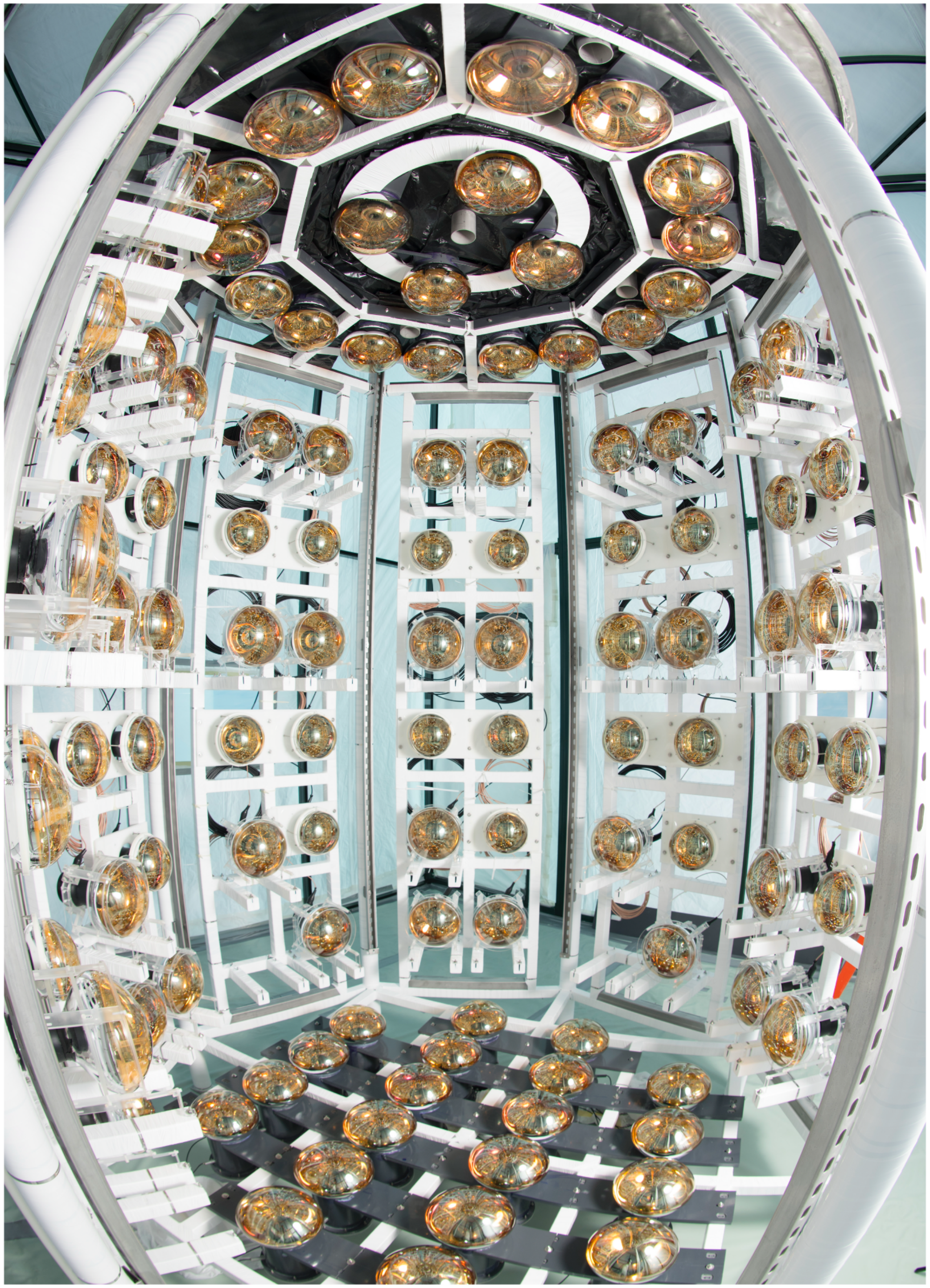


The ANNIE Experiment Status

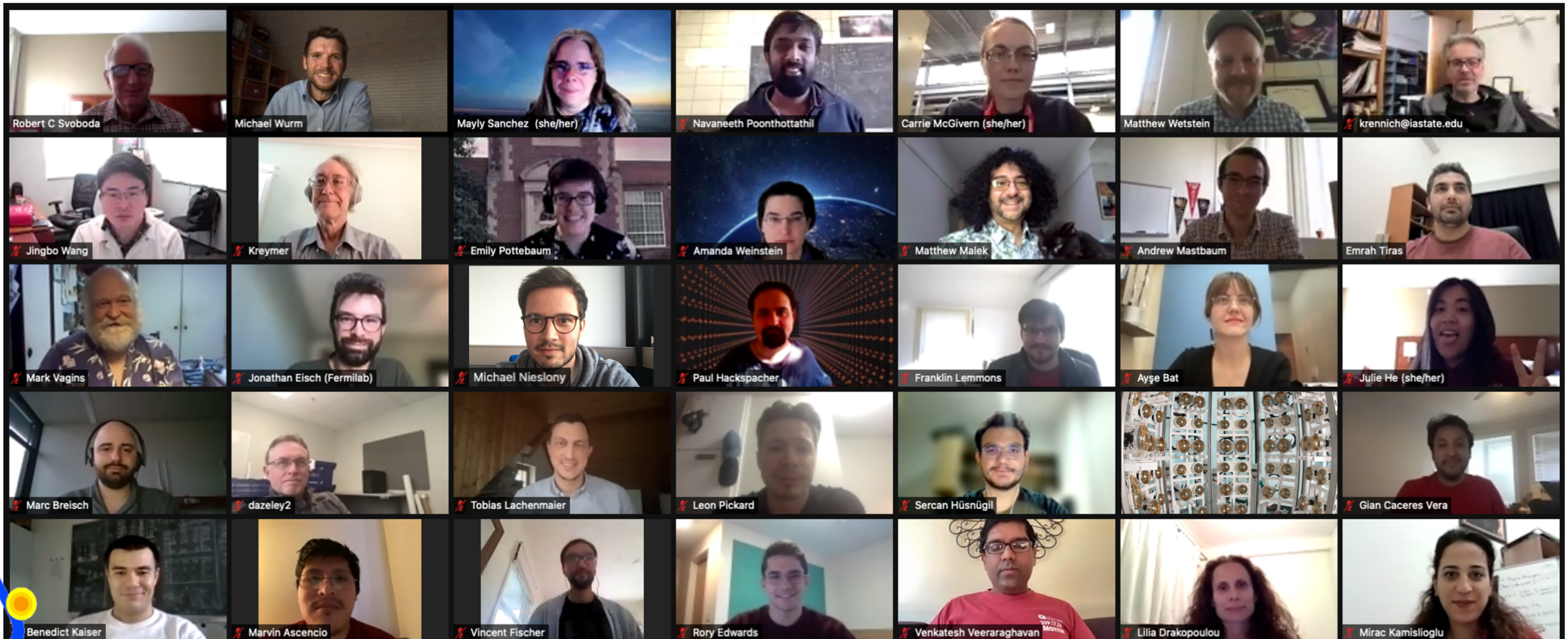
Mayly Sanchez & Michael Wurm
For the ANNIE Collaboration

The Accelerator Neutrino Neutron Interaction Experiment (ANNIE)

- ANNIE is a neutrino experiment deployed on the Fermilab Booster Neutrino Beam.
  - It is aimed at better understanding neutrino-nucleus interactions, specifically the neutron yield.
- It is also an R&D platform to develop and demonstrate new neutrino detection technologies/techniques.
  - Fast photosensors (LAPPDs) and detection media (Gd-loaded water and eventually water-based liquid scintillators).

The almost complete Phase II ANNIE detector is commissioned and taking beam neutrino data!
First LAPPD deployment coming soon !

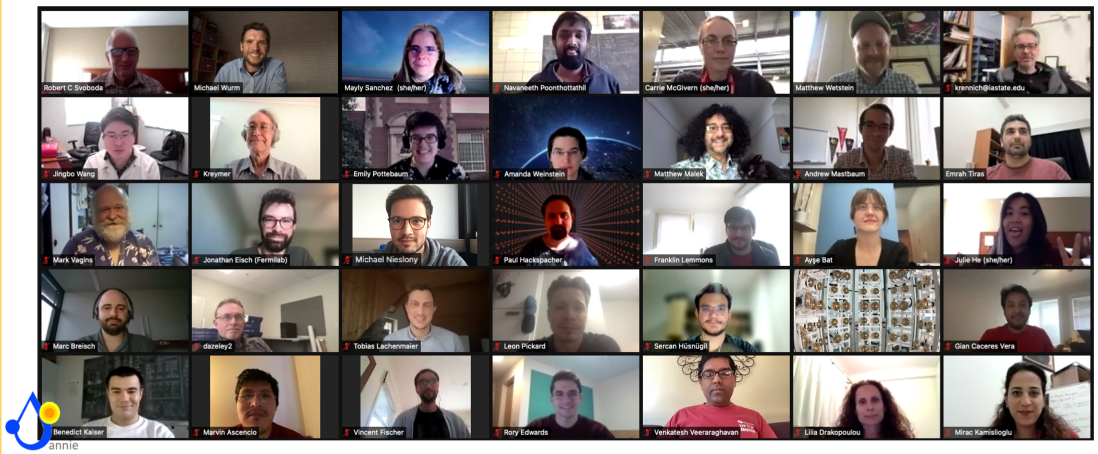
The ANNIE Collaboration



ANNIE has grown to 16 full member institutions (8 US/8 non-US) - 45 collaborators
Some recent additions are former ANNIE members moving to new institutions

The ANNIE Collaboration

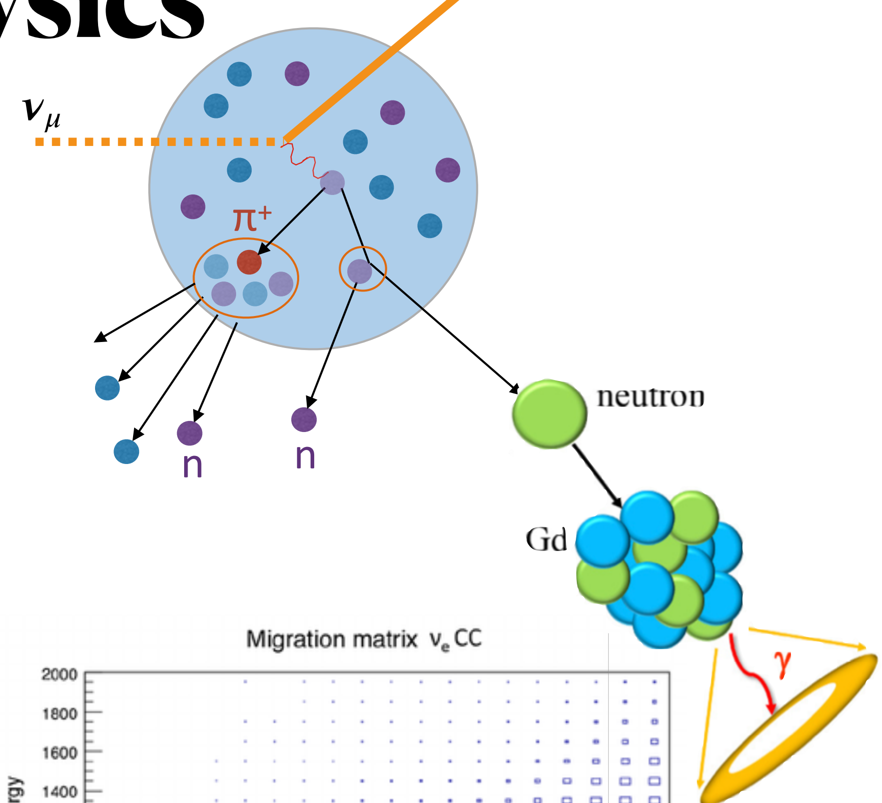
United States
- Iowa State (9)
- UC Davis (5)
- Rutgers (4)
- Livermore (3)
- SDSMT (3)
- UC Irvine (2)
- Ohio State (1)
- UChicago (1)
- (Fermilab, 3)
- Associate:
  UC Berkeley (2)



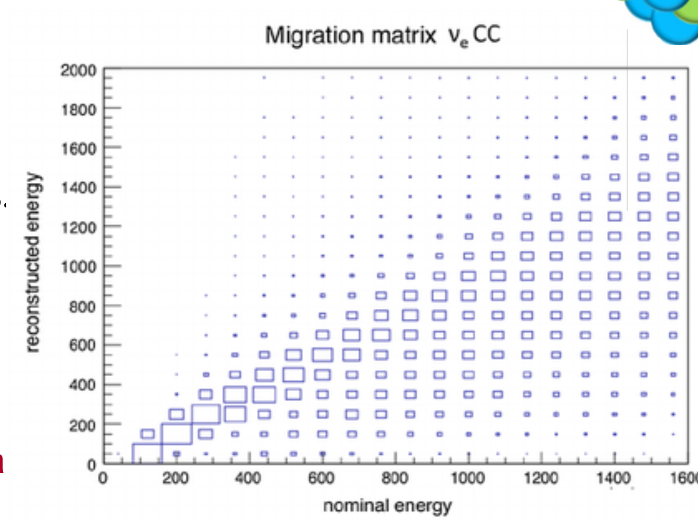
UK/Europe
- Edinburgh (1)
- Sheffield (1)
- Warwick (2)
- Hamburg (3)
- Mainz (3)
- Tübingen (3)
- Erciyes (4)
- Demokritos (1)

ANNIE has grown to 16 full member institutions (8 US/8 non-US) - 45 collaborators
Some recent additions are former ANNIE members moving to new institutions

ANNIE Physics



- ANNIE measures the multiplicity of final state neutrons as a function of the outgoing lepton momentum and direction.
- Neutron detection efficiency is enhanced by addition of gadolinium to the water.
- Neutrons are a major component of the nuclear recoil system and a source of missing energy in neutrino reconstruction/detection.
- ANNIE will provide high-statistics data (10^4 per ton and year) on neutron yield to improve MC generators for GeV neutrino interactions.
  → Reduction of critical systematic uncertainties for energy measurement in NOvA/T2K/DUNE/HyperK.
- Potential NC measurement for DSNB/proton decay backgrounds.
  → ANNIE can provide precision data on the relevant GeV neutrino cross-sections.
- Nearby SBND LAr-detector provides opportunity for combined water/Ar cross section analysis using same neutrino beam.
  → NSF CAREER Award for ANNIE collaborator Andy Mastbaum

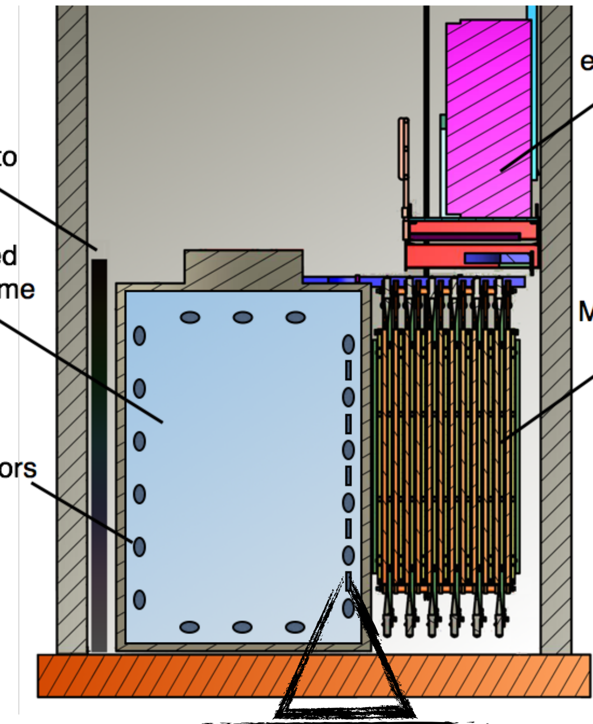


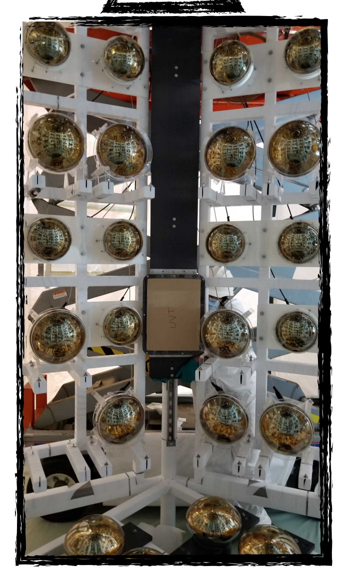
Example Migration Matrix for large-scale Water-Cherenkov Detector

Neutrons from neutrino interactions are a significant systematic uncertainty in a variety of physics measurements

The ANNIE Detector

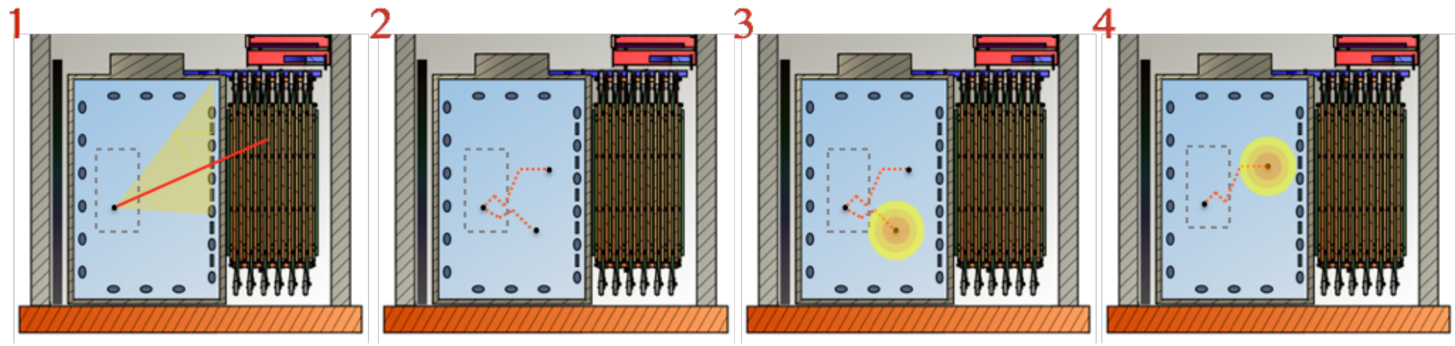
- Steel tank holding 26 tons of **Gd-loaded water**
- **132 (8”-11”) PMTs**
- **5+ fast photosensors (LAPPDs)** / 300 readout channels.
- **Front muon Veto (FV):** 2 overlapping layers of scintillator paddles
- **Muon Range Detector (MRD):** 11 X-Y alternating scintillator layers with 5cm iron absorbers





LAPPDs to be inserted on slide rails between PMTs

Neutrino Interactions in ANNIE

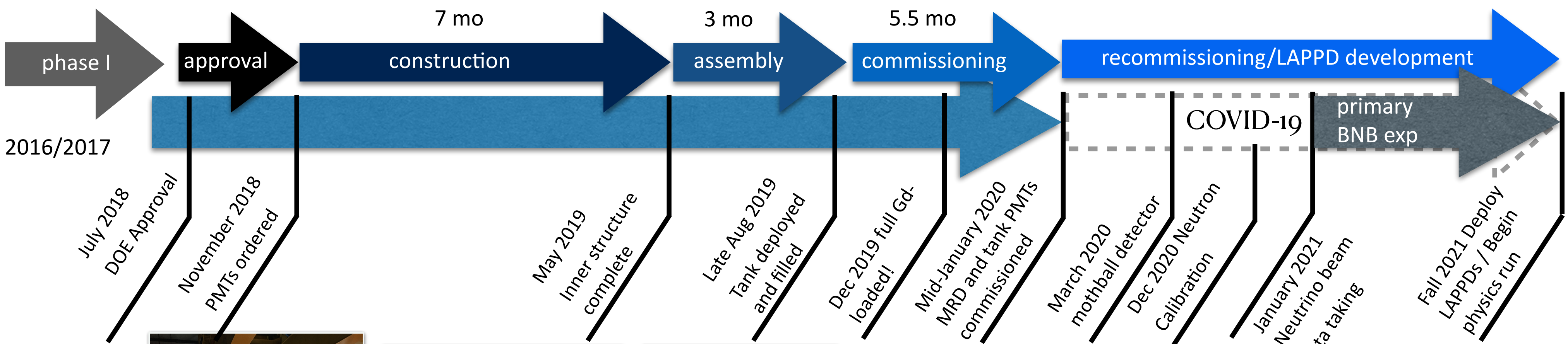


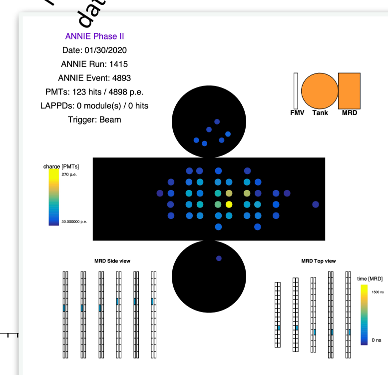
1. Neutrino charged current interaction in the fiducial volume produces a muon. Vertex reconstruction by LAPPDs and muon momentum reconstructed in MRD.

2. Neutrons travel, scatter and thermalize.

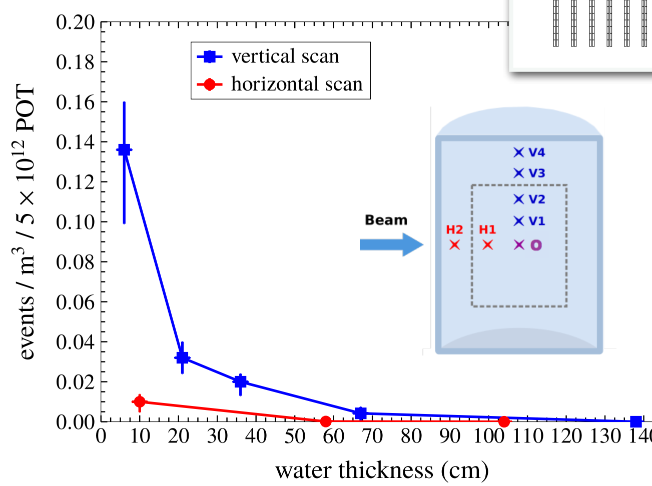
3.- 4. Thermalized neutrons are captured on the Gd producing flashes of light detected by standard PMTs.

ANNIE Timeline





- Data was collected over 2016-2017 in a partially instrumented implementation of the detector (so-called Phase I). This served as an engineering run and an opportunity to characterize background neutrons for the ANNIE physics measurement.
- These backgrounds were found to be small and are mitigated by the buffer layer of water above the detector. Published in: *JINST* 15 (2020) 03, P03011 arXiv:1912.03186.



ANNIE: Most-*gadiated* Neutrino Detector

ANNIE Gd loading was performed in stages:

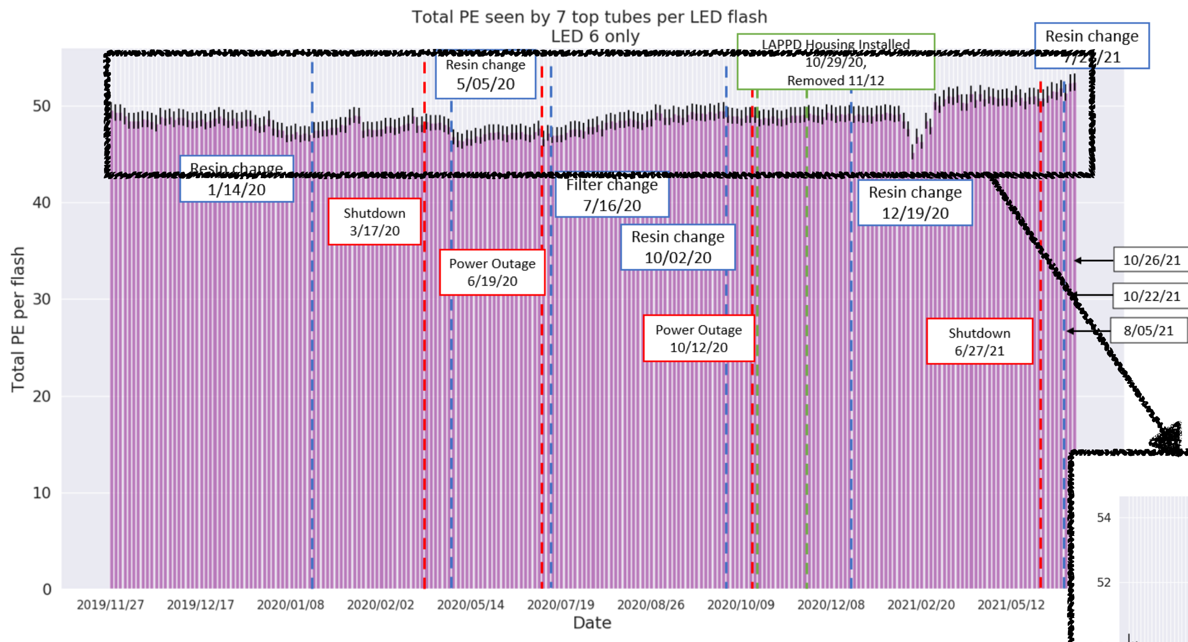
- First stage: ~10 ppm of Gd
    - From 09/25/19 to 11/29/19 → 2 months
- Second stage: ~100 ppm
    - From 11/29/19 to 12/17/19 → 2 weeks
- Full loading: ~1000 ppm Gd
    - Process took a week (12/17/19 to 12/24/19)
- Detector fully loaded since 12/24/19 **(~ 2 years!)**
    - Neutron capture time: 30±1 μs

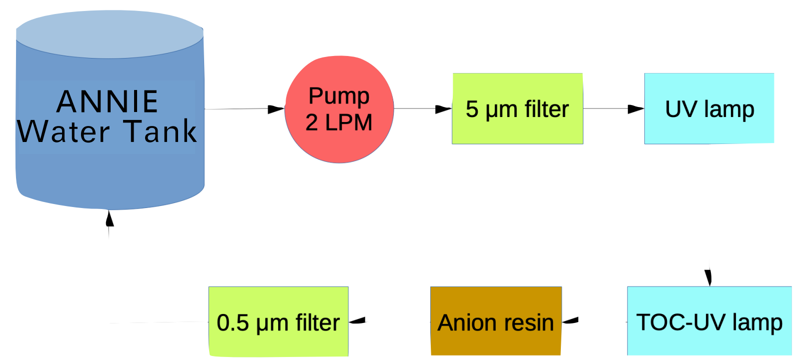
For comparison: **SK-Gd**

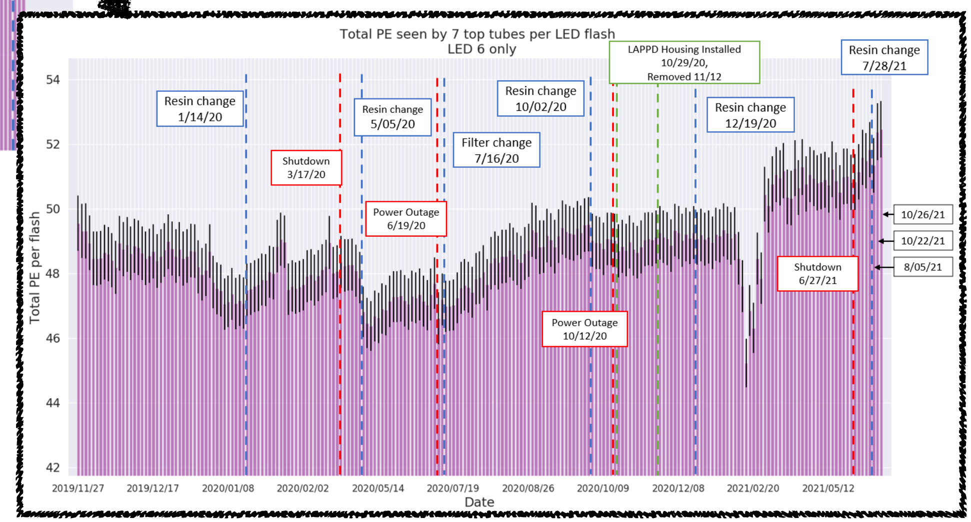
- since 08/17/20, Gd loading at 110.9±1.4 ppm
- Neutron capture time: 115.6±0.6 μs

Custom purification system for small-scale Water Cherenkov detectors developed by UC Davis collaborators. Published in JINST15 (2020) 07 P07004.

Monitoring ANNIE Water Transparency



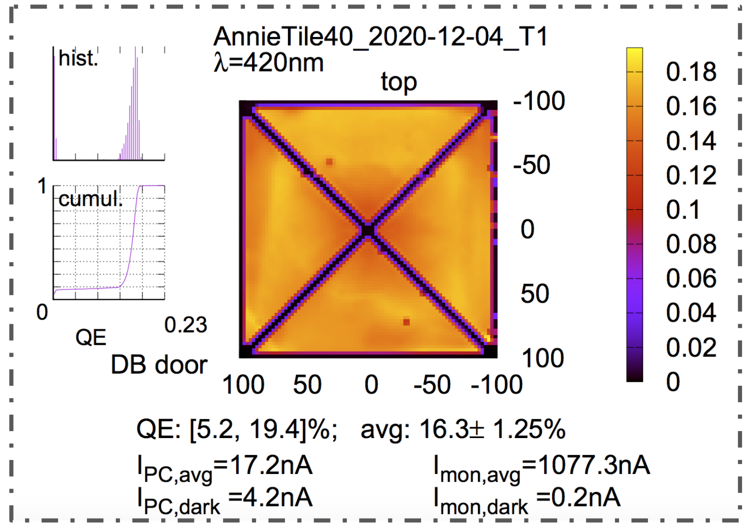


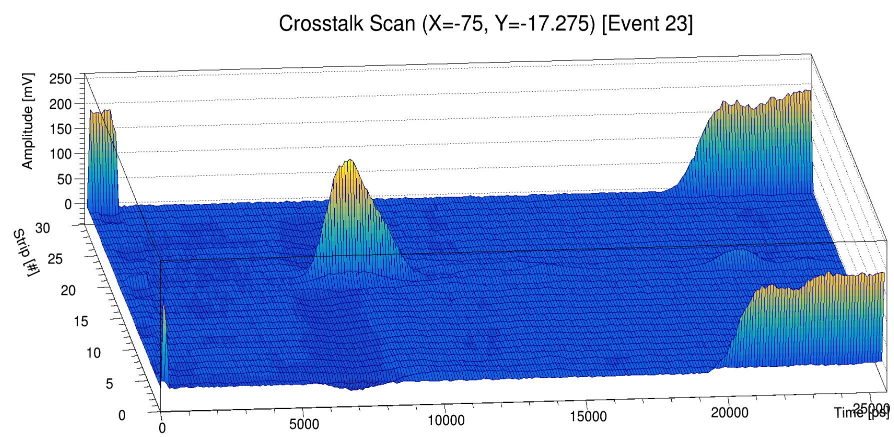


- Water transparency to Cherenkov light has been primary concern of Gd-loaded detectors.
- ANNIE monitors target transparency by measuring intensity of LED flashes with PMTs across the water volume.
- By circulating the water, ANNIE's purification system has kept the water transparency at the initial high levels for almost 2 years now.

Enabling Technology: LAPPDs

- Incom delivered all 5 LAPPDs to ANNIE.
  - They meet the originally stated requirements: gains >10^6, time res < 100ps, QE~20%.
  - The newest four LAPPDs exceed those requirements.
- The collaboration has built a characterization facility at FNAL (Lab 6) to benchmark LAPPD performance and test fully integrated systems.
- The first LAPPD (#40) is fully characterized in prep for deployment.
- A 6th LAPPD purchased by our collaborators at Tubingen will become available this year.

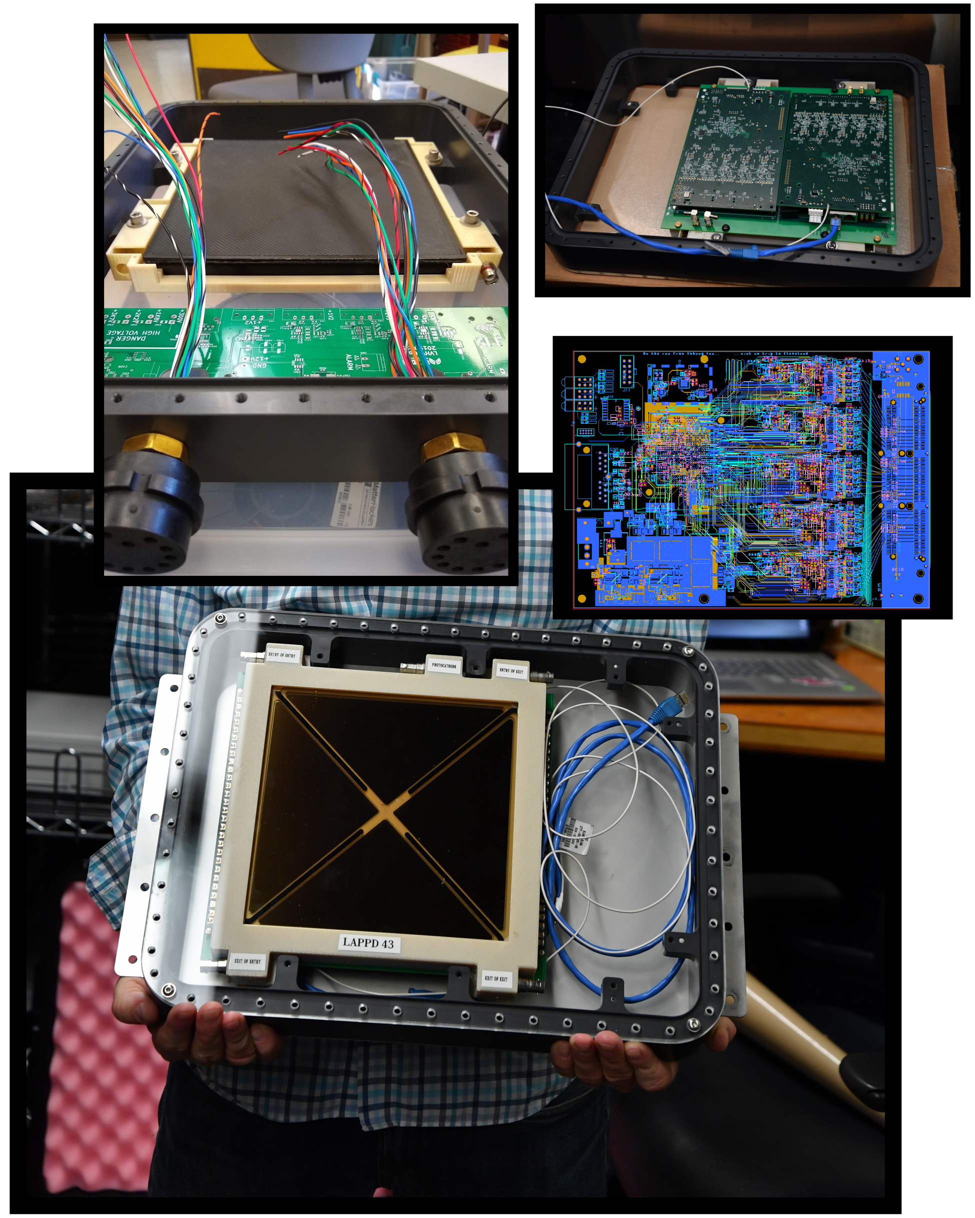




Designing the LAPPD package

- The LAPPD package is composed of:
  - A waterproof housing with acrylic window, steel backplane and PVC sidewalks
  - An Analog Pickup Board, which mounts to the back of the LAPPD and brings signals to the two readout mezzanine cards
  - Two readout cards (ACDC cards)
  - A trigger logic board
  - A slow controls board (LVHV card)

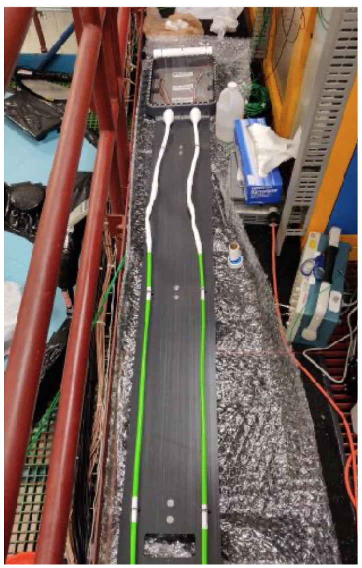
Since our last PAC report (pre-pandemic) major development work on the LAPPD deployment package

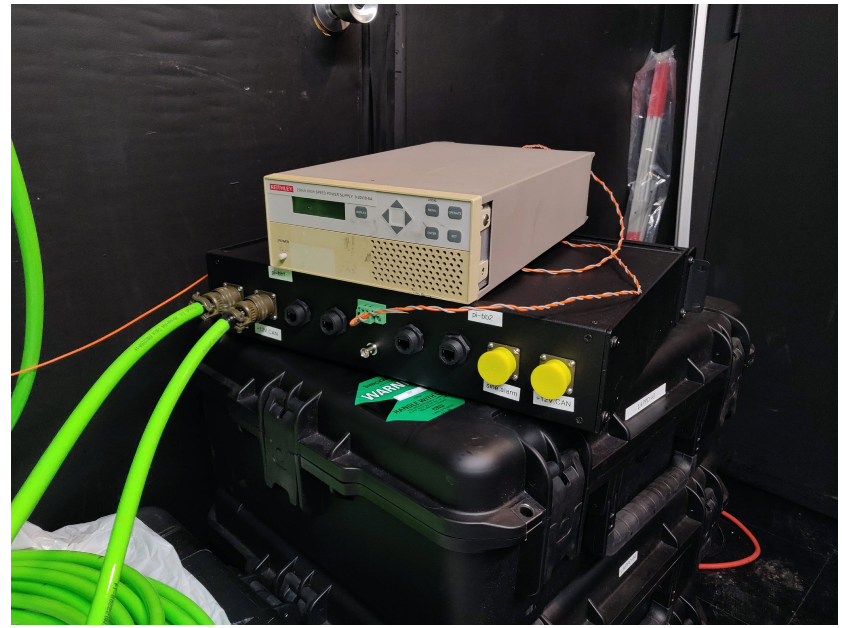


Testing the LAPPD Deployment and Surface Electronics

NEW!

- Successful test deployment of housing in Spring 2021.
- Break out Boxes (BoB) provide slow controls, interface between surface electronics, power and waterproof cable.
- Falmat waterproof Ethernet cables connect BoB to waterproof housing containing LAPPD & readout electronics.
- All housings are in hand. Successful fit test of PSEC electronics in housing.





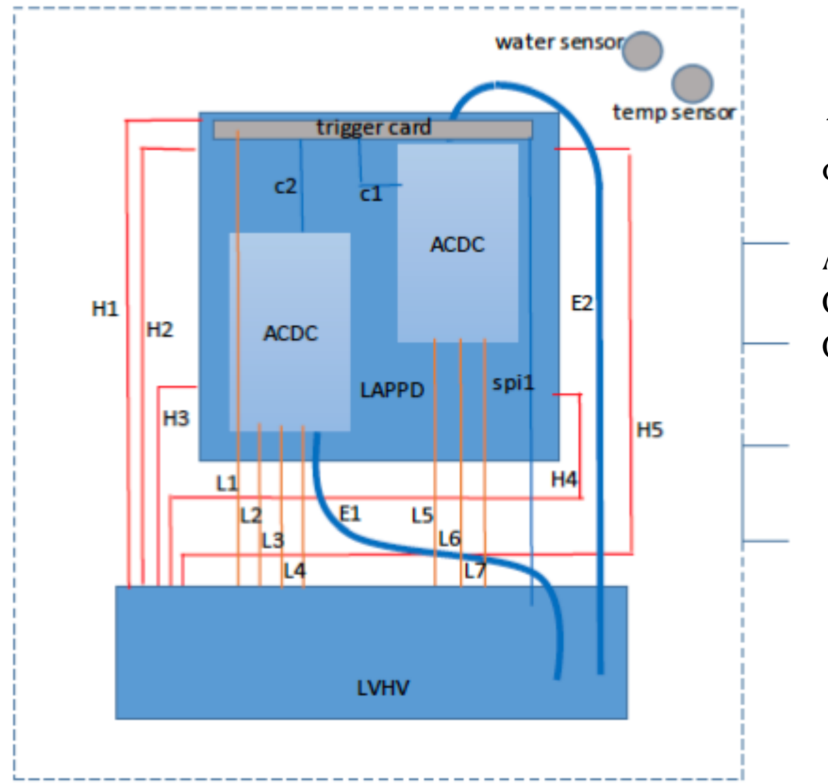
LAPPD surface Breakout Box

Passed preliminary ORC on all of these components

Developing the LAPPD Electronics

- ANNIE has developed the first end-to-end LAPPD readout system using picosecond electronics (PSEC). Several revisions and modifications from the original system were required.
- **Power distribution Revision:** In-situ modifications to the ACDC and the addition of LVHV board were required to reduce power draw and heating.
- **ACC/ACDC Firmware Revision:** The firmware for the ACDC and ACC were completely rewritten for speed increases.
- **Channel Self-trigger:** A standalone board was designed to provide robust channel level and multiplicity triggers.
- **Redesign of the LVHV:** To provide AC coupling for tank-to-surface communication and filter transients from power up and switching power supplies.

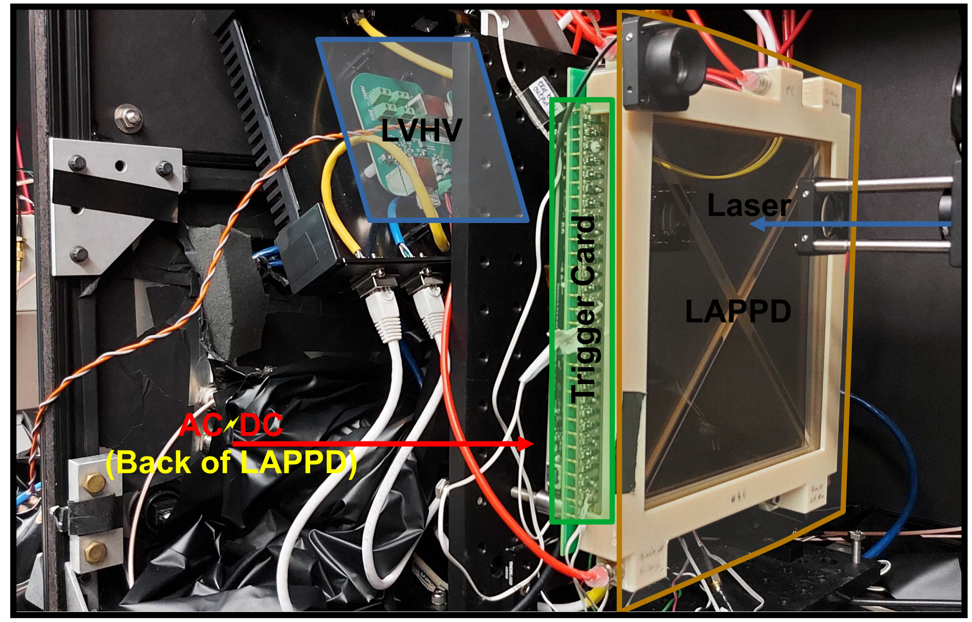
Waterproof housing



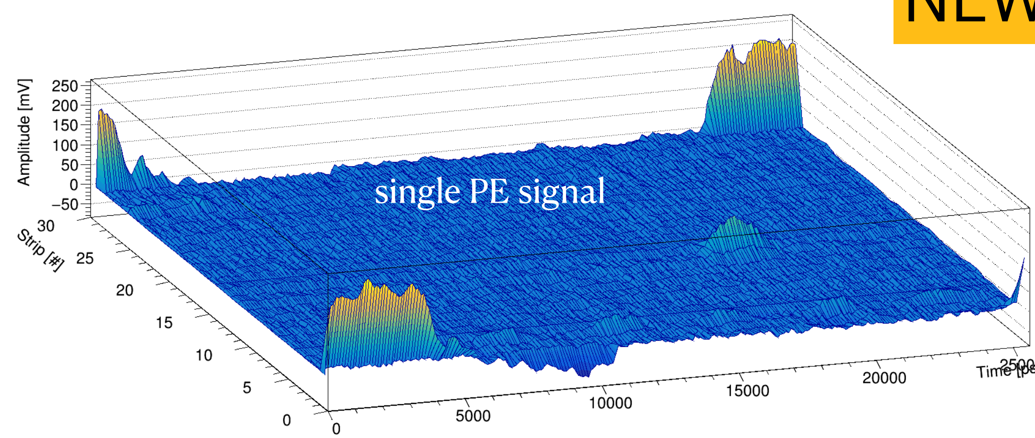
Currently undergoing full system integration test in Lab 6

LAPPD On-site Integration Testing

- New trigger boards have been delivered and successful demonstrated LAPPD self-triggered readout.
- Redesigned LVHV boards have been tested, delivered and are currently being integrated .
- Full system integration test in Lab 6, including waterproof cables
  - First test of AC coupled communications.



NEW!



Testing in progress

Upcoming LAPPD Milestones

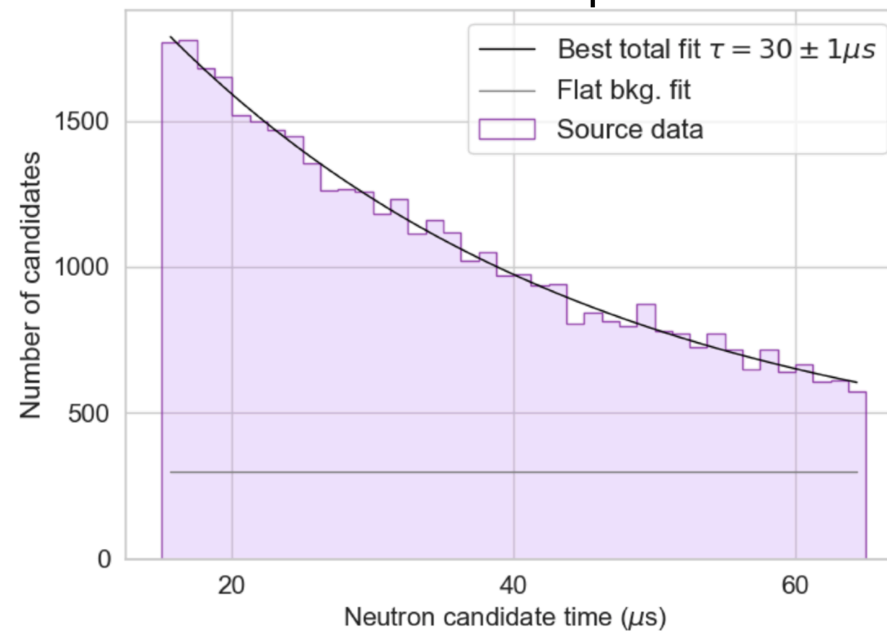
- Demonstrate robust communications and delivery of the beam gate signal in full system operation
- Repeat full system integration test in Lab 6, including waterproof cables.
- Integration of LAPPD/electronics in waterproof housing, retest.
- System deployment in the experimental hall (bucket test) and DAQ integration.
  - LAPPD DAQ readout already validated and tested with simulated hardware.
- Deployment. In-tank LAPPD commissioning with DAQ

→ Start of physics data taking with LAPPDs

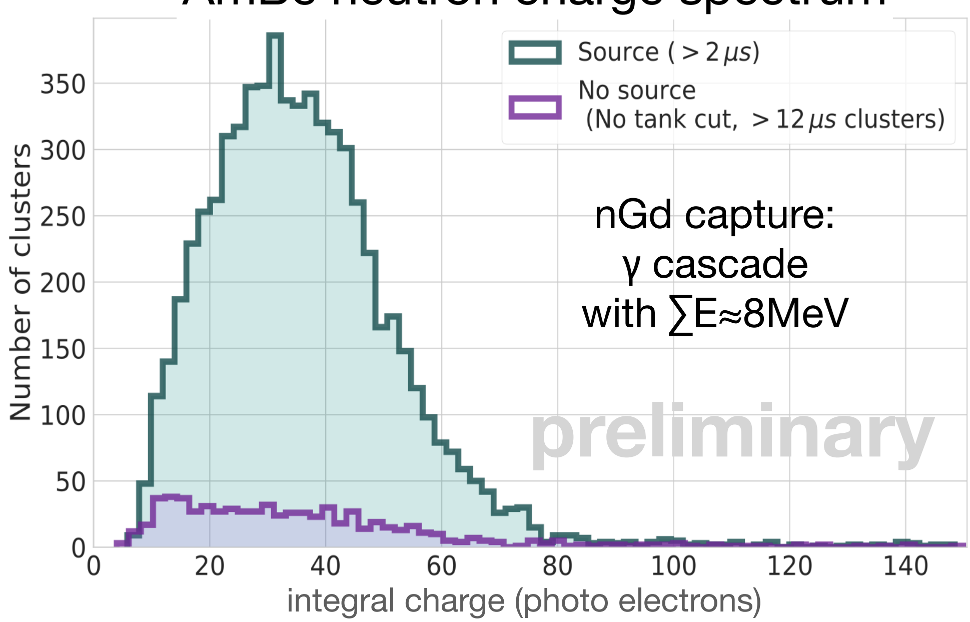
Calibrating using AmBe Neutrons

- Deployment of a tagged AmBe neutron source inside the water volume.
- Neutron capture time matches beam data.
- Background model (event multiplicity) is well understood.
- Neutron detection efficiency: **55-70 %** (depending on source location).

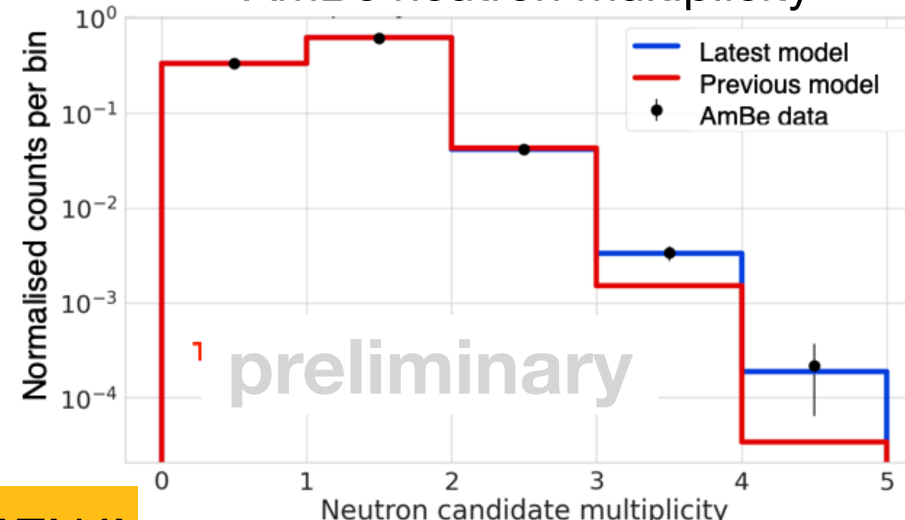
AmBe neutron capture time



AmBe neutron charge spectrum



AmBe neutron multiplicity



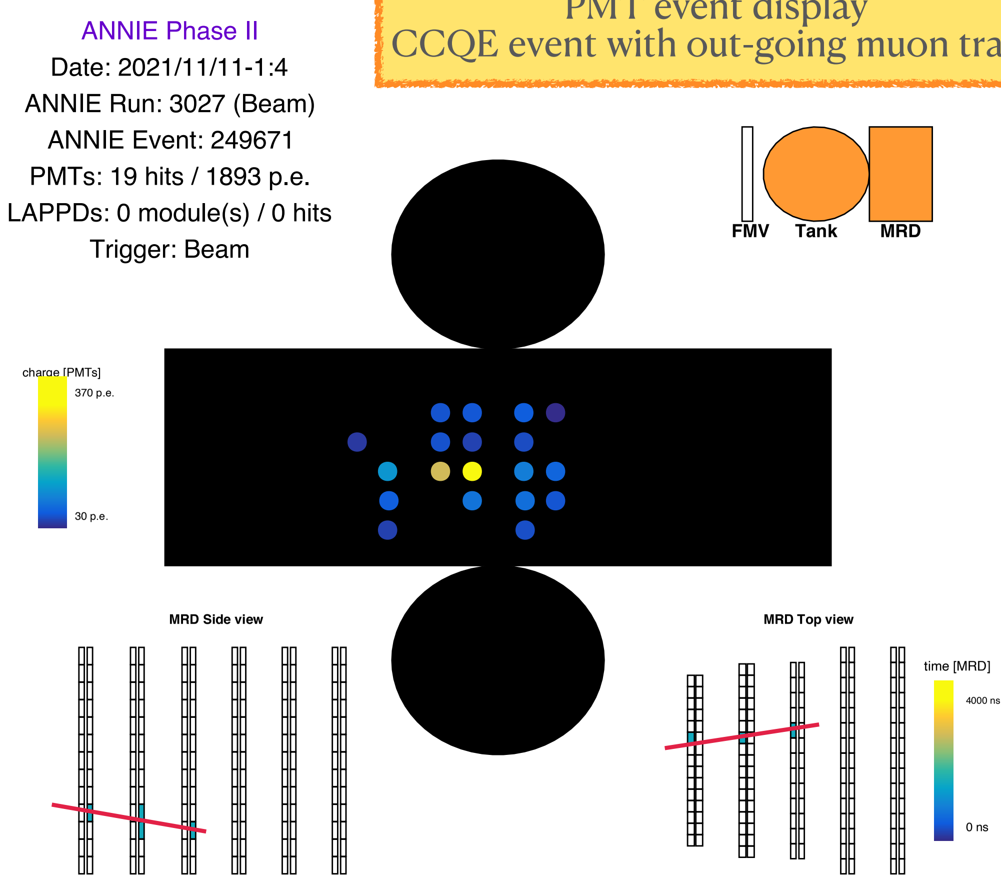
NEW!

Observing Beam Neutrinos

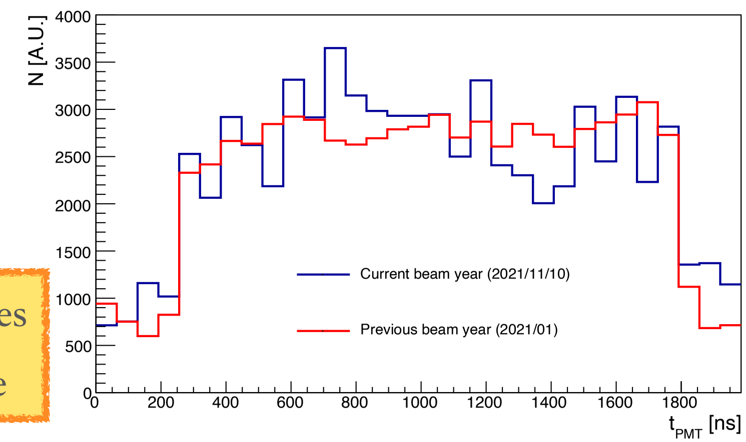
NEW!

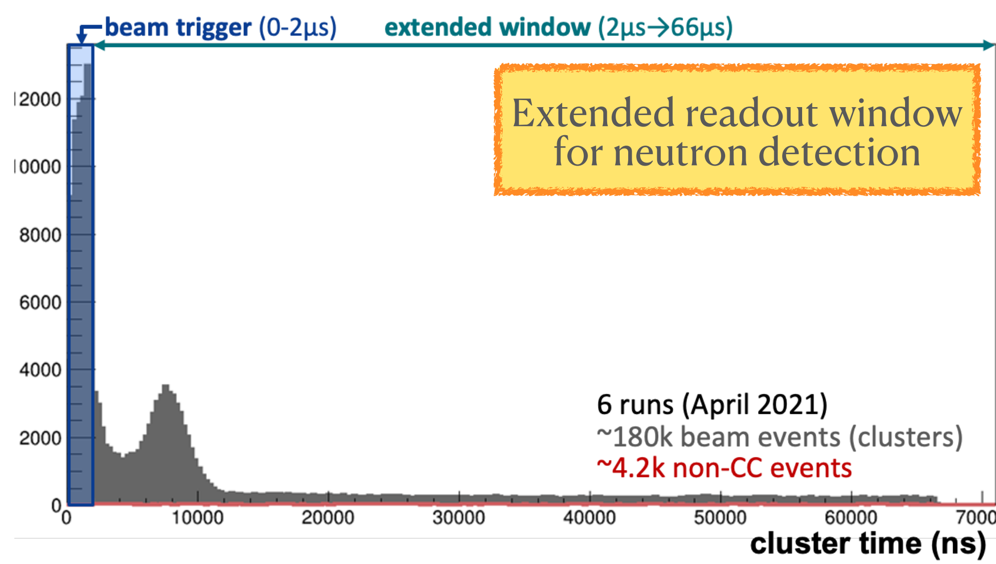
- Beam data taking pre-shutdown for period January-June 2021. Data taking for current beam run resumed last week in time with the start of Booster beam running.
- All "conventional" ANNIE systems up to specs and running on high duty factors.

PMT event display
CCQE event with out-going muon track



PMT cluster times relative to beam reference

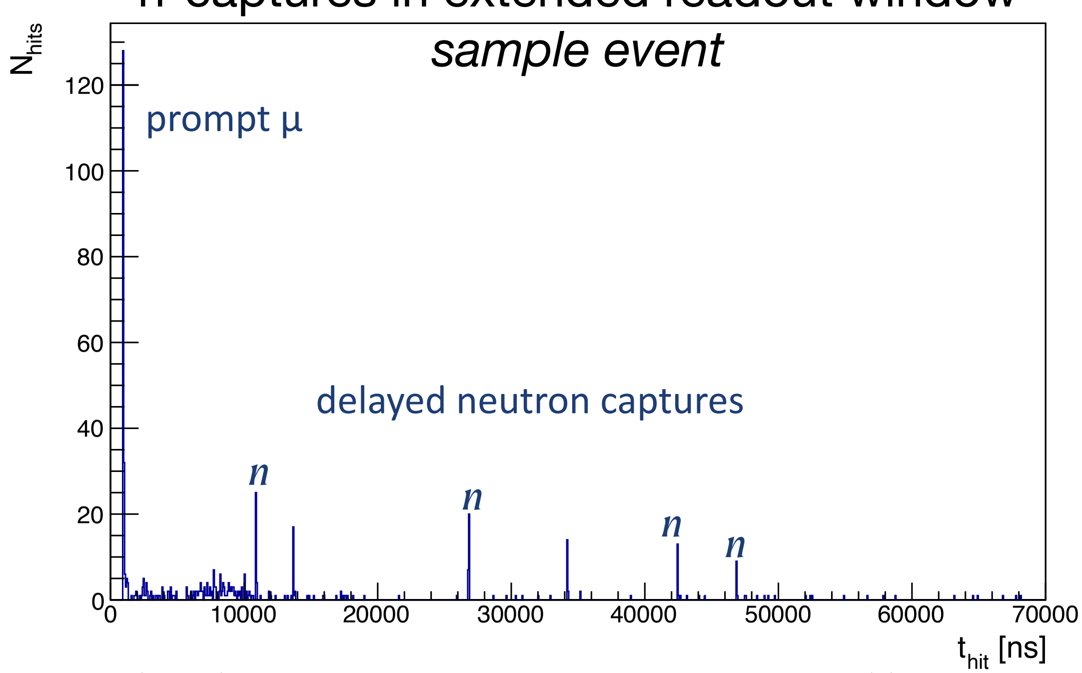


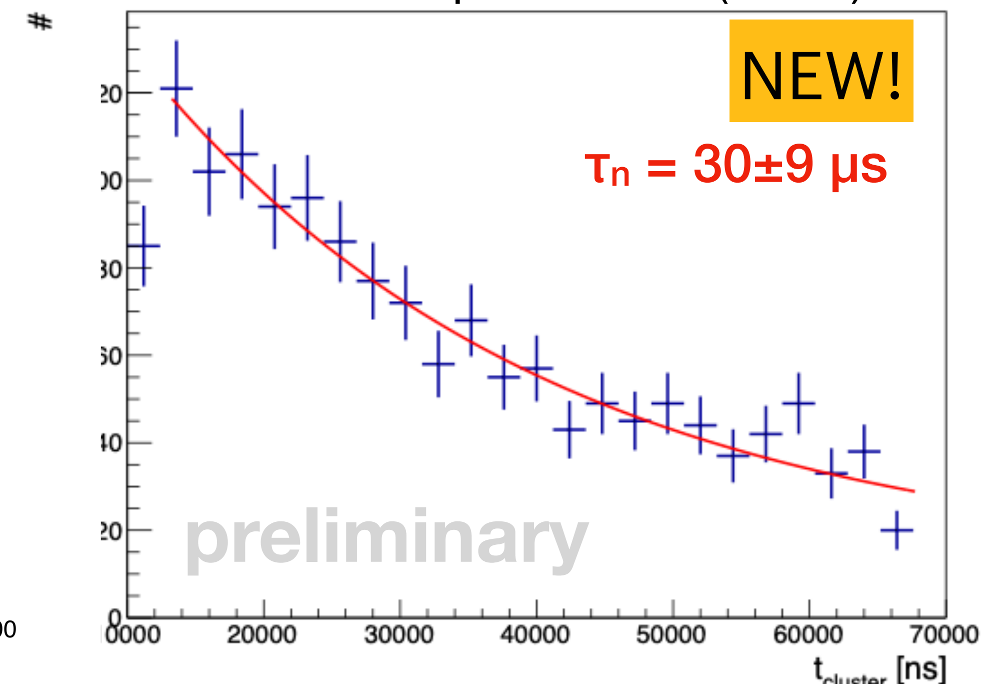


Extended readout window for neutron detection

Detecting Neutrons from Beam Triggers

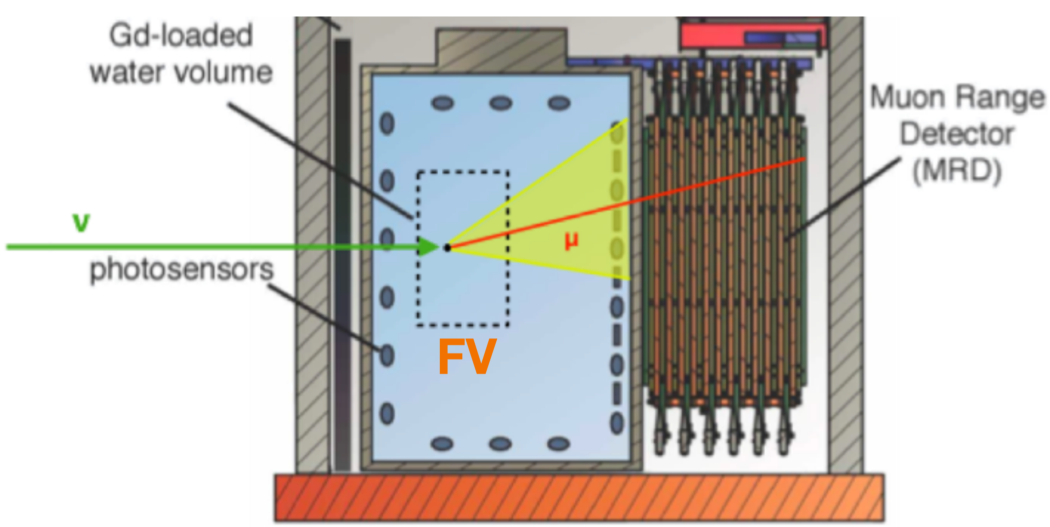
- Beam triggers with a prompt event featuring large PMT signals (≥5 p.e.) are followed by an extended acquisition window of 70 μs.
  - Allows acquisition of subsequent neutron captures without trigger threshold.
- Selected neutron candidates feature the expected capture time profile at nominal Gd concentration.

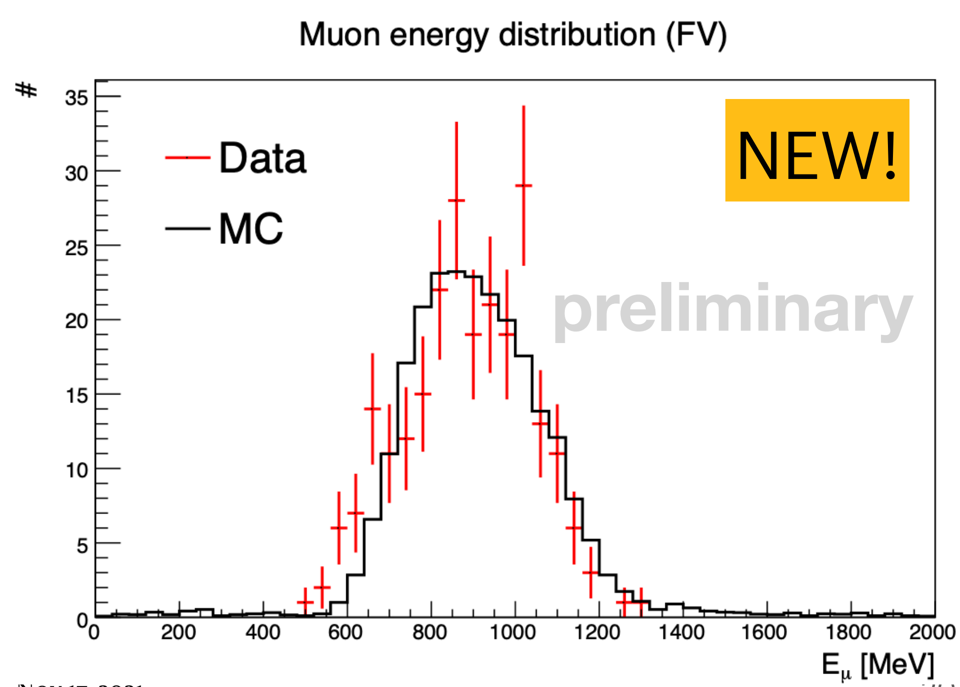




Reconstructing CCQE events

- Muon energy reco in ANNIE relies on PMT light pattern but mostly on the track information of the MRD.
- We define a fiducial volume (**FV)** to optimize detection efficiency for subsequent muons.
- Current reconstruction algorithms nicely reproduce the **data** using the expectation from detector **MC.**

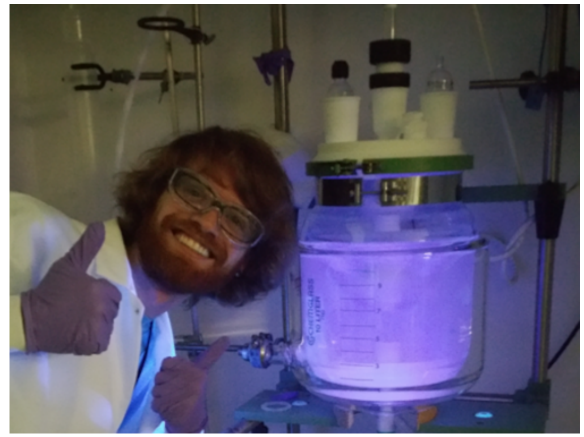




Testing water-based scintillator (WbLS)

- Transparent WbLS permits hybrid detection of scintillation and (unabsorbed) Cherenkov signals
- Enhanced neutrino energy reconstruction: WbLS adds scintillation signal for sub-Cherenkov recoil protons etc.
- Enhanced neutron signals: improved light output (3×), detection efficiency (~90%) and spatial reconstruction (40→20 cm)
- Built acrylic vessel (~3'×3') with 365 kg of Gd-WbLS to be inserted in the ANNIE water tank
- Gd-loaded WbLS (0.5% organic fraction) to be produced at BNL (M. Yeh)
- Potential two-week test run in summer 2022.

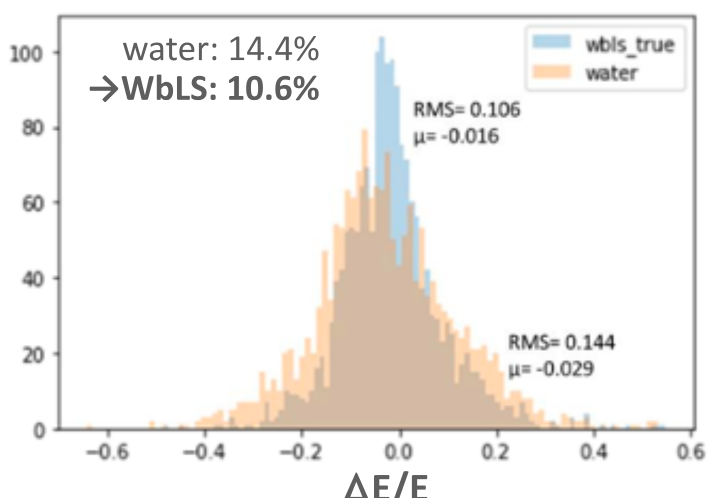
WbLS test at Davis

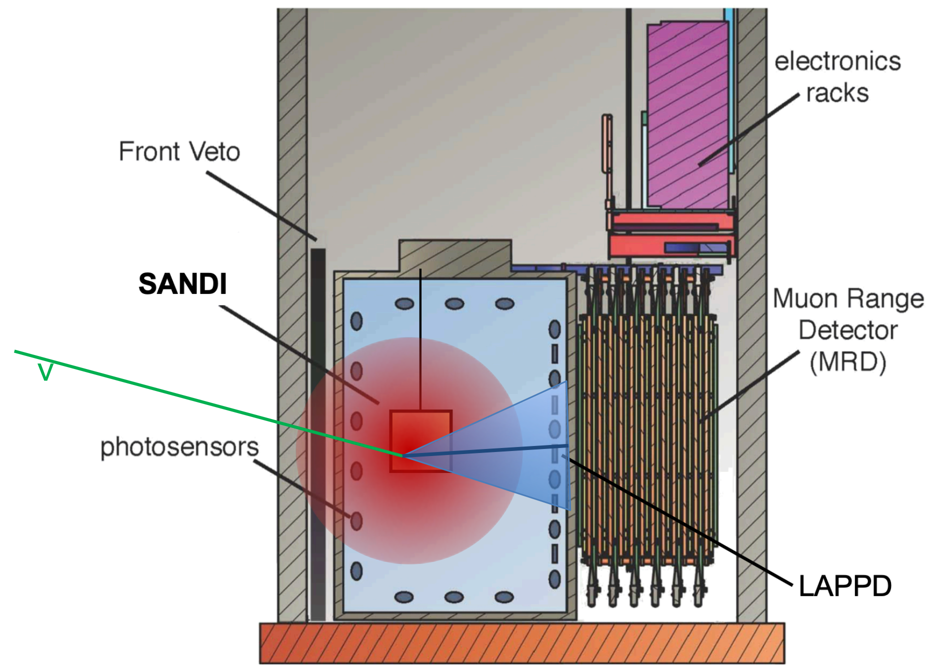


SANDI vessel at Davis

improvement expected for **NEUTRINO energy resolution**

NEW!

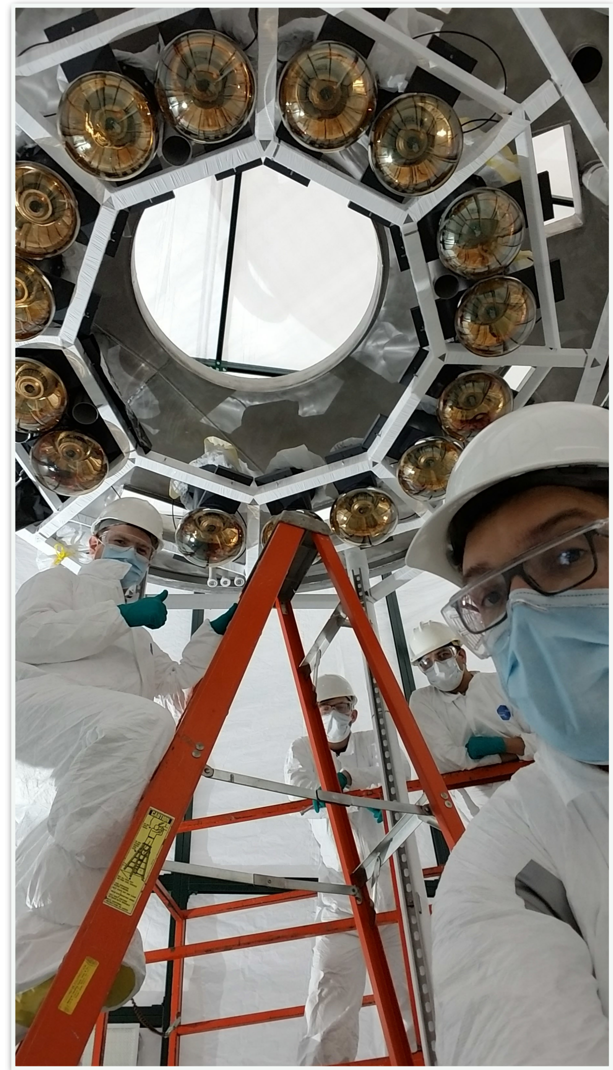




WbLS adds scintillation from hadronic recoil to the muon Cherenkov signal

ANNIE Summary

- The ANNIE collaboration has constructed, assembled and installed the detector which is now taking neutrino beam data.
  - Neutrino beam data taken over the past year will be used in physics analyses.
- The Gd-loading of the detector has been a success. Water transparency has been excellent (~2 years!) and is being continuously monitored.
  - A test of WbLS could happen Summer 2022.
- PMT gain and timing calibration has been completed and the first neutron source calibration run has been accomplished.
  - Fast laser calibration system has been built and is ready for deployment.
- Significant development has been done to enable LAPPD deployment. Currently undergoing full integration tests.
- ANNIE has observed neutrons from AmBe calibration and beam triggers! We are able to find and reconstruct neutrinos.
- We are in the last stages of preparation for LAPPD deployment!




Thank you!

Backup

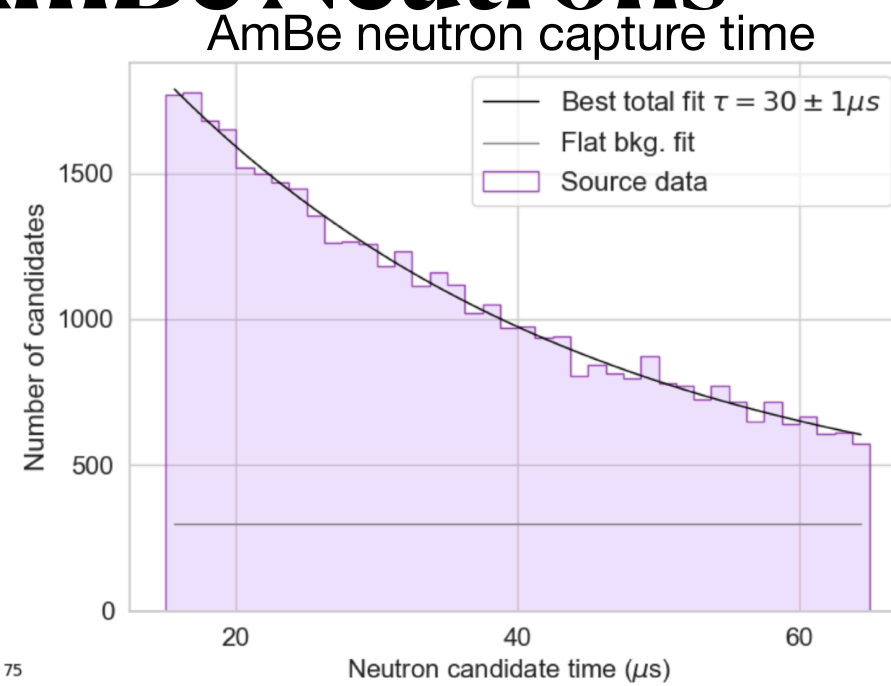
Personnel outcomes

- Lilia Drakopoulou - faculty at NCSR Demokritos (Greece)
- Matthew Malek - faculty at Sheffield (UK)/Watchman co-spokes
- Ben Richards - faculty at Warwick (UK)
- Emrah Tiras - faculty at Erciyes University (Turkey)
- Jingbo Wang - faculty at South Dakota School of Mines (US)
- Andrew Mastbaum - received NSF CAREER Grant for ANNIE+SBND
- Jonathan Eisch - application physicist (CD) at Fermilab
- Vincent Fisher - (soon) application physicist (PPD) at Fermilab
- Carrie McGivern - application physicist (ND) at Fermilab
- Steven Gardiner - postdoc at Fermilab
- Marcus O'Flaherty - postdoc at Warwick
- Teal Pershing - postdoc at Livermore

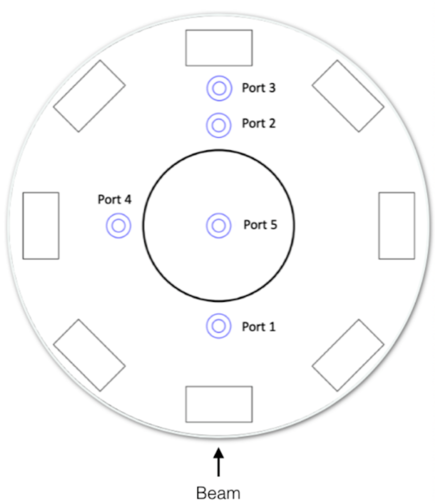
ANNIE Publications

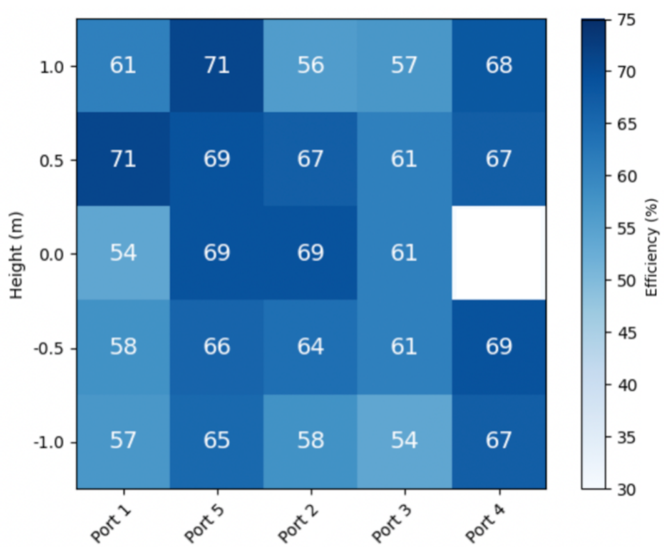
- ANNIE Collaboration, *Measurement of Beam-Correlated Background Neutrons from the Fermilab Booster Neutrino Beam in ANNIE Phase-I*, JINST 15 (2020) 03, P03011, arXiv:1912.03186 [physics.ins-det].
- V. Fischer et.al., Development of an Ion Exchange Resin for Gadolinium-Loaded Water, JINST15 (2020) 07 P07004, arxiv: 2004.04629 [physics.ins-det].
- Proceedings:
  - V. Fischer et al., *ANNIE: Neutron multiplicity in neutrino interactions and new technologies*, J.Phys.Conf.Ser. 1468 (2020) 1, 012226
  - Emrah Tiras et al., *Detector R&D for ANNIE and Future Neutrino Experiments*, arXiv:1910.08715
  - Evangelia Drakopoulou et al., *ANNIE Phase I: Neutron Background Measurements*, arXiv:1903.11879
  - Evangelia Drakopoulou et al., *ANNIE Phase II Reconstruction Techniques*, arXiv:1803.10624
- Proposals:
  - ANNIE Collaboration, *Accelerator Neutrino Neutron Interaction Experiment (ANNIE): Preliminary Results and Physics Phase Proposal*, arXiv:1707.08222
  - ANNIE Collaboration, *Letter of Intent: The Accelerator Neutrino Neutron Interaction Experiment (ANNIE)*, arXiv:1504.01480
  - ANNIE Collaboration, *Expression of Interest: The Atmospheric Neutrino Neutron Interaction Experiment (ANNIE)*, arXiv:1402.6411

Calibrating using AmBe Neutrons



- Deployment of a tagged AmBe neutron source inside the water volume.
- Neutron capture time matches beam data.
- Background model (event multiplicity) is well understood.
- Neutron detection efficiency: **55-70 %** (depending on source location).





Position-dependent efficiency with 12% correction applied due to out of acquisition window neutrons

- Highest efficiency in fiducial region: 64-69%.
- Additional calibration runs planned with calibrated source will improve inconsistency and understanding when comparing to and tuning simulation.

Modeling the neutron multiplicities to extract the true detection efficiency

$$M(x) = B(n; \epsilon_n) + \frac{\lambda_b^x e^{-\lambda_b}}{x!} + \frac{\lambda_{un}^x e^{-\lambda_{un}}}{x!} + \left(\frac{\lambda_\gamma^x e^{-\lambda_\gamma}}{x!} + M_{\gamma n}(n_\gamma) \right)$$

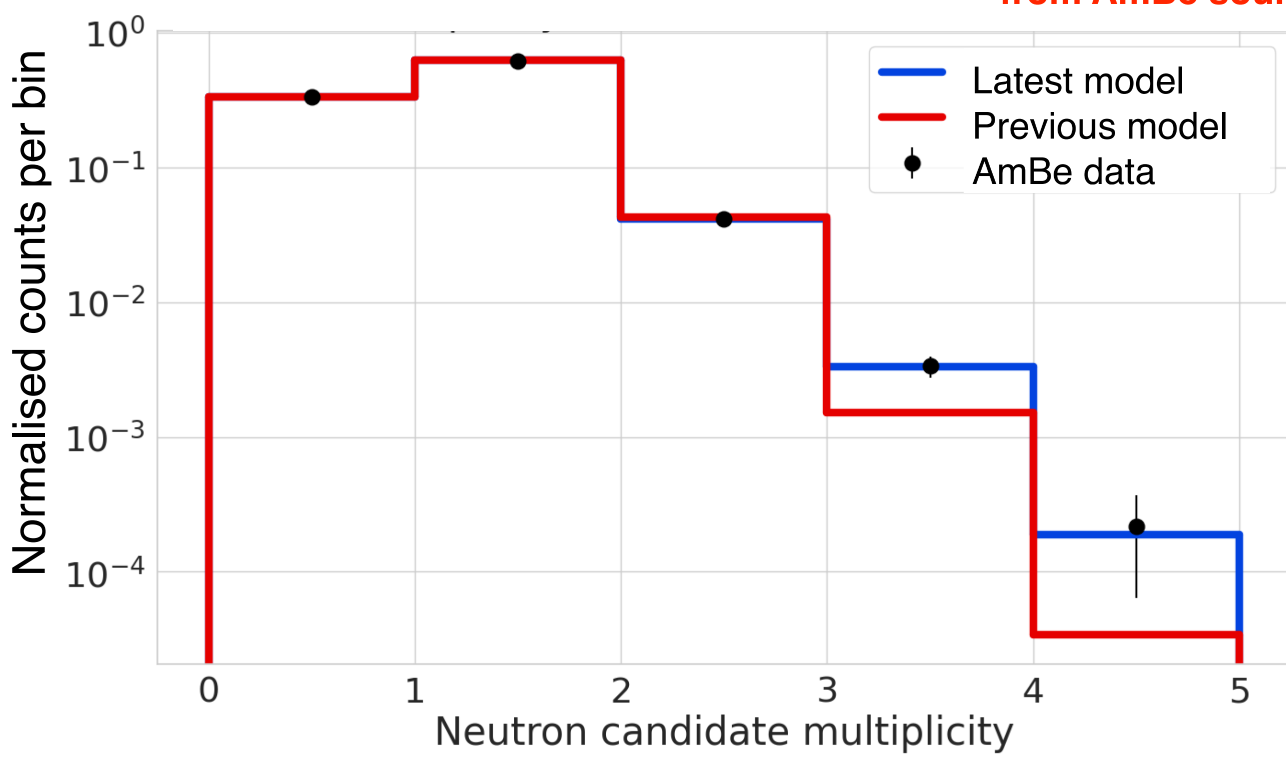
Position dependent multiplicity → $M(x)$

Bernoulli distribution for a given neutron detection efficiency → $B(n; \epsilon_n)$

Uncorrelated background → $\frac{\lambda_b^x e^{-\lambda_b}}{x!}$

Uncorrelated neutrons from AmBe source → $\frac{\lambda_{un}^x e^{-\lambda_{un}}}{x!}$

Uncorrelated neutron-gamma pairs from AmBe source → $\left(\frac{\lambda_\gamma^x e^{-\lambda_\gamma}}{x!} + M_{\gamma n}(n_\gamma) \right)$

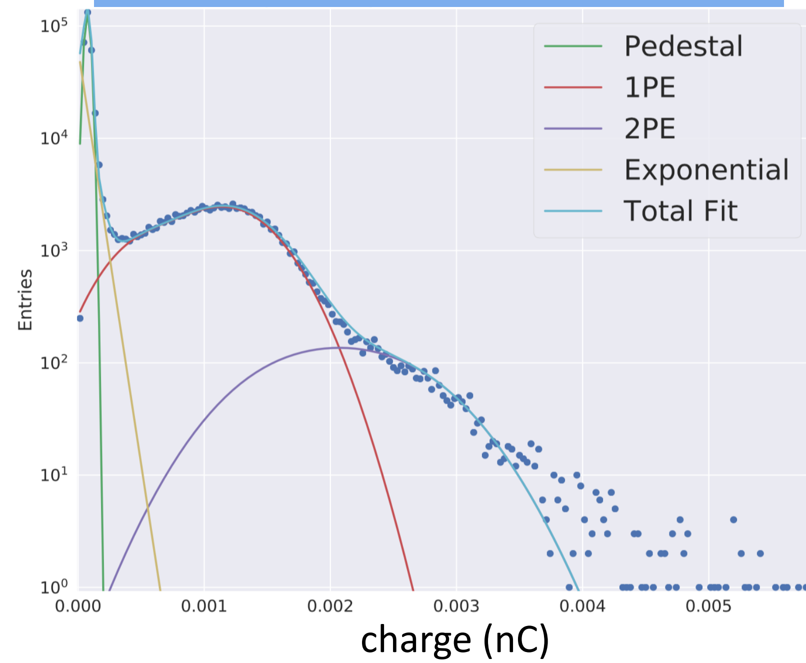


- By floating the background rates and efficiency the best fit to the multiplicity distribution can be found.
- A X^2 best fit is used to determine the free parameters.
- The corresponding efficiency is calculated on a position-by-position basis.
- Agreement better than 0.1% for the first 3 bins, 3-4% for fourth bin (3 neutrons) and 36% for the fifth bin (4 neutrons). All within the statistical errors.

Calibrating Photosensors

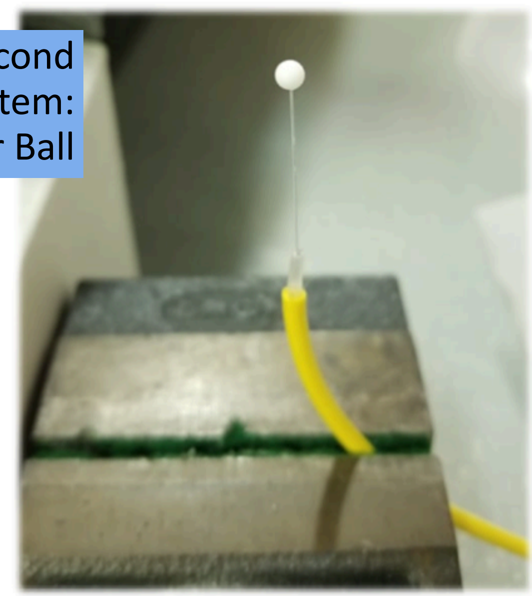
- **Calibration with LED system (completed)**
  - calibration of basic PMT properties:
    average gain of 7×10^6
    cable delays at 5 ns uncertainty level
  - installed and running since 2 years
- **Calibration with Fast LASER system (built, deploying soon)**
  - pulse width: 100 ps
  - diffuser ball to illuminate photo sensors
  - timing cross-calibration of LAPPDs and PMTs on sub-nanosecond level
  - system assembled, ORC completed

Fit to PMT S.P.E. charge spectrum (LEDs)



picosecond laser system: Diffuser Ball

NEW!



LAPPD Achievements

- Deployment Package
    - Produced the first robust realization of PSEC readout firmware.
    - Reworked readout electronics to reduce power consumption.
    - Designed, built and tested two revisions of the LVHV (power distribution) board.
    - Designed, built, and demonstrated auxiliary trigger board for LAPPD. Updated readout firmware to accommodate auxiliary trigger.
    - Developed a sophisticated system for clock and trigger synchronization and monitoring.
    - Built and test-deployed the waterproof housing required for LAPPD deployment

LAPPD Achievements

- Surface Components
    - Wrote and tested all of the software interfaces to integrate with the ANNIE data acquisition system.
    - Solved technical challenges involved with interfacing surface electronics to tank through high-density waterproof cables.
    - Firmware development (see deployment package)
- Calibration systems
    - Built and integrated laser-based LAPPD timing calibration system
    - PSEC readout calibration data in hand (pedestal, timing).