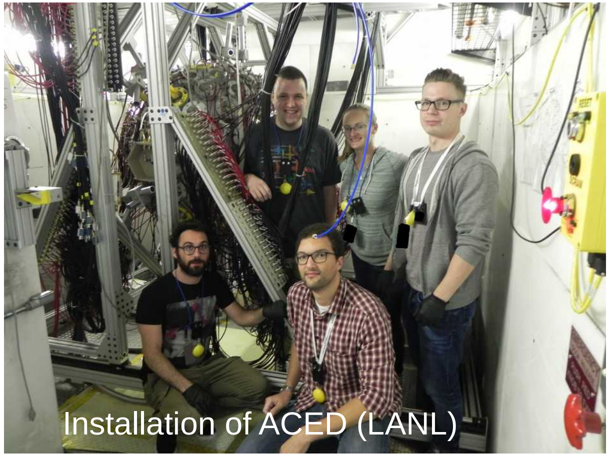
Nuclear Science and Security Consortium
Virtual Scholar Showcase 2020

Neutron multiplicity and new technologies with ANNIE

June 2, 2020

Vincent Fischer
University of California, Davis

Introduction


Installation of ACED (LANL)


Scintillator work (UCD)


Gadolinium work (FNAL)

Focus Area:

Nuclear and Particle Physics

Crosscutting Area:

Nuclear Data

Academic advisor:
Professor Robert Svoboda
Department of Physics
University of California, Davis

Lab mentor:
Dr. Steven Dazeley
Lawrence Livermore National Laboratory

Experiment partnership:
Dr. John Ullmann
Los Alamos National Laboratory

Mission relevance

- **WATCHMAN** (**WAT**er **CH**erenkov **M**onitor for **AN**tineutrinos) is part of **AIT**, the **A**dvanced **I**nstrumentation **T**estbed

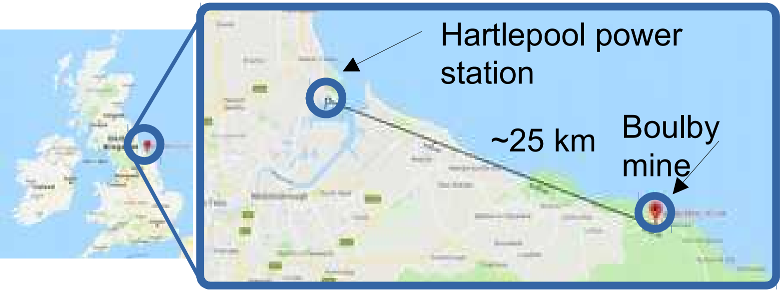
- 1 kt neutrino detector for nuclear non-proliferation

- **US/UK collaboration:** Detector to be built in the **Boulby mine** (UK) ~25km away from the **Hartlepool Nuclear Power Station** (Two 1.5 GW reactors)

- Aims to measure the antineutrino flux from a remote nuclear reactor though the **Inverse Beta Decay** reaction:

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

- Detection medium: **Gadolinium-loaded water** or **Water-based Liquid Scintillator**



Overview of ANNIE

Funded by the DOE Office of Science

Lab partner: Lawrence Livermore National Laboratory

Steven Dazeley
Marc Bergevin

- **ANNIE** is the Accelerator Neutrino Neutron Interaction Experiment
- **Gd-loaded water Cherenkov** detector placed downstream of the **Booster Neutrino Beam** at **Fermilab**
- Aims at **understanding final state neutron multiplicity** from neutrino interactions and demonstrating **new technologies** in the fields of **fast photosensors** and **detection media**
- Taking data since the beginning of 2020 after a successful background measurement (JINST 15 (2020) 03, P03011)

Motivations: Physics and technologies

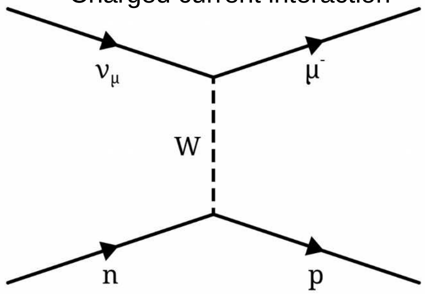
Multiplicity of final state neutrons from neutrino-nucleus interactions in water

- Presence of extra final state neutrons
  → Possible measure of **inelasticity** in neutrino interactions

- Understanding this neutron yield is crucial to **reduce bias** in neutrino energy reconstruction

- Requires **high statistics** and **precise kinematics reconstruction**

Charged current interaction



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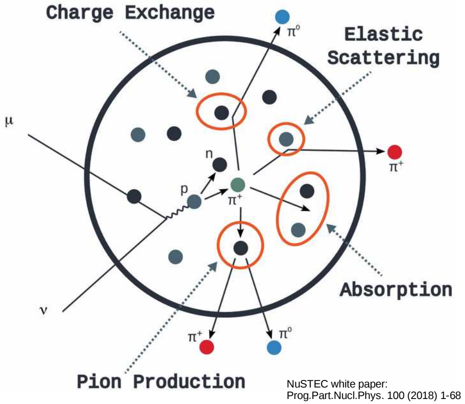


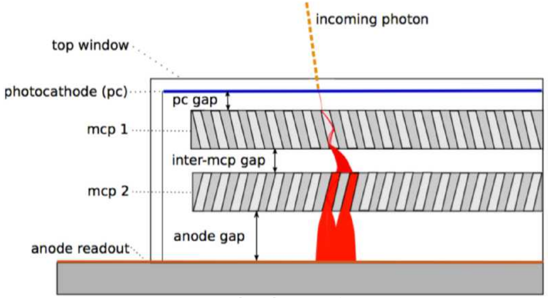
NuSTEC white paper:
Prog.Part.Nucl.Phys. 100 (2018) 1-68

Motivations: Physics and technologies

Fast photosensors and novel detection media

LAPPD R&D and demonstration

- **Large Area Picosecond PhotoDetectors (LAPPDs)**: 20x20 cm micro-channel plates with **~60-ps time** resolution and **<1 cm spatial** resolution
- **First use** of this new technology in a running neutrino experiment
- Demonstrate LAPPDs are **ready for research and deployment** as photosensors for HEP

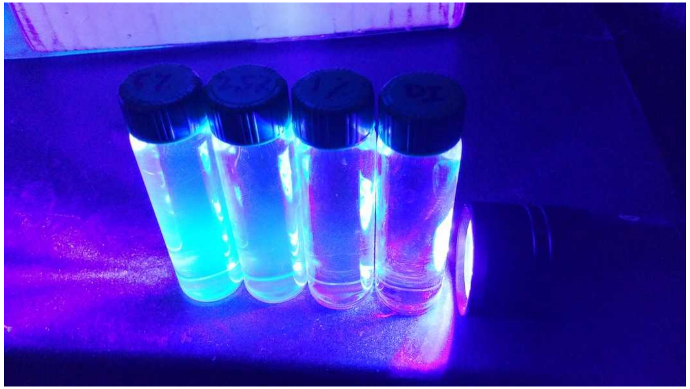


MCP principle of an LAPPD

Novel detection media

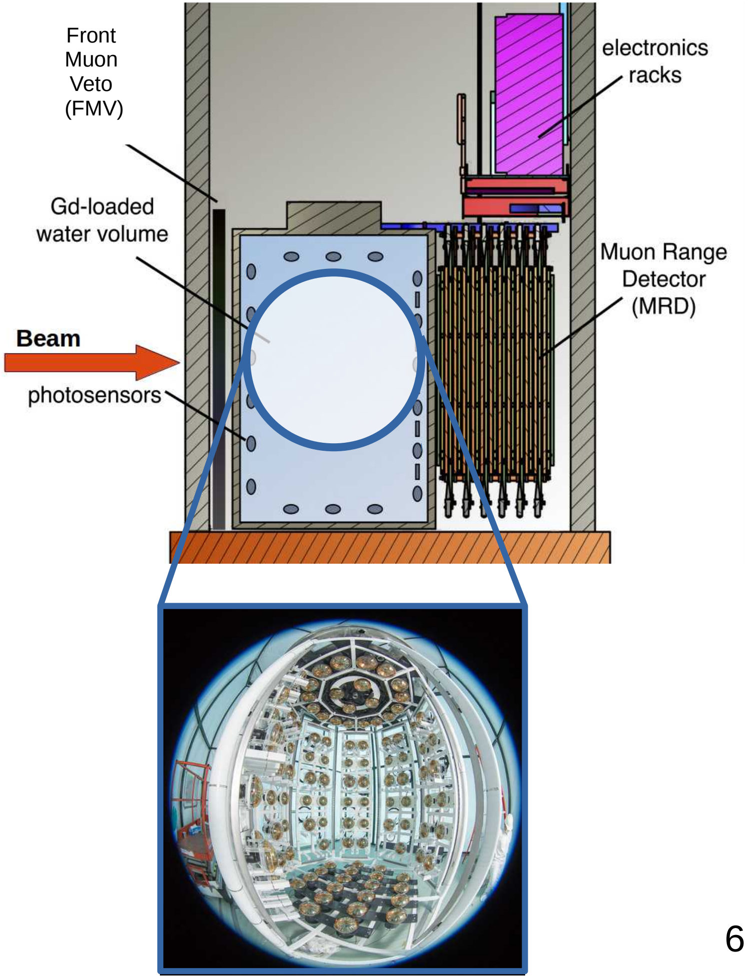
- First application of Gd-loaded water on a neutrino beam
- **Water-based Liquid Scintillator (WbLS):** Mixture of water and liquid scintillator allowing emission of **both Cherenkov and scintillation** light

ANNIE will allow the combined use of all the previous technologies in a single high-statistics experiment


WbLS samples under UV light

The ANNIE detector

- **Gadolinium-loaded water** volume of 26 tons (0.1% by weight)
- Photosensors: **132 PMTs** (8, 10 and 11-inch, ~20% total photocoverage) and more than **5 LAPPDs** distributed in the tank
- **Front Muon Veto**: Scintillator paddles **tagging charged particles** originating from the rock upstream
- **Muon Range Detector (MRD)**: Legacy from SciBooNE, iron-scintillator sandwich detector capable of **muon direction and energy reconstruction**
- **~10,000 CC interactions per ton per year** (2×10^{20} POT) expected



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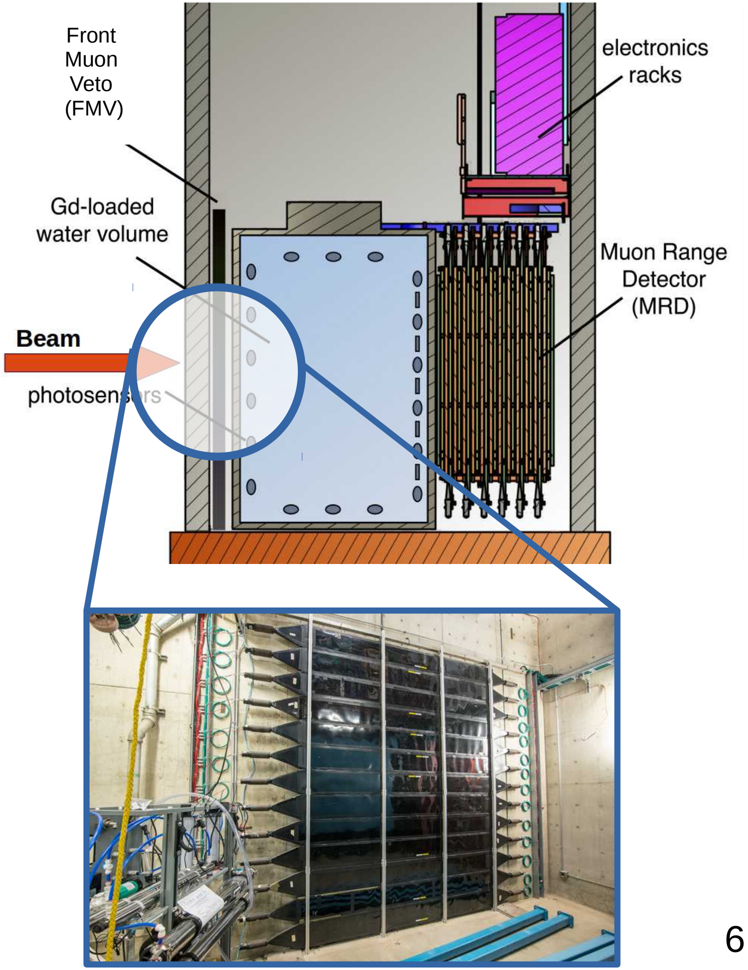

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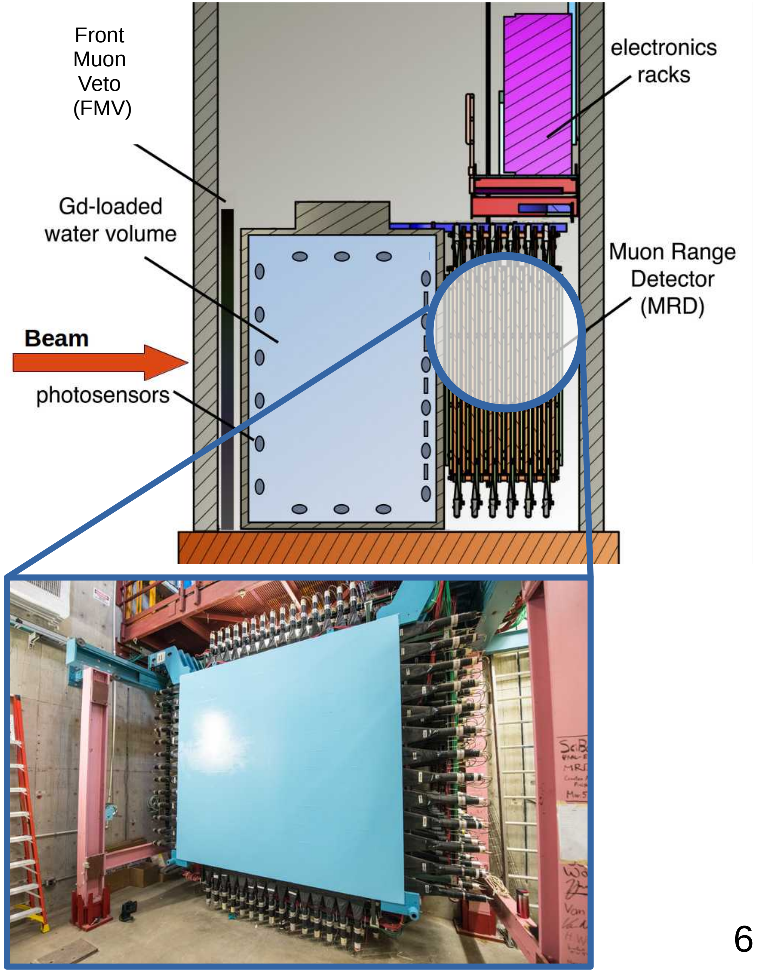
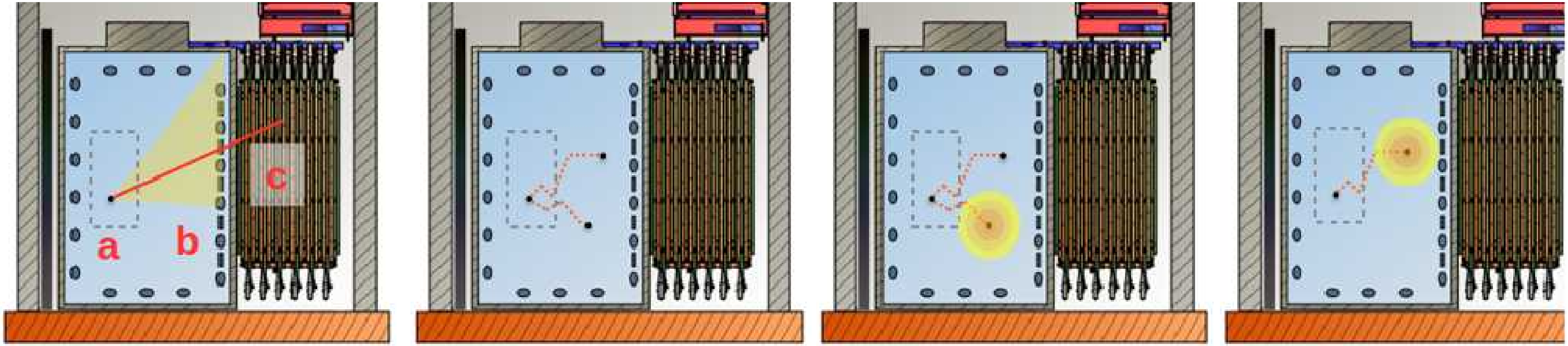


How will ANNIE work?



1 2 3 4

1.a - **CC interaction** in the fiducial volume

1.b - Muon **momentum and interaction vertex reconstructed** using **PMTs** and **LAPPDs**

1.c - Muon **momentum reconstructed** with the **MRD**

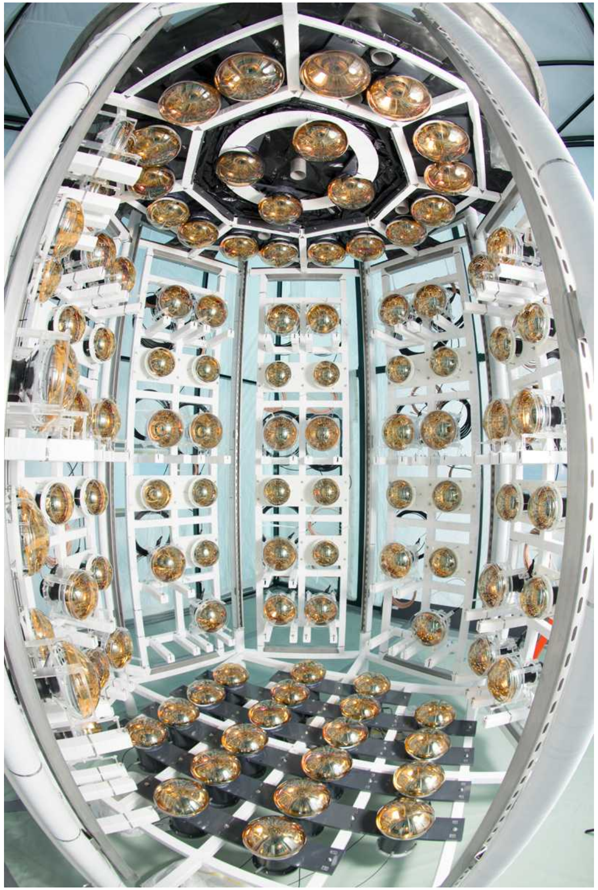
2 - Neutrons **thermalize** in the water volume

3-4 - **Neutron capture on gadolinium** detected by the **PMTs**

Building the detector


Inner structure assembled in 8-9 months


NSSC fellows adding gadolinium in ANNIE




The Muon Range Detector refurbished from its SciBooNE days


The ANNIE water purification system

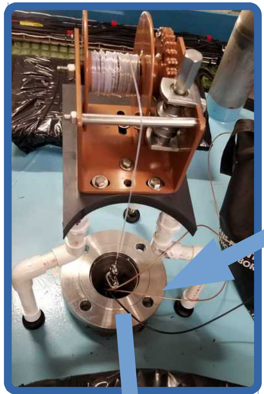
The ANNIE calibration

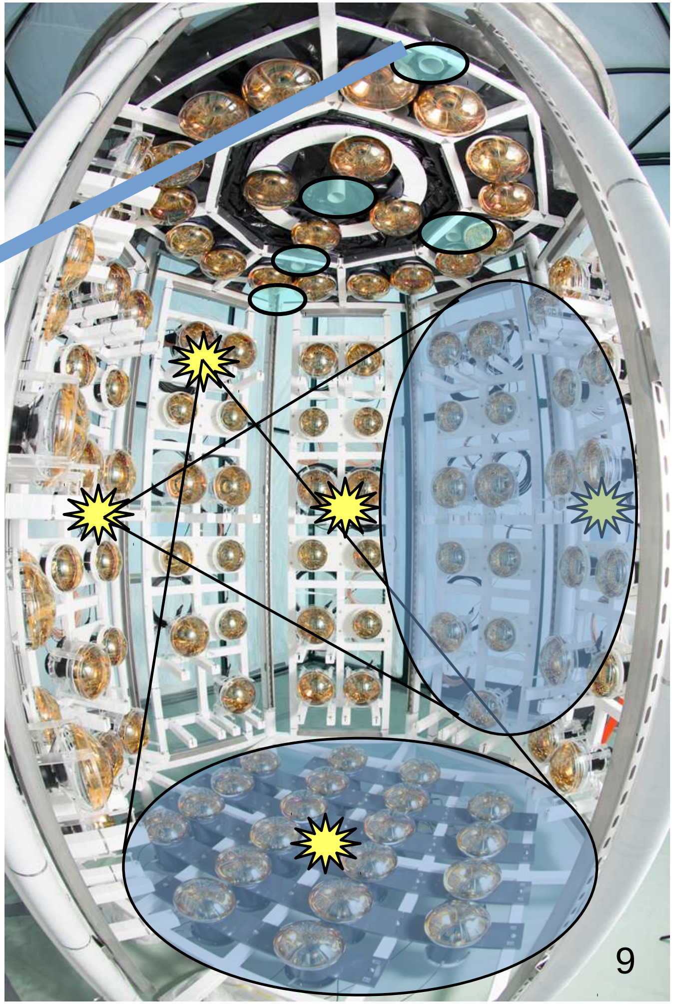
LED calibration

- **6 fibers** distributed in the tank and connected to **LEDs**
- **Purpose**:
  - Water transparency measurement
  - > ns PMT timing
  - PMT gain matching

Source deployment

- **5 deployment ports** on top of the tank
- Main purpose: Deployment of a tagged **Americium-Beryllium gamma-neutron source** built in collaboration with LLNL
- **Neutron efficiency studies** throughout the water volume





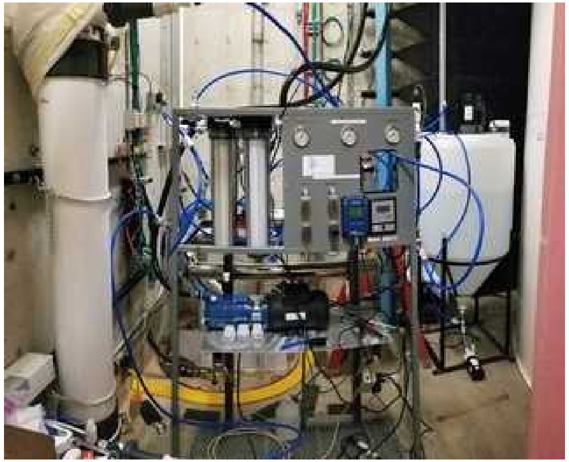
Will be added soon:

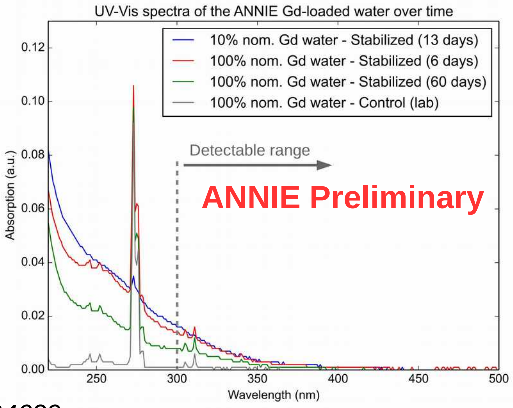
- **Laserball** → sub-ns PMT timing
- **Standard candle** → LED-independent detector stability

Work in collaboration with LLNL → Interest from WATCHMAN

R&D on gadolinium-loaded water

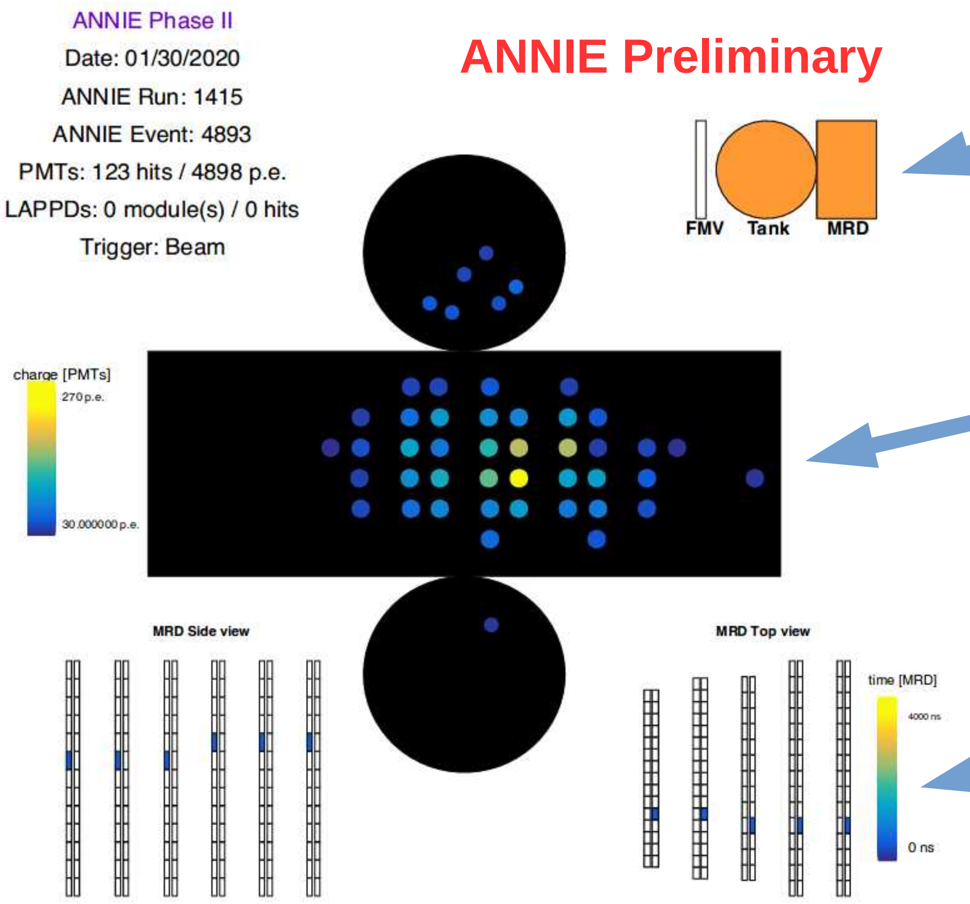
- Large water Cherenkov detectors need to **circulate and purify** their water in order to keep a **high level of transparency**
- ANNIE developed **its own low cost purification system** better suited for its water volume than existing systems
- **Goal**: **Remove impurities** (dust, bacteria, dissolved plasticizers and UV-absorbent ions) from the water **without removing gadolinium**
- **Method** → Use conventional filters and sterilizing lamps in combination with an **ultrafilter** and a ***tuned* ion exchange resin***
- **Promising results** obtained after loading ANNIE with gadolinium
- Such a system could be used by **small to medium scale detectors** using Gd-loaded water as their detection medium





* more details in *Fischer et al., arXiv:2004.04629*

ANNIE's first physics events



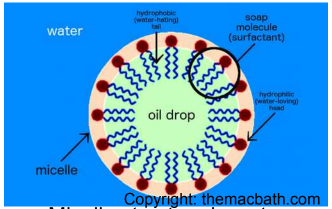
Tank and MRD triggered
Nothing in the veto
→ Not a rock muon

Disk-like Cherenkov pattern

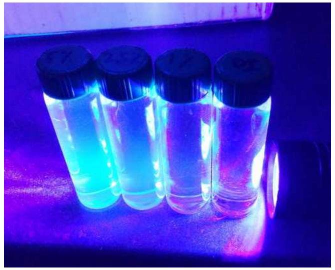
Straight track in the MRD
Corresponds to tank exit point

ANNIE as a testbed for Water-based liquid scintillator

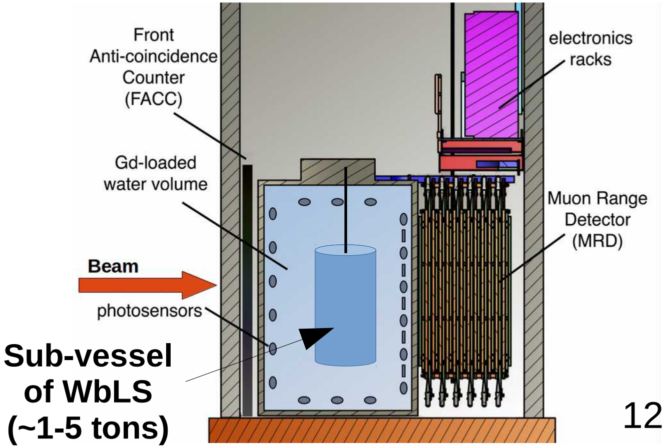
- **W**ater-based **L**iquid **S**cintillator (**WbLS**) is a **mixture** of pure water and oil-based liquid scintillator held together by a surfactant in a “micelle” structure
- **Combines the advantages** of water (low light attenuation, low cost) and liquid scintillator (high light yield) with the emission of Cherenkov and scintillation light
  → **High tunability and attractiveness** for high energy and nuclear physics
- The **modularity** of ANNIE and the collaborators' experience with WbLS are the key points behind **ANNIE as a WbLS testbed**
- Ongoing discussions on the deployment of a smaller **WbLS-filled vessel** in the ANNIE tank this year
- **ANNIE would be the first detector using WbLS as a detection medium on a neutrino beam**
- Valuable inputs for the next generation of water Cherenkov detectors → **WATCHMAN** and **Theia**



Micelle structure in water

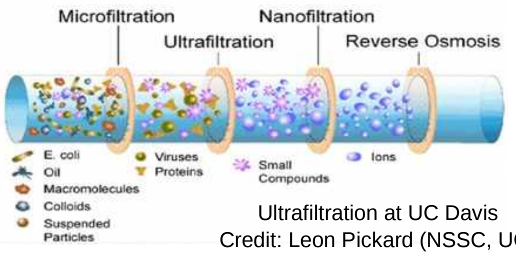


Samples of WbLS with different LS concentrations

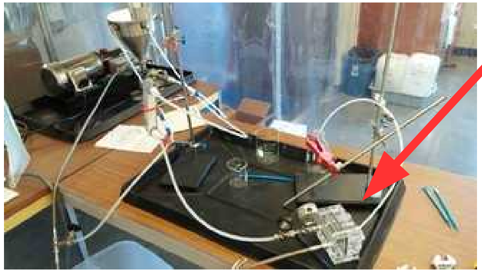


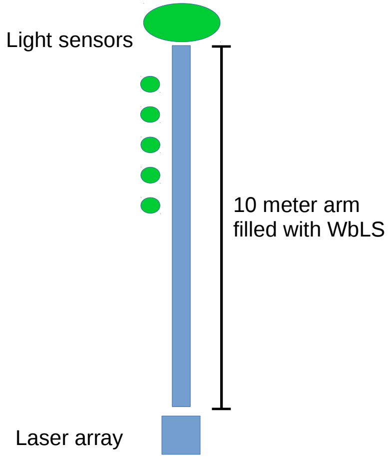
R&D on WbLS

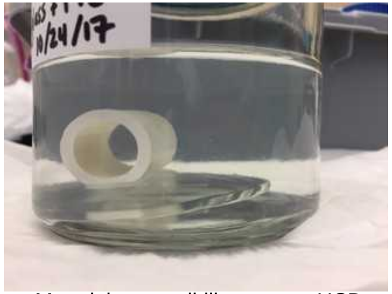
- As a new and promising medium, WbLS is the topic of **several R&D studies**
- **Filtration and purification**:
  - Apply **nanofiltration** to separate organic and water components and purify them separately
- **Material compatibility**:
  - Ensure WbLS isn't damaging materials in the detector and vice versa
  - Thorough screening process for all materials (acrylic, PVC, PTFE, etc..)
- **Optical properties**:
  - Measure the **attenuation** and **scattering** lengths of WbLS using a 10-m long arm
  - In construction at UC Davis
- **Calorimetric properties**:
  - Measure the **light yield** of several cocktails of WbLS
  - Study of **environmental factors** such as temperature



Ultrafiltration at UC Davis
Credit: Leon Pickard (NSSC, UCD)







Material compatibility tests at UCD
Credit: Julie He (NSSC, UCD)

Light yield measurement device at UCD
Credit: Leon Pickard (NSSC, UCD)

Conclusions and take-home message

- **ANNIE Phase II has started** taking **physics data**

- ANNIE will demonstrate the combined use of **new detection media** and **fast photosensors**

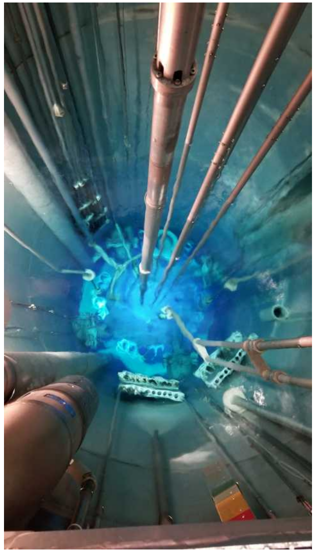
- The resulting R&D will directly **impact** the next generation of **non-proliferation detectors** such as WATCHMAN and the AIT program in general

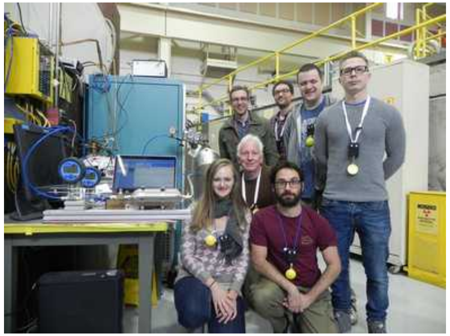
- ANNIE and WATCHMAN have very **strong ties** in terms of **analysis**, **R&D** and **collaborators**

THANK YOU FOR YOUR ATTENTION!

NSSC Experience

- I presented results at the **NSSC Program Reviews** in **2017** and **2018**, **Fall Workshop in 2019**
- Every year, **UC Davis** hosts the **Nuclear Analytical Techniques (NAT) Summer School** and since 2016, I've been giving **lectures** and have been in charge of the **Neutron Activation Analysis (NAA) activity**:
  - Preparing samples → Metals, liquids, mystery samples, etc..
  - Irradiation and HPGe counting at the MNRC reactor
  - Analysis of the HPGe spectra, determination of the mystery element and concentration
- **Very enriching experience** to teach students what we do in our **every day lab life**
- I **collaborated** on several occasions (2 beam runs + follow up studies) with experts at the **LANSCE** neutron beam (**LANL**)
- This helped me develop a lot of skills in **detector design and construction**, **low background assays** and **background mitigation** that I would like to apply to continue to apply to the NNSA mission in a National Laboratory


McClellan nuclear reactor core


ACED team at LANL

Acknowledgments

2019 NSSC Fall Workshop at LLNL

This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003180.

BACK-UP

ANNIE at Fermilab

ANNIE → WATCHMAN → Theia

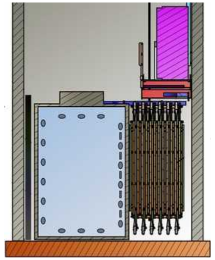
Mass

~50,000 tons
~100,000 sensors

~4,000 tons
~5000 sensors

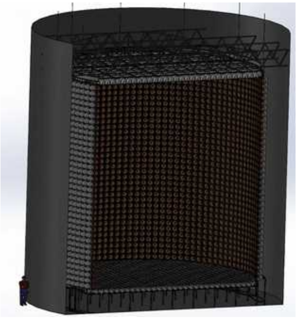
~30 tons
~150 sensors

Demonstration and **R&D**
for WbLS + fast photosensors

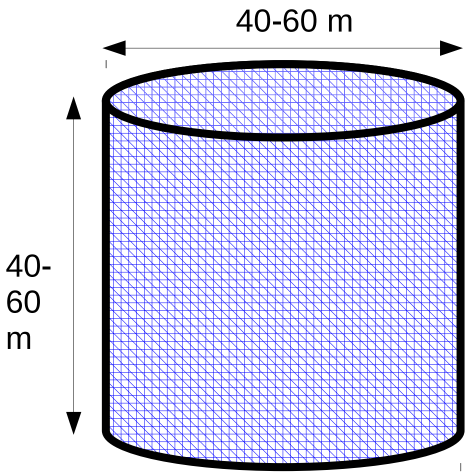


annie

Use of WbLS + fast photosensors in a **large detector**



WATCHMAN



Theia

Data taking

2019+ 2022+ 202?

ANNIE timeline

Pure water → **Commissioning** → **DONE!**
Summer 2019

Gd-loaded water → **Physics data taking**
Fall 2019 - Summer 2020
→ Neutron yield measurement → **In progress**
→ CC cross section measurement
→ Deployment of a WbLS vessel in the detector (temporary)

Additional LAPPDs
Fall 2020
→ More detailed reconstruction of multi-track final states and pions
→ Possible NC cross section measurement

Phase III → **Testbed for new technologies**
~2021

Measuring beam-induced neutron backgrounds with ANNIE Phase I

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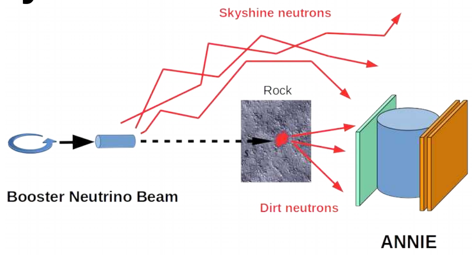
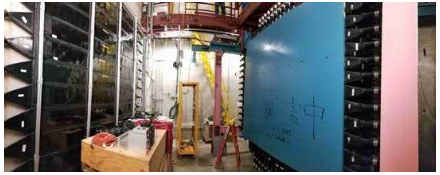
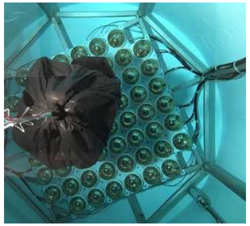
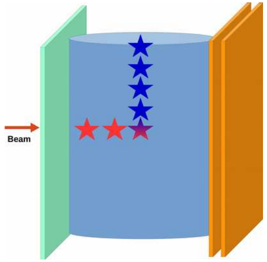
National Nuclear Security Administration

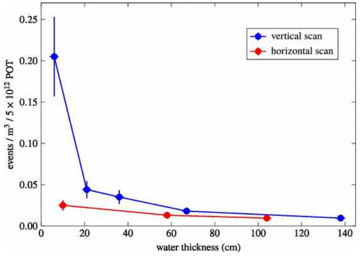
- ANNIE was designed to be a multi-phase experiment:
  - **Phase I → Engineering run and background measurement**
  - Phase II → First physics run
  - Phase III → Physics run and testbed for new technologies
- Phase I → Measurement of beam-induced neutron backgrounds:
- **Key physical infrastructures** common with Phase II





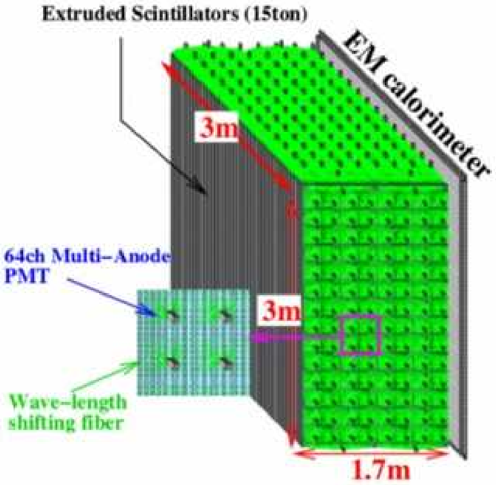


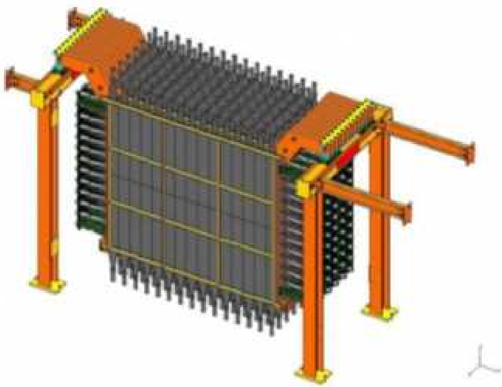




- Background neutron rate per spill per ton **is less than 2%** (5% total rate in the tank)
- Neutron background is **not an issue for the Phase II physics**
- Imminent publication

SciBooNE





- SciBar: Scintillator tracking detector (14'000 bars, 14 tons)
- Electron Catcher: 2 planes of calorimeter (lead and scintillating fibers)
- Muon Range Detector
- Measurement of CC-QE, CC-$\pi^{\pm}$, CC-π^{0}, NC-ES cross-sections

PSEC-4 electronics for LAPPD

PSEC4 chips

- CMOS-based waveform sampling chip
- Up to 15 GSamples/s
- 1 mV noise
- 6 channels per chip

- Operated on a test beam, scalable to large systems
- ANNIE Central Cards to control ACDC cards (30 channels, 5 PSEC ASICs)
- Lots of work done and ongoing at U. Chicago (H. Frisch's group, http://psec.uchicago.edu/) and ISU (M. Wetstein's group)

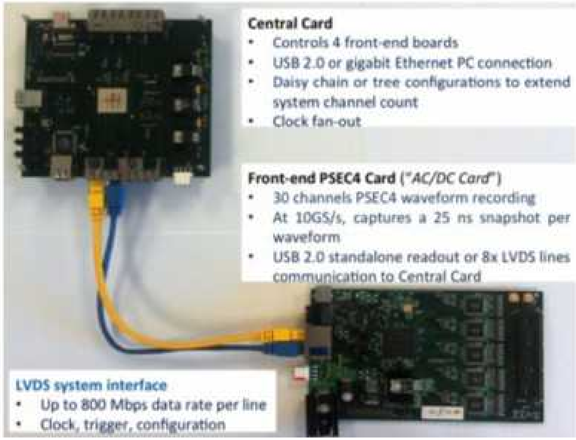


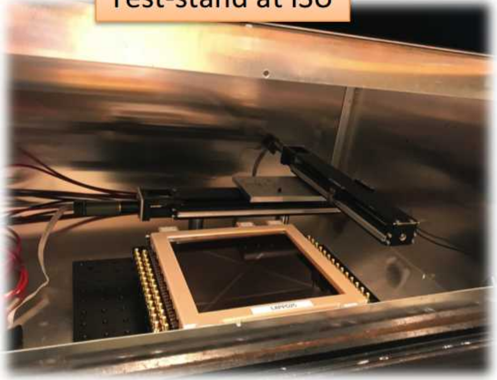
Image source: Jonathan Eisch (ISU)

ANNIE Central Card

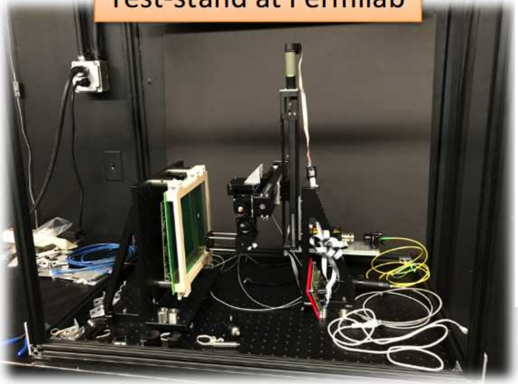
Meticulous characterization of LAPPDs

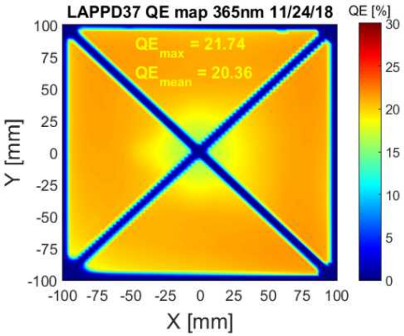
* from E. Tiras, ISU

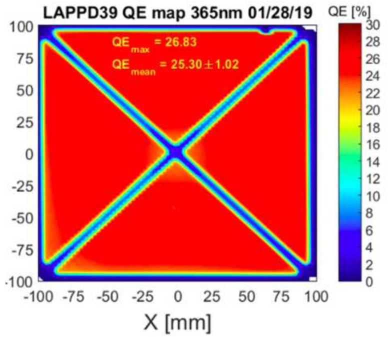
Test-stand at ISU

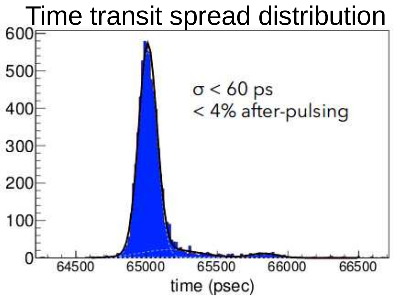


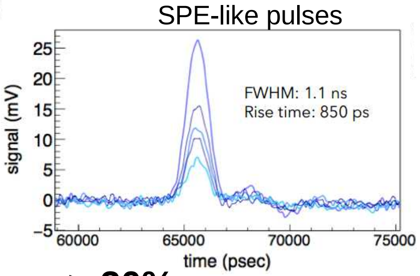
Test-stand at Fermilab

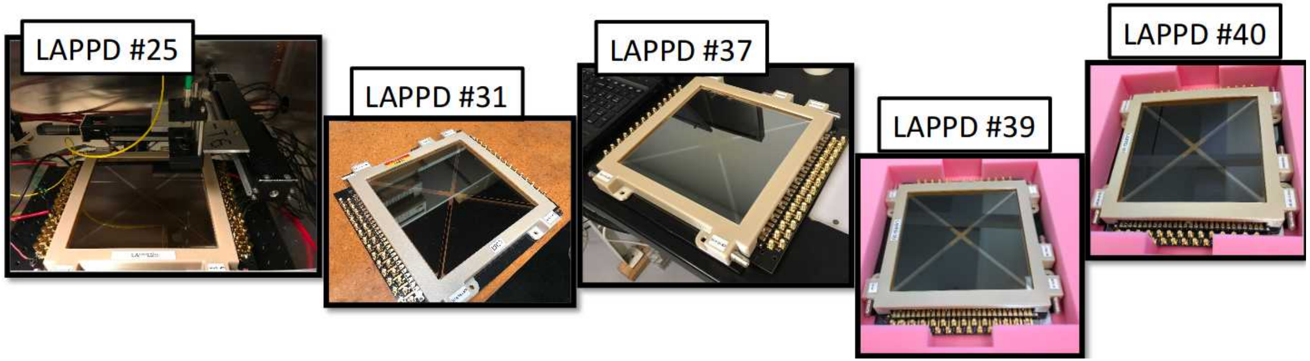










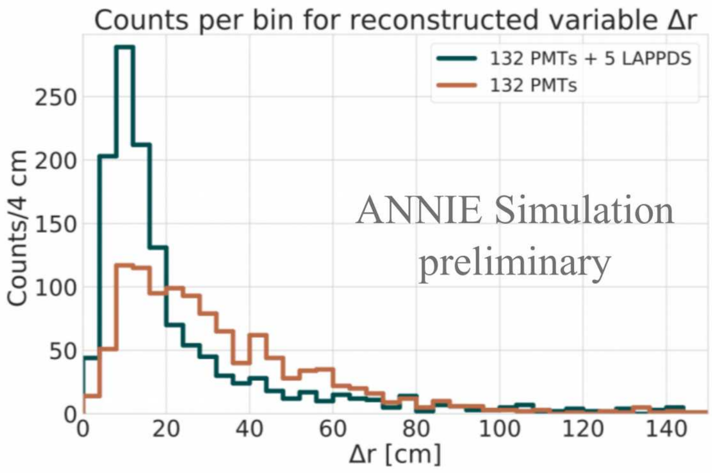


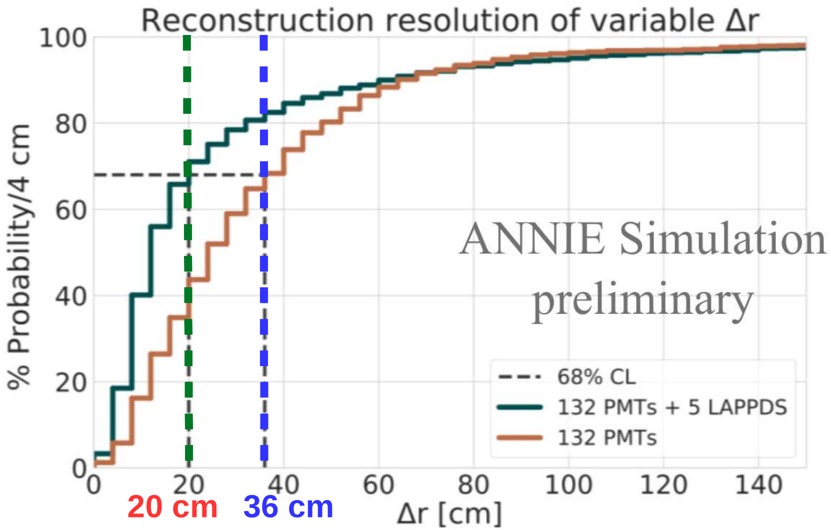
→ All 5 LAPPDs have been received and are being tested at ISU and Fermilab

Uniform quantum efficiency → > 20%
Good timing resolution → < 100 ps

ANNIE and LAPPDs

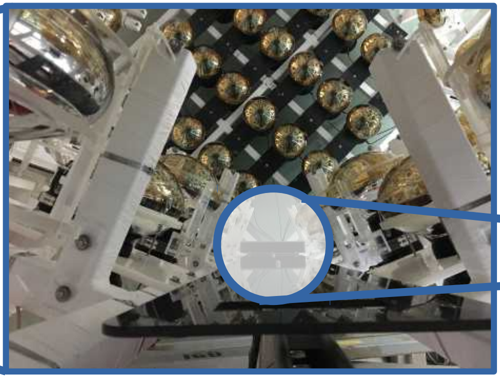
- **LAPPDs dramatically improve vertex and muon kinematics (angle and momentum transfer) resolution**
  - **Vertex resolution** → Interaction point reconstruction and neutron containment
  - **Muon kinematics** → Better energy reconstruction
  - **Precision timing** → Multi-tracks separation
- ANNIE has been an **early LAPPD adopter** since the beginning and maintains strong ties with the **INCOM company**, current **manufacturer** of LAPPDs





→ Significant improvement of vertex reconstruction by adding 5 LAPPDs!

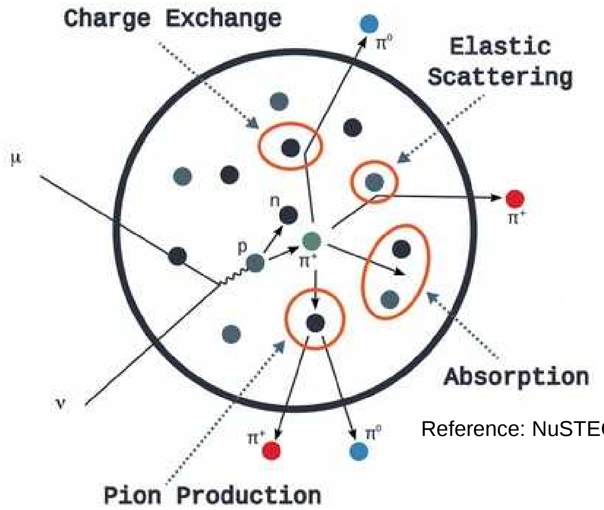
How to deploy an LAPPD in a water tank?



- **LAPPD and integrated electronics** in a **waterproof** housing
- **Deployed** and **moved** along **tracks** on the side of the structure
- **Easily accessible** from the **top** of the tank

Matthew Wetstein, ISU

Neutrons as an indicator of inelasticity

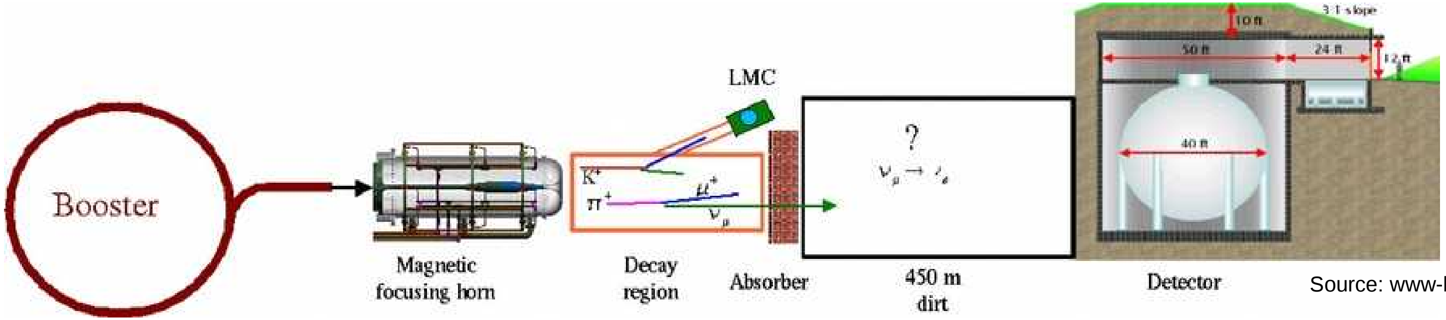


Reference: NuSTEC white paper

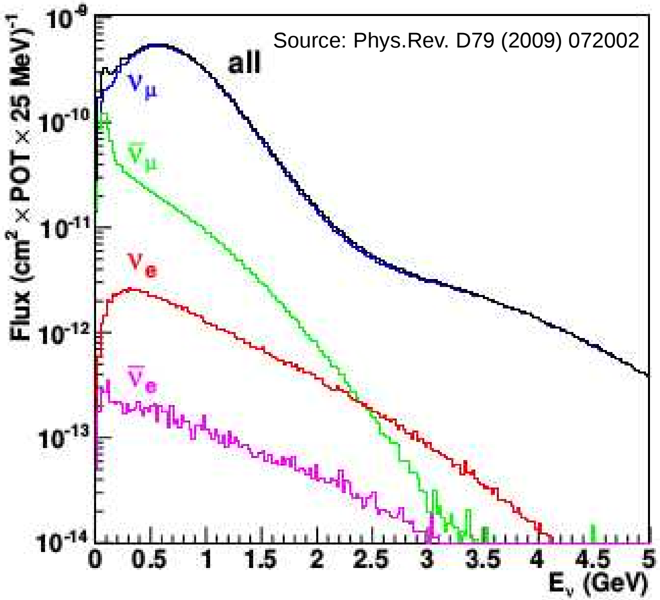
- Pure CCQE interactions should not produce neutrons but inelastic CC interactions do
- The presence of final state neutrons in a CC interaction likely means something inelastic happened
- Neutron-generating processes: Stuck (absorbed) pions, 2p-2h, etc..

→ **Final state neutrons are a sign of inelasticity and ANNIE will be sensitive to these neutrons**

The Booster Neutrino Beam



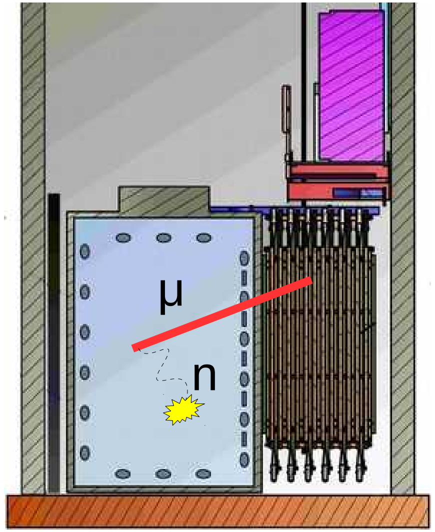
Source: www-boone.fnal.gov



- 8 GeV protons from the Booster beam hitting a beryllium target with reversible horn polarity
- Repetition rate of ~5 Hz, 5×10^{12} protons-on-target per 1.6 μs spill on average
- Mean neutrino energy of 700 MeV
- Composition in neutrino mode: 93 % of ν_μ , 6.4 % of $\bar{\nu}_\mu$ and 0.6 % of ν_e and $\bar{\nu}_e$
- 100 meters upstream from ANNIE
- Provides about one ν_μ charged current interaction in the ANNIE water volume every 150 spills
- Energy range of interest for most long baseline oscillation experiments

On the importance of vertex reconstruction

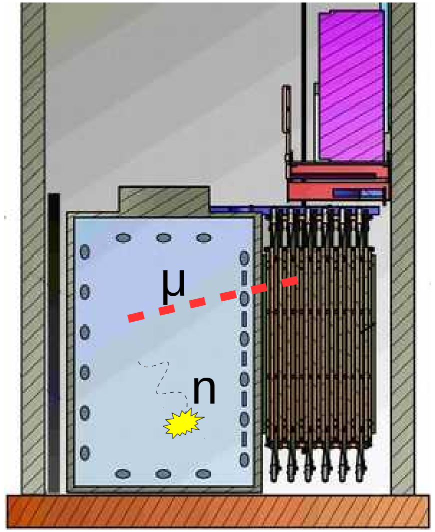
Case 1



Interaction vertex at (x,y,z)
Interaction vertex correctly reconstructed at (x,y,z)
Neutron detection efficiency at (x,y,z) = 50%
1 neutron detected → 2 neutrons expected
→ 2 neutrons really emitted

No neutron yield bias

Case 2



Interaction vertex at (x,y,z)
Interaction vertex mis-reconstructed at (x',y',z')
Neutron detection efficiency at (x,y,z) = 50%
Neutron detection efficiency at (x',y',z') = 20%
1 neutron detected → 5 neutrons expected
→ 2 neutrons really emitted

Neutron yield bias!