NNN 2018

International workshop on Next Generation Nucleon Decay and Neutrino Detectors

ANNIE: The Accelerator Neutrino Neutron Interaction Experiment

Vincent Fischer
on behalf on the ANNIE collaboration

University of California at Davis

November 3, 2018

Overview of ANNIE

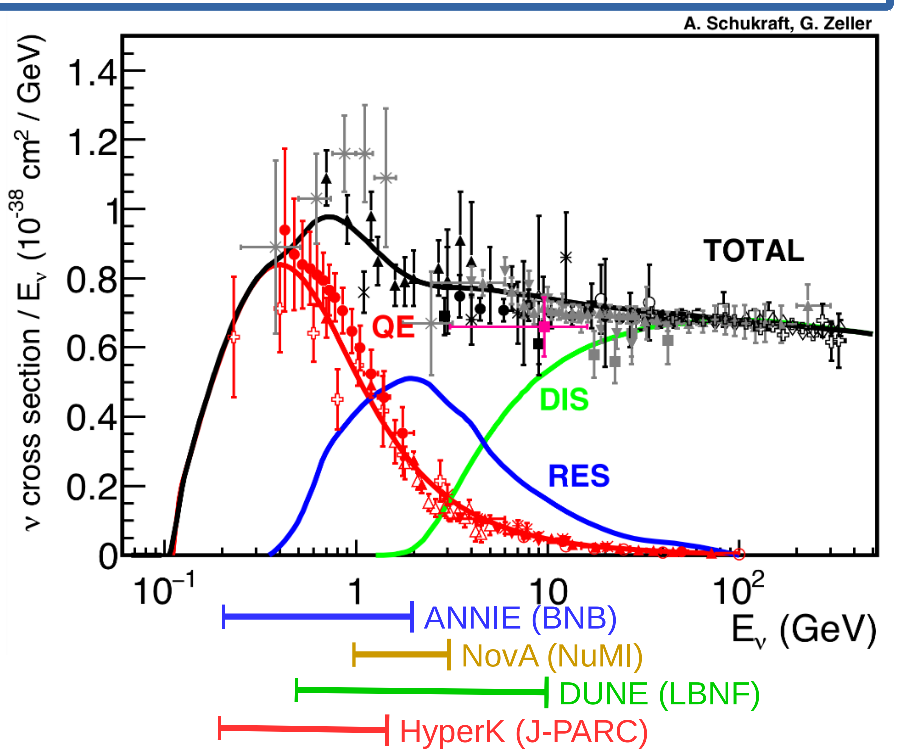
- **ANNIE** is the Accelerator Neutrino Neutron Interaction Experiment
- **Gd-loaded water Cherenkov** detector placed downstream of the **Booster Neutrino Beam** at **Fermilab**
- Aims at **understanding final state neutron multiplicity** from neutrino interactions in **water** as a function of **muon 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 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
- Allows a possible **statistical separation** of neutrino/antineutrino



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

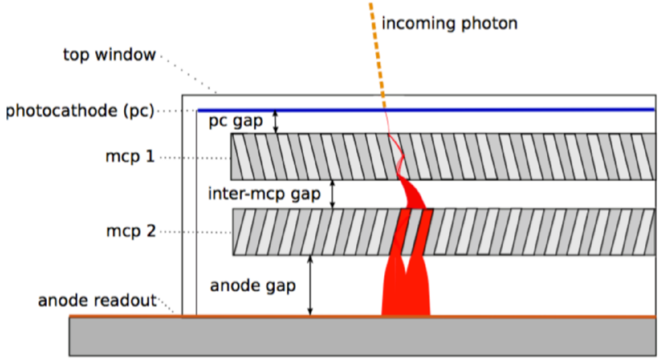
LAPPD R&D and demonstration

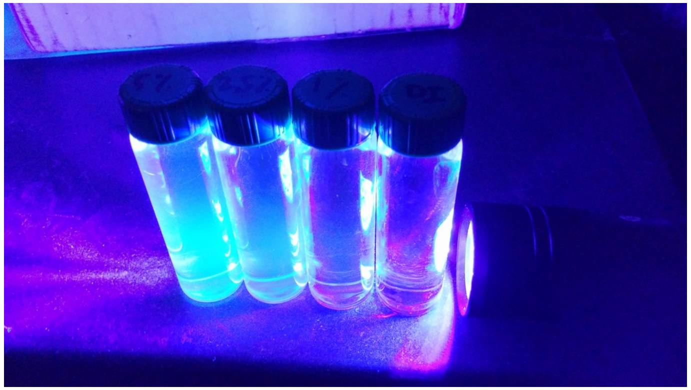
- **Large Area Picosecond PhotoDetectors (LAPPDs)**: 20x20 cm micro-channel plates with **~60-ps time** resolution and **<1 cm spatial** resolution (see talk from Alexey Lyashenko)
- **First use** of this new technology in a running neutrino experiment
- Demonstrate LAPPDs are **ready for research and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

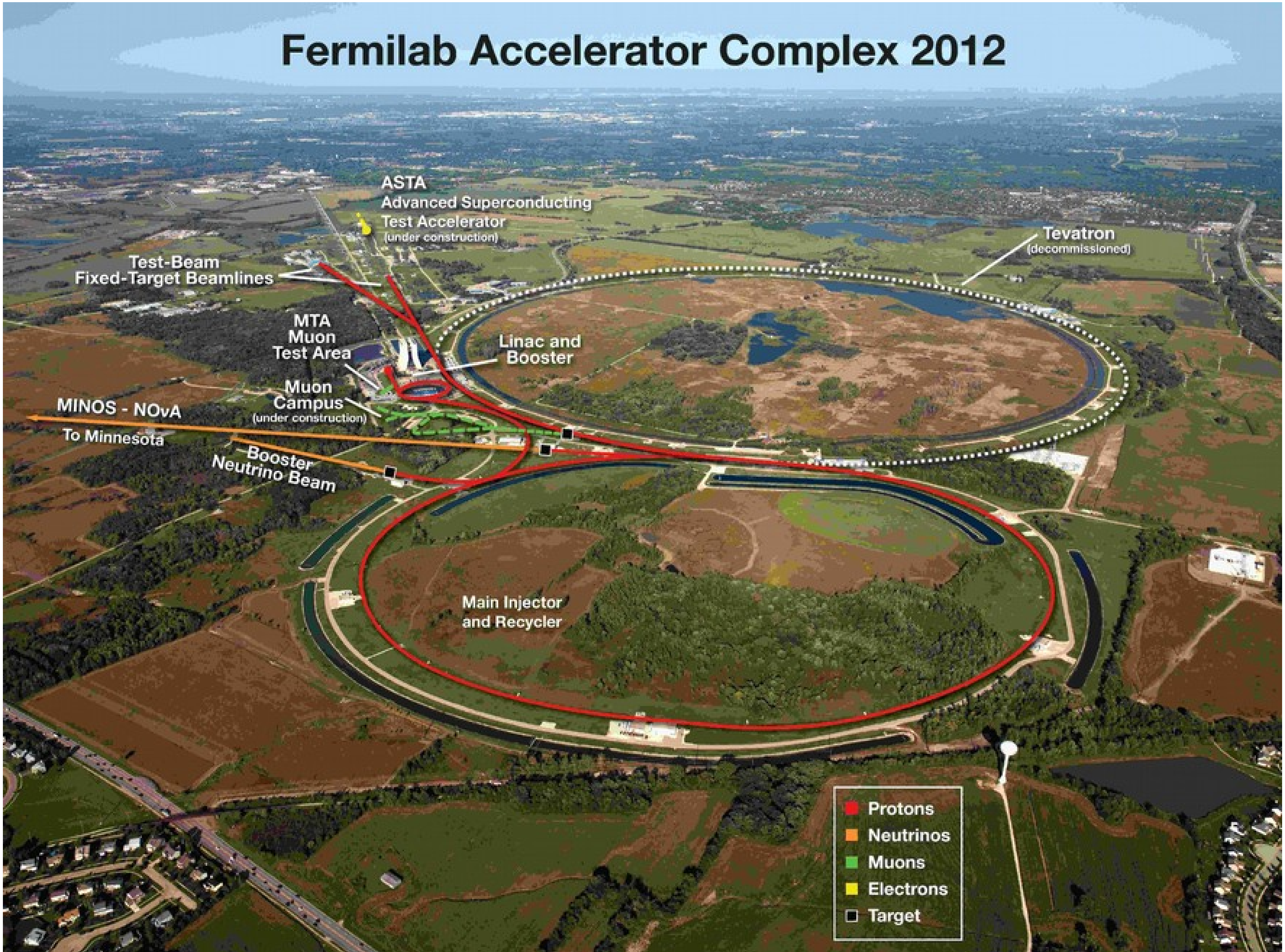
* see previous Theia talk and posters



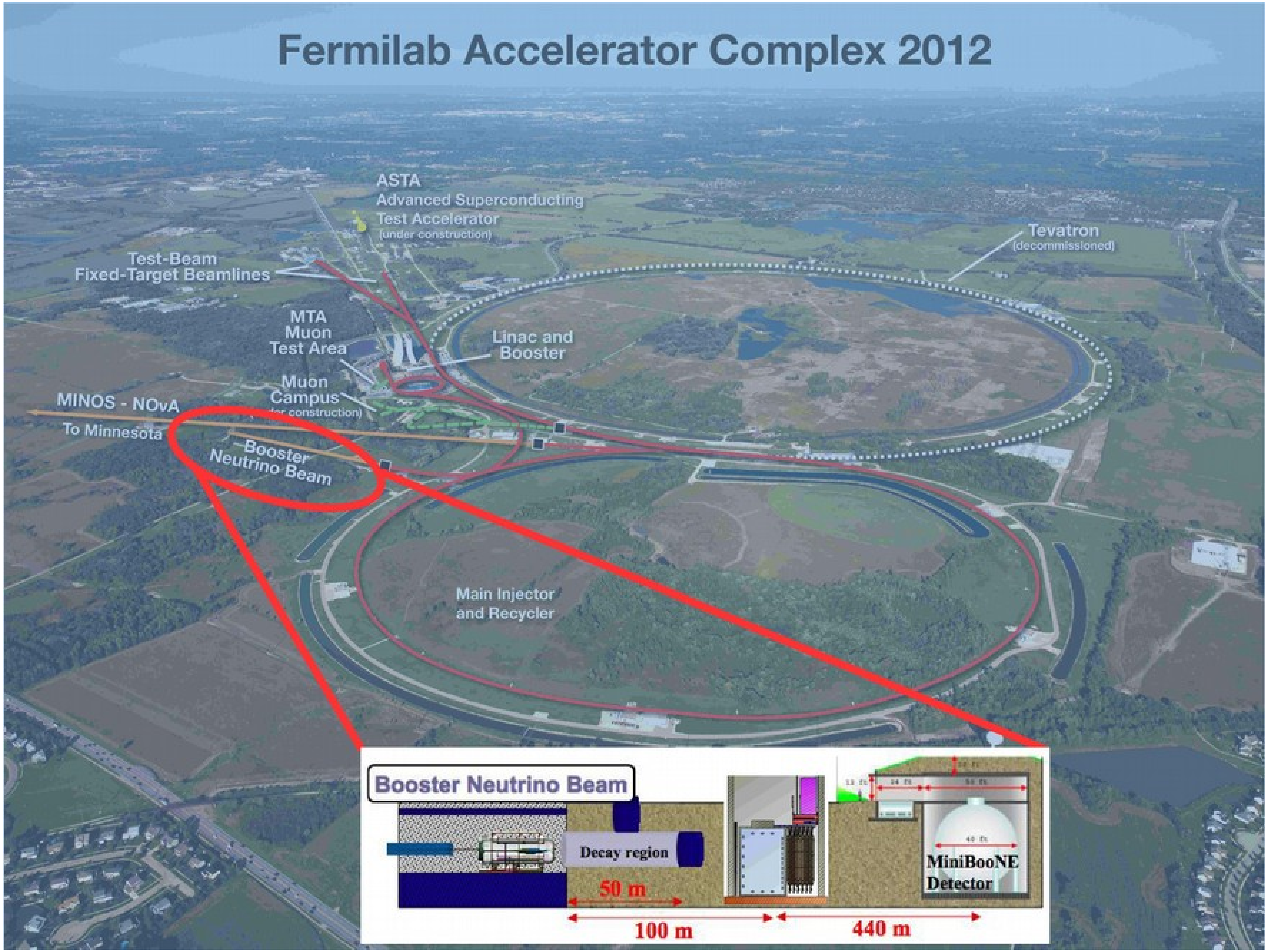


ANNIE will allow the combined use of all the previous technologies in a single high-statistics experiment

ANNIE on the BNB



ANNIE on the BNB



ANNIE on the BNB

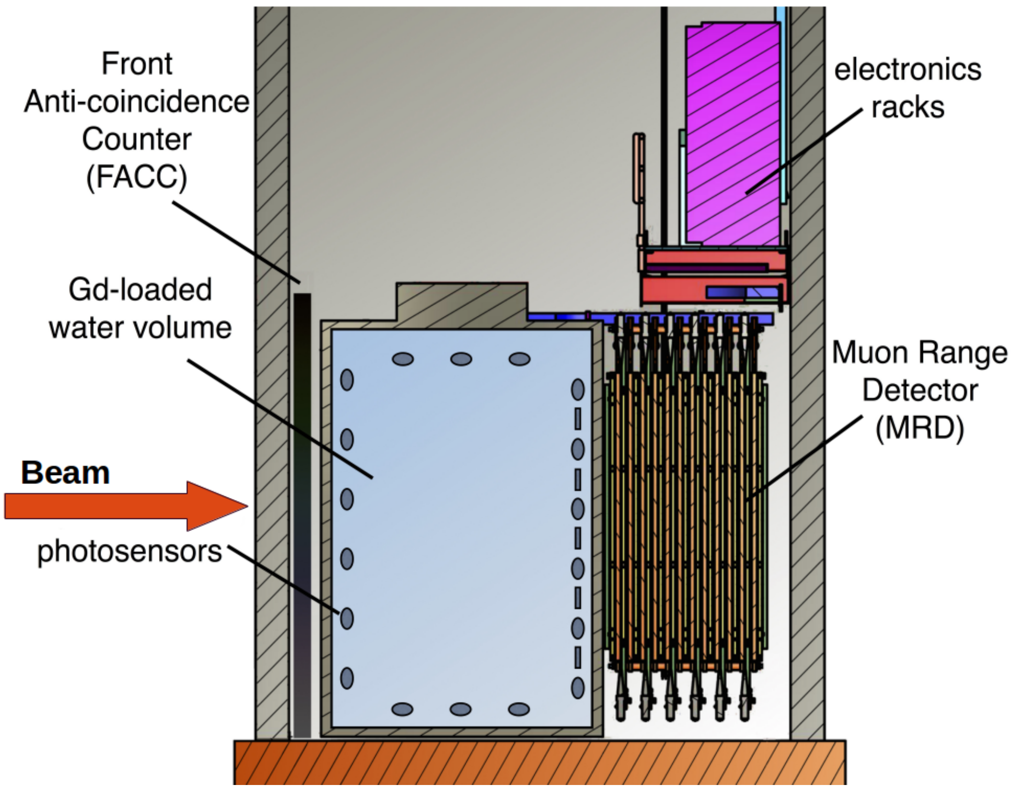
ANNIE on the BNB

UC DAVIS
UNIVERSITY OF CALIFORNIA

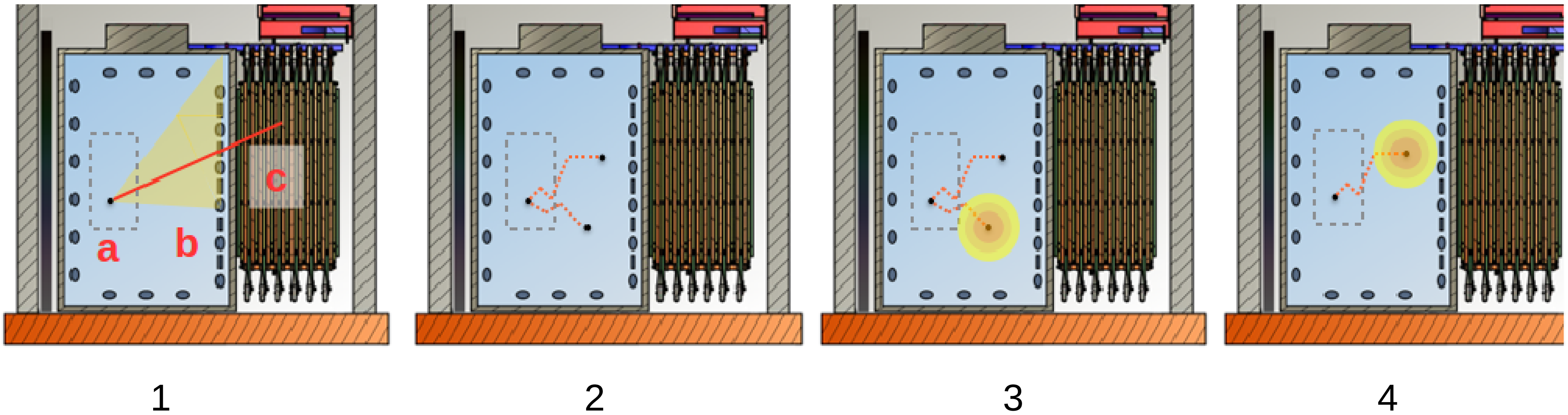
ANNIE on the BNB

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 at least **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 × 10^{20} POT) expected



How will ANNIE work?



1.a - CC interaction in the fiducial volume

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

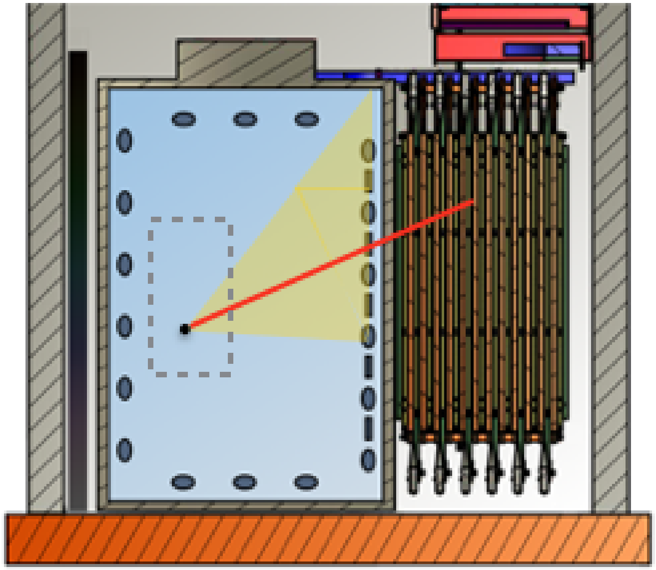
1.c - Muon momentum reconstructed with the MRD

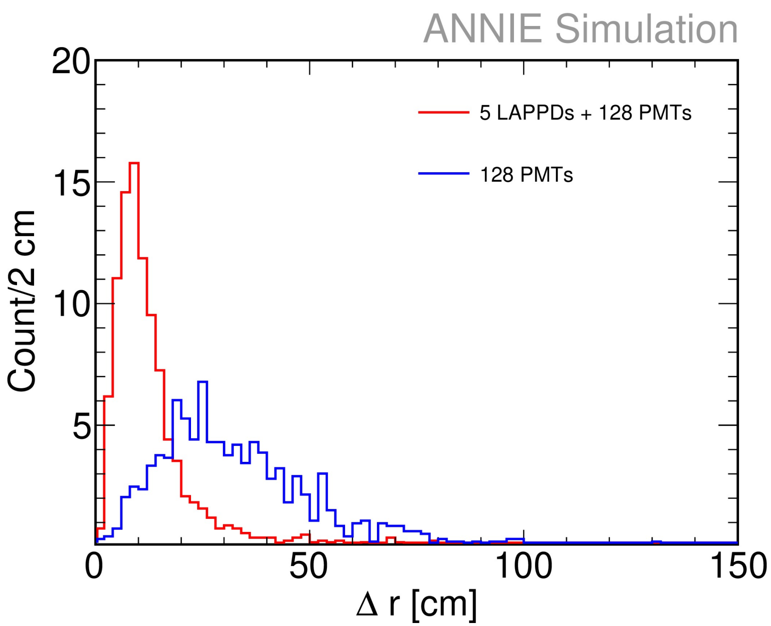
2 - Neutrons thermalize in the water volume

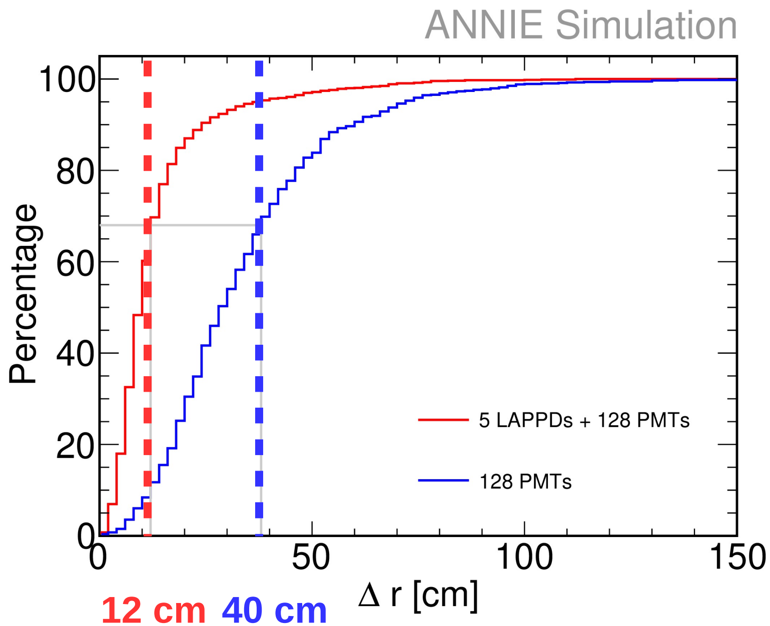
3-4 - Neutron capture on gadolinium detected by the PMTs

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, angular resolution, and momentum transfer resolution**
  - **Vertex resolution** → Interaction point reconstruction and neutron containment
  - **Muon kinematics** → Better energy reconstruction
  - **Precision timing** → Multi-tracks separation





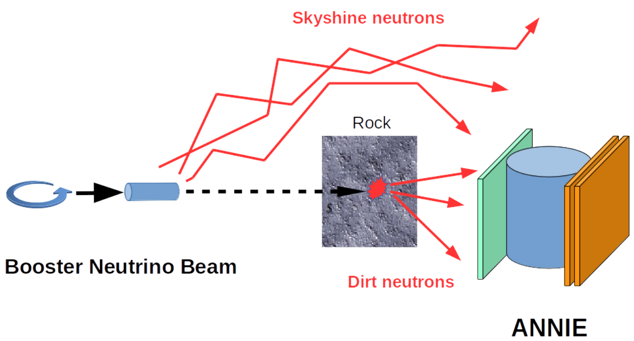


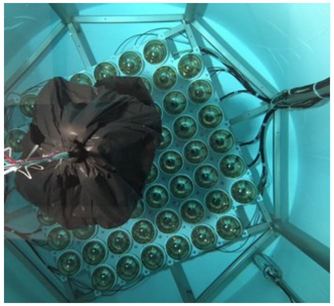
Measuring beam-induced neutron backgrounds with ANNIE Phase I

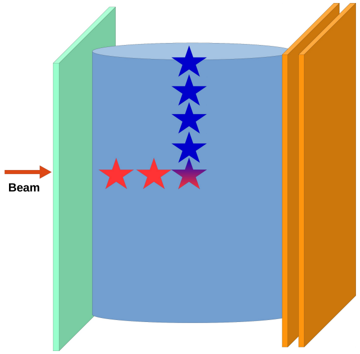
- ANNIE was designed to be a multi-phases experiment:
  - **Phase I** → **Engineering** run and **background** measurement
  - **Phase II** → First **physics** run
  - **Phase III** → Physics run and **testbed for new technologies**

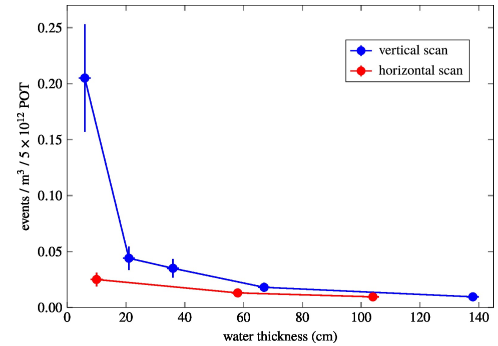
Measuring beam-induced neutron backgrounds with ANNIE Phase I

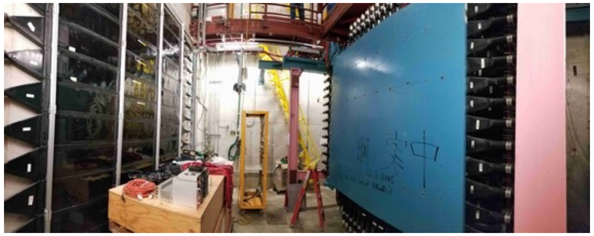
- ANNIE was designed to be a multi-phases experiment:
  - **Phase I → Engineering run and background measurement**
  - Phase II → First physics run
  - Phase III → Physics run and testbed for new technologies
- Phase I → Measurement of beam-induced neutron backgrounds:
  - **Skyshine neutrons** → Neutrons from the beam dump entering the detector
  - **Dirt neutrons** → Neutrons originating from neutrino interactions downstream of the dump

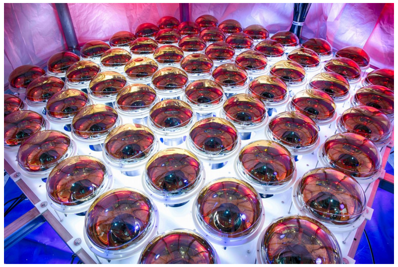












- Background neutron rate per spill **is less than 2%**
- Neutron background is **not an issue for the Phase II physics**

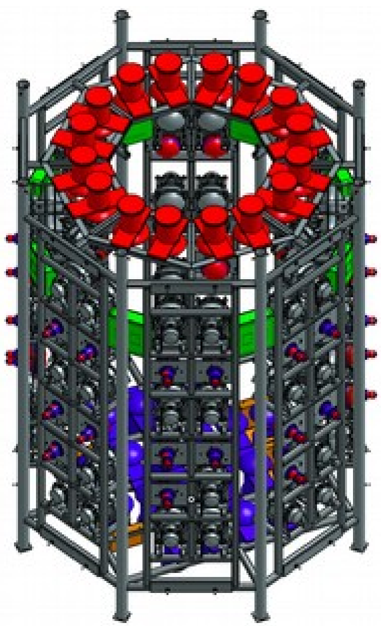
Measuring beam-induced neutron backgrounds with ANNIE Phase I

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

- Beam-induced neutron background **isn't an issue for physics**
- Phase I relied on the **key physical infrastructures of Phase II**

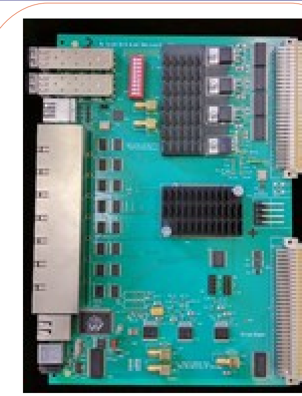
→ We gained critical operational experience that informed the design of our physics run

Towards Phase II - A fully operational detector

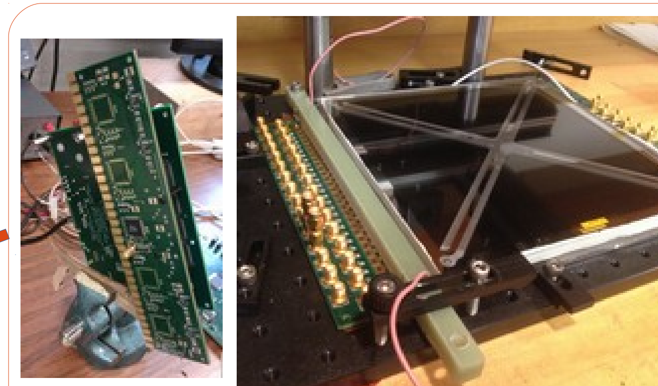


New inner structure

Gadolinium sulfate

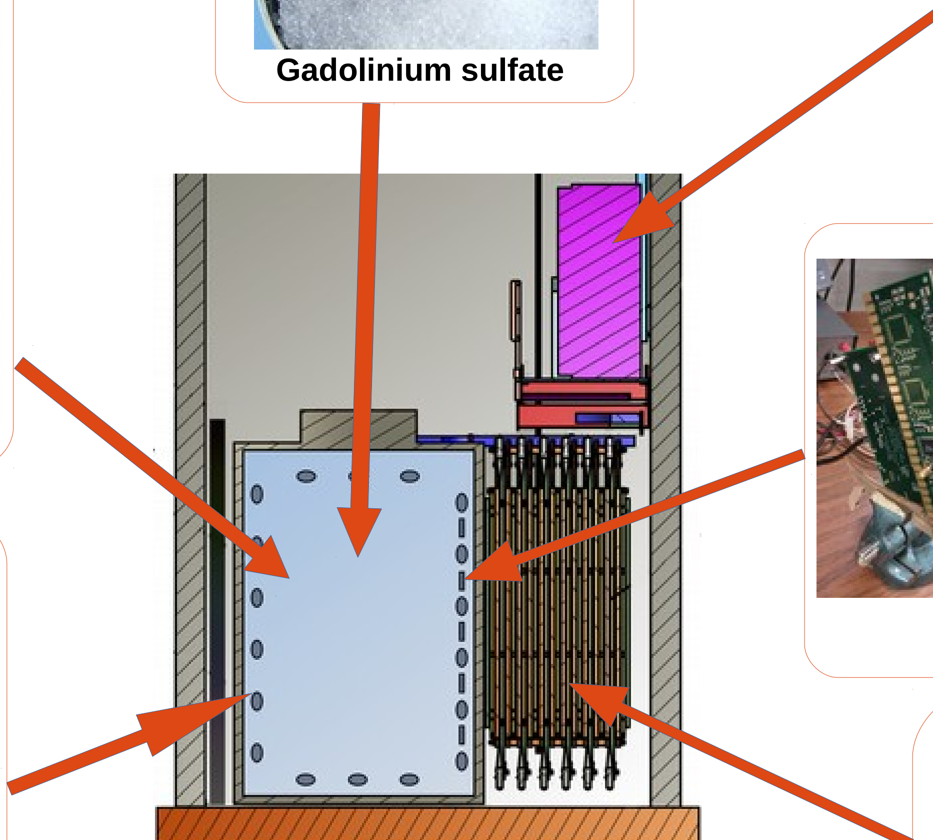


New fast electronics

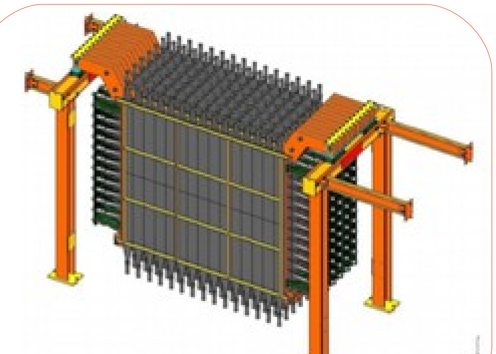


LAPPDs and fast readouts

Additional PMTs

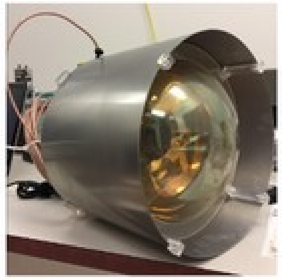


The Phase II detector

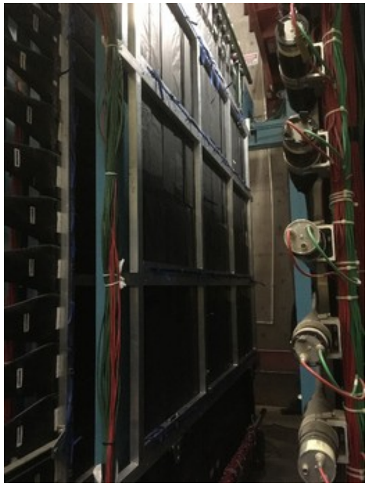


Fully refurbished MRD

Fully funded and under construction at Fermilab!



Most **PMTs onsite** and **ready to be tested/installed**!



Muon Range Detector now **fully refurbished!**

HV and electronics **racks ready** to be populated!

Fully funded and under construction at Fermilab!

Stainless steel **inner structure** being **welded and mounted!**

ANNIE and LAPPDs

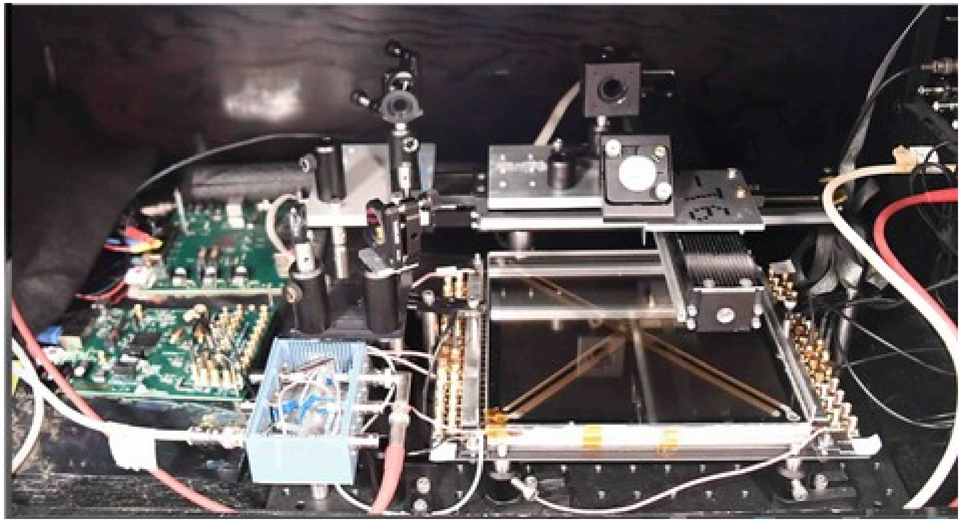
- ANNIE has been an **early LAPPD adopter** since the beginning and maintains strong ties with the **INCOM company**, current **manufacturer** of LAPPDs (see Alexey Lyashenko's talk)
- LAPPDs now commercially available with several buyers already identified
- **Two of the 5 first ANNIE LAPPDs** have been **received and are being throughly tested**

Slide from Matt Wetstein at FROST2016

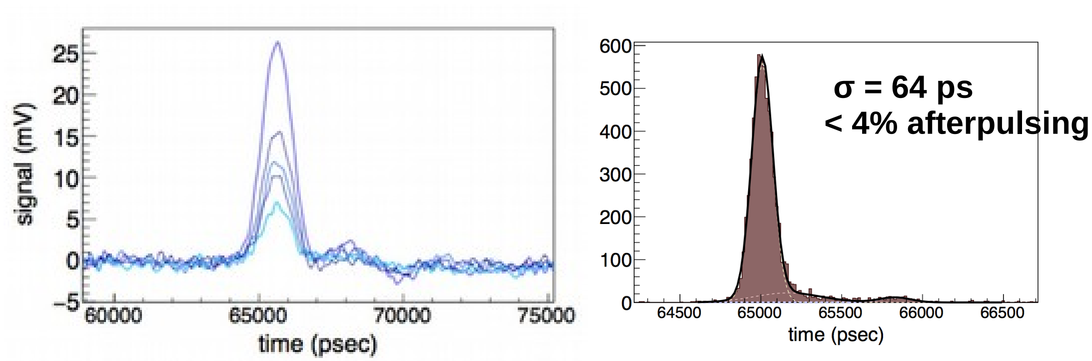
From A. Lyashenko in the Detector parallel session

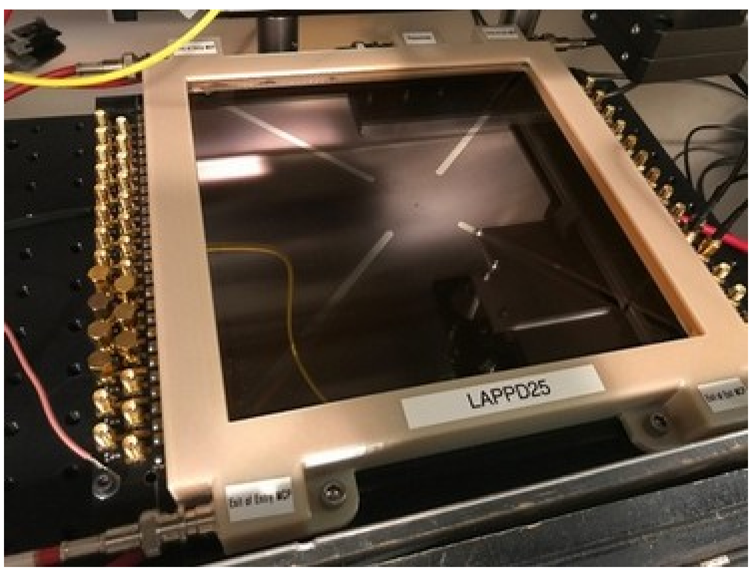
PI & SPONSOR	PROGRAM TITLE
Mayly Sanchez and Matthew Wetstein, Iowa State	ANNIE - Atmospheric Neutrino Neutron Interaction Experiment
Erik Brubaker, Sandia National Lab/CA	Neutron Imaging Camera
Graham Smith, Klaus Attenkofer (BNL)	Gamma & Neutron Detectors
Henry Frisch (U of Chicago) , Dmitri Denisov (Fermilab)	Precision Time-of-Flight with Commercial Photodetectors at the Fermilab Testbeam Facility
Matthew Malek,(u of Sheffield)	WATCHMAN, UK STFC
Josh Klein, U of Penn	Spectrally Sorting of Photons, using Dichroic Films and Winston Cones, WATCHMAN, THEIA
Gabrial D. Orebi Gann (UC Berkeley)	WATCHMAN, THEIA

More LAPPD tests ongoing



Waveforms and transit time spread





Dedicated LAPPD test stand

LAPPD 31 (our second!) before and after opening

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)

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

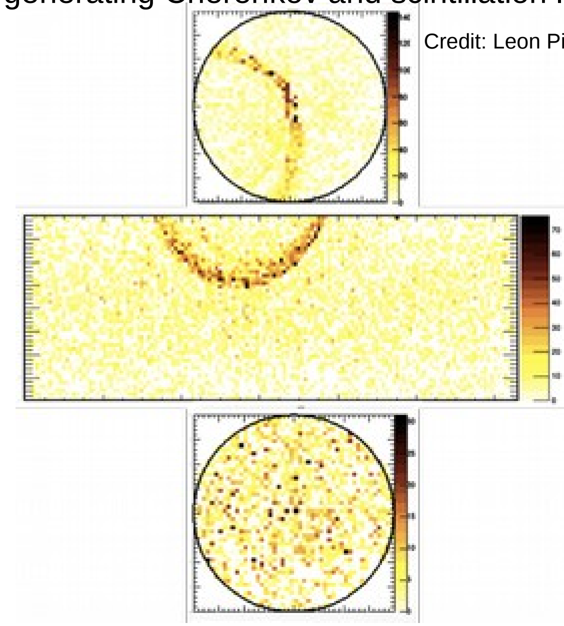
→ **Testbed for new technologies**

LAPPDs and scintillation for the win!

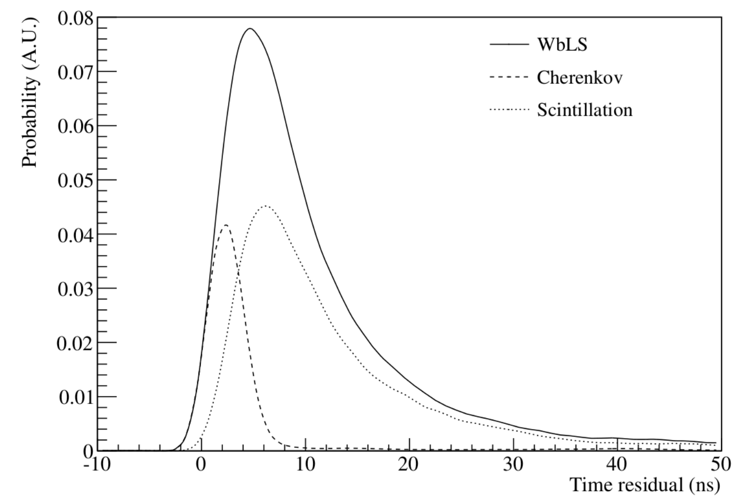
Water-based Liquid Scintillator (WbLS): Mixture of water and liquid scintillator allowing emission of **both Cherenkov and scintillation** light

- **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)



UC DAVIS
UNIVERSITY OF CALIFORNIA

ANNIE → WATCHMAN → Theia

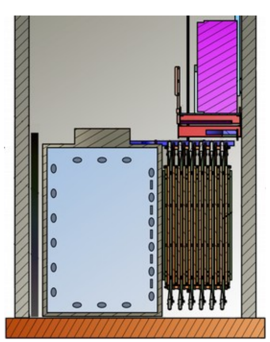
annie

Mass

~50,000 tons
~100,000 sensors

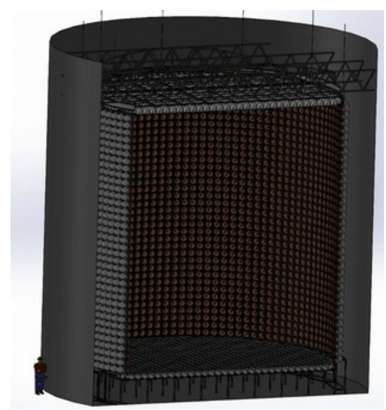
~4,000 tons
~5000 sensors

~30 tons
~150 sensors



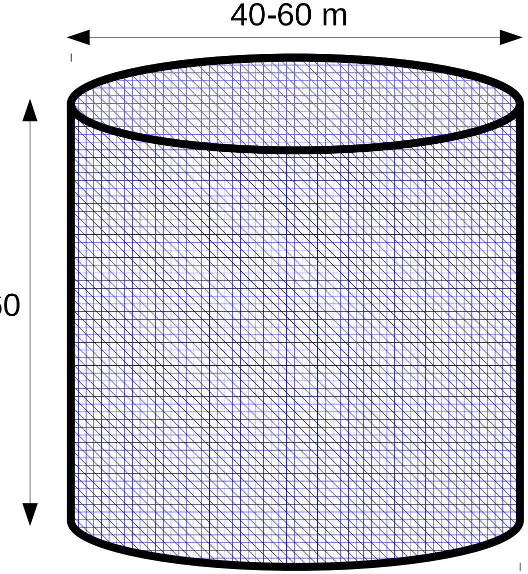
annie

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



WATCHMAN

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



Theia

Data taking

2019+ 2022+ 202?

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 is 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 2019**
- We are discussing adding **WbLS** and more **fast photosensors** for a possible **Phase III**

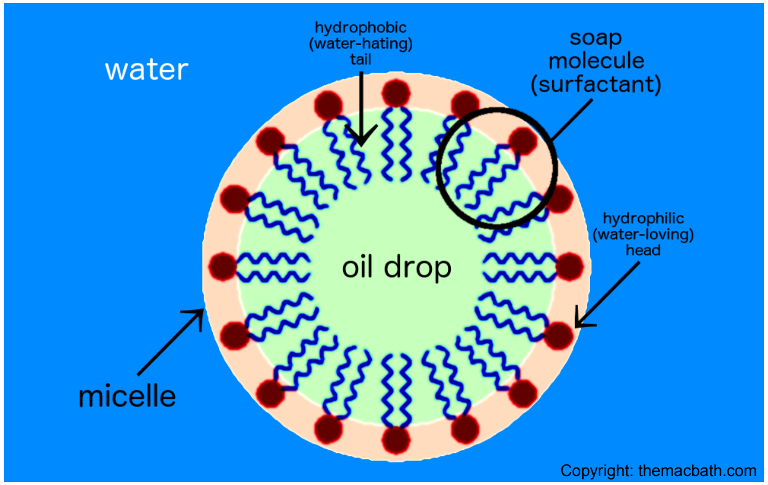
In the next several years, ANNIE will demonstrate and develop the key technologies for next generation water-based neutrino detectors and precision measurements

THANK YOU FOR YOUR ATTENTION!

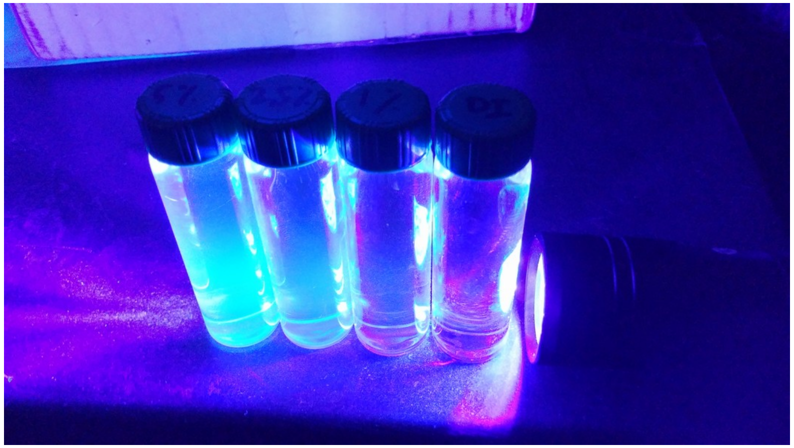
BACK-UP

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**



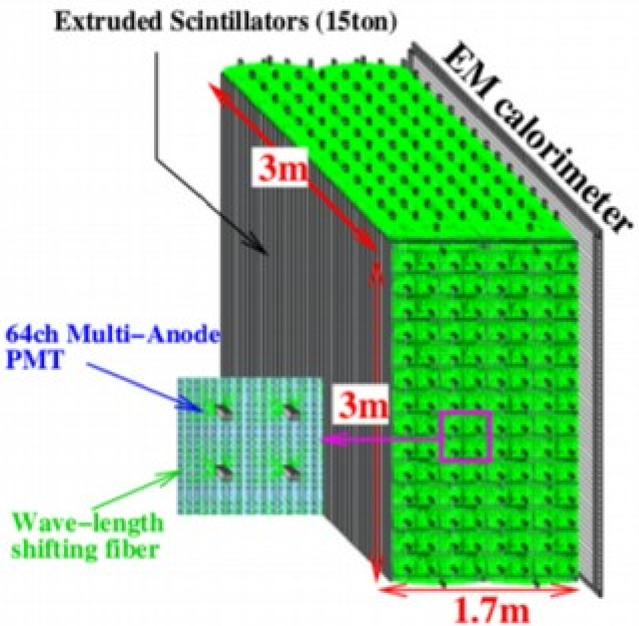
Micelle structure in water

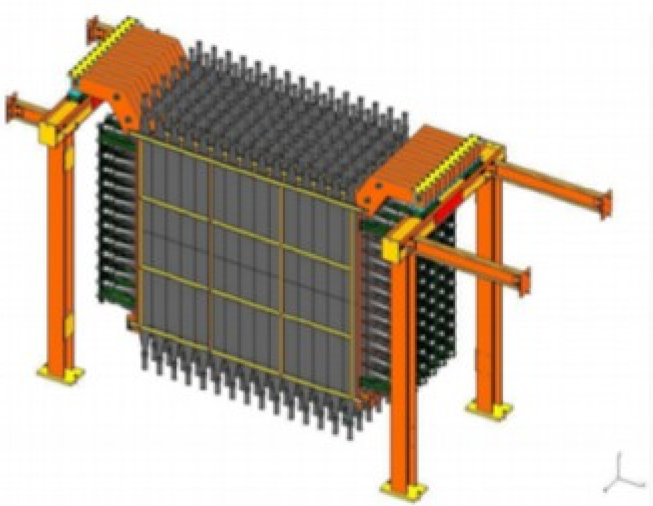


Samples of WbLS with different LS concentrations

*PRS: Linear Alkyl Sulfonate

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 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)

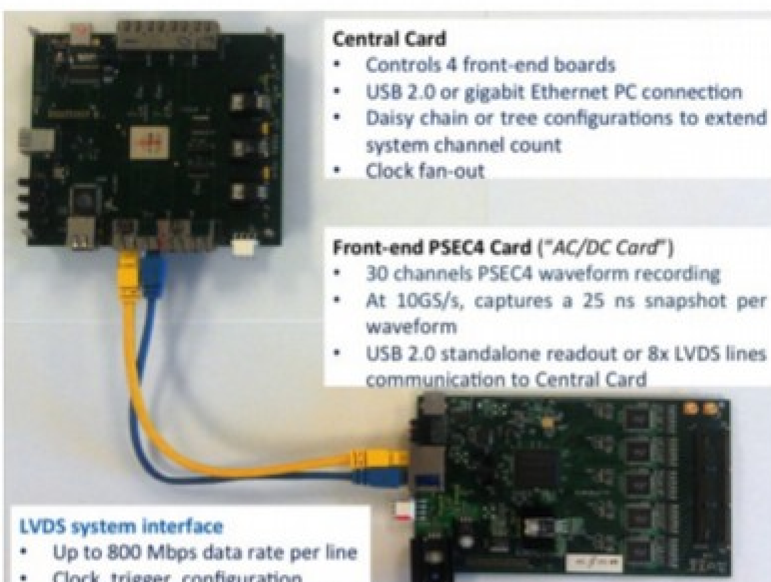
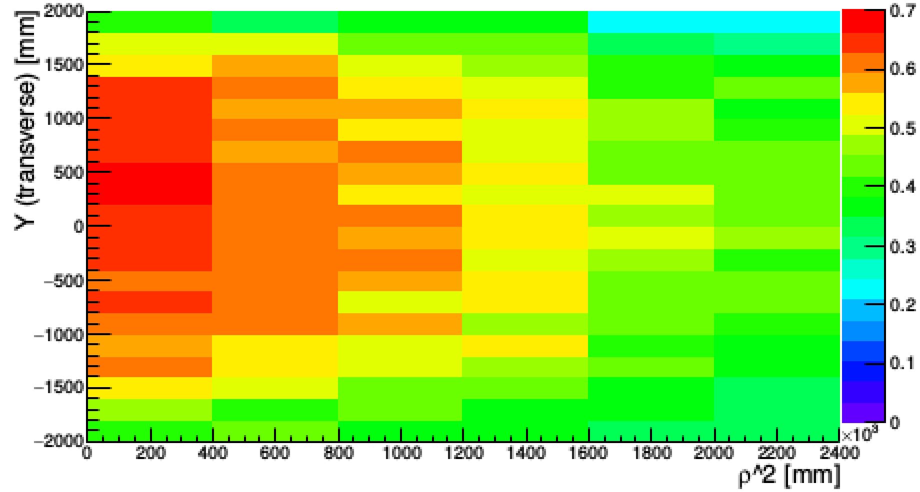


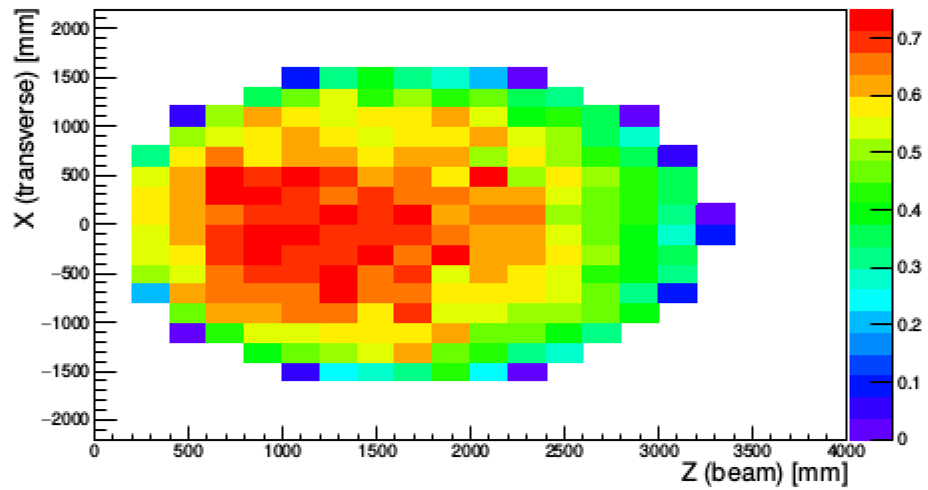
Image source: Jonathan Eisch (ISU)

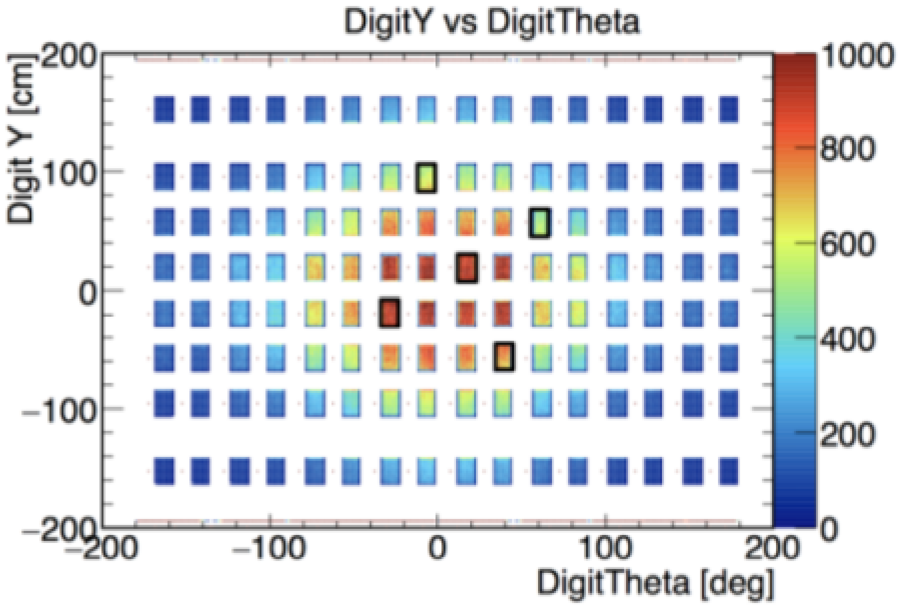
ANNIE Central Card

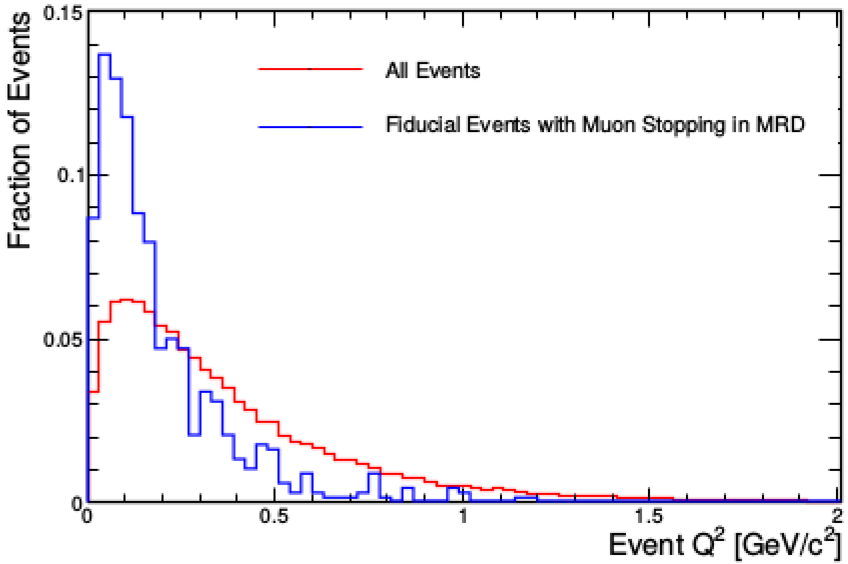
Phase II simulations – Understanding ANNIE

Preliminary neutron detection efficiencies

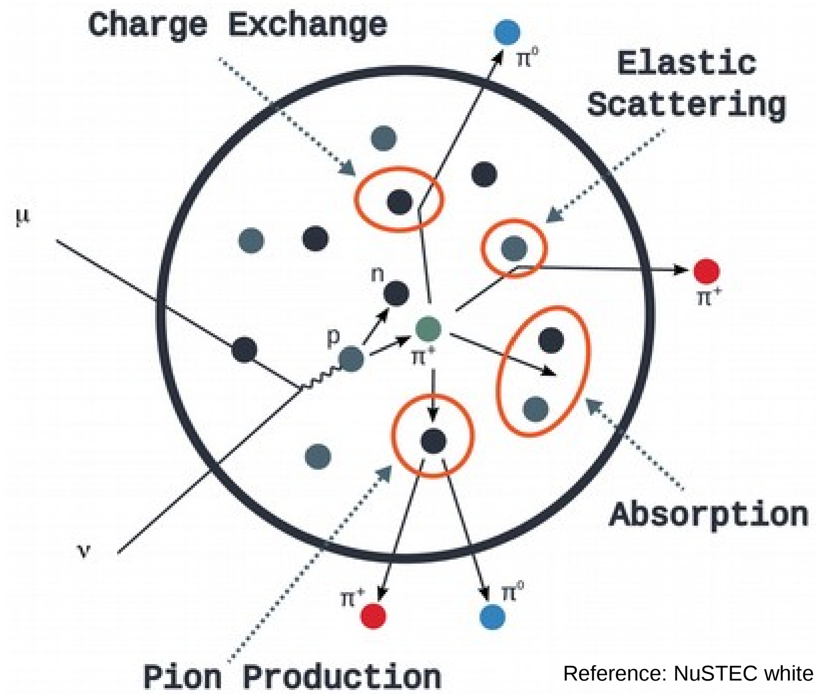








Neutrons as an indicator of inelasticity

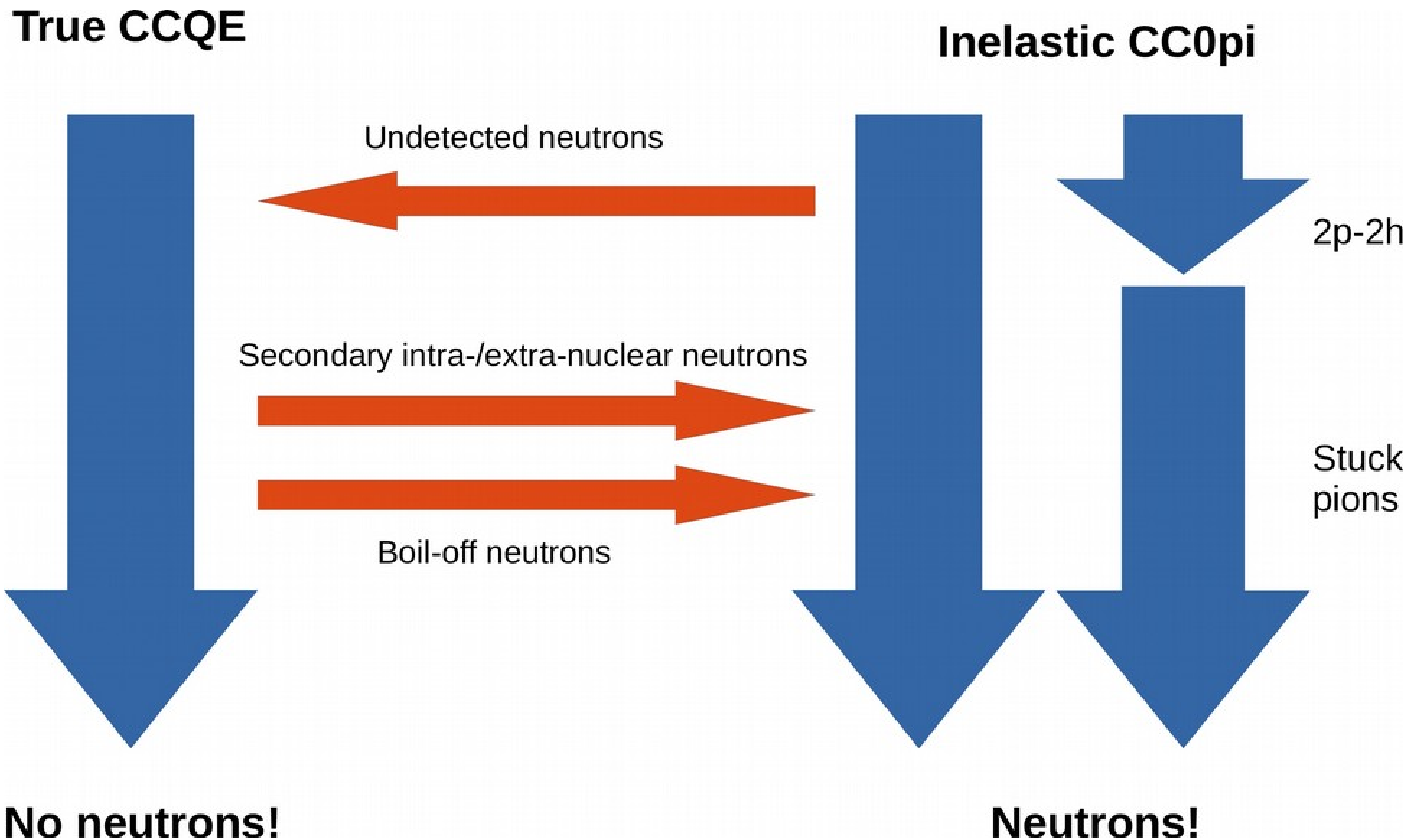


Reference: NuSTEC white paper

- 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



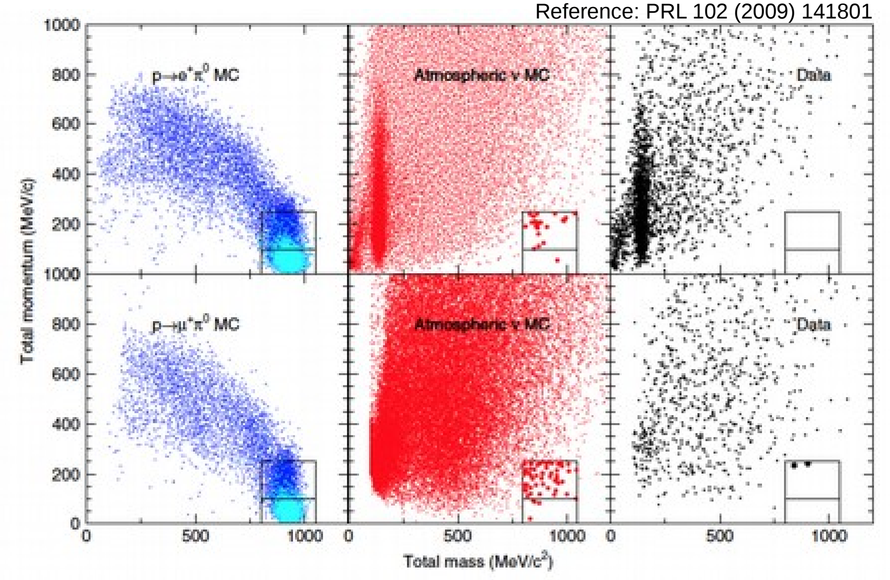
Physics motivation: Energy-dependent neutron yield

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



Physics motivation: Energy-dependent neutron yield

UC DAVIS
UNIVERSITY OF CALIFORNIA

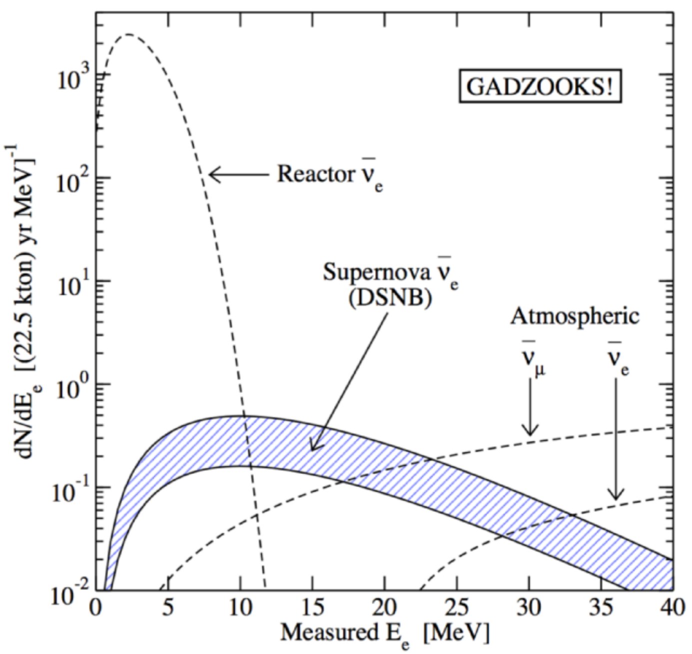
annie

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

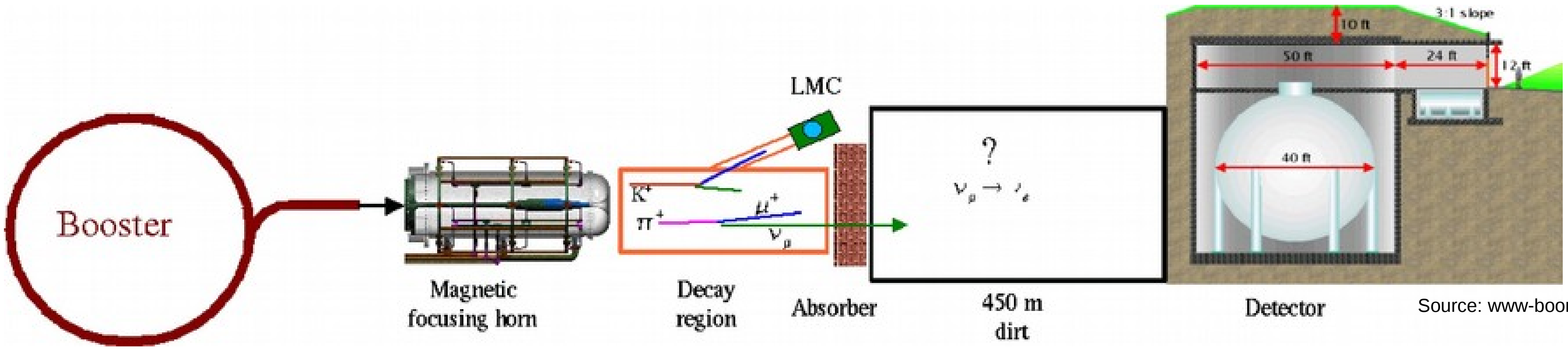
Beacom & Vagins, PRL, 93 (2004) 171101



Supernova neutrino detection

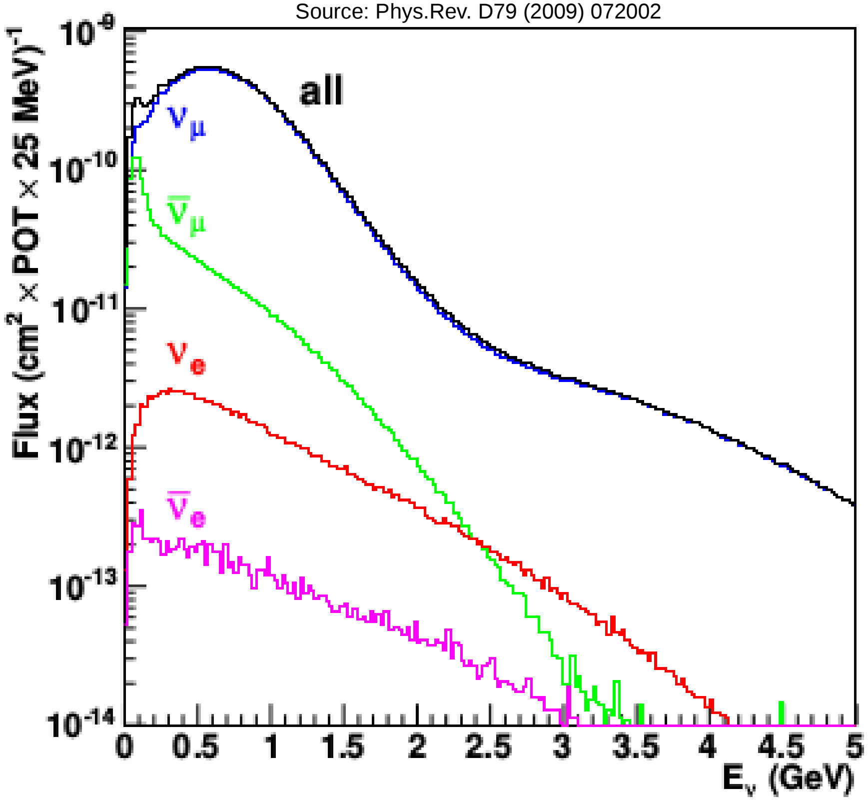
- Diffuse Supernova Background (DSNB): Continuous flux of neutrinos from past supernovae
- Main detection channel for $\bar{\nu}_e$: $\bar{\nu}_e + p \rightarrow e^+ + n$ (Inverse Beta Decay)
- Main background: Decay of sub-Cherenkov muons produced by atmospheric neutrinos + neutron
- Understanding those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

The Booster Neutrino beam



Source: www-boone.fnal.gov

Source: Phys.Rev. D79 (2009) 072002



- 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

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"