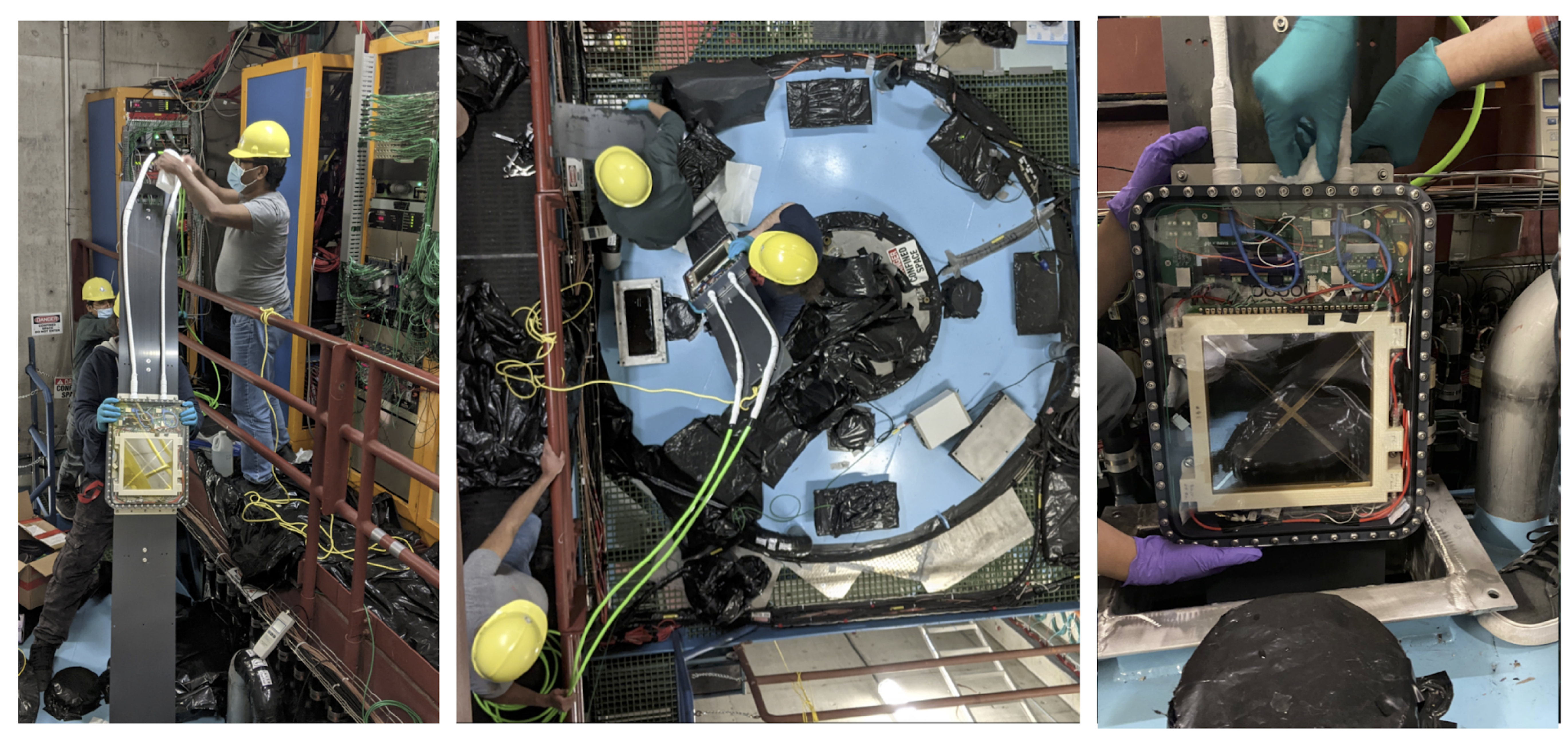
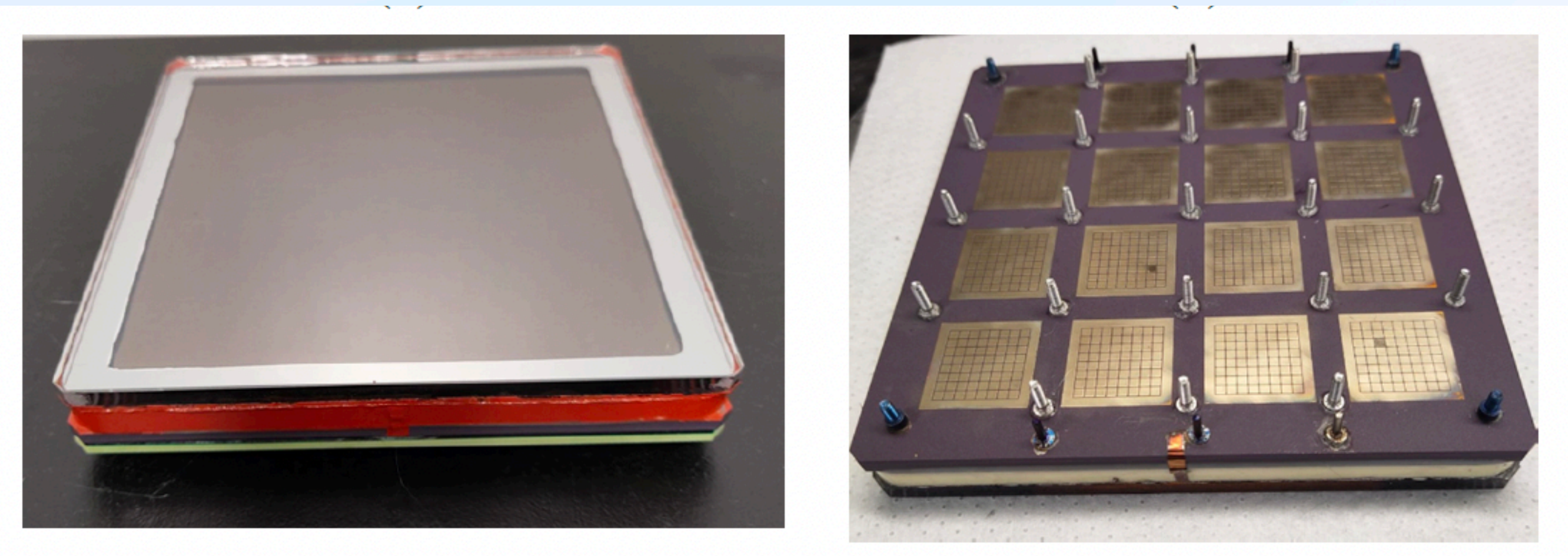
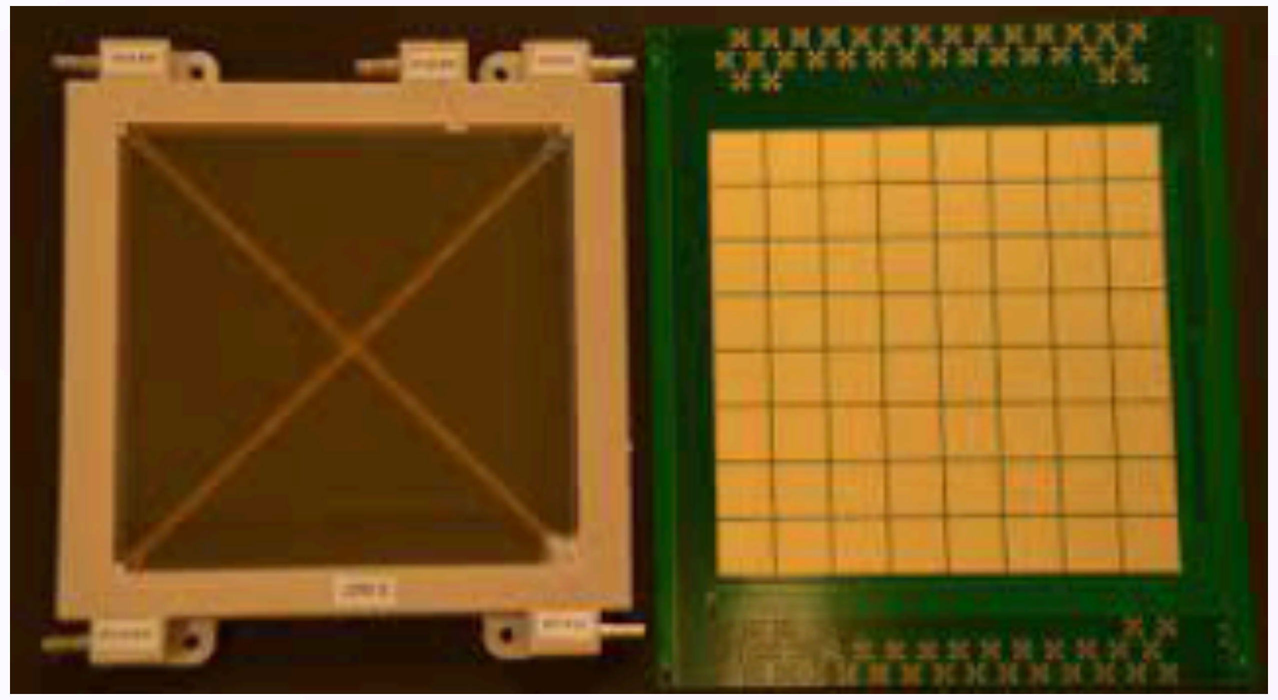
LAPPDs and HRPPDs in 2025





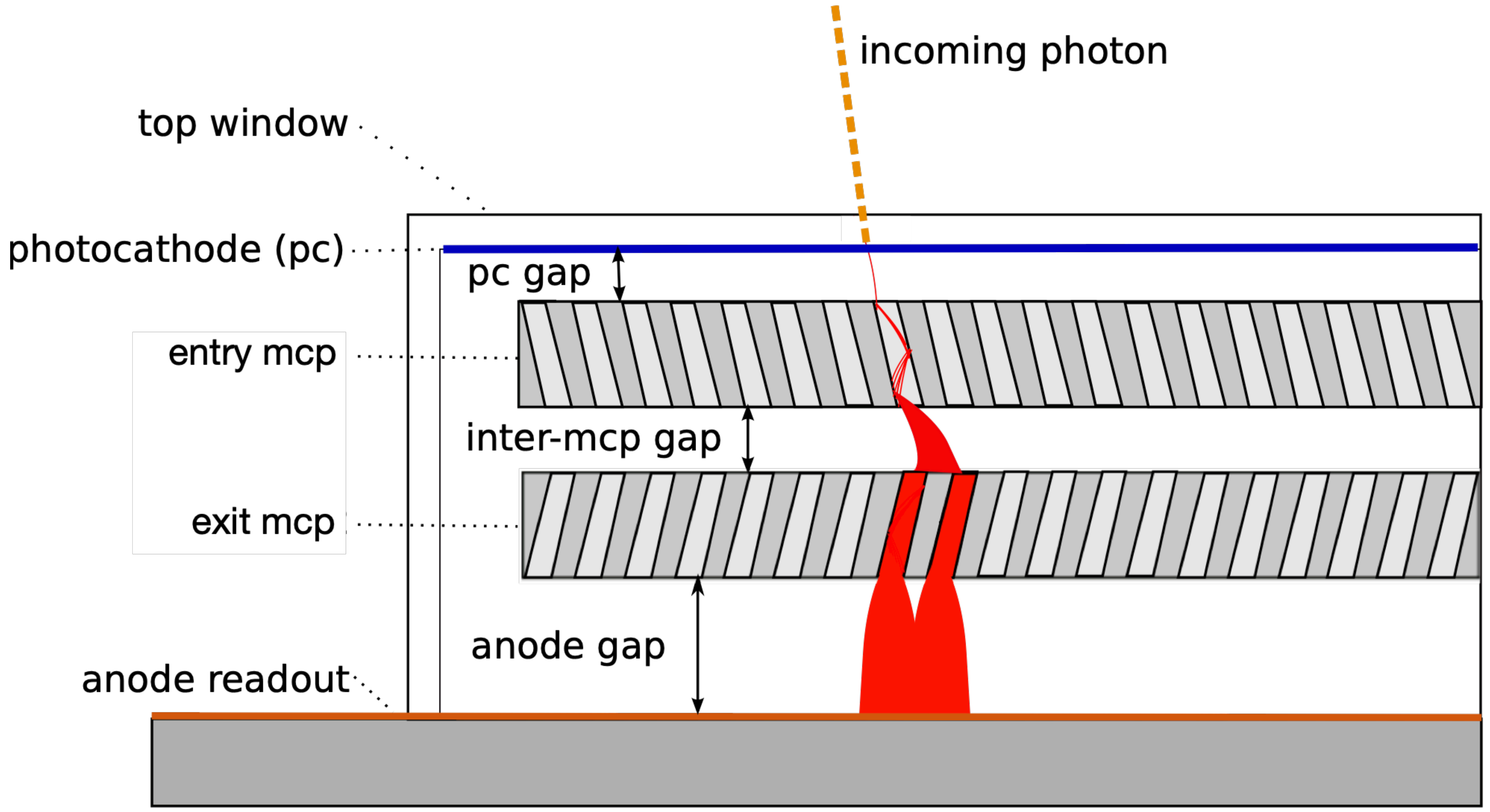
Amanda Weinstein
Iowa State University

Hybrid Cherenkov/Scintillation Detection Workshop, Jun 4, 2025



U.S. DEPARTMENT OF ENERGY

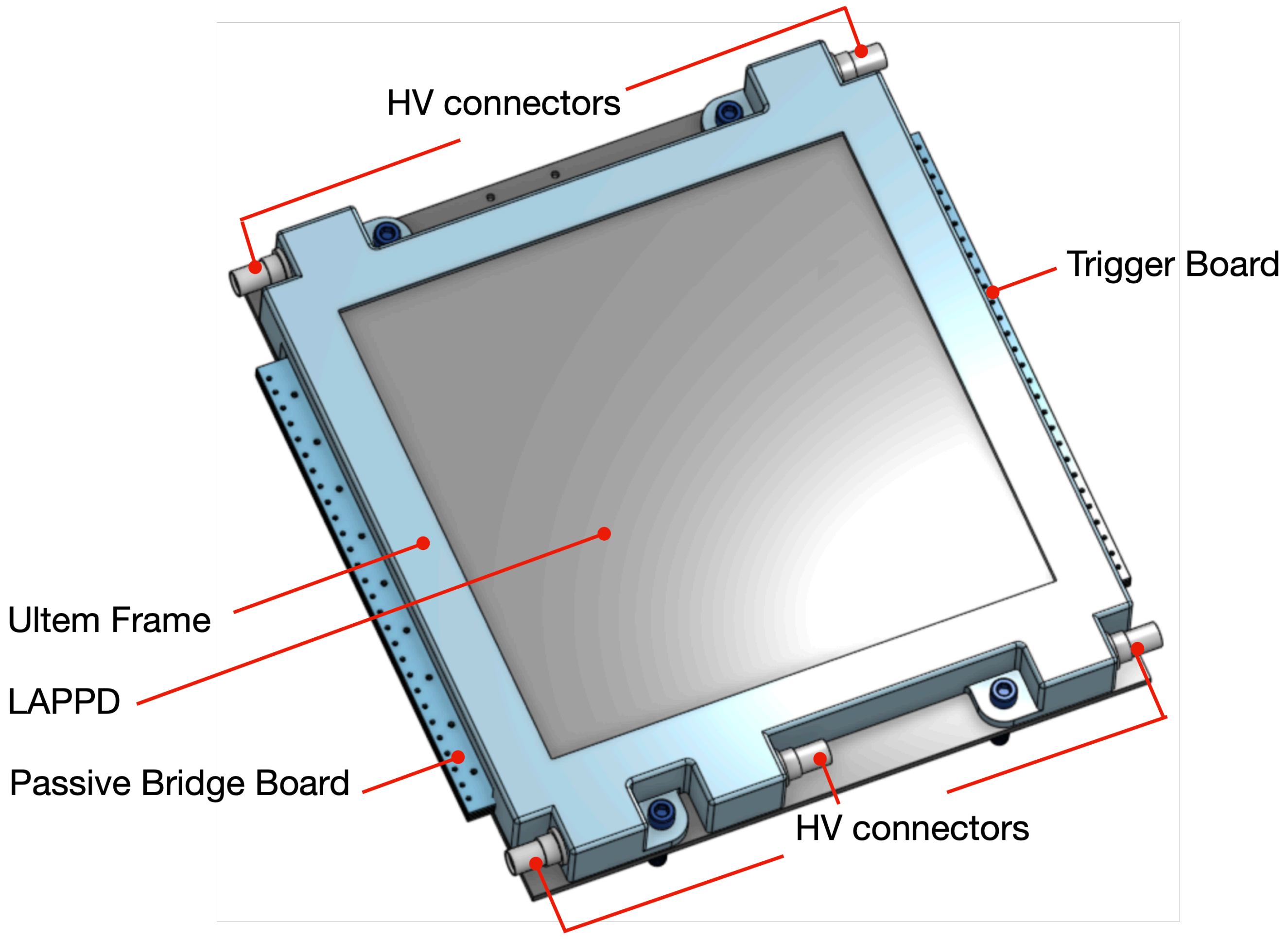
LAPPDs and HRPPDs: General concept



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

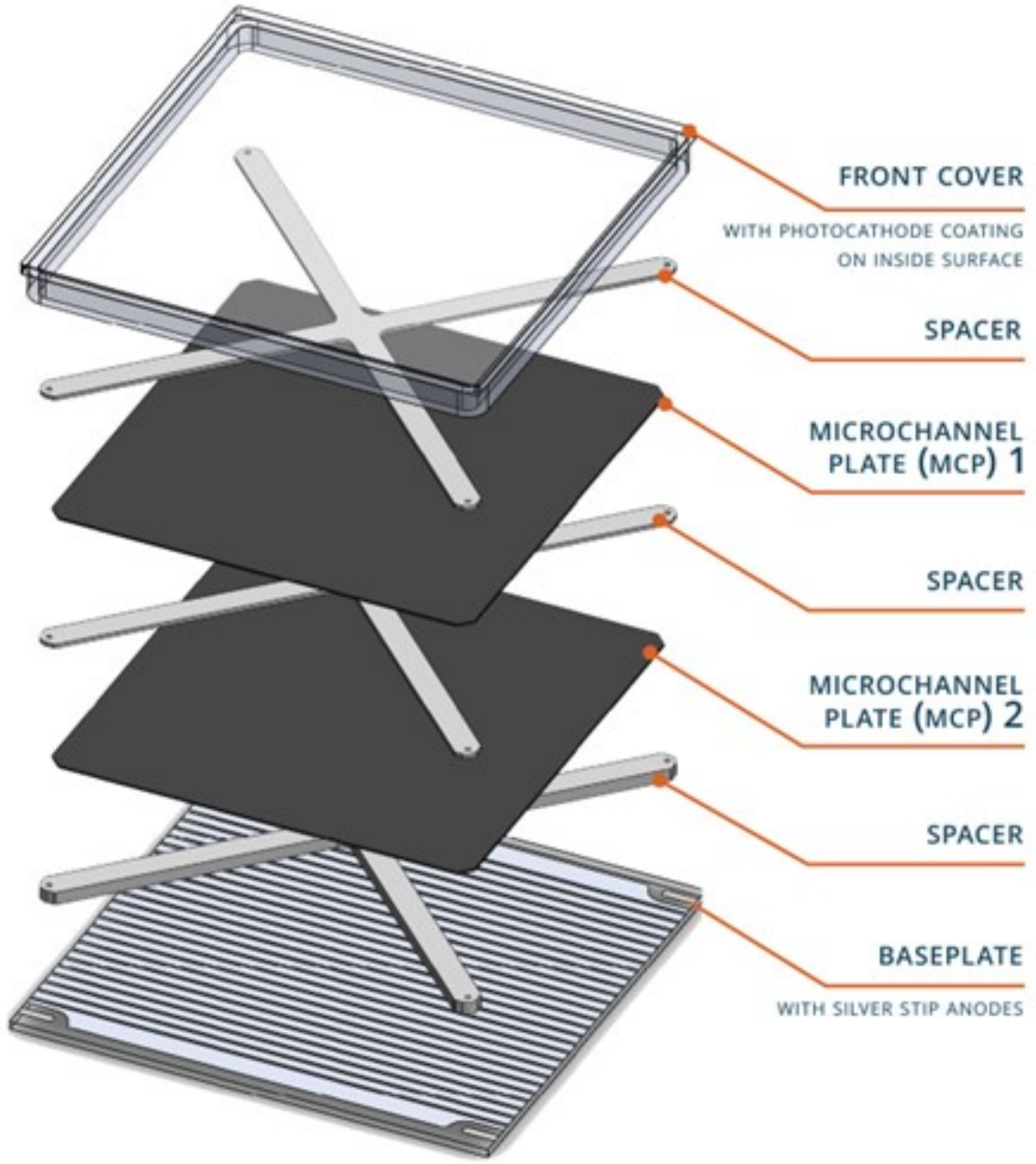
Thin MCP decouples timing resolution from device thickness

- 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

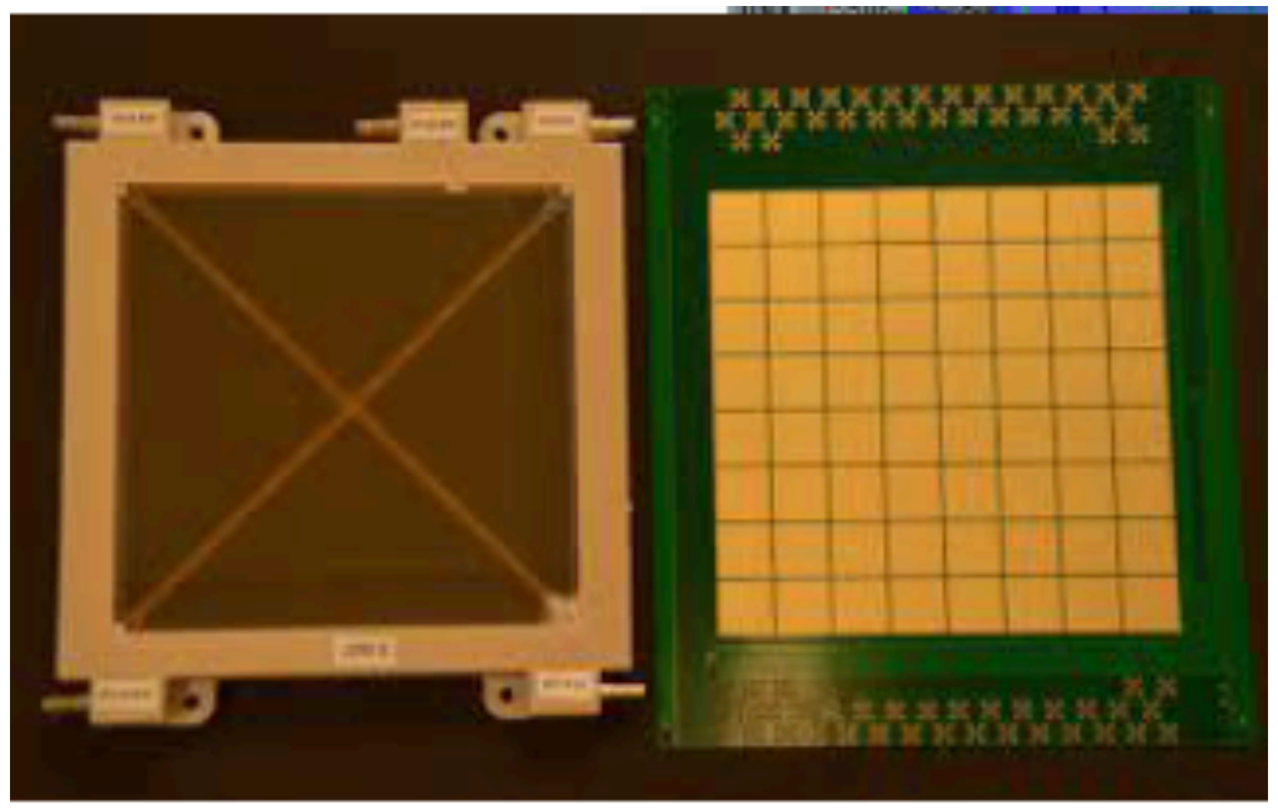
Gen-I LAPPDs: ANNIE, FTBF



20 x 20 cm, 20 μm pores

DC-coupled, 28 microstrip anode inside vacuum package

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

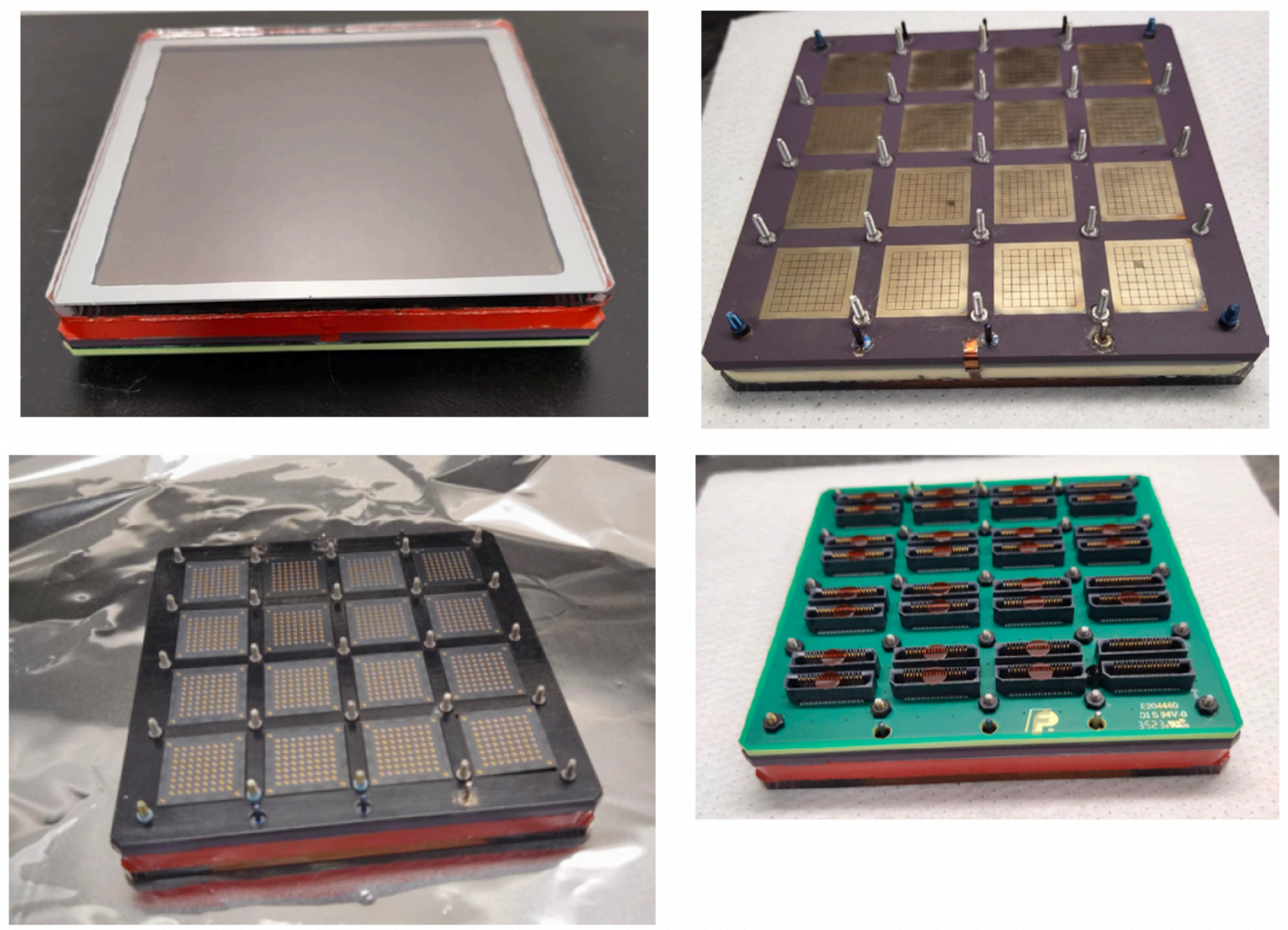


Shares Gen-I dimensions, pore size.

Capacitively-coupled anode allows greater flexibility in readout geometry.

Greater robustness, longevity.

HRPPDs: EIC RICH



Optimized for high rates

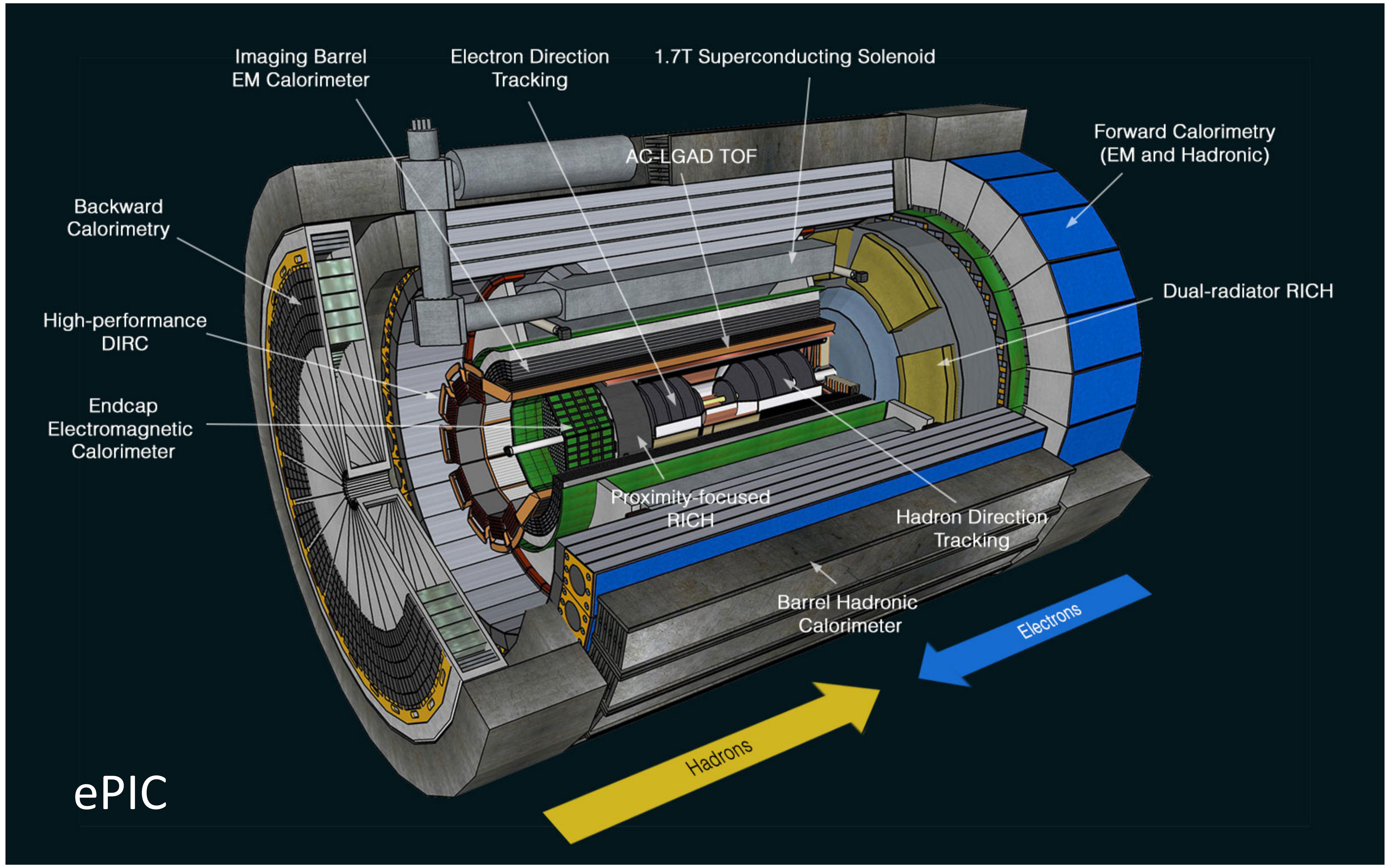
10 cm x 10 cm, 10 μm pores

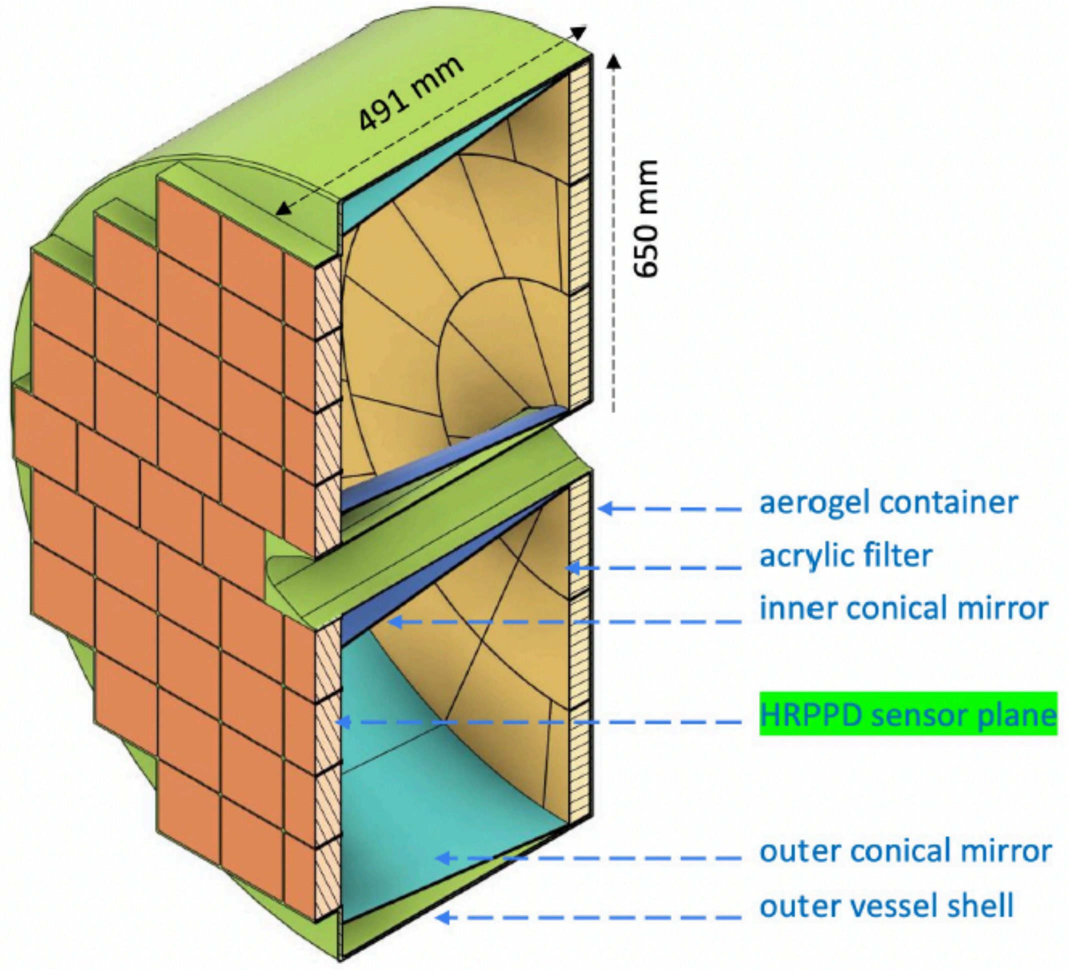
DC-coupled 32 x 32 pixel readout with 3.25 mm pitch

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

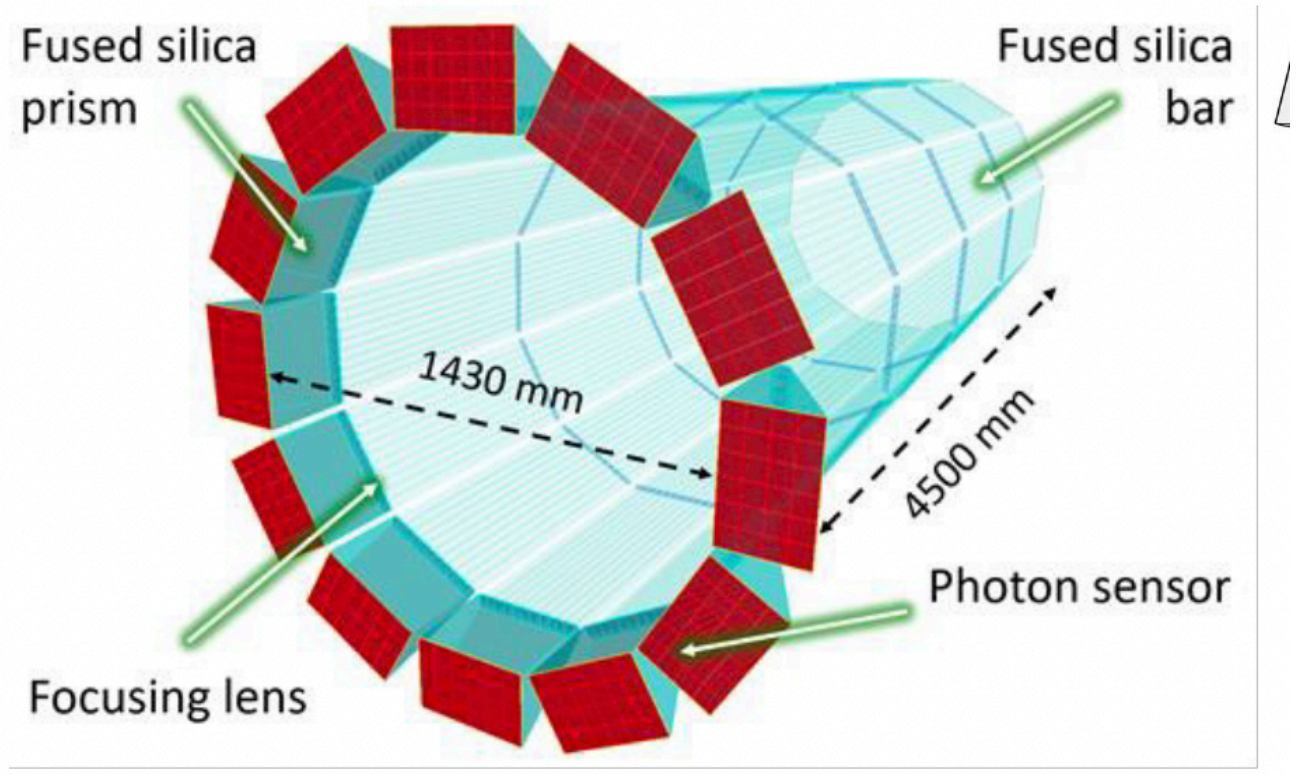
HRPPDs at the EIC

- Electron-ion collider: next-generation nuclear physics experiment in US.
  - Prioritized in 2023 NSAC LRP.
- PID over a wide range of energies crucial for EIC general-purpose detector (ePIC).
  - Proximity-focused RICH (pfRICH) covers backward direction with sub-mm spatial resolution and provides timing reference for **all** ePIC TOF PID systems.
- HRPPDs are the baseline photosensor for the pfRICH for low dark noise, <50 ps timing resolution, and TOF capability.
- Application requires timing resolution, scalability, magnetic field tolerance, robustness.





pfRICH: 68 HRPPDs total

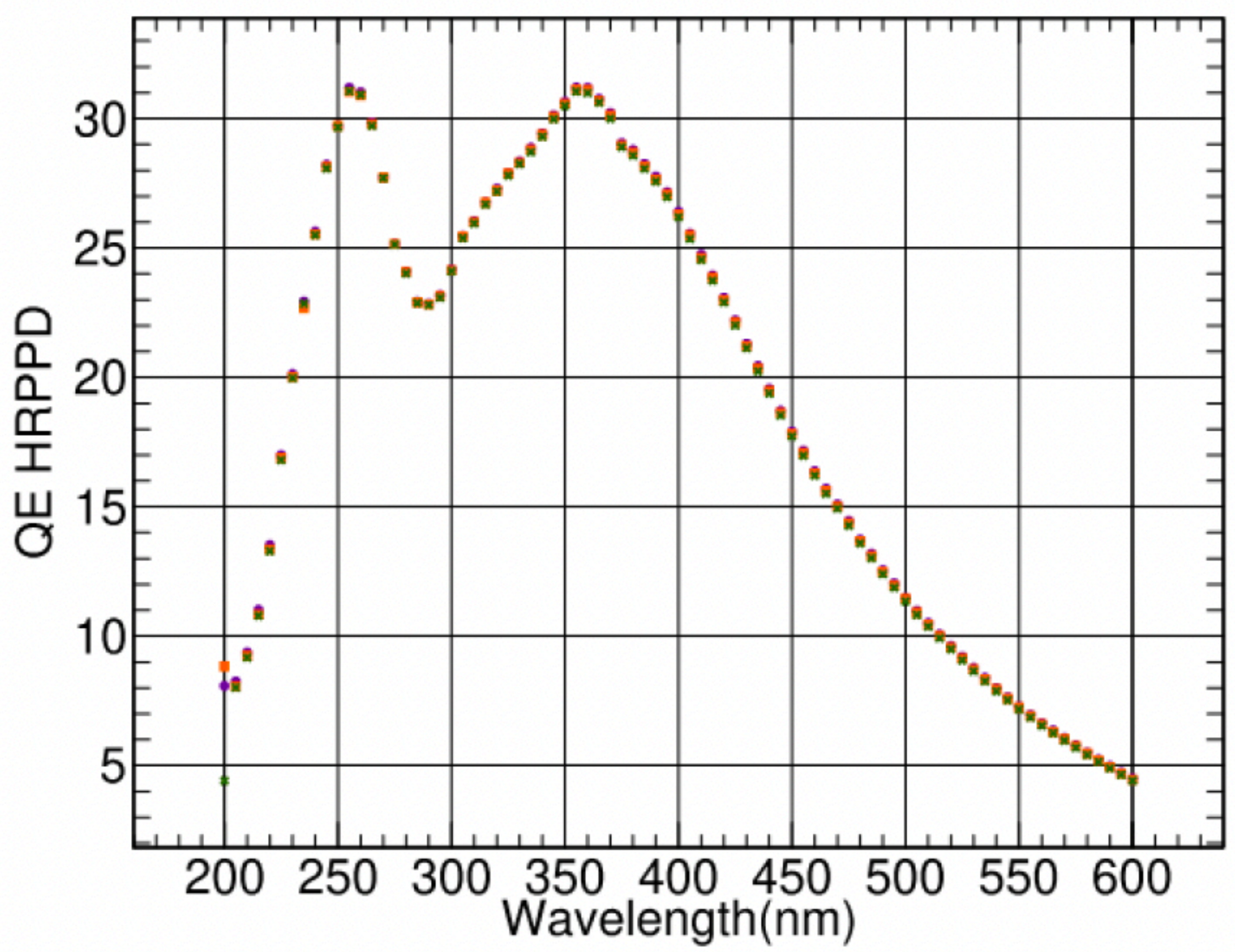


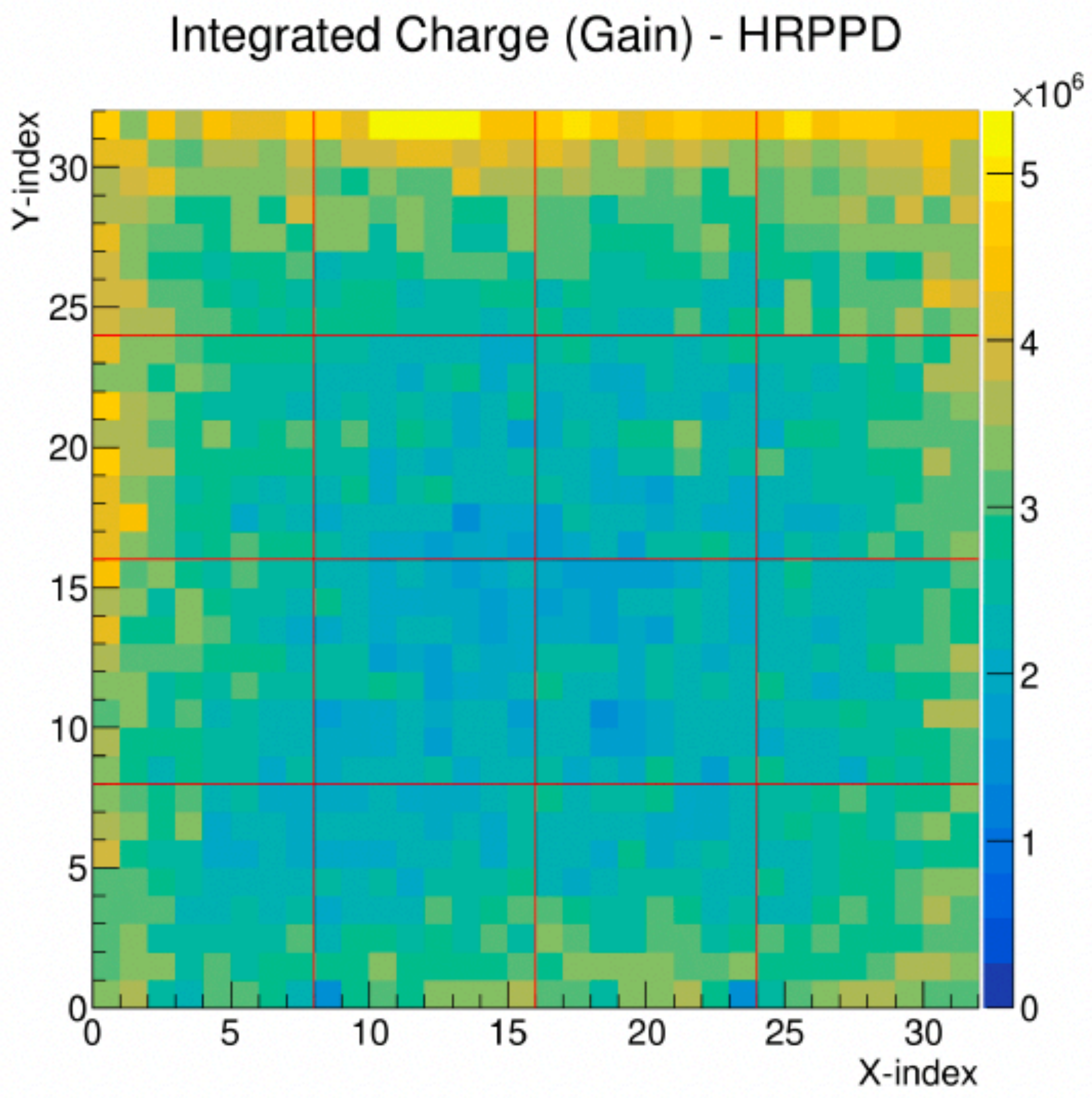
DIRC: 12*3*2 = 72 HRPPDs total

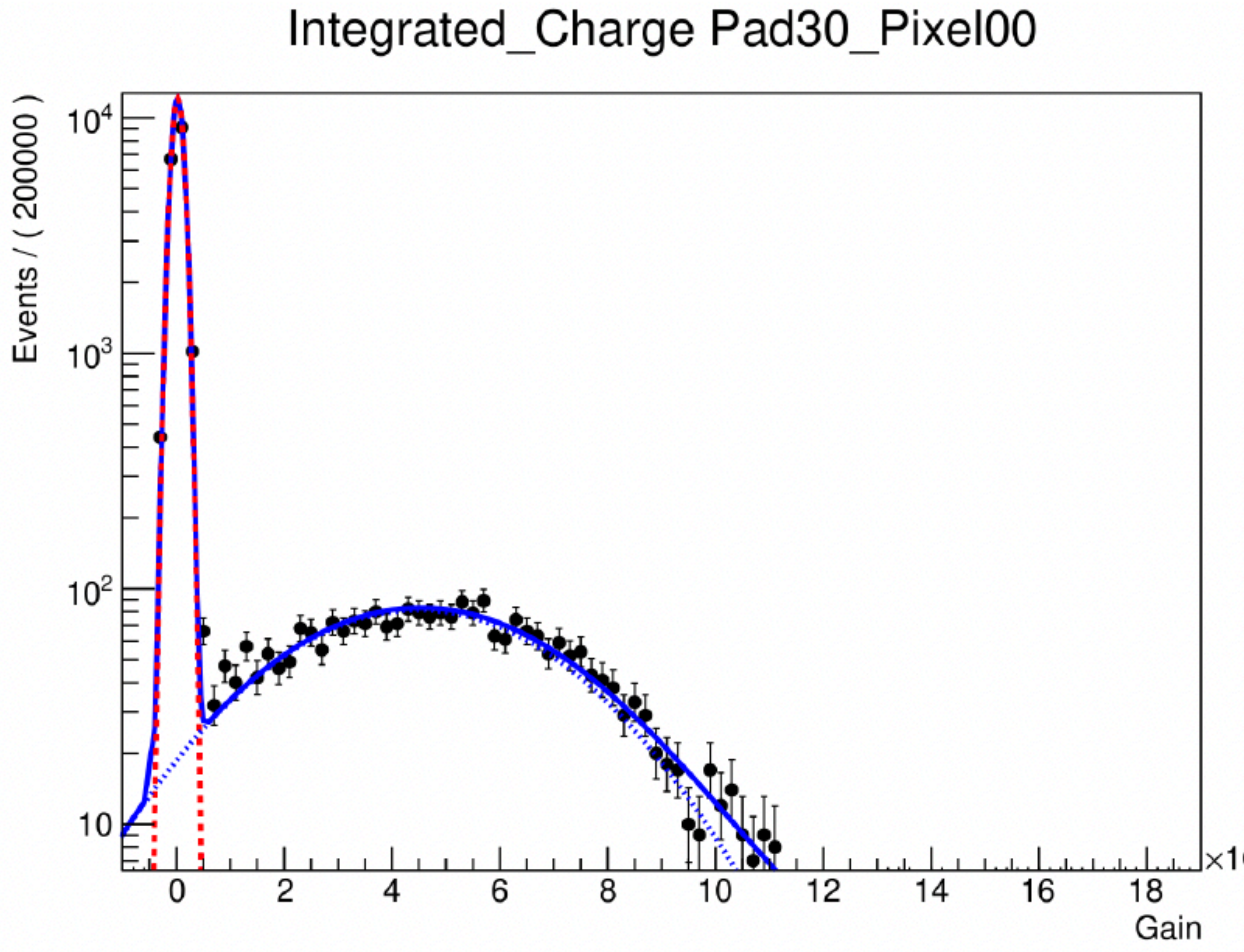
EIC-HRPPD Prototype Testing

- EIC contracted with Incom to re-design HRPPDs for EIC.
- Small test batch from re-design evaluated at several test stations (TJNAL, BNL, INAF) in 2024, results published in arXiv:2505.10658v1 [physics.ins-det] 15 May 2025
    - SPE timing resolution of ~20 ps (MCP bias voltage 775V, PC gap 100 V) down to 15 ps (300 V PC gap)
    - Mean QE of 27-36% for all HRPPDs, DCR < 2 kHz/cm^2.

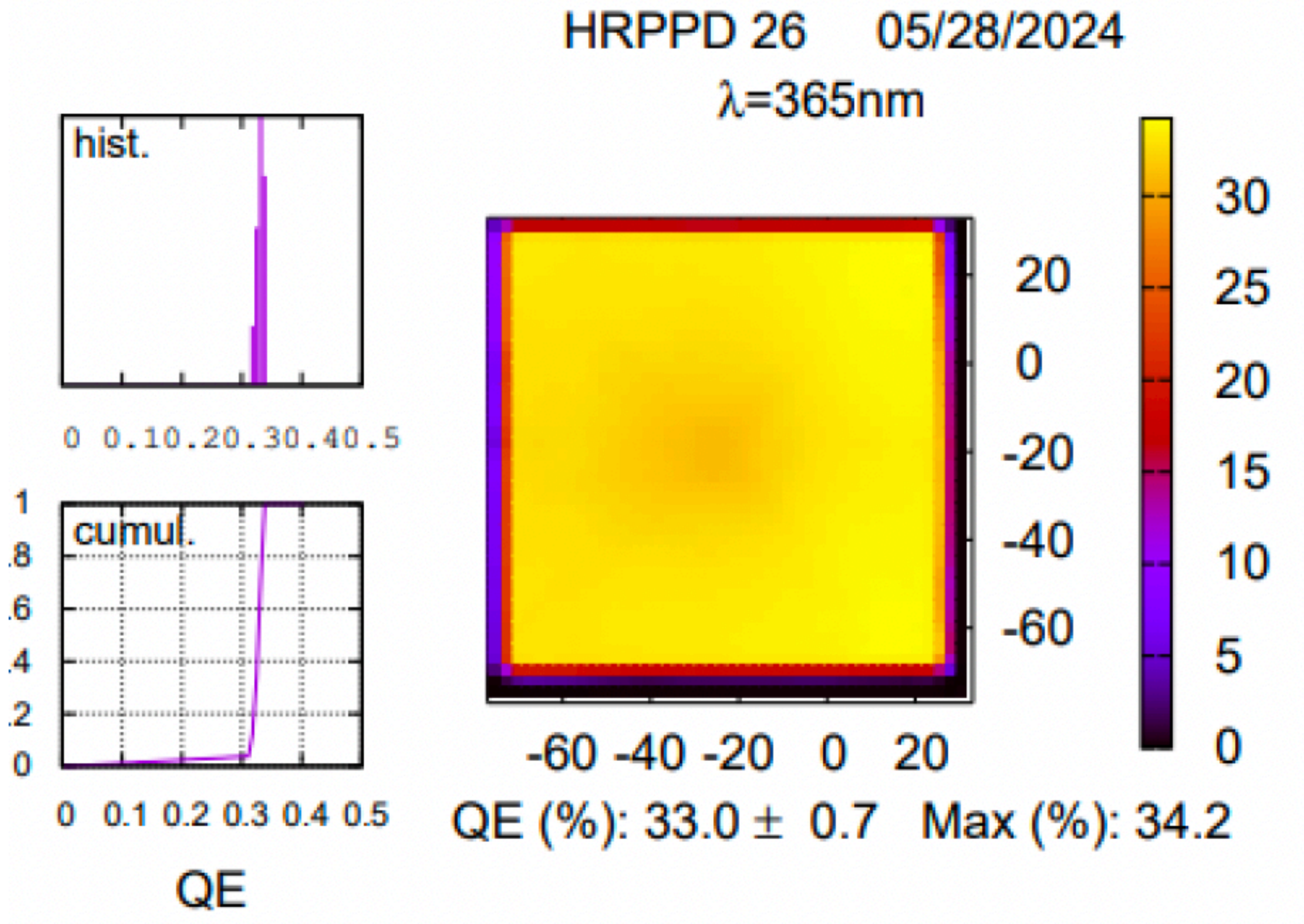
(a)







(b)



Lifetime studies, magnetic field studies ongoing

LAPPDs at FTBF

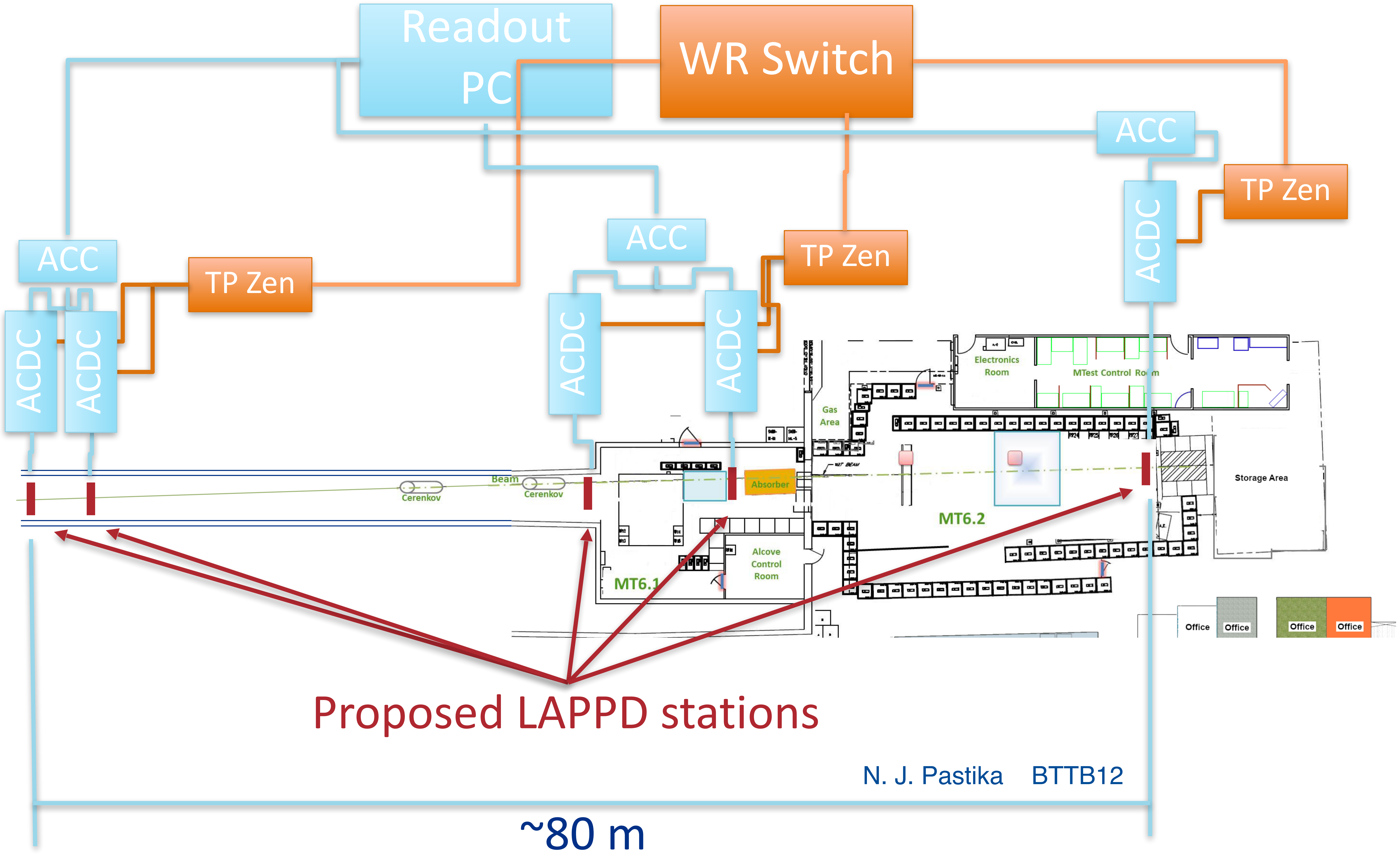
FTBF –
Meson
Detector
Building

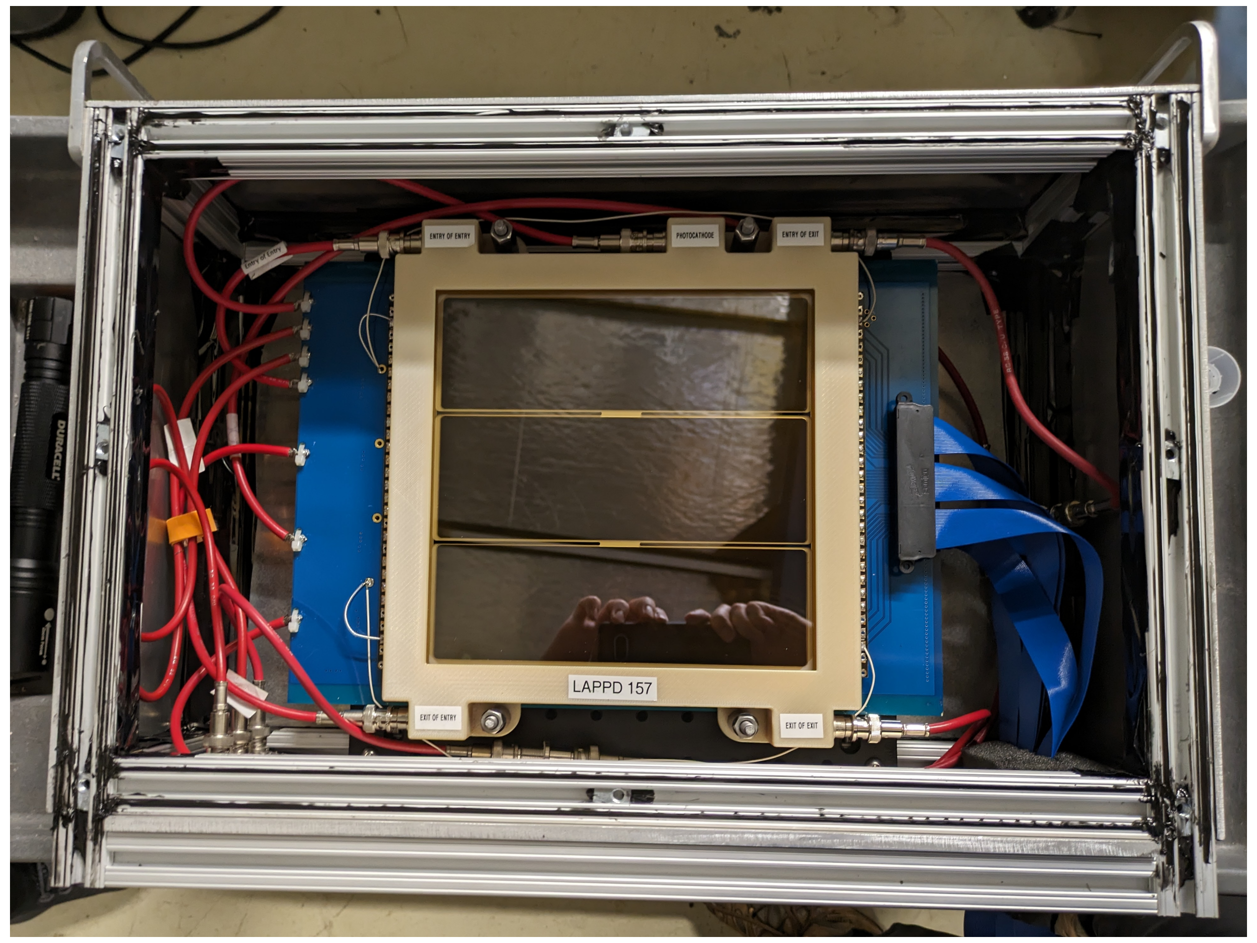
MTest beam line: 120 GeV primary protons, 1-66 GeV secondary beam

~2 cm spot size, 1-4 week runs

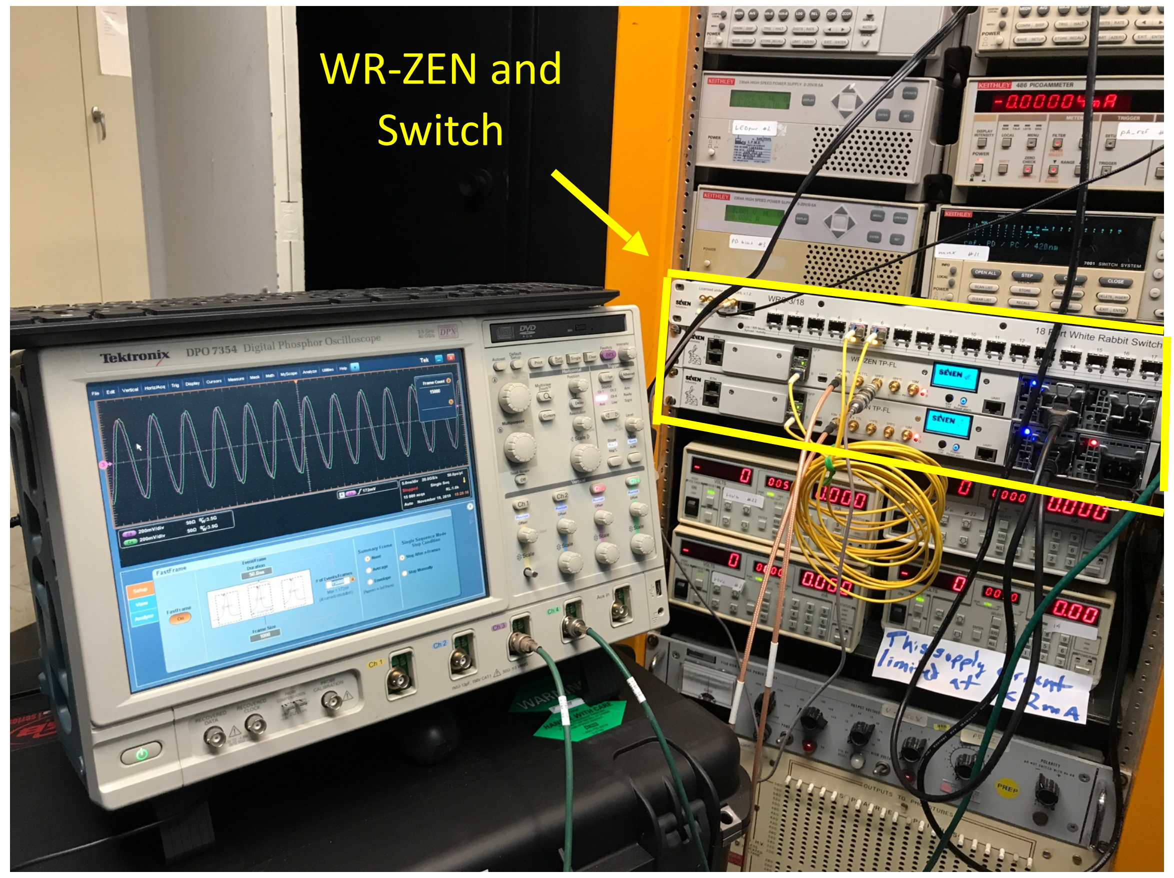
- Fermilab Test Beam Facility (FTBF) – Supports a wide program of research and detector R&D
- Current MTest PID system relies on PMT TOF (not permanent, difficult to set up) and Cherenkov detectors.

- **Idea: New permanent TOF system with LAPPDs.**
- Time-of-flight:
  - $$\Delta t = d\sqrt{1+\frac{m^2}{p^2}}$$
  - Know d, measure p and Δt, infer m.
  - PID: difference in time-of-flight for two particles.
  - $$\tau_{12} \approx \frac{d}{2p^2}\left(m_1^2 - m_2^2\right)$$





TOF station: Gen-II LAPPD in dark box

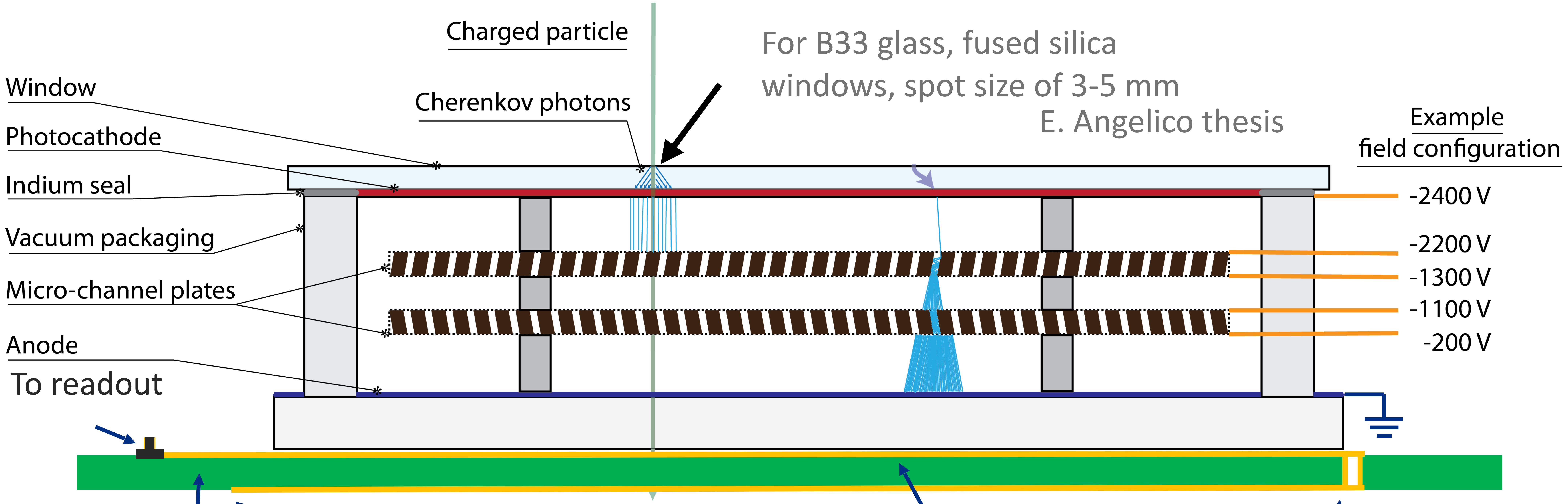


WR-ZEN: 5-10 ps relative timing at km separation.

Provides 250 MHz sine wave, 100 MHz clock signal, 1 Hz sync to each station.

- LAPPD stations measure time-of-flight and localize interaction position.
- Multiple stations allow for PID for a larger range of particle momenta, more precise path length measurement, better coverage and redundancy.

Gen II LAPPD single ended stripline readout



For B33 glass, fused silica windows, spot size of 3-5 mm
E. Angelico thesis

Readout stripline (wraps around back of PCB)

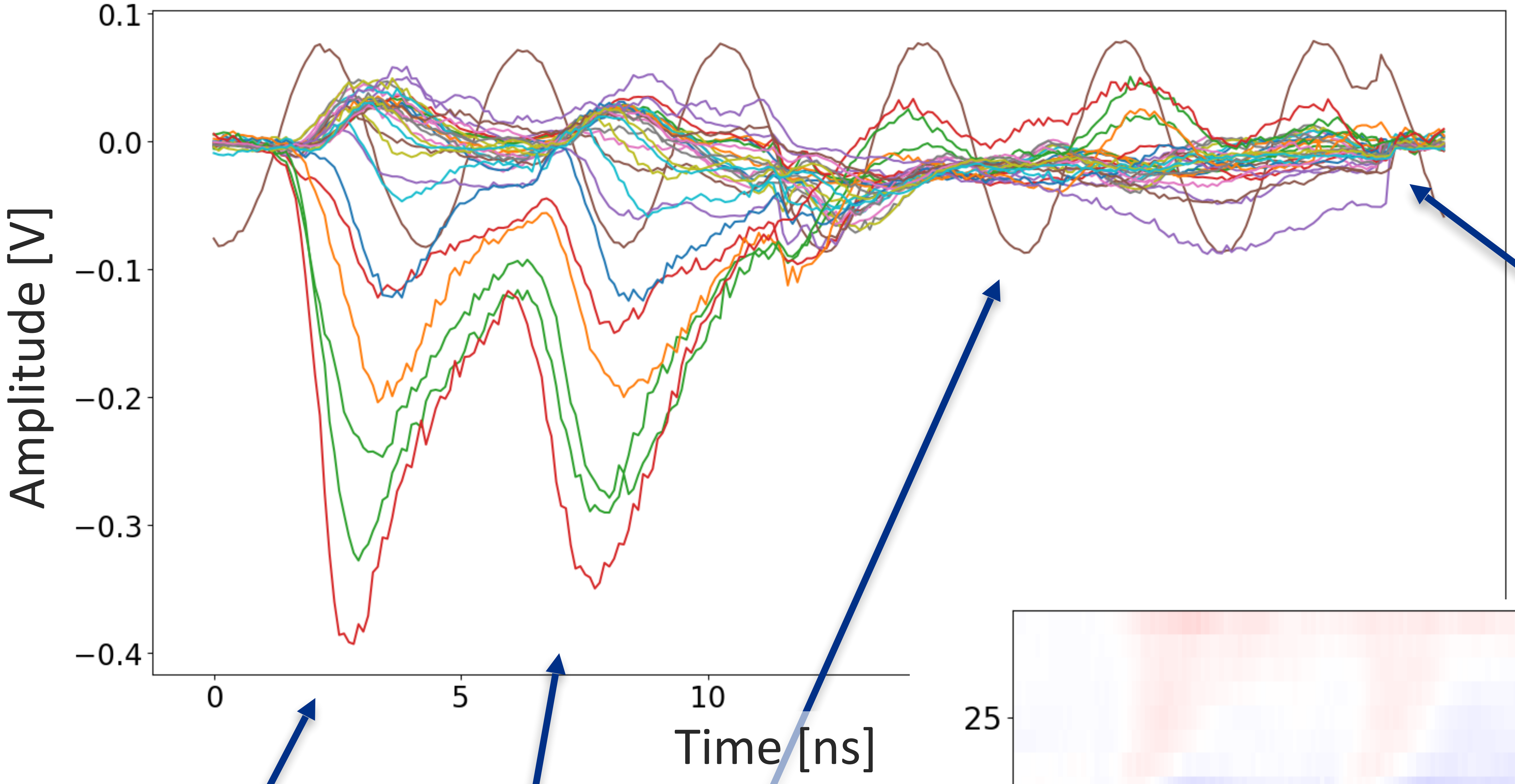
Unterminated to create reflection (reduces the # channels)

Capacitively coupled pickup board

From: N. J. Pastika BTTB12

- Readout electronics: ACC (data concentrator) and ACDC (digitizer). Similar to ANNIE's, but newer ACDC revision with different firmware.

Raw Gen-II LAPPD data



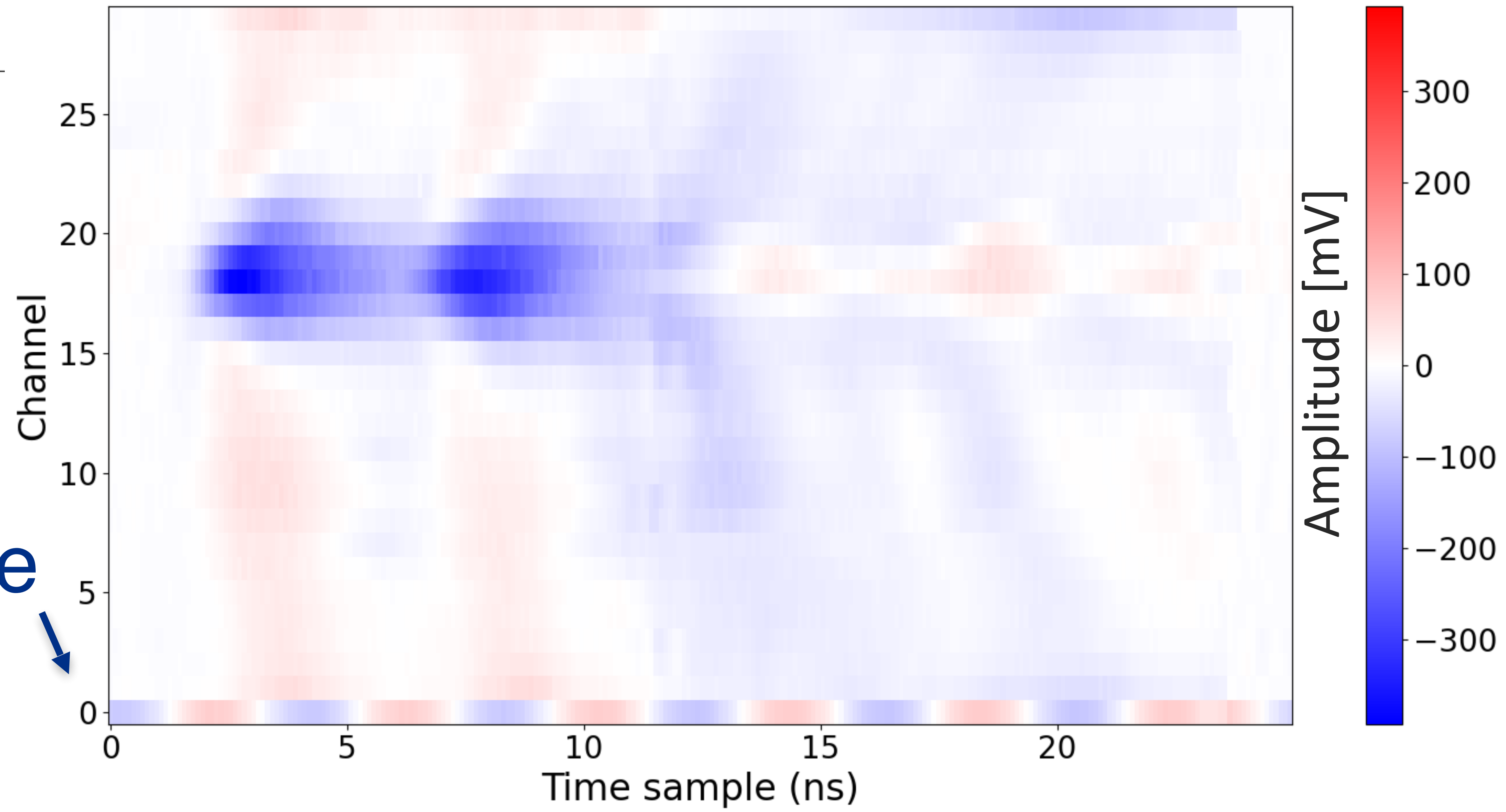
Proton signal in LAPPD 128

Trigger window

Prompt pulse

Reflection

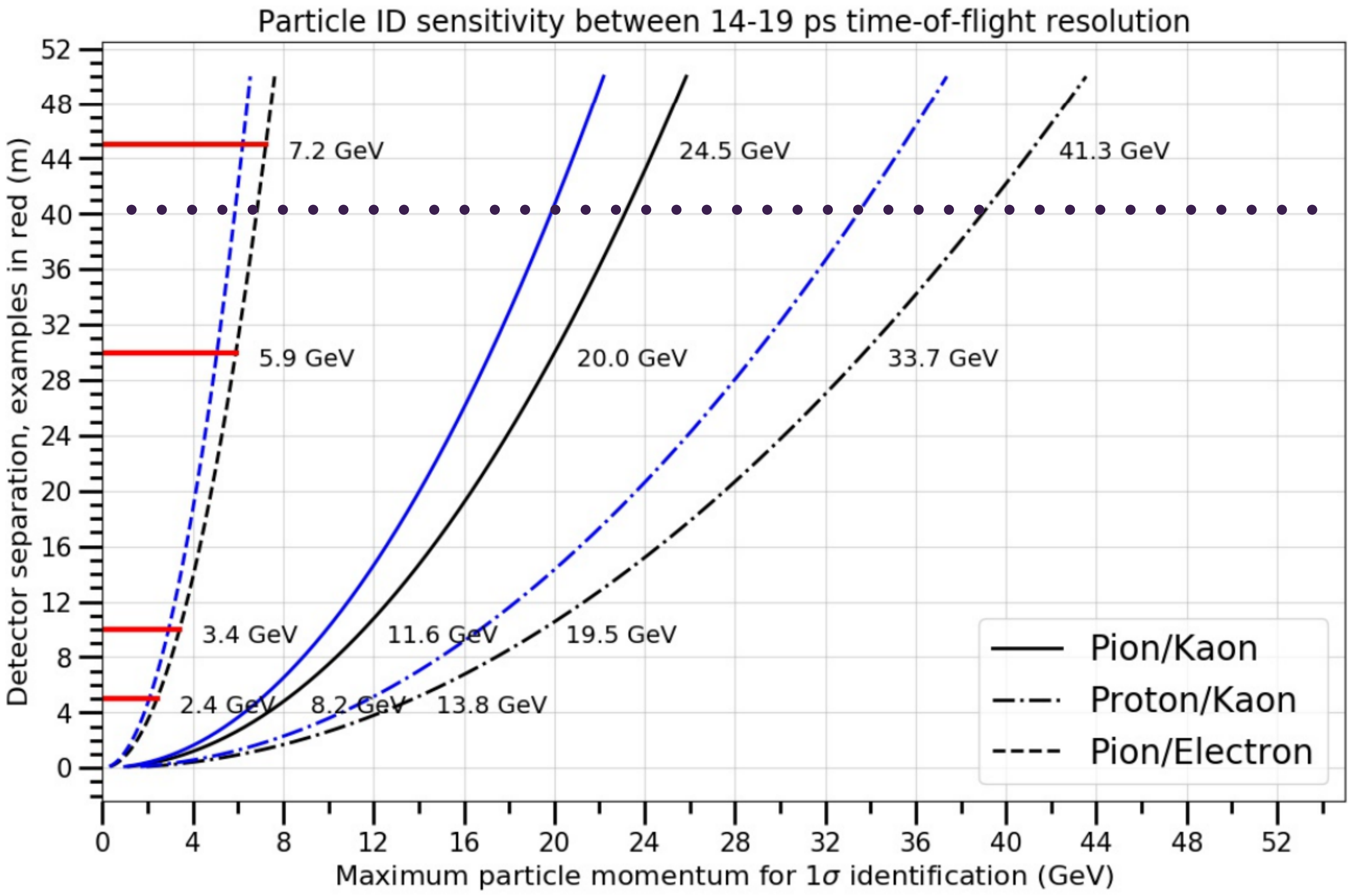
250 MHz timing reference



N. J. Pastika BTTB12

Expected sensitivity

- Projected sensitivity based on calculations and measurements by E. Angelico.
- Want at least 40m max detector separation.
- Note: test stations had 5m max separation.



Angelico, Evan. doi:10.2172/1637600

	$\sigma_L/\sqrt{N_{\mathrm{pe}}}$ PE spread	σ_{pulse} readout	σ_{WR} Inter station timing	σ_{tof}	Maximum π/K momentum at 5 m / 45 m
Gen 1 LAPPD	55 ps / $\sqrt{30}$	7 ps	5 ps	19 ps	7.0 / 21 GeV/c
Use of fused silica window	55 ps / $\sqrt{200}$	7 ps	5 ps	14 ps	8.2 / 25 GeV/c
Low-jitter WR-ZEN	55 ps / $\sqrt{200}$	7 ps	$<$ 0.5 ps	13 ps	8.5 / 25 GeV/c
10 μm pores and higher cathode voltages	10 ps / $\sqrt{200}$	7 ps	$<$ 0.5 ps	11 ps	9.2 / 28 GeV/c
PSEC4 chip development	10 ps / $\sqrt{200}$	1 ps	$<$ 0.5 ps	1.7 ps	24 / 70 GeV/c

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.
  - Beamline shared with LAr short-baseline experiments.
- Technology: An R&D platform to develop and demonstrate new neutrino detection technologies/techniques.
- Training: 10+ Annie postdocs and students now have faculty or permanent lab positions (at least 4 at Fermilab)

45 collaborators from 19 institutions in 6 countries

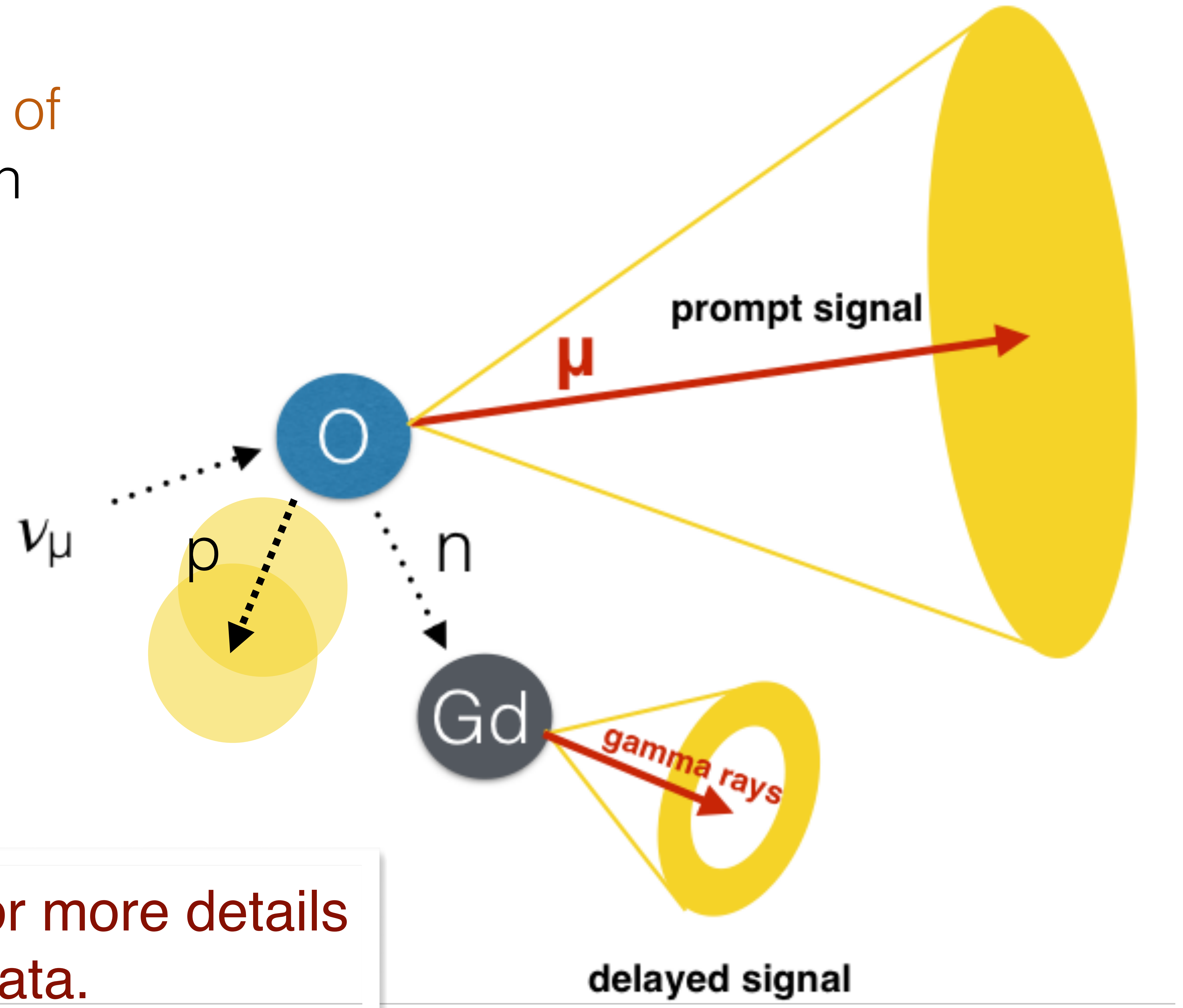
LAPPDs in ANNIE: Goals and Accomplishments

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

End goal: demonstrate improved reconstruction of muon kinematics and neutrino vertex localization transverse to beam, time-based C/S separation for WbLS.

Milestone: First ν's detected with LAPPDs!

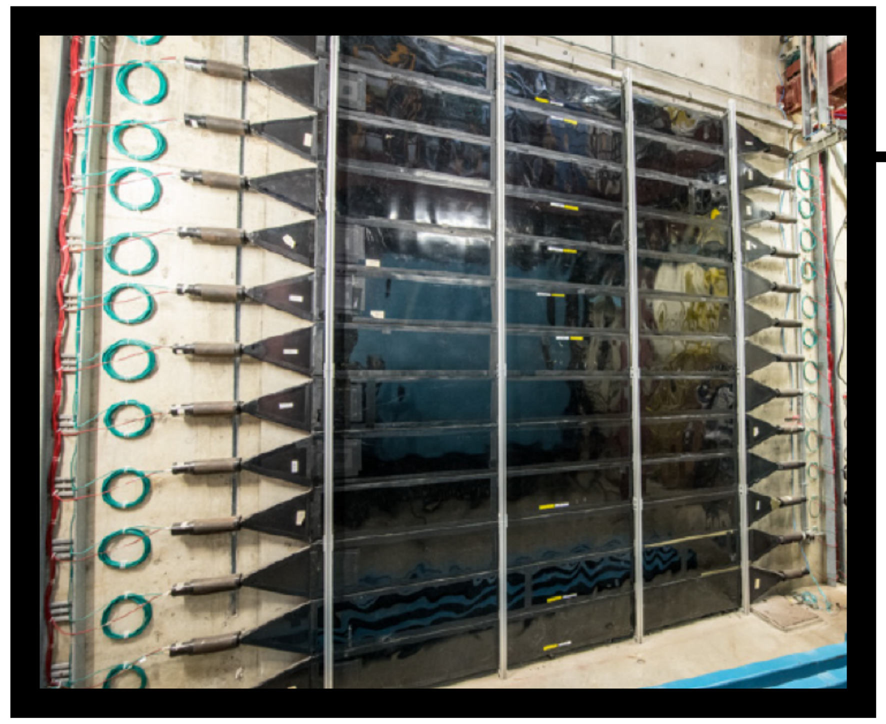
Provides insight into challenges inherent in interpreting LAPPD data as well as practical operational experience.



See Bob Svoboda's talk and Johann Martyn's for more details on neutron tagging with Gd and ANNIE WbLS data.

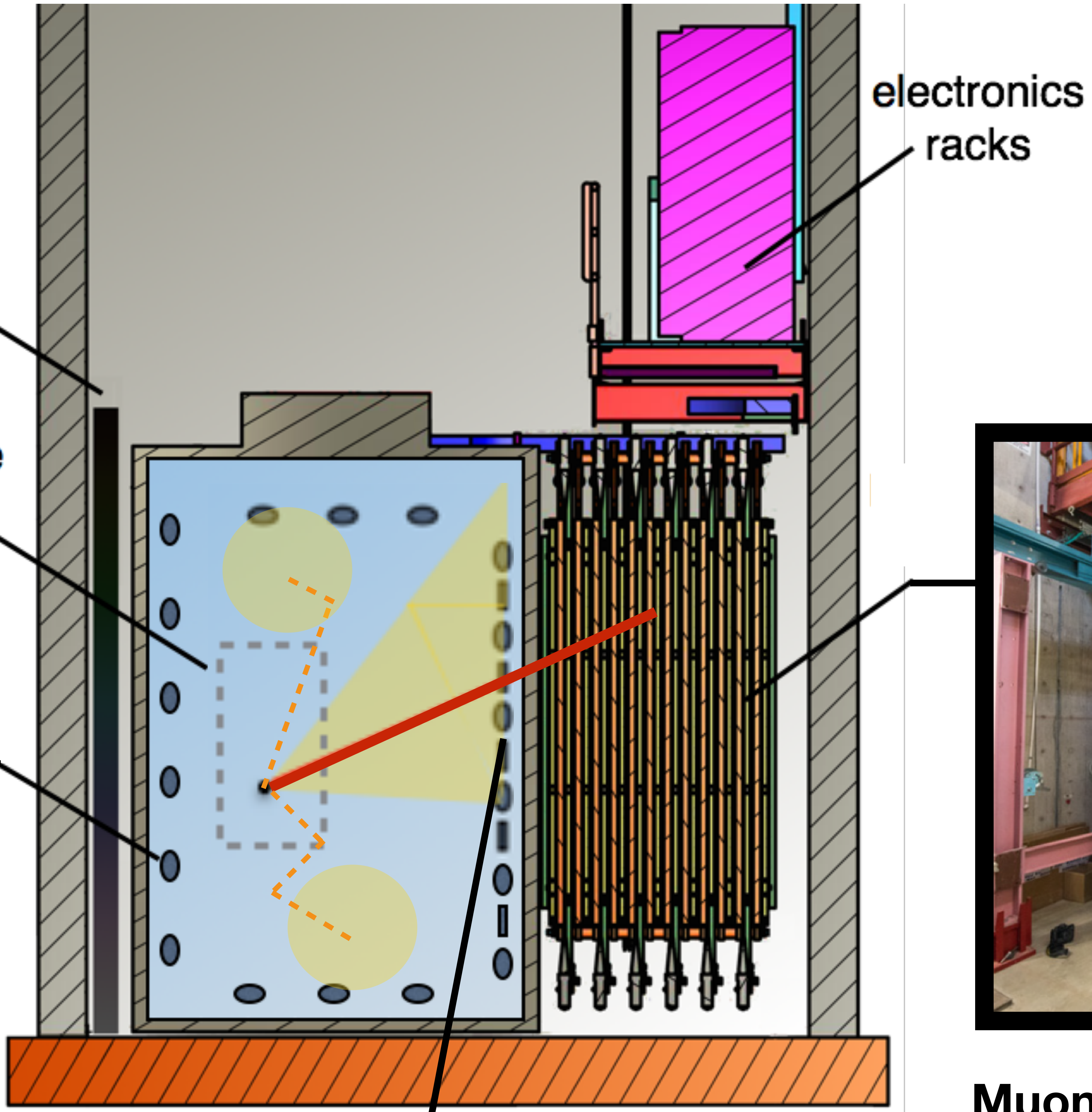
ANNIE Detector

Front Muon Veto (FMV)
(2 overlapping scintillator layers)
Rejects dirt μ

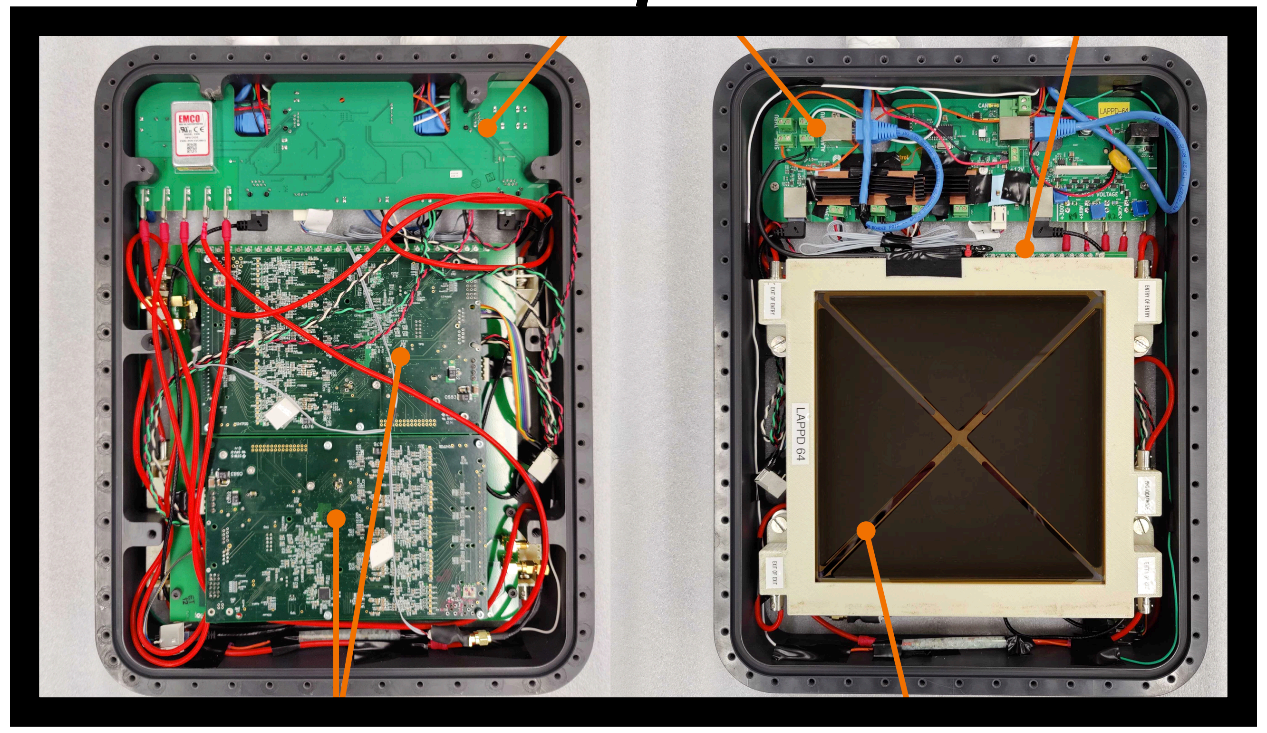


132 PMTs (8”-11”)

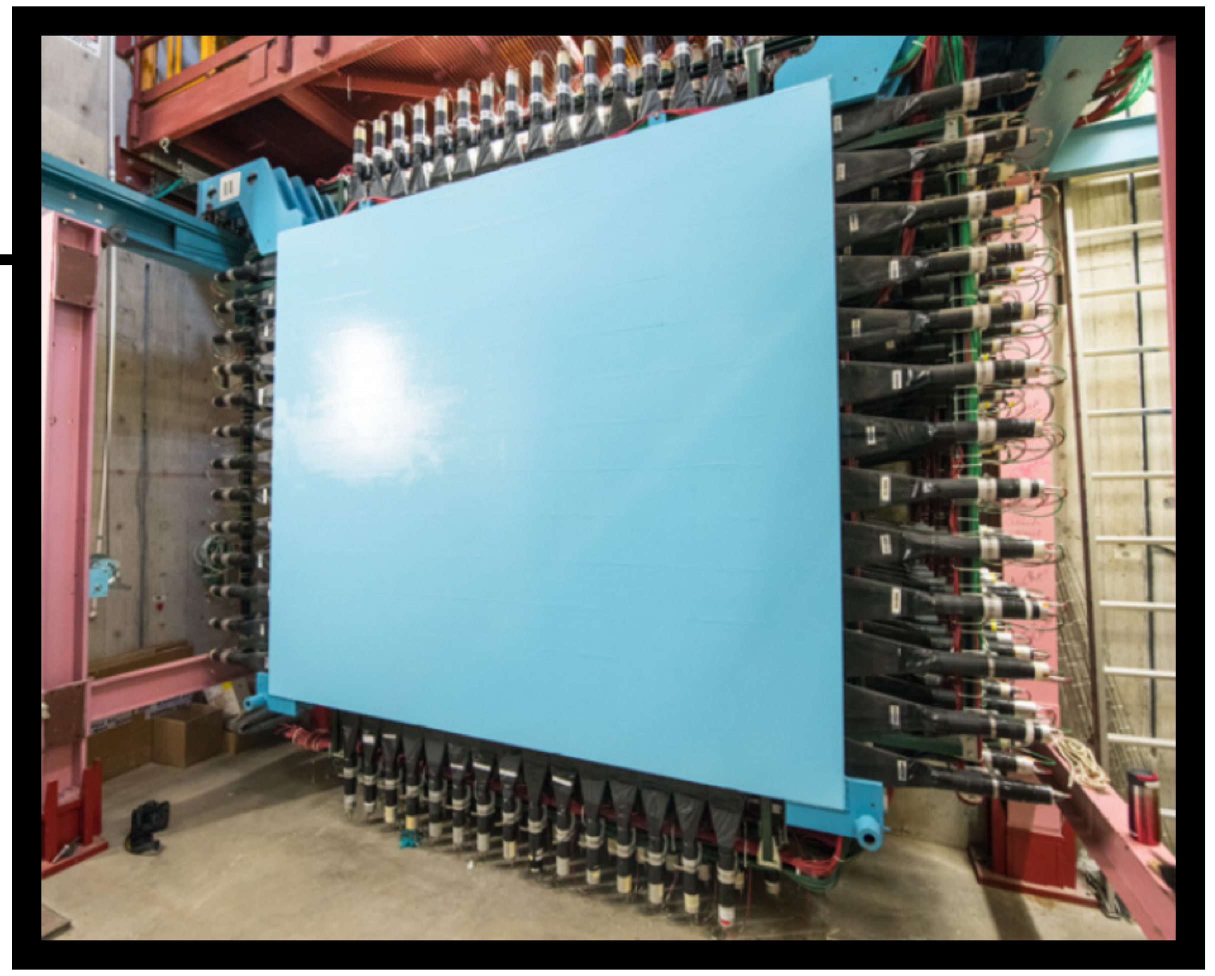
Neutron detection, independent Cherenkov constraints on μ track



Neutron captures on Gd (Neutron counting)



3 20x20 cm LAPPDs

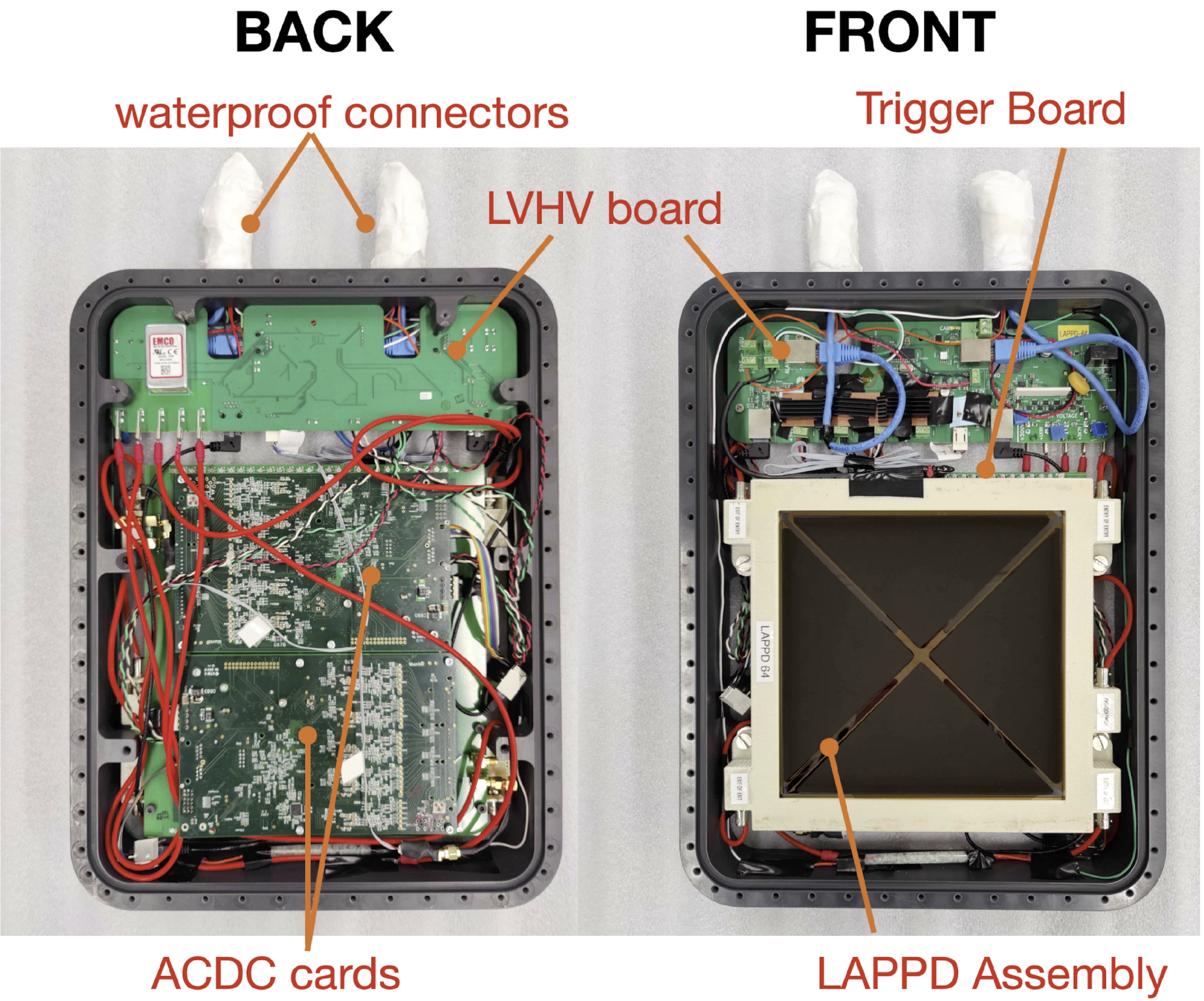


Muon Range Detector (MRD)

11 X-Y layers, alternating scintillator w/ 5cm iron

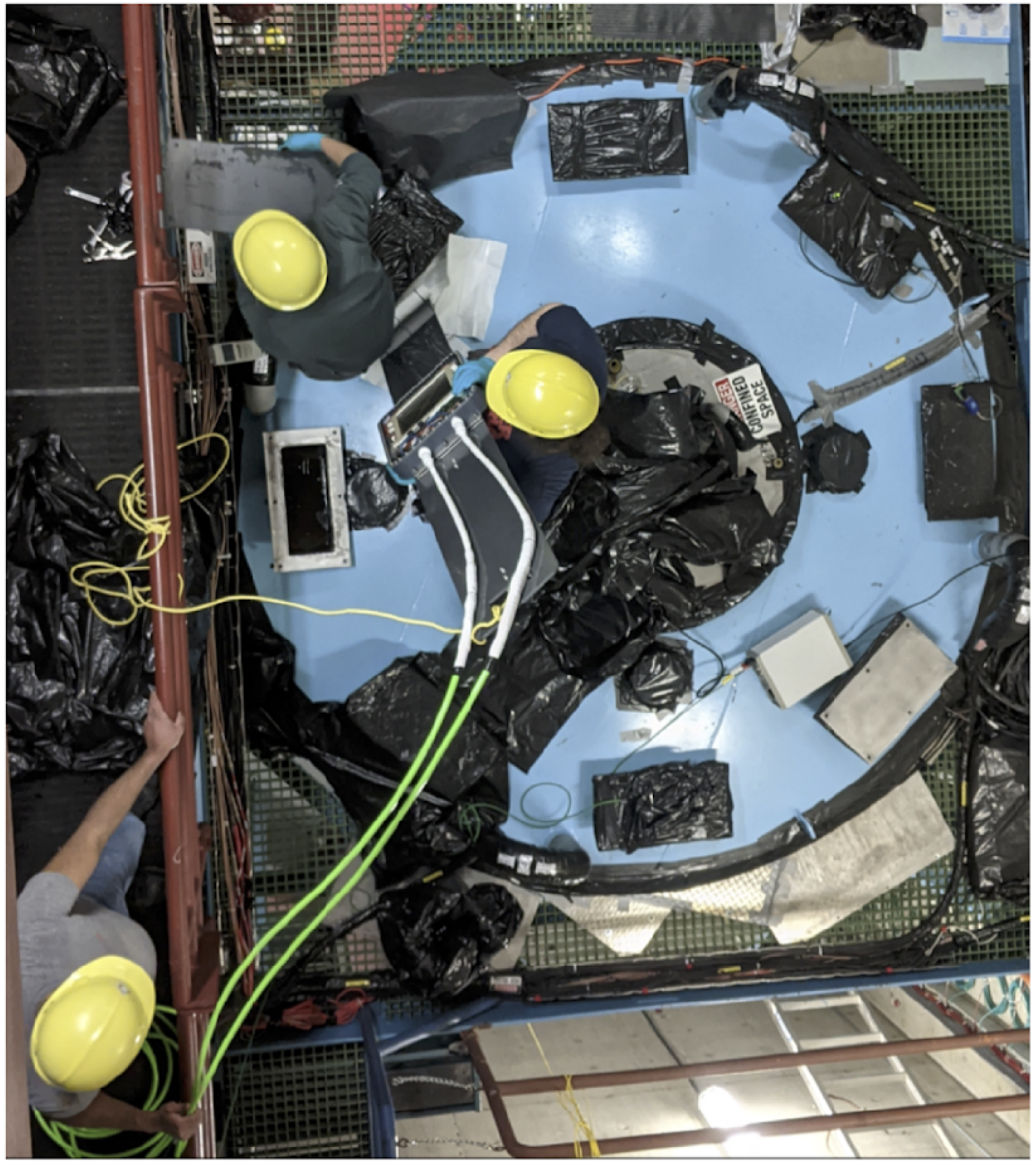
Prompt μ: MRD track + Cherenkov in the tank

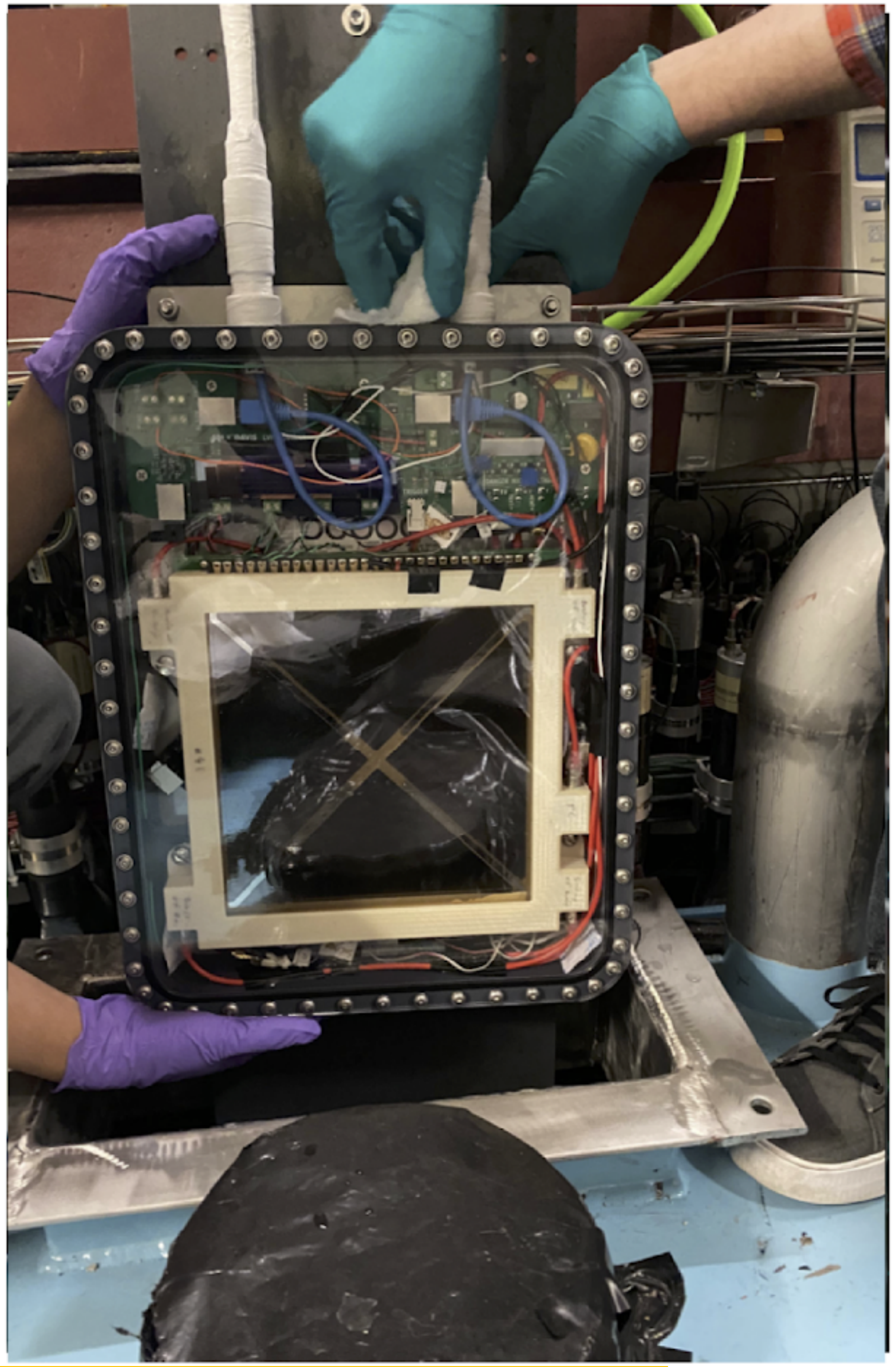
The Packaged ANNIE LAPPD (PAL)



- 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.

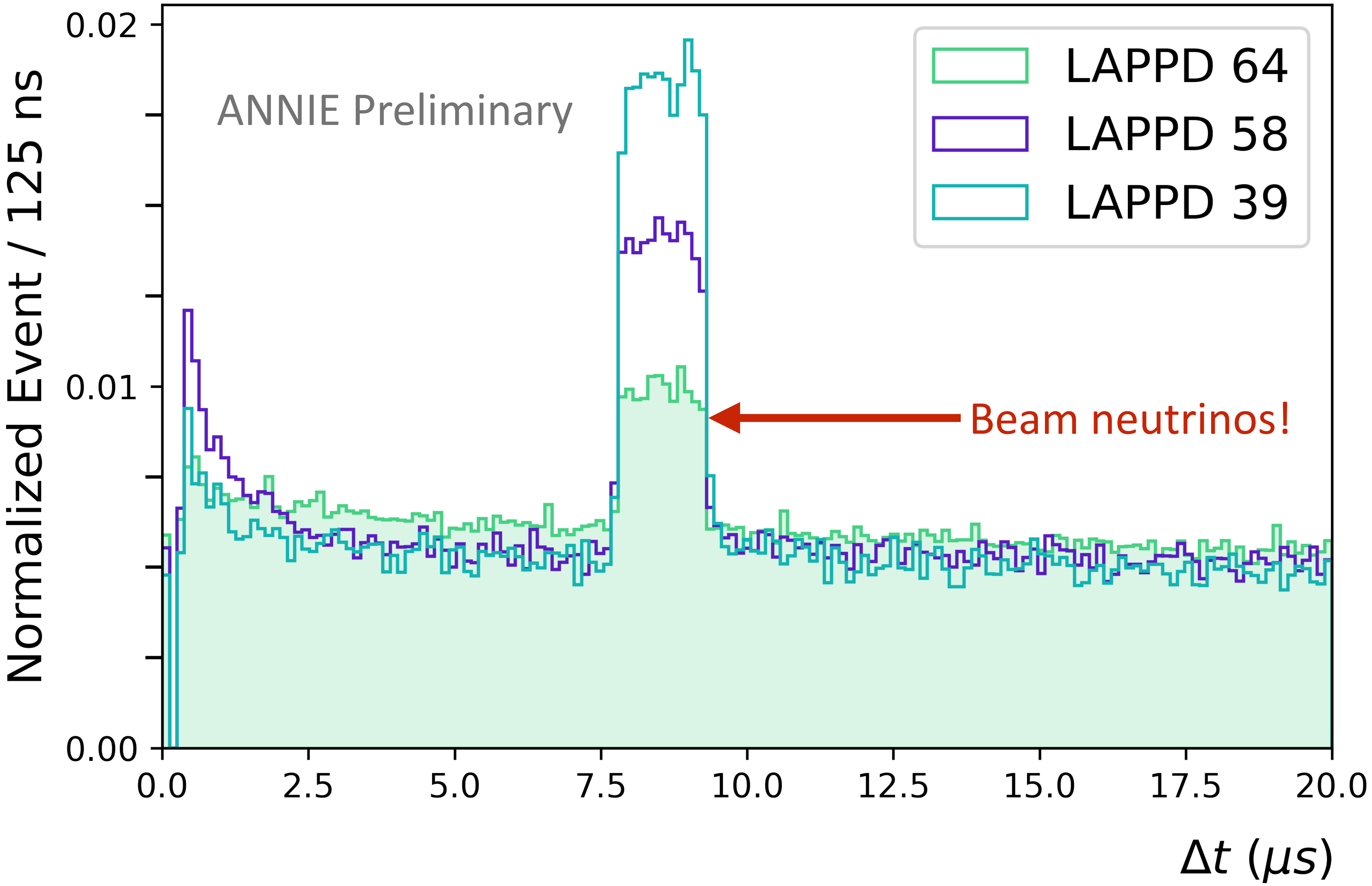
LAPPD Deployment

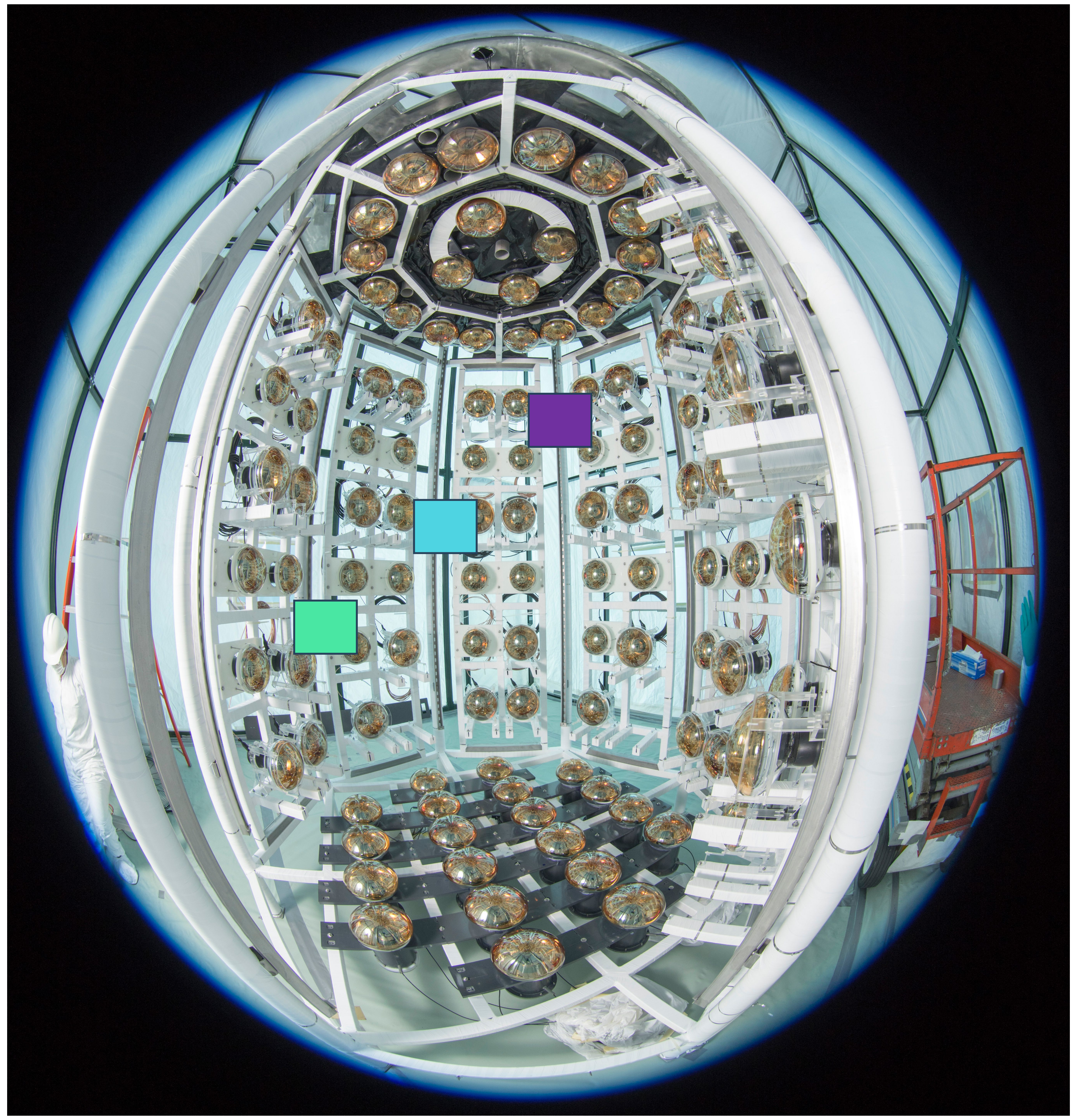




6 LAPPDs deployed in ANNIE (max 3 at one time). Mix of alkali and non-alkali MCP substrates.

First neutrinos observed with multiple LAPPDs

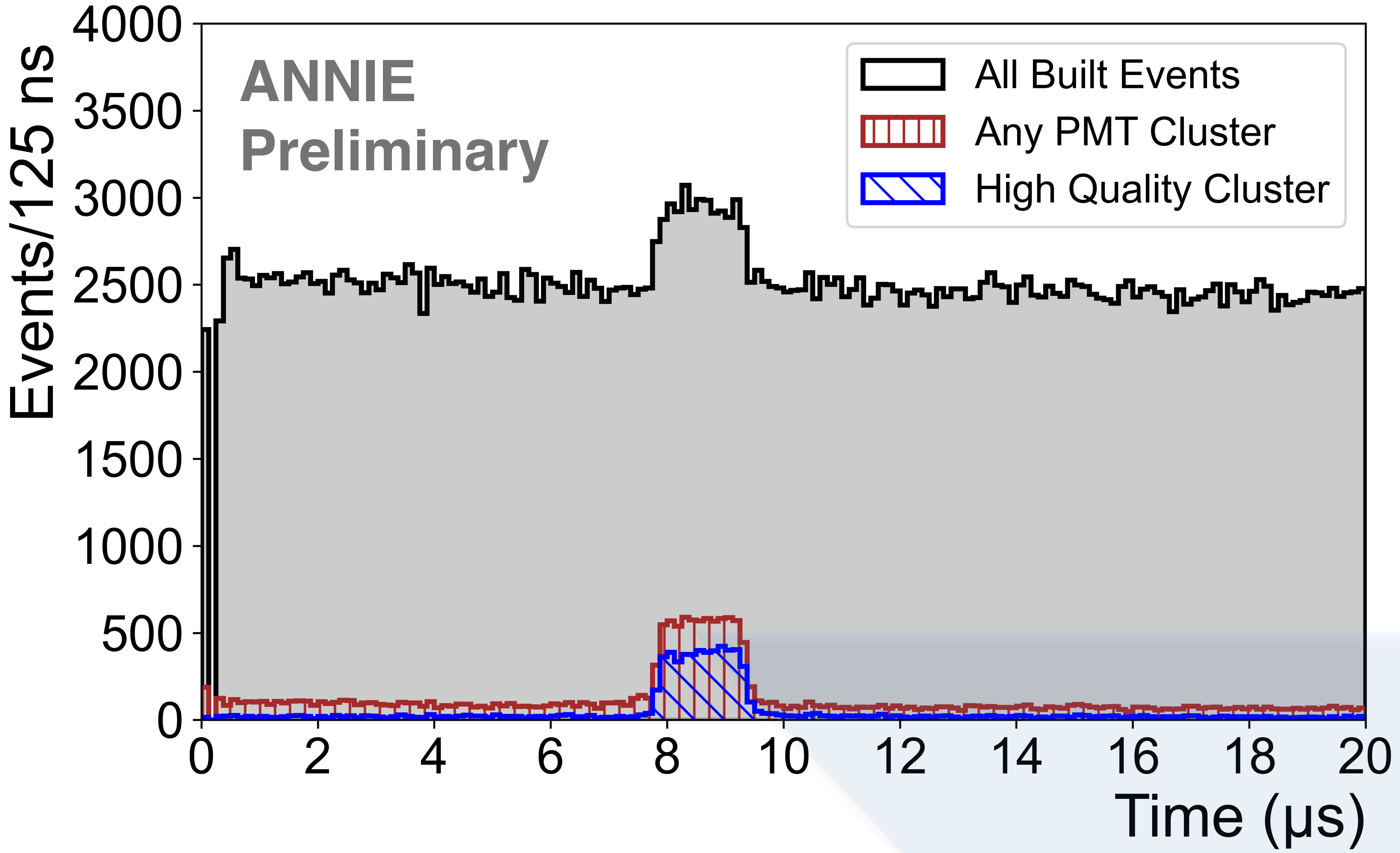




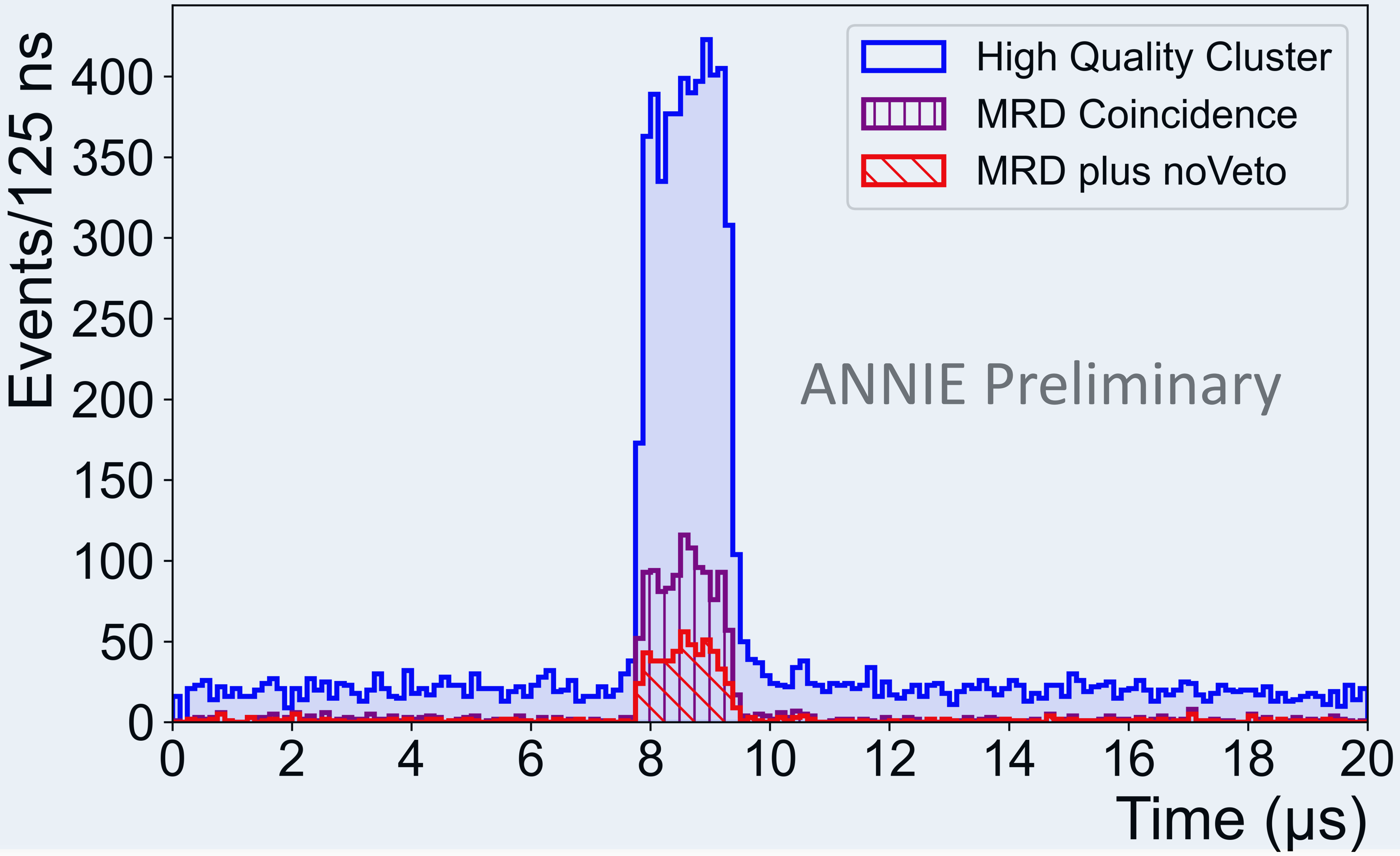
1.6 μsec wide excess = LAPPD-triggered events in-time with the BNB spill.

World's first: neutrinos observed with multiple LAPPDs!

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.

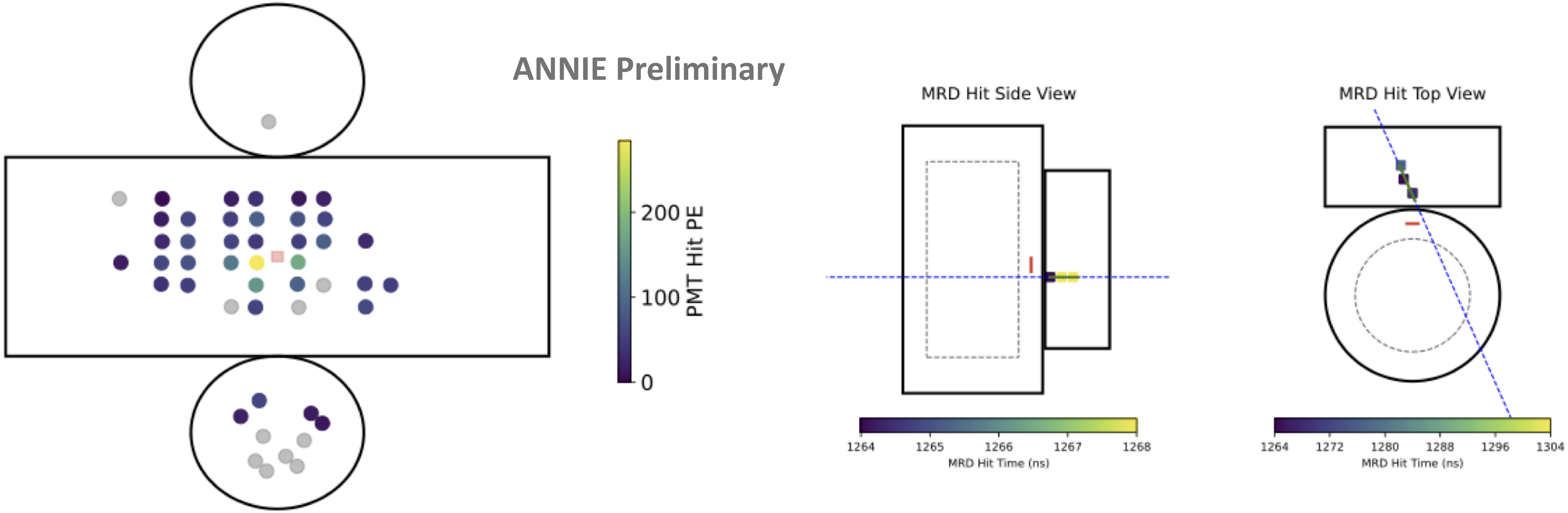


- CC neutrino interactions in the tank selected by requiring a cluster of PMT activity, an MRD coincidence and no signal in the forward veto.
- This high-purity sample can be used to study LAPPD performance in relation to independent event information.

An ANNIE neutrino interaction candidate

Event taken from initial single LAPPD run (~8 x 10^{19} POT → 1000 LAPPD events with CC muons / 500 CC interactions in the detector).

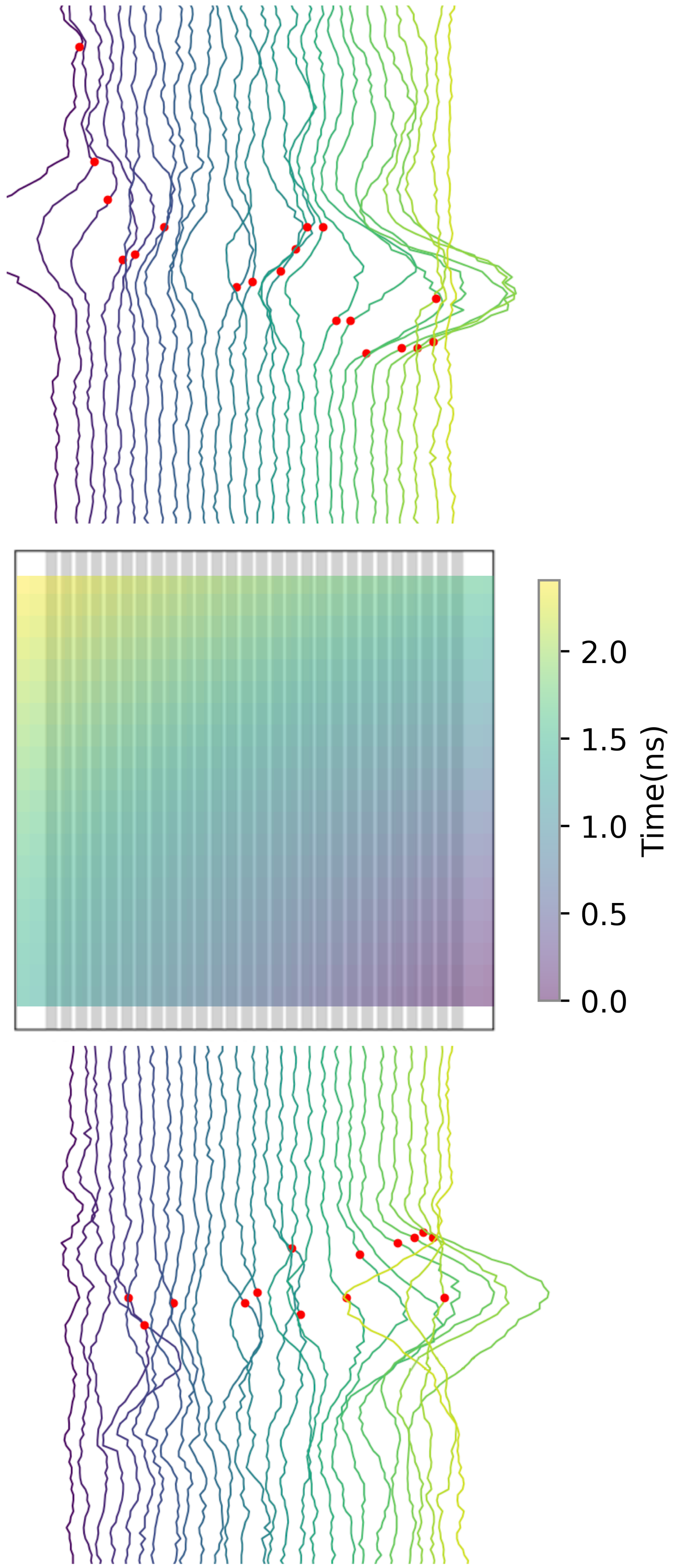
All ANNIE systems: PMT, LAPPDs and MRD are integrated.

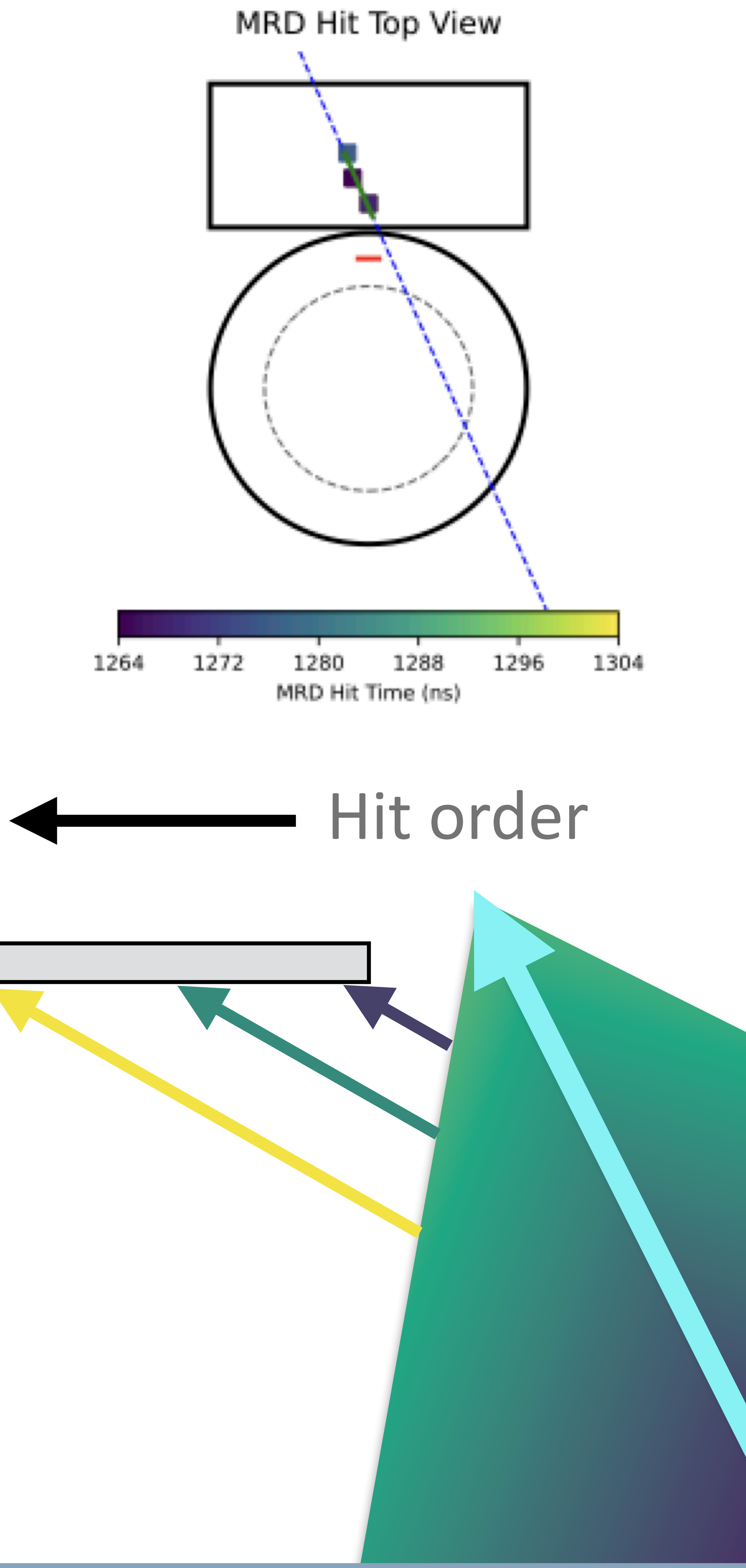


More and multi-LAPPD data on the way!

LAPPDs are IMAGING photosensors

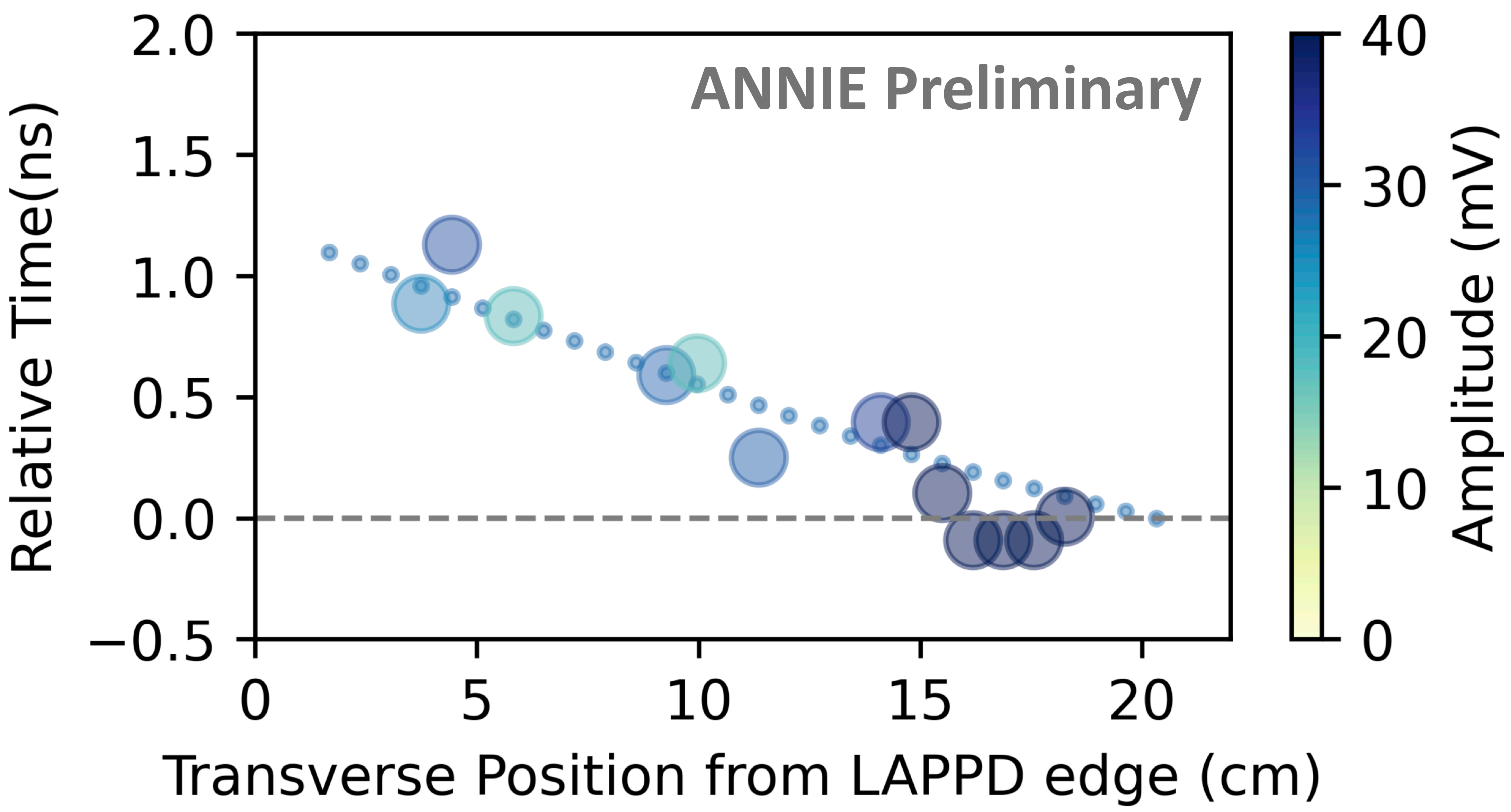
- Time evolution of a Cherenkov ring across the surface of a single LAPPD depends on track direction.
  - It is reflected in the voltage-time pattern registered by the microstrips (56 256-sample waveforms).
  - We can demonstrate this with a simple heuristic by averaging the arrival times of the primary pulses on each microstrip (red dots).
  - Strip location provides a measure of distance from the (right) side of the LAPPD.
  - Note: Unlike FTBF, our readout is double-sided.

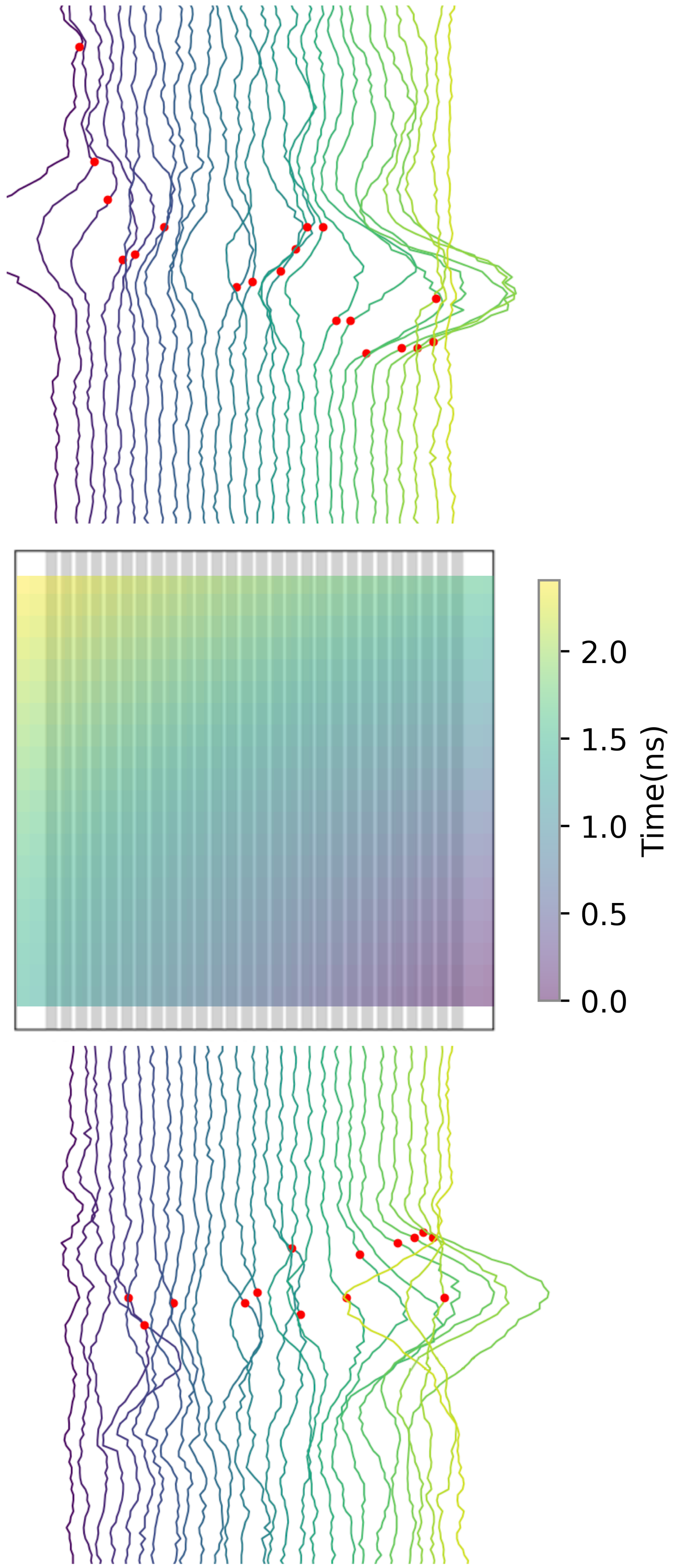


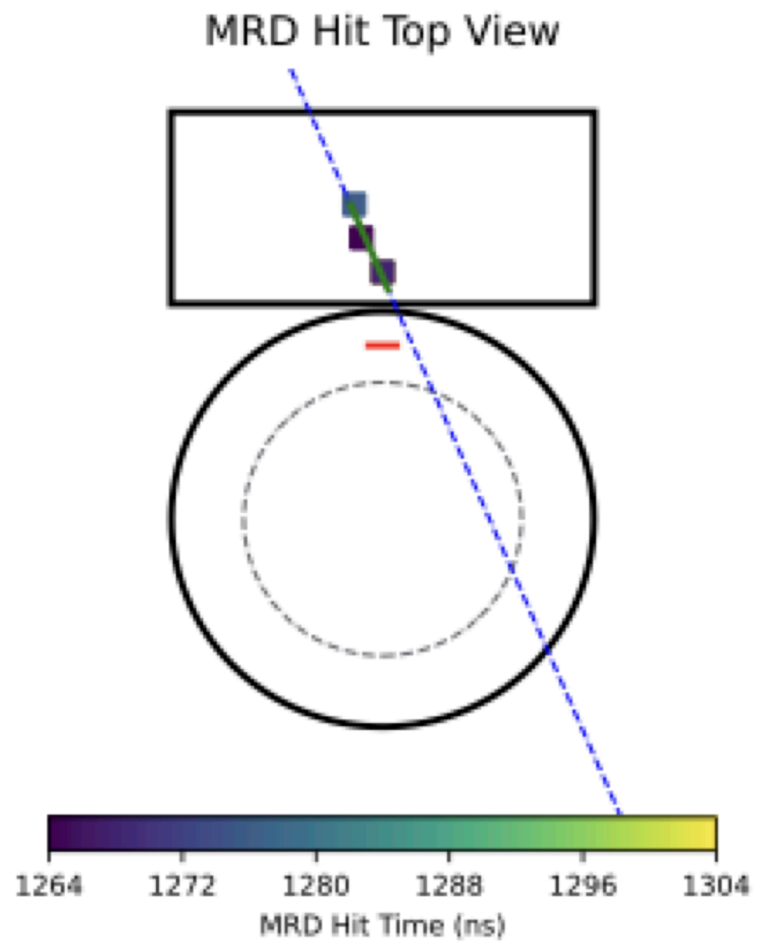


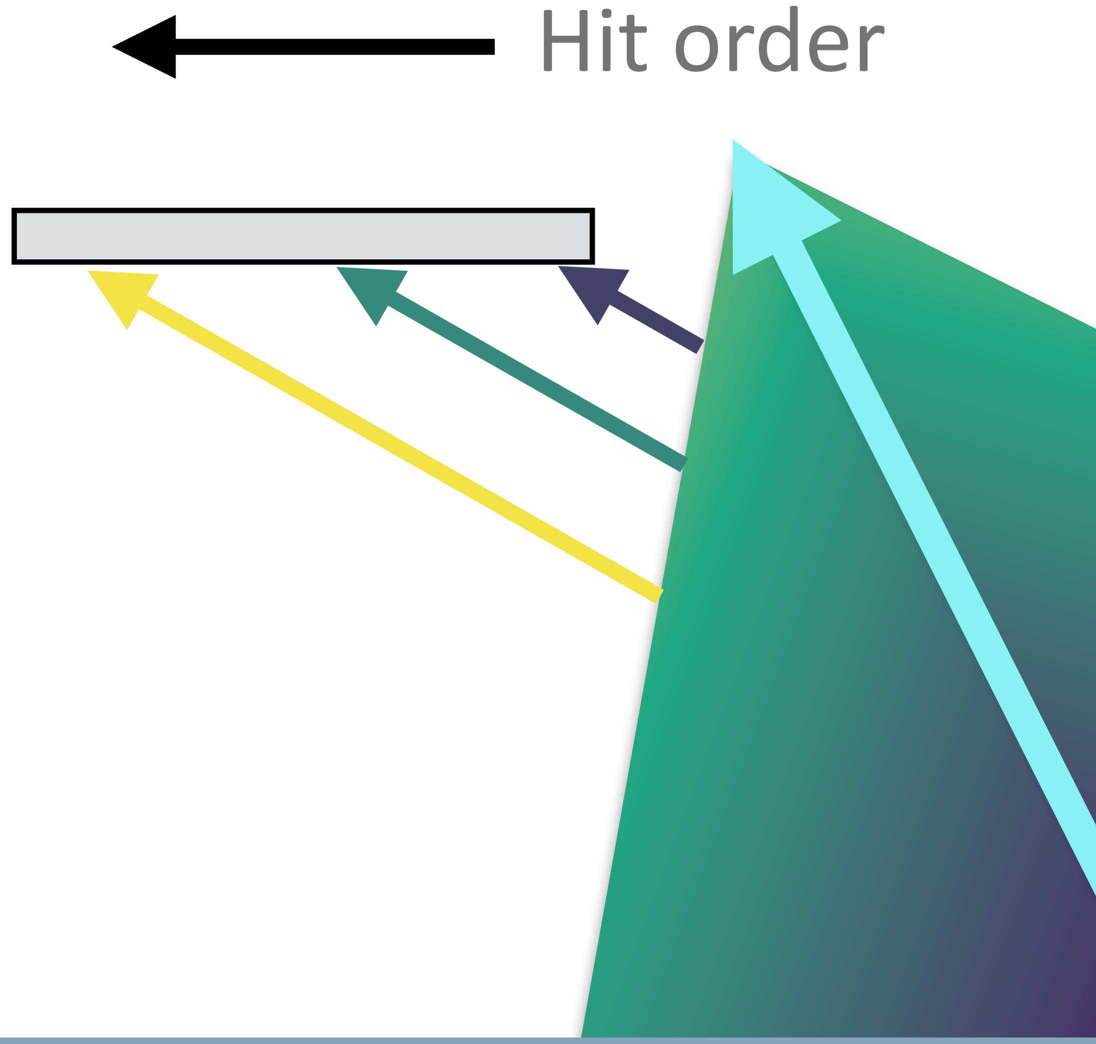
LAPPDs are IMAGING photosensors

Time evolution of a Cherenkov ring across the surface of a single LAPPD depends on track direction.







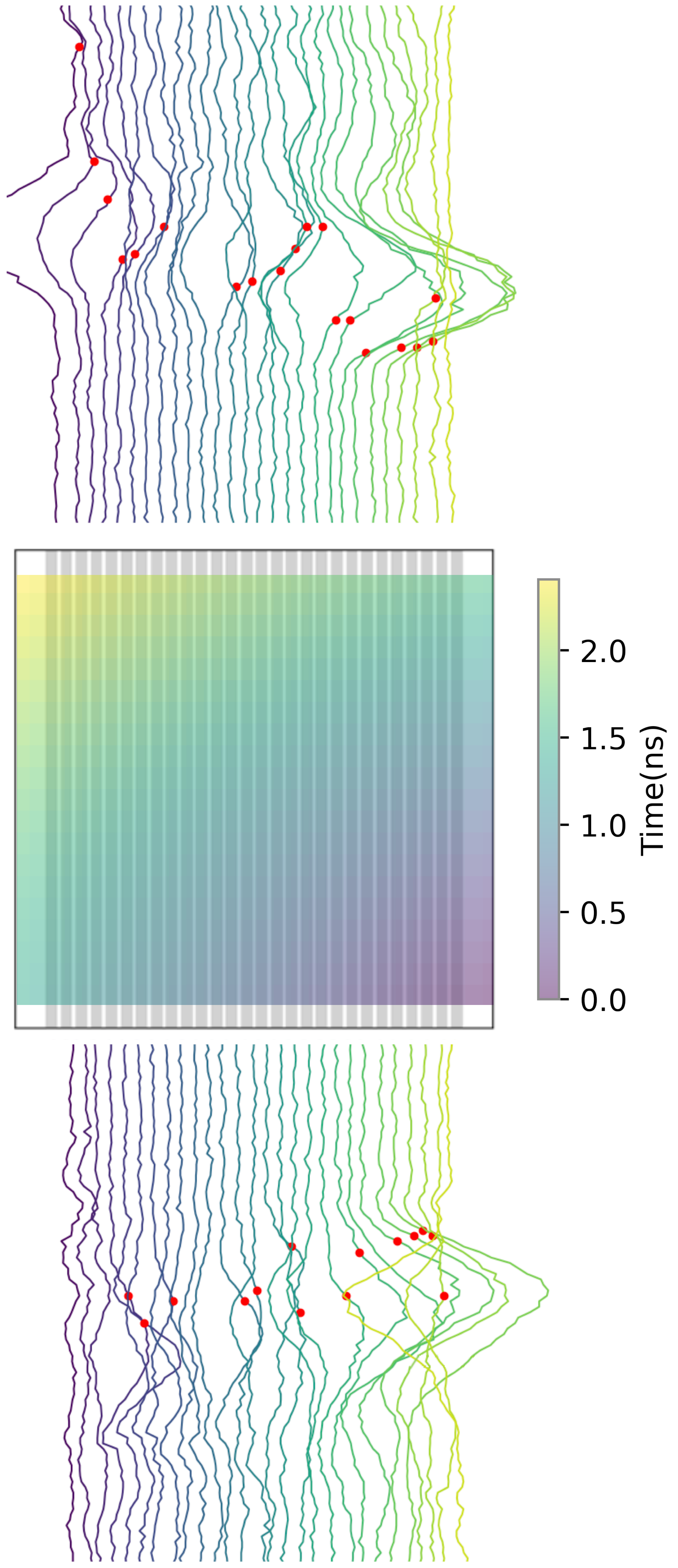


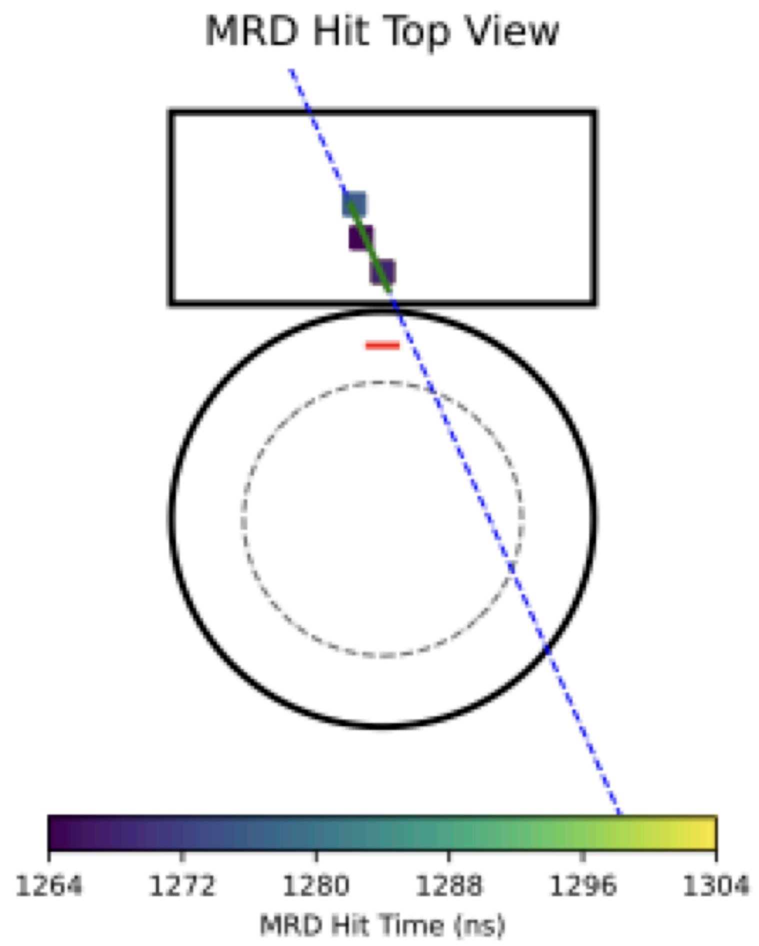
Heuristic: Average arrival time of voltage response on each microstrip, vs predicted gradient based on independent MRD track reconstruction.

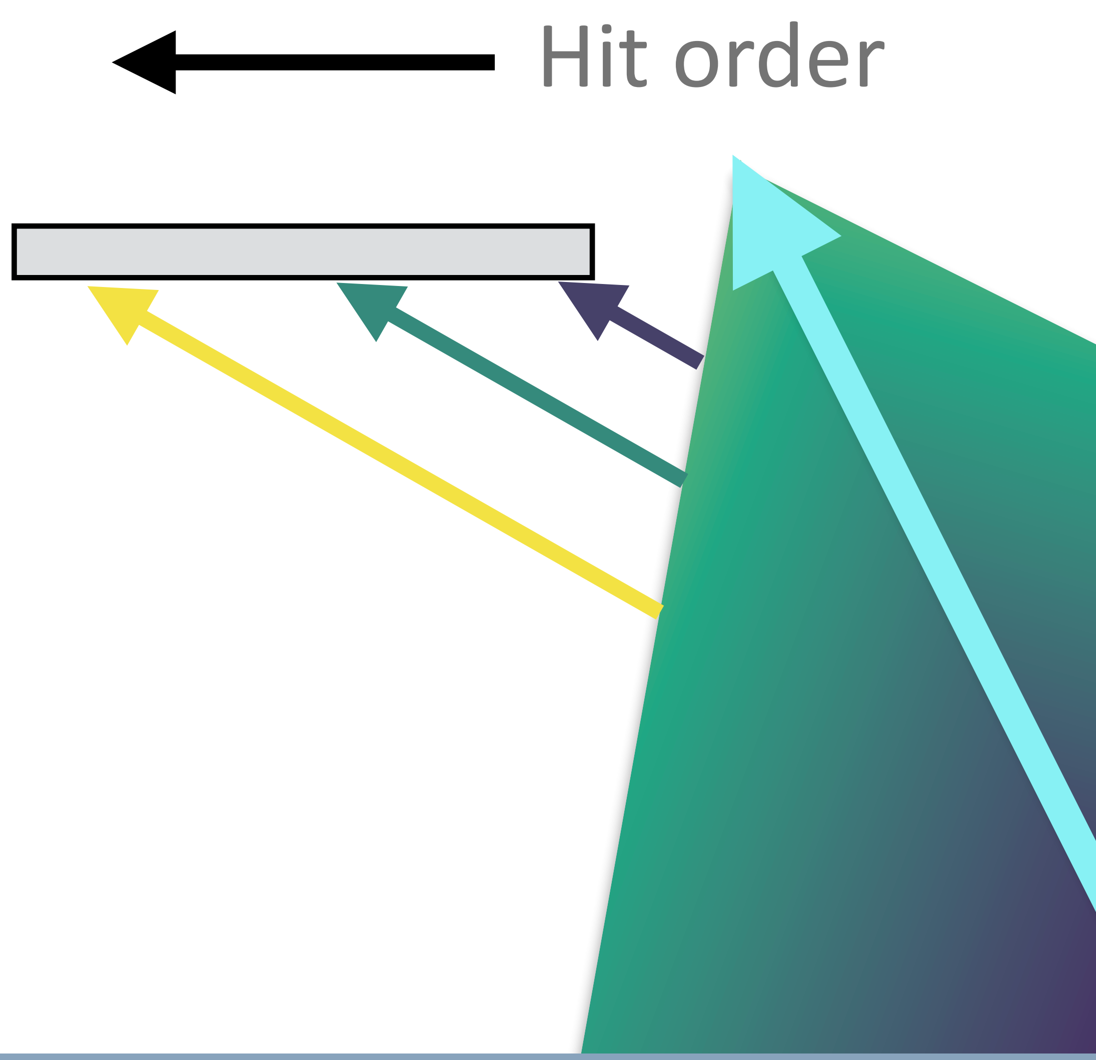
Reconstruction with LAPPD data

- Time evolution of a Cherenkov ring across the surface of a single LAPPD depends on track direction and is reflected in the voltage-time pattern registered by the microstrips.
    - The gradient shown on the previous slide reduces this to 28 arrival times (loss of information).
    - Fine for a quick look—not for demonstrating LAPPDs full capabilities.

What is the right reconstruction approach?



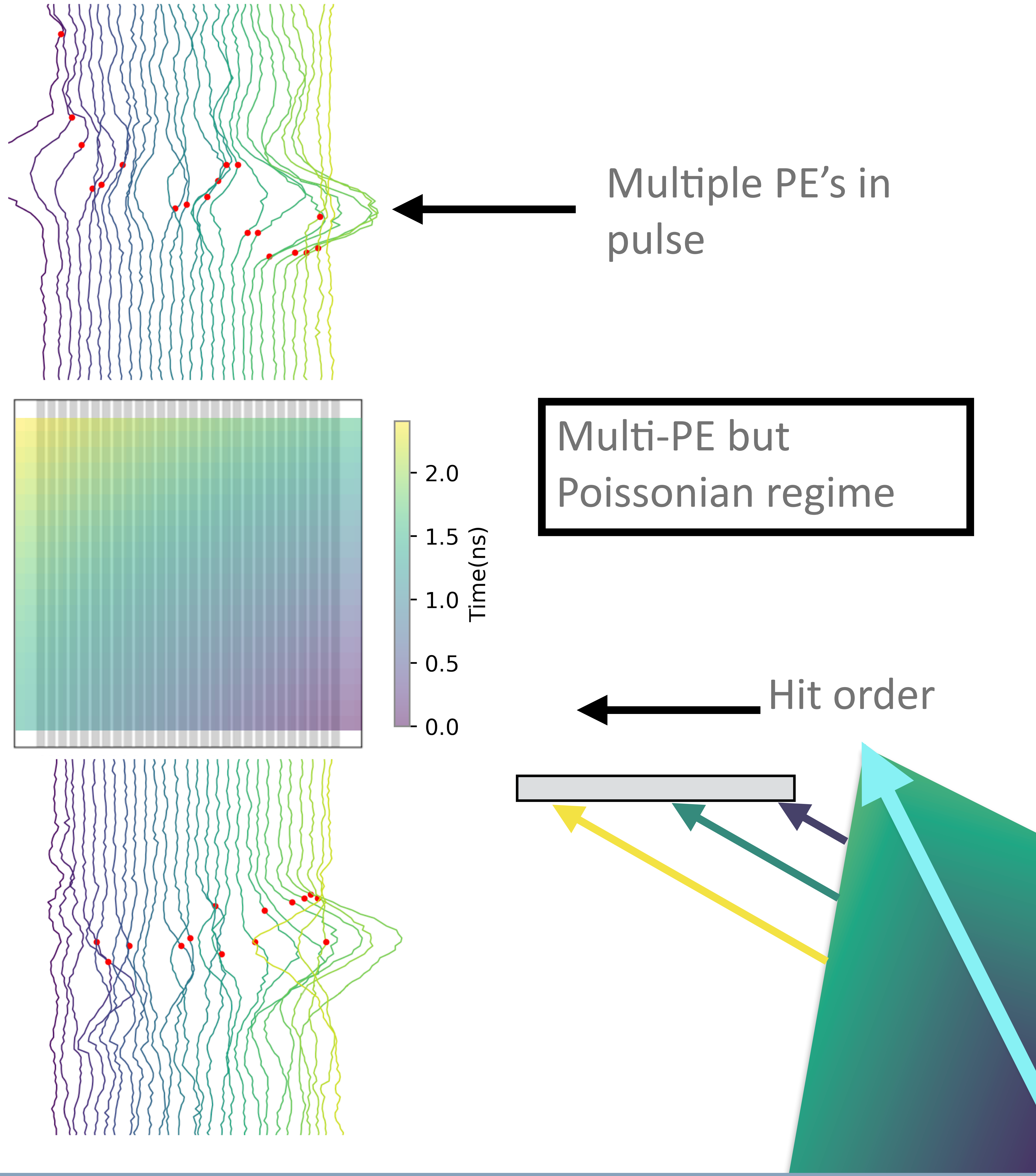




Revising our approach to LAPPD data

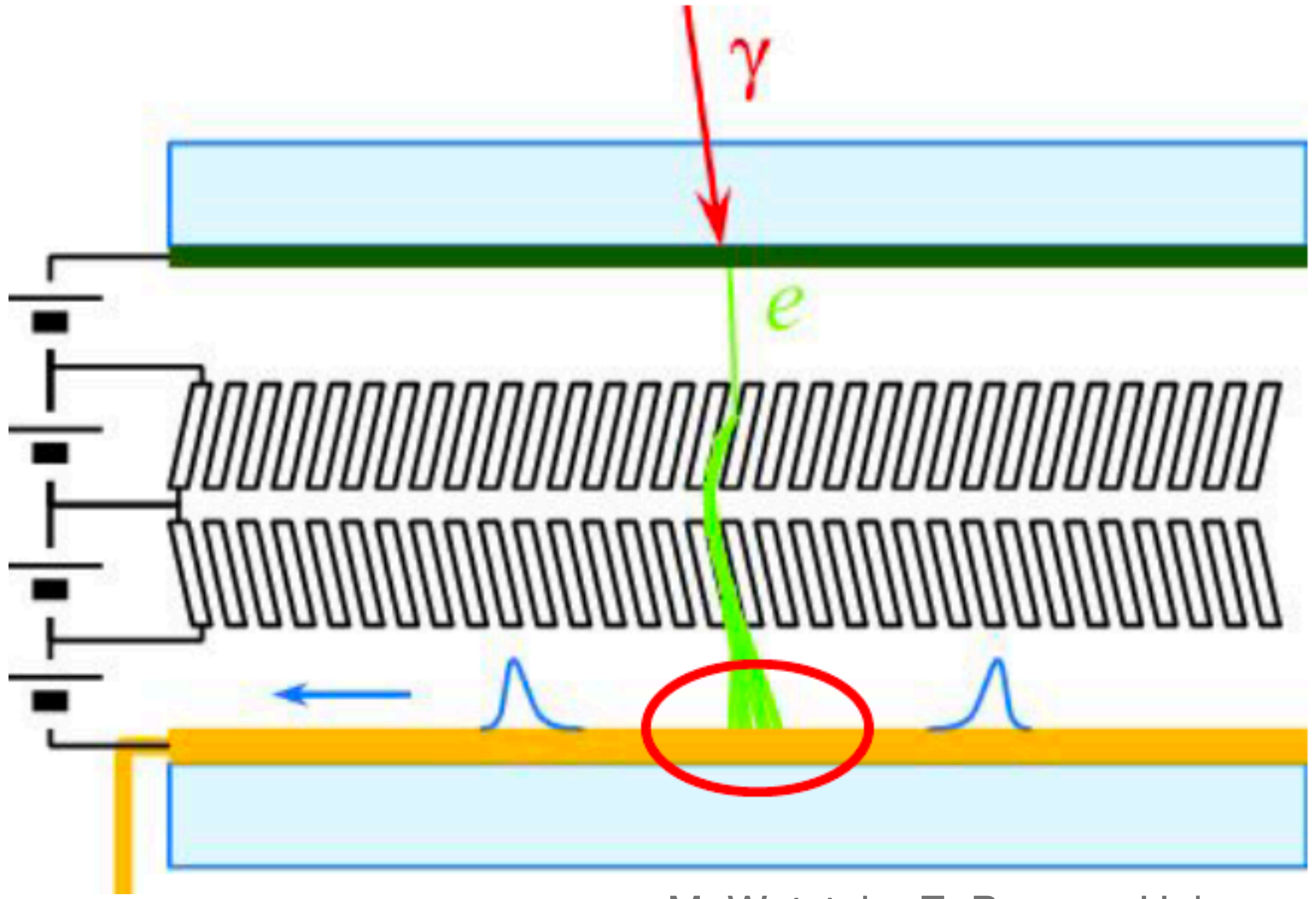
- Voltage-time pattern registered by microstrips reflects time evolution of a Cherenkov ring across the LAPPD surface of a single LAPPD, which in turn reflects track direction.

- **Proposal**: **use V-T pattern directly** in track-fitting rather than trying to extract independent hits.
    - **1 photon on front face** produces a charge cloud that affects **multiple microstrips** (charge sharing)
    - Non-localized crosstalk in LAPPD anode → **each charge cloud affects all waveforms**.
    - Good modeling/MC is crucial.

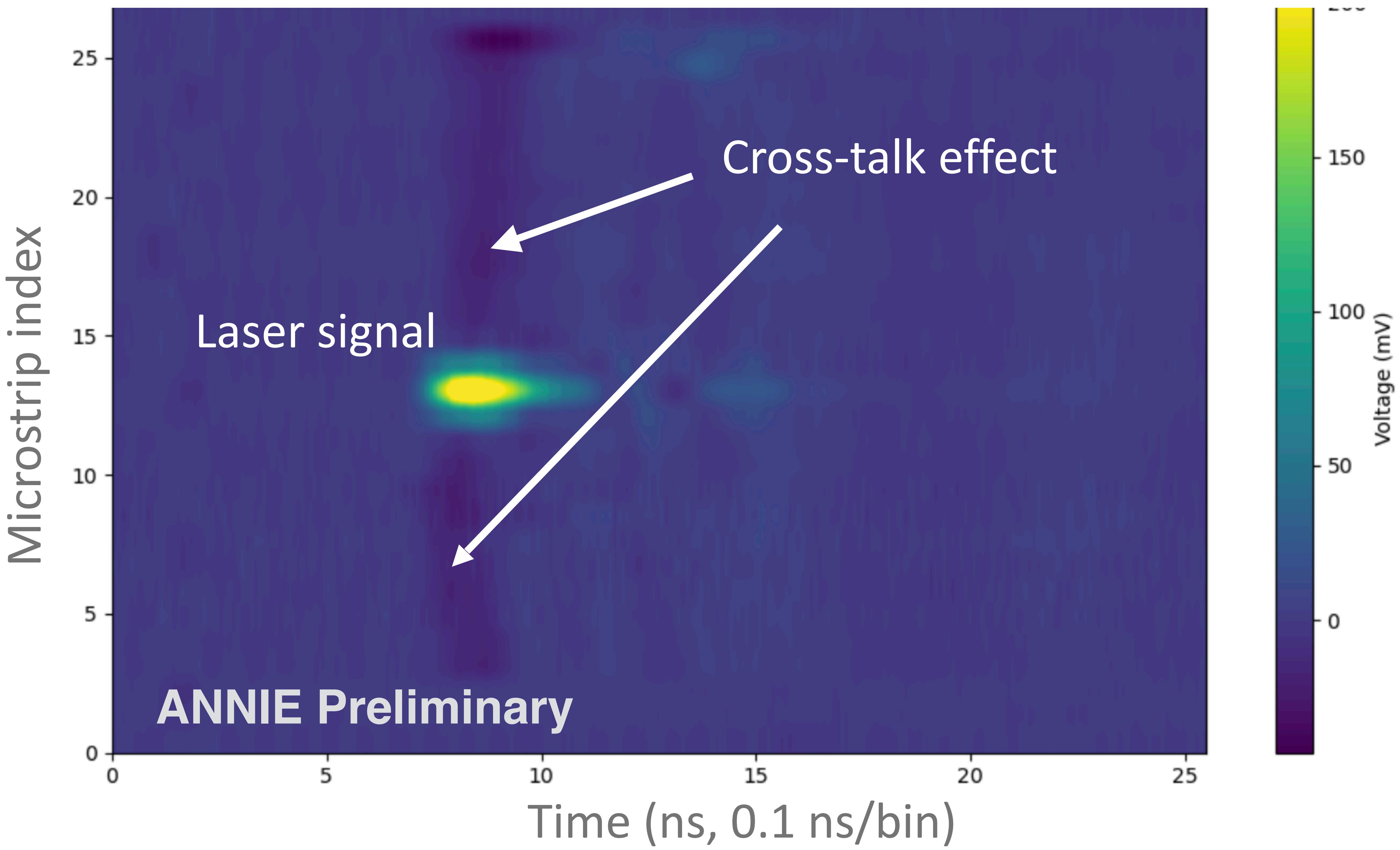


Atypical Crosstalk in LAPPD anode

- Anode-wide, opposite-polarity cross-talk is an intrinsic, non-negligible aspect of LAPPDs (Gen I and II).
- Effect relatively linear, additive, with characteristic strip-to-strip time offset.
- Coupling through the electrode of the bottom MCP plays a significant role (neglected in earlier simulations).



M. Wetstein, E. Brunner-Huber



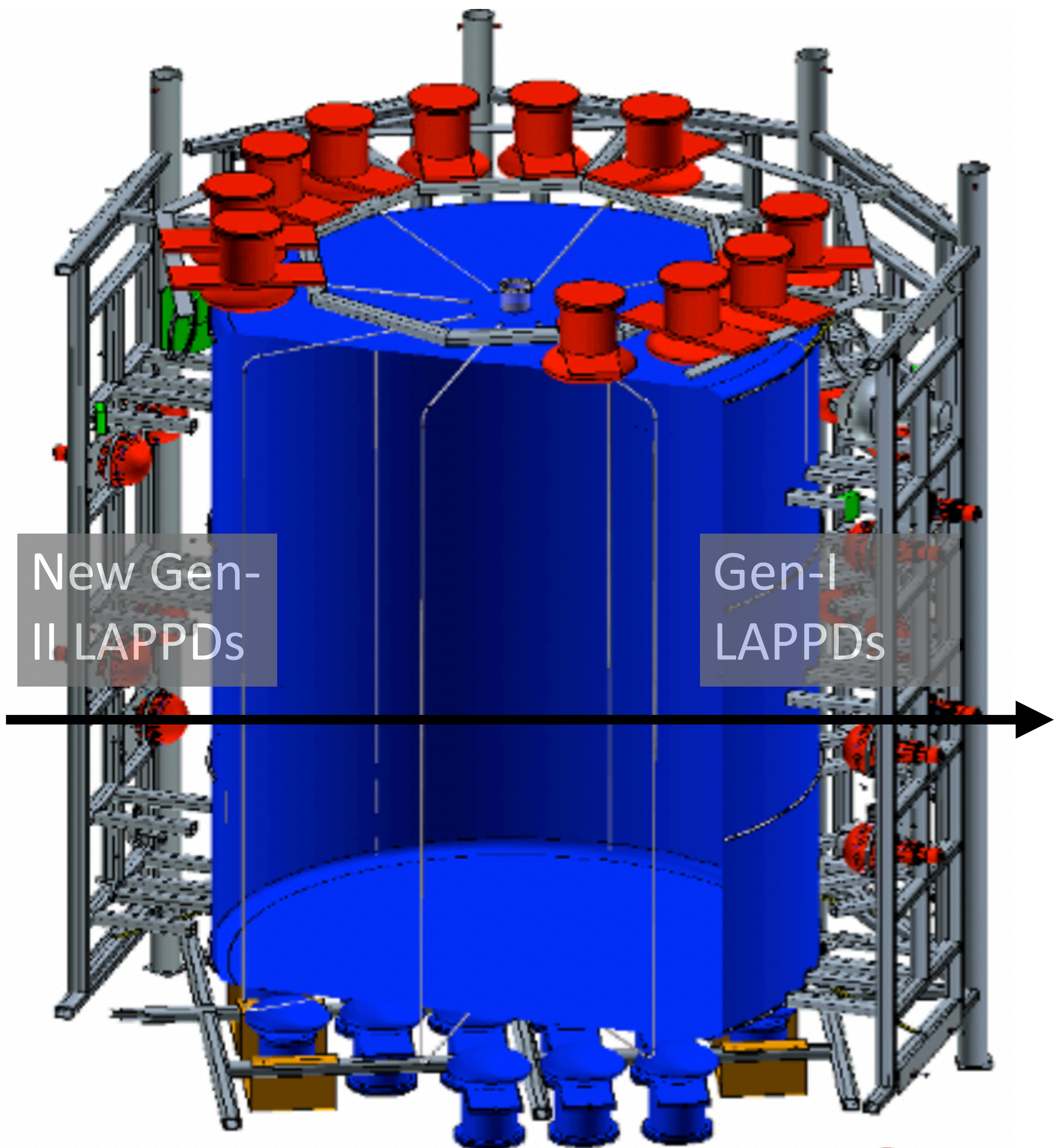
ANNIE laser calibration data (enhanced effect due to strong signal)

Modeling crosstalk correctly is key to successful reconstruction.

(Effect also seen by FTBF, Mainz/Tubingen)

ANNIE in the Future

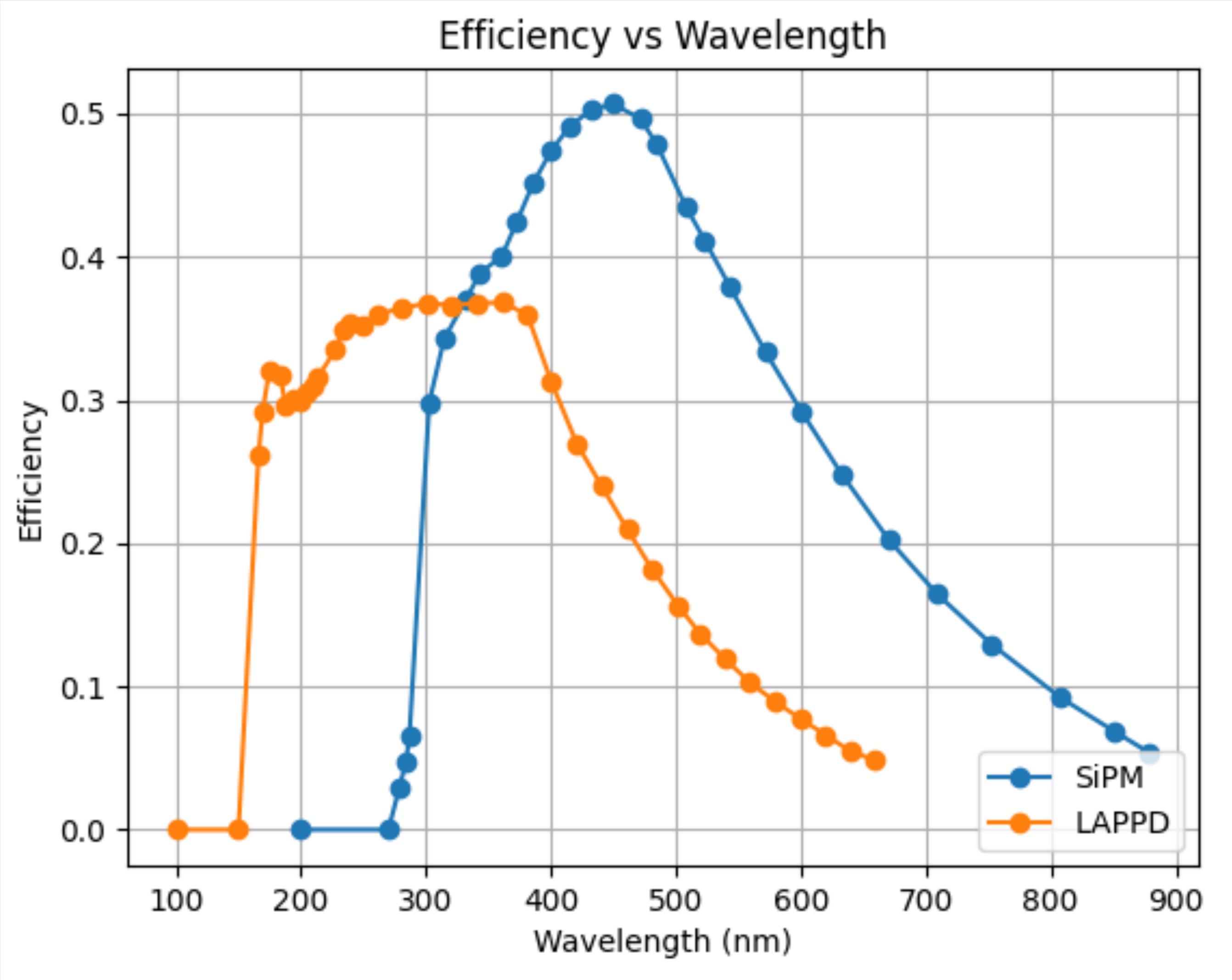
- ANNIE is on its way to reconstruction of single- and multi-LAPPD observations of beam neutrino interactions on a Gd-water target!
  - Demonstrate impacts on muon reconstruction, beam timing.
- Exploit LAPPDs for timing-based separation of scintillation light in first sample of multi-LAPPD Gd-WbLS data.
- 2026: Demonstration of event reconstruction capability in WbLS requires extended scintillator volume.
  - Install 8m^3 cylindrical vessel in inner volume of ANNIE tank.
  - Vessel (balloon) R&D and construction funded at University of Mainz.
  - Gen-II LAPPDs with updated electronics for expanded coverage.

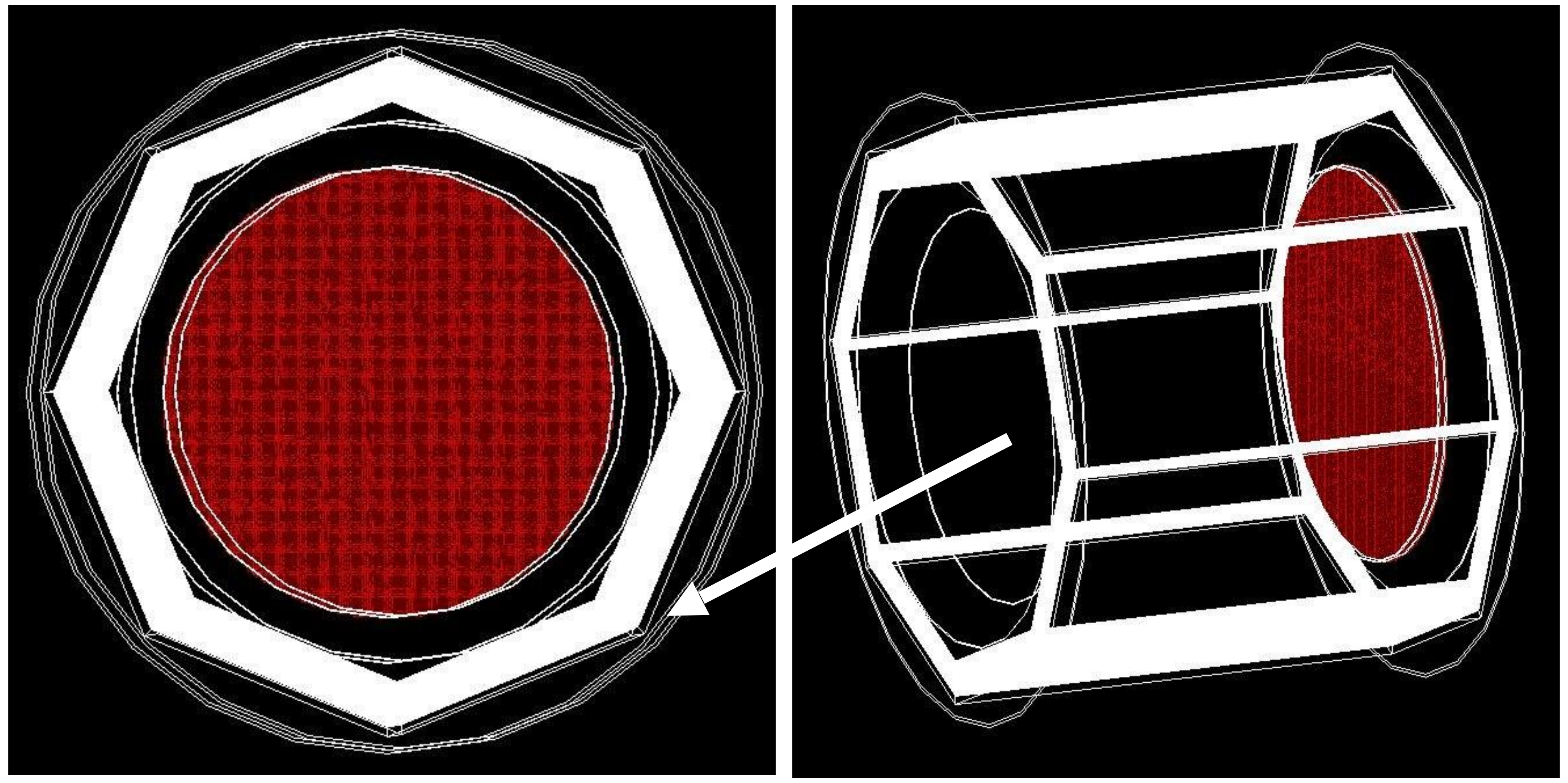


nylon bag holding 8t of WbLS

Gen-II LAPPDs in ND-GAr

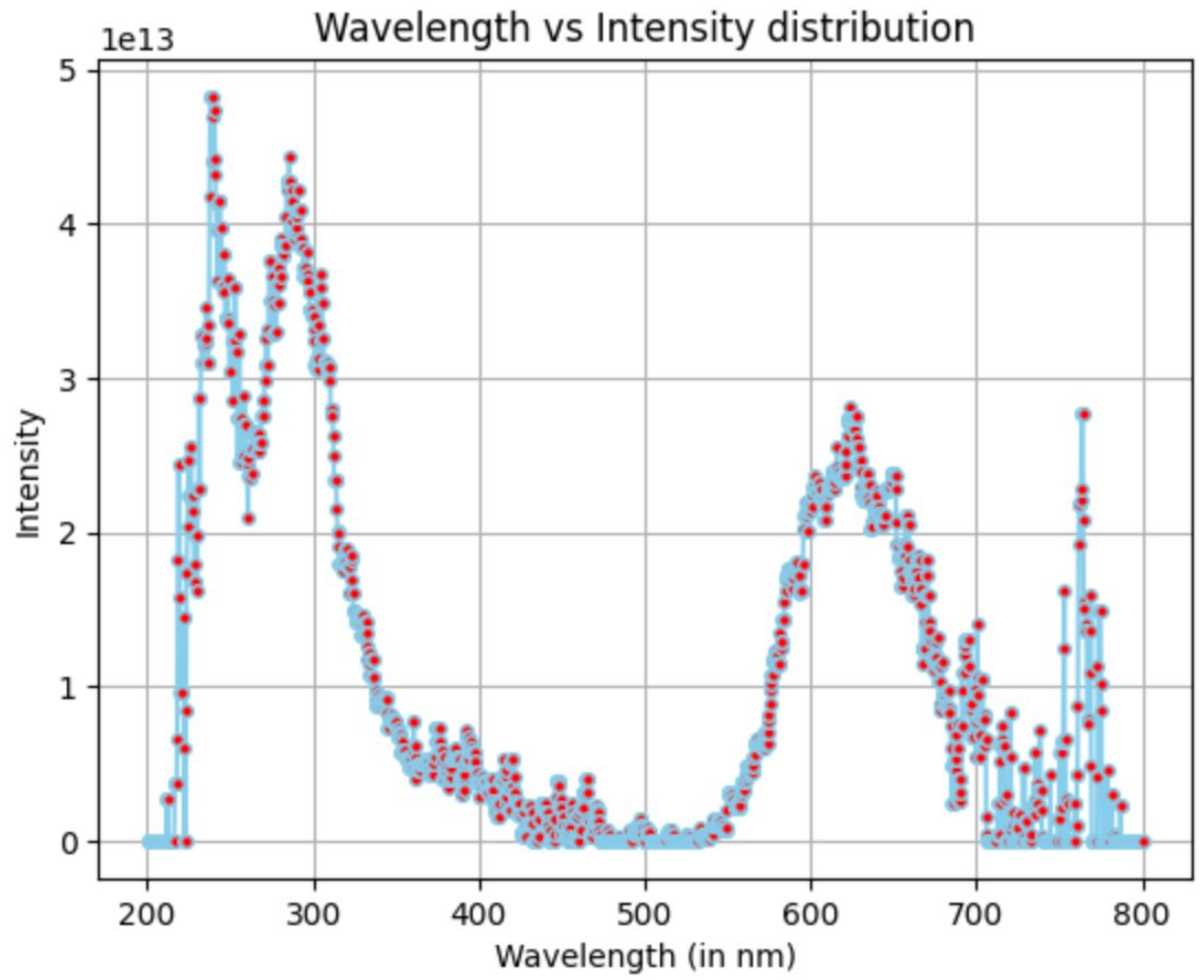
- Room-temperature alternative to SiPMs for **DUNE Phase II MCND** (ND-GAr) (M. Adil Aman, M. Sanchez, A. Weinstein)
  - Measure ν-Ar interactions with low thresholds and high resolution. Multiple photosensor coverage options explored.
  - 60-100 Gen-II LAPPDs =2ns time resolution, 200 LAPPDs→ 1ns (~scintillation rise time).
  - Comparable or better efficiency, lower DCR.





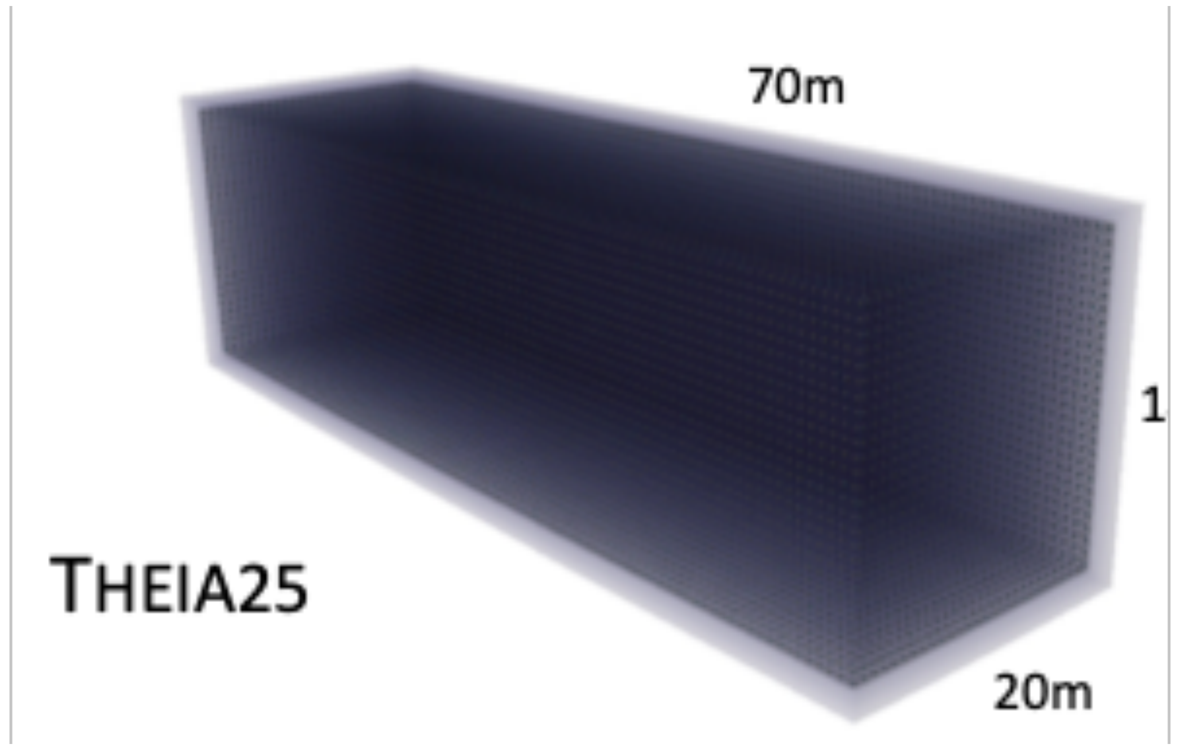
Photosensor wall

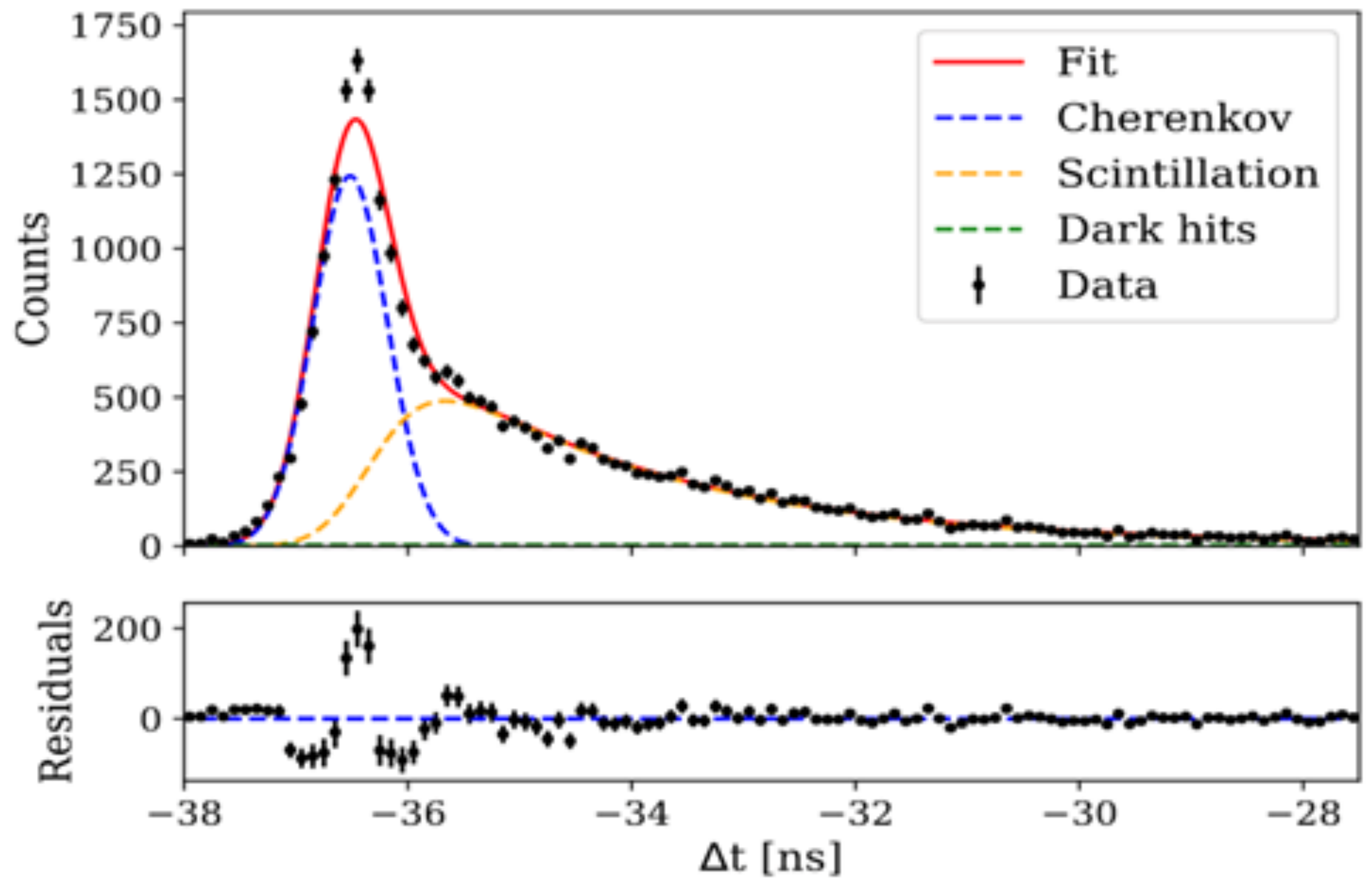
Octagonal Time Projection Chamber



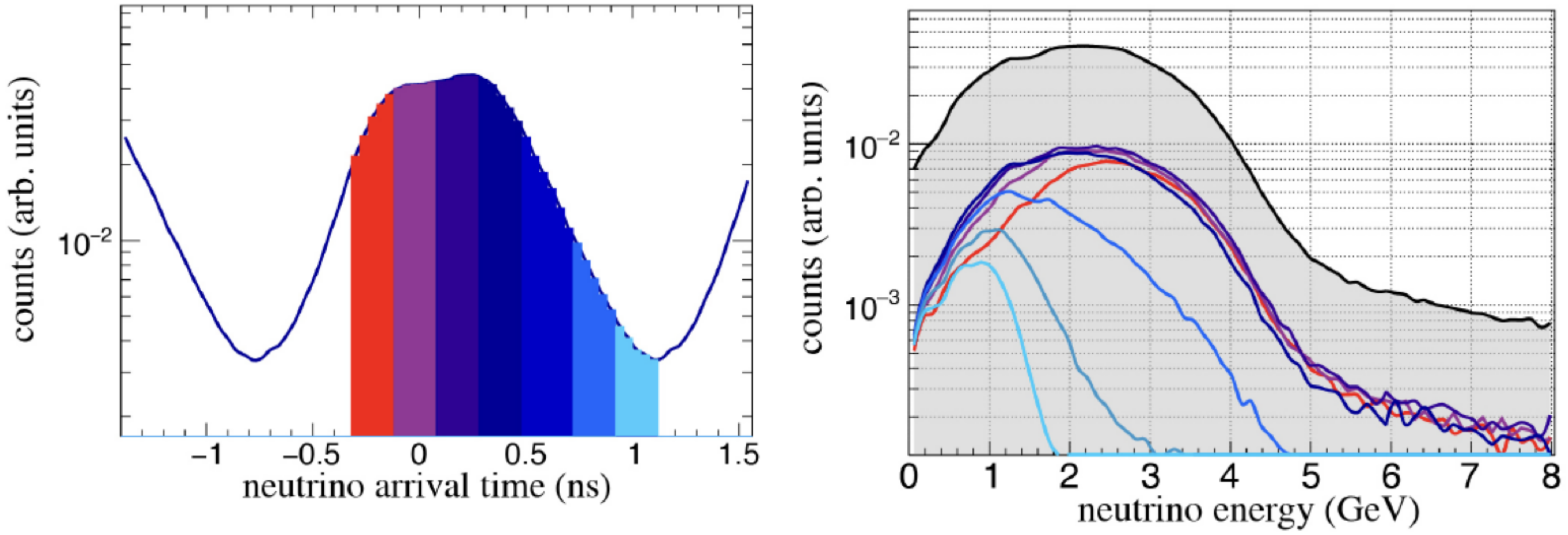
Gen-II LAPPDs: more possible future applications.

- Viable for **THEIA, FD4** options with non-LAR -targets.
  - Cherenkov / scintillation separation using fast timing.
- Fast timing could provide a complementary approach to off-axis "prism" approaches (see M. Wetstein's talk)
  - Lower-energy hadrons →lower β→later ν
- Plan to demonstrate proof-of-principle for both applications in ANNIE.





Separating Cherenkov and scintillation signals with an LAPPD (CHESS@UC Berkeley)



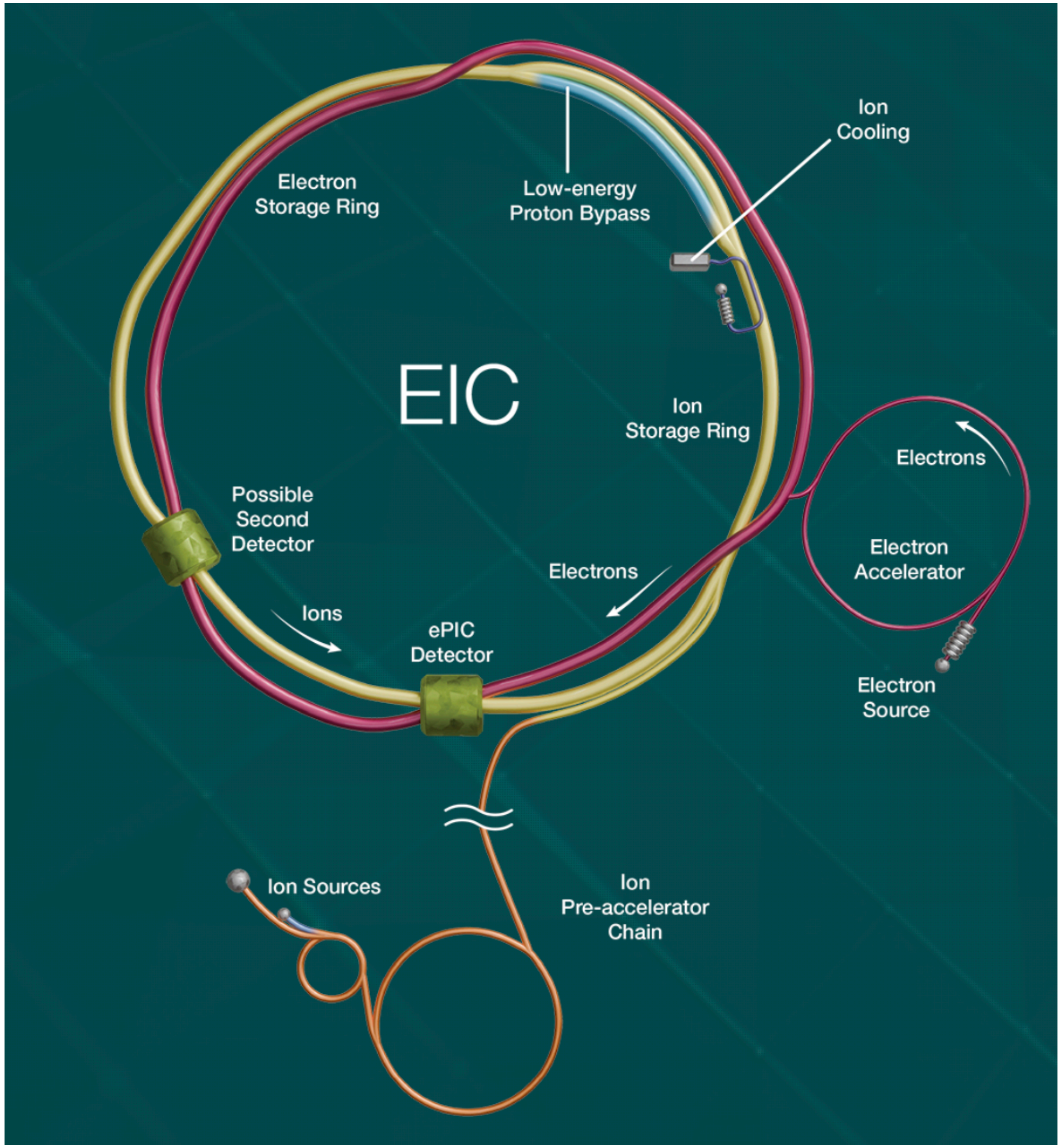
E. Angelico et al. PRD 100, 032008 (2019)

Summing up

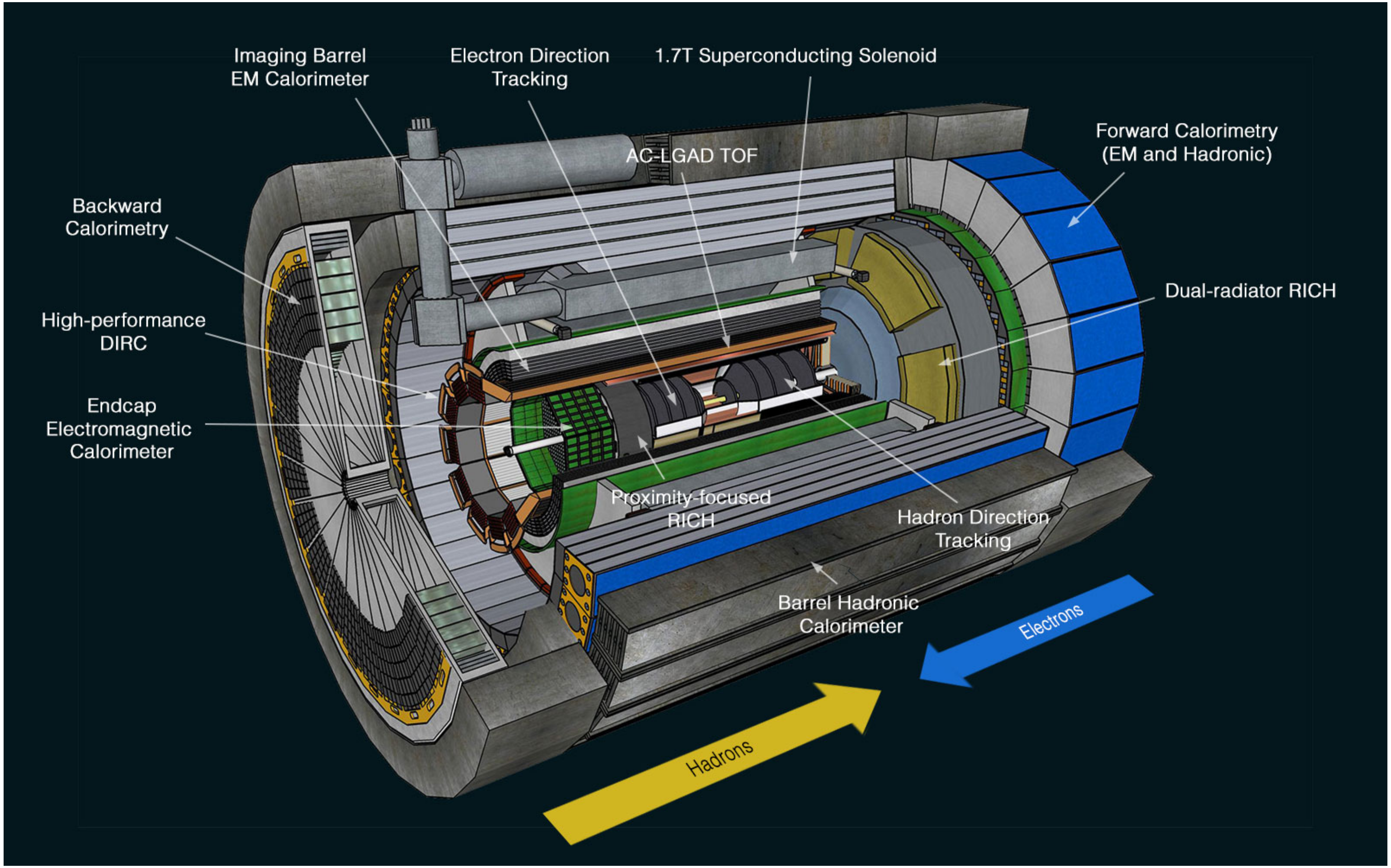
- HRPPDs optimized for high-rate applications and are the baseline photosensor for EIC pfRICH. First test batch for EIC shows good performance.
- More robust, flexible Gen-II LAPPDs show promise for time-of-flight-applications at FTBF, future applications in DUNE Phase-II, and more.
- With good-quality data on beam neutrino interactions in both Gd-water and WbLS with Gen-I LAPPDs (and more to come), ANNIE is:
  - On track to demonstrating the impact of LAPPD imaging on the reconstruction of muon kinematics.
  - Ideal for testing WbLS for hybrid C/S using ultrafast timing reconstruction of beam neutrinos.
  - Implementing an R&D program with enlarged WbLS volume and additional upstream LAPPDs to demonstrate critical R&D milestones before long accelerator shutdown.

Backup Slides

- Re-uses existing RHIC tunnel, infrastructure
- Luminosity of $10^{33} - 10^{34}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.
- (~80k beam crossings per second).
- CMS energies of 20 -140 GeV.
- Up 70% polarized electron and proton beams.

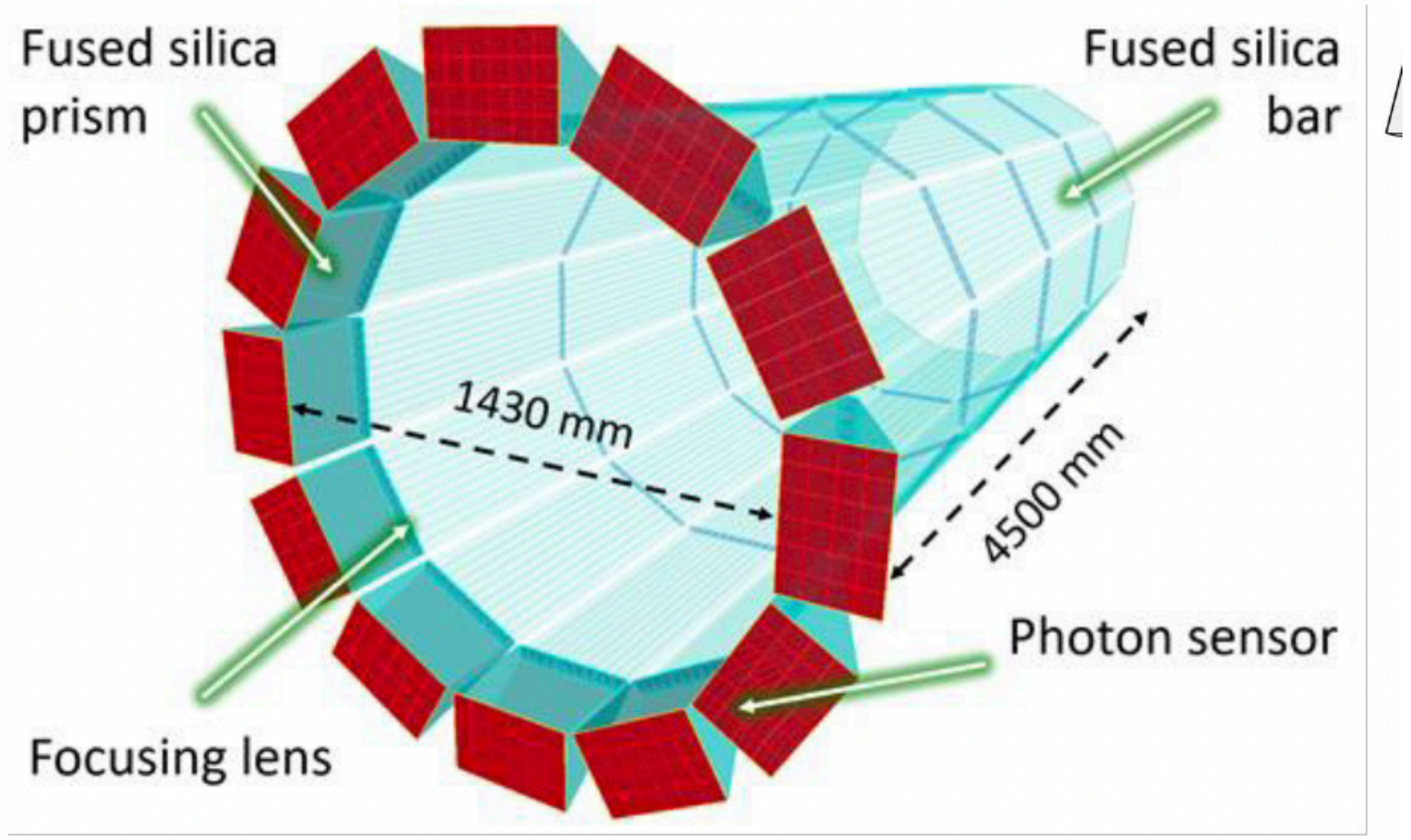


https://www.bnl.gov/eic/machine.php



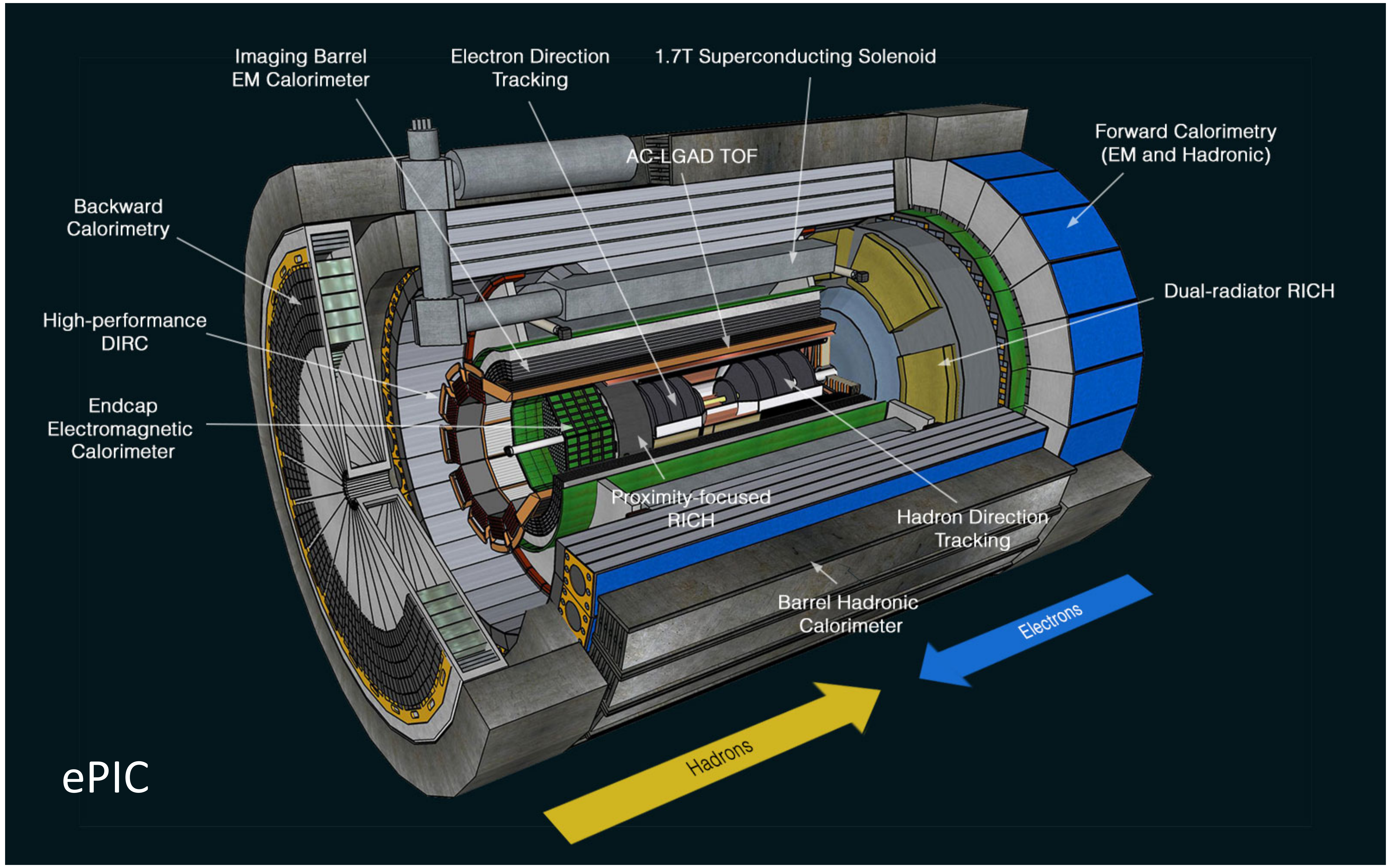
https://www.bnl.gov/eic/epic.php

HRPPDs at the EIC

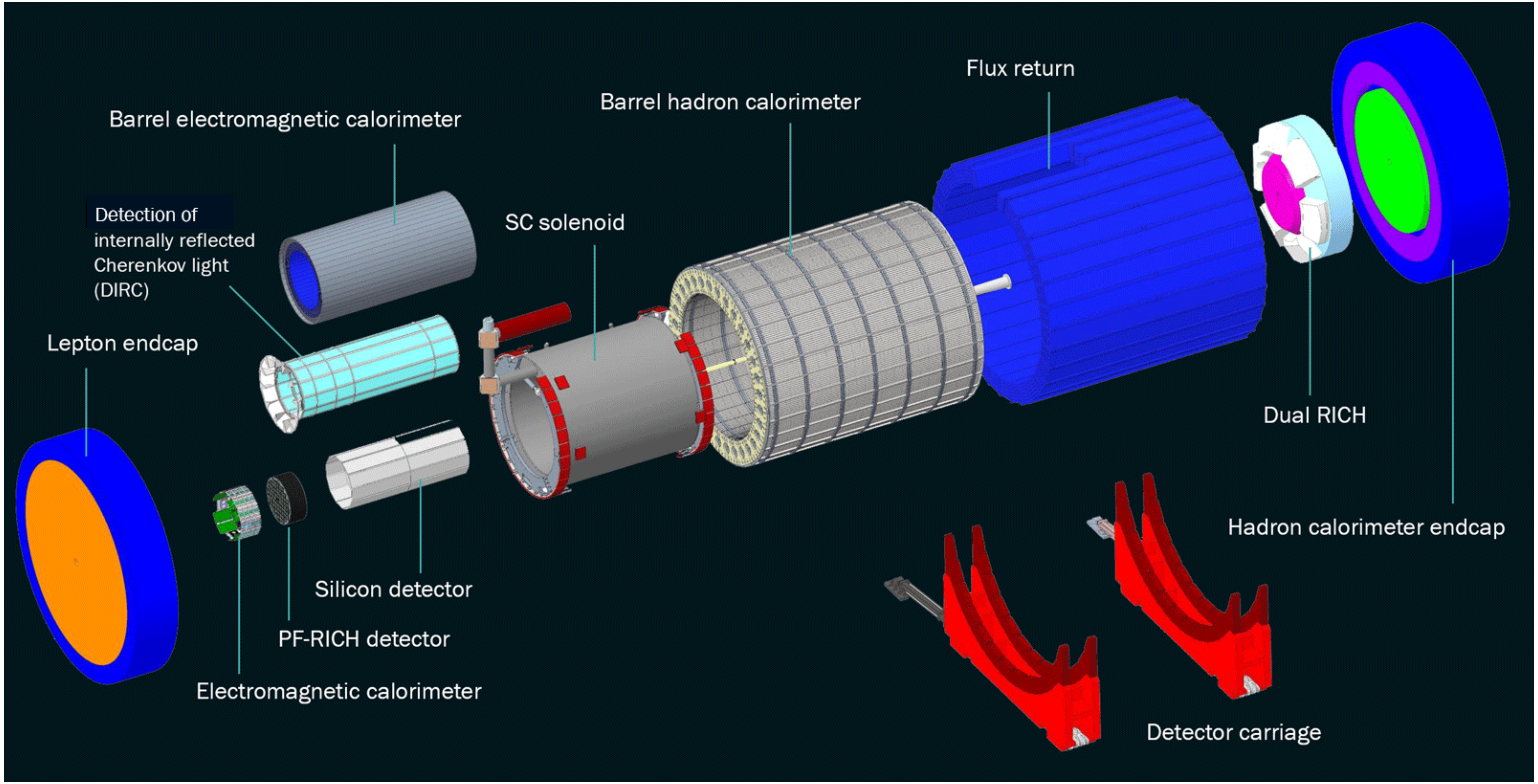


DIRC: 12*3*2 = 72 HRPPDs total

A. Kiselev

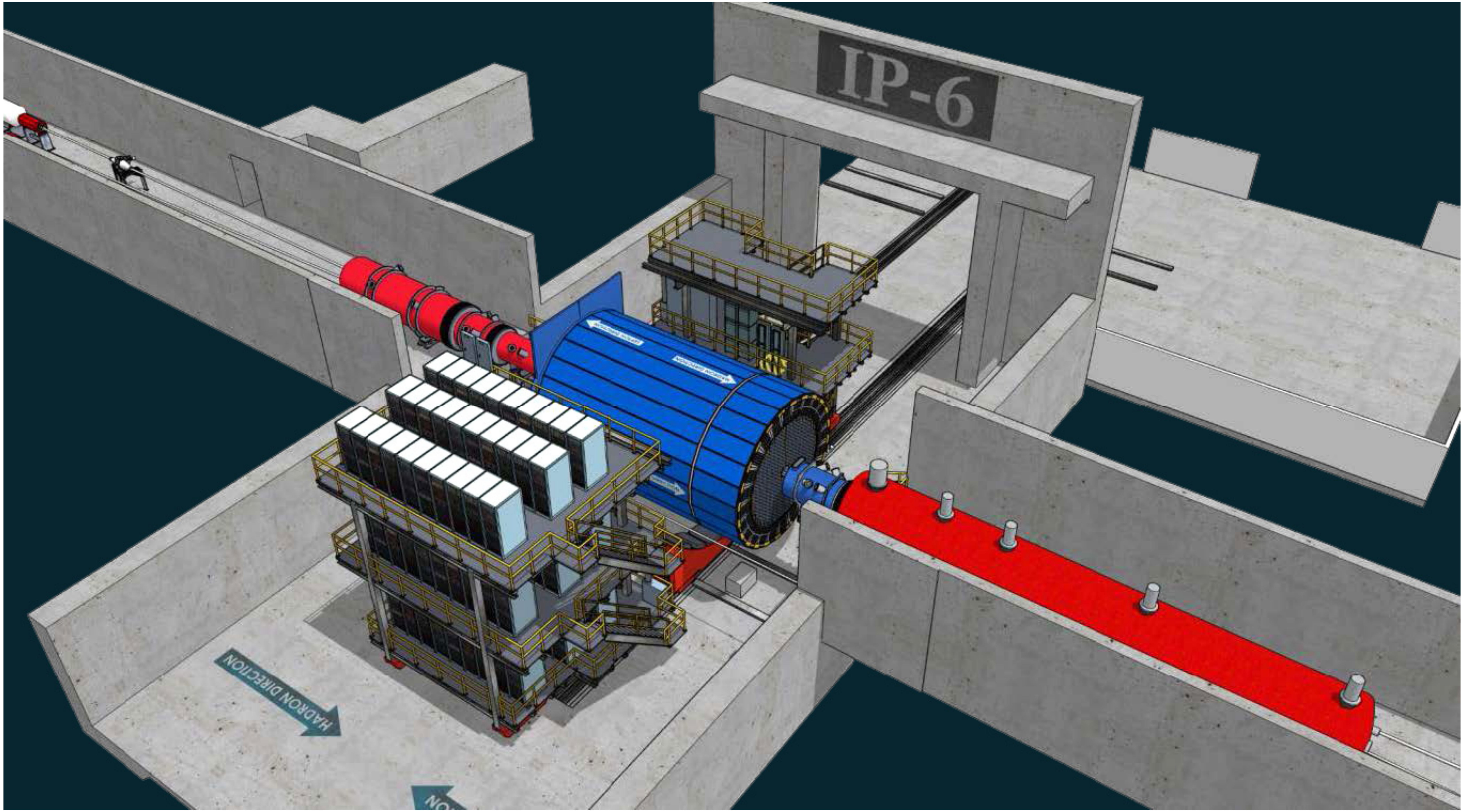


- HRPPDs may be more cost-efficient for high-performance DIRC compared to MCP-PMTs.
  - Requires sub-mm spatial resolution, better than 75 ps timing resolution.
  - DIRC has much higher expected occupancy than pfRICH.

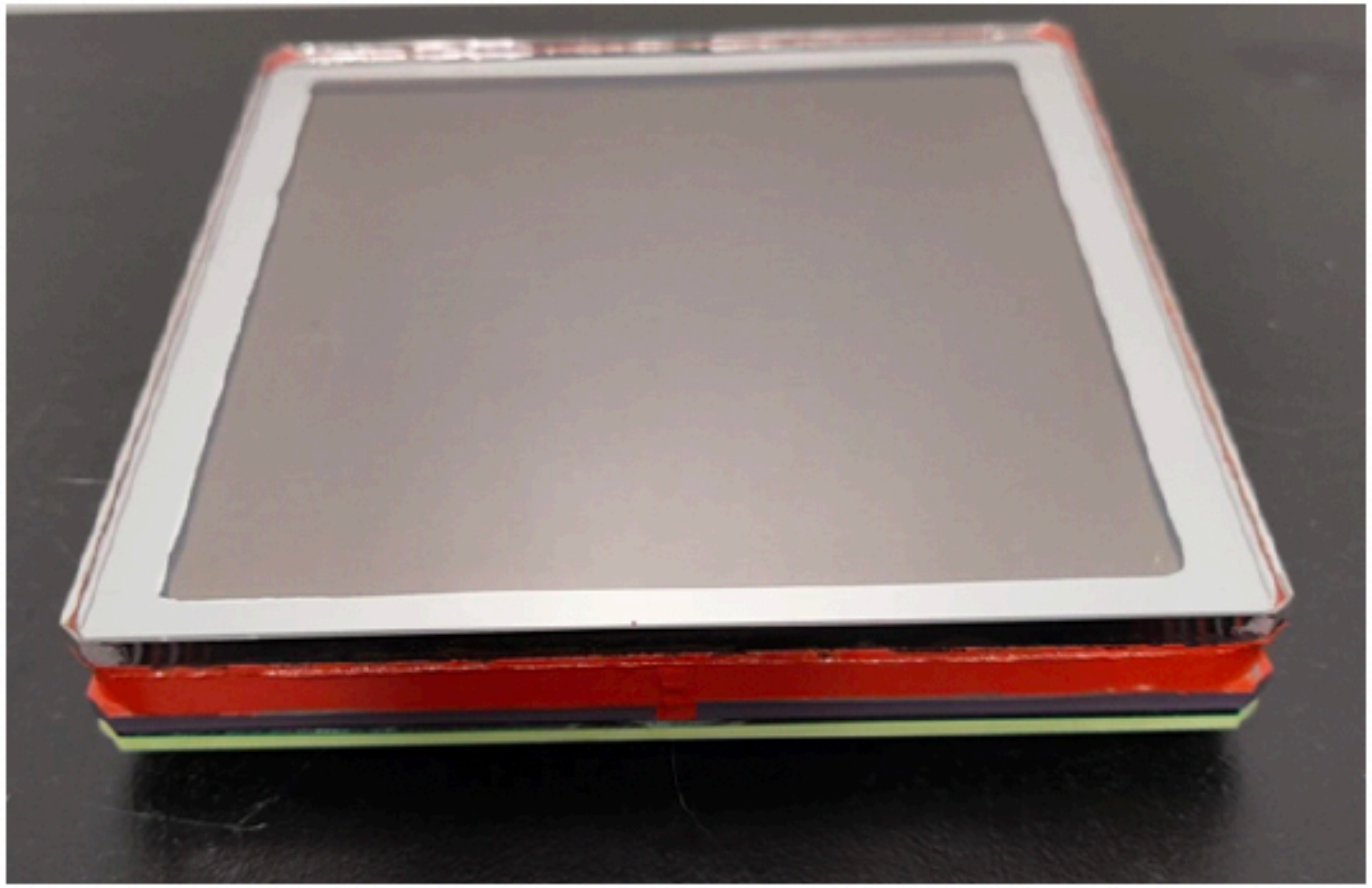


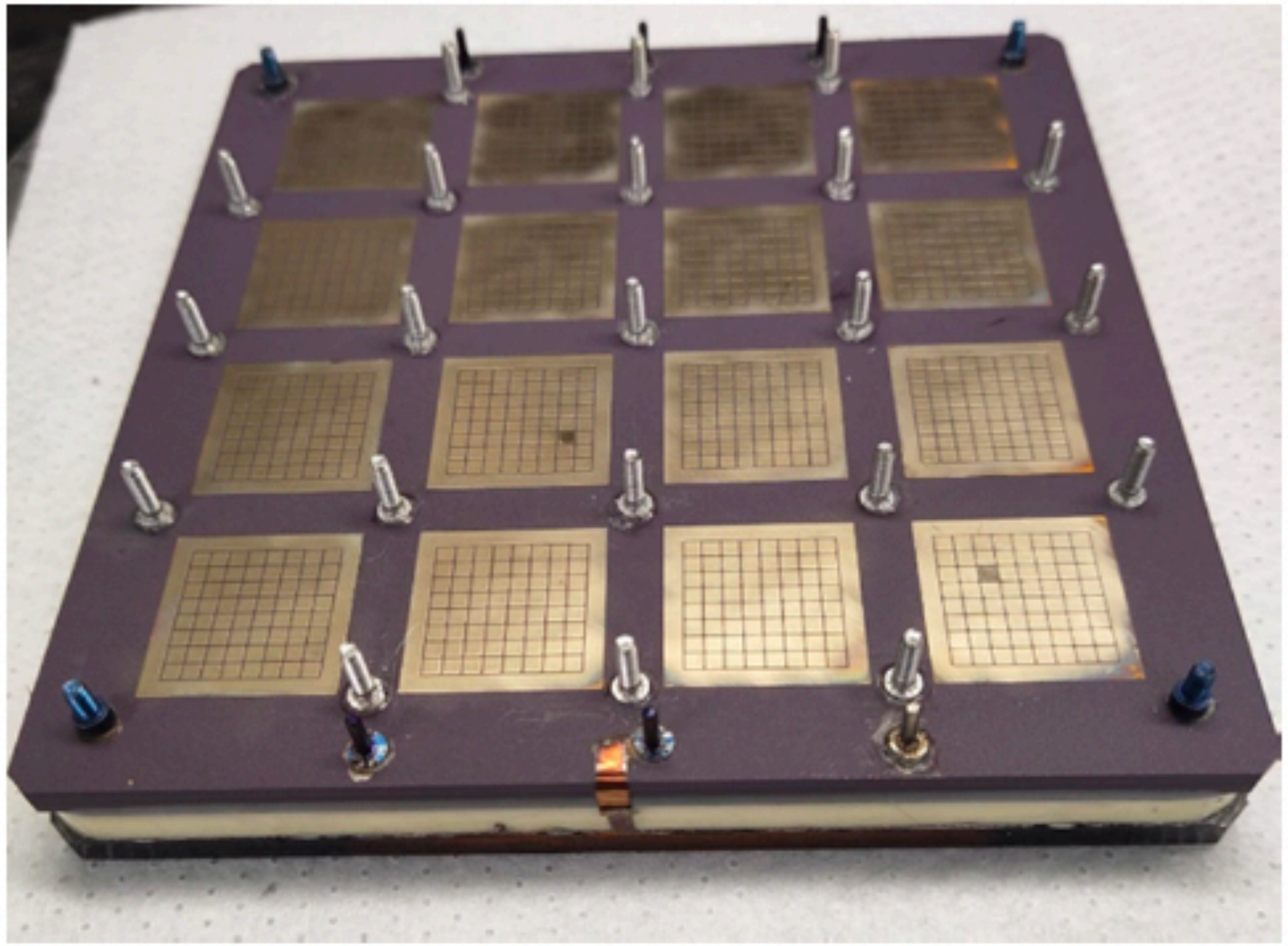
https://www.bnl.gov/eic/epic.php

Expoded view of ePIC detector

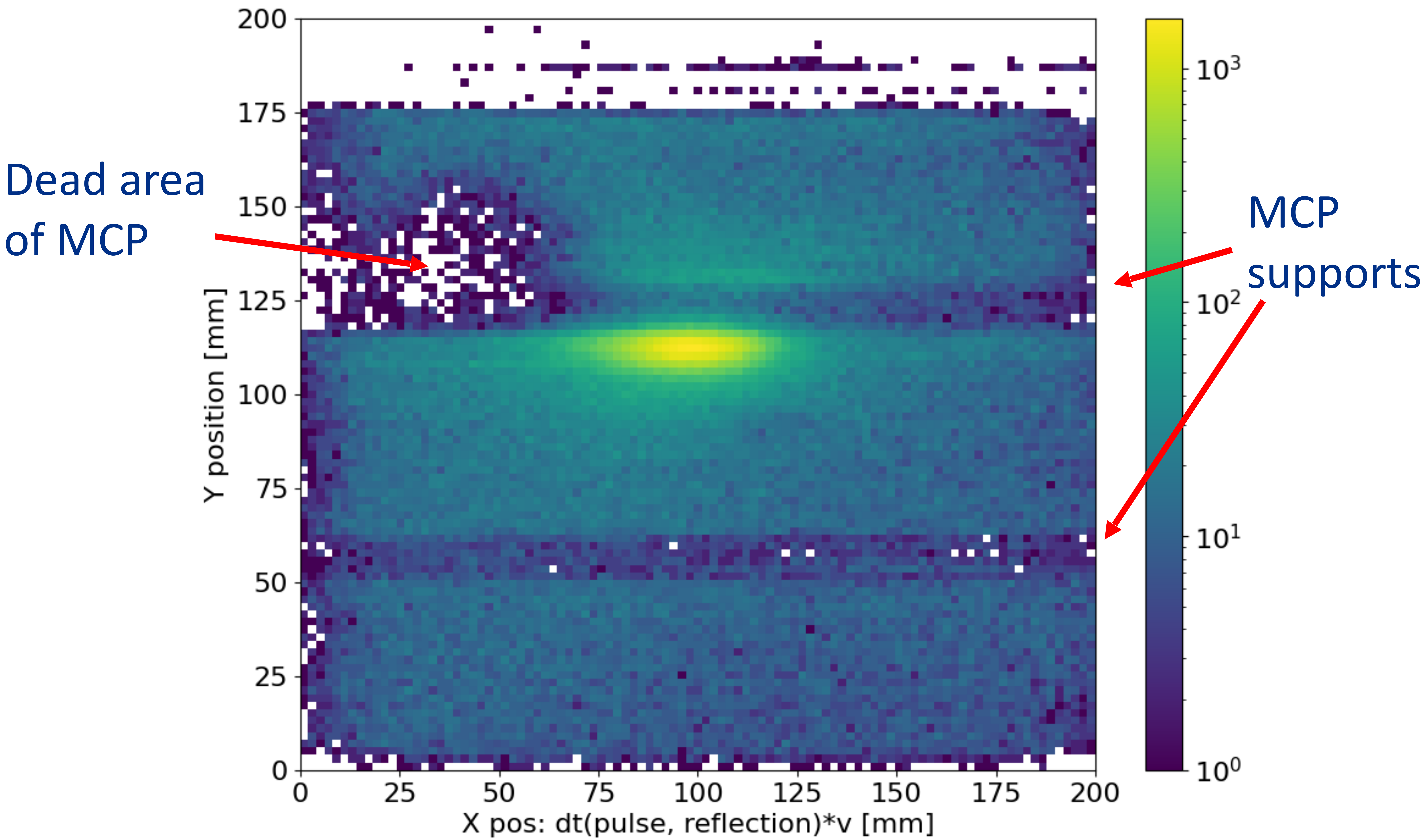


ePIC detector in place in EIC beam line https://www.bnl.gov/eic/epic.php





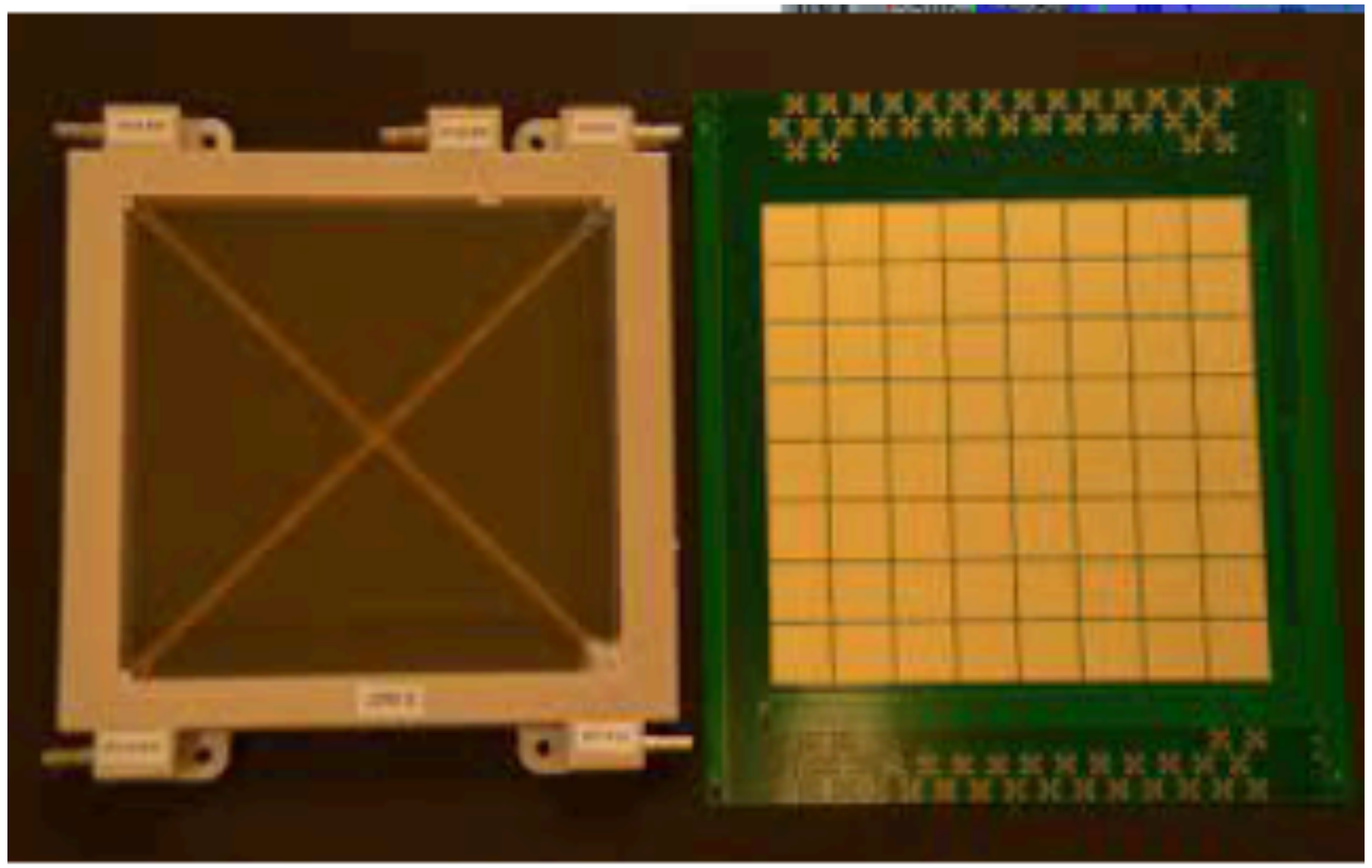
Results from Gen 2 LAPPDs at FTBF

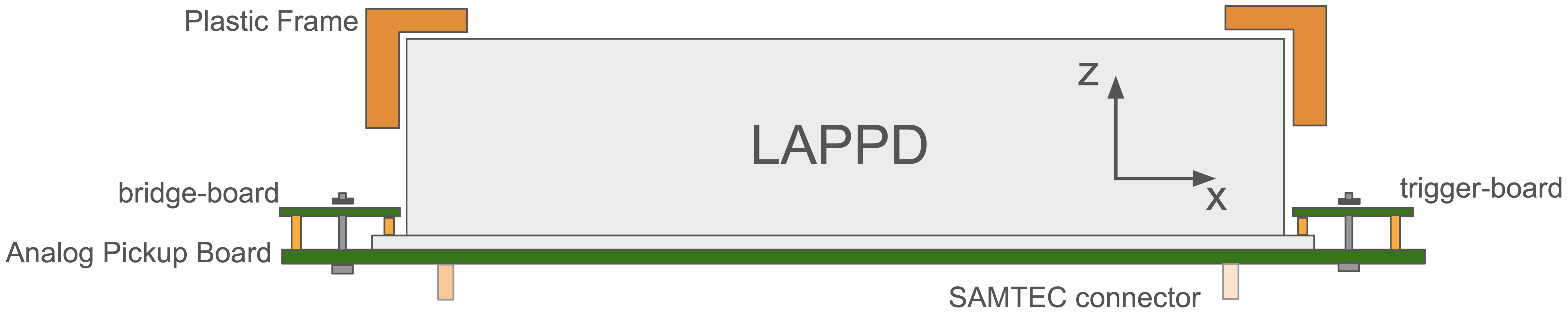


N. J. Pastika BTTB12

Benefits of Gen II (ANNIE and FTBF Perspective)

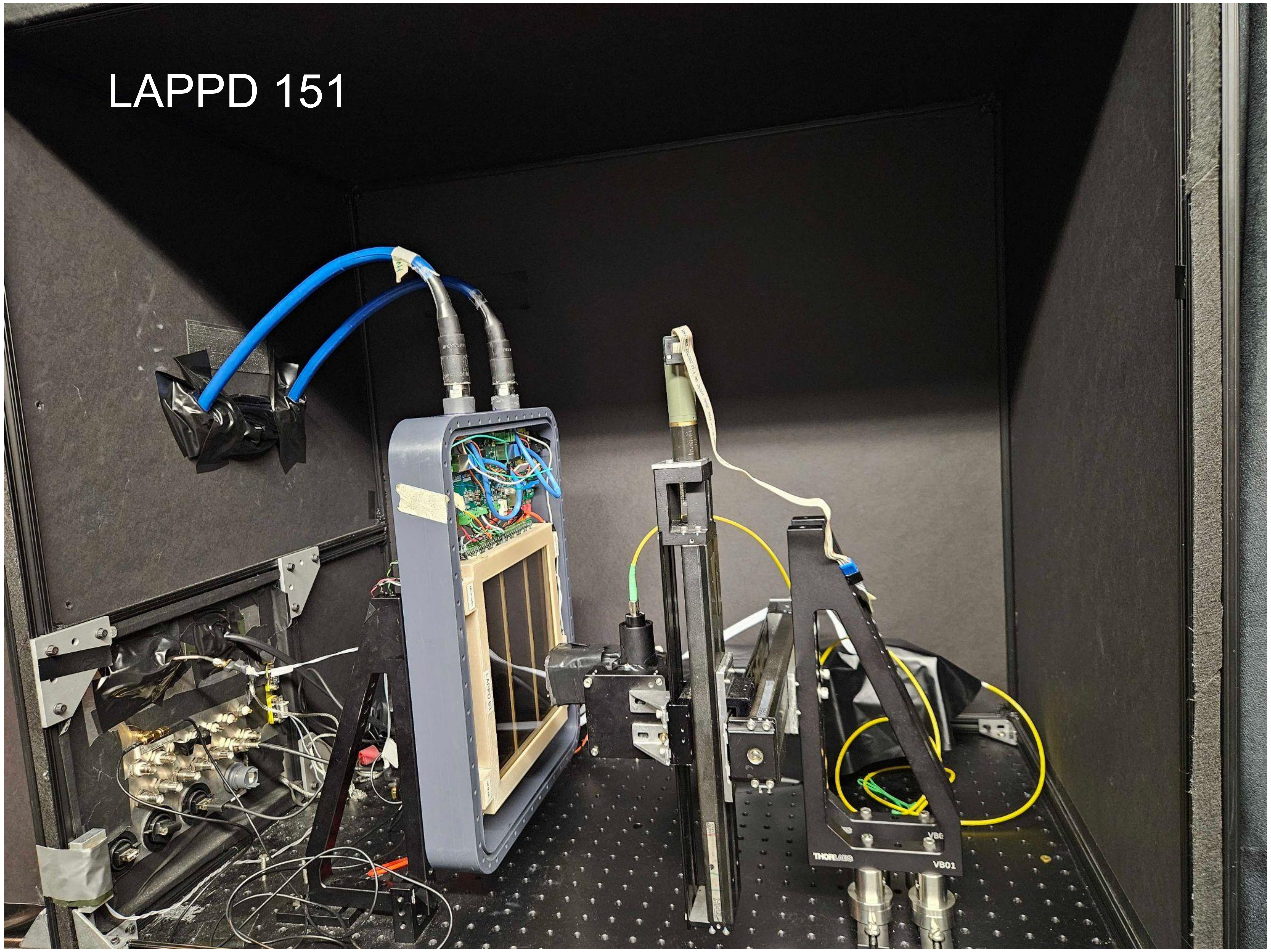
- Gen I:
    - We found pogo pins are prone to slippage, as are HV connections. Thermal and gravitational stress of deployment exacerbates this.
    - Microstrip anode is inside vacuum seal and cannot be changed.





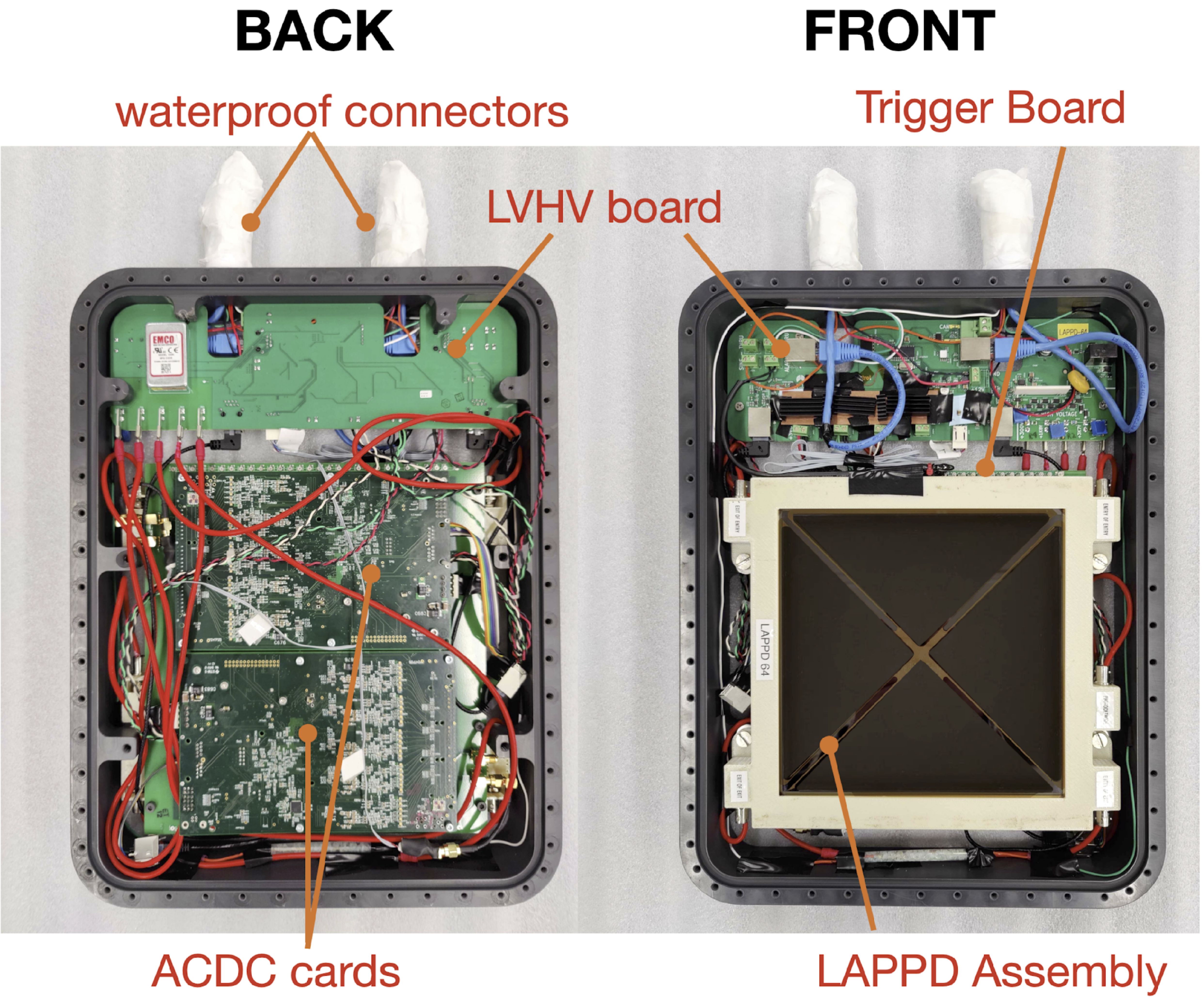
- Gen II:
    - Capacitively-coupled anode allows for more robust electrical-physical connections and greater flexibility in readout geometry.
    - More robust ceramic body.
    - **Future Gen-II:** non-alkali MCP substrate prevents aging due to alkali diffusion.
    - Anode-wide crosstalk present in modified form —needs study.

LAPPD Calibration and Commissioning



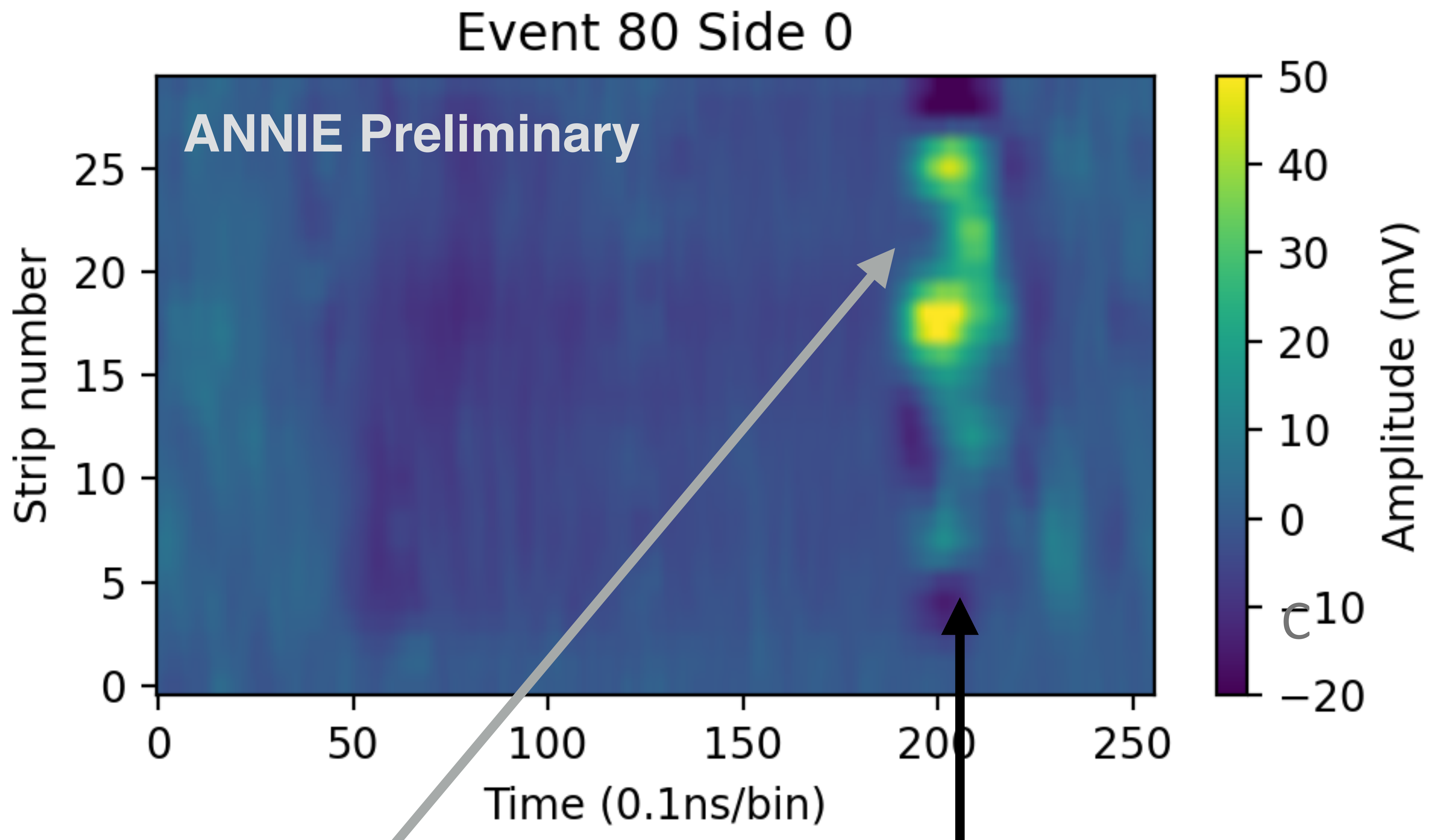
- The HV voltage divider must be tuned to individual LAPPD specs.
- Use PiLAS laser through optical fiber and scanning motor stage to measure:
  - Single PE response and gain as a function of position.
  - Charge-sharing between microstrips.
- Calibrations are done in PAL frame, with final electronics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

PAL Performance

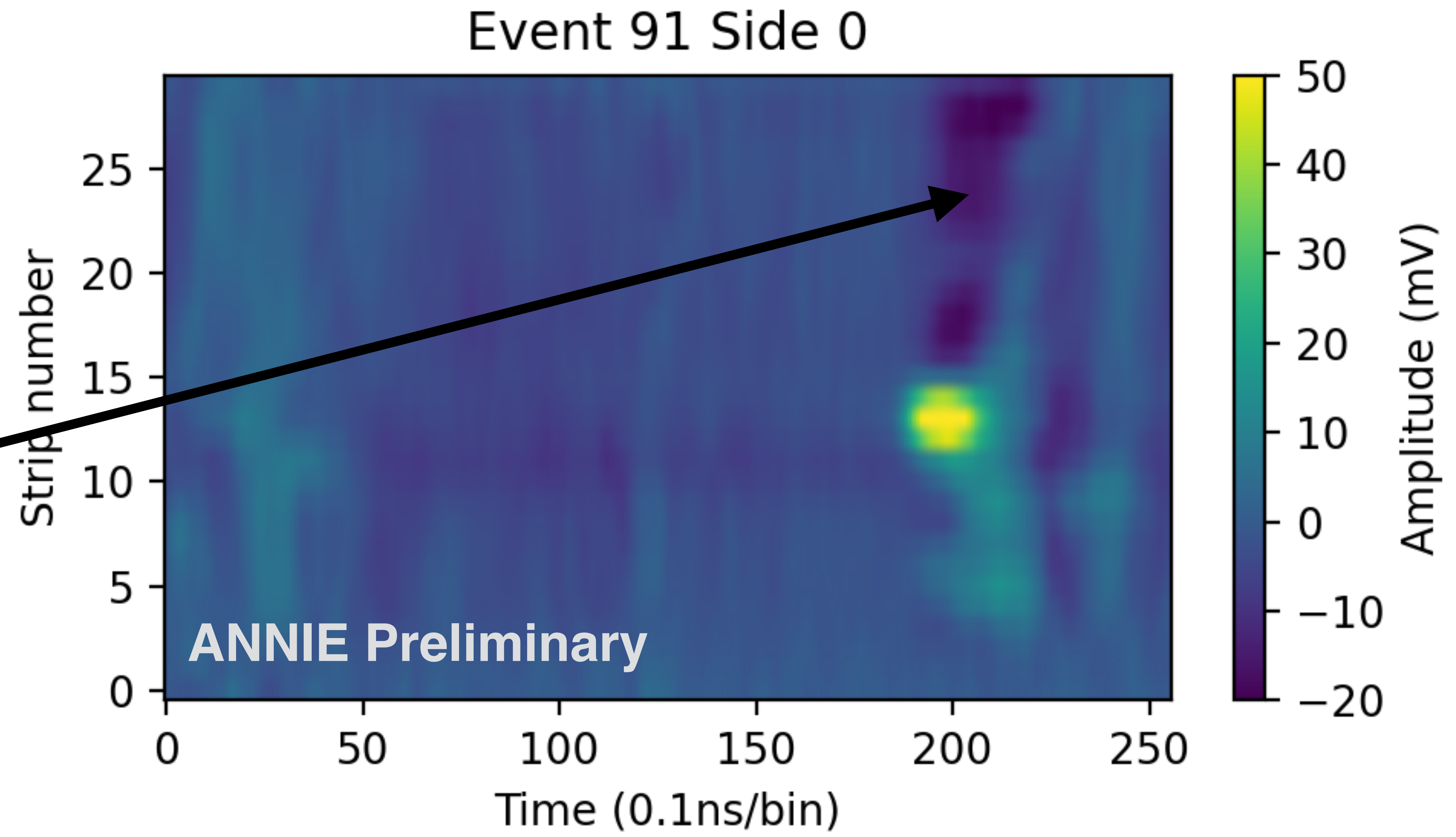


- Deployment package is adequate.
- Potential improvements include:
  - More flexible HV delivery preferable (i.e. independent biasing of MCPs instead of voltage divider).
  - More heat conductive backing to PAL to reduce heating (under study).
  - Onboard triggering (reduced latency, Gen-II compatibility).
  - Singular signal digitization (ACDC) board to reduce signal duplication.
  - Reduction of electronics noise affecting clock synchronization.

Crosstalk in Beam Neutrino Data



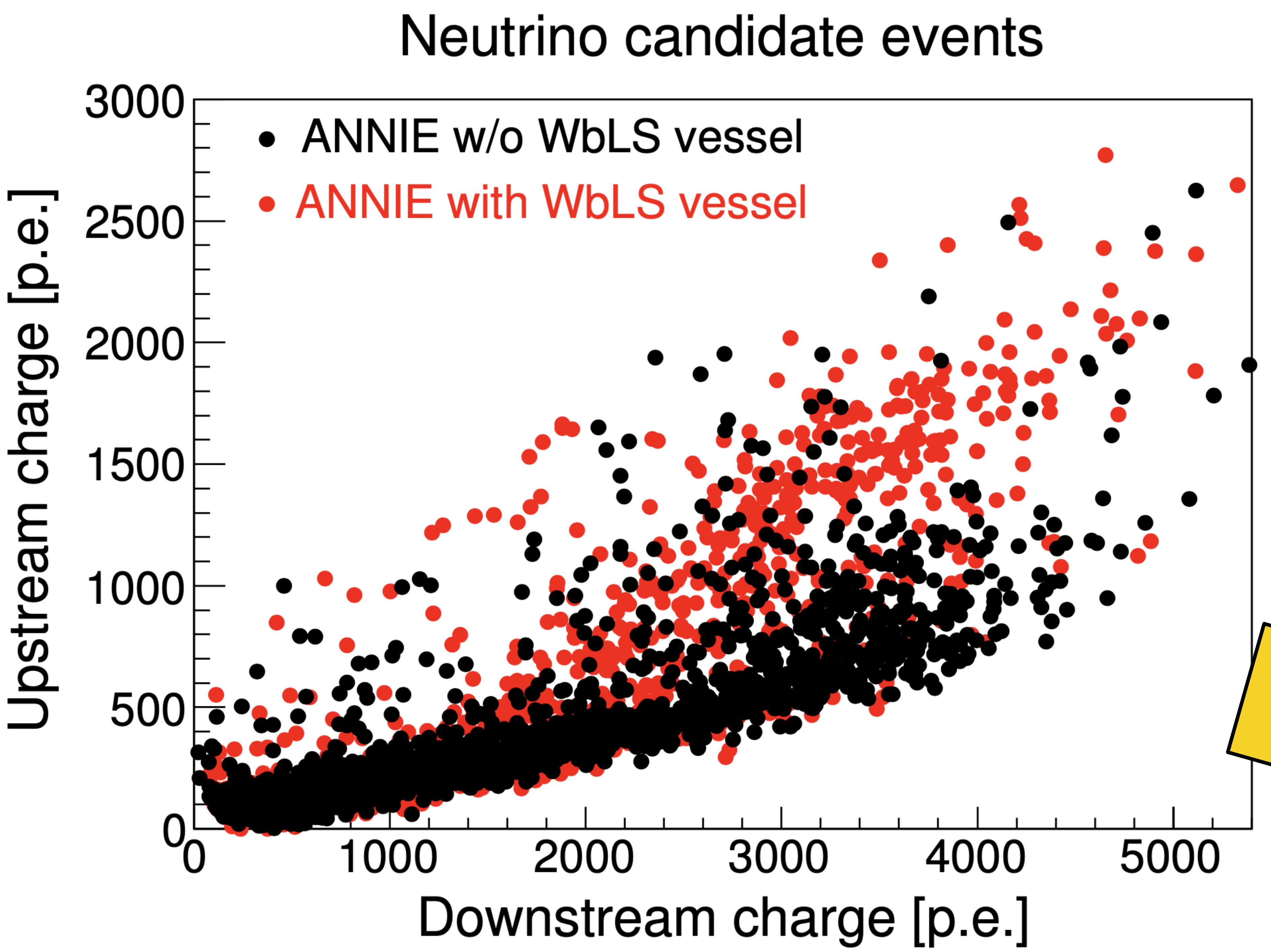
For data, composite of cross talk from multiple hits in ~2 ns time frame, due to the sweep of the Cherenkov ring across LAPPD surface and later hits from reflected light.



Cherenkov signal

Cross-talk effect

First SANDI WbLS data



- 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

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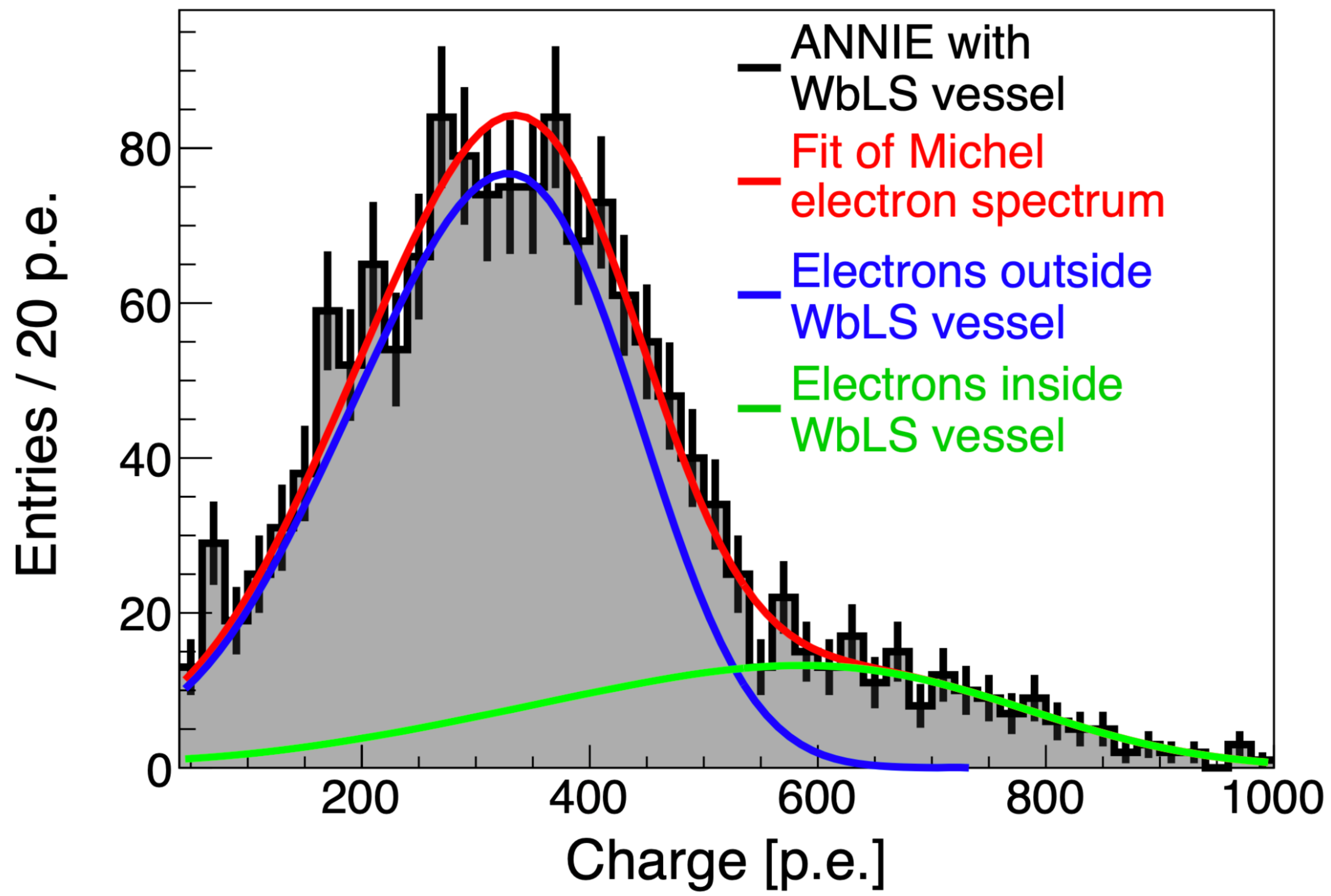
Michel electrons

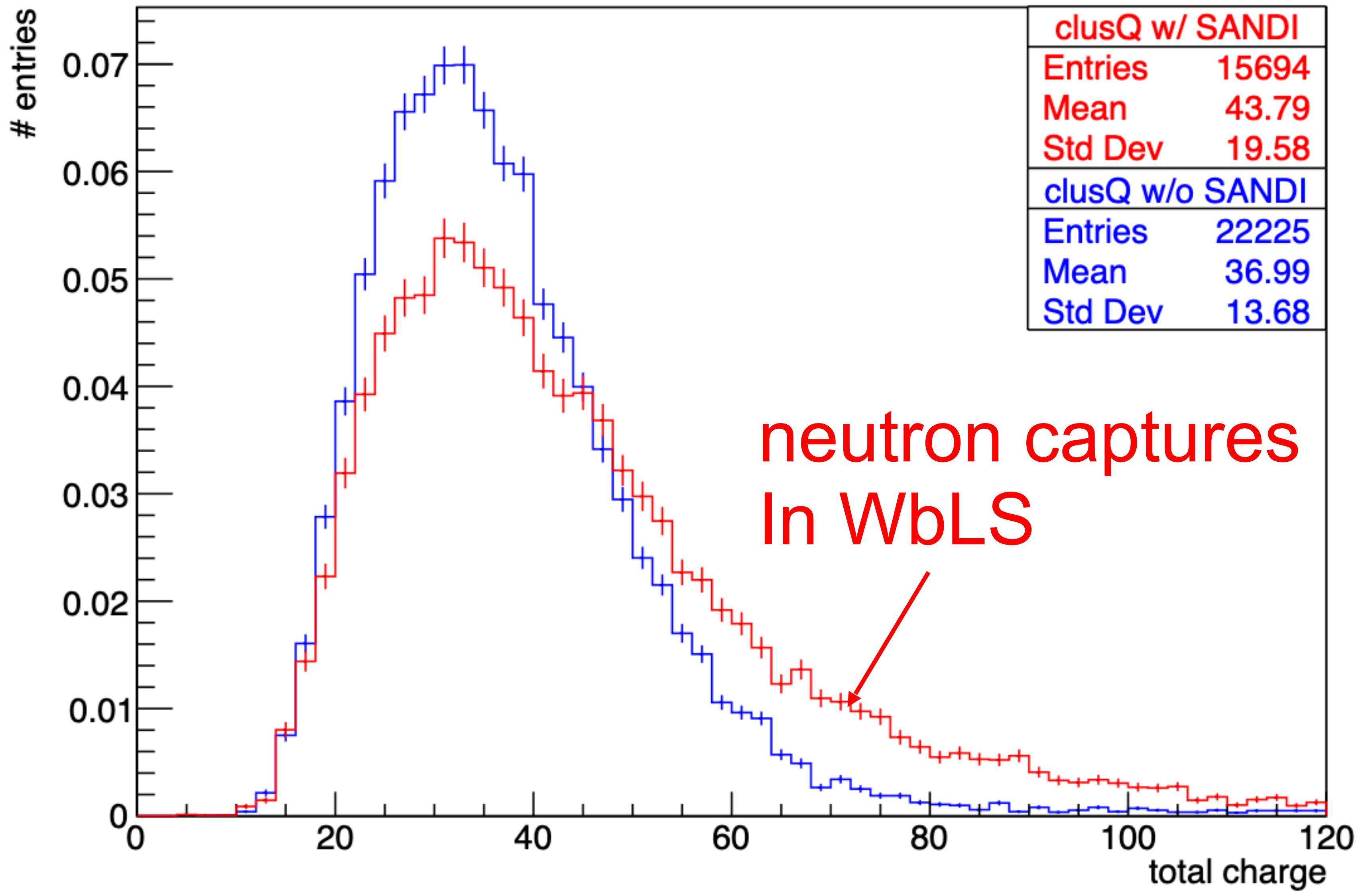


- Selection of Michel electrons from stopped muons
- New population of electrons in WbLS produces significantly more photons than electrons in water

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

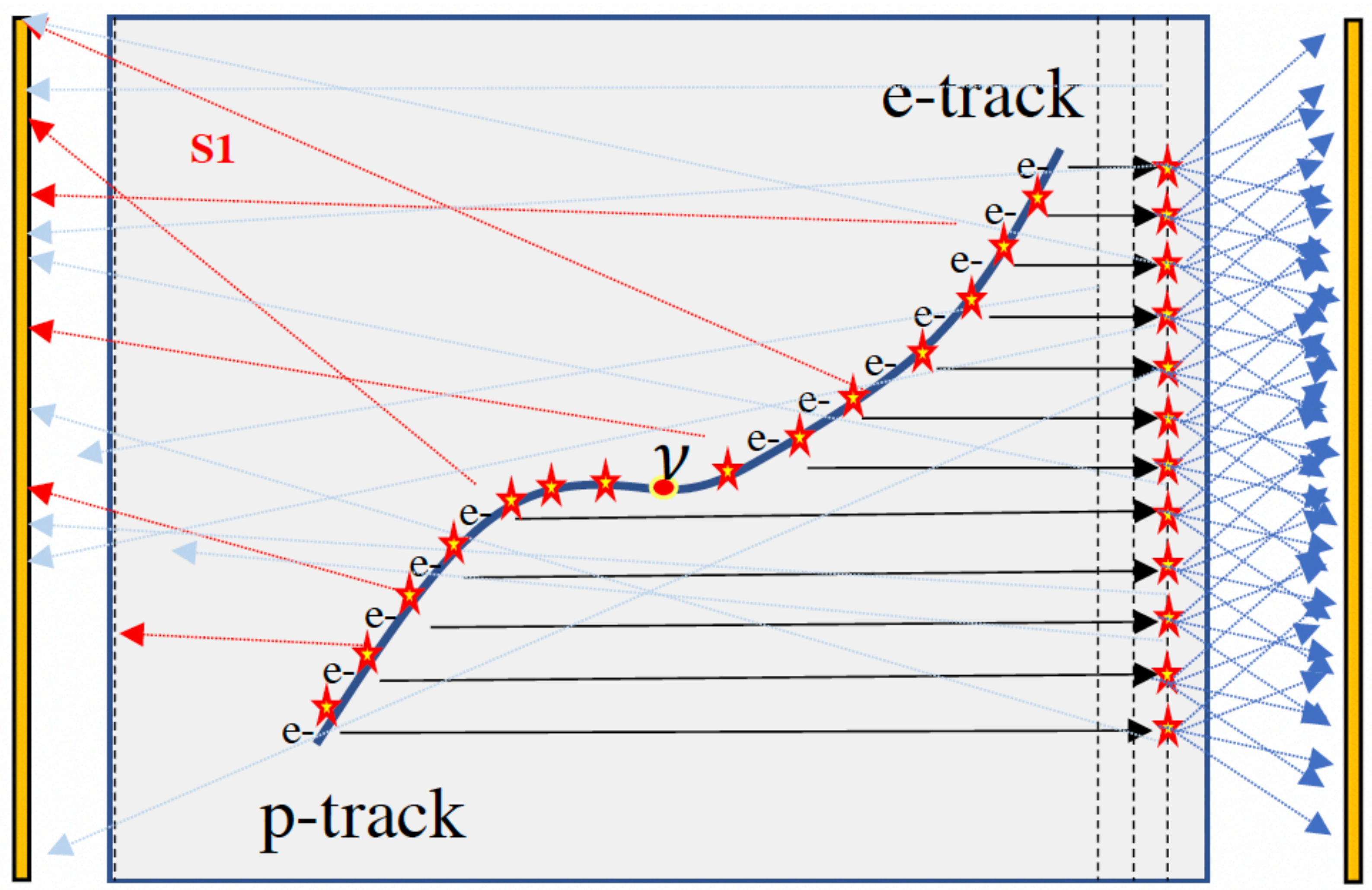
SANDI2 deployment: Gadolinium-loaded WbLS

- Acrylic Vessel redeployed with Gd-WbLS in September
- Expect enhanced neutron signal in WbLS
  → larger signal, better spatial reconstruction
  → extended calibration campaign with AmBe source
- Next step: take 2 weeks of regular neutrino beam data
  → demonstrate C/S separation with 3 LAPPDs



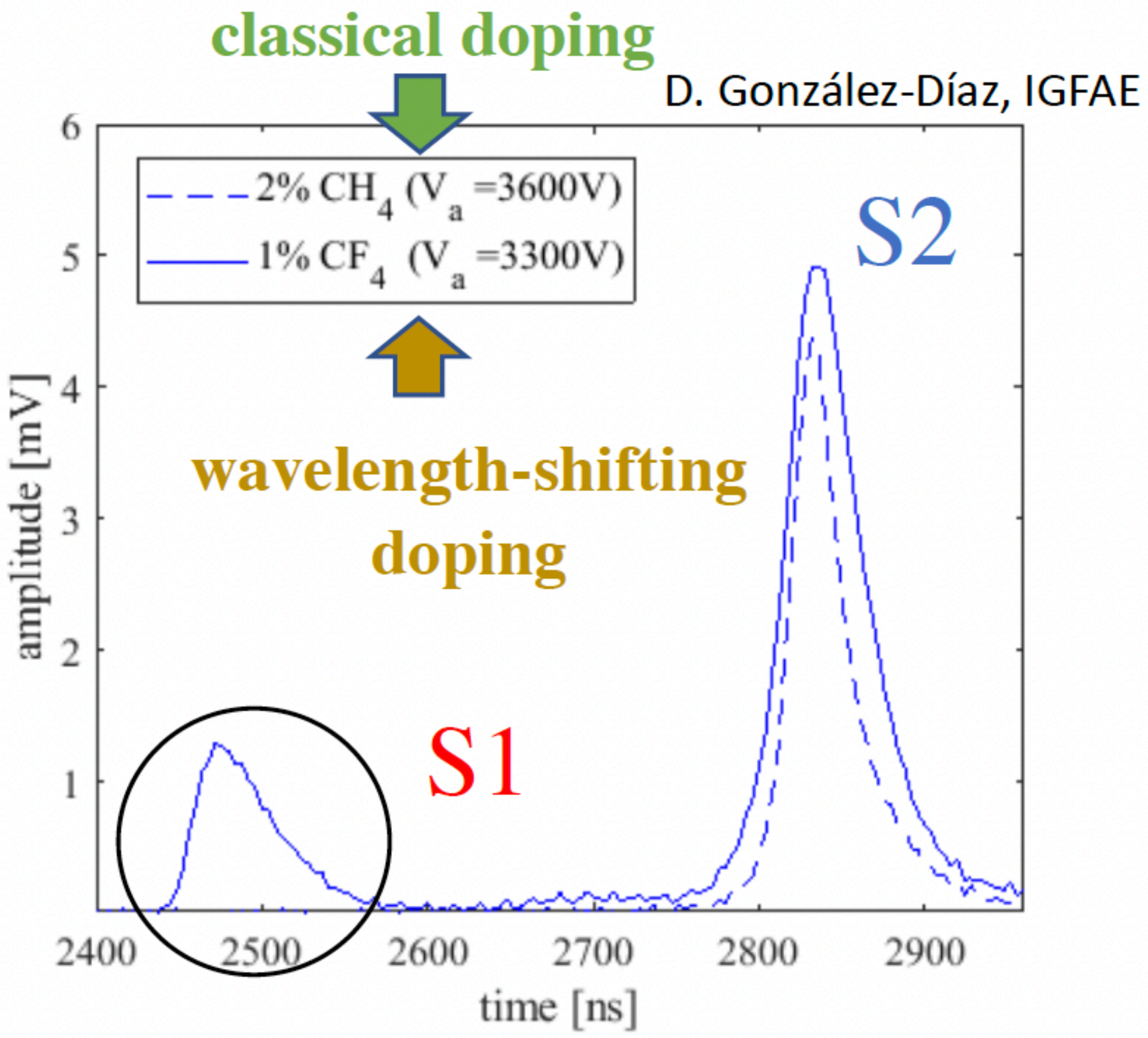
SANDI vessel with GdWbLS and AmBe neutron source

ND-GAr



Photosensor for primary scintillation (S1) → time stamping

Charge readout or photosensor for secondar scintillation (S2) → 3D space sampling



- Gaseous Argon TPC based on the ALICE design, scintillator ECAL
- 10 atm pressure, 0.5T magnetic field
- Intrinsic VUV causes feedback back instability via photoelectric
- Quencher additive to stabilize gain by wavelength shifting