Revisiting antineutrino-based explosion monitoring for Test Site Transparency

Nathaniel Bowden *for the AIT and MAD Projects*

October 30, 2024

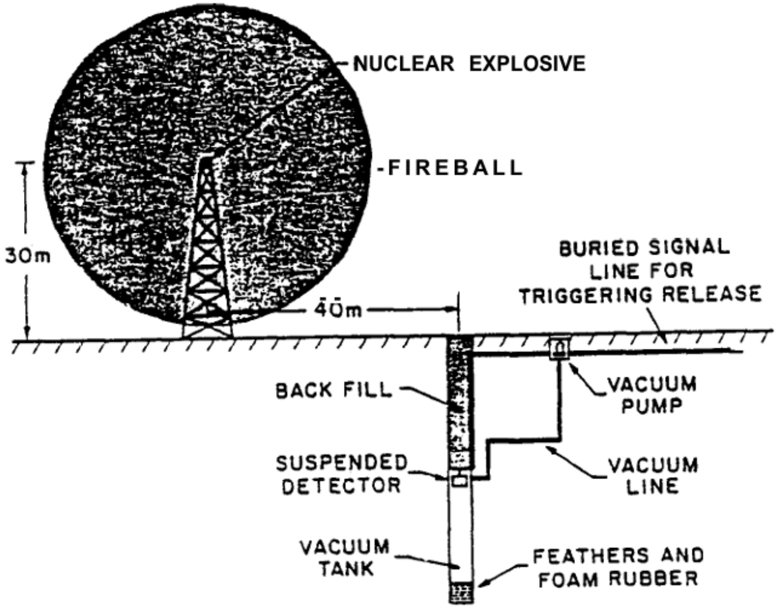
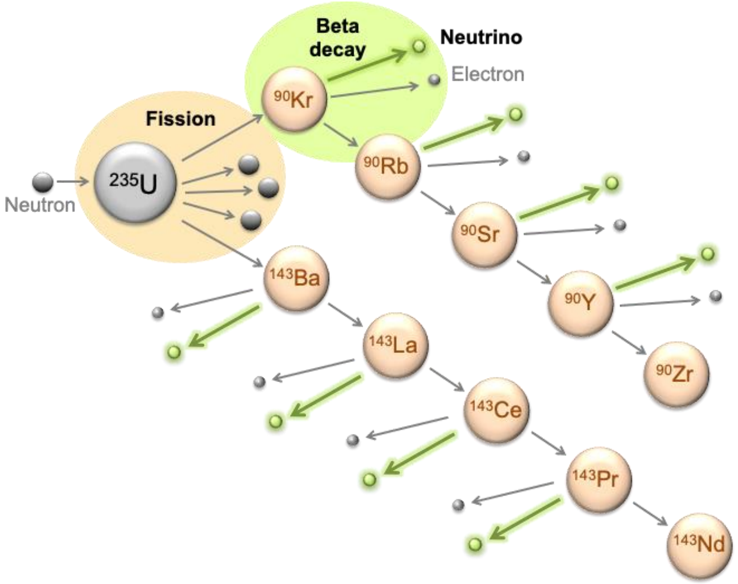


Figure 1. Sketch of the originally proposed experimental setup to detect the neutrino using a nuclear bomb. This experiment was approved by the authorities at Los Alamos but was superceded by the approach which used a fission reactor.



LLNL-PRES-870992
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Renewed activities at test sites increase potential for misunderstanding and misinformation

CNN, Sat September 23, 2023

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

REUTERS

World

Russia accuses US of nuclear testing site activity, says it won't test unless US does

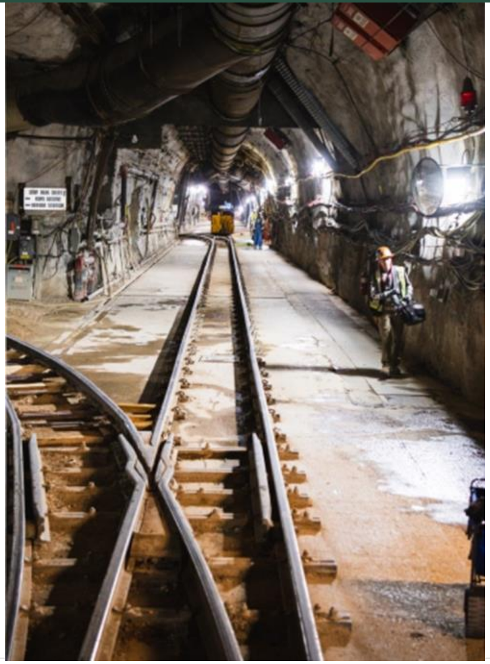
By **Andrew Osborn**

October 10, 2023 3:52 PM EDT · Updated 4 months ago

National Nuclear Security Administration

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

OCTOBER 18, 2023



Renewed interest in Test Site Transparency

NNSA Administrator Jill Hruby delivering remarks at the CTBT: Science and Technology Conference 2023- [NNSA]

"The National Nuclear Security Administration has not been directed to prepare for a new test …

I sincerely look forward to future engagement with Russia and China on participation in bi-or tri-lateral verification confidence building measures…"

Interest in "ideas to further transparency" and "verification confidence building measures and other technological interactions to support future arms control and nonproliferation agreements"

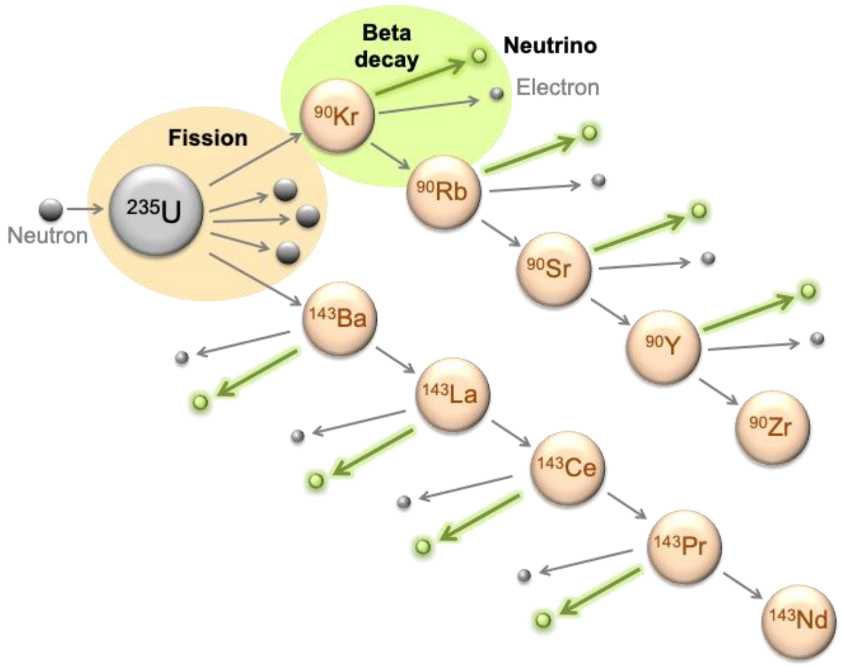
Renewed interest in Test Site Transparency

Joint Test Verification Exercise (1987-1988)

Non-governmental observers at NNSS P-Tunnel in October 2023 - [NNSA](#)

(Anti)neutrinos: A fission "byproduct" for science and applications

Approx. 6 neutrinos produced per fission

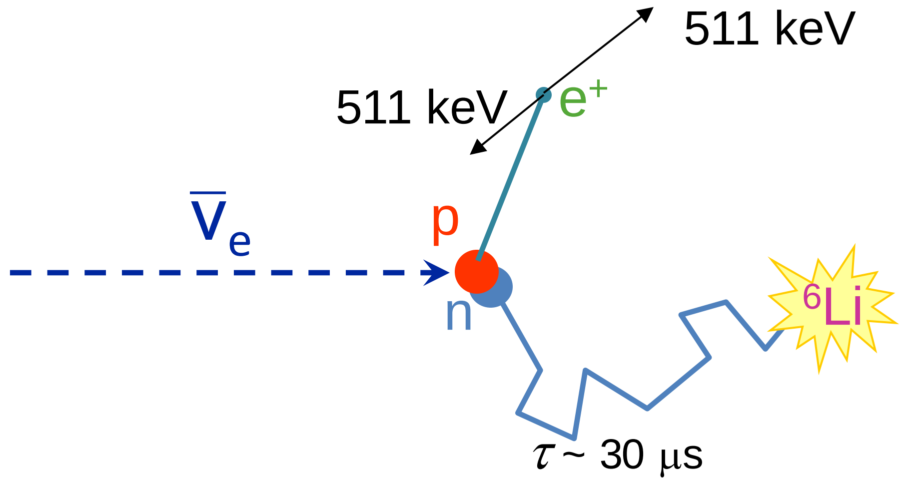


⇒~10^{21} neutrinos	per second	from 3 GW_{th} reactor
⇒~10^{22} neutrinos	in 10 seconds	from 10 ton explosion

Inverse Beta Decay (IBD) detection channel

time & spatial correlation is strong background discriminant

$$\bar{\nu}_e + p \rightarrow e^+ + n$$



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

1 ton organic scintillator detector 25 meters from:

3 GW_{th} reactor	⇒ $O(1000)$ IBD counts per day
10 ton explosion	⇒ $O(1)$ IBD count per event

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 <u>zero neutrino candidates</u> 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

Long connection between explosions and neutrino detection

1950s: Reines & Cowan pursued the first neutrino detection

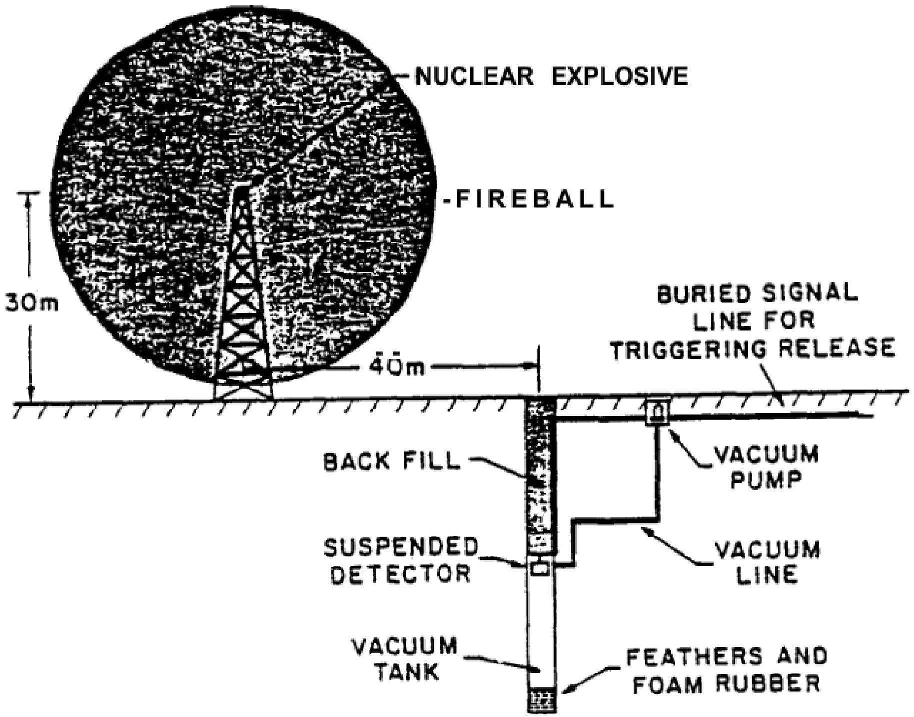
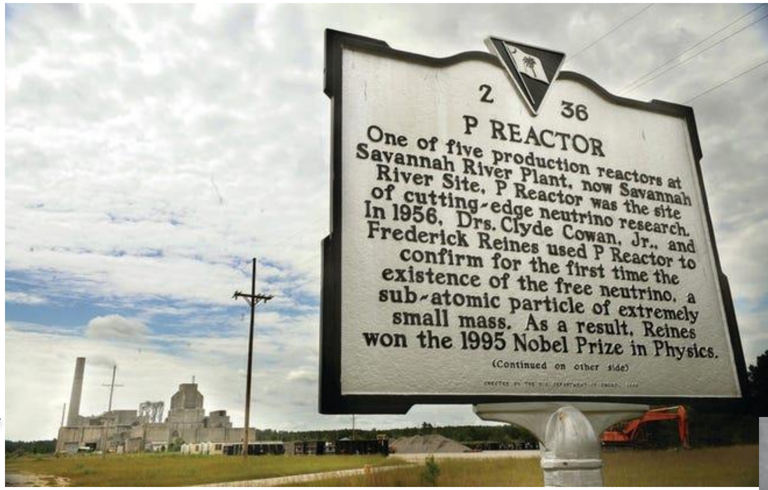


Figure 1. Sketch of the originally proposed experimental setup to detect the neutrino using a nuclear bomb. This experiment was approved by the authorities at Los Alamos but was superceded by the approach which used a fission reactor.

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

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

2001

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An Assessment of Antineutrino Detection as a Tool for Monitoring Nuclear Explosions

Adam Bernstein[a], Todd West[b], Vipin Gupta[c]

The antineutrino is the only real-time inherently nuclear signature from a fission explosion that propagates great distances through air, water, and ground. The size and

2020

Pure Appl. Geophys. 178 (2021), 2753–2763
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https://doi.org/10.1007/s00024-020-02464-6
Pure and Applied Geophysics

Check for updates

Antineutrino Detectors Remain Impractical for Nuclear Explosion Monitoring

Michael Foxe,[1] Theodore Bowyer,[1] Rachel Carr,[2] John Orrell,[1] and Brent VanDevender[1]

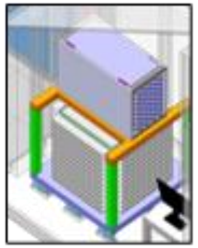
- Test Site Transparency is quantitatively distinct:
  - demonstrate non-fission nature of specific activities conducted at known time and location
    → *relaxed technical constraints on background performance & sensitivity*
  - neutrino detector located well within 1 km of monitored location
    →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

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

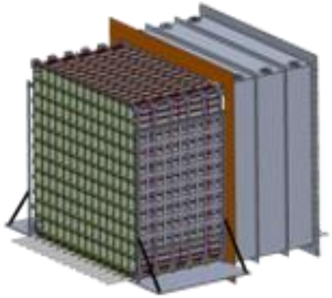
Preliminary Concepts for Test Site Instruments

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

Modular



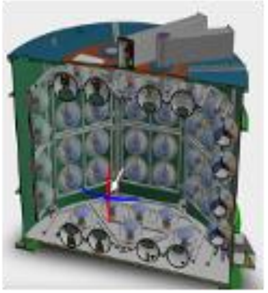
Segmented Solid State (MAD-like)



Segmented Liquid ^{6}Li *PSD LS* *(PROSPECT-like)*

Single Volume Liquid ^{6}Li *PSD LS* *(LLNL 1-ton)*

Monolithic



Single Volume Liquid ^{6}Li *PSD LS* *(BUTTON-like)*

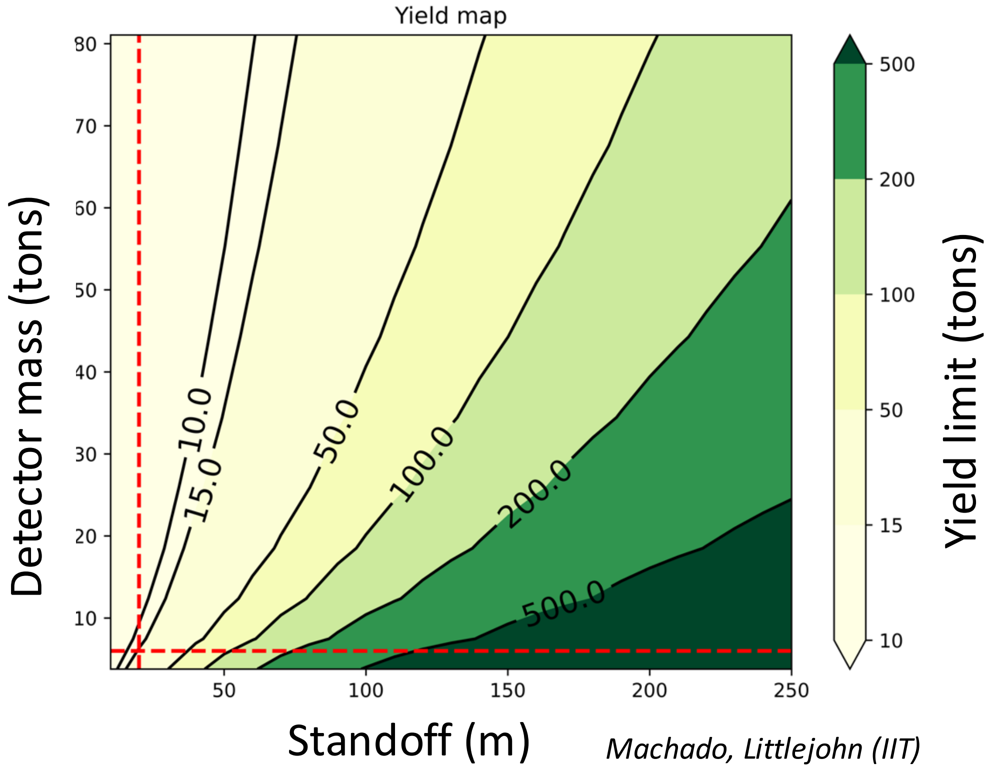
	Modular	Monolithic
Emplacement	Relocatable, Reusable, Redundant, Robust Test Site: Use existing drifts (if possible) or new excavation Fully pre-assembled / Detector pre-assembled, onsite fill	Fixed Test Site: New excavation likely required Onsite construction
Size & Scalability	1-5 ton modules Scale 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

Questions to Address: *Quantified detector performance estimates*
CONOPS validation in application environment (e.g. use of liquids)
Detector survivability in application environment (e.g. tunnel, explosion shock)

Preliminary Test Site Transparency Yield Limits

Yield Limits

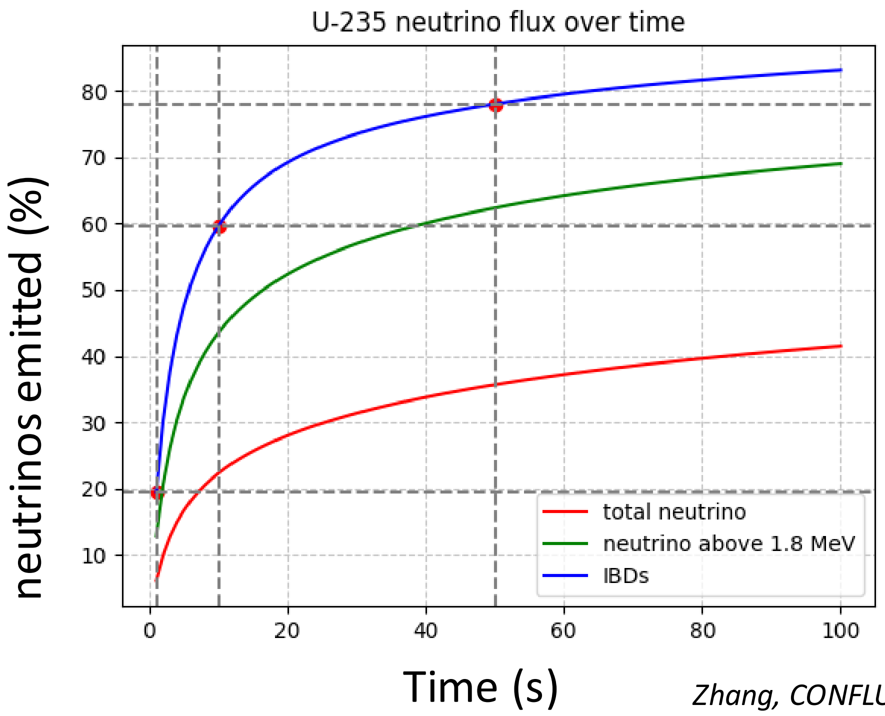
assuming PROSPECT efficiency & reactor backgrounds!



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*

Goals for Measurements at NNSS P-Tunnel

- **Measure backgrounds relevant to test site transparency**
  Test site application requires quantification of accidental and cosmogenic backgrounds at NNSS.

- **Demonstrate reliability**
  Test site transparency application depends on operating a neutrino detector in a stable, semi-autonomous manner for weeks, months, or more.

- **Demonstrate relocatability**
  To be usable at test sites and other remote locations, a neutrino detector system should be successfully operable after transport. Multiple successful relocations would be ideal.

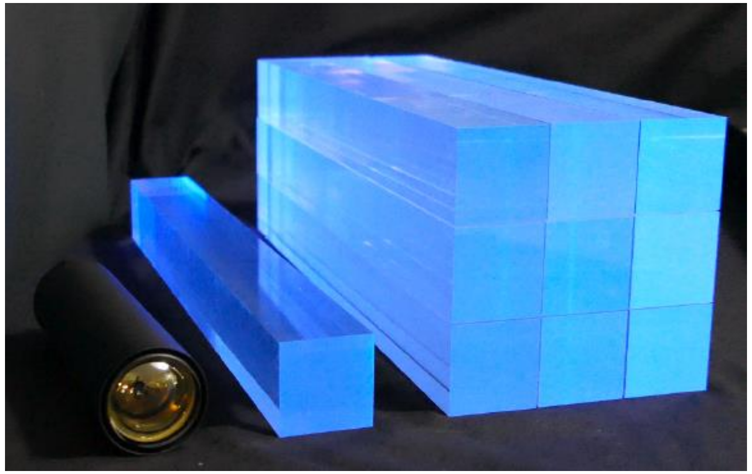
- **Operate in rugged, restricted-access environments**
  Test site is harsher environments than typical lab - important to show that technologies operate.
  Demonstrate that relevant technologies withstand mechanical shocks similar to a nearby explosion.

- **Engagement with facilities and other users**
  Deployments require detailed coordination, creating opportunities for us to better understand requirements and constraints, and for others to learn about this technology and it's characteristics.

ROADSTR Prototype ^{6}Li PSD Plastic Antineutrino Detector

ROADSTR

- 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 tunnel operation (e.g. dust filters, UPS, auto-restart if power lost)



ROADSTR Detector

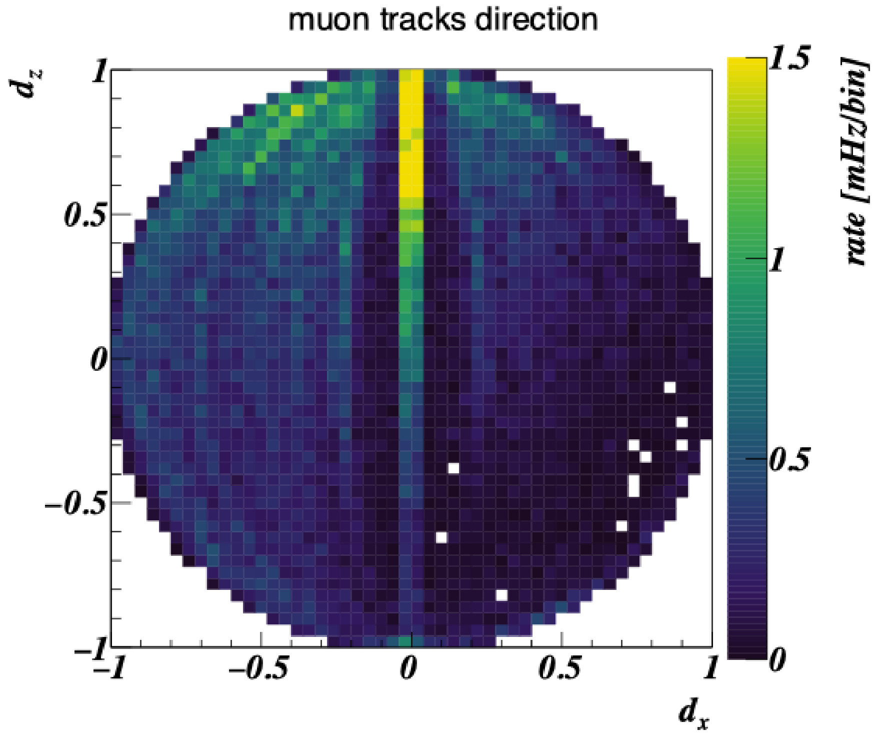
ROADSTR Deployment Crates

ROADSTR COTS Electronics

First ROADSTR P-Tunnel measurements underway

100 mwe location near entrance

Preliminary azimuthal muon distribution under non-uniform overburden



Measurements planned at ~100 mwe and ~ 300 mwe locations

Summary

- Unique characteristics of neutrino detection may provide a valuable test site transparency tool
  - Unspoofable and unconcealable fission signature
  - Instrument can be 10-100 of meters distant from test object
  - Potential to leverage inter-connected global neutrino physics community for multi-lateral engagement

- Recent technology advances are enabling (relatively) compact, efficient, and robust instruments
  - We emphasize practicality in underground environment through solutions that limit footprint, material, and onsite activity

- We plan to mature practical solutions in this space through:
  - A rigorous calculation framework for yield limit sensitivity
  - Advancing compact, space efficient detection instrument concepts
  - Quantifying detection, source term, and background parameters via measurement and simulation

- Background measurements using the MAD prototype detectors will provide important data and operational experience