Antineutrinos as a Nuclear Safeguards Tool

University of California, Davis Physics Seminar

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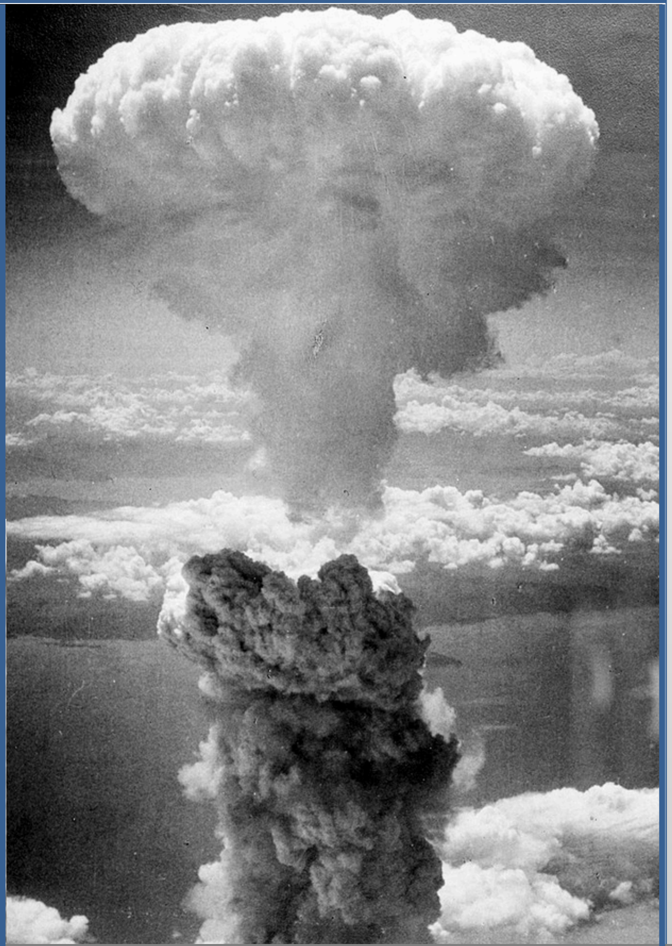
Lawrence Livermore National Laboratory

Progression of Technology Over 50 Years

The Spanish American War
(1898)

World War One
(1914)

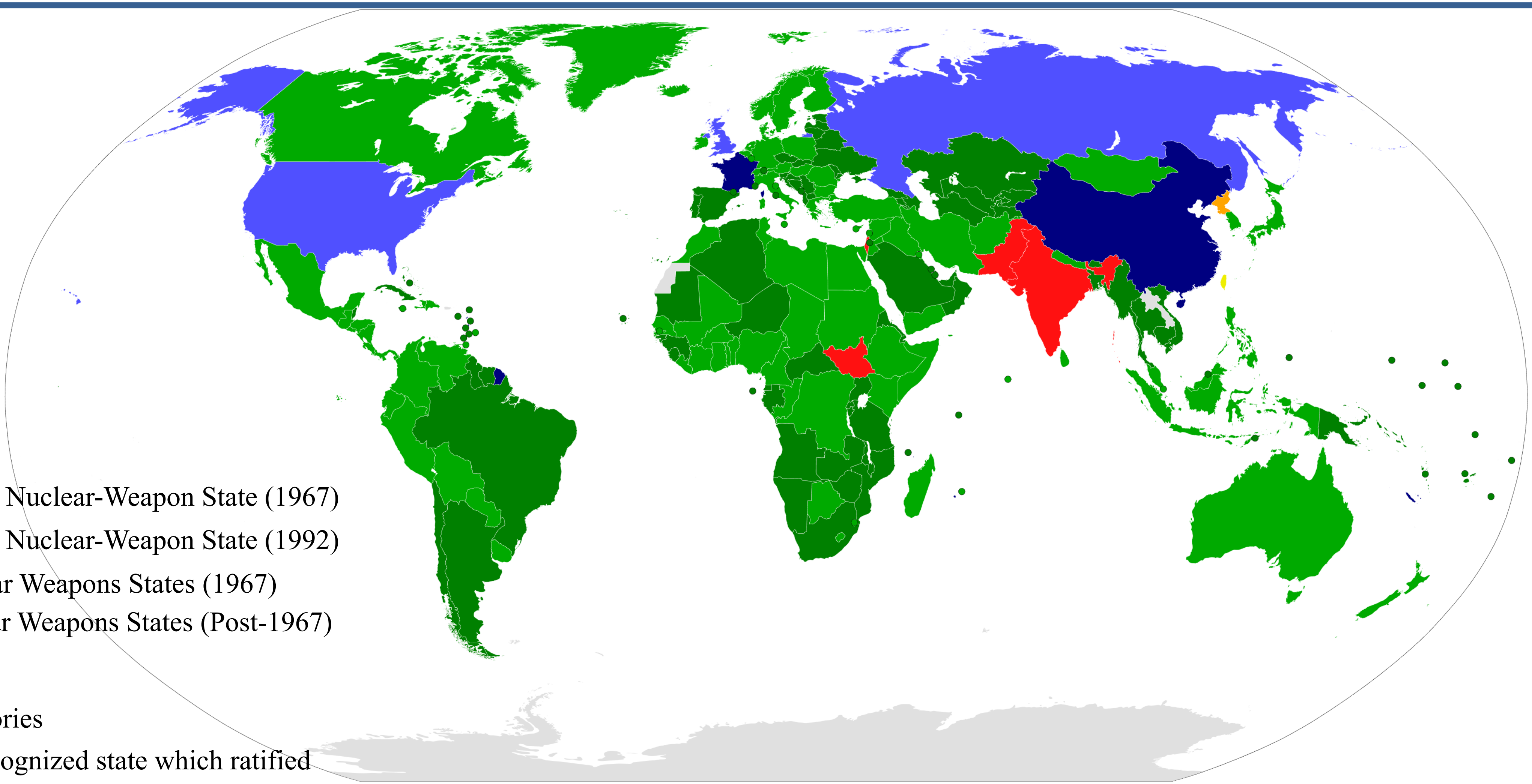


World War Two
(August 1945)

?

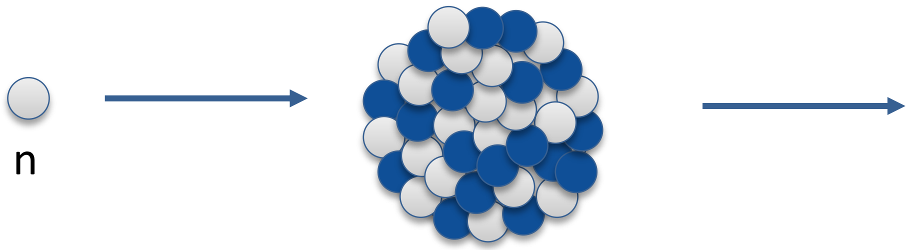
Future Conflicts

The Non-Proliferation Treaty (NPT)

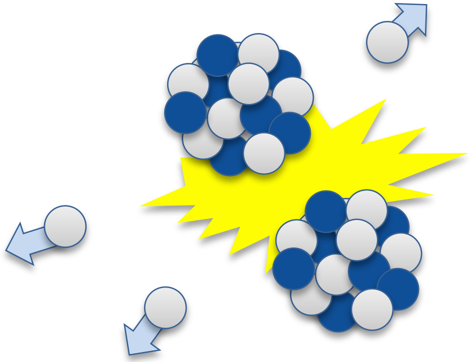


Recognized Nuclear-Weapon State (1967)
Recognized Nuclear-Weapon State (1992)
Non-Nuclear Weapons States (1967)
Non-Nuclear Weapons States (Post-1967)
Withdrawal
Non-signatories
Partially recognized state which ratified

Nuclear Reactors: A Dual use Technology

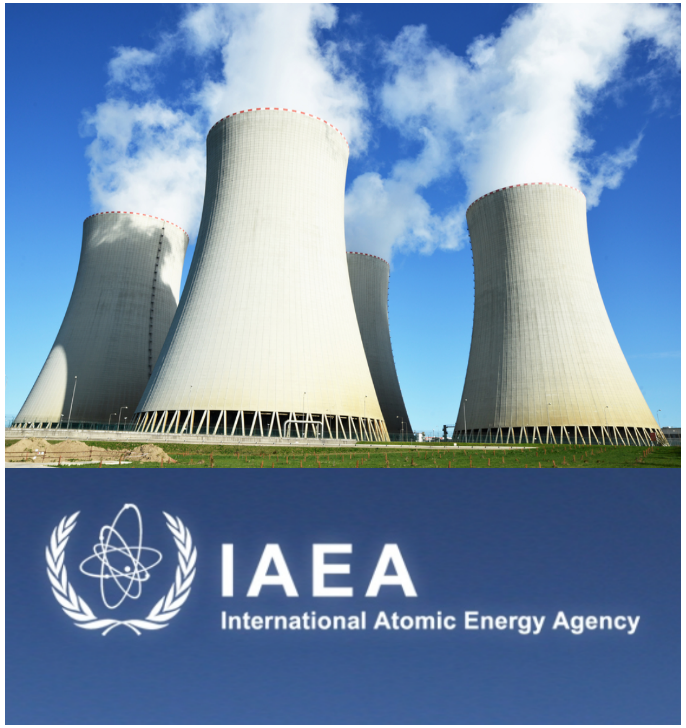


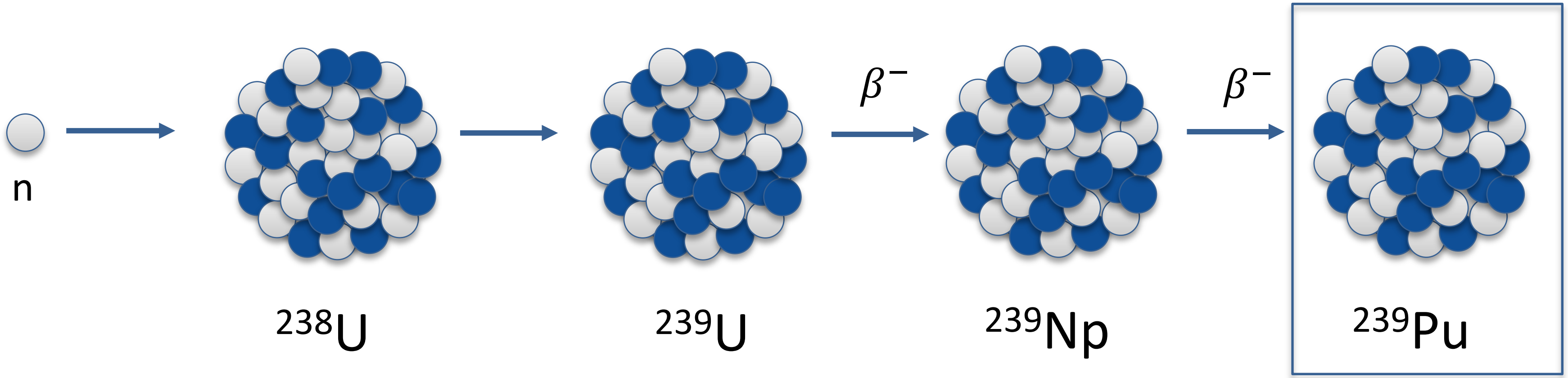
Fissile Isotope:
^{235}U, ^{239}Pu, ^{241}Pu, or ^{238}U



200 Million Electron Volts!

Nuclear Reactors: A Dual use Technology





- To resolve the dual use of this technology the IAEA serves to verify the peaceful use of nuclear reactors.
- The IAEA achieves this mission goal through the on-site inspection of **declared** nuclear facilities.

Current IAEA Safeguards Practices

Reactor
(1-1.5 years)

- Check declarations
- **Item accountancy**
- Containment and surveillance

Onsite Fuel Storage
(months to years)

- Gross defect detection
- **Item accountancy**
- Containment and surveillance

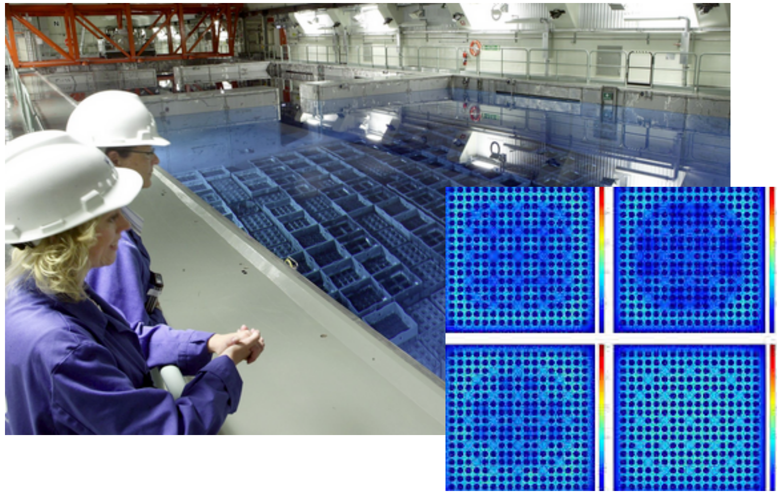
Reprocessing
(months)

Waste Repository
(forever)

- Check declarations
- Bulk accountancy

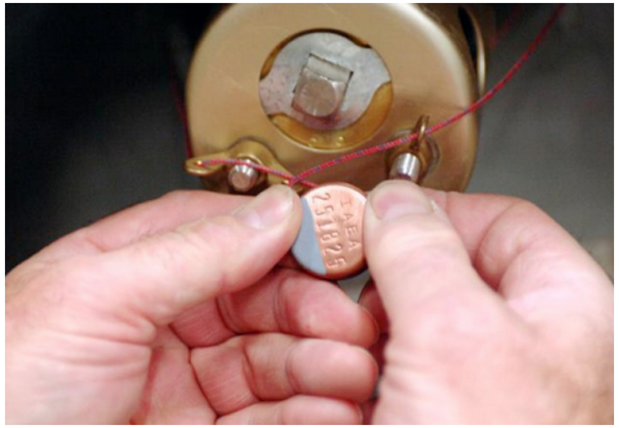
IAEA Reactor Monitoring

Cherenkov Camera



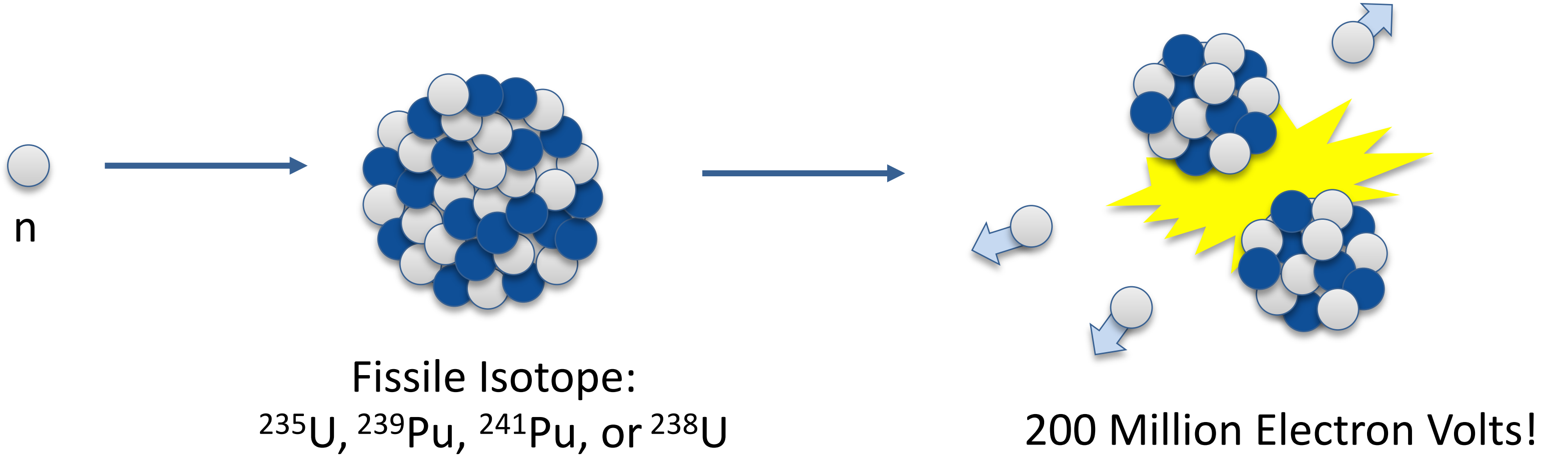
Physical Inspection

Locks and Seals

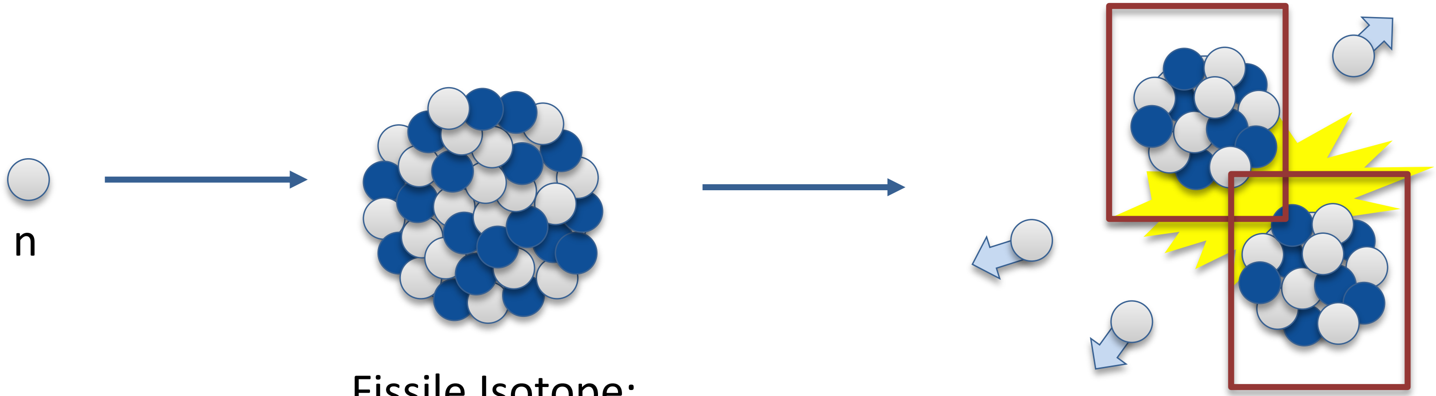


- Many of the practices by the IAEA at Nuclear Reactor Facilities uses “low-tech” solutions such as visual inspections and locks & seals.
- Antineutrino monitoring has been proposed as an additional tool to detect operator malfeasance.

Nuclear Reactors: A Copious Source of Antineutrinos



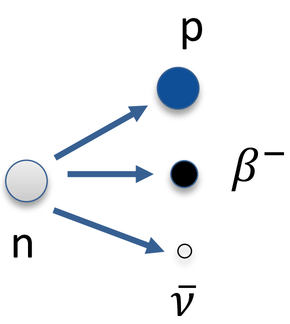
Nuclear Reactors: A Copious Source of Antineutrinos



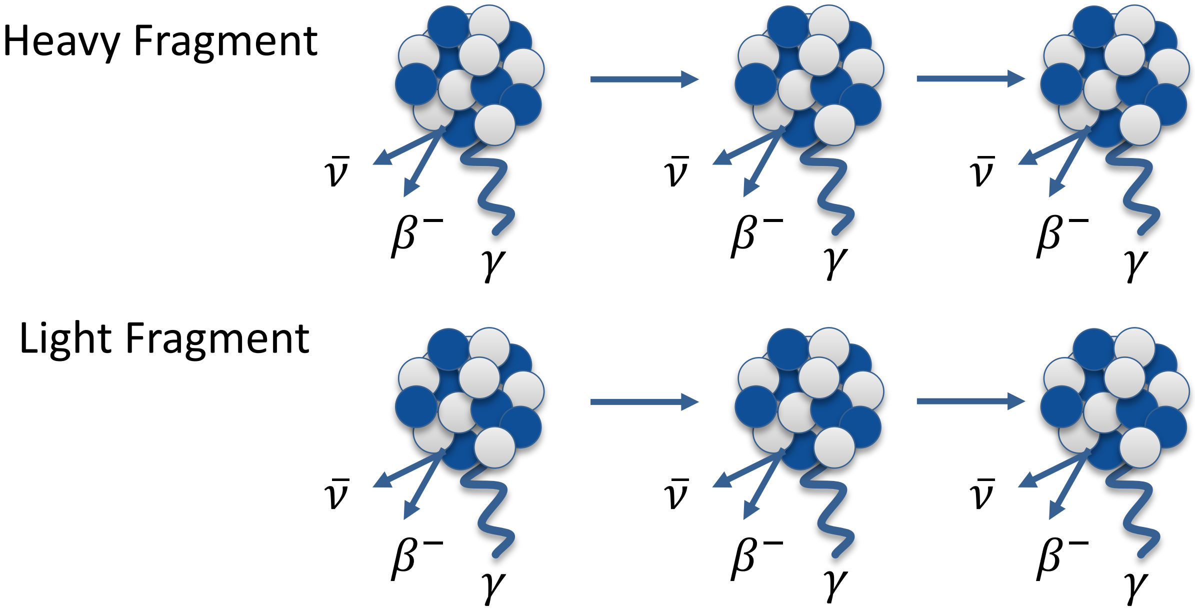
Fissile Isotope:
^{235}U, ^{239}Pu, ^{241}Pu, or ^{238}U

Extremely unstable isotopes

Nuclear Reactors: A Copious Source of Antineutrinos

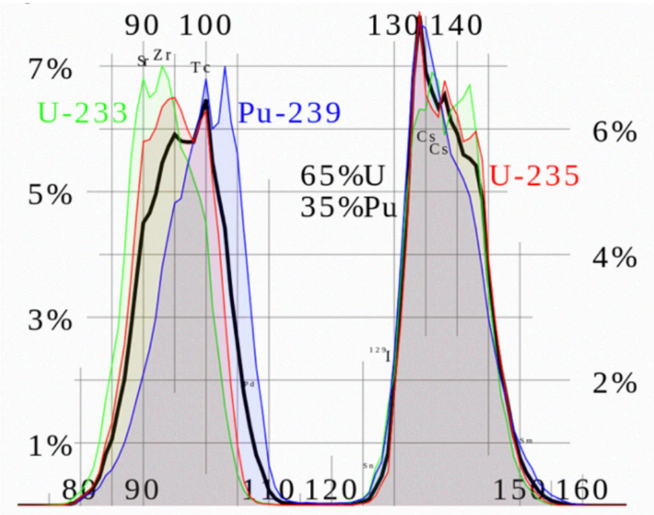


Beta Decay



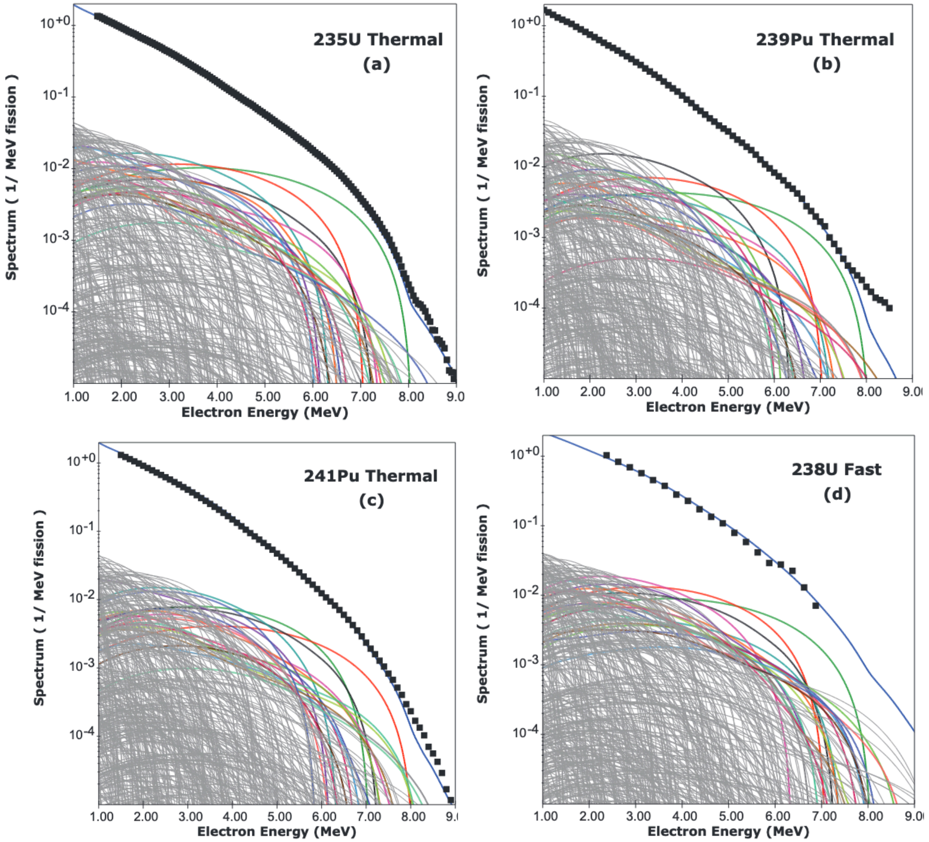
Roughly 6 $\bar{\nu}$ are released per fission and ~10^{21} fission per second in a 3 GW_{th} nuclear facility equating to ~10^{22} $\bar{\nu}$ per second!

Antineutrinos from Fission

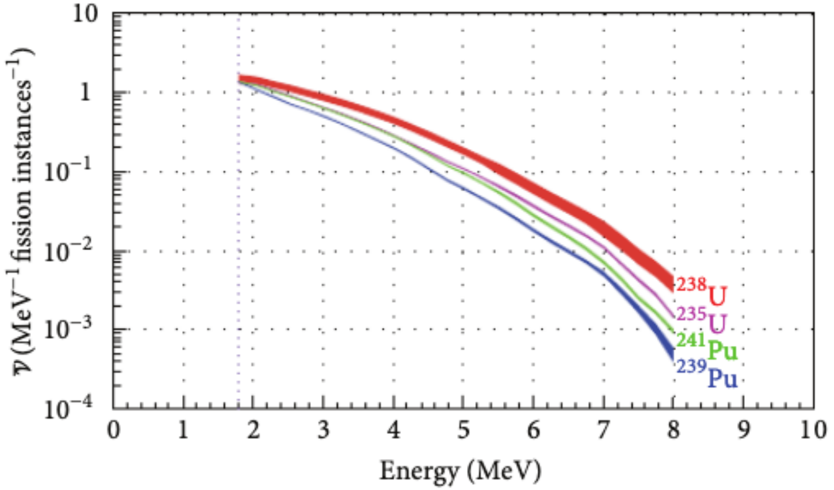


Fission fragment yield
for variable isotopes

For each Fission there are roughly ~100 different isotopes and roughly ~8000 beta branches.



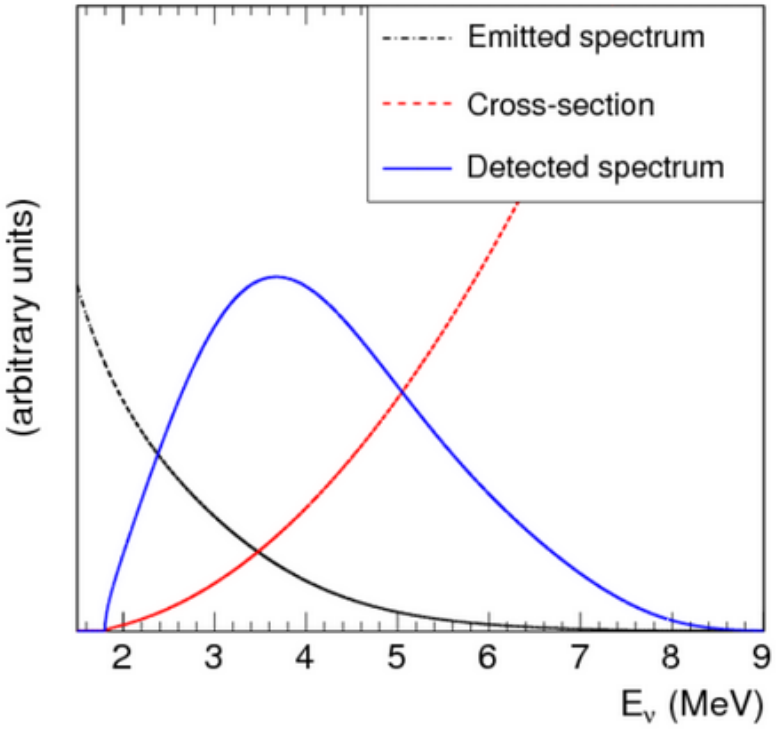
PHYSICAL REVIEW C91, 011301(R) (2015)

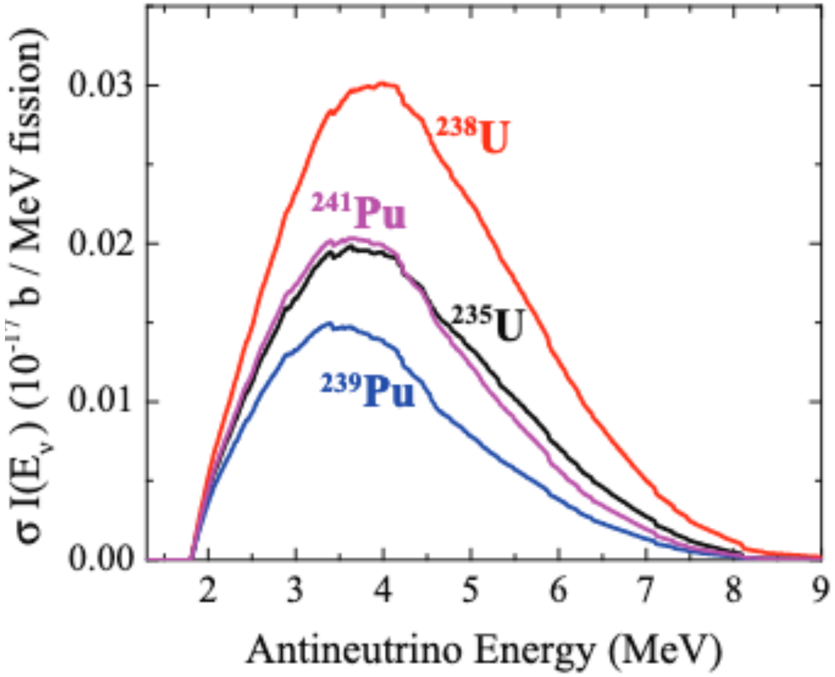


Each isotope generates a unique antineutrino spectra and amplitude.

Antineutrino Interactions

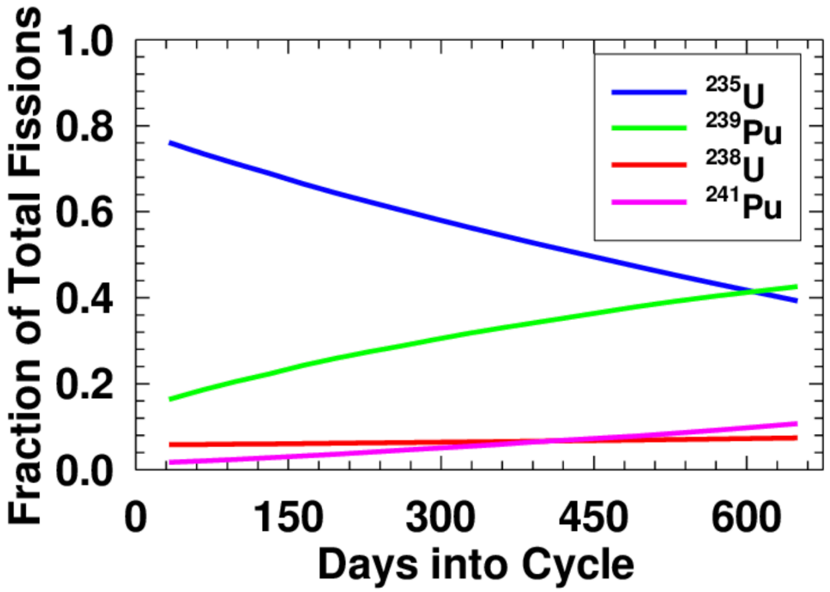
$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$(Q=\text{-}1.8\text{ MeV},\ \sigma \sim 10^{-42} cm^2 E_{\bar{\nu}}^2)$$





For each major actinide there is a unique spectra and amplitude per fission

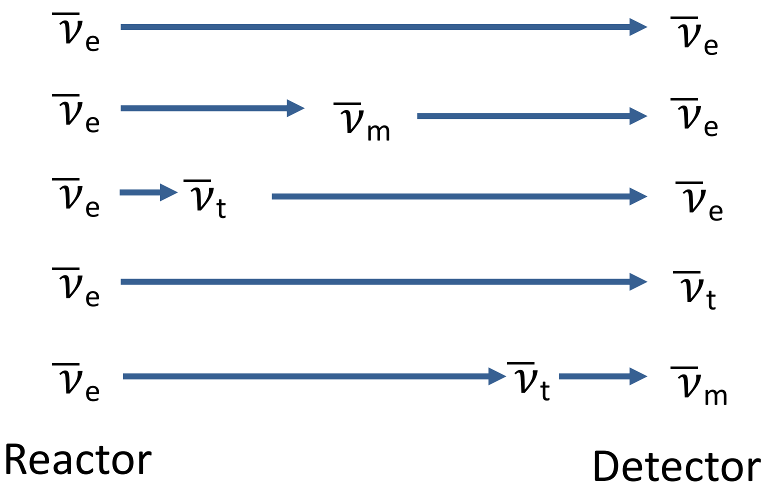
The concentration of actinides is a direct signature of the duration of a nuclear fuel cycle

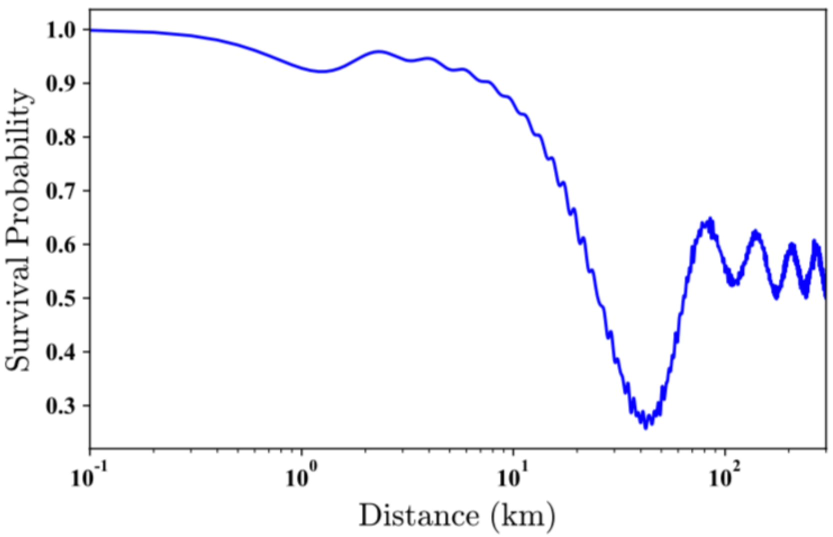


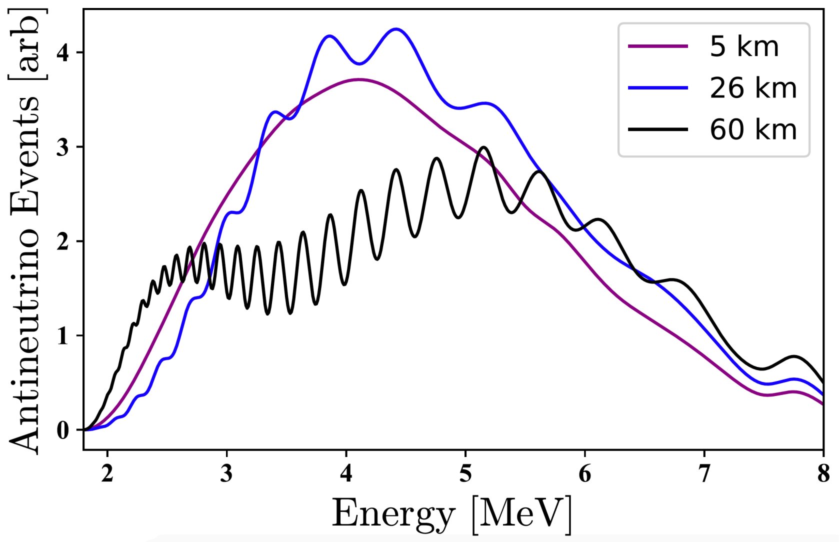
Antineutrino Oscillations

Near Field: Δm^2_{32} Far Field: Δm^2_{21}

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E} + \sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{21}L}{4E}$$

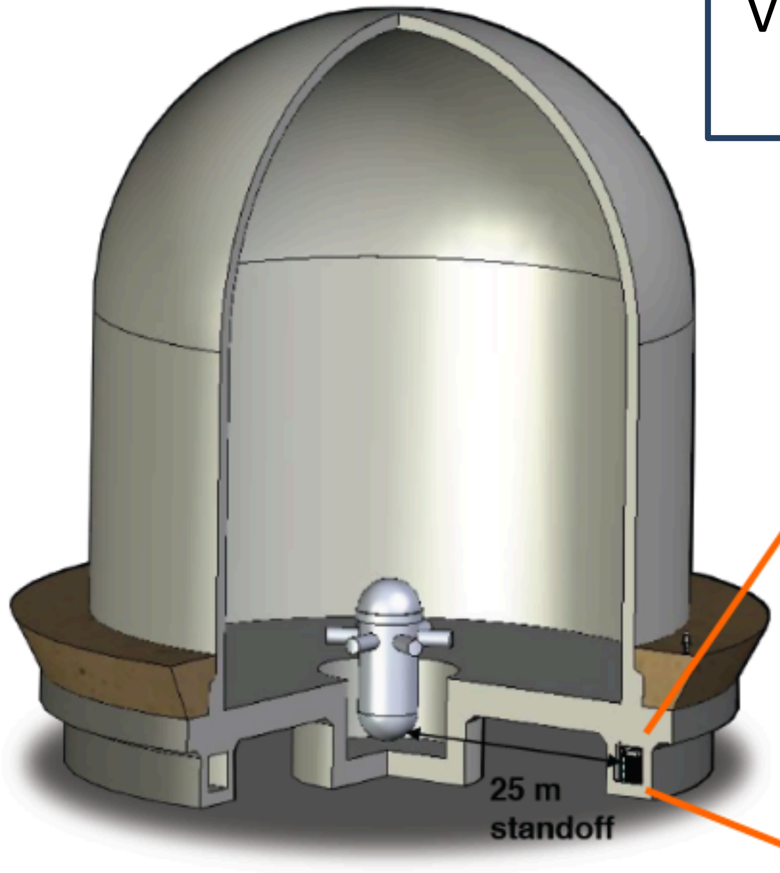




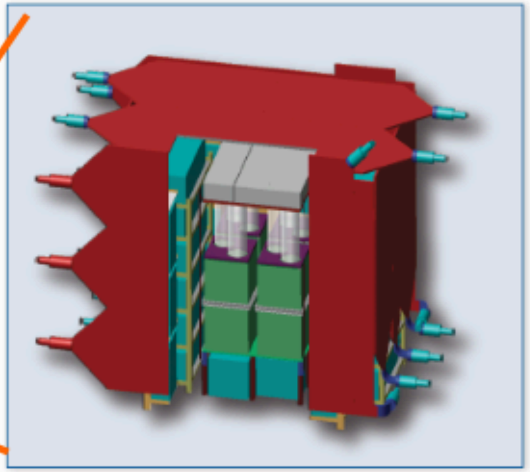


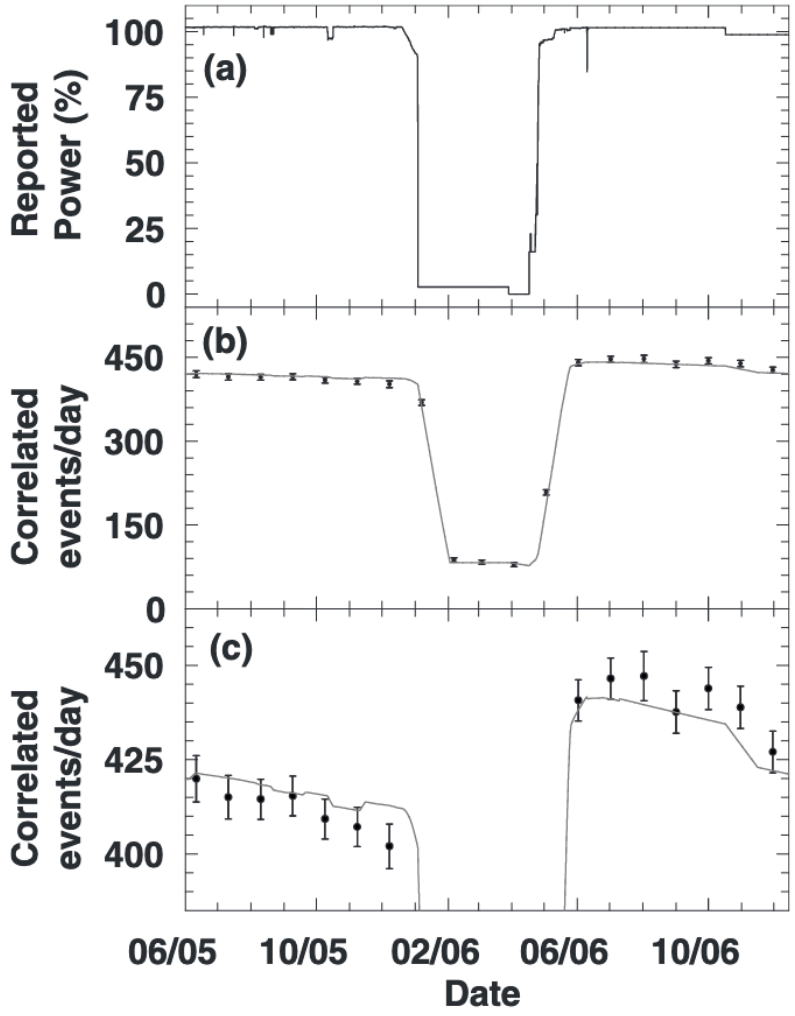
Demonstrations of Power Monitoring

Verification of the power of the reactor



0.64 tons Gd scintillator
Water/polyethylene shield
Plastic muon veto
2.5 meters on a side,

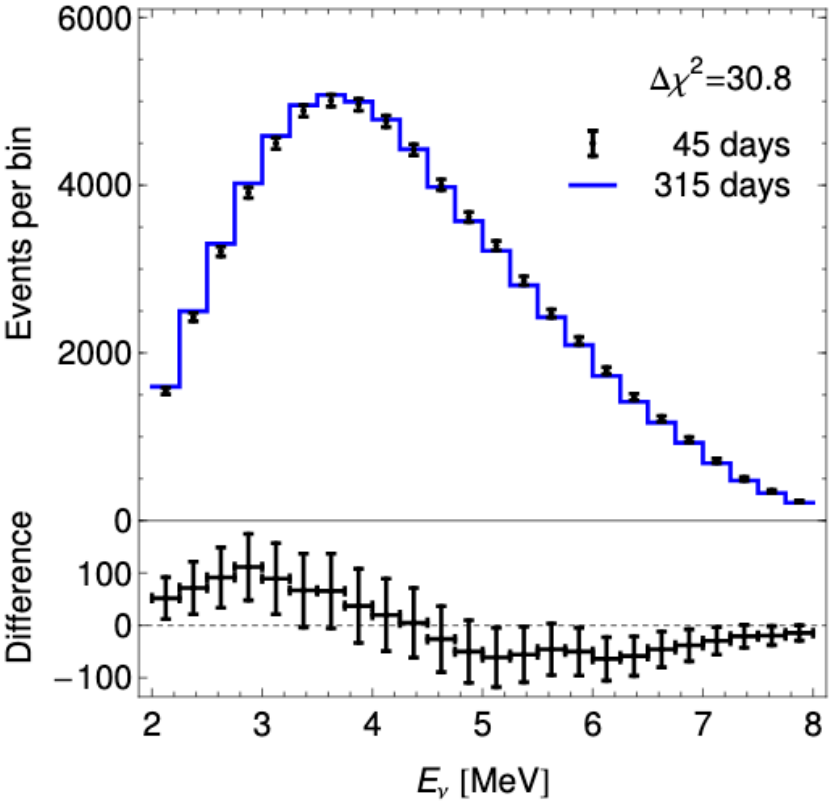


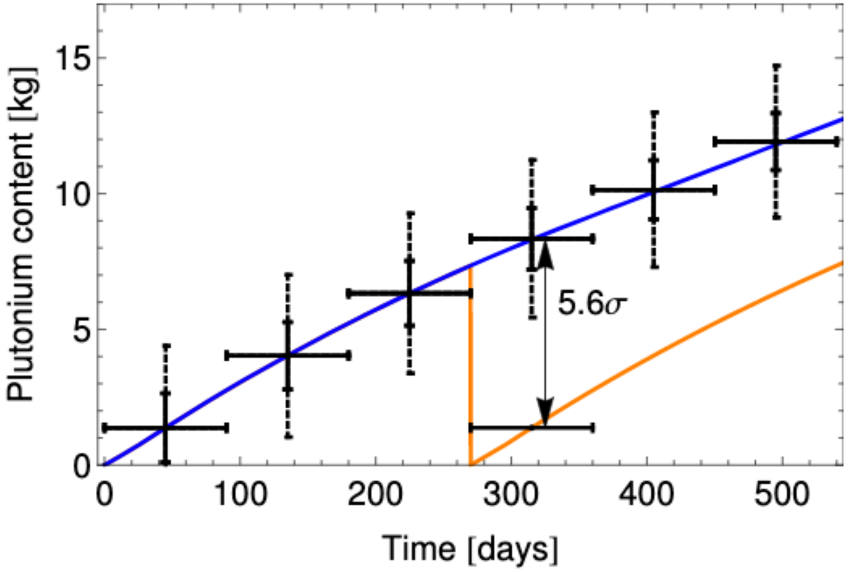


Bowden, N. S., Bernstein, A., Dazeley, et. Al. (2009 *Journal of Applied Physics*, *105*(6), 064902.

Case Studies of Fissile Inventory

Satellite image of the heavy water reactor at Arak, Iran, May 2012. Image credit Digital Globe and Google Earth

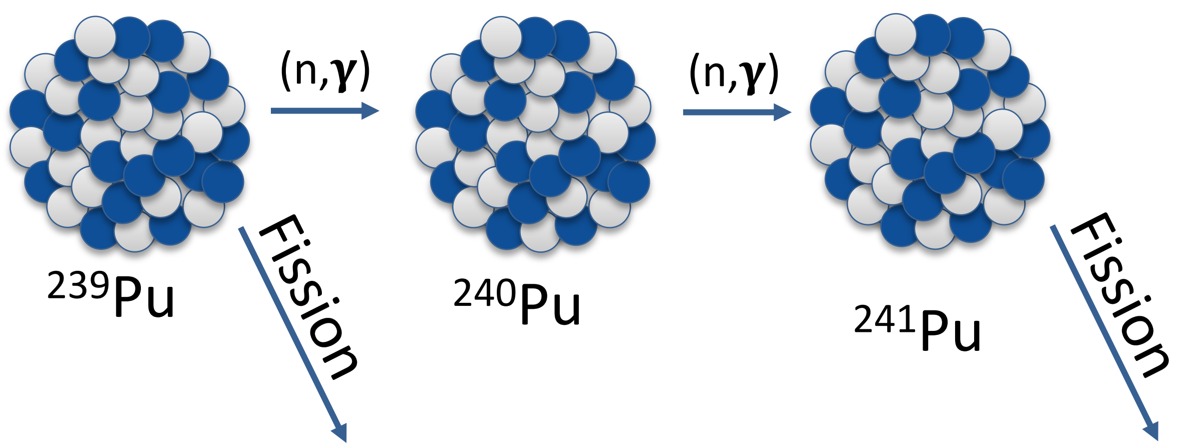


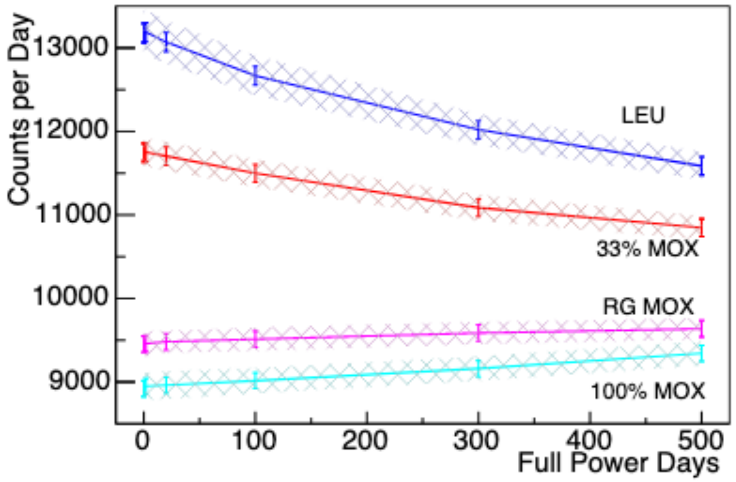


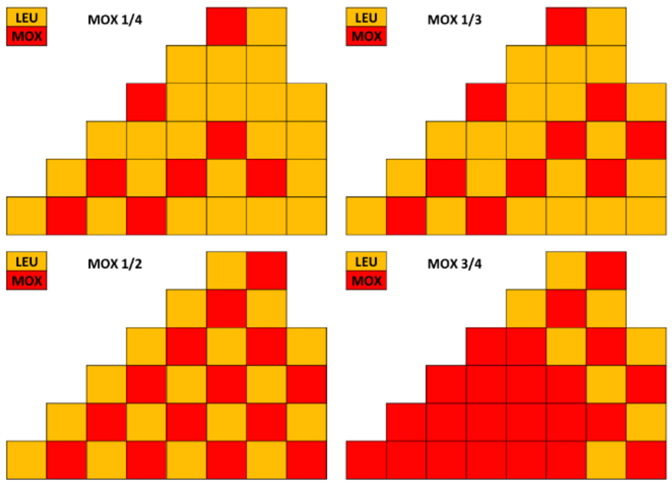
Verification of Pu Content

Huber et al.:arxiv:1403.7065

Plutonium Management and Disposition



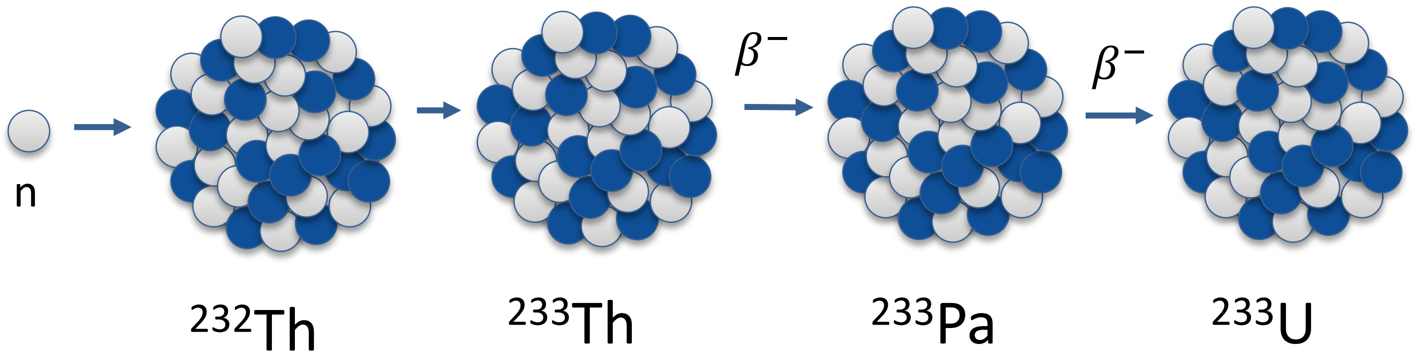


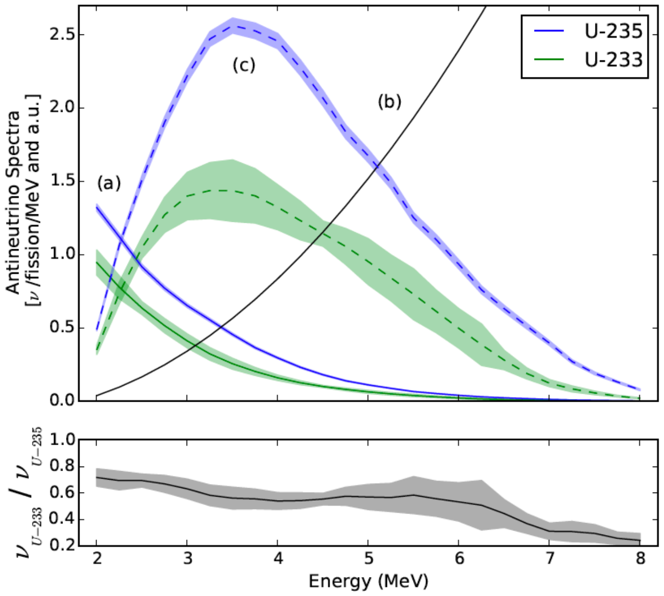


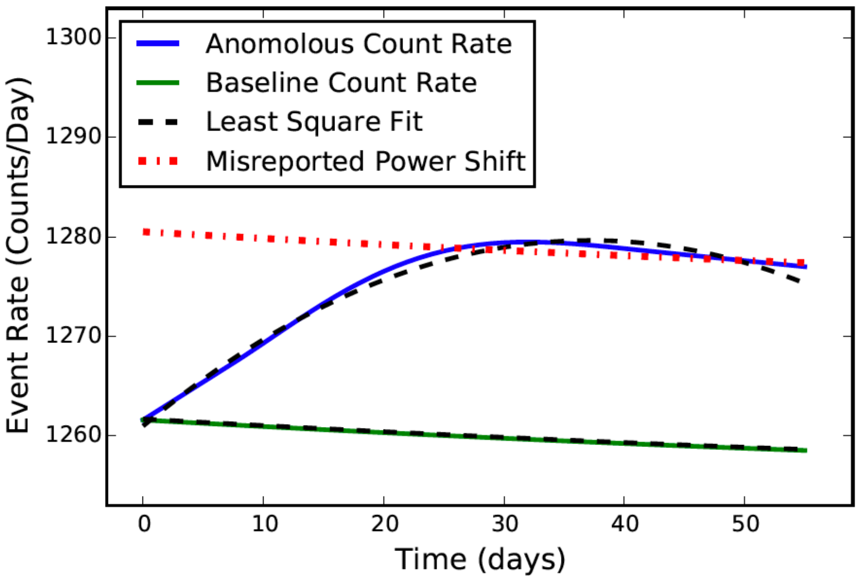
- Former agreement between the U.S. and Russia to render weapons grade plutonium unusable through reactor irradiation.
- Antineutrino monitoring has demonstrated the capability to identify if weapons grade plutonium is being used in the reactor or other fuel types.

Bernstein, Adam,"Reactors as a source of antineutrinos: effects of fuel loading and burnup for mixed-oxide fuels." *Physical Review Applied* 9.1 (2018): 014003.

Advanced Nuclear Reactors: Thorium Fuels







- Generation IV reactors such as thorium fueled reactors pose a proliferation risk due to the breeding of ^{233}U.
- Moreover some designs have
- Antineutrino monitoring can identify the diversion of ^{233}U with the replacements of LEU.
- Antineutrino monitoring has demonstrated the capability to identify if weapons grade plutonium is being used in the reactor or other fuel types.

Akindele, O. A. ,"Antineutrino Monitoring of Thorium Reactors." *Physical Review Applied* 120.12 (2016): 124902.

Reactor Antineutrino Monitoring: Near Field Efforts

Meters

Near-Field

- Antineutrinos are weakly interacting -> **Cannot shield the signal, can be detected at long standoffs.**
- Antineutrino emission is directly proportional to the reactor power -> **Real-time monitoring of the reactor operational status.**
- The antineutrino energy emission is dictated by the parent isotopes-> **Information about the relative fuel-burnup and fissile inventory.**

Reactor Antineutrino Monitoring: Near Field Efforts

Meters → Near-Field → Far-Field ?

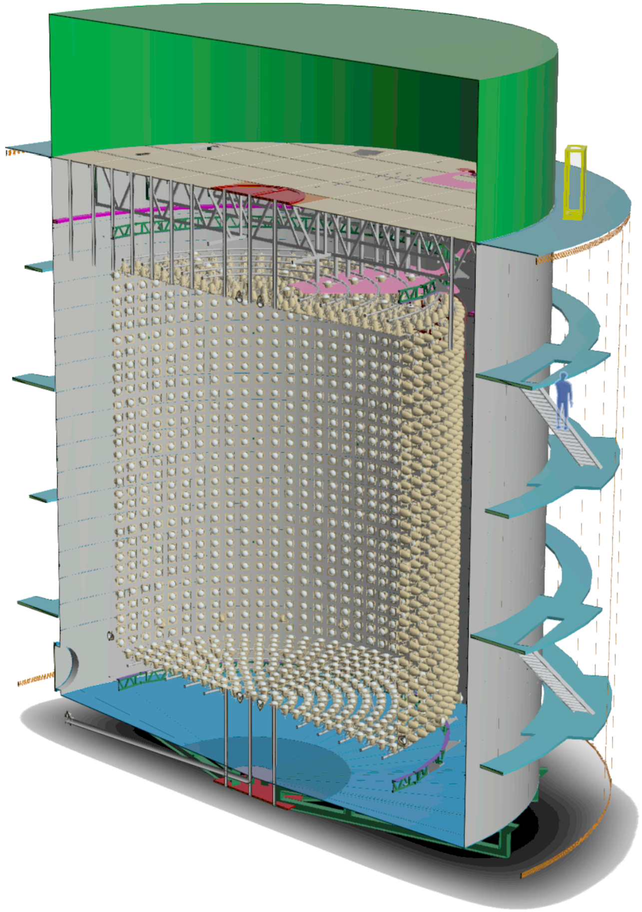
- Antineutrinos are weakly interacting -> **Cannot shield the signal, can be detected at long standoffs.**
- Antineutrino emission is directly proportional to the reactor power -> **Real-time monitoring of the reactor operational status.**
- The antineutrino energy emission is dictated by the parent isotopes-> **Information about the relative fuel-burnup and fissile inventory.**

Reactor Antineutrino Monitoring: Near Field Efforts

Meters

Near-Field

25 km



- Anti**N**eutrino **E**xperiment **O**ne (NEO) may be the first demonstration of reactor monitoring in the far-field.
- A far-field demonstration loses spectral and high statistical capabilities but allows for a higher degree of non-intrusiveness.
- This experiment involves exploring the use of a far-field detector.

Co-spokespersons

Adam Bernstein

Lawrence Livermore National Laboratory

Matthew Malek

The WATCHMAN Collaboration

91 collaborators!

19 institutions from US and UK

Atomic Weapons Establishment
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- J. Gribble
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- S. Quillin
- T. Shaw

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Brookhaven National Laboratory
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Iowa State University
- M. Wetstein
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- M. Bergevin
- S. Dazeley
- R. Hills
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Middlebury Institute of International Studies
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- J. He
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- T. Pershing
- R. Lap Keung Mak
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- X. Lui
- F. Muheim
- A. Murphy
- G. Smith
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- F. Sutanto

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- W. Huang
- R. Van Berg

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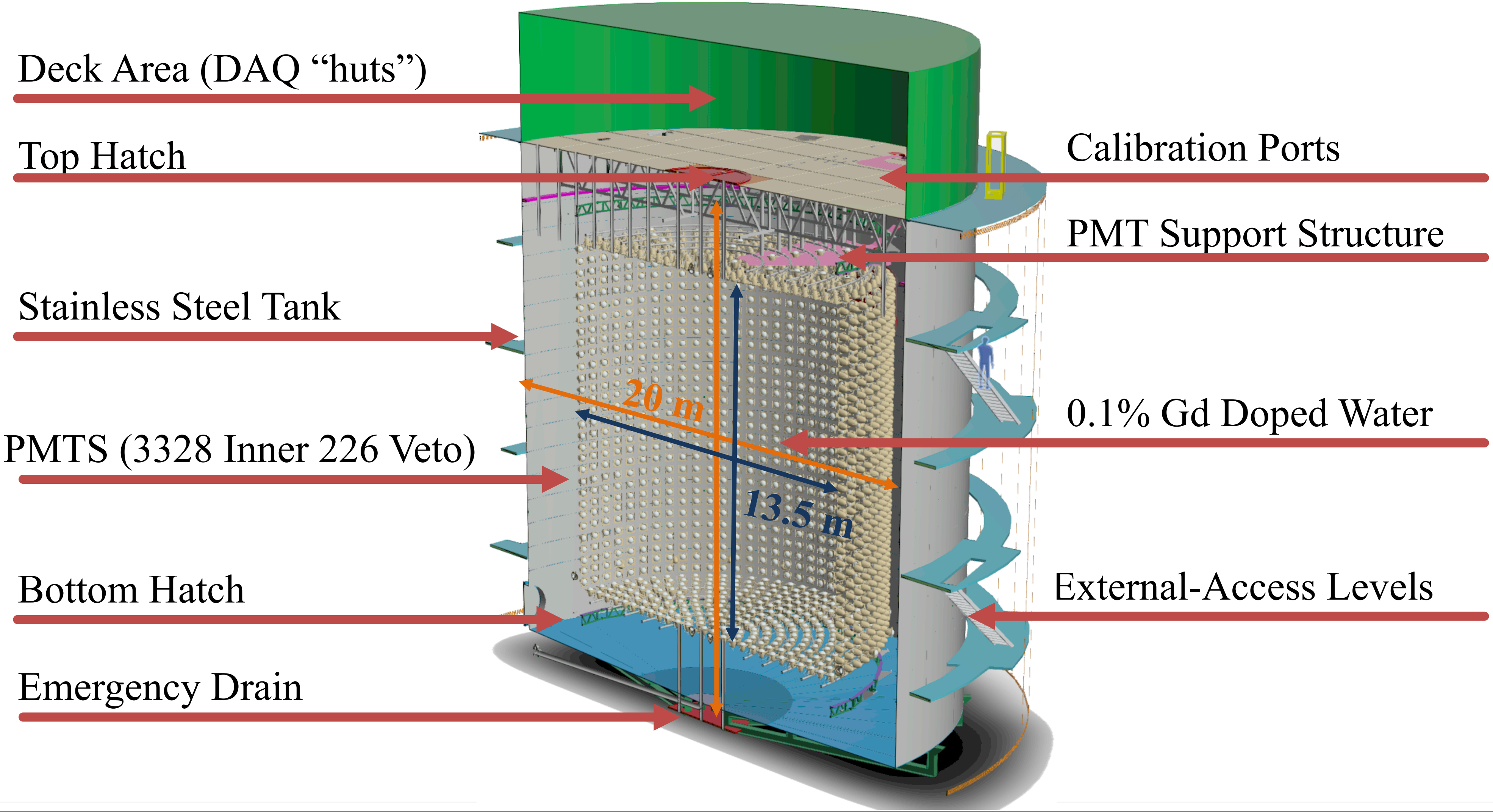
- M. Malek
- A. Ezeribe
- R. Foster
- T. Gamble
- C. Holligan
- E. Kneale
- V. Kudryatsev
- J. McMillan
- J. Mercer
- N. Spooner
- L. Thompson

Far-Field Reactor Monitoring Gd-H_2O Design Concept



Advanced Instrumentation Testbed - antiNeutrino Experiment One

AIT-NEO Project

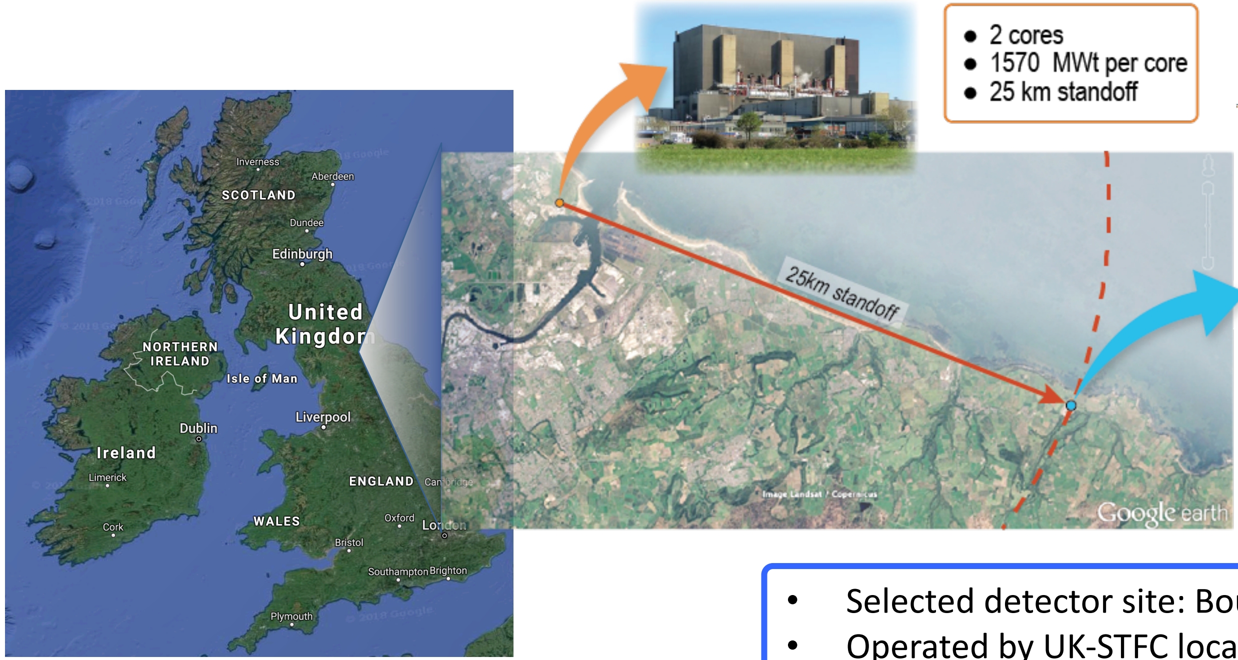
Advanced Instrumentation Testbed
A joint US-UK effort for studies of large-scale antineutrino detection methods, main site located at the Boulby Underground Laboratory

antiNeutrino Experiment One
The first experimental demonstration of remote reactor monitoring at AIT.

WATCHMAN Collaboration

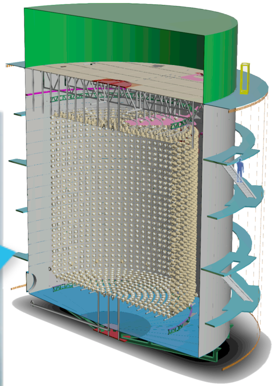
A collaboration to promote the use of antineutrino detection for remote reactor monitoring and fundamental physics

Hartlepool Reactors

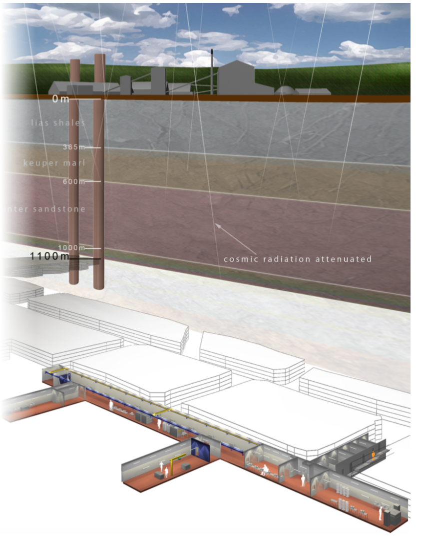


- 2 cores
- 1570 MWt per core
- 25 km standoff

NEO Detector



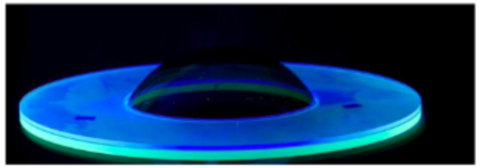
Boulby Underground Laboratory



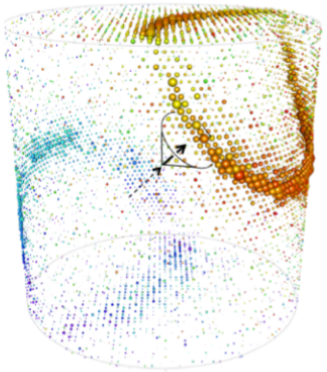
- Selected detector site: Boulby Underground Laboratory
- Operated by UK-STFC located 1100m underground
- Part of an operating potash/polyhalite mine
- Candidate for deployment in the **Advanced Instrumentation Testbed**,
- **Gd-H2O and WbLS under consideration for first fill (NEO)**

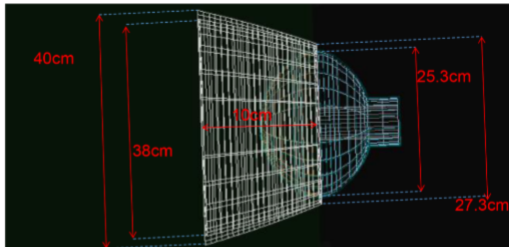
Other Studies for AIT/NEO

Light Collection Tools

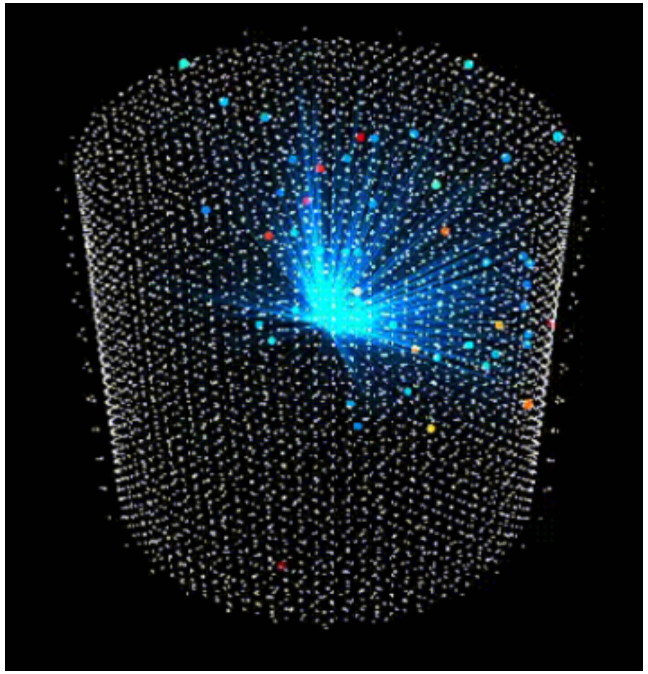


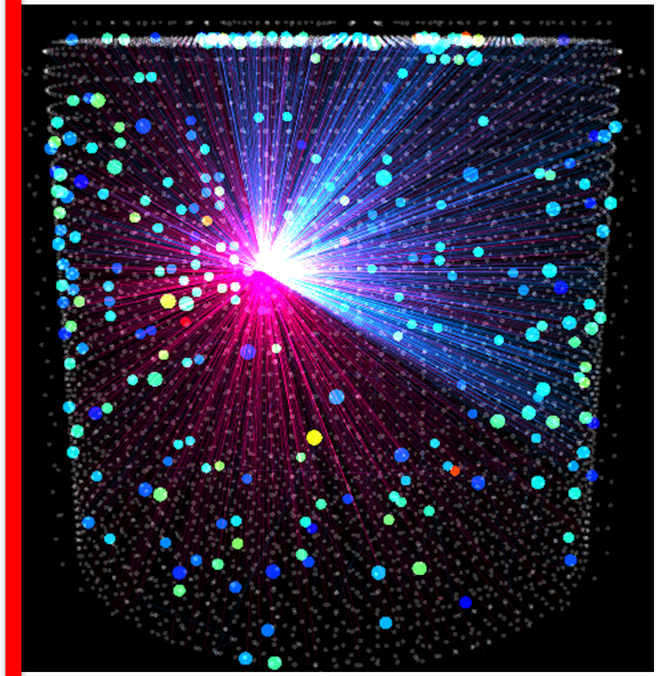
DESIGN, SIMULATION, AND PROTOTYPING OF WAVELENGTH-SHIFTING PLATE LIGHT COLLECTOR FOR A LARGE WATER CHERENKOV DETECTOR
William Albert Johnston , Colorado State University





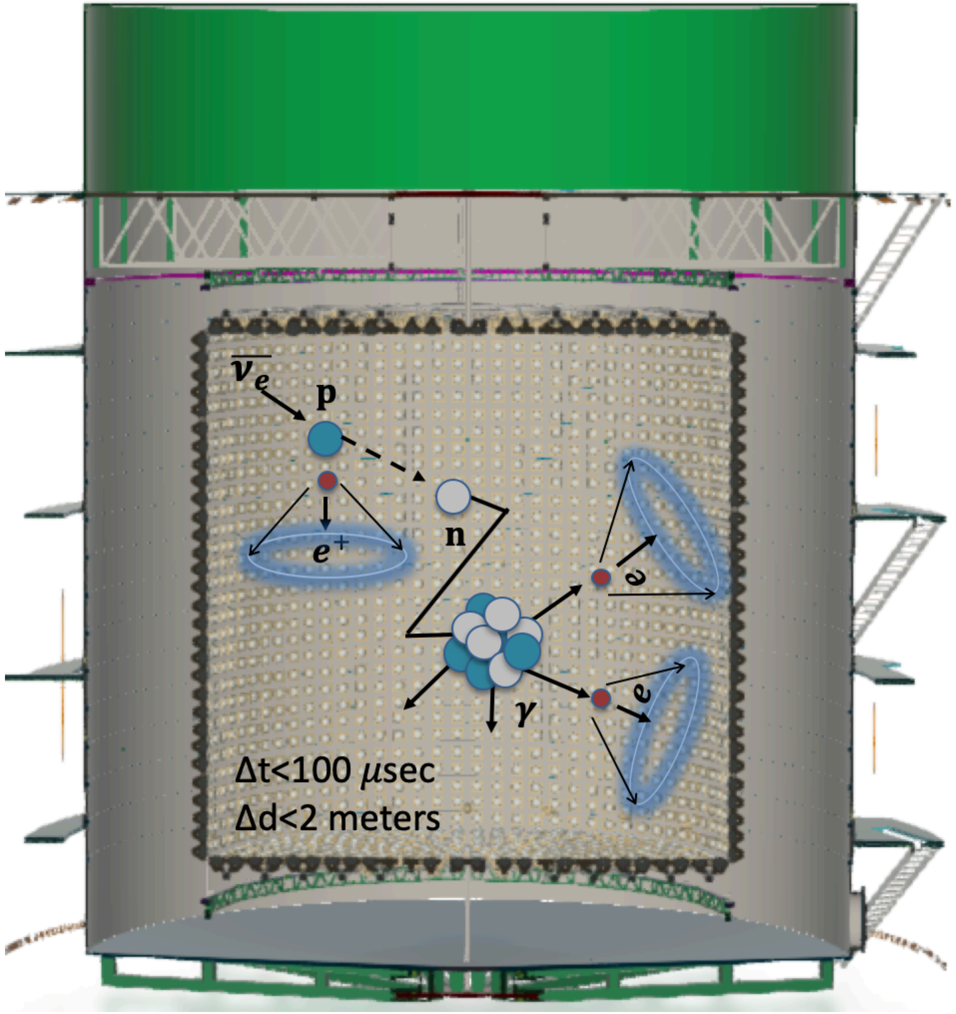
Light Production Tools



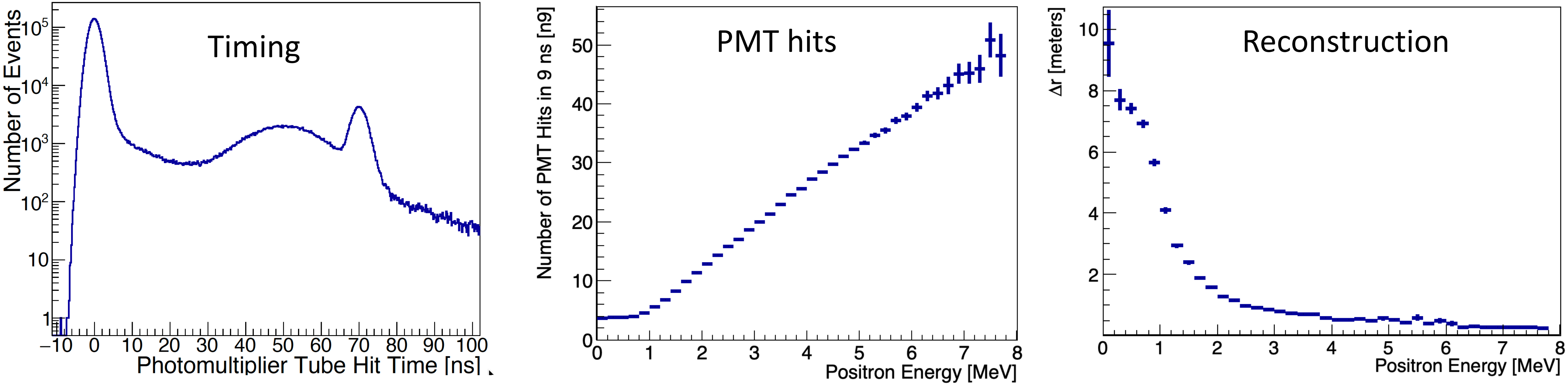


Detecting the Inverse Beta Decay Process

- Antineutrinos detected through inverse beta decay.
  - **(IBD):** $\bar{\nu} + p \rightarrow e^{+} + n$
  - **(Q=-1.8 MeV,** $\sigma \sim 10^{-42} cm^2 E_{\bar{\nu}}^2$ **)**
- Events are simulated using Rat-Pac, a GEANT4 based simulations package.
- Reconstructed by evaluating the spatial, timing, and multiplicity of PMTs hits, using BONSAI (developed by Michael Smy at UCI).
- IBD events are determined by a timing window of 100 μsec, and a spatial separation of 2 meters in the detector.



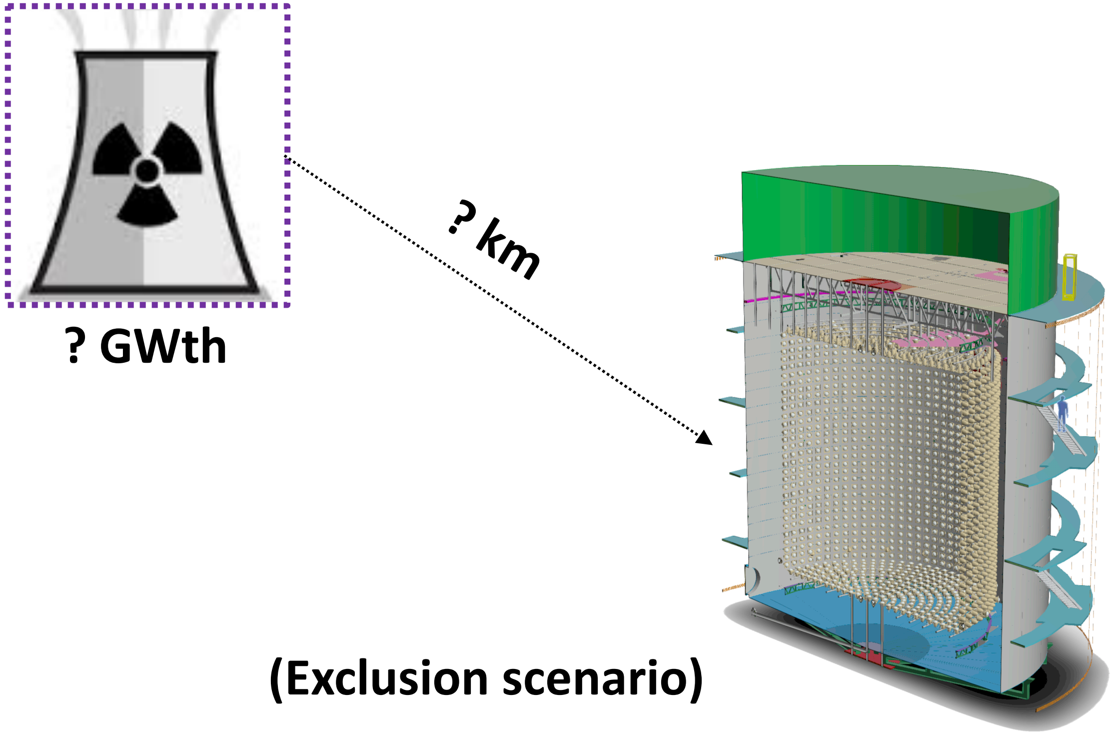
Positron Response



- Given the low light yield from IBD positrons (9 photoelectrons/MeV) we use the prompt light as our denotation for charge in the detector.
- Prompt light in our detector is denoted by how many PMTs fire within 9 ns, which we refer to as n9.
- Due to our energy cuts, we're more sensitive to the higher energy portion of the IBD spectra

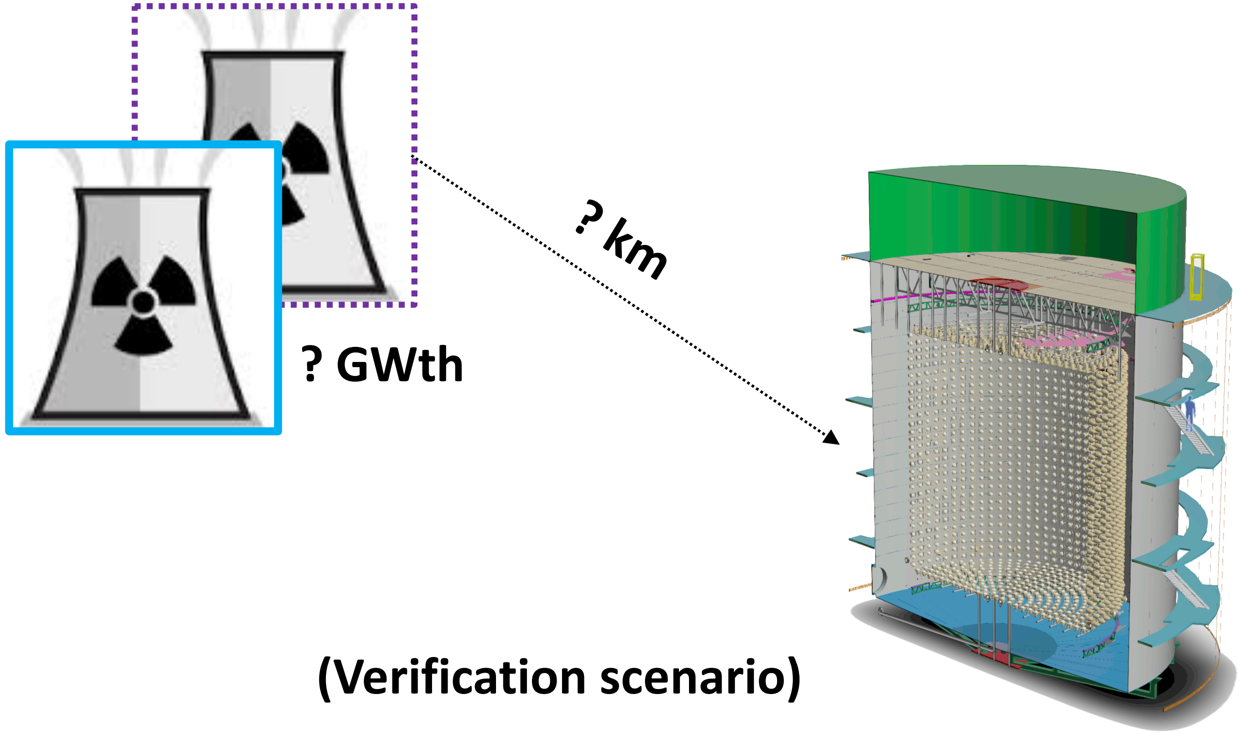
Nonproliferation Goals

How well can the presence of a reactor be excluded?



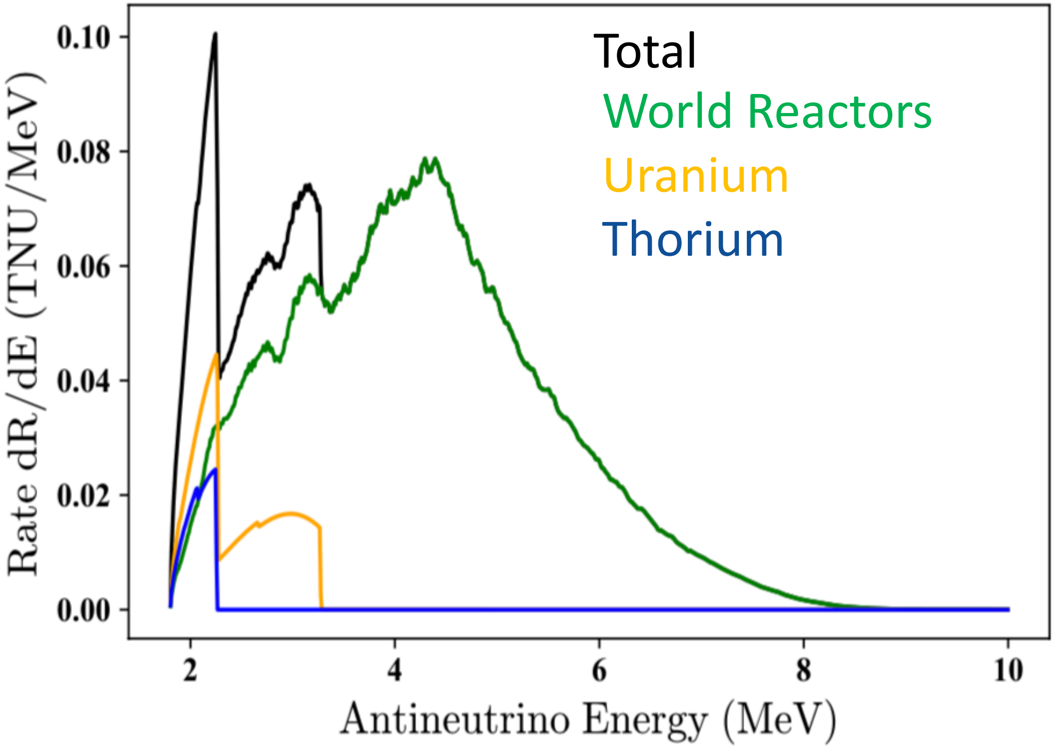
(Exclusion scenario)

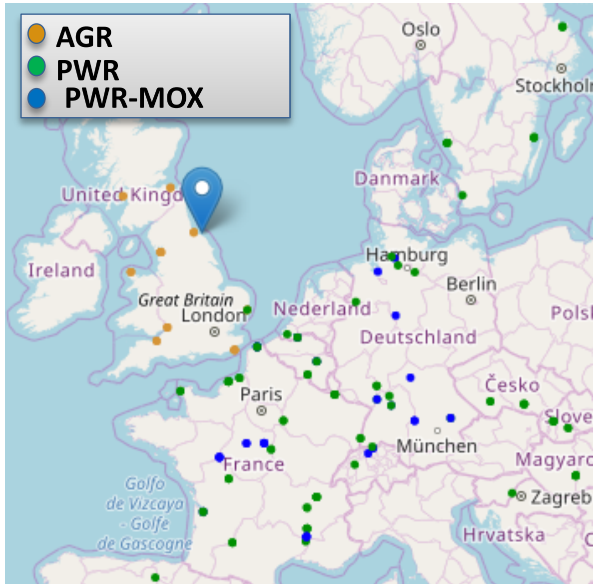
How well can the presence of a known reactor be confirmed?



(Verification scenario)

Antineutrino Backgrounds





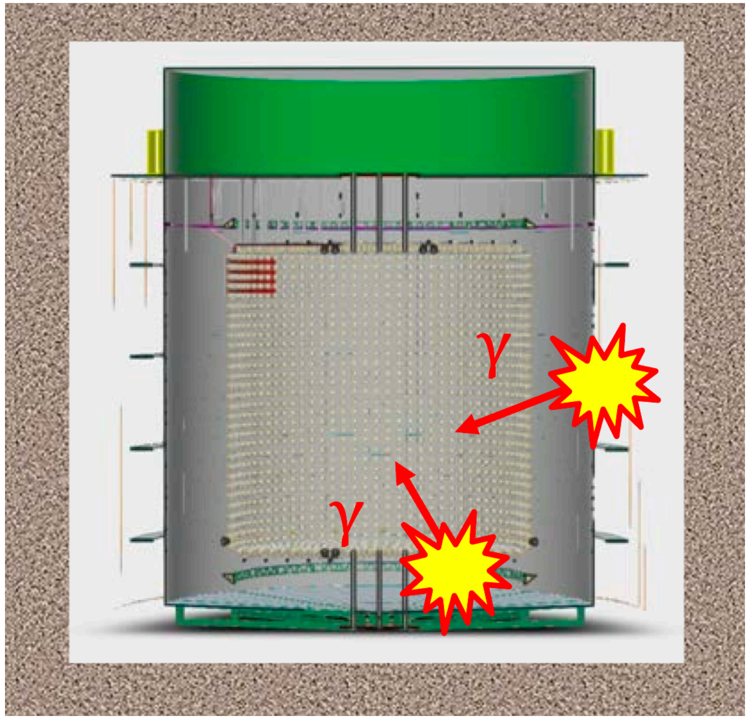
Reactors	Flux Contribution
Hartlepool	85%
Heysham	4%
Other UK Reactors	9%
Geoneutrinos	2%

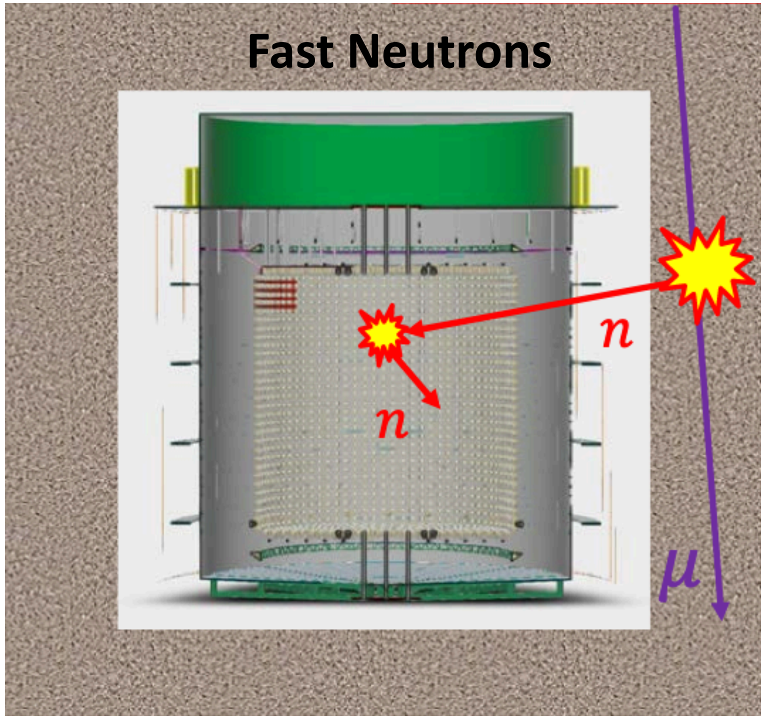
- The total reactor antineutrino background and geoneutrino spectra was taken from Geoneutrinos.org. for the Boulby mine location.
- To accommodate the variation in background due to reactor shut-downs, we associate a 5% systematic uncertainty to the antineutrino background flux.

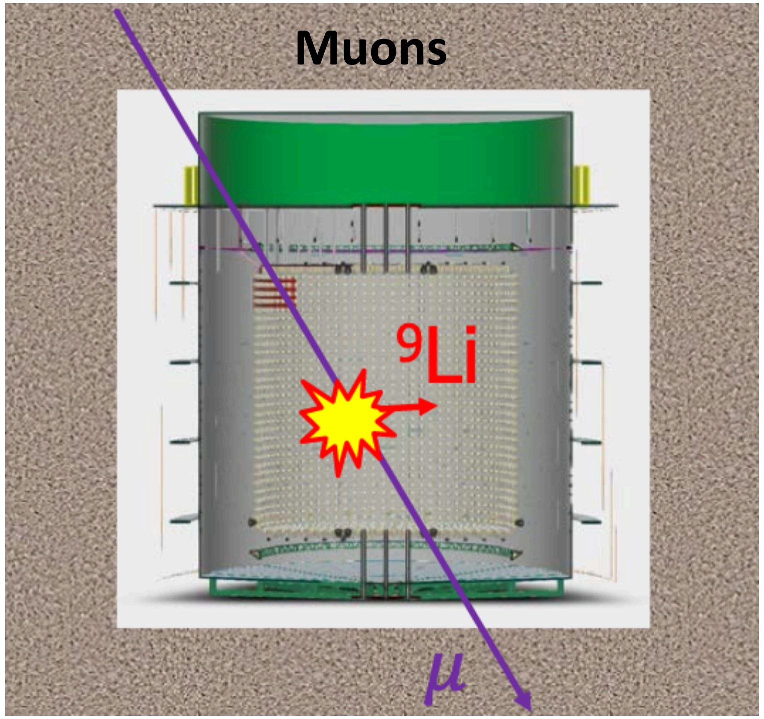
Classification of Backgrounds

Accidentals

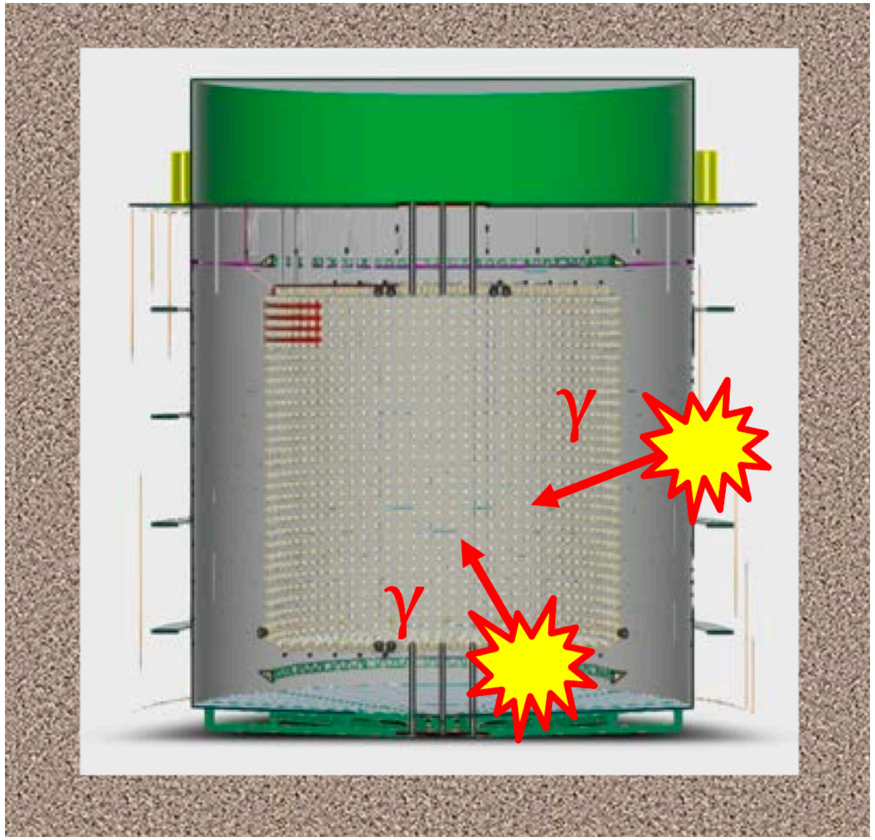
Correlated

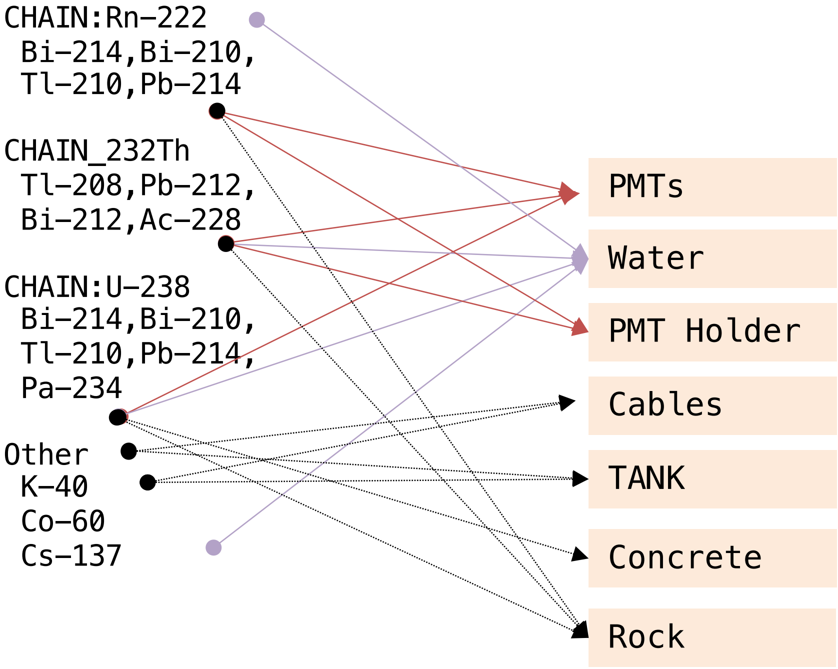




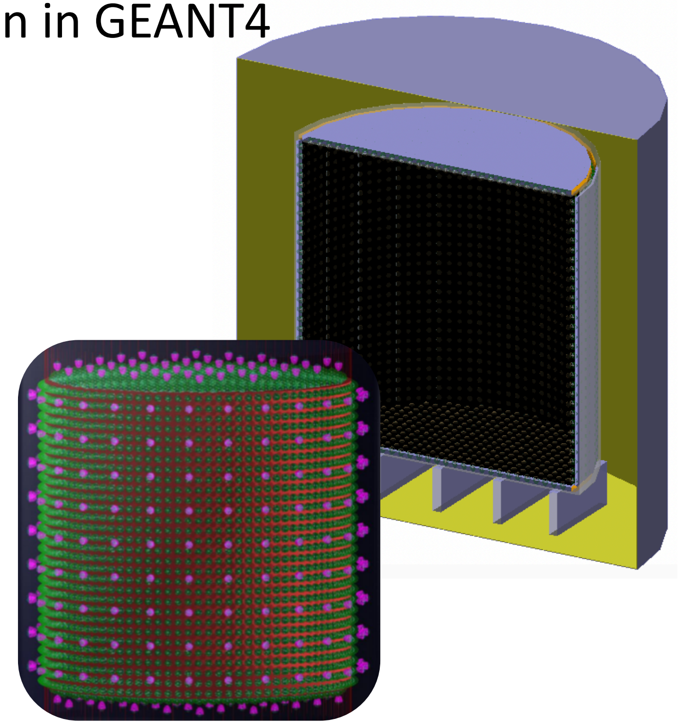


Accidentals



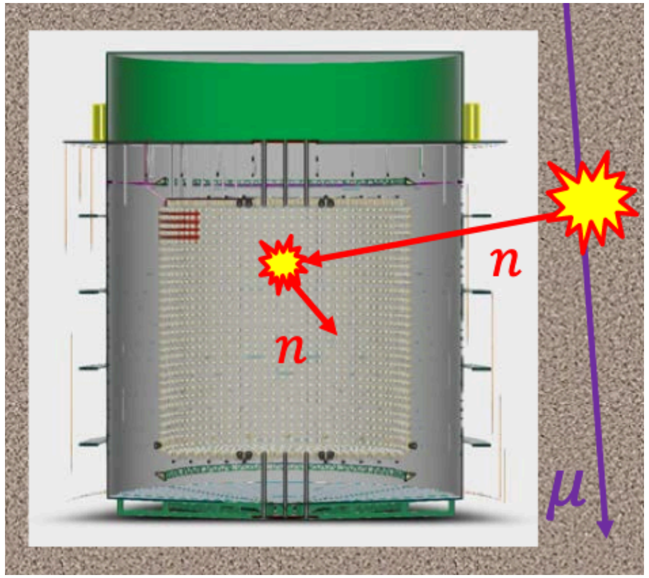


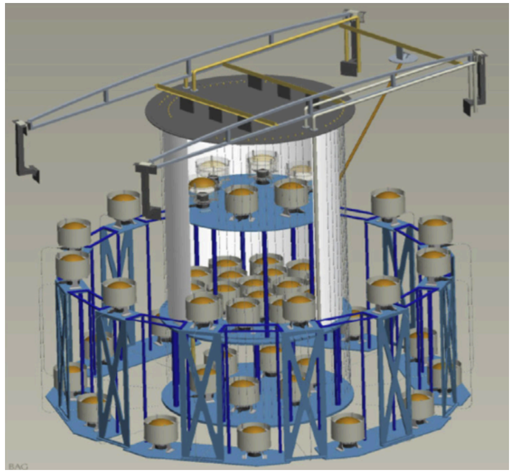
Visualization in GEANT4



- Events in the detector that can result in charge deposition are modeled in the detector using Rat-PAC, a GEANT4 simulation-based framework.
- We treat these backgrounds as uncorrelated, and result in IBD candidates when two events occur within our predetermined spatial and timing cuts.

Correlated Backgrounds: Fast Neutrons

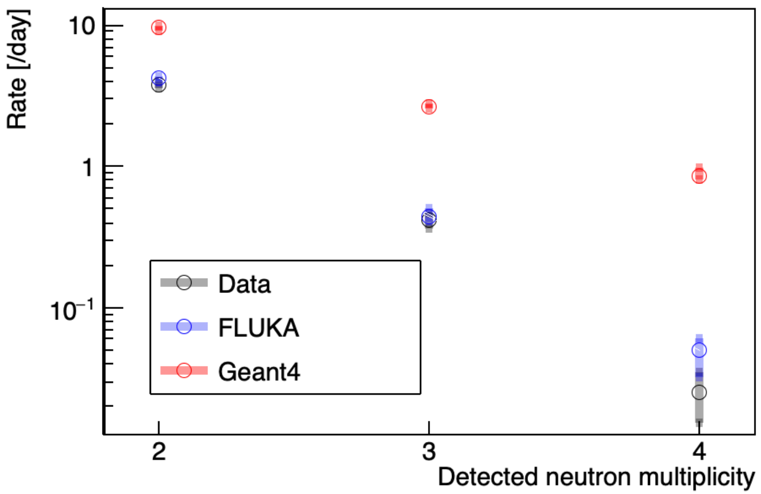




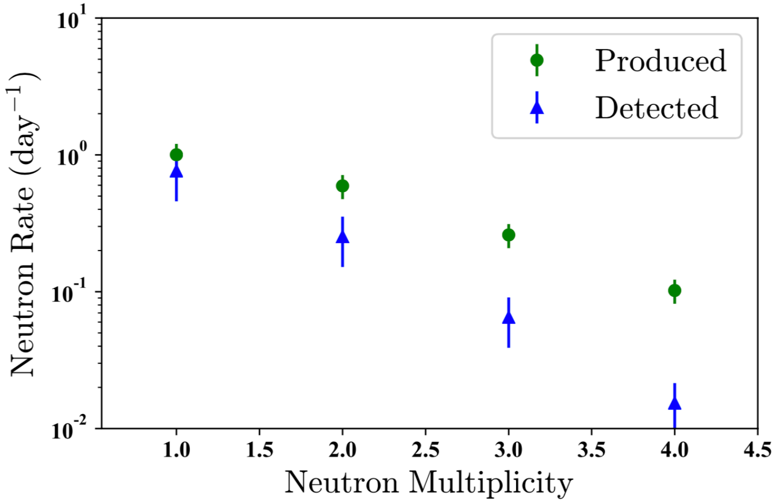
WATCHBOY Detector

- Deployed at the KURF mine
- 400 m.w.e.
- 2 ton Gd-doped water Cherenkov target
- shielded by 40 ton pure water outer muon veto
- 16 target PMTs and 36 veto PMTs
- **S. Dazeley et al. NIMA 821 (2016) 151–159**

Fast Neutron Validation

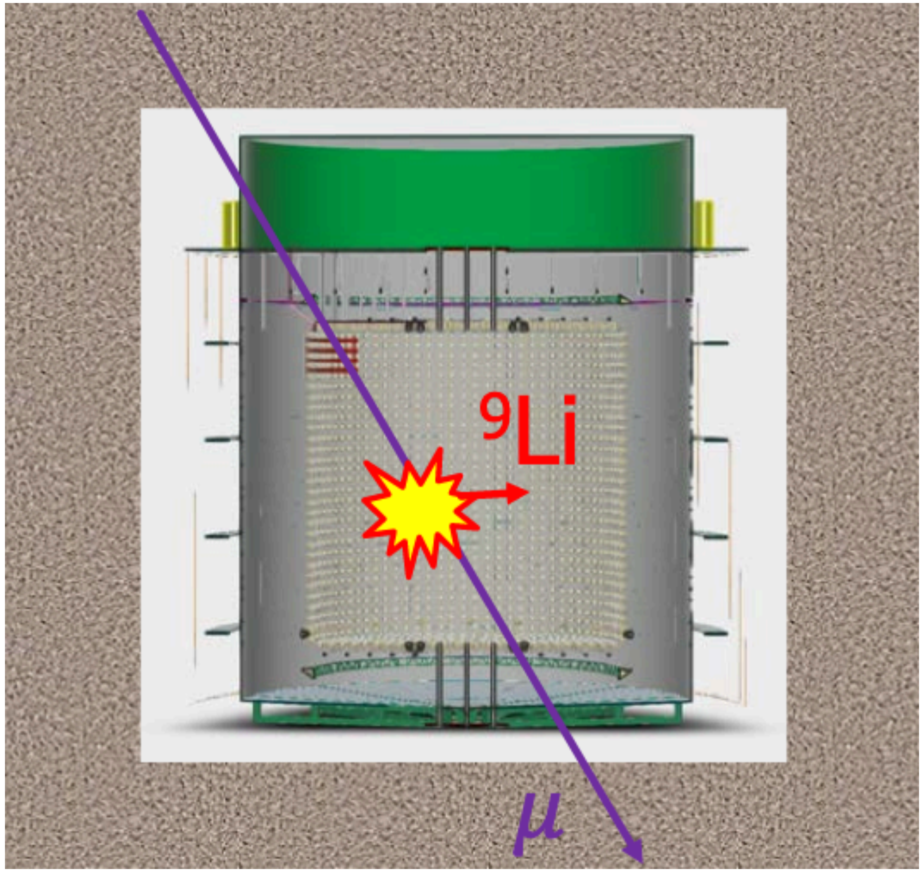


Fast Neutrons In NEO

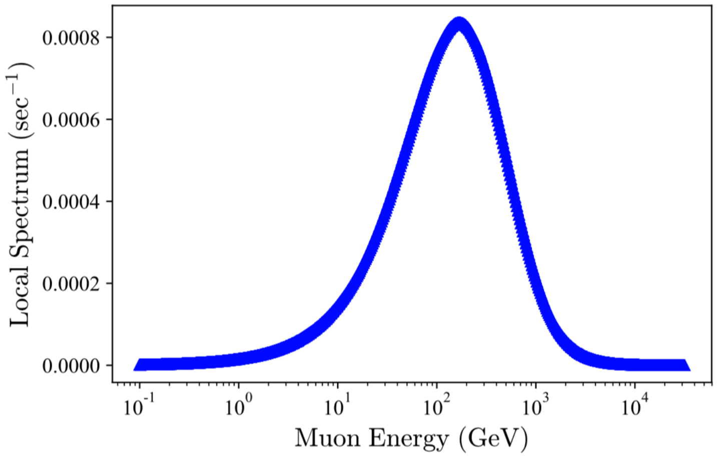


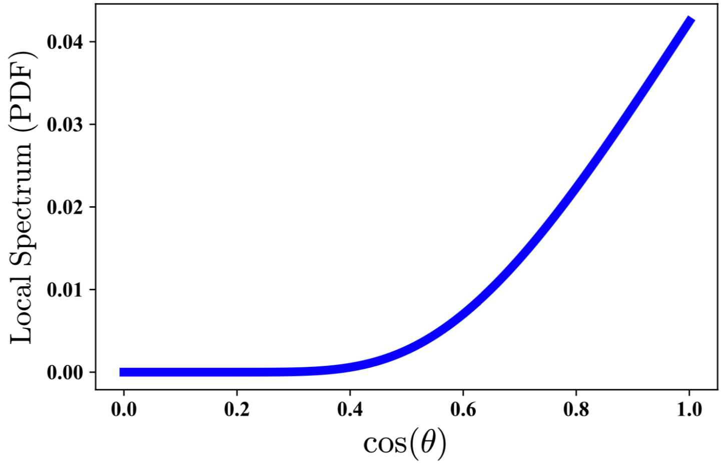
- FLUKA-based neutron detection rates show a better agreement with the data in comparison with the Geant4-based neutron detection rates
- Results by **Felicia Sutanto** (UMICH PhD Candidate) in **Phys. Rev. C 102, 034616.**

Muogenic Response



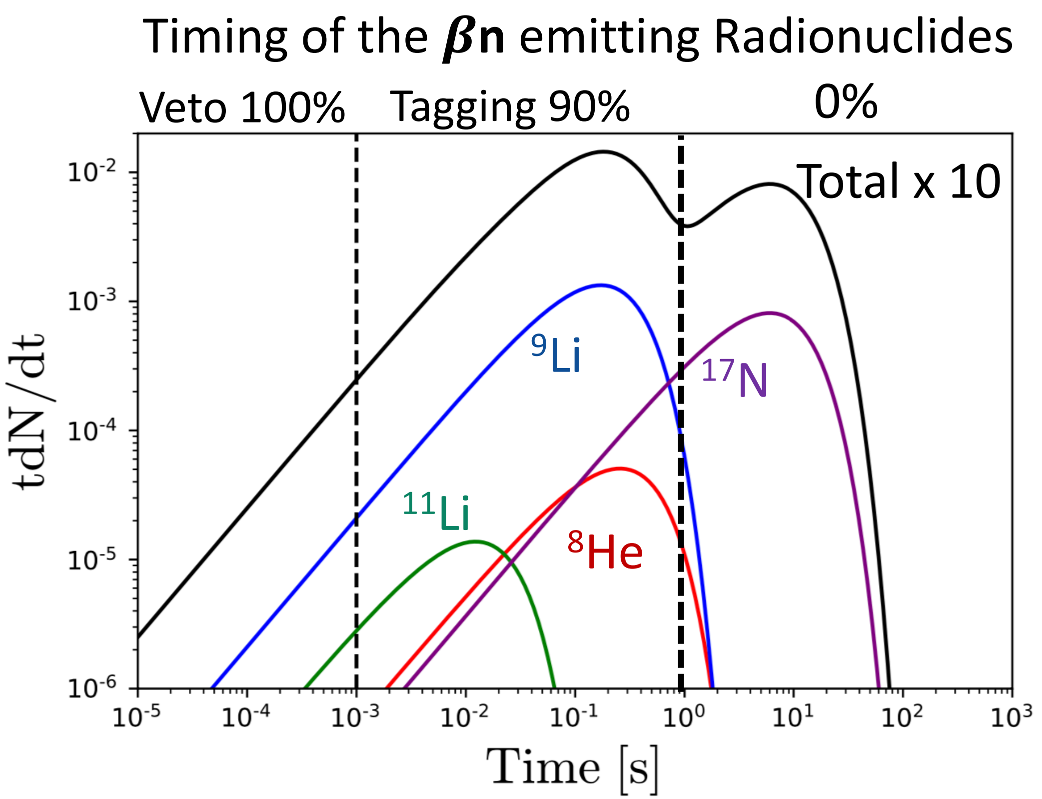
D. M. Mei, A. Hime

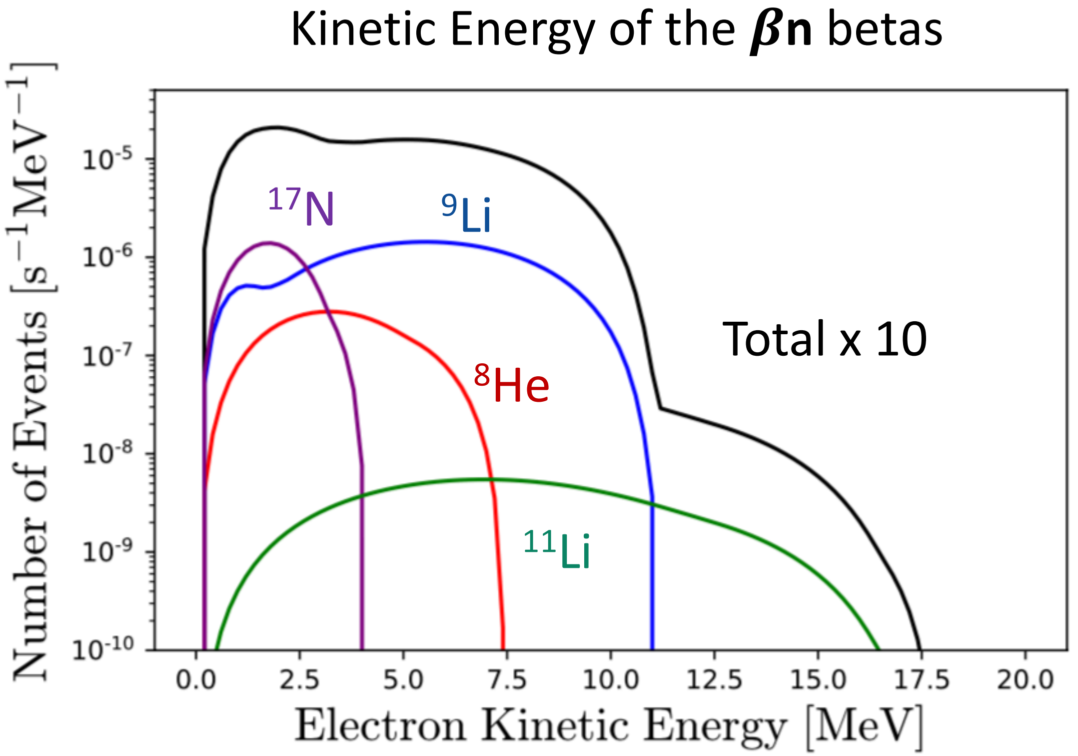




- Muons are modeled using the energy and directionality described in **PhysRevD.73.053004.** The muon rate in NEO is expected to be **0.116±0.004 hz**
- The baseline design will have 236 Veto PMTs to trigger a deadtime in the event that muons pass through the detector.
- Additionally, muons passing through the detector can cause radionuclide production of ^{9}Li and ^{8}He which decay with the emission of a beta and neutron pair.

Muogenic Response: Radionuclides



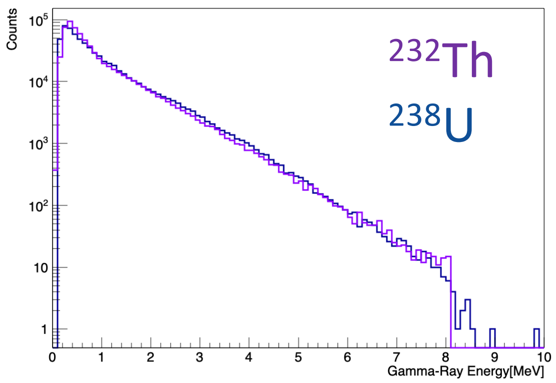


- WATCHBOY set a limit for **^{9}Li** in the detector, the intent is to scale this rate from the Super Kamiokande results (**PhysRevD.93.012004**) and the Li & Beacom Analysis (**PhysRevC.89.045801**).

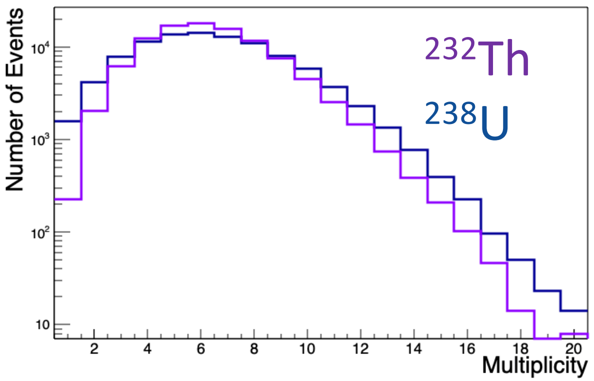
- In addition to ^{9}Li, βn emitters include ^{11}Li, ^{17}N, ^{8}He. Theoretically, contributions from ^{16}C are possible, however NEO would not be sensitive to its rate.

Spontaneous Fission from ^{238}U and ^{232}Th

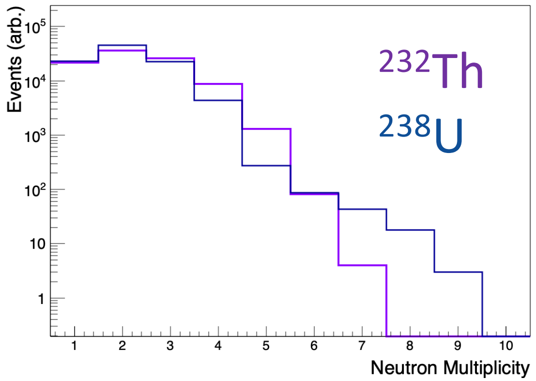
Gamma-Ray Energy



Gamma-Ray Multiplicity

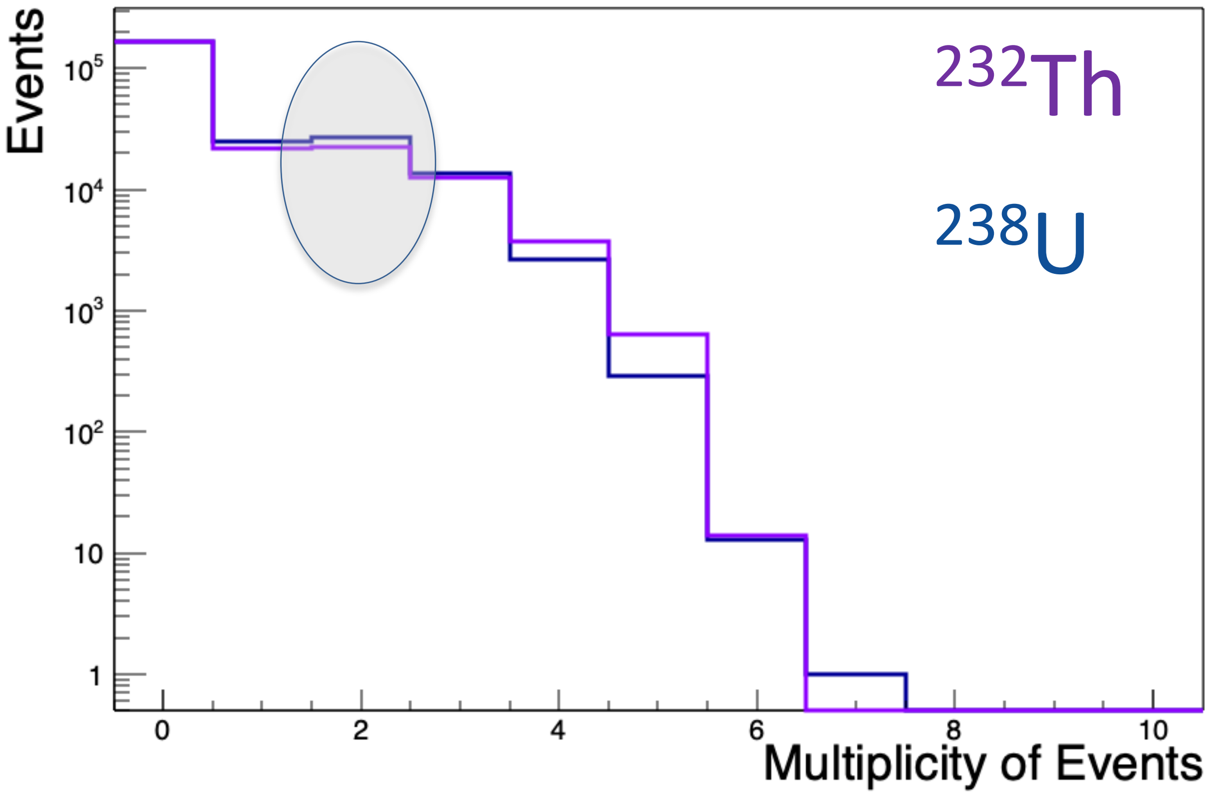


Neutron Multiplicity



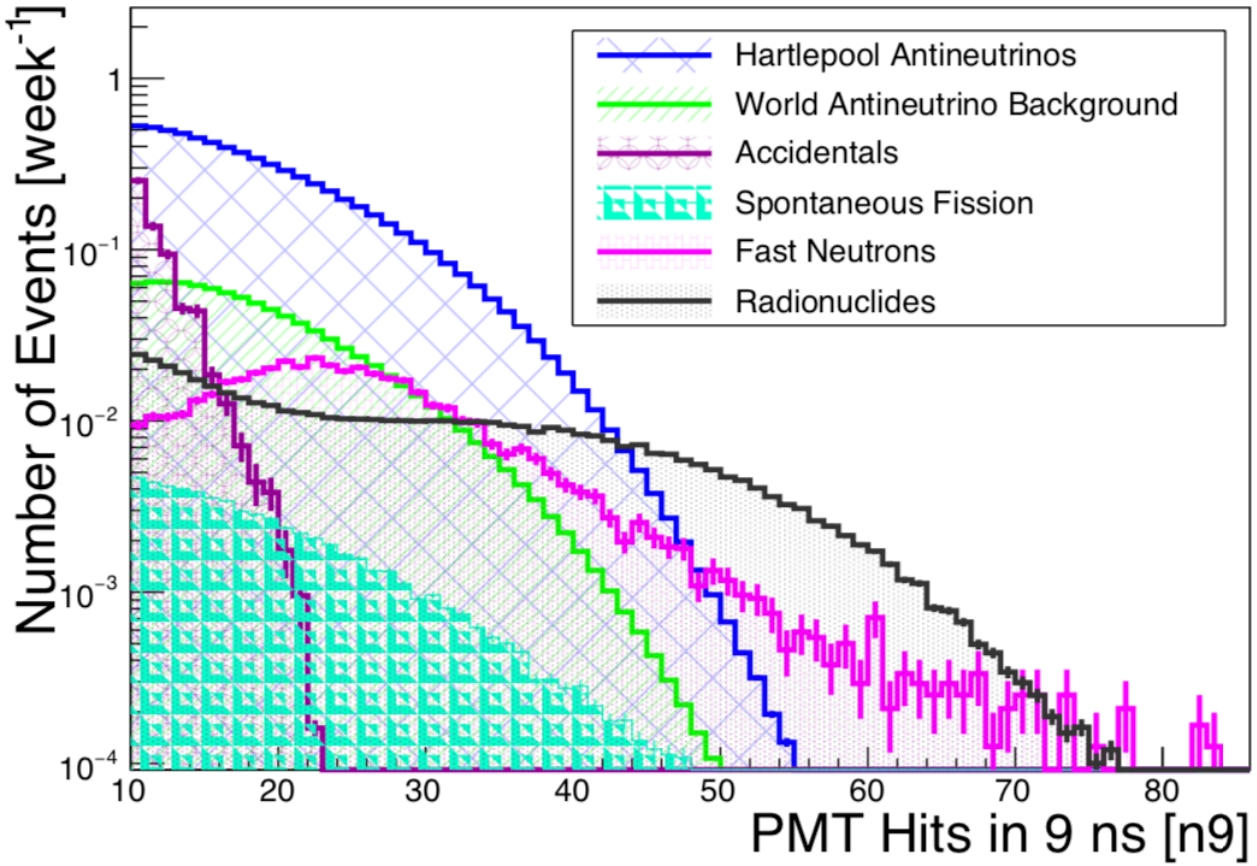
Fission Model using FREYA

- Generates complete fission events: energy, momentum, multiplicities, and correlations of neutrons and gamma-rays.
- These correlated quantities are needed to understand how these events reconstruct in NEO.

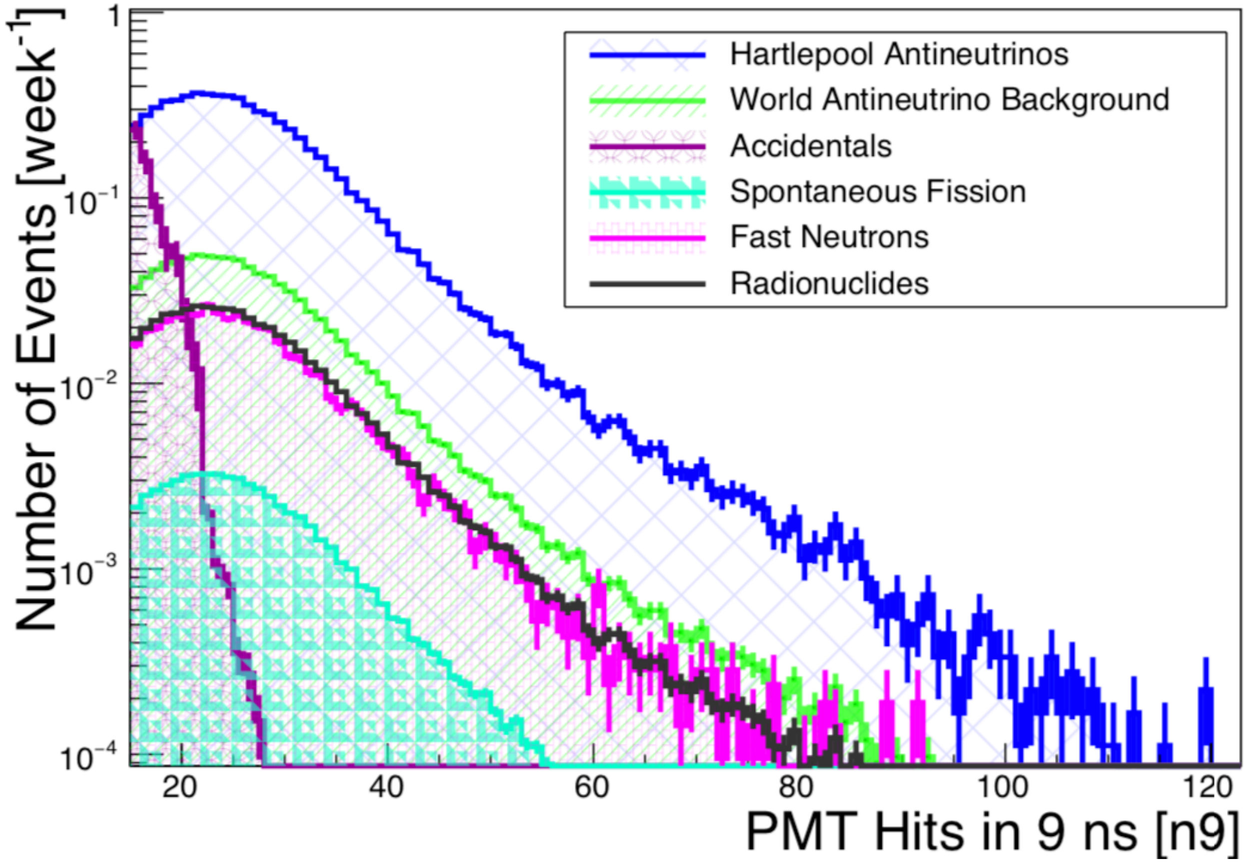


Event Summary

Prompt Events



Delayed Events



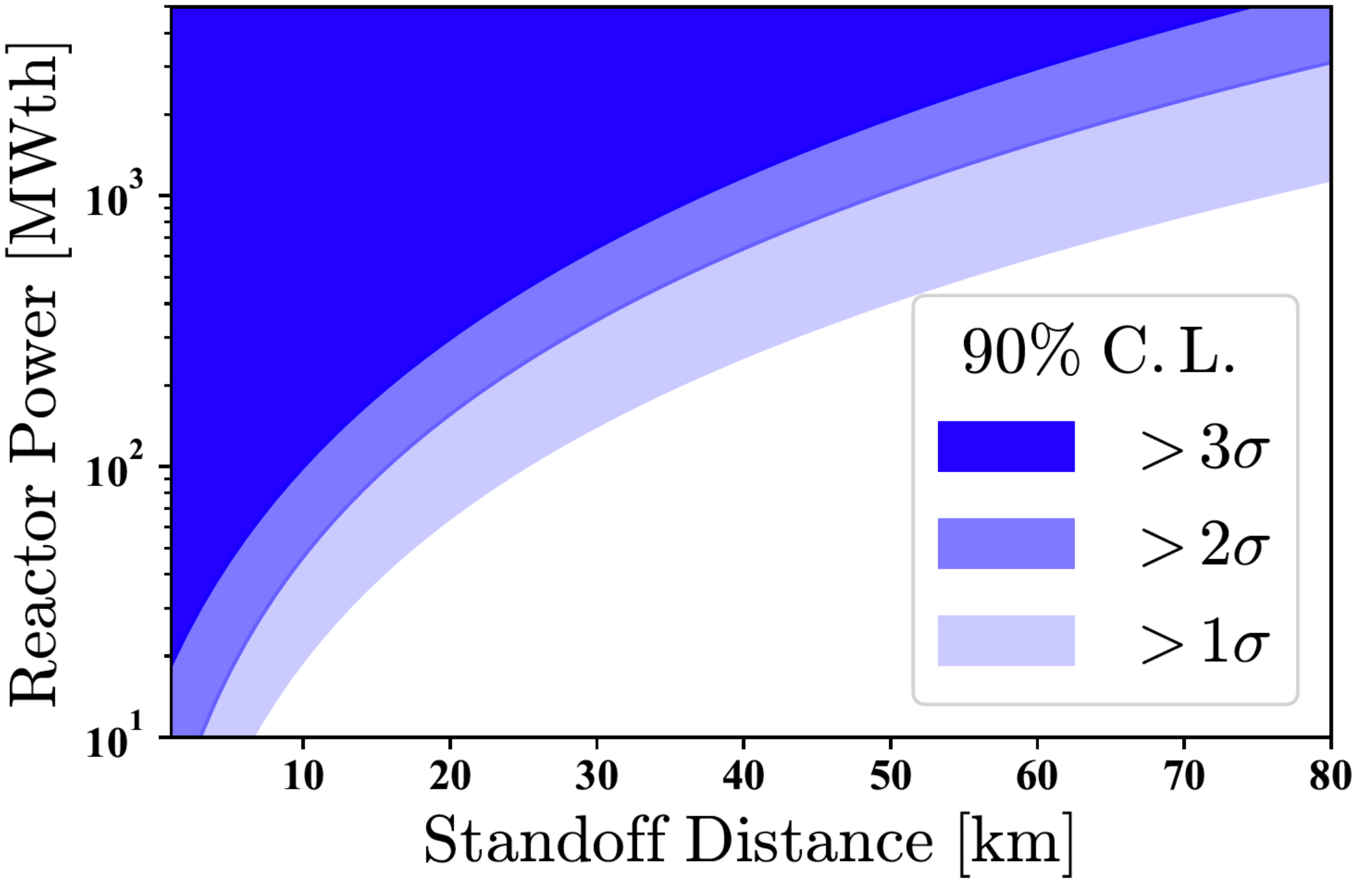
Event Summary

Contribution	Yearly Events
Reactor Signal	354.32 ±31.39
World $\bar{\nu}$ Bkgd	47.41 ±9.01
Accidentals	32.40 ±9.21
Radionuclides	13.73 ±7.80
Dineutrons	13.00 ±6.32
Spontaneous Fission	2.60 ±1.62
Total	463.46 ±68.40

Sensitivity Analysis: A Frequentist Approach

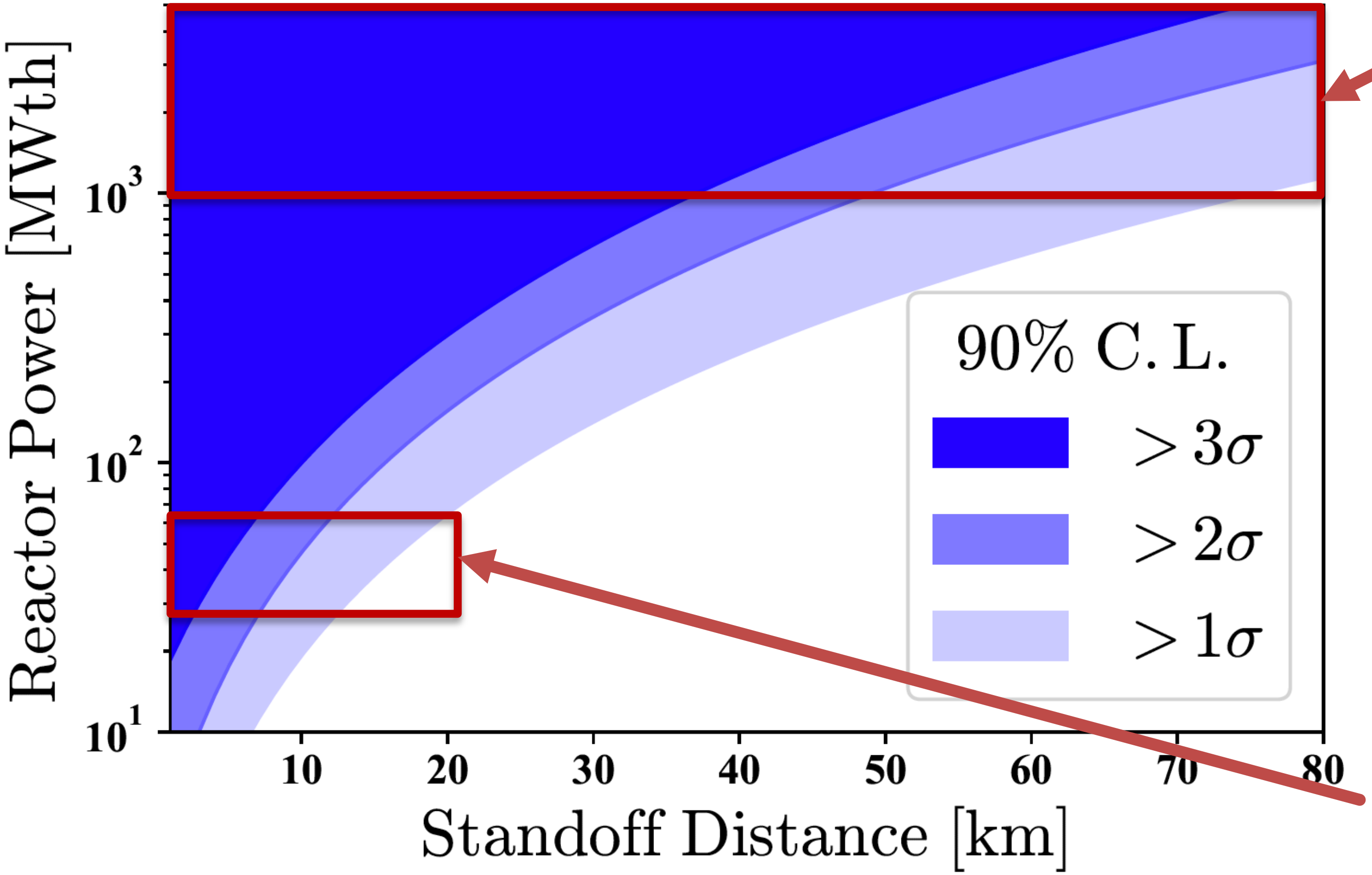
- A Feldman-Cousins based confidence intervals for reactor searches for a one-year dwell time.
- Templates of the signal and background spatial and charge distribution in the detector are generated based on if they are correlated or random events.
- A different template is generated for variable dwell time, detector standoff, and thermal power of the facility.

0 MWth Reactor Power 1-Year Dwell Time



- The exclusion of variable reactor sizes and distances are shown.
- This detector will only be able to confirm the 1500 MWth and 3000MWth at 25 km standoff.
- For a low power reactor, 50 MWth, can be excluded with greater than 3 sigma at 5 km standoff.

0 MWth Reactor Power 1-Year Dwell Time



Exclude the existence of Pu production facilities

Science & Global Security, 19:28–45, 2011

Reactor	Type	Power (MWt) (design/upgraded)
AD	once-through	1450/2000
ADE-1	once-through	1450/2000
ADE-2	closed-circuit	1450/1800

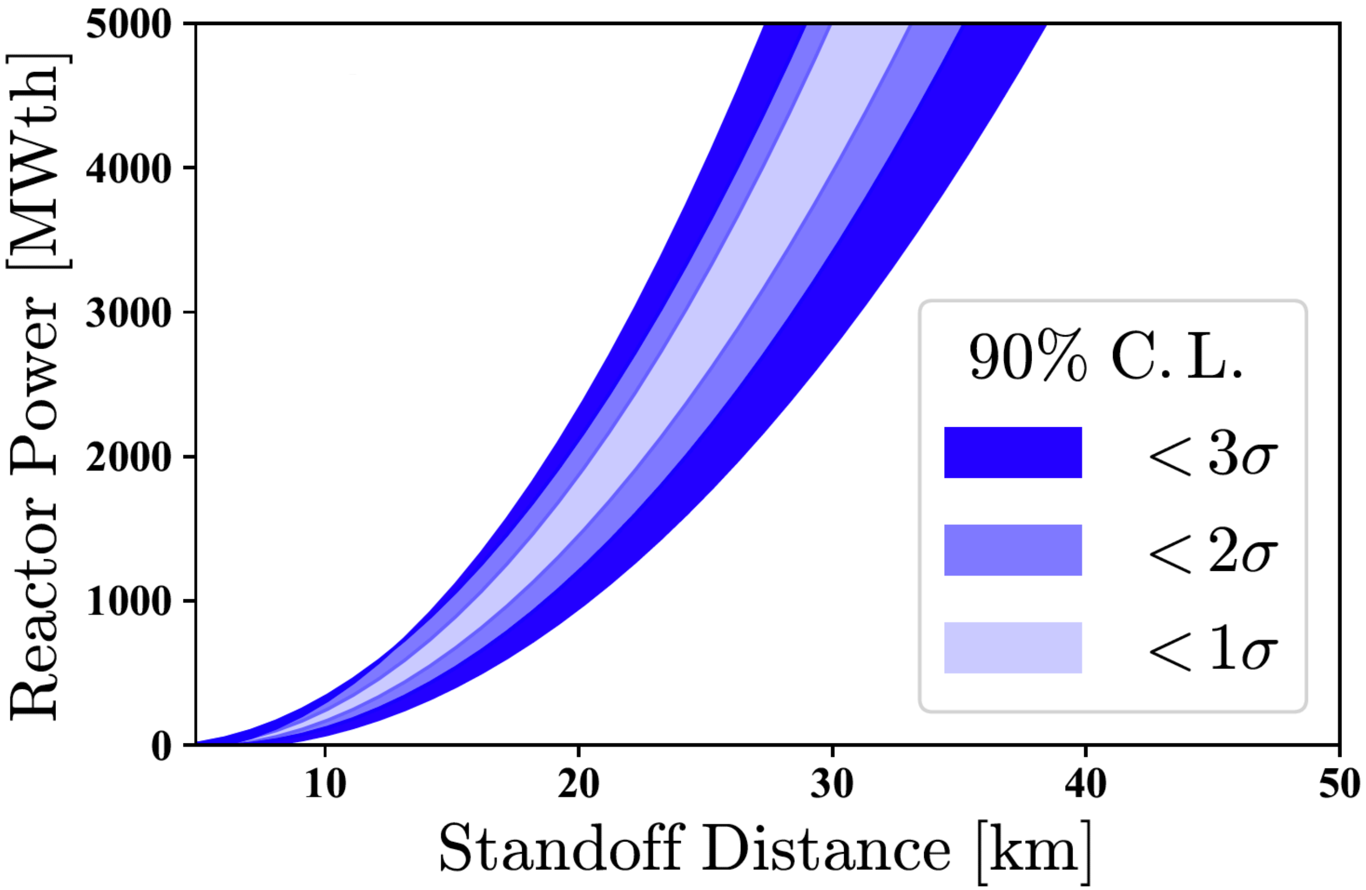
Krasnoyarsk plutonium production reactors.

Exclude the existence of research reactors

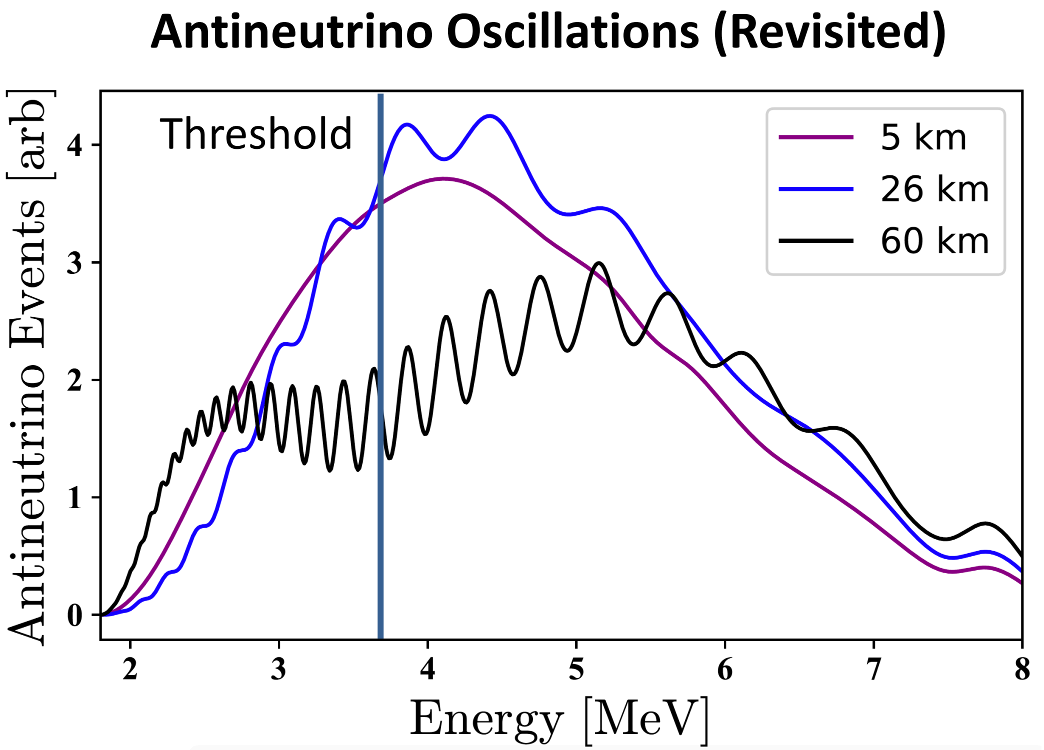
Satellite image of the heavy water reactor at Arak, Iran, May 2012. Image credit Digital Globe and Google Earth

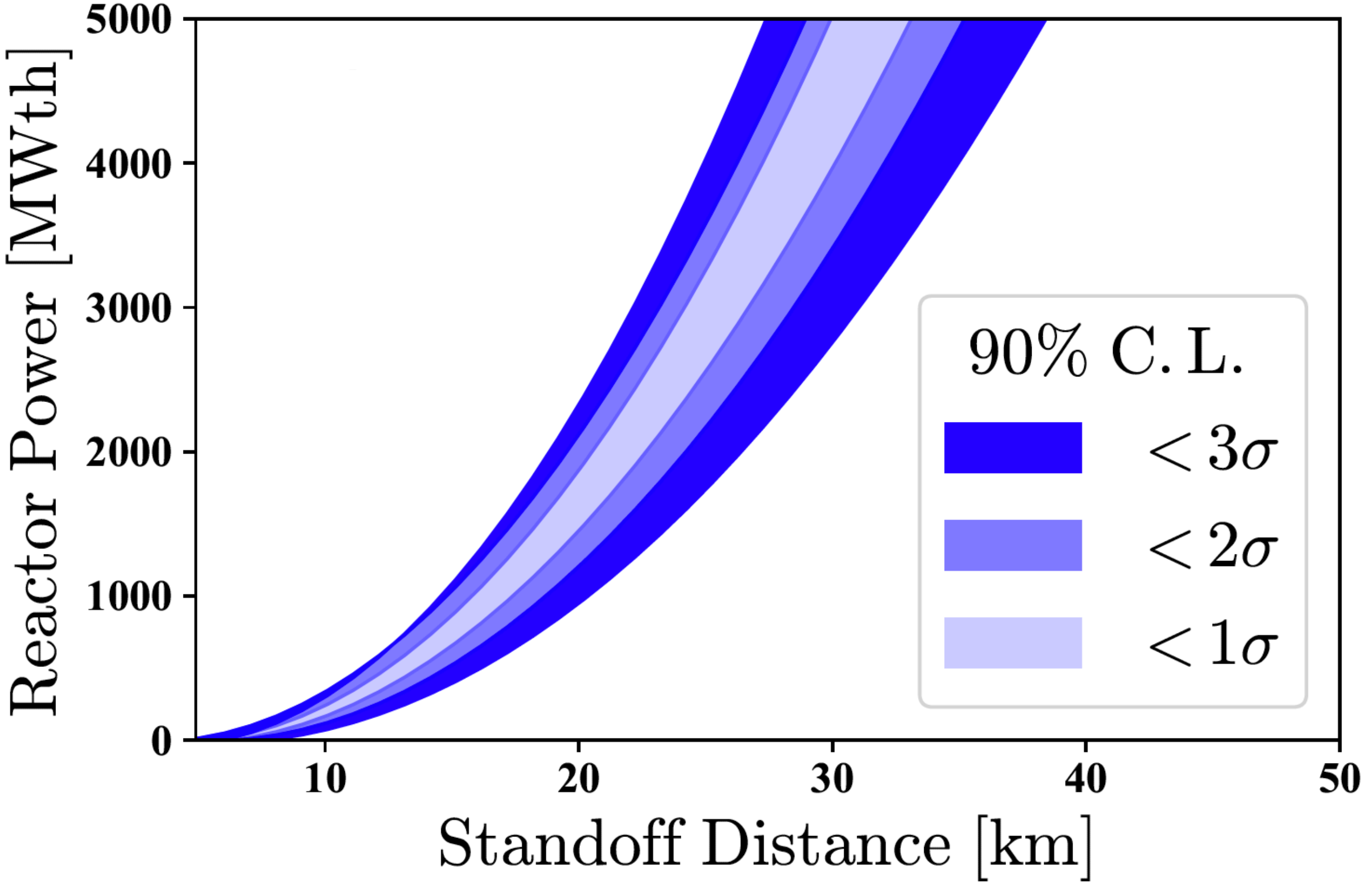
3 GWth Reactor Power 1-year Dwell Time

- When observing the 3GWth reactor at a 25km standoff (Hartlepool Case), we can not delineate between a large reactor core at a far standoff, and a low power reactor at a short standoff distance.
- The combination of low-energy resolution, relatively low statistics, and sensitivity to the higher energy region of the spectra strongly reduces the capability for reactor ranging without prior information.



3 GWth Reactor Power 1-year Dwell Time





Summary

- Antineutrino Monitoring has the capability to address many nuclear reactor safeguards problems.
- Case studies and measurements have demonstrated the capabilities of antineutrino detectors to determine the power of reactors and determine the fissile inventory of multiple reactor designs.
- The Advanced Instrumentation Testbed (AIT) with a gadolinium doped water fill has the capability to monitor antineutrinos from nuclear reactors in the far-field, expanding on the nonproliferation reach of antineutrino monitoring technology.

Join us!

- There are multiple Post-Doctoral Positions open at LLNL for nuclear and particle physcis!
- https://careers-llnl.ttcportals.com/
- https://neutrinos.llnl.gov/
- https://st.llnl.gov/opportunities/postdocs
- https://scholars-llnl.ttcportals.com/

Thank you for your attention!

Questions?

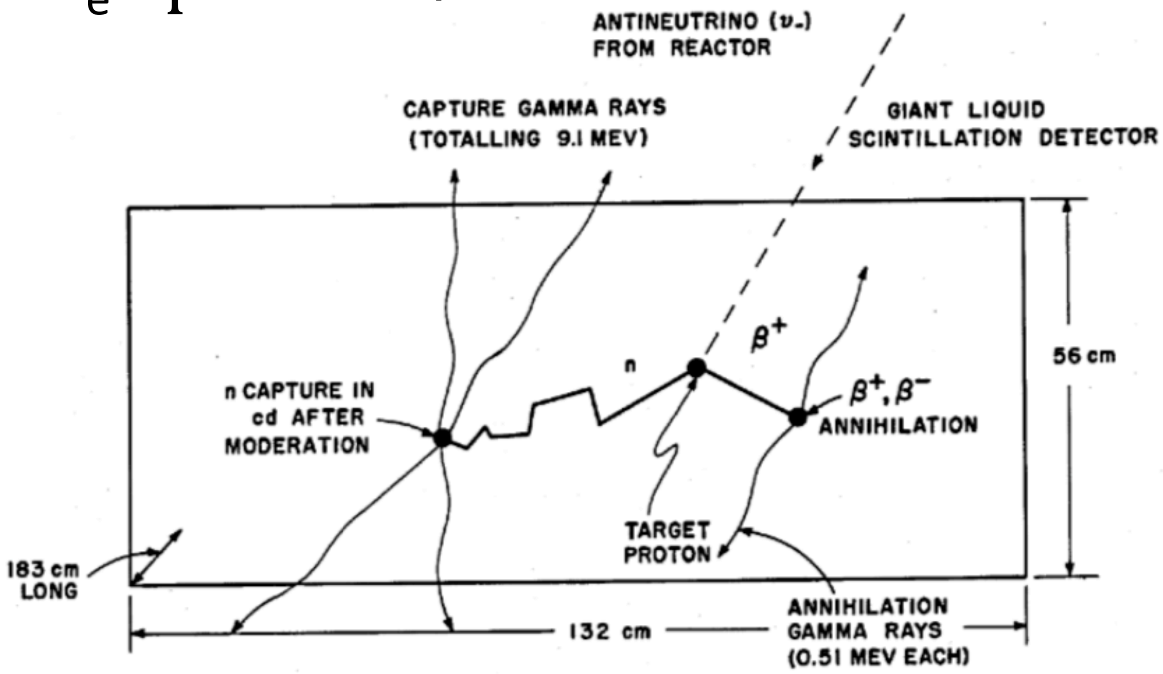
akindele1@llnl.gov

Lawrence Livermore National Laboratory

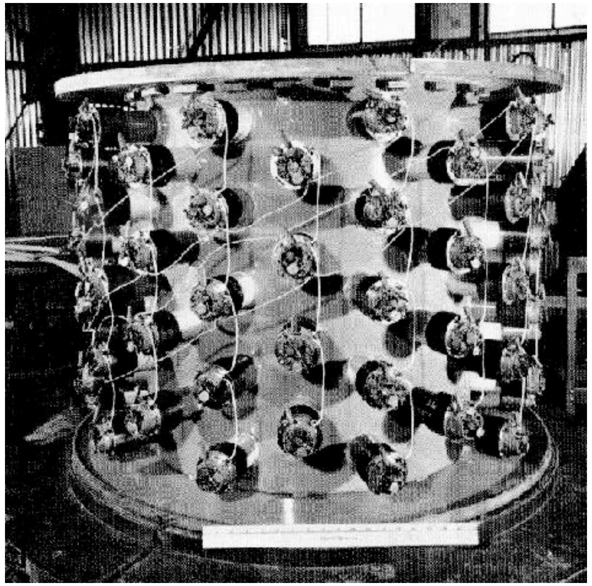
Backup Slides

The First Detection of Antineutrinos

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



- To detect Antineutrinos, Cowan & Reines used a Cd-doped scintillator outside of Savannah River
- The IBD signature from a prompt positron and delayed neutron was read out through oscilloscopes.



Reines and Cowan, 1956

Reines was awarded the Nobel Prize in 1995.

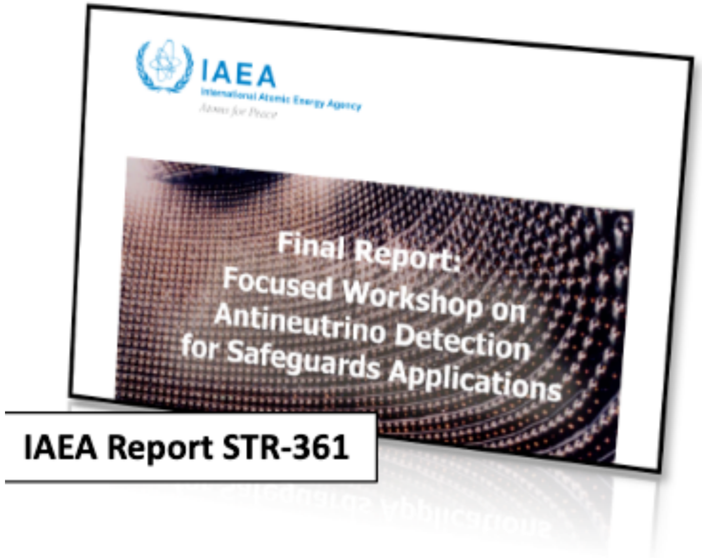
Required Considerations by the IAEA

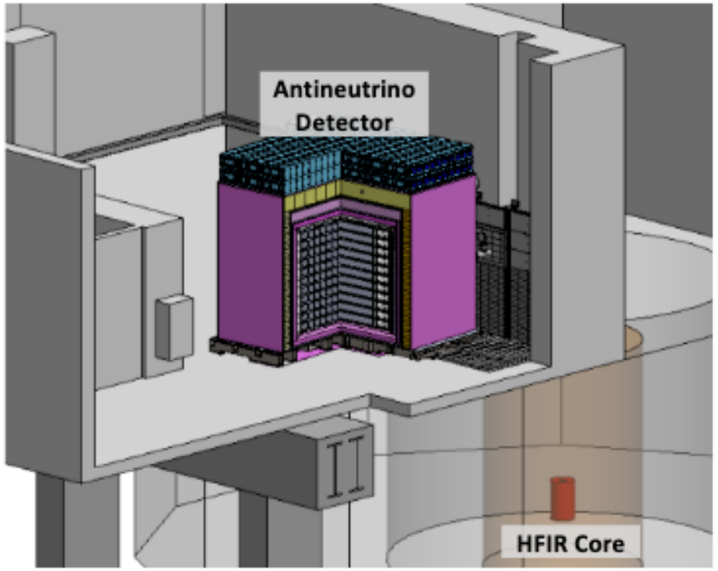
Aboveground operation and **packaging/mobility** are among the utility considerations raised by potential end-users.

IAEA Report STR-361

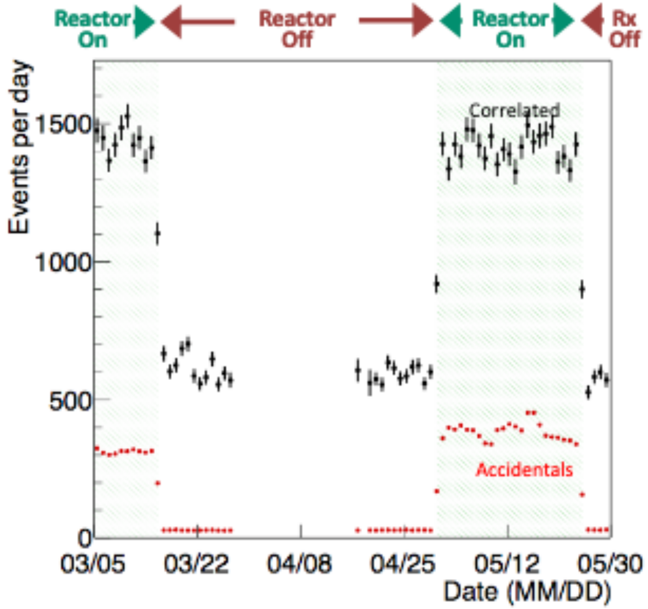
Above Ground Reactor Antineutrino Monitoring

Aboveground operation and packaging/mobility are among the utility considerations raised by potential end-users





*Schematic diagram of **PROSPECT** experiment at High Flux Isotope Reactor (HFIR), **with almost no overburden***

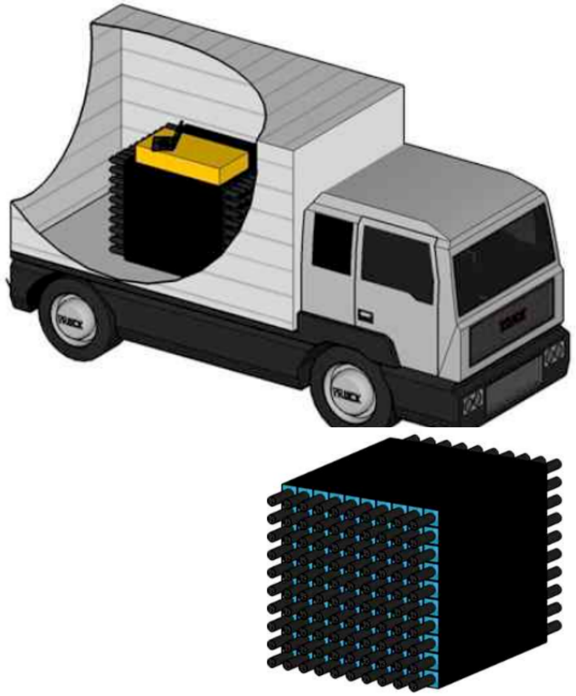


***PROSPECT** measurement of the HFIR antineutrino flux with >1:1 S:B on the earth's surface*

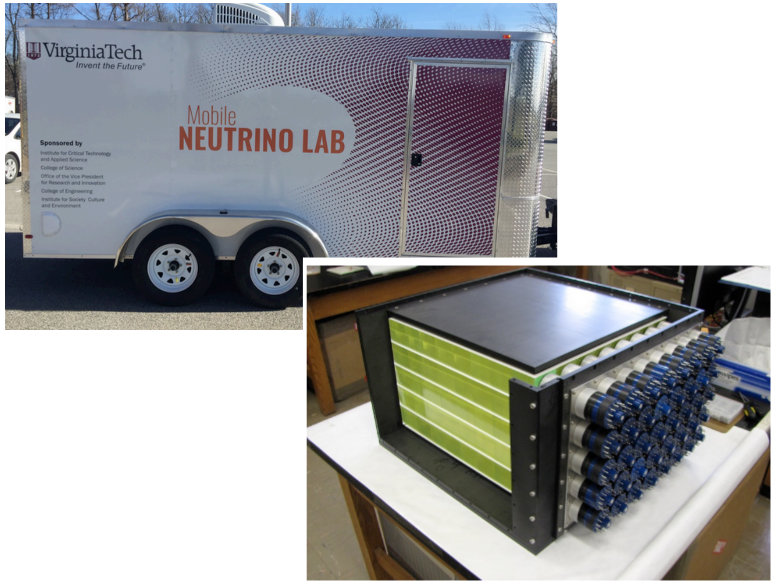
Above Ground Reactor Antineutrino Monitoring

Aboveground operation and **packaging/mobility** are among the utility considerations raised by potential end-users

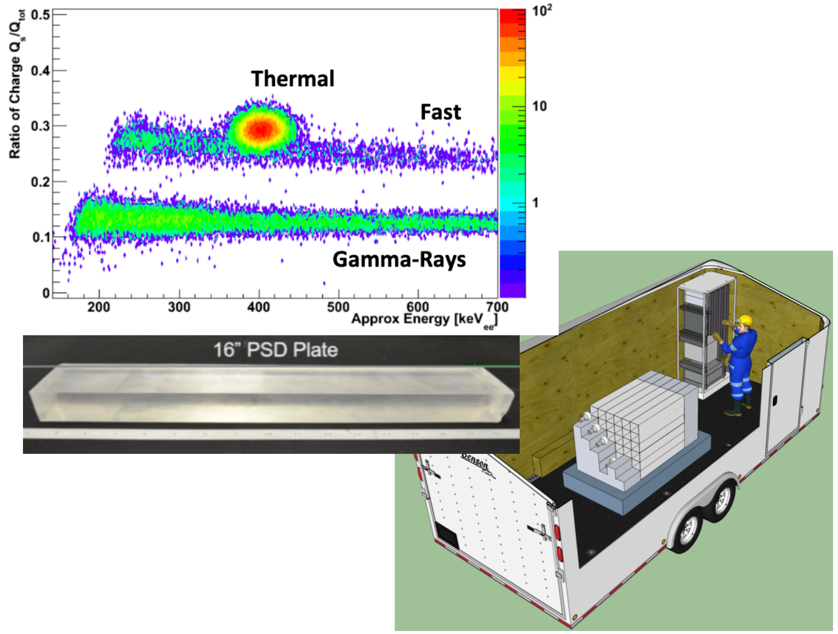
PANDA



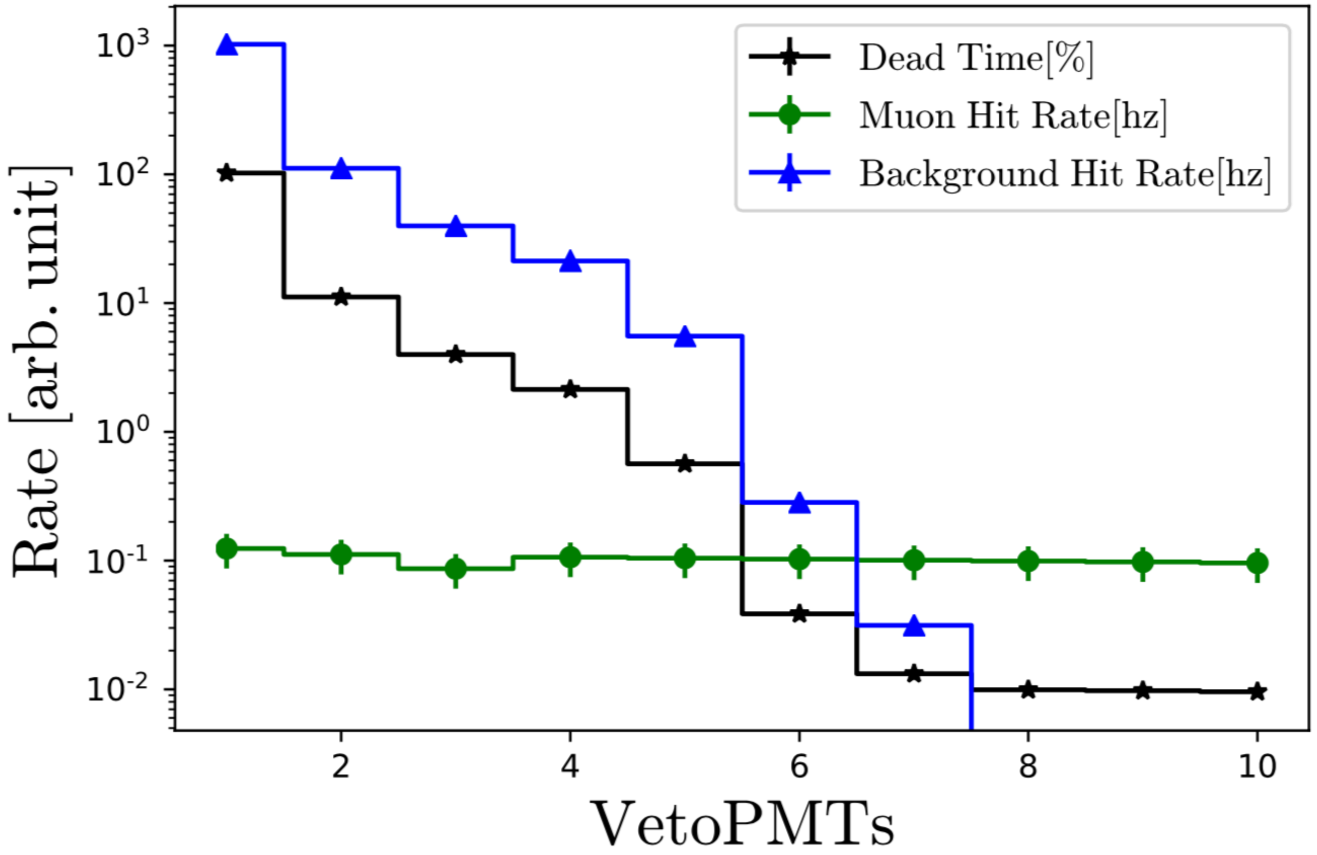
MiniCHANDLER



LLNL R&D

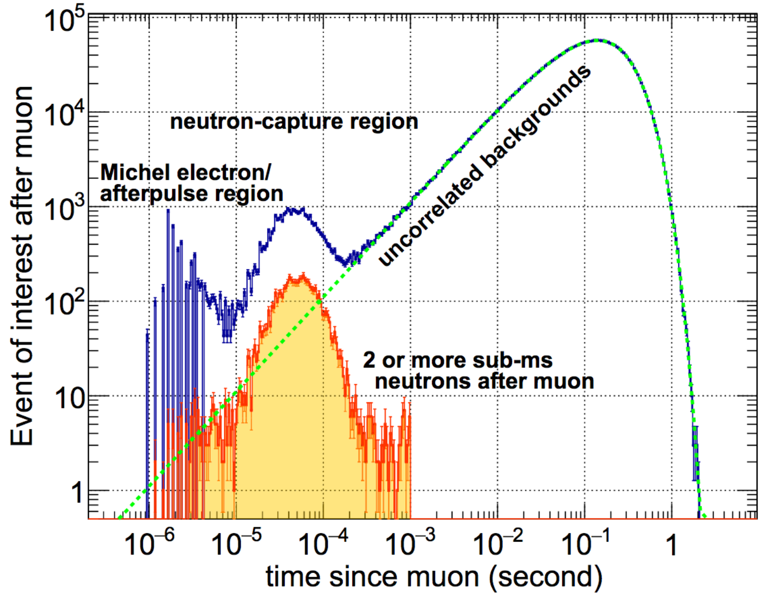


Muogenic Response: Veto Response



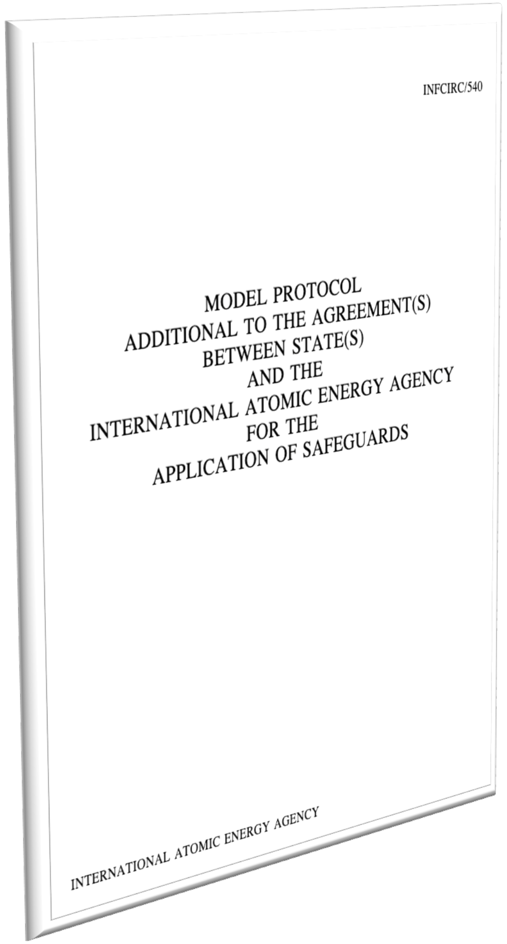
WATCHBOY Result:

S. Dazeley et al. NIMA 821 (2016) 151–159



- Based on the WATCHBOY results, a 1 ms deadtime is imposed on the detector following a muon event (4 Veto PMT hits). The deadtime for the detector is expected to be **2.13%** while the efficiency for detecting muon events is **91.4%**.
- The single largest contributor to veto triggers is the radiation signature from the structural and surrounding detector material. Additionally, the most pernicious muons are the sub 5 GeV muons that capture in the detector.

Additional Protocol: Motivation for Far-Field Reactor Monitoring



Existing treaty language emphasizes minimizing intrusiveness and burden to the state being monitored:

- “avoid hampering economic and technological development”
- “avoid undue interference”
- “take every precaution to protect commercial and industrial secrets and other confidential information coming to its knowledge and implementation of the Agreement”

(C. Jabarri, Center for Nonproliferation Studies, Monterey, CA)