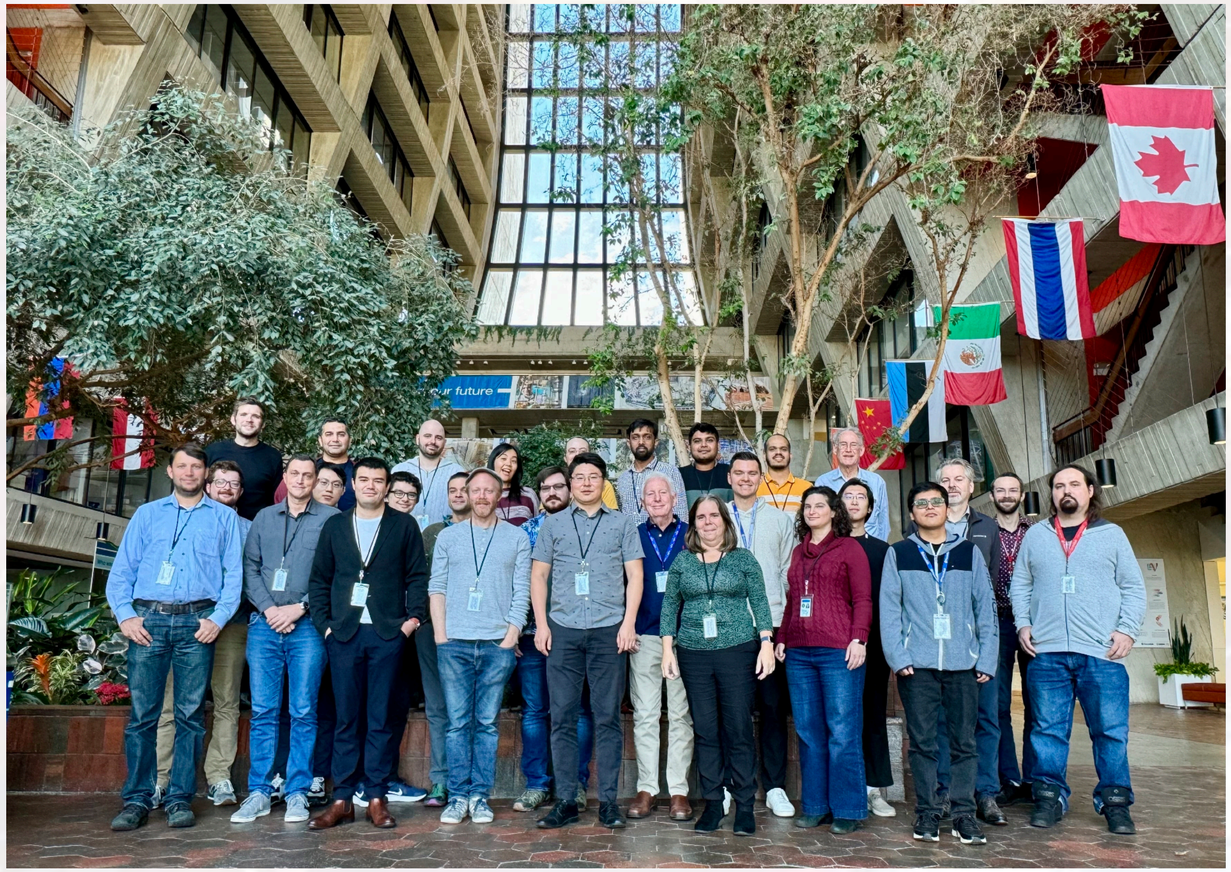
The Pioneering Contributions of the ANNIE Experiment at Fermilab

Marvin Ascencio-Sosa
On behalf of ANNIE collaboration

Prague, July, 2024

Accelerator Neutrino Neutron Interaction Experiment



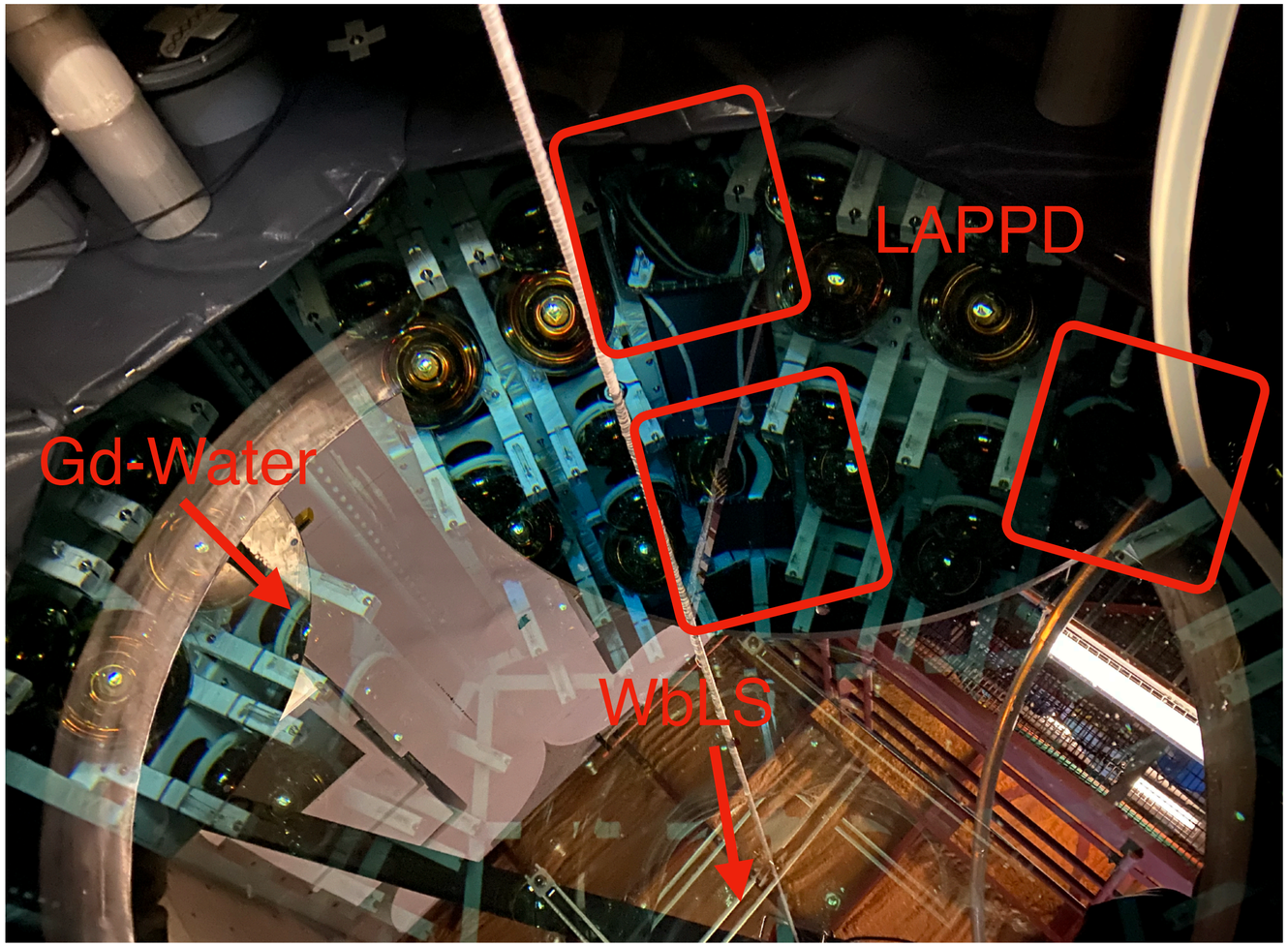
ANNIE has 45 collaborators from 17 institutions in 6 countries

- ANNIE is a 26-ton Cherenkov neutrino detector in the BNB line at Fermilab.

ANNIE Goals

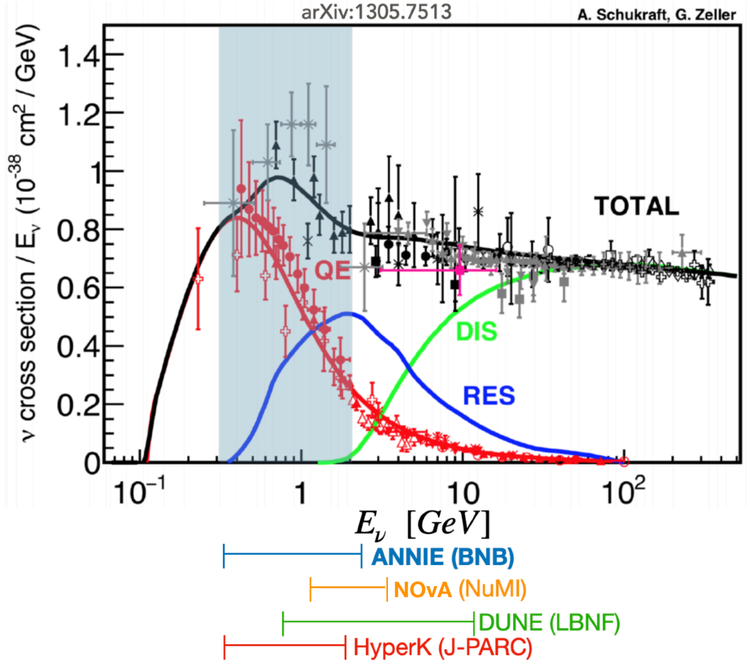
- Detector R&D: Demonstrate novel neutrino detector technologies
  - Fast Photosensors (LAPPDs)
  - Novel target media (Gd-Water and WbLS)
- Physics: Neutrino interaction with Gd-loaded water target focused on neutron yield

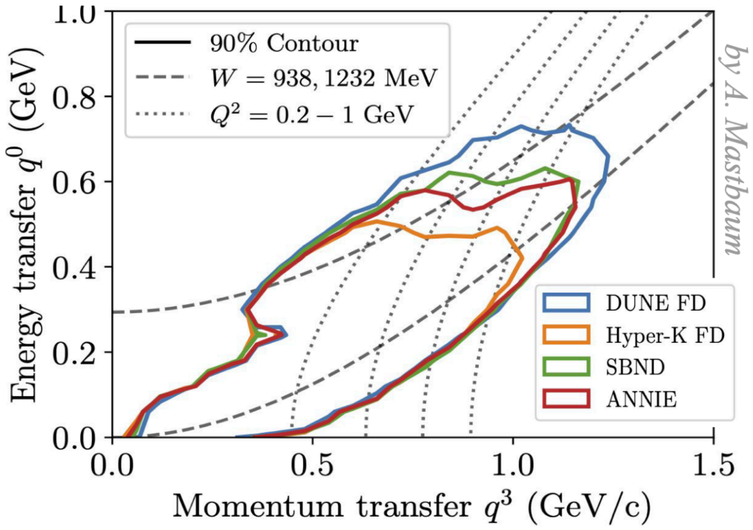
Outline (Spoiler Alert!)



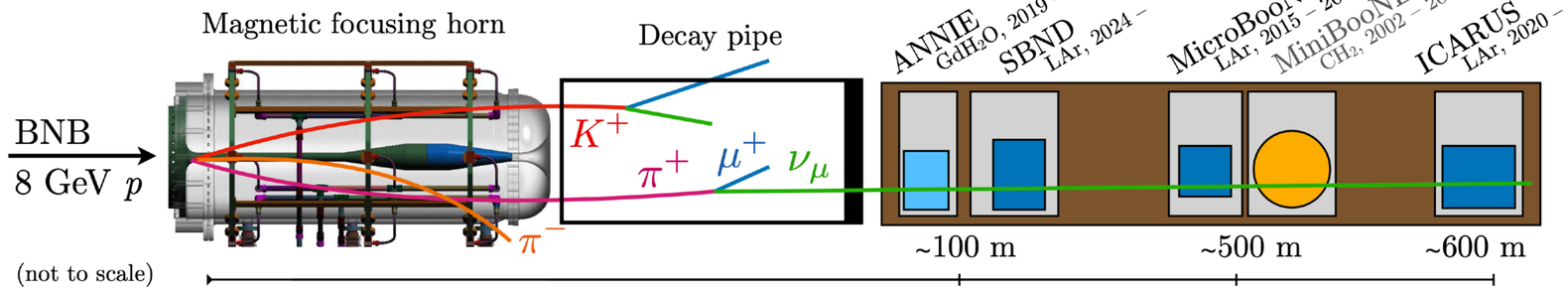
- ANNIE
  - Physics
  - Detector
- First beam neutrino experiment detected by gadolinium-loaded water. **(2019)**
- First neutrino experiment using Large Area Picosecond Photodetectors (LAPPD). **(2022 & 2024 3-LAPPDs)**
- First neutrino experiment using Water Base Liquid Scintillation (WbLS). **(2023)**

ANNIE Physics

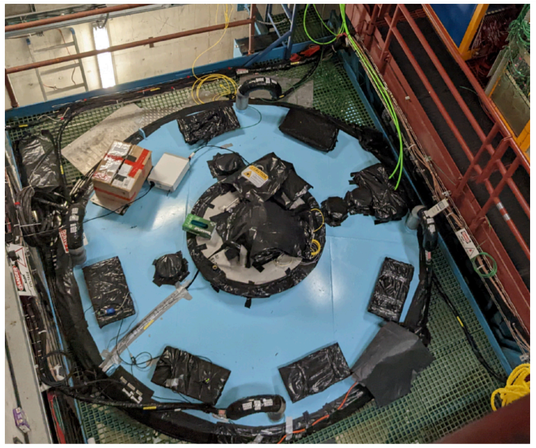


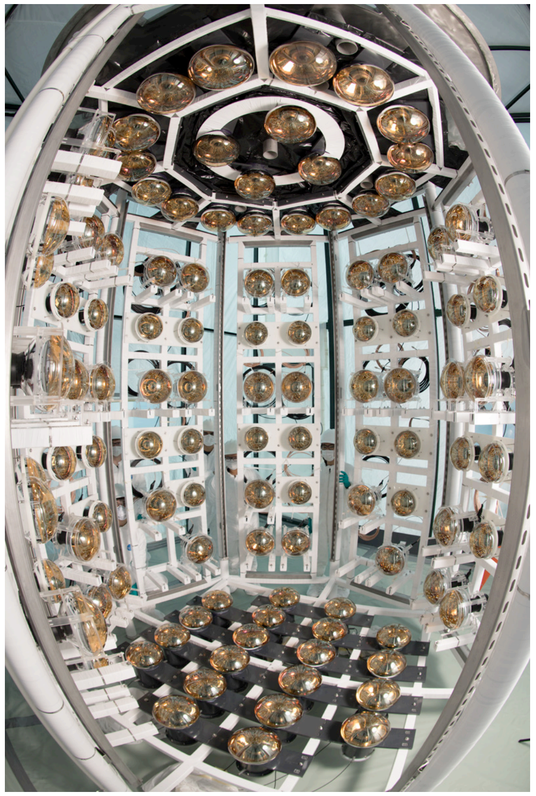


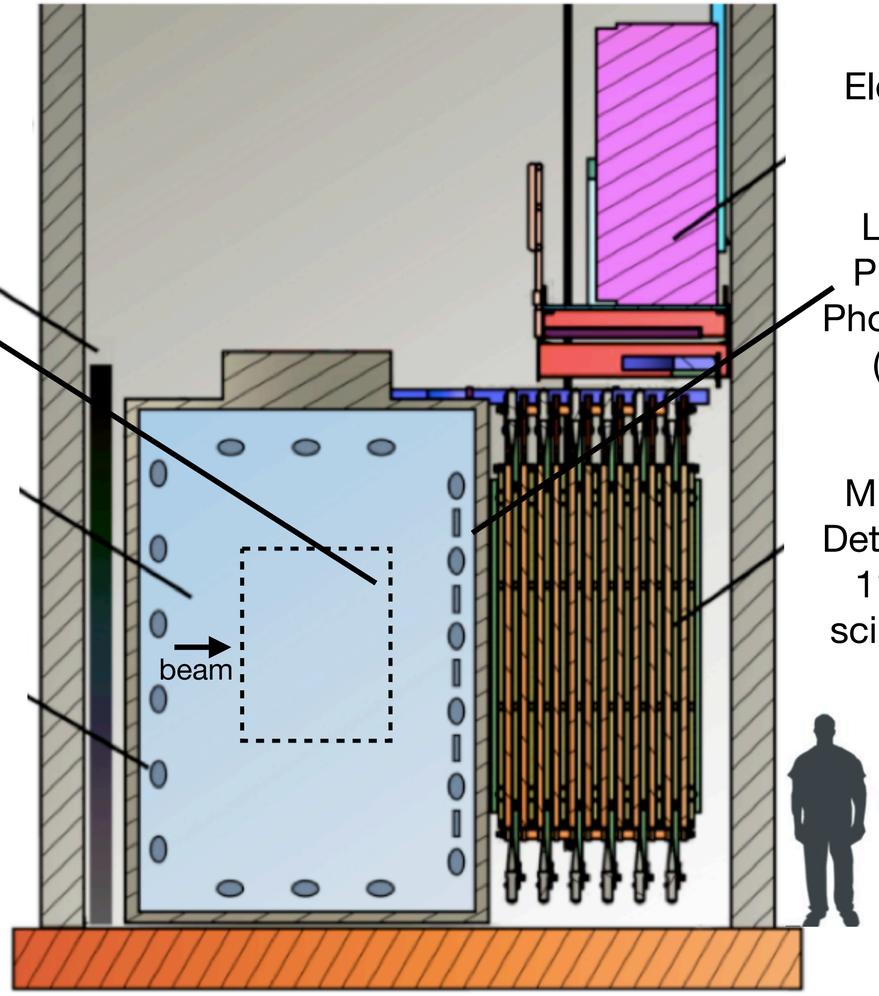
- ν_μ CC differential cross section with water target, final state neutrons.
- ν NC interaction, background constraint for Long Baseline, p-decay, and DSNB searches.
- High flux (close to BNB) overlaps with HyperK/DUNE neutrino energy.
- Multi-target cross-section measurements (^{40}Ar/H_2O). Same neutrino beam as SBN LArTPCs



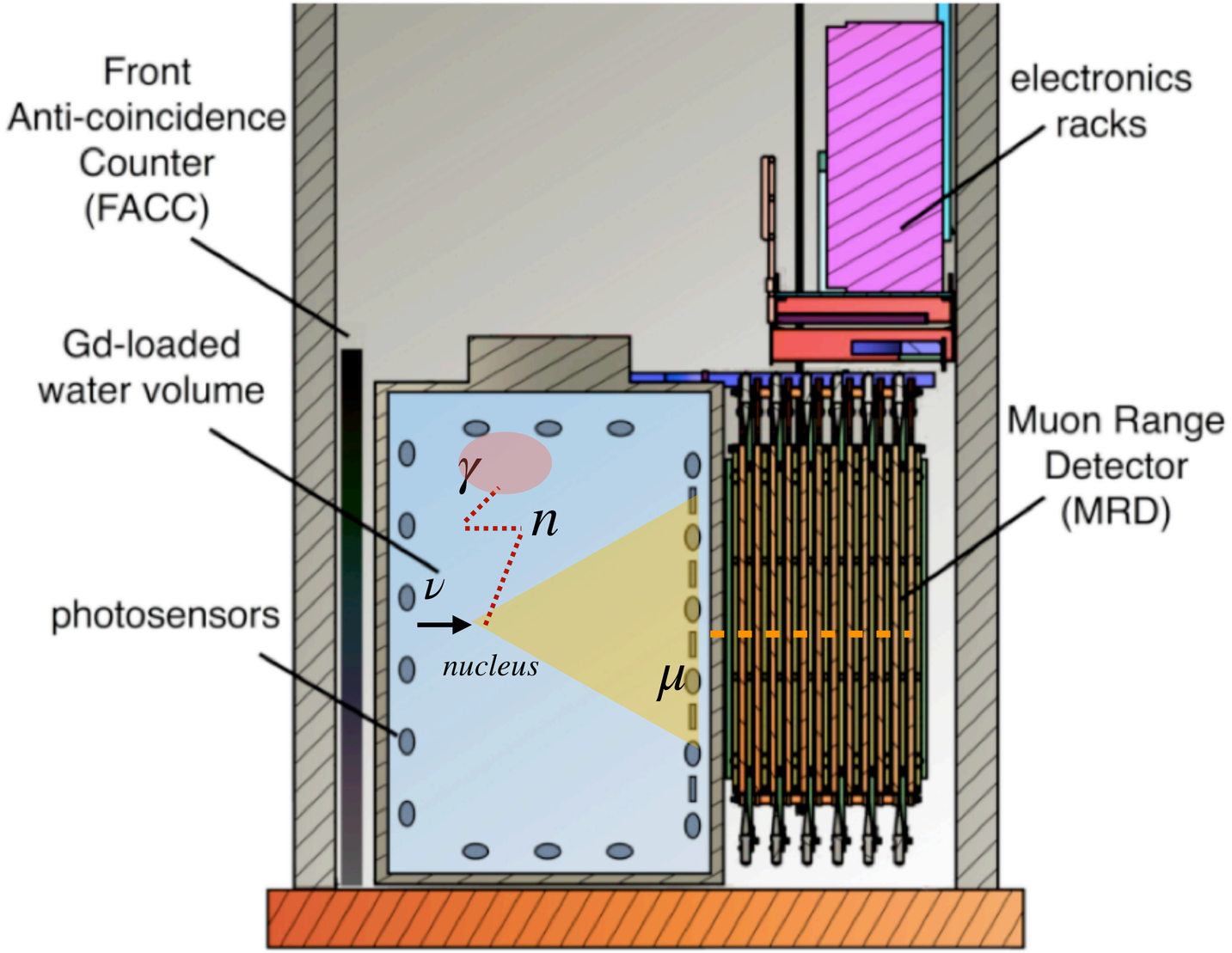
ANNIE detector

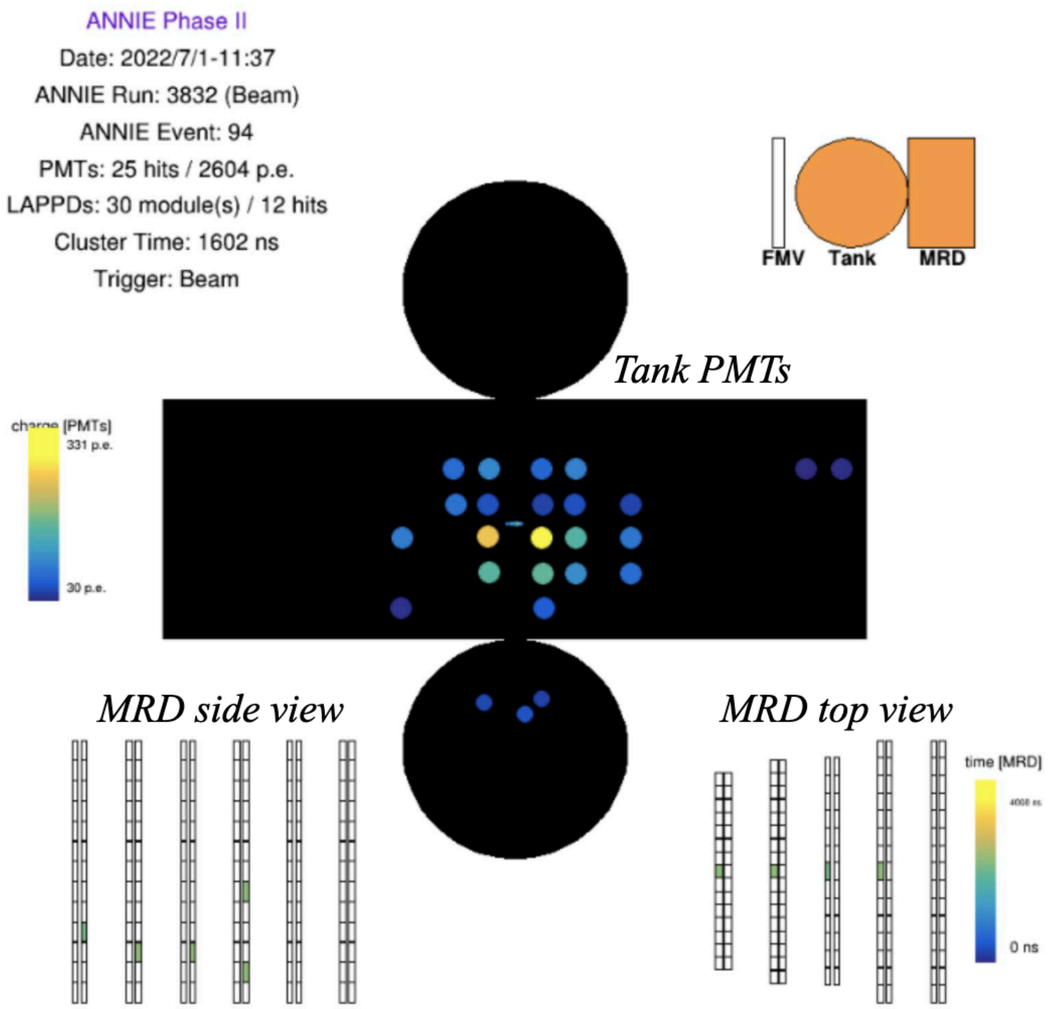






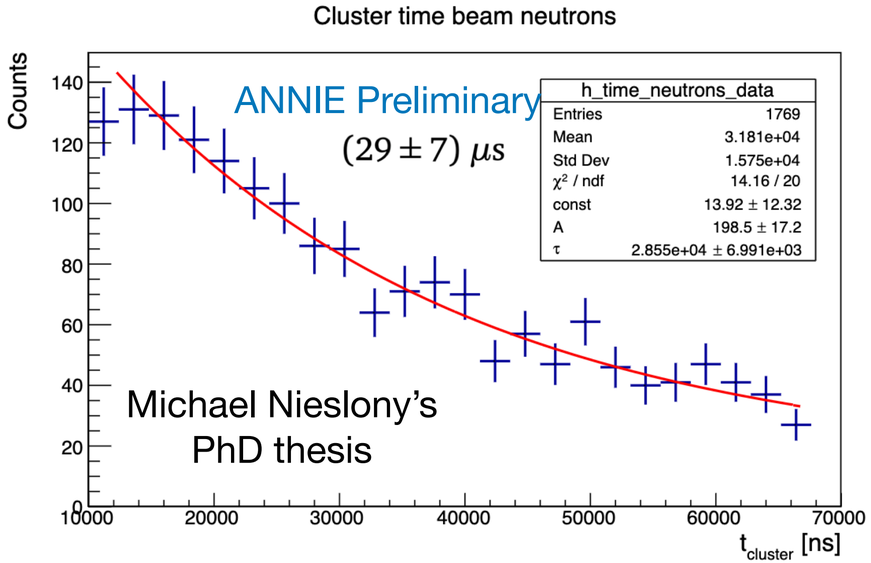
ANNIE detector

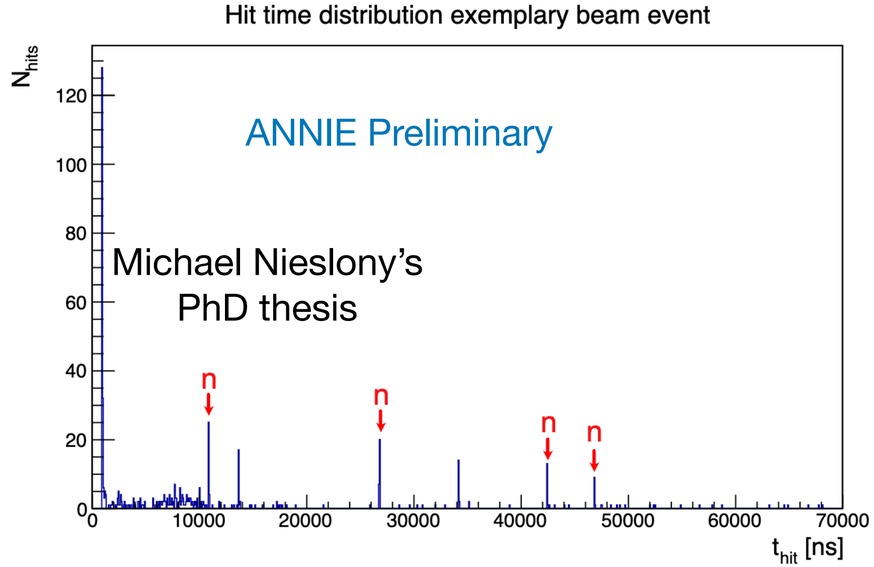




ANNIE's Gd-Loaded water

The first application of Gd-loaded water **on a neutrino beam**

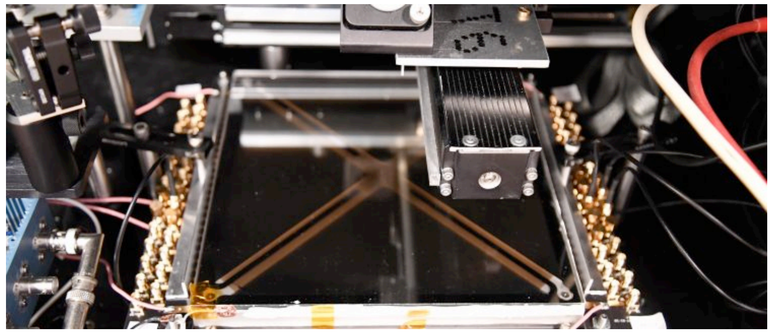


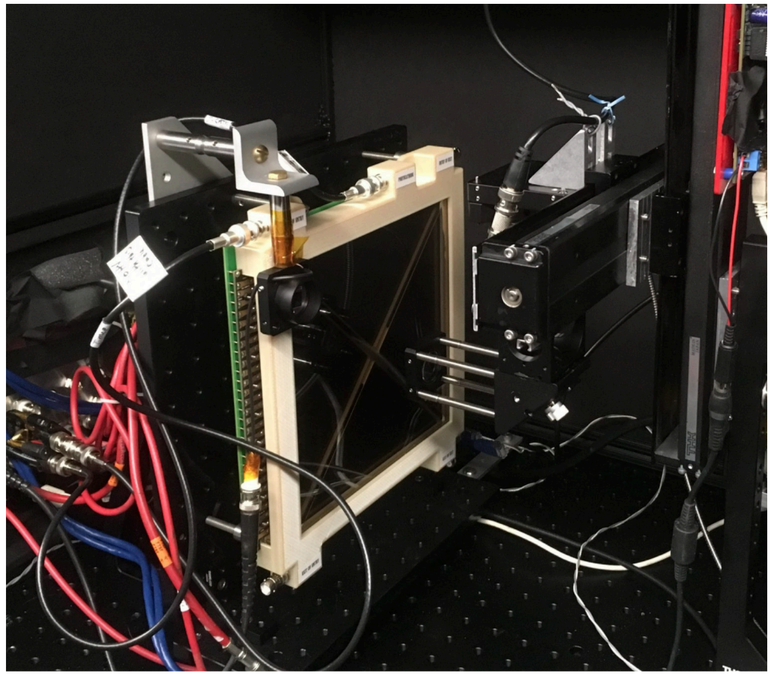


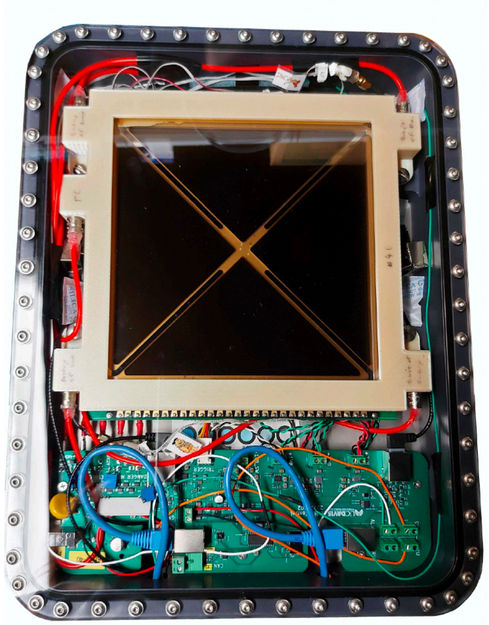
- Gadolinium's average neutron capture cross-section is high compared with pure water.
- Neutrons after thermalization, capture time:
  * Gd: ~30 μs (about **10 times** faster than in pure water)
- Signature:
  * Gd: ~ 8 MeV γ cascade (about **4 time higher energy than single** γ in water).

ANNIE's LAPPD

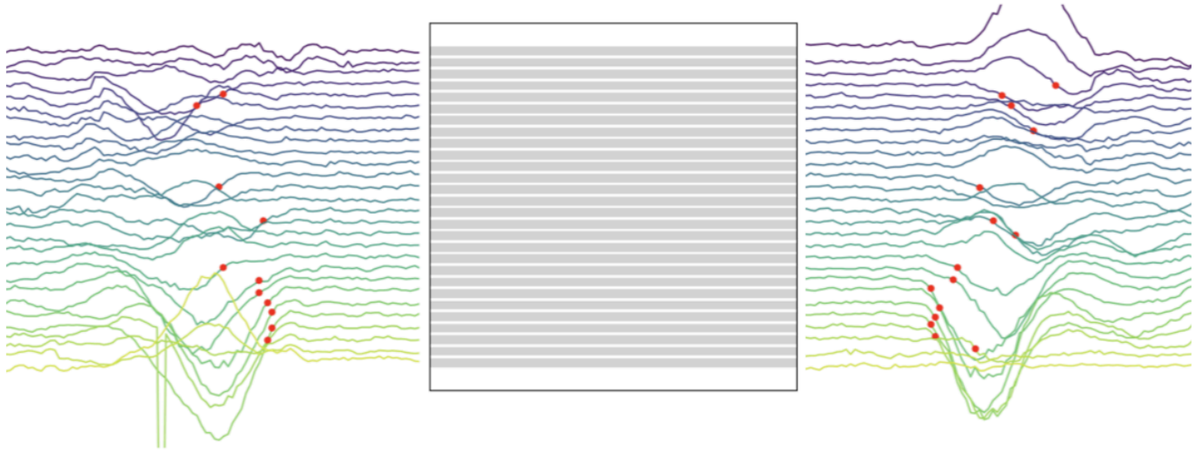
The first application of LAPPD in a **neutrino experiment**



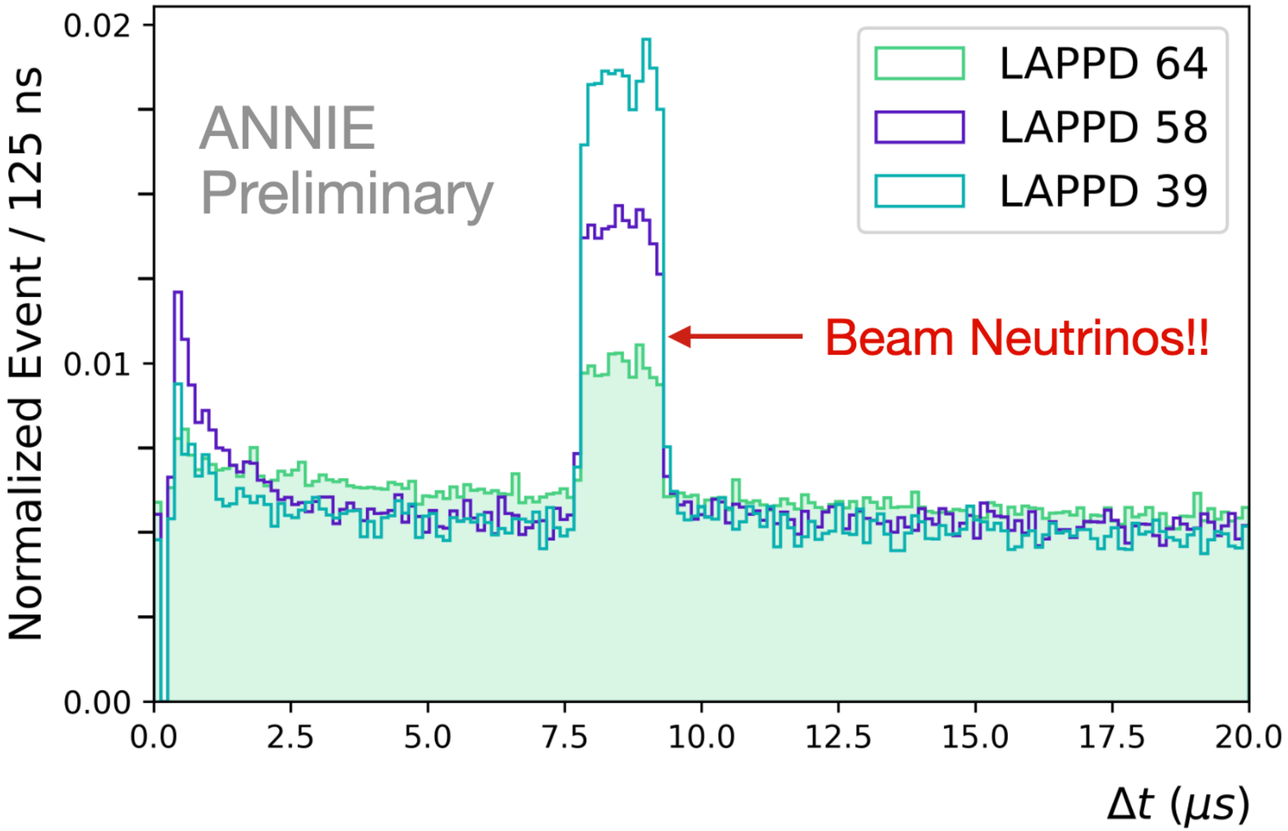


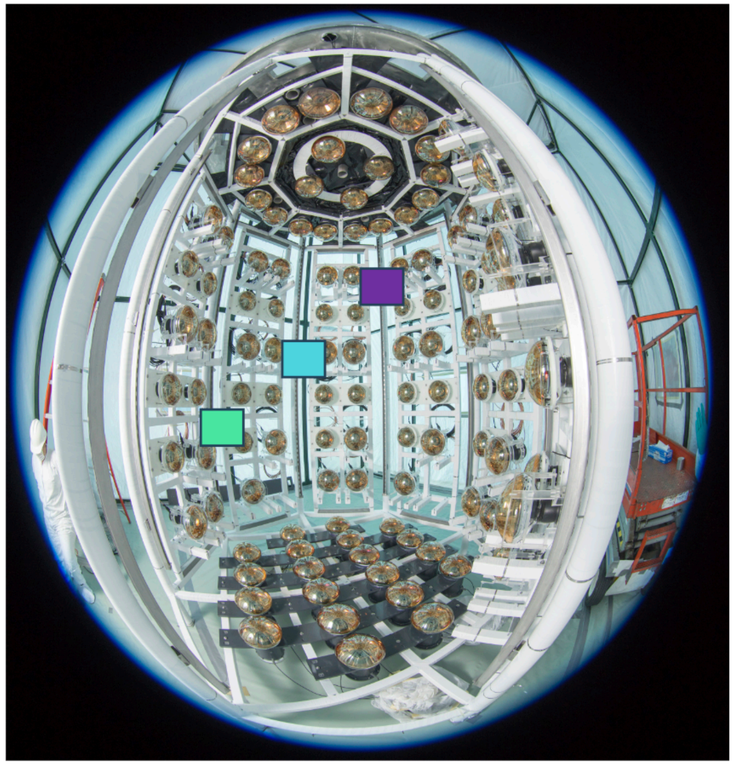


- LAPPDs are 20 cm x 20 cm MCP-based photodetectors.
- Timing resolution **~ 50 ps.**
- Spatial resolution **~ few mm.**
- Dark rate **< 1 Hz/mm^2** at room temperature.



ANNIE's LAPPD

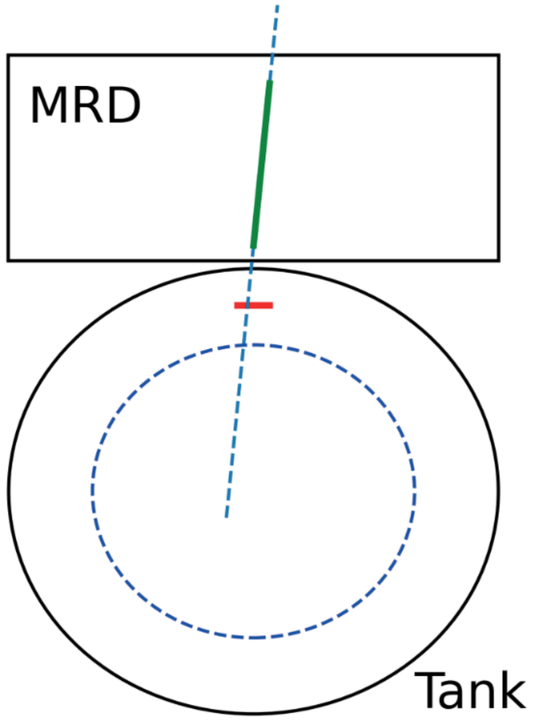


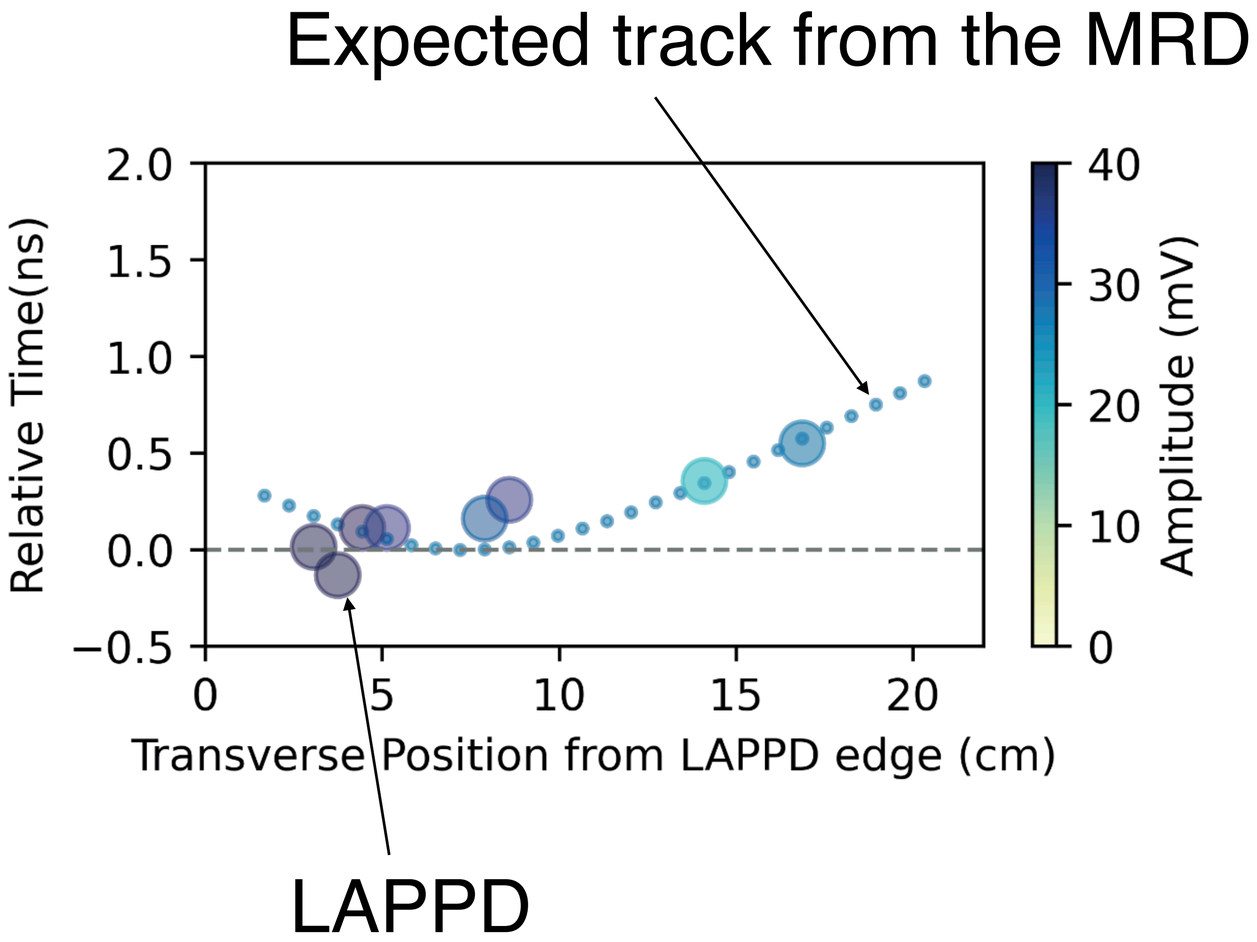


- World's first: neutrinos observed with multiple LAPPDs!
- Stay tuned; the paper is coming.

What a single LAPPD can do?

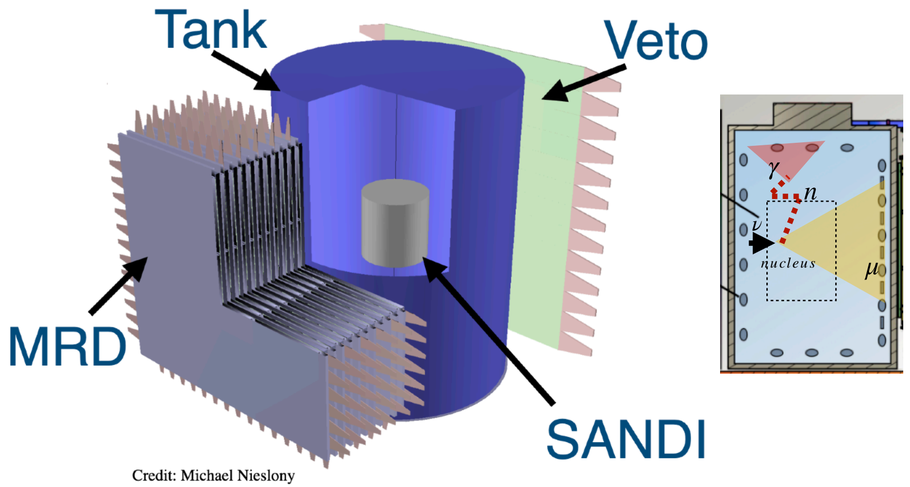
Imaging Photosensors!



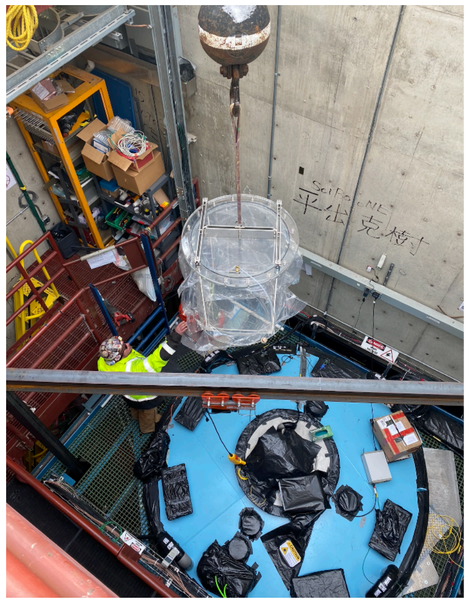


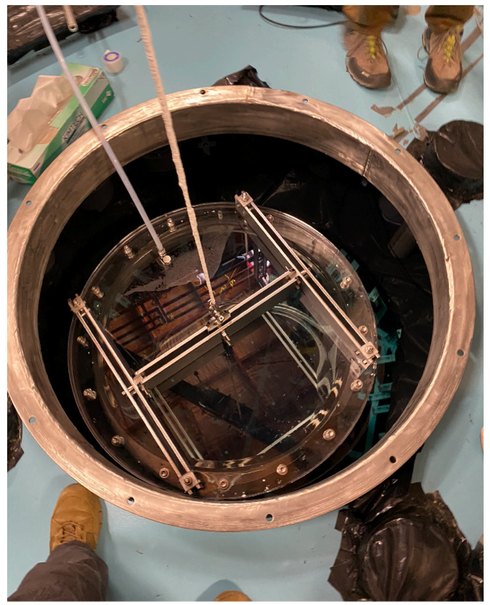
ANNIE's Water-based Liquid Scintillator (WbLS)

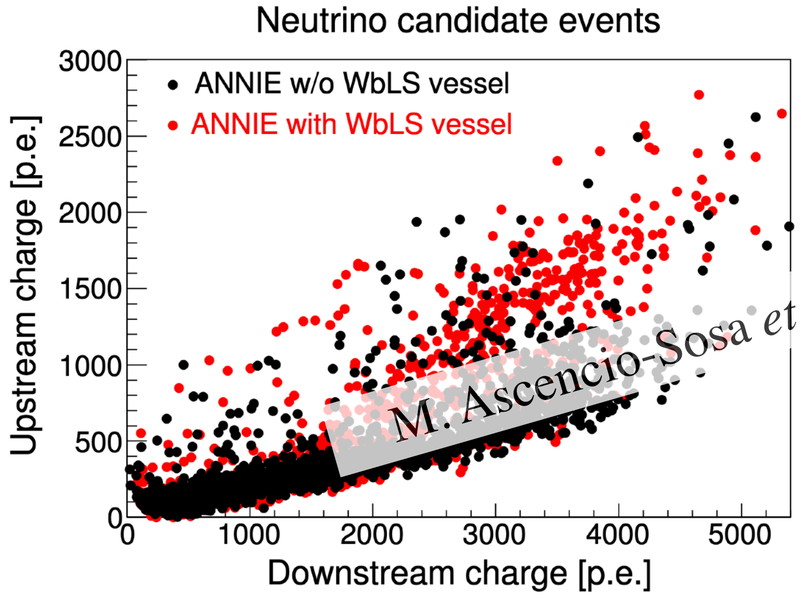
ANNIE is the first experiment to detect beam neutrinos in WbLS!

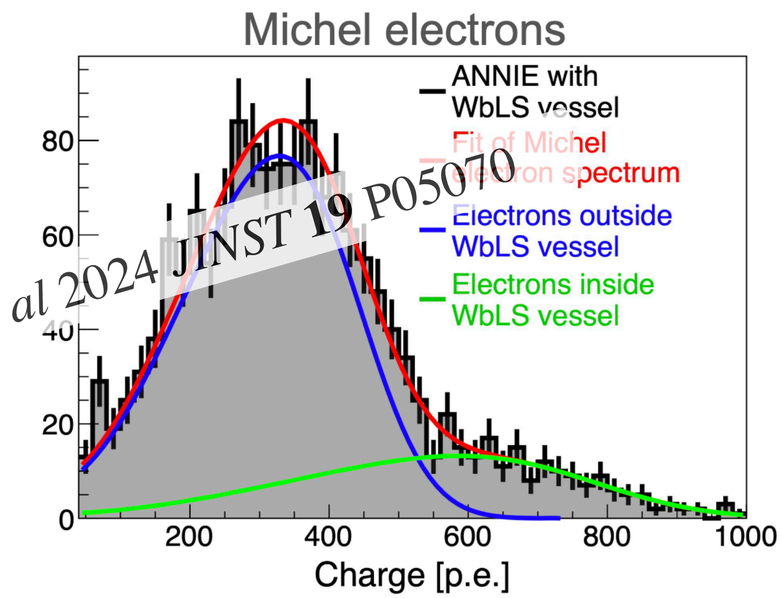


- WbLS allows hybrid detection of scintillation and Cherenkov light: **Good energy resolution** and **directionality.**
- SANDI (acrylic vessel 365kg of WbLS) in ANNIE tank from March - May 2023.
- Posible technology for DUNE FD4 (THEIA)









M. Ascencio-Sosa et al 2024 JINST 19 P05070

Summary

The ANNIE experiment achieved several milestones:

- First detection of beam neutrinos in Gd-loaded water
- First detection of beam neutrinos using LAPPDs
- First detection of beam neutrinos in WbLS

With these technologies in place, ANNIE is poised to make high-impact neutrino cross-section measurements and ratios with LAr targets.

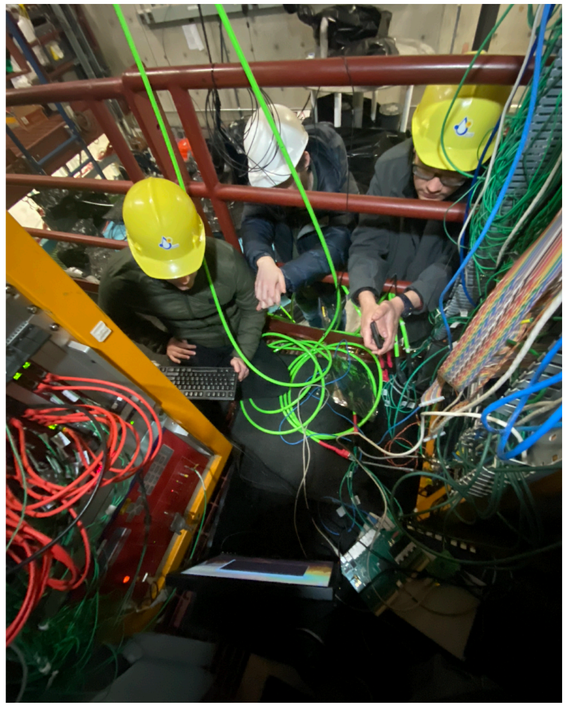
Future plans:

- Re-deploy the WbLS
- Add more LAPPDs

Stay Tuned!

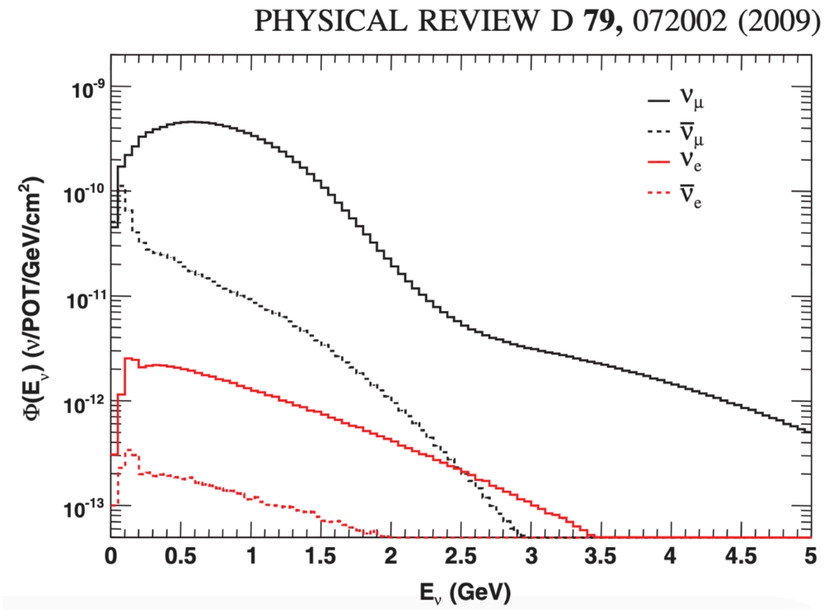
Thank you!

Any ANNIE questions?



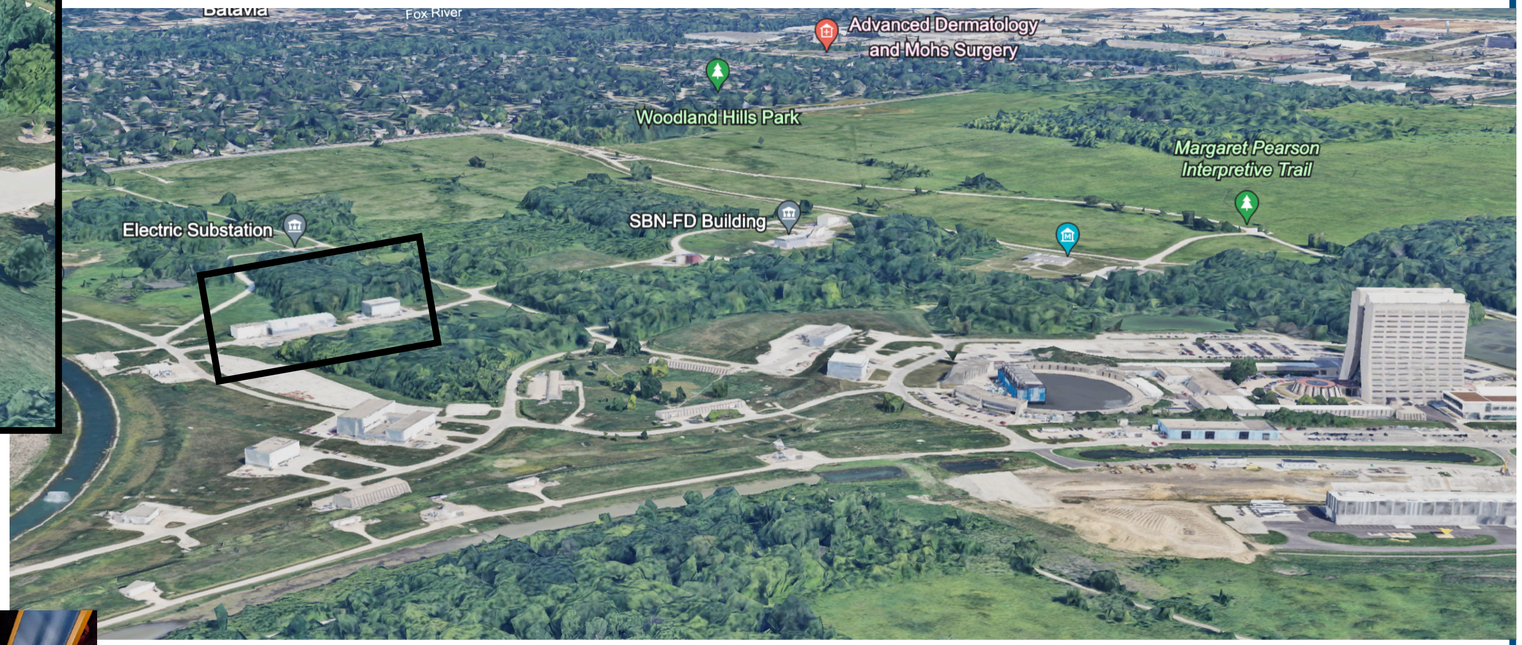
Back up

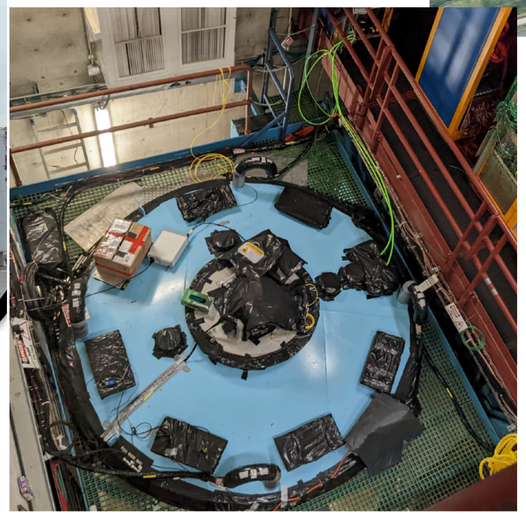
ANNIE (…..)



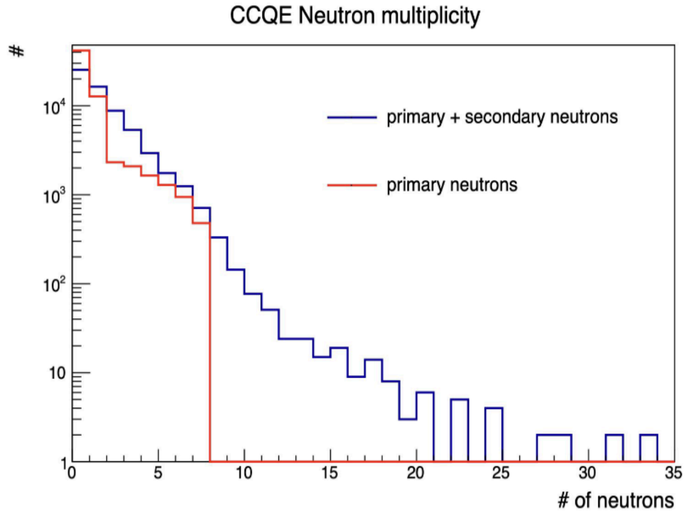
- ANNIE is placed on-axis in the BNB beamline at Fermilab.
- Neutrino energy is around 800 MeV.

ANNIE Experiment

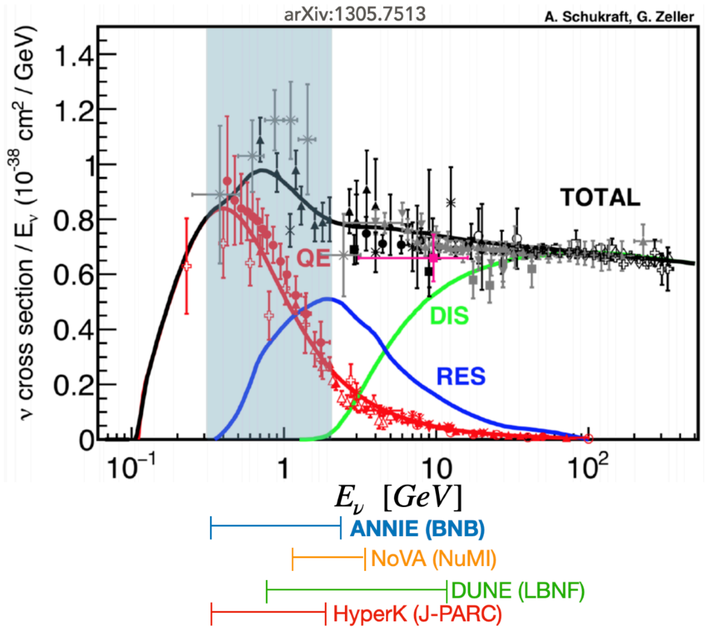


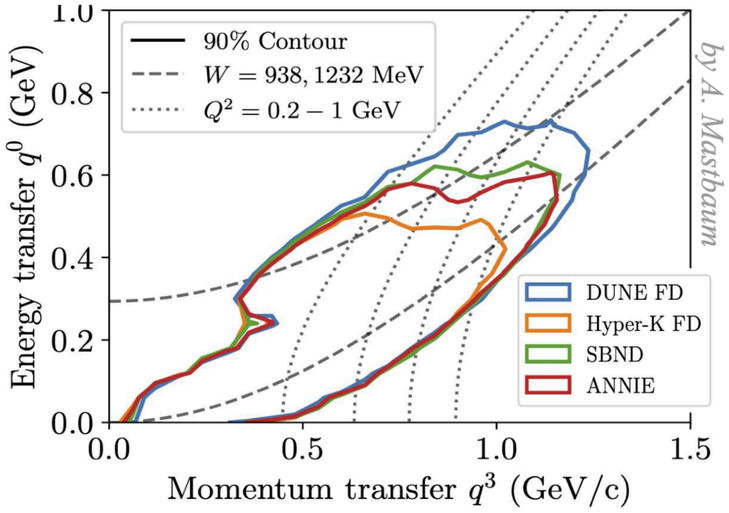


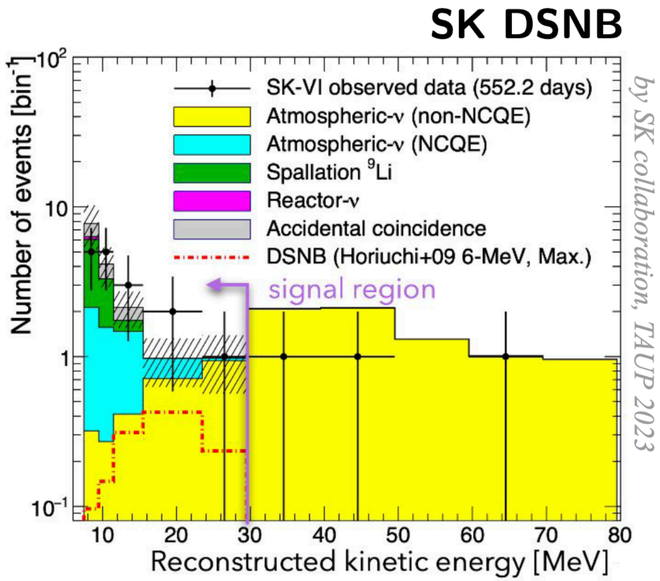
ANNIE's physics



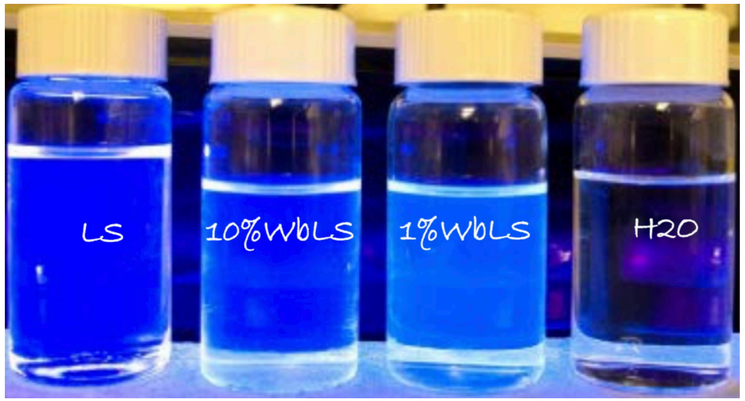
- Neutron multiplicity from CC interactions and differential cross-sections.
- ANNIE shares the BNB with several liquid-argon experiments (oxygen & argon cross-section comparison).
- NC interactions: background for
  Long-baseline oscillation experiments
  Diffuse Supernova Neutrino searches
  Proton decay searches







Water-based Liquid Scintillator (WbLS)

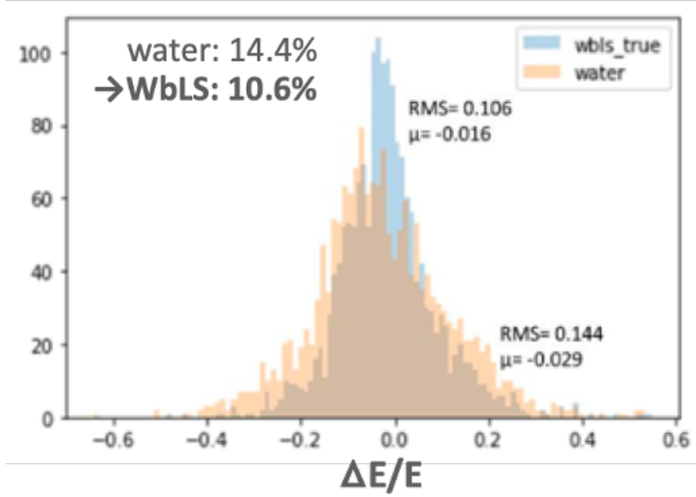


WbLS: We are using 99% water, 0.5% surfactant, 0.5% organic solvent Linear Alkyl Benzen (LAB), and 2,5-Diphenyloxazole (PPO) as fluor.

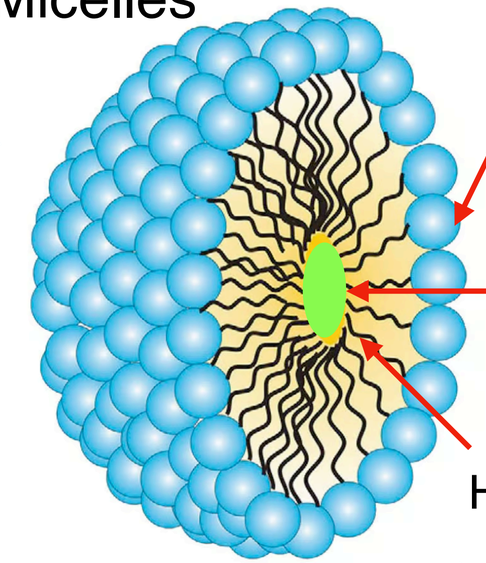
Allows hybrid detection of scintillation and (unabsorbed) Cherenkov signals.
1) Enhanced neutrino energy reconstruction.
2) Enhanced neutron signals.

WbLS for ANNIE produced at BNL (M. Yeh).
Studying possible Gd-loading.

Improved energy reco in ANNIE



Micelles

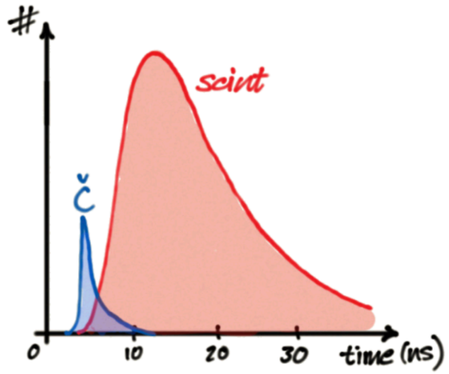


Hydrophilic head

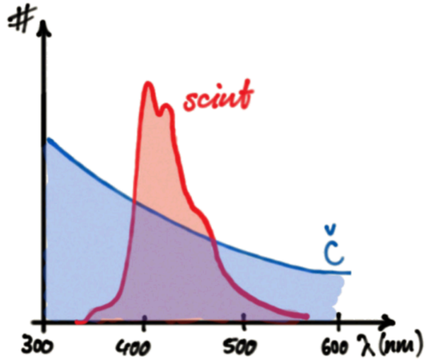
Solvent + fluor

Hydrophobic tail

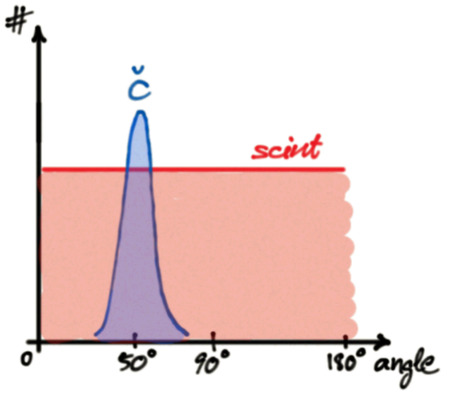
Credit: Gnác Capek



We will see in ANNIE

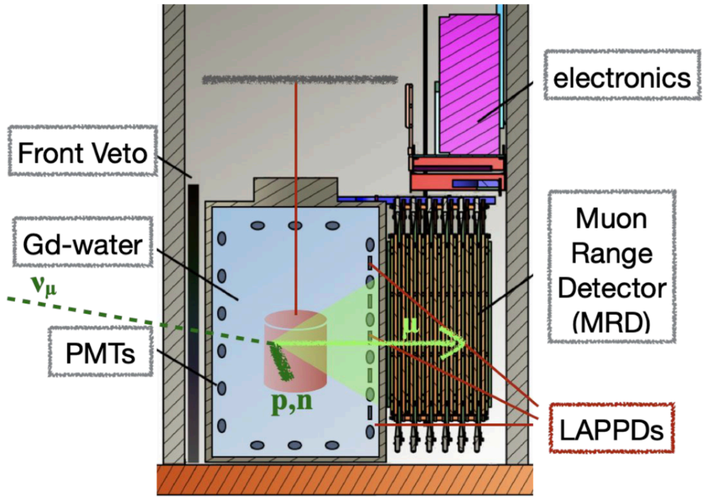


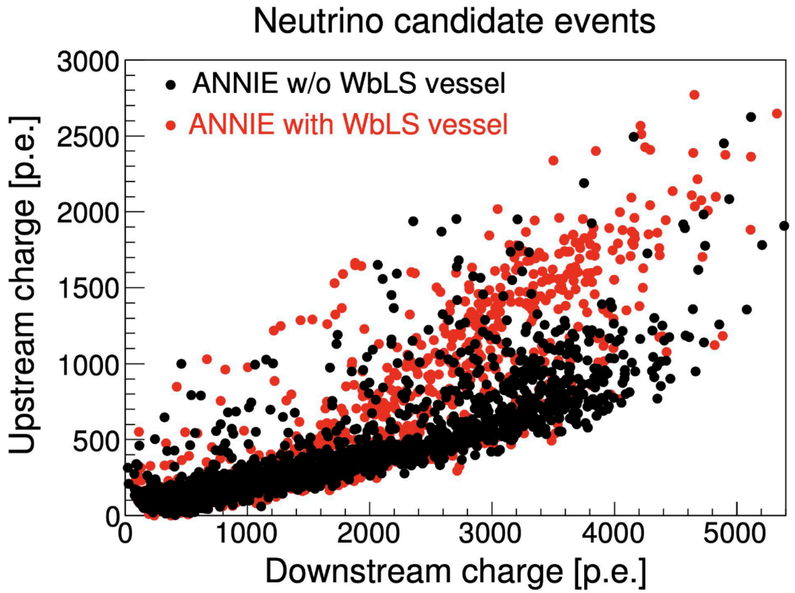
We won't see in ANNIE



We will see in ANNIE

ANNIE's WbLS (First Results & Prospects)

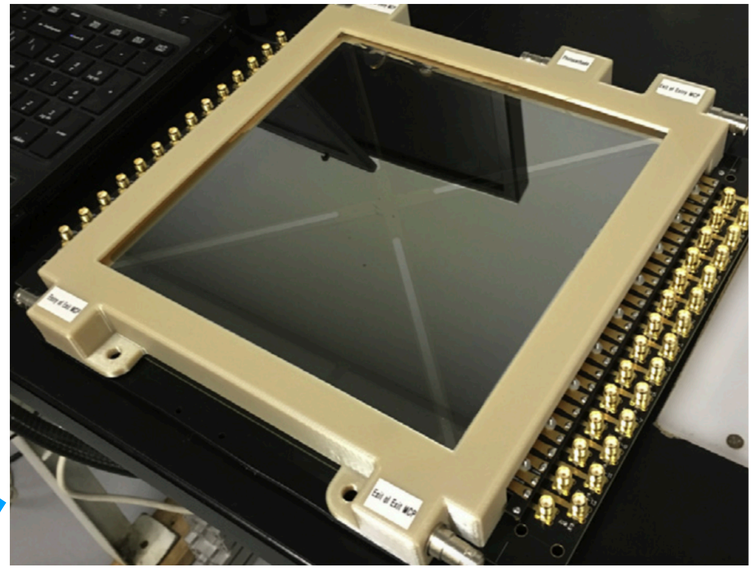




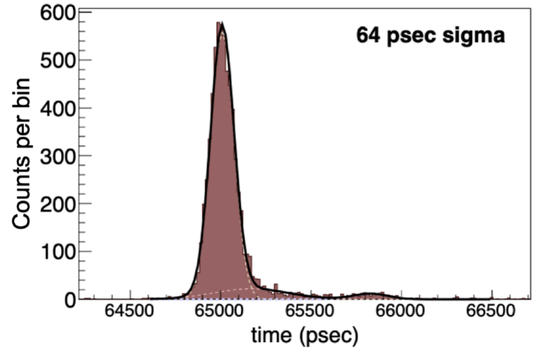
- "SANDI" acrylic vessel with 365kg of WbLS
- 2 months: few 10^3 events

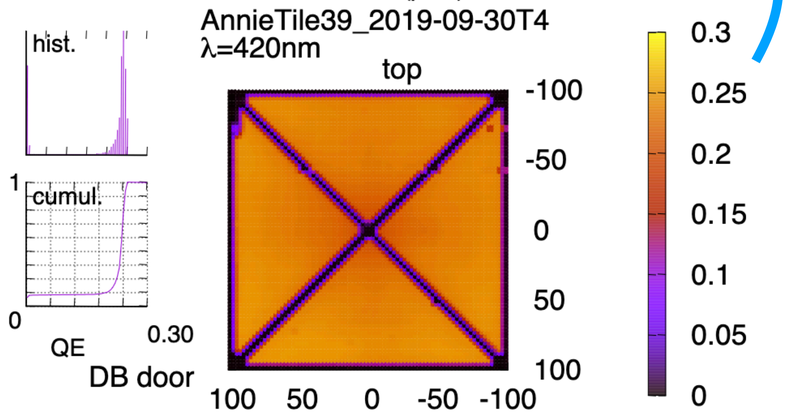
- Selecting neutrino candidates with (no) Front Muon Veto and track in Muon Range Detector.
- New population of electrons in WbLS produces significantly more photons than electrons in water

Large Area Picosecond Photo Detector (LAPPD)



- LAPPDs are 20 x 20 cm tiles based on microchannel plates (MCPs) detectors. Each MCP is a borosilicate glass structure with millions of 20-micron-diameter **coated** capillary pores.
- The LAPPD contains 28 anode strip lines with double-sided readout mechanics, which enables a reconstruction of the photon hit on the differential timing information.
- Excellent position resolution (sub-cm scale) and timing (< 100 psec).





QE[%]: [5.8, 25.4]; avg: 23.7, σ[1]: 1.311e-02

Nuclear Inst. and Methods in Physics Research, A 936 (2019) 527–531

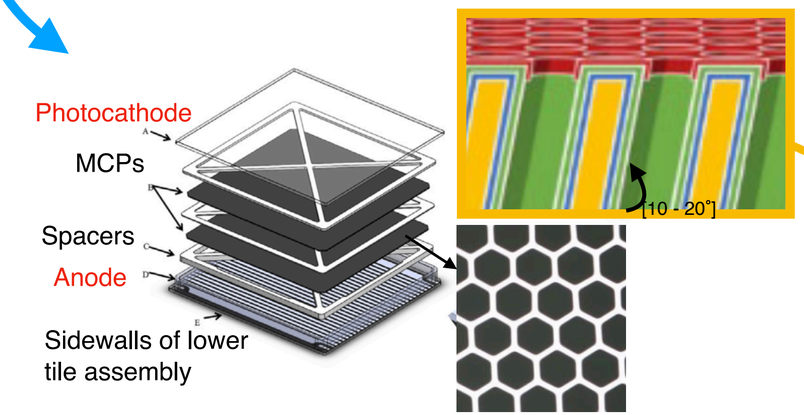
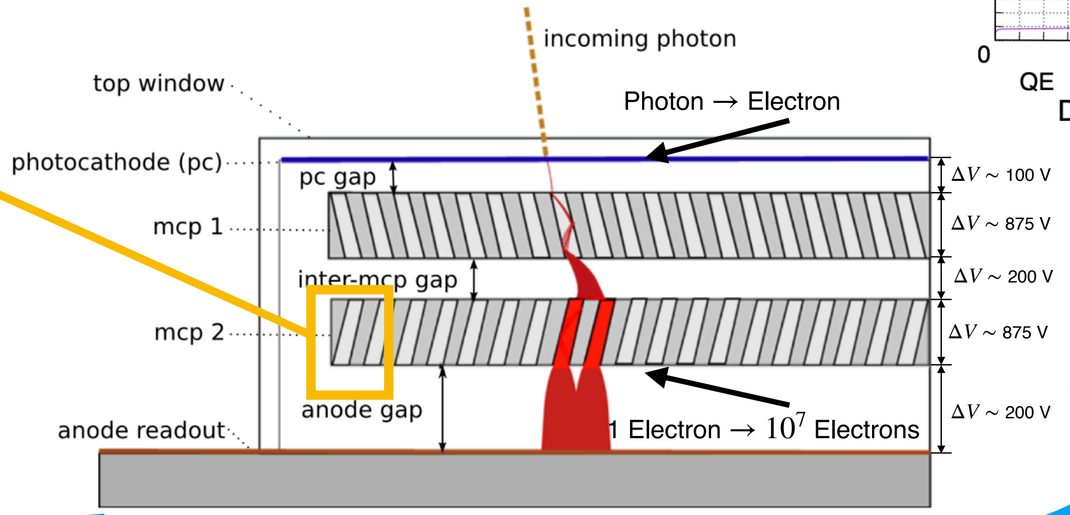
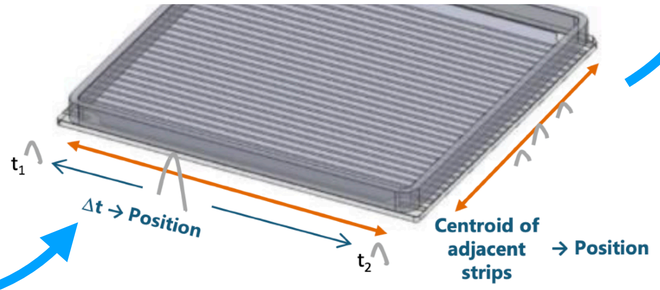
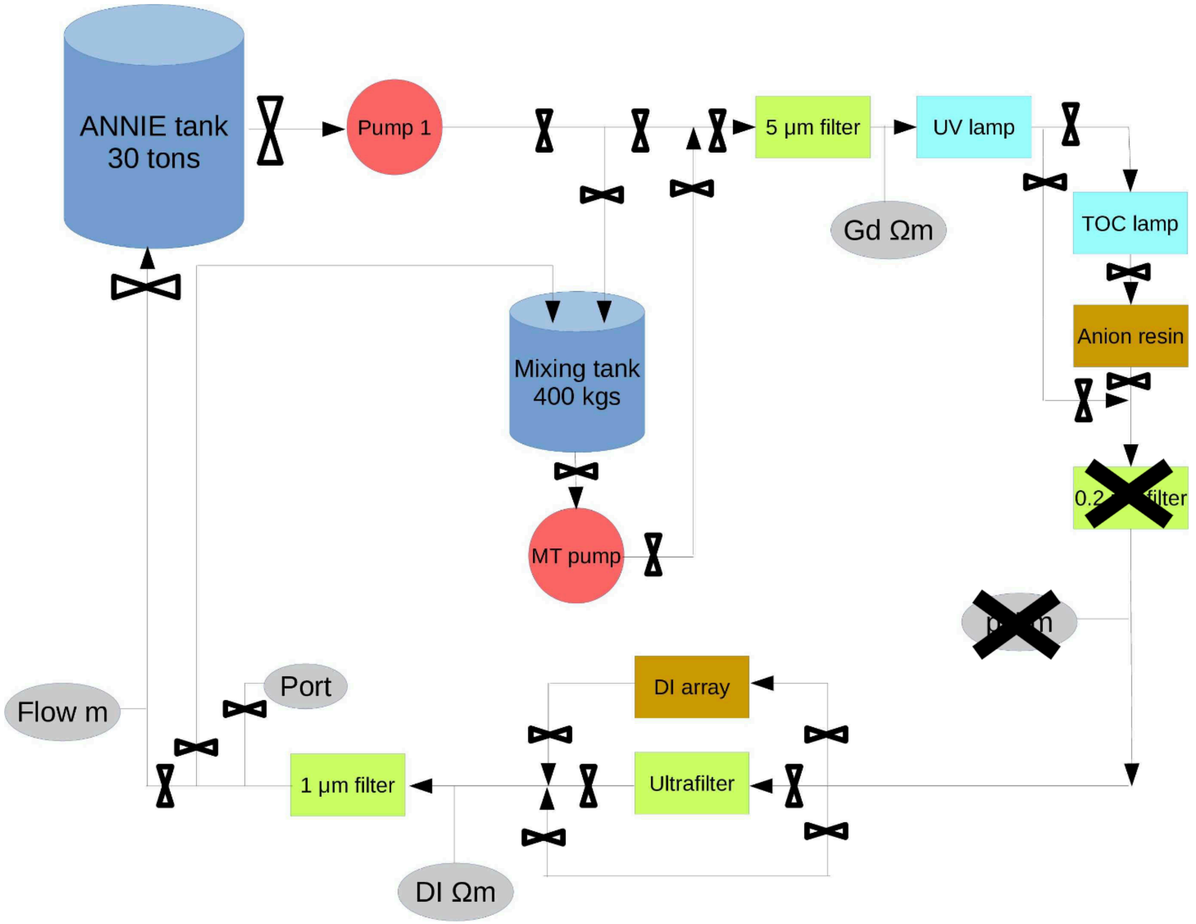


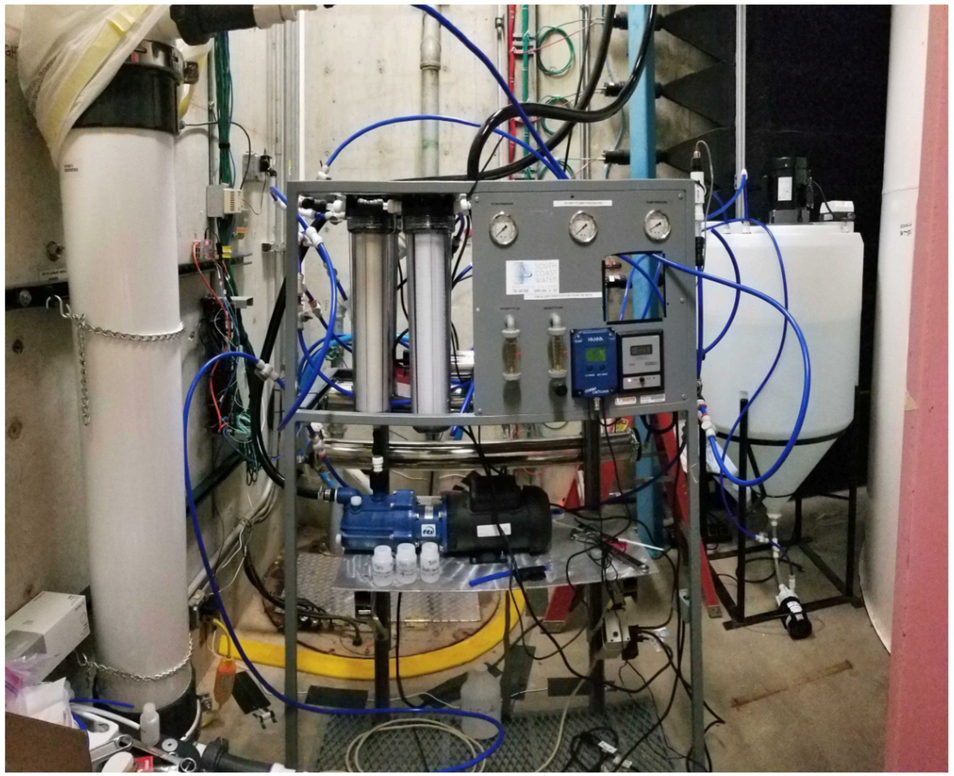
Fig. 1. Schematic design of the LAPPD.





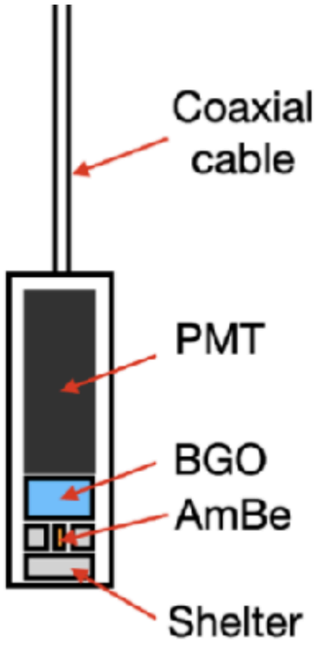
ANNIE water system

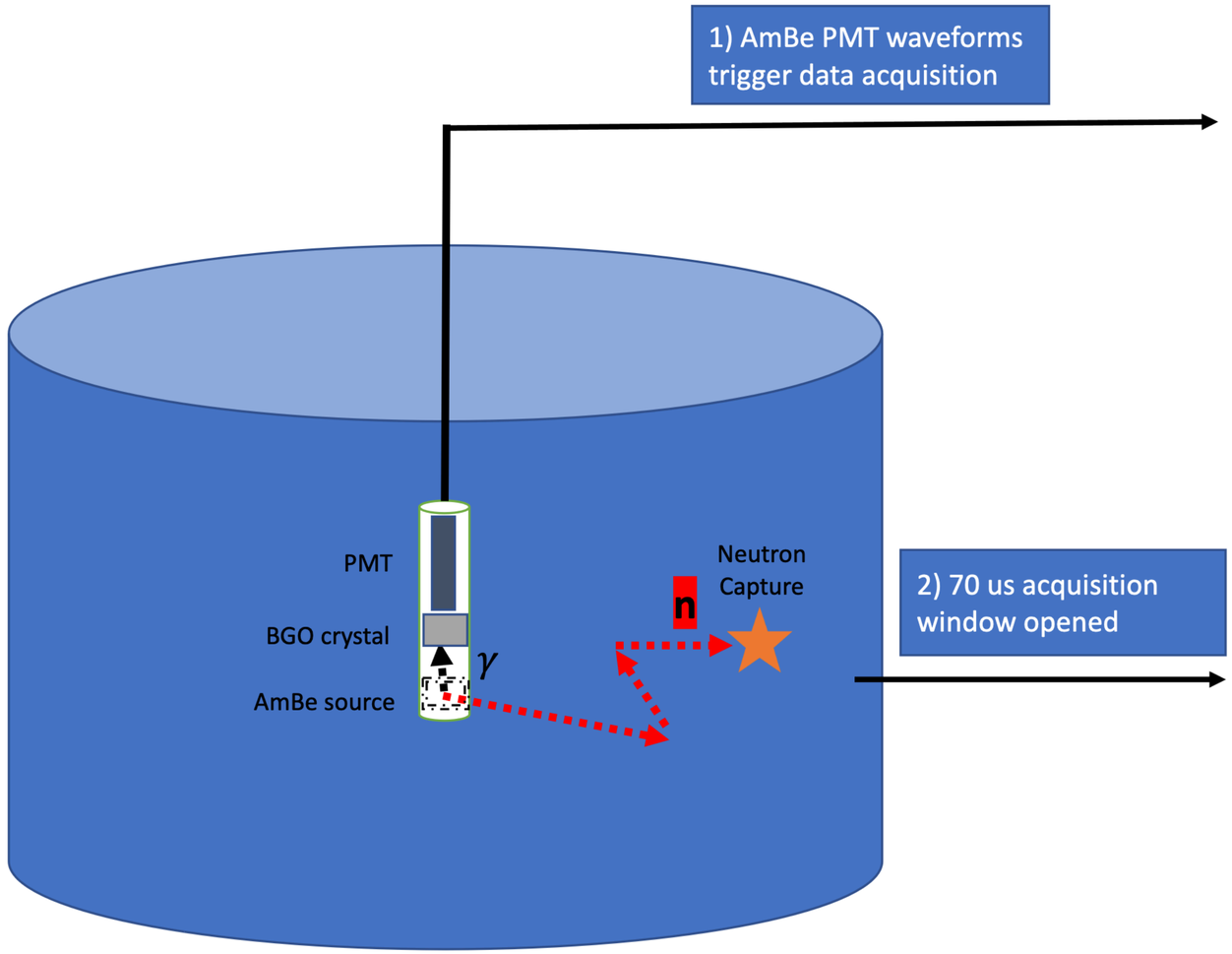




- From Vincent Fischer

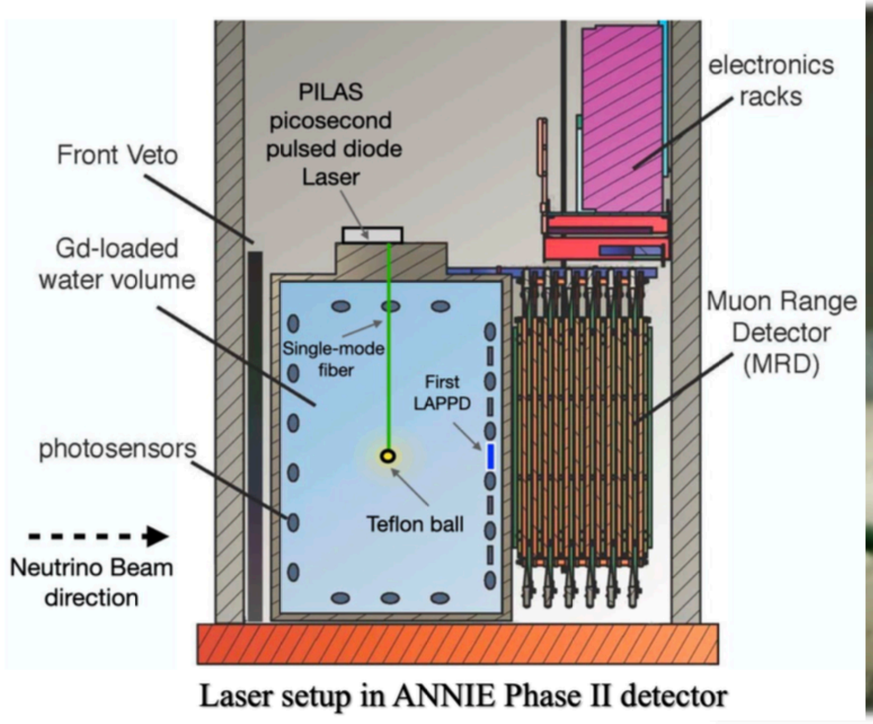
ANNIE AmBe setup



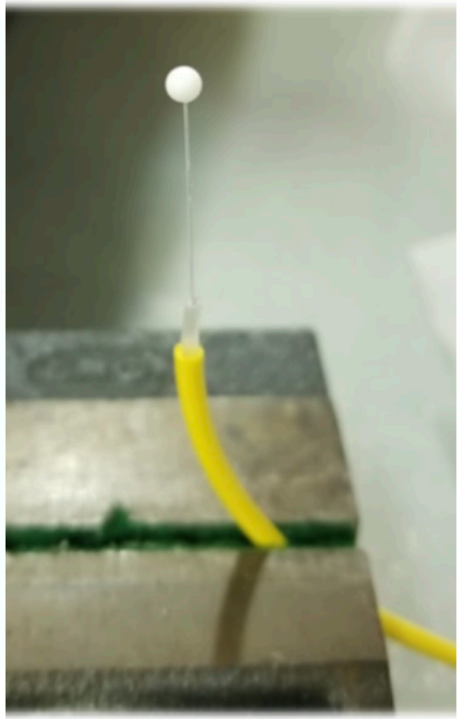


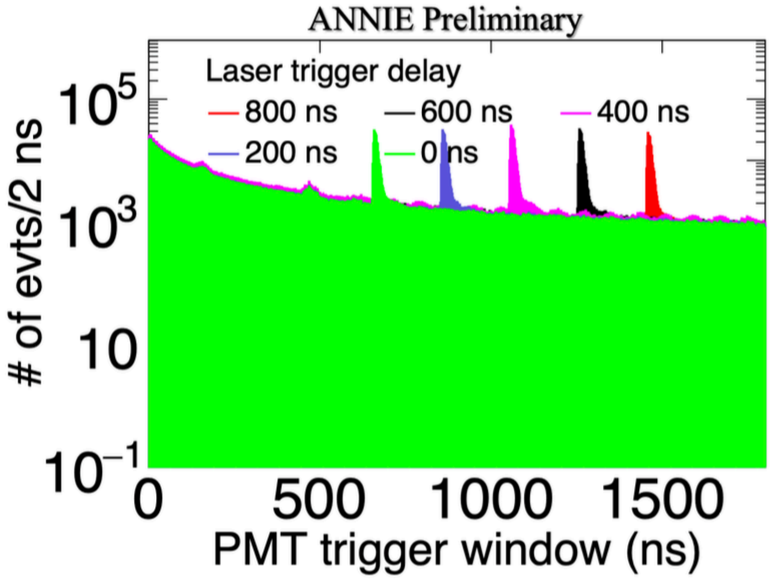
- From Gian Caceres

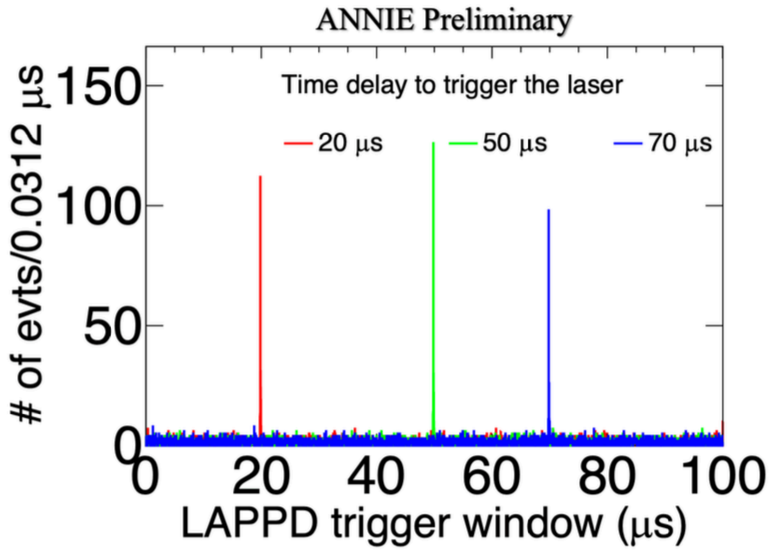
ANNIE Laser setup



Laser setup in ANNIE Phase II detector

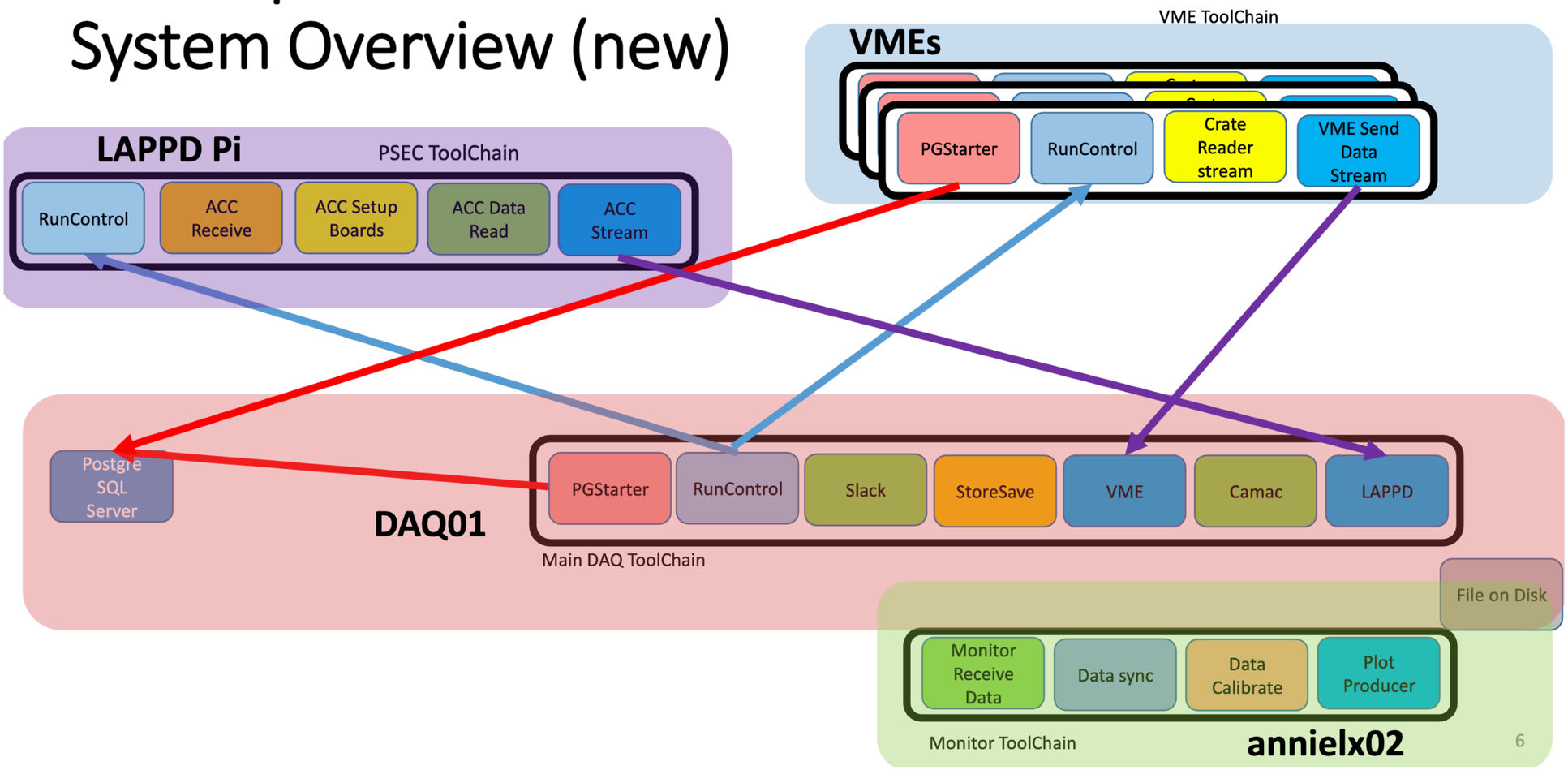


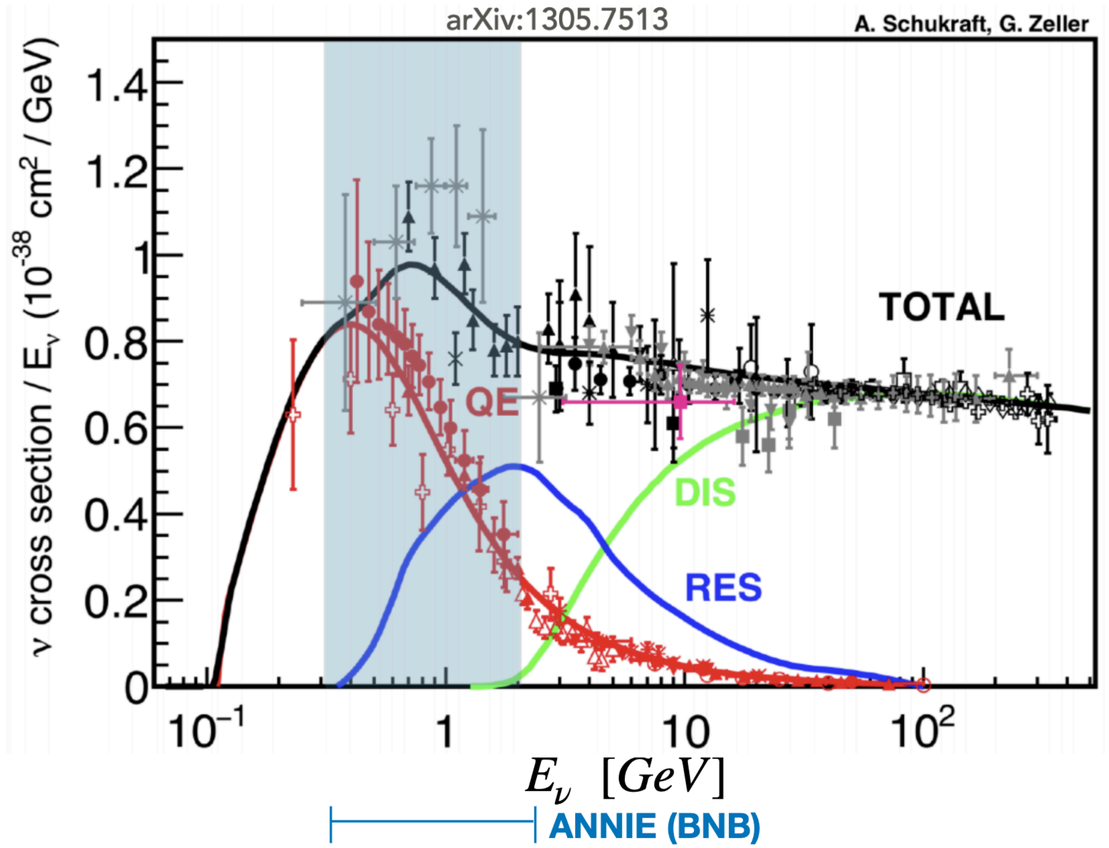




ANNIE DAQ

Code updates in detail
System Overview (new)

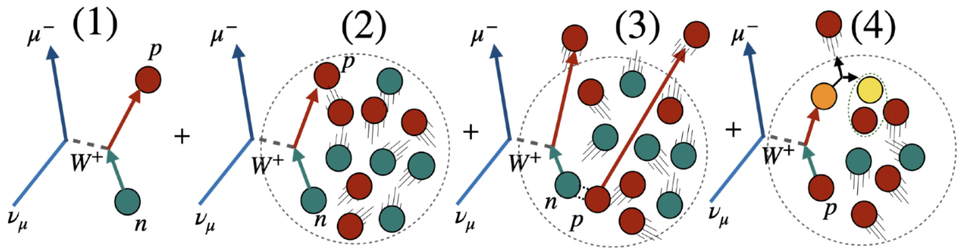




- Requires a precise neutrino energy reconstruction

$$N(E_{\text{reco}}) \sim \phi(E) \times P(E) \times \sigma(E) \times f_\sigma(E, E_{\text{reco}})$$

- δ CP oscillation parameter requires $\nu/\bar{\nu}$ events comparison. The number of final state neutrons impacts the hadronic recoil energy.



Free nucleon scattering | Initial Nuclear State | Nuclear Effects | Final State