Near-field Antineutrino Application Developments in the U.S.

3rd IAEA Technical Meeting Nuclear Data for Antineutrino Spectra Applications

4/8/2025

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on behalf of MAD & CASC-NN porjects

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Project Team

Virginia Tech, Georgia Tech, Oak Ridge National Laboratory, USNA United States Naval Academy, Illinois Institute of Technology, NIST

Mobile Antineutrino Demonstrator

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Lawrence Livermore National Laboratory

AIT

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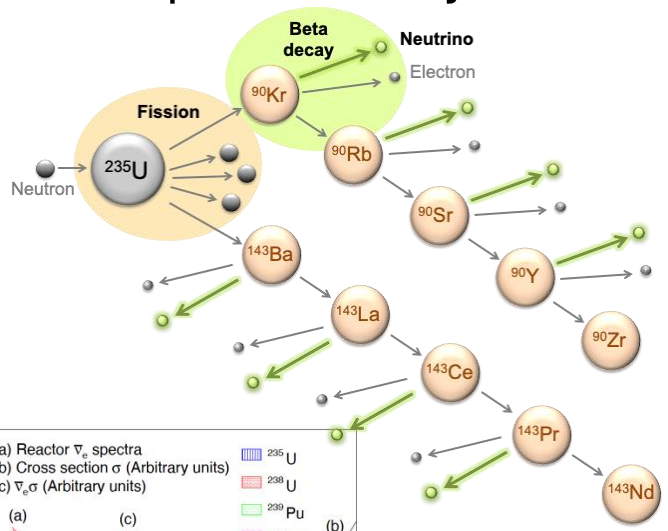
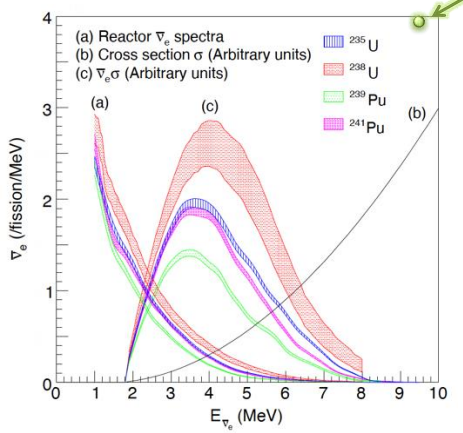
Pacific Northwest National Laboratory

Near-field Reactor Antineutrino Monitoring

Potential non-intrusive measurement capability for reactor power and Pu production

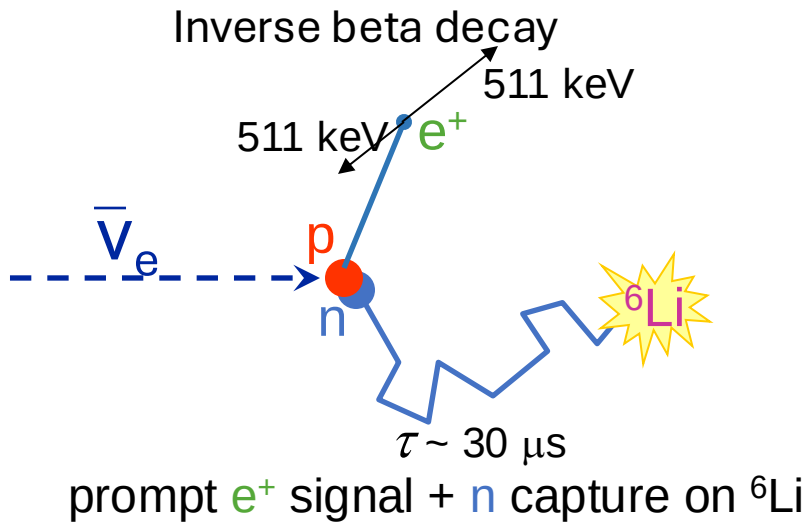
- ~6 neutrinos per fission
- Rate & spectrum vary with fuel mix



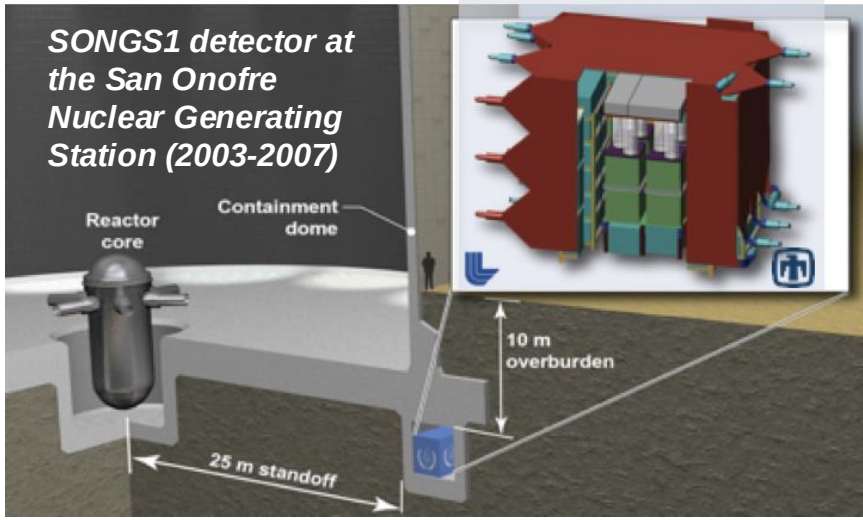


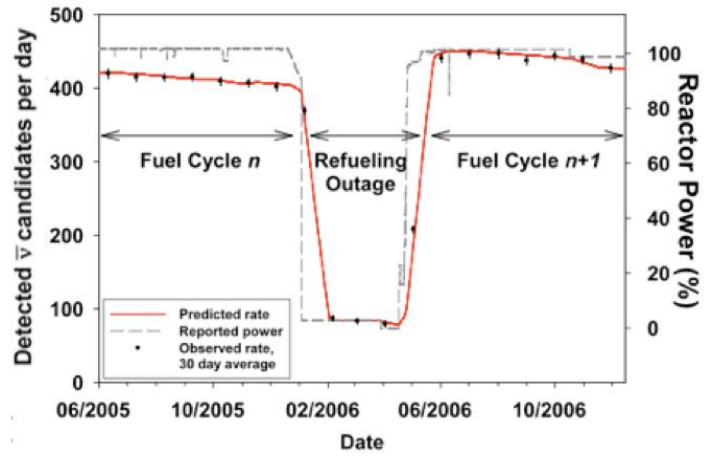
Techniques from neutrino physics enabled demonstrations:

- Proposed (1970's) & first demonstrated (1980s) in USSR
- U.S. demonstration, early 2000s
- … and several other countries



prompt e^+ signal + n capture on ^{6}Li



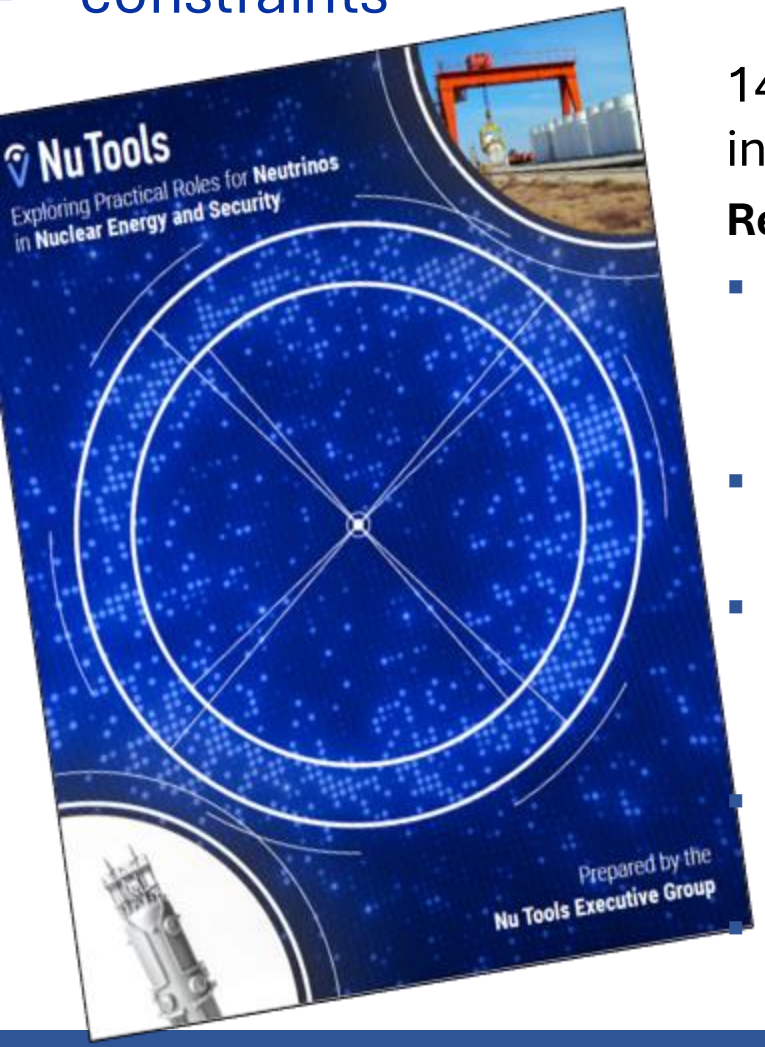


End-user feedback: neutrino applications required technical advances and improved utility understanding

The Nu Tools Study (2019-2021)

https://nutools.ornl.gov/

An effort to evaluate practical uses for neutrinos via broad input on needs and constraints



14 member Nu Tools study group engaged experts from the nuclear energy industry, regulatory, safeguards researcher and practitioner communities

Relevant Findings:

- **End User Engagement:** *".. neutrino technology R&D community is only beginning to engage attentively with end users … further coordinated exchange is necessary"*
- **Technical Readiness:** *"… novel system such as a neutrino detector requires a dedicated qualification exercise."*
- **Neutrino System Siting:** *"… requires a balance between intrusiveness concerns and technical considerations, where the latter favor a siting as close as possible"*
- **Advanced Reactors:** *"… present novel safeguards challenges which represent possible use cases for neutrino monitoring"*
- **Future Nuclear Deals:** *"… interest within the policy community in neutrino detection as a possible element of future nuclear deals"*

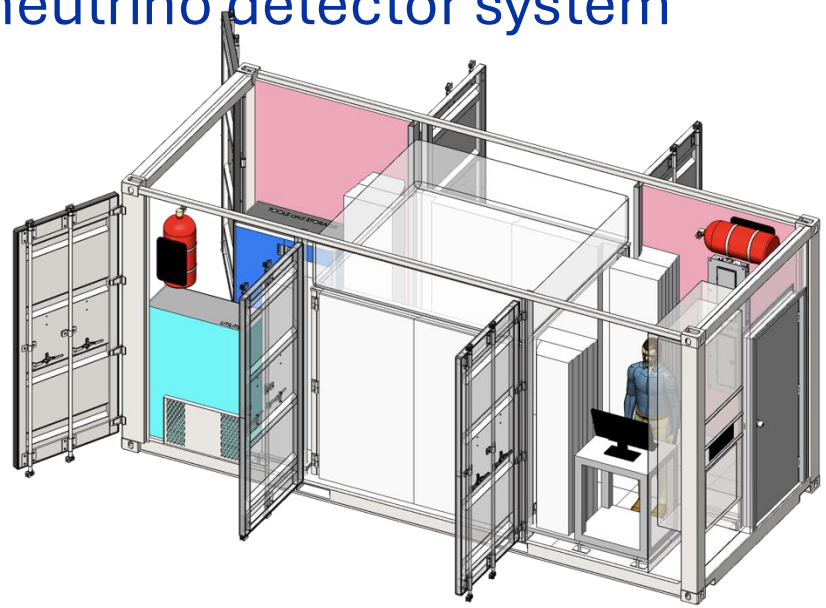
Nu Tools provides motivation & guiding principles for our R&D : Compact, efficient ^{6}Li-based systems

Mobile Antineutrino Demonstrator

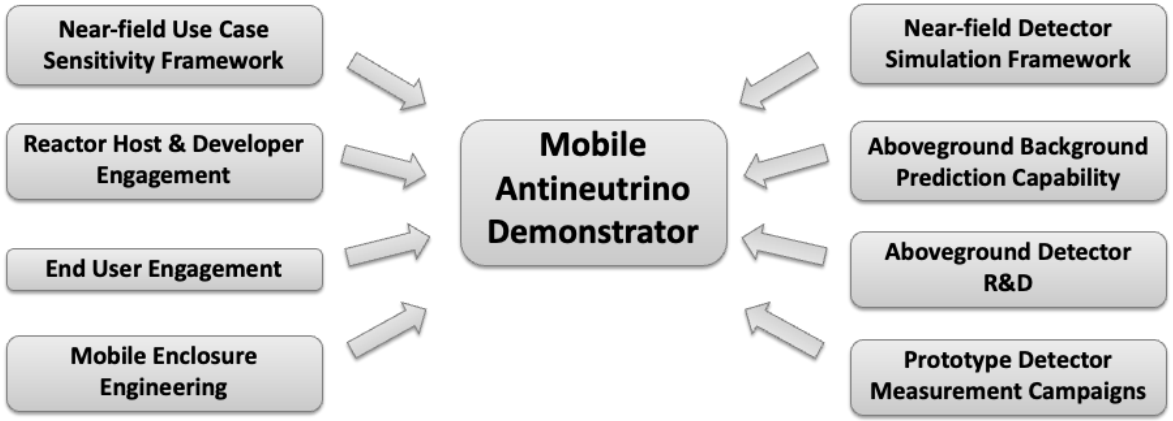
Goal: Develop & construct readily mobile ton-scale antineutrino detector system

The Mobile Antineutrino Demonstrator:

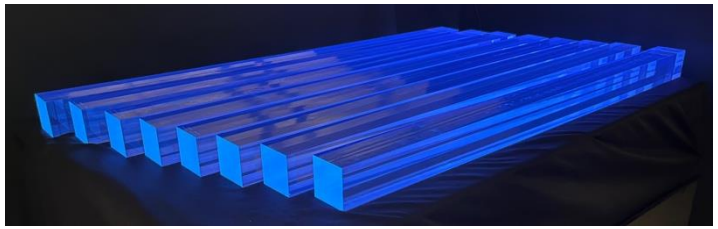
- requires no infrastructure beyond power & deployment footprint
- operates aboveground without significant shielding
- incorporates potential end-user input
- advances "Technical Readiness" of neutrino applications by performing capability demonstrations in operationally relevant environments



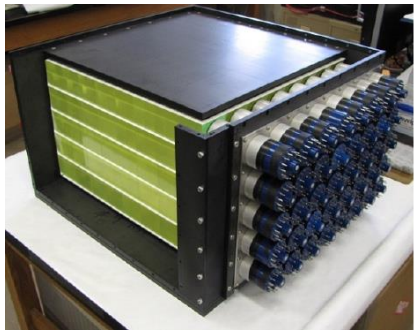
Comprehensive effort providing foundational capabilities for any near-field use case



Advancing Two Solid-State Detector Technologies



2D segmentation with ^{6}Li-doped PSD plastic scintillator



3D segmentation with ^{6}LiZnS & WLS plastic (CHANDLER)

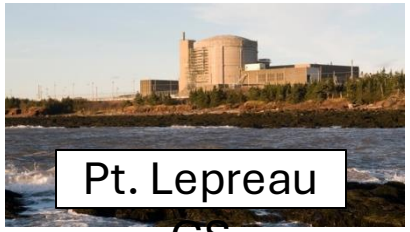
Engagement:
Potential End-Users, Reactor Sites, & Other Mobile Projects

Utility topics:

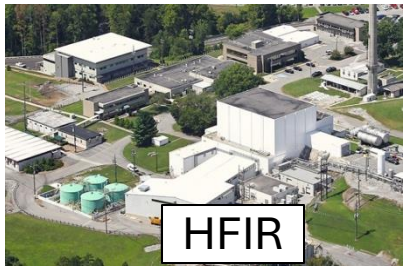
- Reliability
- Demonstration fidelity
- …

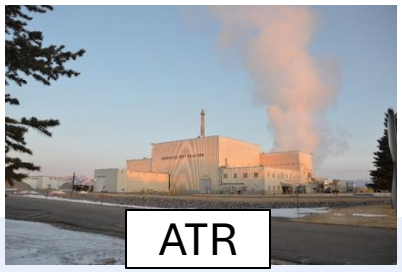
Logistical topics:

- Security inspection for PA access
- Fire Suppression
- Environmental Control
- Safety & Mechanical Assessment
- Physical Site & System Access
- …


Pt. Lepreau


Hope Creek NGS


HFIR

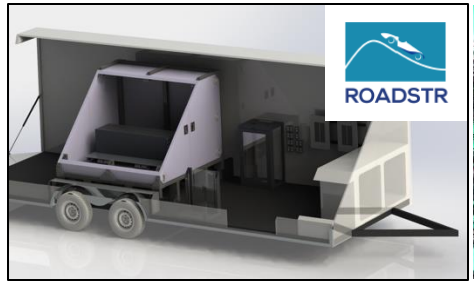

ATR


SONGS


PANDA


VIDAAR

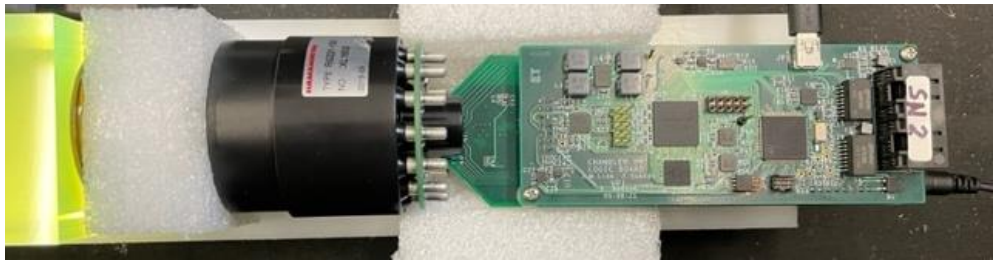
miniCHANDLER



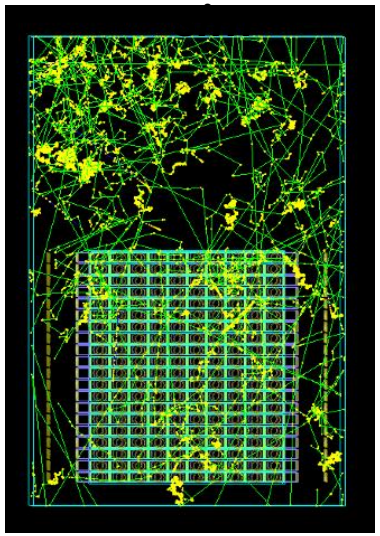
Aboveground Detector Concept R&D

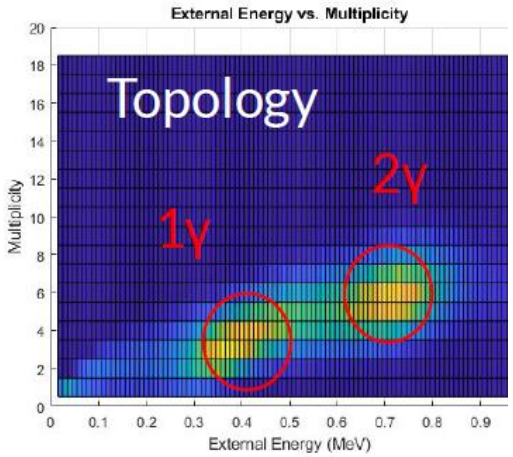
- Advance maturity of 2D and 3D detector concepts:
  - Materials qualification and packaging
  - Detector mechanical design
  - PMTs and readout
  - IBD Selection and Background studies

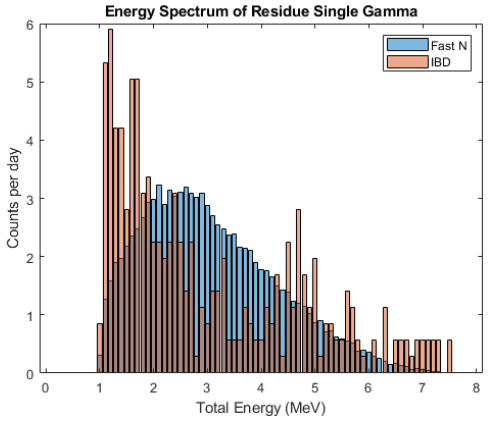
Readout and low-power HV



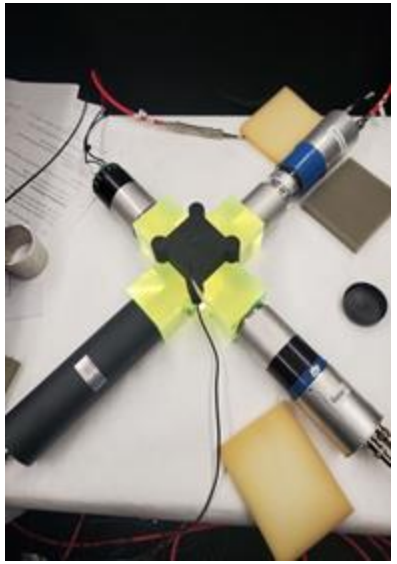
Background simulation and IBD event selection



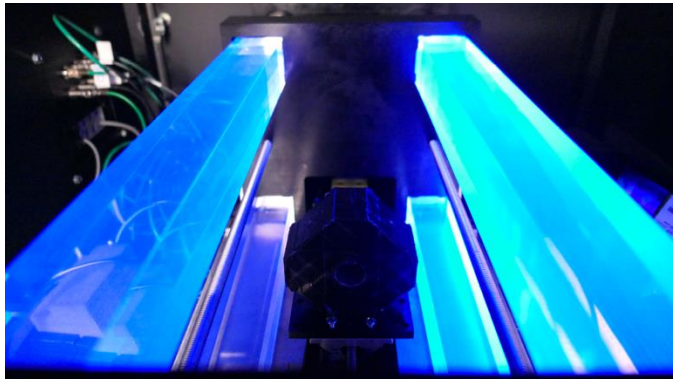




PMT Selection



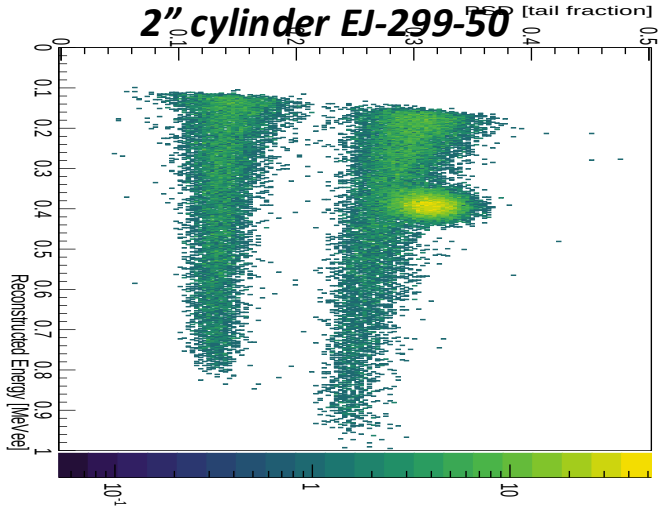
Materials



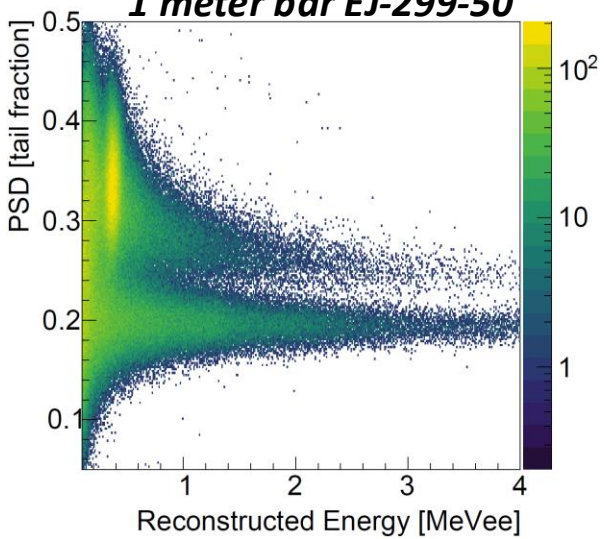
2D Concept R&D Example: Large-scale EJ-299-50 ^{6}Li-doped PSD Plastic

- Developed by Eljen Technology, new material has been cast at meter scales
- Light output (~65% of EJ-200), PSD, meter-scale optical attenuation length suitable for IBD application
- No significant performance degradation over 6-12 month time-scales operated in standard atmosphere
- Mechanical properties suitable for ton-scale detector construction
- Outgassing & configuration dependent surface precipitation of primary dye observed; address via formulation and packaging studies

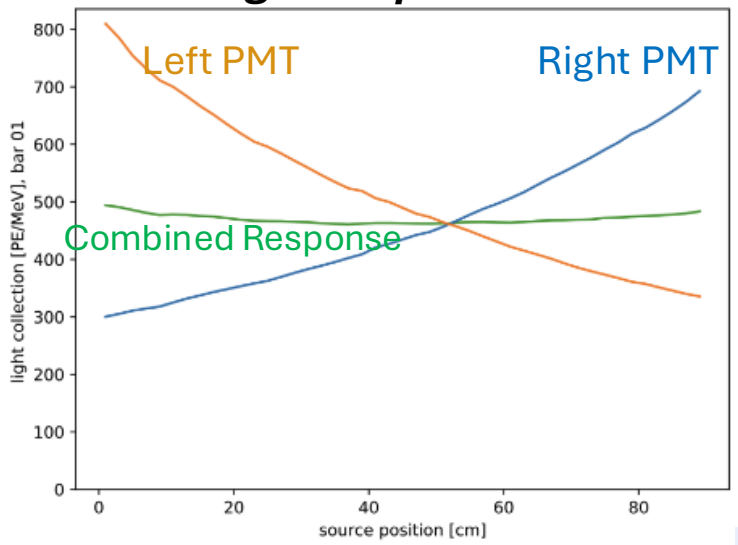
2" cylinder EJ-299-50



1 meter bar EJ-299-50



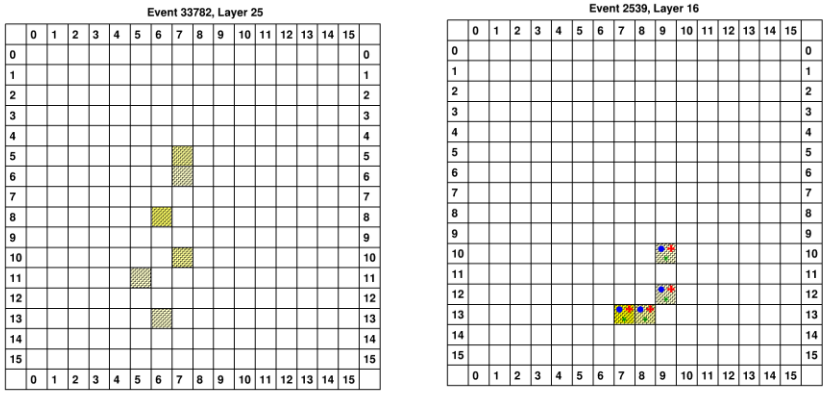
1 meter bar light output & attenuation



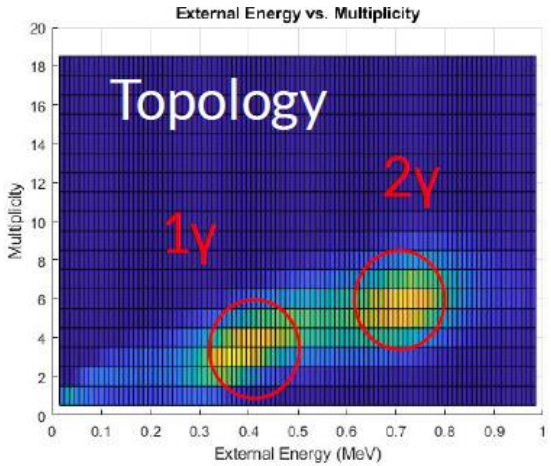
https://doi.org/10.1016/j.nima.2024.169916

3D Concept R&D Example: Reconstruction & Topological Event Selection

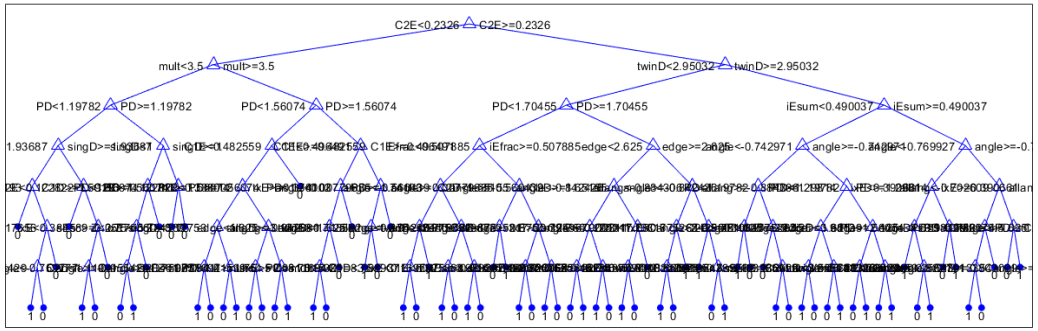
- 3D reconstruction use element-specific light distribution profiles measured using vertical muons
- Complex events reconstructed via superposition of measured response functions and minimization of weighting factors to find best-fit hit pattern
- Multiple observables for identifying Inverse Beta Decay positron and neutron developed using topology, energy, and pulse shape
- Classification and Regression Trees (CART) algorithm used to explore event selection in complex multivariate space

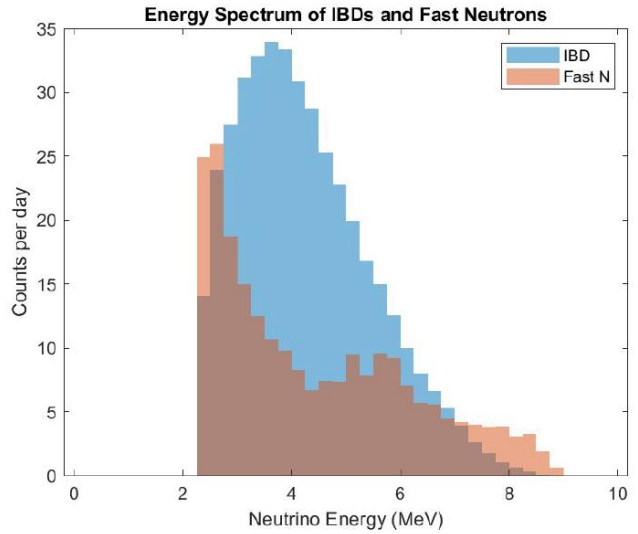


3D hit reconstruction



Topology based observable



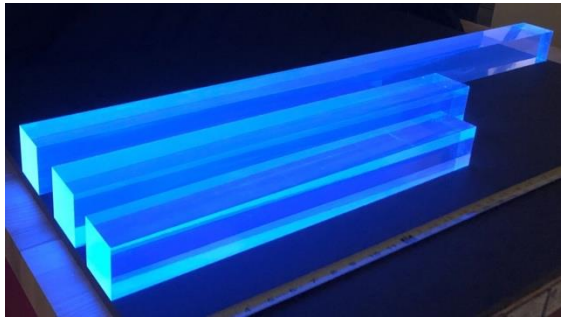


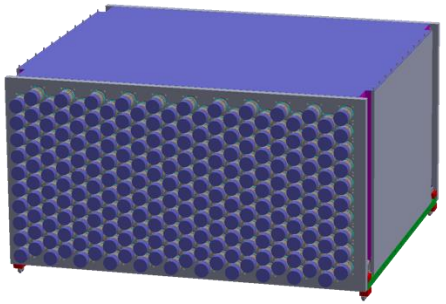
Predicted 3D subsystem signal/background

https://doi.org/10.1103/PhysRevApplied.13.034028

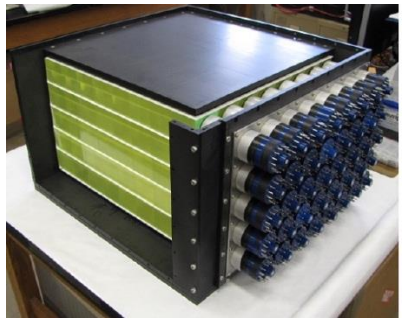
R&D Phase established two concepts with good performance potential
Predicted sensitivity comparable for systems within project budget envelope

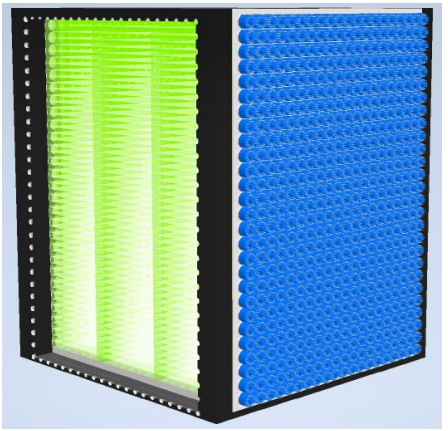
2D segmentation with ^{6}Li-doped PSD plastic





3D segmentation with ^{6}LiZnS & WLS plastic (CHANDLER)





Concept	x	y	z	Volume	Elements	PMTs	"Eff. Counts"
2D	14 bars 84.0 cm	14 bars 84.0 cm	- 100 cm	0.71 m^3	196	392	130 day^{-1}
3D	16 cubes 92.8 cm	16 cubes 92.8 cm	41 ½-cubes 116.9 cm	1.01 m^3	10,496	1,344	131 day^{-1}

@ 2MW/m^2 flux, e.g. 39m from 3GW reactor

<u>Residual Technical & Schedule Risks</u>:

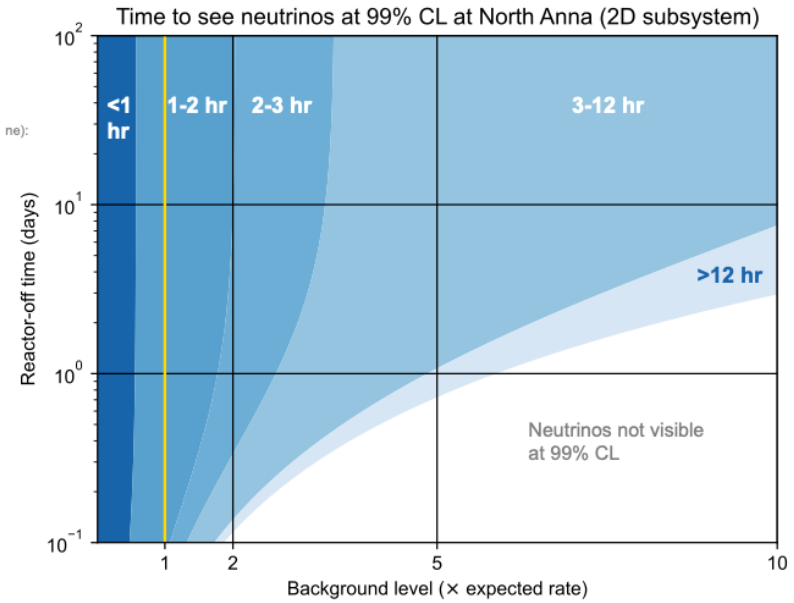
- plastic stability not fully qualified over multiple years
- standup of new material production
- 3D event reco & topological observables at scale
- PMT and readout delivery/construction schedule

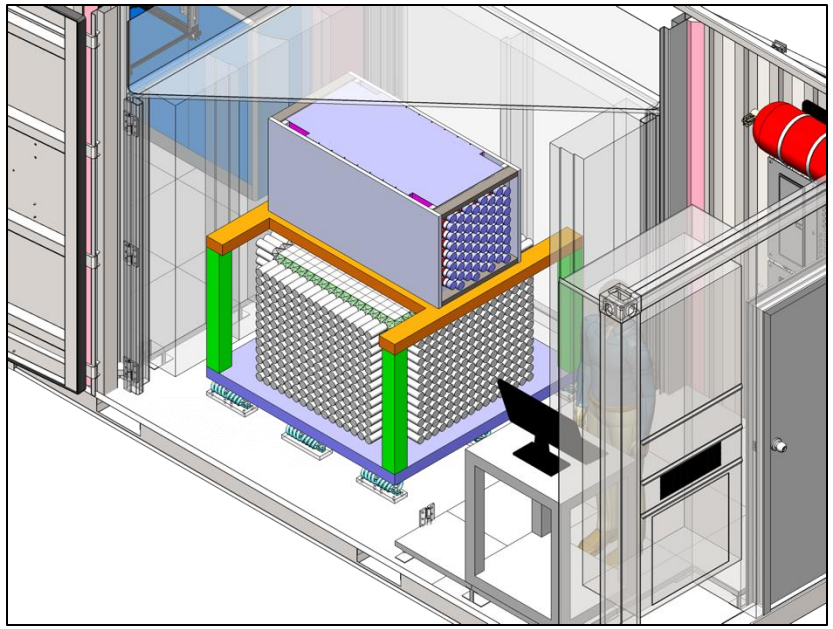
Residual technical risks for both concepts most effectively resolved through build out at larger scale

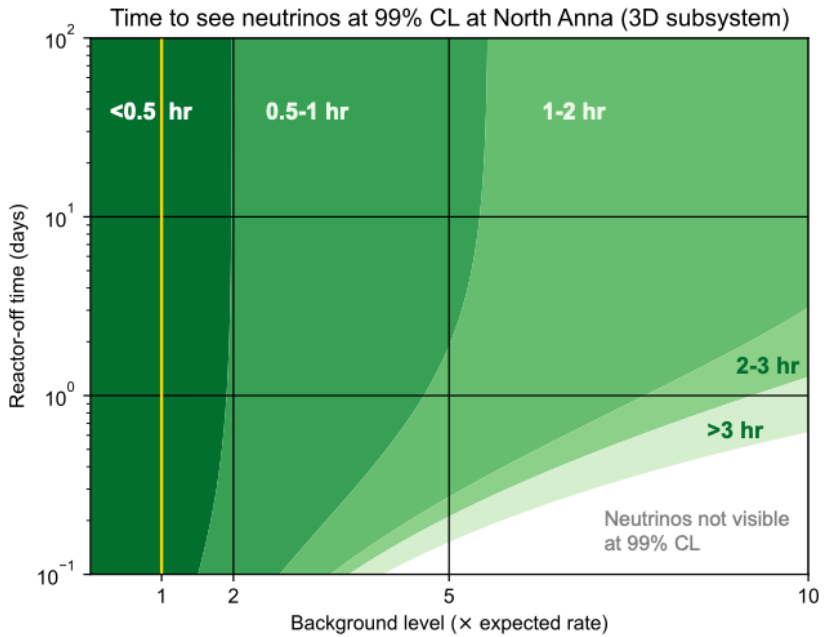
Neither relative performance nor technical considerations provided a strong preference for either concept

Path selected: Equip Mobile Antineutrino Demonstrator with 2 detector subsystems

Concept	x	y	z	Volume	PMTs
2D	8 bars 48.0 cm	8 bars 48.0 cm	- 100 cm	0.23 m^3	128
3D	16 cubes 92.8 cm	16 cubes 92.8 cm	25 ½-cubes 73 cm	0.61 m^3	832







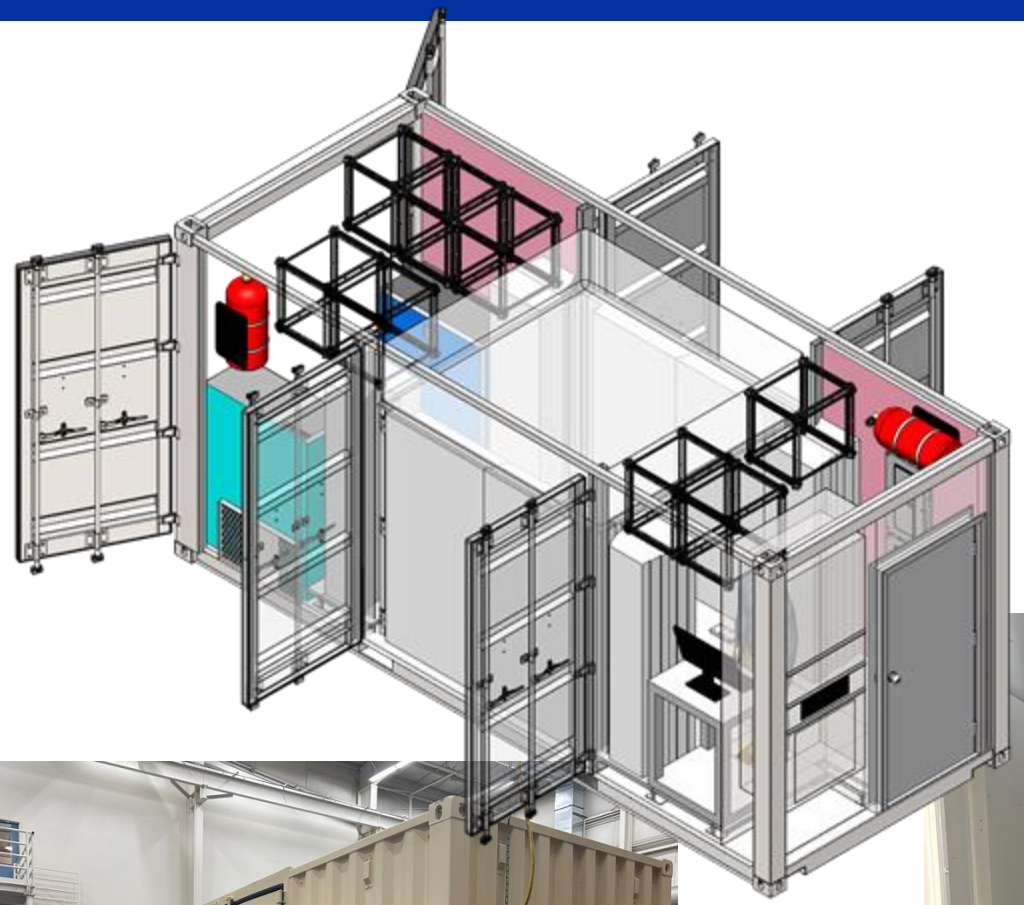
Demonstrator with two subsystems will perform capability demonstrations and advance both technology concepts

Mobile Enclosure

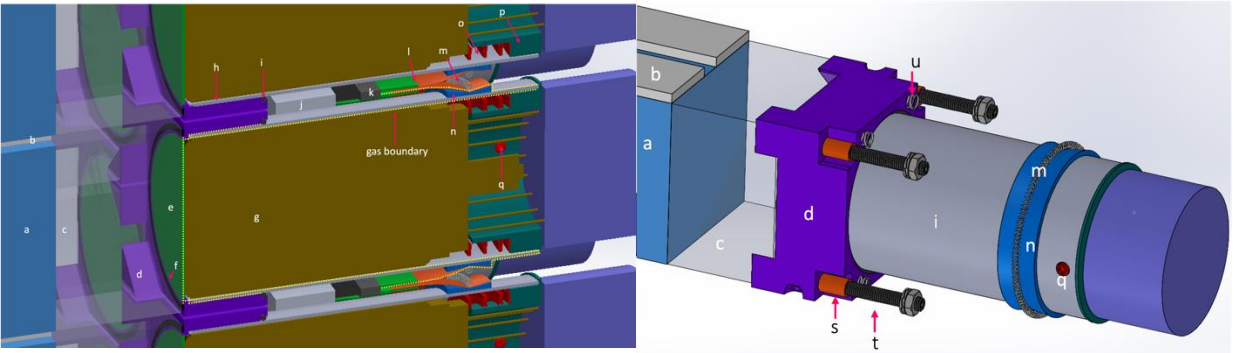
Provides:

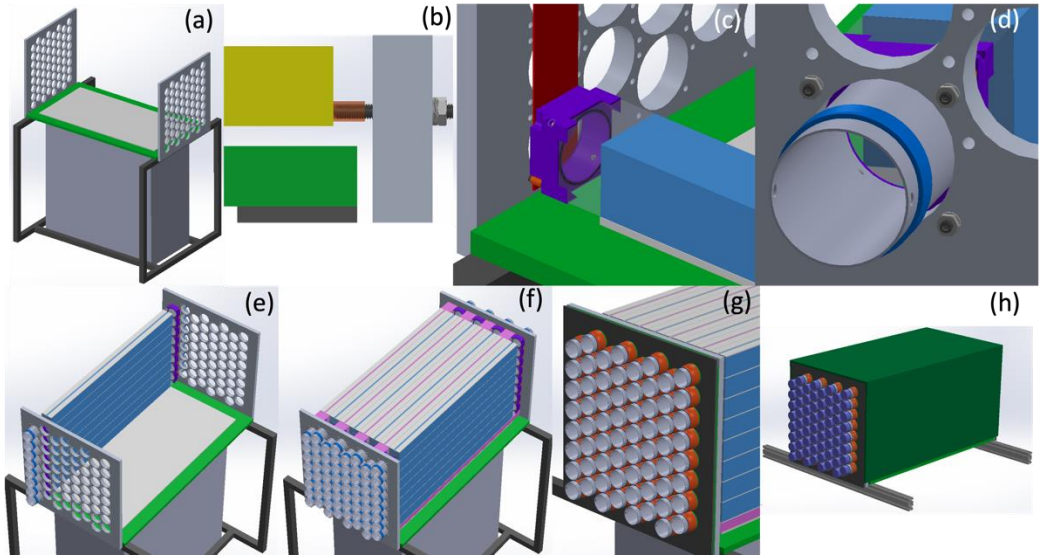
- compliance with host requirements for safety, security, and inspections
- environmental control, power distribution, and connectivity
- modest detector shielding
- safe detector transport

Fit out ongoing at LLNL

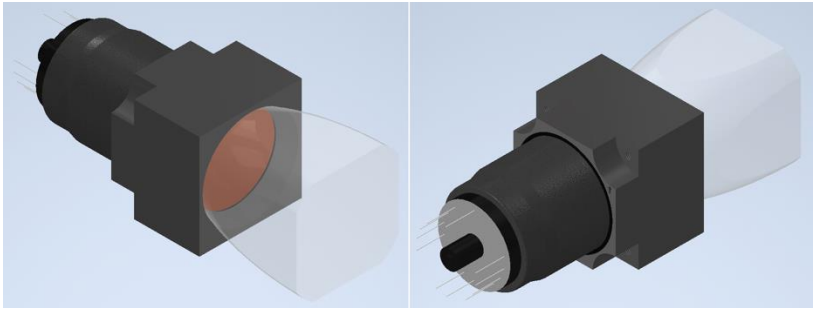


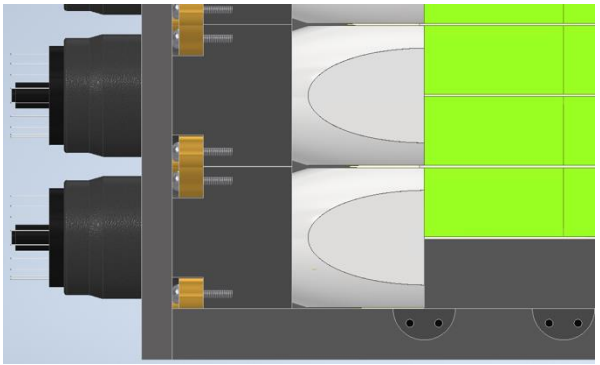
Detailed mechanical design phase completed

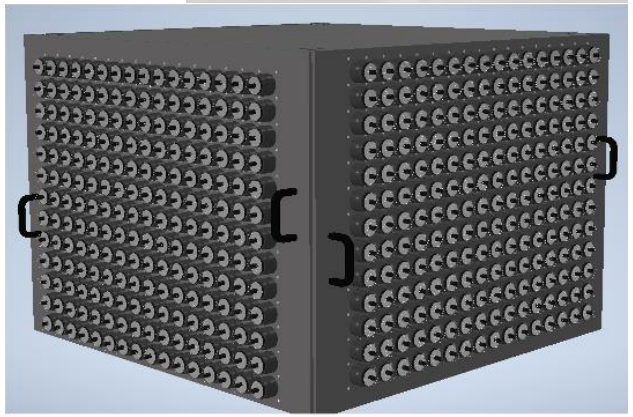




2D Subsystem Mechanical Design and Assembly

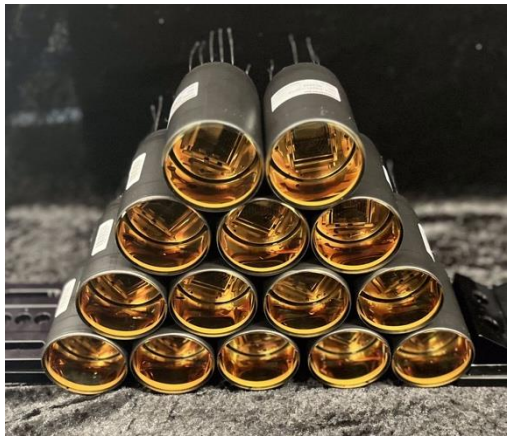


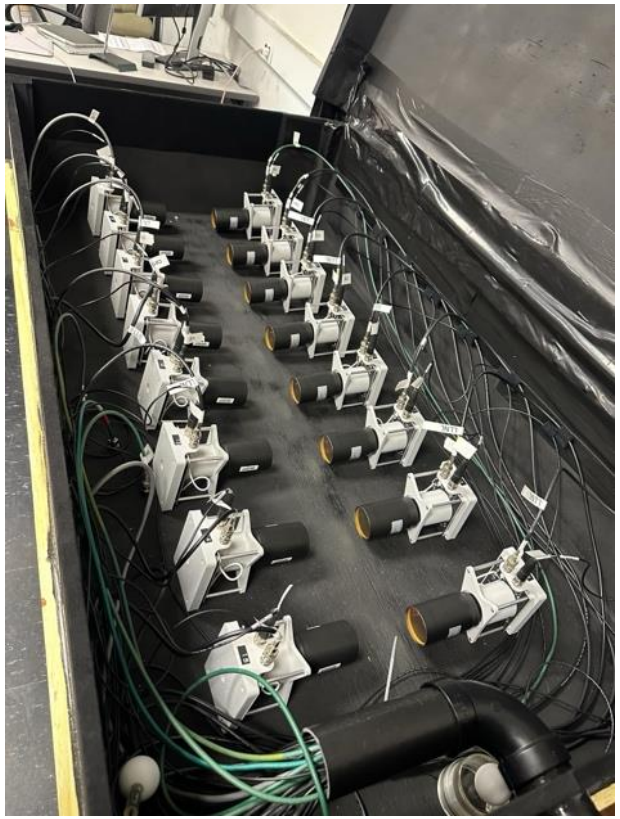




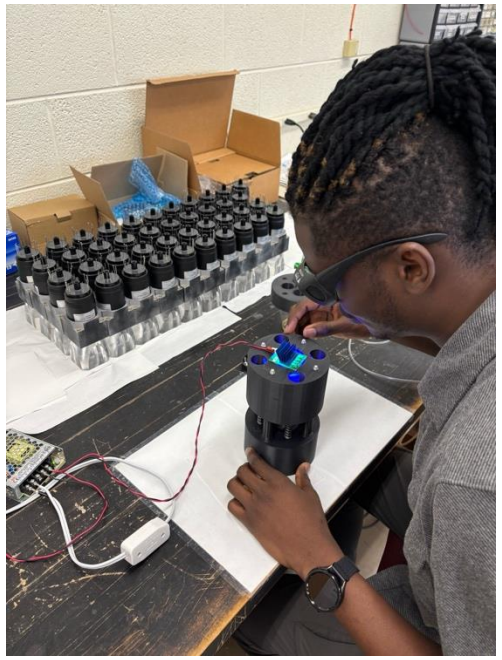
3D Subsystem Mechanical Design and Assembly

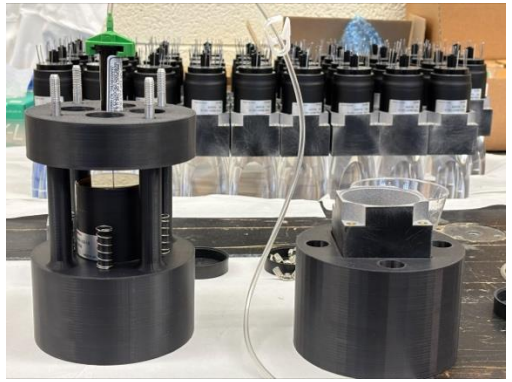
Construction & assembly phase nearing completion





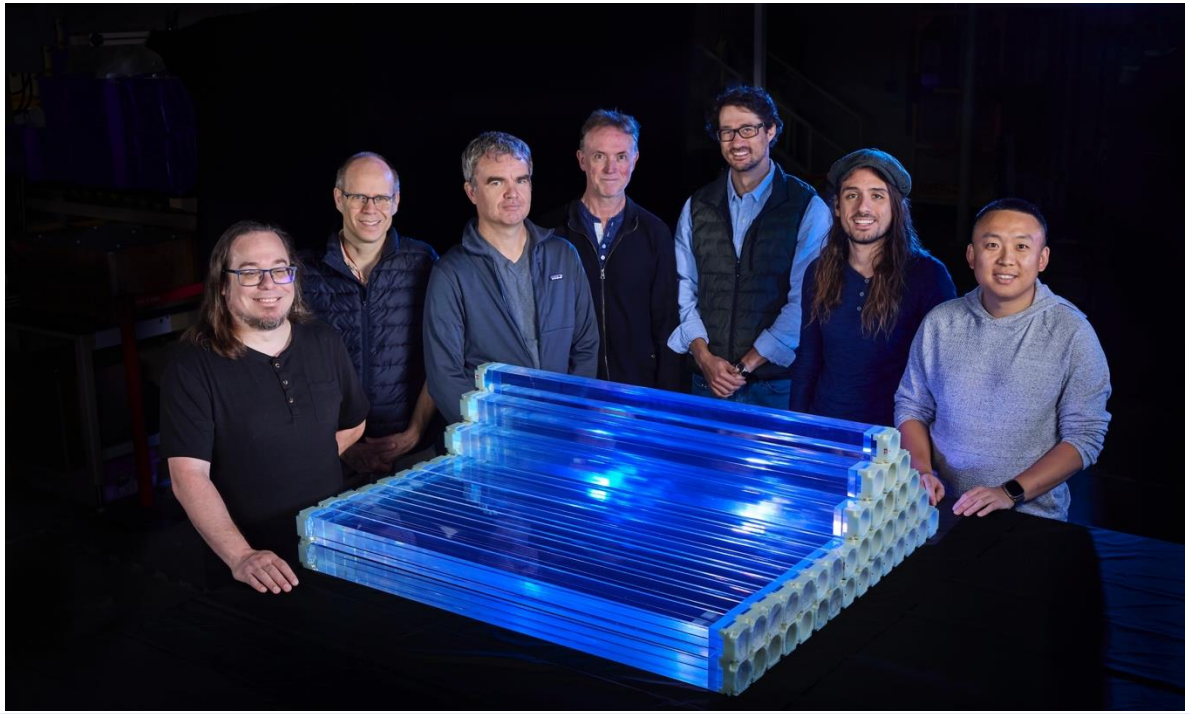
PMT characterization complete

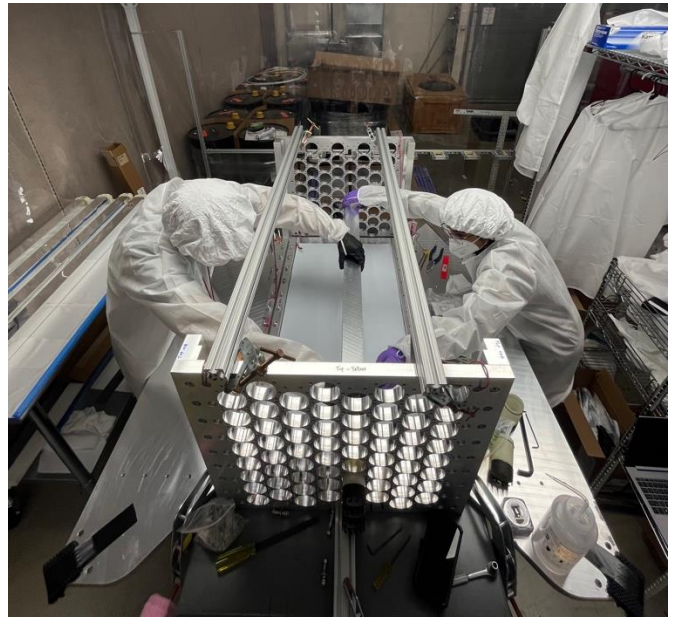


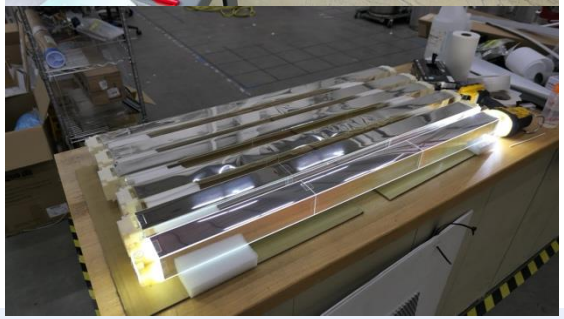


3D Optical Module Assembly

Construction & assembly phase nearing completion







2D PSD plastic bar & detector mechanics preparation

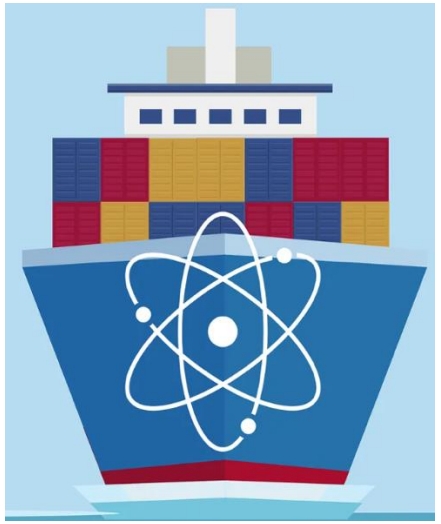
Goals for forthcoming MAD testbed measurements

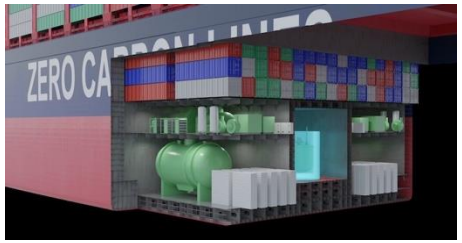
Support use case assessment, advance technical readiness, increase stakeholder familiarity

- **Validate detection technologies and demonstration of reactor monitoring capabilities**
  Performance information to inform use case studies.
- **Measure backgrounds relevant to use cases of interest**
  Require quantification of accidental and cosmogenic backgrounds, in range of use case relevant locations
- **Demonstrate reliability**
  Applications depend on operating in a stable, semi-autonomous manner for weeks, months, or more.
- **Demonstrate relocatability**
  To increase utility, easy and efficient relocation is desirable. Multiple successful relocations would be ideal.
- **Operate in rugged, restricted-access environments**
  Application occur in harsher environments than typical lab - important to show that technologies operate.
- **Engagement with facilities and other users**
  Deployments require detailed coordination, creating opportunities for us to better understand requirements and constraints, and for stakeholders to learn about this technology and it's characteristics.

Use Cases of Interest: Maritime Reactor Verification

- Historically, countries under safeguards have not operated nuclear-powered ships
- If more nuclear-powered vessels enter maritime fleets, that could present new challenges for tracking nuclear materials
- Strong connection to SMR development
- Can non-intrusive neutrino measurements provide useful verification capabilities?





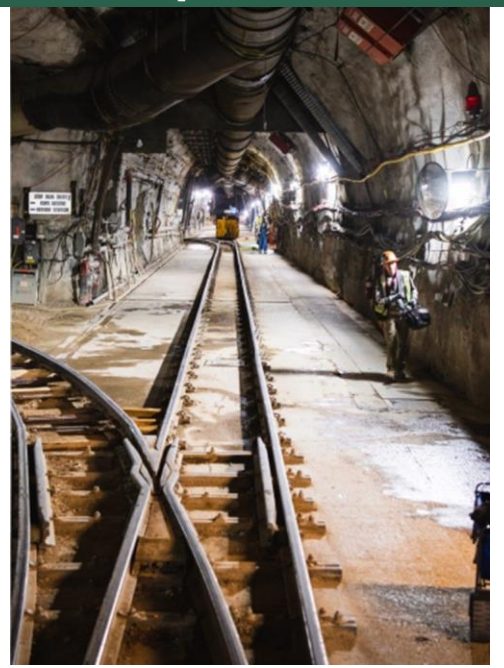
Use Cases of Interest: Revisiting Neutrinos for Test Site Transparency

- Renewed interest due to several nations increasing activities at former test sites
- Popular misunderstanding and promotion of misinformation is a risk
- Specific and unspoofable nature of neutrinos may provide powerful new tool to communicate non-nuclear nature of activities & encourage multi-lateral engagement

CNN

Exclusive: Satellite images show increased activity at nuclear test sites in Russia, China and US

NNSA conducts experiment to improve U.S. ability to detect foreign nuclear explosions



Long connection between explosions & neutrinos

1950s: Reines & Cowan pursued the first neutrino detection

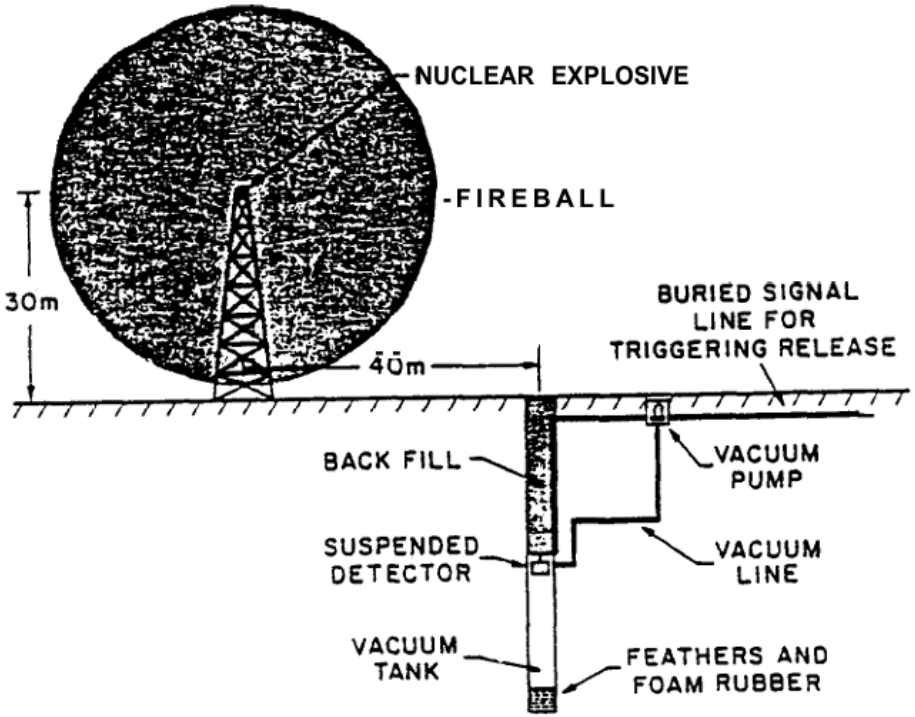
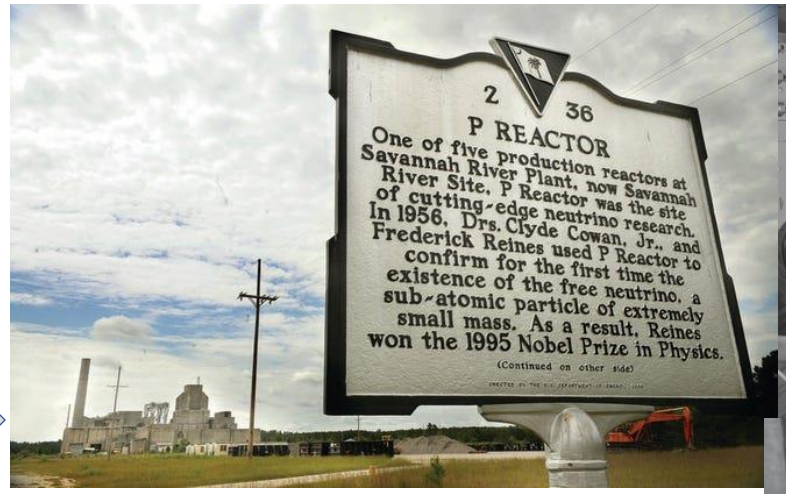


Figure 1. Sketch of the originally proposed experimental setup to detect the neutrino using a nuclear bomb. This experiment was approved by the authorities at Los Alamos but was superceded by the approach which used a fission reactor.

Schematic of LANL approved neutrino detection experiment using explosion as source



1995 Nobel Prize

Soon realized IBD background rejection could enable steady-state experiment at reactor → neutrino discovery in 1956

Neutrino-based Test Site Transparency
Potential Advantages and Approach

- Compared to other fission signatures (e.g. neutrons, gamma rays, and seismic signals), neutrinos offer unique advantages:
  - an intense neutrino burst is emitted following fission, but none are emitted in chemical explosions
  - the neutrino signature is unspoofable and unconcealable
  - a neutrino detector can be physically separated from the monitored event by a solid barrier
    → *potentially non-intrusive, intrinsic information barrier*
  - neutrinos are of scientific interest, with existing collaborations between scientists across the globe
    → *potential for bilateral or multilateral confidence-building exercises*

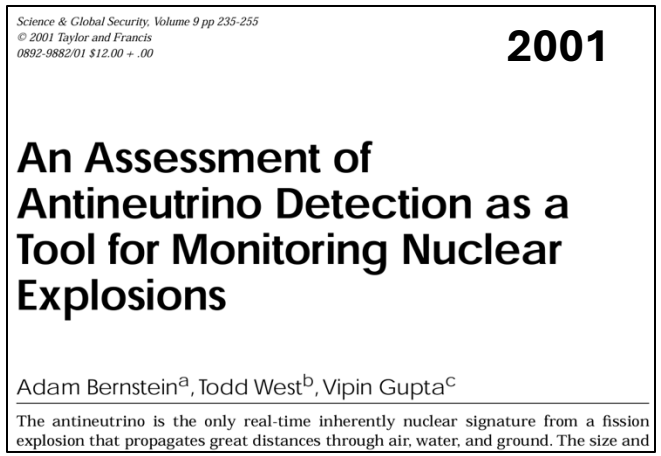
- Approach
  - place neutrino detector relatively close to activity (10s-100s of meters)
  - Observation of zero neutrino candidates gives upper limit on fission yield depending on:

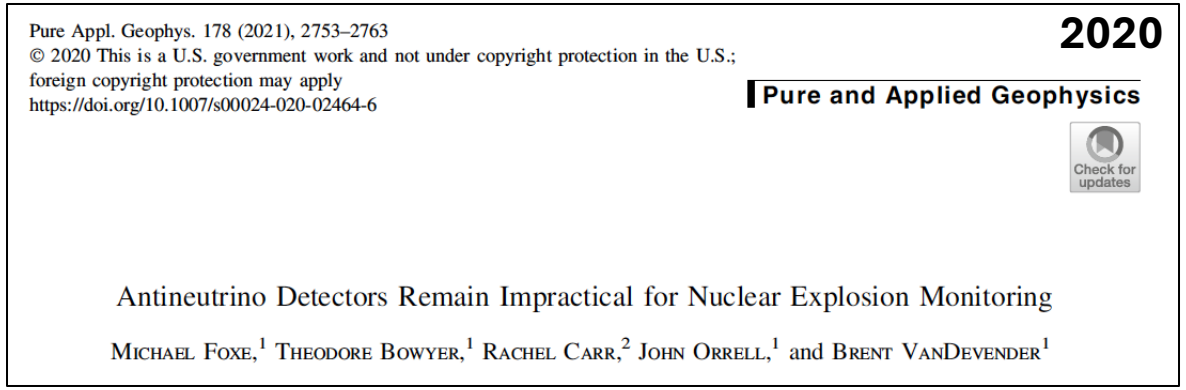
detector size & efficiency, expected background, source term, and statistical fluctuations

→*Important and nontrivial to properly combine parameters and uncertainties, carefully communicate result to stakeholders*

Previous studies focused on site monitoring and large ranges

- Site monitoring at 1-100 km standoff required huge neutrino detectors (1,000 – 1,000,000 ton)
- Without detailed cooperation, cueing to reduce background difficult or impossible





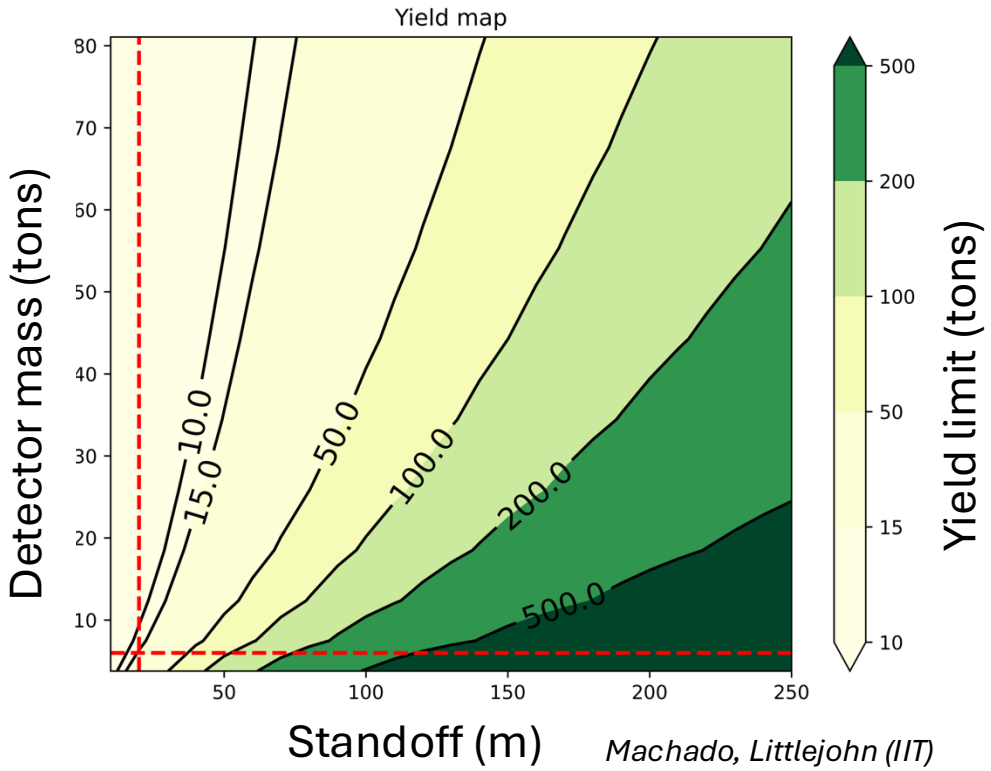
- Test Site Transparency is quantitatively distinct:
  - demonstrate non-fission nature of specific activities conducted at known time and location
    → *relaxed technical constraints on background performance & sensitivity*
  - neutrino detector located well within 1 km of monitored location
    → *greatly reduced system size*

New technologies and narrow focus make it practical to consider neutrinos as additional transparency tool

Preliminary Test Site Transparency Yield Limits

Yield Limits

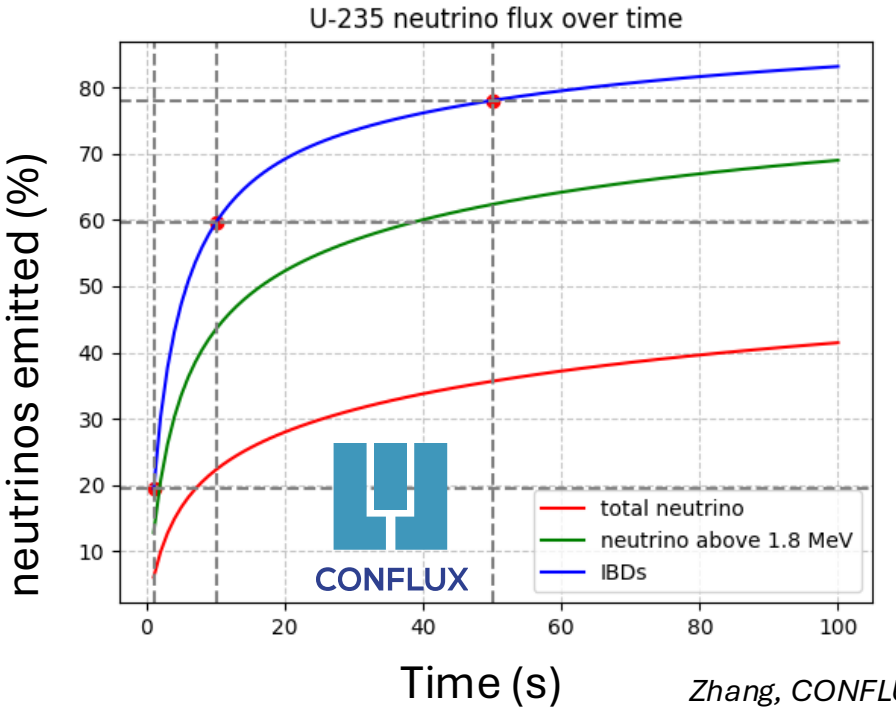
assuming PROSPECT efficiency & reactor backgrounds!



Machado, Littlejohn (IIT)

^{235}U explosion neutrino source term

60% of detectable neutrinos emitted within 1-10s



Zhang, CONFLUX (LLNL)

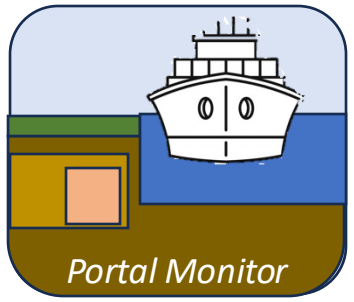
Questions to Address: *Quantified background rate and source term estimates*

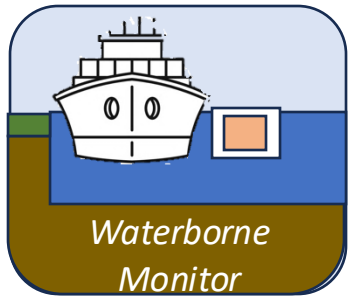
Preliminary ‘Deployment Concepts’

Maritime Reactor

Consider docked vessels and limited overburden (background rejection critical):

- Portal Monitors: system permanently emplaced close as practical to dedicated dock
- Waterborne Monitors: detection system stationed close to docked vessel to conduct verification

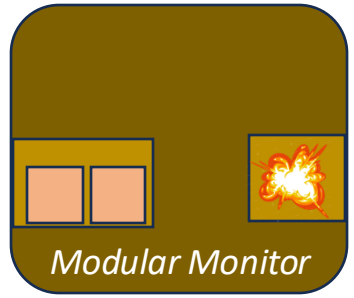


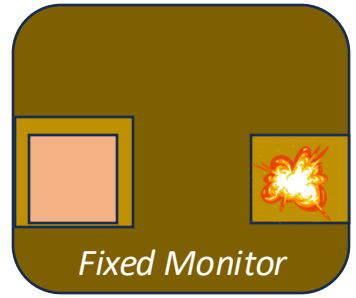


Test Site

Consider Modular and Fixed Monitors emplaced as close as practical:

- Modular: practical solution that is relocatable, reusable, robust, and redundant, fitting in existing drifts, assembled offsite
- Fixed: solution that might be more cost effective for larger area monitoring

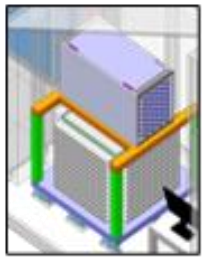
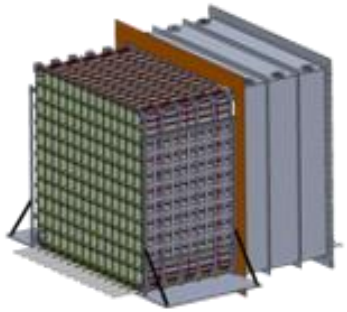
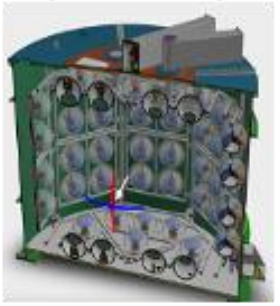




Some of the questions to Address: *Practical distance of closest approach, optimization of volumetric efficiency, sensitivity Logistical constraints on materials, size, emplacement, operational compatibility, …*

Preliminary Concepts for Technology Solutions

Emphasize practicality through solutions that limit footprint, material, and onsite activity

	Modular			Monolithic
				
	Segmented Solid State (MAD-like)	Segmented Liquid ^{6}Li PSD LS (PROSPECT-like)	Single Volume Liquid ^{6}Li PSD LS (LLNL 1-ton)	Single Volume Liquid ^{6}Li PSD LS (BUTTON-like)
Emplacement	Relocatable, Reusable, Redundant, Robust Test Site: Use existing drifts (if possible) or new excavation Fully pre-assembled — Detector pre-assembled, onsite fill			Fixed Test Site: New excavation likely required Onsite construction
Size & Scalability	1-5 ton modules Scale via multiple modules			10-100 ton fiducial Inherently scalable
Background Rejection	Good demonstrated performance Tunable complexity vs performance			Liquid performance under investigation Some overburden likely required PSD-based fast neutron rejection under investigation

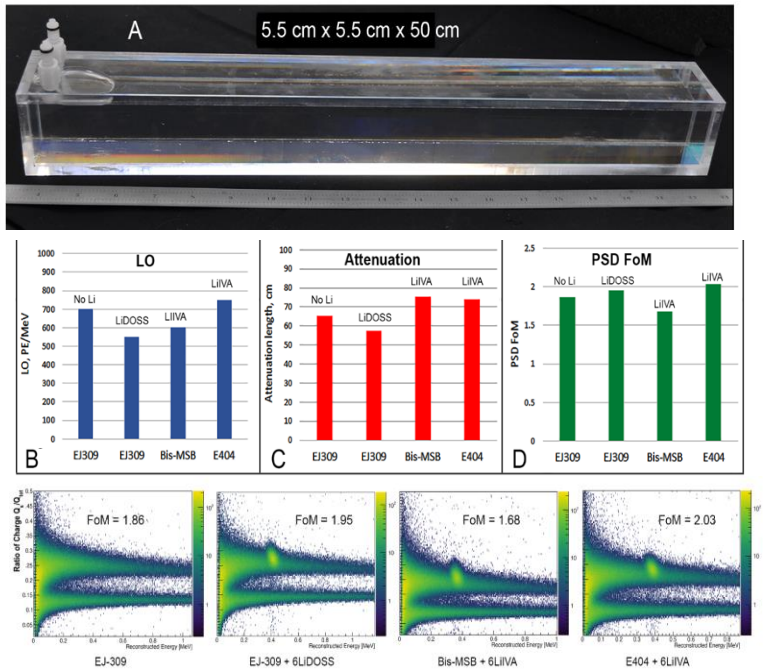
Some of the questions to Address:

Quantified detector performance estimates
CONOPS validation in application environment *(e.g. use of liquids)*
Detector engineering in application environment *(e.g. tunnel, explosion shock)*

Low neutrino flux detector concept – using new liquid scintillators

^{6}Li-doped PSD plastic spinoff:

directly dissolved ^{6}Li-doped PSD liquid



First test of PSD and ^{6}Li-doping in ROADSTR-sized liquid modules

N. Zaitseva et al. Nucl. Inst. And Meth. A. V1054, 168389 (2023)

Monolithic detector concept:

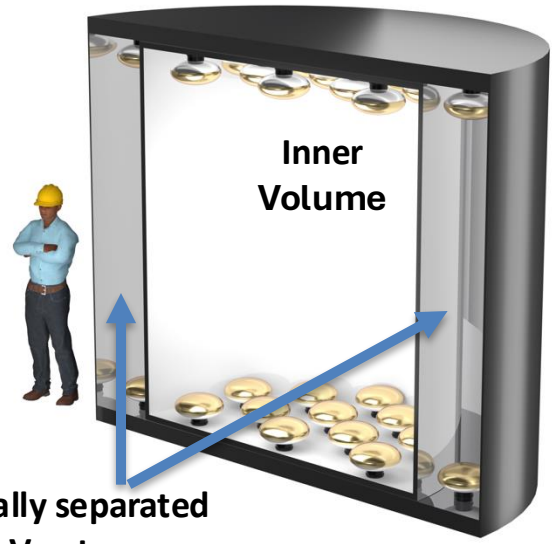
- Fixed monolithic detectors (~10-100 tons) may be optimal for scenarios requiring sensitivity to lower neutrino fluxes, and simplified engineering

Utility of ^{6}Li-doped PSD liquids (questions being addressed):

- How much particle ID discrimination does PSD provide?
- Does PSD & ^{6}Li provide sufficient background discrimination at shallow depth?

Reflective walls maximize photon collection

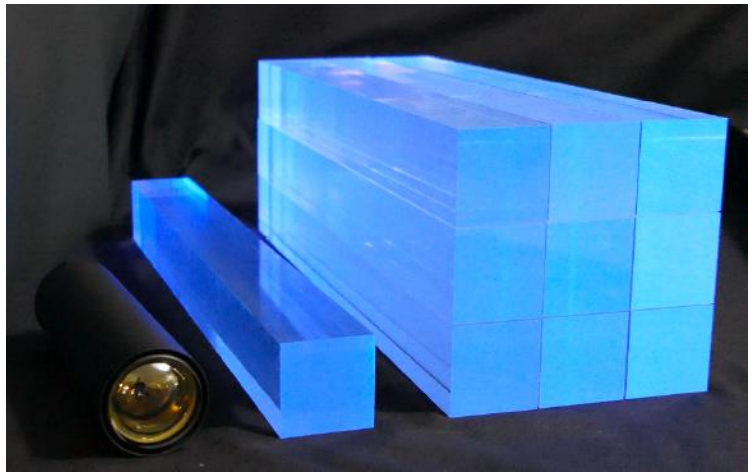
PMTs top and bottom (up/down position sensitivity)



Optically separated 511 keV veto

ROADSTR Prototype ^{6}Li PSD Plastic Antineutrino Detector

- Prototype detector developed for materials demonstration and IBD background measurement
- Passive device that measures gammas, neutrons, and their correlations with high efficiency
- 6x6 array of PSD plastic bars (60kg) with PMT readout
- Packaged for transport and autonomous operation (e.g. UPS, auto-restart if power lost)



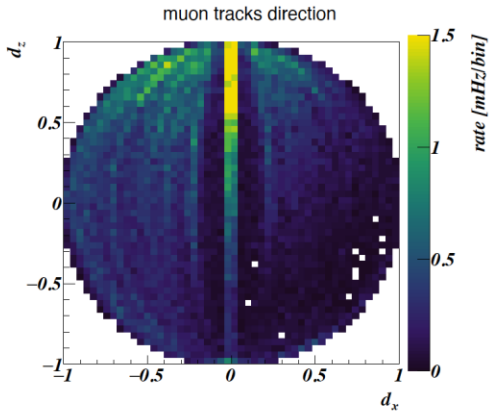
ROADSTR Detector

ROADSTR Deployment Crates

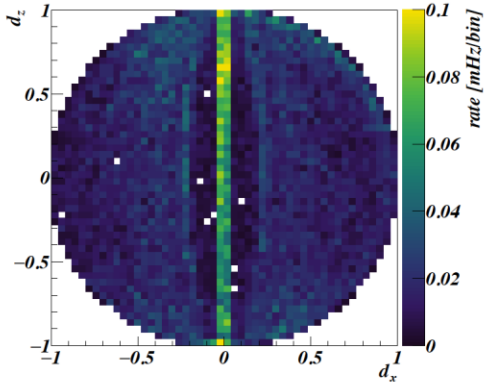
ROADSTR COTS Electronics

Underground background measurements for Test Site use case

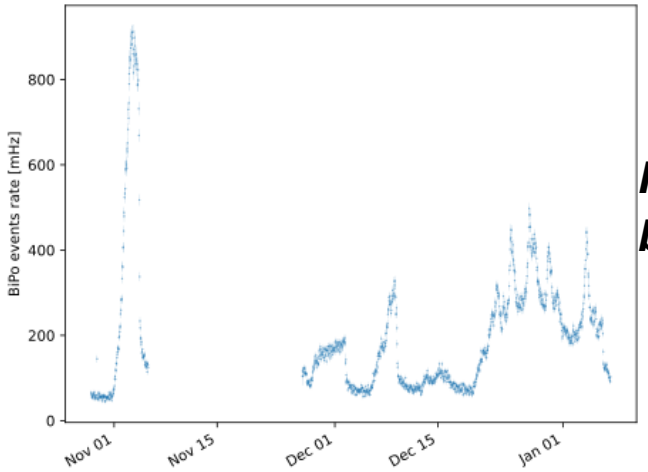
muon distribution under non-uniform overburden



Mechanics Alcove



Refuge Chamber Alcove



Radon-induced background variation

Gaining operational experience & background knowledge. Planning for CHANDLER system measurements

Summary

- There have been advances in technology and understanding of neutrino utility that motivate the MAD project to develop a readily-mobile detection system
- Two plastic-based detection concepts with complementary characteristics and good performance potential have been established
  - MAD will incorporate subsystems based on both concepts to further advance these technologies
- MAD is close to completion and will provide a mobile system able to perform capability demonstrations, validate detection technologies at scale and provide supporting measurements for a broad range of Use Cases
- Unique characteristics of neutrino detection may provide a valuable tools for maritime reactor verification and test site transparency
  - Unspoofable and unconcealable fission signature
  - Instrument can be 10-100 of meters distant
  - Potential to leverage inter-connected global neutrino physics community for multi-lateral engagement
- Recent technology advances, like those in MAD, are enabling (relatively) compact, efficient, and robust instruments
  - We emphasize practicality in application environments through solutions that limit footprint, material, and onsite activity