SiPM detectors for the LHCb SciFi tracker

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The LHCb experiment

The LHCb experiment

- **Asymmetric forward spectrometer ($2 < \eta < 5$)**
- **Designed for b and c physics**

  - Vertex Locator:

  excellent secondary vertices detection

  - RICH 1 & 2 :

  very good particle identification

  - Tracker:

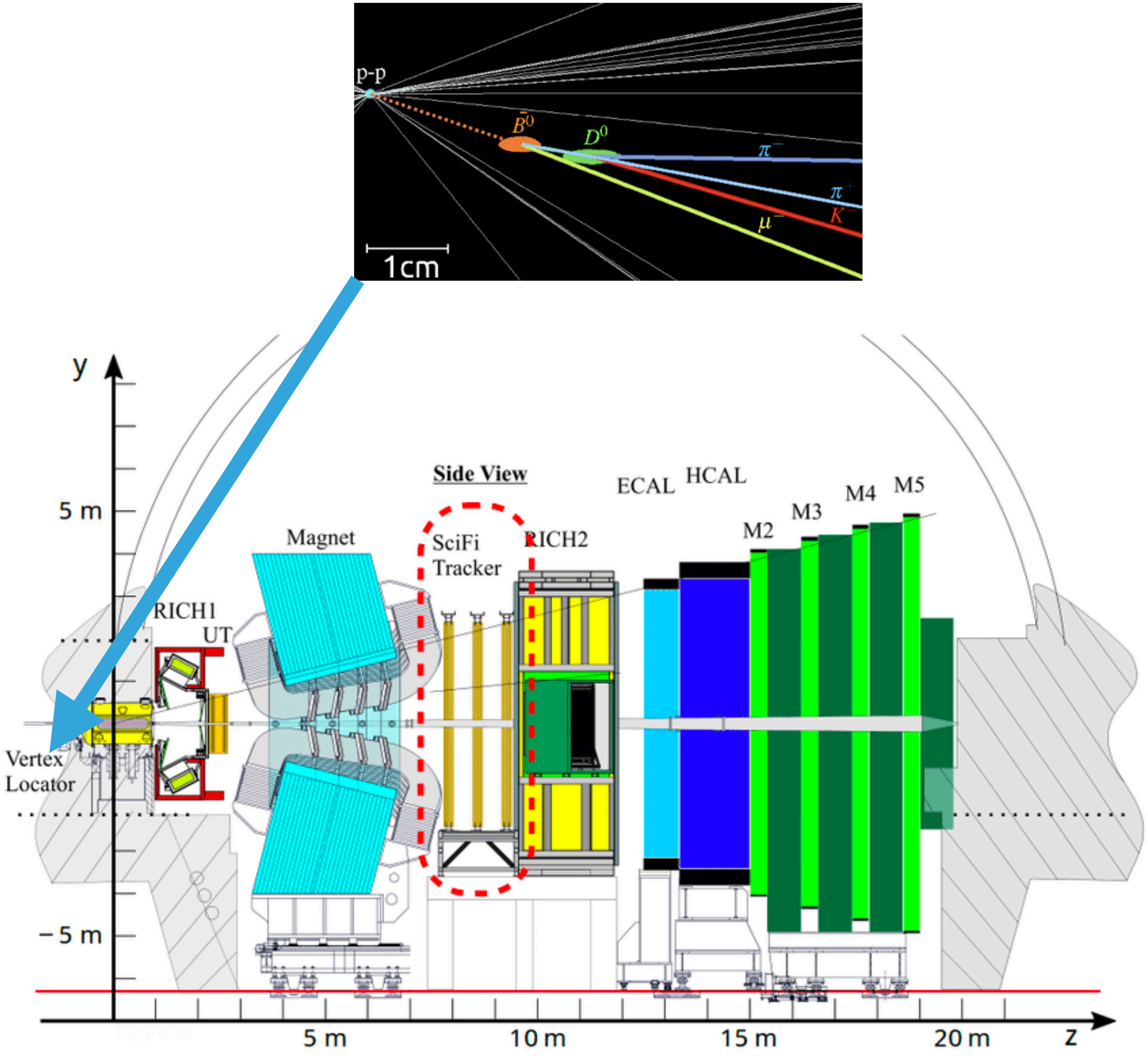
  tracking of charged particles

  - Calorimeter system:

  detection of electrons, photons and hadrons

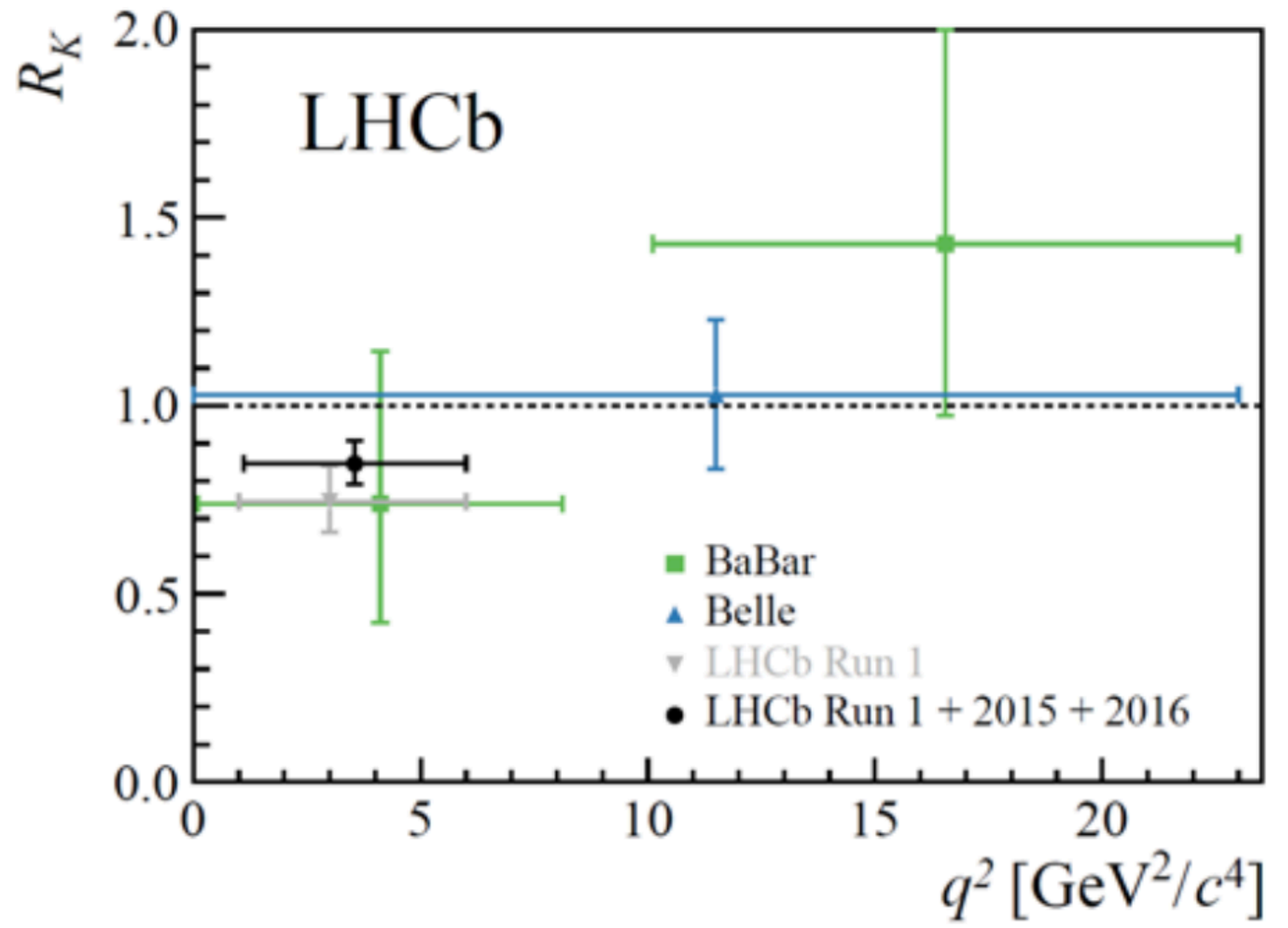
  - Muon chambers:

  tracking of muons



LHCb data and results

- **Outstanding results from LHCb data:**
  - Observation of the Pentaquark states [Phys. Rev.Lett. 115 (2015) 072001]
  - Observation of CP violation in charm decays [Phys. Rev. Lett. 122 (2019) 211803]
  - Observation of the rare decay $B_s \to \mu^\pm\mu^\mp$[Nature 522 (2015) 68-72]

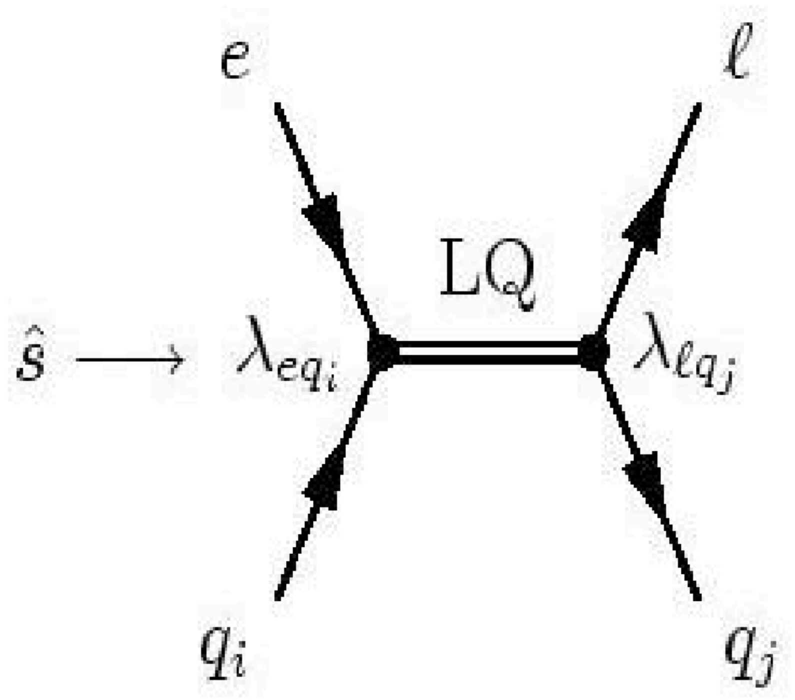


- **Interesting results in lepton flavour universality (LFU) tests:**
  - Weak coupling of leptons is assumed to be universal
  - New scenarios opened by recent hints of LFU anomalies

  [LHCb collaboration, Phys.Rev.Lett.122, 191801]]

$$R_K = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)}$$

$$0.01\left(\frac{1-R_K}{0.23}\right)^2 \sim \frac{\mathcal{B}(B_s \to \mu^+e^-)}{\mathcal{B}(B_s \to \mu^+\mu^-)_{SM}}$$

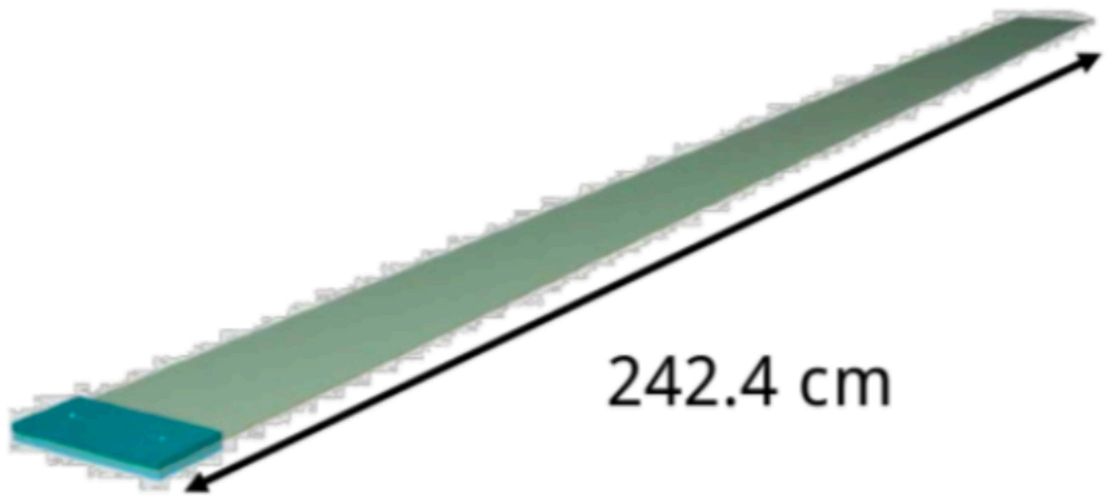


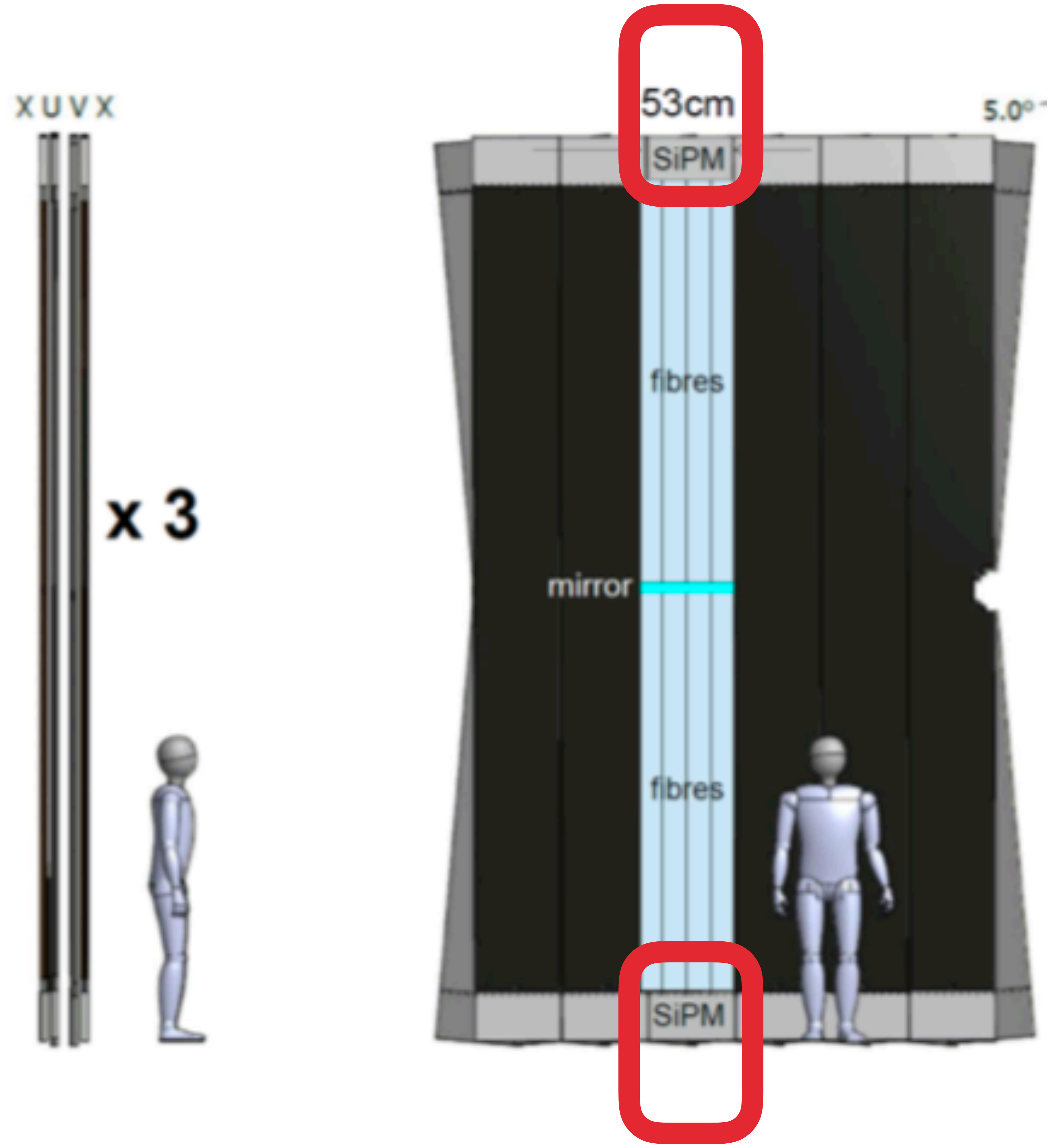
LHCb SciFi tracker upgrade

- **Upgrade the detector for an integrated Luminosity of 50 fb^{-1} for Run 3 & Run 4 :**
  - 40 MHz readout, software based trigger
  - Current tracker technology (scilicon micorstrip and straw tubes) can not fulfil the requirements

- **Scintillating fibre tracker:**
  - Based on scintillating fibres arranged into fibre mats
  - Detection of scintillating light with SiPMs

- **Detector design:**
  - 3 tracking stations with 4 layers of 12 modules (total 144 modules)
  - Station midlayers rotated by 5°
  - Each fiber mat is attached to 4 SiPMs



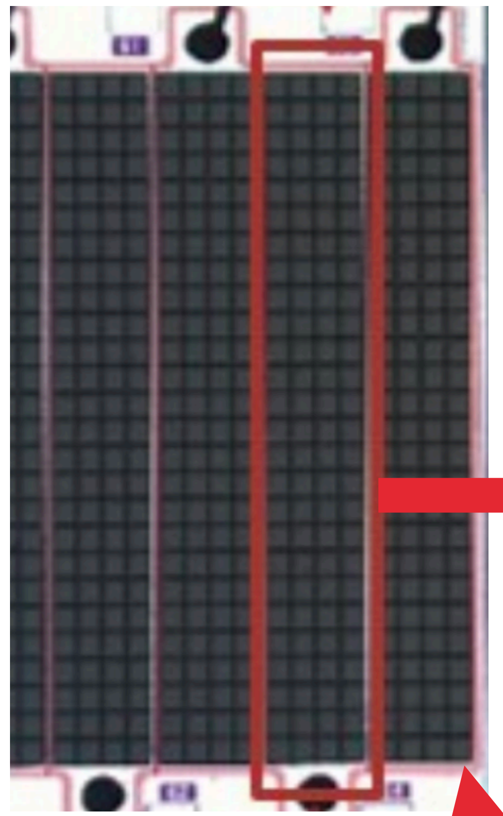


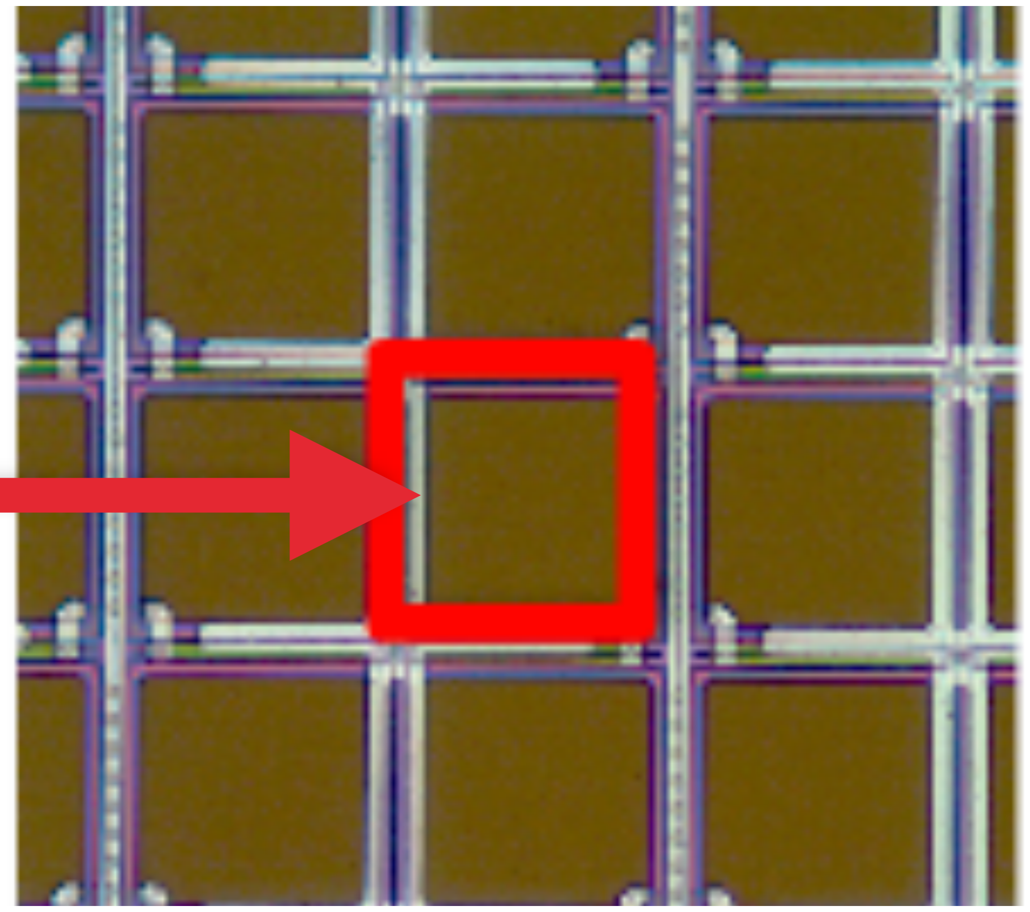
[CERN/LHCC 2014-001]

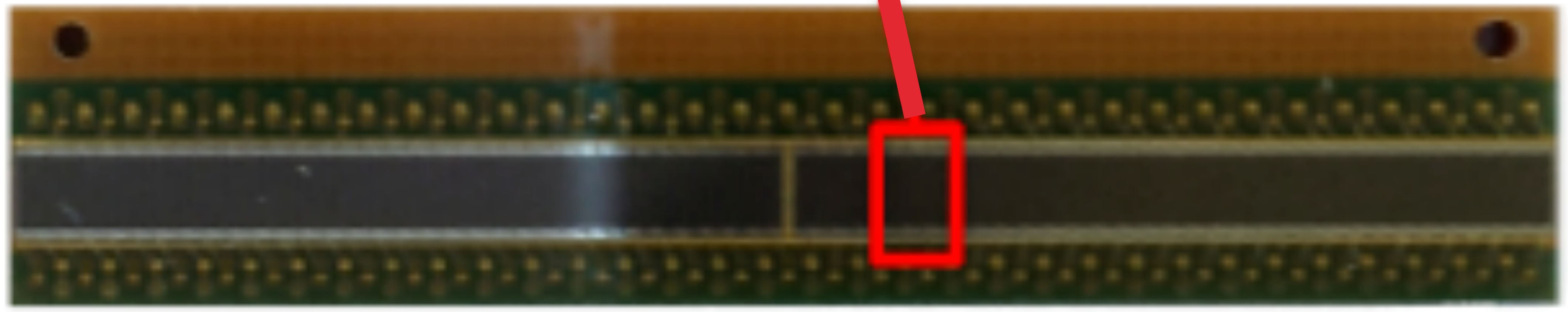
Silicon Photomultipliers

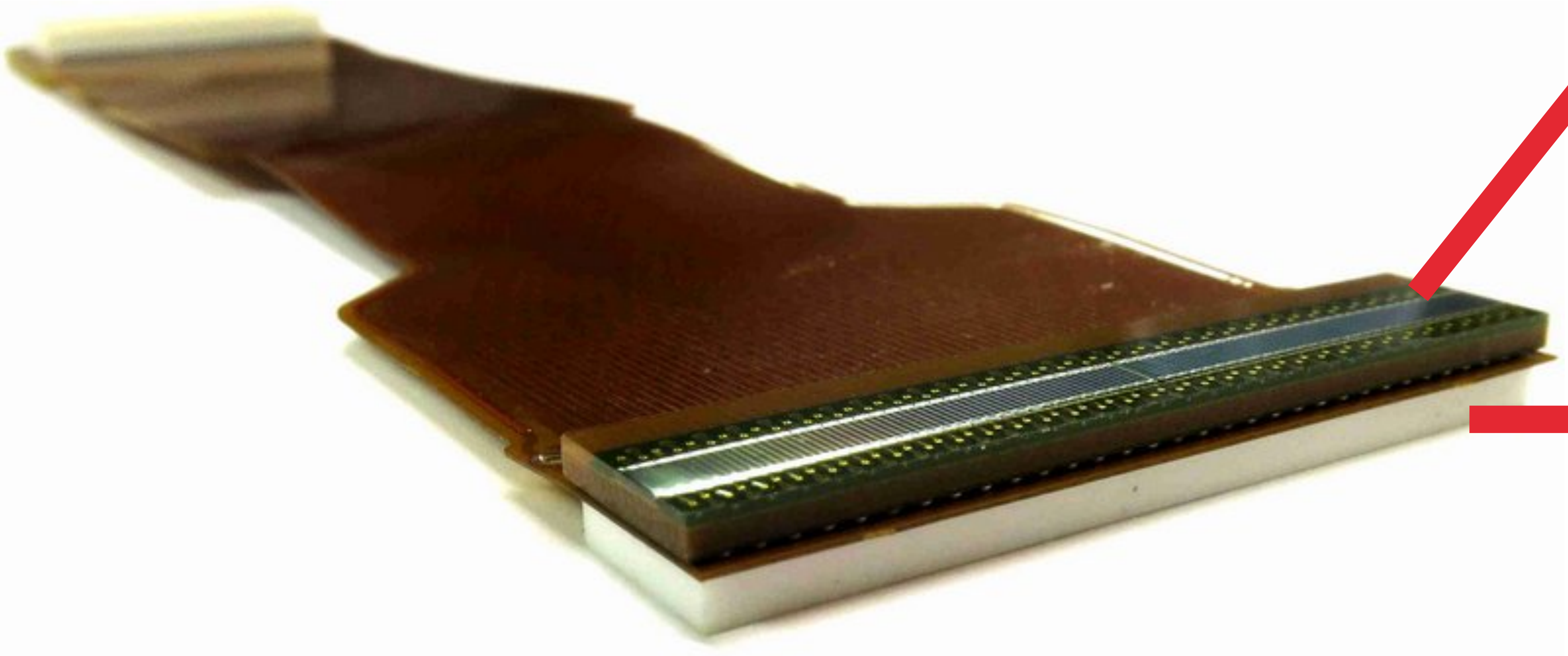
SiPMs for the SciFi

- Two silicon dies 128 channels (Hamamatsu)
- 104 pixels, electrical connected (57.5 x 62.5) μm^2
- Silicon is protected by an epoxy layer

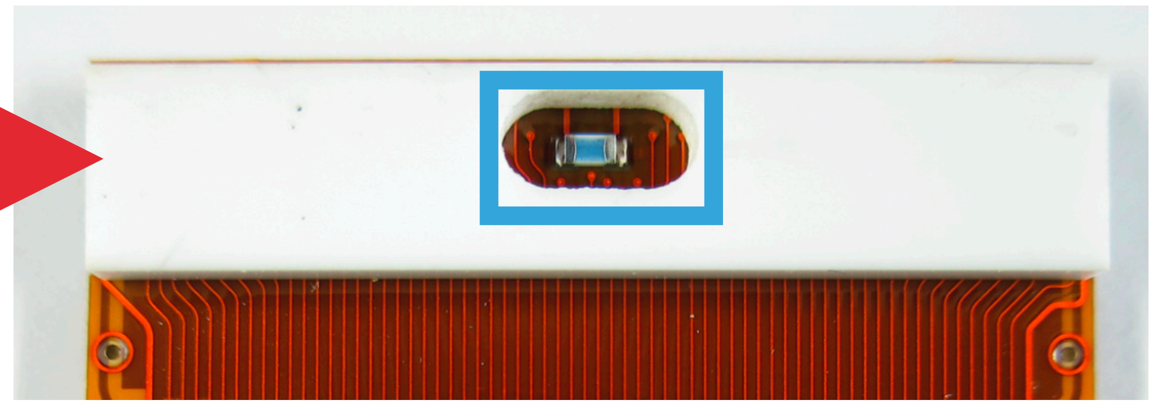








- Stiffener plate and temperaturen sensor
  - Devices will be operated at -40°C



SiPM characterisation

Device characterisation

➡ **For the optimal operation point of the SiPMs, several parameters need to be studied:**

- Breakdown voltage (V_{BD})
- Correlated Noise
- Dark count rate (DCR)

➡ **Challenges:**

- Radiation
- Fast readout
- Temperatur dependence
- Geometry

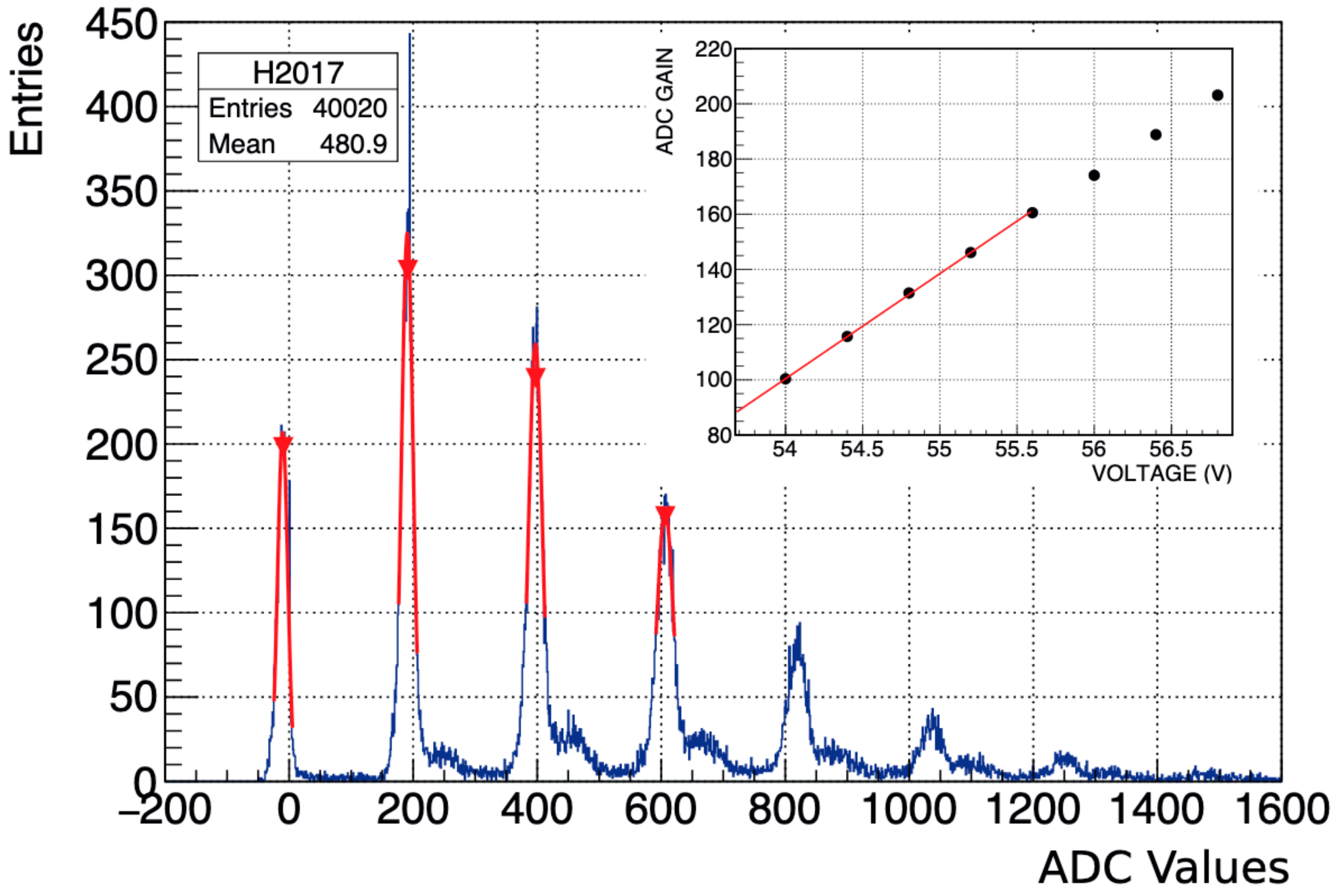
Low light amplitude spectrum analysis

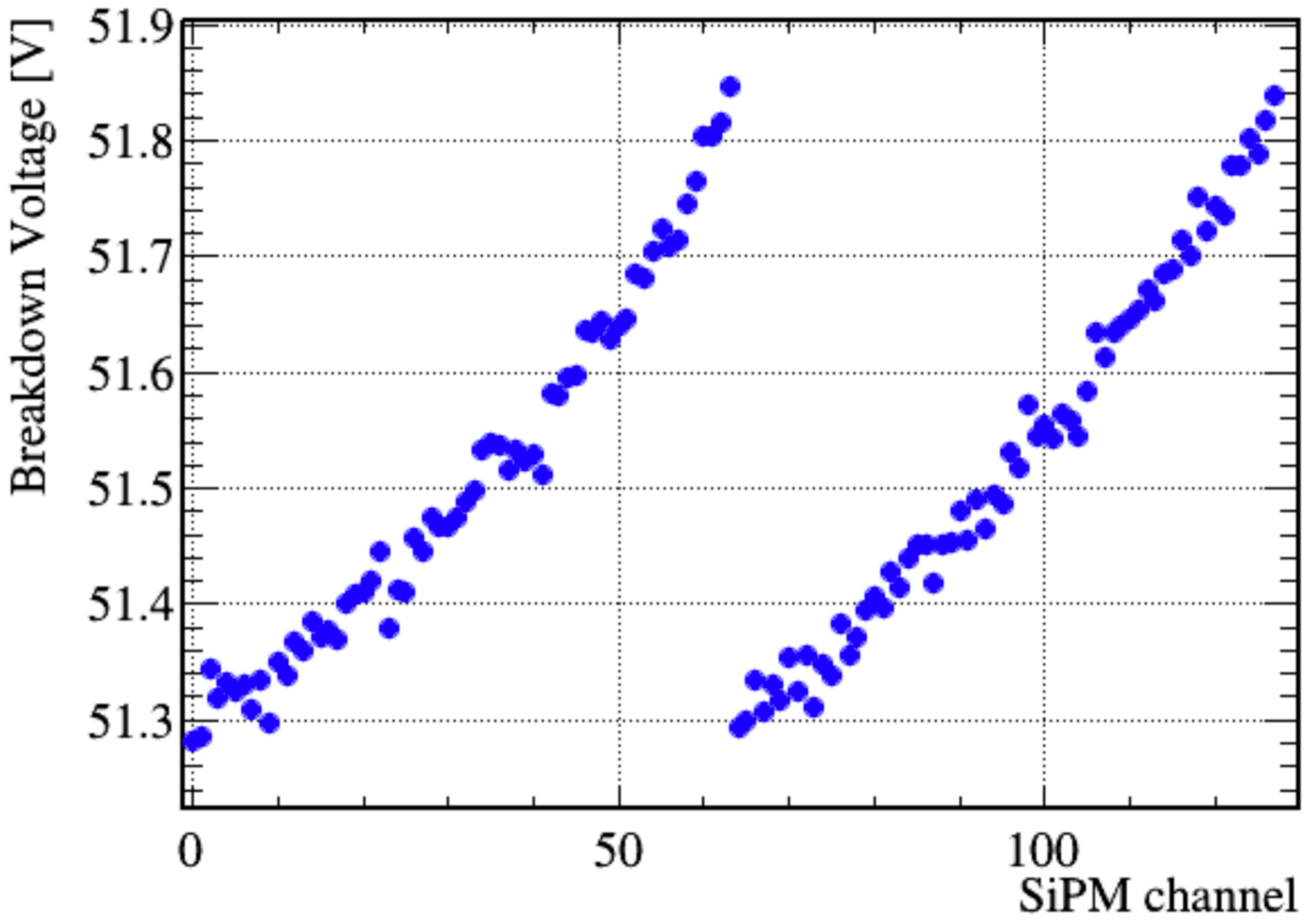
- **V_{BD} is the voltage needed to trigger the avalanche**

$$Q_A \sim \Delta V = V_{Bias} - V_{BD}$$

- **Measurement with multichannel charge sensitive amplifier ASIC (VATA64)**

  - Measure dark spectrum for pedestal determination
  - Measure low photon spectrum with fast light pulses
  - Determine gain from distance of the photon peaks
  - Extrapolate V_{BD} from fit to 0 gain

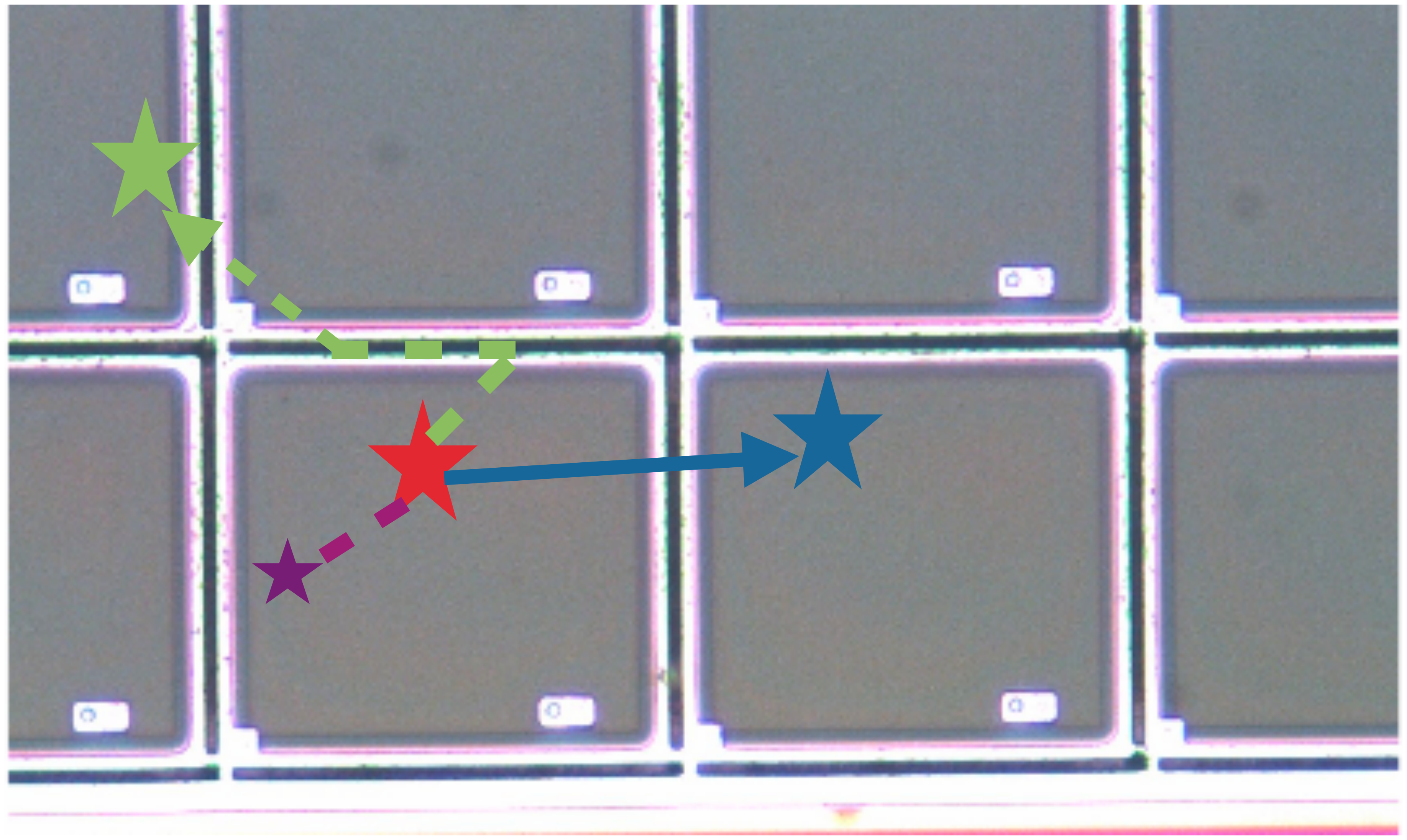




Noise characterisation

Dark count rate (DCR):

- Random thermal generated pulses
- Proportional to the active area
- Increases with temperature and radiation

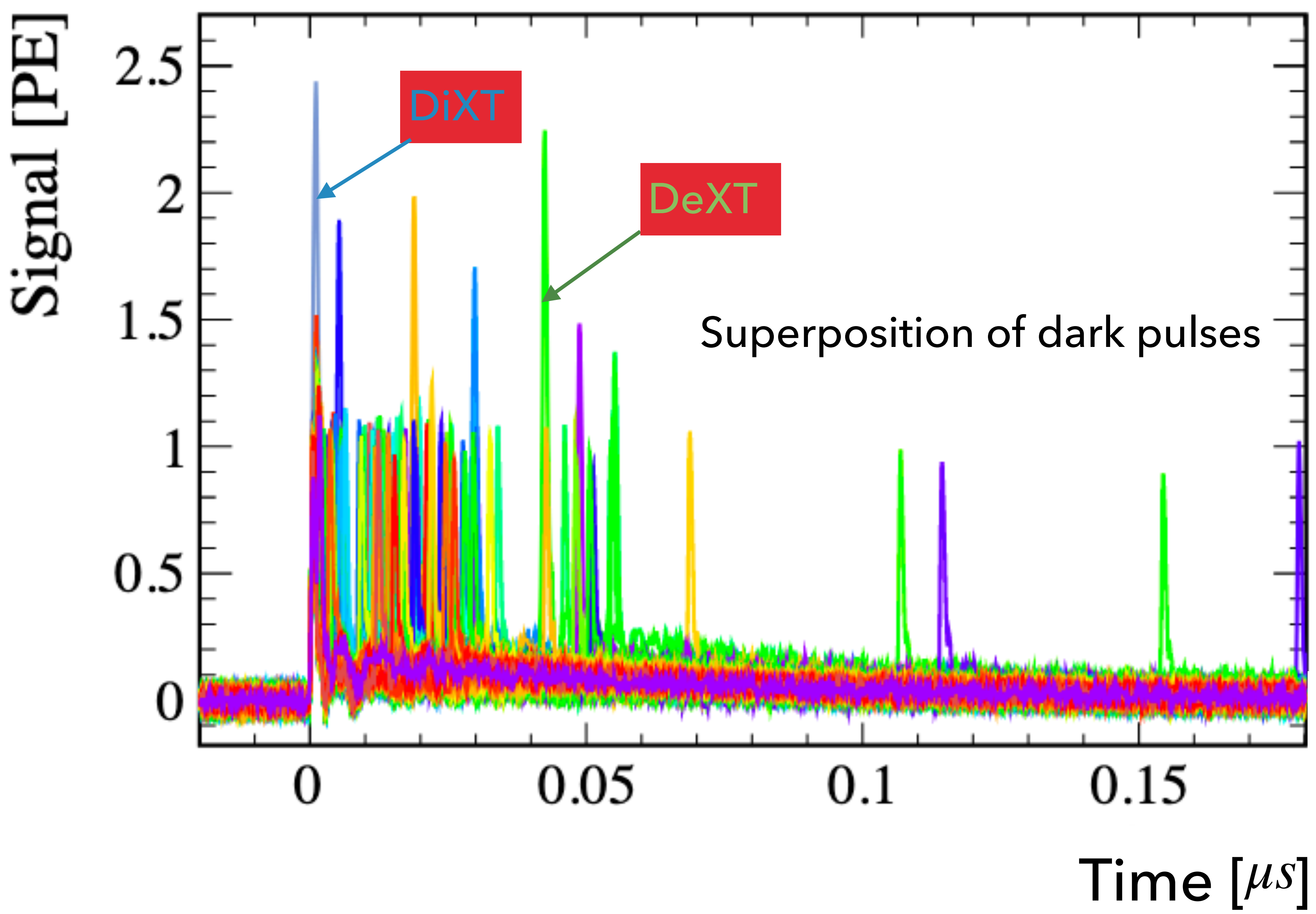


Correlated Noise

- Direct pixel-to-pixel cross-talk (DiXT)
- Delayed pixel-to-pixel cross-talk (DeXT)
- After-pulse (AP)

Analysis with an oscilloscope: [arXiv:1808.05775]

- Acquire a large number of dark pulses
- Analyse offline



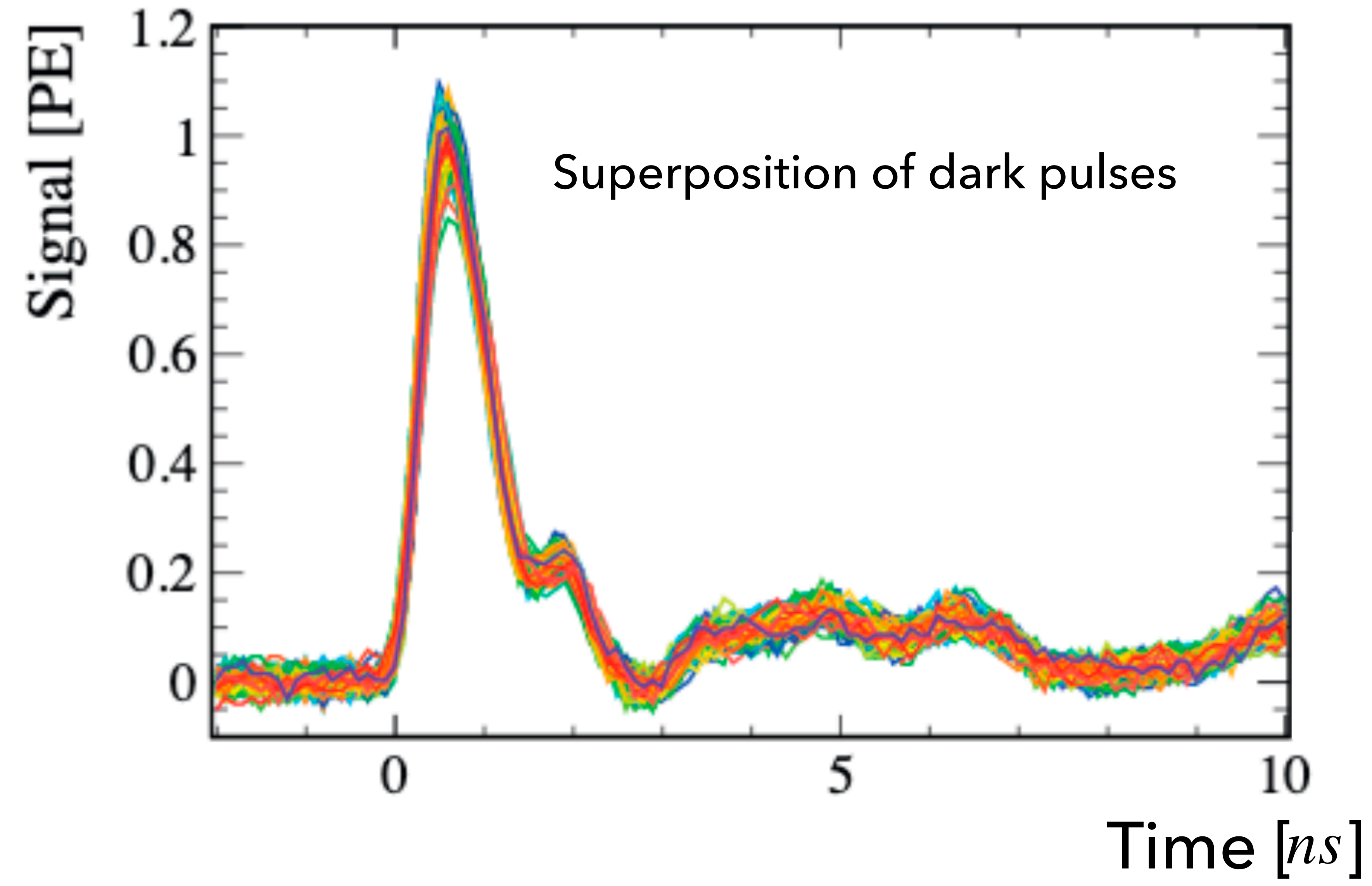
SiPM waveform characterisation

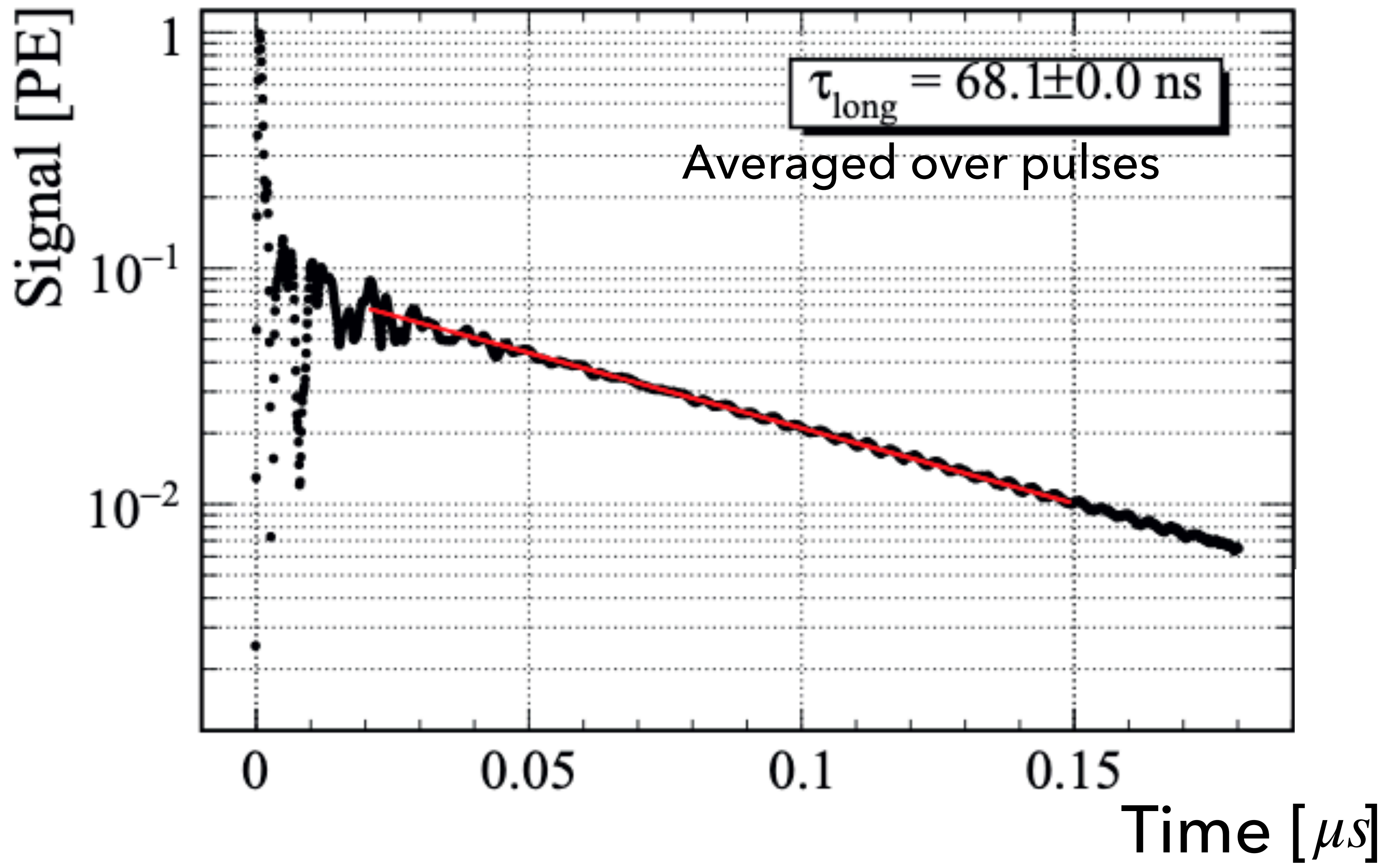
[arXiv:1808.05775]

◉ **Pulse has fast and slow components:**

- τ_{short} < 1.0 ns dominated by acquisition bandwidth
- τ_{long} characterises the device

➡ determined with an exponential fit





➡ Pixel recovery time:

$$\tau_{rec} = 70\text{ns (H2017)}$$

SiPM assembling

SiPM operation

- **Groups of 4 SiPMs are mounted in cold box and operated with a common bias voltage supply:**

  - Grouping of devices with similar V_{BD}

    ➡ Compensate differences of 500mV

  - Similar total thickness

[LHCb collaboration, LHCb-INT-2016-019]

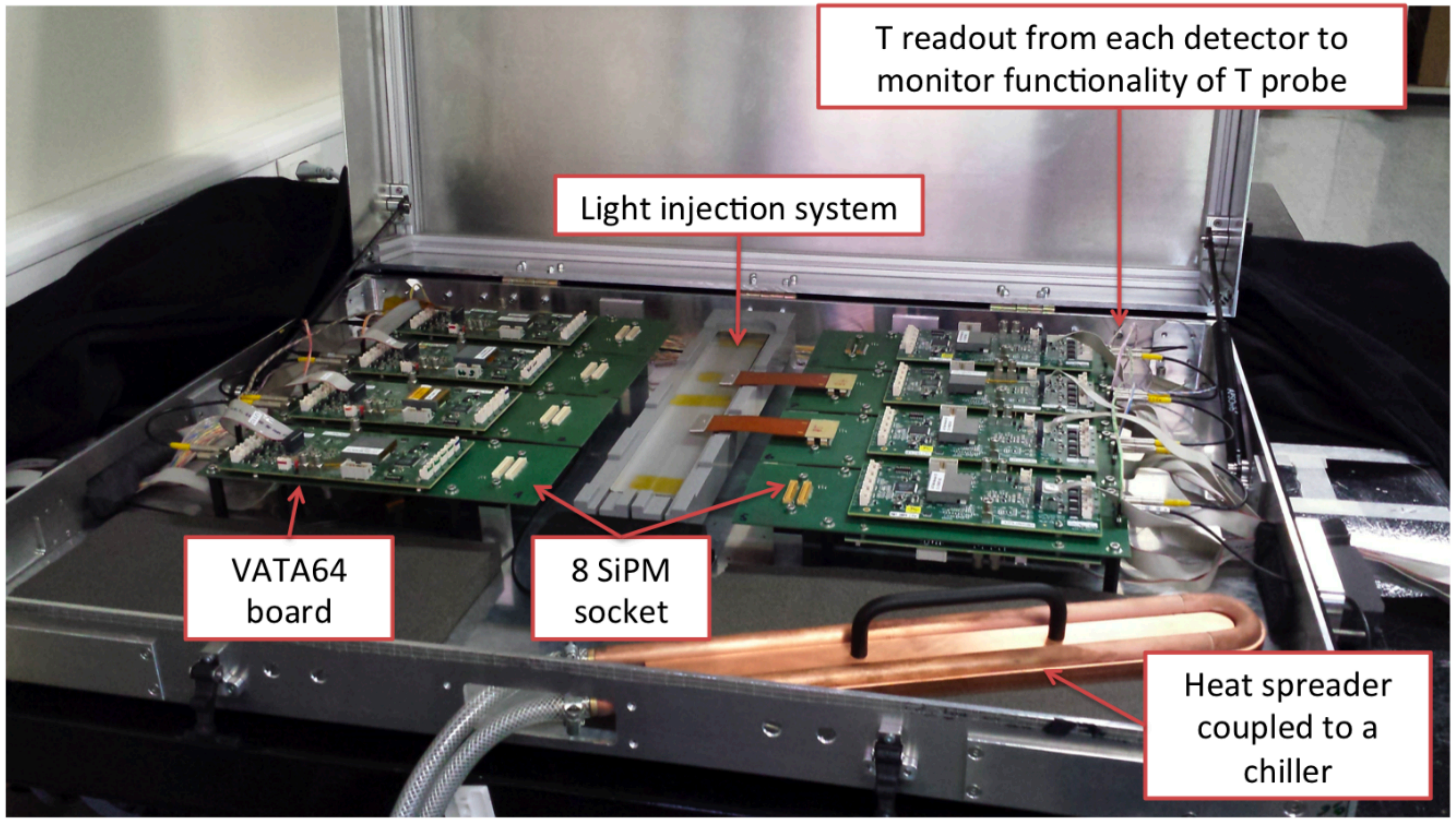
SiPM testing at EPFL

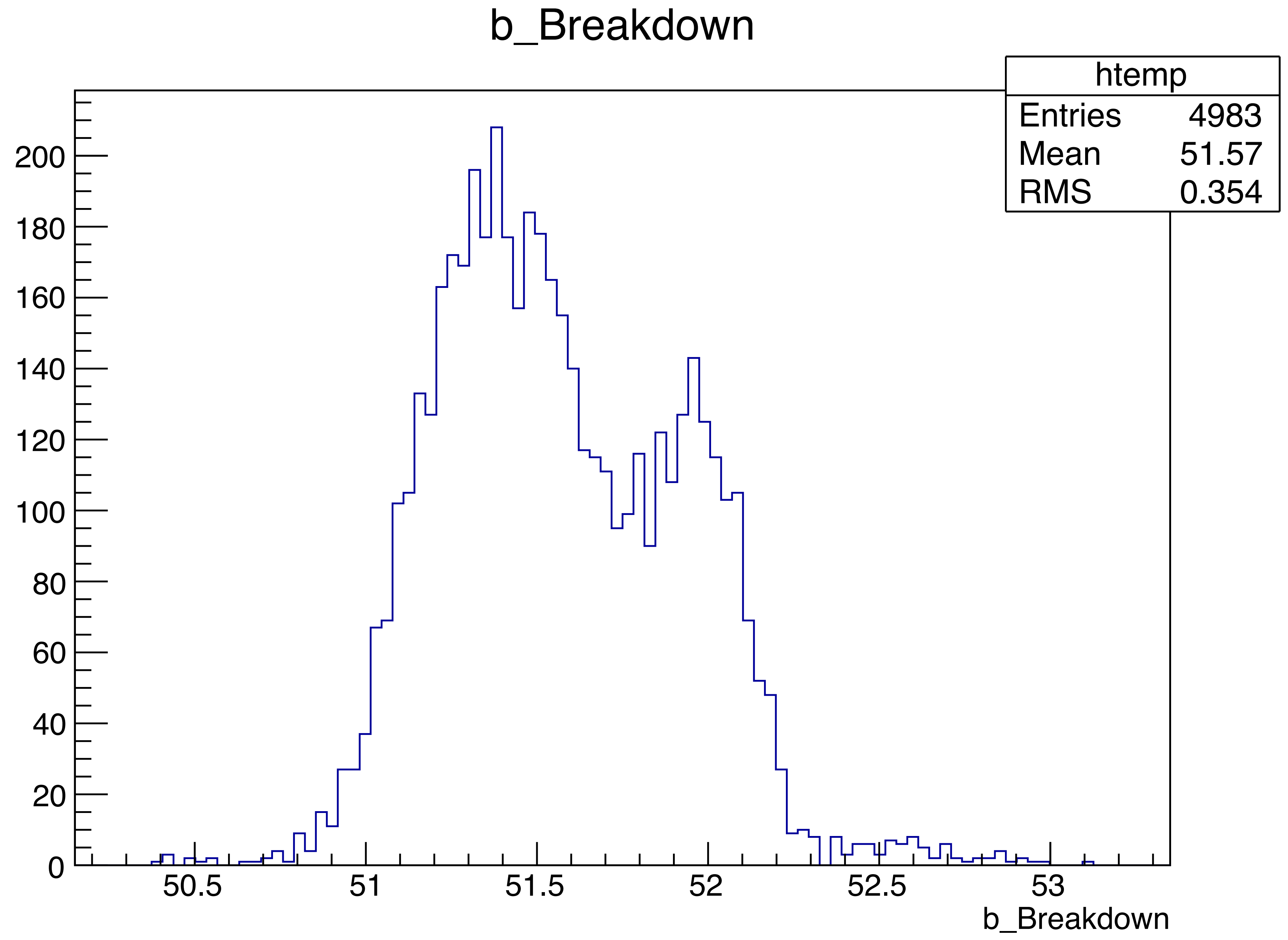
Devices are fully tested and characterised

1. **Full electrical tests:**
   - Dead channel test
   - Temperature sensor test
   - V_{BD} measurement
2. **Thickness measurement**
3. **Optical inspection**

Low light amplitude spectrum analysis

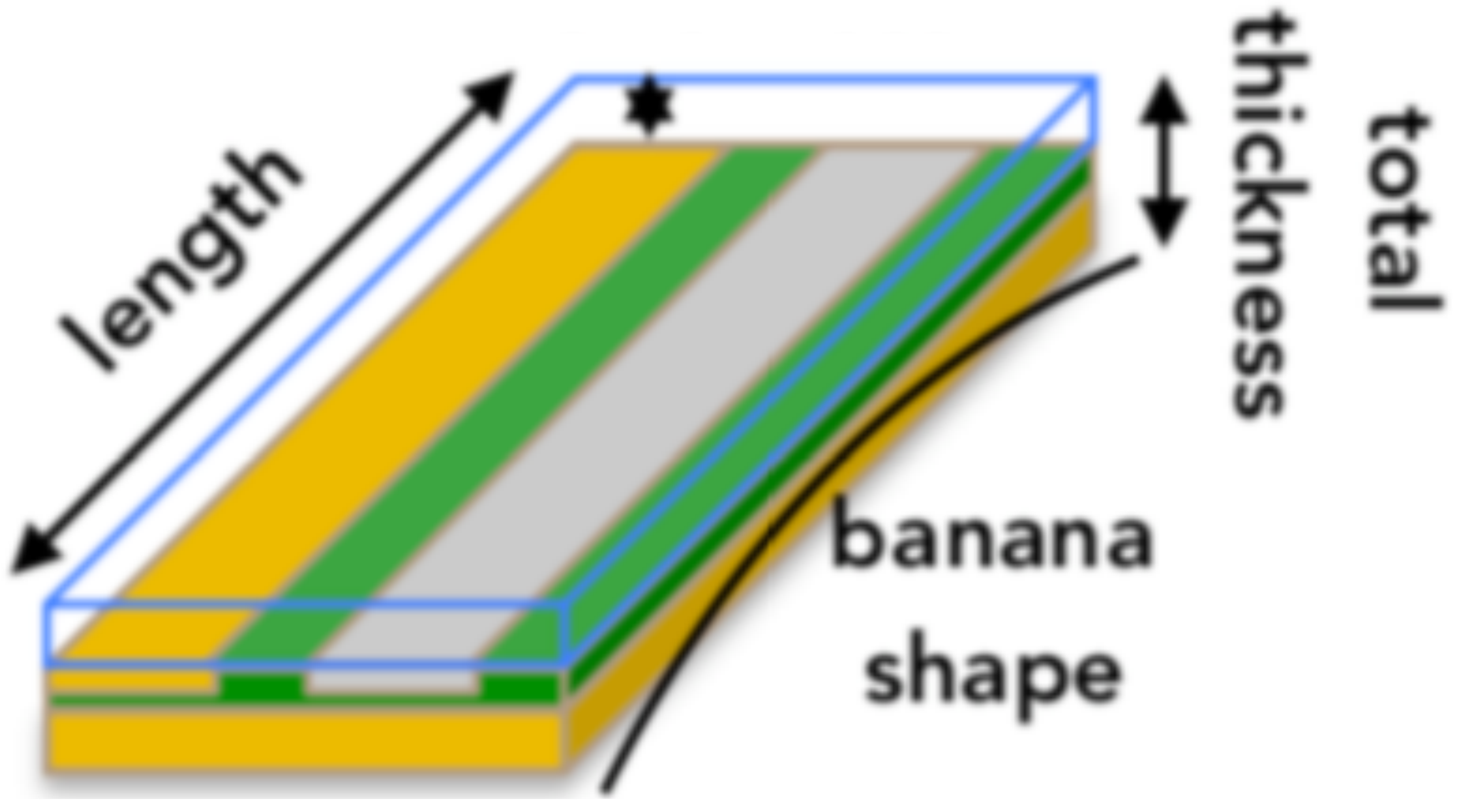
- **Measurement with multichannel charge sensitive amplifier ASIC (VATA64)**



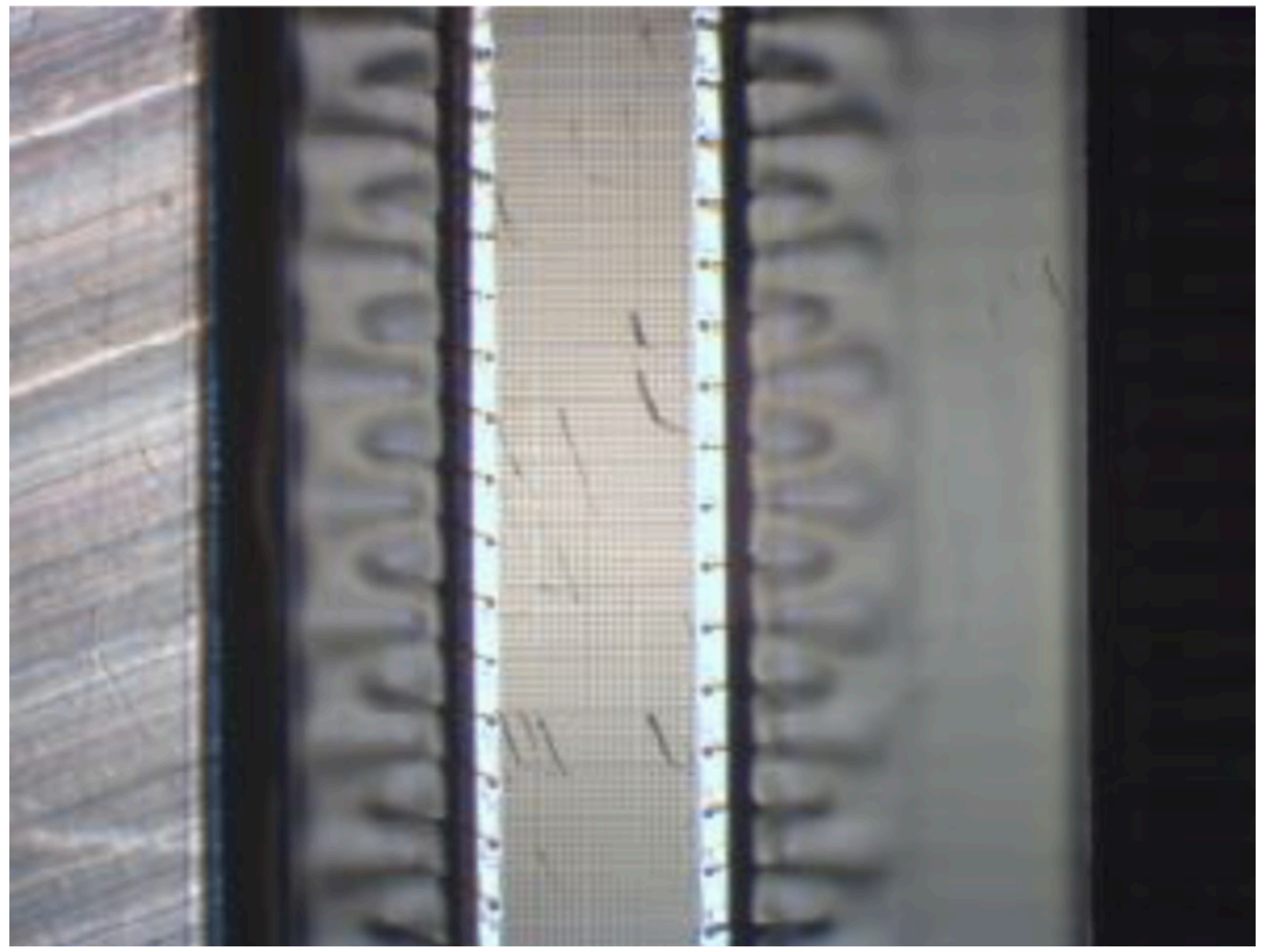


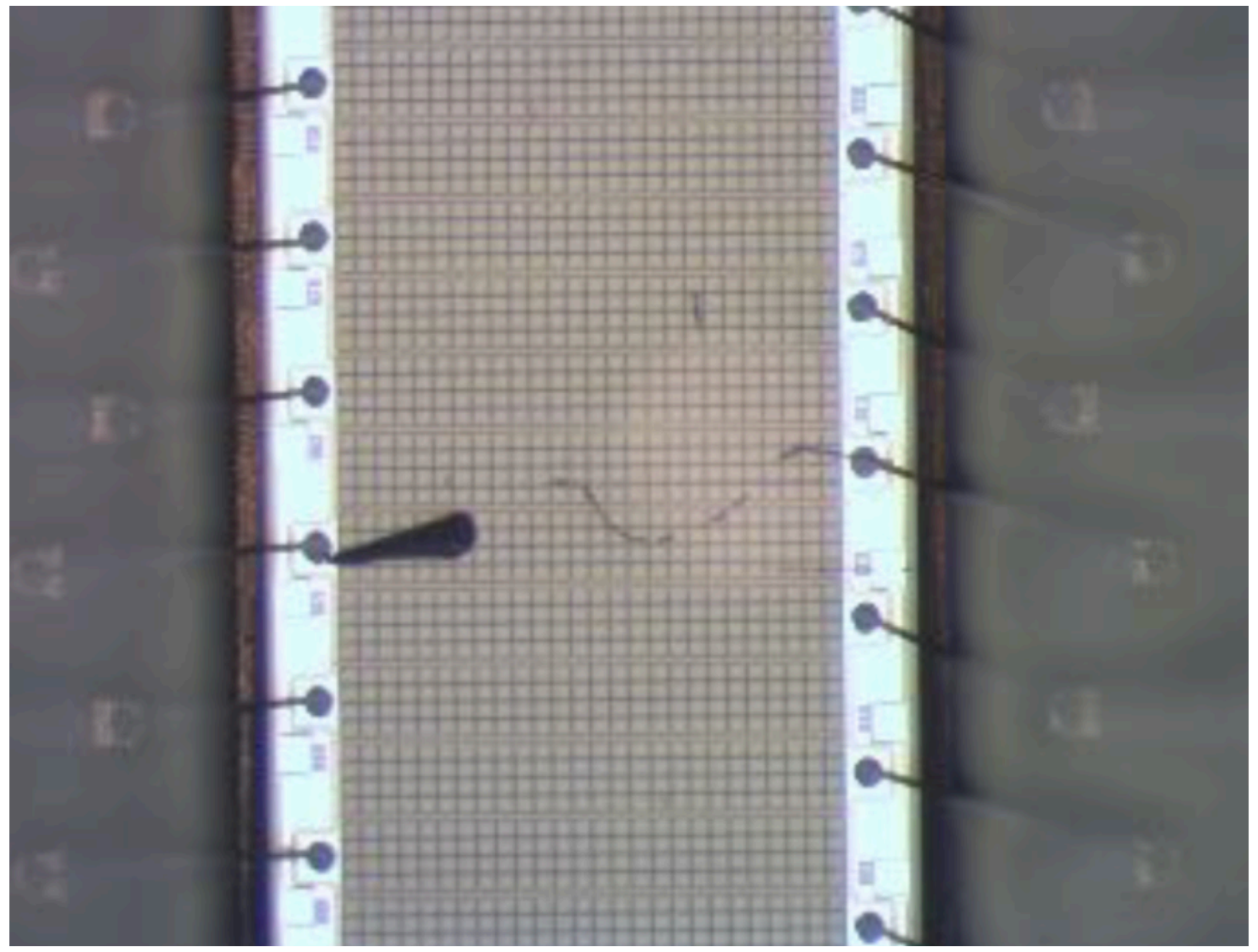
Geometrical and optical inspection

- **Thickness measurement with optical focusing system under a microscope**
- **Mean deviation in thickness is evaluated:**
  - In general a banana-like shape is observed



- **Devices with a deviation >100 μm are considered as bad**
- **Optical inspection via microscope**





Summary

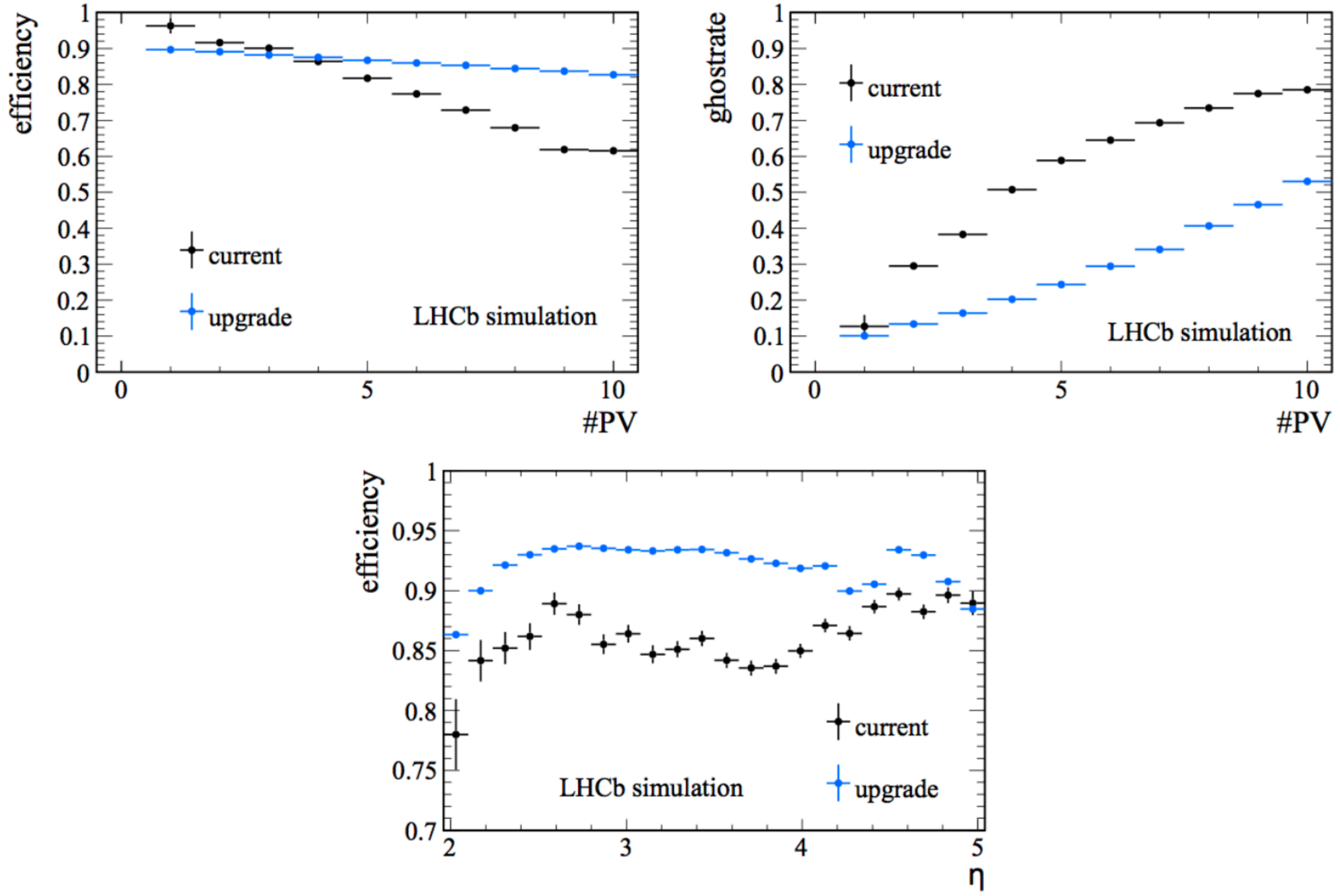
- **Assembling summary:**
  - Measured all 5000 SiPMs
  - 1.5% discarded due to optical imperfections
  - 0.6% discarded due to electrical issues

- **SiPMs fulfil all expectations**
- **Currently the SciFi modules are assembled**

➡ **Preparation for the installation next year**

Backup

SCIFI PERFORMANCE



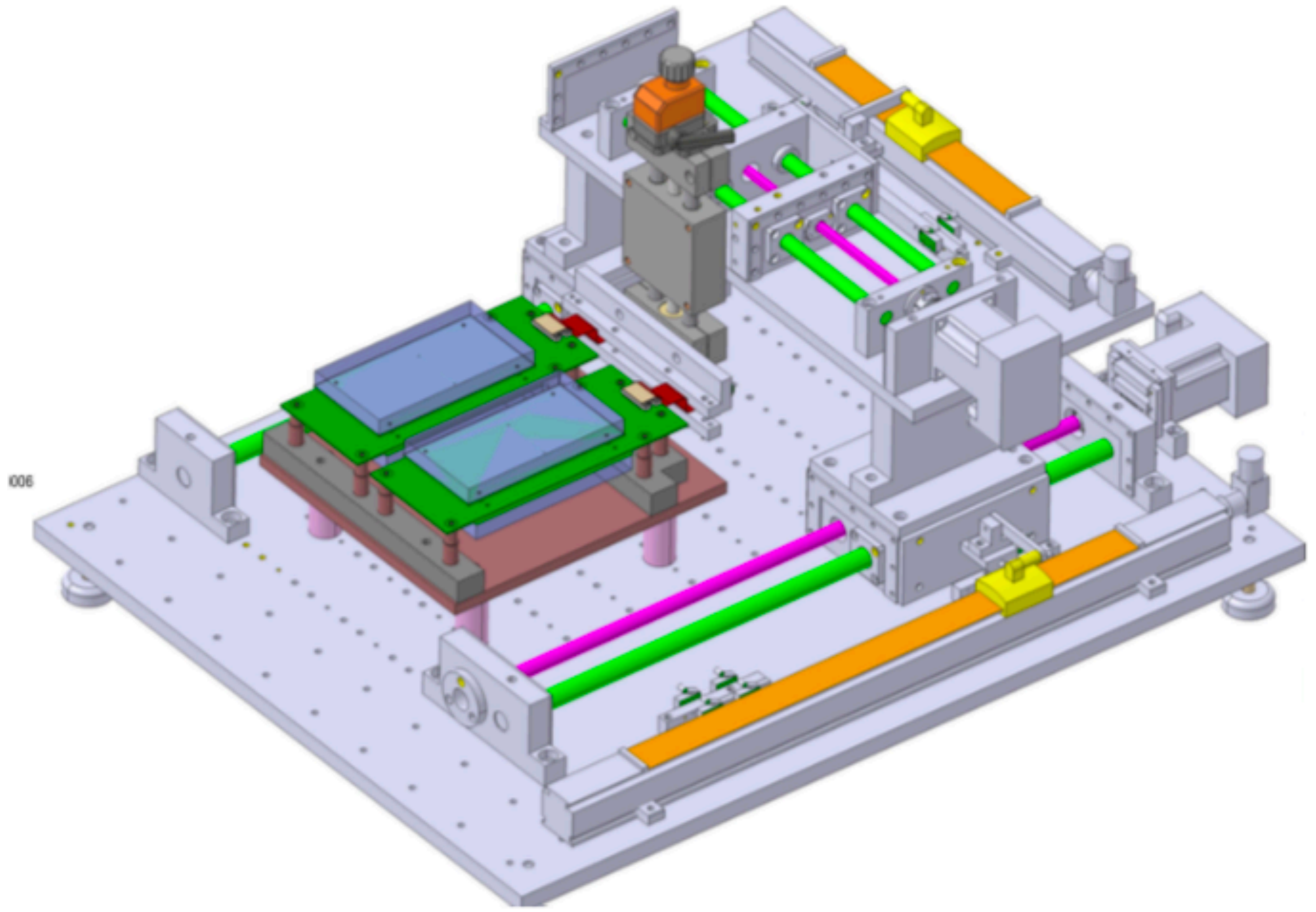
Requirements :

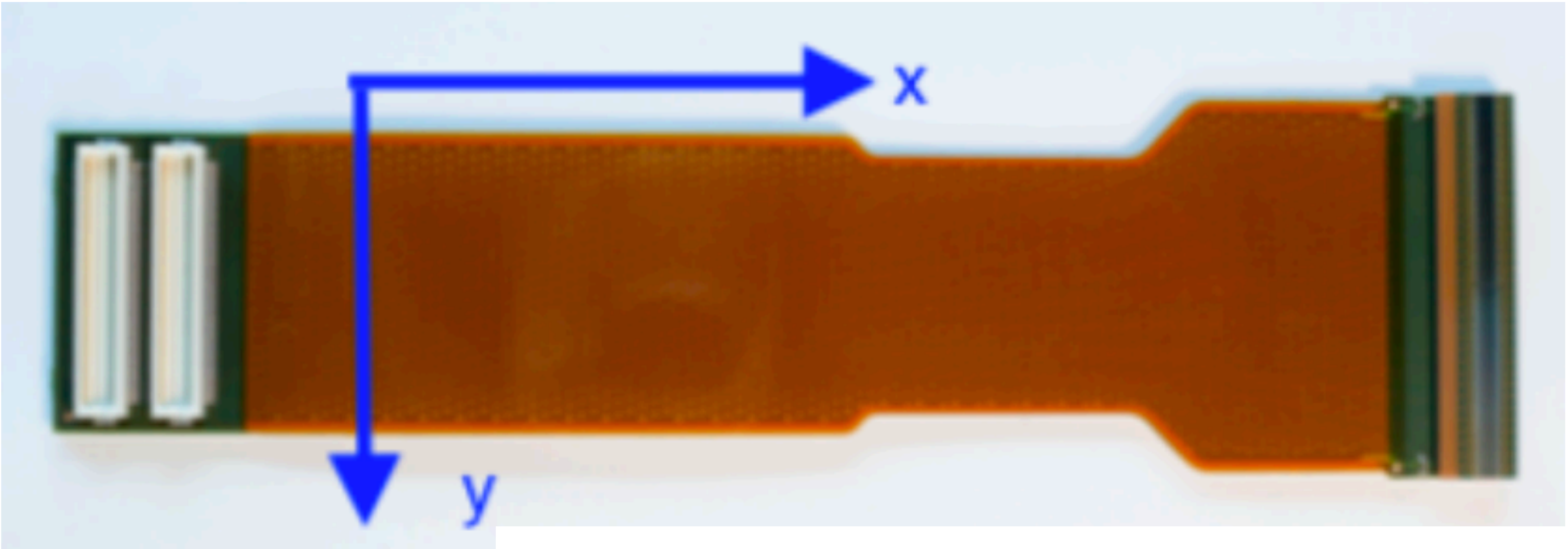
- Hit detection efficiency higher than 98%
- Spatial resolution better than 100µm
- 40MHz readout without dead time
- Operation in radiation environment, fibres 3 neutron shielding) + 100 Gy ionising dose
- Low material with X/X0≤1% per detection lay

Quality assurance

◉ **Tests of the mechanical stability:**

➡After 1000 cycles of displacement in y directions channels start to break

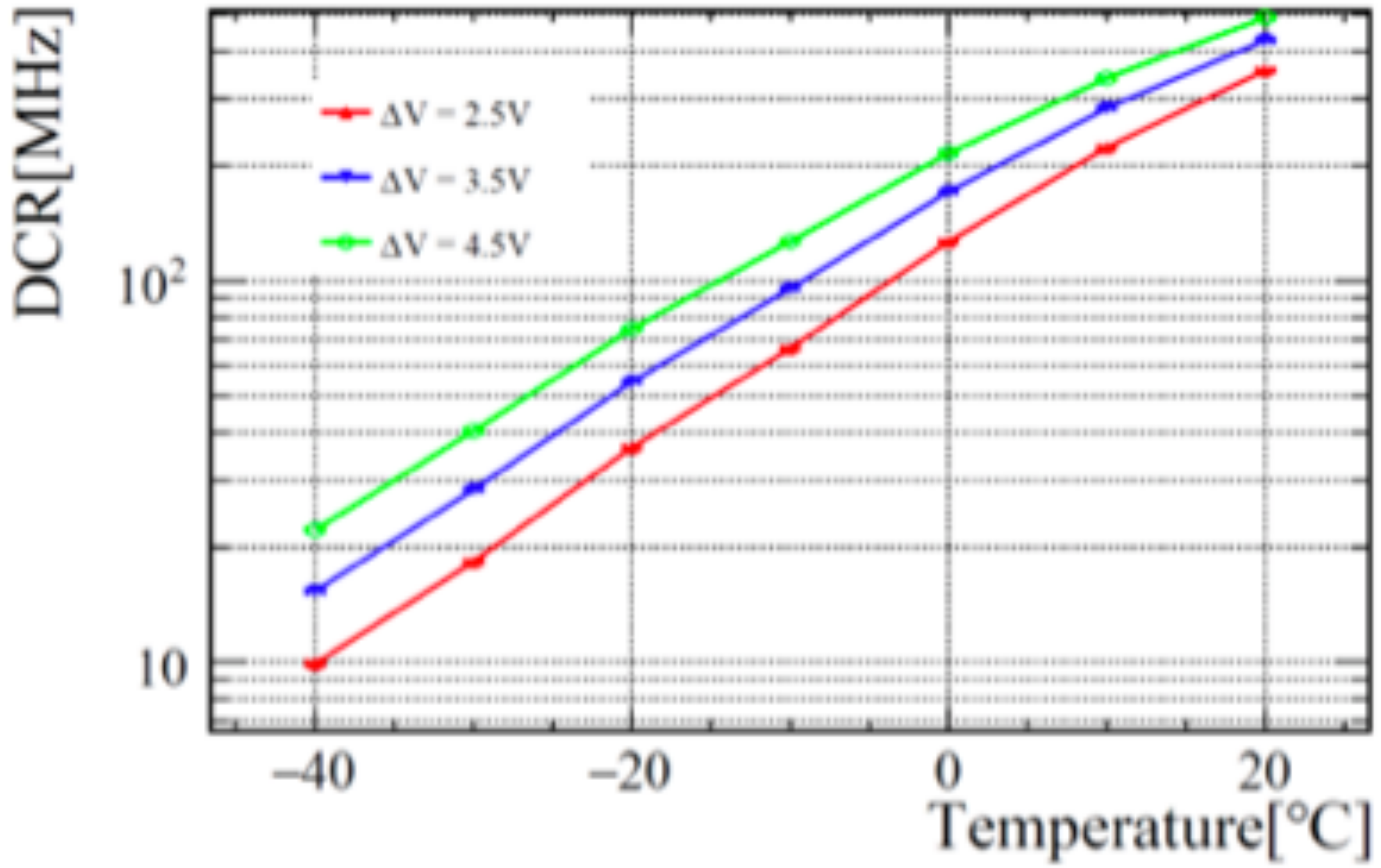




◉ **Simulation of aging with thermal cycling**

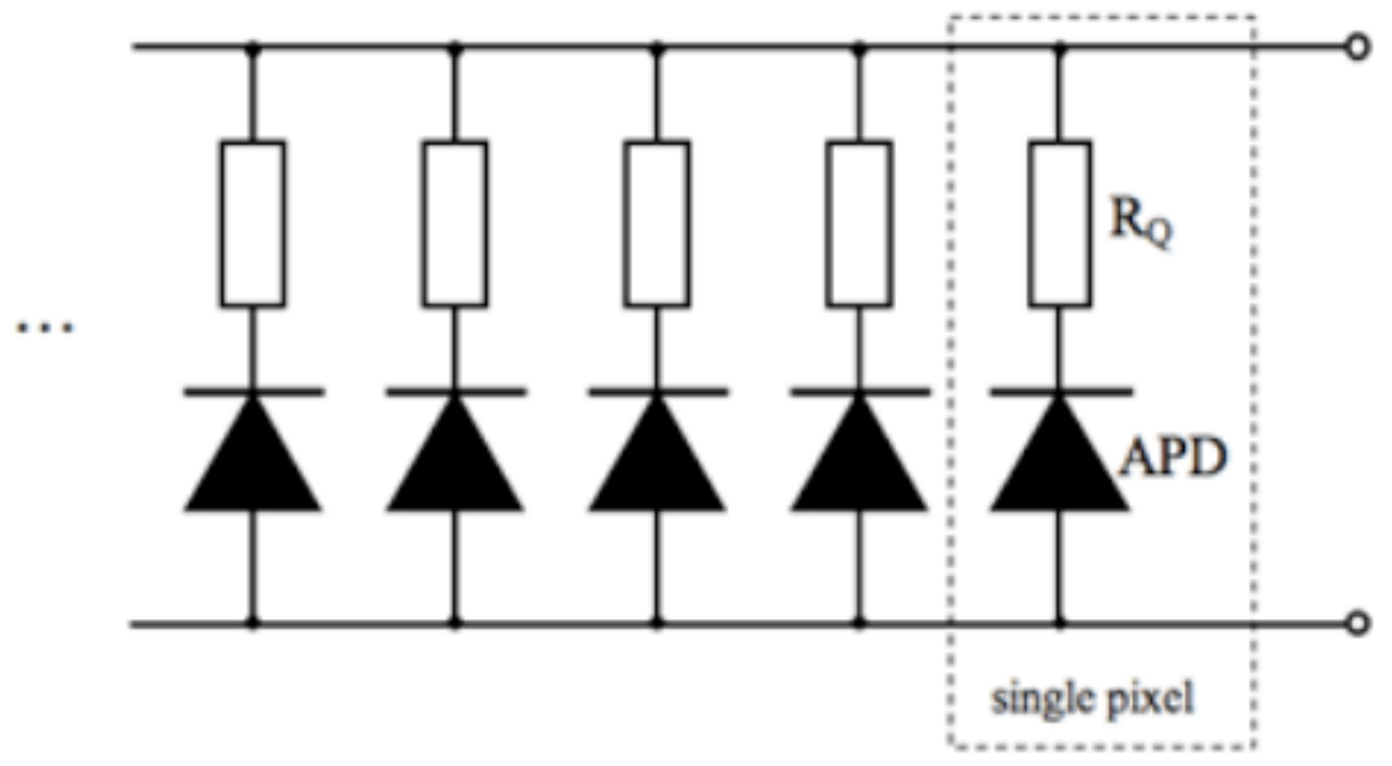
◉ **Irradiation tests:**

➡Increase of DCR from 10kHz at room temperature to 15MHz after annealing at -40°C



Silicon Photomultipliers

- **SiPMs are connected pixels of Avalanche Photodiodes (APDs)**

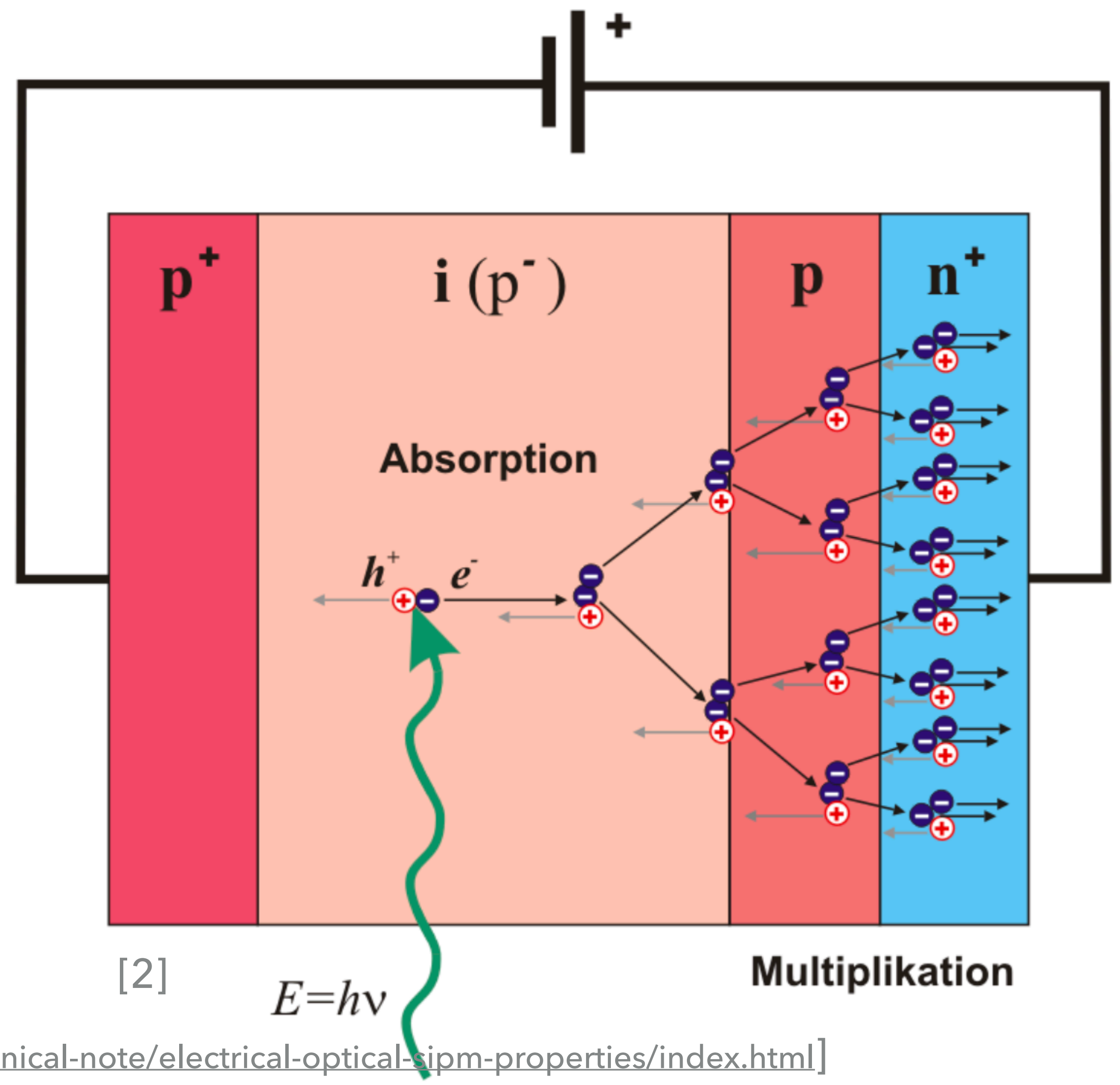


[1]

- **Working principle:**
  - Operated in Geiger-Müller mode with reverse bias voltage V_{Bias}
  - An avalanche effect can be observed in the high electric field region
  - The voltage necessary to obtain a gain larger than 1 is called break-down voltage V_{BD}
  - The gain is proportional to the over-voltage:

$$Q_A \sim \Delta V = V_{Bias} - V_{BD}$$

  - The avalanche is quenched by R_Q

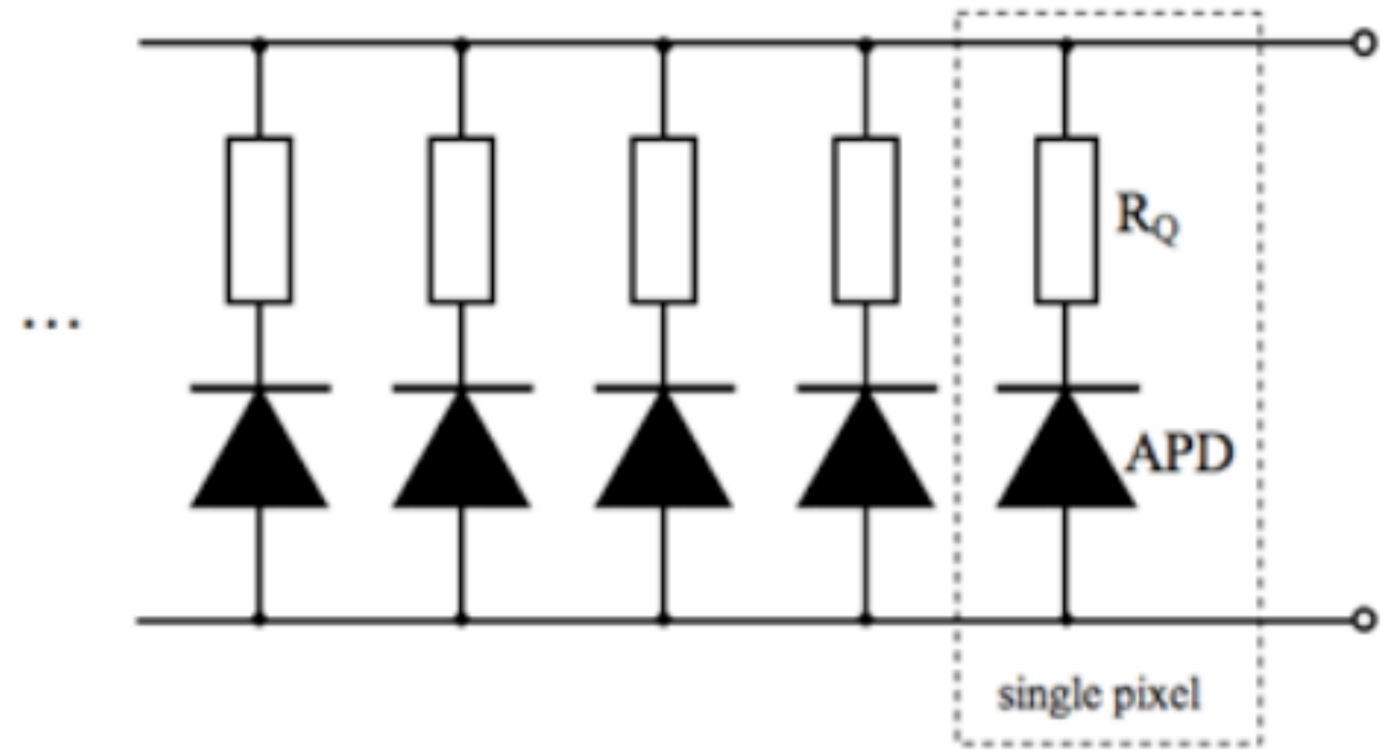


[2]

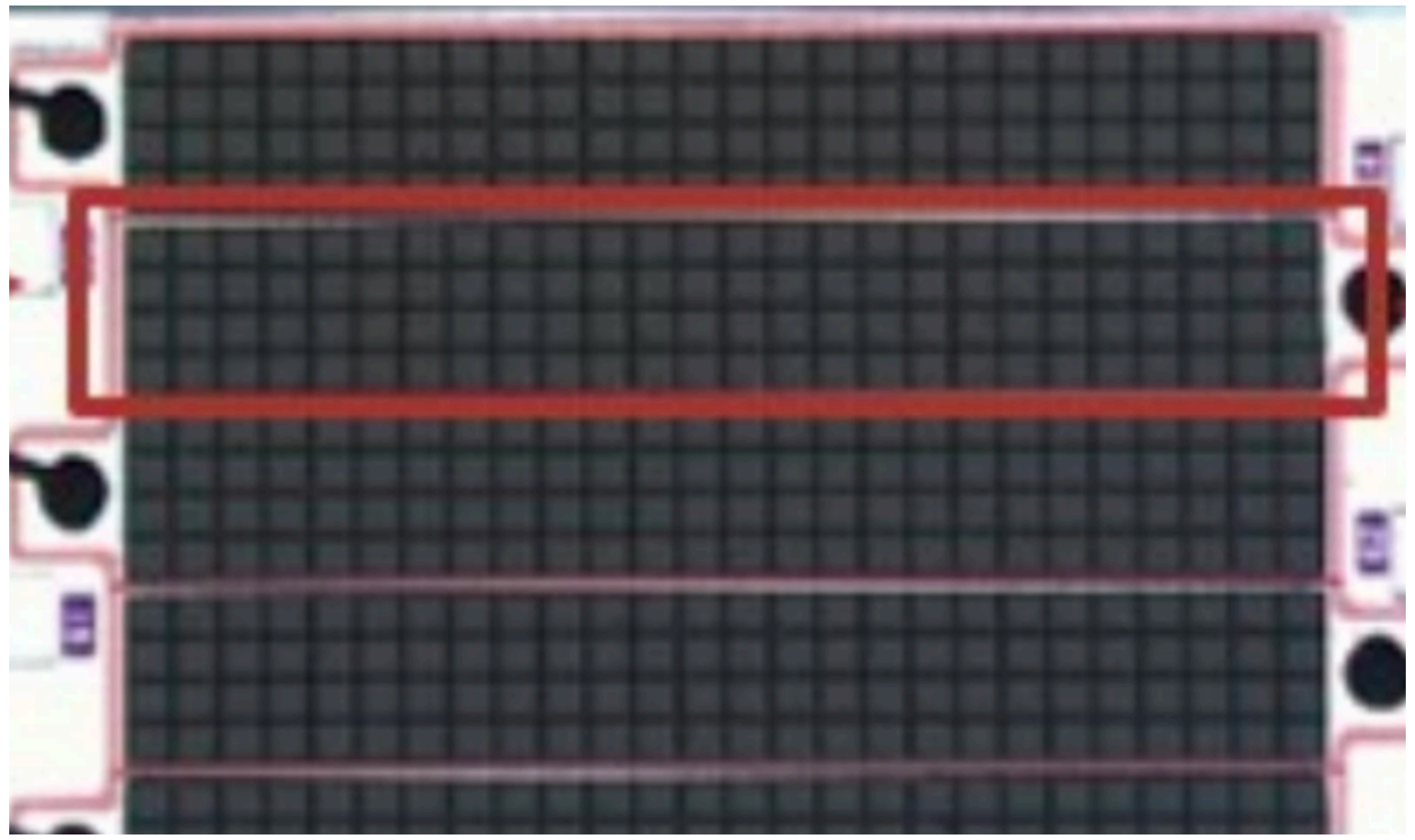
[1] [https://hub.hamamatsu.com/us/en/technical-note/electrical-optical-sipm-properties/index.html]
[2] [https://de.wikipedia.org/wiki/Avalanche-Photodiode]

SiPM design

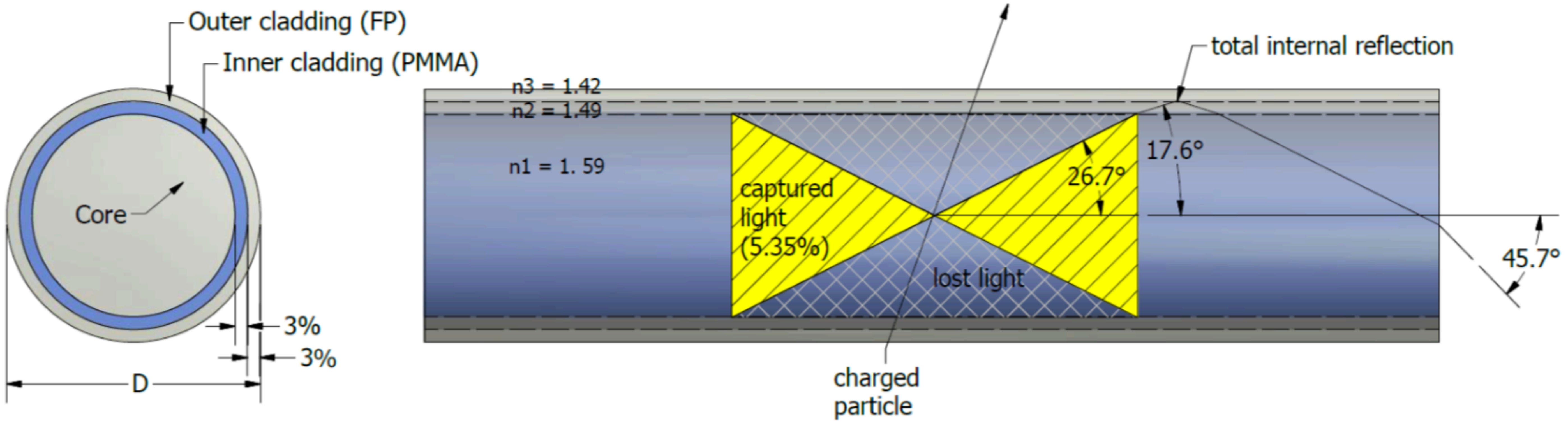
- SiPMs are connected pixels of Avalanche Photodiodes (APDs)

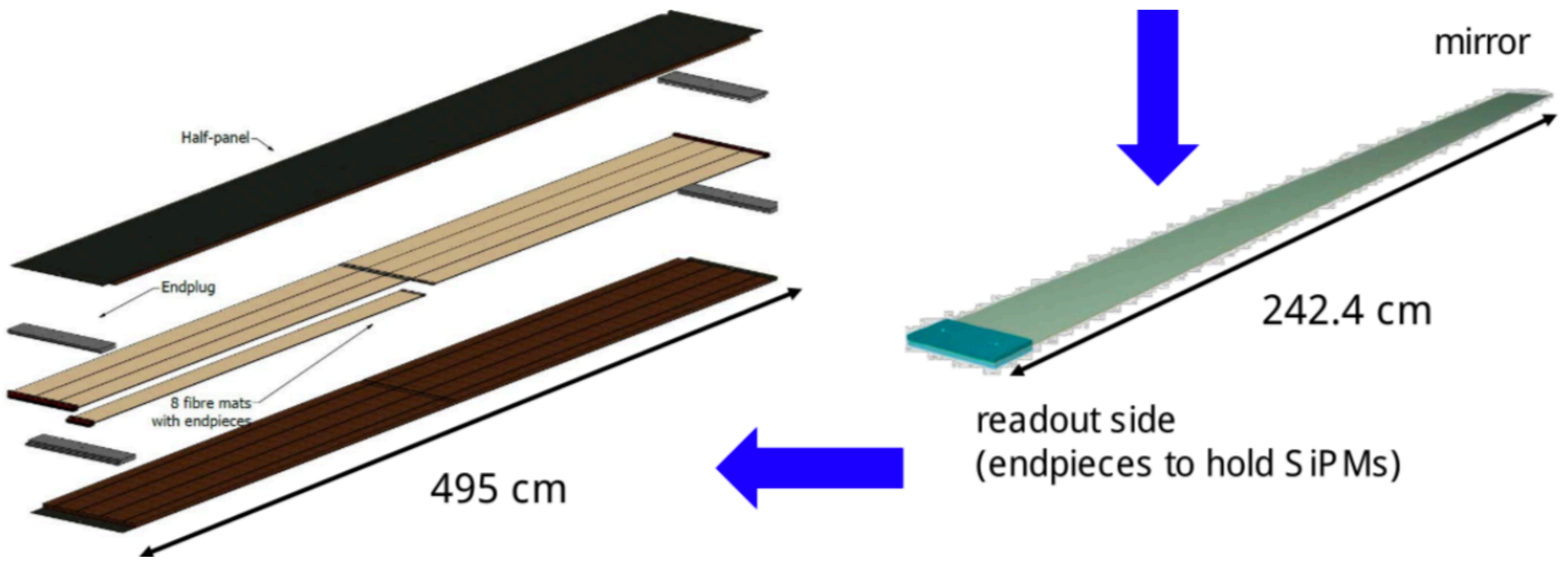


- SiPMs are affected by different noise sources:
  - Studie characteristics for optimised operation of the device
    - ➡ analyse the waveform

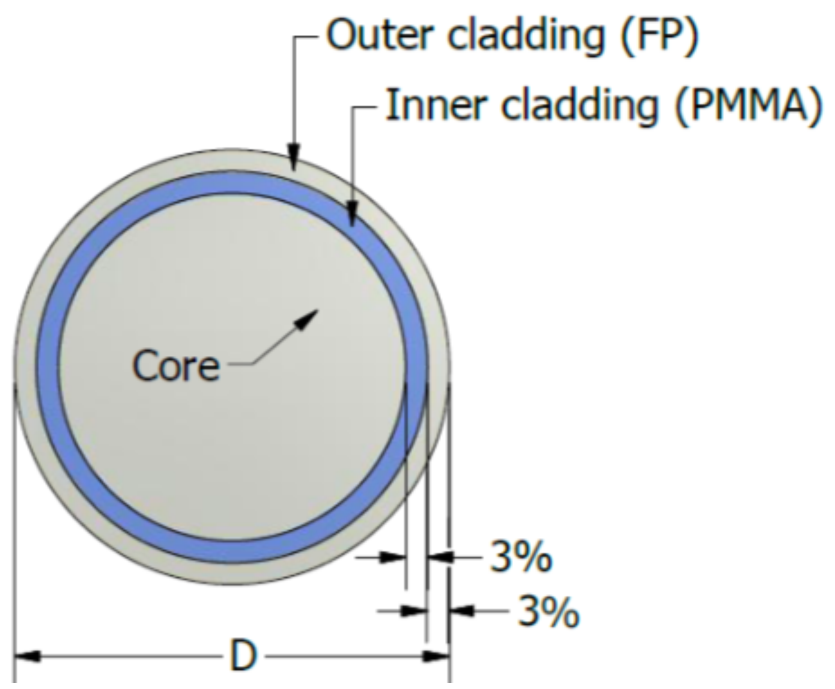


Scintillating fibers



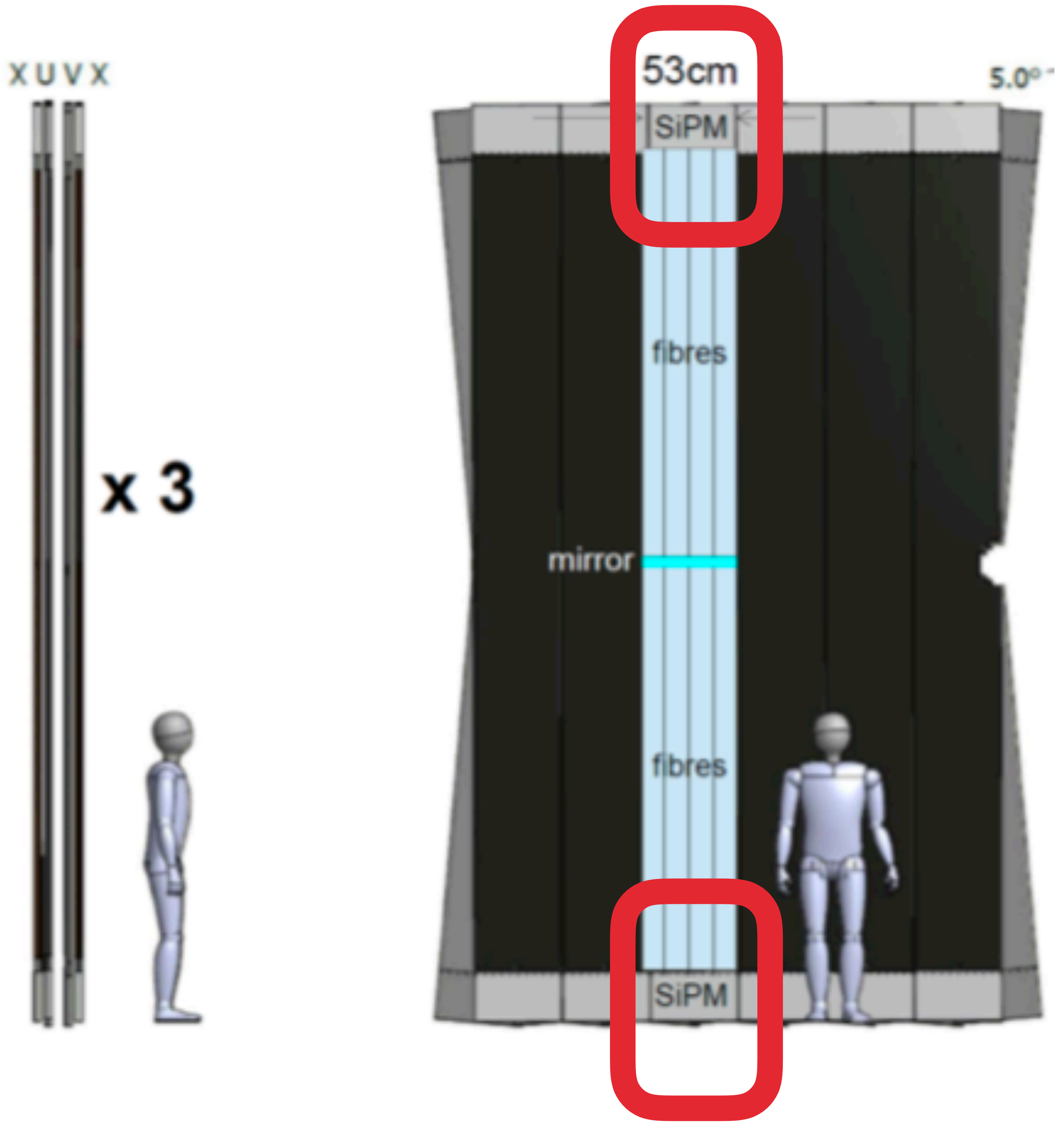


The SciFi project



- **Scintillating fiber mats:**
  - Energy deposition by charged particles
  - Emission of scintillating light
  - El. signal is generated via Silicon Photomultipliers (SiPMs)

- **Detector design:**
- **Fiber mat and modules**
  - 3 tracking stations with 4 layers of 12 modules (total 144 modules)
  - Station midlayers rotated by $\pm 5°$
  - Each fiber mat is attached to 4 SiPMs



[CERN/LHCC 2014-001]

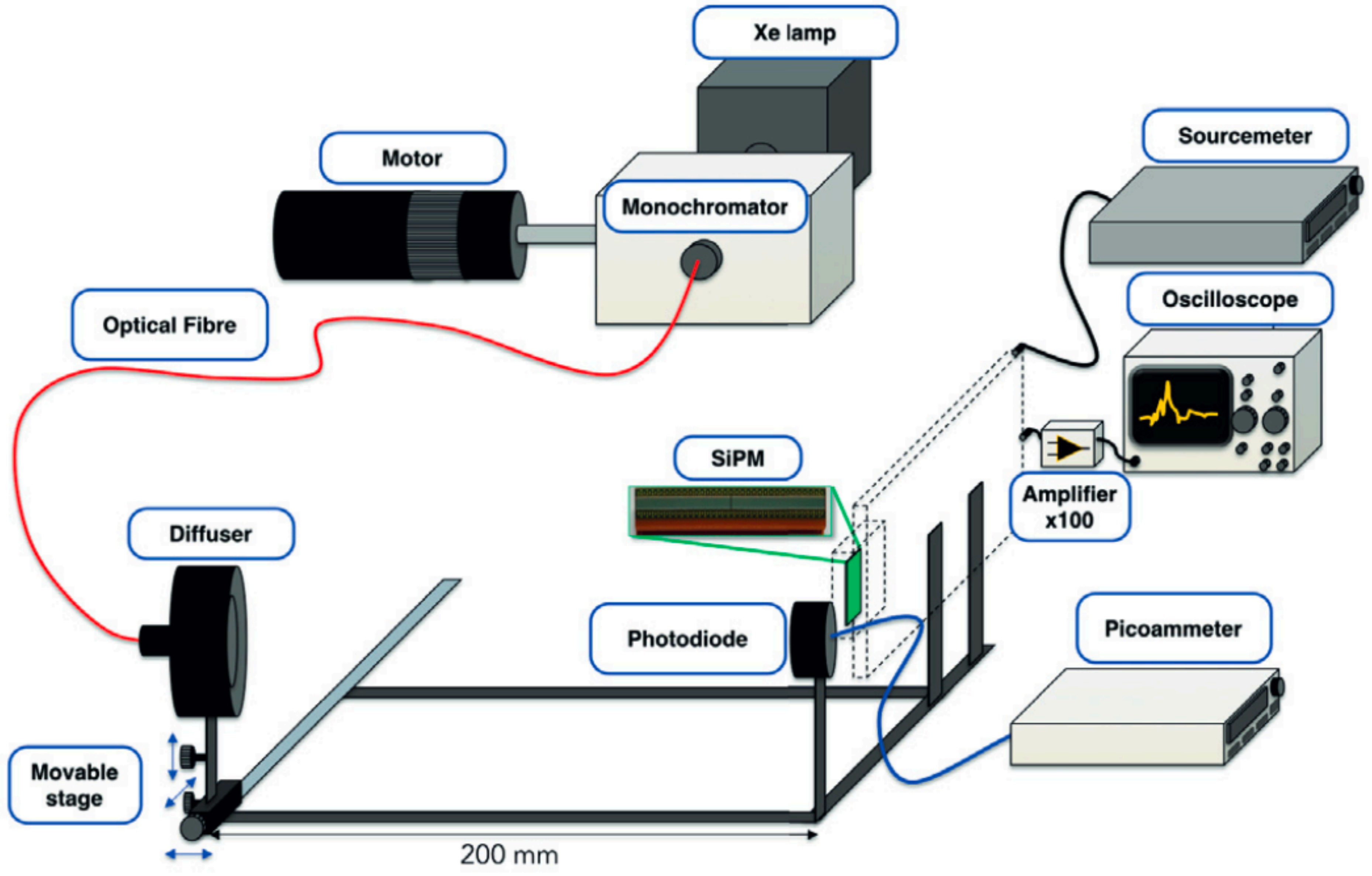
PDE Measurement

- **Measure photo-current in SiPM:**
  - Approximation with
    - ➡ Light current + dark current
    - ➡ Corrections for correlated noise

$$I = R_{detection} \cdot G \cdot e$$

$$PDE = QE_{PD} \cdot \frac{I_{light}}{G \cdot I_{PD}} \cdot \frac{A_{PD}}{A_{SiPM}}$$

- Compare measured values with values from photodiode



[A. KUONEN,EPFL_TH8842.pdf]

Gain measurement

- Measuring gain with voltage or charge amplifier
- Gain determination via numerical integration of single dar or low light pulses

Measured int for a single pulse

$$G = \frac{1}{R_{load} \cdot G_{Amp} \cdot e} \cdot \int U dt$$

$50\ \Omega$

Alternatively:

- Gain determination via I_{dark} and DCR pulse frequency
- Method requires corrections for correlated noise

$$I_{dark} = DCR \cdot G \cdot e$$

SiPM characteristics

- **Photo detection efficiency (PDE):**

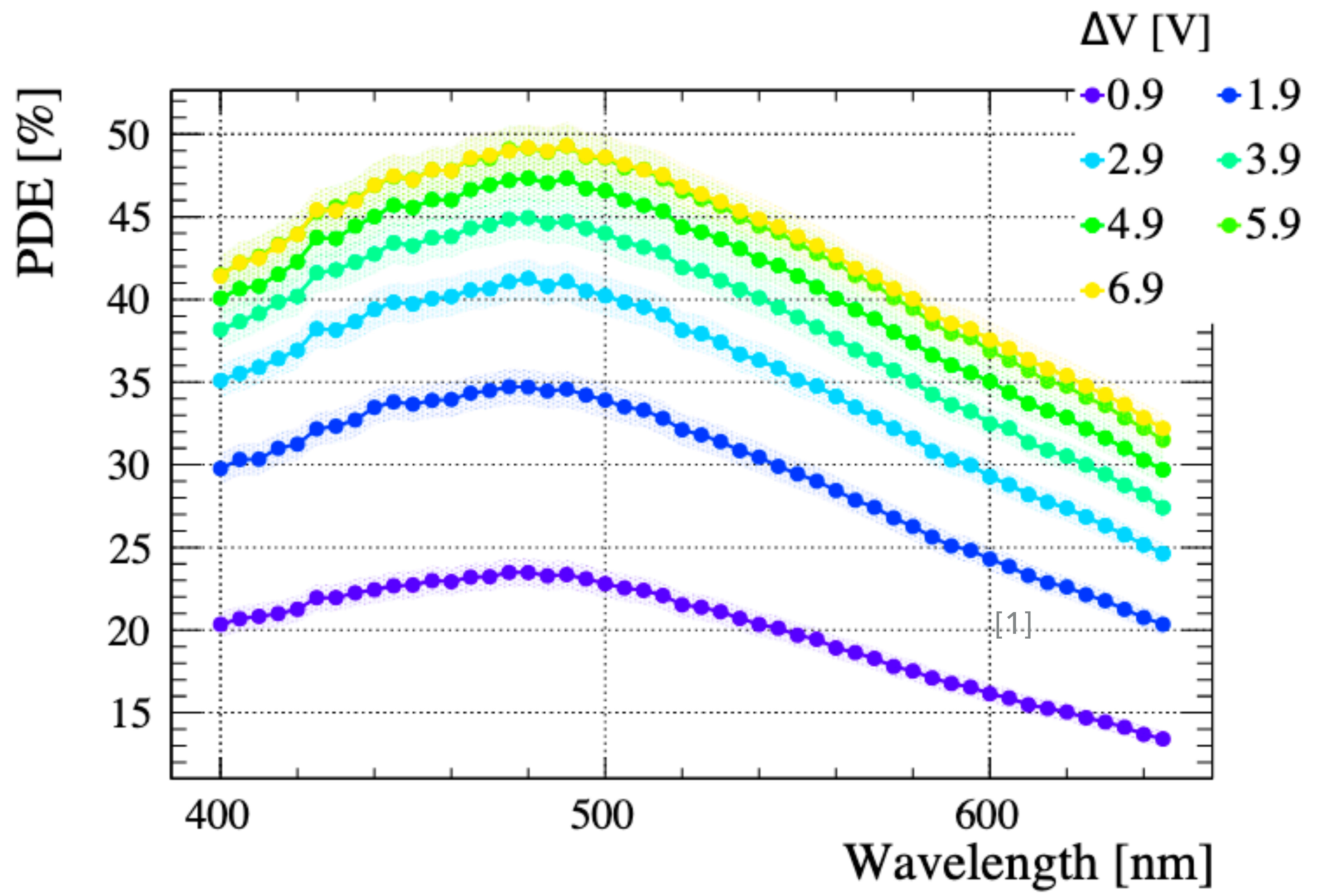
$$PDE = \frac{\#\gamma_{det}}{\#\gamma_{inc}} = QE \cdot \epsilon_{geo} \cdot P_{01}$$

Quantum efficiency

AV probability

Fillfactor

  - Measured as a function of λ and ΔV



- **The created charge from AV divided by the electron charge defines the gain:**
  - Detector is a capacitor : $Q = C \cdot \Delta V$
  - Larger pixels have a higher capacity and therefore, higher gain
  - Typical values for a detector with (50 $\mu m)^2$pixels: $10^6 e/ph \cdot 10^7 e/ph$

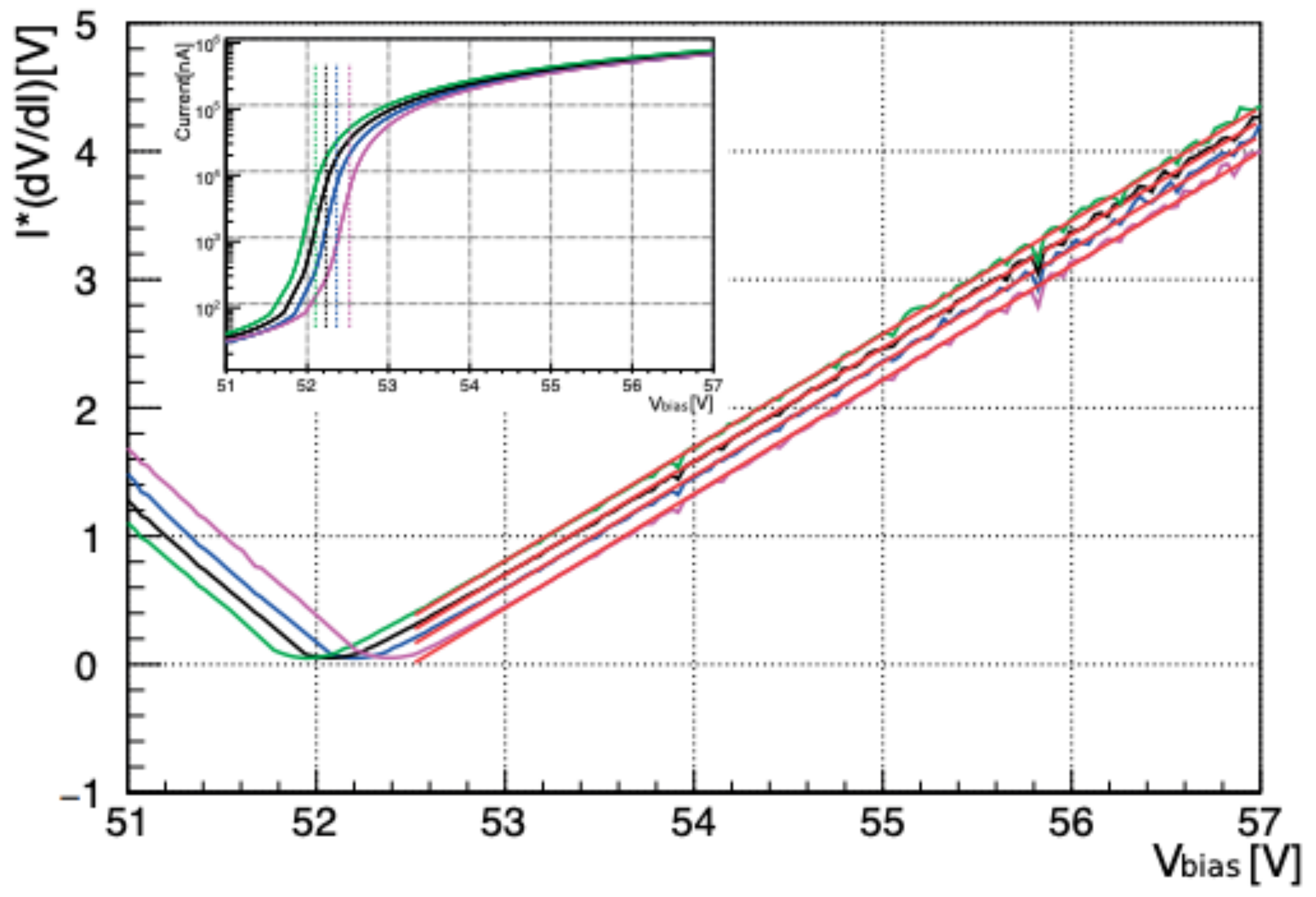
$$(\Delta V = 1 - 7V)$$ [1]

[1] [O. Girard *et al.* ,arXiv:1808.05775]

IV Measurment

- Determination of V_{BD}:
  - ➡ V_{BD} is obtained via a linear fit

$$\left[\frac{d\ln(I)}{dV_{bias}}\right]^{-1} = I \cdot \left[\frac{dI}{dV_{bias}}\right]^{-1} = \frac{V_{bias} - V_{BD}}{\epsilon} \sim \Delta V$$

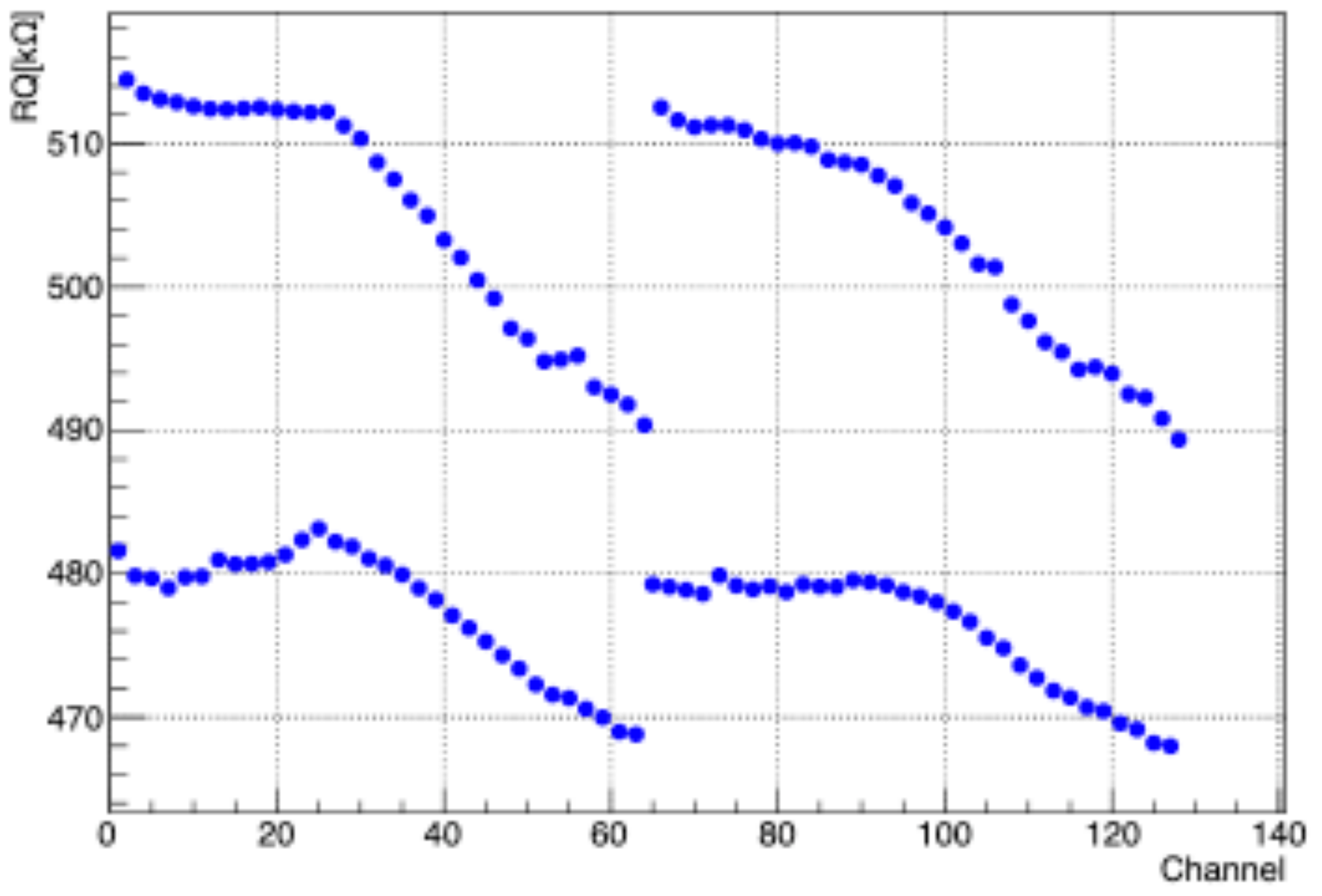


[A. KUONEN,EPFL_TH8842.pdf]

- Measurement of R_Q :
  - ➡ IV scan in forward direction
  - ➡ Linear fit in $\Delta V \subseteq [-3.5, -1]$ V

$$R_Q = N_{pixels} \cdot (dV/dI)$$

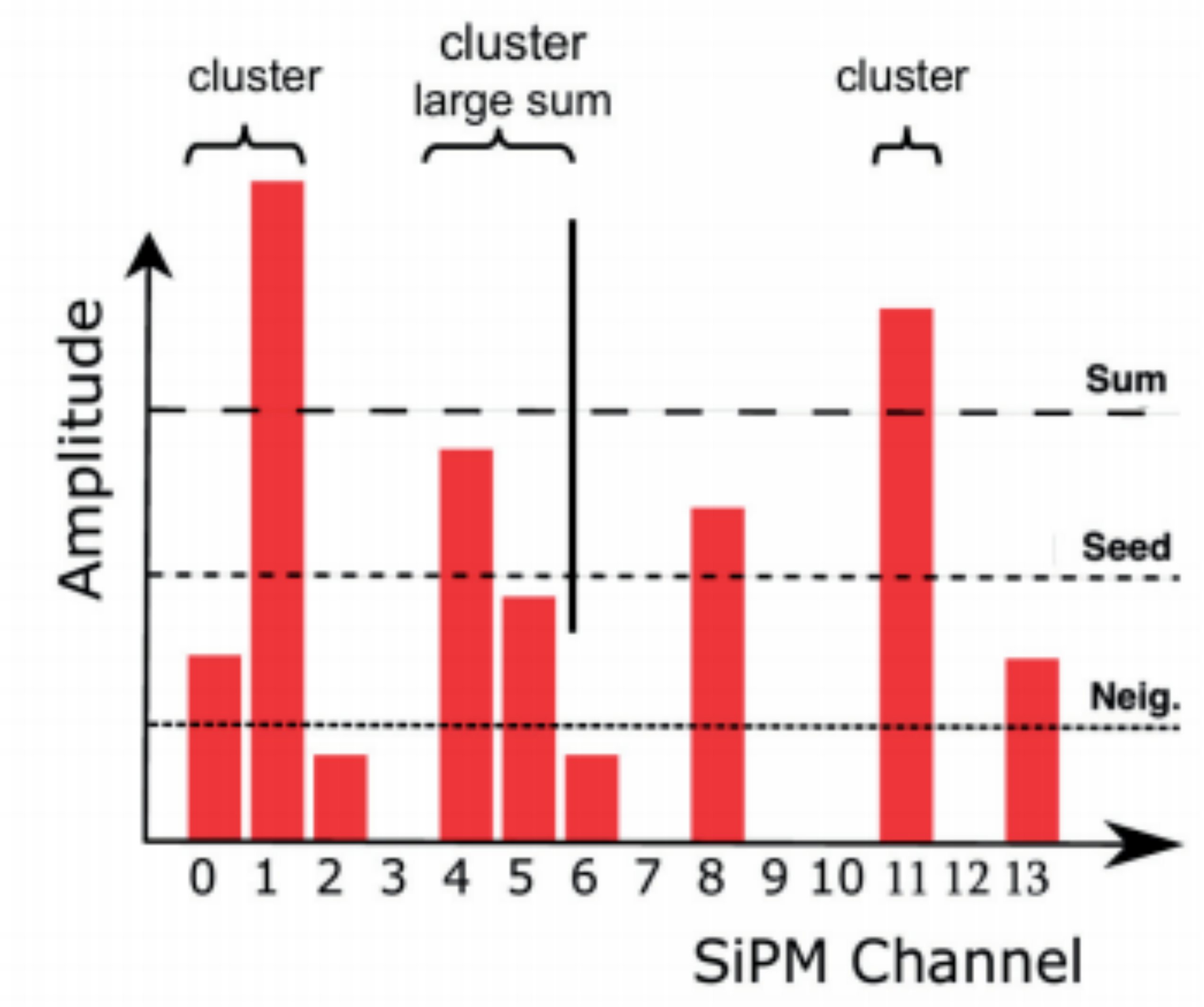
$$R_Q \sim 470 - 570\Omega$$



Light yield and noise cluster rate

- **Light yield measurement with a short fiber module:**
  - Inject e- into fiber module (34 cm)
  - 10-bit clustering algorithm
  - Light yield is the most probable value of the cluster sum for a MIP
  - Corrections for DCR

- **Noise cluster rate (NCR):**
  - Produced by correlate
  - Random overlap dark pulses



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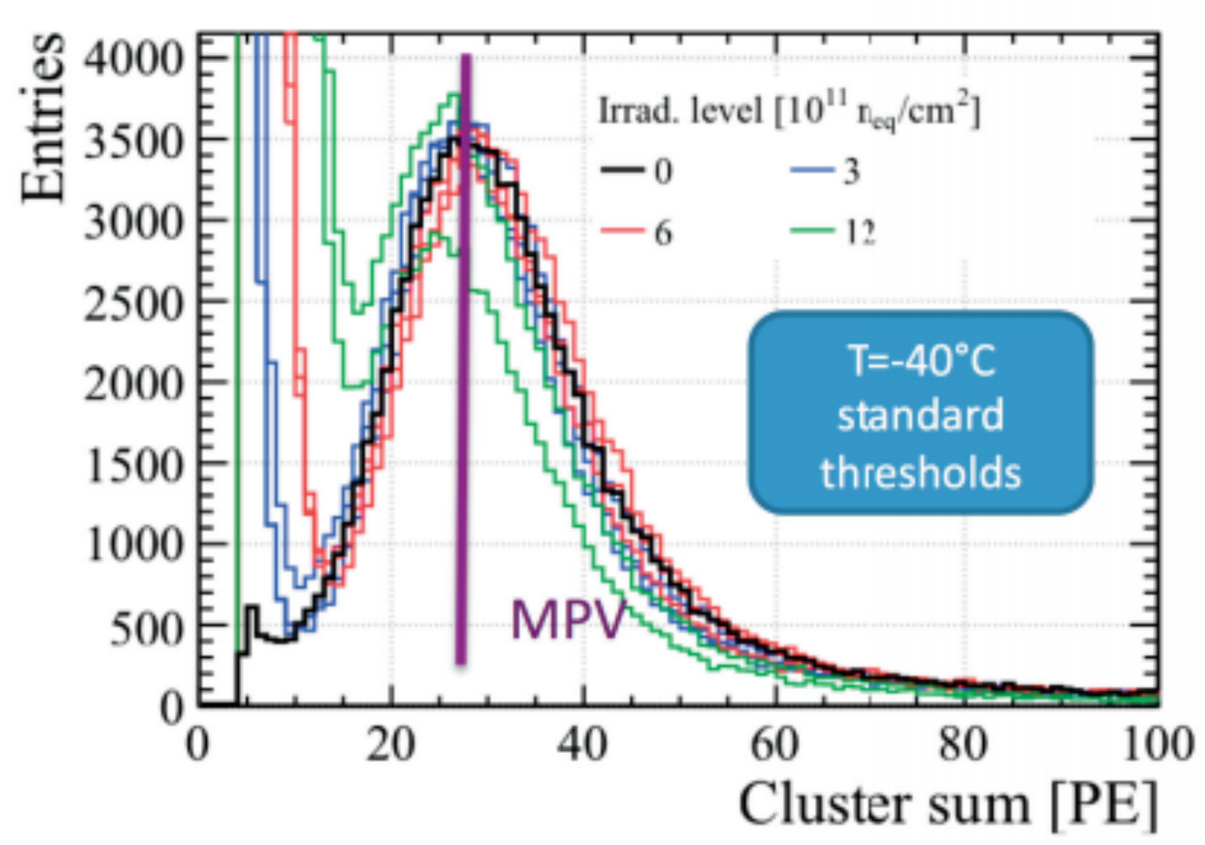
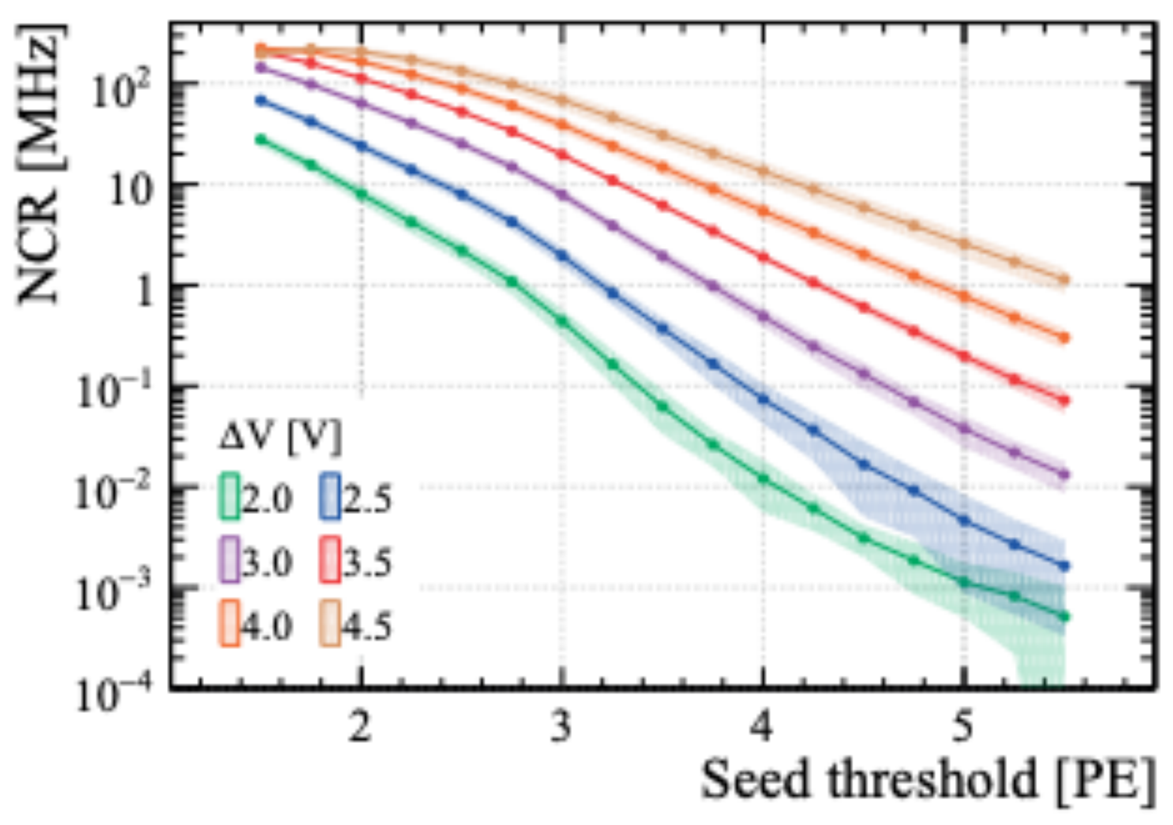


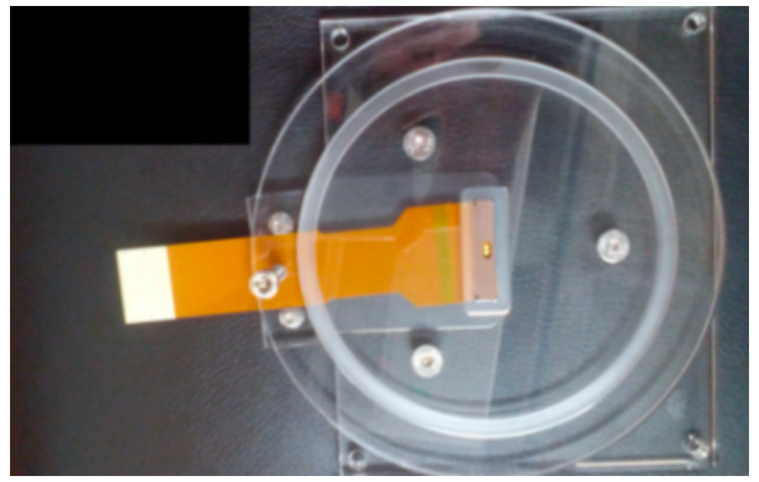


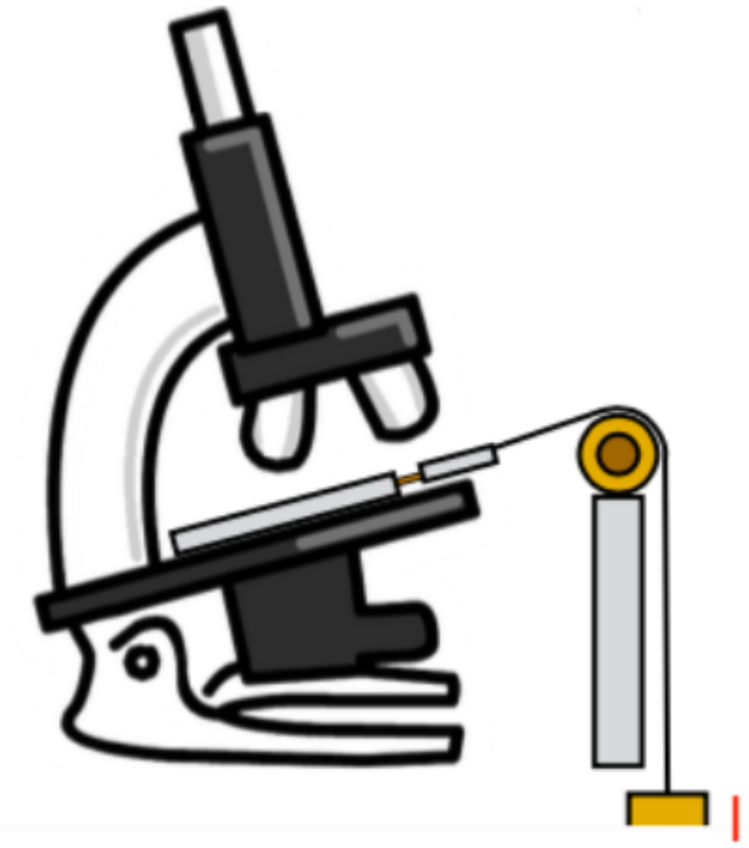
$$f_{NCR} = \frac{N_{NC}}{N_{ev}} \cdot 40\text{MHz}$$

[A. KUONEN,EPFL_TH8842.pdf]

Quality assurance

- **Gluing tests:**
  - No failures under 7h with 3kg
  - No failures under peak traction <10 kg





- **Thermal chamber test (ageing):**
  - 100 cycles -55 to 100 ℃ (= 10 years)
  - Electrical tests

  ➡ No failures

Irradiation tests

- **8 detectors irradiated in Ljubljana (Slowenia):**
  - Neutrons with 3, 6 and $12 \cdot 10^{11} MeV n_{eq}/cm^2$
  - 4 days of annealing at $40°C$
  - DCR measurement:
    - ➡ 15 MHz at $-40°C$ after $6 \cdot 10^{11} MeV n_{eq}/cm^2$
    - ➡ Batch 1: 12 MHz