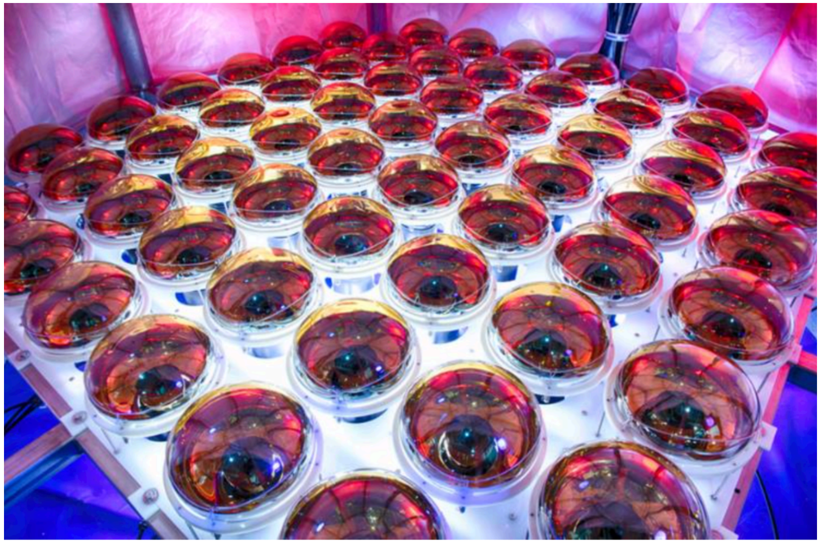
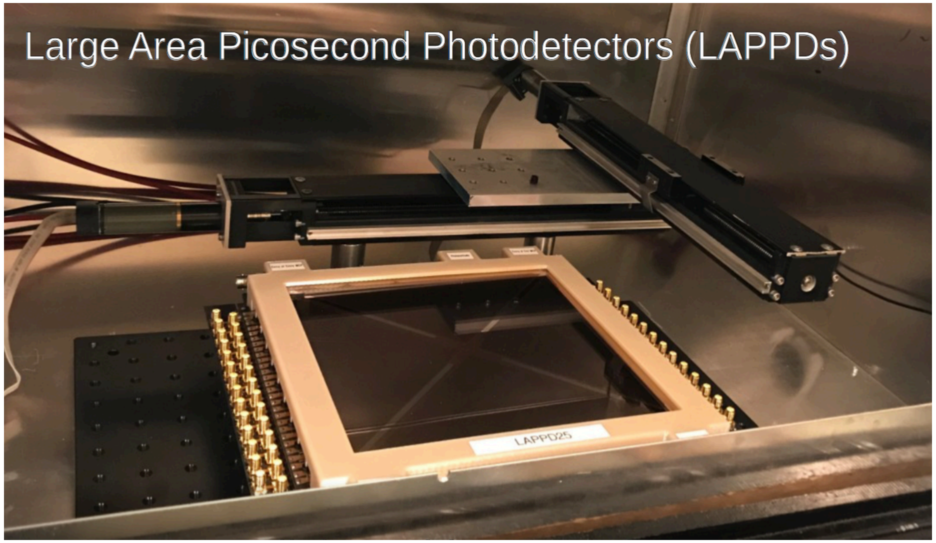
ANNIE Phase II Reconstruction and LAPPDs





Evangelia Drakopoulou for the ANNIE Collaboration

NEPTUNE 2018 - 18-21 July, Naples, Italy

Outline

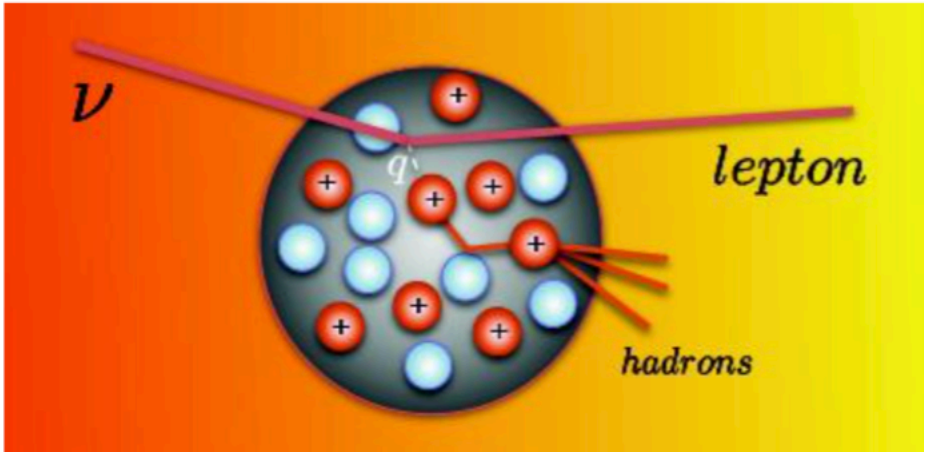
- Physics and Technological Goals
- The ANNIE Experiment
- ANNIE Phase I
- ANNIE Phase II

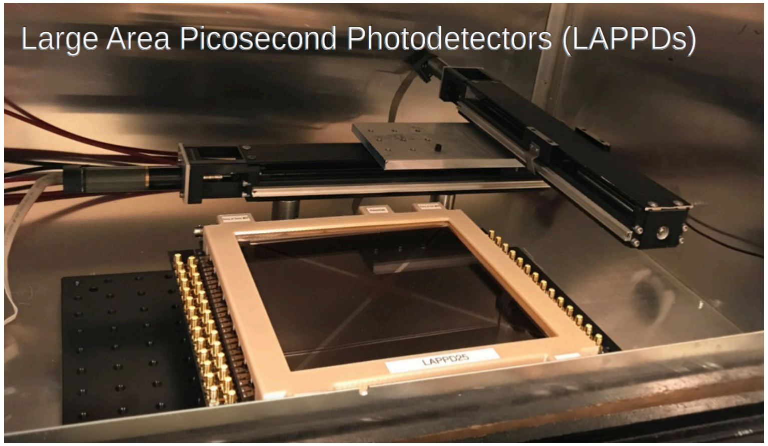
Physics and Technological Goals

Physics & Technological Goals

Two main goals:

- Measure the final state **neutron multiplicity** from Charged Current neutrino-nucleus interactions in water
  - → Reduce systematic uncertainties on neutrino energy reconstruction in oscillation searches
  - → Constrain backgrounds in proton decay searches
- Demonstrate the use of fast-timing Large Area Picosecond PhotoDetectors (**LAPPDs**) for event reconstruction





[arXiv:1603.01843 [physics.ins-det]]

Physics Goals (2)

- **Neutrino/Antineutrino separation:**

As neutrino-antineutrino event-rate comparisons are important for δ_{CP} measurements, the relative neutron composition of final hadronic states is significant.

NuSTEC white paper

- **Signal/Background separation:**

Multiplicity and absence of neutrons is also a strong handle for signal-background separation in a number of physics analyses!

ANNIE Letter of Intent
arXiv:1707.08222 [physics.ins-det]

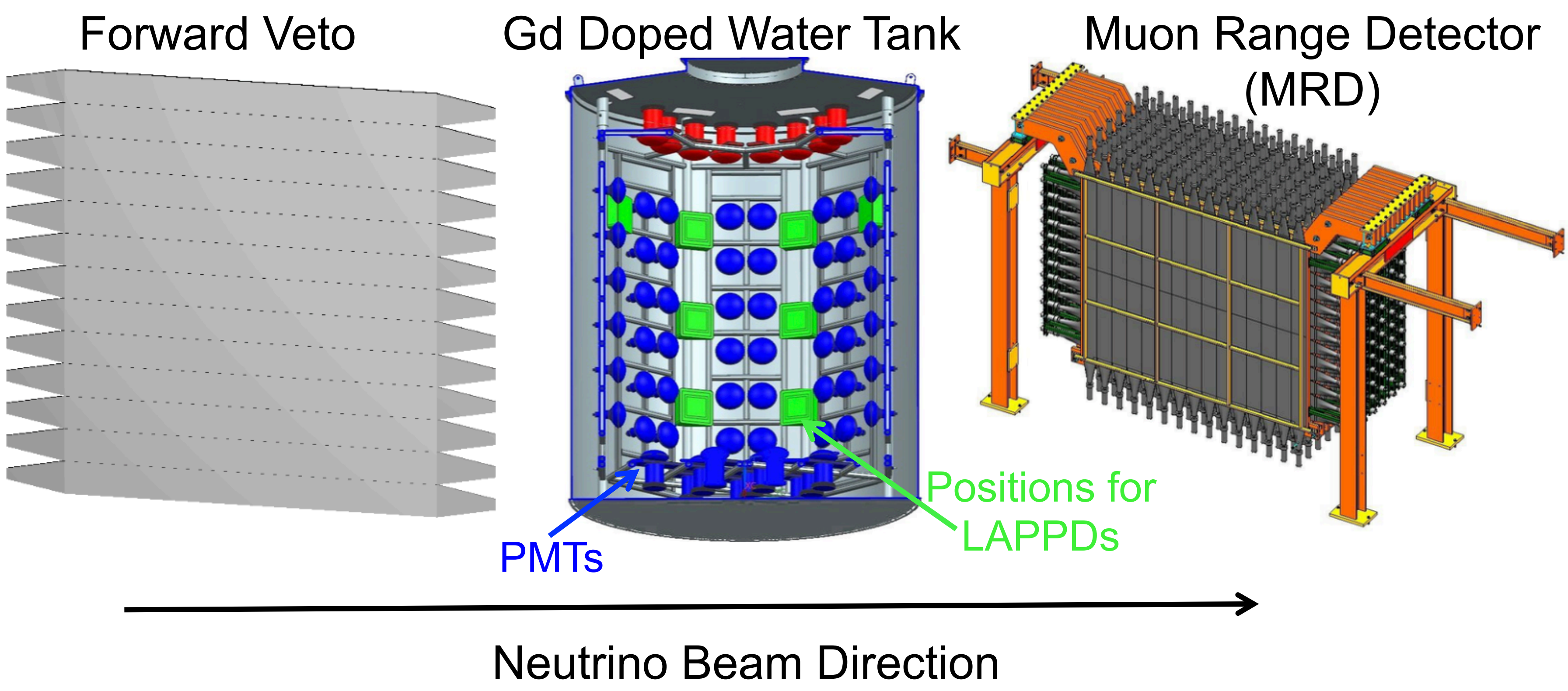
Atmospheric neutrino interactions in water may produce final state neutrons!

The knowledge of neutron yield will reduce background for:
Proton Decay searches, Diffuse Supernova Background (DSNB)

The ANNIE Experiment

The ANNIE Detector

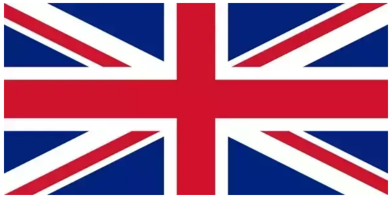
- **A**ccelerator **N**eutrino **N**eutron **I**nteraction **E**xperiment (**ANNIE**): a 26-ton Gd-doped water Cherenkov detector installed in the Booster Neutrino Beam at Fermilab (flux peaks at 600 MeV).



The ANNIE Collaboration

13 Universities/Laboratories from USA, UK & Germany:

- Fermi National Accelerator Laboratory
- University of California, Berkeley
- University of California, Davis
- University of California, Irvine
- University of Chicago
- University of Edinburgh
- Iowa State University
- Lawrence Livermore National Laboratory
- Ohio State University
- Queen Mary University
- University of Sheffield
- University of Hamburg
- Johannes Gutenberg University Mainz


Status of the Experiment

2016

ANNIE – Phase I

Completed

- Neutron background measurements in the detector site in Fermilab.
- Successful operation phase of the detector.

2018

ANNIE – Phase II

- Measure the neutron yield from CCQE events in water
- First deployment and use of LAPPDs

Status:
- Detector Upgrade and Commissioning ← **NOW**
- Physics Data Taking ← **late 2018**

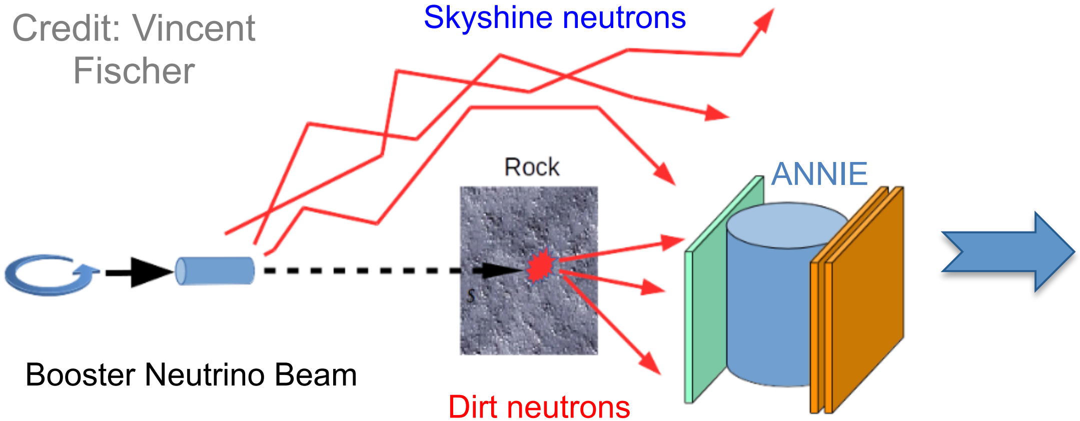
ANNIE Phase I

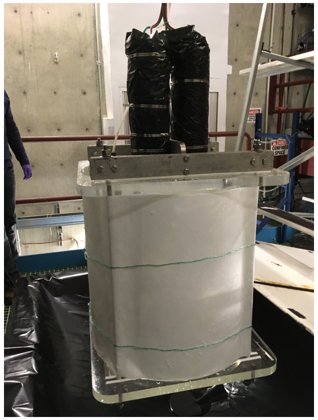
ANNIE Phase I

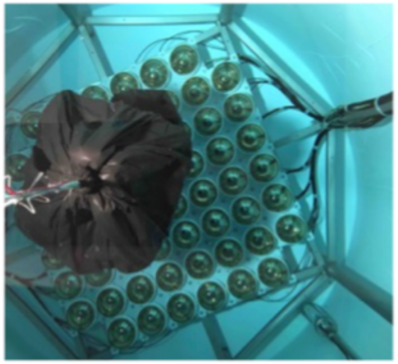
Completed

- In ANNIE Phase I we measured the neutron background in the ANNIE hall.
- Neutron Backgrounds are: dirt neutrons, skyshine neutrons
  → simulations are very complicated → measurements are needed.

Credit: Vincent Fischer





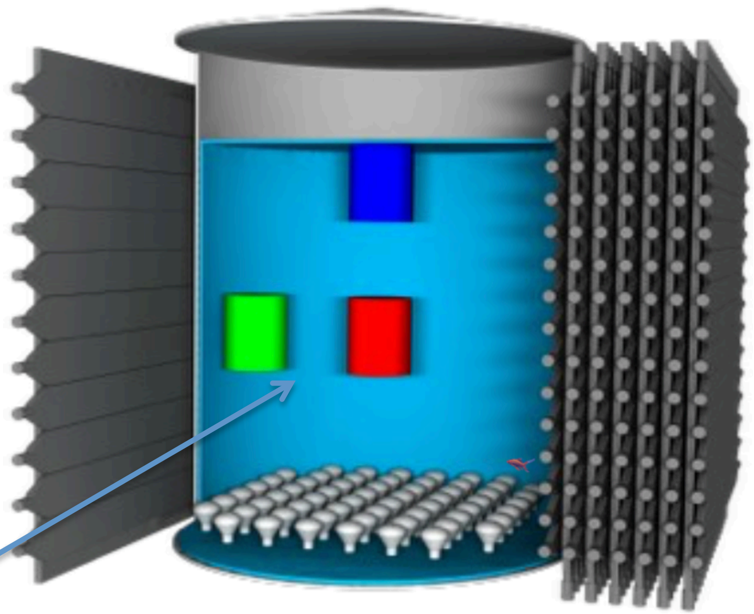


- For the neutron background measurements we used two PMTs in a sub-volume of liquid scintillator doped with 0.25% Gd.
- This volume was optically isolated from the tank.
- ANNIE Phase I was partially instrumented with 60 PMTs on the bottom to veto muons by Cherenkov light.

ANNIE Phase I

Completed

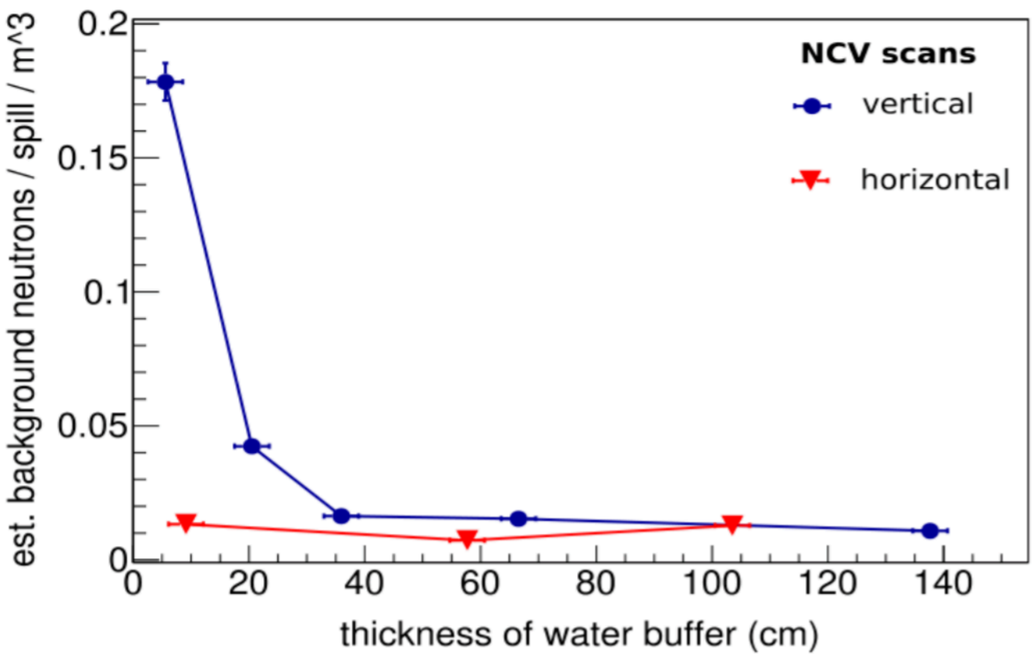
- The detector neutron response was calibrated using ^{252}Cf source.
- The Gd-doped sub-volume was moved to several positions.
- Positional scan was performed to measure the drop-off of neutron background flux with overburden and distance from the beam-side wall.



different sub-volume positions

Completed

Neutron capture rate results



Blue curve: the drop-off of skyshine with increasing water overburden

Red curve: the drop-off of dirt events with increasing distance from the front wall

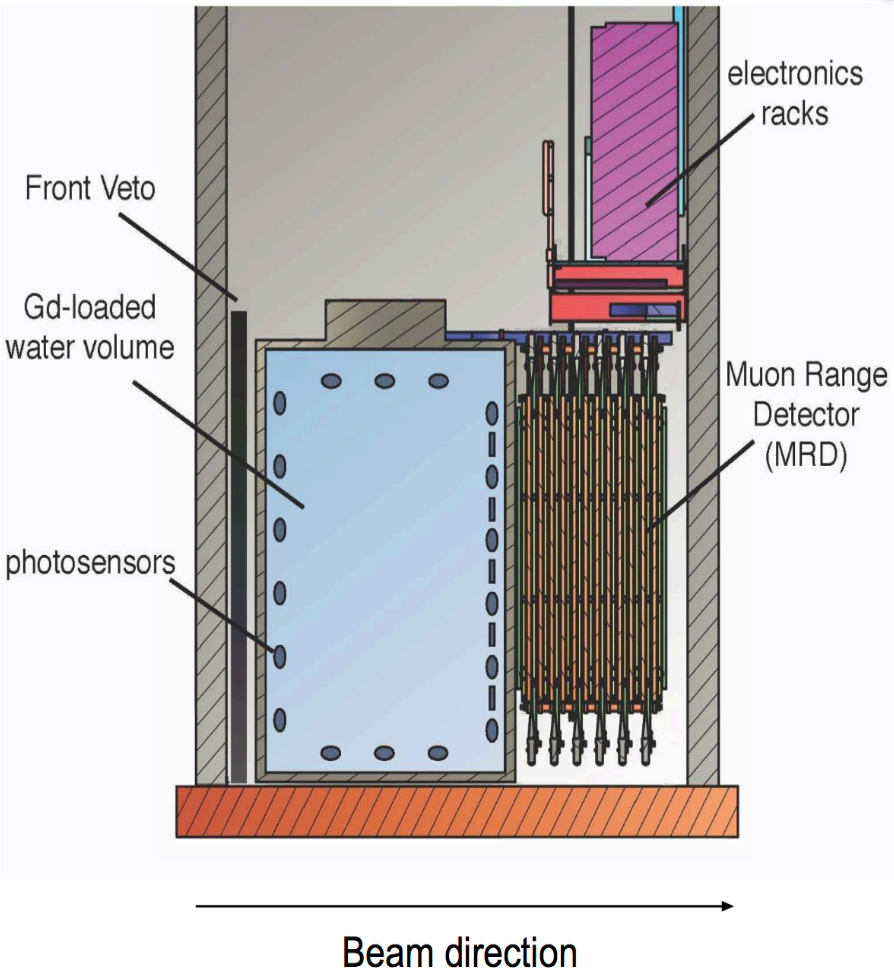
- Background neutron rates are less than 0.02 per spill per m^3 for water overburden more than 0.5 m.
- ANNIE Phase II will use the full 2.5 ton fiducial volume with good detection efficiency → sufficiently low neutron backgrounds for physics goals.

ANNIE Phase II

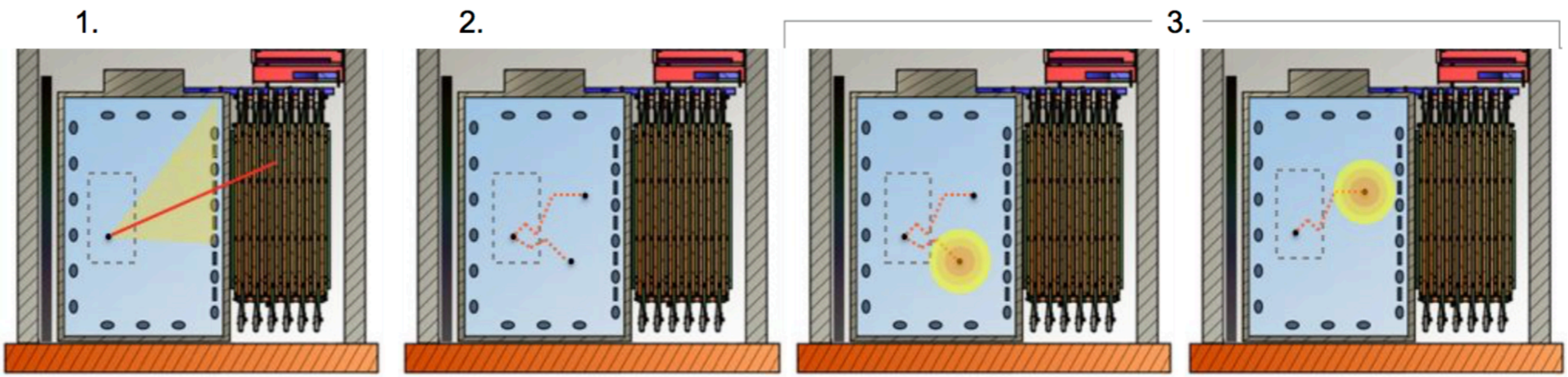
ANNIE Phase II

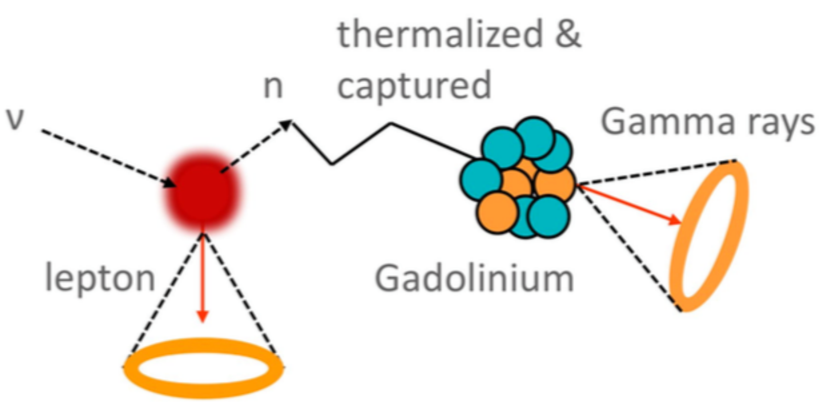
Commissioning in 2018

- 3 m x 4 m tank filled with Gd (0.2%) loaded water
- ~125 PMTs + 5 LAPPDs:
  → LAPPDs will be placed downstream
  → Flexibility to add additional LAPPDs
- Fully instrumented MRD
  → 11 layers and 310 channels
- Upgraded electronics and readout



Event Signatures in ANNIE





1. Charged Current neutrino interactions in fiducial volume
   → Cherenkov cone incident on PMTs and LAPPDs
   → Scintillation light from stopping muons in MRD
2. Final state neutrons thermalised and captured in Gd
3. Cascade of 8 MeV detected by PMTs

The Detector Upgrade

NOW

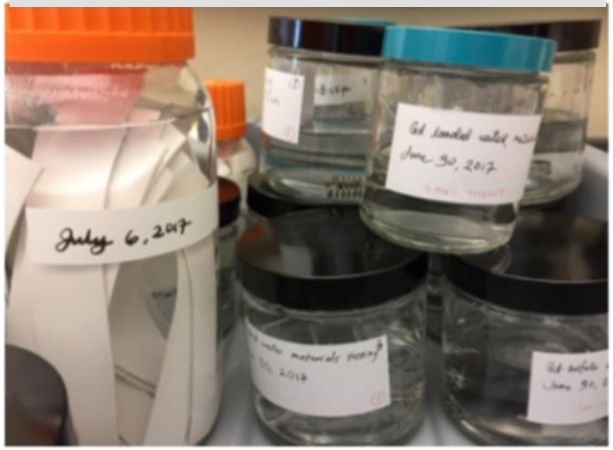
The detector is being upgraded for Phase II:

- Gd compatibility tests
- LAPPDs and electronics are being integrated and characterised
- The MRD is being refurbished

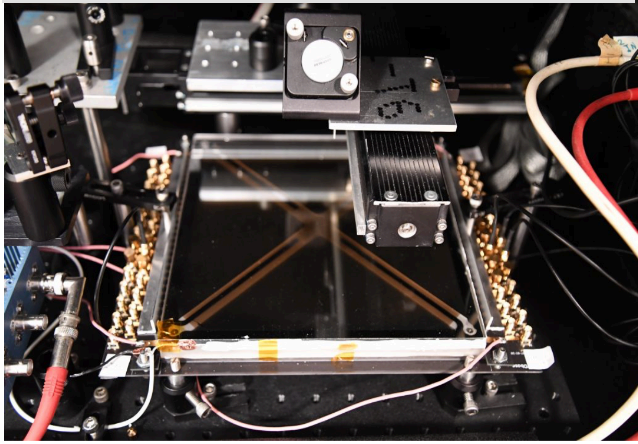
MRD-paddle efficiency test station

MRD refurbishment

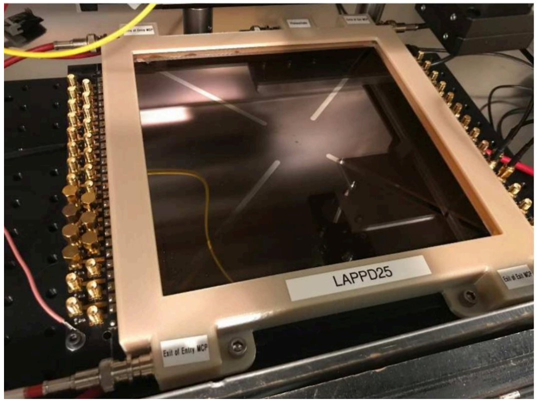
Gd compatibility tests



LAPPD lab tests

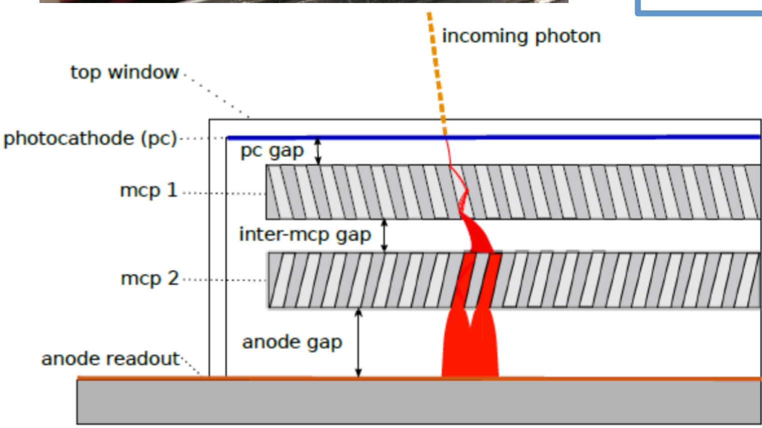


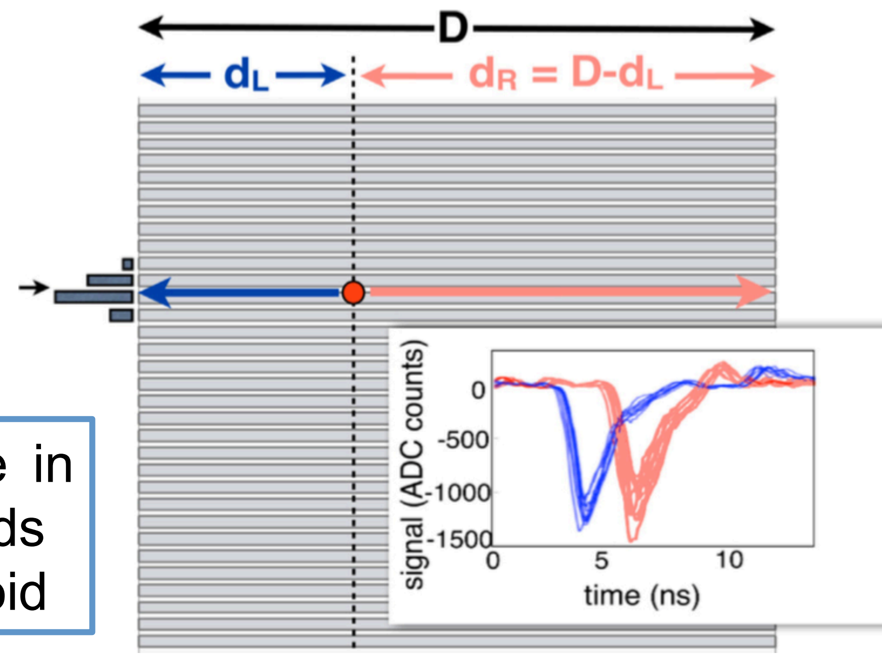
LAPPDs – A new technology tested in ANNIE



Micro-channel plate, fast-timing photodetectors

- Large-area: 20 × 20 cm
- Fast timing: <100 ps for a single photoelectron
- High quantum efficiency (QE): >20 %
- Position resolution: sub-mm
- Operable in a magnetic field



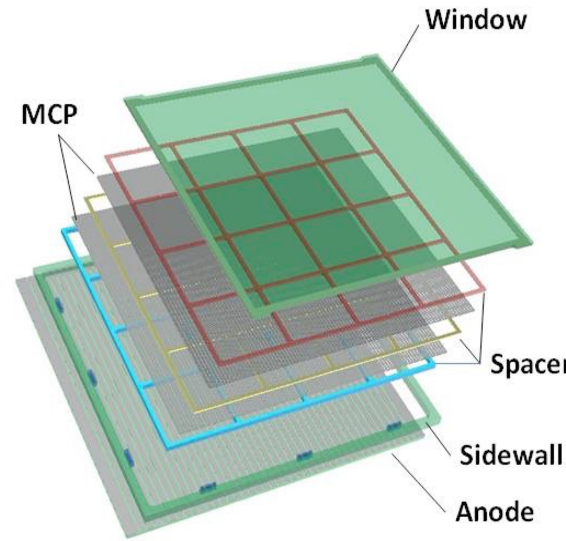


- Photoelectron position → difference in arrival time between the two strip ends
- Transverse position → charge centroid

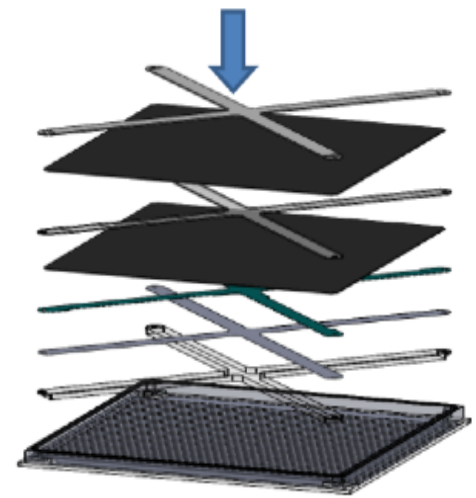
For more details see: *Nucl. Instr. and Meth. in Phys. Res. A 822 (2016) 25–33*

LAPPDs – A new technology tested in ANNIE

- Glass body, minimal feedthroughs
- MCPs made using atomic layer deposition
- Transmission line anode
- Fast and economical front-end electronics
- Large area, flat panel photocathodes



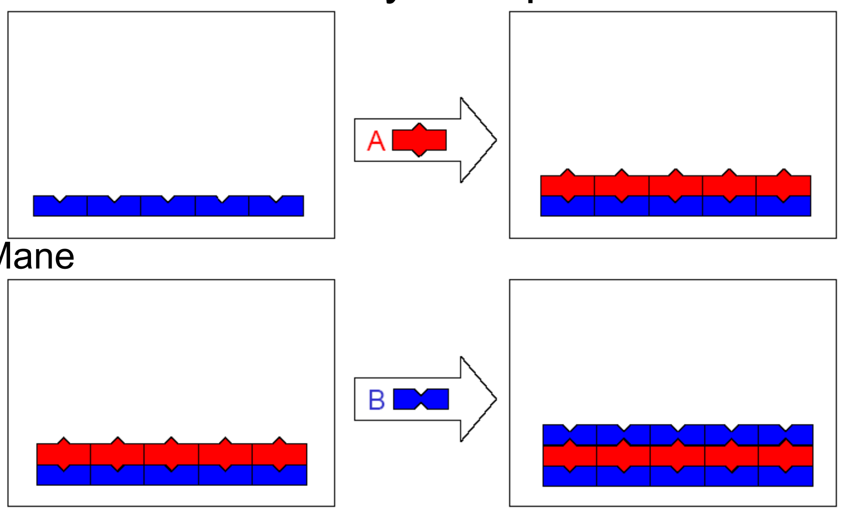
Design Drawing - September 2010



Atomic Layer Deposition

A)

B)

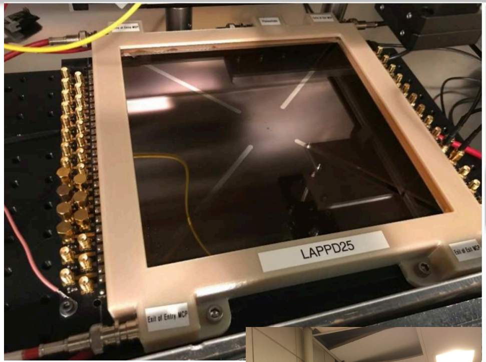


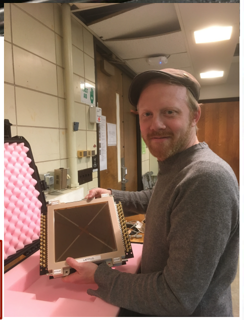
J. Elam, A. Mane

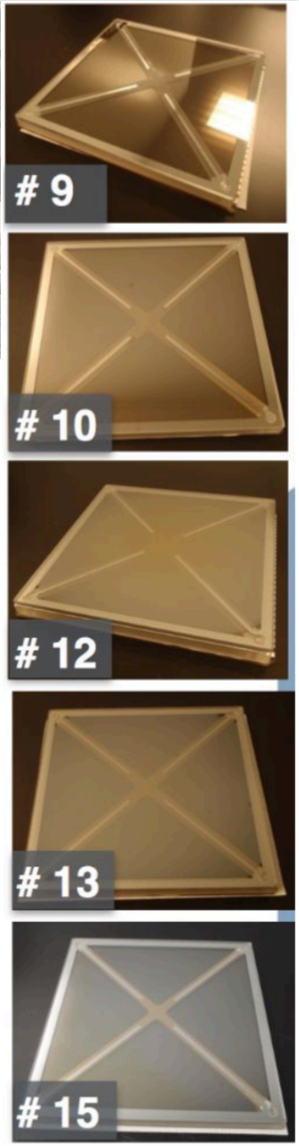
LAPPDs – A new technology tested in ANNIE

Incom Inc has now produced multiple LAPPD devices http://www.incomusa.com

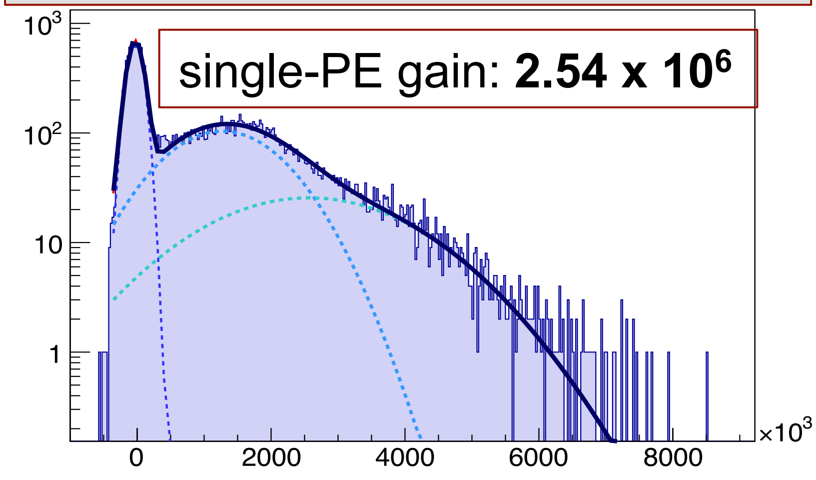
- A number of tiles have been produced and tested → gain, timing and QE
- Purchased tile #25 from INCOM
  → Thorough testing ongoing at ISU
  → Expected to be deployed in ANNIE Phase II



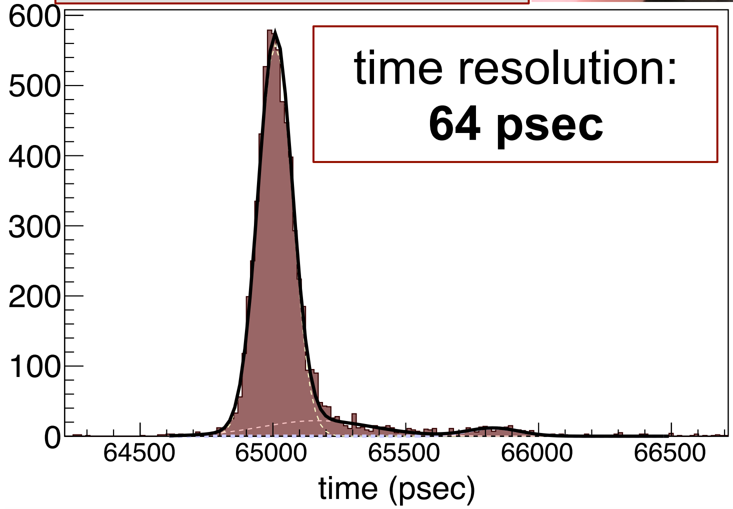




Gain - in units of elementary charge



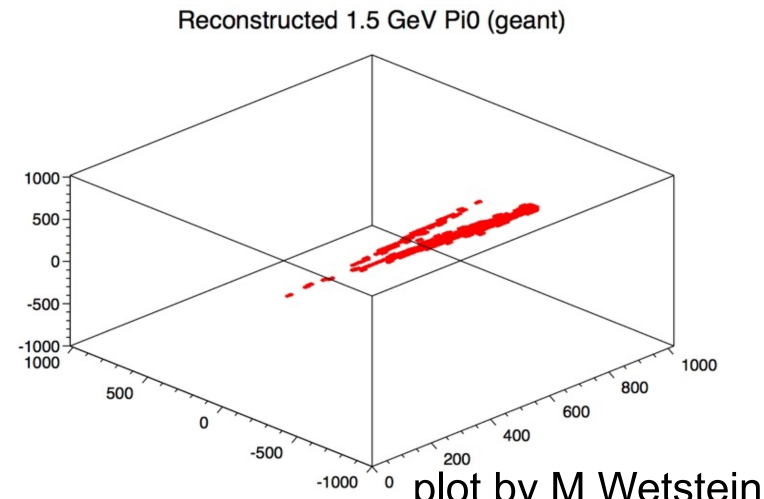
Transit Time Spread



LAPPDs Applicability

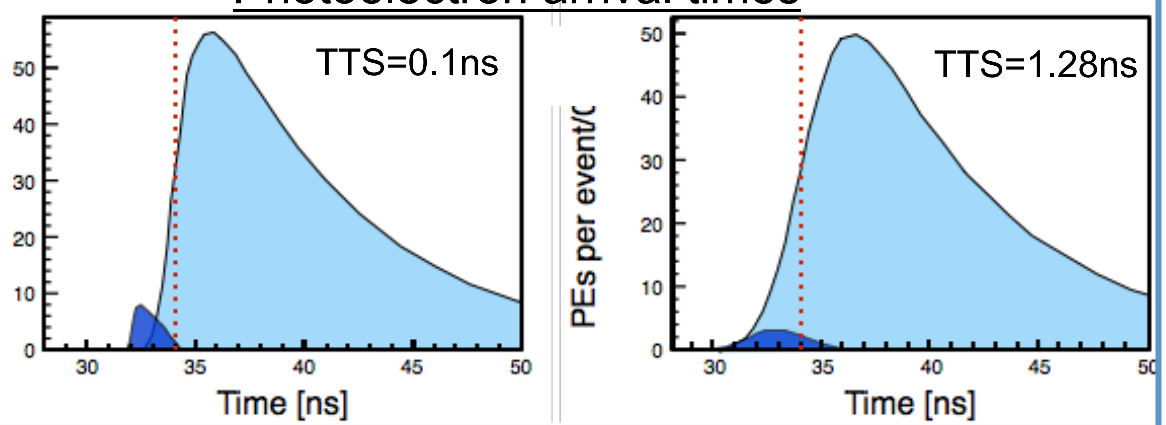
<u>LAPPD Applicability</u>:

- Detailed topological/directional reconstruction
- Scintillation-Cherenkov separation
- Imaging optics (more spatial coverage but using timing and imaging qualities of LAPPDs)



plot by M Wetstein

<u>Photoelectron arrival times</u>



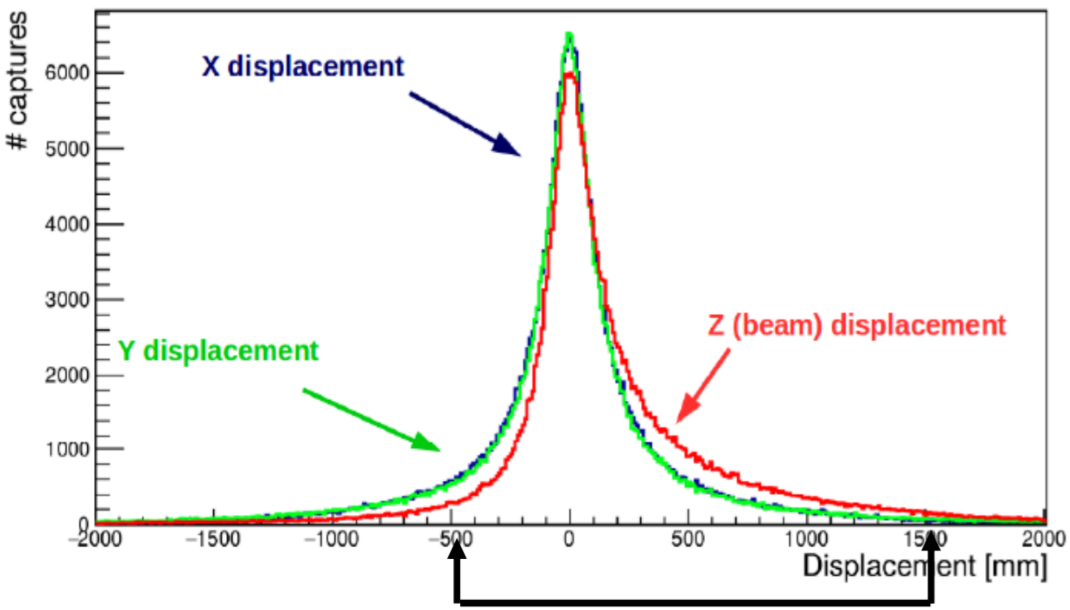
C Aberle, A Elagin, H J Frisch, M Wetstein and L Winslow (2013) 10.1088/1748-0221/9/06/P06012

"Next-generation" LAPPD concept (U.Chicago): H. Frisch & A. ELagin
1) ceramic body
2) simpler fabrication technique
→ may bring prices down even further than a scaled-up Incom production line

Why LAPPDs in ANNIE?

LAPPDs enable the ANNIE physics:

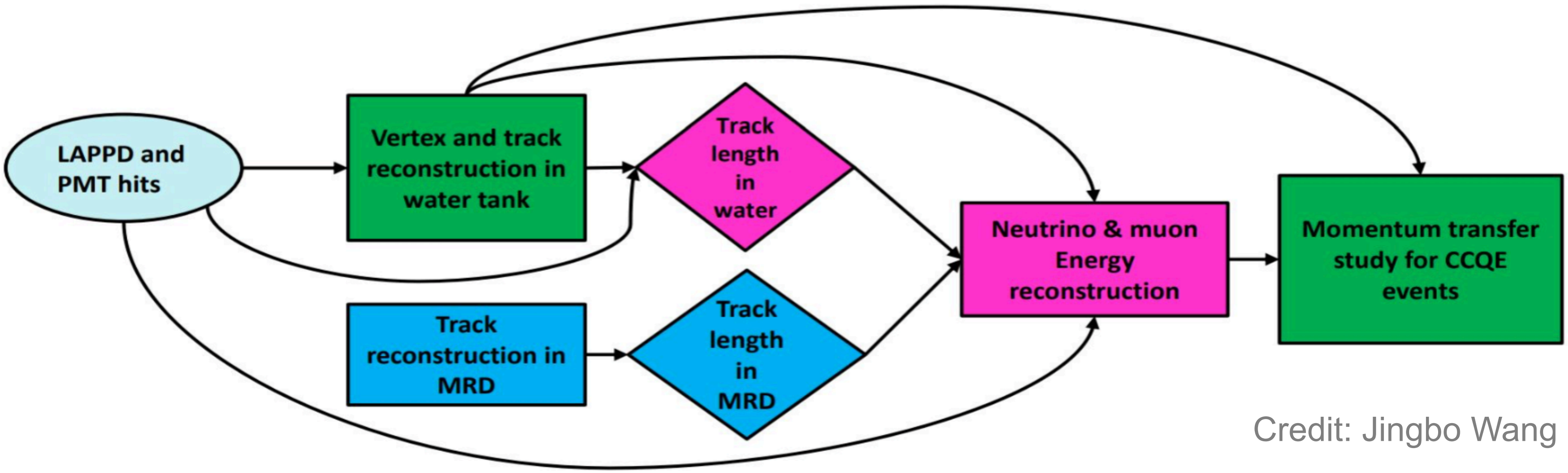
- Neutrons created in ANNIE can drift up to 2 m:
  → drift is symmetric in the direction transverse to beam
  → drift is mostly forward in the beam direction
- Given ANNIE's small size it is crucial to maximize the fiducial volume
- A vertex resolution of ~ 10 cm is needed to properly identify events in the fiducial volume.



- Such resolution is beyond the capability of traditional PMTs!
- Precise timing-based reconstruction enabled by LAPPDs is essential.

ANNIE Reconstruction Strategy

- Full ANNIE Phase II simulation using WCSim for two configurations:
  → PMT only: 128 PMTs (~20 % coverage of the inner walls)
  → LAPPD+PMT: 128 PMTs + 5 LAPPDs on downstream

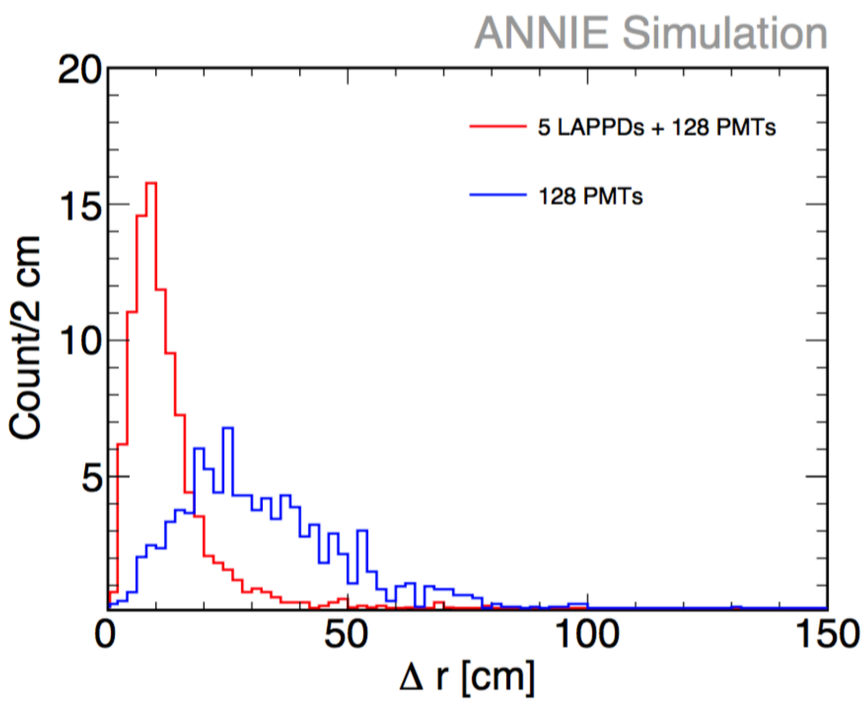


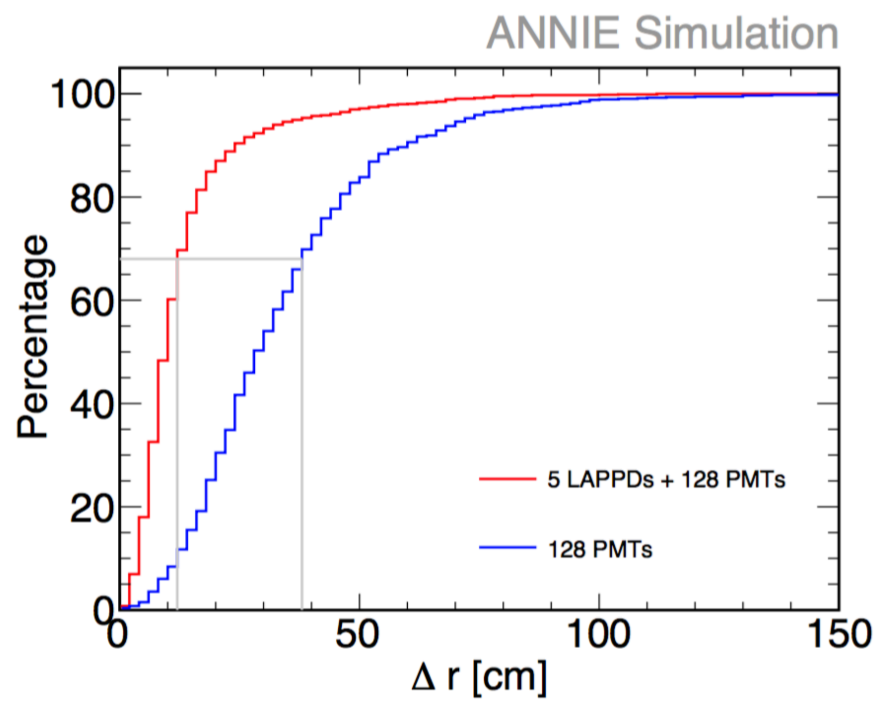
Credit: Jingbo Wang

- Reconstruct vertex and track using an extended vertex fit
- Reconstruct track length in water using a Deep Learning Neural Network
- Fit track position in all MRD layers → track length in MRD
- Reconstruct muon and neutrino energies using Boosted Decision Tree
- Calculate Q^2 assuming CCQE interaction

Vertex Resolution

- For muons produced within the fiducial volume and stopped in the MRD





- Vertex resolution at the 68th percentile of selected events:

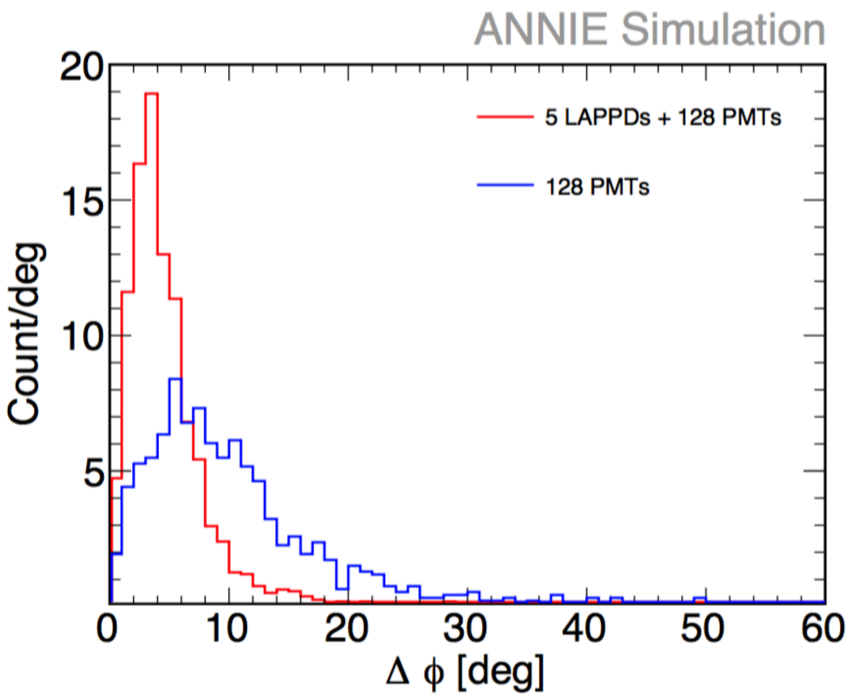
→ 128 PMT-only (20% coverage): 38 cm

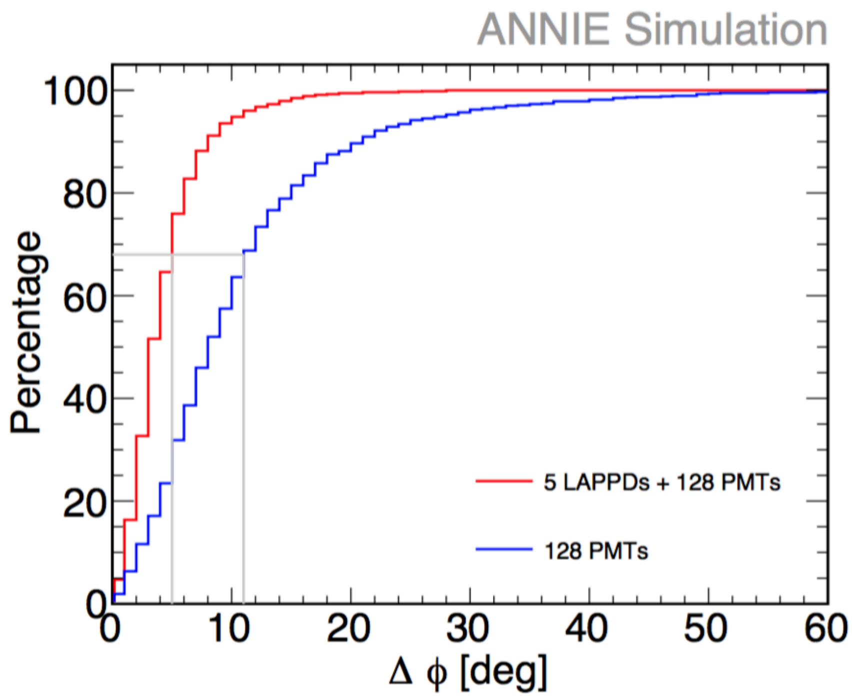
→ 5 LAPPDs + 128 PMTs: 12 cm

- The vertex resolution is improved by about a **factor of three** when we include LAPPD hits in the reconstruction.

Muon Angular Resolution

- For muons produced within the fiducial volume and stopped in the MRD





- Angular resolution at the 68th percentile of selected events:

→ 128 PMT-only (20% coverage): ~11°

→ 5 LAPPDs + 128 PMTs: ~5°

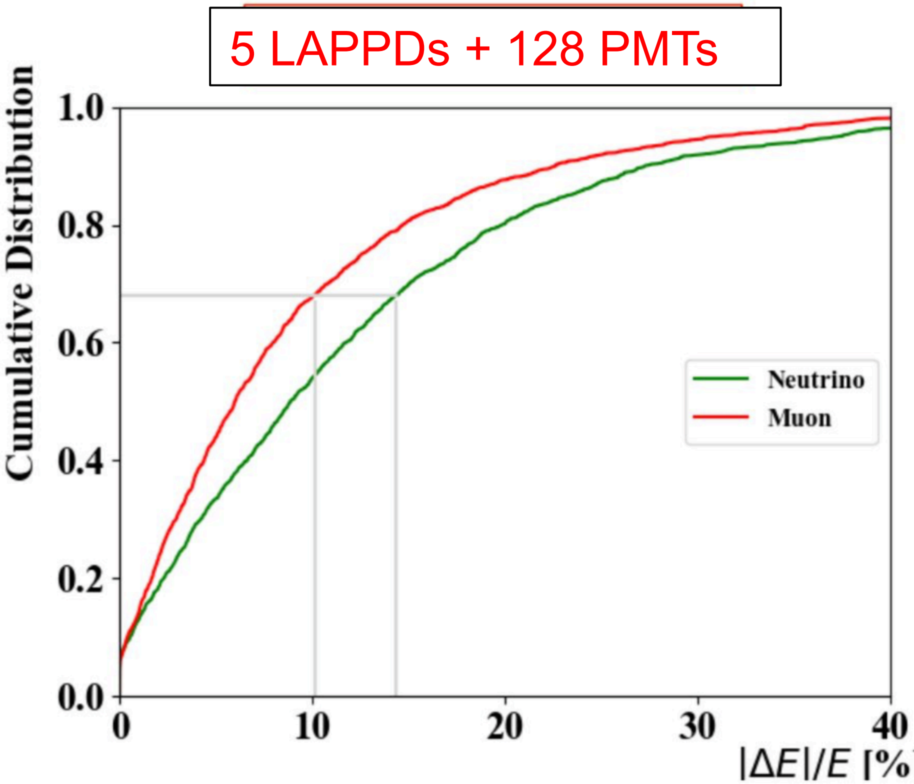
- The angular resolution is improved by about a **factor of two** when we include LAPPD hits in the reconstruction.

Energy Reconstruction

- The track length in water and the track length in the MRD are used among other variables as inputs to a **B**oosted **D**ecision **T**ree to reconstruct the muon and neutrino energy.

- At the 68th percentile of all selected events in the sample, we achieve an energy resolution of:

→ 10 %, for the muon
→ 14 %, for the neutrino



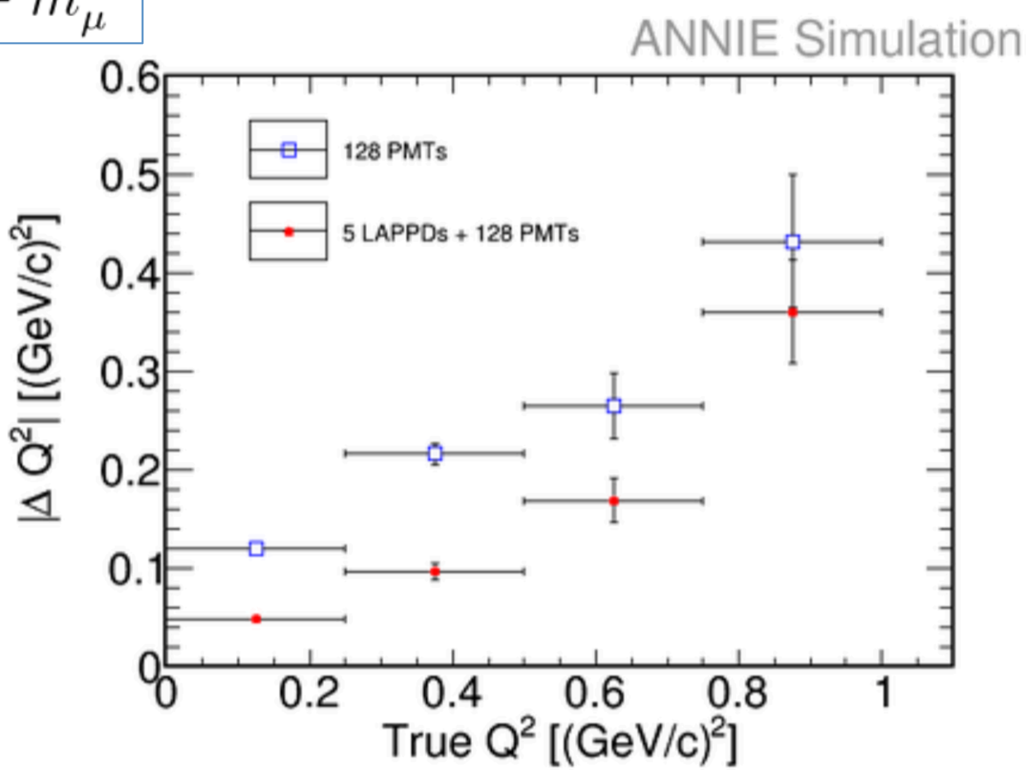
For more details on the reconstruction see: arXiv:1710.05668v3

Momentum Transfer: Q^2

- Momentum transfer for CCQE events: the primary interaction channel in ANNIE
- CCQE events are completely described by the energy of the incoming neutrino and the energy and momentum of the outgoing muon.

$$Q^2_{QE} = 2E_\nu^{QE}(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$$

- 1-σ Q^2 resolution for four bins in true Q^2
- The addition of LAPPDs considerably improves the Q^2 resolution.

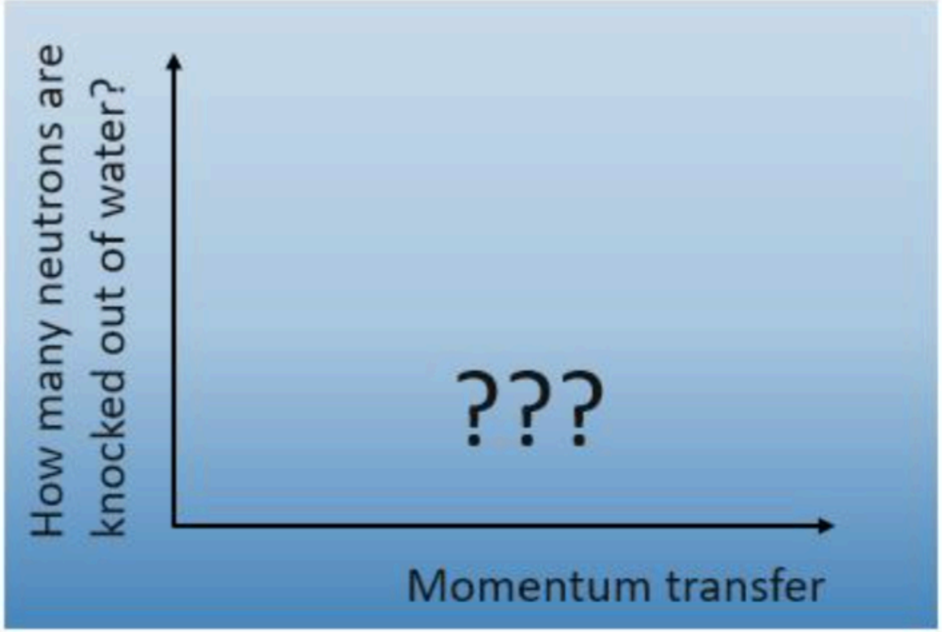


Plans

Coming Soon

"The main deliverable from this experiment is a measurement of the final-state neutron abundance as a function of momentum transfer from charged current (CC) neutrino interactions."

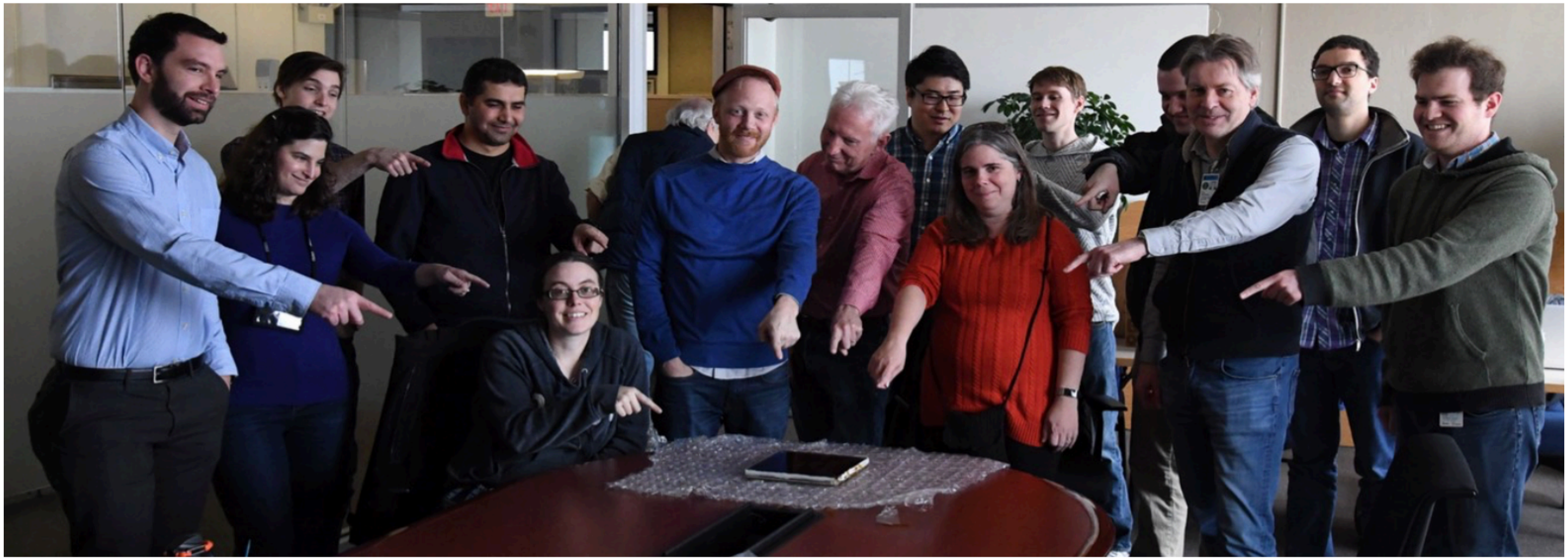
ANNIE Letter of Intent



Conclusions

- ANNIE will measure the neutron yield as a function of the momentum transfer from neutrino-nucleus interactions in water.
- To fulfill its scientific goals ANNIE will use LAPPDs and Gd-doped water.
- In Phase I, ANNIE demonstrated sufficiently low neutron backgrounds for physics goals.
- The key technological component of Phase II, LAPPDs, are being produced by Incom Inc.
- Simulation and Reconstruction tools for ANNIE Phase II are in place and show good performance.
- ANNIE Phase II data taking is foreseen in late 2018.

Thank you !

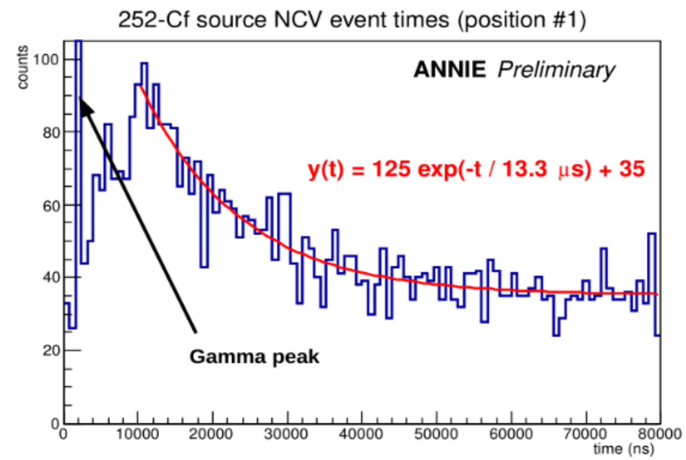


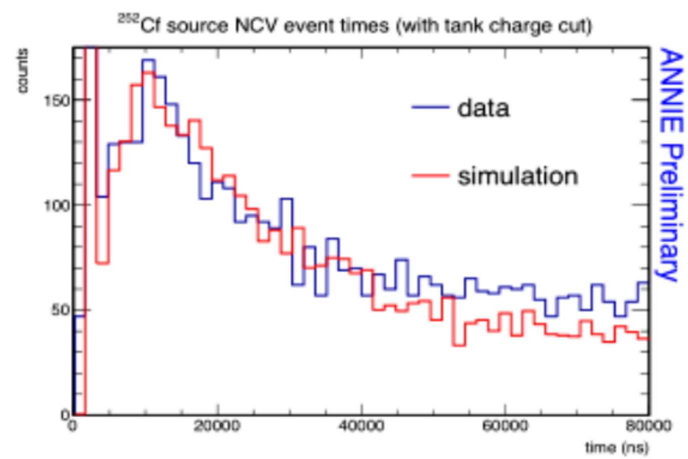
ANNIE Collaboration Meeting, January 2017

Backup

ANNIE Phase I – Detector Calibration

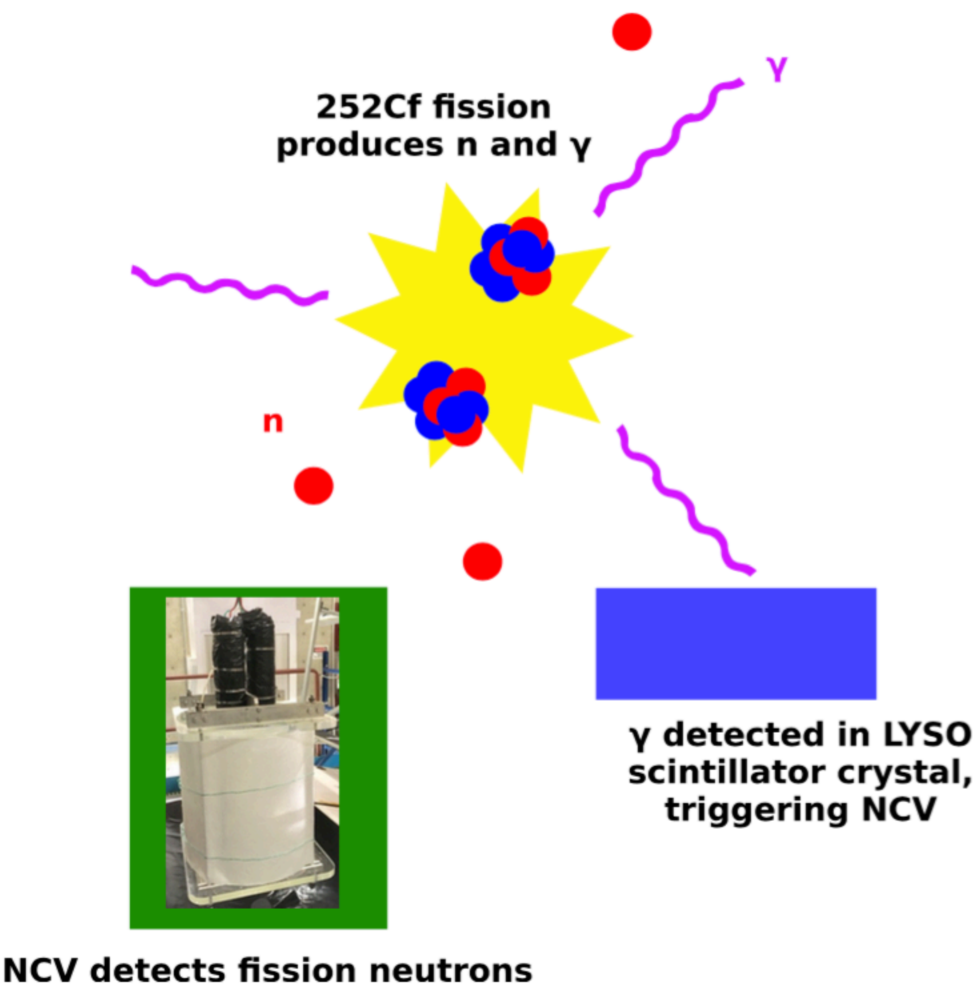
- Neutron response was calibrated with a ^{252}Cf source, using a scintillator crystal to trigger on gammas emitted during fission
- Source activity was measured using a commercial neutron detector and another source of well-known activity
- Results show the expected 13μs capture time and agree fairly well with Monte Carlo simulations
- Multiple methods of NCV efficiency calculation were used, with good agreement between them





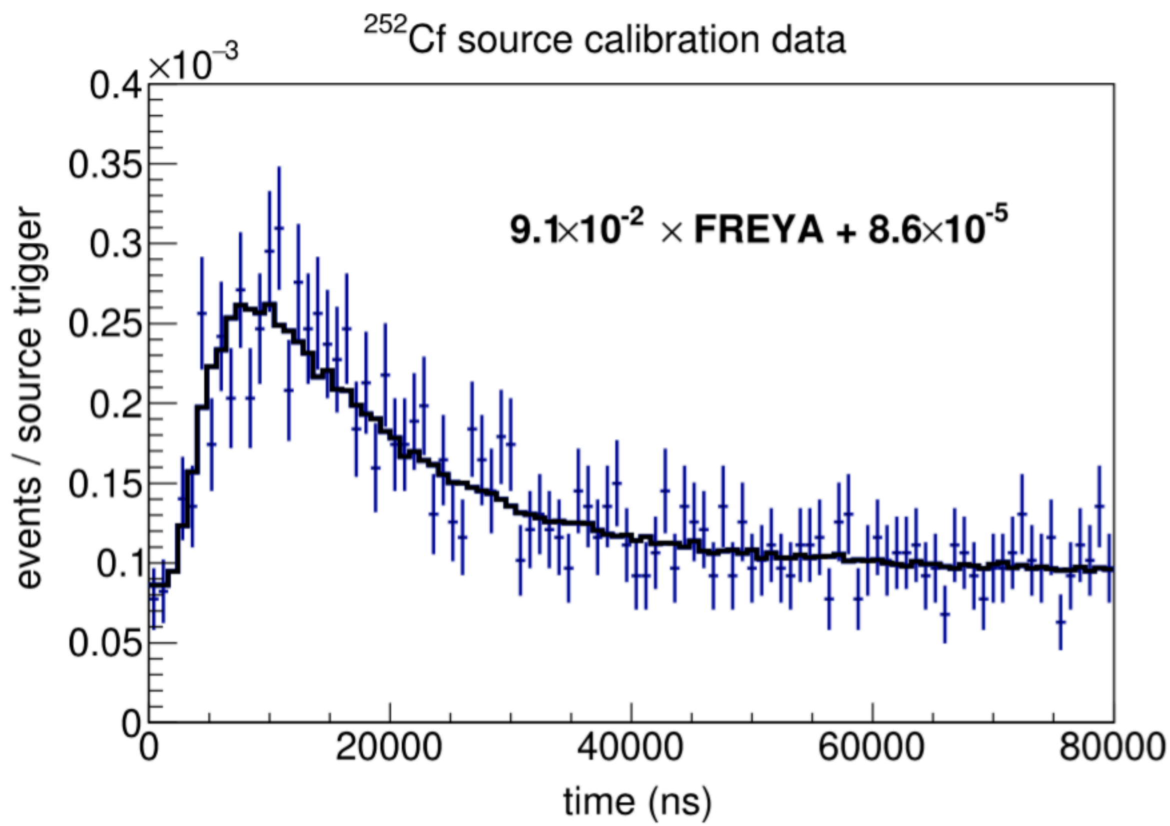
ANNIE Phase I – NCV efficiency calibration

- A ^{252}Cf fission neutron source was used to calibrate the NCV
- LYSO crystal + small PMT used to trigger ANNIE on fission γ-rays
- Subsequent neutron captures detected in NCV
- Compared with Monte Carlo simulation to determine efficiency

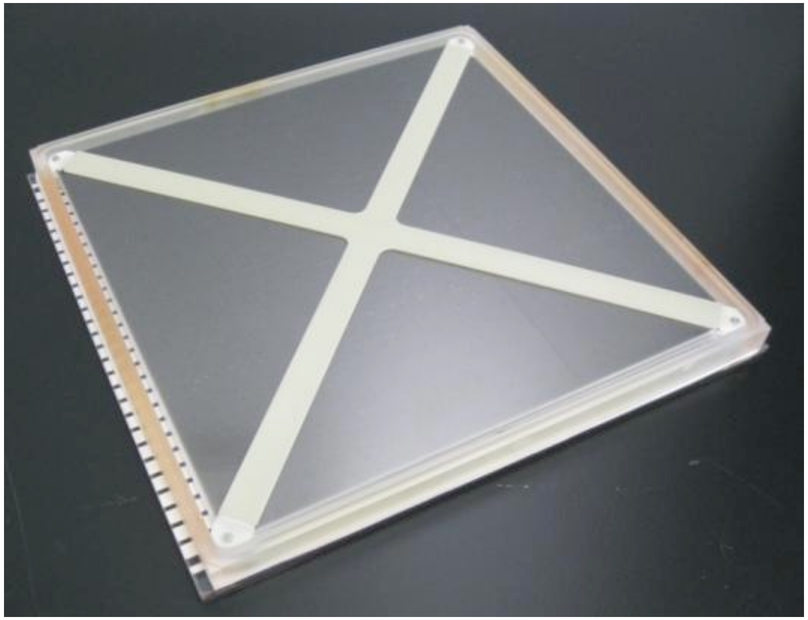


ANNIE Phase I – NCV efficiency calibration

- ^{252}Cf calibration runs were simulated
  - FREYA (Fission Reaction Event Yield Algorithm) generator
  - RAT-PAC detector simulation
- Simulation results were fit to data using a scaling factor and flat background
- 9.1% efficiency close to independent estimate from cosmic trigger data (about 11.6%)



The LAPPD Concept



LAPPD detectors:

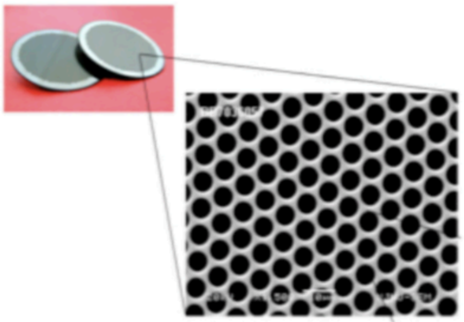
- Thin-films on borosilicate glass
- Glass vacuum assembly
- Simple, pure materials
- Scalable electronics
- Designed to cover large areas

Conventional MCPs:

- Conditioning of leaded glass (MCPs)
- Ceramic body
- Not designed for large area applications

The LAPPD Concept

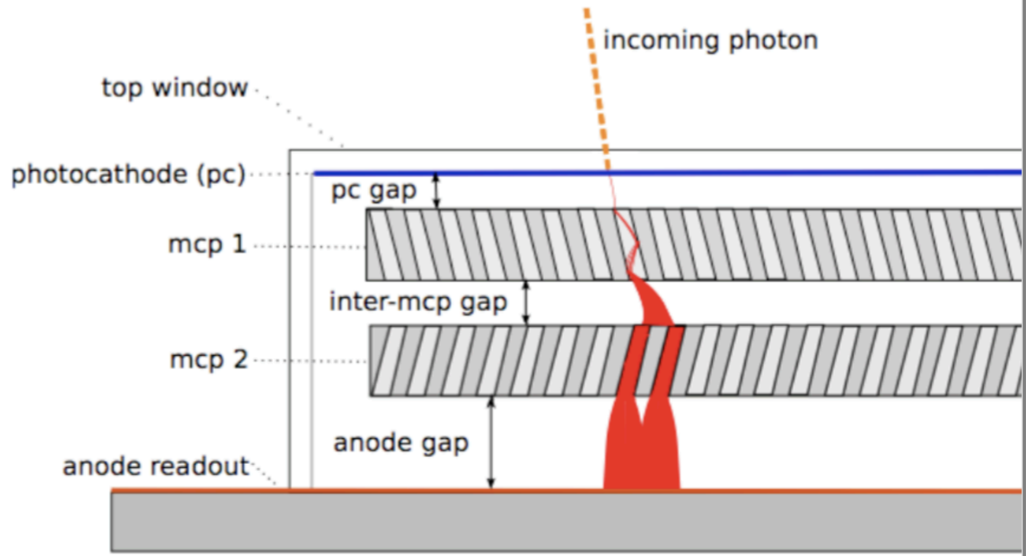
What is an MCP-PMT?



Microchannel Plate (MCP):

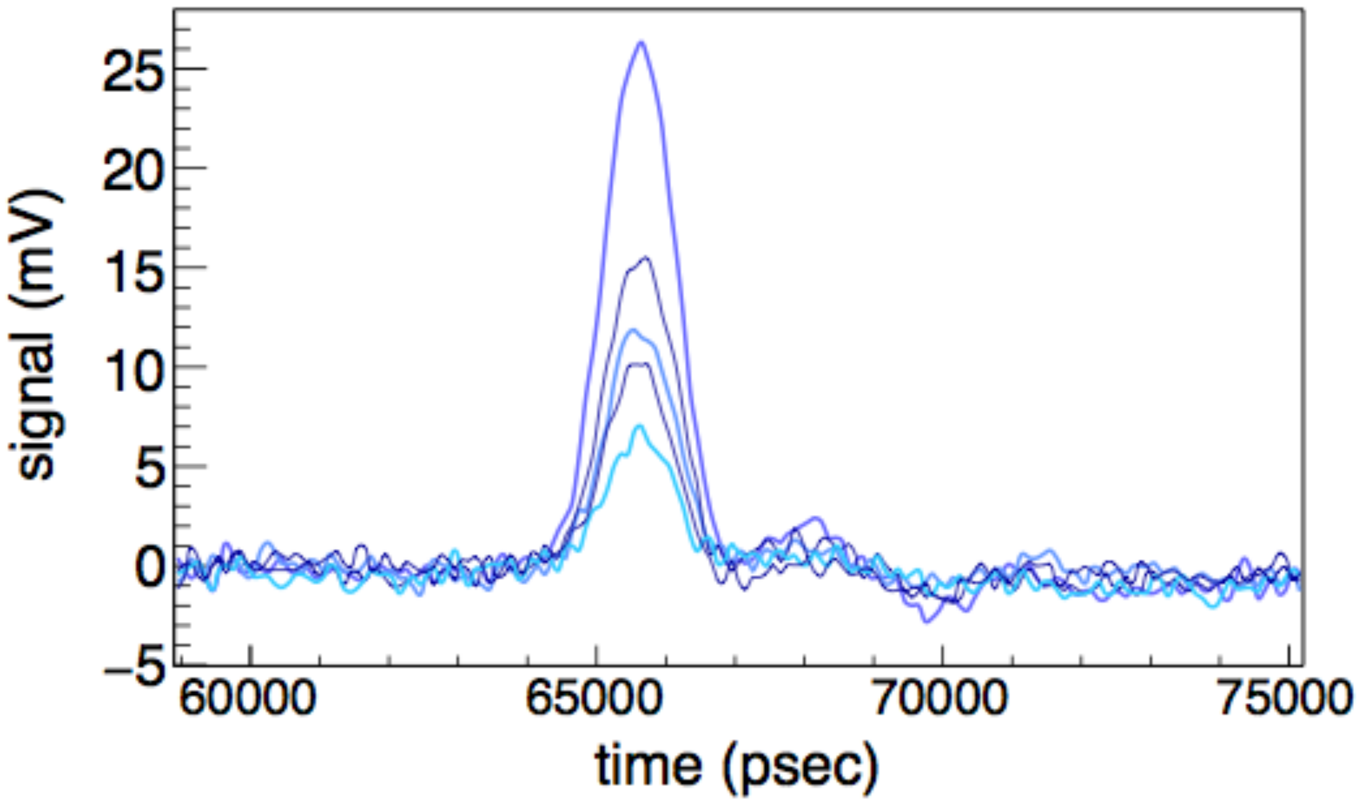
- a thin plate with microscopic (typically <50 μm) pores
- pores are optimized for secondary electron emission (SEE).
- Accelerating electrons accelerating across an electric potential strike the pore walls, initiating an avalanche of secondary electrons.

- An MCP-PMT is, sealed vacuum tube photodetector.
- Incoming light, incident on a photocathode can produce electrons by the photoelectric effect.
- Microchannel plates provide a gain stage, amplifying the electrical signal by a factor typically above 10^6.
- Signal is collected on the anode



Results: Typical Single-PE Pulses

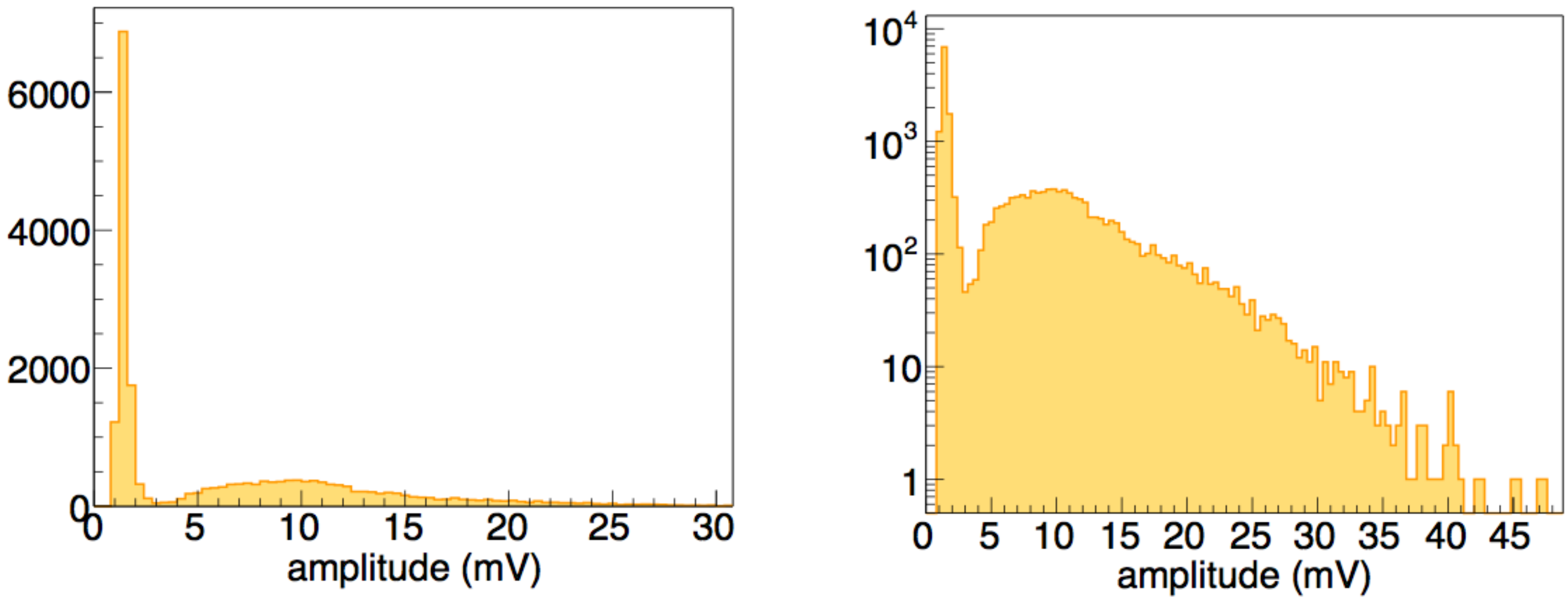
FWHM: 1.1 nsec
rise time: 850 psec



voltages: PC=350V MCP1=800V interMCP=200V MCP2=950V anode=200V

Results: Amplitude

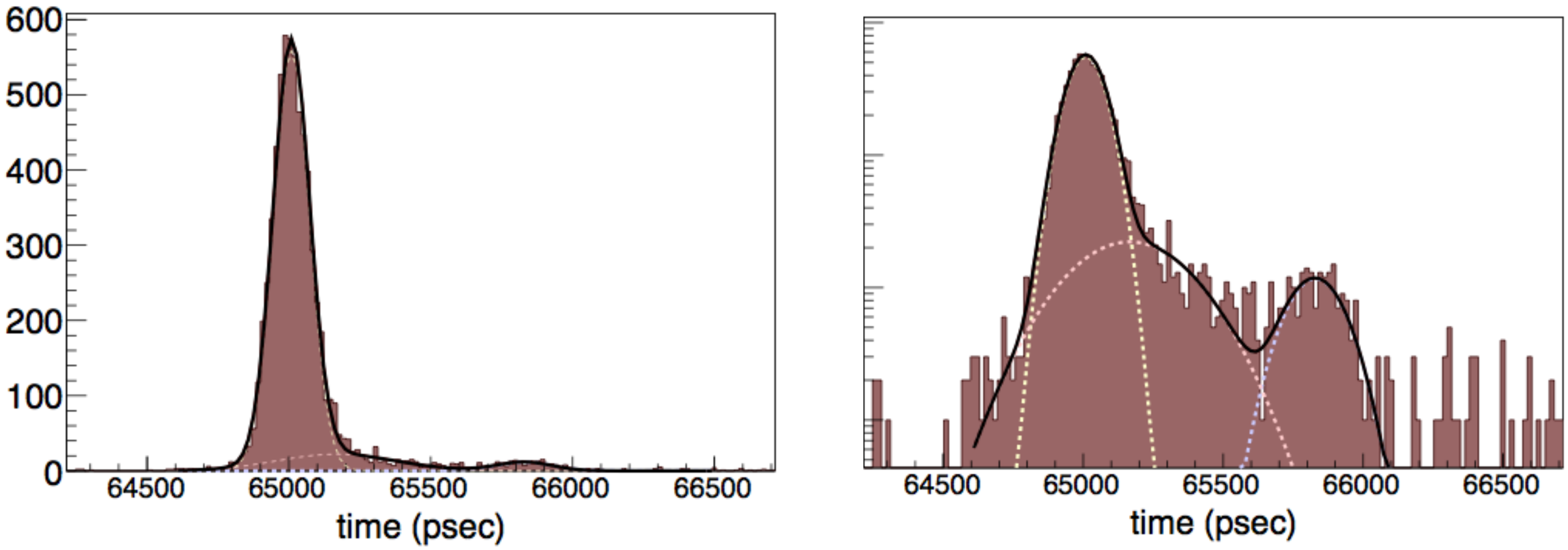
We see very clean separation from pedestal
Pulses are typically above 5mV (single-sided) compared to <1 mV noise



voltages: PC=350V MCP1=800V interMCP=200V MCP2=950V anode=200V

Results: Time Resolution

We observe 64 psec time resolution in the main peak of the TTS with small contribution from after-pulses (~4%), typical of any photodetector



voltages: PC=350V MCP1=800V interMCP=200V MCP2=950V anode=200V

annie

LAPPDs Cost & Commercial Status

Commercial Status:

- Incom is commissioning a second processing chamber which could eventually bring their production rate to 1 per week → this can continue to scale as demands and yields grow
- Current pricing is not where they intend it to be in the longer run - it will go down with market scope and volume
- LAPPDs will likely benefit from a much broader market than HEP - medical imaging, security, x-ray imaging, etc
- Incom welcomes new, and interested early adopters, holding periodic Measurement and Testing workshops

Cost:

- Price is not where it is going to be
- There is a growing market for LAPPDs
- New efforts will further reduce the price

LAPPDs Commercial Status

Trial #	LAPPD#	Sealed	Incom Inc. Cummulative Sealing Yield [%]	QE Performance	LAPPD Performance & Disposition
1	22	Yes Sealed 10/10/17	100.00%	QE (%Max, Mean, Max, s)= 14.7/12.6/1.2	Sandia
		YES Ceramic Sealing Trial 10/17/2017	NA		
2	23	NO	50.00%		
	24	Full ceramic tile trial Seal date = 11/16/2017	NA	NA	GEN II Program experiment
3	25	Yes Sealed 12/14/2017	66.70%	QE (%Max, Mean, Max, s)=10/7.1/,	ANNIE
4	26	No	50.00%		Glass Anode Cracked at Frit Seal Line
	27	Full ceramic tile trial Seal Date = 1/23/2018	NA	NA	GEN II Program experiment
5	28	Yes 2/8/2018	60.00%	Experimental PC, no Sodium Average QE: 1.96% ± 0.6%	Report Pending, Heavy level of afterpulses but usable for triggered applications. Used for Proton Beam Trials at MGH
6	29	**Yes** **3/21/2018**	66.70%	Electrical Short during Photocathode deposition Mean QE=13.0%±6% QEmax: 19.6% QEmin: 3.0%	Final Report Available

LAPPDs Commercial Status

Trial #	LAPPD#	Sealed	Incom Inc. Cummulative Sealing Yield [%]	QE Performance	LAPPD Performance & Disposition
7	30	YES, 4/10/2018	71.40%	Mean QE=17.2%±2.5% QE_{max}: 22.9% QEmin: 13.0%	Electrical Short between Photocathode and bottom of top MCP renders this LAPPD Unusable
	30.1	NO 4/24/2018	NA	NA	GEN II Program experiment
8	31	Yes 5/25/2018	75%	QE (365nm) = 17% RT Sealed	Final Report Due 7/20.2018 **Looks Good! ANNIE Candidate**
9	32	Yes 6/27/2018	78%	QE(365nm) = 16% at 138C	Performance Evaluation Underway
10	33			Planned, MCPs assigned	

LAPDP Performance reports are available at: http://www.incomusa.com/mcp-and-lappd-documents/

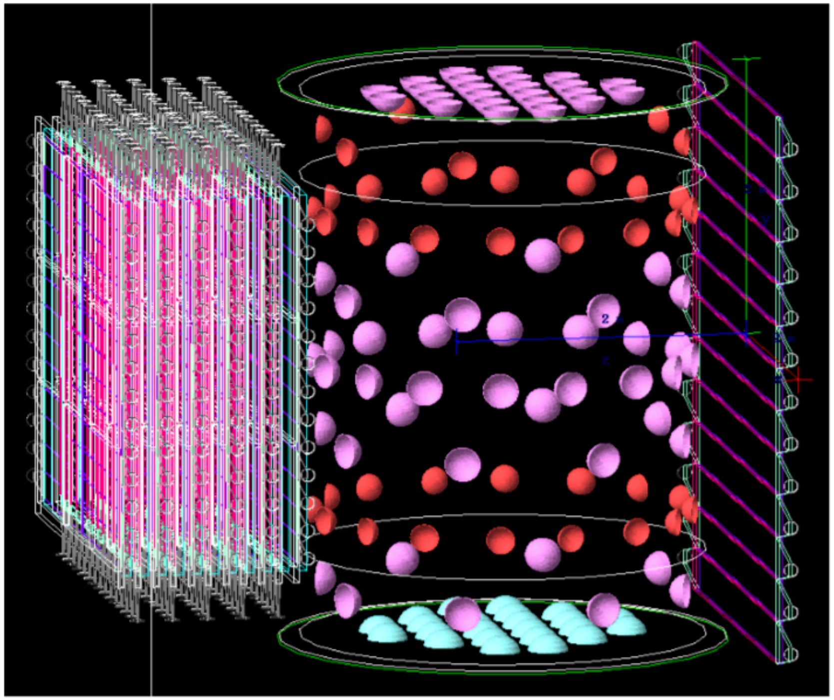
ANNIE Phase II Simulation

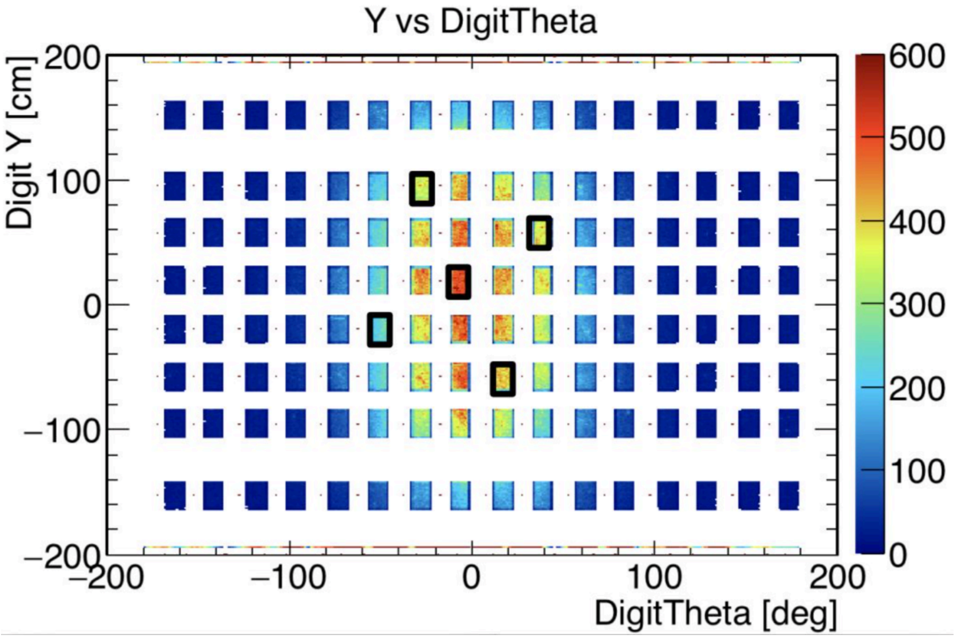
Full ANNIE Phase II simulation using WCSim:

- We have used a dataset of neutrinos from GENIE and propagated through WCSim testing two configurations:

→ PMT only: 128 PMTs (~20 % coverage of the inner walls)

→ LAPPD+PMT: 128 PMTs + 5 LAPPDs on downstream





Vertex and Track Reconstruction

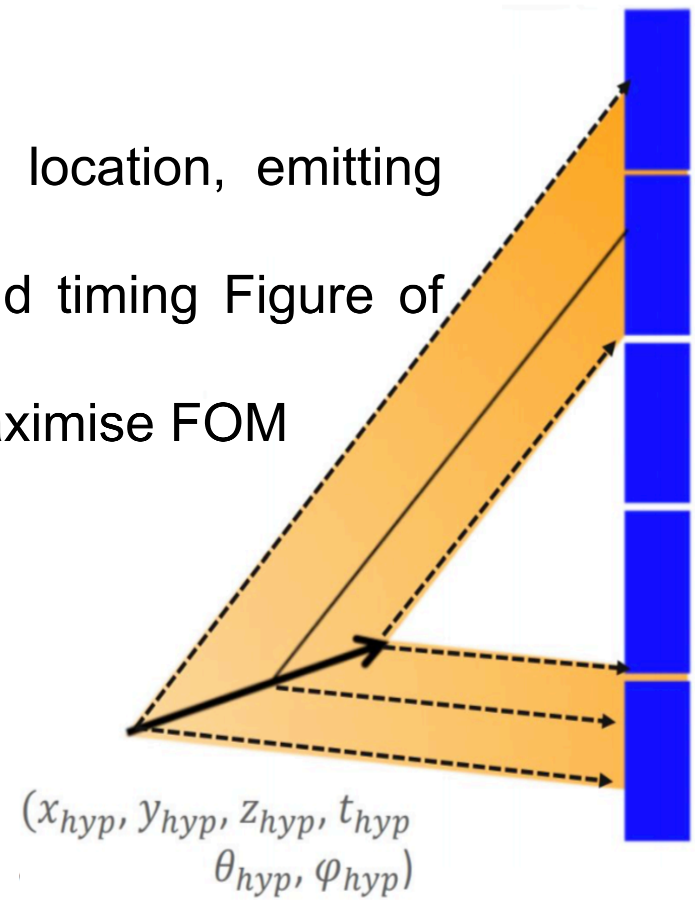
Steps:

1. **"Simple vertex" fit → (x, y, z, t)**

- Consider a point source at a hypothesised location, emitting Cherenkov light
- For each hit calculate the timing residual and timing Figure of Merit (FOM)
- Adjust the four hypothesised parameters to maximise FOM

2. **Extended vertex fit → (x, y, z, t, θ, φ)**

- Start with position from simple vertex fit and add hypothesised track direction
- For each hit calculate extended time residual including muon travel time
- Calculate cone FOM by comparing predicted to measured Cherenkov cone
- Adjust all six parameters to maximise total FOM (time FOM + cone FOM)



Credit: Jingbo Wang