ANNIE R&D Relevant for THEIA

Jonathan Eisch
for the ANNIE Collaboration

THEIA Workshop at UC Davis
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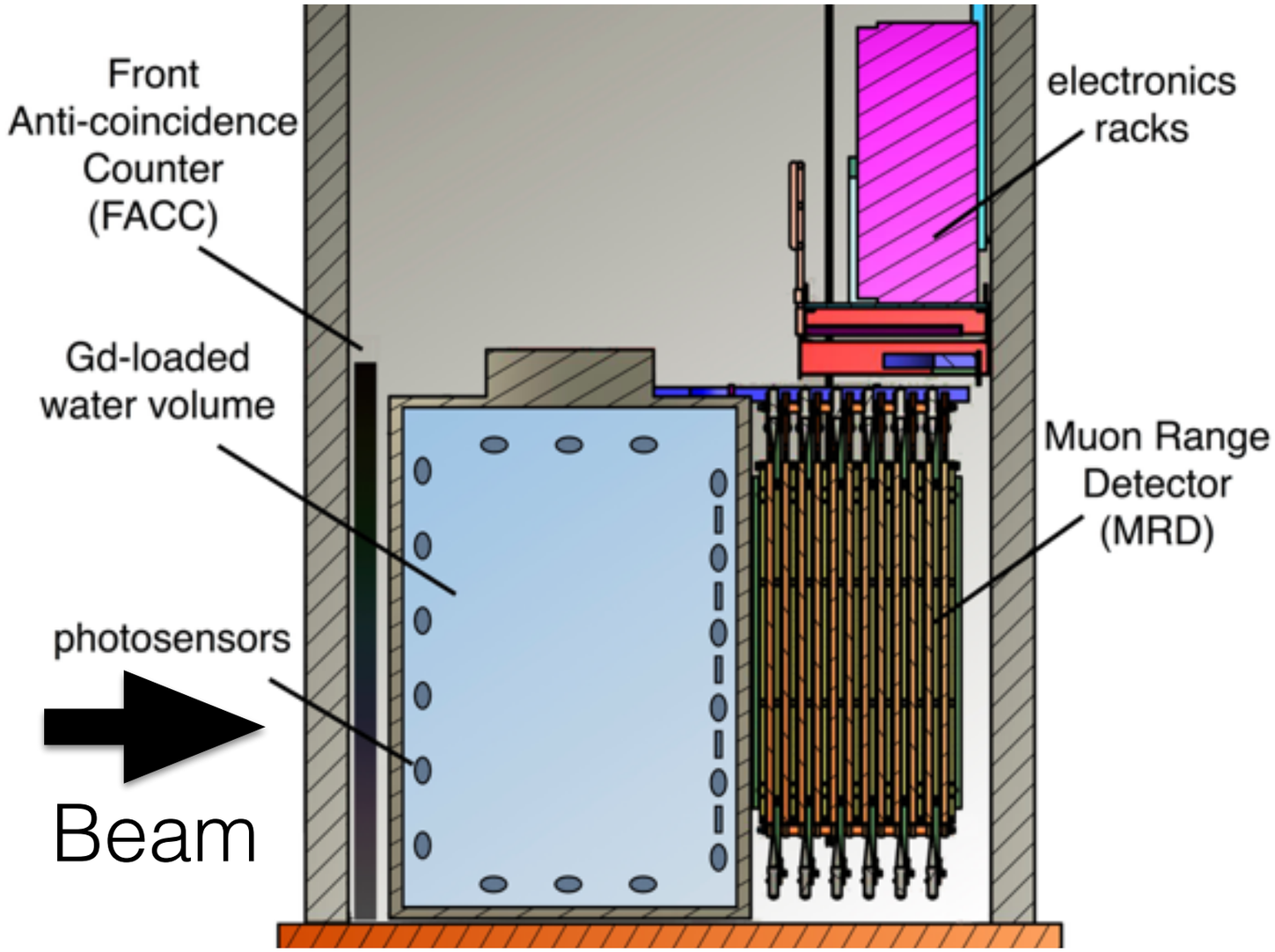
Overview

- ANNIE as a step towards THEIA
- R&D Efforts:
  - Water Quality
  - Electronics Development
  - LAPPD Integration
  - Supporting Software
  - Reconstruction Techniques
- Roadmap and Future Opportunities

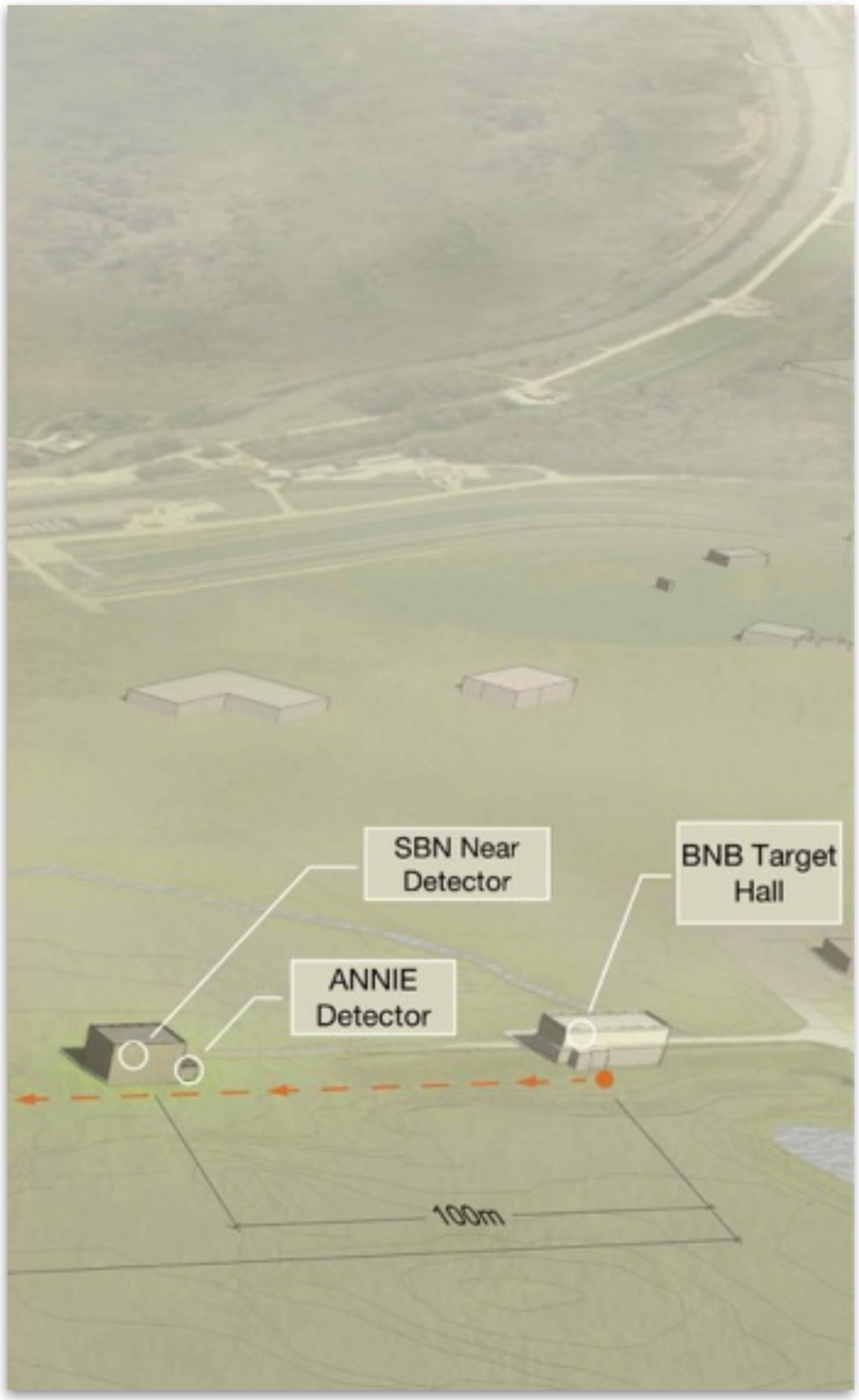
The ANNIE Experiment

- 26 ton water-Cherenkov detector.
- 10 foot diameter, 13 feet tall steel tank with a plastic liner.
- Filled with ultra-pure water doped with Gadolinium sulfate.
  (Phase I: water only)
- Detection volume instrumented with conventional PMTs with 500 MHz full-waveform digitization and newly developed high-speed photo-detectors (LAPPDs).
- Also includes an upstream muon veto detector and the SciBooNE Muon Range Detector (muon tracker) installed downstream.



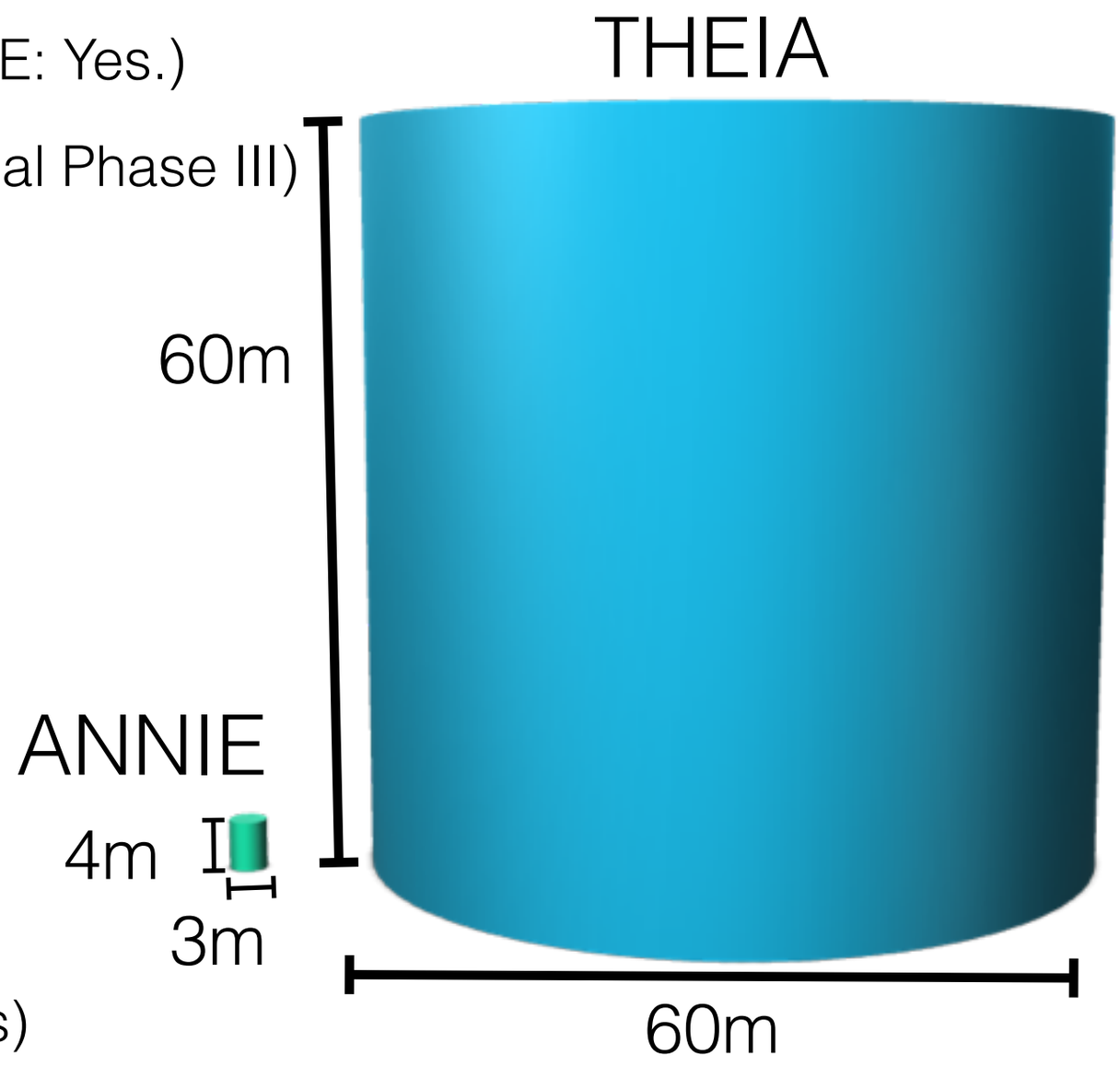
Gd + Water-Cherenkov on a ν-beam

- ANNIE will be the first Gadolinium-doped water-Cherenkov neutrino detector on a ν-beam.
- Phase I (Spring 2016-Fall 2017):
  - Pure water with movable inner-volume filled with liquid scintillator with gadolinium.
  - Fast waveform sampling and digital self-trigging on neutron captures.
  - Measured beam-induced neutron backgrounds.
- Phase II (proposed for Fall 2018):
  - Add Gadolinium sulfate
  - Higher PMT coverage
  - Photon multiplicity trigger
  - Add LAPPDs w/self-triggering
  - Neutrino-physics run!

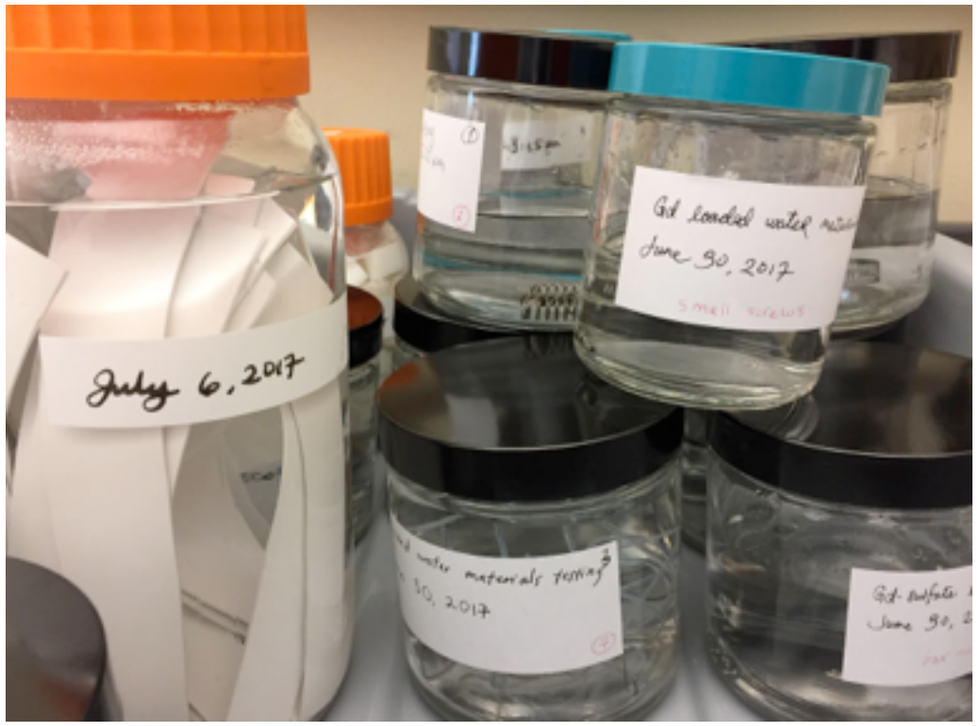


ANNIE and THEIA

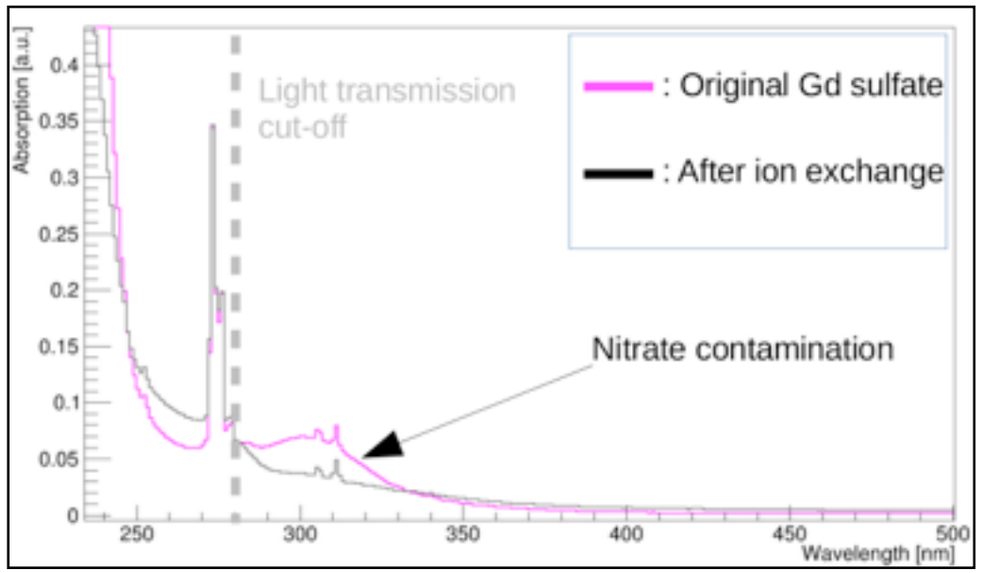
- Detection Medium:
  - Water
    - +Gadolinium (THEIA: Maybe? ANNIE: Yes.)
    - +WbLS (THEIA: Yes, ANNIE: potential Phase III)
- Timescales:
  - Prompt: ~10s of ns (both)
  - Captures: ~10s of μs (both)
- Signal Source:
  - Neutrino beam (both)
  - Other untriggered sources (both)
- Channel count:
  - ANNIE: 150 (PMTs) + 1200 (20 LAPPDs)
  - THEIA: 50,000 (PMTs) + 720,000 (12000 LAPPDs)



Materials Testing/Filtration



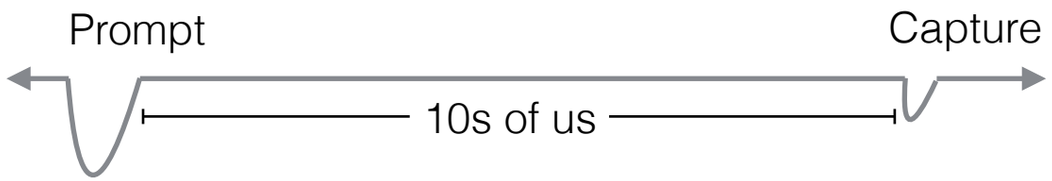
Long term material compatibility testing



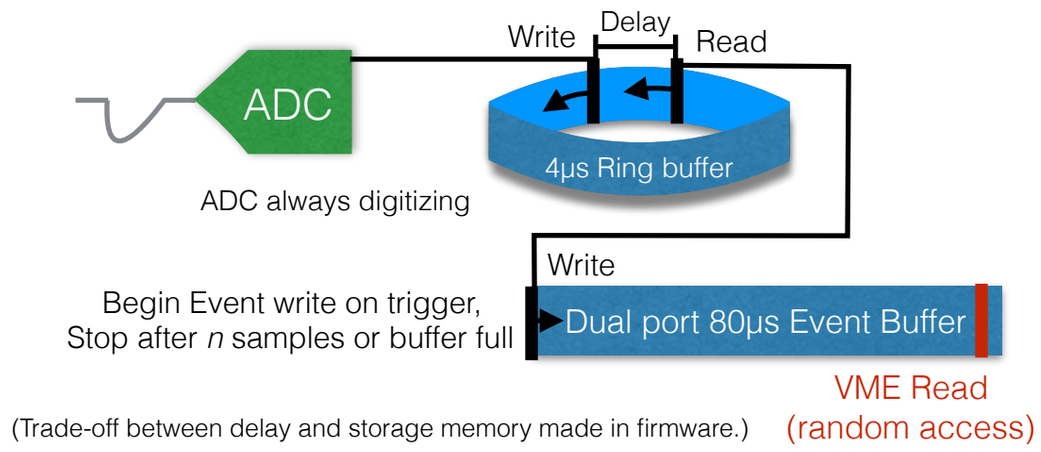
Removing nitrate contamination from Gadolinium sulfate

- ANNIE uses Gadolinium sulfate for neutron capture, may also be used in THEIA.
- High water transparency is a critical design requirement for both experiments.
- UC Davis group is doing extensive materials testing to ensure gadolinium sulfate compatibility.
- They are also designing a water filtration system to filter out organic carbon, particulates, iron, etc.
- Expertise in these tests will translate over to similar tests on WbLS.
- See Vincent Fischer's talk tomorrow morning.

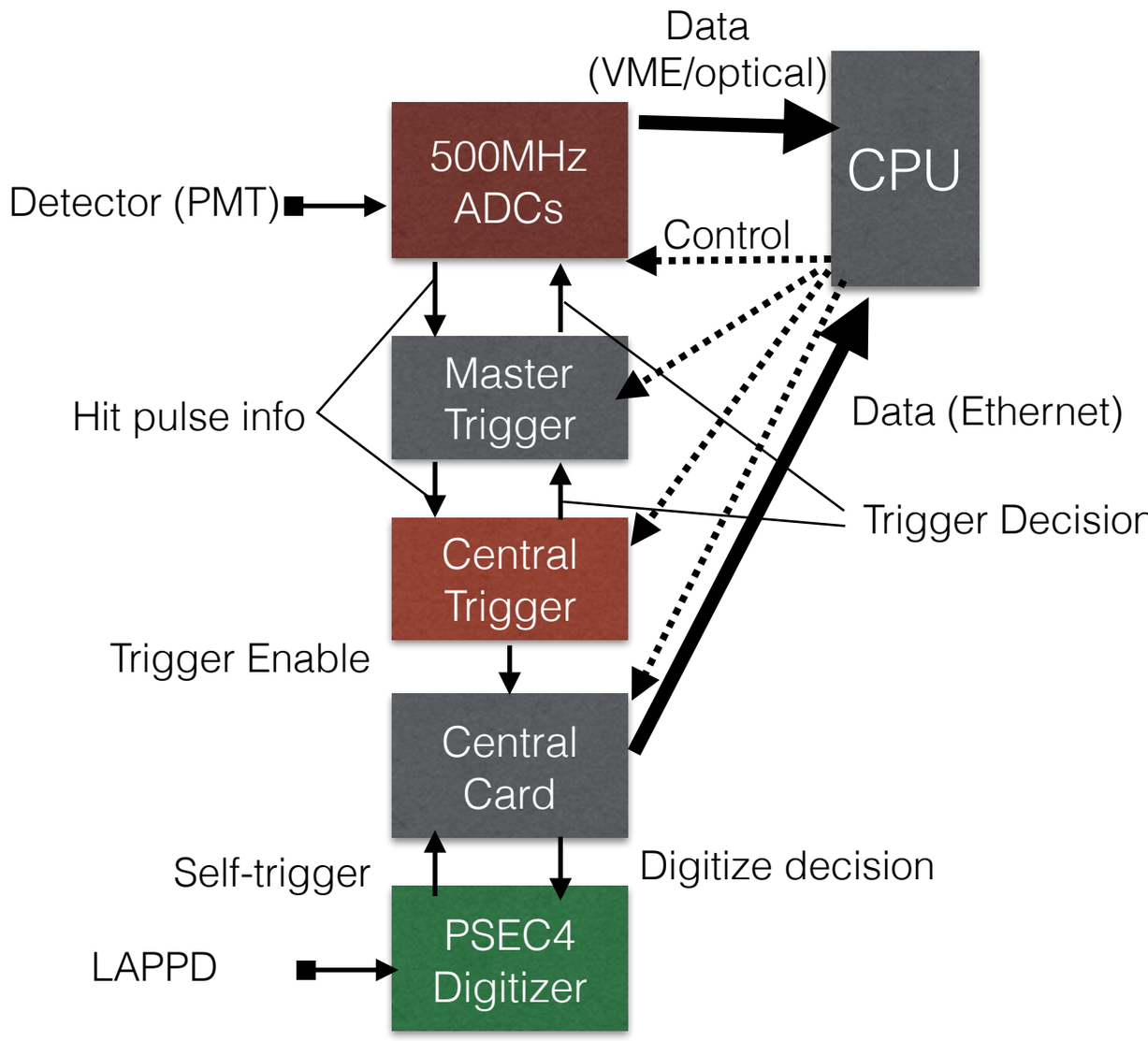
Signal Digitization in ANNIE



- The ANNIE Digitization scheme is driven by the timescales of the signal:
- Direct Cherenkov from muons and pions from neutrino interactions require high speed digitization.
- Neutron capture happens 10s of microseconds later.



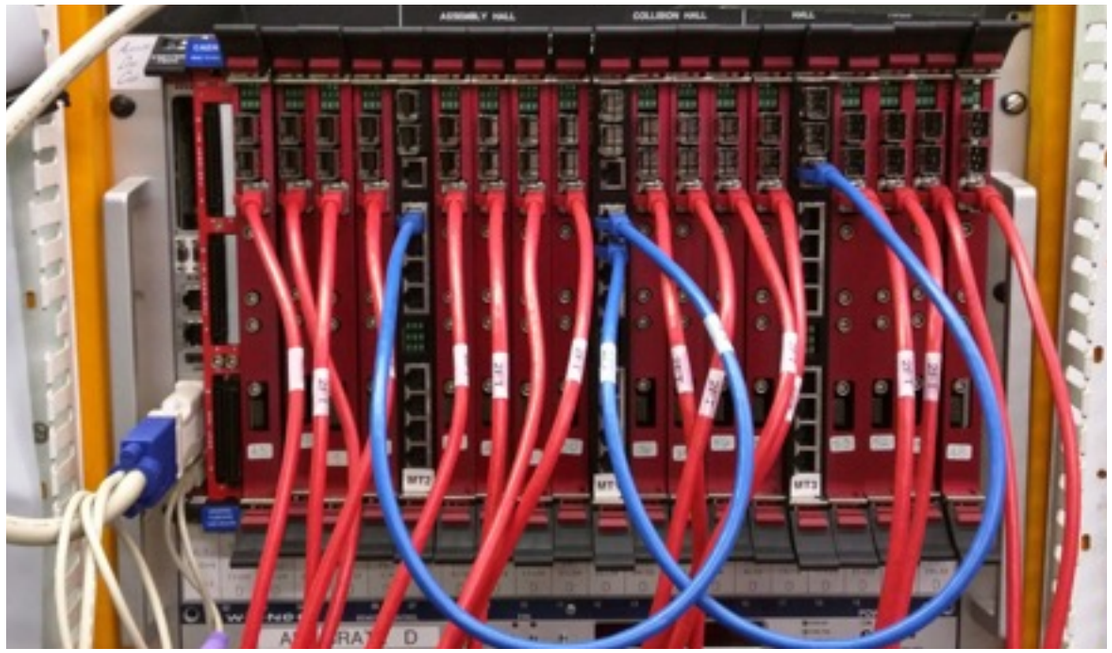
(Trade-off between delay and storage memory made in firmware.)



Electronics Development

- 4-channel 500MHz ADC boards developed for K0TO at the University of Chicago, built for ANNIE.
- These cards are used in a several thousand channel DAQ in K0TO.
- Continuous full-waveform digitization:
  - pipeline self-triggering algorithm
  - digital delay-line ring-buffer.
- Custom firmware developed at Iowa State for recording prompt and delayed capture signals
- 16-channel board developed by University of Chicago also available.

4-channel 500MHz ADC card



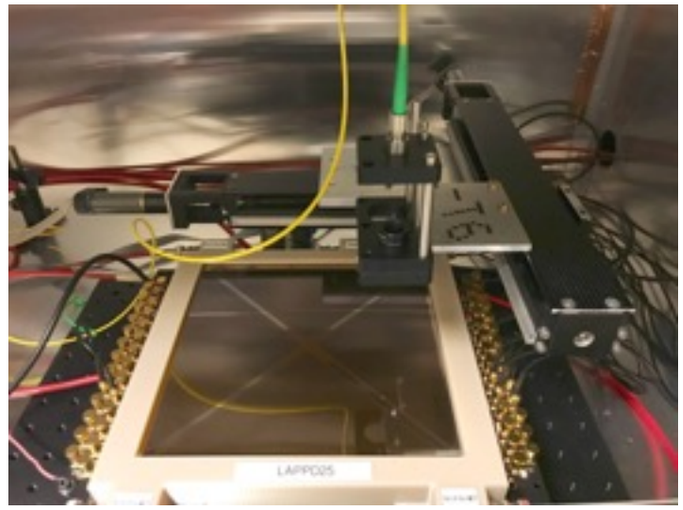
64-channel+trigger cards

Triggering and Timing

- ADC cards receive triggering and timing signals through dedicated Master Trigger (MT) cards.
- Digital online triggering.
  (Single analog front-end for trigger and recording.)
- ANNIE Phase II will implement a digital channel-multiplicity trigger to trigger on neutron captures following beam-neutrino interactions.
- FPGA-based architecture to add future functionality.
- Sub-nanosecond timing with LAPPDs to resolve beam structure. (see the ANNIE Science talk)
  - Exploring the use of White Rabbit to synchronize with the rest of the short baseline program at Fermilab.

Development of LAPPDs

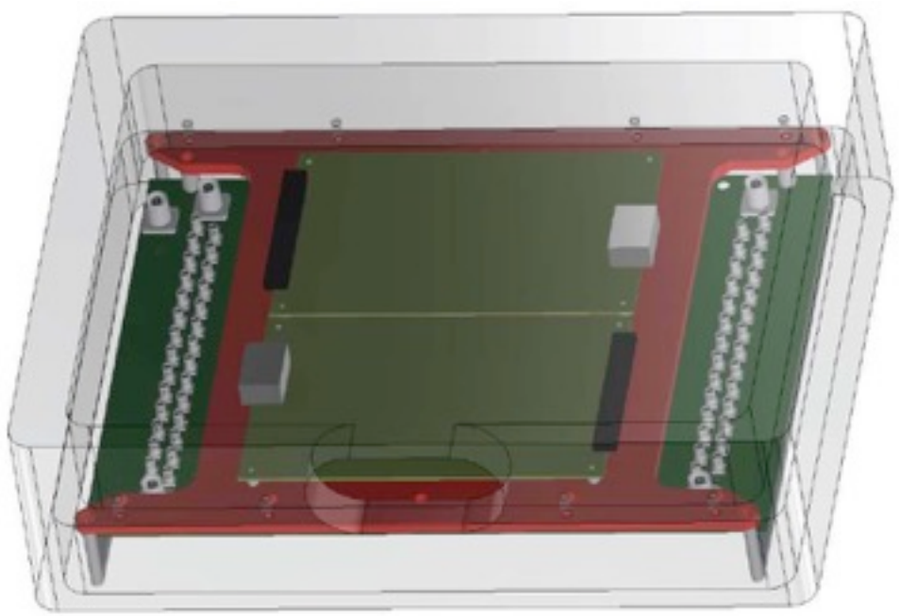
- LAPPDs have been commercialized by Incom. (You can buy one. We already have.)
  - See Matt Wetstein's talk tomorrow morning.
- ANNIE will be the first high-energy physics application of LAPPDs and is actively developing water deployment technologies.
- Developing compact integrated modules with low-power PSEC4 10GHz readout.
- ANNIE Central Card for high-speed LVDS communication and triggering developed at University of Chicago, firmware and software development also at Iowa State and UC
- Central cards can be cascaded to support thousands of channels from one interface.



LAPPD characterization at ISU

ANNIE Central Card

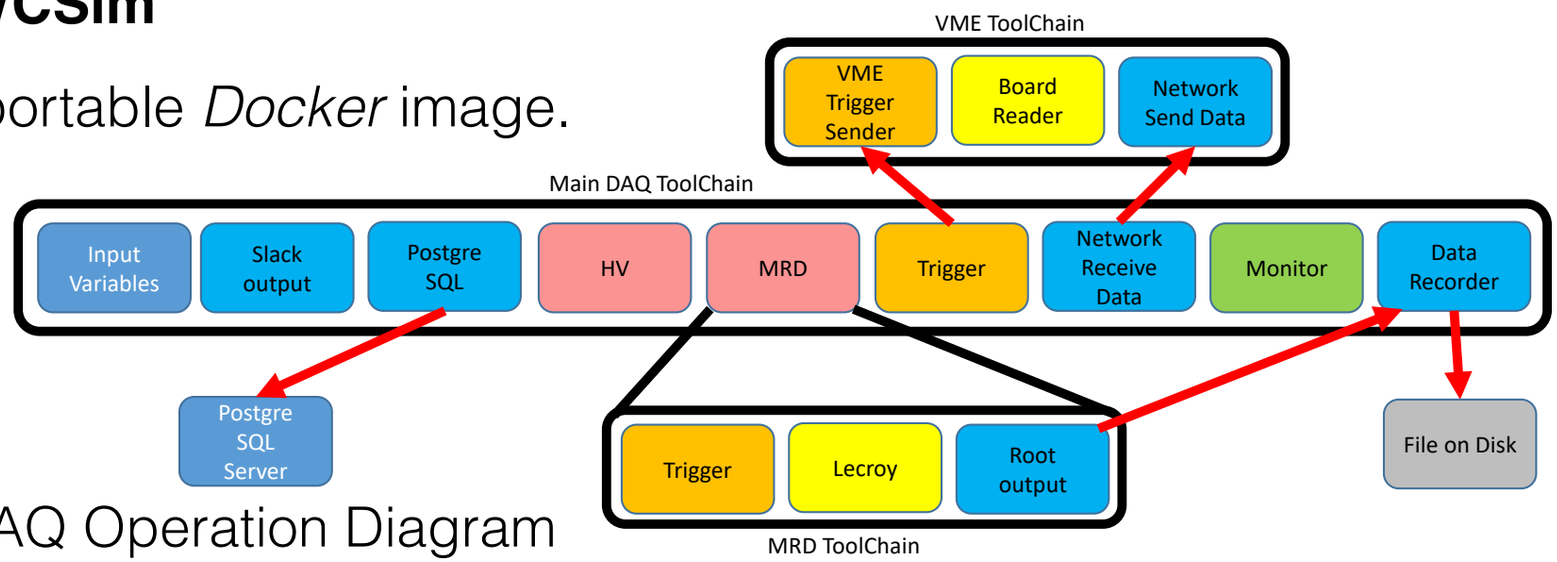
Water Deployment of LAPPDs



- Currently in development (UC Davis &ISU):
  - Compact water-tight enclosures
  - Robust long distance communication
  - Low noise power delivery
  - Thermal management
  - Sub-nanosecond timing synchronization between LAPPD modules.
  - Combined triggering with ADC system

Support Software

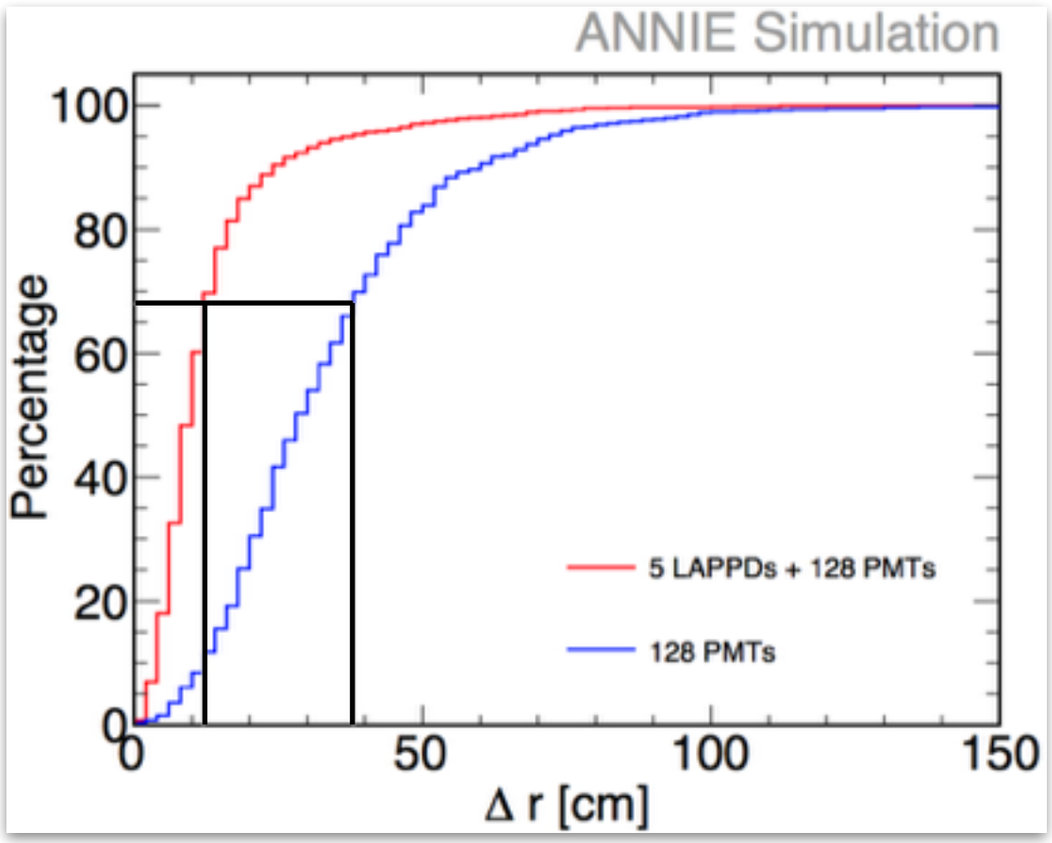
- ToolDAQ
  - Modular, high-performance, distributed DAQ for configuration, monitoring and readout.
  - Developed by Benjamin Richards at Queen Mary, shared development with Hyper-K.
- ToolAnalysis
  - Scalable, modular analysis system sharing a common framework with ToolDAQ
  - Flexible system of inheritable data classes can be easily adapted for future experiments
- A developing ecosystem of simulation, reconstruction and analysis software for water-Cherenkov experiments.
  - **Including RAT-PAC and WCSim**
- Available pre-configured in a portable *Docker* image.



ANNIE ToolDAQ Operation Diagram

Testing Reconstruction Techniques

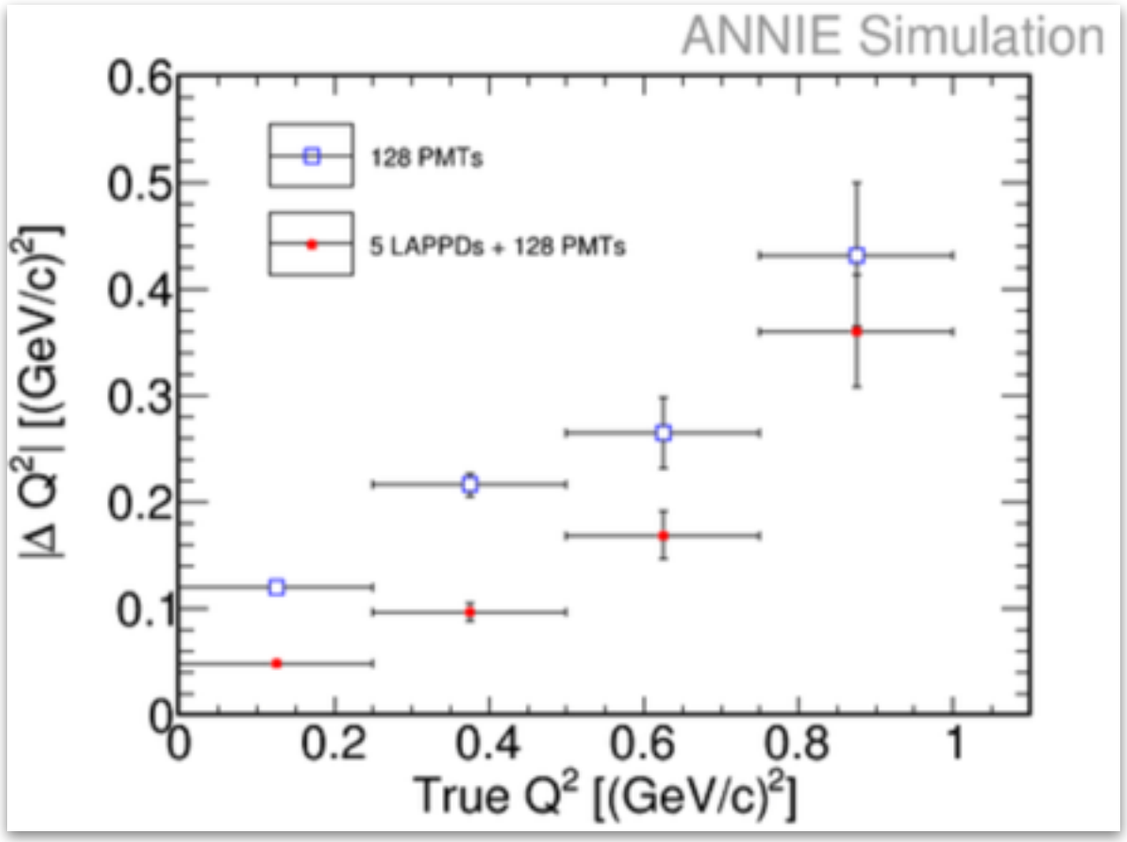
- High-speed, high-resolution photosensors like LAPPDs have never been available for water-Cherenkov before.



Vertex resolution w/128 PMTs: 38cm
with 128 PMTs + 5 LAPPDs: 12cm

- New techniques for reconstruction need to be developed and tested
- See Jingbo Wang's presentation later today!

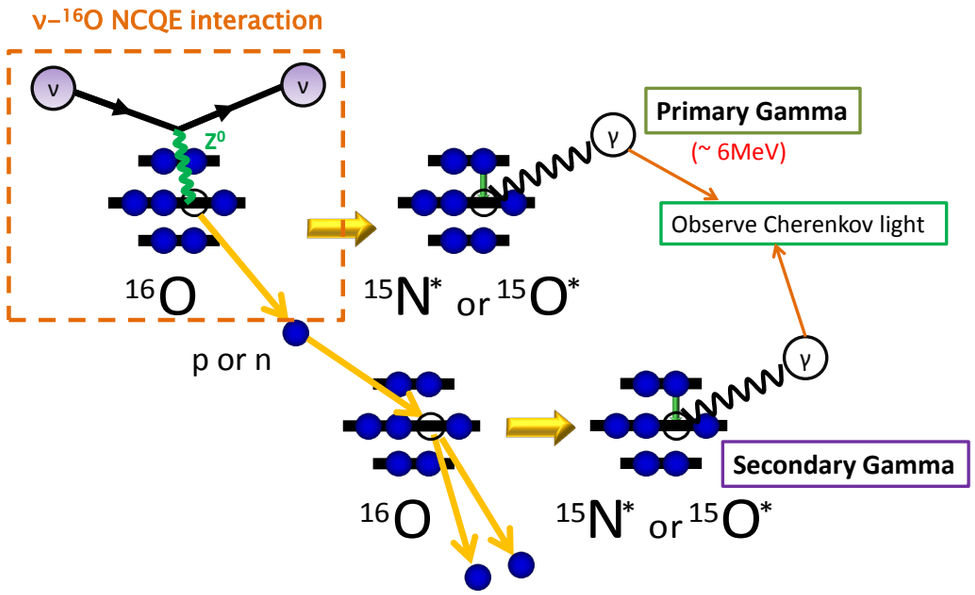
arXiv:1803.10624



Developing New Experimental Techniques

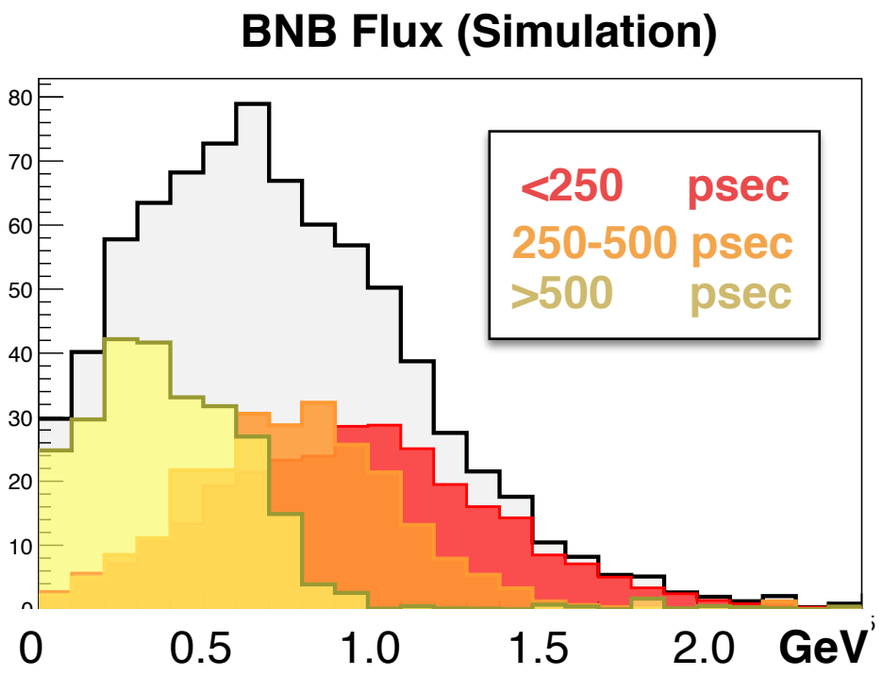
- Since ANNIE is on a very intense neutrino beam, it provides an ideal location to demonstrate new experimental water Cherenkov experimental techniques.
- For more details, see Matt Wetstein's ANNIE Science talk from this morning.

Nuclear de-excitation gammas



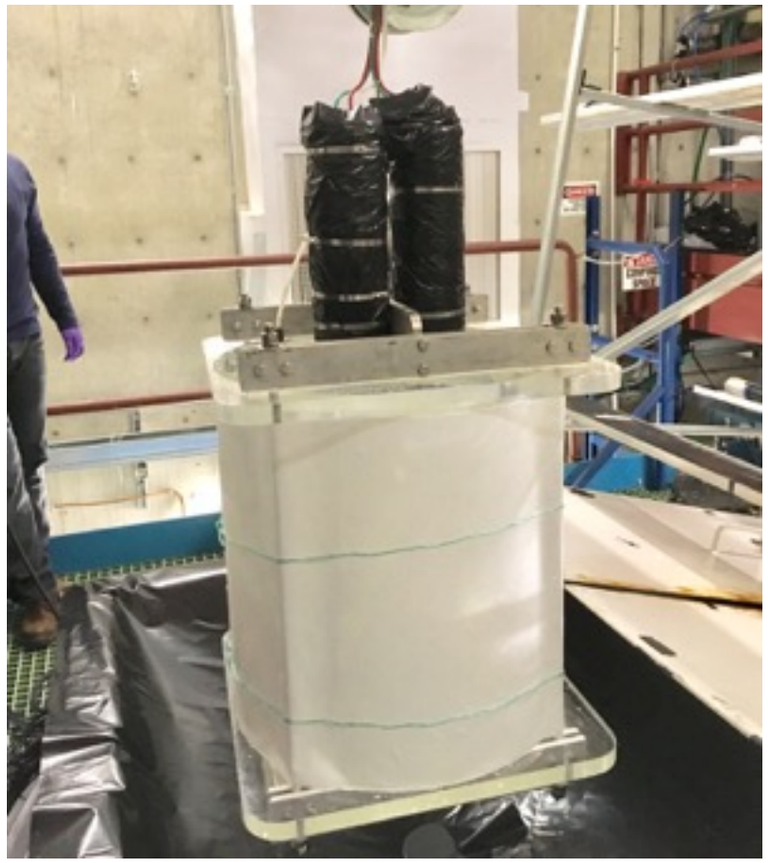
source: dissertation of Huan Kuxian (T2K)

Fast Timing beam physics

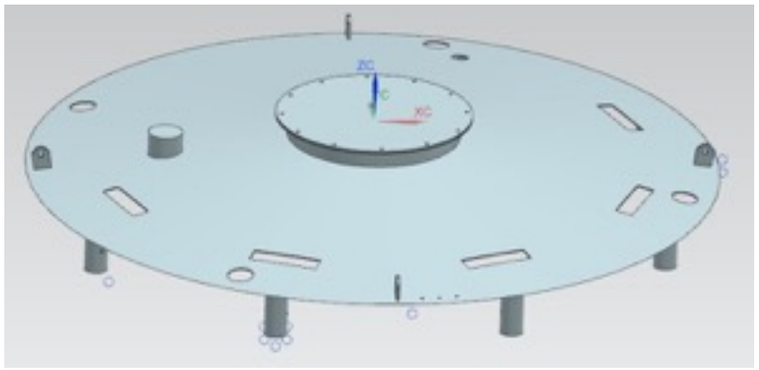


Building a Broader Water Cherenkov R&D Program at FNAL

- ANNIE is an operating water-Cherenkov neutrino detector at Fermilab
- The ANNIE detector is built to be adaptable:
  - Phase I used a movable, instrumented acrylic vessel filled with Gd-doped liquid scintillator.
  - During Phase II, LAPPDs will be installed using tracks from above as they become available.
    - Inner structure has space for up to 200 PMTs.
    - Each subsystem (PMT, MRD, LAPPD) produces an independent data stream, joined offline using timestamps.
- ANNIE can be used as a testbed for advanced detector development for future water-based experiments.
- The ANNIE detector itself is portable and individual subsystems can be run independently, especially between physics runs.



Phase I sub-detector



Phase II lid concept with hatch and slots

Possible Timeline

- Phase I (Spring 2016 to Fall 2017)
  - Neutron Capture Volume (NCV) for neutron background measurement
- Phase IIa (Proposed Fall 2018 to Summer 2019)
  - Additional PMTs, add Gadolinium, and LAPPDs for physics measurement.
- Phase IIb (2019+)
  - Add more LAPPDs - More mature infrastructure for LAPPD readout
- “Phase III”
  - Water based liquid scintillator (WbLS)
    - Direct Cherenkov/scintillation separation
  - WbLS+Gd
- Test Beam Activities
  - Possibly run ANNIE (or subsystems) on a testbeam.
- Redeployable
  - ANNIE is housed in a commercially available water tank, the PMTs and electronics could be disassembled and re-assembled elsewhere to take advantage of emerging opportunities.

Conclusion

- ANNIE is an active water-Cherenkov experiment on a neutrino beam at a world-class facility.
- We are currently actively developing many of the technologies required for a future large scale water-based neutrino experiment.
- Everything in ANNIE; software, hardware, reconstruction techniques, etc, are built with scaling in mind.
- ANNIE is an accessible and extensible testbed for the development of future technologies and techniques in the context of a rich neutrino physics experiment.