SOUTH DAKOTA MINES
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Accelerator Neutrino Neutron Interaction Experiment (ANNIE)

Jingbo Wang - South Dakota School of Mines & Technology
On behalf of the ANNIE collaboration

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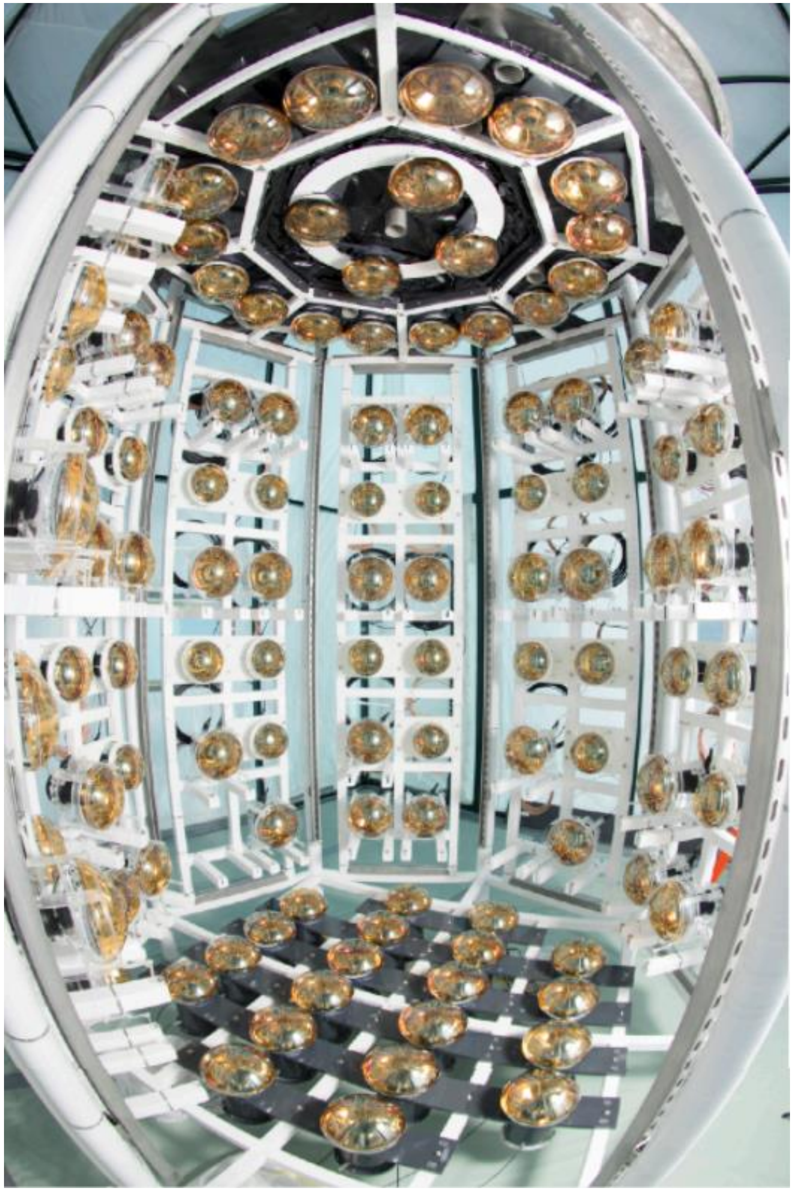
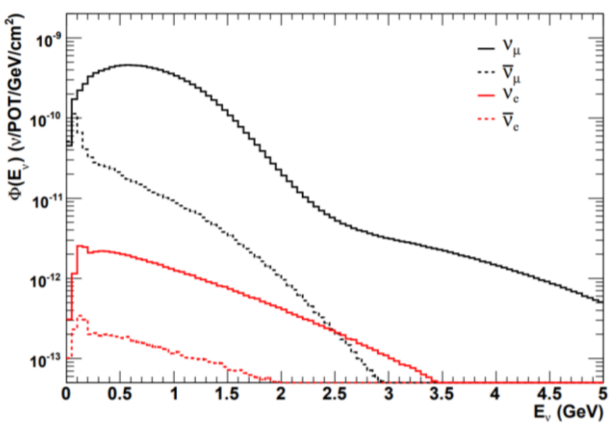
NuFact 2022, Aug 5th

What is ANNIE?

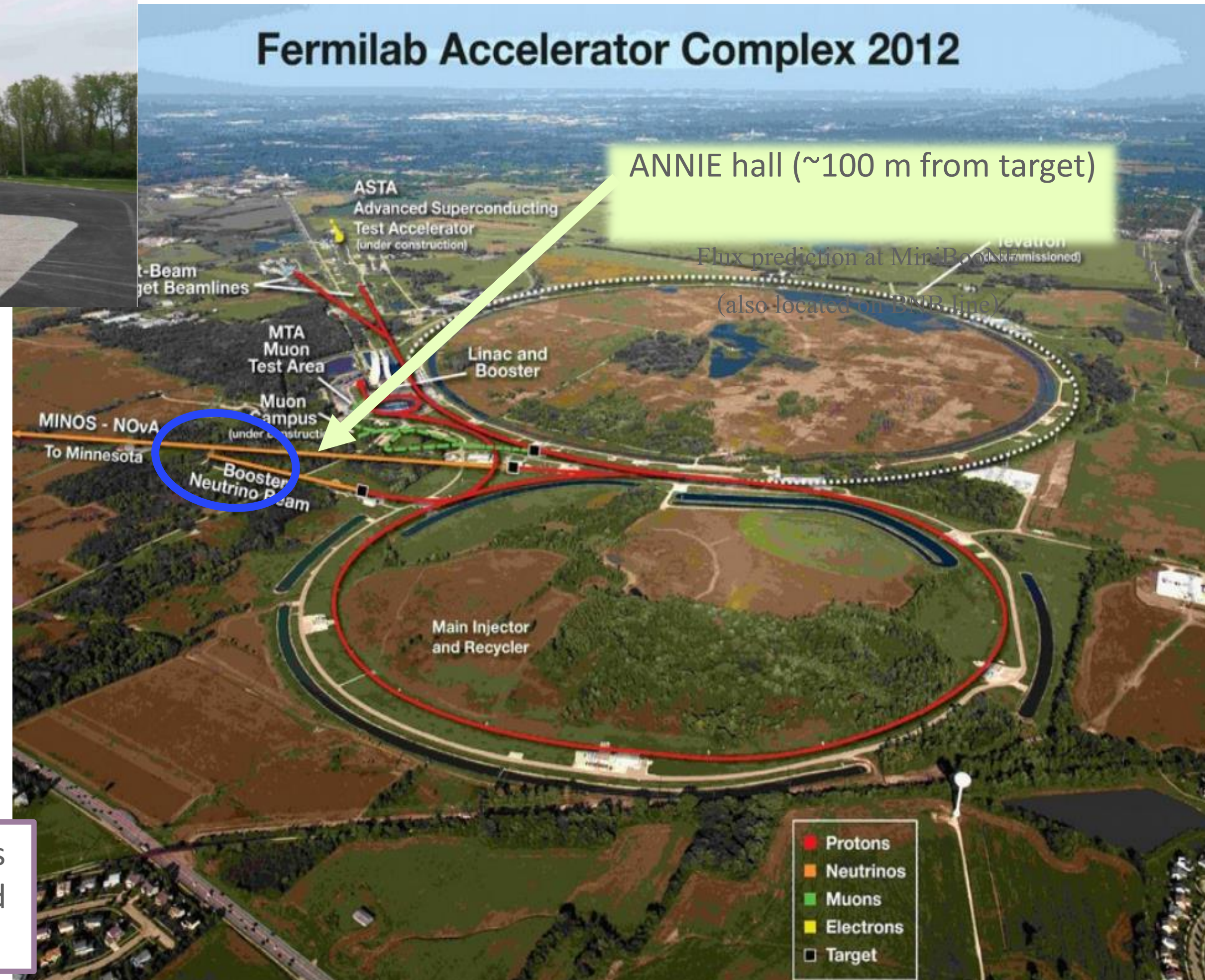
- The **A**ccelerator **N**eutrino **N**eutron **I**nteraction **E**xperiment
- 26-ton **Gd-loaded Water Cherenkov** detector
- Located 100 m downstream at the Booster Neutrino Beam line at Fermilab
- Measure **neutron multiplicity** from neutrino-nucleus interactions in water
- Demonstrate and progress the use of **new enabling technologies**
  - Gadolinium-doped water for neutron detection
  - Large Area Picosecond PhotoDetectors (LAPPDs)
  - Water-based Liquid Scintillator (WbLS) as a new detection medium



ANNIE Location at Fermilab



Flux prediction at MiniBooNE (also located on BNB line)

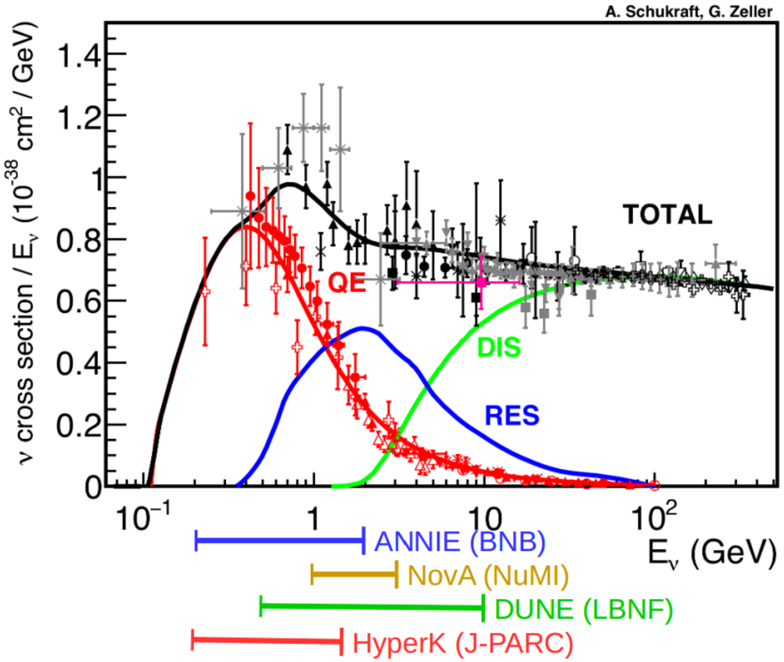


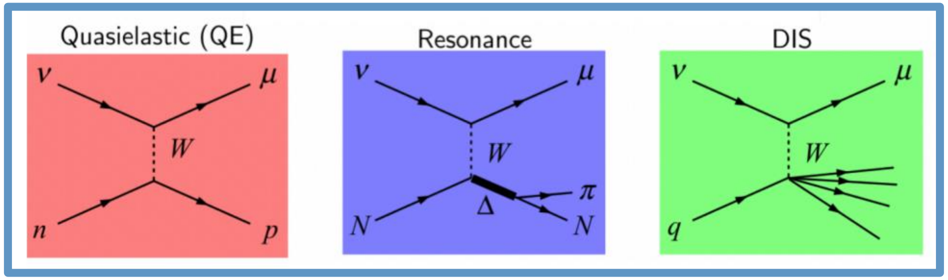
~10,000 Charged current neutrino events per ton of target water per year expected at ANNIE hall!

ANNIE Physics

- To turn neutrino physics into precision science, experiments must precisely measure neutrino energies
  - Charged current quasi-elastic interactions are preferred for accurate energy reconstruction
- However, as neutrino energies increase to the GeV-scale, numerous types of interactions become possible
- Nuclear effect complicates energy determination and QE identification
- Understanding neutrons from interactions is essential
  - Reduce energy reconstruction uncertainty
  - Reduce atmospheric neutrino backgrounds in Proton Decay and DSNB searches

Total neutrino current cross-sections divided by energy (arXiv 1305.7513, 2013)



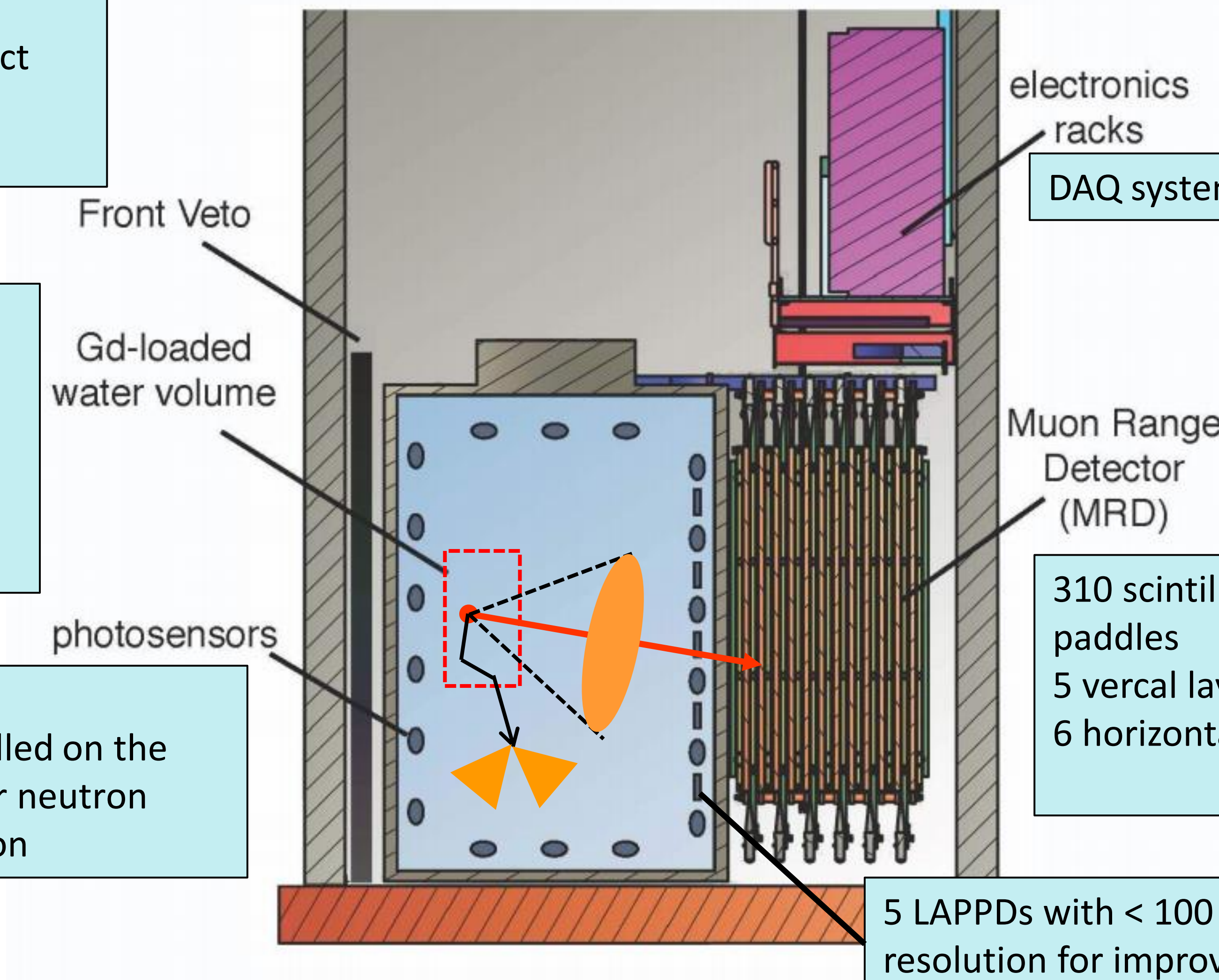


ANNIE Detector

26 scintillator paddles to reject muons from upstream

3 m x 4 m tank filled with 26-ton Gd-loaded water
- 0.2% Gd2(S04)3

Inside the tank:
132 PMTs installed on the inner surface for neutron capture detection



DAQ system

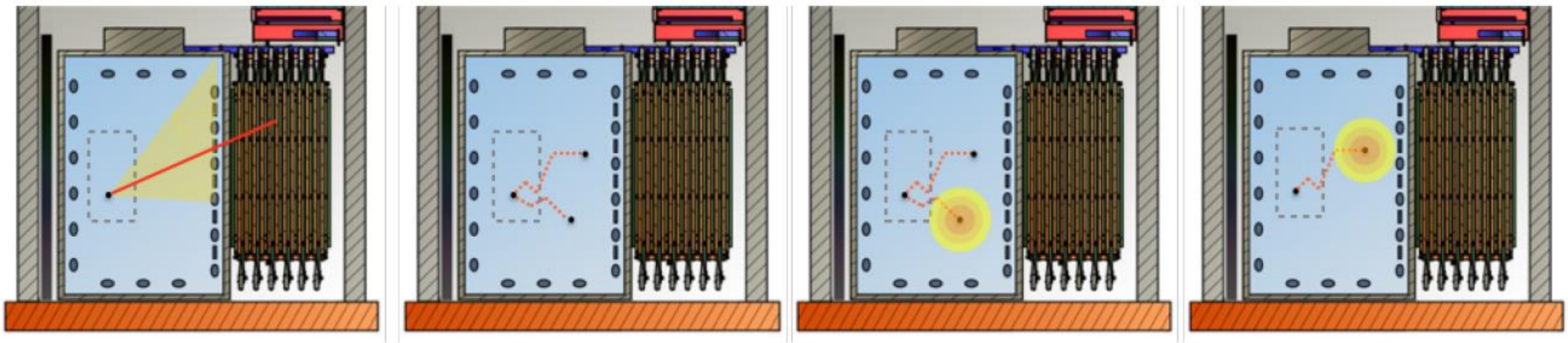
310 scintillator paddles
5 vercal layers
6 horizontal layers

5 LAPPDs with < 100 ps time resolution for improved muon track reconstruction

ANNIE Event Schematic

Example of Charge-Current neutrino event

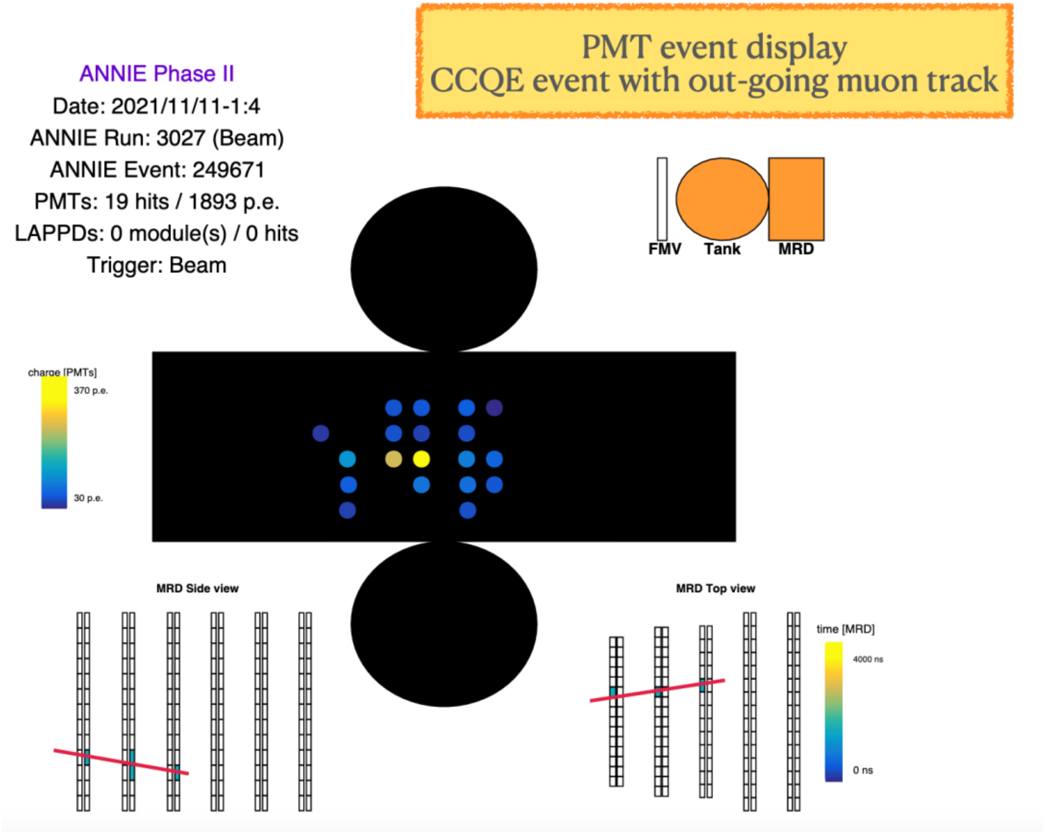
1 2 3 4



- 1 – **Charge Current neutrino interaction** in the fiducial volume
- 1 - Muon direction reconstructed using LAPPDs
- 1 - Muon momentum reconstructed by the MRD
- 2 - Final state neutrons are getting thermalized in the Gd-water volume
- 3 - Neutron capture on Gd emitting 8 MeV gammas
- 4 – Delayed gamma rays are detected by PMTs

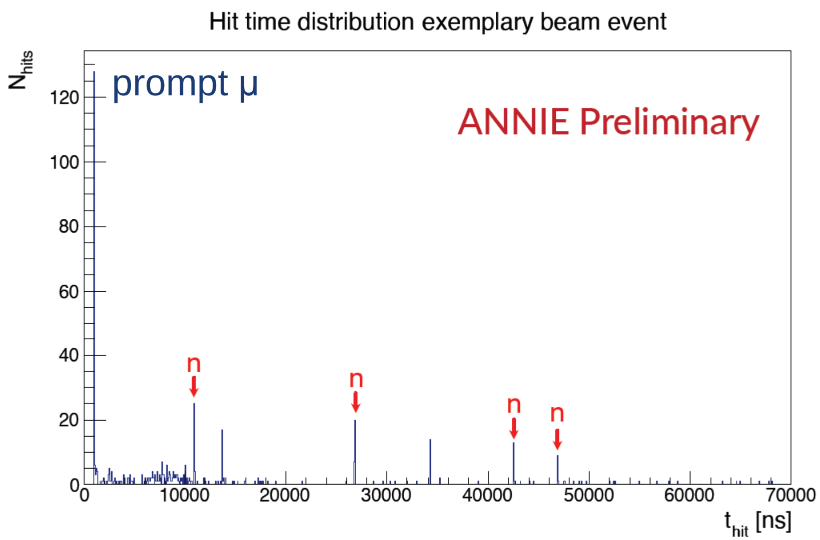
ANNIE Sees Neutrino Interactions

- ANNIE has been taking neutrino data for over a year with Gd-loaded water and all PMTs installed in the tank.
- Charge Current Quasi-Elastic (CCQE) interaction candidates are selected for the determination of neutron multiplicity.
- Candidates are identified by a Cherenkov disk in the tank, a coincident track in the MRD and no signal in the FMV.

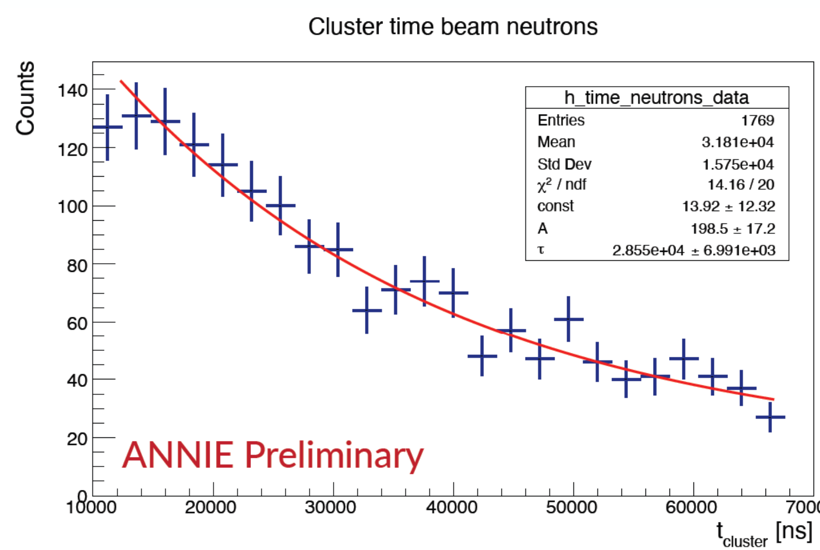


Neutrons Following Neutrino Candidates

- Beam triggers with a prompt event featuring large PMT signals (≥5 p.e.) are followed by an extended acquisition window of ~70 μs to enable neutron detector
- Selected neutron candidates feature the expected capture time in Gd-loaded water
- More physis analysis will come soon!
- Next step: complete the deployment of five LAPPDs

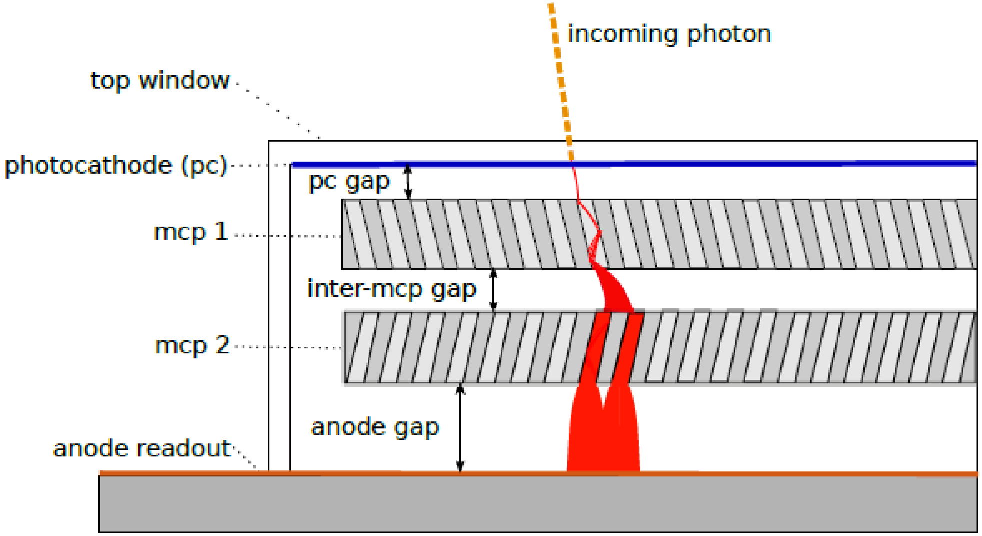


multiple neutron candidates in exemplary event



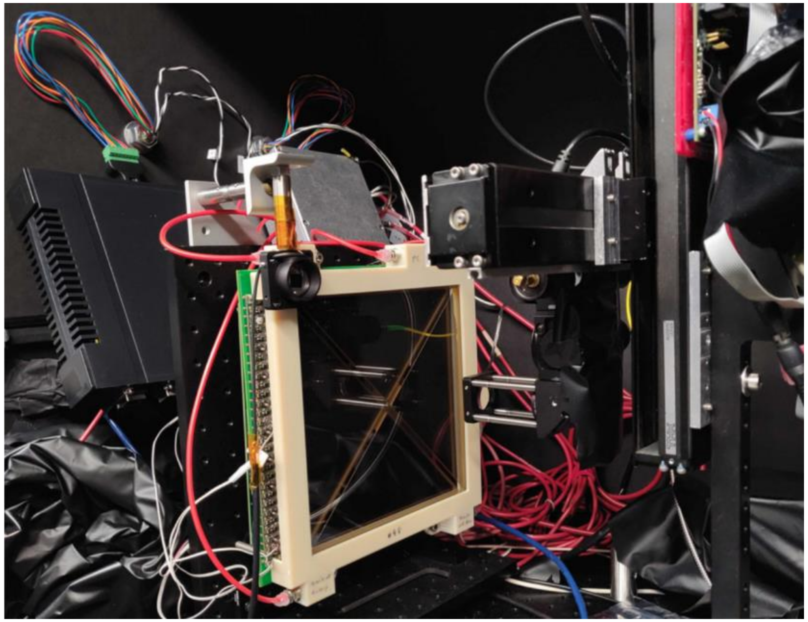
τ ~ (29 ± 7) μs in agreement with theoretical expectation (30 μs)

Enabling Technology: LAPPD



LAPPDs are Micro-channel Plate-based fast-timing photodetectors

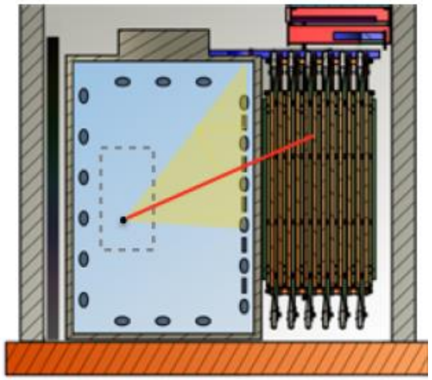
- Flat, Large-area: 20 cm × 20 cm
- Picosecond timing: <100 ps for SPE
- Quantum efficiency: >20%
- Position resolution: sub-mm

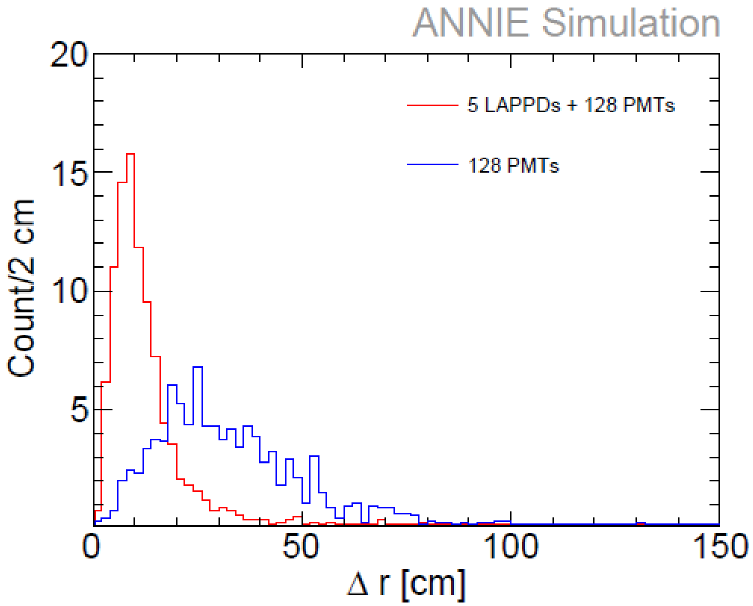


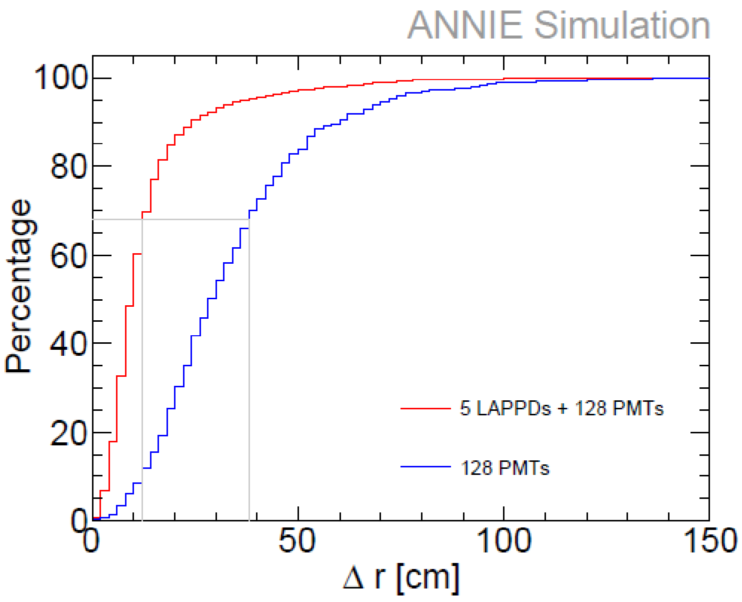
- ANNIE is the first physics experiment employing LAPPDs
- We have advanced LAPPDs from test-stand prototypes into a deployable technology.
- ANNIE has obtained five LAPPDs being deployed into the water tank

LAPPDs are Essential for ANNIE

- LAPPDs provide high time and spatial resolutions to enhance neutrino vertex resolution and tracking angular resolution
  - Reduce uncertainties on fiducialization
  - Improve precision of energy reconstruction
- By adding 5 LAPPDs to the existing PMTs the accuracy of the vertex reconstruction is improved by a factor of >2 allowing for more precise reconstruction of the muon and thus neutrino energy

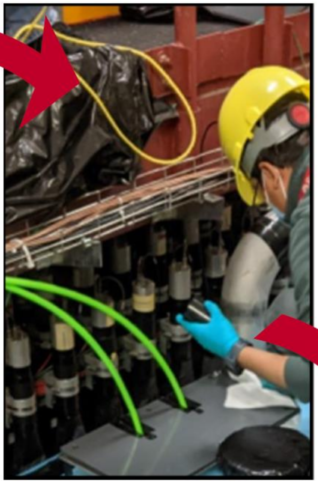






LAPPD Deployment

30 March 2022: The first LAPPD was deployed in ANNIE

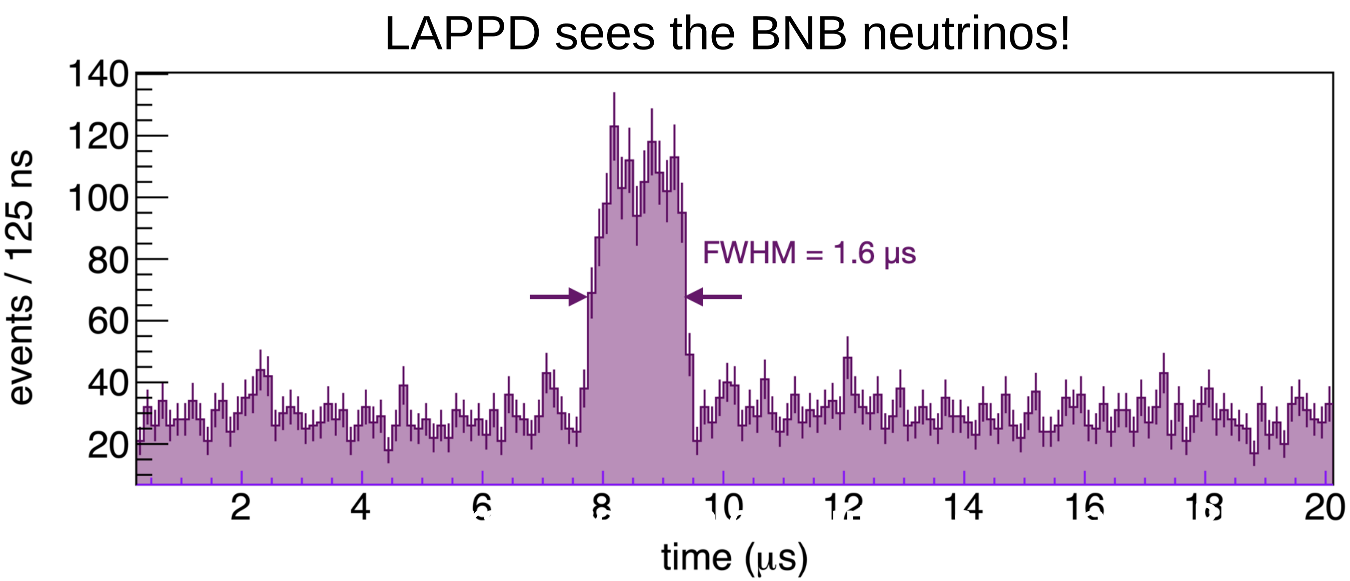


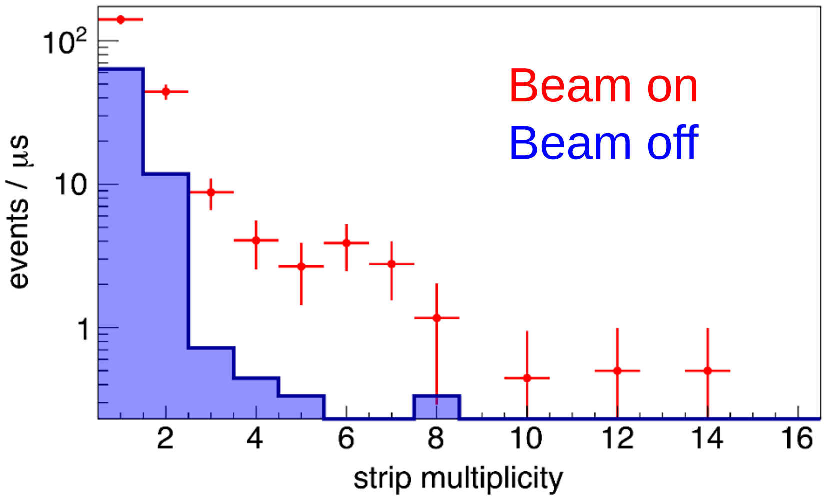
LAPPD is in the water

Everything light-tight

Four more on the way: planned for two months from now!

First Neutrinos Seen by LAPPD



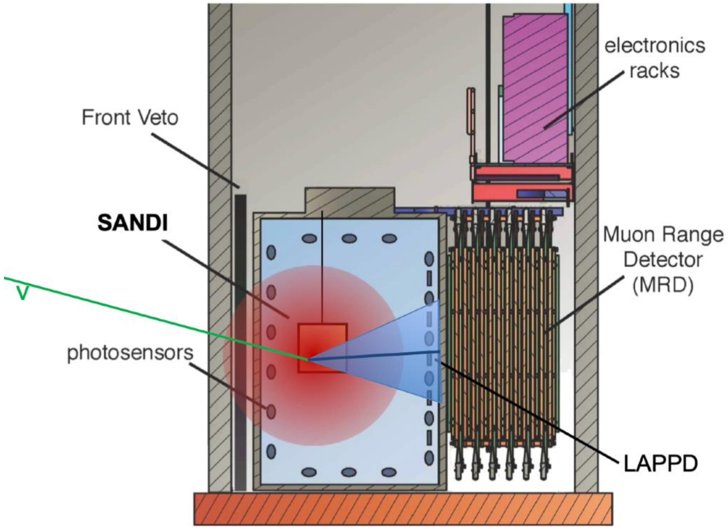


- The first LAPPD is under commissioning in neutrino beam
- First detection of neutrinos using LAPPD!
- The excess above background are LAPPD-triggered events in-time with the BNB.
- Need to deploy four more LAPPDs, new analysis result will come soon

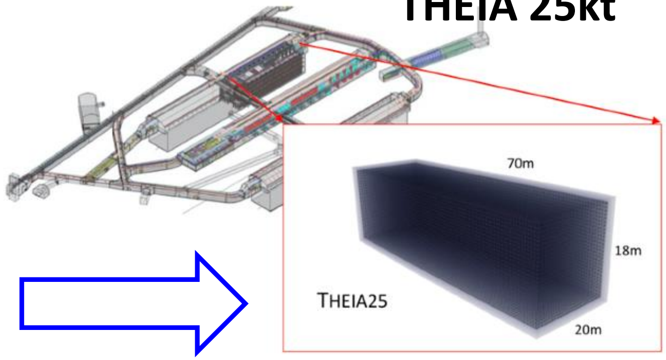
The Future test of WbLS

- **Water-based Liquid Scintillators:** novel detection medium combining advantages of both scintillation and Cherenkov light
- ANNIE WbLS test: deploy acrylic vessel filled with WbLS (3' x 3', 365kg, already delivered to Fermilab)
  - Neutrino energy reconstruc'on expected to improve by ~4% based on preliminary studies
  - Neutron detec'on expected to improve (3x light output, efficiency ~ 90%)
- Two-week test run planned for fall 2022 can show feasibility of WbLS in next-generation neutrino experiments, such as THEIA.

ANNIE 365 kg vessel



THEIA 25kt



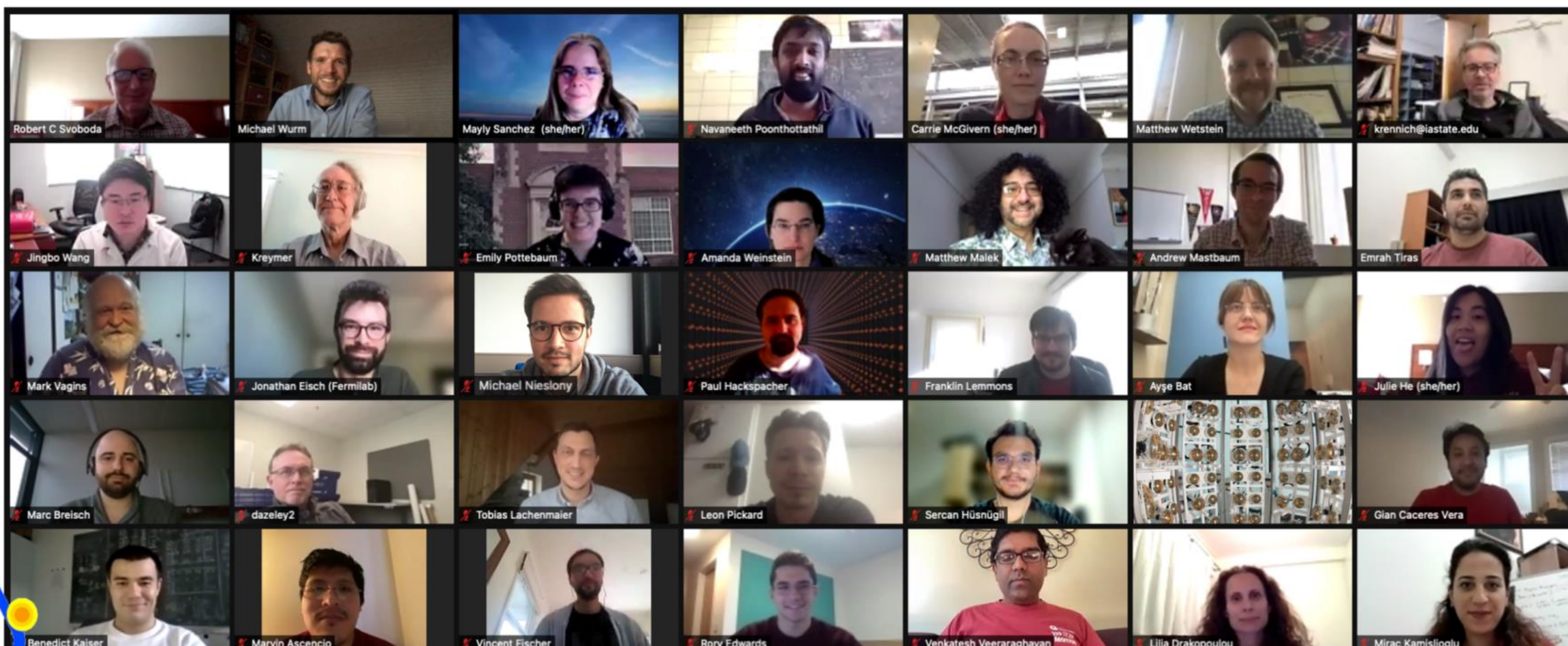
THEIA 100kt

Summary

- **ANNIE** is a **Gd-loaded water Cherenkov detector (26 tons mass)** located in the Booster Neutrino Beam at Fermilab
- **ANNIE goals:**
  - Neutron multiplicity measurement as a function of lepton momentum
  - Demonstrate enabling technologies: Gd-loaded water, fast-timing LAPPDs
- ANNIE has installed the detector, and is now taking **neutrino beam data**
- The first LAPPD has been deployed, which sees beam neutrinos. Four more LAPPDs will be deployed soon, and we will move into physics data taking mode.
- ANNIE will take a test run with WbLS vessel to demonstrate the new neutrino detection technology

ANNIE Collaboration

Thank you!



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Backup

Proton Decay

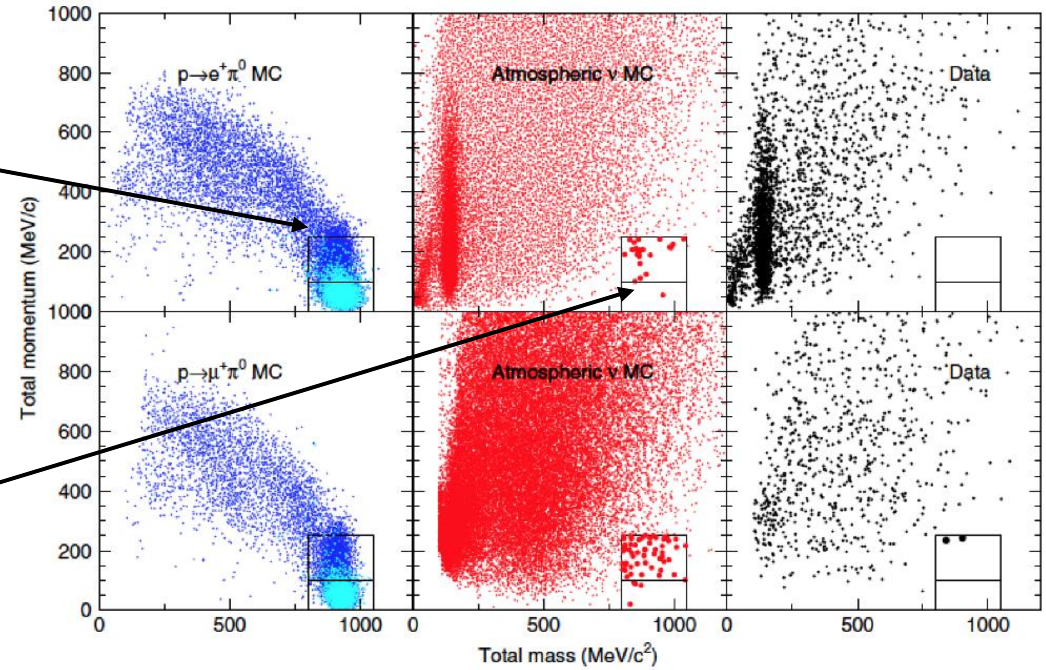
- Proton decay (PDK) remains one of the generic predications made by Grand Unification Theories (GUT)
- Main background from atmospheric neutrino interactions
- Backgound rejection using neutron tagging (n-Gd capture)
- Data is needed to implement the neutron yield in simulation of PDK backgrounds

$p \rightarrow e^{+} + \pi^{0}$

K.Abe et al., Phys. Rev. D, 95:012004, 2017

Proton decay events rarely produce
neutrons in the final state (<10% of the time)

Atmospheric neutrino interactions is likely to produce final state neutrons



Diffuse SuperNova Background

- Supernova neutrino is detected via the Inverse Beta Decay (IBD):

$$\overline{\nu_e} + p \rightarrow e^+ + n$$

- Main background (E>20 MeV): from decay of sub-Cherenkov muons produced by atmospheric neutrinos:

$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu_\mu}$$

$$\mu^- \rightarrow e^- + \overline{\nu_e} + \mu$$

- Michel electrons (positrons) from muon decay may be mistaken for positrons produced in an IBD reaction
- Neutron tagging helps to reduce the background.

Beacom & Vagins, PRL, 93 (2004) 171101