# ANNIE Phase II Physics Proposal

Matt Wetstein (ISU) on behalf of the ANNIE collaboration

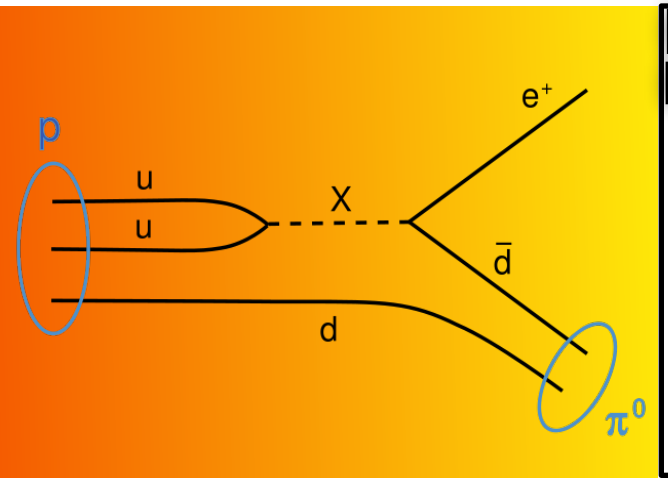
July, 2017

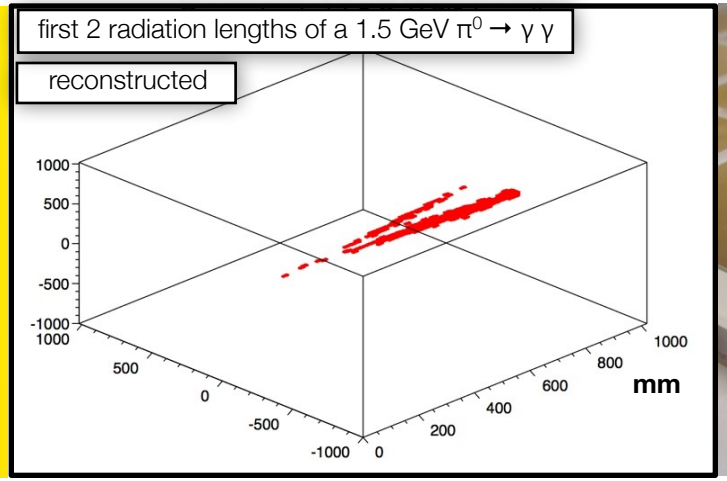


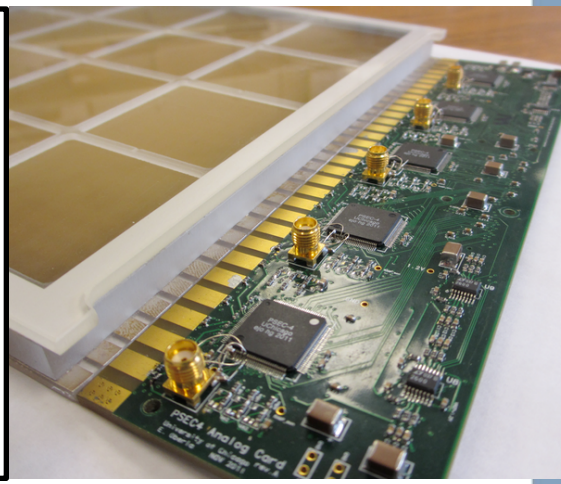
# The Accelerator Neutrino Neutron Interaction Experiment

- A measurement of the abundance of final state neutrons from neutrino interactions in water, as a function of energy
- A new technological path for the long-term Fermilab program
- A community that broadens the Fermilab user base

*for understanding neutrino-nucleus interactions and addressing a limiting factor in oscillation physics, proton decay, and supernova neutrino physics*

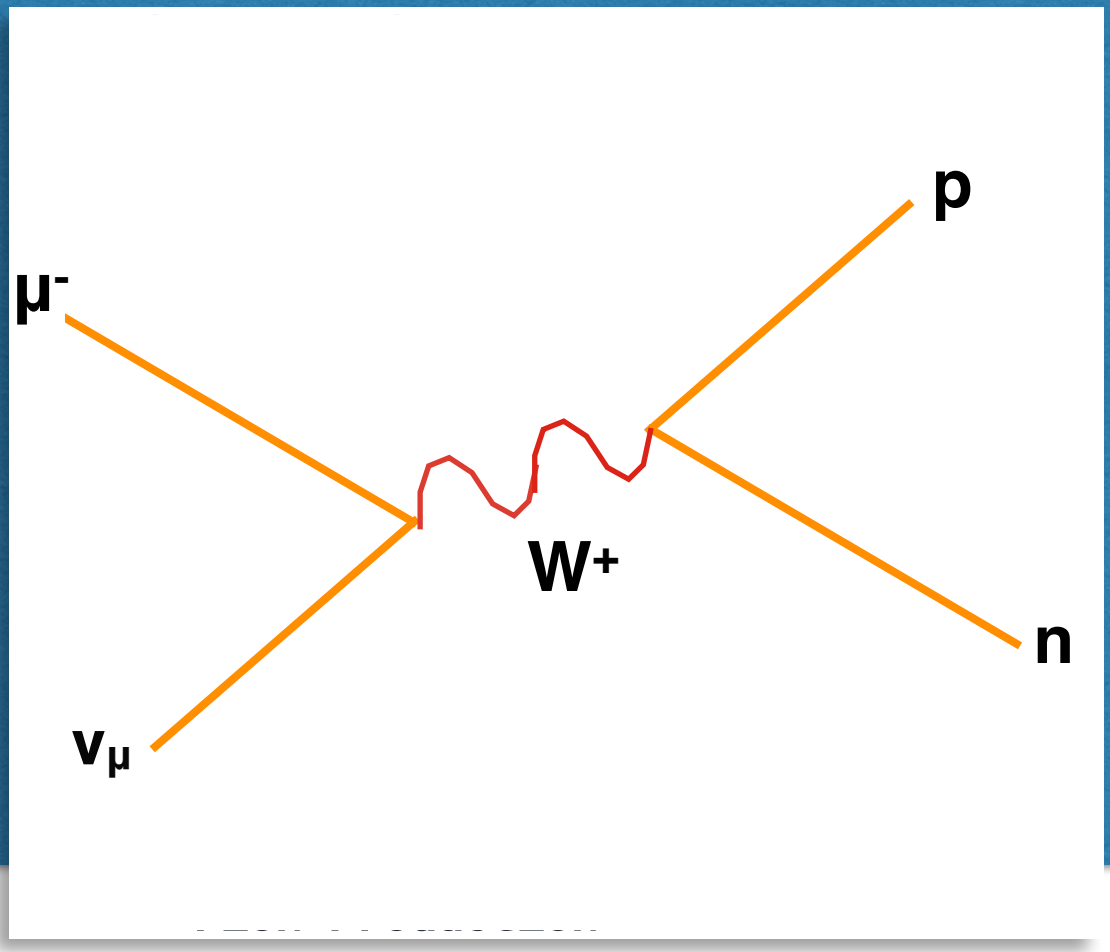


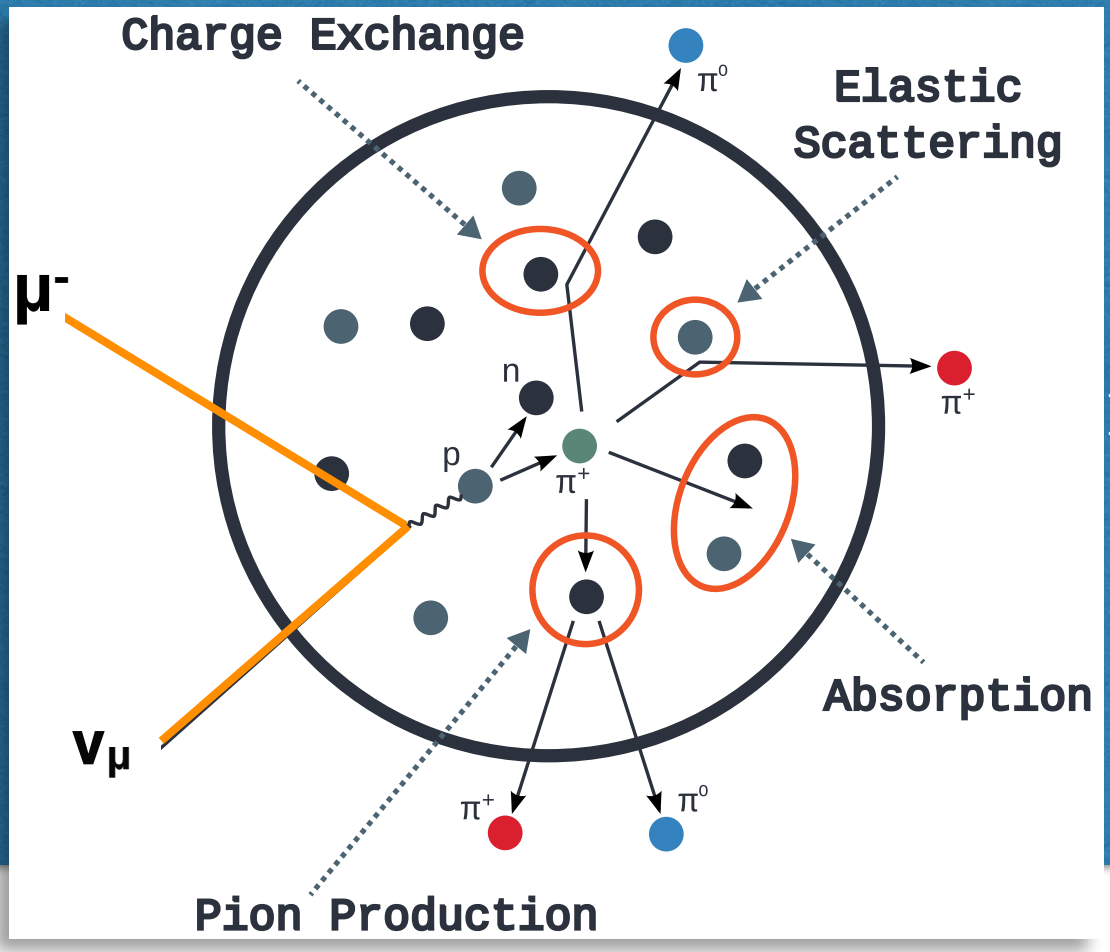
- 6 US institutions, 3 UK institutions, 2 national labs, and 31 collaborators

# Neutrino-Nucleus Interactions Are Complicated




A simple picture of a charged-current quasi-elastic (CCQE) interaction

# Neutrino-Nucleus Interactions Are Complicated

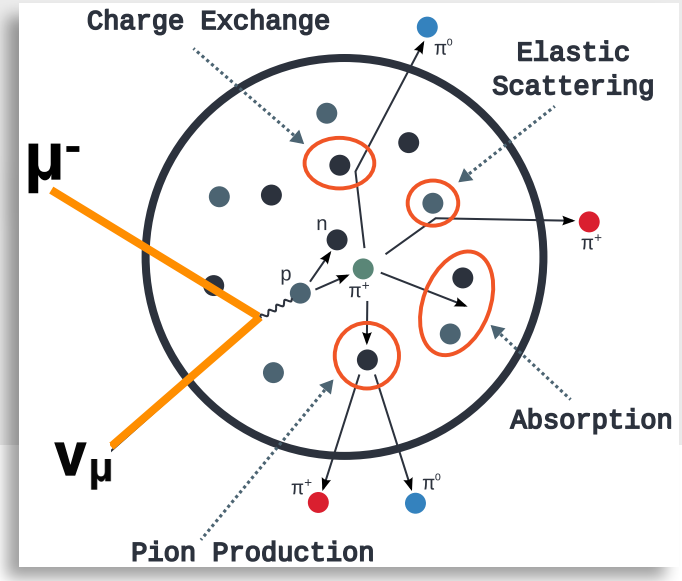



Real nuclear scattering is a many-body problem

# ANNIE Physics

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/$E_\nu$




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

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

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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

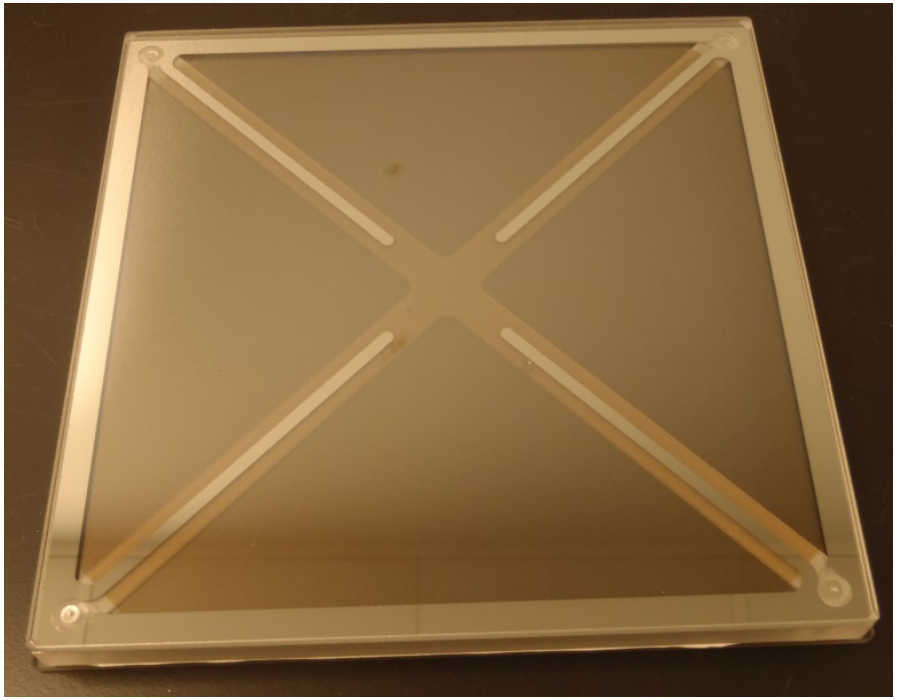
ANNIE is a final-state X + Nn program to complement X + Np measurements in LAr

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

# ANNIE Detector R&D

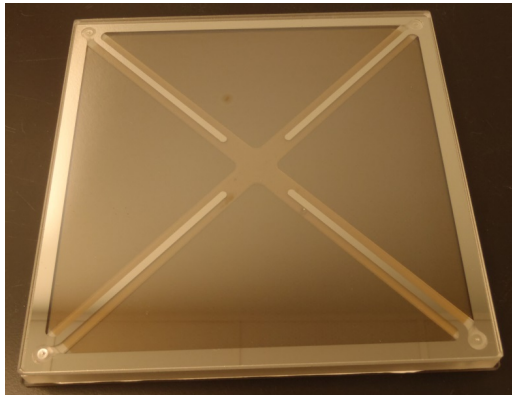
- A first application of Large Area Picosecond Photodetectors (LAPPDs) in a neutrino experiment
- Demonstrate operation of multiple LAPPDs, integrated with a larger hybrid detector system

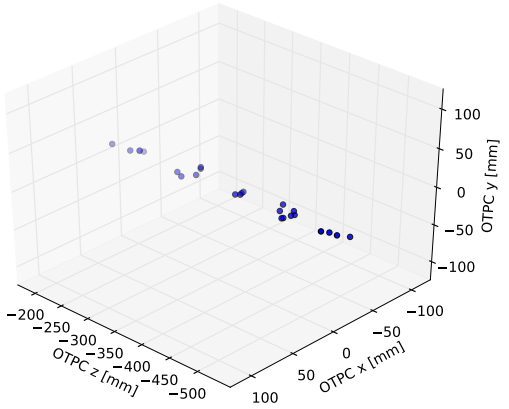
- LAPPDs are 8” x 8” MCP-based imaging photodetectors, with target specifications of:
  - ~50 picosecond single-PE time resolution
  - < 1 cm spatial resolution
  - > 20% QE
  - > $10^6$ gain
  - low dark noise (<100 Hz/ch)



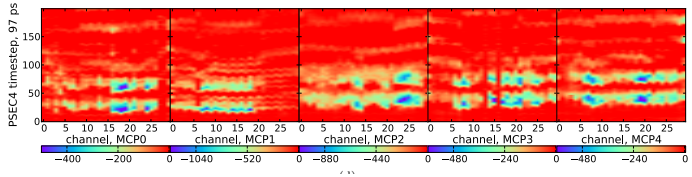
# ANNIE Detector R&D

- 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
- Use LAPPDs to meet physics specifications that cannot be met with the conventional PMT system
- Develop new and advance timing-based reconstruction techniques, pave the way for advanced water-base neutrino detection in the future
- First Gd-loaded detector on a neutrino beam
- Possible addition of water-based liquid scintillator beyond Phase II

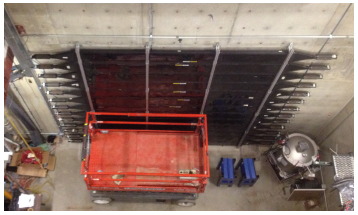


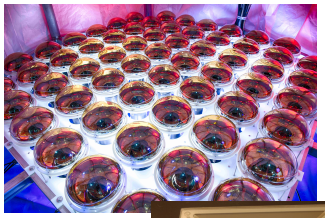


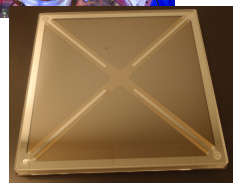

optical time-projection chamber
E Oberla/ H Frisch (UC)

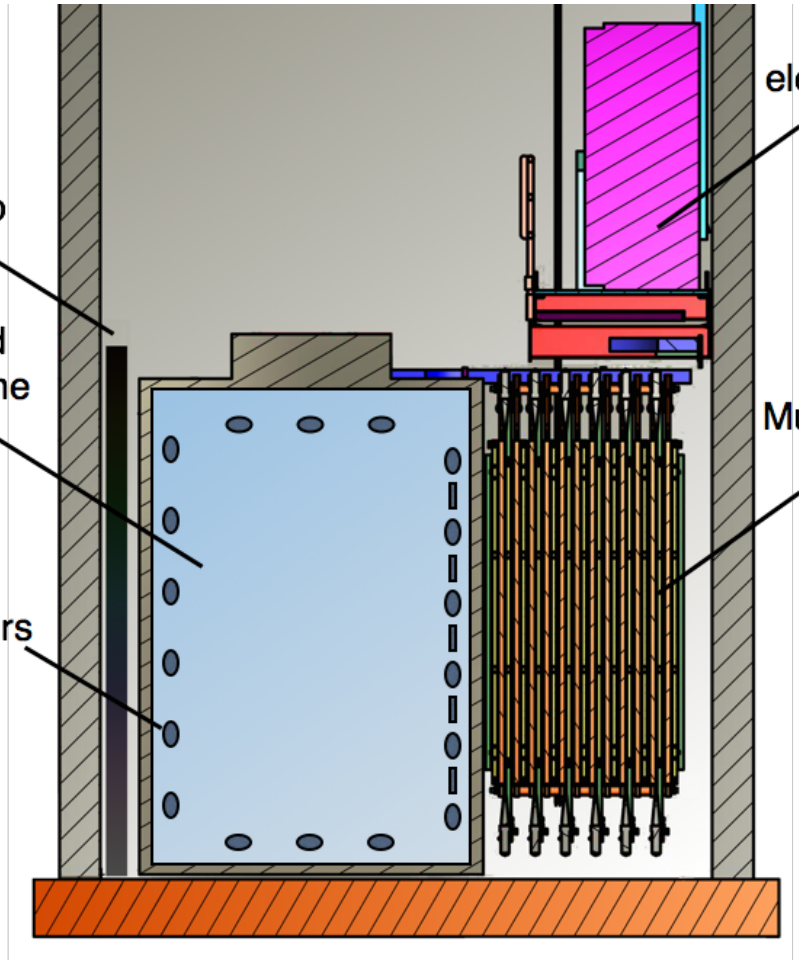


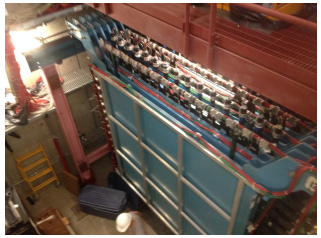
# ANNIE Experimental Design









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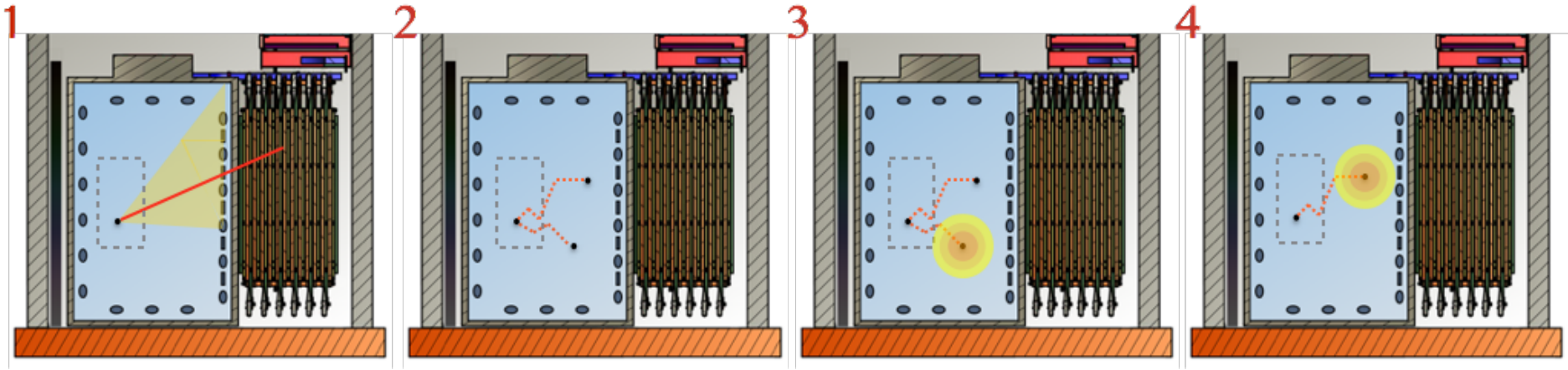
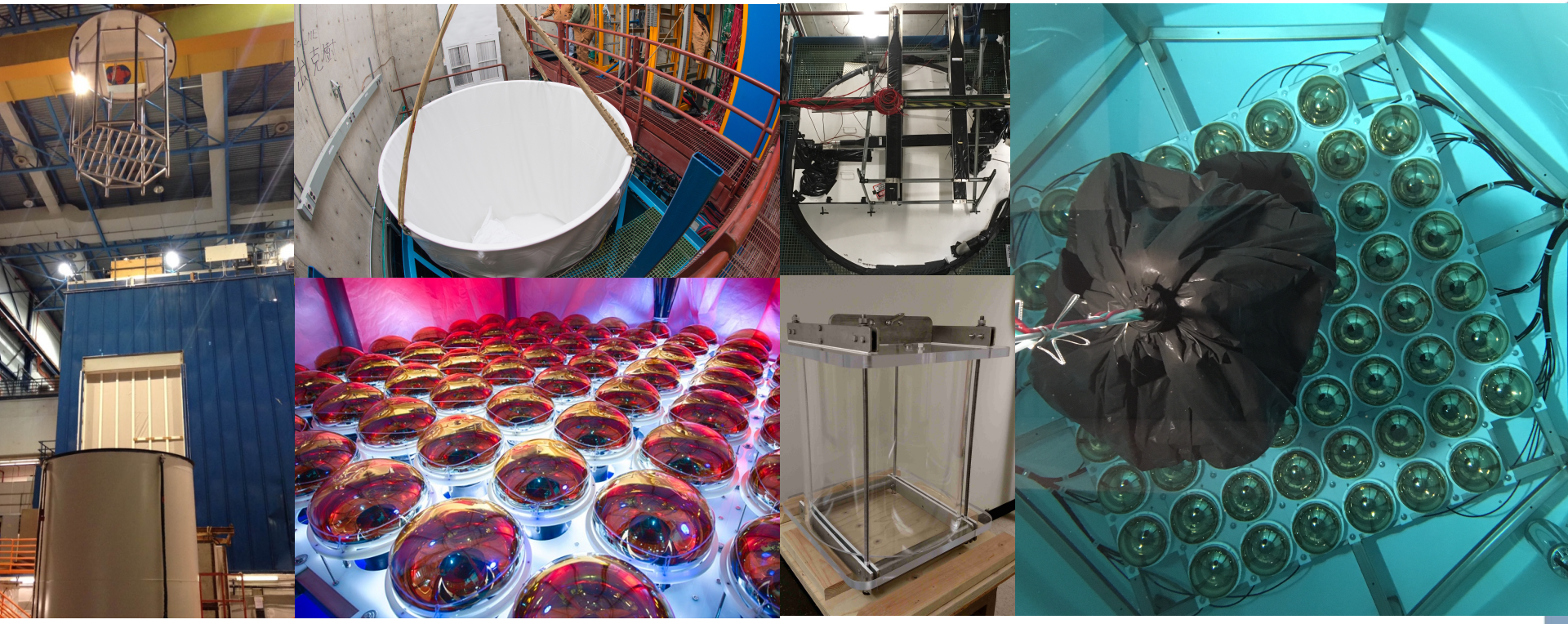



1. CC interaction in the fiducial volume produces a muon, reconstructed in the water volume and MRD
2. Neutrons scatter and thermalize
3. - 4. Thermalized neutrons are captured on the Gd producing flashes of light

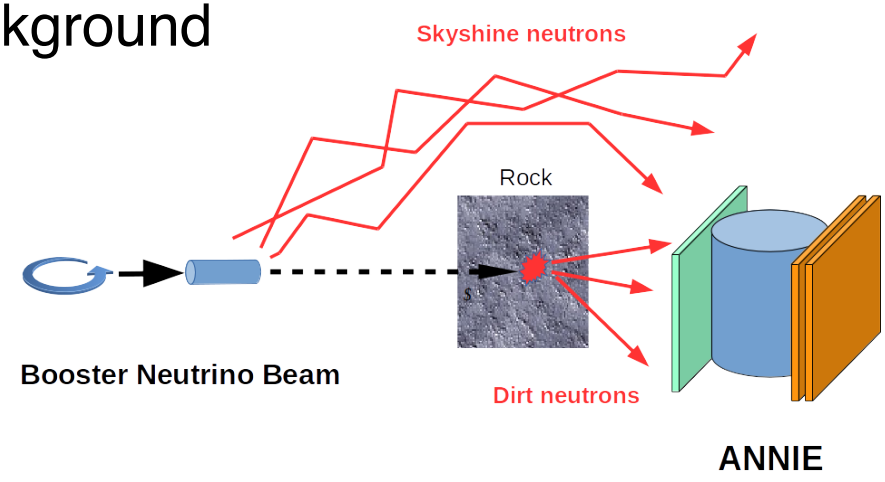
# ANNIE Phase I: built, commissioned, completed

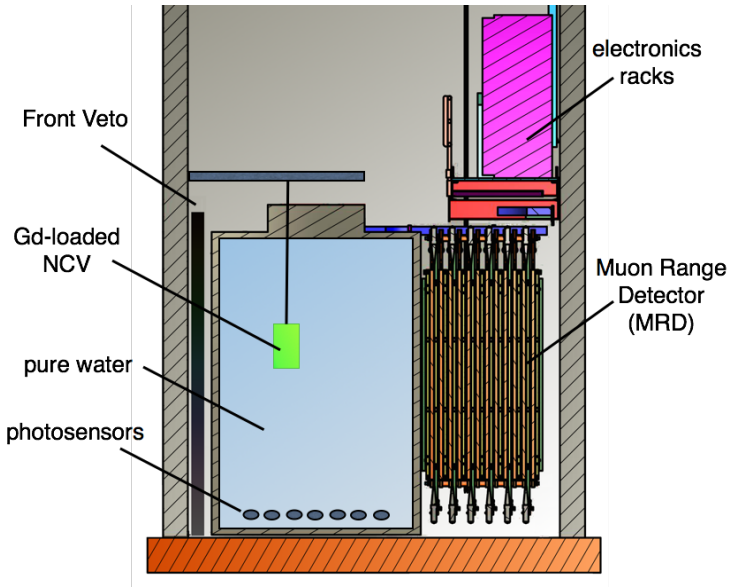
- ANNIE Phase I received PAC approval in February 2015
- The detector was built by April of 2016
    - taking data by May of 2016
    - finished data taking July 2017



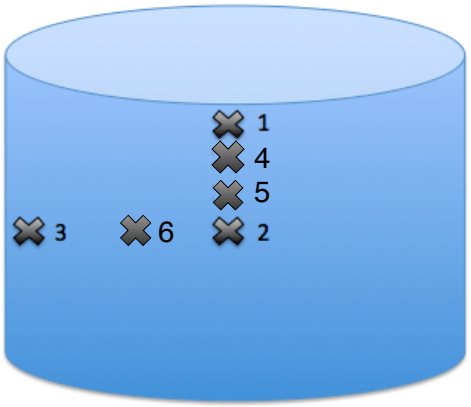
# ANNIE Phase I: built, commissioned, completed

- 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



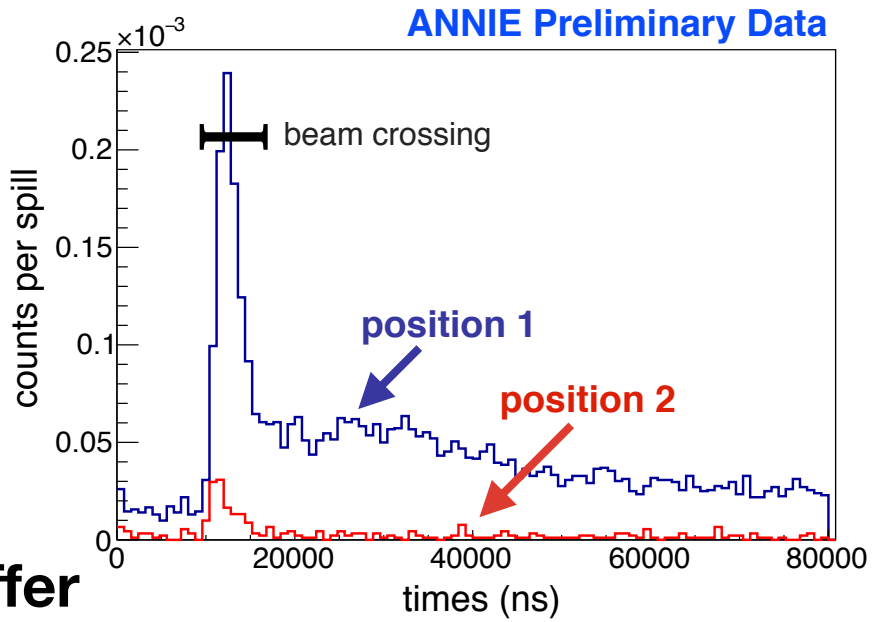



# Phase I: background measurement



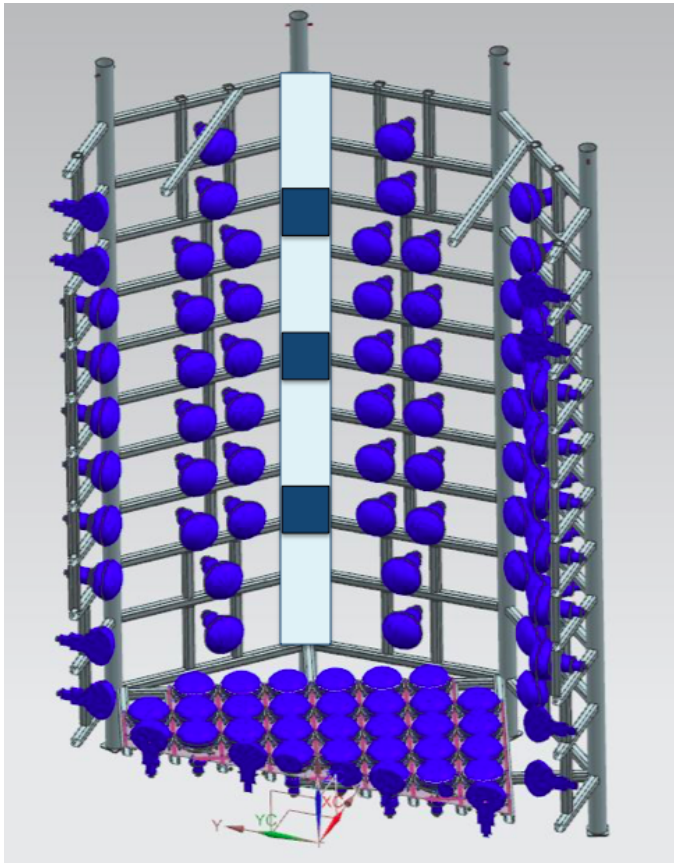

- the NCV was moved to 6 positions, scanning the neutron rates as a function of depth and distance from the beam
- strong suppression of skyshine neutrons was observed with increasing depth

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




**backgrounds are acceptable and can be mitigated with <2 ft of buffer**

# 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

# From Phase I to Phase II

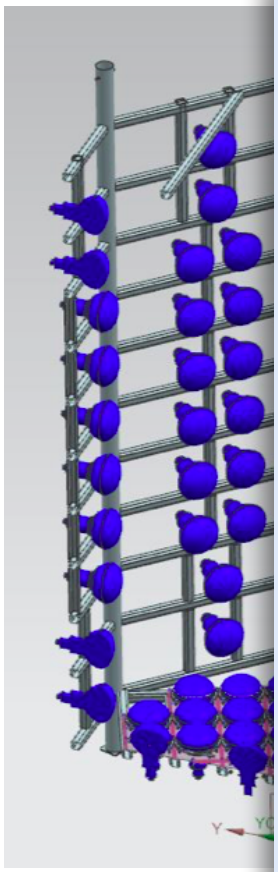


Table 1: Essential differences between ANNIE Phase I and Phase I

| detector component | Phase I | Phase II |
|---|---|---|
| MRD | 2 layers | fully active |
| Gd in water | No | Yes |
| NCV | Yes | No |
| Front Veto | fully active | fully active |
| Conventional PMTs | 60 | 127 |
| LAPPDs | 0 | 5-20 |
| ADC readout cards | 16 | 30 - 50 |
| PSEC readout cards | 0 | 10-40 |
| CAMAC TDC cards | 3 | 12 |
| CAMAC discriminator cards | 3 | 12 |
| Positive-HV channels | 60 | 127 |
| Negative-HV channels | 71 | 361 |
| Inner structure | 60% | 100% |
| Tank and lid | 80% | 100% |
| Platform | 100% | 100% |

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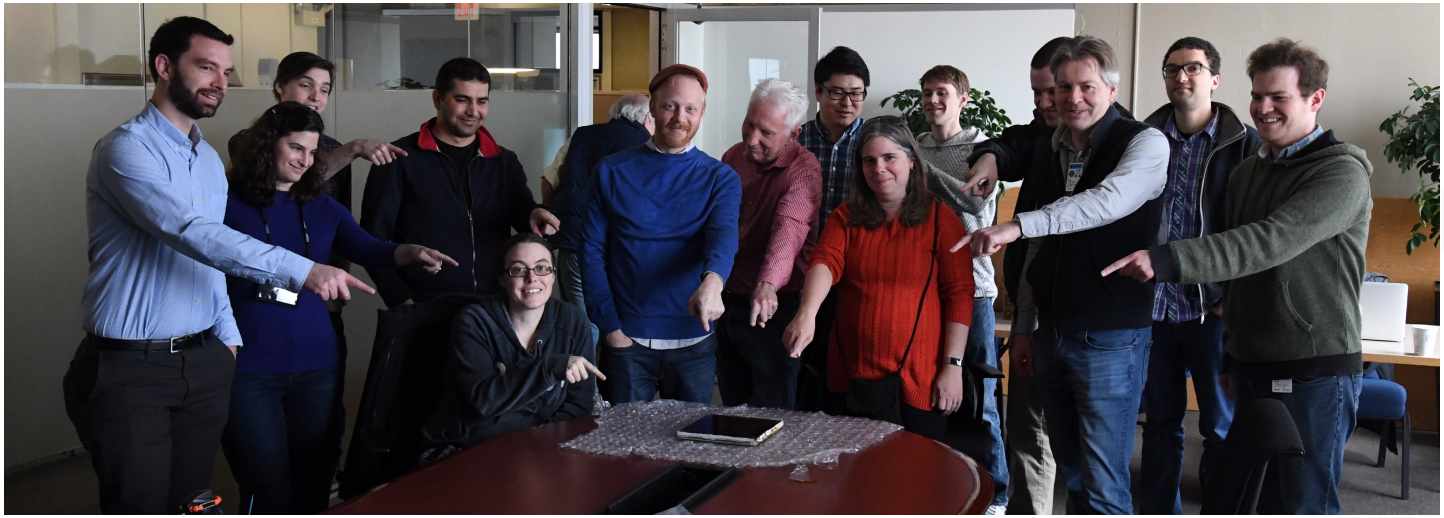
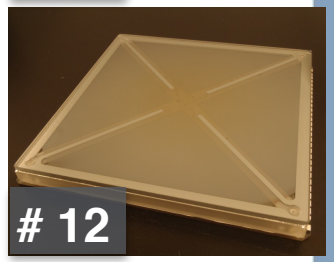
# LAPPDs Are Ready







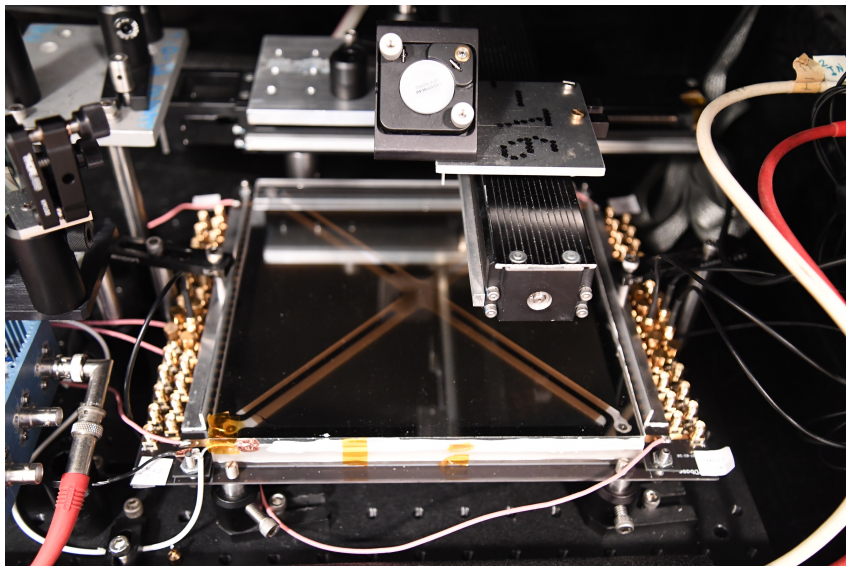


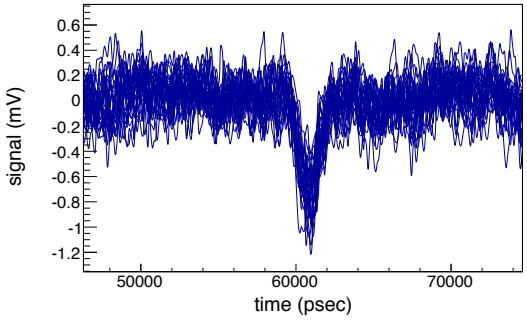
Incom has now produced multiple LAPPD prototypes, quickly approaching the specifications needed by ANNIE

- 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 LAPPD Test Facility is Ready

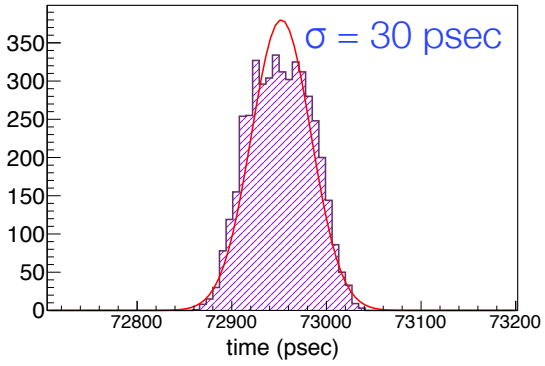
- A test facility was constructed at ISU for testing Incom LAPPDs using a pulsed laser and fast electronics
  - LAPPD-9 and LAPPD-12 have already been sent to ISU for testing
- The system is also being used for testing and development of the ANNIE PSEC electronics
- Vertical integration tests are planned for early fall






single PE pulses (LAPPD-10)

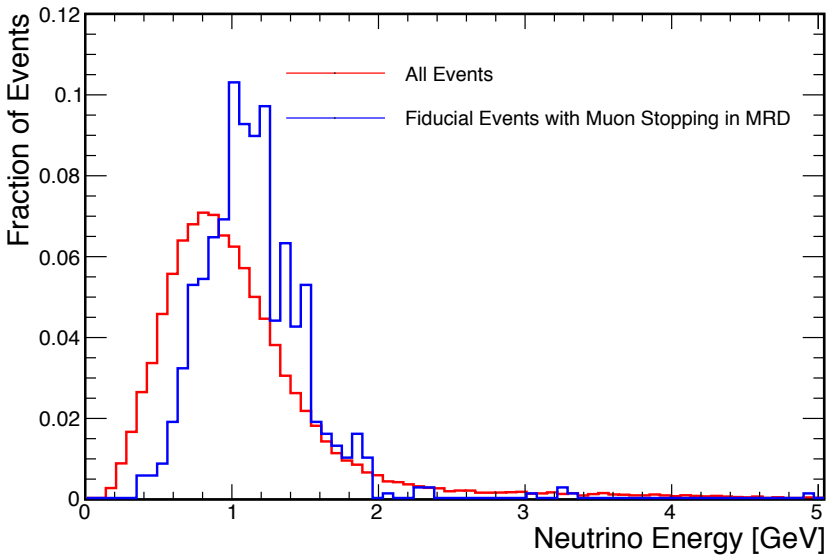

multi-PE pulses
(LAPPD-12 on PSEC electronics)

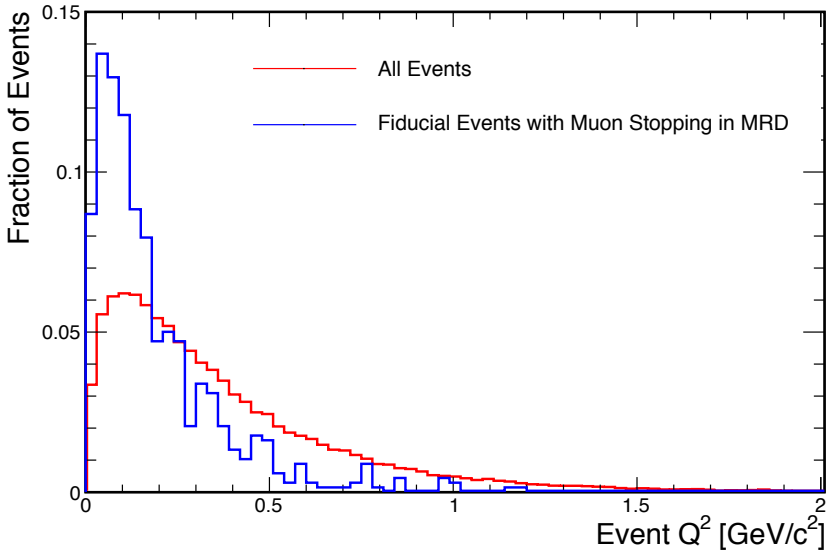



multi-PE time resolution (LAPPD-12)

# Phase II Simulations and Design Specs

**Geometric acceptance cuts select a representative sample of BNB neutrinos**

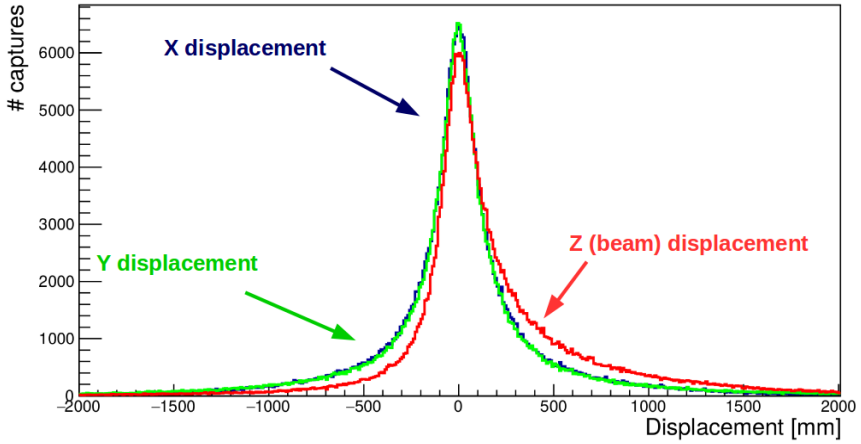


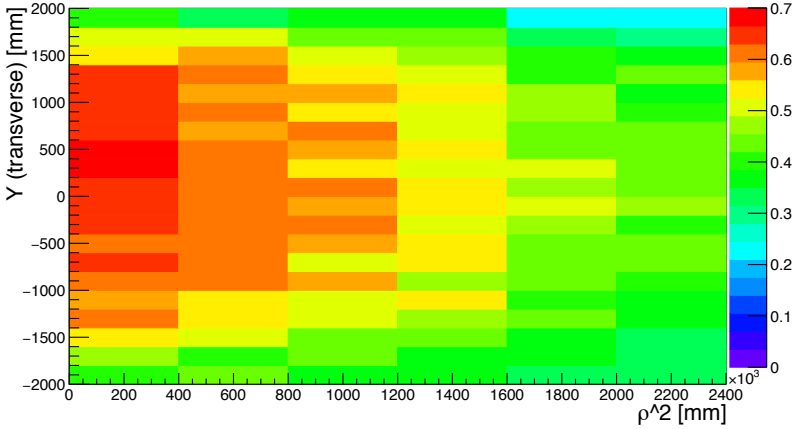



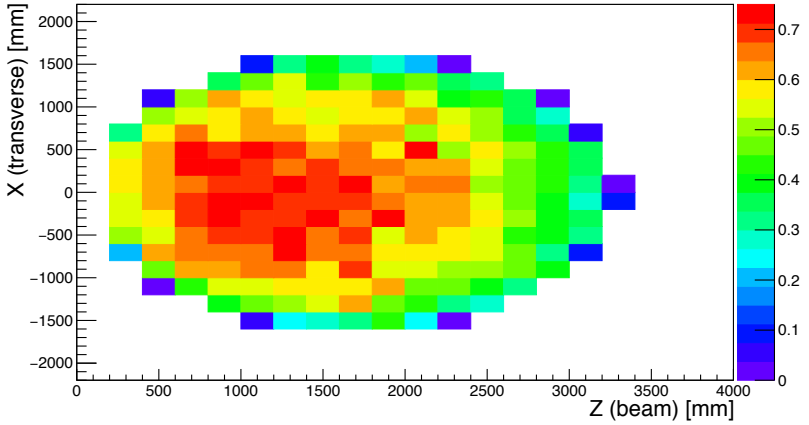

It is important to measure neutron multiplicity as a function of these parameters and therefore we want a wide spread in neutrino energy and $Q^2$

# Phase II Simulations and Design Specs

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

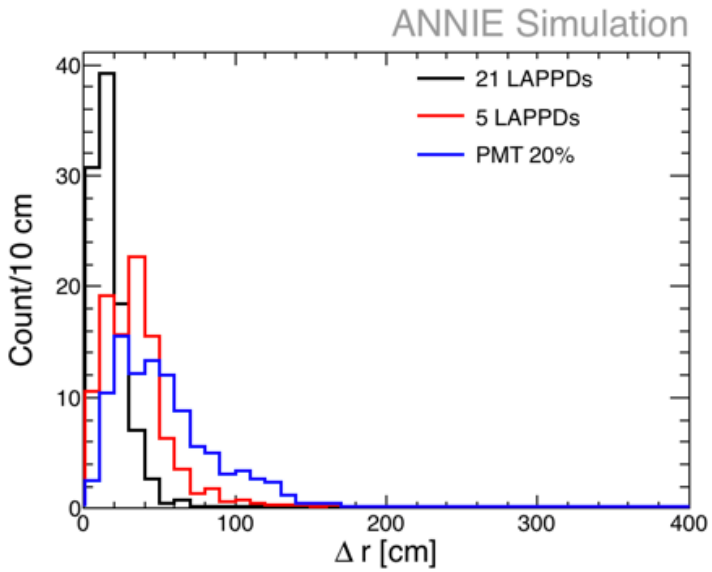


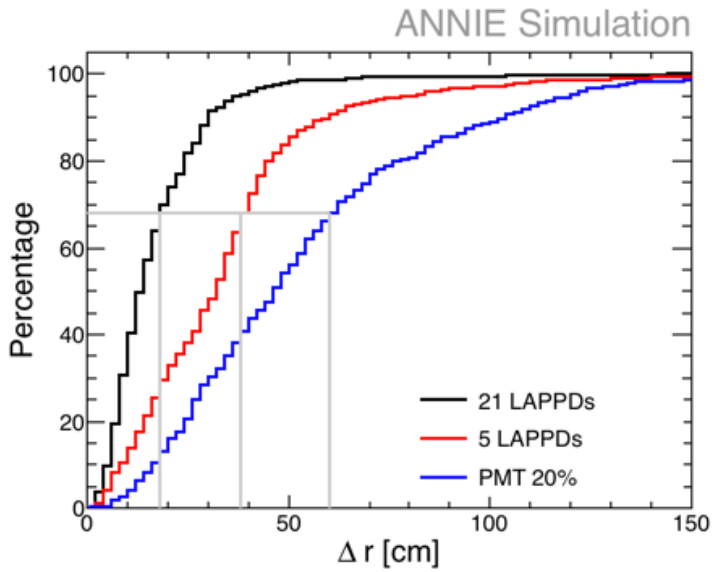



# Phase II Simulations and Design Specs

## LAPPDs provide needed vertex resolution to select fiducial events



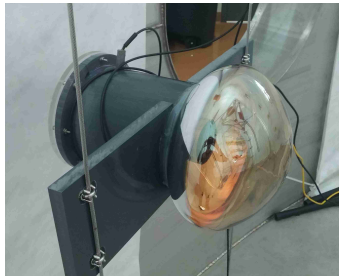




| | |
|---|---|
| 20% conventional PMTs: | 60 cm resolution |
| 5 LAPPDs (only): | 38 cm resolution |
| 21 LAPPDs (only): | 16 cm resolution |

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

# Progress Towards Phase II

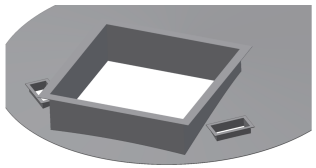
19 LUX PMTs



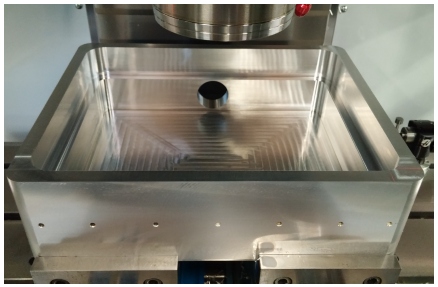
45 WATCHMAN PMTs

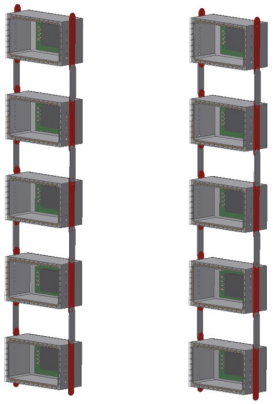
22 LBNE PMTs

LAPPD deployment



LAPPD housing





- We have identified several stocks of free large area PMTs, significantly reducing the number of new tubes we need to purchase
- 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 and pre-built functionality meets most of our needs. Integration work is in progress at ISU and UC

# Phase II: growing the collaboration

Two new institutions have joined the ANNIE collaboration:

Edinburgh University (UK), Lawrence Livermore National Lab (US)

Five new German institutions are submitting a proposal to join ANNIE:

Mainz, Hamburg, Tübingen, TU Dresden, TU Munich

**"To support this effort, we intend to submit a proposal with the German Bundesministerium für Bildung und Forschung (BMBF) in order to secure funding for a significant fraction of the required photosensors and to contribute to the initial installation and commissioning of the detector at Fermilab starting from 2018."**

(see ANNIE letters of support)

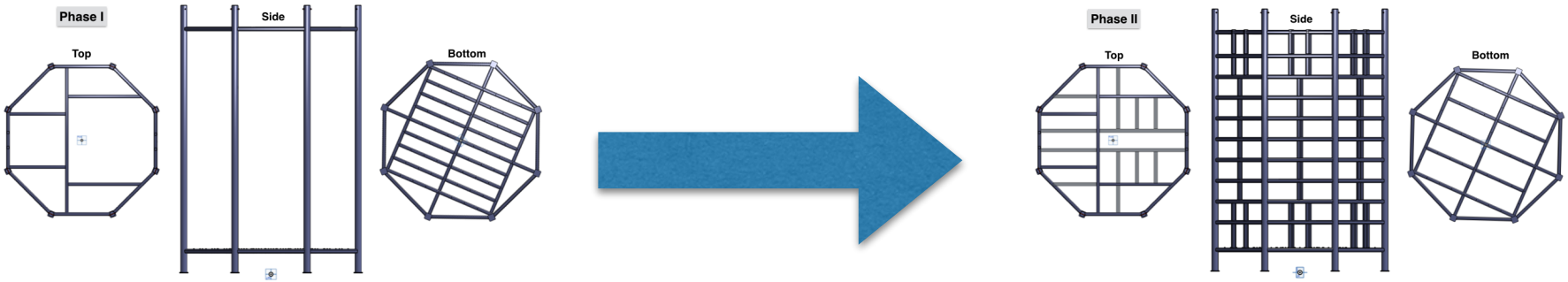
# Phase II: resources requested from DOE

- For Phase II, we will request funding for:
  - 35 10” HQE photomultiplier tubes
  - 5 LAPPDs (and readout boards)
  - additional electronics channels for the expanded PMT coverage

- ANNIE has already received $150k from the DOE through the Intermediate Neutrino program. This is being used to:
  - purchase replacements for borrowed electronics
  - demonstrate LAPPD readiness for Phase II
  - purchase of 1 LAPPD

# Phase II: resources requested from Fermilab

- Modifications to the inner structure of the tank to accommodate more PMTs
- Modifications to the tank lid: new openings and feedthroughs + rustproofing
- Engineering design consultation to interface the different PMT types with the inner structure design.
- Operational support at the level of current Phase I operations.

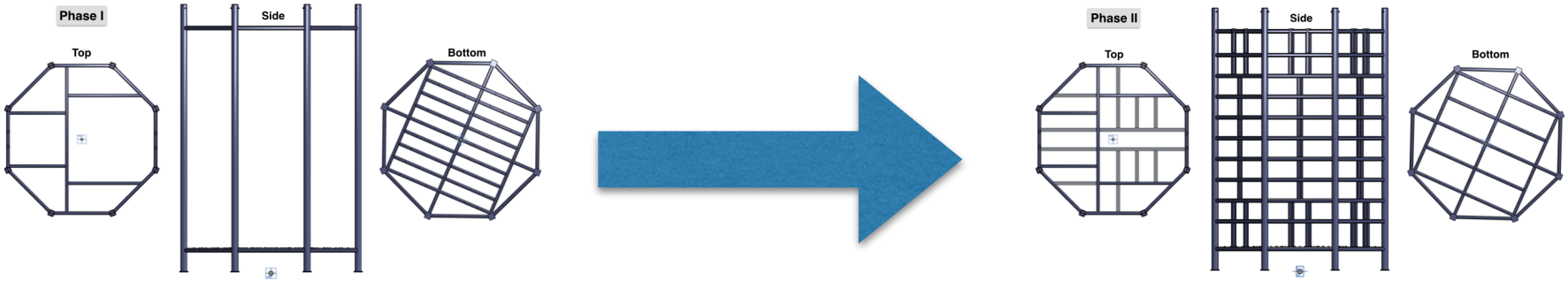


# Phase II: resources requested from Fermilab

- Modifications to the inner structure of the tank to accommodate more PMTs
- M… …ghs + …
- E… P…
- O… …ons.

**Estimated Fermilab effort is**

- based on direct experience from Phase I
- a fraction of the modest labor needed for Phase I



# ANNIE Timeline

**Summer 2017**

Removal of the tank from the Hall

Finish MRD refurbishment

**Fall/Winter 2017**

Completion of Phase II inner structure and tank lid

**Spring 2018**

PMT refurbishment and acquisition

Electronics acquisitions

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**

# Conclusion

- ANNIE brings exciting and varied physics and tech R&D to the lab at little cost
- LAPPDs exist and are on track to meet ANNIE specs
- Phase I: We built it and backgrounds are acceptable
- Our work on simulations and reconstruction show that we can execute the Phase II measurement
- Resources requested from Fermilab for the completion of Phase II are modest compared to Phase I

# Requested PAC/Fermilab Support

- Strong endorsement of the ANNIE physics and technology missions
- Commitment to support the completion and operations of Phase II, pending DOE support
- Permission to continue using the SciBooNE Hall

Many thanks to the PAC, Fermilab, and the DOE for their support in the successful completion of Phase I!