Accelerator Neutrino Neutron Interaction Experiment

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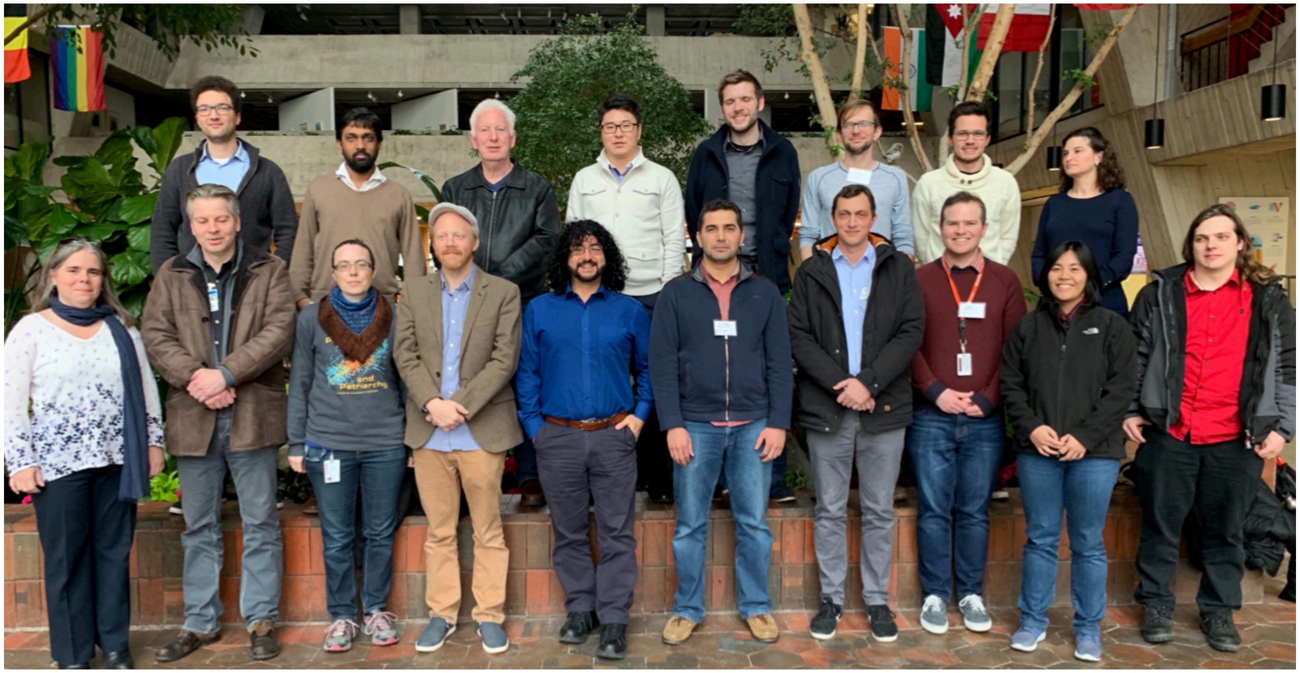
on behalf of the ANNIE Collaboration

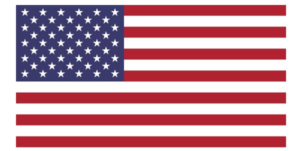
Iowa State University

Physics Goals

1) Measure the abundance of final state neutrons of neutrino interactions in water.

2) Demonstrate improved event reconstruction with picosecond scale — high spatial resolution photodetectors (LAPPDs).



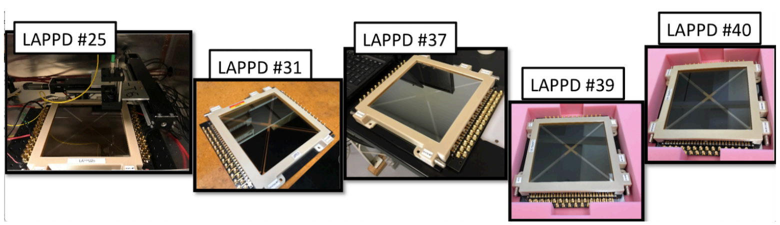


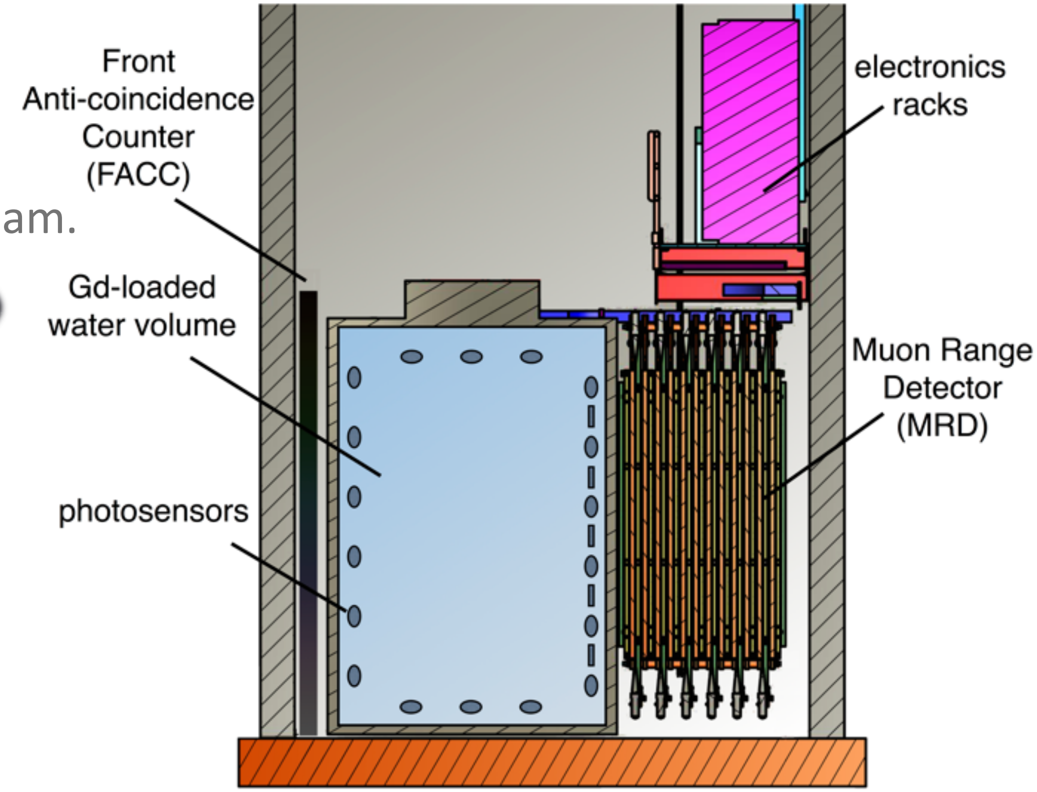
- Fermi National Accelerator Laboratory
- Iowa State University
- Lawrence Livermore National Lab.
- Ohio State University
- University of California at Davis
- University of California at Irvine
- University of Chicago, Enrico Fermi Institute
- University of Edinburgh
- Johannes Gutenberg University Mainz
- University of Hamburg
- University of Sheffield
- University of Warwick
- Queen Mary University of London

What is ANNIE?

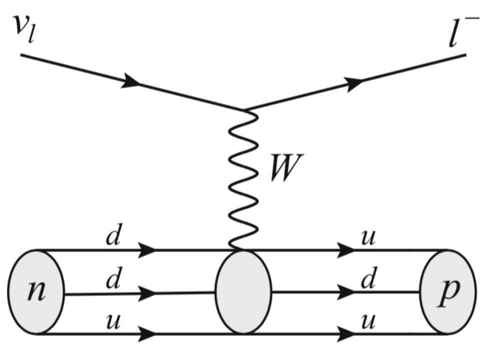
- Study **final state neutron abundance of neutrino interactions** as a function of energy and momentum transfer.
- Uses a **neutrino beam** at Fermilab (BNB).
- **First use of Gd-doped water** on a neutrino beam.

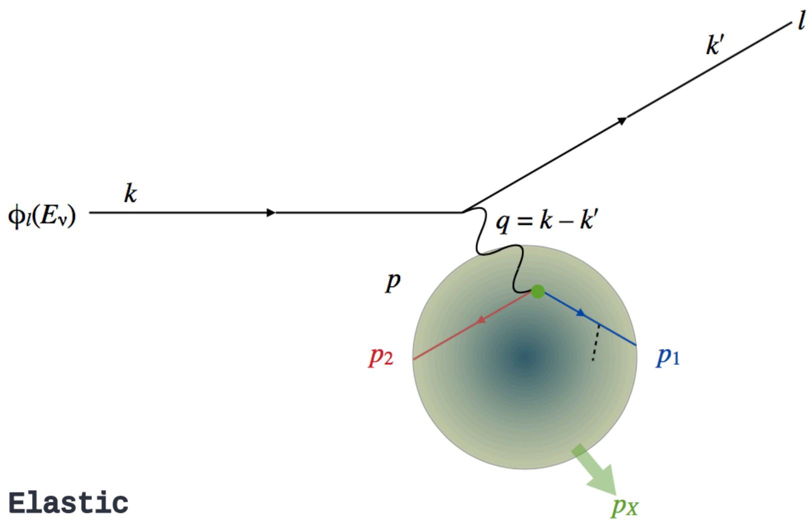
- **First use of LAPPDs** in a physics experiment.

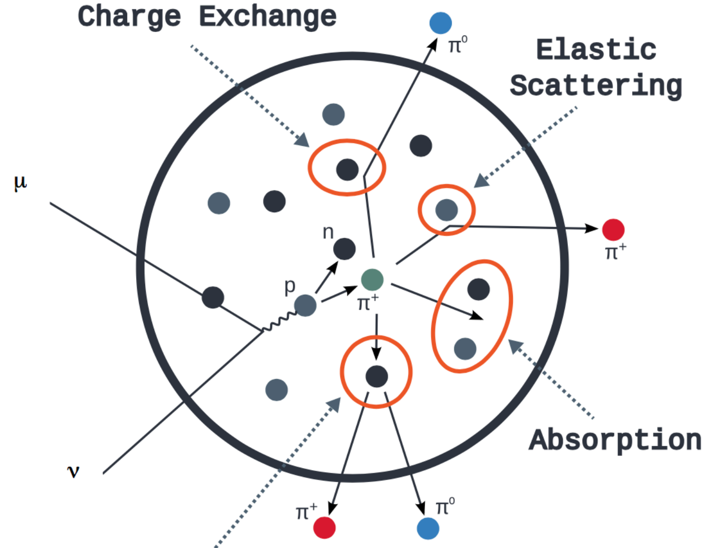




Physics Motivations: Nuclear Physics Effects

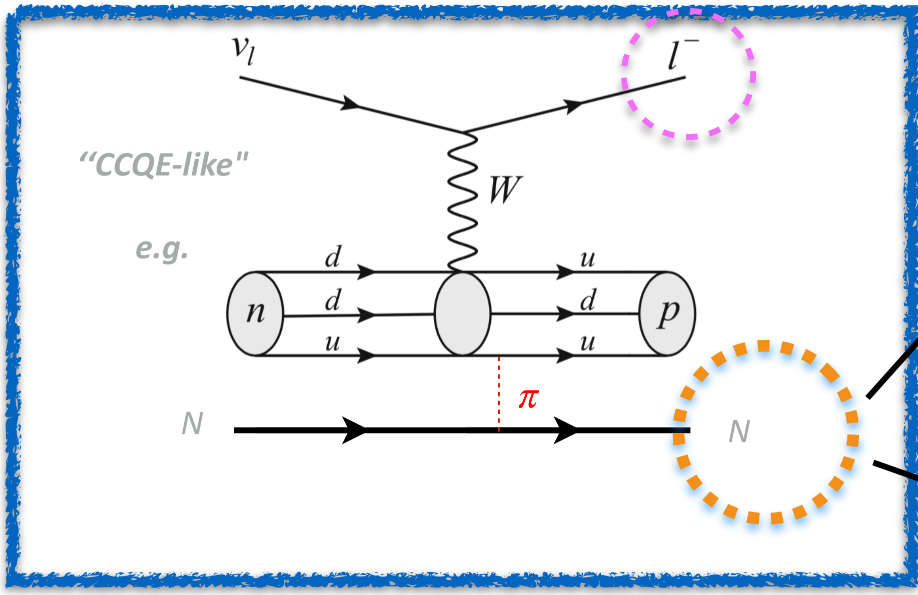






CCQE-like: no pions

… additional processes …



neutron(s):
neutron capture in Gd-doped water produces delayed signal (30 us)

proton multiplicity:
liquid-argon technique

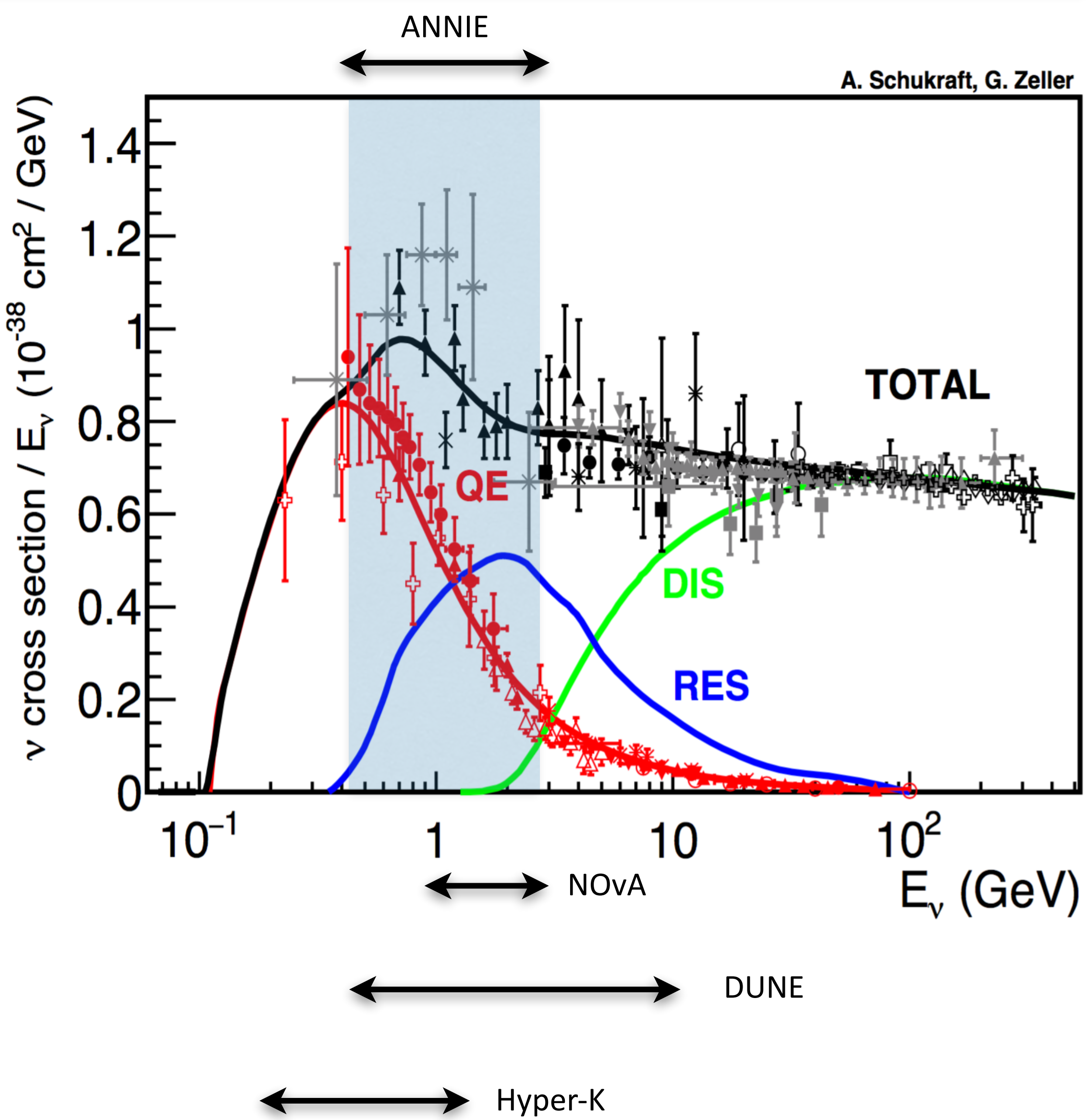
i) **Initial state** nucleon-nucleon correlations: excitation of particles.

ii) **Final state correlations**: scattering between a struck nucleon and spectator particles.

iii) Two-nucleon meson currents: **meson exchange** between two interacting nucleons.

Physics Motivations: Nuclear Physics Effects

- **Measure the abundance of final state neutrons** from neutrino interactions in water at 0.5 - 3 GeV.
- A key physics measurement, e.g., to model the **nature of "CCQE-like" neutrino/nucleus interactions.**
- Cr**oss section in the QE-regime** is **substantially affected by multi-nucleon ejection (np-nh)** and of great interest for models, and relevant for precision oscillation experiments.
- **ANNIE** will measure neutron yields as a **function of energy** and **direction of the final state muons.**
- **ANNIE will provide** a sample of **dominantly-pure neutrino events**.



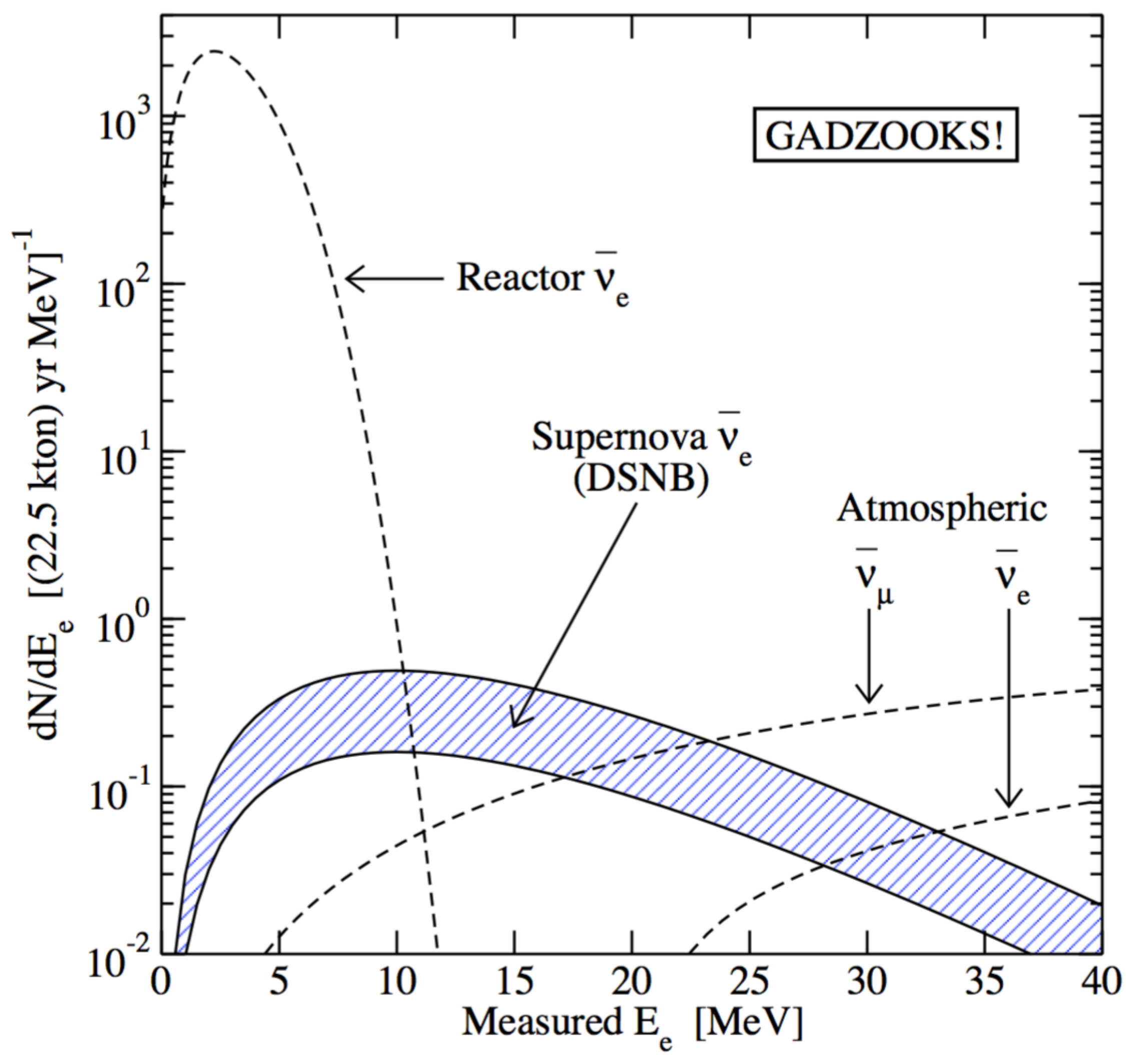
Physics Motivations: Supernova Neutrino Background

- Accumulation of neutrinos from all past supernovae provide **important cosmological constraints** to supernova rate, star formation rate & cosmic infrared background (cosmological consistency test!)
- **Neutron tagging** of neutrino signal:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- **dominant background (E > 20 MeV)**: from the **decay of low energy** (sub-Cherenkov) **muons** in water produced by atmospheric neutrinos.
- Neutron production in atmospheric neutrino interactions is important to estimate remaining background.

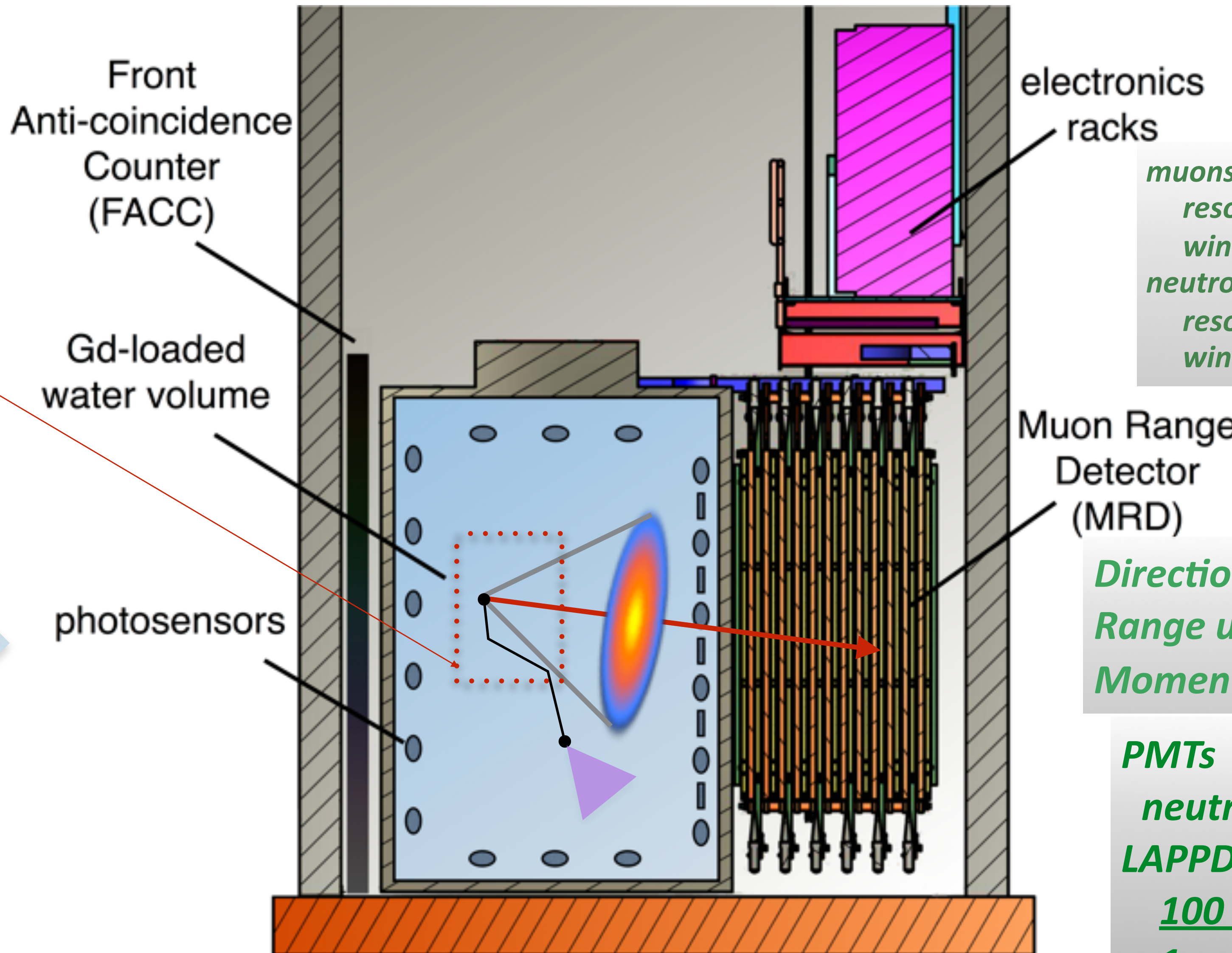
Beacom & Vagins, PRL, 93 (2004) 171101



... very relevant for Super-K-Gd ... approved and going forward

Basic Design Considerations

Fiducial Volume (selectable in off-line analysis)



Beam

muons
- *resolution ~ 50 ps*
- *window ~ 20 ns*

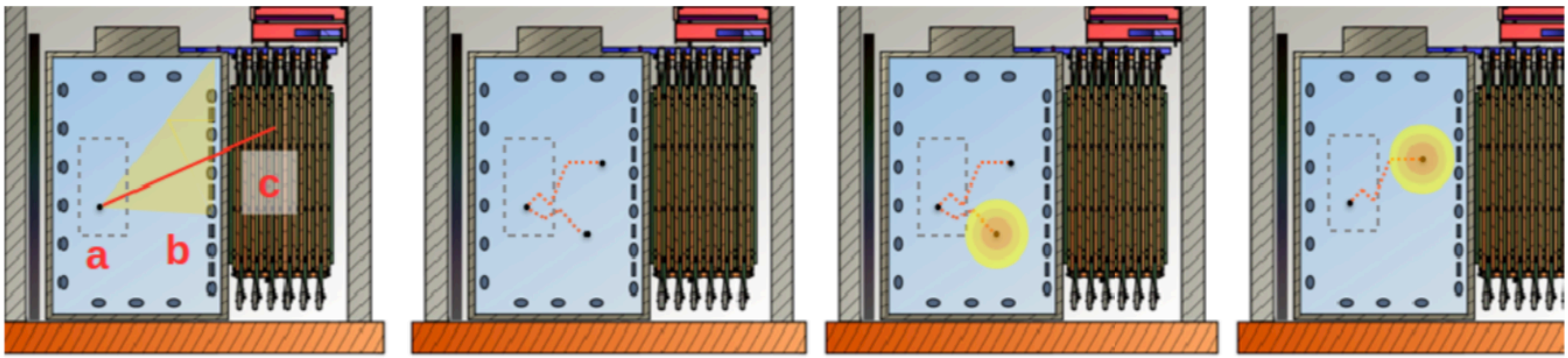
neutron capture
- *resolution ~ few ns*
- *window ~ 100 us*

Direction ~ 10 deg.
Range up to 1.2 GeV/c
Momentum res. ~ 20%

PMTs
- *neutron capture*

LAPPDs
- *100 ps resolution*
- *1 cm granularity*

Chronology of an Event



10 ns | 3 us | 20 - 80 us

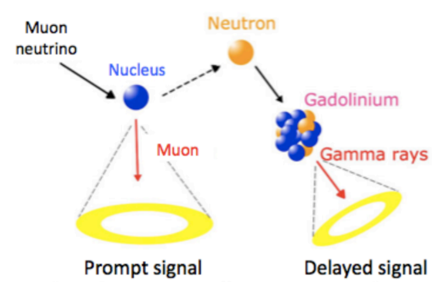
CC interaction — prompt muon

muon momentum/vertex
reconstruction using LAPPD

muon momentum/direction
reconstruction with MRD

neutron(s) thermalize(s)

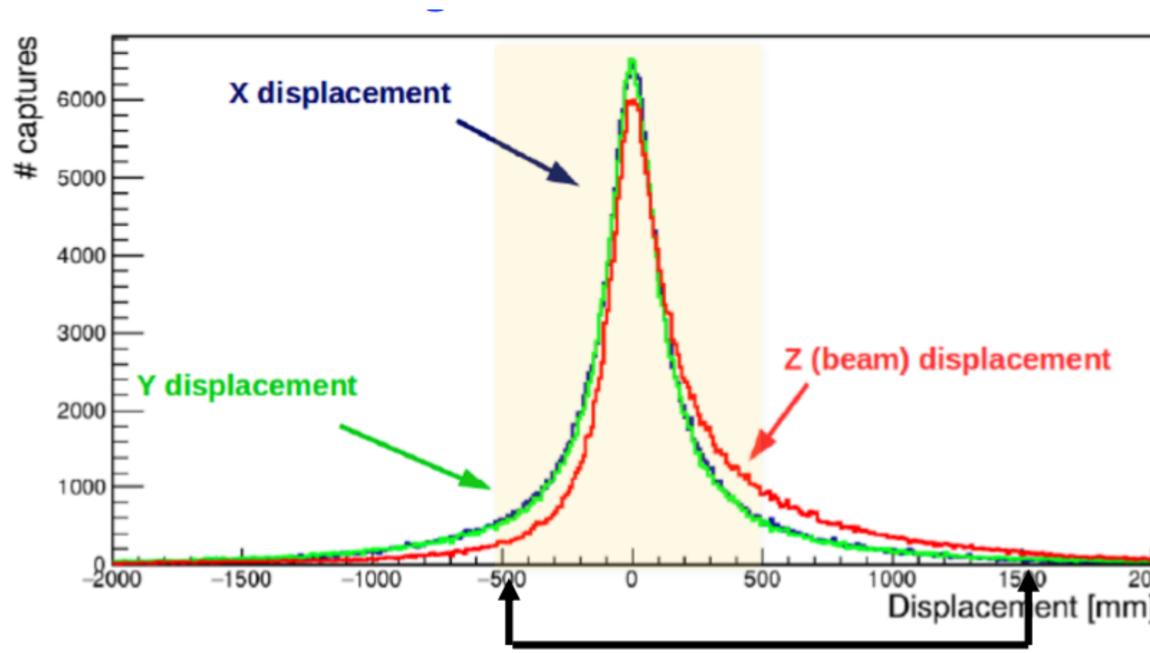
neutron(s) capture(s) on Gadolinium & light detection by PMTs

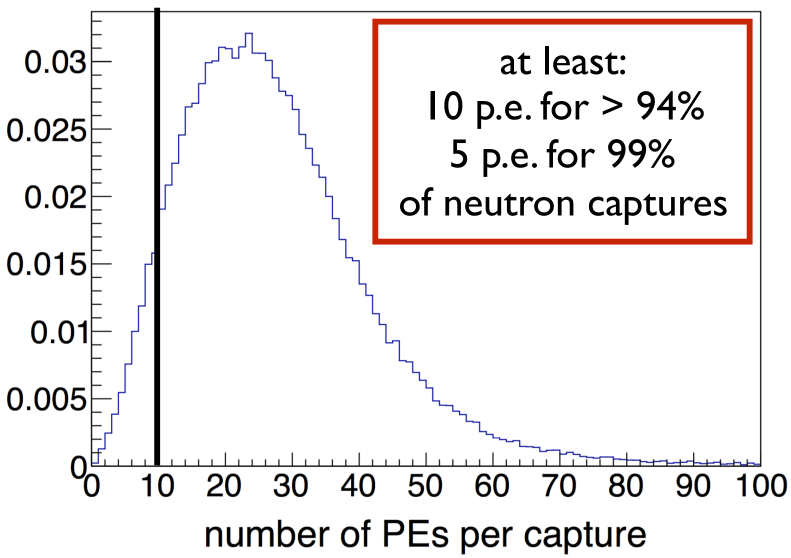


Why we need LAPPDs?

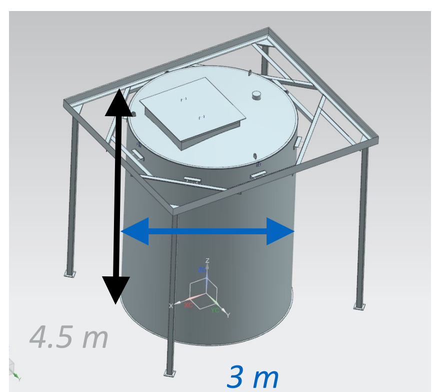
- Appropriate **size of fiducial volume** (set by analysis and **enabled by LAPPDs**) to stop neutrons within the water tank.

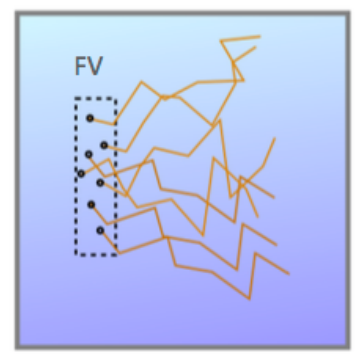
- **PMT coverage** to ensure the detection of sufficient light from neutron captures (simple case with 100 PMTs, 20% Q.E.)





stopping distance of neutrons






Ramsey Auditorium
Schwahn Rd
Schwahn Rd
Kautz Rd
Fnal
Booster Ring Rd
Fnal
Giese Rd
Kautz Rd
Indian Creek Rd
Outer Ring Rd
100m
deployable 25 m absorbers
Horn
Target
Protons hit the beryllium target, creating positive pions
Magnetic horn focuses the positive pions
π^+
μ^+
ν_μ
50 m absorber
Decay region (~ 50 m)
Pions decay into muons and muon neutrinos
Muons are absorbed
Beam of neutrinos travels to experiment

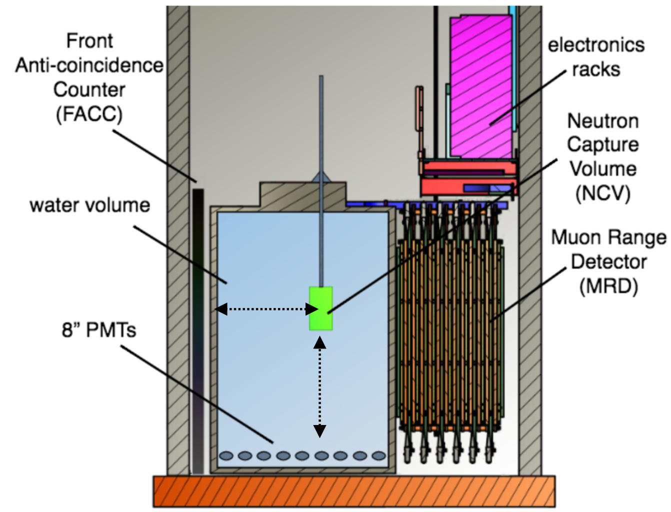
ANNIE: Phased Approach

Phase I: Fall 2015 - 2017 (completed)

a) **Construction** of the water tank, mechanical support structure, 60 PMTs, HV-system, trigger & readout electronics, DACQ.

b) **Measurement of the neutron background**

c) **Readiness for testing LAPPDs**.



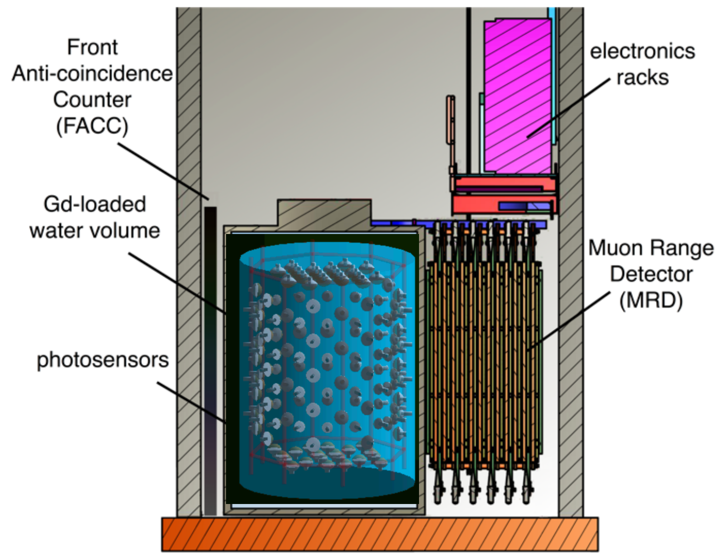
Neutron **C**apture **V**olume: Gd-loaded liquid scintillator

pure water

Phase II: 2017 - 2021

a) Physics Run (1 year) with limited LAPPD coverage, enhanced PMT coverage (130), focus on CCQE-like events.

b) Physics Run (2 years) with full LAPPD coverage (up to 20 LAPPDs), study neutron yields for CC, NC and inelastic scattering.

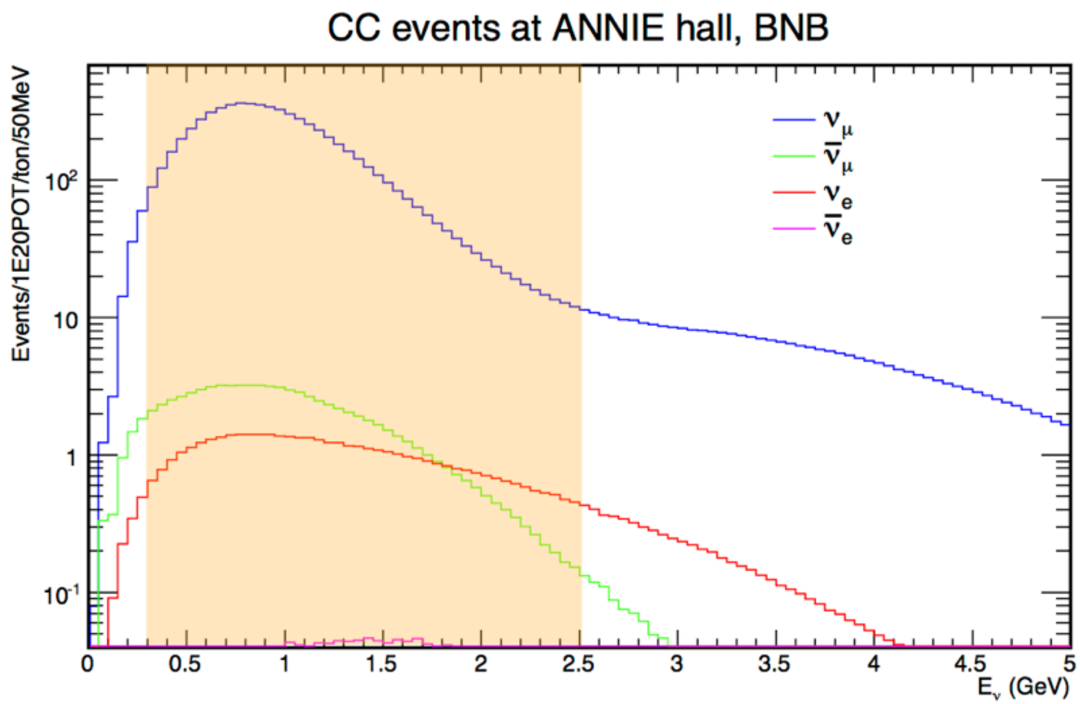


Gd-loaded water (0.1%)

Booster Neutrino Beam (BNB)

- **Energy range**: spectrum similar to the atmospheric neutrino spectrum, and range comparable to future oscillation experiments.
- 93% purity in neutrino mode.
- **Statistics**: **# of interactions** expected in **1 ton of water** over 6 months.

ν-type	Total Interactions	Charged Current	Neutral Current
ν_μ	9892	6991	2900
$\bar{\nu}_\mu$	130	83	47
ν_e	71	51	20
$\bar{\nu}_e$	3.0	2.0	1.0

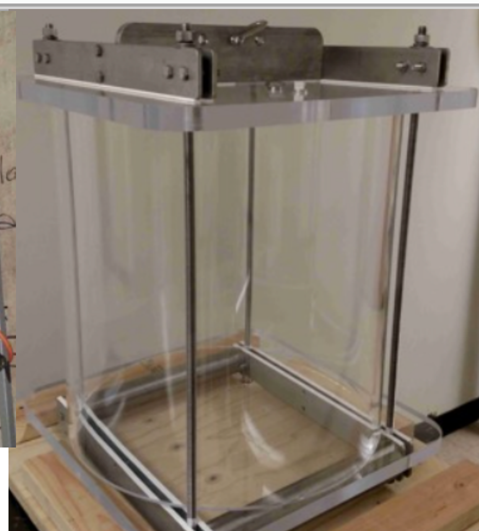


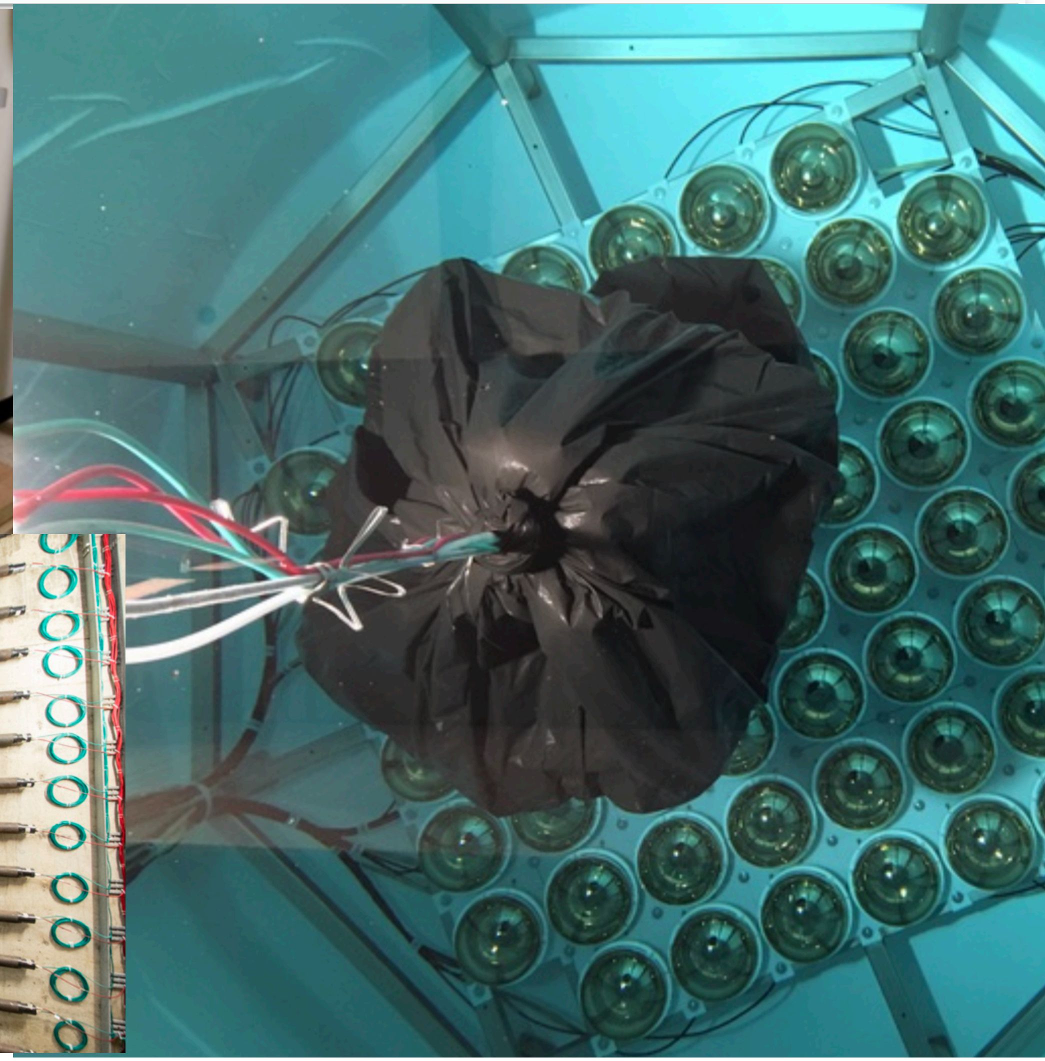
- **Low pileup rate**. 1 neutrino interaction every 150 spills.

Location	ν_μ events/POT/ton	ν_μ events/spill	Avg. pileup/spill
SciBooNE	$2.80 * 10^{-16}$	0.03	5.0×10^{-5}
NOvA ND	$6.04 * 10^{-16}$	0.65	0.0045
MINOS ND	$1.85 * 10^{-14}$	20	3.76

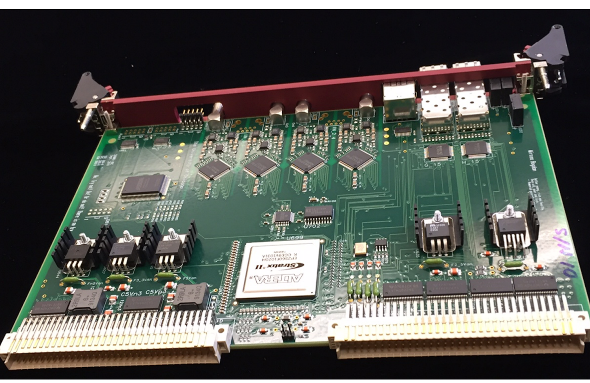
annie

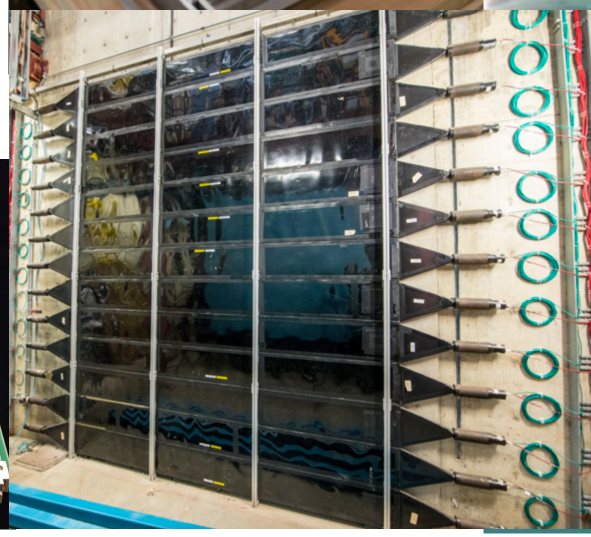
Phase-I: Development of Key Components





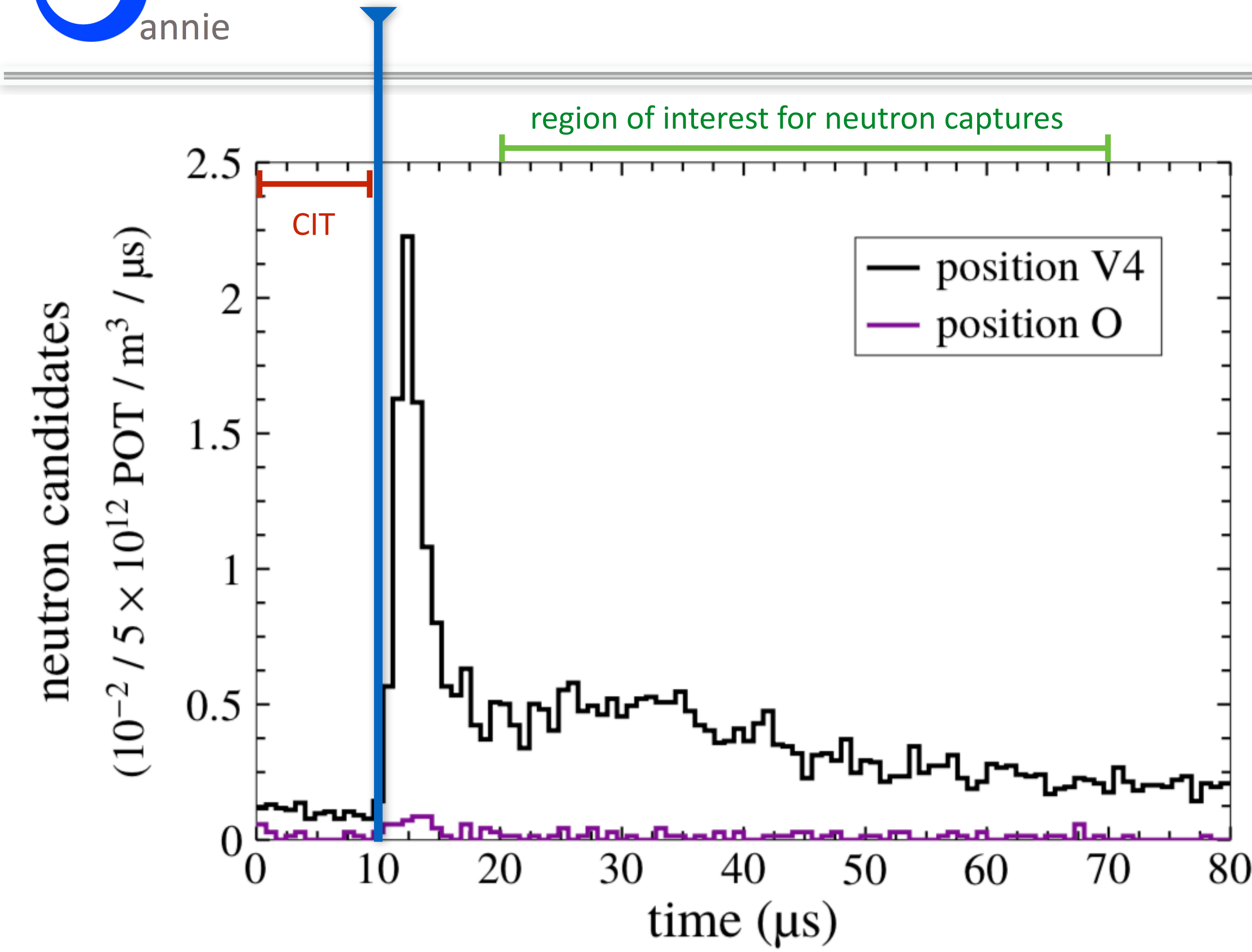
- deionizing water purification system
- resistivity > 10 MOhm/m

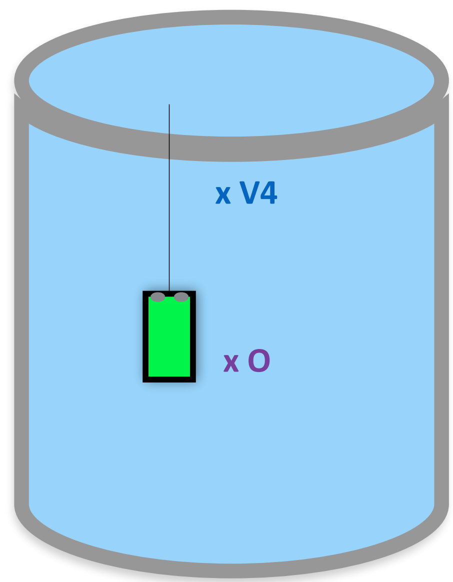




- PMT readout: 500 MHz custom VME-ADC boards: 80 microsecond buffer (neutron capture).
- Other systems: DACQ, Clock/Trigger distribution, HV for water/MRD PMTs, FMV, …

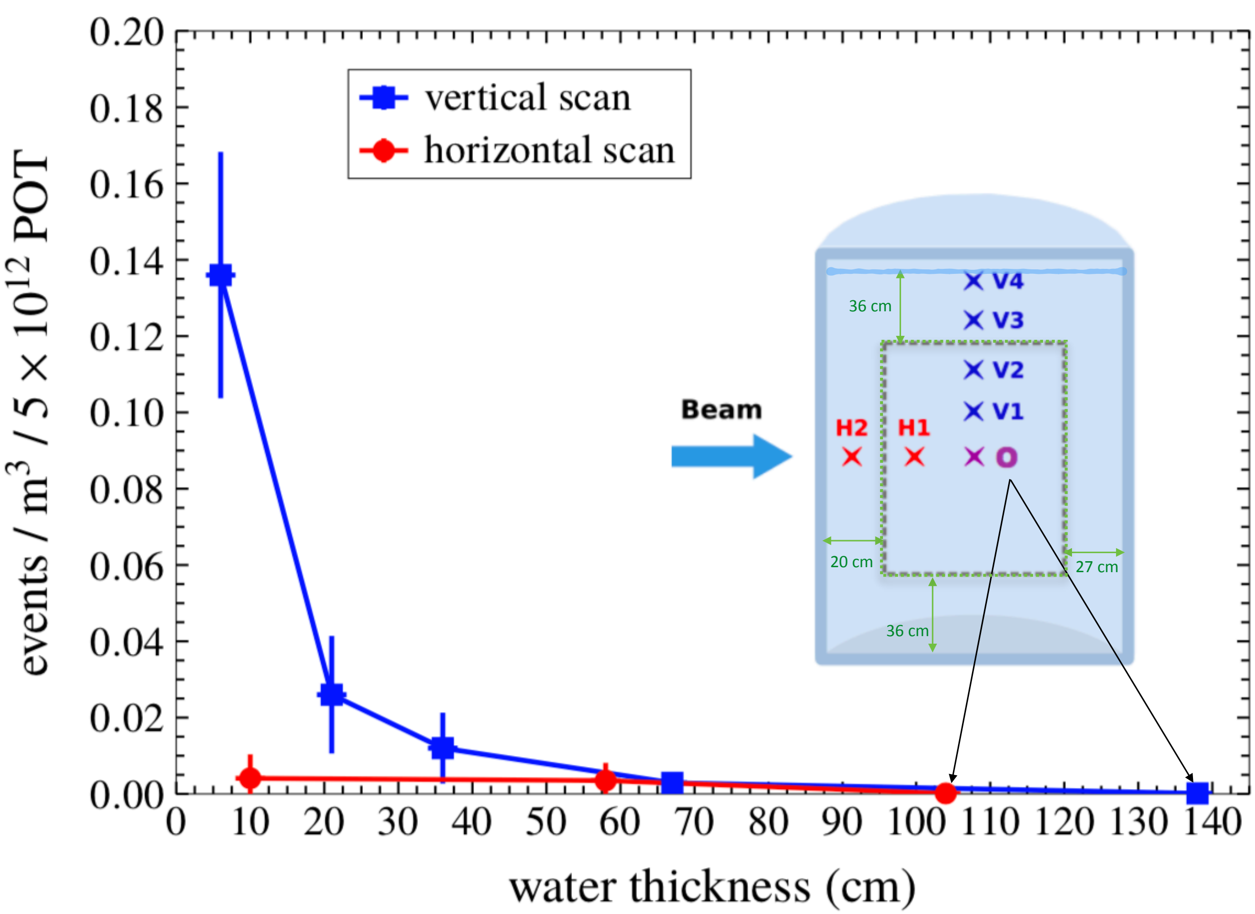
Beam-Induced Neutron Event Rate





- beam trigger + NCV-PMTs trigger
- Gd-loaded liquid scintillator (NCV) volume and water tank PMTs allow separation of neutron captures and cosmic-ray muons.
- Results: beam-correlated neutron background rates are sufficiently low to count final state neutrons from neutrino interactions.

Beam Correlated Background Neutrons



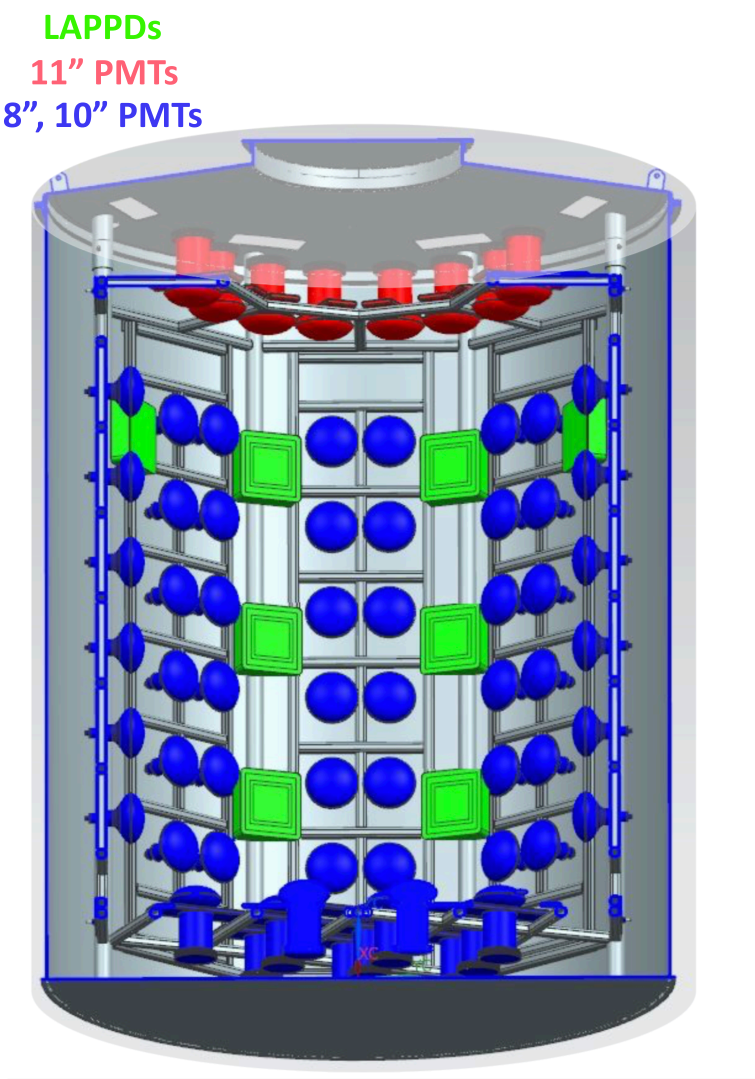
NCV position	N_n^{ROI}	N_n^{CIT}	N_n	$\mathcal{R}_n^{NCV}$ (% m^{-3} spill^{-1})
O	339	$333 \pm 45_{stat} \pm 69_{syst}$	$5 \pm 48_{stat}$	$0.013 \pm 0.11_{stat} \pm 0.16_{syst}$
H1	60	$41 \pm 11_{stat} \pm 21_{syst}$	$19 \pm 13_{stat}$	$0.35 \pm 0.24_{stat} \pm 0.40_{syst}$
H2	743	$609 \pm 56_{stat} \pm 192_{syst}$	$133 \pm 62_{stat}$	$0.41 \pm 0.19_{stat} \pm 0.60_{syst}$
V1	254	$206 \pm 30_{stat} \pm 22_{syst}$	$47 \pm 34_{stat}$	$0.29 \pm 0.20_{stat} \pm 0.15_{syst}$
V2	866	$540 \pm 51_{stat} \pm 229_{syst}$	$325 \pm 59_{stat}$	$1.2 \pm 0.23_{stat} \pm 0.9_{syst}$
V3	368	$140 \pm 22_{stat} \pm 124_{syst}$	$227 \pm 29_{stat}$	$2.6 \pm 0.35_{stat} \pm 1.5_{syst}$
V4	3825	$1207 \pm 90_{stat}$	$2613 \pm 109_{stat}$	$13.6 \pm 0.9_{stat} \pm 3.1_{syst}$

Neutron rate for 14-ton active volume for ANNIE Phase-II detector:

$$R_n = 0.053^{+0.053}_{-0.025} \text{ stat+syst}$$

per ANNIE signal event

ANNIE Phase-II Construction

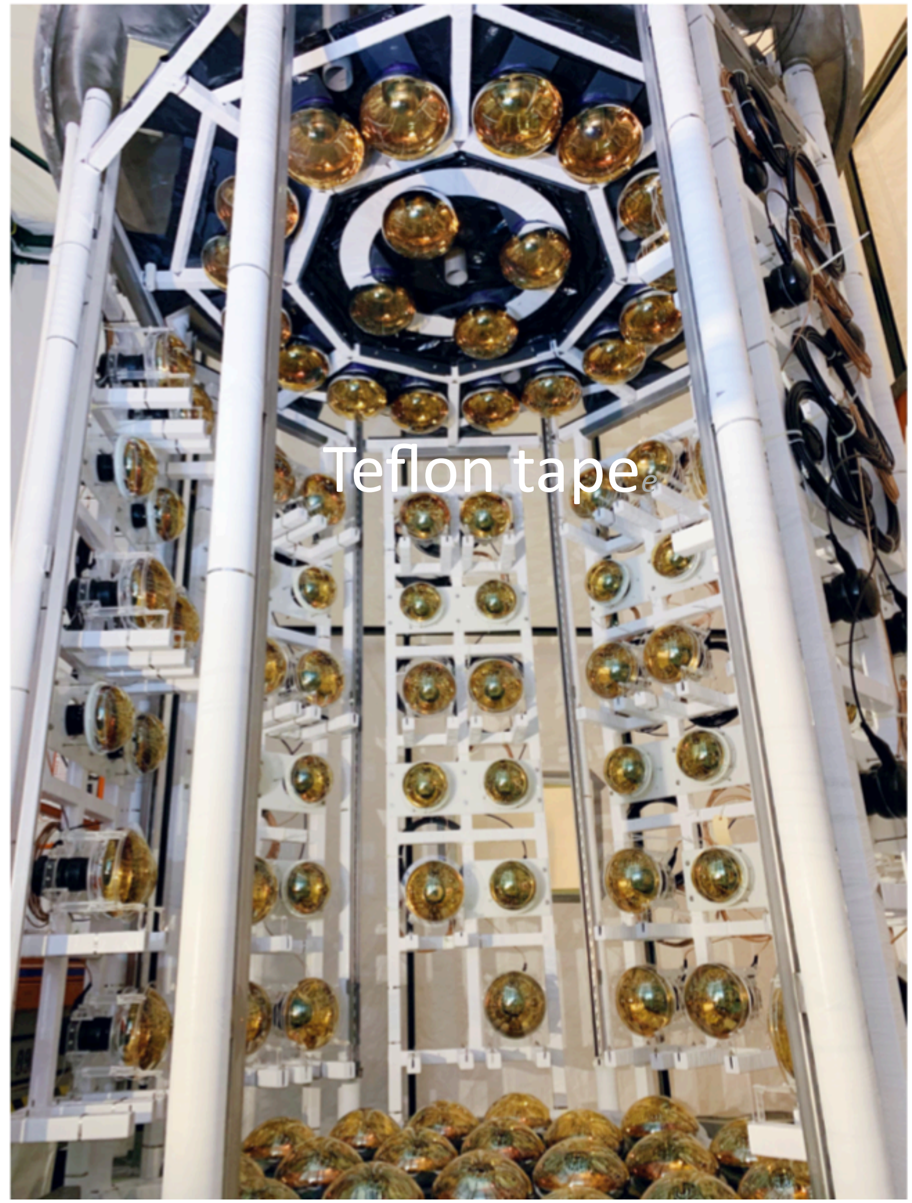


Mechanical design

Inner structure

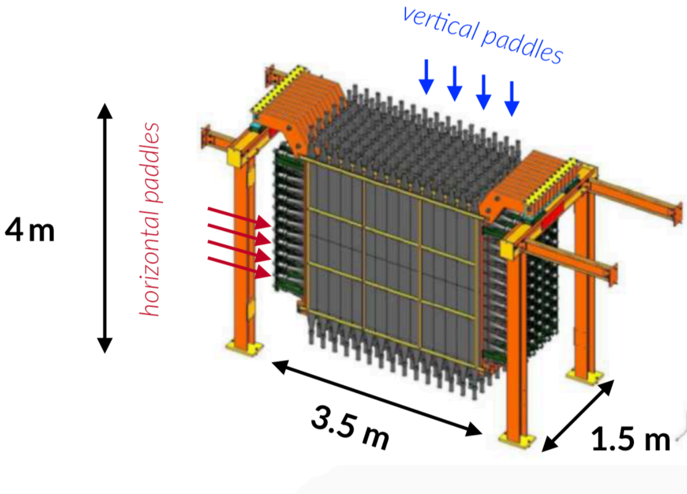
Gd-loaded water filtration

ANNIE Phase-II Construction

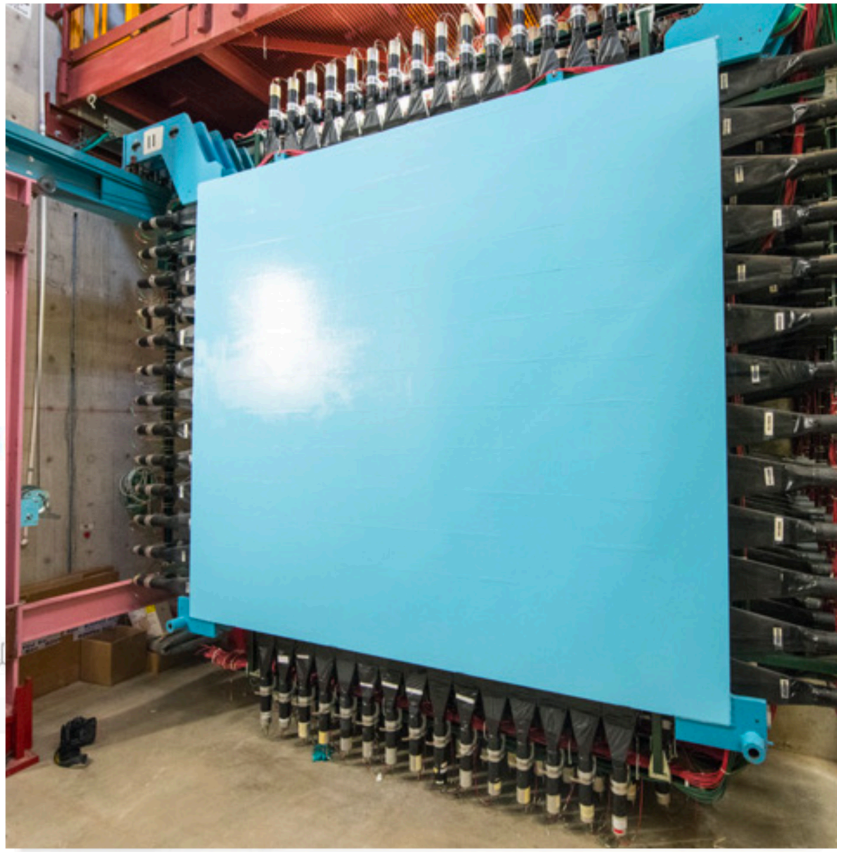


Is it Gd compatible?

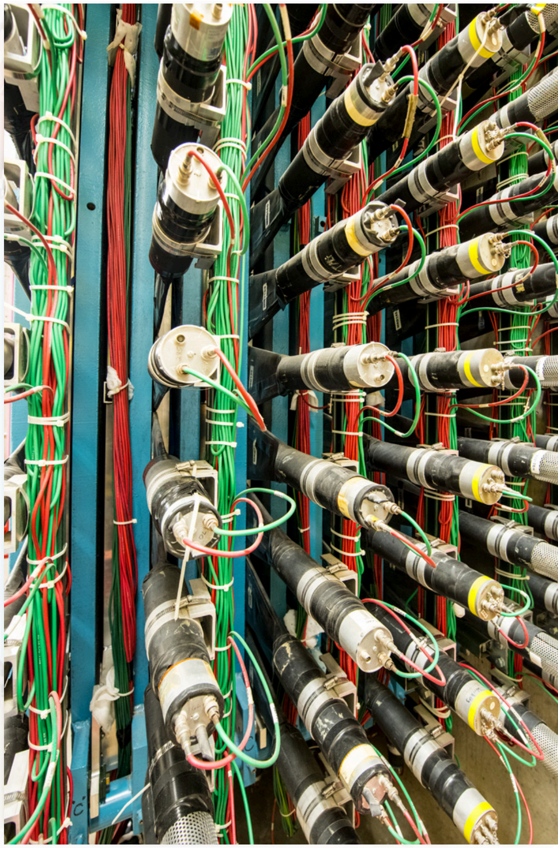
Muon Range Detector Refurbishment



Partial (2/3 intact) MRD system



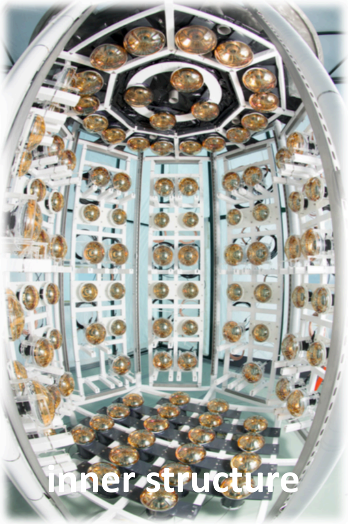
Refurbishment of scintillator panels



2” PMTs

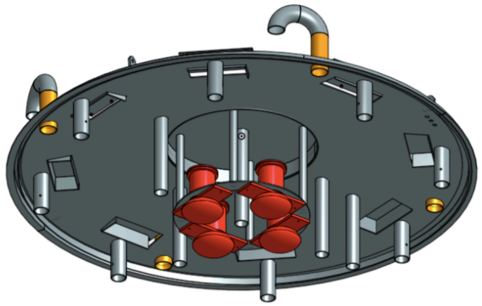
ANNIE Phase-II Deployment

ANNIE Phase-II Commissioning

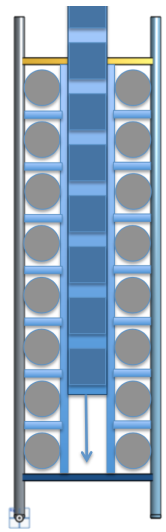


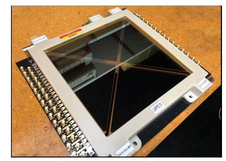
- filled with de-ionized water

- staged Gd-loading

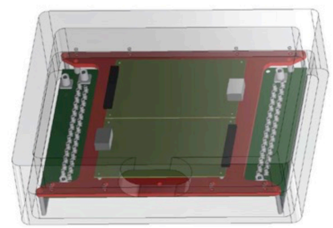


cassette - slot

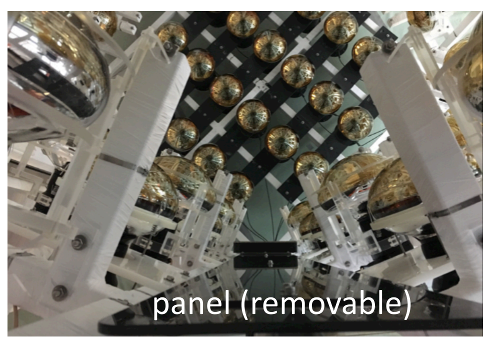


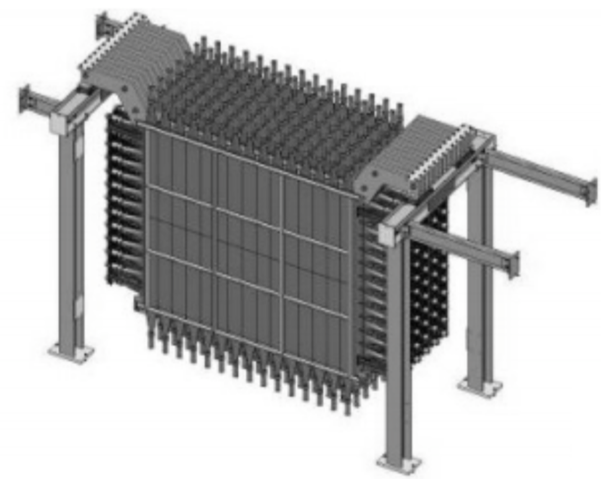


5 LAPPDs in hand



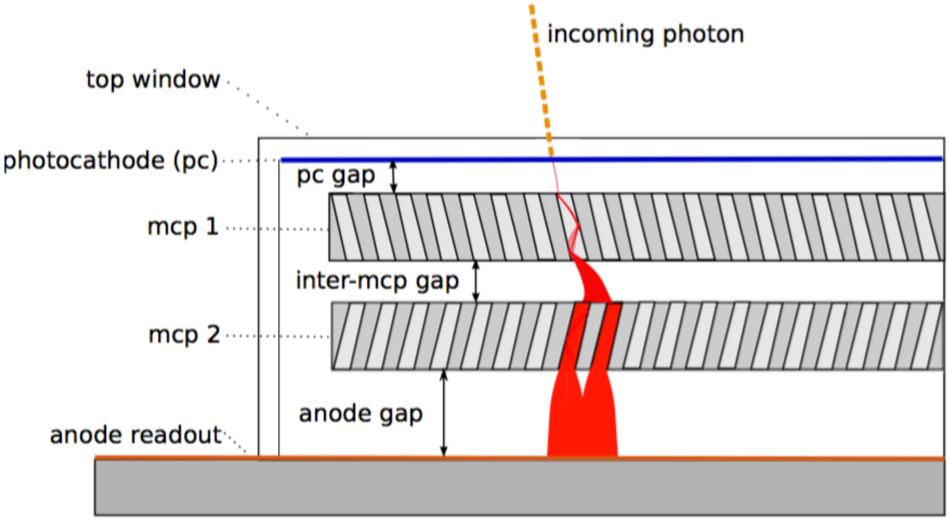
water proof LAPPD housing

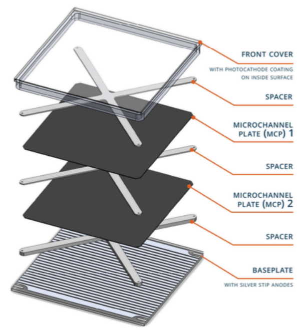


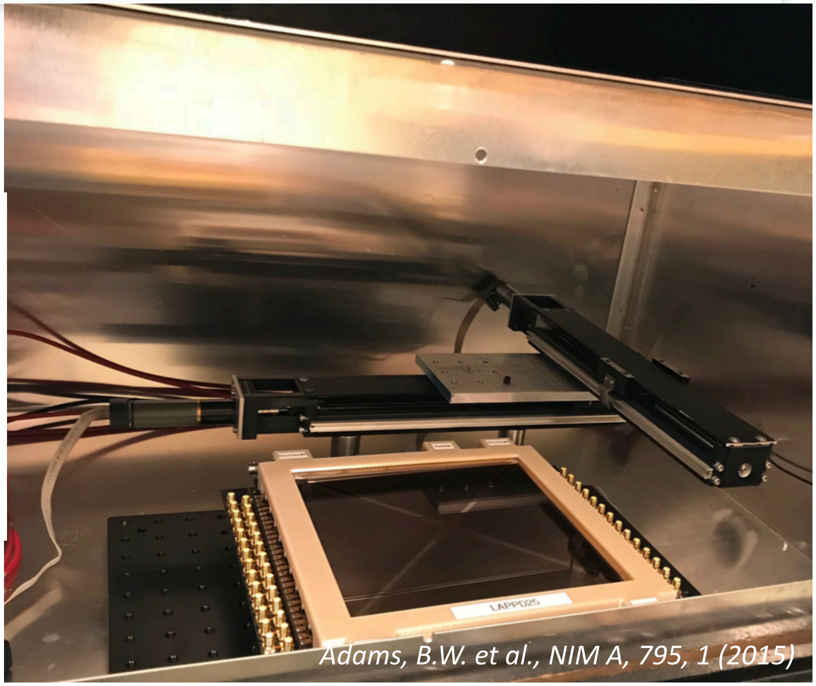


- MRD refurbishment complete
- beam & cosmic ray muons detected at expected rates.

LAPPD (Large Area Picosecond Photo Detector)





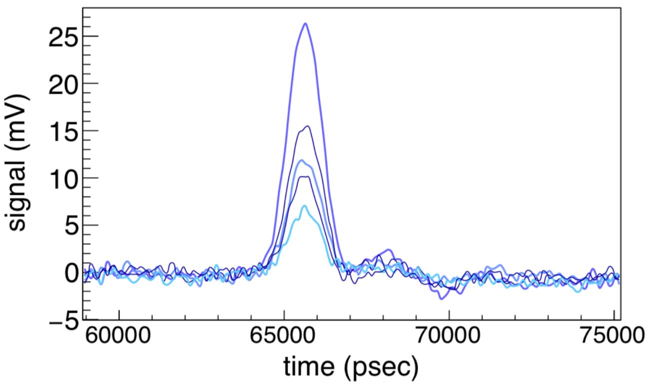


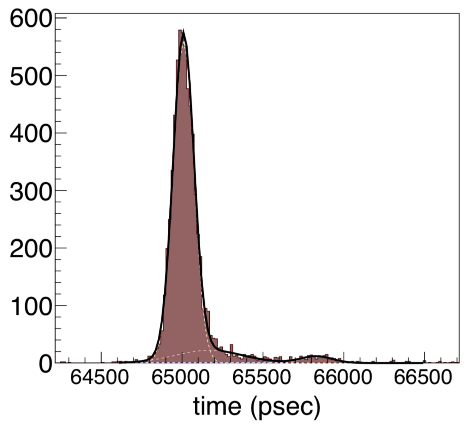
Adams, B.W. et al., NIM A, 795, 1 (2015)

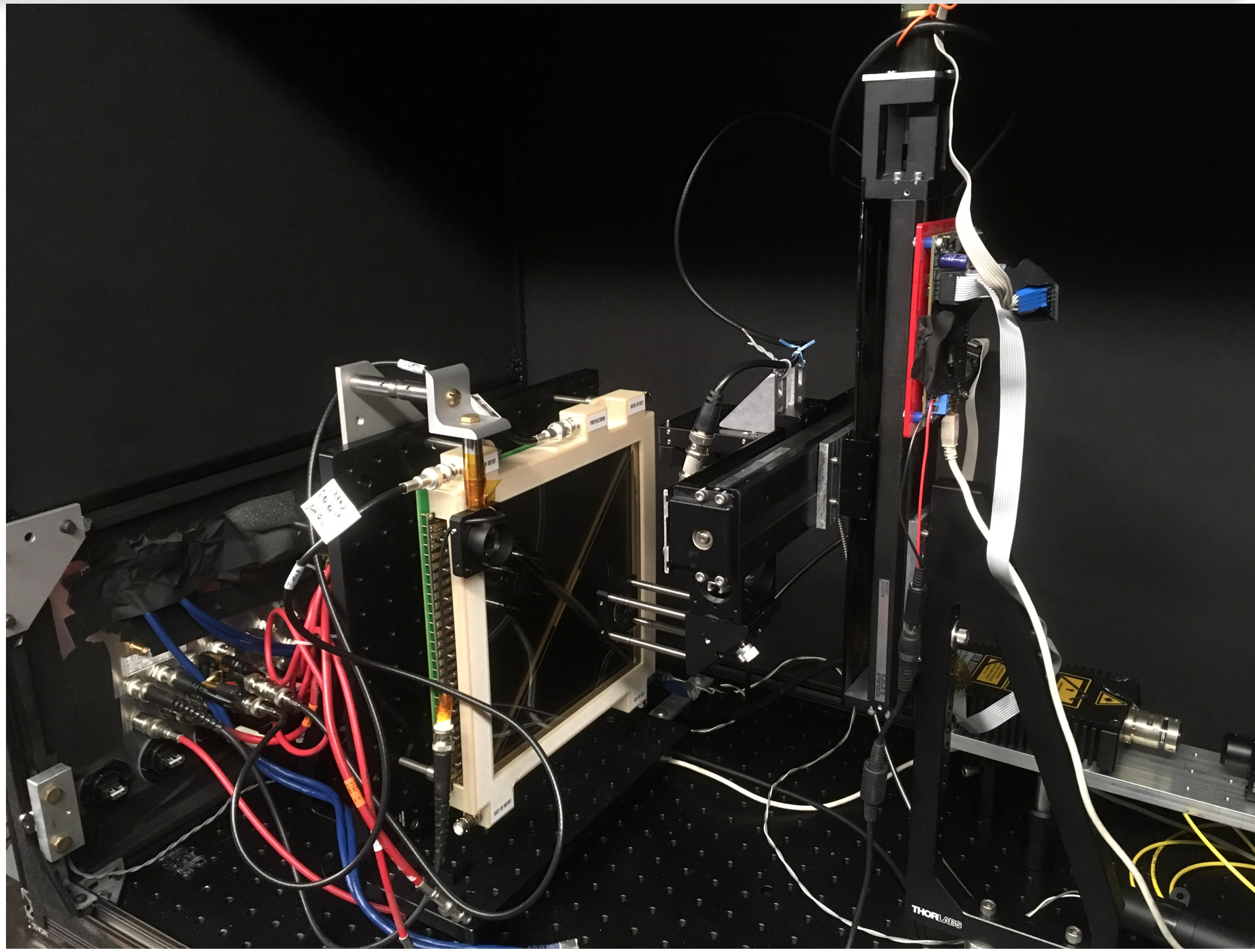
- LAPPD: 20 cm x 20 cm flat panel photocathode.
- 2 MCPs (ALD): <**100 ps time resolution**, multi-anode readout gives **mm scale spatial resolution**.
- ANNIE: minimal pileup and **single photon resolution** are the basis for vertex reconstruction, single-/multi-particle separation, …
- **Incom Inc.** has set up **commercial production facility — ANNIE purchased first LAPPD in 2018!**
- 5 LAPPDs in hand — meeting the requirements.

LAPPD Test Facilities (ISU, Fermilab)

- Test & calibration using a picosecond Laser
- single p.e. time resolution 50 ps

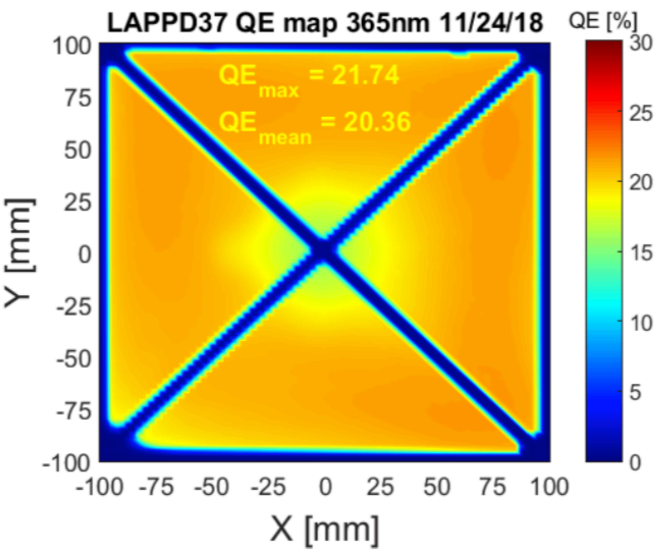


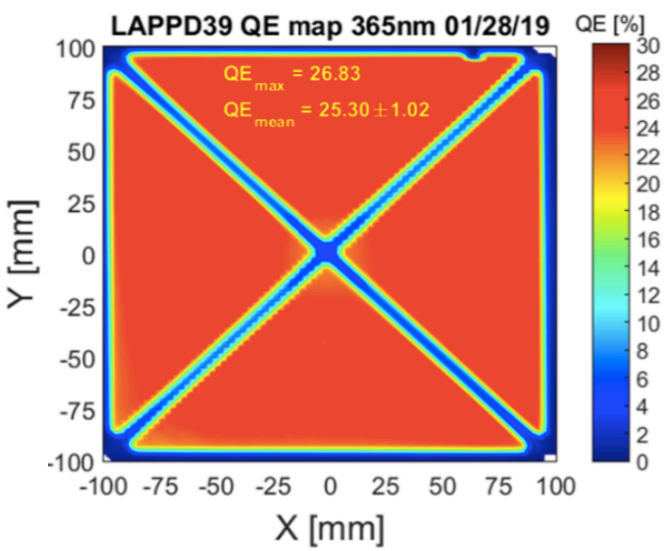


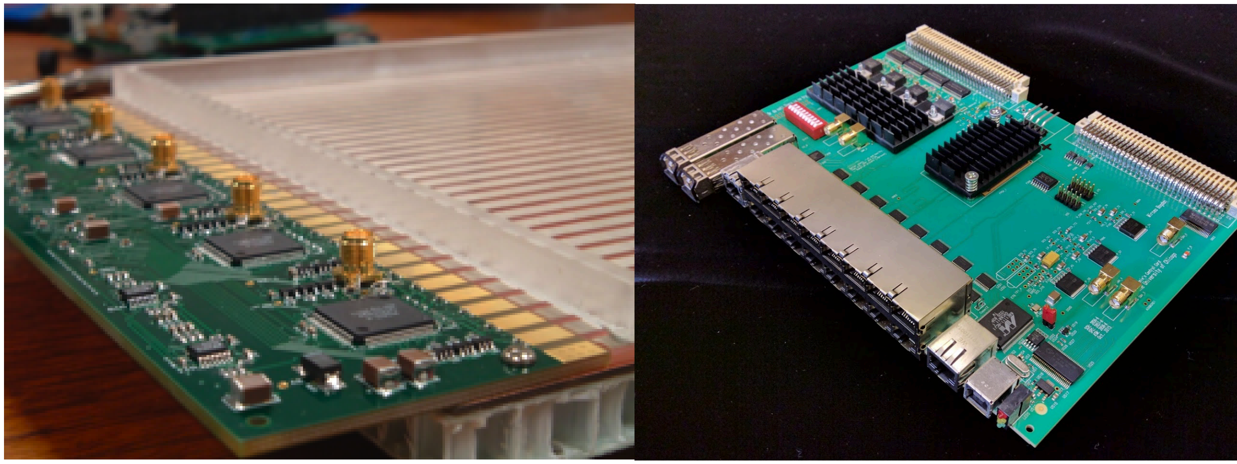


- Transit time spread

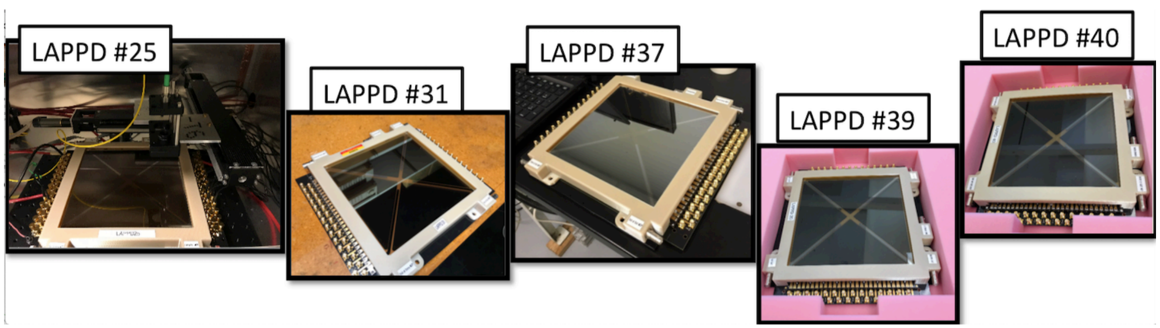
LAPPDs made by Incom Inc. & Fast Readout



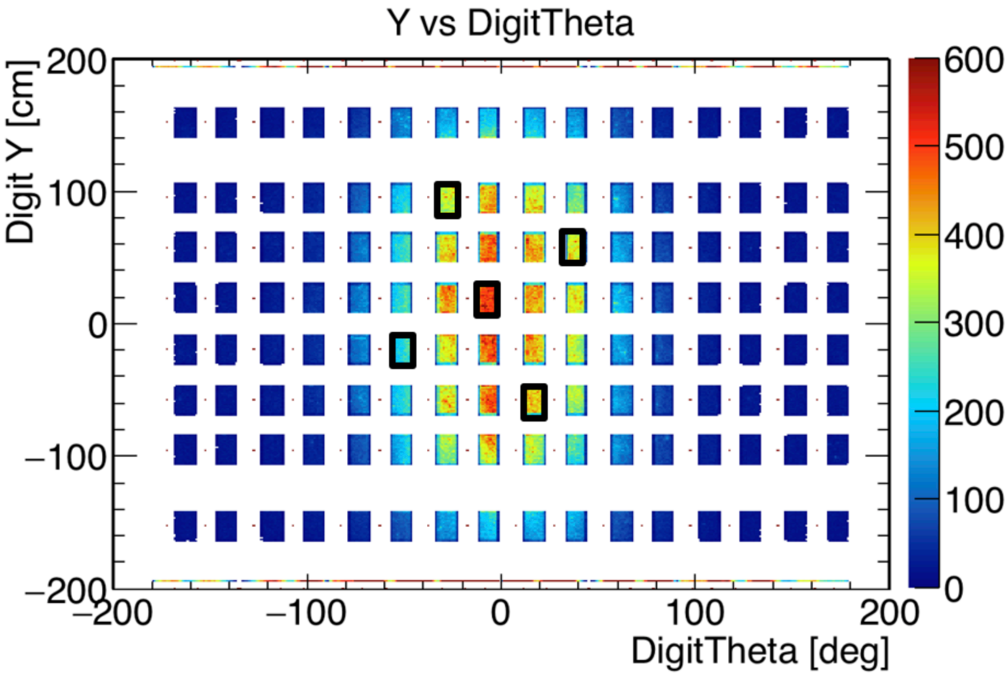


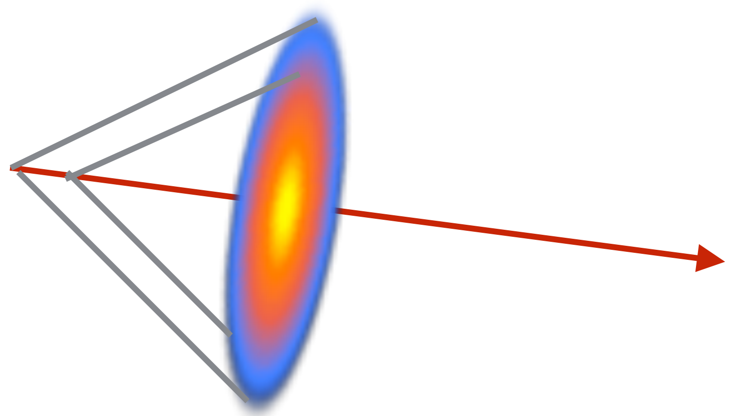


- **Fast readout** (track reconstruction):
- **PSEC4 chip** samples at **10 GHz for 30 ns**.
- **Central Card** provides synchronization, triggering and readout for 240-channels.



Photodetector Coverage





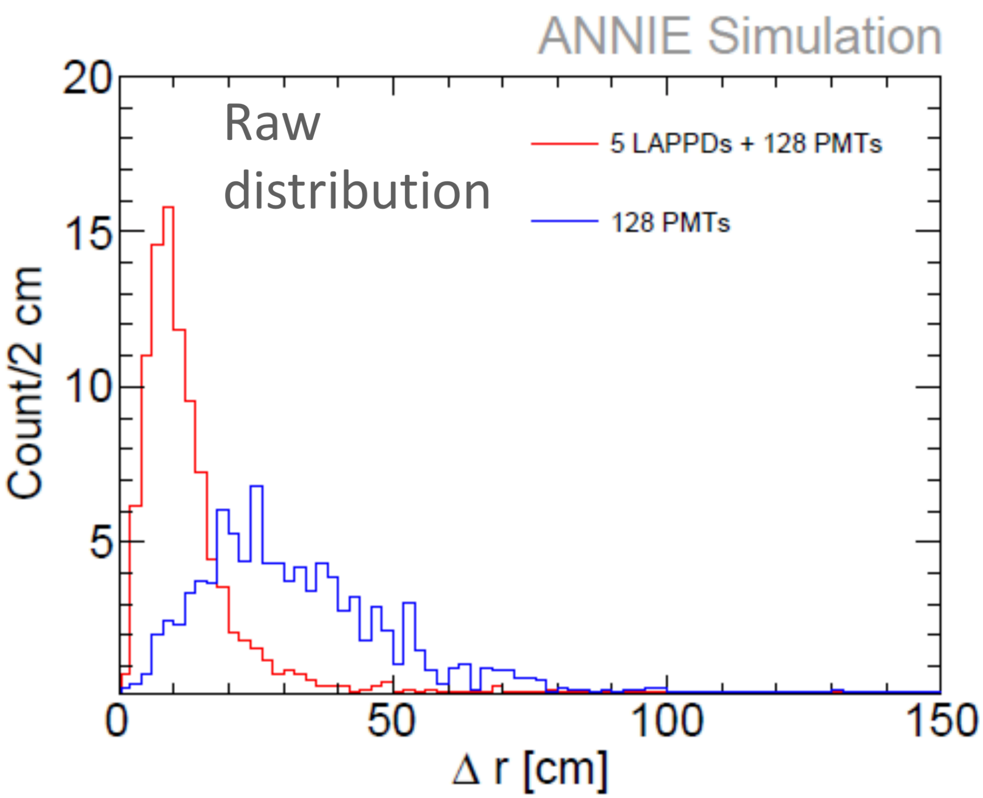
Basic strategy:

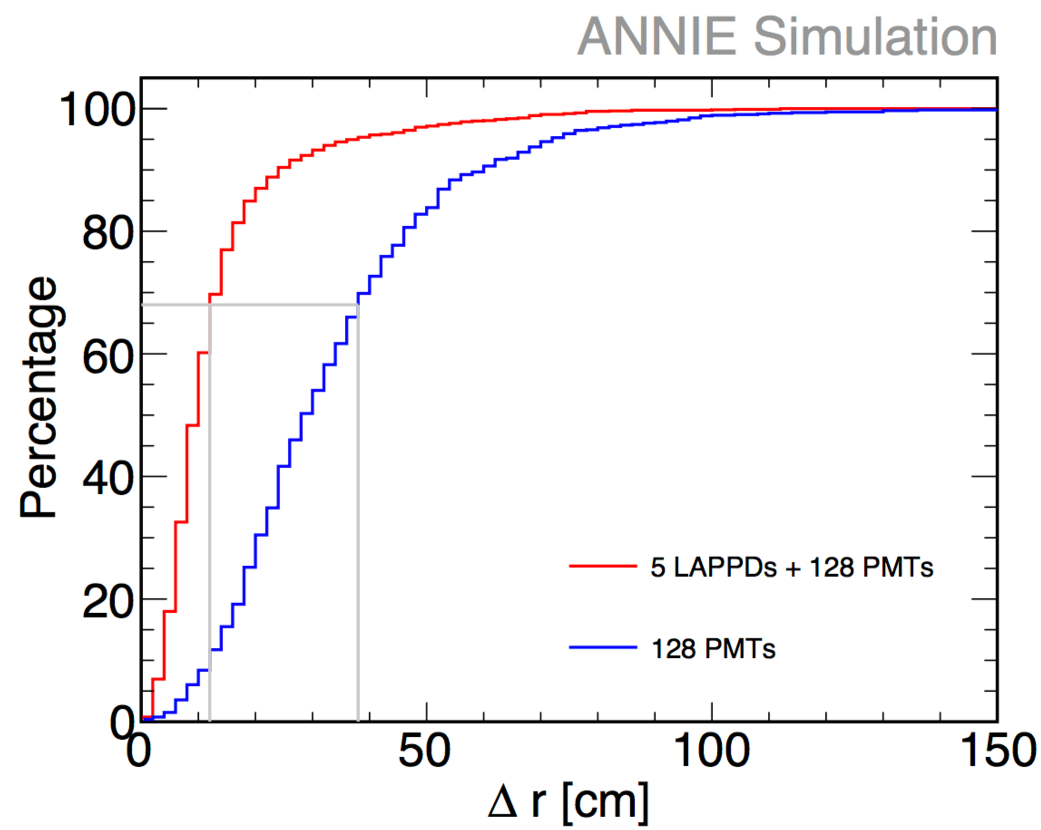
- Timing-based likelihood function to fit vertex.
- Six parameters (X, Y, Z, T, Theta, Phi) are varied to calculate a combined likelihood to fit the track.

Muon track reconstruction:

- 128 8-inch PMTs
- 5 LAPPDs + 128 8-inch PMTs

Vertex Resolution (longitudinal)





The addition of 5 LAPPDs **greatly improves (x 3)** the vertex and track reconstruction

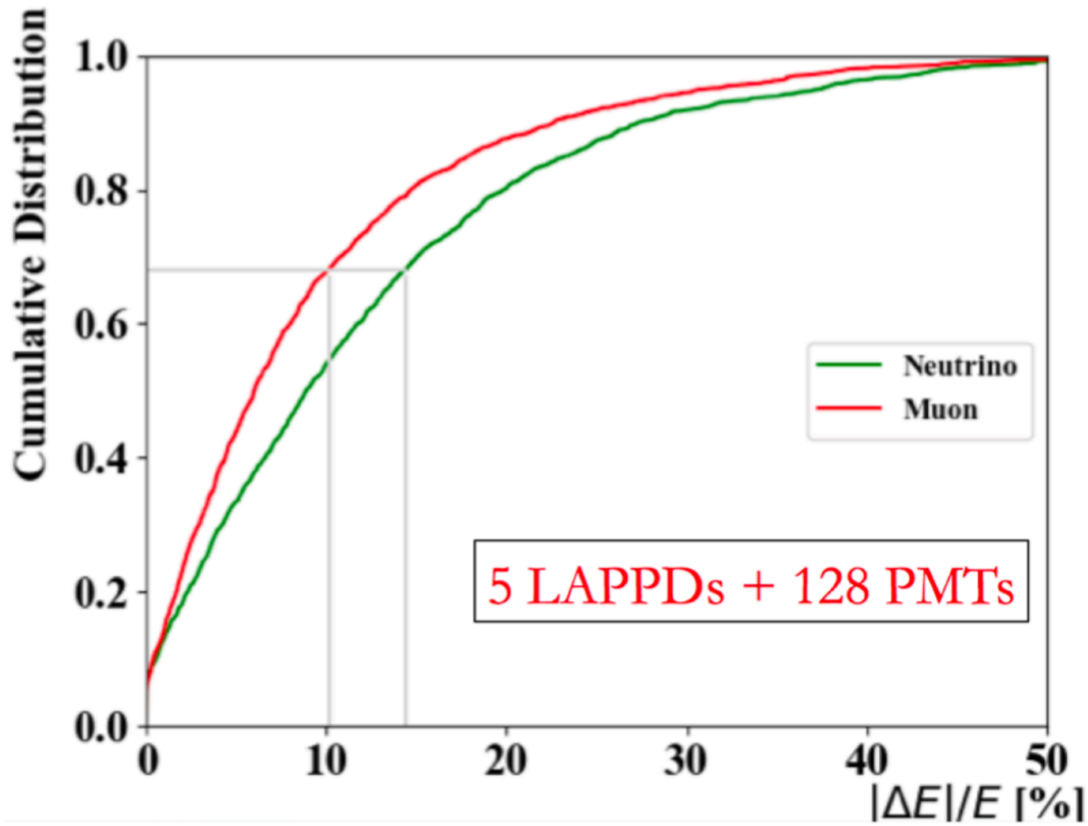
128 conventional PMTs: 38 cm resolution

5 LAPPDs + 128 PMTs: 12 cm resolution

Energy Reconstruction

Muon energy reconstruction:

- based on track length in water/MRD, angle between muon & beam direction, number of hits (p.e.) in PMTs and LAPPDs vertex coordinates — distances.
- critical to measure momentum transfer.
- **energy resolution** for muons is ~ **10%**.

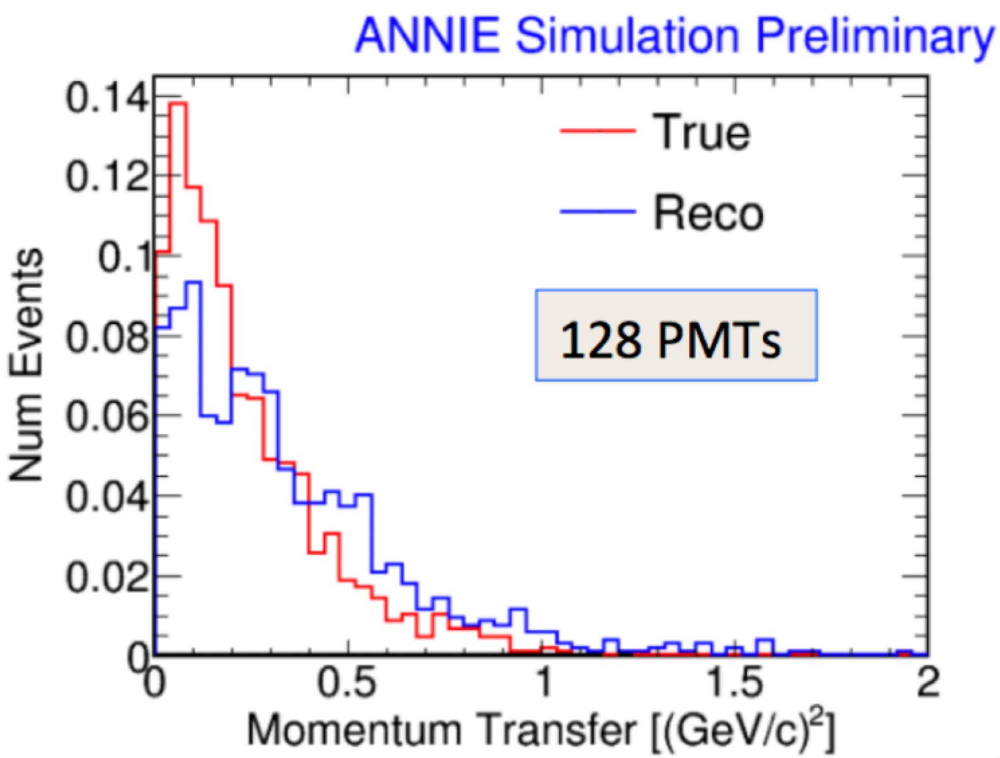


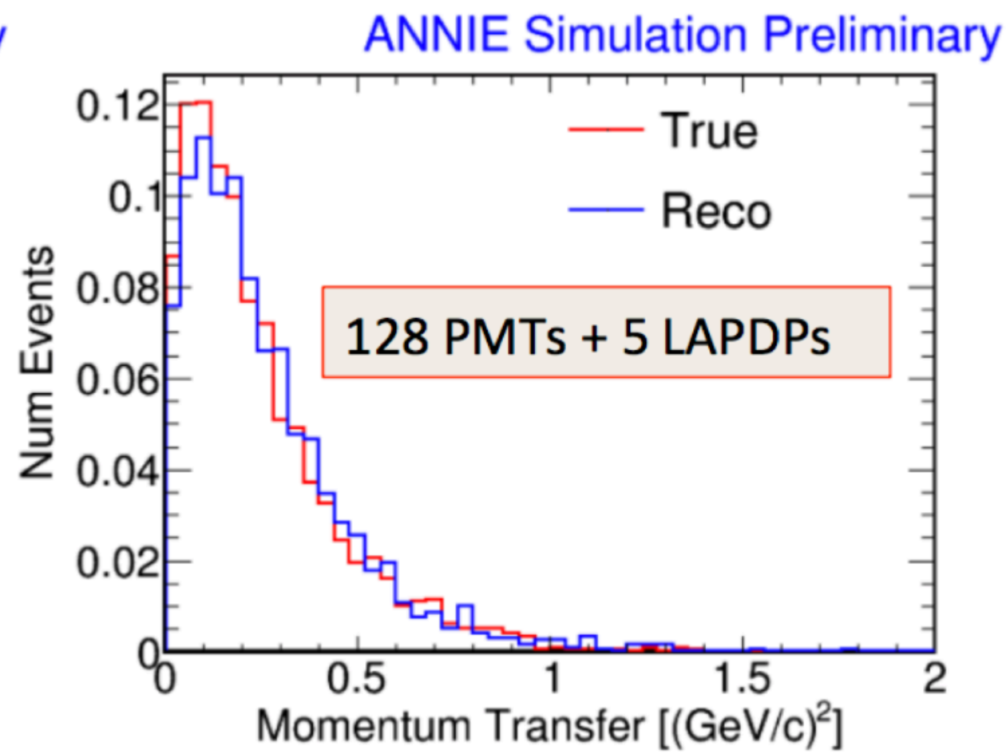
arXiv:1803.10624

Momentum Transfer

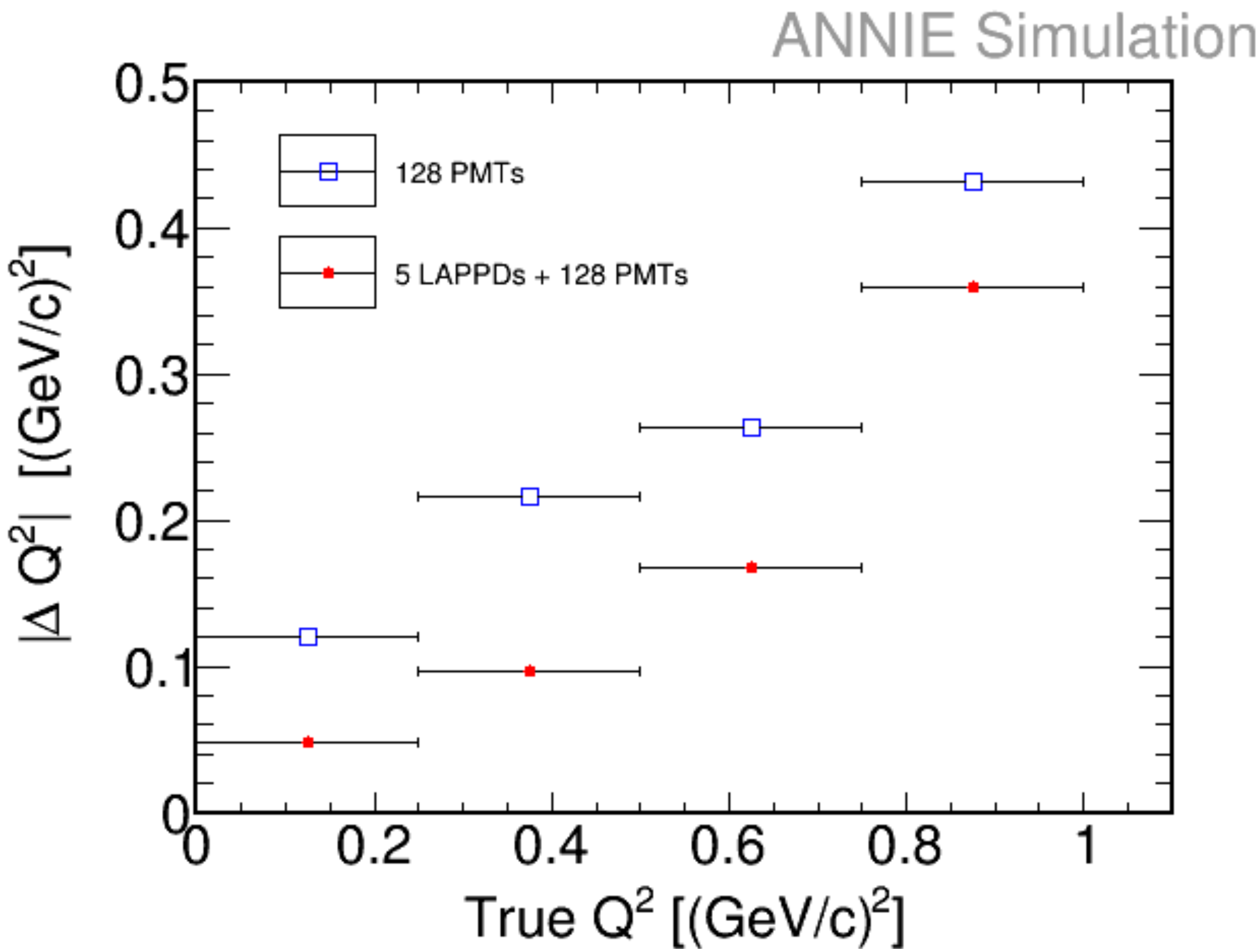
Momentum transfer reconstruction:

- based on Stopped muon events for which the muon energy is measurable as the sum of energy deposited in the water tank and the MRD.



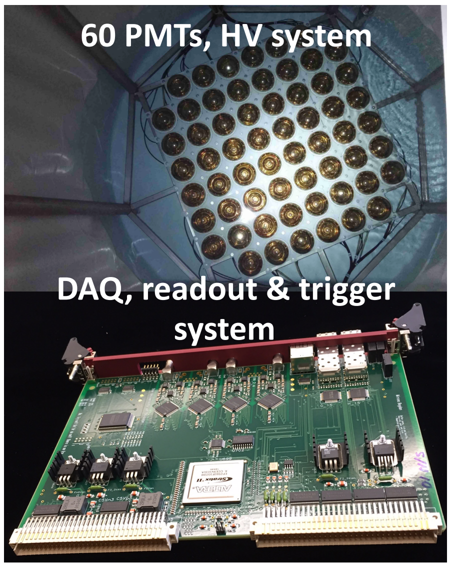


Momentum Transfer



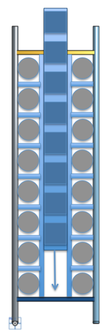
ANNIE Timeline

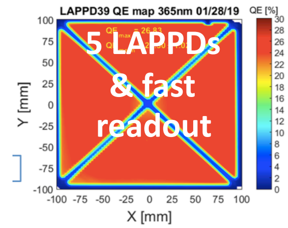
Phase I: completed

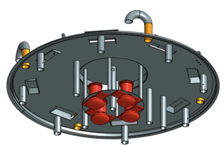


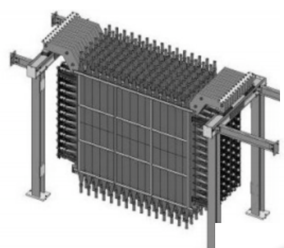
Fall 2017

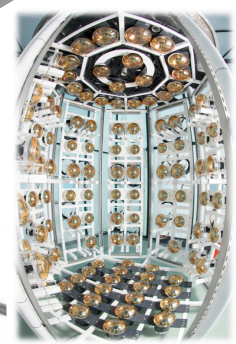
Phase II construction











Fall 2019

Phase II operations

opportunity
Phase II Upgrade
Phase III

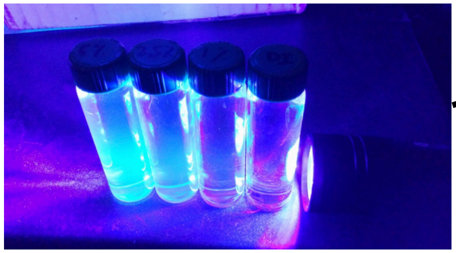
ANNIE R&D Platform: Phase II Upgrade

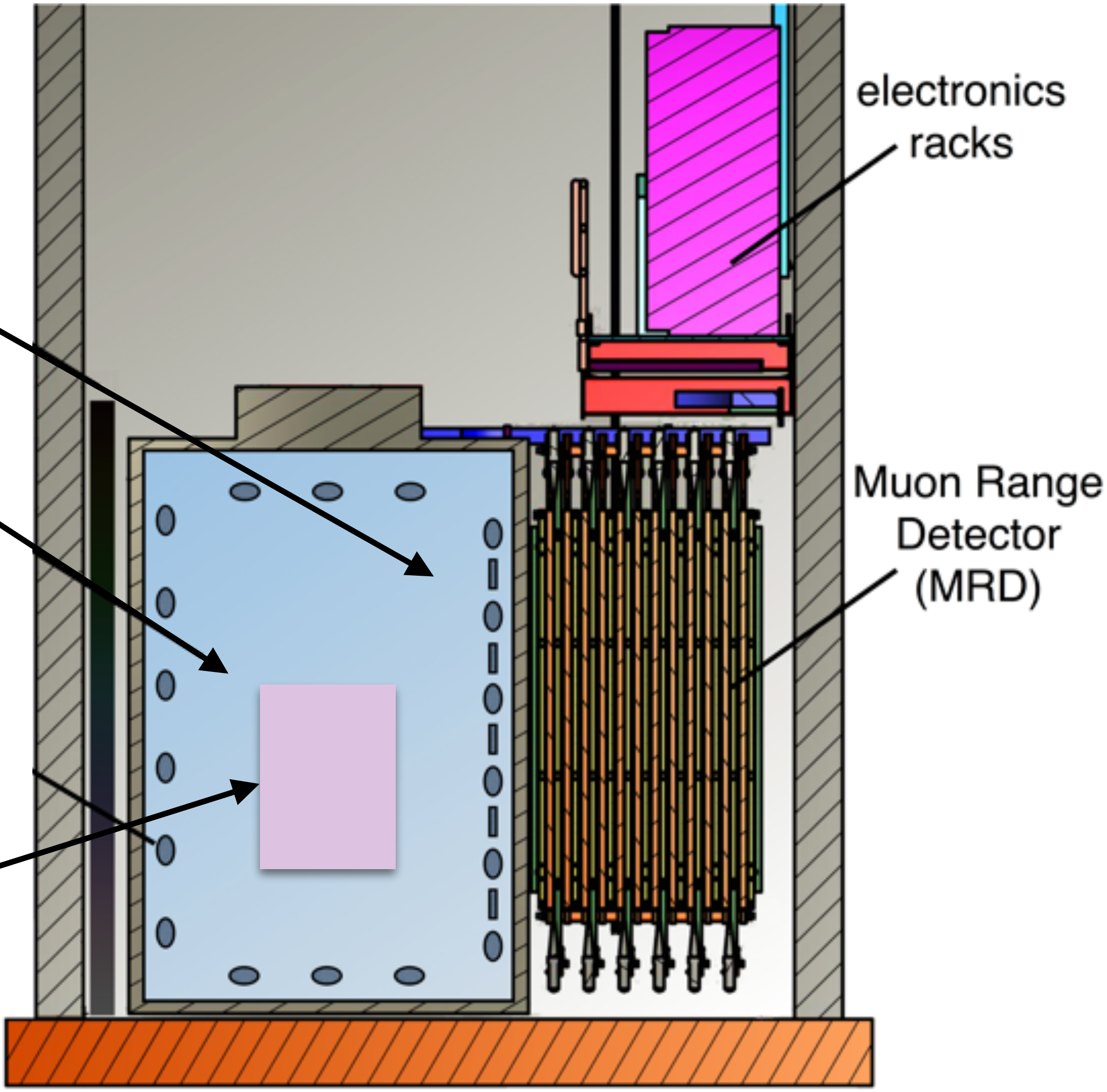
- more LAPPD coverage

- Gadolinium loaded water

- Reconstruction with scintillation and Cherenkov light

  —> use of WbLS in fiducial volume (UVT acrylic tank)





Conclusions

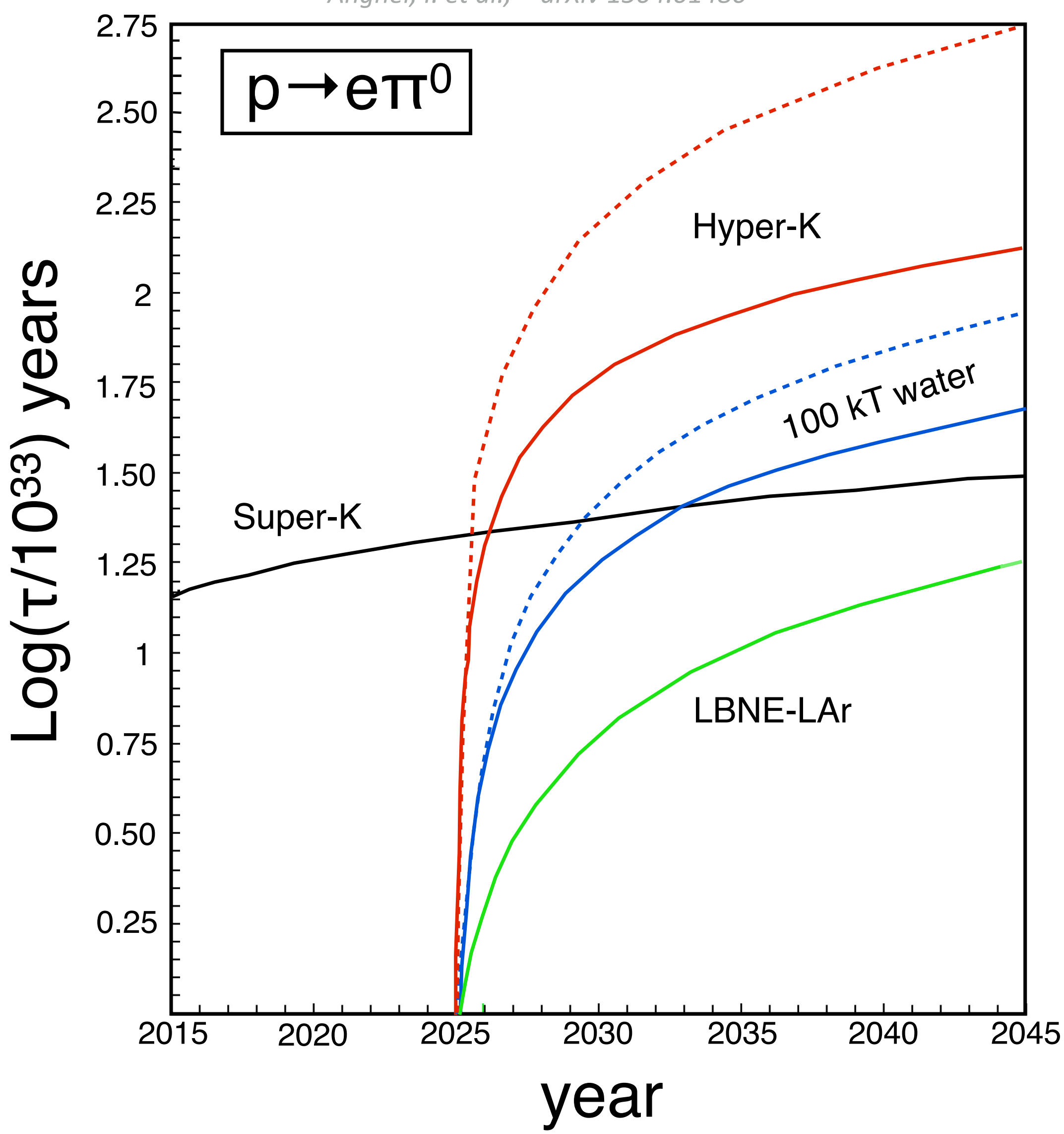
- ANNIE will measure neutron production as a function of Q^2 in an energy regime of long baseline experiments — this will also provide a better understanding of neutron tagging techniques for reducing background from atmospheric neutrinos (proton decay, supernova neutrinos).
- ANNIE Phase I was successfully built and operated. Backgrounds are shown to be sufficiently low for Phase II.
- ANNIE Phase II construction is complete and commissioning has started.
- Data taking will start very soon.

Backup Slides

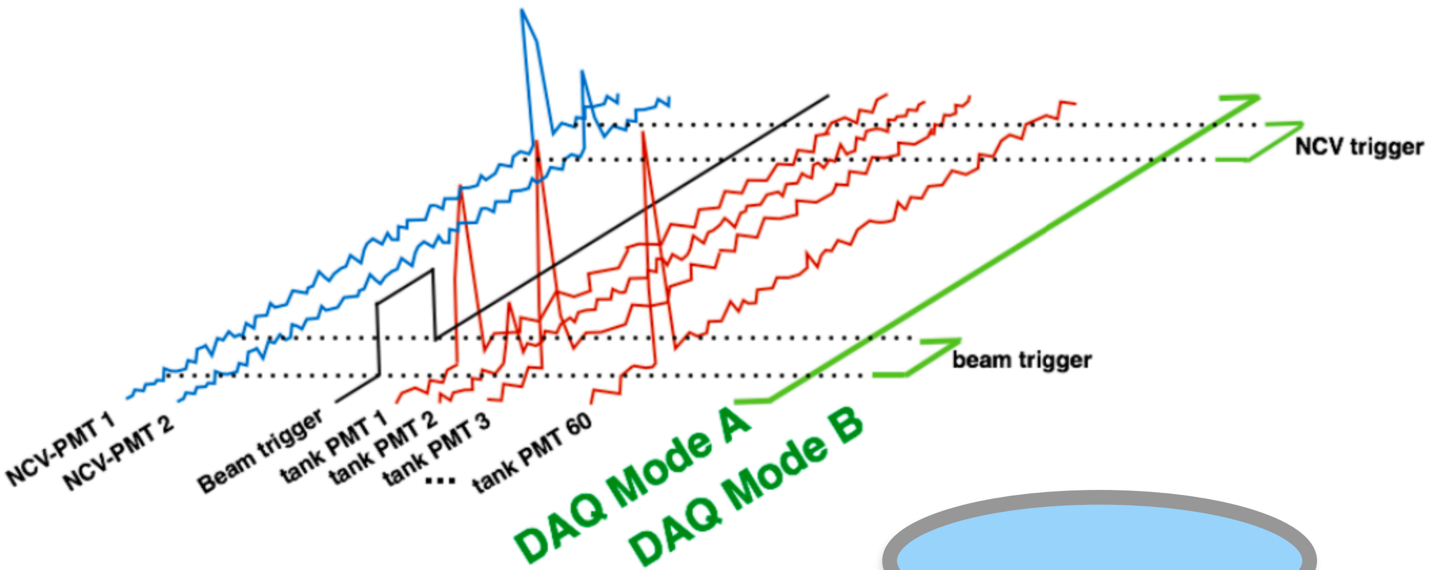
Physics Motivations: Proton Decay

- Proton decays, e.g., $p \rightarrow e^{+} + \pi^{0}$
- > **90% of proton decays** in water are **not expected to yield neutrons**.
- Background: **atmospheric neutrinos**, have **many ways** to produce **secondary neutrons**, however, predictions are not data driven.
- **ANNIE measurements** of neutron abundance in QE regime **will provide important input for simulations** of atmospheric neutrinos.
- BNB/atmospheric neutrino spectrum similar.
- Better **understanding of background rejection from neutron tagging** (Gd-doped water) is critical for future proton decay experiments.

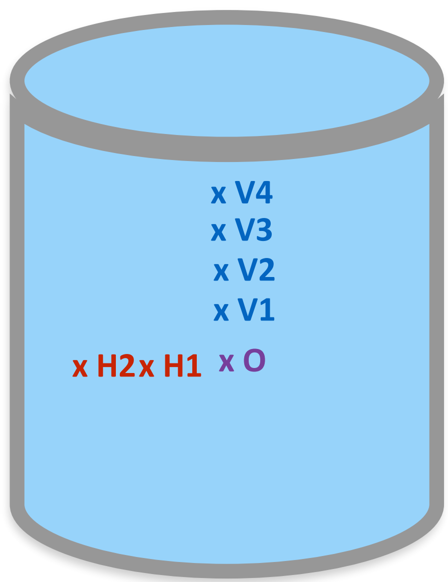
Anghel, I. et al., - arXiv 1504.01480



Constant in time background



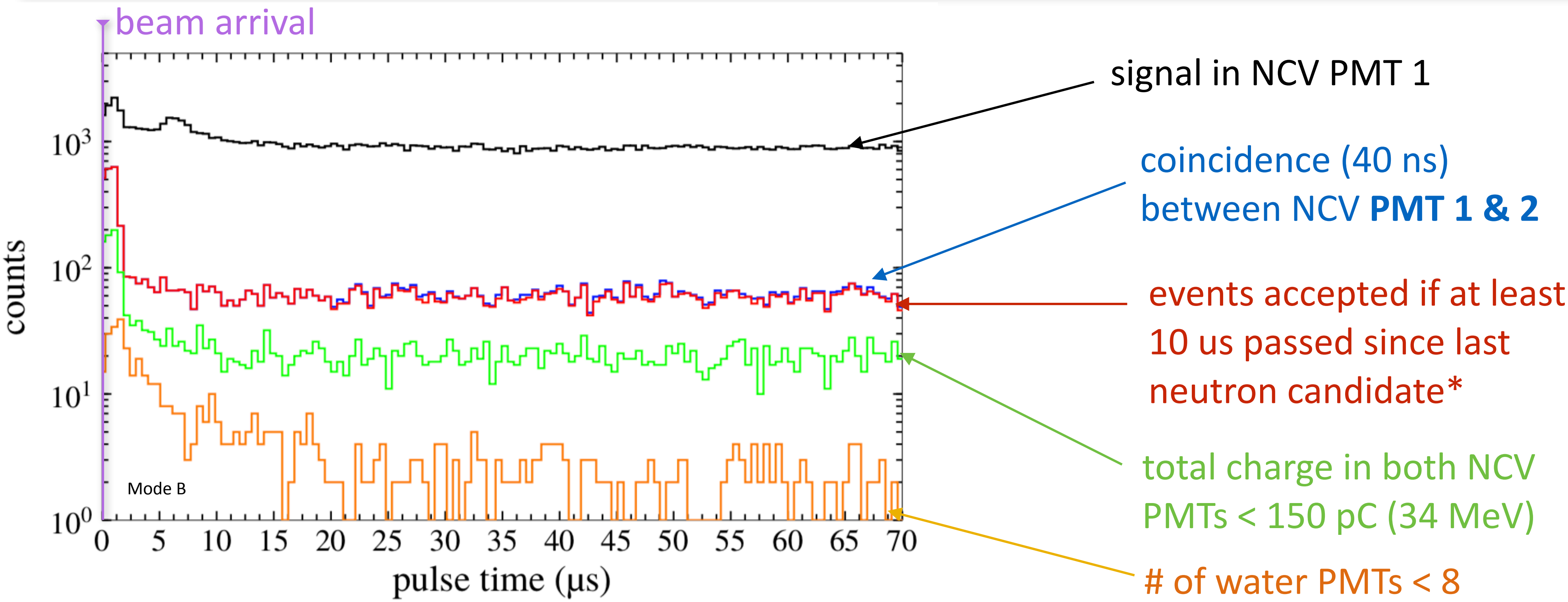
	NCV position	CIT event rate (Hz)
pre-beam (Mode A)	V4	11.4 ± 0.8
	O	1.5 ± 0.4
late-time (Mode B)	O	1.2 ± 0.2
	H1	0.8 ± 0.3
	H2	2.6 ± 0.2
	V1	1.8 ± 0.3
	V2	3.1 ± 0.3
	V3	4.5 ± 0.7



—> 10^{-4} **per trigger window (80 -100 us)**

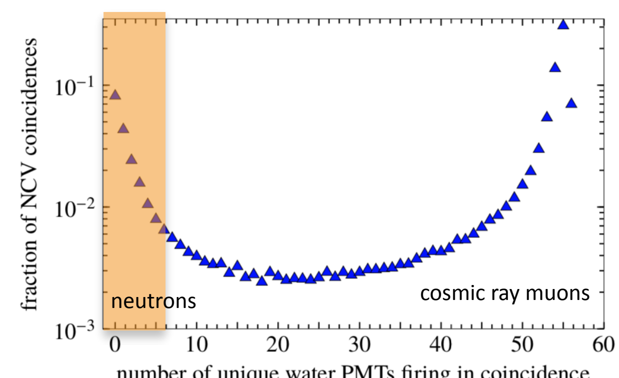
- CIT in Mode A: 9 us before beam trigger.
- CIT in Mode B: 70-80 us window after the beam trigger.

Neutron Time Distribution (O) — Cuts



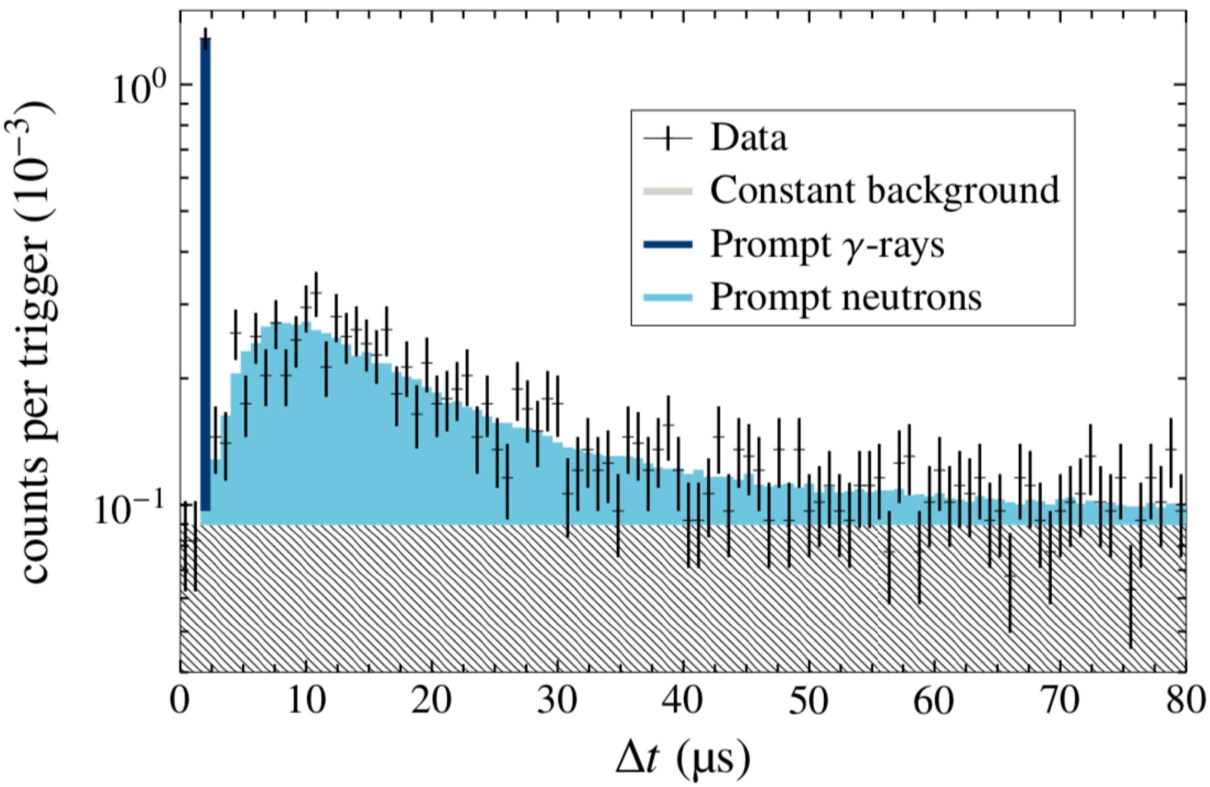
neutrons captures seen in NCV:

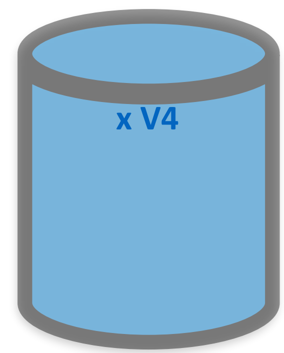
- scintillation light **10 - 70 us** after beam
- no evidence for a prompt neutrino interaction in tank
- compact size of NCV provides some localization of neutrons



* only applied for 20 - 70 us, but not in the 10 - 20 us regime, where fast neutrons can scatter — same signature as after-pulsing

Calibration of NCV efficiency

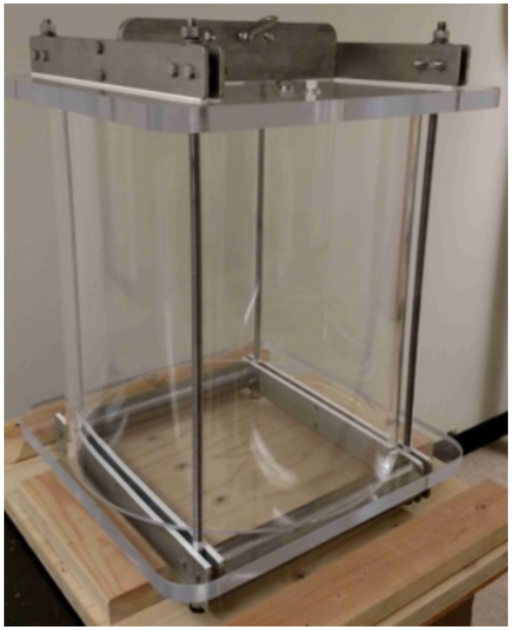


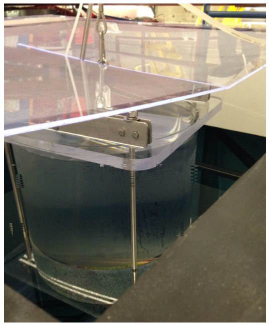


- A californium-252 fission neutron sources was used to calibrate the NCV
- LYSO crystal was used to **trigger** the ANNIE DAQ **on fission gamma rays**
- Neutron captures detected by NCV in position V4
- Simulations (FREYA, RAT-PAC detector simulation) —> NCV efficiency: $(9.6 \pm 0.57_{stat})\%$

Phase-I Water Purification, Neutron Capture Volume

- Ultra pure water (0.5 ppm).
- Resistivity > 10 MOhm/m.
- 7,000 Gallons are continuously flushed with nitrogen and filtered through a deionizing purification system.





- Neutron capture volume (NCV) is an acrylic vessel.
- NCV can be moved vertically and along the beam axis.
- Filled with 100 liters of Gd-doped liquid scintillator
- EJ-335 contains pseudocumene and 0.25% Gd (weight)
- Peak wavelength 424 nm

Angular resolution (transverse)