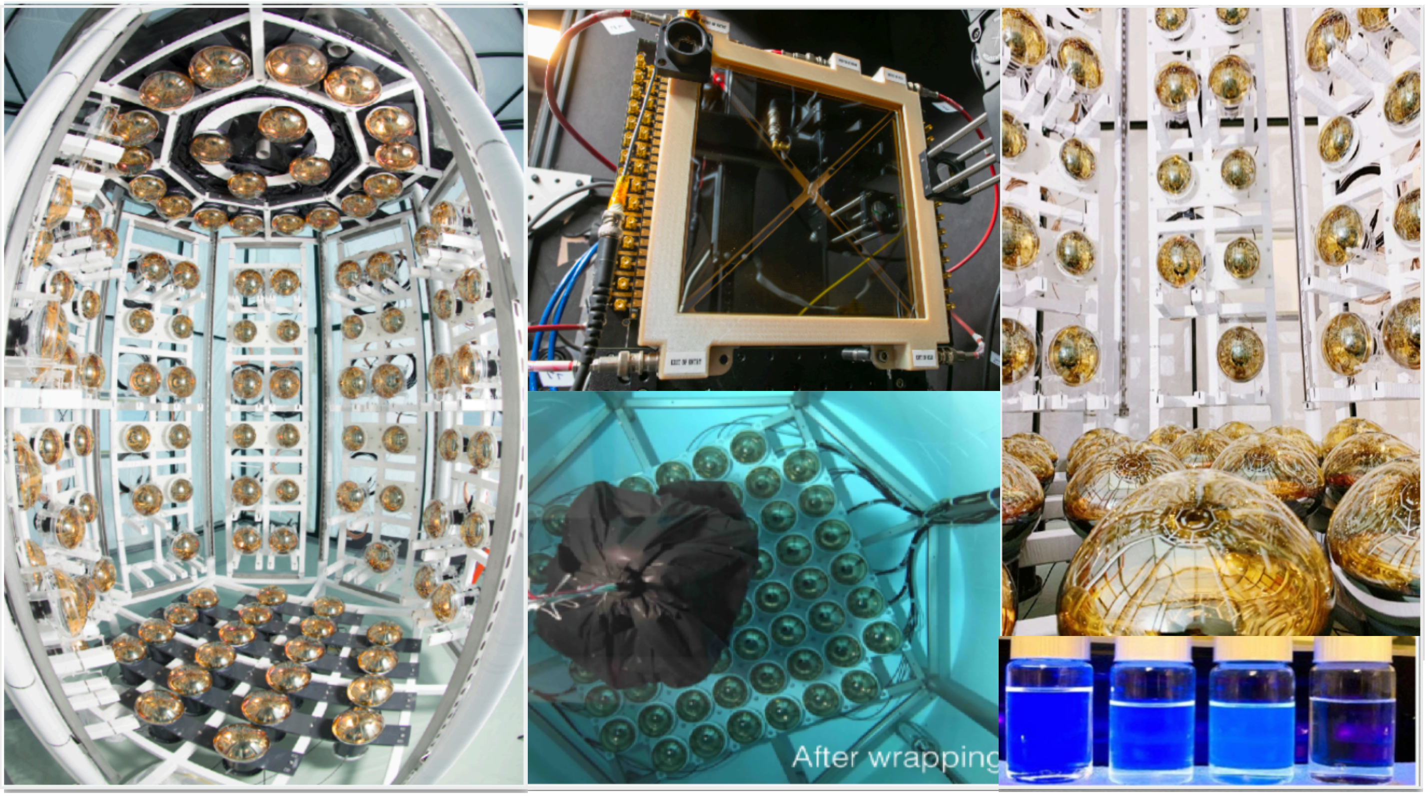
ANNIE Phase II: Experiment Overview and first data

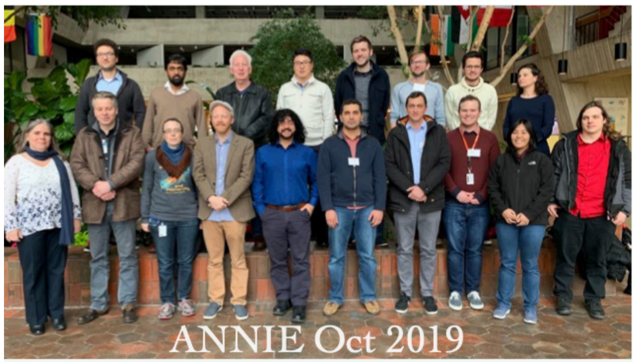


Evangelia Drakopoulou for the ANNIE Collaboration

XIX International Workshop on Neutrino Telescopes – 19 February 2021

The ANNIE Collaboration

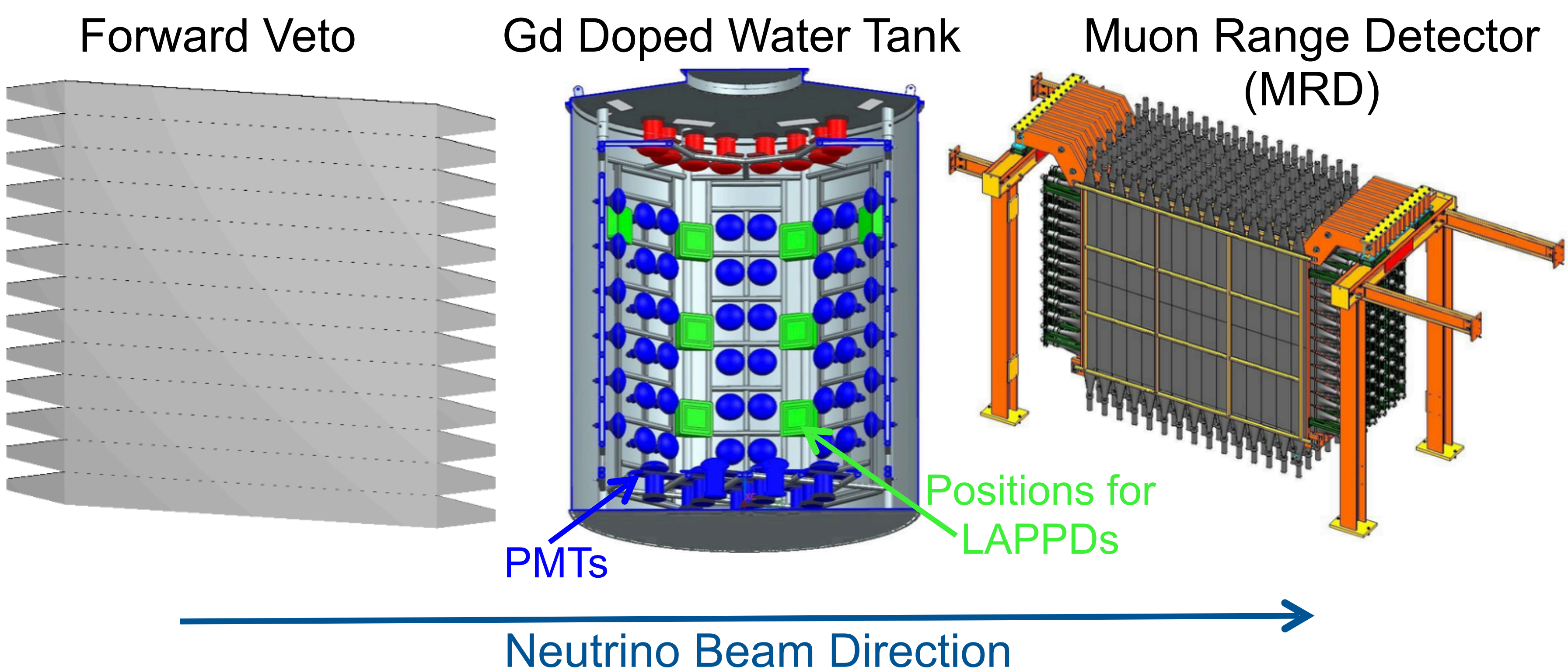
- **ANNIE** is an international collaboration with 17 institutions from 4 countries.



The detector is built and is seeing neutrinos!

The ANNIE Detector

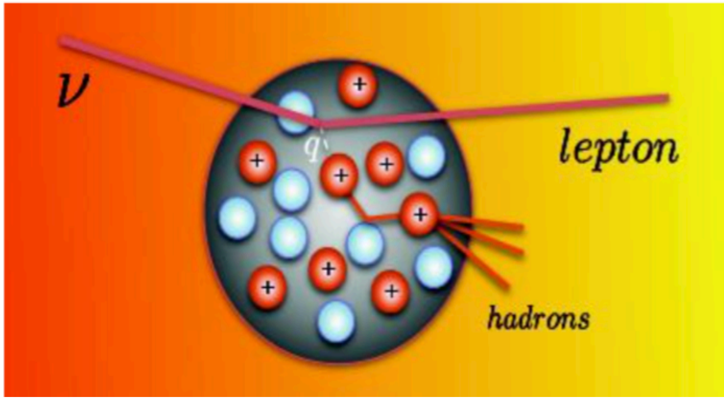
- **A**ccelerator **N**eutrino **N**eutron **I**nteraction **E**xperiment (**ANNIE**): a 26-ton Gd-doped water Cherenkov detector installed in the Booster Neutrino Beam at Fermilab (flux peaks at 600 MeV).

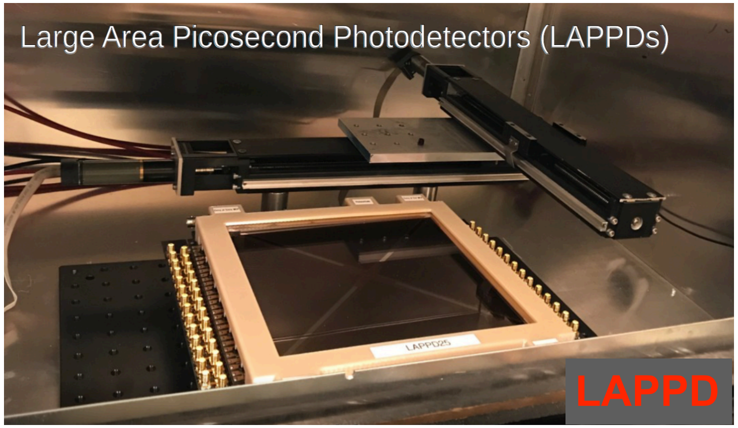


Physics & Technological Goals

Two main goals:

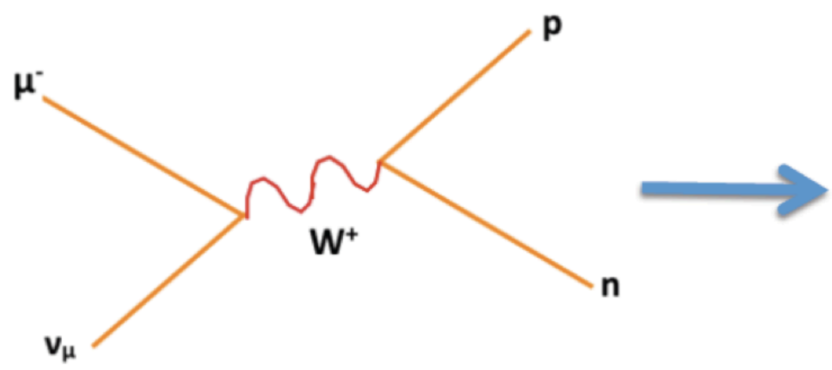
- Better understanding of neutrino-nucleus interactions.
  - Measure the final state **neutron multiplicity** from Charged Current neutrino-nucleus interactions in water.
  - Measure the neutrino cross section in water.
- R&D platform to test new neutrino detection technologies and techniques.
  - Demonstrate the use of fast-timing **Large Area Picosecond PhotoDetectors** (**LAPPDs**) for event reconstruction
  - Detection Medium: Gd-loaded water and eventually Water-based Liquid Scintillator



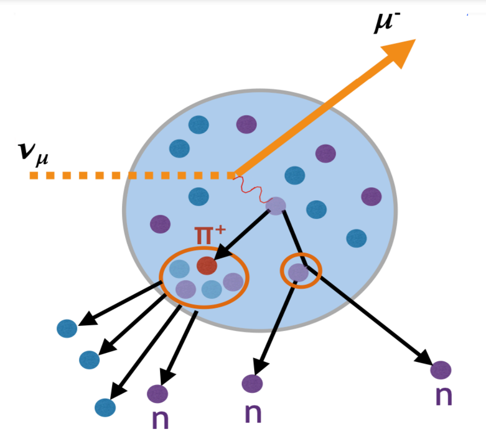


[arXiv:1603.01843 [physics.ins-det]]

Physics Motivation



A simple picture of CCQE interaction



Real nuclear scattering is a many-body problem!

- Neutrons are a major component of the nuclear recoil system and a source of missing energy in neutrino reconstruction/detection.
- ANNIE measures the multiplicity of final state neutrons as a function of the outgoing lepton momentum and direction.

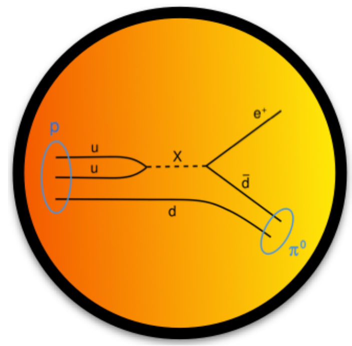
Understanding neutron yields from neutrino interactions is critical to understanding and controlling systematics uncertainties on neutrino energy reconstruction in precision **oscillation physics**.

Impact on Astronomical Neutrinos/Rare Processes

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

- In searches for the **Diffuse Supernova Neutrino Background (DSNB)**, the presence of any additional neutrons beyond the single inverse beta decay neutron can be used to tag and remove higher energy atmospheric neutrino backgrounds (mostly Neutral Current).

- For **proton decay searches**, the presence of final state neutrons can be used to efficiently identify backgrounds from atmospheric neutrinos.



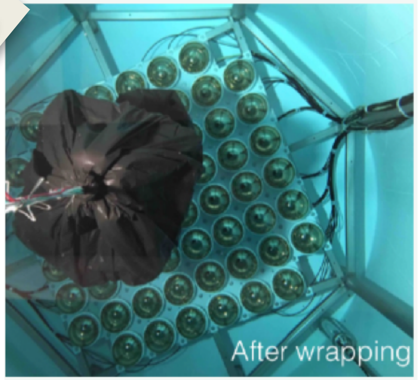
Estimates of signal purity require an accurate understanding of the neutron multiplicity from the specific class of background events that fake these rare signals.

Status of the Experiment

2016 — 2018 — 2021

Past:
ANNIE – Phase I

Completed



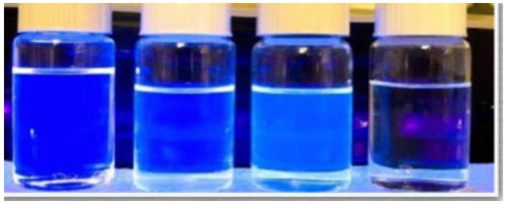
- Neutron background measurements in the detector site in Fermilab.
- Successful operation phase of the detector.

Present:
ANNIE – Phase II

NOW

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

Future:
ANNIE – Phase III

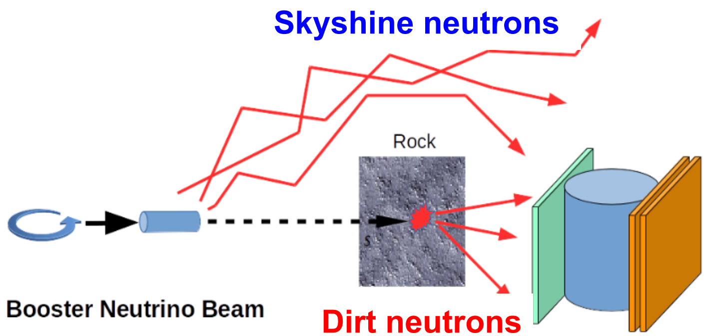


- More LAPPDs: multi-track reconstruction
- Water-based Liquid Scintillator (WbLS)

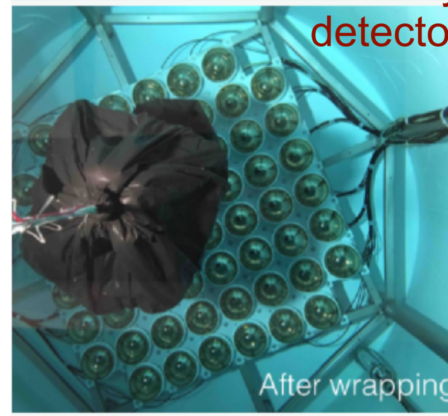
ANNIE Phase I

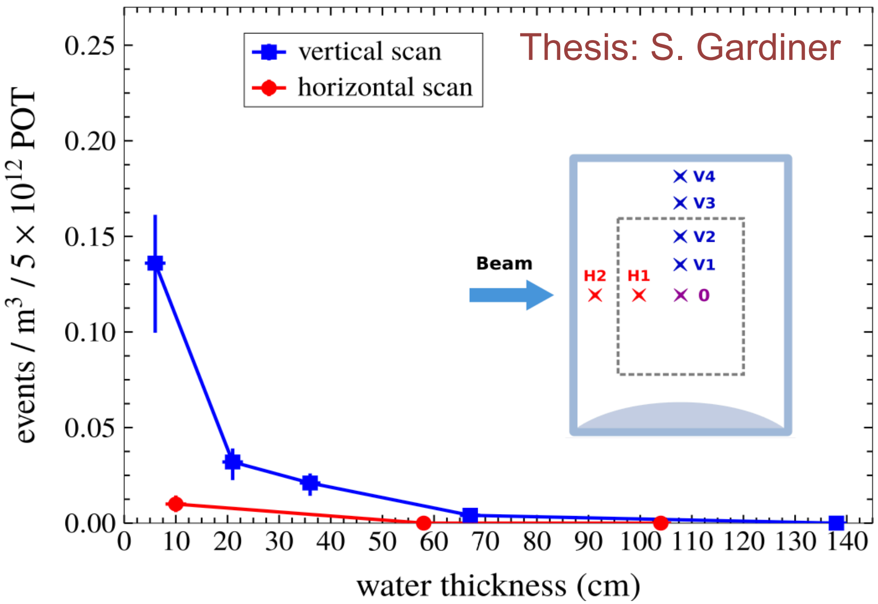
Completed

- ANNIE Phase I: Measurement of the neutron background (dirt neutrons and skyshine neutrons) in the detector site.



- Partially instrumented detector: 60 PMTs
  - Data from: 2016-2017





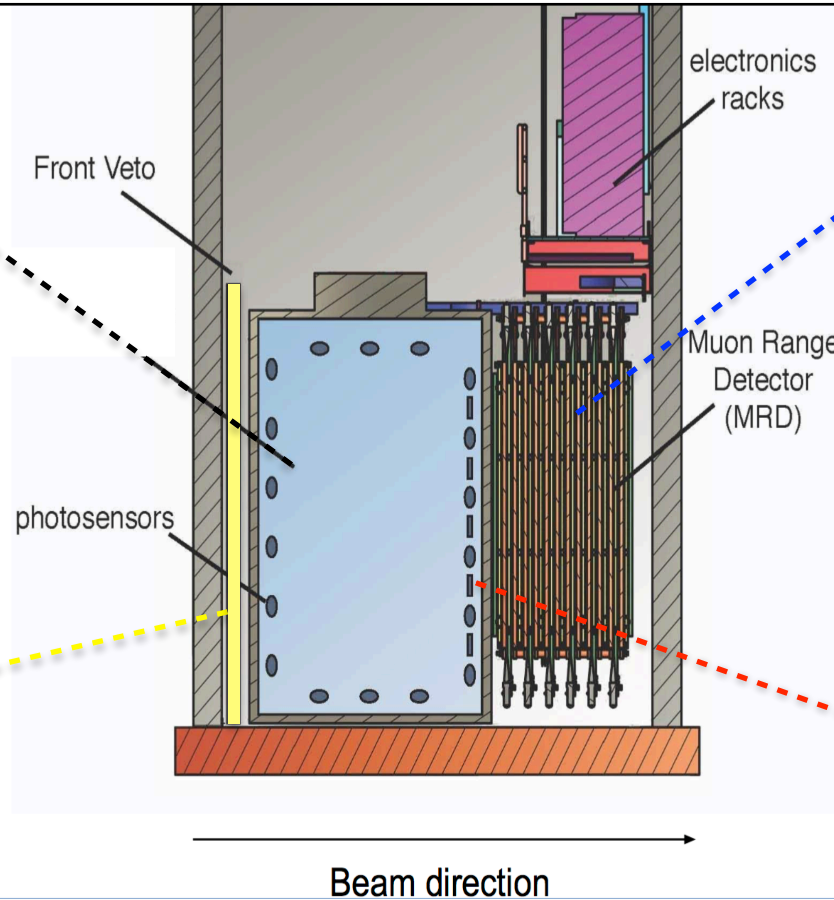
- These backgrounds were found to be small and will be mitigated by the buffer layer of water above the detector.

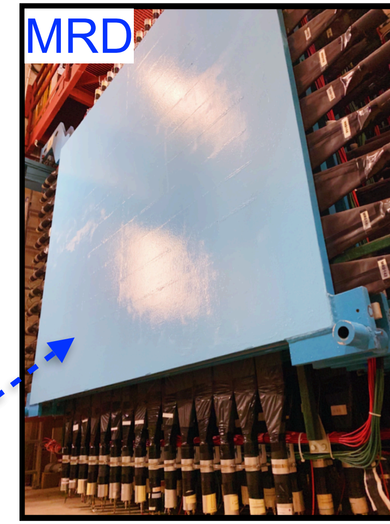
Published in JINST: arXiv:1912.03186 [physics.ins-det].

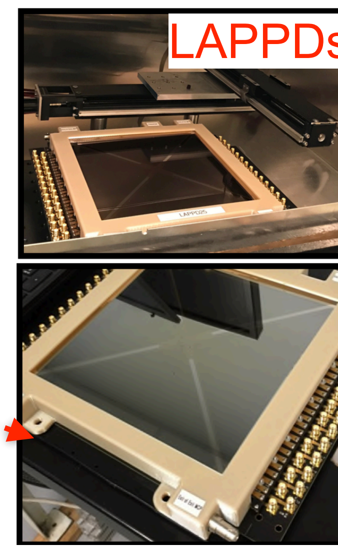
ANNIE Phase II

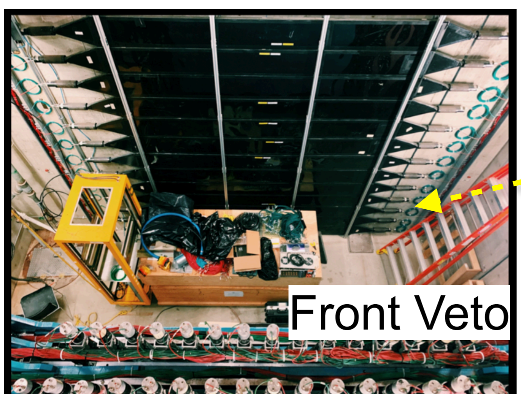
- 132 8-11” PMTs
- 5 fast photosensors (LAPPDs)
- MRD: muon paddles with 2” PMTs and 2” iron absorber in between

Steel tank holds 26-ton of Gd-loaded water

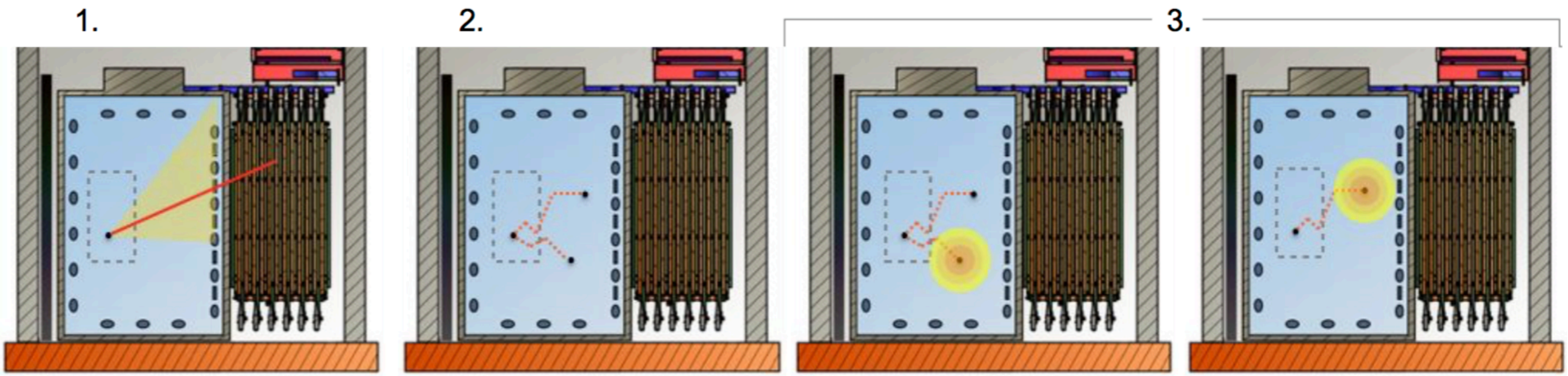


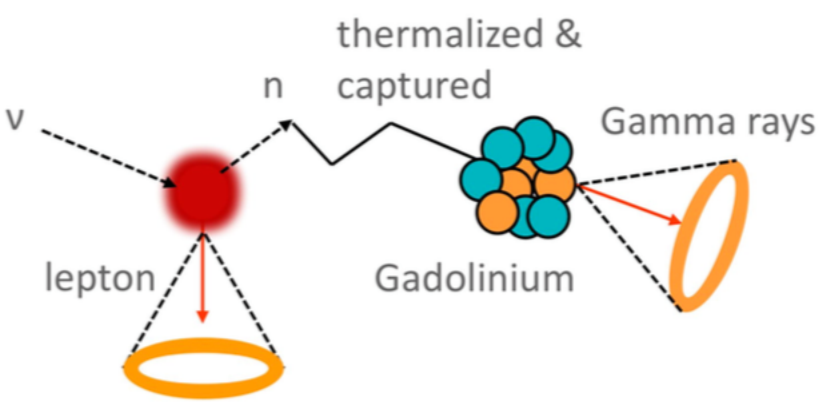






Event Signatures in ANNIE



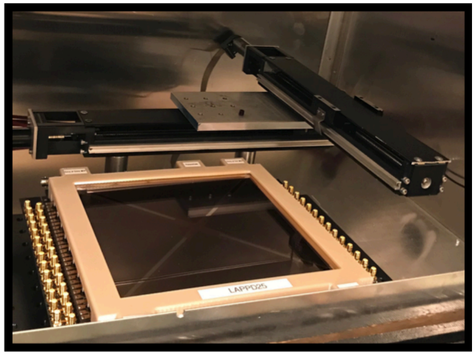


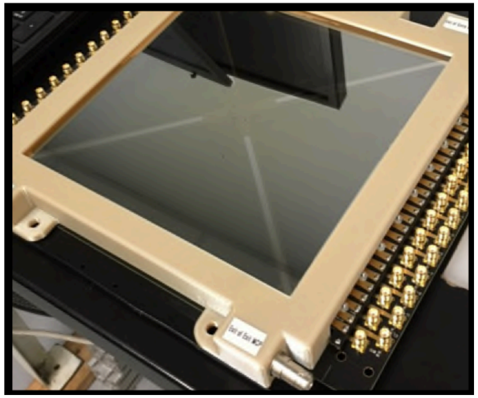
1. Charged Current neutrino interactions in fiducial volume
→ Cherenkov cone incident on PMTs and LAPPDs
→ Scintillation light from stopping muons in MRD

2. Final state neutrons thermalised and captured in Gd

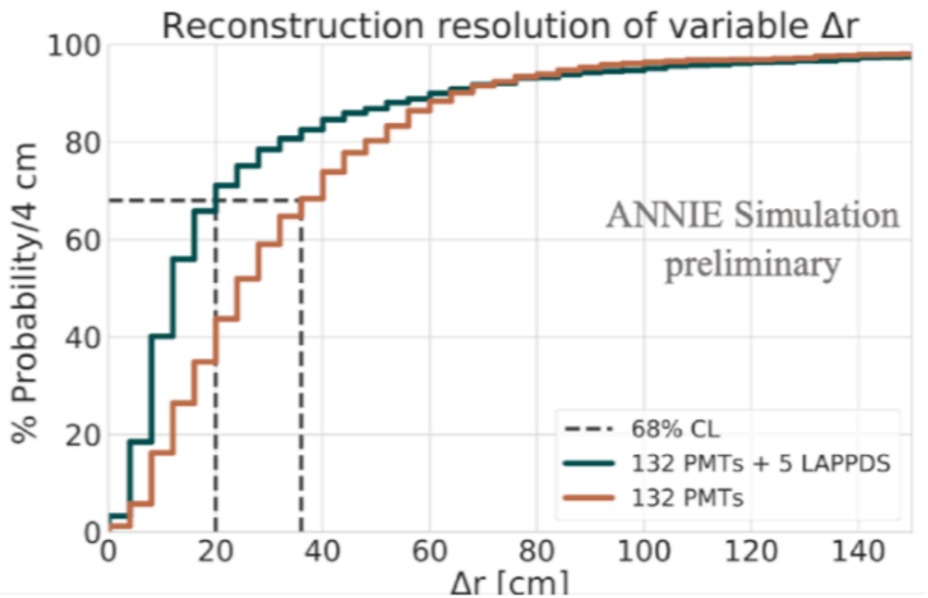
3. Cascade of 8 MeV detected by PMTs

LAPPDs – A new technology tested in ANNIE





Micro-channel plate, fast-timing photodetectors
- Large-area: 20 × 20 cm
- Fast timing: ~60 psec time resolution
- High quantum efficiency (QE): >20 %
- Position resolution: mm scale
- Operable in a magnetic field

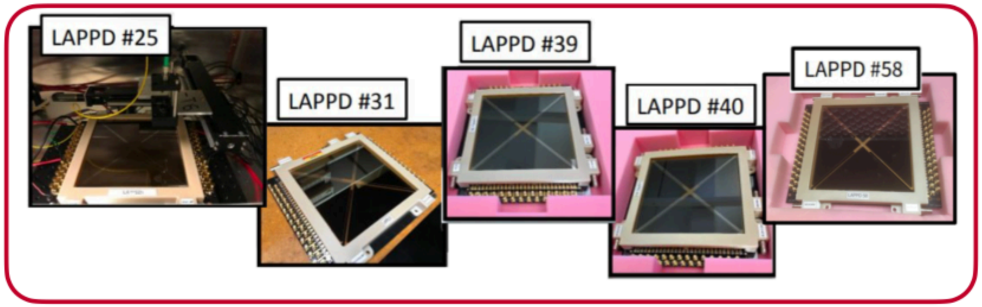


- Both angular and spatial resolutions benefit substantially from using LAPPDs.

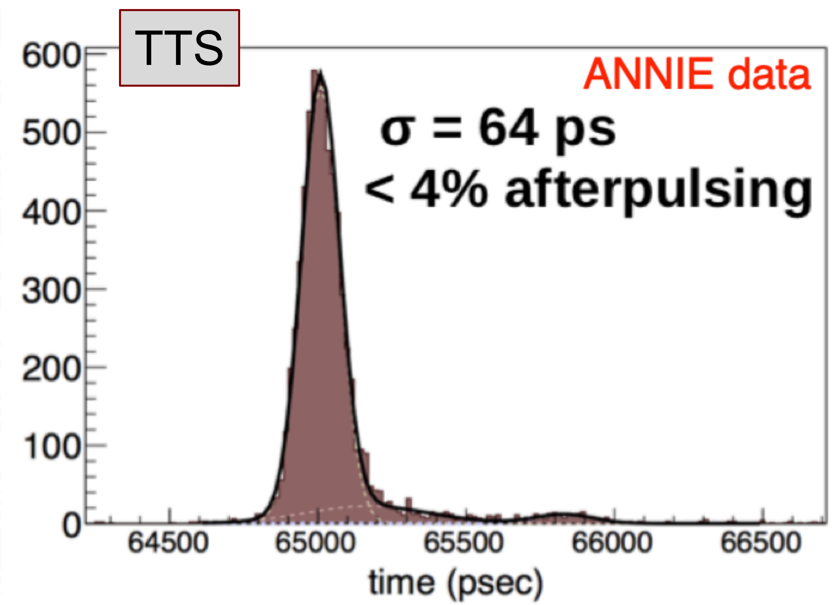
For more details on LAPPDs see: *Nucl. Instr. and Meth. in Phys. Res. A 822 (2016) 25–33*

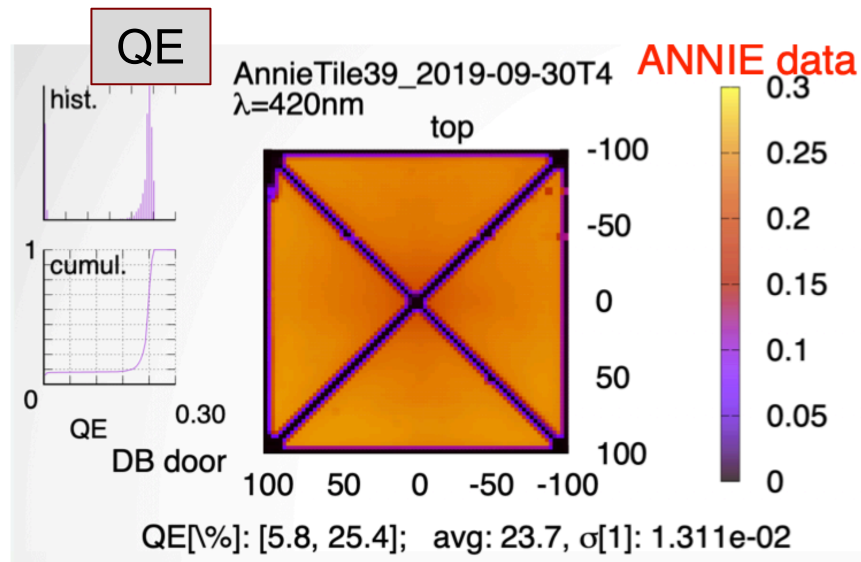
Characterisation of the 5 ANNIE LAPPDs in Fermilab

ANNIE LAPPDs



- Timing resolution and after pulsing within ANNIE specs: ~60 second and < 4 % afterpulsing.
- Scan results for tile show average QE at 23.7% and very uniform distribution over whole area.

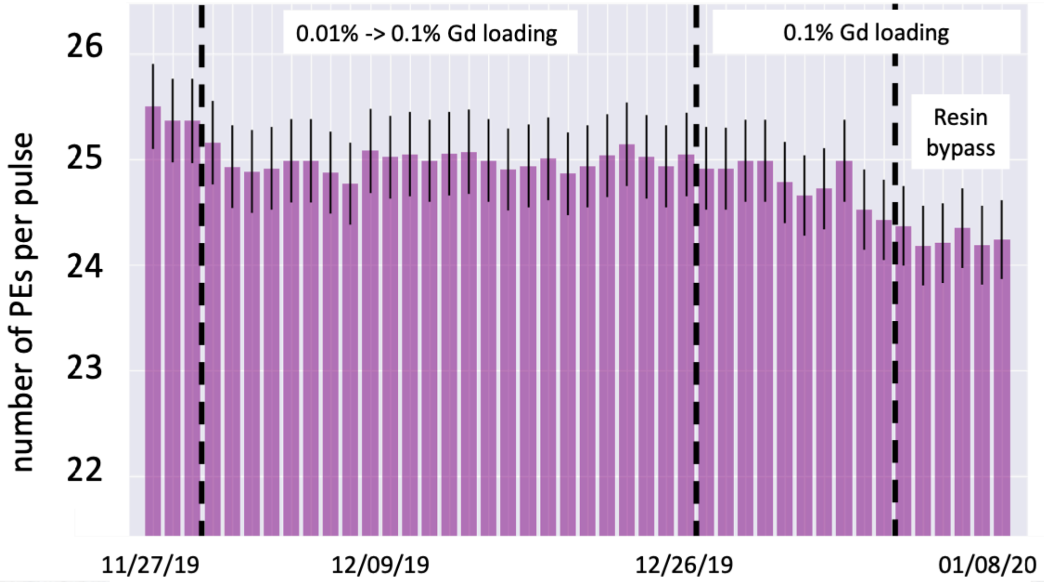




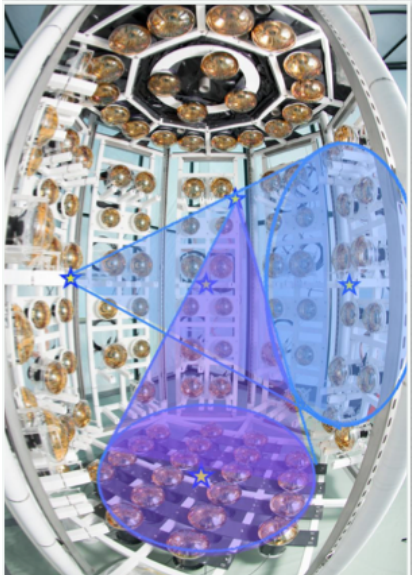
Detector Operation with Gd-loaded water

ANNIE reached its nominal Gd-loading on December 24th (2019) !

- Custom purification system for small-scale Water Cherenkov detectors developed by UC Davis collaborators. Published in *JINST15 (2020) 07 P07004*.
- Water is nicely transparent with no rust observed.

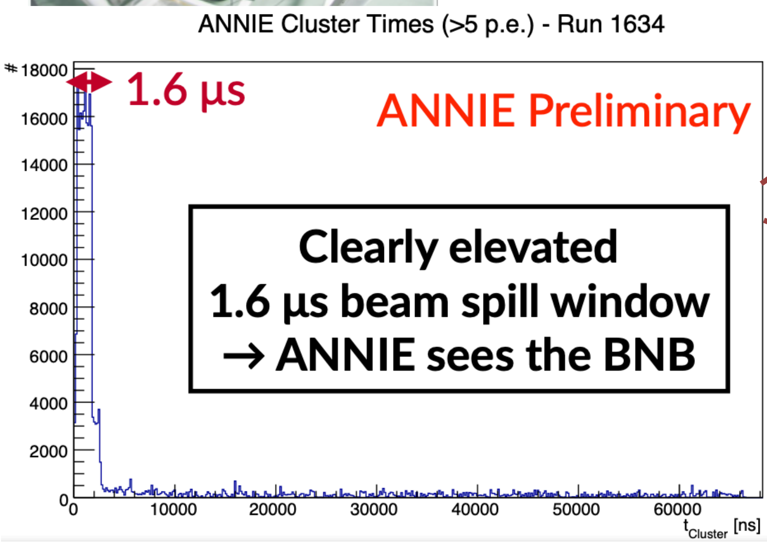


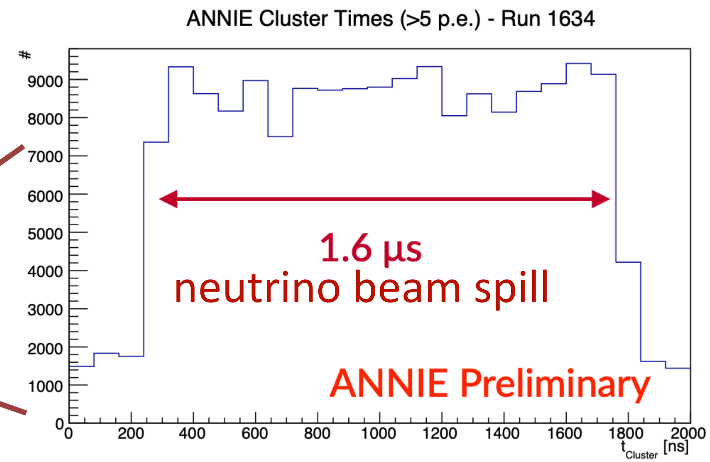
Detector Calibration & Commissioning



Neutron Calibration using AmBe:
- Evaluate the efficiency of the neutron captures

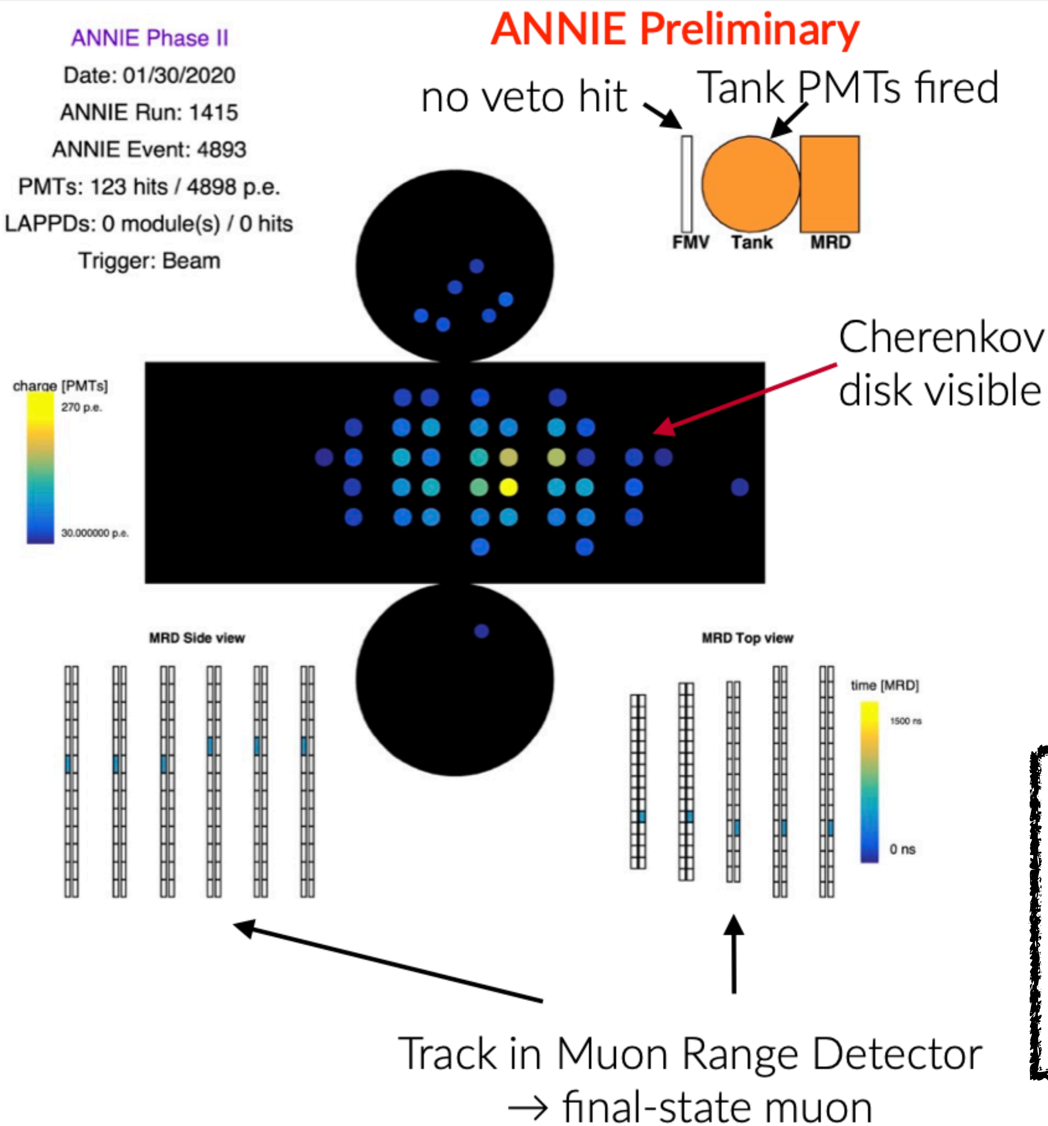
Calibration using LEDs:
- Track transparency of the detector
- PMT gain calibration
- 1st order PMT cable delay corrections





- ANNIE reads out a 70-80 μsec window from the PMT system which results in >90% neutron capture efficiency.

First Neutrinos in ANNIE



- PMTs hits closely clustered in time.
- Clear Track in MRD.
- No veto activity.

ANNIE observed the first beam neutrinos!

Next Steps:

- Deploying the LAPPDs to the tank - February 2021.
- Physics Measurements.

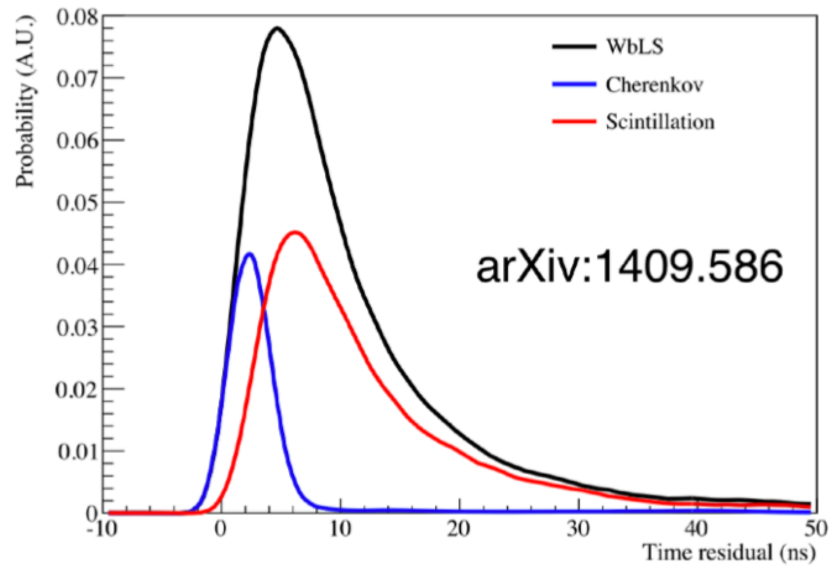
ANNIE Phase III - The Future

WbLS: Novel Technology

<u>Combining the best of both worlds</u>:

- **Water-based Liquid Scintillator (WbLS):** a novel detection medium for which Liquid Scintillator droplets are dissolved in water.
- Directionality and kinematic reconstruction from Cherenkov light and high light yield and calorimetric reconstruction from scintillation light; while maintaining high transparency and low cost.
- **Fast photosensors** would allow to separate Cherenkov from scintillation light.

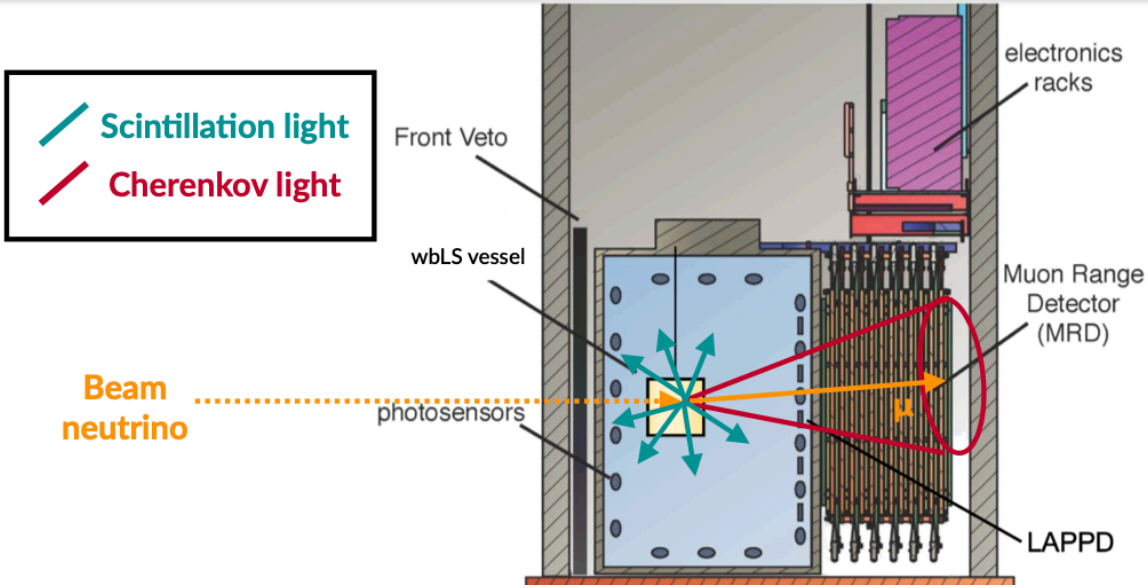
Water-based Liquid Scintillator time profile



WbLS samples with different concentrations

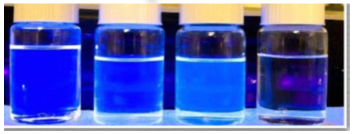
ANNIE Phase III - The Future

WbLS: Novel Technology

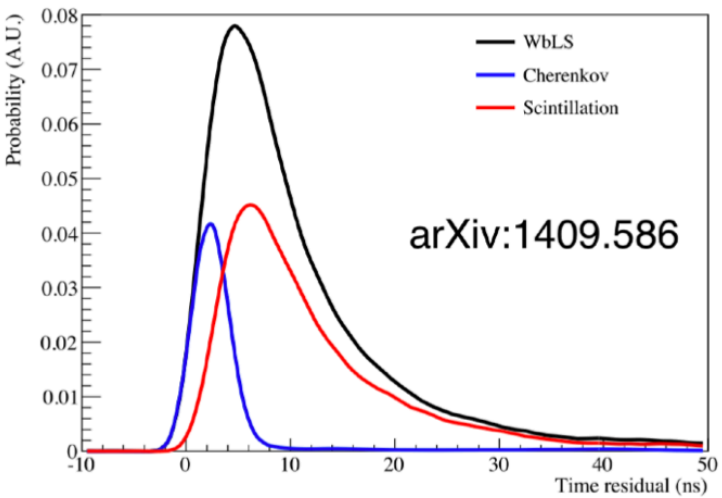


WbLS vessel
500 litres

Rough visualization of vessel
(NOT final design)

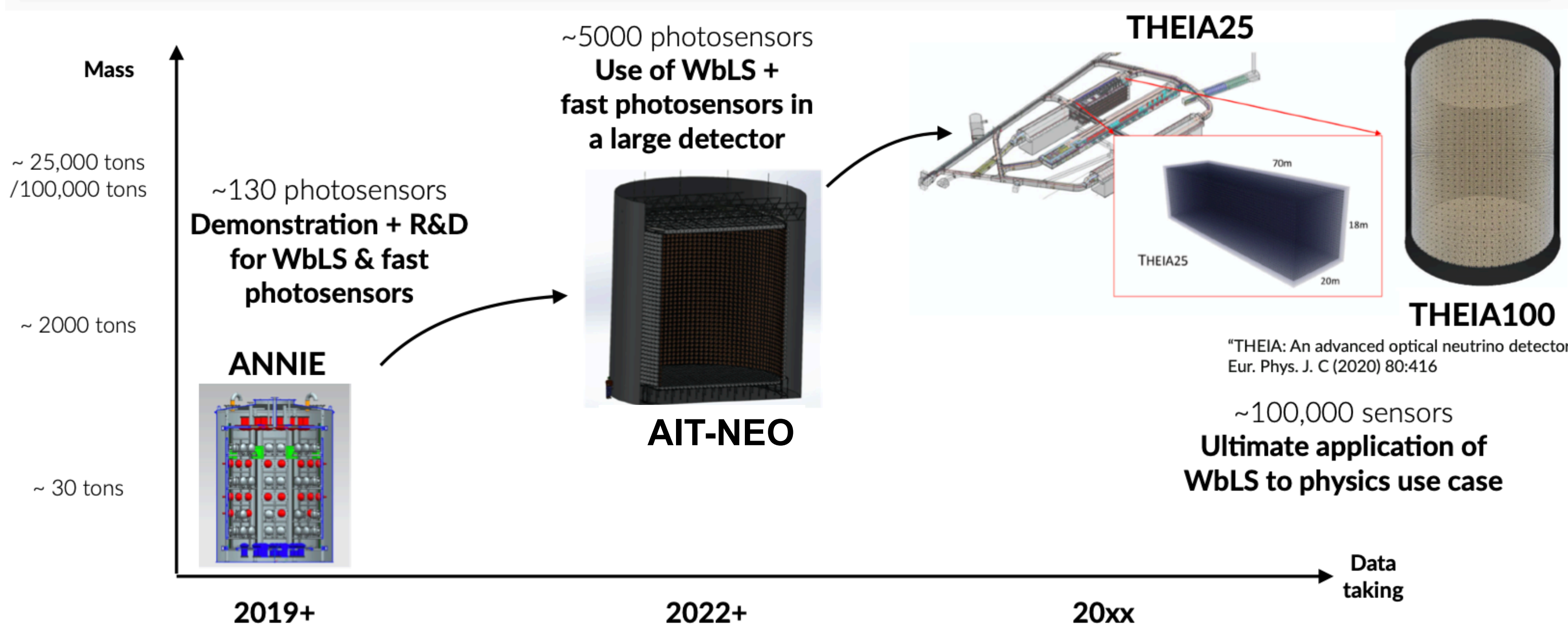


Water-based Liquid Scintillator time profile



- Different amounts of LS loading (1%,5%,10%) → evaluate benefits on reconstruction.
- Show feasibility of WbLS in a neutrino-beam environment.

ANNIE as a testbed for next-gen experiments



- ANNIE is the first step in a series of efforts to develop a series of detectors that will offer new capabilities.
- WbLS efforts will offer valuable input to AIT-NEO and THEIA.

Conclusions

- ANNIE will measure the neutron yield as a function of the momentum transfer from neutrino-nucleus interactions in water and the neutrino cross section in water.
- To fulfil its scientific goals ANNIE will use LAPPDs and Gd-doped water.
- The detector has been calibrated and is now taking data.
- First beam neutrinos and neutrons have been observed.
- LAPPDs will be added this month followed by physics data taking.

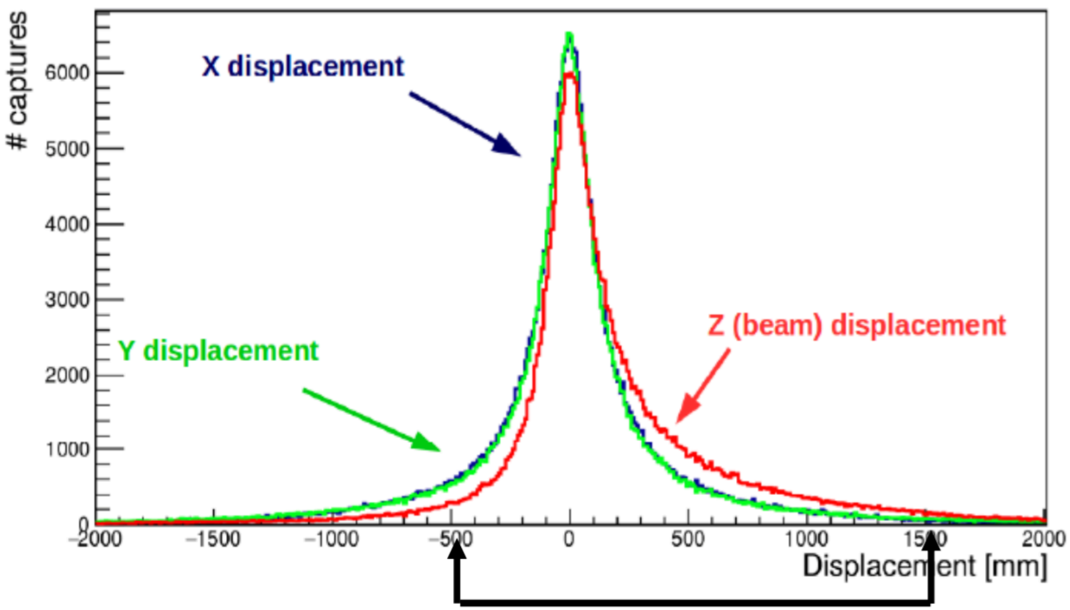
Thank you !

Backup

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 ~ 20 cm is needed to properly identify events in the fiducial volume.

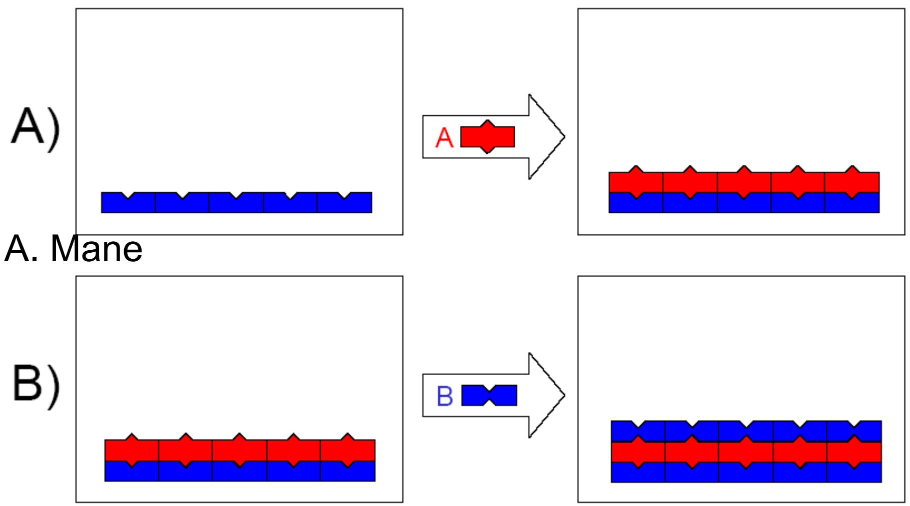


- Such resolution is beyond the capability of traditional PMTs!
- Precise timing-based reconstruction enabled by LAPPDs is essential.

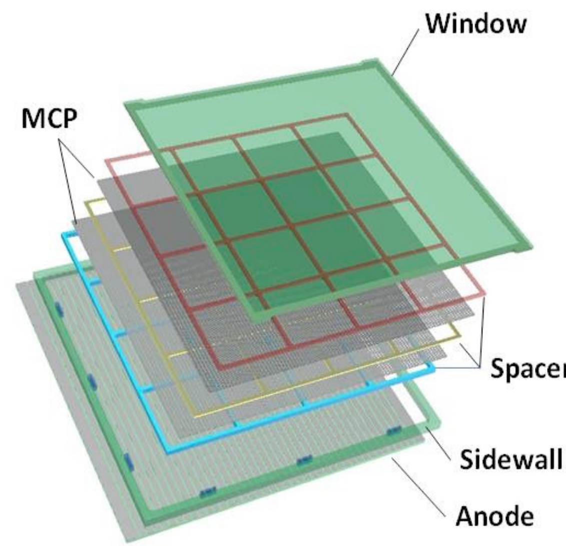
LAPPDs – A new technology tested in ANNIE

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

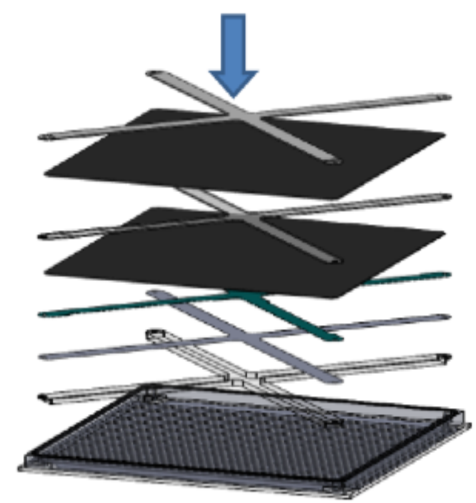
Atomic Layer Deposition



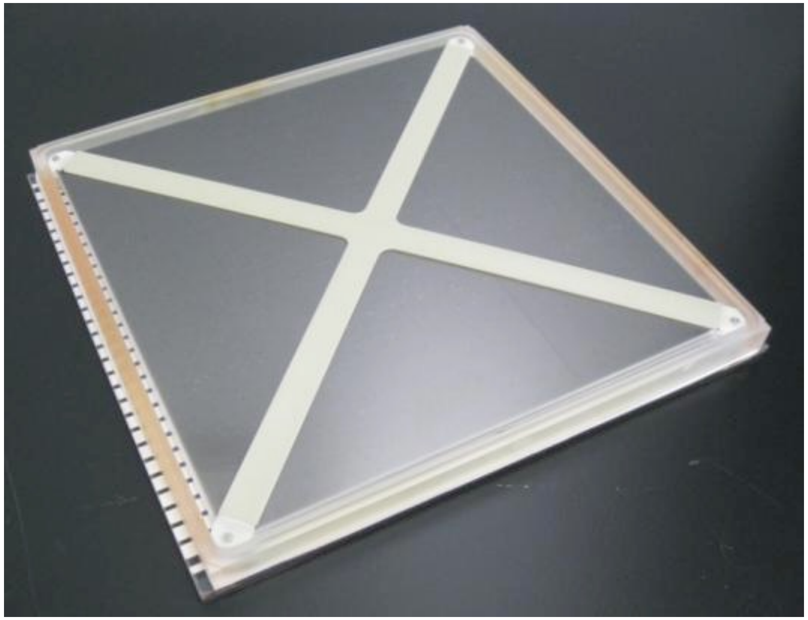
J. Elam, A. Mane



Design Drawing - September 2010



The LAPPD Concept



LAPPD detectors:

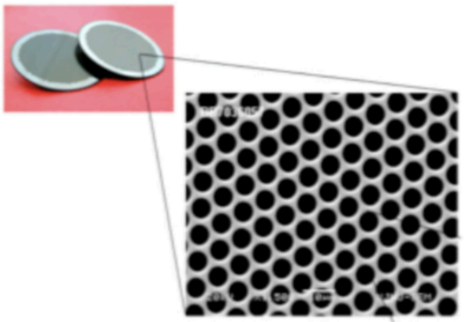
- Thin-films on borosilicate glass
- Glass vacuum assembly
- Simple, pure materials
- Scalable electronics
- Designed to cover large areas

Conventional MCPs:

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

The LAPPD Concept

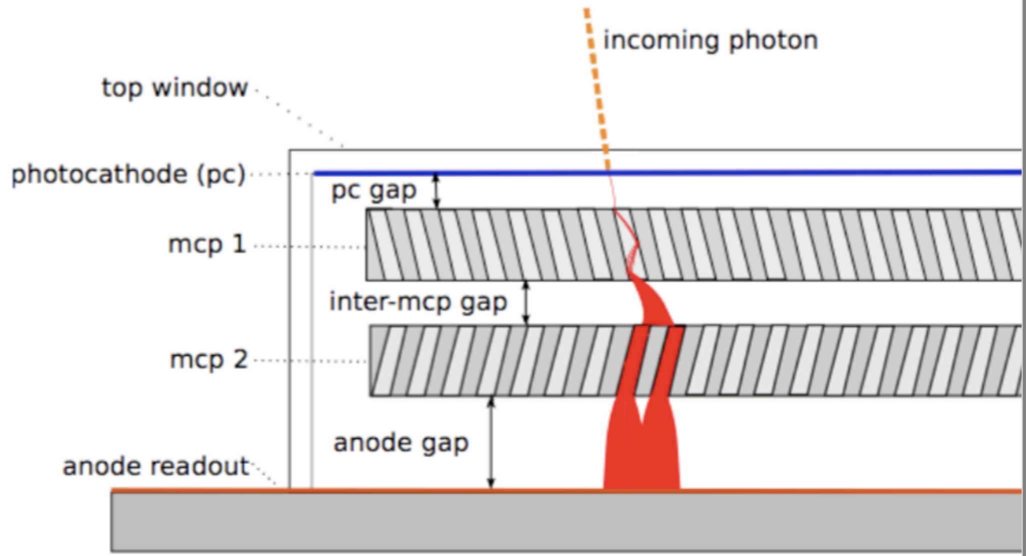
What is an MCP–PMT?



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

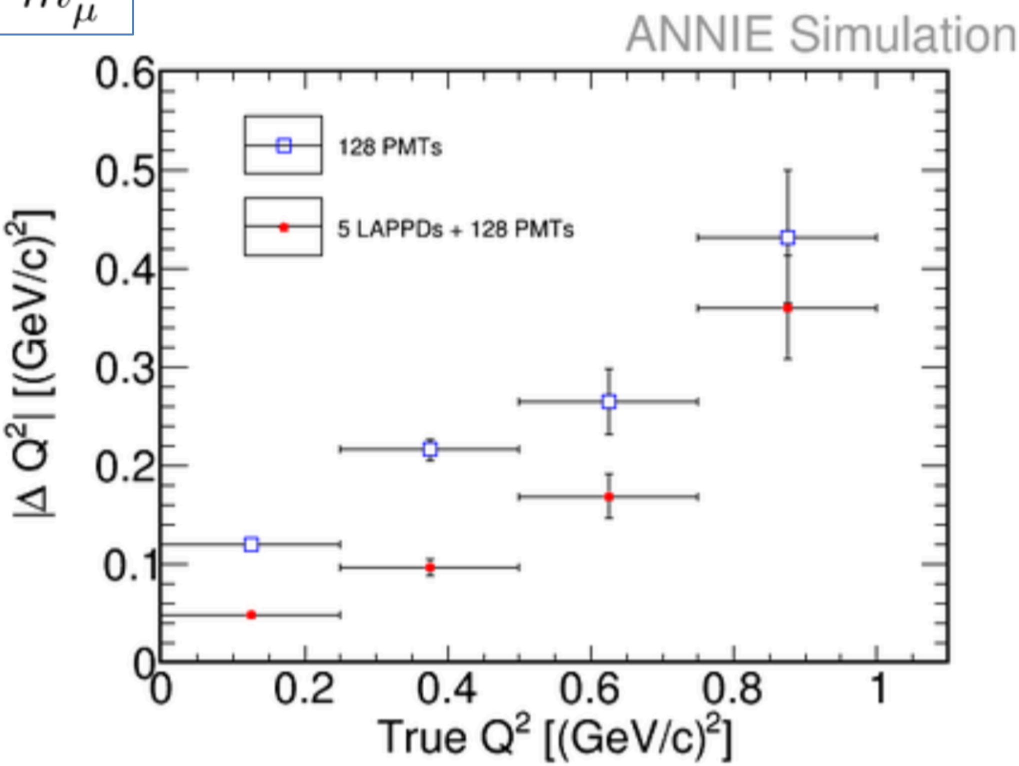


Momentum Transfer: Q^2

- 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.



Vertex and Track Reconstruction

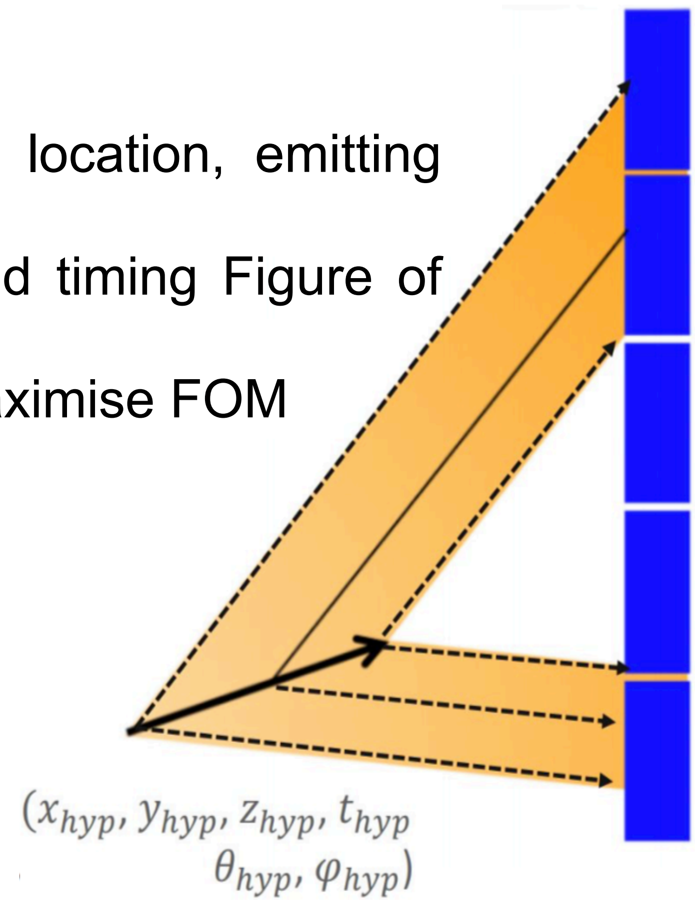
Steps:

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