ANNIE Phase I and Plans for Phase II

R. Svoboda, UC Davis, TAUP 2017, Sudbury

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

The ANNIE Collaboration

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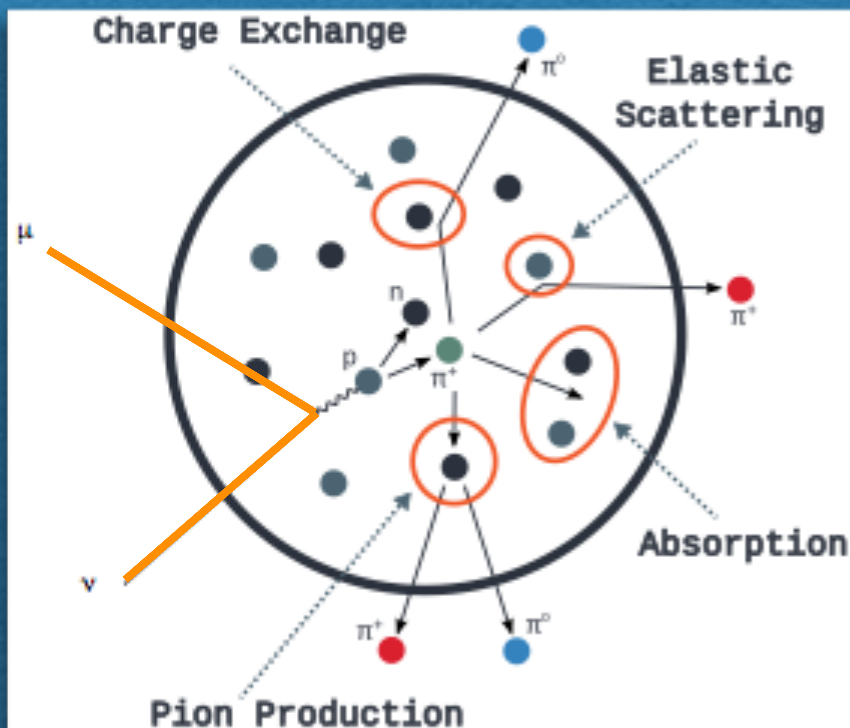
TWO GOALS:

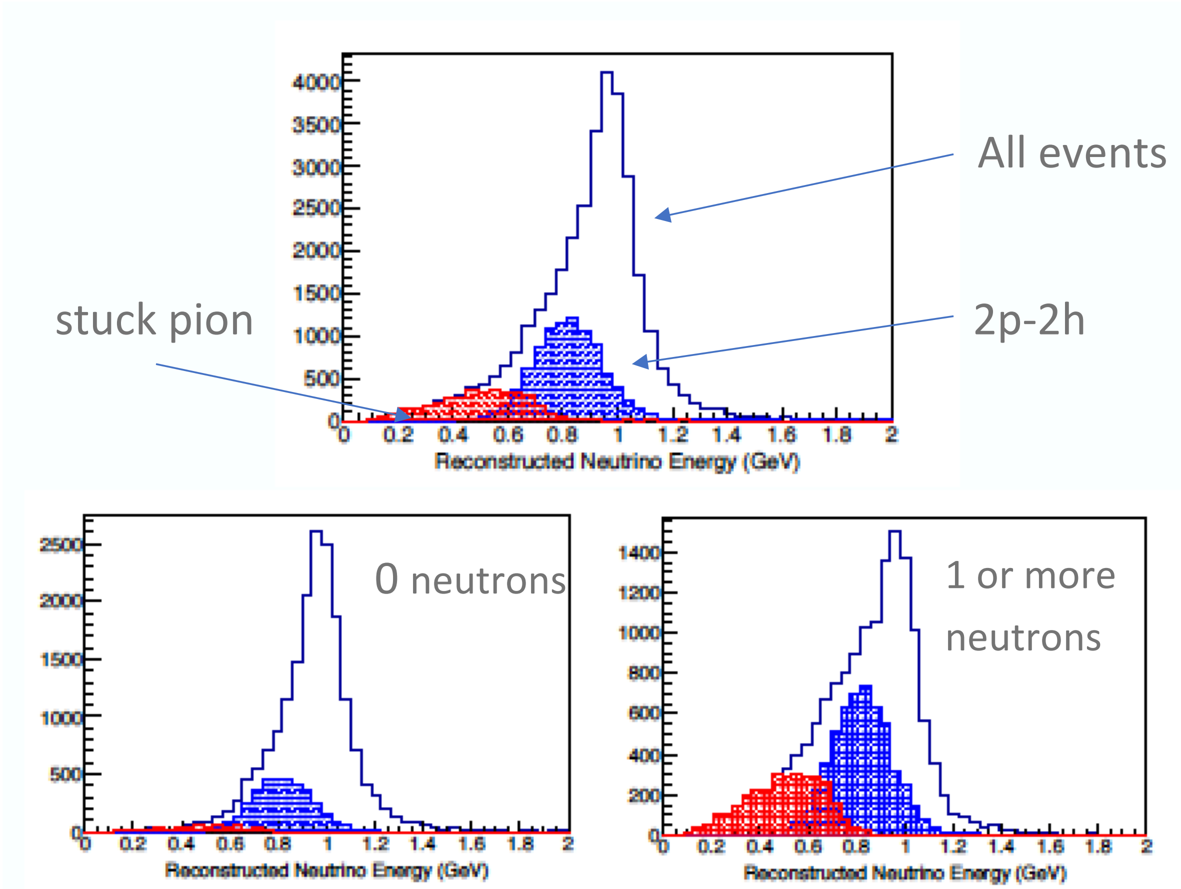
- Measure the abundance of final state neutrons from neutrino interactions in water, as a function of energy and momentum transfer
- Demonstrate the use of fast, large format MCPs for event reconstruction in the GeV range

Neutrino-Nucleus interactions are complex and difficult to model



from the NUSTEC white paper

Effect of 2p-2h and stuck pions on events interpreted as QECC is significant



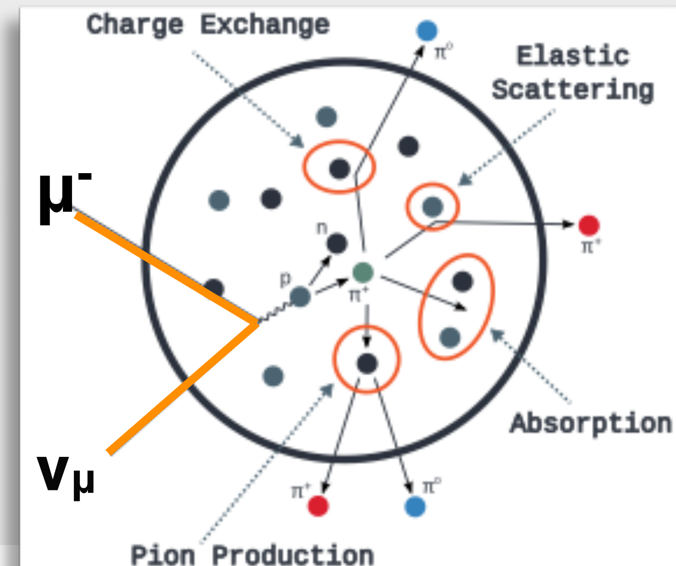
FS neutrons are an excellent indicator of inelasticity

GENIE 1 GeV monoenergetic ν_μ beam with reconstructed energy from FS lepton reconstruction

ANNIE Physics Motivation

To turn neutrino physics into a precision science we need to understand the complex multi-scale physics of neutrino-nucleus interactions

- Dominant source of systematics on future long-baseline oscillation physics
- Possible source of uncertainty in short-baseline anomalies
- We need comprehensive and precise measurement for a variety of targets/E_ν



ANNIE is a final-state X + Nn program to complement X + Np measurements in LAr

The presence, multiplicity and absence of neutrons is **also** a strong handle for signal-background separation in a number of physics analyses!

ANNIE Physics Motivation

To turn neutrino physics into a precision science we need to understand the complex
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" **...**As neutrino-antineutrino event-rate comparisons are important for δCP measurements, the relative neutron composition of final hadronic states is significant. It is important to understand the prospects for semi-inclusive theoretical models that can predict this neutron composition. **Experimentally, programs to detect neutrons are essential."**

Neutrino Scattering Theory and Experiment Collaboration
NuSTEC white paper

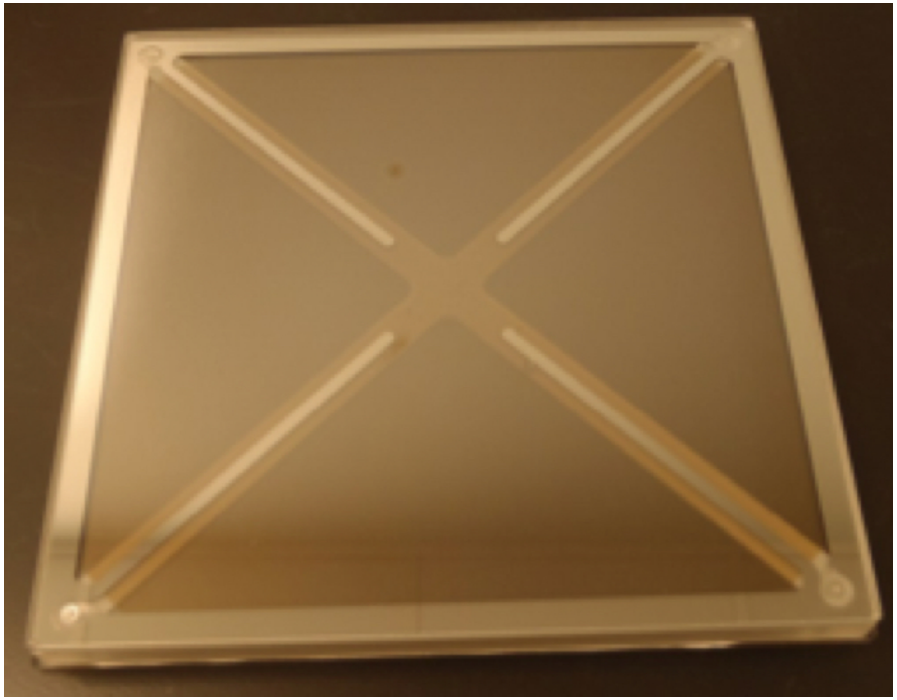
ANNIE ... in LAr

The presence, multiplicity and absence of neutrons is **also** a strong handle for signal-background separation in a number of physics analyses!

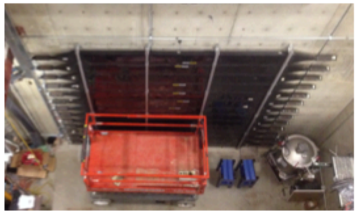
ANNIE Detector R&D

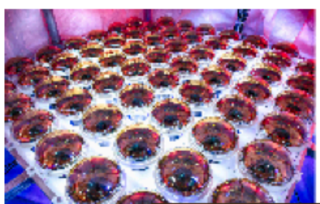
- A first application of Large Area Picosecond Photodetectors (LAPPDs) in a neutrino experiment
- Demonstrate operation of multiple LAPPDs, integrated with a larger hybrid detector system

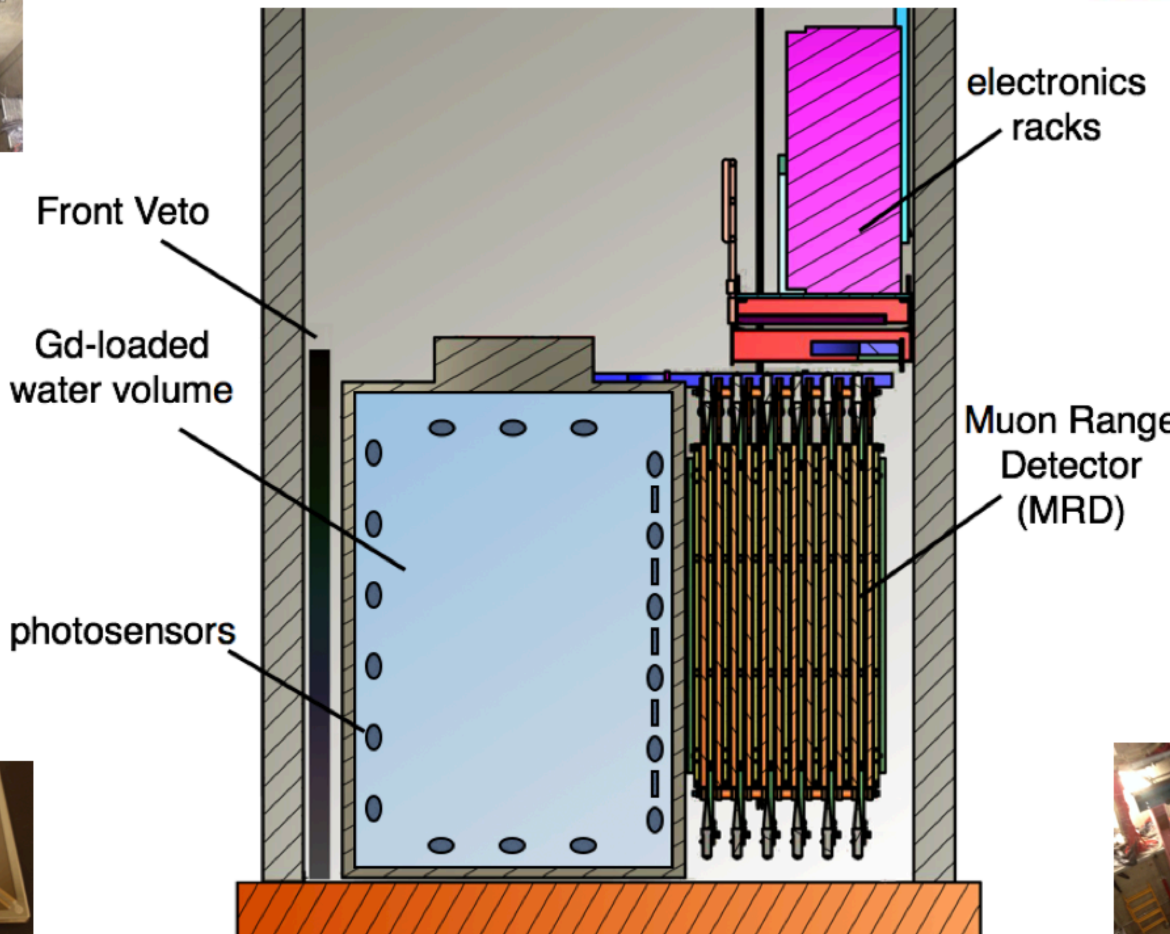
- LAPPDs are 8” x 8” MCP-based imaging photodetectors, with target specifications of:
  - ~50 picosecond single-PE time resolution
  - < 1 cm spatial resolution
  - > 20% QE
  - > 10^6 gain
  - low dark noise (<100 Hz/ch)

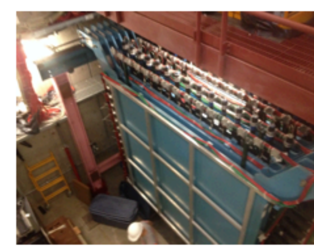


ANNIE Experimental Design

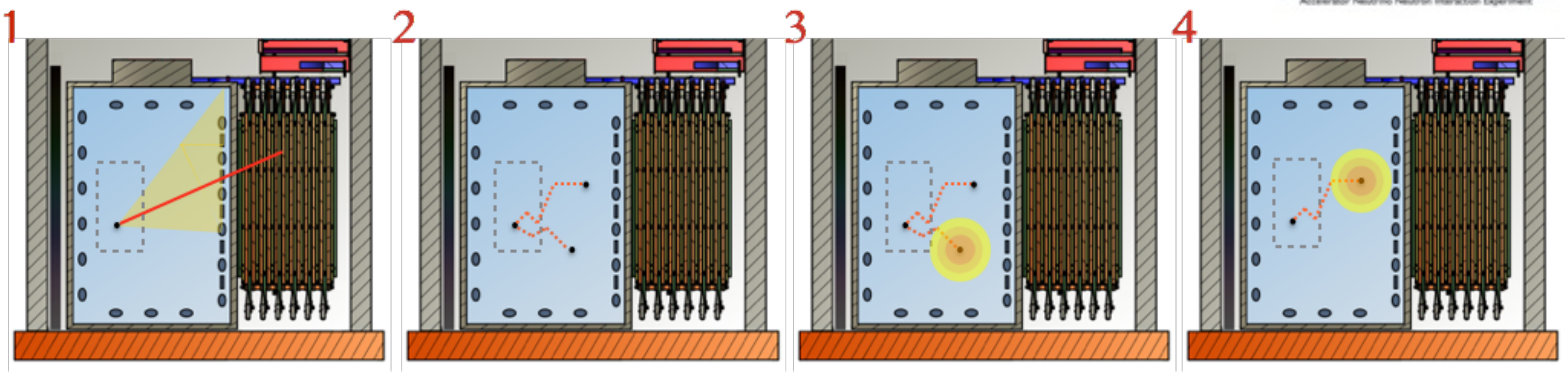








ANNIE Experimental Design



1. CC interaction in the fiducial volume produces a muon, reconstructed in the water volume and MRD
2. Neutrons scatter and thermalize

3. - 4. Thermalized neutrons are captured on the Gd producing flashes of light

ANNIE Experimental Design

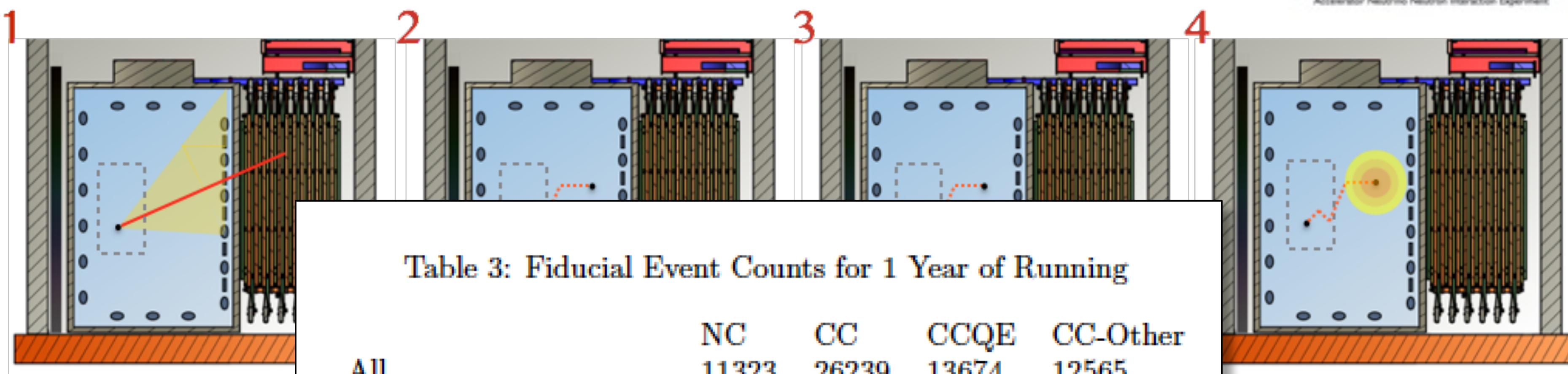


Table 3: Fiducial Event Counts for 1 Year of Running

	NC	CC	CCQE	CC-Other
All	11323	26239	13674	12565
Entering MRD	2	7466	4279	3187
Stopping in MRD	2	4830	2792	2038
Fully Penetrating MRD	0	1454	761	693
Exiting Side of MRD	0	1181	726	455

1. CC interact ... ed in the water volume and MRD
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ANNIE Q^2 Acceptance

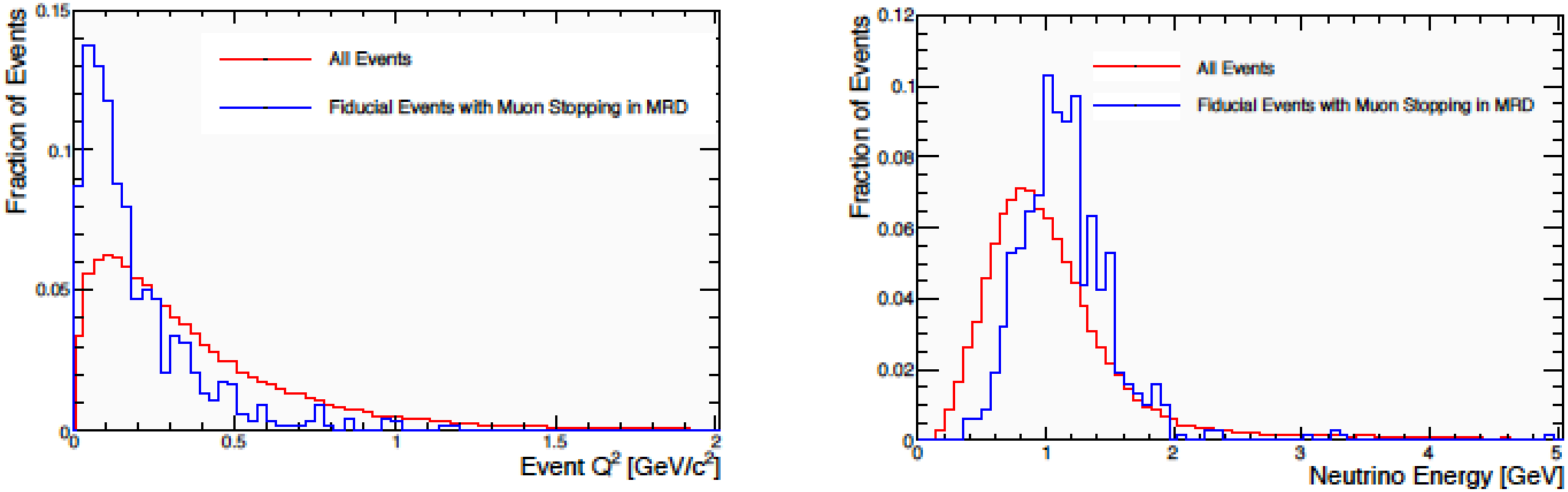
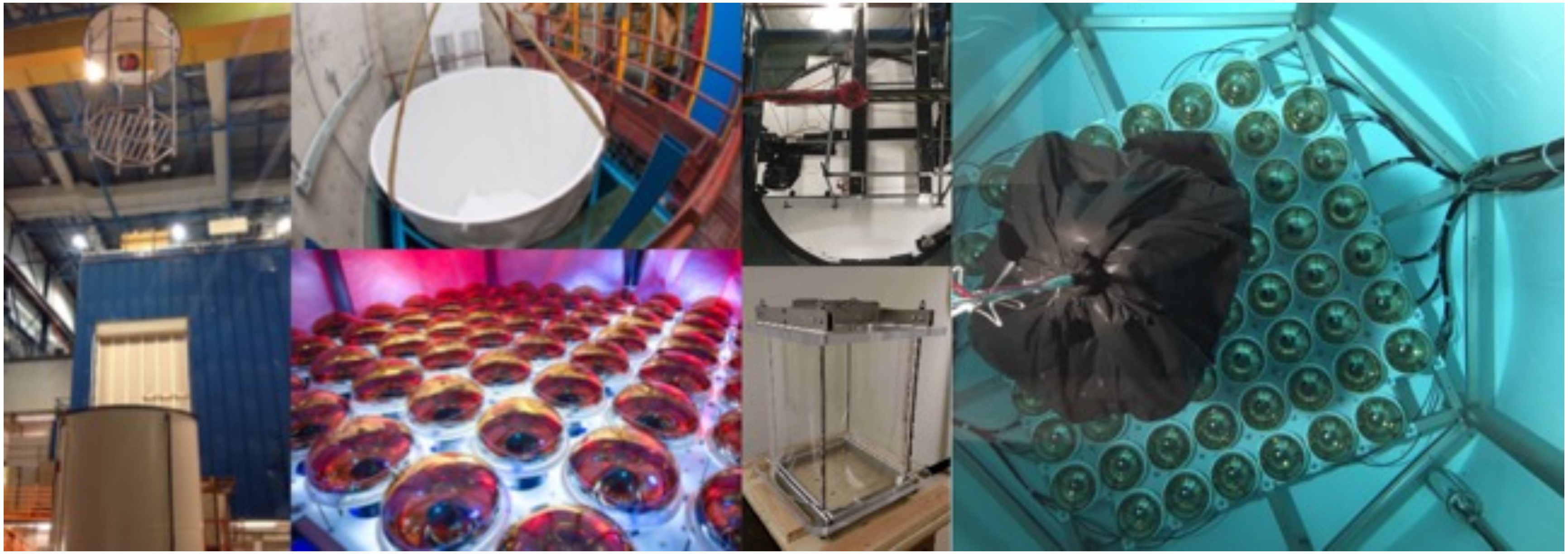


Figure 18: LEFT: The normalized Q^2 distribution for all events (red line) and for 2.5-ton fiducial events with muons ranging out in the MRD (blue line). RIGHT: The normalized E_ν distribution for all events (red line) and for 2.5-ton fiducial events with muons ranging out in the MRD (blue line).

It is important to measure neutron multiplicity as a function of these parameters and therefore we want a wide spread in neutrino energy and Q^2

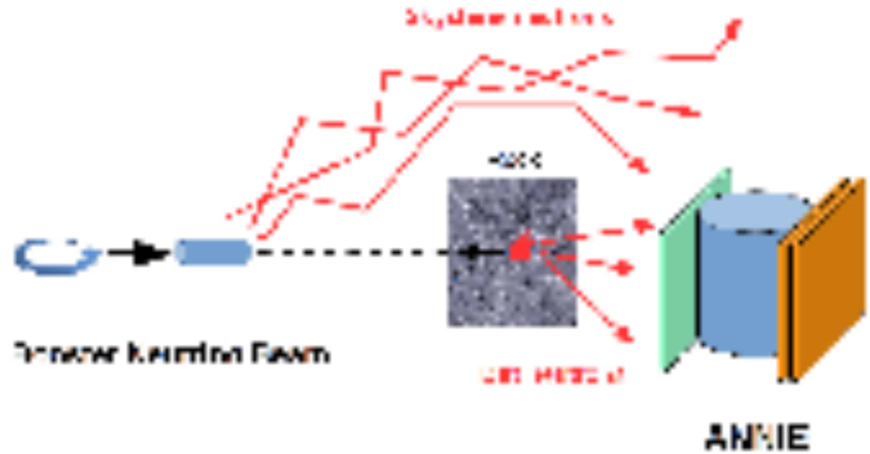
ANNIE Phase I: built, commissioned, completed Phase 1 this month

- ANNIE Phase I received PAC approval in February 2015
- The detector was built by April of 2016
    - taking data by May of 2016
    - finished data taking July 2017



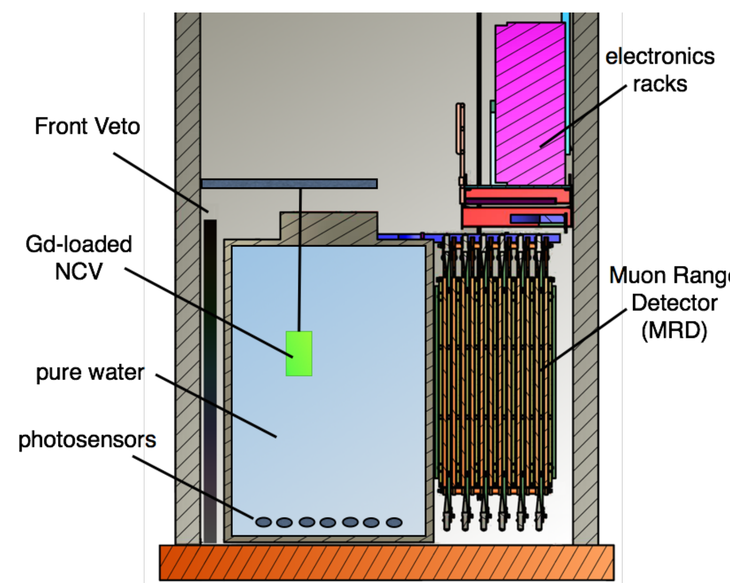
ANNIE Phase I:

- A measurement of potential background neutrons in ANNIE Phase II
    - rock neutrons
    - “skyshine”

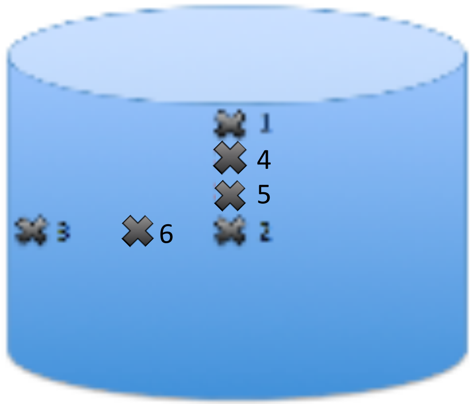


- A Neutron Capture Volume (NCV) measures position dependent neutron rates

- Phase I enabled ANNIE to build and operate all the main components of the detector
- It also provided an opportunity to anticipate, understand, and mitigate major risks for Phase II



Phase I: background measurement

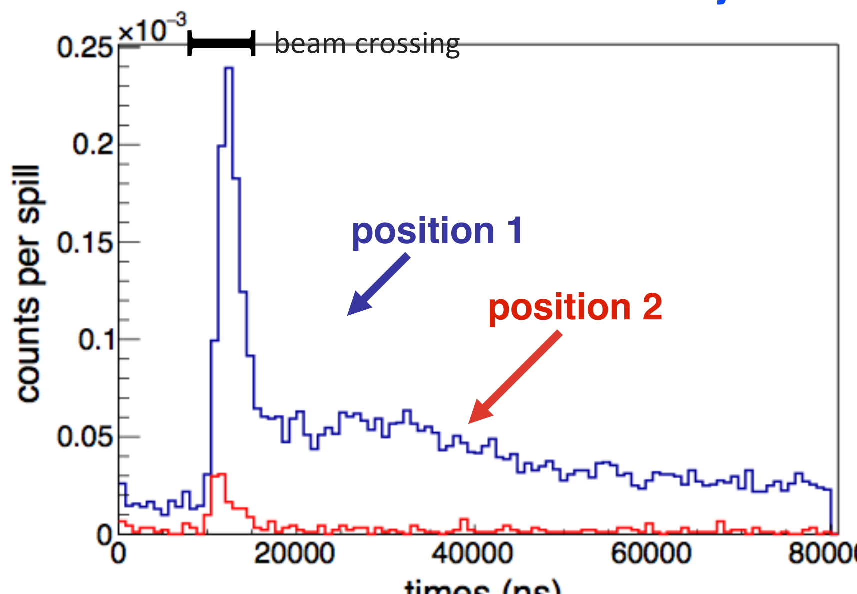


- the NCV was moved to 6 positions, scanning the neutron rates as a function of depth and distance from the beam
- strong suppression of skyshine neutrons was observed with increasing depth

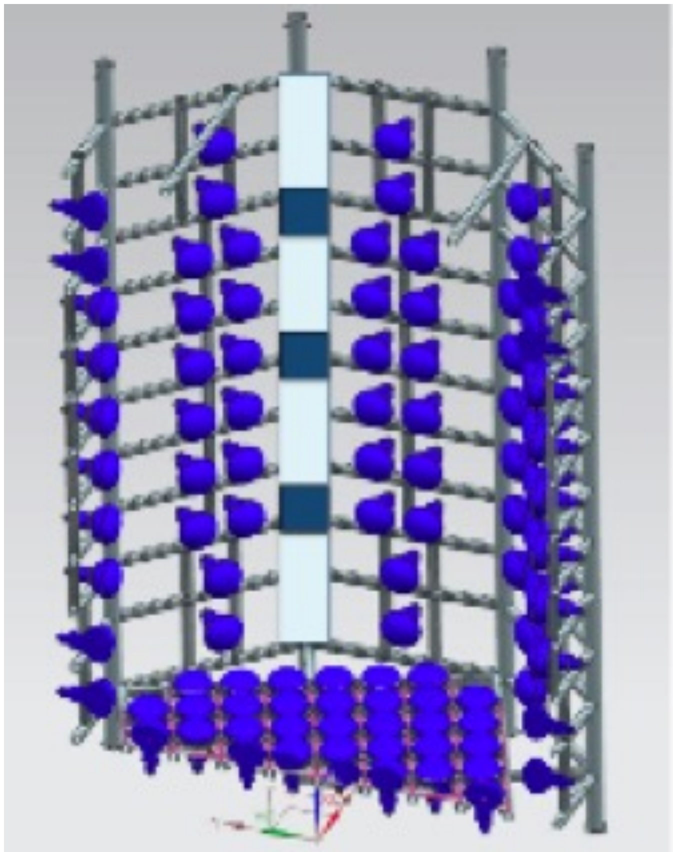
- preliminary estimates based on measurements below the surface indicate neutron backgrounds in less than 2% of spills

Backgrounds are suppressed at depths > 50 cm and sufficiently low for Phase II

ANNIE Preliminary Data

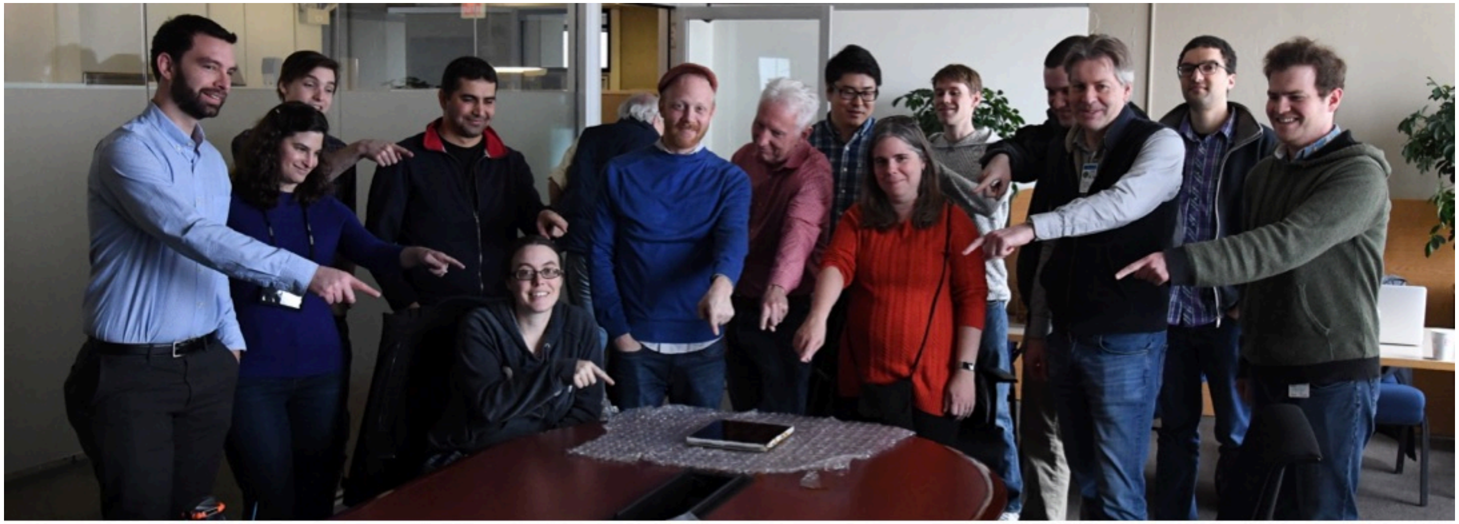


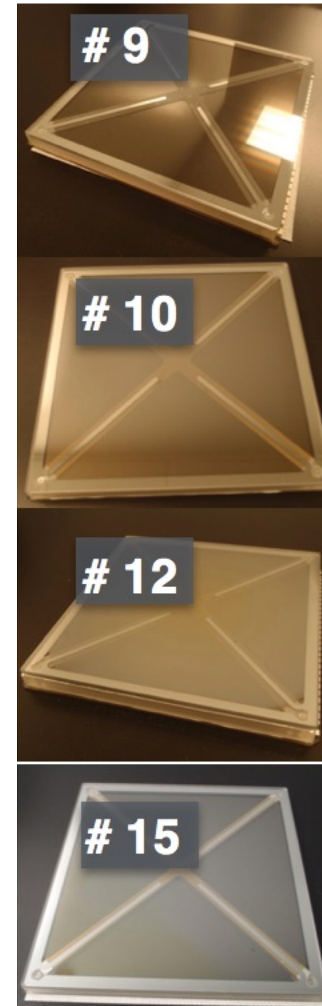
From Phase I to Phase II



- Finish refurbishing the muon range detector (reinstall paddles)
- Complete the tank inner structure
- Expand standard photocathode coverage w/ more PMTs
- Expand electronics channel count
- Add Gadolinium
- Add the LAPPD System

LAPPDs Are Ready for Phase II



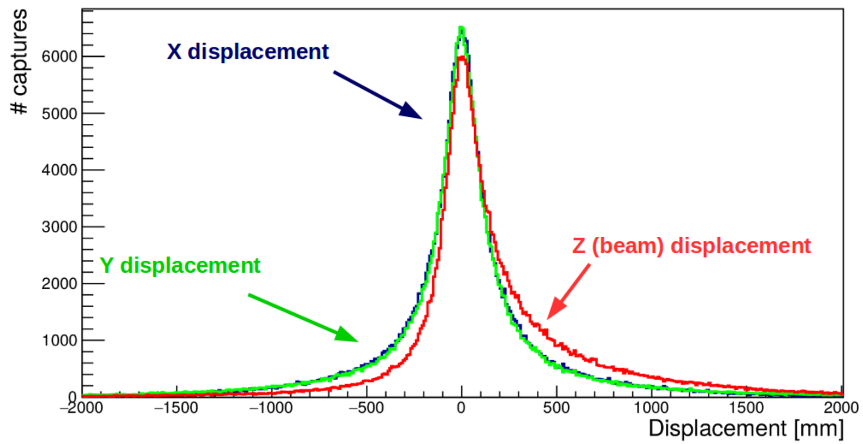


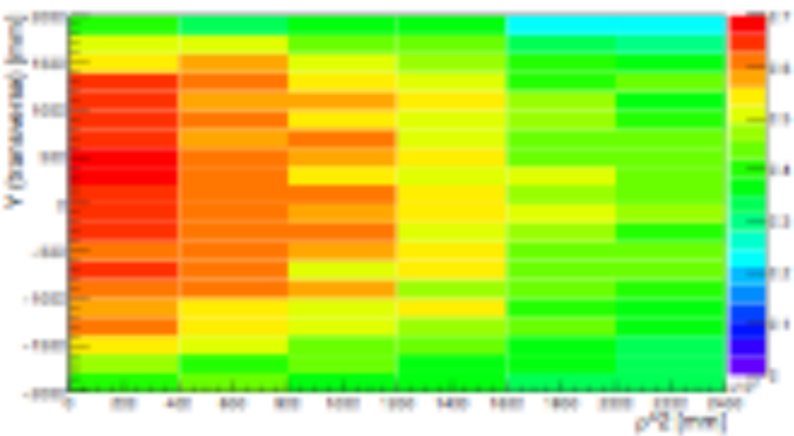
Incom has now produced multiple LAPPD prototypes, quickly approaching the specifications needed by ANNIE

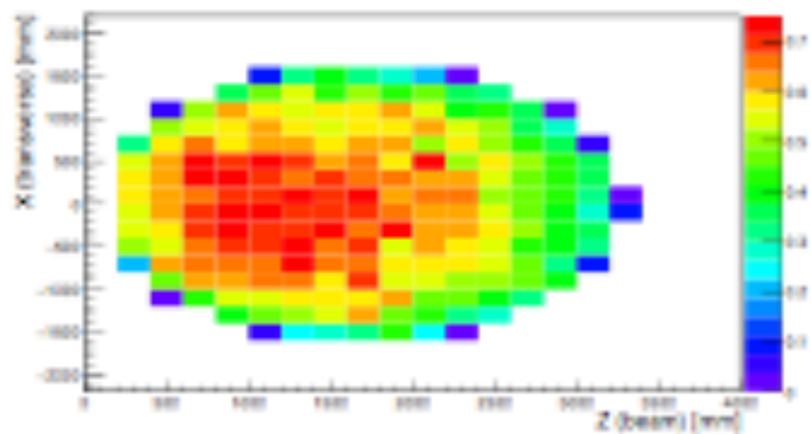
- Tile #9: fully sealed detector with an aluminum photocathode
- Tile #10: sealed detector with multi-alkali photocathode (~5 % QE)
- Tile #12: ~10% QE
- **Tile #15: uniform photocathode >25% QE**

ANNIE neutron capture efficiency

- The detector is large enough to fully contain neutrons
- Requested PMT coverage is sufficient to efficiently detect neutrons

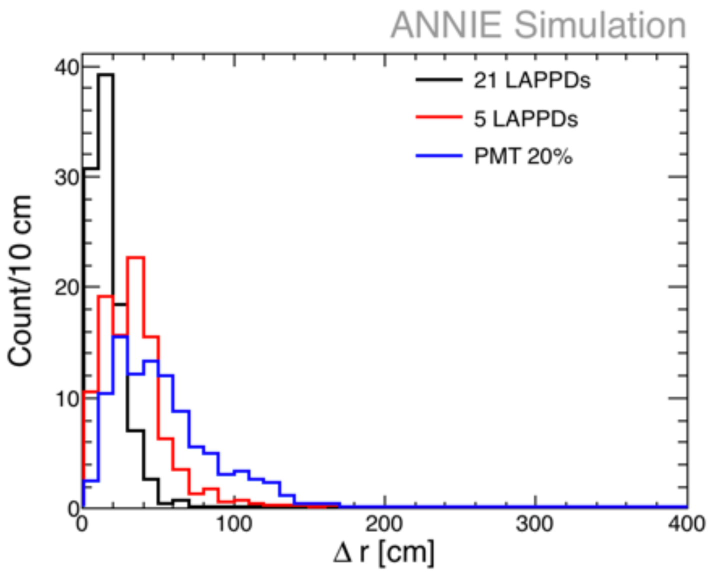


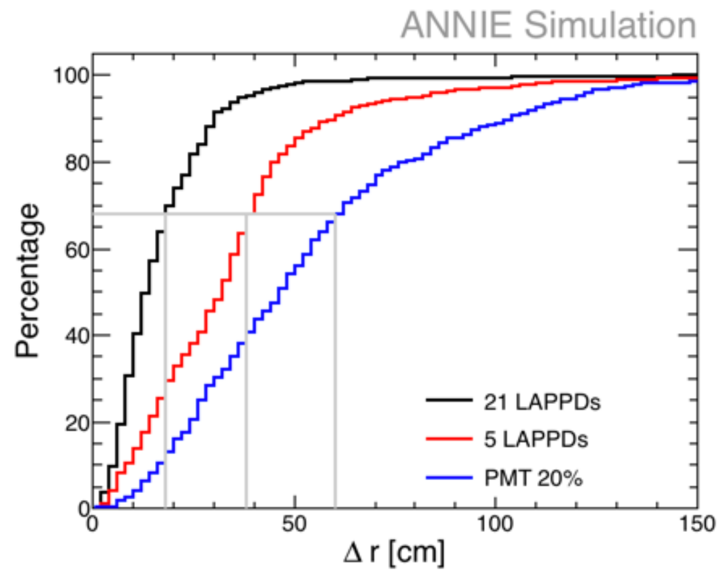




Why ANNIE needs LAPPDs

LAPPDs provide needed vertex resolution to select fiducial events





20% conventional PMTs: 60 cm resolution

5 LAPPDs (only): 38 cm resolution

21 LAPPDs (only): 16 cm resolution

More advanced reconstruction tools and techniques, as well as further MC production are under way

ANNIE Timeline

Summer 2017

Completion of Phase II inner structure and tank lid

Removal of the tank from the Hall

Finish MRD refurbishment

Fall/Winter 2017

PMT refurbishment and acquisition

Electronics acquisitions

Spring 2018

PMT installation

Reinstallation of inner structure and water fill

Summer 2018

Phase II commissioning

Introduction of Gd

LAPPD installation

Fall 2018

Phase II data taking

Conclusions

- ANNIE will measure neutron production as a function of Q^2 in the ROI for long baseline experiments and proton decay, complementing proton production measurments.
- Phase I built and operated successfully. Backgrounds shown to be sufficiently low for Phase II
- LAPPDs exist and are on track to meet ANNIE requirements for Phase II, according to our simulations
- ANNIE Phase II has been recommended for approval by Fermilab PAC this month

Backup

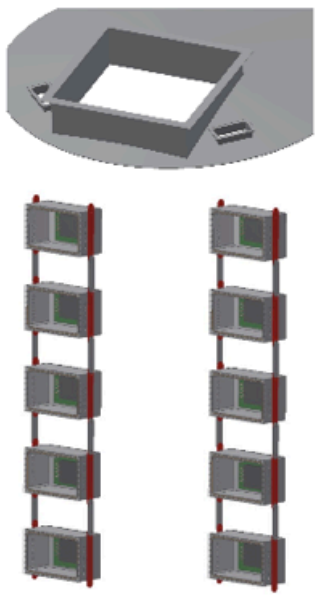
Progress Towards Phase II

19 LUX PMTs

45 WATCHMAN PMTs

22 LBNE PMTs

LAPPD deployment



LAPPD housing

- We have in hand free large area PMTs to use for Phase II. Need only ~40 8in new ones
- New design for the LAPPD housing assemblies allows for LAPPDs to be installed into the already assembled detector
- PMT and MRD readout systems and DAQ are already working and expandable.
- The LAPPD, PSEC-4 readout system is largely complete

Phase I data sets

Table 2: Summary of Phase I data taken as of 12 June 2017. The triggering modes are **beam** for IRM triggers from the BNB, **source** for ^{252}Cf calibration source triggers (see Sec. 2.3), **cosmic** for cosmic muon triggers, and **hefty** for beam data taken in the "Hefty mode".

NCV position	DAQ triggers by type Beam	Source	Cosmic	Hefty	Total DAQ triggers	Approximate # of recorded beam spills
1	1.96×10^6	2.58×10^5	1.72×10^4	5.19×10^3	2.24×10^6	2.13×10^6
2	9.25×10^5	0.00	2.25×10^3	2.91×10^5	1.22×10^6	11.98×10^6
3	0.00	0.00	0.00	1.62×10^5	1.62×10^5	6.16×10^6
4	0.00	0.00	0.00	3.80×10^4	3.80×10^4	1.44×10^6

ANNIE NCV Calibration with 252-Cf

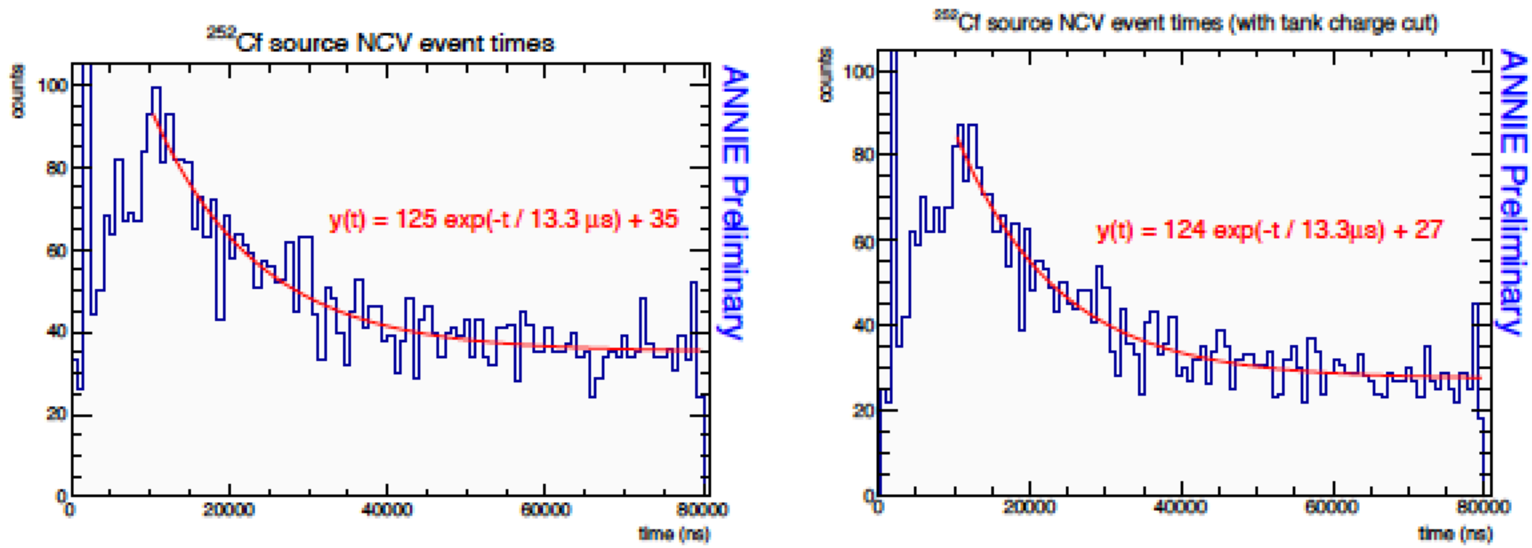


Figure 10: LEFT: Time distribution of NCV events (coincidences of both NCV PMTs) observed using the ^{252}Cf calibration source trigger with the NCV at position #1 with the trigger occurring at 2 μs. RIGHT: Time distribution of NCV events from the same dataset after applying an analysis cut on the total integrated charge observed on the water tank photomultiplier tubes.

ANNIE NCV Calibration with 252-Cf

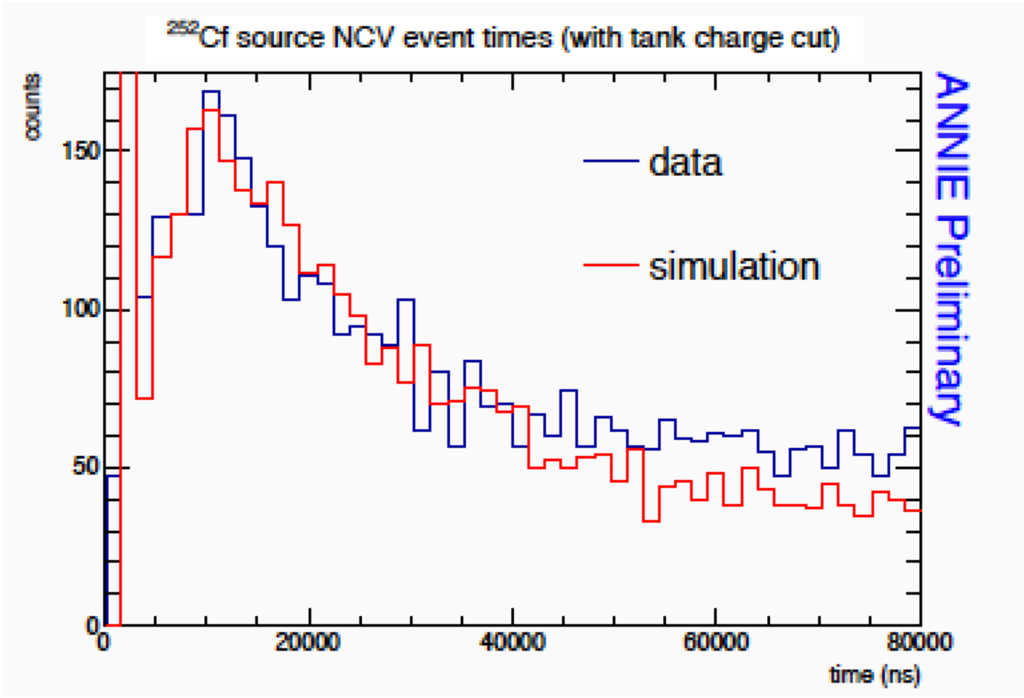


Figure 12: Comparison of the calibration source data (blue) with the results of a RAT-PAC simulation (red). The data histogram contains the same events as the right-hand panel in Fig. 10 (the same analysis cut has been applied), but it has been rebinned. The simulation histogram contains zero events in the first bin because the pre-trigger time region was not modeled.

LAPPD Fabrication and Testing

Figure 14: Working LAPPD prototypes from Incom.

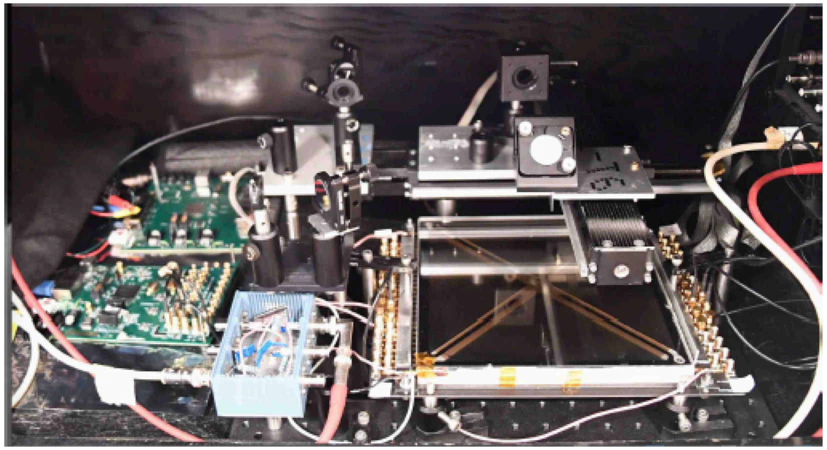


Figure 16: LAPPD-12 installed in the ISU test stand.

LAPPD Fabrication and Testing

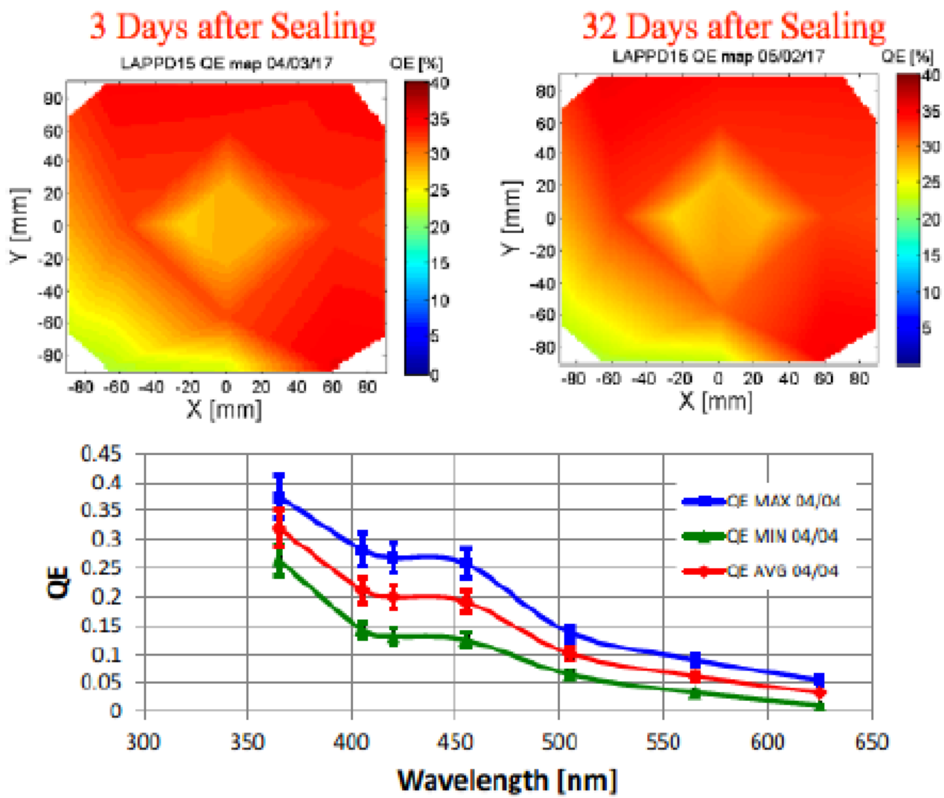


Figure 15: TOP: LAPPD-15 QE map at 3 days (LEFT) and 32 days (RIGHT) after sealing. BOTTOM: The average QE at 375 nm remains at 30%, with a maximum 35% and minimum of 22%.

LAPPD Fabrication and Testing

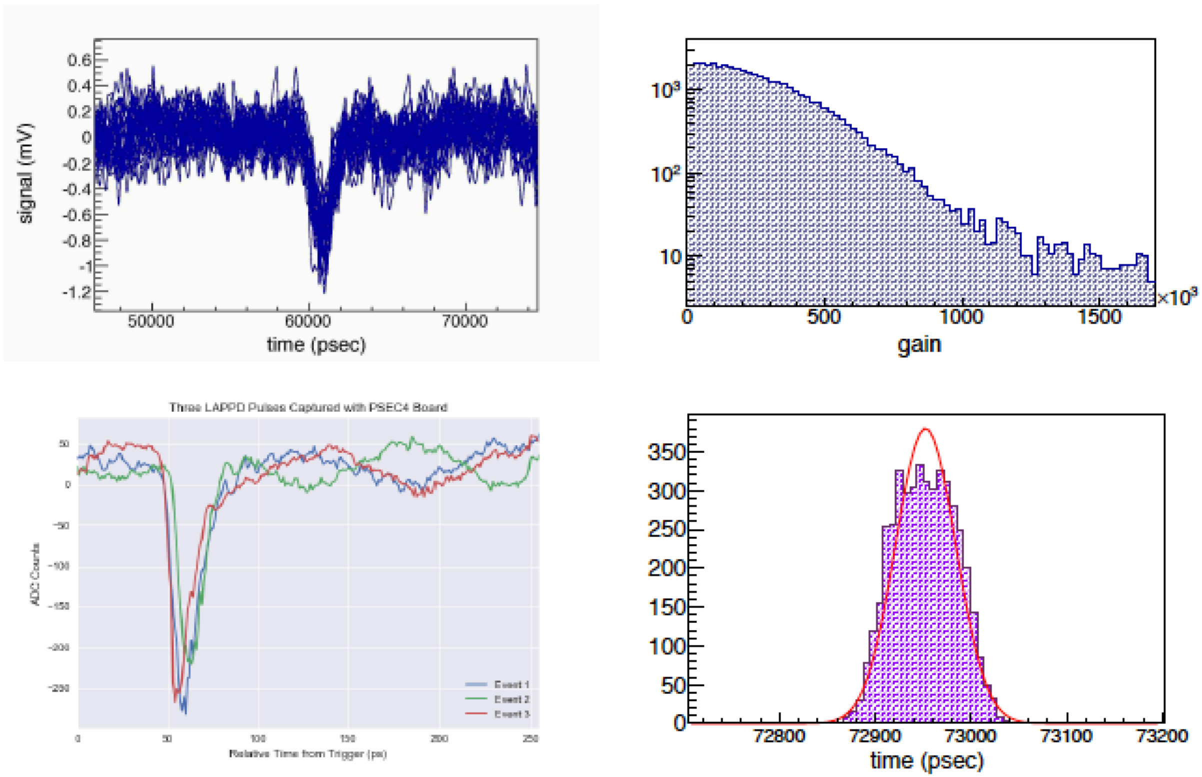


Figure 17: TOP LEFT: Example of single photoelectron pulses from LAPPD-9. TOP RIGHT: The single-PE gain distribution of LAPPD-9. BOTTOM LEFT: Several example multi-PE pulses from LAPPD-12, acquired using the PSEC front end readout. BOTTOM RIGHT: The multi-PE TTS distribution measured using the ISU test stand. The 30 psec sigma and non-Gaussian shape is due to the limitations of the laser, which should be sufficient for characterizing 50 psec photosensors.