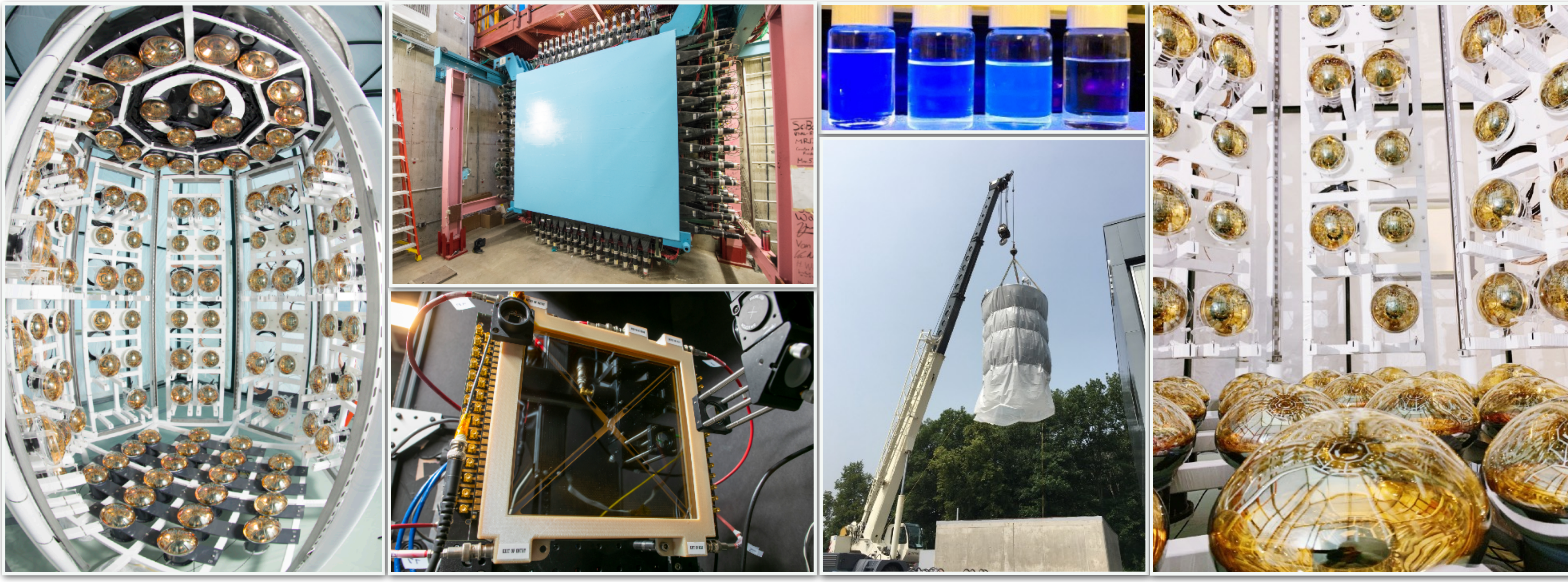


The future of ANNIE in 10 minutes

New Perspectives
07/20/2020-07/21/2020

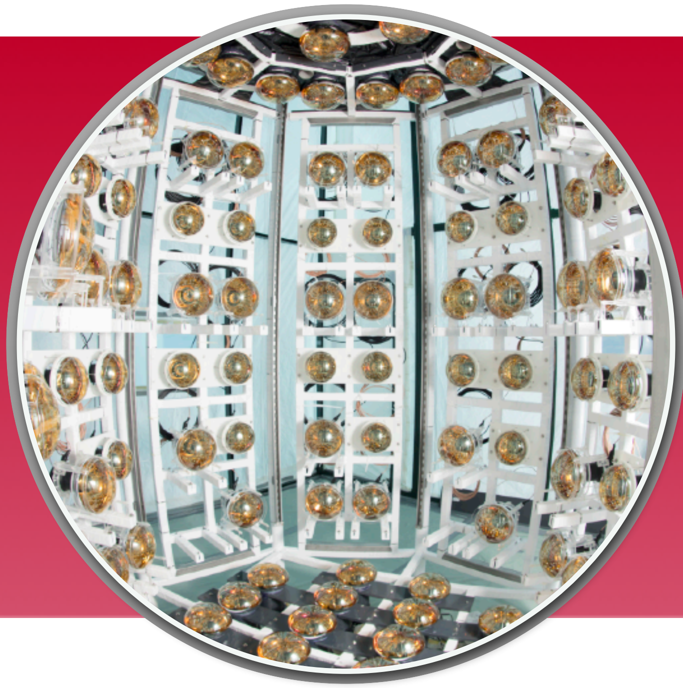
Michael Nieslony
on behalf of the ANNIE collaboration

annie

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JG|U

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



Detector

Collaboration (Mar 2020)

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)

Physics motivation

- **Neutrino cross-section in water:**

  Minimize systematic uncertainty in long-baseline neutrino oscillation studies

- **Neutron multiplicity:**

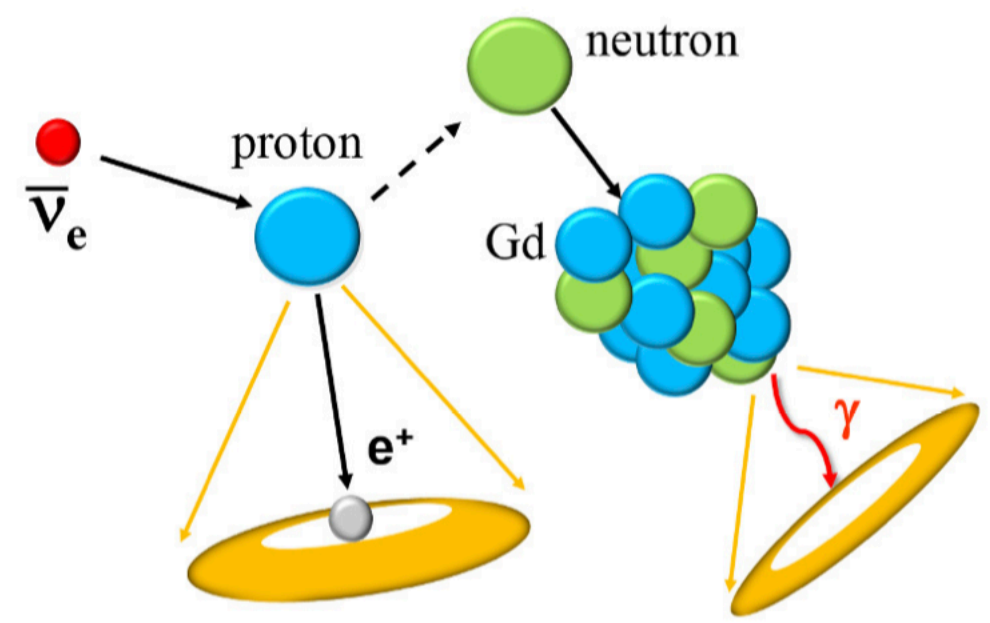
  Help model atmospheric background for DSNB & proton decay searches

Features of ANNIE's measurement:

- Close proximity to beam target
  → high flux of neutrinos
  (~10,000 CC-interactions / ton /year)

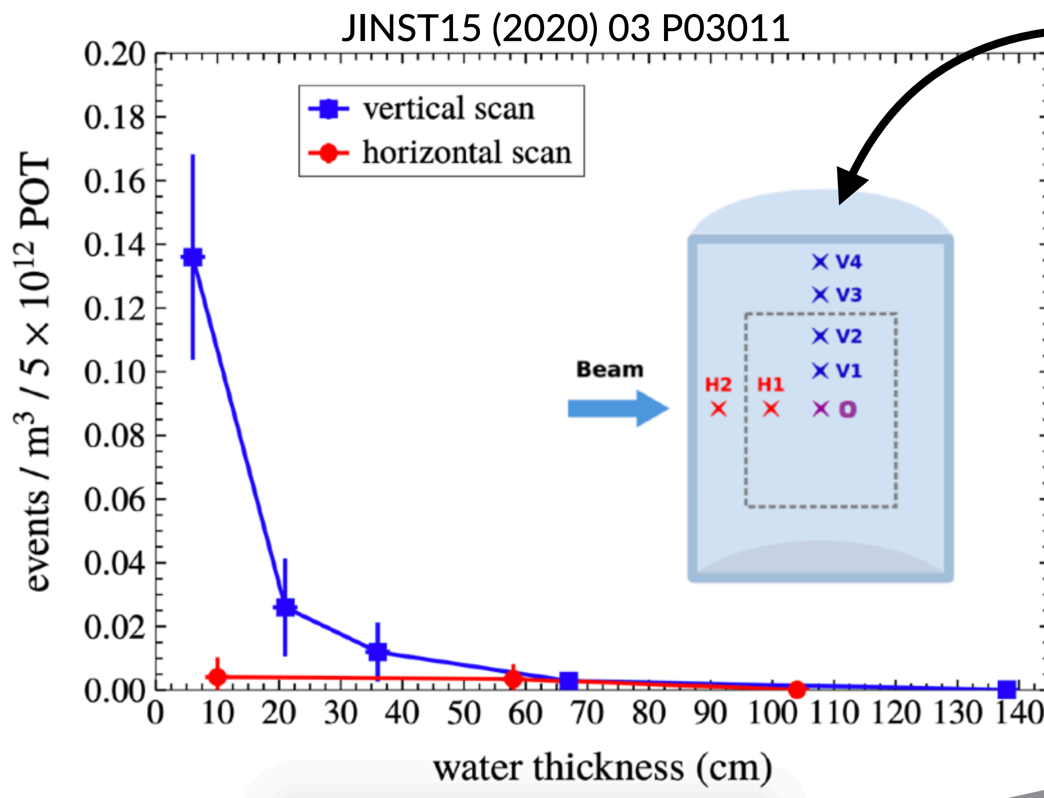
- Nearby SBND Liquid Argon detector
  → opportunity for combined
  argon/water cross-section analysis

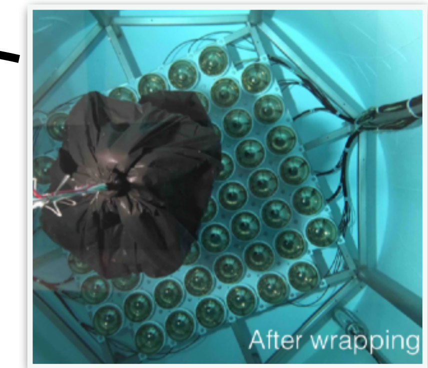
Capturing neutrons:



Neutron capture cross-section: ~50,000 barn
Total emitted gamma energy: ~8 MeV
Loading in water possible as sulfate or chloride

The past, present and future of ANNIE





Neutron Capture Volume (NCV)

Past:

Phase I

2018

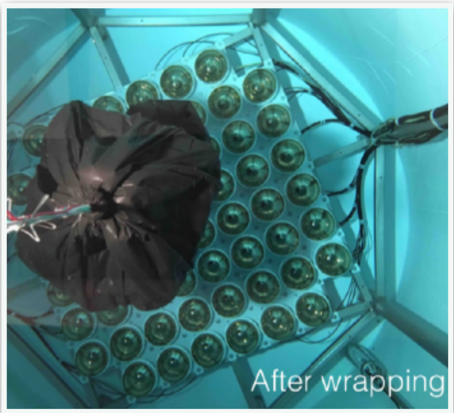
2016

- Feasibility demonstration & background evaluation
- 60 PMTs (veto) & Gd-loaded scintillator Fiducial volume (NCV)

Background neutron rate < 0.02/m³/spill

→ Background no problem for phase II

The past, present and future of ANNIE



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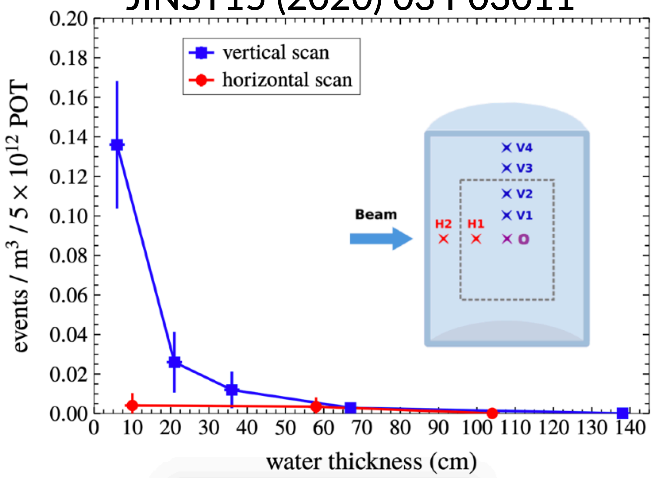
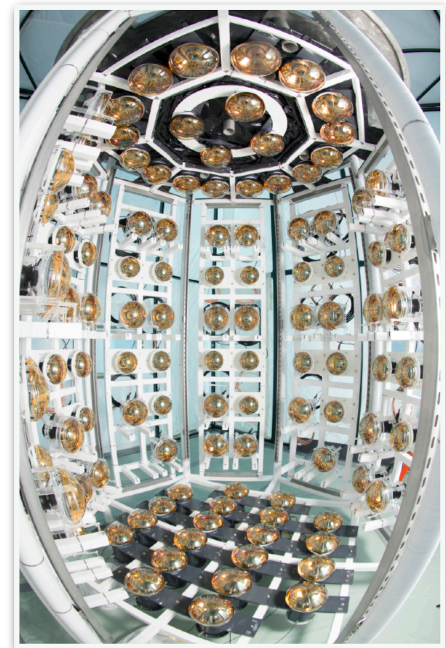




Past: Phase I

2016

2018

- Feasibility demonstration & background evaluation
- 60 PMTs (veto) & Gd-loaded scintillator Fiducial volume (NCV)

Present: Phase II

2020

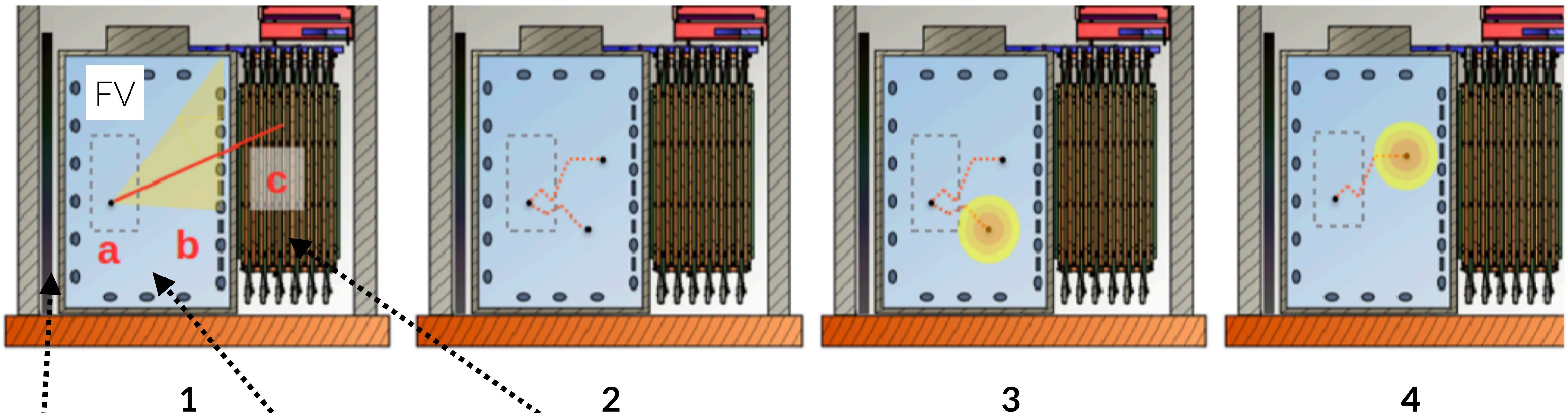
- Physics phase
- Full 26-ton Gd-loaded Water Cherenkov detector
- First commissioning & calibration runs with 132 PMTs done

Up next:

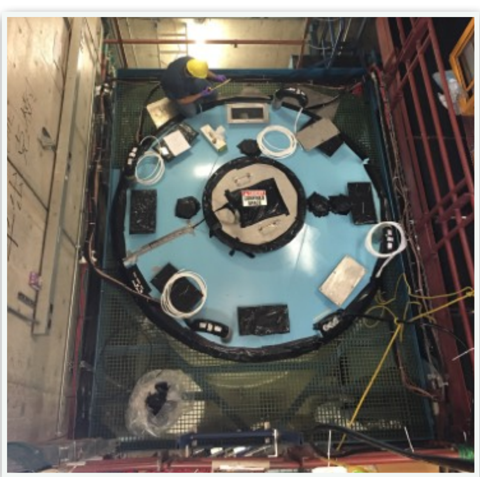
- First deployment of LAPPDs into ANNIE
- Further calibration campaigns:
  - Laser diffuser ball
  - ^{137}Cs standard candle

The present: Phase II - Event schematic

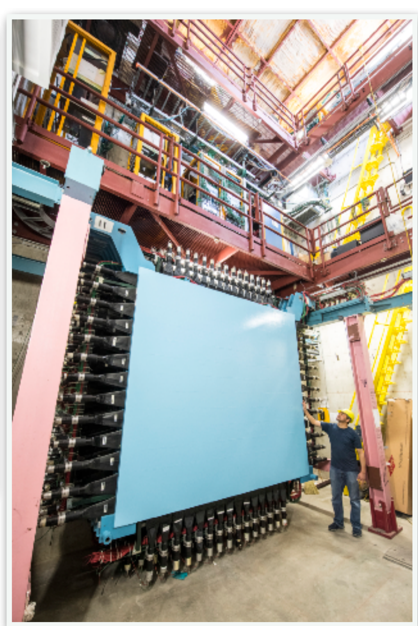
Phase II measurement: ν_μ *CCQE event*



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

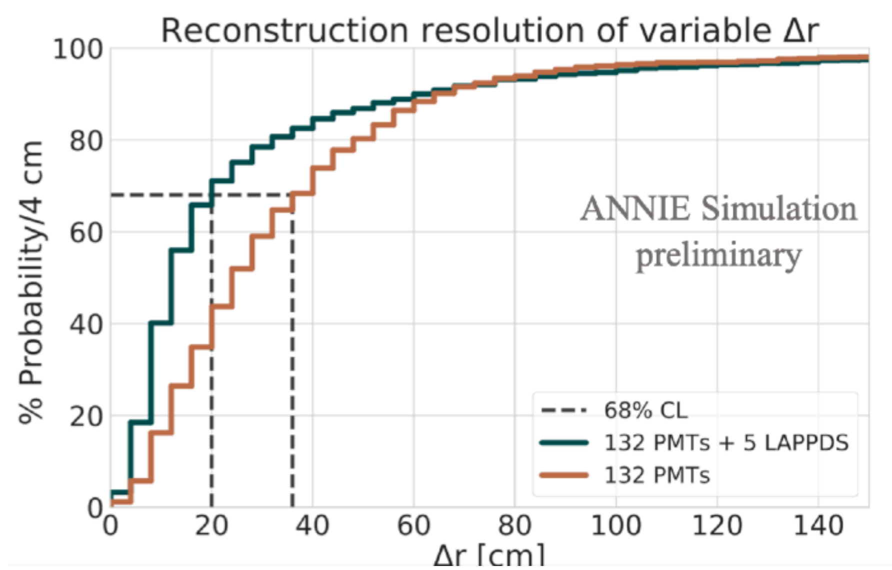
2. Neutron(s) travel, scatter around the detector

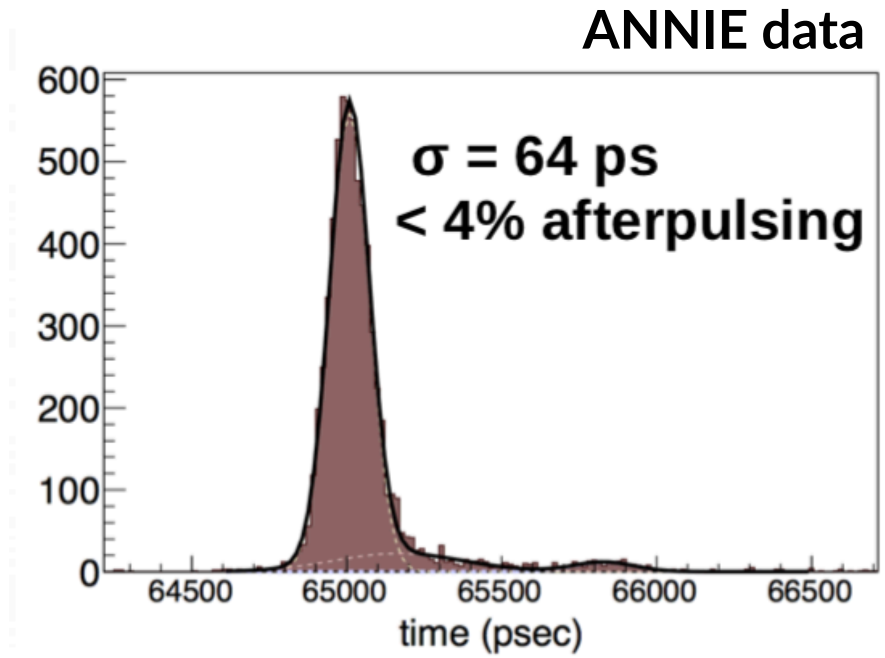
3. Neutron capture 1, detection by PMTs

4. Neutron capture 2, detection by PMTs

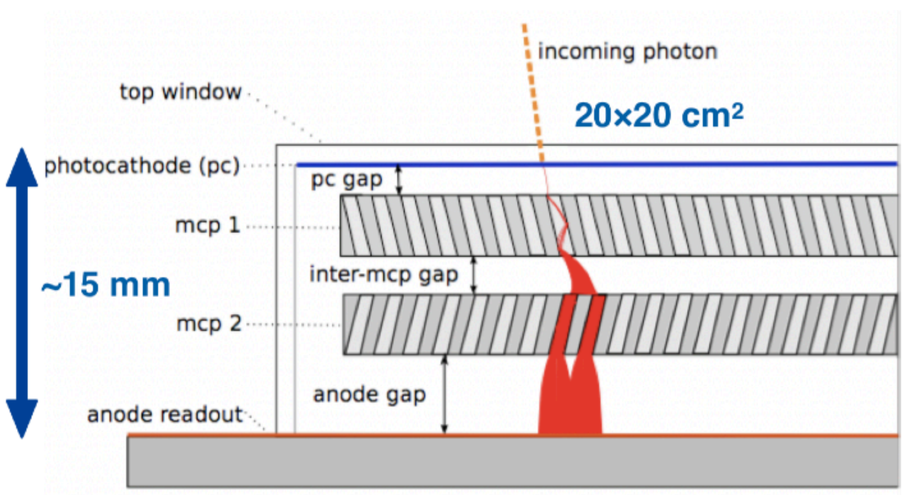
The present: Phase II - LAPPDs

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

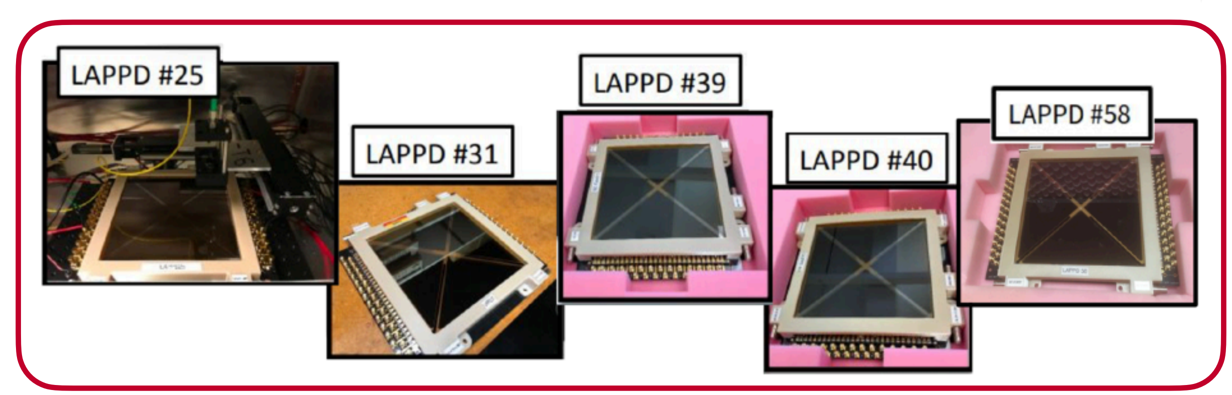




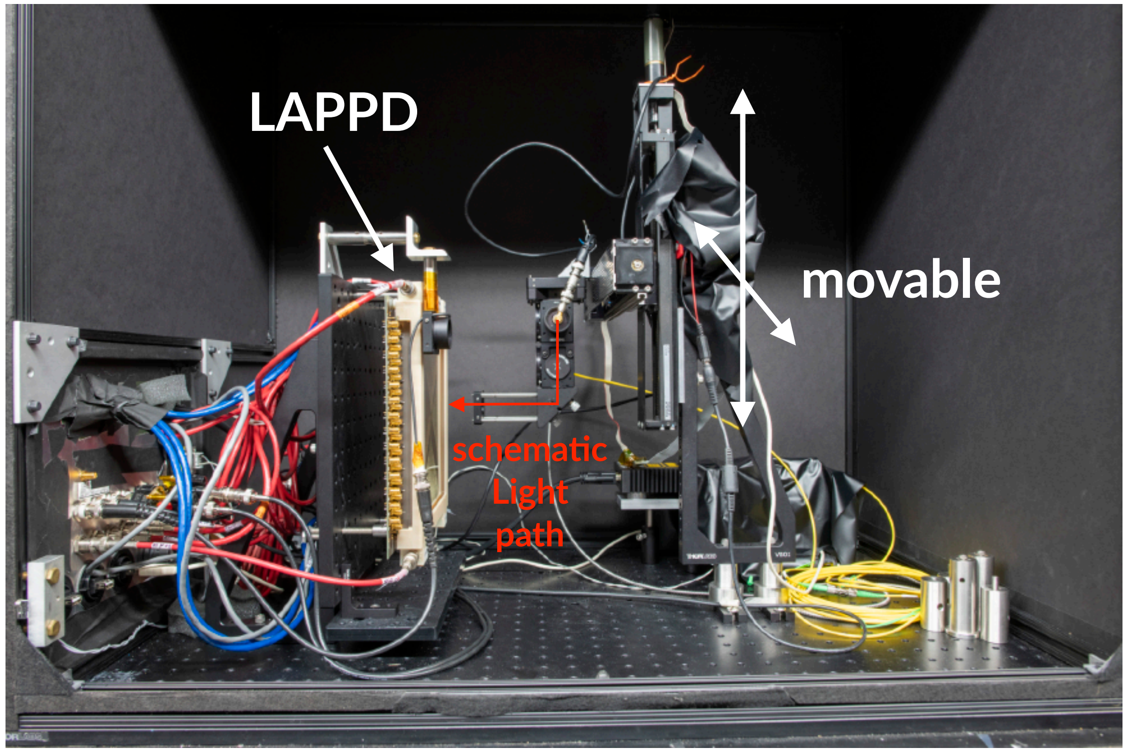
- 20 cm x 20 cm photodetector with intrinsic position resolution (mm-cm scale)
- Microchannel plate structure with resistive & emissive coating + microstrip anode readout
- Fast detection capabilities (time resolution ~60 ps)
- ANNIE has 5 LAPPDs at hand, characterization ongoing at Fermilab test stand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



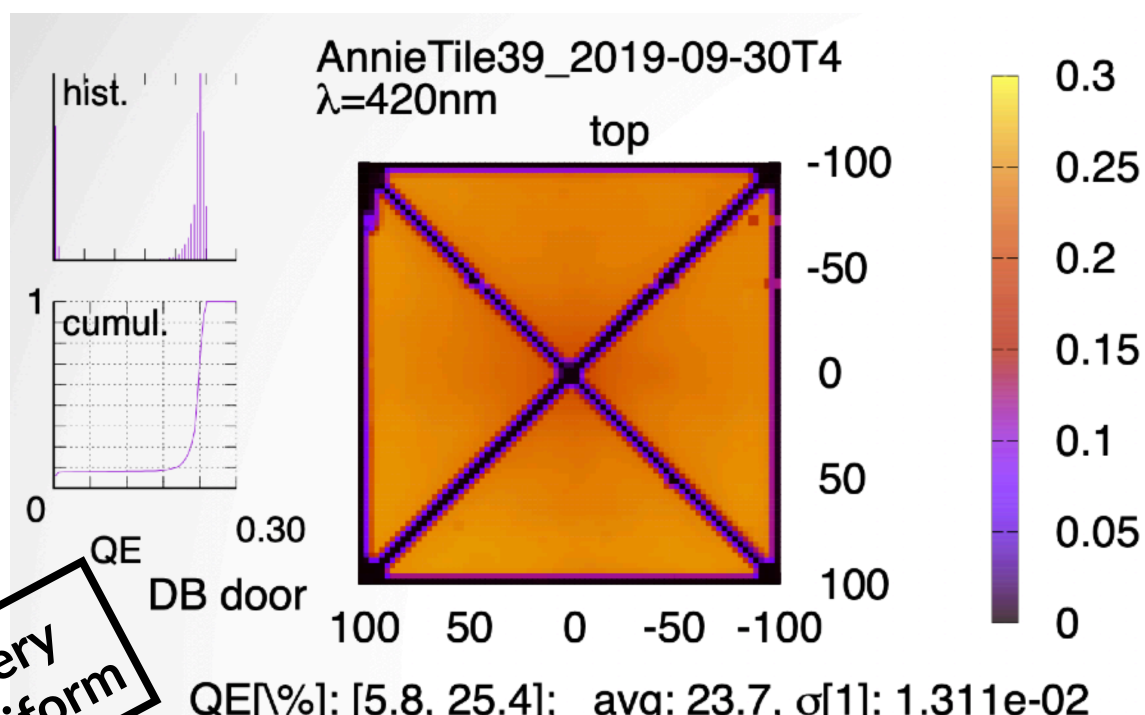
ANNIE LAPPDs



The present: Getting ready for LAPPD deployment



LAPPD test stand at Fermilab



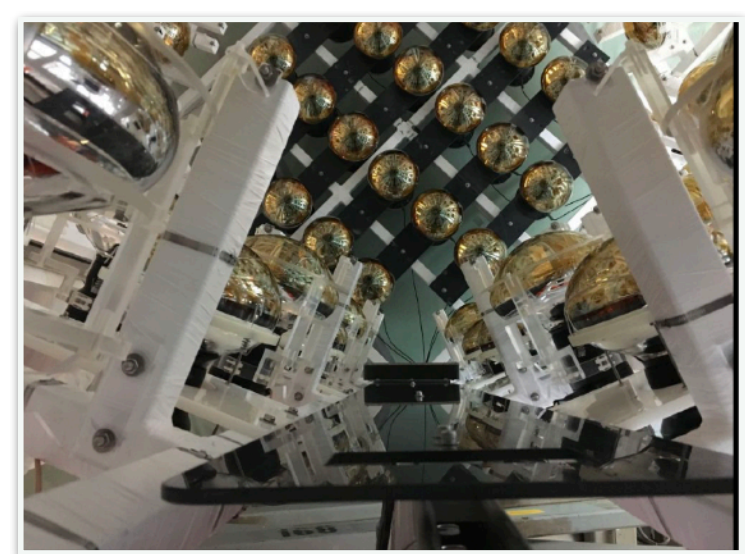
very uniform

good Q.E.

1) Characterization of the LAPPDs

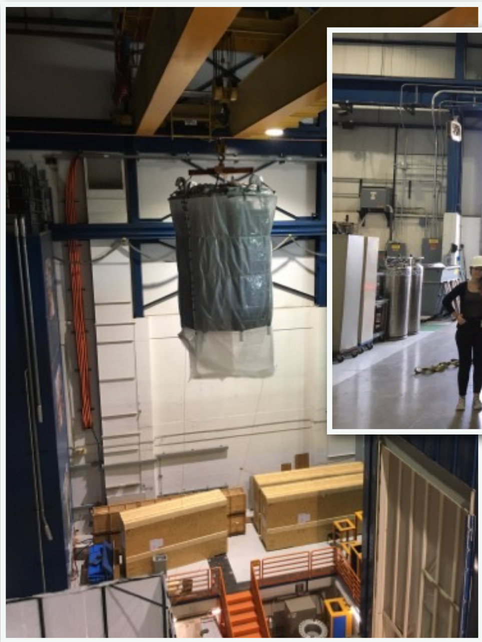
- Systematic tests of all 5 LAPPDs at dedicated facility at Fermilab
- Q.E., gain & timing calibration scans:
  - Movable & motorized LED/laser setup
  - Automated scans over the whole surface

2) Deployment



The present: Phase II - Detector construction

Insertion of the Inner Structure into ANNIE hall (July 2019)



DAB

Wilson Hall

ANNIE hall

Gadolinium loading

Custom water purification system developed by UC Davis collaborators:
"V. Fischer et. al, "Development of an ion exchange resin for gadolinium-loaded water"

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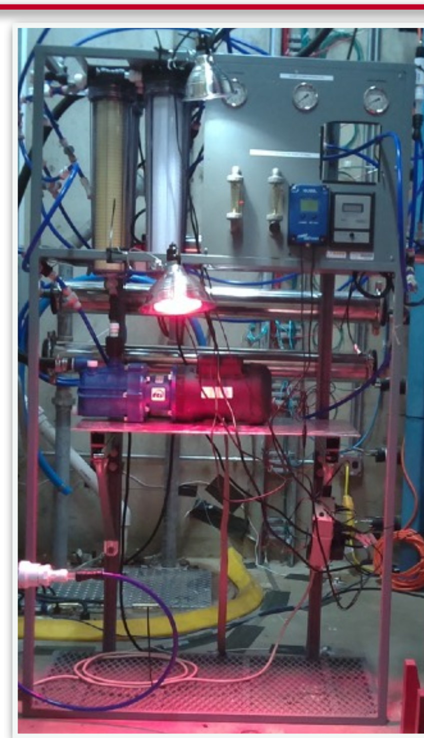
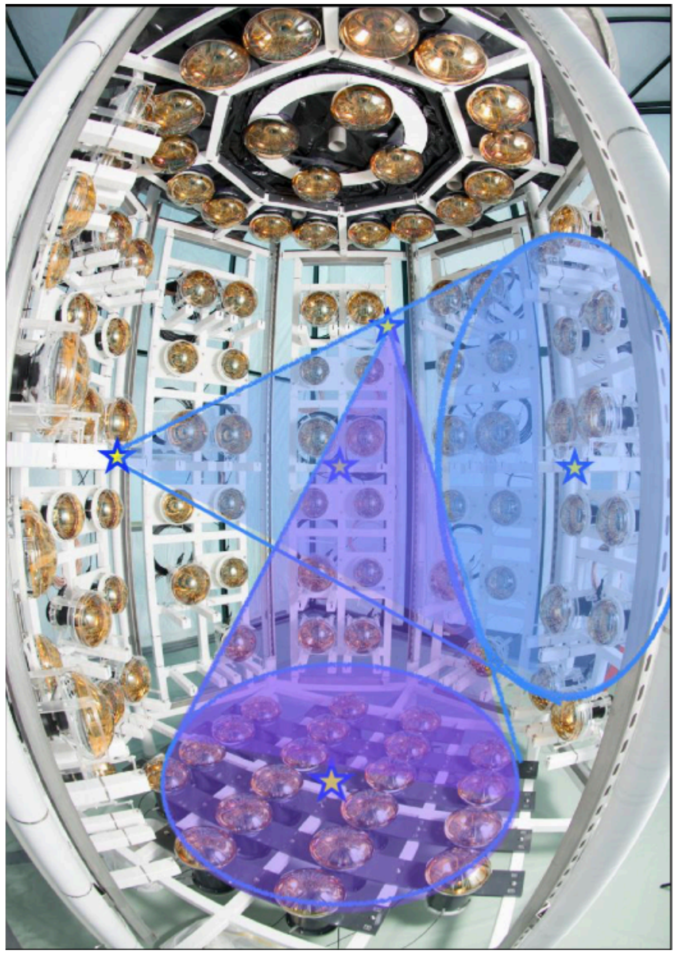


ANNIE reached its nominal Gd-loading on December 24th (2019) !

The present: Phase II - Detector commissioning

Calibration campaigns



LED calibration campaign

- Track transparency of the detector
- PMT gain calibration
- PMT cable delay corrections

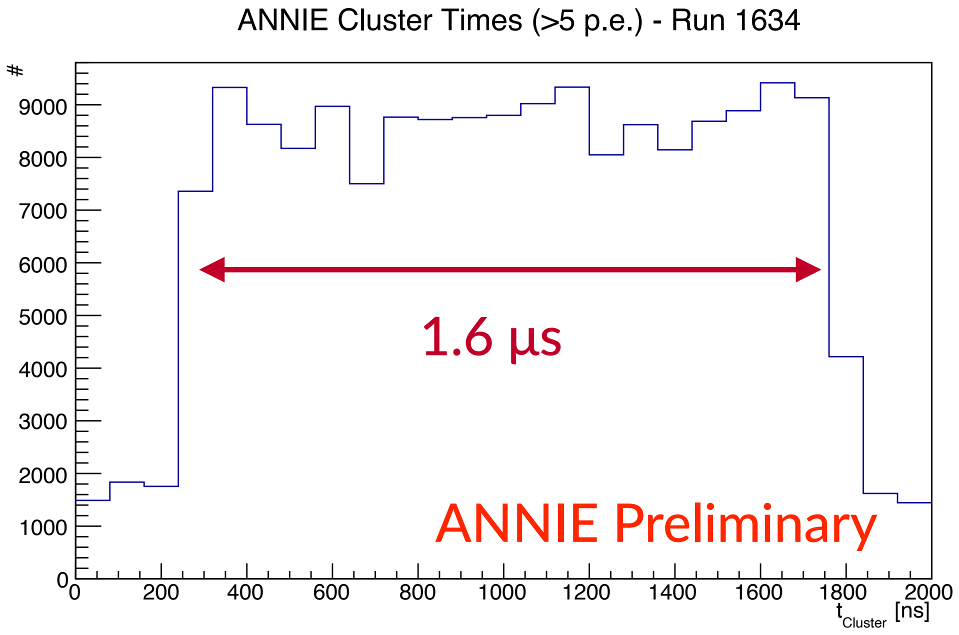
AmBe neutron calibration

Evaluate efficiency of neutron captures

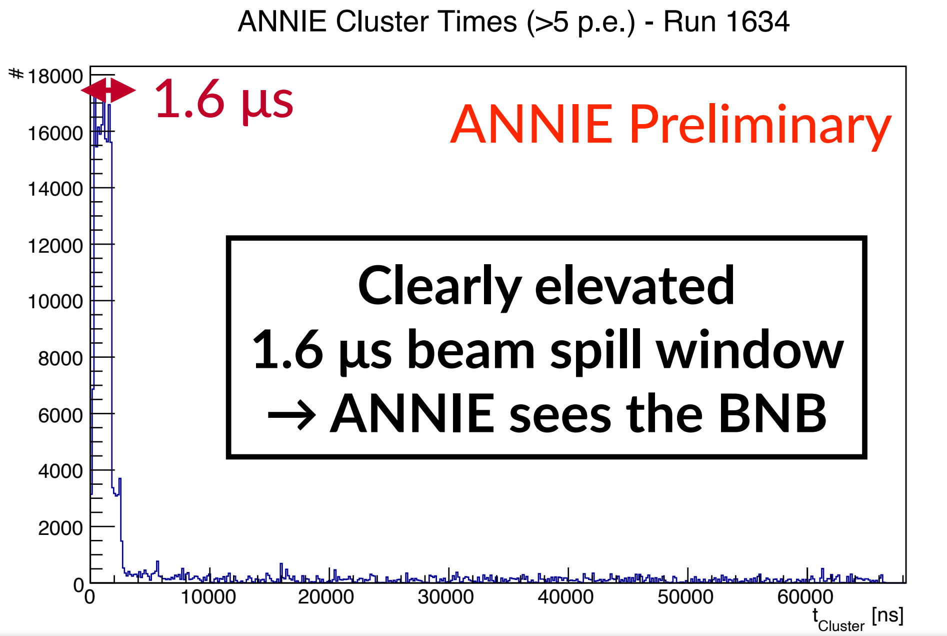
→ Leon Pickard, "First Neutron Capture Results In ANNIE"

Looking for the beam...

... in the prompt acquisition window



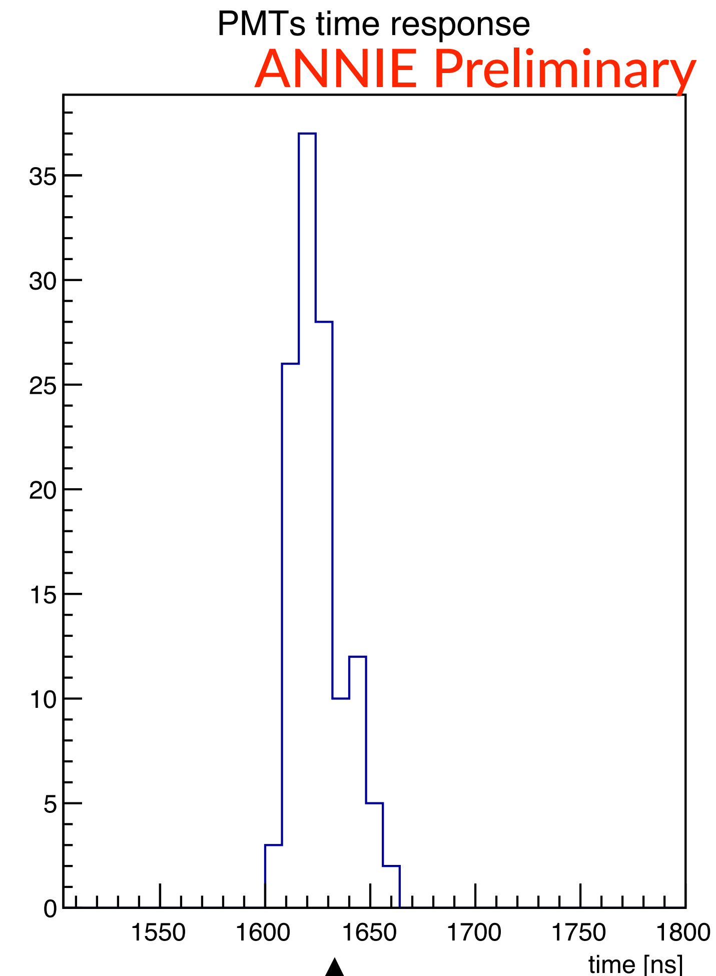
... in the full acquisition window



Clearly elevated 1.6 μs beam spill window → ANNIE sees the BNB

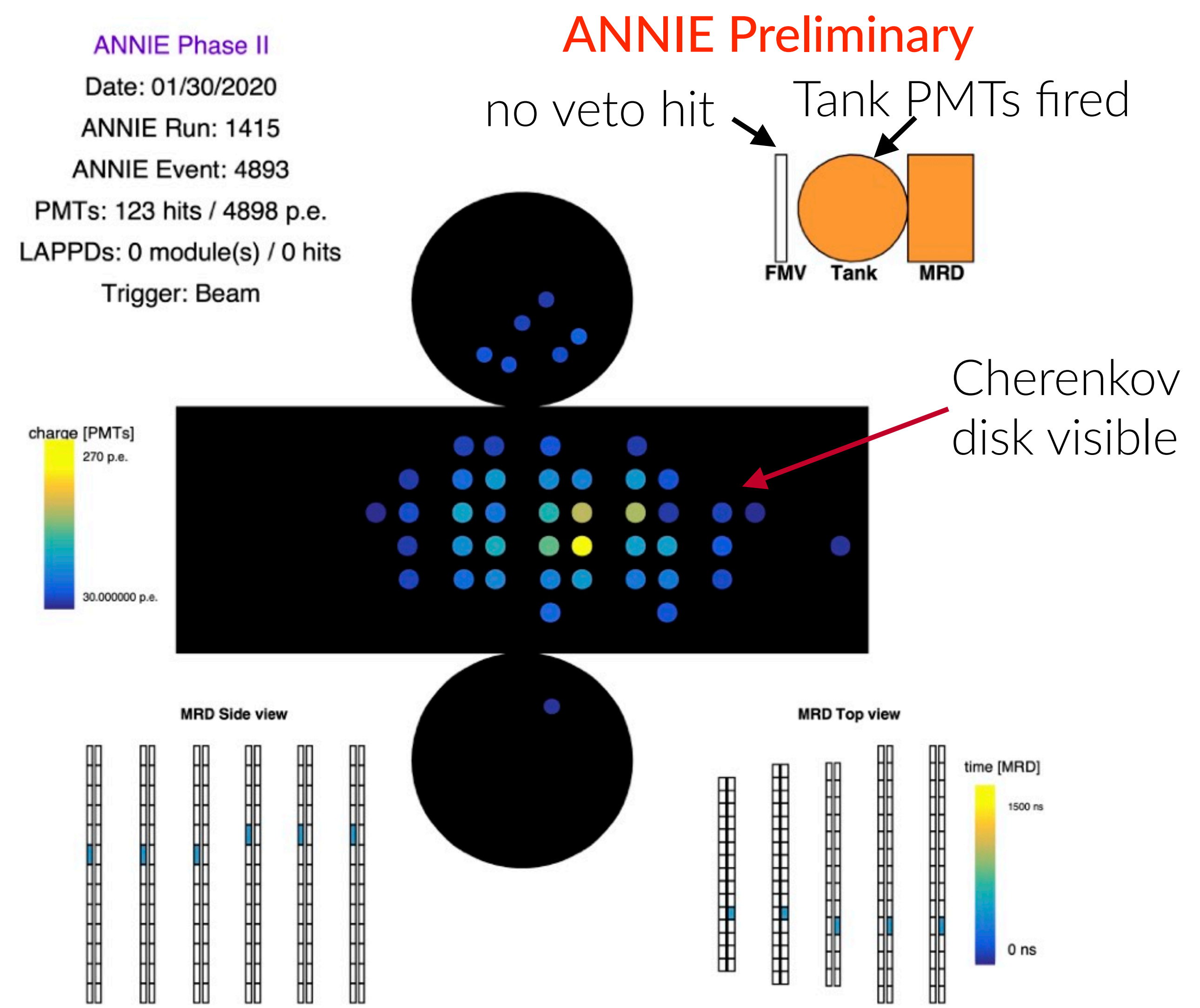
The present: Phase II - Detector commissioning

Time profile of beam commissioning neutrino candidate



PMT hits closely clustered in time

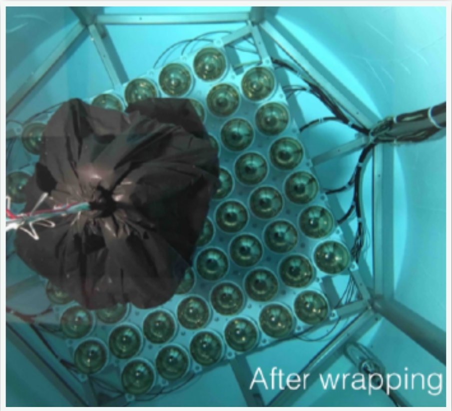
Event display of beam commissioning neutrino candidate



Track in Muon Range Detector
→ final-state muon

ANNIE observed first neutrino event candidates

The past, present and future of ANNIE



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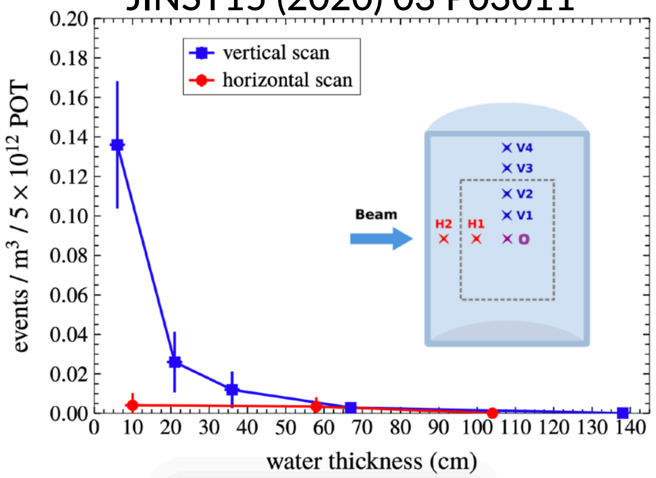
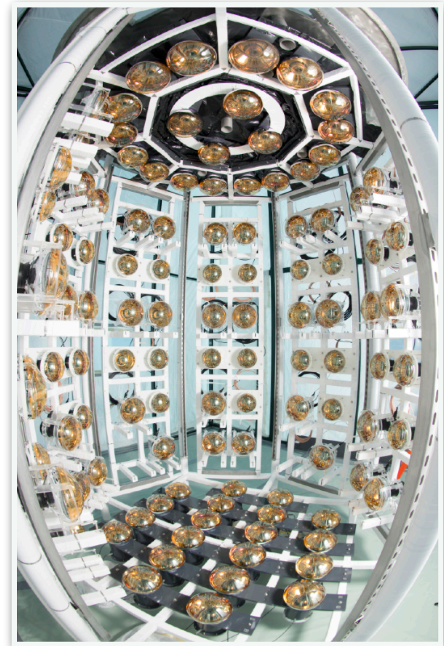
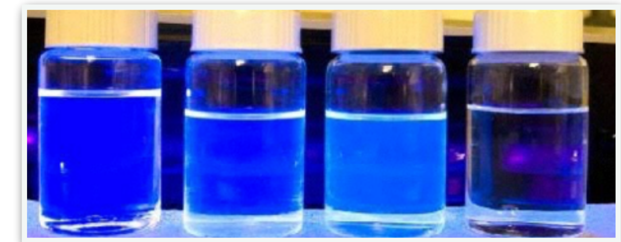






Past: Phase I

2016

2018

- Feasibility demonstration & background evaluation
- 60 PMTs (veto) & Gd-loaded scintillator Fiducial volume (NCV)

Present: Phase II

2020

- Physics phase
- Full 26-ton Gd-loaded Water Cherenkov detector
- First commissioning & calibration runs with 132 PMTs done

Future: Phase III

2020+

Further extensions to the detector:

- More than five LAPPDs

→ multi-track reconstruction

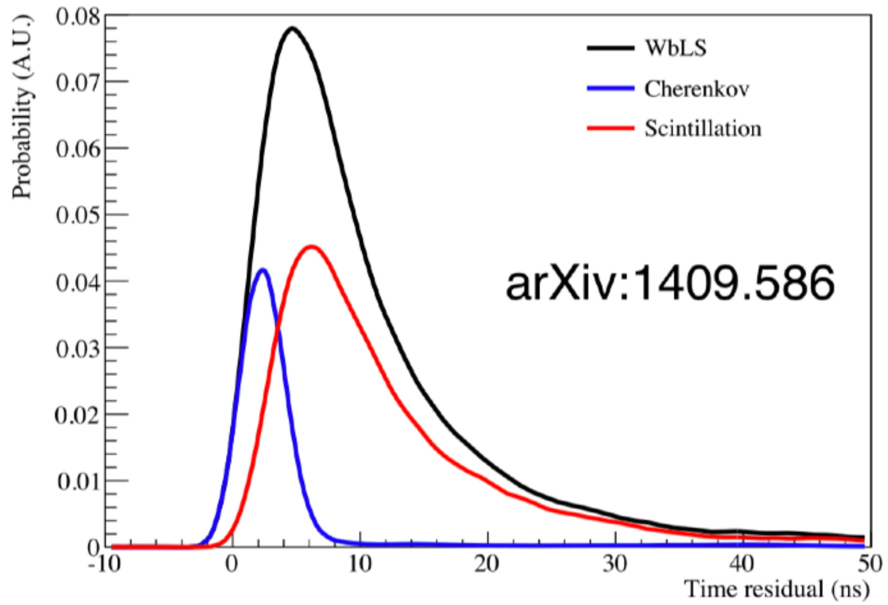
Testbed for new technologies:

- Water-based liquid scintillator volume in ANNIE

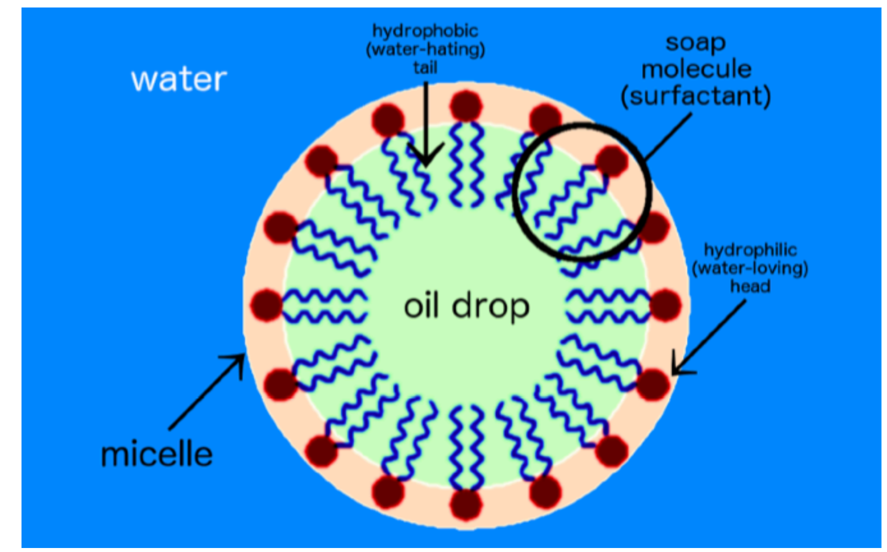
The future: Phase III - Water-based Liquid Scintillator

Separate Cherenkov- & scintillation light → ultrafast photosensors

Water-based Liquid Scintillator time profile



Micelle structure

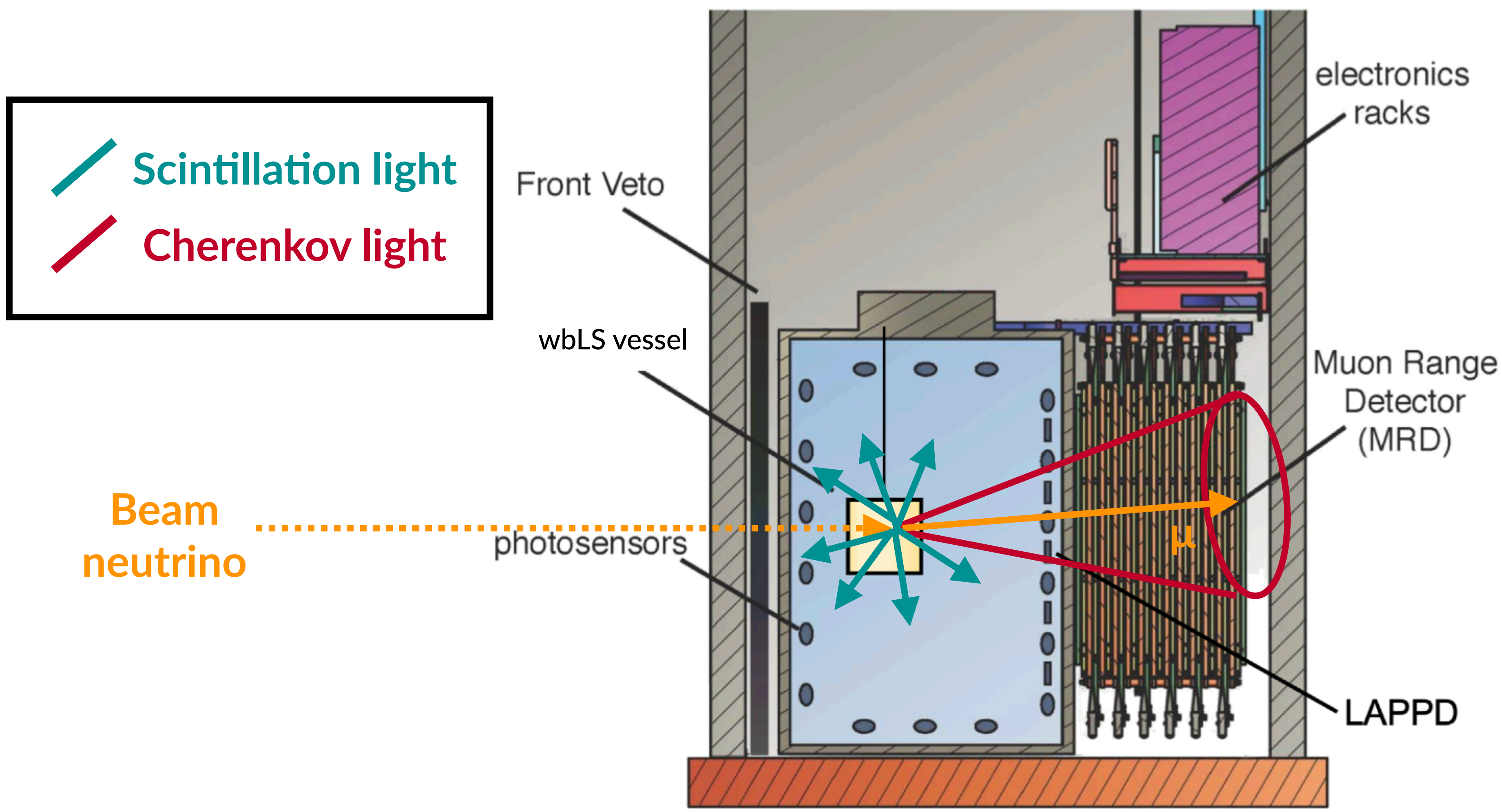


- **Water-based Liquid Scintillator (WbLS):** Novel detection medium for which Liquid Scintillator droplets are dissolved in water

- The medium has the following advantages:
  - 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

WbLS samples with different concentrations

The future: Phase III - Water-based Liquid Scintillator

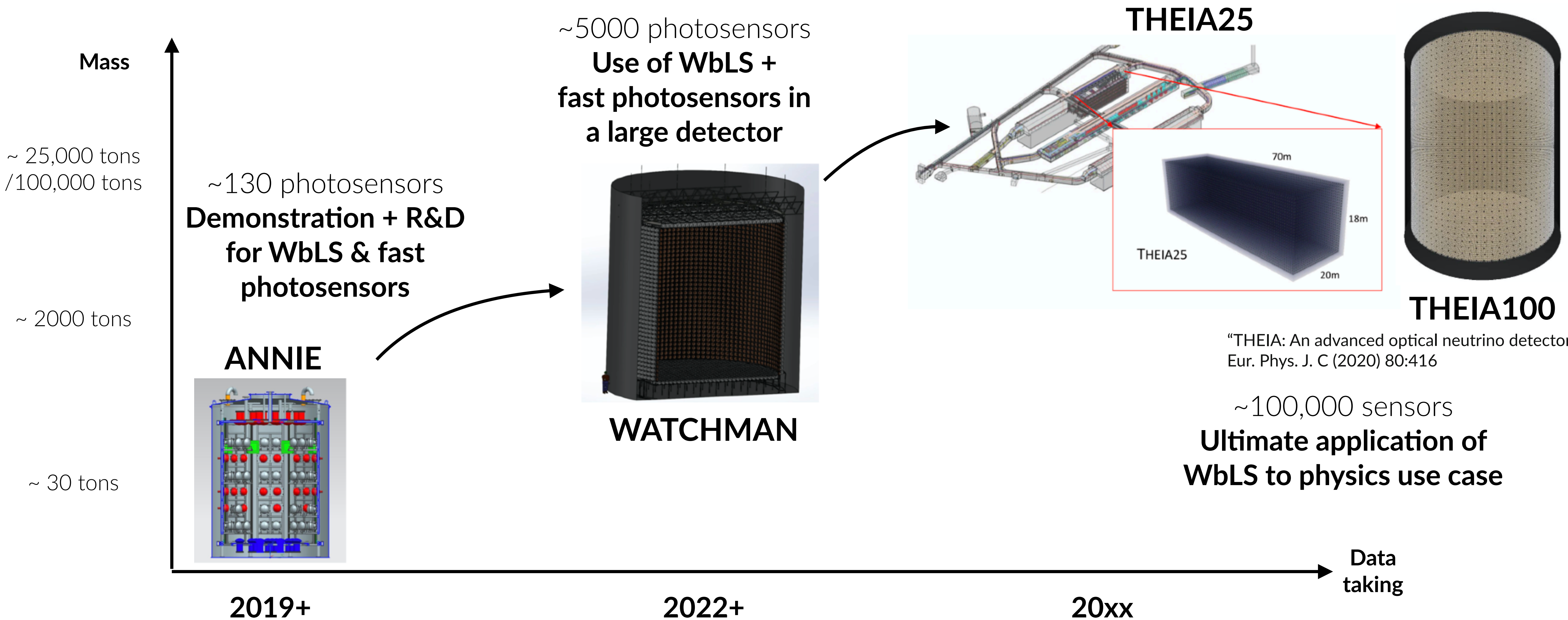


WbLS vessel

Rough visualization of vessel (NOT final design)

- **Insertion of a WbLS-volume (500l) into ANNIE**
  - Dimensions: cylinder with ~0.8m height, ~0.8m diameter
  - Different amounts of LS loading (1% / 5% / 10%) → evaluate benefits on reconstruction
  - Show feasibility of WbLS in a neutrino-beam environment

The future: ANNIE as testbed for next-gen experiments



- **WATCHMAN - 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

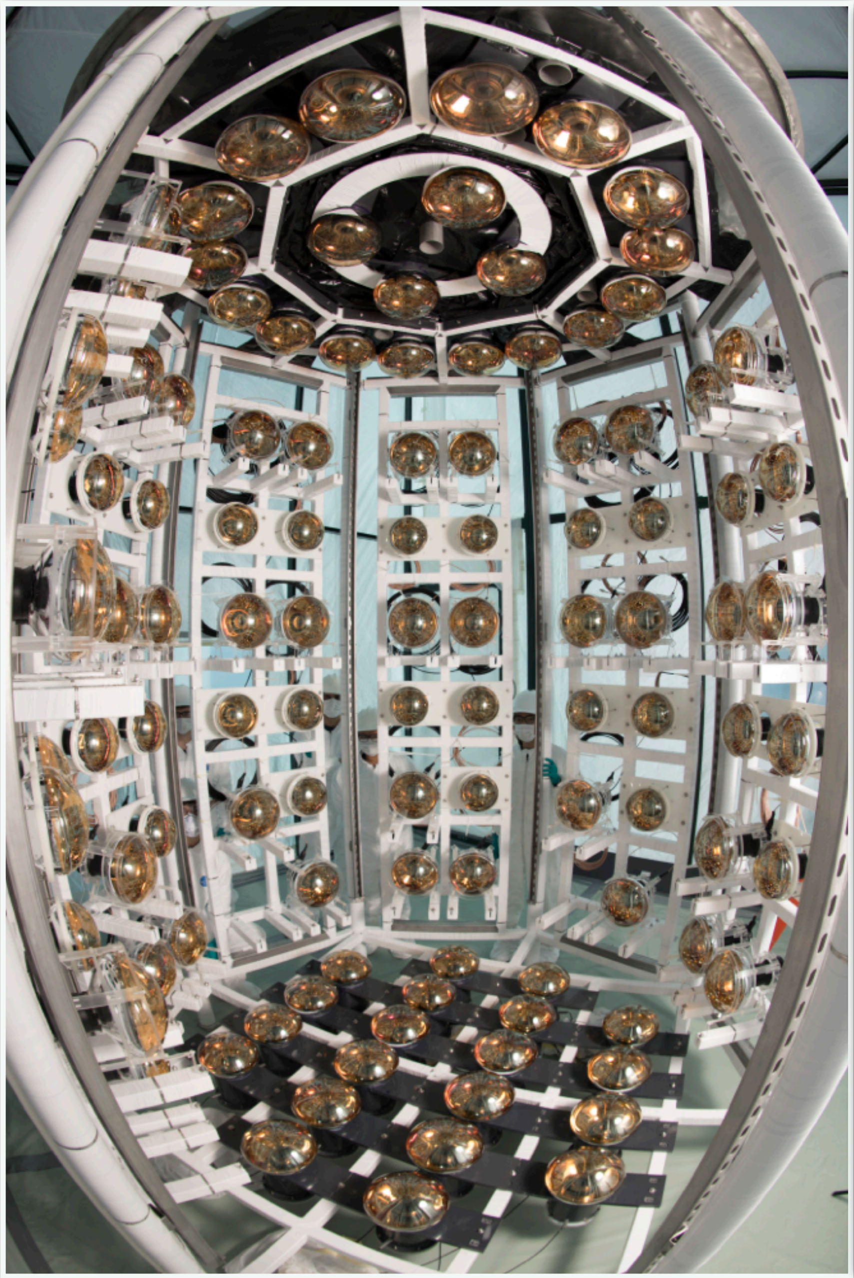
Summary

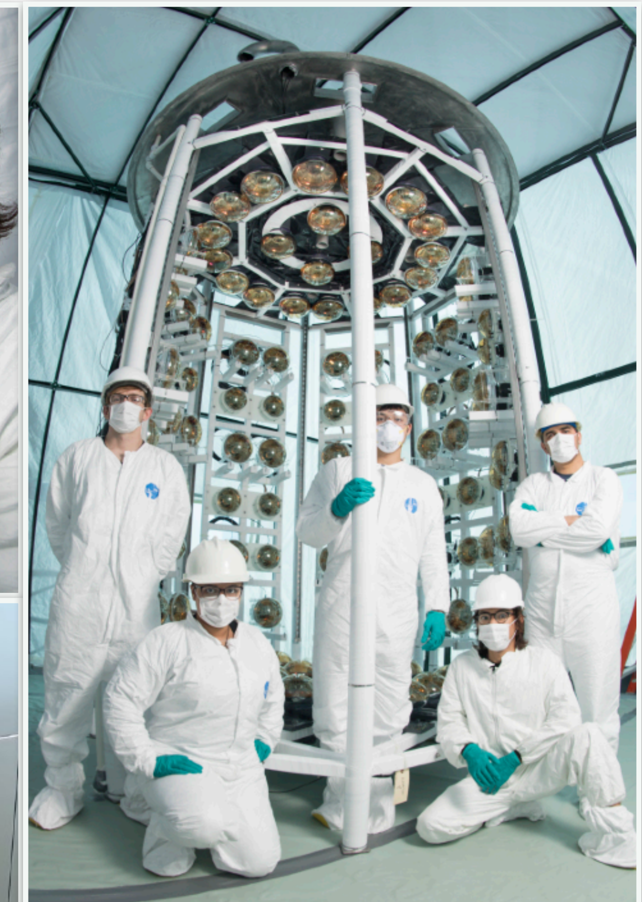
- **ANNIE** is a **Gd-loaded water Cherenkov detector (26 tons mass)** located in the BNB at Fermilab

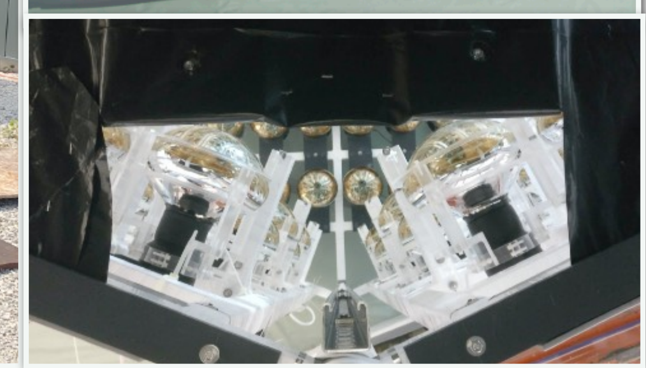
- **Physics measurement goals:**
  - Neutron multiplicity as a function of primary lepton momentum
  - Neutrino cross-section in water

- **Milestones:**
  - **July 2019**: Installation of Inner Structure in the hall, water fill
  - **December 2019**: Nominal Gadolinium-loading achieved (0.2% weight)
  - **Early 2020:**
    - Detector commissioning, first beam neutrinos detected
    - Active water transparency monitoring (LED)
    - Neutron capture efficiency calibration (AmBe)
    - Characterization of all 5 LAPPDs
  - **Soon:**
    - ANNIE's first LAPPD deployment

- **Future:**
  - Testbed for new detection medium of water-based Liquid Scintillators







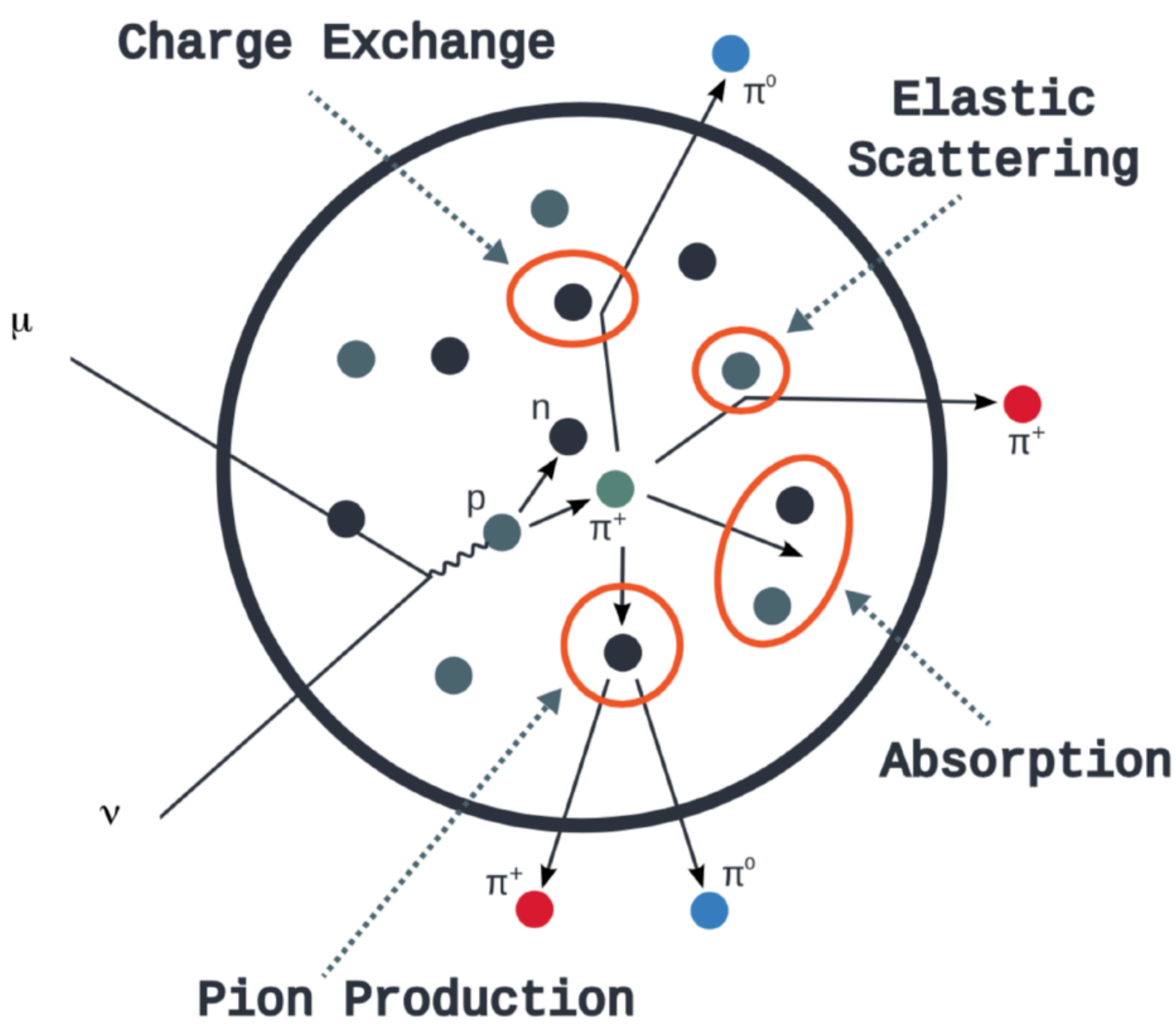
- Fermi National Accelerator Laboratory
- Brookhaven National Laboratory
- Lawrence Livermore National Laboratory
- Iowa State University
- University of California, Davis
- University of California, Irvine
- University of Chicago

- Ohio State University
- The University of Warwick
- The University of Edinburgh
- The University of Sheffield
- The University of Hamburg
- The University of Tübingen
- Johannes Gutenberg University Mainz

annie

THANK YOU!
… ANY QUESTIONS?

Backup - Inelastic processes



taken from: *NuSTEC white paper*

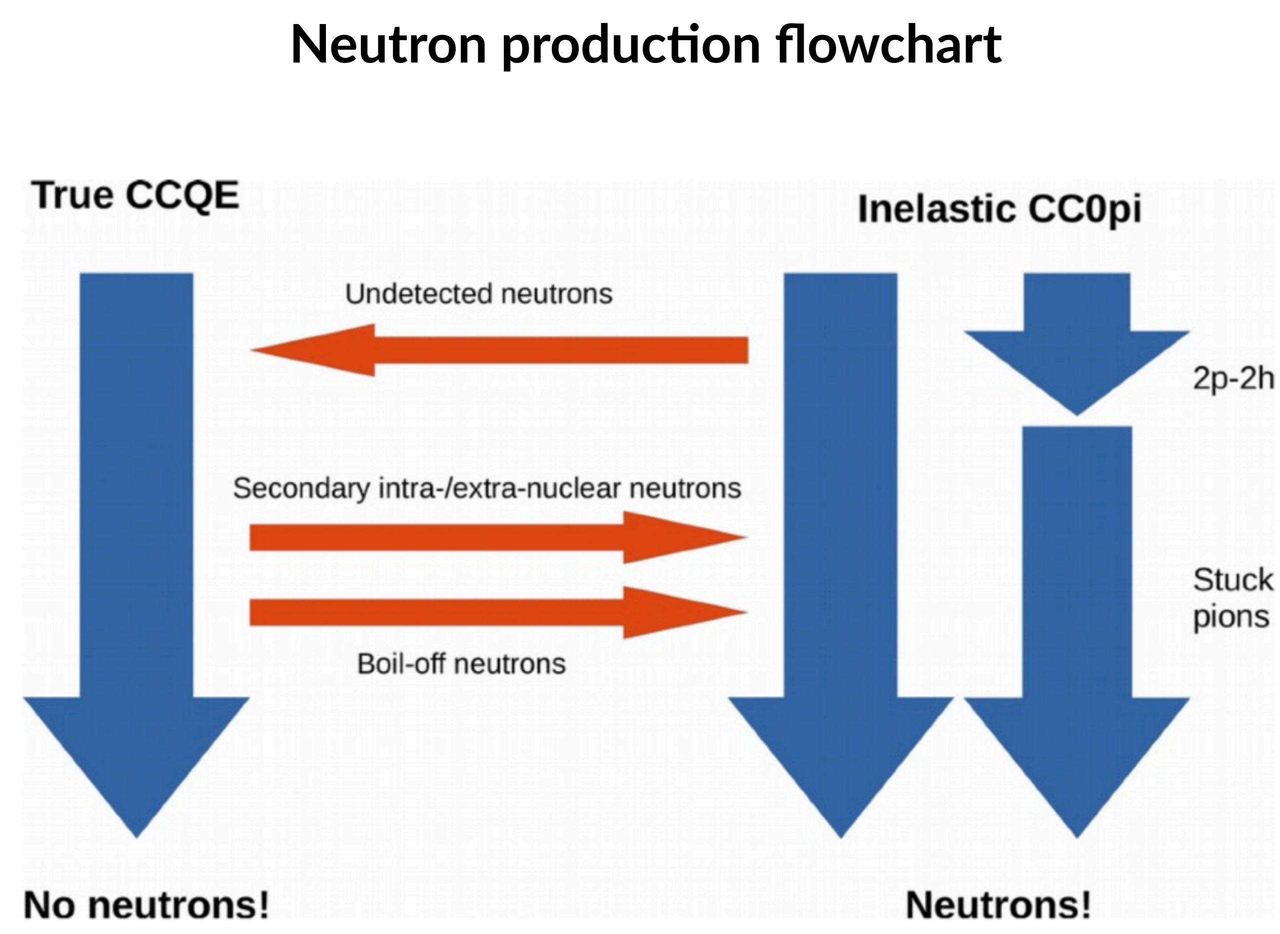


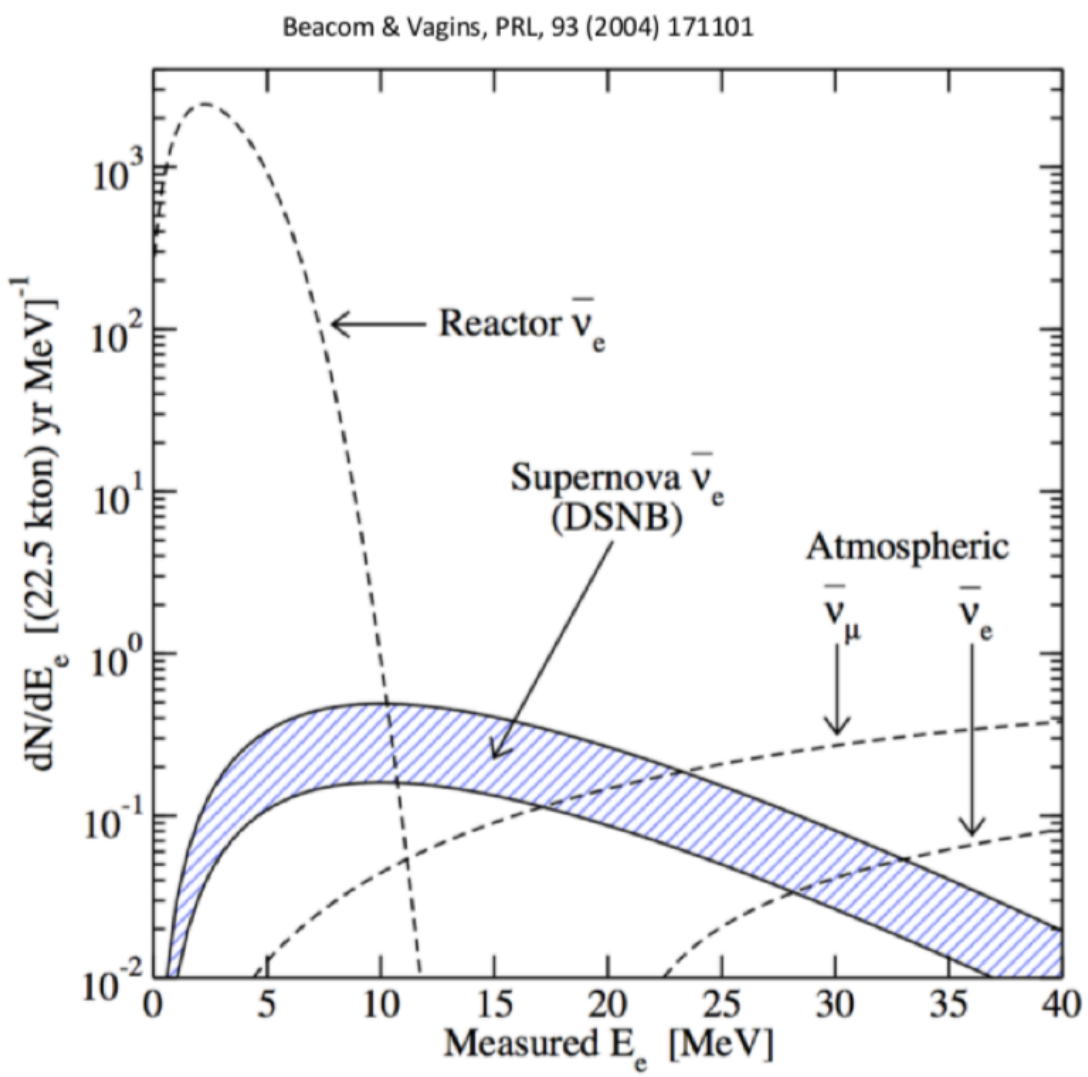
Diagram by Vincent Fisher, UC Davis

→ Move to **event topologies (1μ + 1/0π + Xn + Yp)** instead of **MC generator-based categories (CCQE, RES,DIS,...)**

→ **Neutrons** as possible signs of **inelasticity →** multiplicity measurement by ANNIE

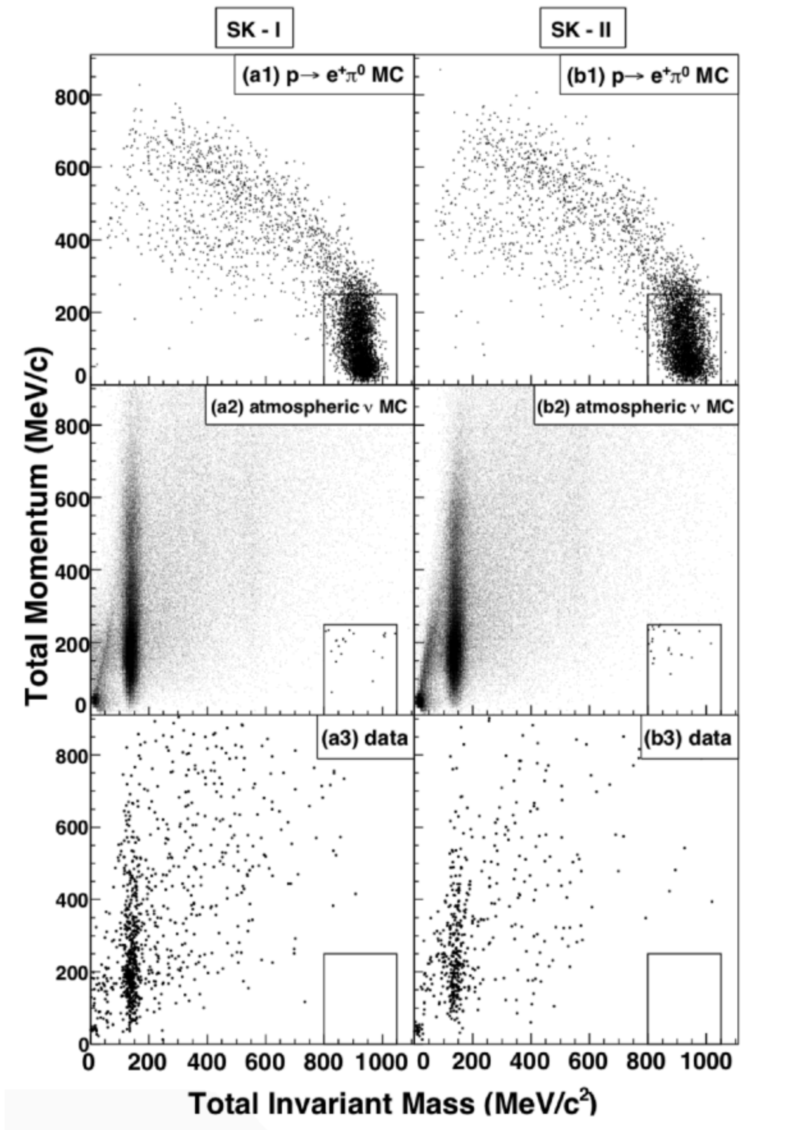
Backup - DSNB & Proton decay

DSNB search



Proton decay search

PRL 102 (2009) 141801



proton decay

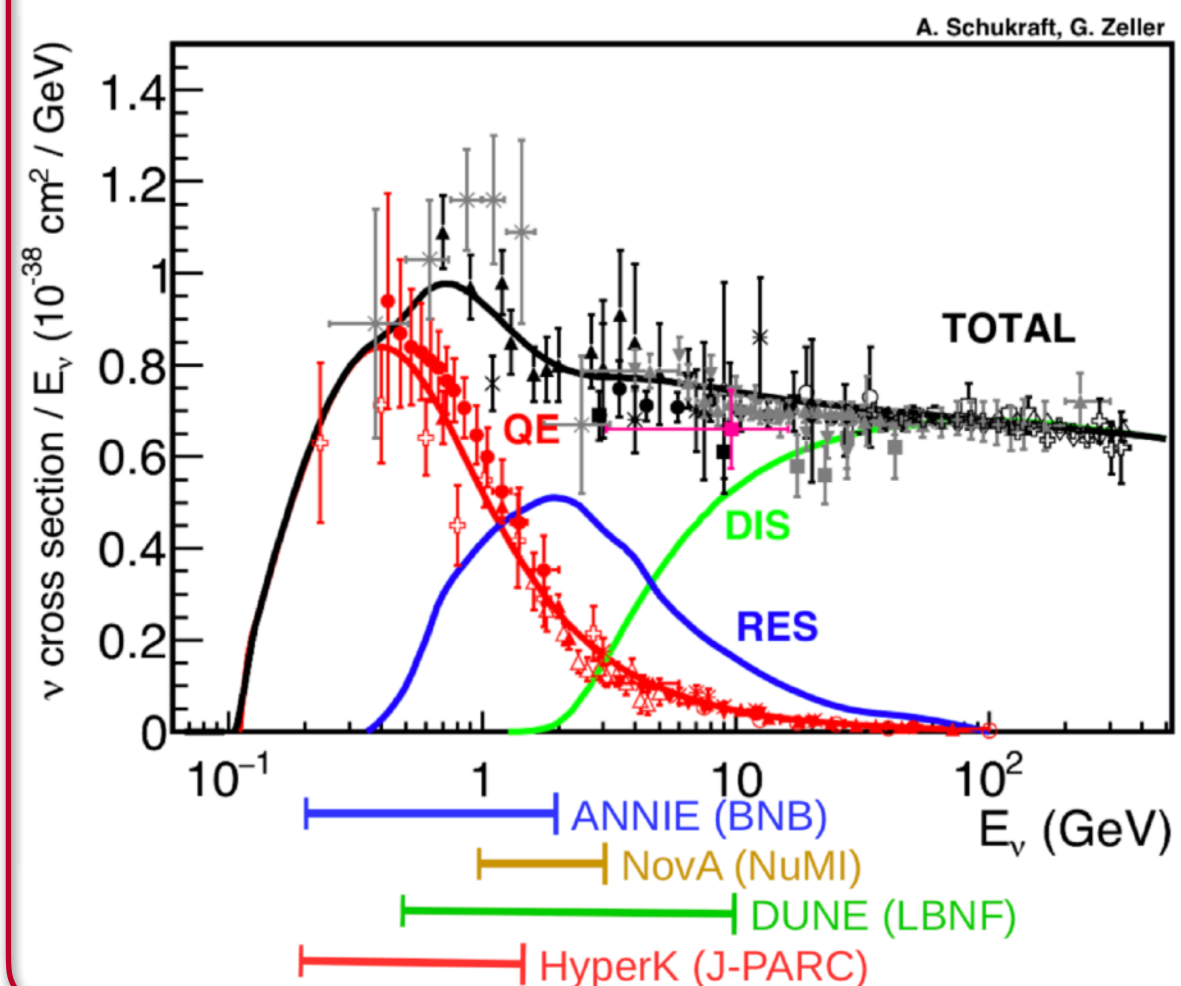
atmospheric

data

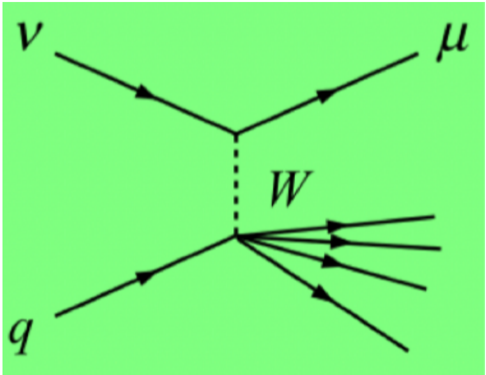
→ Improve signal-to-background discrimination by better models of atmospheric neutron yield

Physics motivation - Inelastic processes

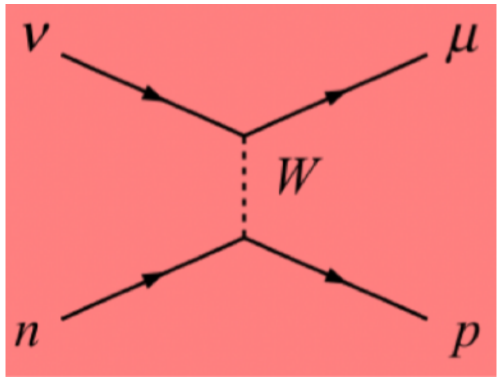
Relevant interactions in ANNIE:



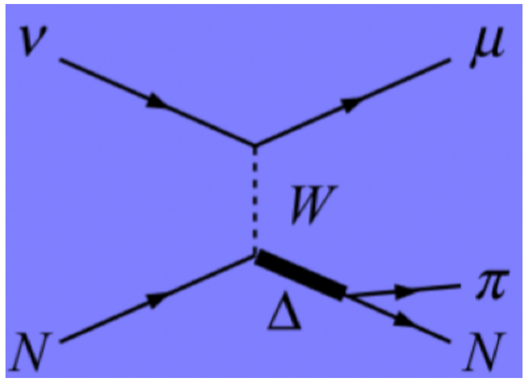
Deep Inelastic Scattering



Quasi-Elastic

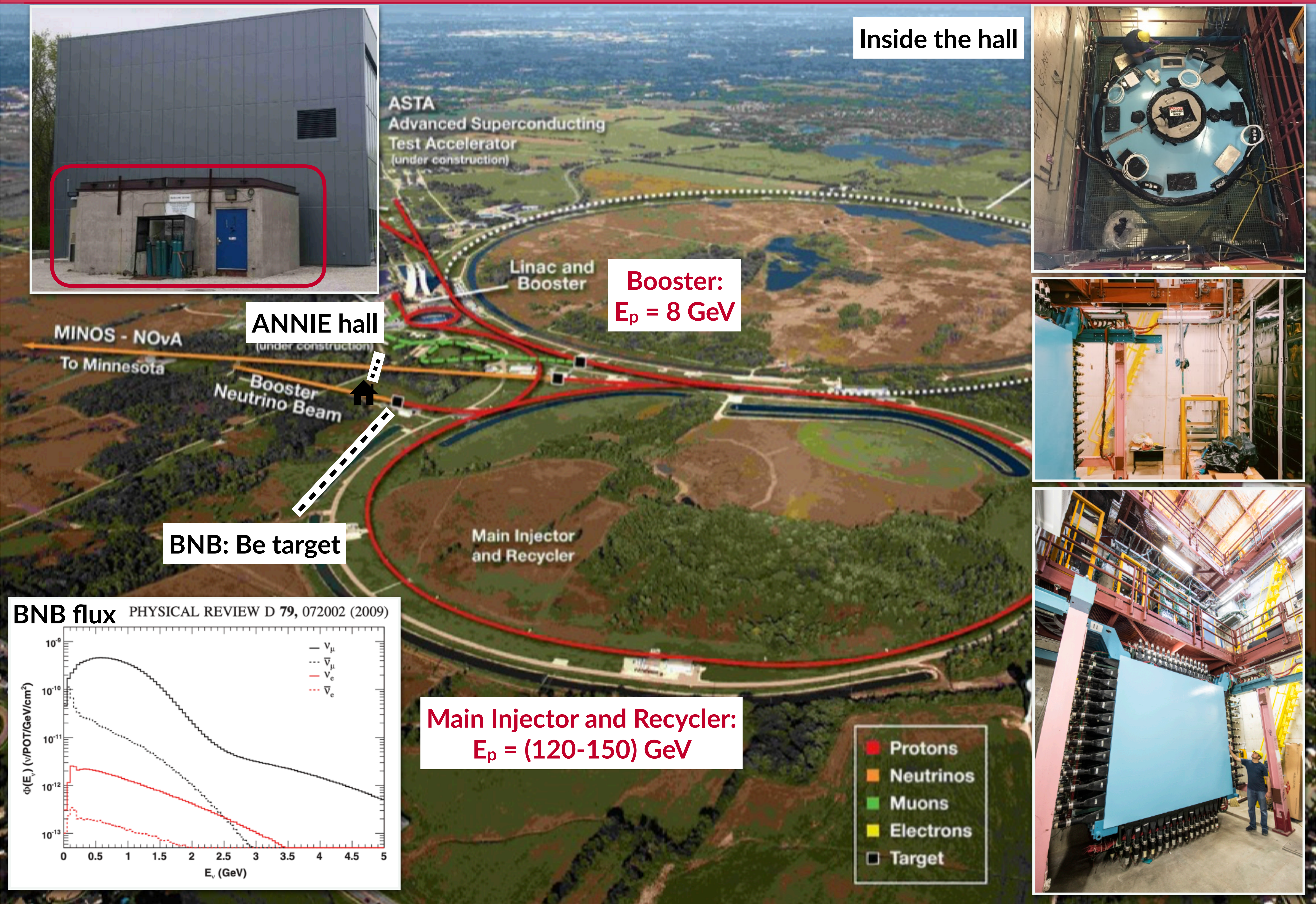


Resonance

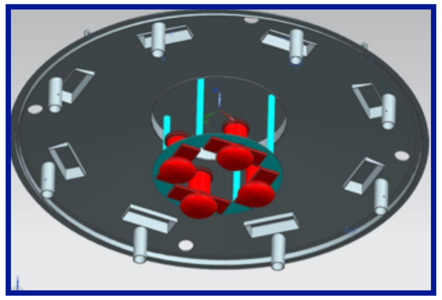


- **Discriminating elastic and inelastic processes**
  - Misidentification of elastic/inelastic processes results in energy reconstruction bias
  - neutron presence indicative of inelastic processes → can help to minimize such biases

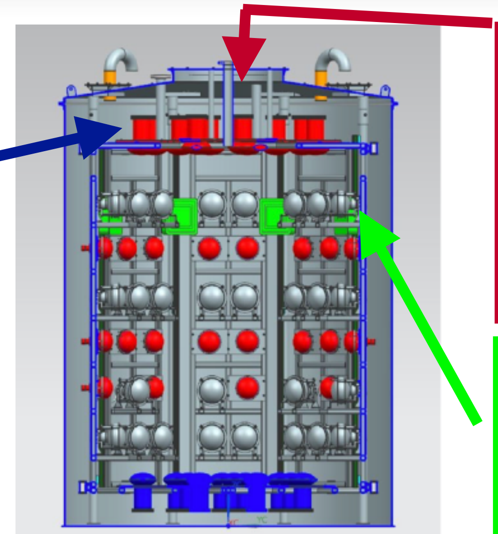
Fermilab Accelerator Complex



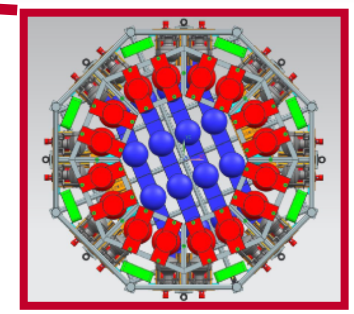
Backup: Phase II - Detector setup



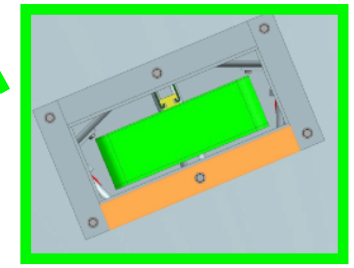
Top lid with
4 PMTs



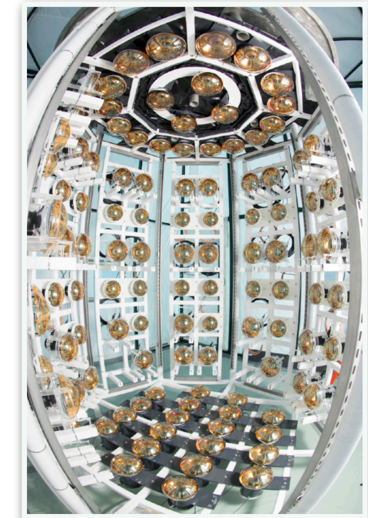
Side view of ANNIE



Top view



LAPPD deployment
cassettes

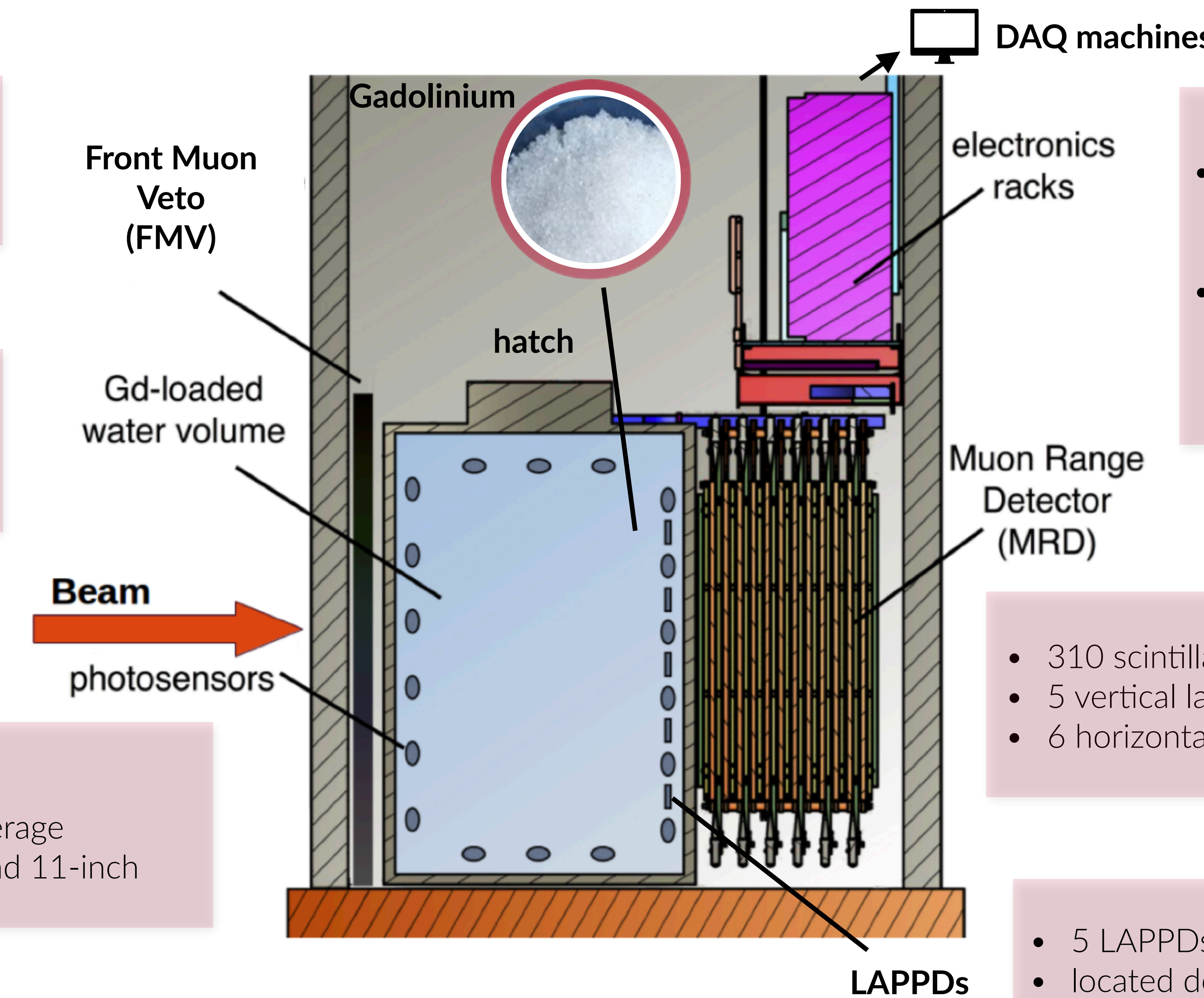


Inner Structure with PMTs

- 26 scintillator paddles
- reject muons from upstream

- 26 tons water volume
- loaded with $Gd_2(SO_4)_3$ (0.2% by weight)

- 132 PMTs
- 20 % coverage
- 8-, 10-, and 11-inch



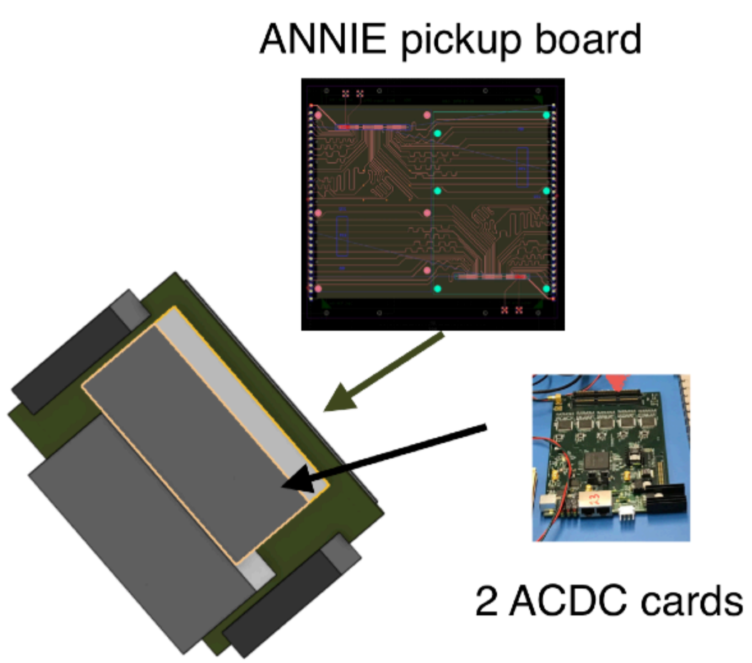
- VME acquisition system for PMT signals (500MHz)
- ACDC cards sampling LAPPD response (10 GHz)

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

- 5 LAPPDs
- located downstream

Backup - Data Acquisition

- ANNIE will have a **dual readout design** to accommodate deep-buffered PMT signals (neutron capture) alongside ultra-fast LAPPD digitization
- **PMTs: VME-based data acquisition system (500 MHz)**, global trigger for all PMTs
- **LAPPDs**: **ACDC card** hosting **5 PSEC sampling ASICs with multi-channel readout (10 GHz)**, independent triggers for every single LAPPD
- **MRD: CAMAC-based data acquisition system**, global trigger for all channels
- DAQ processes interfaced by **ANNIE central card** (8 nodes)



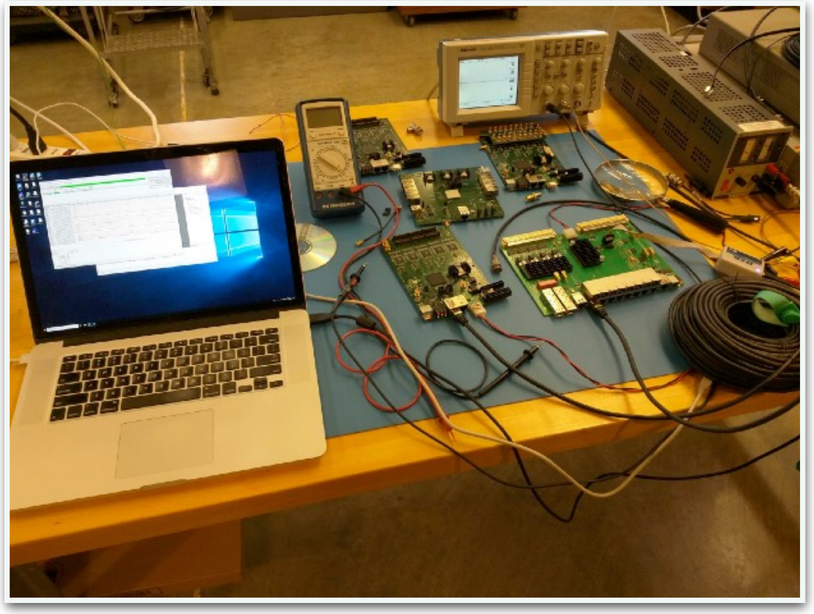
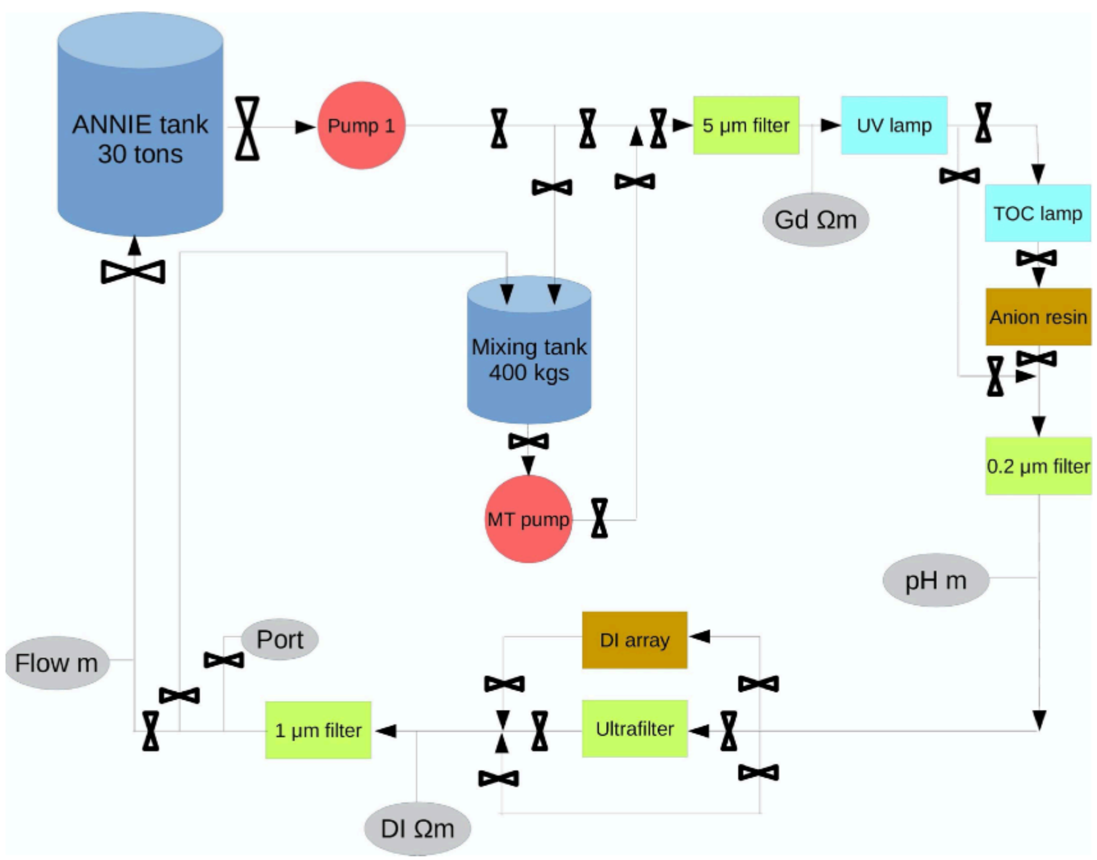


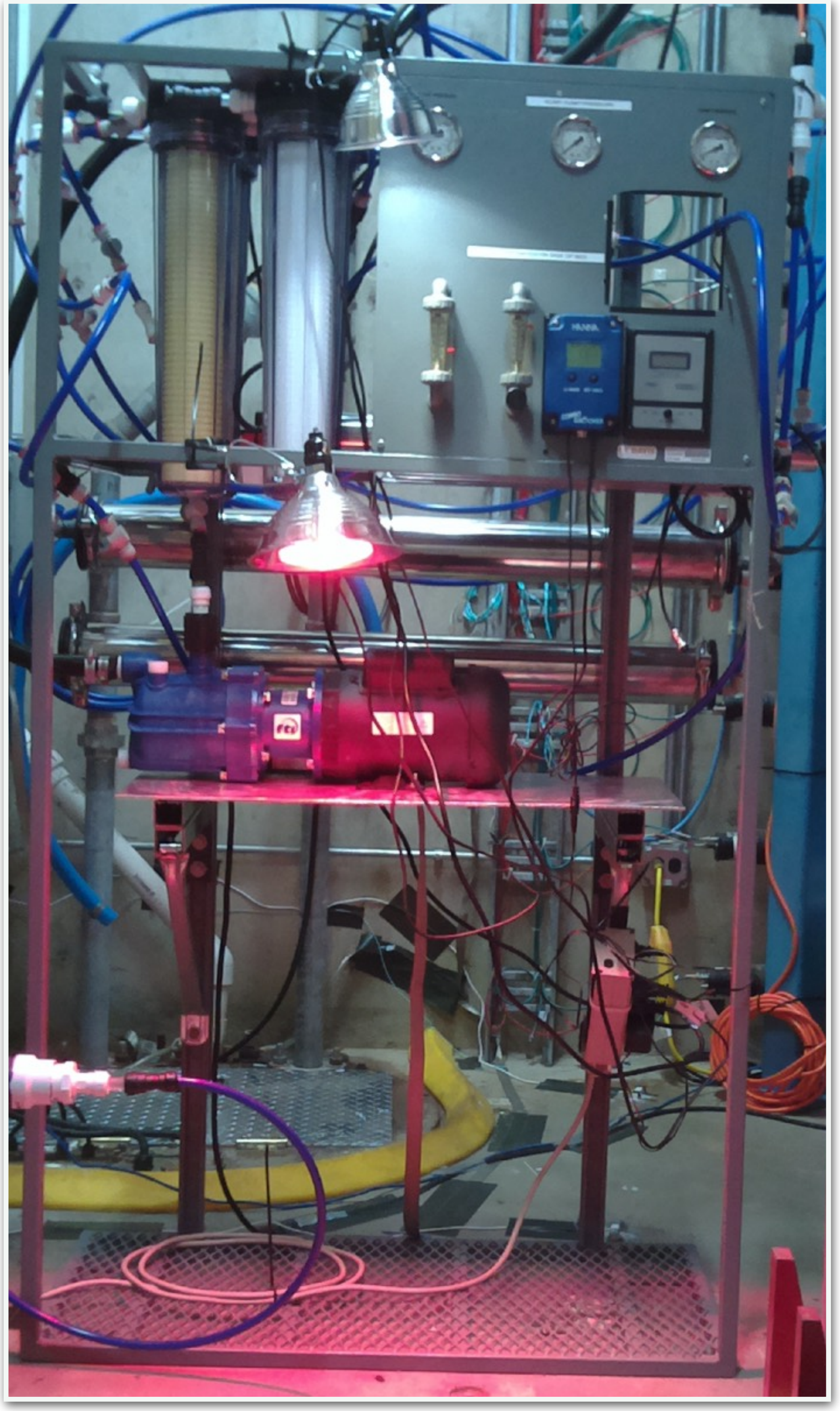
photo: Jonathan Eisch, Iowa State University

Test setup for communication of ANNIE central card & ACDC card

Backup - Water filtration

- 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

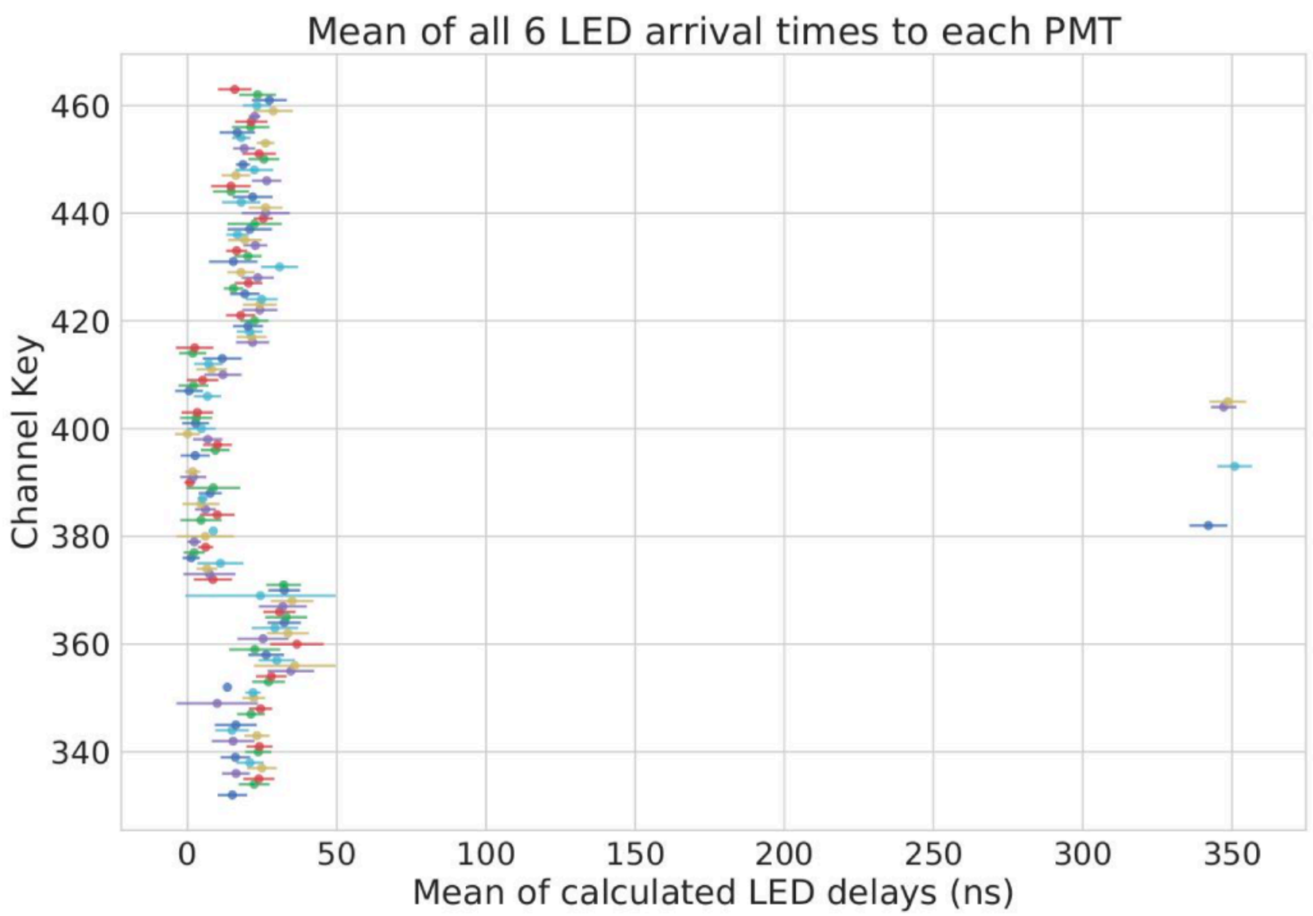




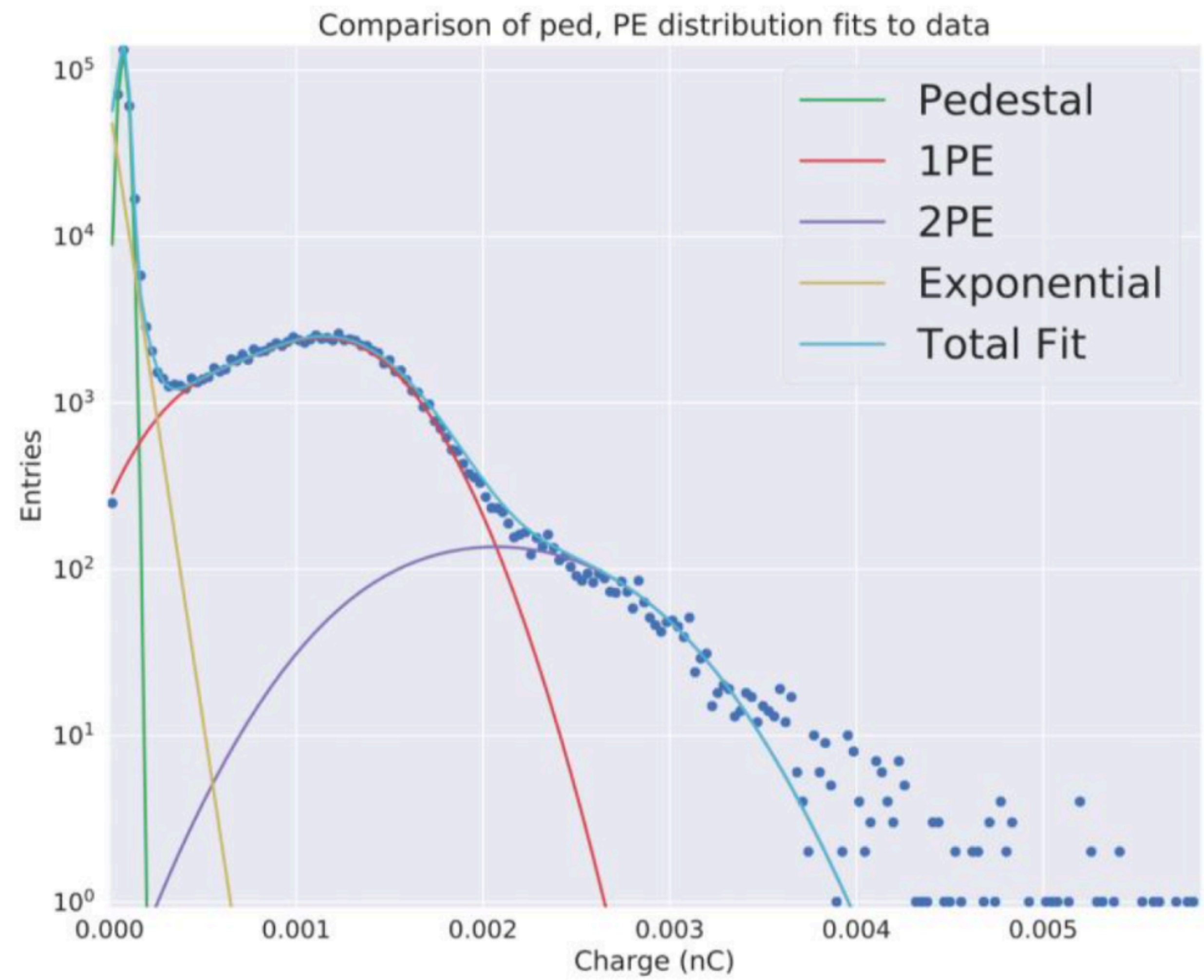
Vincent Fischer, UC Davis

Backup - LED calibration

Cable delay calibration



Gain calibration

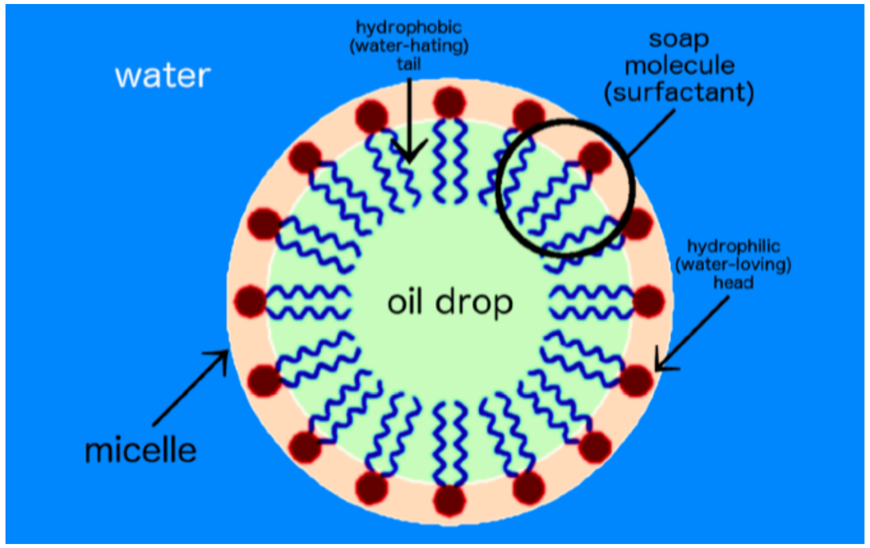


- Current timing uncertainty: 5ns
- Different groupings ↔ different PMT types
- Laser ball calibration will improve precision

Average PMT gain: 7×10^6

Backup - Water-based Liquid Scintillator

Micelle structure



Chemistry behind WbLS

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

More WbLS properties

- 1% LS loading corresponds to ~ 100 photons / MeV
- Ongoing work on extended reconstruction techniques for fitting Cherenkov + scintillation light
- Enhanced detection of hadronic recoils (especially protons) → better event topology discrimination

WbLS for detectors at Advanced Instrumentation Testbed

- First neutrino detector at AIT (NEO) considers both Gd-loaded water & WbLS options
- WbLS is seen to be the natural progression for future detectors at AIT