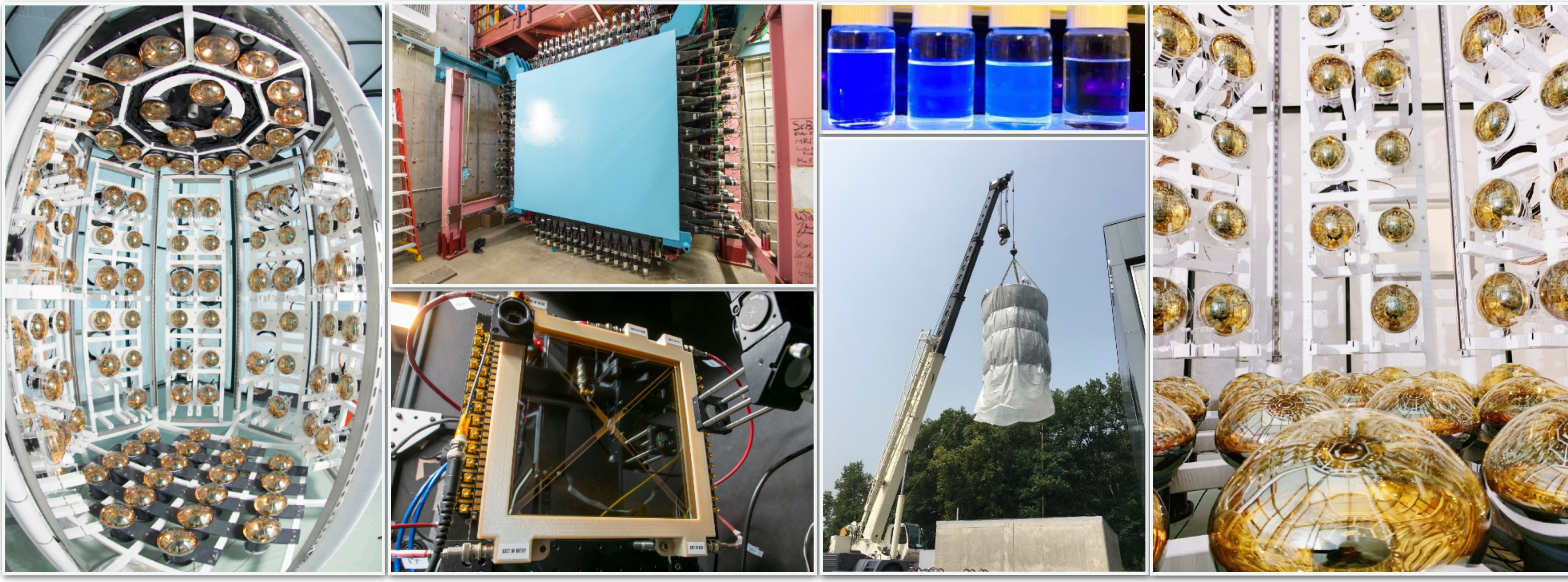


Status of the ANNIE experiment

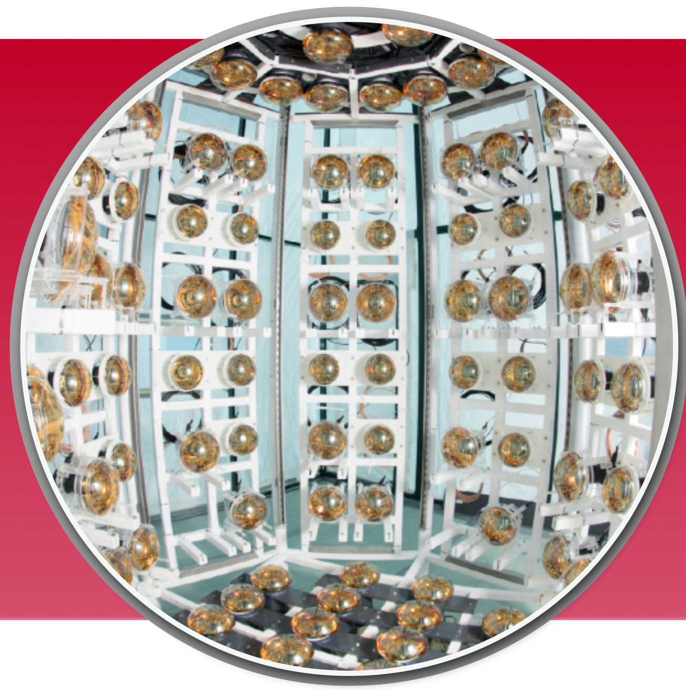
International Conference on High Energy Physics (ICHEP) 2022
07/07/2022

Michael Nieslony
on behalf of the ANNIE collaboration

annie

JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JGU

The **A**ccelerator **N**eutrino **N**eutron **I**nteraction **E**xperiment



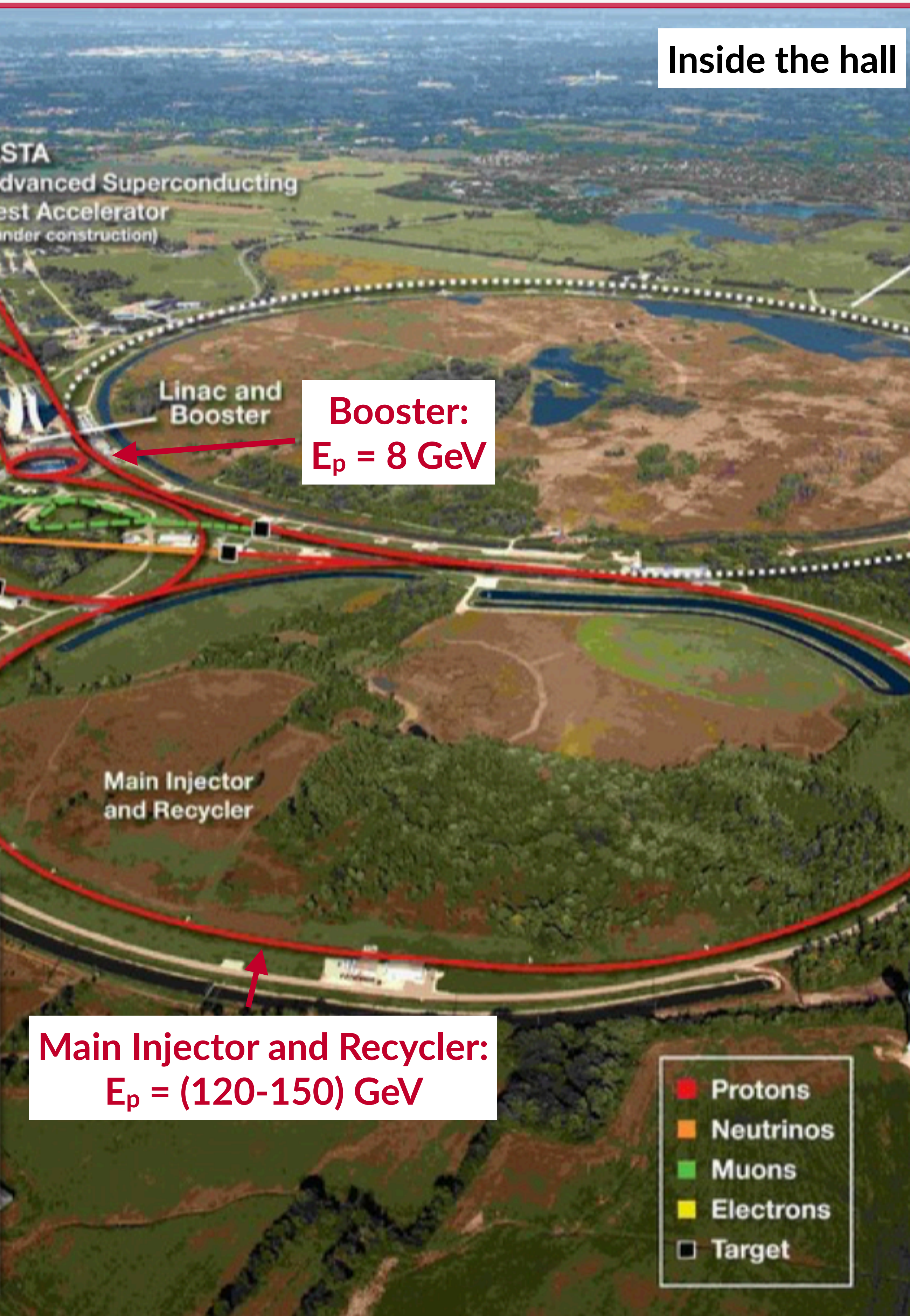
Detector

Collaboration

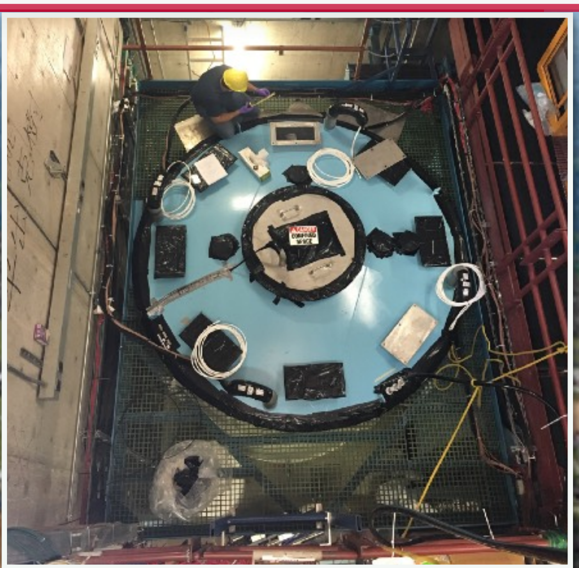
New technologies:
LAPPDs/WbLS
Gd-loaded water

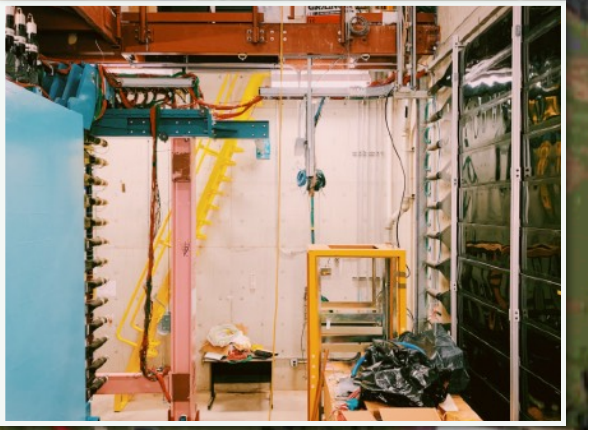
- **Gd-loaded water Cherenkov detector** placed 100m downstream from target of the Booster Neutrino Beam (BNB) at Fermilab
- Measurement: **final state neutron multiplicity & CCQE cross-section** in water
- Test of **new technologies** in the fields of fast photosensors (LAPPDs) and detection media (Gd-loaded water/Water-based Liquid Scintillators)

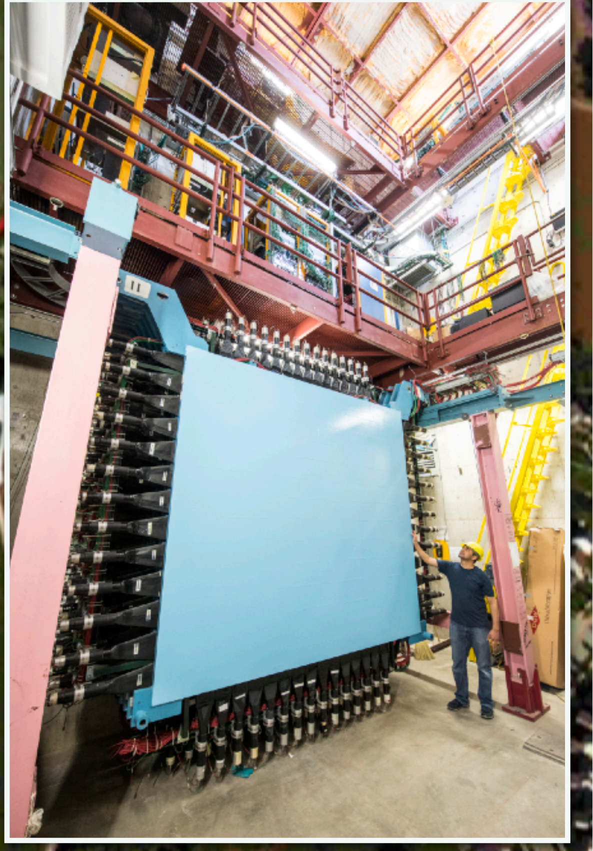
Fermilab Accelerator Complex



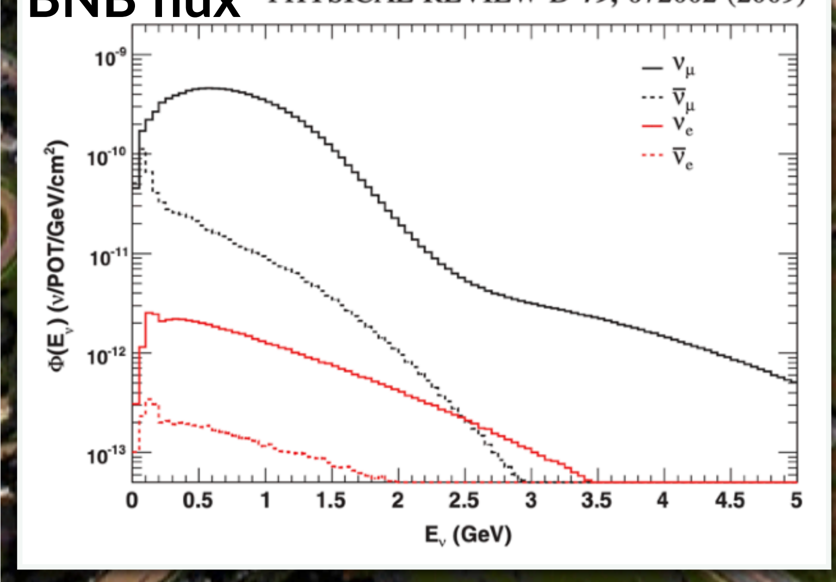
Inside the hall





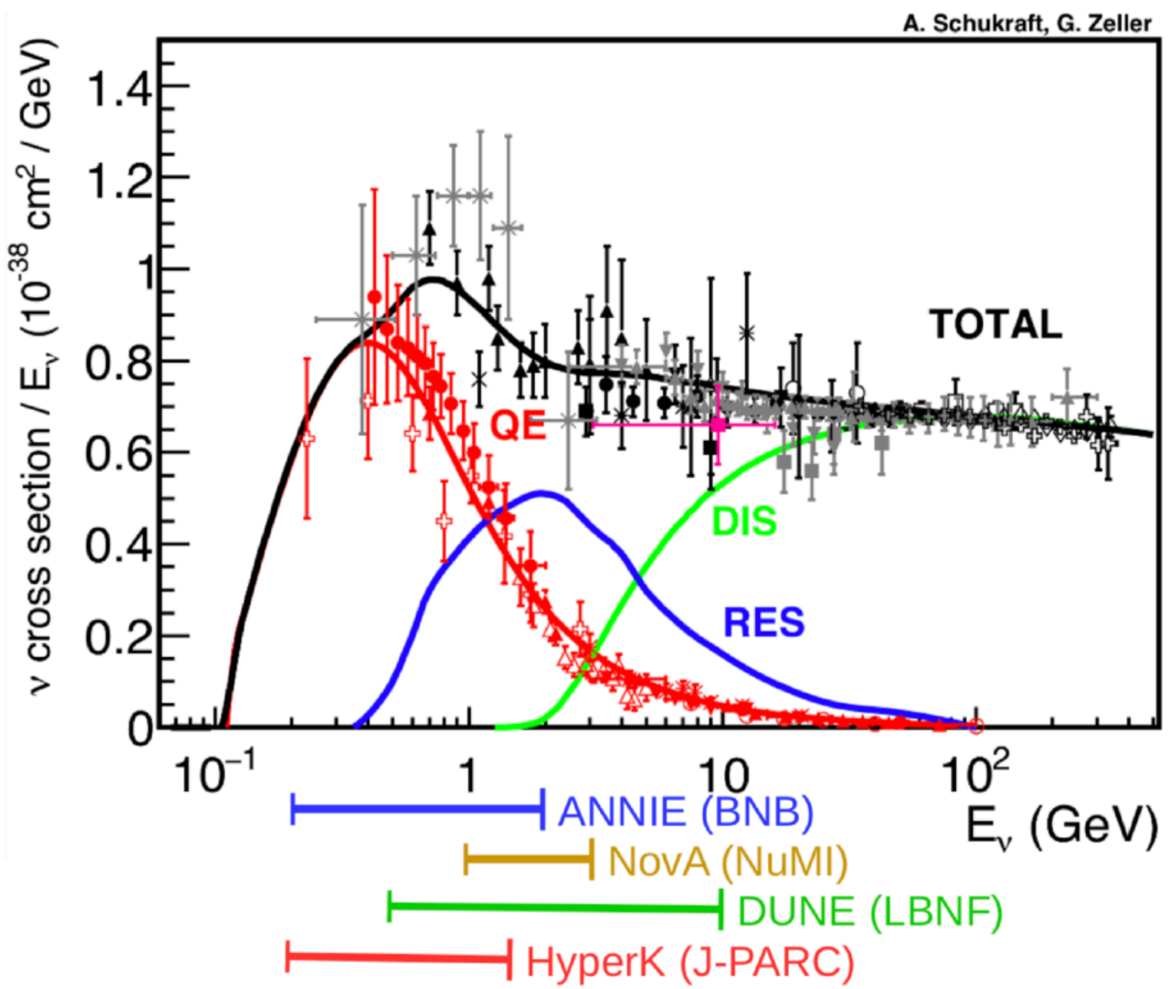


BNB flux

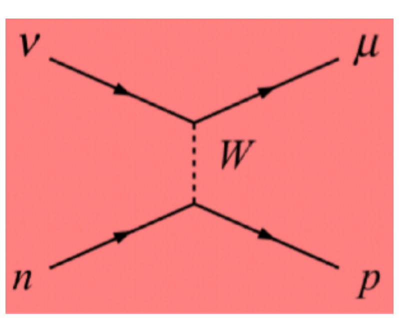


ANNIE physics motivation

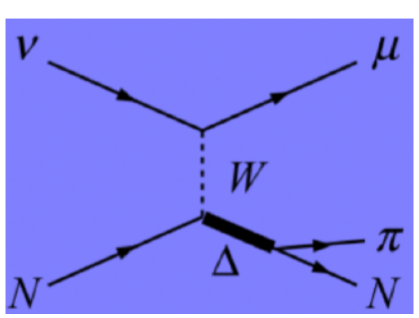
Relevant interactions in ANNIE:



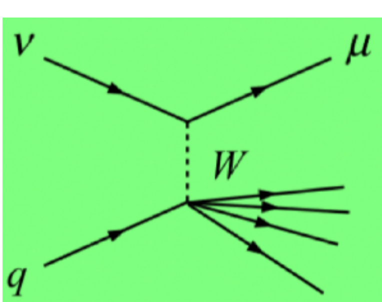
Quasi-Elastic



Resonance



Deep Inelastic Scattering



CCQE cross-section in water:

- reduce systematic uncertainty in long-baseline neutrino oscillation studies

Neutron multiplicity:

- model atmospheric background for DSNB & proton decay searches
- minimize neutrino energy reconstruction bias

Features:

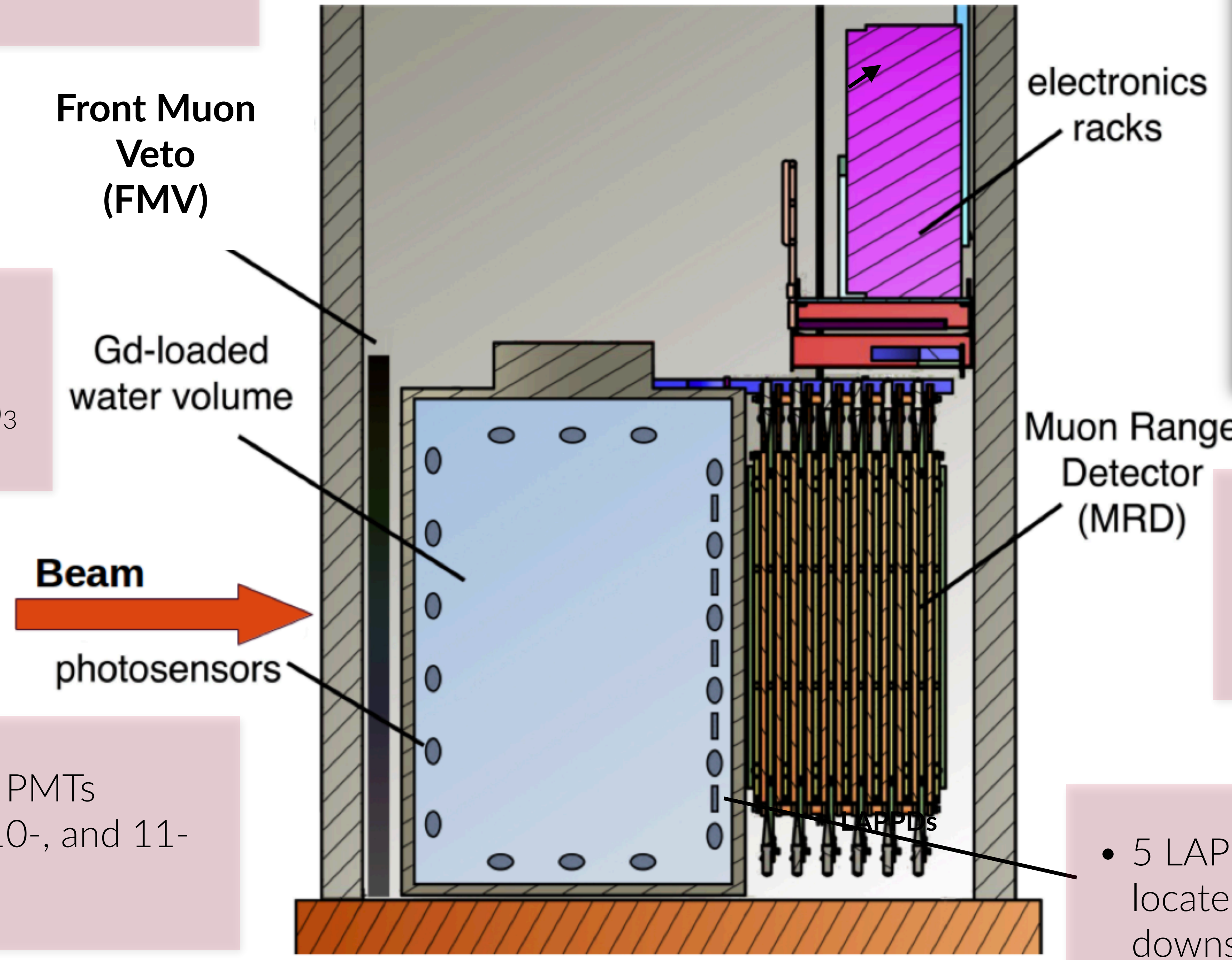
- Close proximity to beam target
  → high flux of neutrinos
  (~10,000 CC-interactions / ton /year)
- Nearby SBND Liquid Argon detector
  → opportunity for combined argon/water cross-section analysis
- Gadolinium loading
  → high neutron detection efficiency due to 8 MeV gamma cascade

ANNIE Detector setup

- 26 scintillator paddles
- reject muons from upstream

- 26 tons water volume
- 0.2% $Gd_2(SO_4)_3$

- 132 PMTs
- 8-, 10-, and 11-inch

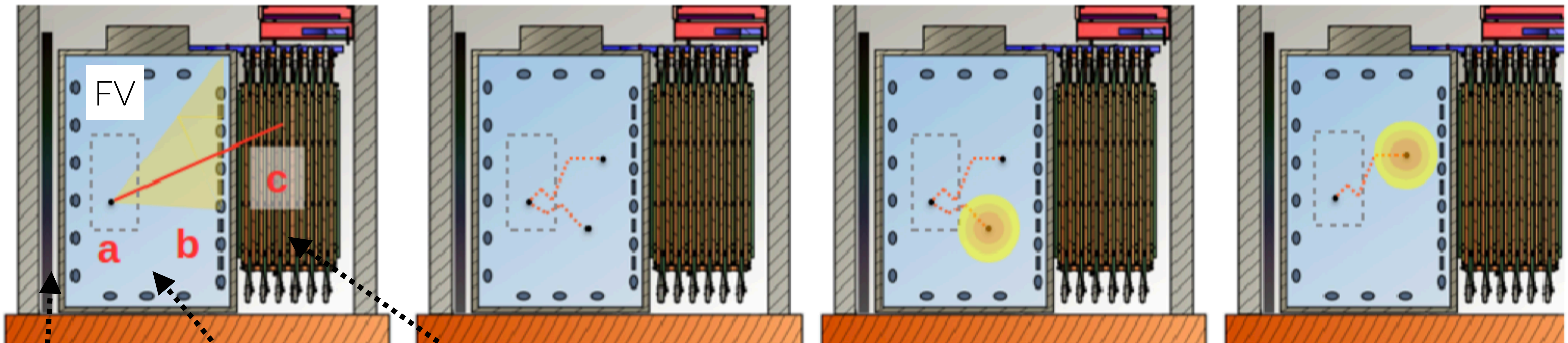


Gadolinium-loaded!
(0.1% Gd mass fraction)

- 310 scintillator paddles
- 5 vertical layers
- 6 horizontal layers

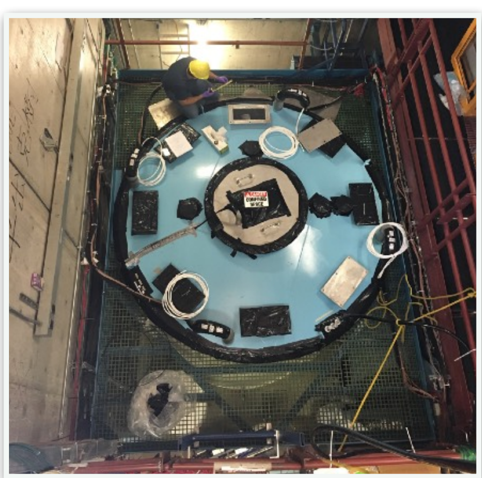
- 5 LAPPDs located downstream

Event schematic (ν_μ CCQE event)

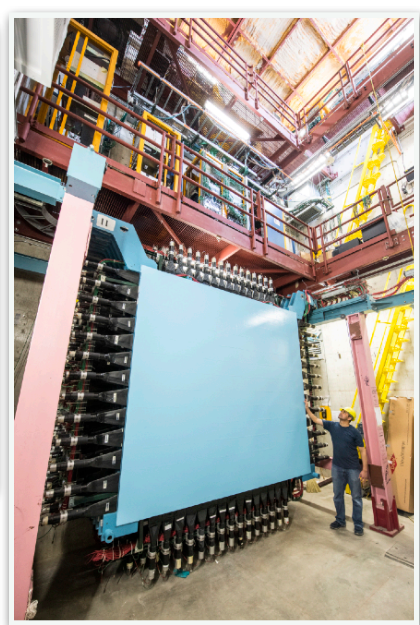


1 2 3 4

Front Muon Veto



Water tank



Muon Range Detector

1. **a)** Muon gets created in CC-interaction
   b) Vertex reconstruction by LAPPDs
   c) Muon momentum reconstructed in MRD

2. Neutron(s) travel, scatter around the detector

3. Neutron capture 1, detection by PMTs

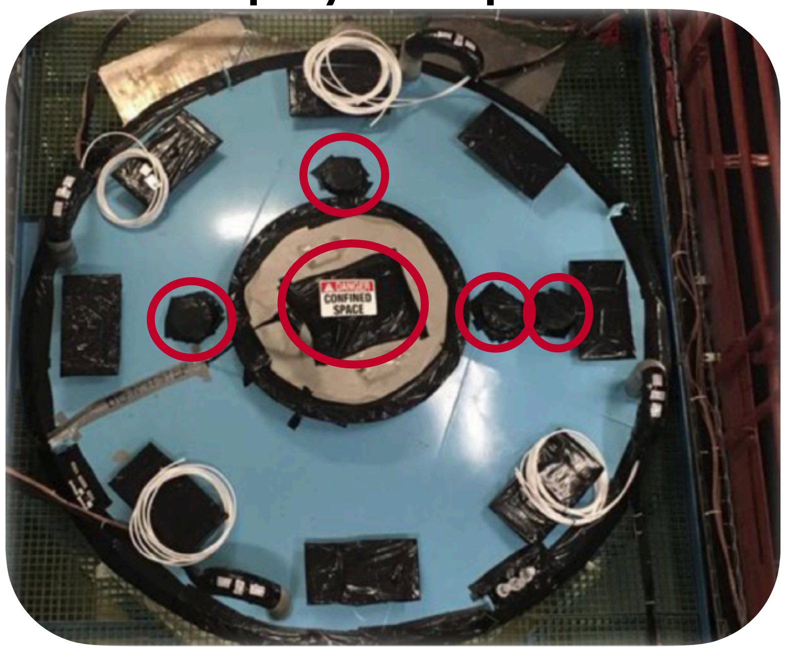
4. Neutron capture 2, detection by PMTs

Calibration in ANNIE

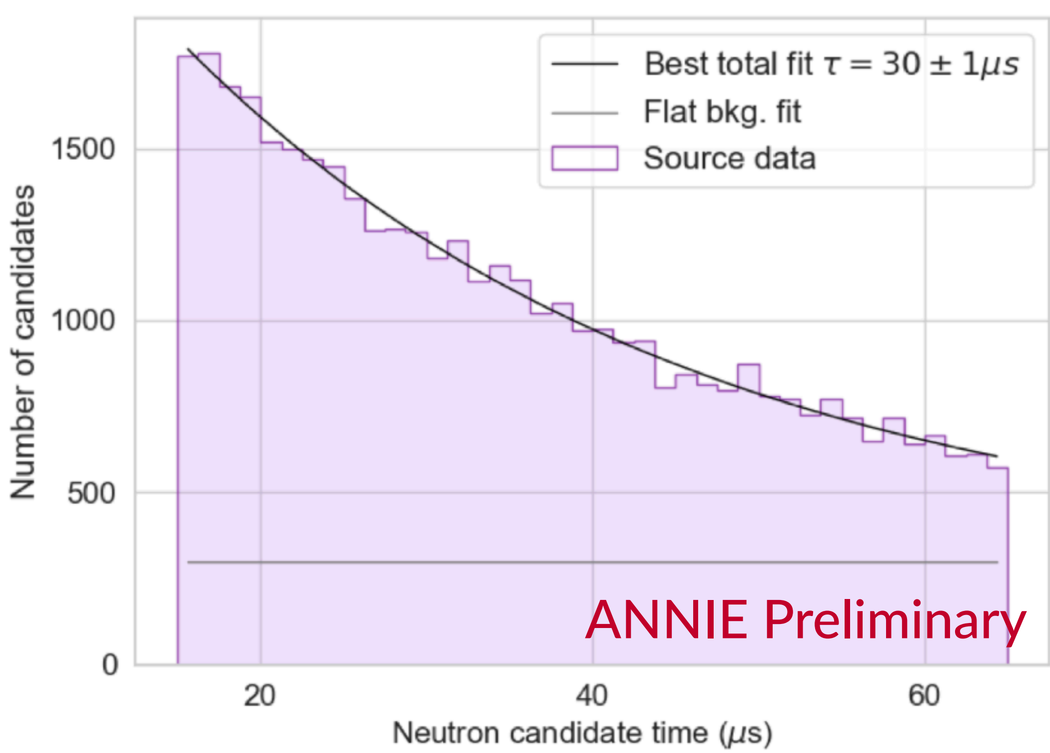
- AmBe neutron calibration campaign performed in fall of 2020
- Purpose: Neutron detection efficiency map
- Deployment in a UVT acrylic container via 5 deployment ports

UVT acrylic container

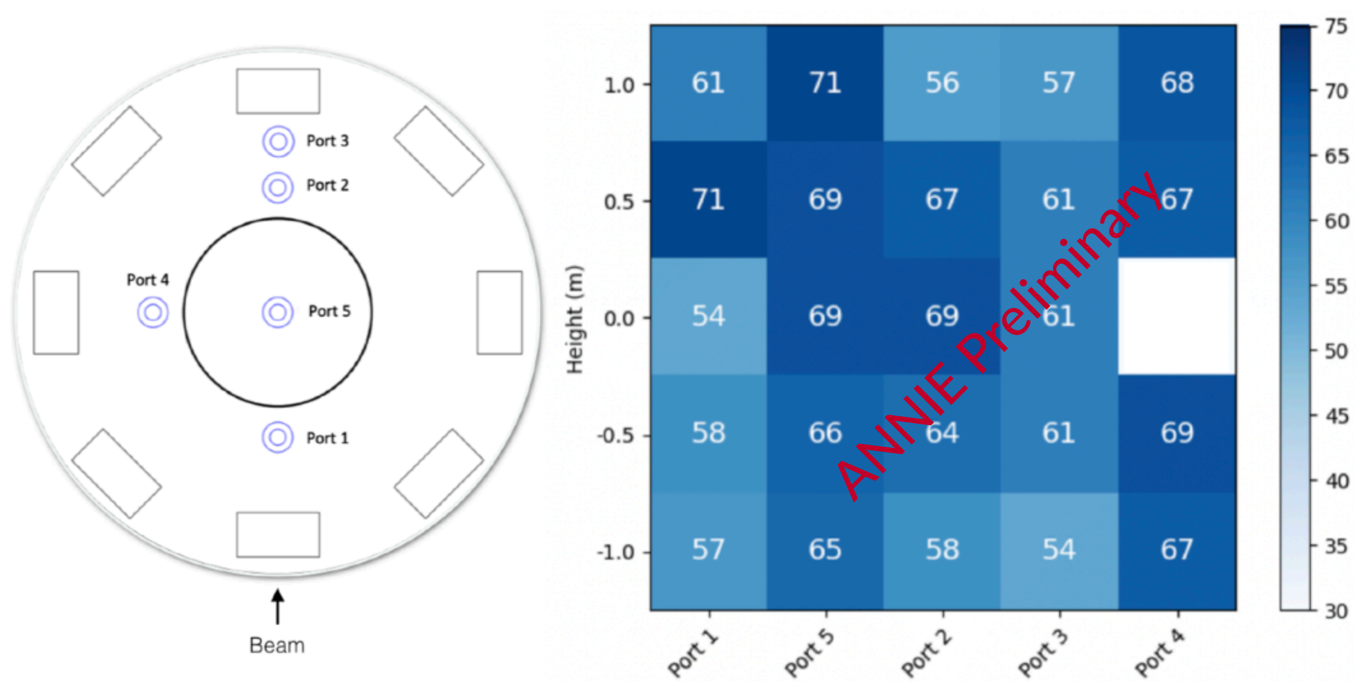
Deployment ports



Neutron capture time profile

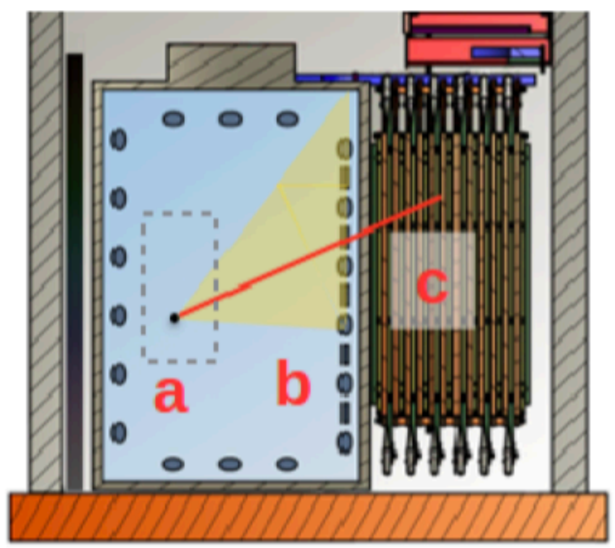


Neutron detection efficiency map



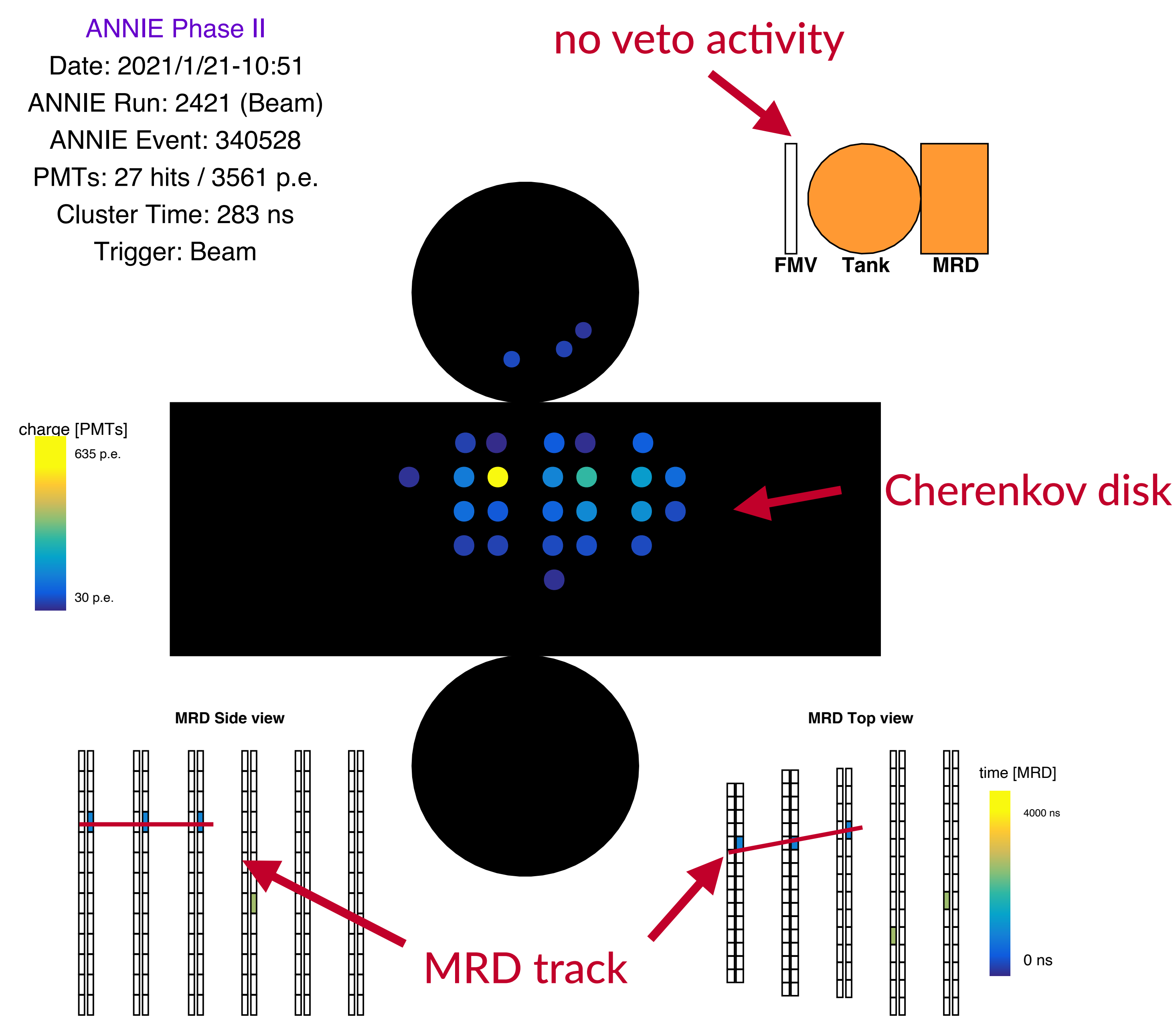
Height (m)	Port 1	Port 5	Port 2	Port 3	Port 4
1.0	61	71	56	57	68
0.5	71	69	67	61	67
0.0	54	69	69	61	
-0.5	58	66	64	61	69
-1.0	57	65	58	54	67

Beam neutrinos in ANNIE

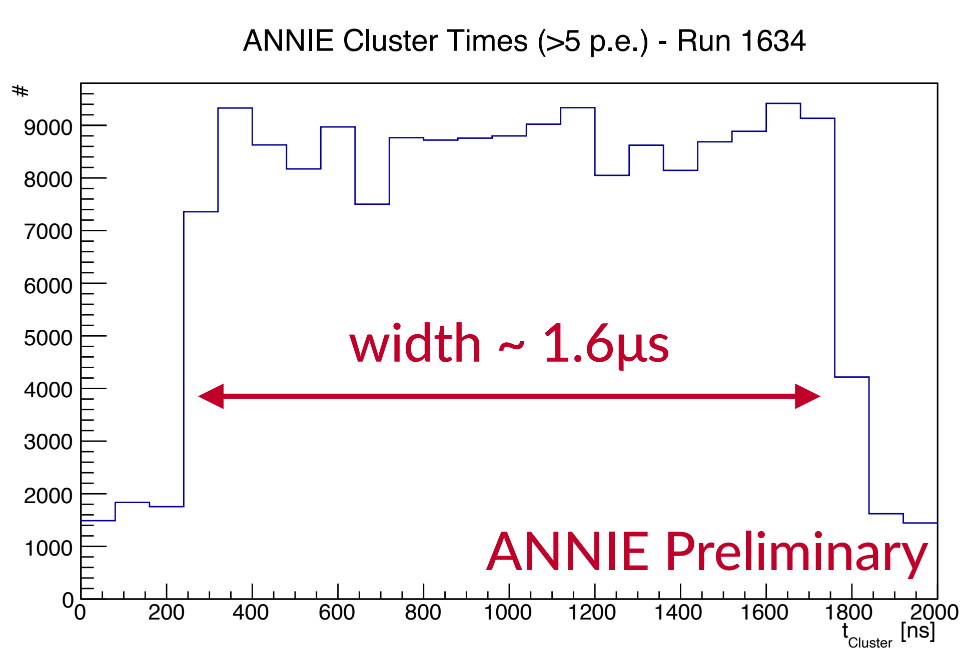


in the data

Beam neutrino candidate



PMT hit timing plot



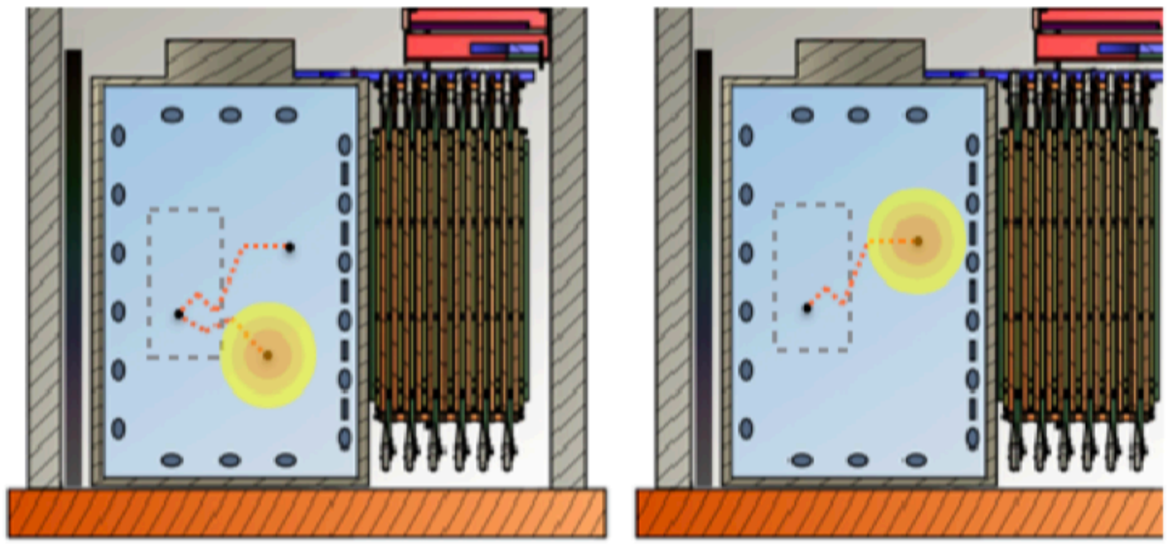
The BNB spill is visible in the PMT beam data

ANNIE sees beam neutrino candidates

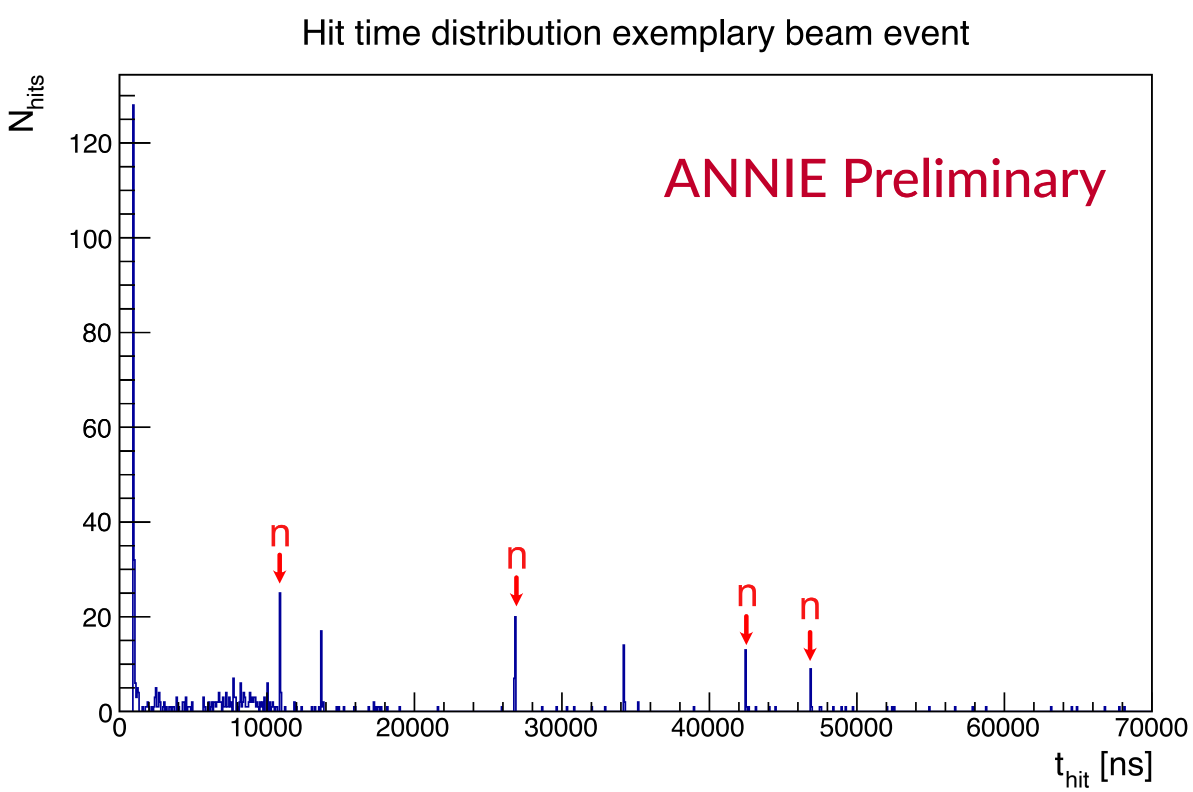
Neutron multiplicity in beam neutrino interactions

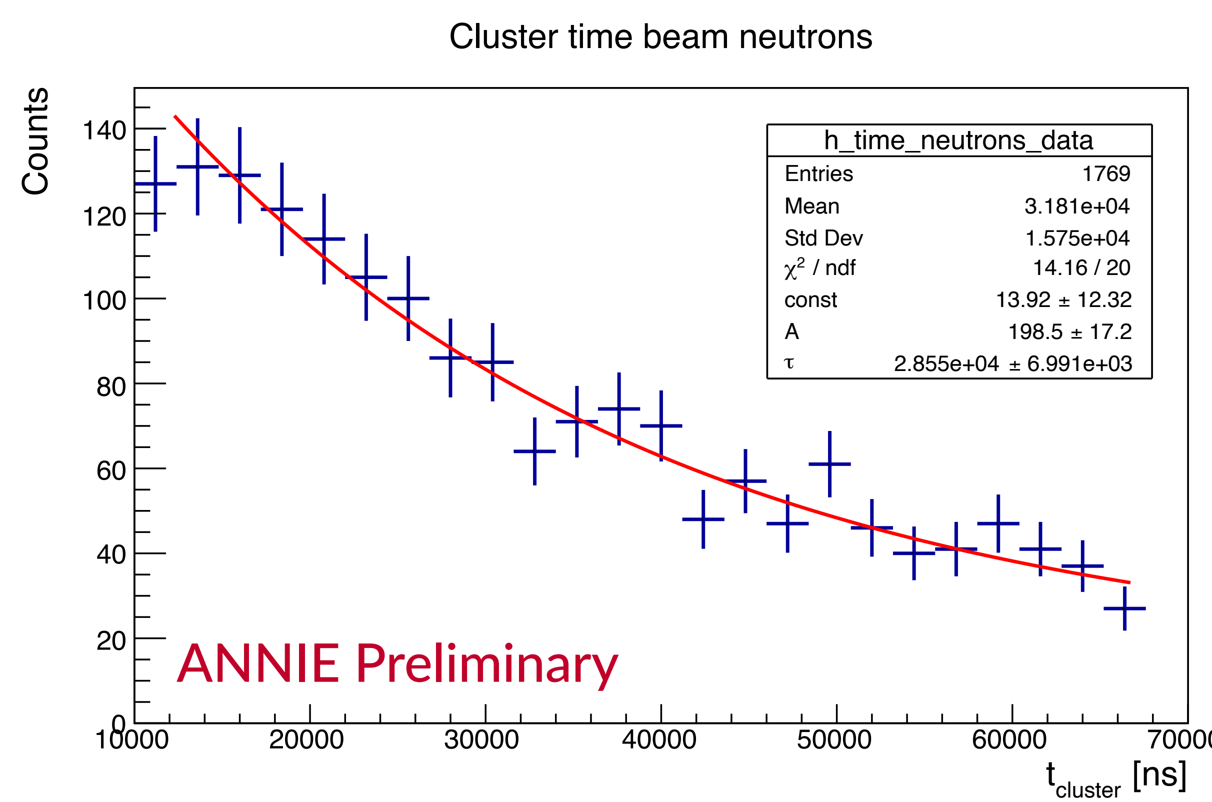
Look for neutrons following beam neutrino candidates

Neutron multiplicity analysis ongoing at the moment



in the data



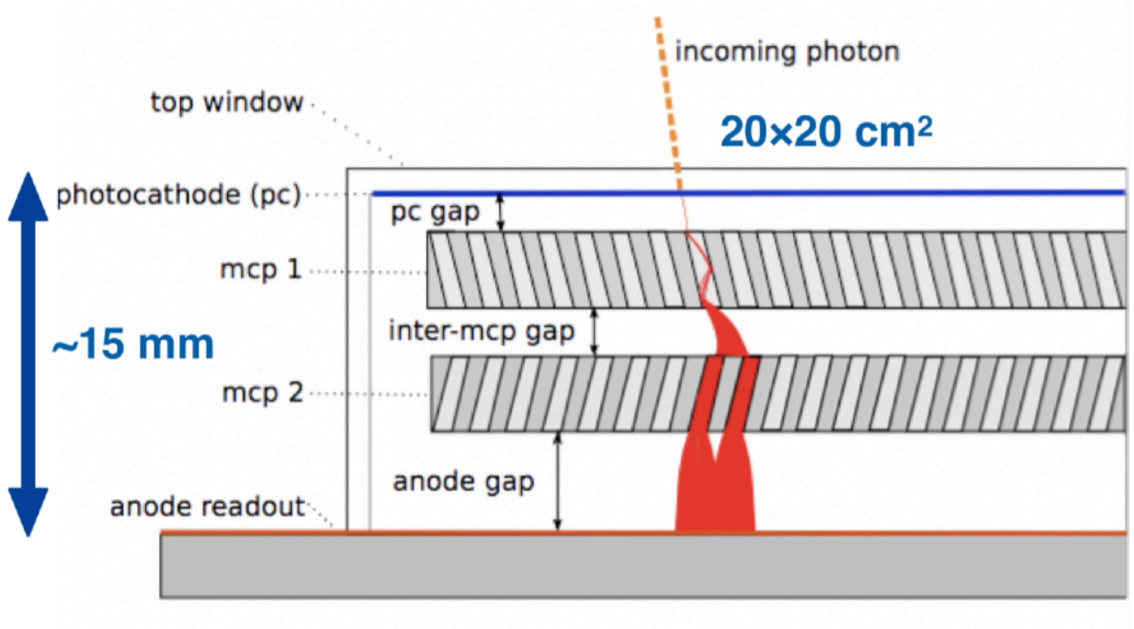


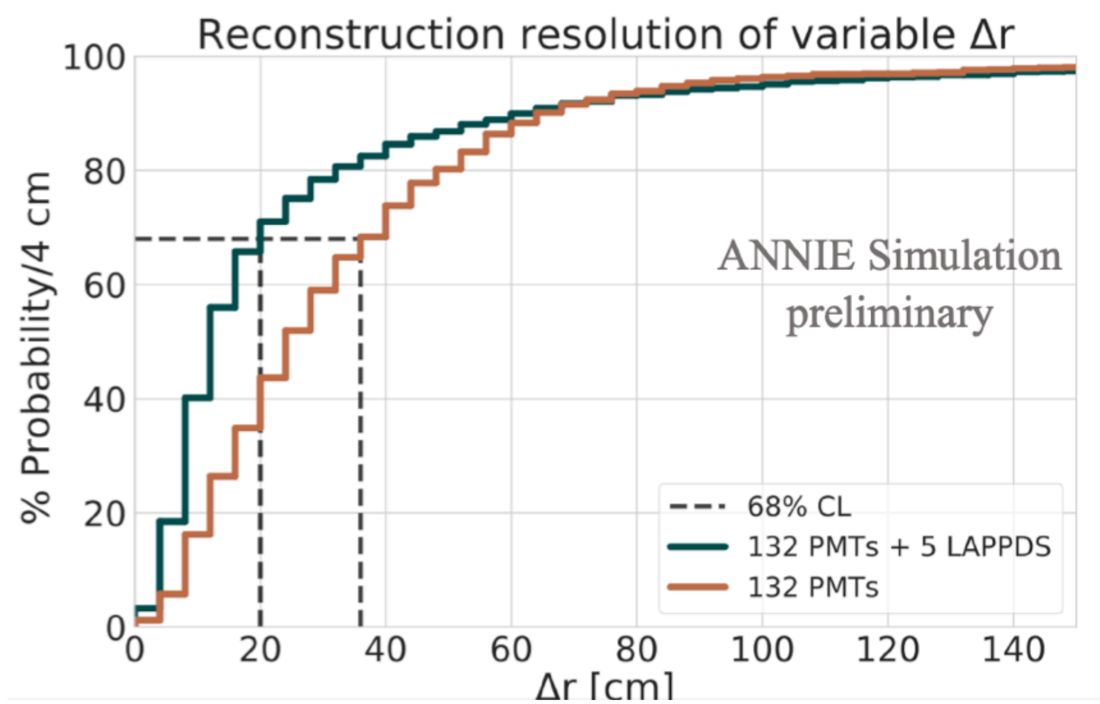
multiple neutron candidates in exemplary event

$\tau \sim (29 \pm 7)\ \mu s$ in agreement with theoretical expectation (30 µs)

Large Area Picosecond Photodetectors

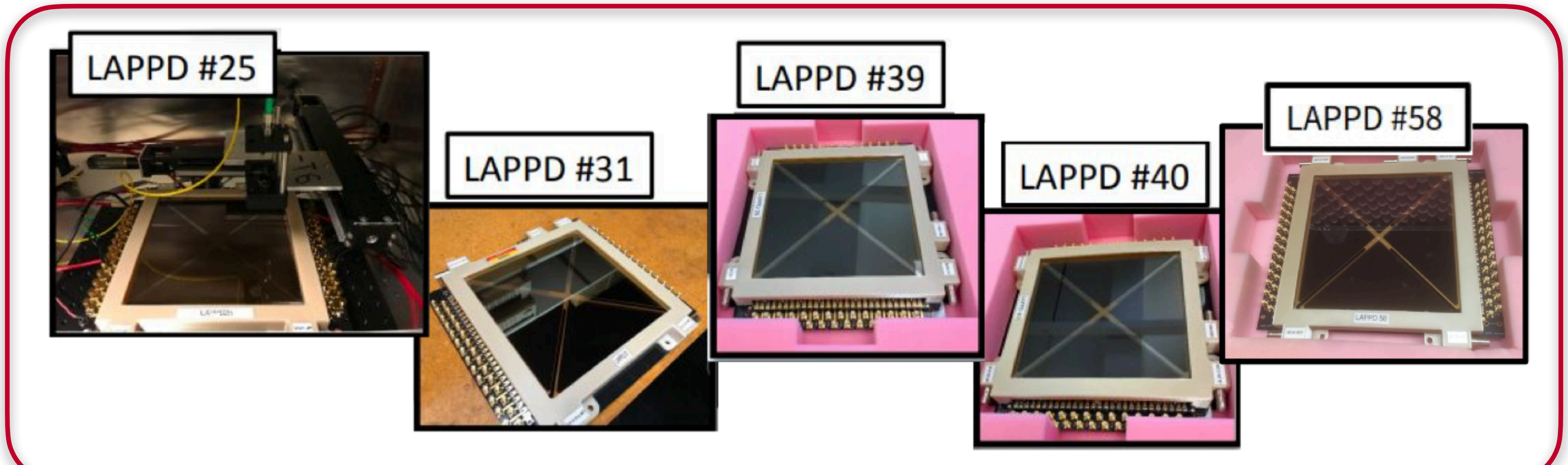
LAPPD: **L**arge **A**rea **P**icosecond **P**hoto **D**etector





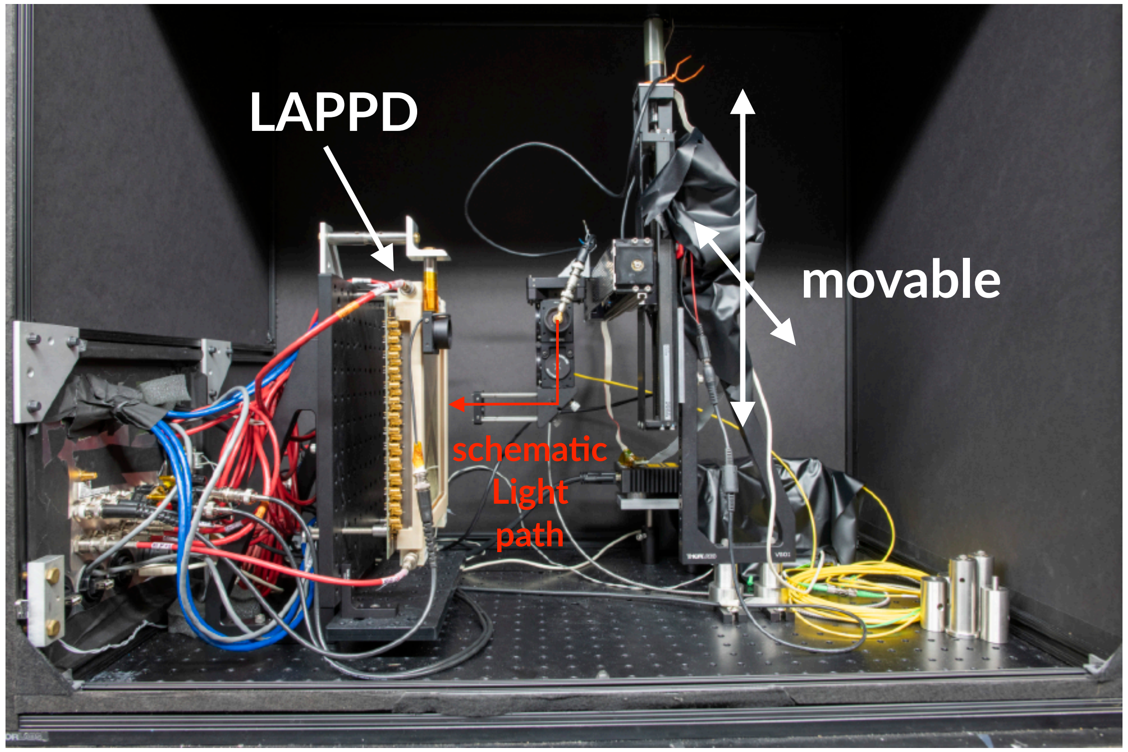
- 20 cm x 20 cm photodetector with intrinsic position resolution (mm-cm scale)
- Microchannel plate structure with resistive & emissive coating + microstrip anode readout
- Fast detection capabilities (time resolution ~60 ps)
- ANNIE has 5 LAPPDs at hand, characterization ongoing at Fermilab test stand
- Both angular and spatial resolution profit substantially from using 5 LAPPDs

ANNIE LAPPDs



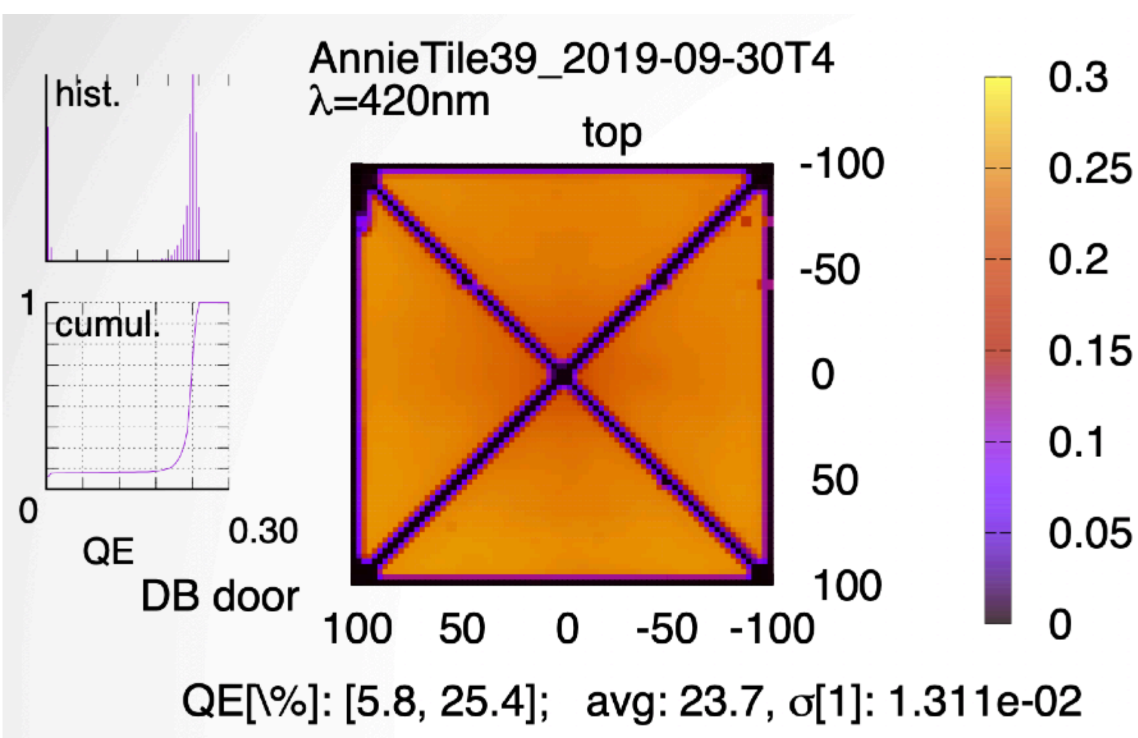
LAPPD characterization

Dedicated test stand at Fermilab

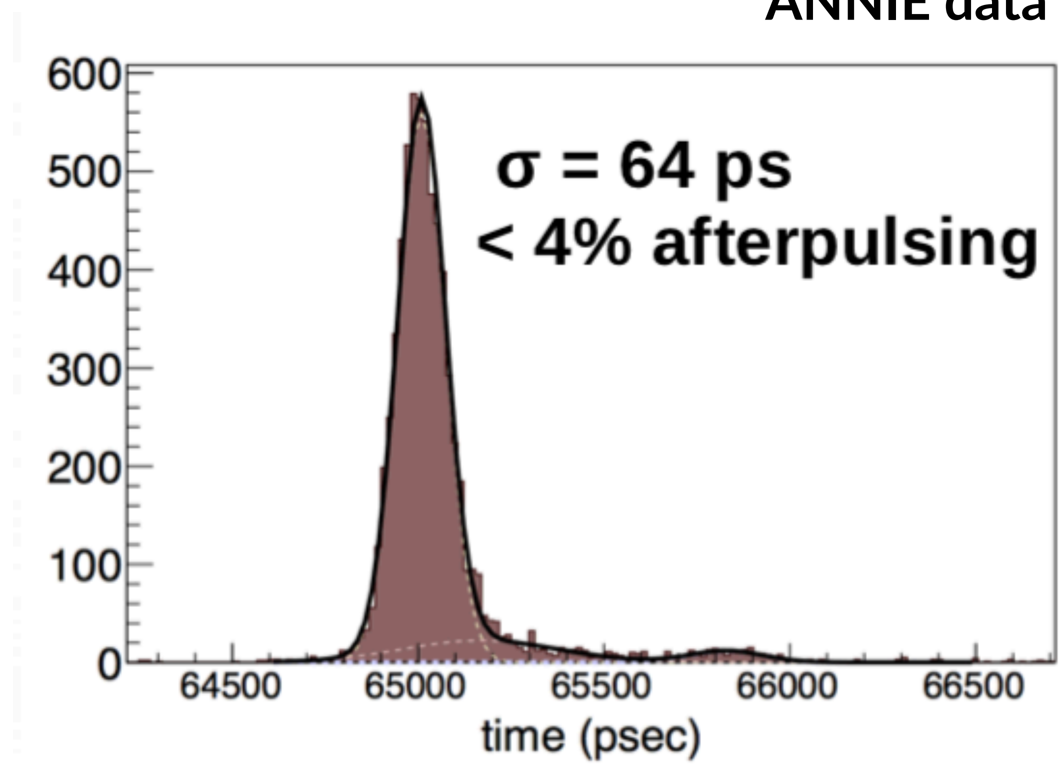


- Systematic tests of all 5 LAPPDs at dedicated facility at Fermilab
- Q.E., gain & timing calibration scans:
  - Movable & motorized LED/laser setup
  - Automated scans over the whole surface
- The LAPPDs meet their requirements: QE ~20%, uniformity, gains > 1E6, time resolution < 100ps

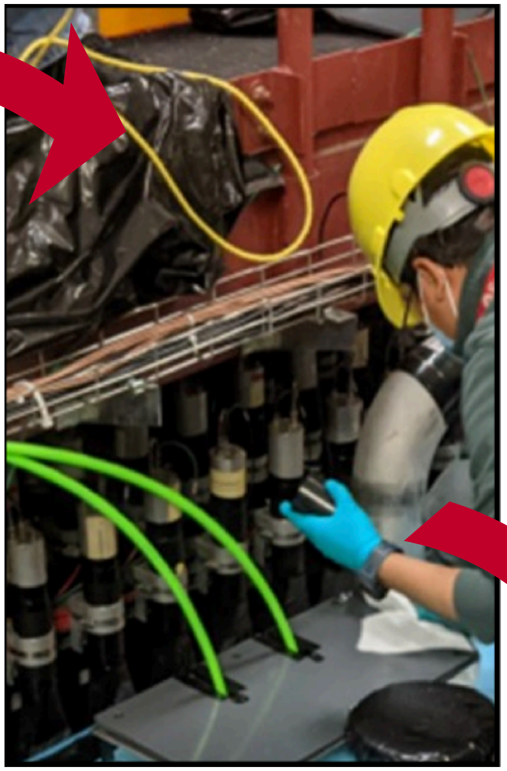
ANNIE data



ANNIE data



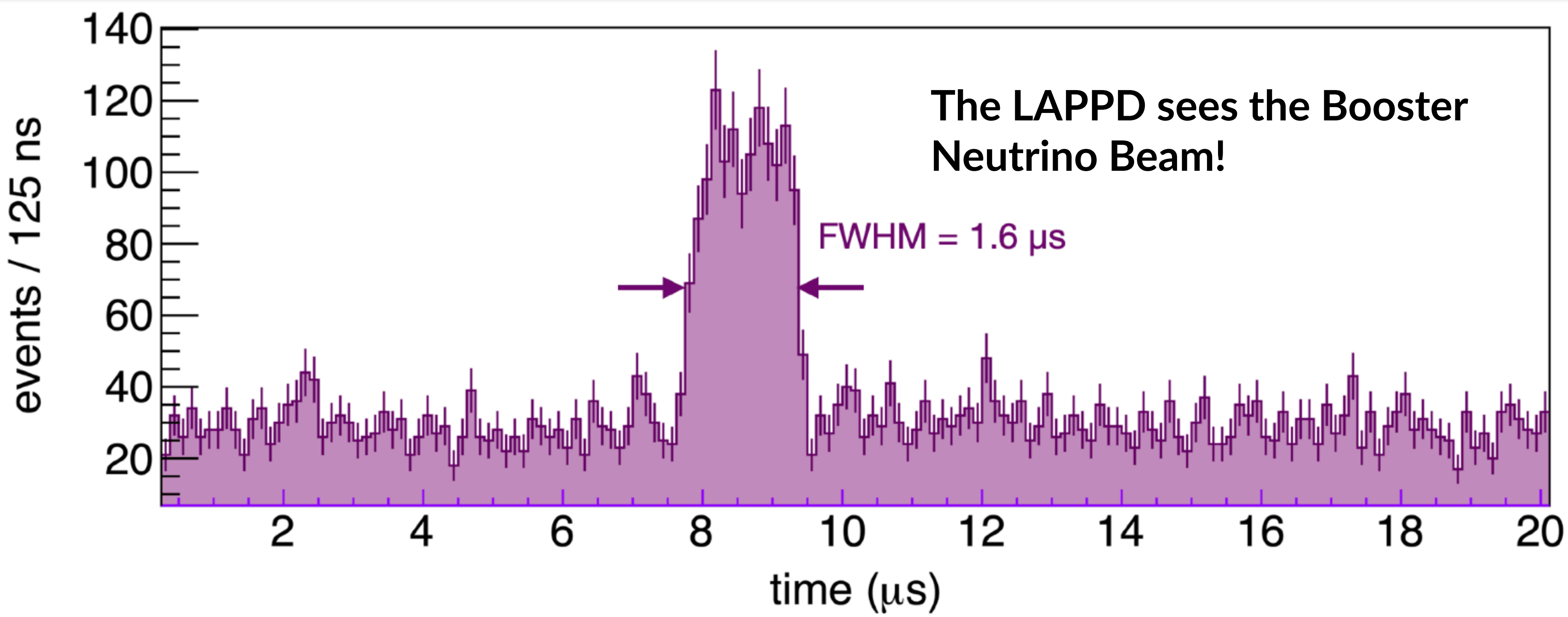
30 March 2022: The first LAPPD was deployed in ANNIE

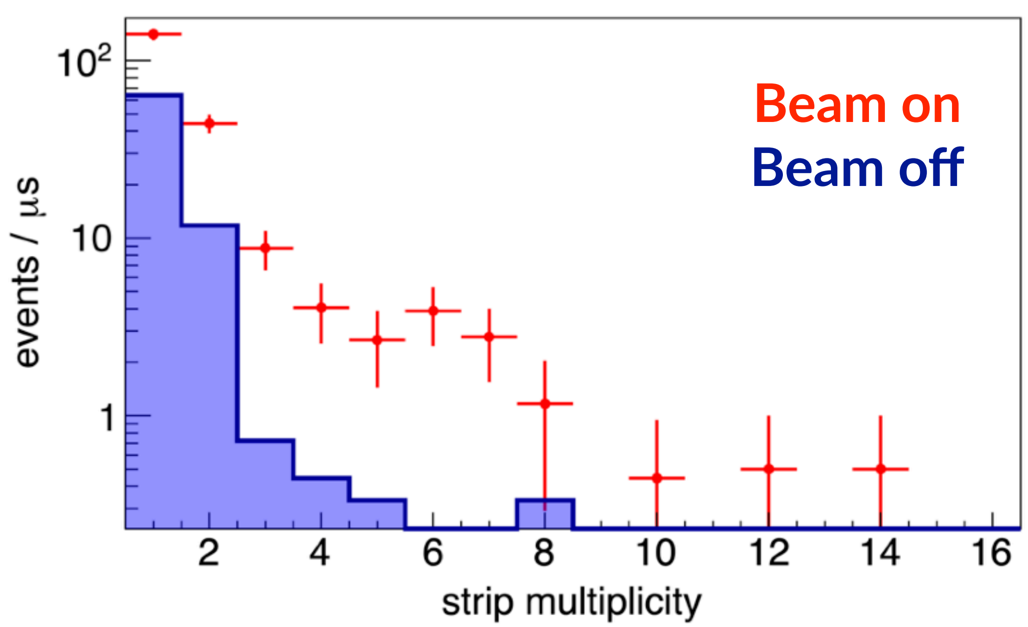


LAPPD is in the water

Everything light-tight

First LAPPD light in ANNIE



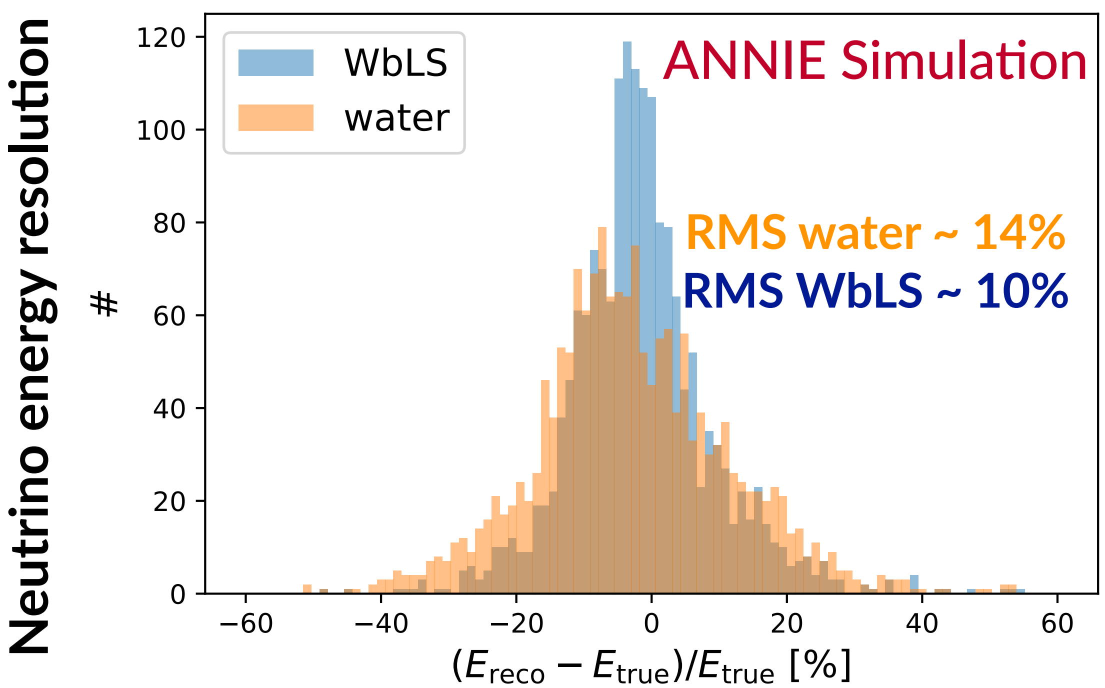


Hit multiplicity on LAPPD is higher when beam is on

First detection of neutrinos with a LAPPD!

Water-based Liquid Scintillators (WbLS) in ANNIE

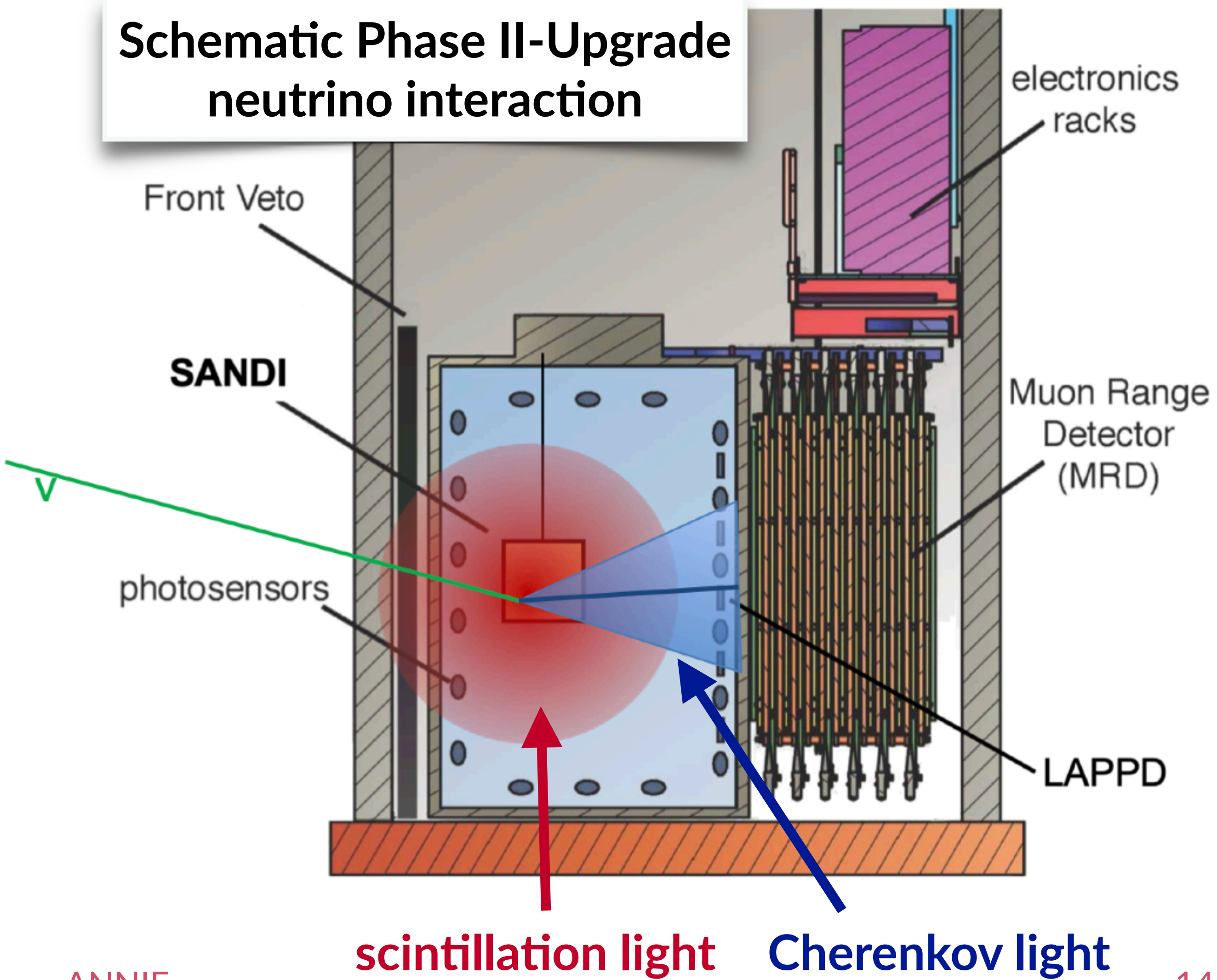
- **Water-based Liquid Scintillators:** novel detection medium, combines advantages of both scintillation and Cherenkov light
- Phase II-Upgrade in ANNIE: Deploy acrylic SANDI vessel filled with WbLS in ANNIE (3’ x 3’, 365kg of WbLS)
- SANDI test run planned for this year
- Neutrino energy reconstruction expected to improve by ~4% based on preliminary studies
- Neutron detection expected to improve (3x light output, efficiency ~ 90%, better spatial reconstruction)



WbLS test at UC Davis

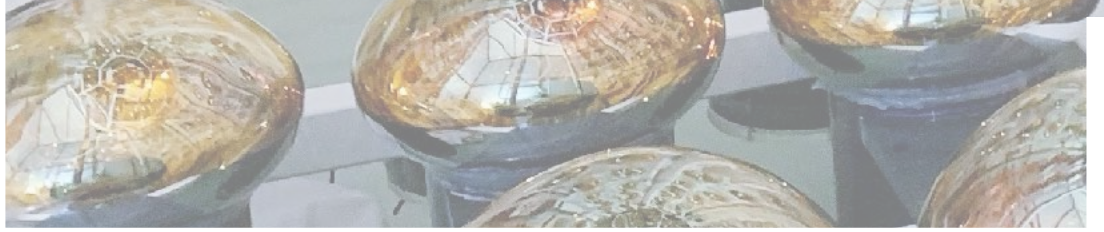
SANDI vessel

Schematic Phase II-Upgrade neutrino interaction



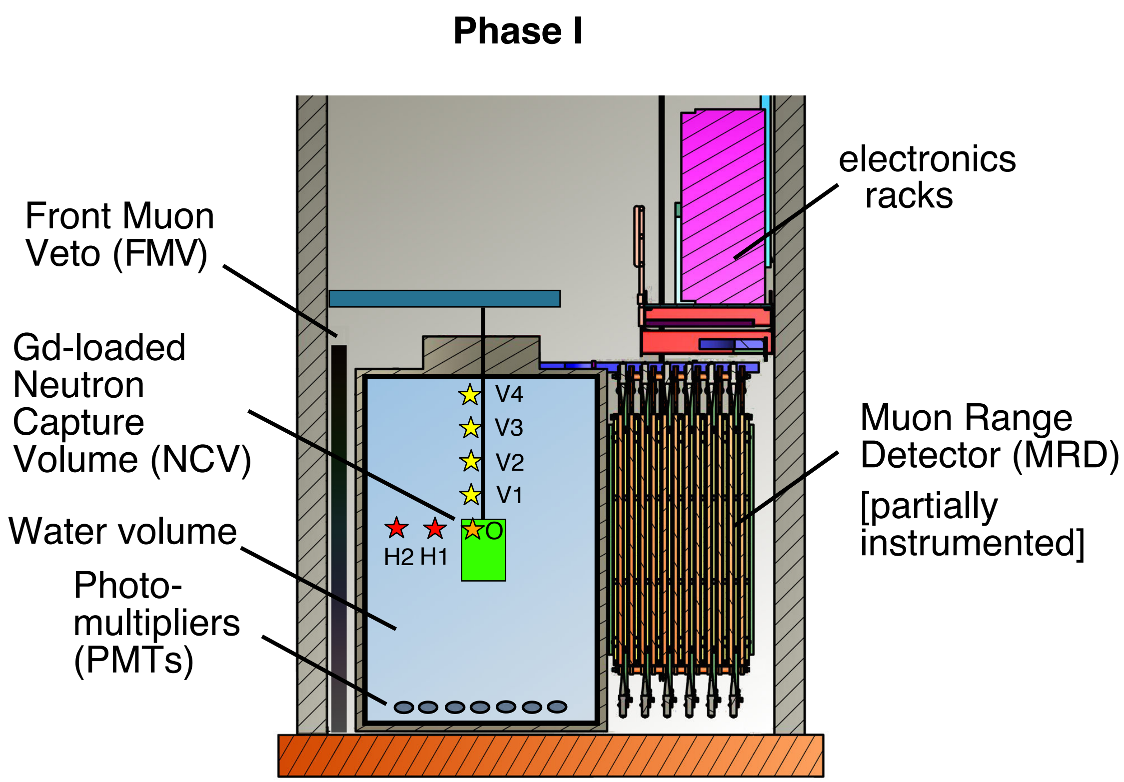
Summary & Outlook

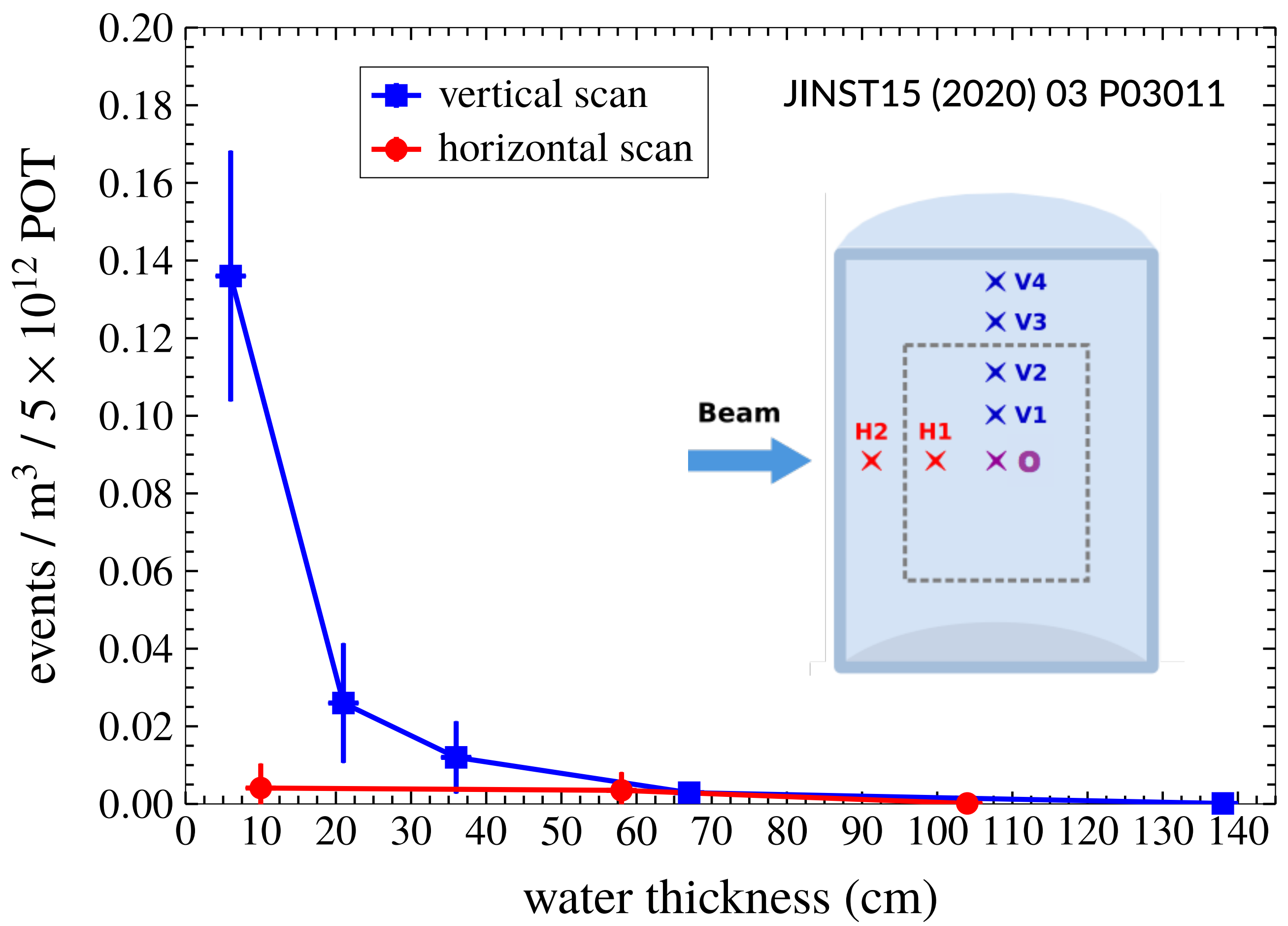
- **ANNIE** is a **Gd-loaded water Cherenkov detector (26 tons mass)** located in the Booster Neutrino Beam at Fermilab
- **Physics measurement goals:**
  - Neutron multiplicity as a function of primary lepton momentum
  - CCQE neutrino cross-section in water
- **Milestones:**
  - Full Gadolinium loading of ANNIE achieved end of 2019, excellent water transparency over a time frame of more than 2 years
  - Calibration of PMT gains and PMT timing complete
  - Successful detection of neutrons in calibration and beam runs
  - Significant efforts leading to the deployment of the first LAPPD in ANNIE
  - First detection of neutrinos with a LAPPD
- **Currently ongoing / outlook:**
  - Characterization & preparations for the deployment of the remaining four LAPPDs
  - Preparations for WbLS-filled SANDI deployment this year

Backup

Backup: ANNIE Phase I



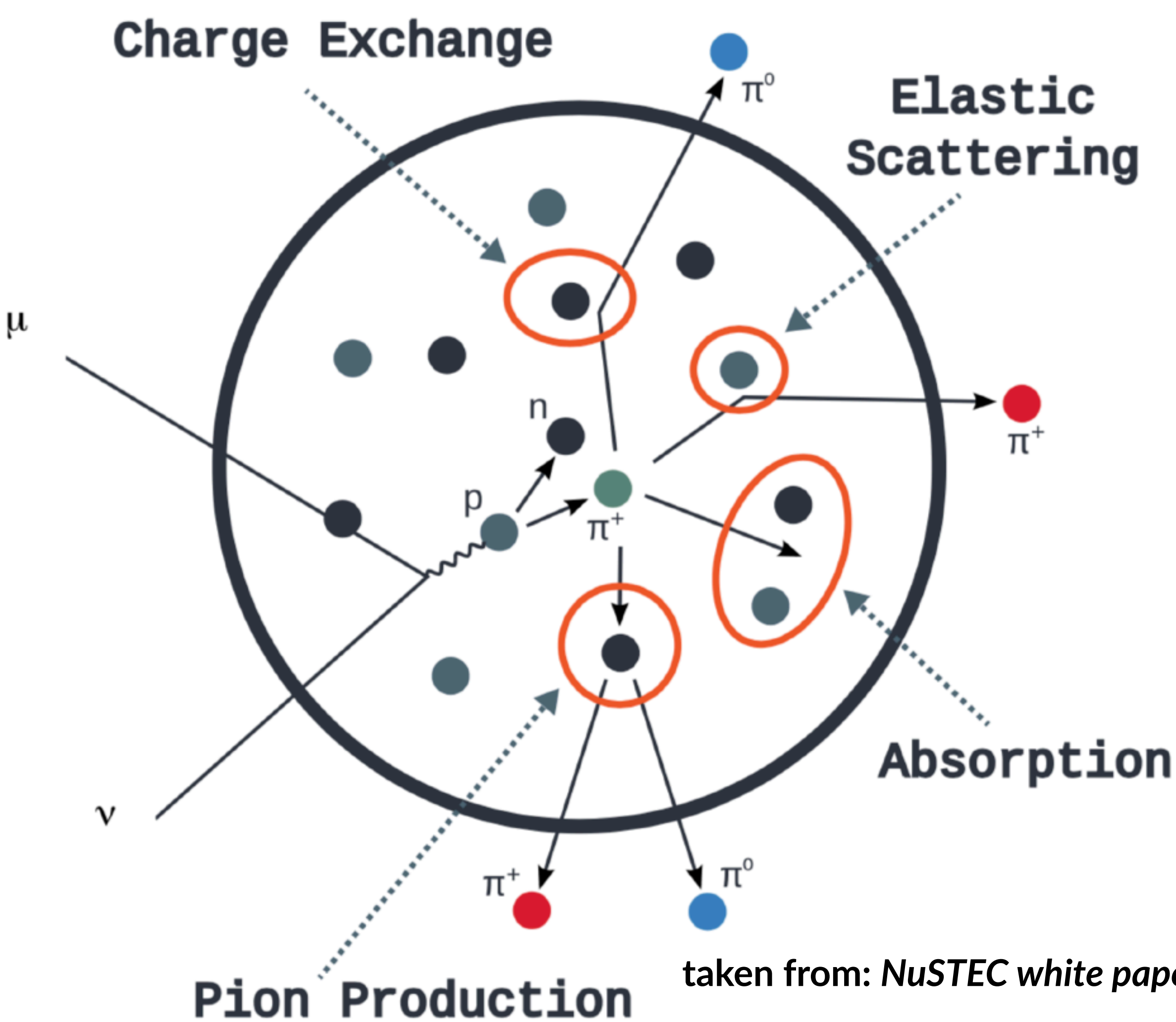


- partially instrumented water tank (only bottom PMTs)
- scintillator-filled Neutron Capture Vessel at different positions within the water tank
- measure beam-correlated neutron background rate across the detector

- Fiducial Volume: Background rate < 0.02 /m^3 / spill
- Background sources:
  - "skyshine neutrons" (scattered off molecules in the atmosphere)
  - "dirt neutrons" (neutrino interactions in rock upstream of ANNIE)

Backup: Modeling atmospheric interactions

Final state interactions

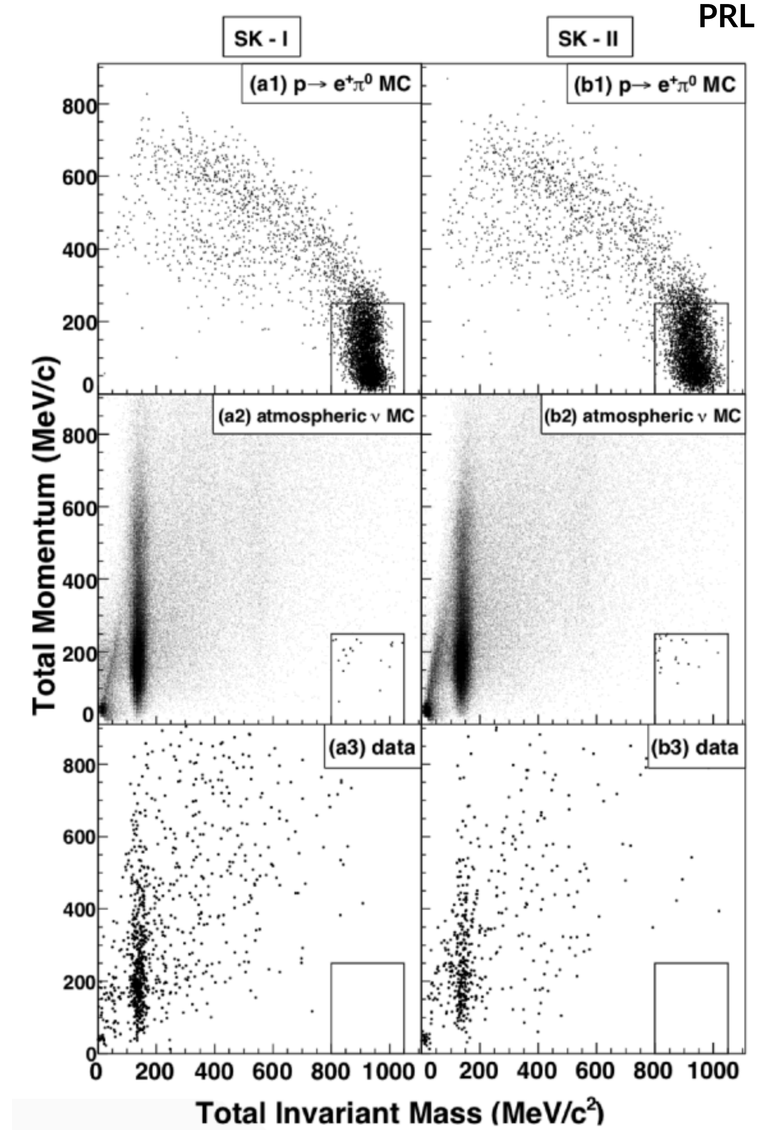


taken from: *NuSTEC white paper*

Neutrons as possible signs of **inelasticity** → multiplicity measurement by ANNIE to minimize biases in neutrino energy reconstruction

Atmospheric neutrino interactions

PRL 102 (2009) 141801



proton decay

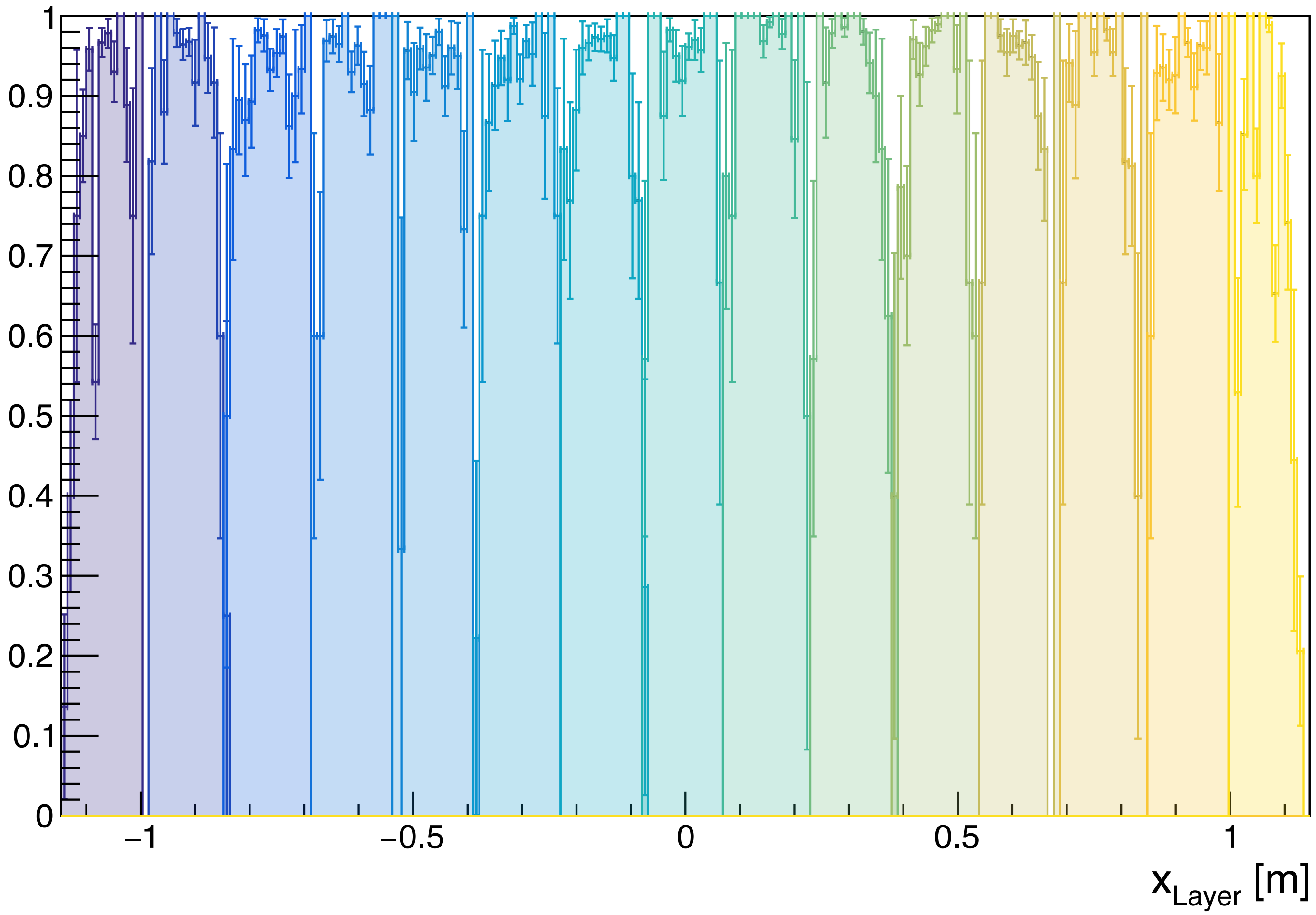
atmospheric

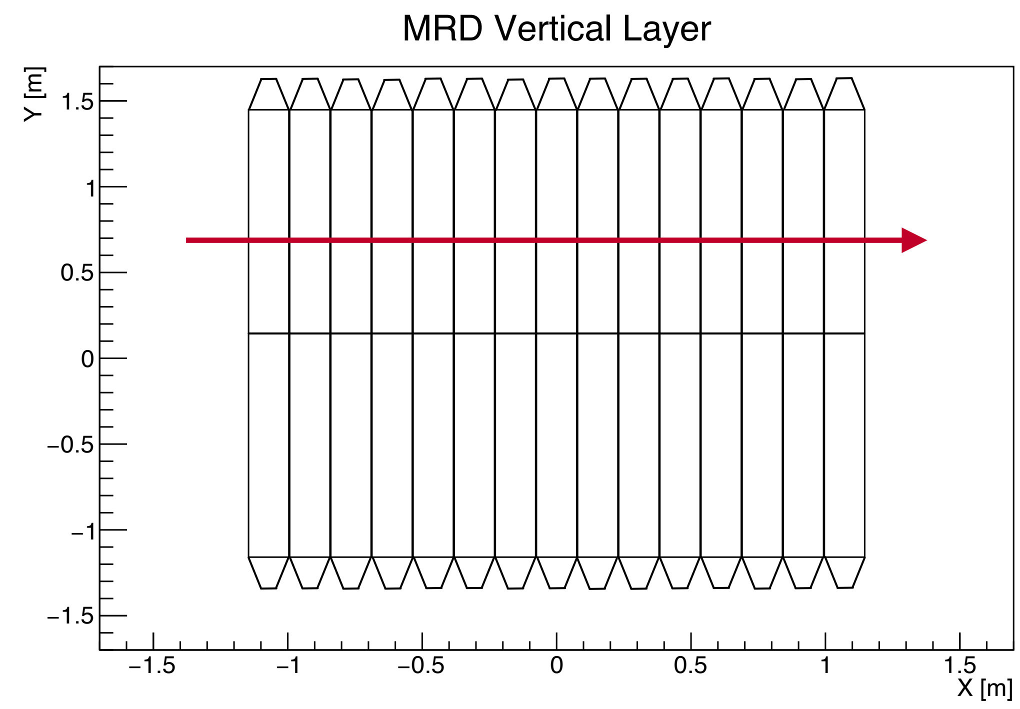
data

Better models for atmospheric neutron yield improves S-B ratio for proton decay and DSNB searches

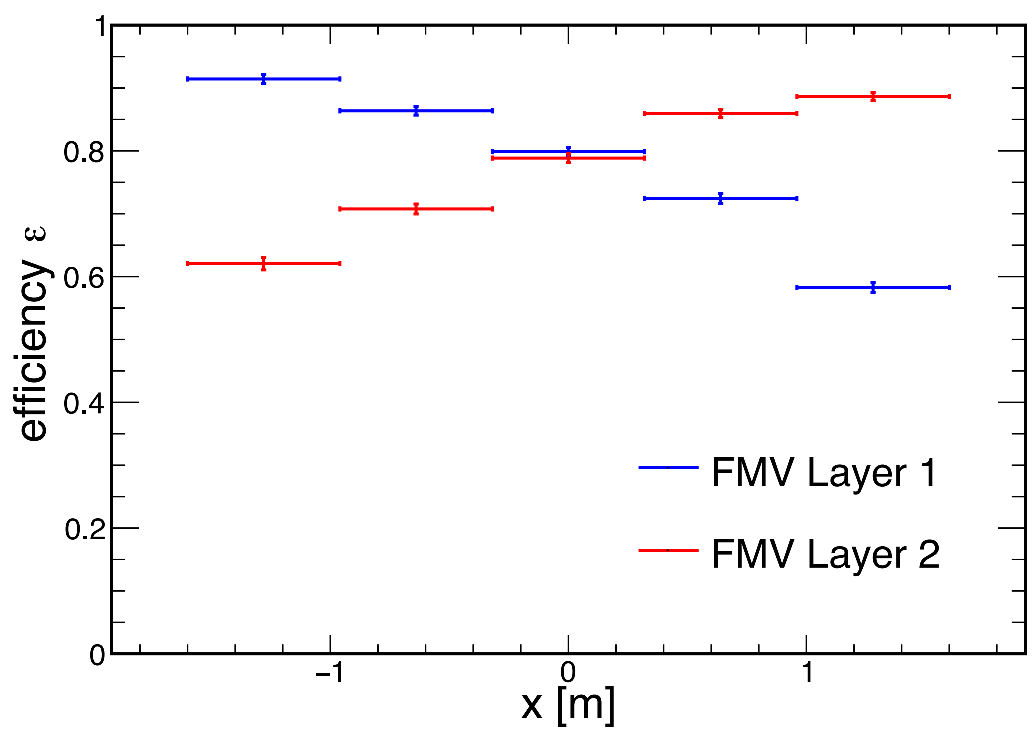
Backup: MRD + FMV efficiencies

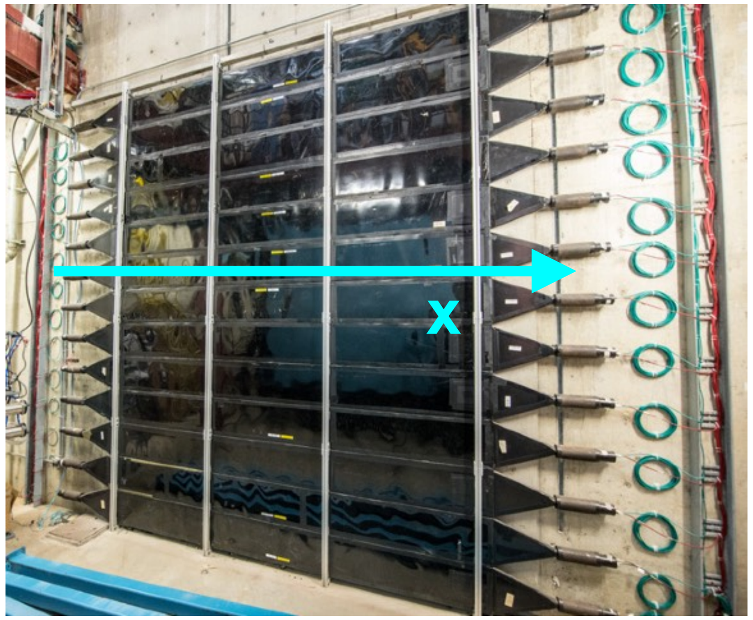
MRD





FMV

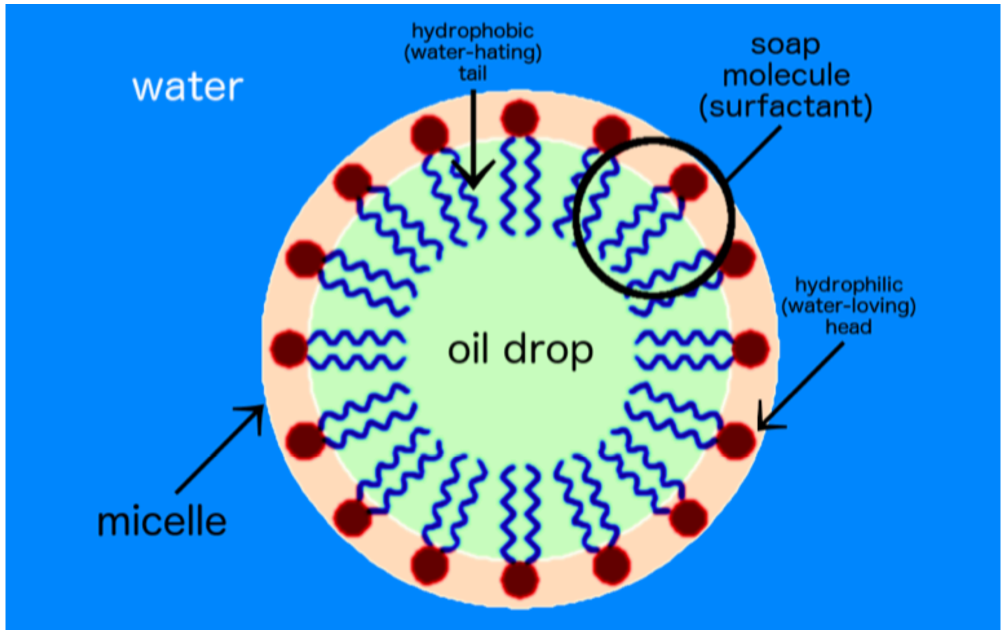




Backup: Water-based Liquid Scintillators (WbLS)

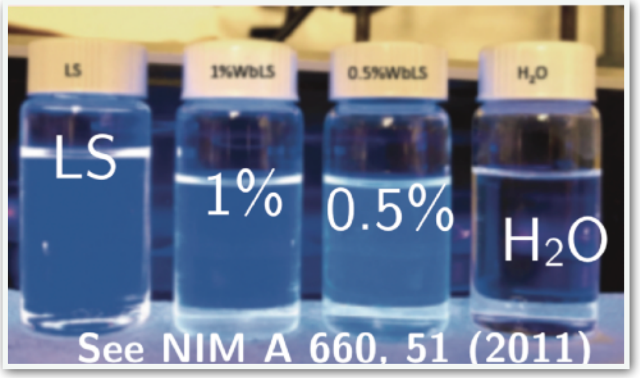
Separate Cherenkov & scintillation light → ultrafast photosensors

Chemistry behind WbLS

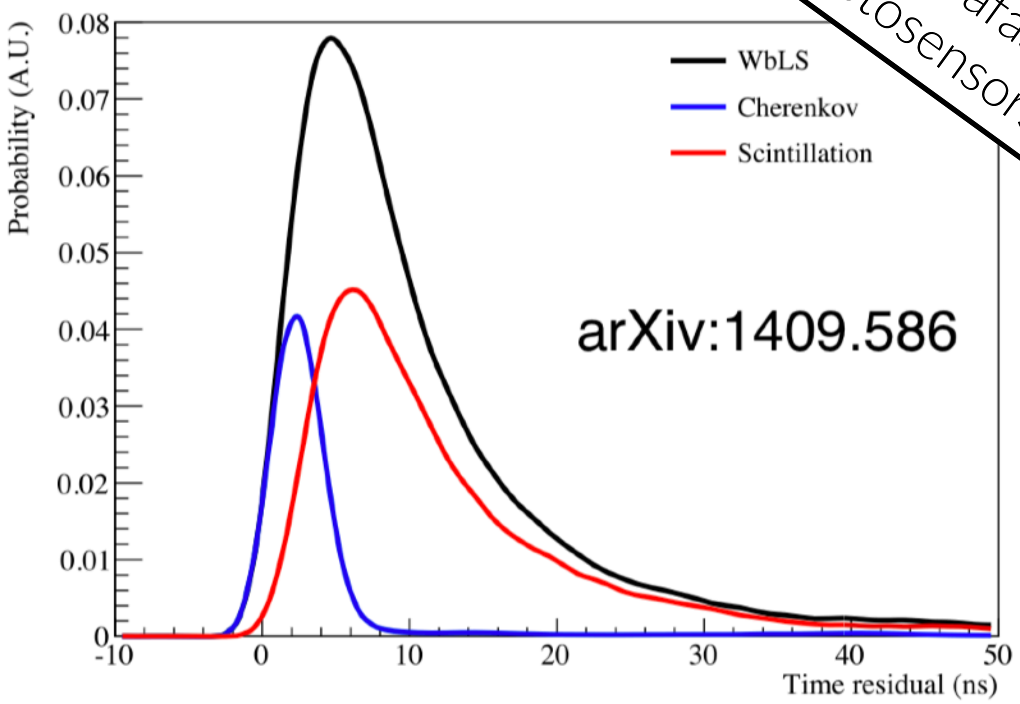


Water & Liquid Scintillator generally don't mix
→ need surfactant to bind liquid scintillator oil in water
→ possible surfactants: LAS, Triton X100

- 1% LS loading corresponds to ~ 100 photons / MeV



Features:



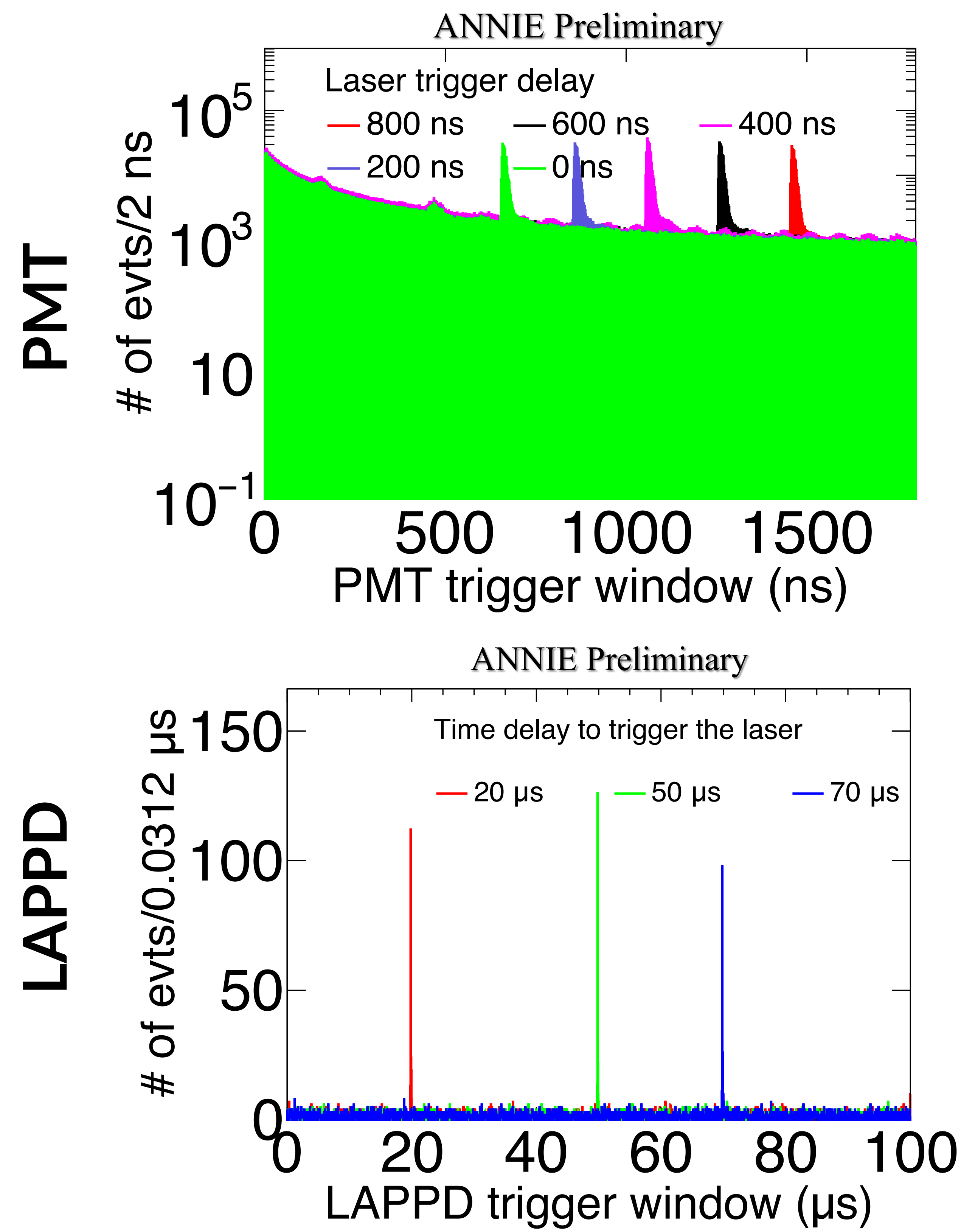
Water-based Liquid Scintillator time profile

- Directionality & kinematic reconstruction (Cherenkov)
- High light yield & calorimetric reconstruction (scintillation)
- Charged particle detection below Cherenkov threshold (protons)
- High transparency + low cost of water
- Tunable liquid scintillator concentration, isotope loading

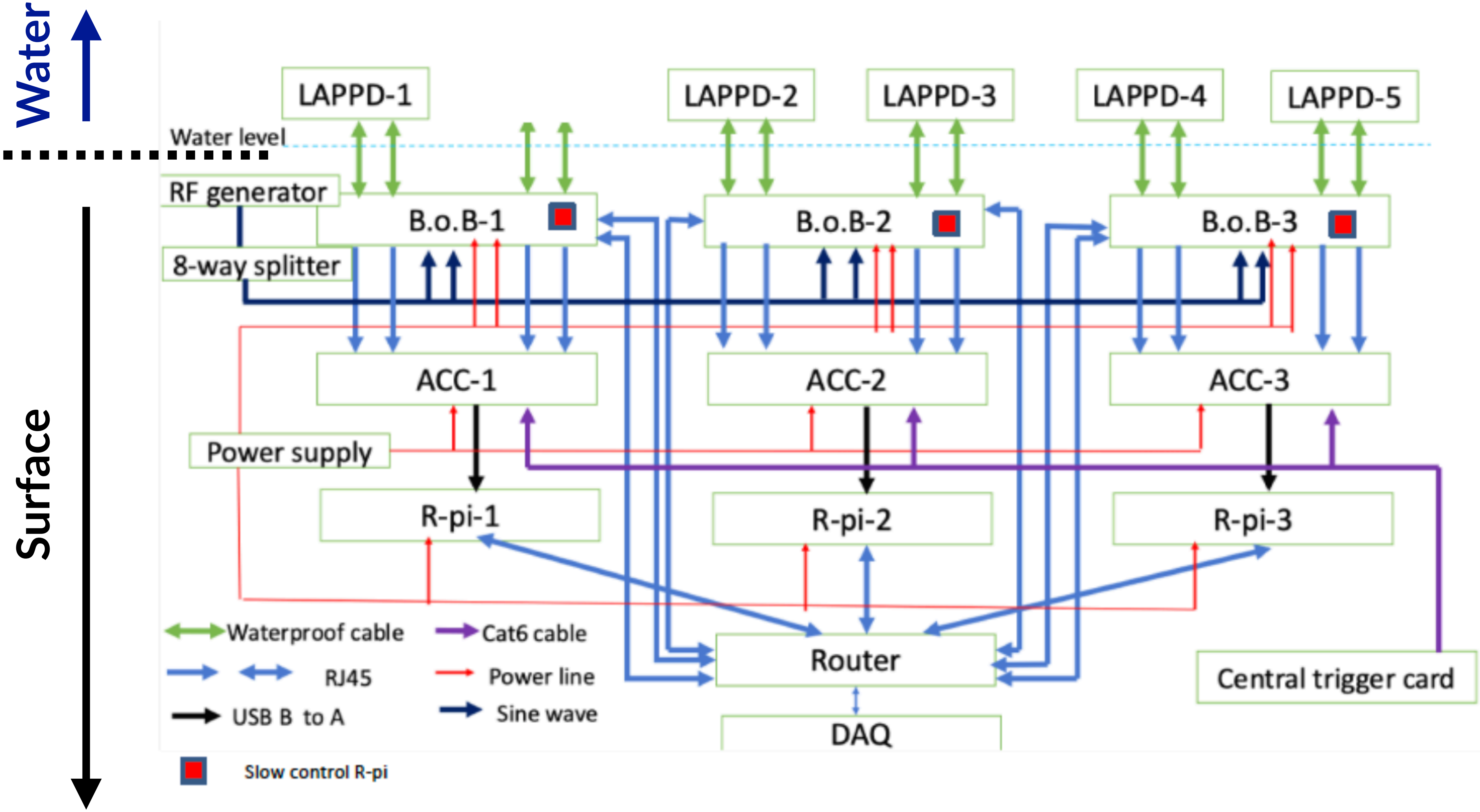
Backup: LAPPD waterproof housing

Backup: LAPPD laser calibration

- Pulse timing plot for laser runs with different delays
- Time distributions show the timing of pulses with respect to the start of the laser-induced trigger window
- Clear peaks above background are visible both for the PMTs and the LAPPD
- Precise timing delay calibration ongoing

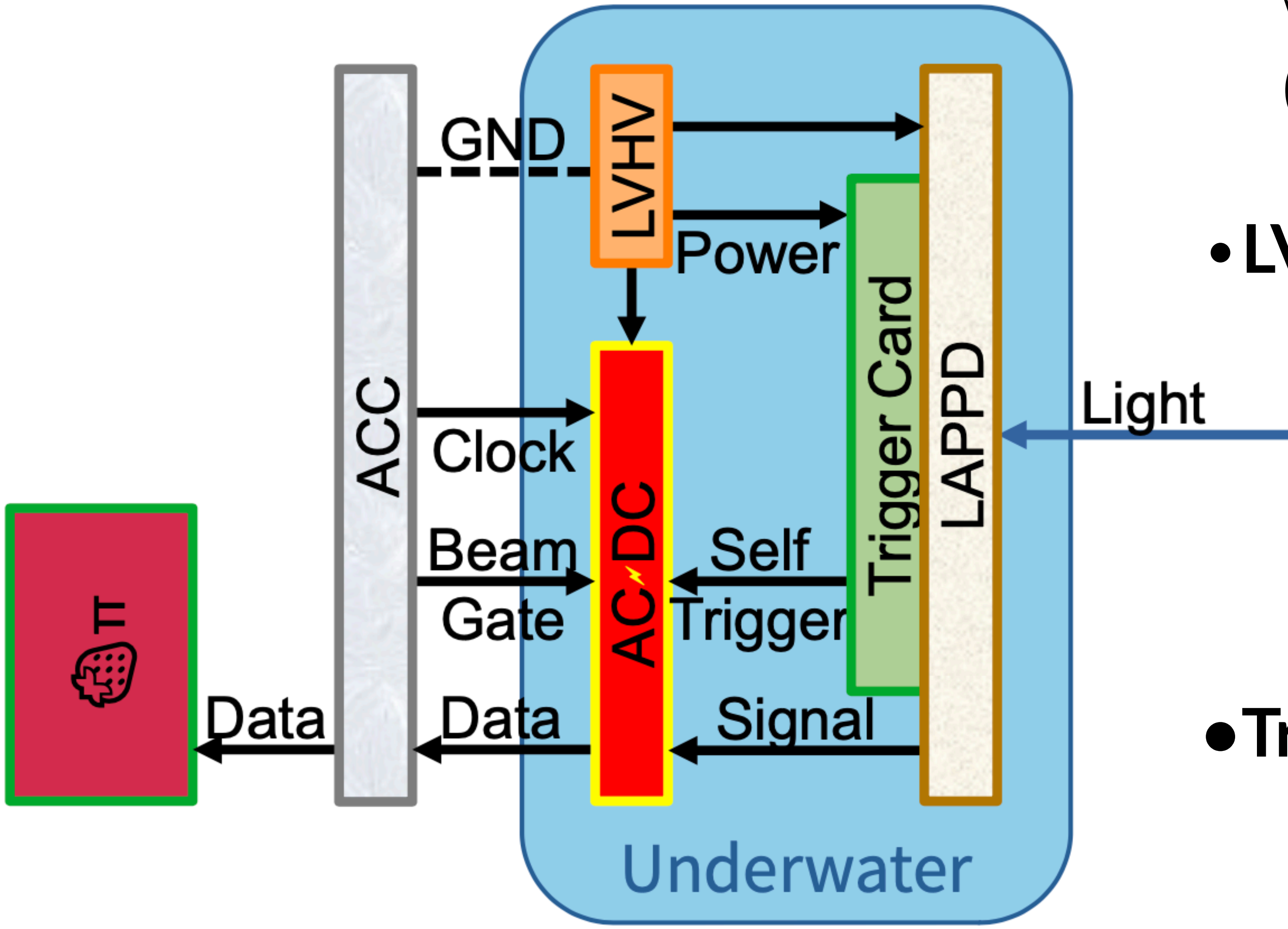


Backup: LAPPD surface electronics



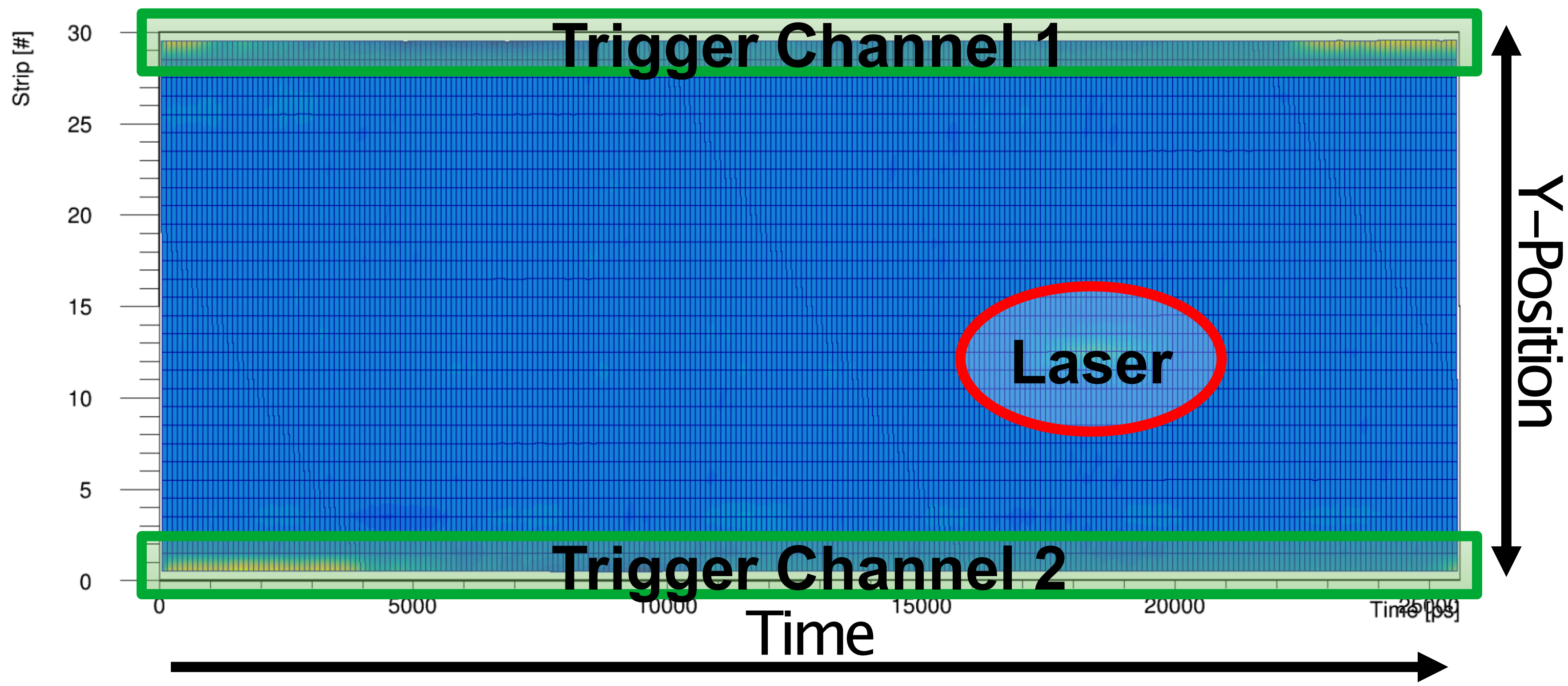
Backup: LAPPD electronics

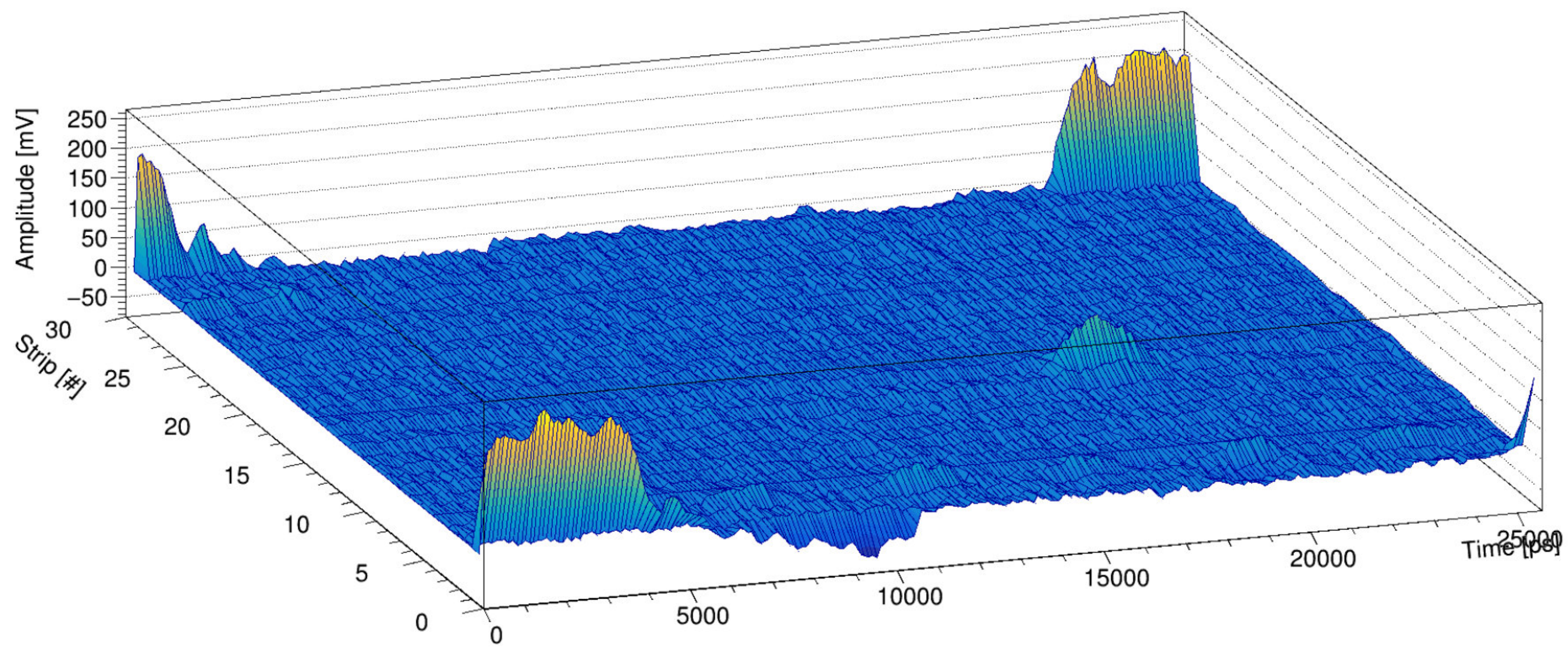
LAPPD electronics package



- **ACDC**:
  - signal digitization
  - 5 PSEC sampling ASICs with multi-channel readout (10 GHz)
- **LVHV**:
  - power, slow control
  - AC-coupled communications pass-through
- **Trigger Card:**
  - passive signal bridge from striplines to ACDC
  - replacement for on-bard ACDC trigger

Backup: LAPPD laser calibration exemplary event





Modeling the neutron multiplicities to extract the true detection efficiency

Position dependent multiplicity

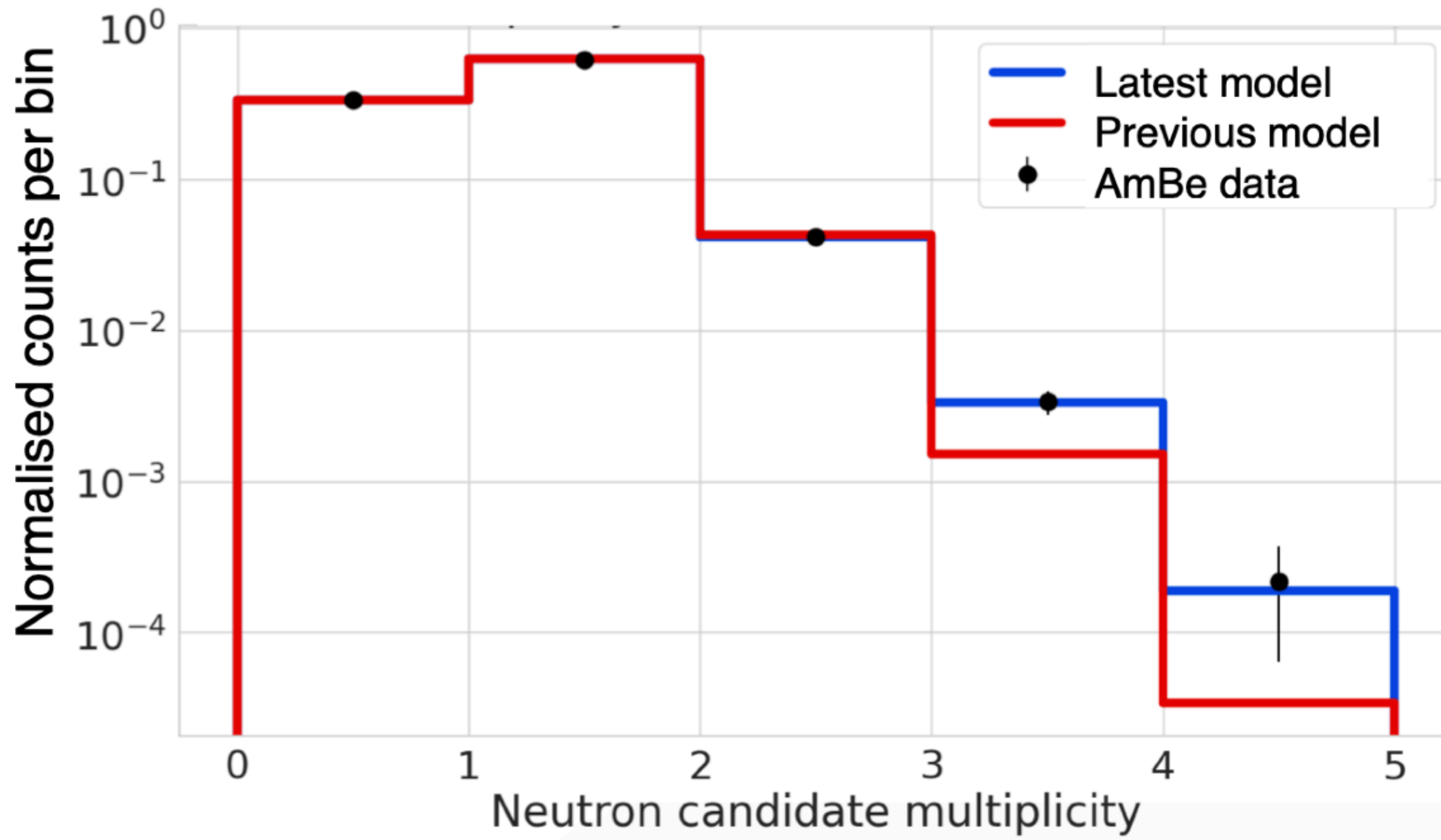
Uncorrelated background

Uncorrelated neutron-gamma pairs from AmBe source

$$M(x) = B(n; \epsilon_n) + \frac{\lambda_b^x e^{-\lambda_b}}{x!} + \frac{\lambda_{un}^x e^{-\lambda_{un}}}{x!} + \left(\frac{\lambda_\gamma^x e^{-\lambda_\gamma}}{x!} + M_{\gamma n}(n_\gamma)\right)$$

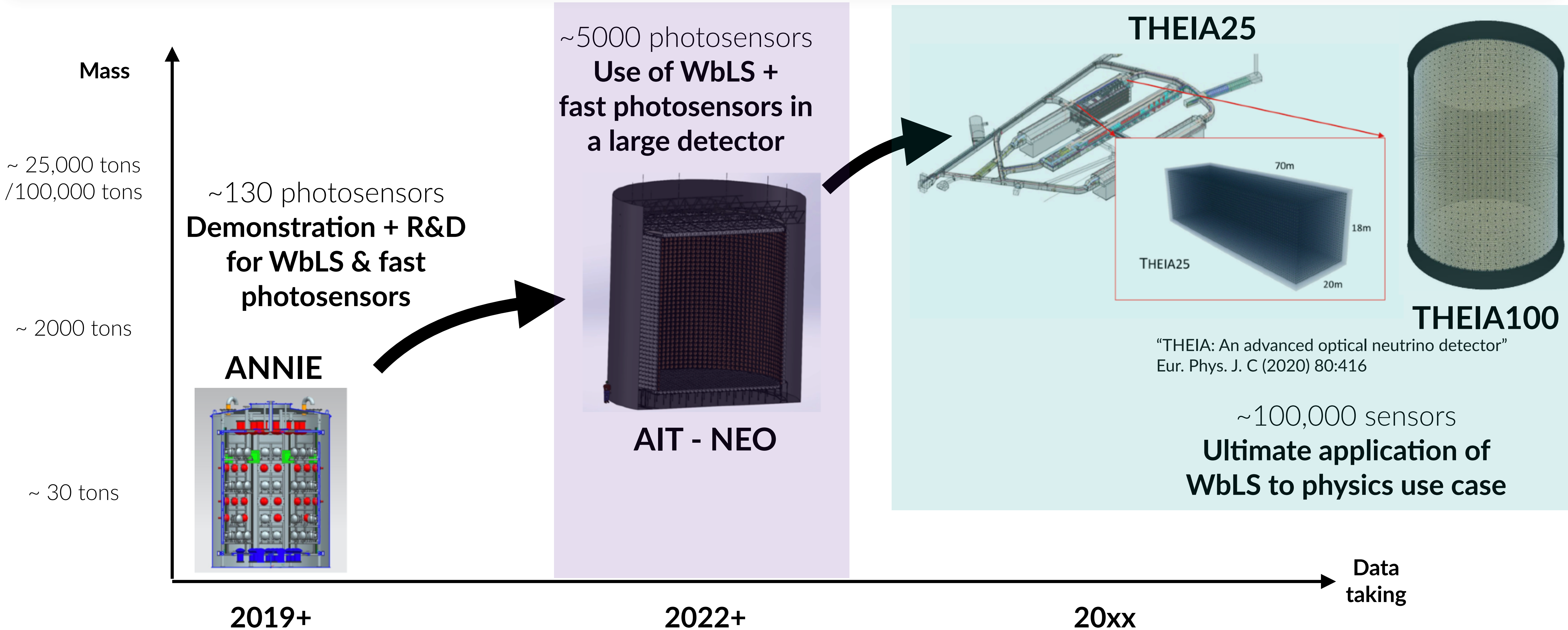
Bernoulli distribution for a given neutron detection efficiency

Uncorrelated neutrons from AmBe source



- By floating the background rates and efficiency the best fit to the multiplicity distribution can be found.
- A X^2 best fit is used to determine the free parameters.
- The corresponding efficiency is calculated on a position-by-position basis.

Backup: ANNIE as testbed for next-gen experiments



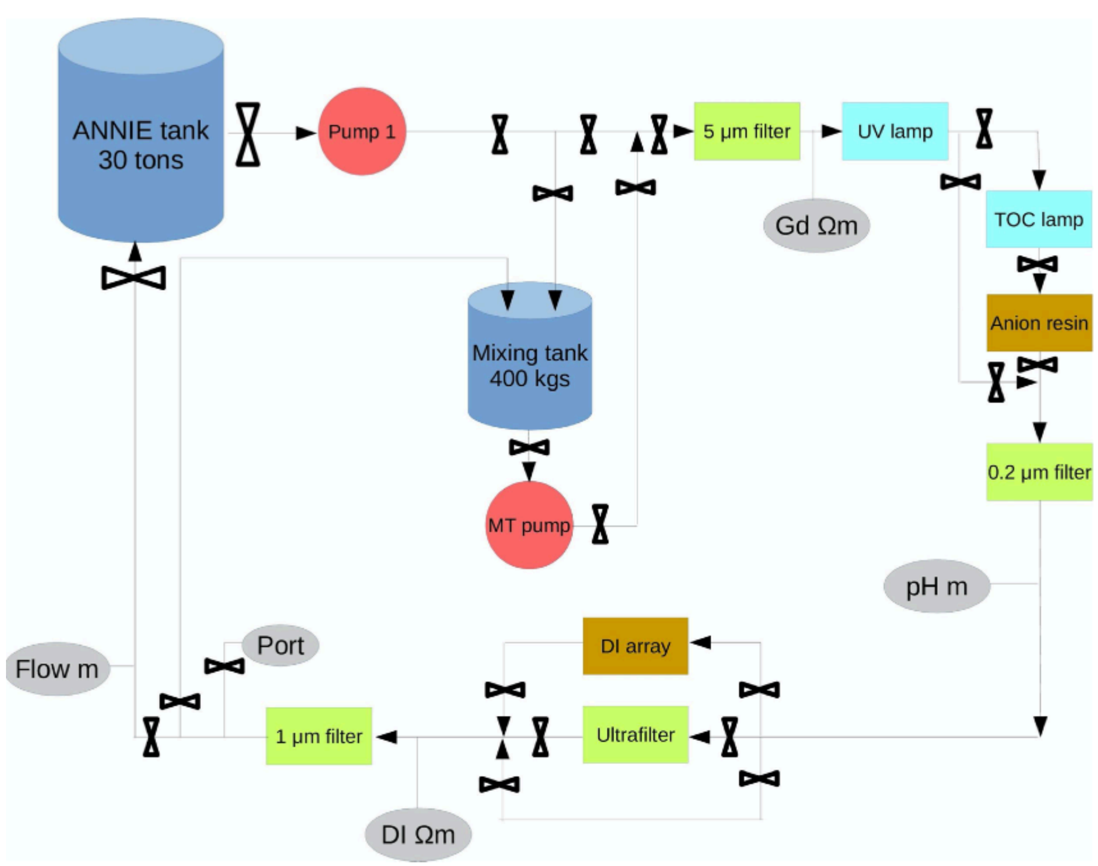
- **NEO - Advanced Instrumentation Testbed (AIT):**
  - Remote reactor monitoring through Inverse Beta Decay, 2kt Cherenkov detector
  - Both Gd-loaded water / WbLS considered as medium

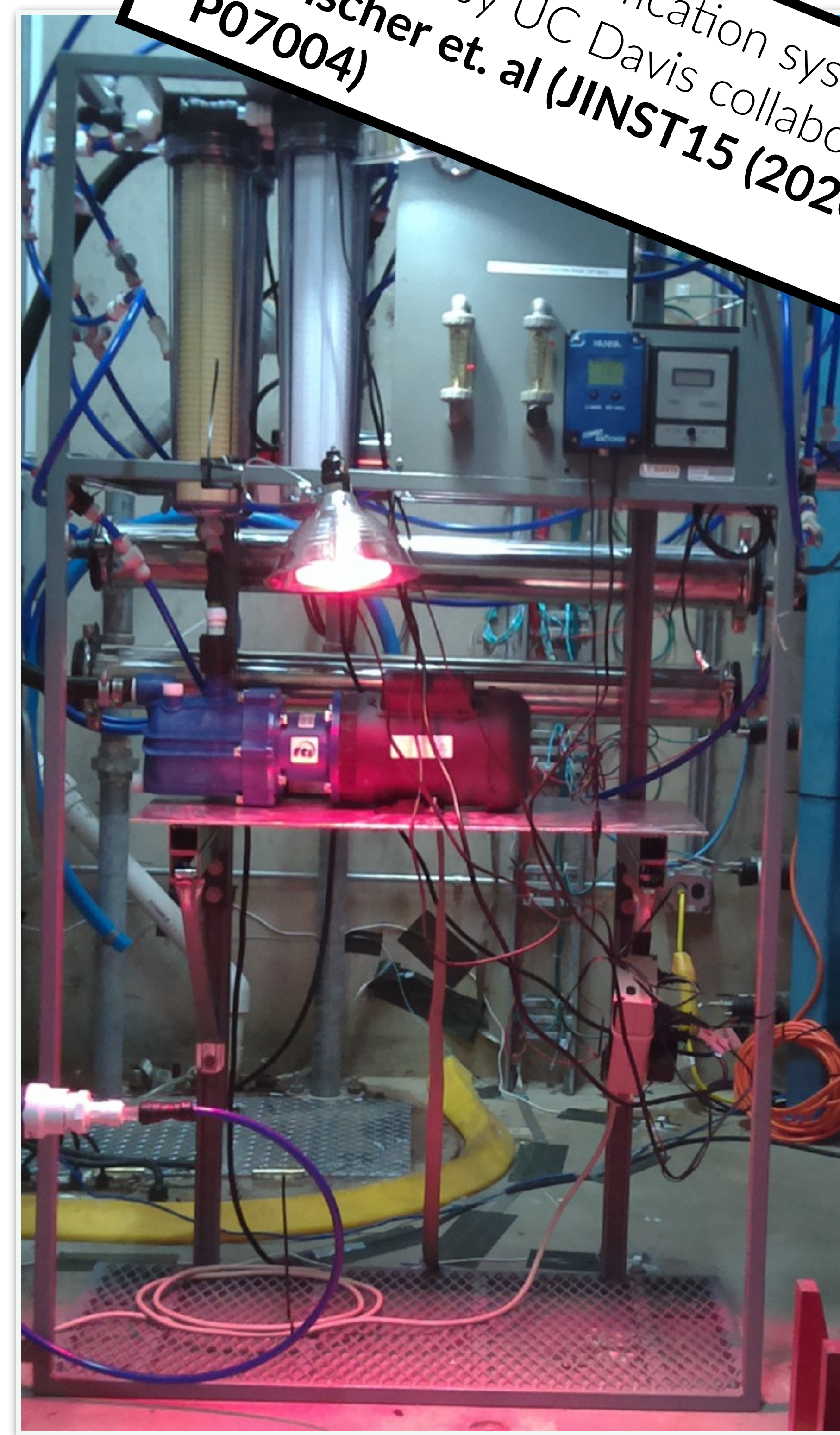
- **THEIA (25/100):**
  - 25kt Cherenkov detector (WbLS) option in one of the DUNE caverns (module of opportunity)
  - Broad physics program: Long baseline neutrinos, $0\nu\beta\beta$, CNO neutrinos, SN neutrinos, geoneutrinos

Backup - Water filtration

- Custom water purification system developed by UC Davis collaborators: **"V. Fischer et. al (JINST15 (2020) 07 P07004)**

- Combination of different subsystems to obtain filtered Gd-loaded and ultrapure water
  - **Pumps:** Transport water
  - **UV lamps**: Microbes, biological contamination
  - **TOC lamp:** Plastic (carbon) compounds
  - **Microfilters:** Bacteria, sediments, microbes (5 µm & 0.2 µm version)
  - **Ultrafilters**: Iron removal (30nm pore size)
  - **Anion resin**: Nitrates and TOC lamp products





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