The Accelerator Neutrino Neutron Interaction Experiment (ANNIE)

R. Svoboda, 2019 JPARC Symposium

The ANNIE Collaboration

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

12 Institutions
3 Countries
~30 Collaborators

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ANNIE
Accelerator Neutrino Neutron Interaction Experiment

TWO GOALS:

- Measure the abundance of final state **neutrons** from neutrino interactions in water, as a function of energy and momentum transfer
- Demonstrate the use of fast, large format MCPs for event reconstruction in the GeV range

Why are these important goals?

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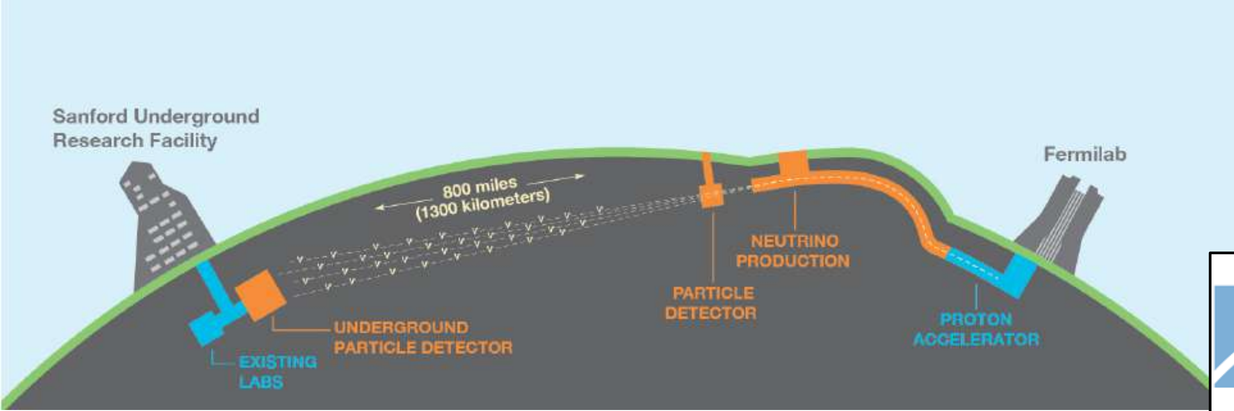


DEEP UNDERGROUND NEUTRINO EXPERIMENT

The Deep Underground Neutrino Experiment (DUNE) now under construction will send an artificial neutrino beam from Chicago to South Dakota. DUNE will be able to determine the **MASS ORDERING** and look for **CP VIOLATION**

The 1,300 km baseline is needed to oscillate in patterns uniquely sensitive to these properties

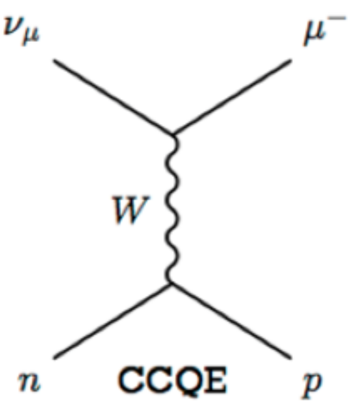
$$1.27\Delta m^2(L/E_\nu) = \pi/2$$

$$L = \pi(1.5\ GeV)/(1.27 \cdot 2.4 \times 10^{-3})$$

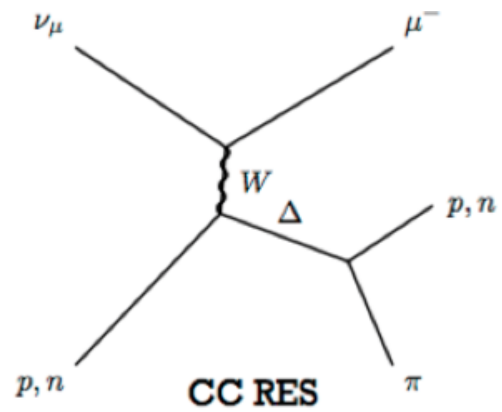
$$= 1,500\ km$$

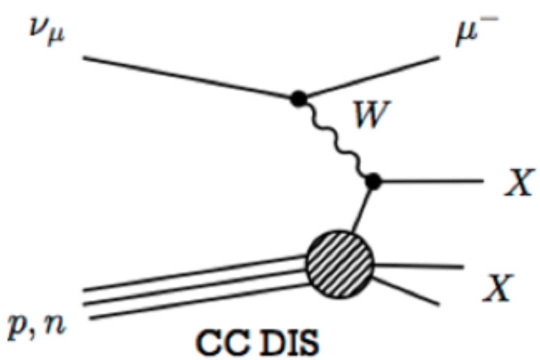
CC Neutrino Interactions at 1 GeV

Charged Current Quasi-Elastic

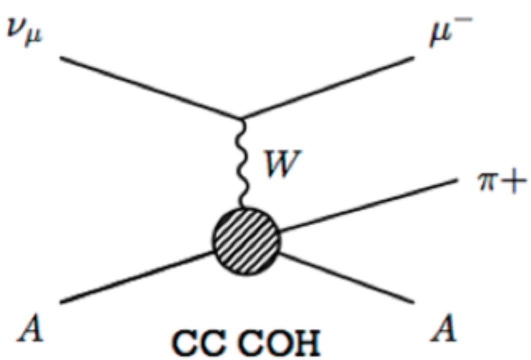


Charged Current Resonant





Charged Current Deep Inelastic Scattering



Charged Current Coherent Scattering

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The Neutrino Wavelength

$$\lambda = h/p = 2\pi\hbar c/pc \simeq (1200\ MeV \cdot fm)/E_\nu$$

$= 3\ fm$ at 400 MeV.

The size of an oxygen (argon) nucleus is $\simeq 1.2\ A^{1/3} = 3\ fm (4\ fm)$

$= 1\ fm$ at 1200 MeV (the size of a nucleon)

$= 0.5\ fm$ at 2400 MeV (individual quarks inside the nucleons)

This means that the energy range from 500-2400 MeV is the range where the interaction mode is changing from **nuclear** to **individual nucleons**, to **quarks** inside the nucleons

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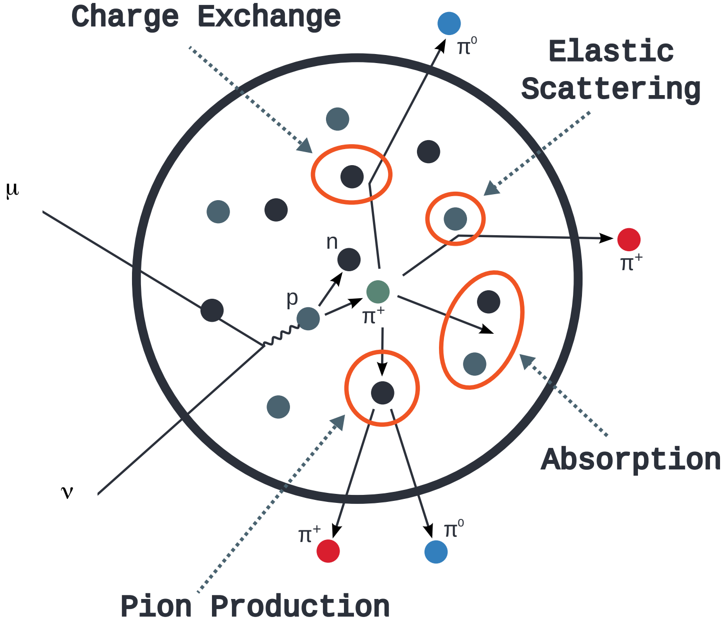
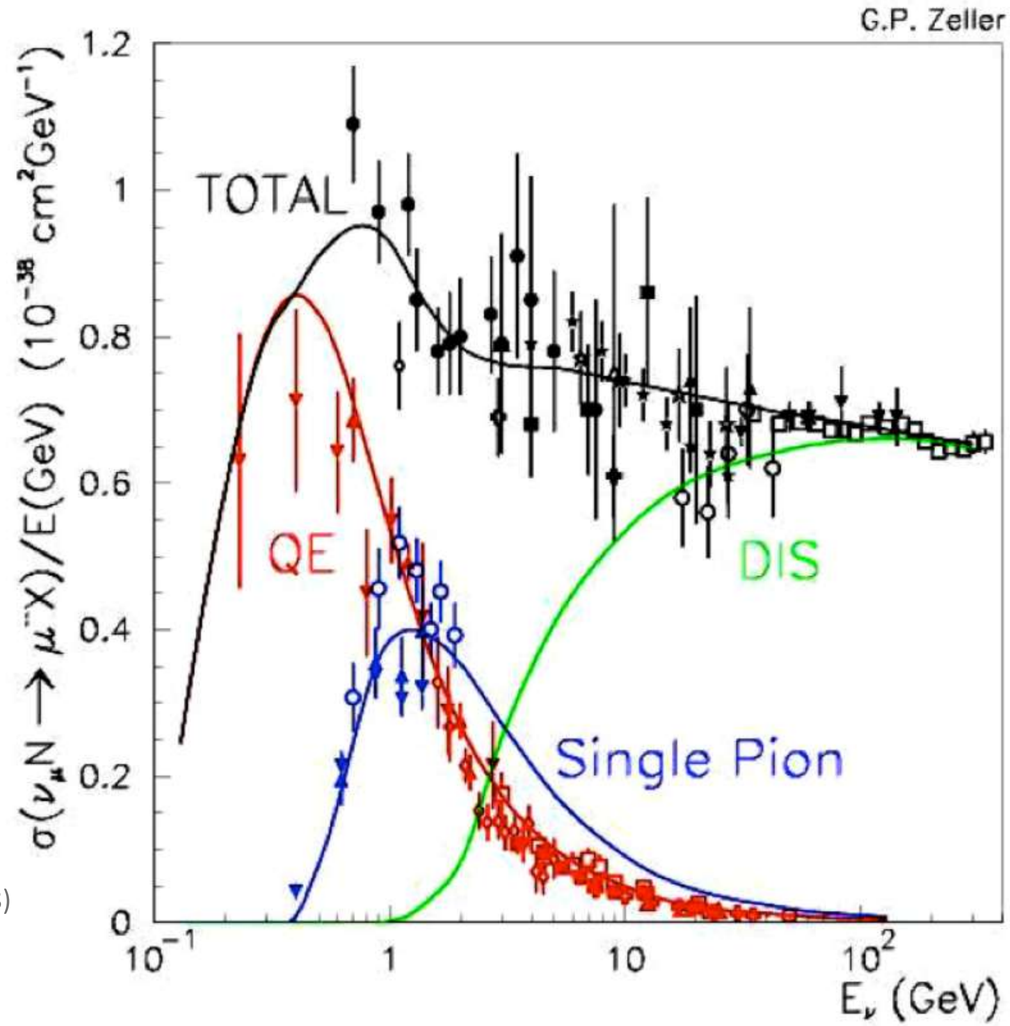
It is not surprising then that neutrino interactions in this energy range are complex



L. Alvarez-Ruso et al., Prog. Part. Nucl. Phys. 100, 1–68 (2018)



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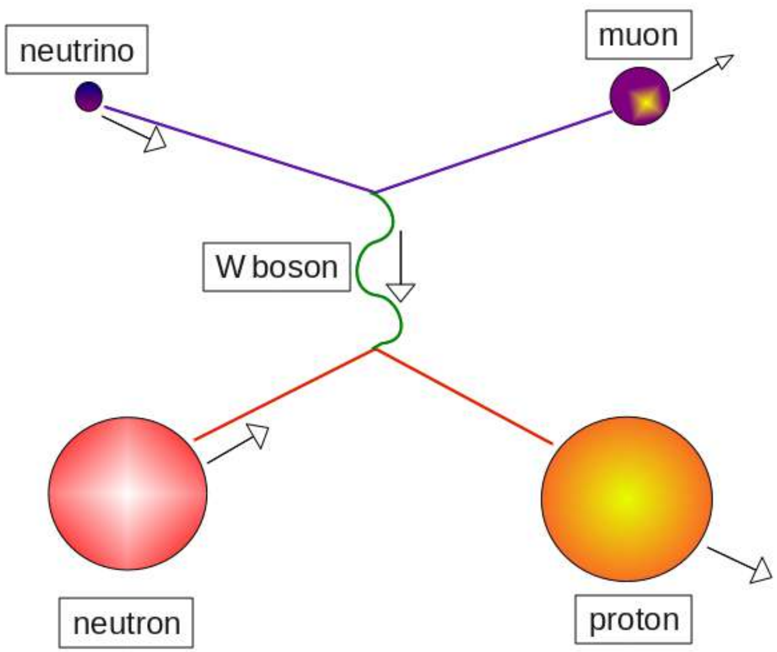
Charged Current Quasi-Elastic Interaction are relatively simple to understand



$$E_\nu = \frac{m_N E_\mu - \frac{1}{2} m_\mu^2}{m_N - E_\mu + p_\mu \cos\theta}$$

In this model the neutrino energy is directly related to the muon energy
and direction, which can be measured.

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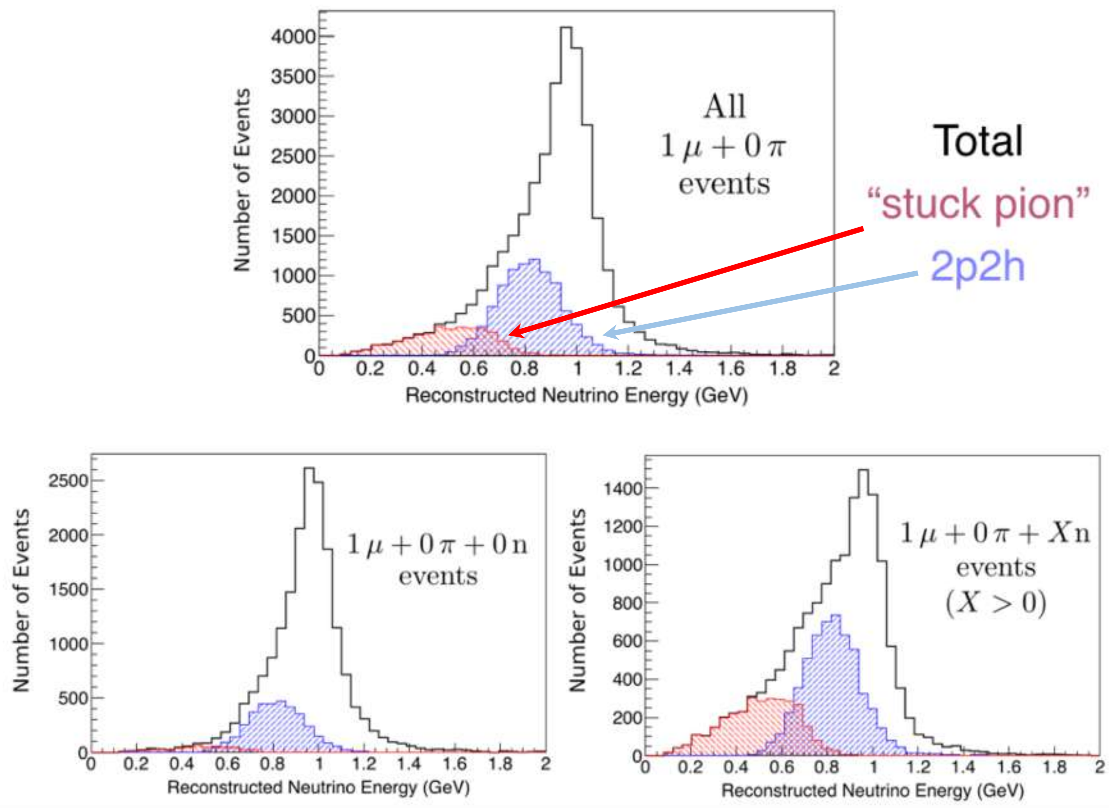
Neutrino energy reconstruction

- Event generators are routinely used to correct for biases in the reconstructed neutrino energy
- Stuck pion and two-particle two-hole (2p2h) events significantly contaminate a CCQE-like 1μ + 0π sample
- GENIE simulations suggest that neutron tagging can help improve the energy reconstruction

GENIE simulations

1 GeV ν_μ scattering in water



Energy reconstruction improved by neutron detection

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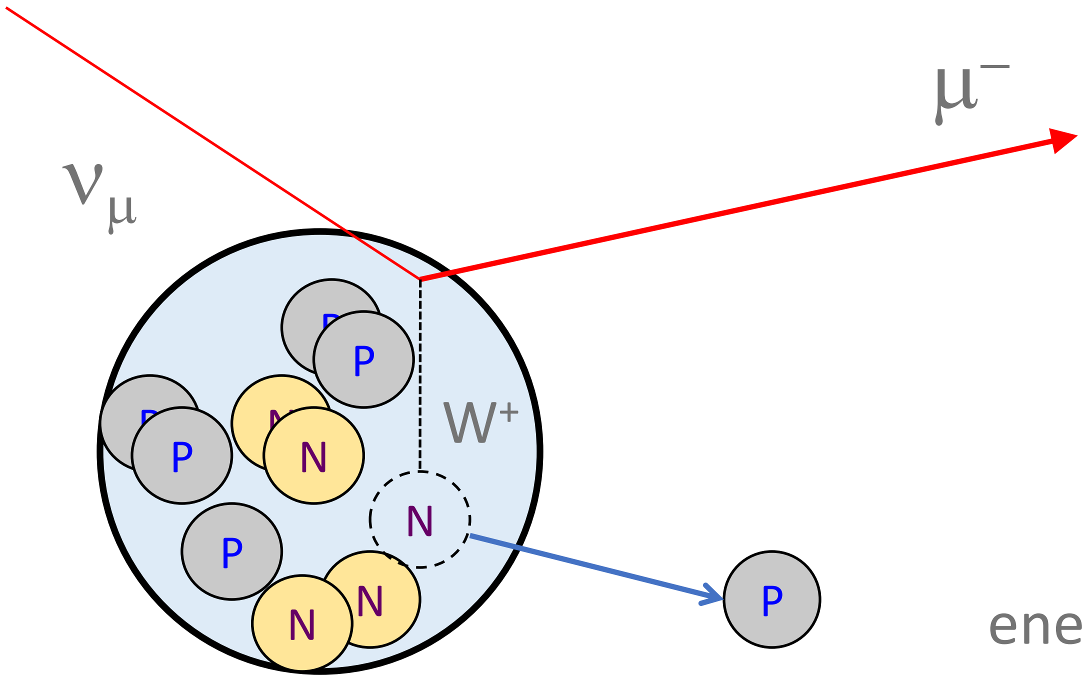
ANNIE Physics Motivation

" **...**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

Direct neutron production in CCQE



energetic
struck nucleon

NEUTRINO CCQE

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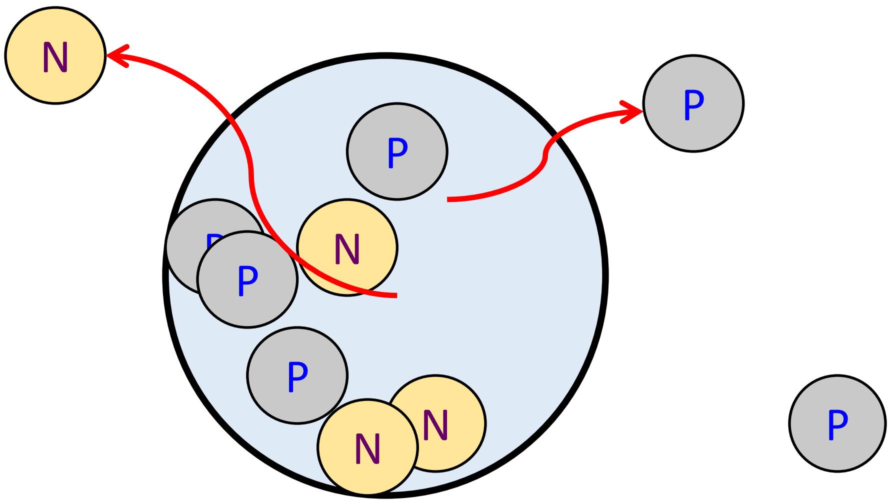
Direct neutron production in CCQE

~1 MeV "boil off" nucleons



energetic
struck nucleon

NEUTRINO CCQE

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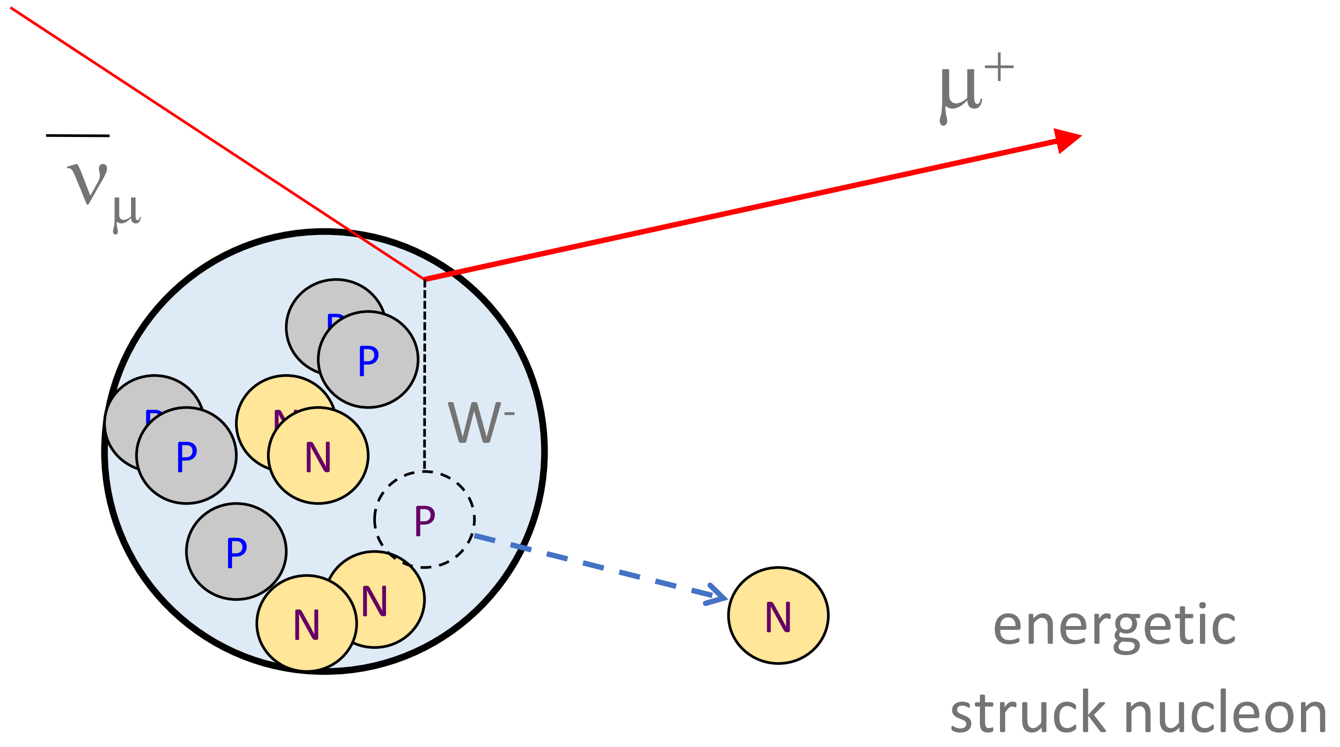
Direct neutron production in CCQE



ANTI-NEUTRINO CCQE

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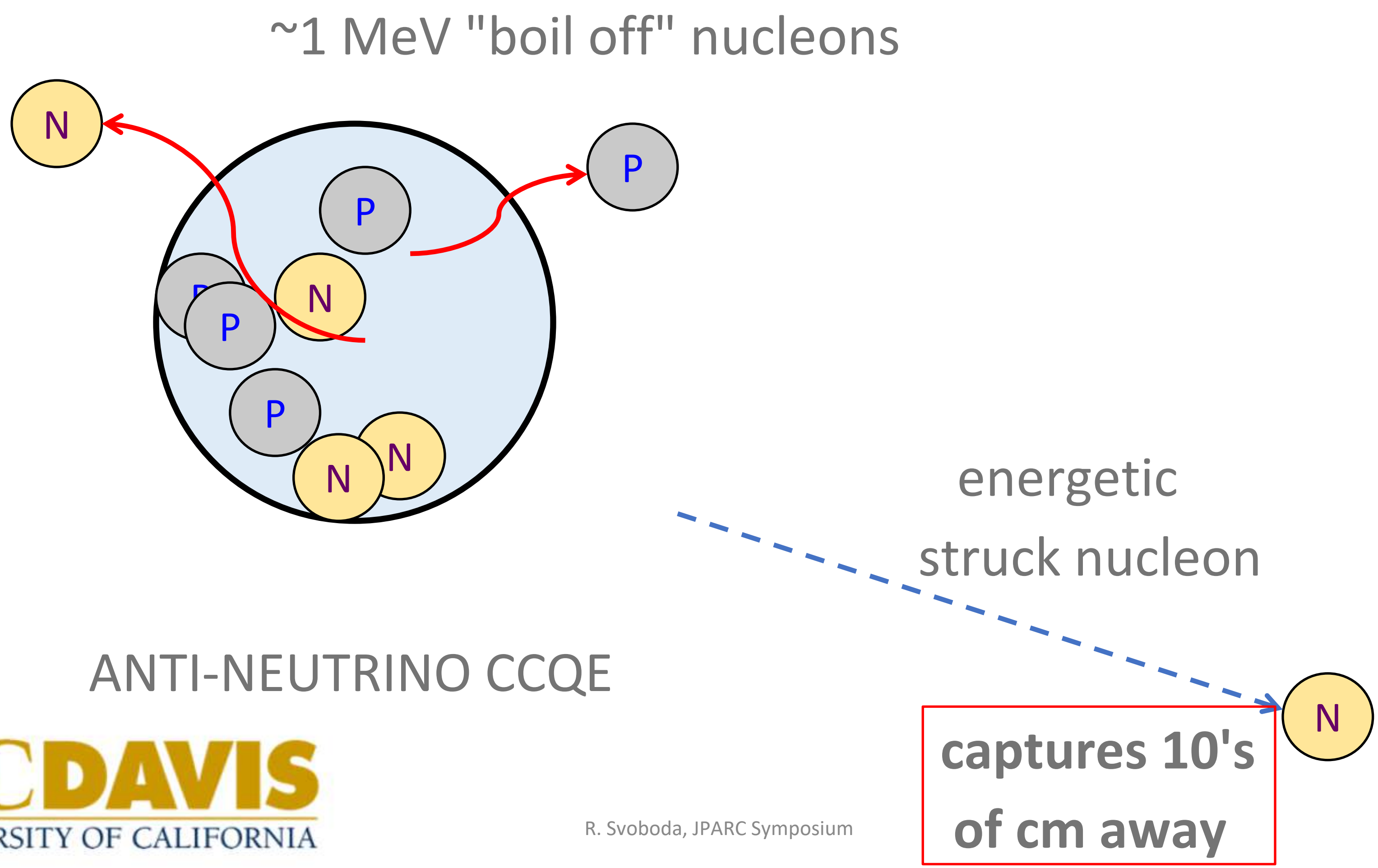
Direct neutron production in CCQE



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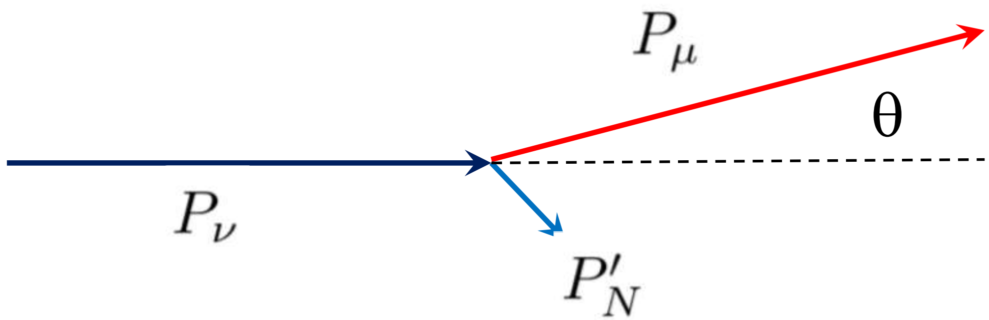

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Accelerator Neutrino Neutron Interaction Experiment

$$P_\nu = (E_\nu, \vec{p}_\nu);\ P_N = (M, 0);\ P_\mu = (E_\mu, \vec{p}_\mu);\ P'_N = (M + K, \vec{P})$$

$$P_\nu + P_N = P_\mu + P'_N$$

$$Q^2 = (P_\mu - P_\nu)^2 = m_\mu^2 - 2E_\nu(E_\mu - p_\mu \cos\theta)$$

$$E_\nu = \frac{m_N E_\mu - \frac{1}{2} m_\mu^2}{m_N - E_\mu + p_\mu \cos\theta}$$

(CCQE)

We expect that Q^2 will be the relevant variable for boil off neutrons. **ANNIE will measure this for CCQE**

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Description of the ANNIE Detector and Beam

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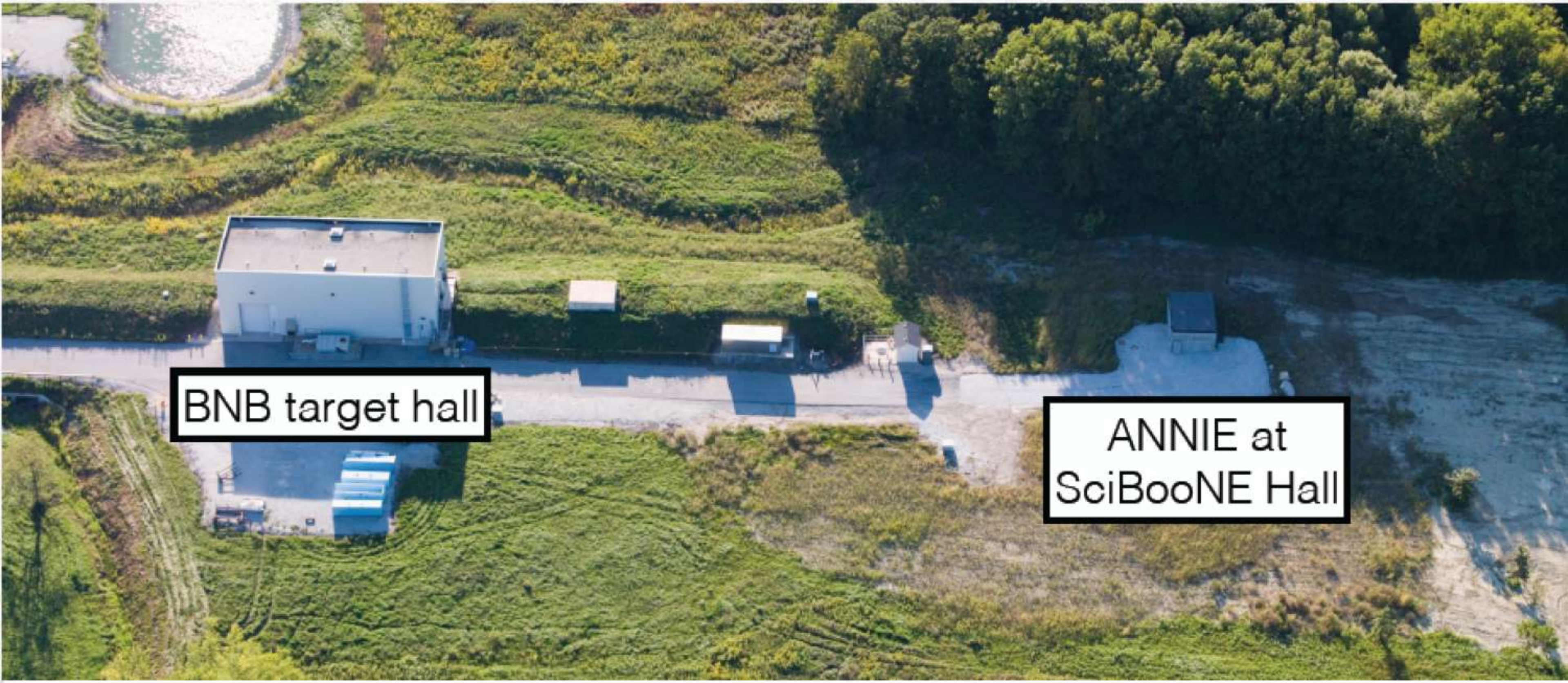

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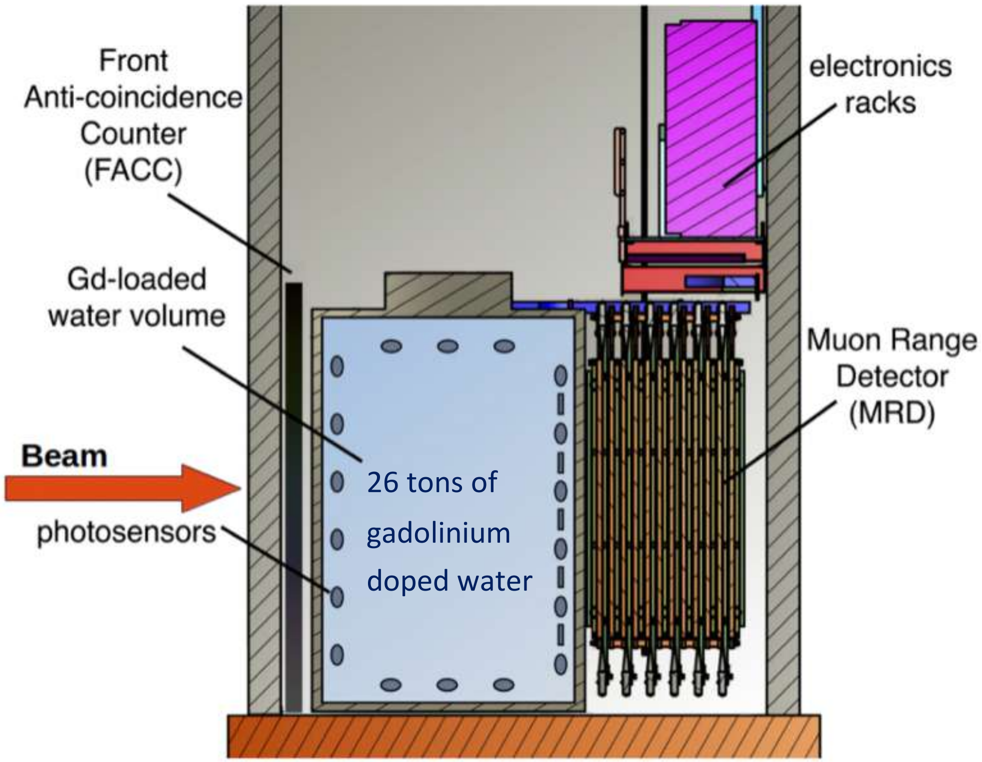
ANNIE Hall next to SBND Hall

The ANNIE detector

- 26 tons of **gadolinium-loaded water** (0.1% Gd by weight) in a steel tank
- **135 PMTs** and at least **5 LAPPDs** (~20% total photocoverage)
- **Front veto**: Scintillator paddles **tagging charged particles** originating from the rock upstream
- **Muon Range Detector (MRD)**: Steel-scintillator sandwich detector originally built for SciBooNE. Used for muon momentum reconstruction.
- **~10^4 CC interactions per ton per year** (2×10^{20} POT)



- Water Cherenkov event reconstruction with LAPPDs and PMTs.

- Gadolinium doped water for neutron capture detection

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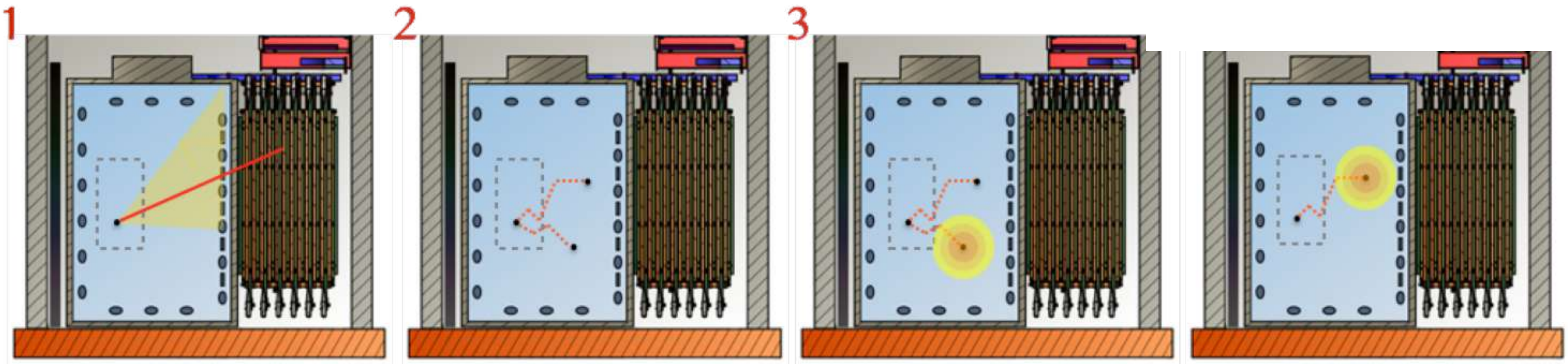
ANNIE Experimental Design

How it works…

ANNIE
Accelerator Neutrino Neutron Interaction Experiment



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

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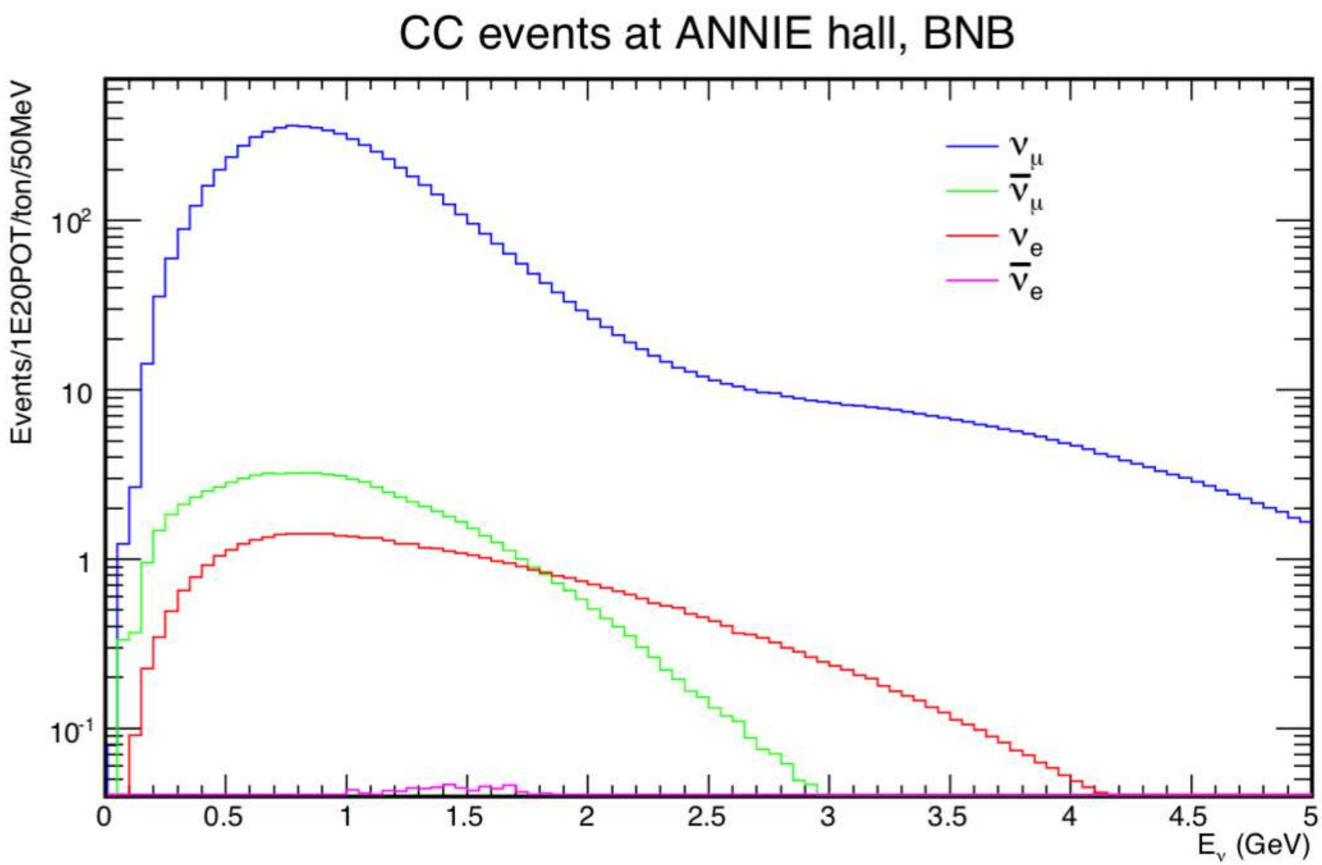
ANNIE expects a CC interaction every 30 seconds



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ANNIE expects a CC interaction every 30 seconds

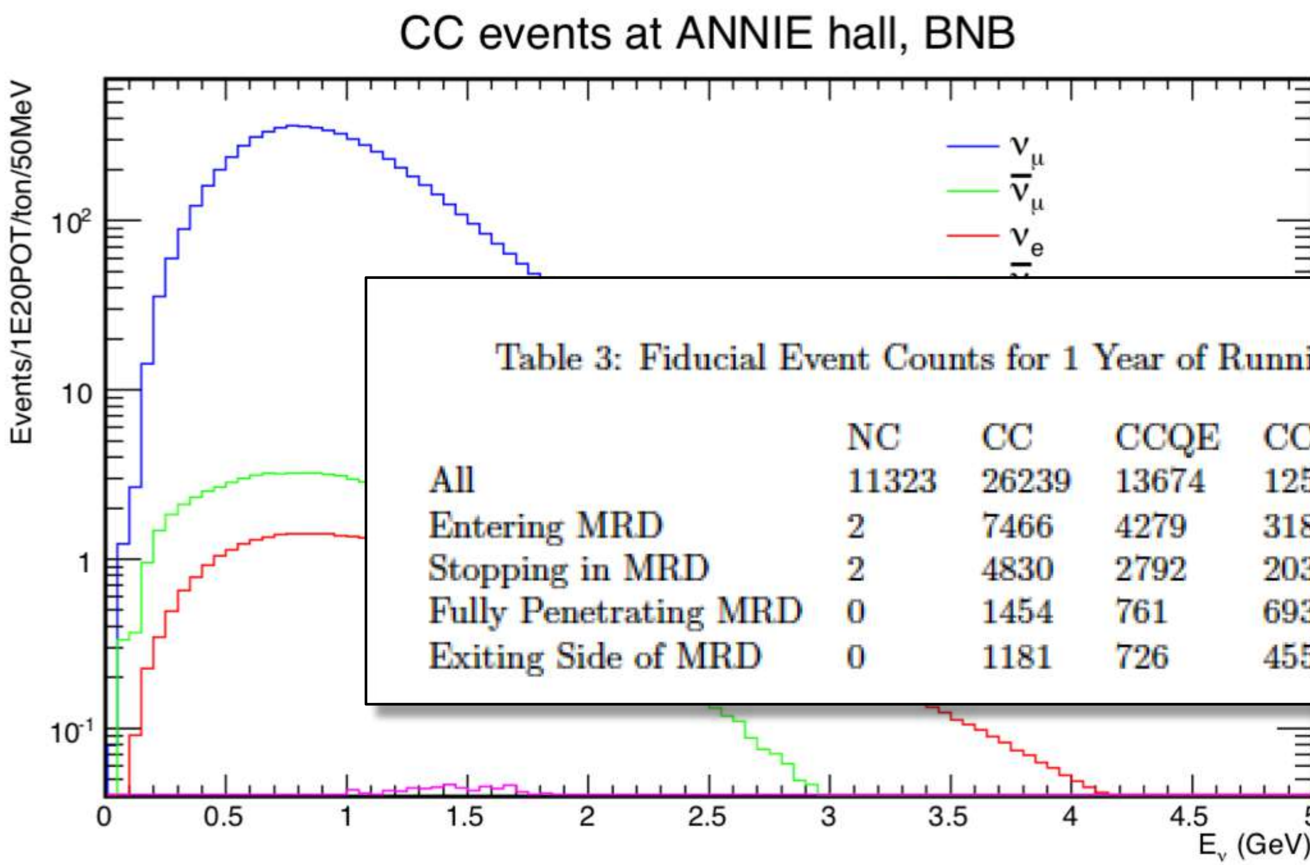


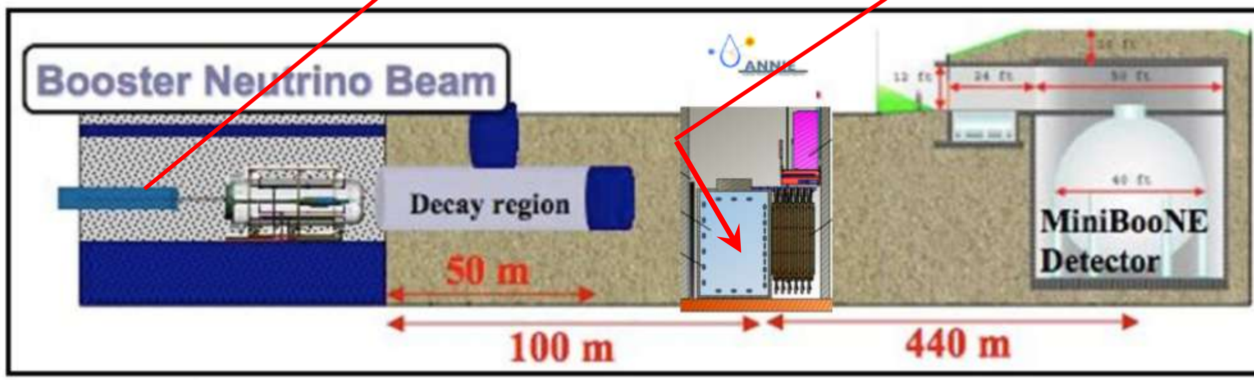
Table 3: Fiducial Event Counts for 1 Year of Running

	NC	CC	CCQE	CC-Other
All	11323	26239	13674	12565
Entering MRD	2	7466	4279	3187
Stopping in MRD	2	4830	2792	2038
Fully Penetrating MRD	0	1454	761	693
Exiting Side of MRD	0	1181	726	455

ANNIE Phase I: 2016-2017

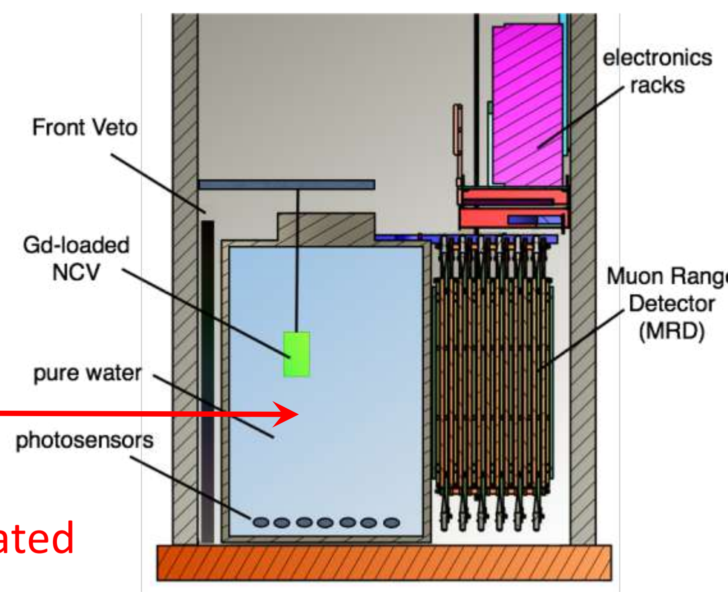
- A measurement of potential background neutrons in ANNIE Phase II
    - rock neutrons
    - “skyshine”

skyshine neutron



- A Neutron Capture Volume (NCV) measures position dependent neutron rates

- Phase I: build and operate all the main components of the detector



beam related rock neutron

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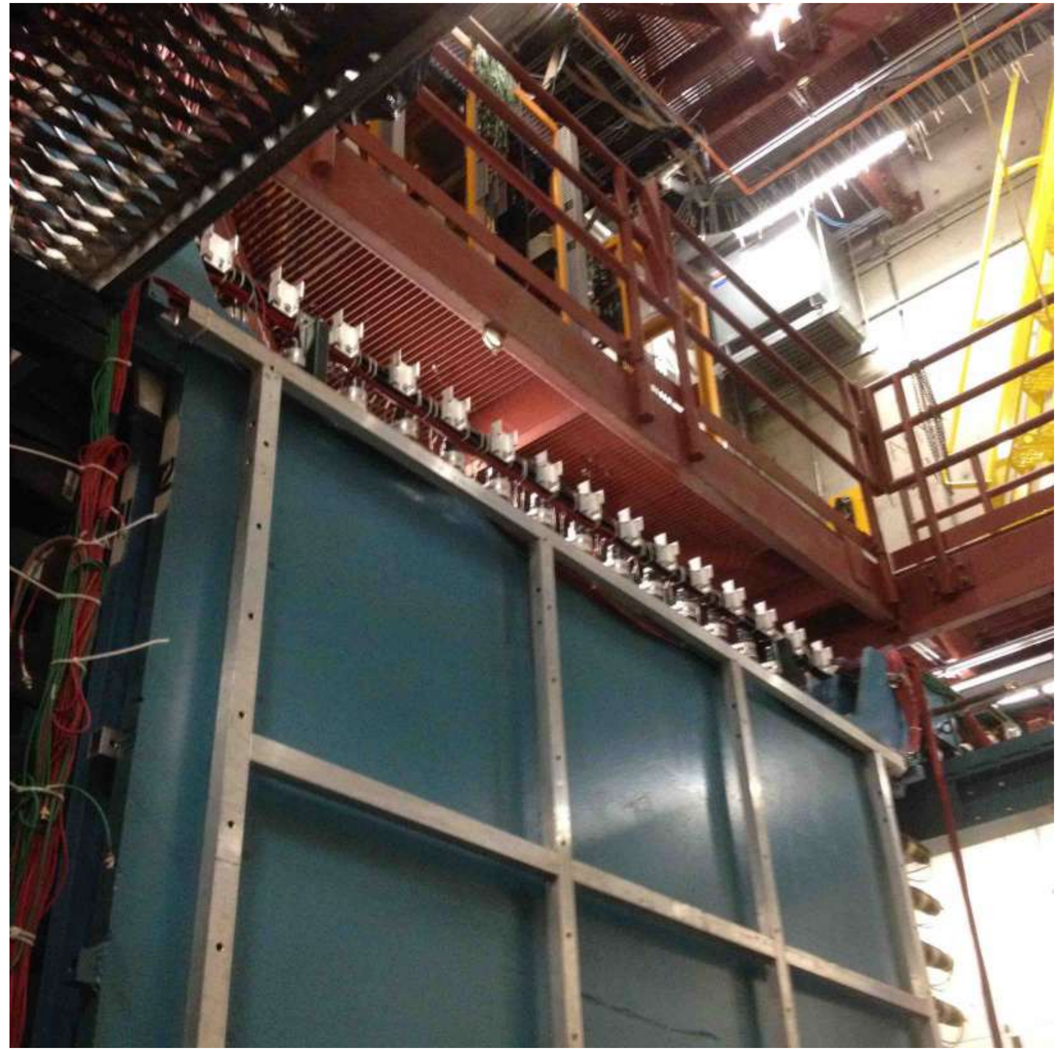
Pretty Big!


Will it fit?
SciBooNE (E954)

Neutrino Target Installed



SciBooNE Muon Range Detector

Water System and Electronics Racks.

ANNIE electronics are similar to ones used in the KOTO Experiment

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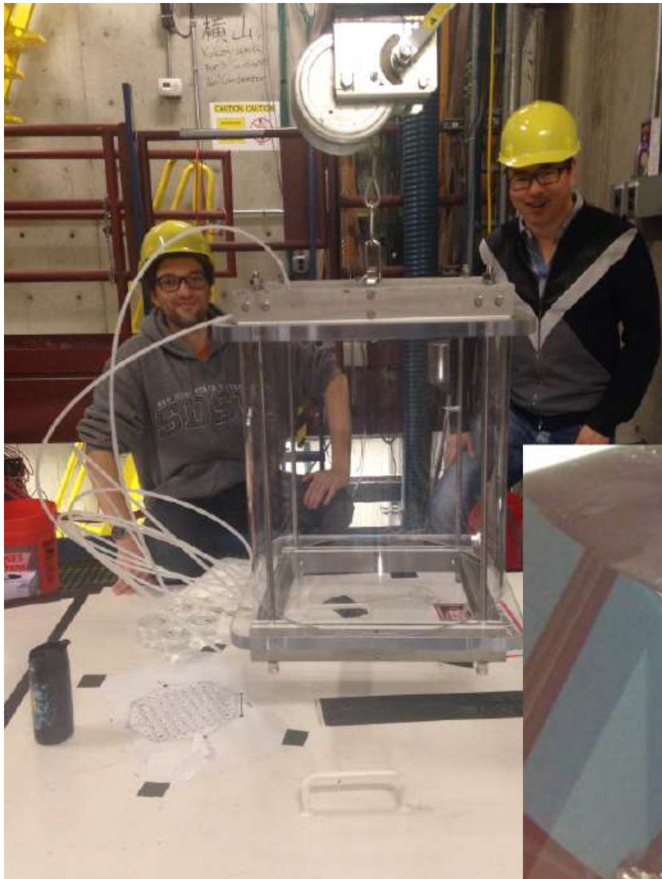
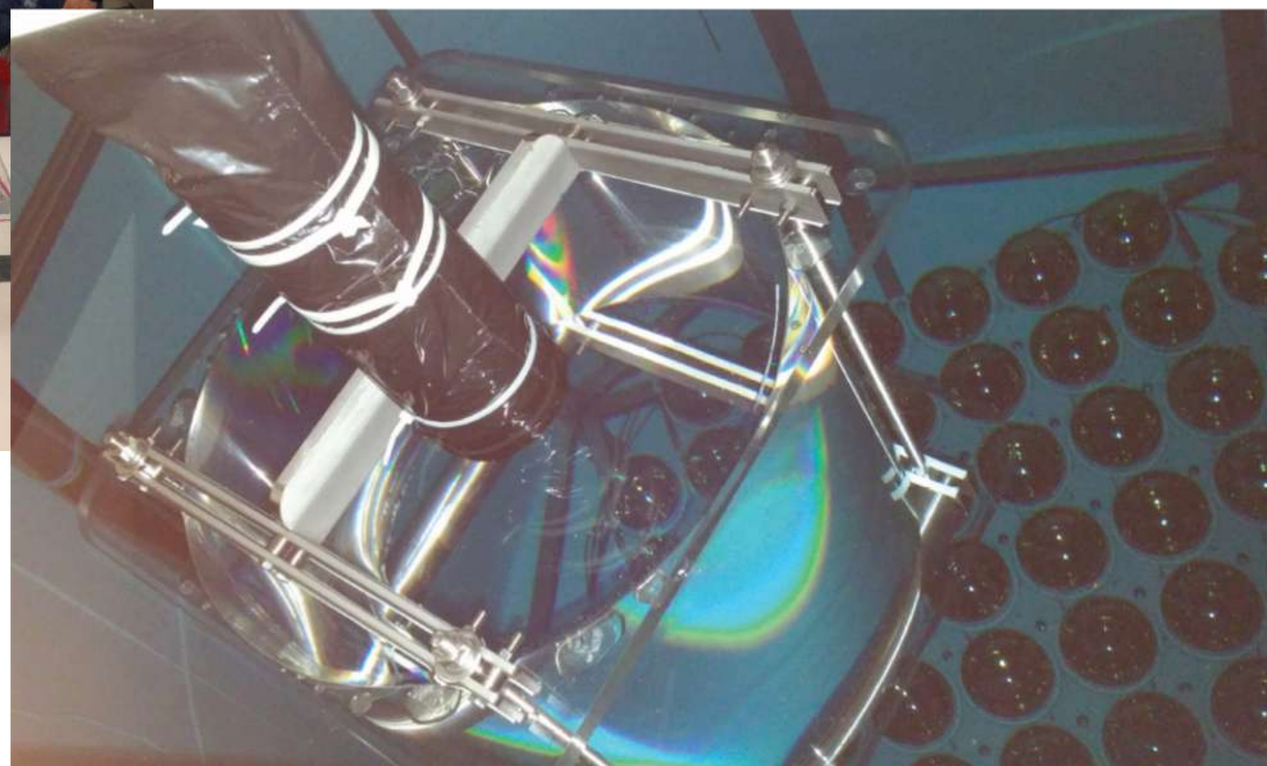


Gadolinium-doped liquid scintillator filled Neutron Capture Volume (NCV)



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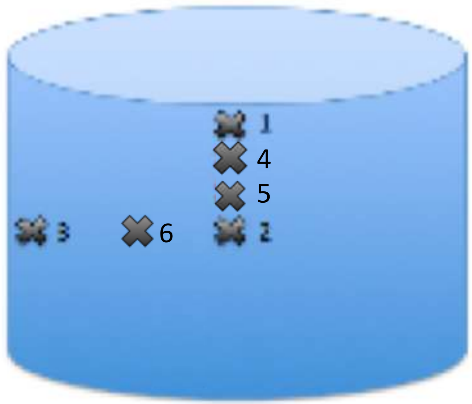
Phase I: background measurement

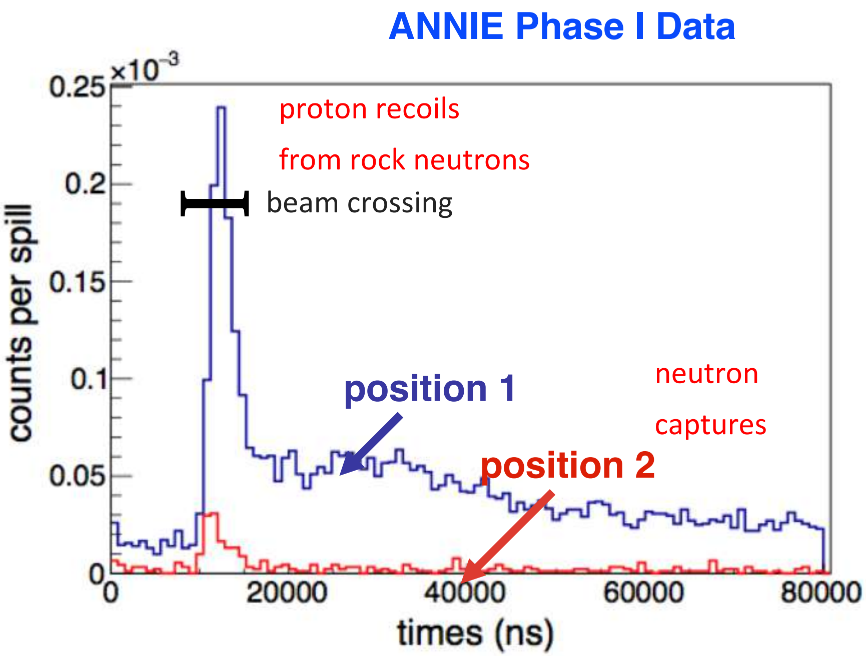


- the NCV was moved to 6 positions, scanning the neutron rates as a function of depth and distance from the beam
- strong suppression of skyshine neutrons was observed with increasing depth

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

Backgrounds are suppressed at depths > 50 cm and sufficiently low for Phase II

We are OK!



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ANNIE Phase II

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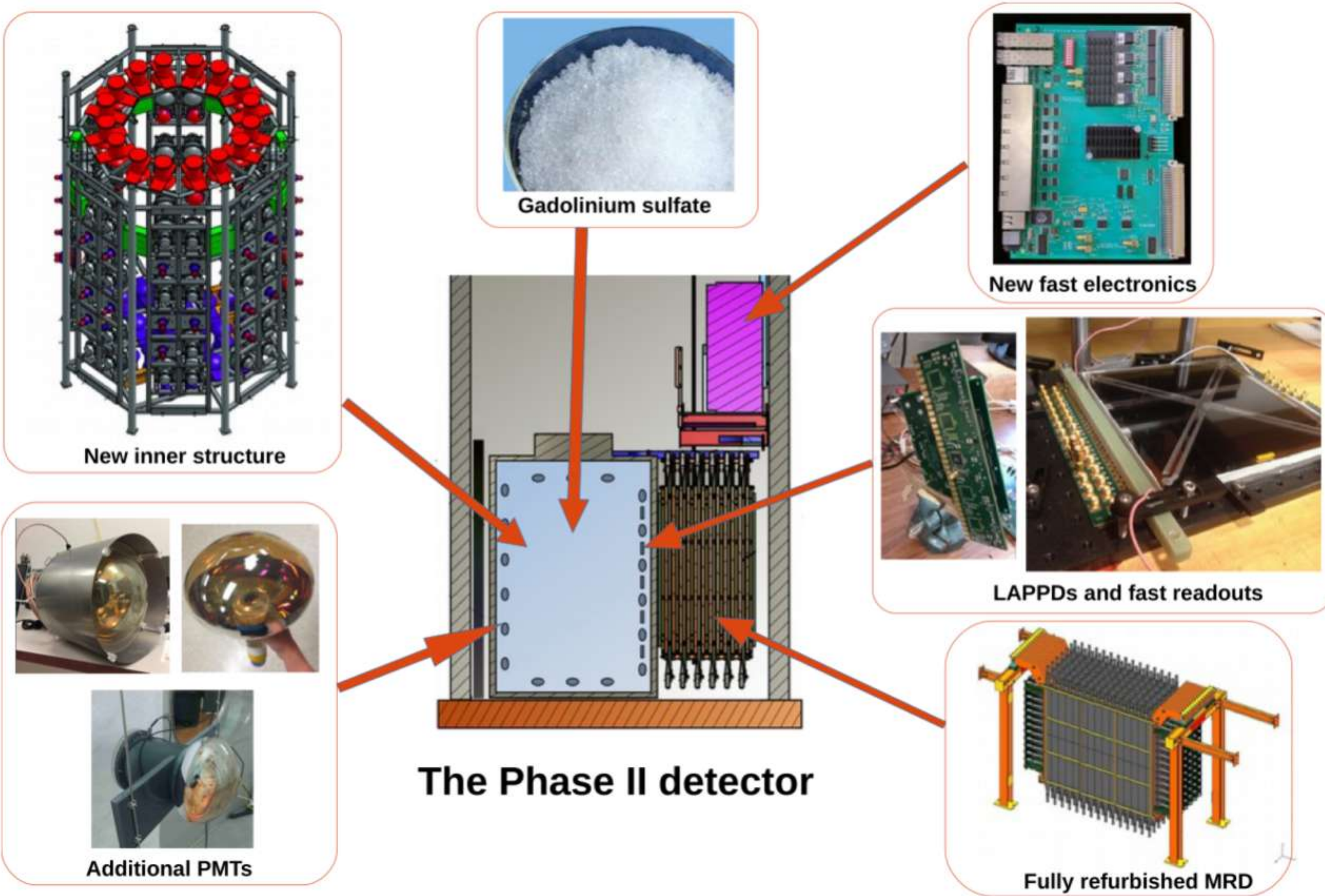
Phase II is fully funded and under construction at Fermilab



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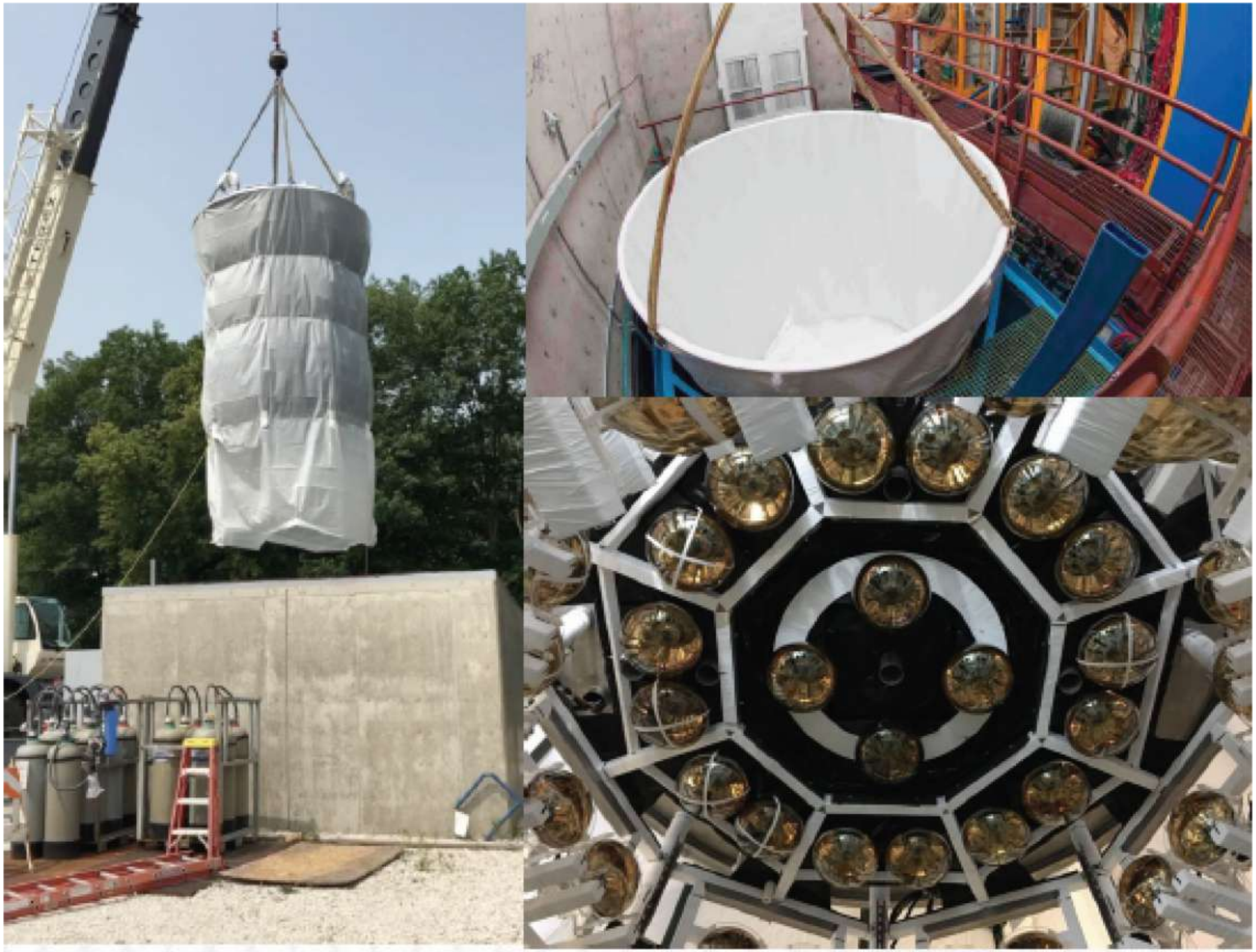

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ANNIE Q^2 Acceptance

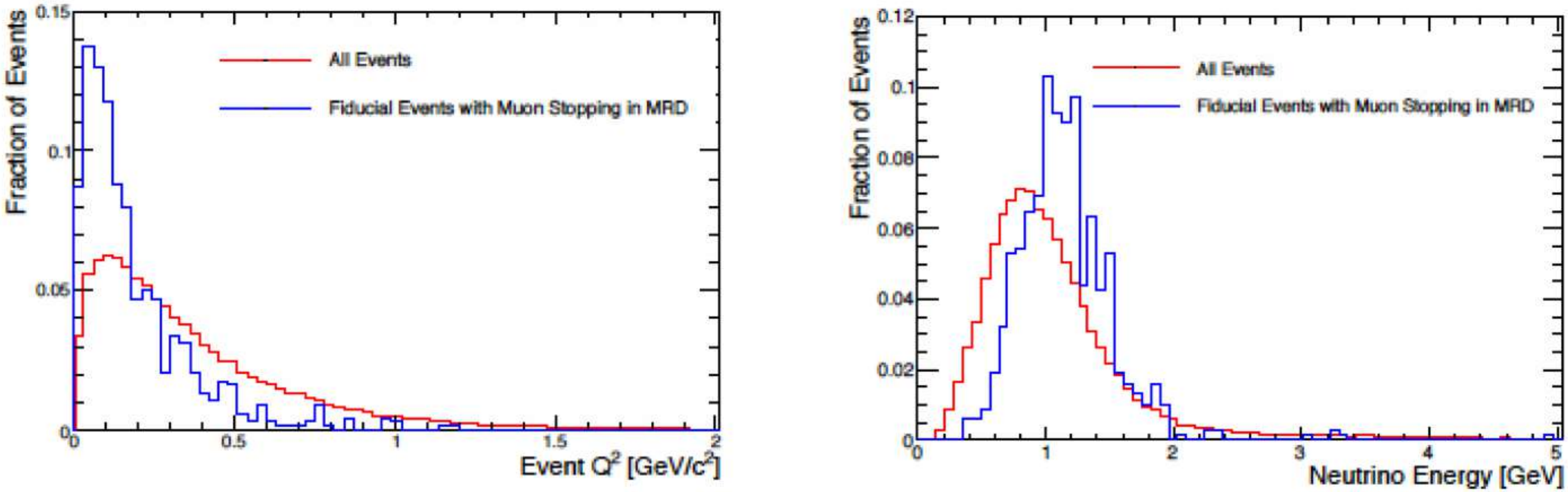

Figure 18: LEFT: The normalized Q^2 distribution for all events (red line) and for 2.5-ton fiducial events with muons ranging out in the MRD (blue line). RIGHT: The normalized E_ν distribution for all events (red line) and for 2.5-ton fiducial events with muons ranging out in the MRD (blue line).

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**

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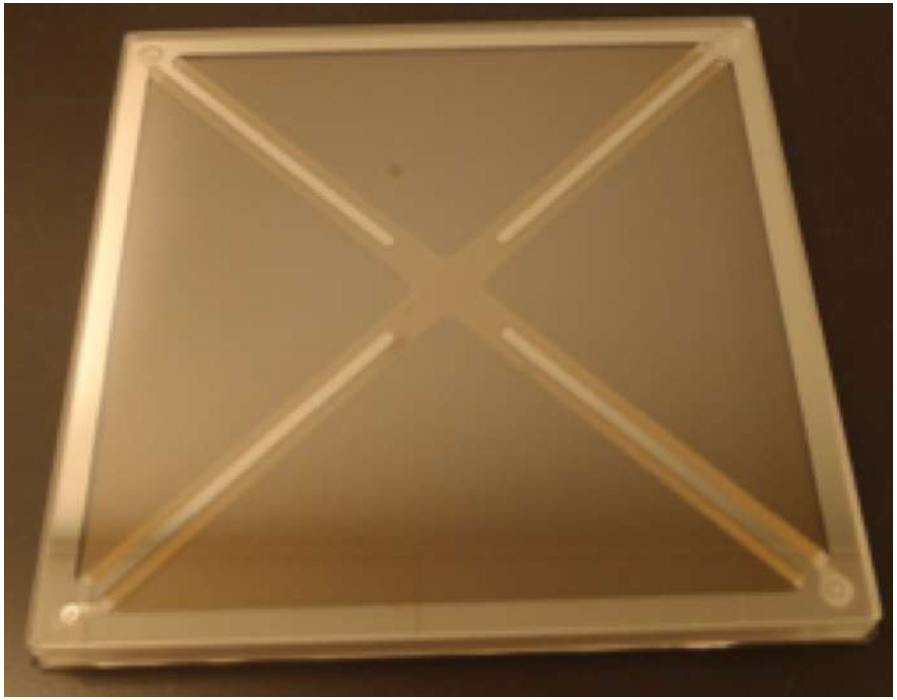
LAPPD's for ANNIE

- 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)



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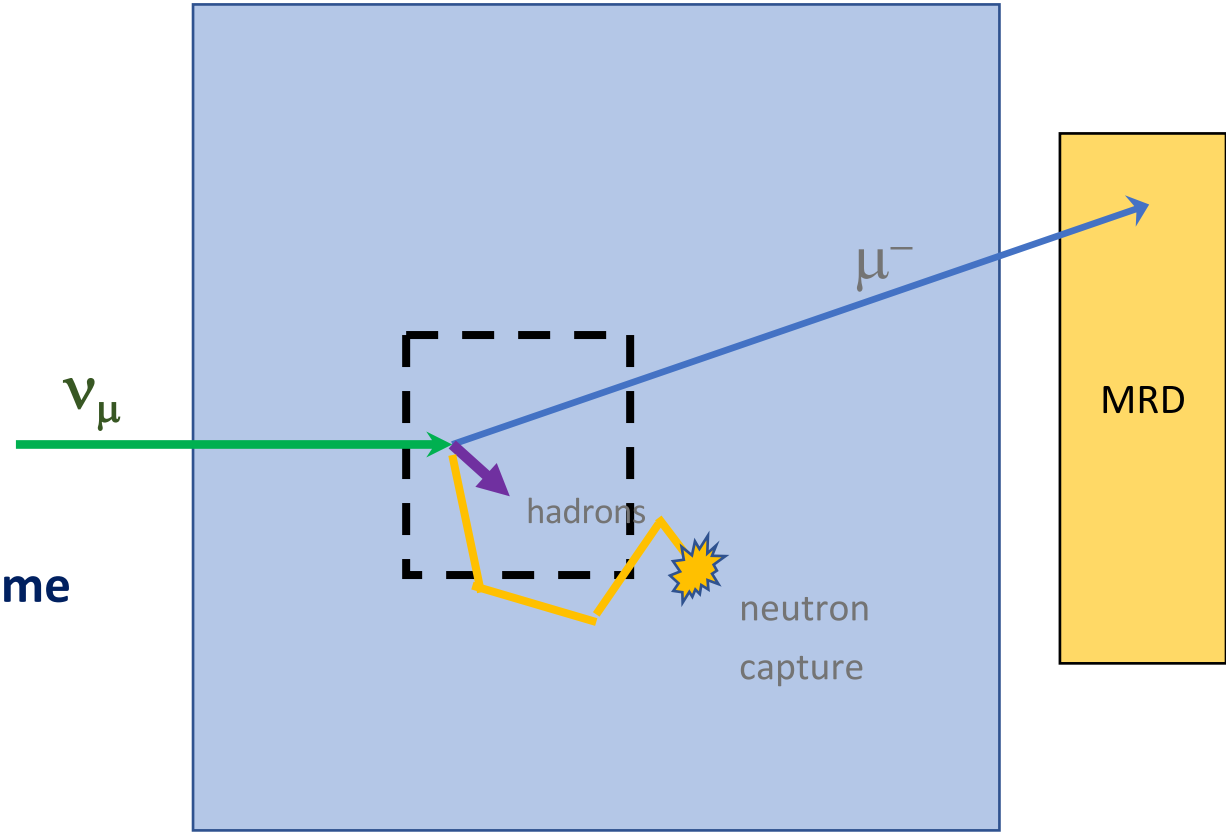
Importance of Vertex Resolution: Why ANNIE needs LAPPDs

To make sense of the neutron multiplicity measurement we have to know the **efficiency** for detecting neutron capture inside a **Fiducial Volume**



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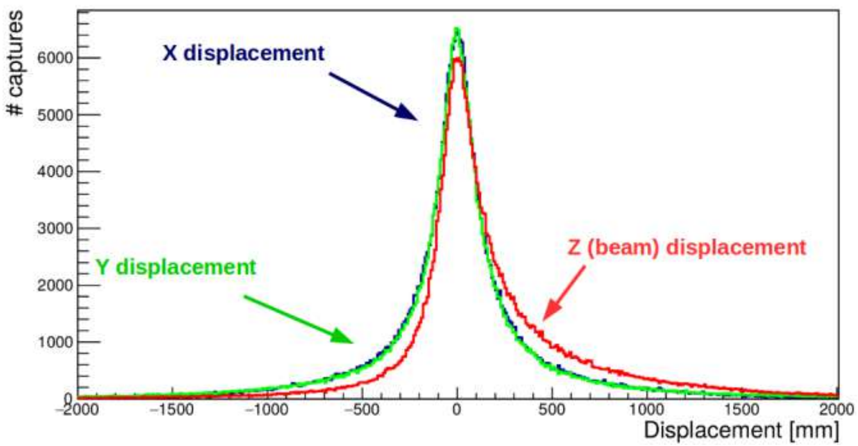
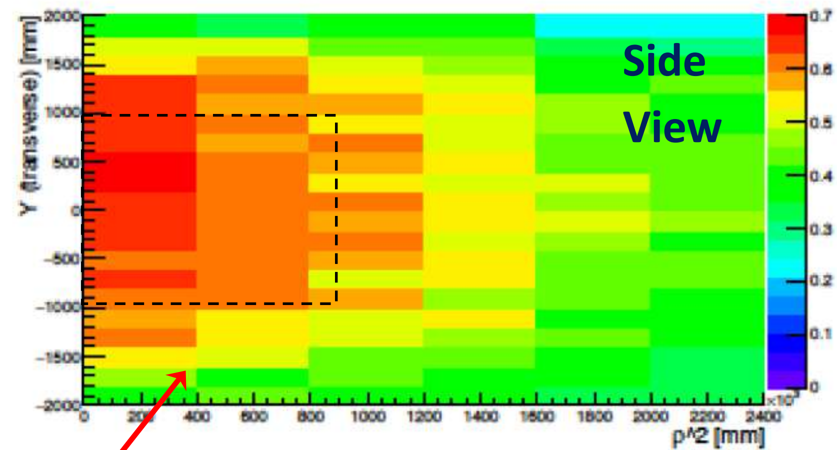
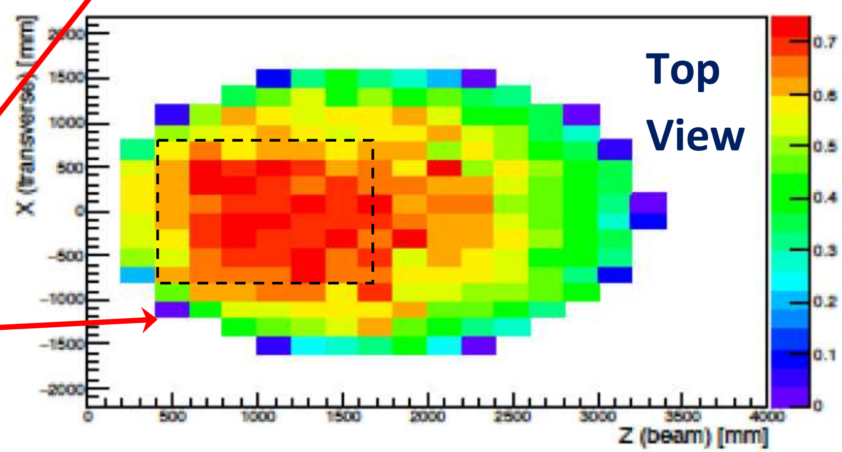
ANNIE neutron capture efficiency

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

Neutrons are captured within 50 cm or so from the vertex



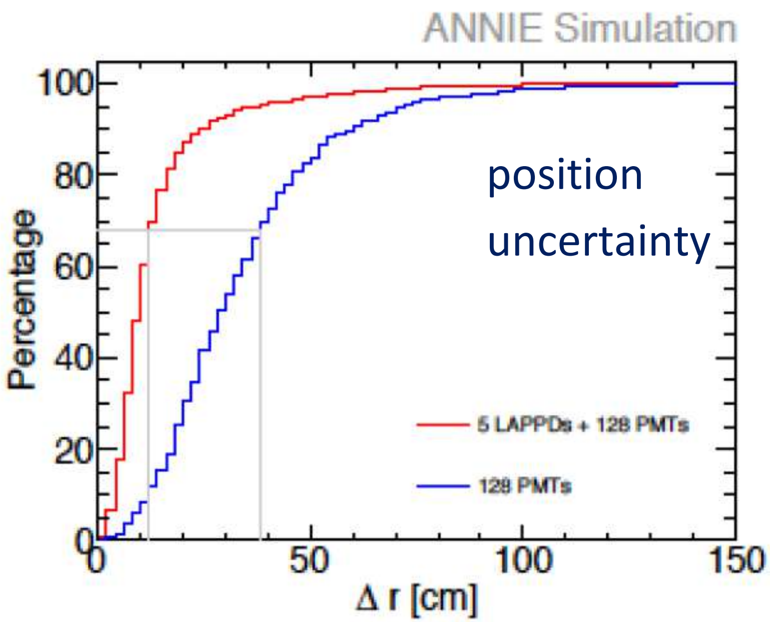


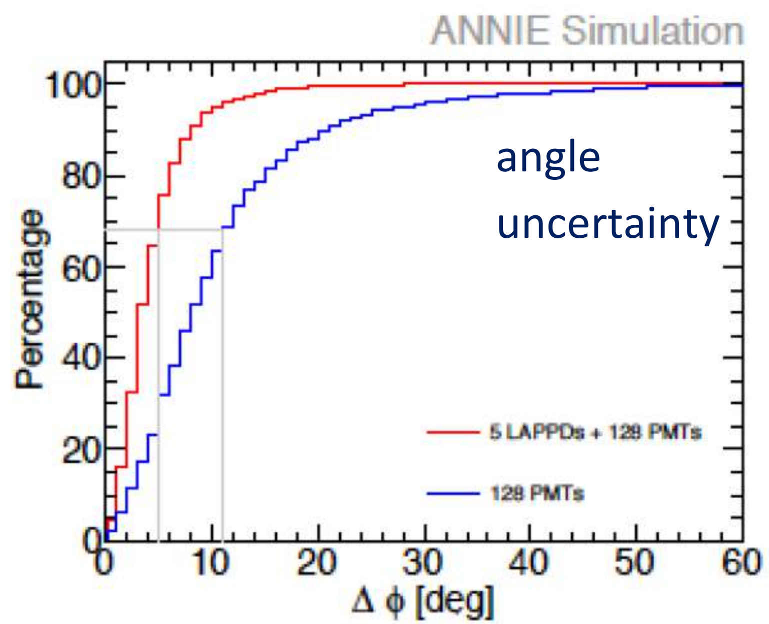


Neutron capture detection efficiency as a function of *neutrino* interaction position.

Why ANNIE needs LAPPDs

LAPPDs provide the needed vertex resolution to select only fiducial volume events





PMTs only

PMTs+LAPPDs

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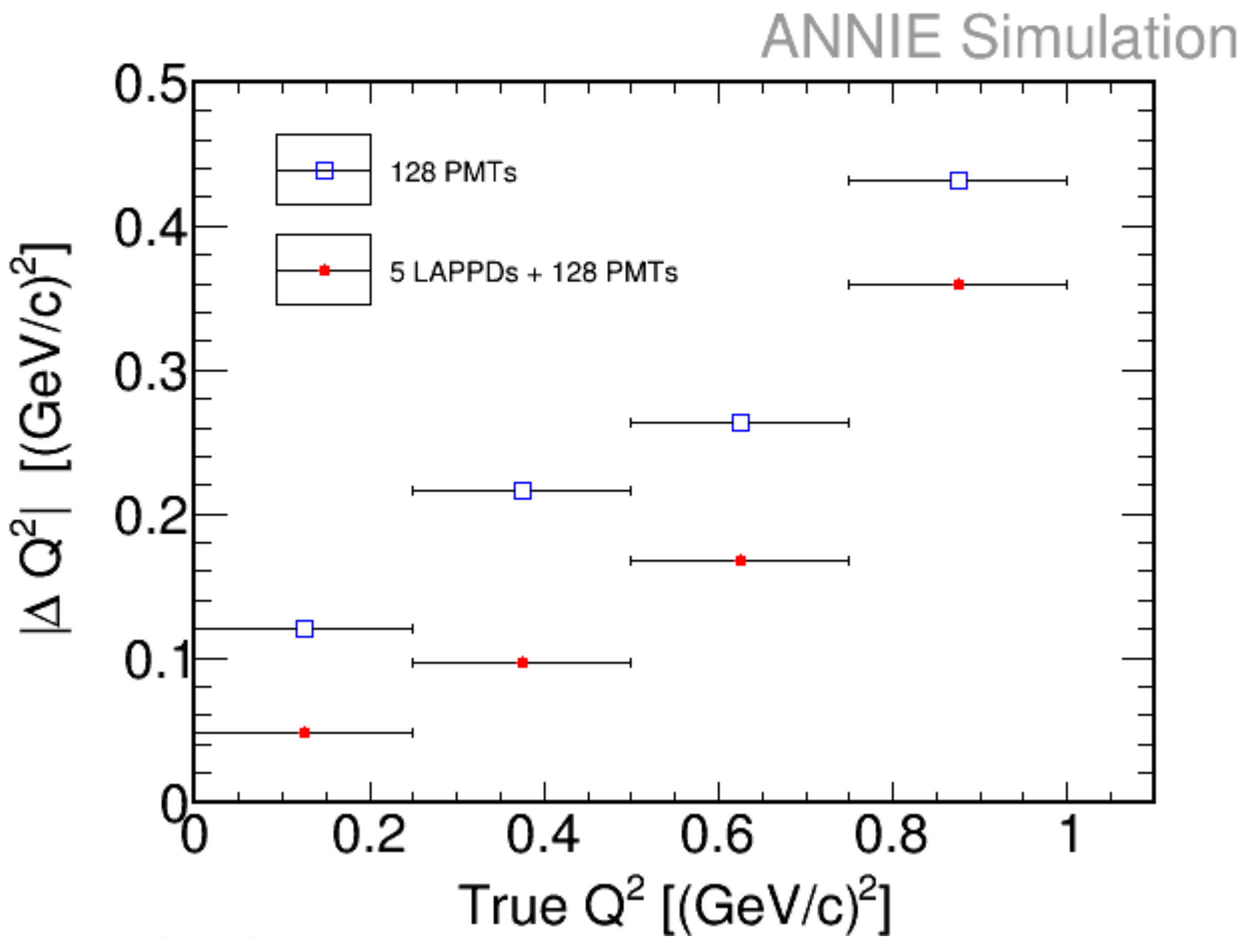
Why ANNIE needs LAPPDs: Significant Improvement in Q^2 Resolution



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ANNIE Timeline

Fall 2017

Removal of the tank from the Hall

Tank and Water System Design and Development

Finish MRD refurbishment

Spring 2018

Completion of Phase II inner structure and tank lid

PMT refurbishment and acquisition

Electronics acquisitions

Fall 2018

PMT installation

Reinstallation of inner structure and water fill

Spring 2019

Phase II commissioning

Introduction of Gd

LAPPD installation

Fall 2019

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Phase II data taking to start soon!

ANNIE

Accelerator Neutrino Neutron Interaction Experiment

Opportunities for an ANNIE **Phase III?**

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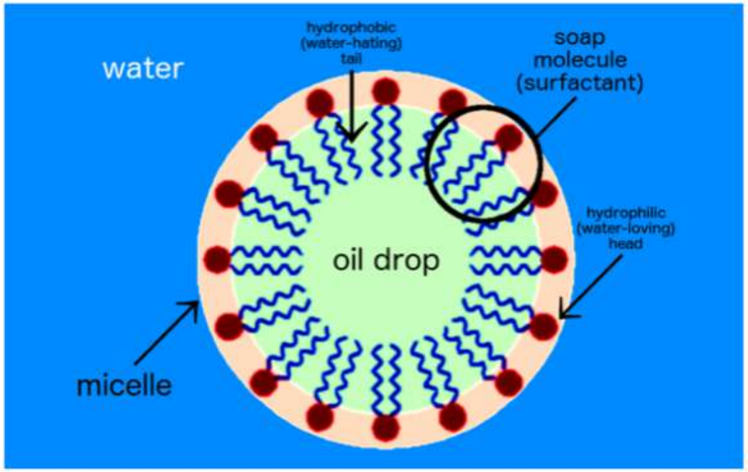
Water-based Liquid Scintillator (WbLS)

- Combination of pure water and hydrocarbon liquid scintillator
- **Water and oil don't mix, but we can cheat**: stable scintillator droplets (called micelles) can be formed in water using a surfactant!
- Combines the advantages of water (low light attenuation, low cost) and liquid scintillator (high light yield)
- Emission of **prompt Cherenkov** light and **delayed scintillation** light
- **Great flexibility**: tunable liquid scintillator concentration, isotope loading possible



micelle structure in water

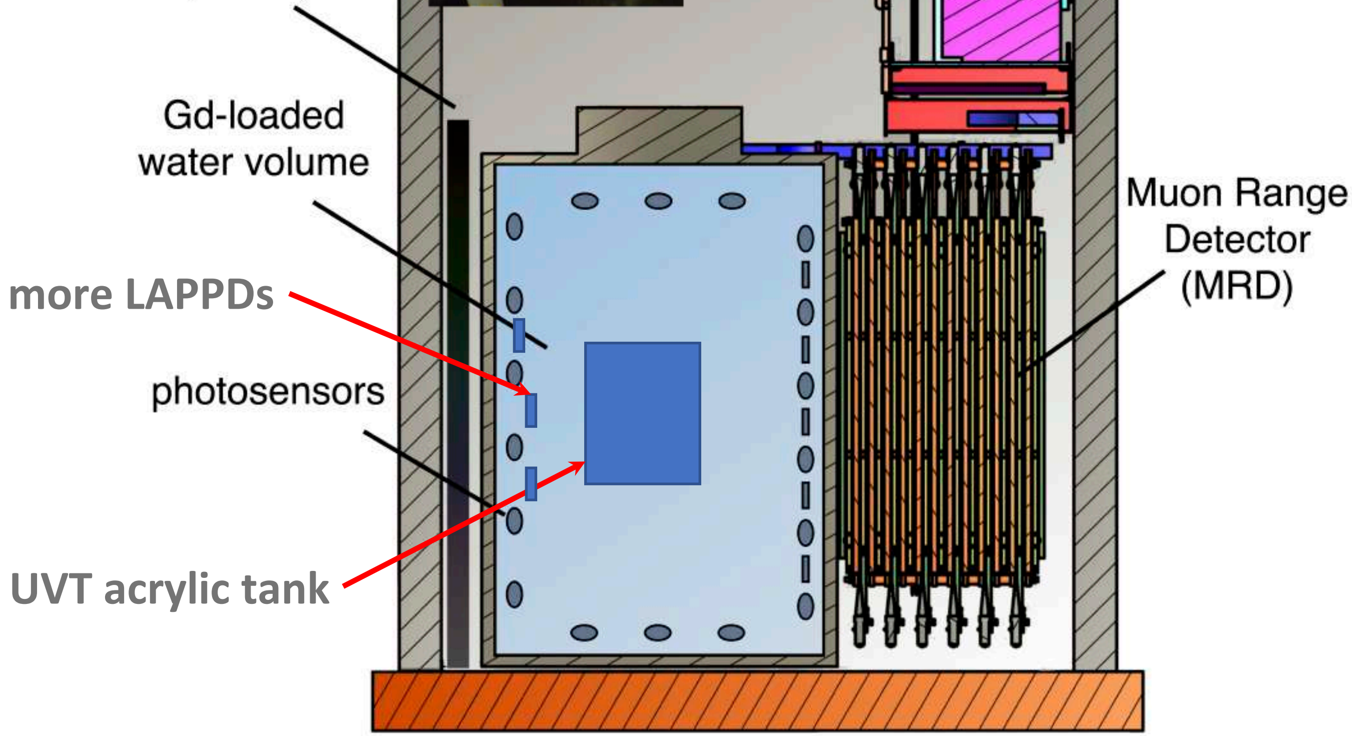
samples of WbLS with different LS concentrations

ANNIE may test WbLS reconstruction in a Phase III

Making WbLS can be fun!

The addition of a WbLS target to ANNIE, plus more LAPPD's would be very useful for future neutrino experiments

We will propose this as part of a detector development effort



Conclusions

- ANNIE will measure neutron production as a function of Q^2 in the ROI for long baseline experiments, complementing proton production measurements, which together can be used to validate nuclear models.
- ANNIE Phase I was built and operated successfully. Backgrounds shown to be sufficiently low for Phase II
- ANNIE Phase II construction is nearly complete and commissioning has now started. Physics data taking will start soon!

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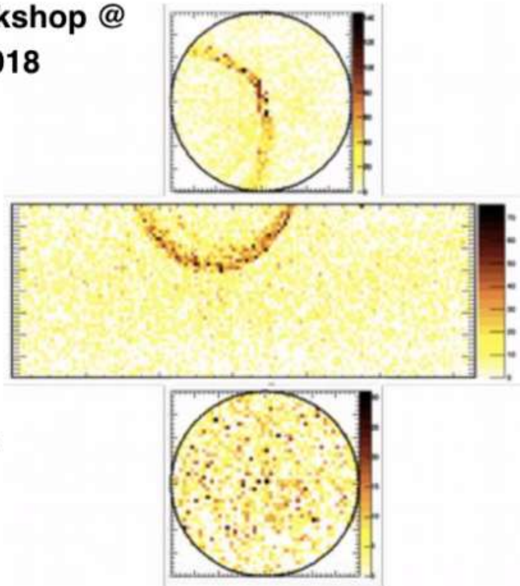
Backup

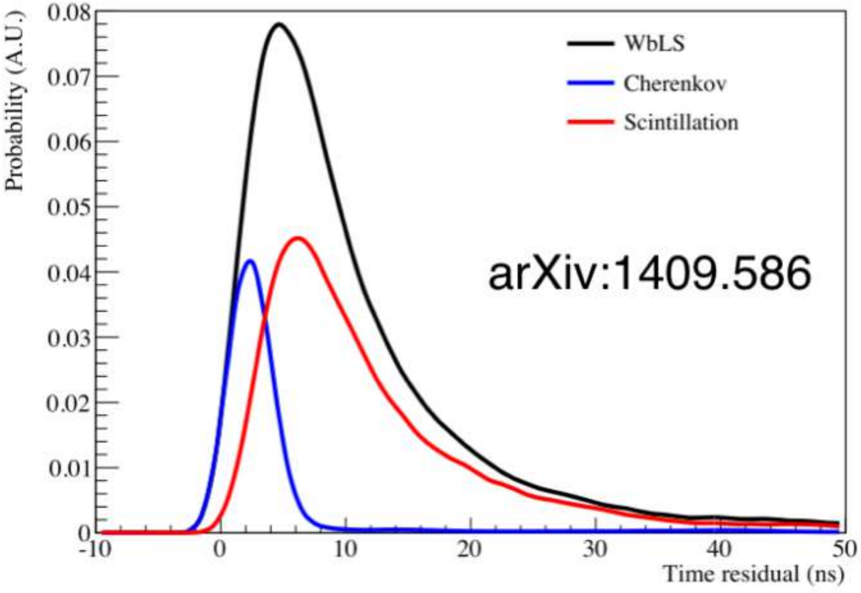
Physics impact of WbLS

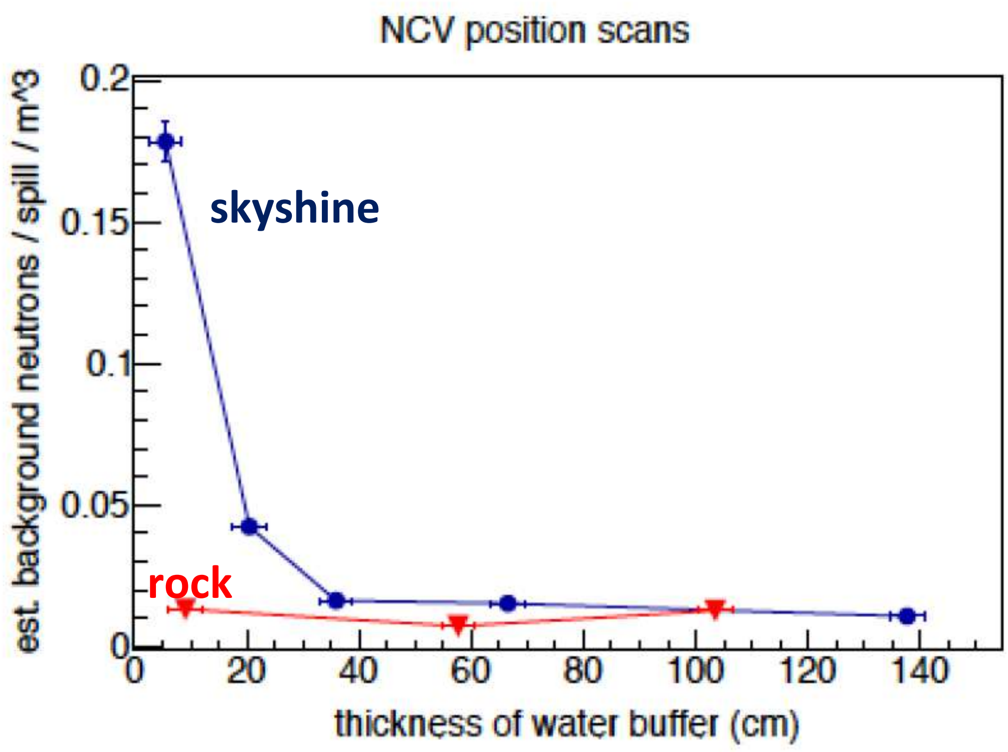
- Separating Cherenkov and scintillation light allows for **combined kinematic and calorimetric energy reconstruction**
- Fast timing capabilities of LAPPDs make this a viable strategy
- Potential for **greatly expanded physics information**
  - Neutron capture vertex reconstruction
  - Charged particle detection below the Cherenkov threshold (protons?)
  - Low-energy activity (inelastic neutron scatters?)

L. Picard, Theia Workshop @ UC Davis, 12 April 2018



Simulated photon hits from a CCQE event in WbLS. The Cherenkov ring is clearly visible over the homogeneous scintillation light.





vertical and horizontal scan of neutron flux

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LAPPD Fabrication and Testing

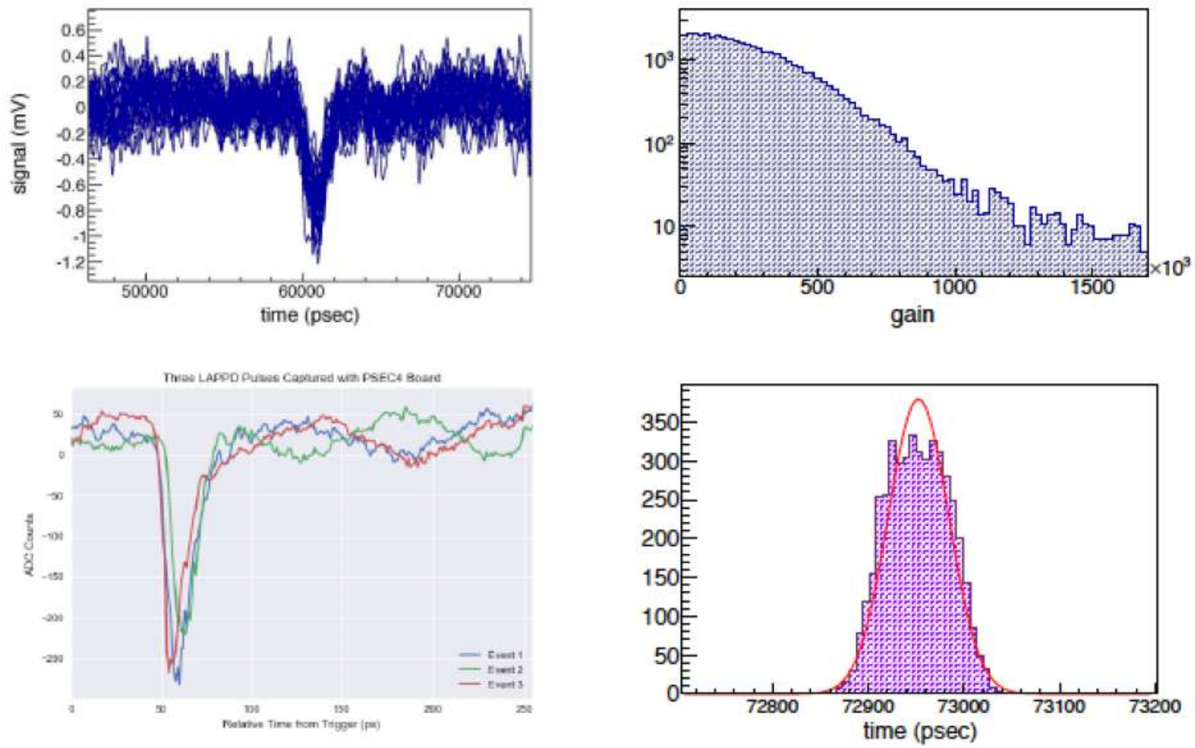
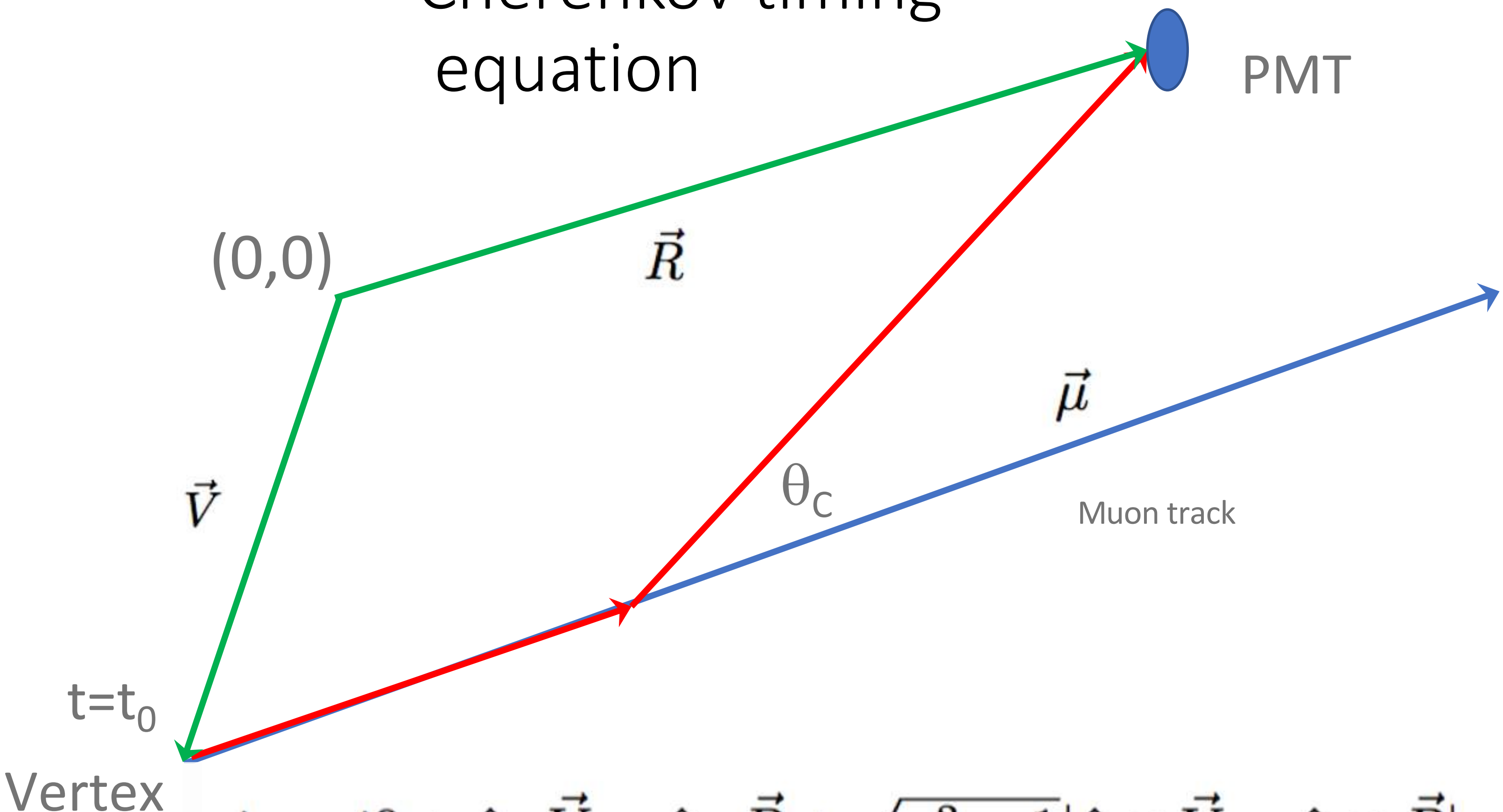


Figure 17: TOP LEFT: Example of single photoelectron pulses from LAPPD-9. TOP RIGHT: The single-PE gain distribution of LAPPD-9. BOTTOM LEFT: Several example multi-PE pulses from LAPPD-12, acquired using the PSEC front end readout. BOTTOM RIGHT: The multi-PE TTS distribution measured using the ISU test stand. The 30 psec sigma and non-Gaussian shape is due to the limitations of the laser, which should be sufficient for characterizing 50 psec photosensors.

Cherenkov timing equation



$$ct = ct0 + \hat{\mu}\cdot\vec{V} - \hat{\mu}\cdot\vec{R} + \sqrt{n^2-1}\,|\hat{\mu}\times\vec{V} - \hat{\mu}\times\vec{R}|$$

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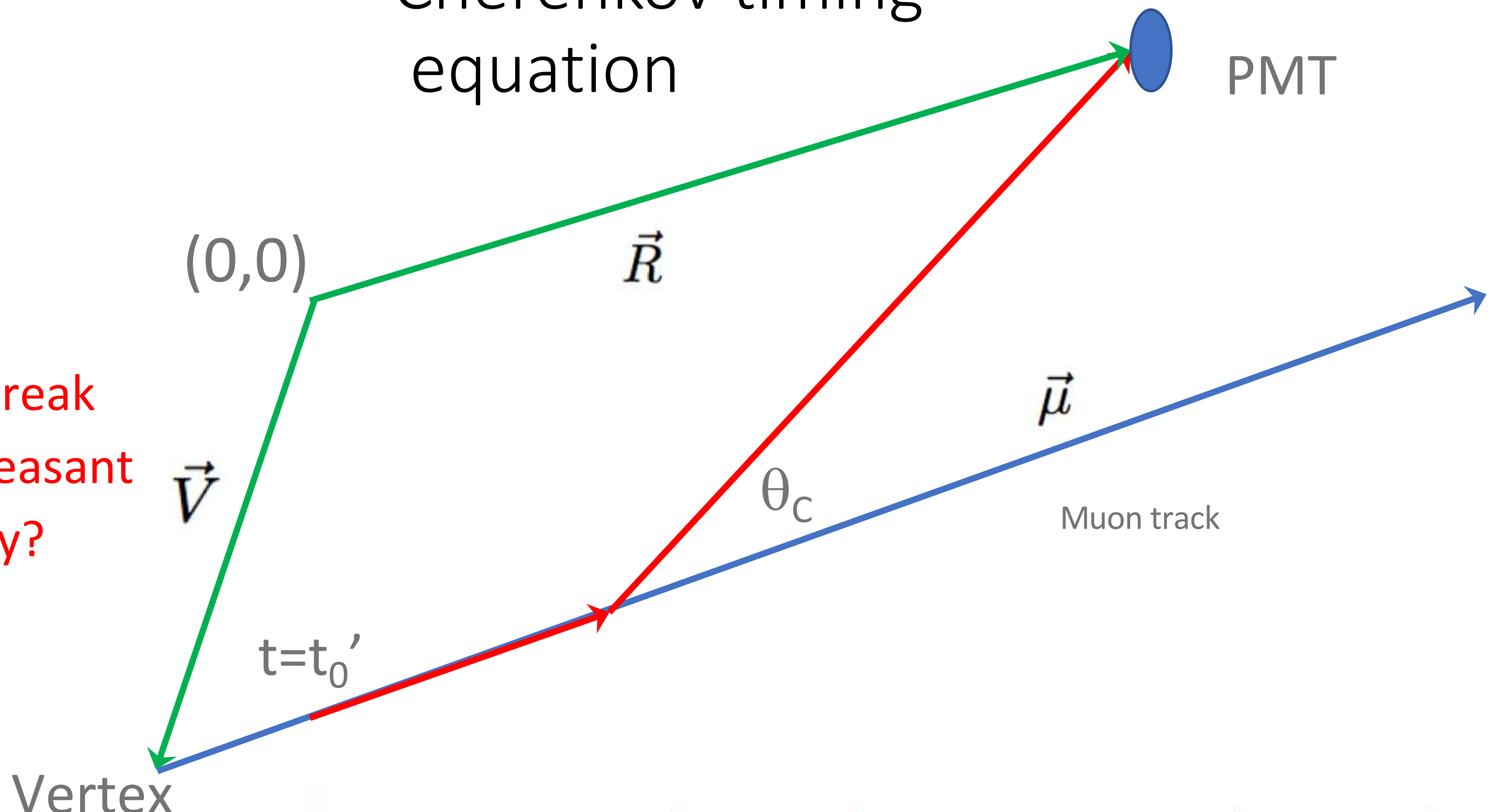
Cherenkov timing equation

How to break this unpleasant symmetry?



$$ct = (ct0 + \hat{\mu}\cdot\vec{V}) - \hat{\mu}\cdot\vec{R} + \sqrt{n^2-1}|\hat{\mu}\times\vec{V} - \hat{\mu}\times\vec{R}|$$

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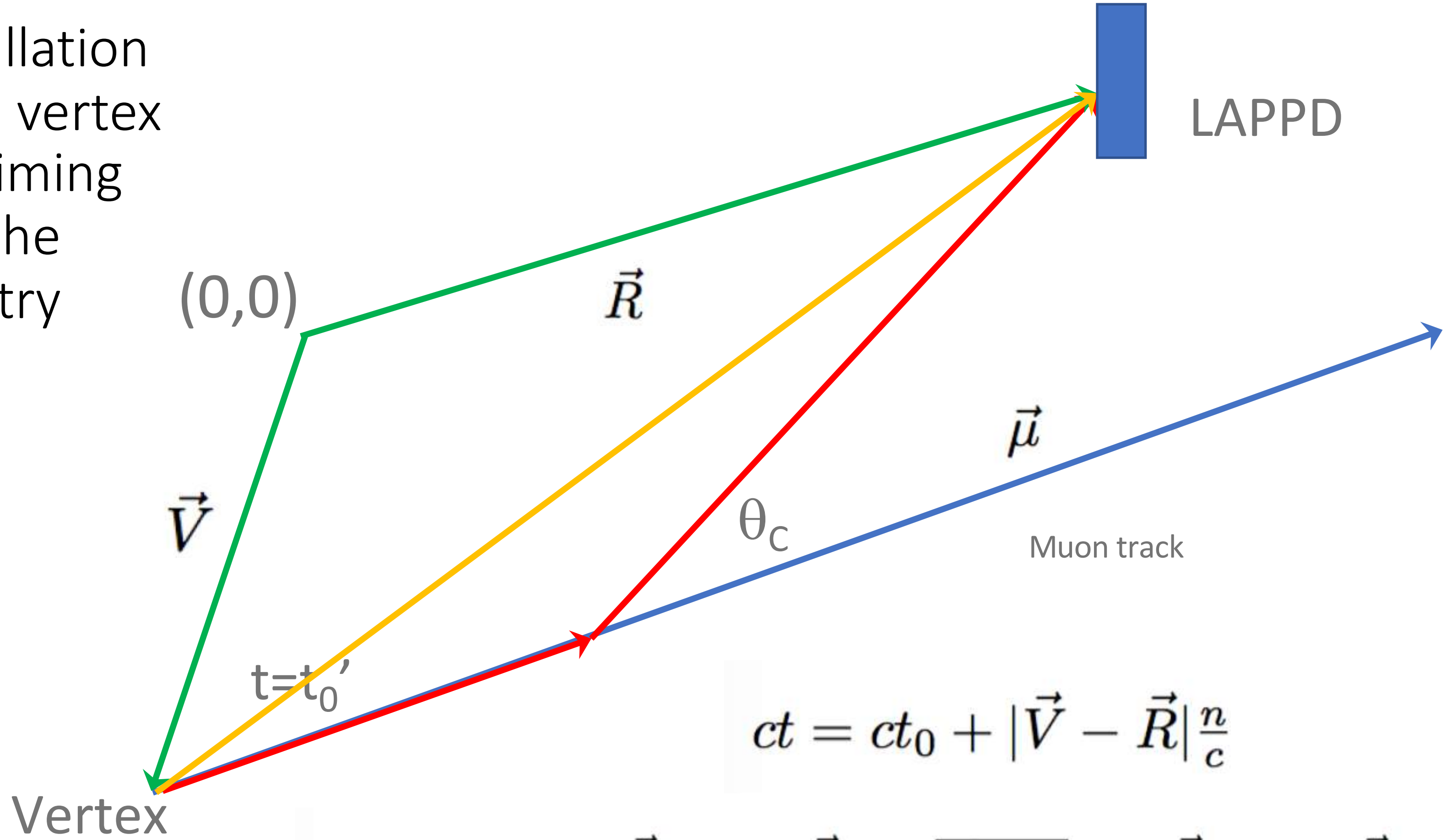
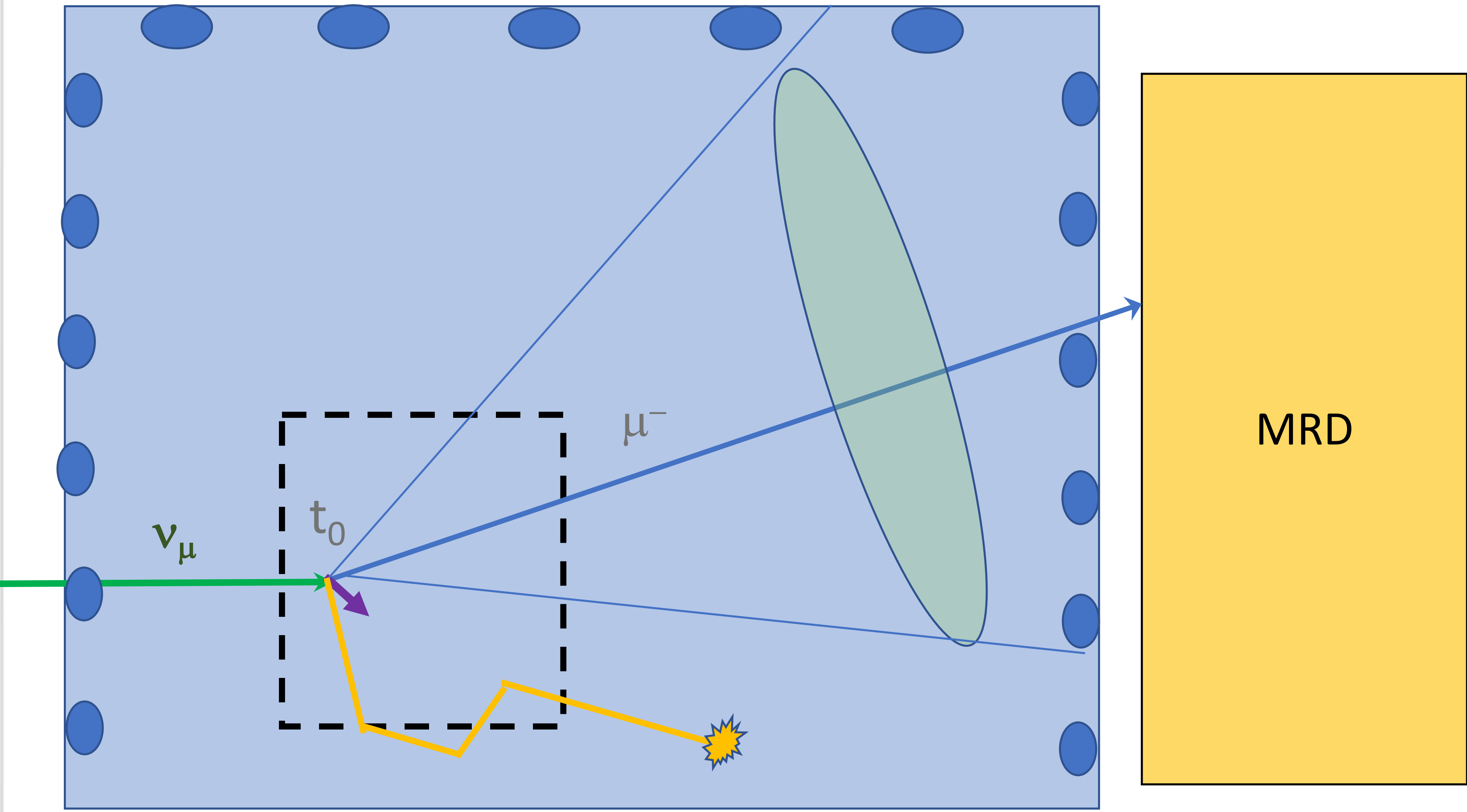
Add scintillation light from vertex and fast timing to break the t_0 symmetry



$$ct = ct_0 + |\vec{V} - \vec{R}|\frac{n}{c}$$

$$ct = (ct0 + \hat{\mu}\cdot\vec{V}) - \hat{\mu}\cdot\vec{R} + \sqrt{n^2-1}|\hat{\mu}\times\vec{V} - \hat{\mu}\times\vec{R}|$$



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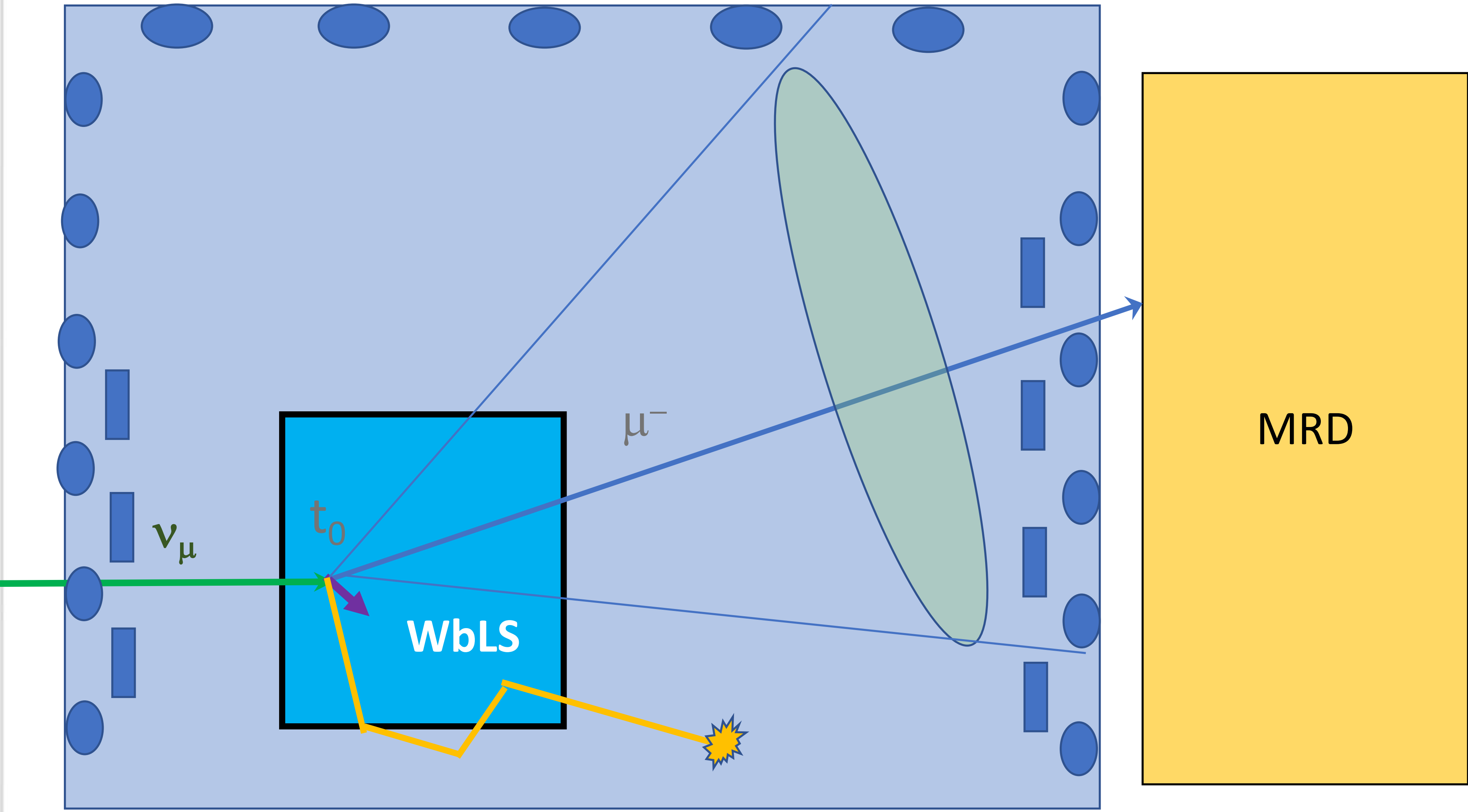

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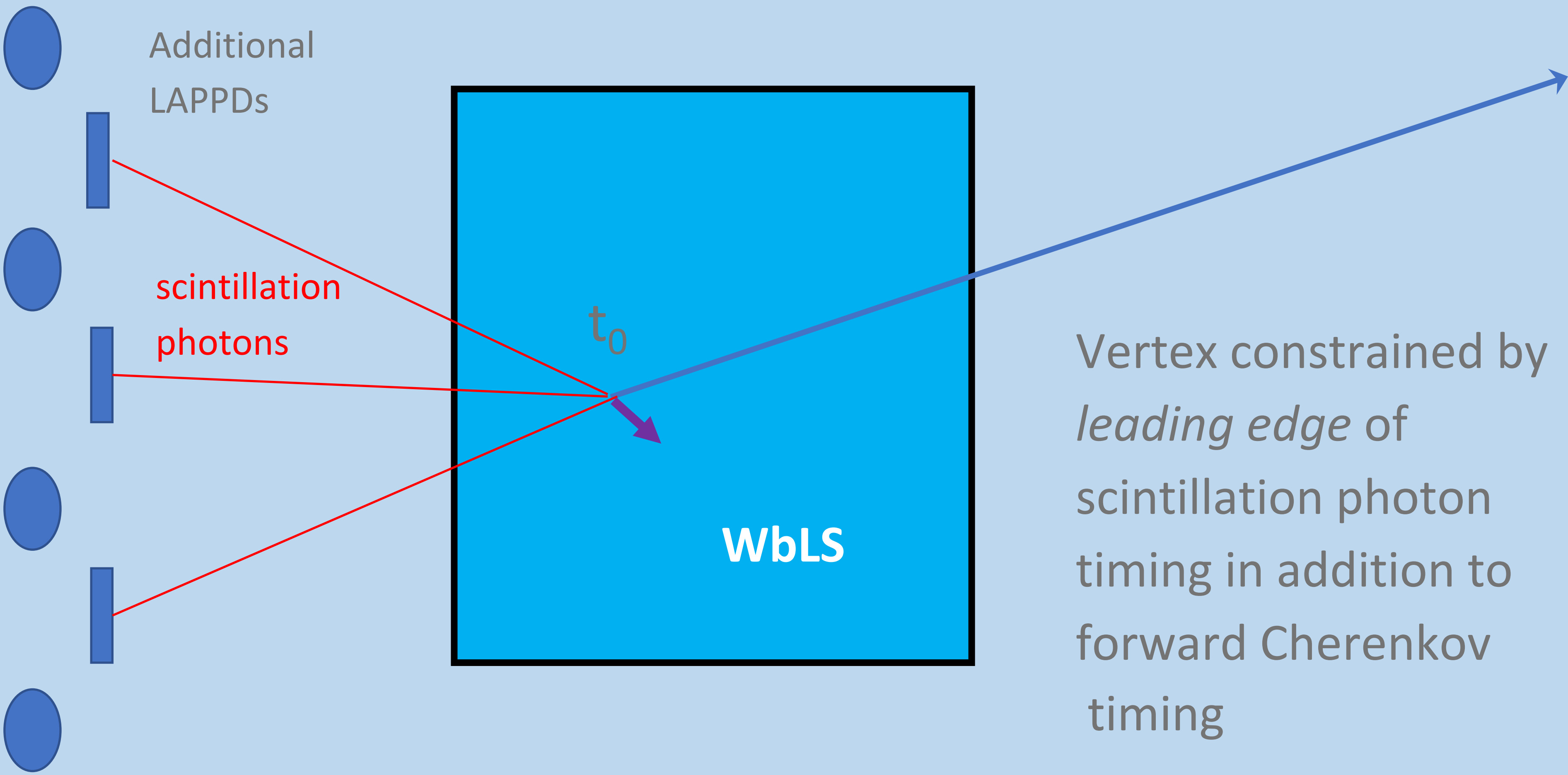
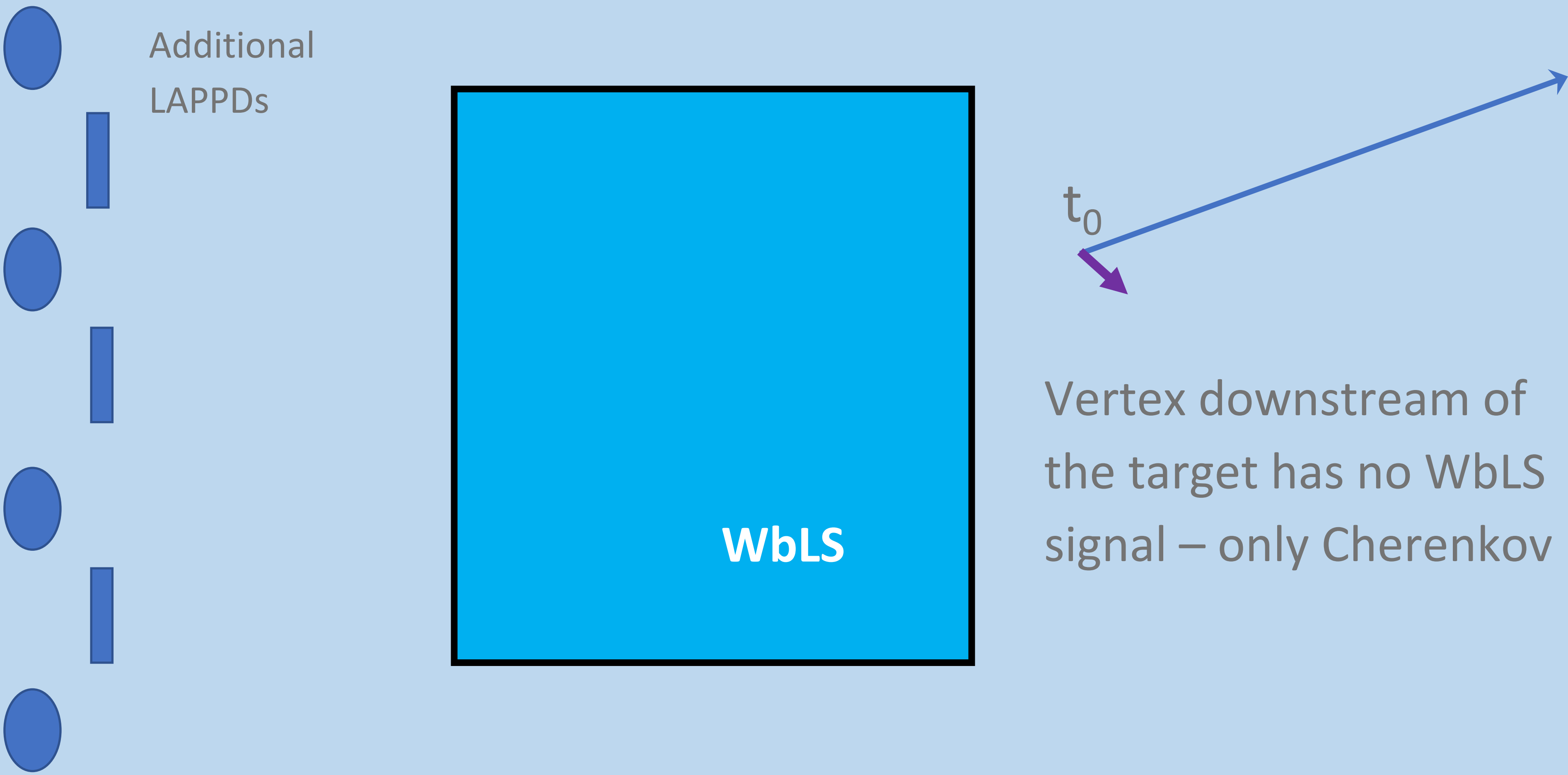
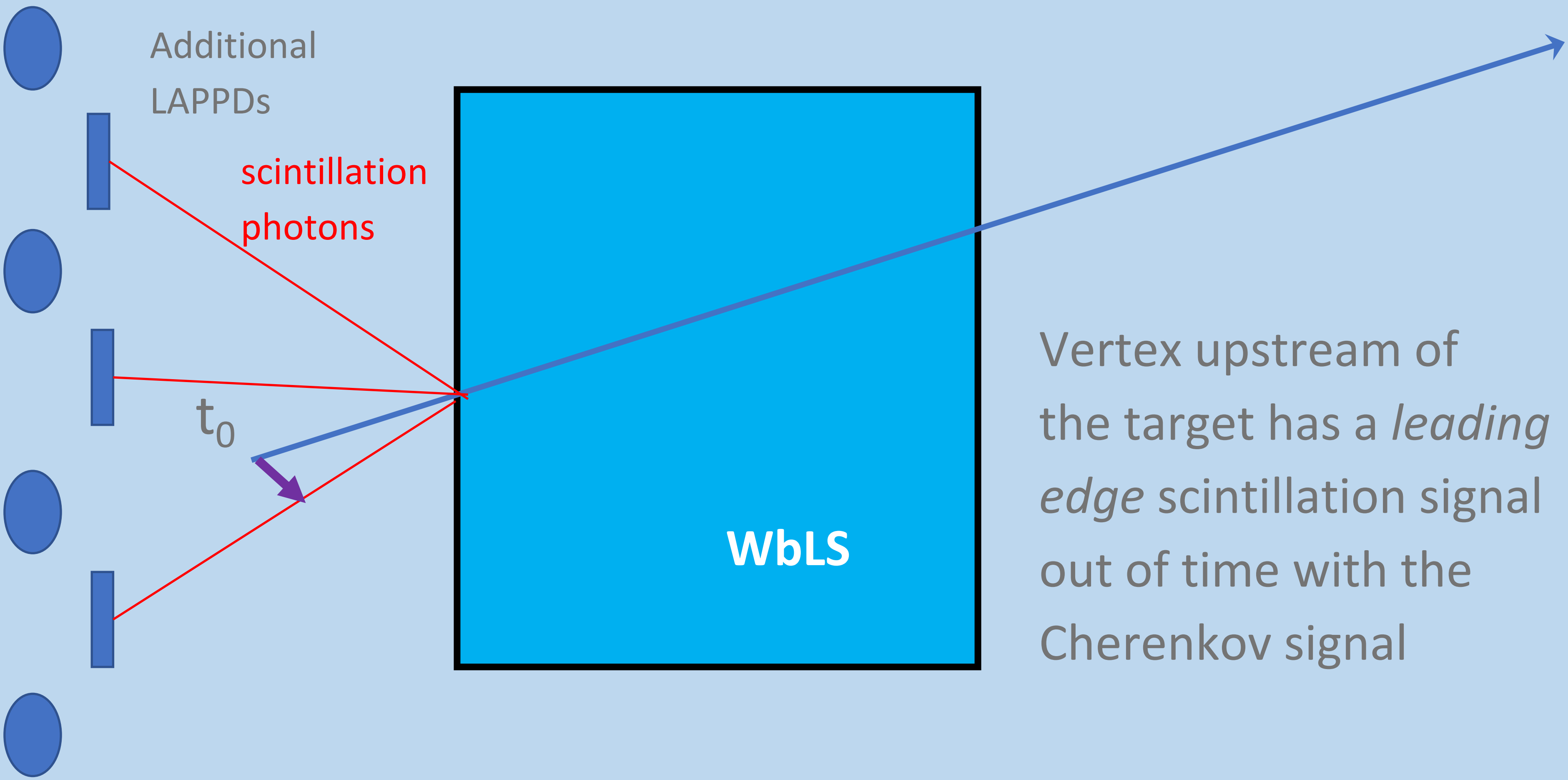
Run 3: Adding additional LAPPD's



Vertex constrained by *leading edge* of scintillation photon timing in addition to forward Cherenkov timing

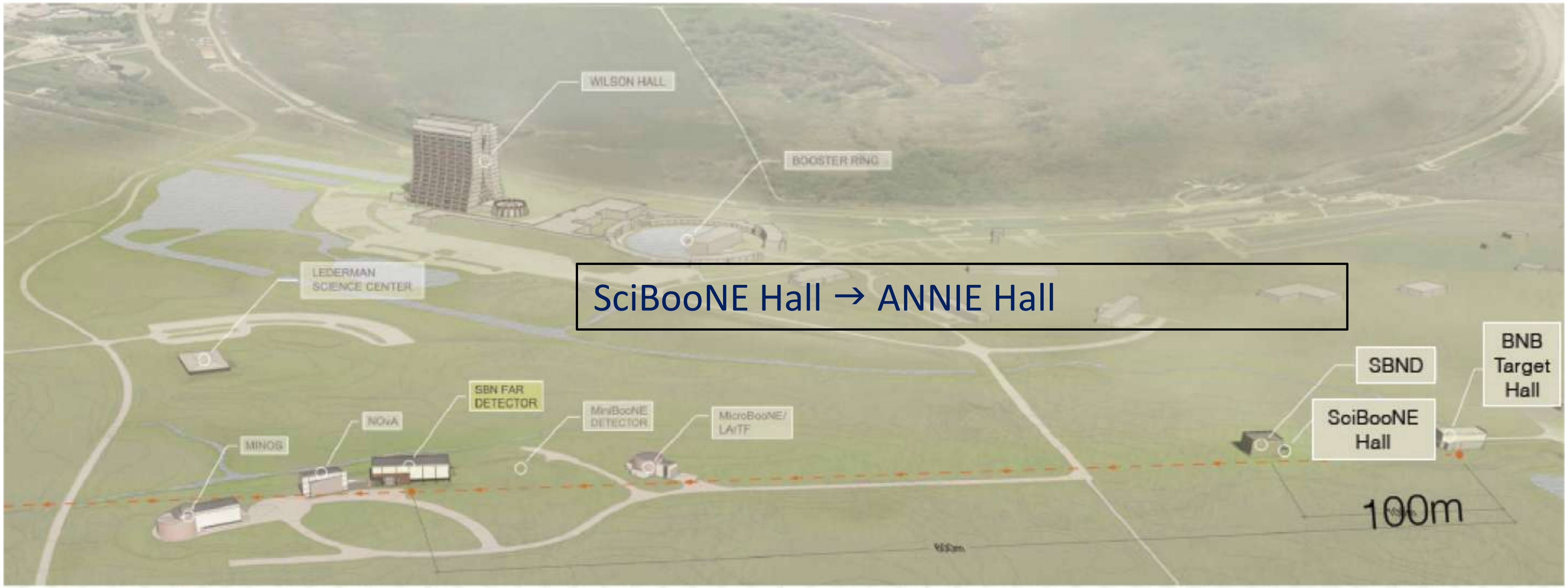


Vertex downstream of the target has no WbLS signal – only Cherenkov



Vertex upstream of the target has a *leading edge* scintillation signal out of time with the Cherenkov signal

Fermilab Booster Neutrino Beam



ANNIE shares the same beam as the MicroBooNE and SBND Experiments

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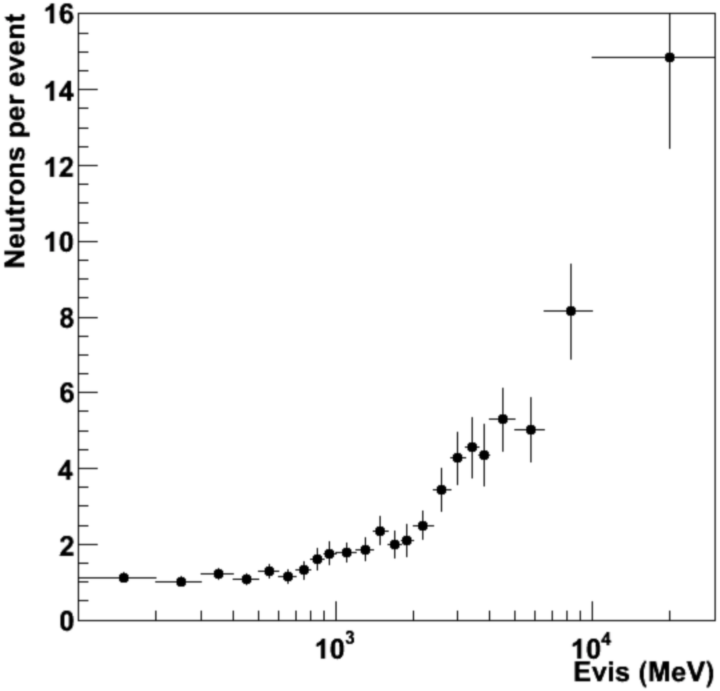
Super-K has a 17% efficiency for detecting neutrons, and has measured neutron production as a function of visible energy in atmospheric neutrinos.

This is not so useful as the neutrino energy, flavor, sign, and interaction type is not known – difficult to incorporate into simulations, but shows that neutron production is common.

Super-K neutron production measurement in atmospheric neutrinos (*)



* Uncertainties shown are statistical only

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LAPPD Fabrication and Testing

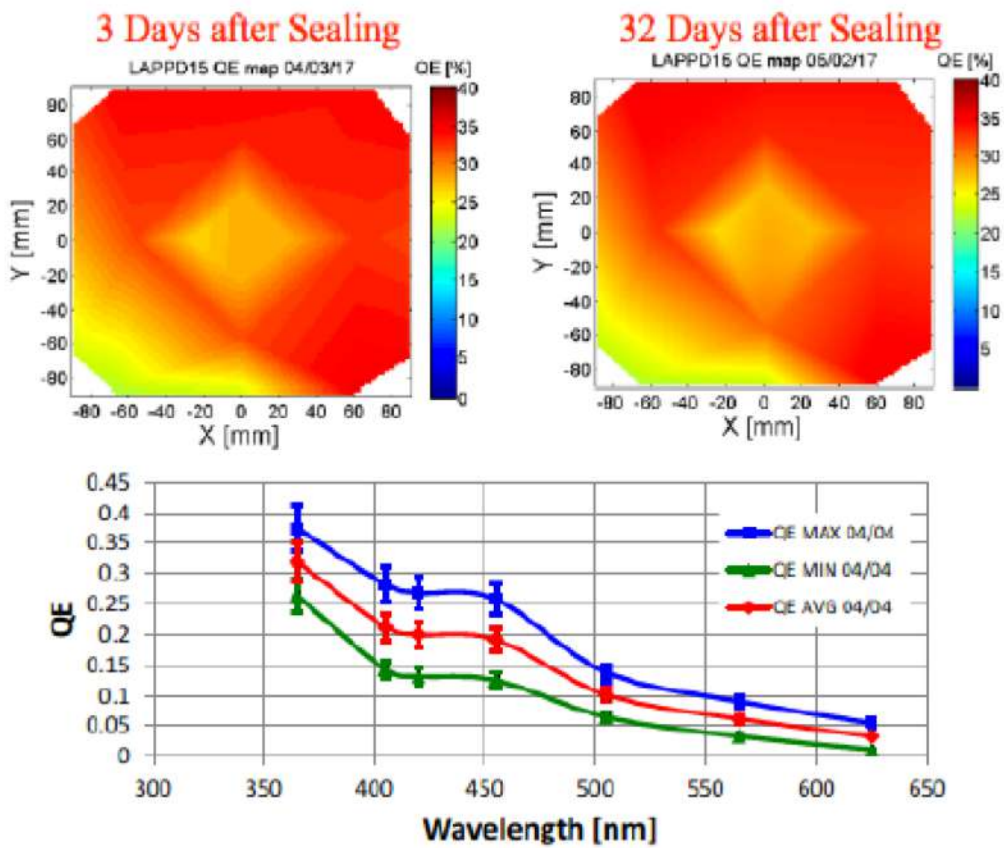

Figure 15: TOP: LAPPD-15 QE map at 3 days (LEFT) and 32 days (RIGHT) after sealing. BOTTOM: The average QE at 375 nm remains at 30%, with a maximum 35% and minimum of 22%.

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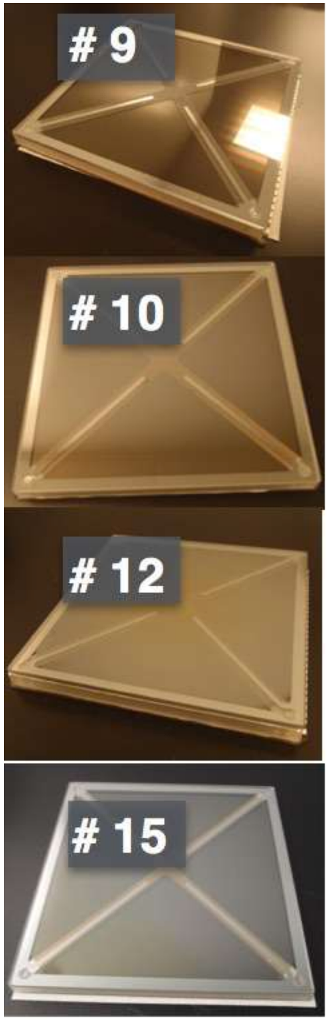
5 LAPPDs Are Ready for Installation

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**



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