Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

The CMS MIP Timing Detector

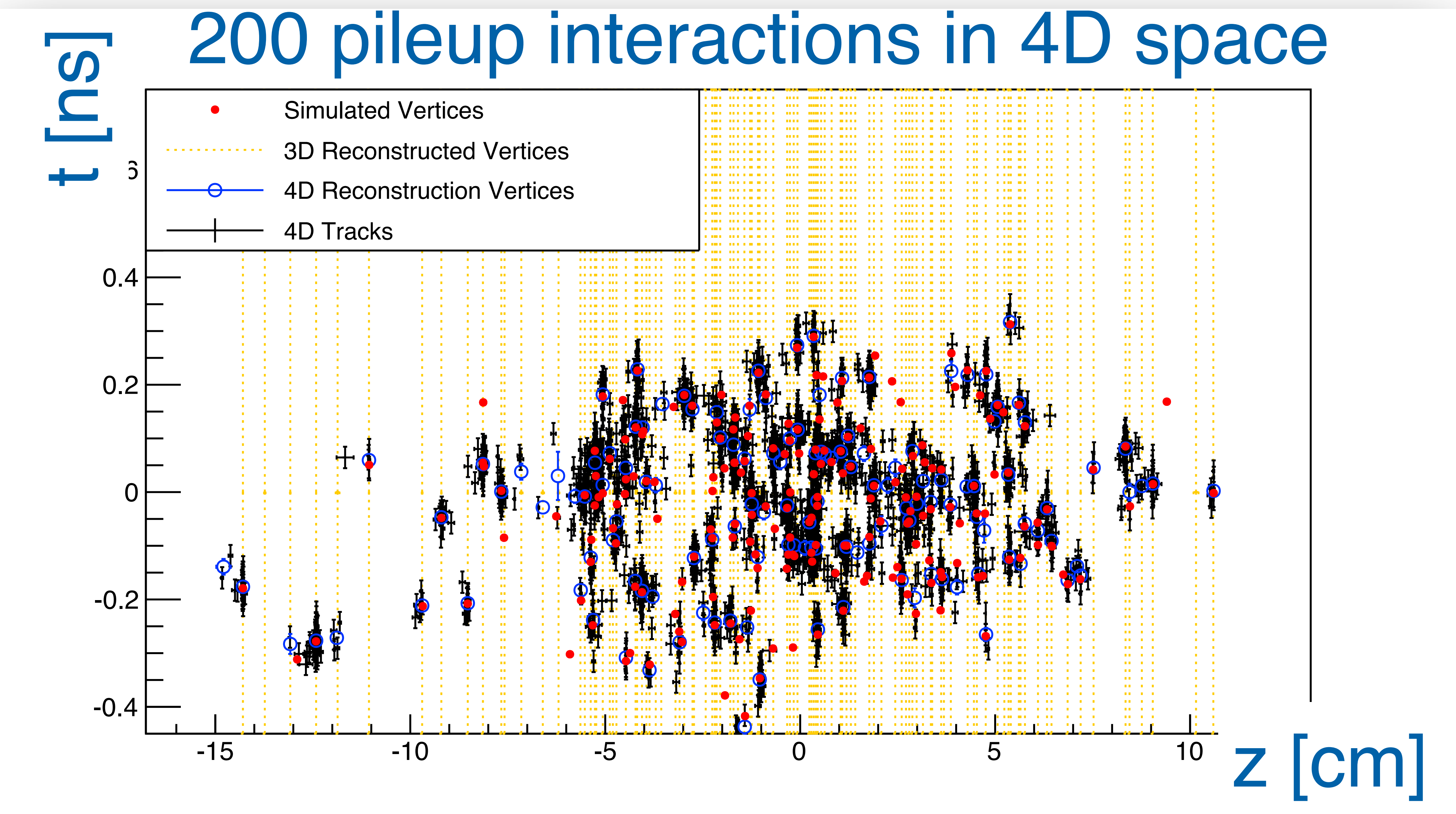
Ryan Heller on behalf of the CMS Collaboration

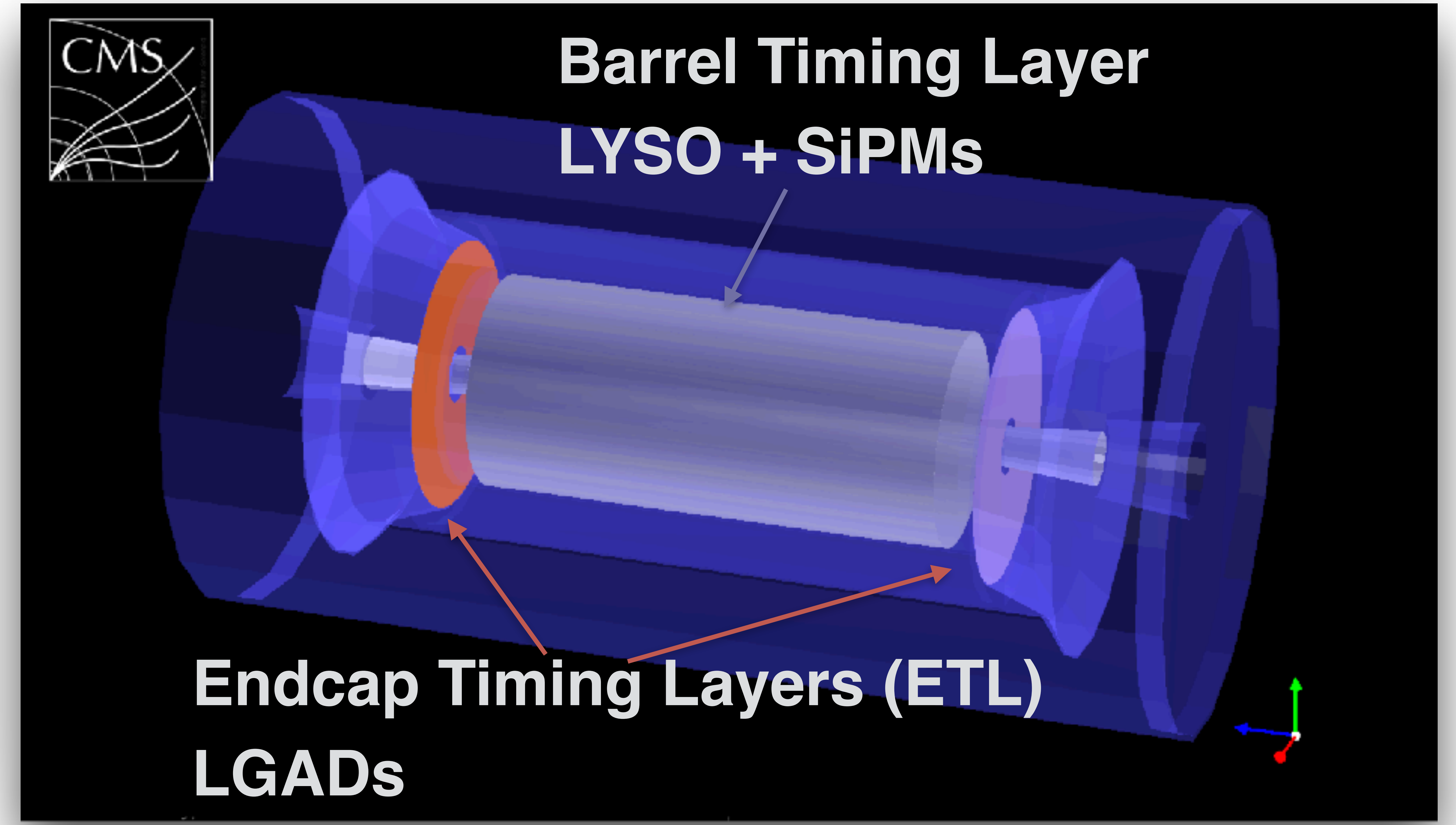
TIPP2021

May 25th, 2021

Precision timing for HL-LHC

- HL-LHC will reach pileup of approximately 200 simultaneous interactions!
- Precision timing can help maintain detector performance





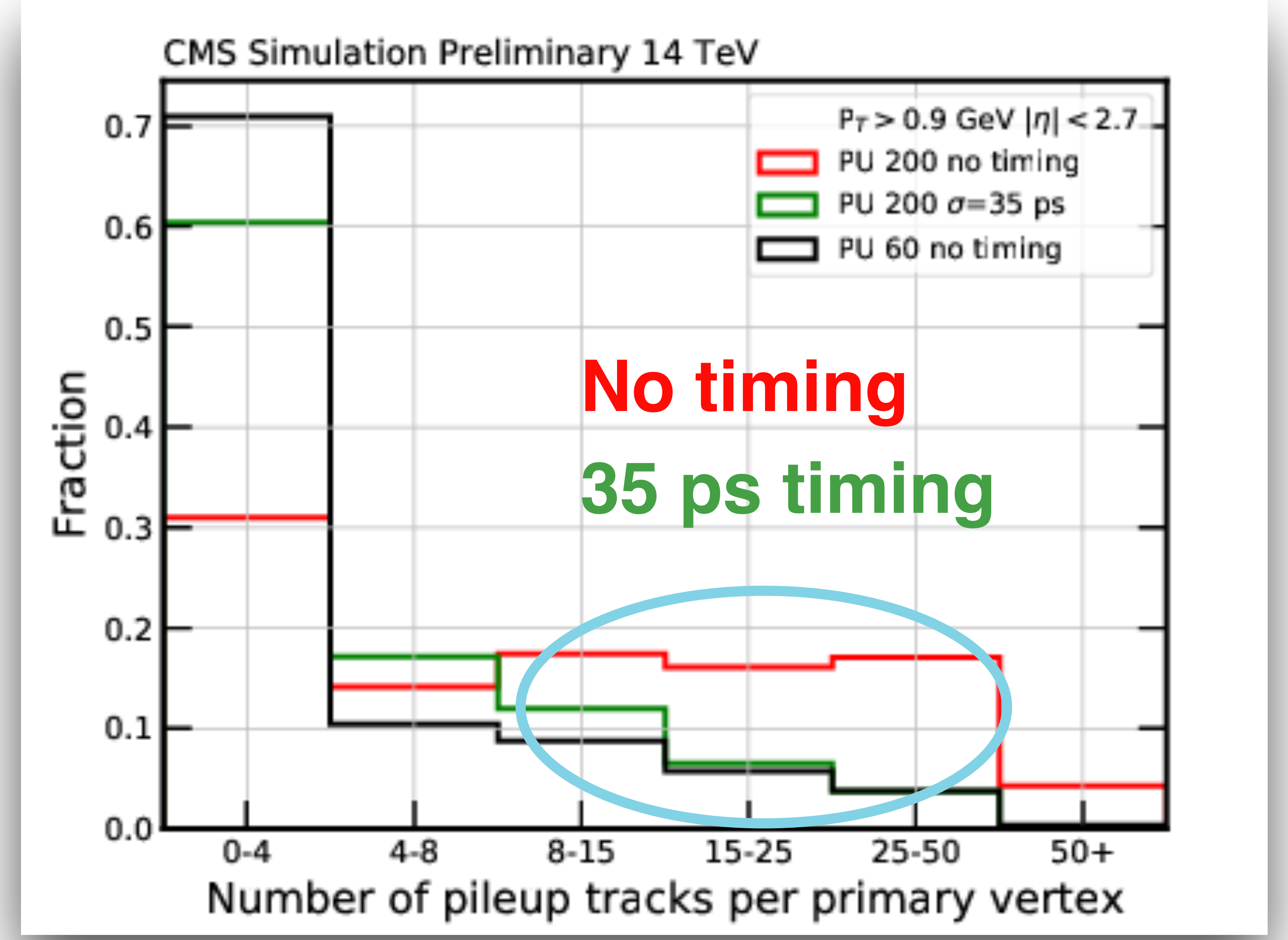
- CMS MIP Timing Detector (MTD): timestamp every track with 30 ps resolution at beginning of HL-LHC, up to 50 ps resolution after 4000 fb^{-1}

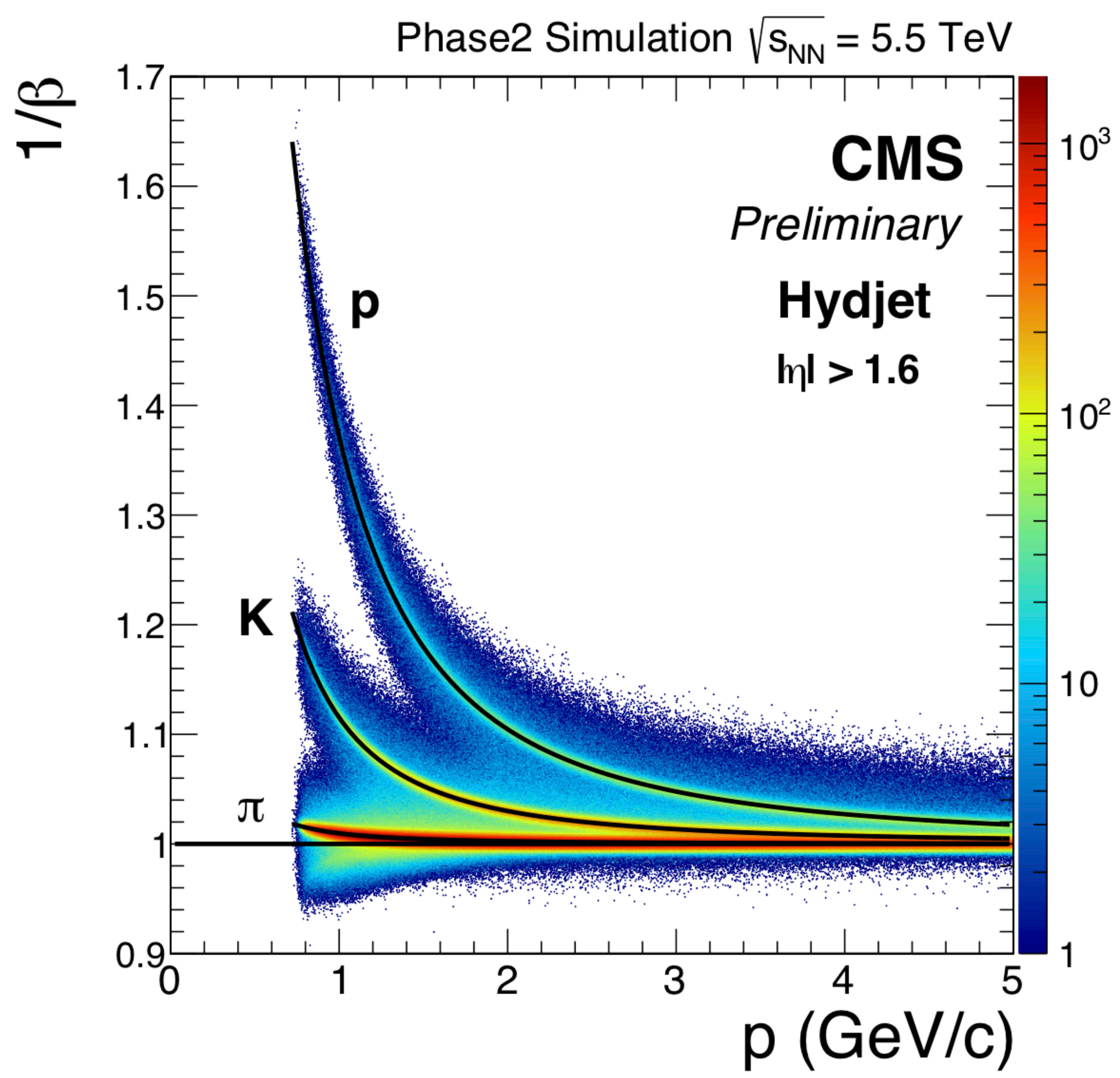
Fermilab

MTD impact on physics performance

- Substantial reduction in pileup mis-association
  - Improved isolation, tagging efficiency, MET resolution..
- Particle ID for heavy ion/B-physics
- Enhanced sensitivity to BSM long-lived particles

Heavy ion physics: Hadron ID from TOF

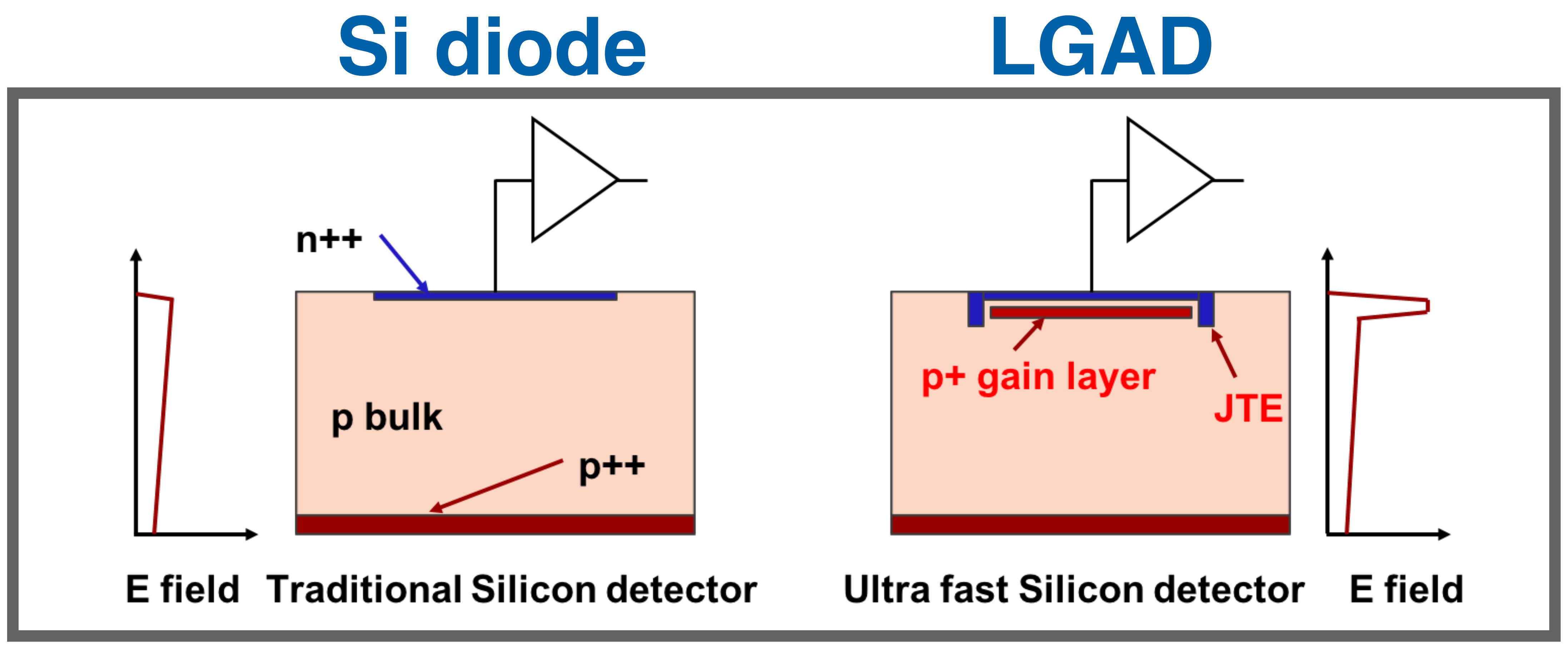


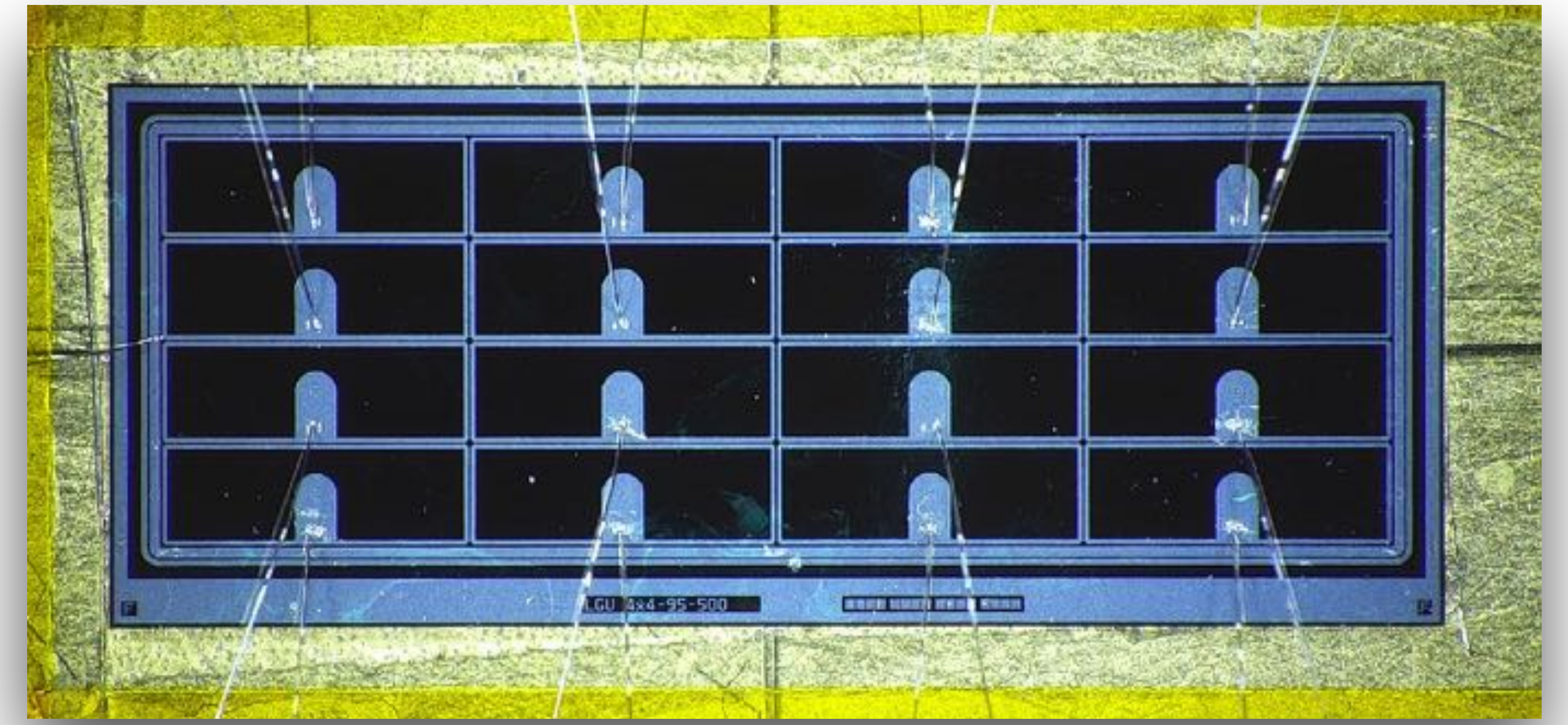


Fermilab

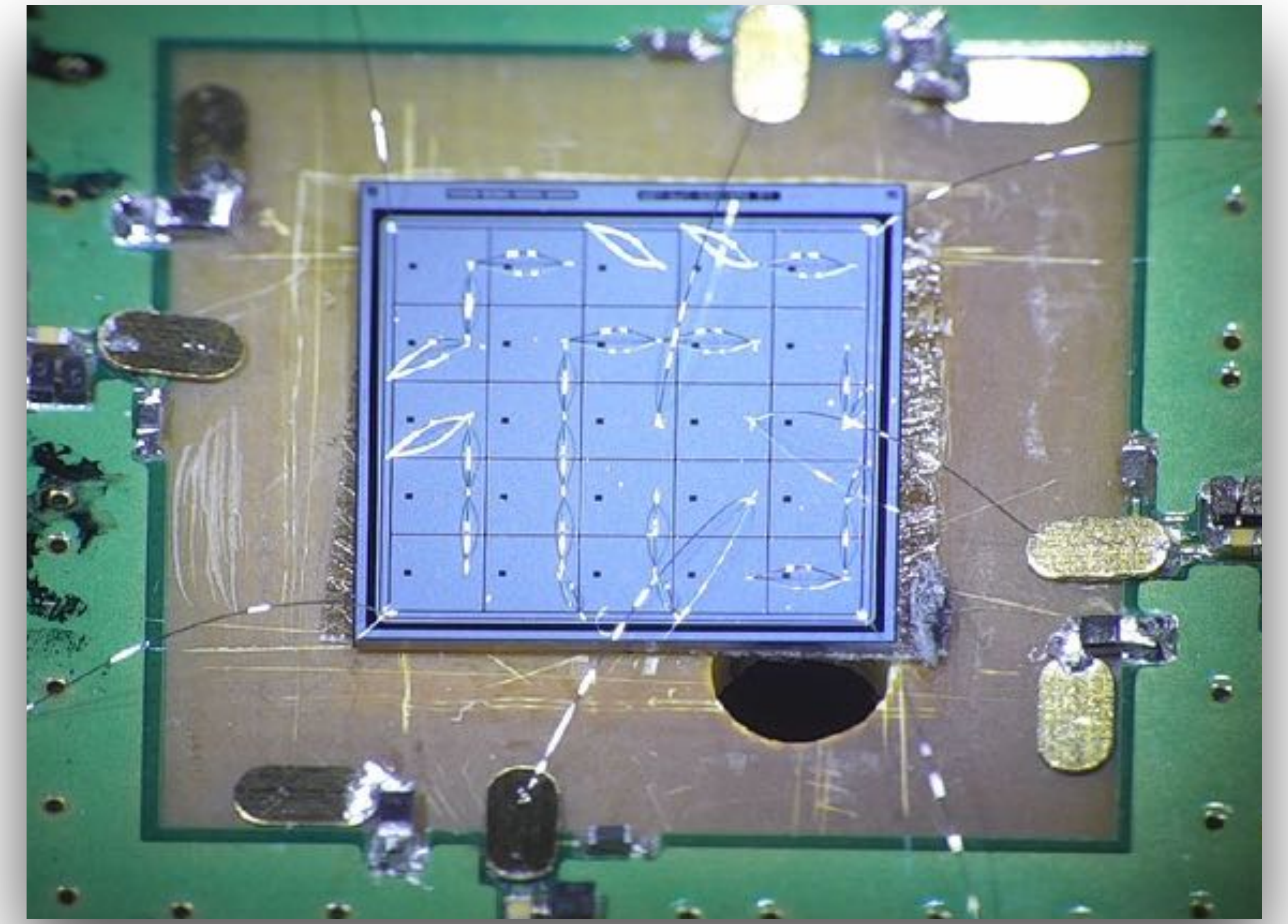
Sensors for Endcap Timing Layer

- CMS Endcap: high occupancy & radiation
  → Highly granular silicon detector
- Low-Gain Avalanche detectors (LGADs): novel ultra-fast silicon detectors
  - Moderate internal gain (10-20)
  - Thin (50 micron depletion region)
- ETL: $(1.3\ \text{mm})^2$ pads, $(2.1\ \text{cm})^2$ sensors





4x4 LGAD array, HPK

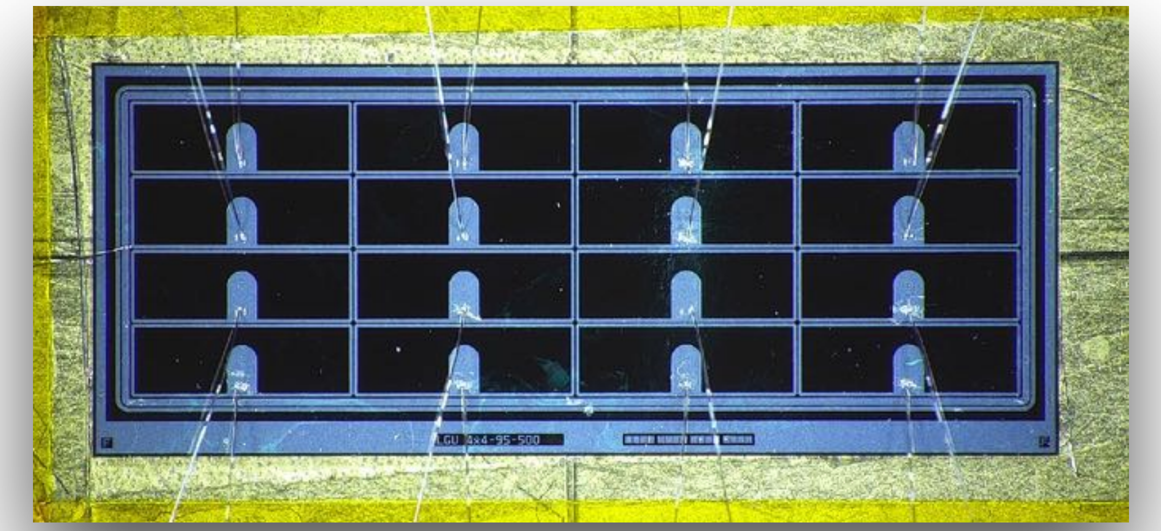


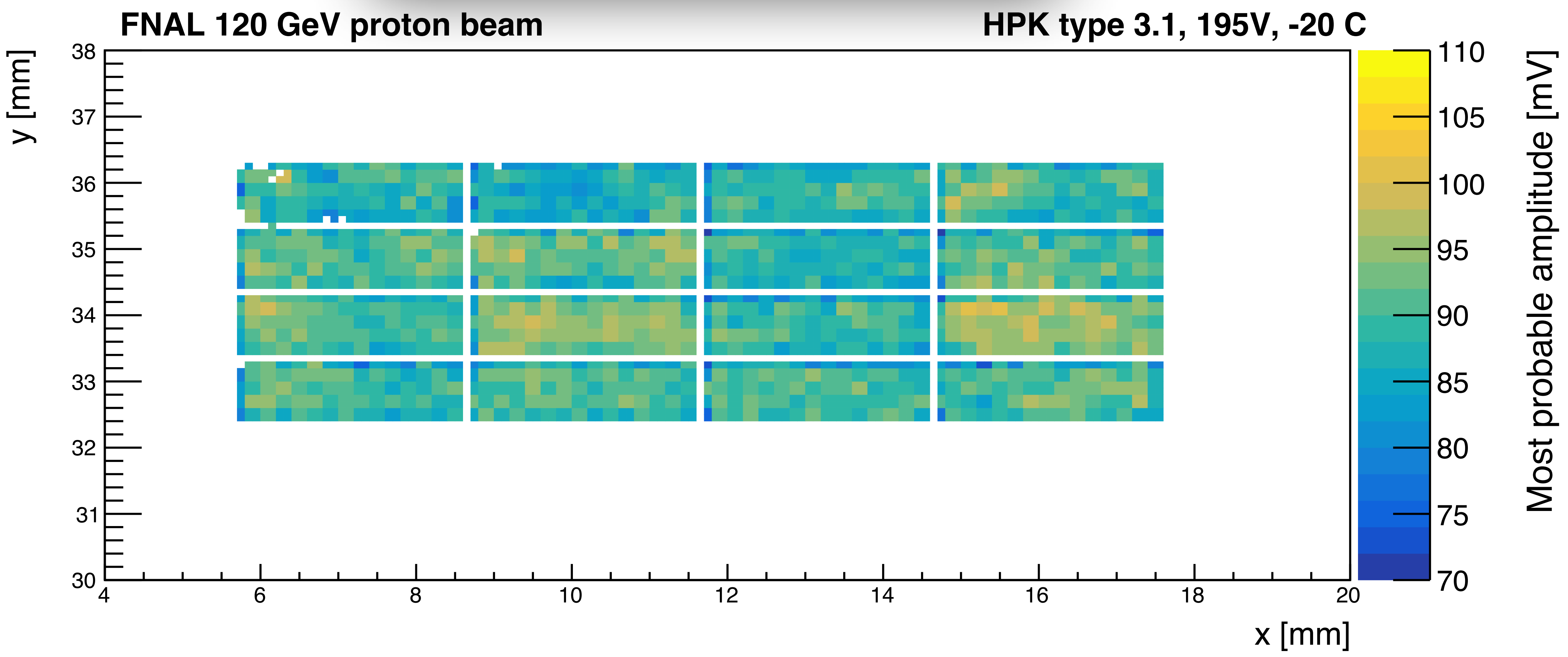
5x5 LGAD array, HPK

LGAD sensor characterization

- Leverage diverse set of characterization facilities
  1. Fermilab test beam (120 GeV protons): highly detailed information; limited sensor statistics

Fermilab test beam facility with Si tracker & dedicated LGAD test stand

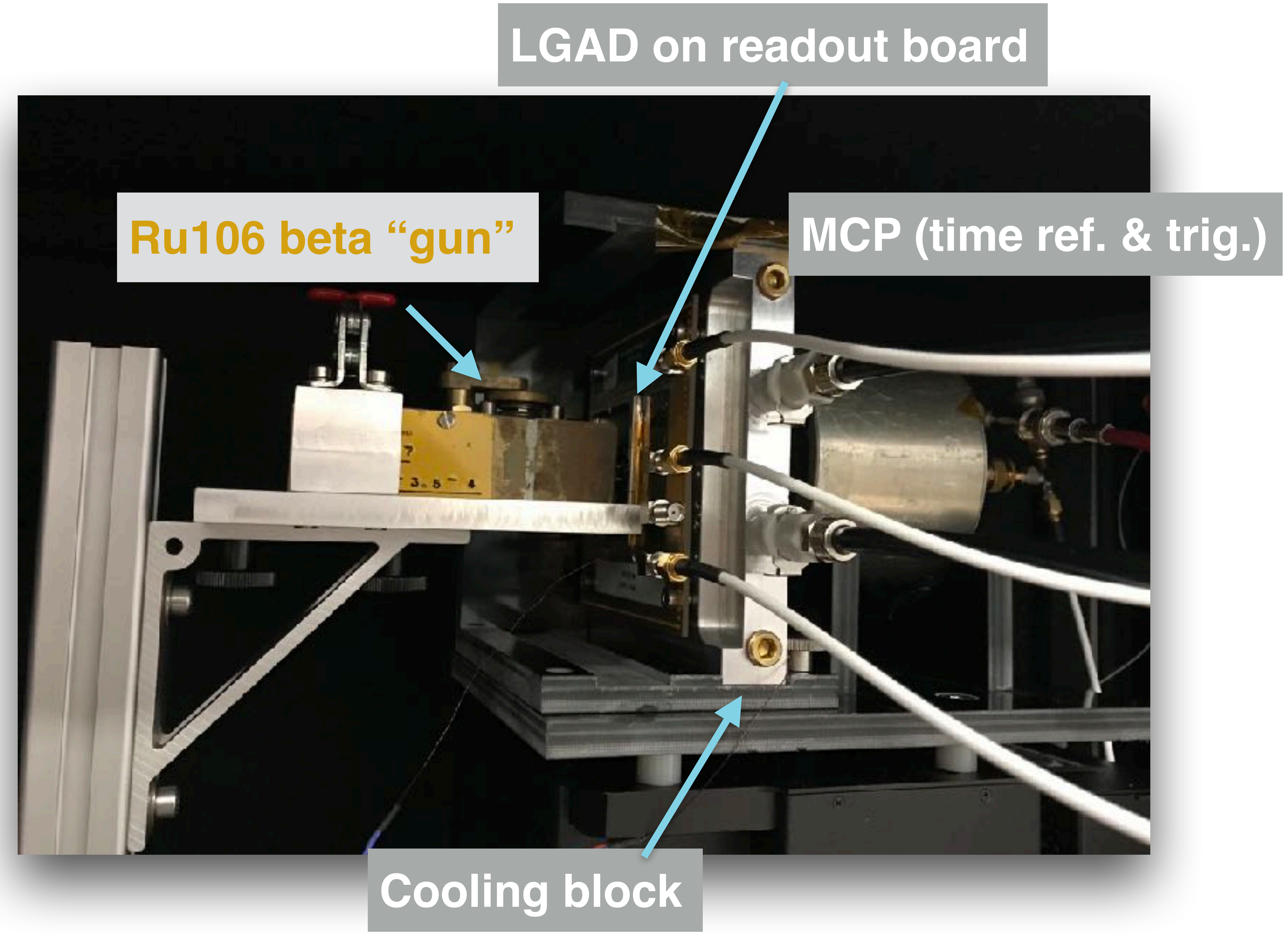




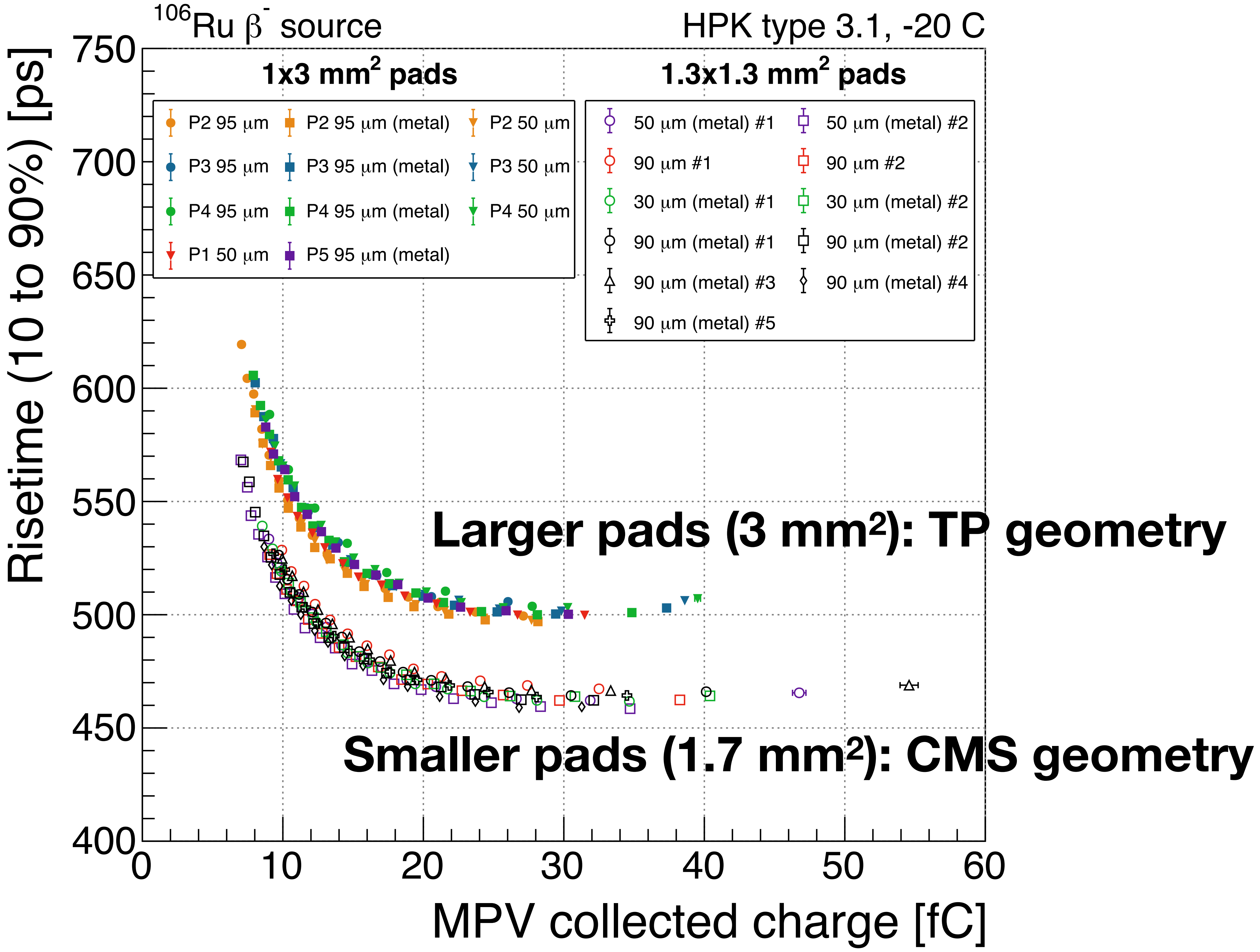
Good signal uniformity across 4x4 LGAD array

LGAD sensor characterization

- Leverage diverse set of characterization facilities
  1. Fermilab test beam (120 GeV protons): highly detailed information; limited sensor statistics
  2. Beta source: high volume testing with MIP signal



Deep understanding of dozens of sensors with beta source

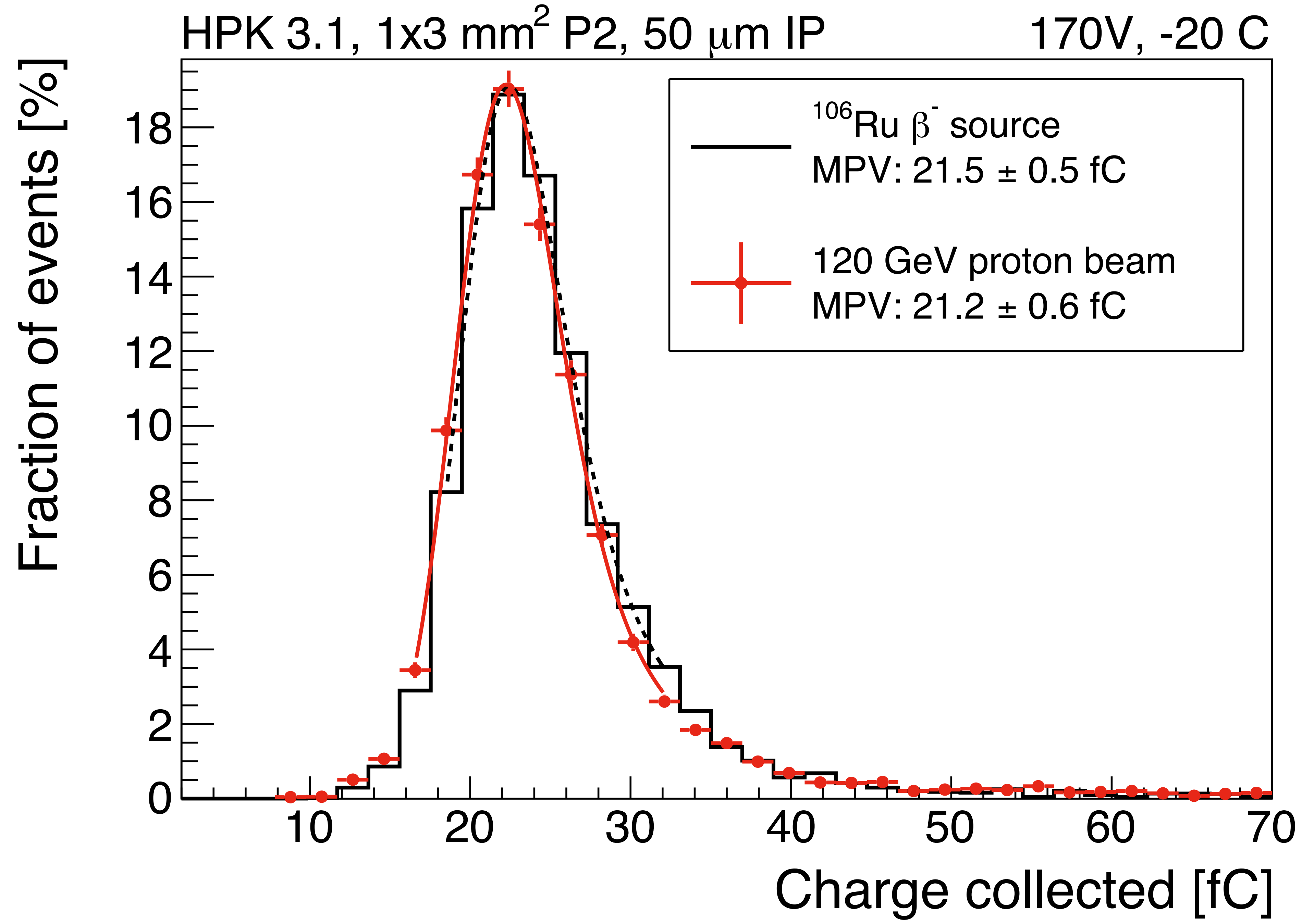


Beta source: MIP signal available 365 days a year!

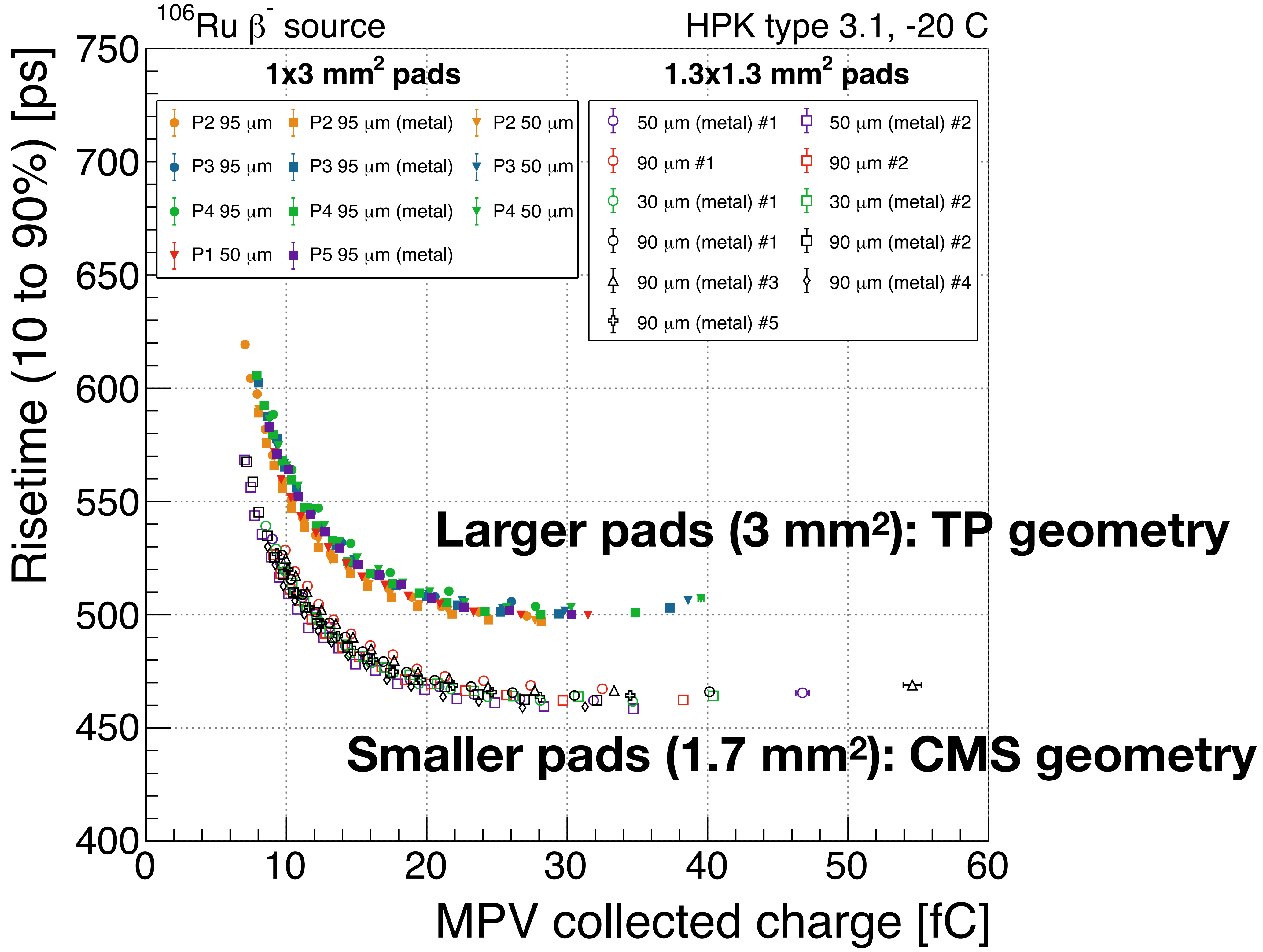
LGAD sensor characterization

- Leverage diverse set of characterization facilities
  1. Fermilab test beam (120 GeV protons): highly detailed information; limited sensor statistics
  2. Beta source: high volume testing with MIP signal

Detailed validation of beta source results with beam data.



Deep understanding of dozens of sensors with beta source

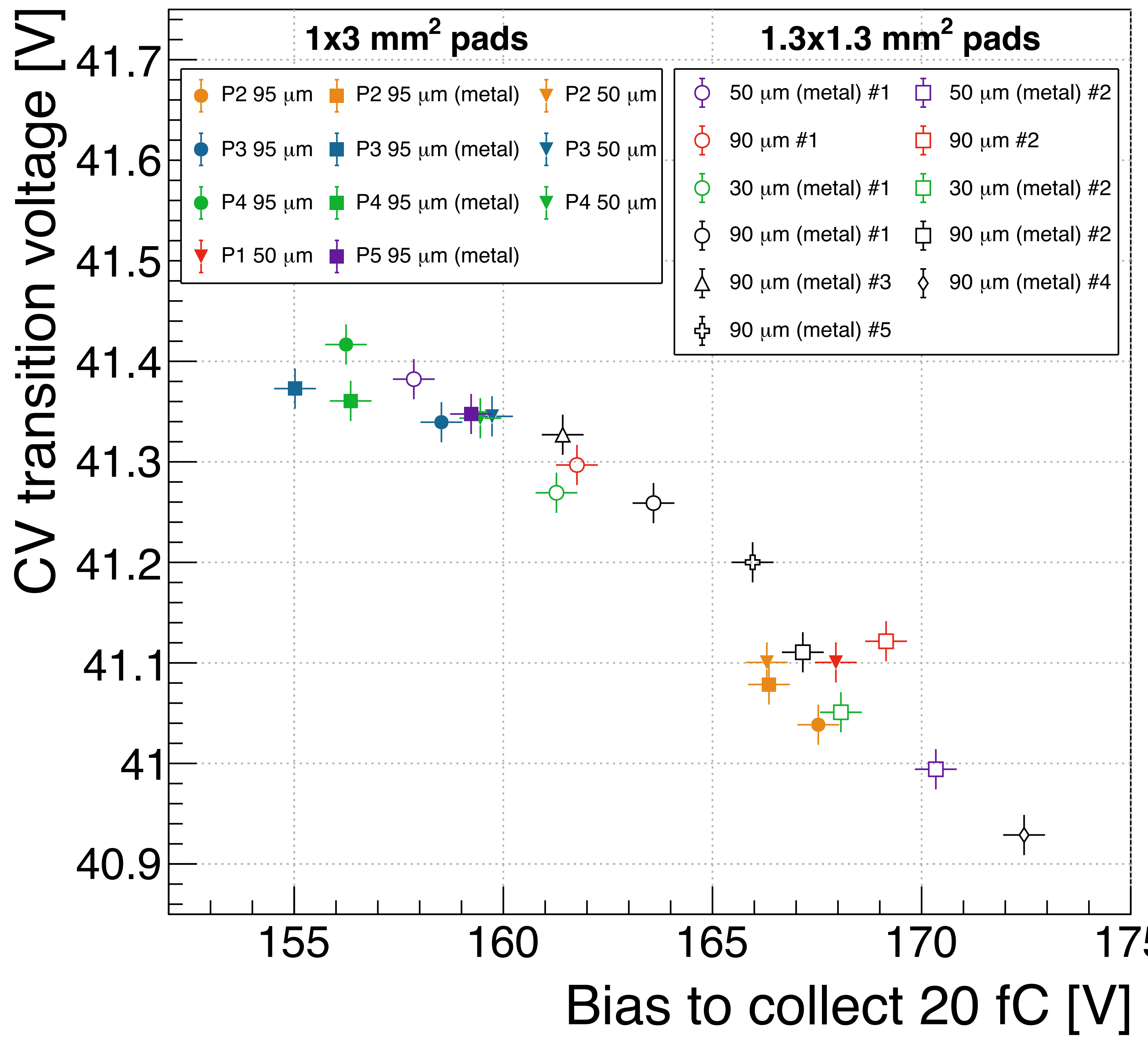


Beta source: MIP signal available 365 days a year!

fermilab

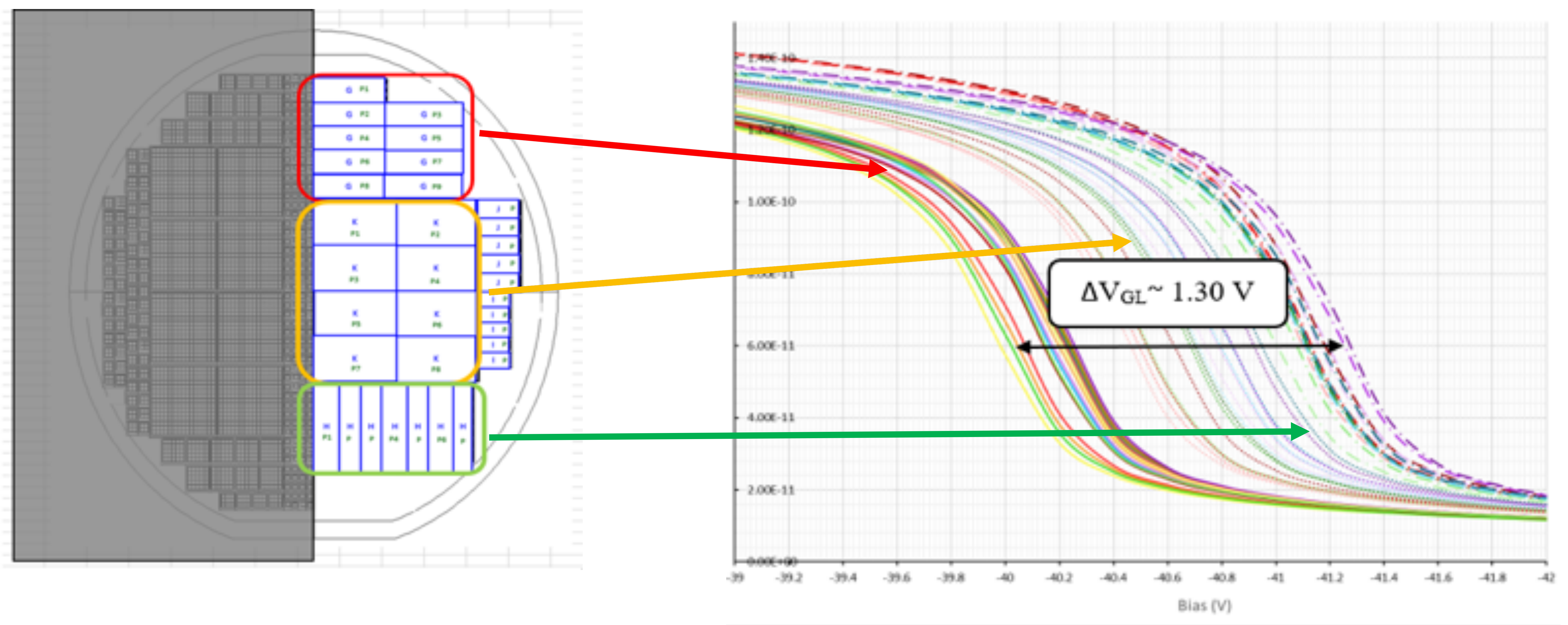
LGAD sensor characterization

- Leverage diverse set of characterization facilities
  1. Fermilab test beam (120 GeV protons): highly detailed information; limited sensor statistics
  2. Beta source: high volume testing with MIP signal
  3. Probe station CV: wafer-scale uniformity studies



Accurately predict MIP response from probe station

Probe measurements for sensors across wafer

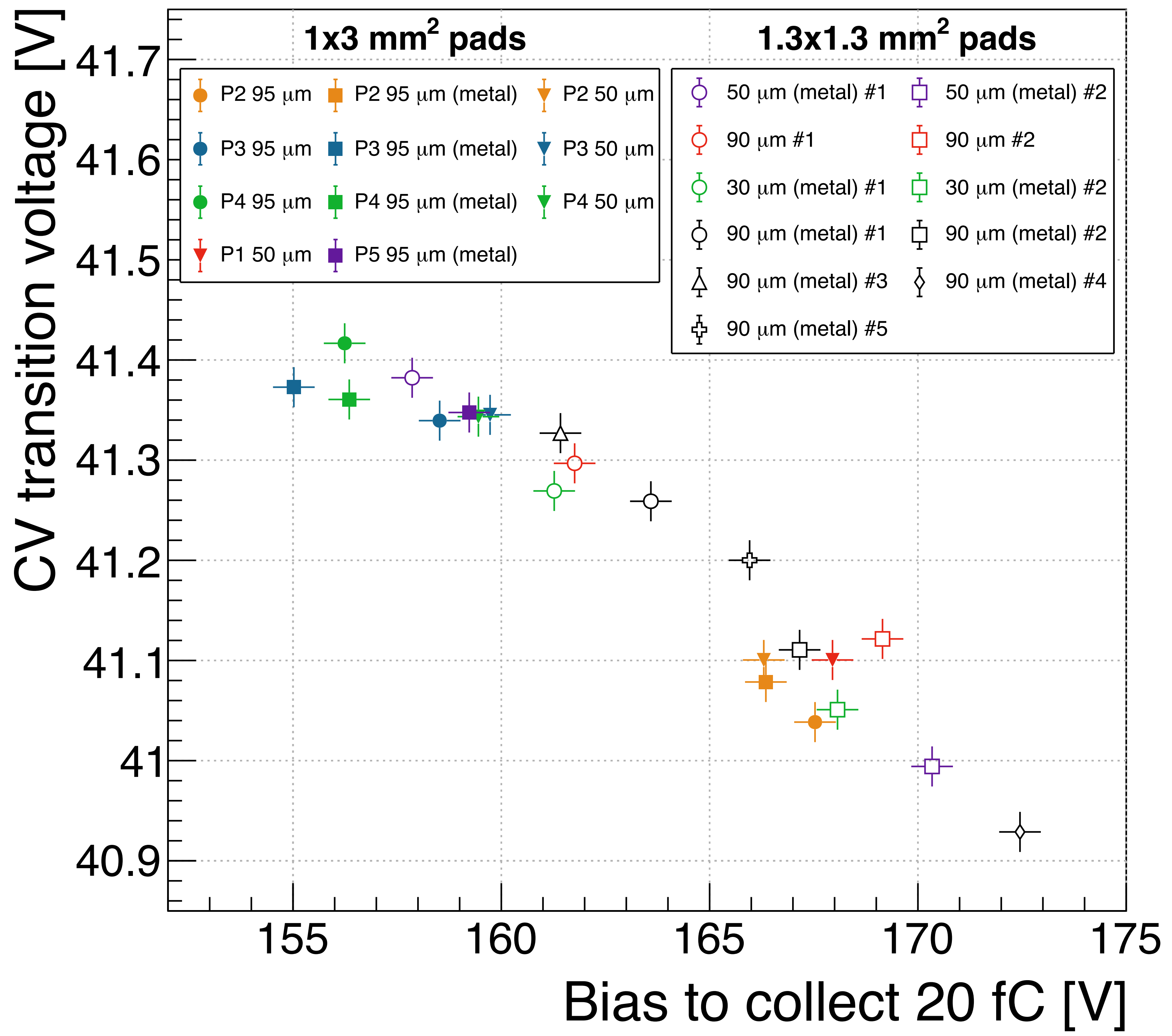


Easily characterize wafer uniformity: essential for QA/QC

More results in arXiv 2104.08369

LGAD sensor characterization

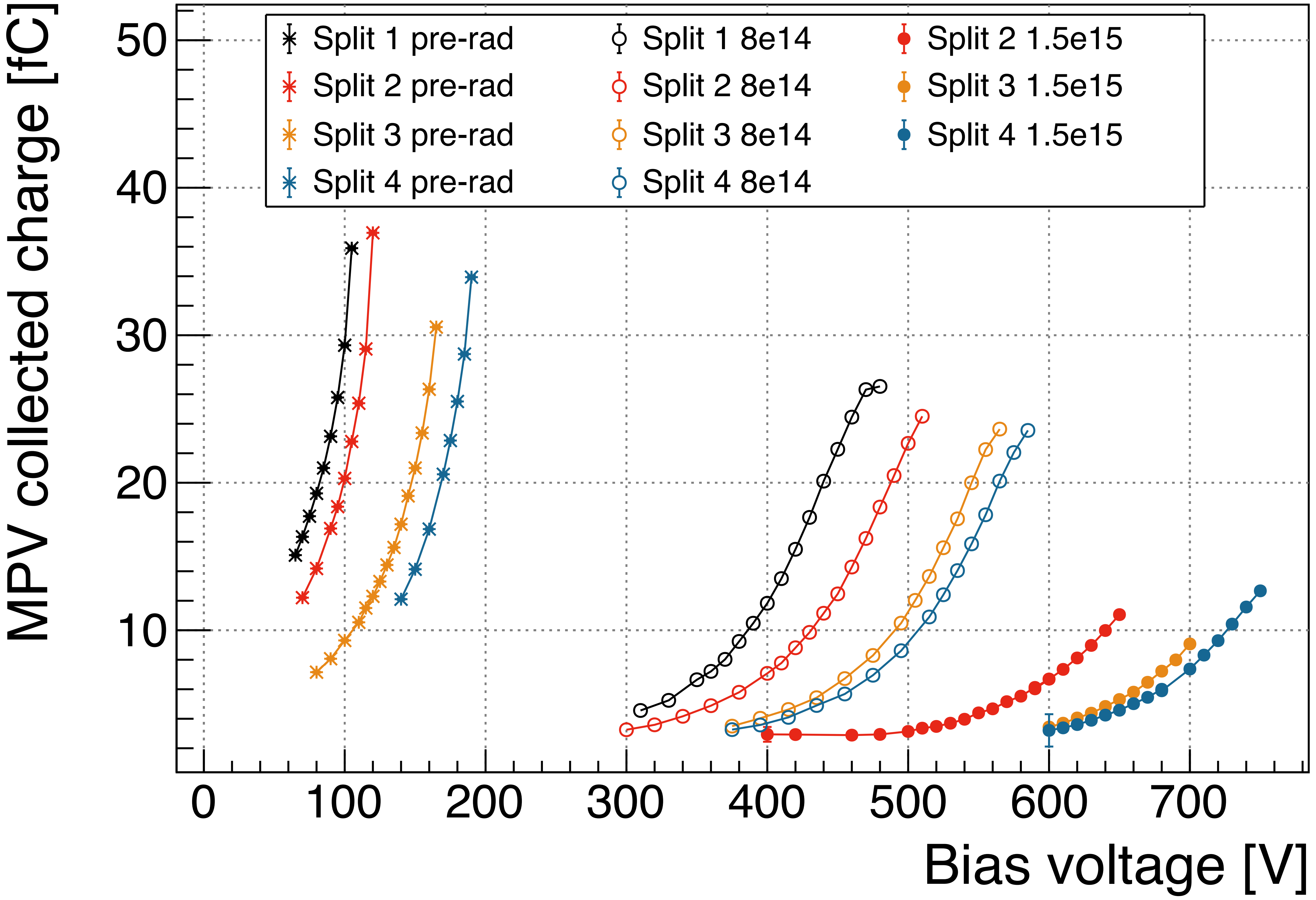
- Leverage diverse set of characterization facilities
  1. Fermilab test beam (120 GeV protons): highly detailed information; limited sensor statistics
  2. Beta source: high volume testing with MIP signal
  3. Probe station CV: wafer-scale uniformity studies

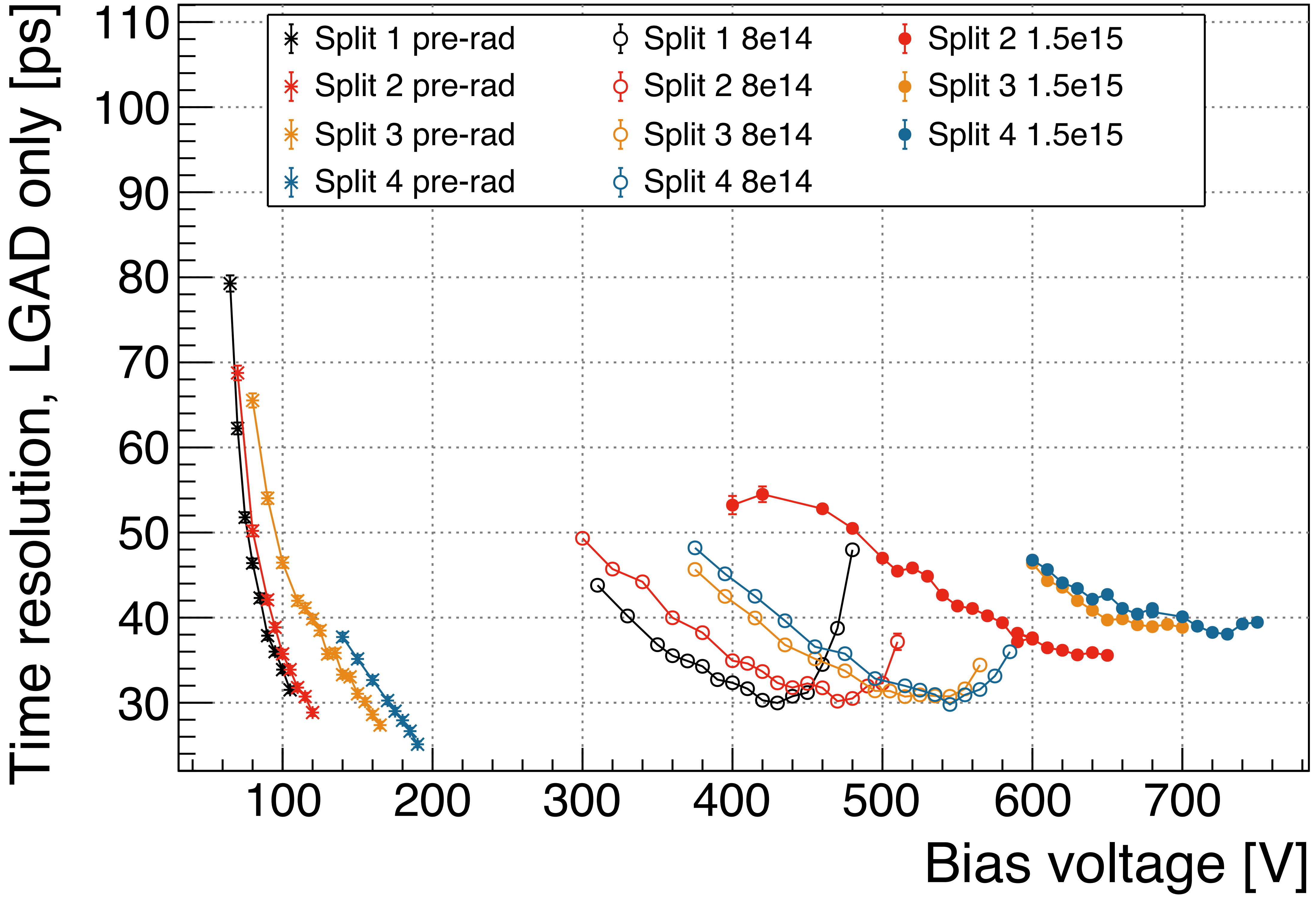


Accurately predict MIP response from probe station

LGAD radiation tolerance

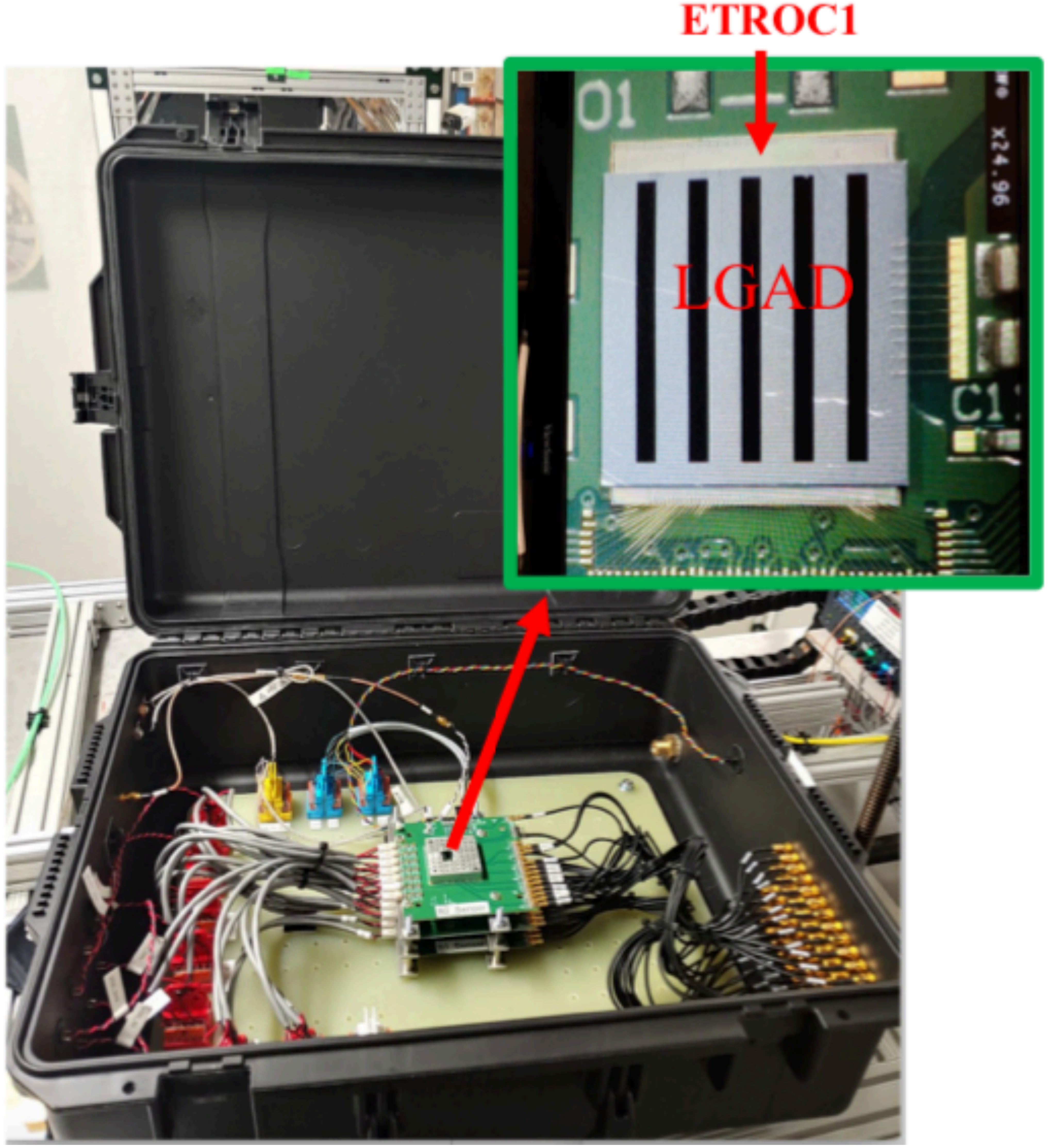
- Increase bias voltage to maintain gain after irradiation
- Radiation tolerance in latest prototypes: keep 40 ps resolution to end of life.



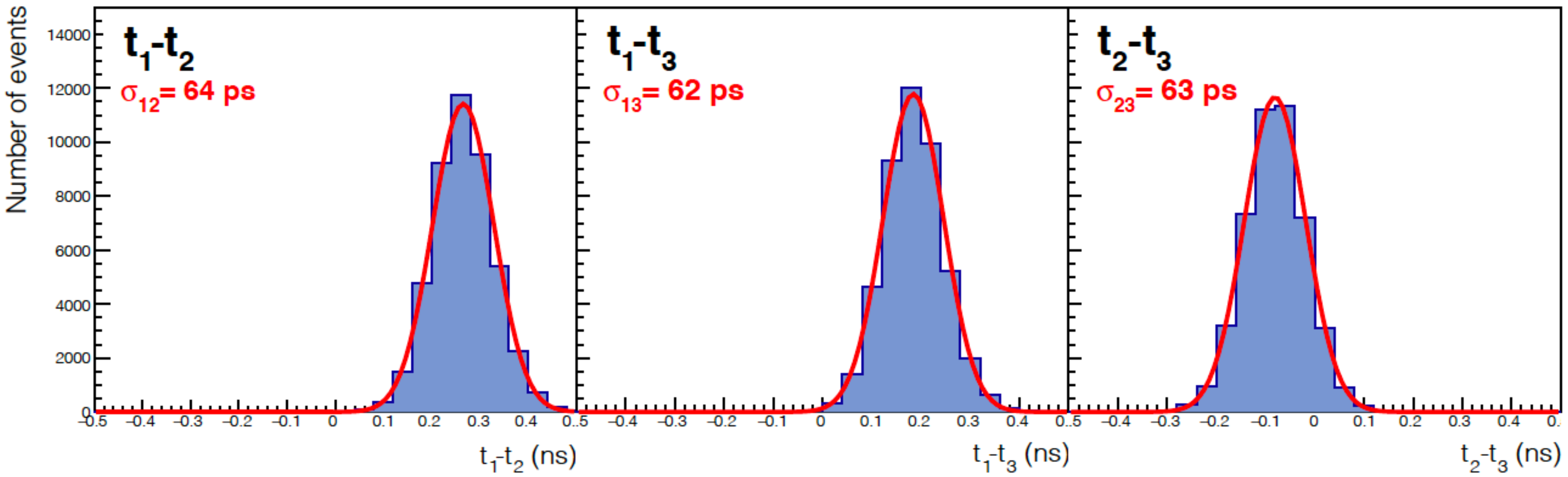


Fermilab

ETROC ASIC prototyping



- Timing measurement performed by ETROC ASIC (ToA + ToT correction)
- Preliminary test beam results with LGAD and ETROC1 prototype: **σ = 42-46 ps**



Extract single-layer resolution from 3-layer ΔT:

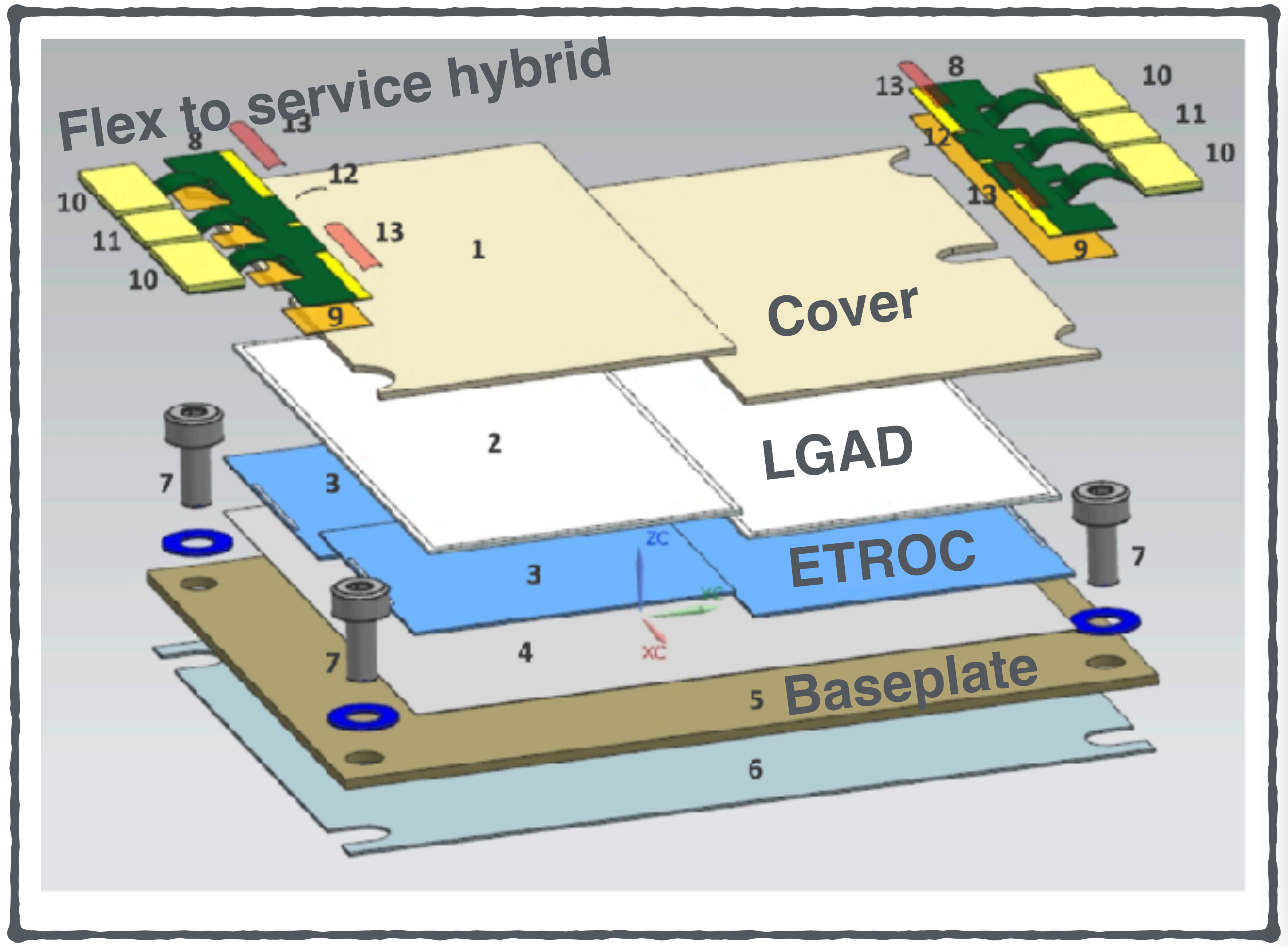
$$\sigma_i = \sqrt{0.5 \cdot \left(\sigma_{ij}^2 + \sigma_{ik}^2 - \sigma_{jk}^2\right)}$$

Fermilab

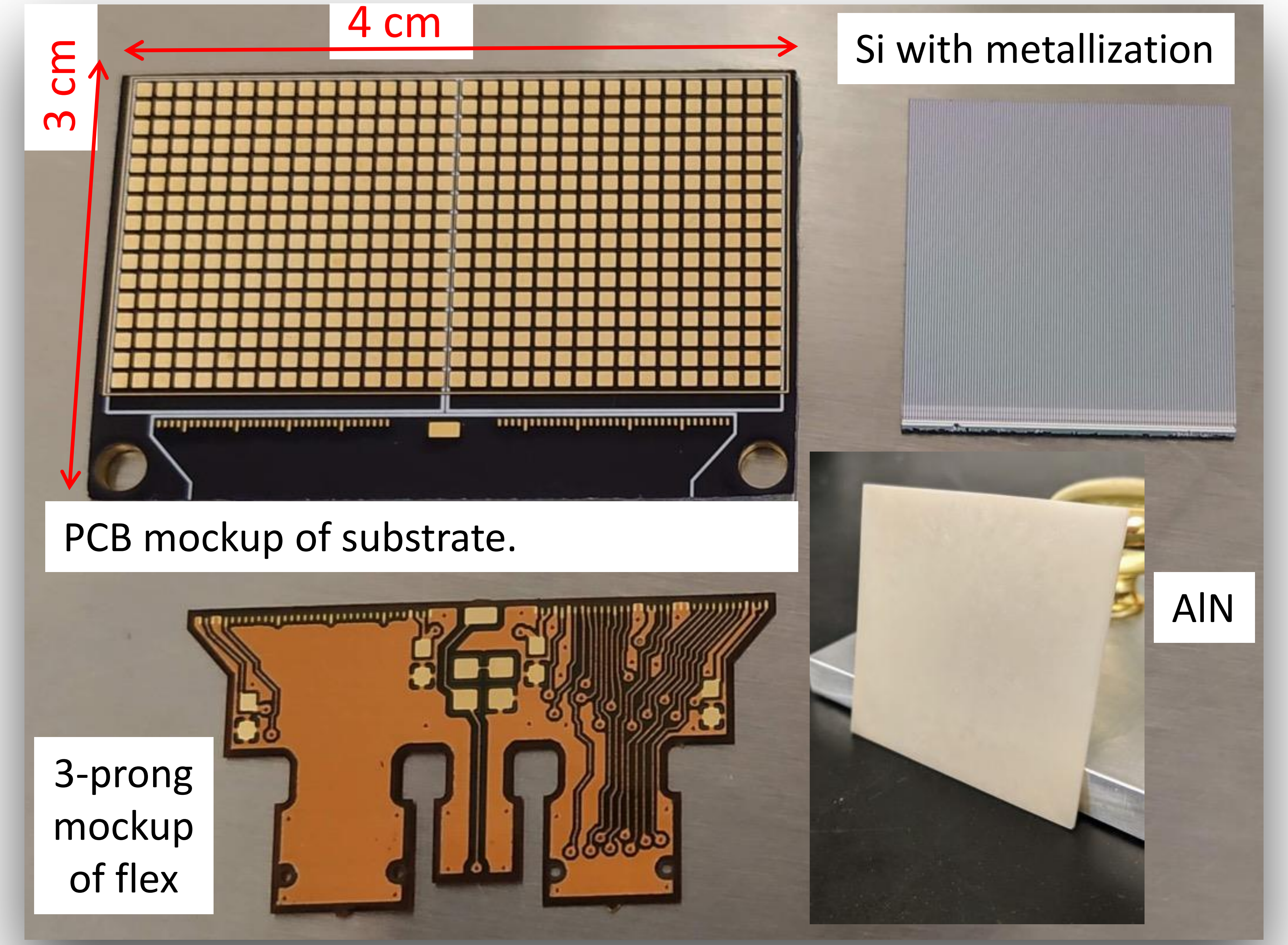
ETL modules

- Intense activity in module prototyping & development of assembly procedures

Module schematic

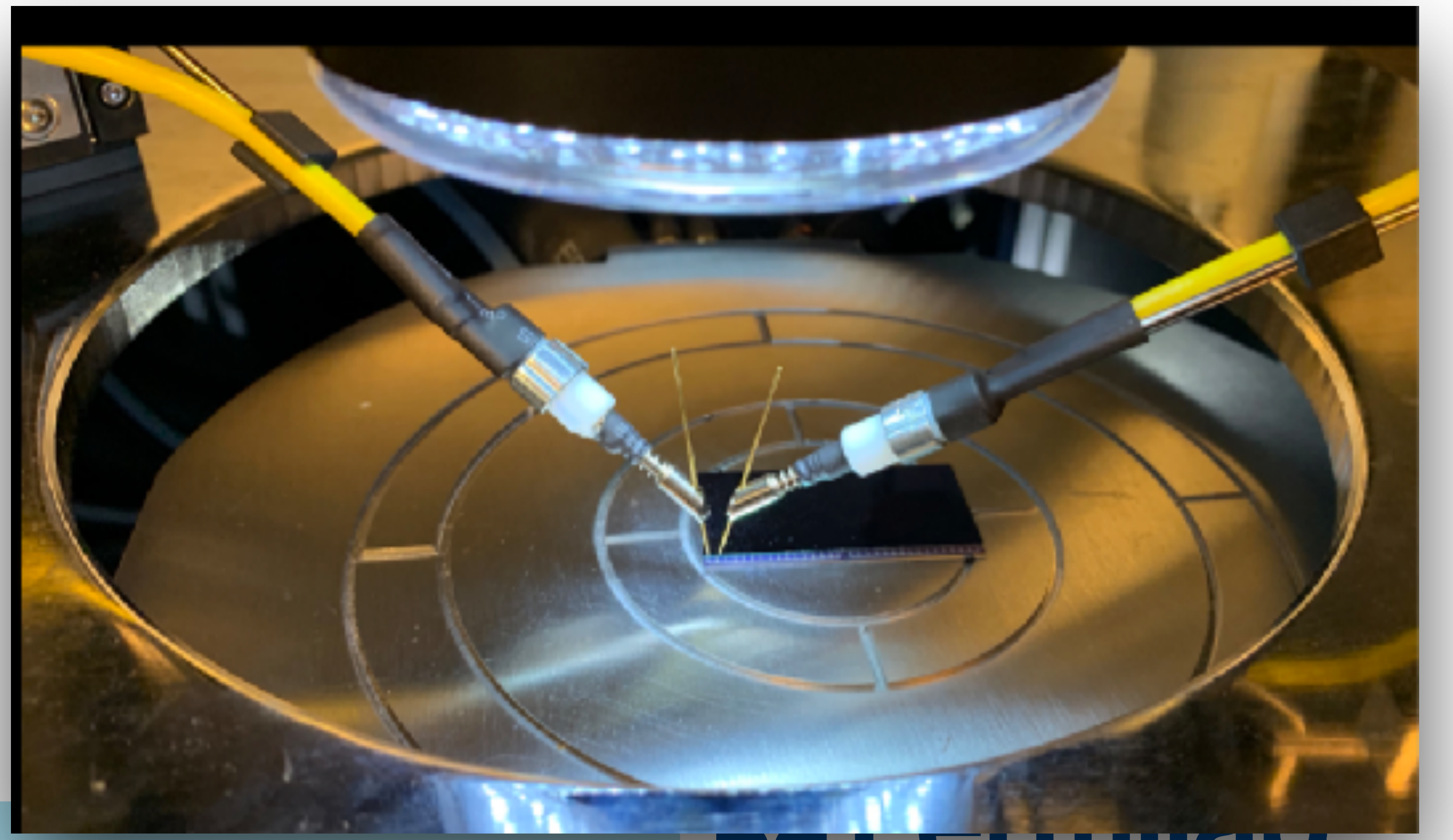


Mockups for thermal & mechanical testing



Assembly via jig or gantry

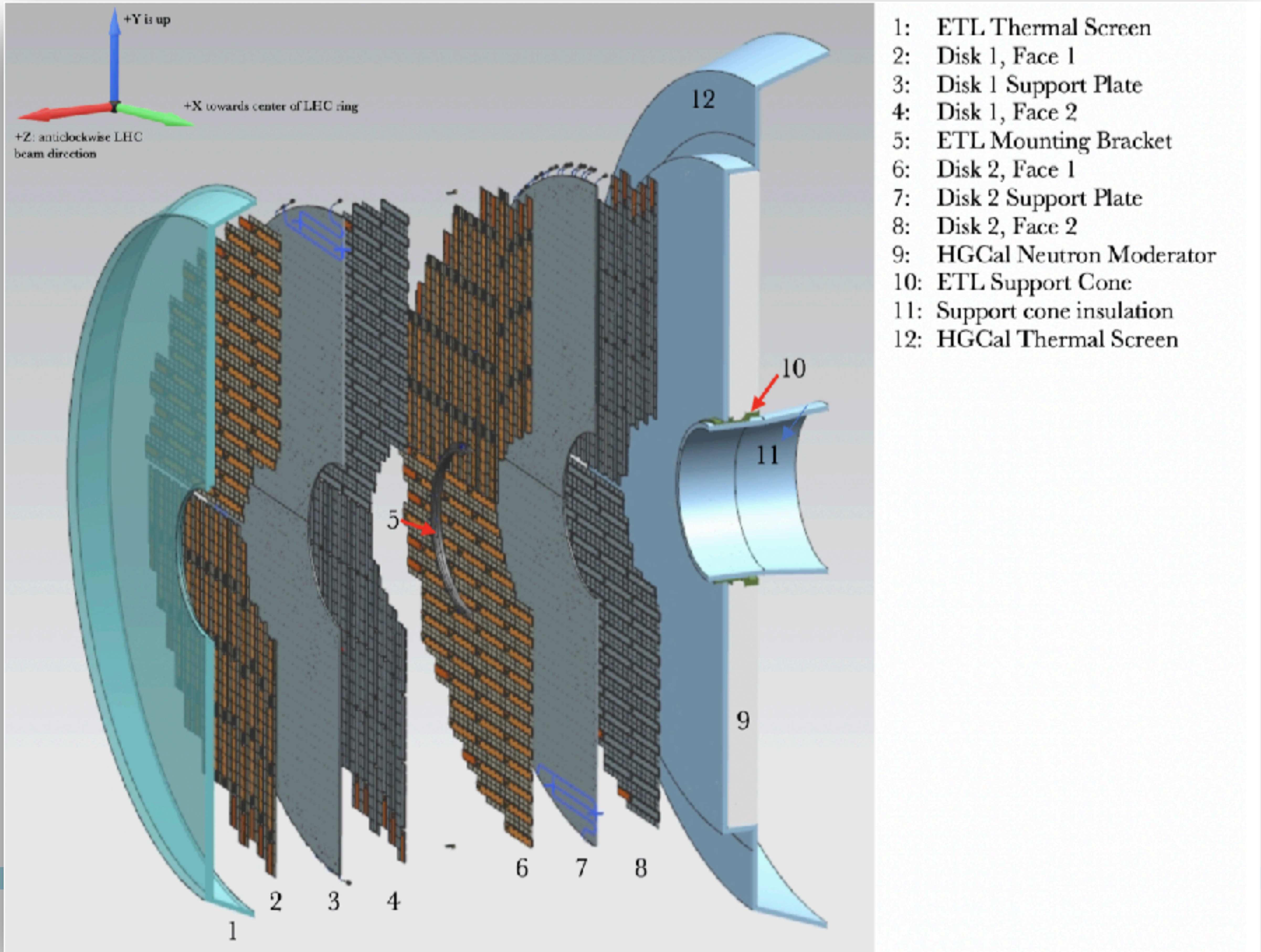
Bump-bonding prototypes



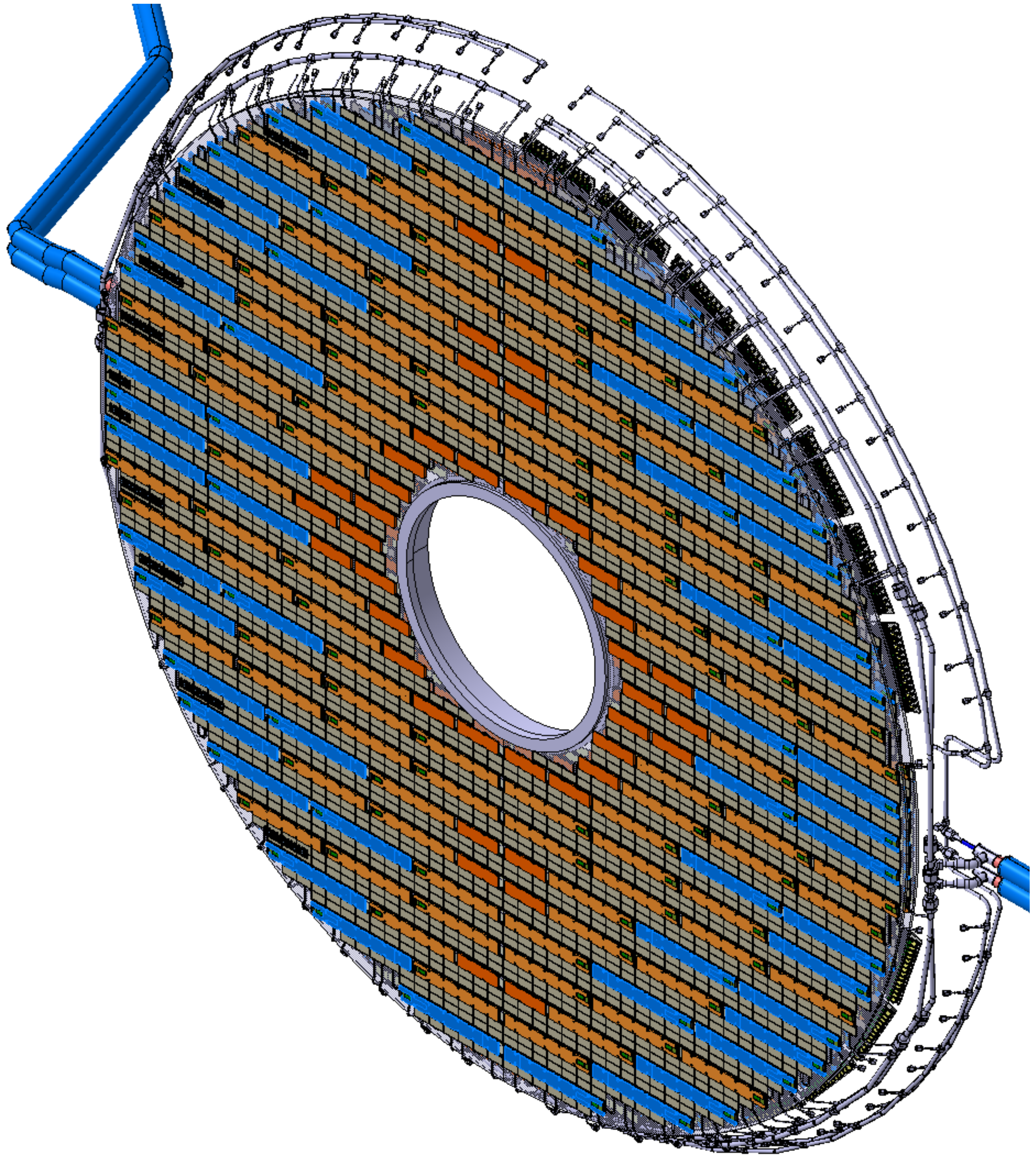
Endcap Timing Layer

- Attach modules to service hybrids; assemble into D's
- 2 disks at each endcap: 2 hits per track.
  - Single-hit resolution < 50 ps → track resolution < 35 ps.

ETL 2-disk stack



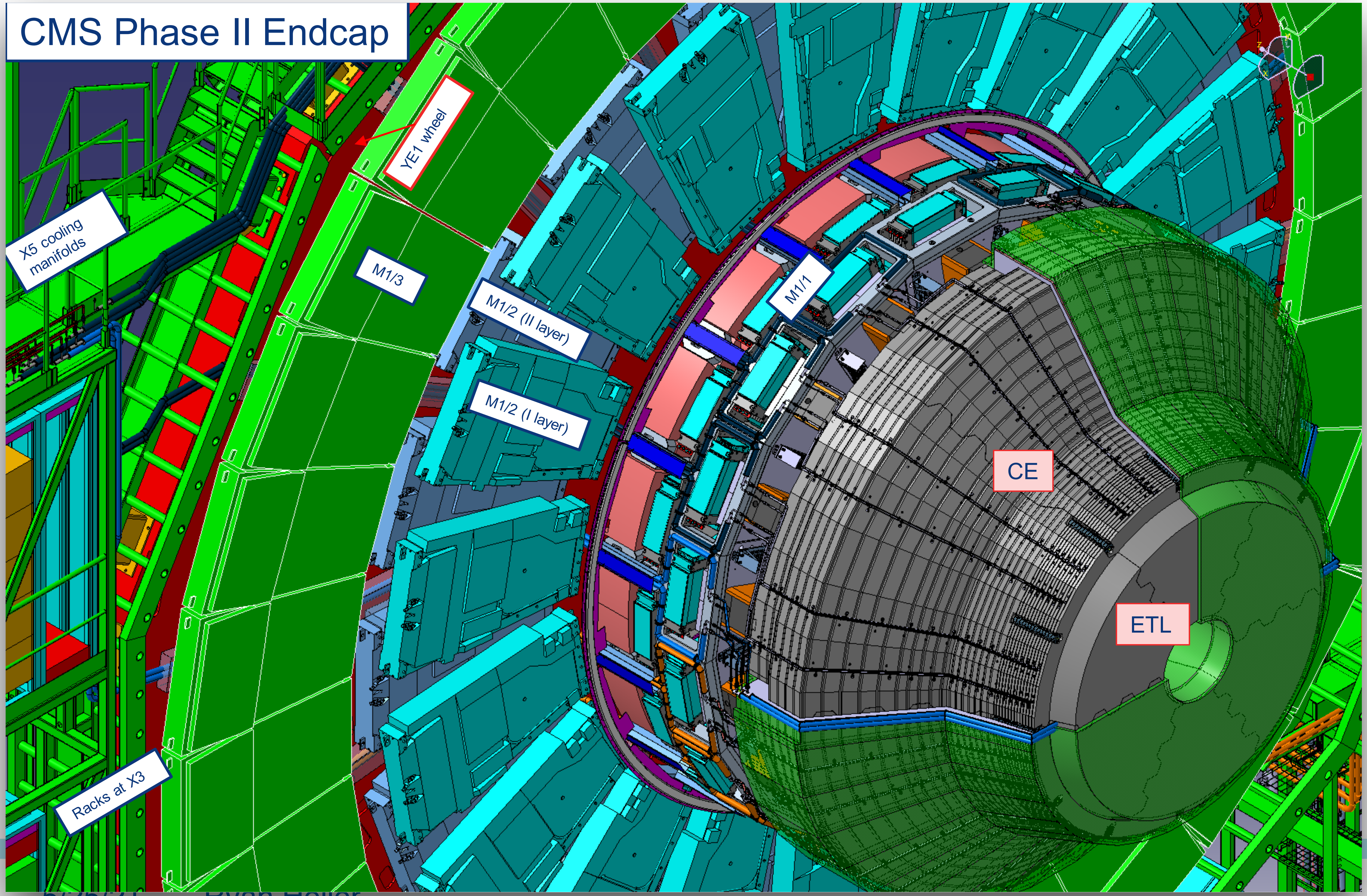
One endcap (2-layer)



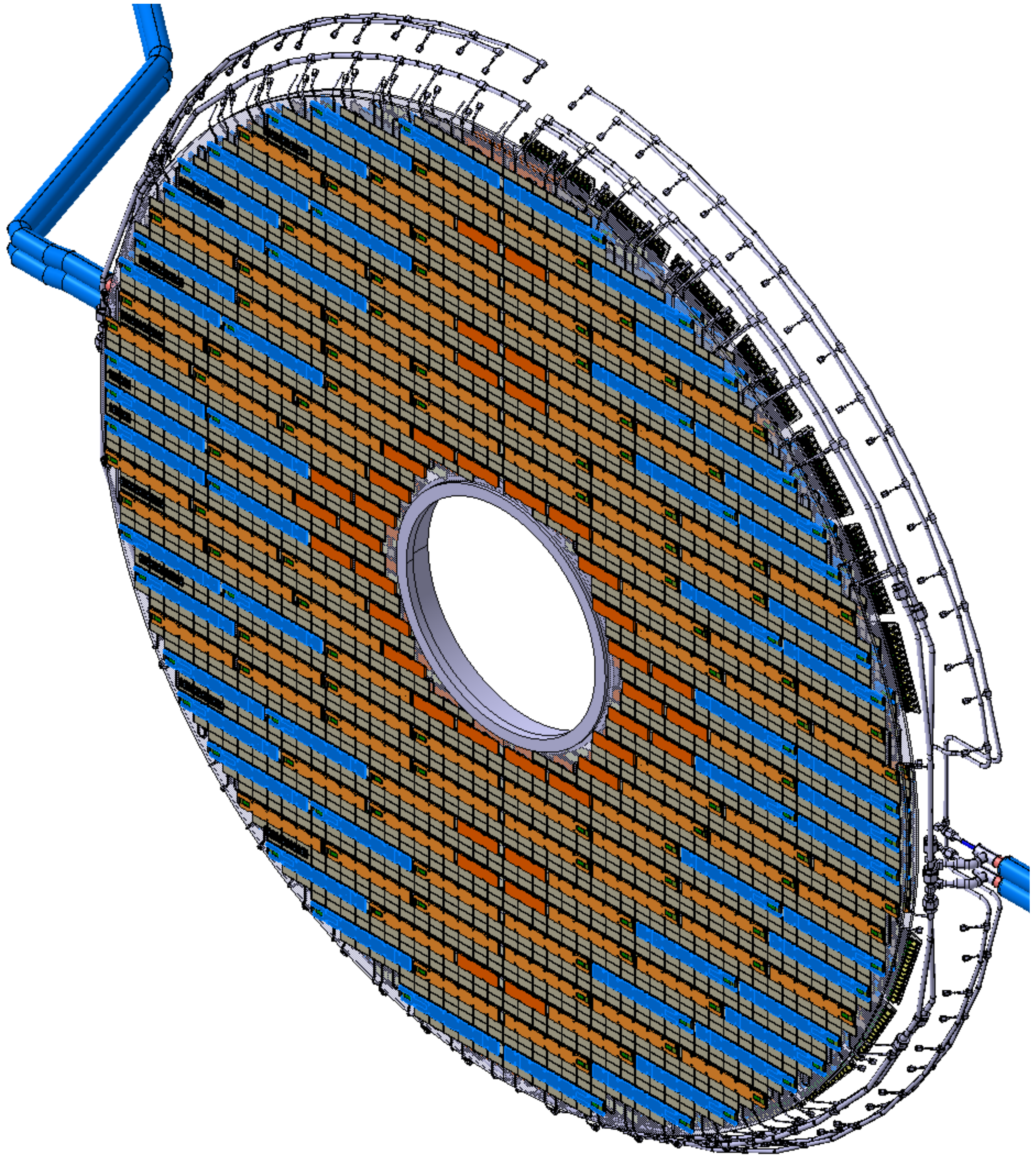
Fermilab

Endcap Timing Layer

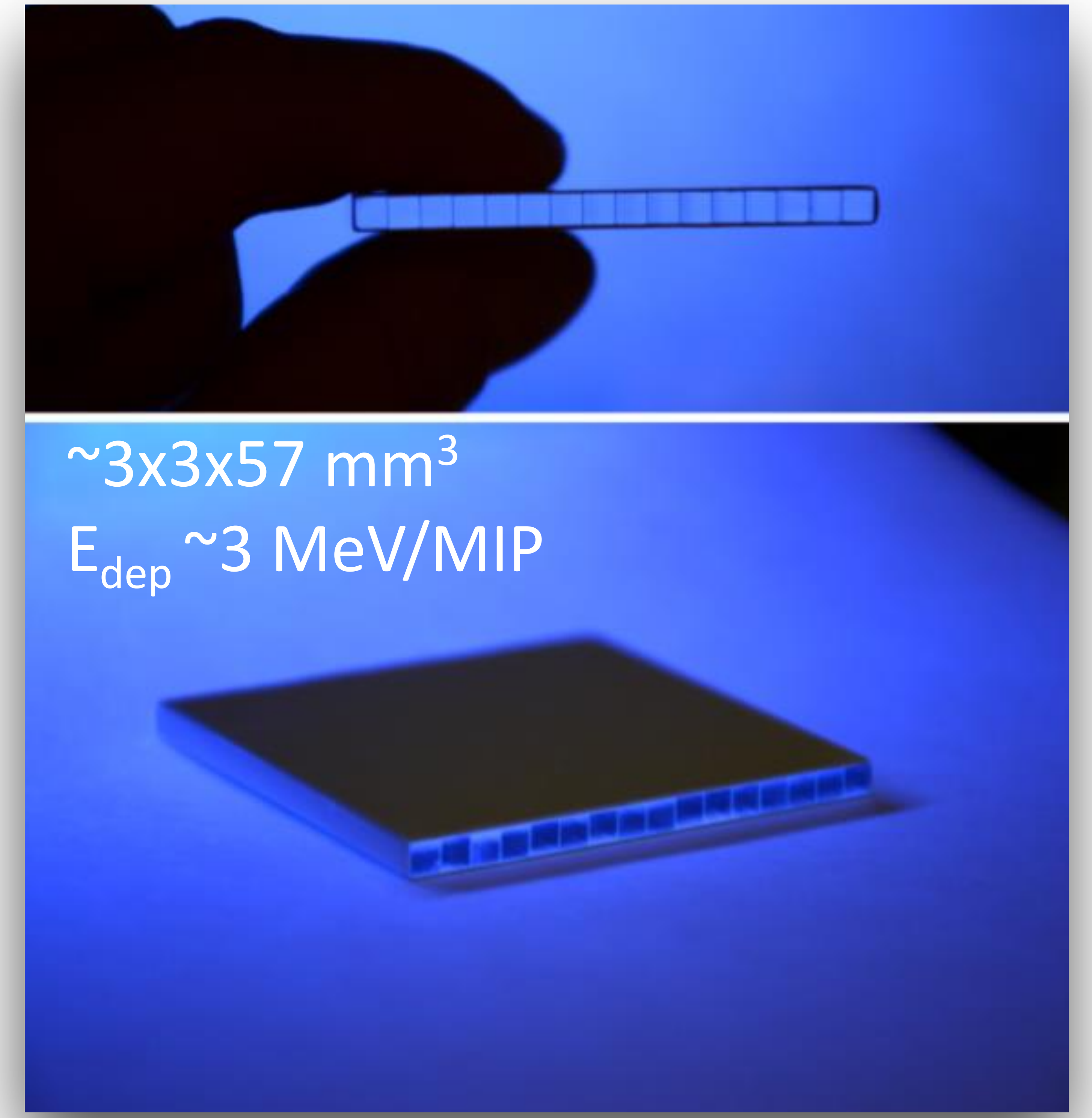
- Attach modules to service hybrids; assemble into D's
- 2 disks at each endcap: 2 hits per track.
  - Single-hit resolution < 50 ps → track resolution < 35 ps.

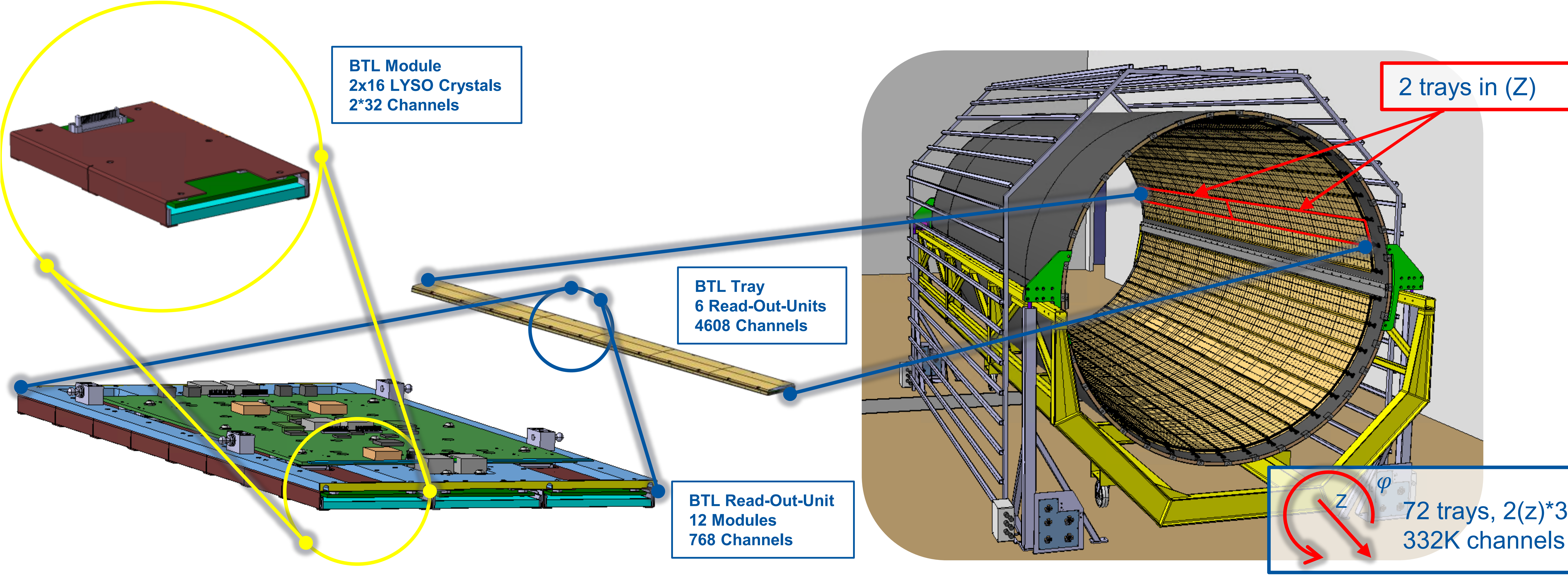


One endcap (2-layer)



Barrel Timing Layer (BTL) Overview



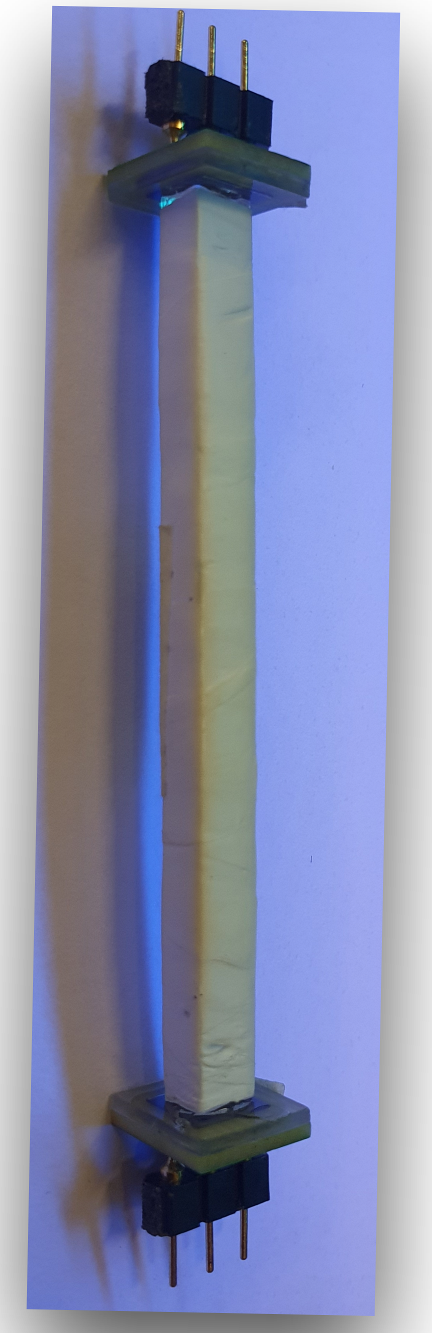


- LYSO crystal bars read by SiPMs at both ends
- Tracker/ECAL interface: ~40 mm
- Hermetic coverage for |η| < 1.45. Surface: 38 m², 332k channels

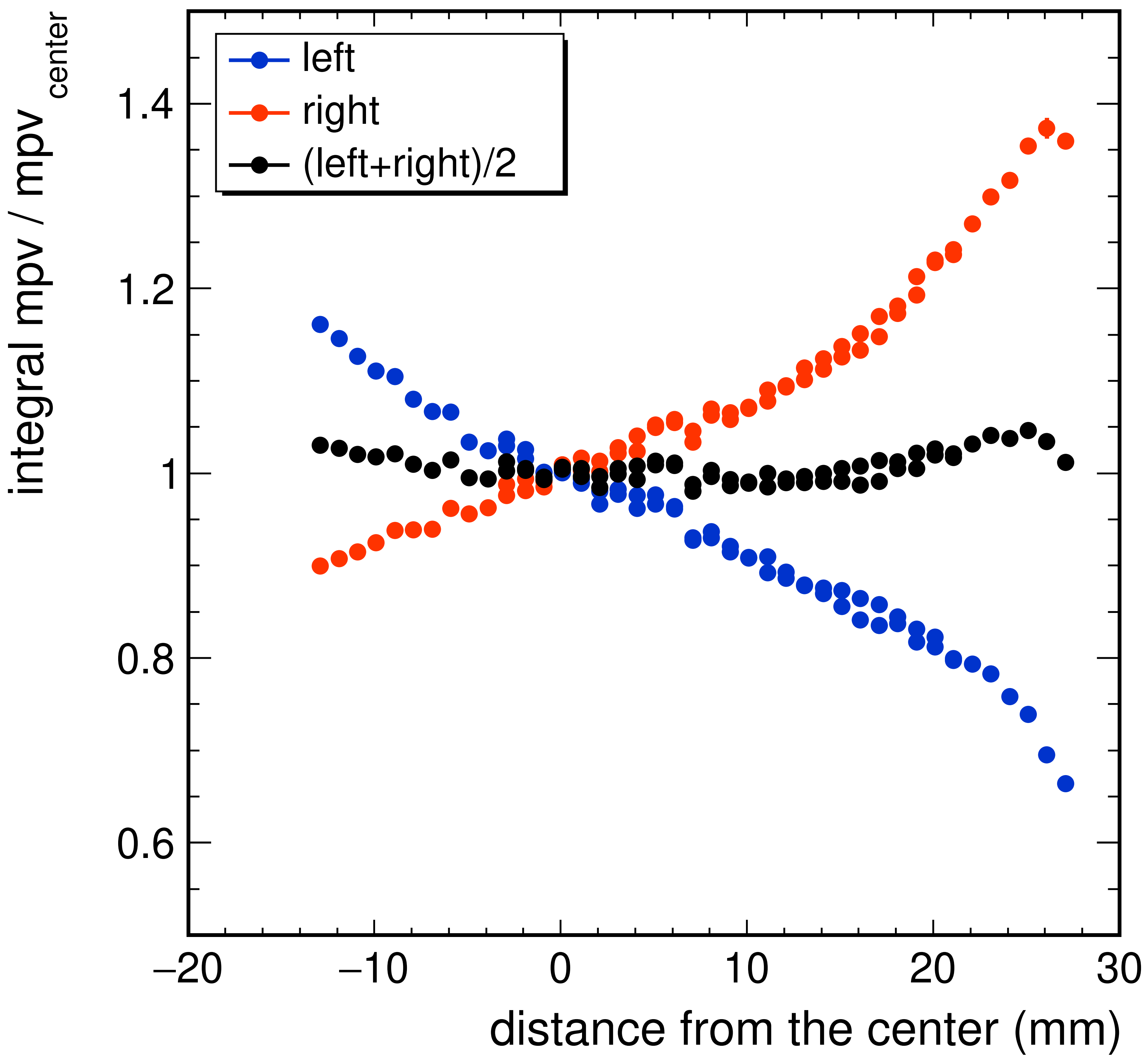
BTL sensor prototypes

- Extensive studies of sensor prototypes using Fermilab test beam
  - Manuscript under review at JINST: arXiv 2104.07786

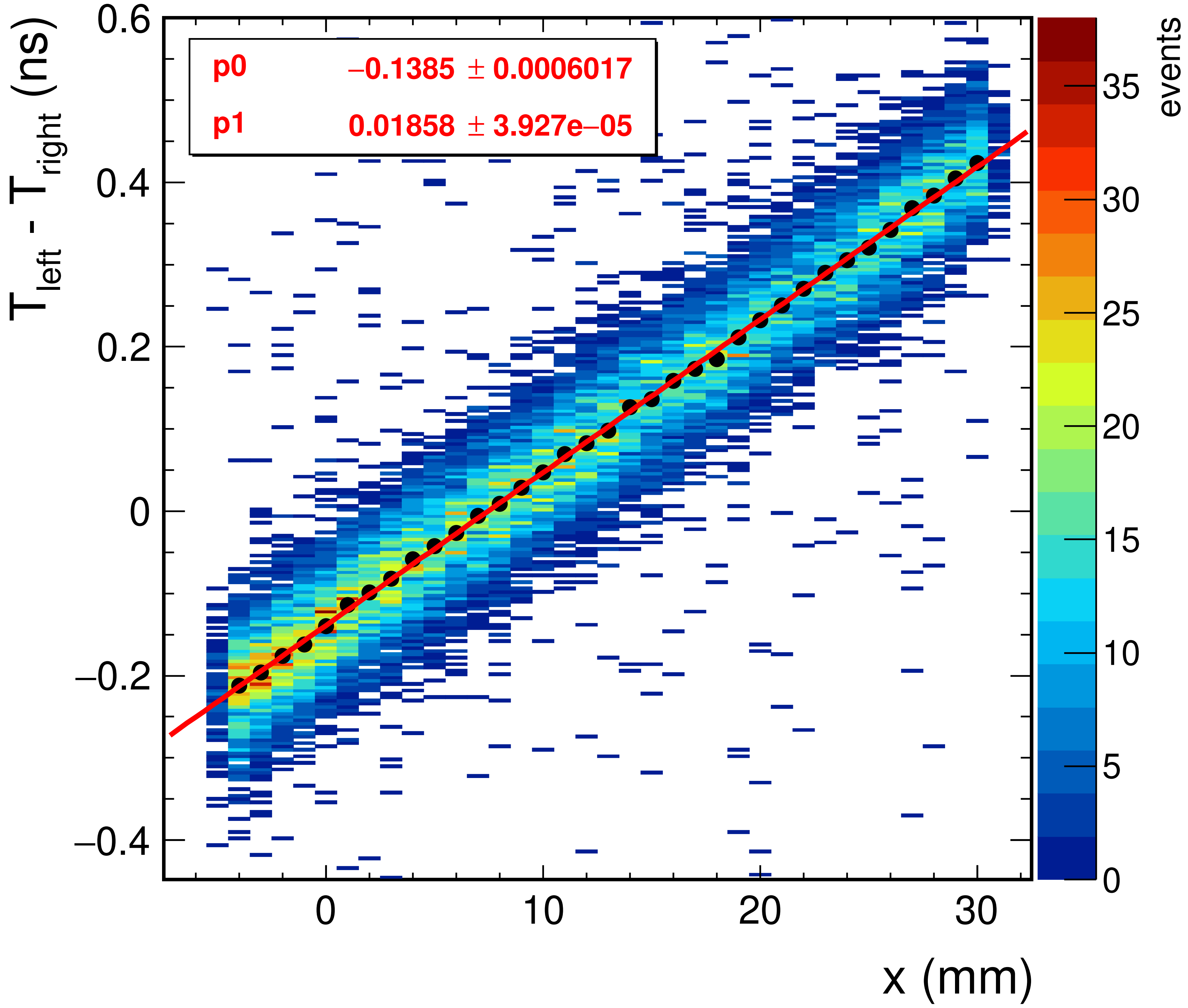
Single bar with 2x SiPMs



Amplitude response variation across bar



Left-right time difference



Double-ended readout → uniform response along 5.7 cm length

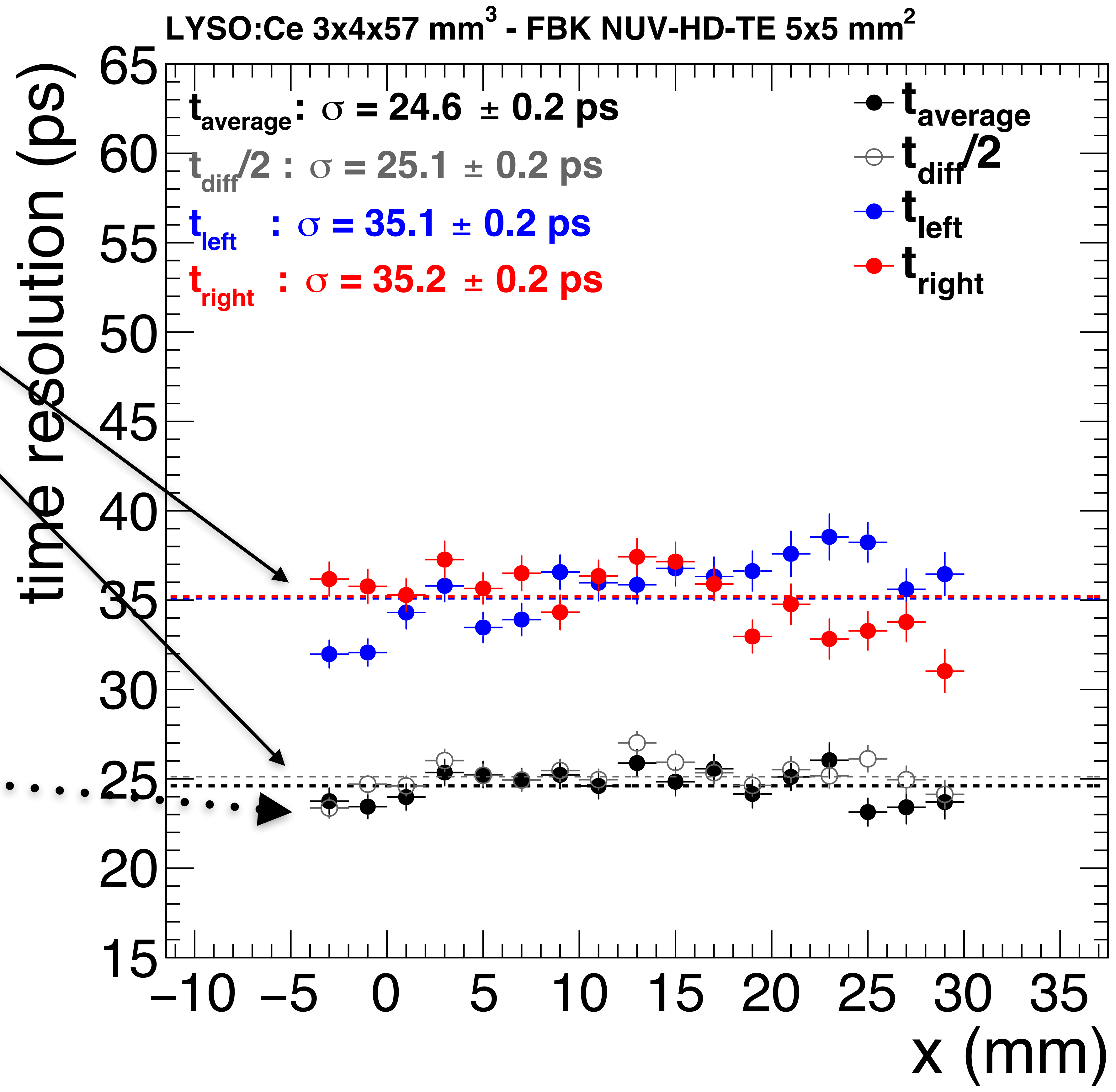
BTL sensor prototypes

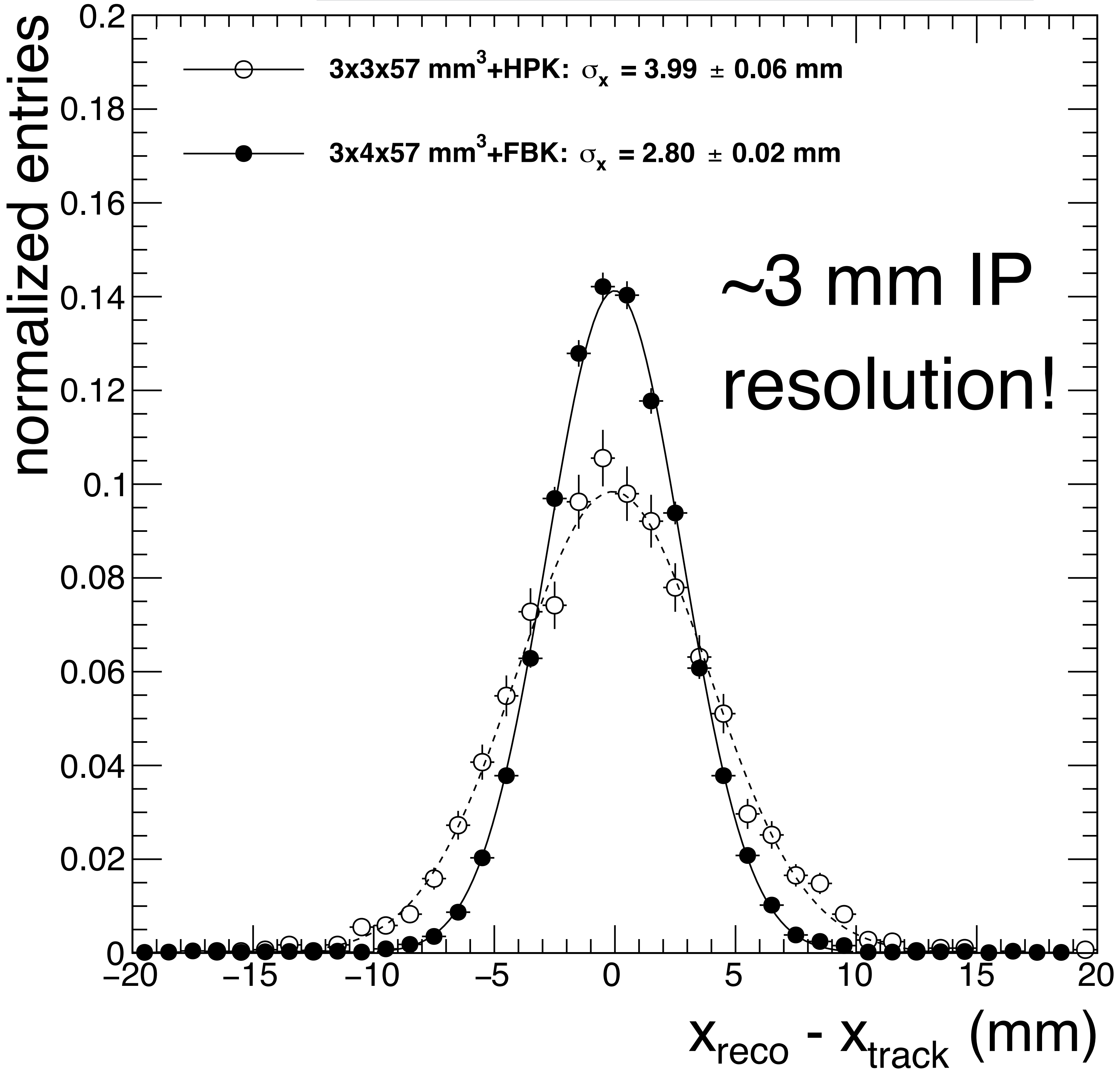
- Two-channel timestamp: uniform 25 ps resolution

Extract impact parameter from left-right ΔT!

ΔT vs 10 ps ref. (MCP): Gold standard

Left vs right ΔT:
- Monitor σ without ext. reference
- Check for correlated noise





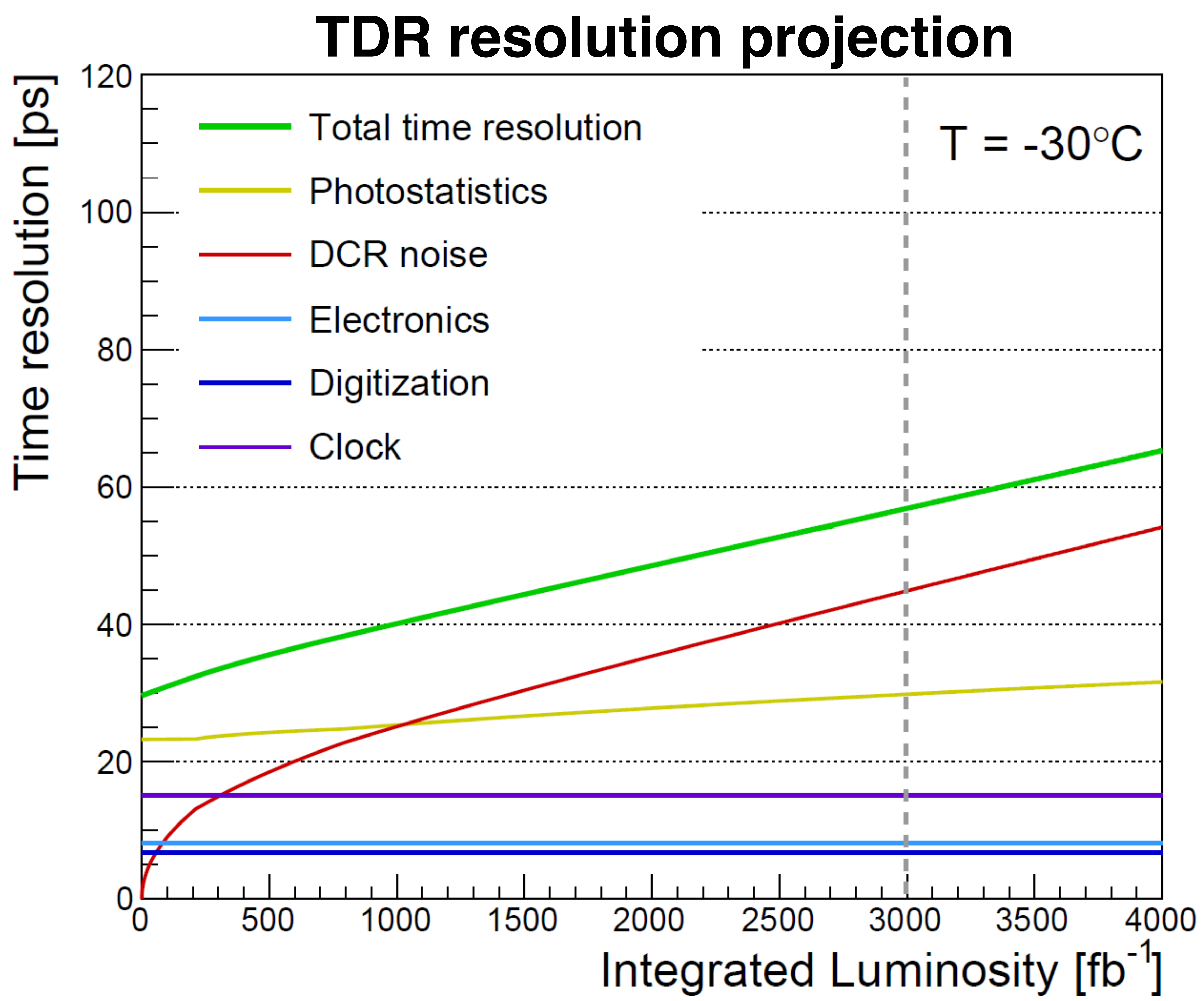
~3 mm IP resolution!

$$\frac{1}{2}\sigma_{t_{diff}} = \frac{1}{2}\sqrt{\sigma^2_{t_{left}} + \sigma^2_{t_{right}}} = \sigma_{t_{average}}$$

Double end readout provides rich set of information.

Many more results in paper: arXiv 2104.07786

BTL evolution with fluence

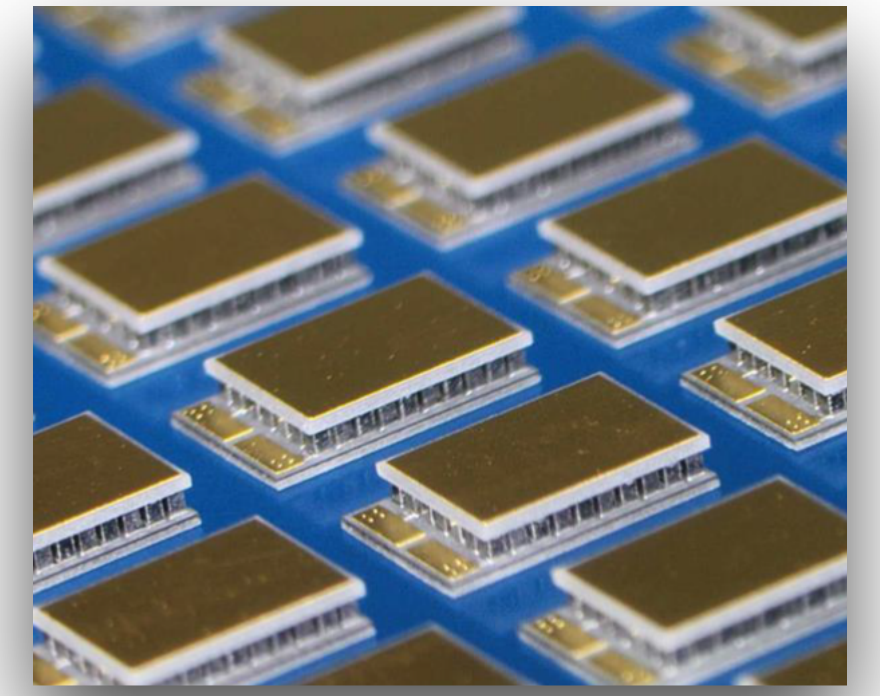


- Photostatistics dominates resolution at beginning of life
- SiPM dark rate becomes significant after irradiation—O(10 GHz)
- Key innovations to fight SiPM DCR:
  - Noise cancellation in ASIC (TOFHIR)
  - Clever thermal management

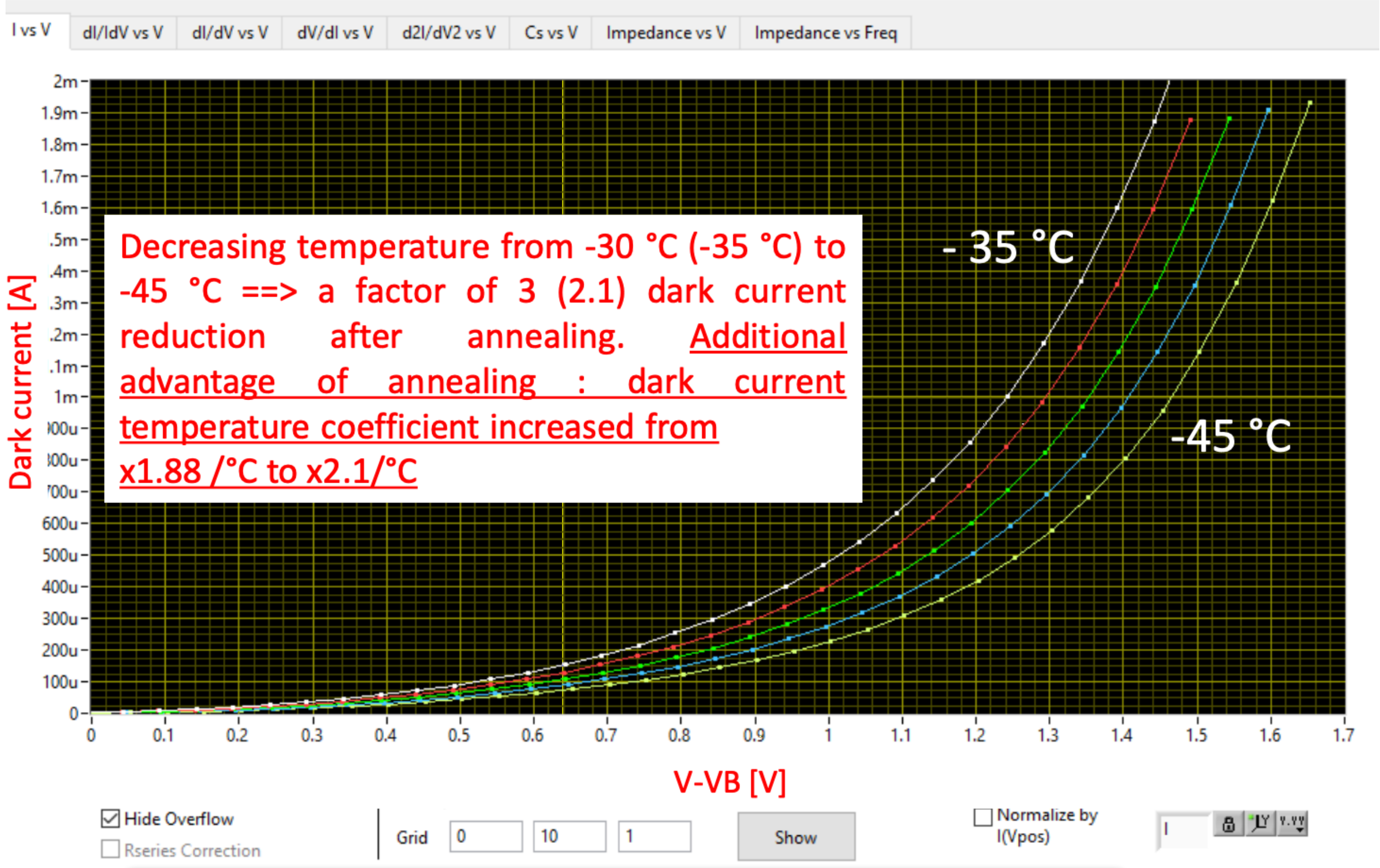
Thermal management with TECs

- BTL cooled by dual-phase CO_2 to reach -35 C
- Post-TDR: observe SiPM radiation damage larger than anticipated
- Compensate with thermoelectric coolers (TEC): <u>double advantage</u>
  - SiPM operating temp: -35 C → -45 C
  - Reverse operation: anneal at +40 C without heating tracker volume!

TECs (Peltier)

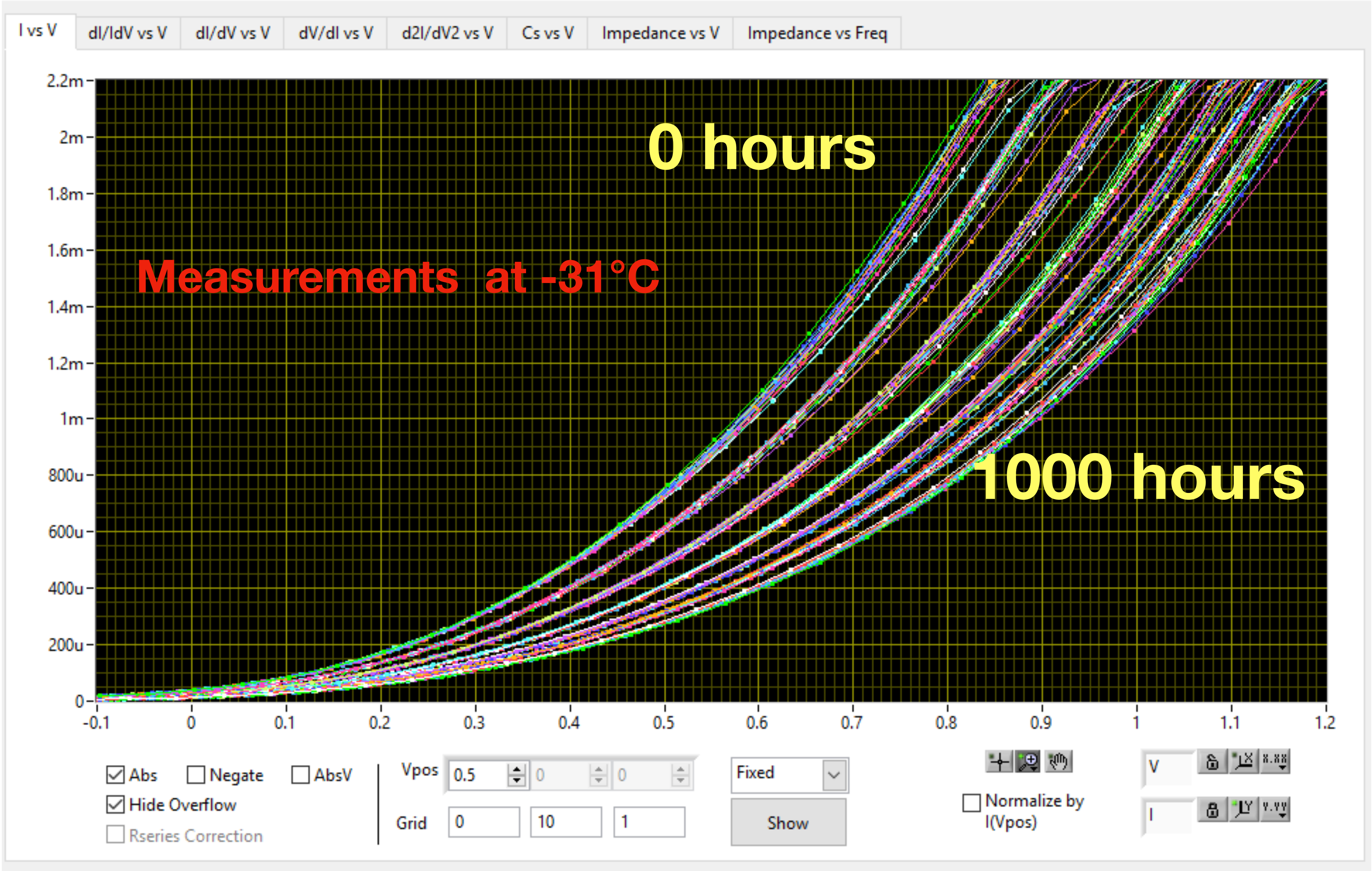


Dark current for -35 C vs -45 C



Half current → half noise.

Dark current after +40C annealing

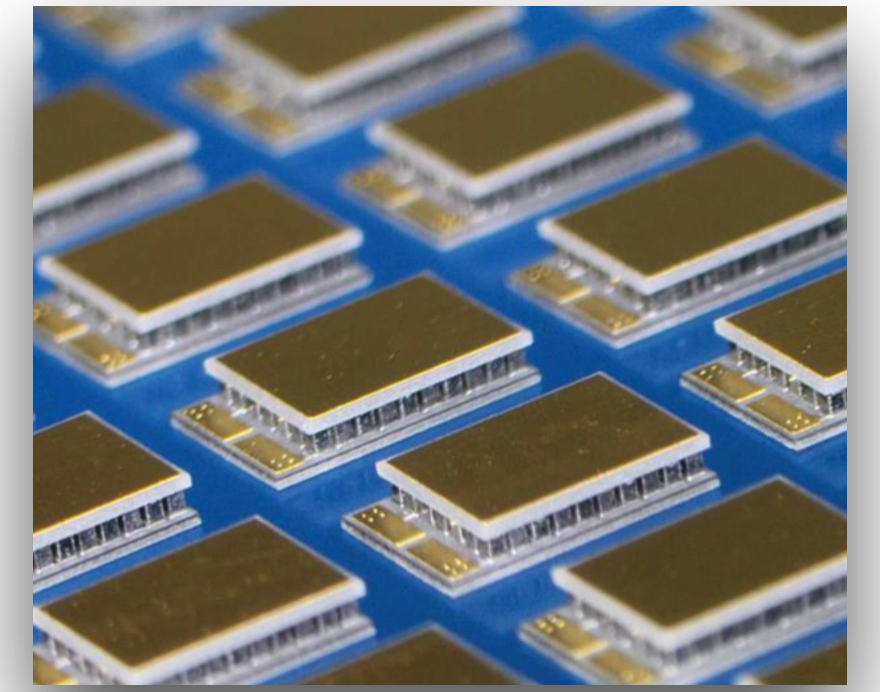


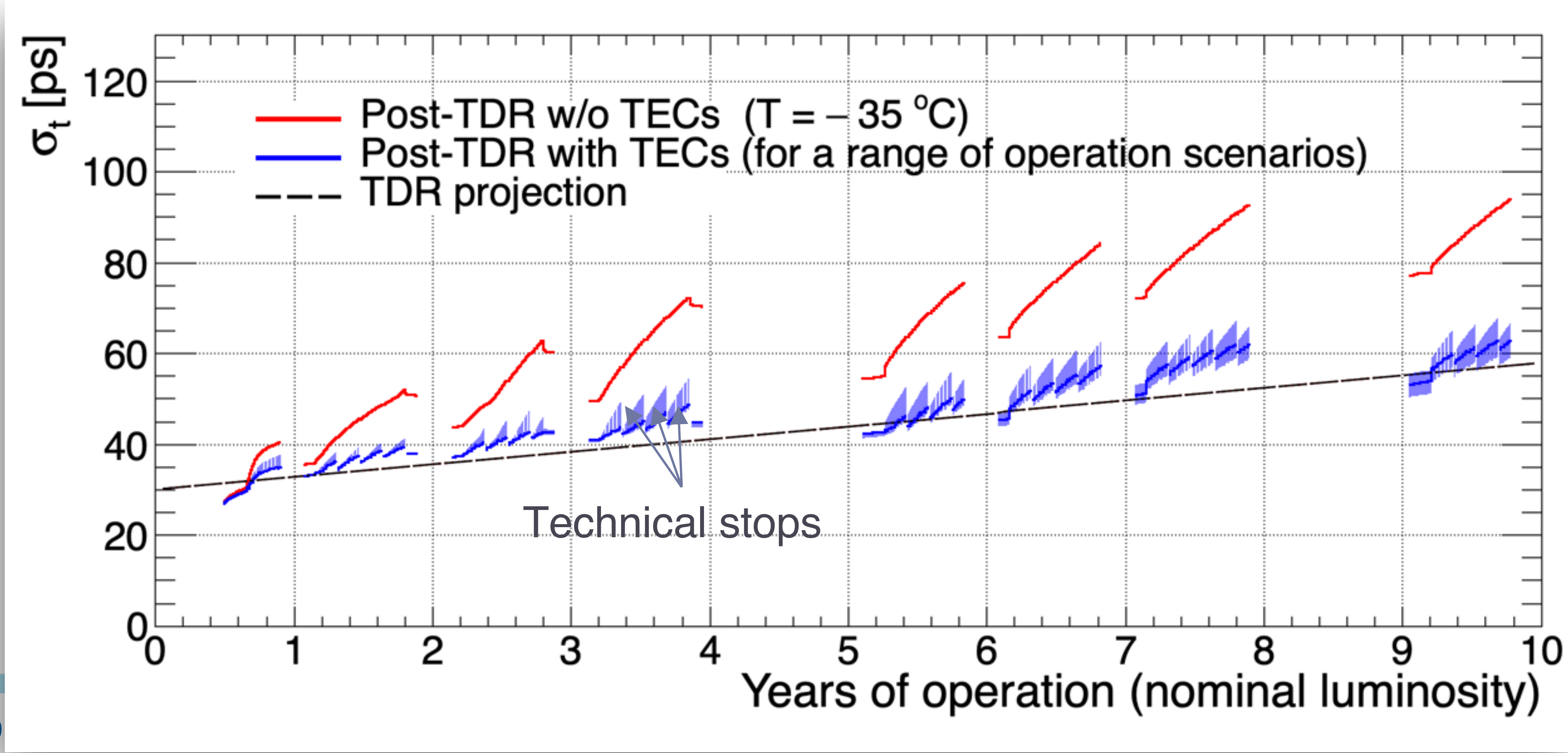
Periodic annealing: reduce noise by x2.5

Thermal management with TECs

- BTL cooled by dual-phase CO_2 to reach -35 C
- Thermoelectric coolers (TEC): double advantage
  - SiPM operating temp: -35 C → -45 C
  - Reverse operation: anneal at +40 C during shutdowns.

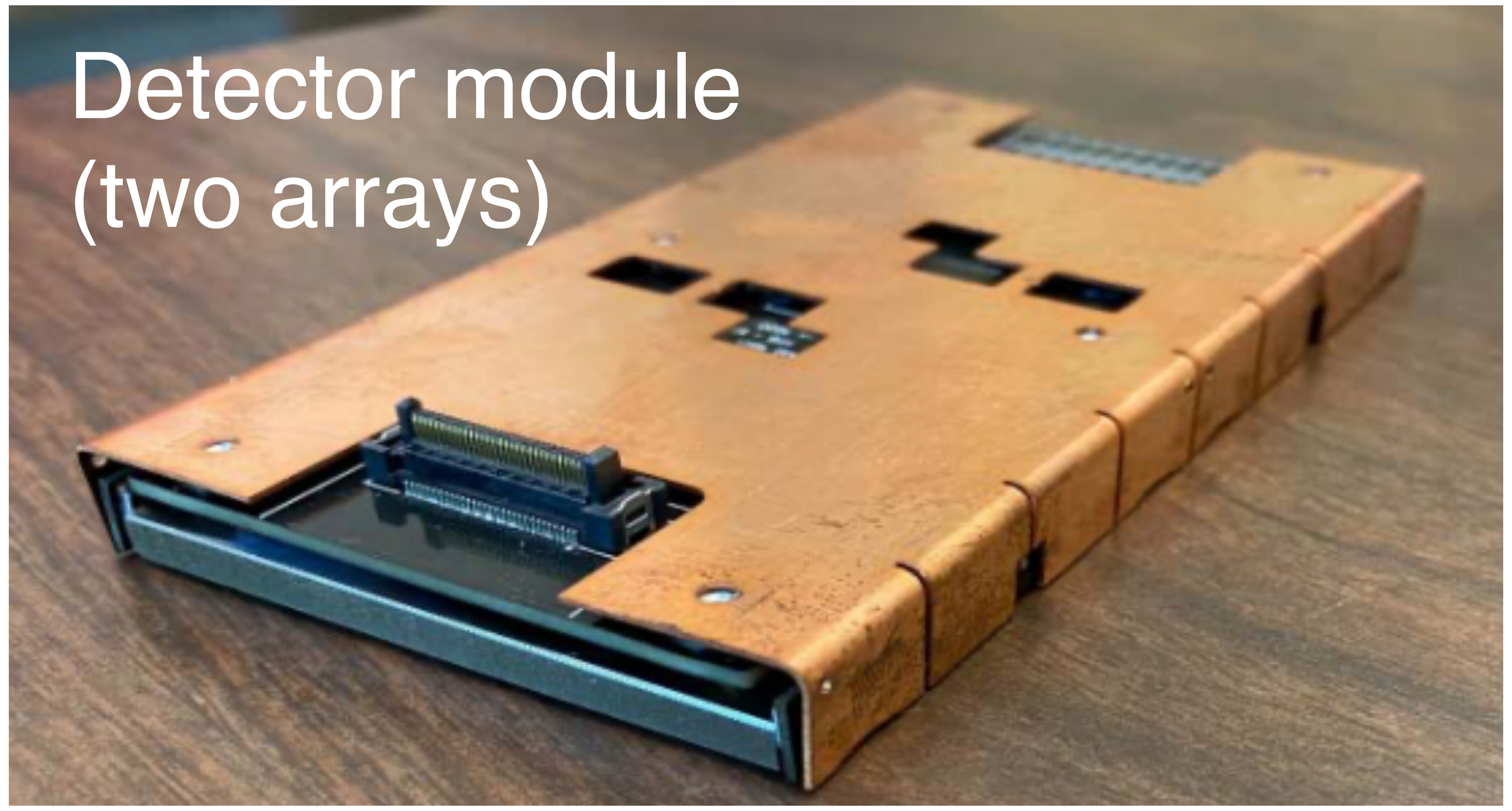
TECs (Peltier)

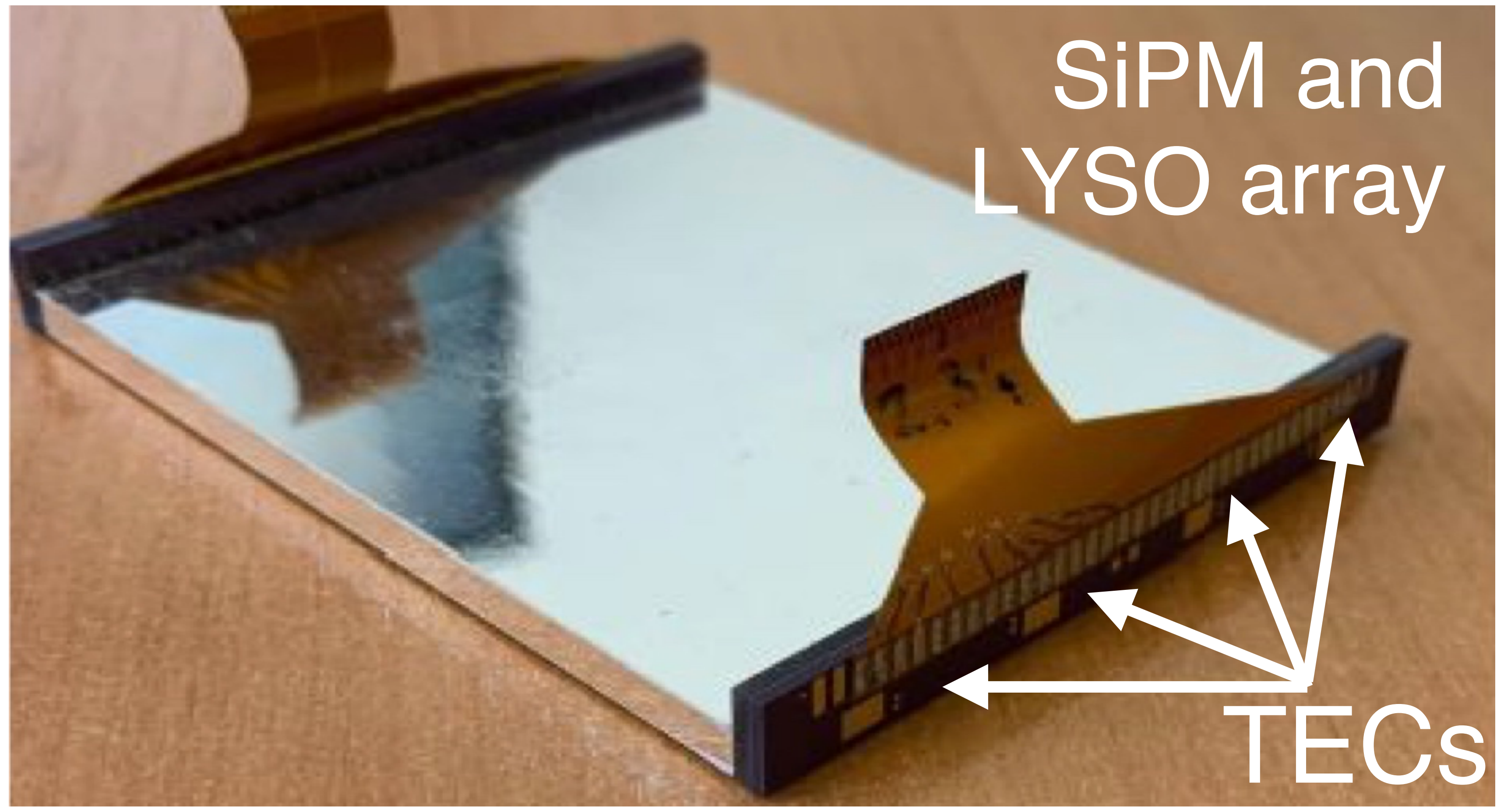


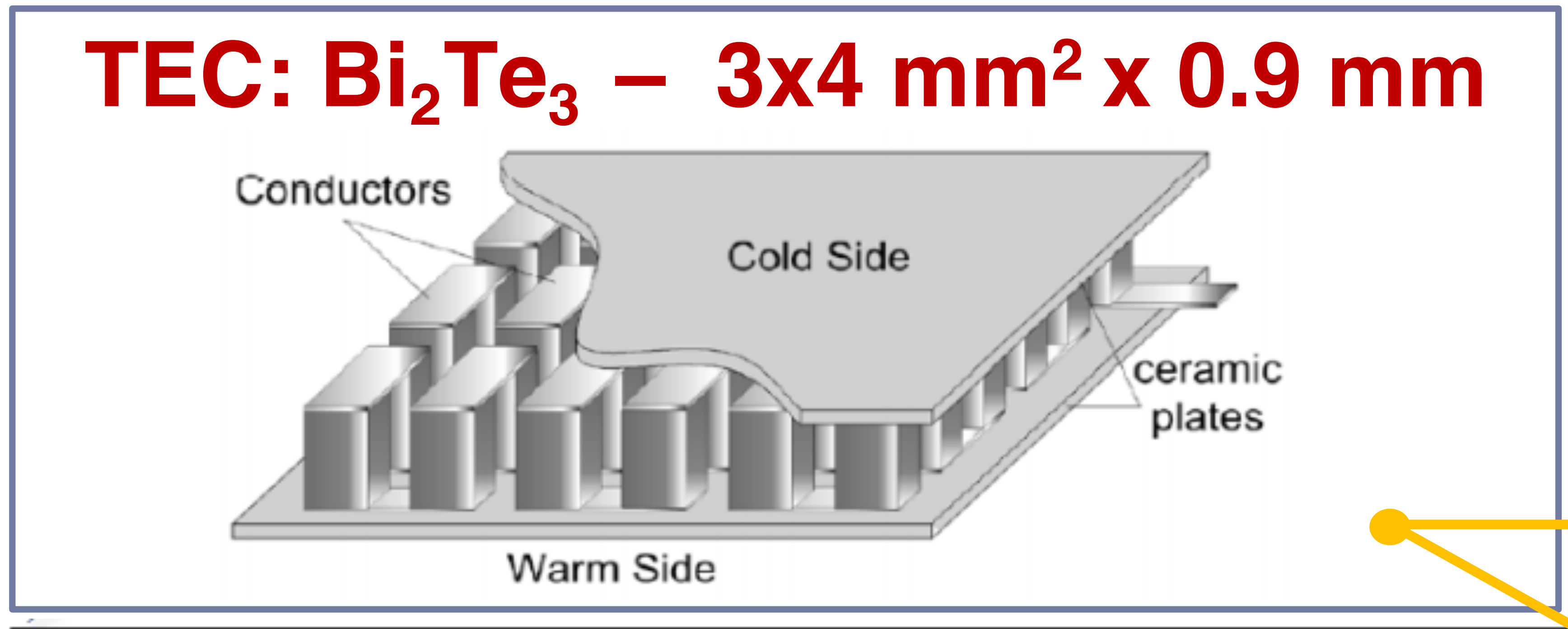


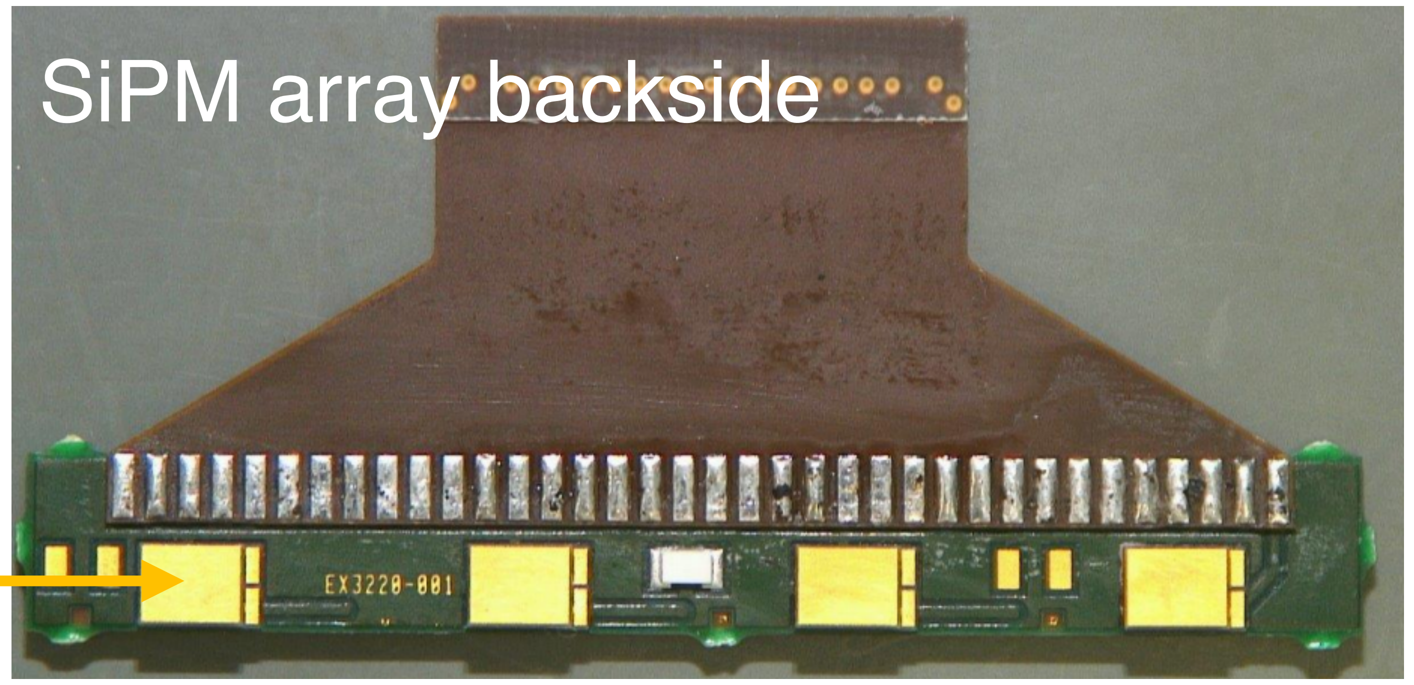
- Maintain σ < 60 ps at end of life.
- Provides operating margin.

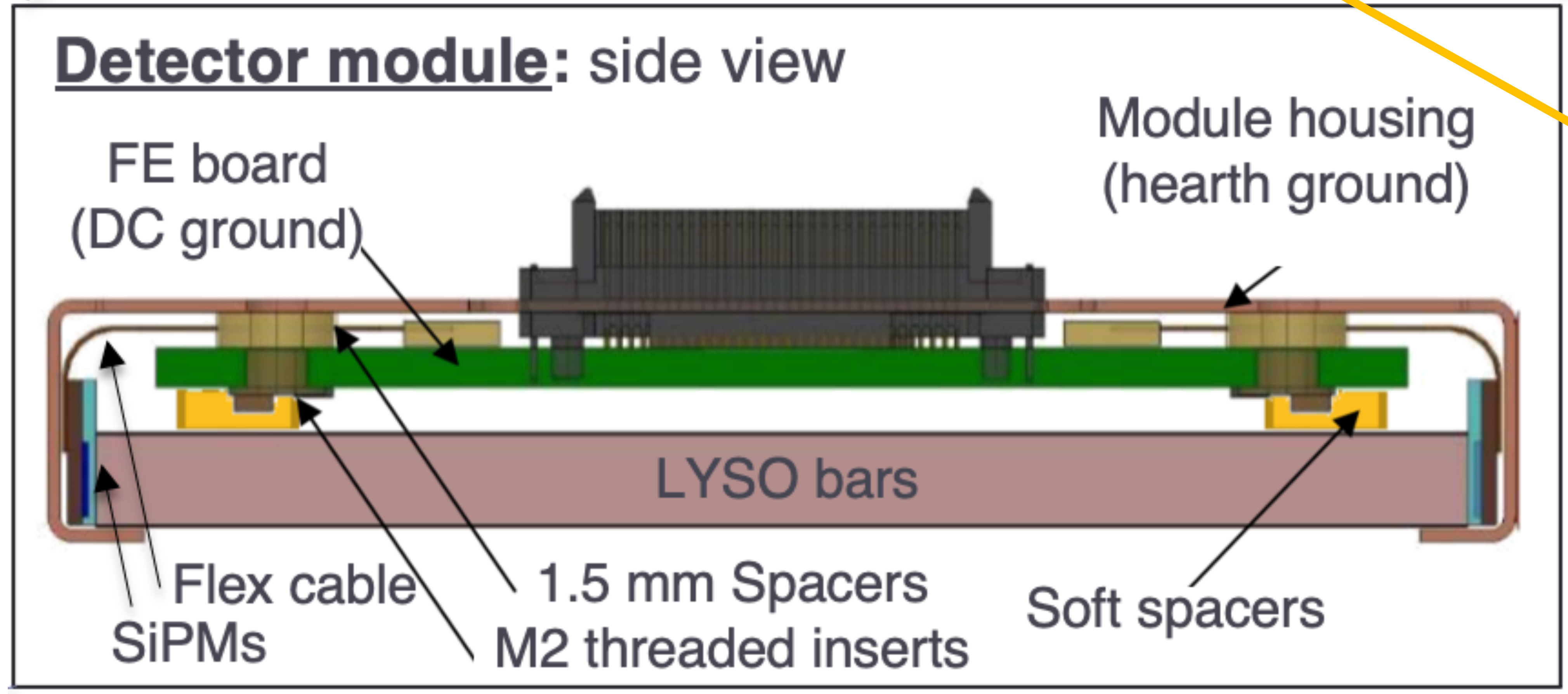
BTL modules

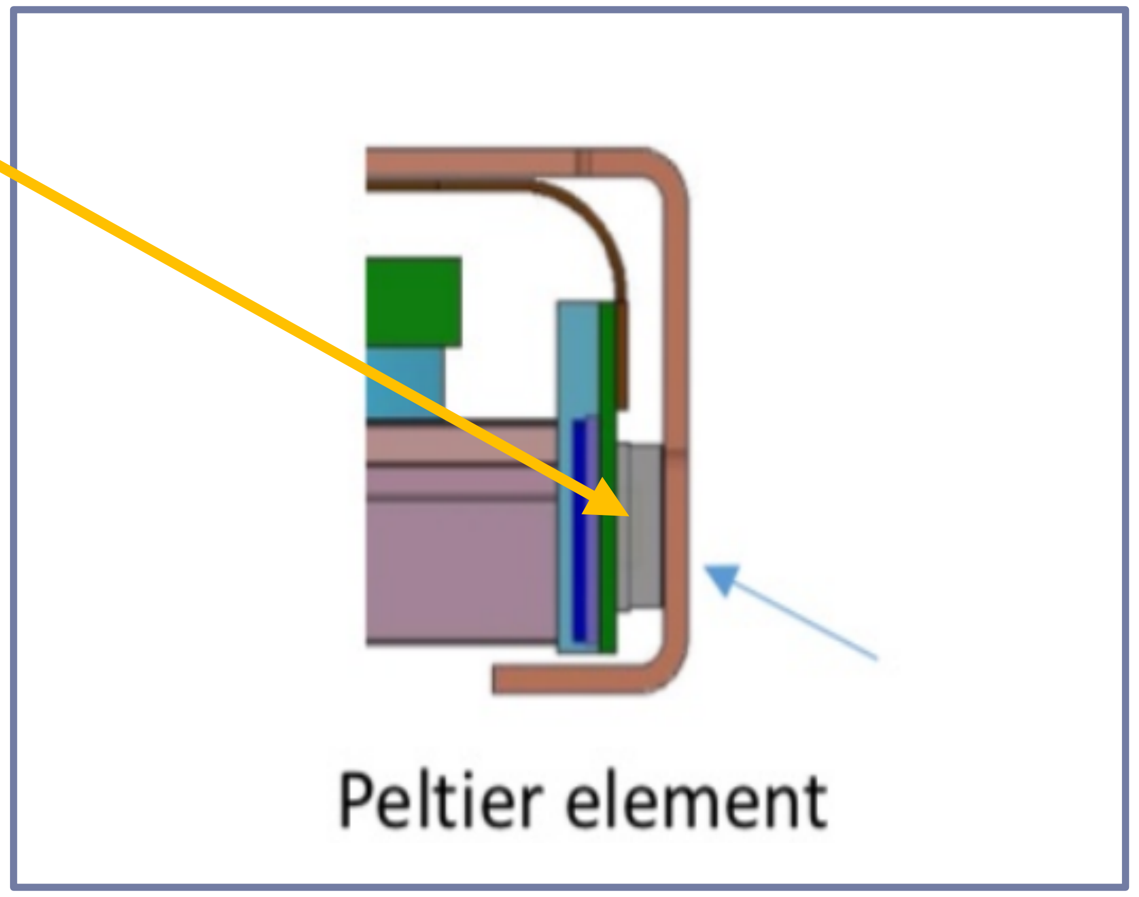

Detector module
(two arrays)


SiPM and
LYSO array
TECs


TEC: Bi_2Te_3 – 3x4 mm^2 x 0.9 mm
Conductors
Cold Side
ceramic
plates
Warm Side


SiPM array backside

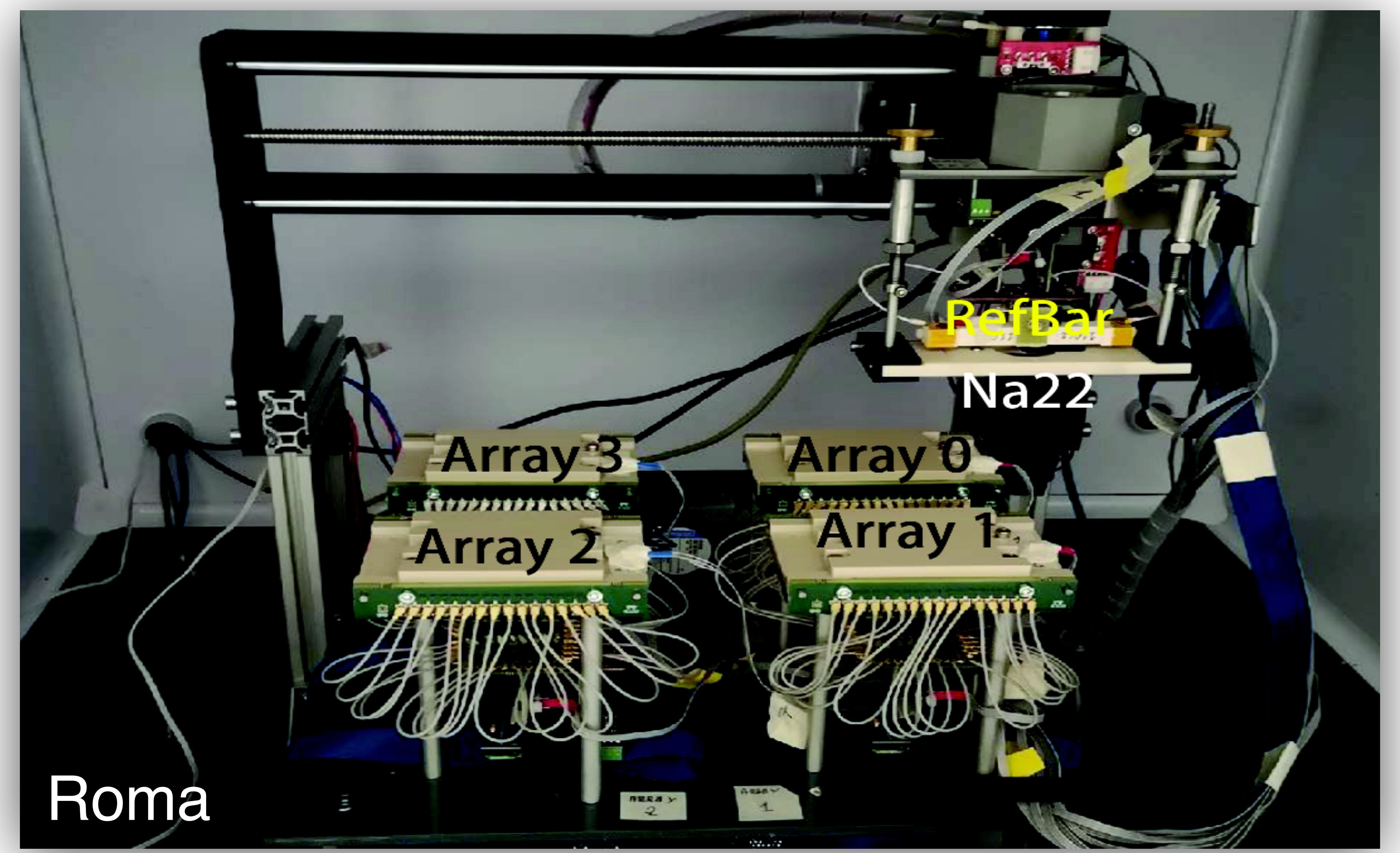

Detector module: side view
FE board
(DC ground)
Module housing
(hearth ground)
LYSO bars
Flex cable
SiPMs
1.5 mm Spacers
M2 threaded inserts
Soft spacers


Peltier element

BTL sensor market survey

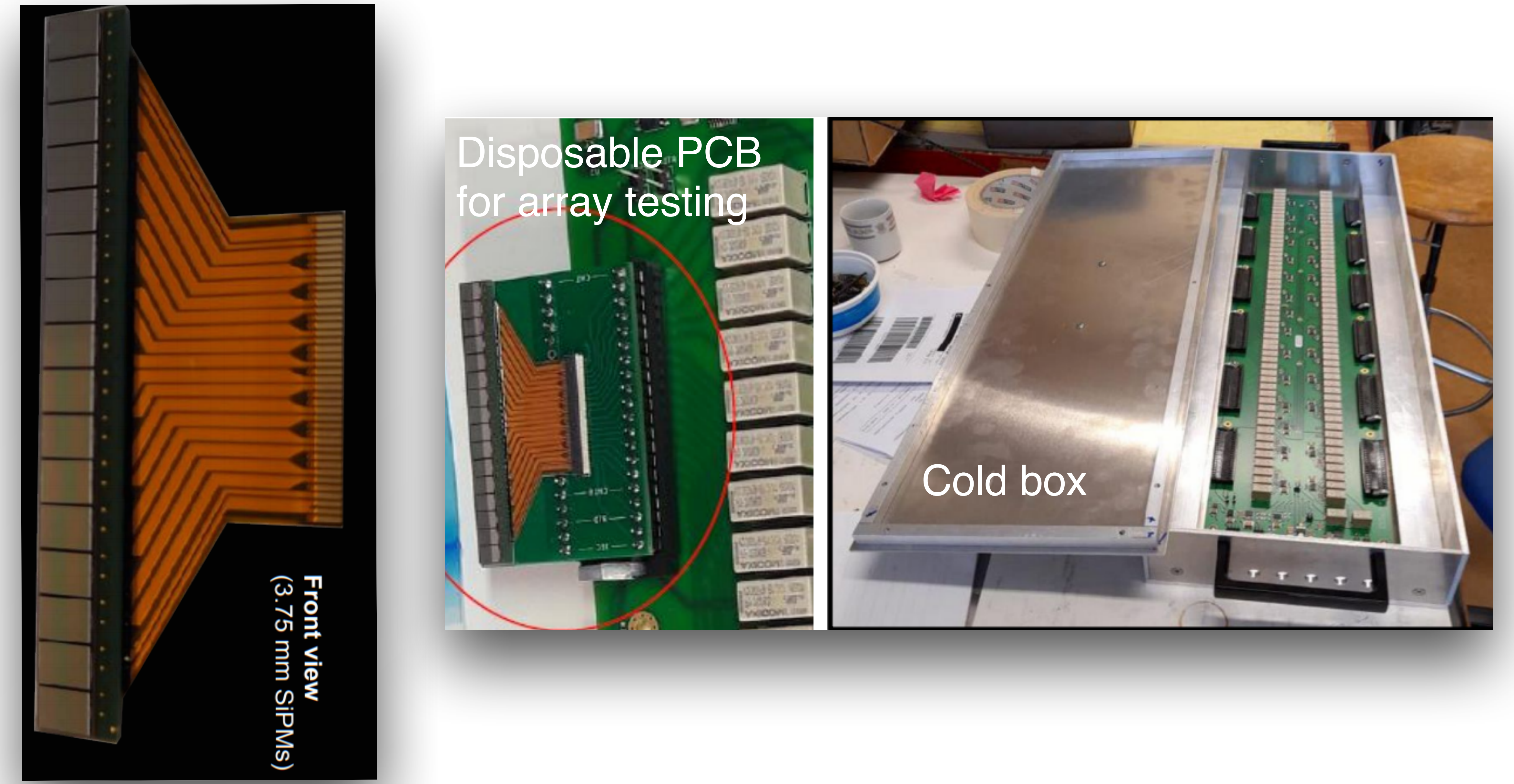
- Massive campaigns to characterize LYSO and SiPM arrays from several vendors
- Sensor properties well understood: proceed towards procurement!

Automated LYSO scanner with Na22 source



Scan 100s of sensors w/ high reproducibility; practice QA/QC
Measure light yield, σ_t, etc. Study pre/post irradiation.

SiPM characterization setup



Cold box allows testing 12 arrays at once
Assess vendor capability for high-volume, uniform production

Summary

- CMS MTD on track to be first-of-its kind hermetic timing detector
- Mature design established through extensive prototyping and testing
- Key system tests forthcoming
- Transition towards procurements and high-volume production