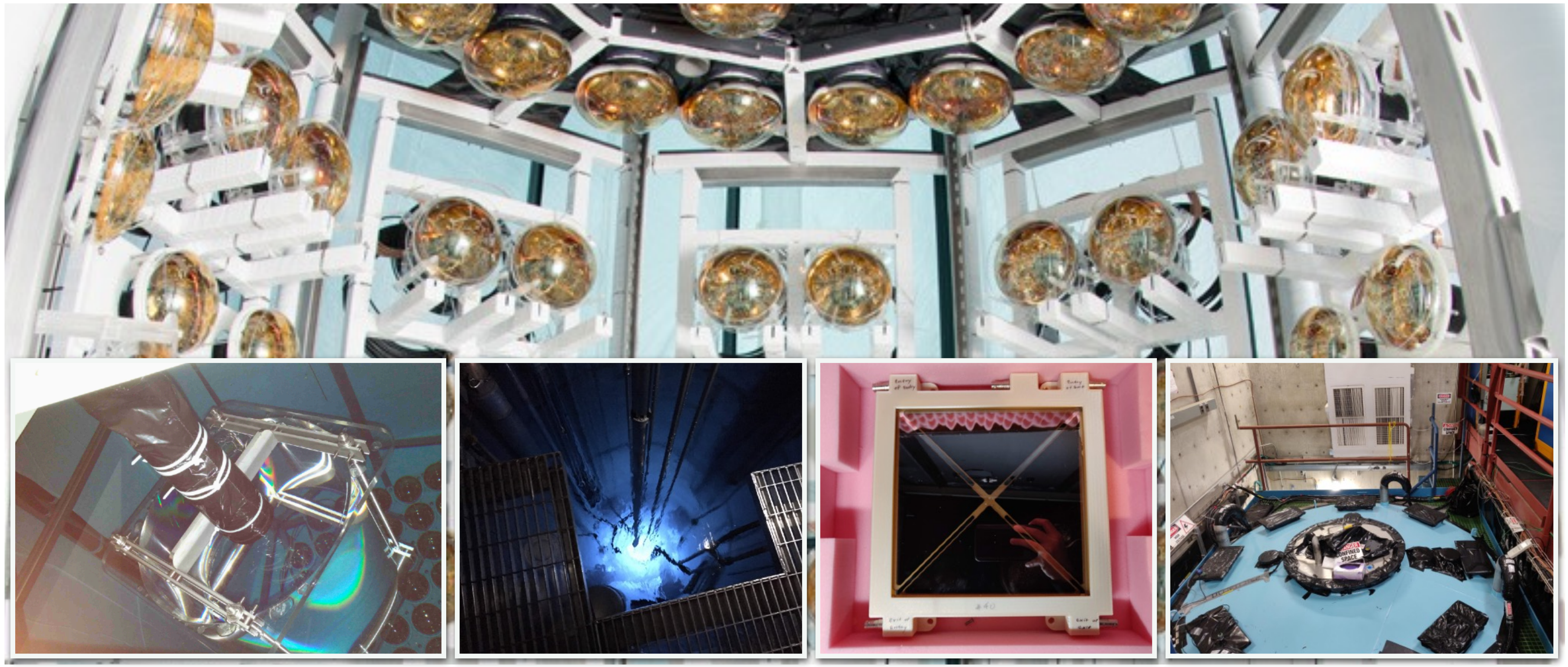


ANNIE
IN 10 MINUTES

Julie He

—

on behalf of the ANNIE collaboration

UCDAVIS
UNIVERSITY OF CALIFORNIA

—

New Perspectives 2021
August 16-19, 2021

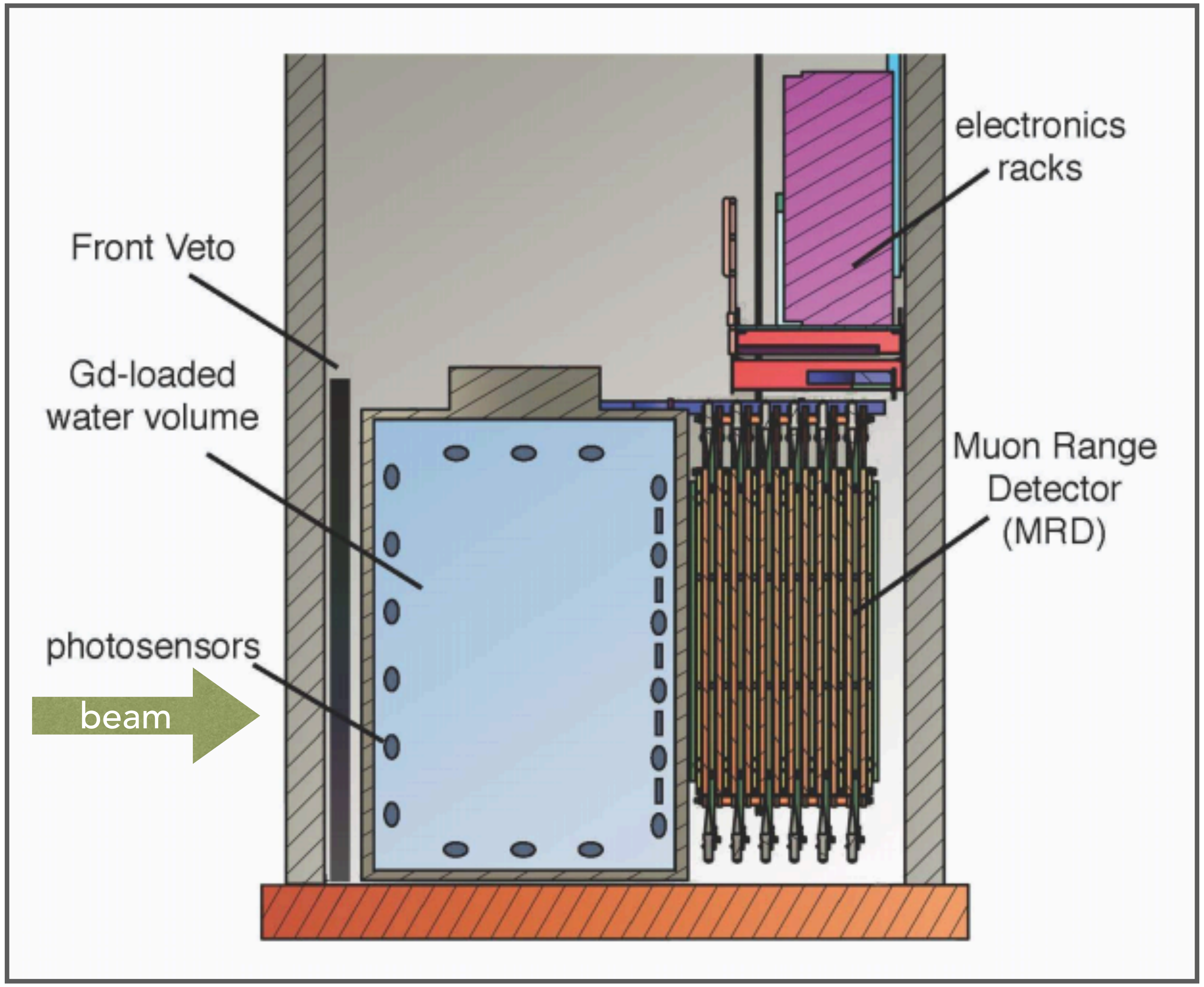
annie

OUTLINE

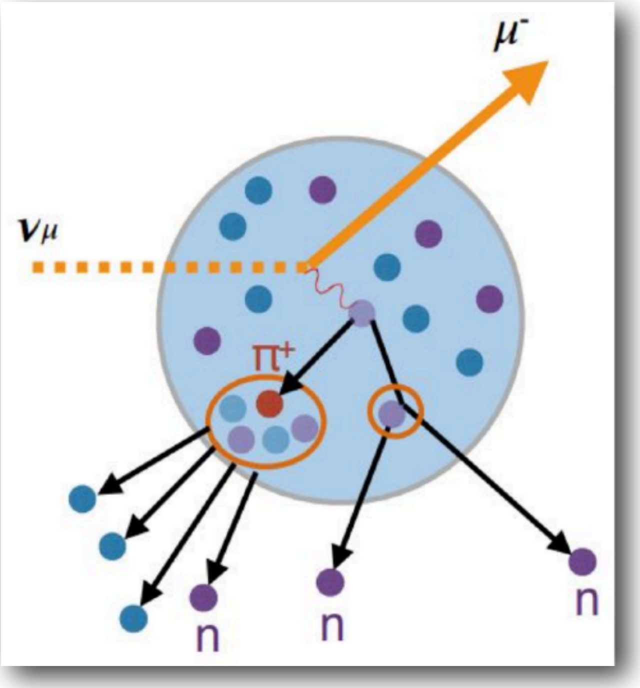
- What is ANNIE all about?
- Physics goals and some cool, new technologies
- Progress during a global pandemic
- Current status: Active and Determined

ACCELERATOR NEUTRINO NEUTRON INTERACTION EXPERIMENT

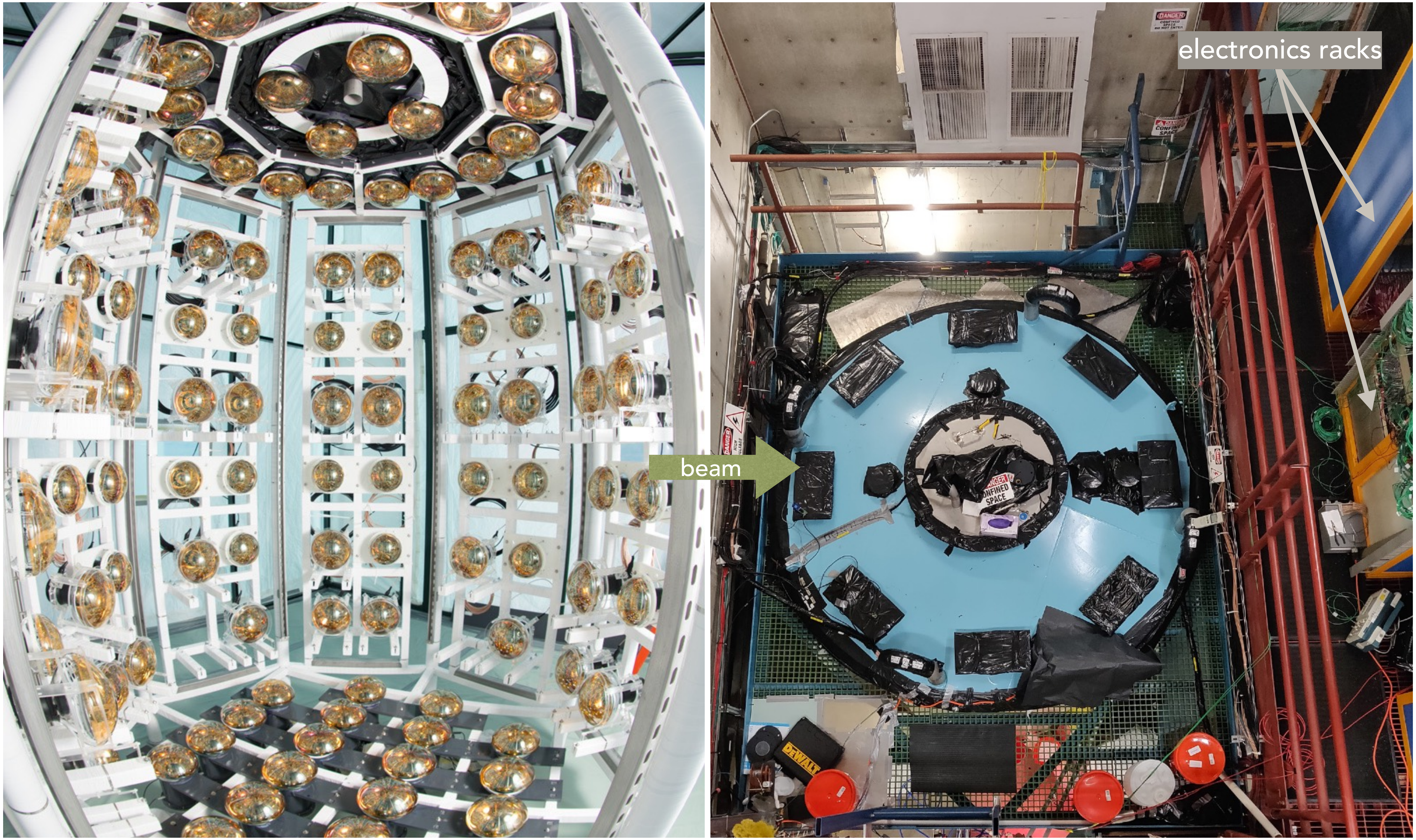
- 3-m (10 ft) dia. x 4-m (13 ft) tall cylindrical **water Cherenkov detector**, located 100 m down-stream in Fermilab's Booster Neutrino Beam (BNB)
- Equipped with **132 conventional PMTs** and **5 novel Large Area Picosecond Photodetectors**
- Completed Phase I ✅
  - Background characterization
- **Currently in Phase II**:
  - Commission full detector
  - Deployment of LAPPDs
  - Physics data-taking; neutron multiplicity measurement



ANNIE'S PHYSICS GOALS: WHAT WE AIM TO MEASURE



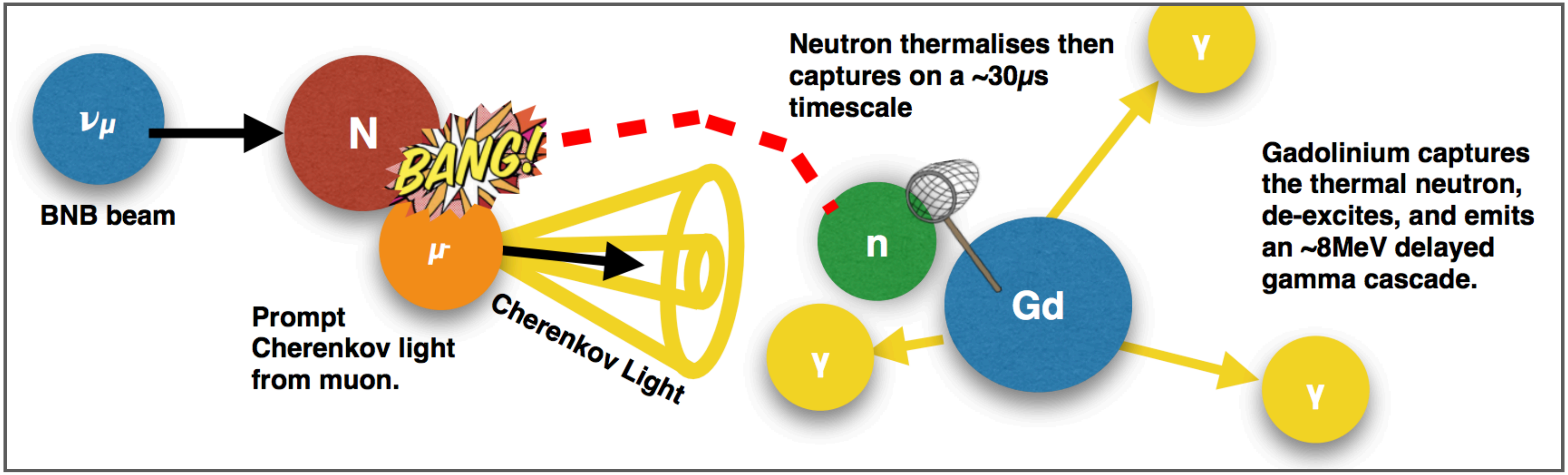
- Measurement goals:
  - **Final state neutron multiplicity** of neutrino-nucleus interactions, as a function of momentum transfer
    - Important for quantifying atmospheric background of DSNB and proton decay searches
  - **Neutrino cross section on water**, specifically on oxygen
    - Beneficial to long-baseline neutrino oscillation experiments by helping reduce the associated systematic uncertainties
    - Potential joint analysis of water/liquid argon cross section with SBND
- Unique capabilities of ANNIE:
  - Detector sits on a neutrino beam — **high statistics** measurement
  - **High sensitivity to neutrons**



(left) Inner structure with 132 PMTs mounted. (right) Top view of the tank lid in ANNIE Hall (formerly SciBooNE Hall).

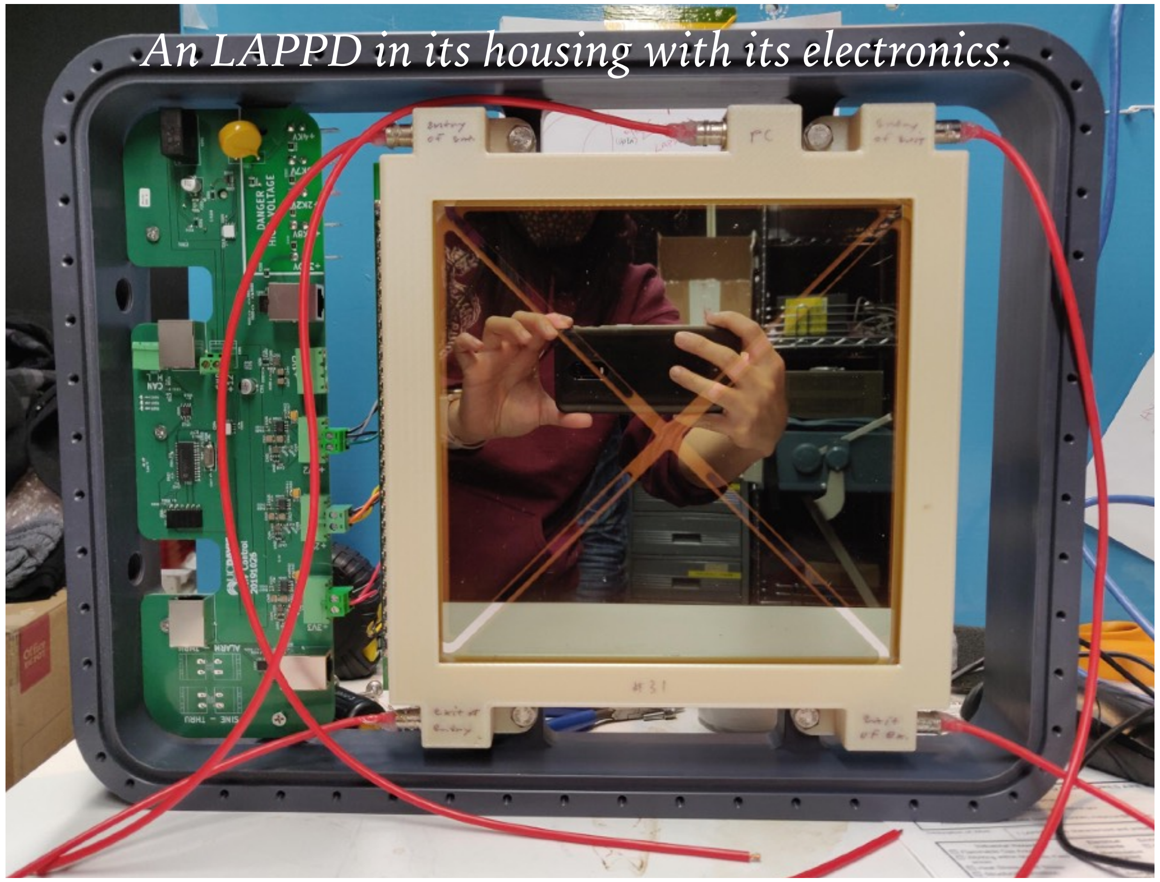
TESTBED FOR NEW TECHNOLOGIES: GD-LOADED WATER

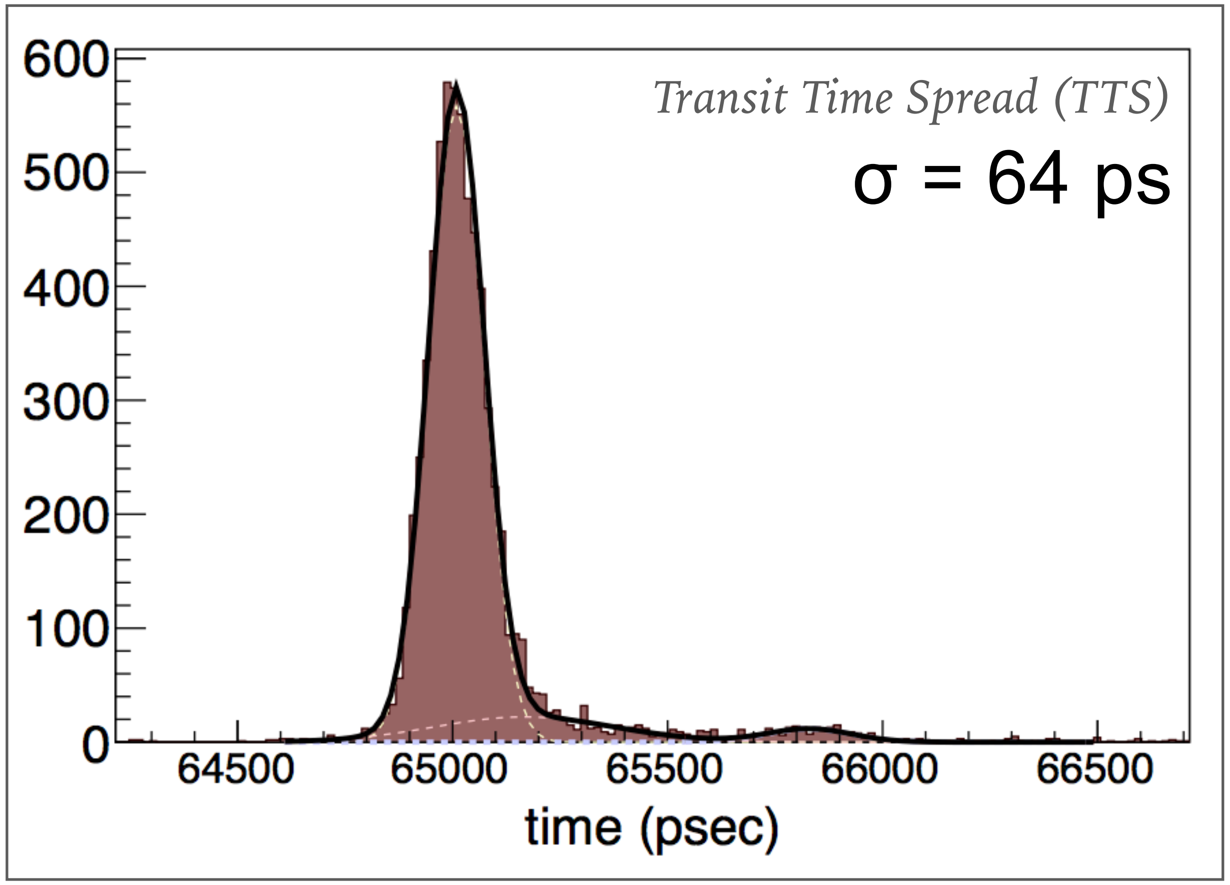
- **Gadolinium(Gd)-loaded water** (26 tons of 0.1% Gd solution)
  - Gadolinium has a **high average neutron capture cross section** (~49,000 barns) compared to hydrogen's 0.33 b in pure water
  - Signature ~8 MeV gamma cascade follows a neutron capture (compared to hydrogen's 2.2 MeV)
  - **Greatly improves our sensitivity to neutrons**
  - ANNIE is the first user of Gd-loaded water* in a neutrino beam experiment



TESTBED FOR NEW TECHNOLOGIES: LAPPDS

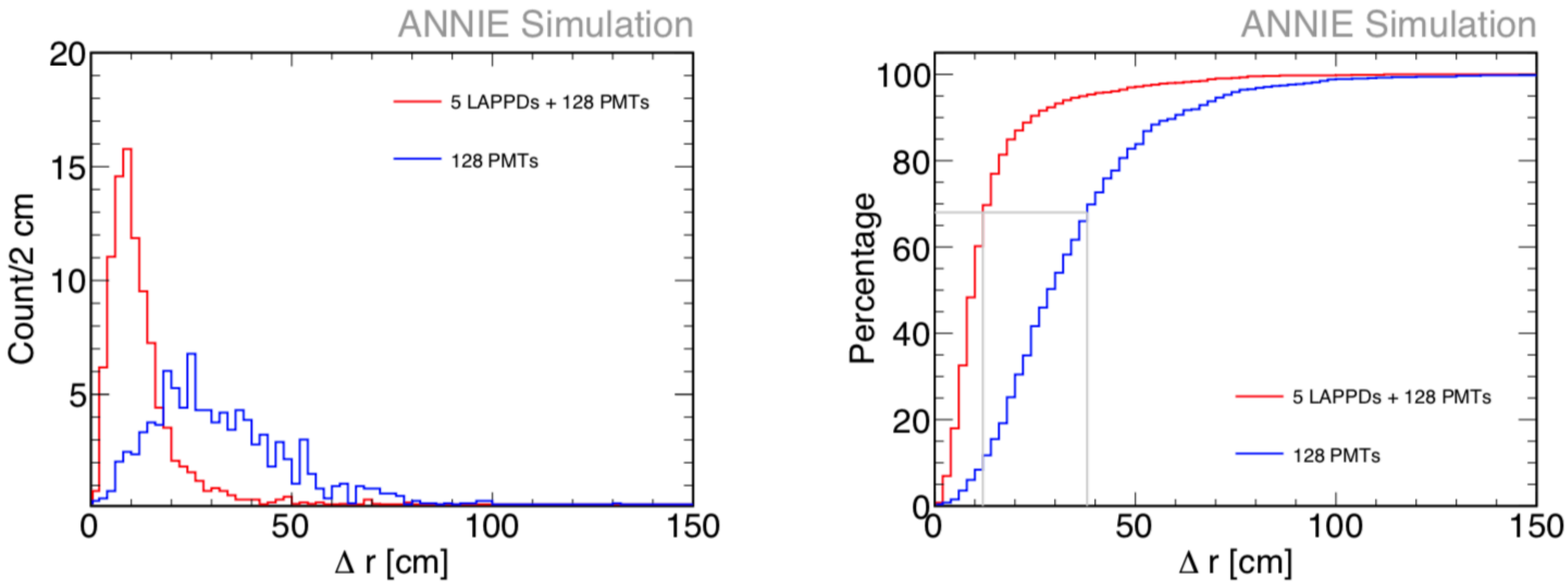
- **Large Area Picosecond PhotoDetector** (LAPPD)
  - 20 cm x 20 cm photodetector based on MCP (microchannel plate) technology
  - 28 anode striplines, with readout at both ends
  - Sub-centimeter spatial resolution with picosecond (~60 ps) timing
  - Uniform, high quantum efficiency


An LAPPD in its housing with its electronics.



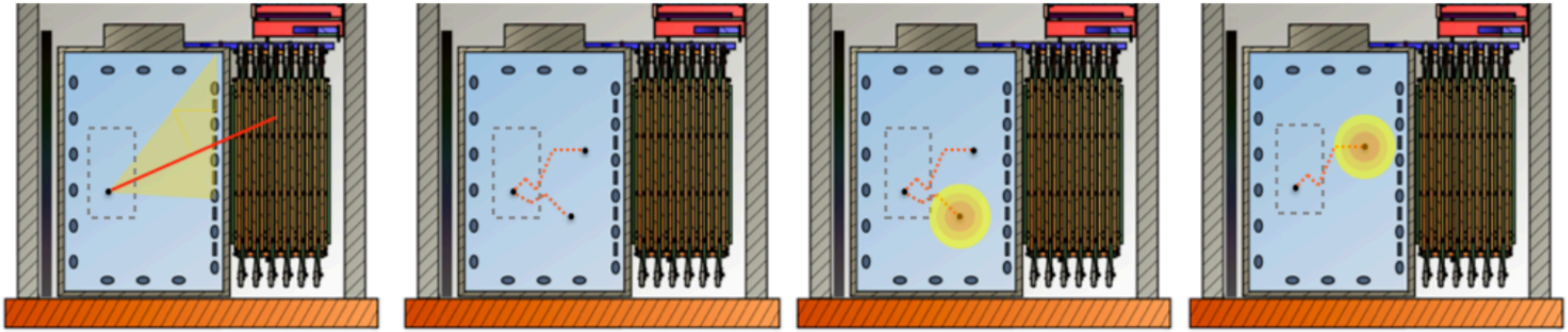
WHY LAPPDS ARE GOOD FOR ANNIE

- **5 LAPPDs** will be deployed in the ANNIE detector
- Improves vertex reconstruction ability to more accurately determine the energy of the produced muon
  - LAPPDs will provide us better timing, spatial, and angular resolution



With the addition of just 5 LAPPDs, we can see a vast improvement in position resolution, for example.

TYPICAL ANNIE EVENT



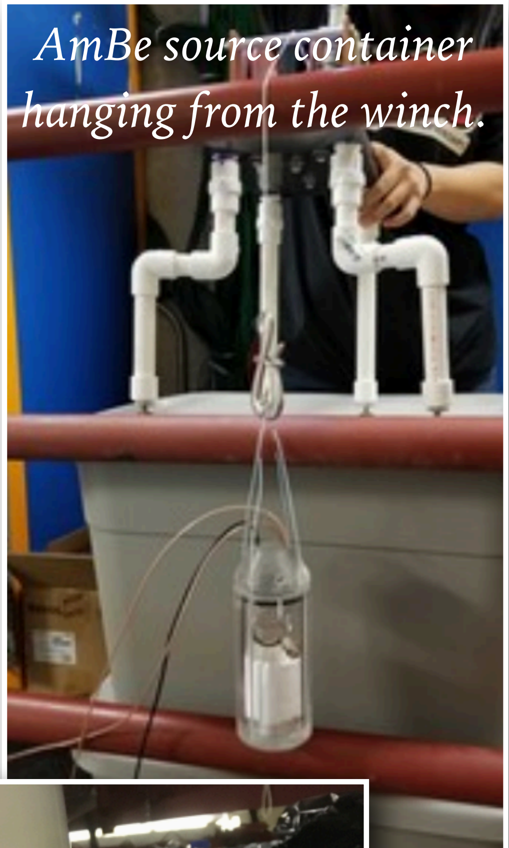
(a) (b) (c) (d)

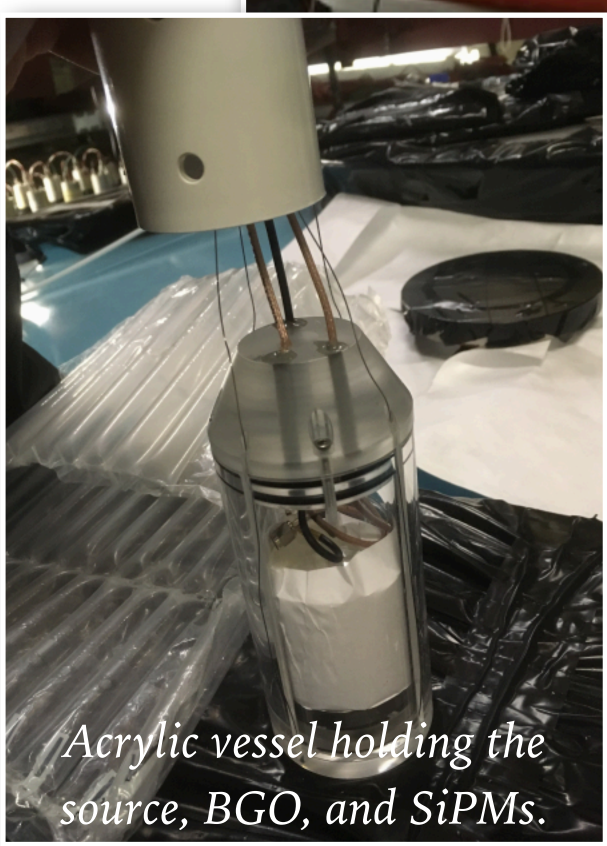
(a) a neutrino-nucleus interaction produces a muon (red line) that travels out of the detector and stops in the MRD

(b) final state neutrons are produced and thermalize in the water

(c)-(d) neutrons are captured by Gd isotopes

PROGRESS: NEUTRON DETECTION EFFICIENCY MEASURED

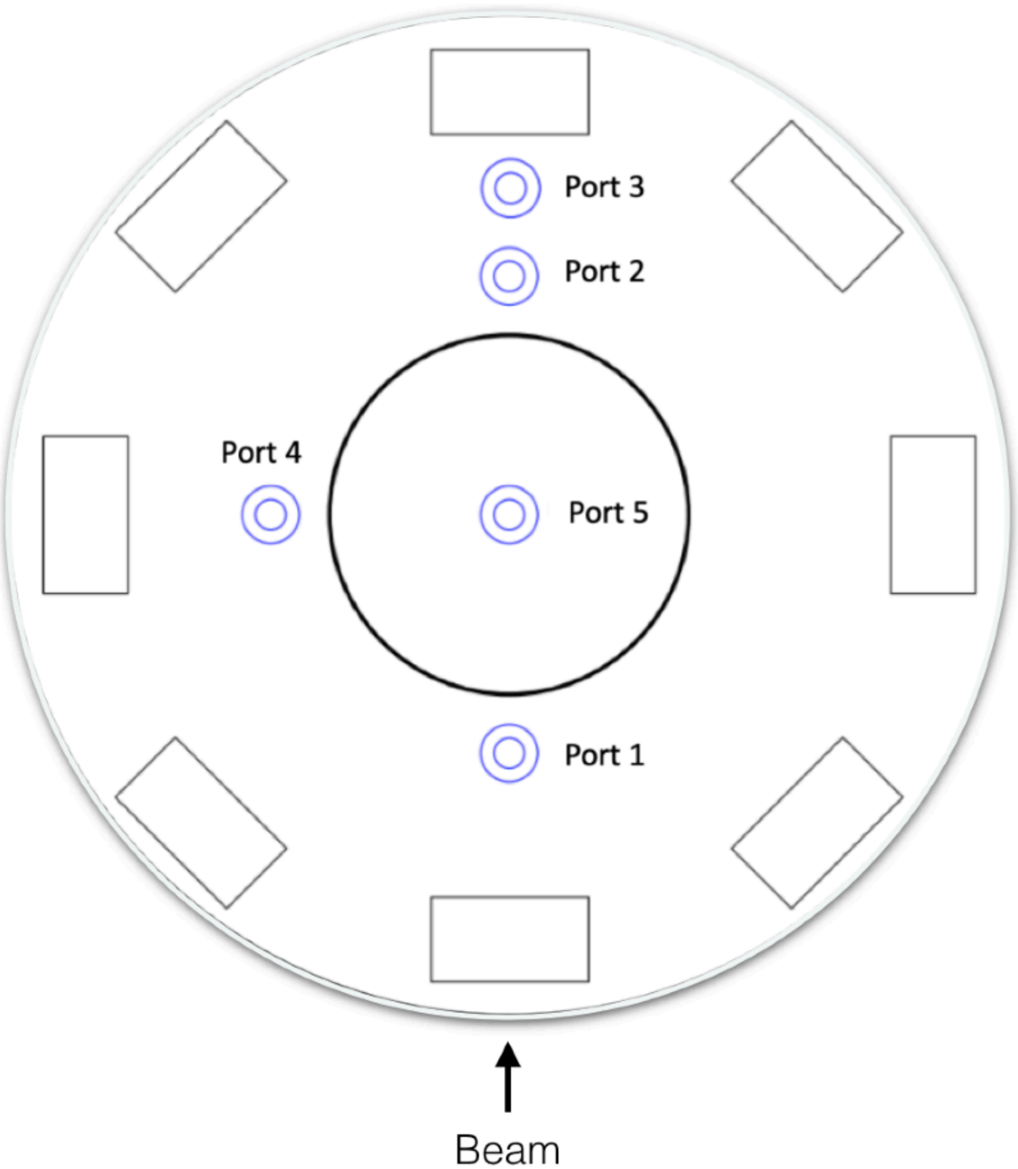

AmBe source container hanging from the winch.

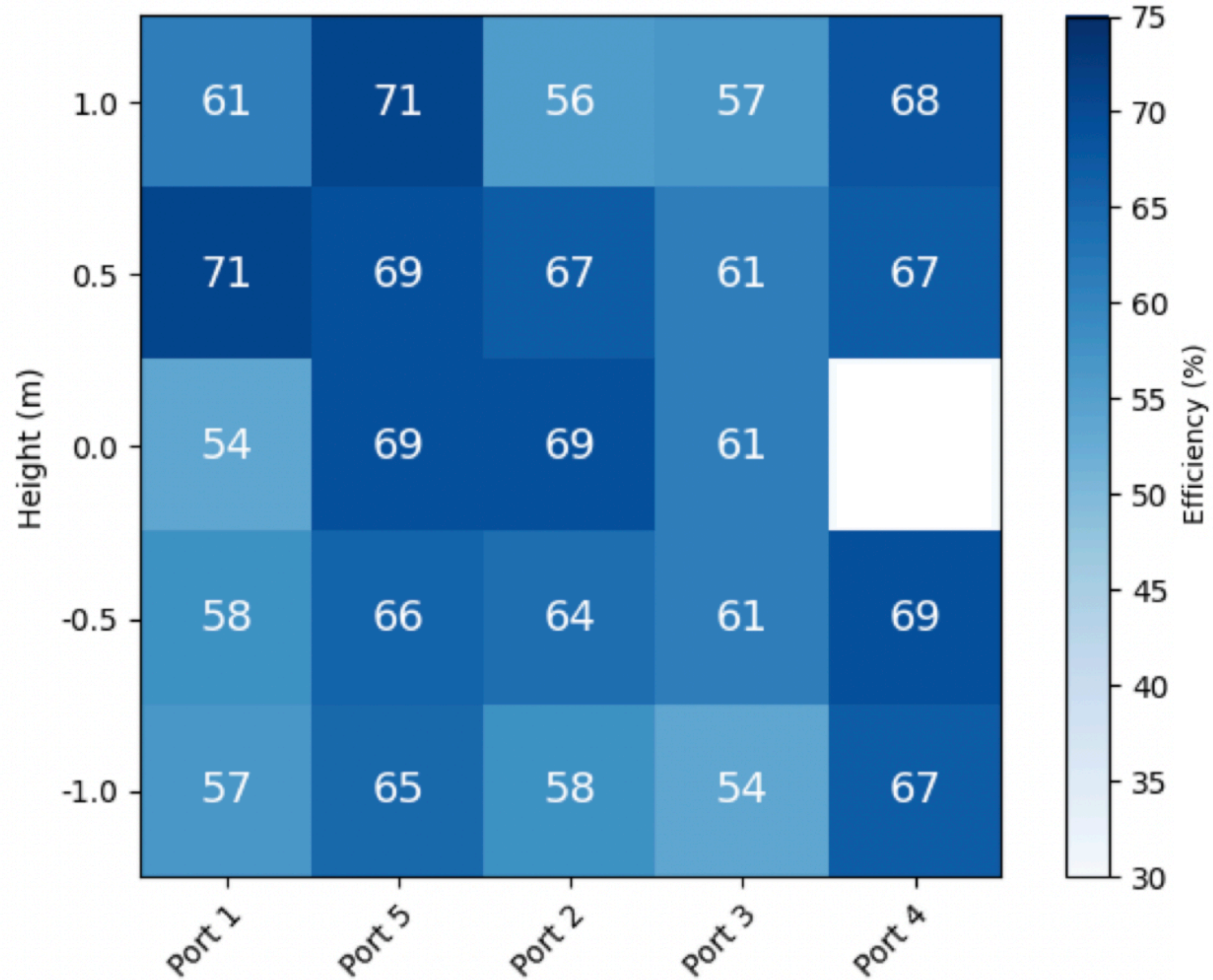

Acrylic vessel holding the source, BGO, and SiPMs.

- Completed a calibration campaign with AmBe source to **characterize neutron detection efficiency throughout the detector** in the fall of 2020
- AmBe source + BGO crystal + 2 SiPMs in an acrylic vessel
- Deployed at various positions in the detector
- Process: $a + {}^{9}Be \rightarrow {}^{13}C^{*} \rightarrow {}^{12}C + \gamma(4.4\ \mathrm{MeV}) + n$
  - Neutron is captured by Gd, while the prompt gamma provides a trigger

RESULTS OF AMBE SOURCE CALIBRATION

ANNIE Preliminary

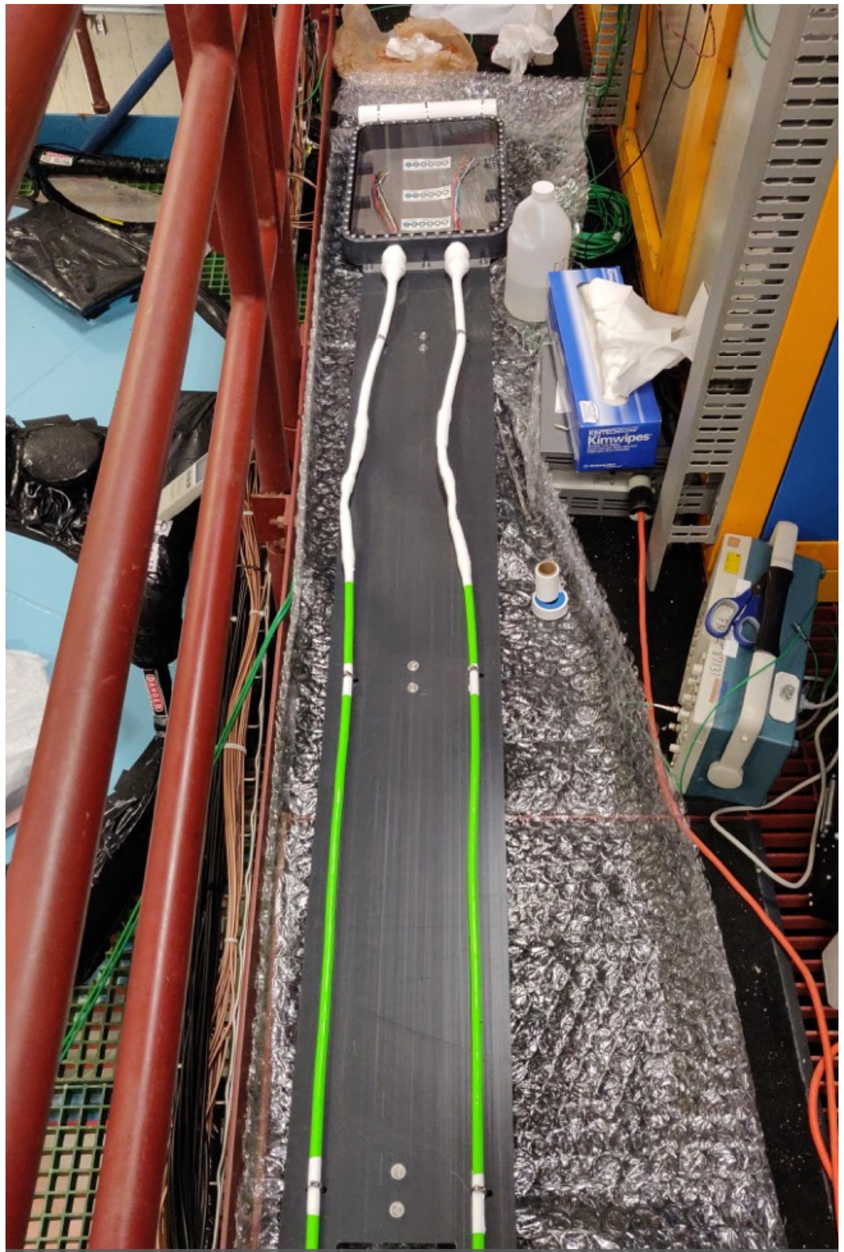




courtesy of Leon Pickard

PROGRESS: LAPPD DEPLOYMENT TESTS SUCCESSFUL

➤ Tested the deployment mechanism of LAPPD with great success!



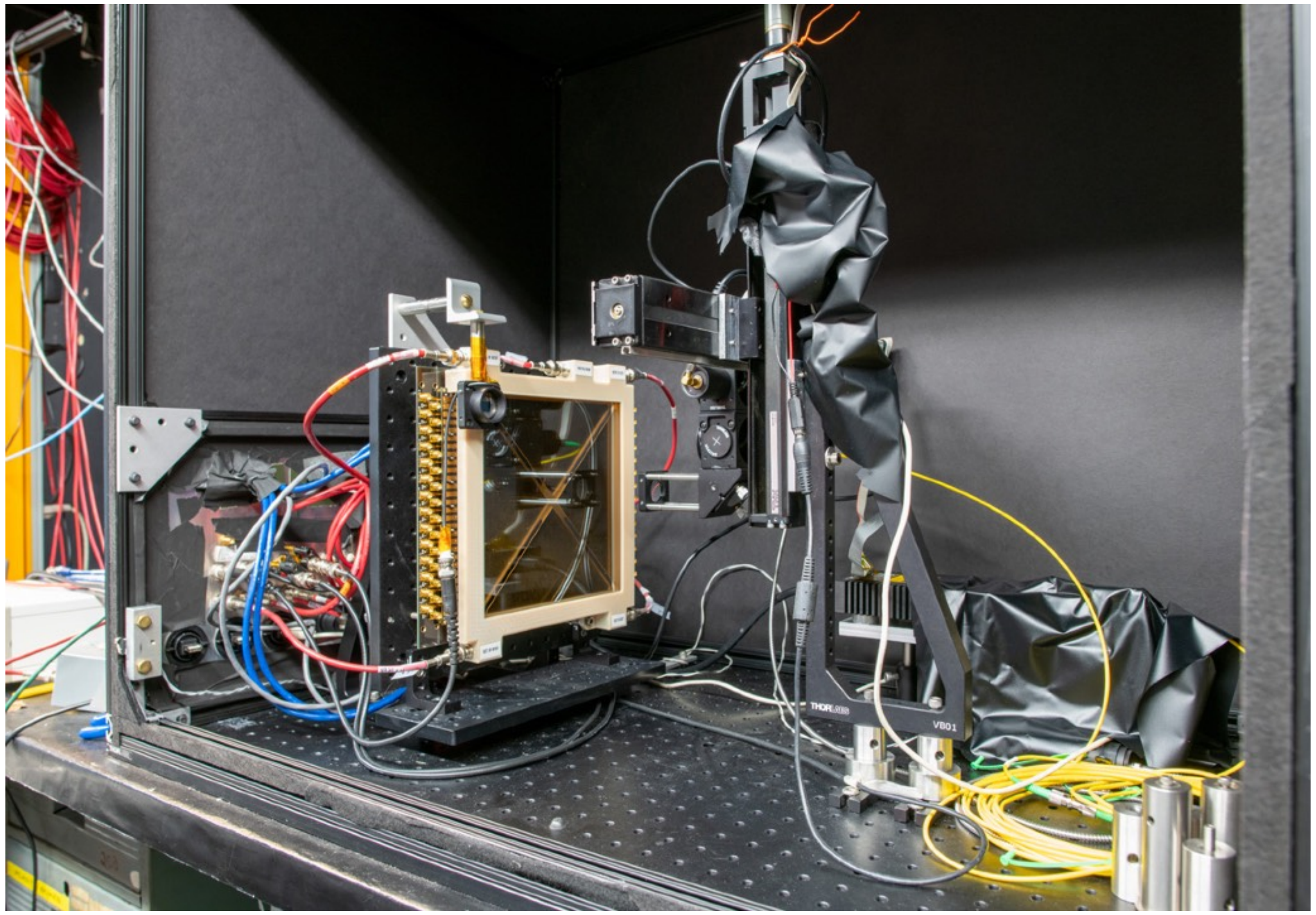
An empty waterproof housing attached to a 10-ft PVC panel.

Waterproof cables through which data and power are delivered.

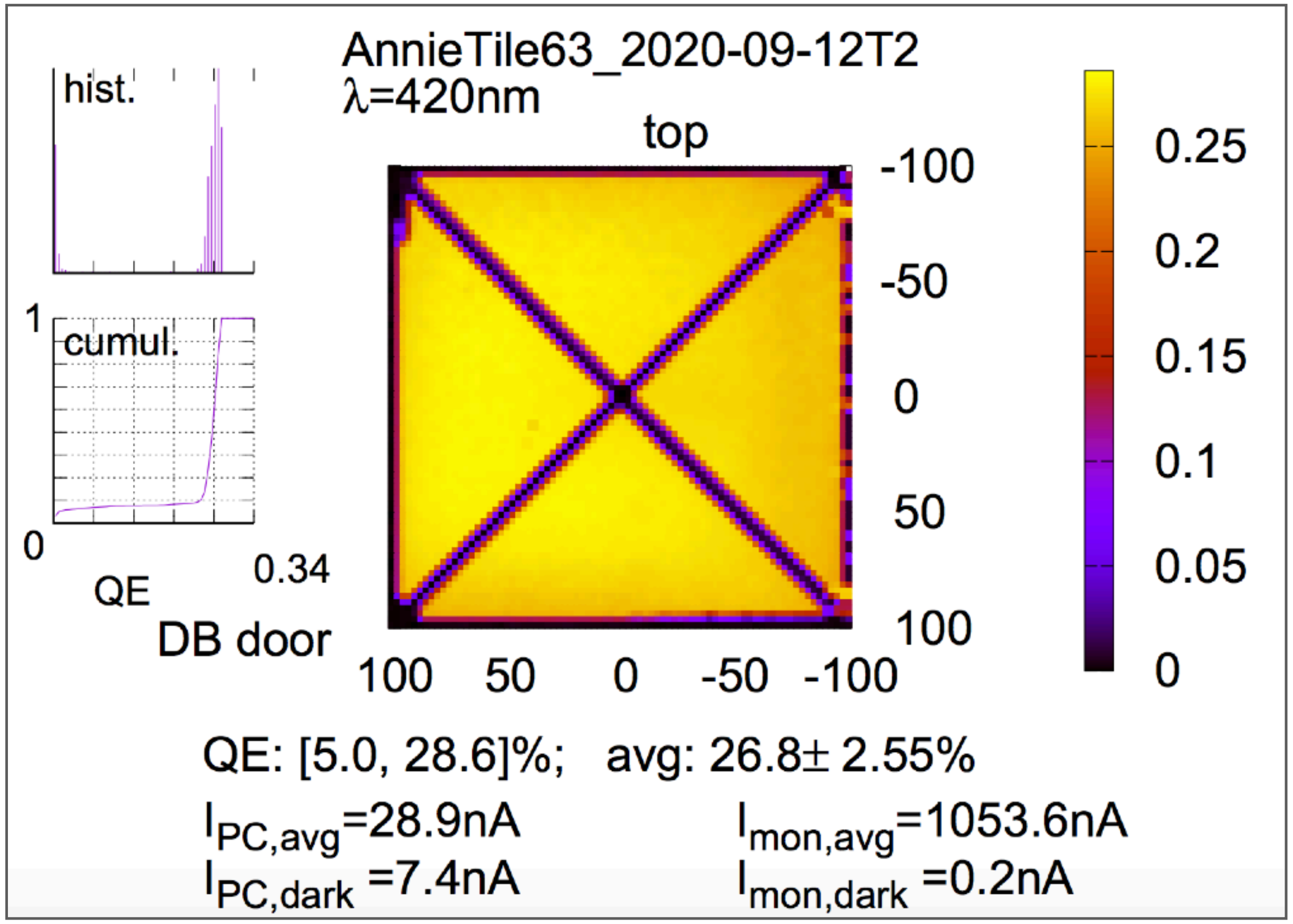
They say she is still holding those cables to this day…

PROGRESS: COMPLETED CHARACTERIZATION OF LAPPD

- Characterized QE and timing capabilities of LAPPD
  - QE scans were performed with an LED
  - Laser scans were used for timing measurements



The LAPPD test-stand in a dark box at Fermilab.

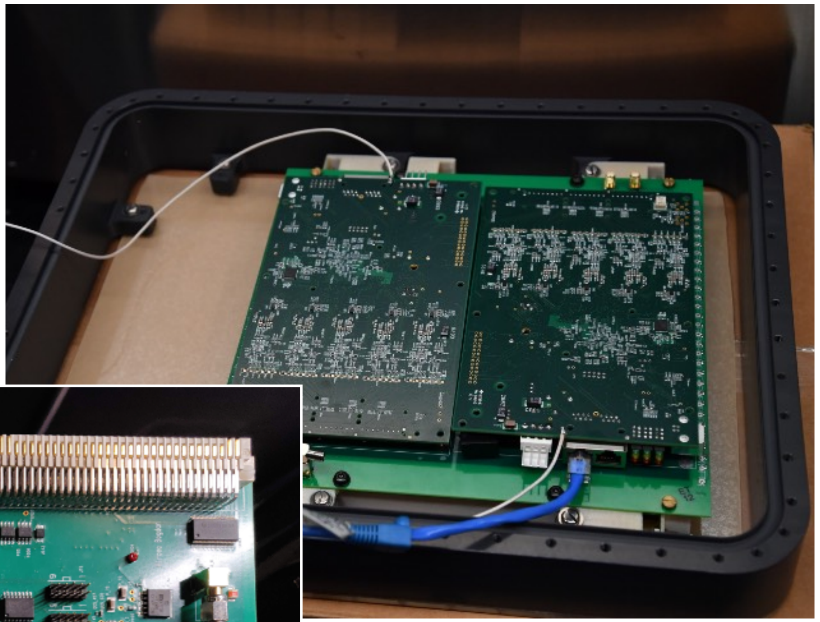


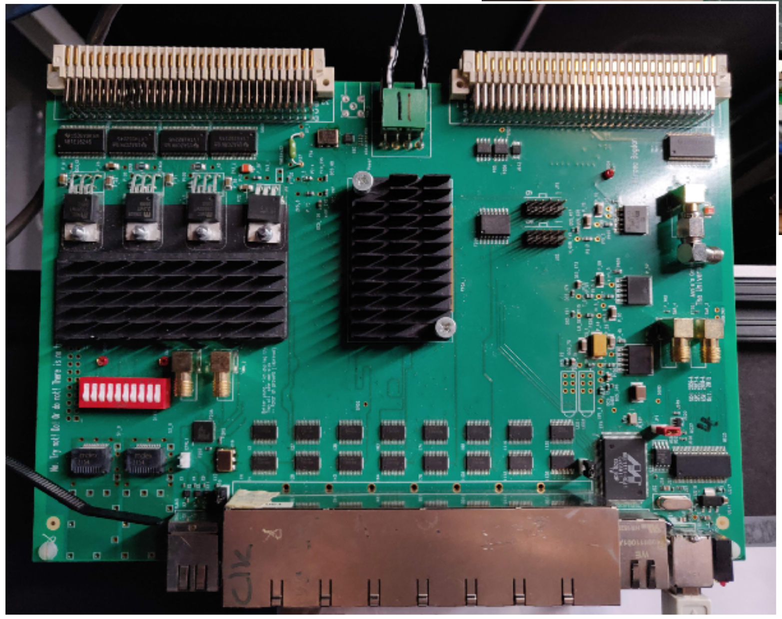
A quantum efficiency map of LAPPD #63.

PROGRESS: LAPPD ELECTRONICS WORKING IN TANDEM

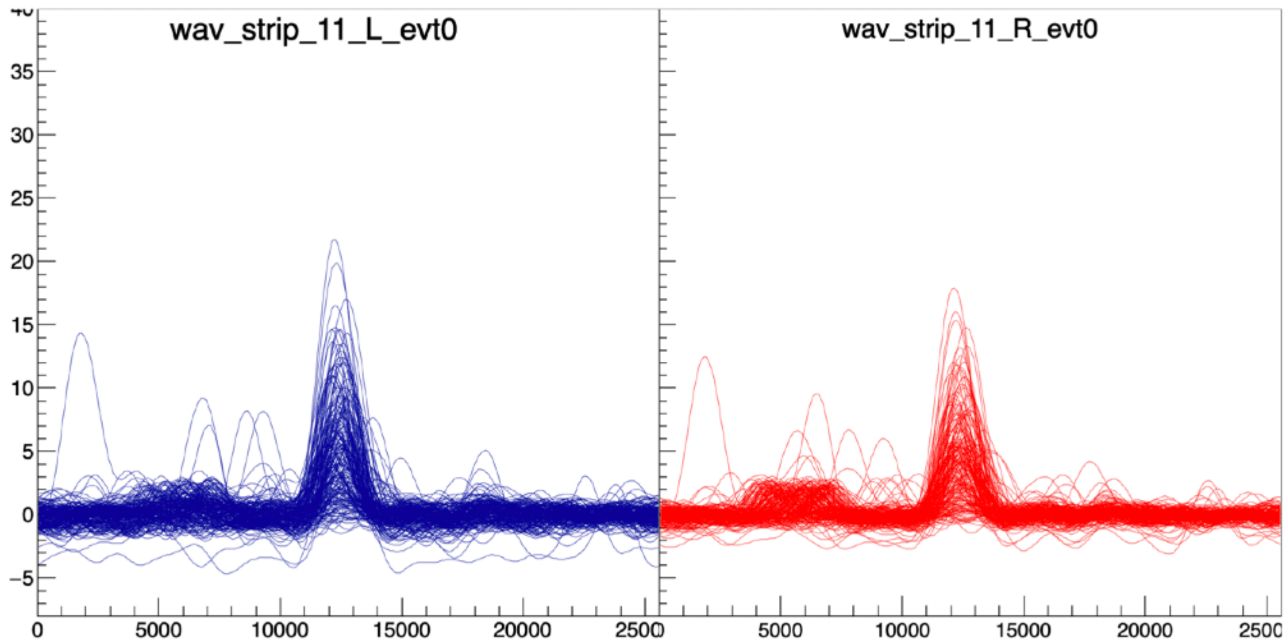
- Tested the PSEC readout electronics with improved LAPPD data acquisition software — can clearly see acquired waveforms!
- Made significant progress on data analysis software
- Slow controls system fully tested and integrated into monitoring system

Two ACDC boards attached to an LAPPD analog pickup board. These read out the 28 anode striplines





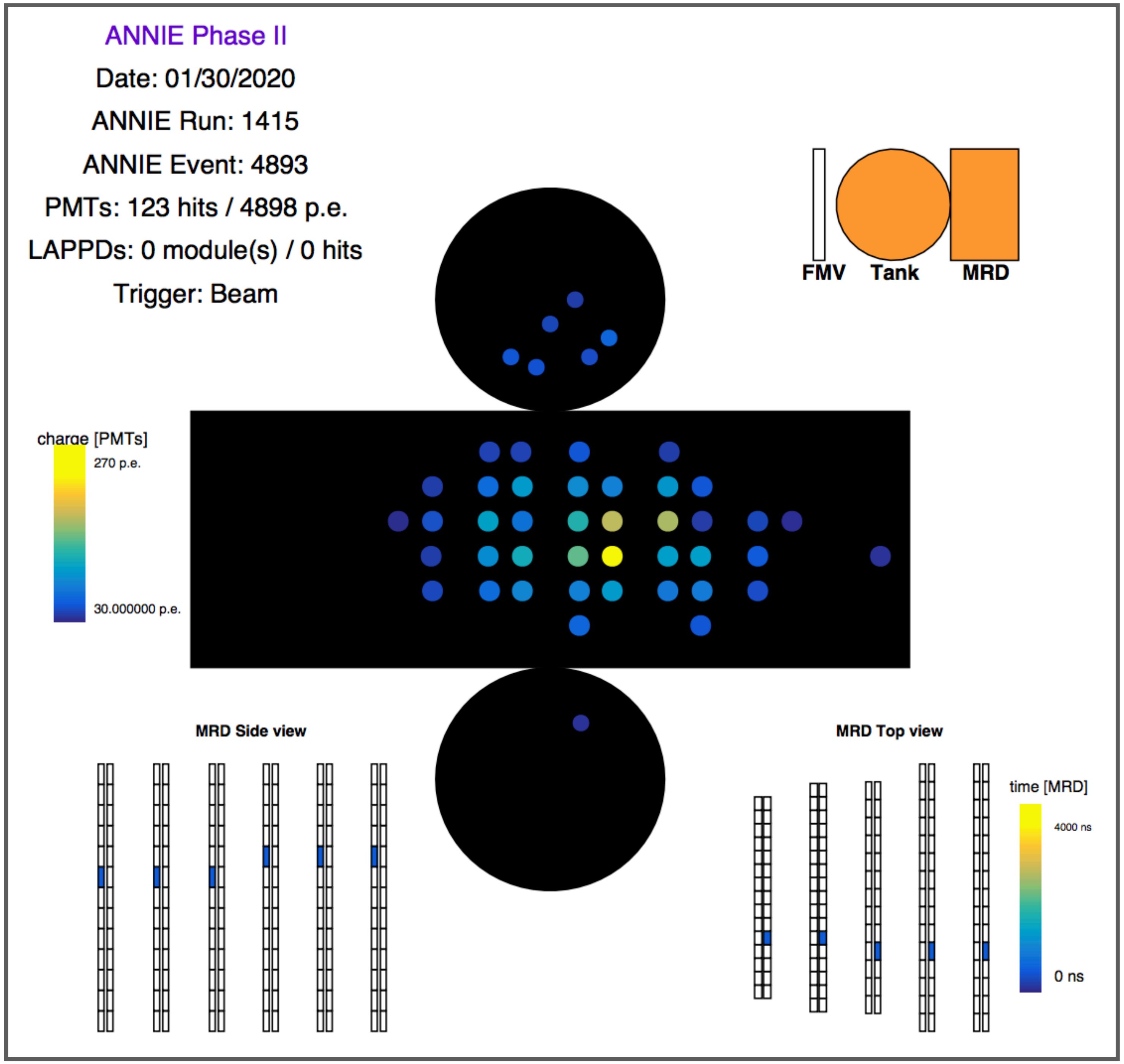
An ACC board mounted on the outside of the dark box. This manages the ACDC boards.



Processed waveforms that have been smoothed out using FFT. These are pulses read out from the left and right sides of the anode stripline.

ANNIE'S FIRST EVENTS

- Took beam data throughout the entire beam year without major issues
- Coming soon with LAPPD data!



WHAT IS THE CURRENT STATUS?

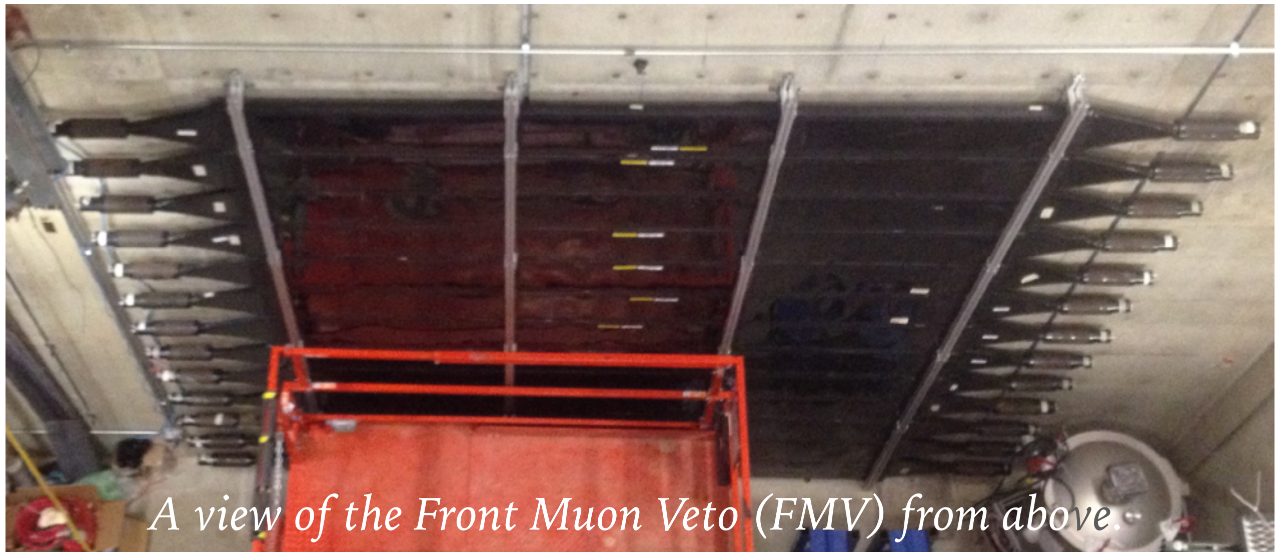
- The ANNIE Phase II detector had a successful beam run despite external factors and obstacles
- LAPPD development testing saw significant progress and is wrapping up at Lab 6. Moving to the experimental hall soon!
  - Testing of the LAPPD trigger board remains
- DAQ upgrades are underway for the summer
  - Updates to the trigger scheme to include laser calibration
  - Integration of LAPPD data frame into the main framework
- Regular maintenance of water system
- Deployment of LAPPD soon!

Spring Collaboration Meeting 2021

We can do ANNIE-thing! 🇺🇸🇬🇧🇩🇪🇹🇷 *Thank you for listening!*

BACK UP

FRONT MUON VETO & MUON RANGE DETECTOR


A view of the Front Muon Veto (FMV) from above

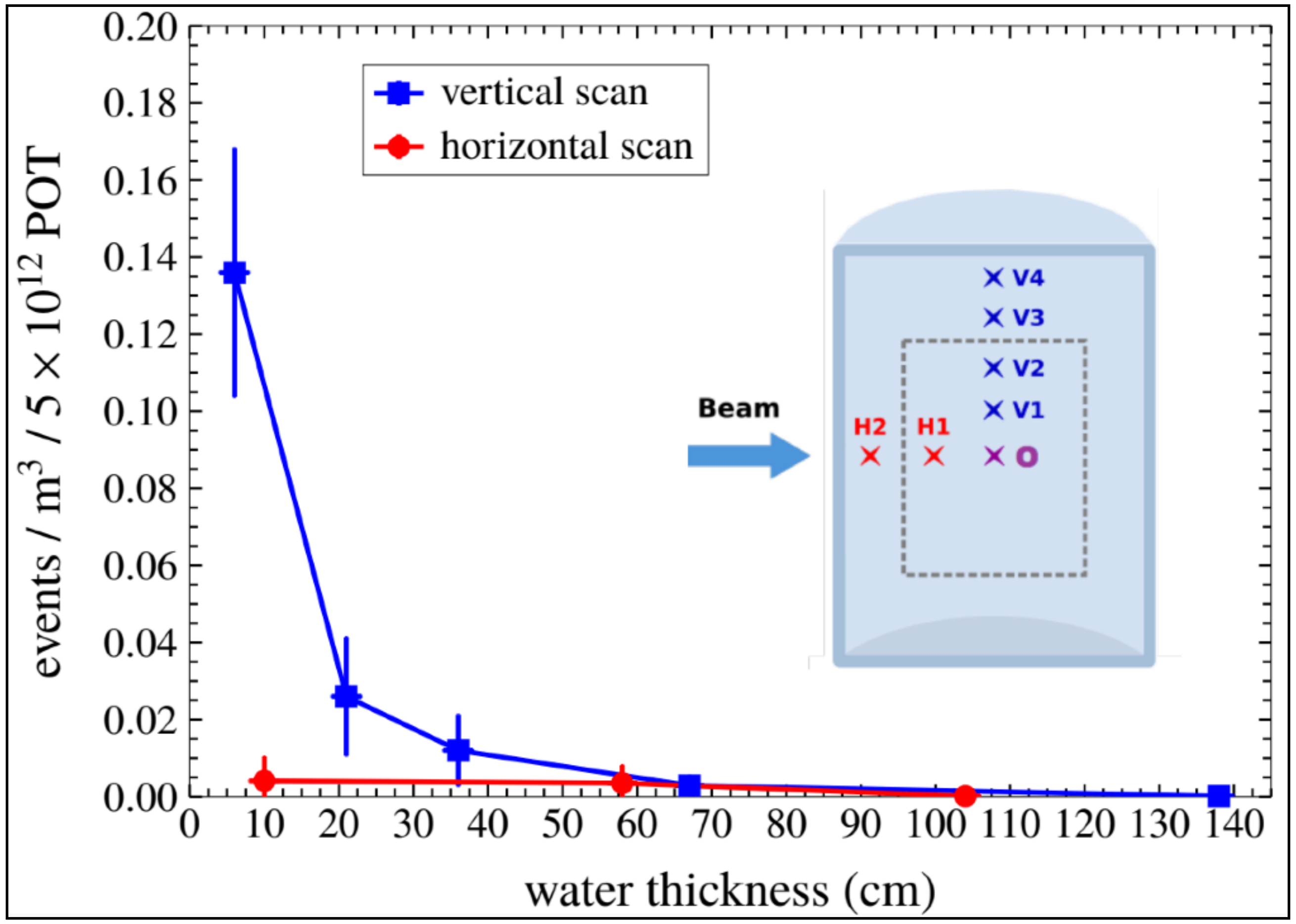
Me and a few MRD layers, pre-pandemic.

- **Front Muon Veto (FMV):** 2 layers of 13 scintillator paddles each; tags muons that are produced upstream of the detector

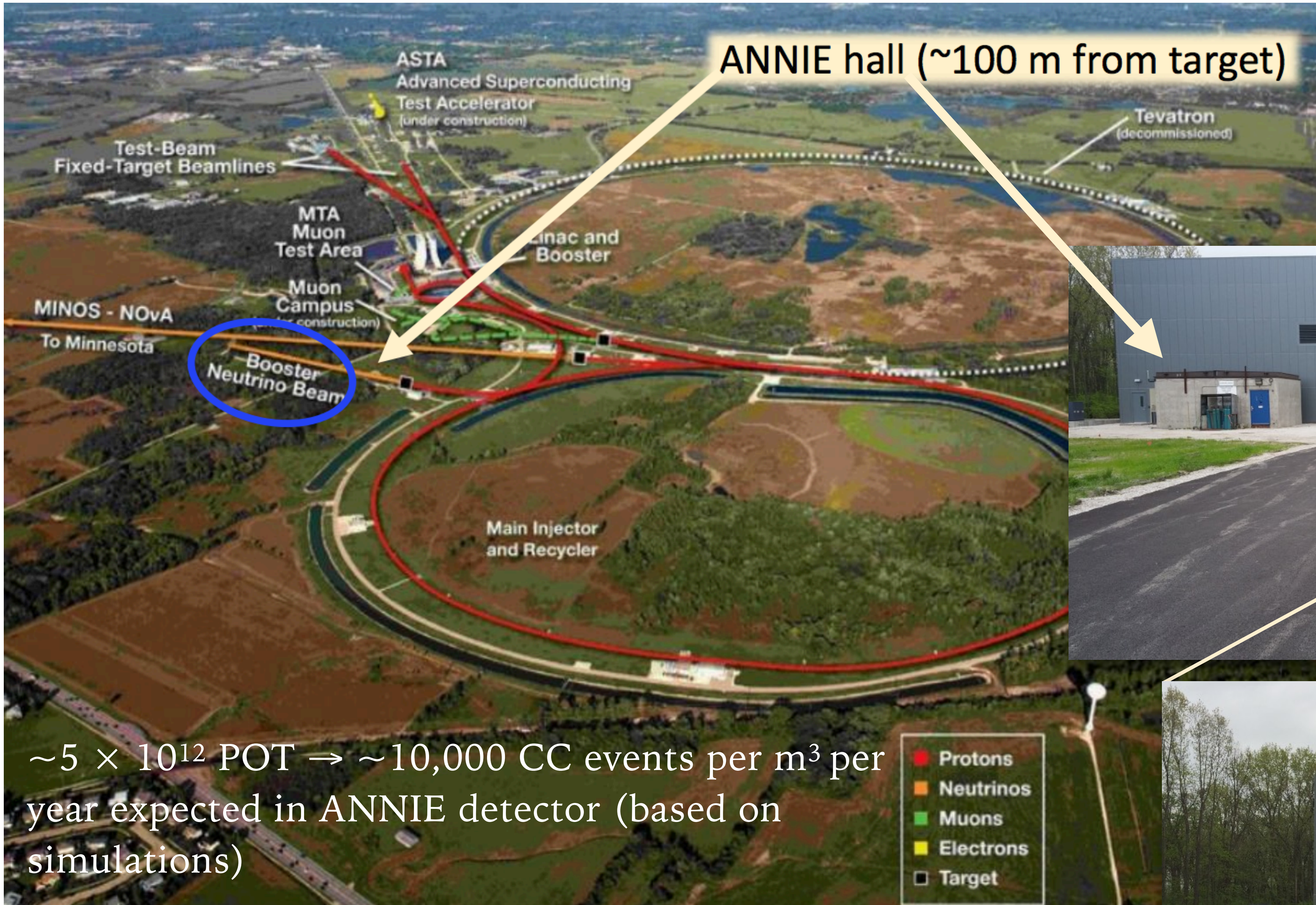
- **Muon Range Detector (MRD):** 11 layers of scintillator paddles (310 total) alternating with 11 layers of iron; tags muons downstream of the detector

ANNIE PHASE I RESULTS: NEUTRON BACKGROUND

- Deployed a **neutron capture volume (NCV)**, an acrylic vessel filled with Gd-doped scintillator
- Neutron background rates drop significantly as we move down the tank — "self-shielding"
- Background rate measured to be **<0.02 / m³ / spill**
- Source of background: dirt neutrons, "skyshine" neutrons



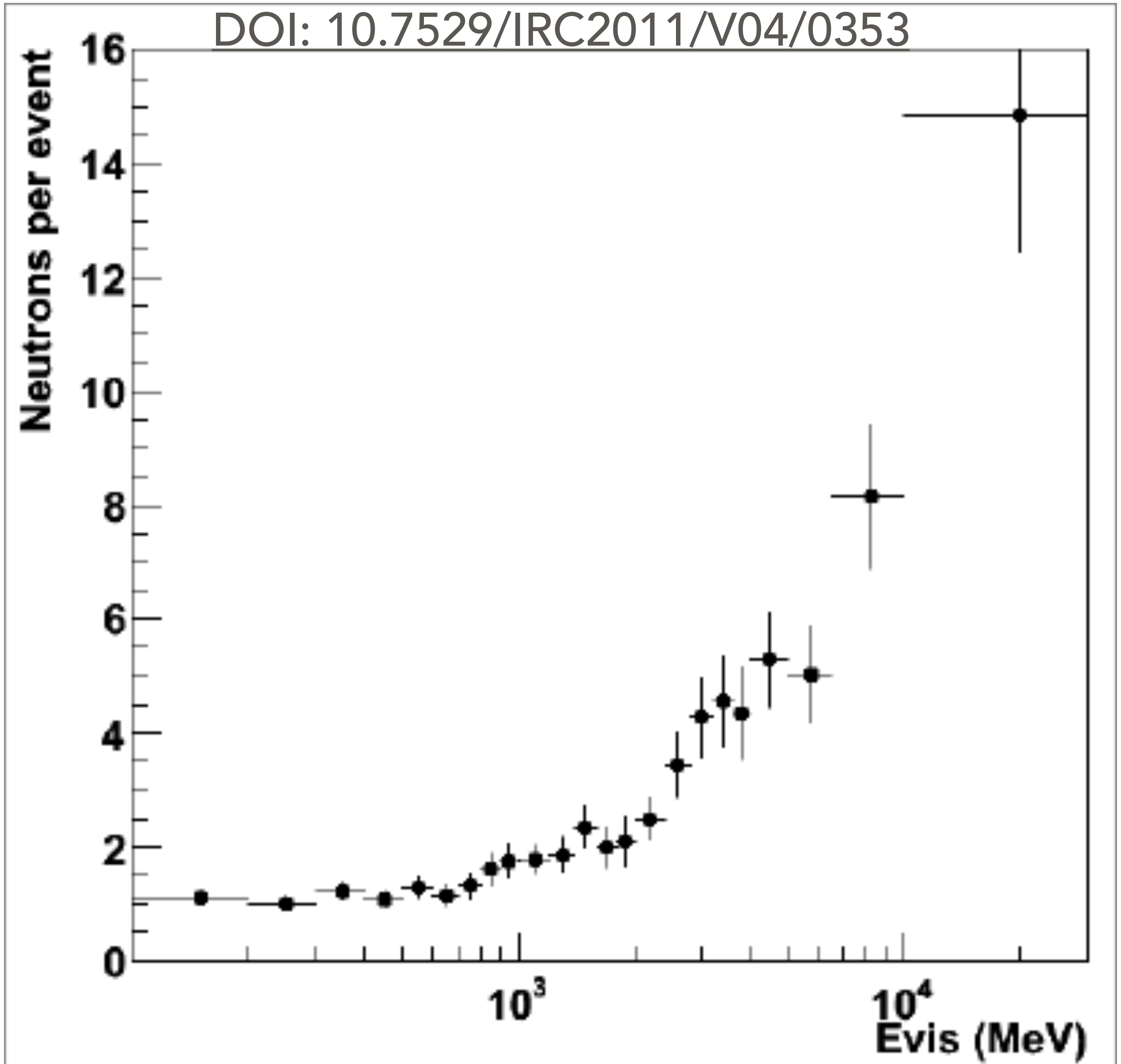
BOOSTER NEUTRINO BEAM AT FERMILAB



$\sim 5 \times 10^{12}$ POT → ~10,000 CC events per m^3 per year expected in ANNIE detector (based on simulations)

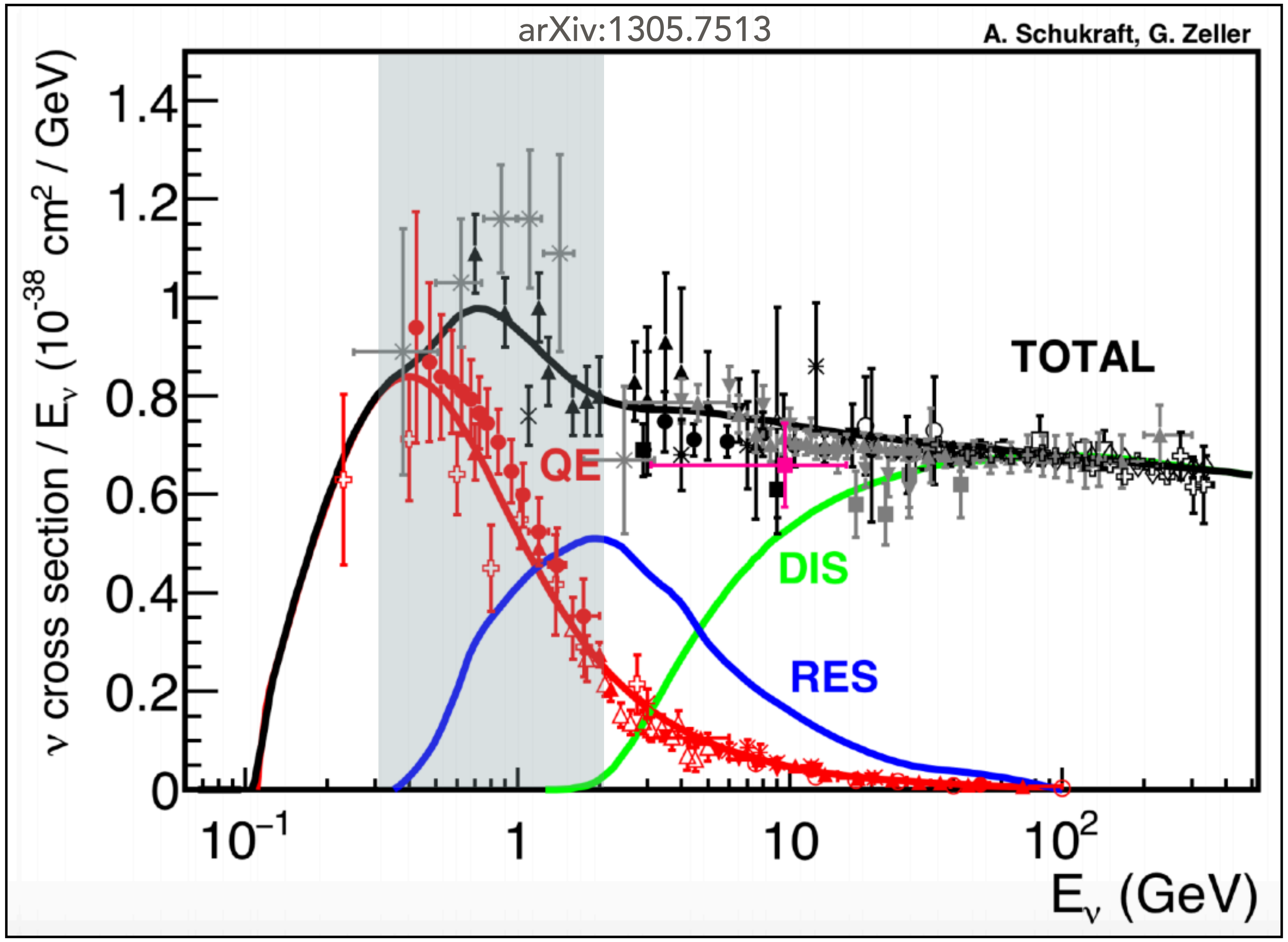
Flux peaks at ~700 MeV, which is in the energy region of interest for long baseline and atmospheric neutrino experiments

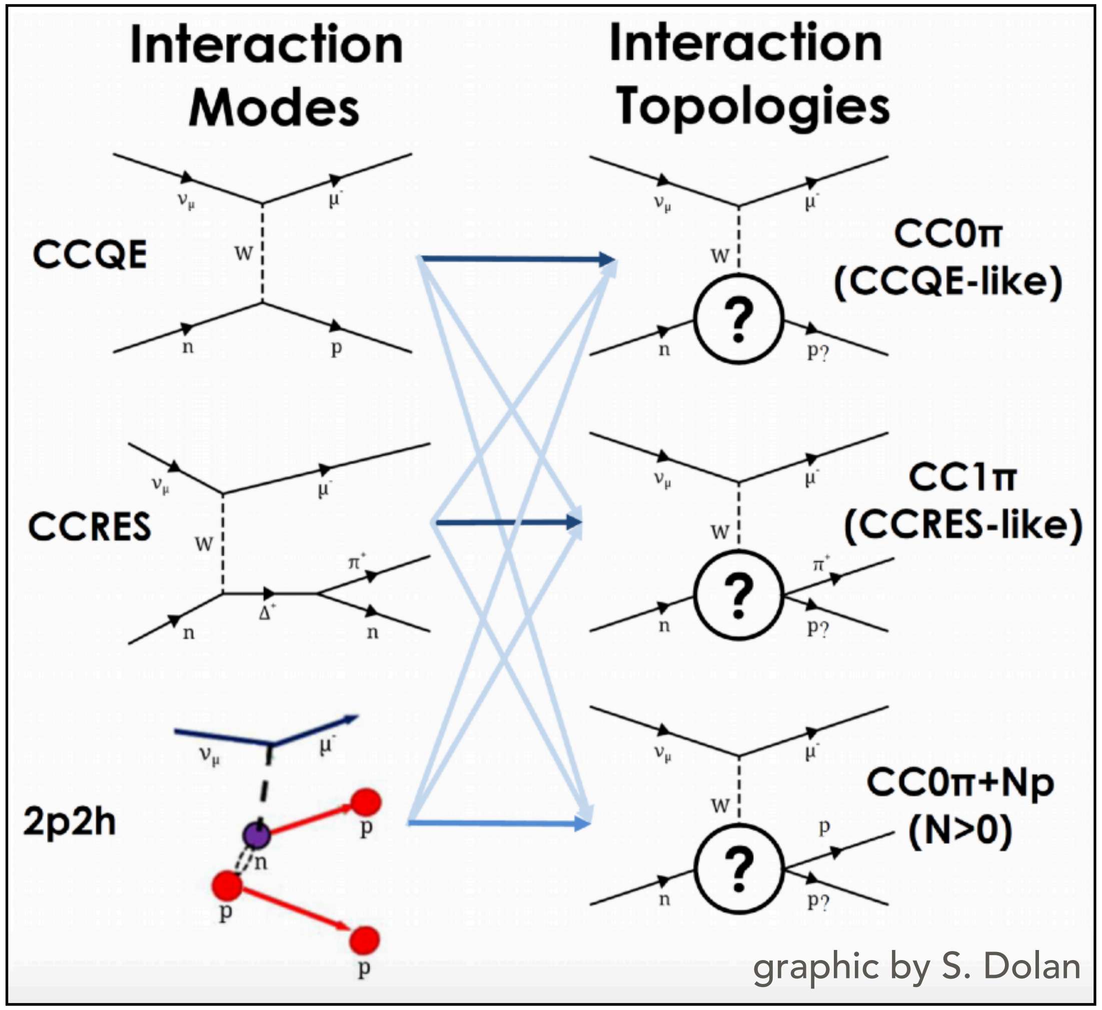
SUPERKAMIOKANDE'S NEUTRON MULTIPLICITY MEASUREMENT



- ➤ SuperK's neutron multiplicity measurement using atmospheric neutrinos in pure water
- ➤ Neutron multiplicity is plotted as a function of visible energy
- ➤ ANNIE's neutron multiplicity measurement will be an improvement because we will have high statistics and we know where our neutrinos are coming from

PHYSICS MOTIVATION: WHY MEASURE NEUTRON MULTIPLICITY?

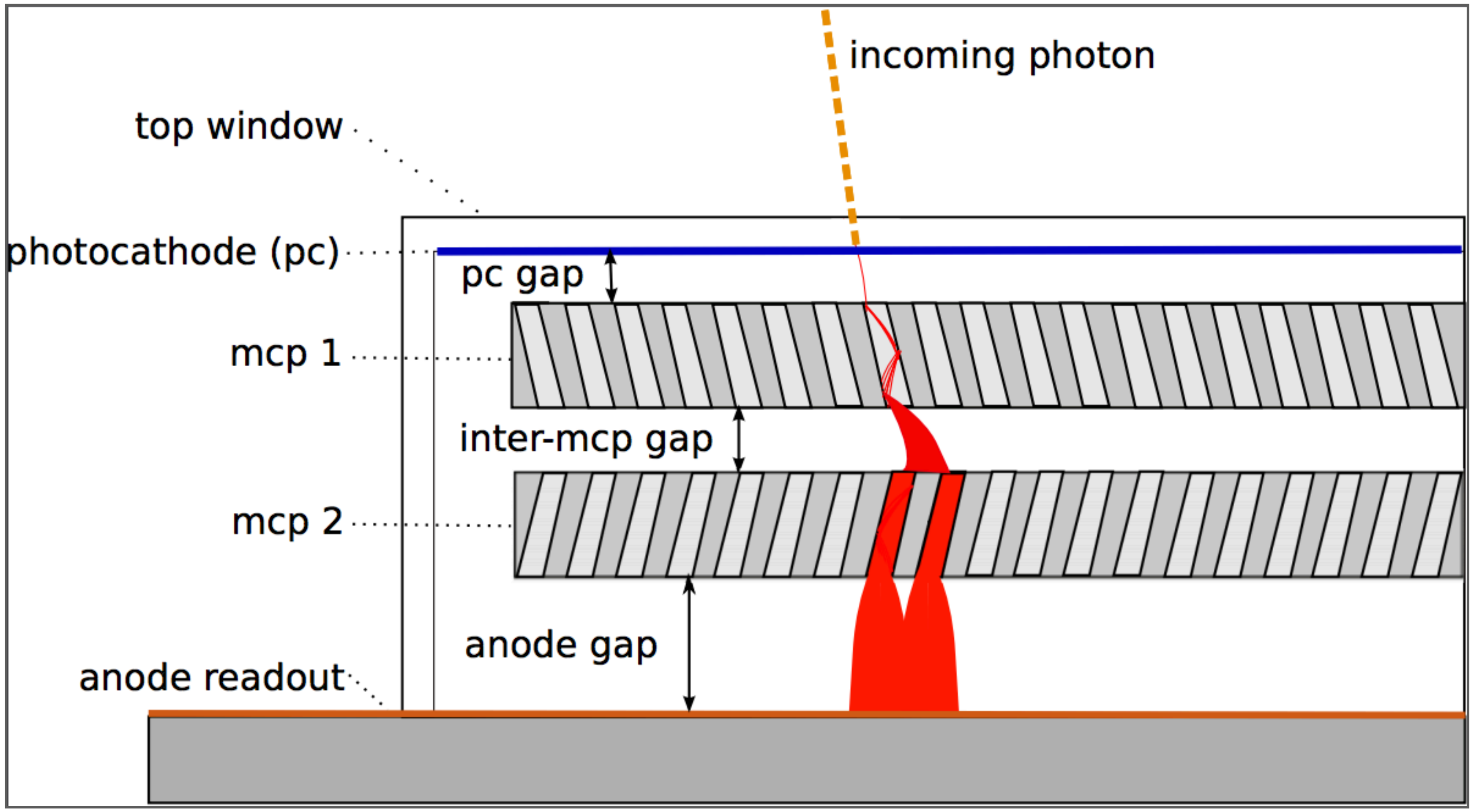




- The highlighted energy region is where many neutrino experiments operate (including ANNIE!)
- Several types of interactions (quasi-elastic, resonant) start to become significant and neutrons are one of the final state products
- However, neutrons hint at inelasticity and misidentifying elastic and inelastic processes could bias energy reconstruction

THE TECHNOLOGY BEHIND LAPPDS

- Alkali photocathode
- Highly uniform gain of 10^7 (comparable to conventional PMTs)
- 64 ps timing resolution in main peak of transit time spread (TTS)



- Resistive (~100nm) and emissive (~20nm) coating applied via atomic layer deposition (ALD)
- <4% contribution from after-pulses (typical of any photodetectors)
- Thickness of an LAPPD tile (window, MCPs, etc.) ~15mm