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annie

## Lake Louise Winter Institute 2019

# ANNIE: The Accelerator Neutrino Neutron Interaction Experiment

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on behalf on the ANNIE collaboration

University of California at Davis

February 13, 2019

# Overview of ANNIE

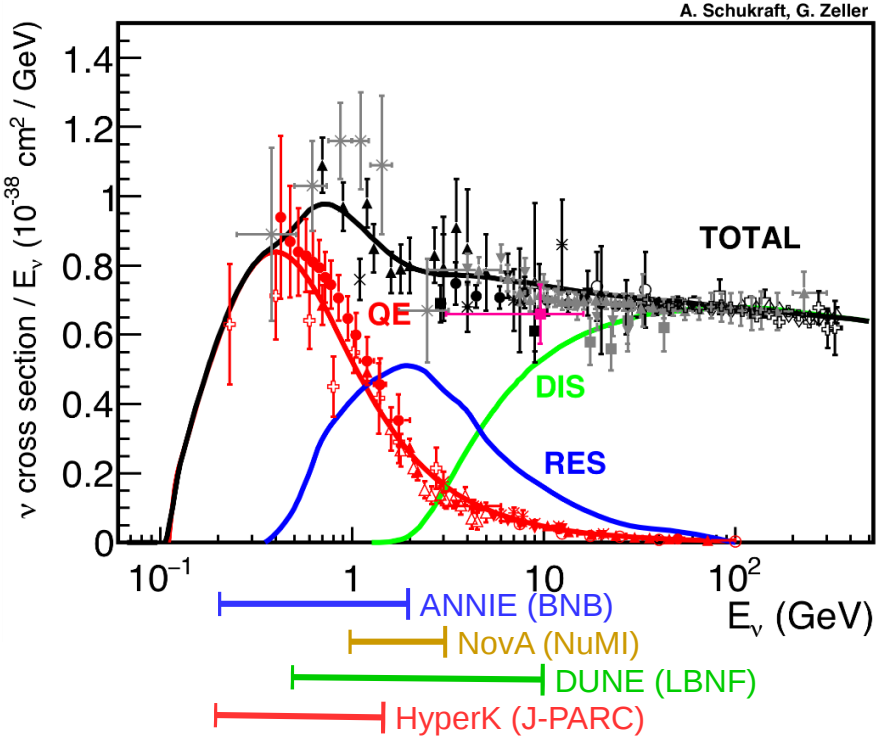
- **ANNIE** is the Accelerator Neutrino Neutron Interaction Experiment
- **Gd-loaded water Cherenkov** detector placed downstream of the **Booster Neutrino Beam** at **Fermilab**
- Aims at **understanding final state neutron multiplicity** from neutrino interactions in **water** as a function of **muon kinematics**
- Demonstration of **new technologies** in the fields of **fast photosensors** and **detection media**
- Finished taking background data (Phase I), soon to be taking **physics data** (Phase II fully funded and under construction)

# Physics motivation: Kinematics-dependent neutron yield

**Study the multiplicity of final state neutrons from neutrino-nucleus interactions in water**

## Long baseline oscillation physics

- The presence of extra final state neutrons is a possible measure of **inelasticity** in neutrino interactions
- Understanding this neutron yield is crucial to **reduce bias** in neutrino energy reconstruction




## Neutron tagging

- **Proton decay searches** and **Diffuse Supernova Neutrino Background detection** rely on a good understanding of neutron yield in atmospheric neutrino interactions

**ANNIE** will provide a **high statistics measurement** of this neutron yield **in the energy range of interest**

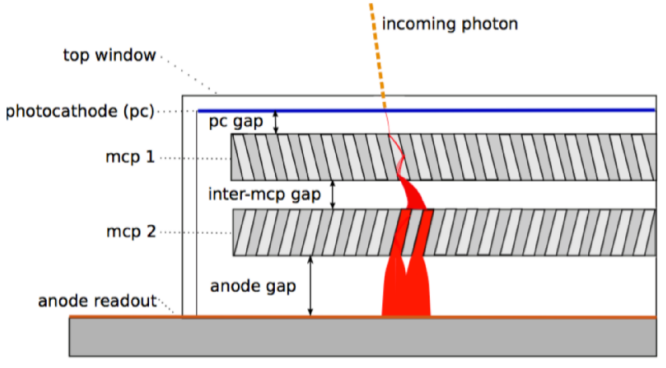
# Technological motivation: Fast photosensors and novel detection media

## 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

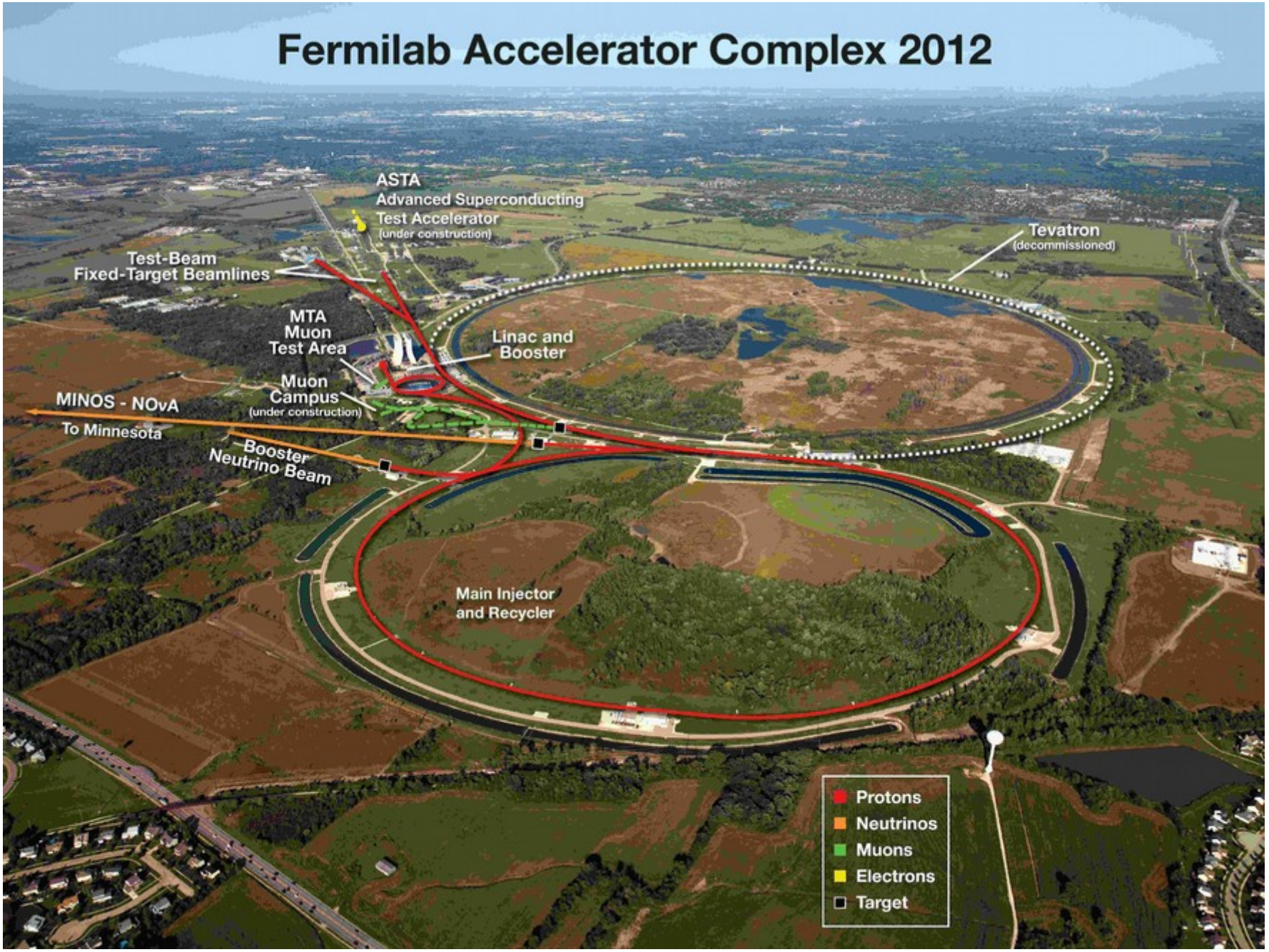
## Novel detection media

- 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

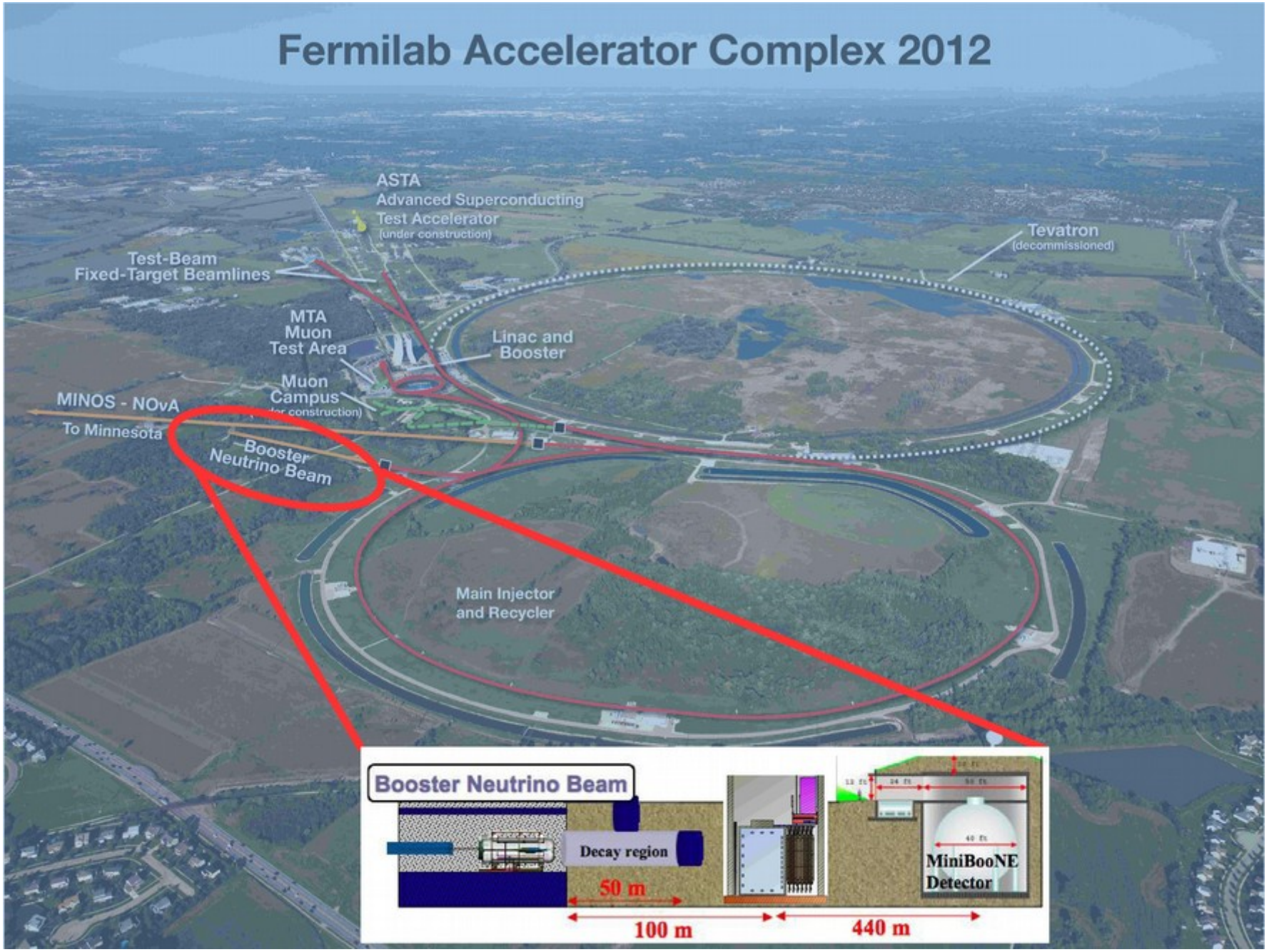



**ANNIE will allow the combined use of all the previous technologies in a single high-statistics experiment**

# ANNIE on the BNB



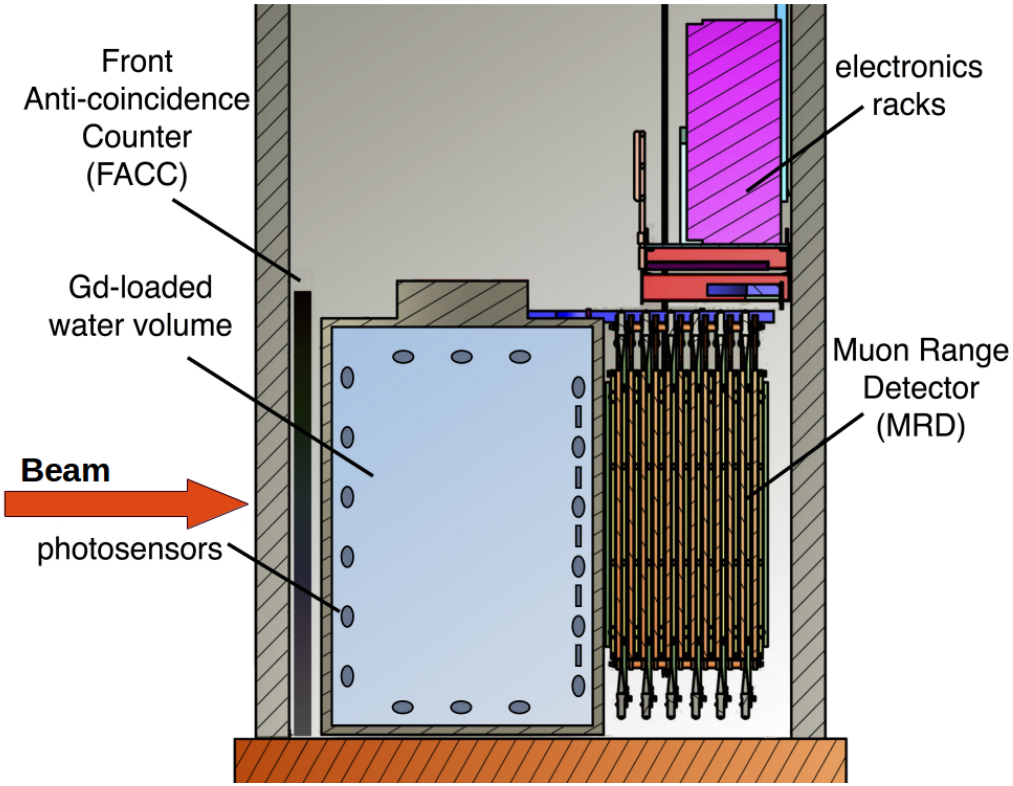
# ANNIE on the BNB



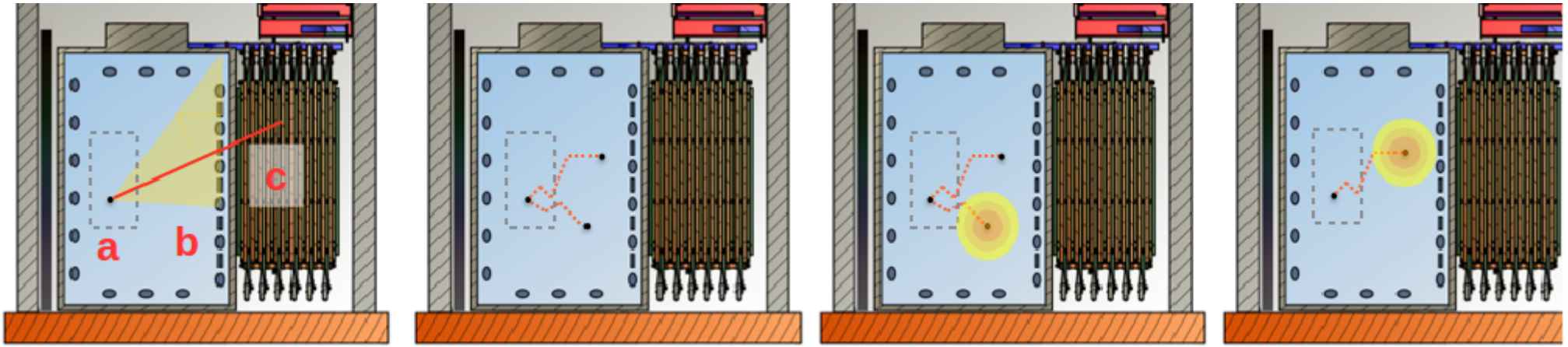
# ANNIE on the BNB

# The ANNIE detector

- **Gadolinium-loaded water** volume of 30 tons (0.1% by weight)
- Photosensors: ~**130 PMTs** (8, 10 and 11-inch, ~20% total photocoverage) and more than **5 LAPPDs** distributed in the tank
- **Front veto**: Scintillator paddles **tagging charged particles** originating from the rock upstream
- **Muon Range Detector (MRD)**: Legacy from SciBooNE, steel-scintillator sandwich detector capable of **muon direction and energy reconstruction**
- **~10,000 CC interactions per ton per year** ($2 \times 10^{20}$ POT) expected



# 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 LAPPDs

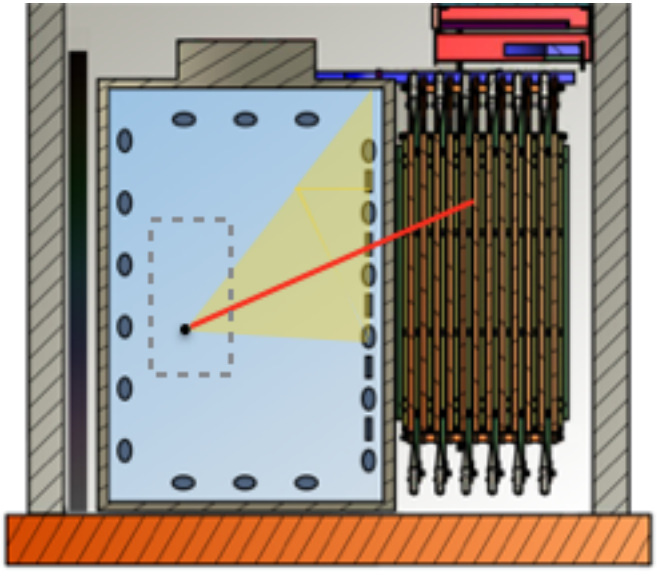
1.c - Muon momentum reconstructed with the MRD

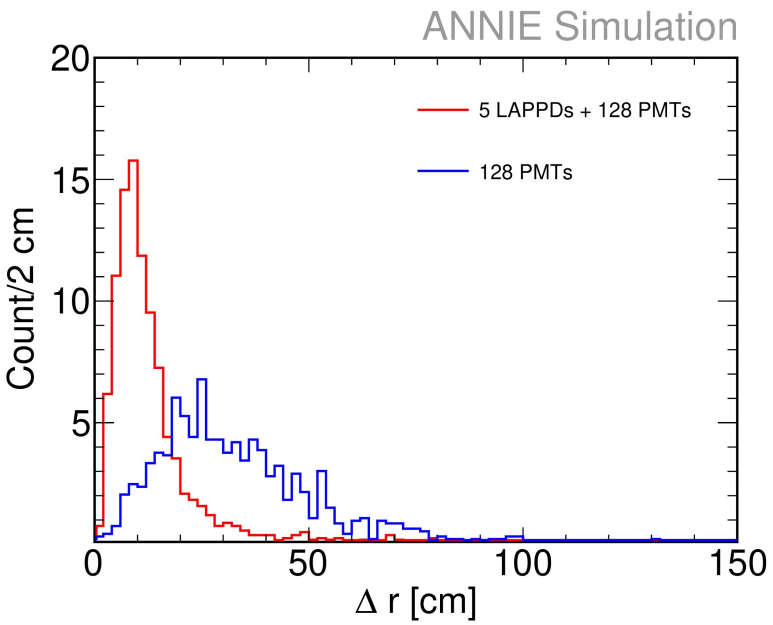
2 - Neutrons thermalize in the water volume

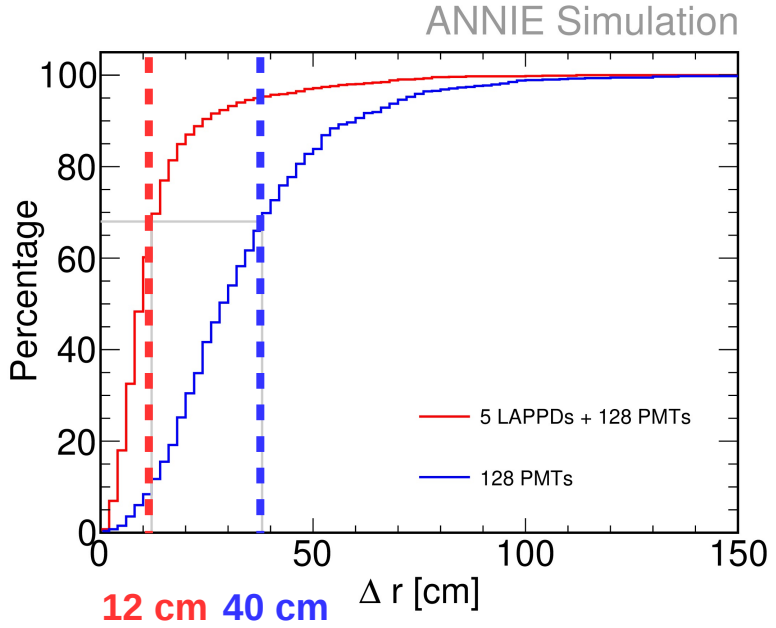
3-4 - Neutron capture on gadolinium detected by the PMTs

# Why does ANNIE need LAPPDs?

- Using a **well-known neutrino beam** as well as being able to **reconstruct** muon **kinematics** and **understand interactions is crucial** to the ANNIE physics goals
- **LAPPDs drastically 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





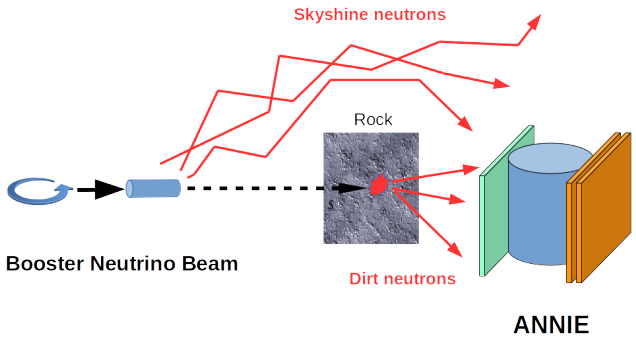



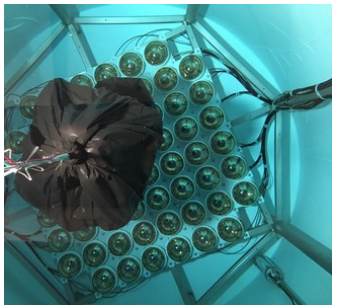
# Measuring beam-induced neutron backgrounds with ANNIE Phase I

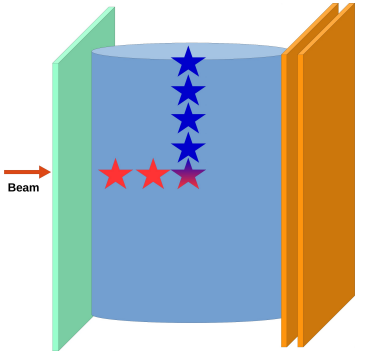
- ANNIE was designed to be a multi-phases experiment:
  - **Phase I** → **Engineering** run and **background** measurement
  - **Phase II** → First **physics** run
  - **Phase III** → Physics run and **testbed for new technologies**

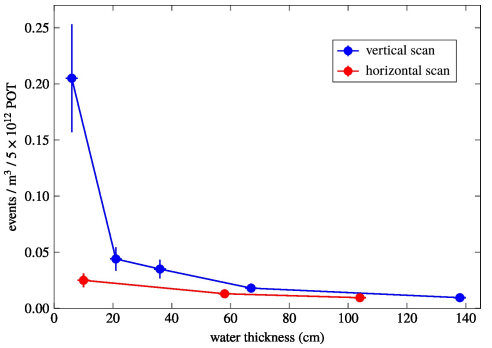
# Measuring beam-induced neutron backgrounds with ANNIE Phase I

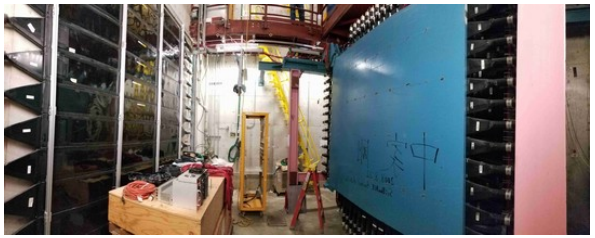
- ANNIE was designed to be a multi-phase experiment:
  - **Phase I → Engineering run and background measurement**
  - Phase II → First physics run
  - Phase III → Physics run and testbed for new technologies
- Phase I → Measurement of beam-induced neutron backgrounds:
- **Key physical infrastructures**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

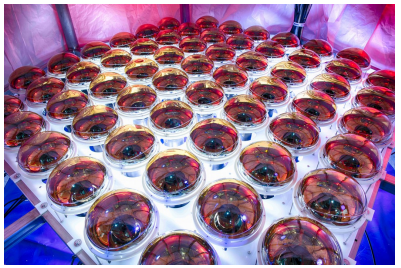




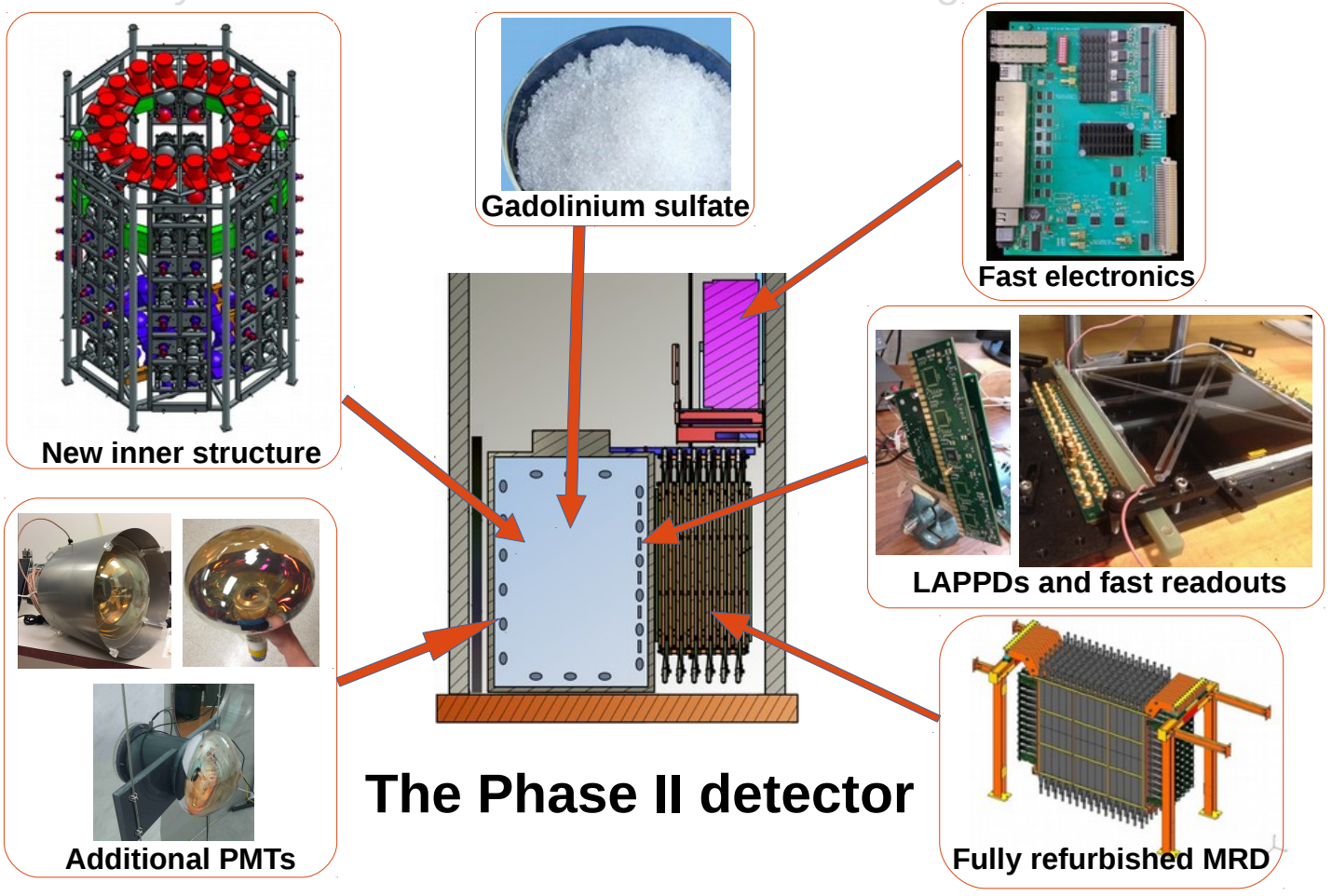





- Background neutron rate per spill per ton **is less than 2%** (5% total rate in the tank)
- Neutron background is **not an issue for the Phase II physics**
- Imminent publication

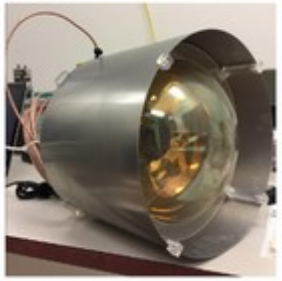
# Measuring beam-induced neutron backgrounds with ANNIE Phase I

- ANNIE was designed to be a multi-phase experiment:
  - ~~**Phase I → Engineering run and background measurement**~~ → **DONE!**
  - **Phase II → First physics run → UNDER CONSTRUCTION**
  - Phase III → Physics run and testbed for new technologies

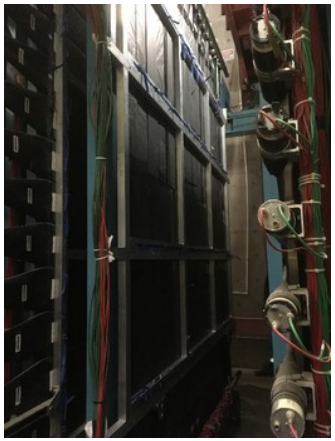
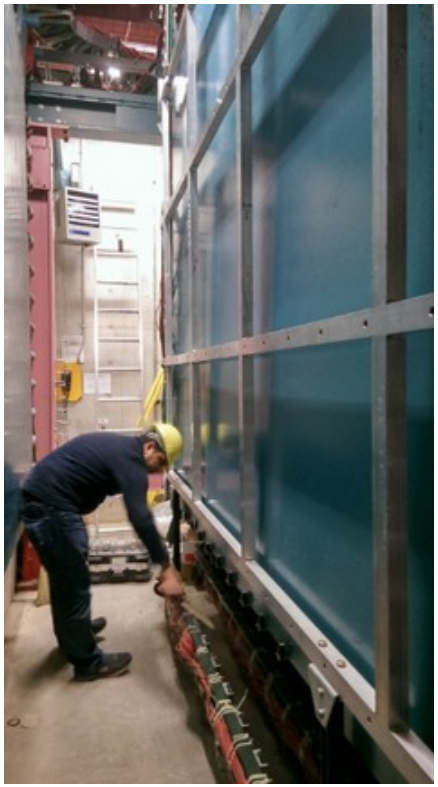


# Active construction at Fermilab!

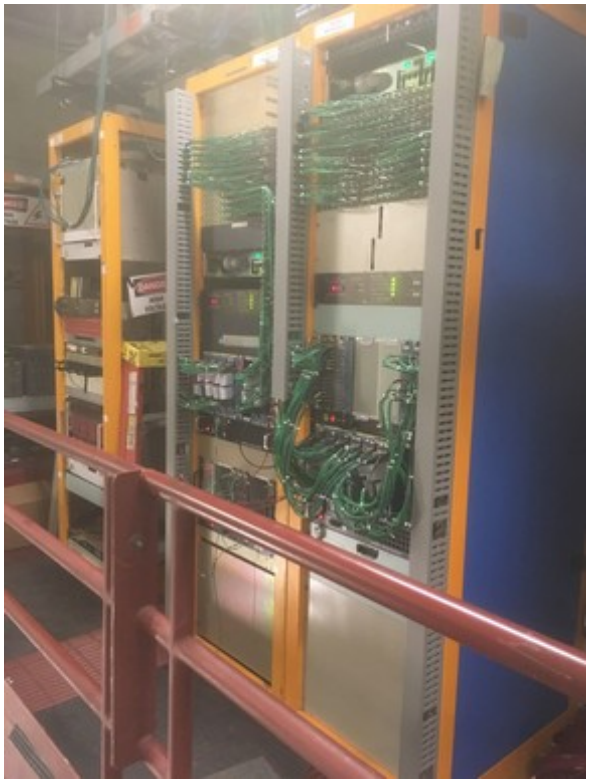




Most **PMTs are onsite, tested** and **ready to be installed**!

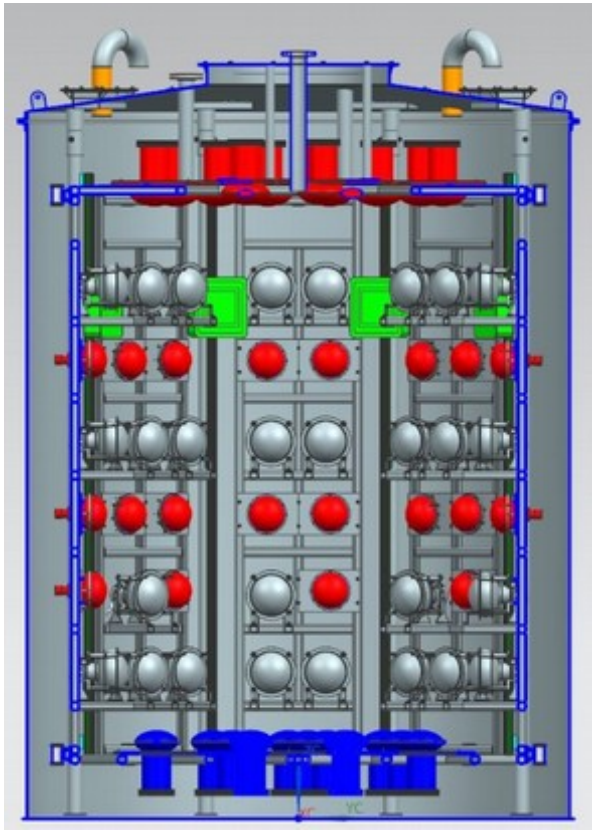




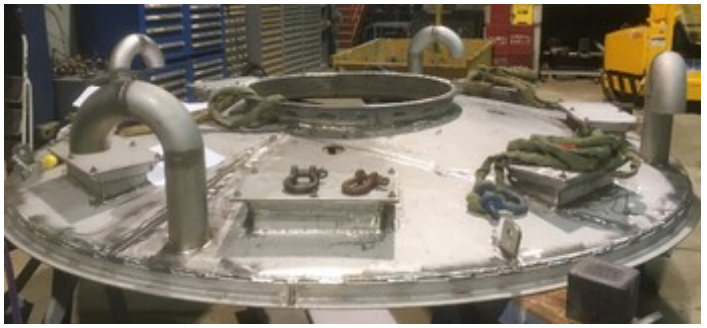

**Muon Range Detector** now **fully refurbished and taking data!**

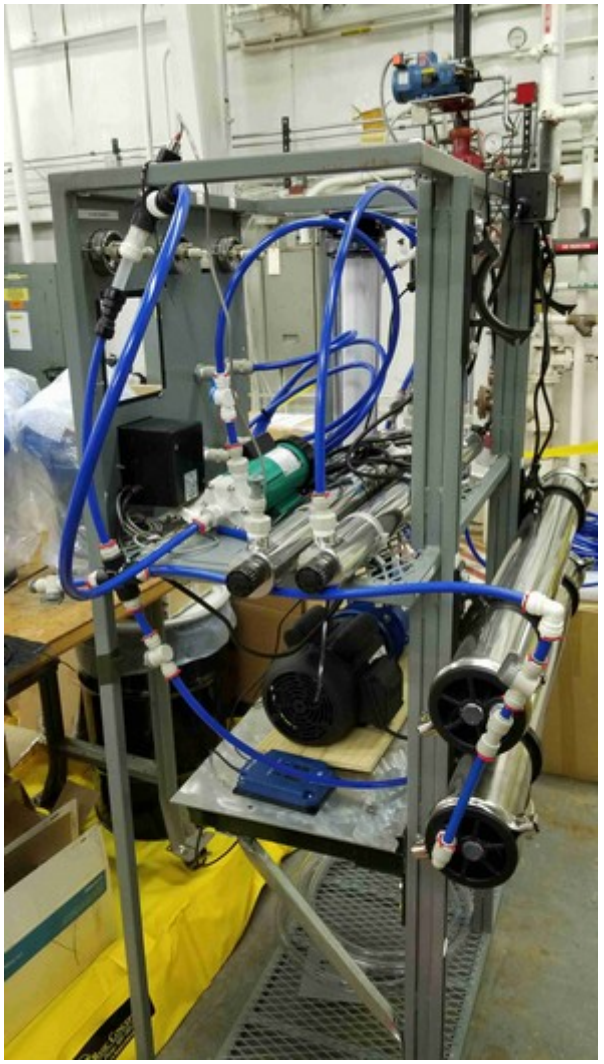


Electronics **racks being populated!**

# Active construction at Fermilab!







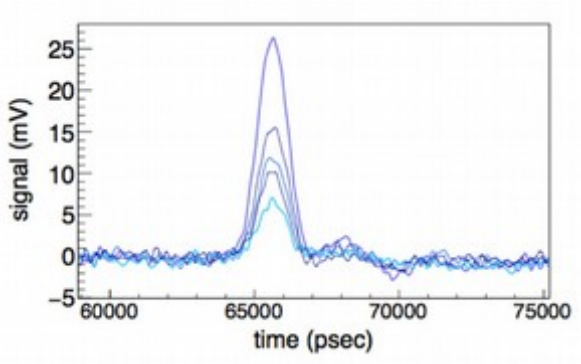
Stainless steel structure **built** and **ready to hold PMTs and LAPPDs!**

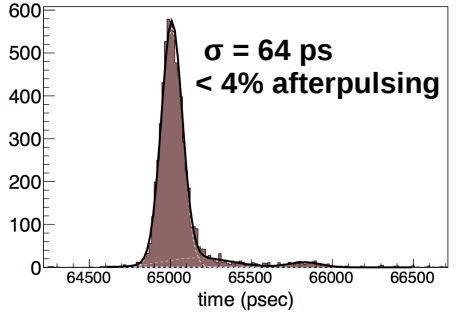
Water **filtration system operational!**

# ANNIE and LAPPDs

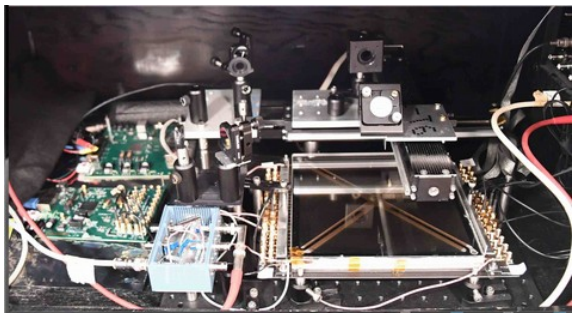
- ANNIE has been an **early LAPPD adopter** since the beginning and maintains strong ties with the **INCOM company**, current **manufacturer** of LAPPDs
- LAPPDs now commercially available with several buyers already identified
- **Three of the 5 first ANNIE LAPPDs** have been **received and are being throughly tested**

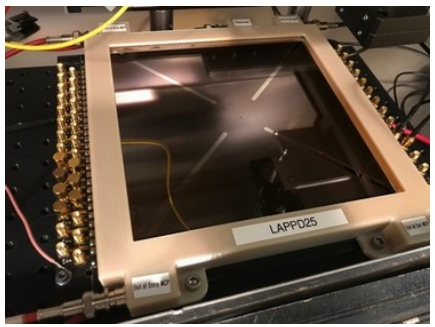
Waveforms and transit time spread




**LAPPD 31 (our second!)** before and after opening






Dedicated LAPPD test stand at ISU

# Phase II timeline

**Pure water**
*Spring 2019*

→ **Commissioning**

**Gd-loaded water**
*Spring 2019 - Summer 2020*

→ **Physics data taking**
→ Neutron yield measurement
→ CC cross section measurement
→ CC0π cross section measurement

**Additional LAPPDs**
*Fall 2020*

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

**Phase III**
*~2021*

→ **Testbed for new technologies**

# Conclusion and take-home message

- The goals of ANNIE:
  - **Study the multiplicity of final state neutrons from neutrino-nucleus interactions in water**
  - **Perform a measurement of the charged current cross section on water as a function of muon kinematics**
  - **Demonstrate the combined use of new detection media and fast photosensors**
- **Phase I was a success** and demonstrates Phase II is feasible with a low neutron background

  → Neutron background measurement **publication in progress**
- **ANNIE is moving into Phase II and** will take **physics data in a few months**
- A possible **Phase III** with **WbLS** and **more fast photosensors** is under discussion

**In the next several years, ANNIE will demonstrate and develop the key technologies for next generation water-based neutrino detectors and precision measurements**

## THANK YOU FOR YOUR ATTENTION!

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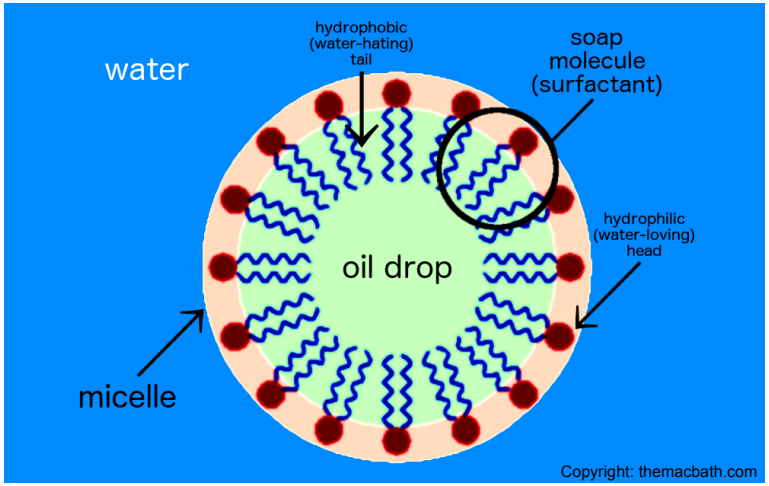
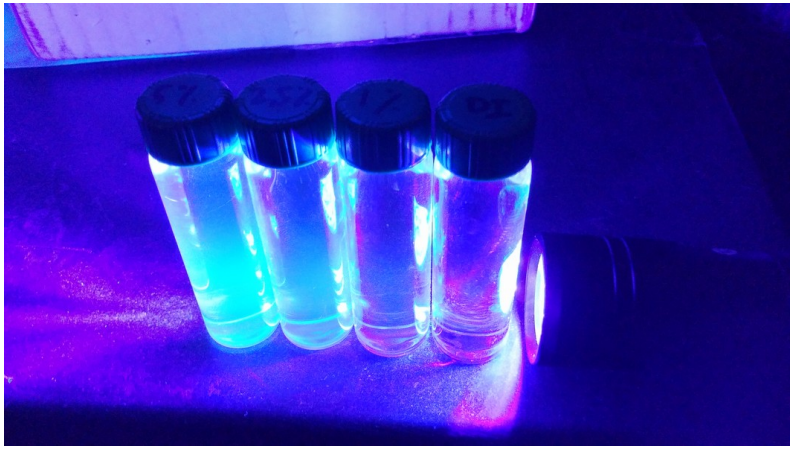
# BACK-UP

# Water-based Liquid Scintillator

- **W**ater-**b**ased **L**iquid **S**cintillator (**WbLS**) is a mixture of pure water and oil-based liquid scintillator
- While water and oil don't mix, WbLS is made using a **surfactant** (soap-like) such as PRS* (hydrophilic head and hydrophobic tail) to hold the scintillator molecules in water in a "**micelle**" structure
- **Combines the advantages** of water (low light attenuation, low cost) and liquid scintillator (high light yield)
- Emission of **prompt Cherenkov** light and **delayed scintillation** light
- **Tunable LS content** for a broad range of physics goals
- **Low cost** and **environmentally-friendlier** than pure LS
- Strong R&D effort ongoing at **Brookhaven and Berkeley** Nat. Labs and **UC Davis**



Micelle structure in water


Samples of WbLS with different LS concentrations

*PRS: Linear Alkyl Sulfonate

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# SciBooNE

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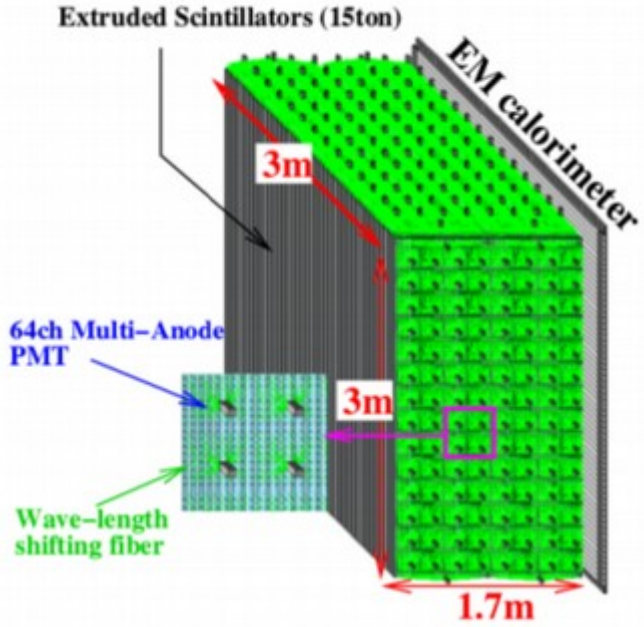
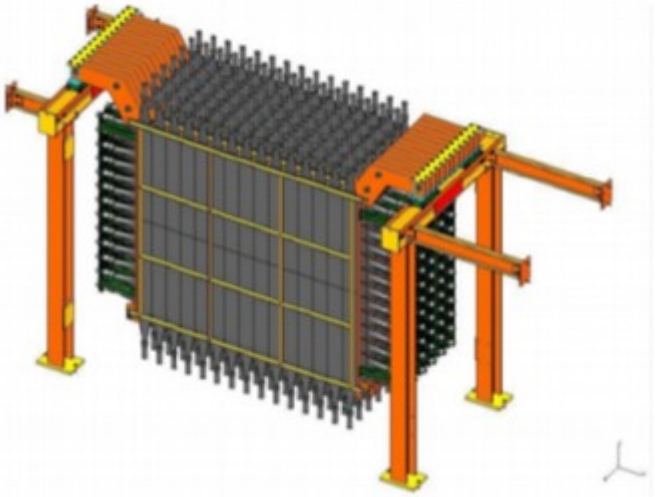


- SciBar: Scintillator tracking detector (14'000 bars, 14 tons)
- Electron Catcher: 2 planes of calorimeter (lead and scintillating fibers)
- Muon Range Detector
- Measurement of CC-QE, CC-$\pi^{\pm}$, CC-$\pi^{0}$, NC-ES cross-sections

# PSEC-4 electronics for LAPPDs

## 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)

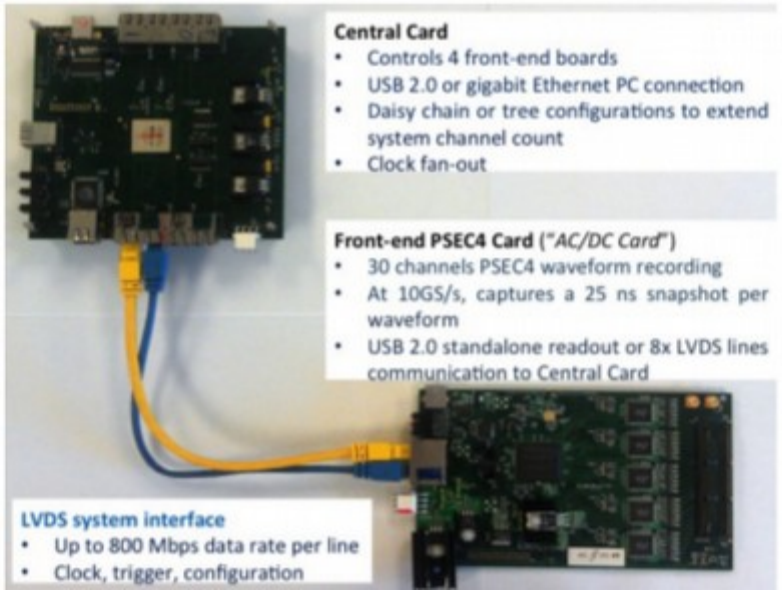
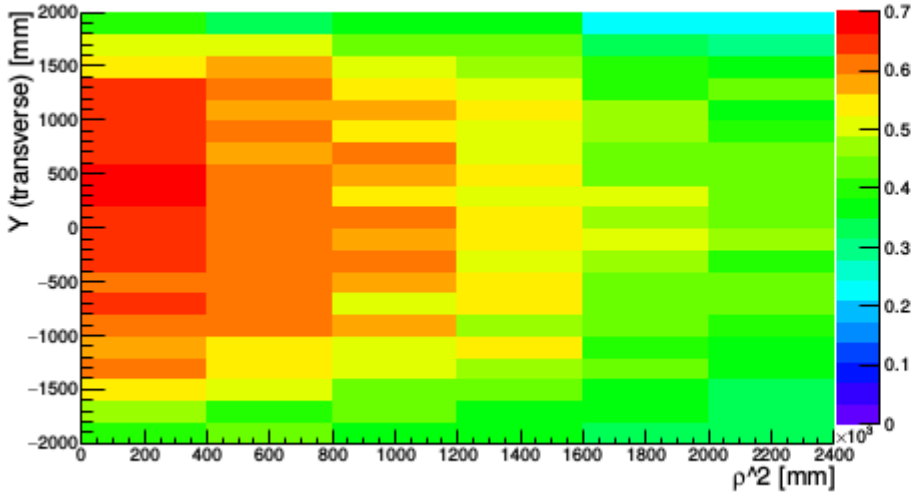


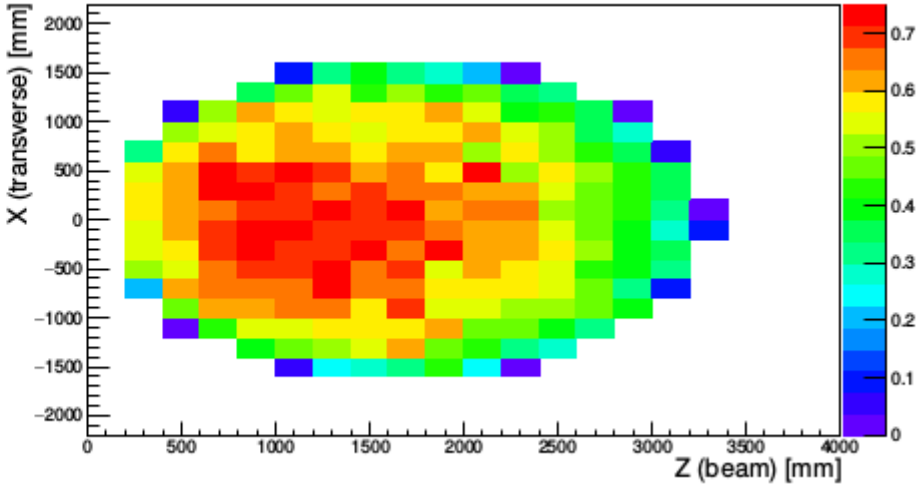

Image source: Jonathan Eisch (ISU)

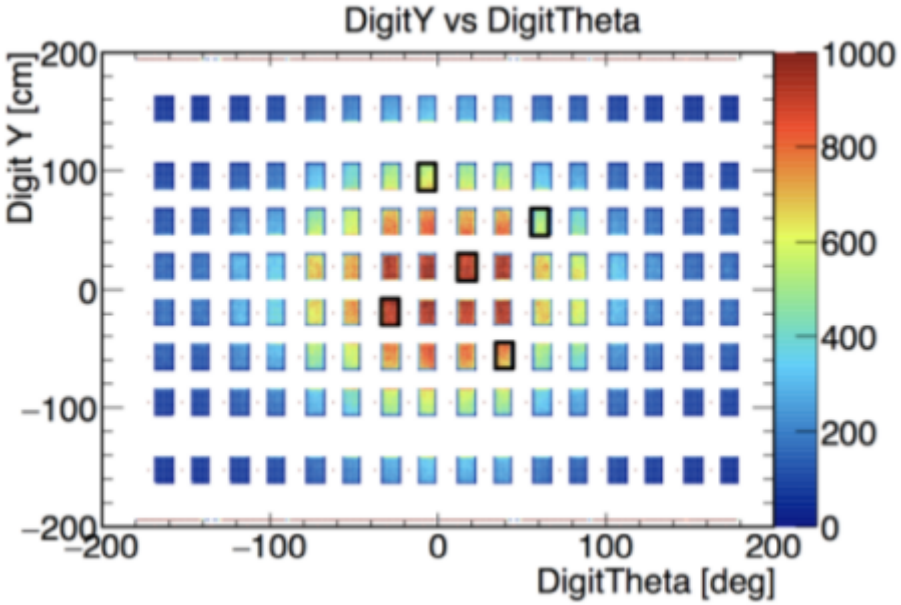
ANNIE Central Card

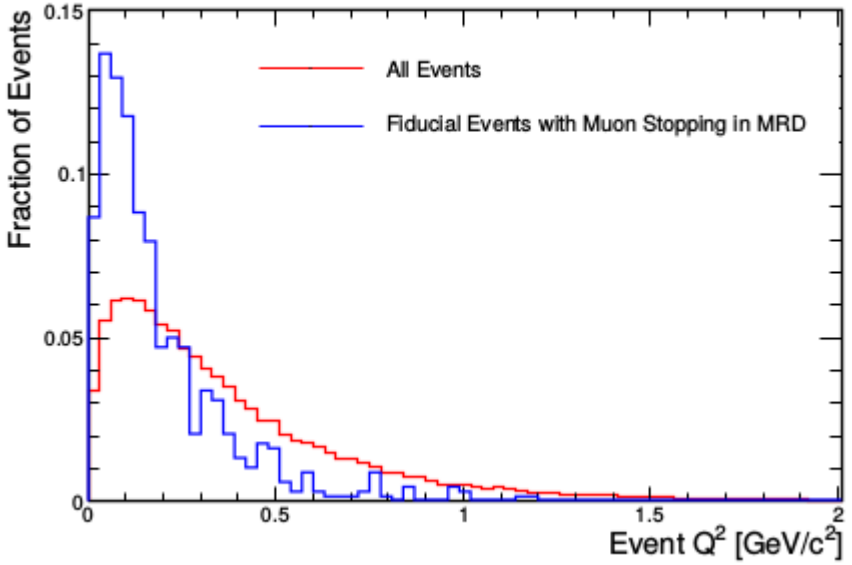
# Phase II simulations – Understanding ANNIE

Preliminary neutron detection efficiencies

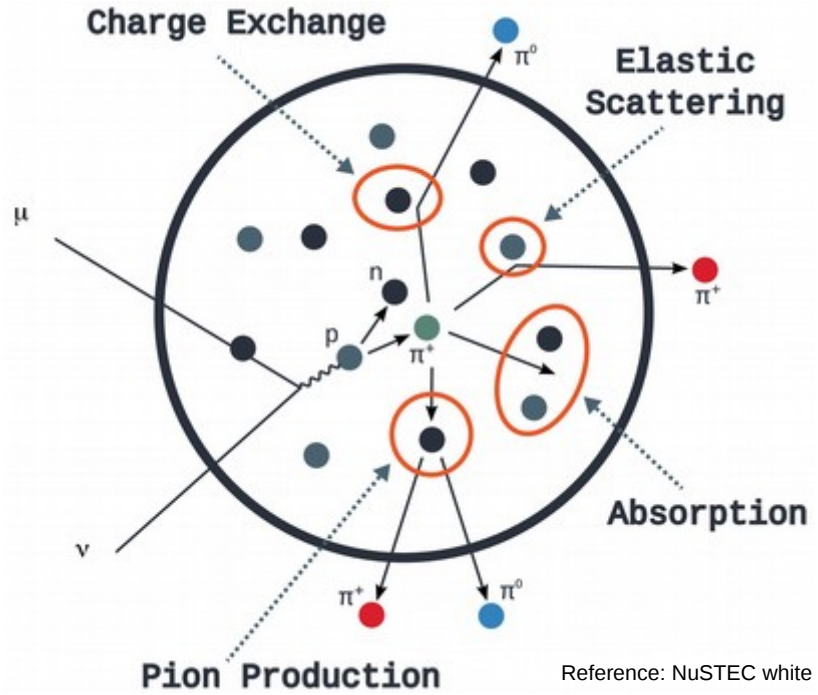


# Neutrons as an indicator of inelasticity

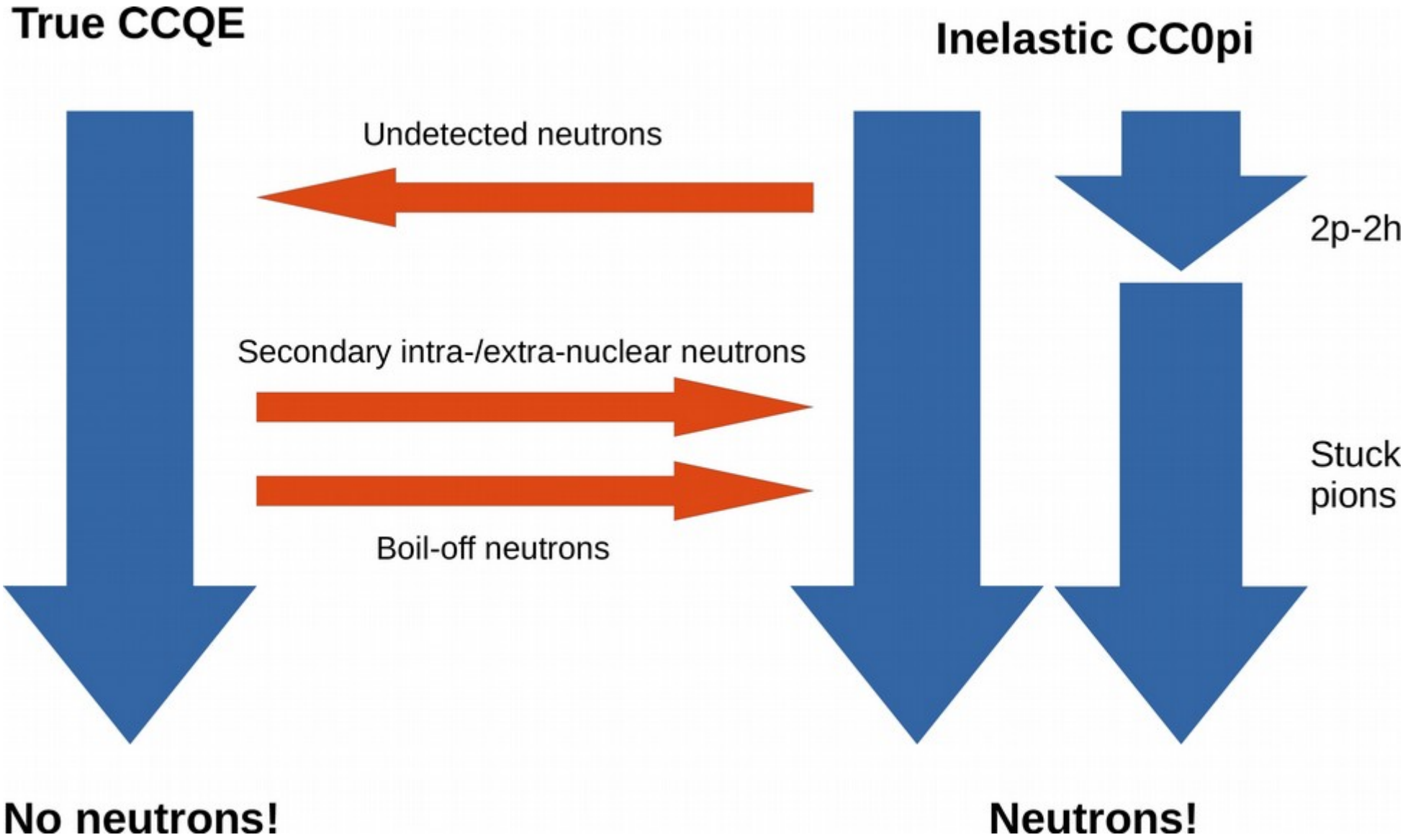



Reference: NuSTEC white paper

- 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**

# Neutron production and 0n ↔ Xn confusion



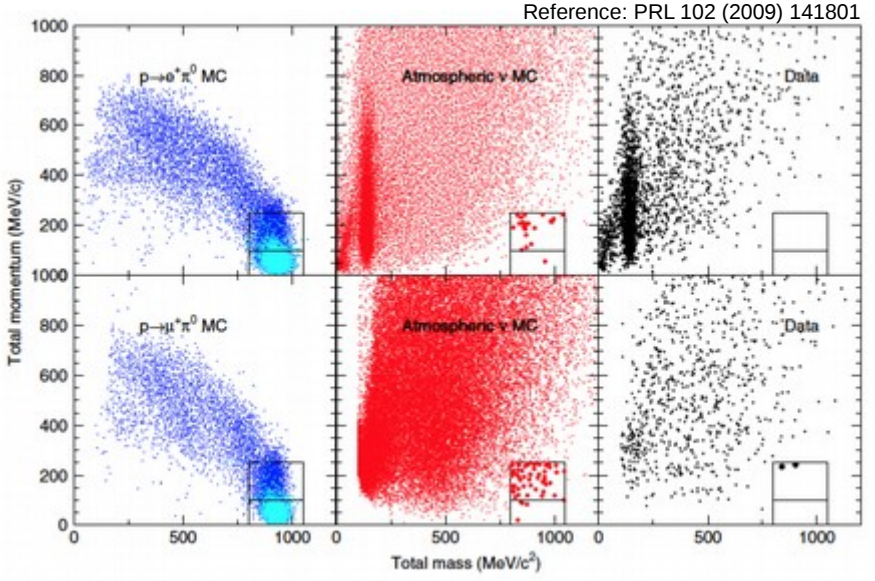
# Physics motivation: Energy-dependent neutron yield

**Study the multiplicity of final state neutrons from neutrino-nucleus interactions in water**

## Proton decay searches

- No neutrons produced in 90% of proton decays ($p \rightarrow e^+ + \pi^0$)
- Main background → Atmospheric neutrinos likely to produce neutrons
- Data in needed to implement this neutron yield and improve simulations and signal to background separation

Reference: PRL 102 (2009) 141801



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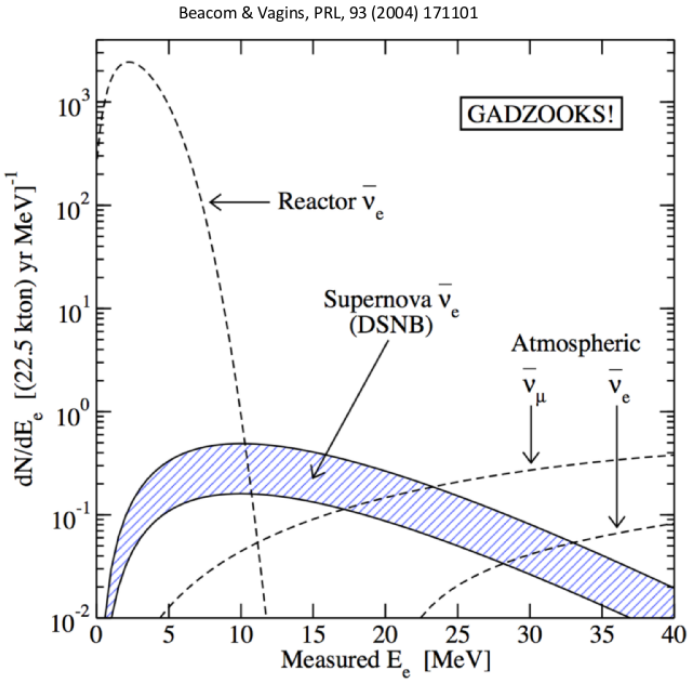
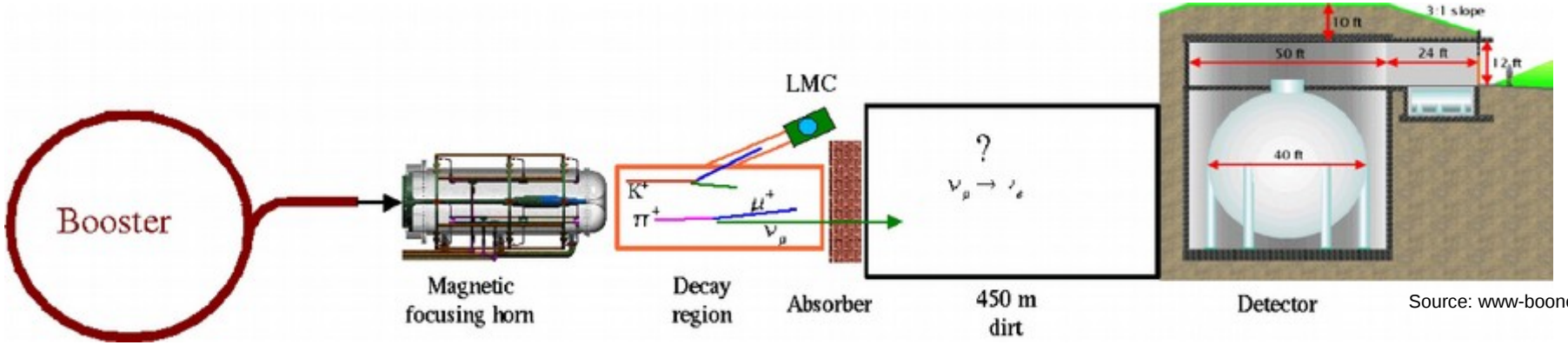


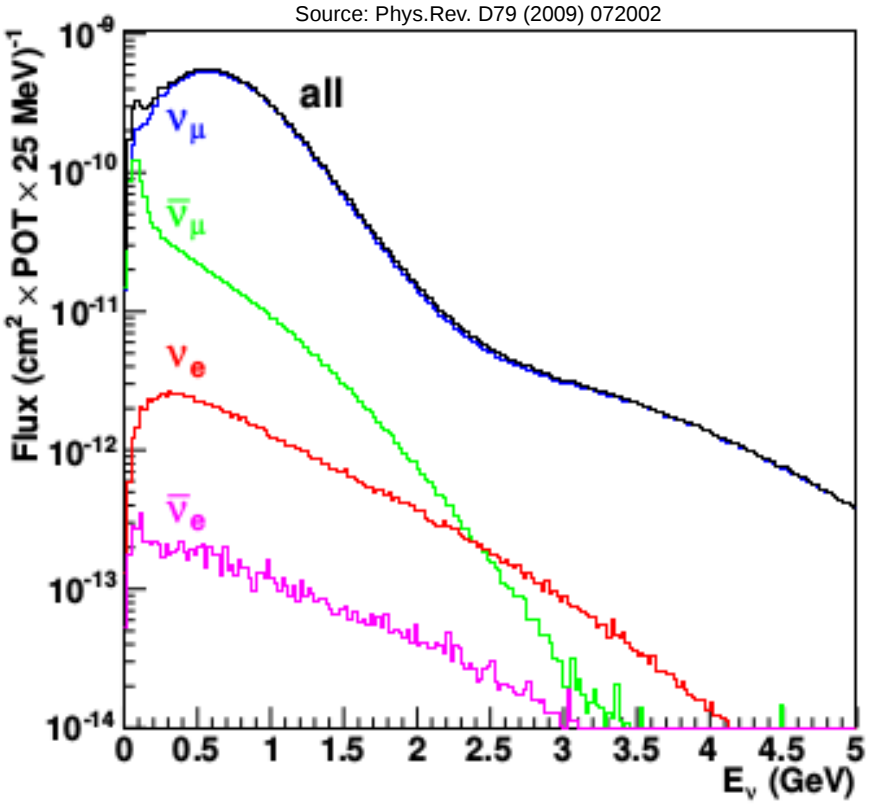

## Supernova neutrino detection

- Diffuse Supernova Background (DSNB): Continuous flux of neutrinos from past supernovae
- Main detection channel for $\bar{\nu}_e$: $\bar{\nu}_e + p \rightarrow e^+ + n$ (Inverse Beta Decay)
- Main background: Decay of sub-Cherenkov muons produced by atmospheric neutrinos + neutron
- Understanding those atmospheric neutrino interactions is needed

# The Booster Neutrino beam




Source: www-boone.fnal.gov

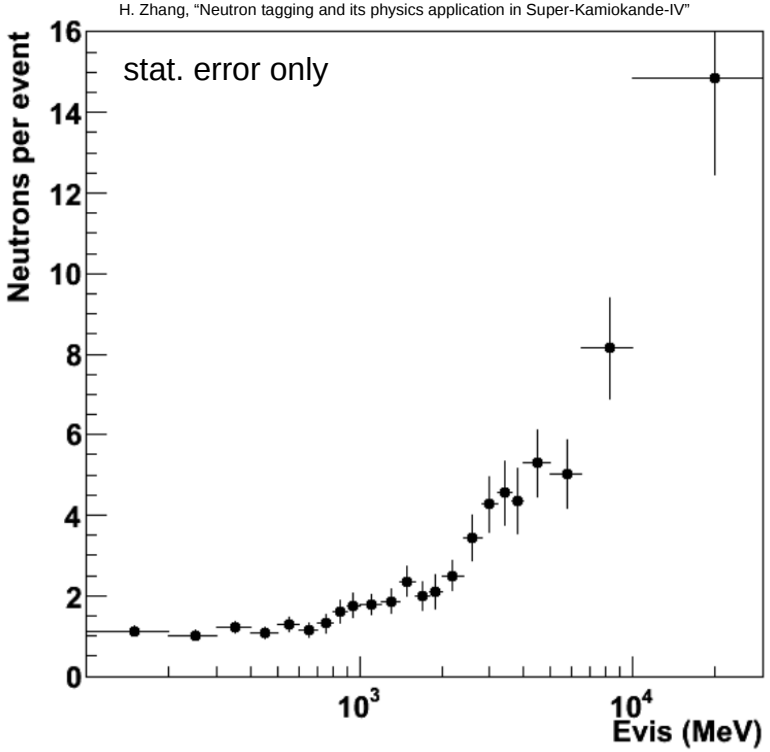



- 8 GeV protons from the Booster beam hitting a beryllium target with reversible horn polarity
- Repetition rate of ~5 Hz, $5 \times 10^{12}$ protons-on-target per 1.6 μs spill on average
- Mean neutrino energy of 700 MeV
- Composition in neutrino mode: 93 % of $\nu_\mu$ , 6.4 % of $\bar{\nu}_\mu$ and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

# Super Kamiokande neutron yield

- Super Kamiokande measured the neutron yield as a function of the visible neutrino energy using atmospheric neutrinos
- However:
  - Low neutron detection efficiency of 17% (before SK-Gd)
  - **Only visible energy** → Unknown neutrino energy and angle
  - Unknown neutrino flavor and unknown interaction type

H. Zhang, "Neutron tagging and its physics application in Super-Kamiokande-IV"



# The physics goals of Phase II

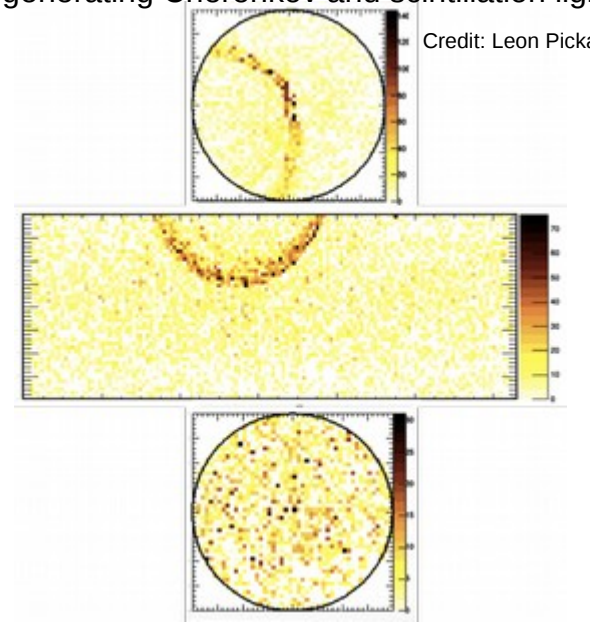
- **In addition** to the primary physics goal:
  - Measurement of **charged current cross section** on oxygen
- As more and more data is being collected and the detector is being upgraded, a **broader range of physics programs** becomes available...
  - Measurement of **charged current resonant** pion production cross section
  - Measurement of **neutral current cross section**
- … as well as a **wide range of experimental techniques**:
  - Detection of **de-excitation gammas** in water
  - Hybrid **kinematic-calorimetric energy reconstruction** (Phase III)
  - **Cherenkov-Scintillation light separation** using WbLS and fast photosensors (Phase III)

# LAPPDs and scintillation for the win!

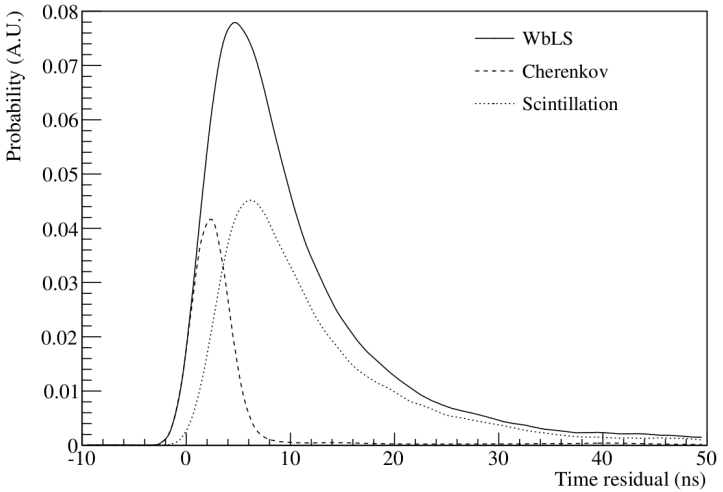
**Water-based Liquid Scintillator (WbLS):** Mixture of water and liquid scintillator allowing emission of **both Cherenkov and scintillation** light

- **Separating** Cherenkov and scintillation allows a combined **kinematic** and **calorimetric** measurement
- Doing so in a detector such as ANNIE **requires fast photosensors**
- Scintillation light allow neutron **capture point reconstruction** and lowers the **detection threshold** for charged particles such as protons
- The combination of WbLS with fast photosensors is the **main physics case** for a possible ANNIE Phase III
- **Crucial contribution** to WATCHMAN and Theia

CCQE interaction in a 50 kt WbLS detector generating Cherenkov and scintillation light



Credit: Leon Pickard (UC Davis)



# ANNIE → WATCHMAN → Theia

Mass

~50,000 tons
~100,000 sensors

~4,000 tons
~5000 sensors

~30 tons
~150 sensors

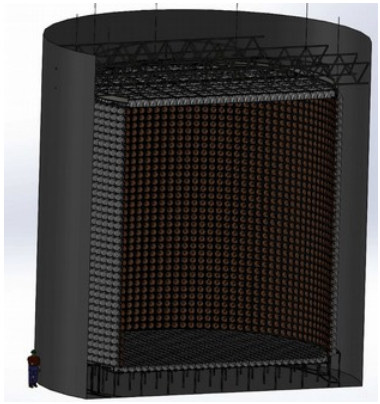
**Use** of WbLS + fast photosensors in a **large detector**

40-60 m

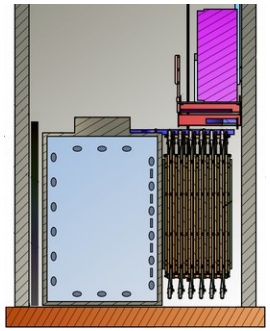
40-60 m

Theia

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



**WATCHMAN**



Data taking

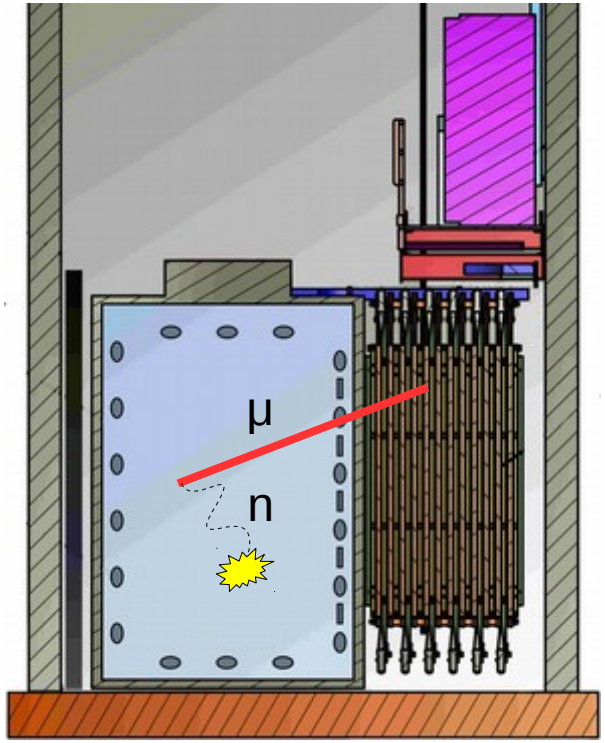
2019+

2022+

202?

# On the importance of vertex resolution

Case 1




Interaction vertex at (x,y,z)

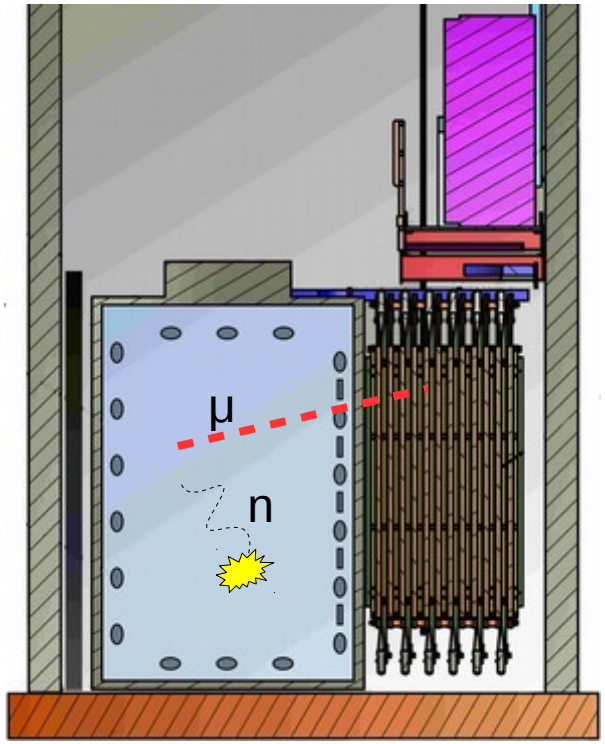
Interaction vertex correctly reconstructed at (x,y,z)

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!**