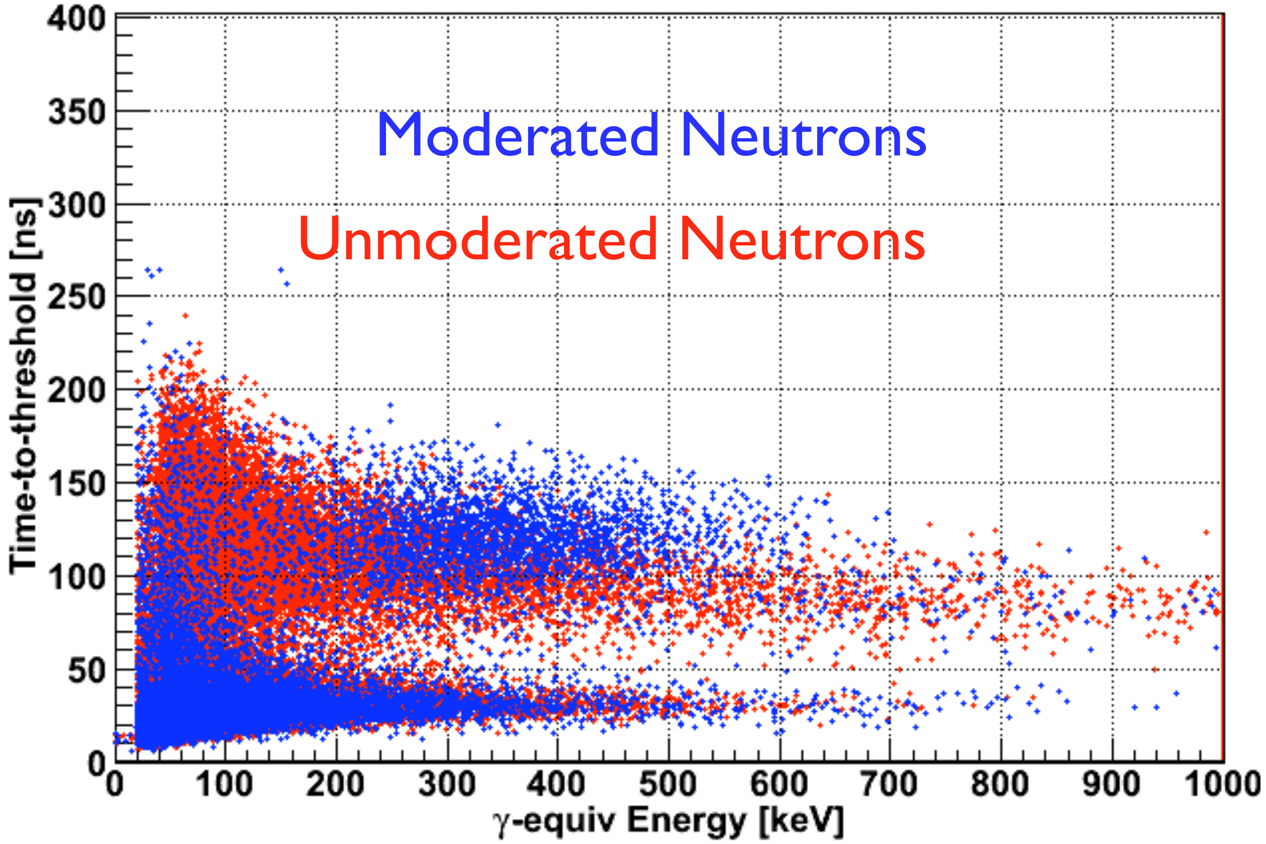


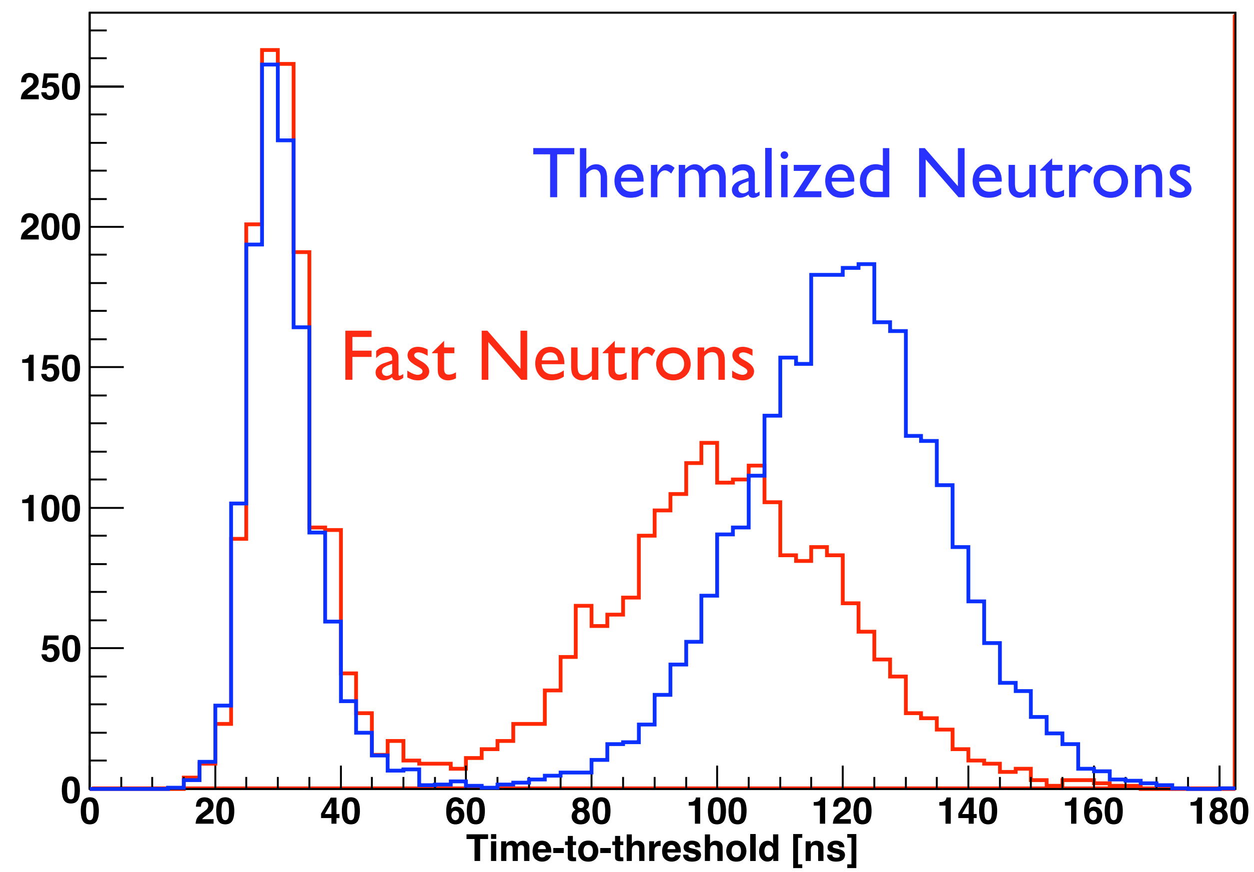




- Each process has unique pulse-shape
- Variations observed in both prompt and delayed light yields
- Slow Neutrons/Gammas FOM 1.4

New and Promising Candidates...

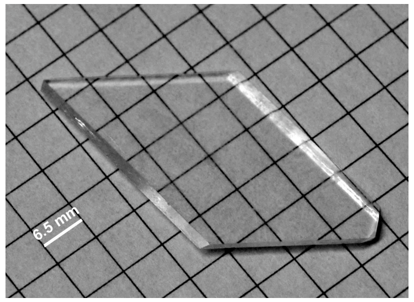


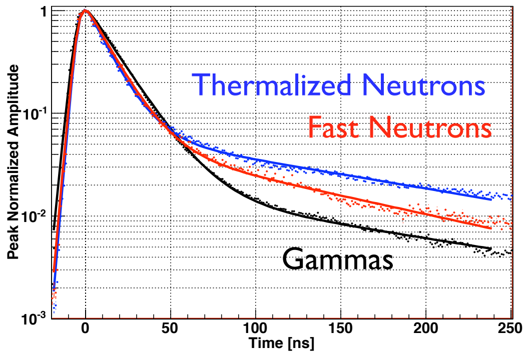


- Lithium chemistry presents many possibilities with organic acids.
- Even small sub-mm size crystals have good PSD.
- Candidate Lithium containing crystal with much higher light yields, faster growth, and perhaps better slow/fast neutron separation are currently being examined.

Summary

- We present the first results of large Lithium Salicylate crystal growth and performance.
- Large single crystals successfully grown from solutions of water and methanol.
- γ's (Compton electrons), Fast Neutrons (recoil proton), and Slow Neutrons (lithium capture) all produce light curves of characteristically different shapes.
- Alternative lithium crystals being examined now show promising advantages in ease of growth and performance.





Acknowledgments

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  - N. Zaitseva, G. Hull, C. Saw, L. Carmen, N. Cherepy, S. Payne, M. Pearson, W. Stoeffl
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  - K. Shah, J. Glodo
- DOE NA-22
  - D. Beach