Large Area Picosecond Photo-Detectors for ANNIE and Future Neutrino Experiments

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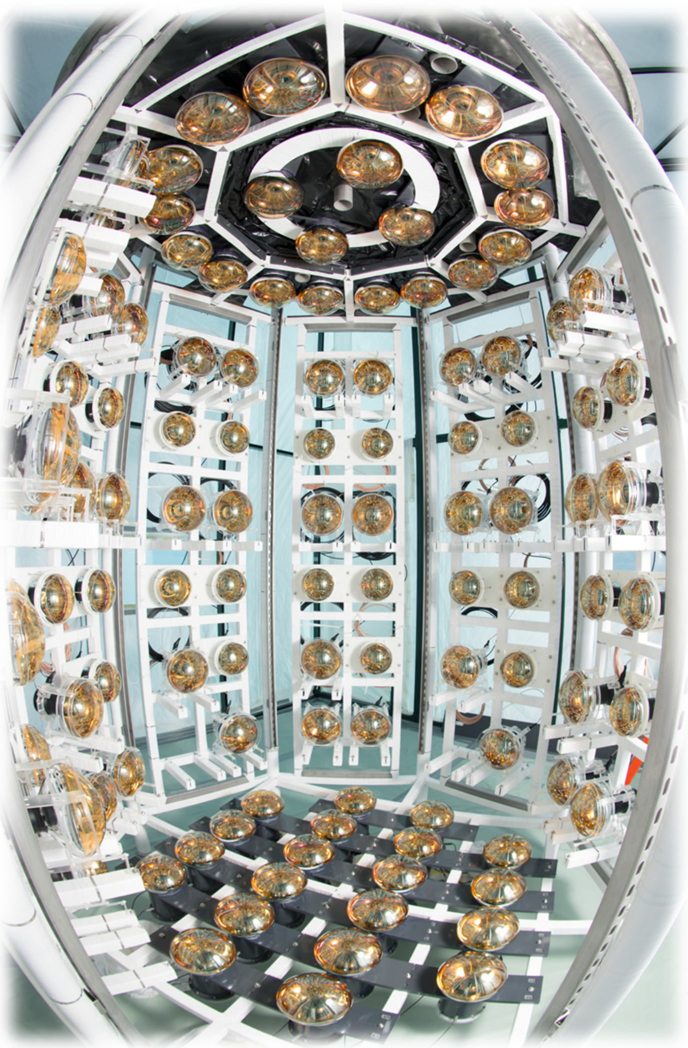
on behalf of the ANNIE collaboration

Erciyes University

CPAD Workshop, Stony Brook, NY
March 18-22, 2021

ANNIE: The Accelerator Neutrino Neutron Interaction Experiment



- 26-ton **Gadolinium (Gd)-loaded water Cherenkov Detector**.
- Located 100 m downstream from the target of the Booster Neutrino Beam (BNB) at Fermilab.
- Main goals:
  - Measure the beam induced final state neutron multiplicity & CC inclusive cross section on water.
  - **Demonstrate new detection technologies:**
    - **Large Area Picosecond Photodetectors (LAPPDs)**
    - **Neutron tagging in Gd-loaded water.**
    - **Possible addition of WbLS**

ANNIE Collaboration

➢ 35+ Collaborators from 16 institutions and 3 national labs in 4 countries work together to achieve the goals of ANNIE.

- Fermi National Accelerator Laboratory
- Lawrence Livermore National Laboratory
- Brookhaven National Laboratory (Assoc.)
- Iowa State University
- University of California, Davis
- University of California, Irvine
- University of California, Berkeley (Assoc.)
- South Dakota School of Mines and Technology (SDSMT)
- Ohio State University
- University of Chicago
- Rutgers University
- University of Sheffield
- University of Warwick
- University of Edinburgh
- Kings College London
- University of Hamburg
- University of Tübingen
- Johannes Gutenberg University Mainz
- Erciyes University

Spring 2020 Collaboration Meeting at Fermilab

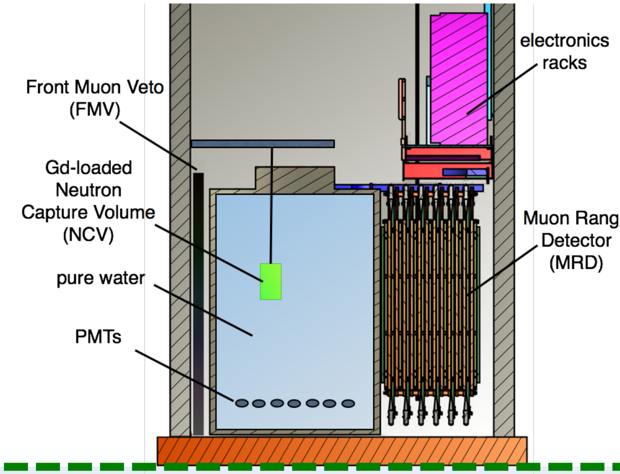
Timeline of ANNIE

June 2016

Sept 2017

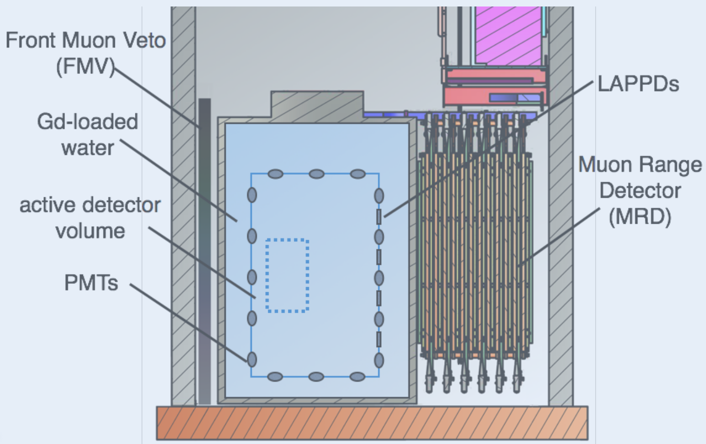
Background Measurements
(arXiv:1912.03186 and JINST: 15(2020)03, P03011)

- Partially instrumented detector
- Feasibility demonstration
- Beam induced background neutron flux was measured to be <0.02 neutrons/beam-spill/m^3.



Fall 2019

2022



Physics Phase

- First Gd-doped water Cherenkov detector in a neutrino beam.
- Neutron multiplicity and CC-inclusive meas.
- First LAPPD deployment in a neutrino beam.

202X

Testing new tech for future experiments

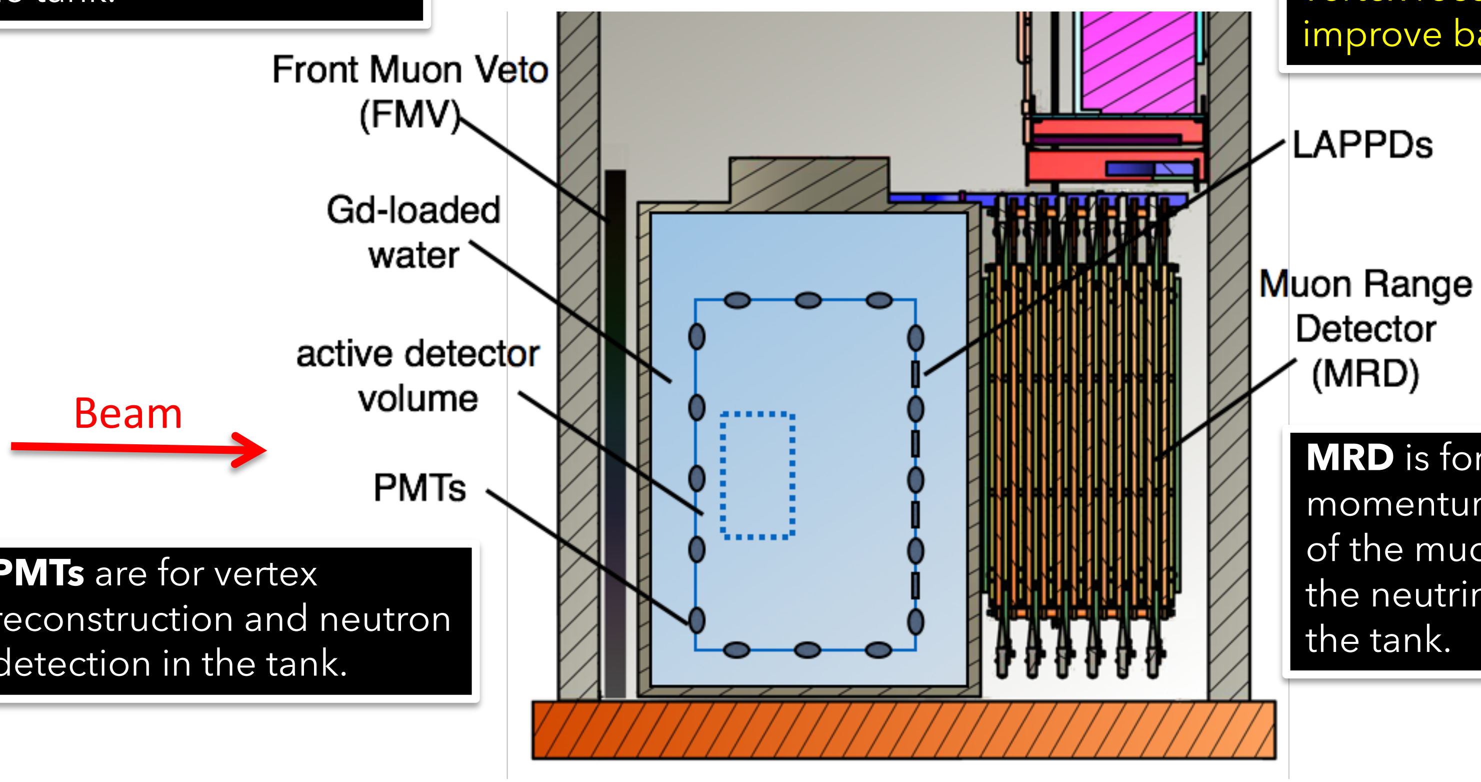
- Testbed for a new active medium (WbLS), LAPPDs and other technologies.

ANNIE Detector Components

- 26 tons of de-ionized water loaded with 0.2% Gadolinium sulfate (50 kg) as an active medium to capture neutrons and study charged current neutrino interactions.

FMV is used to veto muons not originating in the tank.

LAPPDs are used for better vertex reconstruction and to improve background rejection.



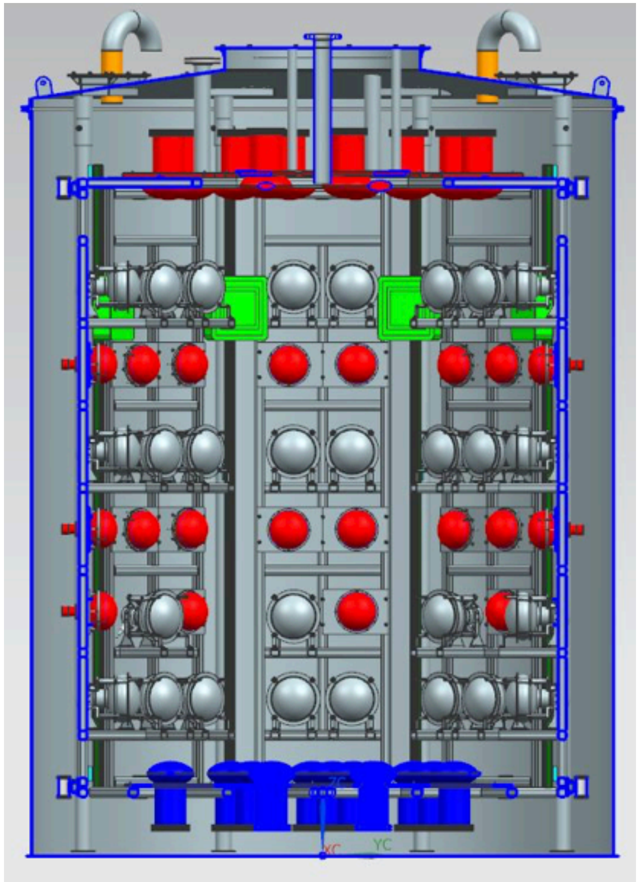
PMTs are for vertex reconstruction and neutron detection in the tank.

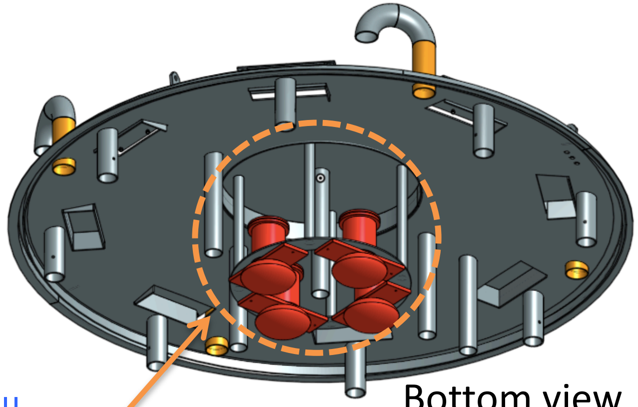
MRD is for measuring the momentum and direction of the muons coming from the neutrino interactions in the tank.

Flexible, Portable Detector Design

LAPPDs deployable in-situ

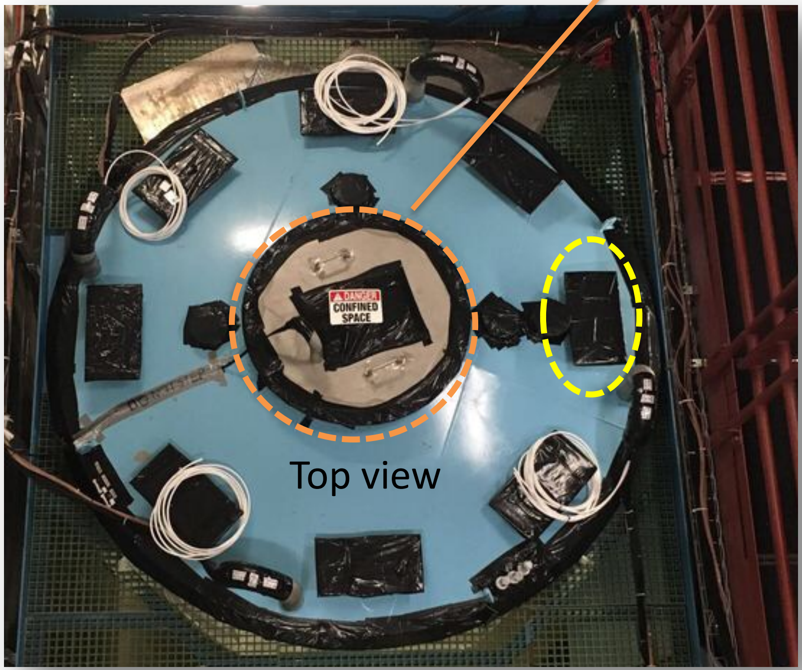
- The inner frame attached to the tank lid is an octagonal structure.
- It was designed for 132 PMTs and ~40 LAPPDs which are deployable in-situ
- A unistrut as an LAPPD tracker was mounted at each corner (vertex).





Bottom view

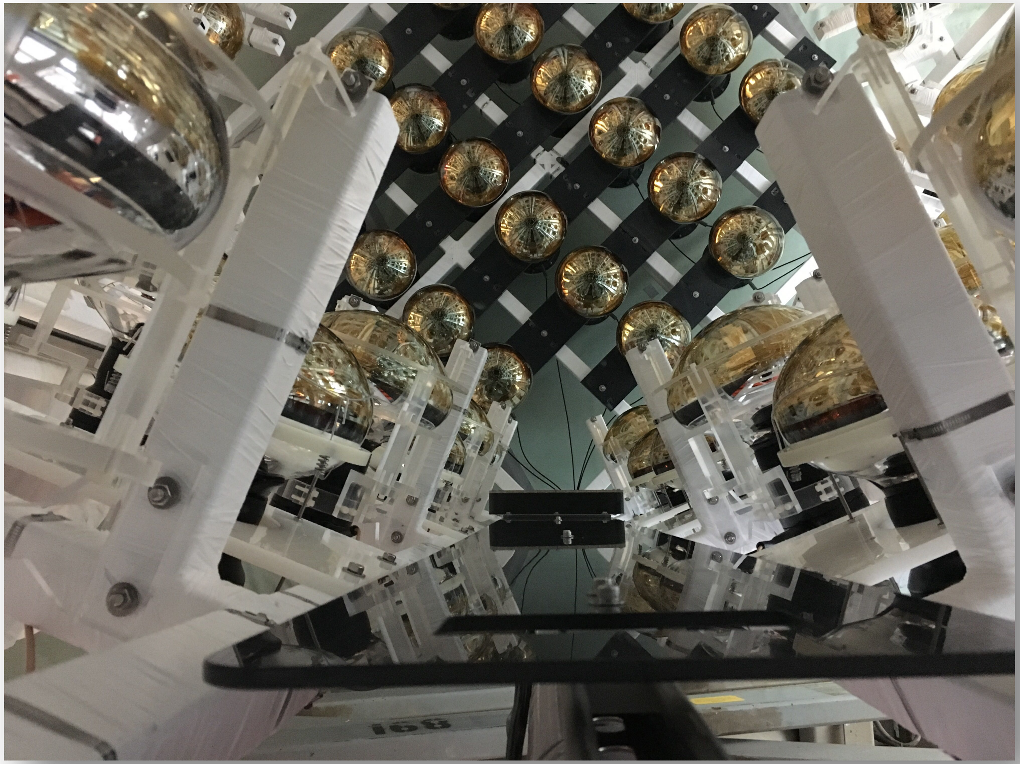
ANNIE Detector in the hall



Top view

LAPPD Deployment

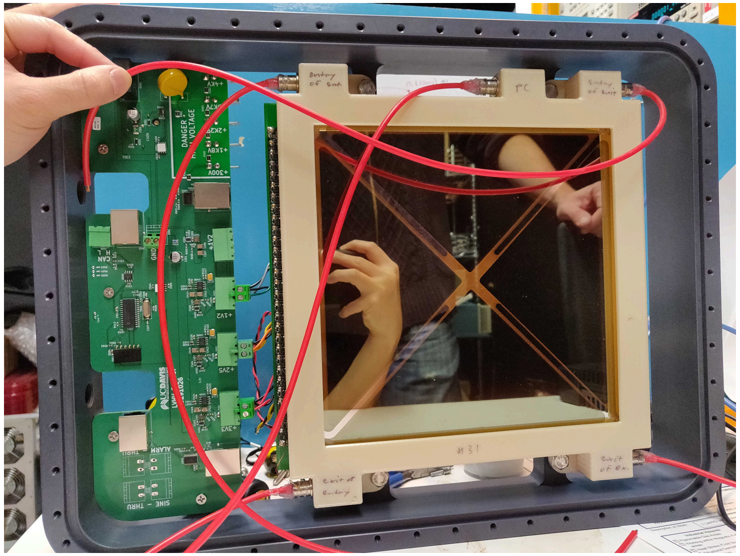
- The LAPPD housing is mounted on ¼ inch PVC panel and it slides on the track with Polypropylene sliders screwed on the back of the panels.
- Deployment was successfully tested before the ANNIE detector was installed.



LAPPD panel on a track

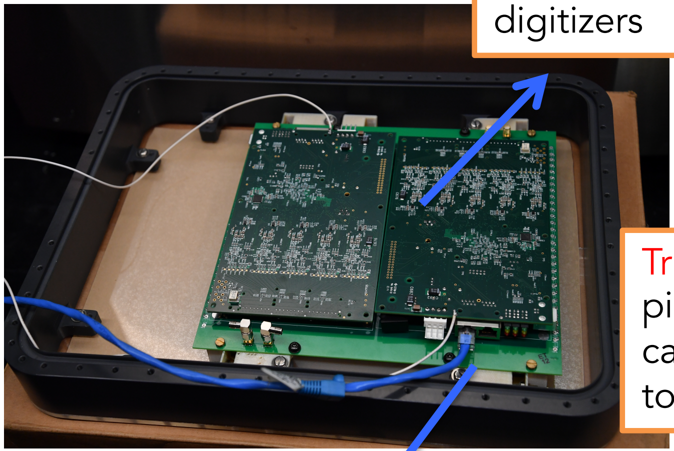
LAPPD Housing Design

- The housing was designed at UC-Davis.
- It was made of 2-inch thick PVC frame with a ¼ inch UVT acrylic window and thin SS back plate.
- Enough space for LV-HV board, fan, humidity and temperature sensors etc.
- O-rings on both sides of the housing provide water-tightness.
- Water-tightness tests and electronics integration are underway.



LAPPD Housing with Electronics Integration

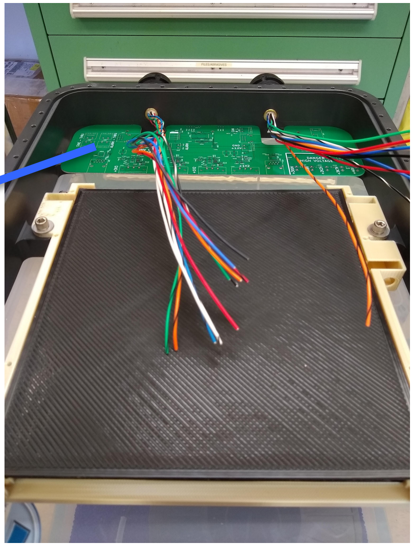
2 ACDC Cards as waveform digitizers

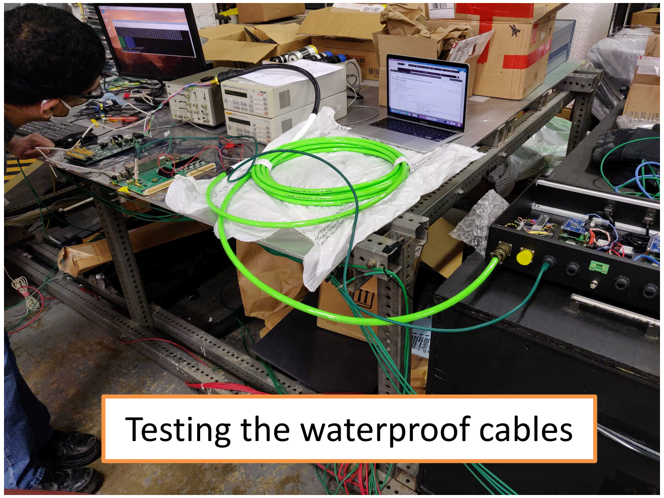


Trigger card in between pickup board and ACDC cards to provide trigger to the ACDCs.

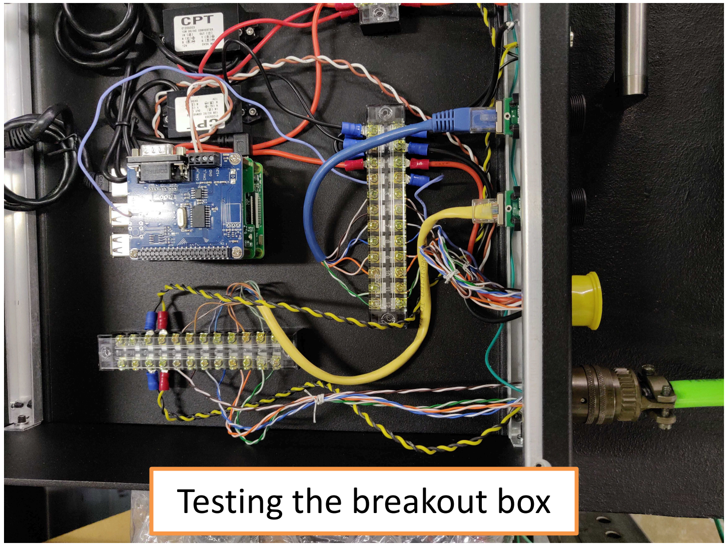
Analog pickup board

LV-HV board to provide power and slow controls





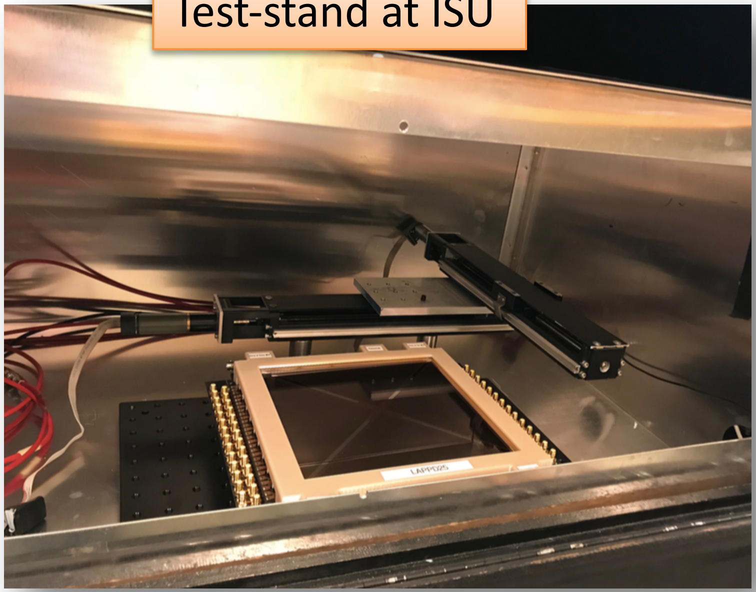
Testing the waterproof cables



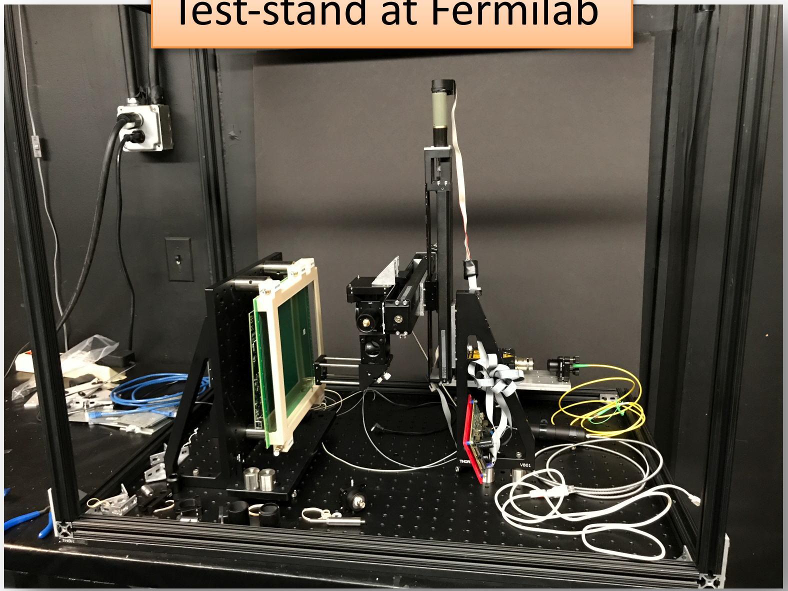
Testing the breakout box

LAPPD Characterization at ISU and Fermilab

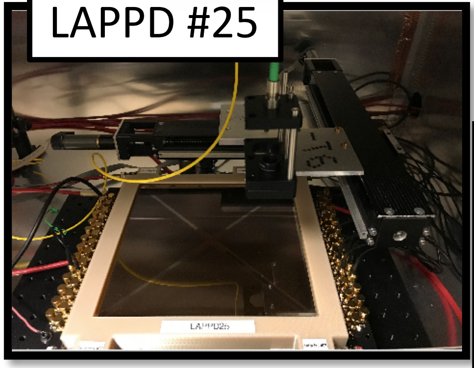
Test-stand at ISU



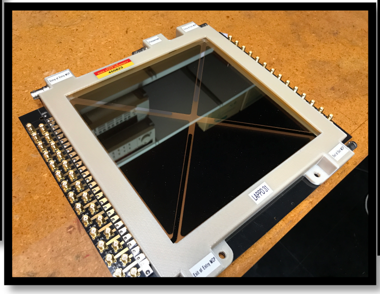
Test-stand at Fermilab



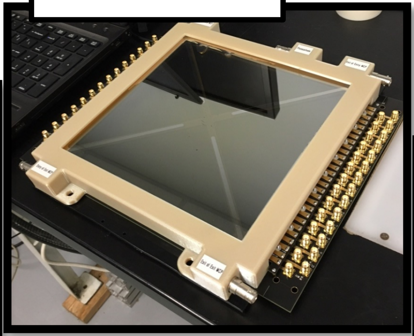
LAPPD #25



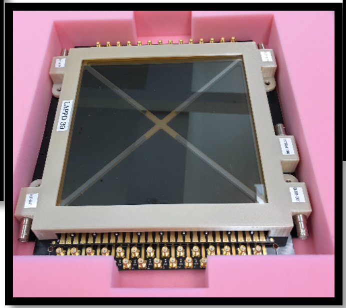
LAPPD #31



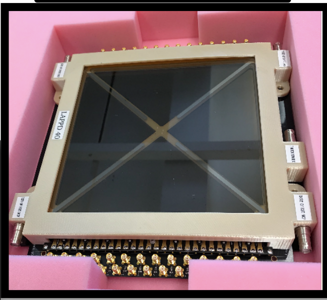
LAPPD #37



LAPPD #39

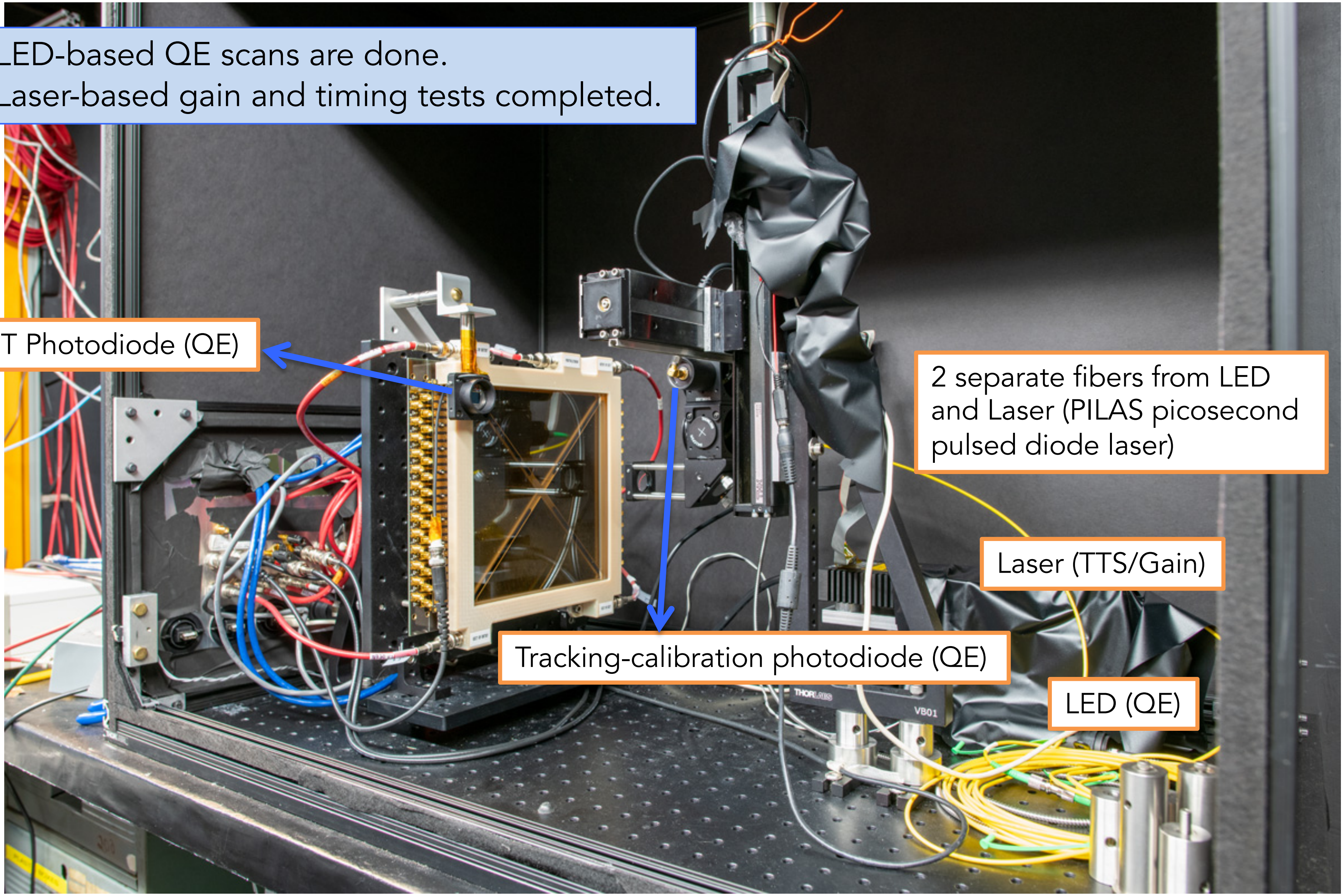


LAPPD #40

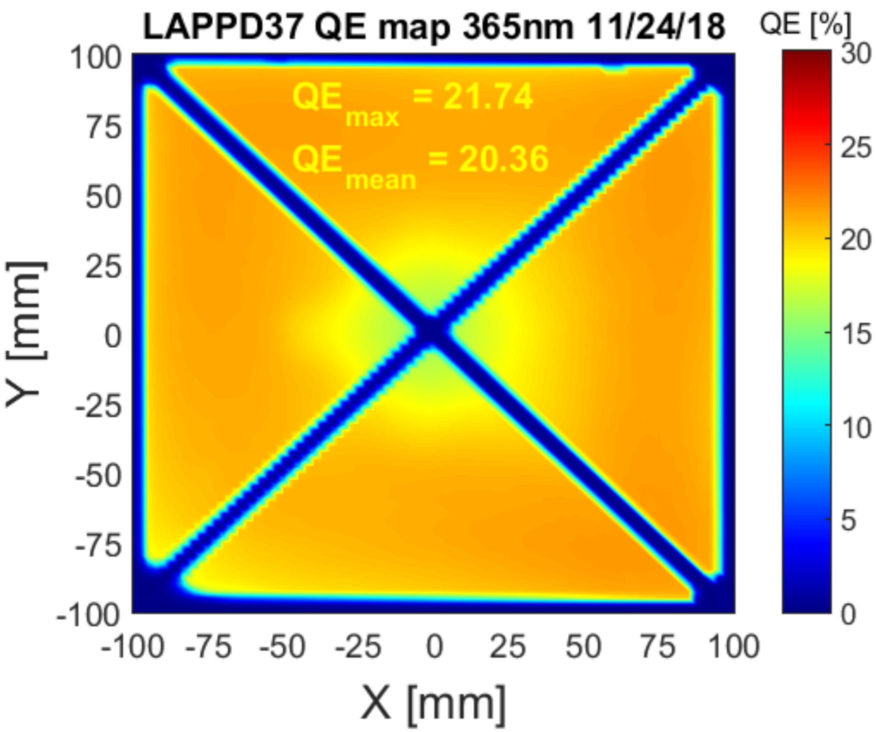


LAPPD Characterization at Fermilab

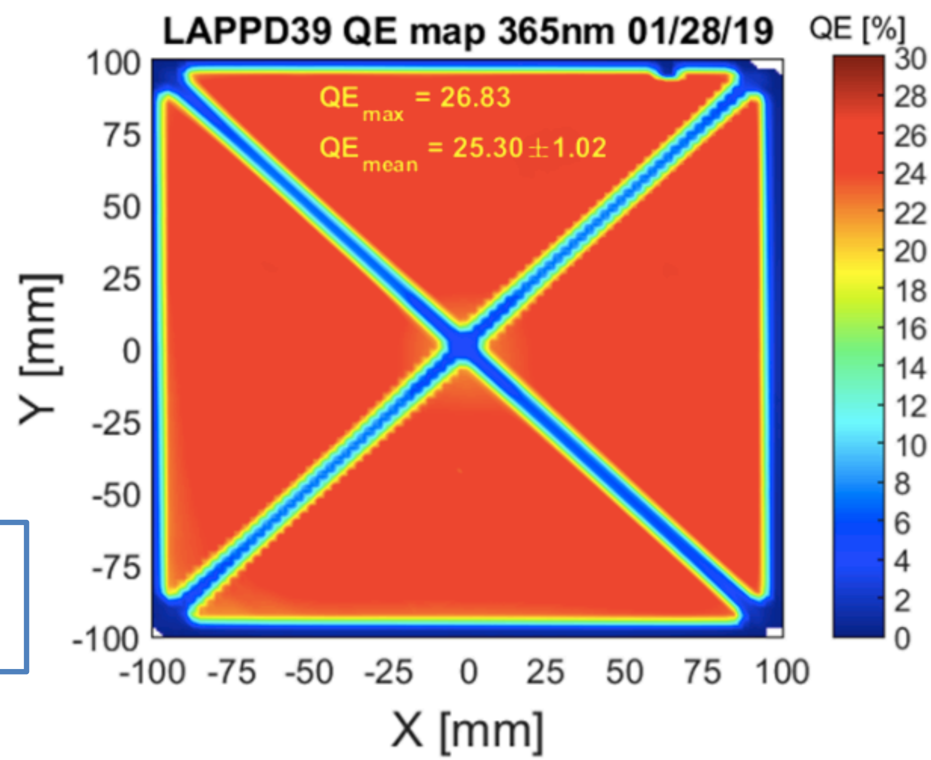
- LED-based QE scans are done.
- Laser-based gain and timing tests completed.



Quantum Efficiency of LAPPDs



- The QE results of 2 LAPPDs, #37 and #39
- QE characterization of all five LAPPDs were completed.

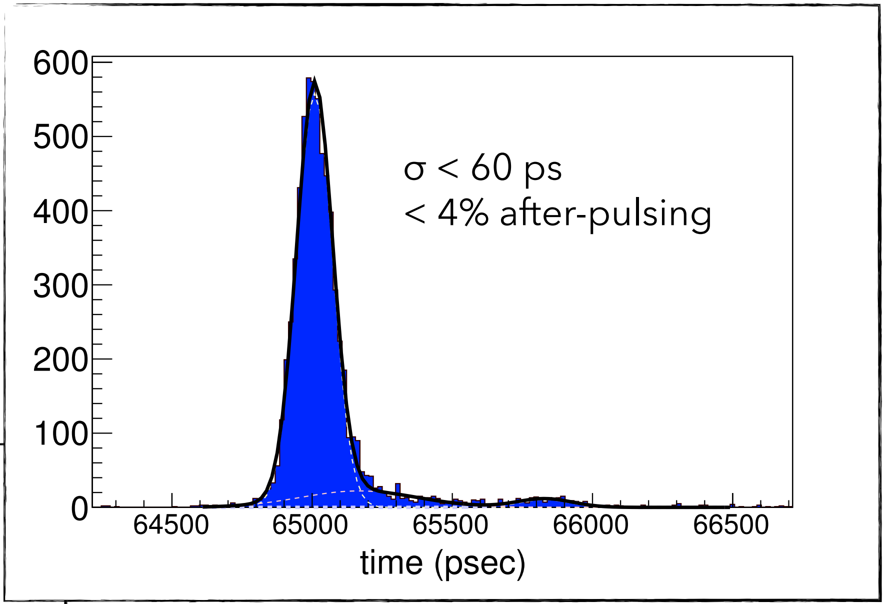


- Quantum Efficiency (QE) is more than 20%
- Nice uniform response from the LAPPDs

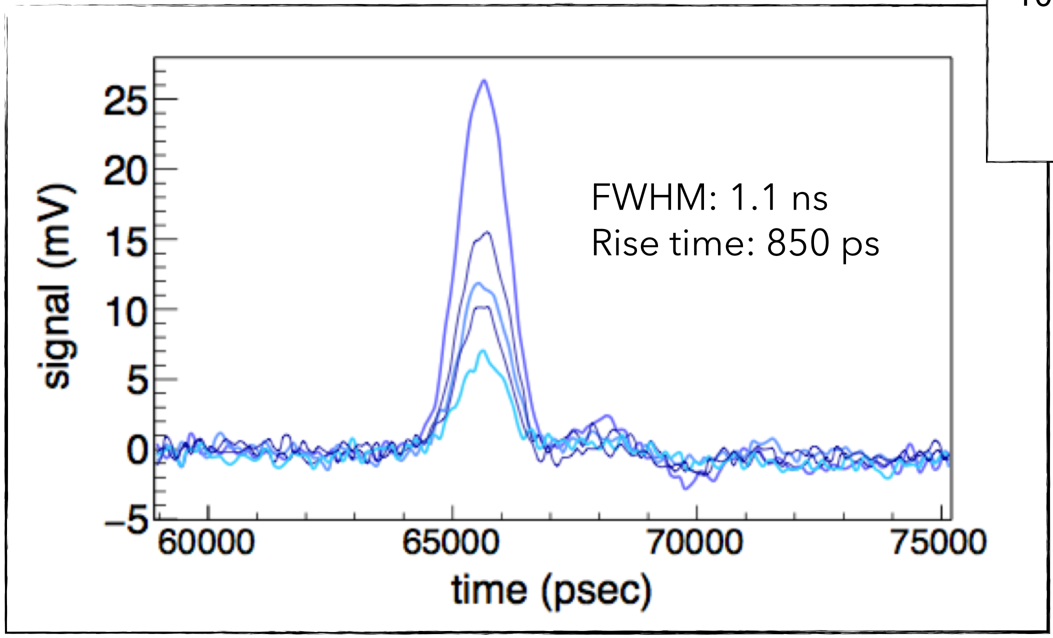
Timing Characteristics of LAPPDs

Timing resolution is less than 60 psec.

Transit Time Spread



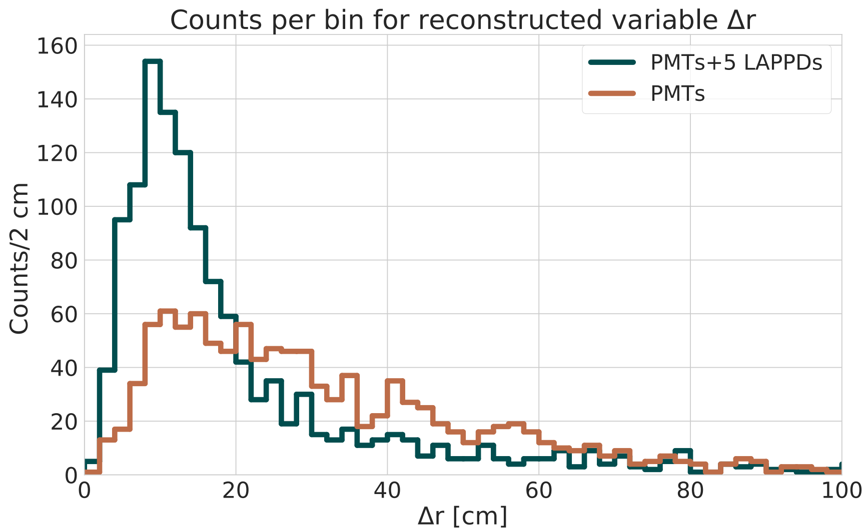
Typical Single-PE Pulses



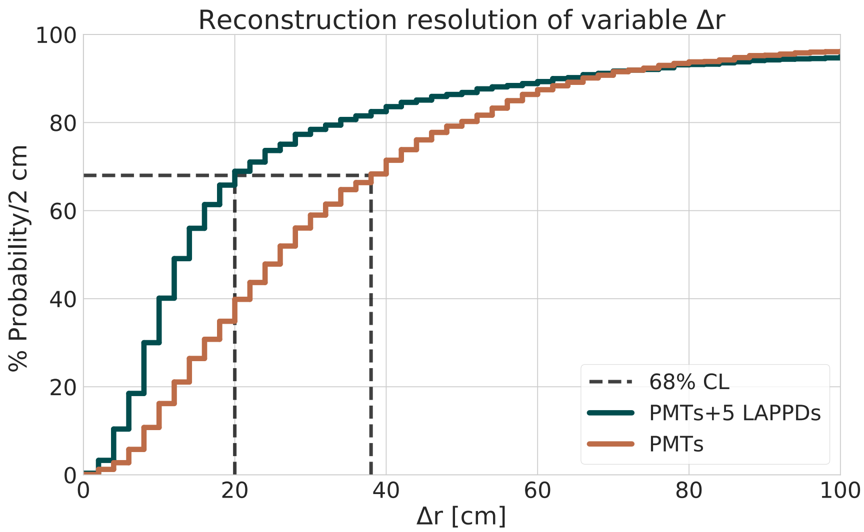
- Laser-based gain and timing data taking were completed.
- The analysis effort is ongoing.

Physics Benefits of LAPPDs in Neutrino Experiments

- The addition of 5 LAPPDs greatly improves reconstruction of muon track parameters.



Raw distribution



Cumulative distribution

132 conventional PMTs (20%)	: 40 cm resolution
5 LAPPDs +132 PMTs	: 20 cm resolution (a factor of 2 improvement)

- They enable significant improvement for vertex and track reconstruction.
- They will improve energy resolution, background rejection and aid reconstruction of multi-track events.

Physics Benefits of LAPPDs in Neutrino Experiments

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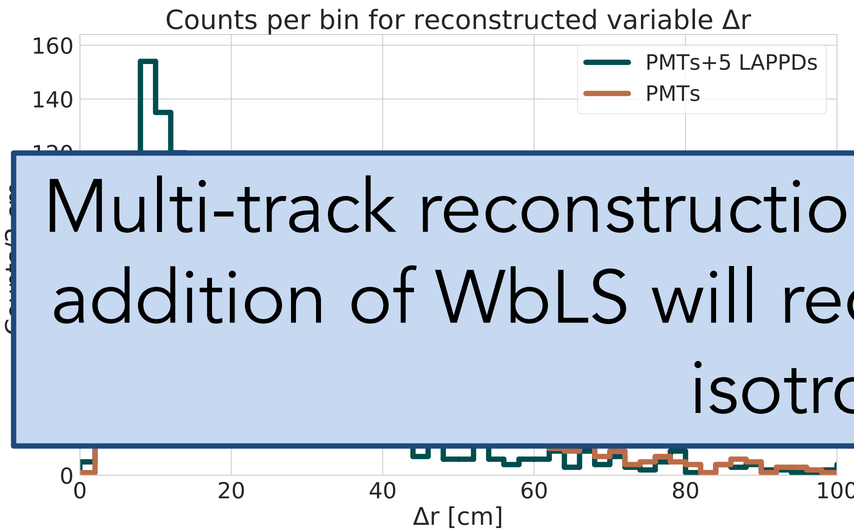
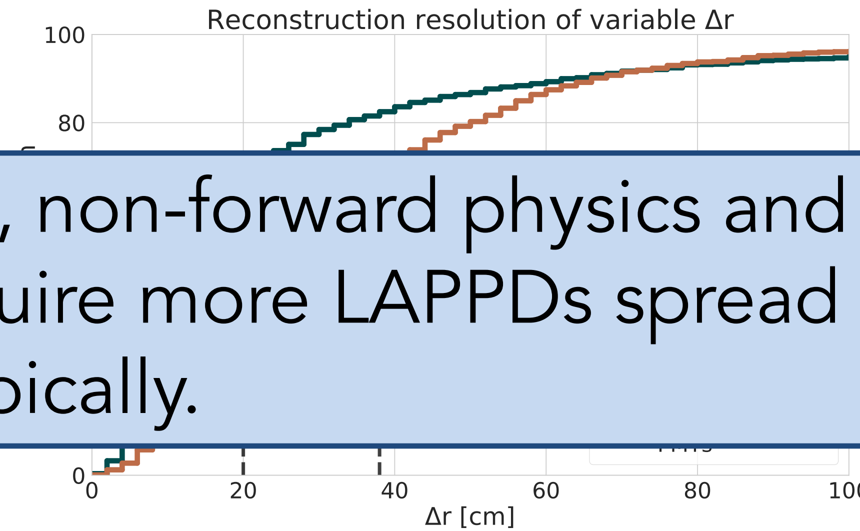




Multi-track reconstruction, non-forward physics and addition of WbLS will require more LAPPDs spread isotropically.

Raw distribution

Cumulative distribution

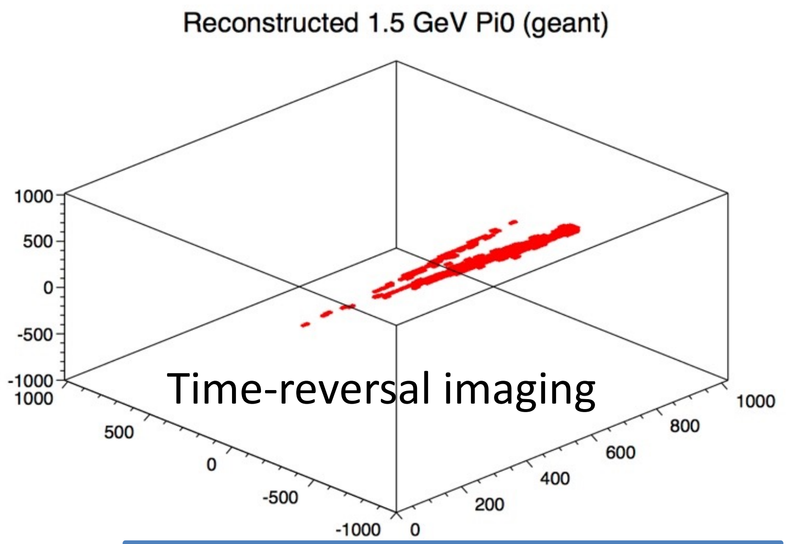
132 conventional PMTs (20%)	: 40 cm resolution
5 LAPPDs +132 PMTs	: 20 cm resolution (a factor of 2 improvement)

- They enable significant improvement for vertex and track reconstruction.
- They will improve energy resolution, background rejection and aid reconstruction of multi-track events.

LAPPD Applicability

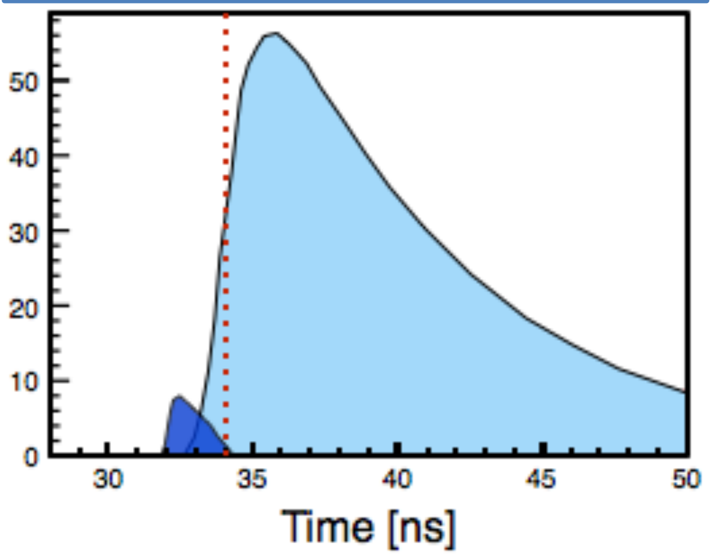
Fast timing

- better vertex reconstruction
- ability to reconstruct overlapping events and tracks
- better able to resolve structure of EM showers
- improved background rejection and energy reconstruction in higher energy beams



(from M. Wetstein, talk at ANT2013)

C. Aberle et. al., 2013 arXiv: 1307.5813



Cherenkov and Scintillation Separation

- Cherenkov light arrives earlier
- Timing information of photons makes the separation possible.

See also:

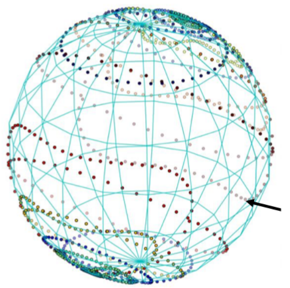
J.R. Alonso et. al., arXiv: 1409.5864
B. Wonsak et. al., arXiv: 1803.08802

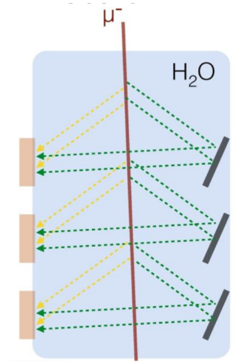
LAPPD Applicability

- **Imaging** is a powerful capability
- Because LAPPDs are imaging photodetectors, their marginal value increases with more dense occupancy. Could we develop interesting schemes to better concentrate the light?

① Multi-bounce optics (UChicago - Oberla, Frisch, Angelico, Elagin)

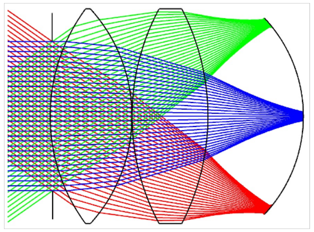
https://arxiv.org/abs/1510.00947





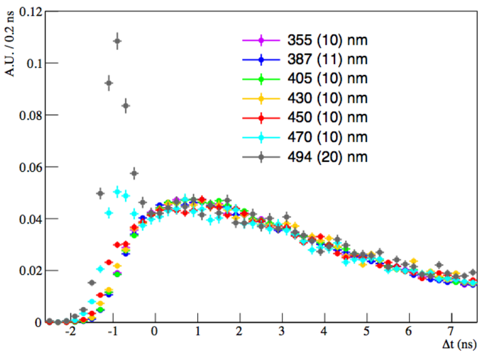
② Plenoptic imaging (intensity, color and directional information) (J. Dalmasson et. al.)

https://arxiv.org/abs/1711.09851



③ Chromatic Separation (by using dichoric filters) (U Penn - Kaptanoglu, Luo, Klein): Dichroicons

https://arxiv.org/abs/1811.11587

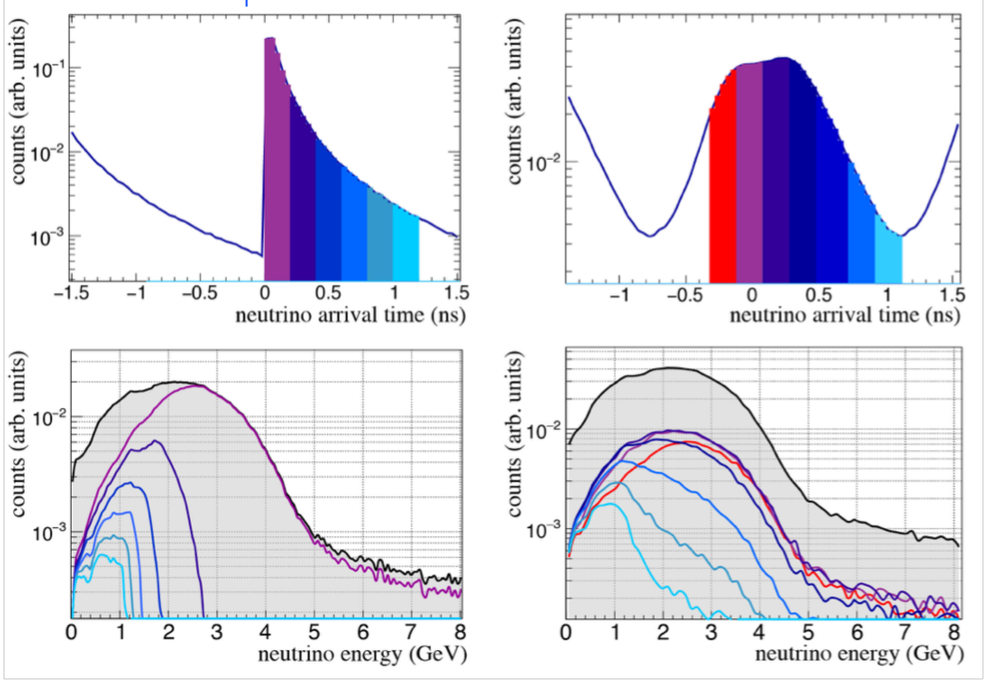


- Timing + Imaging photosensors could enable a very different kind of Cherenkov/scintillator detector with the advantage that it can be used to view all different fluxes in same detector.

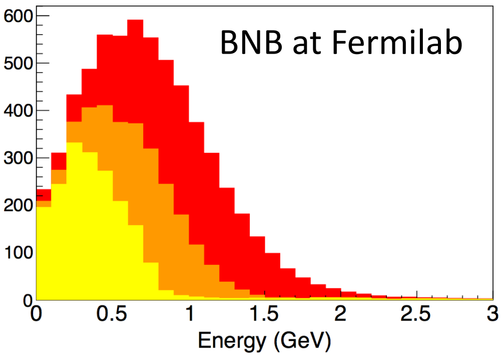
Beam Timing

- Timing can be used to select different energy fluxes from a wide-band neutrino beam.
- Lower energy neutrinos come from slower pions and arrive later.
- Will require precision time stamping O(100) ps.
- ANNIE might be able to provide a first demonstration of this approach, albeit on wide (1 nsec) bunches.
- It will be more visible in small bunch sizes.

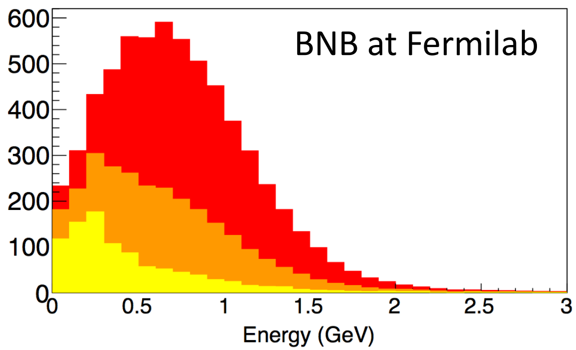
"delta-function" proton bunches   realistic 5.31x10 MHz bunches



"delta-function" proton bunches



realistic bunches spread out in time



https://arxiv.org/abs/1904.01611

Water Based Neutrino Detectors (ANNIE, WATCHMAN, THEIA)

Fiducial Mass

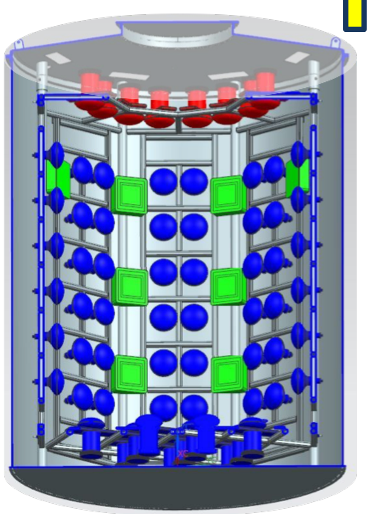
~50 ktons

~4 ktons

~30 tons

Potential future testbed for new technologies, WbLS and additional LAPPDs

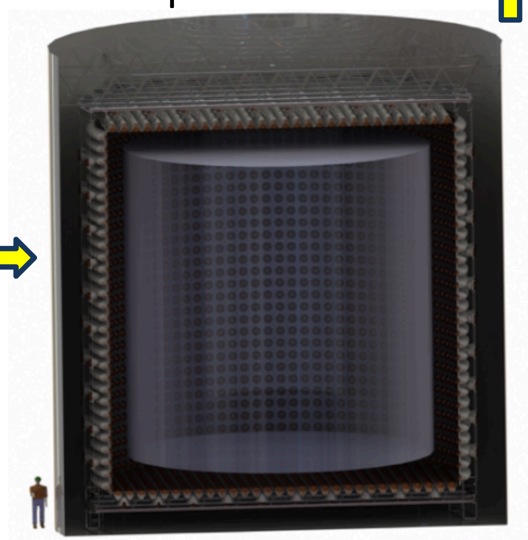
~ 150 photosensors



ANNIE

Gd in a large detector with possible LAPPDs

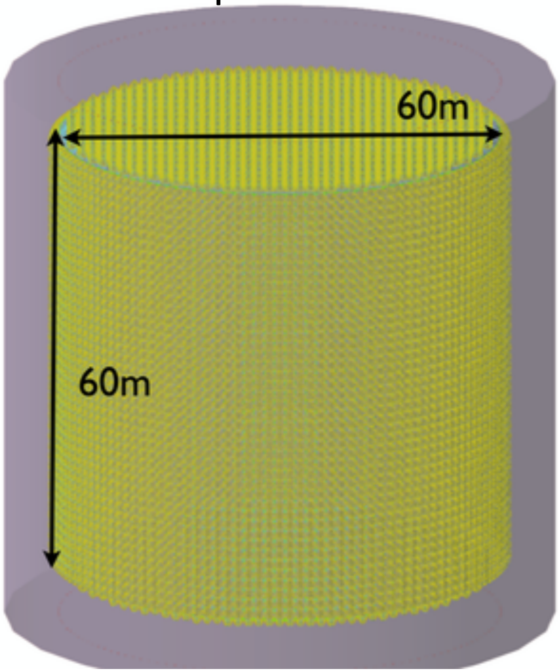
~ 5k photosensors



WATCHMAN - NEO

(AIT-WATCHMAN with WbLS)

~ 100k photosensors



THEIA

arXiv: 1911.03501

Directional (Cherenkov light), low-threshold, capable of flavor identification and signal-background separation detectors….

2019 +

2022 +

?

CONCLUSIONS

- Physics Phase detector of ANNIE has been taking good beam data since Dec. 2020.
- ANNIE will measure the beam induced final state neutron multiplicity & CC inclusive cross section on water
- ANNIE is pioneering R&D of photodetection technologies/techniques:
  - Neutron tagging in Gd-loaded water
  - 5 LAPPDs characterized at FNAL being readied for installation
  - LAPPD coverage can be expanded in-situ to enable multi-track reconstruction and measurements of more exclusive final states.
  - Possible addition of WbLS to combine the tracking capabilities of Cherenkov reconstruction with the energy resolution and expanded sensitivity of scintillation light.