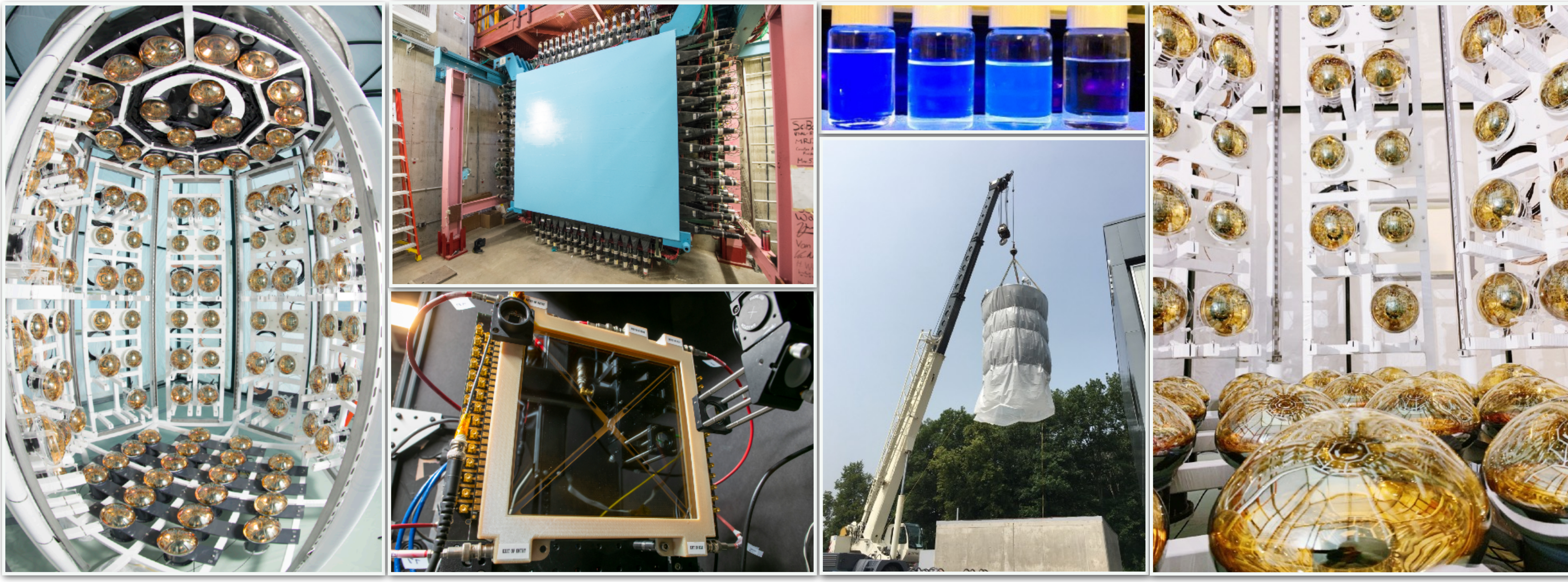


ANNIE

Roadmap to neutron multiplicity in neutrino interactions

New Directions in Neutrino-Nucleus Scattering (NDNN)
03/18/2021

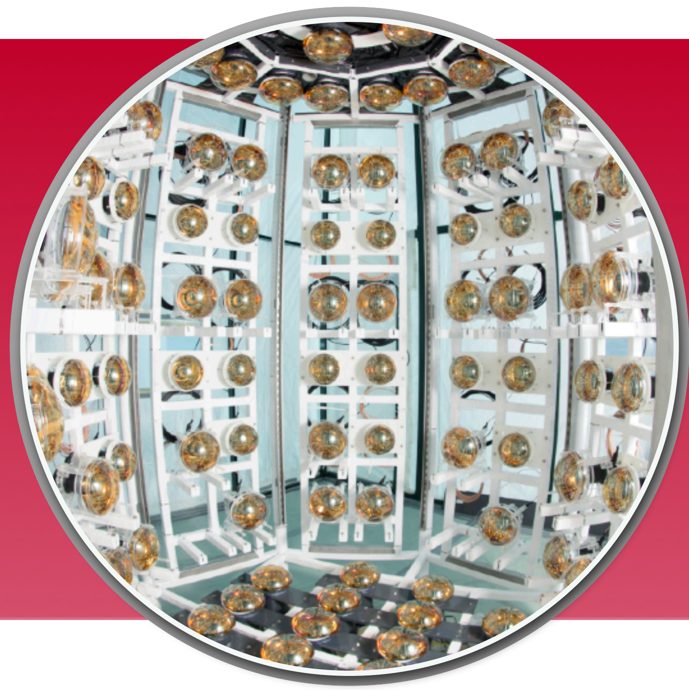
annie

Michael Nieslony
on behalf of the ANNIE collaboration

JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JG|U

ANNIE

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



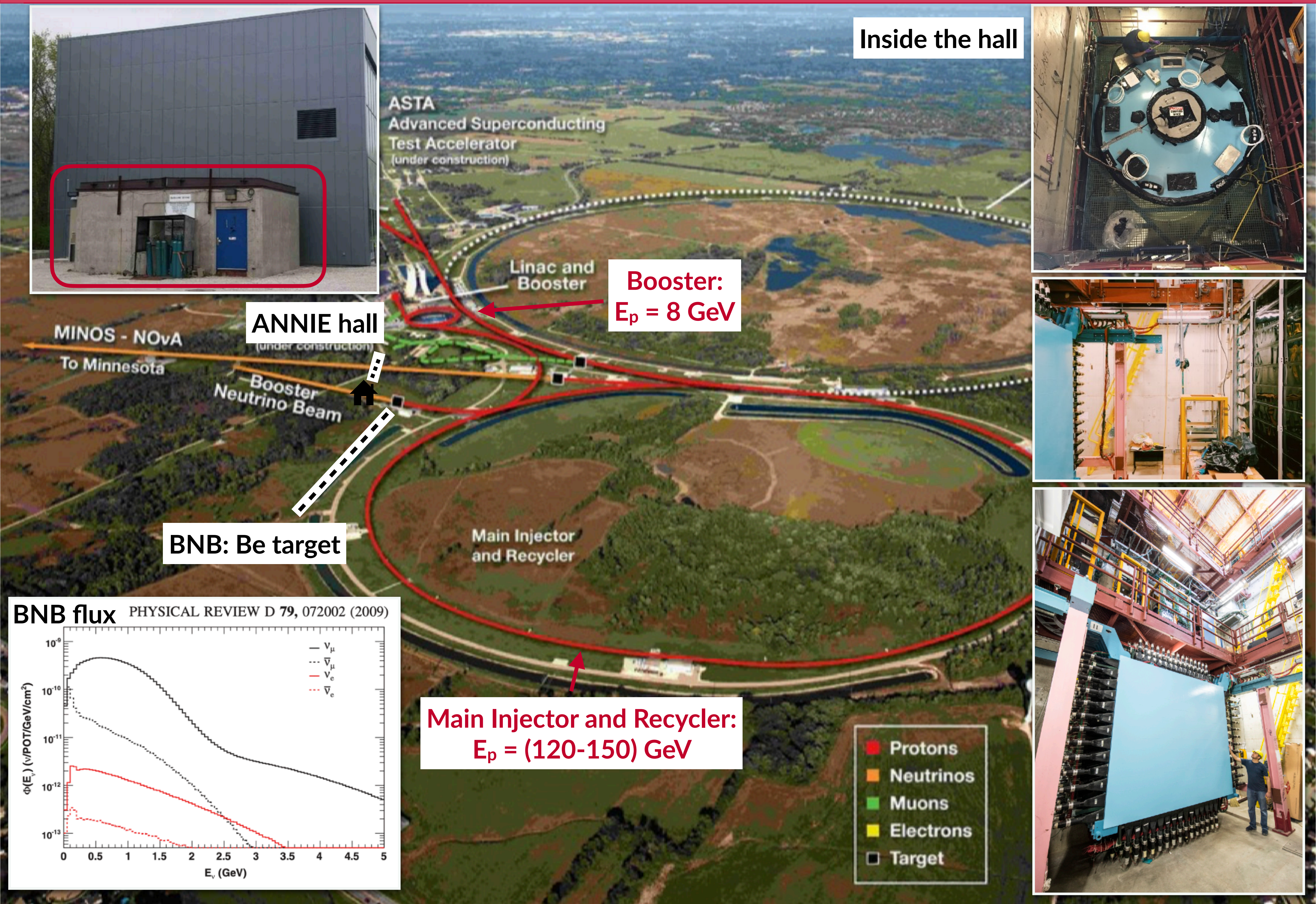
Detector

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 & CC-0π 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



Physics motivation - 2 measurements

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

  Minimize systematic uncertainty in long-baseline neutrino oscillation studies

- **Neutron multiplicity:**

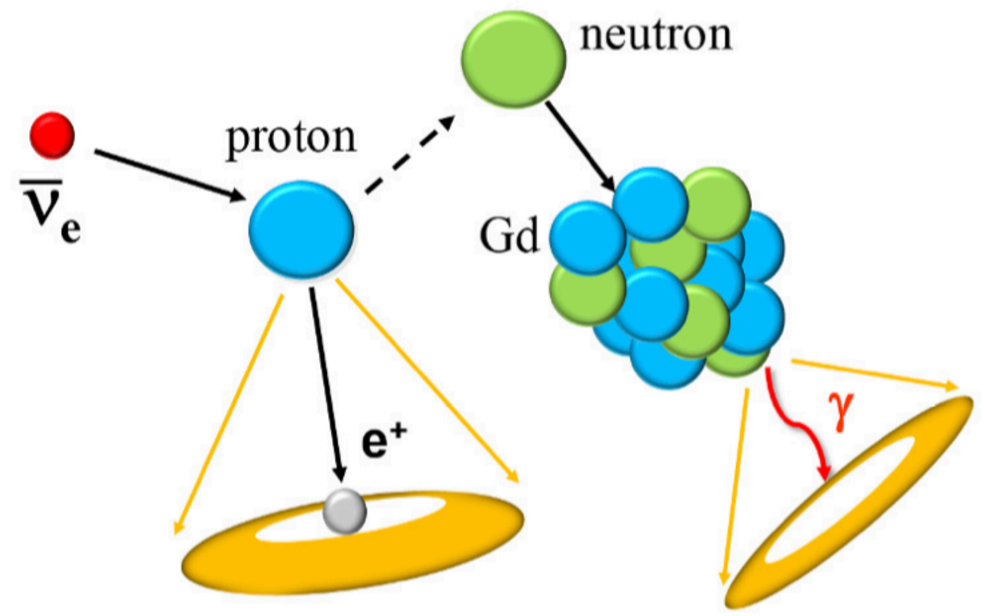
  Help model atmospheric background for DSNB & proton decay searches

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

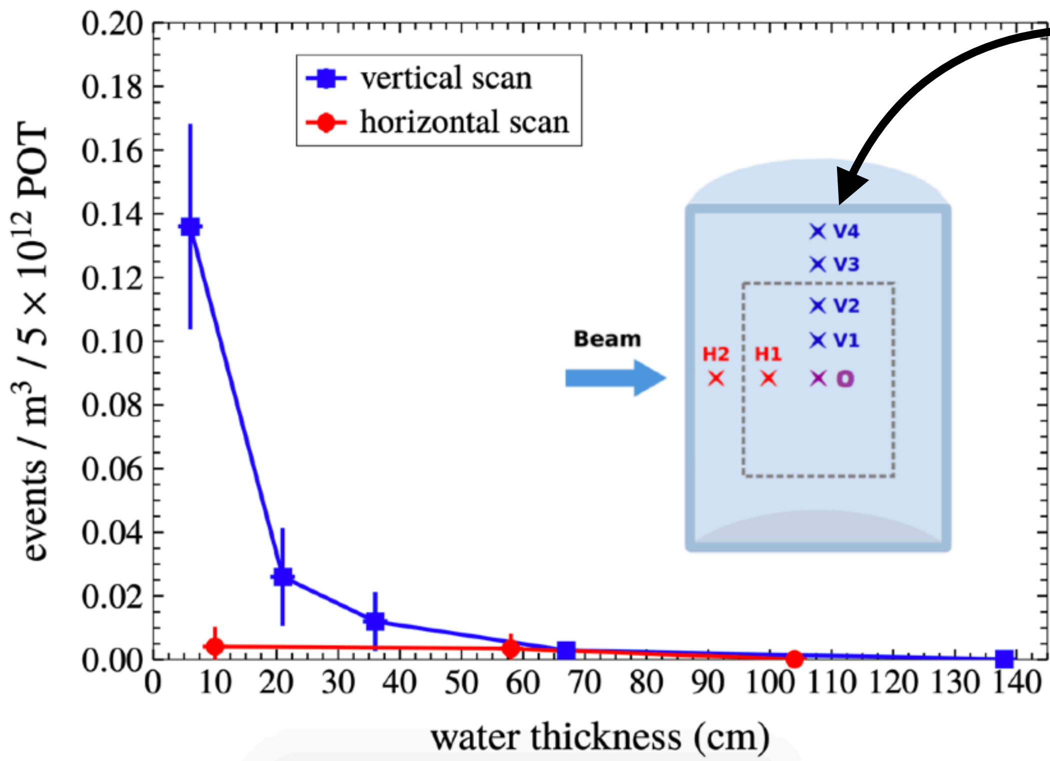
Capturing neutrons:

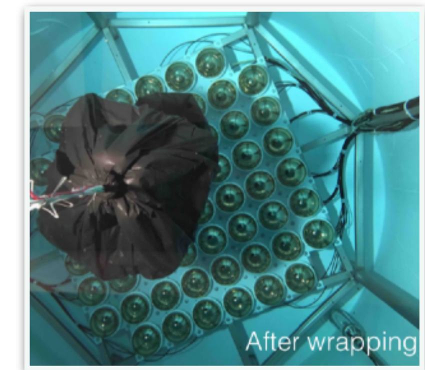


Neutron capture cross-section: ~50,000 barn
Total emitted gamma energy: ~8 MeV
Loading in water possible as sulfate or chloride

Roadmap to neutron multiplicity

JINST15 (2020) 03 P03011





Neutron Capture Volume (NCV)

Prerequisite:

Phase I

2018

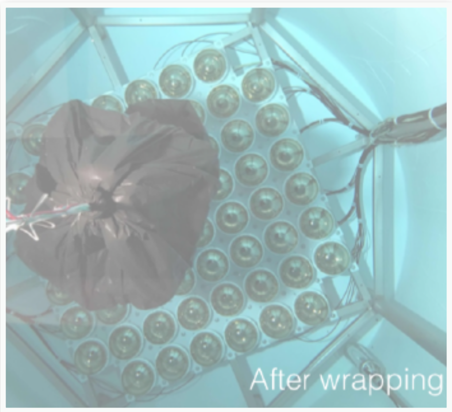
2016

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

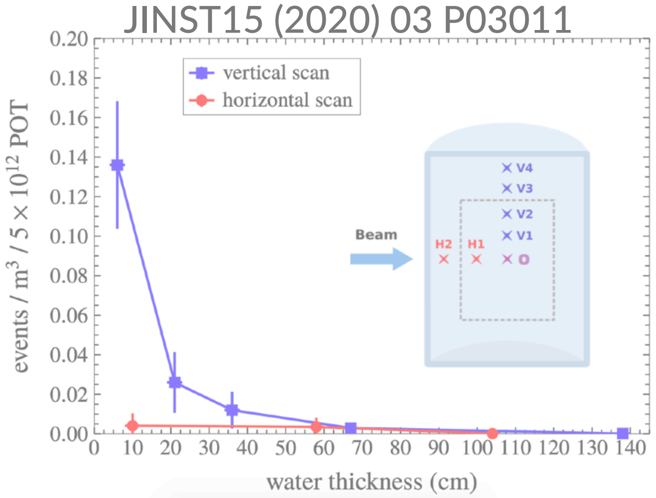
Background neutron rate < 0.02/m³/spill

→ Background no problem for phase II

Roadmap to neutron multiplicity



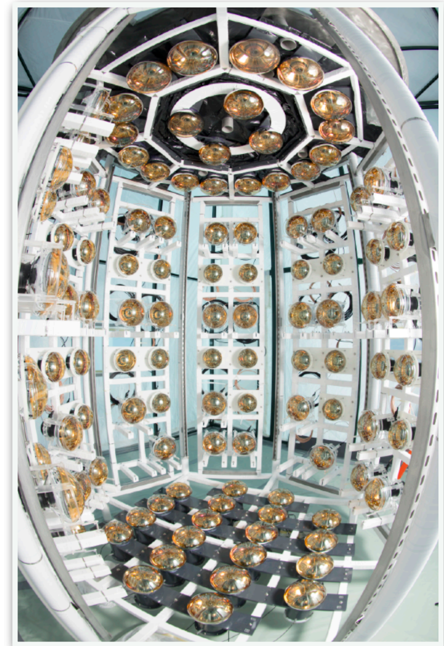
JINST15 (2020) 03 P03011



Prerequisite:
Phase I

2016

2018



Neutron multiplicity:
Phase II

2020

2021

- Physics phase
- Full 26-ton Gd-loaded Water Cherenkov detector
- Commissioning & neutron calibration runs with 132 PMTs completed

Up next:

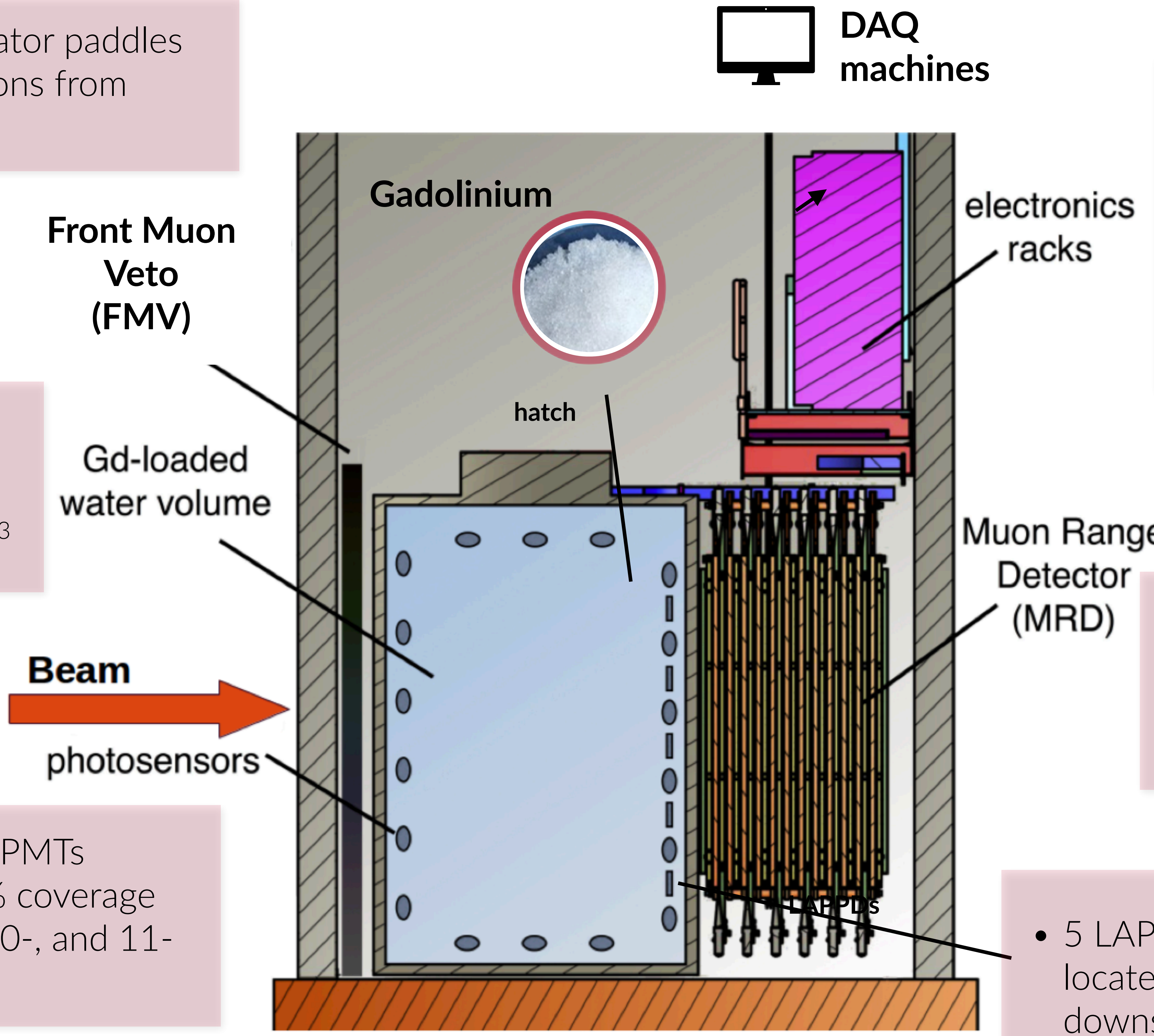
- First deployment of LAPPDs into ANNIE
- Further calibration campaigns:
  - Laser diffuser ball
  - ^{137}Cs standard candle

Phase II - Detector setup

- 26 scintillator paddles
- reject muons from upstream

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

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

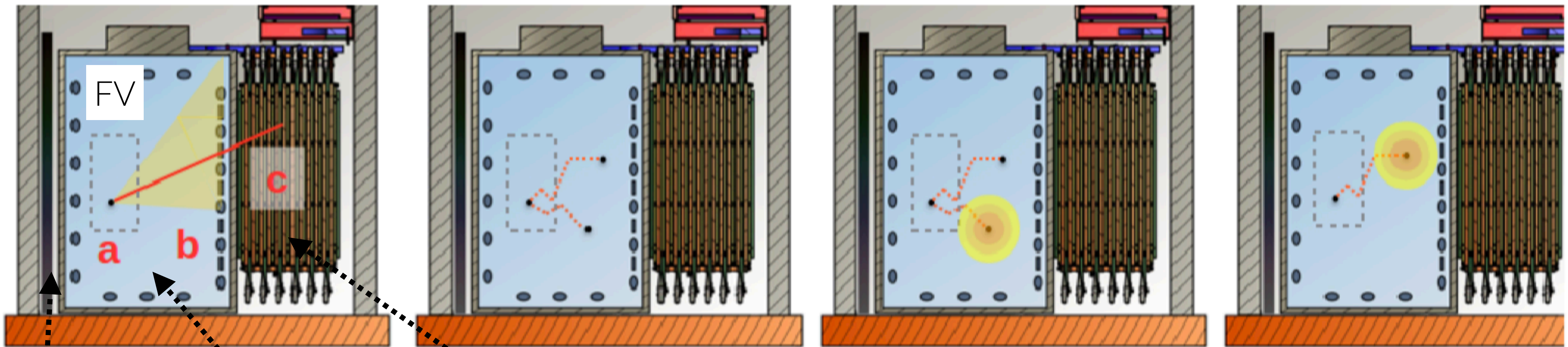


- VME acquisition system for PMT signals (500MHz)
- ACDC cards sampling LAPPD response (10 GHz)

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

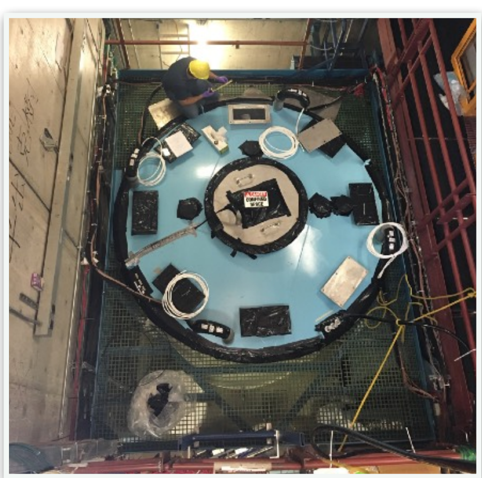
- 5 LAPPDs located downstream

Phase II - Event schematic (ν_μ CCQE event)

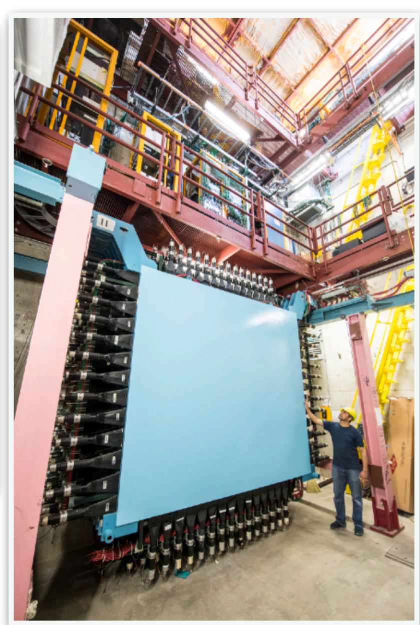


1 2 3 4

Front Muon Veto



Water tank

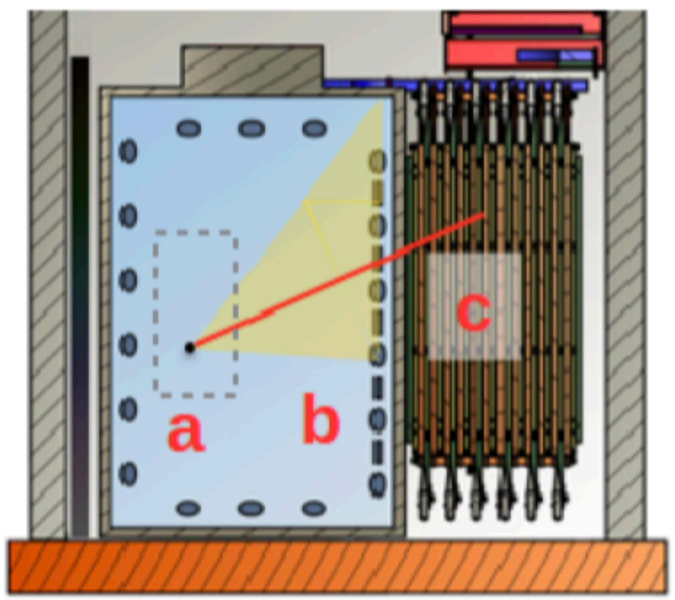


Muon Range Detector

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

Phase II - Neutron multiplicity components

Neutrino interaction + prompt muon signal



Milestones & next goals

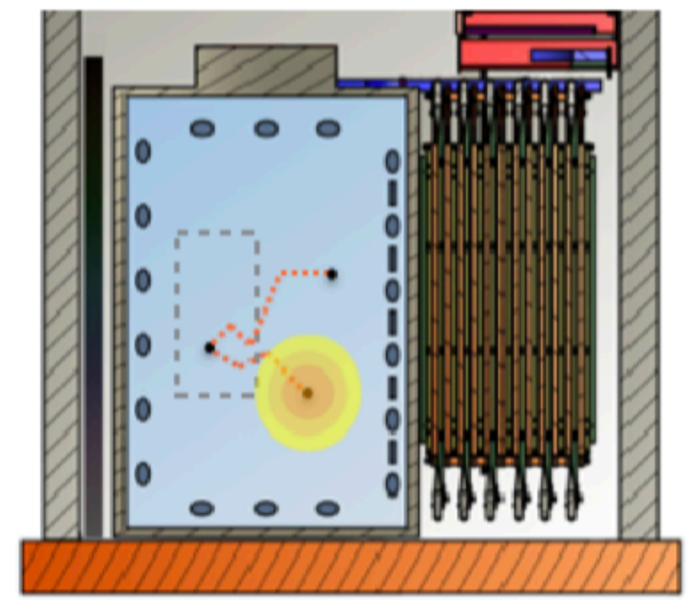
→ Identify the beam & neutrino interactions in the tank

→ Reconstruct muon tracks in MRD

→ Characterize & deploy LAPPDs for boosted reconstruction performance

+

Neutron capture signals

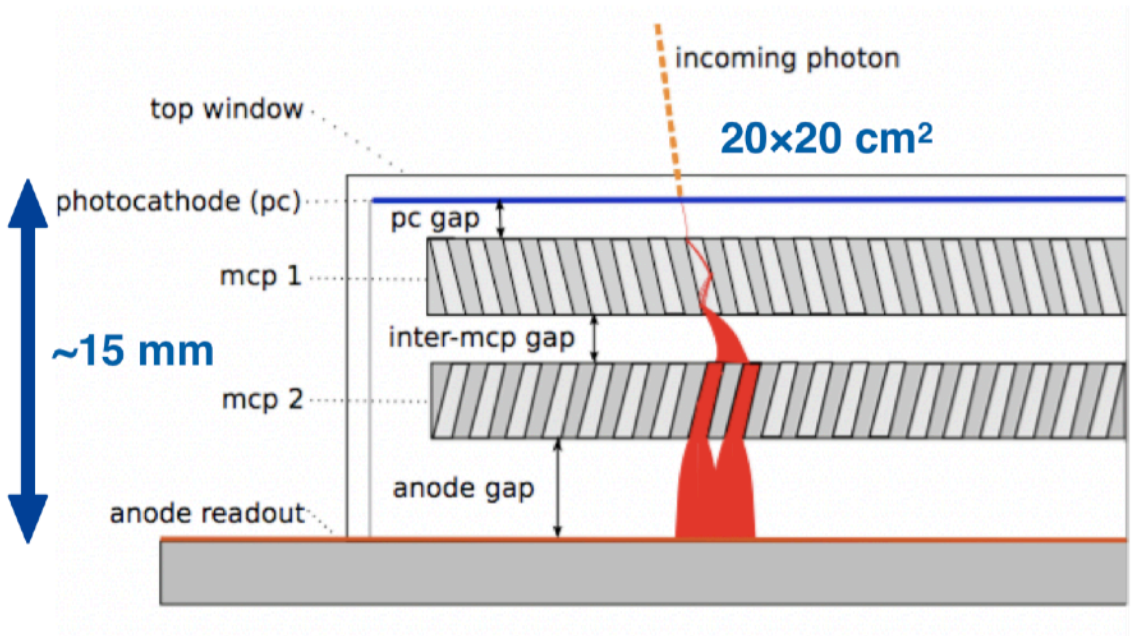


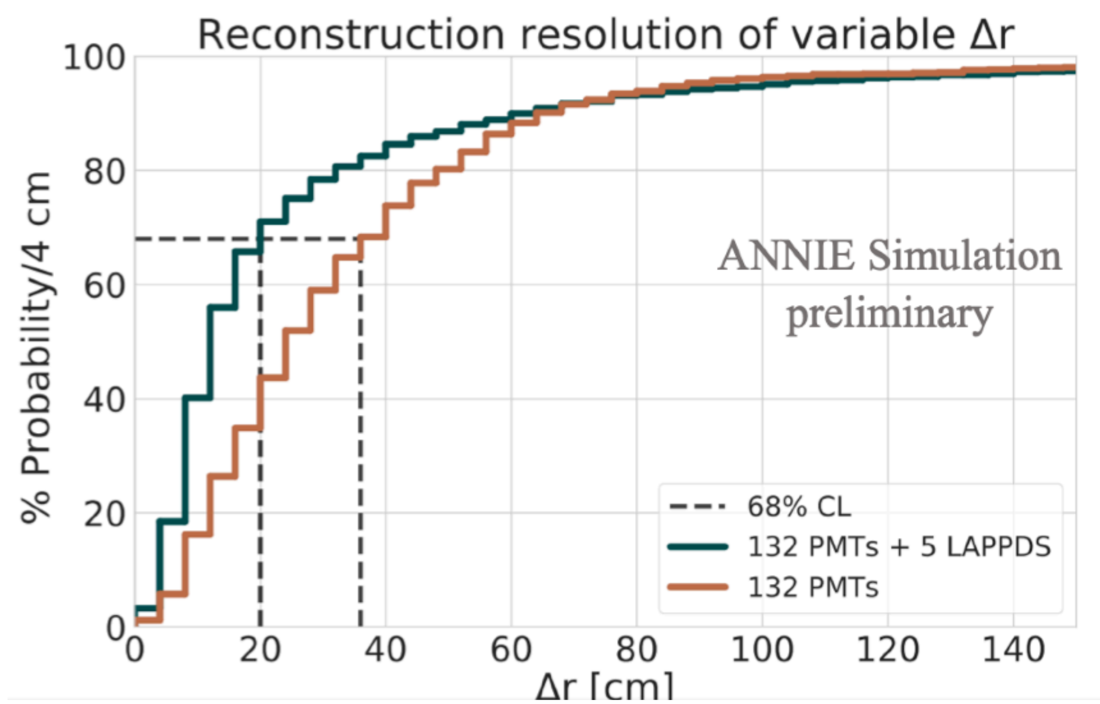
Milestones

→ Full Gadolinium-loading with stable transparency

→ Neutron calibration campaign (capture efficiency)

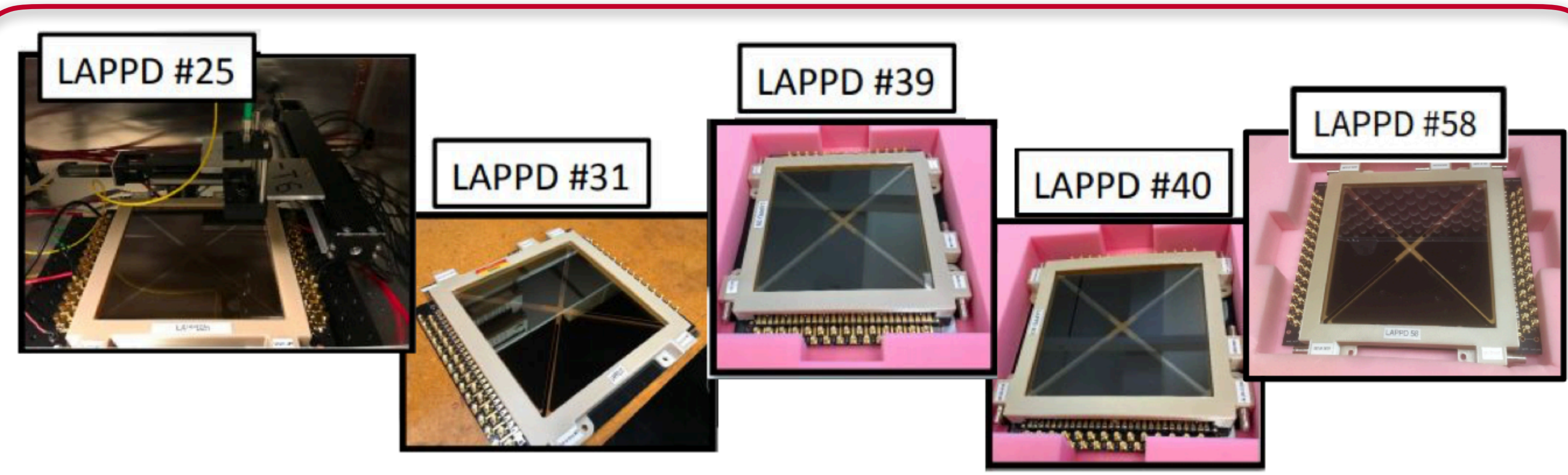
LAPPD: **L**arge **A**rea **P**icosecond **P**hoto **D**etector





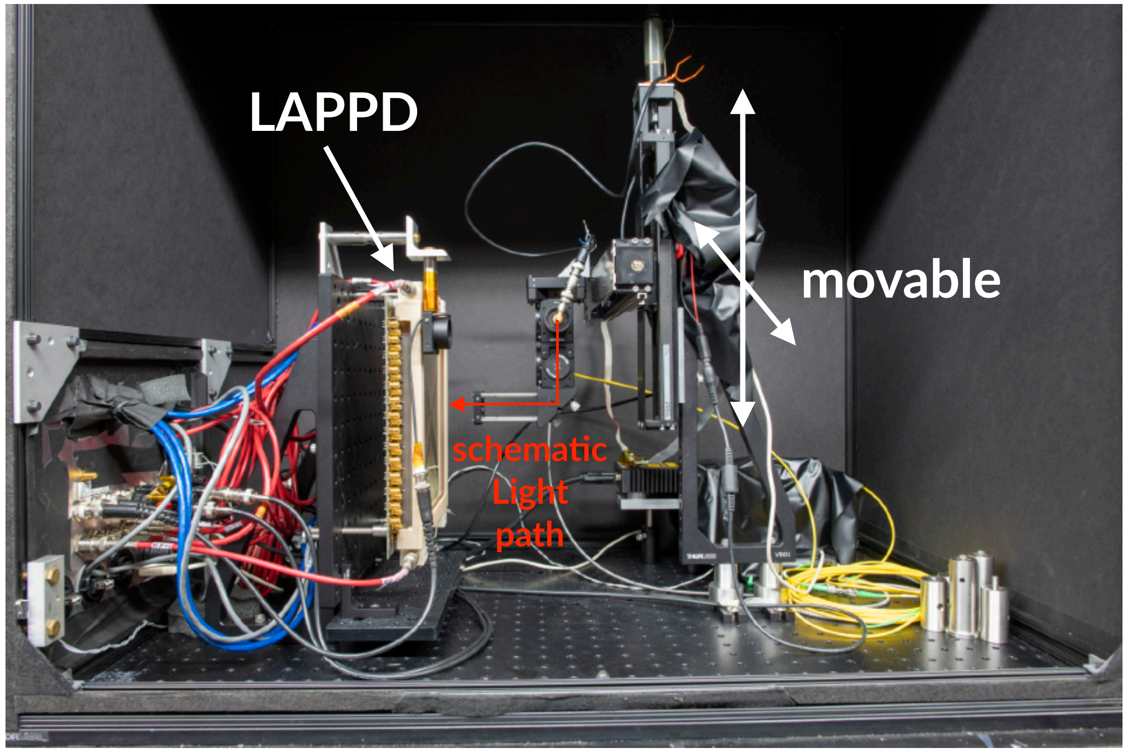
- 20 cm x 20 cm photodetector with intrinsic position resolution (mm-cm scale)
- Microchannel plate structure with resistive & emissive coating + microstrip anode readout
- Fast detection capabilities (time resolution ~60 ps)
- ANNIE has 5 LAPPDs at hand, characterization ongoing at Fermilab test stand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

ANNIE LAPPDs



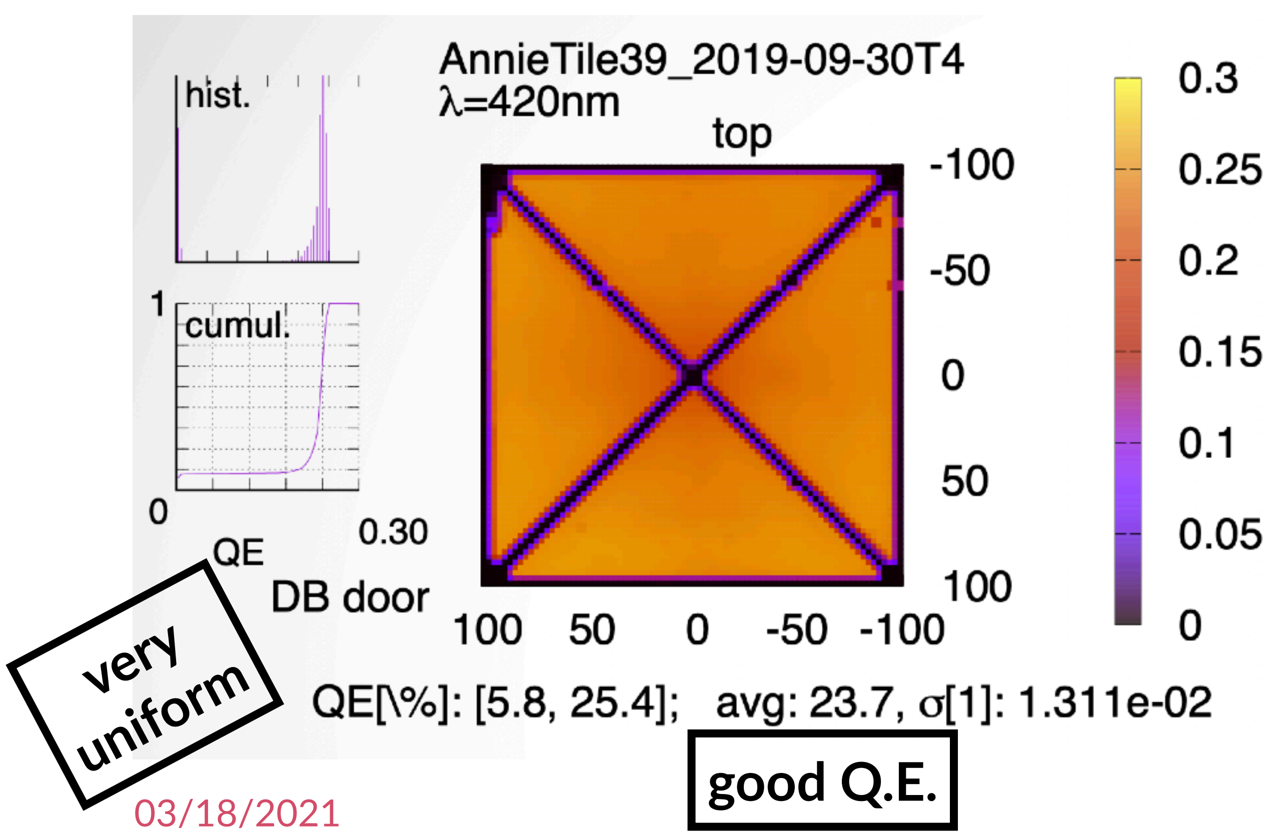
Phase II - LAPPD characterization

Dedicated test stand at Fermilab

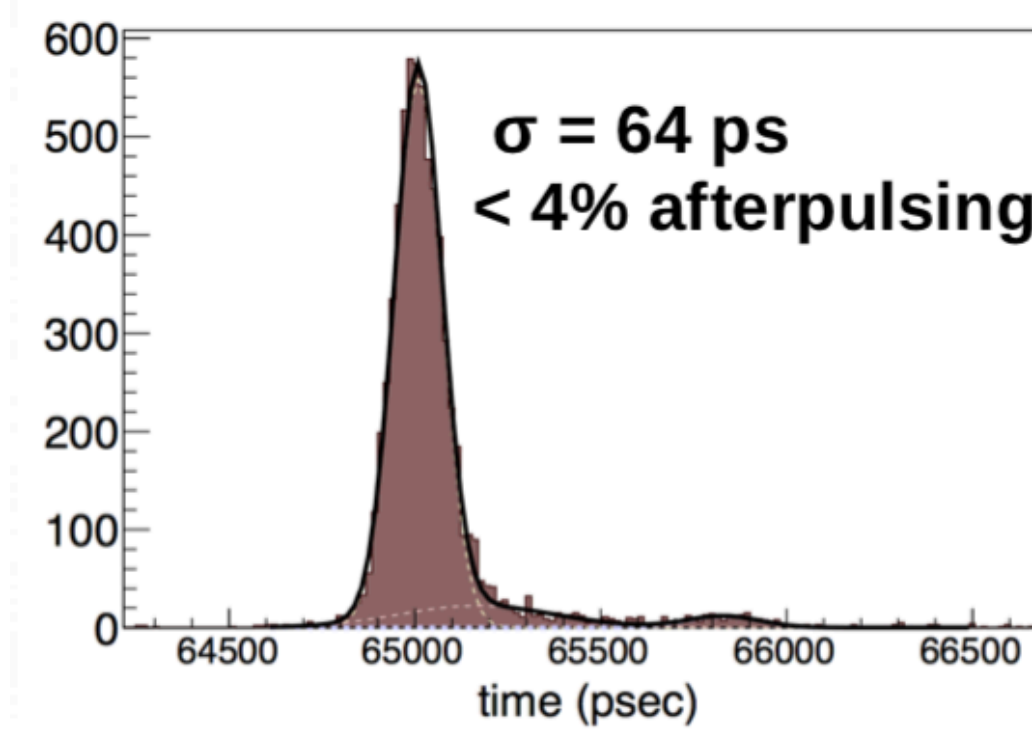


- Systematic tests of all 5 LAPPDs at dedicated facility at Fermilab
- Q.E., gain & timing calibration scans:
  - Movable & motorized LED/laser setup
  - Automated scans over the whole surface
- Deployment planned soon

ANNIE data

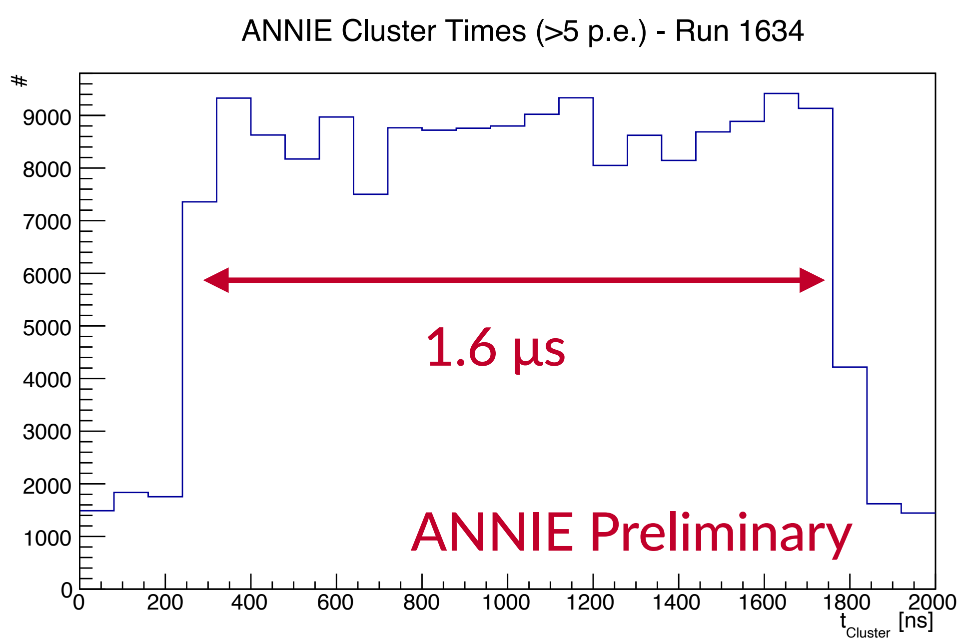


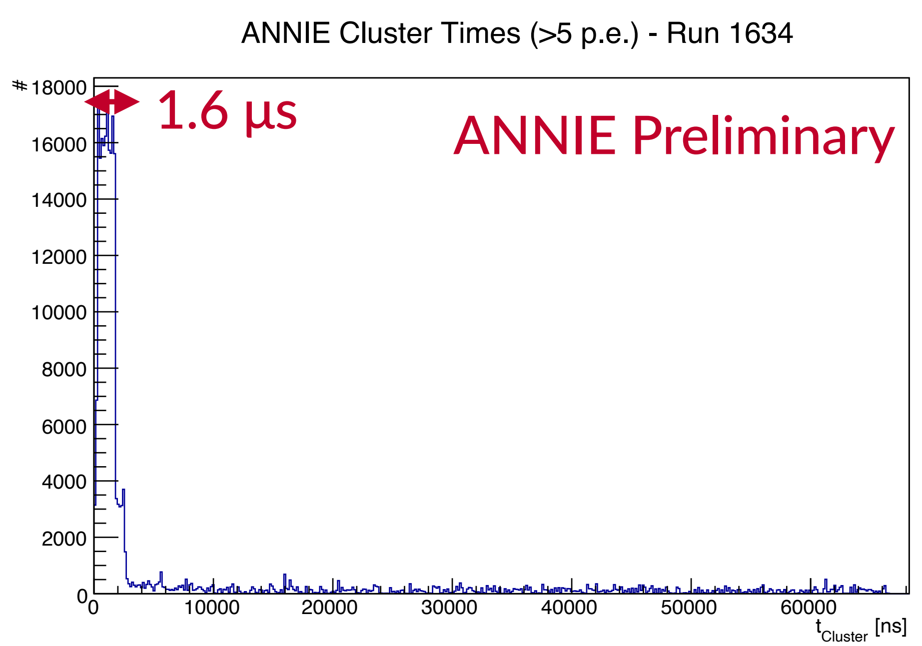
ANNIE data



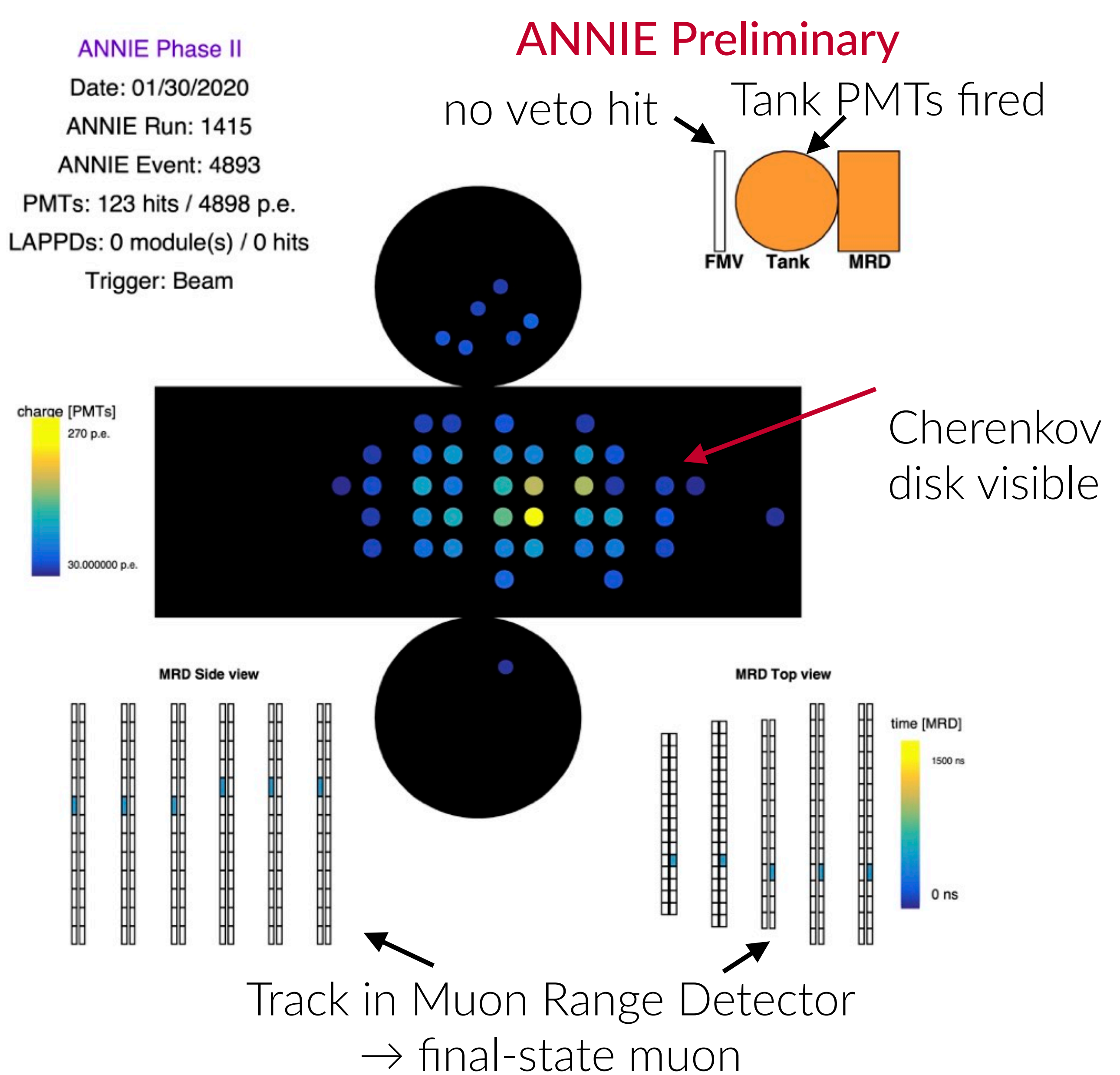
Phase II - Neutrino interactions

Detect the beam spill in the data





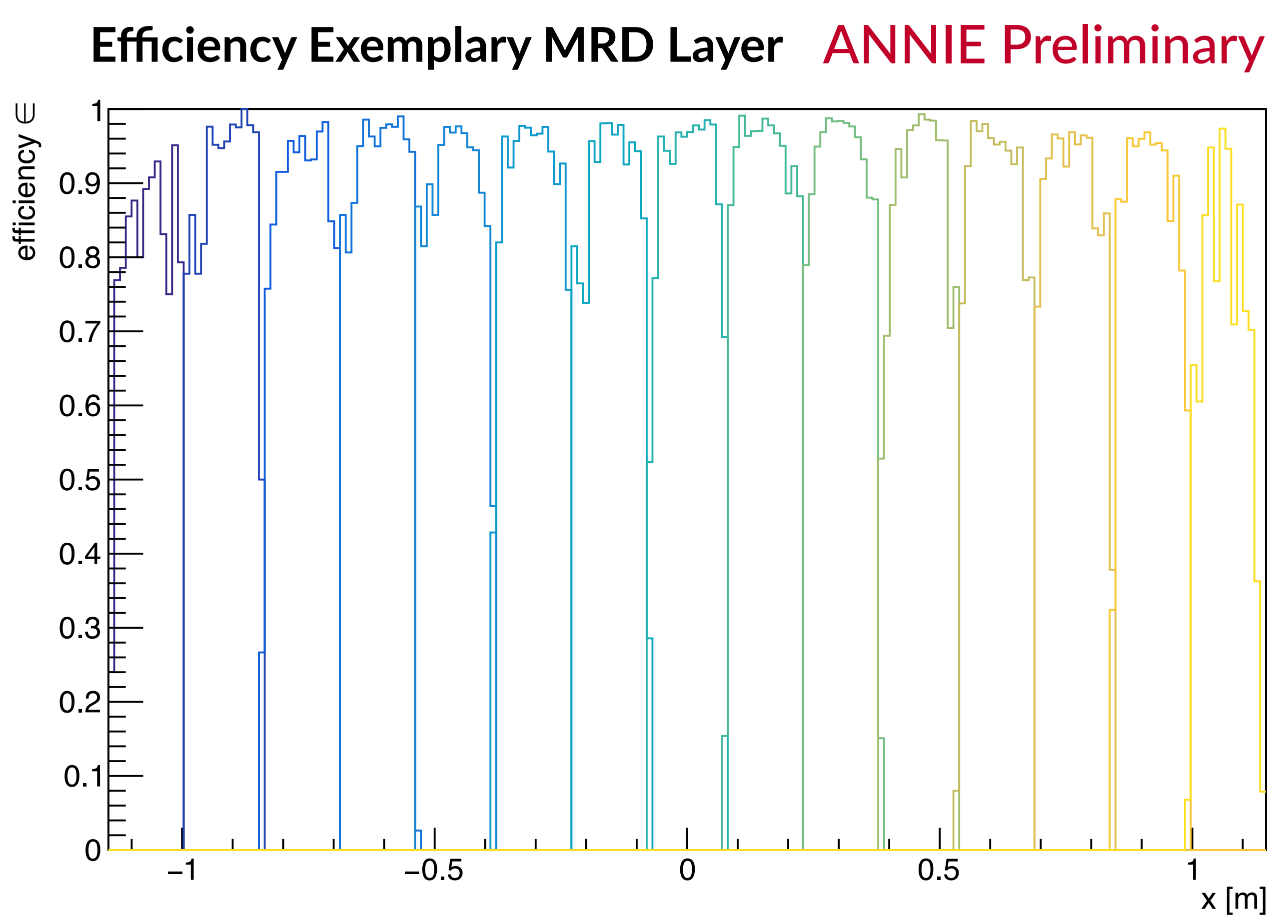
Event display of beam commissioning neutrino candidate

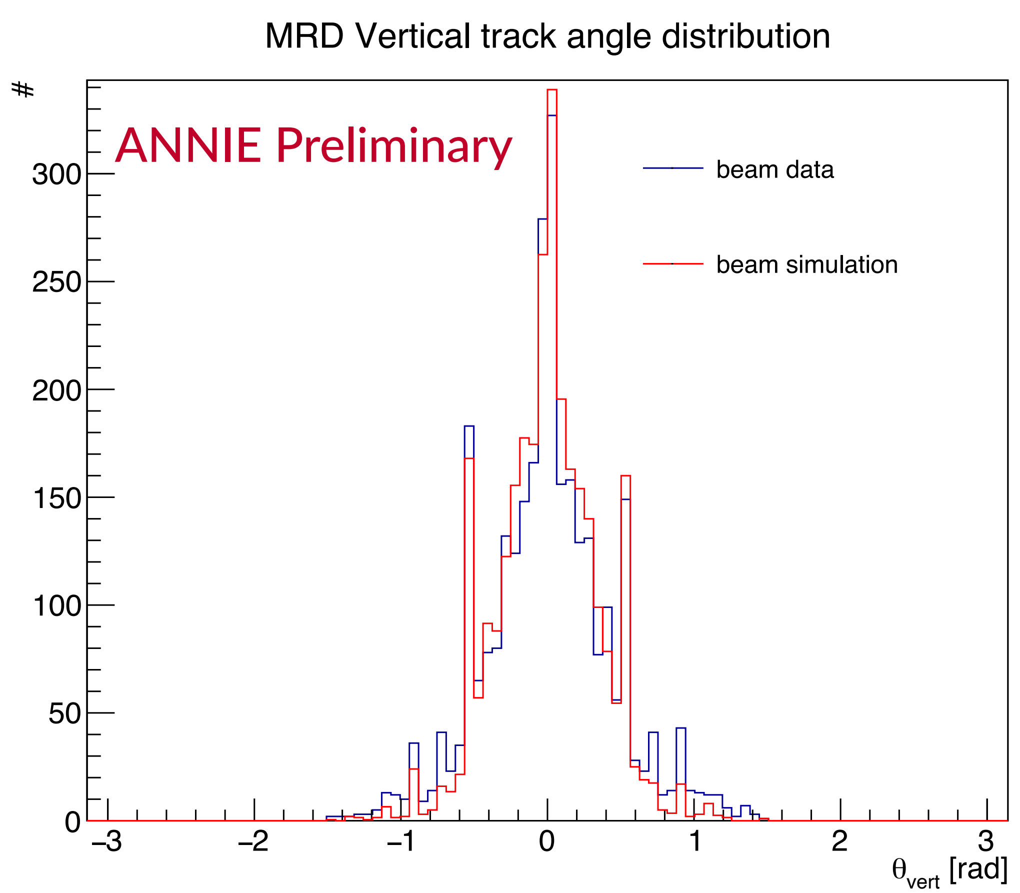


ANNIE observes neutrino candidates!

Phase II - Muon track reconstruction in MRD

- In-situ calibration of MRD scintillator paddle efficiencies shows good results with ε > 95%
- Reconstructed muon angle distribution in agreement with MC beam simulations
- Muon characterization in the MRD works as intended



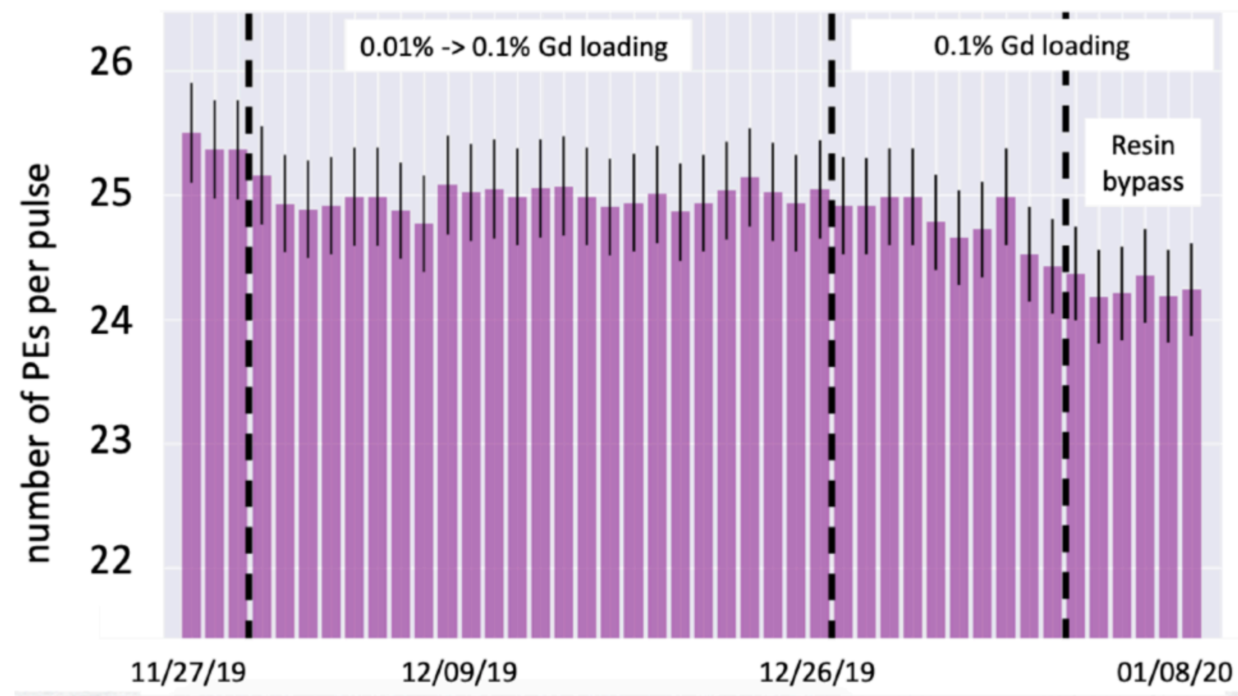


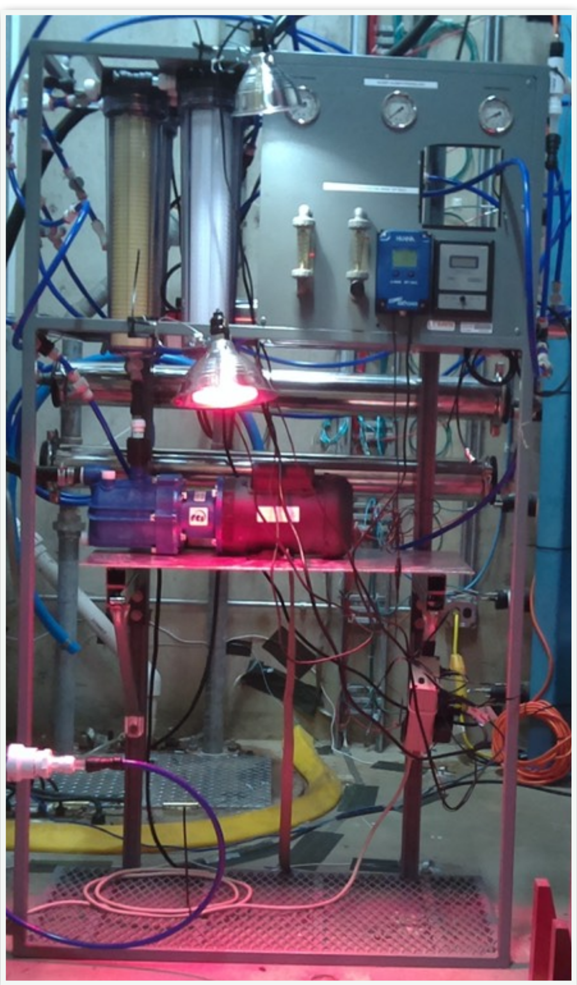
Phase II - Gadolinium loading

- Custom water purification system developed by UC Davis collaborators:
  "V. Fischer et. al, "Development of an ion exchange resin for gadolinium-loaded water" [JINST15 (2020) 07 P07004]

- Nominal Gd loading of 0.2% $Gd_2(SO_4)_3$ achieved Dec 24th, 2019

- Water transparency stable for more than a year now (LED measurement)

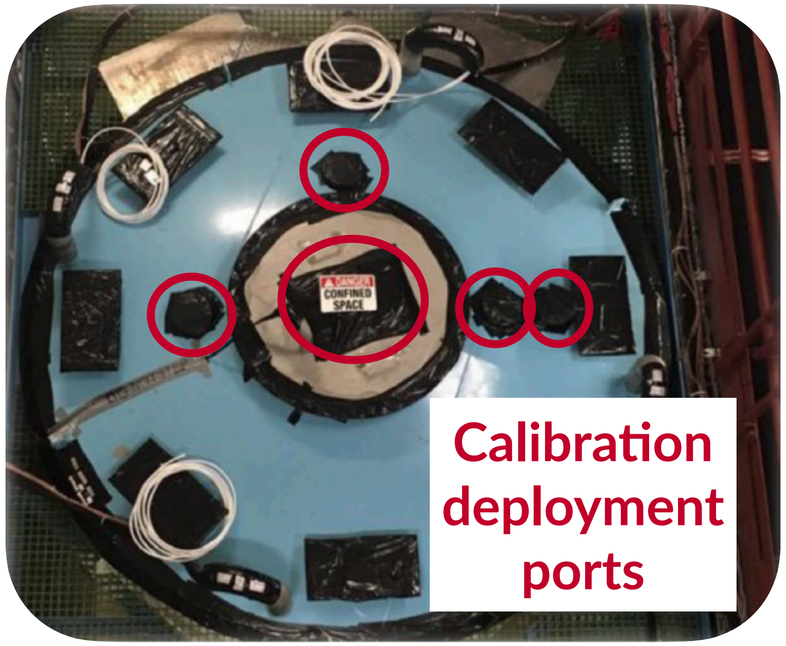




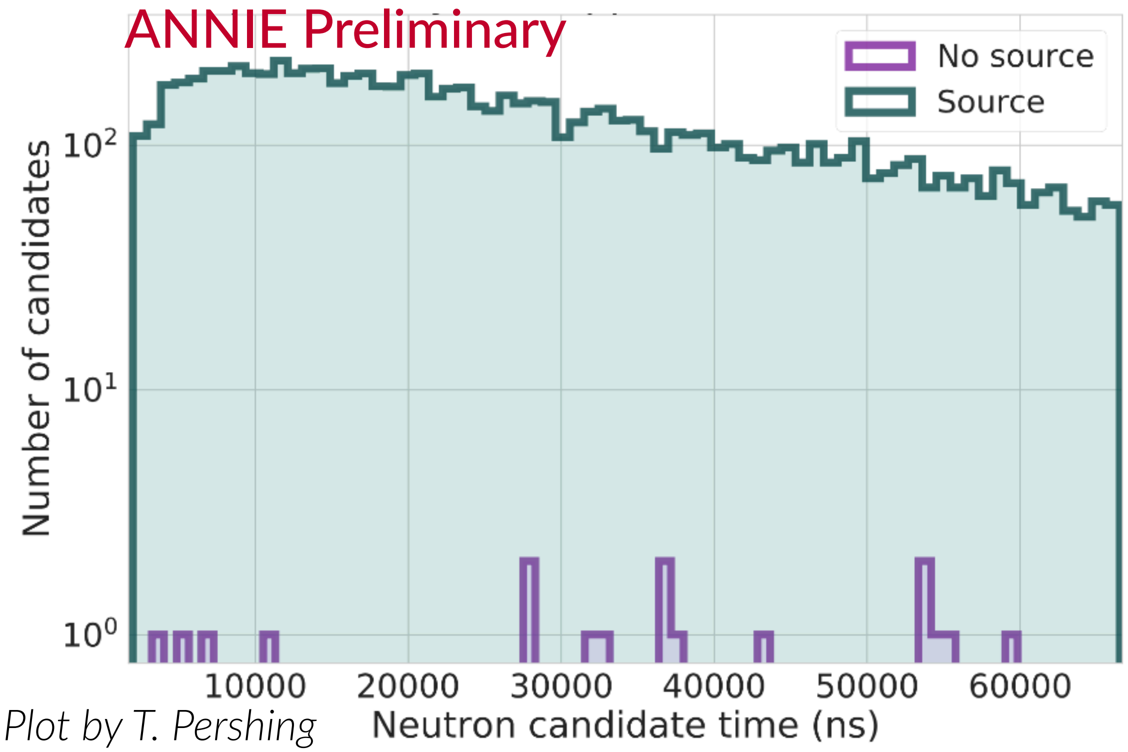
Phase II - Neutron capture calibration

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

UVT acrylic container



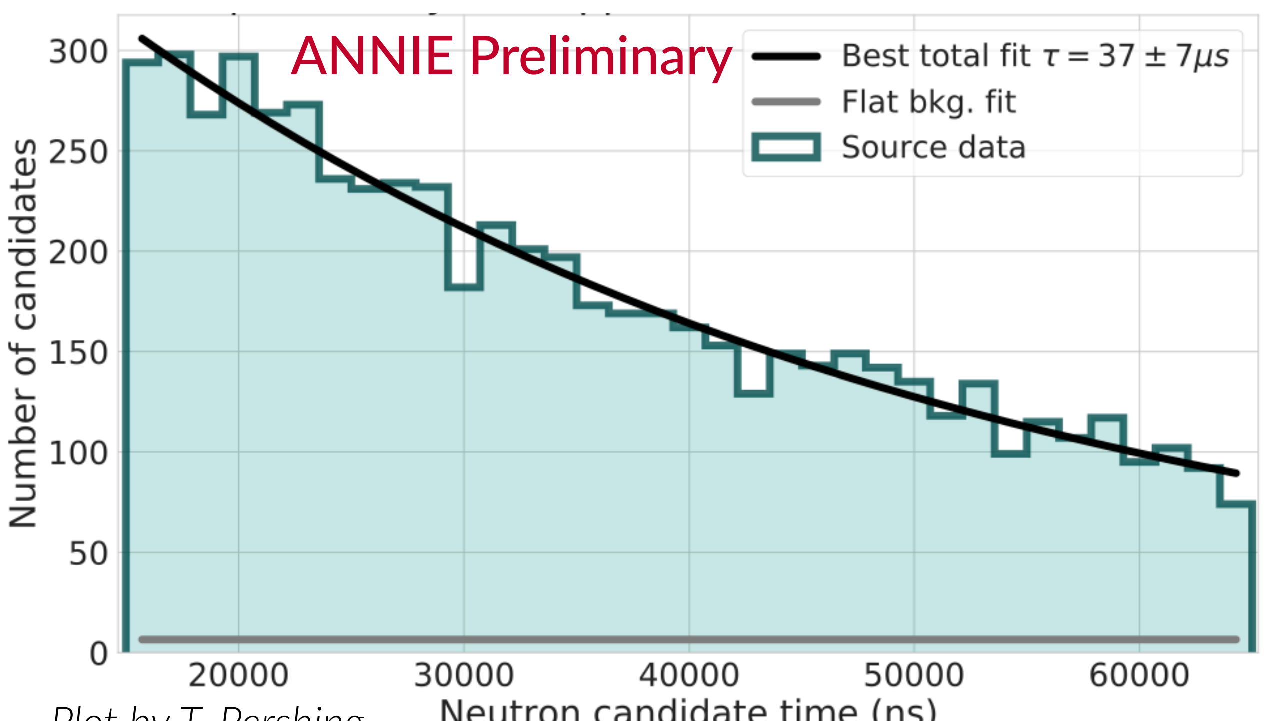
Selection cuts



Plot by T. Pershing

Neutron selection cuts provide pure neutron sample

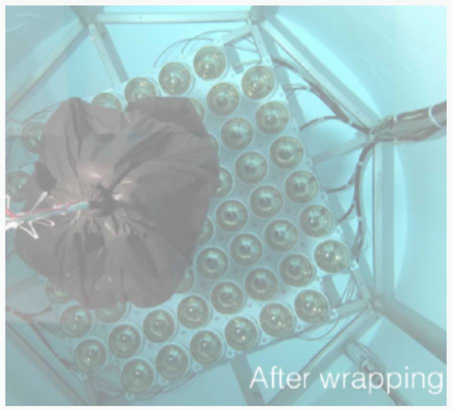
Neutron time profile



Plot by T. Pershing

Capture time profile consistent with expectations

Roadmap to neutron multiplicity



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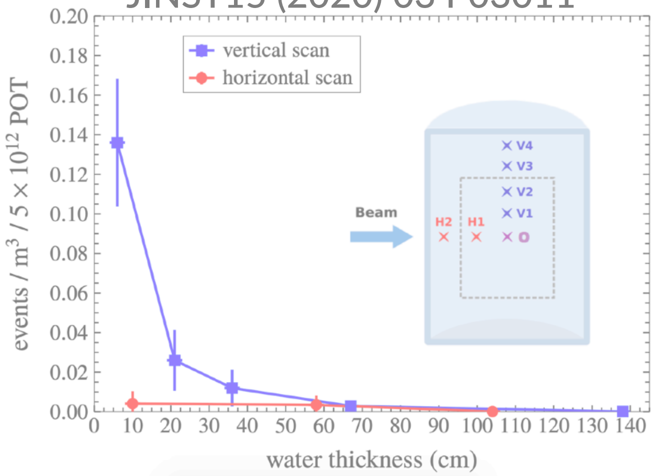
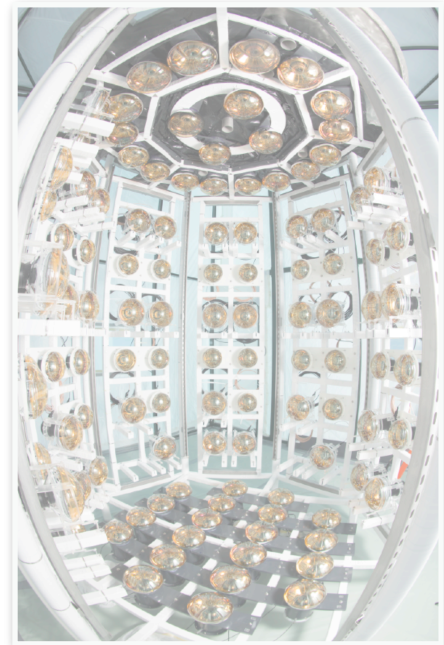


Prerequisite: Phase I

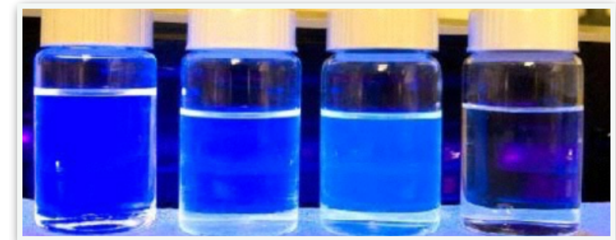
2016

2018



Neutron multiplicity: Phase II

2020



The future: Phase III

2021+

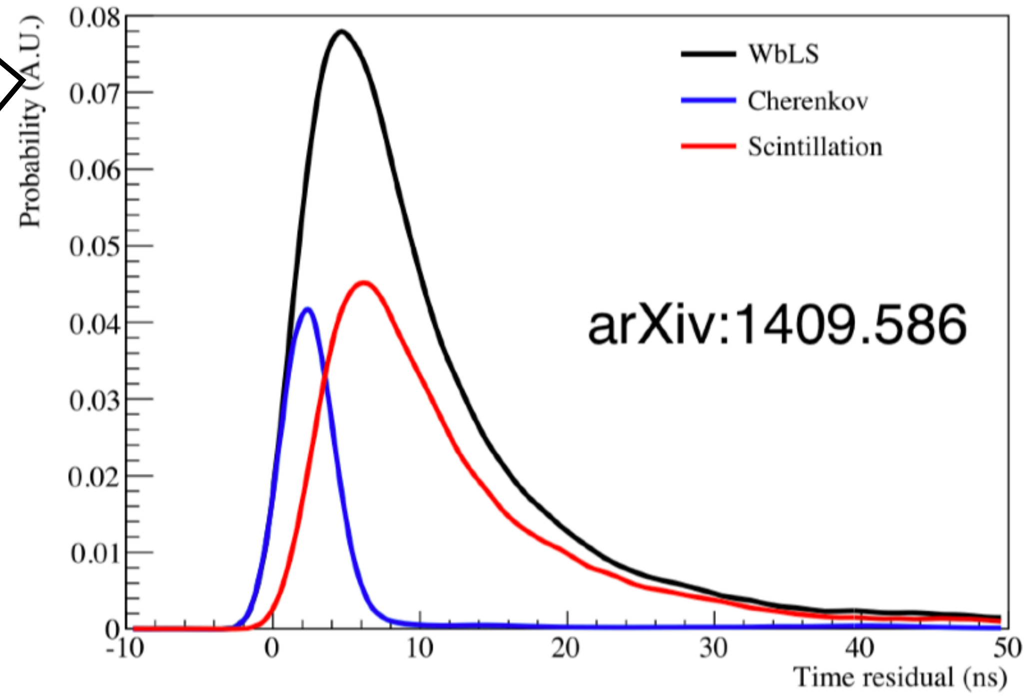
Further extensions to the detector:
- More than five LAPPDs
→ multi-track reconstruction

Testbed for new technologies:
- Water-based liquid scintillator volume in ANNIE

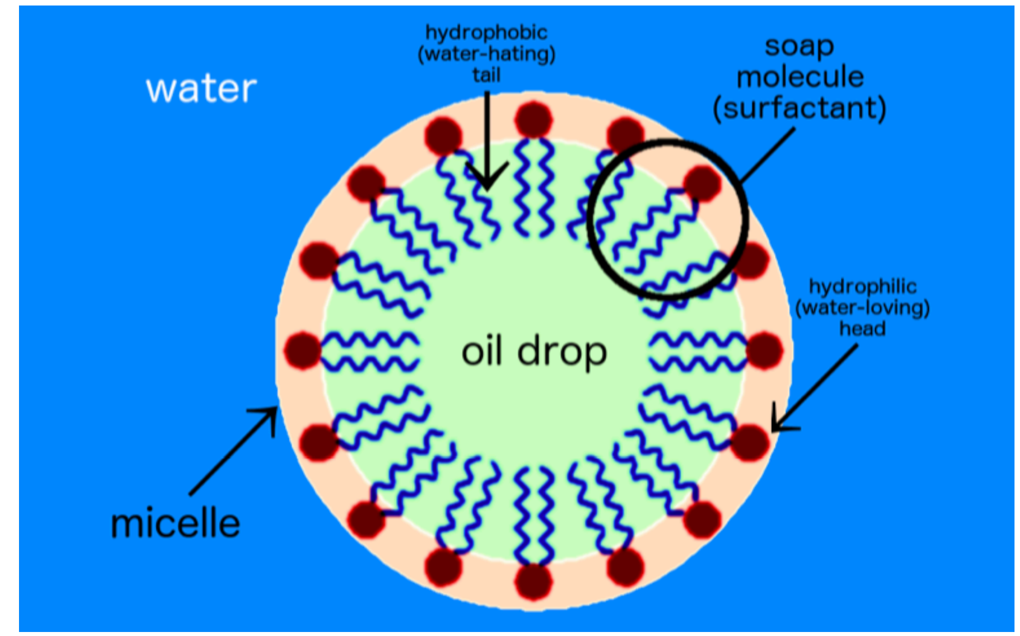
The future: Phase III - Water-based Liquid Scintillator

Separate Cherenkov- & scintillation light → ultrafast photosensors

Water-based Liquid Scintillator time profile



Micelle structure

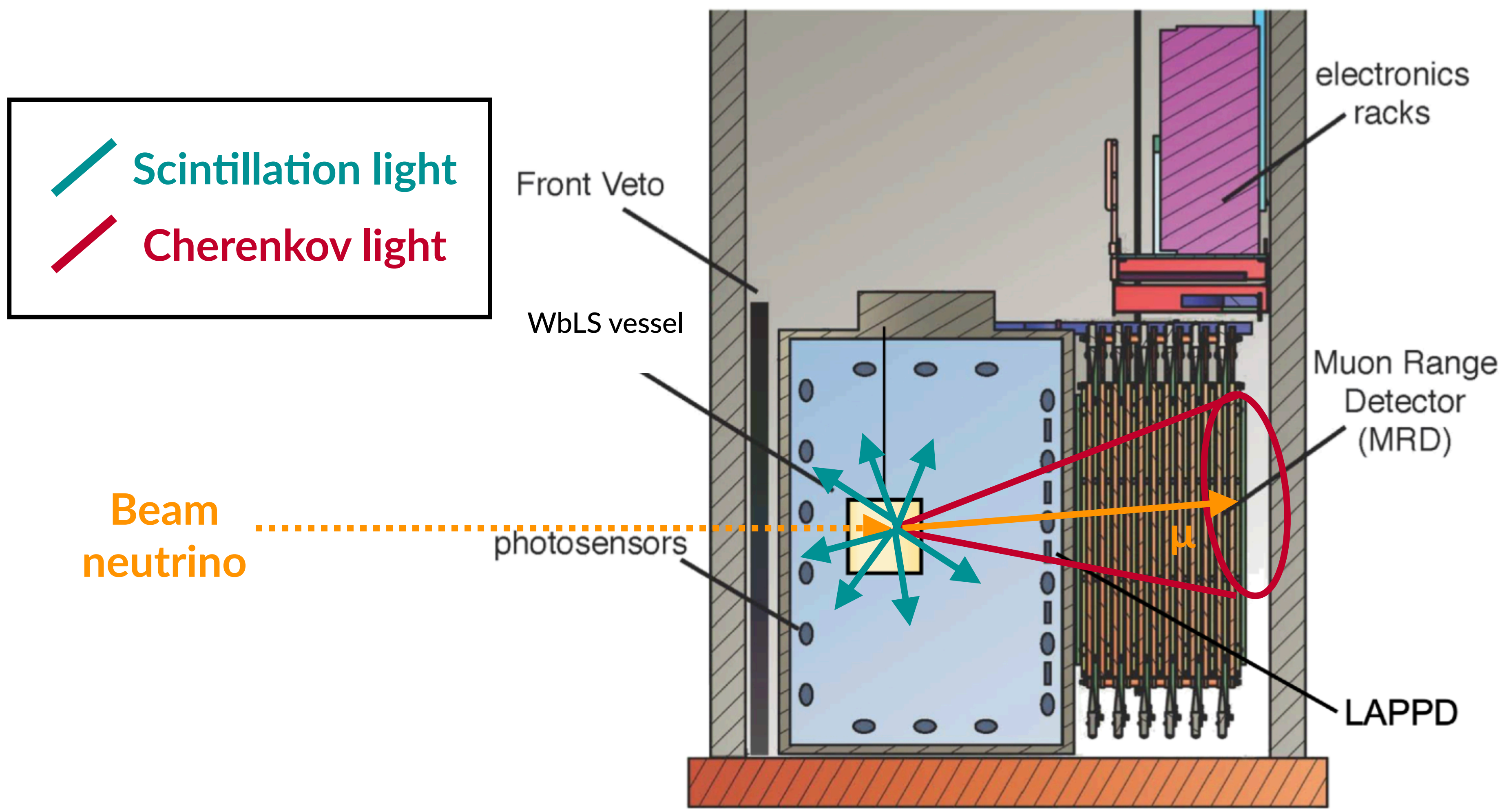


- **Water-based Liquid Scintillator (WbLS):** Novel detection medium for which Liquid Scintillator droplets are dissolved in water

- 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

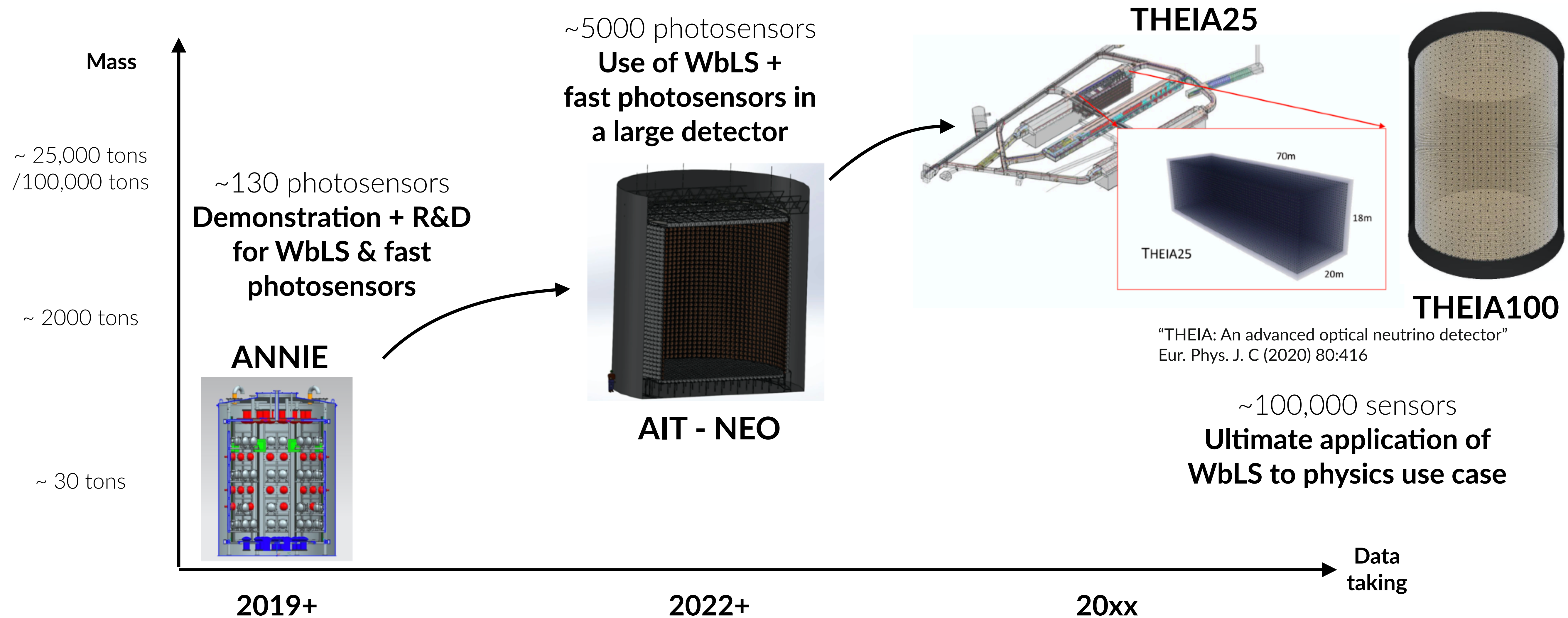


WbLS vessel

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

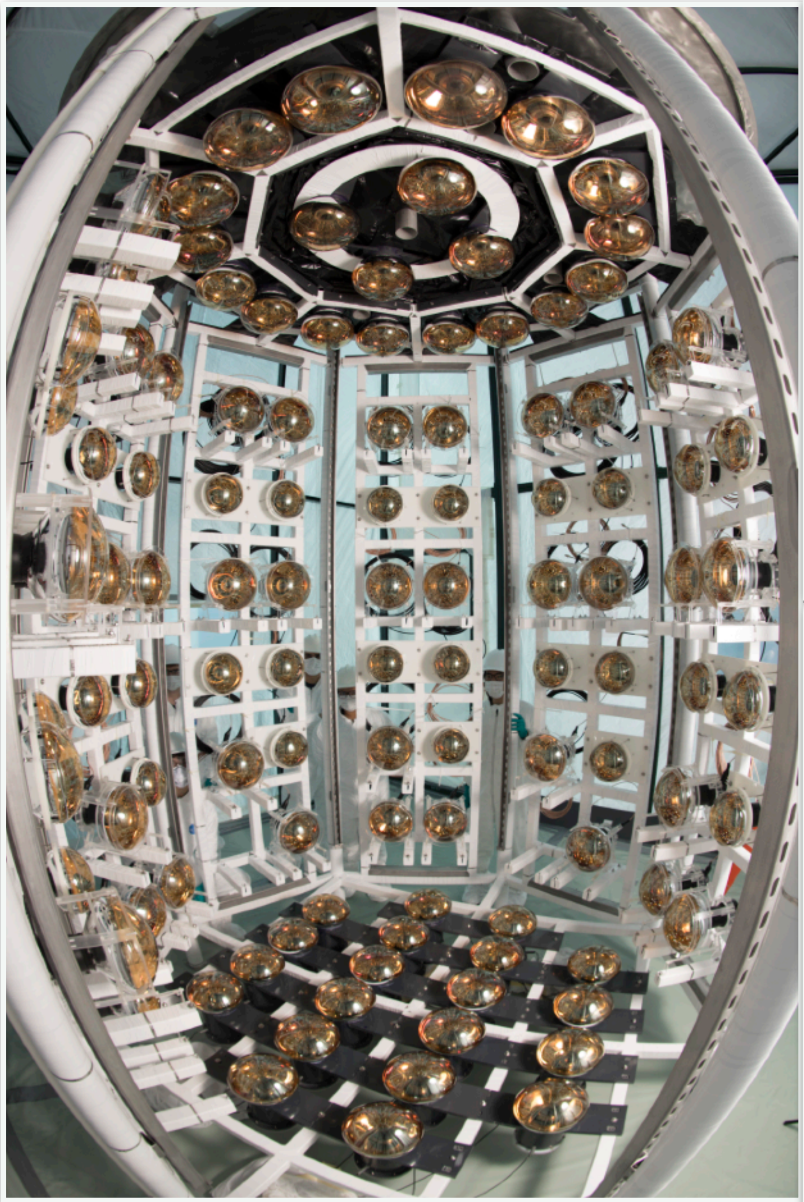


- **NEO - Advanced Instrumentation Testbed (AIT):**
  - Remote reactor monitoring through Inverse Beta Decay, 2kt Cherenkov detector
  - Both Gd-loaded water / WbLS considered as medium

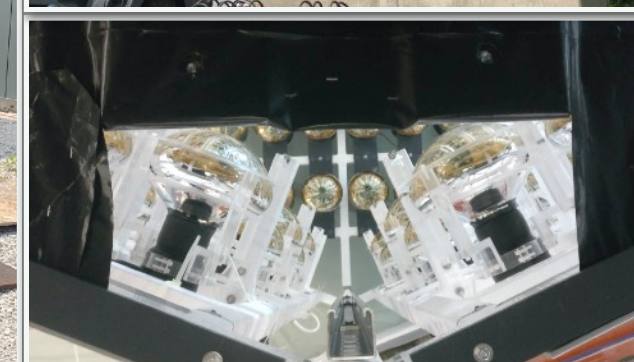
- **THEIA (25/100):**
  - 25kt Cherenkov detector (WbLS) option in one of the DUNE caverns (module of opportunity)
  - Broad physics program: Long baseline neutrinos, 0νββ, CNO neutrinos, SN neutrinos, geoneutrinos

Summary

- **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
  - CC-0π 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)
  - **2020:**
    - Detector commissioning, first beam neutrinos detected
    - Active water transparency monitoring (LED)
    - Neutron capture efficiency calibration (AmBe)
  - **2020/2021:**
    - Characterization of all 5 LAPPDs
  - **Soon:**
    - ANNIE's first LAPPD deployment
- **Future:**
  - Testbed for new detection medium of water-based Liquid Scintillators







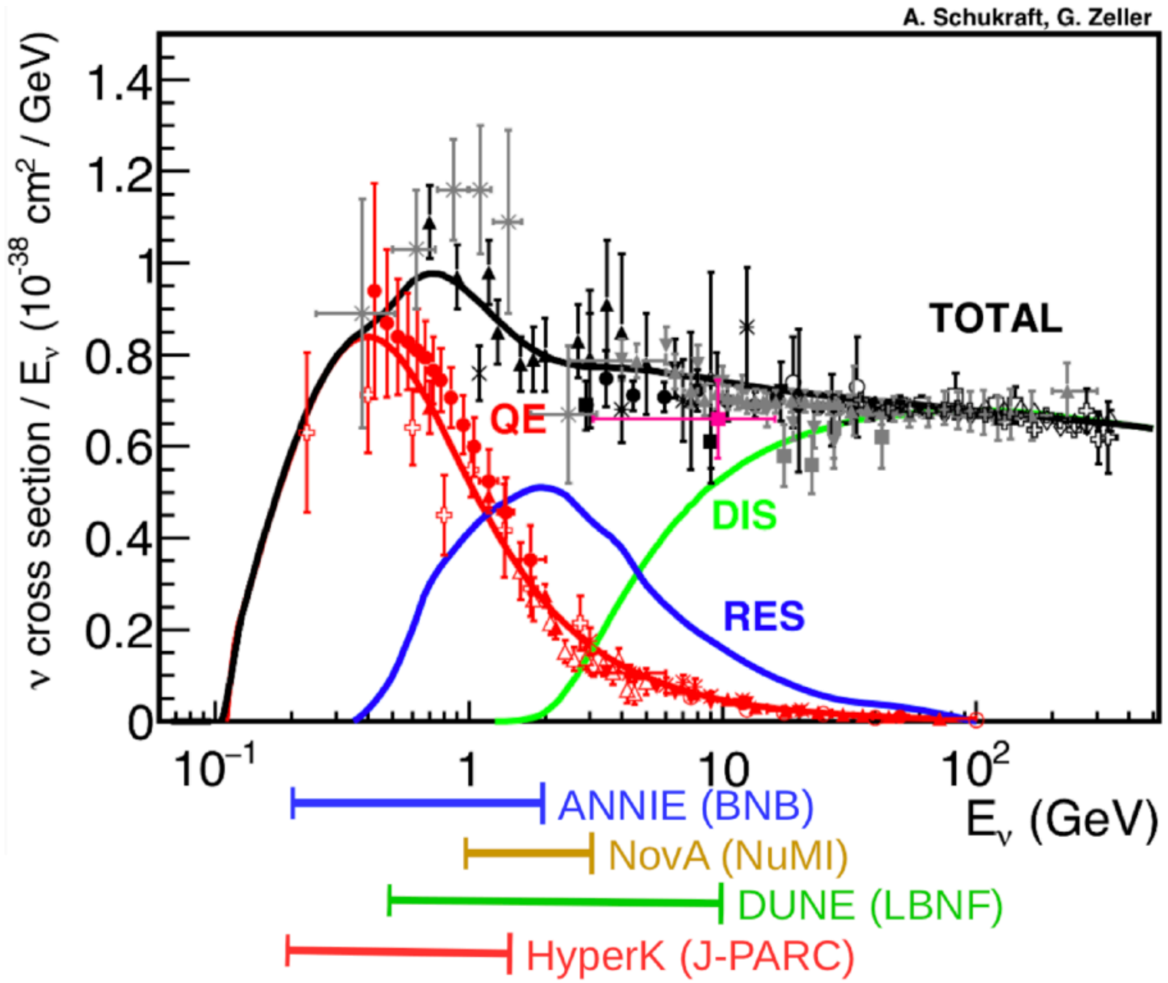
annie

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
Erciyes University

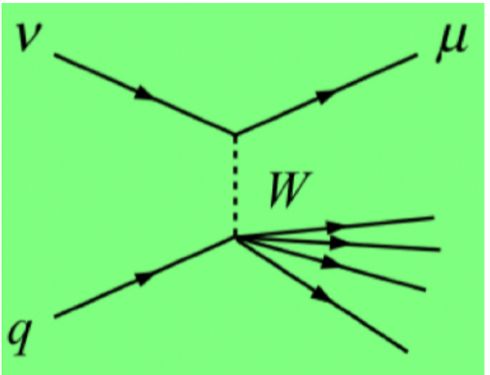
Thank you for your attention!
Any questions?

Physics motivation - Inelastic processes

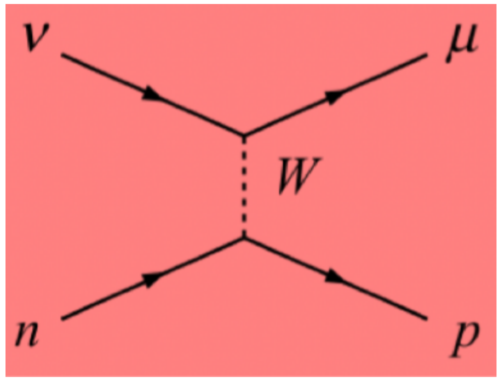
Relevant interactions in ANNIE:



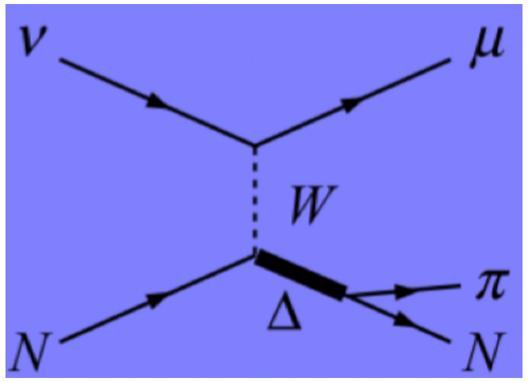
Deep Inelastic Scattering



Quasi-Elastic

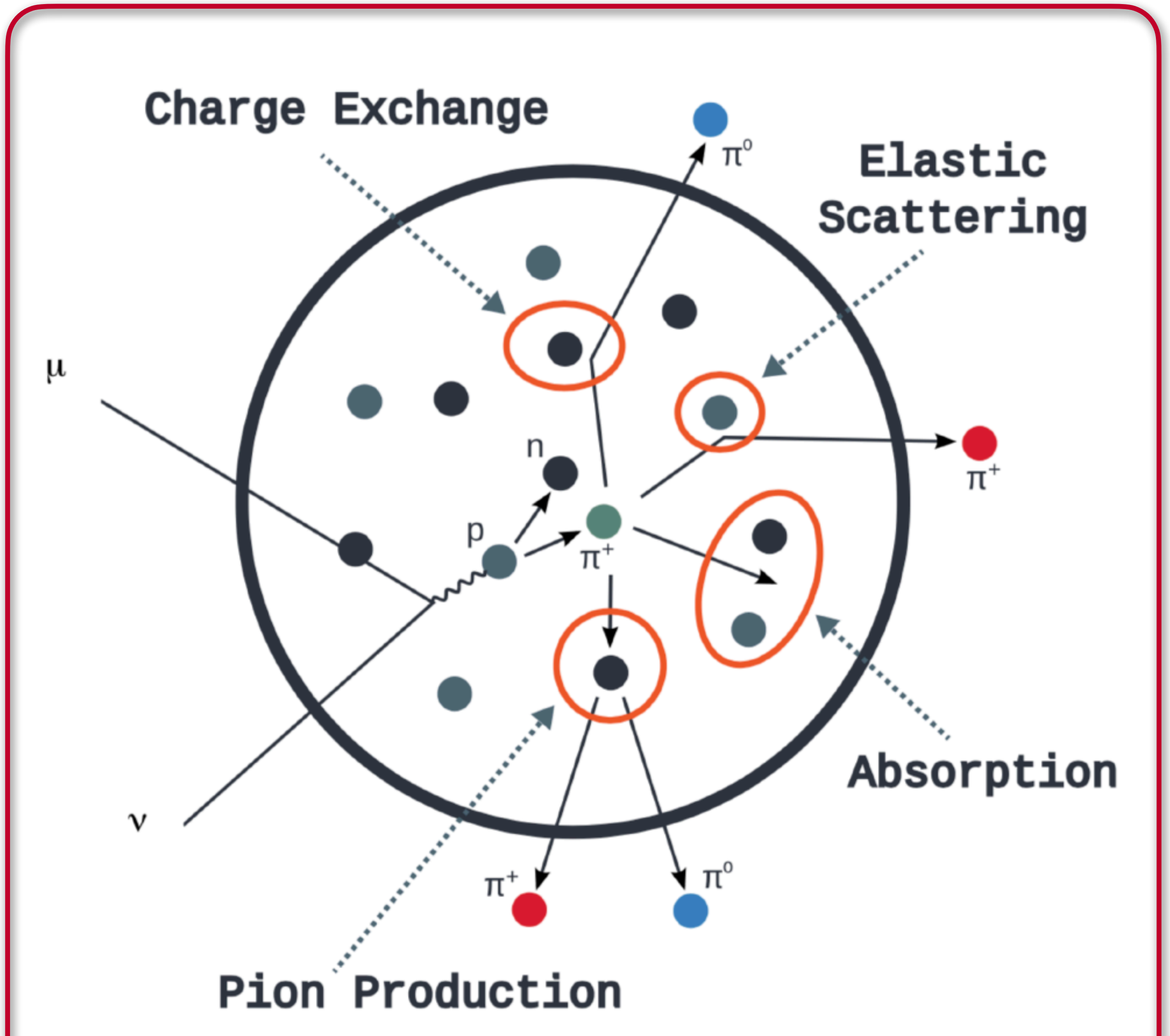


Resonance



- **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

Backup - Inelastic processes



taken from: *NuSTEC white paper*

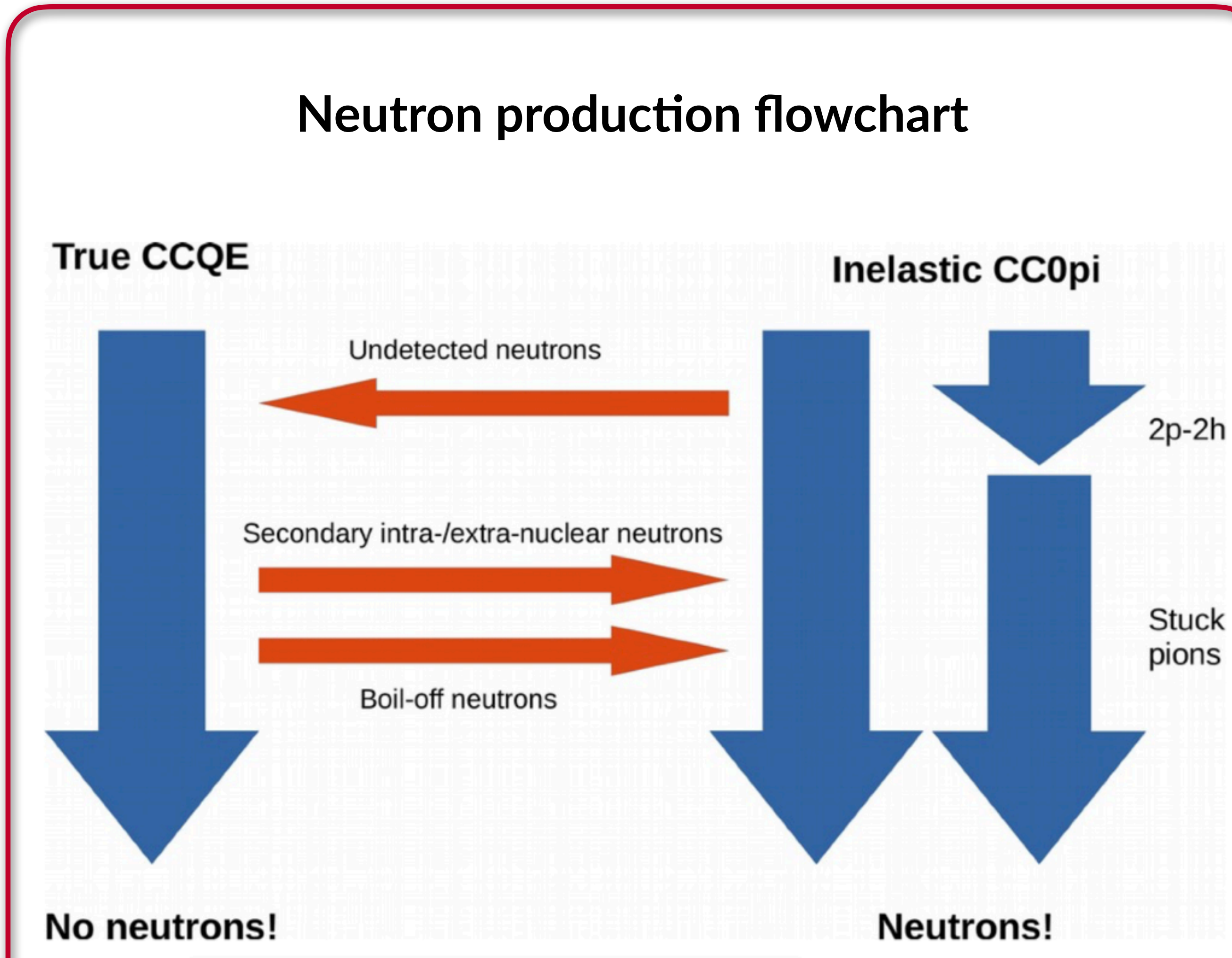


Diagram by Vincent Fisher, UC Davis

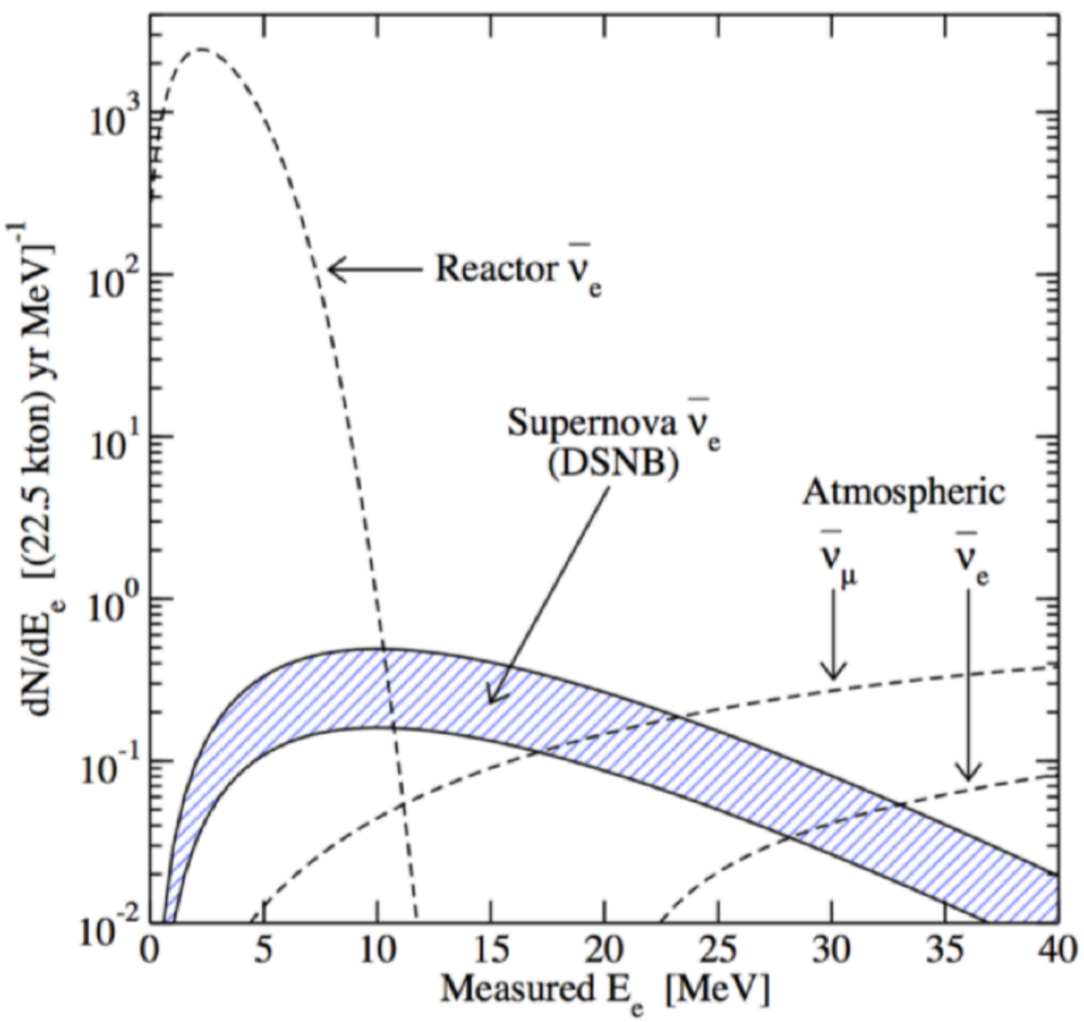
→ Move to **event topologies (1μ + 1/0π + Xn + Yp)** instead of **MC generator-based categories (CCQE, RES,DIS,…)**

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

Backup - DSNB & Proton decay

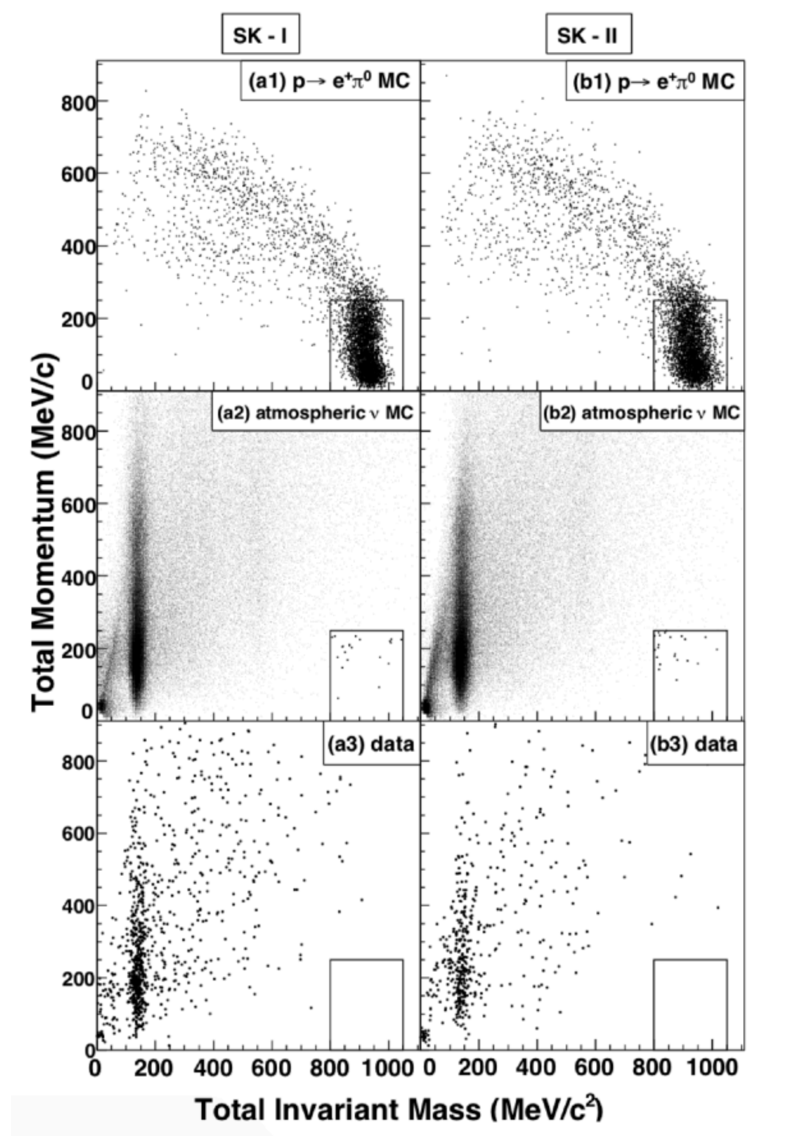
DSNB search

Beacom & Vagins, PRL, 93 (2004) 171101



Proton decay search

PRL 102 (2009) 141801



proton decay

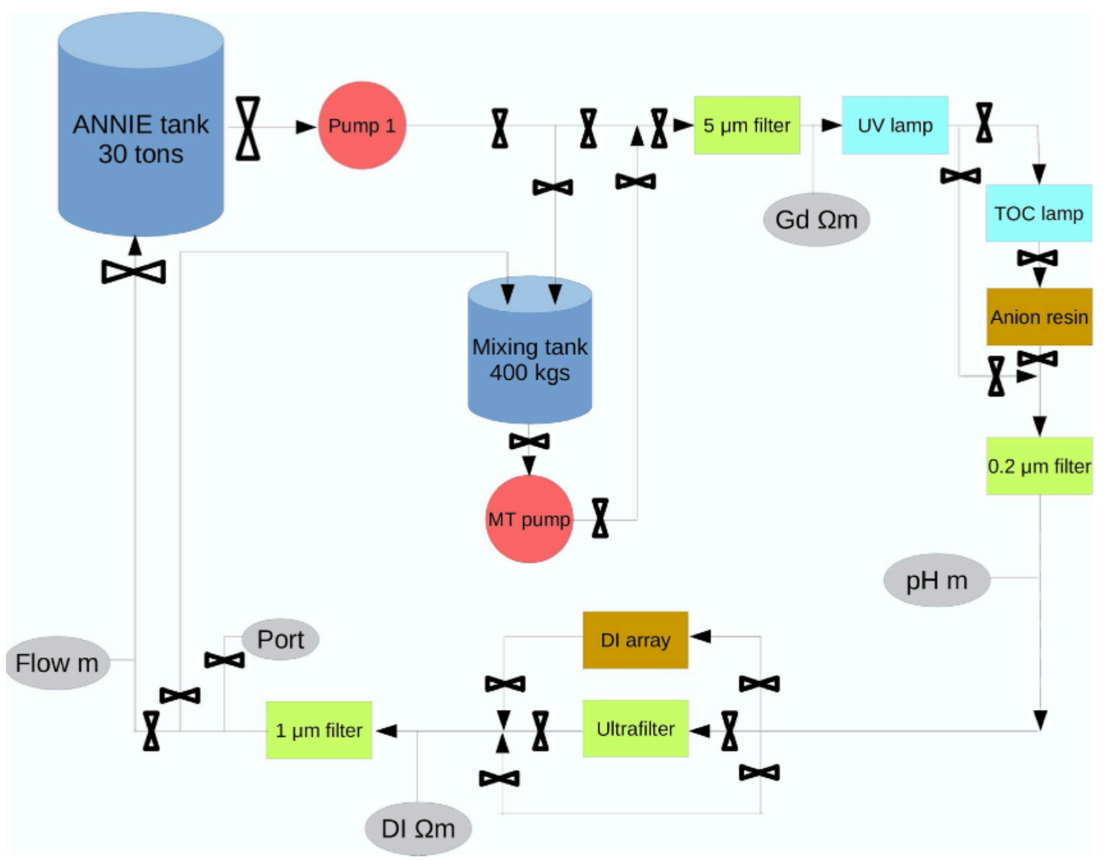
atmospheric

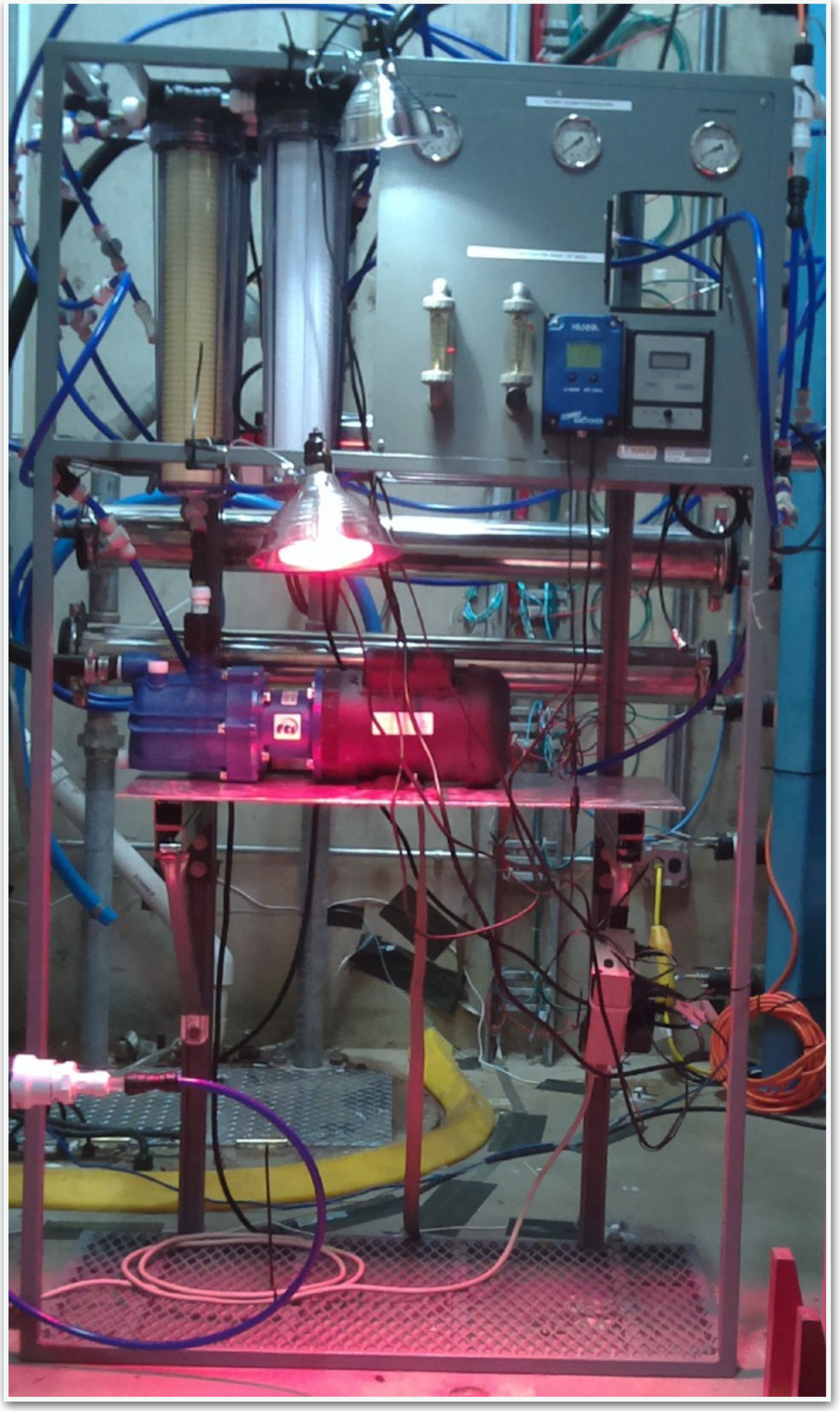
data

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

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

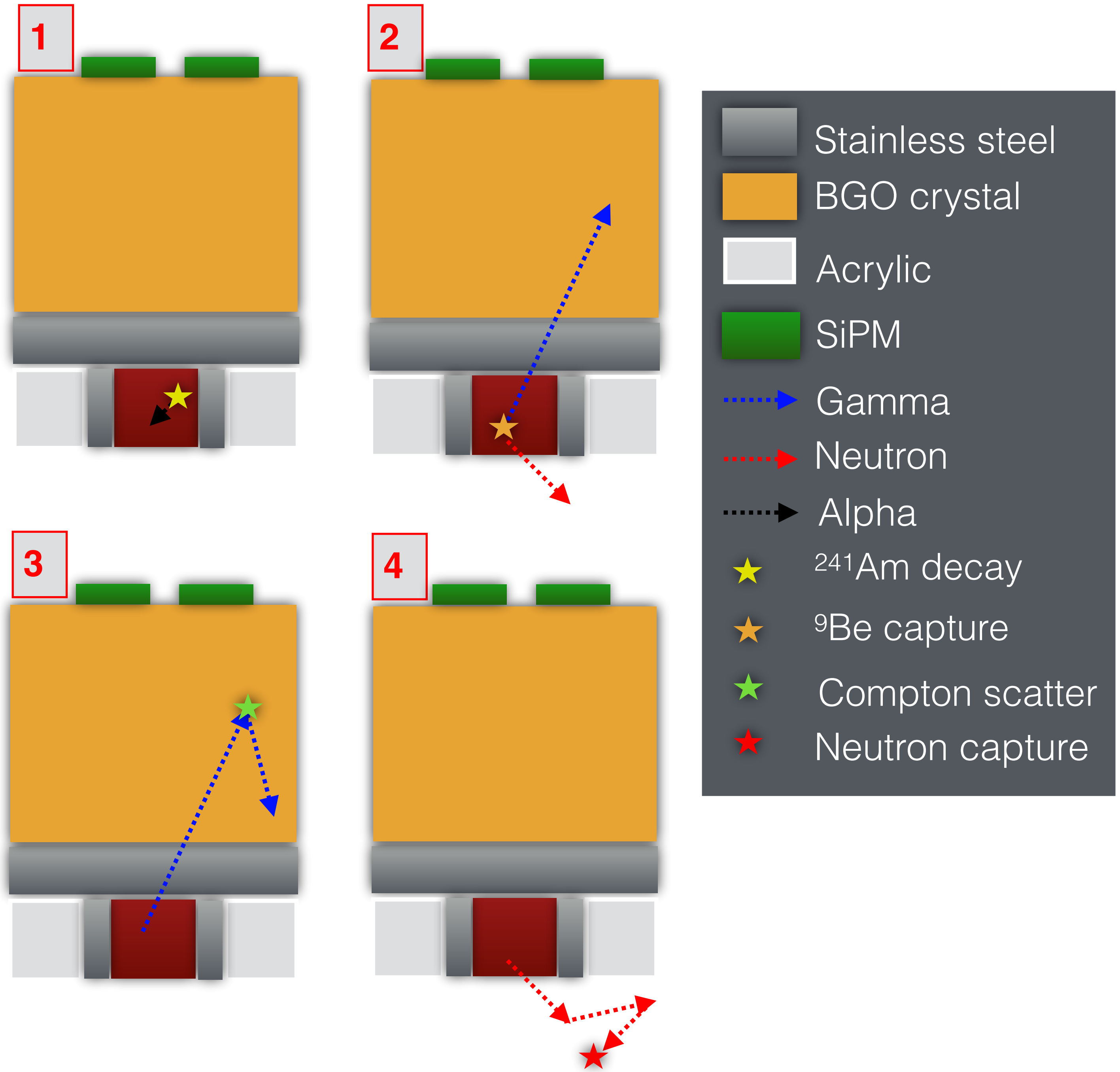




Vincent Fischer, UC Davis

Backup - Neutron calibration: AmBe source

- The AmBe source is a mixture of ^{241}Am and ^{9}Be.
- Produces a neutron and a 4.44 MeV gamma.
- SiPMs and a bismuth germanium oxide (BGO) crystal are used to detect this gamma.
  - High light yield of ~8500 photons per MeV.
  - Emits in a favourable wavelength regime (480 nm peak emission with a range of 375-650 nm).
  - Dense (7.13 g/cm^3), increasing Compton scatter likelihood.
- The neutron detection efficiency is then determined by searching for the 8MeV gamma cascade produced upon capture.



1. **^{241}Am decays to ^{237}Np via alpha emission (half-life = 432.2 yr).**
2. **^{9}Be can capture the emitted alpha to produce ^{12}C* and a neutron. ^{12}C* produces a prompt 4.44MeV gamma.**
3. **4.44 MeV gamma can Compton scatter in the BGO crystal - this gives us a trigger.**
4. **Neutron thermalises in ANNIE and is captured on Gd.**

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