The ANNIE Experiment

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

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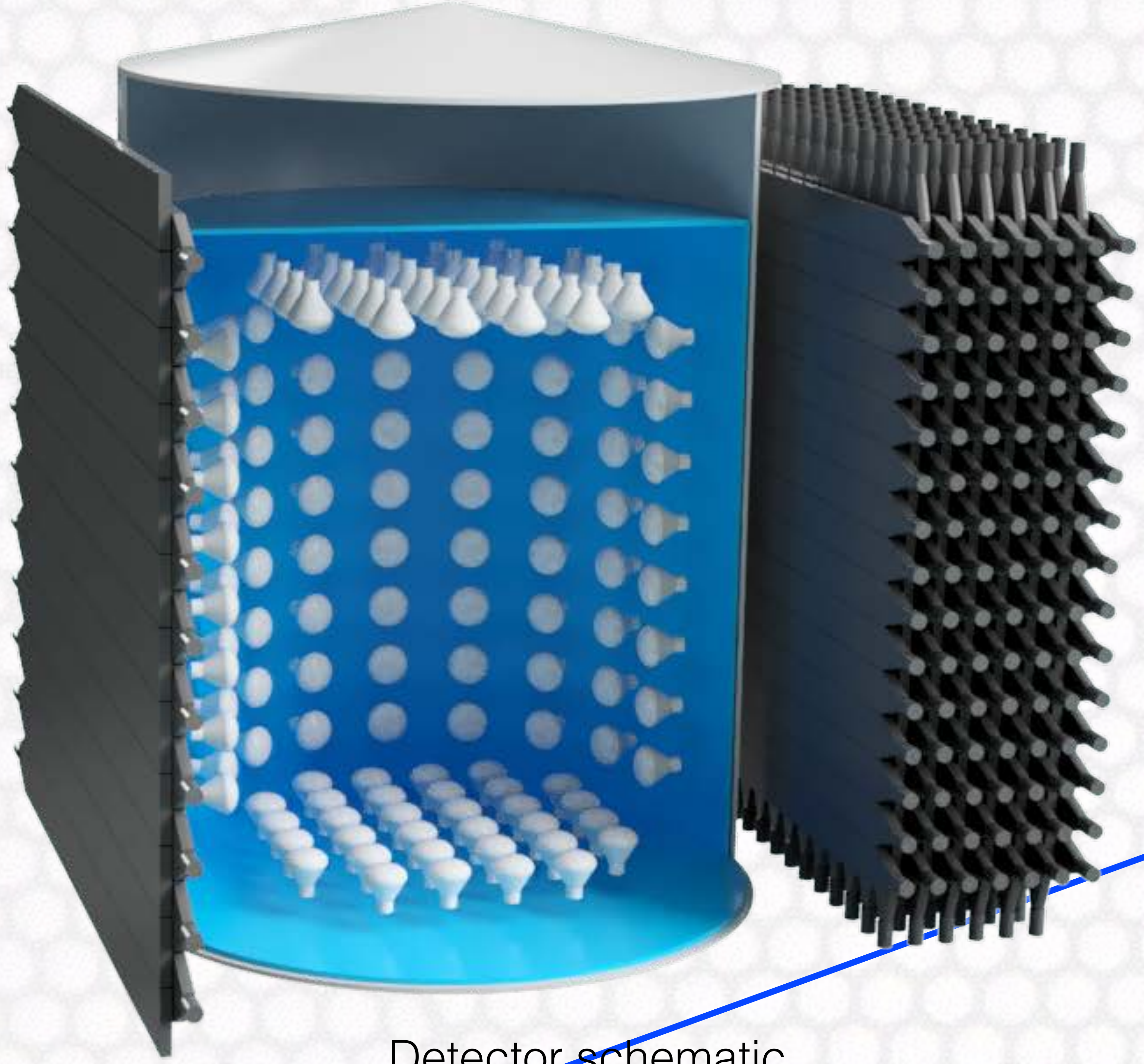
Iowa State University

NuInt 2018 - GSSI
October 18, 2018

What is ANNIE?



Detector schematic

- ANNIE is a water-Cherenkov neutrino experiment on the Booster Neutrino Beam at Fermilab.
- ANNIE has two goals:
  - Measure neutrons from neutrino interactions on water.
  - Demonstrate new detection technologies
- ANNIE will run in two phases:
  - Phase I (Complete): Partial detector engineering demonstration and background measurement.
  - Phase II (Early 2019): Physics measurement with advanced detection technologies.

The ANNIE Collaboration

- 12 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
- Ohio State University
- Queen Mary University
- The University of Hamburg
- The University of Sheffield
- University of California, Davis
- University of California, Irvine
- University of Chicago
- University of Edinburgh

First LAPPD Delivery

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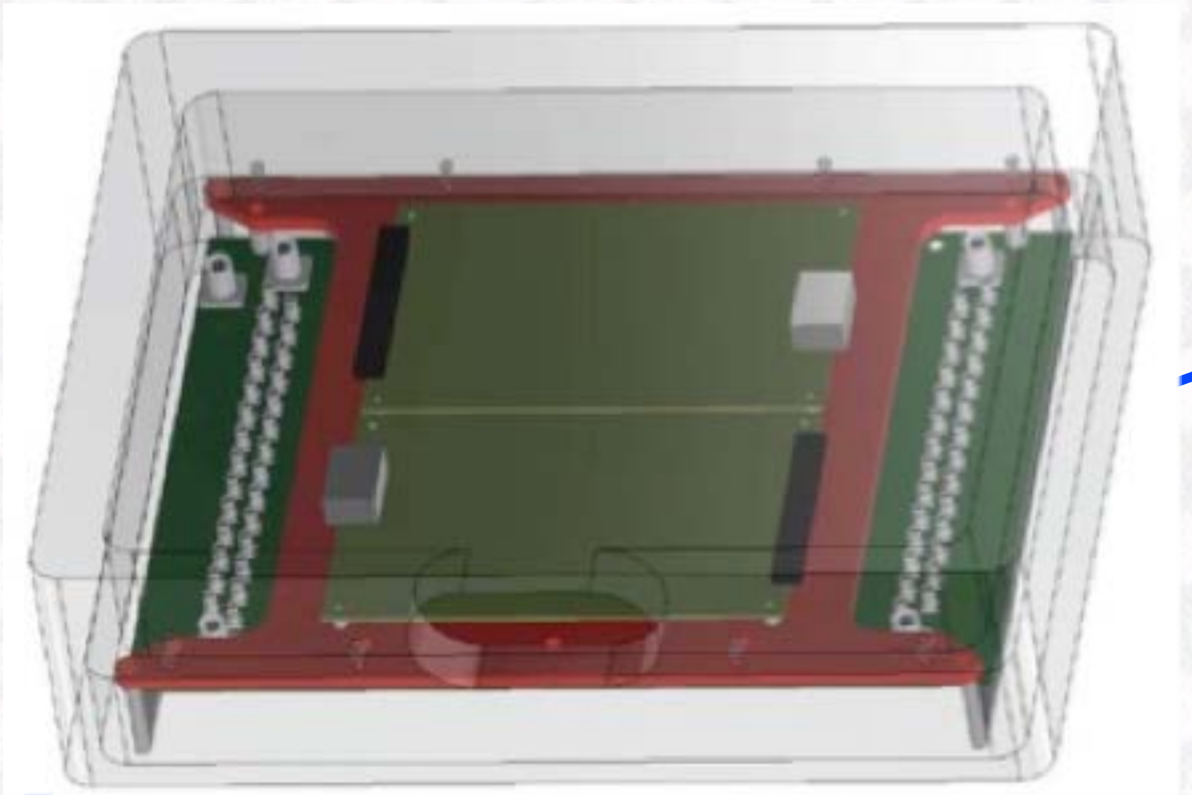
- University of Edinburgh

ANNIE is a young and growing collaboration!

Motivation

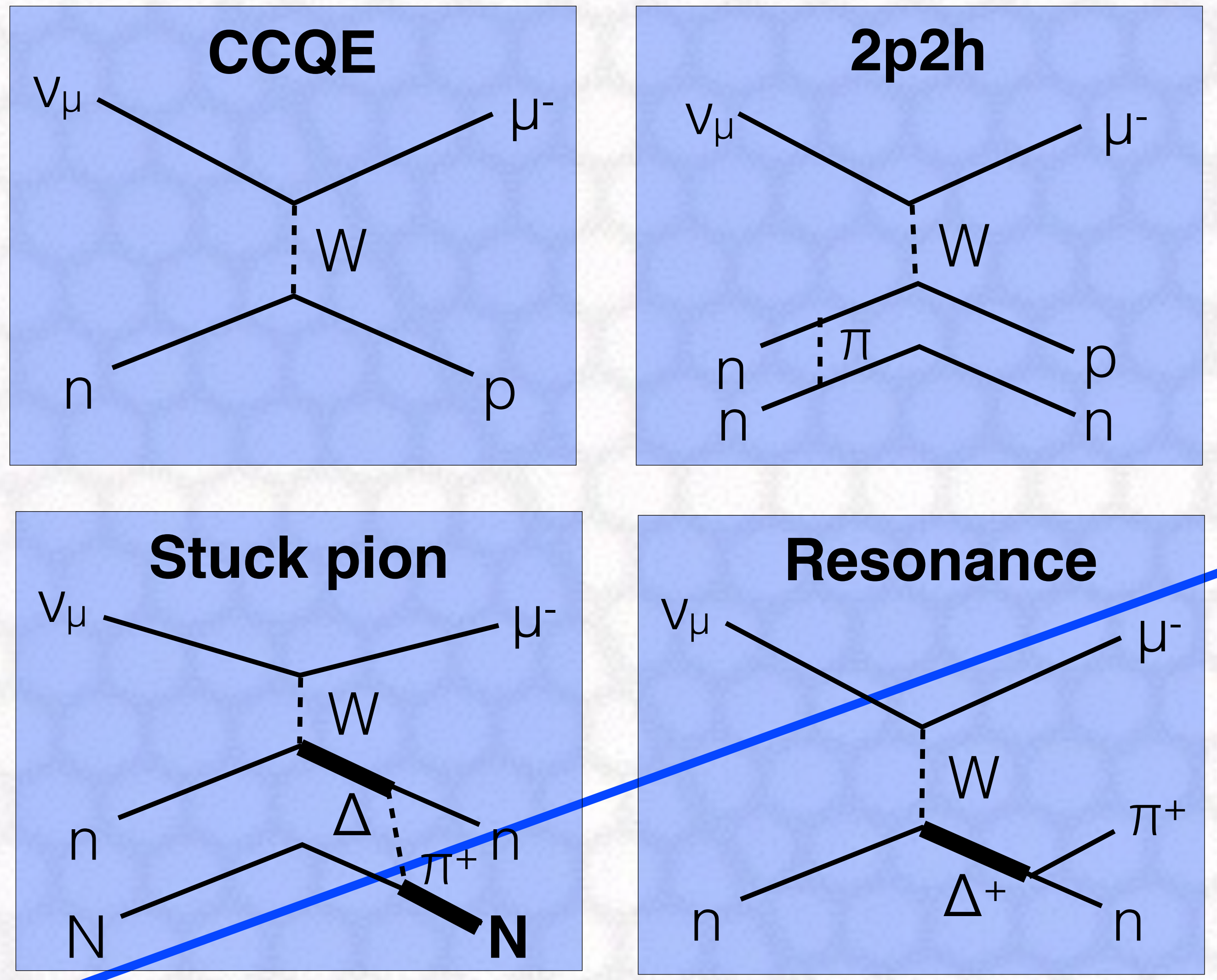
- Primary science goal: Measure the abundance of final state neutrons from neutrino interactions in water as a function of lepton kinematics.
  - Understand neutrino-nucleus interactions
  - Understand and reduce backgrounds for rare processes, such as proton decay and diffuse supernova neutrino background.

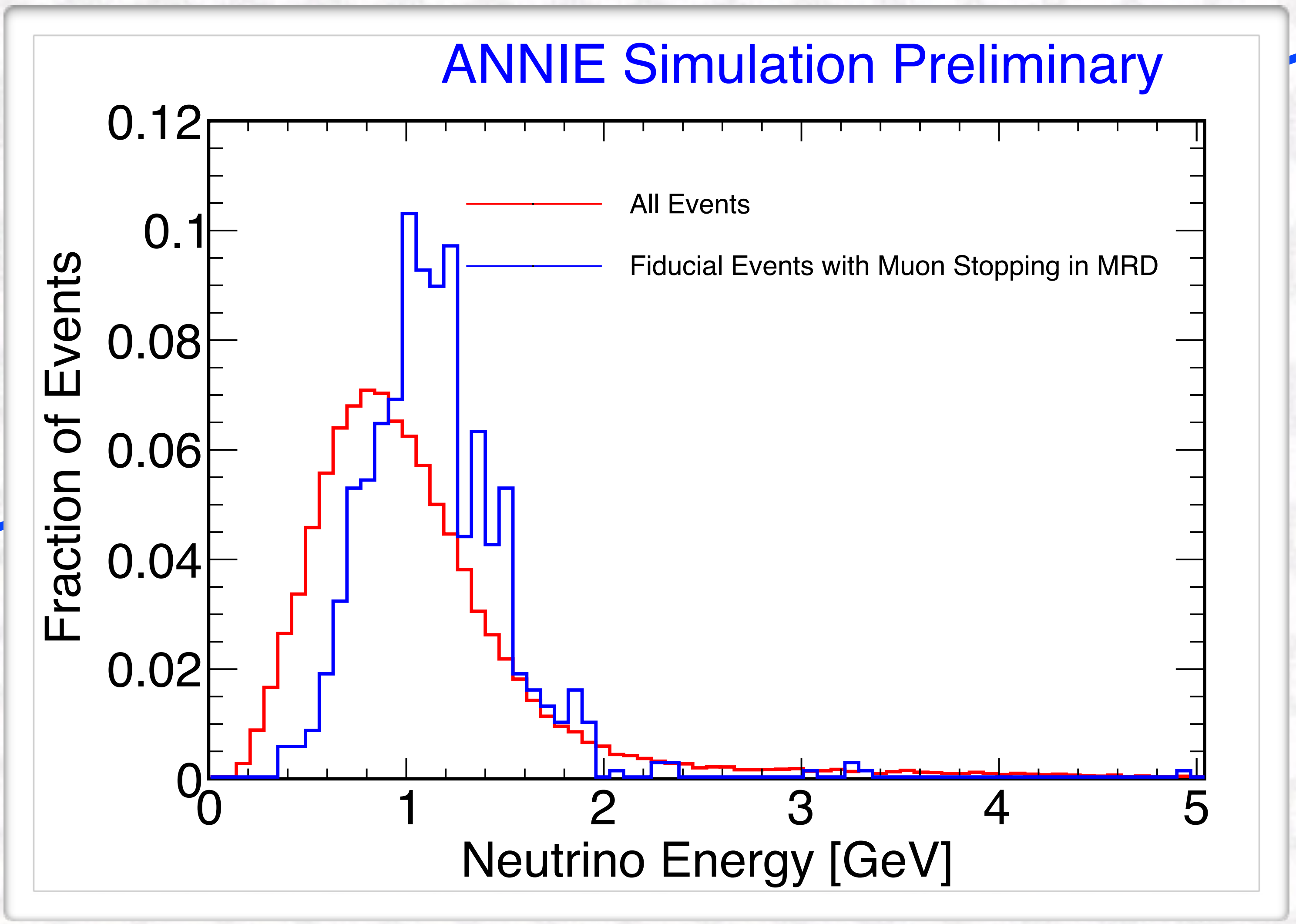


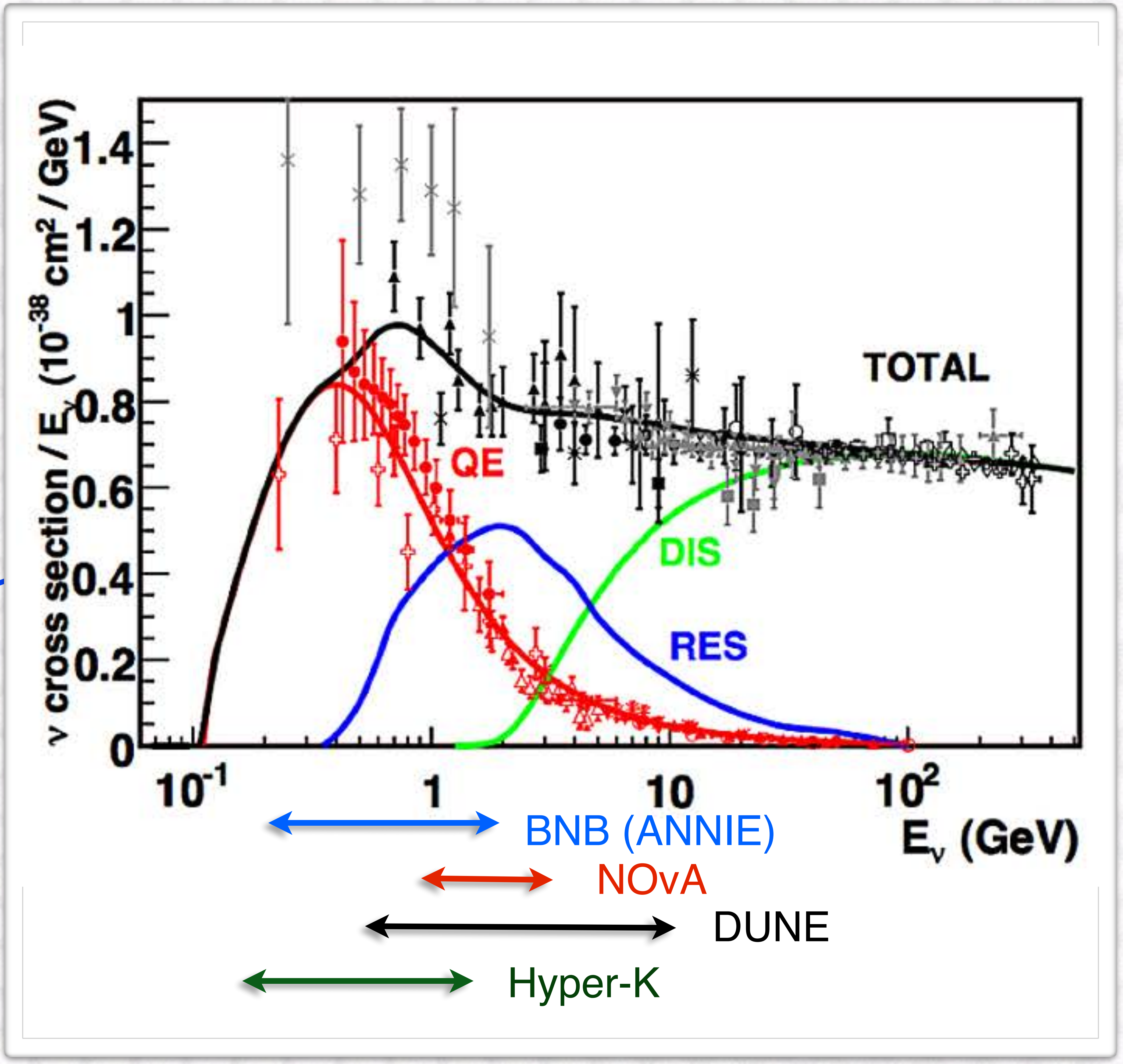
- Demonstrate new detection technologies:
  - Large Area Picosecond Photo Detectors (LAPPD)
  - Waveform digitization with 100 ps samples
  - Neutron tagging in Gadolinium-loaded water

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.

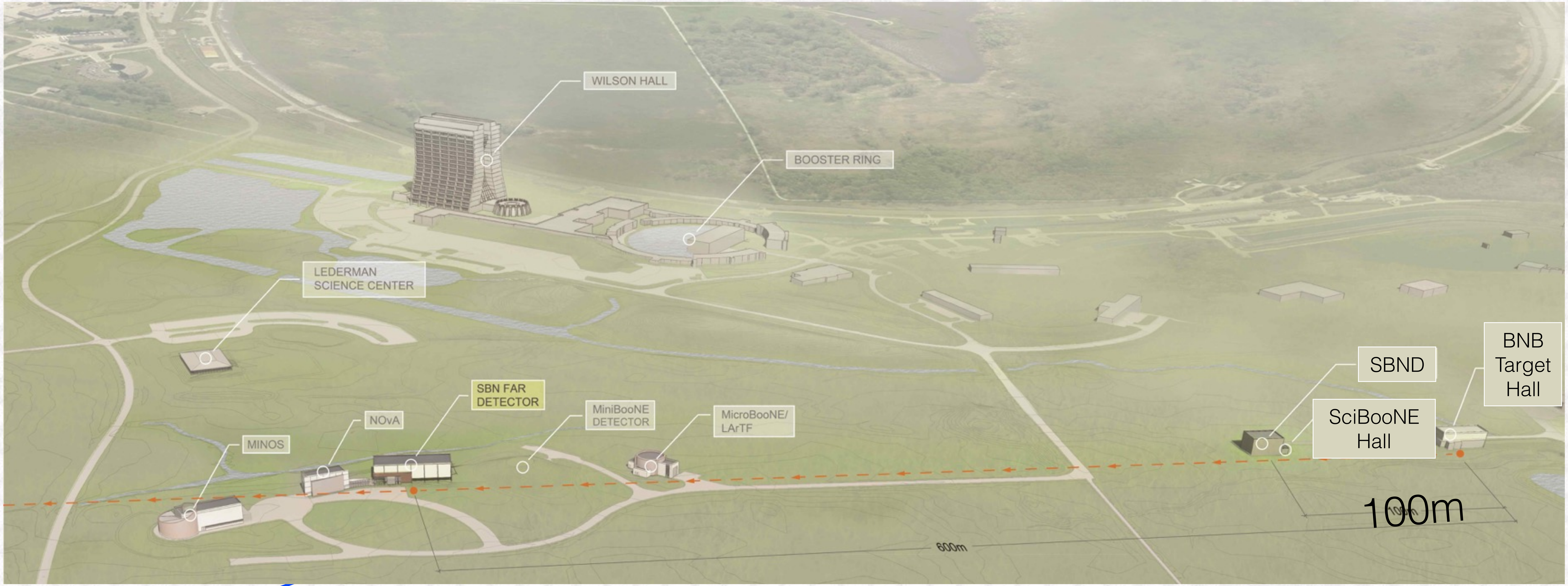




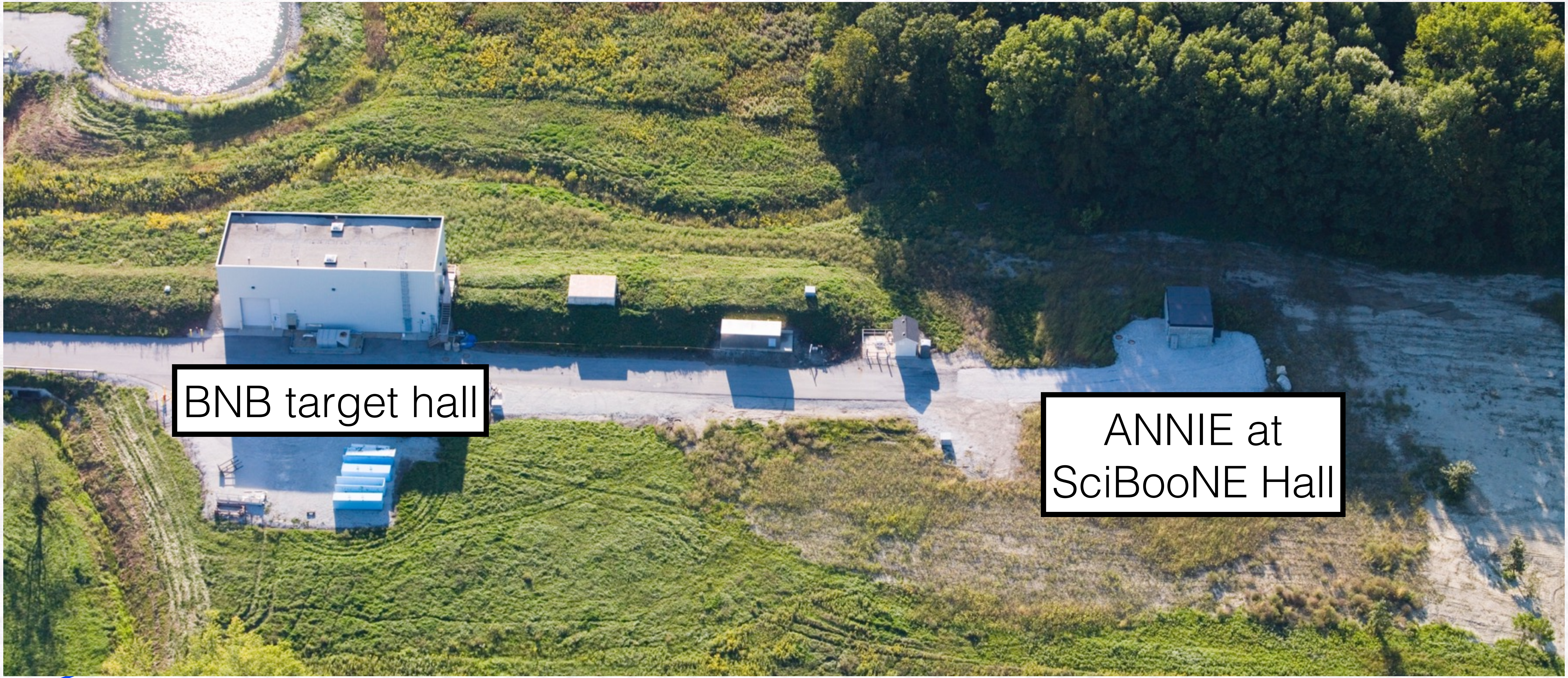


The ANNIE Experiment

The Booster Neutrino Beam

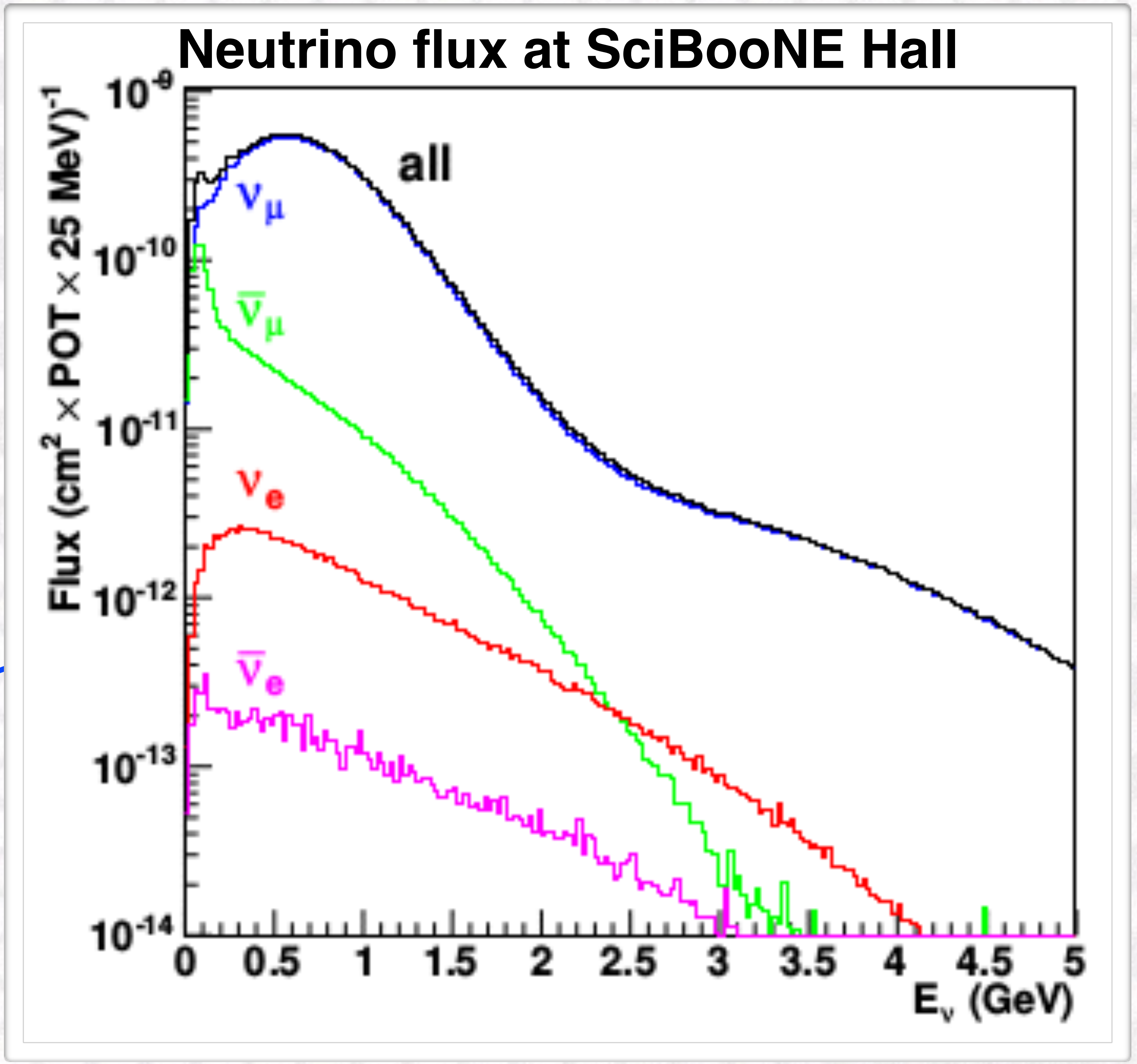


The Booster Neutrino Beam



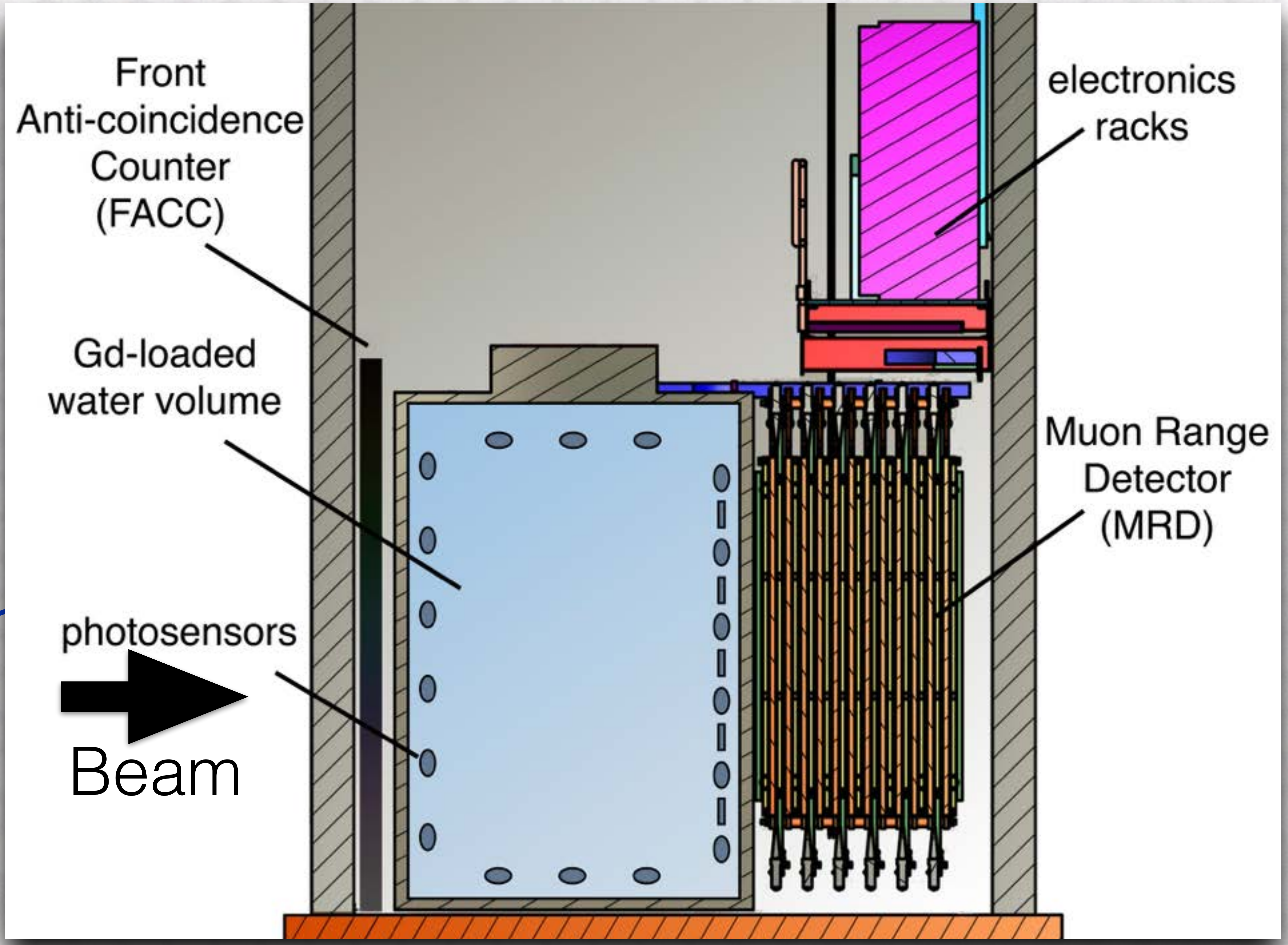
The Booster Neutrino Beam

- 700 MeV peak energy
- 100 m from the ANNIE detector at SciBooNE Hall
- 93% ν_μ purity
- 4×10^{12} POT per 1.6 μS spill at 5 Hz
- One ν_μ charged-current interaction in the ANNIE water volume every 150 spills (~30 s)
- Energy overlaps with LBNF oscillation 2nd-maximum and Hyper-K neutrino beam.



The ANNIE Detector

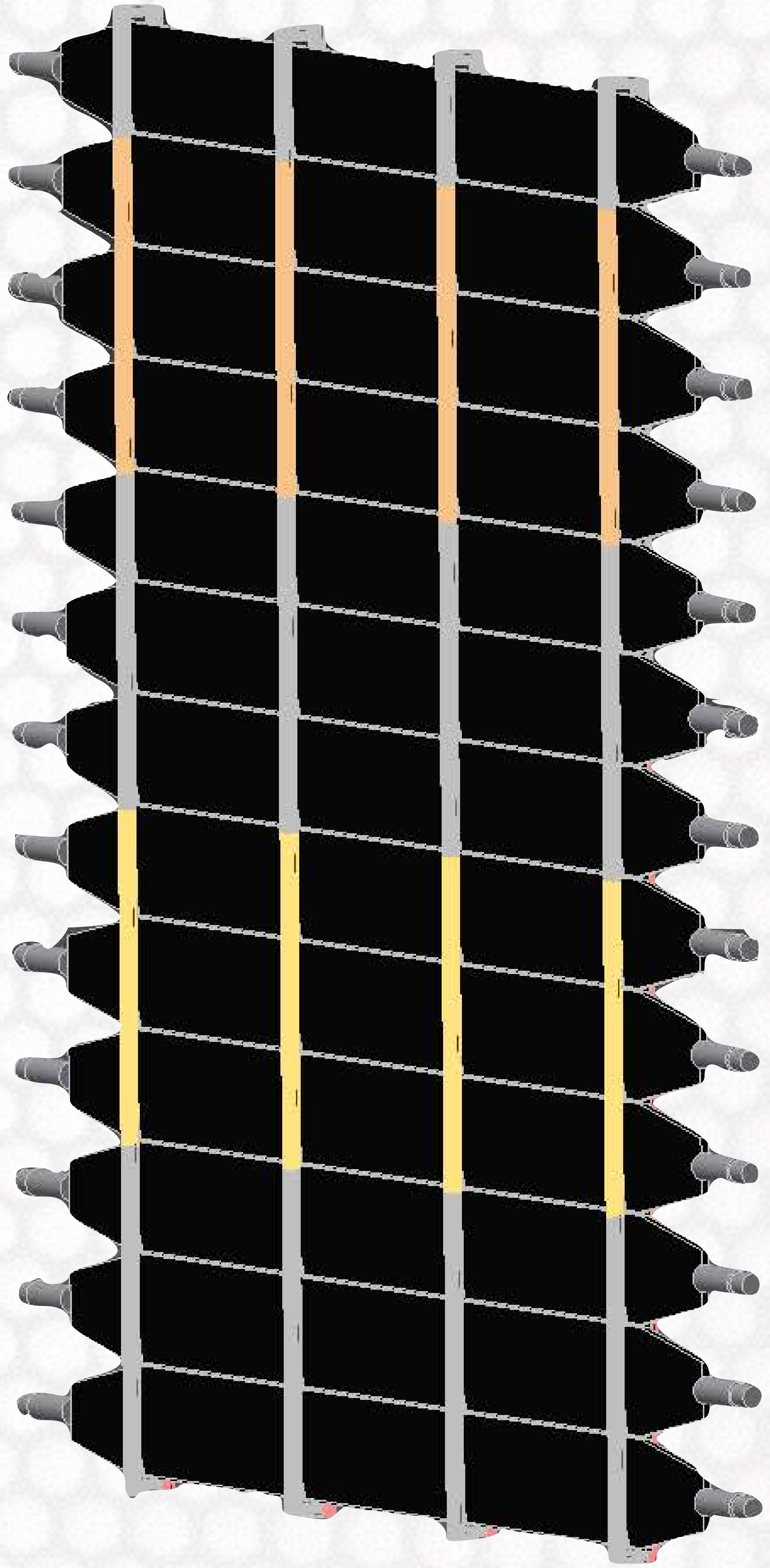
- 30 ton water-Cherenkov detector
- 3 m diameter, 4 m tall steel tank with a plastic liner
- Filled with ultra-pure water loaded with Gadolinium sulfate.
- Detection volume instrumented with conventional PMTs with 500 MHz full waveform digitization and newly developed high-speed photo-detectors.
- Also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



Forward Veto

- Used to veto muon from neutrino interactions in the rock upstream of the detector.
- 26 staggered scintillator panels with PMTs.
- PMT signals are discriminated and recorded by a TDC system for every beam trigger.

Installation, August 2015

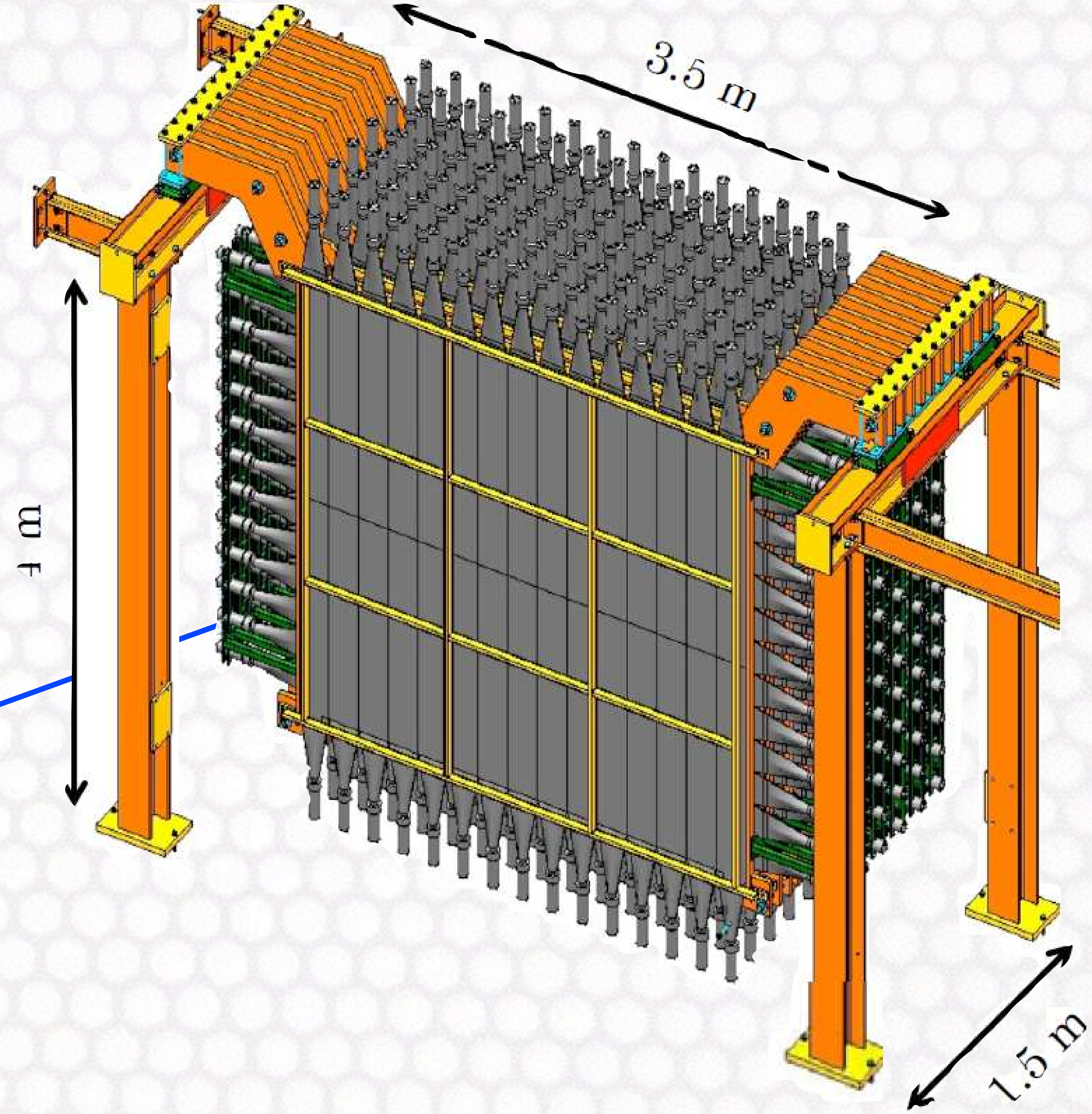


The ANNIE Water Volume

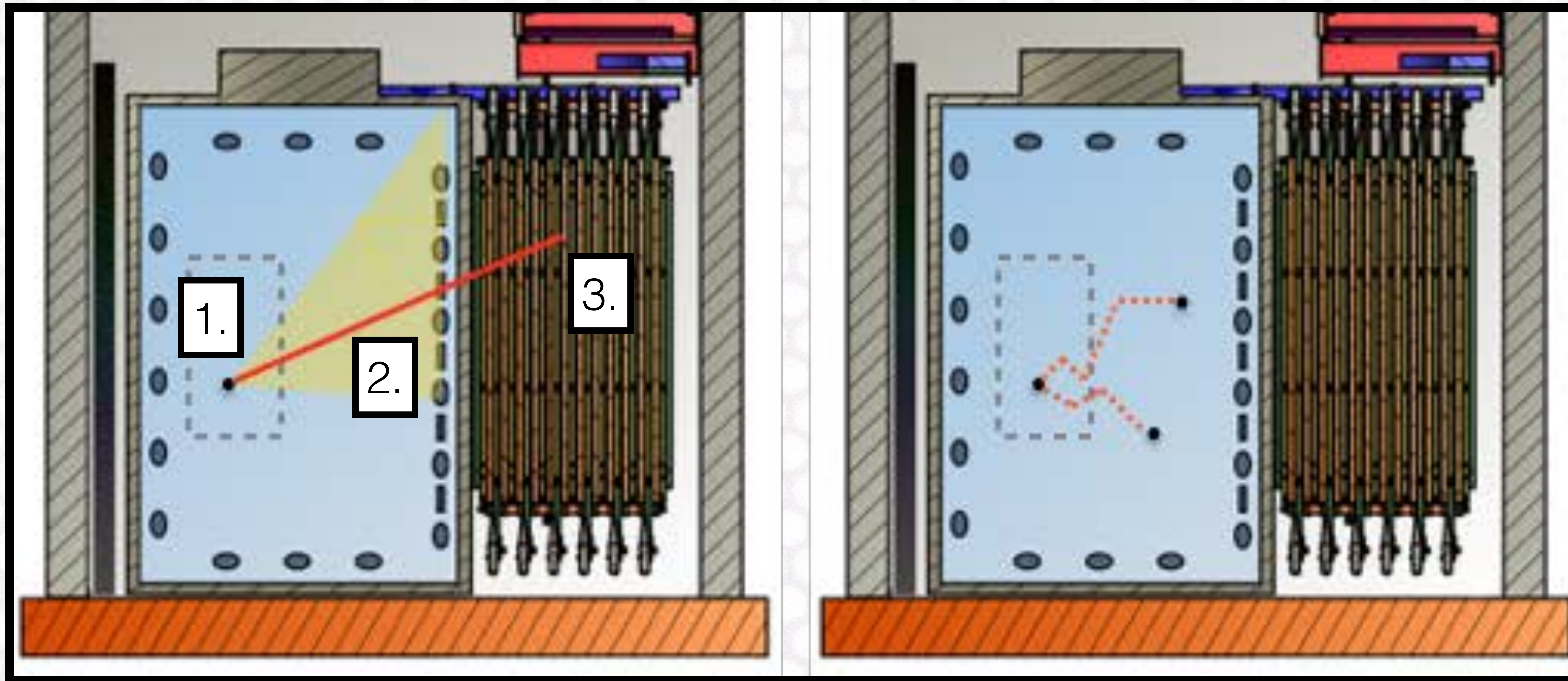
- **3 m diameter, 4 m tall** steel tank with a plastic liner.
- **30 tons** of ultra-purified water loaded with **gadolinium sulfate**
- The water moderates and captures external neutrons.
- PMTs and LAPPDs attached to a stainless steel inner structure.
- **Full-waveform digitization** with custom 500 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, 5 vertical)
- 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

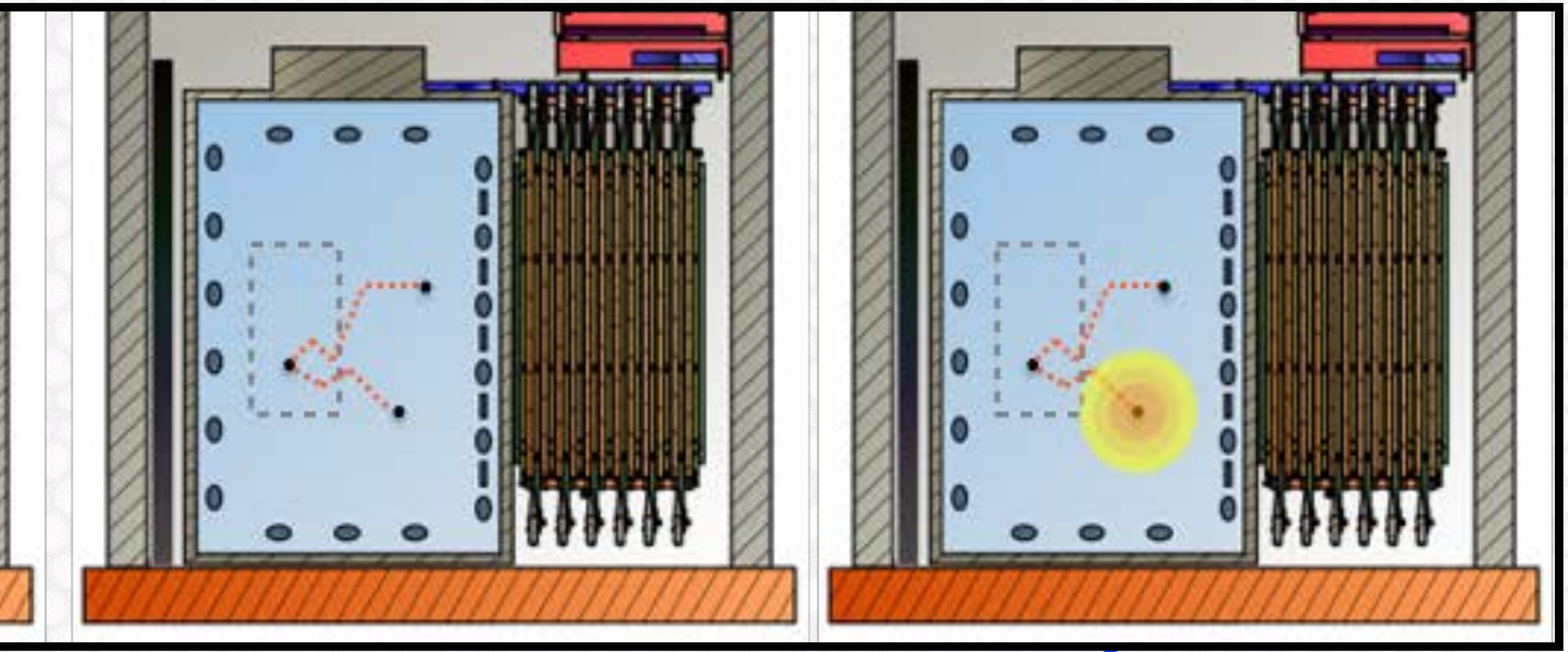


1. Charged current muon-neutrino interaction within the fiducial volume
2. Cherenkov light from the muon is detected by photodetectors on the walls of the water volume
3. Muon is tracked and ranges out in the Muon Range Detector (MRD)

ANNIE Detection Principle

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

ANNIE Detection Principle



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

ANNIE Operation Timeline

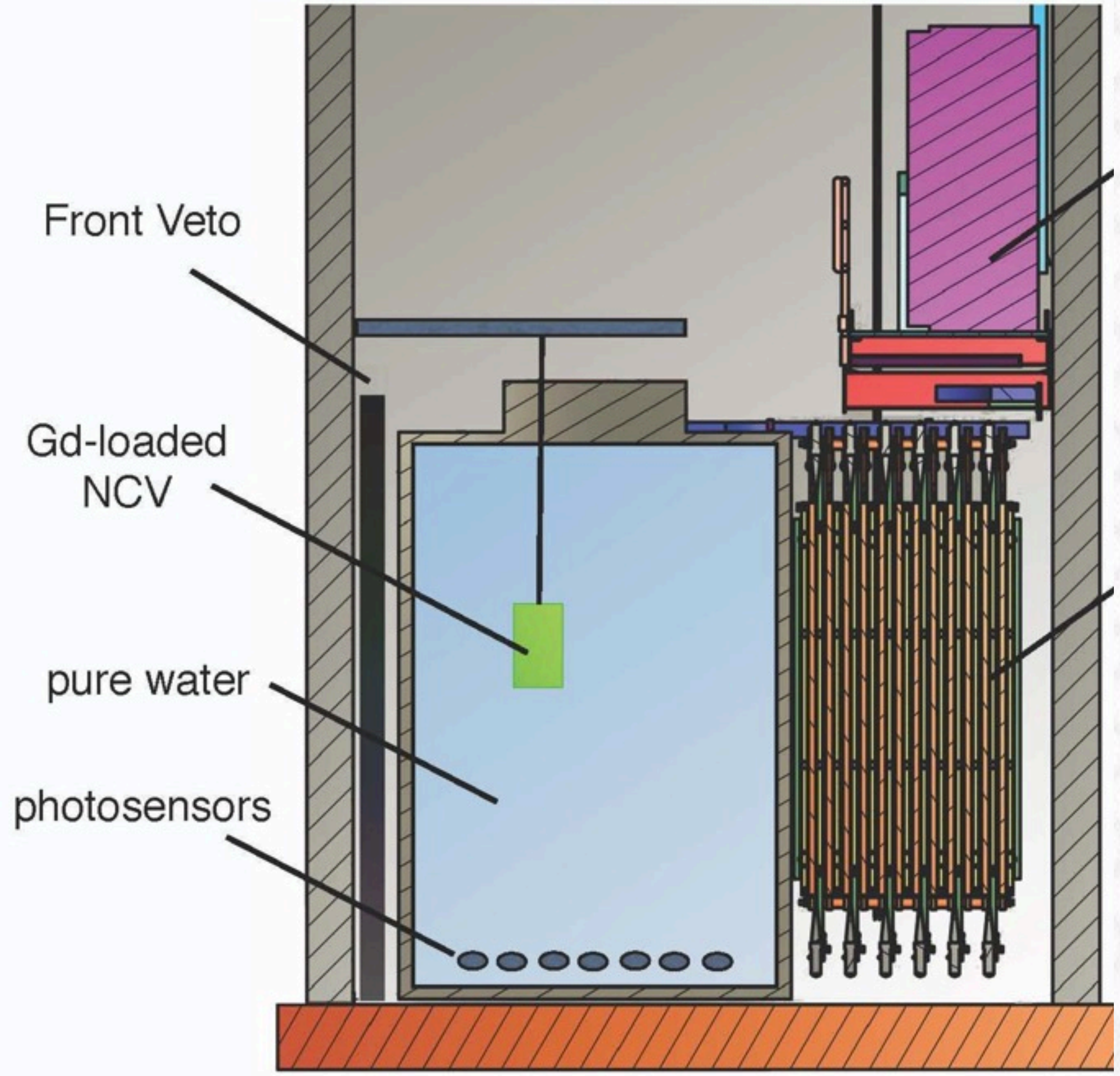
- **Phase I** - Engineering run and Background Measurement. **(Complete)** (Spring '16-Summer '17)
  - Operated with conventional PMTs and pure water with a small movable vessel filled with Gd-loaded liquid scintillator.
  - Measured neutron backgrounds as a function of position inside the tank.
  - LAPPD Testing, characterization and integration R&D.
- **Phase II** - Physics Run **(Funded, currently under construction)**
  - Data-taking will start in February.
  - 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

Phase I installation-Lowering the tank

Feb. 2016

Will it fit?

Phase I installation-Lowering the tank

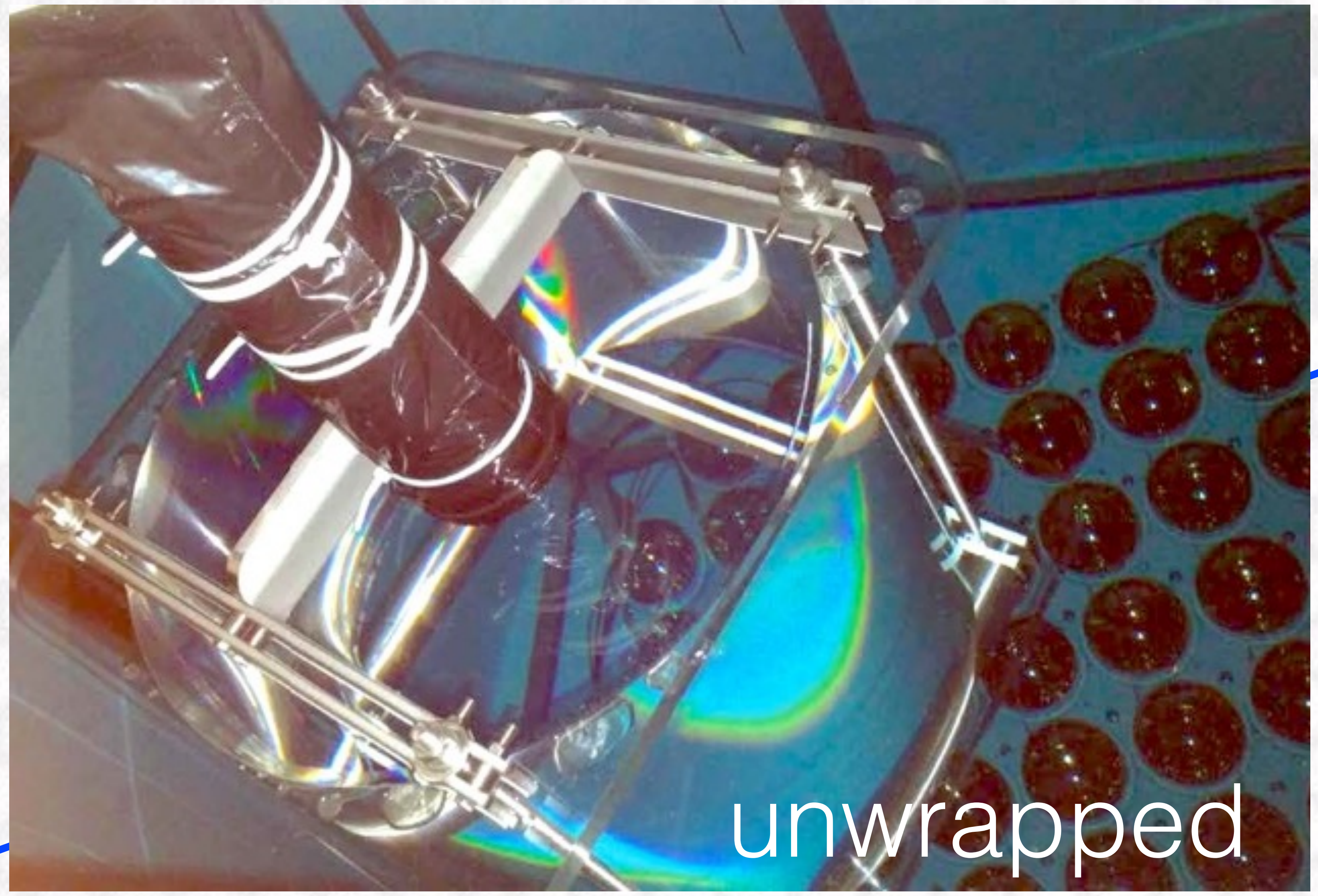
So far, so good…

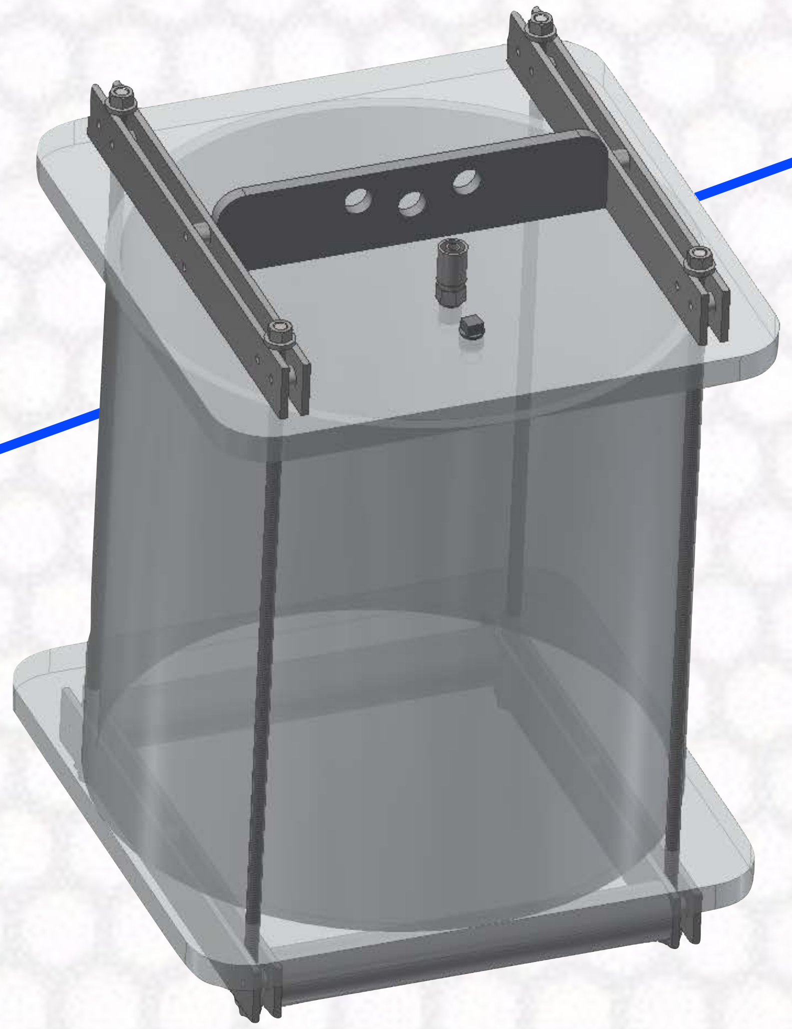
Phase I installation-Lowering the tank

Ok, great!

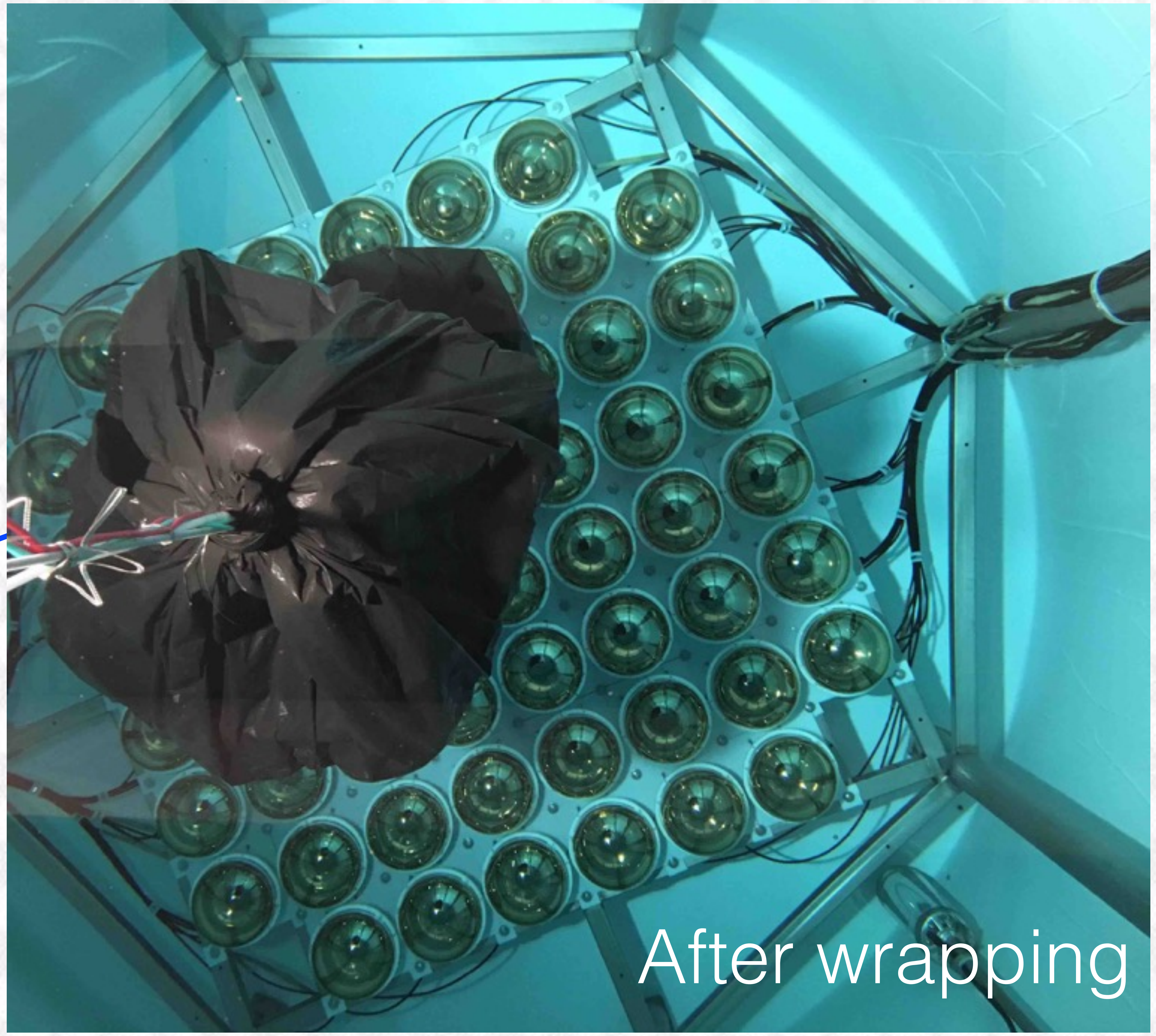
The NCV

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



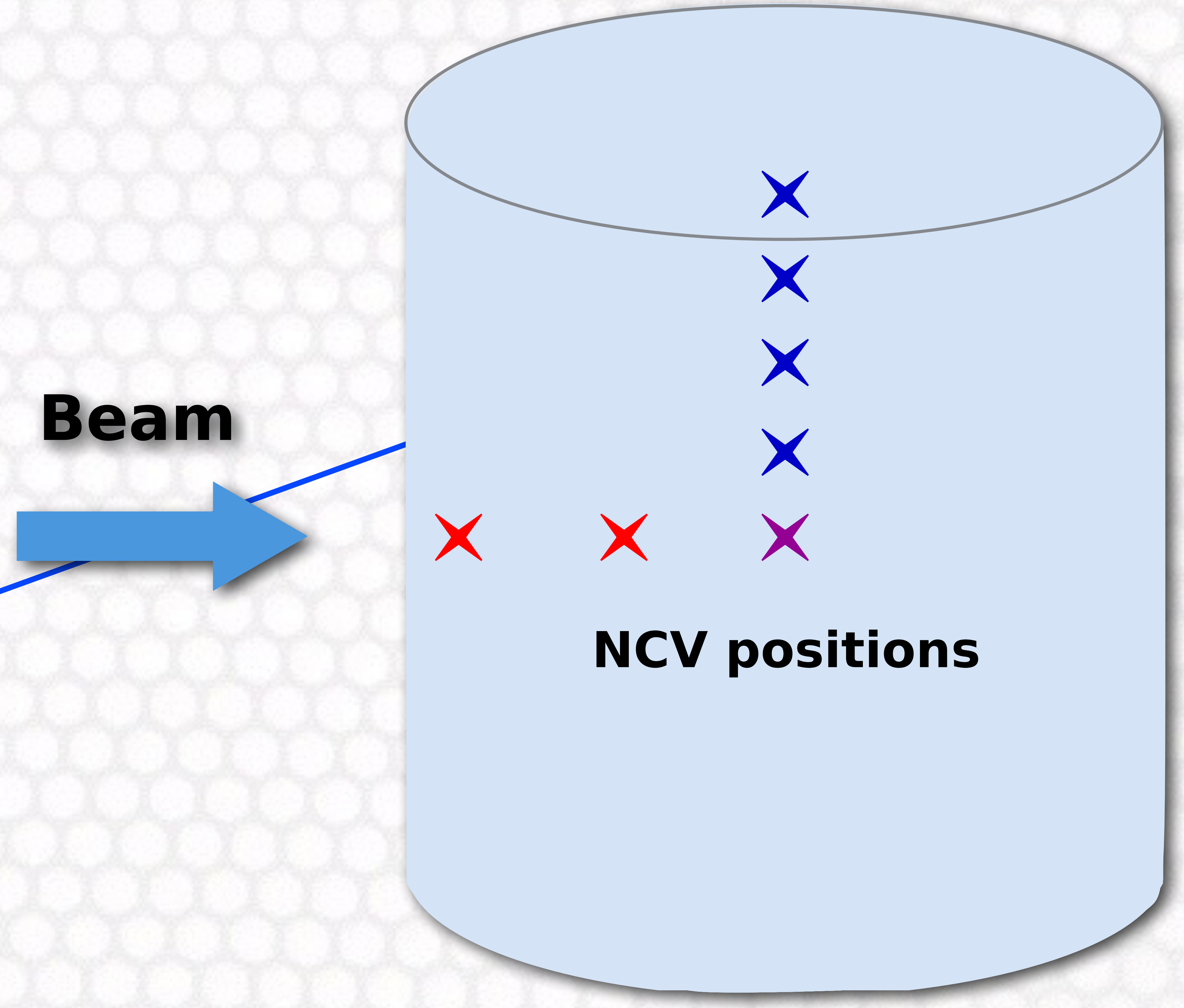


design



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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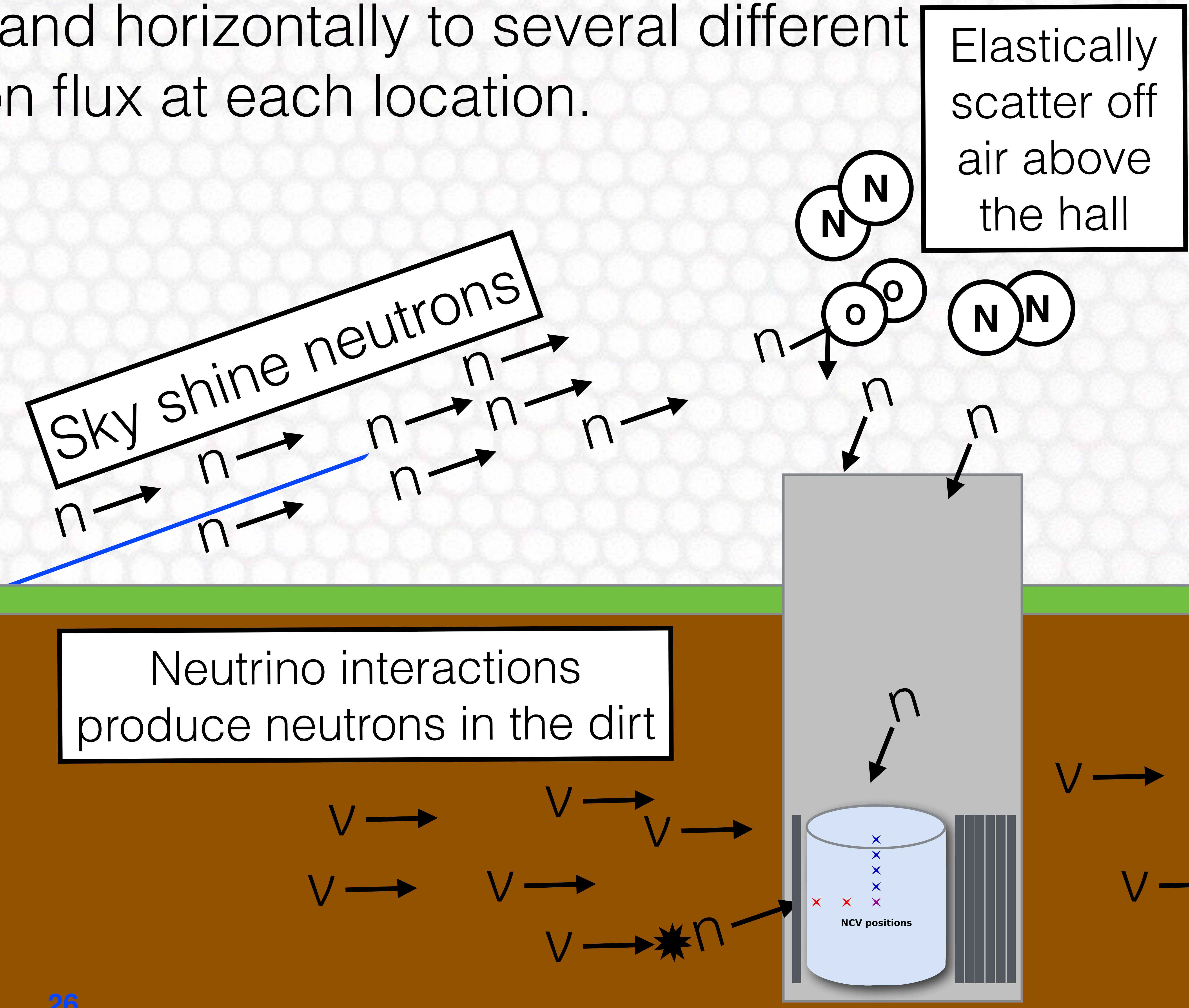
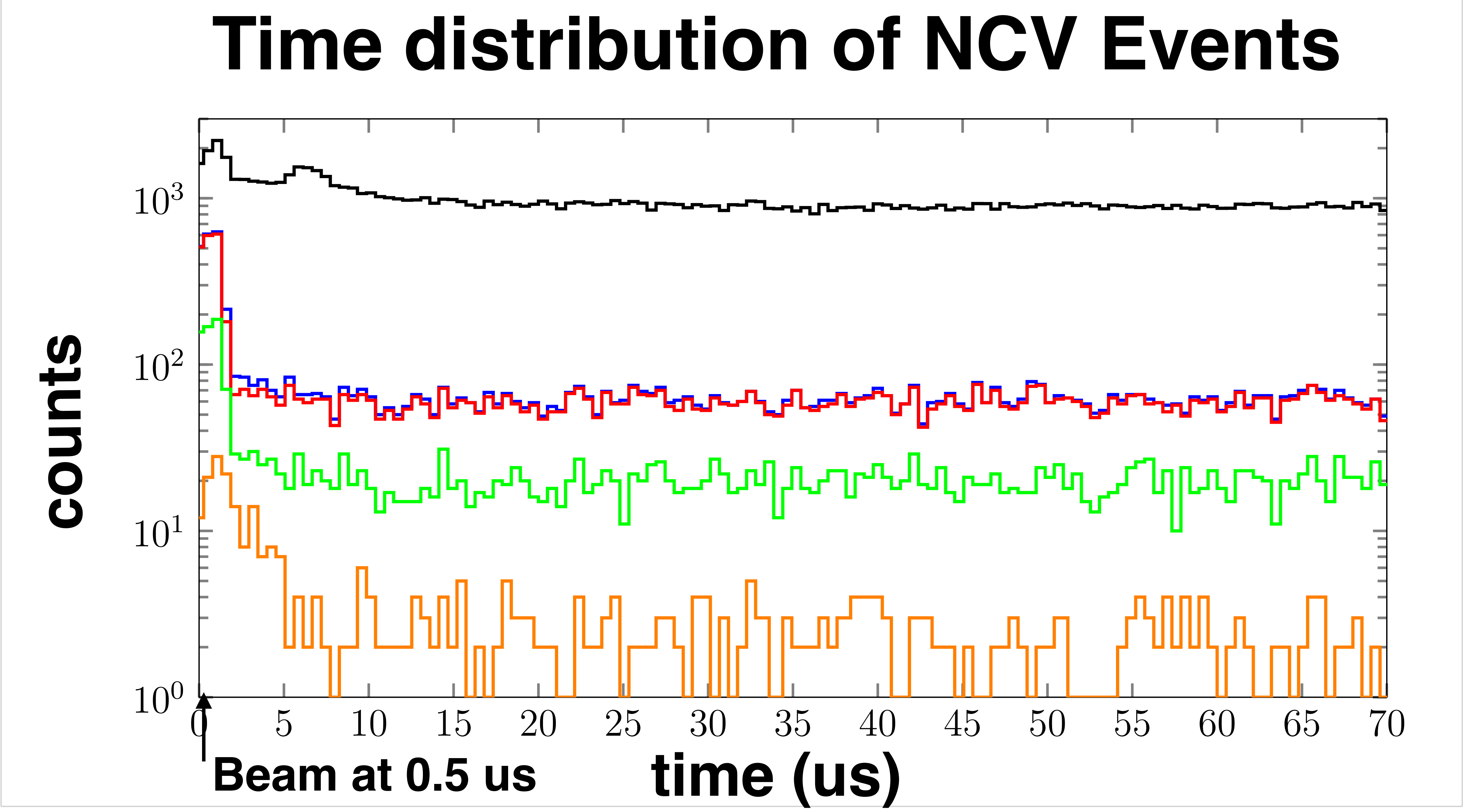
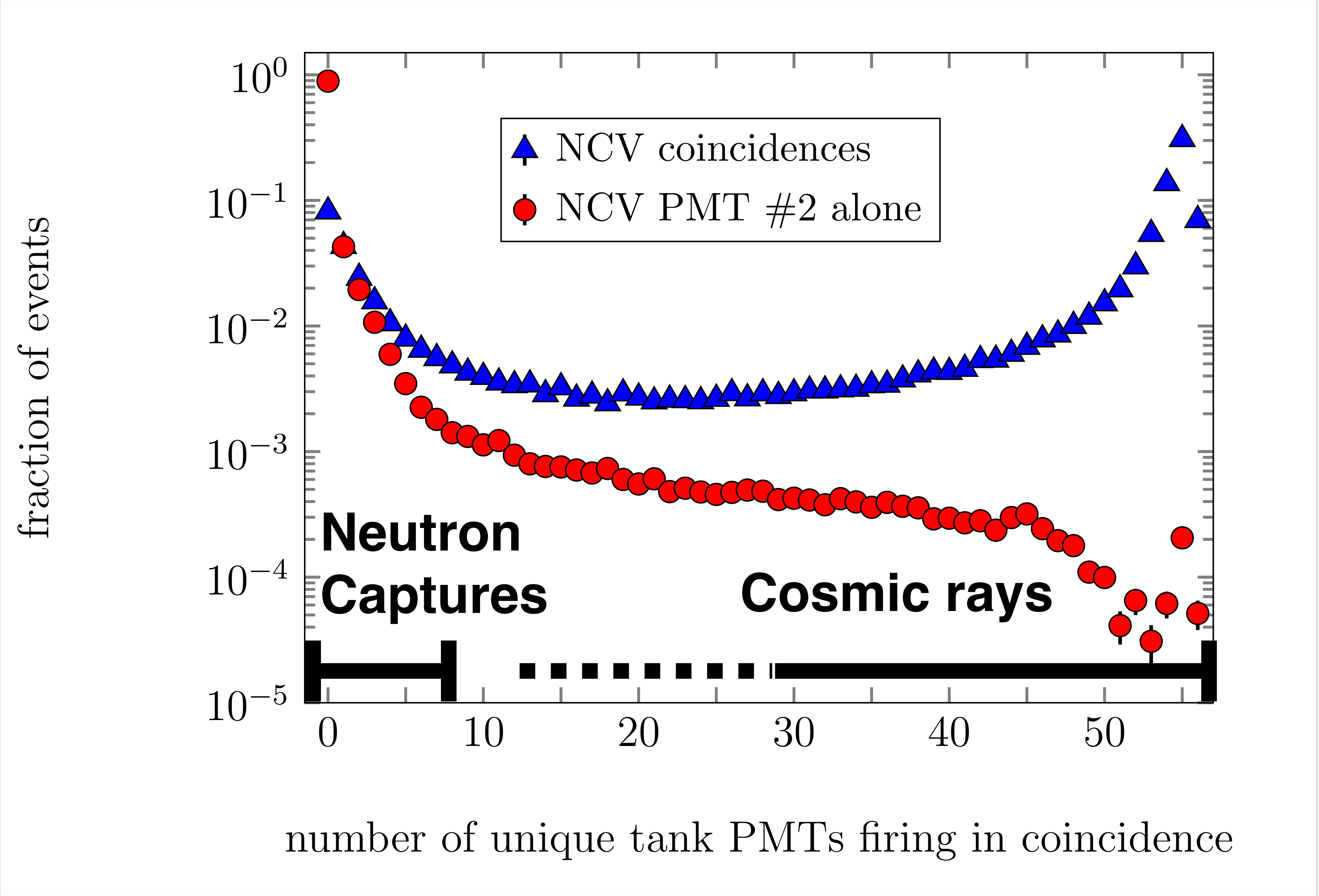


Booster Neutrino Beam

Neutron Background Analysis





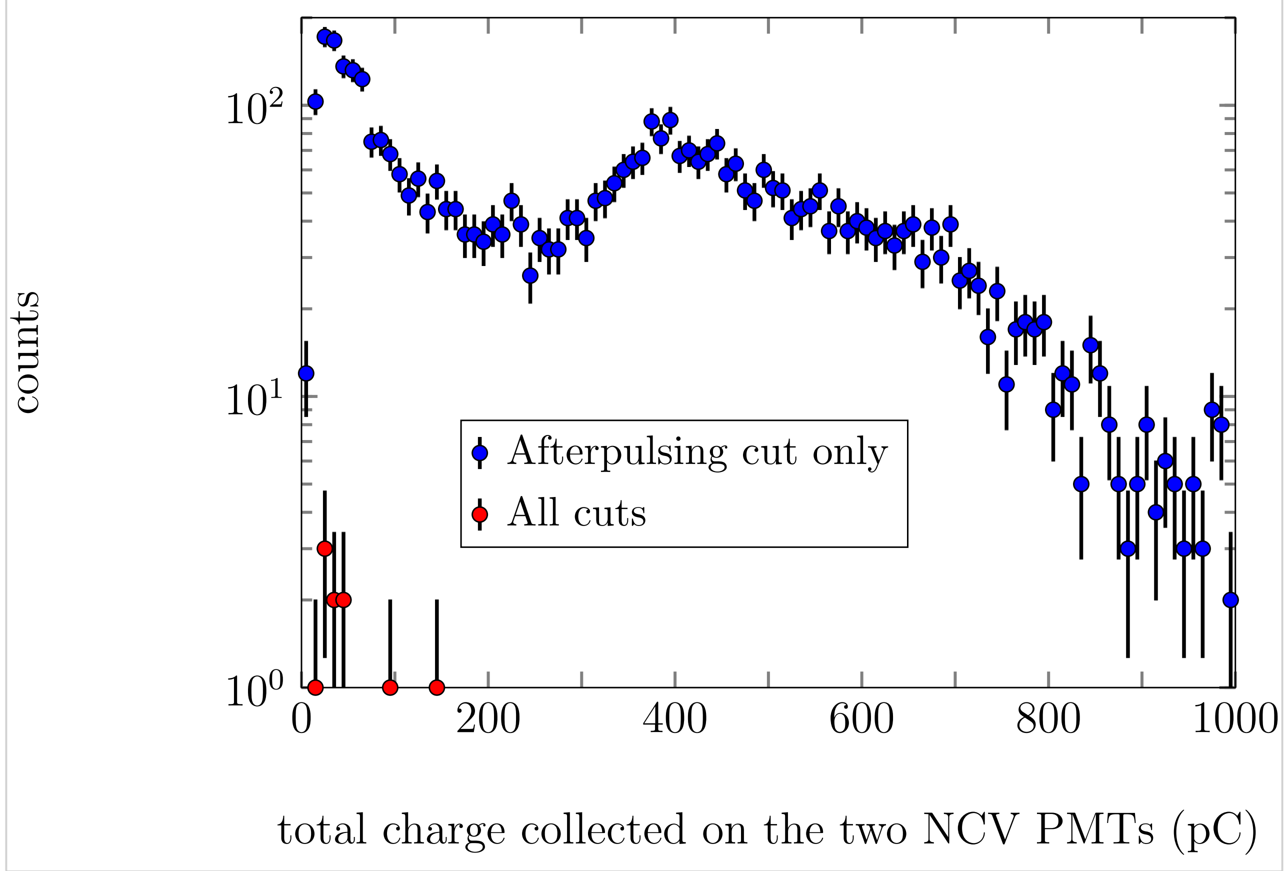
(black) Raw event counts

(blue) Coincidence of both NCV PMTs

(red) At least 10 μs since last event (afterpulsing veto)

(green) Total NCV PMT charge < 150 pC

(orange) < 8 coincident water tank PMTs



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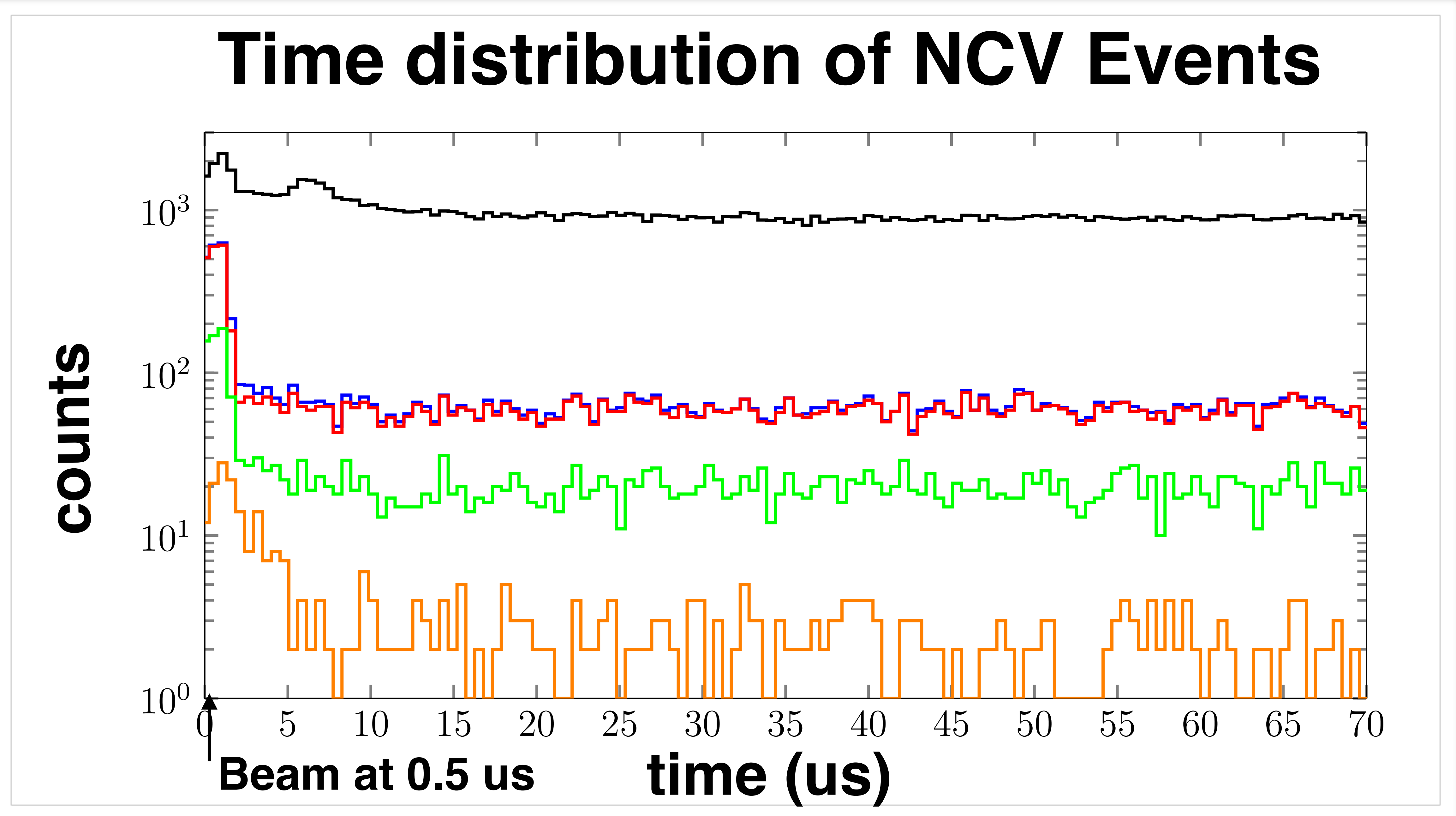

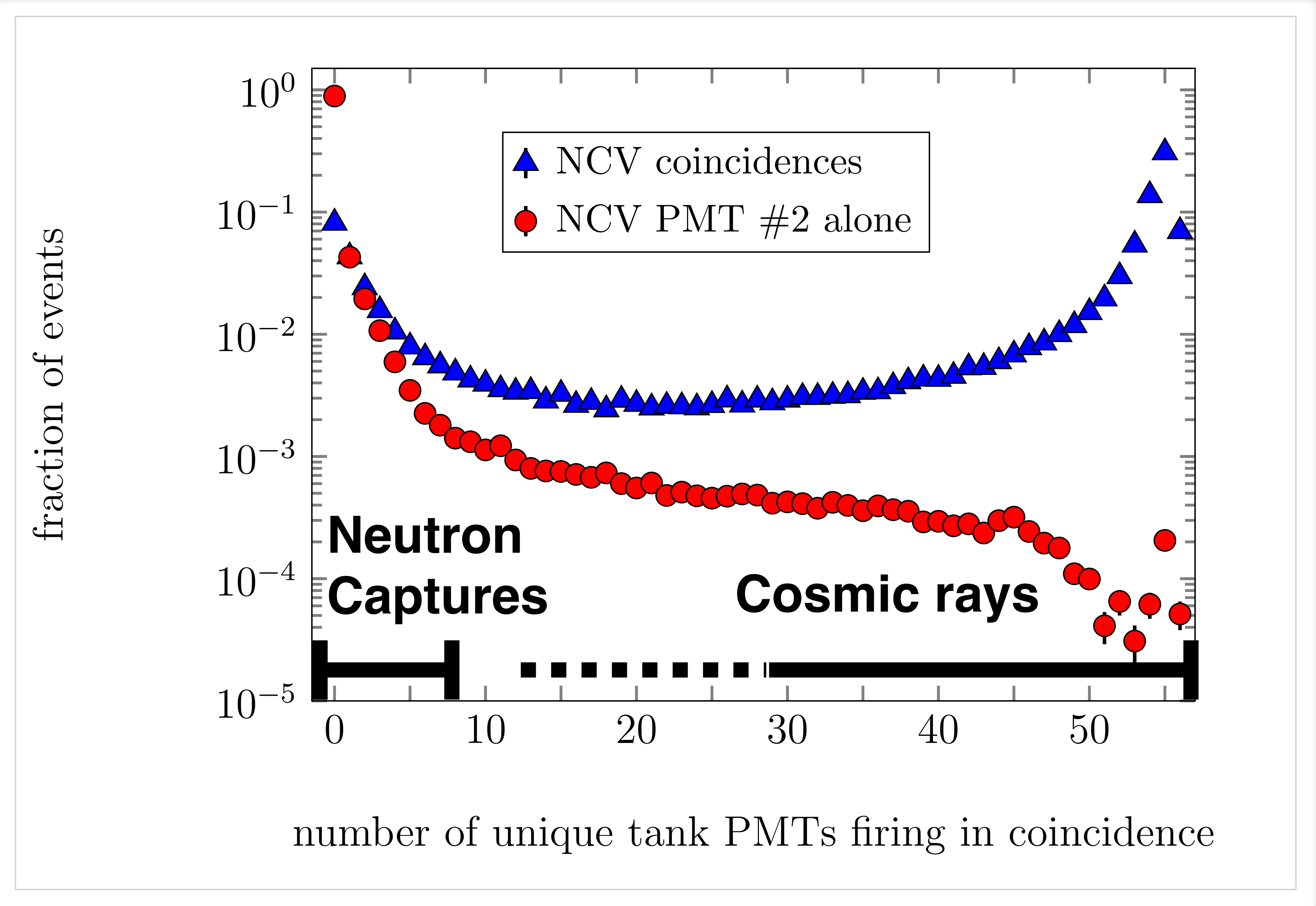

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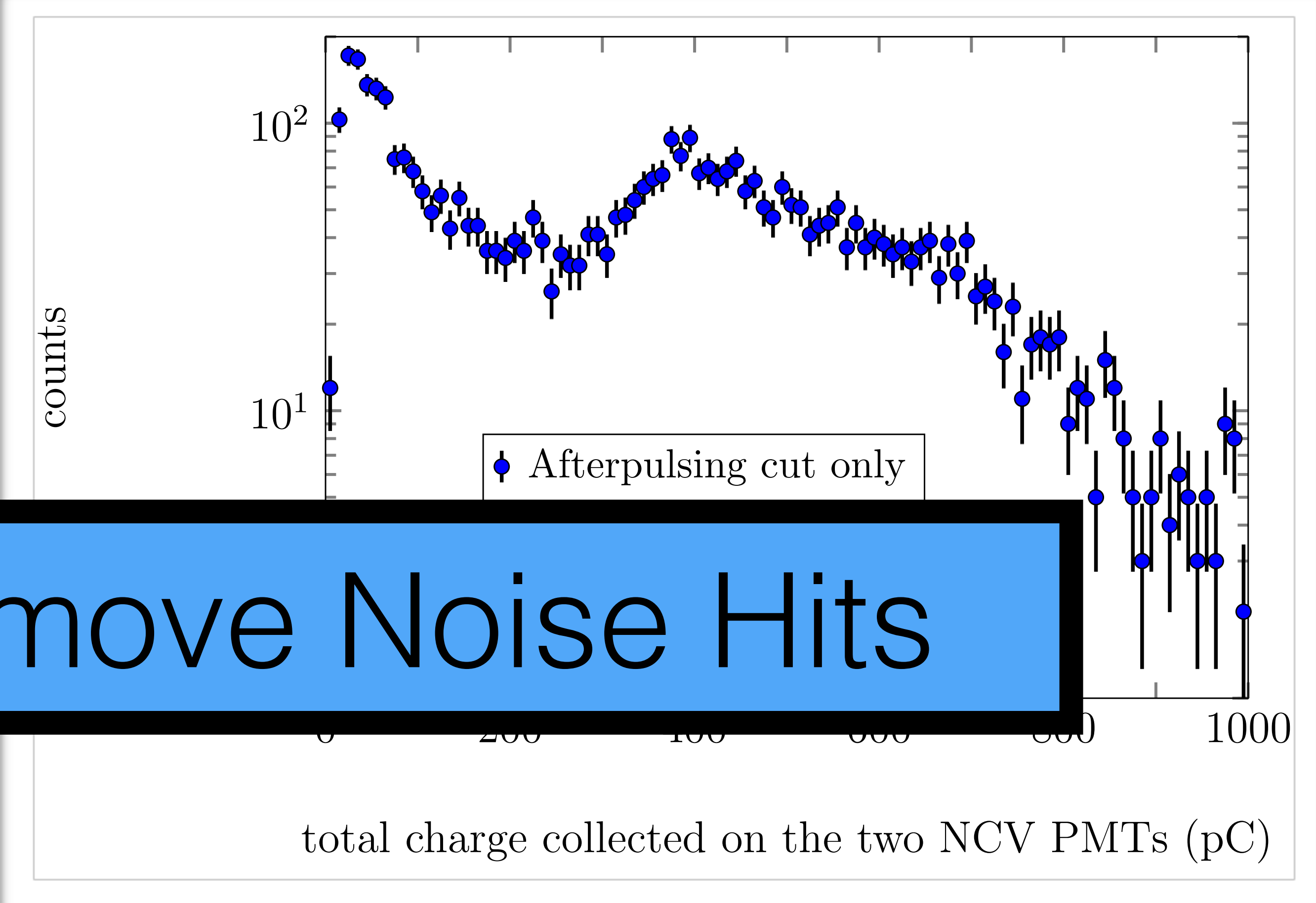
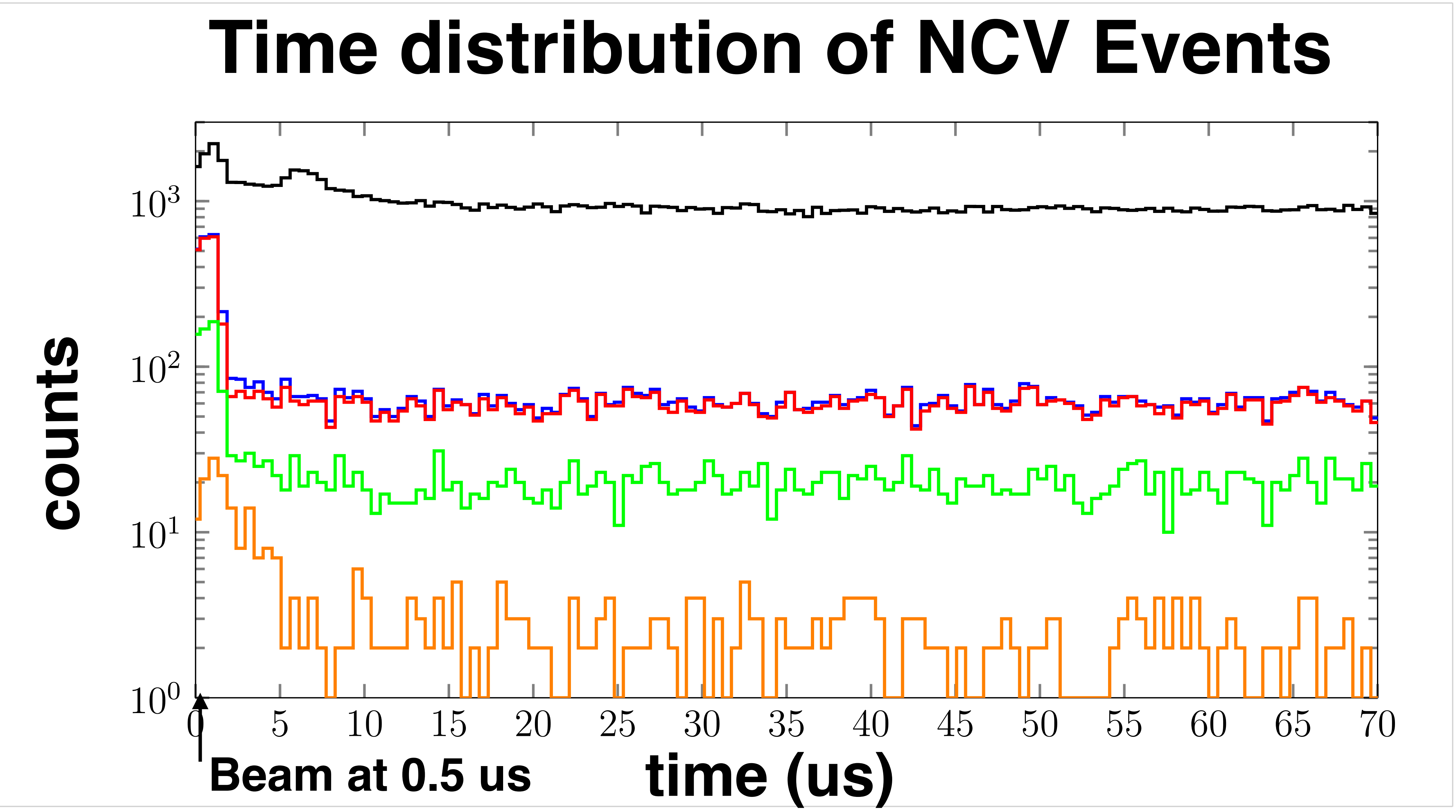
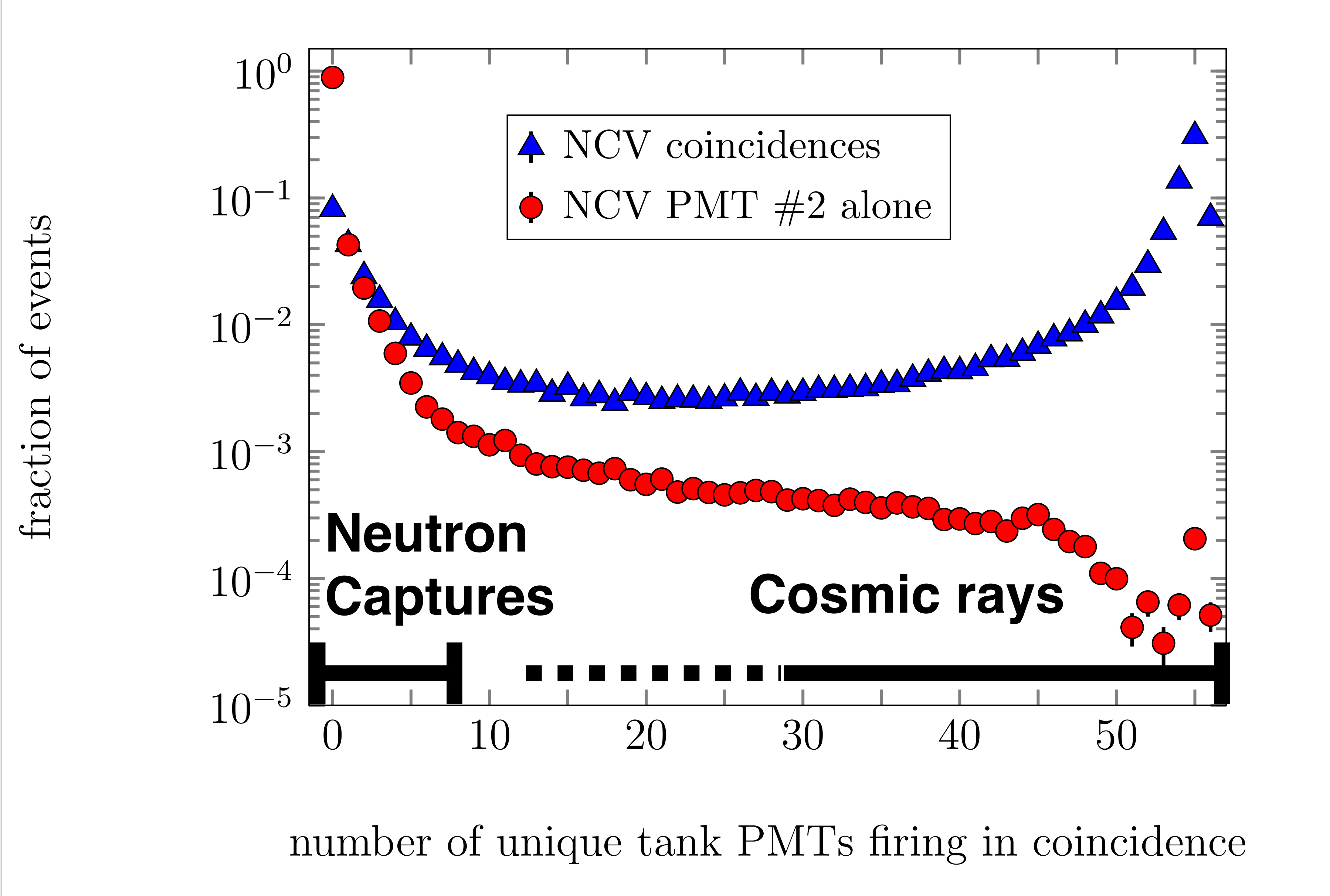


Remove Noise Hits

Neutron Background Analysis





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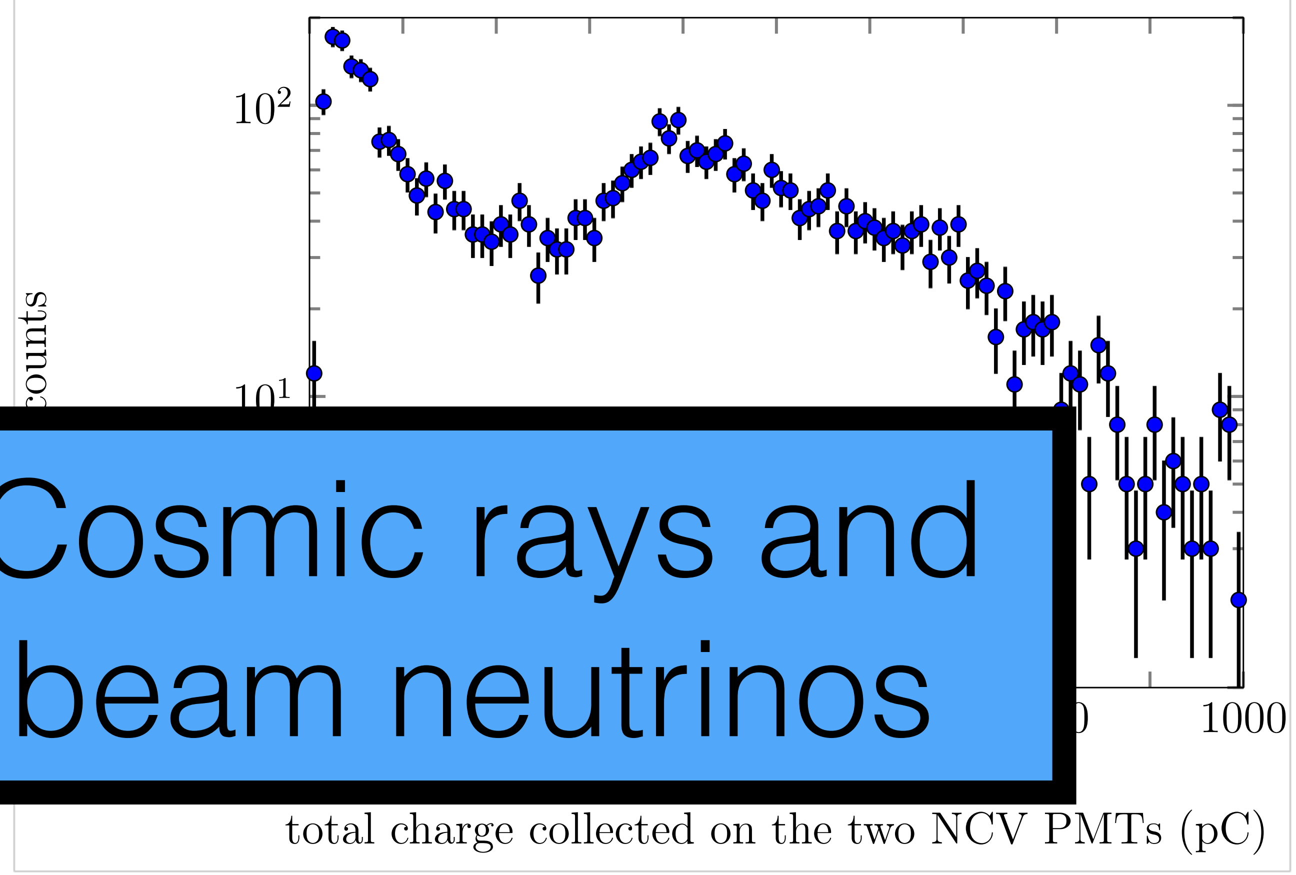
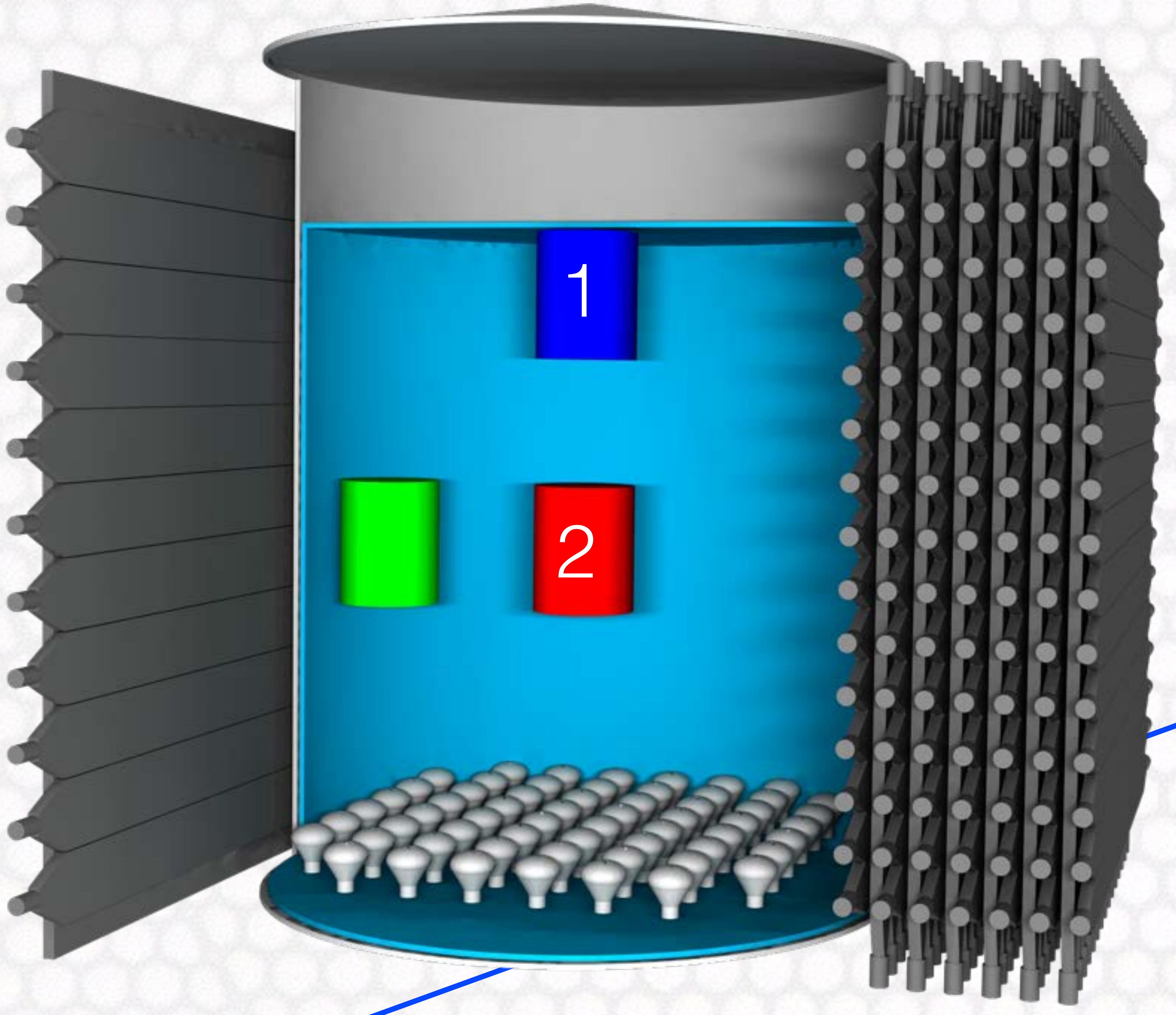
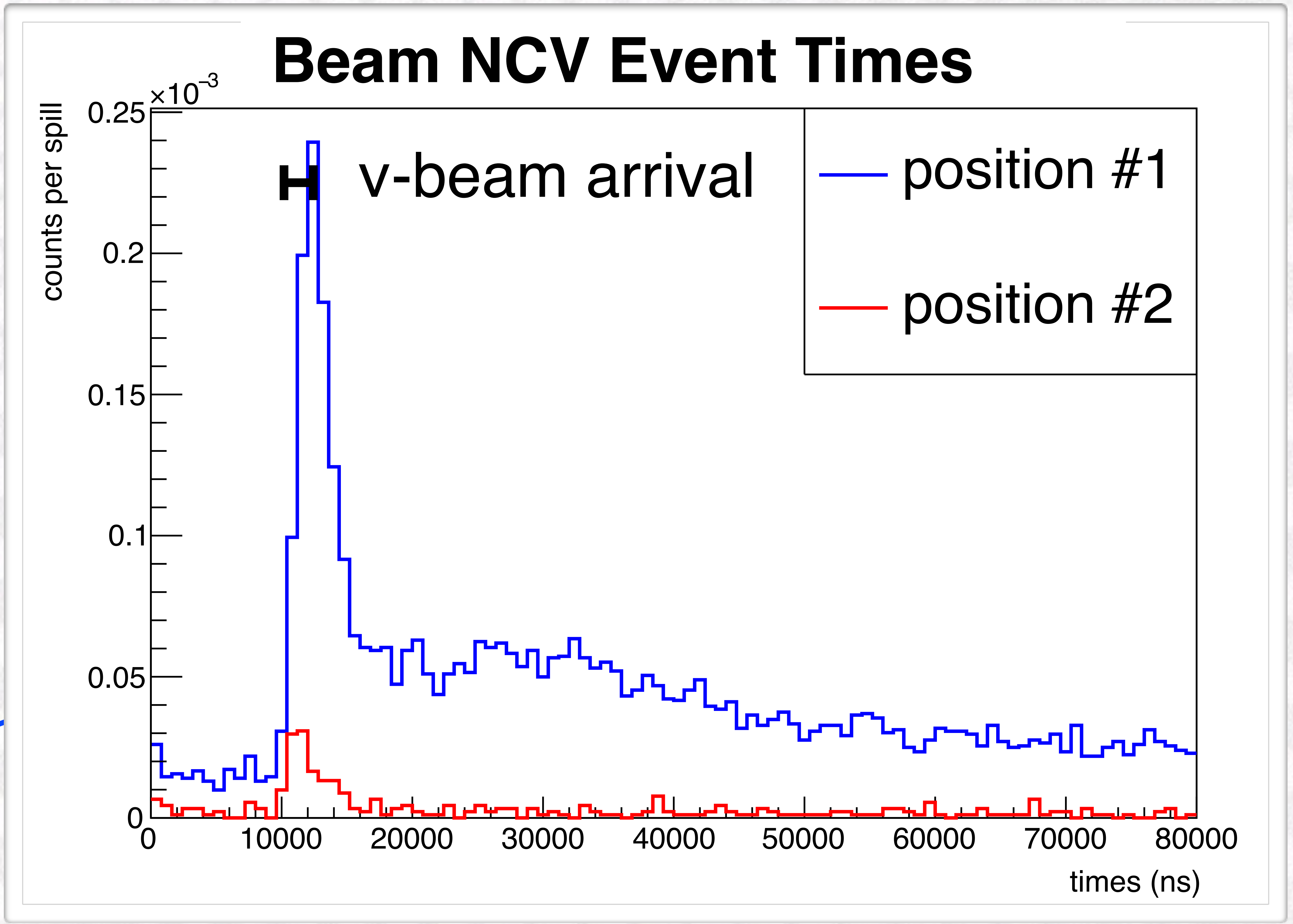


Remove Cosmic rays and obvious beam neutrinos

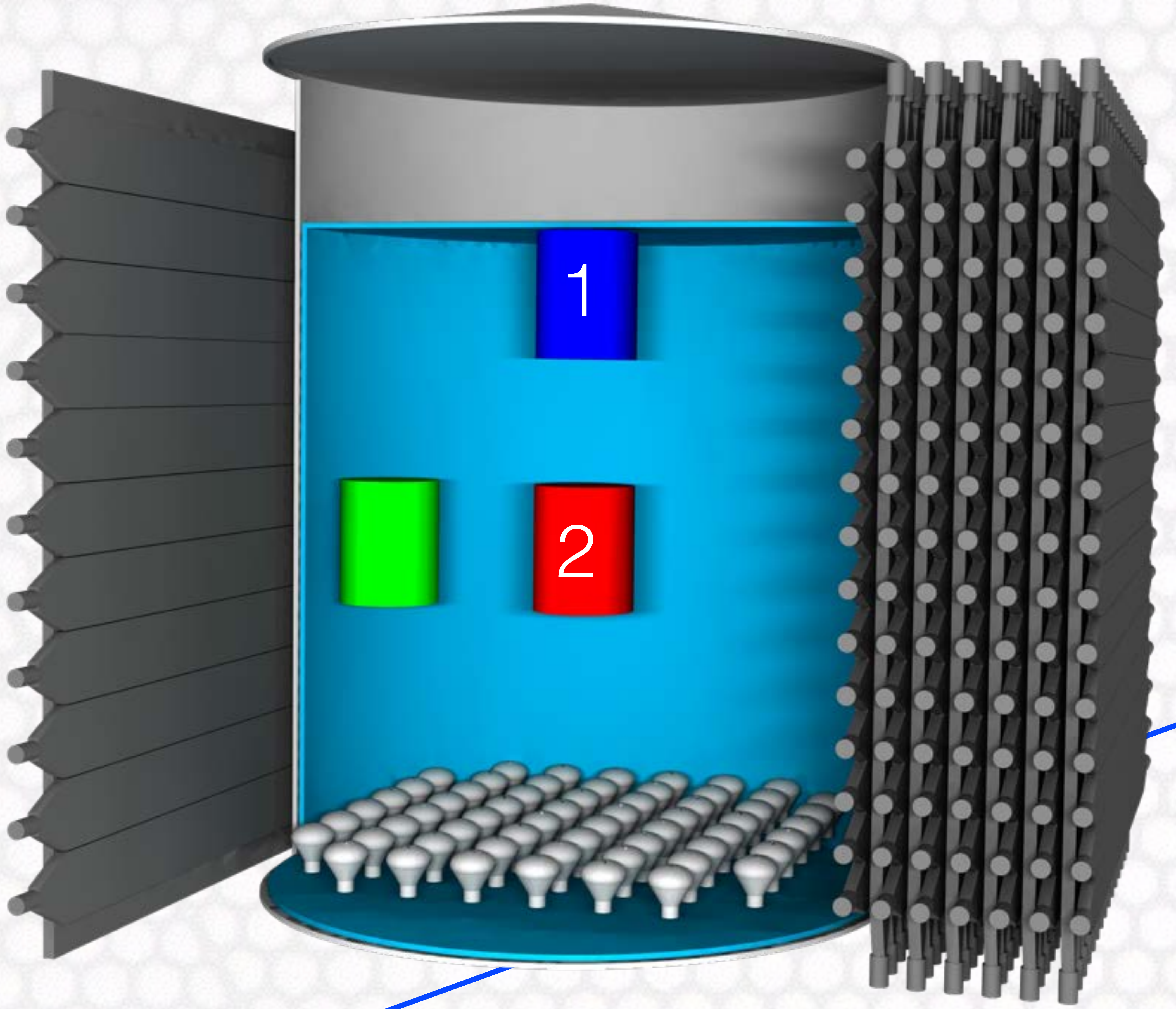
NCV Position Scan

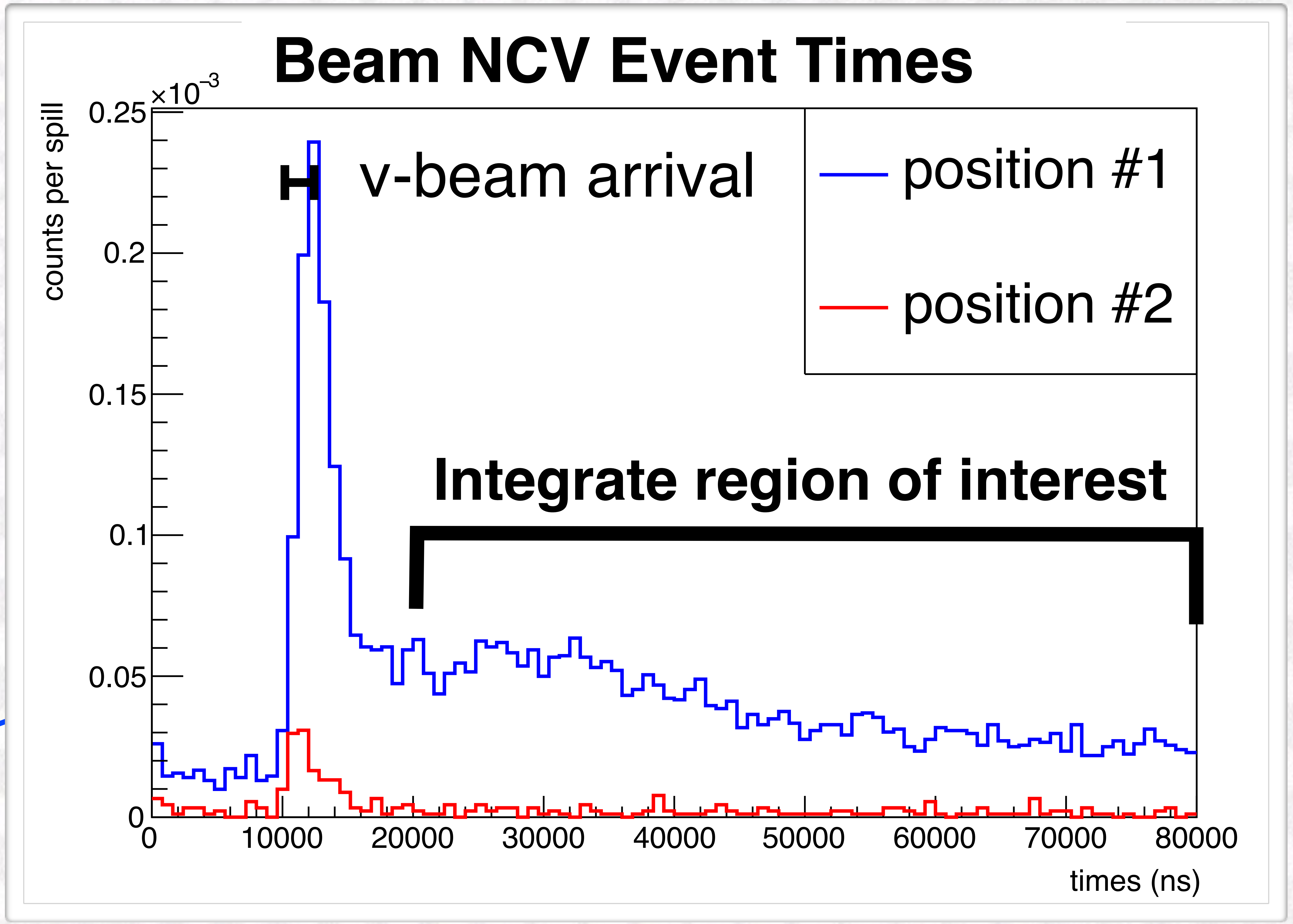




- 0-10 us: Pre-beam background
- 10-15 us: Proton recoils
- 15 us+: Neutron captures

NCV Position Scan





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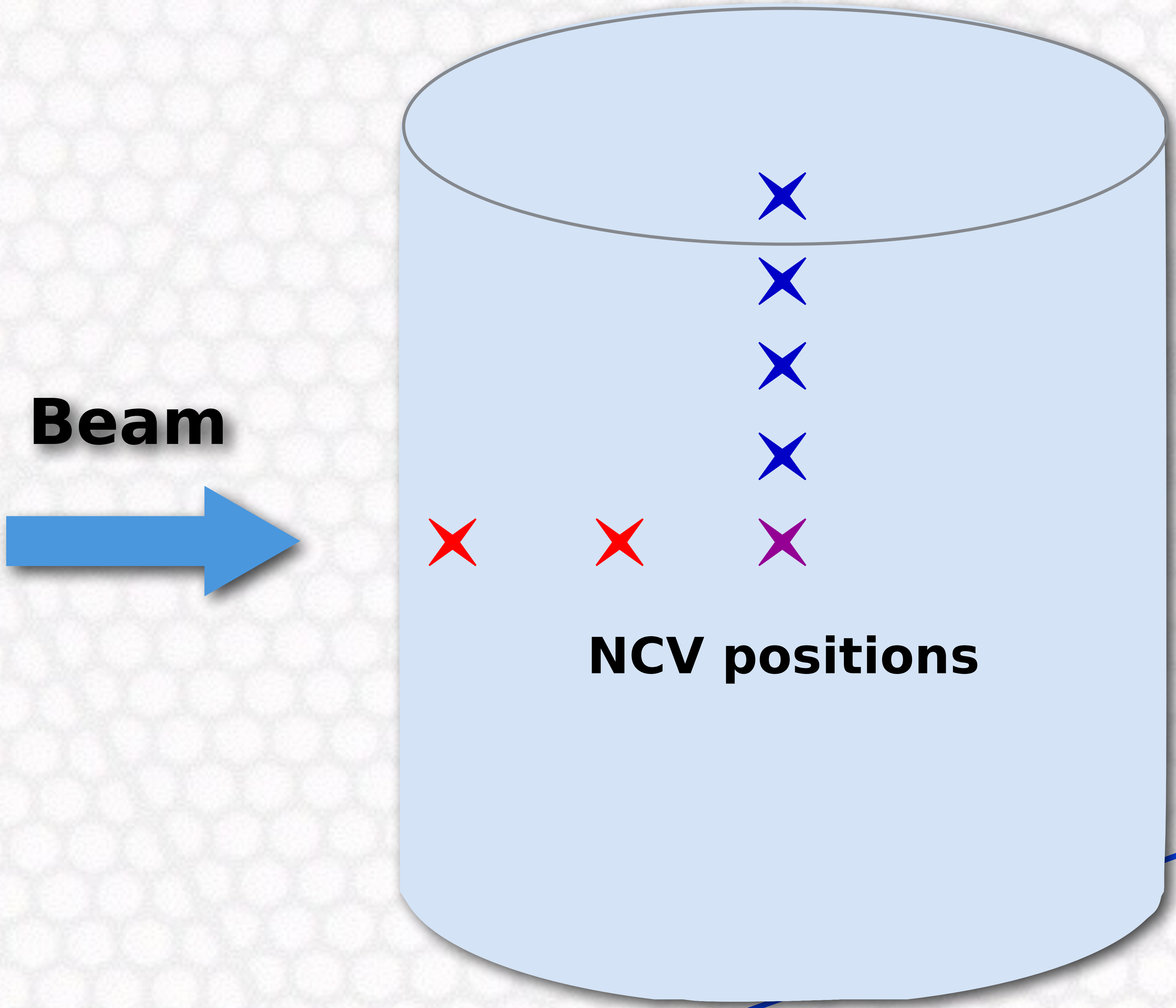
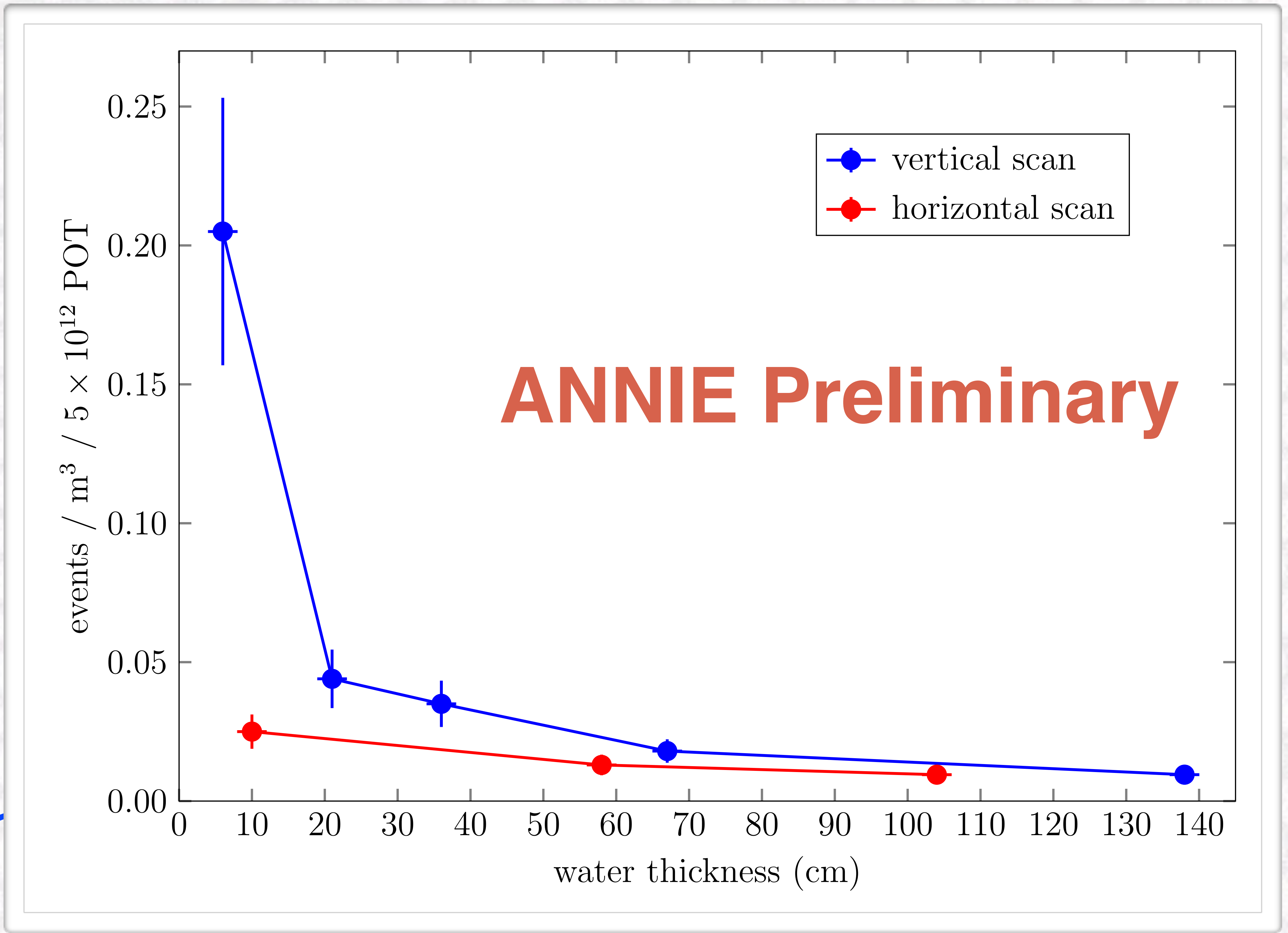
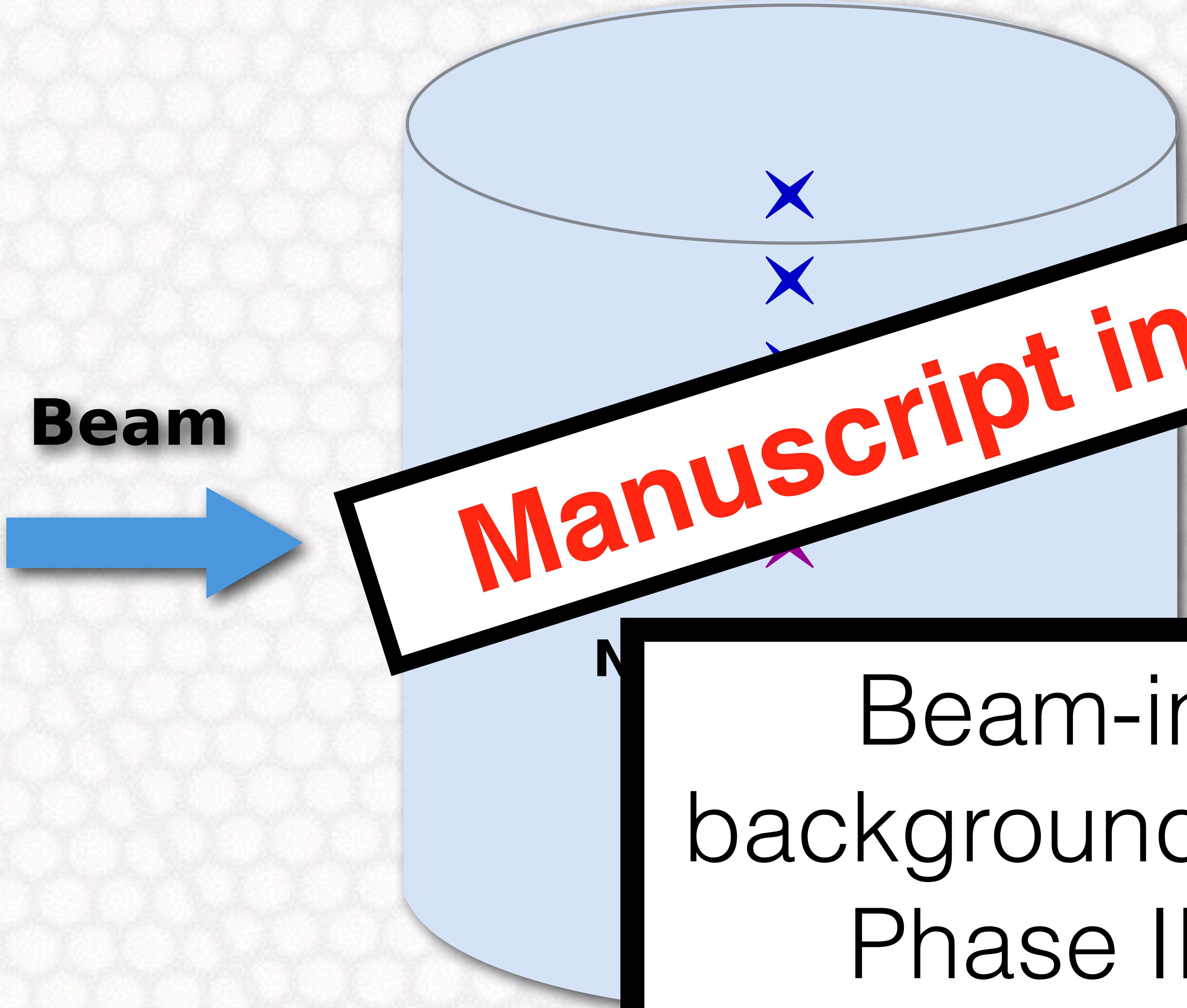
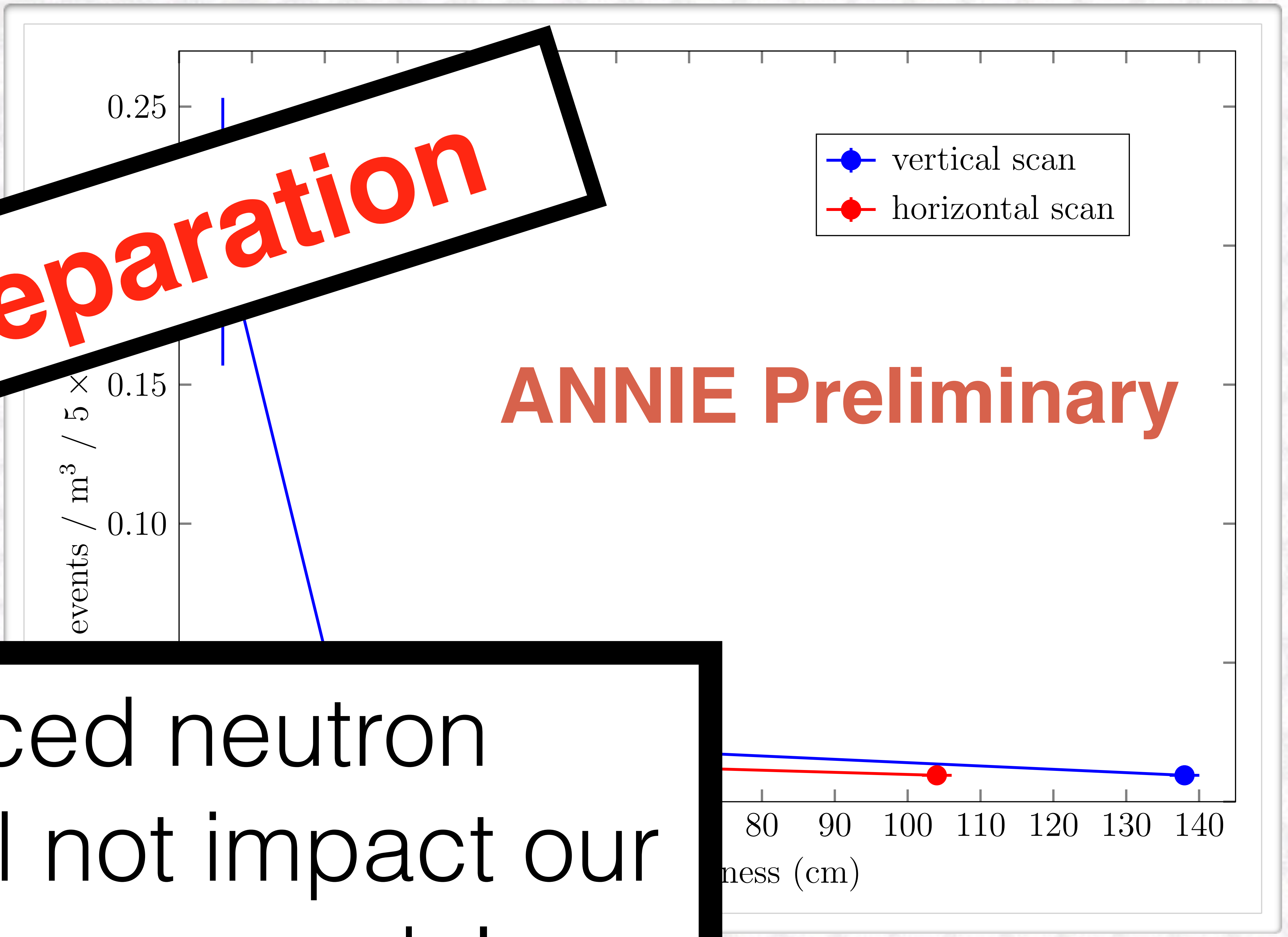




Average 0.02 neutrons/beam-spill/m^3 in the Phase-II fiducial volume

NCV Position Scan





Manuscript in preparation

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

…ns/beam-spill/m^3 in the Phase-II fiducial volume

Phase II

Neutrino Physics run

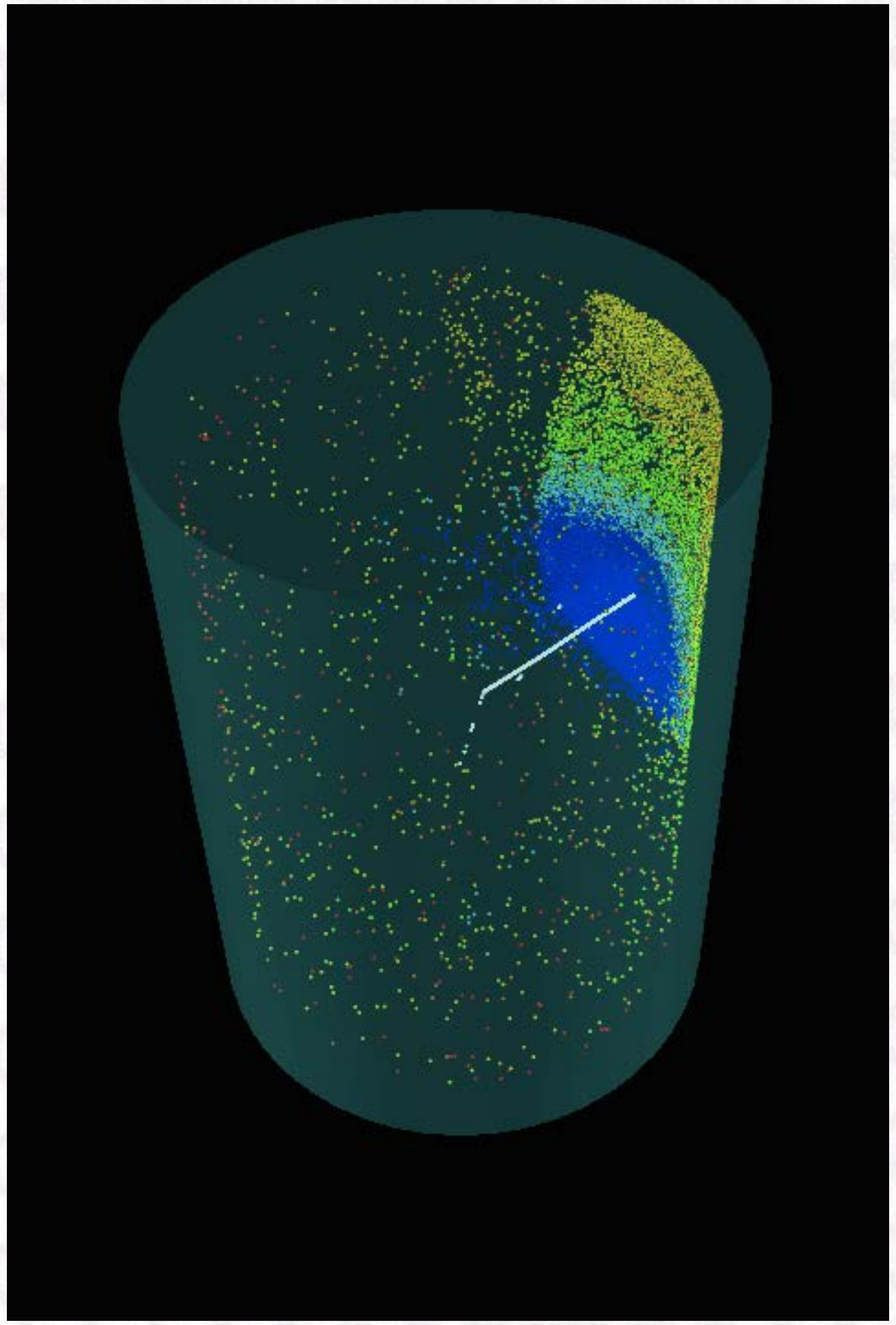
FUNDED!!!

Neutrino

and UNDER CONSTRUCTION

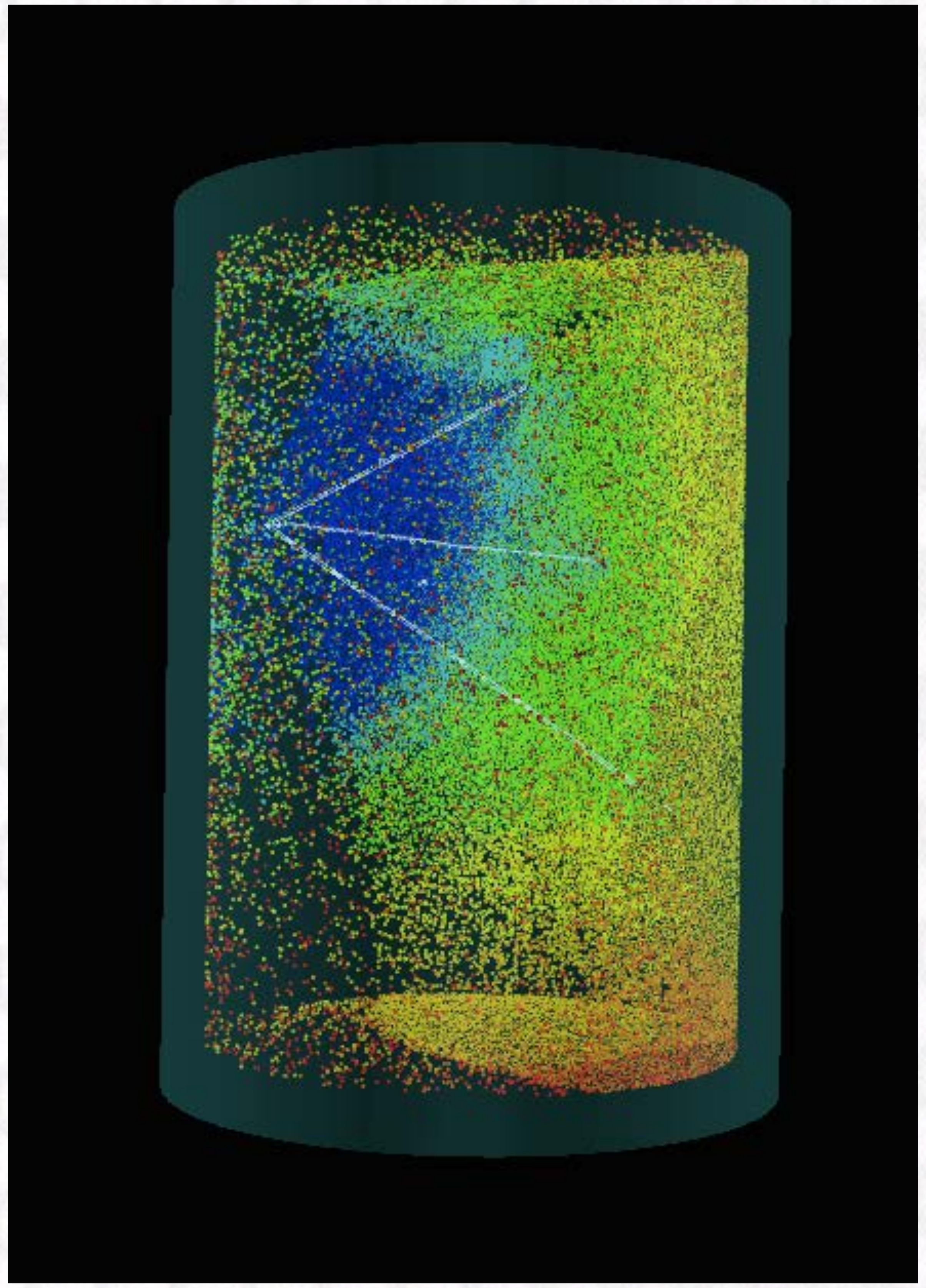
ANNIE Physics Goals

- 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…



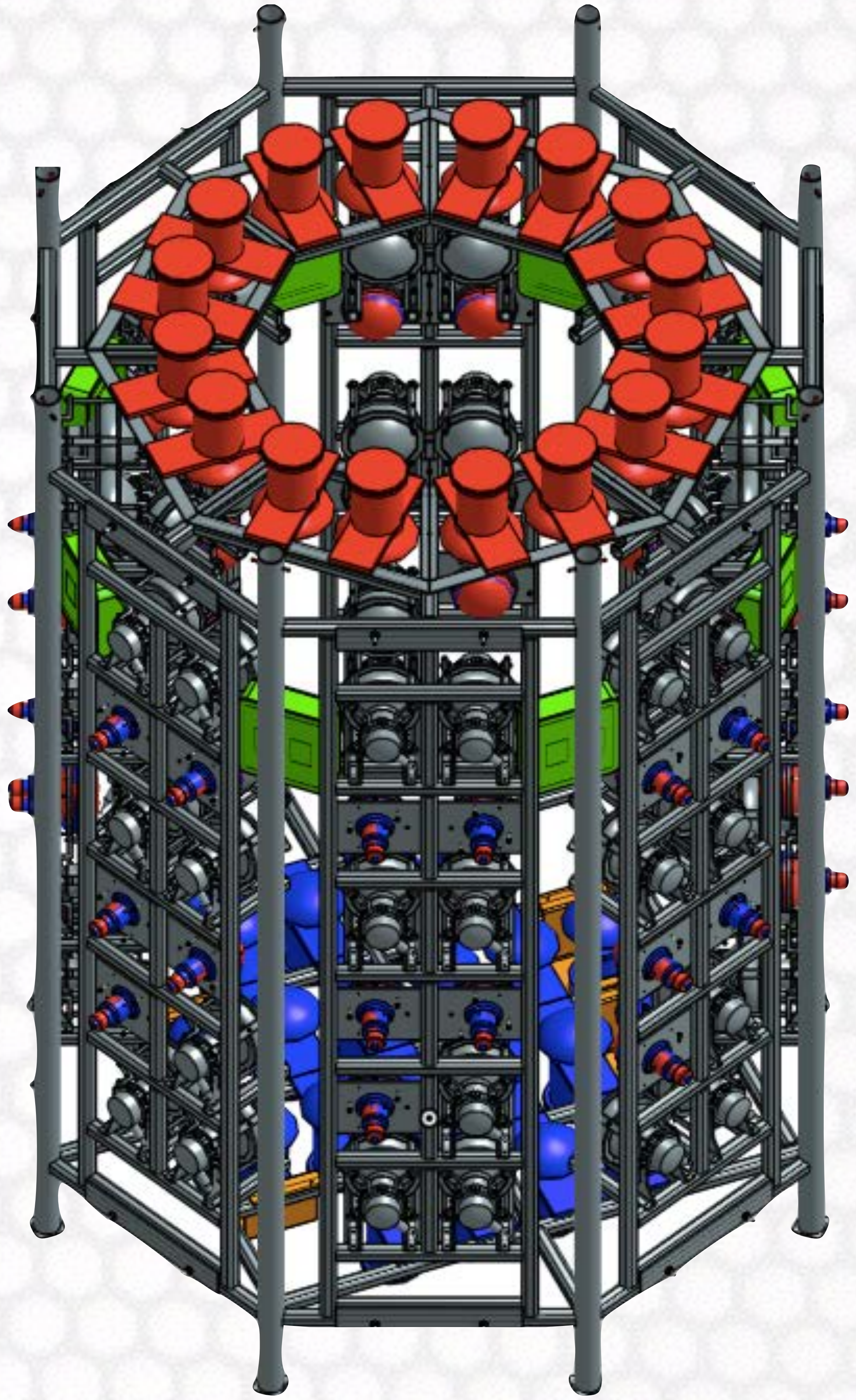
ANNIE Physics Goals

- 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



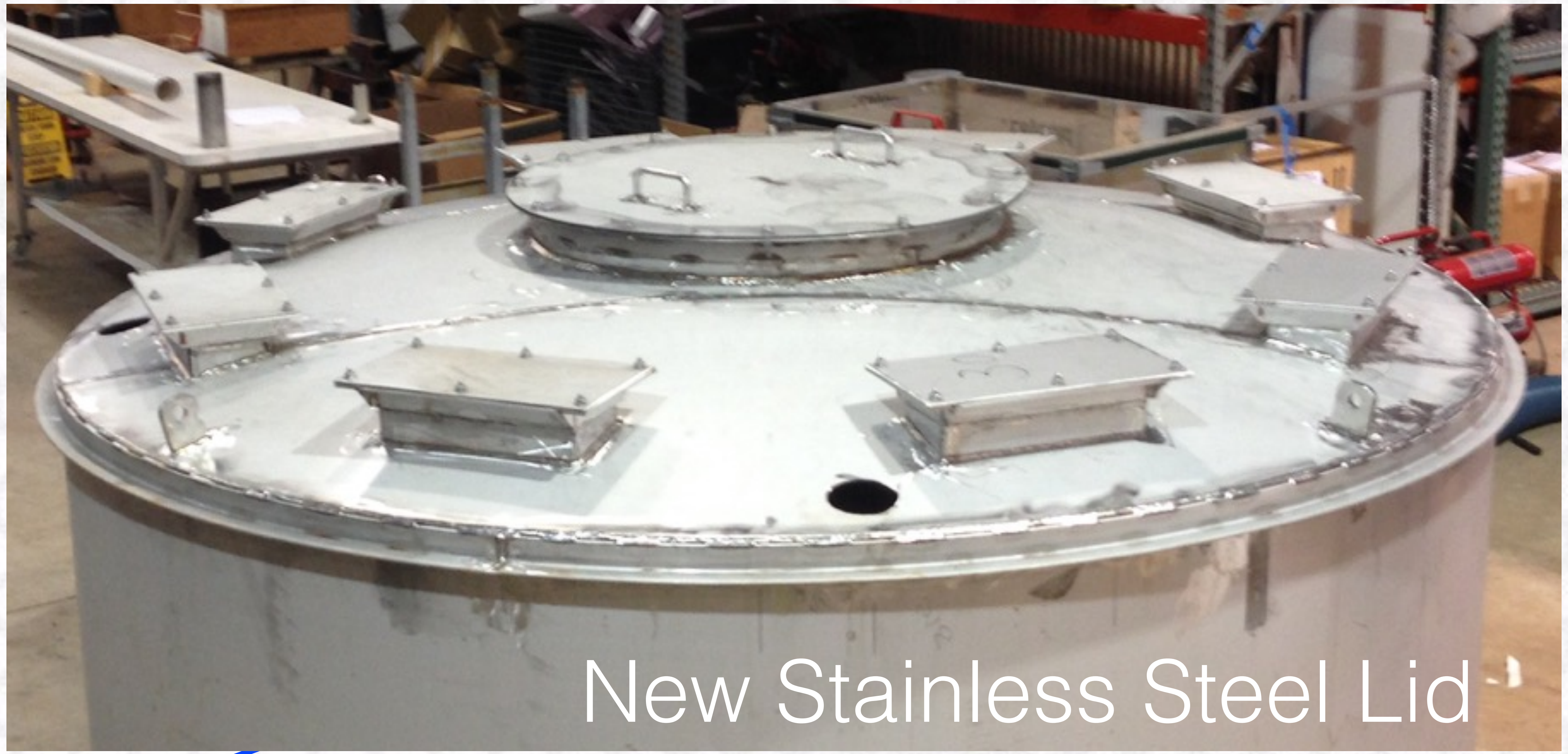
Phase II

- Physics run
- 135 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 Inner Structure design

Phase II—Under Construction at FNAL



ANNIE Detector Needs

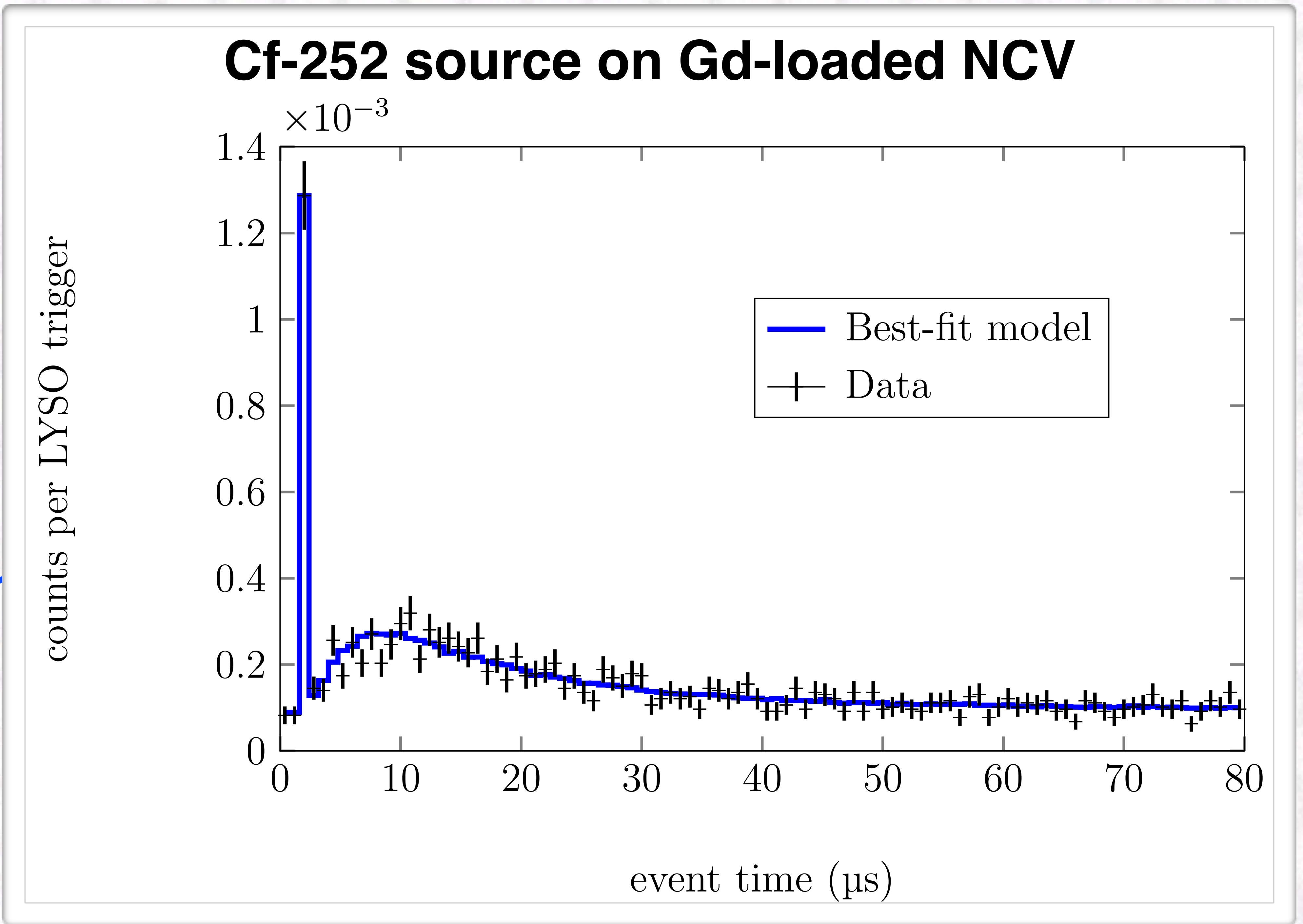
Making the main ANNIE physics measurement requires a detector with:

- 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

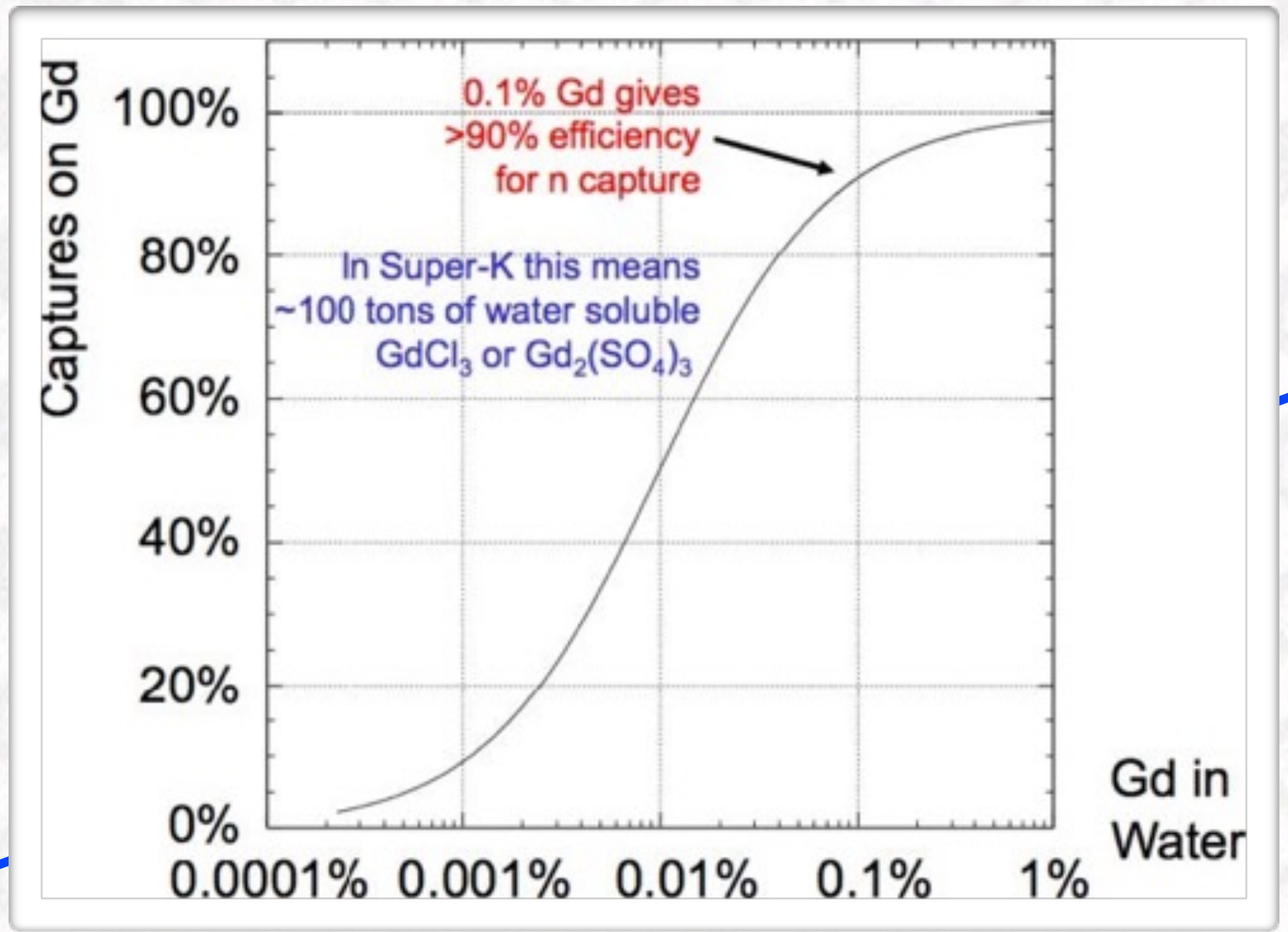
- Neutron capture doesn't have a minimum neutron energy.
- Neutron capture cross section for Gadolinium is ~150000 times that of a free proton.
  - Average capture time ~**30 µs** (0.1% Gd)
  - **E_γ=8 MeV**
- In pure water neutrons capture on protons.
  - Average capture time ~200 µs
  - E_γ=2.2 MeV

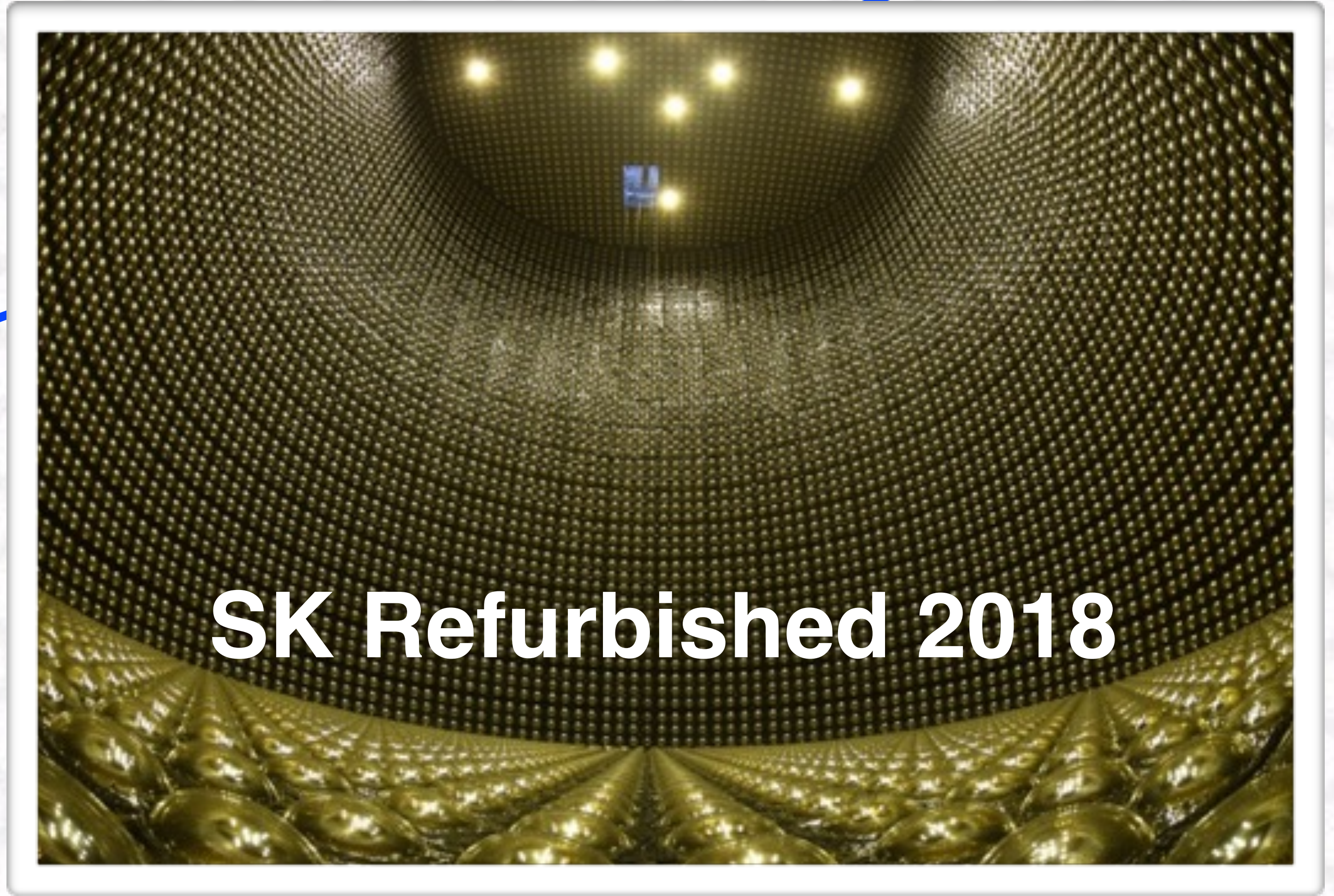


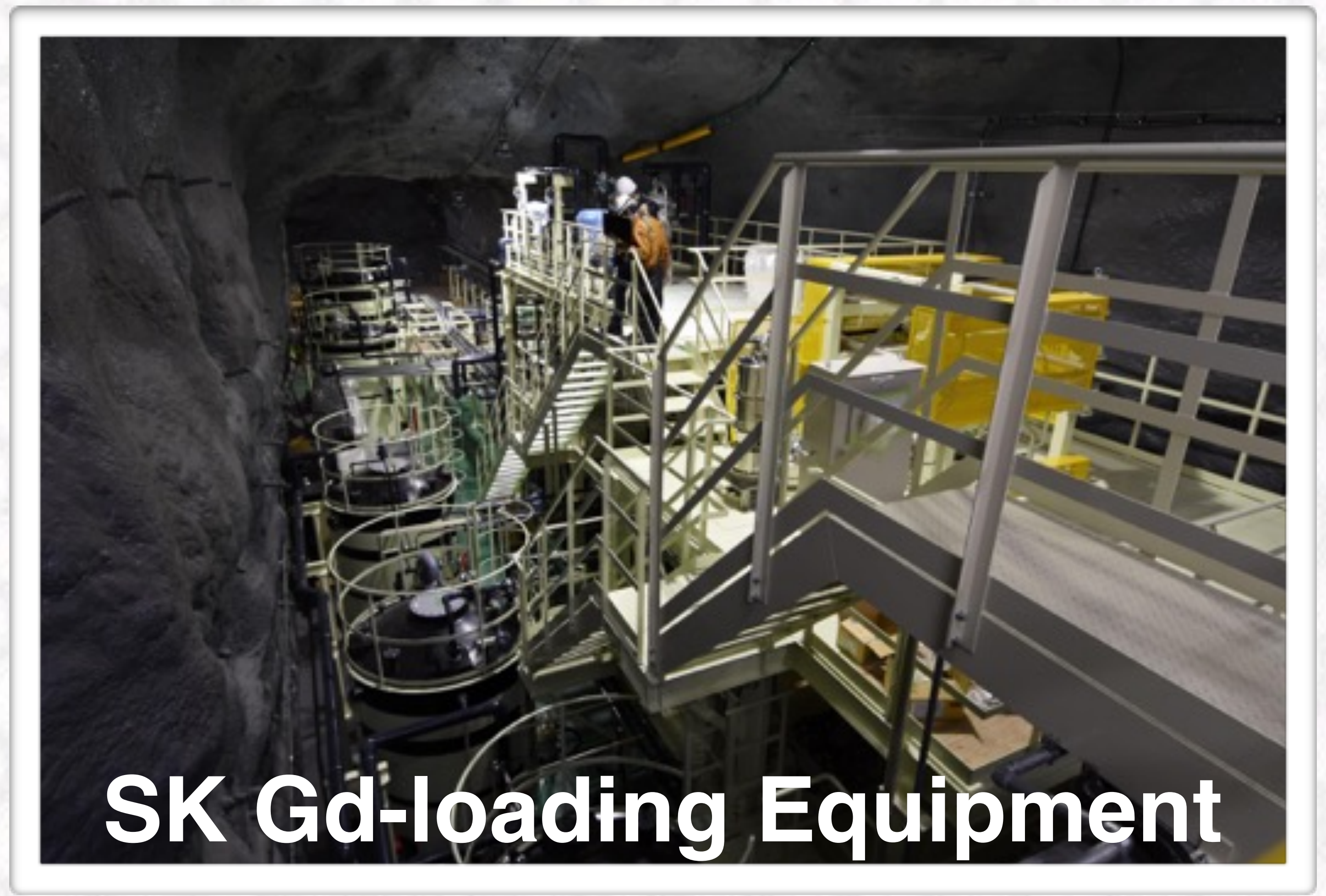
Gadolinium neutron capture

GADZOOKS!: (2016)

- ANNIE will load to 0.1% Gadolinium (by weight) in early 2019.   (90% efficiency)
- Super-K will re-start observation in 2019 after refurbishment.
  - 2020, Gadolinium load to 0.01% (50% efficiency)
  - Later, load to 0.1% (90% efficiency)
- ANNIE will have a high-statistics sample of neutrino-beam neutron captures.

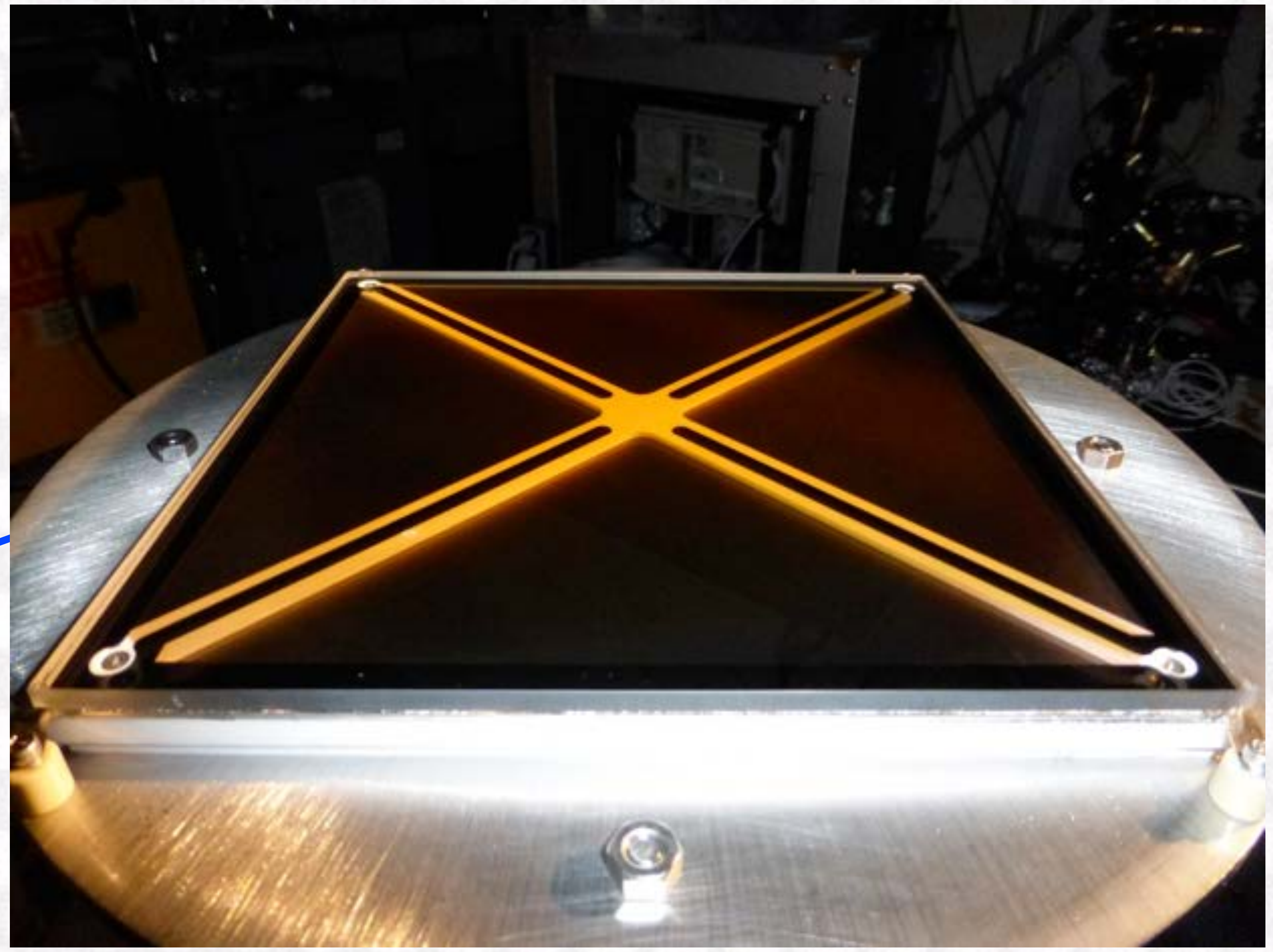






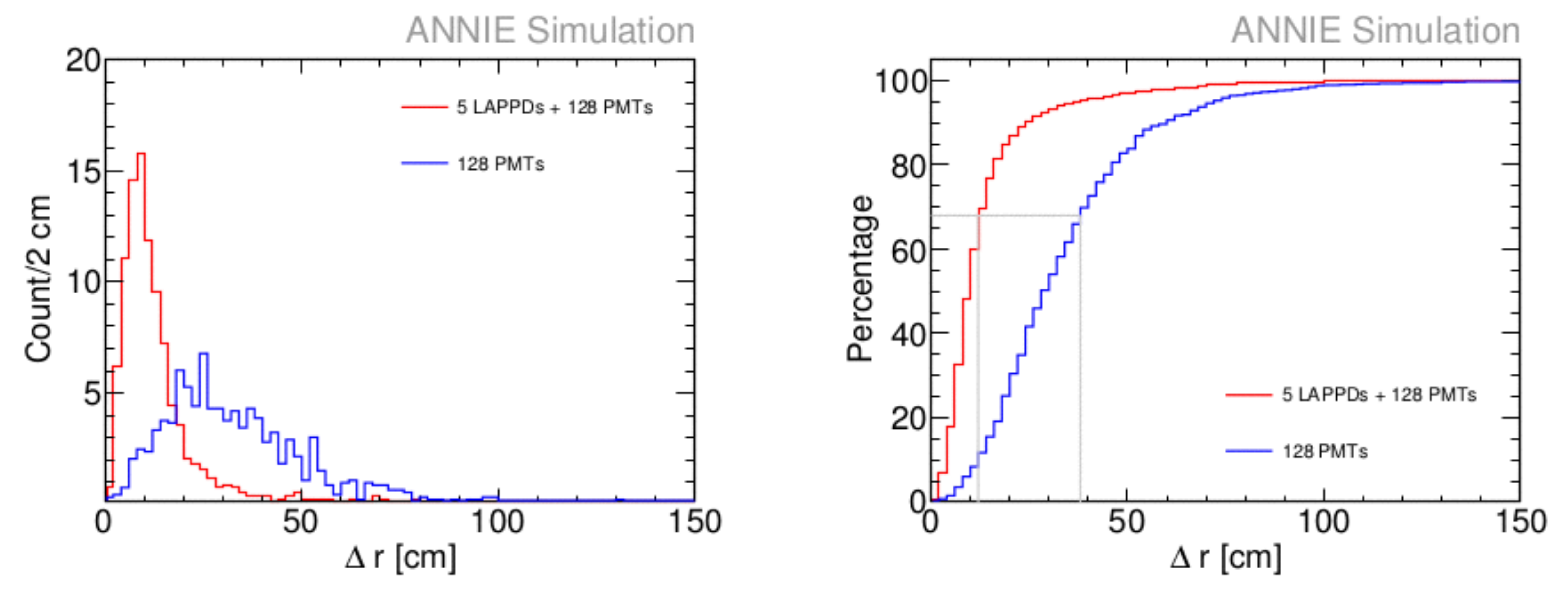
Large Area Picosecond Photo Detectors (LAPPDs)

- 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.

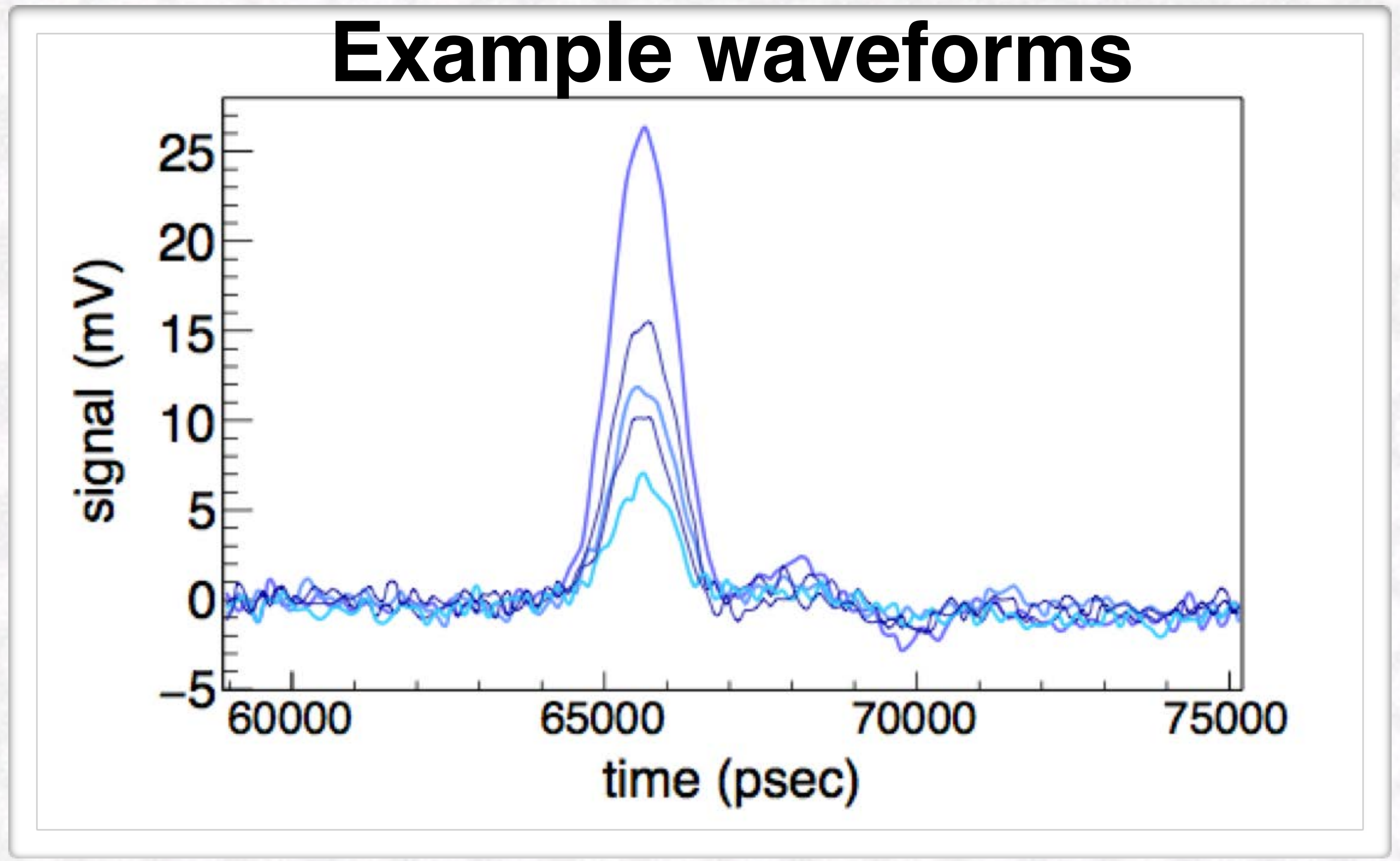
Event reconstruction with LAPPDs

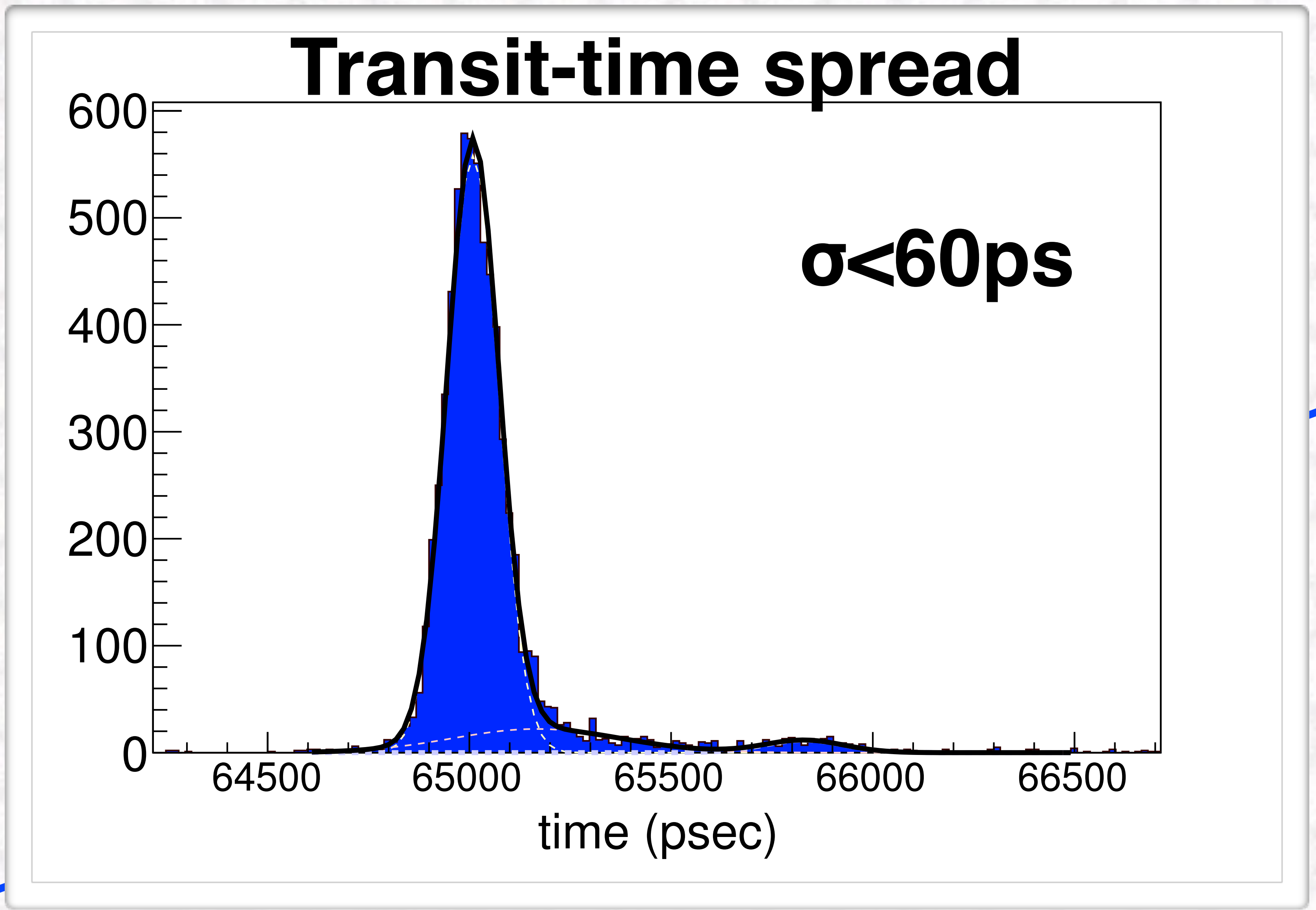


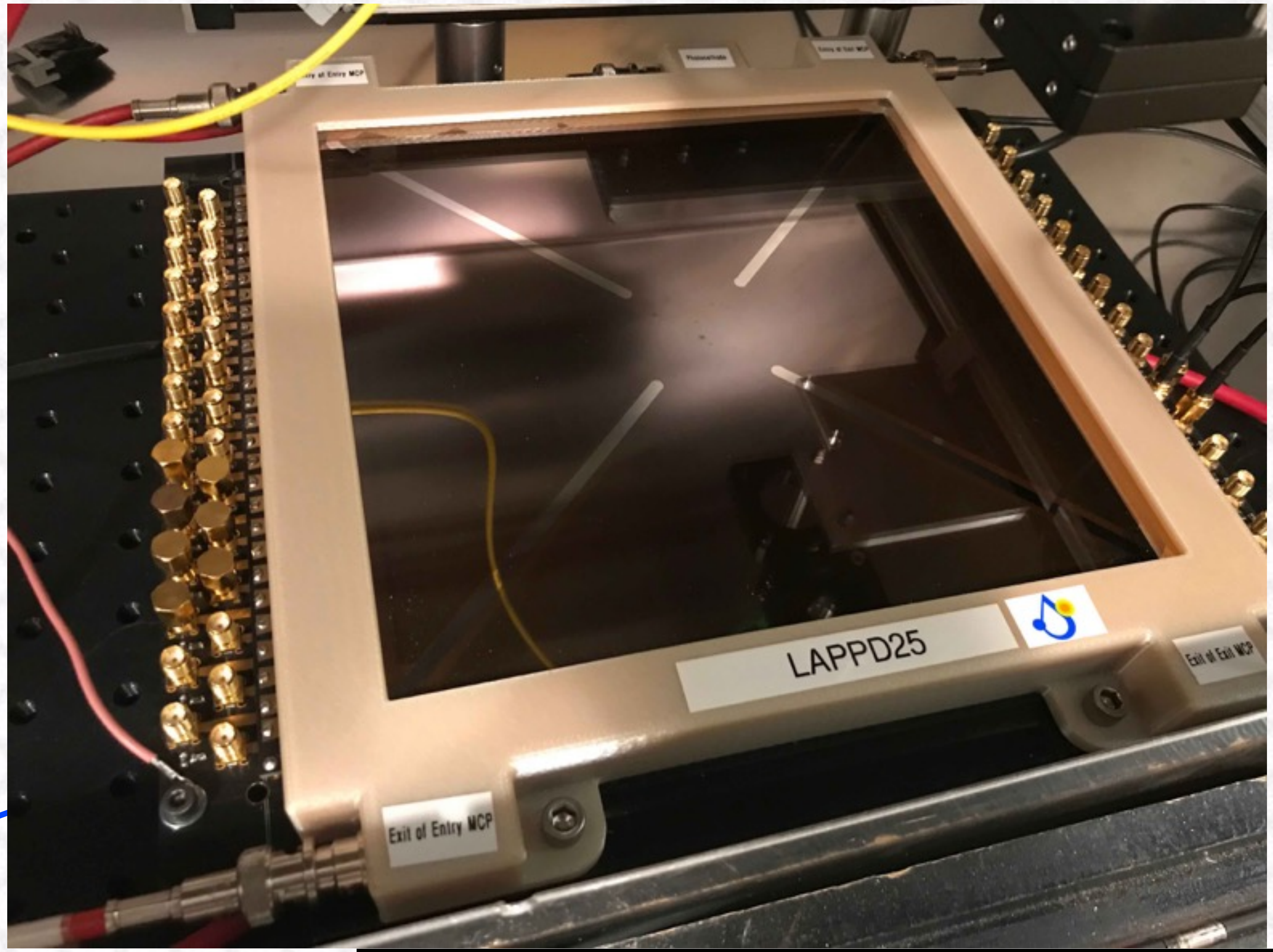
Adding just 5 LAPPDs makes a big improvement in reconstructed vertex resolution, from 40 to 15 cm.

Similar improvements in other reconstructed variables.

LAPPD testing ongoing



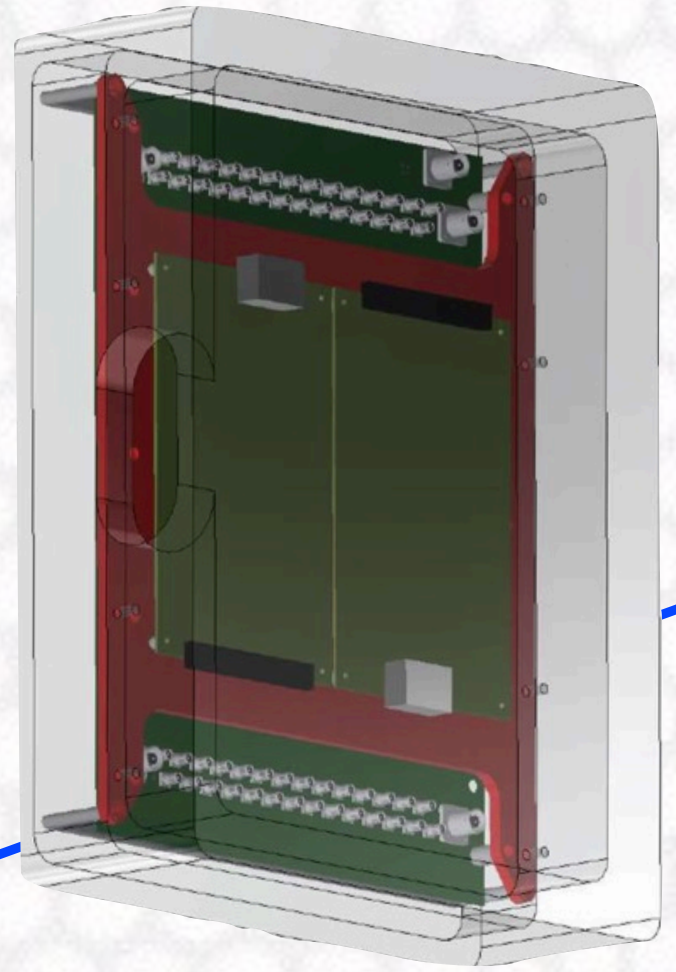




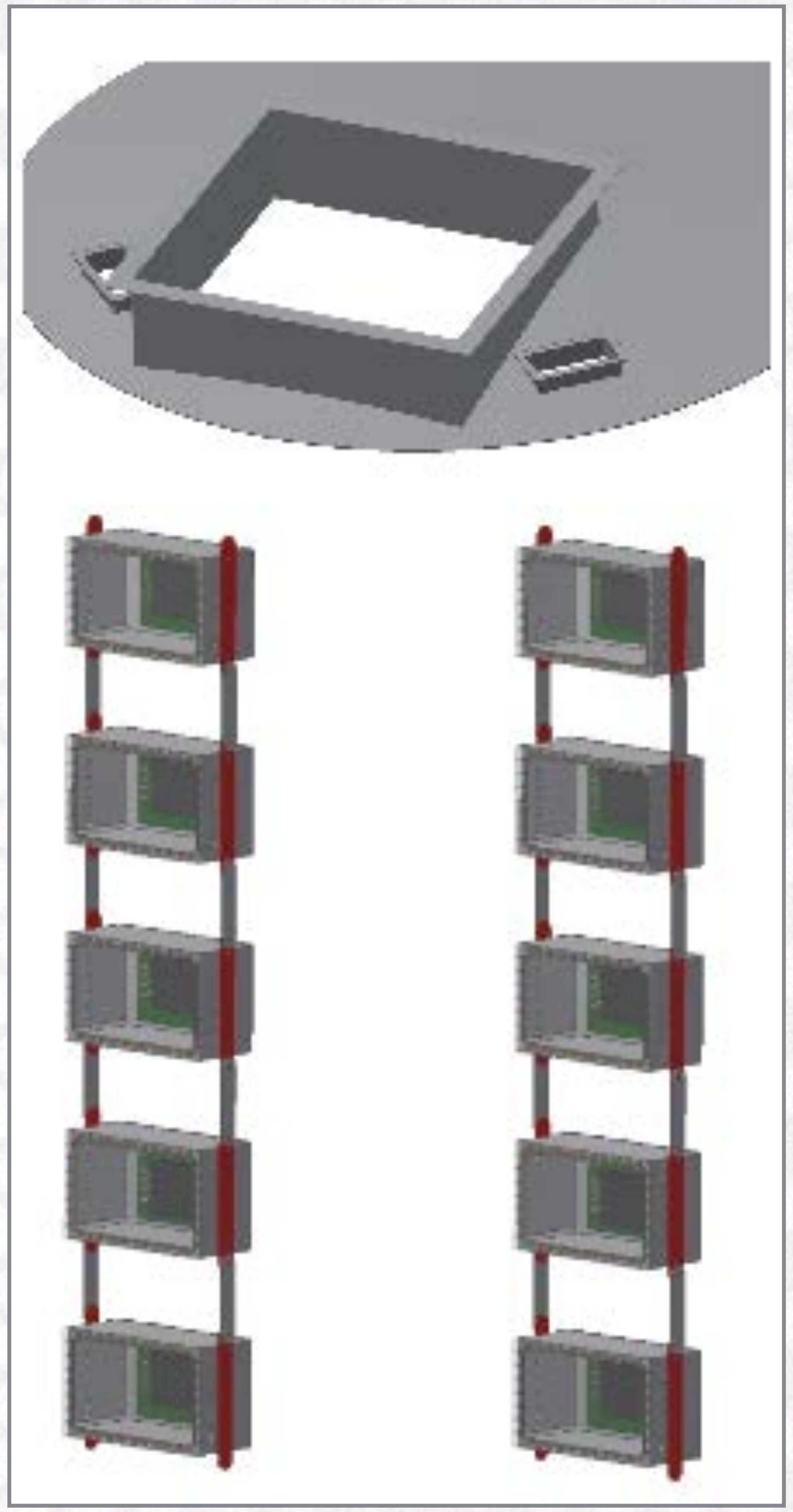
As an early adopter of LAPPDs, ANNIE has been independently testing LAPPDs.

Look what just came in the mail:

LAPPDs in ANNIE



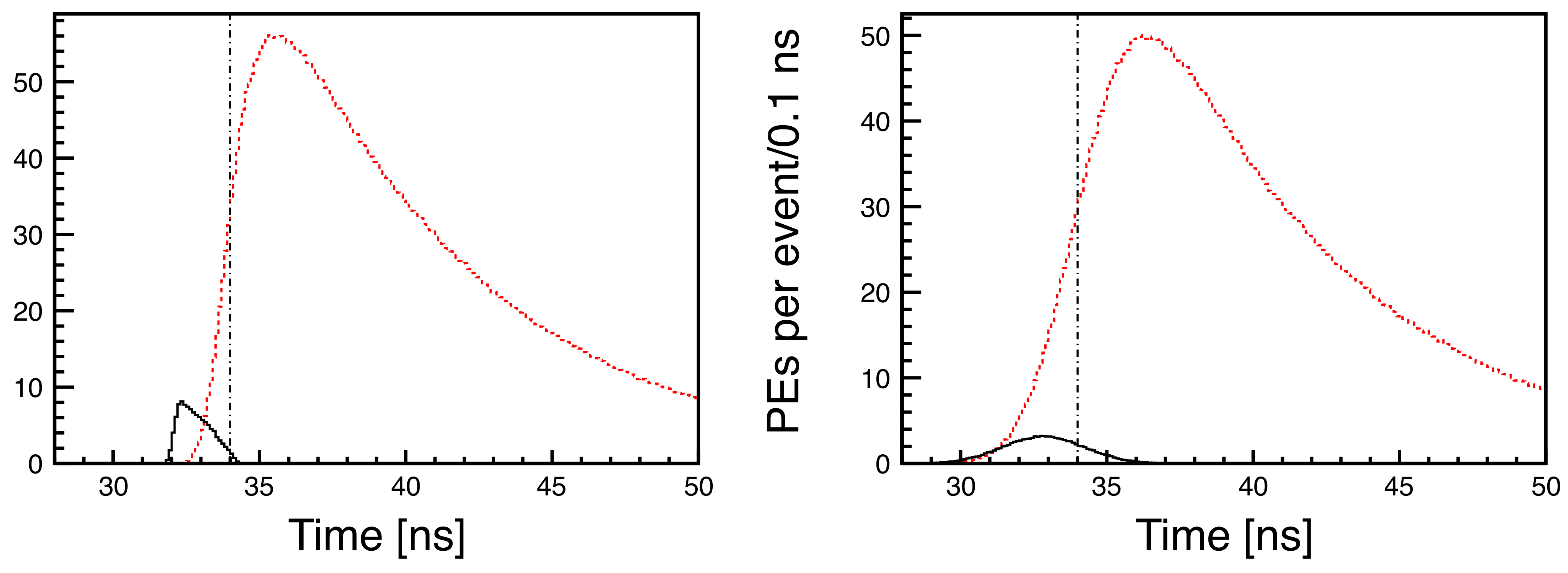
- LAPPDs and their digitizing electronics will be installed in movable waterproof housings.
- The housings will slide down rails, accessible from the top hatch, to allow installation and removal by hand.
- Phase II will support up to 20 LAPPDs.



ANNIE Phase III

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.

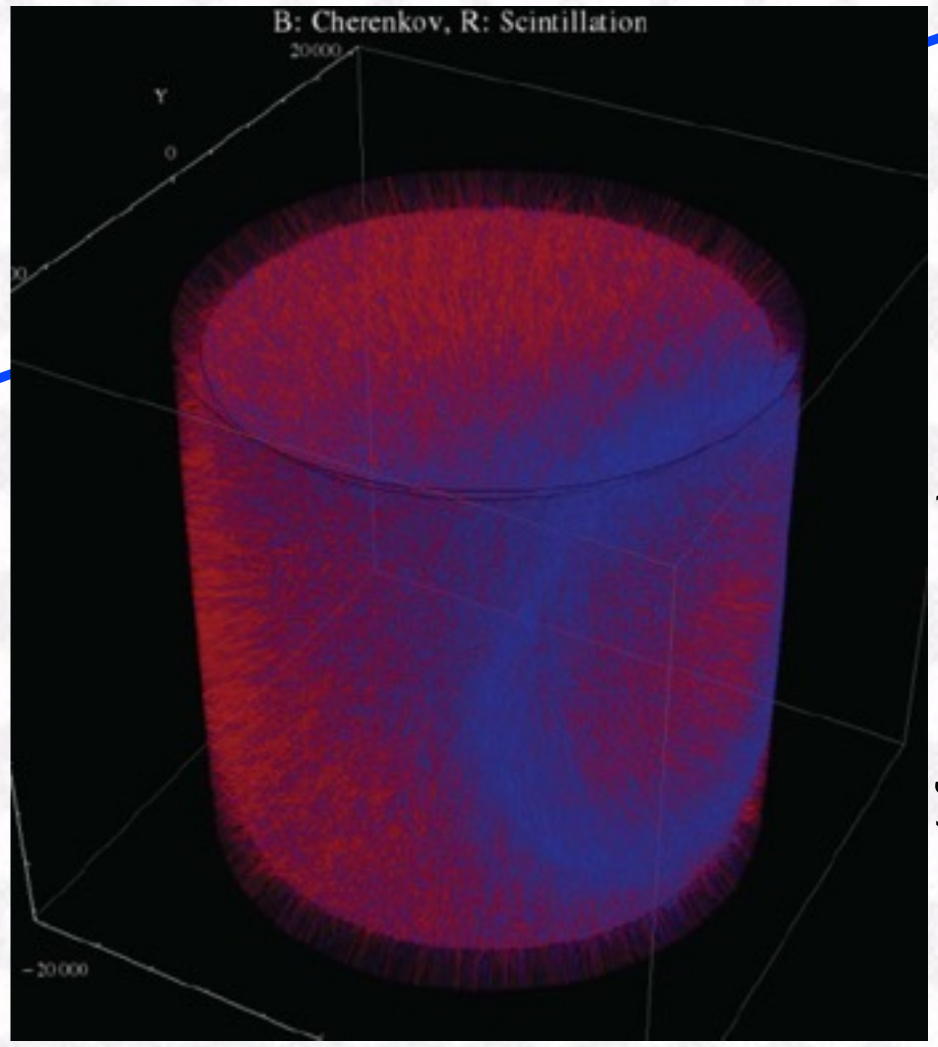
(b) Increased TTS (1.28 ns).

Application to Future Experiments

WATCHMAN-AIT

- 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.

J. Brennan (Sandia)



B. J. Land (Berkeley)

THEIA

- 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 modifications are in progress, operation early 2019
- ANNIE Phase II will measure the neutron multiplicity from neutrino-nucleus interactions in water as a function of lepton kinematics.
- Production LAPPDs ready for Phase II installation.
- ANNIE will be the first high-statistics Gd-loaded water Cherenkov detector in a neutrino beam.