ANNIE:

The **A**ccelerator **N**eutrino **N**eutron **I**nteraction **E**xperiment

Jonathan Eisch
Iowa State University

DPF 2019
July 29, 2019

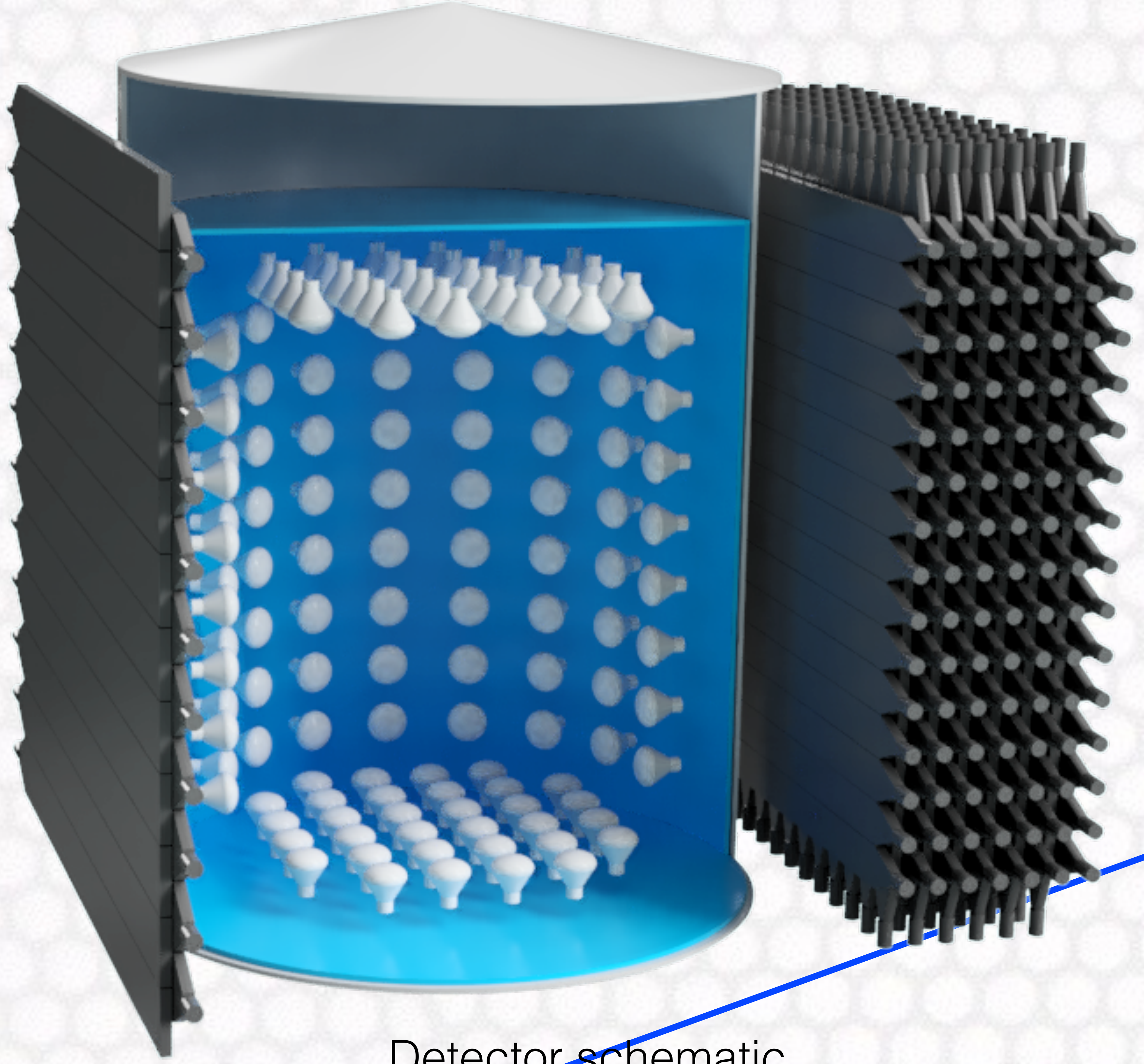
The ANNIE Collaboration

- 13 Institutions
- 3 Countries
  - USA
  - Germany
  - UK
- 30+ Collaborators

- Brookhaven National Laboratory
- Fermi National Accelerator Laboratory
- Iowa State University
- Johannes Gutenberg University Mainz
- Lawrence Livermore National Laboratory
- The Ohio State University
- Queen Mary University
- University of California, Davis
- University of California, Irvine
- University of Chicago
- University of Edinburgh
- University of Hamburg
- University of Sheffield

First LAPPD Delivery, January 2017

What is ANNIE?

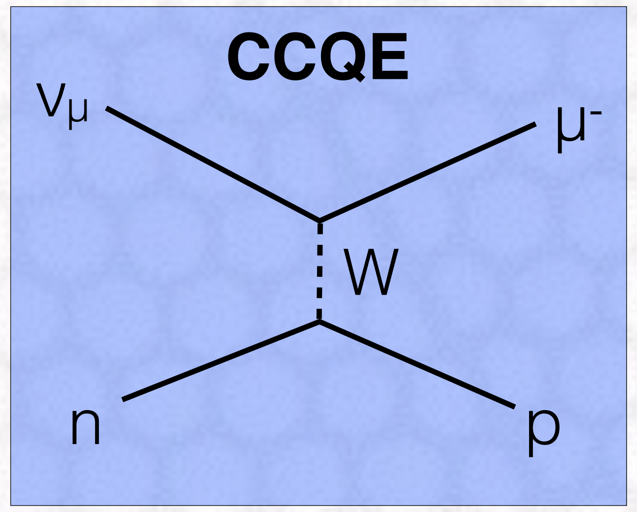


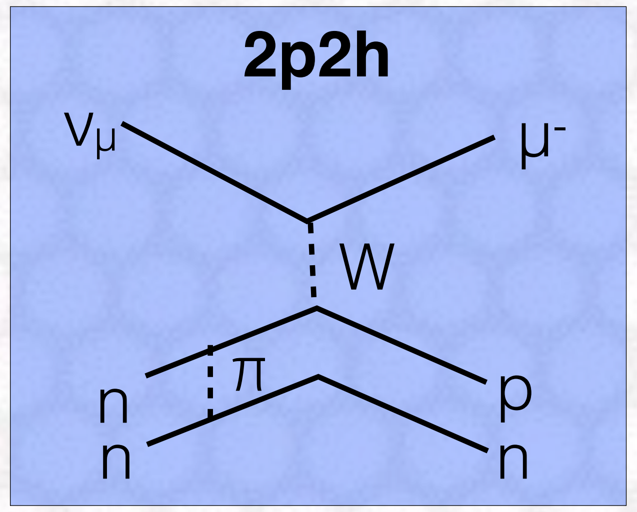
Detector schematic

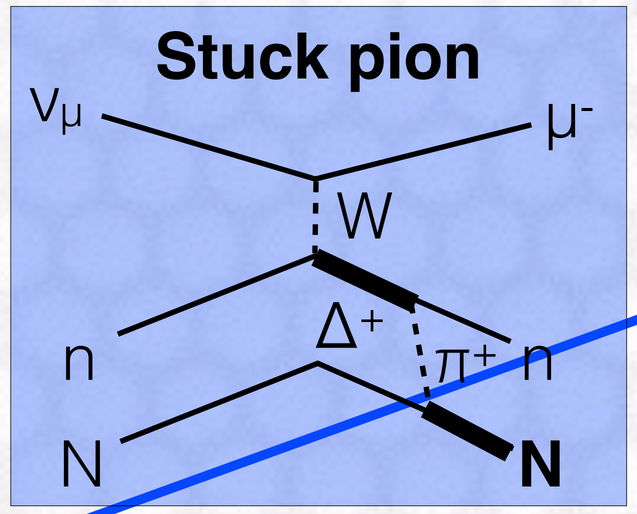
- ANNIE is a water-Cherenkov neutrino experiment on the Booster Neutrino Beam at Fermilab.
- ANNIE has two main goals:
  - Measure the abundance of final state neutrons from neutrino interactions in water as a function of lepton kinematics.
  - Demonstrate new detection technologies such as:
    - LAPPDs with 10GHz digitization.
    - Neutron tagging in Gadolinium-loaded water.
- ANNIE will run in two phases:
  - Phase I (Complete): Partial detector engineering demonstration and background measurement.
  - Phase II (Fall 2019): Physics measurement with advanced detection technologies.

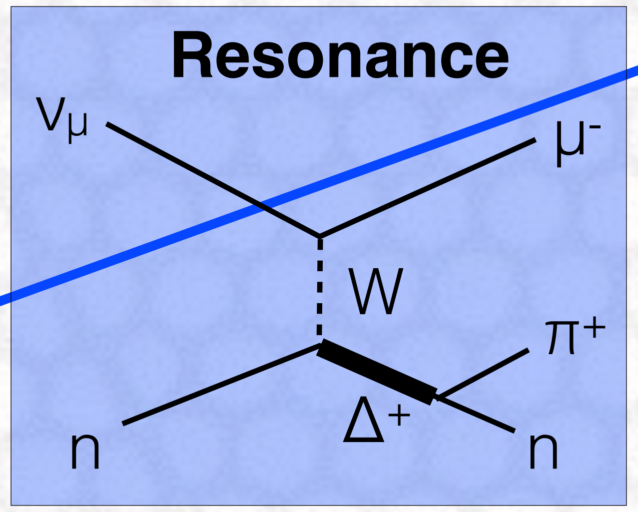
ANNIE Neutrino-Nucleus Interactions

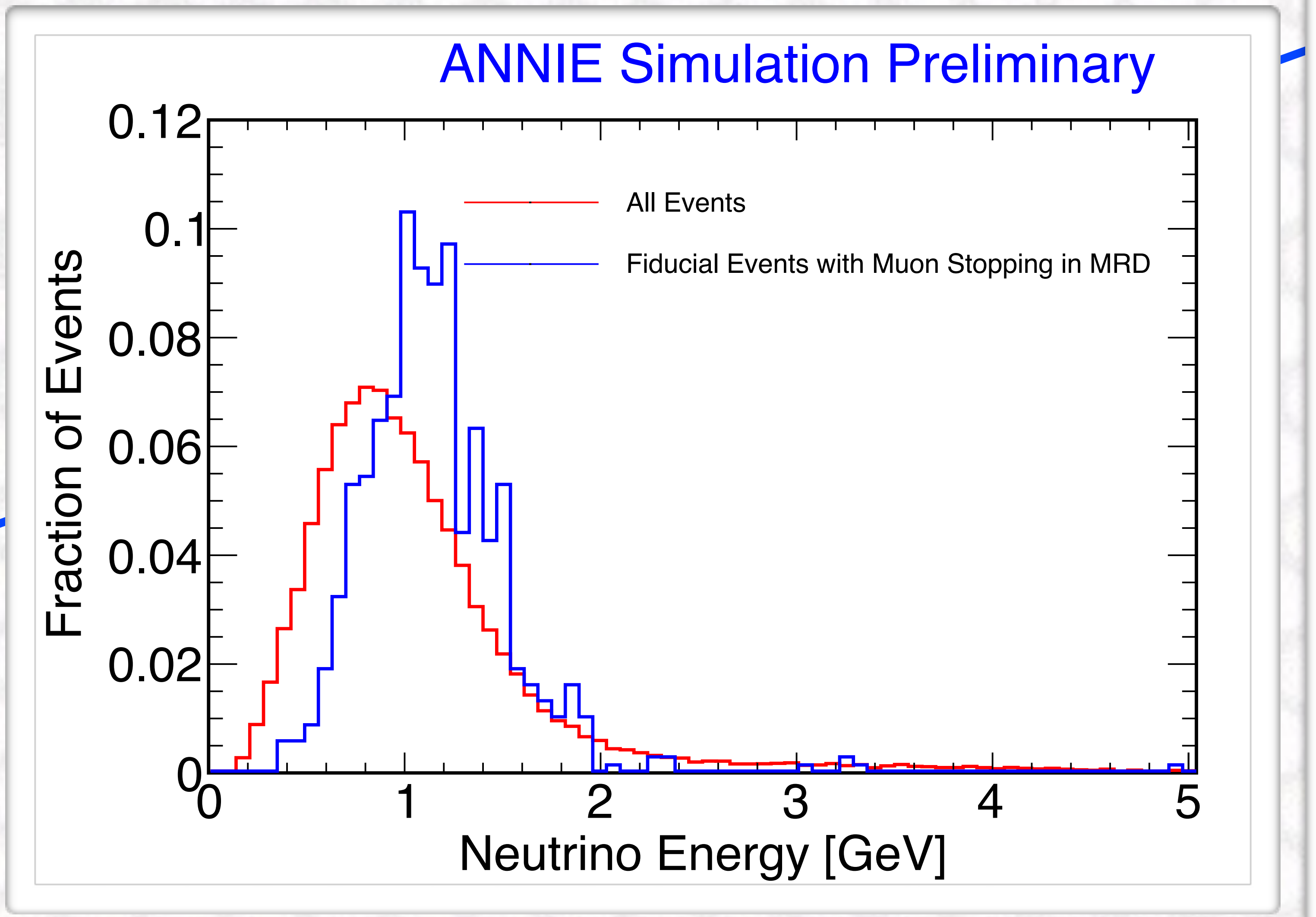
- ANNIE will collect a high-statistics sample of GeV-scale charged-current neutrino interactions on water from the well-studied Booster Neutrino Beam (BNB).
- High-efficiency neutron detection will provide a new handle for more detailed separation of final-states.
- This is an interesting energy range for neutrino-nucleus interactions.

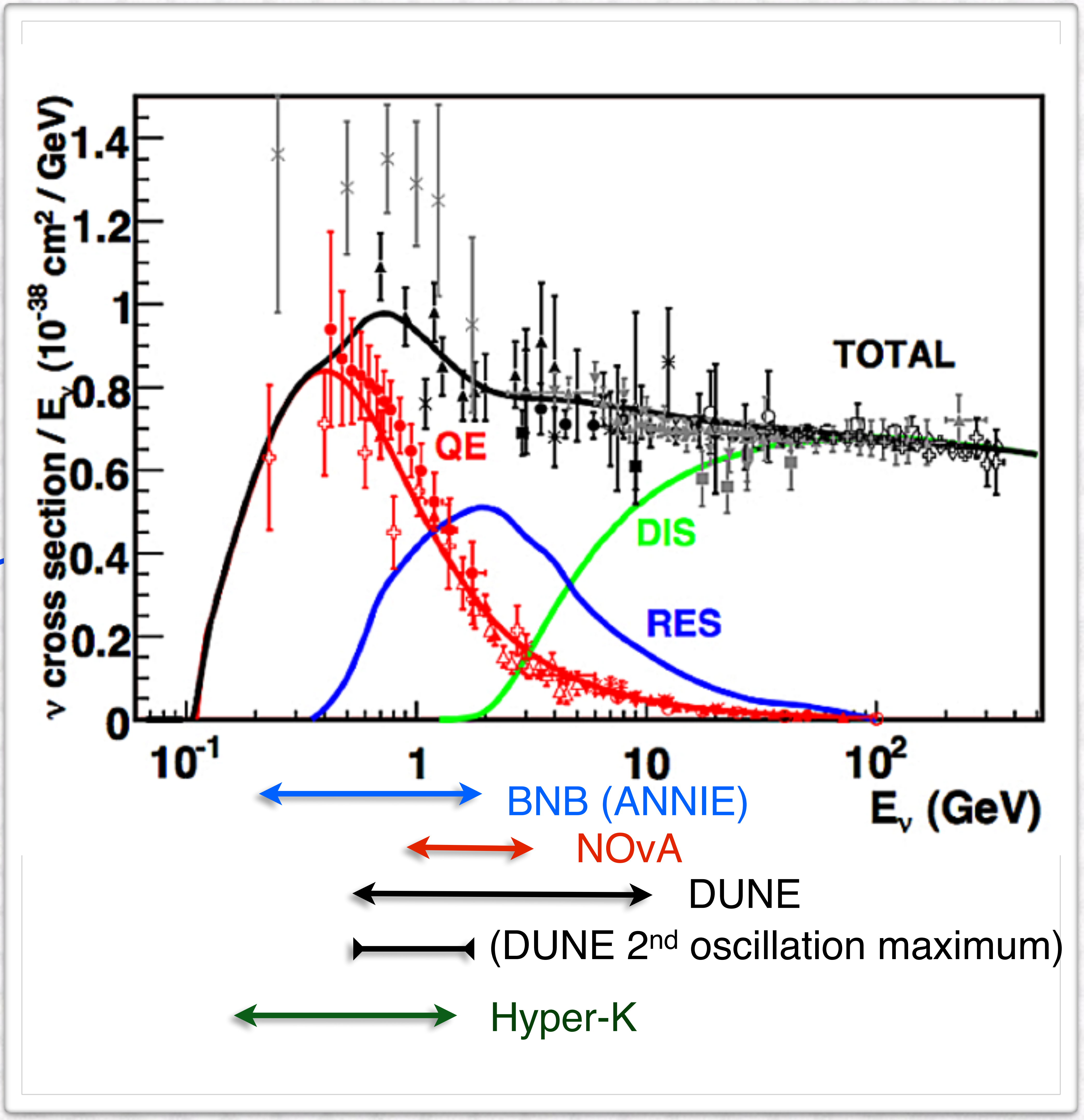






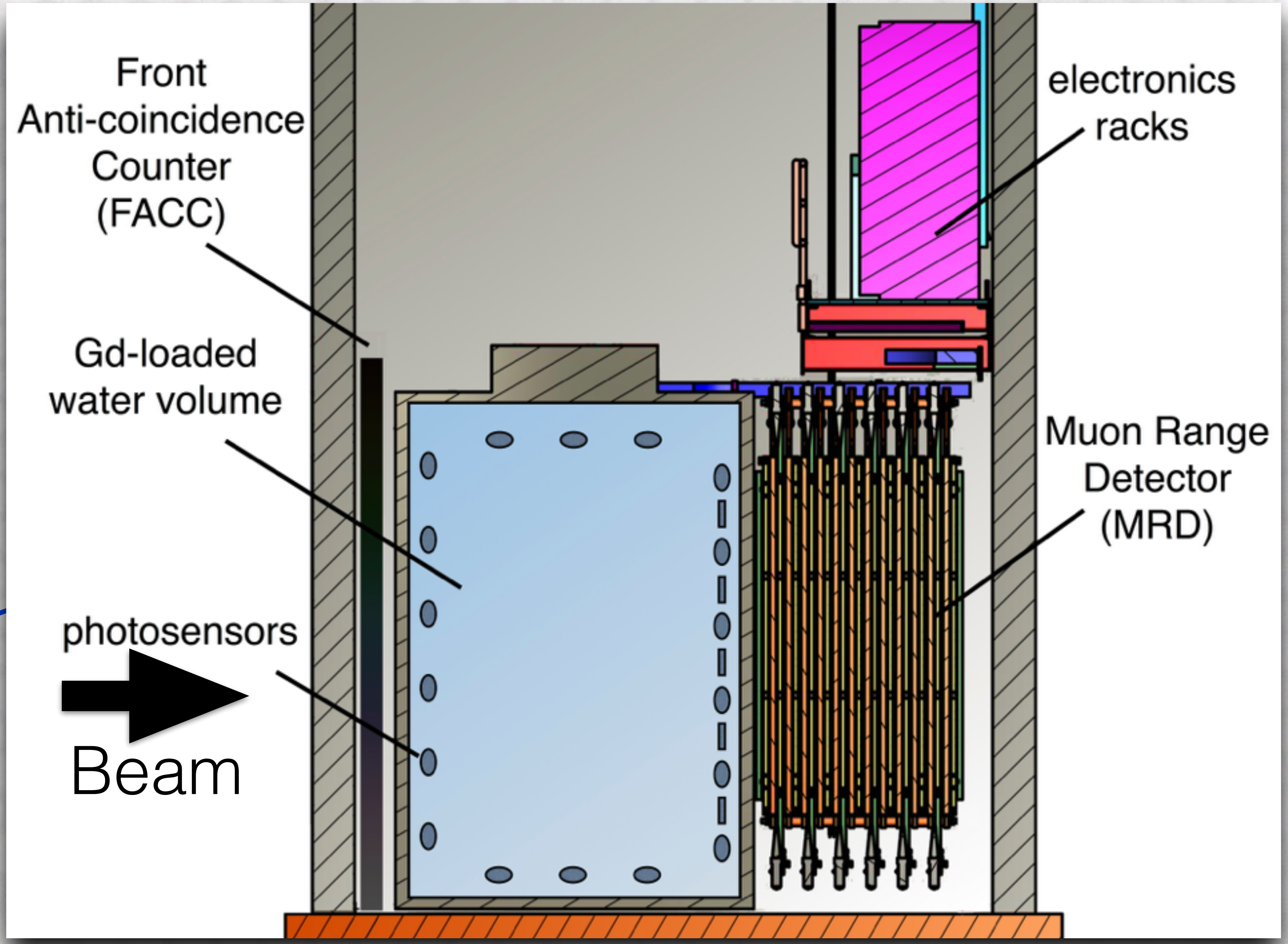






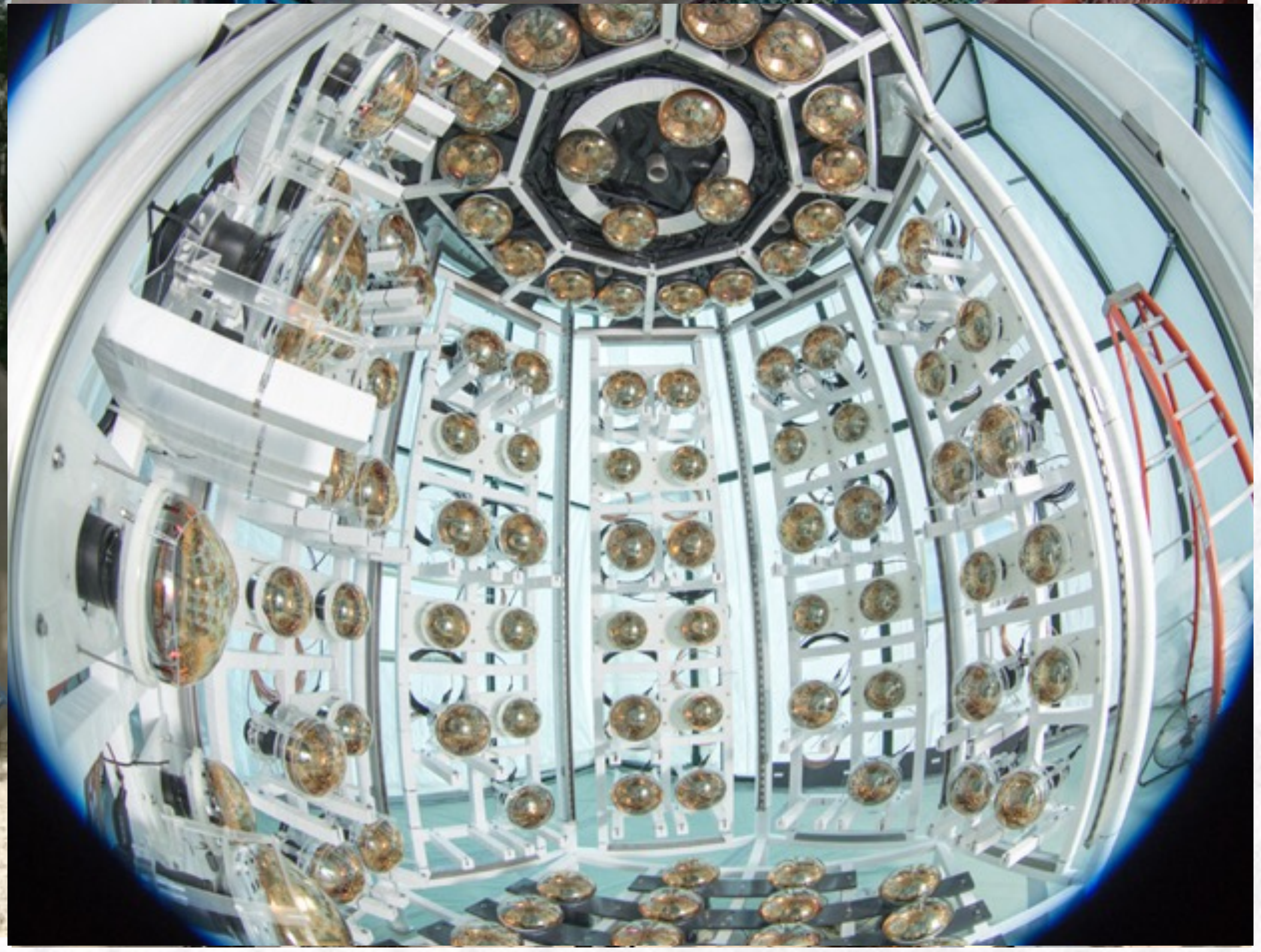
The ANNIE Detector

- 26 ton water-Cherenkov detector.
- 3 m diameter, 4 m tall steel tank with a plastic liner.
- Filled with ultra-pure water loaded with Gadolinium sulfate.
- Detection volume instrumented with conventional PMTs with 500 MHz full waveform digitization and newly developed high-speed photo-detectors.
- Also includes an upstream muon veto detector and the SciBooNE Muon Range Detector (muon tracker) installed downstream.



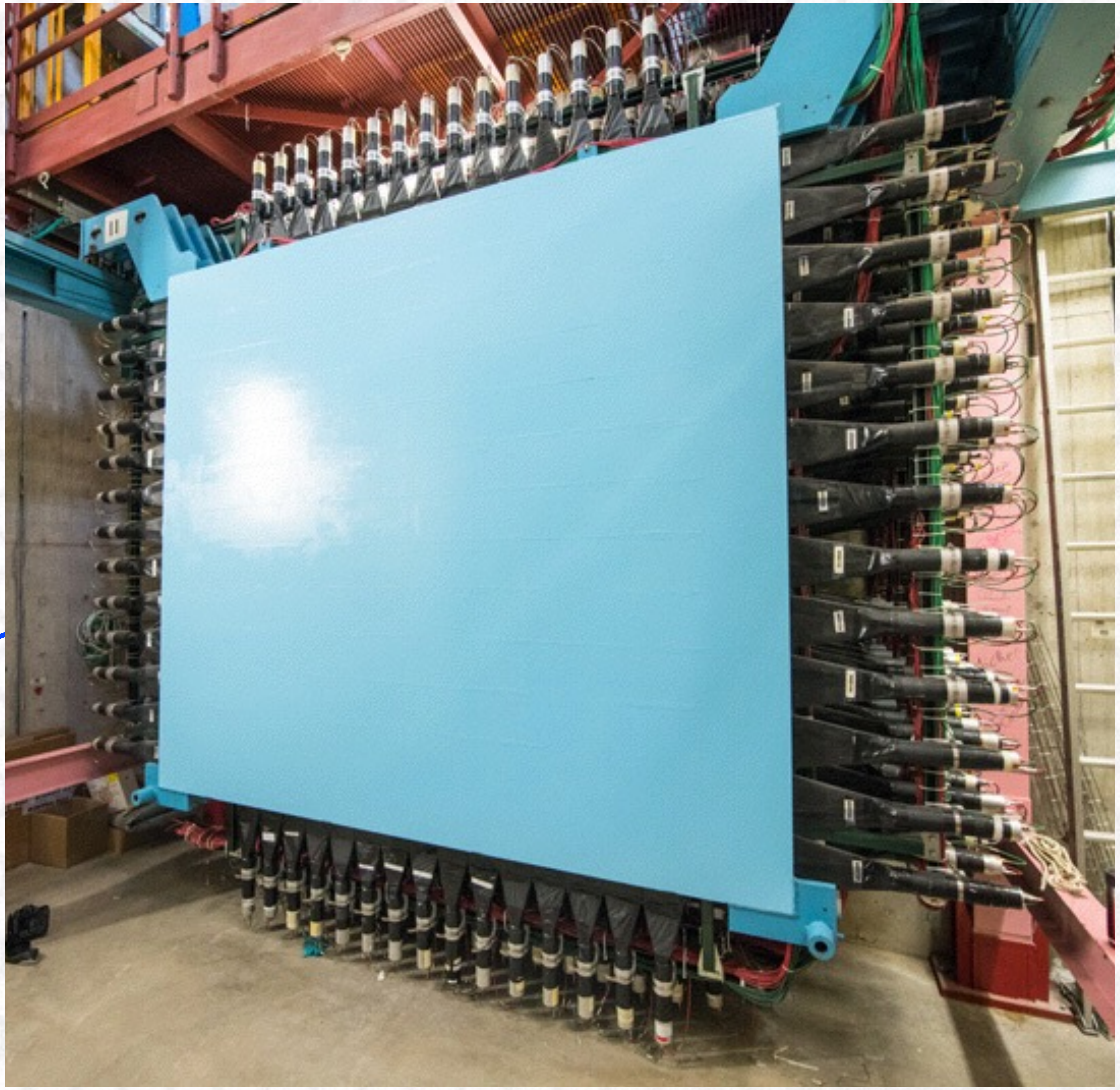
The ANNIE Water Volume

- **3 m diameter, 4 m tall** steel tank with a plastic liner.
- **26 tons** of ultra-purified water loaded with **gadolinium sulfate**.
- The water moderates and captures external neutrons.
- PMTs and LAPPDs attached to a stainless steel inner structure.
- **Full-waveform digitization** with custom 500 MHz ADCs.

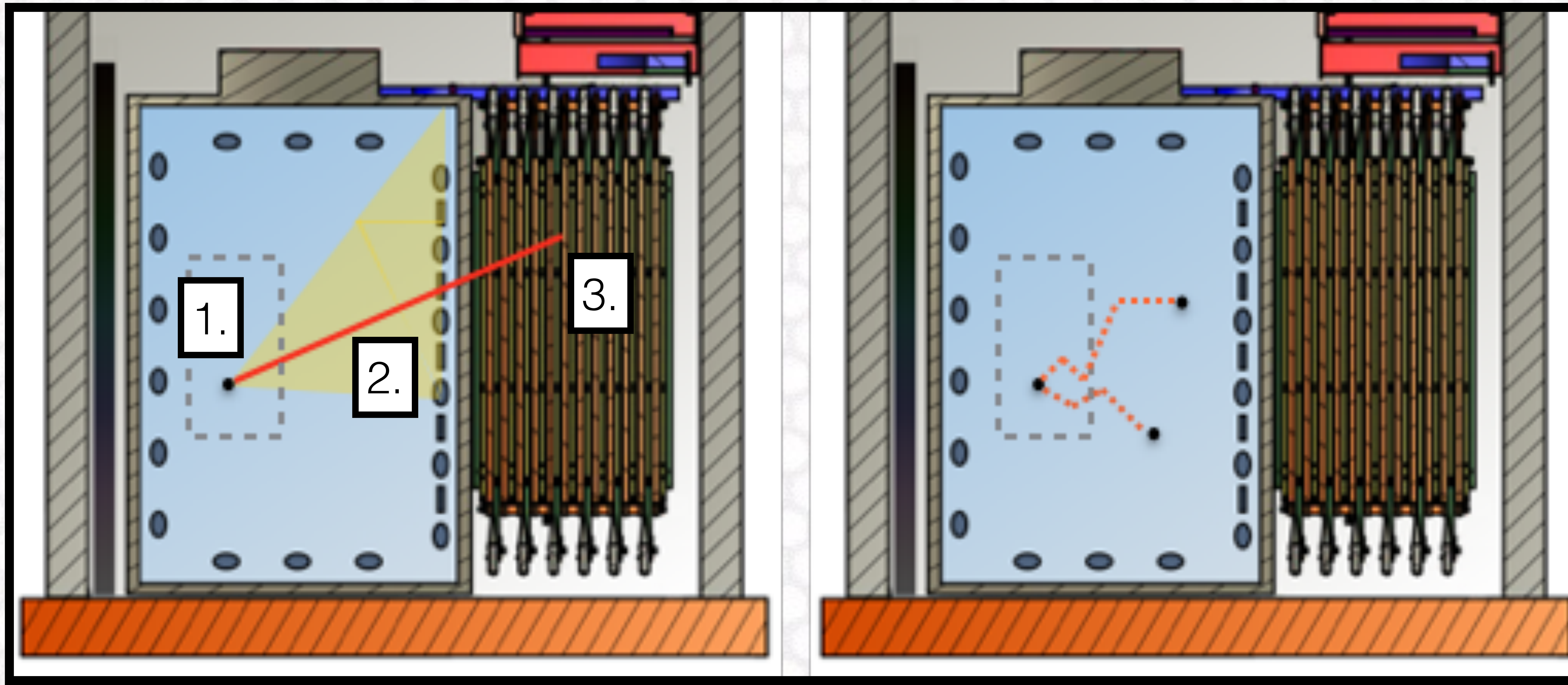


Muon Range Detector

- Built by by the SciBooNE Collaboration.
- **Segmented tracker** with 11 layers of scintillator read out by 310 PMTs (6 horizontal and 5 vertical planes).
- **Eleven** 2” thick **9’x10’ sheets of steel**.
- Will range out **muons up to 0.9 GeV**.
- PMT signals are discriminated and recorded by a TDC system.



ANNIE Detection Principle

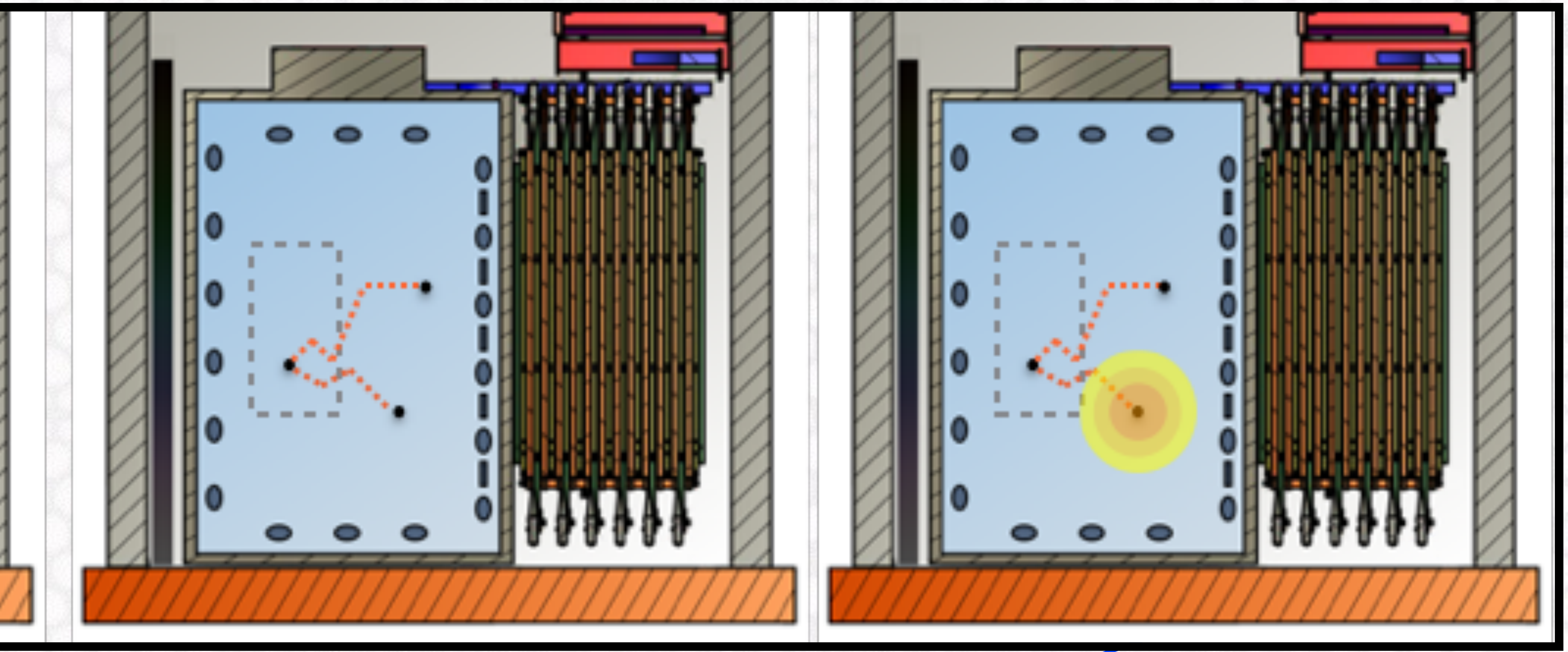


1. Charged current muon-neutrino interaction within the fiducial volume.
2. Cherenkov light from the muon is detected by photodetectors on the walls of the water volume.
3. Muon is tracked and ranges out in the Muon Range Detector (MRD).

ANNIE Detection Principle

4. Final-state neutrons scatter and thermalize within the water volume (~3 us).

ANNIE Detection Principle



5. Tens of microseconds later neutrons capture on the dissolved Gadolinium in the water, producing 8 MeV gamma cascades.
6. Photons from the gamma cascade are detected by the water-volume photodetectors.

ANNIE Operation Timeline

- **Phase I** - Engineering run and Background Measurement: **(Complete)** (Spring ’16-Summer ’17)
  - Operated with conventional PMTs and pure water with a small movable vessel filled with Gd-loaded liquid scintillator.
  - Measured neutron backgrounds as a function of position inside the tank.
  - LAPPD Testing, characterization and integration R&D.

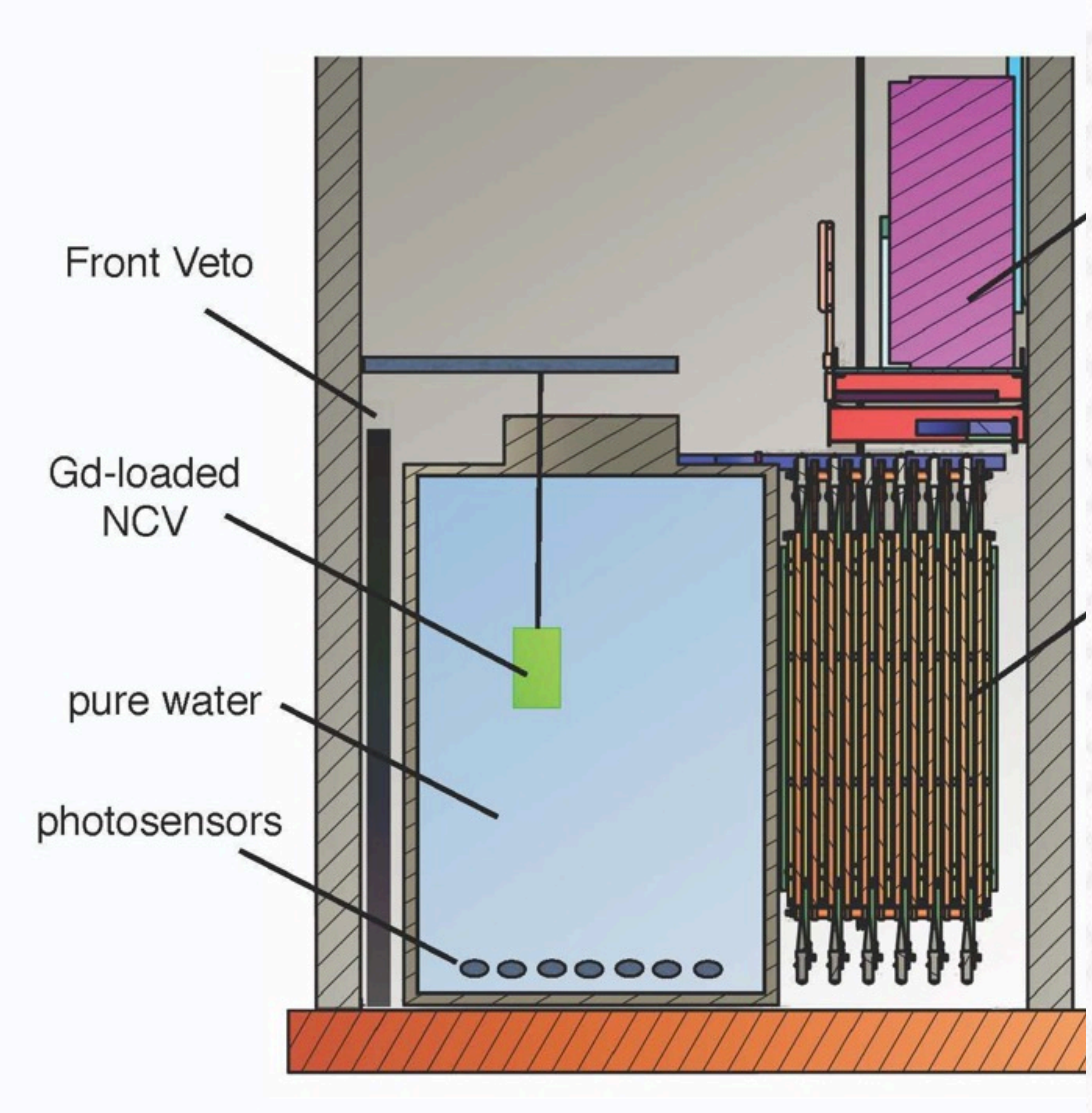
- **Phase II** - **Physics Run: (Currently commissioning)**
  - Physics data will start with the return of Beam operations in the fall.
  - Measure neutron multiplicity as a function of lepton kinematics.
  - Gd-loaded water.
  - Addition of LAPPDs and additional conventional PMTs.
- Possible **Phase III:**
  - Operate with water-based liquid scintillator sub-volume.

Phase I

Measuring the neutron background

Phase I detector configuration

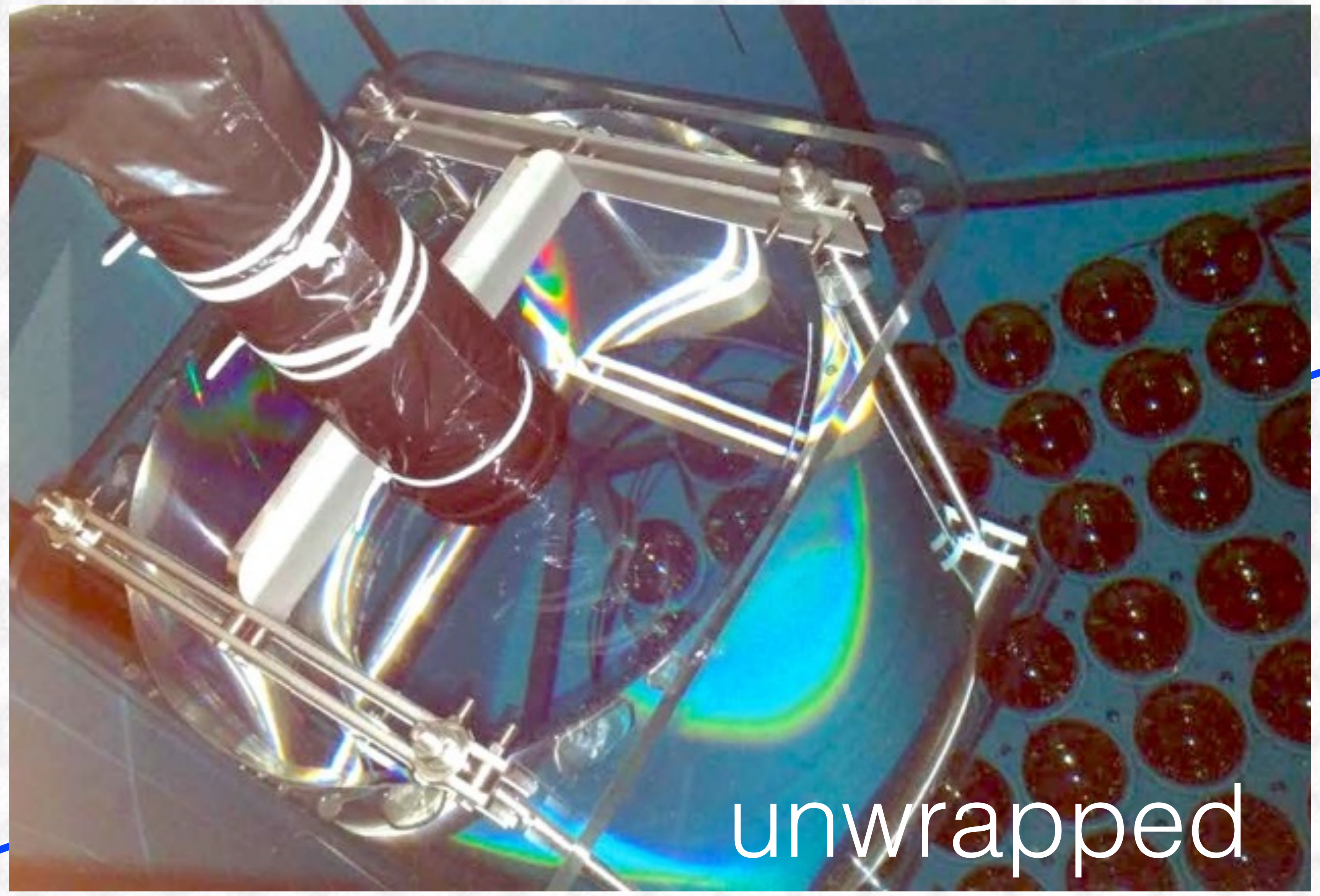
- **60 PMTs** installed on the bottom layer, reflective white tank liner installed.
  - PMTs used to detect cosmic-ray and beam-induced muons.
- **Neutron Capture Volume (NCV)**
  - A movable acrylic vessel filled with gadolinium-loaded liquid scintillator used to measure neutron flux at different positions within the tank.
    1. Neutrons capture on gadolinium and produce 8 MeV in gamma rays.
    2. The gamma rays scatter electrons in the liquid scintillator producing light.
    3. PMTs on the NCV detect this light.

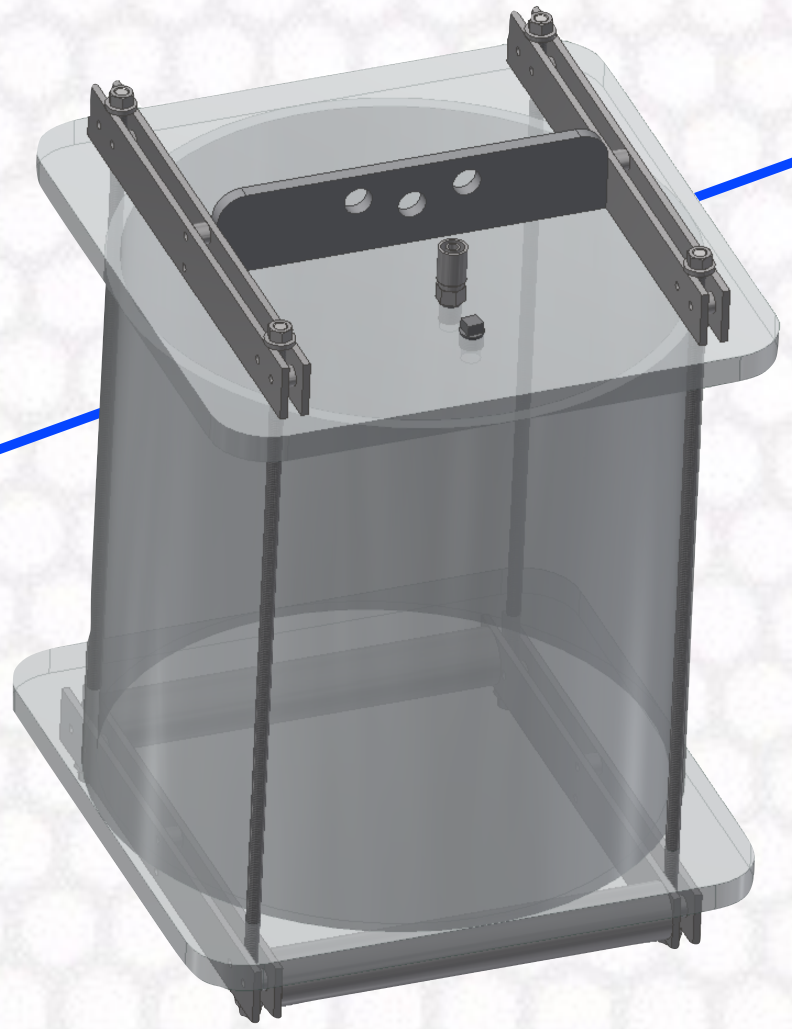


Phase I configuration

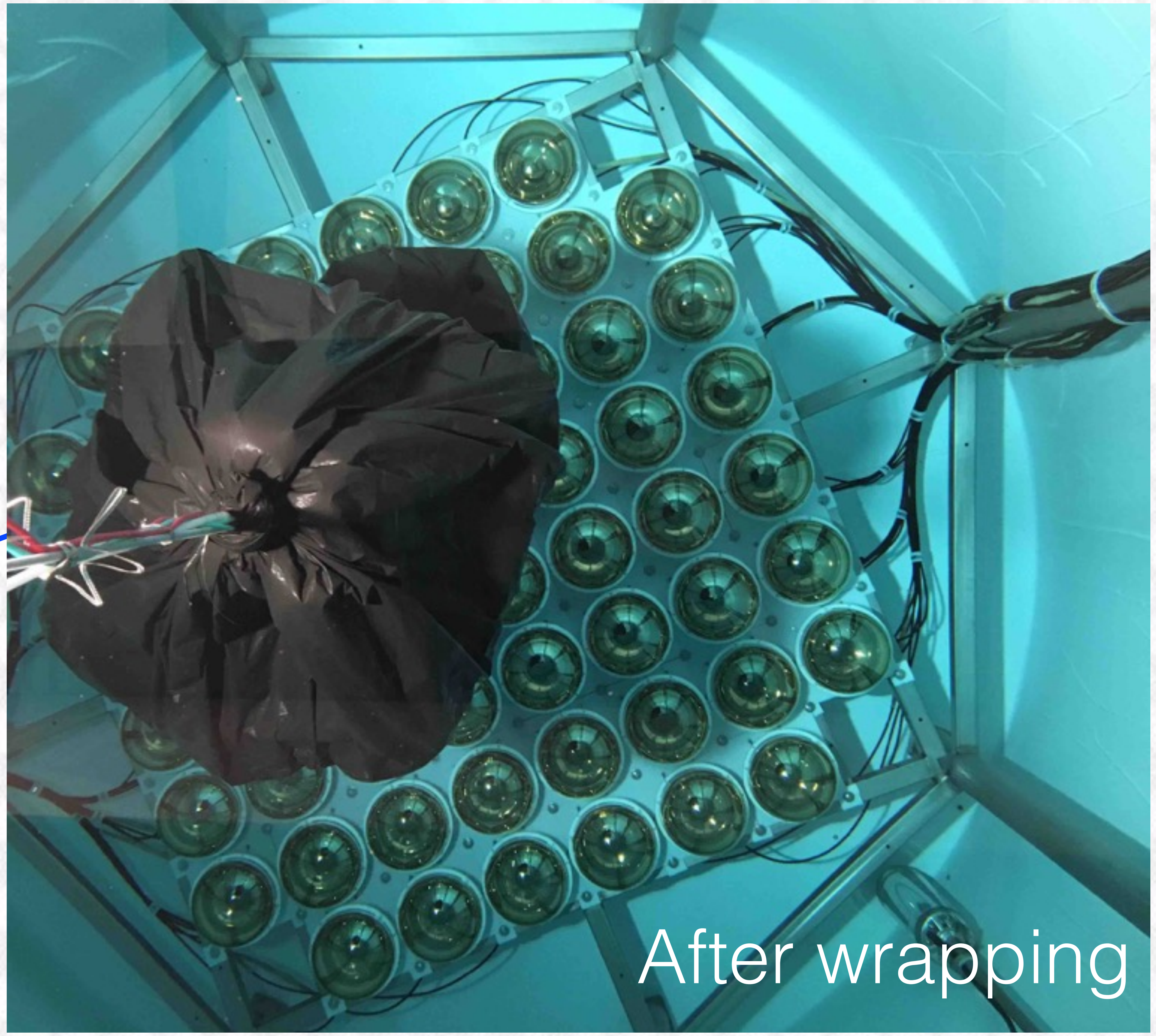
The NCV

- Acrylic vessel filled with gadolinium loaded liquid scintillator.
- Two PMTs installed at the top of the vessel.
- Optically isolated from the water volume.





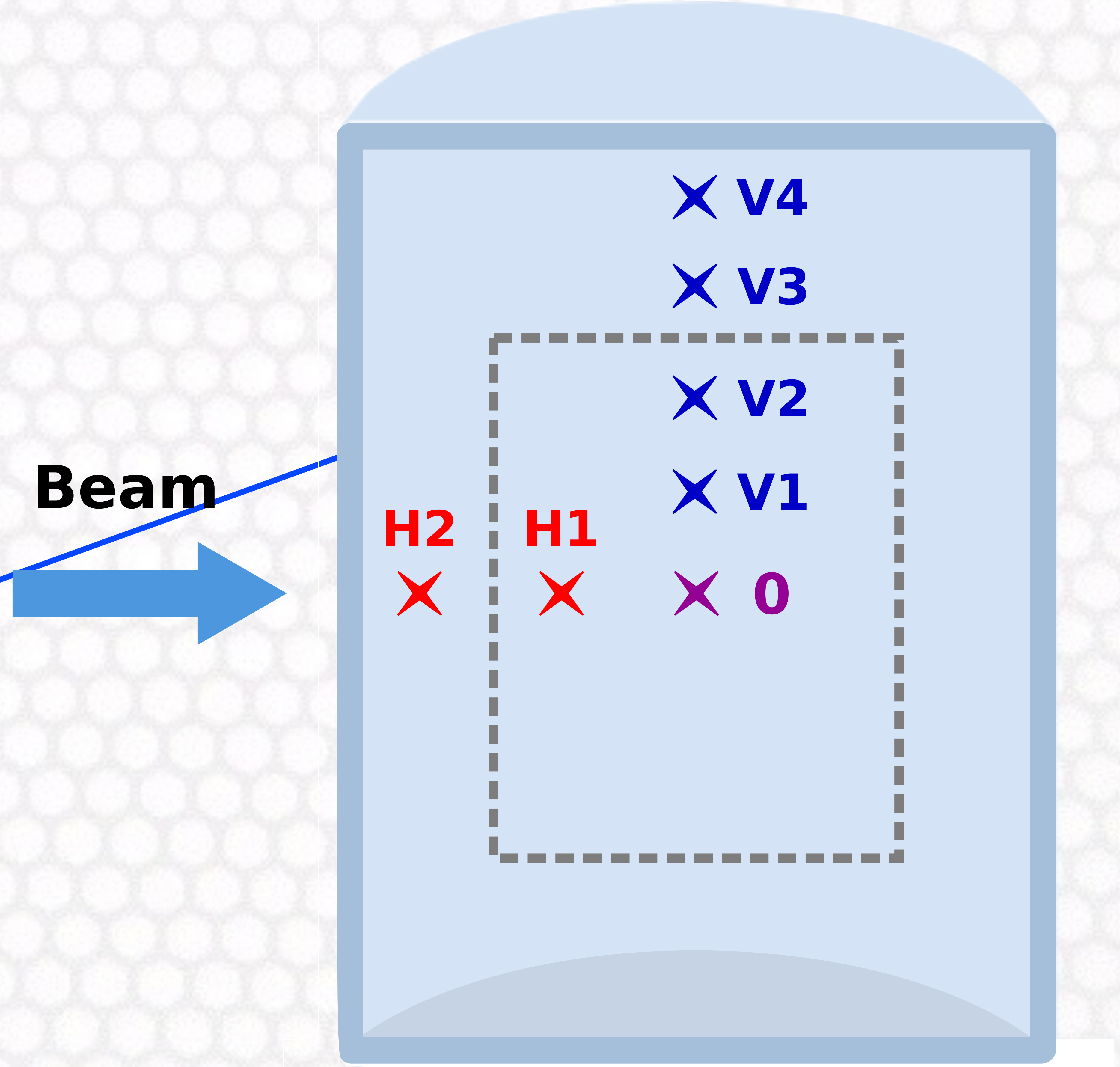
design



NCV Position Scan

- The NCV was moved vertically and horizontally to several different positions to measure the neutron flux at each location.

- The measured flux is a combination of beam-induced neutrons from above and from neutrino interactions in and around the detector.



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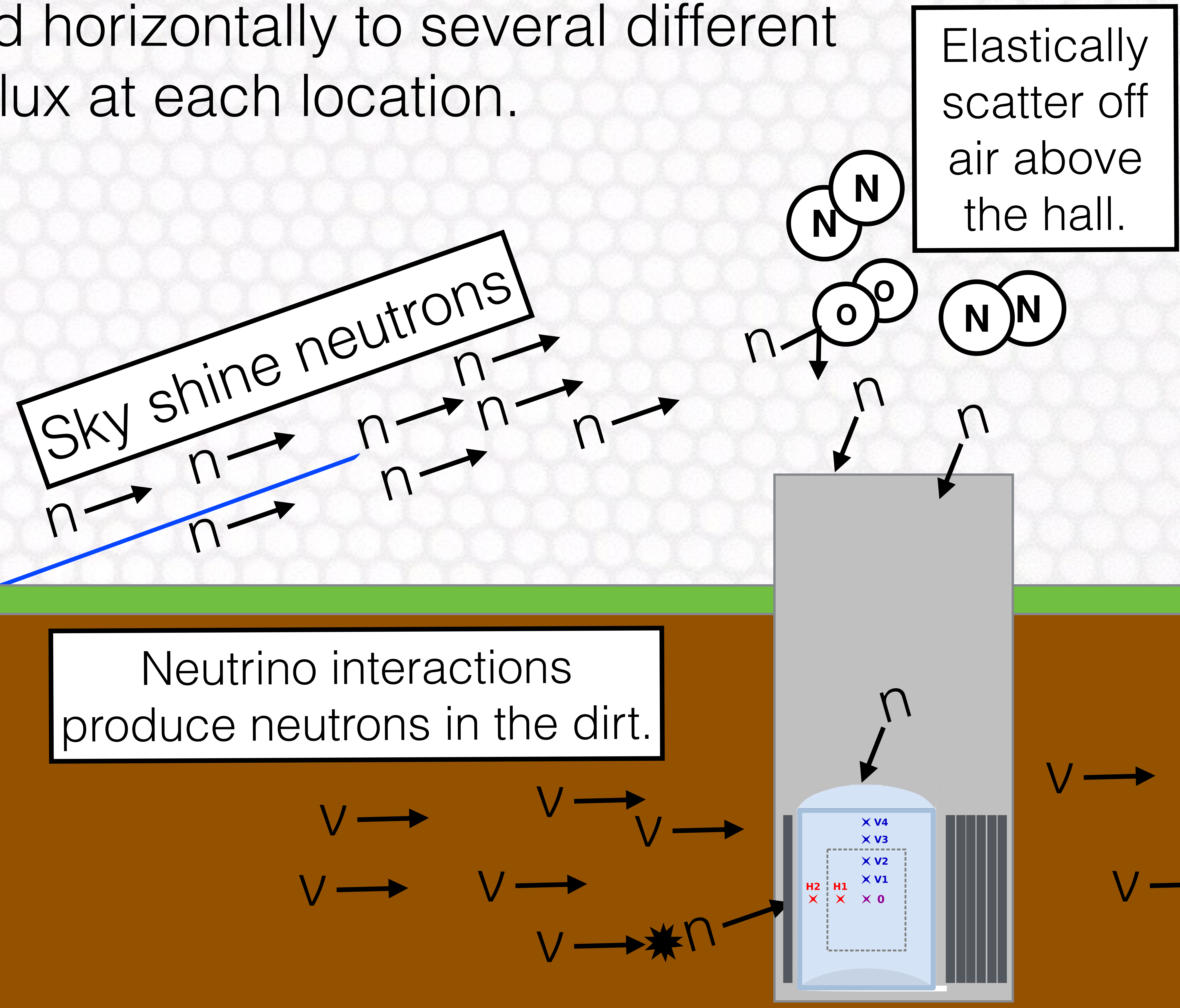
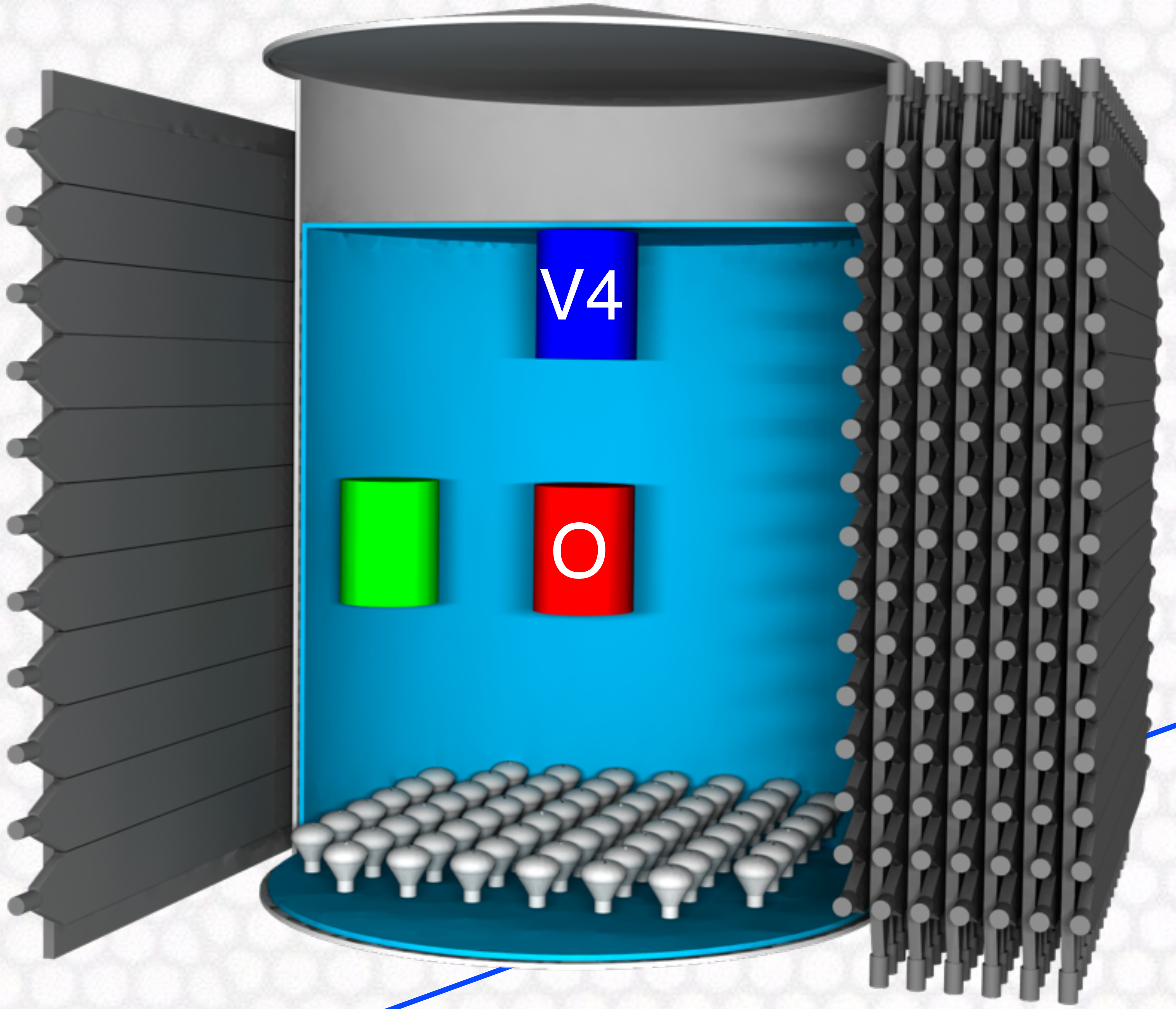
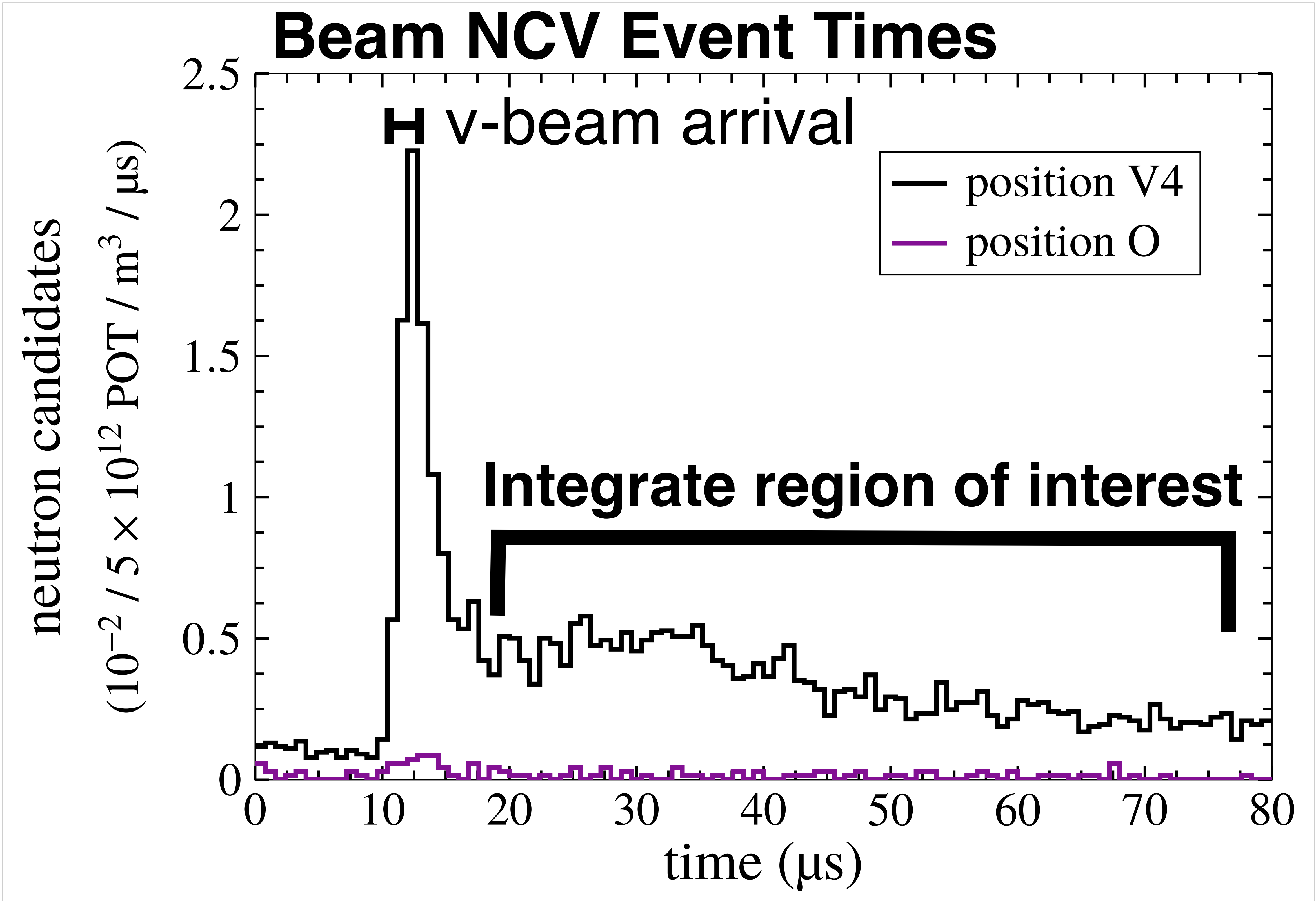


Booster Neutrino Beam

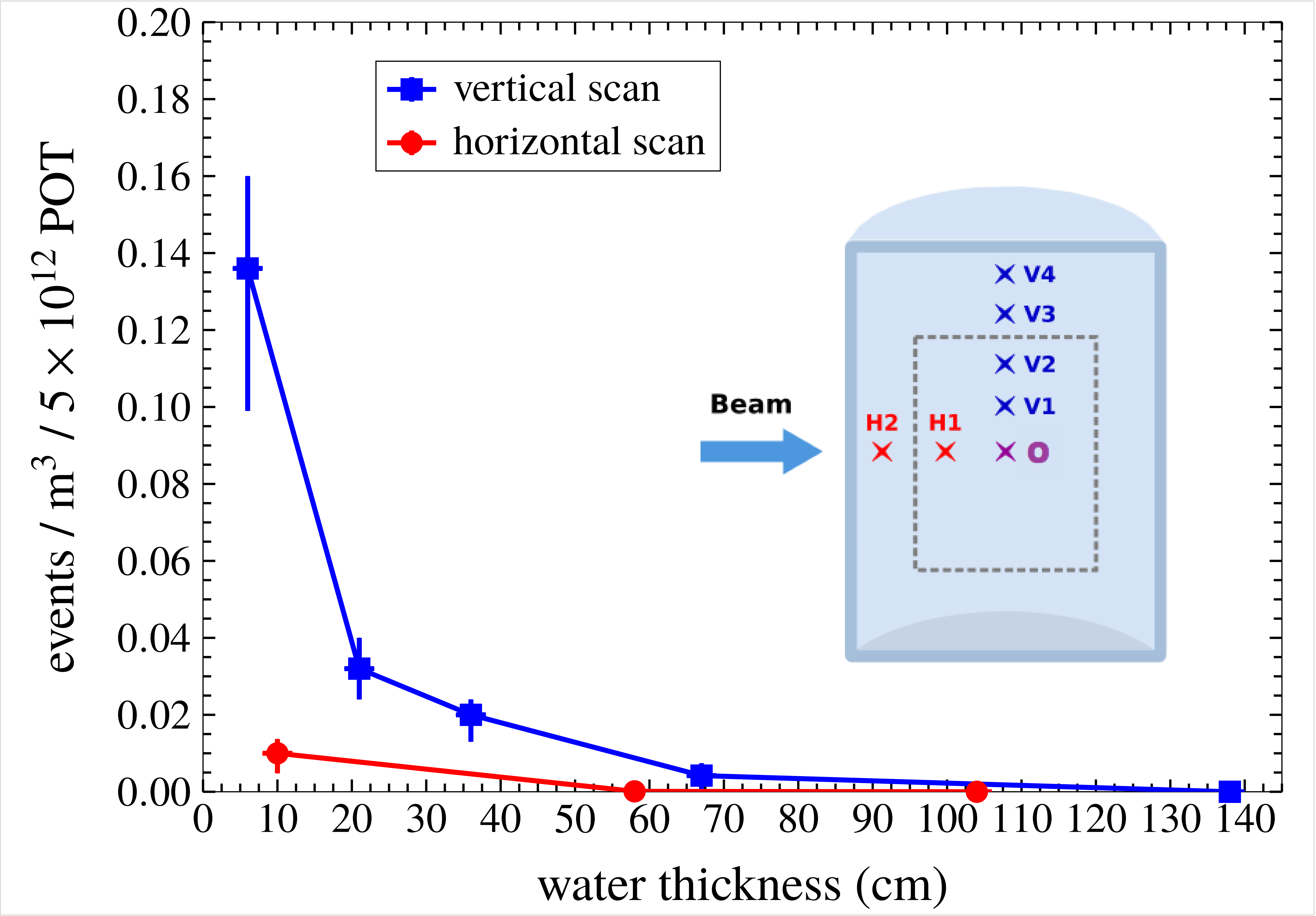
NCV Position Scan





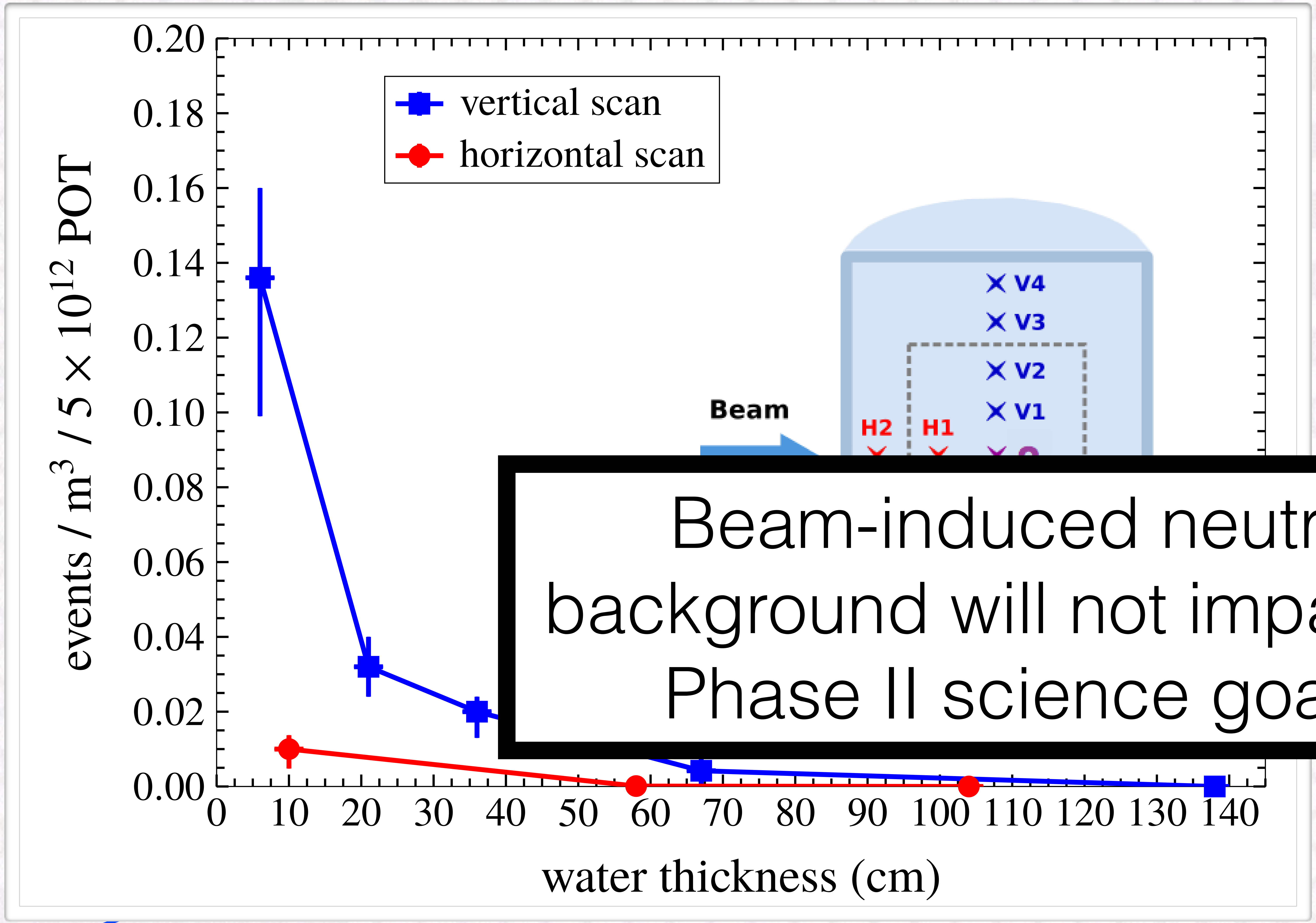
- 0-10 us: Pre-beam background
- 10-15 us: Proton recoils
- 15 us+: Neutron captures

NCV Position Scan



Average 0.02 neutrons/beam-spill/m^3 in the Phase-II fiducial volume.

NCV Position Scan



Average 0.02 neutrons/ beam-spill/m^3 in the
-II fiducial volume.

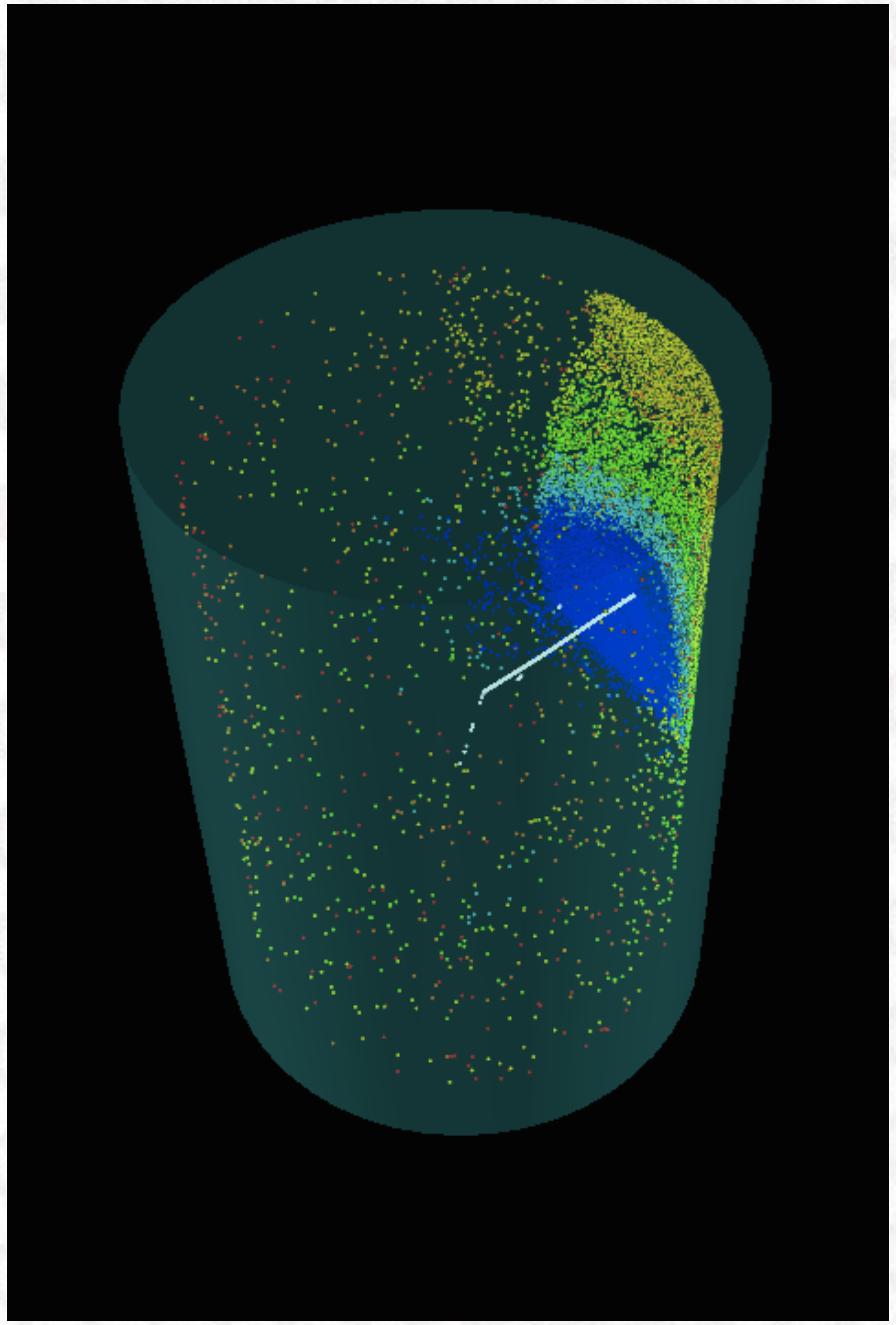
Beam-induced neutron background will not impact our Phase II science goals!

Phase II

Neutrino Physics run

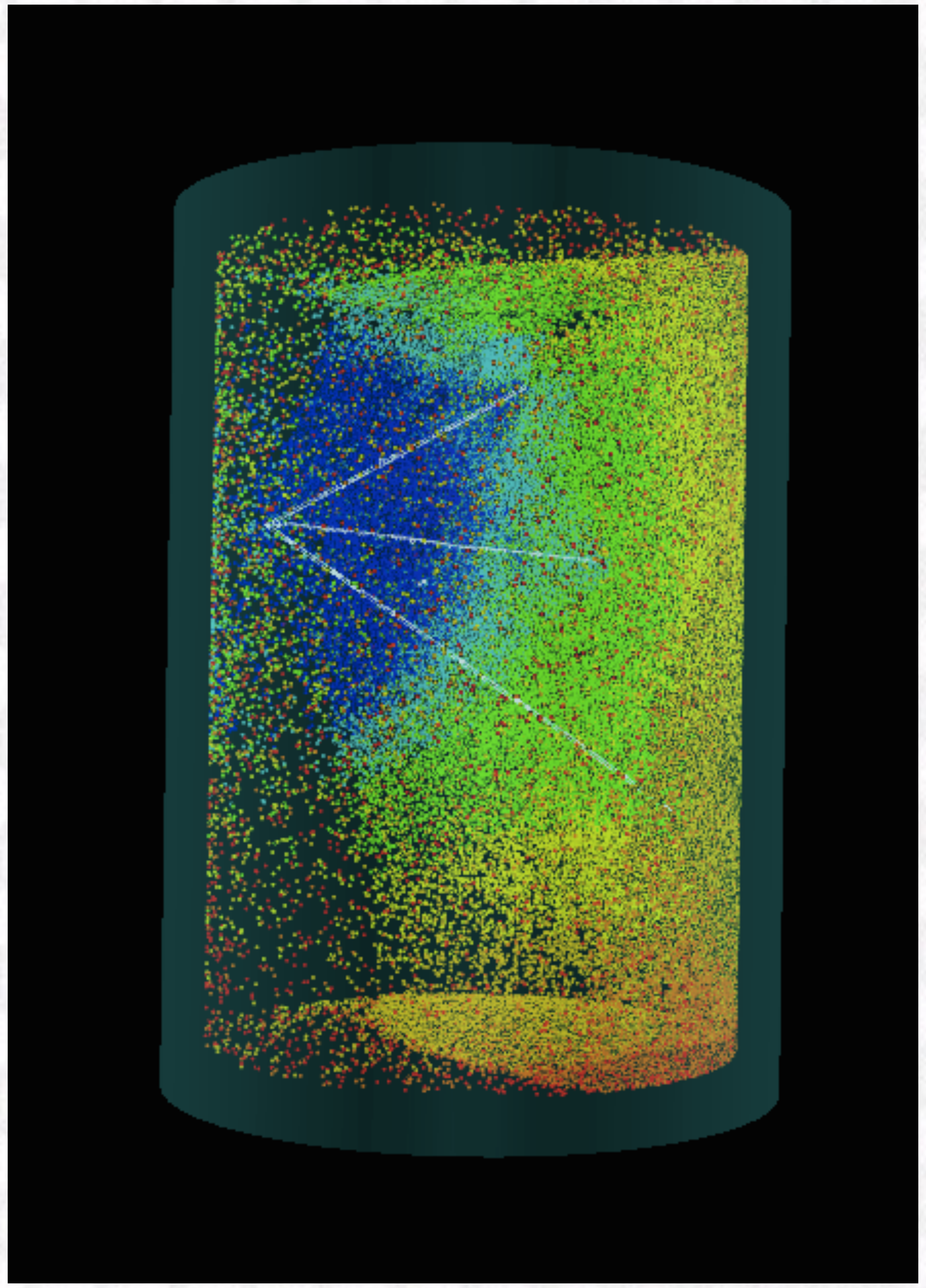
ANNIE Physics Goals

- The primary physics analysis to be realized in ANNIE phase II is **a measurement of CC cross sections and neutron yields in bins of lepton kinematics.**
    - We are particularly interested in isolating events with a single muon and no additional tracks.
- As we continue to collect data and develop the detector capabilities, a much richer physics programs is possible…

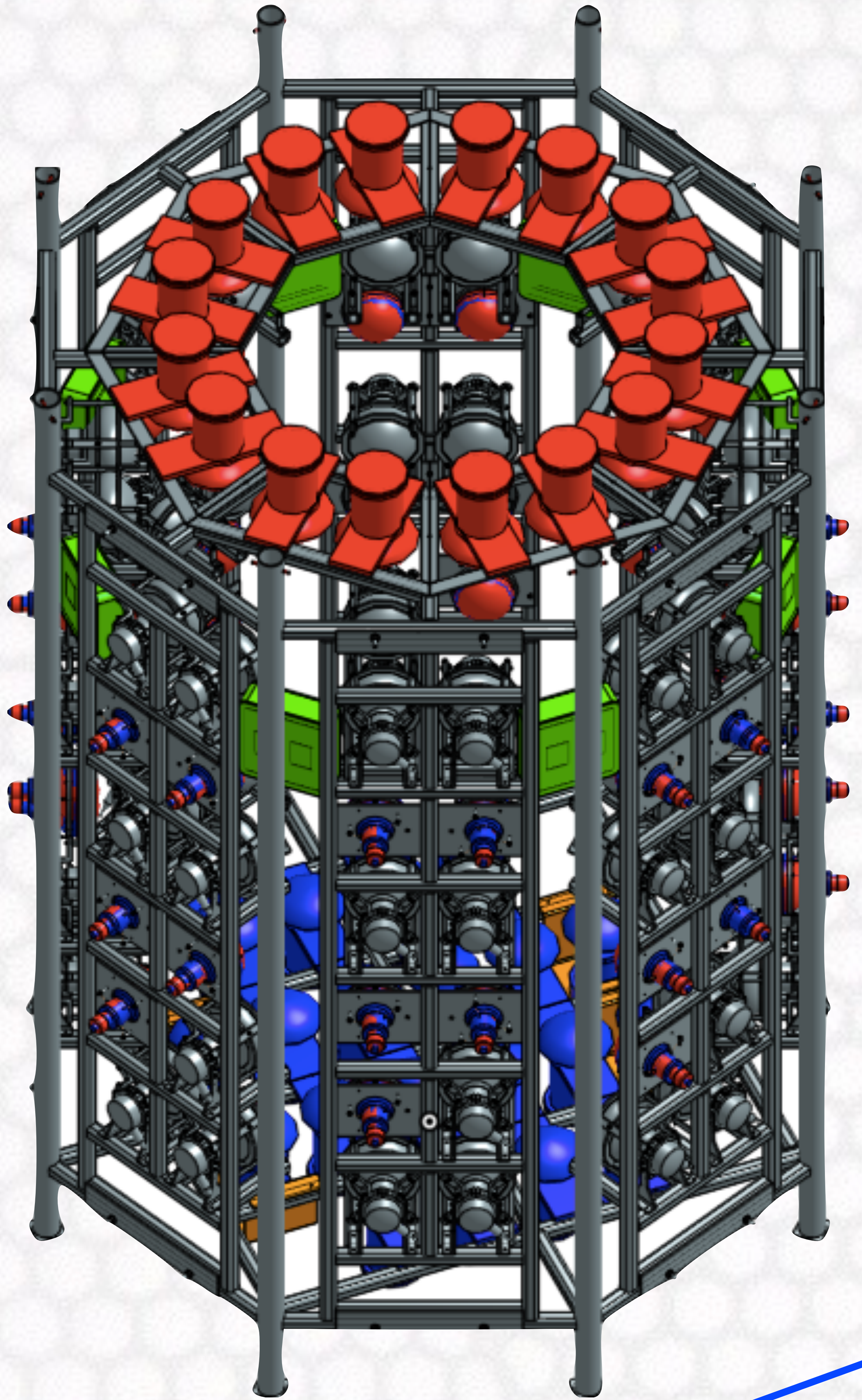


ANNIE Physics Goals

- ANNIE Phase II could also explore cross sections and neutron yields for more complex even types:
    - resonant pion production
    - neutral current cross sections.
- Phase II and a possible Phase III could explore new experimental detection techniques.
    - Calorimetric energy reconstruction
    - Detection of de-excitation gammas in water
    - Oxygen neutron capture rates
    - Cherenkov-scintillation separation with WbLS.



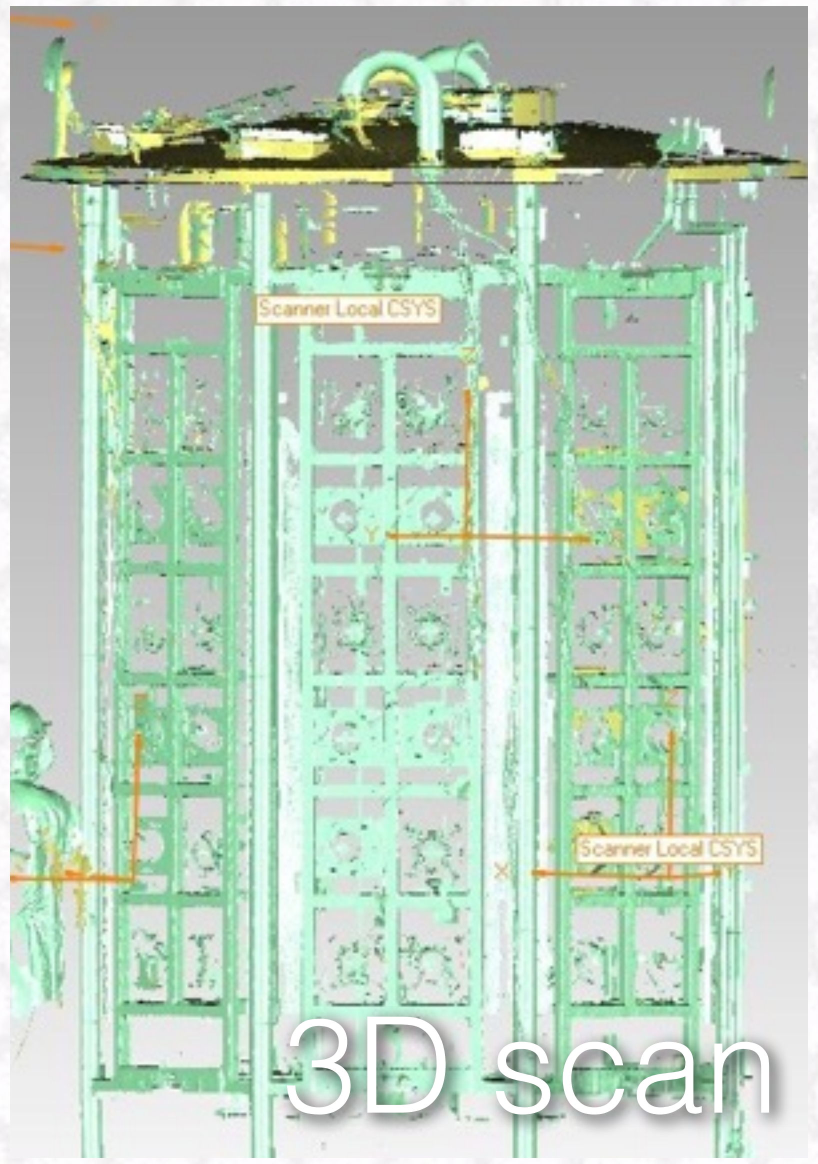
Phase II Detector

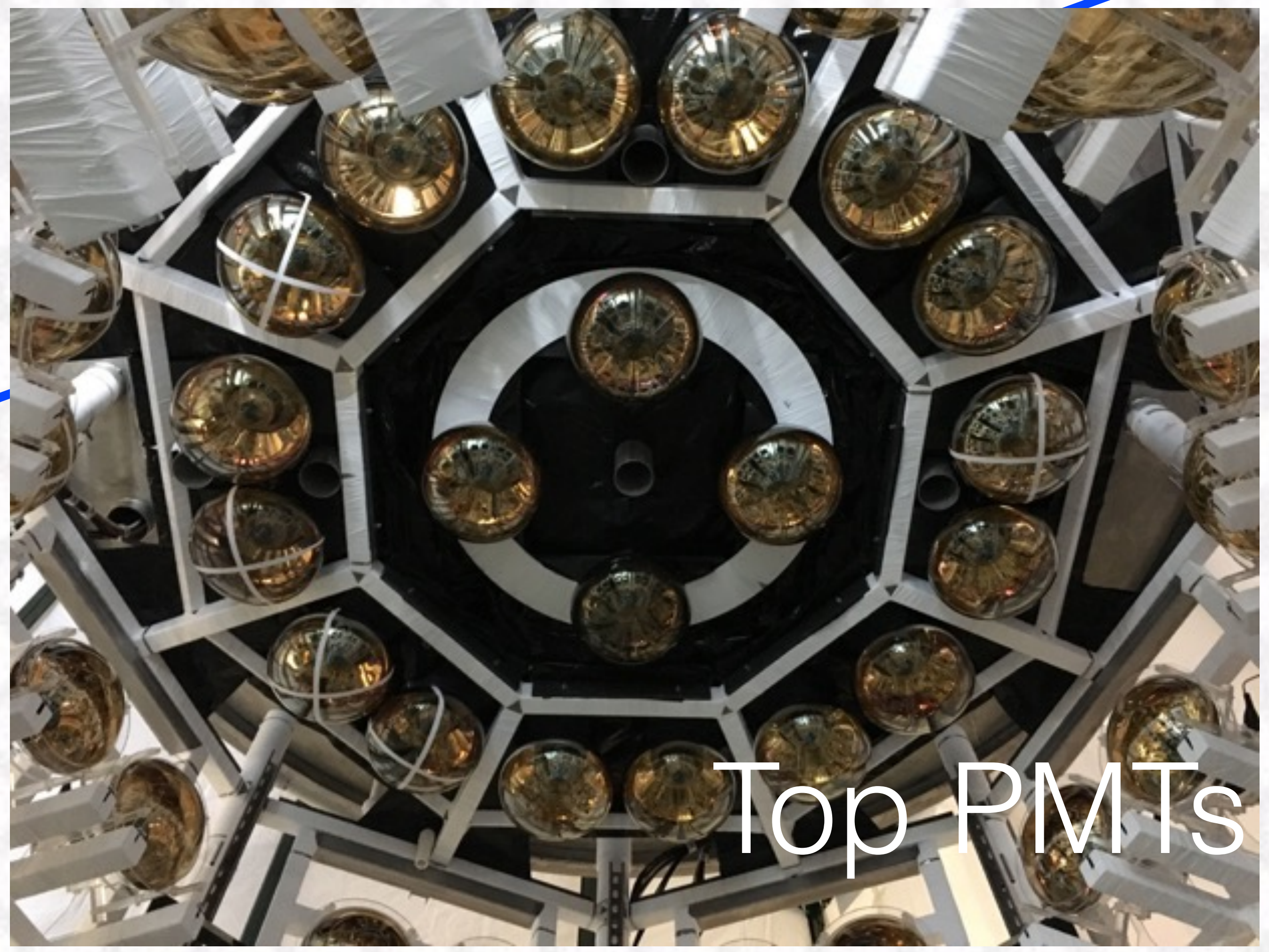


Phase II Inner Structure design

- Physics run.
- 132 PMTs installed on all surfaces of the tank.
- 5 LAPPDs installed on the *downstream* side of the tank.
- Neutrons capture on gadolinium dissolved in the water and produce 8 MeV gamma cascades.
- Water behind the PMTs optically isolated from the inner volume.

Phase II Construction





ANNIE Detector Needs:

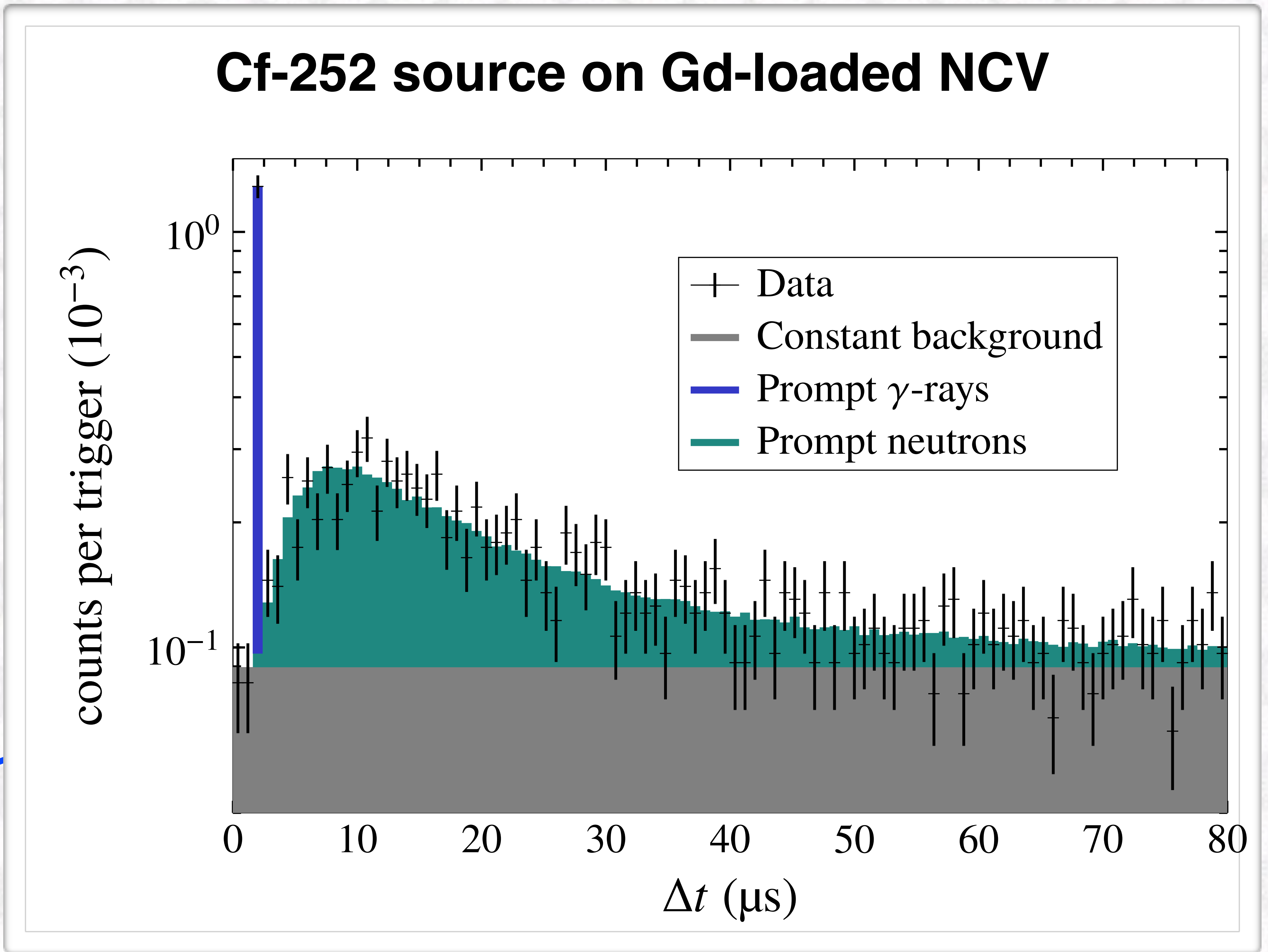
Making the main ANNIE physics measurement requires a detector with:

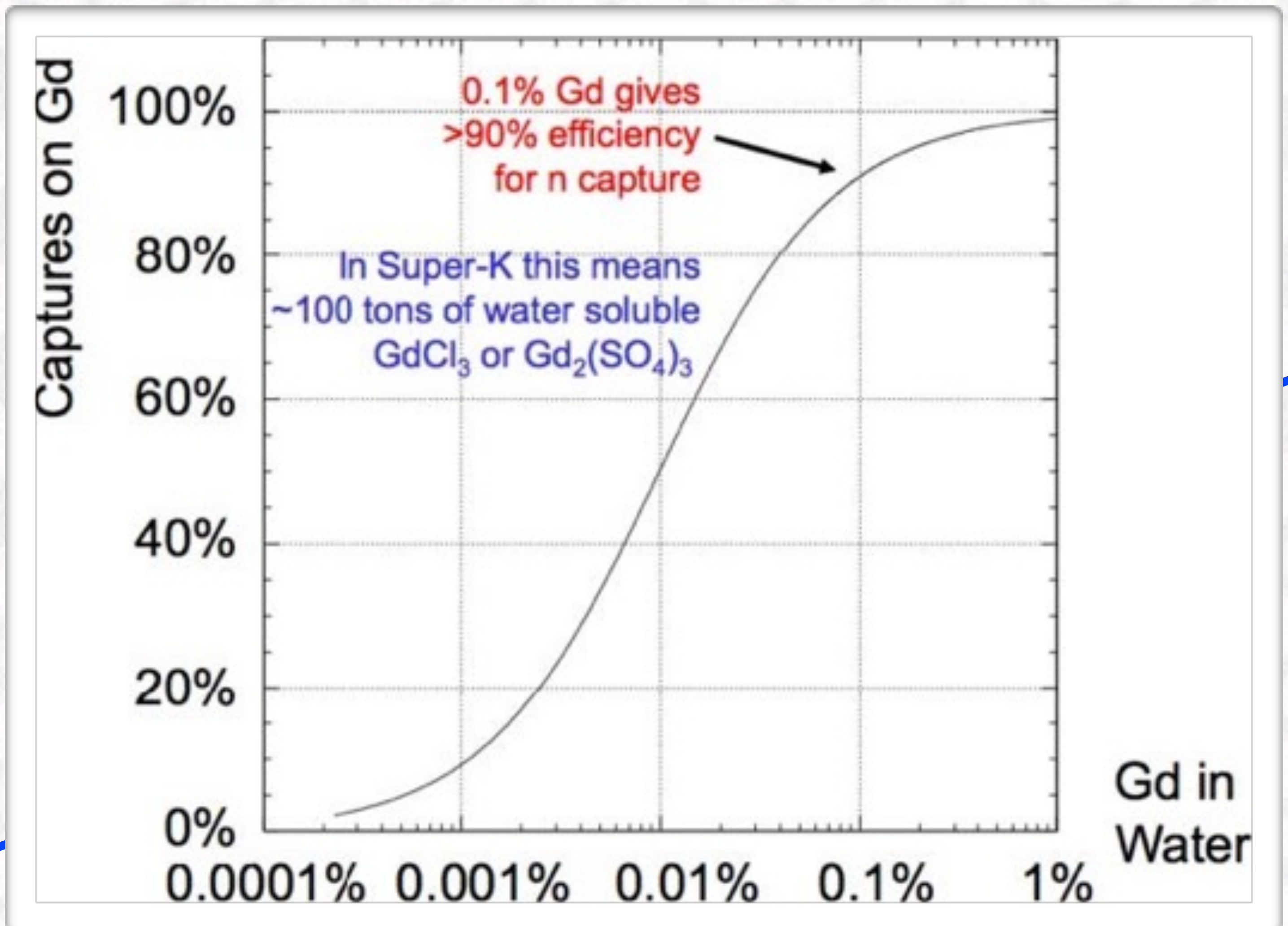
- Efficient neutron detection
- cm-scale vertex resolution to:
    - Select events where the interaction vertex is far enough from the tank edges to fully contain neutrons
    - Accurately estimate muon energy loss in the water.
- single- versus multi-track separation.

In ANNIE, those detector capabilities are achieved by using advanced high-resolution photodetectors and Gd-loaded water.

Efficient neutron detection with Gadolinium

- **Neutron capture doesn't have a minimum neutron energy.**
- Neutron capture cross section for Gadolinium is ~150000 times that of a free proton.
  - Average capture time ~**30 μs**. (0.1% Gd)
  - **E$_\gamma$=8 MeV**

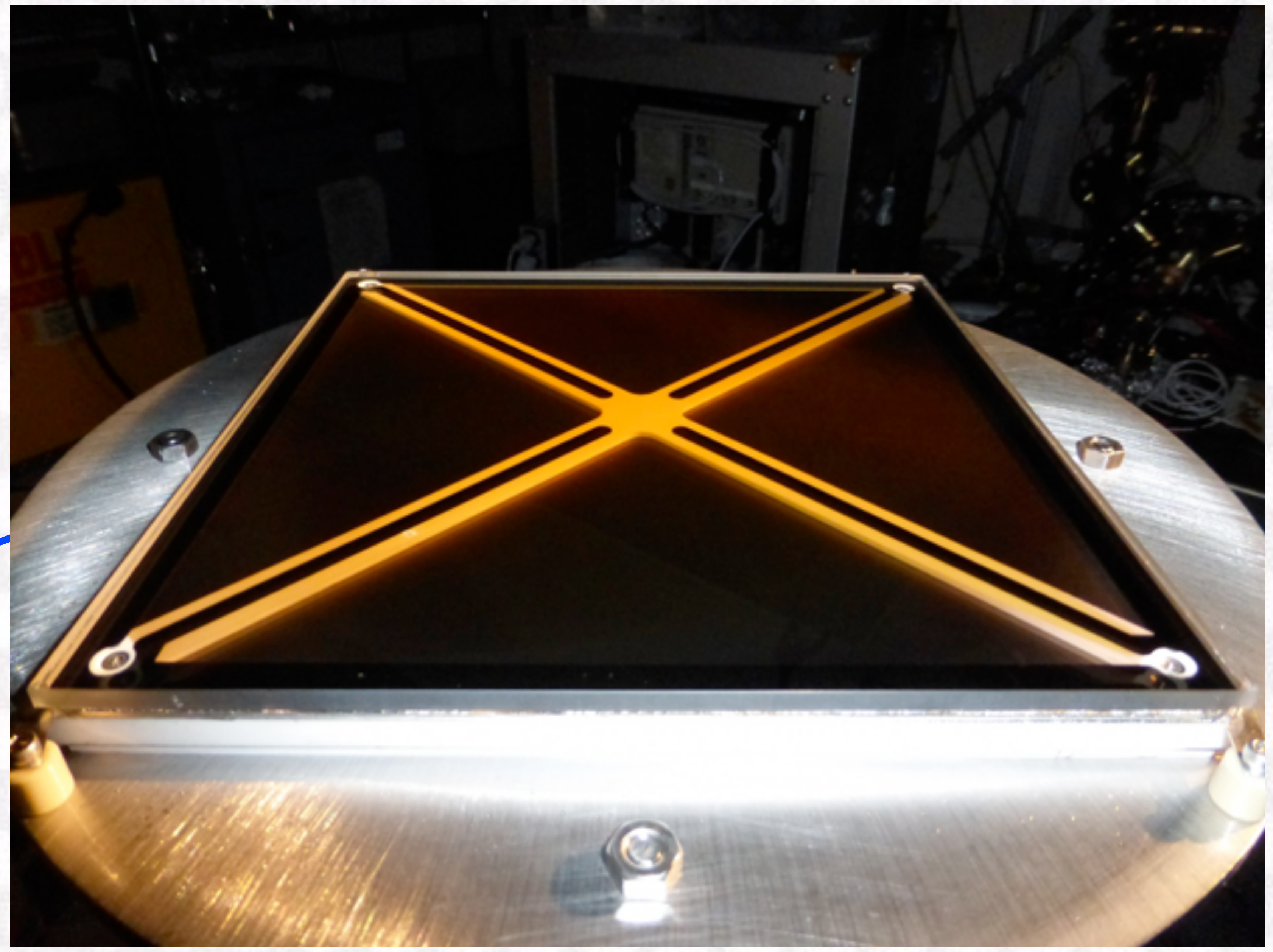




- In pure water neutrons capture on protons.
  - Average capture time ~200 μs.
  - E$_\gamma$=2.2 MeV.

Large Area Picosecond Photo Detectors (LAPPDs)

- **8” square** MicroChannel Plate (MCP).
- **60 ps** time resolution.
- Multi-microstrip readout gives **~1 cm spatial resolution**.
- Good spatial and time resolution allows **multiple individual-photon detection**.
- Centimeter-level vertex and track reconstitution improves energy resolution, background rejection and allows multiple particle detection.
- **Thin profile** maximizes fiducial volume.
- Flat square shape simplifies mounting.



Incom USA Inc.

Large Area Picosecond Photo Detectors (LAPPDs)

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- Good... **indivi...**
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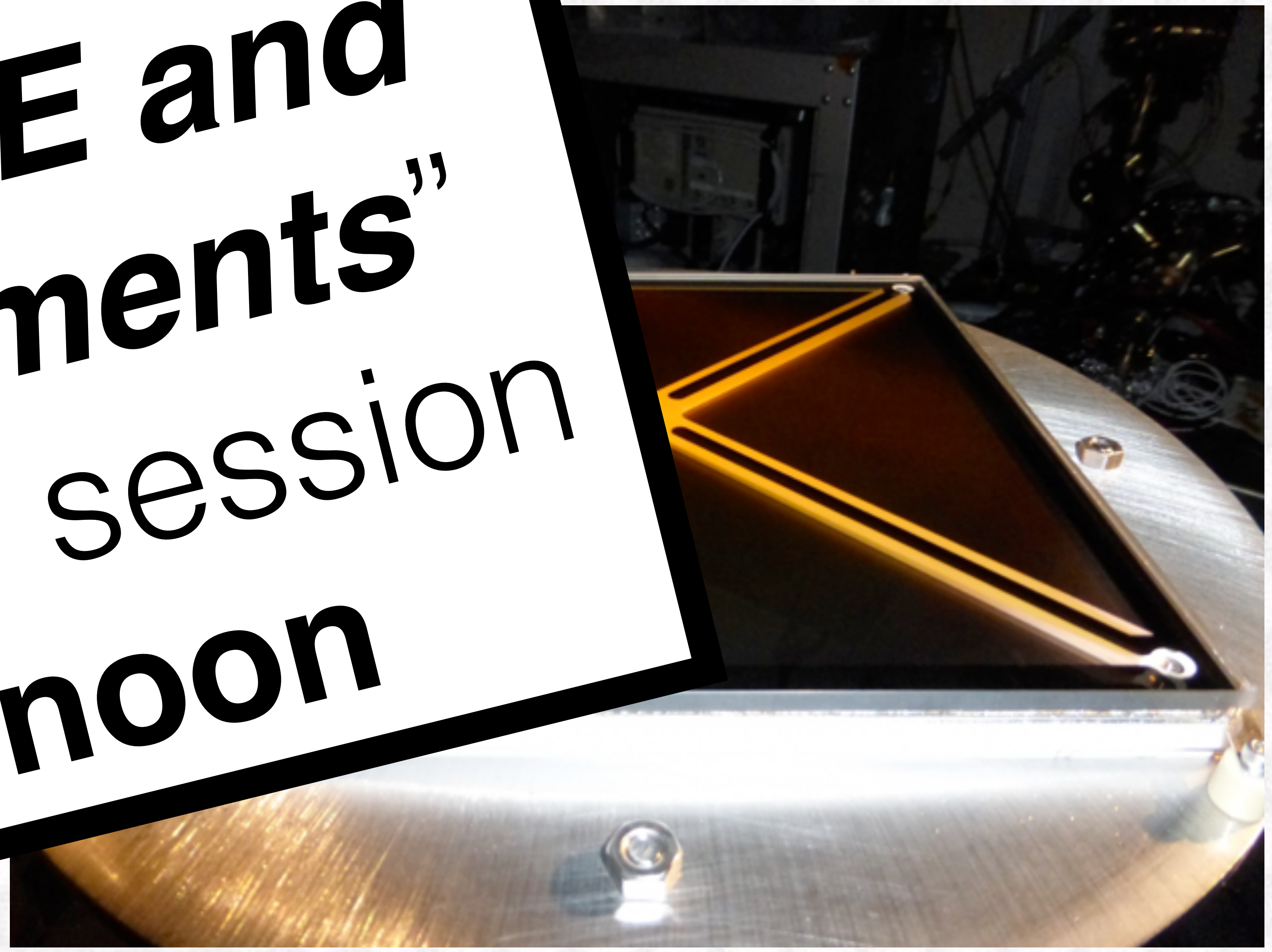
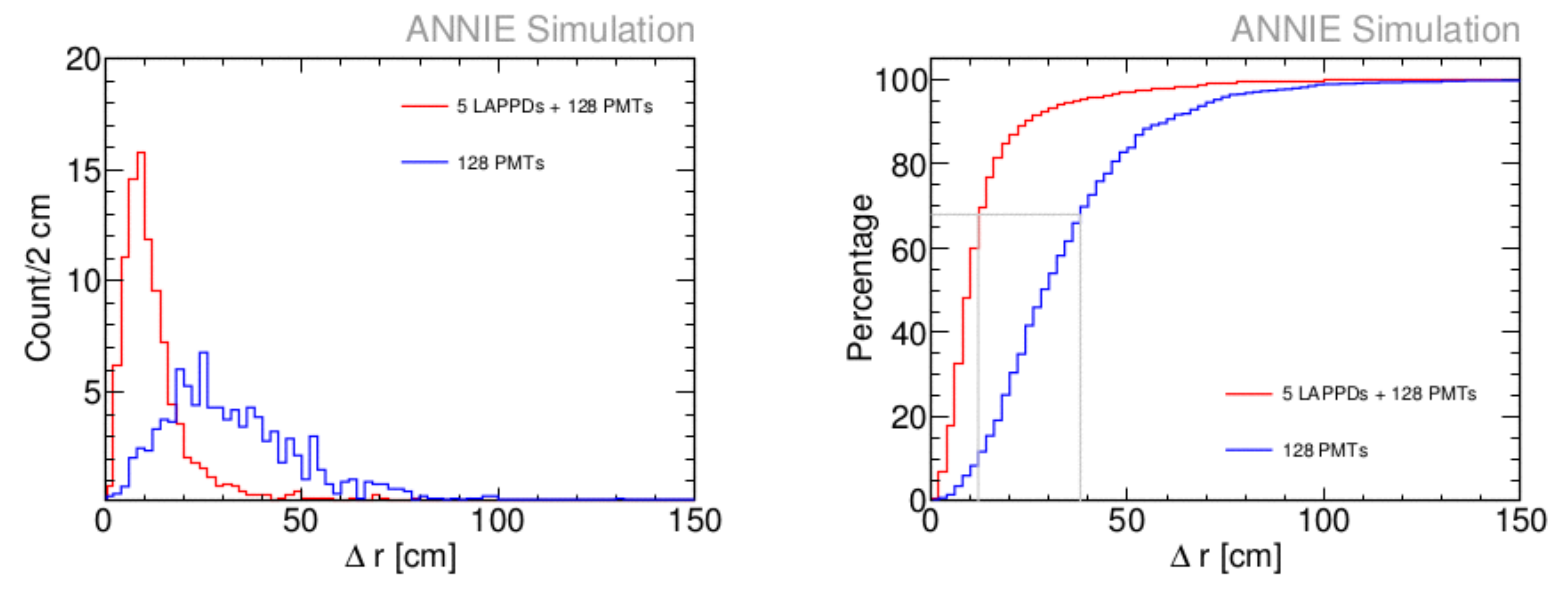
- **Thin pro...** ...iducial volume.
- Flat square shape simplifies mounting.

See **Emrah Tiras**’ talk
“ **Detector R&D for ANNIE and Future Neutrino Experiments**”
in the **Particle Detectors** session
on **Wednesday afternoon**



Incom USA Inc.

Event reconstruction with LAPPDs



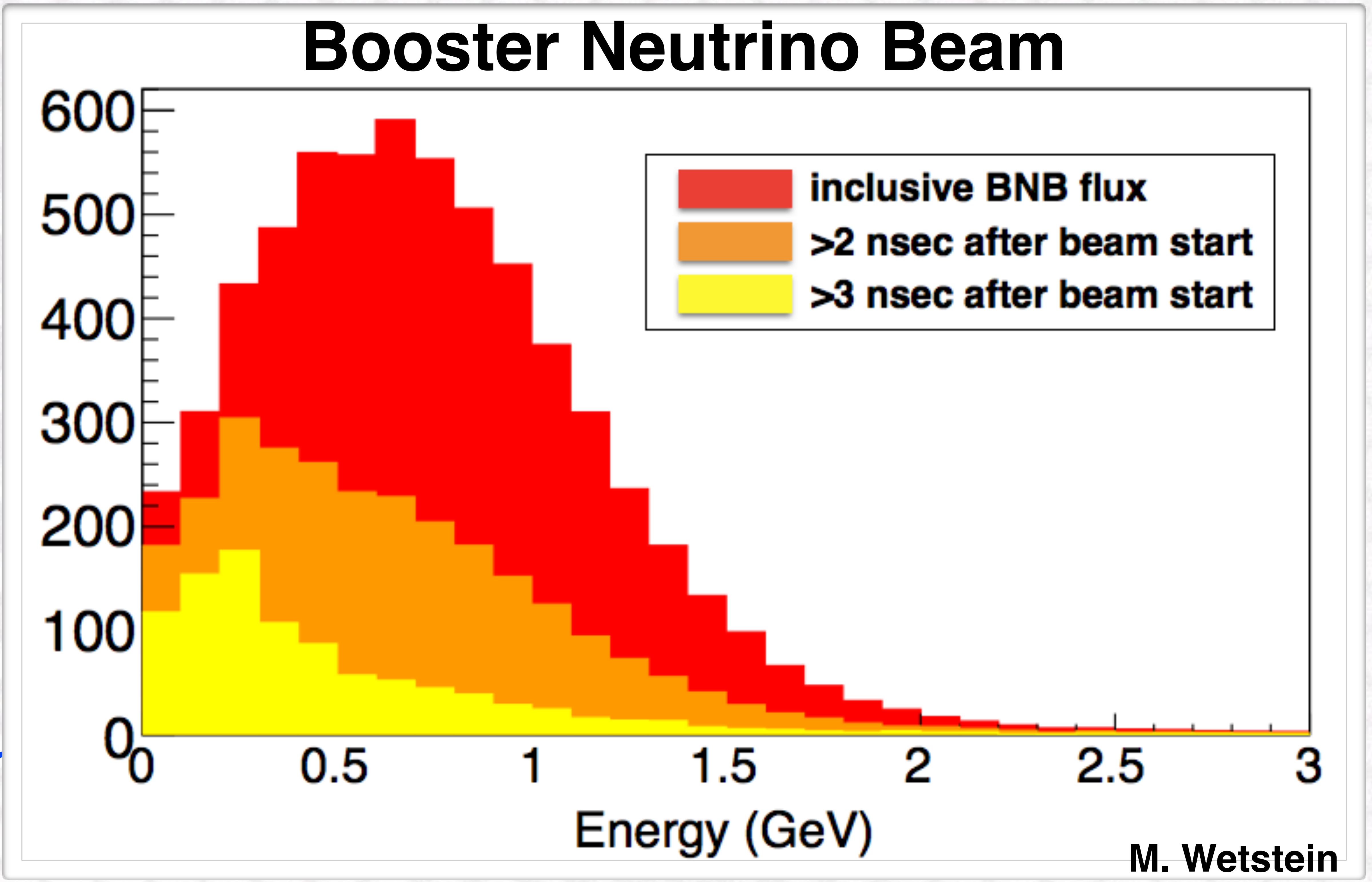
Adding just 5 LAPPDs makes a big improvement in reconstructed vertex resolution, from 40 to 15 cm.

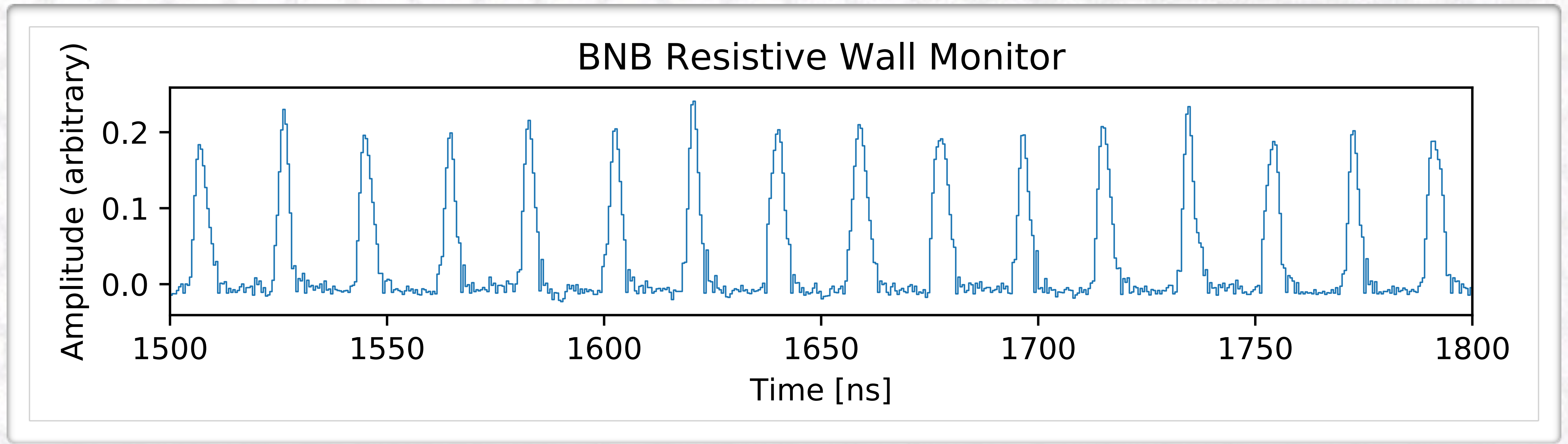
Similar improvements in other reconstructed variables.

Beyond Phase II

Precision timing

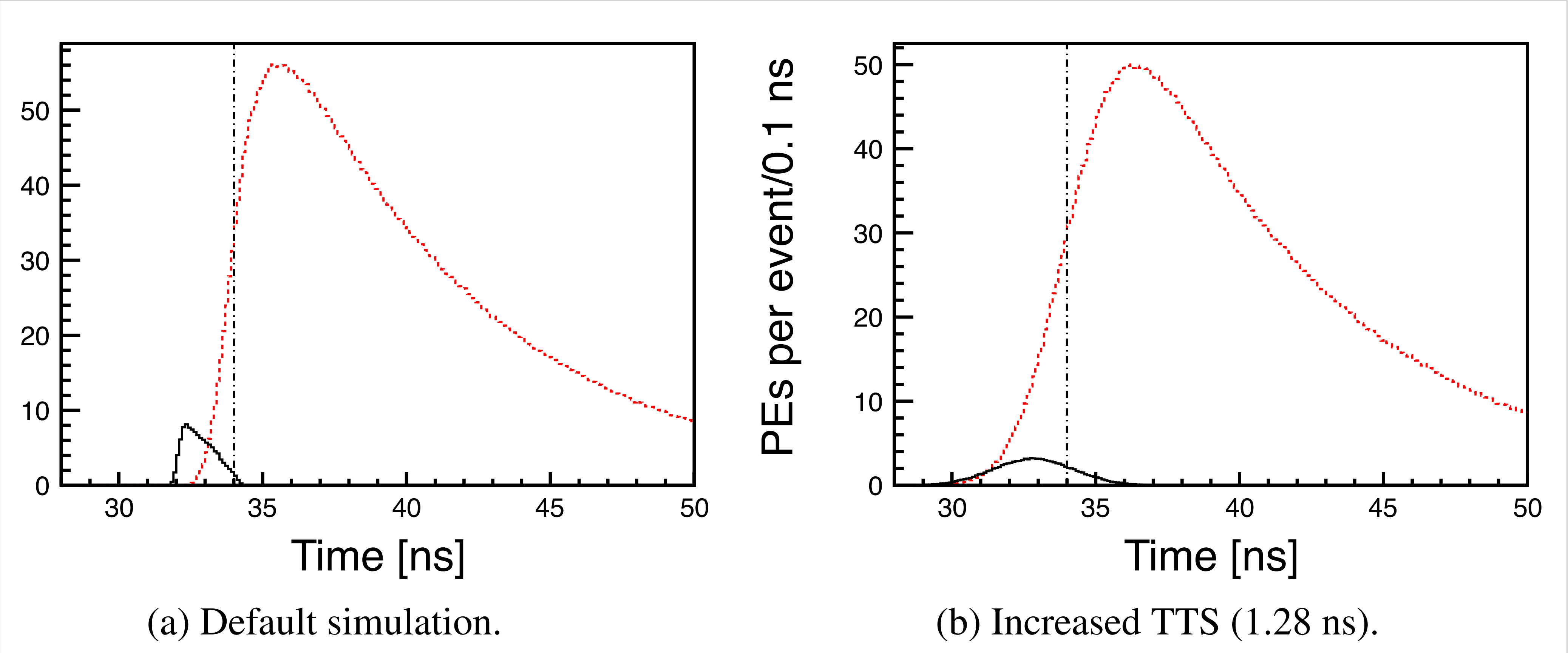
- BNB bunch width is typically <1.5 ns.
- Precision Beam timing (<1ns) can be used to select neutrino energy populations.
- Concept being explored for Phase II.
- Similar to off-axis experiments, but using an on-axis detector.
- Time dispersion is a result of energy-dependent pion time-of-flight difference in the decay pipe.
- Aided by precision timing from LAPPDs.





Water-based Liquid Scintillator

- The ANNIE collaboration is interested in the possibility of an additional run with **Water-based Liquid Scintillator** (WbLS).
- Hybrid reconstruction scheme: **Calorimetric** reconstruction (scintillation) + **kinematic** reconstruction (Cherenkov) + **neutron counting** (Gd-capture).
- Observation of particles below threshold.
- Improved sensitivity to NC gammas and recoil protons.



(a) Default simulation.
(b) Increased TTS (1.28 ns).

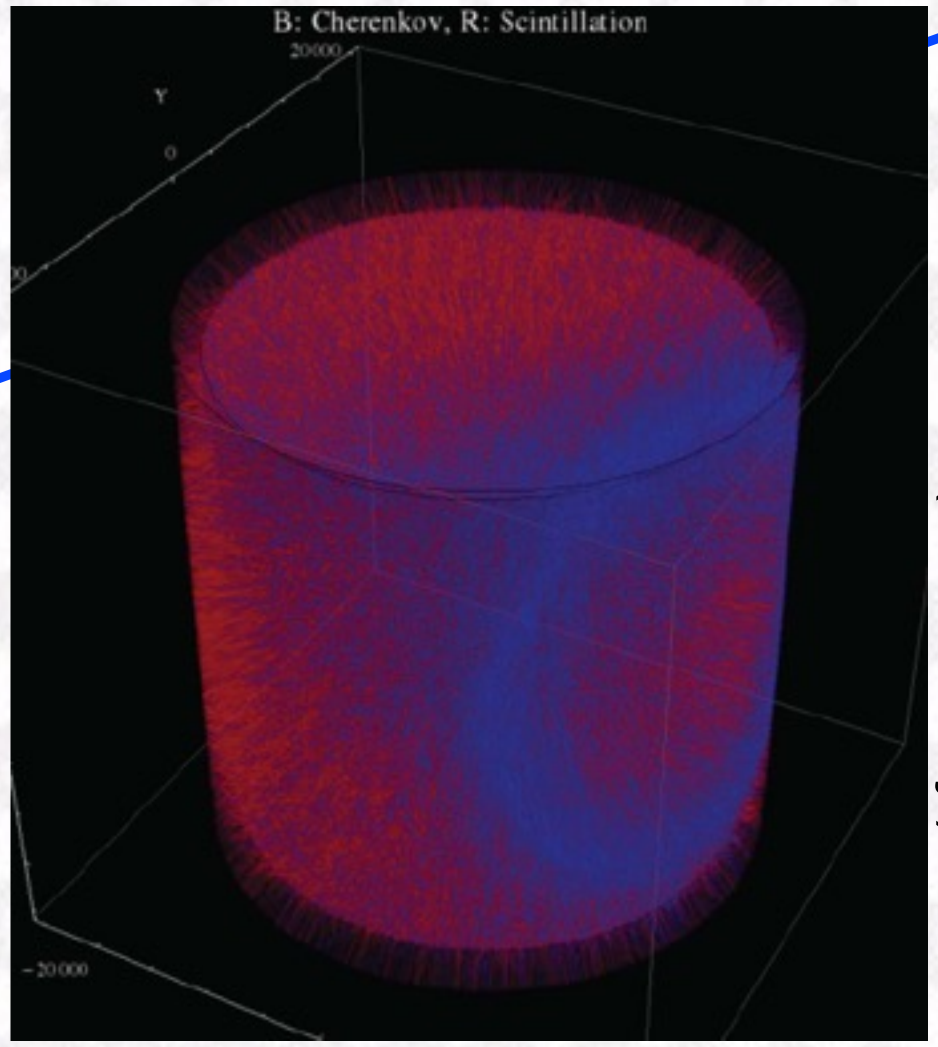
Application to Future Experiments

WATCHMAN-AIT

J. Brennan (Sandia)

- 2 kTon Gadolinium-loaded water Cherenkov detector.
- Demonstrate remote reactor monitoring through Inverse Beta Decay (IBD).
- Advanced Instrumentation Testbed (AIT)—Future R&D platform.
- Potential to add WbLS inner volume and/or LAPPDs.
- Construction started Oct 1.
- Online by Autumn 2022.

THEIA



B. J. Land (Berkeley)

- 50 kTon water with WbLS.
- Combine water-Cherenkov with scintillation for a wide energy range.
  - Long baseline ν
  - ββ0ν
  - CNO-cycle solar neutrinos
  - Geo- neutrinos
  - Supernova.

Conclusion

- ANNIE has successfully completed Phase I.
  - The background neutron flux in the detector has been measured to be <0.02 neutrons/spill/m^3.
- **Phase II currently in commissioning**; physics data when beam returns in the fall.
- ANNIE Phase II will measure the neutron multiplicity from neutrino-nucleus interactions in water as a function of lepton kinematics.
- **Five Production LAPPDs** currently being characterized prior to Phase II installation.
- ANNIE will soon be the first high-statistics Gd-loaded water Cherenkov detector in a neutrino beam.