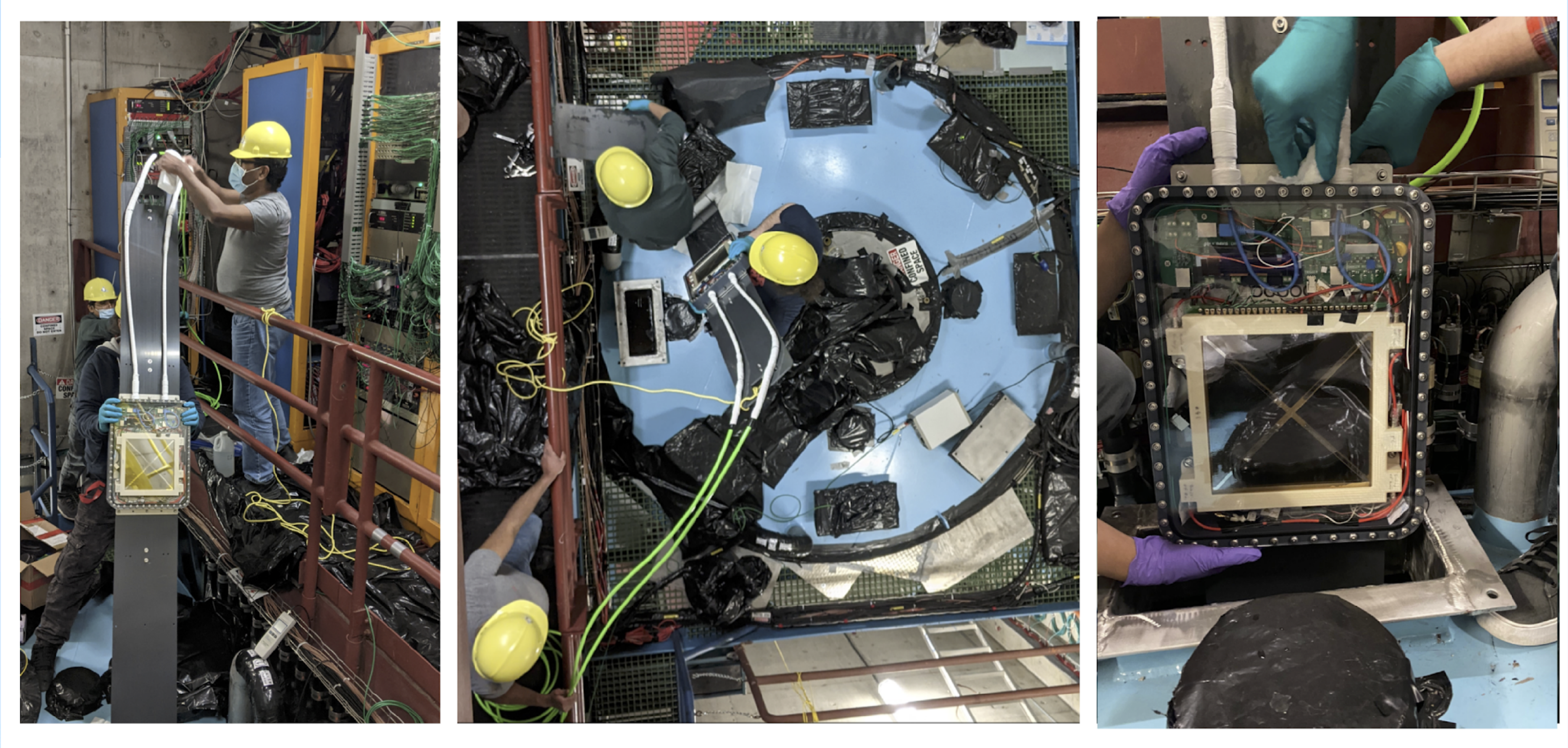
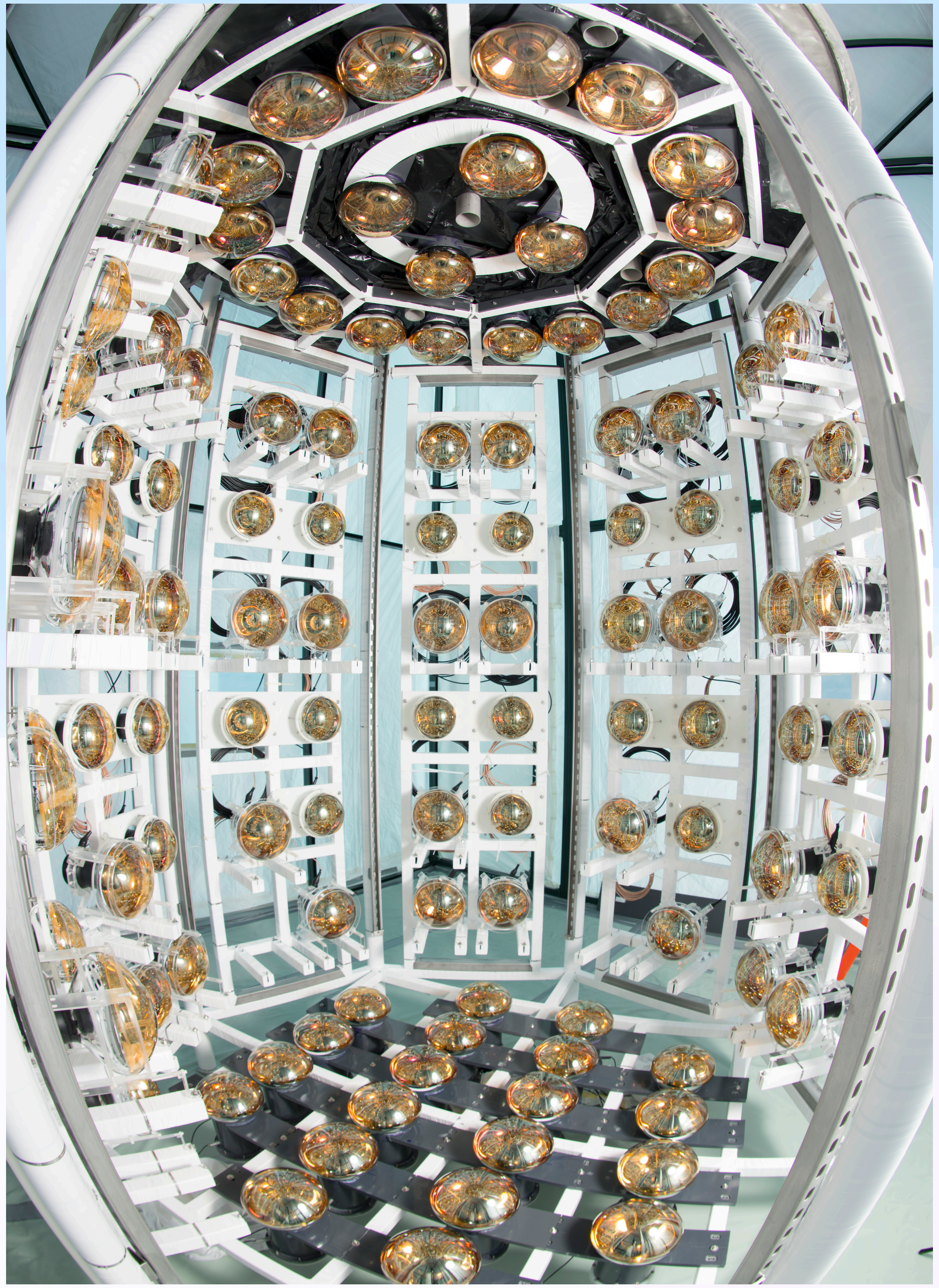
ANNIE:
Milestones and Prospects

Amanda Weinstein
Iowa State University





U.S. DEPARTMENT OF ENERGY

The Accelerator Neutrino Neutron Interaction Experiment

ANNIE is a neutrino experiment deployed on the Fermilab Booster Neutrino Beam (BNB)

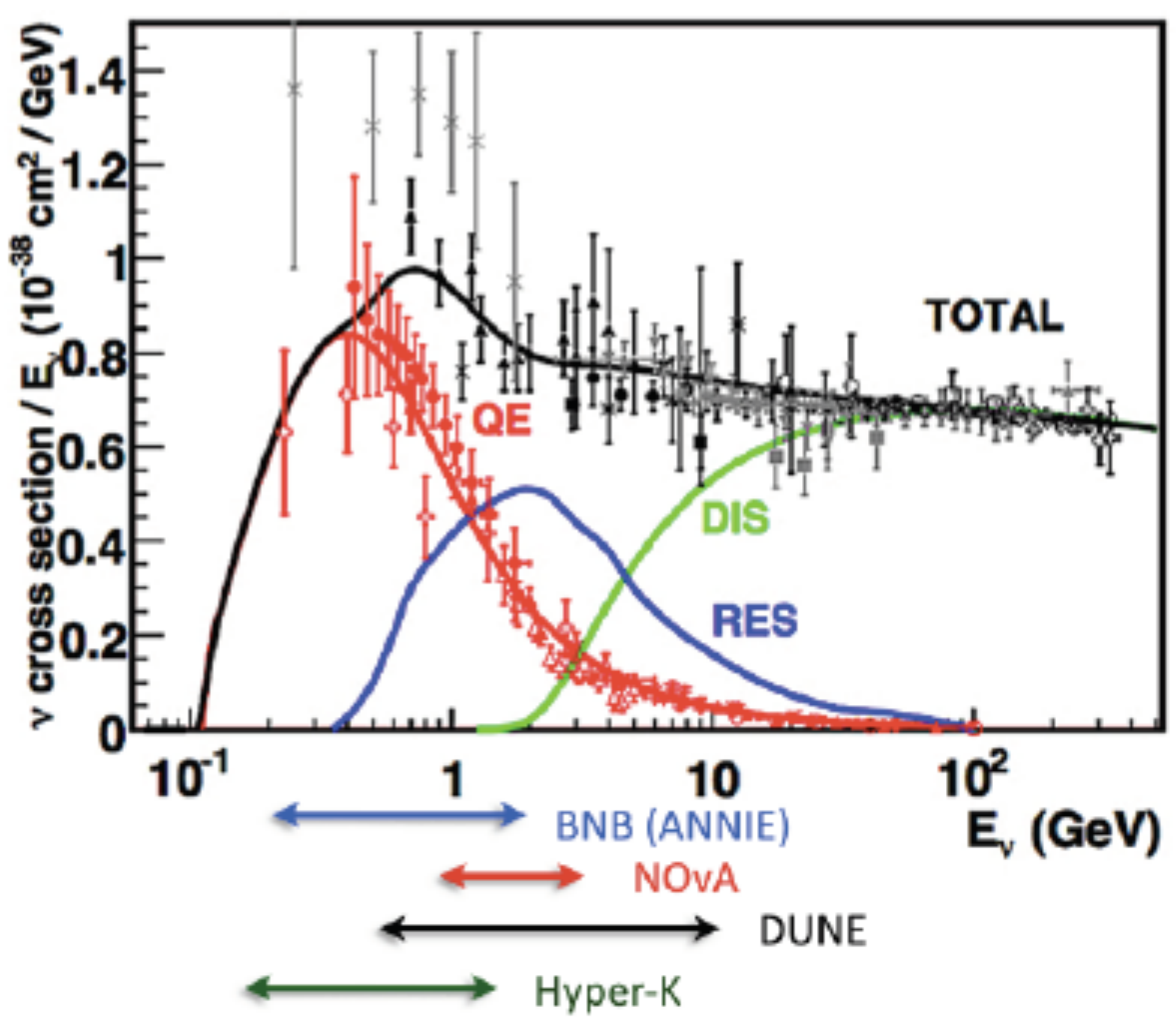
- Physics: Study beam neutrino interactions in water (on oxygen), especially the neutron yield.
- Technology: Flexible R&D platform to develop and demonstrate new neutrino detection technologies/techniques.

45 collaborators from 19 institutions in 6 countries

ANNIE Neutrino-Nucleus Interaction Program

Final-state neutron multiplicity in ν_μ CC interactions as function of lepton kinematics to constrain E_ν reconstruction systematics

(critical source of uncertainty for long-baseline neutrino oscillation measurements)



High-flux ν_μ on fixed target

Energy range overlaps with T2K/Hyper-K, LBNF/DUNE

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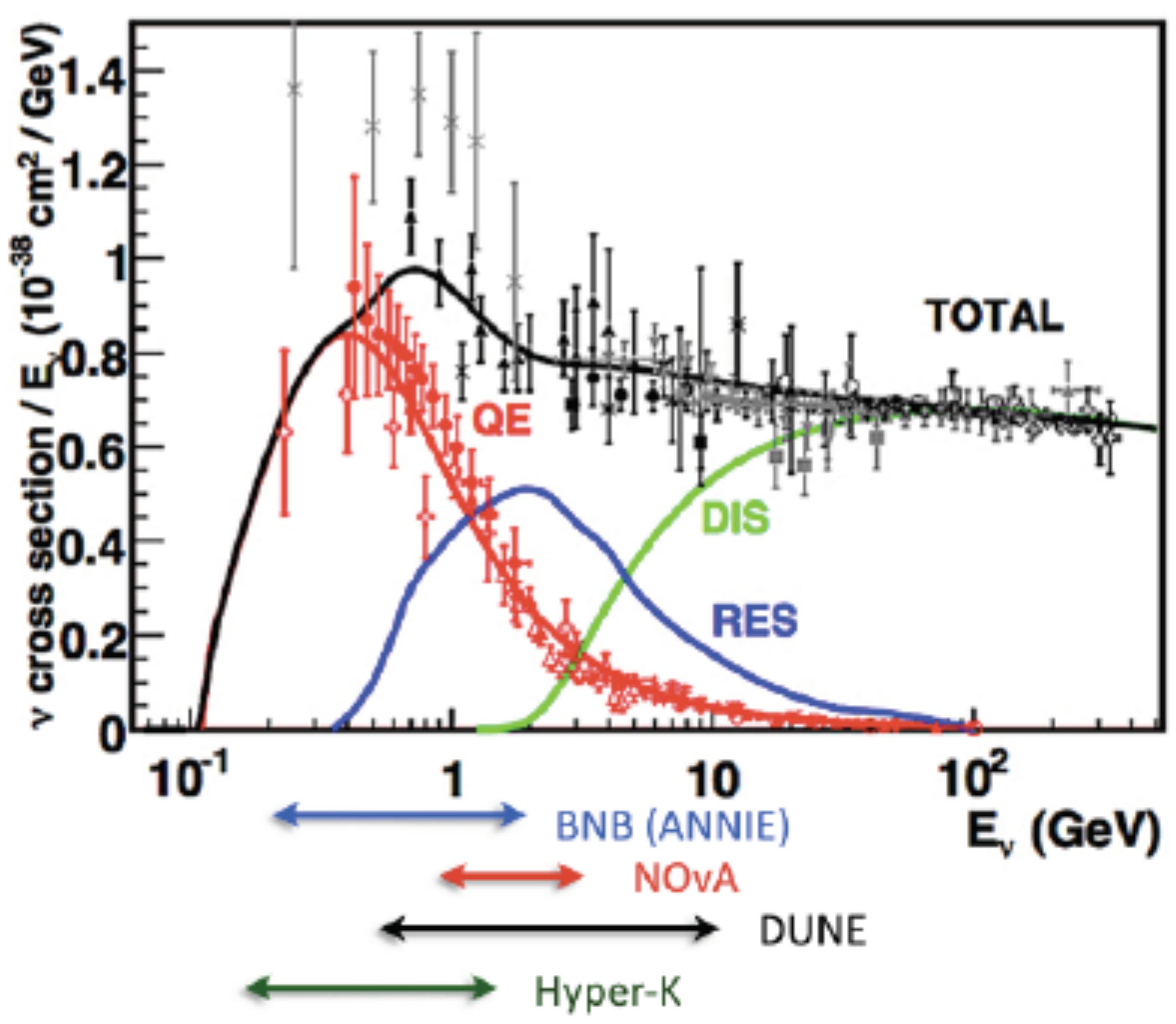
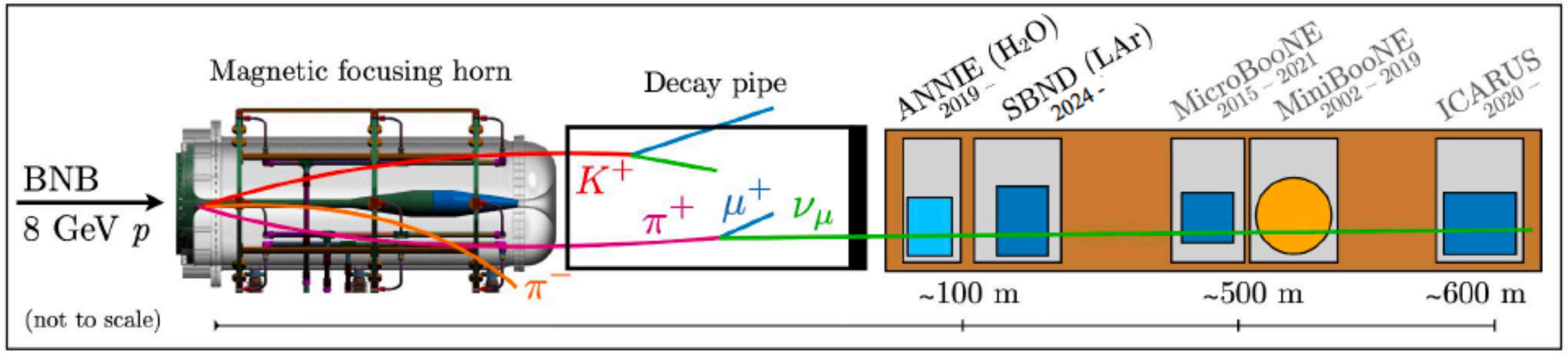
Same neutrino beam as LAr short-baseline experiments:

Precision cross-section comparisons and correlations in hadron production (n/p) with water vs ^{40}Ar.

High-statistics measurement of ν_μ NC interactions:

Constrain background for DSNB searches, &c.





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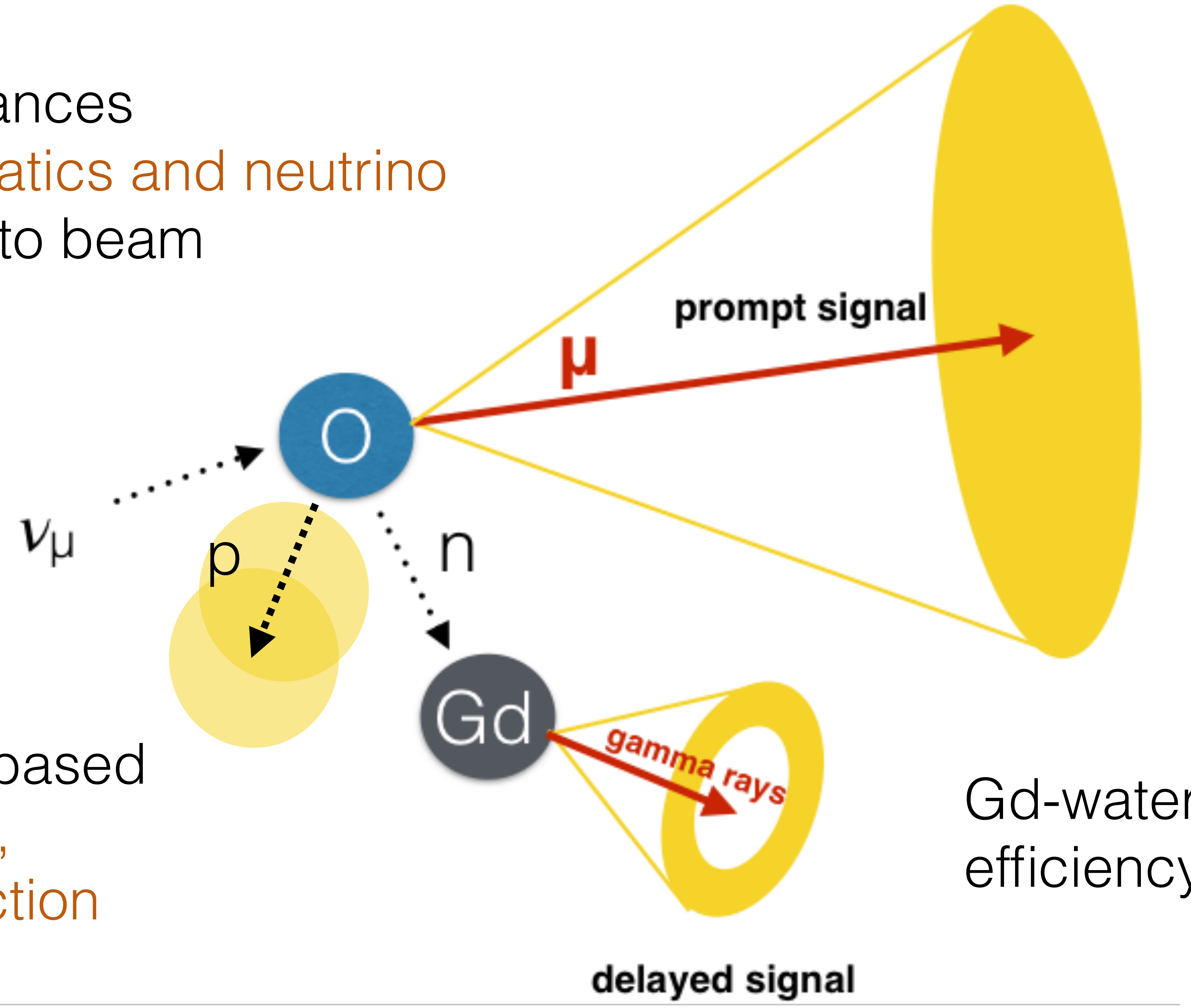
Emerging Technologies and ANNIE

ANNIE's physics goals are entwined with its role as a test-bed for next generation detector technologies (novel photosensors/fast-timing and novel detection media).

Adding LAPPDs to PMTs enhances reconstruction of muon kinematics and neutrino vertex localization transverse to beam (fiducialization)



Deployable volume of water-based liquid scintillator (Calorimetry, access to elements of interaction below Cherenkov threshold)

Gd-water/Gd-WbLS: high-efficiency neutron tagging

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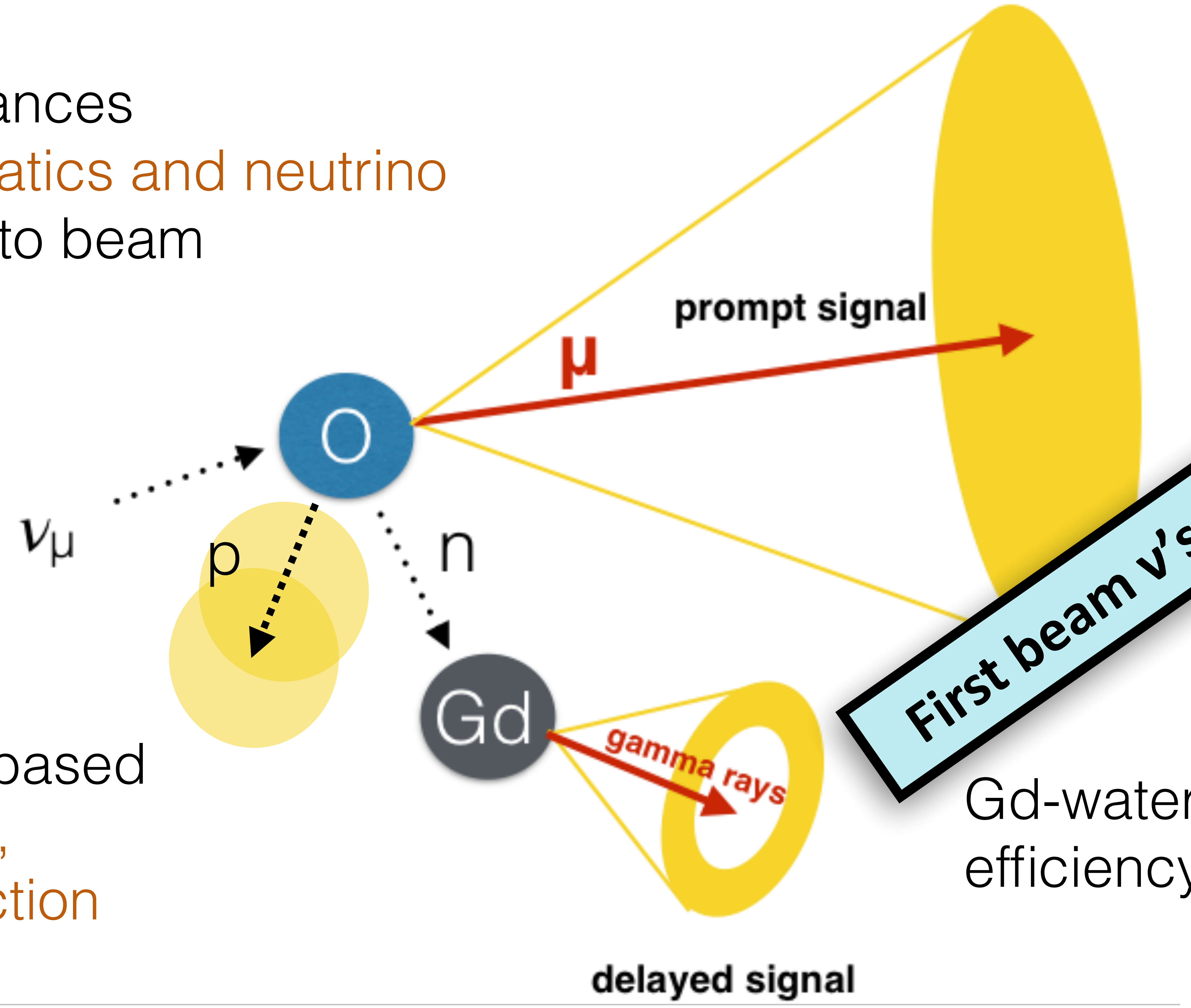

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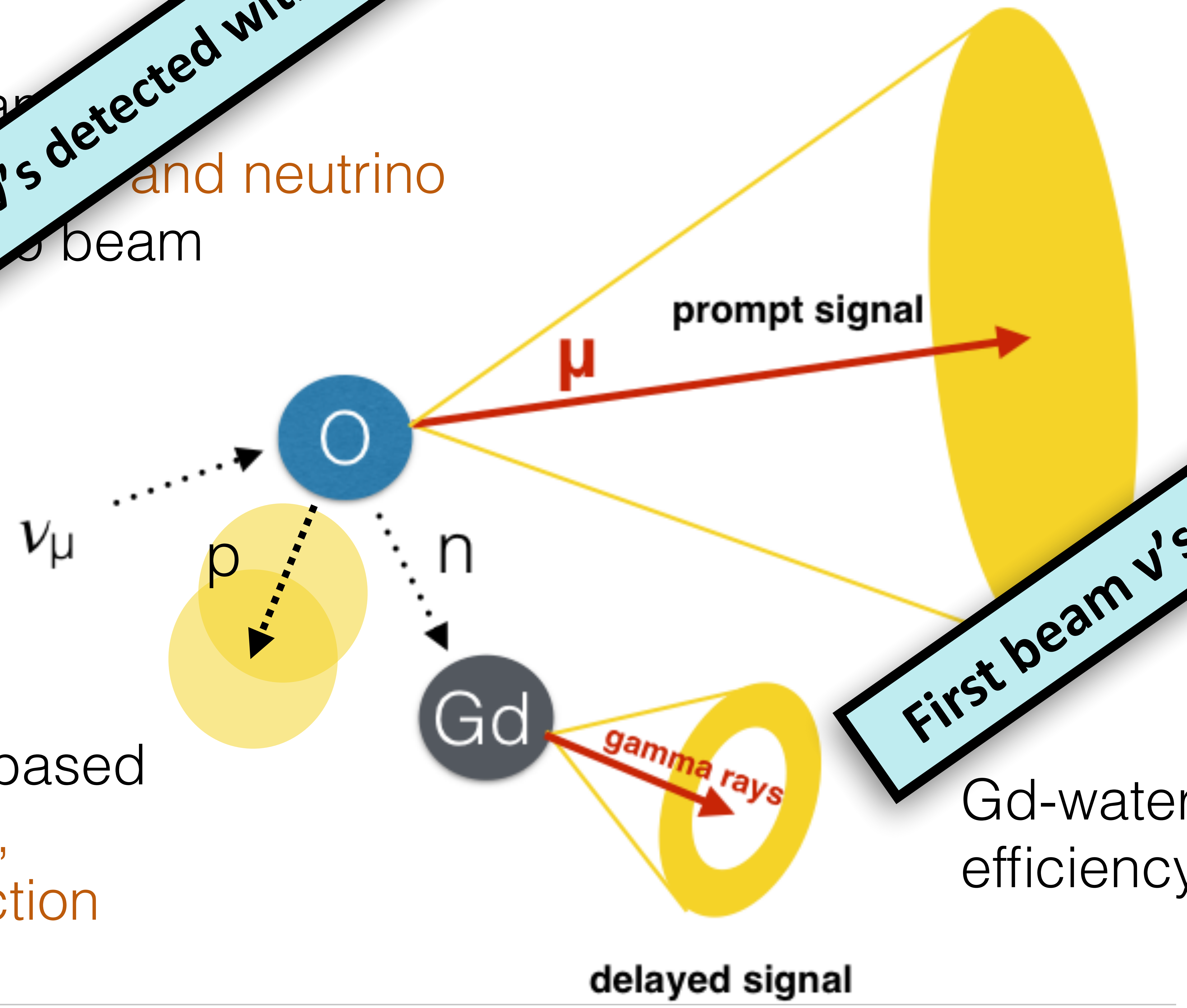

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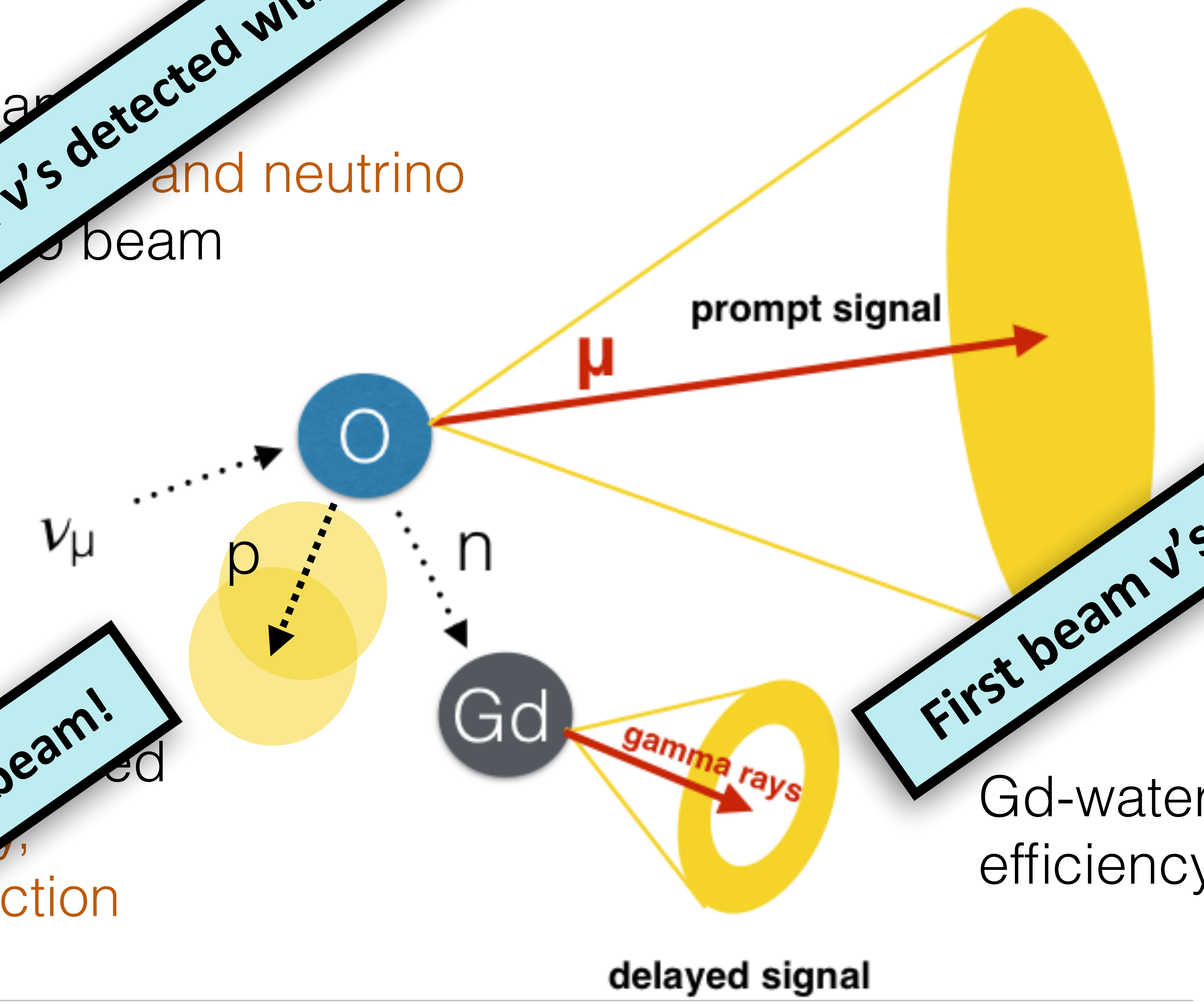

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Time-based Cherenkov/ scintillation separation for WbLS with LAPPDs

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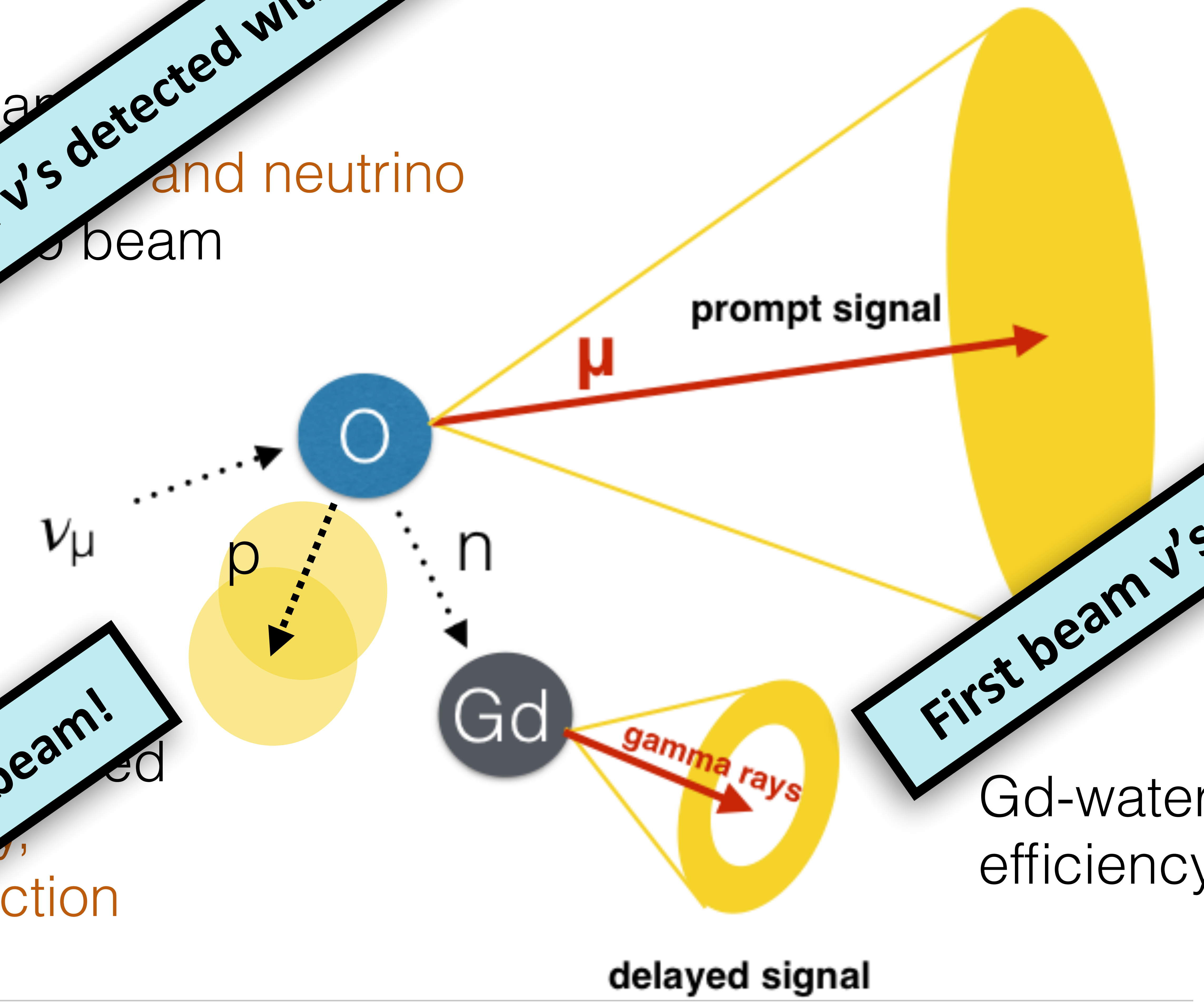

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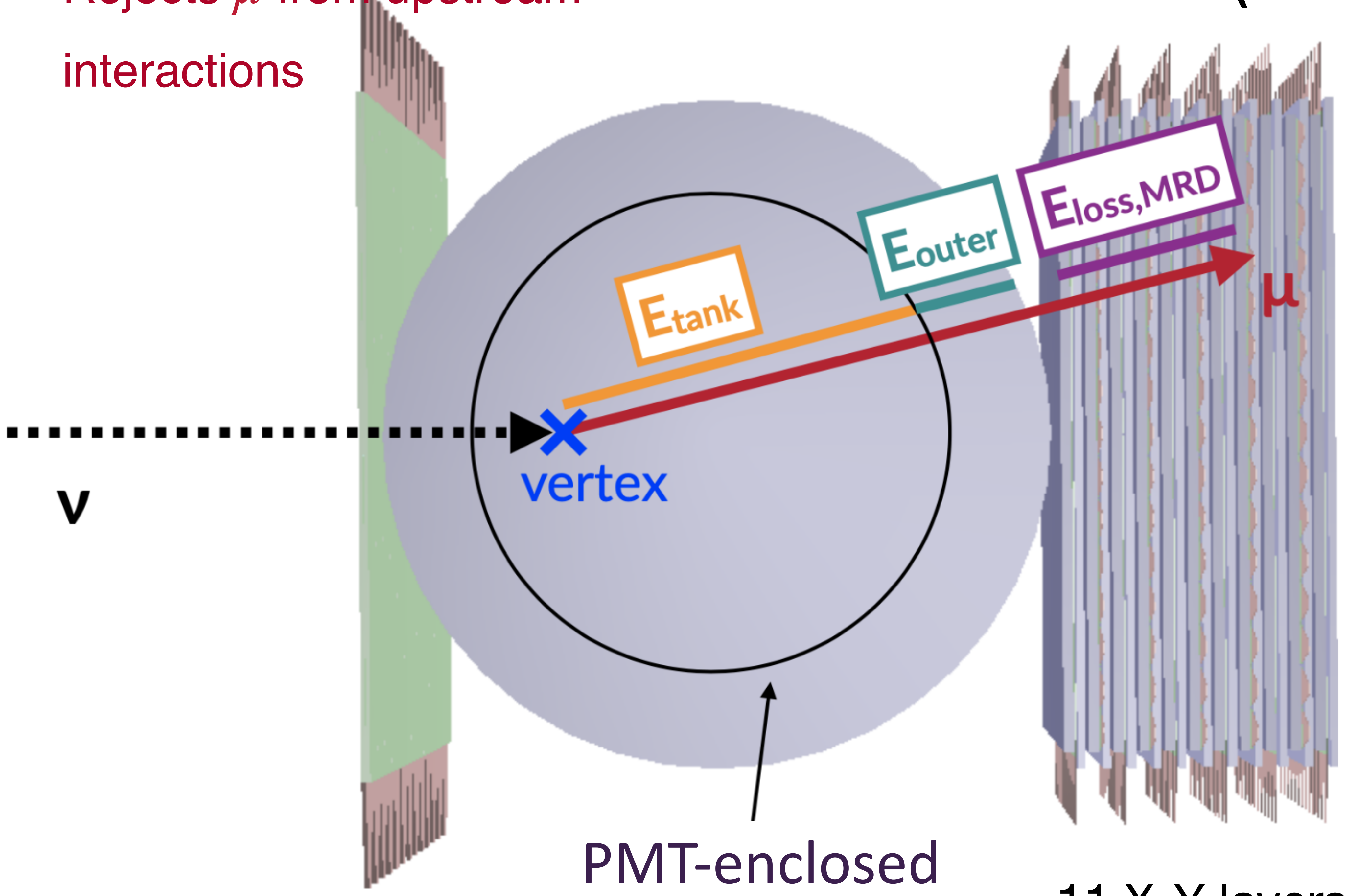
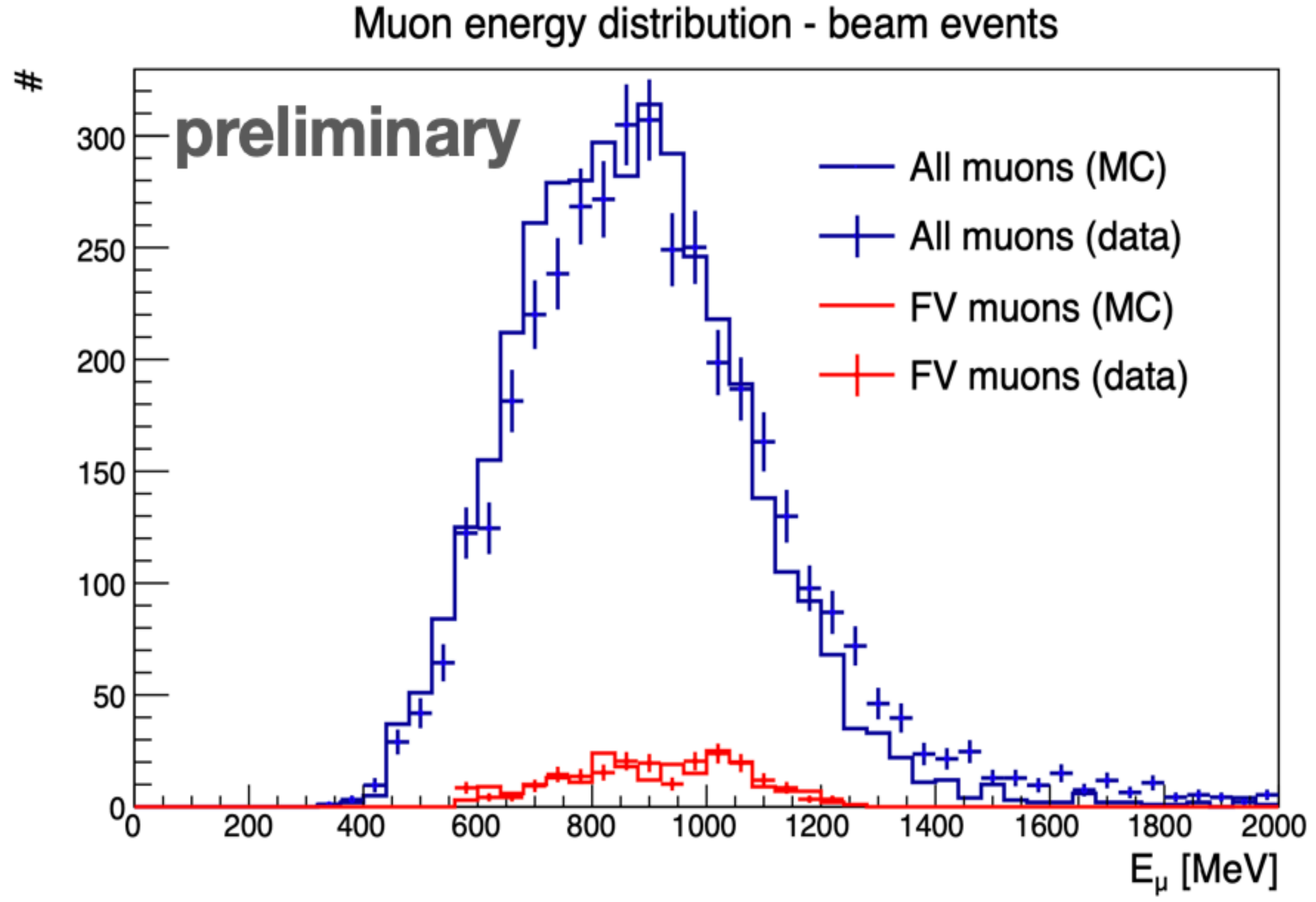
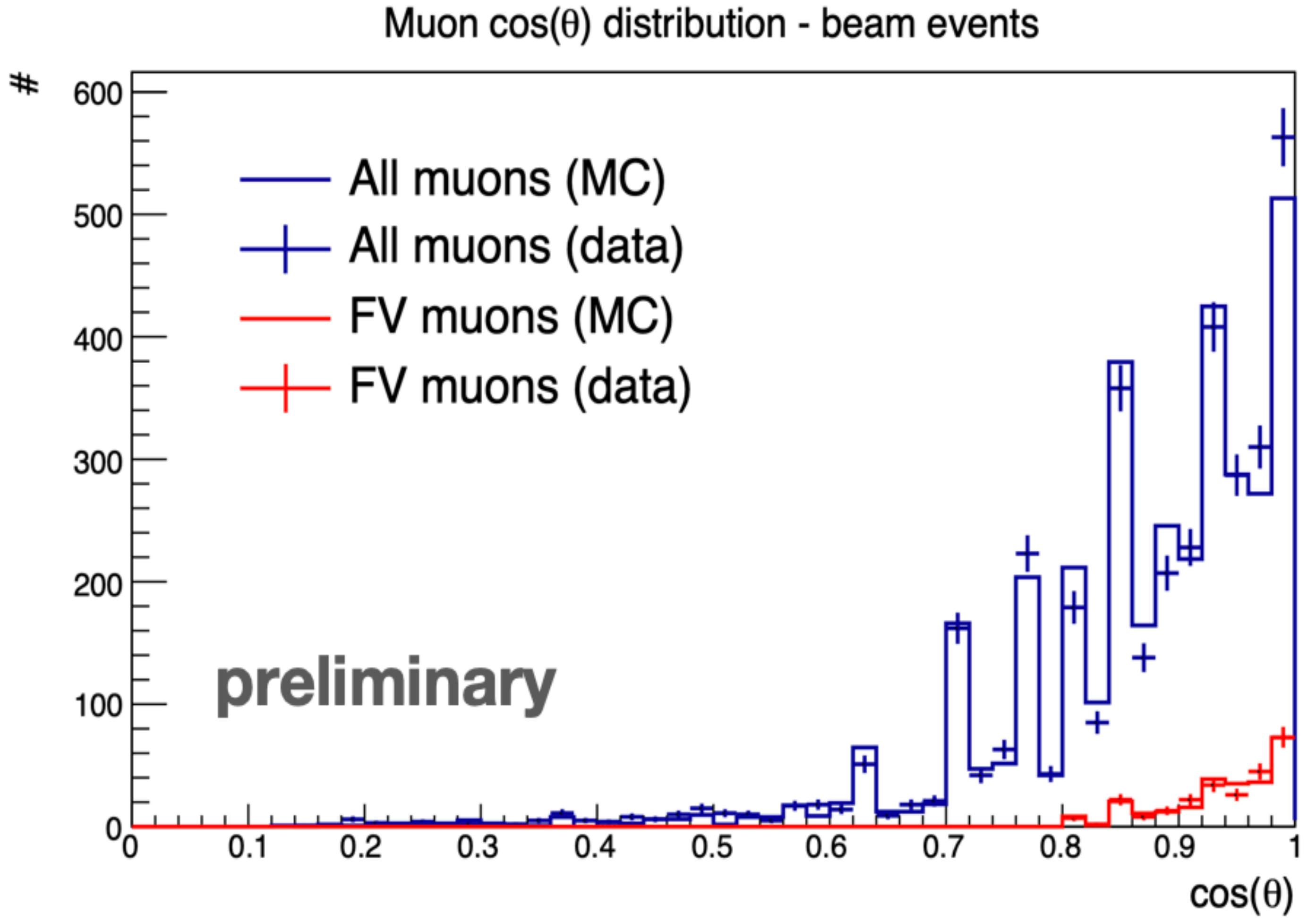
Reconstructing νs in ANNIE

Reconstruction of final-state muon scattering angle using PMTs in tank and MRD track information

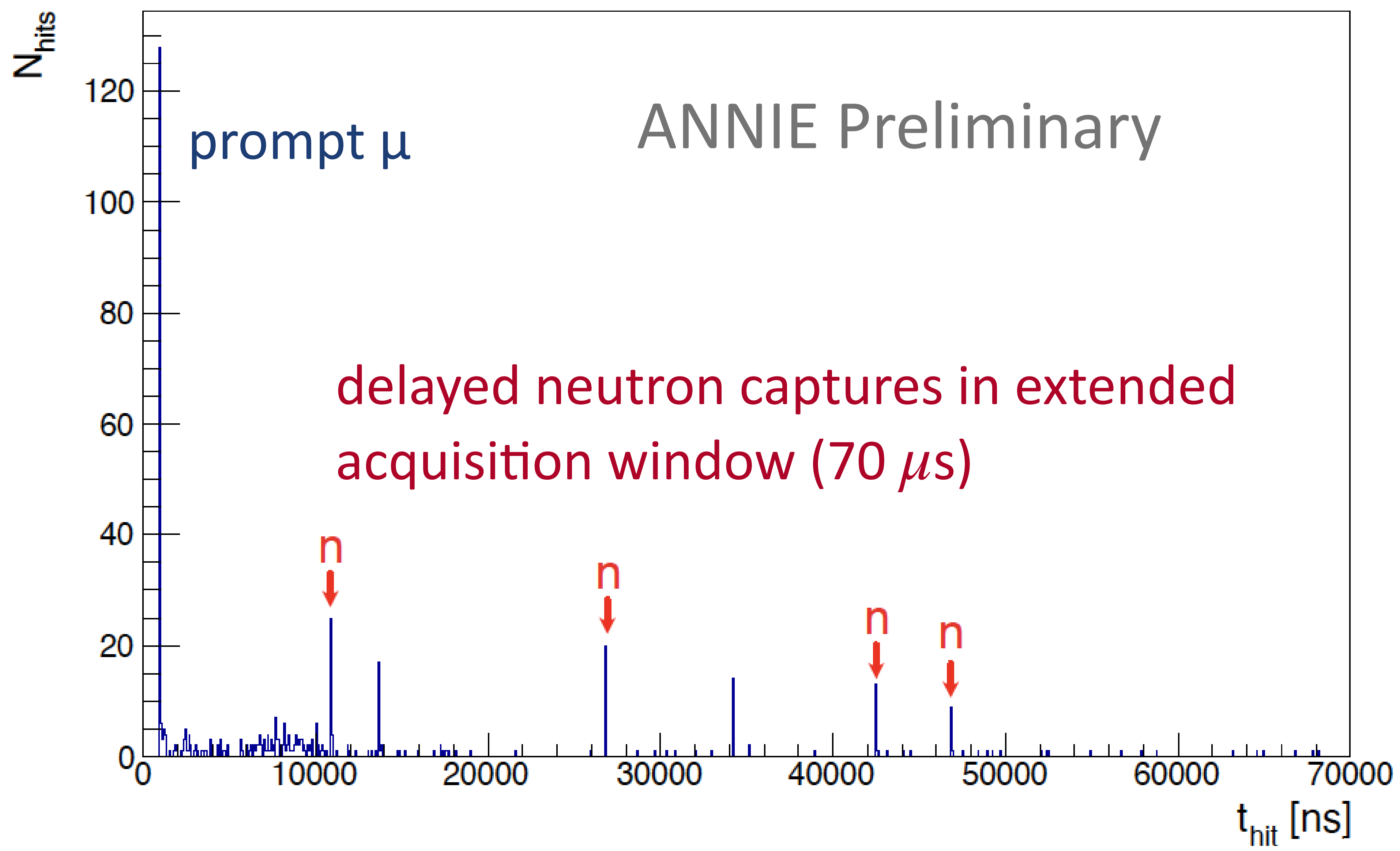
132 PMTs (8”-11”)







Detecting neutrons in ANNIE



Sample event
M. Nieslony, PhD thesis
(2022)

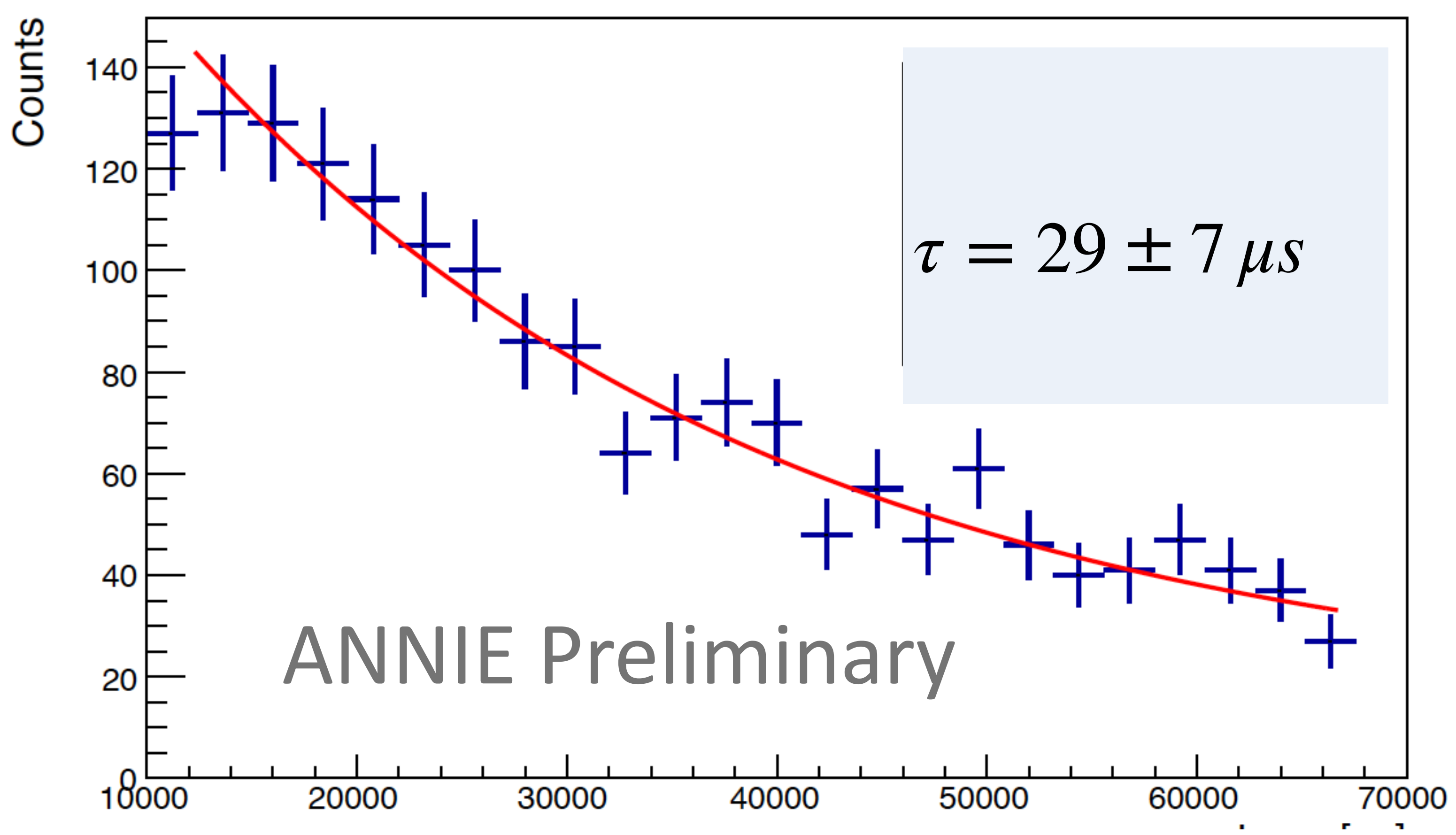
	H	Gd
σ	0.33 bn	49000 bn
τ	300 μs	30 μs
E_γ	2.2 MeV	8 MeV

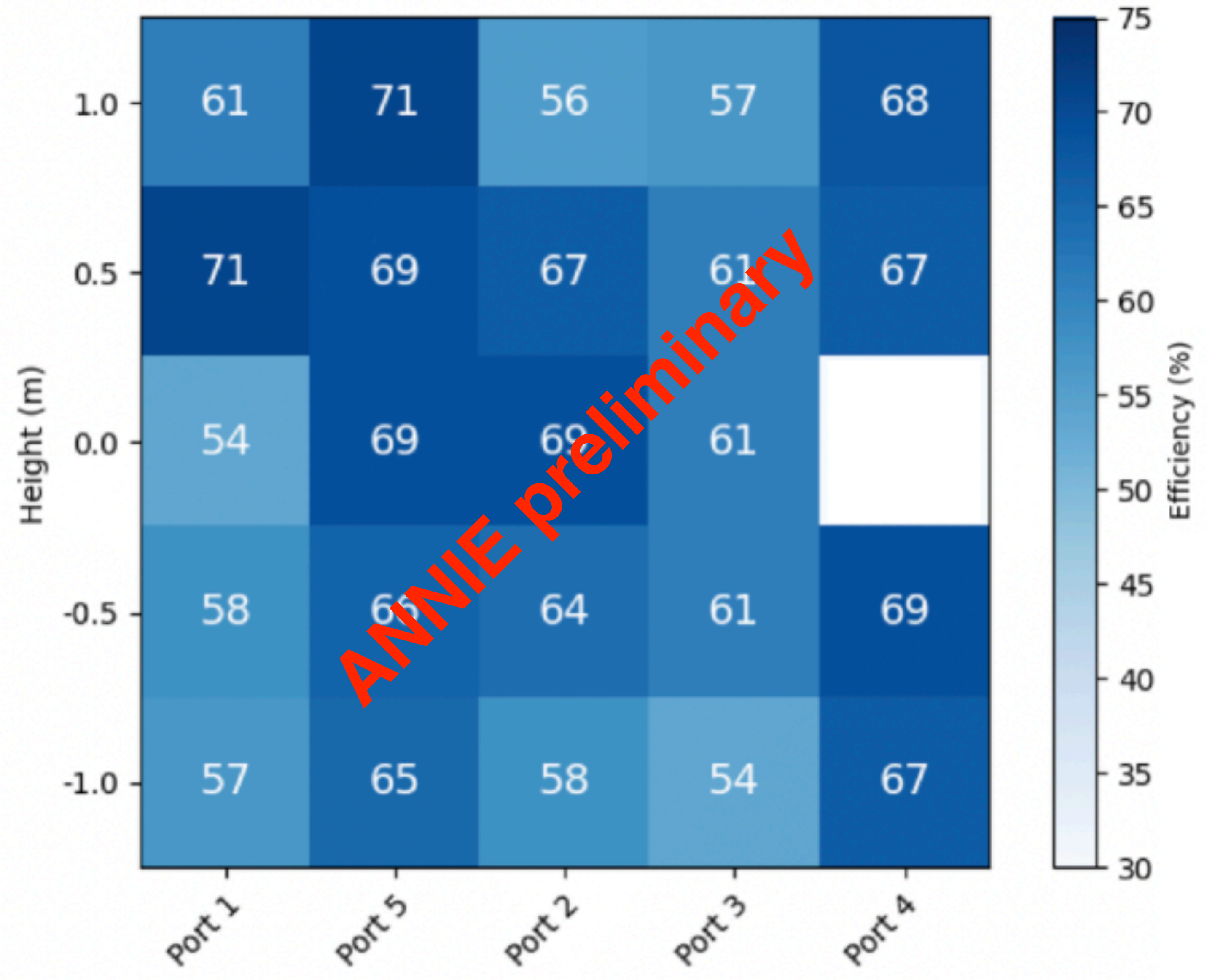
Tank PMTs used to detect neutrons

Neutron capture time profile from beam data agrees well with prediction for nominal 0.1% Gd concentration.

Position dependent neutron capture efficiency has been measured to be consistent with expectations: ~55-70%.

1.5 months of beam data





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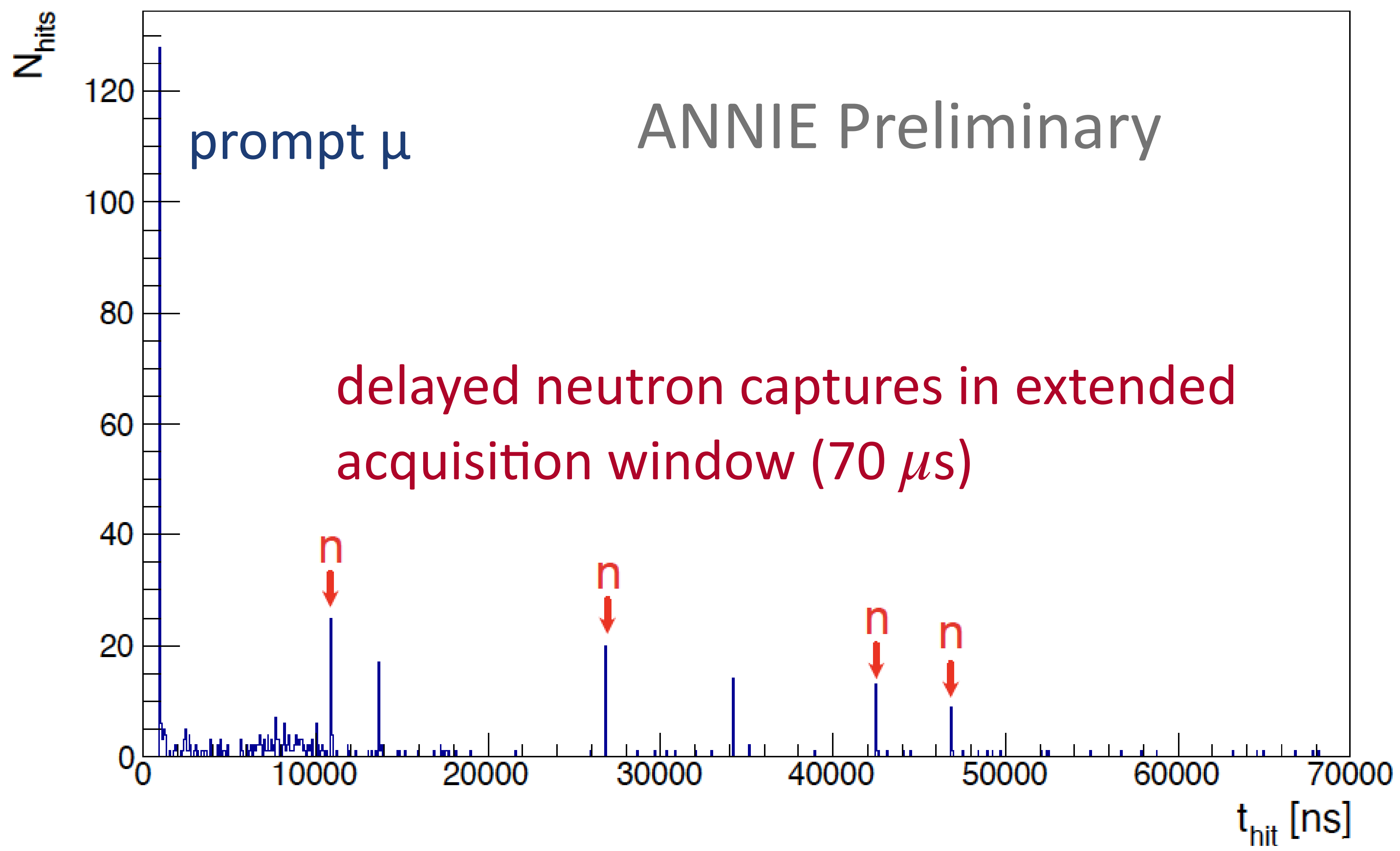

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Scaffolding of neutron multiplicity measurement in place

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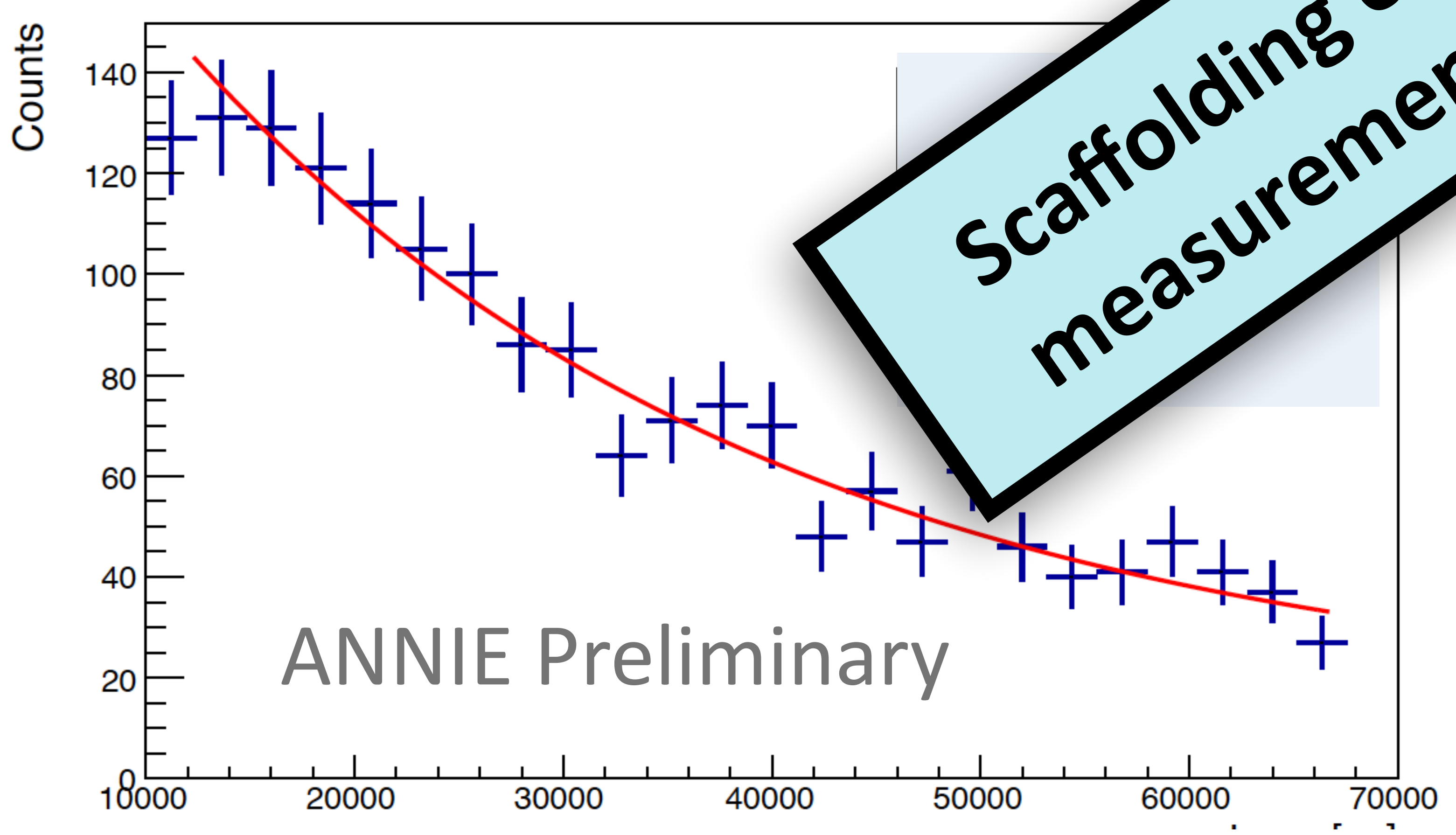
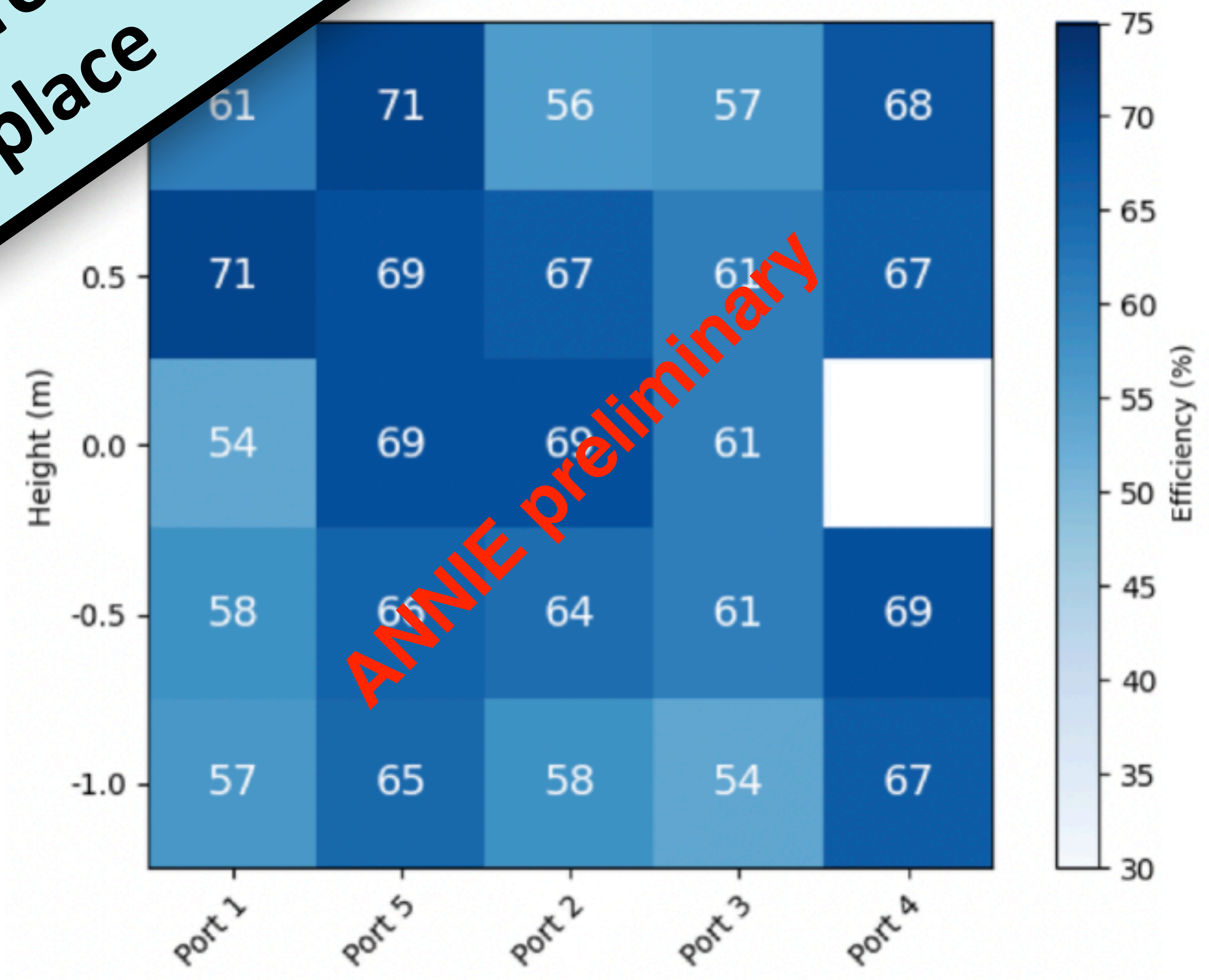


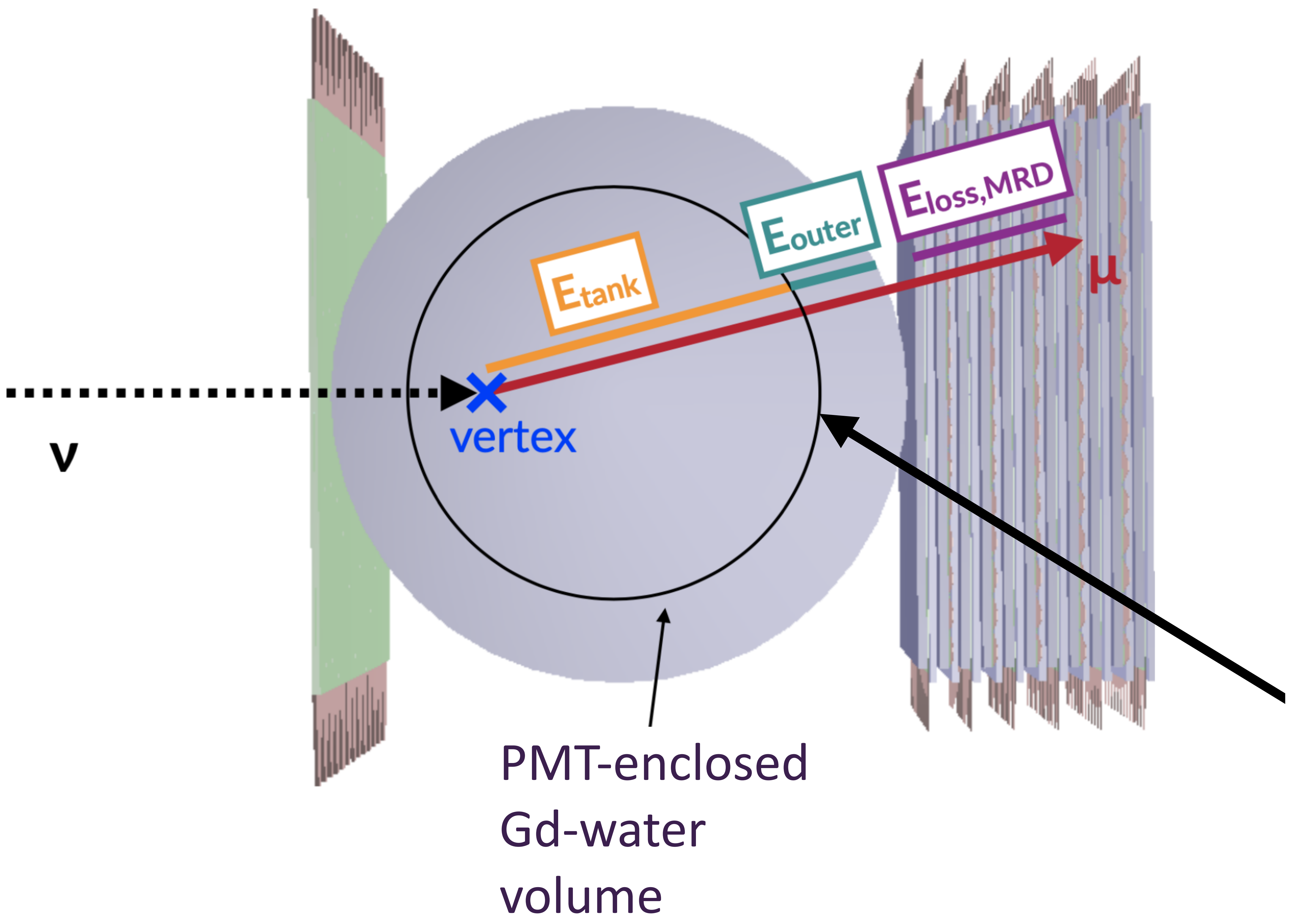


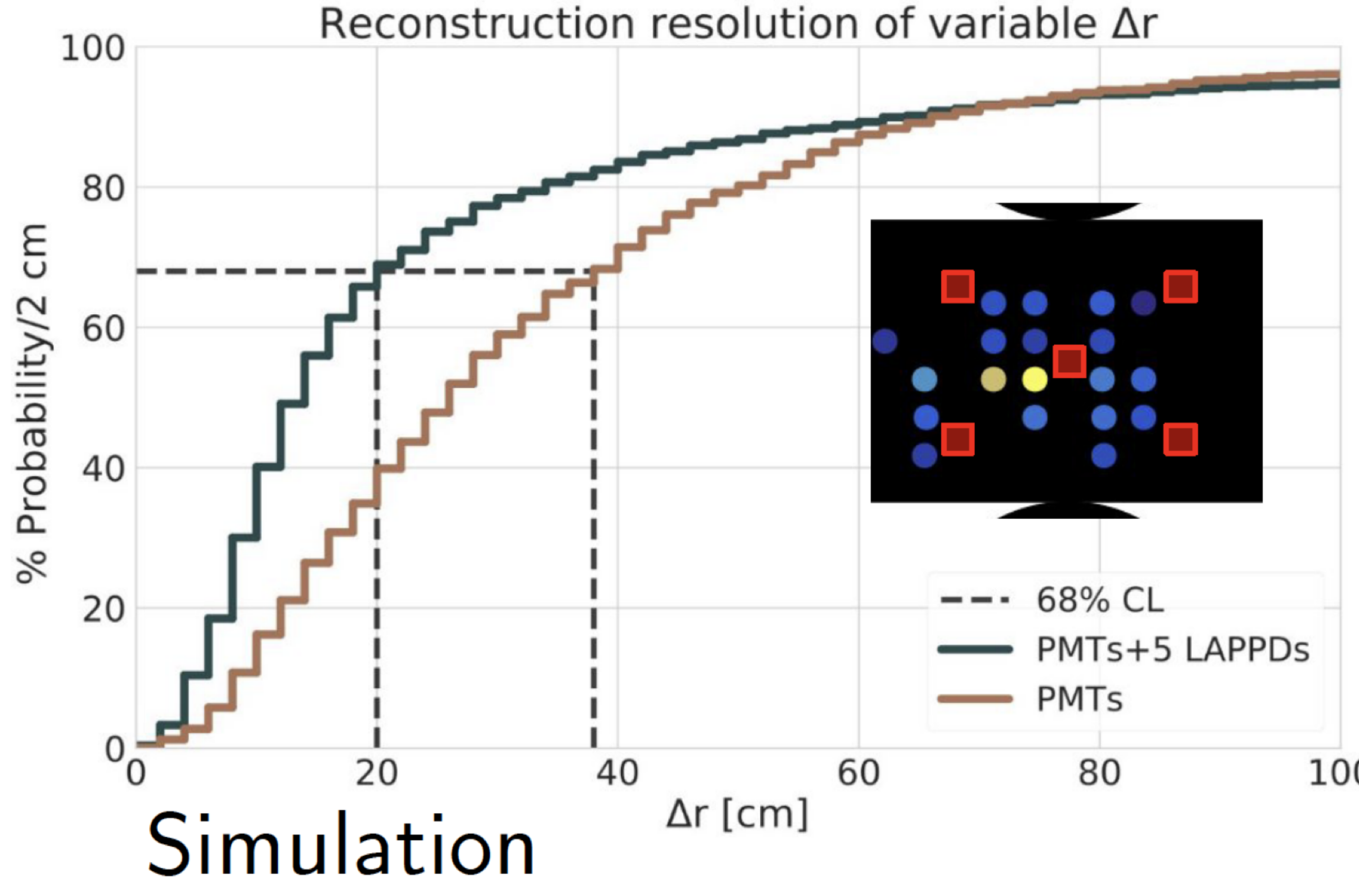
Reconstructing νs in ANNIE: Benefit of LAPPDs

Adding LAPPDs to PMTs enhances reconstruction of muon kinematics and neutrino vertex localization transverse to beam

Large Area Picosecond Photodetectors

Microchannel-plate-based amplification stages permit fast timing (< 100 ps TTS) and sub-cm spatial resolution





LAPPDs on wall downstream of beam

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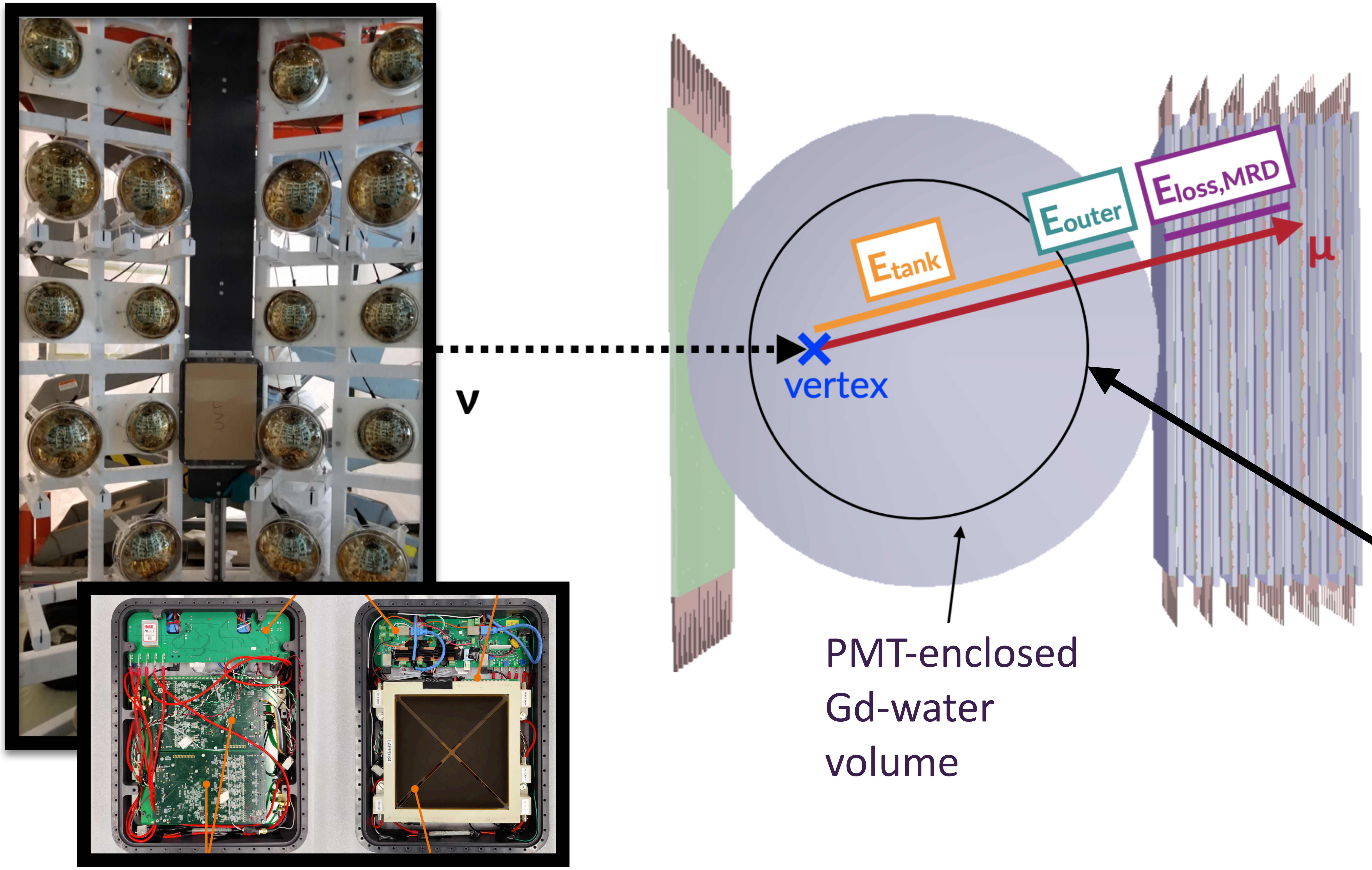

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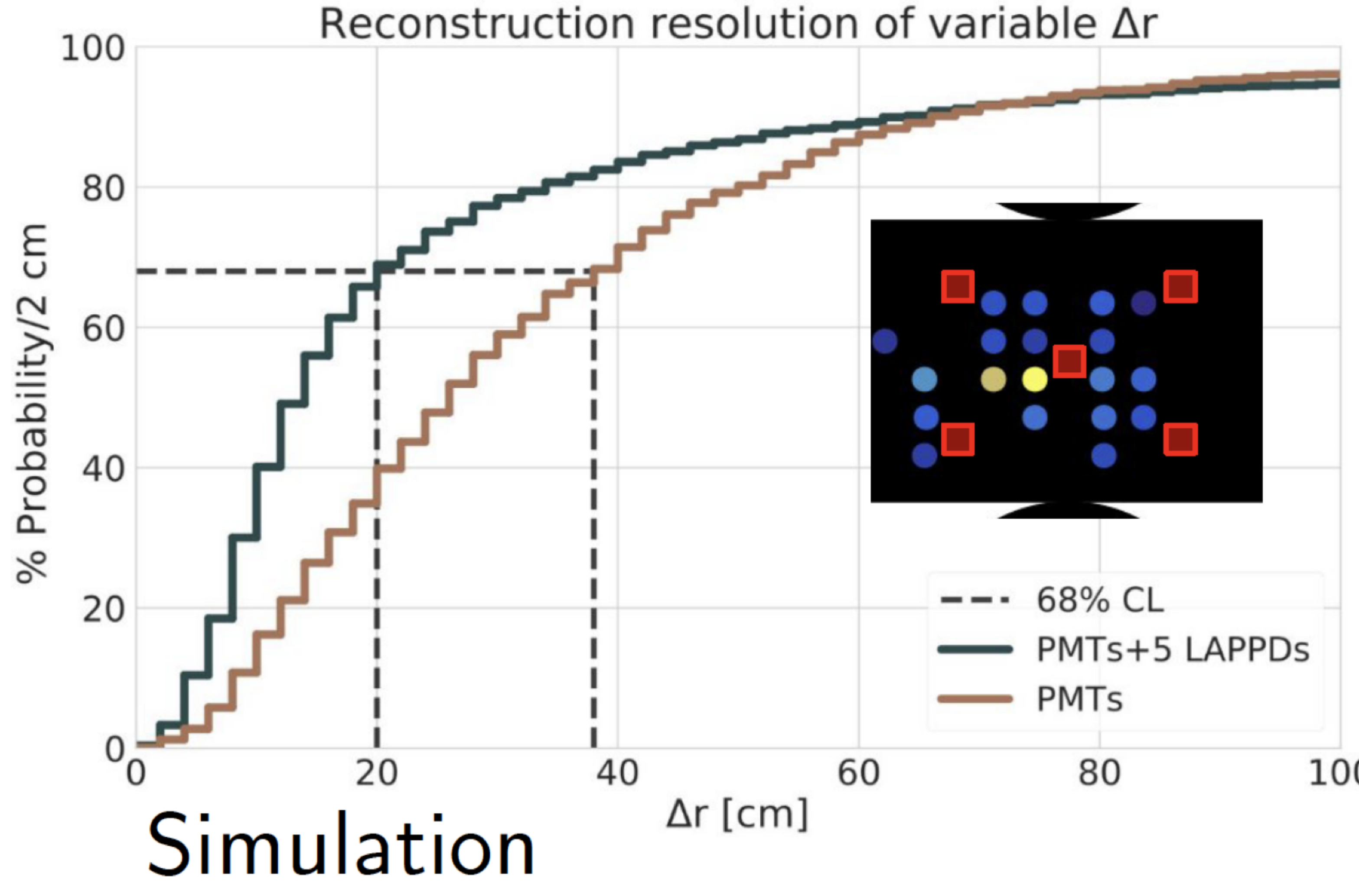

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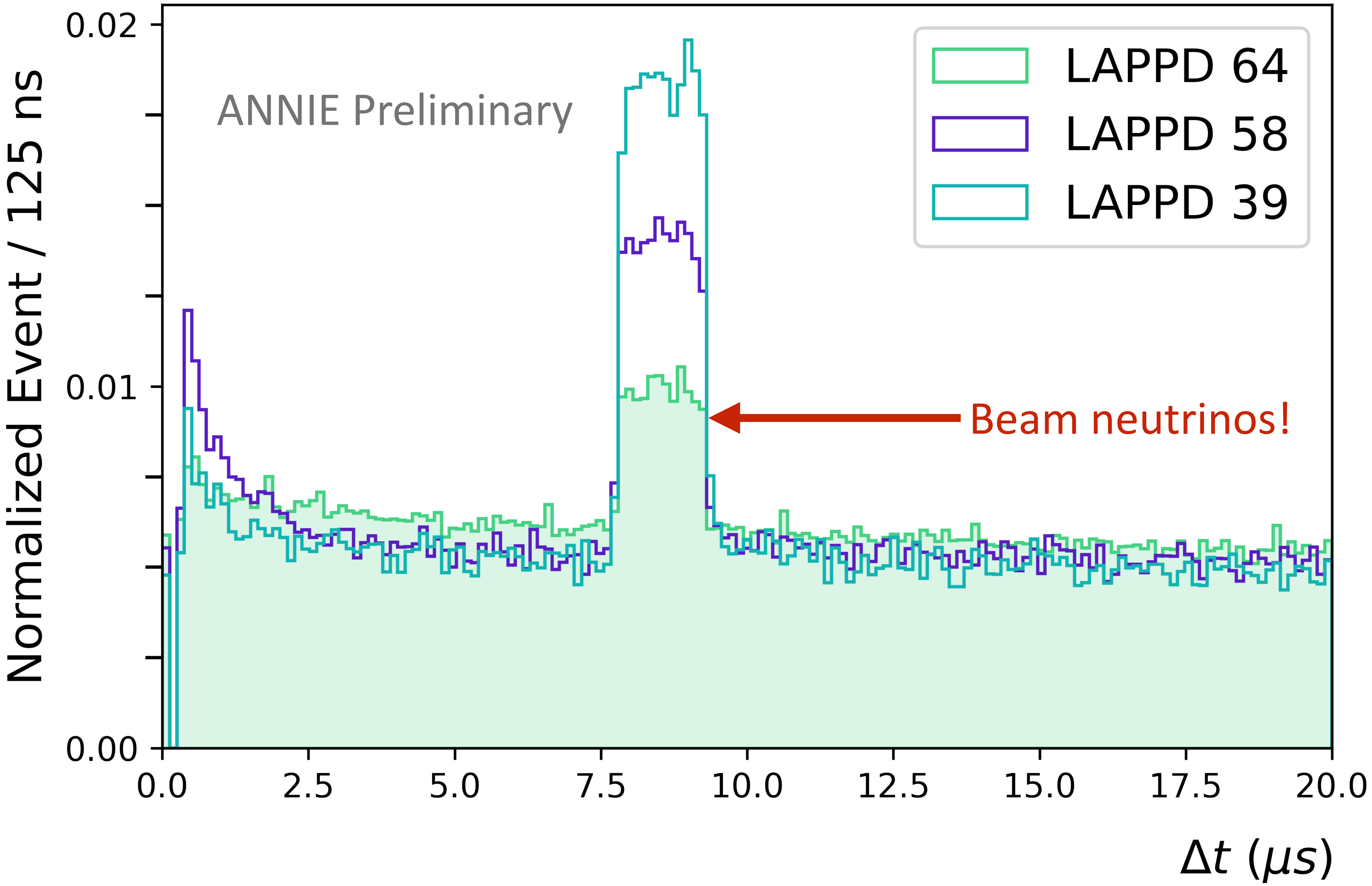
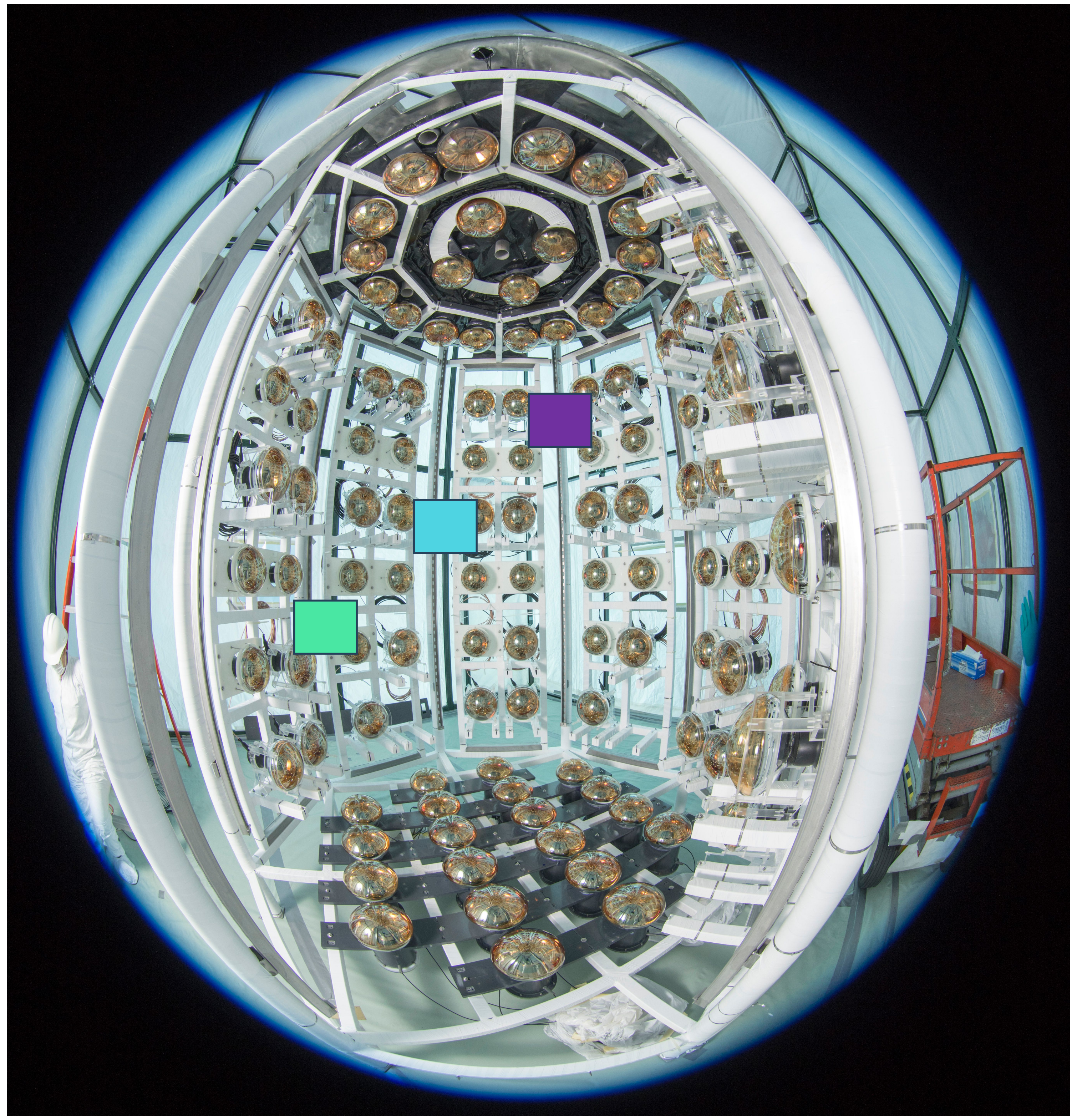
First neutrinos observed with multiple LAPPDs





LAPPD triggers are permitted in a 20 μs window around the BNB beam spill

1.6 μsec wide excess corresponds to LAPPD data frames in time with spill

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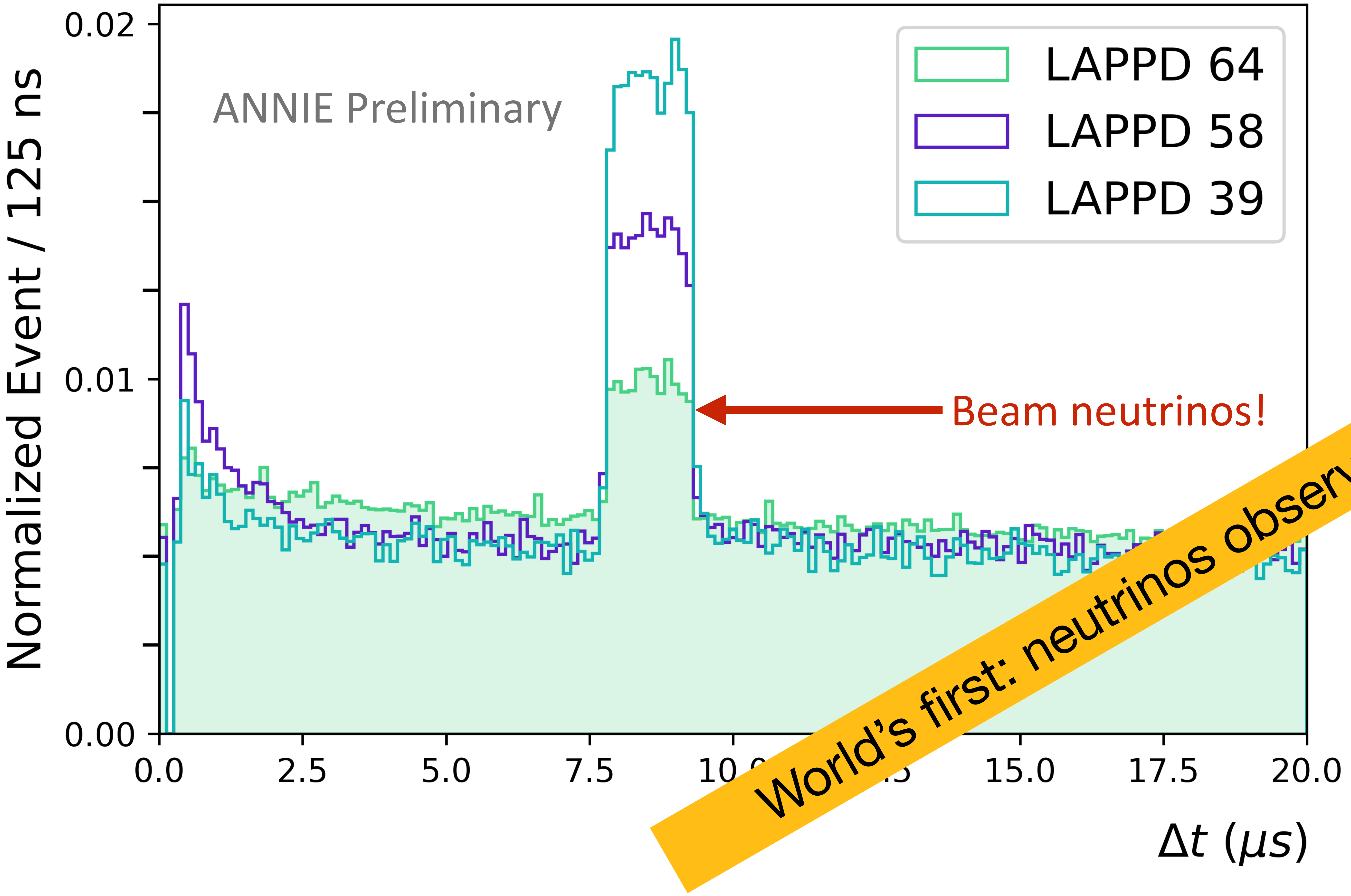

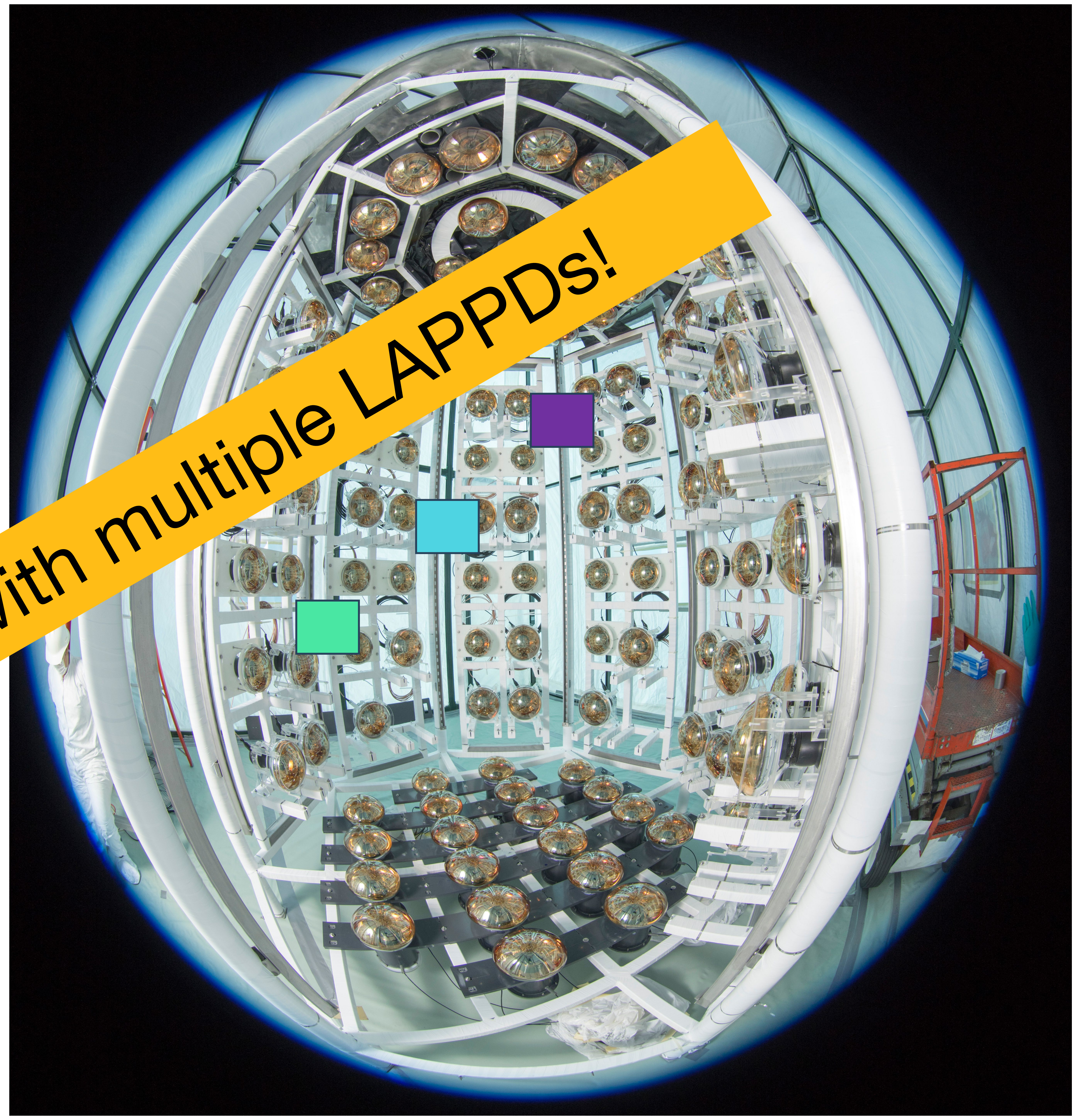

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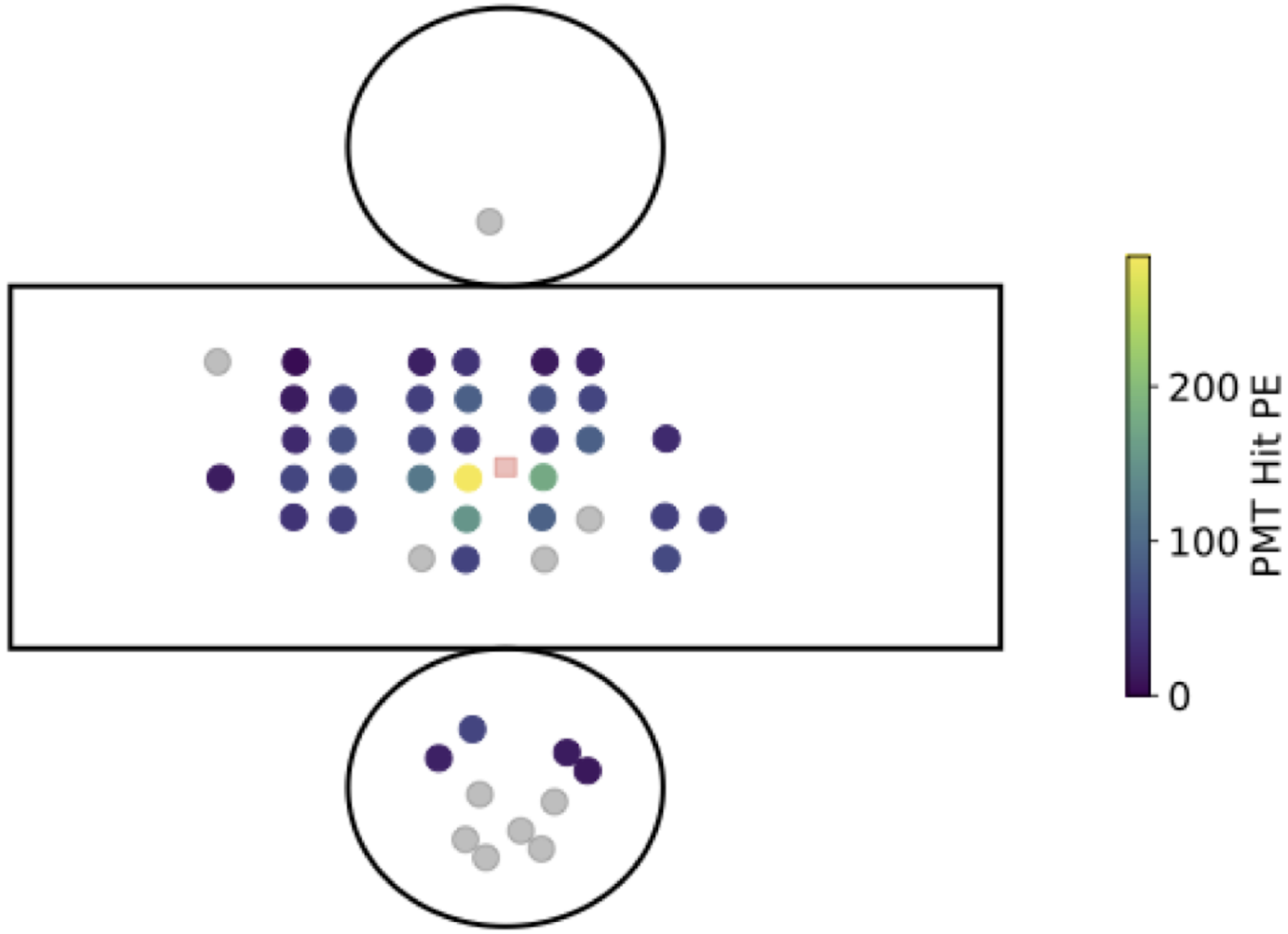
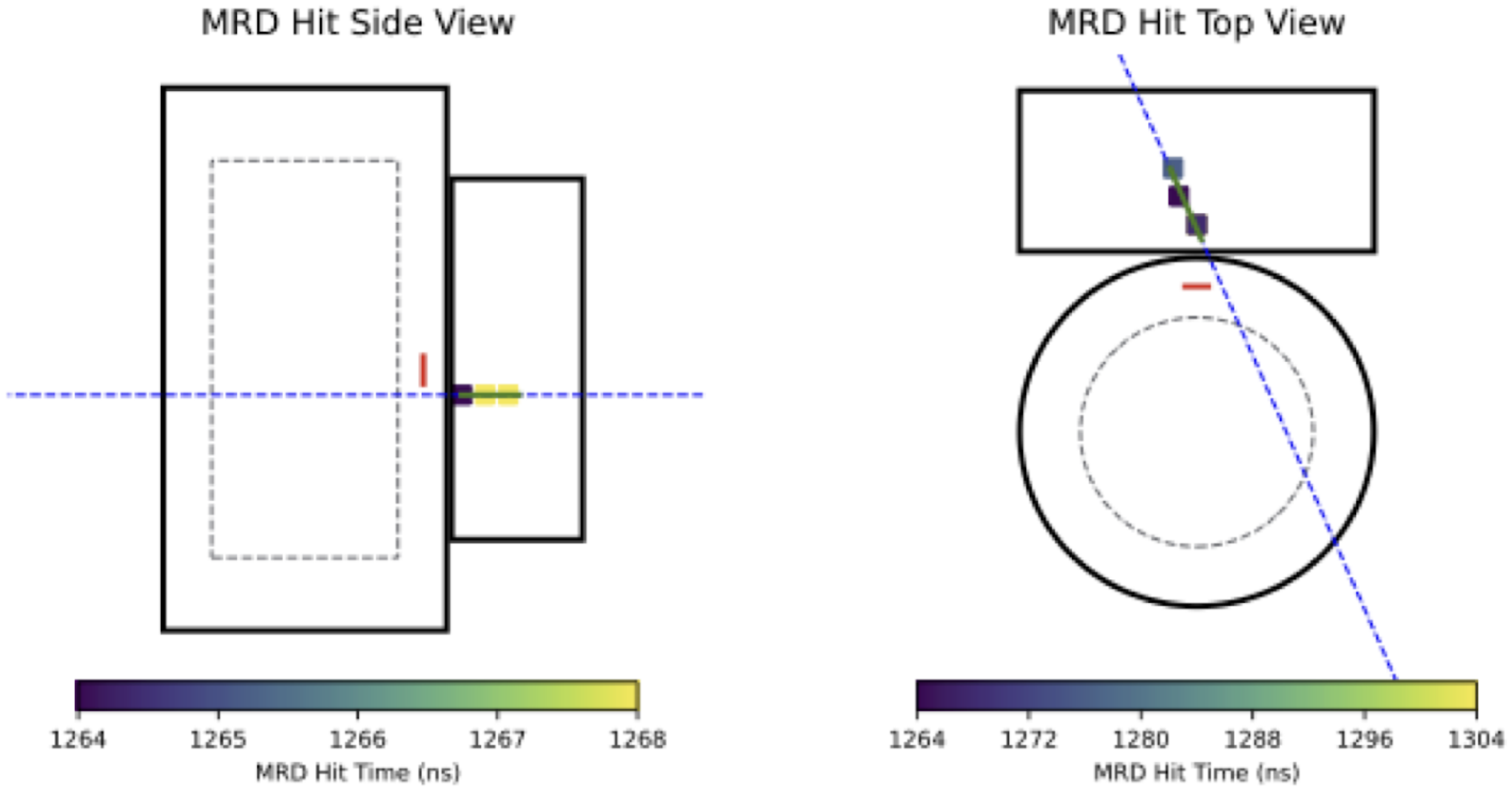
An ANNIE neutrino interaction candidate

Sample event taken from initial single LAPPD run (~8 x 10^{19} POT).





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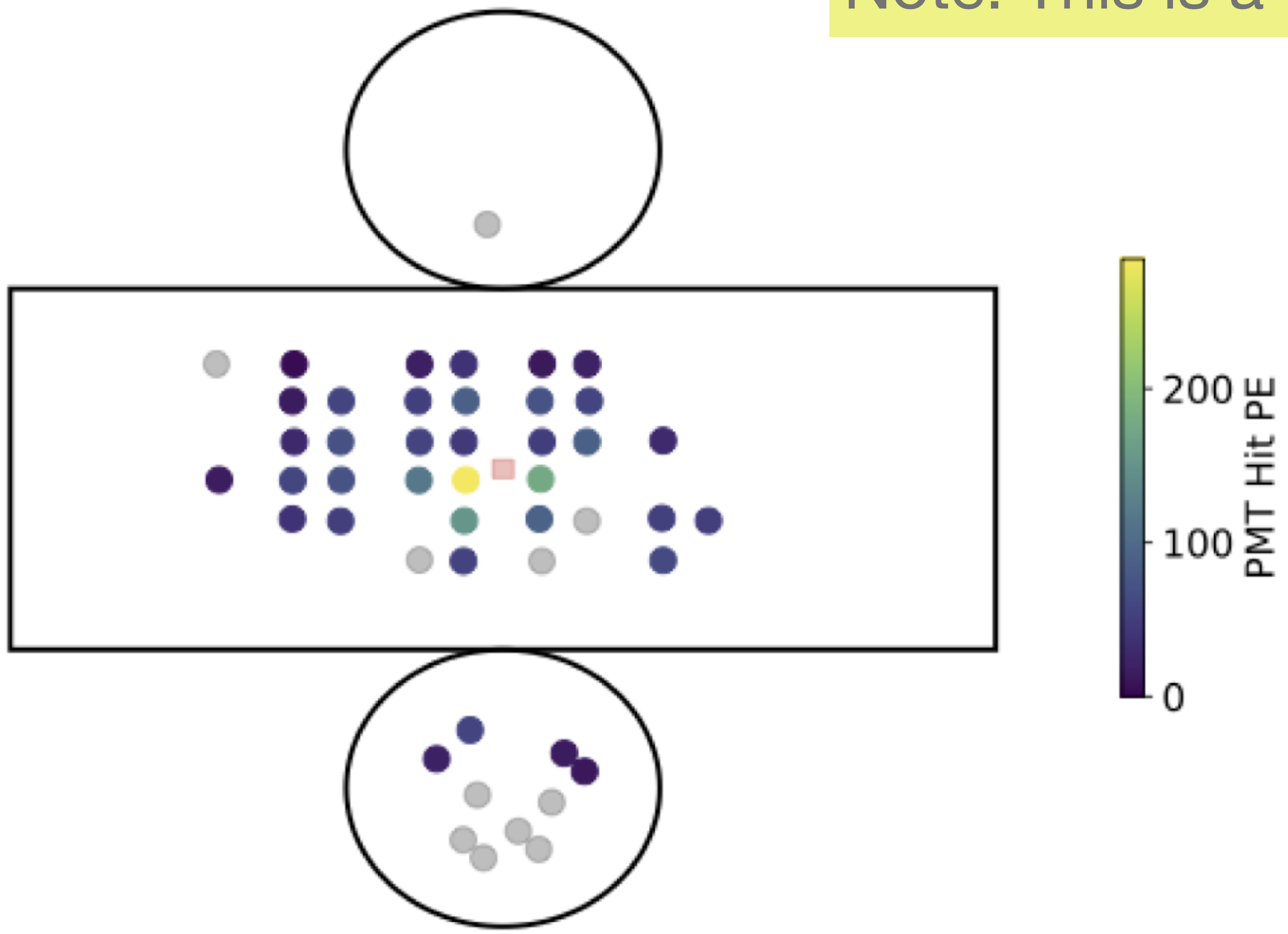

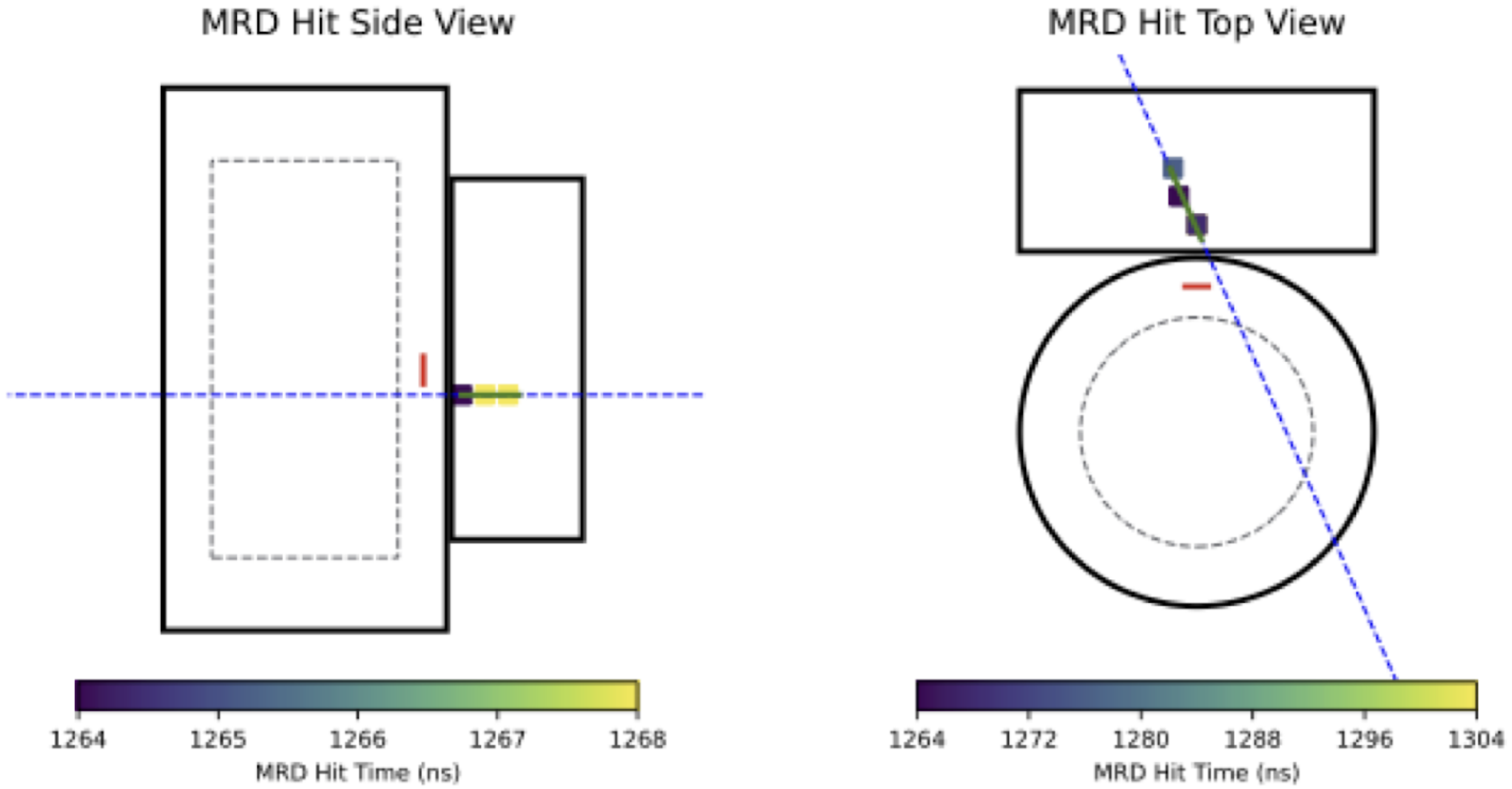

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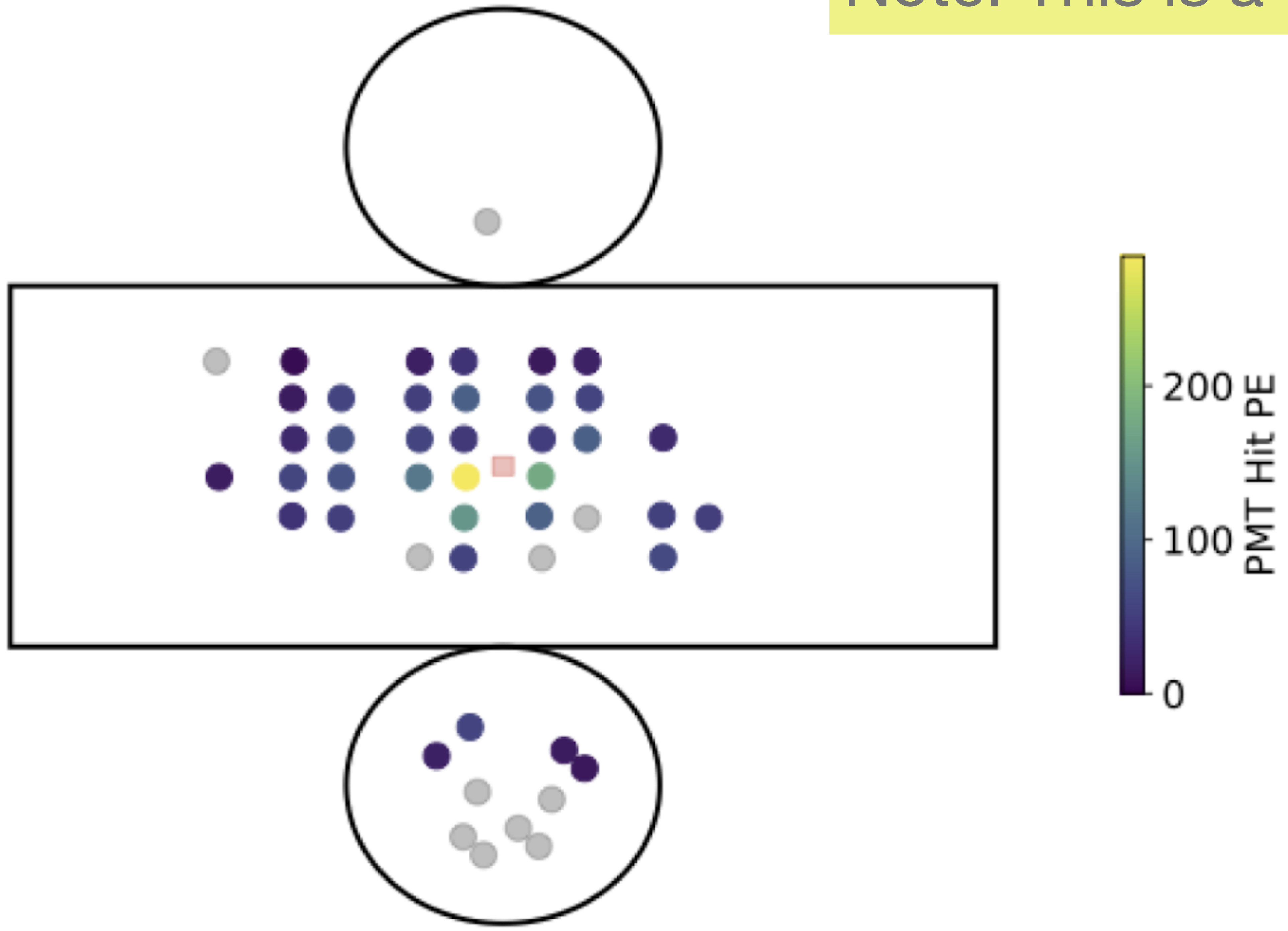
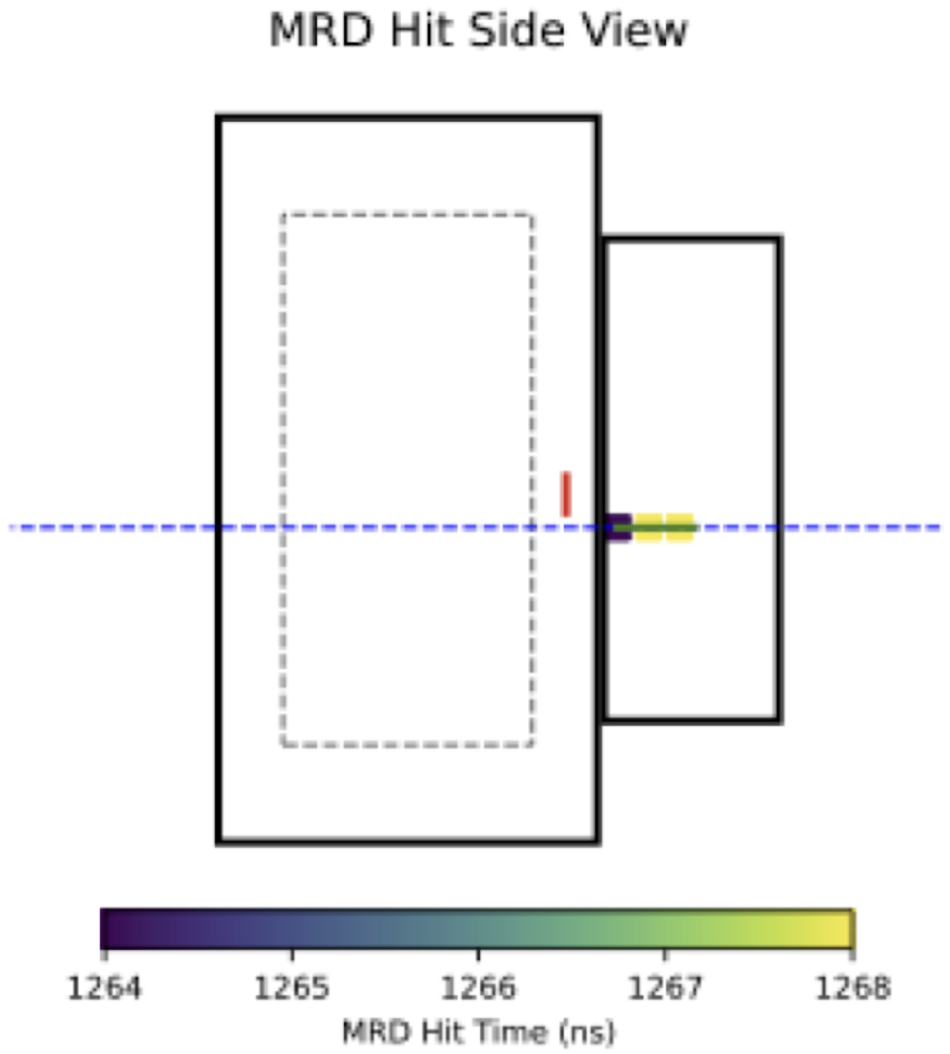
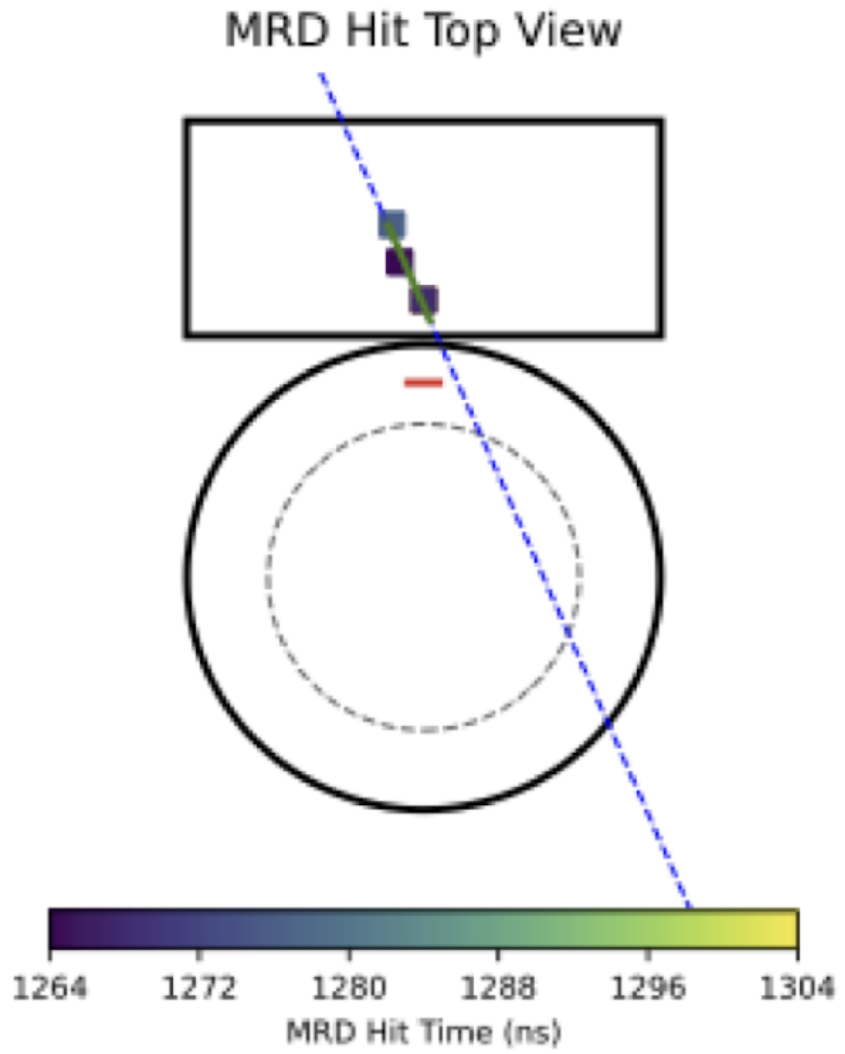
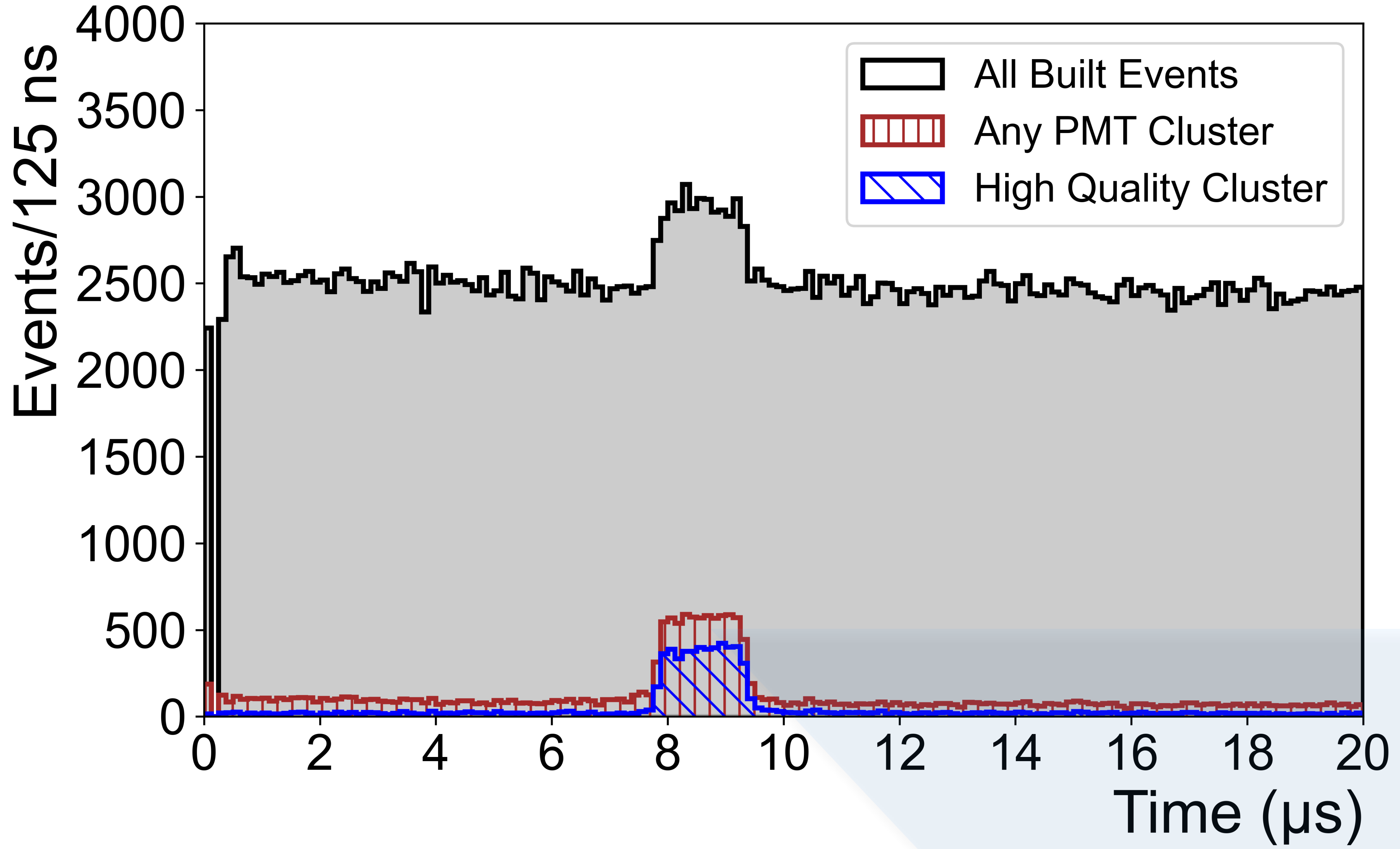






With all ANNIE systems (PMT, LAPPDs and MRD) integrated we can select a sample to study LAPPD performance with respect to independent information from other subsystems.

Analyzing LAPPD observations of beam neutrinos

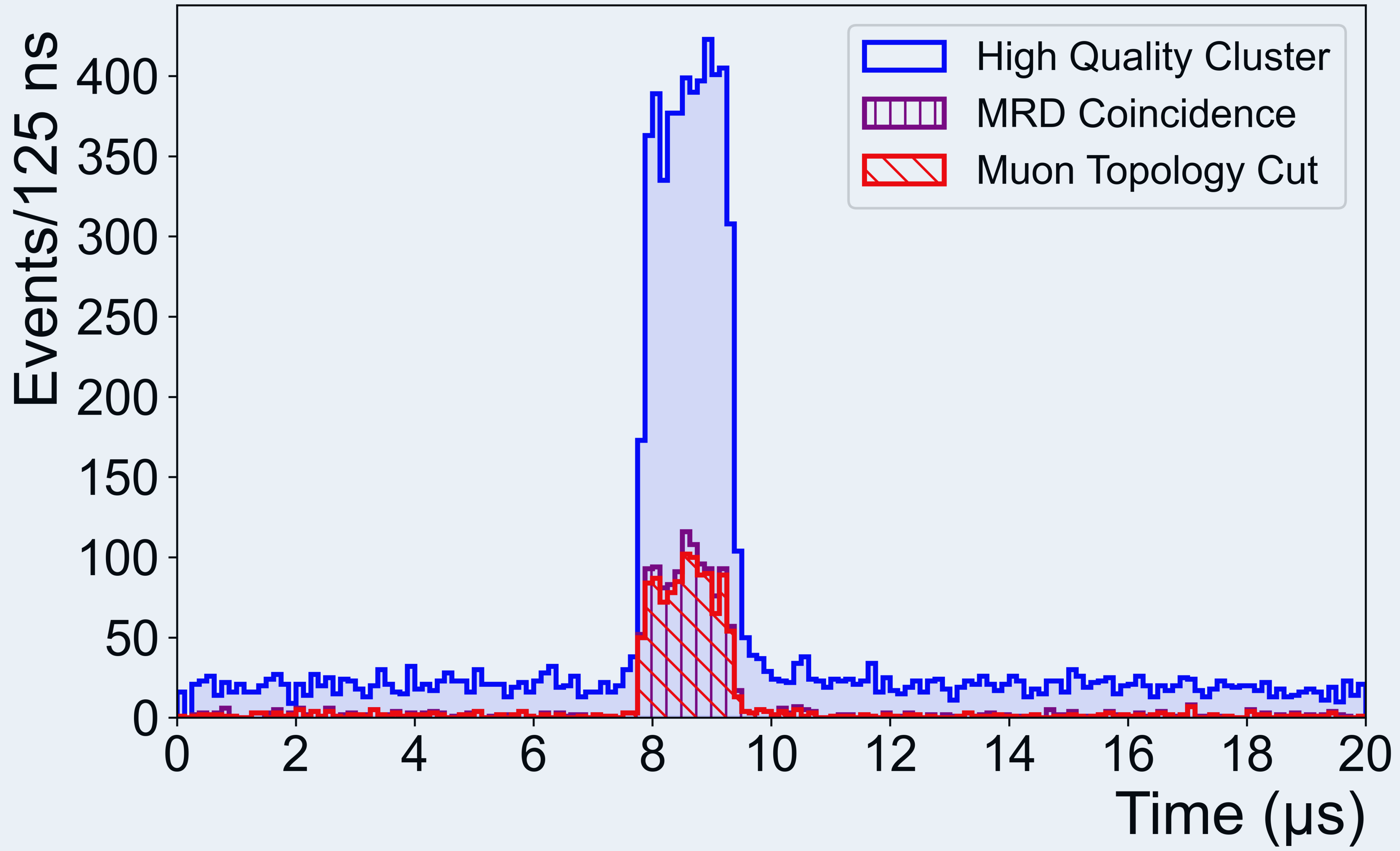


LAPPD triggers are issued in a 20 μs window around the beam spill.

We can leverage multiple detector systems to eliminate dark noise with near 100% efficiency.

Requiring a cluster of PMT activity, an MRD coincidence and a Cherenkov disk that overlaps the LAPPD provides a high-purity sample (~1000 events).

Requiring no activity in front veto restricts to CC ν interactions in tank (~450 events)



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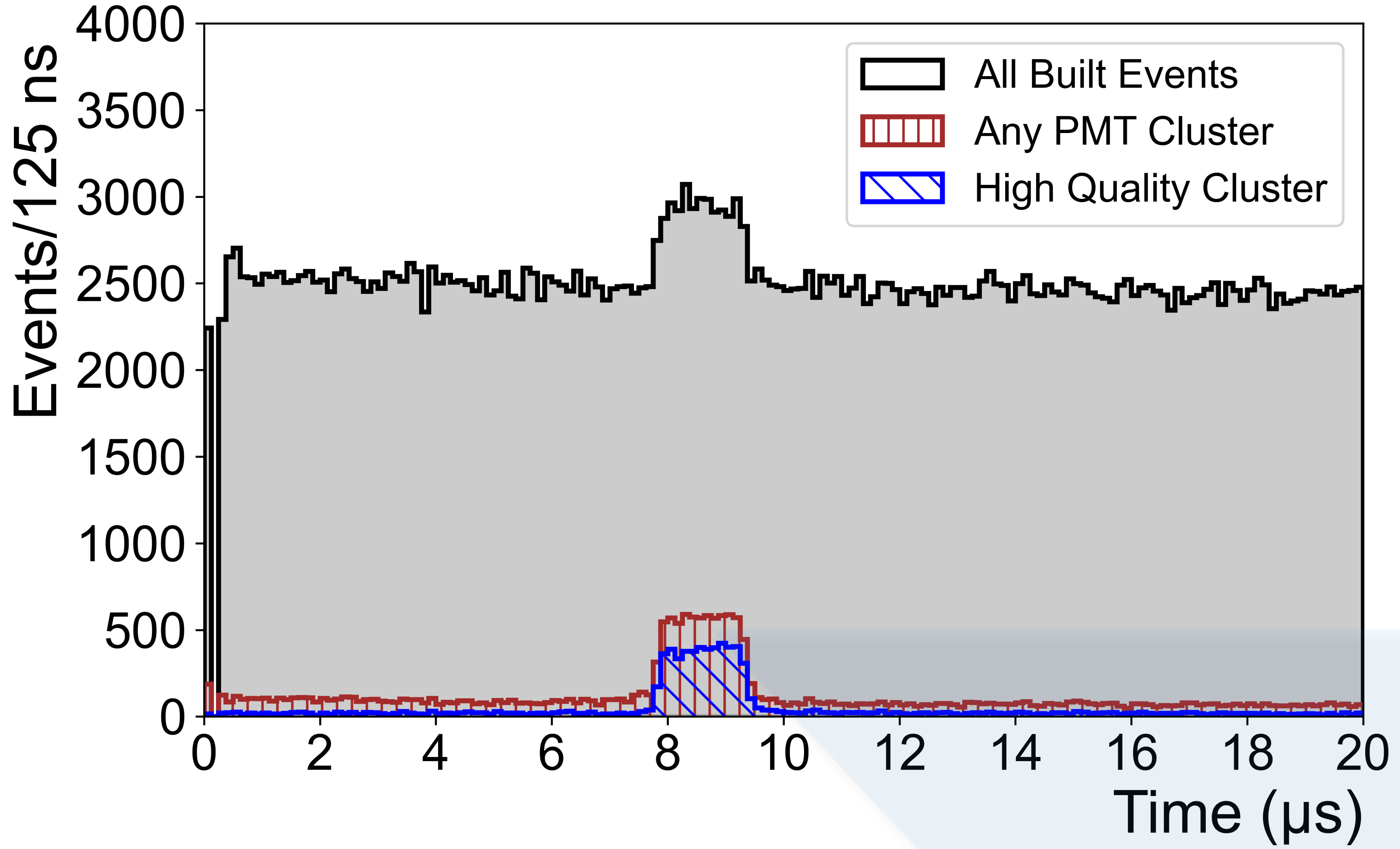

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B.W. Adams et al. (https://doi.org/10.48550/arXiv.2508.11111, submitted to JINST)

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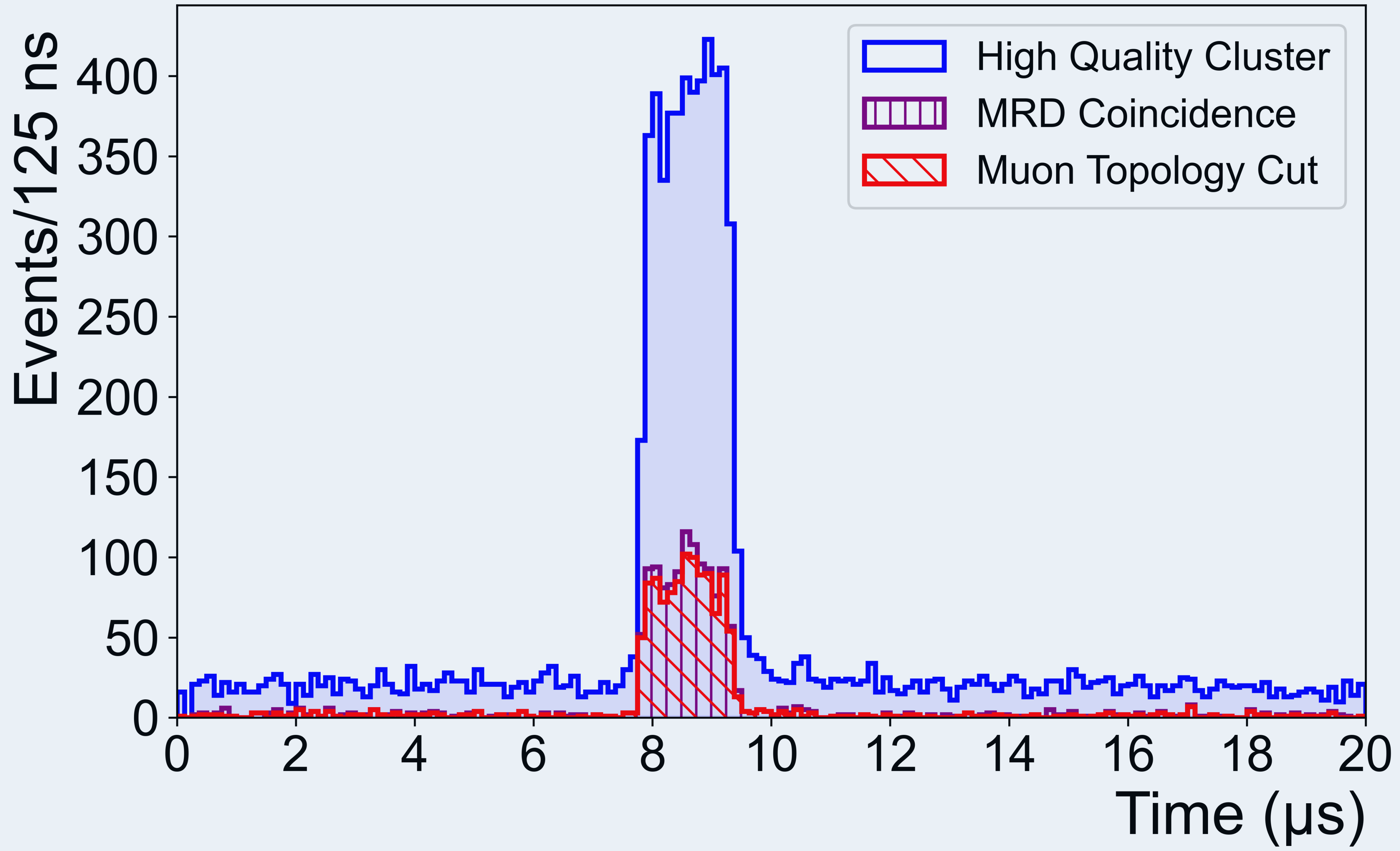
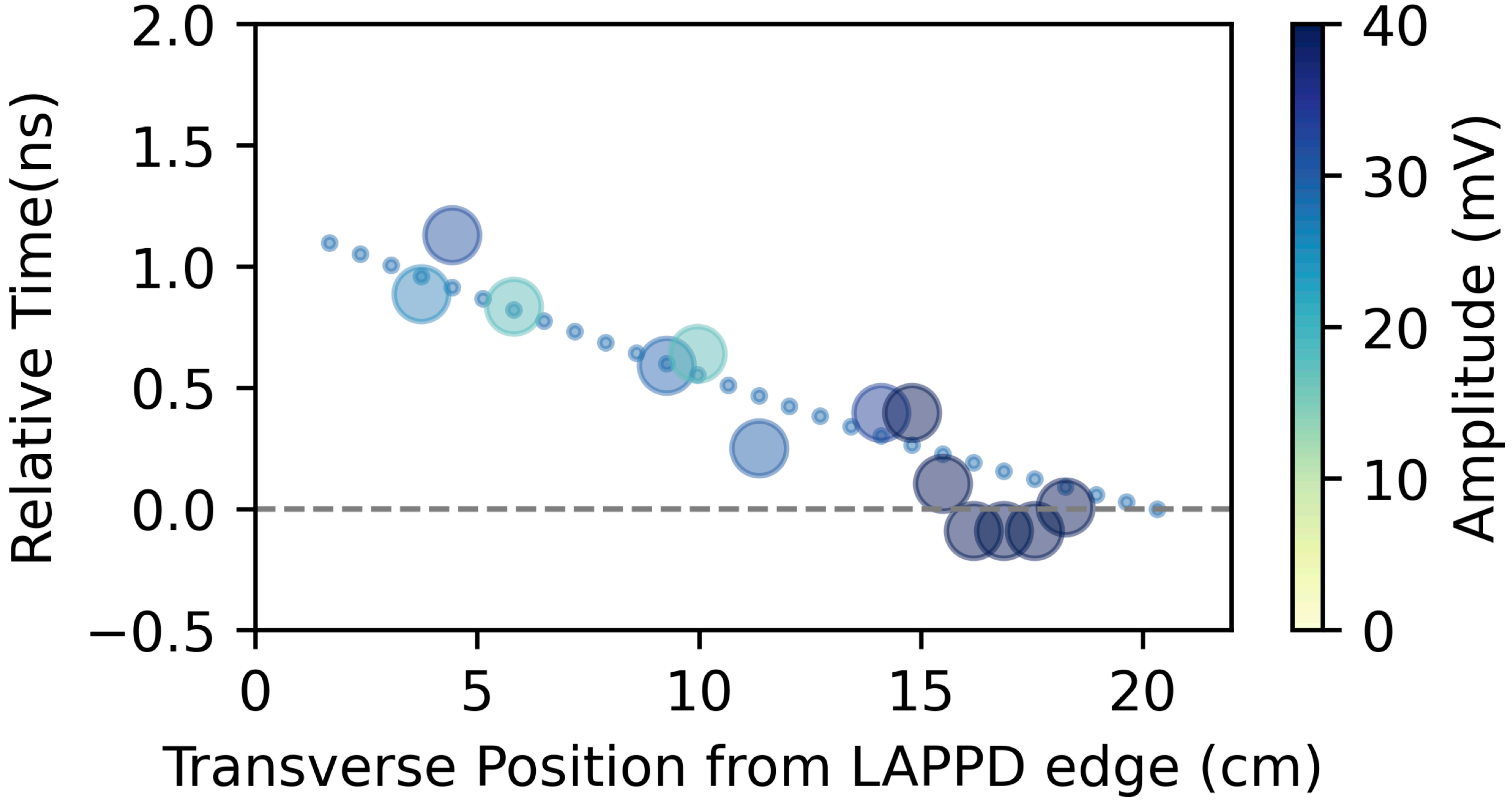


LAPPDs are IMAGING photosensors

Time evolution of a Cherenkov ring across the surface of a single LAPPD depends on track direction and is reflected in the waveform pattern.



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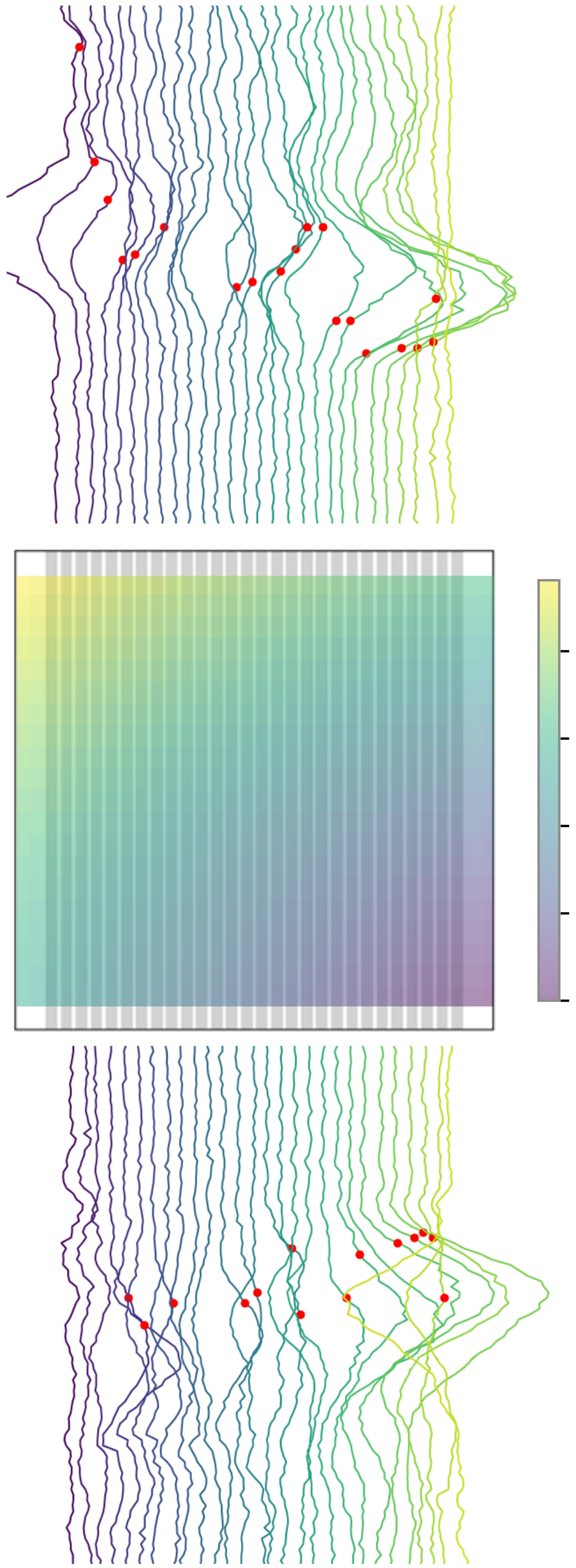
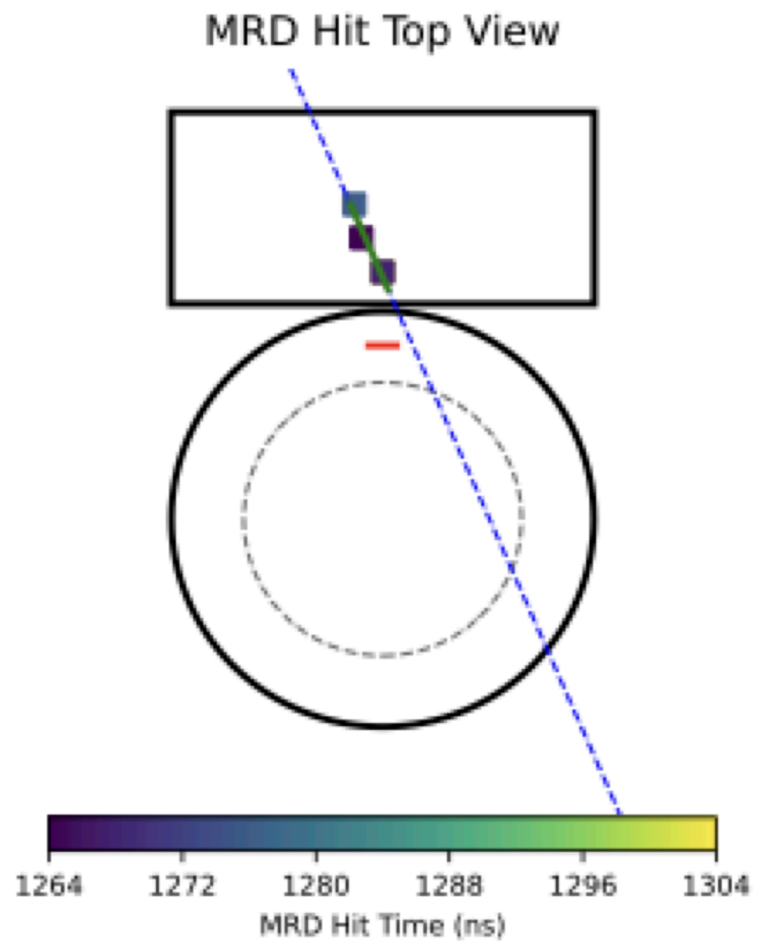
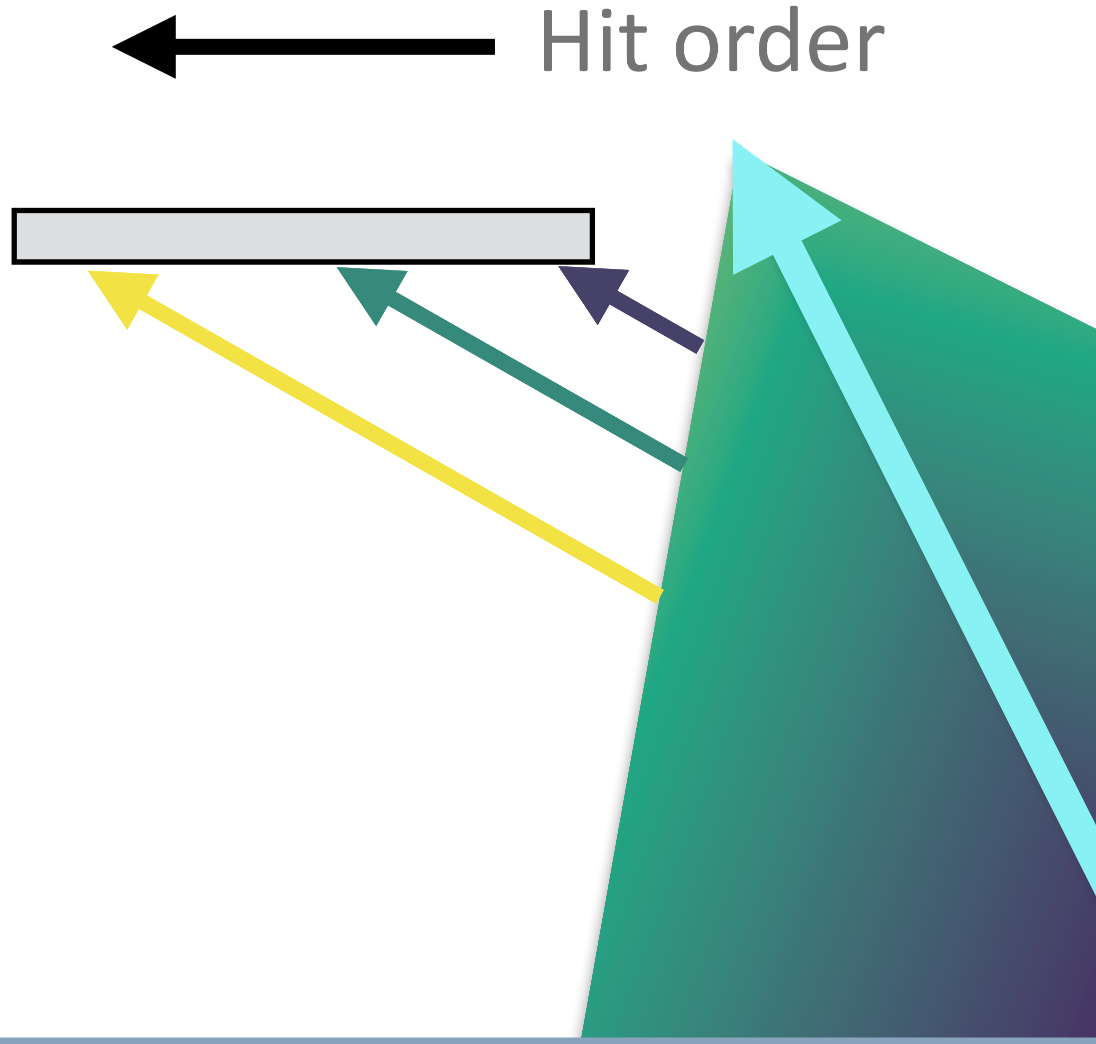
Heuristic: Average arrival time of voltage response on each microstrip, vs predicted gradient based on independent MRD track reconstruction.







Stroboscopic beam timing with LAPPDs

ANNIE is on its way to full reconstruction of single- and multi-LAPPD observations of beam neutrino interactions on a Gd-water target.

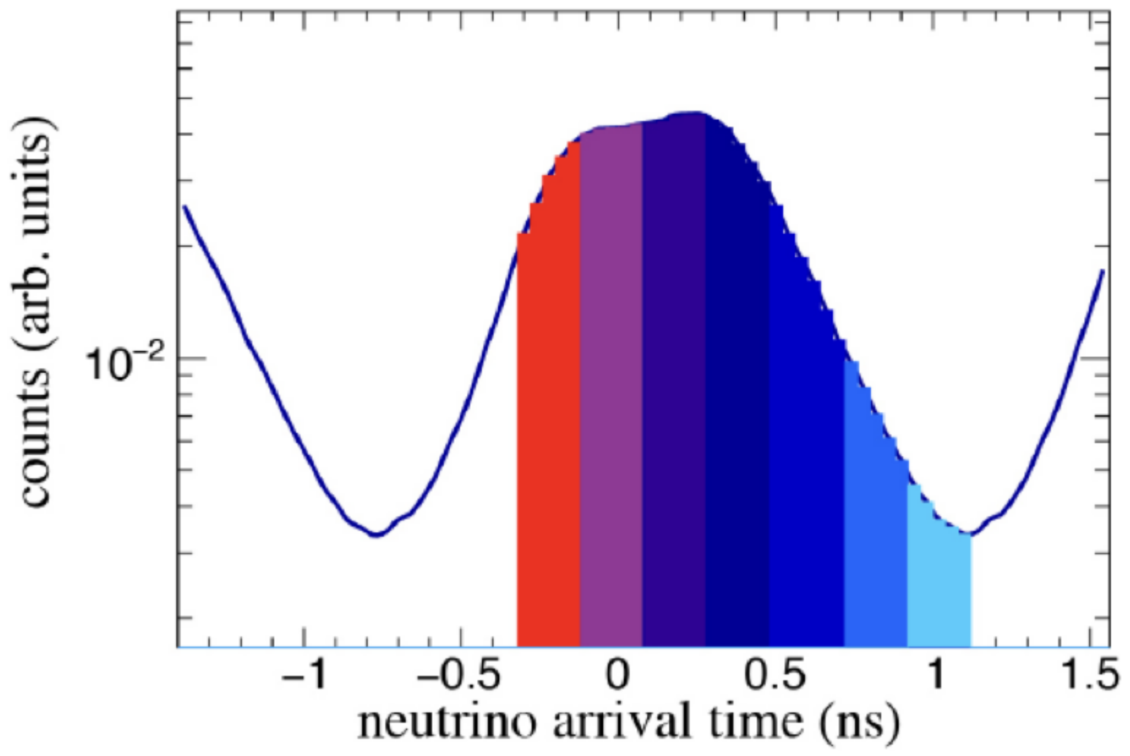
Enables reconstruction of BNB bunch structure

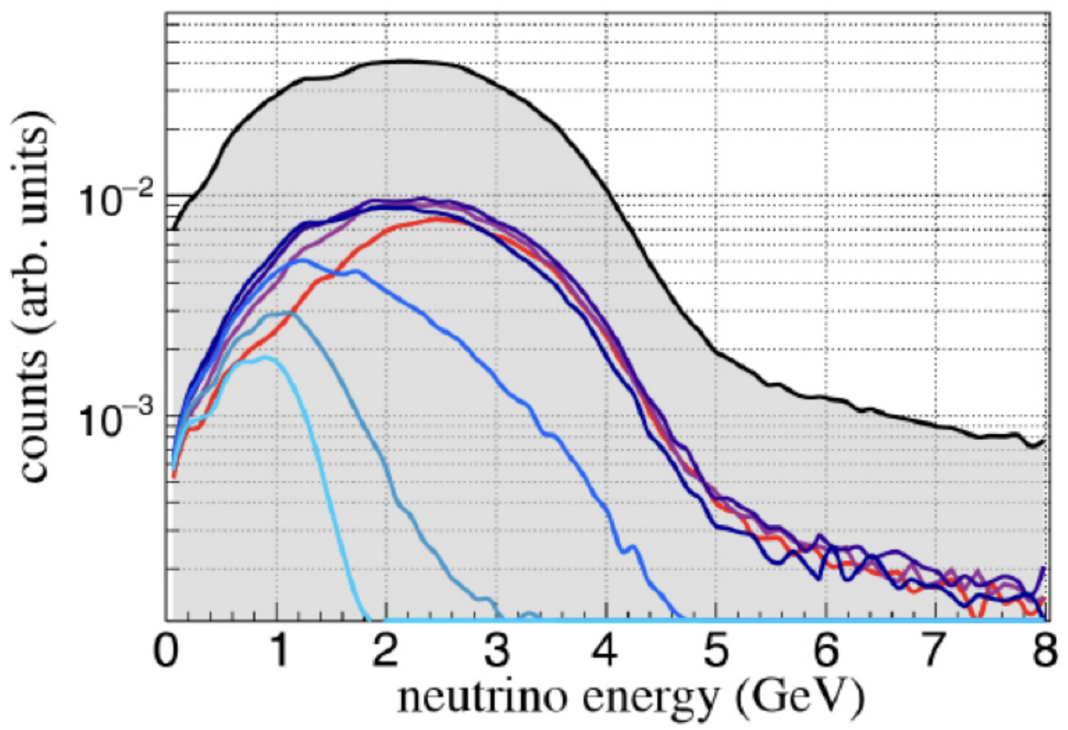
With fast timing, theoretically possible to select different neutrino energies based on timing with respect to beam RF.

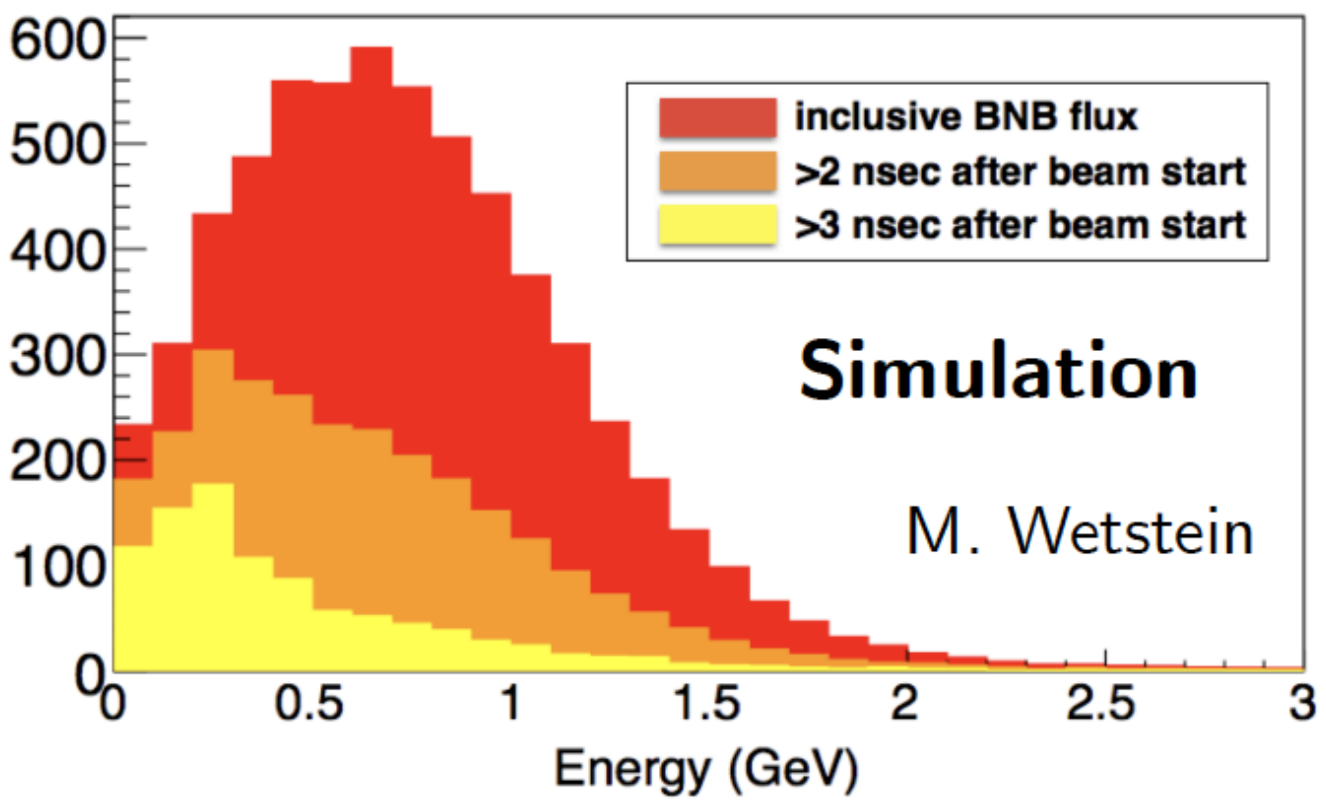
Complementary to off-axis "prism" approaches

ANNIE could demonstrate with BNB beam using LAPPDs (with ns-scale binning).

E. Angelico et al. PRD 100, 032008 (2019)





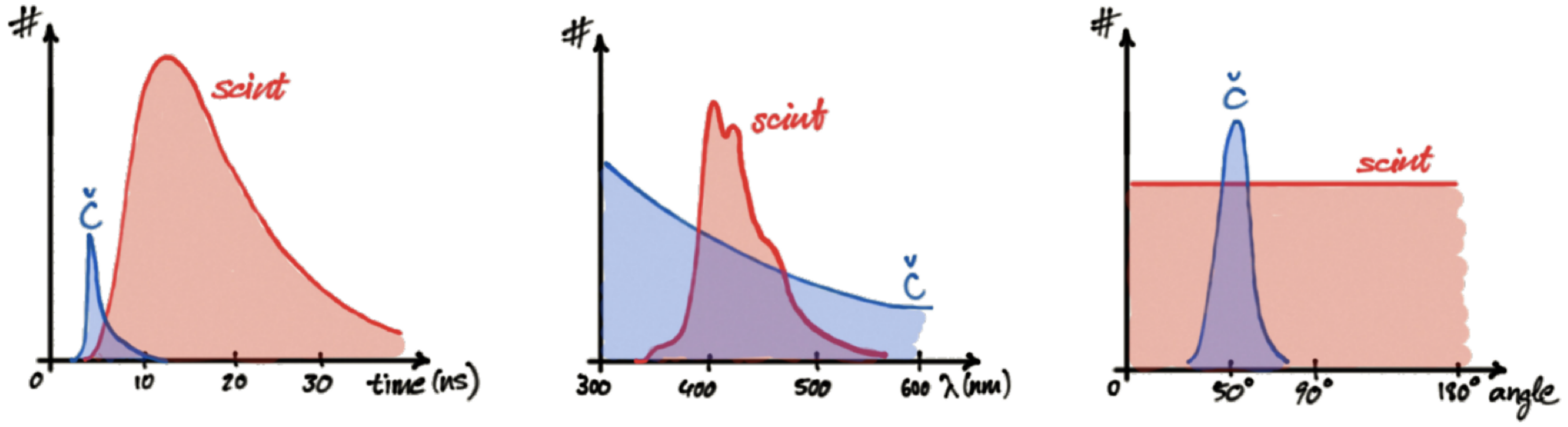


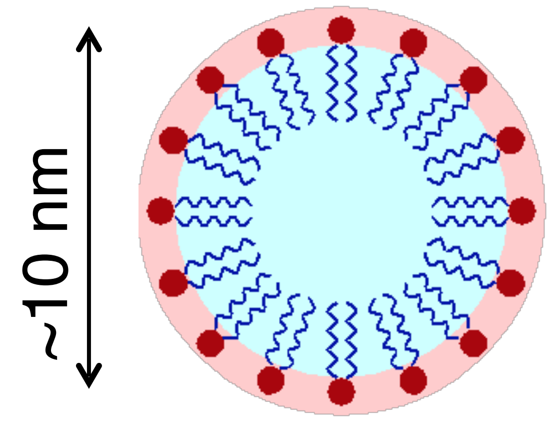
Simulation of energy-separation effect in BNB

First WbLS deployment in a ν beam

Water-based liquid scintillator (WbLS) allows hybrid detection of scintillation light and (unabsorbed) Cherenkov signals

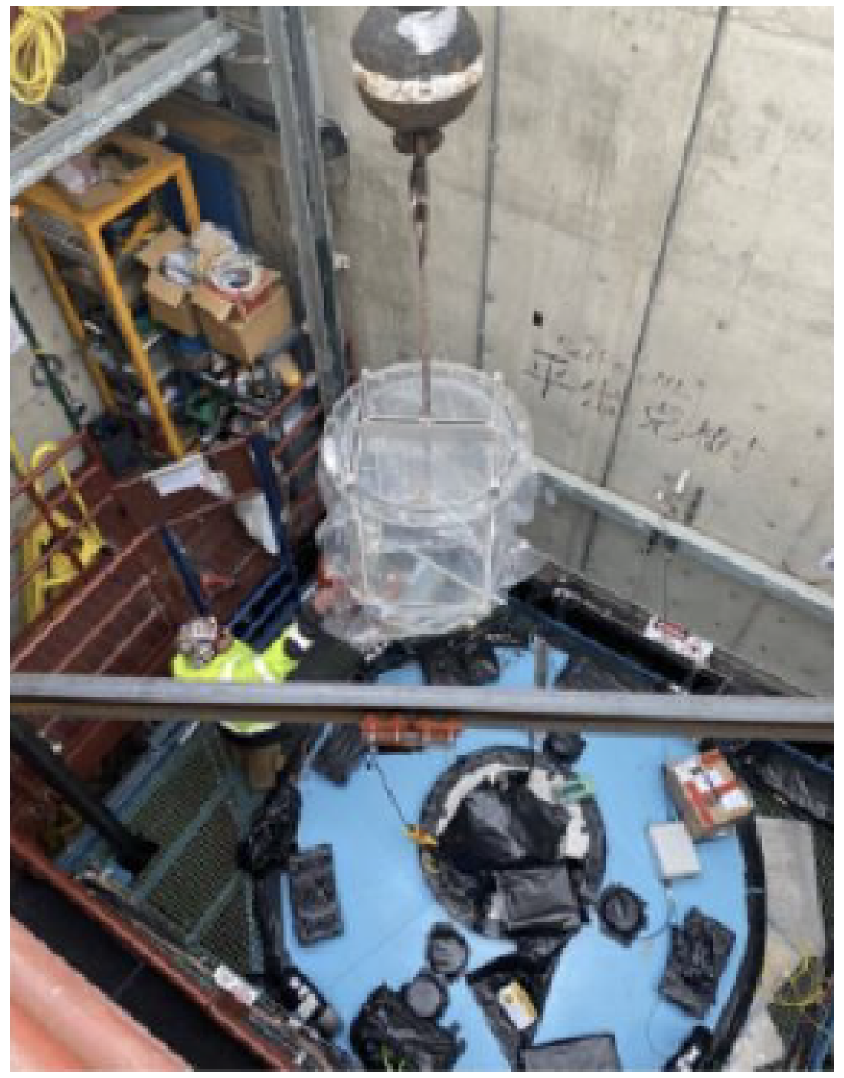
- Enhanced neutrino energy reconstruction
- Enhanced background rejection, particle ID
- Enhanced neutron signals





In ecosystem of WbLS demonstrators ranging from ~0.5 ton to 30 ton (ANNIE, NuDOT, BNL, EOS, BUTTON) ANNIE has unique access to a neutrino beam.

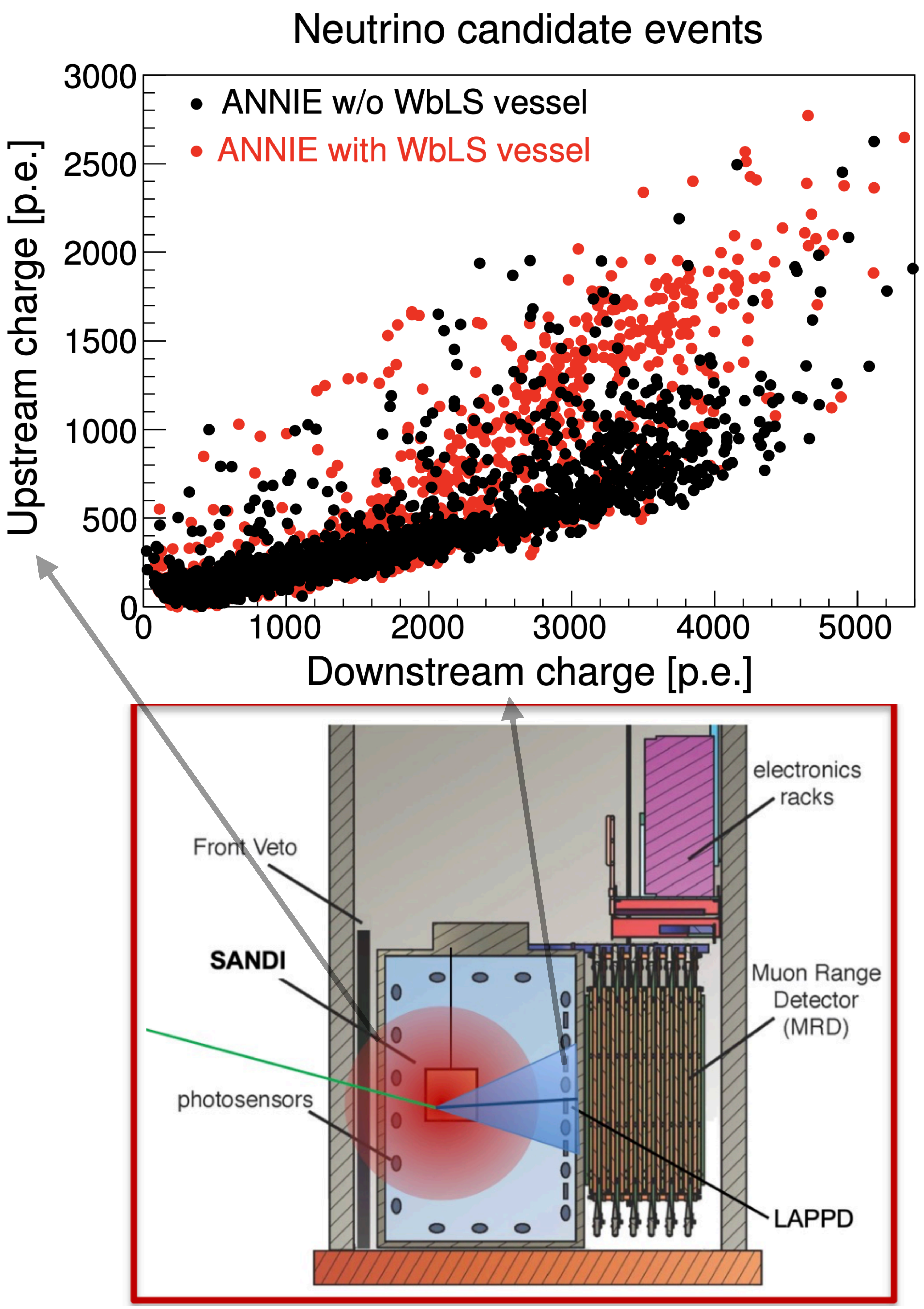
- SANDI in ANNIE: 3' by 3' acrylic vessel containing 365 kg of WbLS
- Deployed March 2023 (2 months, few thousand events)



WbLS and Gd-WbLS in ANNIE

Candidate neutrino events in WbLS vessel show substantially more light in upstream PMTs

Estimates from Michel electron sample confirms increased light output due to scintillation (77 ± 8 %)



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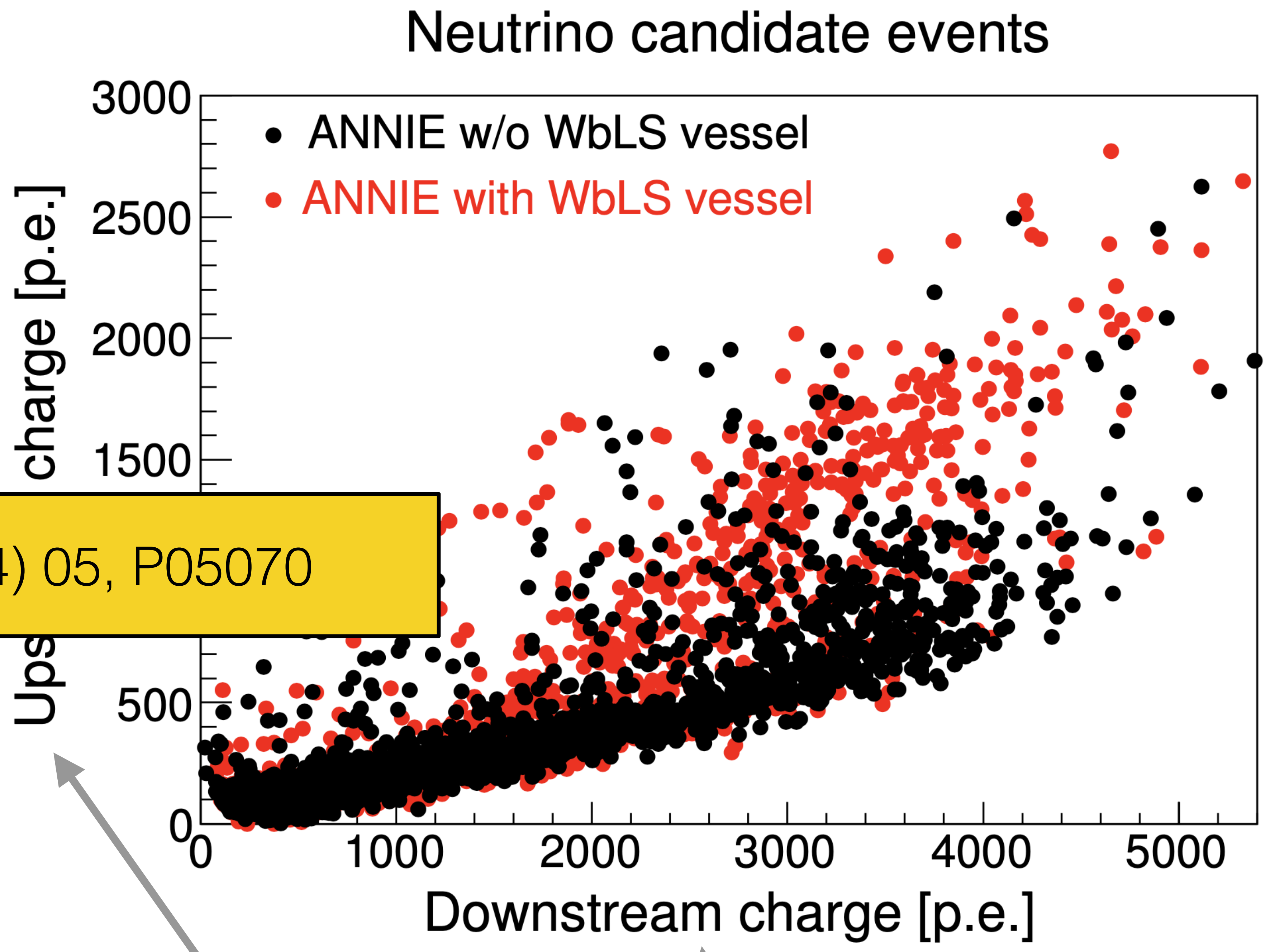
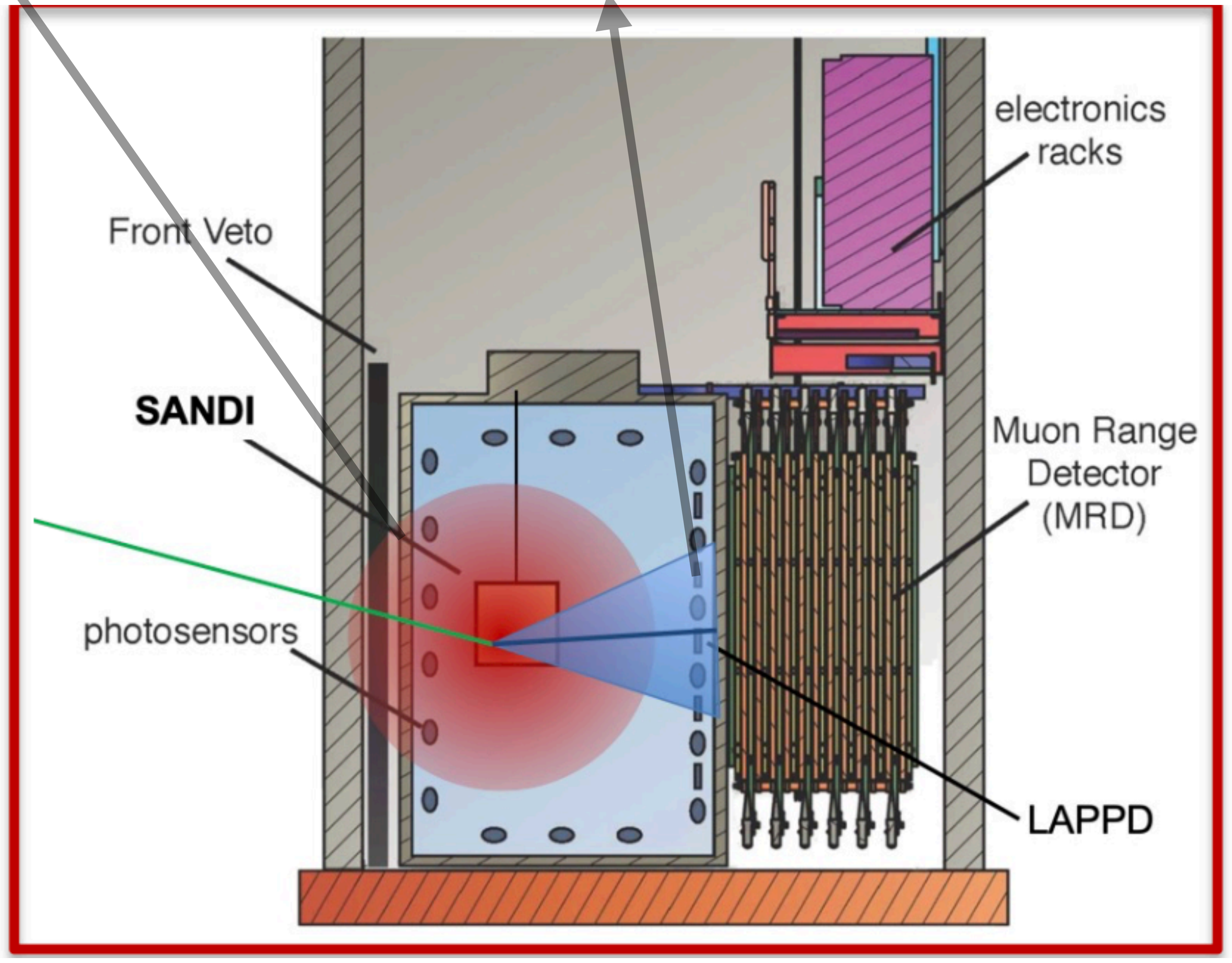
JINST 19 (2024) 05, P05070





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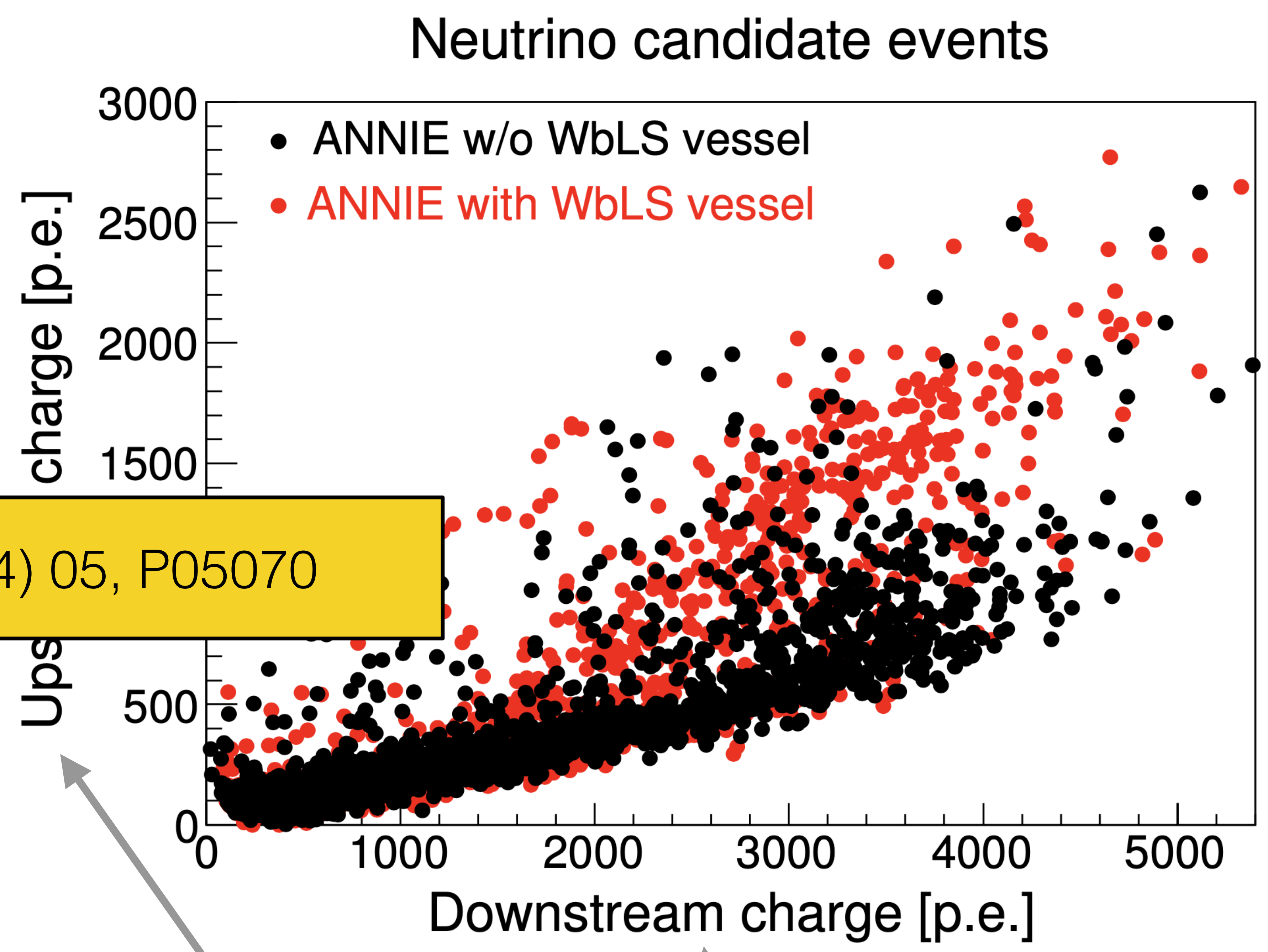
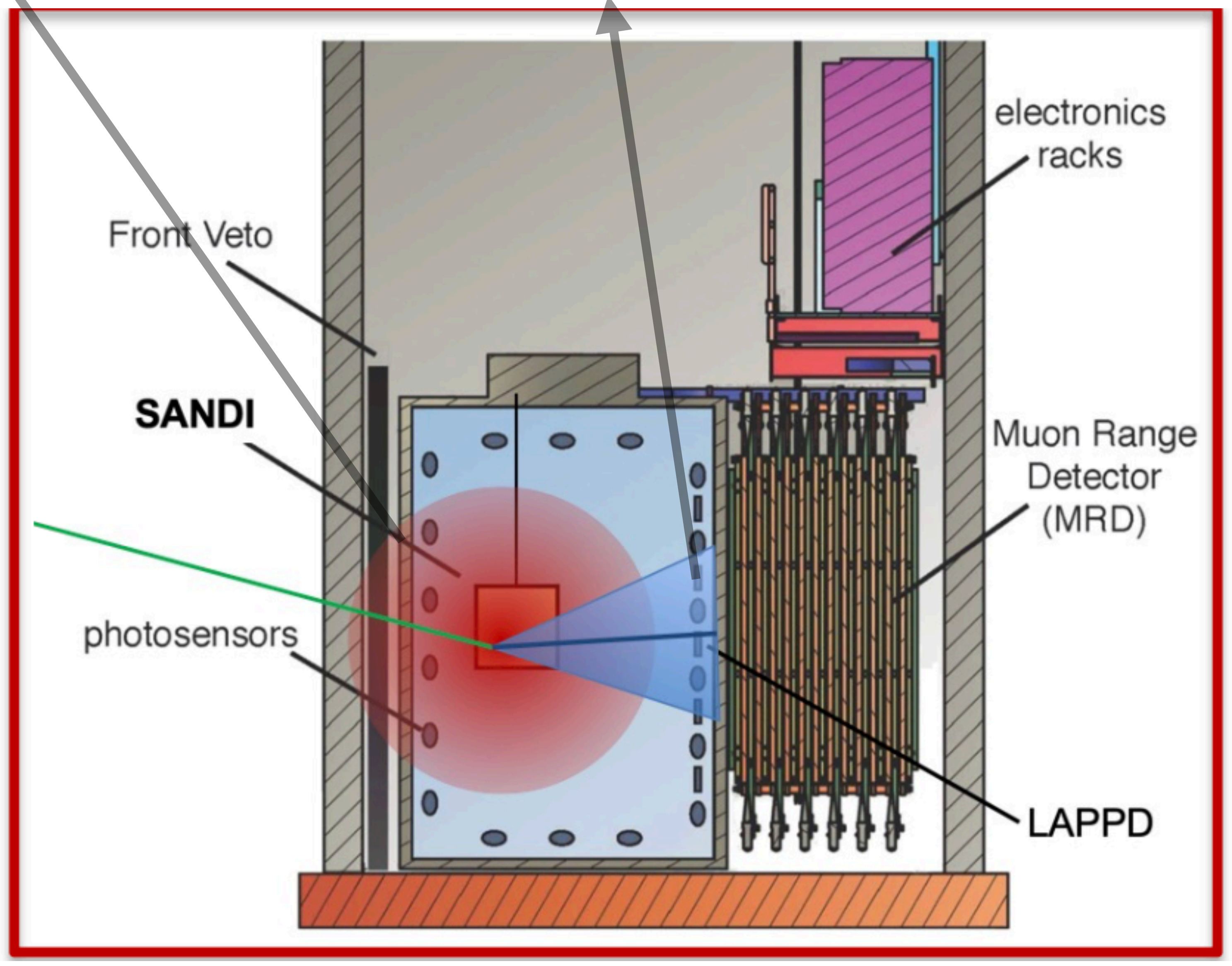


SANDI redeployed with Gd-WbLS

- Gd enhances neutron signal leading to better spatial reconstruction.
- Sep. 2024-Feb. 2025: source calibration campaign, 2 mos. beam neutrino data
- Multiple LAPPDs deployed (potential C/S timing separation test).

SANDI vessel with Gd-WbLS and AmBe neutron source



What's Next?

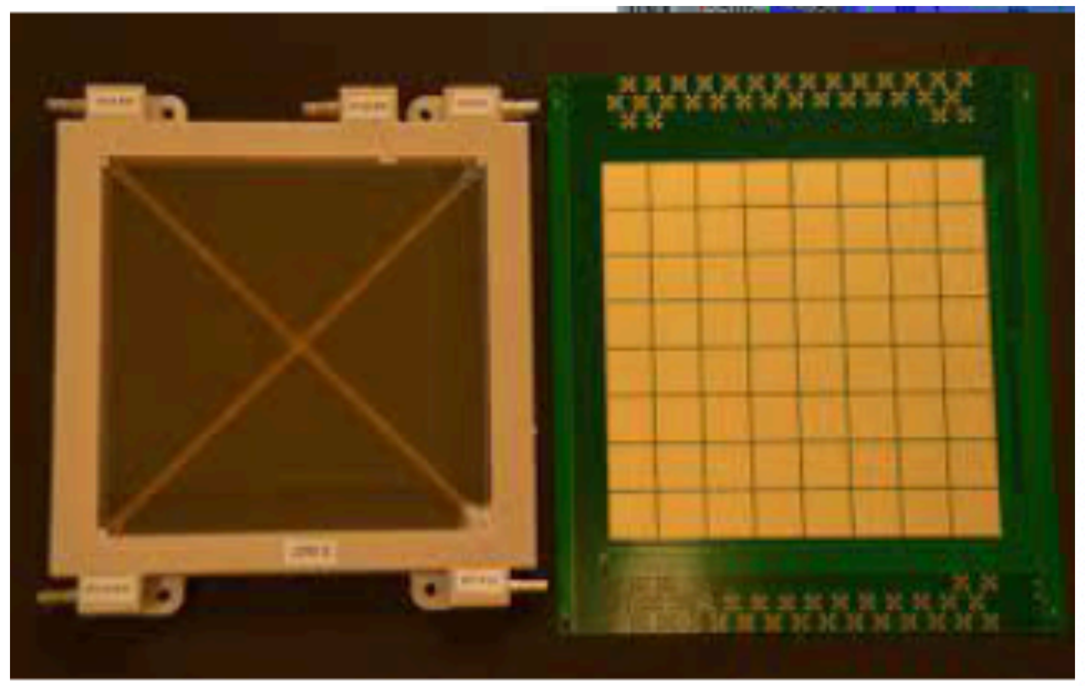
Gen-II LAPPDs with updated electronics for expanded coverage →better vertex constraints **parallel** to beam.

Demonstration of full event reconstruction capability in WbLS requires extended scintillator volume.

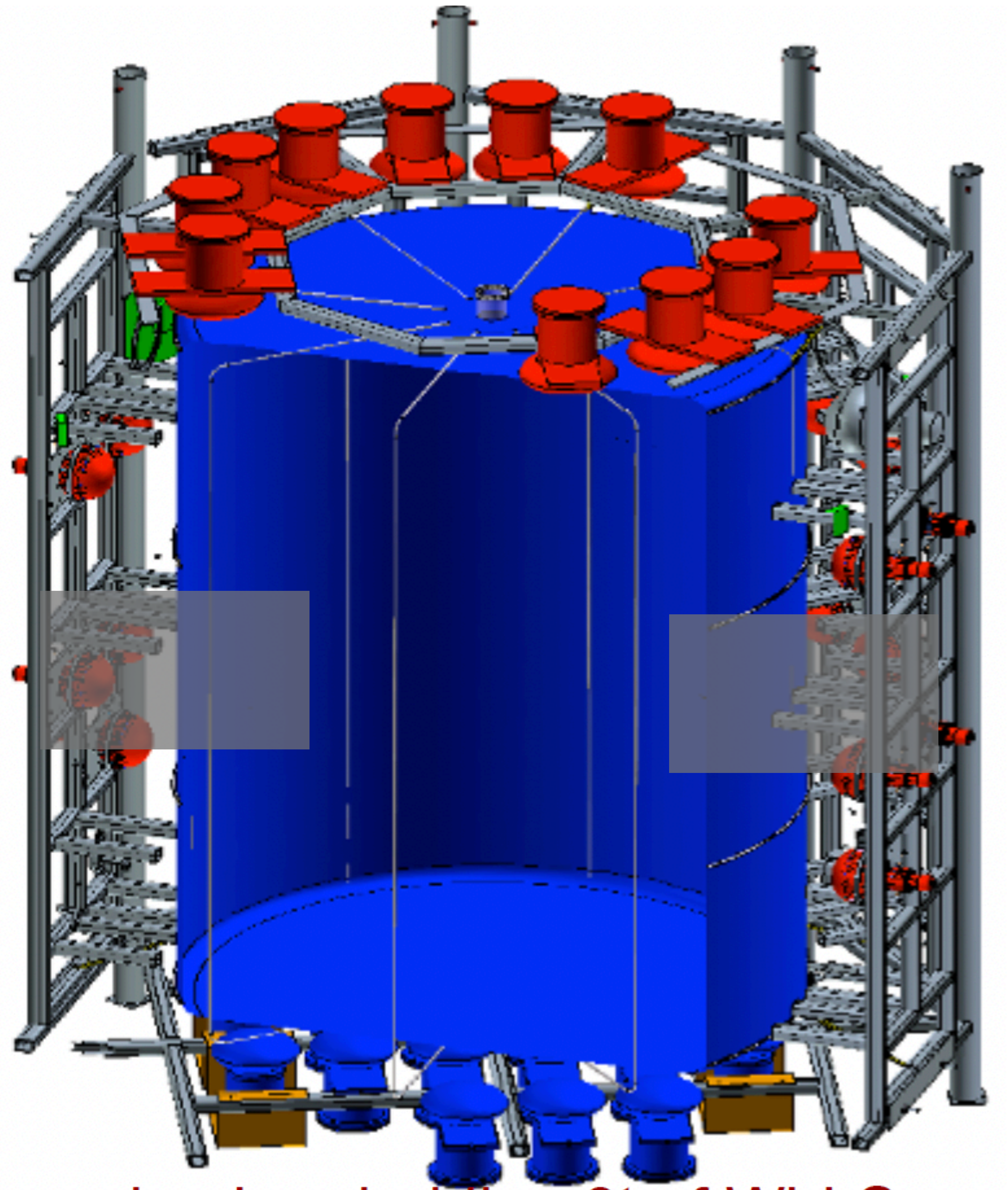
- Install 8m^3 cylindrical vessel in inner volume of ANNIE tank (R&D and construction funded at University of Mainz).
- C/S separation, C/S ratio identification of hadronic, scintillation-dominated NC interactions.

Positive feedback from Fermilab PAC.

Coming to a beam run in 2026-2027



Gen-II LAPPDs



nylon bag holding 8t of WbLS

Summary

ANNIE is now in a unique position to measure neutrino-nucleus cross-sections in water—a program that is complementary and synergistic to the short-baseline program at FNAL

ANNIE has achieved many important technical milestones

- First detection of neutrinos with Gd-water
- First detection of neutrinos with LAPPDs
- First detection of neutrinos with WbLS

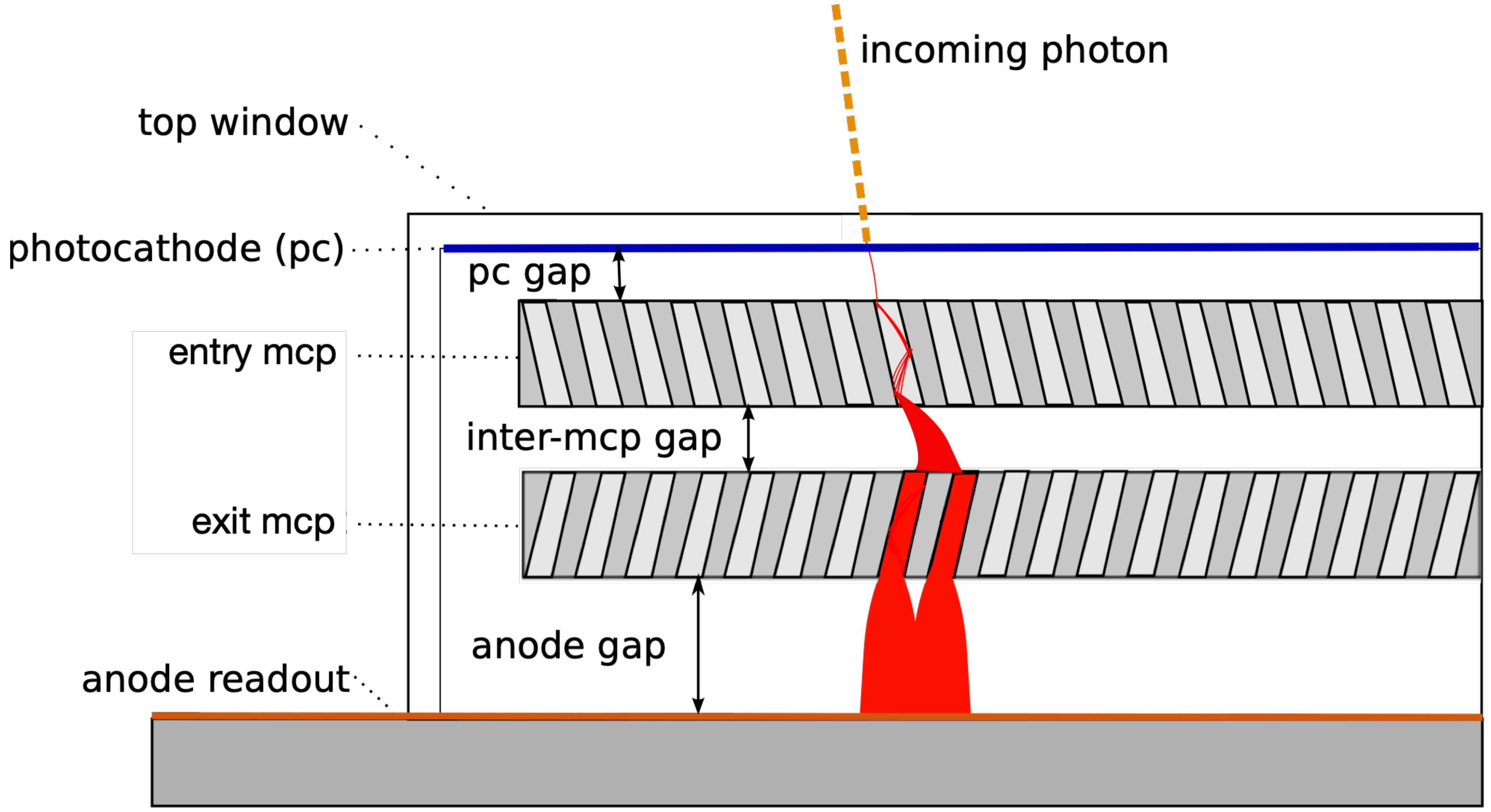
We have gained significant operational experience with these technologies

- First data with LAPPDs shows powerful imaging capabilities.
- Early proof-of-principle data with WbLS (and Gd-WbLS) shows promise.

With 3+ LAPPD modules installed and commissioned, a larger-scale WbLS demonstration planned, and ~2 more beam-years ahead, ANNIE is an excellent position to carry out its program and leverage the excellent event reconstruction enabled by multiple LAPPDs.

Backup Slides

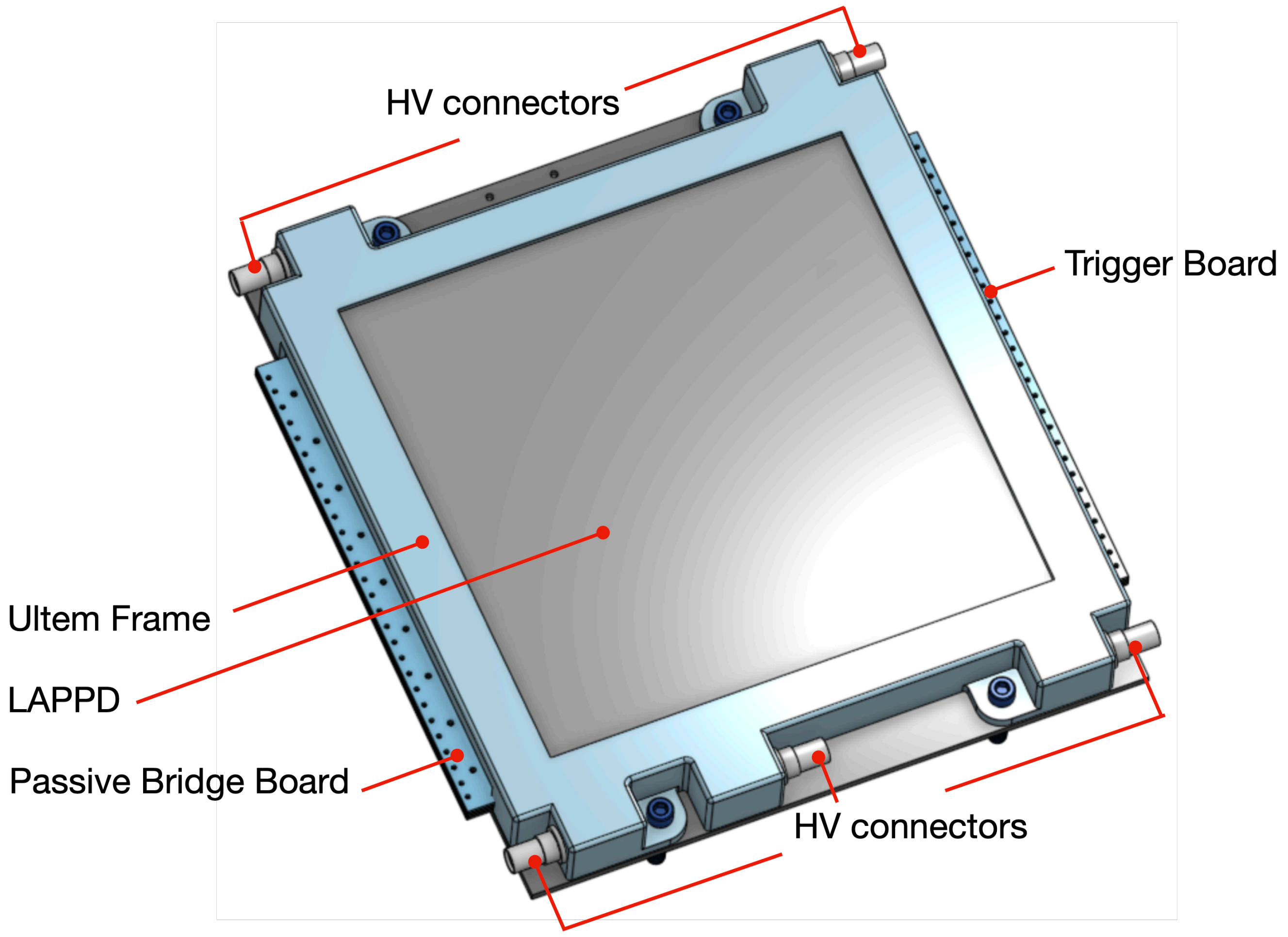
LAPPDs and HRPPDs: General concept



Multiple amplification stages (pores) allow localization of particle point-of-impact on surface

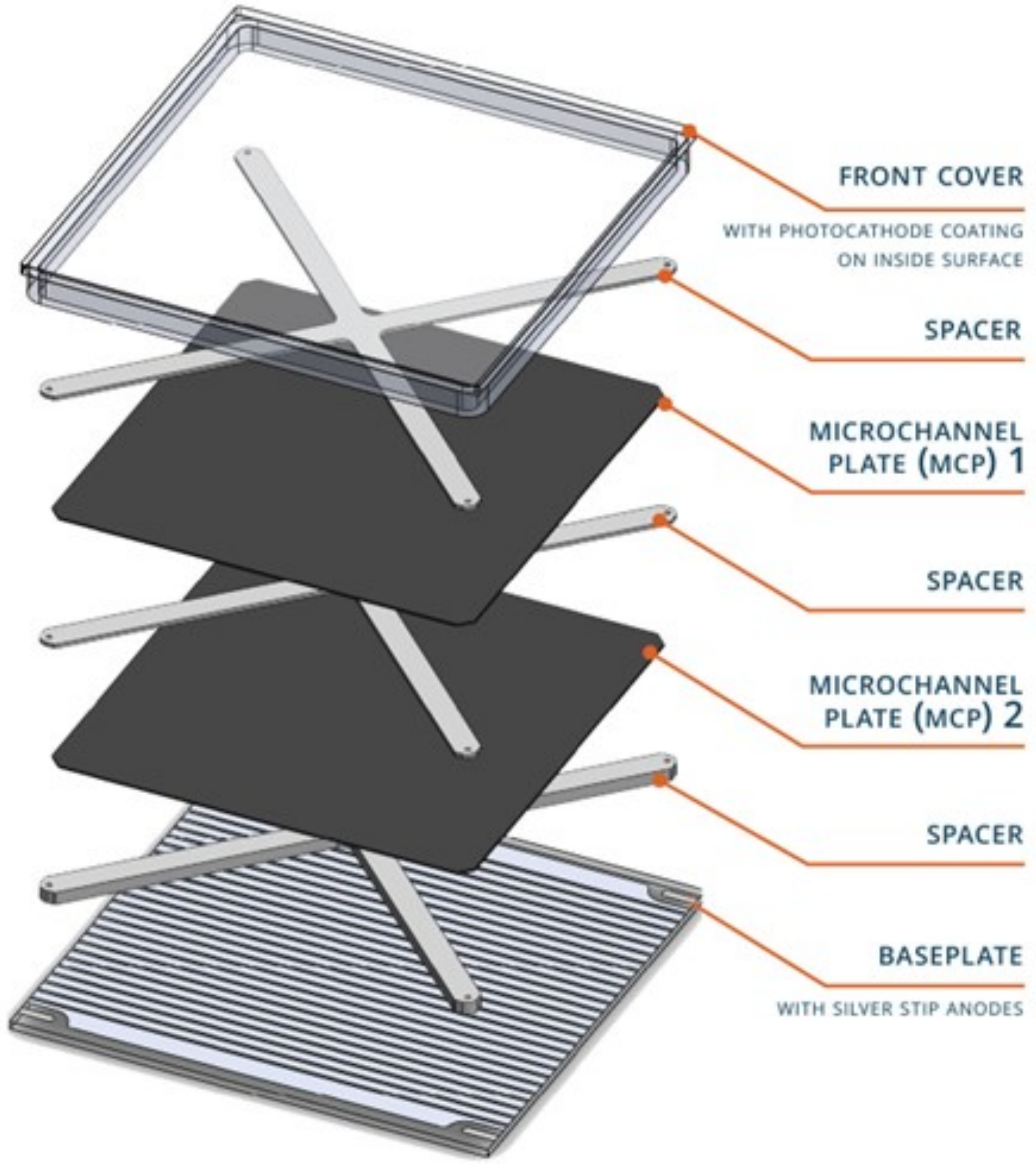
Thin MCP decouples timing resolution from device thickness

- Large Area Picosecond Photodetector (LAPPD) Features:
  - Electron amplification in a flat geometry (100-400 cm^2 active area)
  - Amplification in the pores of micro-channel plates (MCPs)
  - Position resolution limited by pore size, gaps, and geometry of signal readout
  - Pore size, gain influence intrinsic timing (~50 ps)



LAPPD Variations and Applications

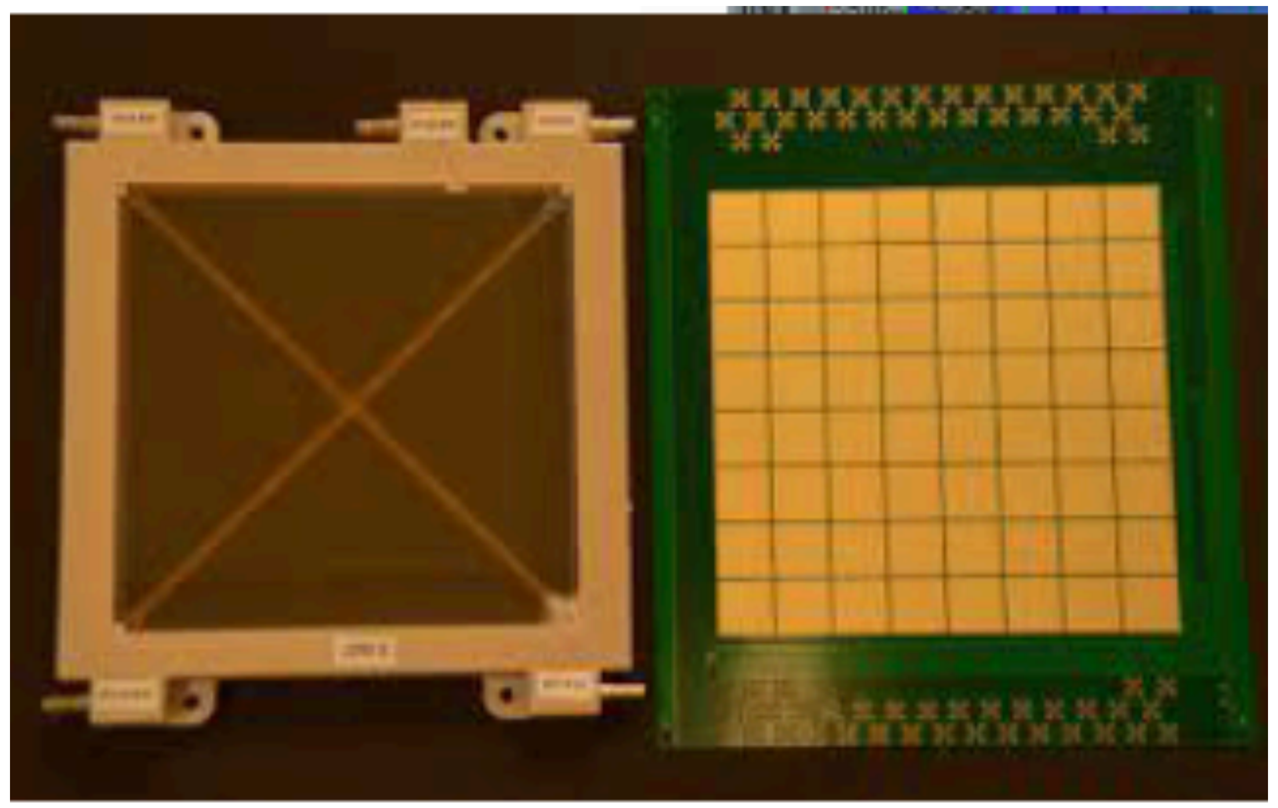
Gen-I LAPPDs: ANNIE, FTBF



20 x 20 cm, 20 μm pores

DC-coupled, 28 microstrip anode inside vacuum package

Gen-II LAPPDs: FTBF (ANNIE, ND-GAr)

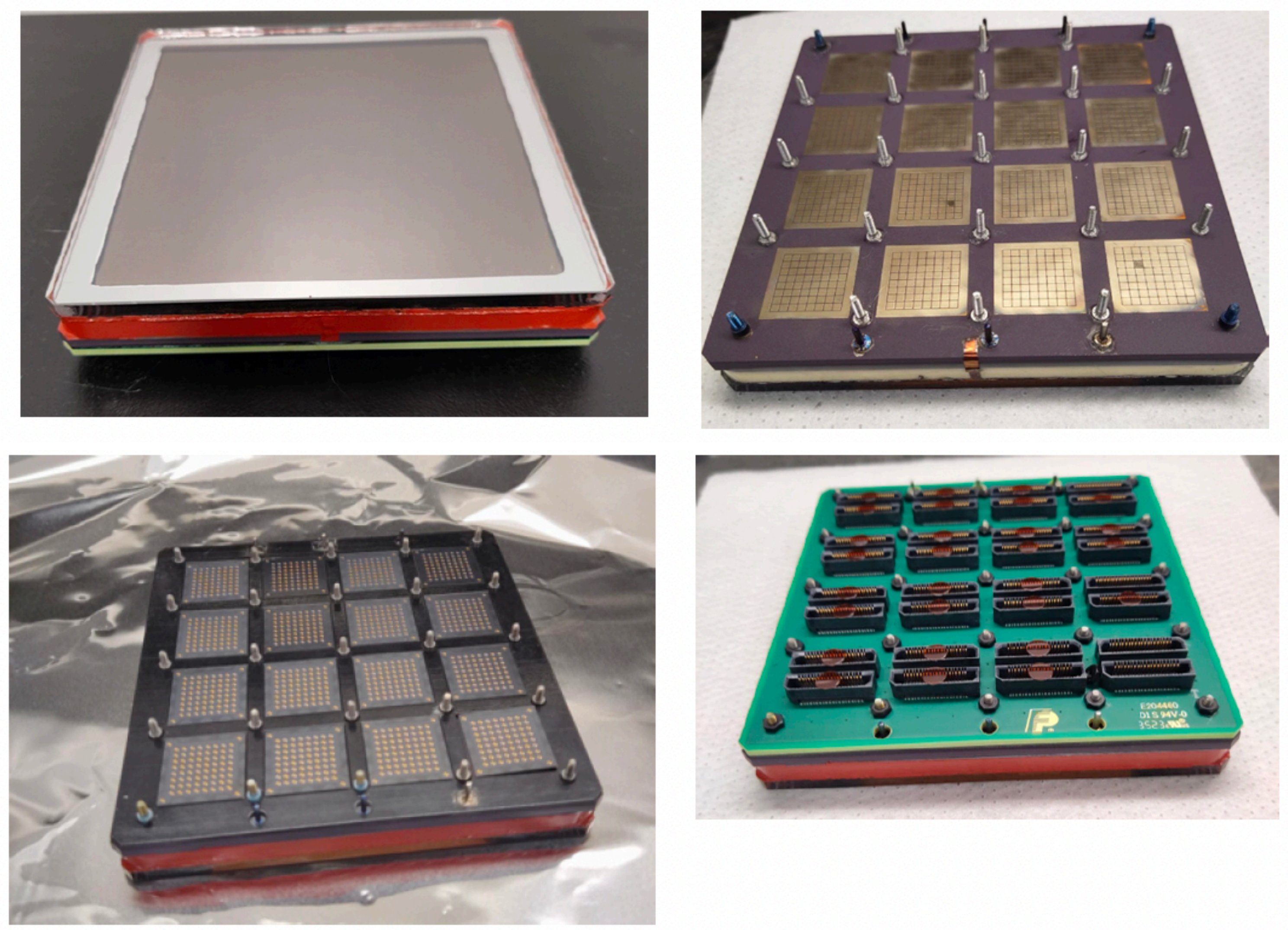


Shares Gen-I dimensions, pore size.

Capacitively-coupled anode allows greater flexibility in readout geometry.

Greater robustness, longevity.

HRPPDs: EIC RICH



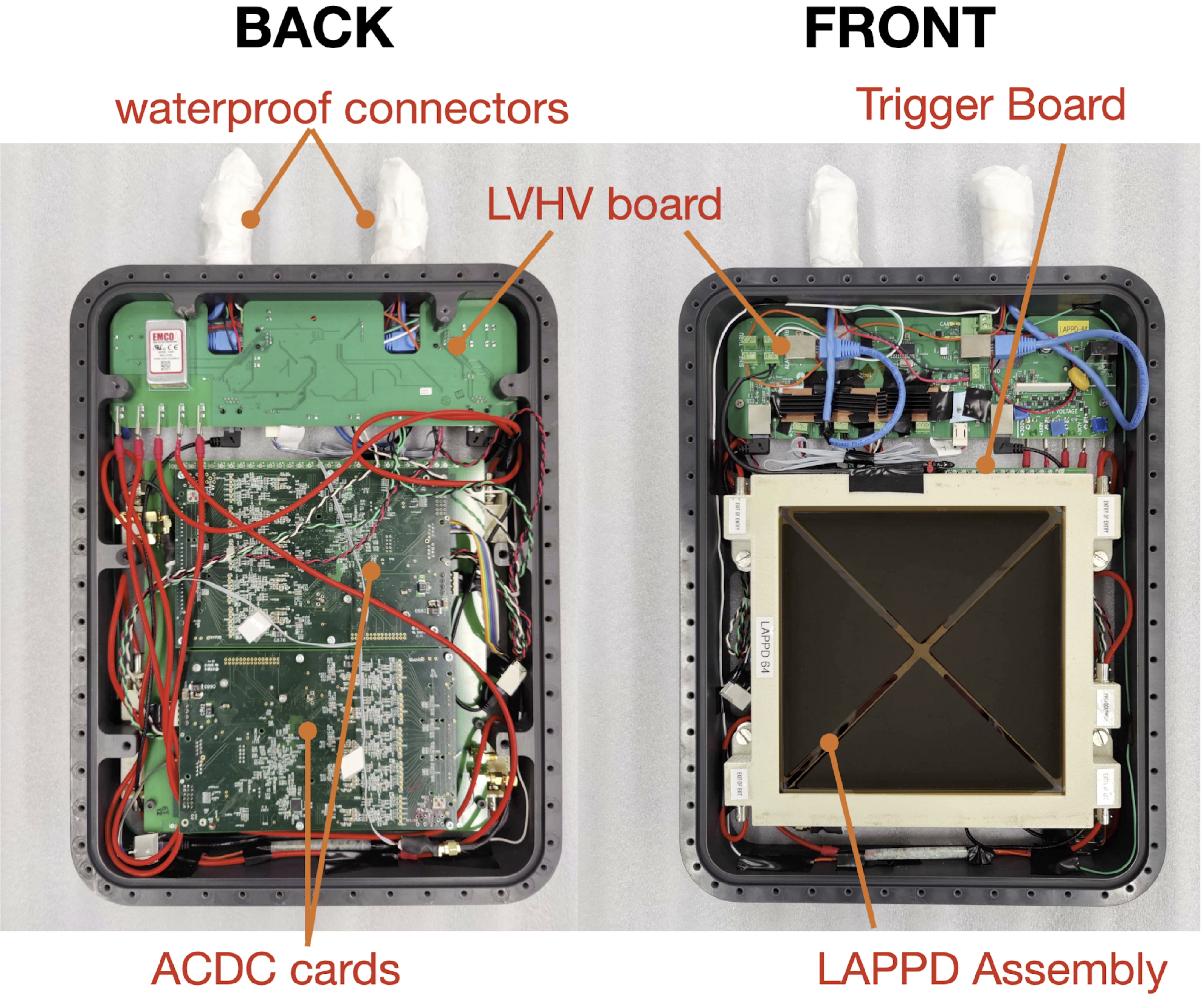
Optimized for high rates

10 cm x 10 cm, 10 μm pores

DC-coupled 32 x 32 pixel readout with 3.25 mm pitch

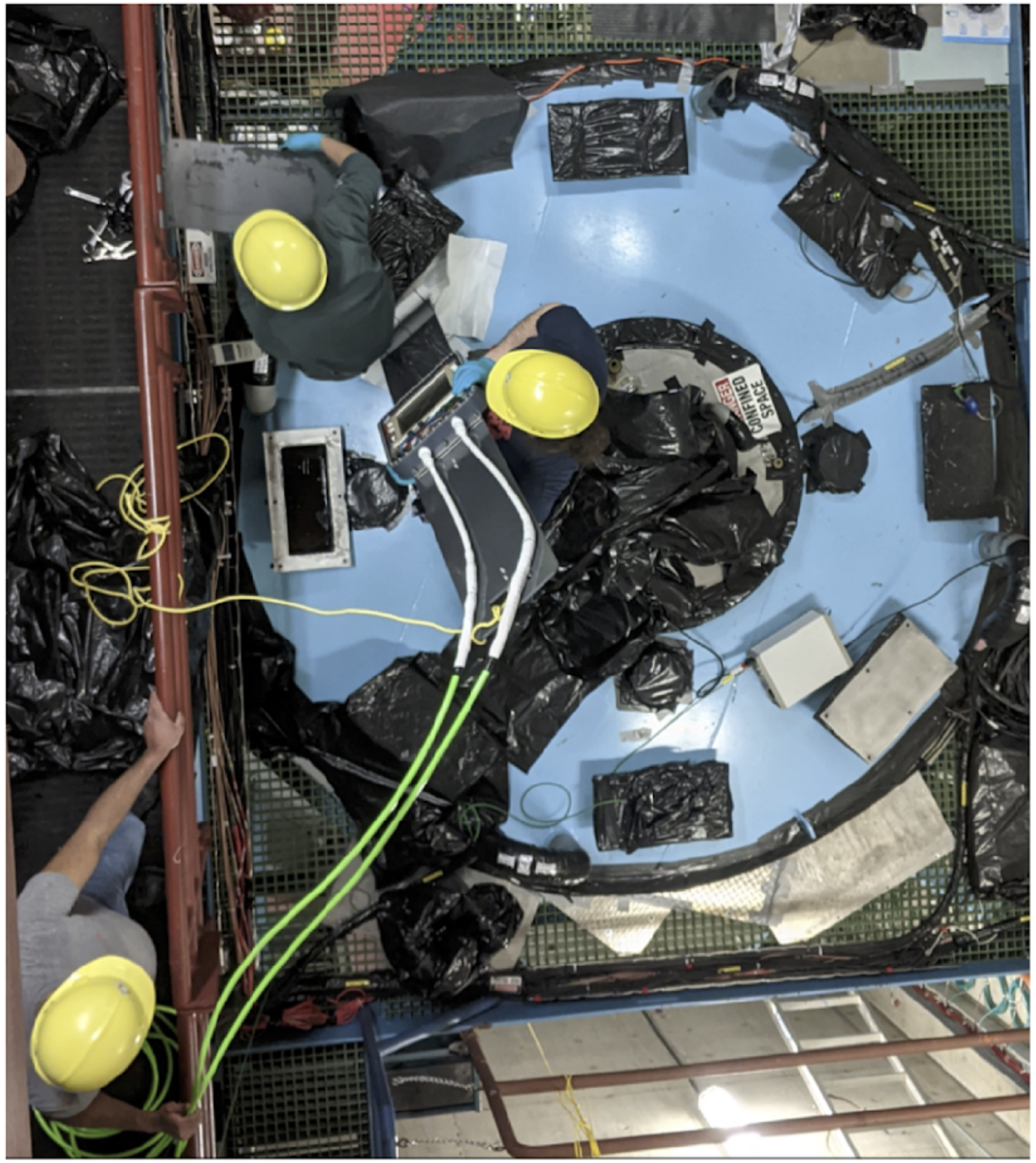
- Note: not an exhaustive list. Highlights a handful of distinct, well-defined applications at different stages of maturity, using different LAPPD designs.

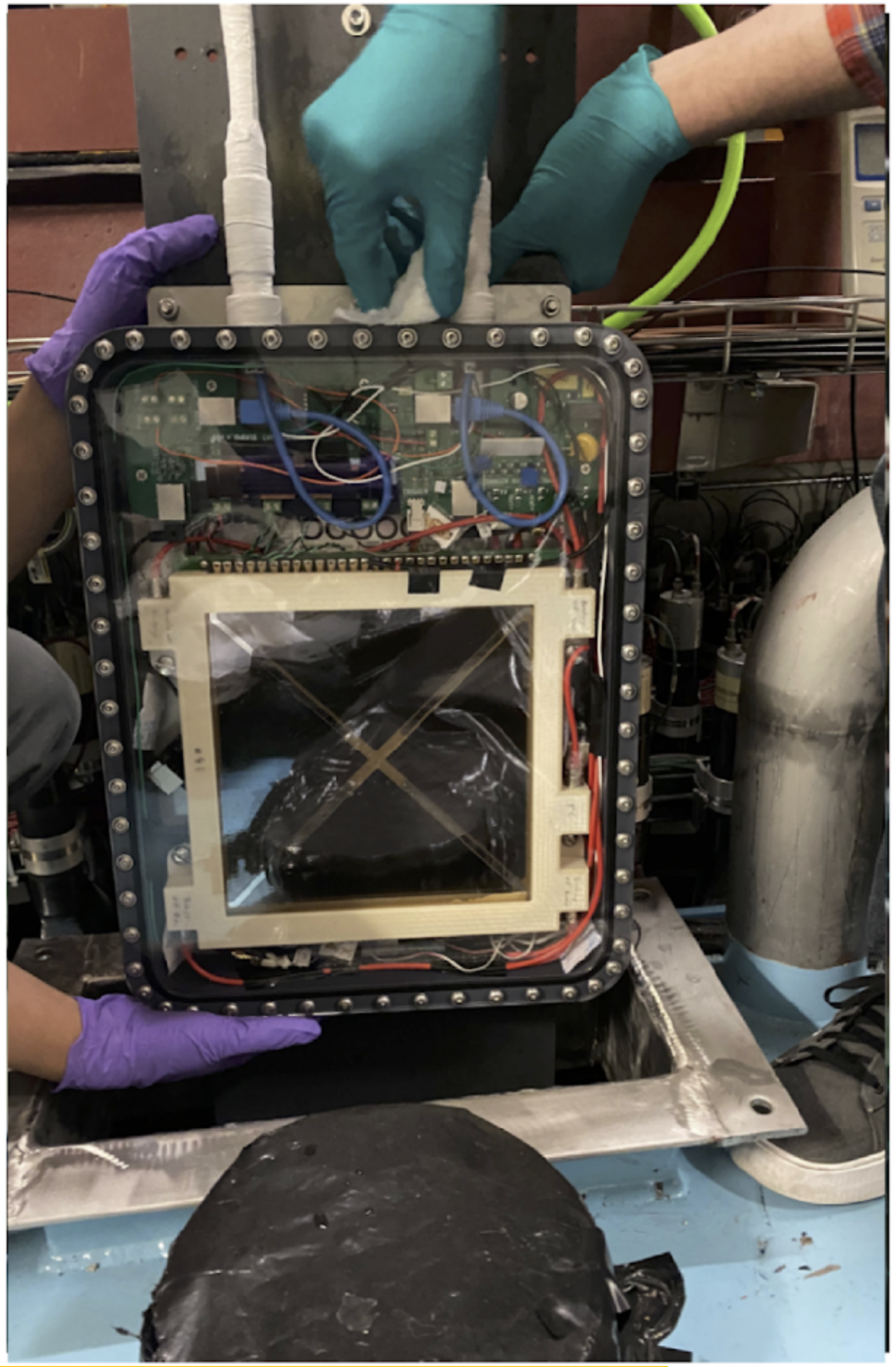
The Packaged ANNIE LAPPD (PAL)



- 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.

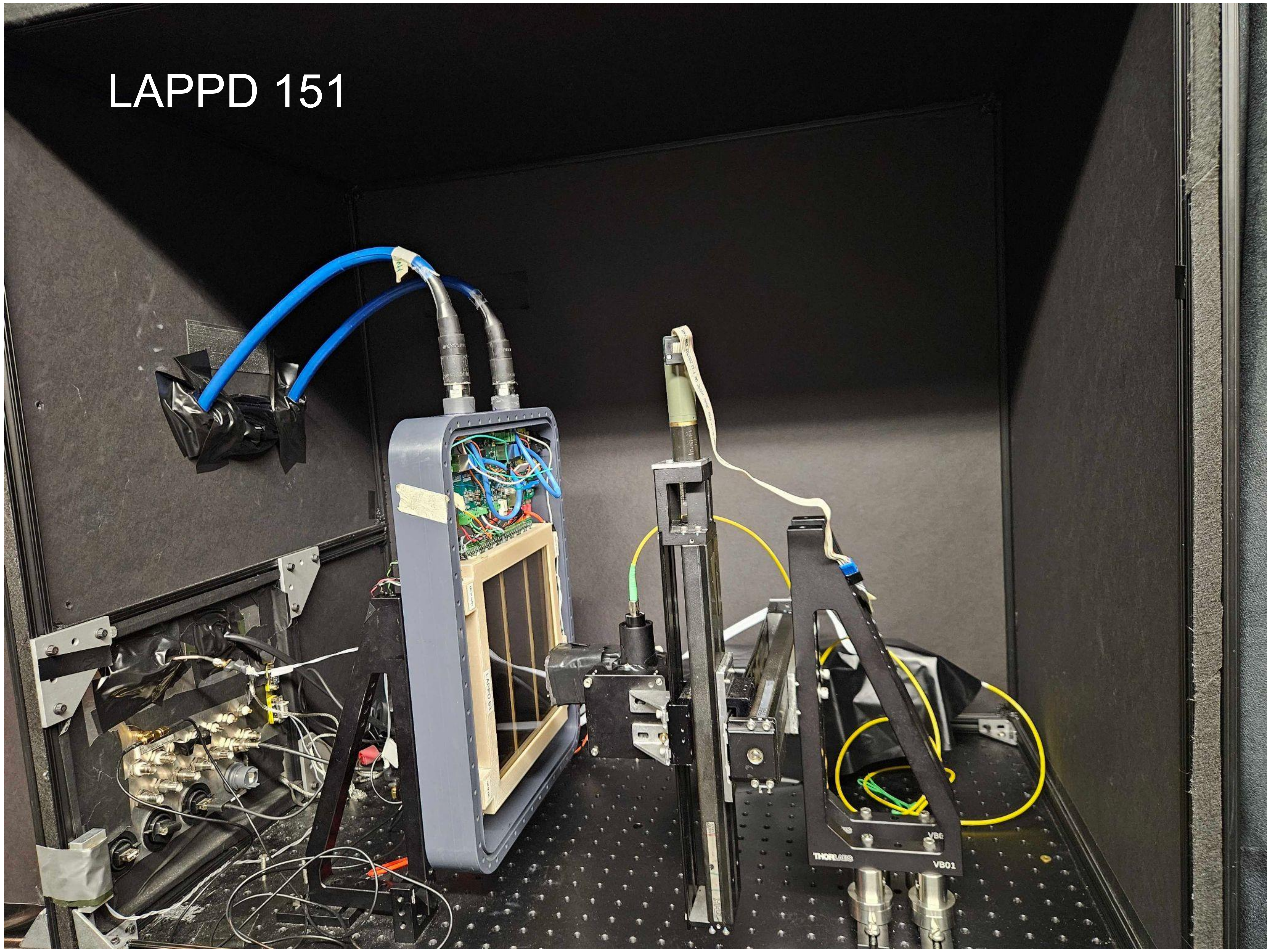
LAPPD Deployment





6 LAPPDs deployed in ANNIE (max 3 at one time). Mix of alkali and non-alkali MCP substrates.

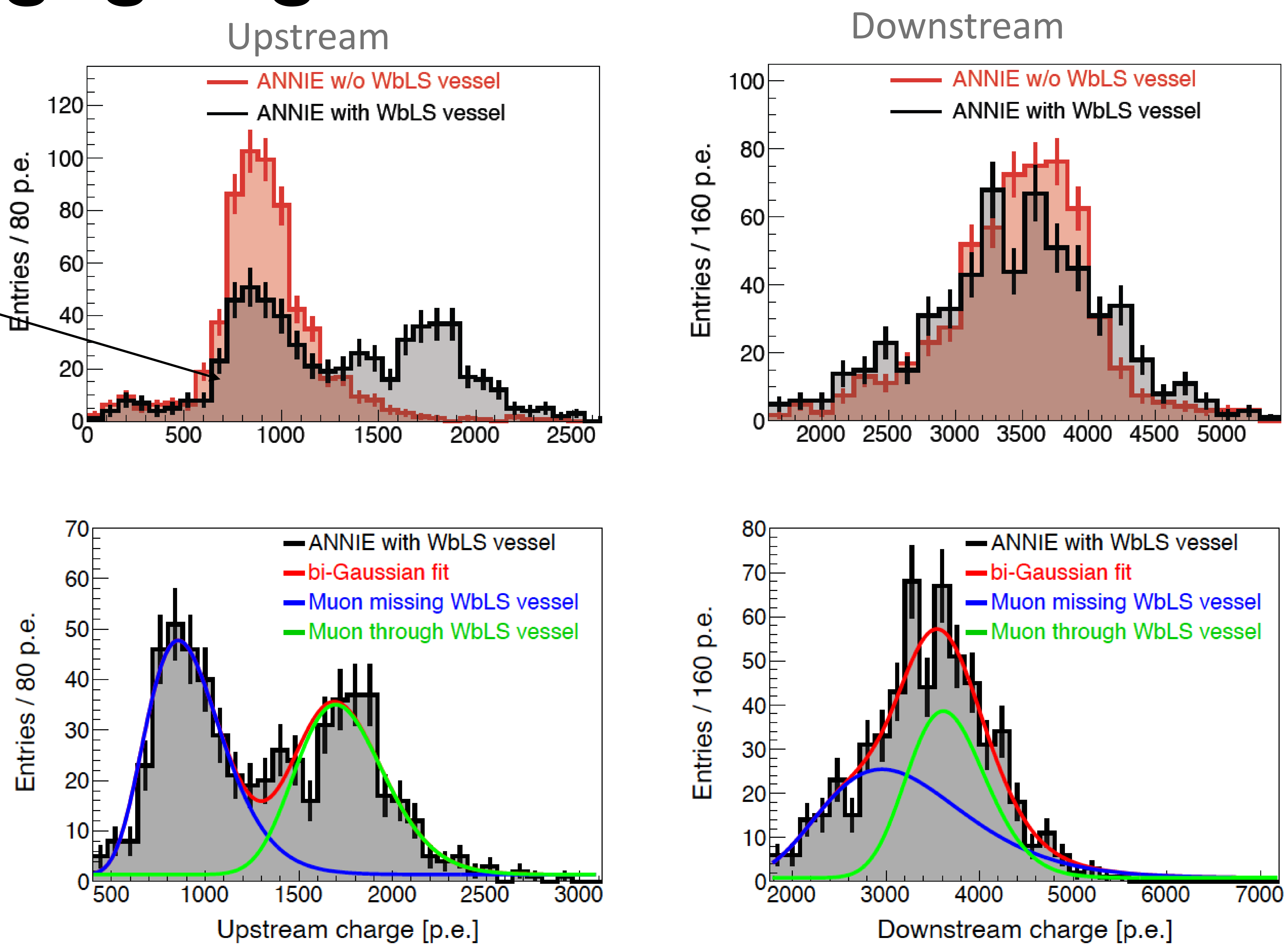
LAPPD Calibration and Commissioning



- The HV voltage divider must be tuned to individual LAPPD specs.
- Use PiLAS laser through optical fiber and scanning motor stage to measure:
  - Single PE response and gain as a function of position.
  - Charge-sharing between microstrips.
- Calibrations are done in PAL frame, with final electronics and cabling.
- Studies, sealing, bucket-tests now require ~1 month/LAPPD.

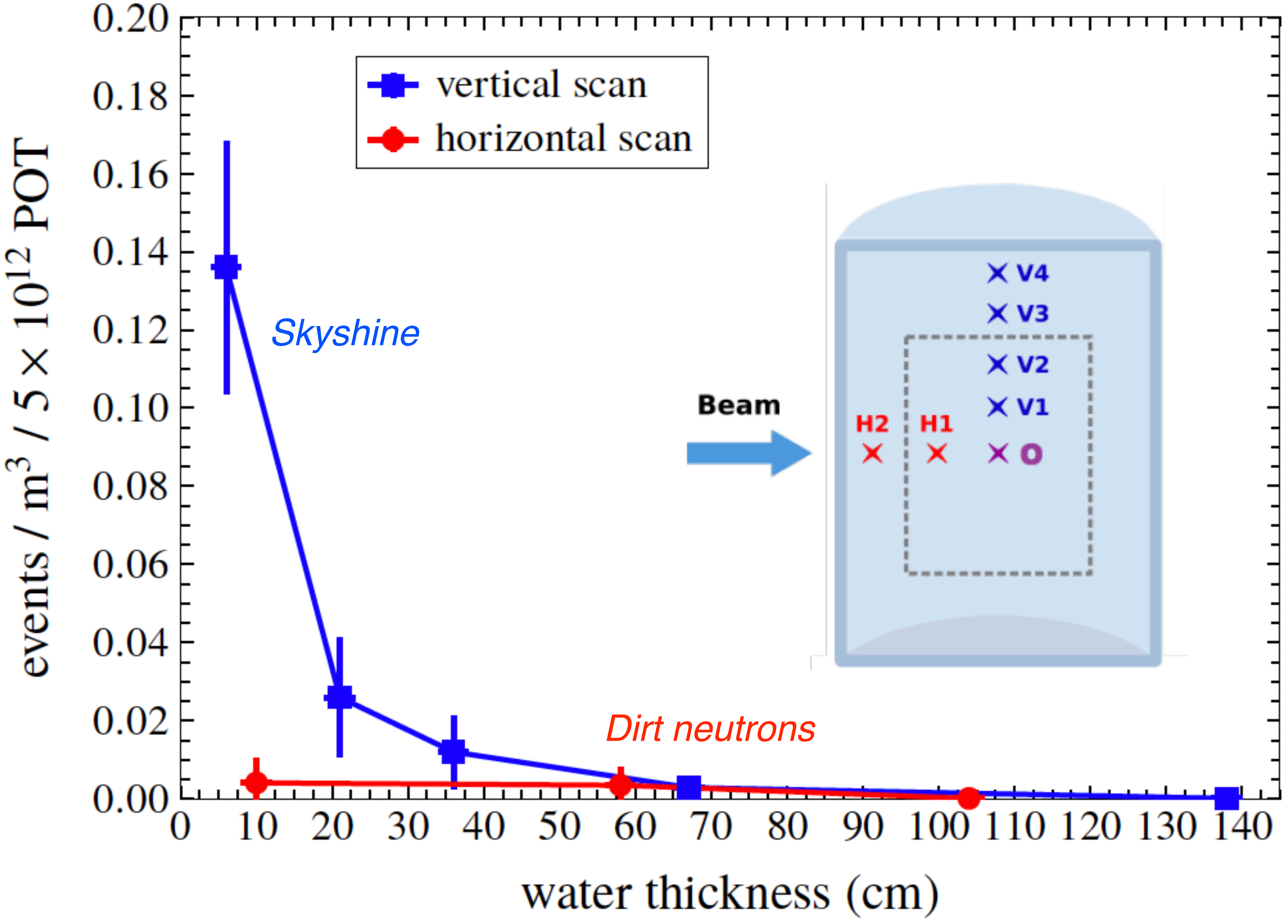
SANDI: Thoroughgoing muons

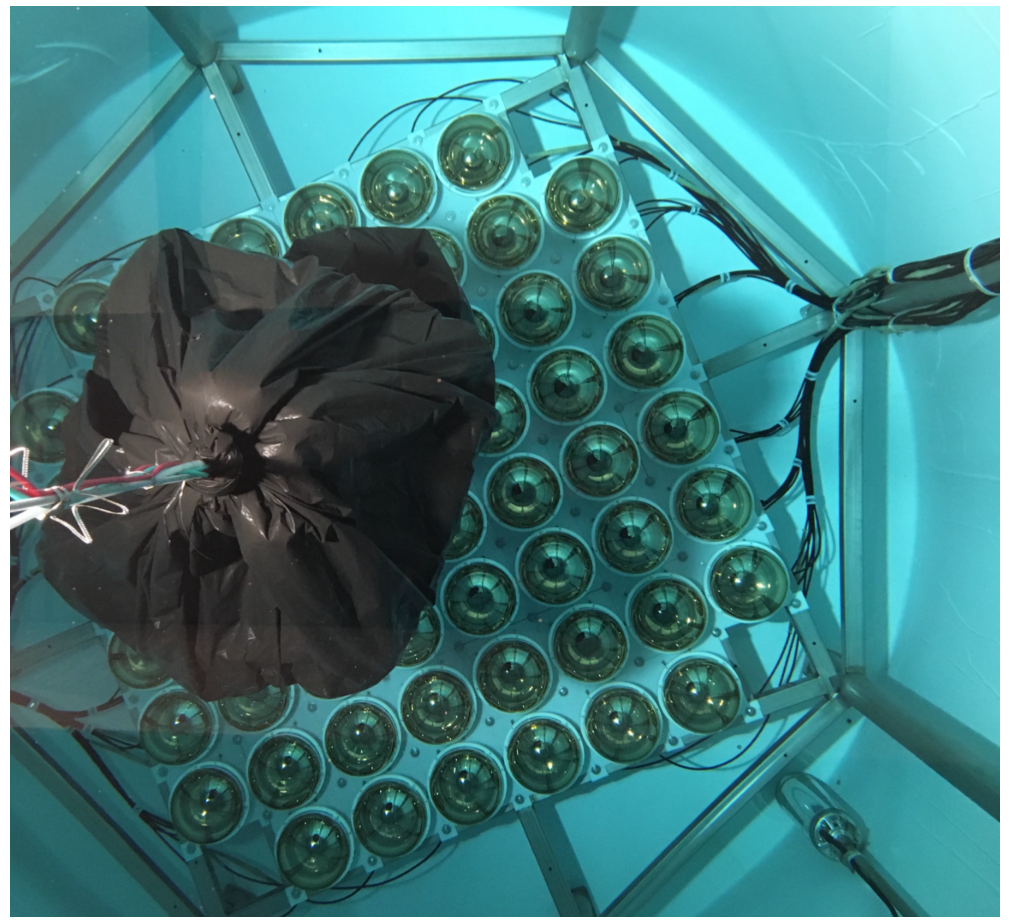
Tracks reconstructed through SANDI that actually missed it



Beam-correlated neutron backgrounds

JINST 15 (2020) 03, P03011 arXiv:1912.03186.





Measurement done with partially-instrumented detector

Skyshine: beam dump neutrons that enter the tank after leaking into the atmosphere.

Dirt neutrons: neutrons from beam neutrino interactions in the upstream rock.

Backgrounds small, mitigated by the buffer layer of water above detector. .