ANNIE

WIN conference
06/03/2019-06/08/2019

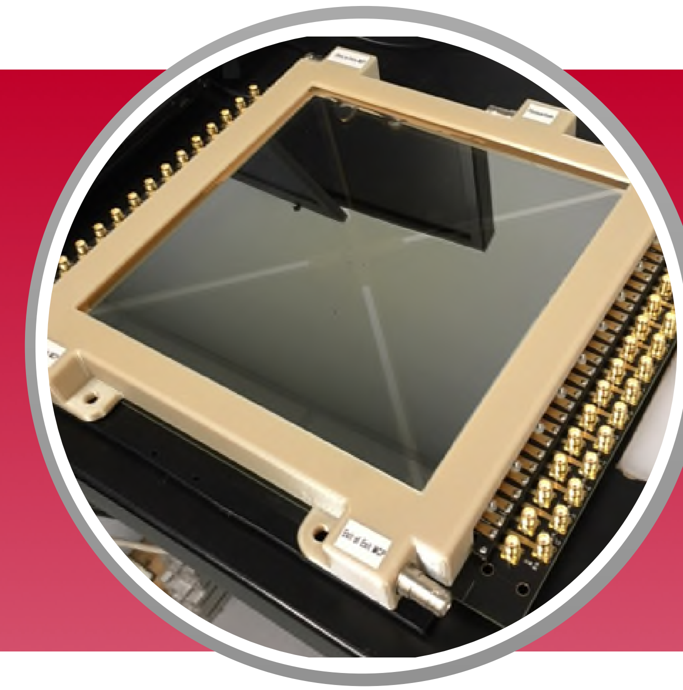
Michael Nieslony
on behalf of the ANNIE collaboration

ANNIE

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

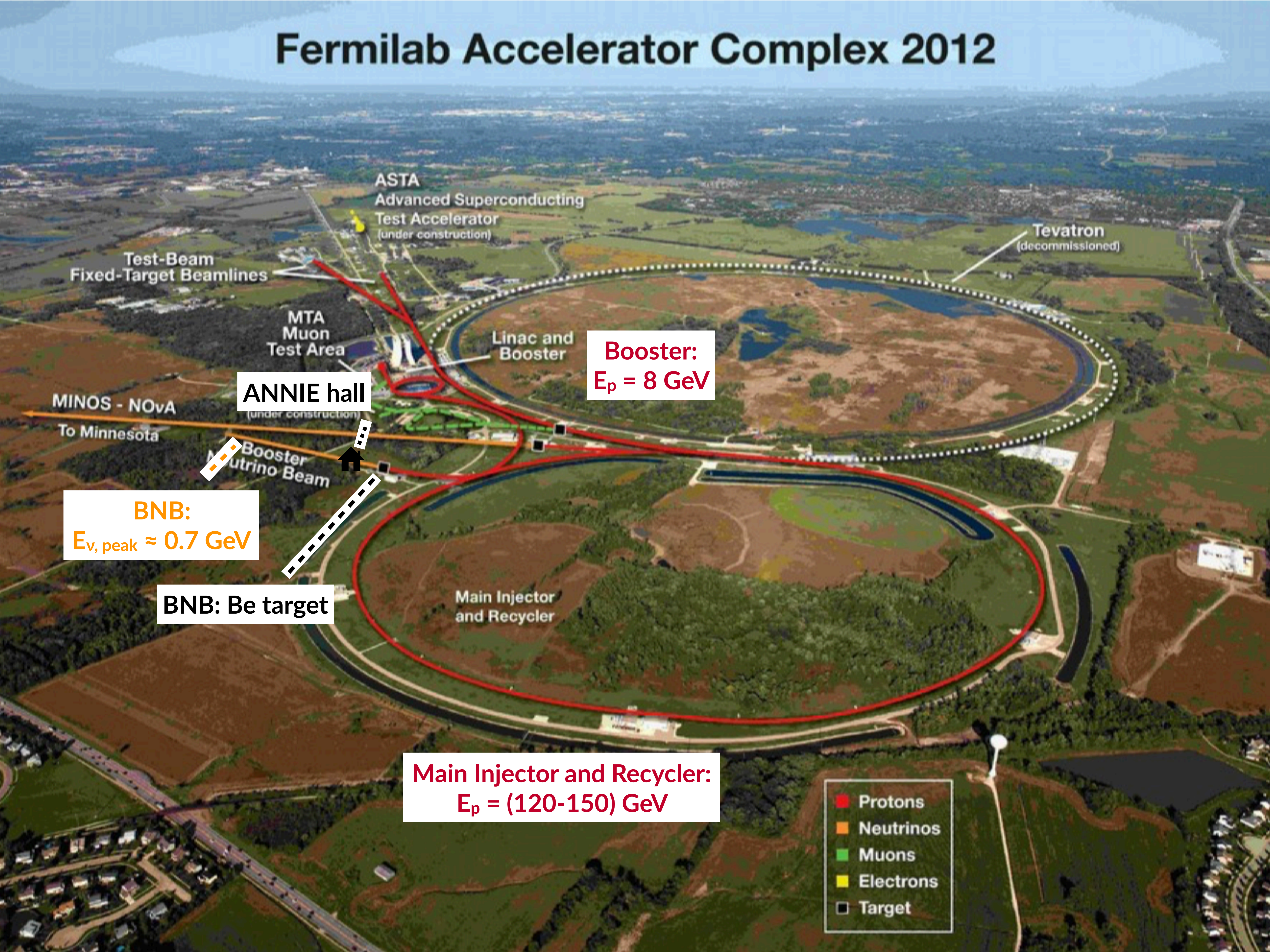
detector

collaboration (Mar 2019)



LAPPDs

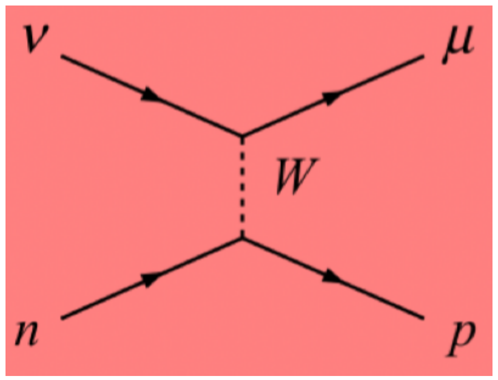
- **Gd-loaded water Cherenkov detector** placed 100m downstream from target of the Booster Neutrino Beam (BNB) at Fermilab
- measurement: **final state neutron multiplicity & CCQE cross-section** in water
- test of **new technologies** in the fields of fast photosensors and detection media


Fermilab Accelerator Complex 2012
ASTA
Advanced Superconducting
Test Accelerator
(under construction)
Test-Beam
Fixed-Target Beamlines
Tevatron
(decommissioned)
MTA
Muon
Test Area
Linac and
Booster
Booster:
E_p = 8 GeV
ANNIE hall
(under construction)
MINOS - NOvA
To Minnesota
Booster
Neutrino Beam
BNB:
$E_{\nu,\, peak} \approx 0.7$ GeV
BNB: Be target
Main Injector
and Recycler
Main Injector and Recycler:
E_p = (120-150) GeV
Protons
Neutrinos
Muons
Electrons
Target

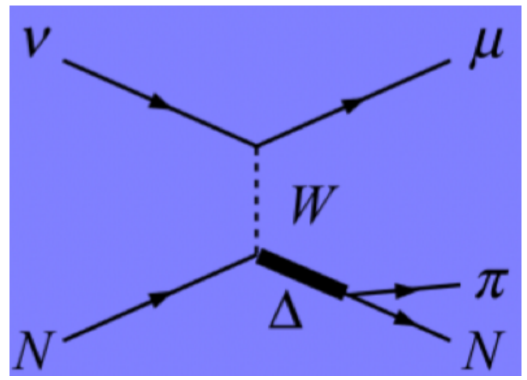
ANNIE - Location

Physics motivation

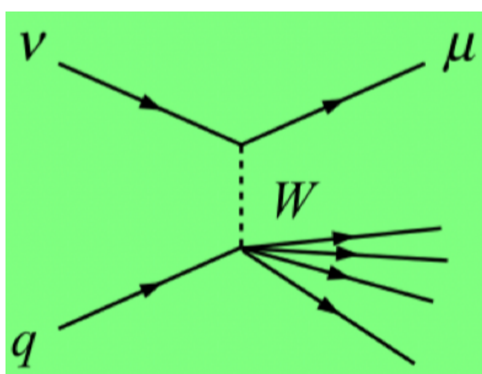
QE

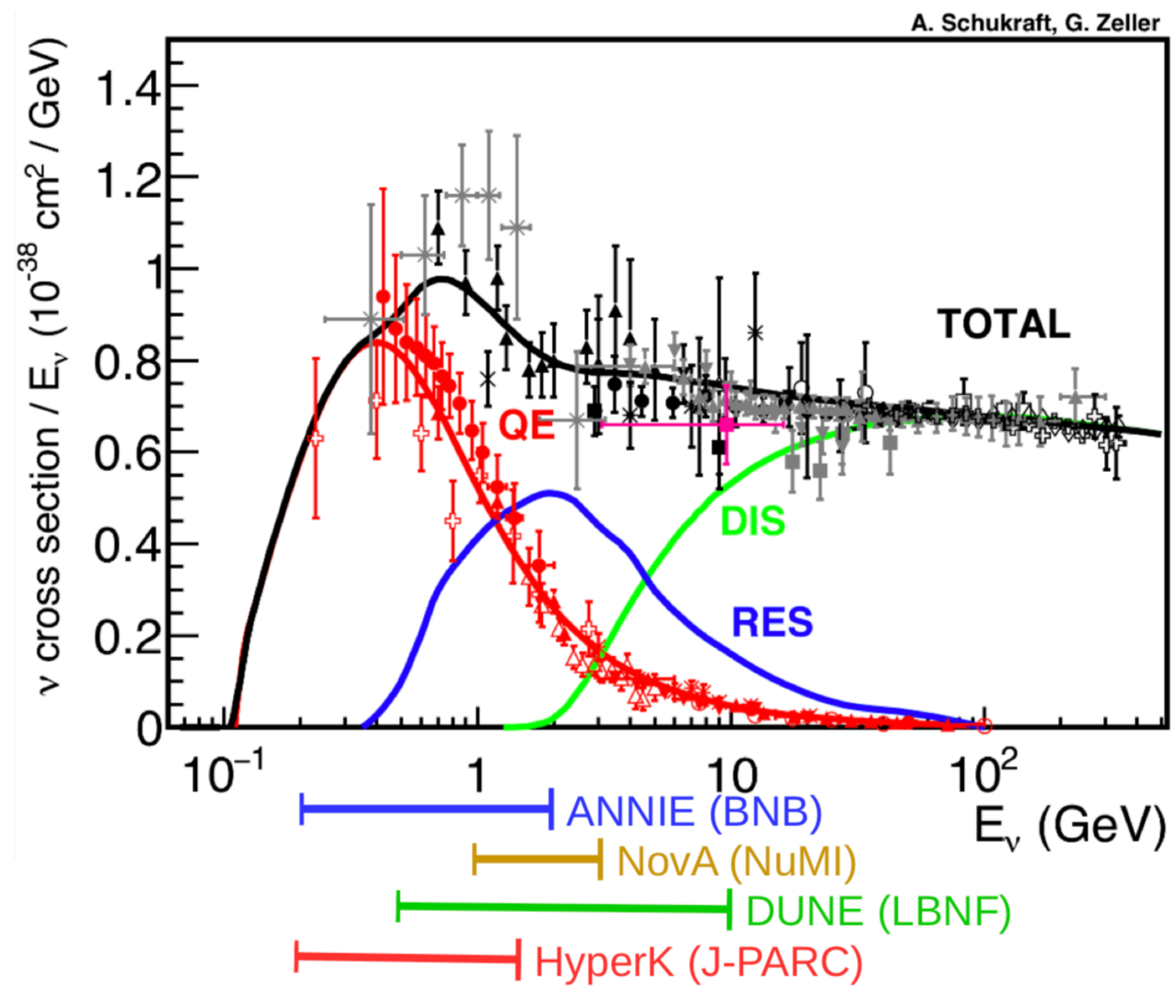


Resonance



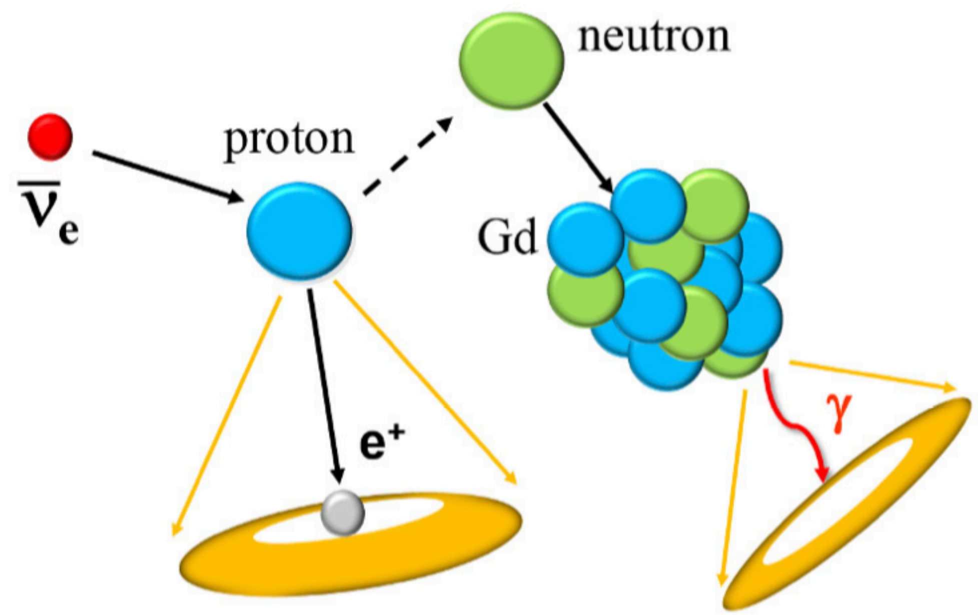
DIS





- knowledge of cross-section important for long-baseline neutrino oscillation studies
- distinguishing between elastic & inelastic processes is important for correct energy reconstruction (minimize bias)
- neutron presence indicative of inelastic process → measurement of multiplicity

Physics motivation



neutron capture cross-section: ~50,000 barn
total emitted gamma energy: ~8 MeV
loading in water possible as sulfate or chloride

ν energy reconstruction

reduce bias by correct tagging of (in-) elasticity

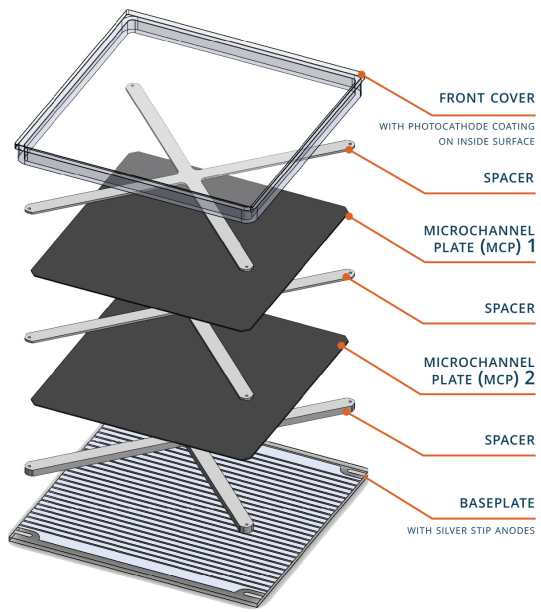
DSNB searches

background: atmospheric neutrinos
→ study their neutron yield

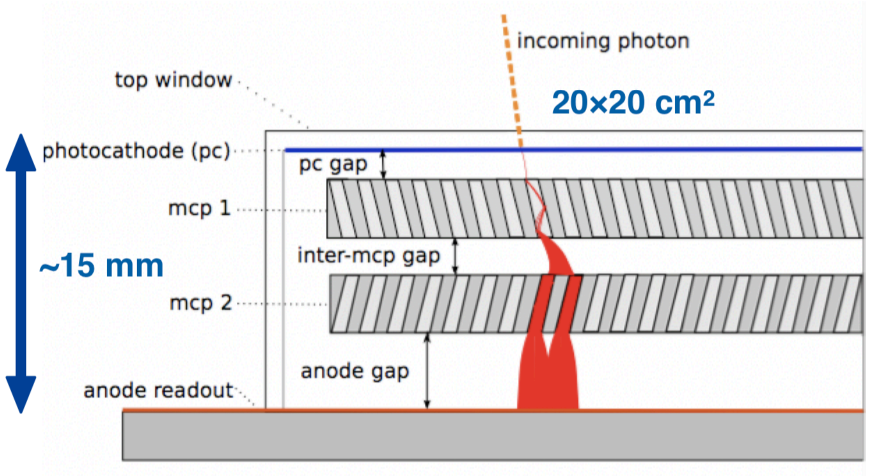
proton decay searches

> 90% of decays involve no neutron
background: atmospheric neutrinos

Research & Development: LAPPDs



20 cm x 20 cm imaging detector with intrinsic position resolution (mm-cm scale)



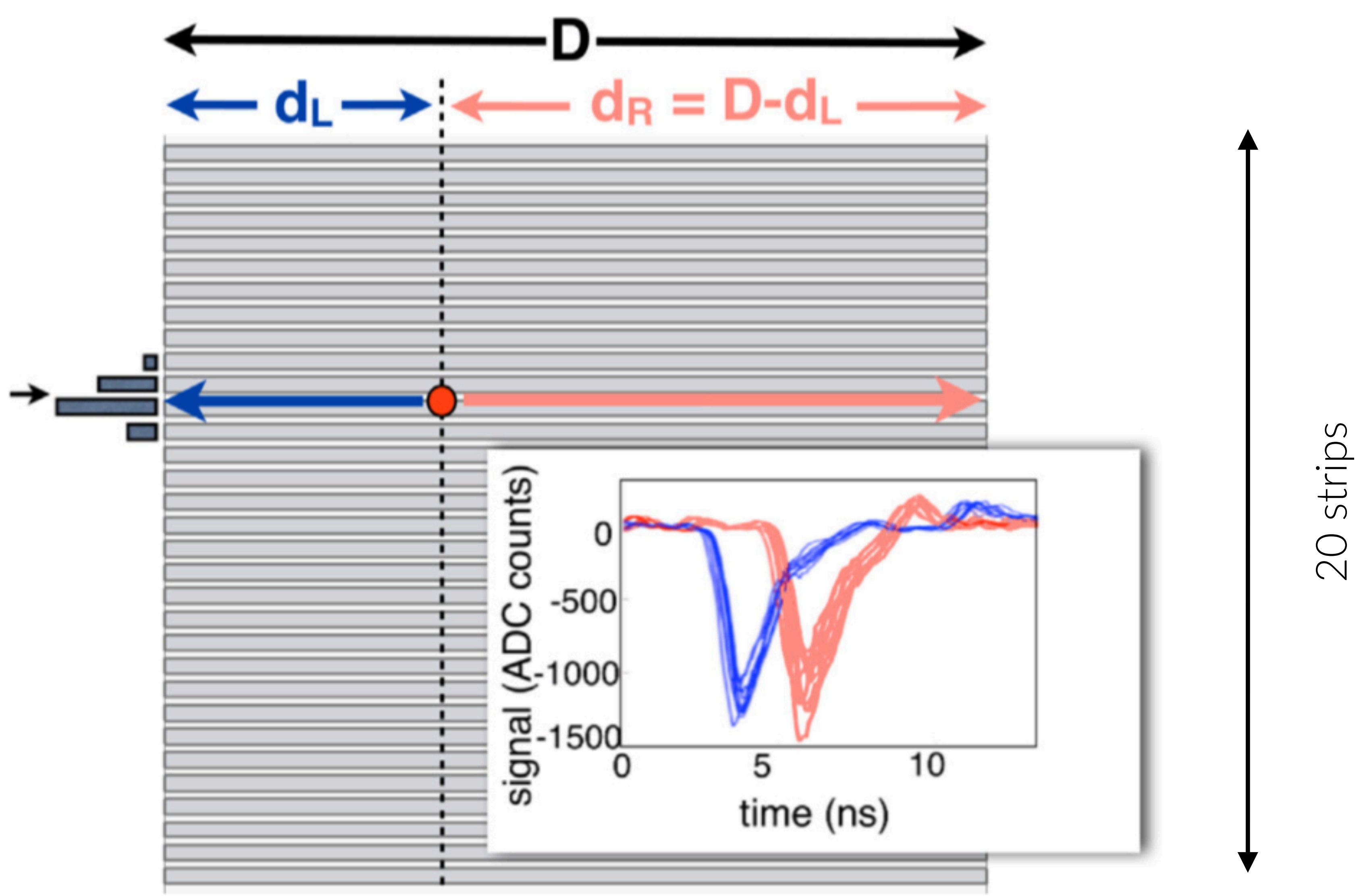
microchannel plate structure with resistive & emissive coating microstrip anode readout

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

fast detection capabilities (time resolution ~60 ps)

Research & Development: LAPPDs

Position Resolution

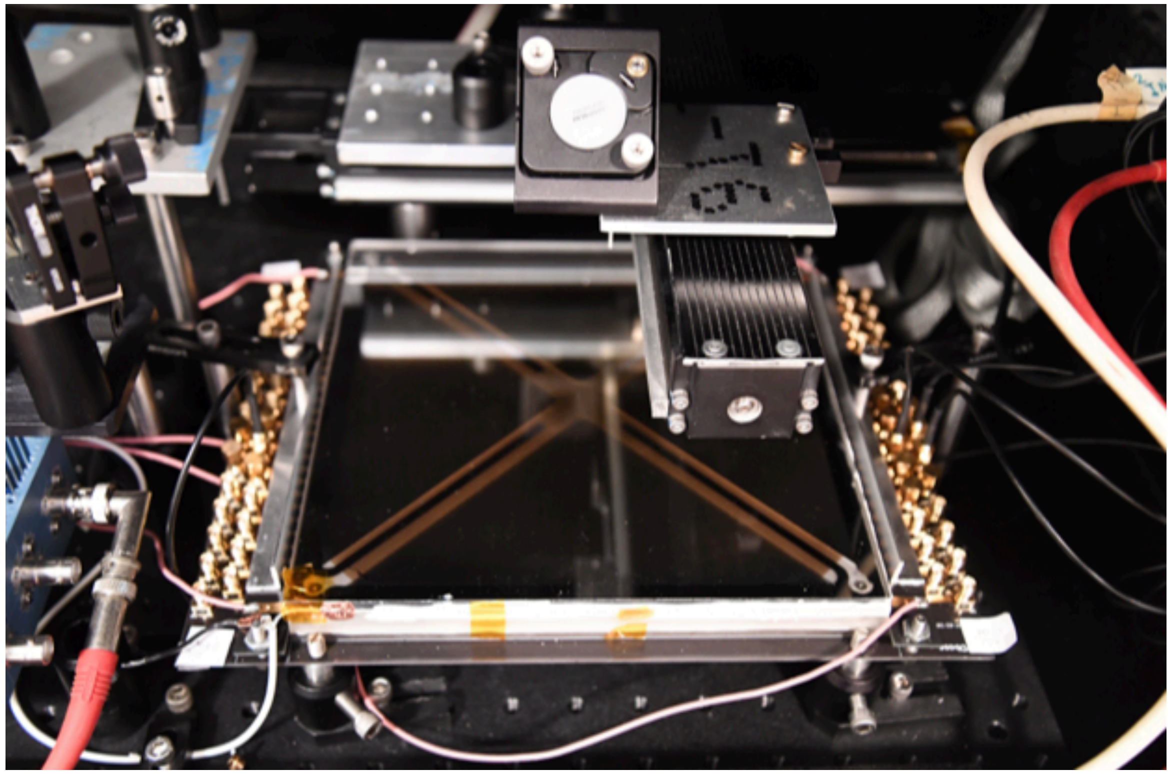


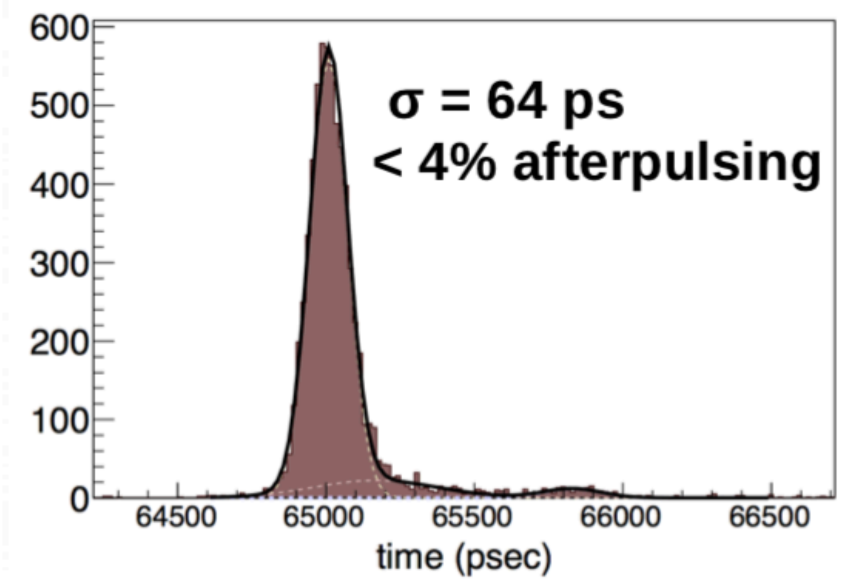
- 25 ps single-PE differential resolution → **5 mm horizontal** position resolution
- **< 1 cm vertical** position resolution (charge centroid)

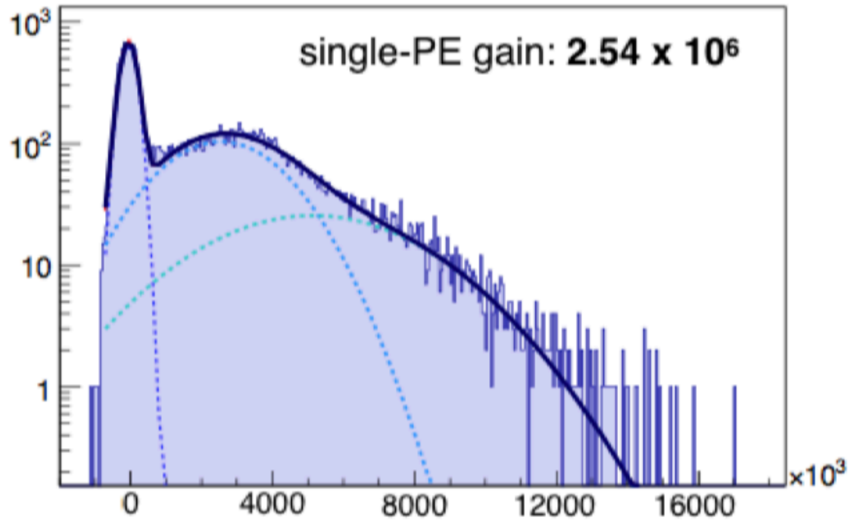
Research & Development: LAPPDs

Specifications

Test stand @ Iowa State University



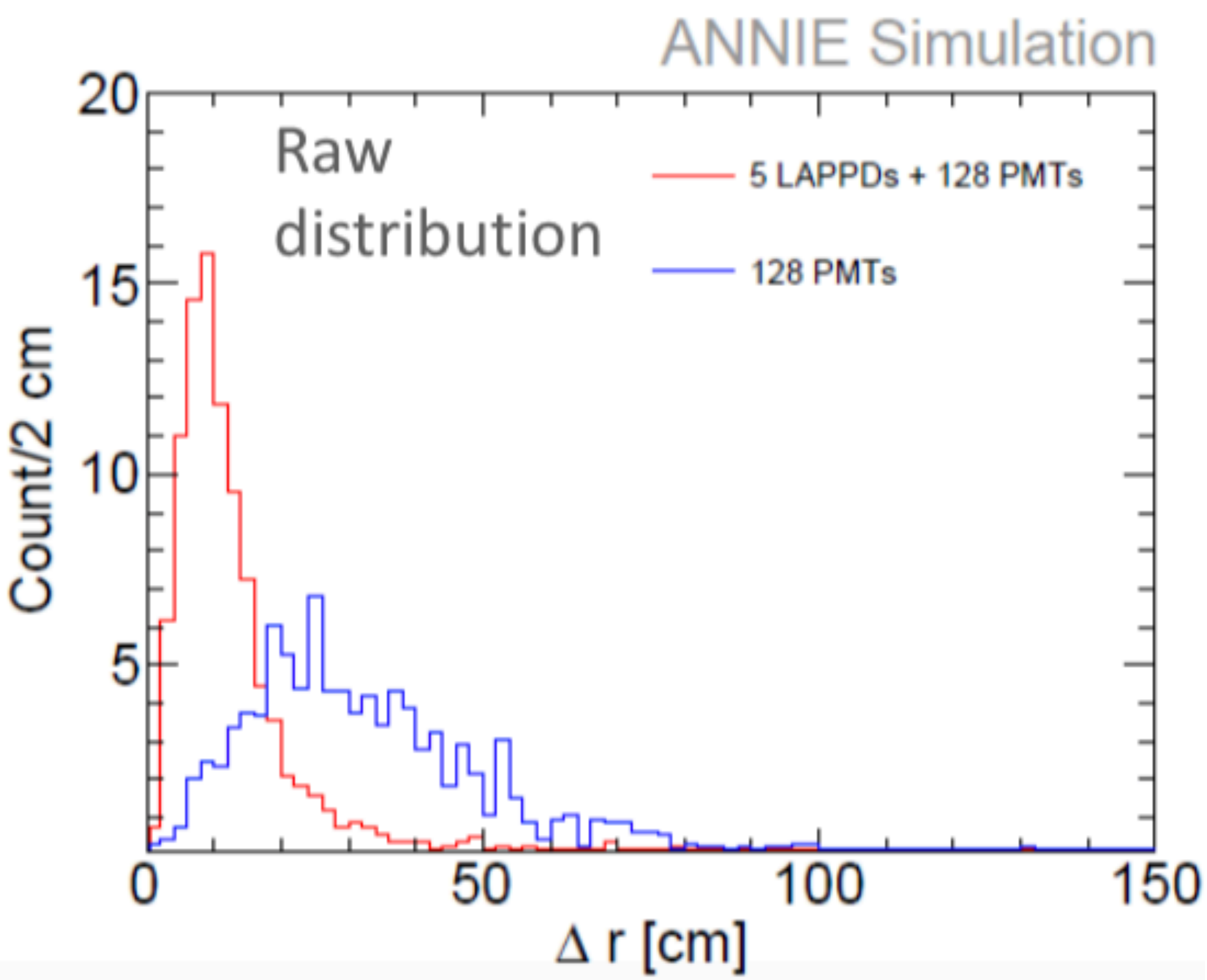


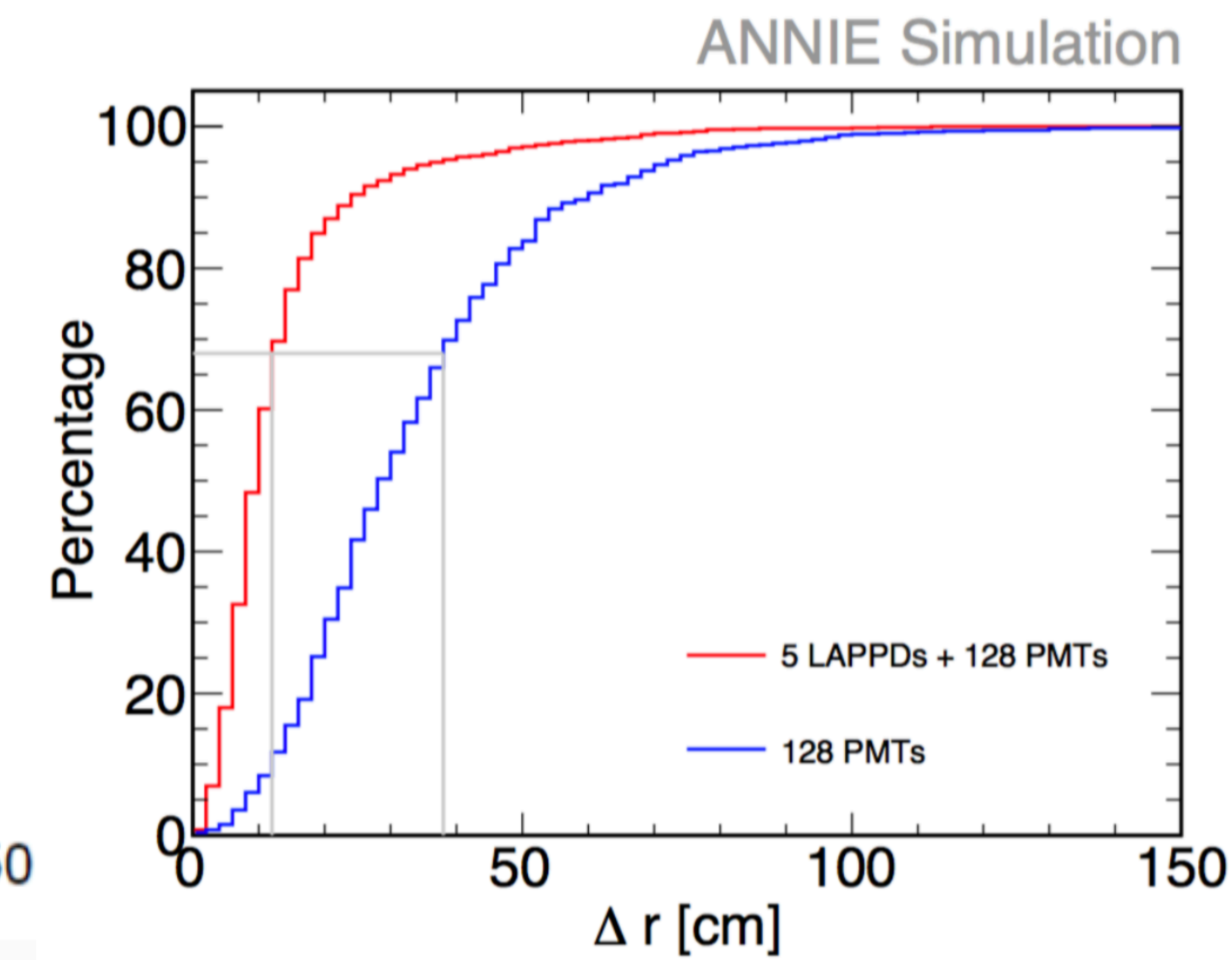


ANNIE LAPPDs

Research & Development: LAPPDs

Importance for reconstruction capabilities





Both **angular and spatial resolution** profit substantially from using **5 LAPPDs**:

- 68th percentile vertex resolution: **38 cm** → **12 cm** **(factor 3 improvement)**
- 68th percentile angular resolution: **11°** → **5°** **(factor 2 improvement)**

Timeline

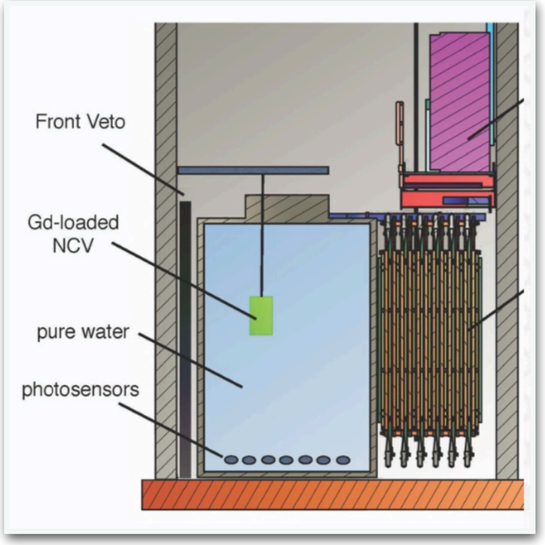
3 phases of the experiment

June 2016

Phase I

Sep 2017

- partially instrumented detector
- 60 PMTs (veto) & Gd-loaded scintillator Fiducial volume (NCV)
- feasibility demonstration & background evaluation



Summer 2019

Phase II

Summer 2020

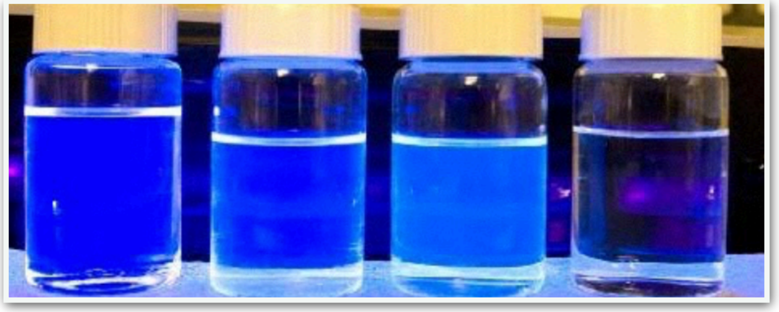
- physics phase
- first Gd-doped water Cherenkov detector in neutrino beam
- CCQE cross-section and multiplicity measurement

- first LAPPD deployment in neutrino beam
- ~10,000 CC interactions per ton per year expected (2×10^{20} POT)
- possible additional LAPPD deployment in fall 2020 → broader physics program

202x?

Phase III

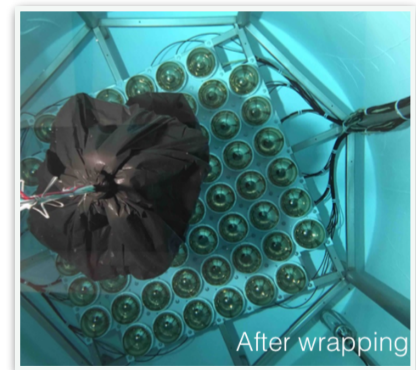
- water-based liquid scintillator volume
- testbed for new technologies



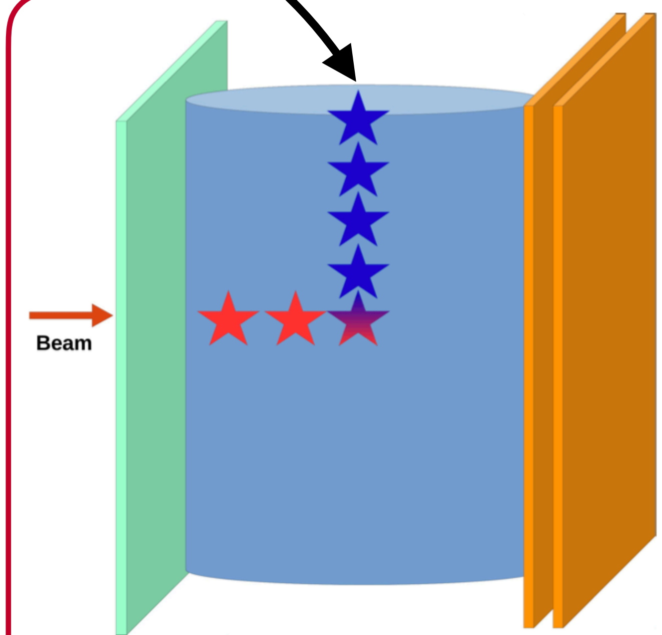
Phase I - Backgrounds measurement

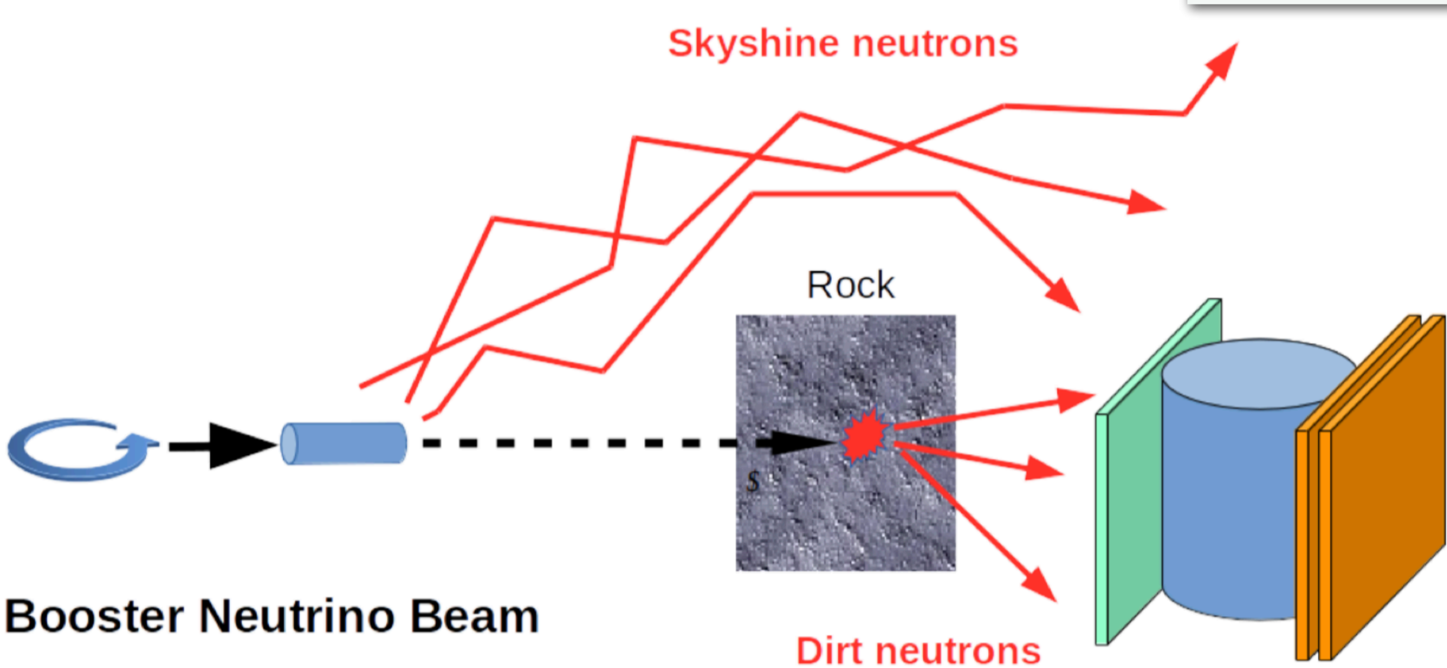
neutrons from beam dump, scattered by molecules in the atmosphere

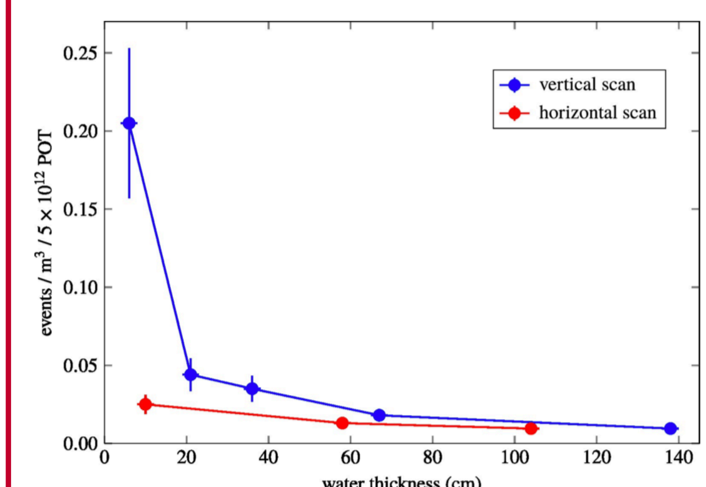
NCV



Results







neutrons originating from neutrino interactions in the rock (upstream of ANNIE)

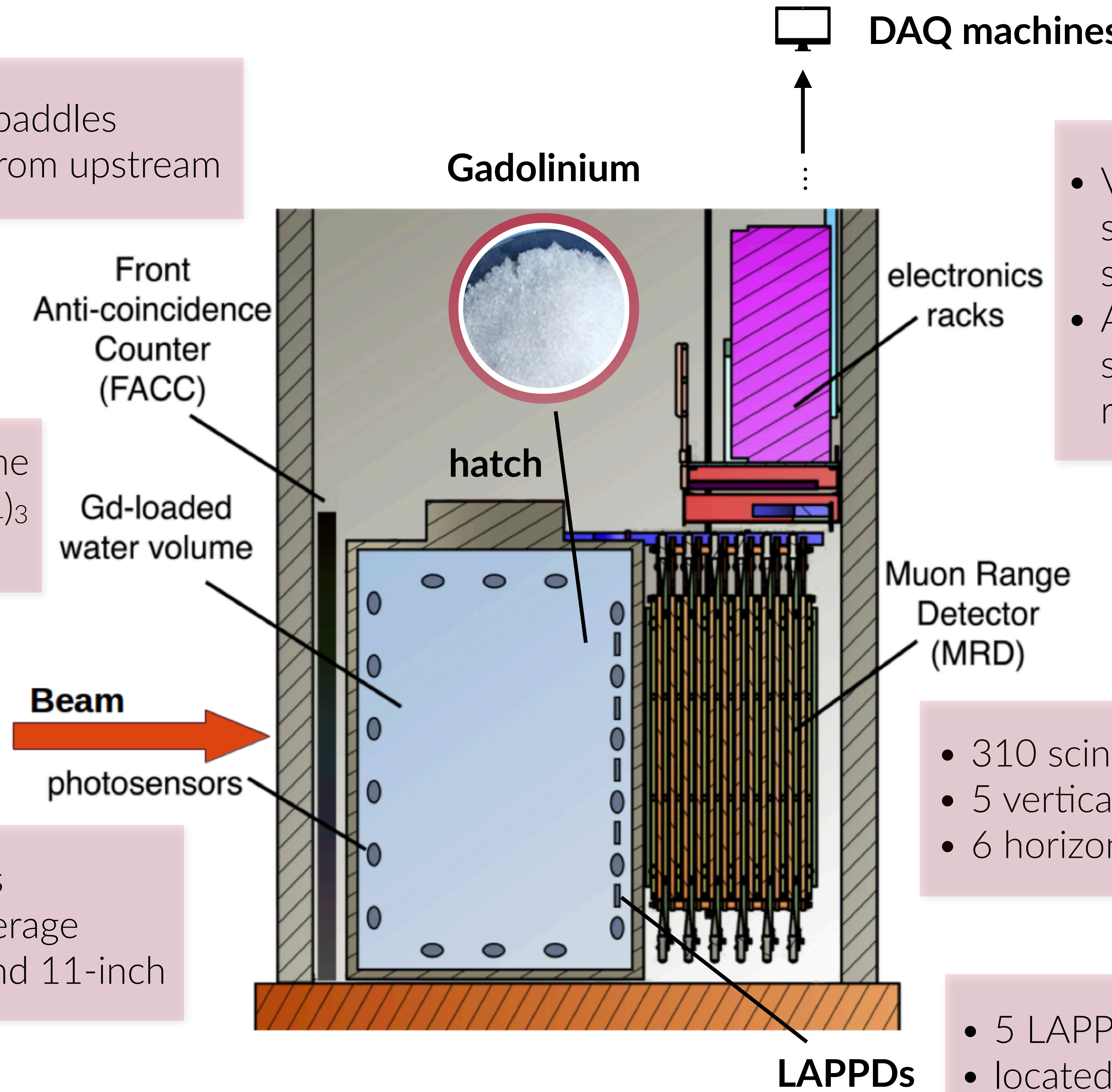
- **bg rate < 0.02/m³/spill**
- no problem for phase II
- publication of results soon

Phase II - Physics run

Phase II detector

- 26 scintillator paddles
- reject muons from upstream

- 26 tons water volume
- loaded with $Gd_2(SO_4)_3$ (0.1% by weight)



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

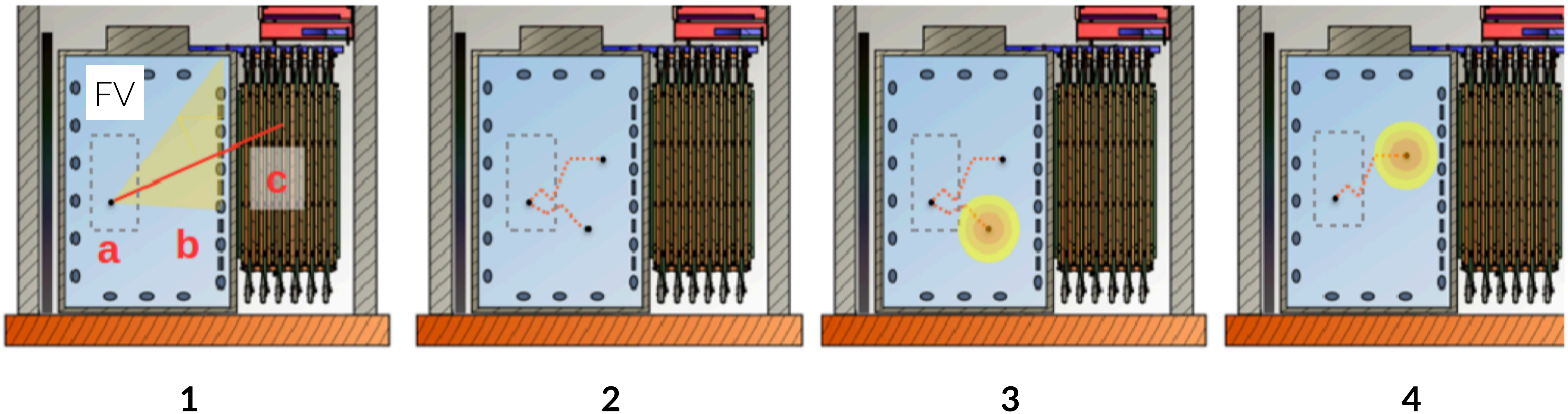
- 134 PMTs
- 20 % coverage
- 8-, 10-, and 11-inch

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

- 5 LAPPDs
- located downstream

Phase II - Physics run

Phase II measurement: ν_μ *CCQE event*



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

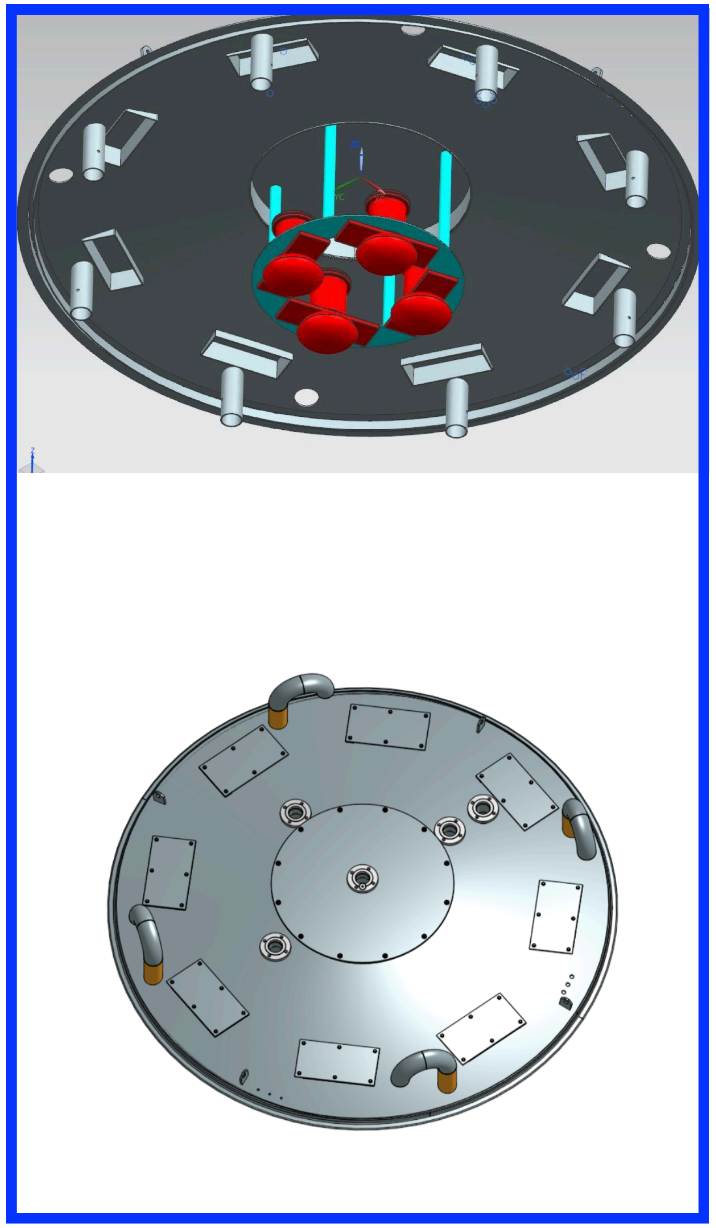
3. neutron capture 1, detection by PMTs

4. neutron capture 2, detection by PMTs

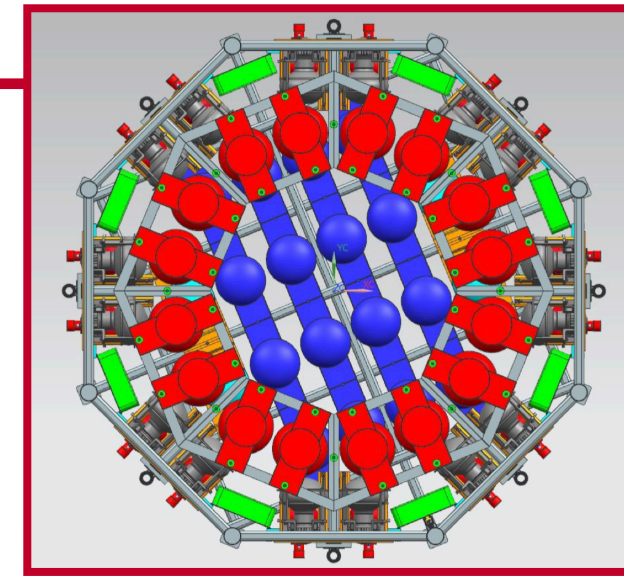
Phase II - Physics run

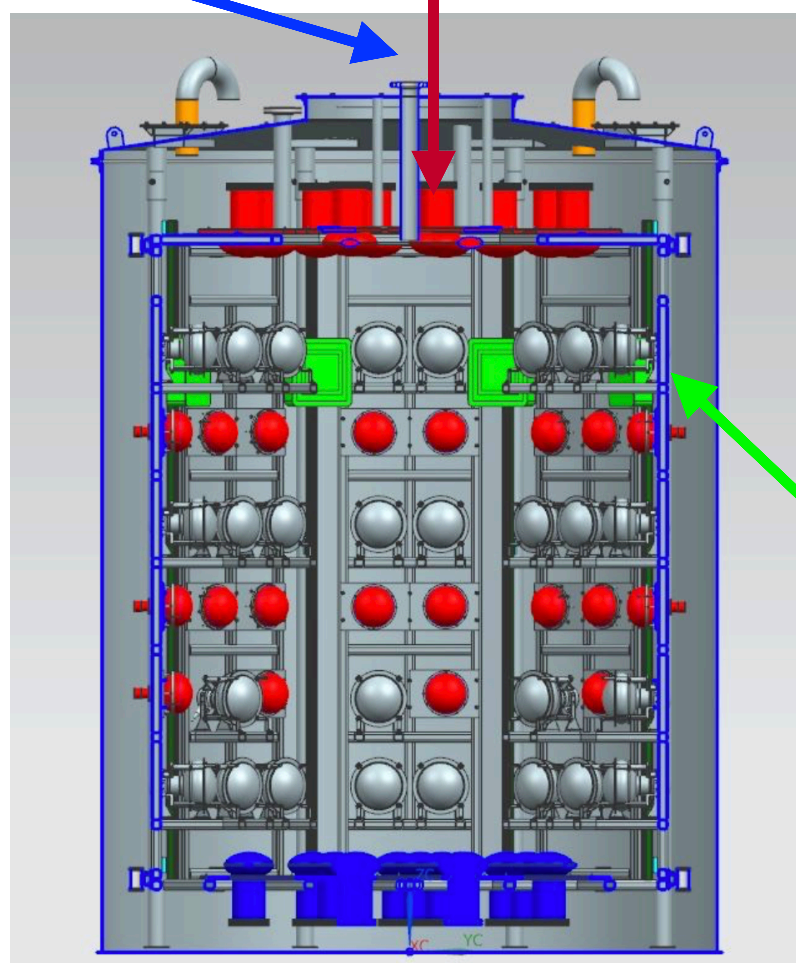
Tank Design

lid



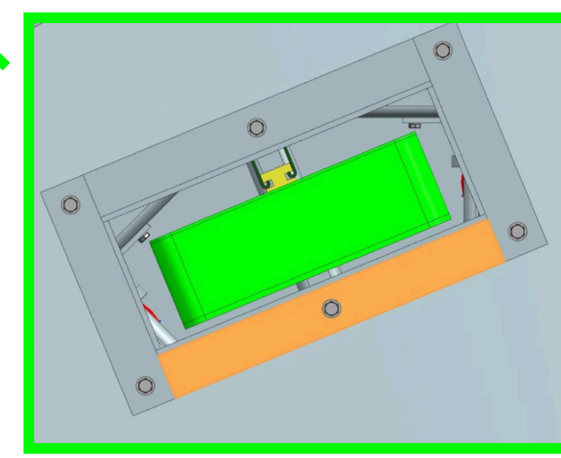
top view





side view

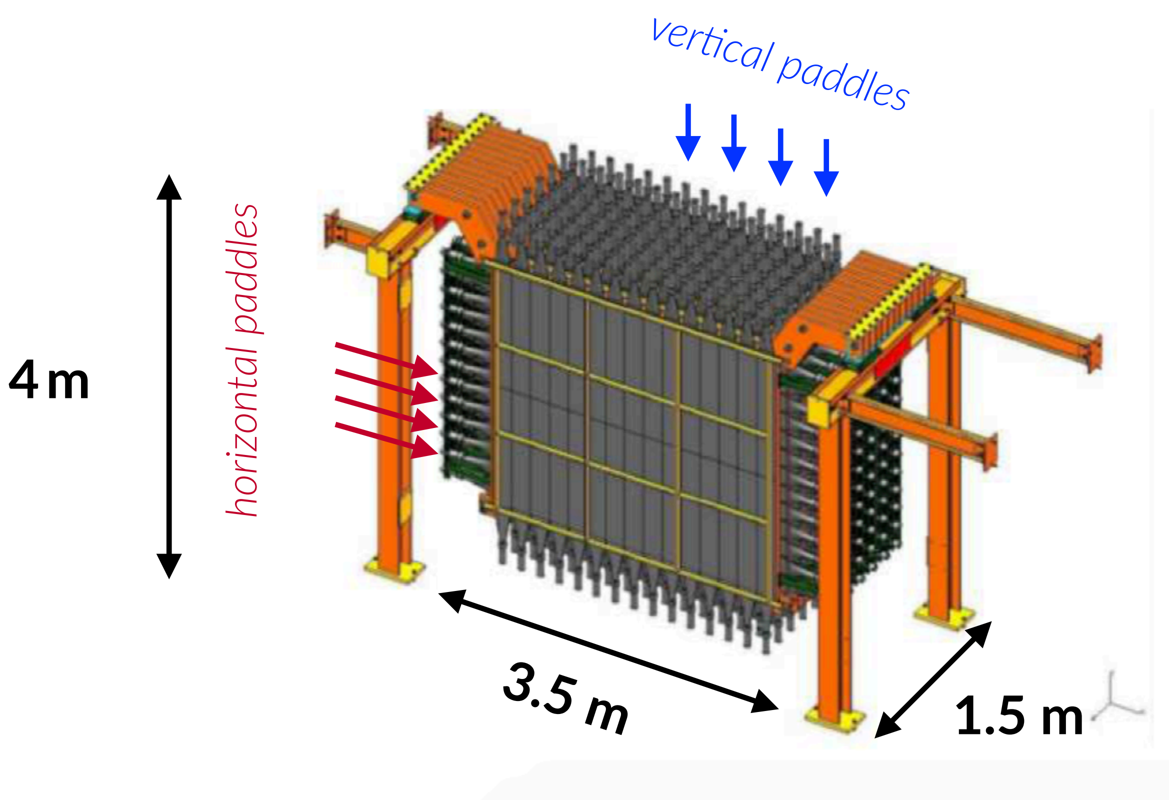
LAPPD deployment (cassettes)



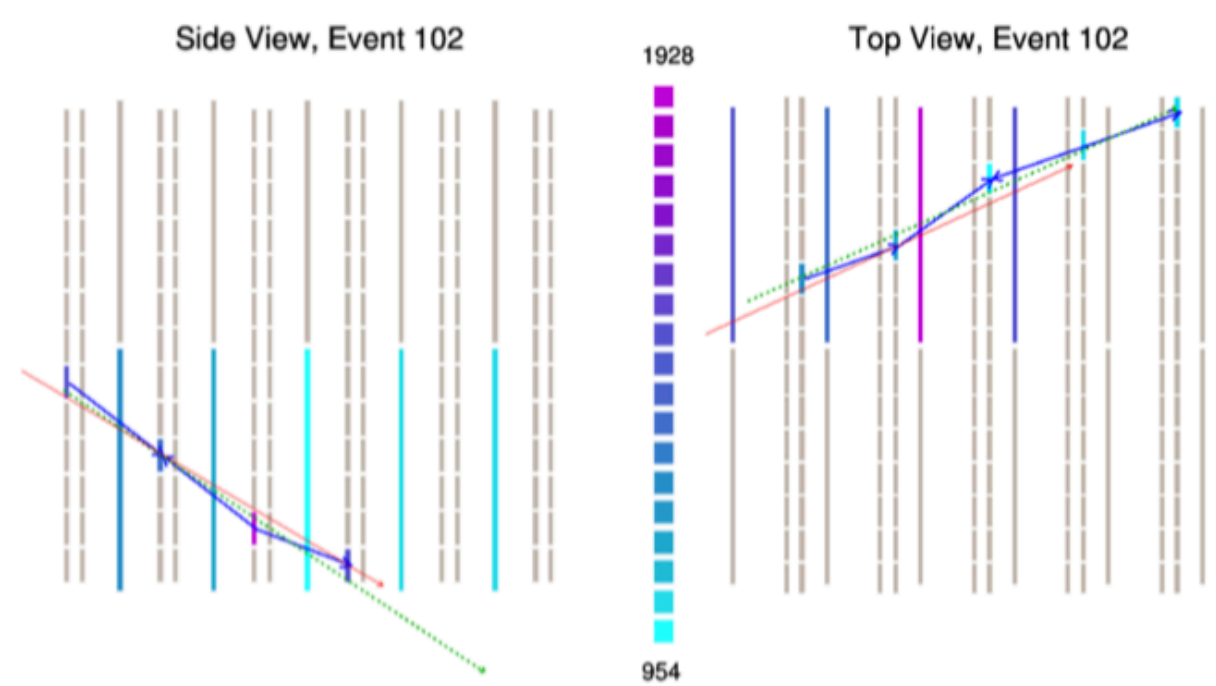
Phase II - Physics run

MRD

- Subdetector consisting of sandwiched scintillator paddles and 2” iron layers
    - 6 horizontal layers (156 paddles)
    - 5 vertical layers (154 paddles)
- inherited from the SciBooNE experiment
- fully refurbished & operational
- capable of muon direction and energy reconstruction



reconstruction example (simulation)

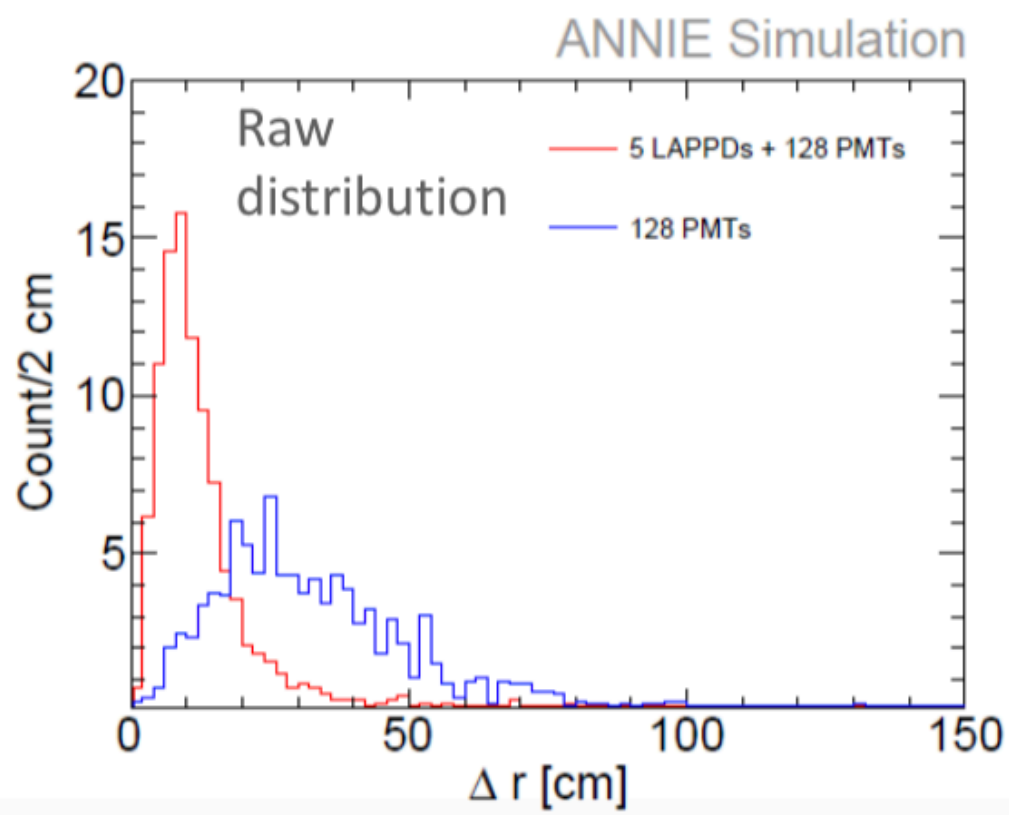


plot by Marcus O’Flaherty (University of Sheffield)

Phase II - Physics run

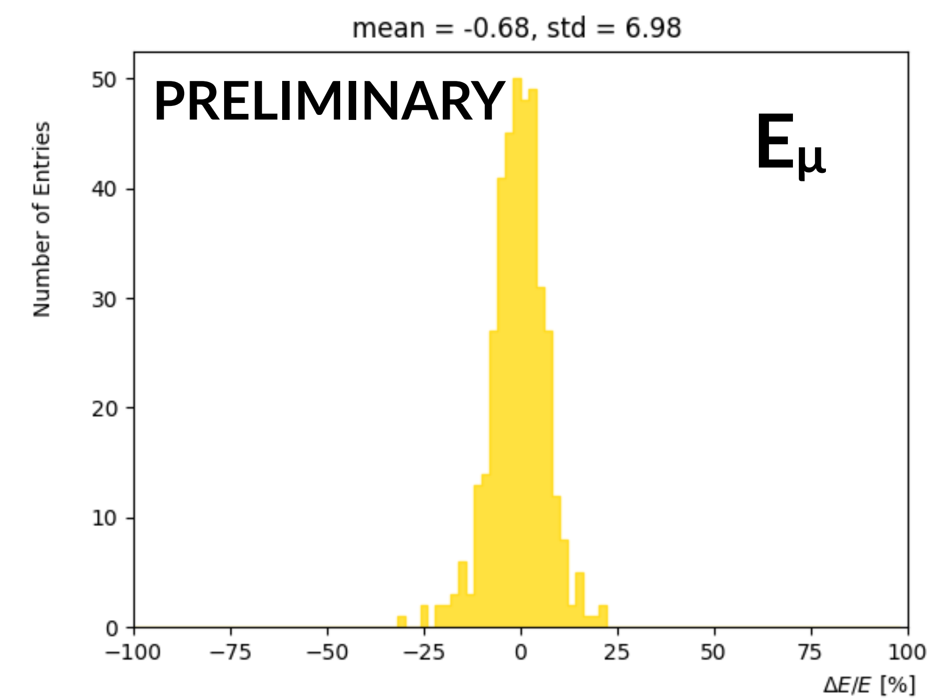
Vertex & energy reconstruction

Vertex



- time-based FOM → vertex, time
- charge-based FOM → cone edge, track direction
- LAPPDs significantly improve resolution

Energy

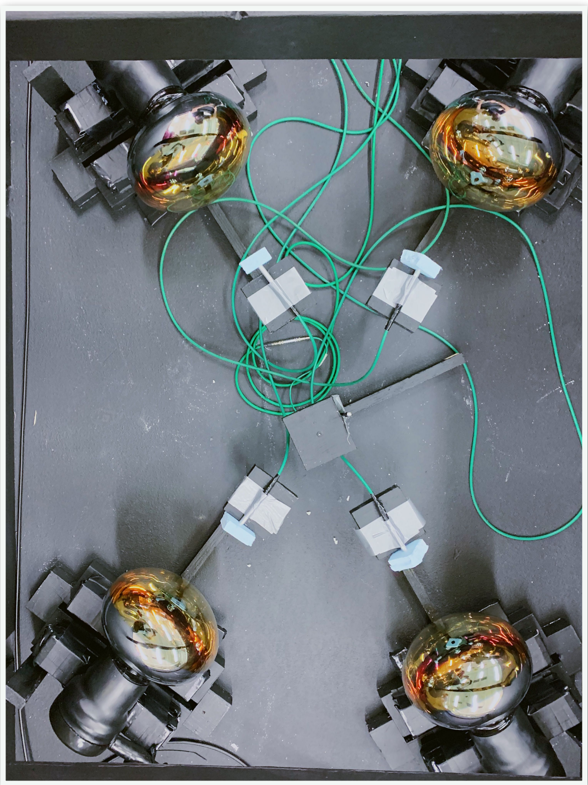


input for BDT for energy reconstruction:

- track length in water and MRD
- # PMT + #LAPPD hits
- distance to walls
- angle difference beam / track

plots by Jingbo Wang (UC Davis)
& Evangelia Drakopoulou (University of Edinborough)

Detector construction - current events

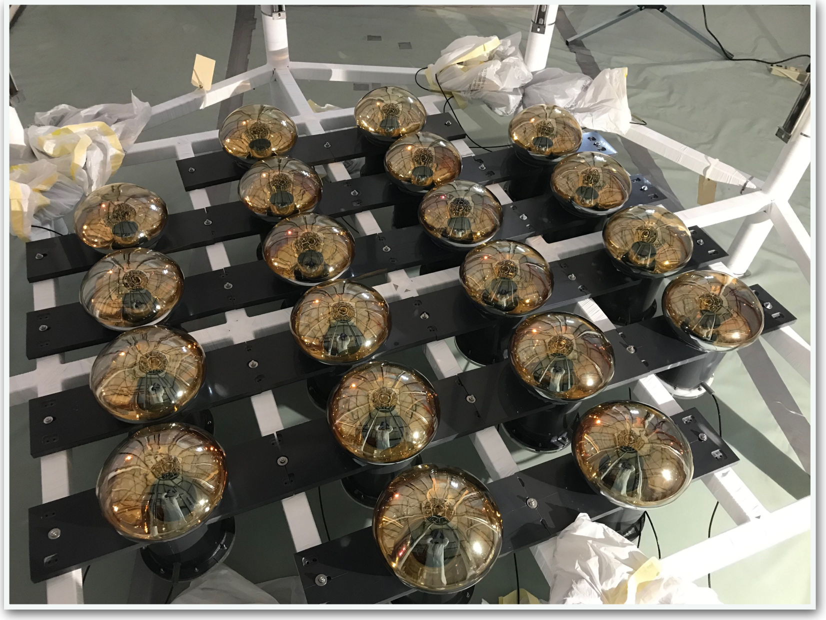


PMT characterisation
+ waterproofing

mounting PMTs on side panels

mounting top PMTs

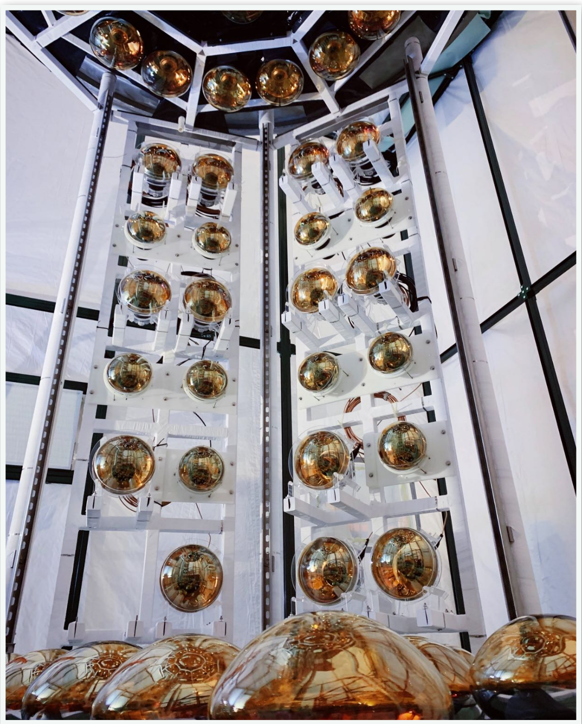
teflon wrapping structure



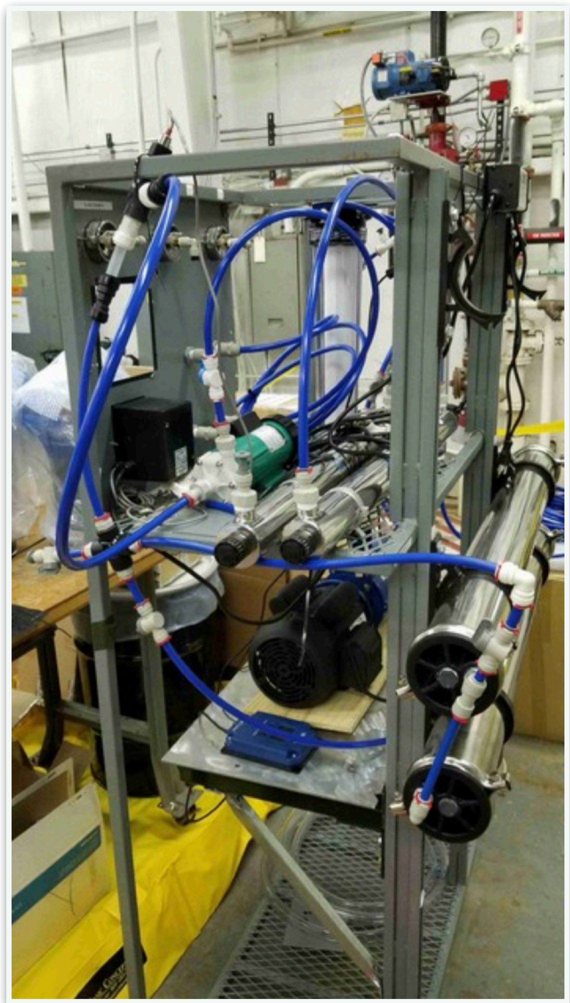
bottom PMTs mounted

Detector construction - current events

Current status of other subsystems



Side panels partly mounted on the Inner Structure



Water filtration system ready for water fill

MRD fully refurbished & operational

EVERYTHING ALMOST READY

SOON

tank deployment at ANNIE hall

planned ~ June 2019

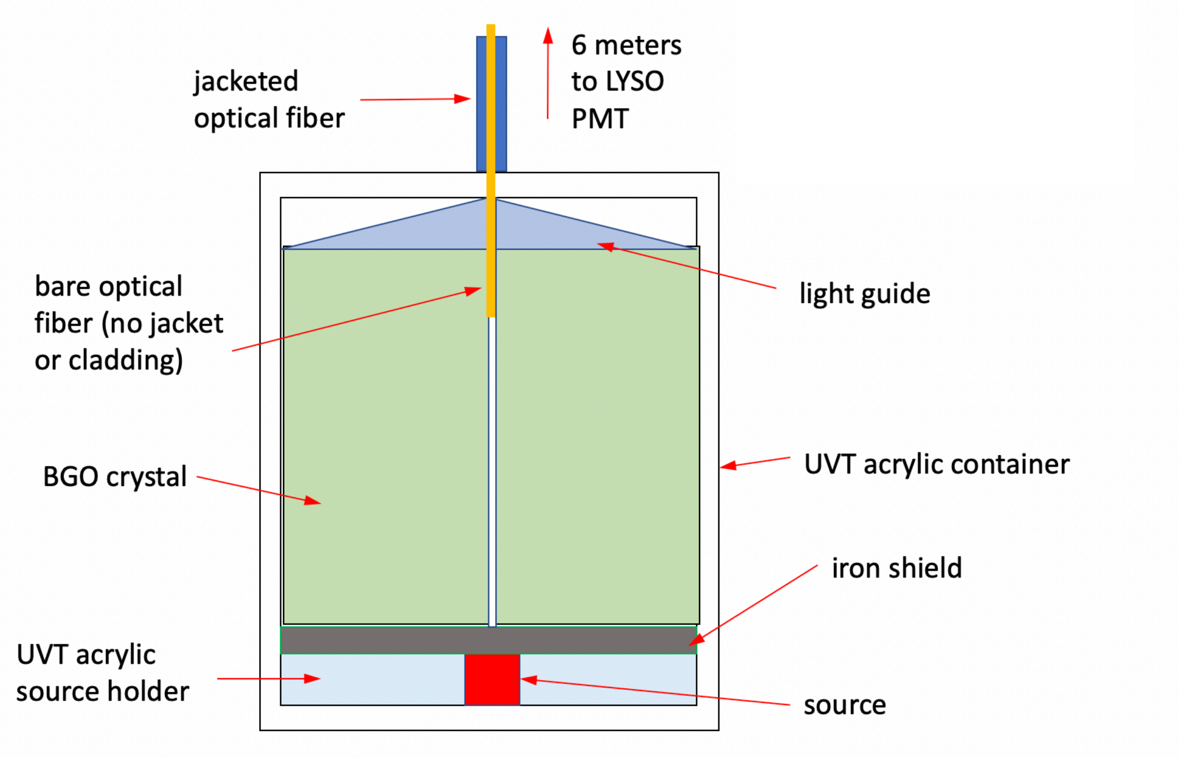
Detector calibration

PMT timing and single-p.e. calibration: LED fibers with attached diffuser tip

LAPPD timing calibration: 405nm picosecond laser + diffuser ball calibration strategy

Neutron calibration: AmBe source, tag neutron events by using coincidentally emitted gamma
100 µs detection window
100 µCi source → 100 tagged neutrons/second (<1% pile up)

$$\alpha + {}^9Be \rightarrow {}^{13}C^{(*)} \rightarrow {}^{12}C + \gamma(4.4MeV) + n$$



pictures & design by Robert Svoboda, UC Davis

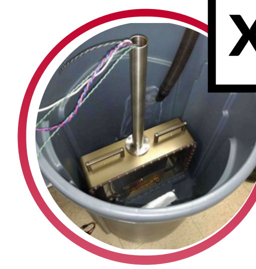
Phase II - Physics run

Timeline - Next steps

June 2019

Water fill
& commissioning

Gd-loading
& commissioning



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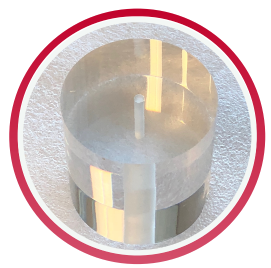
LAPPD
deployment



calibration

data taking

Summer 2020

Fall 2020

up to 20
additional LAPPDs

more detailed reconstruction:
- multi-track final states
- NC cross section measurement

202x

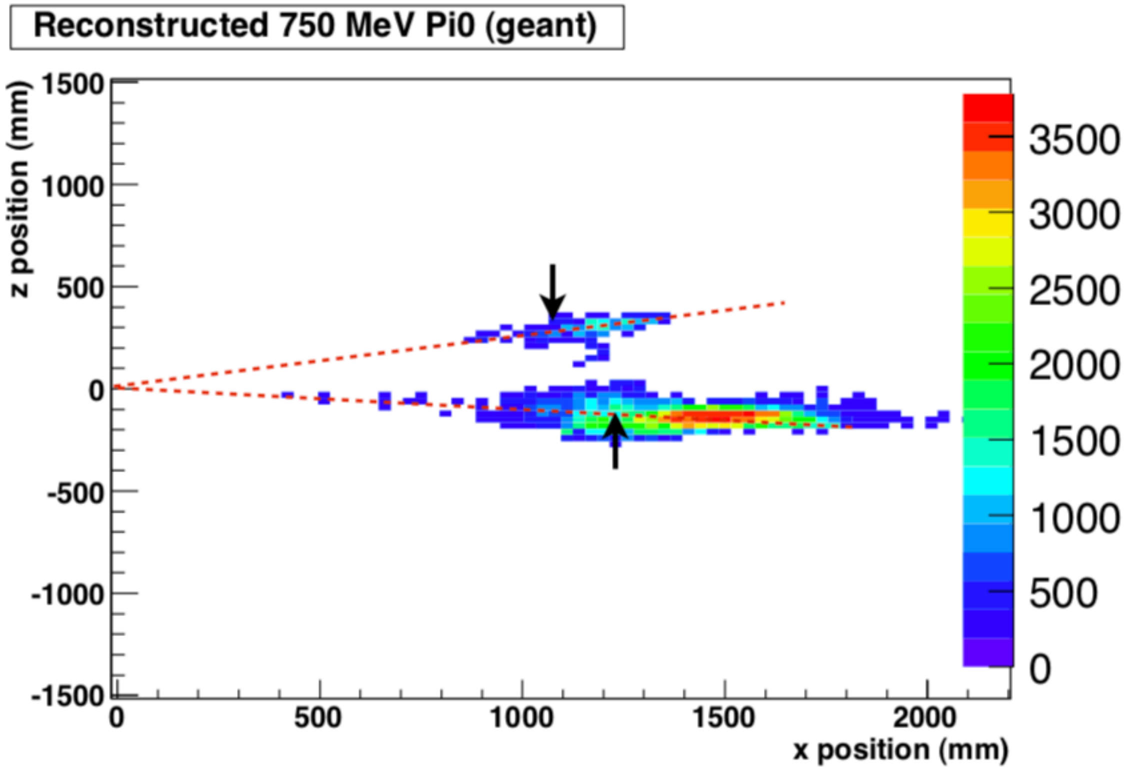
Phase III

- testbed for water-based Liquid Scintillators
- separation of Cherenkov and scintillation light

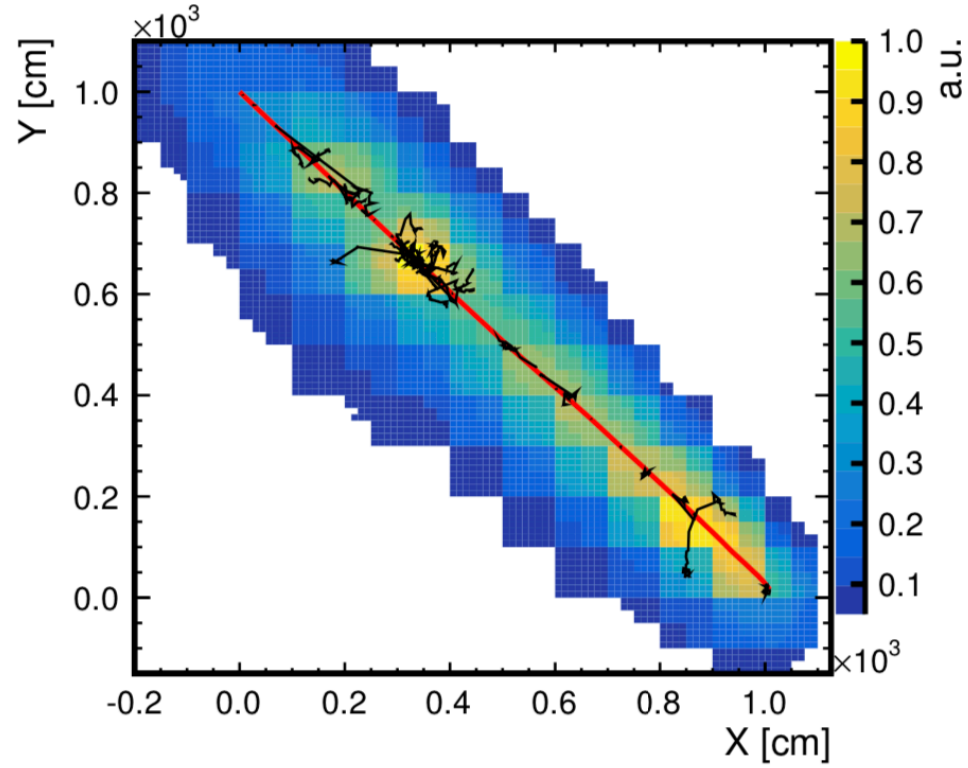
Phase II - LAPPD Upgrade

Additional LAPPD reconstruction possibilities

- additional LAPPD coverage would probably enable ANNIE to do topological reconstruction via time-reversal imaging techniques
- multi-track event reconstruction would broaden ANNIE's physics program

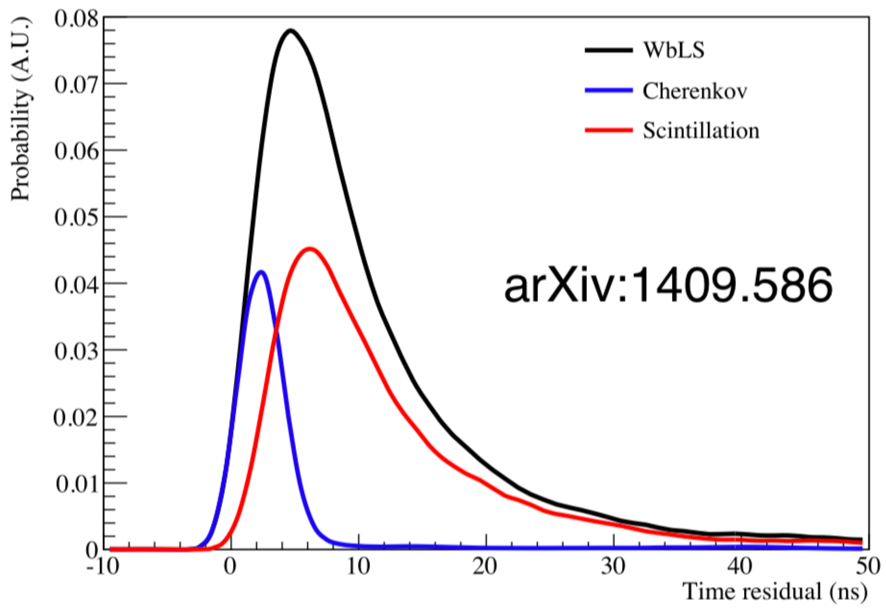


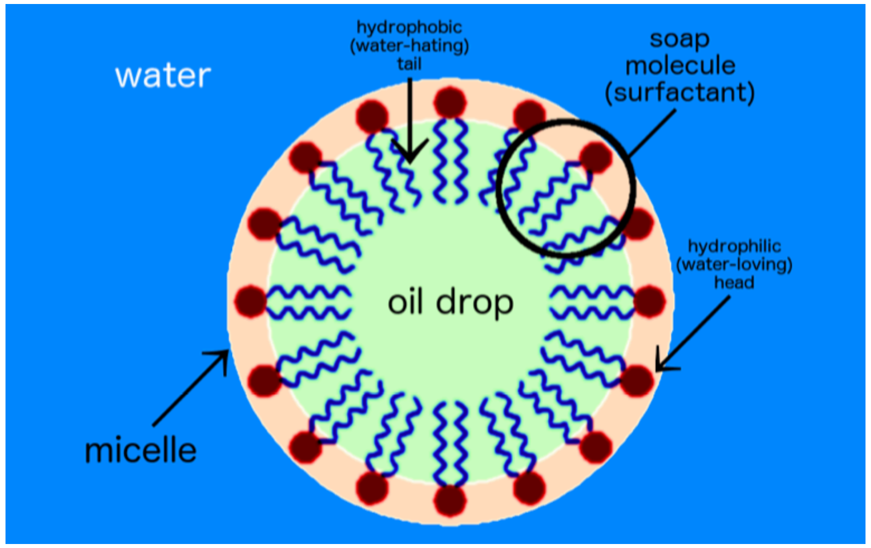
M. Wetstein, ANT11



B. Wonsak et. al, "Topological track reconstruction in unsegmented, large-volume liquid scintillator detectors"
"

Phase III - Water-based LS





micelle structure

- Best of both worlds:
  - Directionality & kinematic reconstruction (Cherenkov)
  - High light yield & calorimetric reconstruction (scintillation)
  - High transparency + low cost of water
- Tunable liquid scintillator concentration, isotope loading
- Charged particle detection below Cherenkov threshold → enables detection of protons
- Need surfactant to bind liquid scintillator oil in water

Future detectors

ANNIE → WATCHMAN → Theia

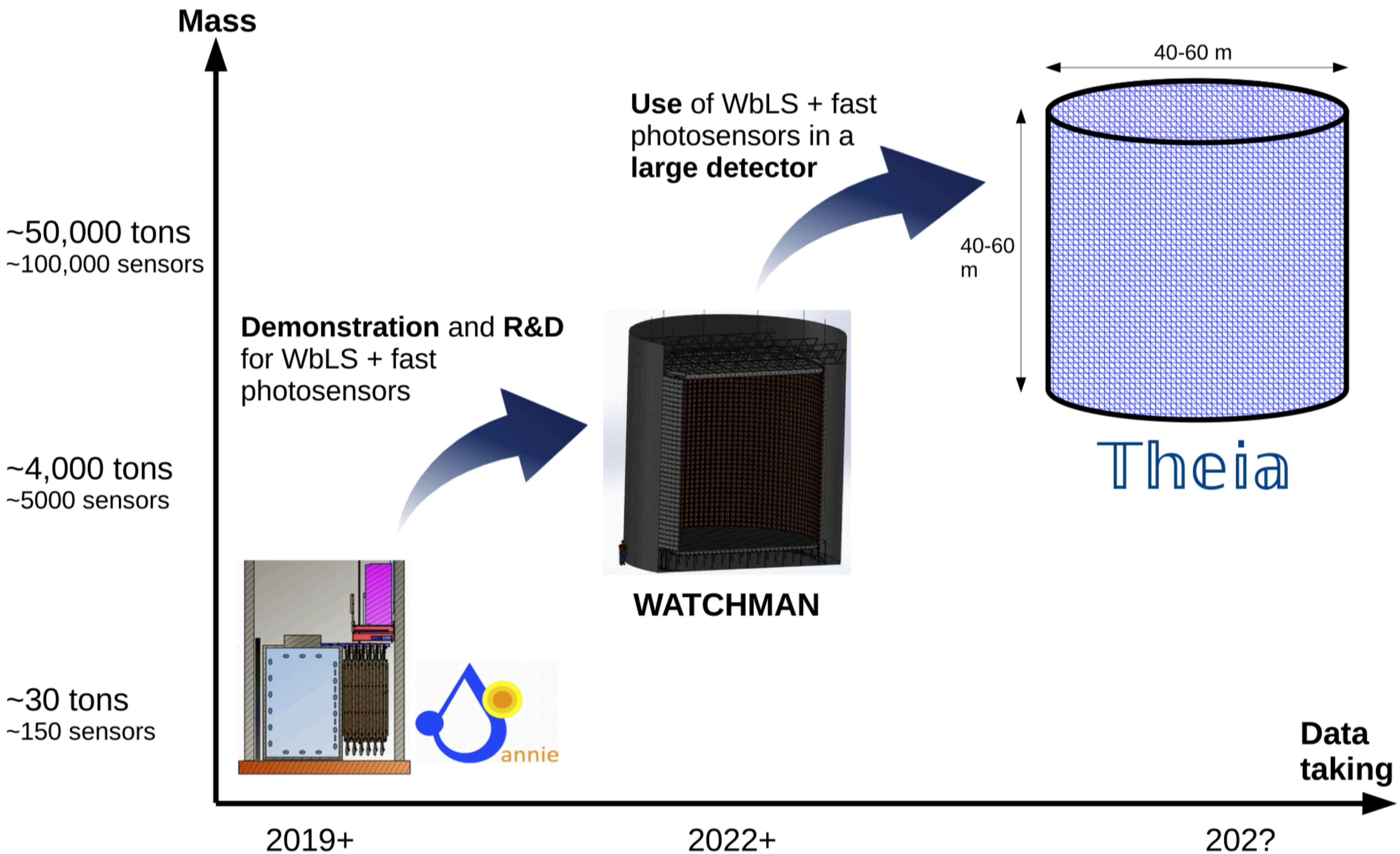


diagram by Steven Gardiner

Summary

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

- Testbed for **new technologies**:
  - LAPPDs (phase II)
  - First Gd-loaded water Cherenkov detector in a beam (phase II)
  - Water-based Liquid Scintillators (phase III)

- **Last preparations for phase II** taken at the moment:
  - Mounting the last PMTs onto the Inner Structure
  - Transport and installation of tank into ANNIE hall
  - Finalization of LAPPD deployment structure
  - Development & integration of calibration systems

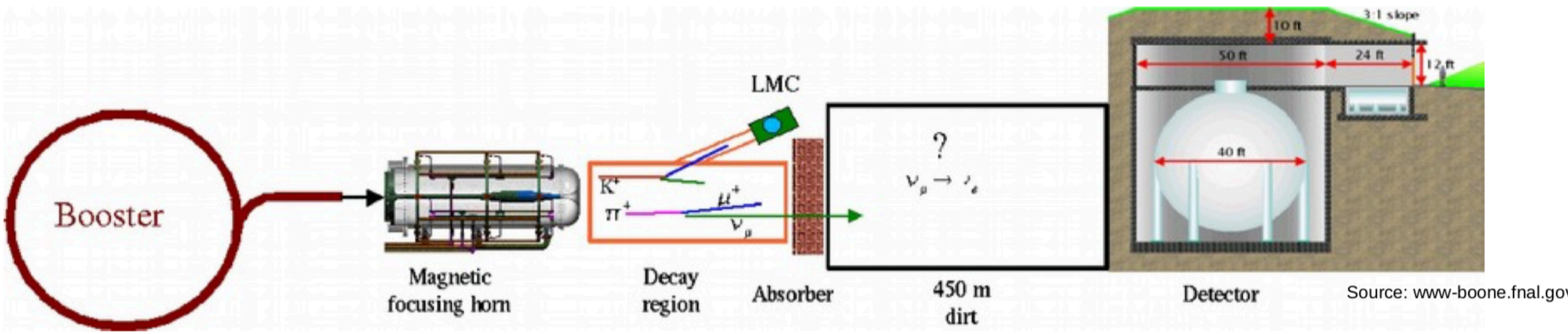
- **Commissioning and first physics data** starting mid June 2019

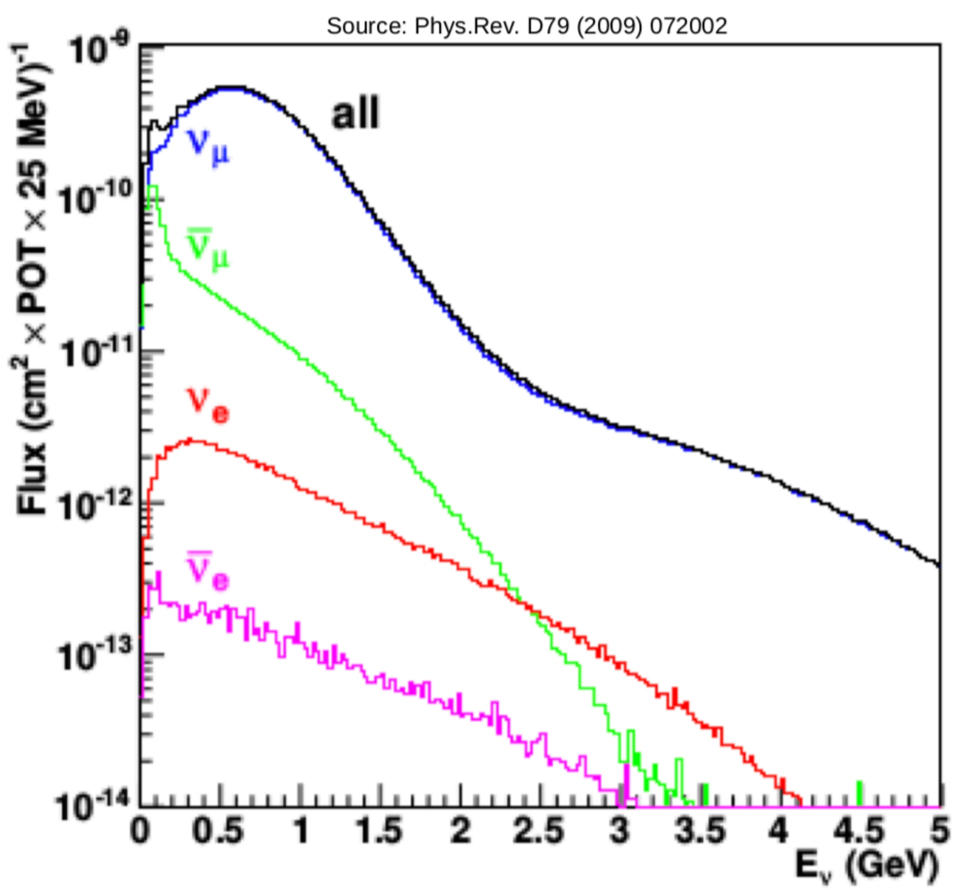
- Brookhaven National Laboratory
- Fermi National Accelerator Laboratory
- Iowa State University
- Johannes Gutenberg University Mainz
- Lawrence Livermore National Laboratory
- Ohio State University
- Queen Mary University
- The University of Hamburg
- The University of Sheffield
- University of California, Davis
- University of California, Irvine
- University of Chicago
- University of Edinburgh

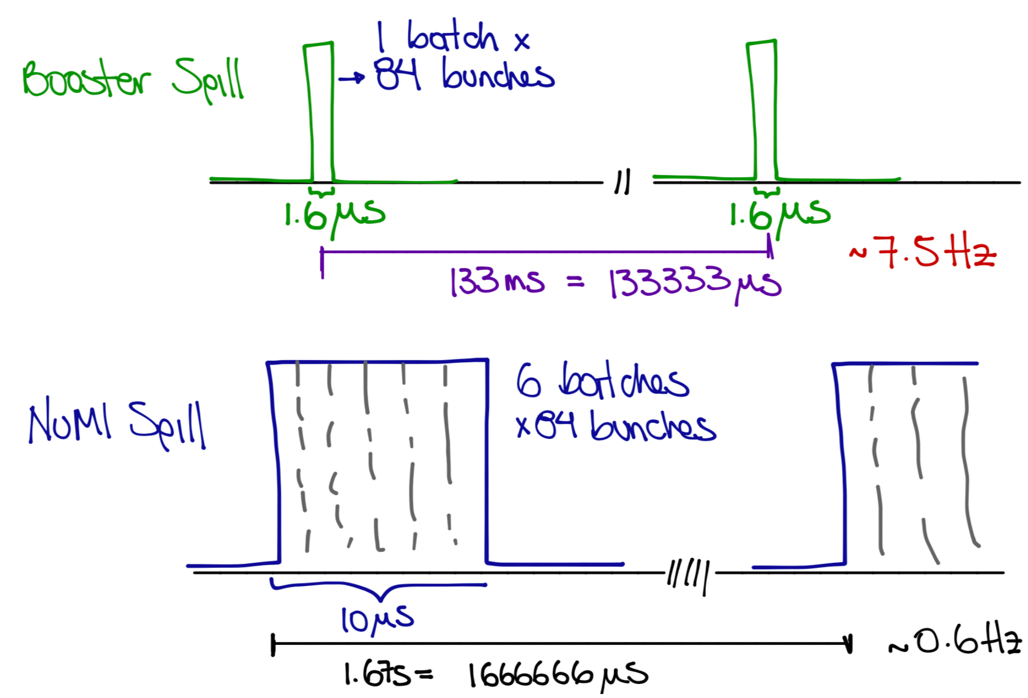
annie

THANK YOU!
… ANY QUESTIONS?

Backup - BNB





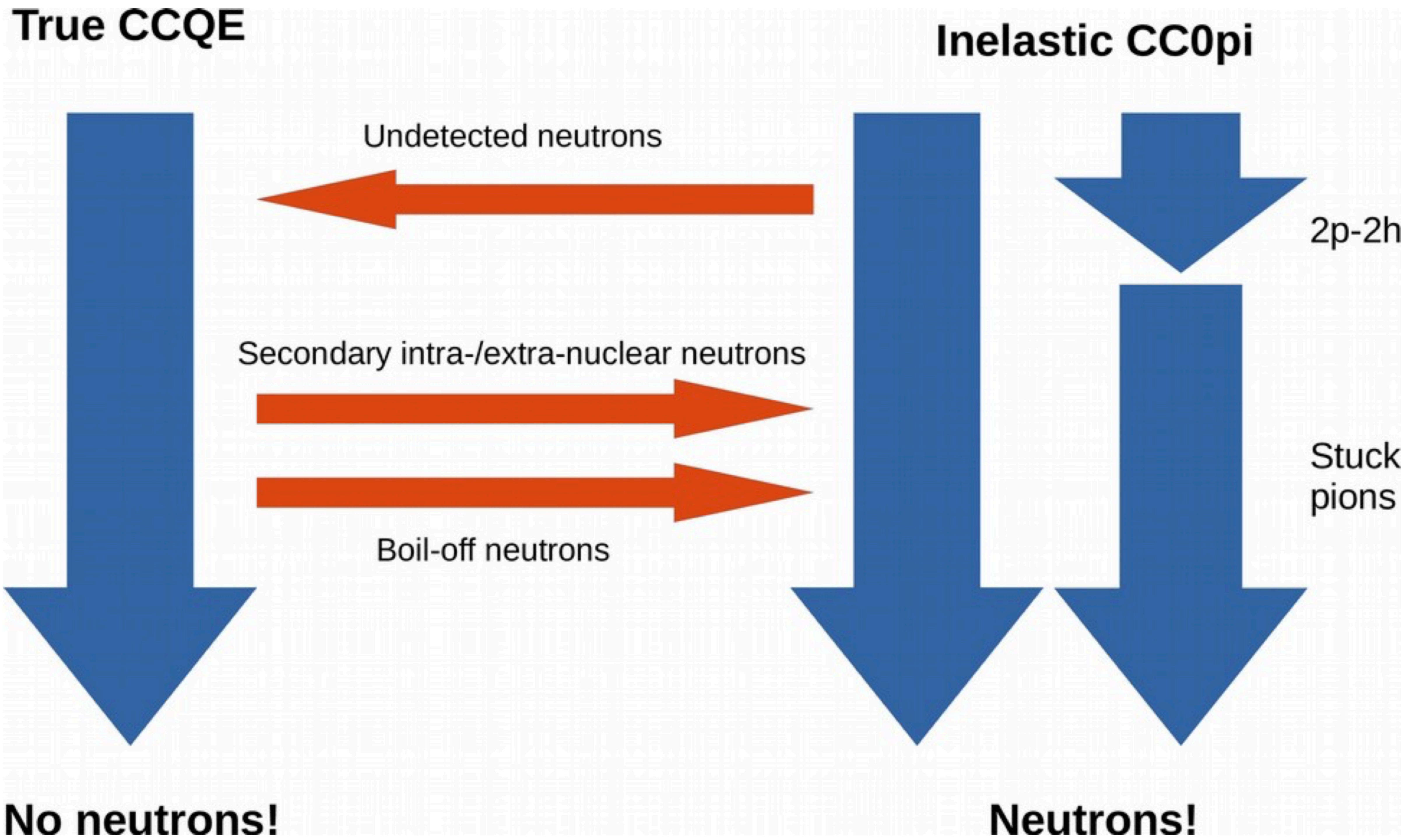


Composition: 93 % of ν_μ, 6.4 % of $\overline{\nu}_\mu$ and 0.6% of ν_e and $\overline{\nu}_e$

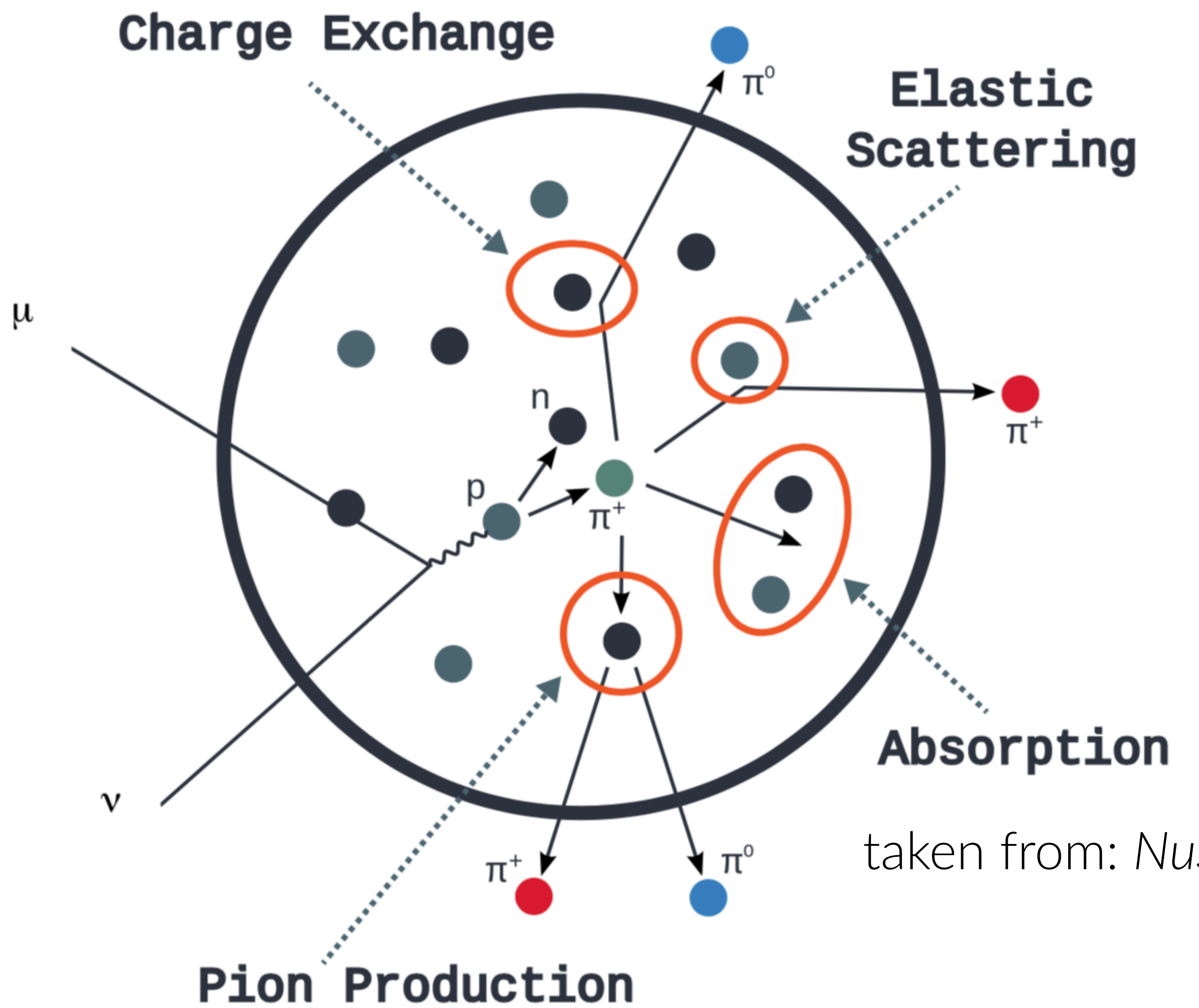
Repetition rate: ~7.5 Hz, 5 × 10^{12} protons-on-target per 1.6 μs spill on average

Backup - Neutron production

diagram by Vincent Fisher, UC Davis



Backup - Inelastic processes

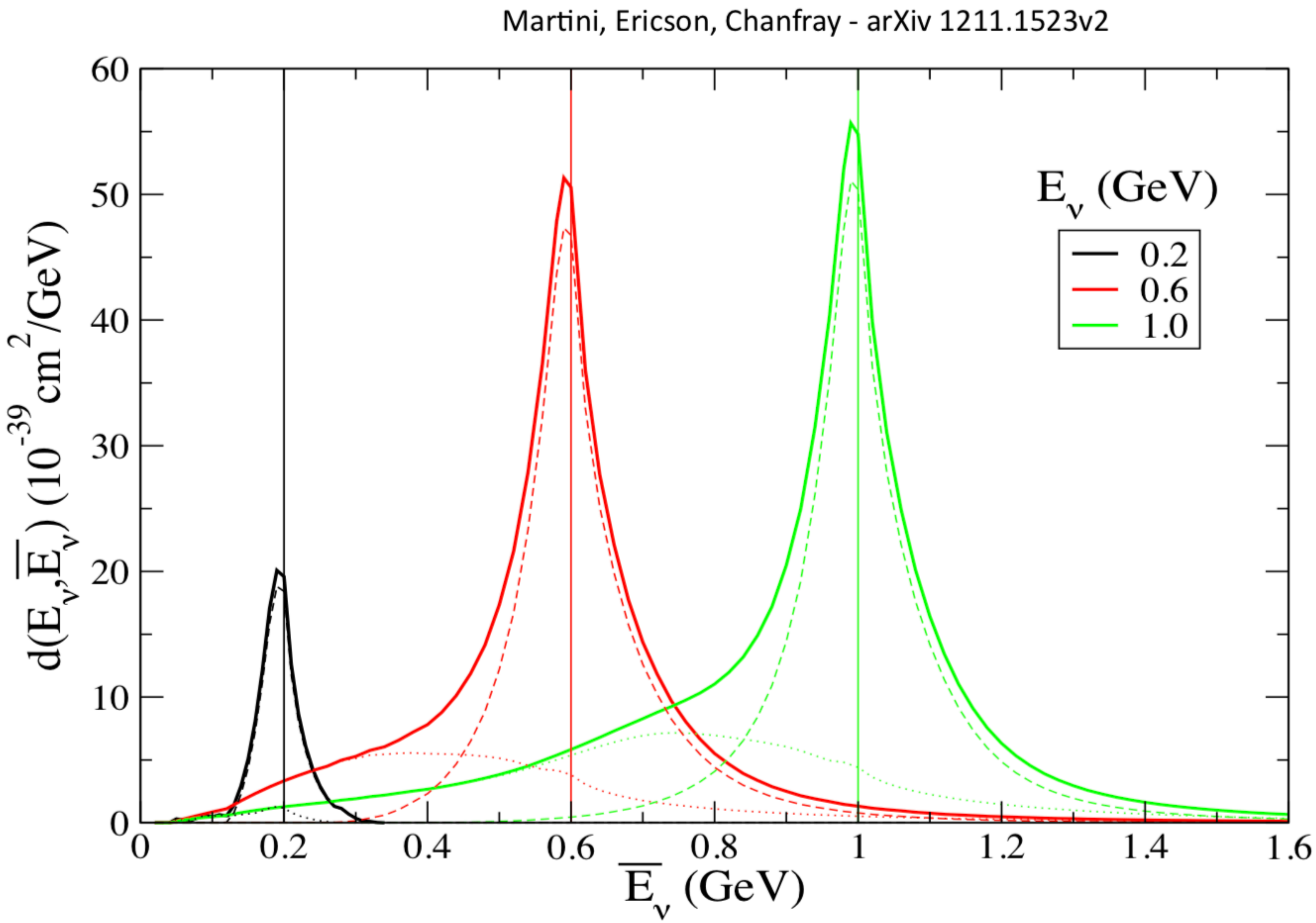


taken from: *NuSTEC white paper*

→ move to **event topologies (1μ + 1/0π + Xn + Yp)** instead of **MC generator-based categories**

- **neutrons** as possible signs of **inelasticity**
- final state **neutron multiplicity** measurement → ANNIE

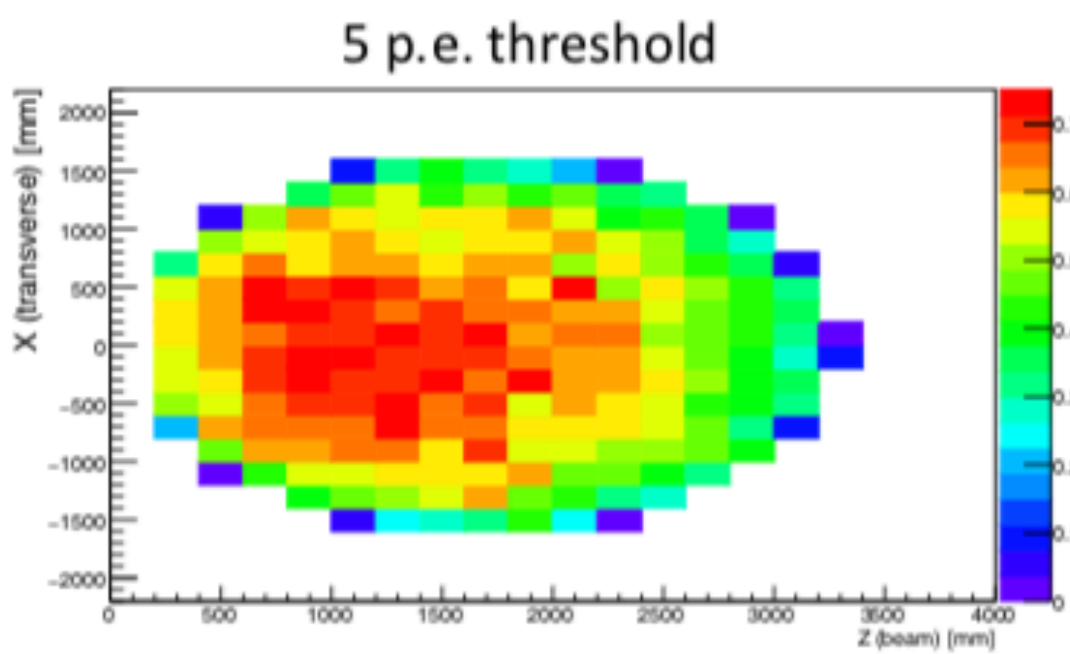
Backup - Inelastic processes

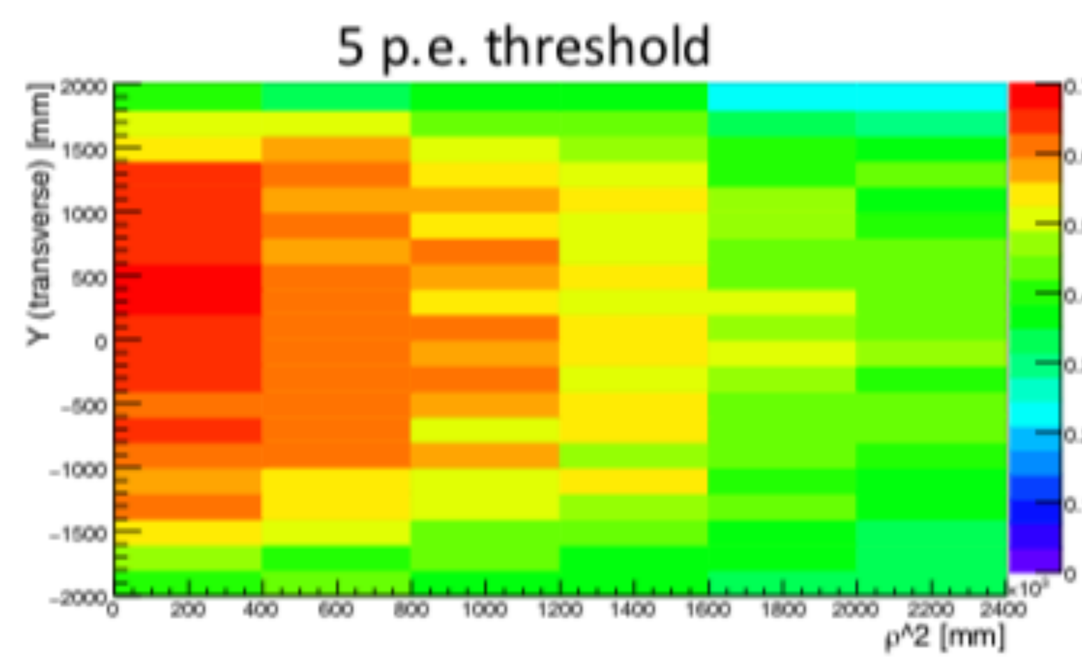


dotted: multi-nucleon contributions to energy reconstruction bias

Backup - Neutron detection efficiency

- Neutron detection efficiency as a function of the interaction position in X (the transverse direction) and Z (the beam direction)



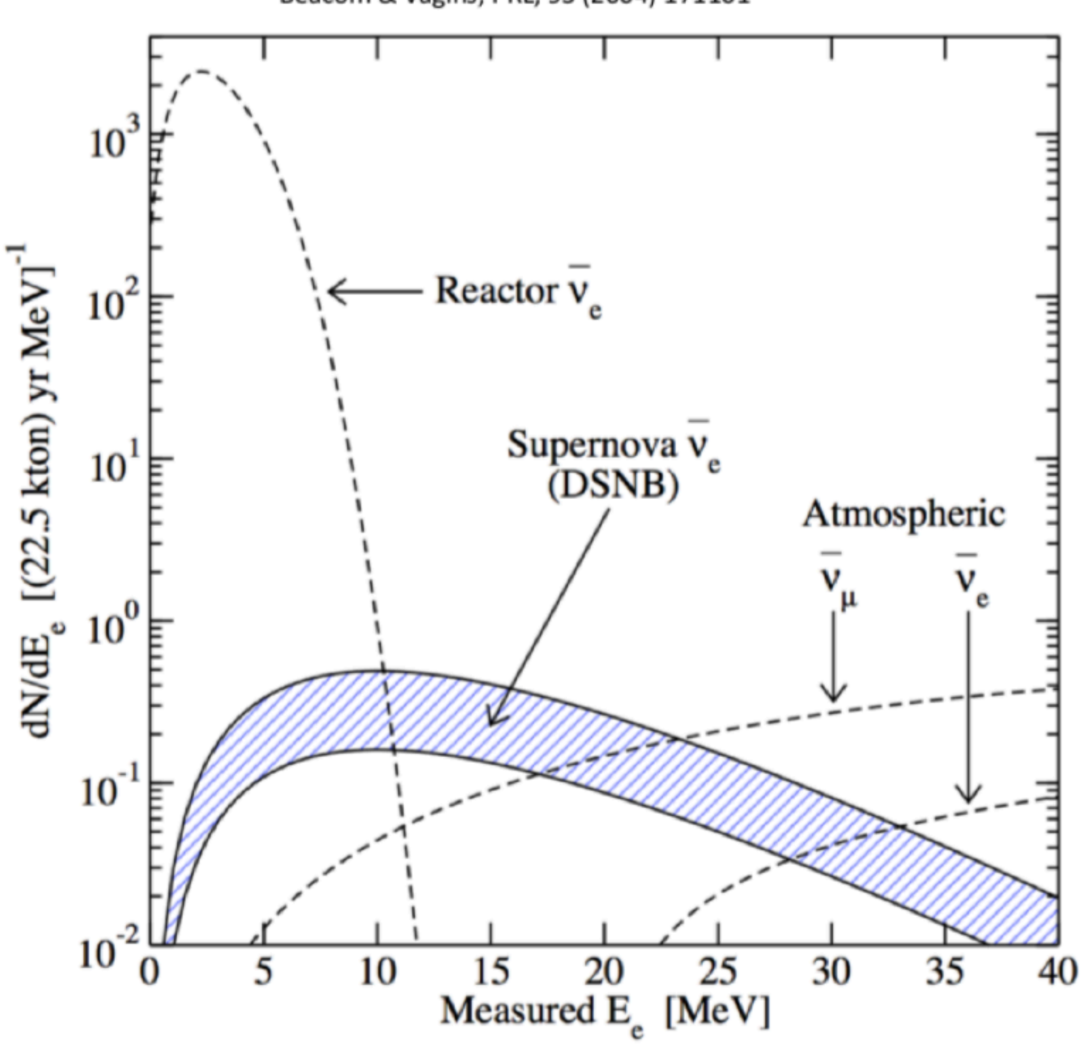


- The detector is large enough to fully contain neutrons
- Requested PMT coverage is sufficient to efficiently detect neutrons.

simulation & plots by Vincent Fischer

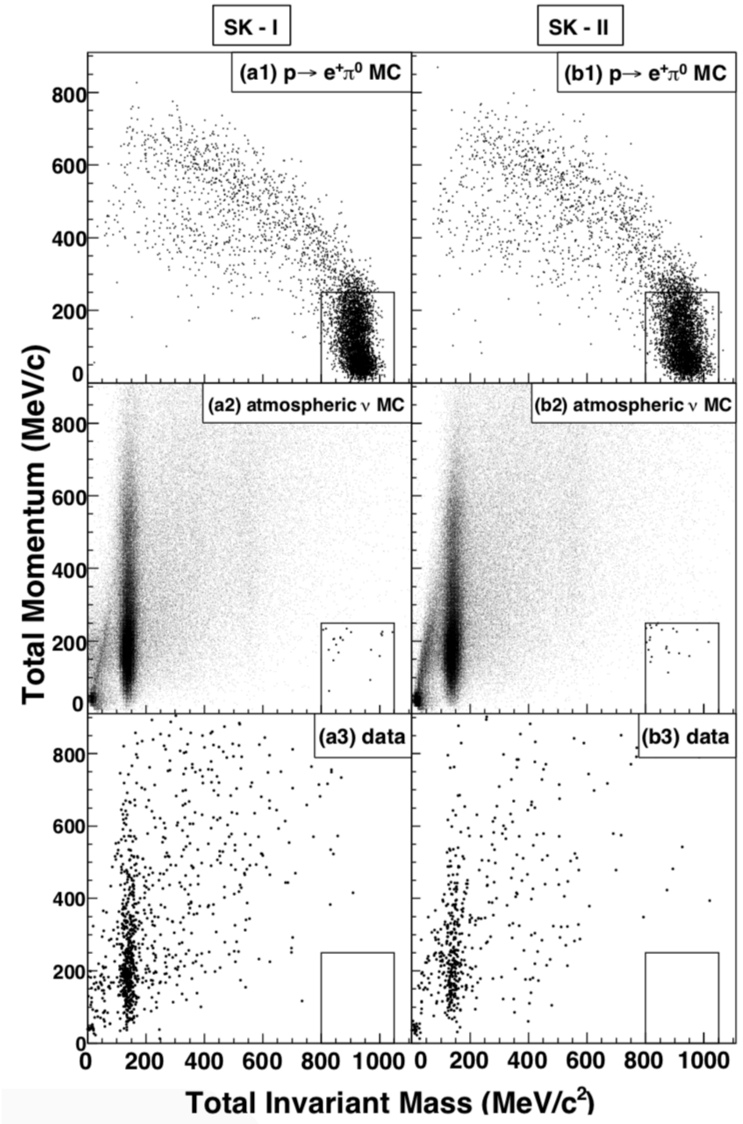
Backup - DSNB & Proton decay

Beacom & Vagins, PRL, 93 (2004) 171101



backgrounds for DSNB searches

PRL 102 (2009) 141801



proton decay

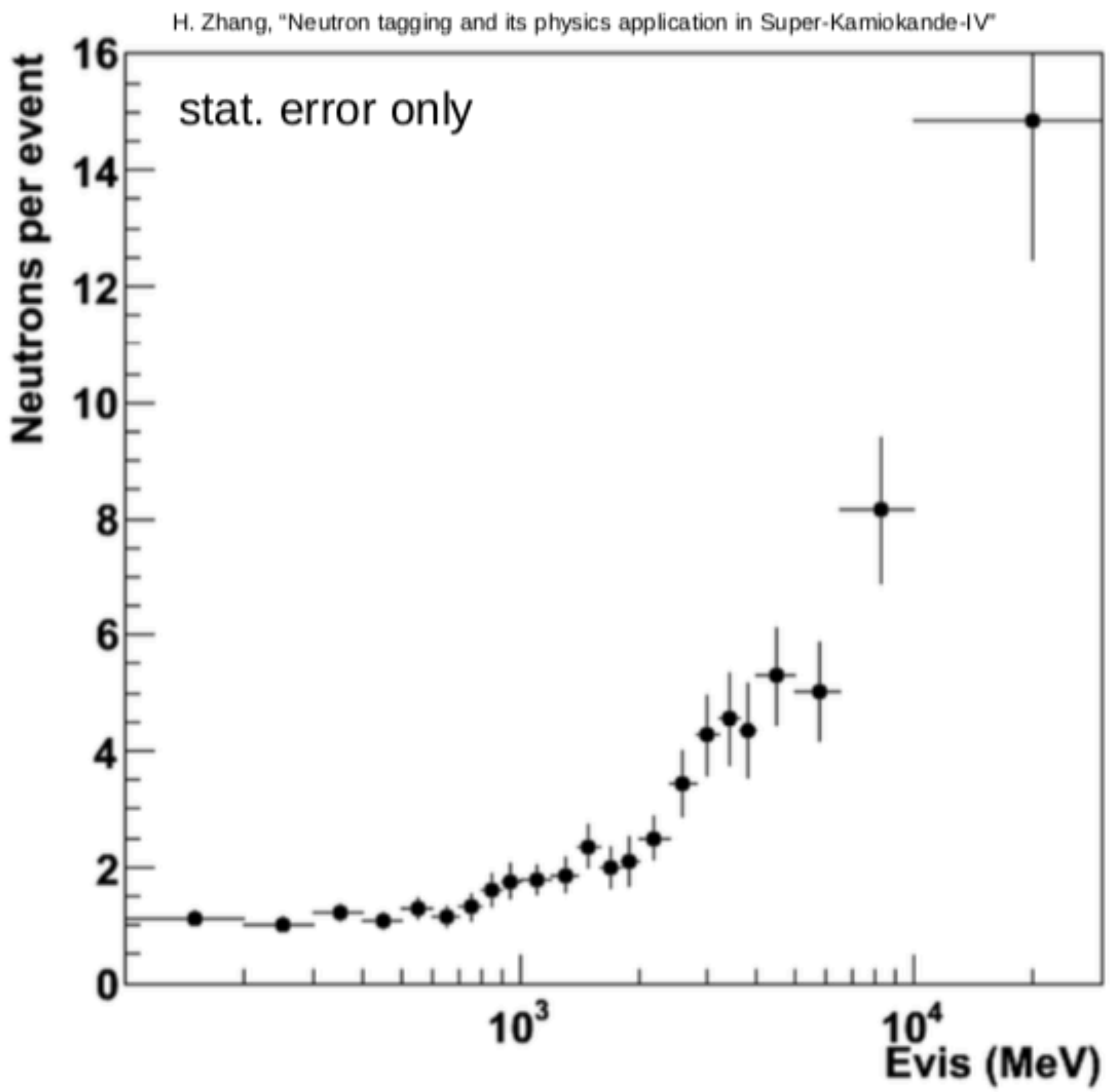
atmospheric

data

backgrounds for proton decay searches

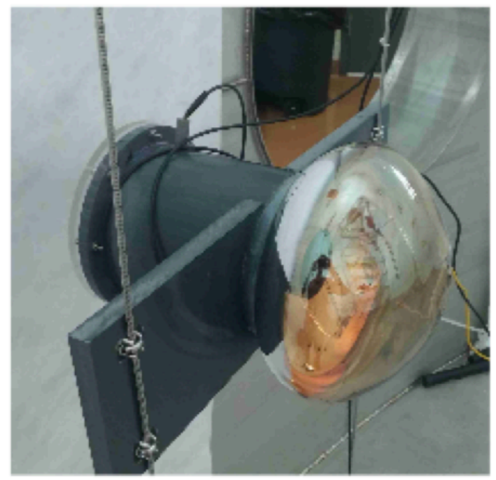
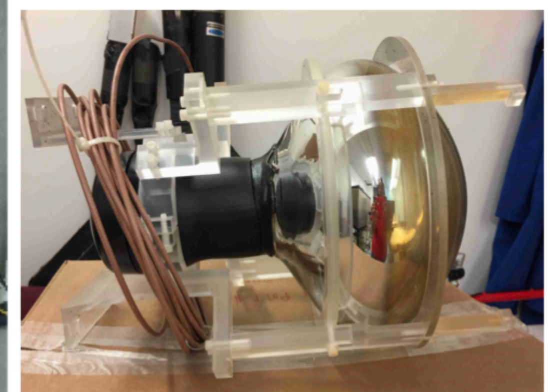
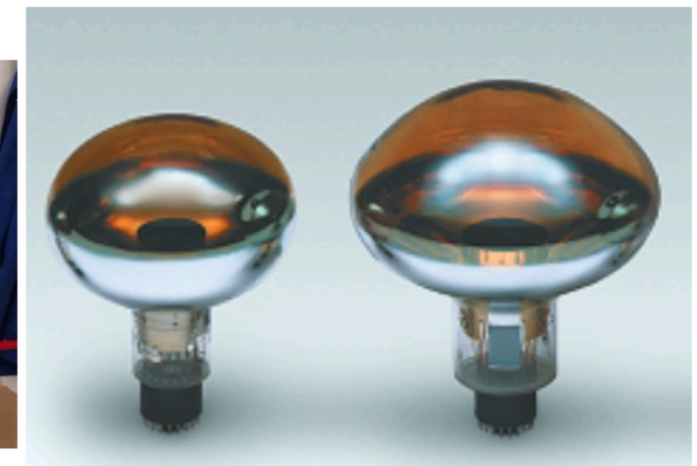
improve signal-to-background discrimination by better models of atmospheric neutron yield

Backup - Super-K neutron multiplicity



- **Super-K** measurement of neutron multiplicity only as a function of the **visible energy,** since precise information about the initial particle conditions are missing
- **ANNIE** will provide a **complimentary measurement** since the beam properties like **neutrino energy, angle, flavor and the interaction type** are much better known

Backup - PMT types

Manufacturer	ETEL	Hamamatsu	Hamamatsu	Hamamatsu	Hamamatsu
Origin	LBNE R&D	LUX	Watchboy	New	WATCHMAN
Type	D784KFLB	r7081	r7081	r5912	r7081
“Name”	LBNE (LB)	LUX (LX)	Watchboy (WB)	New (HM)	Watchman (WM)
Size	11”	10”	10”	8”	10”
HQE?	Yes?	No	No	Yes	Yes
Quantity	22	20	45	40	10

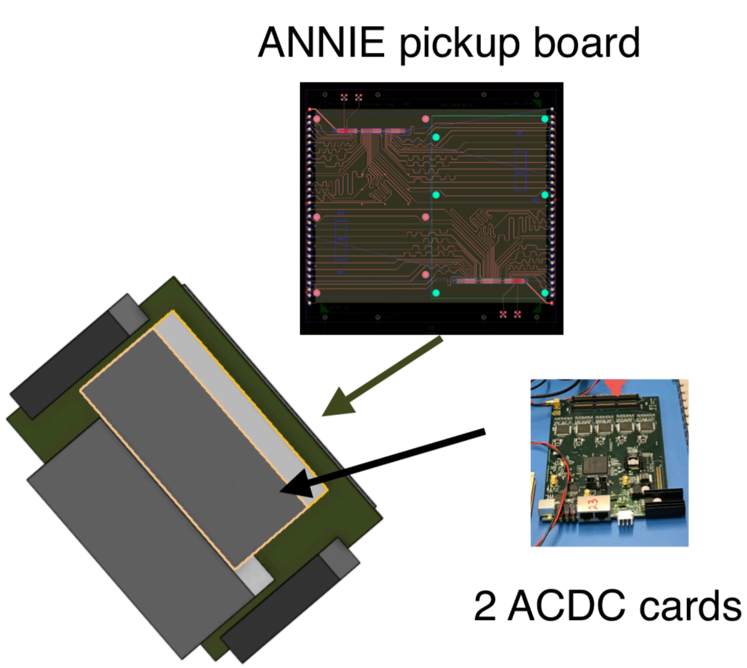
Backup - DAQ

- ANNIE will have a **dual readout design** to accommodate deep-buffered PMT signals (neutron capture) alongside ultra-fast LAPPD digitization

- **PMTs: VME-based data acquisition system (500 MHz)**, global trigger for all PMTs

- **LAPPDs**: **ACDC card** hosting **5 PSEC sampling ASICs with multi-channel readout (10 GHz)**, independent triggers for every single LAPPD

- DAQ processes interfaced by **ANNIE central card** (8 nodes)



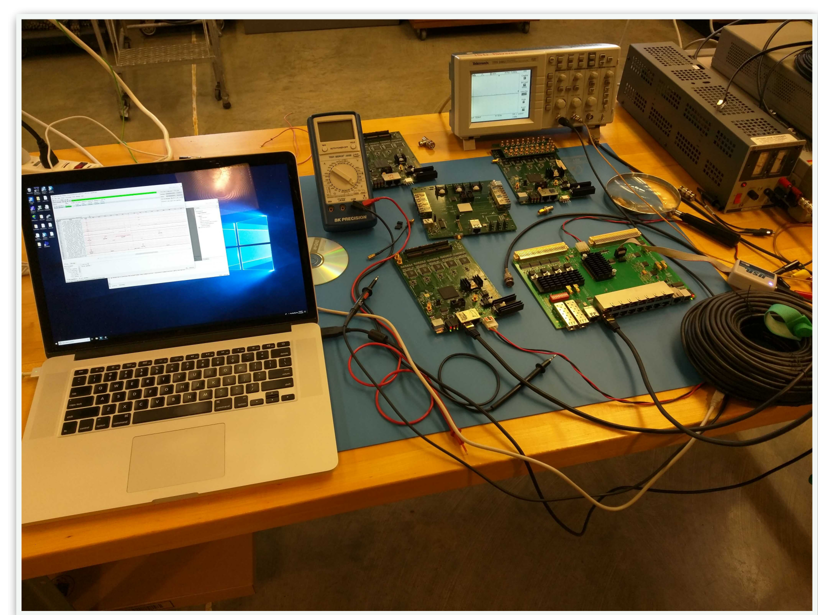
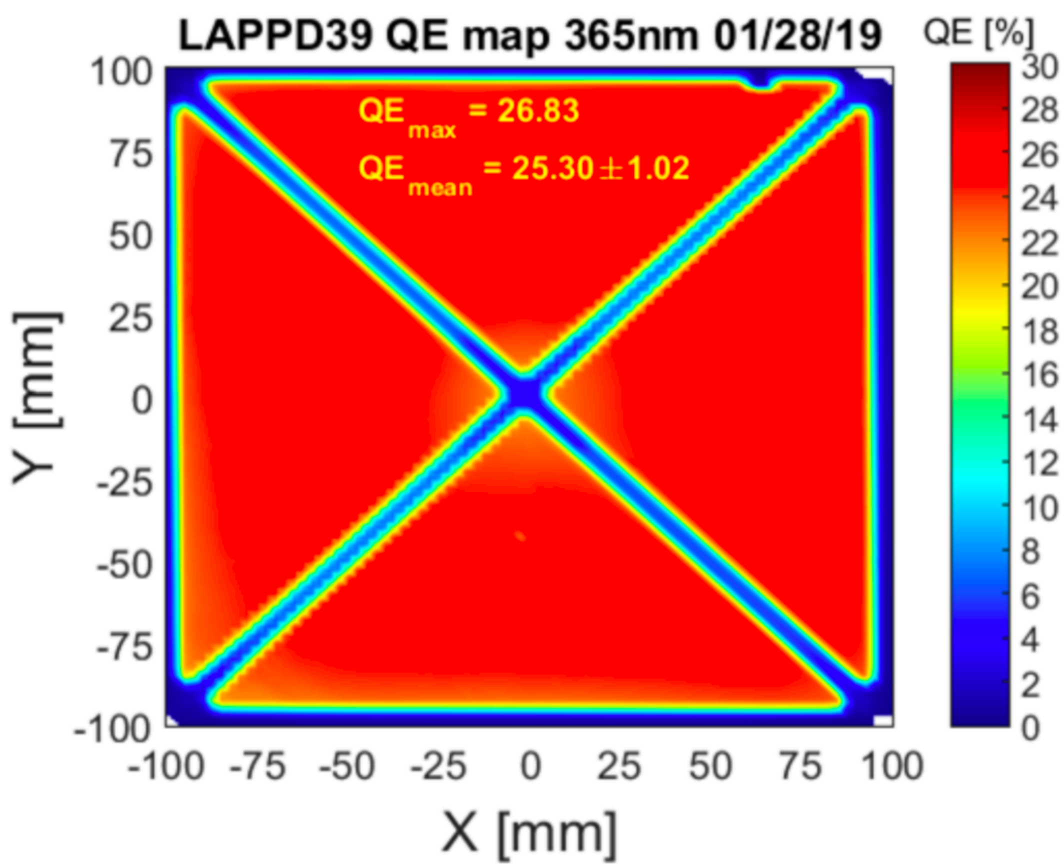


photo: Jonathan Eisch, Iowa State University

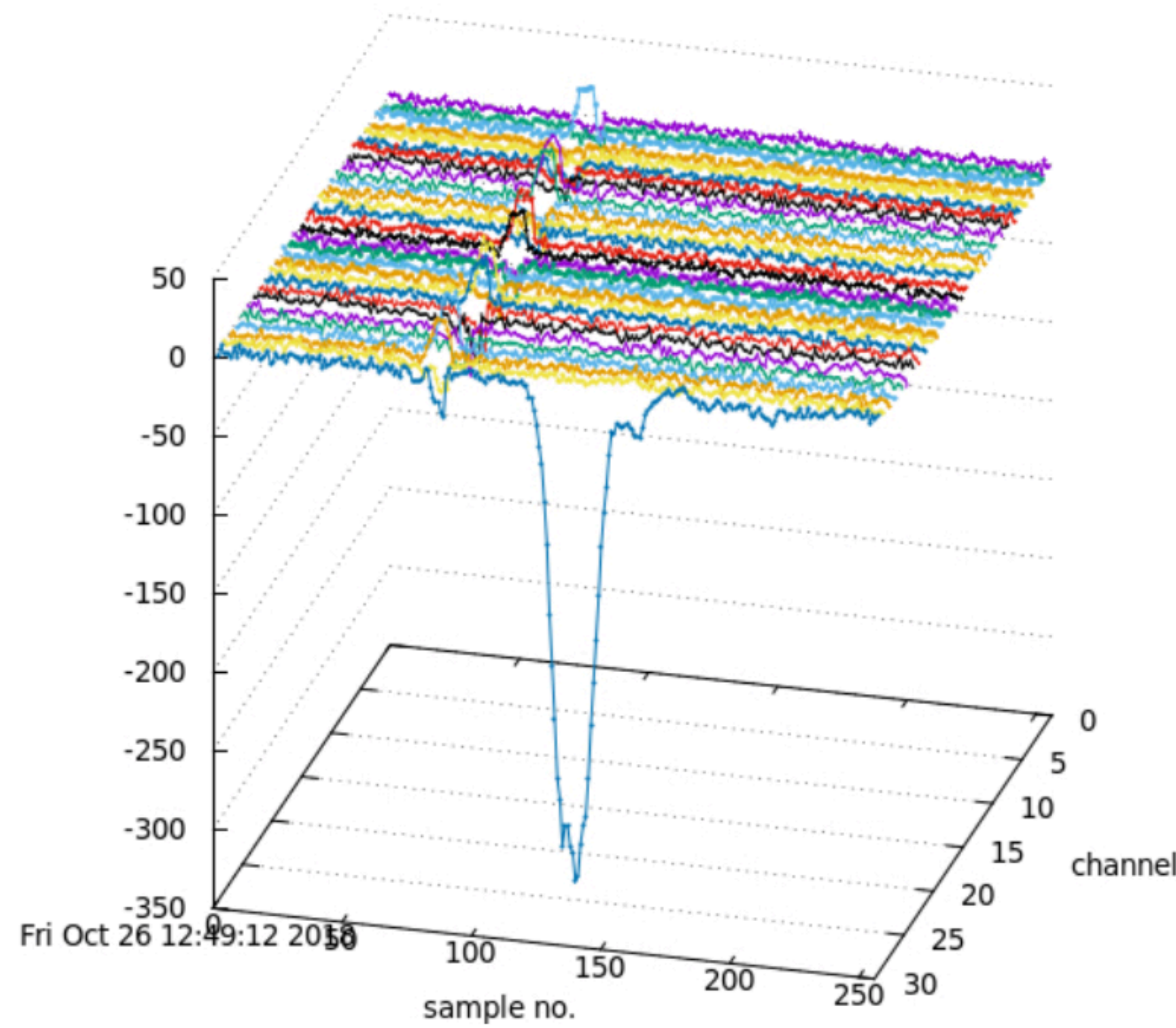
test setup for communication of ANNIE central card & ACDC card

Backup - LAPPDs

Quantum Efficiency



Channel Signals



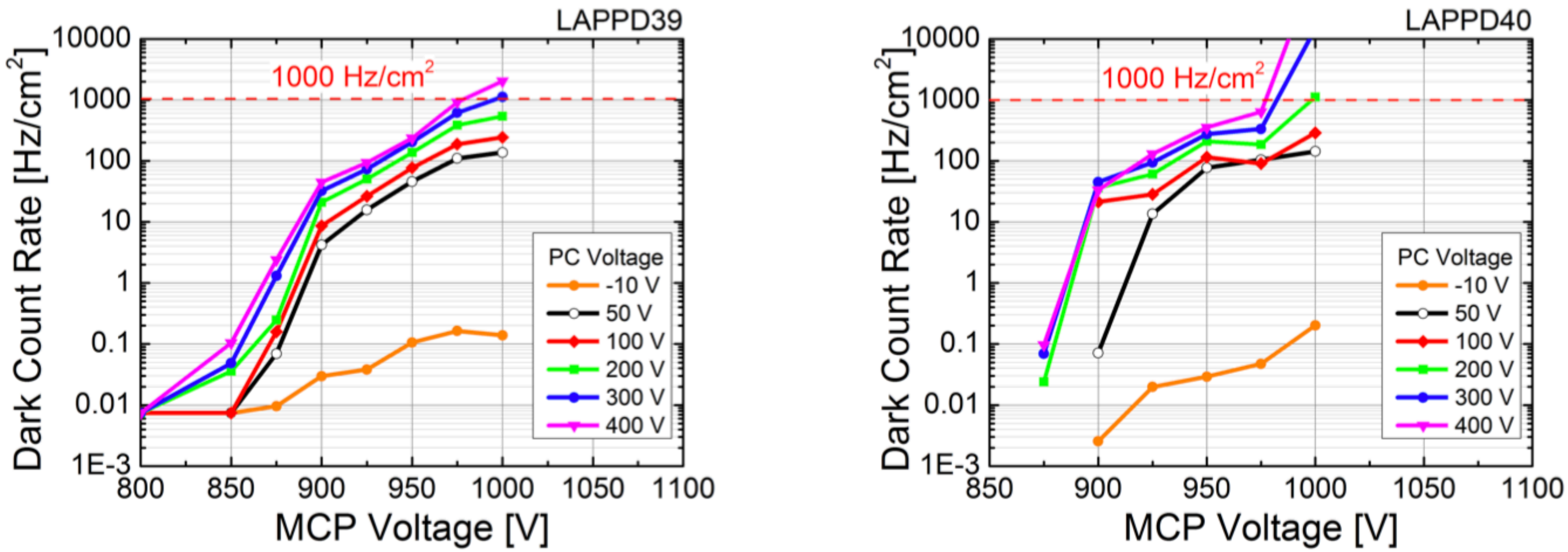
A. Lyashenko et. al, *"Performance of Large Area Picosecond Photo-Detectors (LAPPD)"*

plot by M. Wetstein

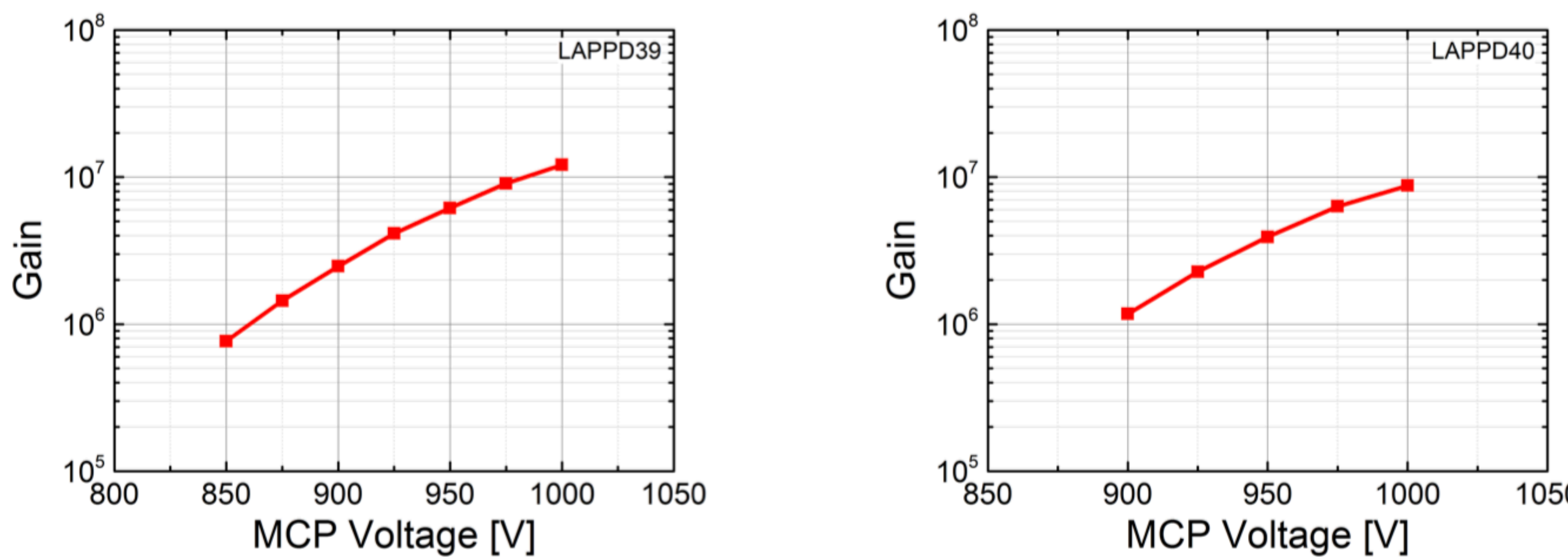
Backup - LAPPDs

Dark Count Rate:

A. Lyashenko et. al, *"Performance of Large Area Picosecond Photo-Detectors (LAPPD)"*



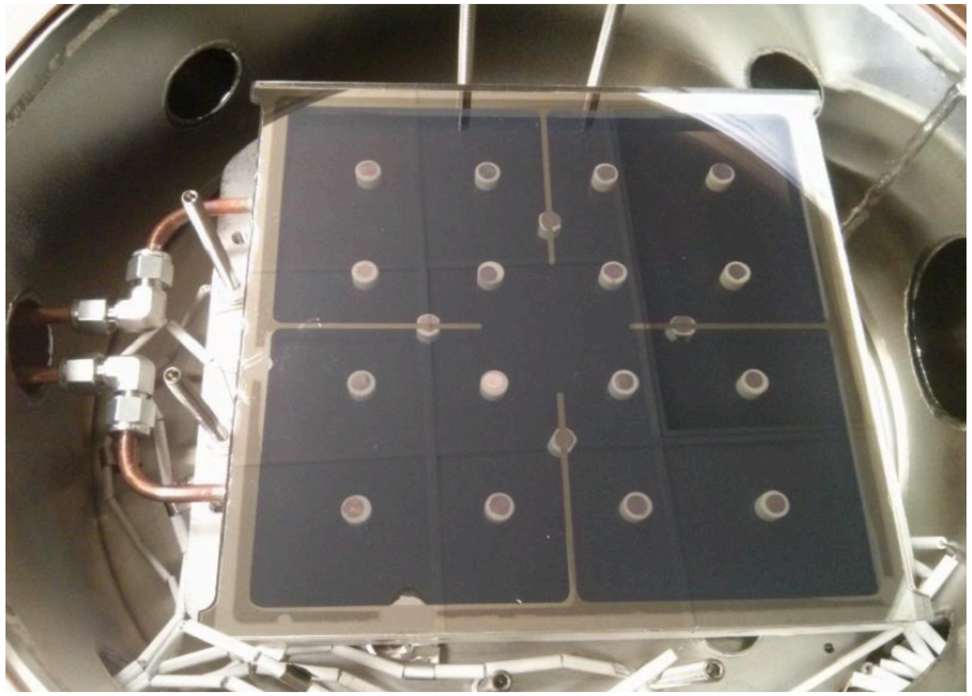
Gain:



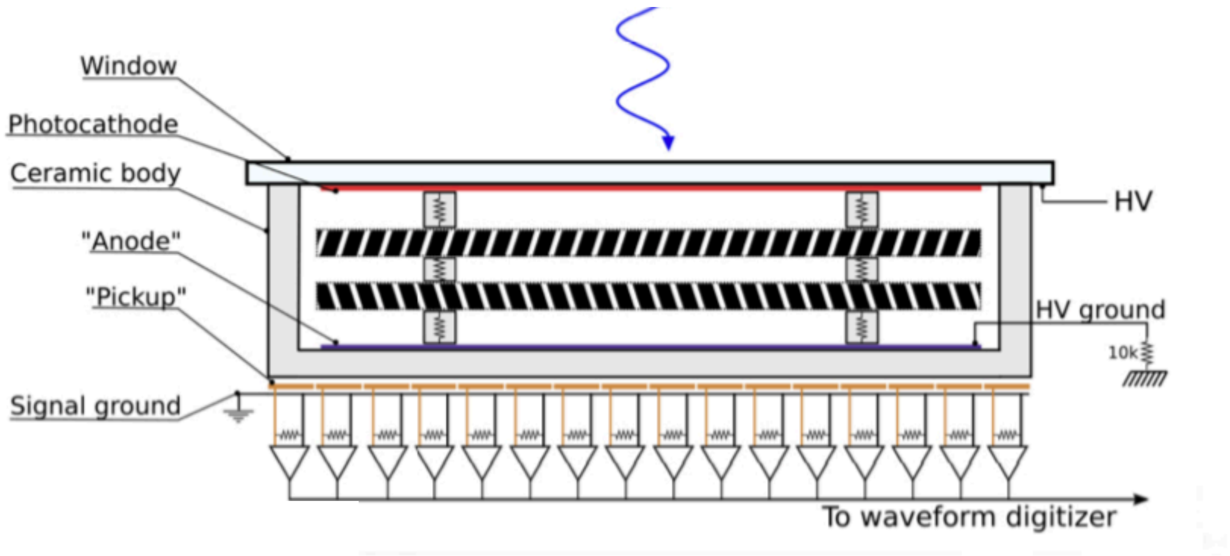
Backup - Gen-II LAPPDs

- new method developed at University of Chicago for photocathode production, eliminate need for vacuum transfer procedure
- use ceramic body with capacitive coupling to external anode
- enabling faster production cycles for LAPPDs, compatible with high rate applications

Next generation prototype



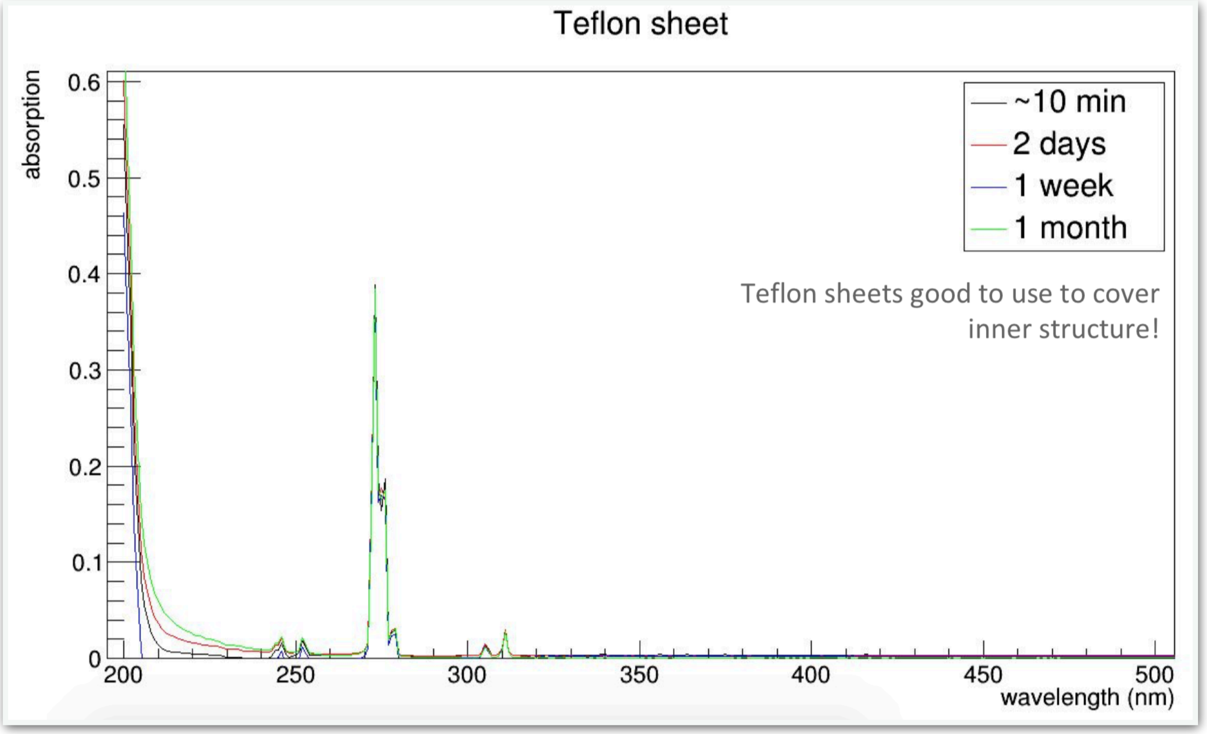
Next generation anode readout

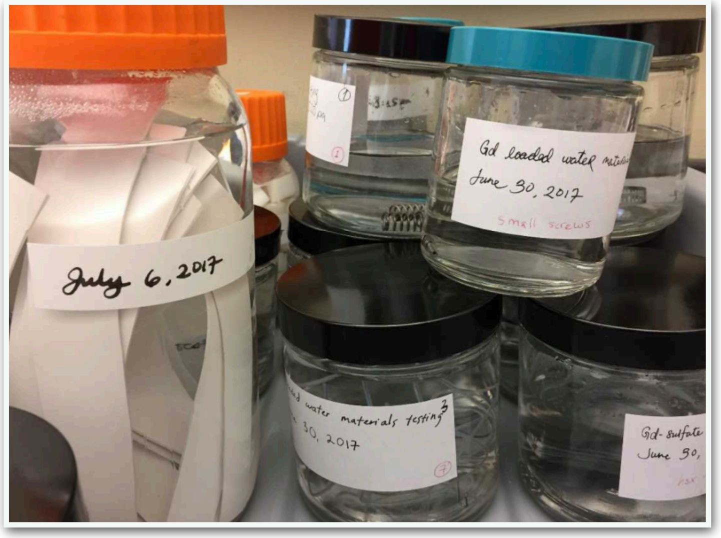


Backup - Gd compatibility tests

Julie He, UC Davis

- $Gd_2(SO_4)_3$ not corrosive, but reactions with different materials possible
- need to make sure that Gadolinium loaded water does not degrade tank materials
- at the same time tank materials should not degrade water transparency
  - all materials put in 1% Gd solution
  - reasonably low absorption lengths after an extended period of time required for all materials



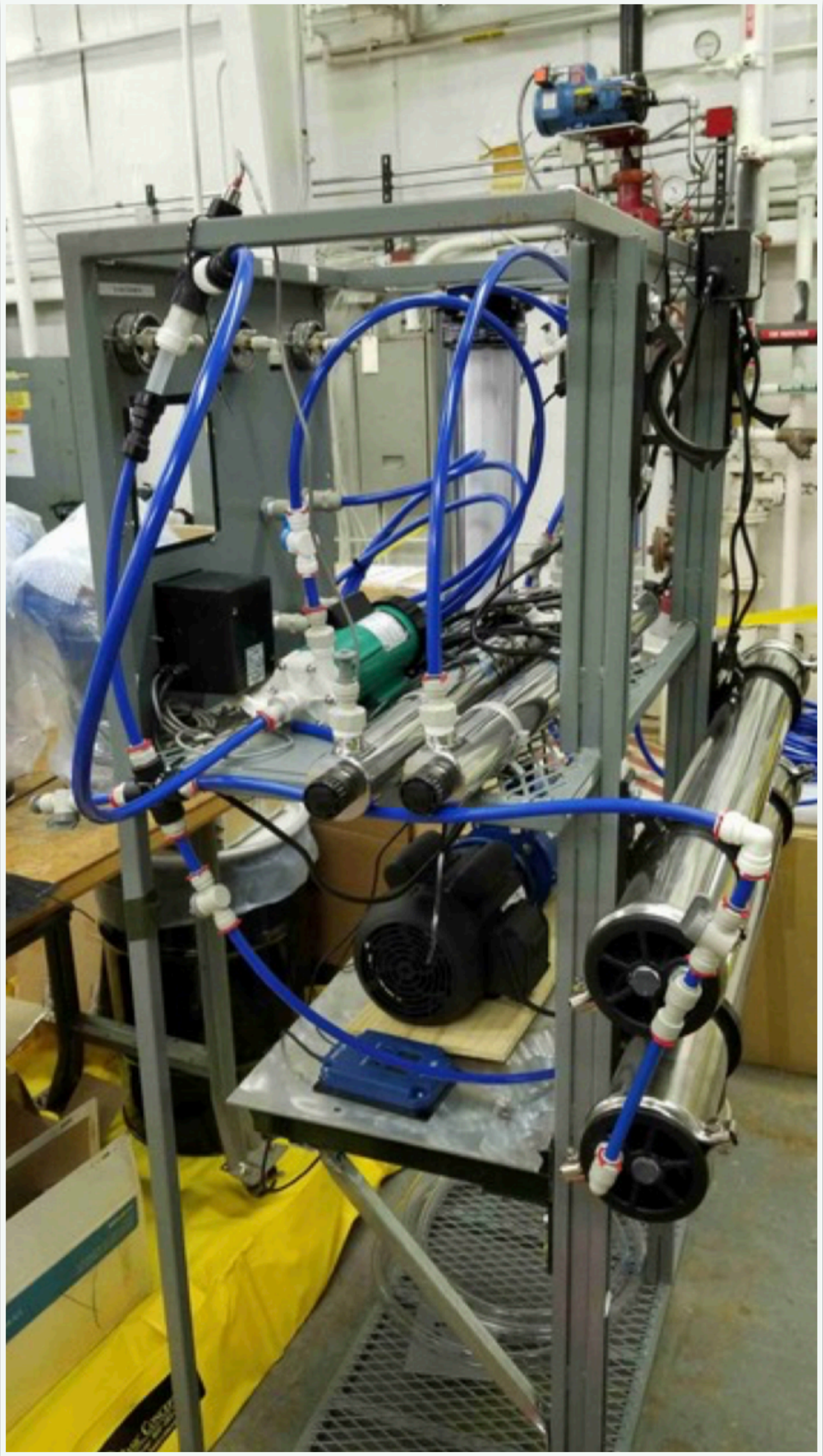


materials in Gd-loaded water

Backup - Water filtration

Vincent Fischer, UC Davis

- 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



Backup - Gd sulfate vs. chloride

$GdCl_3$

✔
- high transparency
- no UV absorption
- high solubility (→ 50% by weight)
- good tolerance to bacterial growth

✘
- **lower material compatibility**

$Gd_2(SO_4)_3$

✔
- **higher material compatibility**
- high transparency
- no UV absorption

✘
- lower solubility (→ 2% by weight)
- some bacteria eat sulfur

~52 kg of sulfate required for one detector loading

compatibility:
- known problematic materials: *nylon, copper, steel*
- known "safe" materials: *PTFE, polypropylene, acrylic, 304/316 stainless steel*