SiPMs for astroparticle physics applications: Two specific examples

Thomas Huber (DESY / KIT-IKP), on behalf

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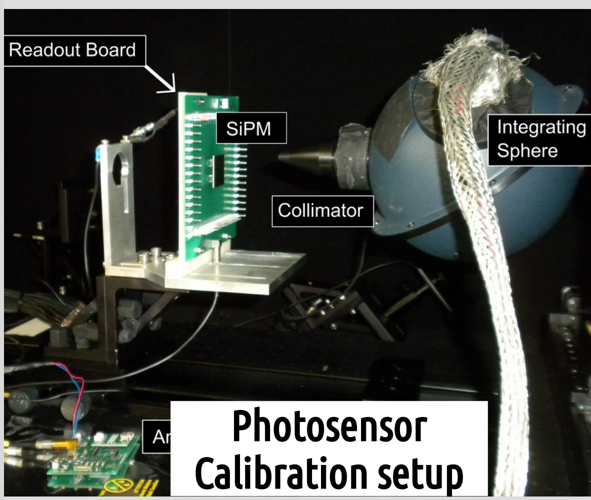
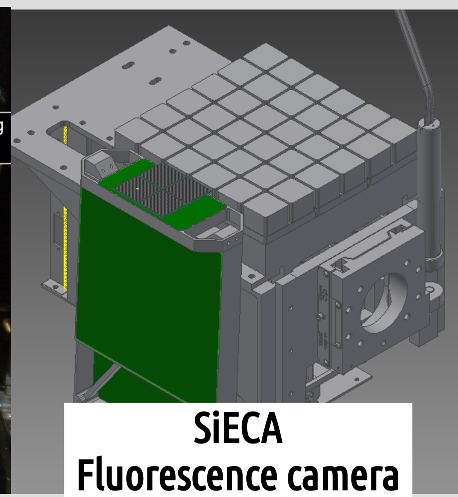
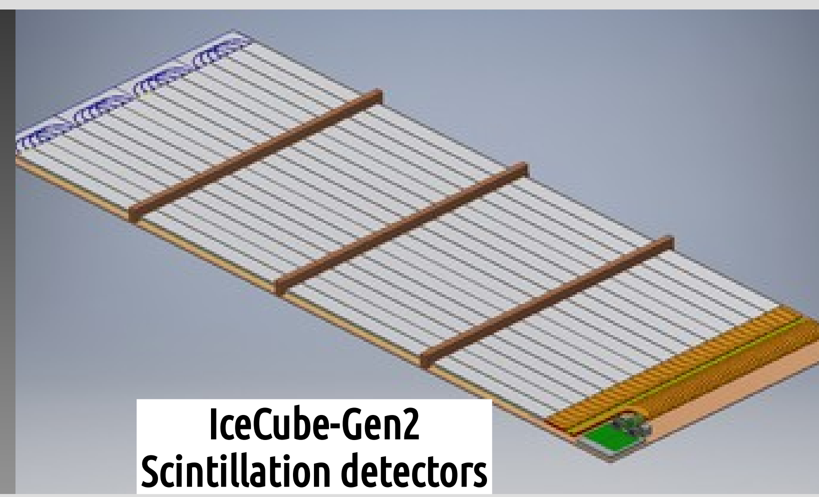
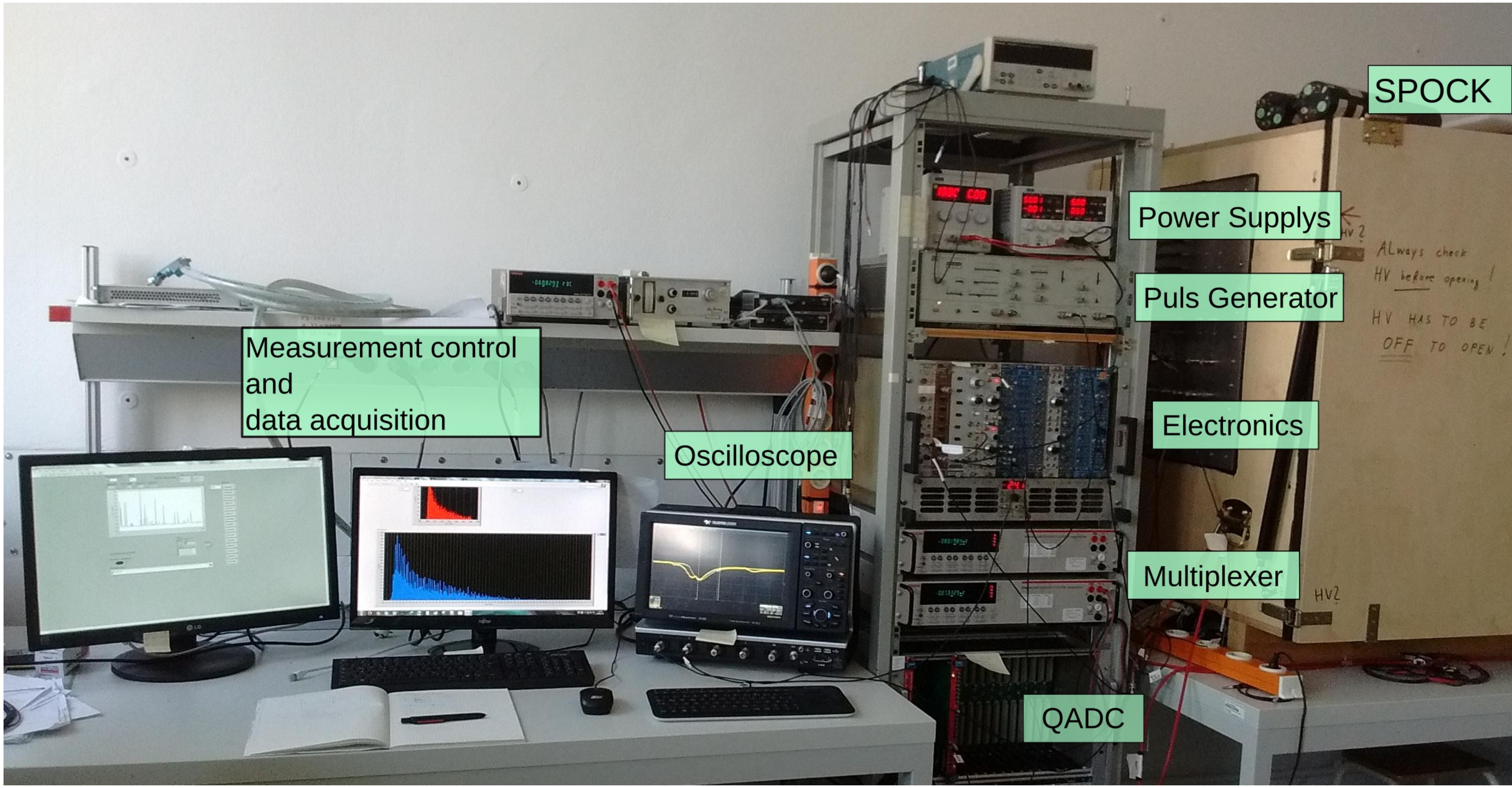
Institut für Kernphysik (IKP)
Karlsruhe Institut für Technologie







Characterising measurement setup (SPOCK)



SPOCK: Single PhOton Calibration stand at KIT

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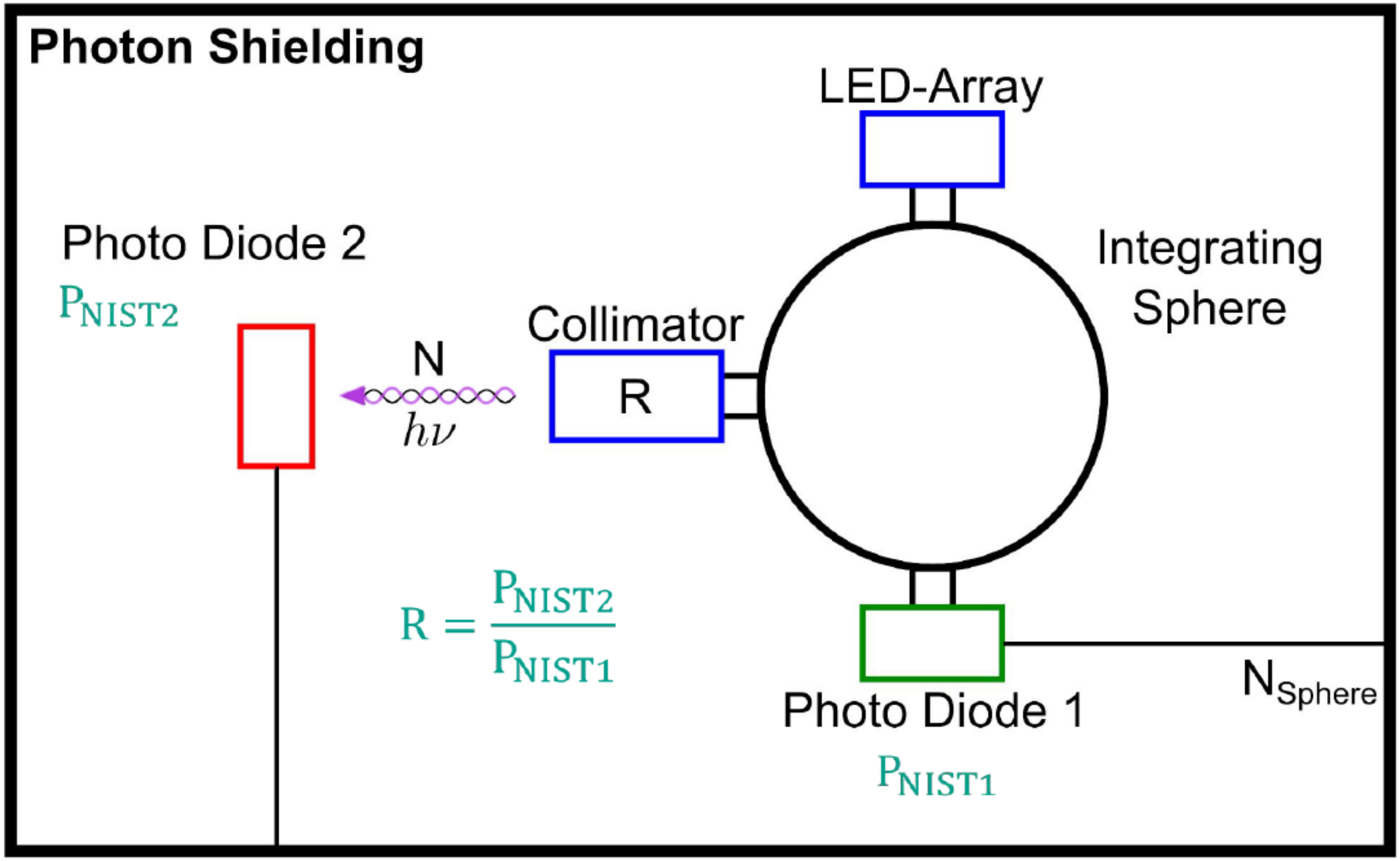
Simplified sketch of measurement method

1 st step: Calibrating the measurement setup:



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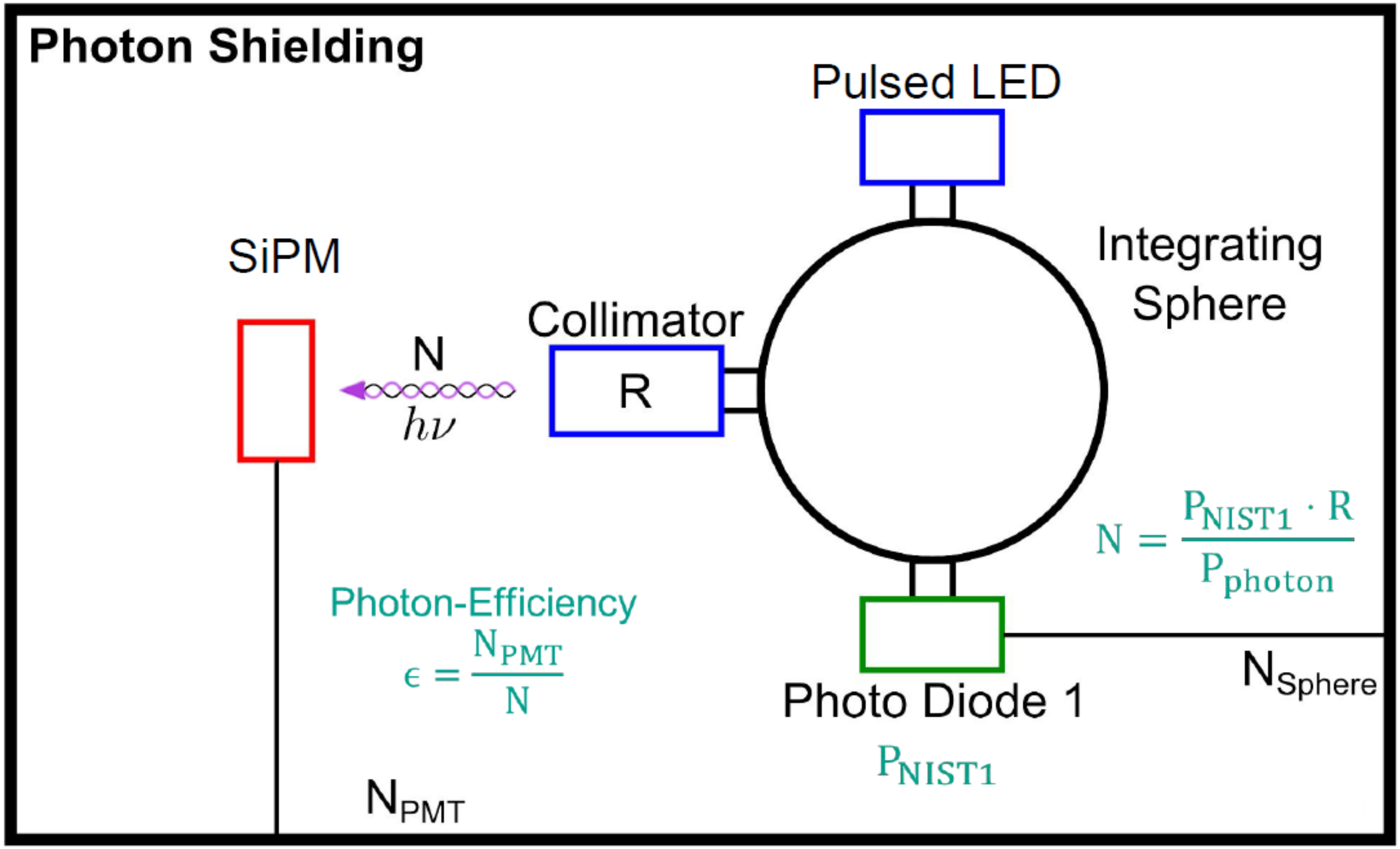
Simplified sketch of measurement method

2 nd step: Charaterize the photo sensor



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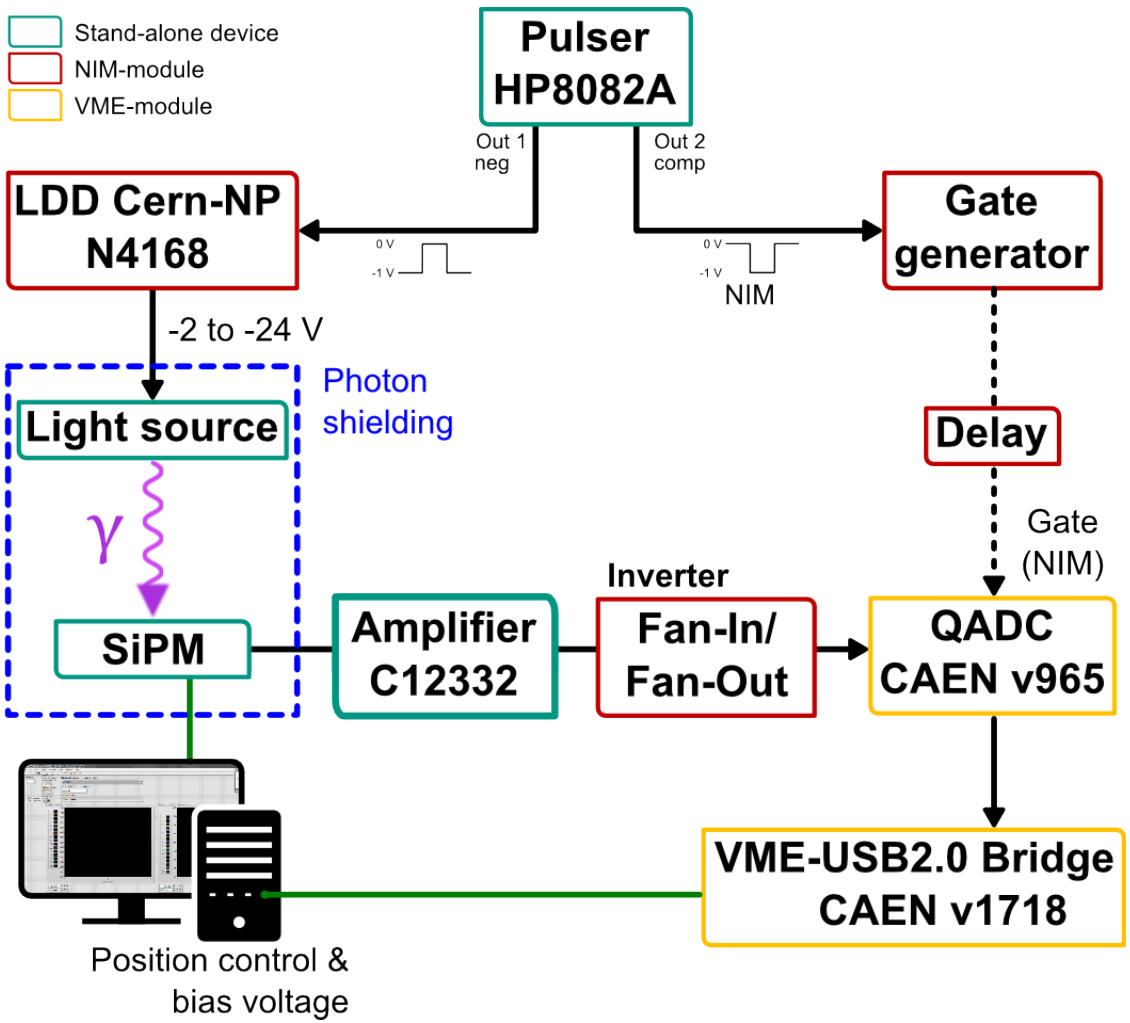
Characterizing SiPMs



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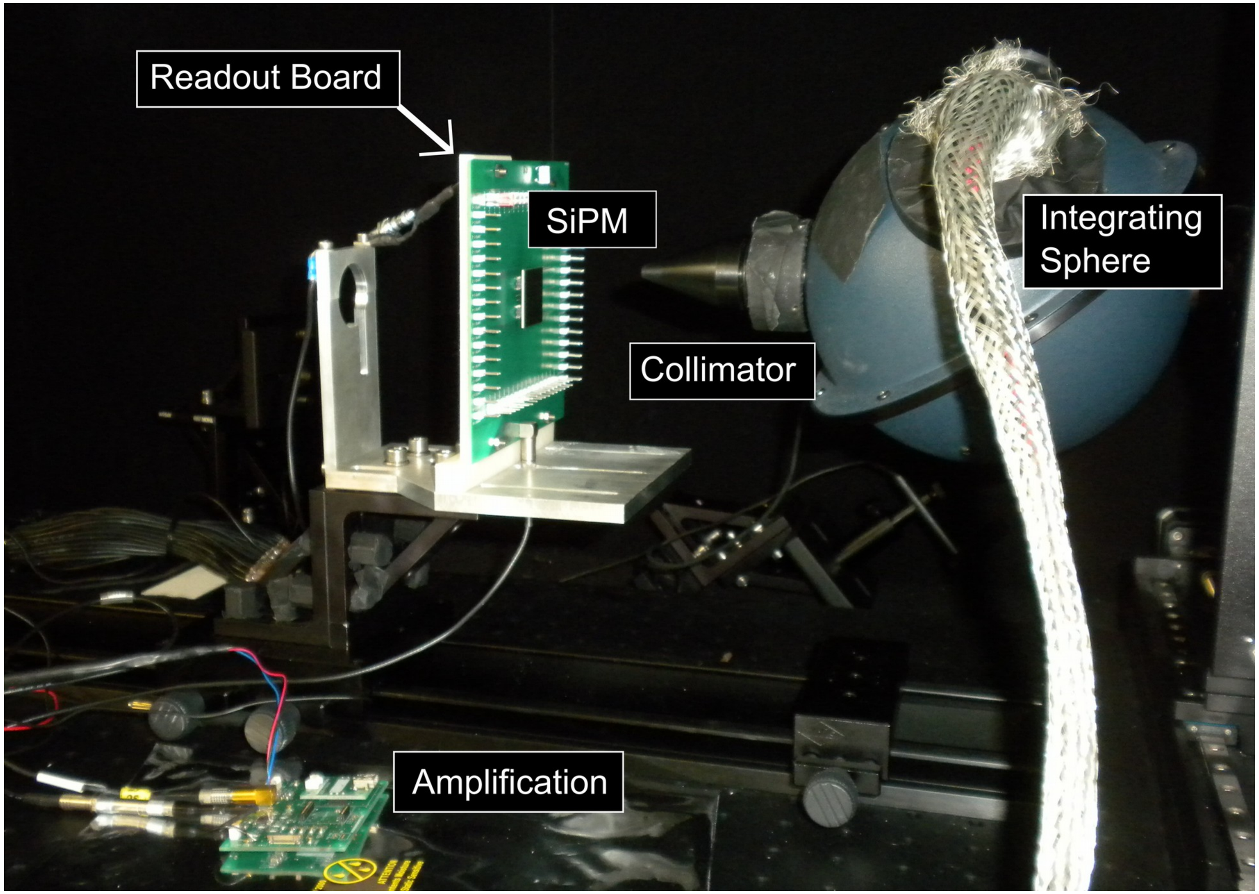
Inside of SPOCK



Collimator Attenuation
- ~10^6 (→ Single photon pulses)

Available Wavelengths:
- 423nm
- 395nm
- 376nm
- 371nm

- Linear stage to automated measurement of more SiPM channels

- Only room Temperature (yet)

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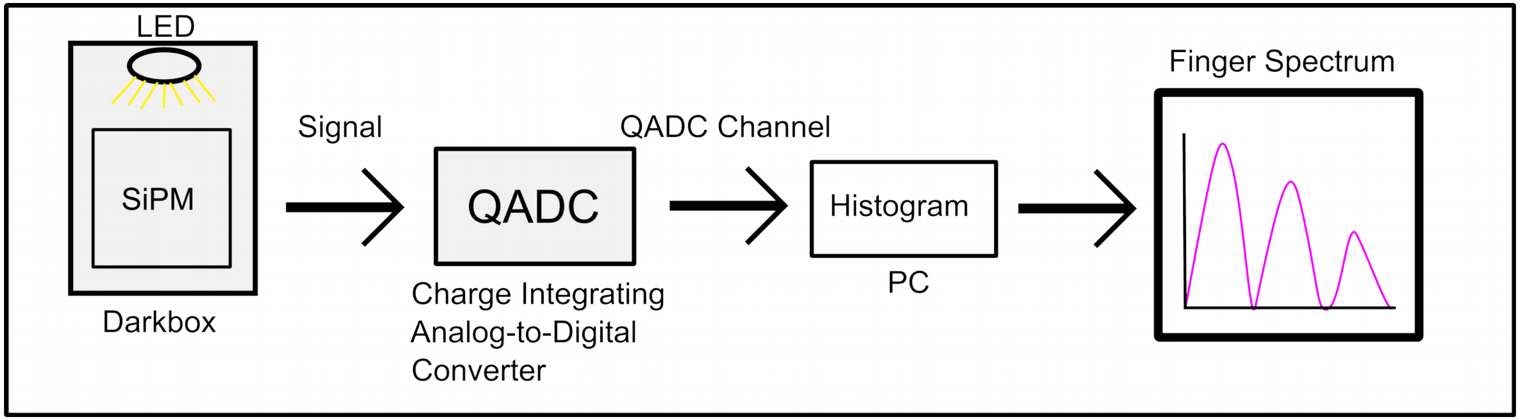
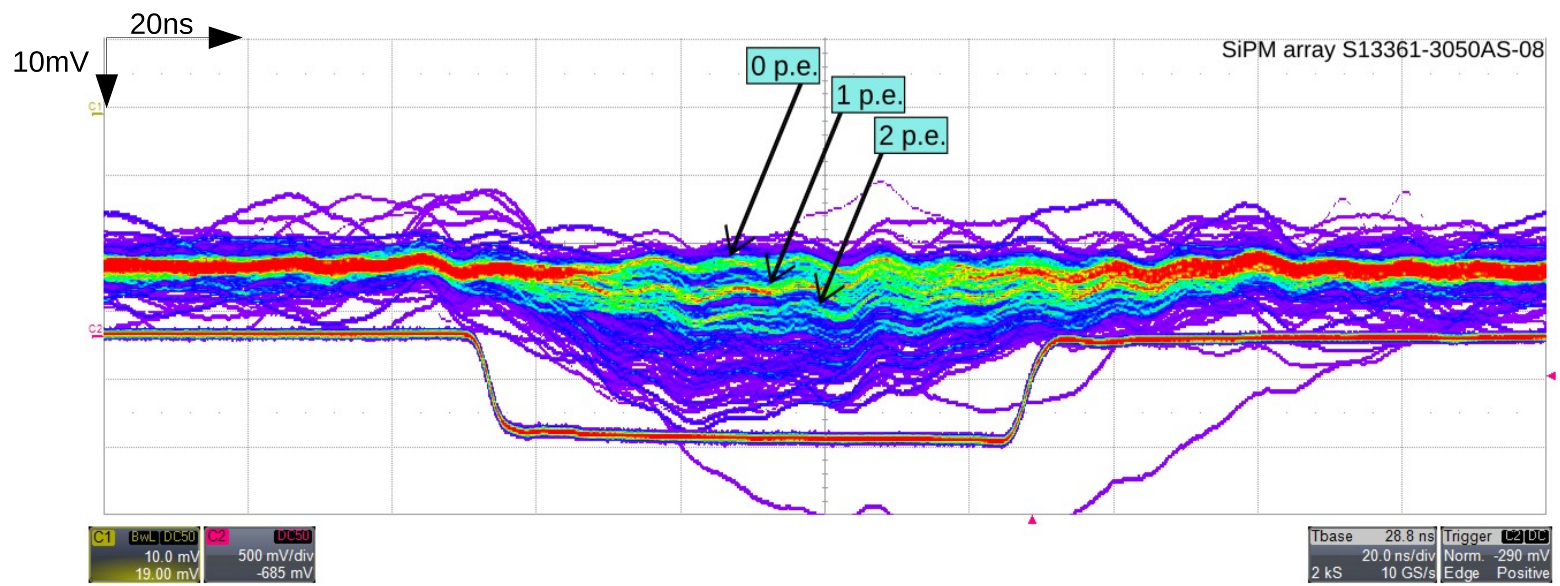
Towards charge spectra





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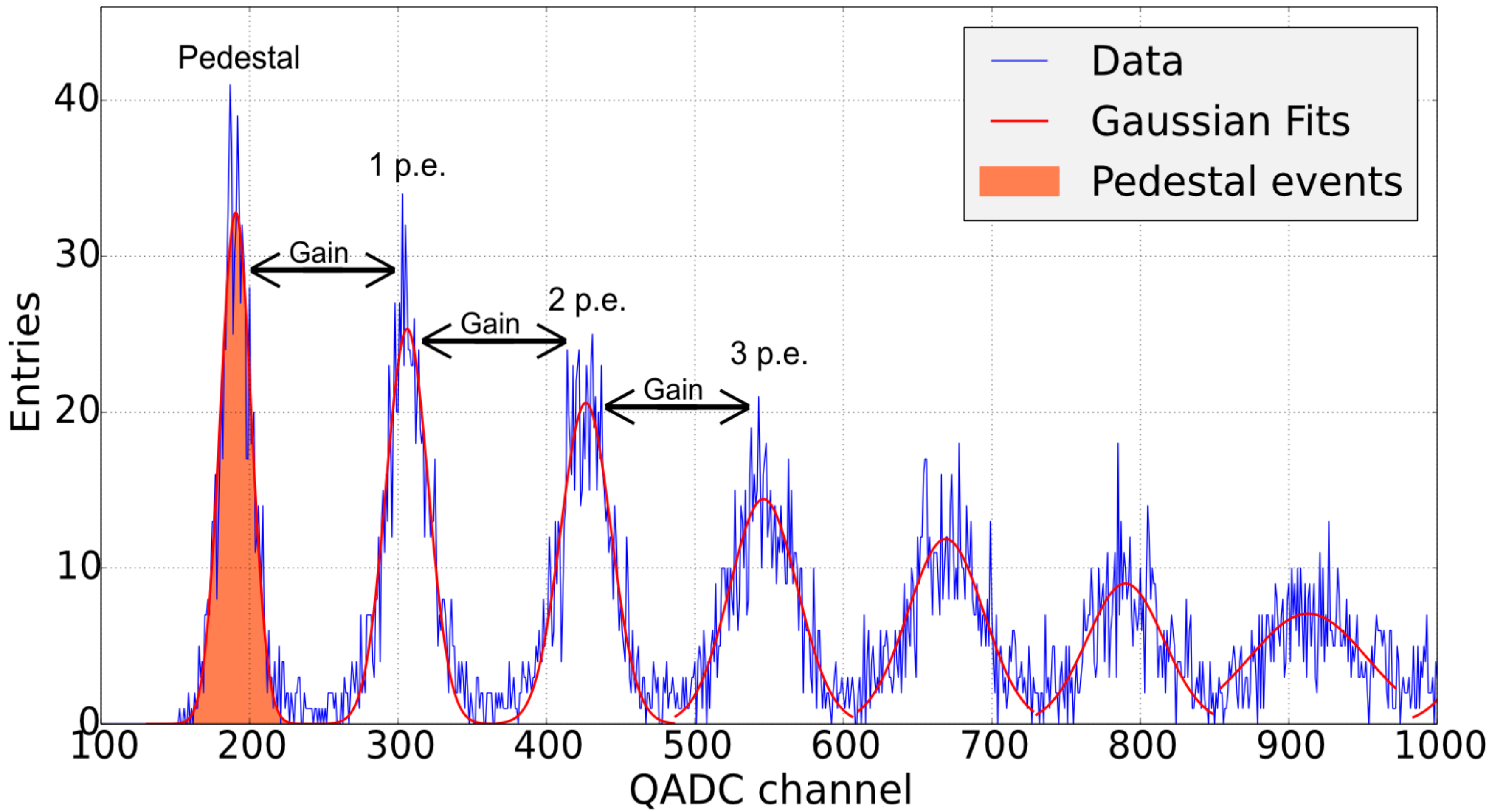
Characterizing SiPMs – Finger spectrum



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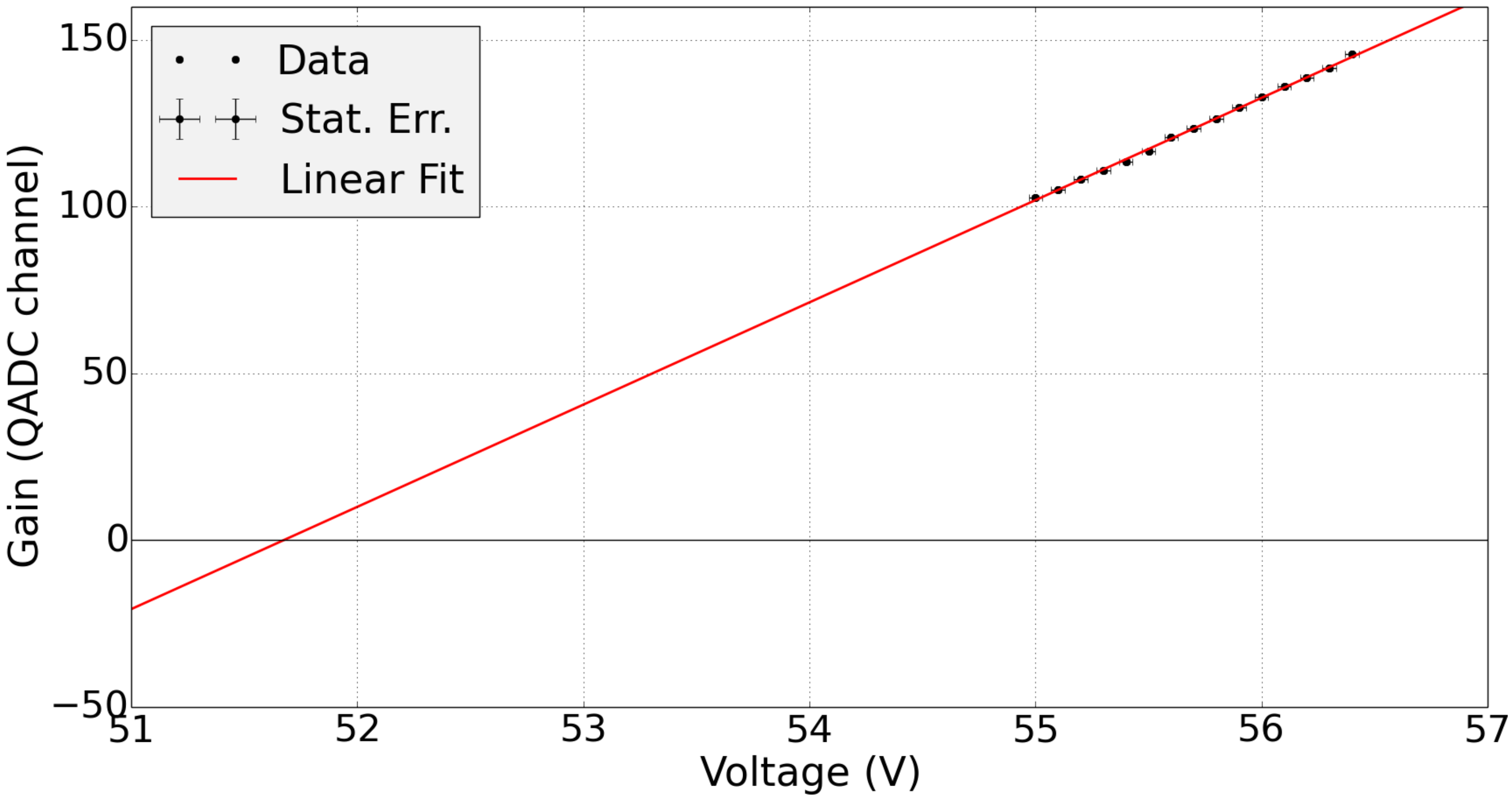
Characterizing SiPMs – Breakdown Voltage



Gain-measurements at different over voltages
→ Extrapolating gives breakdown voltage estimate

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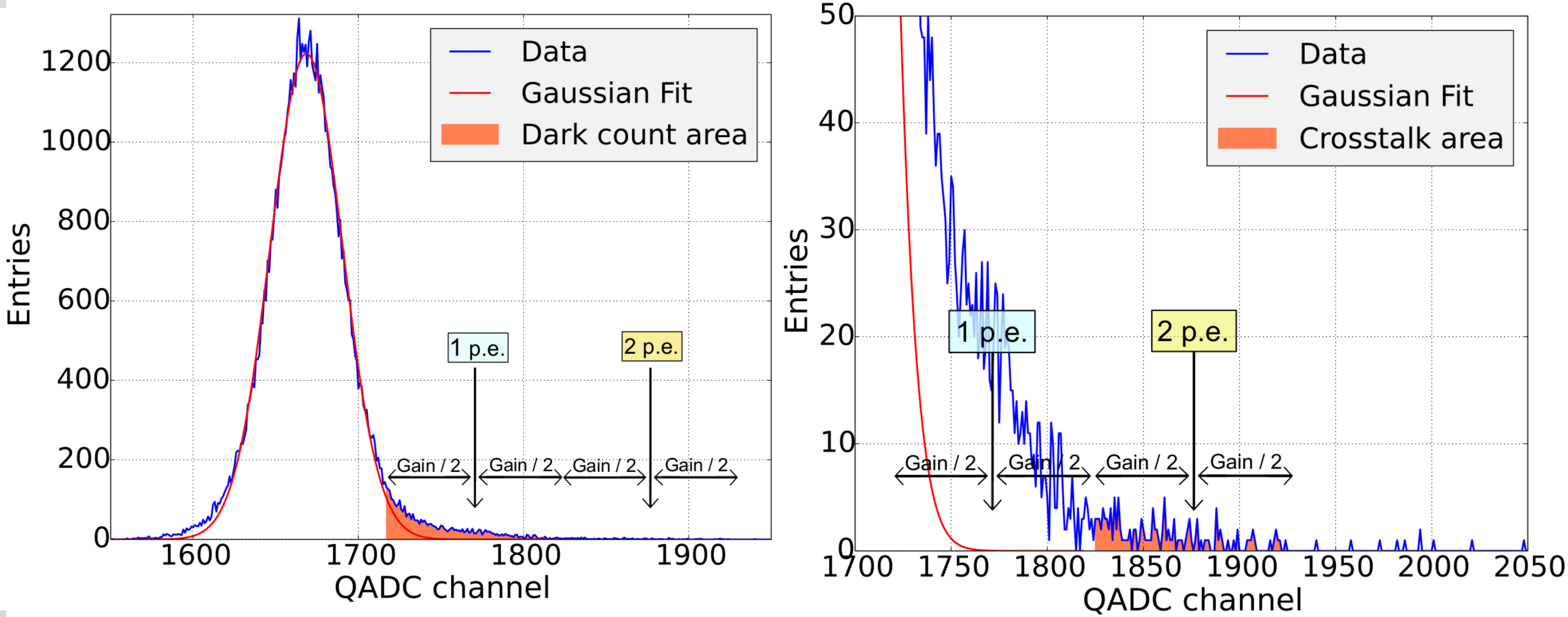
Characterizing SiPMs – Dark Spectrum



(p.e. peak positions as result of gain measurement before)

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Characterizing SiPMs – Dark Count Rate and Crosstalk Probability

<u>Dark Count Rate</u>

All dark events after the pedestal are assumed to be dark count events.
→ Dark Count Rate ξ :

$$\xi = \frac{N_{p.e.>0}}{t_{gate} \cdot N_{tot}}$$

<u>Crosstalk Probability</u>

All dark events in the second p.e. region are assumed to be crosstalk events generated by dark counts.
→ Crosstalk Probability ε :

$$\epsilon = \frac{N_{p.e.=2}}{N_{p.e.>0}}$$

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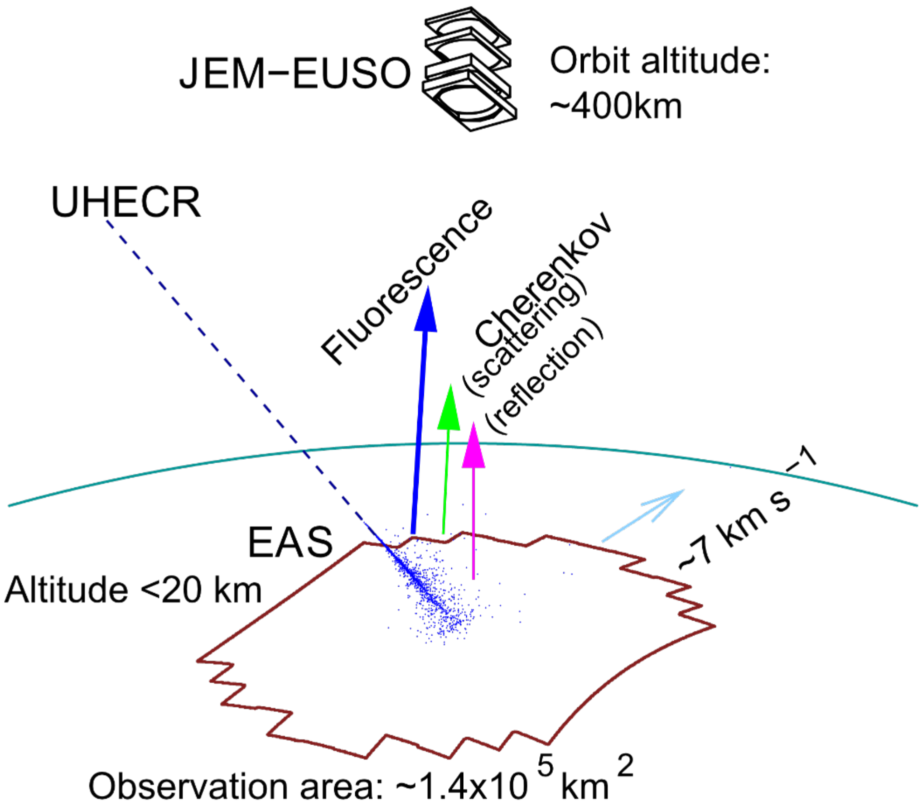
The JEM-EUSO program



- Detection of Ultra High Energy Comsic Rays by measuring induced Fluorescence light and scattered Cherenkov light
- 1.9m x 2.3m focal surface out of 4932 PMTs with 64 channel each PMT (standard design)
- Pathfinder Mission:
  EUSO – Super Pressure Balloon

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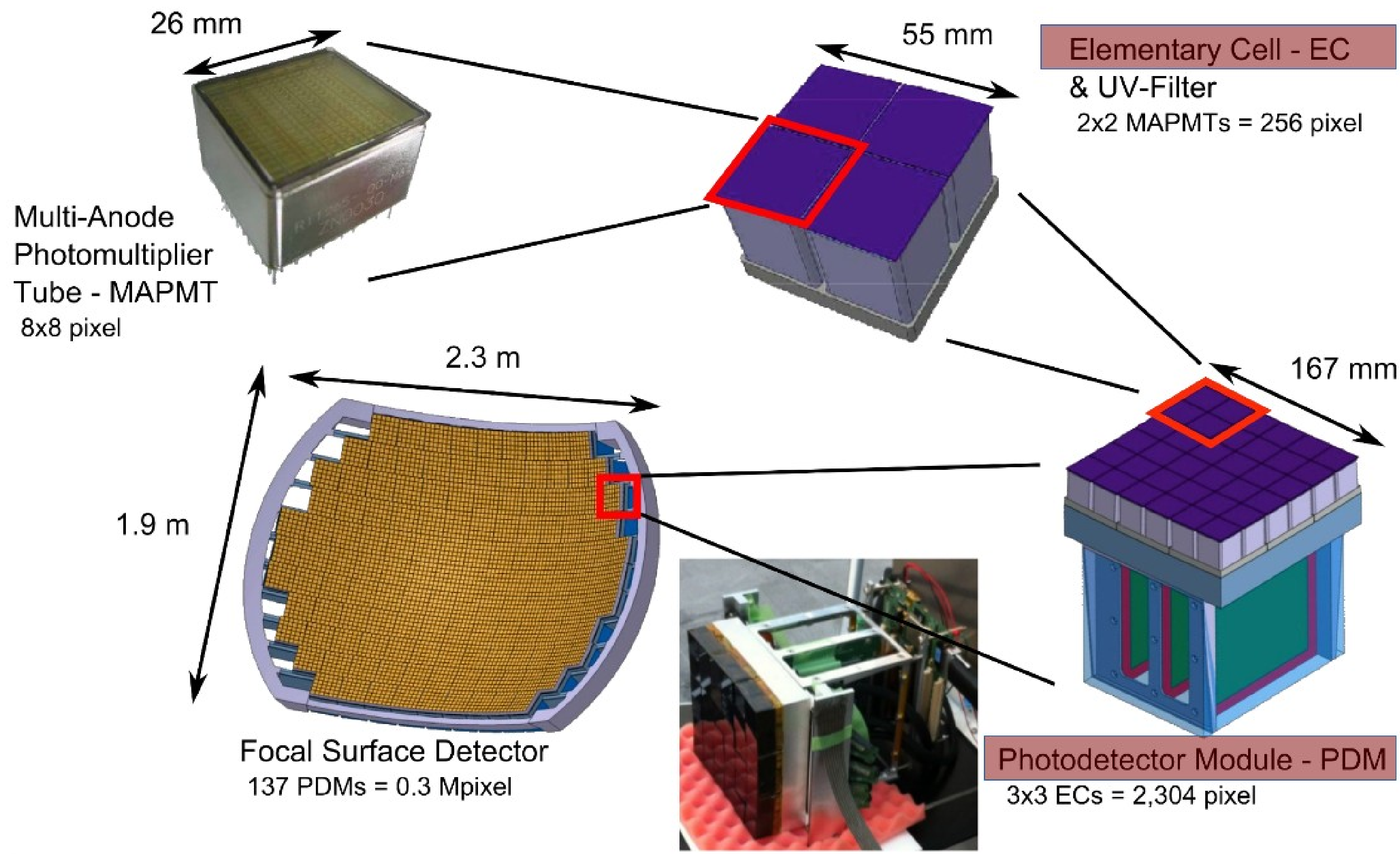
The JEM-EUSO program



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SiECA
Silicon EC Add-on for EUSO-SPB.

- Fluorescence camera with 265 SiPM channels

- Placed next to an EUSO photo detection module (PDM)
→ (Next slides)

(Used: 4x 64 channel SiPM array S13361-3050AS)

EUSO-SPB.

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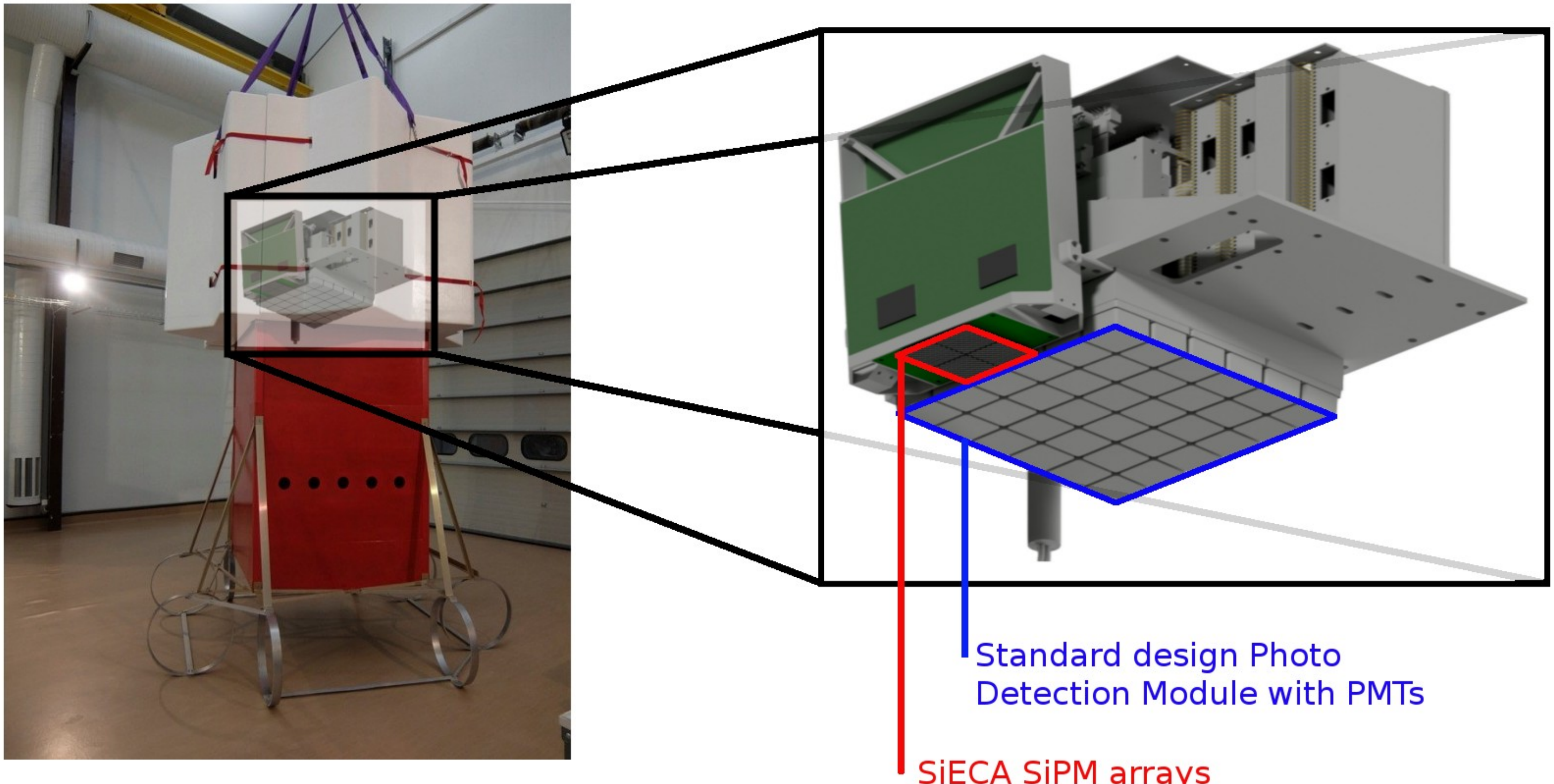
SiECA integration in Super pressure balloon gondola



EUSO Balloon Gondola
New Gondola has been built for EUSO-SPB

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Measured 64 channel SiPM arrays

S12642 (old series)

- 64 Channels
- 50µm pitch
- Specifications by Hamamatsu:
    - Breakdown Voltage: 65 ± 10 V
    - Dark Count: 2 - 3 M counts/s
    - Gain: 1.25 x 10^6
    - Photo Detection Efficiency: 35%
- **Epoxy resin**
  → Down to λ = 320nm

S13361

- 64 Channels
- 50µm pitch
- Specifications by Hamamatsu:
    - Breakdown Voltage: 53 ± 5V
    - Dark Count: 0.5 – 1.5 M counts/s
    - Gain: 1.7 x 10^6
    - Photo Detection Efficiency: 40%
    - Reduced Crosstalk
- **Silicone resin**
  → Down to λ = 270nm

→ chosen for SiECA

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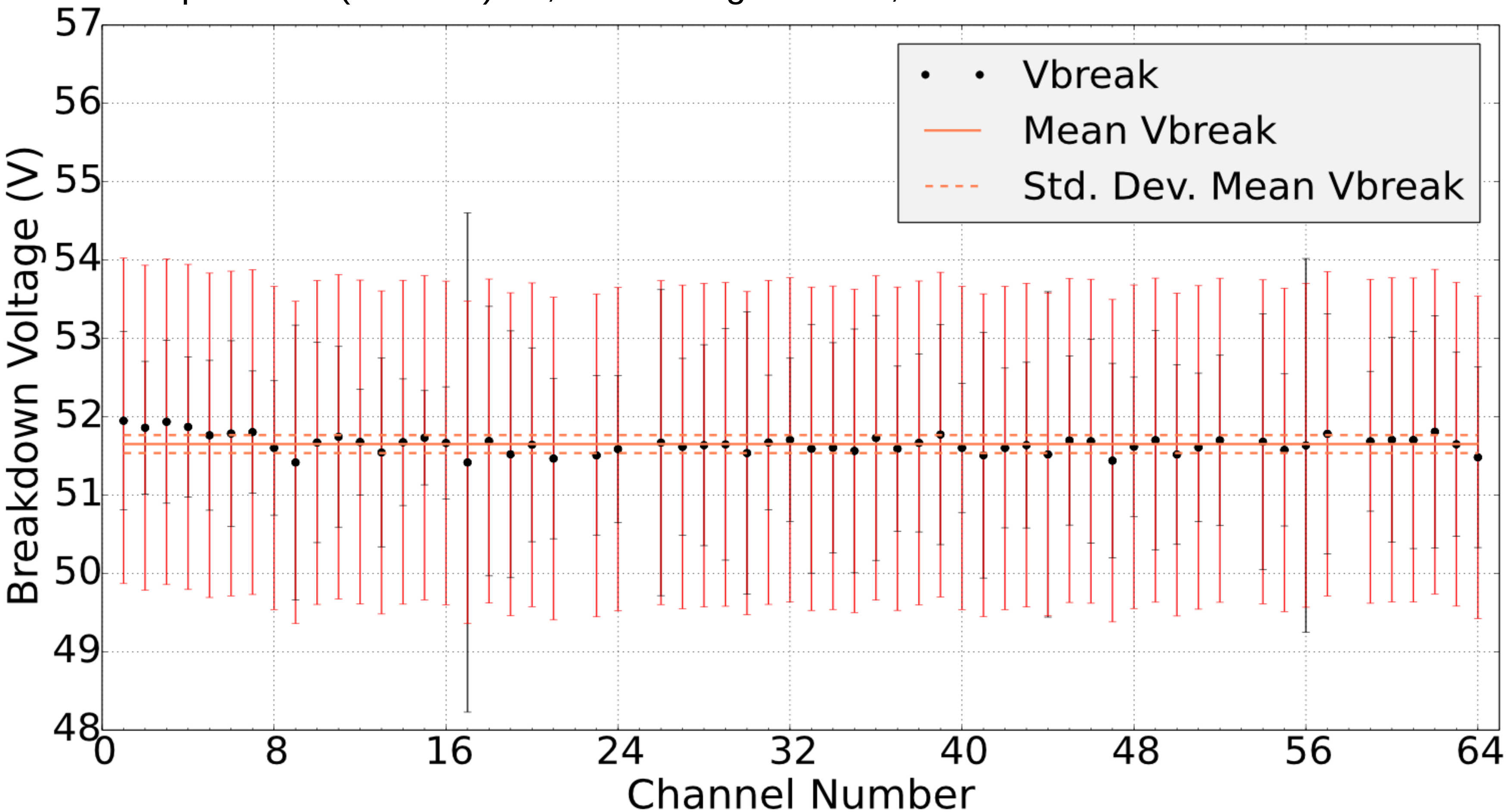
S13361 – Breakdown Voltage

Temperature: (19.5 ± 1)°C , Bias voltage: 55.2 V, λ = 423nm



Mean breakdown voltage: (51.65 ± 0.12) V

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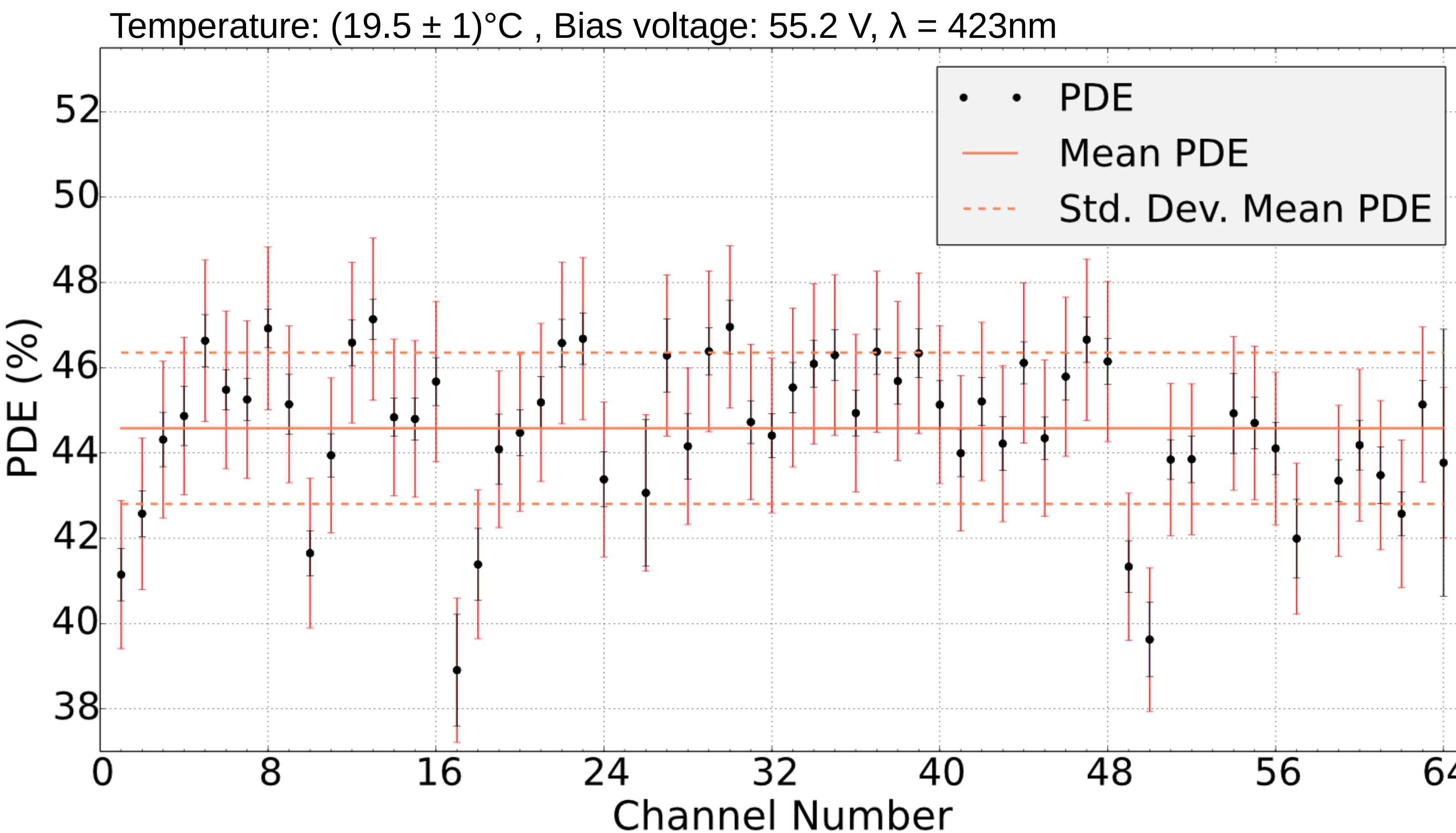
S13361 – Photo Detection Efficiency



Mean PDE : (44.60 ± 1.78) %

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Characterising results and Comparison Hamamatsu S12642 ↔ S13361

	S12642	S13361	Comp.
Vbreak (V)	64.62 ± 0.1	51.65 ± 0.12	20%
Gain (E+06)	1.65 ± 0.04	2.12 ± 0.07	28 %
PDE (%)	35.96 ± 1.09	44.60 ± 1.78	25 %
Dark Counts (MHz)	1.29 ± 0.14	0.68 ± 0.11	43 %
Crosstalk Prob. (%)	11.17 ± 1.27	3.9 ± 0.66	65 %

- Temperature : (19.5 ± 1)°C
- Overvoltage:
  - S13361: 3.58 V (+0.58 V than recommended)
  - S12642: 2.95 V (+0.55 V than recommended)
- Wavelength: 423nm

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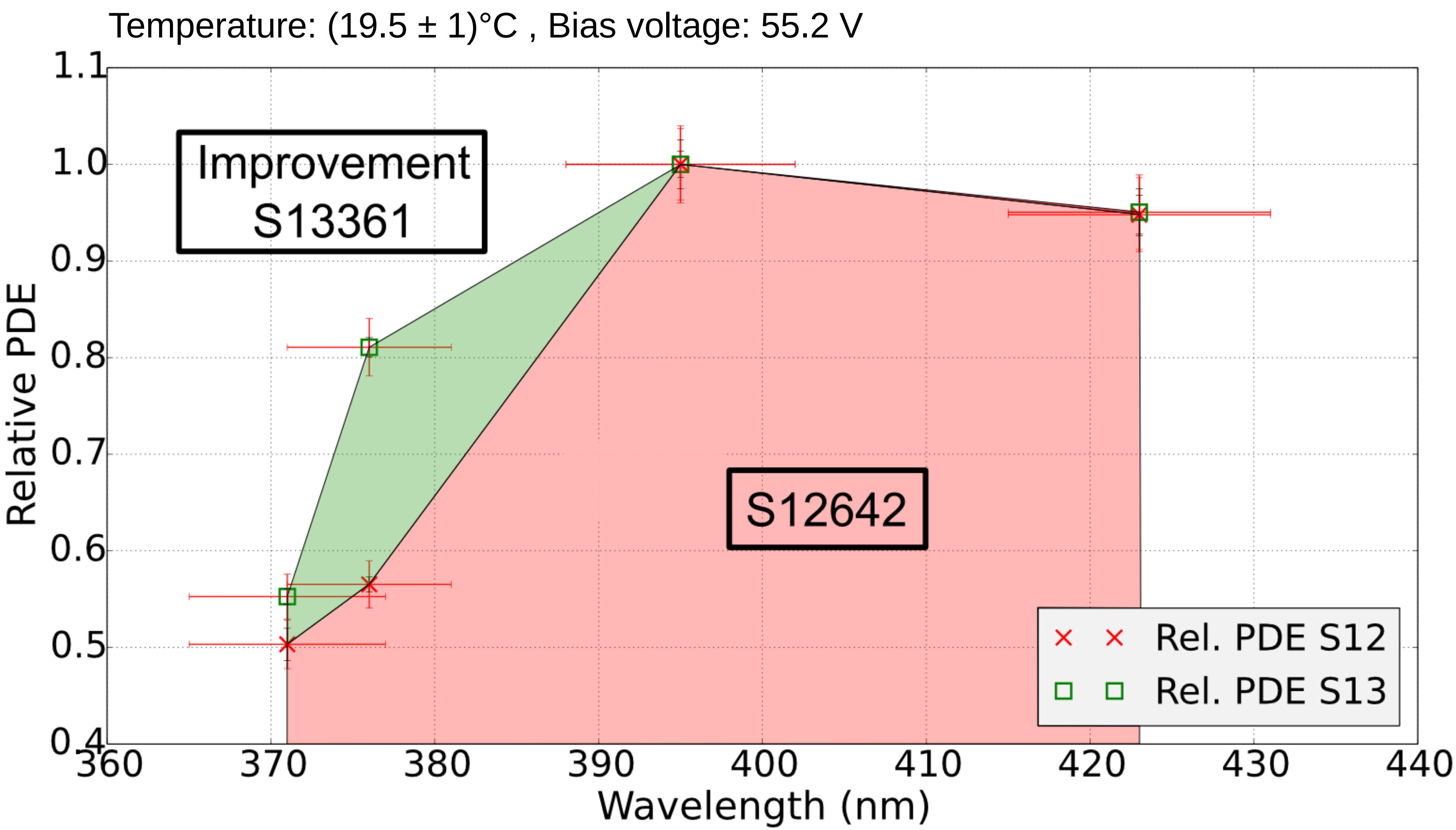
Wavelength Sensitivity



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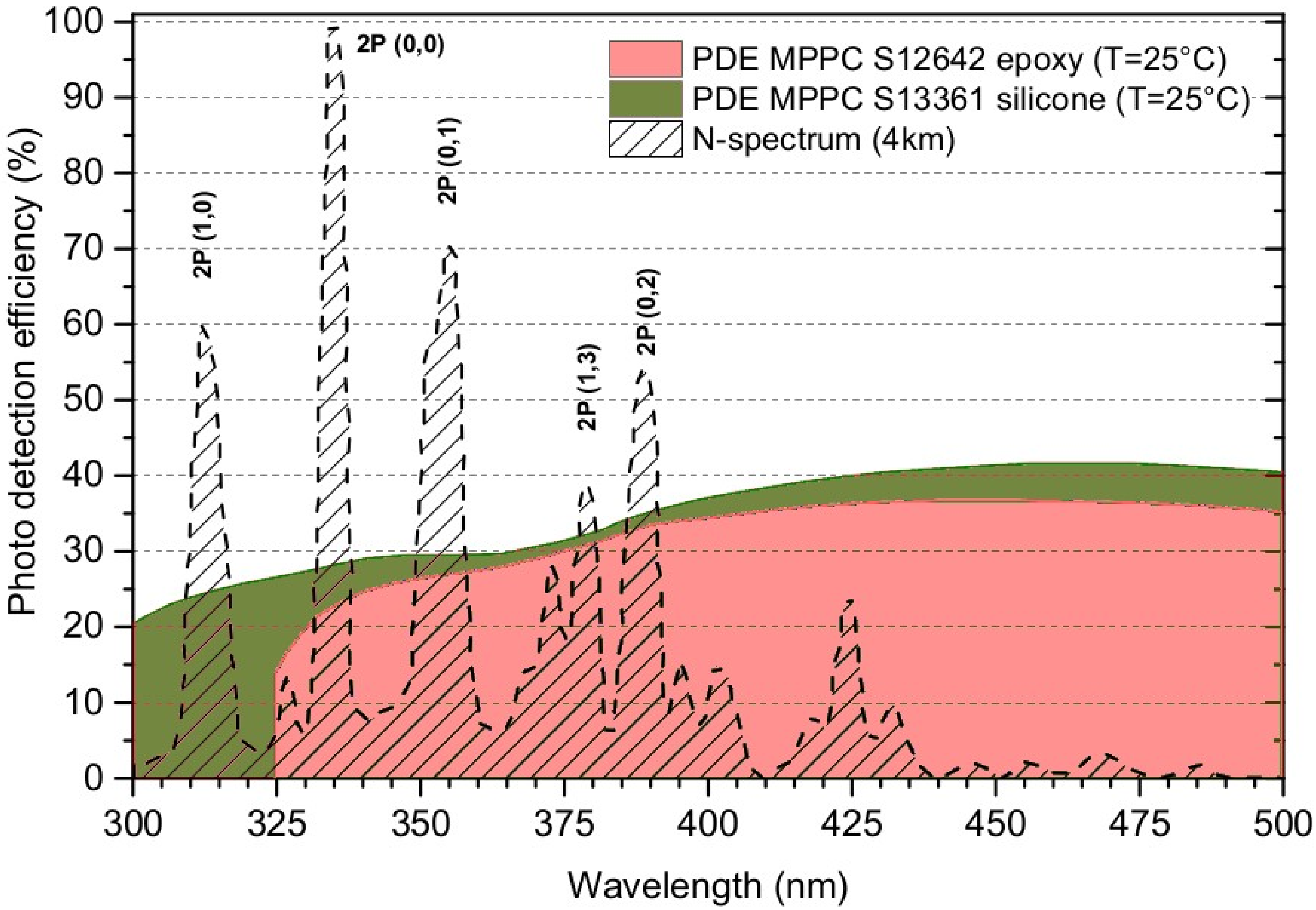
Predicted effect of different SiPM resins



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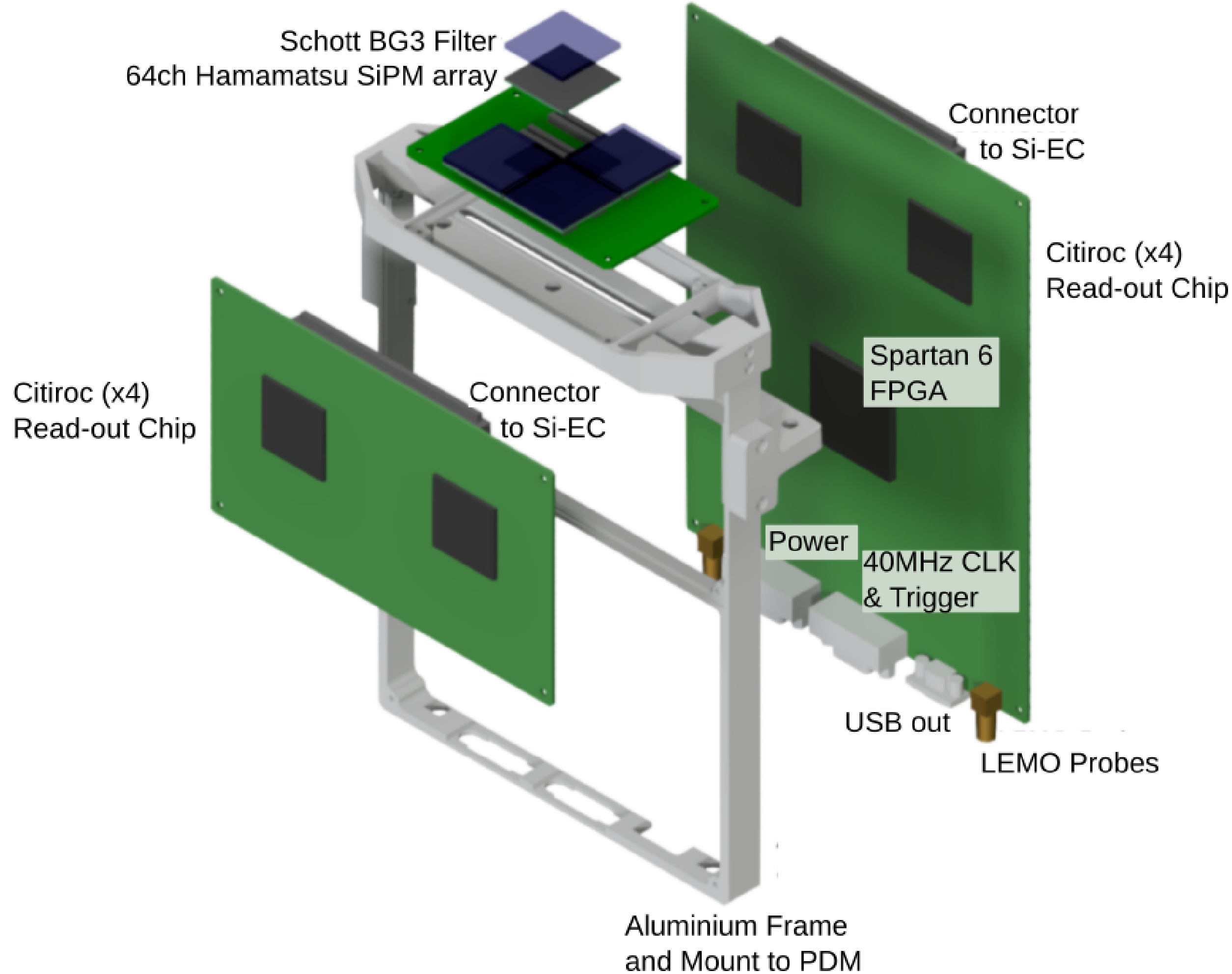
SiECA in detail



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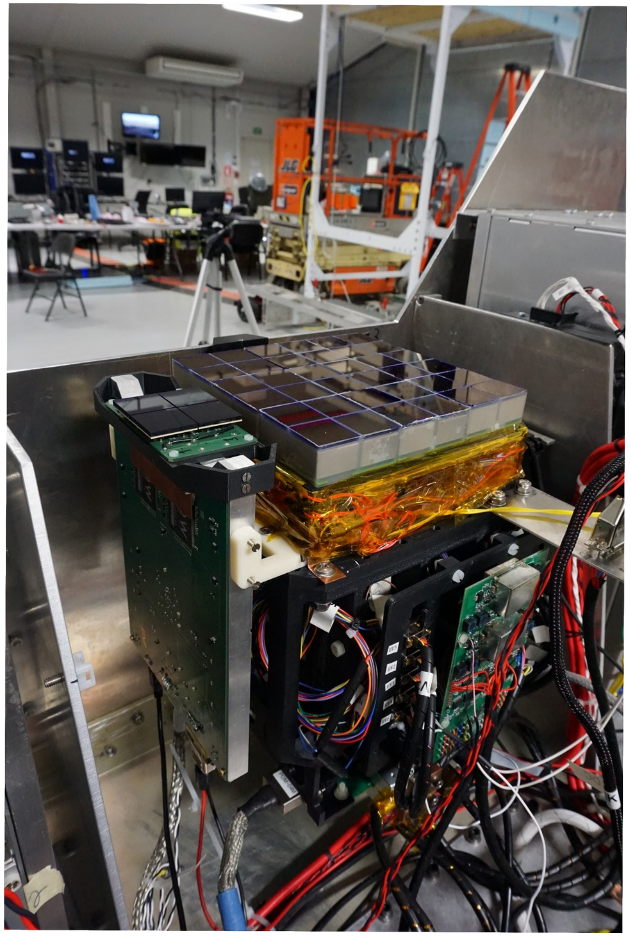
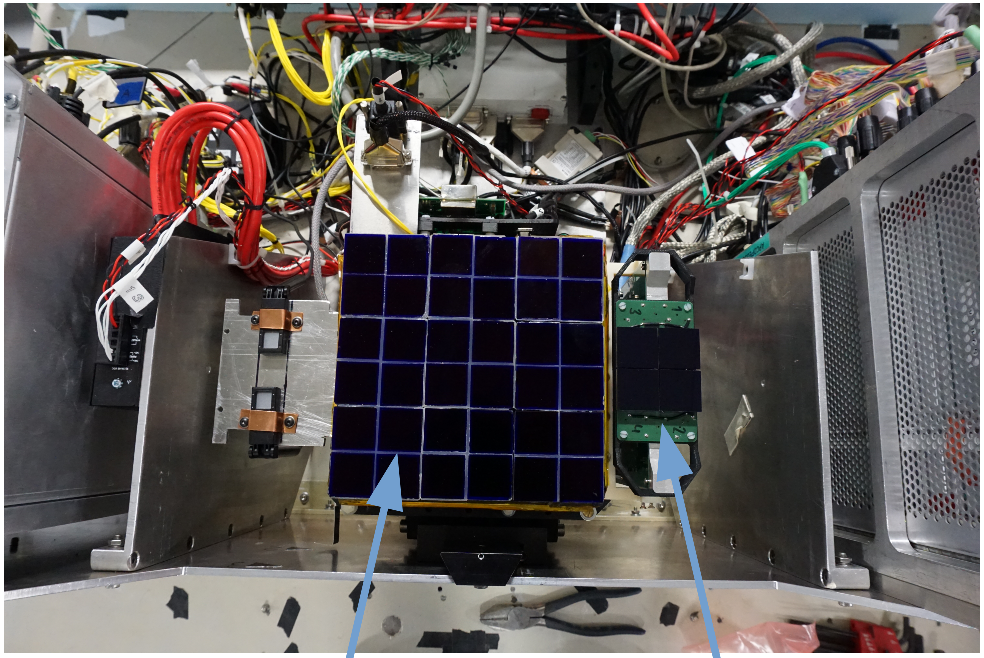
Euso-SPB with SiECA: ready to start





PDM
(MAPMT
camera)

(SiECA
SiPM
camera)

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First super pressure baloon flight 2015

NASA's first Super Pressure Balloon flight, March 2015, Wanaka, NZ:

- Flight duration 32 days

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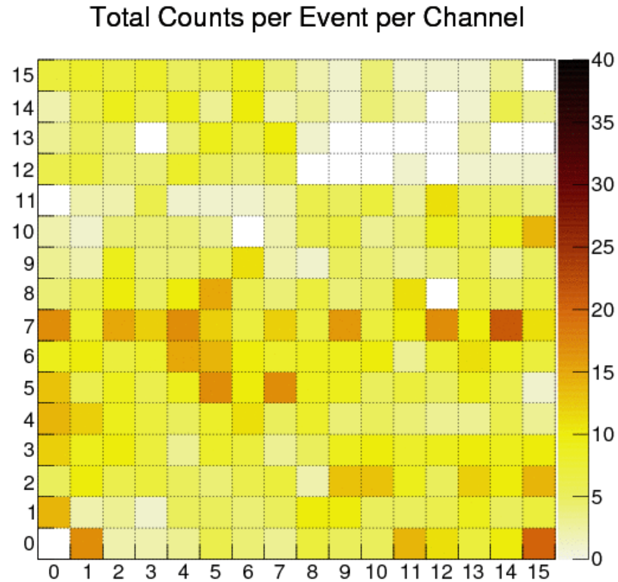
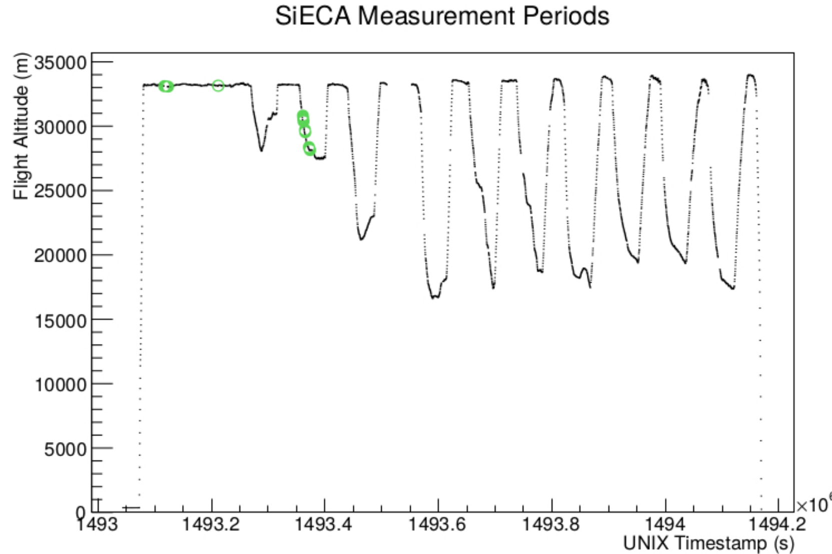
SiECA Results



SiECA background measurement



SiECA measurement periods (green circles)

SPB flight path

- Successful measurements with SiECA during flight time
- Super pressure balloon went down after 12 days due to leak in balloon

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IceCube-Gen2 scintillation detectors
(1 channel SiPM S13361-6025PE)

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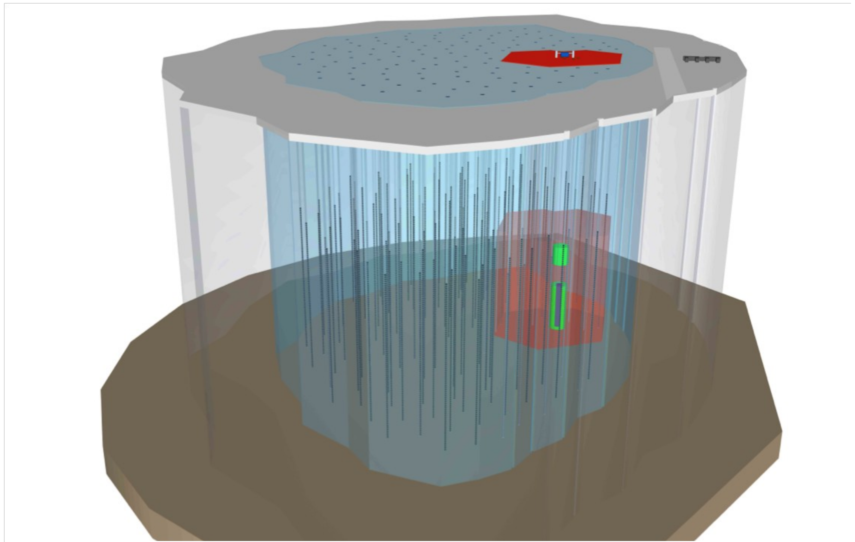
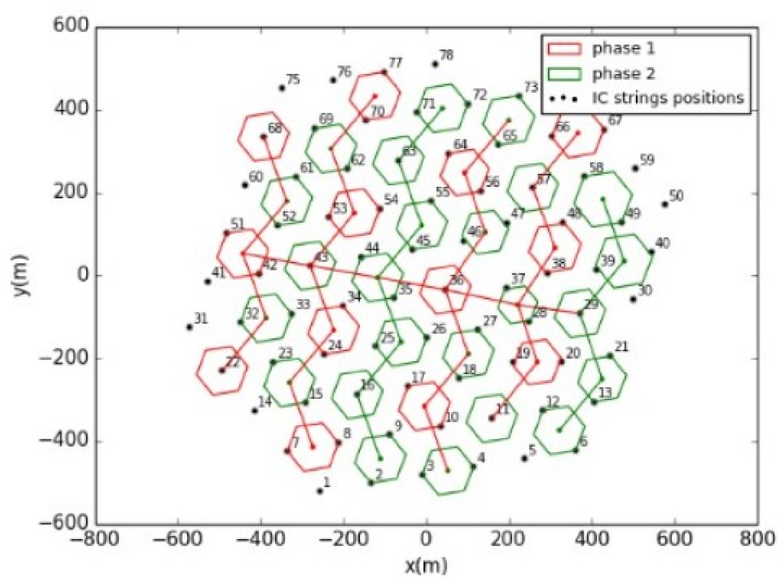
IceCube-Gen2 scintillation detectors





- Extended surface array consisting of scintillation detector panels with SiPM read-out
- Veto for in-ice detector and improved measurement of cosmic ray air showers
- Prototype study for IceCube-Gen2 upgrade

- Seven scintillation panels in one station
- One TAXI-DAQ for every station
  - SiPM signal sampling with DRS4 sampling chips @ 1GSamples/s

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IceCube-Gen2 scintillation detectors

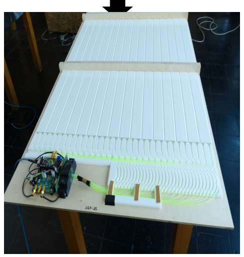
Minimum Ionizing Particle (**MIP**)

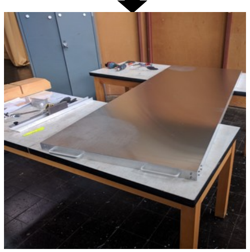
A surface detector array for IceCube-Gen2 ☺ =

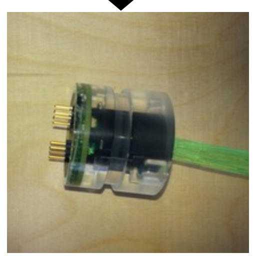
Synchronization with ICL, Trigger, Fieldhub connection

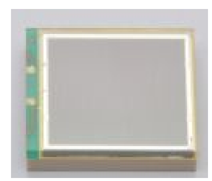
White Rabbit compatibility

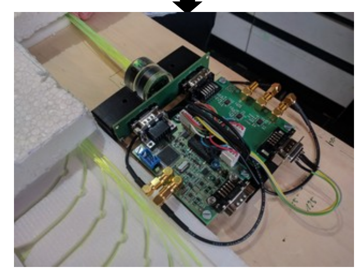
Scintillator → Frame → Optical Coupling → Photosensor (SiPM) → Analog Readout → DAQ System

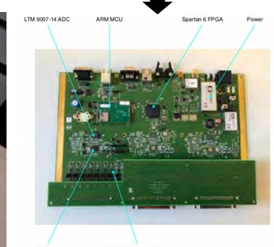












IceTAXI
(DESY)

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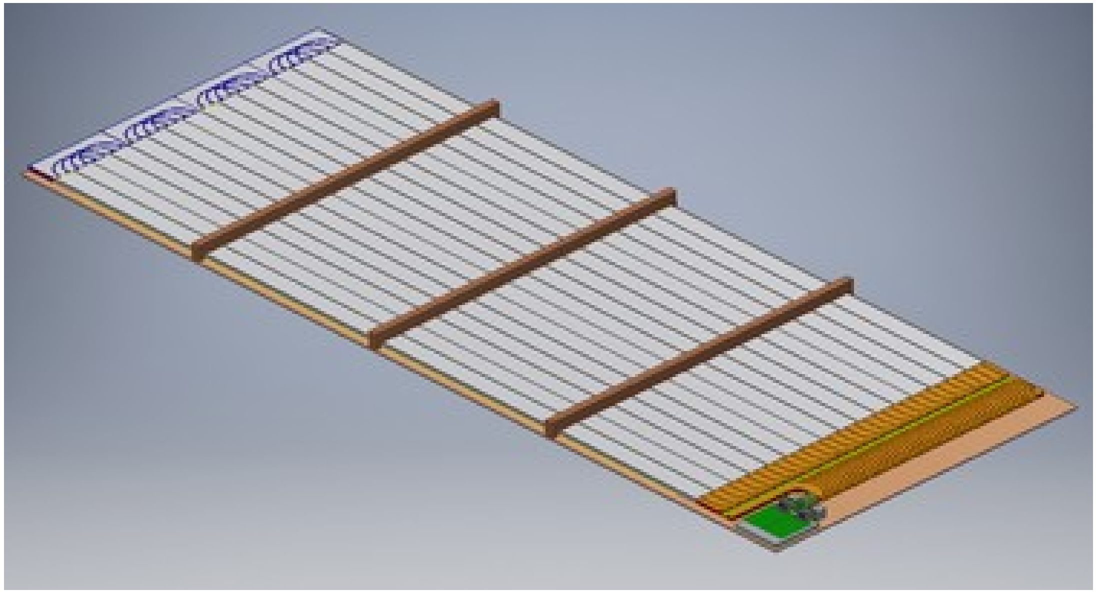
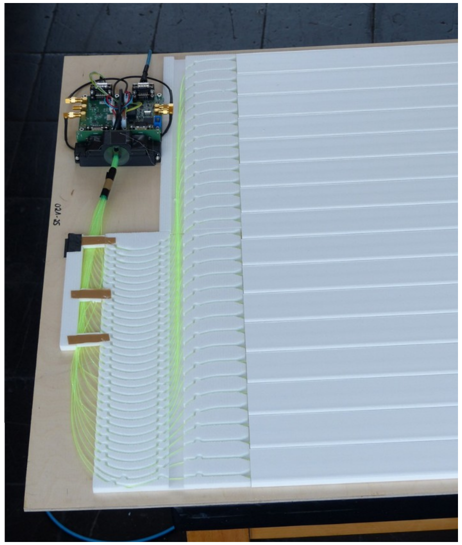
Detector design – bars and fibers





- 16 Fermilab scintillator bars, 2 optical fiber ports each bar
- 32 Kururay wavelength shifting fiber ends coupled to SiPM
- MIP-Sensitive Area: 1.5 m²

- Dimensions: 2.2m x 0.8m x 0.05m

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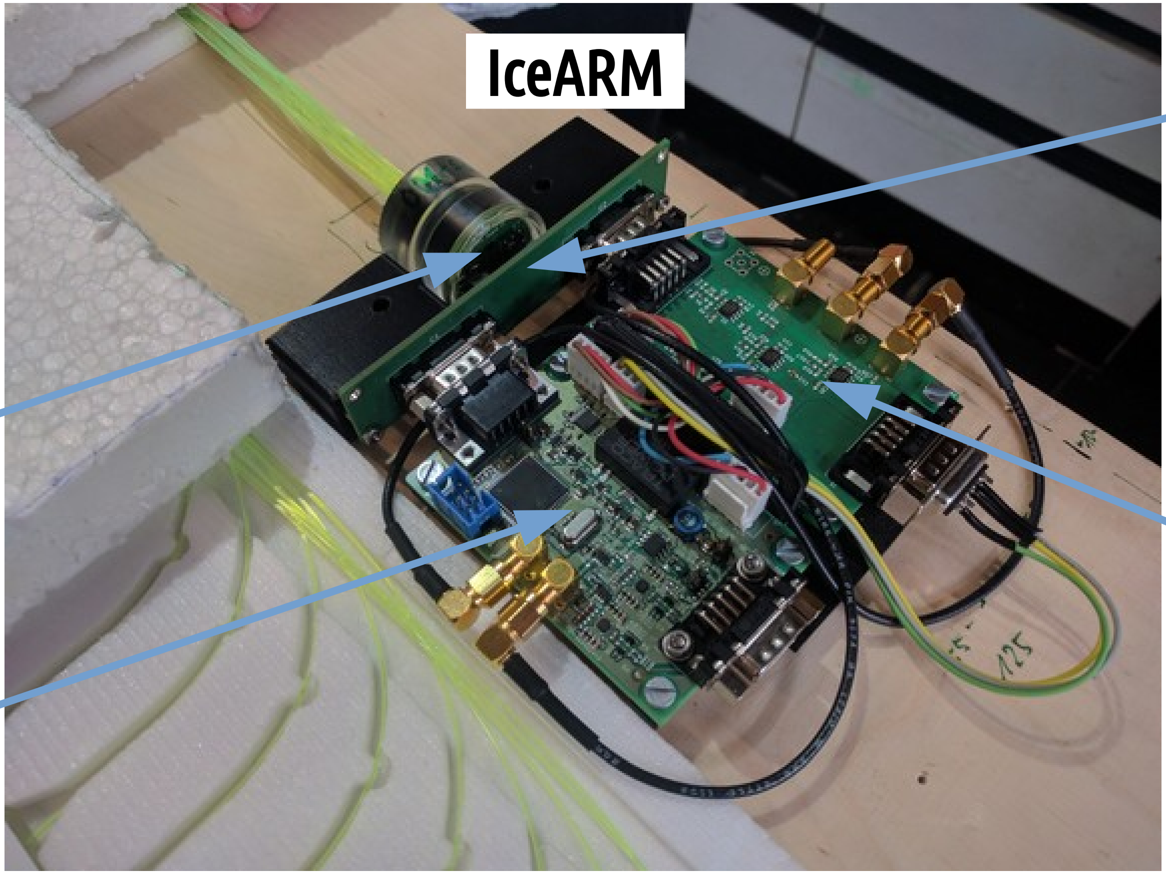
Analog readout

Adapter board

Cookie board

Readout board

General purpose board (DESY)



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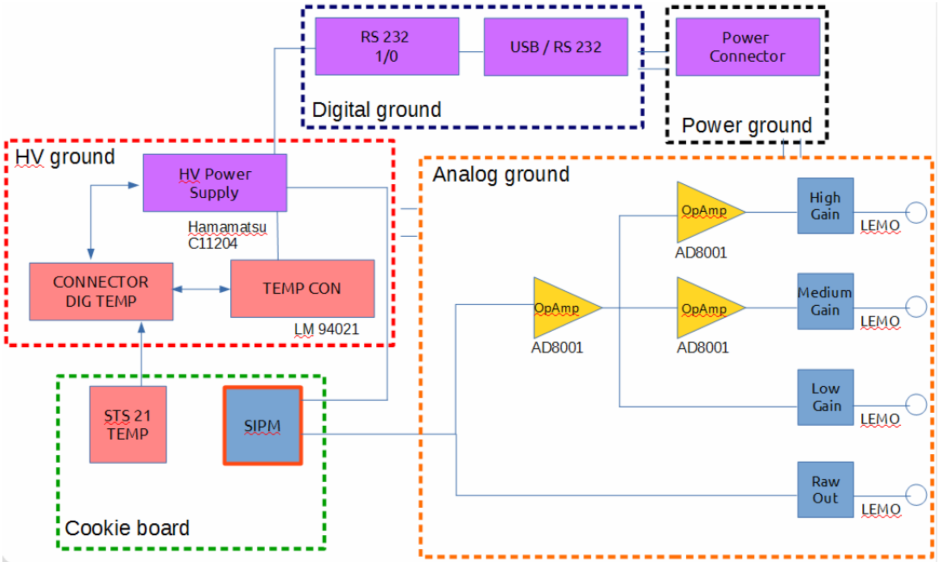
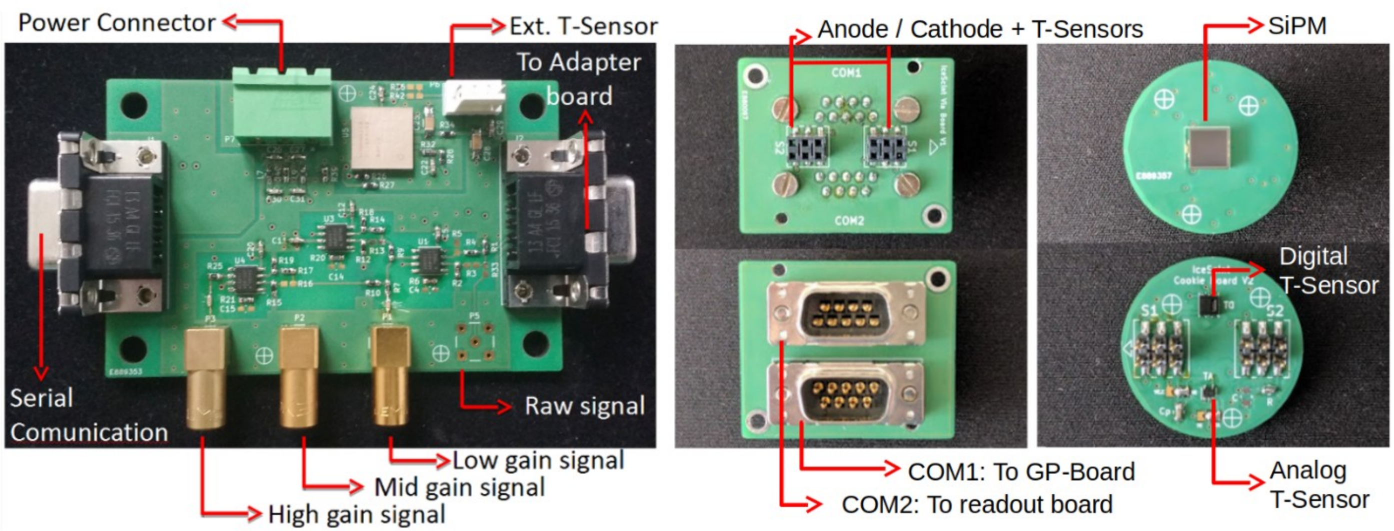
Analog readout



Simplified ARM block diagram with amplifier chain for lab tests

- SiPM amplification and voltage control
- Automatic temperature compensation implemented in microcontroller
- High gain (x17) and low gain (x1.7) (after 70m cable)



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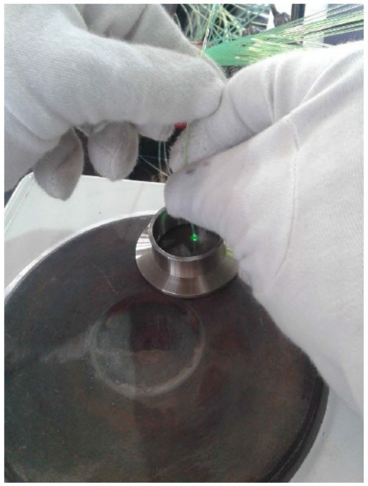
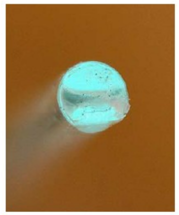
Optical coupling

Optical Fibers → “Cookie” → Cut and glued optical fibers → SiPM →
→ Cookie board → Adapter board → Readout electronic

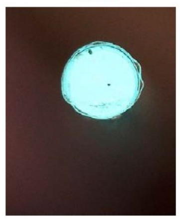
Melting Fiber



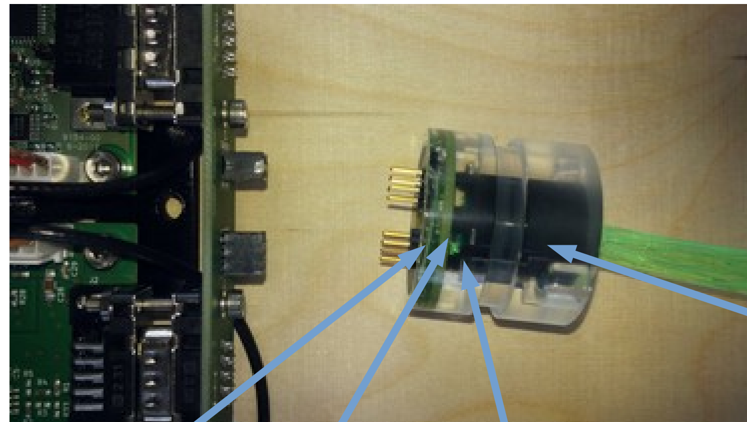
cut



melt



Melting process

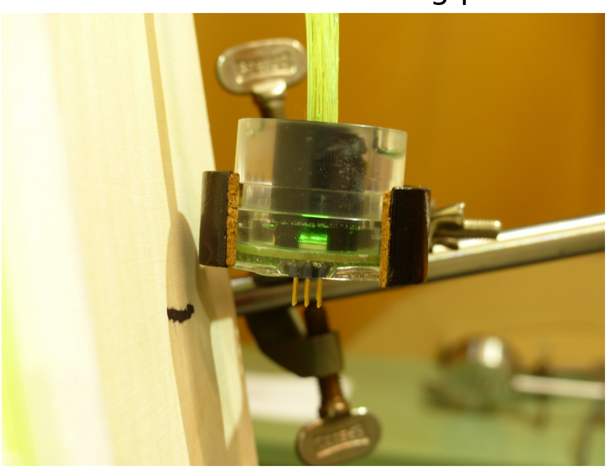


Cookie board

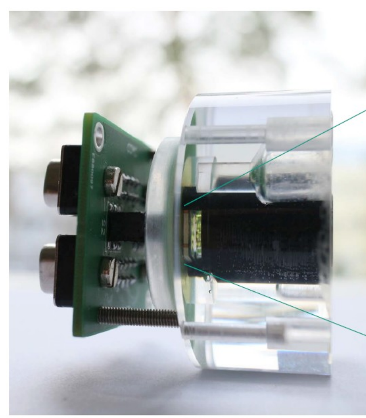
SiPM

Glued optical coupling

3D printed socket (“round” to “squared”)



Gluing process



Fiberend and SIPM

1-2mm gap, filled with optical glue, to ensure triggering every APD cell to increase the dynamic range

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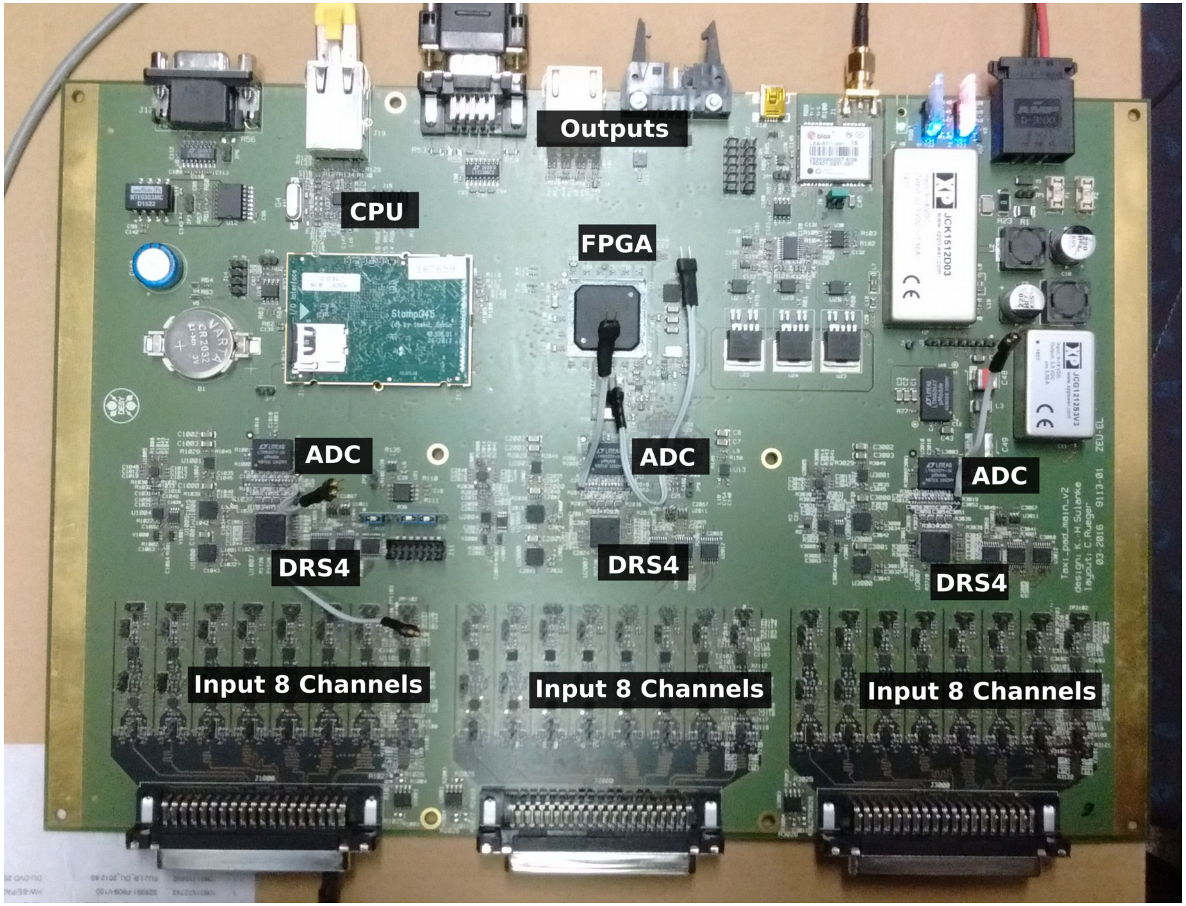
DAQ: IceTAXI board (DESY)



(Not actual version)

- Three DRS4 sampling chips with 8 input channels each chip
- Adjustable sampling rate 0.7GHz – 5GHz
- Triggered by signal-over-threshold
- DRS4 sampling cells are read out through slow ADCs (33MHz)

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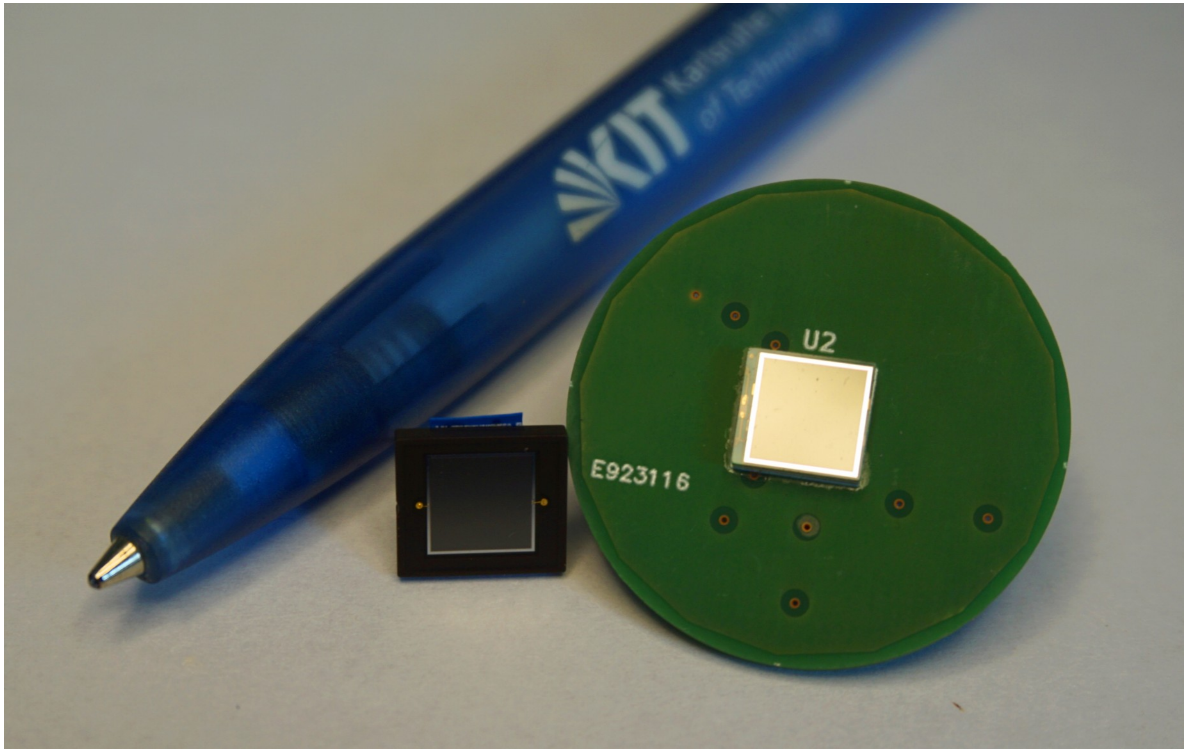
Chosen: Silicon Photomultiplier S13360

Hamamatsu S13360-6025

- 25µm pitch
- 6mm x 6mm active area
- Recommended overvoltage = 5V

Chosen for the IceCube-Gen2 scintillator prototype study, shipped for this season to the South Pole for deployment



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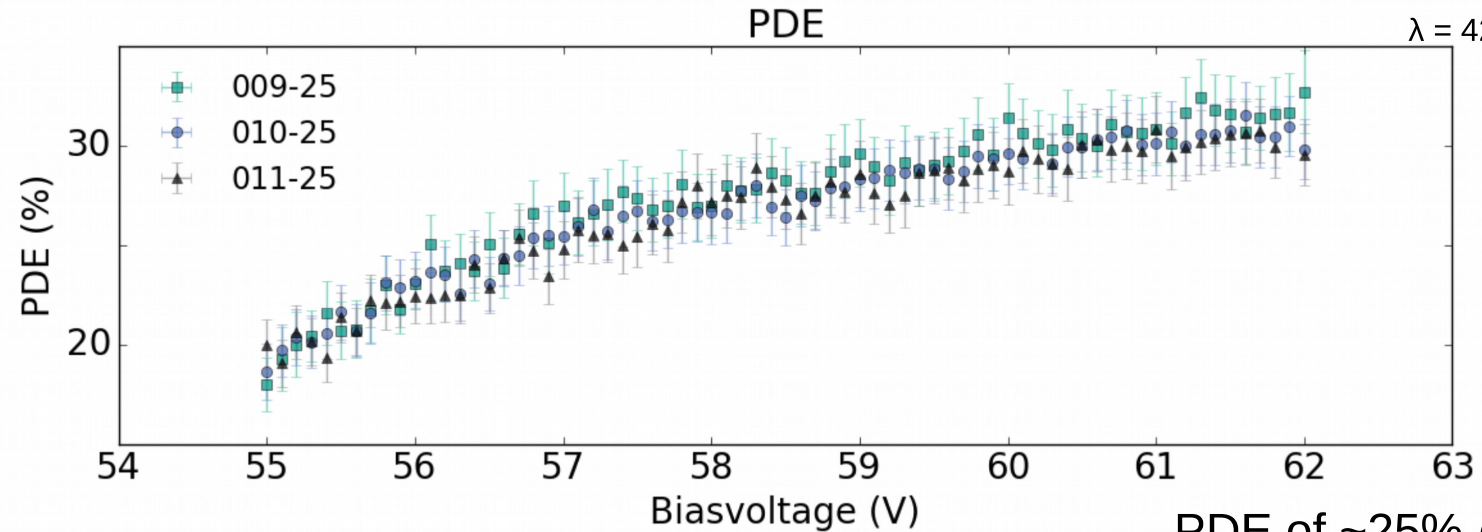
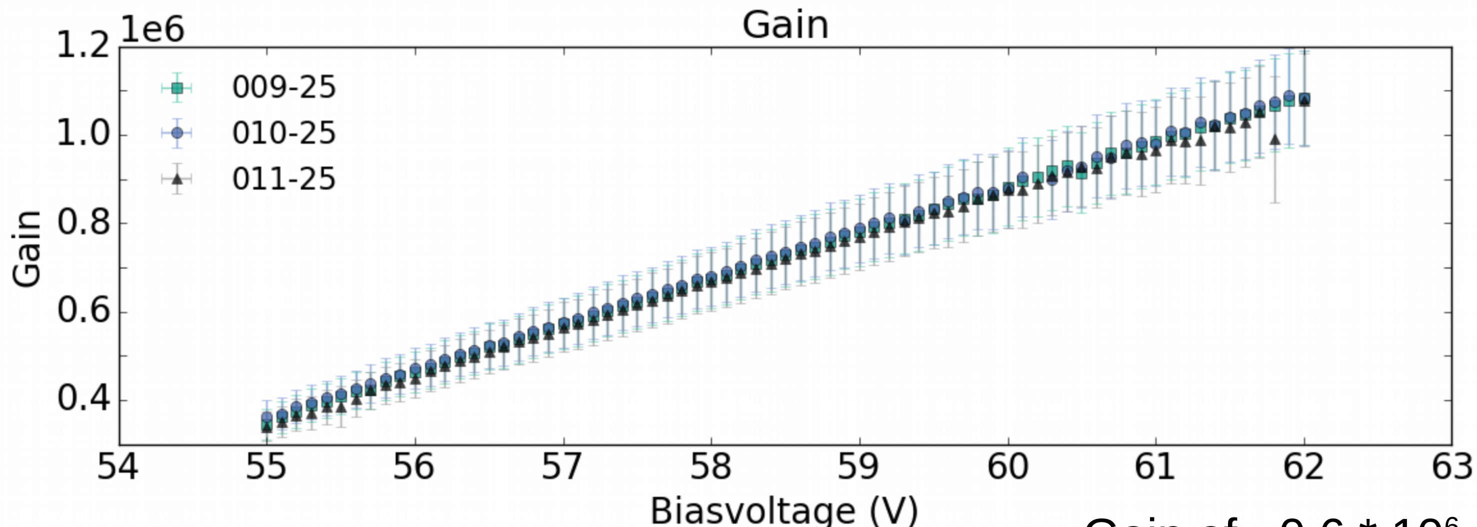
Results SiPM Characterization

λ = 423nm



PDE of ~25% @ 5V OV



Gain of ~0.6 * 10^6 @ 5V OV

Measurements made by Marie Oehler

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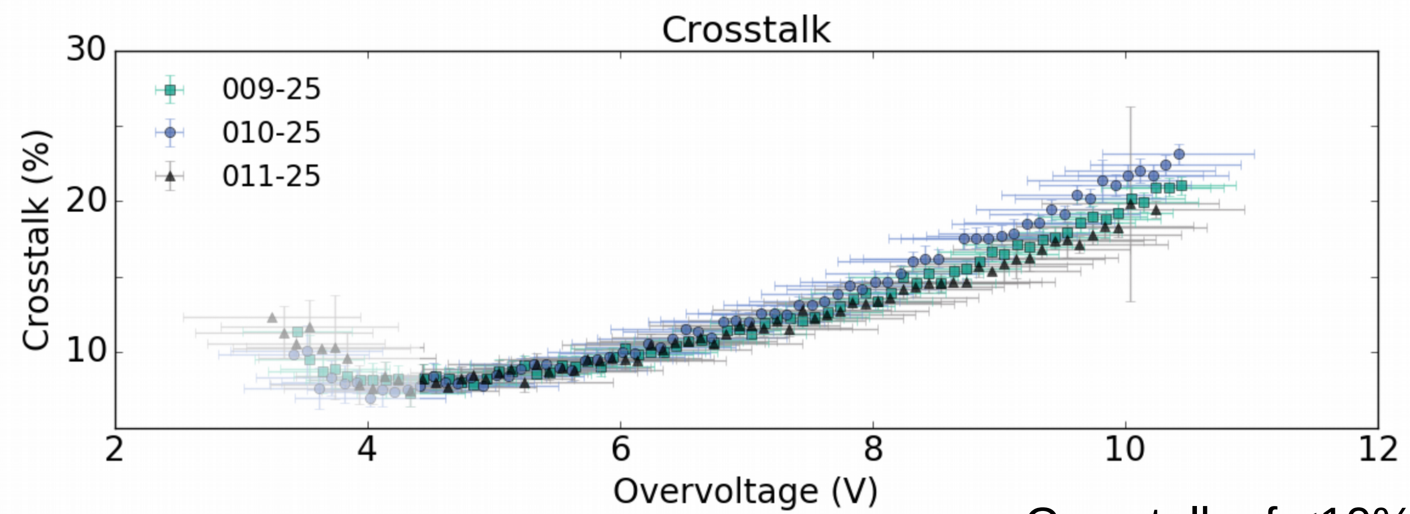
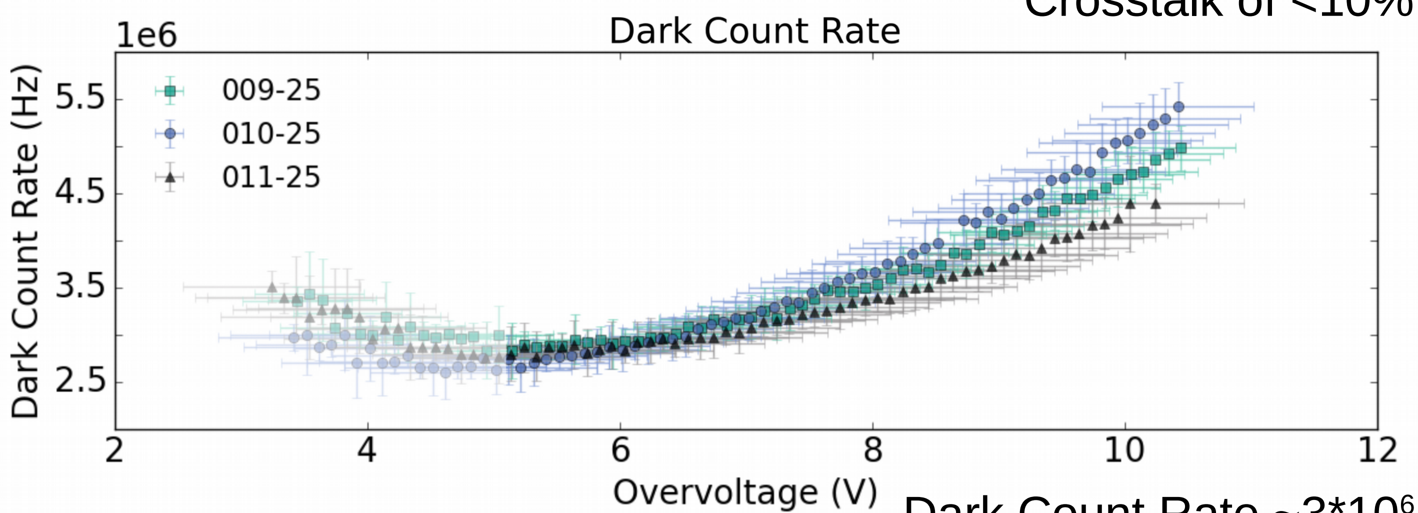
Results SiPM Characterization



Crosstalk of <10% @ 5V OV



Dark Count Rate ~$3*10^6$ @ 5V OV

Measurements made by Marie Oehler

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Temperature dependent SiPM Characterization

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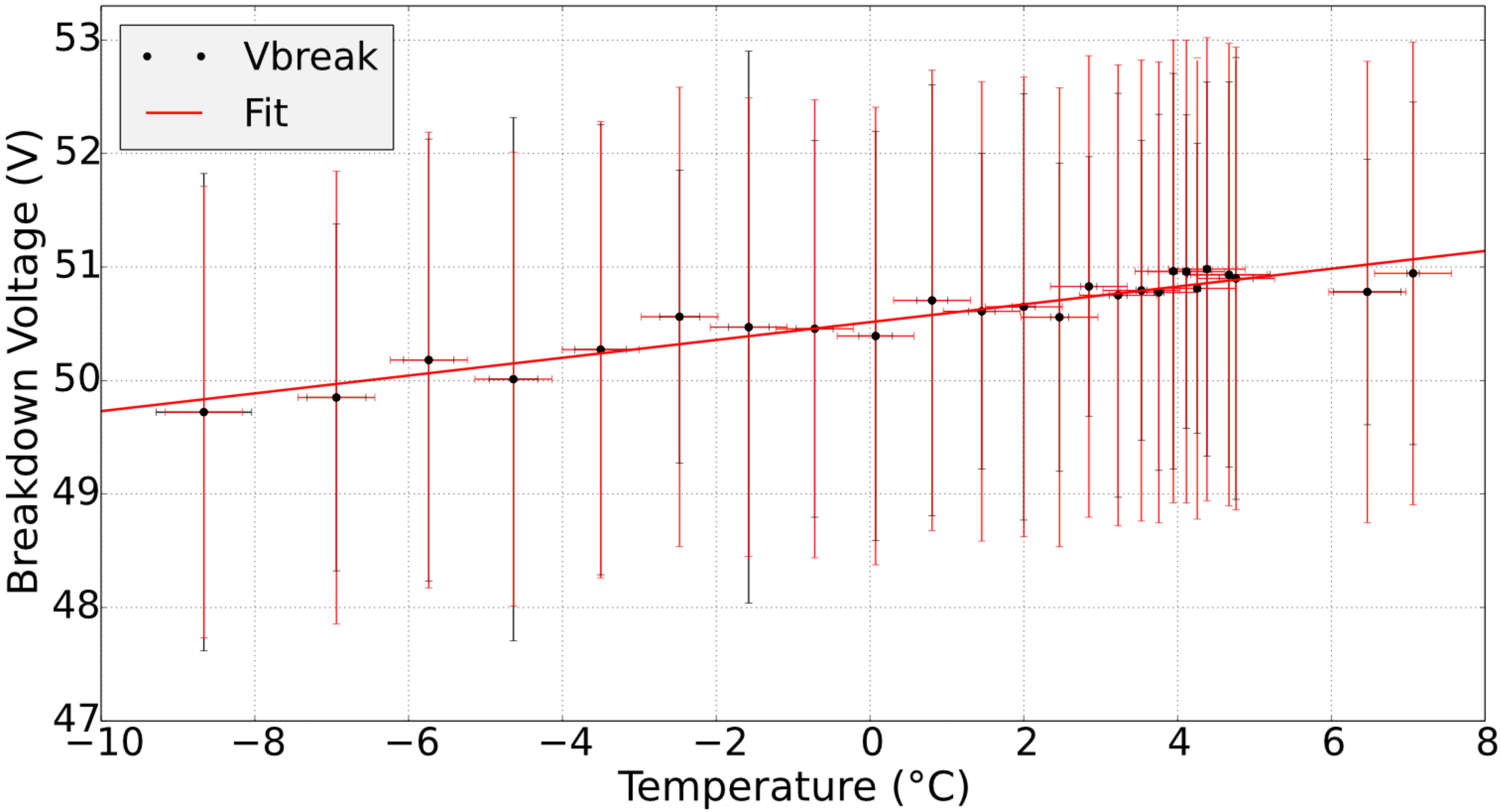
Temperature dependent breakdown voltage

S13361 / 1 channel, constant bias voltage: 55.2 V, λ = 423nm



Fit: $V_{break}(T) = 0.078\,\frac{V}{{}^\circ C} * T + 50.514\,V$

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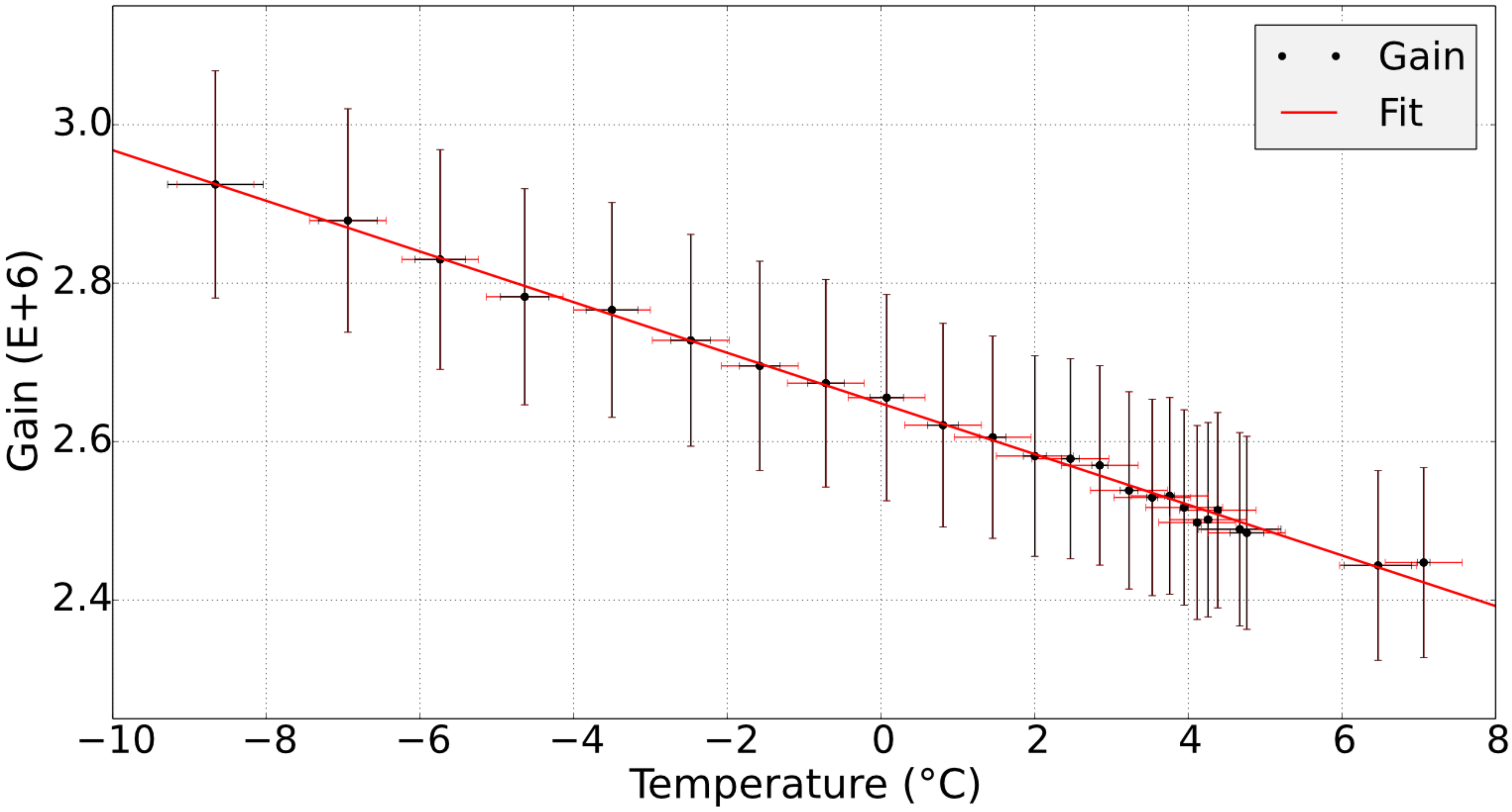
Temperature dependent gain

S13361 / 1 channel, constant bias voltage: 55.2 V, λ = 423nm



Fit: $G(T) = -0.03 \frac{10^6}{°C} * T + 2.65 * 10^6$

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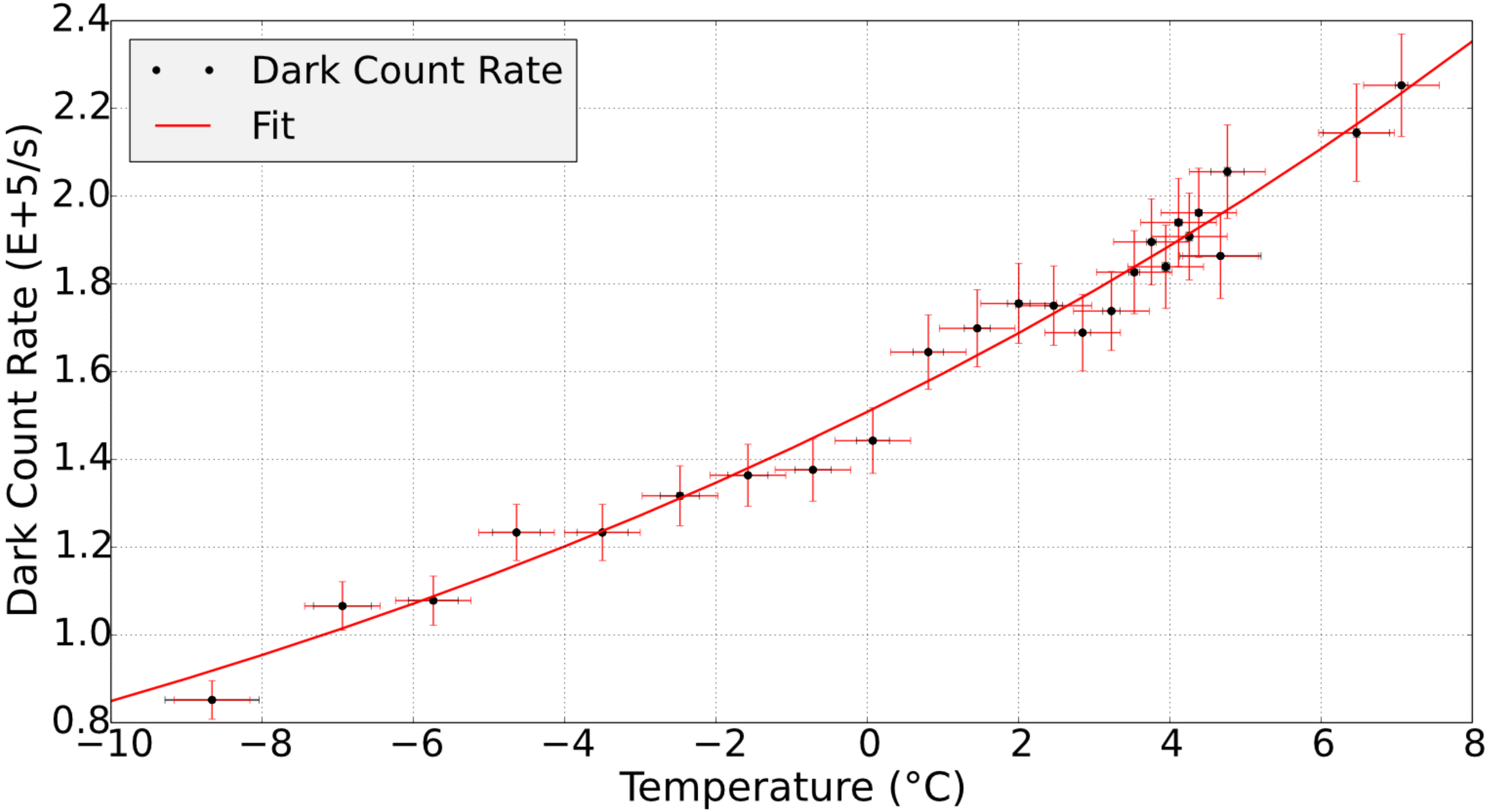
Temperature dependent dark count rate

S13361 / 1 channel, constant bias voltage: 55.2 V, λ = 423nm



Fit: $\xi(T) = 4.55 * 10^{-33} \frac{Hz}{K} * T^{15.4}$

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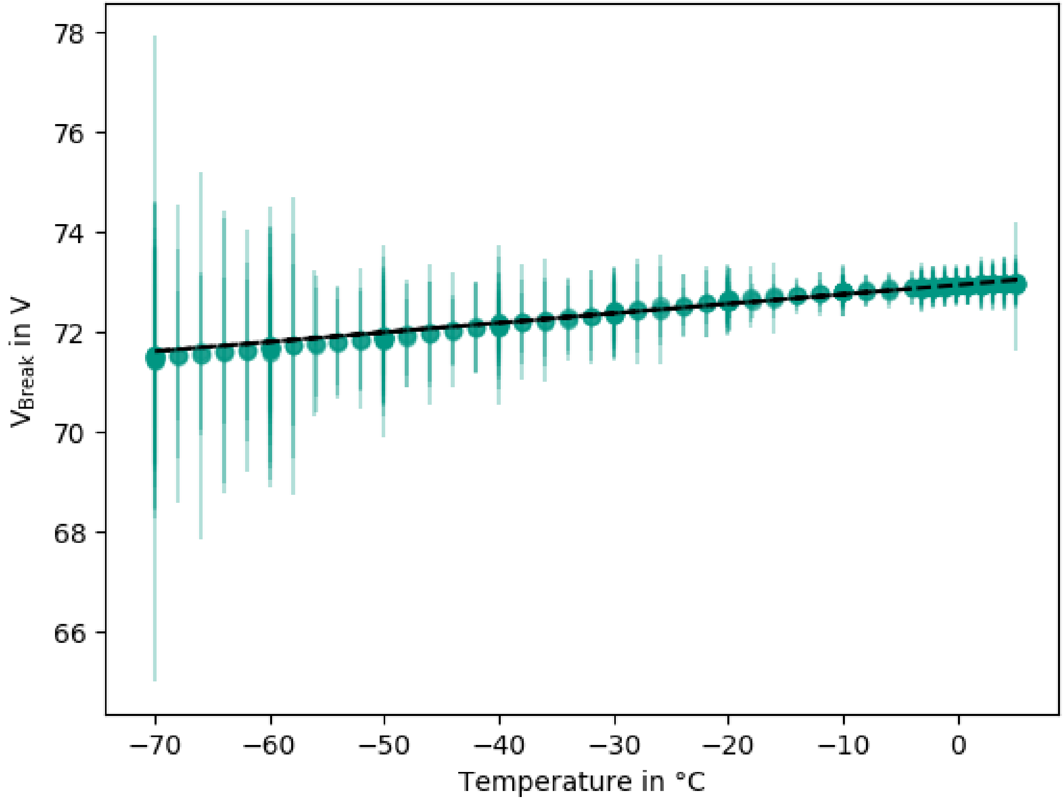
Temperature dependent measurements with S13360-6025

- First Measurements with SiPM S13360-6025 with analog read-out placed in temperature chamber (-70°C – 120°C)
- Measurements of the “breakdown voltage” by recording U-I-curves in darkness
- Additional measurements planned



Slope: 19 mV/K

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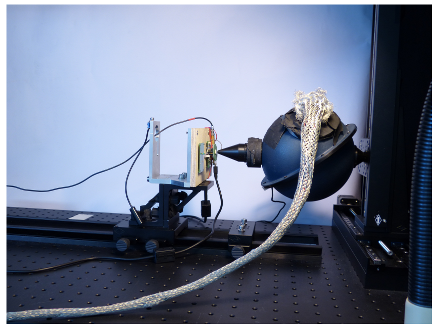
Conclusion and Outlook

SPOCK photosensor calibration setup

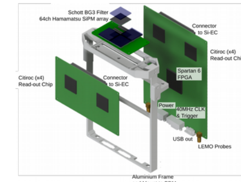
SiPM characterisation measurement stand SPOCK at KIT able to make a full SiPM characterization (One channel SiPMs and SiPM arrays)

Ongoing:
- Measuring the unifmority of single channel SiPMs
- Characterization and comparison of SiPMs from different companies



SiECA fluorescence camera

SiECA V 2.0 in development



Plan:
Place it next to the PMTs of an Auger fluoerescence telescope

IceCube-Gen 2 scintillator surface extension

-7 detectors and IceTAXI DAQ on their way to the south pole.
Deployment this season.

-7 detectors in Madison for low temperature test with a large cooling chamber

-7 detectors at KIT for cross calibration

-1 detector at DESY for signal processing development with IceTAXI

SiPM Temperature tests

“Cold SPOCK” in a temperature chamber in development:

SiPM charaterization to temperatures down to -70°C

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Backup

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Characterizing SiPMs - PDE

Photo Detection Efficiency: $$PDE=\frac{N_{pe}}{N}$$

N_{pe} : Number of detected photoelectrons per pulse
N : Number of incident photons per pulse

Number of incident photons per pulse:

$$N=\frac{P\cdot R\cdot R_{geom}}{E_{photon}\cdot f_{pulse}}$$

Number of detected photoelectrons per pulse:

$$N_{pe}=\ln\left(\frac{N_{tot}}{N_{ped}}\right)-\ln\left(\frac{N_{tot}^{dark}}{N_{ped}^{dark}}\right)$$

Characterisation Studies of Silicon Photomultipliers; ArXiv:1003.6071v2

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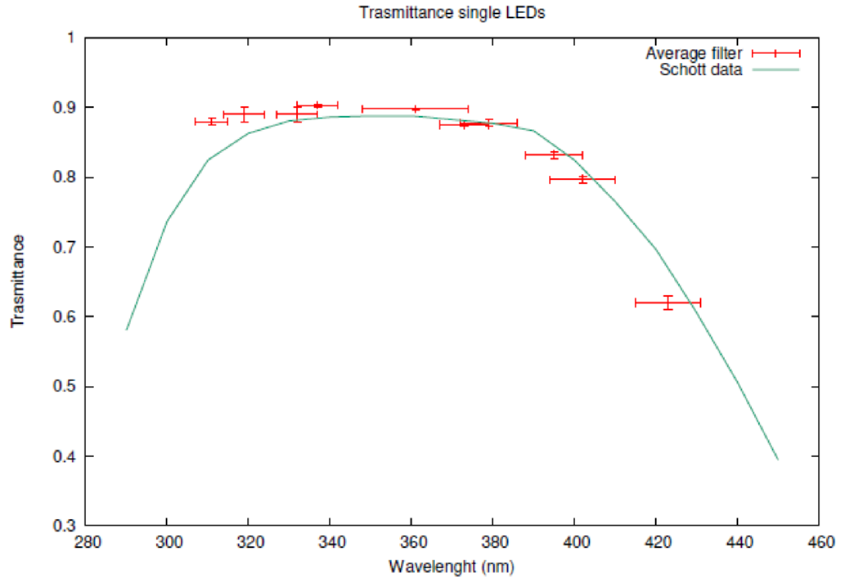
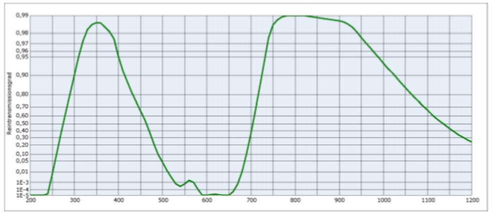
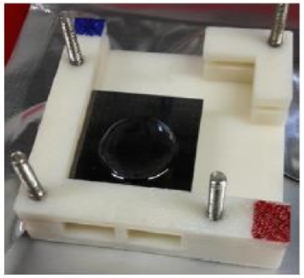
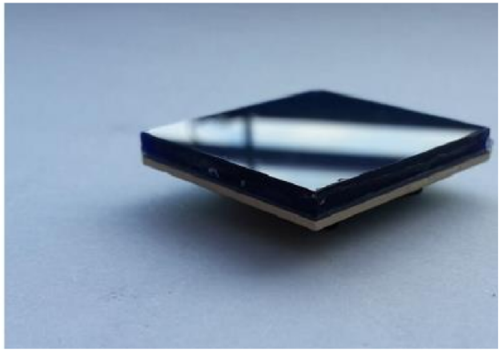
Schott BG3 filter glass SiPM covering









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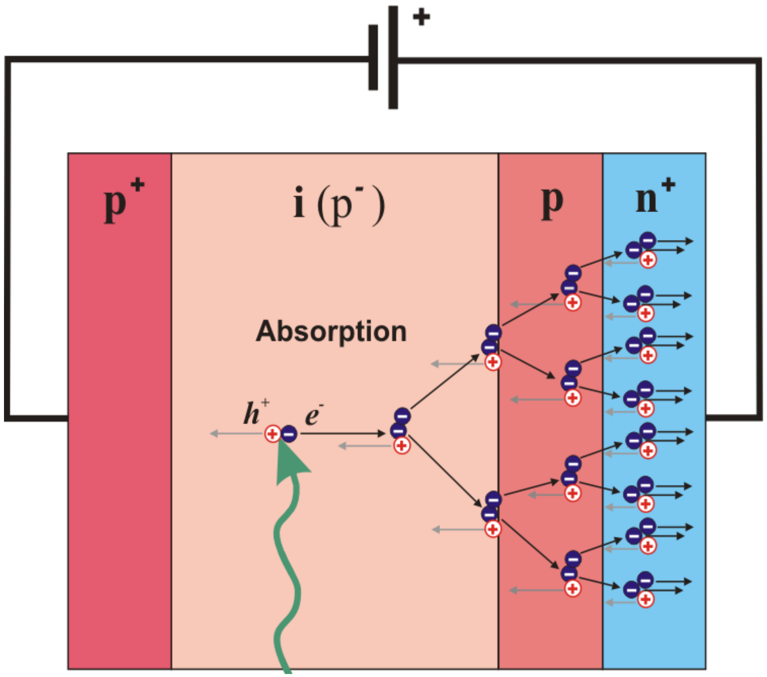
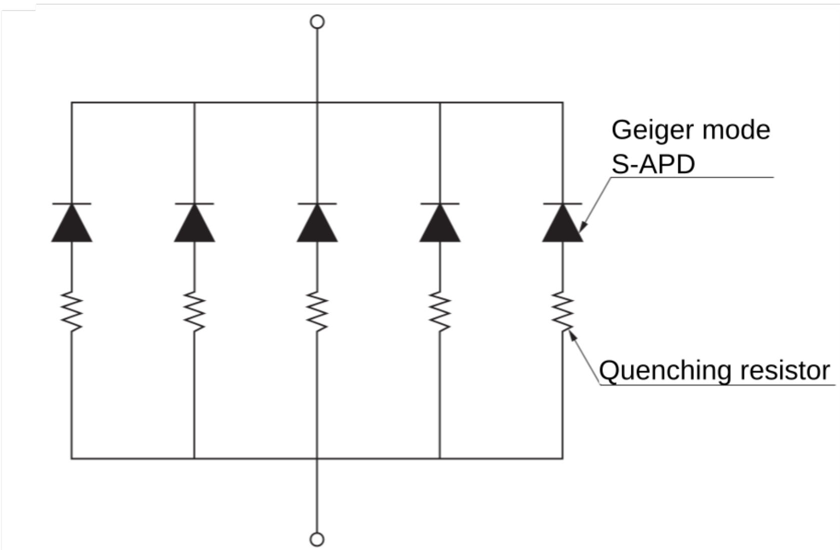
Silicon Photomultiplier

Avalanche Photo Diode



- Photon enters the APD and produces Electron/Hole pair
- Electrons are accelerated to n+-layer and produce avalanche

Silicon Photomultiplier



- Array of parallel connected APDs form a SiPM

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Comparison PMT ↔ SiPM

	PMT	SiPM
PDE	20-40%	20-60%
Gain	10^6	10^6
Dark noise rate	~Hz 🙂	~MHz 🙁
Behaviour in magnetic fields	🙁	🙂
Operation Voltage	1000+ V 🙁	50-70 V 🙂
Temperature sensitivity	🙂	🙁
Robustness and compactness	🙁	🙂

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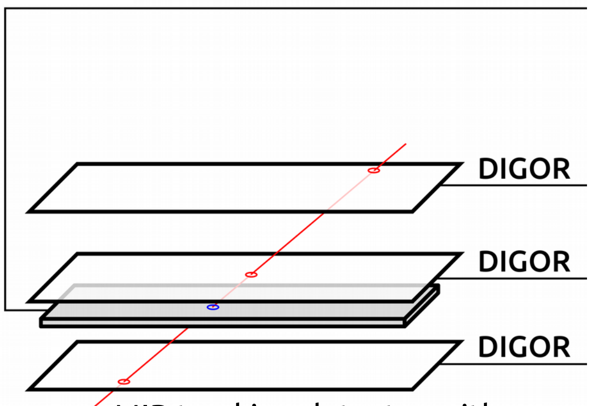
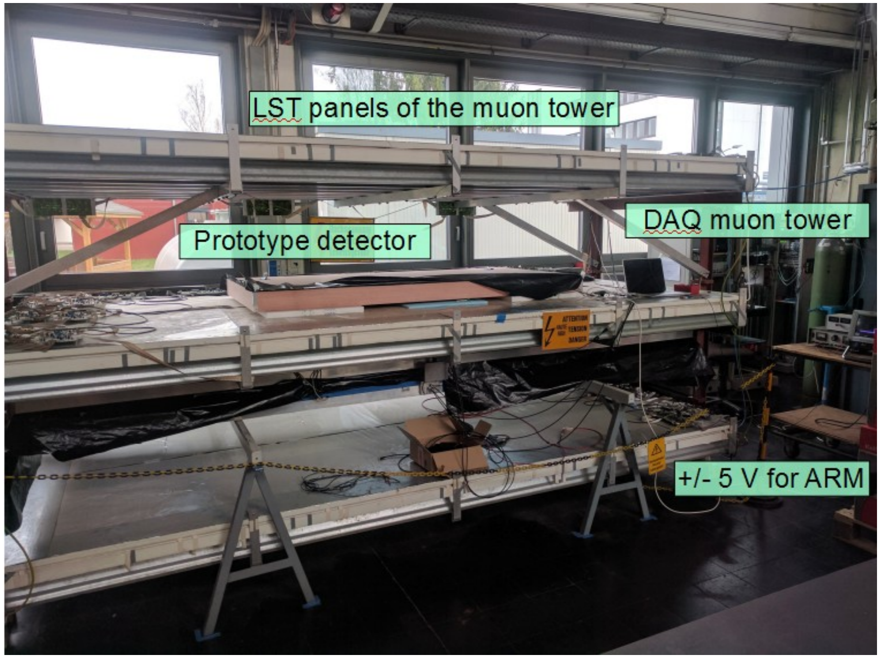
Muon Tower

Prototype detector



MIP tracking detector with
limited streamer tube (LST) chambers

Spatial resolution possible!
(1cm x 1cm, later)



Muon tower with the prototype detector

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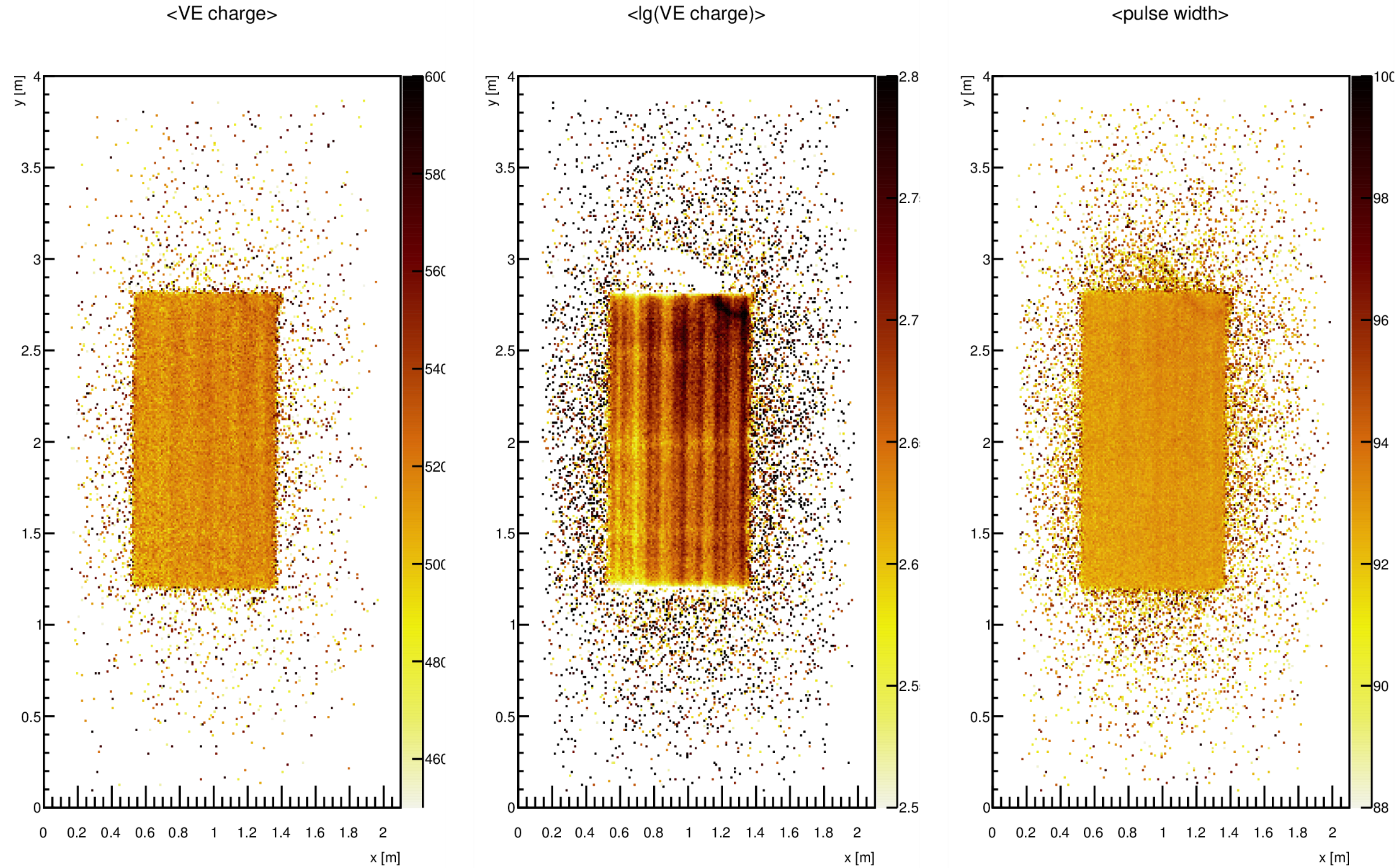
Uniformity



Left: Average pulse charge depending on the particle detection position
Center: In logarithmic scale. Single optical fibers are visible!
Right: Average pulse width

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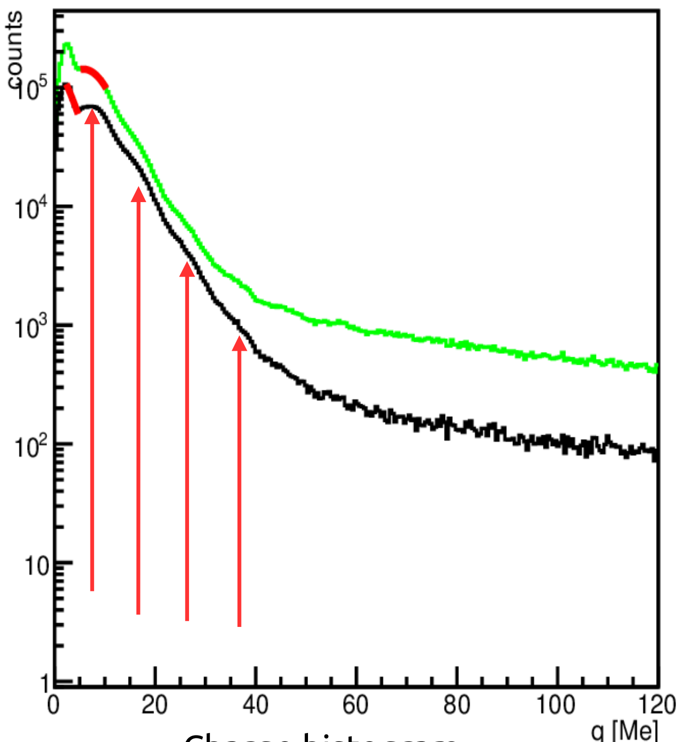
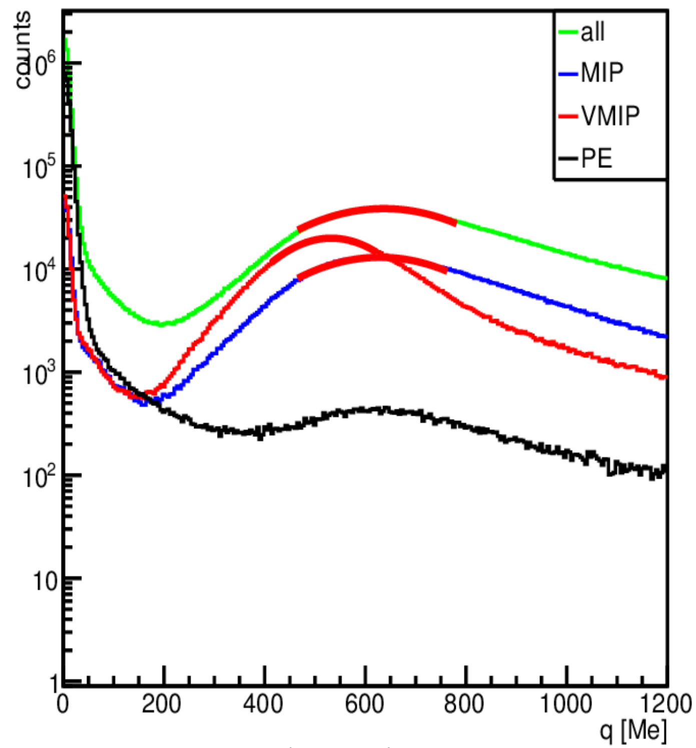
MIPs



Charge histogram,
“zoomed” into 0-120 Me



Charge histogram

PE: 25/3 = 8.3 Me
(mid gain 5x → 1.6 Me low gain)

MIP/PE: 630/8.3 = 75 photons

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Temperature dependent measurements with S13361-3050

- SiPM array S13361-3050AS cooled down in isolating cooling box together with heat reservoirs
- Measurements made in SPOCK as the system returned to ambient room temperature
- Measurement of one channel out of the 64 channels in the array

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