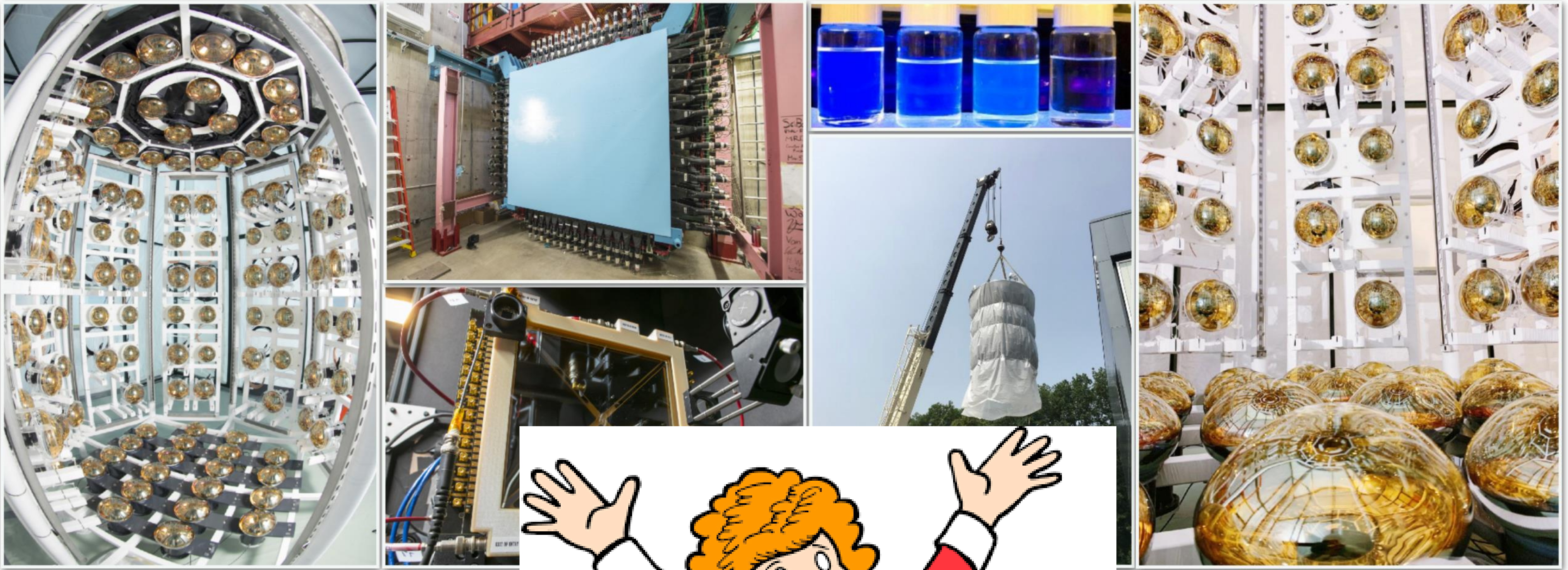
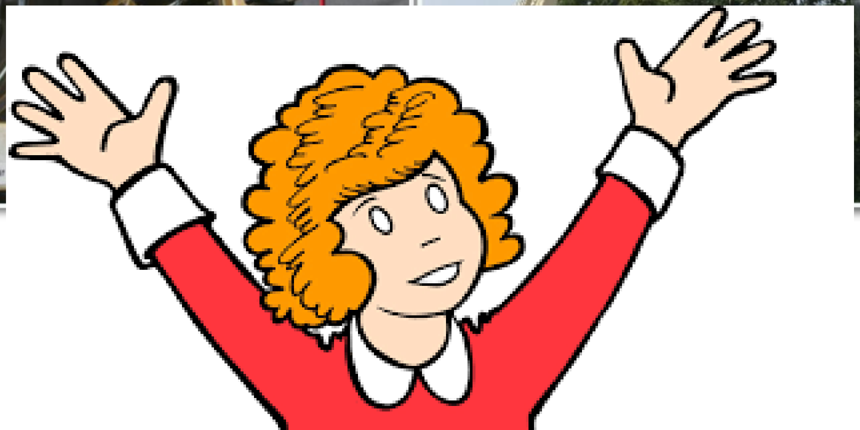
The Accelerator Neutrino Neutron Interaction Experiment

annie



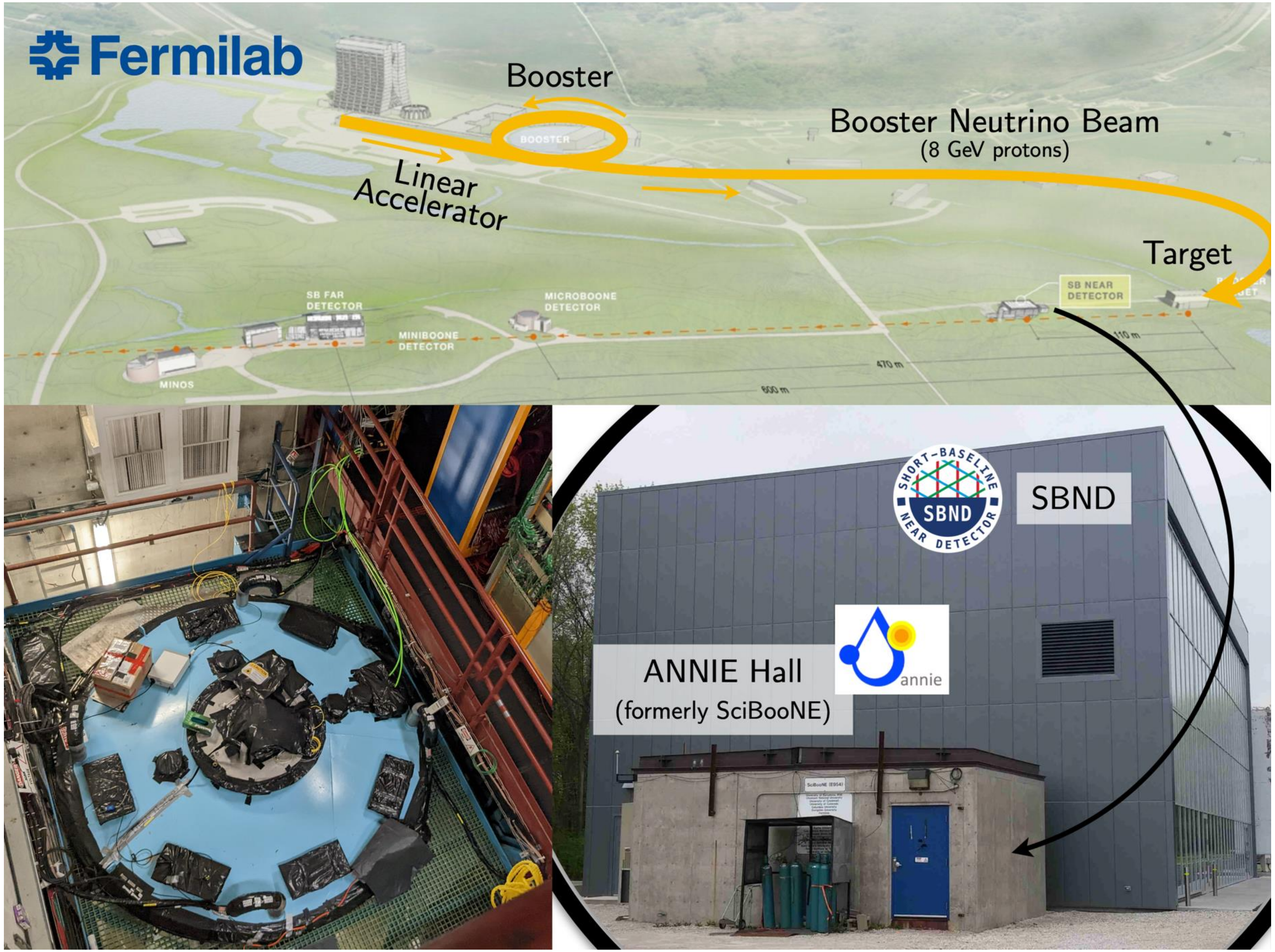


R. Svoboda, IPMU, April 2025

UCDAVIS
UNIVERSITY OF CALIFORNIA

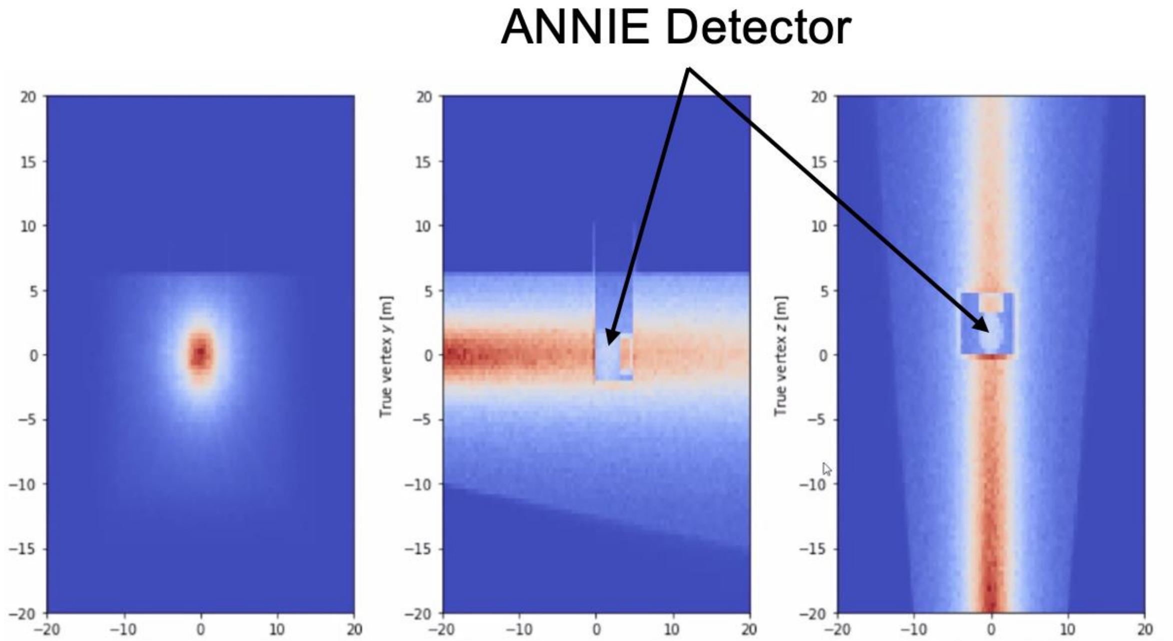
17 Institutions from 6 Countries, ~40 collaborators

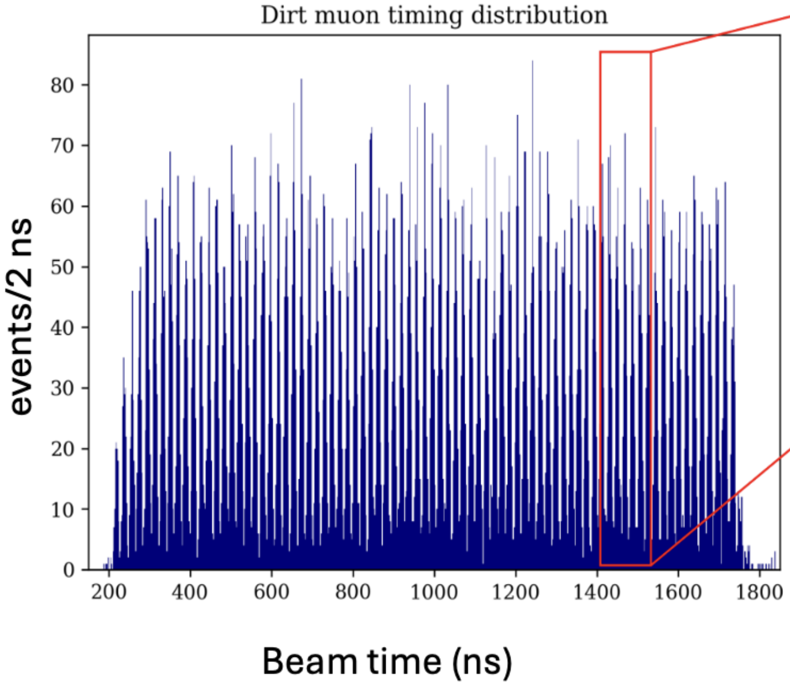
ANNIE is located on the Fermilab Booster Neutrino Beam (BNB) in the same hall formerly occupied by SciBooNE

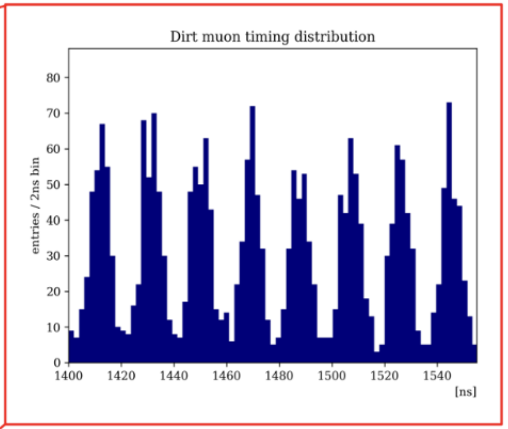


Neutrino Flux

Note: The BNB has a bunch structure that ANNIE will seek to exploit - more on this later







Energy

$E_\nu \sim 800\ MeV$

Composition

$\nu_\mu(92.9\%)$, $\bar{\nu}_\mu(6.6\%)$, $\nu_e + \bar{\nu}_e(0.5\%)$

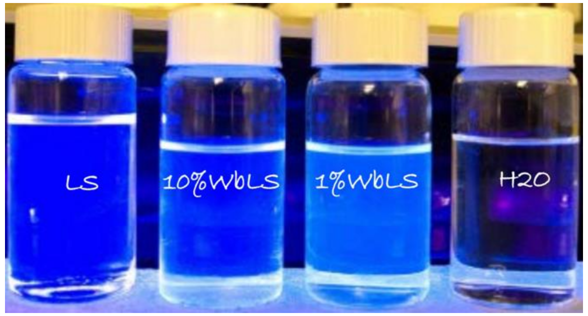
BNB delivers these neutrinos as 81 bunches, across a 1.6μs spill

[1] A. M. Ankowski et al., Phys. Rev. Lett. 108, 052505 (2012)

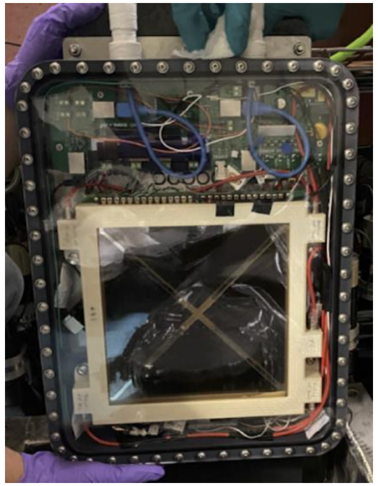
UNIVERSITY

Physics Goals of ANNIE

- **Conduct a broad physics program using ν_μ interactions in water**
- **Demonstrate new technology for a future hybrid optical neutrino detector (e.g. THEIA)**



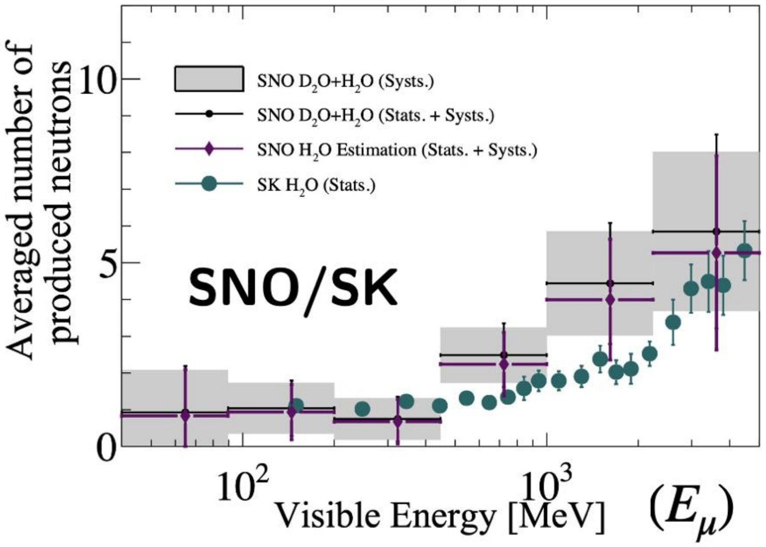
  - Water-based Liquid Scintillator (e.g. SANDI)
  - Fast timing (e.g. Large Area Picosecond Photo Detectors - LAPPDs)

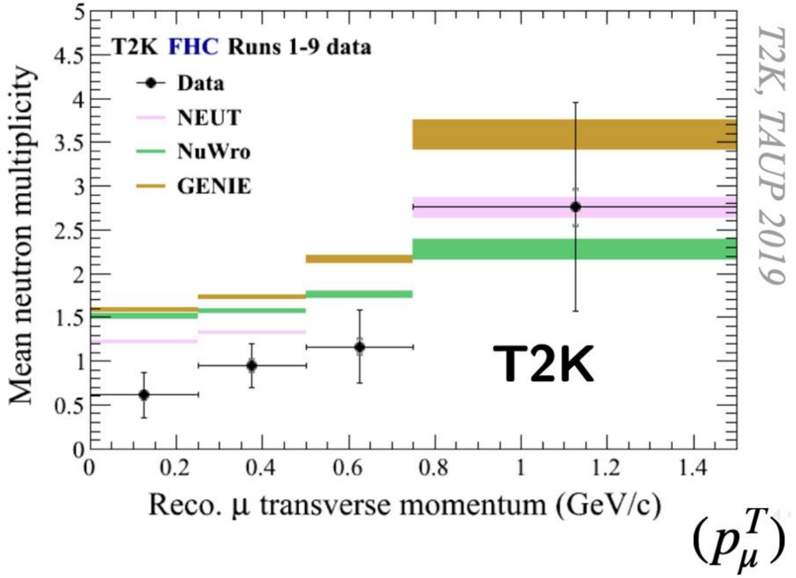


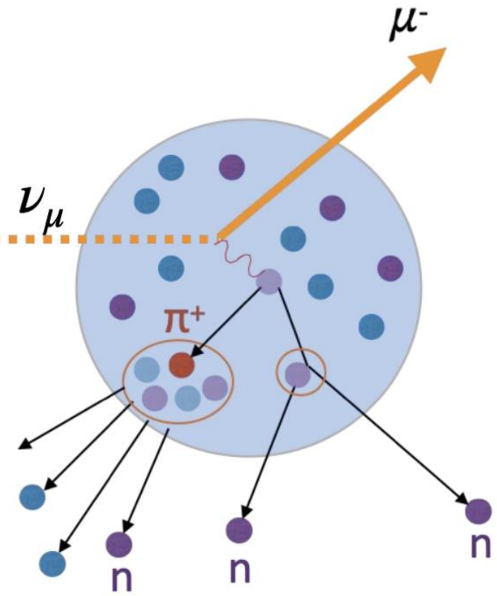
ANNIE Physics Program

- ν_μCC interactions with oxygen, final state neutrons
  - Differential cross sections, *high-statistics* n multiplicity vs. Q^2
  - Improved modeling of FS neutral production, input to generators

SNO, PRD 99 (2019) 11, 112007



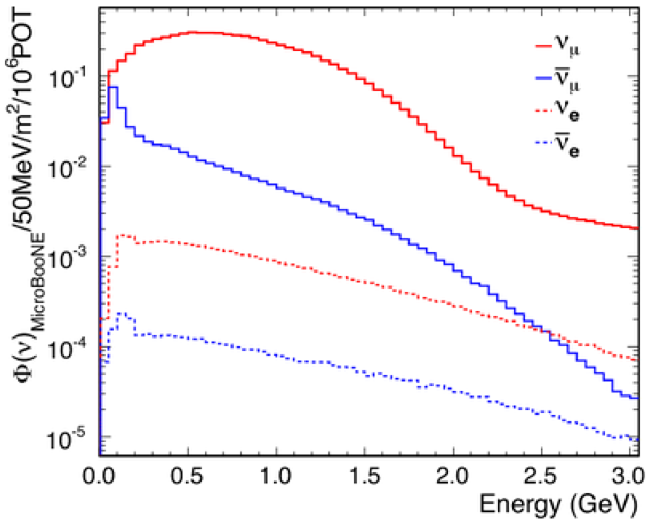




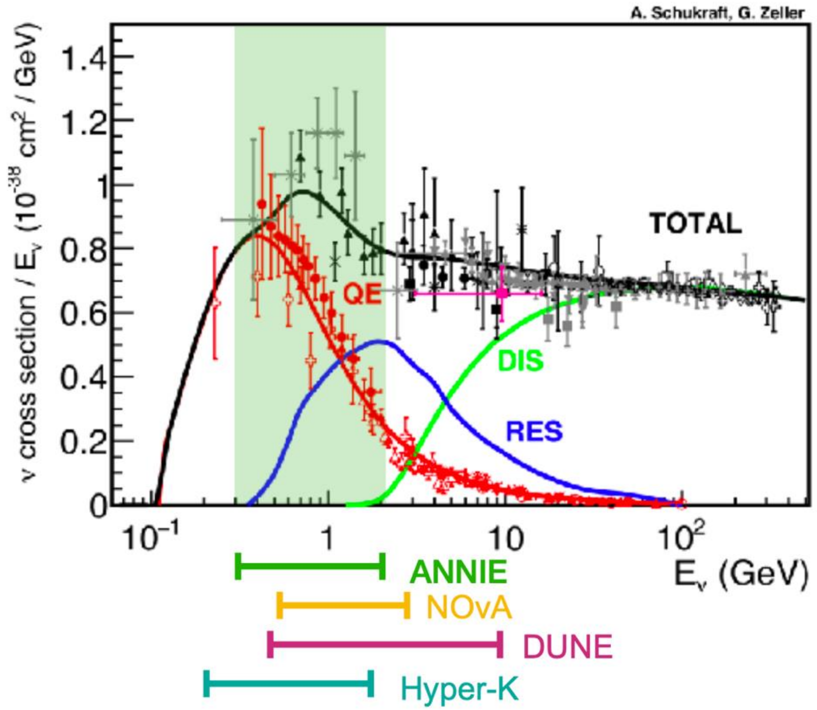
ANNIE Physics Program

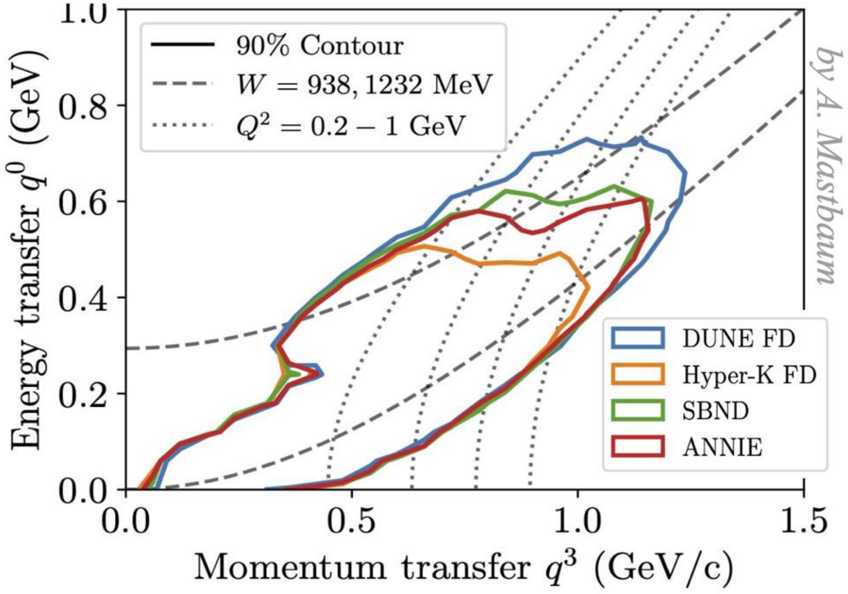
Measurements relevant to the neutrino oscillation program:

- Proximity to BNB target → high flux, overlap with T2K/LBNF
  - Spans the neutrino energy range where DUNE & HK overlap
  - Currently taking data, analyzing existing ~2 year dataset



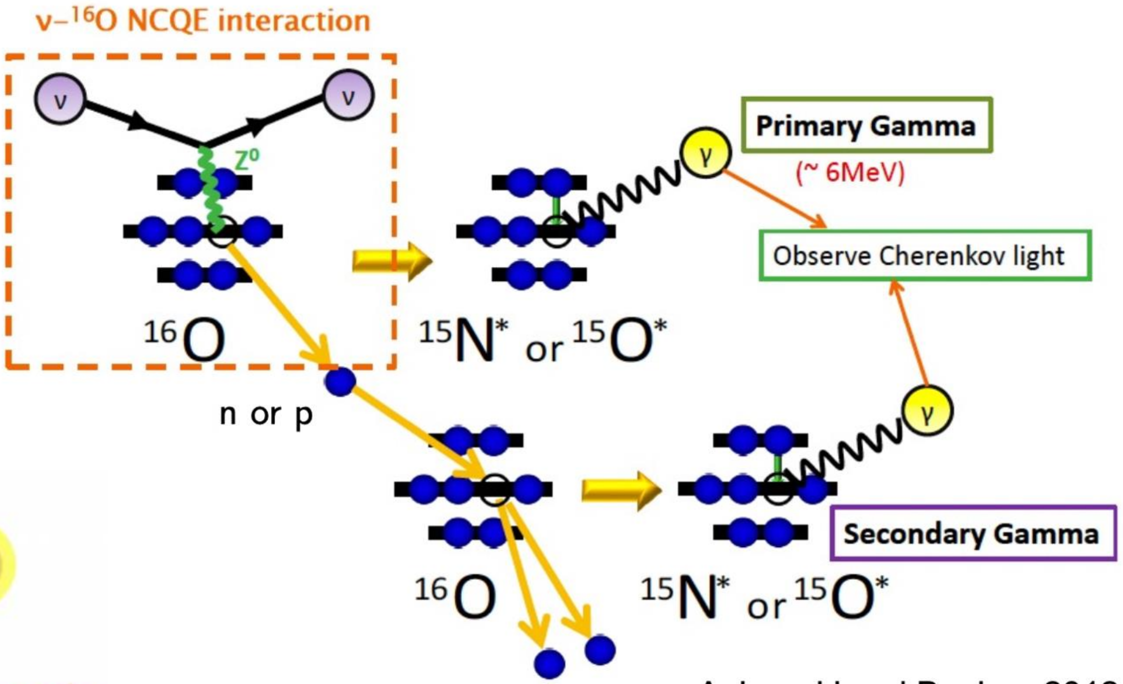
Booster Neutrino Beam energy spectrum





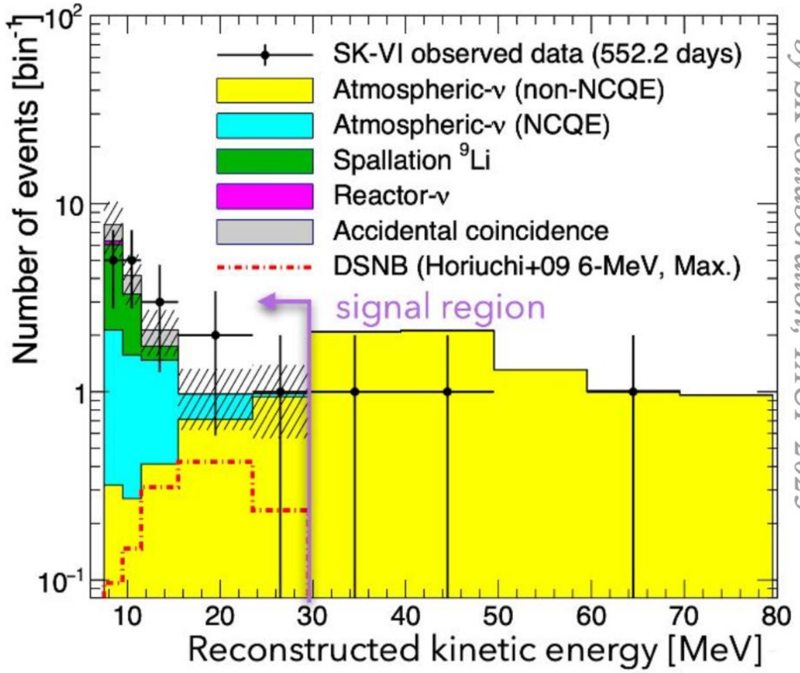
ANNIE Physics Program

- νNC interactions (γ cascade and neutrons)
  - Constrain backgrounds for LBL & p decay, DSNB searches
  - ~10k fiducial NC events/beam year, ~50% of which are NCQE



Ankowski and Benhar, 2012

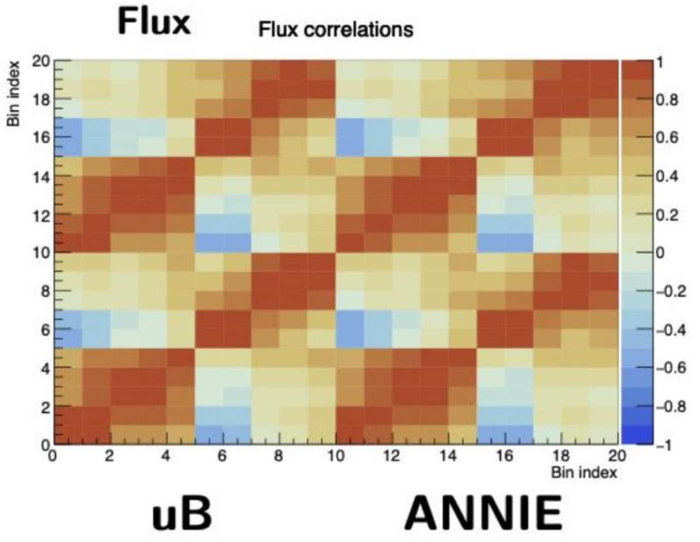
SK DSNB

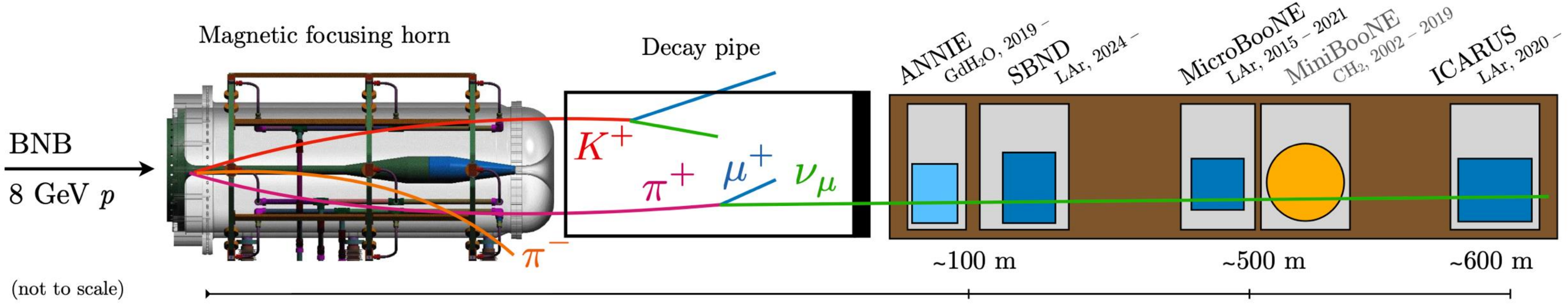


by SK collaboration, TAUP 2023

ANNIE Physics Program

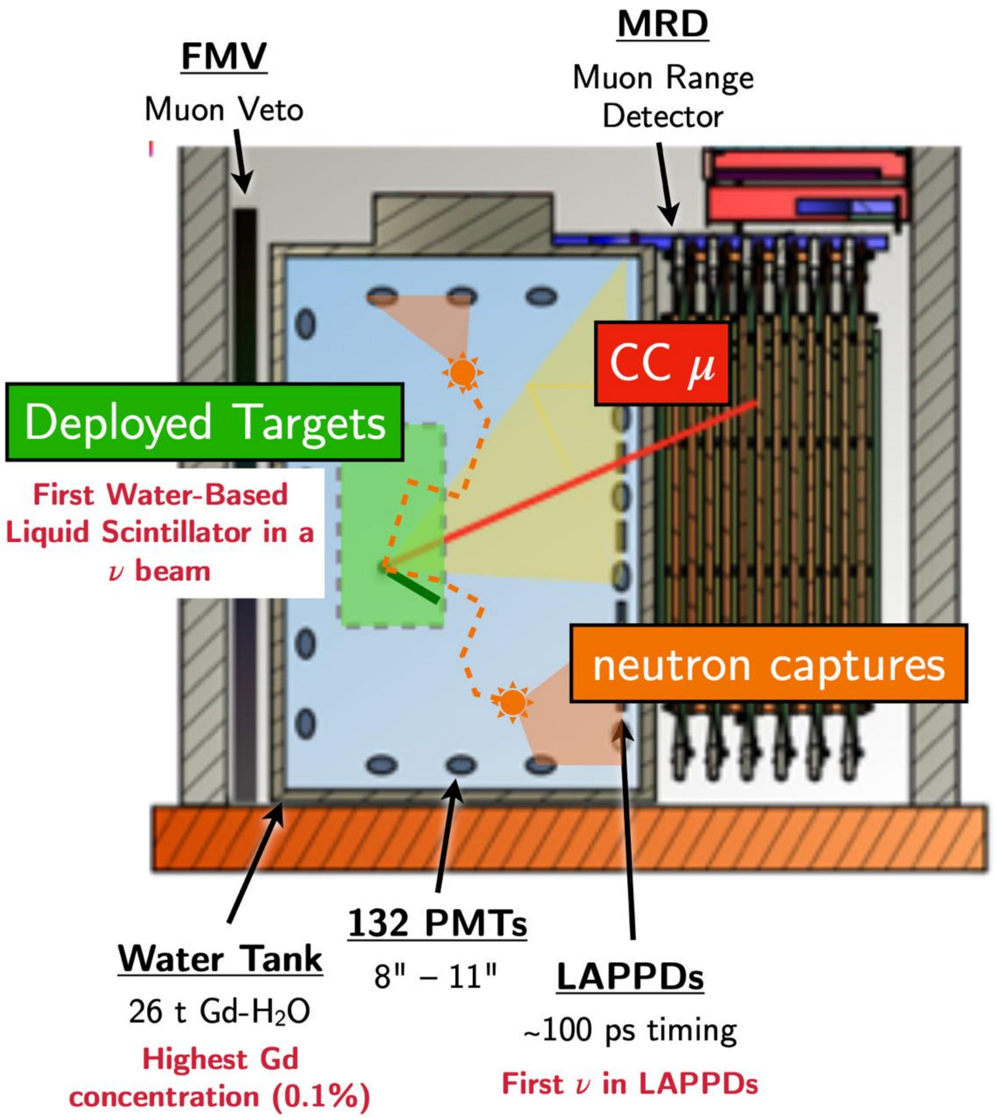
- Same neutrino beam as SBN LArTPCs
  - Precision $^{40}Ar/H_2O$ σ comparisons
  - Probe A scaling, simultaneous tuning
  - Correlations in hadron production (n/p)



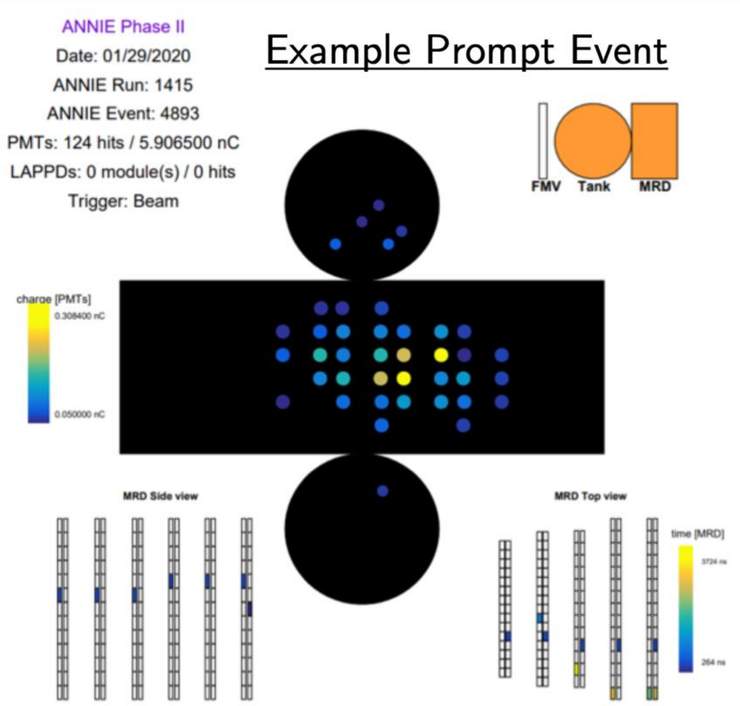


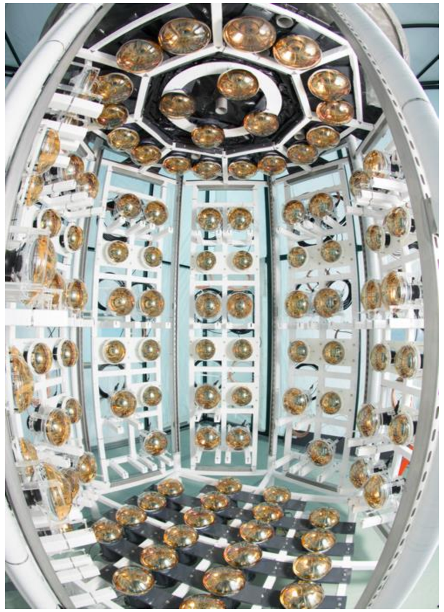
annie

ANNIE Detector



Neutrino
Beam



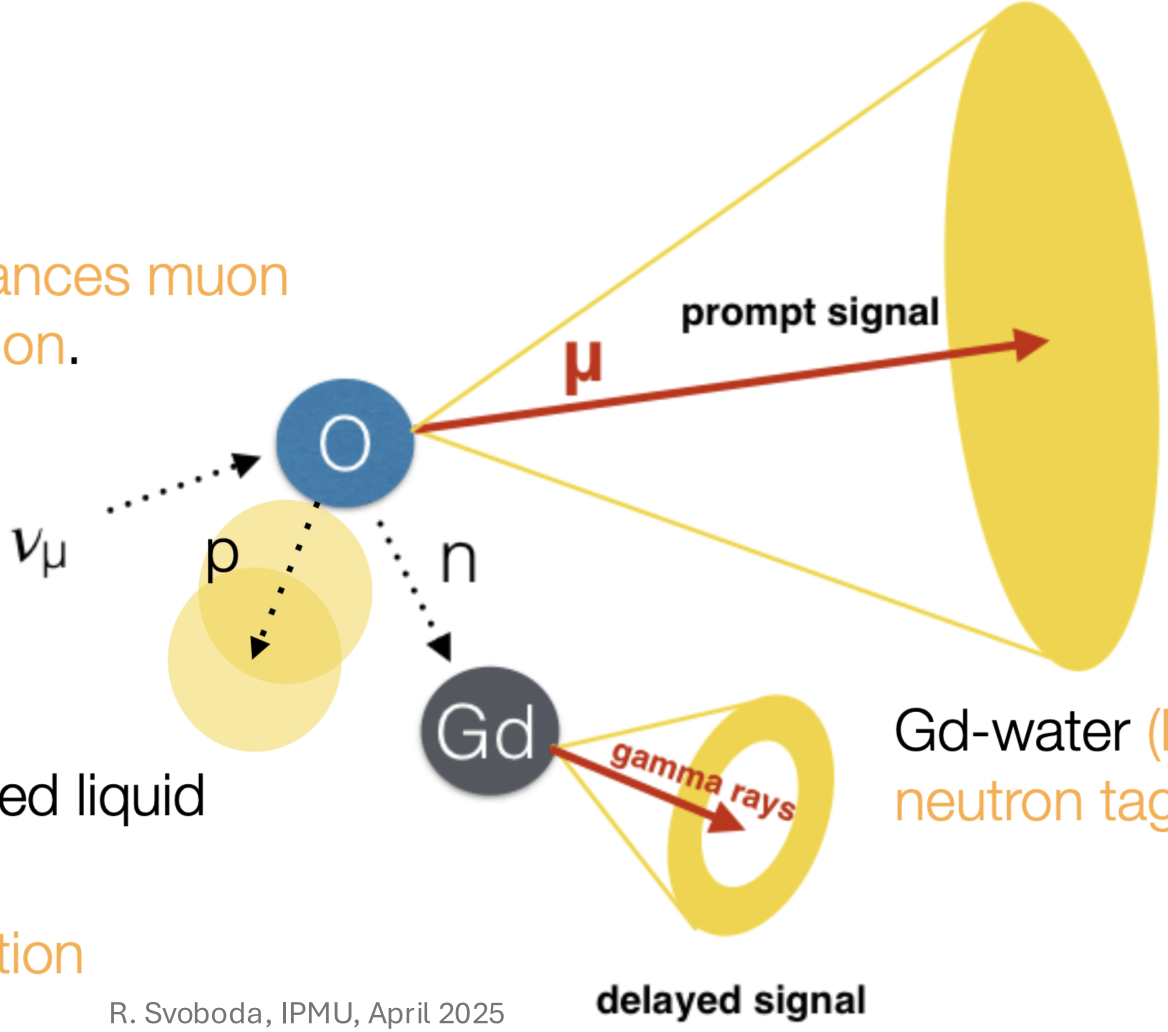


Prompt μ Cherenkov + MRD track
Delayed Gd neutron capture γ
Front veto rejects upstream μ
Deployable target volumes

ANNIE R&D Technologies

ANNIE is a flexible test-bed for next generation detector technologies (novel photosensors/fast-timing and novel detection media)

Adding LAPPDs to PMTs enhances muon reconstruction and fiducialization.



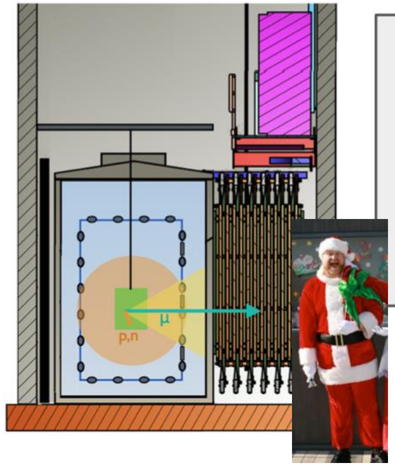
Gd-water (High efficiency neutron tagging)

Deployable volume of water-based liquid scintillator (WbLS)

(Calorimetry, elements of interaction below Cherenkov threshold)

ANNIE in the broader R&D ecosystem

Ton-scale demonstrator projects to show the feasibility and versatility of a future large-scale neutrino detectors using hybrid Cherenkov/scintillation detection.



ANNIE: 26 ton Gd-H_2O (365kg WbLS) Optimized for reconstruction on a neutrino beam, Cher/Scint separation with LAPPDs

EOS: 20 ton WbLS Low-energy reconstruction, model validation, chromatic sorting

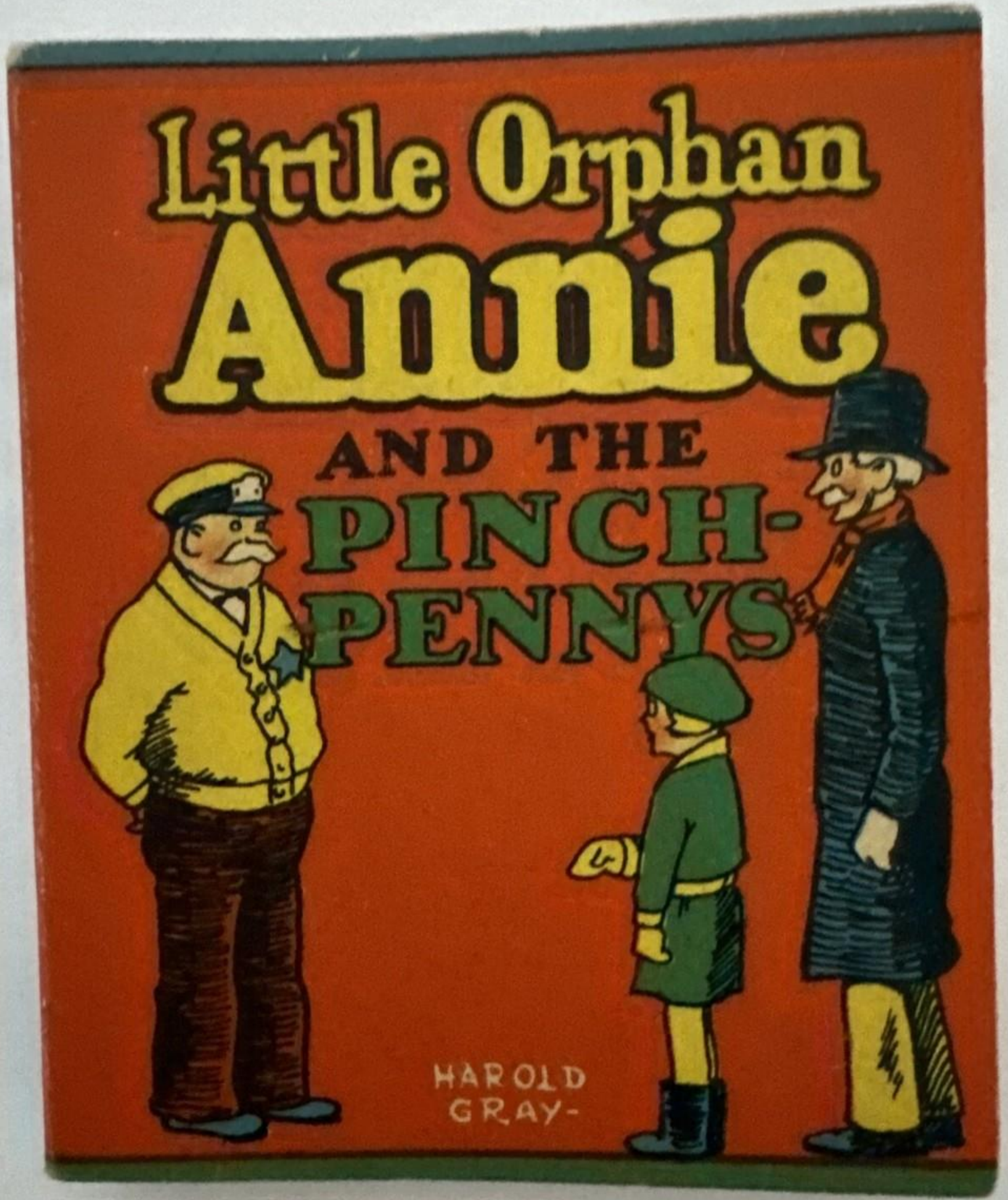
Large-scale detectors for non-proliferation & physics

BNL: 1 ton and 30 ton WbLS deployment, purification, recirculation, transparency

NUDOT: Isotope loading NLBDB topology

BUTTON: 30 ton, WbLS underground deployment, low bkgd verification

ANNIE is complementary and synergistic with these projects



The ANNIE Gd Water System

In order to load ANNIE with WbLS
it will be necessary to have a system
than can continuously clean the water

...but ANNIE has very little money!

What to do?

Why does the water need to be cleaned?

Quantitative tests using a 19 meter attenuation arm at LLNL showed that even clean stainless steel exposed to ultrapure water will leech impurities into the water that absorb UV light.

It was also shown that this could be due to iron ions going into solution <u>even at ppb levels.</u>

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Transparency of 0.2% $GdCl_3$ doped water in a stainless steel test environment

W. Coleman [a,*], A. Bernstein [b], S. Dazeley [b], R. Svoboda [b,c]

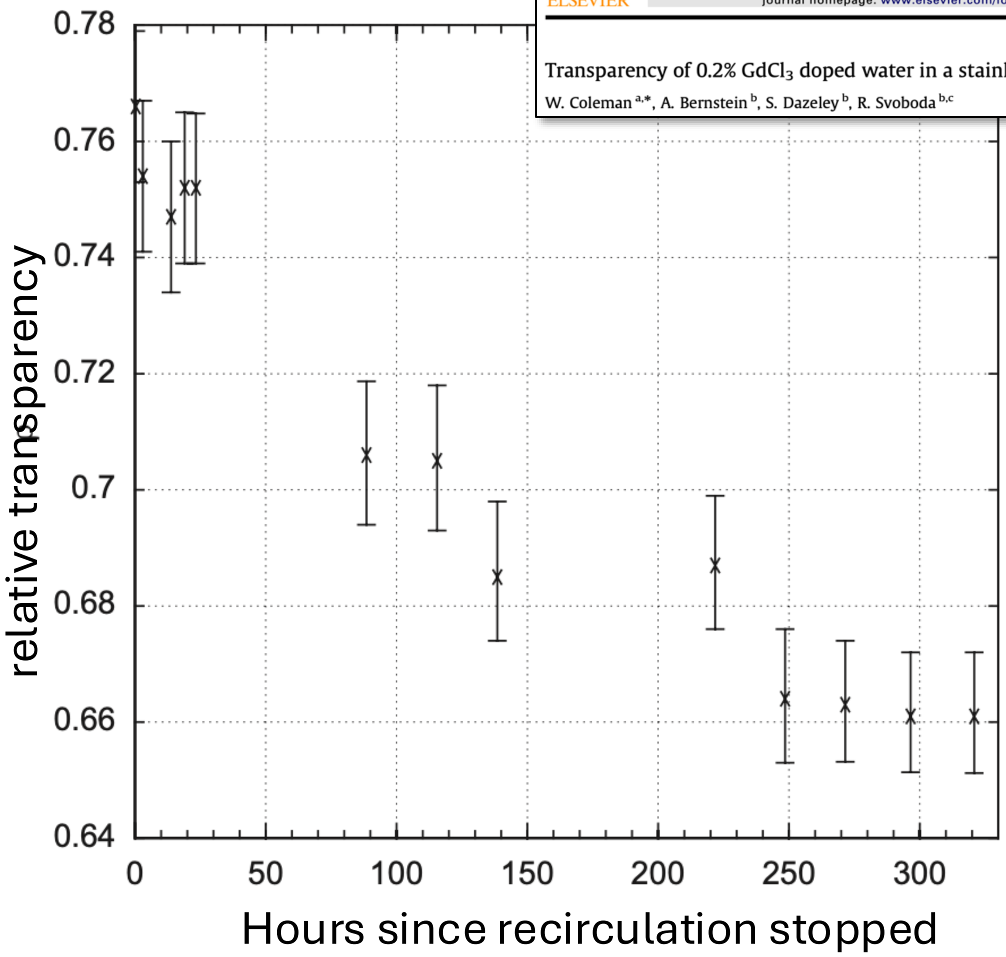


Fig. 5. ρ of pure water measured over approximately 14 days at 337 nm. Recirculation of the water through the system was turned off at $t = 0$. From this point, the water remained undisturbed in the LTA and ρ decreased at the rate of ~1% per day.

Table 3
The change in ρ resulting from the addition of $FeCl_3$ to pure water

Pure water value	14 ppb $FeCl_3$ in water	28 ppb $FeCl_3$ in water
0.901 ± 0.018	0.355 ± 0.018	0.156 ± 0.008

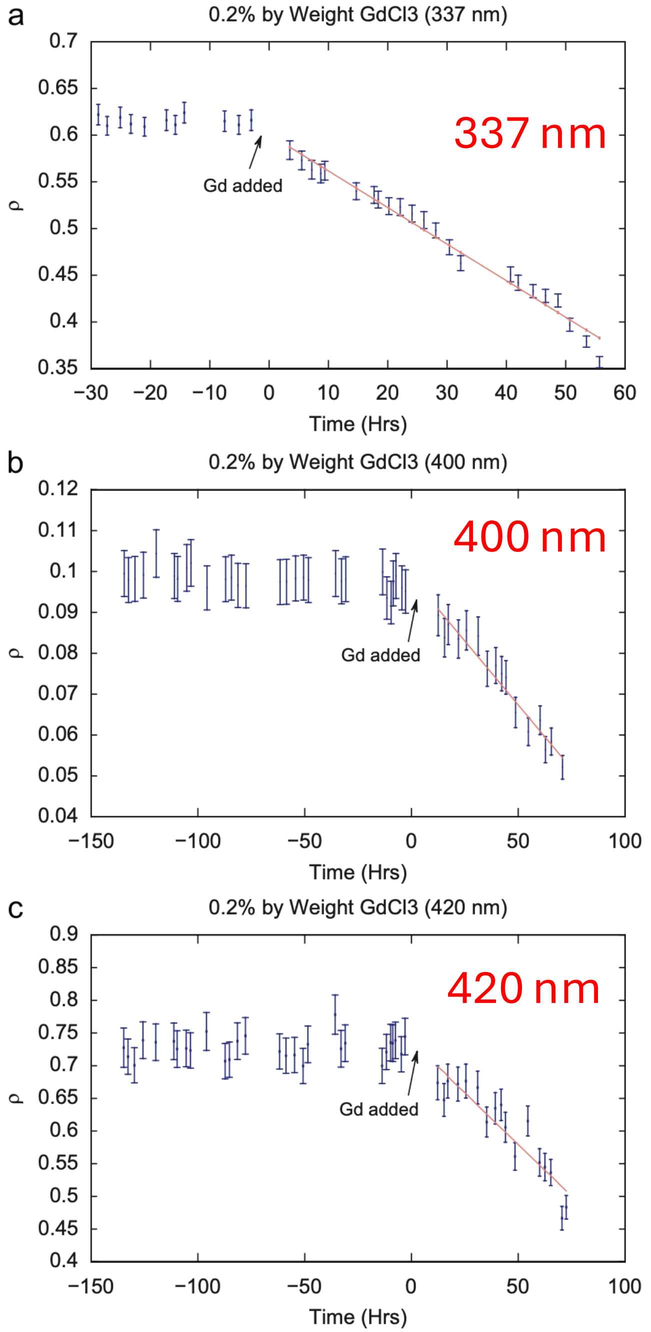
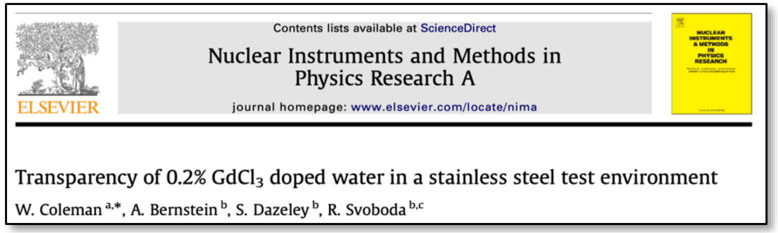


Fig. 7. Decrease in transparency versus time resulting from addition of 0.2% $GdCl_3$ in pure water for 337 nm (a), 400 nm (b) and 420 nm (c). The red line shows the least squares best fit to the data after addition of the $GdCl_3$.



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Transparency of 0.2% $GdCl_3$ doped water in a stainless steel test environment

W. Coleman [a,*], A. Bernstein [b], S. Dazeley [b], R. Svoboda [b,c]

LLNL tests showed that the loss of transparency is broad spectrum, not just Gd absorption lines

These same tests showed that for Gd the ion itself did not cause a loss of transparency - it was just that fact that the liquid can now conduct charge that accelerated the leeching of steel contaminants

ANNIE needs a cheap Gd water system!

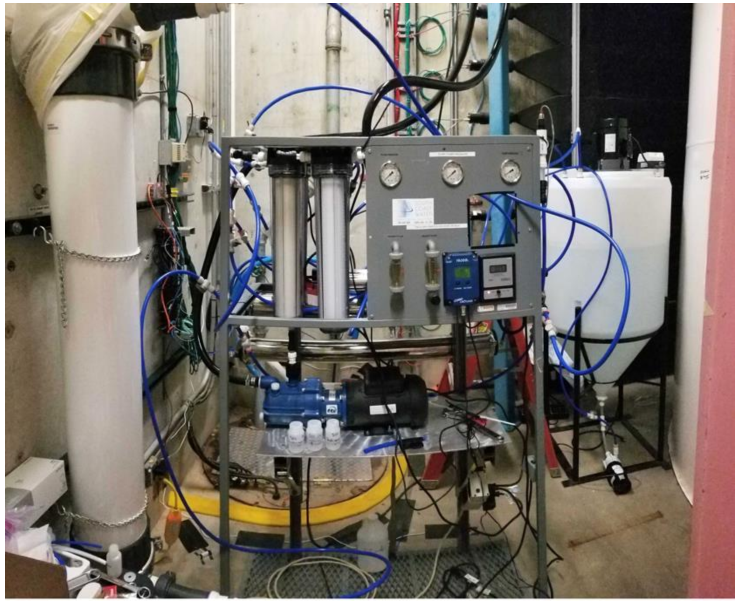
ANNIE Gd Water System

Development of an ion exchange resin for gadolinium-loaded water

V. Fischer, [a] **J. He,**[a] **M. Irving,**[a] **R. Svoboda**[a]

[a]*Department of Physics, University of California, Davis, CA 95616, USA*

Abstract: Large water Cherenkov detectors have bee
low-energy particle physics. Nevertheless, detecting neu
since a neutron capture on a hydrogen atom doesn't release a sufficient amount of gamma energy to be observed efficiently. The use of gadolinium in the form of soluble salts has been explored extensively to remedy this issue, as gadolinium exhibits both a very large neutron capture cross section and a subsequent high-energy gamma cascade. However, in order for large gadolinium-loaded detectors to operate stably over long time periods, water optical transparency must be maintained by *in situ* purification. New methods have been developed involving band-pass molecular filtering. While these methods are very successful, they are expensive and consume considerable power and space as they seek to minimize loss of gadolinium while removing other impurities. For smaller detectors where some gadolinium loss can be tolerated, a less expensive way to do this is very desirable. In this paper, we describe the design, development and testing of a system used to purify the gadolinium-loaded water in the 26-ton ANNIE neutrino detector.



ABSTI … detectors have beer
low-e … neless, detecting neu
since … atom doesn't release a sufficient amount of gamma energy to be
obser … linium in the form of soluble salts has been explored extensively
to ren … exhibits both a very large neutron capture cross section and a
subse … cade. Ho
to ope … iods, wat
purifi … en devel
these … hey are e
as the … olinium v
where … e tolerate
In thi … gn, deve
gadol … on ANNI

Development of an ion exchange resin for gadolinium-loaded water

V. Fischer,[a] J. He,[a] M. Irving,[a] R. Svoboda[a]

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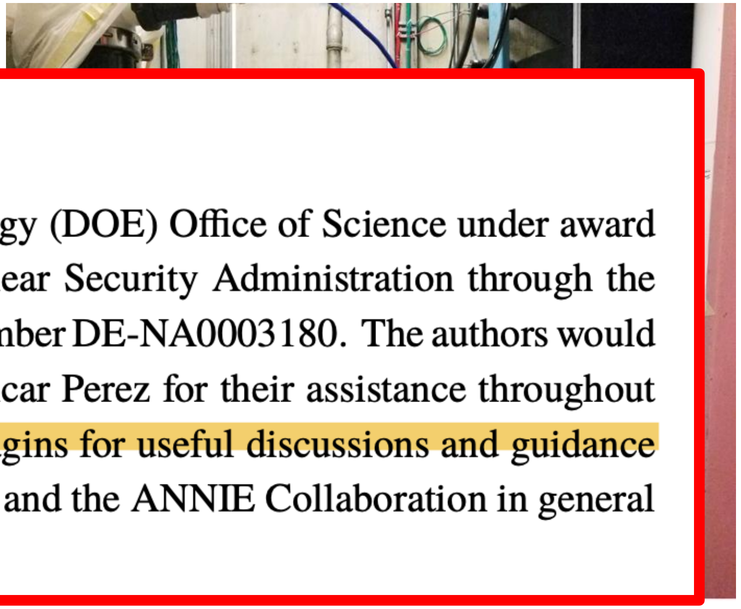


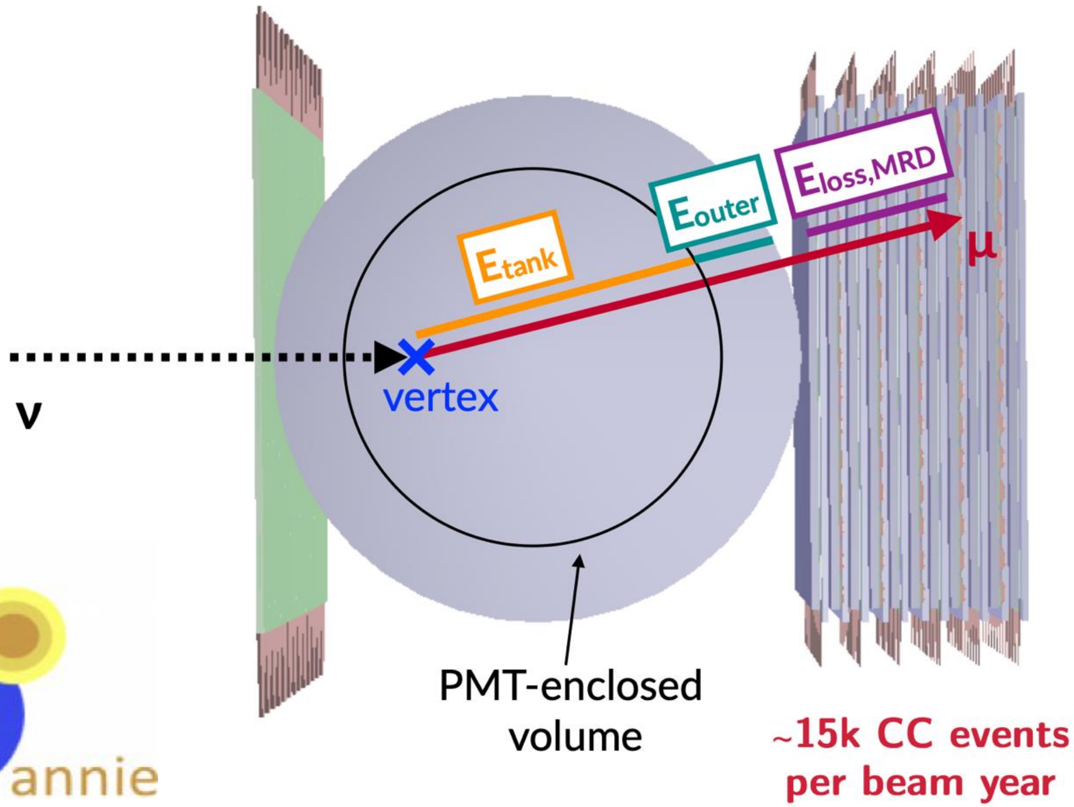
Acknowledgments

This work was supported by the U.S. Department of Energy (DOE) Office of Science under award number DE-SC0009999, and by the DOE National Nuclear Security Administration through the Nuclear Science and Security Consortium under award number DE-NA0003180. The authors would like to thank UC Davis students Lena Korkeila and Amilcar Perez for their assistance throughout the tests. The authors particularly wish to thank Mark Vagins for useful discussions and guidance regarding gadolinium sulfate and water filtration systems, and the ANNIE Collaboration in general for motivating this work.

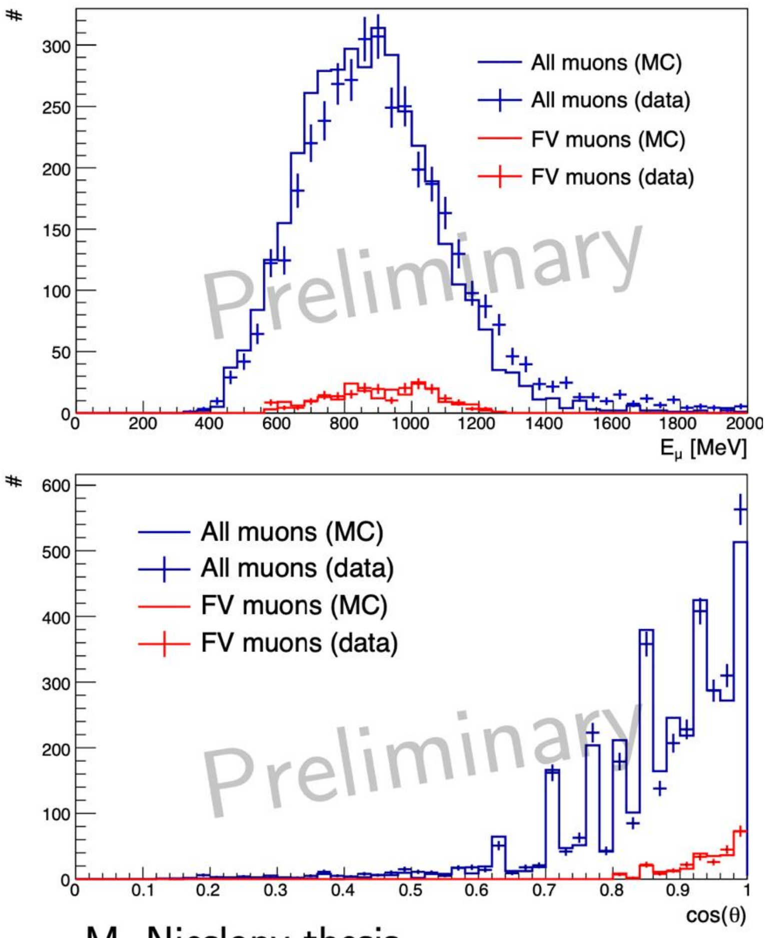
Interactions

Prompt Scattering Events

Prompt: Final state muon energy and angle reconstruction using tank PMTs + MRD tracking



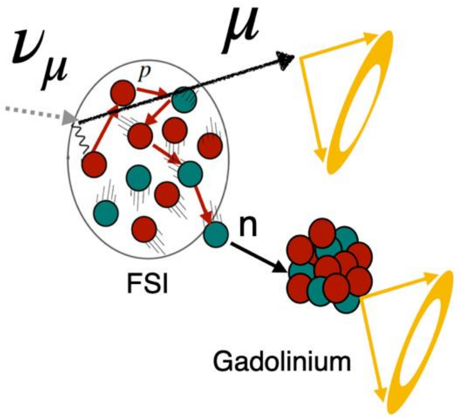
- MRD requirement restricts μ momentum and angle coverage
- $0.4 \lesssim E_\mu \lesssim 1.2$ GeV, $\theta_\mu \gtrsim 60^\circ$
- Tank-only ring reconstruction (under development) enables wide coverage for CC kinematics



M. Nieslony thesis

Good agreement between MC and data in muon energy and angles

Interactions
Delayed Neutron Events

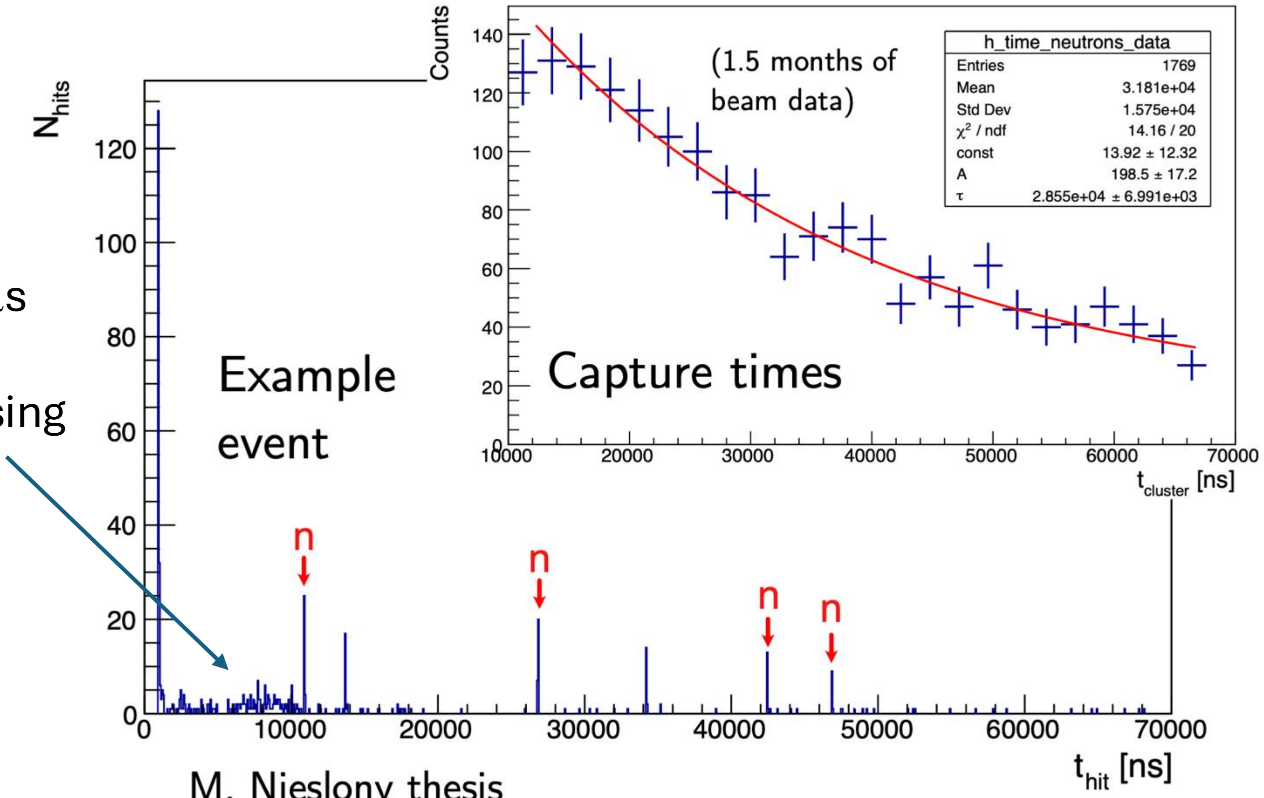


	H	Gd
σ	0.33 bn	49000 bn
τ	300 µs	30 µs
E_γ	2.2 MeV	8 MeV

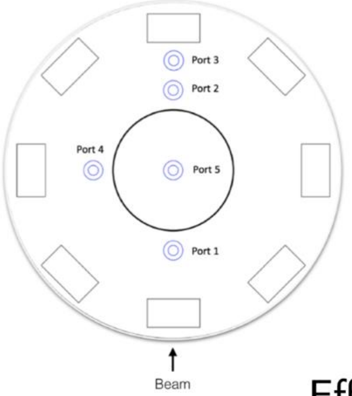
Delayed: 8 MeV γ signal from neutron captures on gadolinium

AmBe source calibrations

need to wait 10 µs due to afterpulsing of PMTs

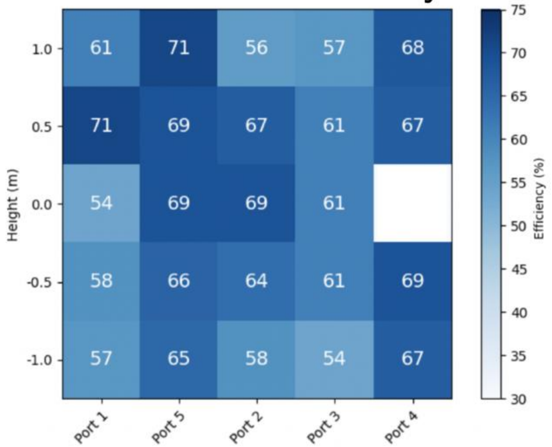


M. Nieslony thesis

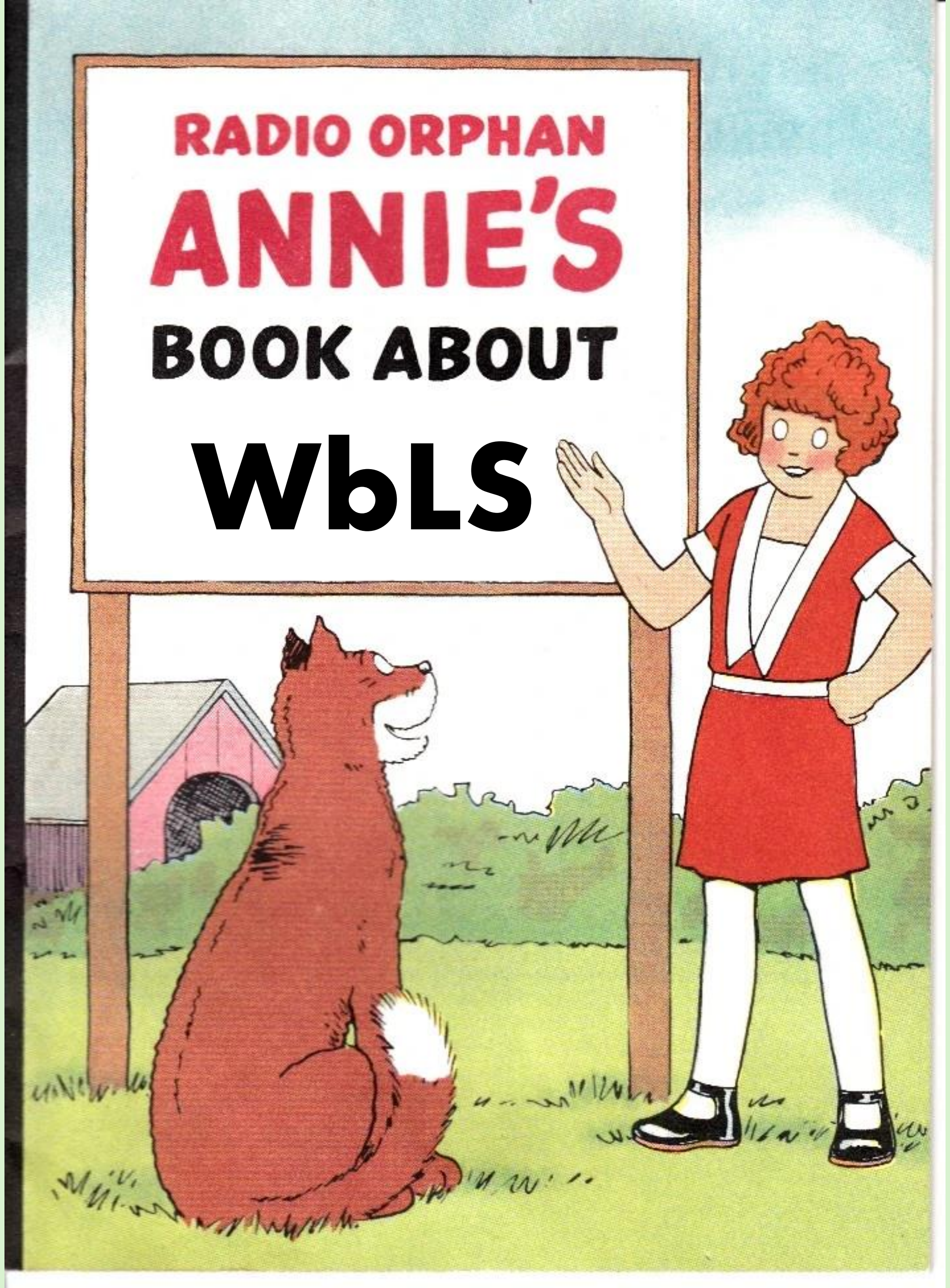


triggered AmBe souce

Efficiency

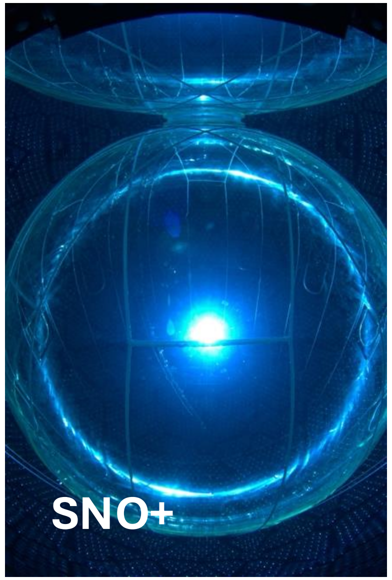


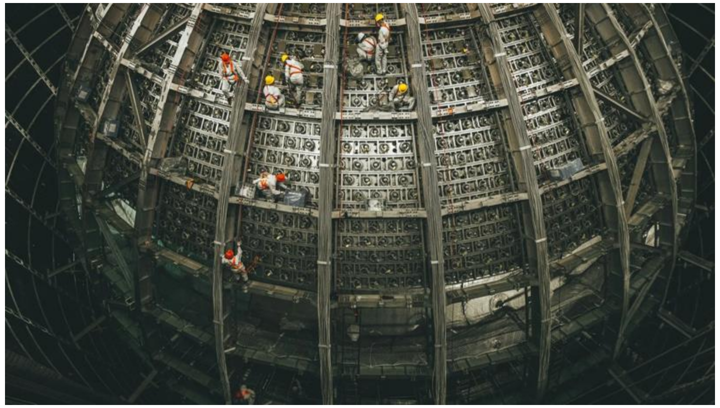
port versus depth map of efficiency



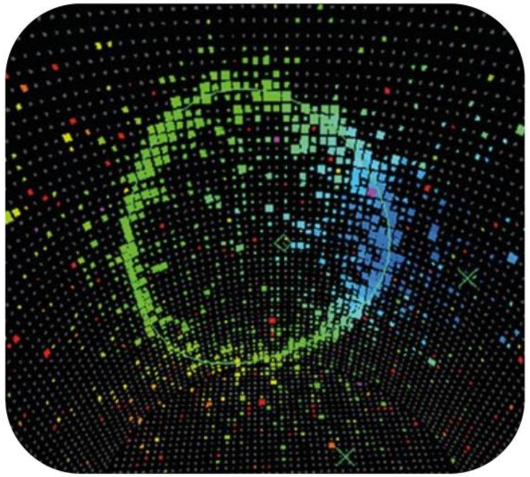
ANNIE and Water-based Liquid Scintillator

- Water Cherenkov detectors are great for detecting leptons but no signal for low energy hadrons
- Cherenkov directionality and ring counting allows for powerful discrimination of event topologies
- Scintillation has no energy threshold => detection of sub-Cherenkov particles
- Hybrid event detection: Combine Cherenkov and scintillation signals

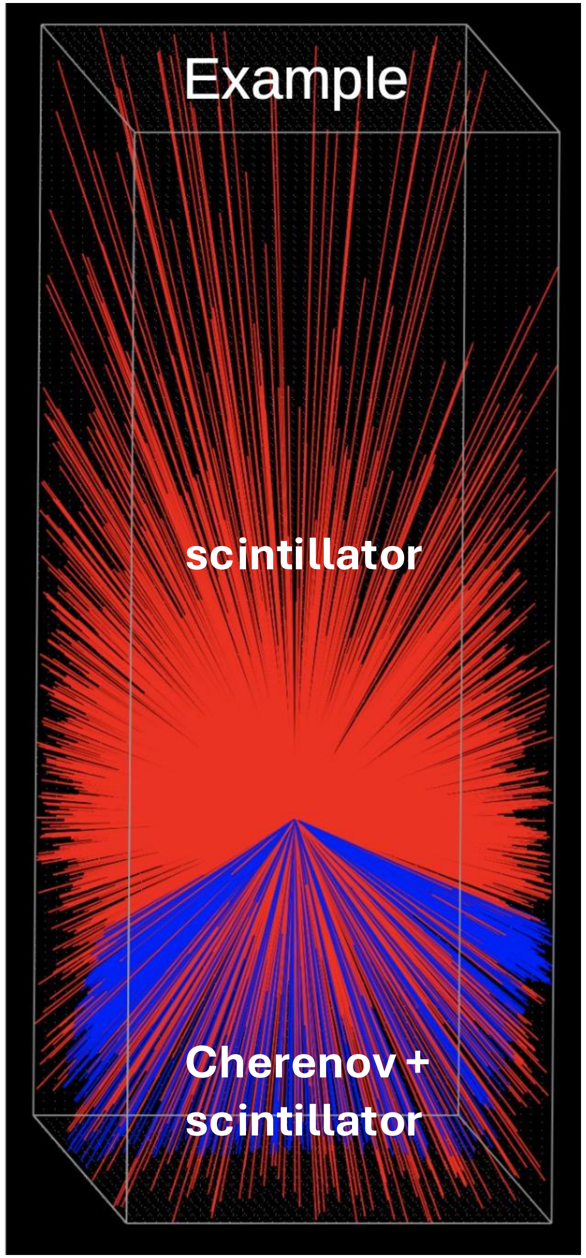




JUNO



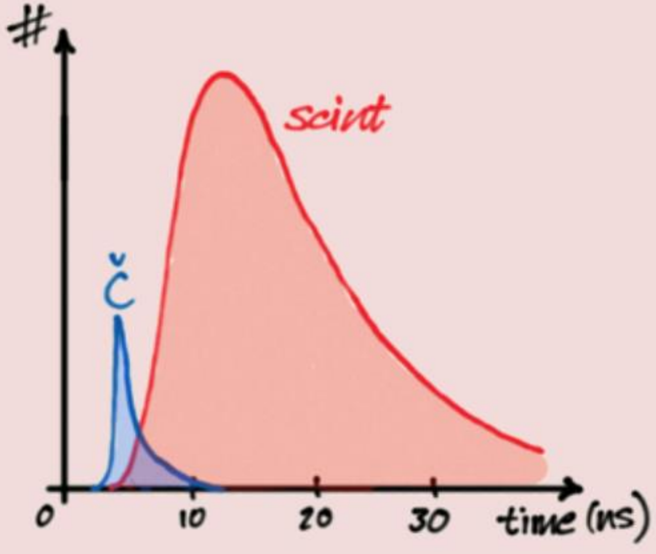
Super-Kamiokande



Practical Cherenkov/Scintillation Light Separation

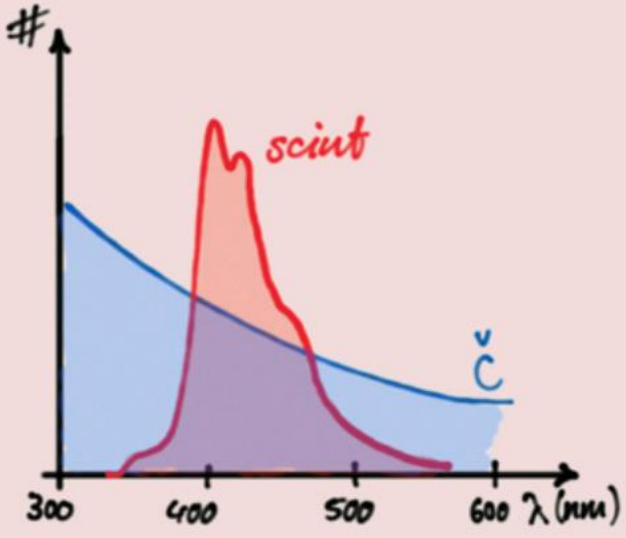
Timing

"instantaneous chertons" vs. delayed "scintons"
→ ns resolution or better



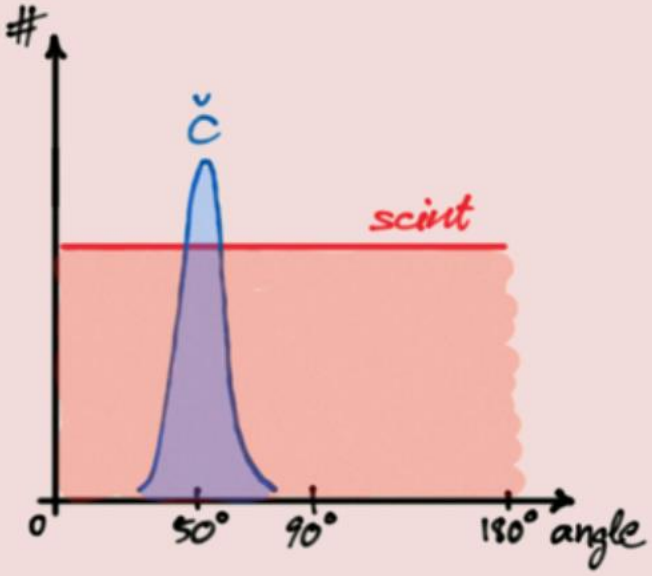
Spectrum

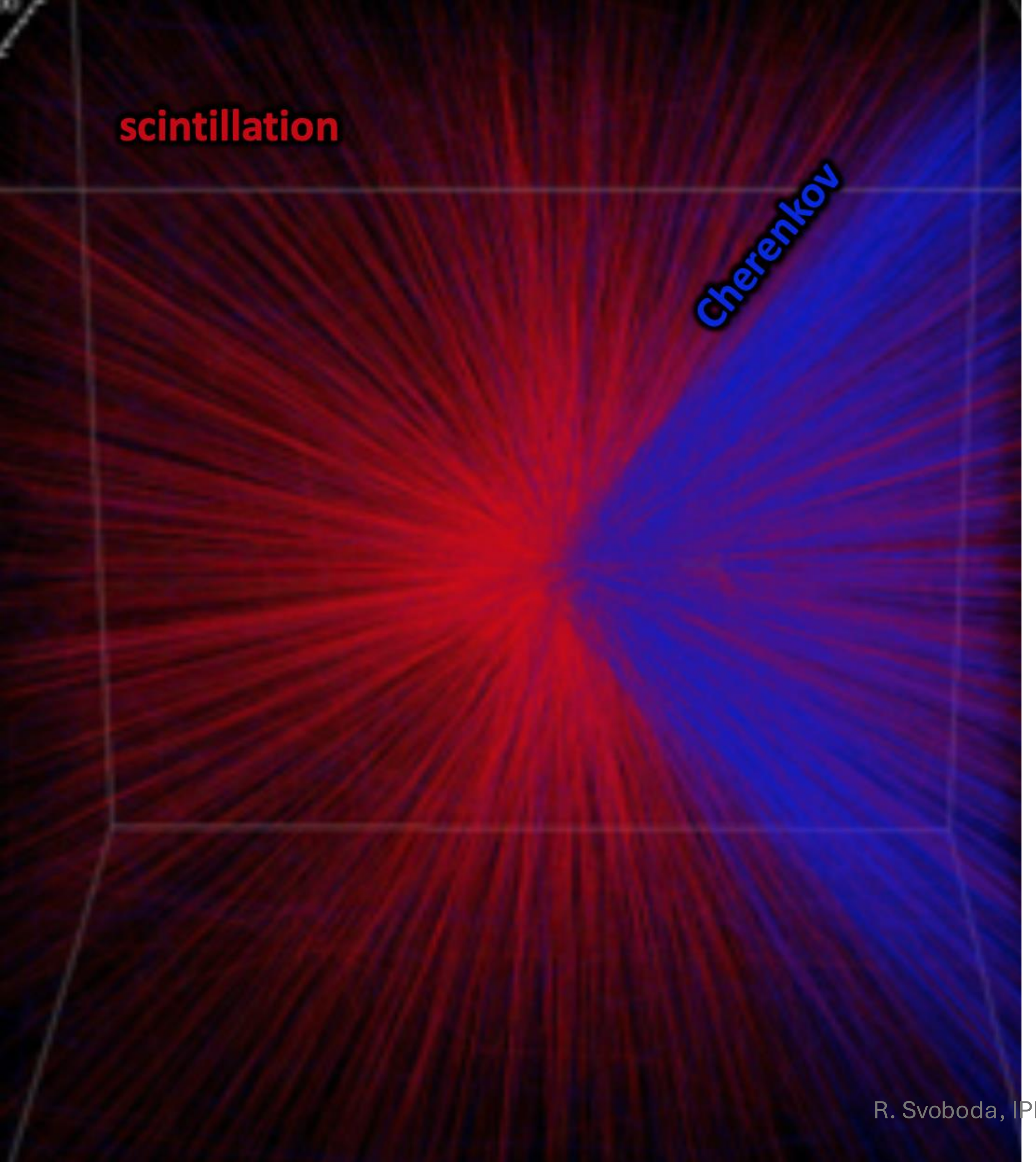
UV/blue scintillation vs. blue/green Cherenkov
→ wavelength-sensitivity

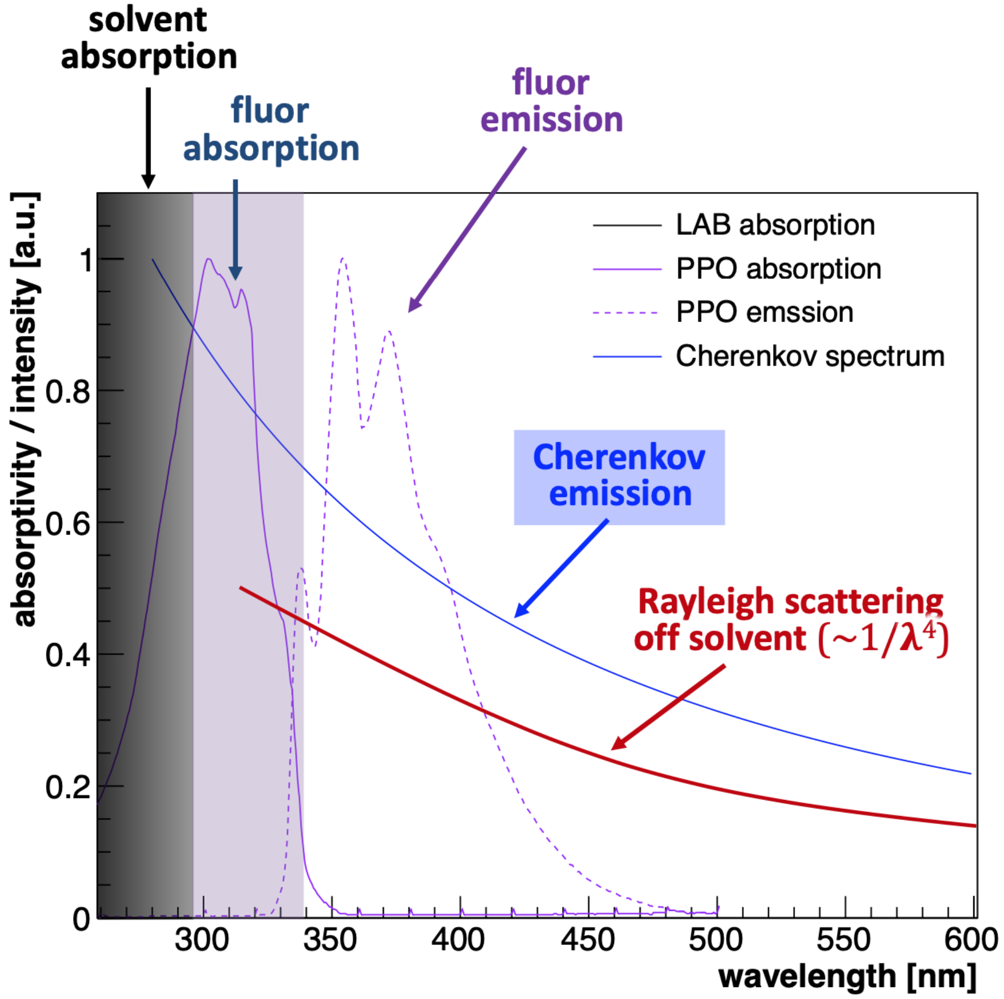


Angular distribution

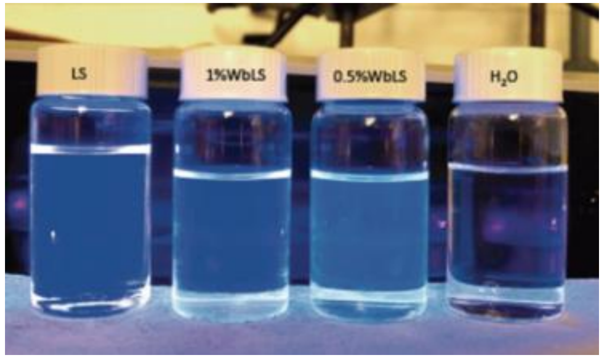
increased PMT hit density under Cherenkov angle
→ sufficient granularity

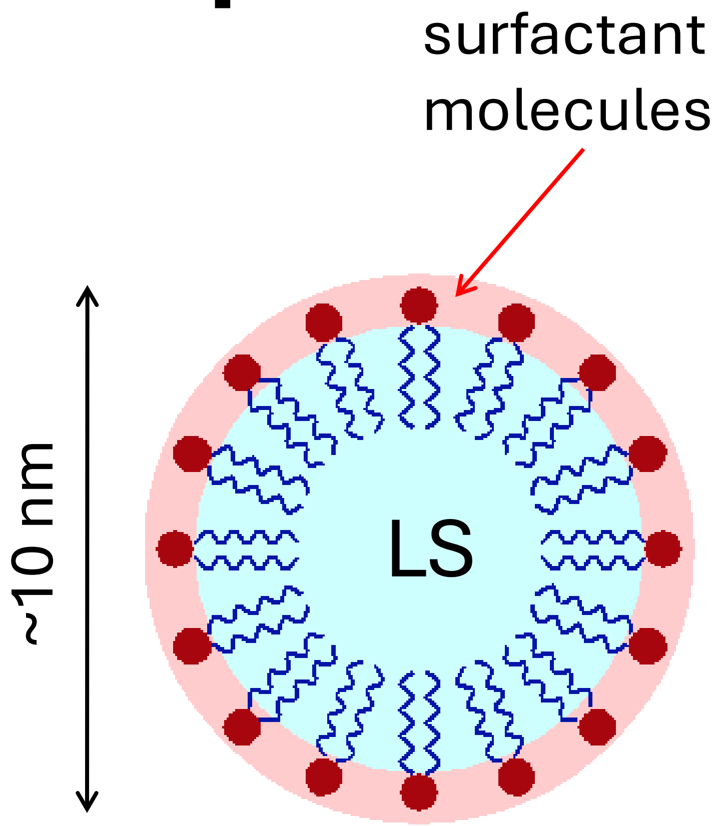



scintillation
Cherenkov


solvent absorption
fluor absorption
fluor emission
LAB absorption
PPO absorption
PPO emssion
Cherenkov spectrum
Cherenkov emission
Rayleigh scattering off solvent (~1/λ⁴)
absorptivity / intensity [a.u.]
wavelength [nm]
0
0.2
0.4
0.6
0.8
1
300
350
400
450
500
550
600

ANNIE and Water-based Liquid Scintillator (WbLS)





Liquid scintillator forms small (~10 nm scale) droplets called *micelles* in water that are stabilized by surfactant molecules with a hydrophilic head and hydrophobic tail. Micelles form under controlled chemical conditions and are shown to be stable over year time scales.

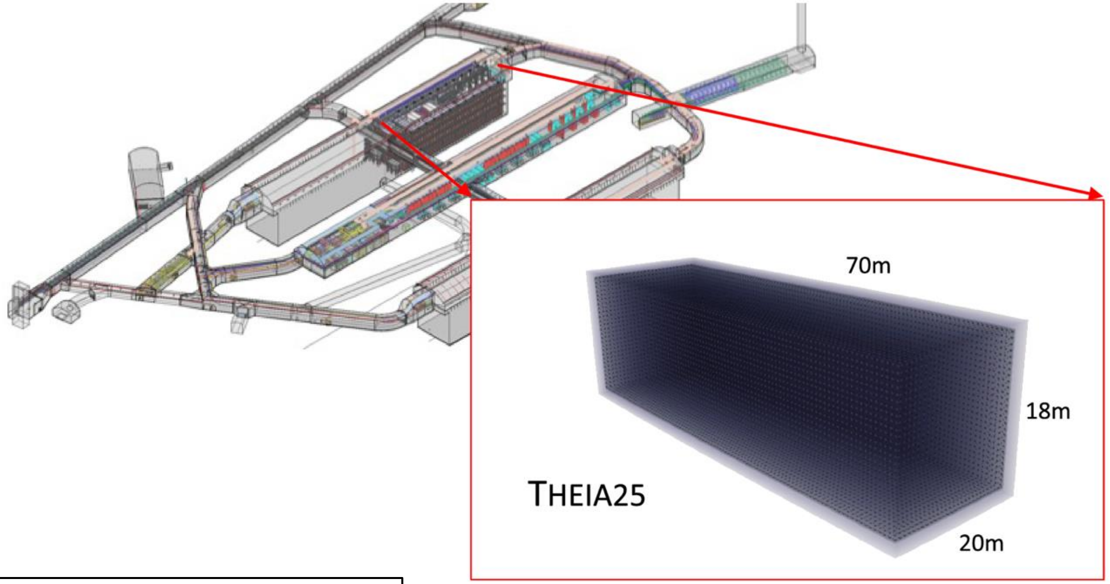
Advantages:

- Cheaper than LS
- Non-combustible
- Ease of loading
- Environmentally better
- Oxygen nuclei

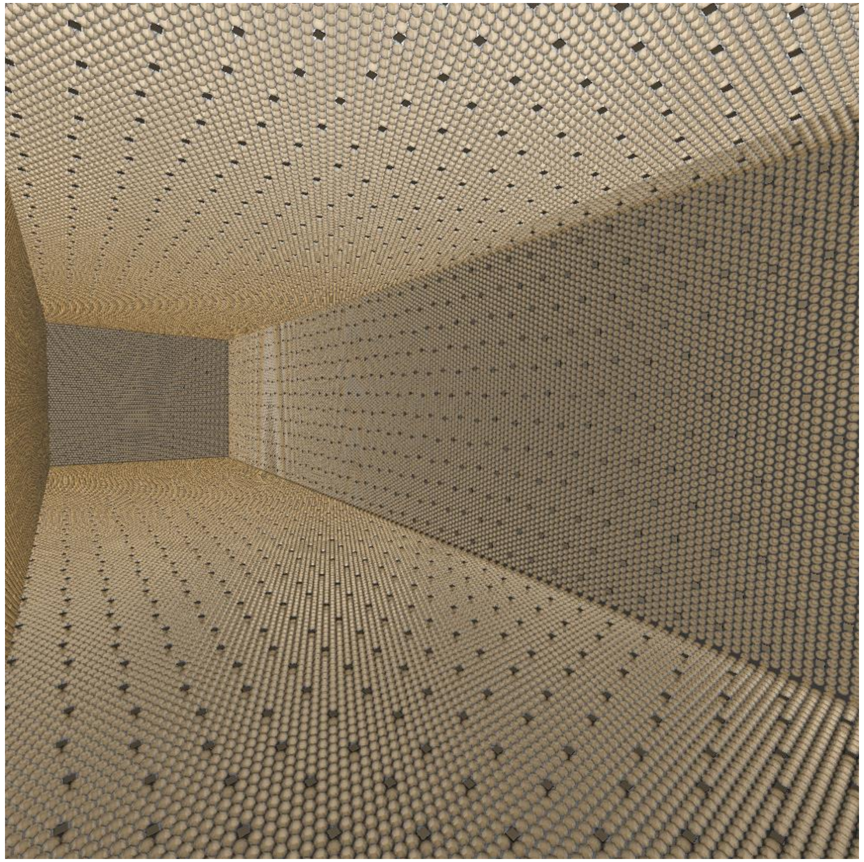
Disadvantages

- Radiological cleanliness?
- Faster than LS?
- Lower light yield

Theia-25 detector at SURF as part of DUNE



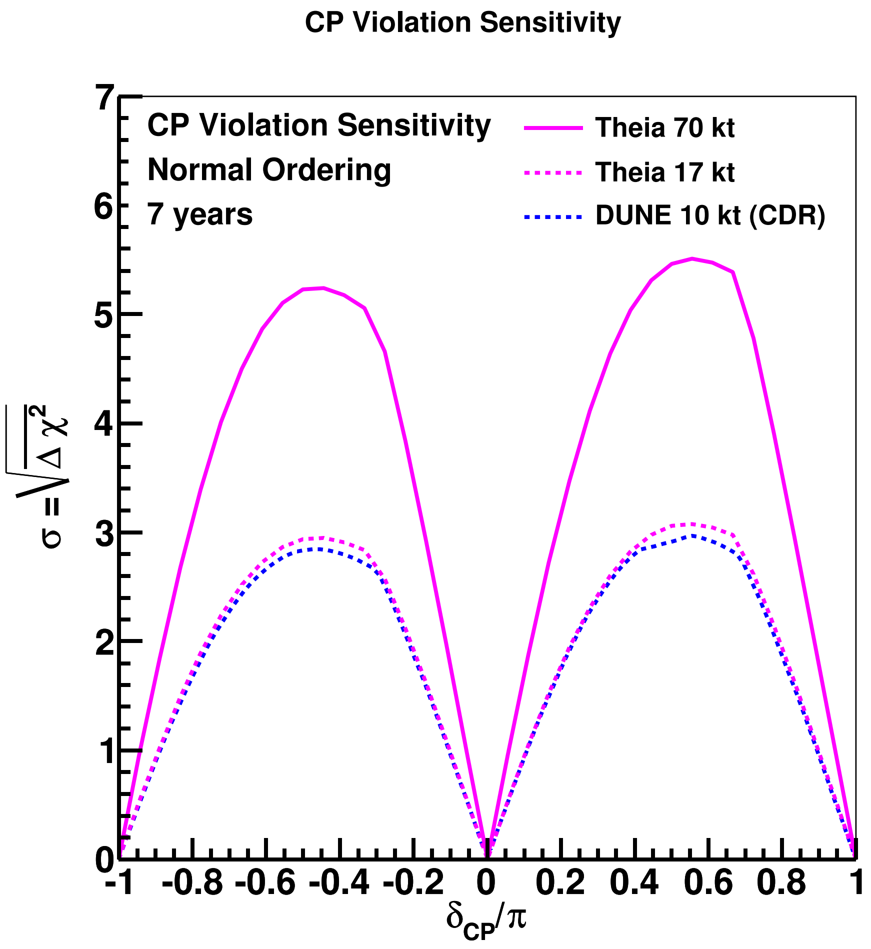
Askins, *et al.* EPJC **80** 416 (2020)

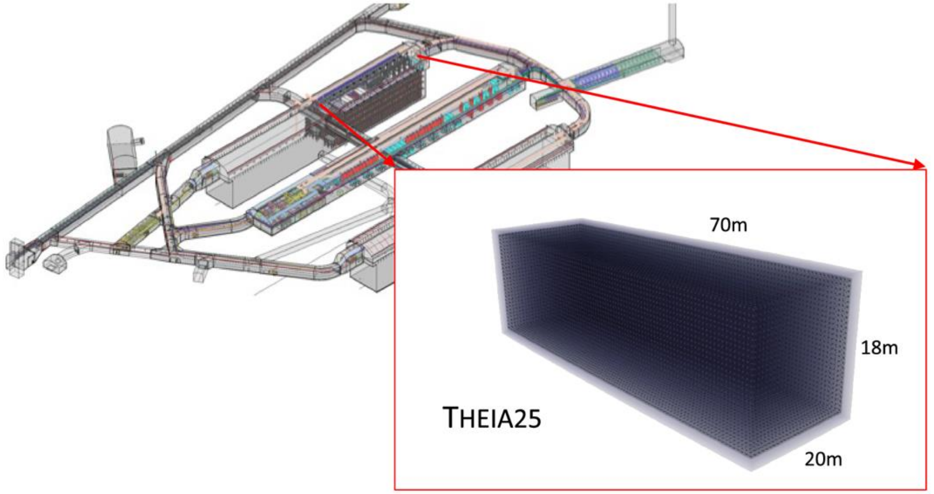


THEIA-25 is proposed as the 4th DUNE module at the Sanford Underground Research Facility (SURF), sometimes referred to as the Module of Opportunity.

Activities in Germany, U.S., and U.K. are now supporting R&D activities for Theia.

Theia-25 very sensitive to neutrino CP violation





Theia-25* performance in the Long-Baseline Neutrino Facility (LBNF) was studied for sensitivity to CP violation detection.

Initial Result: Theia-25 similar performance to a DUNE liquid argon detector. Would have different systematics and **broader program**

Askins, *et al.* EPJC **80** 416 (2020)

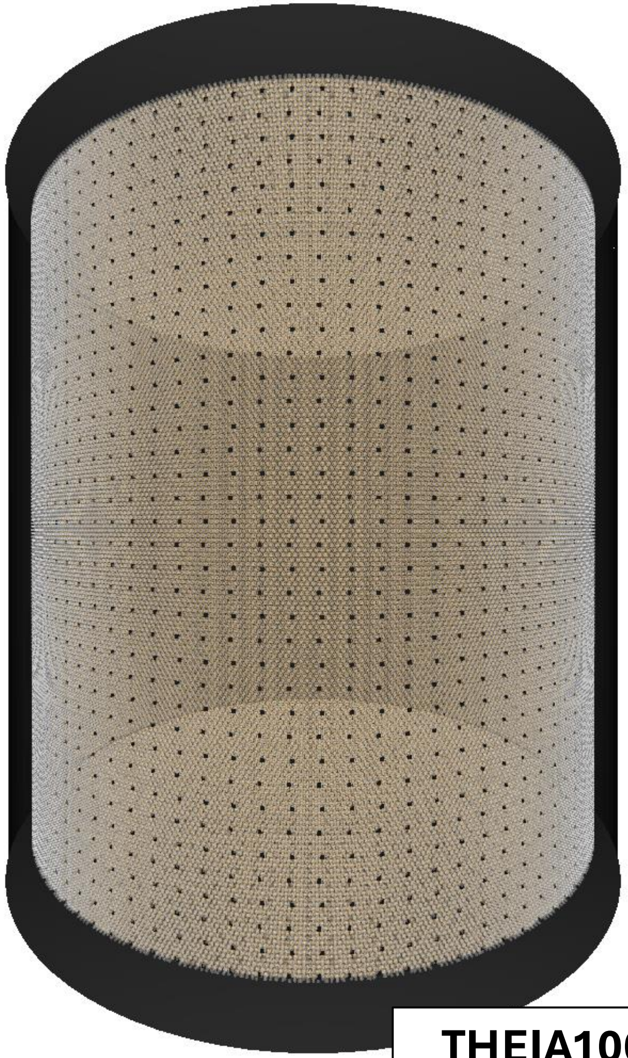
* Theia-25 would have a 17 kton fiducial mass

Theia Physics Program

A 100 kton stand-alone detector and a 25 kton DUNE detector were both studied in the 2020 White Paper. Detailed studies of performance across a broad spectrum of science.

Phase	Primary Physics Goals	Configuration
I	Long-Baseline Oscillations ^{8}B flux Supernova burst, DSNB	Low-yield WbLS, Low photosensor coverage Fast timing
II	Long-Baseline Oscillations ^{8}B MSW Transition CNO, *pep* solar Reactor and geo $\bar{\nu}$ Supernova burst ($\bar{\nu}_e$ and ν_e), DSNB (ν_e and $\bar{\nu}_e$)	High-yield WbLS, Potential ^{7}Li loading High photosensor coverage Dichroicons
III	$0\nu\beta\beta$ ^{8}B MSW Transition Reactor and geo $\bar{\nu}$ Supernova burst and DSNB ($\bar{\nu}_e$)	Inner vessel with LAB+PPO+isotope High photosensor coverage Dichroicons

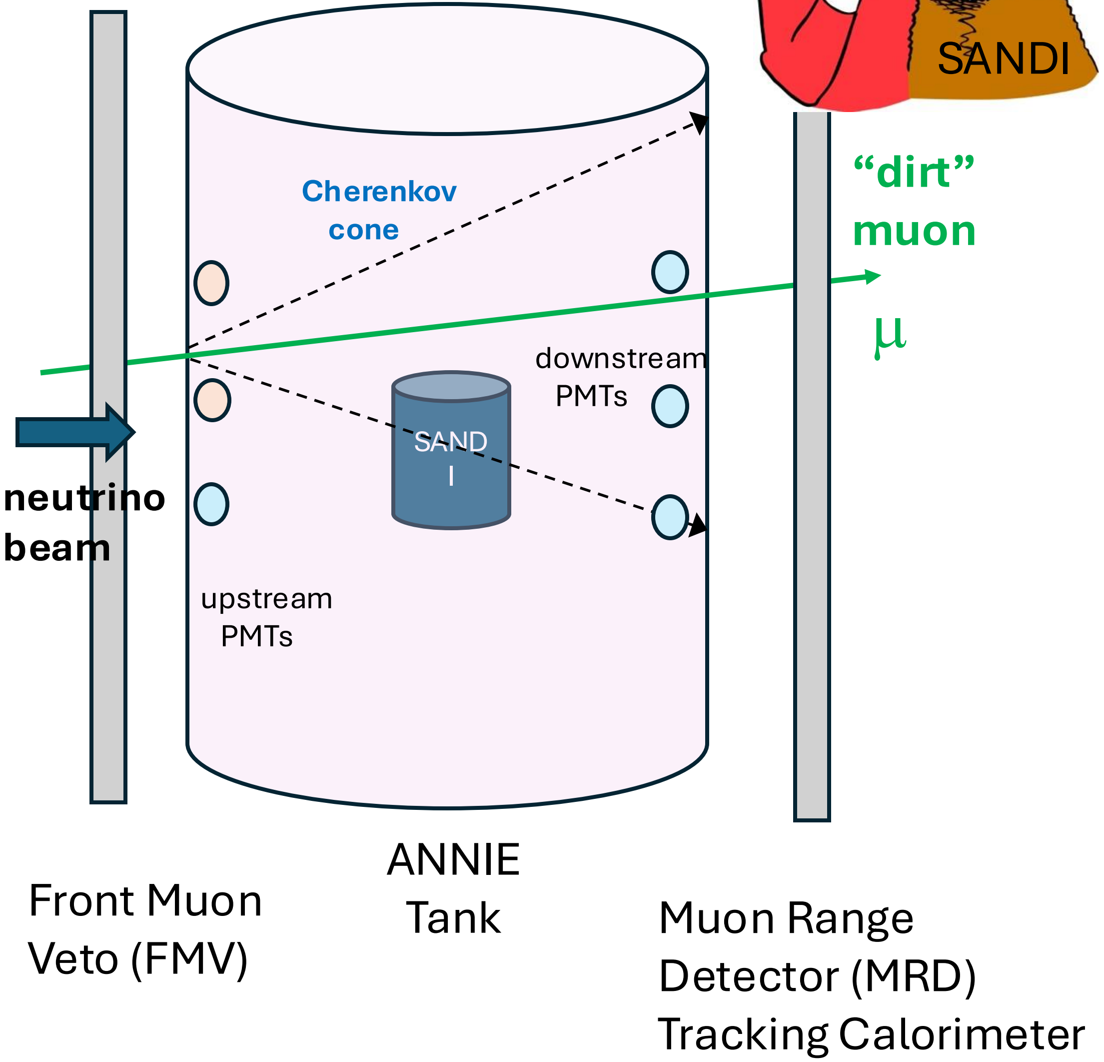
Askins, *et al.* EPJC **80** 416 (2020)

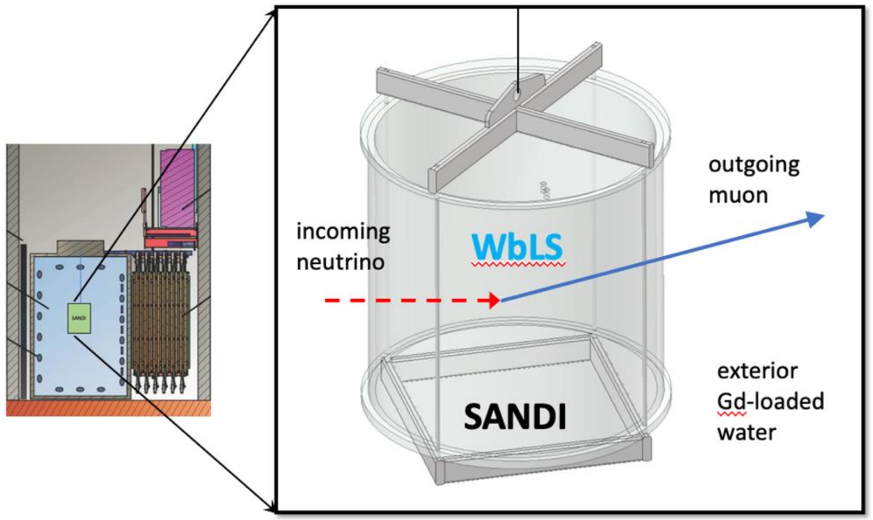


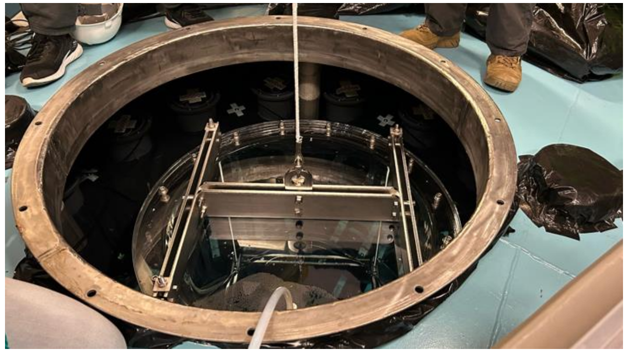
ANNIE WbLS High Energy Reconstruction Test

SANDI

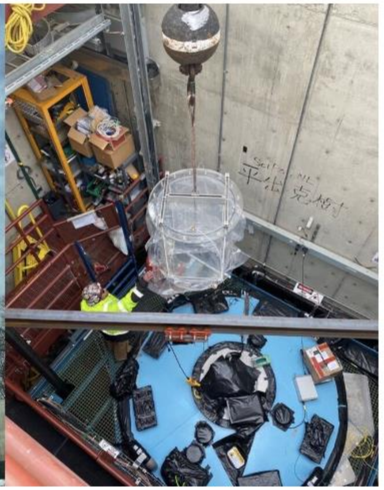
(Scintillator for ANNIE Neutrino Detection Improvement)











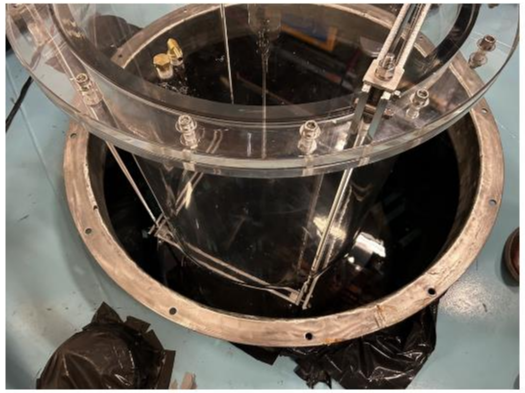
SANDI Acyrlic Vessel

- cylinder holding 365 kg of WbLS submerged in ANNIE water tank
- WbLS produced at BNL

→ **goals of first run:**

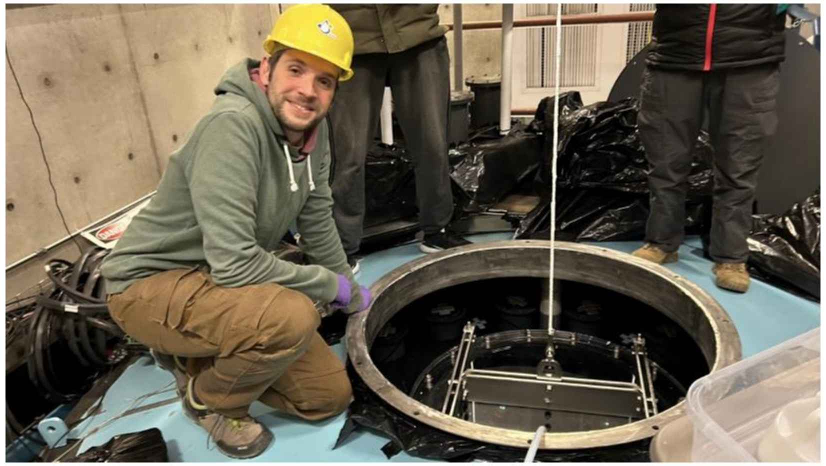
- detect scintillation of hadrons
- use LAPPDs for C/S separation
- detect neutron capture on H
- show general compatibility for second GdWbLS run

removed in May after taking 2 months worth of beam data

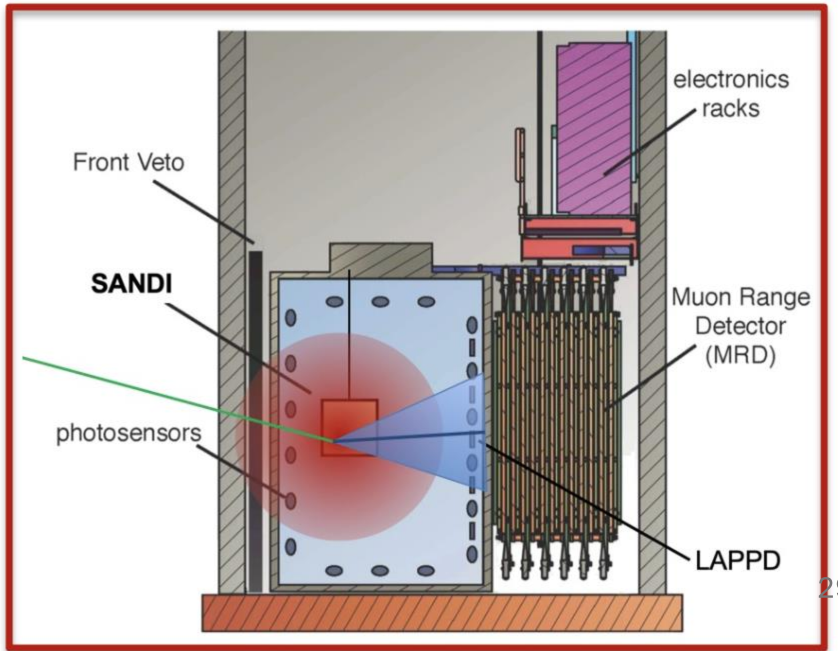


SANDI vessel & support frame inserted in Jan

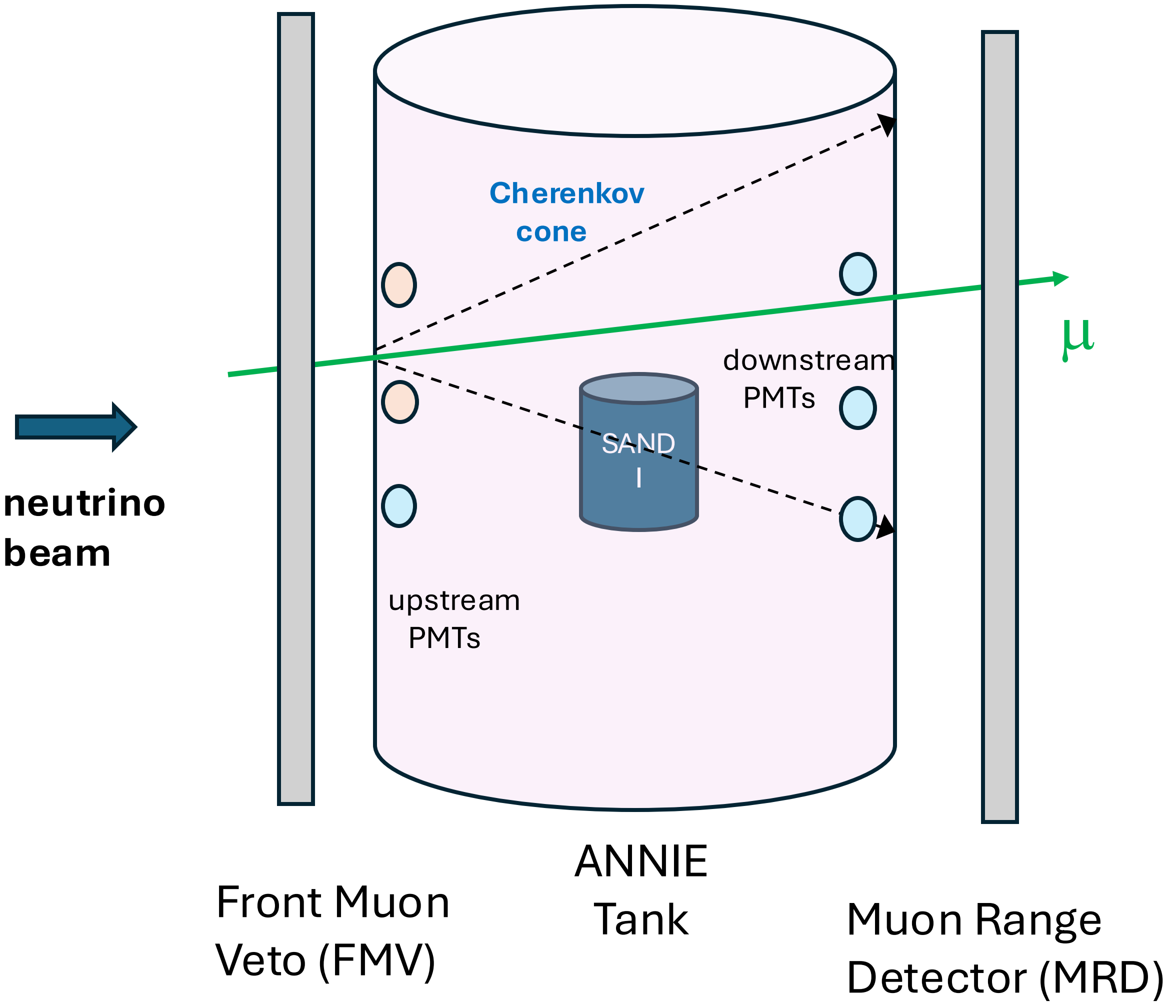
Insertion of vessel inside ANNIE tank in March

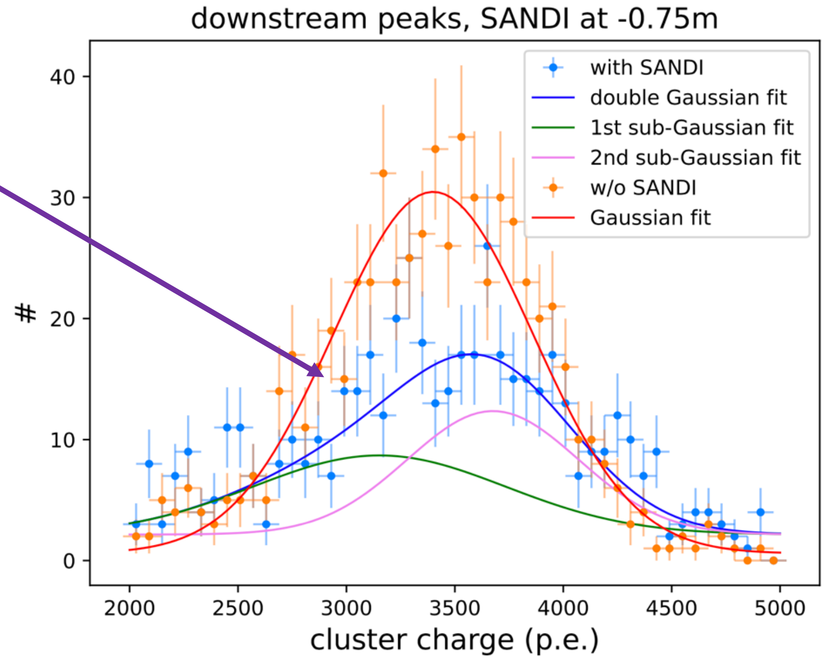


2024 deployment

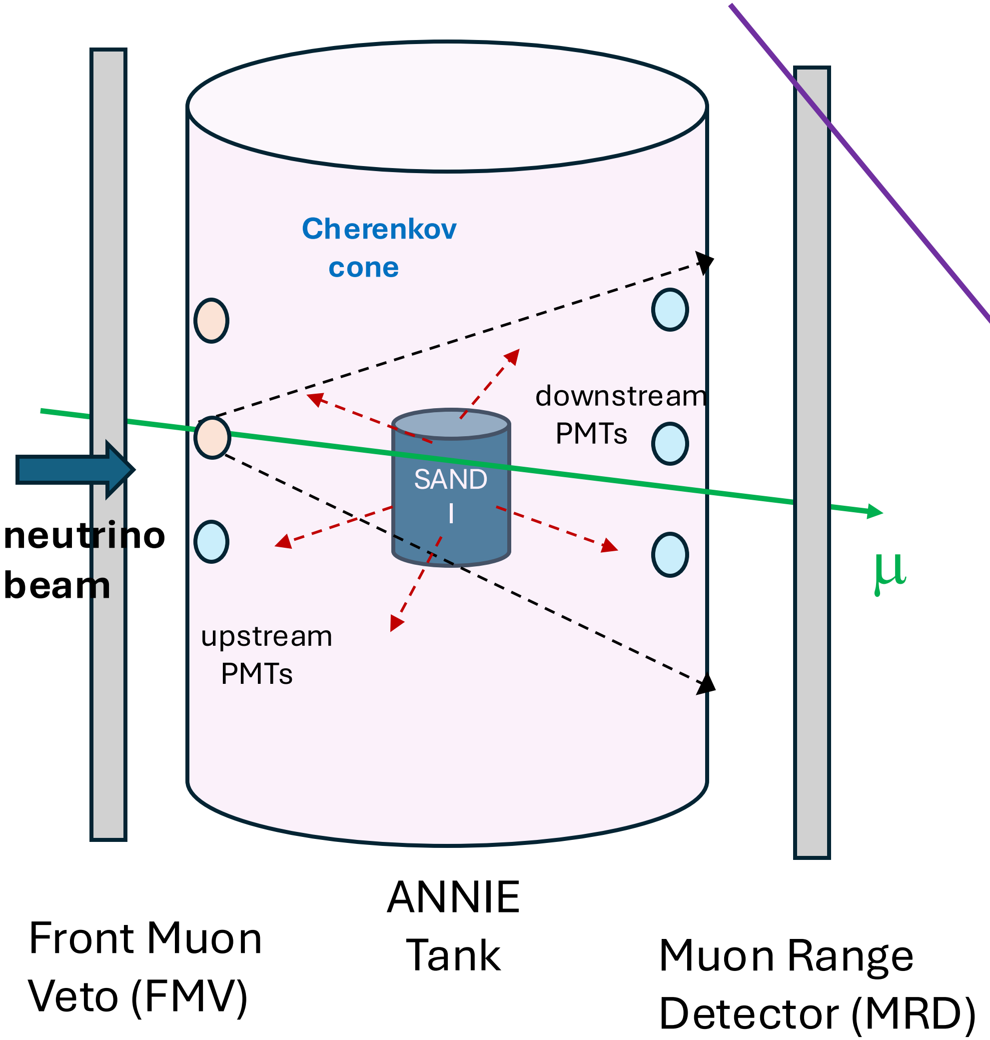


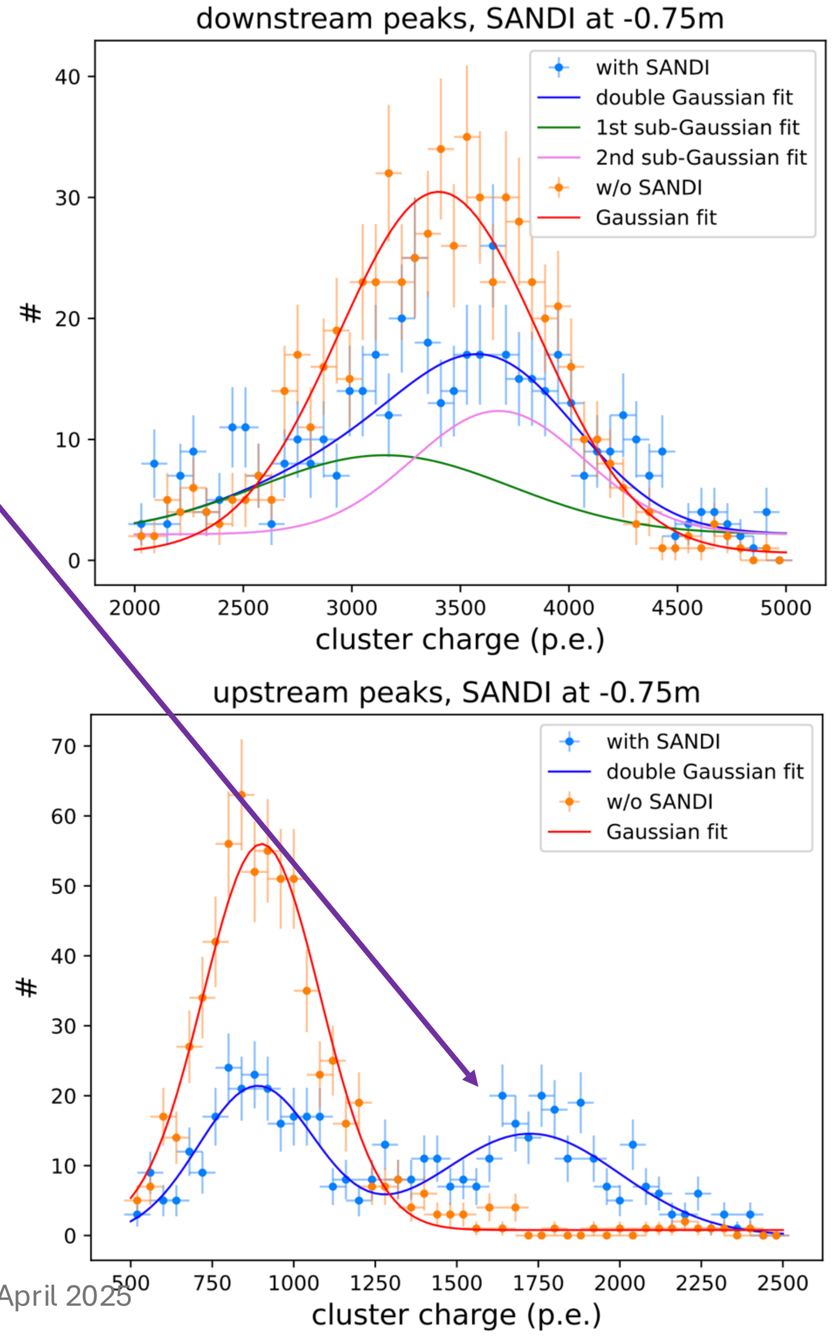
When a muon misses SANDI the light from the Cherekov cone is partially absorbed by the WbLS downstream





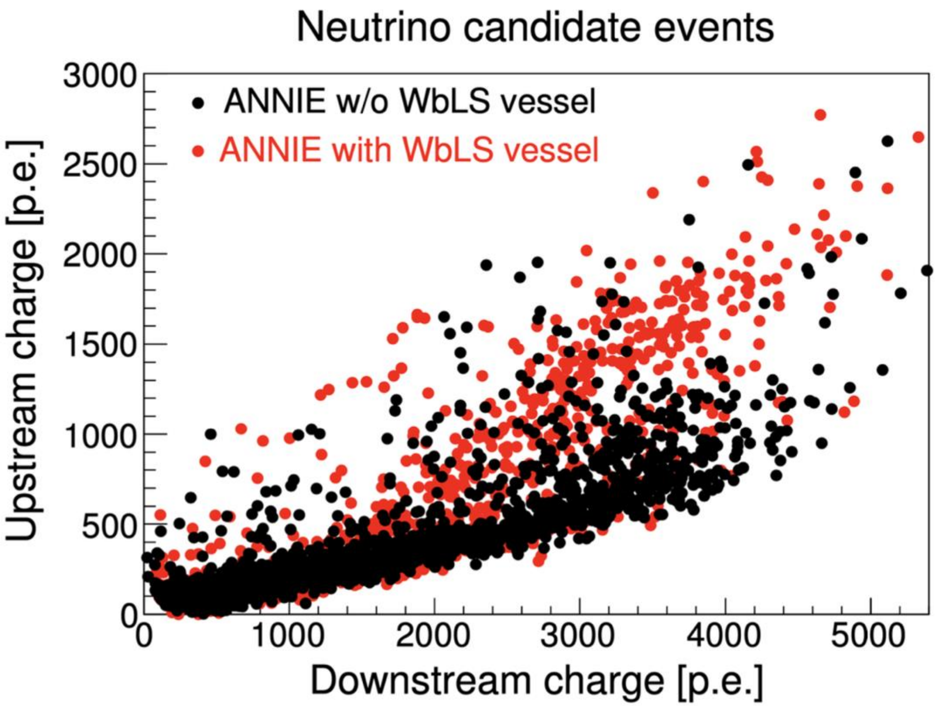
When a muon hits SANDI isotropic light is generated, which is especially apparent upstream





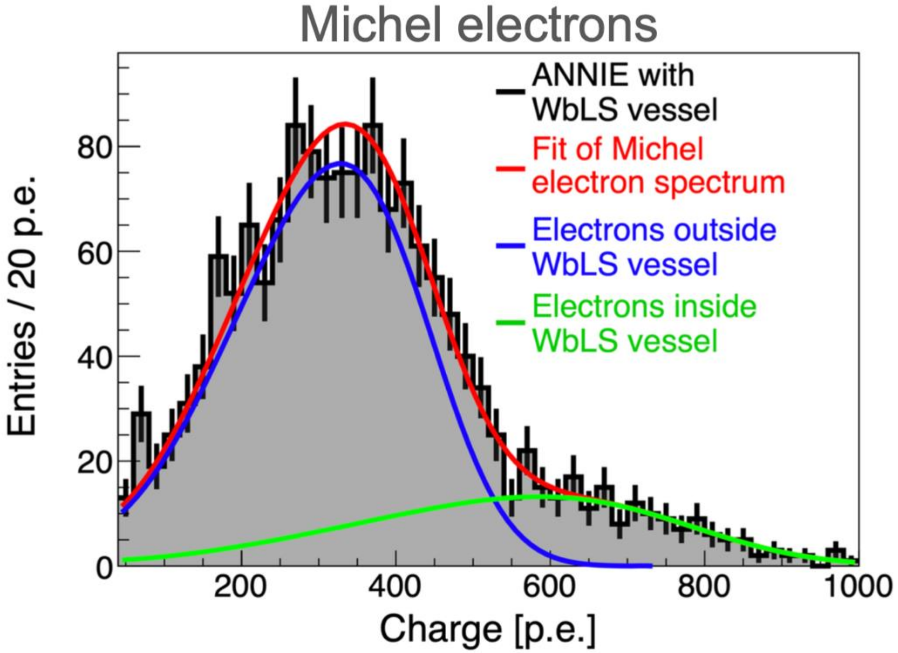
First SANDI WbLS data

JINST 19 (2024) 05, P05070



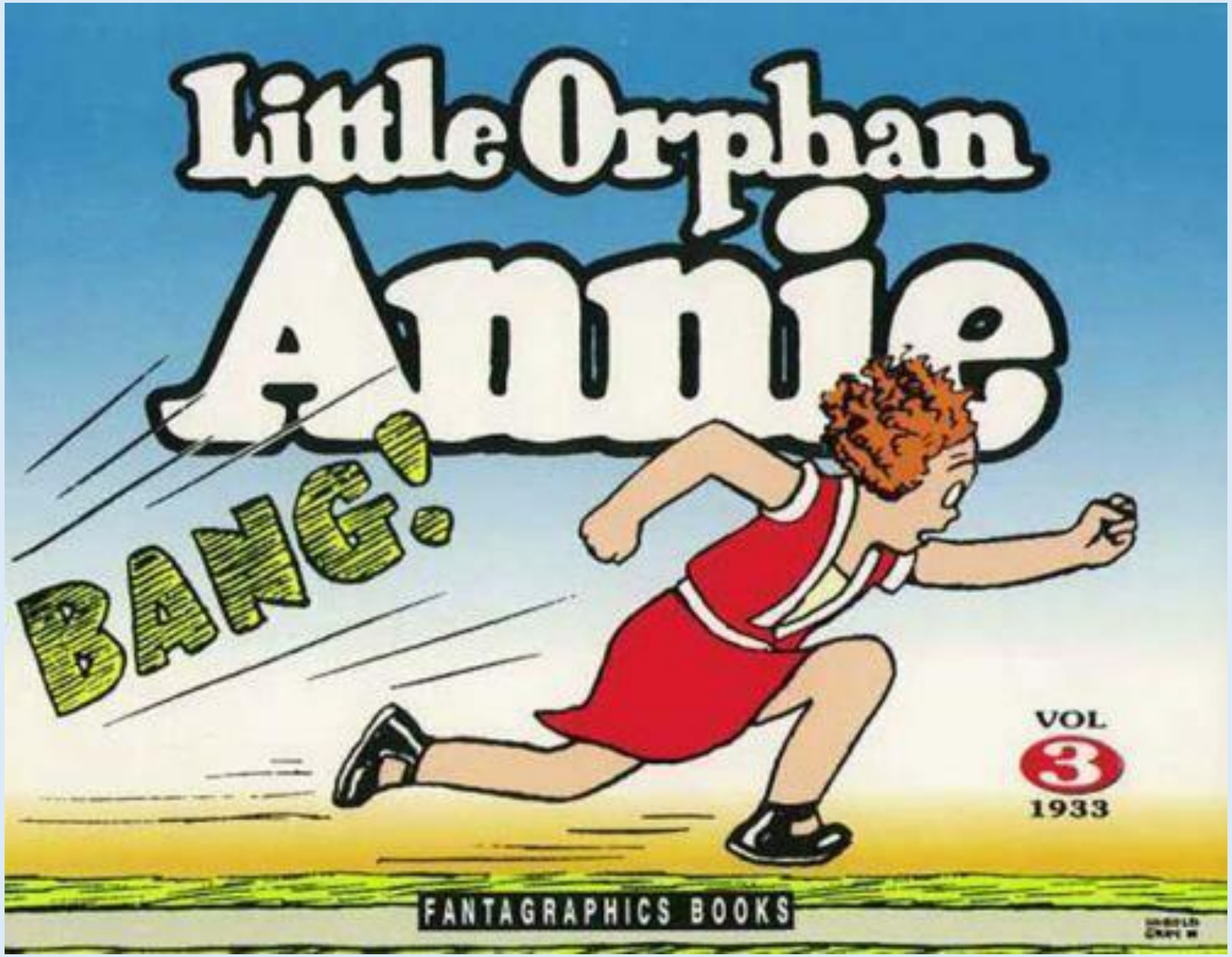
- Selecting neutrino candidates with (no) Front Muon Veto and track in Muon Range Detector
- Compare data with and without WbLS vessel

→ **WbLS:** new population of events with significantly more photons detected by upstream PMTs



- Selection of Michel electrons from stopped muons
- New population of electrons in WbLS produces significantly more photons than electrons in water

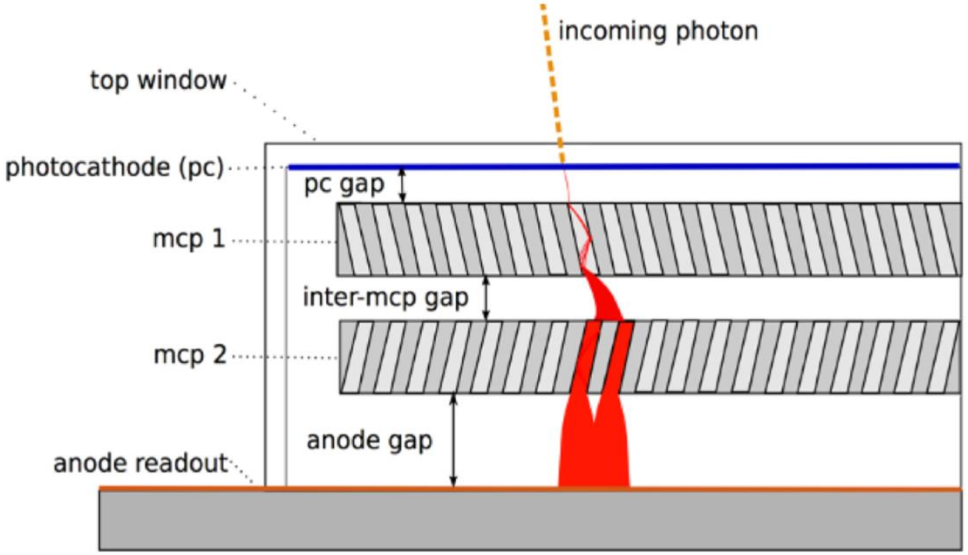
→ effective increase in light output: (77±8)%



ANNIE and Fast Timing with LAPPDs

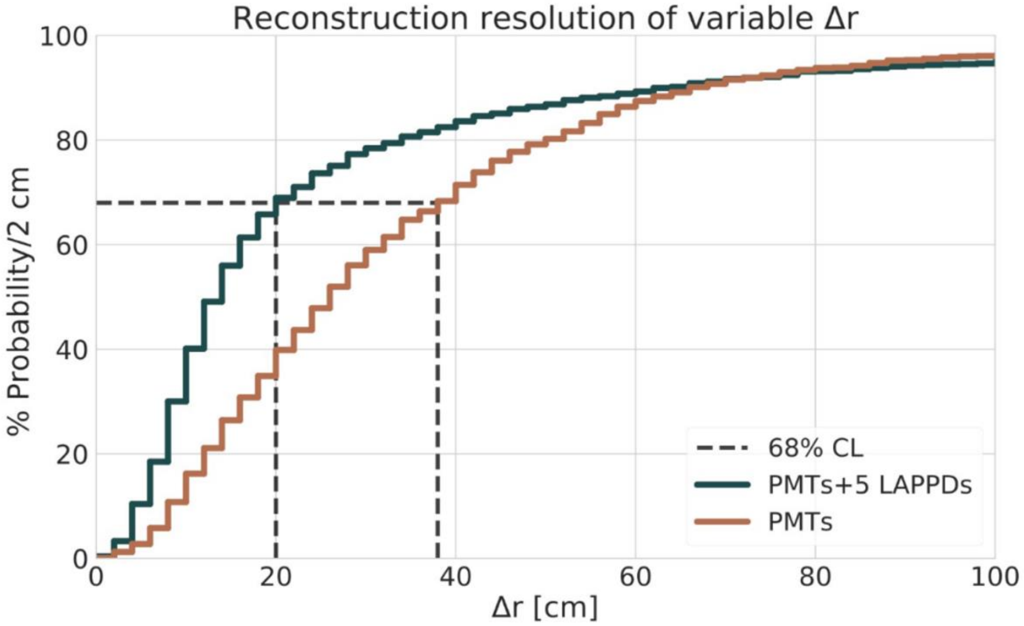
LAPPDs in ANNIE

- Incom's Gen-I LAPPDs feature
  - Large detection area (8" x 8")
  - Timing: - intrinsic ~ 50ps
    - in situ goal ~ 100ps
  - Anode: 28 microstrips with double-sided readout
    → spatial resolution better ~1cm

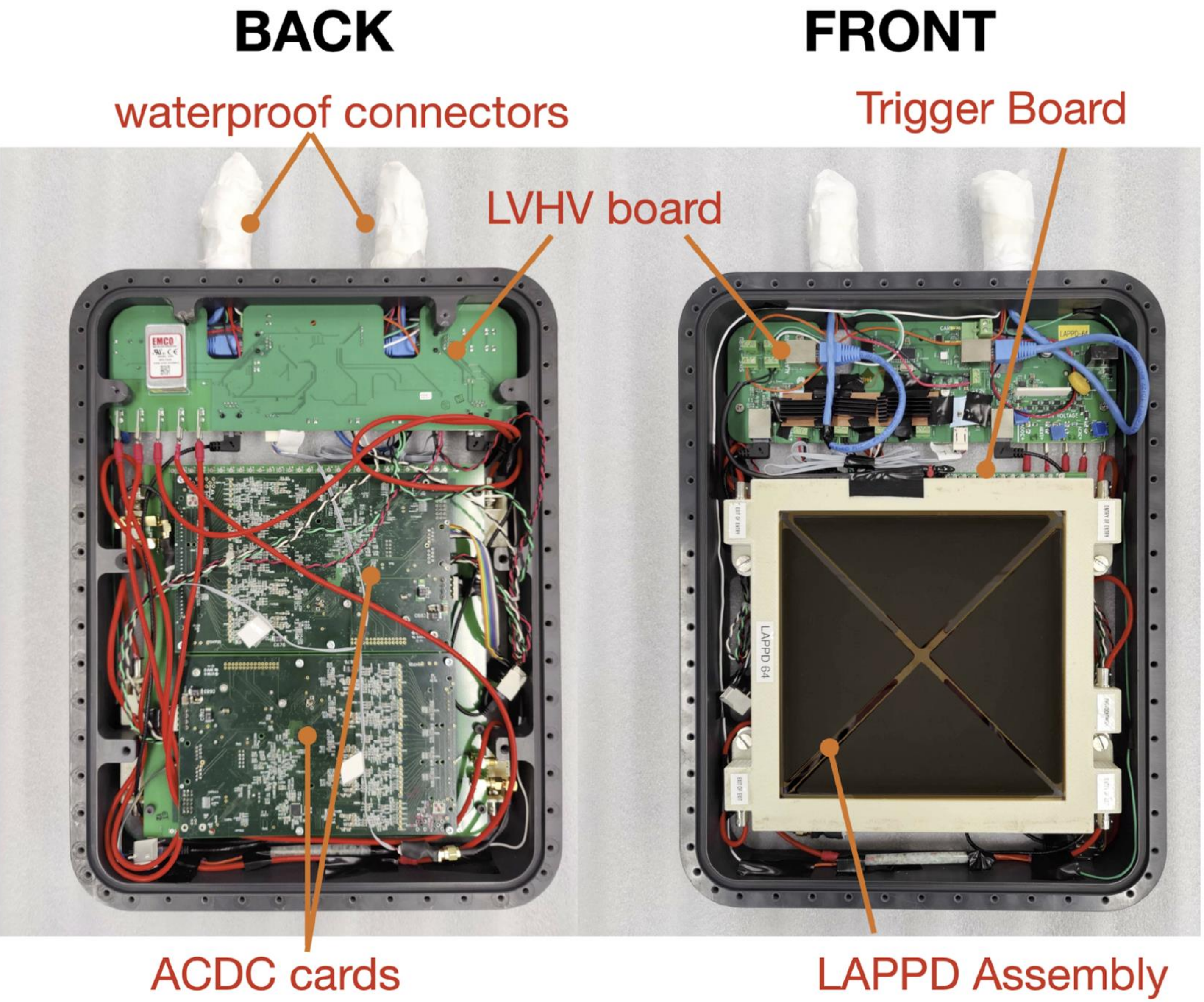


LAPPDs use two layers of multi-channel plates to enable electron amplification in a very uniform geometry for a large photocathode

- ANNIE has the first data from multiple LAPPDs operating in a neutrino beam.
  - Precious operational experience.
  - Data provides insights into the challenges inherent in interpreting LAPPD data.
- We aim to demonstrate improved muon kinematics and neutrino vertex reconstruction with LAPPDs.



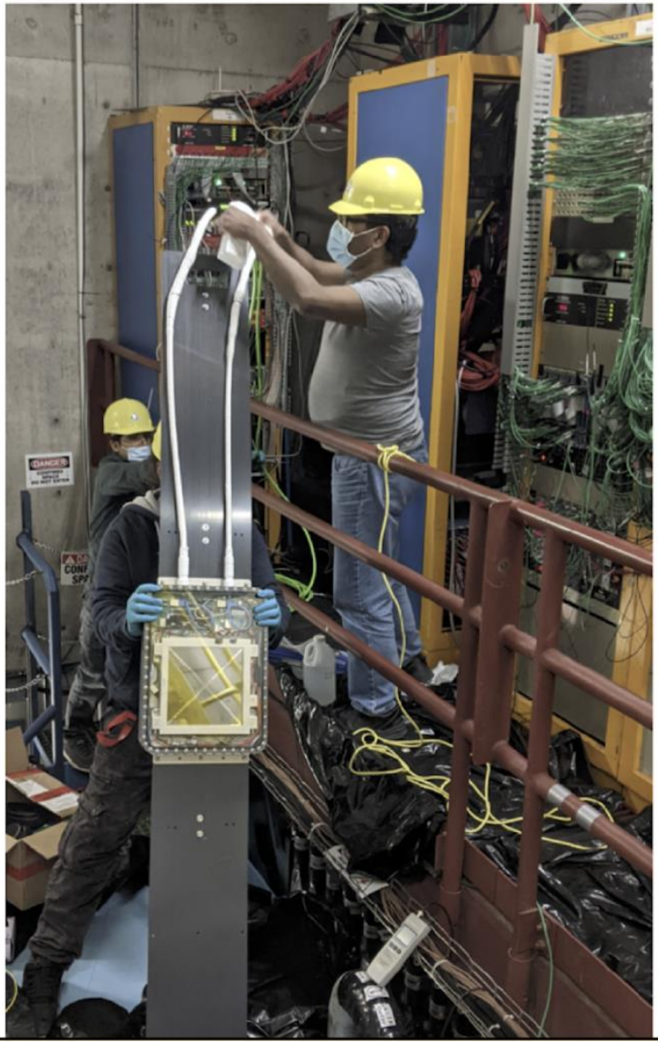
The Packaged ANNIE LAPPD (PAL)

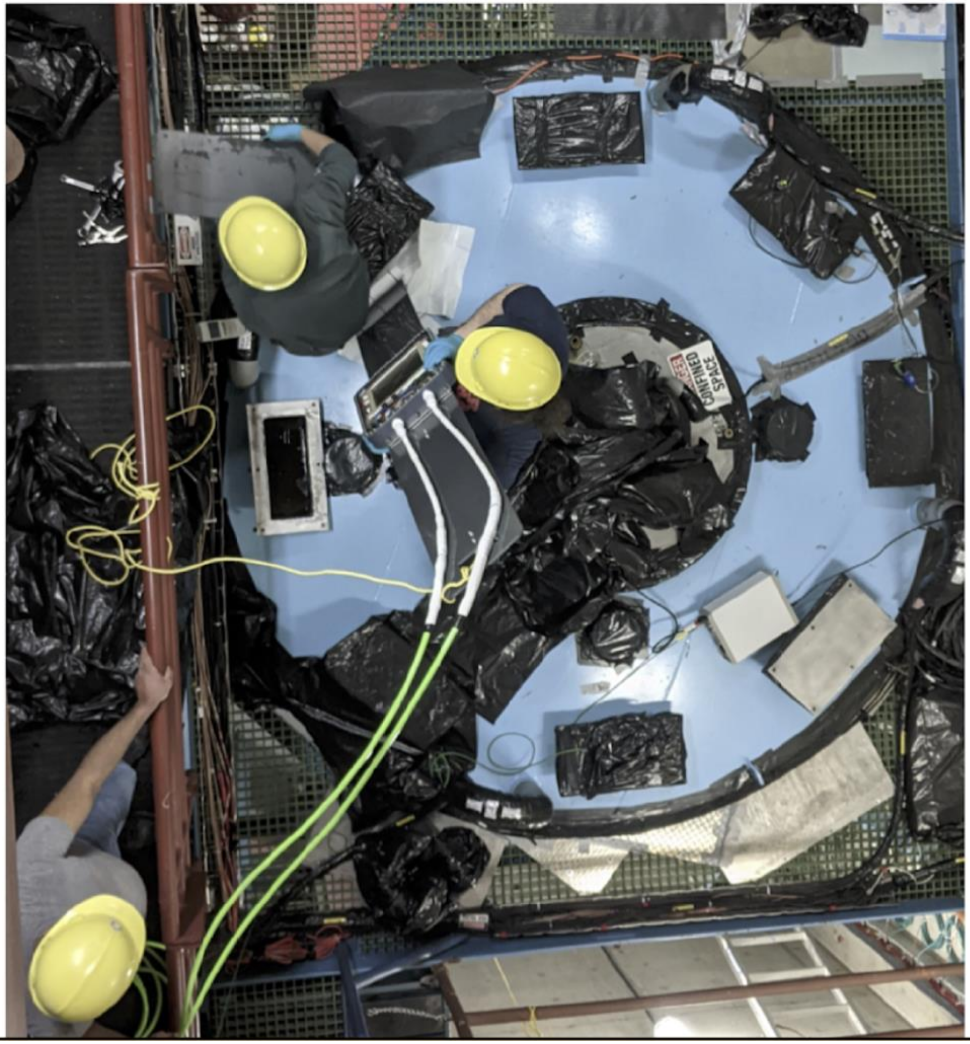


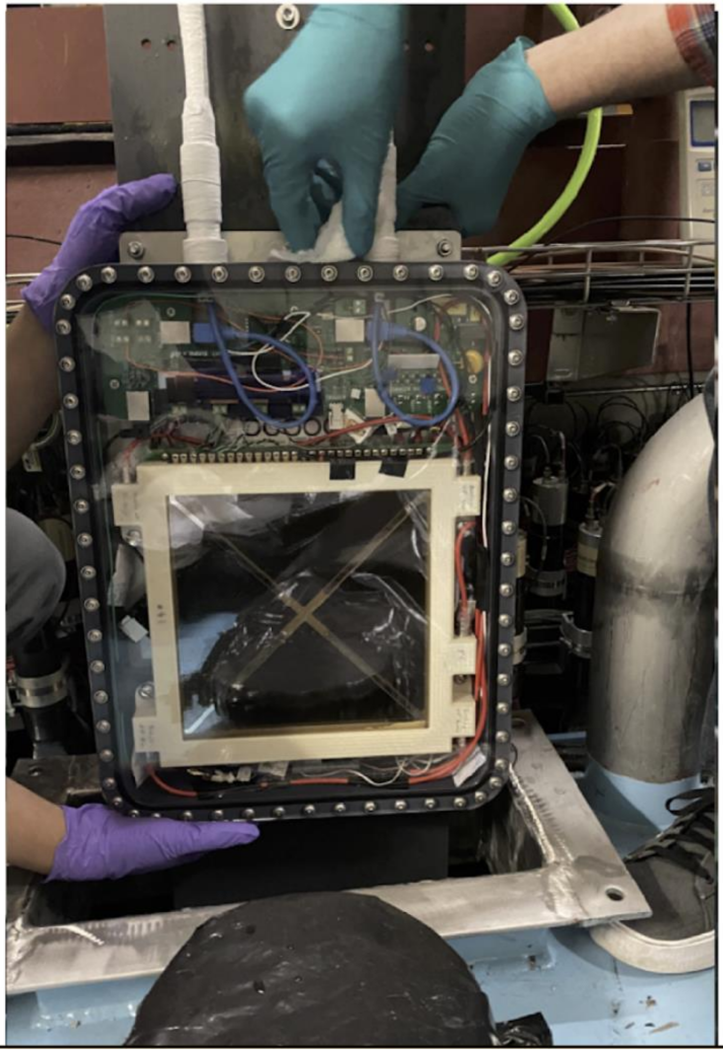
- We packaged LAPPDs in waterproof housing in order to operate underwater.
- We kept digitization close to the detector to ensure sub-ns timing.
- 25ns digitization buffer required LAPPD trigger inside housing.
- Environmental monitoring, slow controls, and power also needed to be handled inside housing.
- Laser-calibrated prior to deployment.

The package performance is adequate. We have identified key potential improvements.

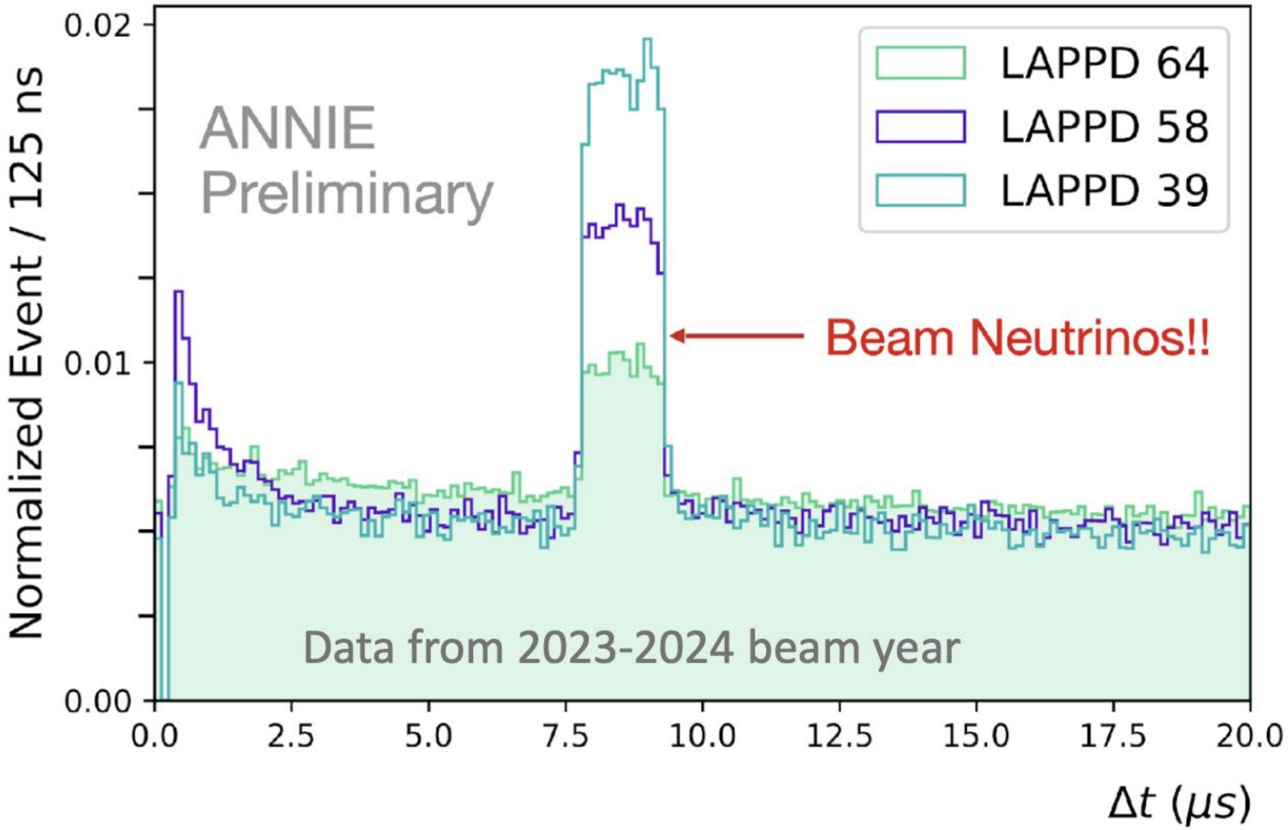
LAPPD Deployment

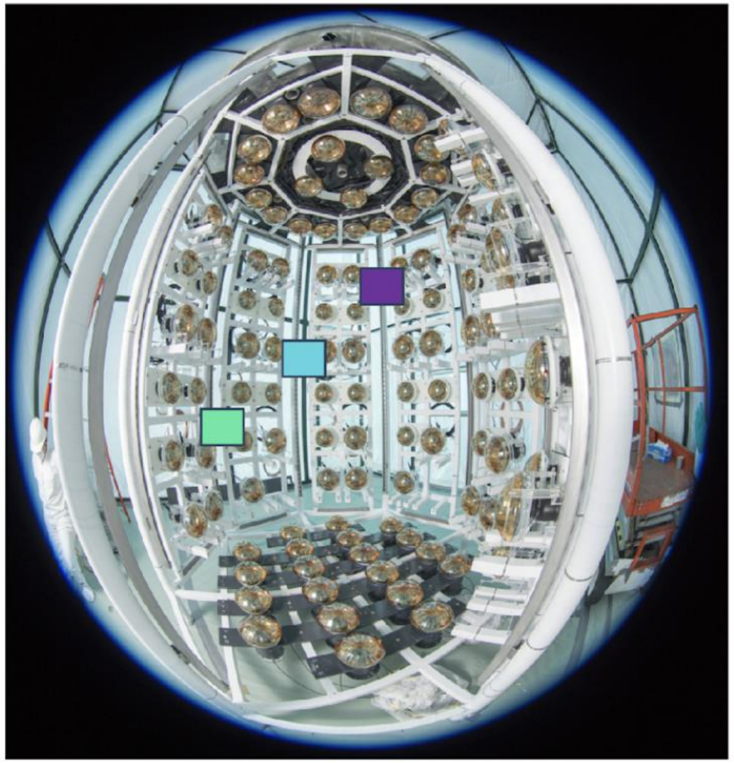






First Neutrinos on (multiple) LAPPDs





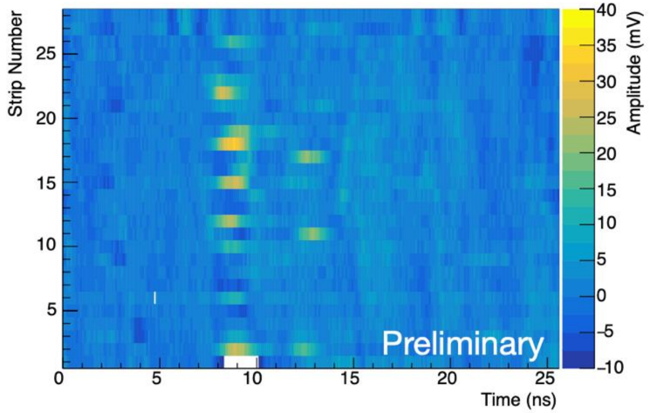
Neutrinos seen concurrently by three LAPPDs operating in ANNIE

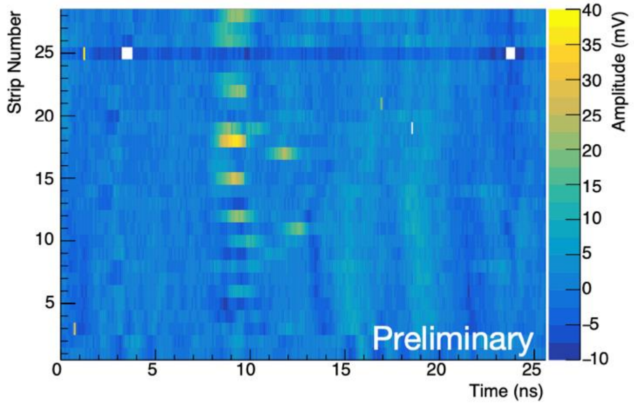
World's first: Neutrinos observed with LAPPDs!

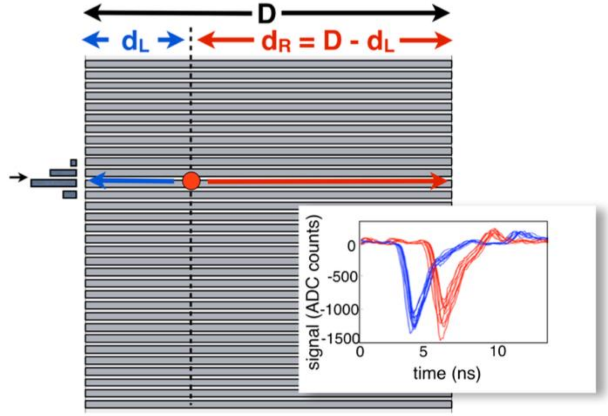
First-ever detection of neutrinos with LAPPDs

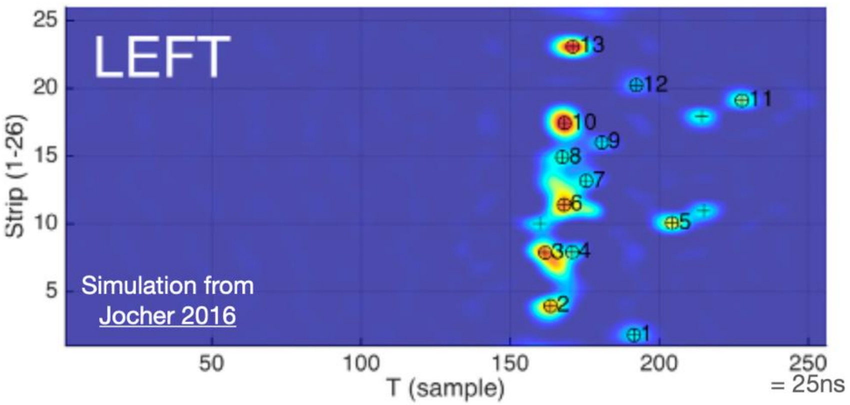
- BNB spill width $1.6\mu s$ was correctly detected.
- ~1200 neutrino candidates identified after cuts for data in ~half beam year.
- Pulse response on LAPPD strip lines detected.
- Imaging feature match the muon information.

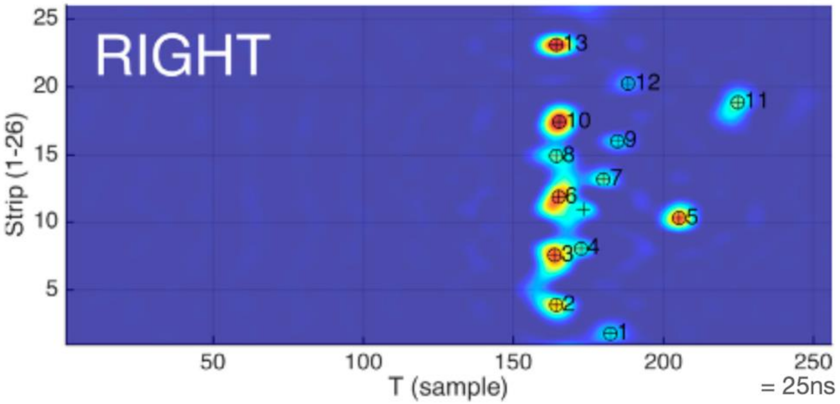
A neutrino candidate in 2023 beam year





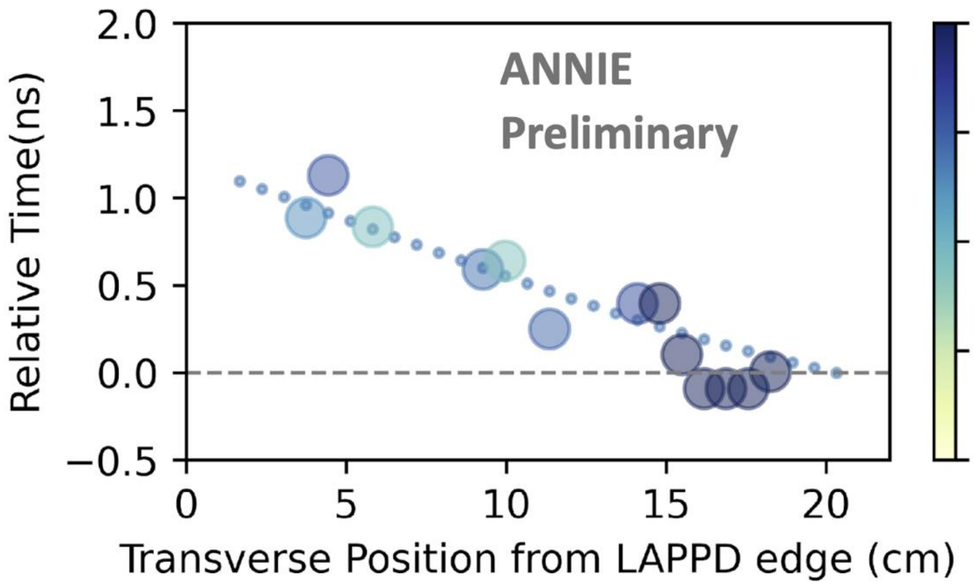






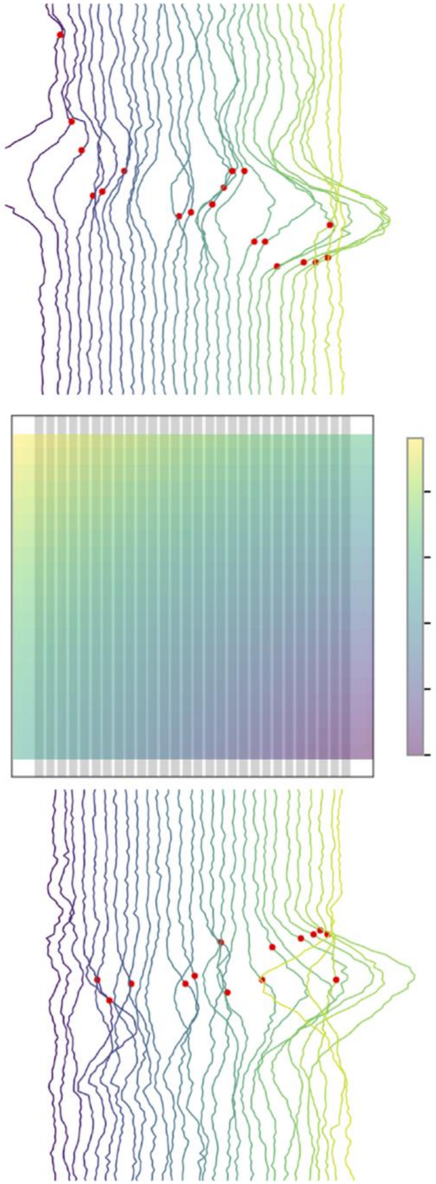
LAPPDs as imaging photosensors

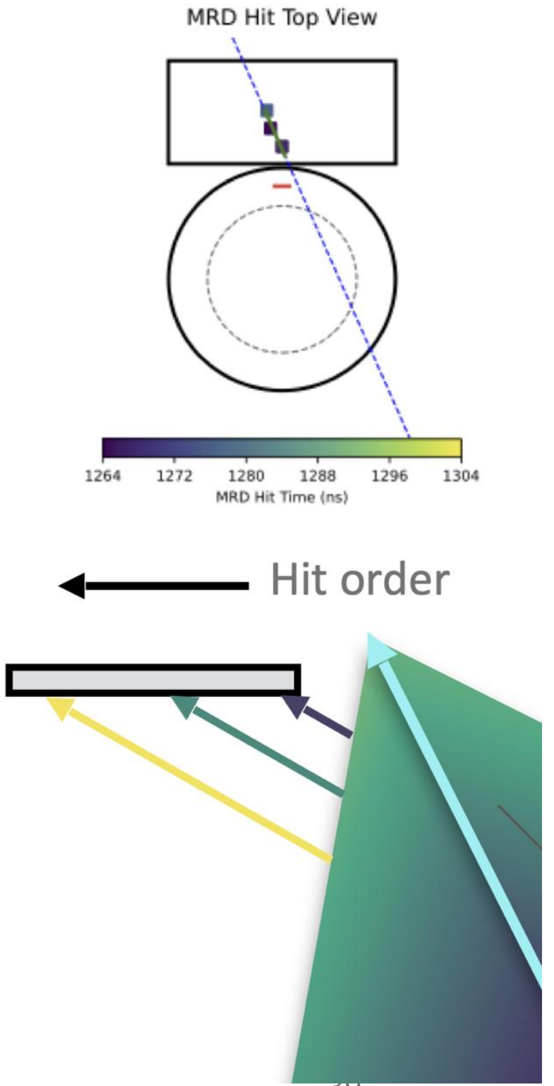
Time evolution of a Cherenkov ring across the surface of a photosensor depends on track direction. Imaging LAPPDs can capture this.



Gradient matches predicted (sub-ns) gradient based on independent MRD track reconstruction!

Cross-talk makes this challenging for other events.





MegaANNIE

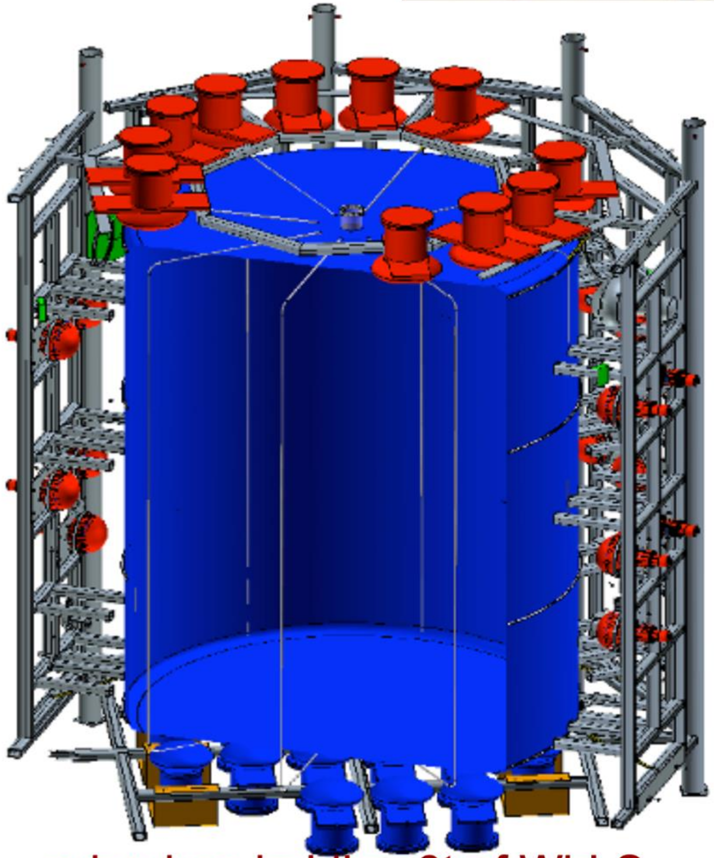
What's Next?

Next steps in R&D: 8 tons of WbLS in Super-SANDI

Compatibility test of WbLS and nylon sample

- Demonstration of event reconstruction capability in WbLS requires extended scintillator volume.
- **Super-SANDI:** install an 8m³ cylindrical nylon vessel in the inner volume of the ANNIE tank.
- Builds on experience from Borexino/KamLAND.

- German collaborators recently received a DFG grant for construction of the balloon vessel.
- Mock-up installation in Mainz next summer.
- Installation in ANNIE tank in summer break 2026.
- Potential for 1.5 years of data until long shutdown.



nylon bag holding 8t of WbLS

Next steps in R&D: Addition of upstream Gen-II LAPPDs

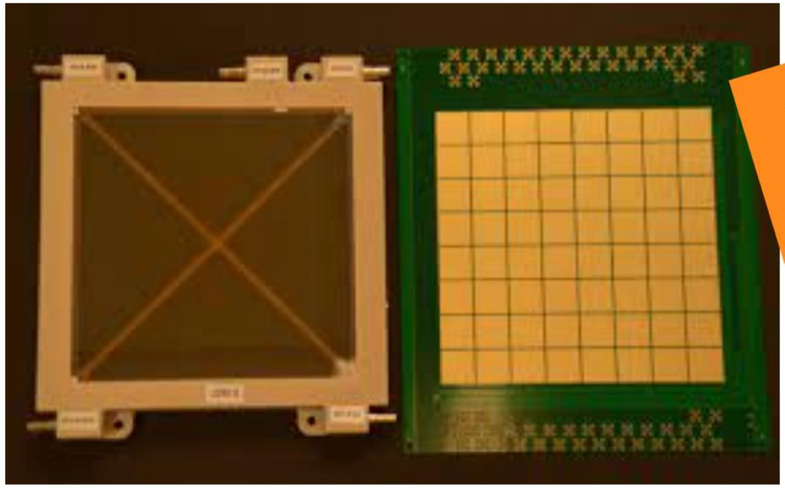
- Isotropic scintillation signal will hit upstream PMTs first → additional LAPPDs improve vertex position reconstruction and hadronic signal detection.

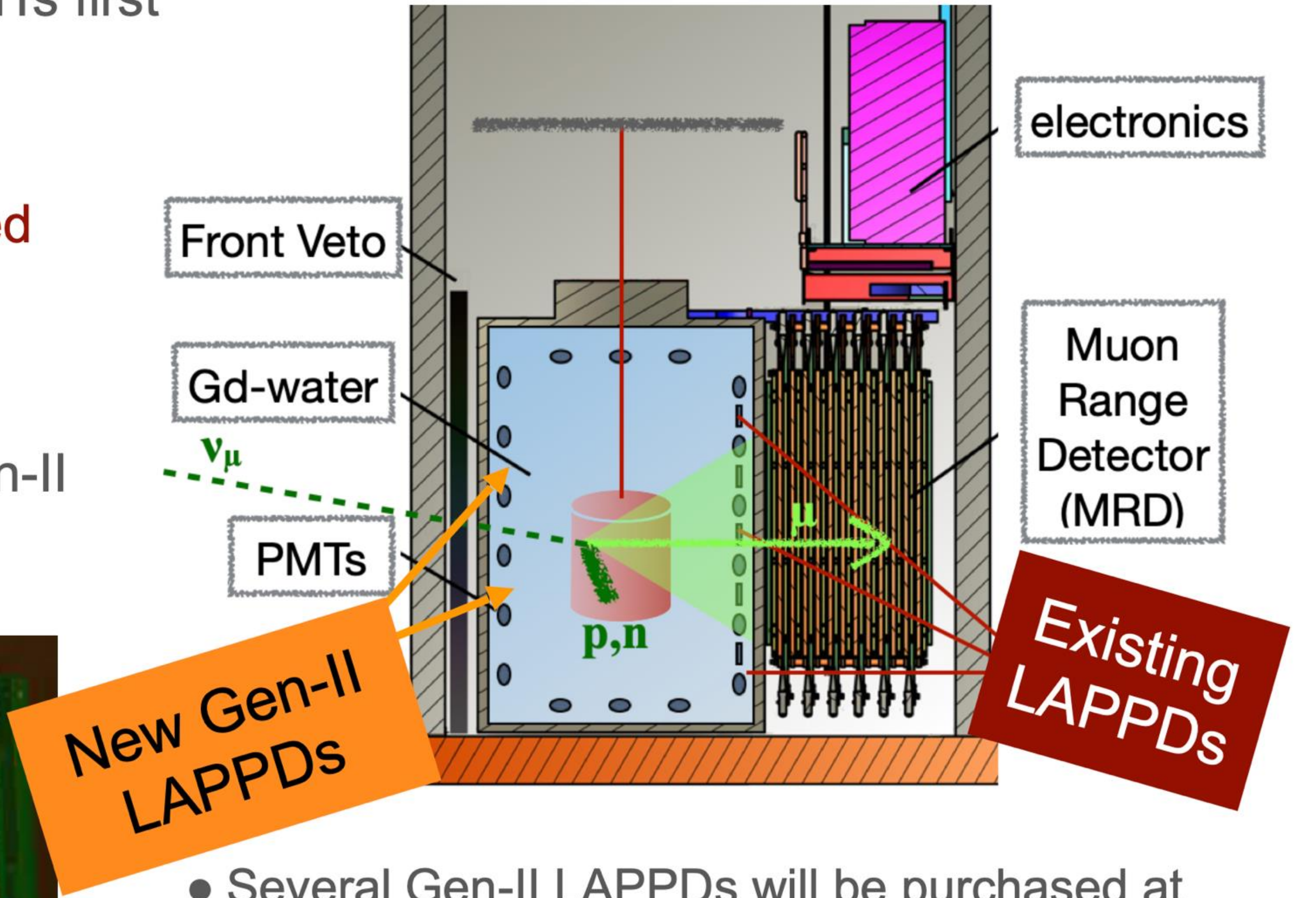
- Deploy Gen-II LAPPDs with capacitively-coupled anode and flexible readout geometry.

  → Future Incom production will be Gen-II.
  → Substantial community interest in testing Gen-II under realistic experimental conditions.

Recent Gen-II LAPPDs with a pad-style anode geometry (potentially reduces photon pile-up).

Anode geometry defined on electronics external to LAPPD





- Several Gen-II LAPPDs will be purchased at FSU.

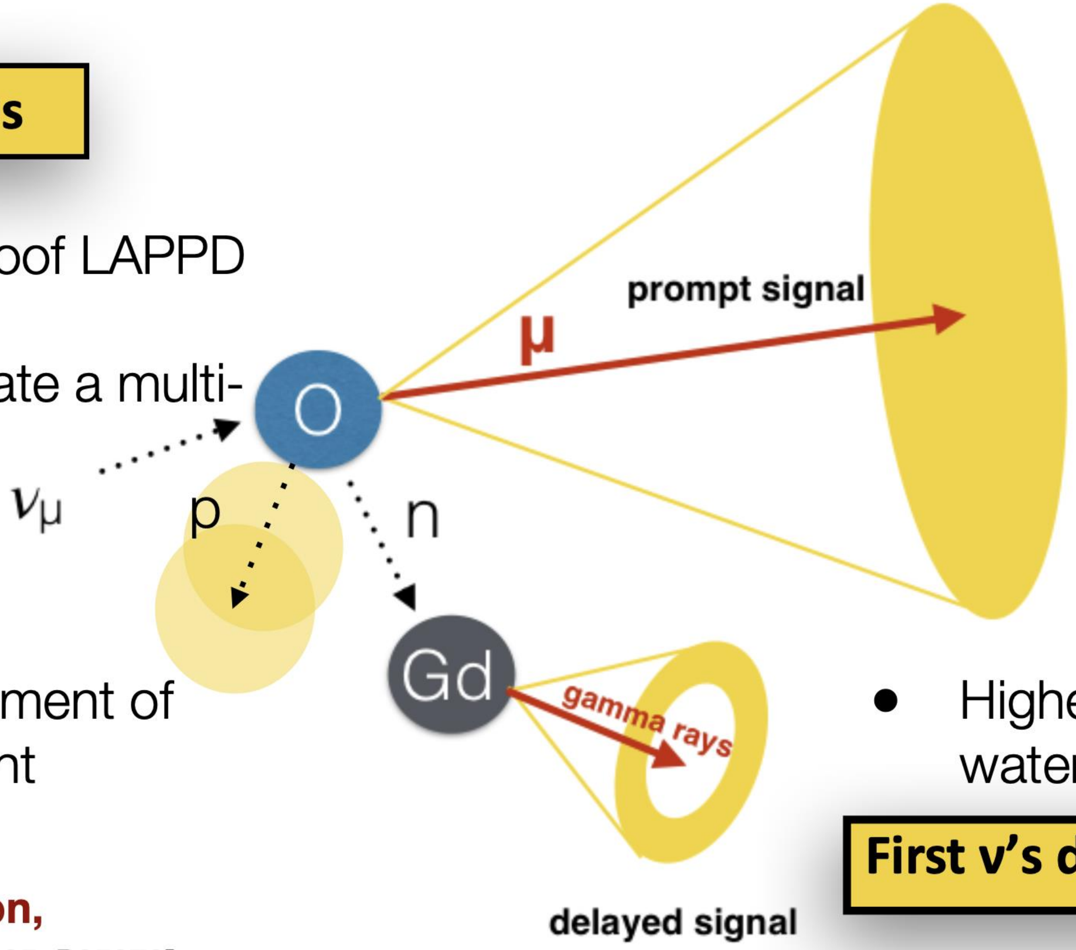
- ISU/FSU-led team is developing plan to update electronics and PAL.

ANNIE Accomplishments

ANNIE is a flexible test-bed for next generation detector technologies (novel photosensors/fast-timing and novel detection media)

First ν's detected with LAPPDs

- First deployable waterproof LAPPD modules
- First experiment to operate a multi-LAPPD system



First ν's detected in WbLS

- First near-to ton-scale deployment of WbLS in a neutrino experiment

- Highest-concentration of Gd-water in a neutrino exp.

First ν's detected in Gd-water

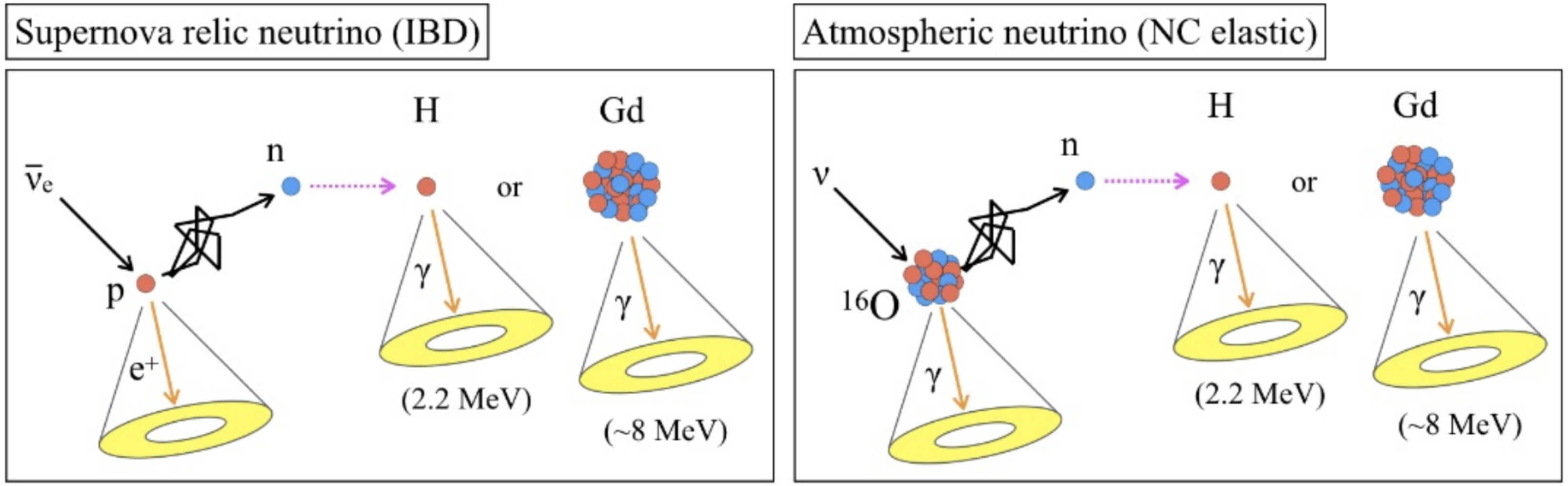
Several technical papers in preparation, first WbLS published [JINST 19 (2024) 05, P05070]

Thanks!

DSNB Primary Background

M. Harada *et al* 2023 *ApJL* **951** L27

No significant excess over background yet observed



Yosuke Ashida, The 32nd SRN Workshop, 2019

"Present uncertainty on [νNCQE] interactions induces a large error on atmospheric neutrino backgrounds, limiting the sensitivity at low energies where the [DSNB] flux is predicted to be large." – T2K collaboration

PHYSICAL REVIEW D 100, 112009 (2019)

annie IOWA STATE UNIVERSITY