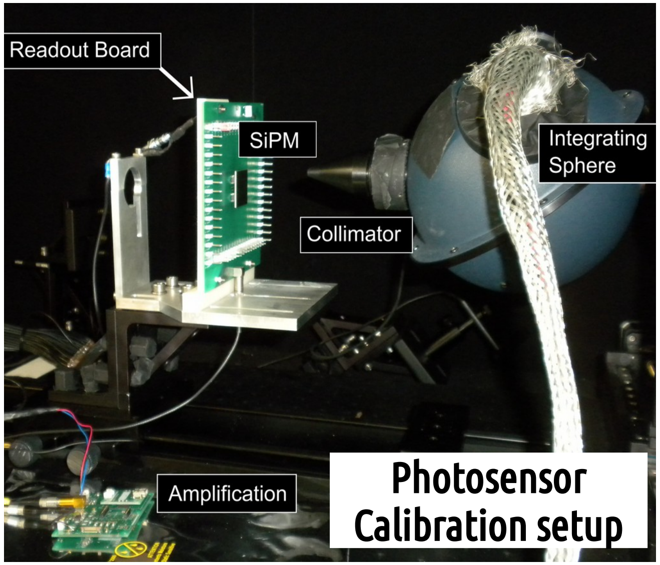
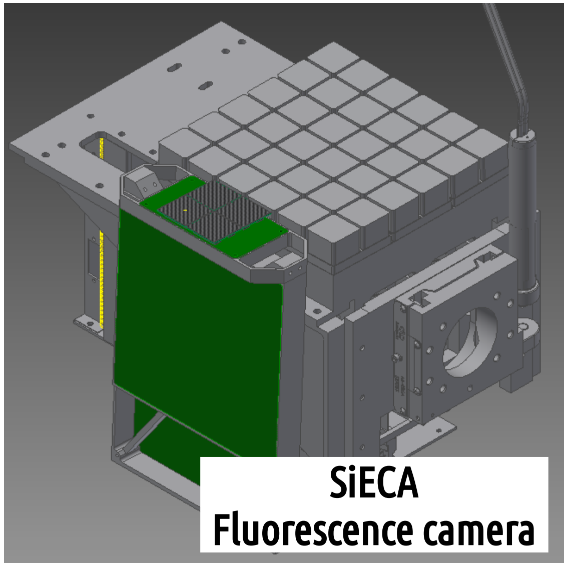
Photosensors and detector development in Astroparticle Physics

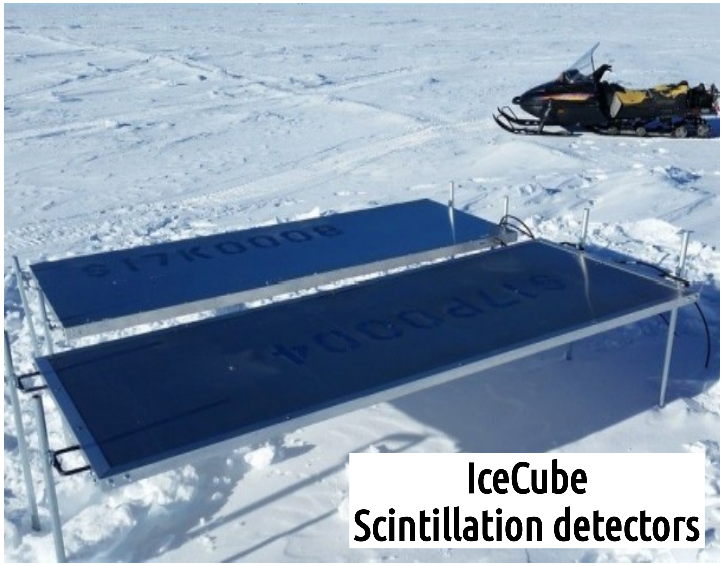
Thomas Huber – Baksan School on Particles and Cosmology



Photosensor Calibration setup

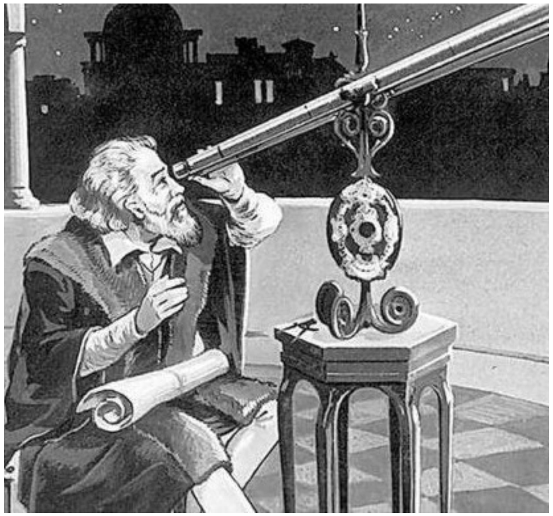


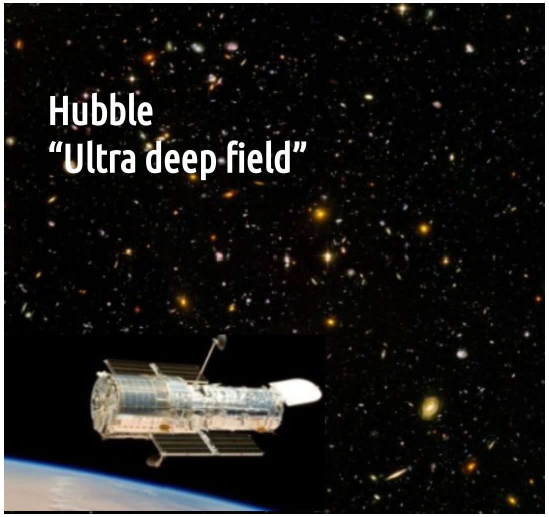
SiECA Fluorescence camera



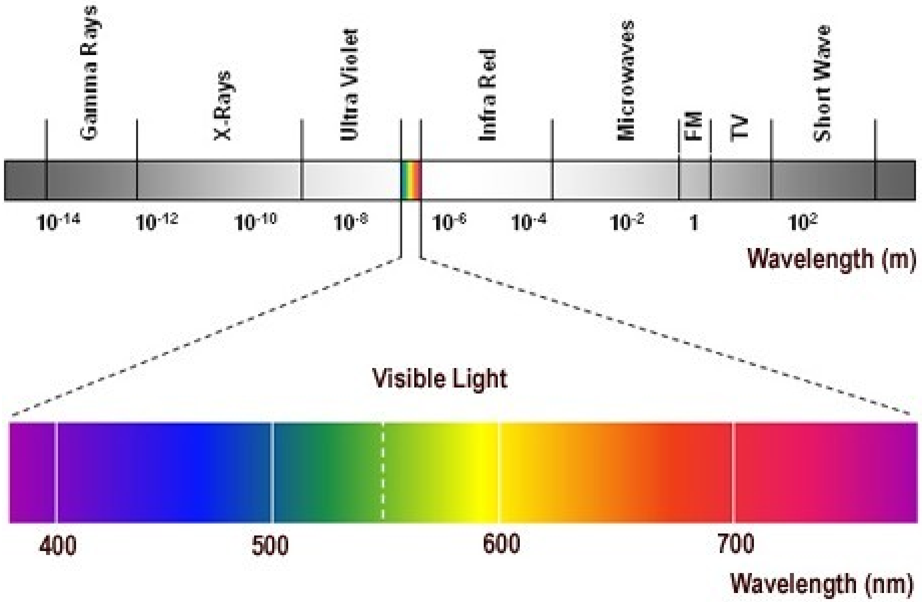
IceCube Scintillation detectors

How to (steady) find something out about the universe
Or: What is all about :-)





→ Steady upgrade of the human “Instrumentation” (= The eye)



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The optical sky – Visible via human eyes

Wavelength = 10^{-6} m $\leftrightarrow$ 1eV

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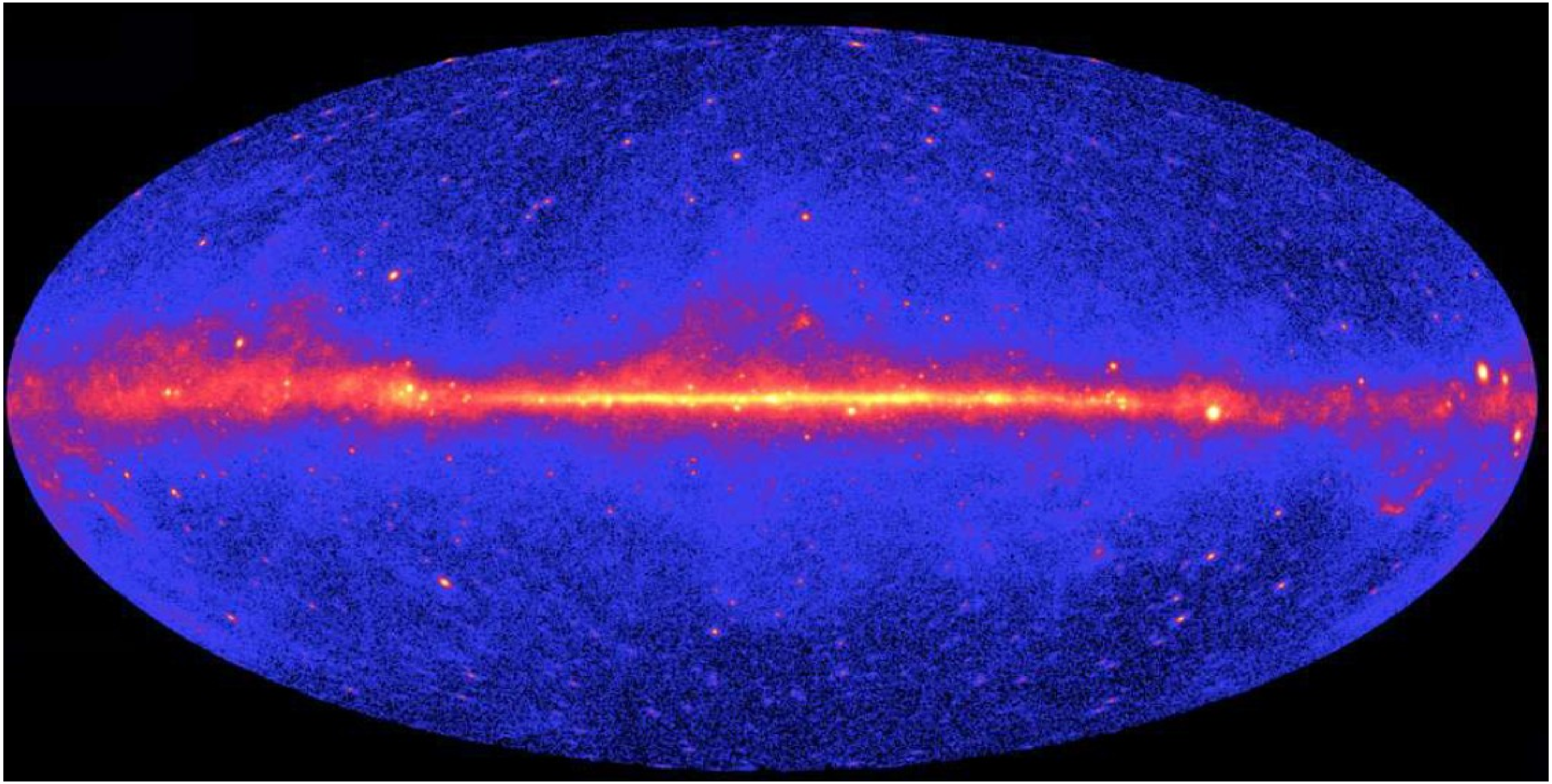
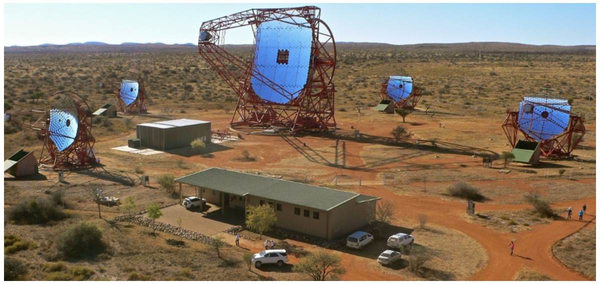
The optical sky – Visible via detecting gamma rays





Wavelength = 10^{-12} m ↔ 1 GeV

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The optical sky – At very high energies

Wavelength = 10^{-15}m ↔ 1 PeV

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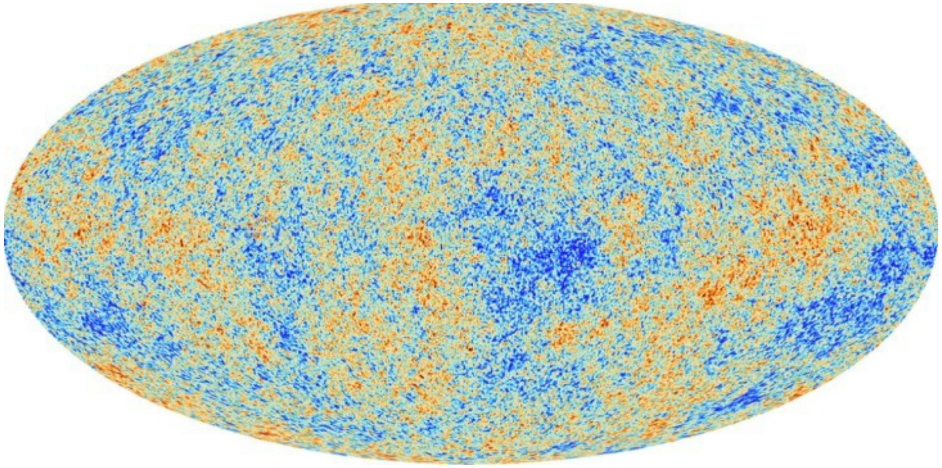
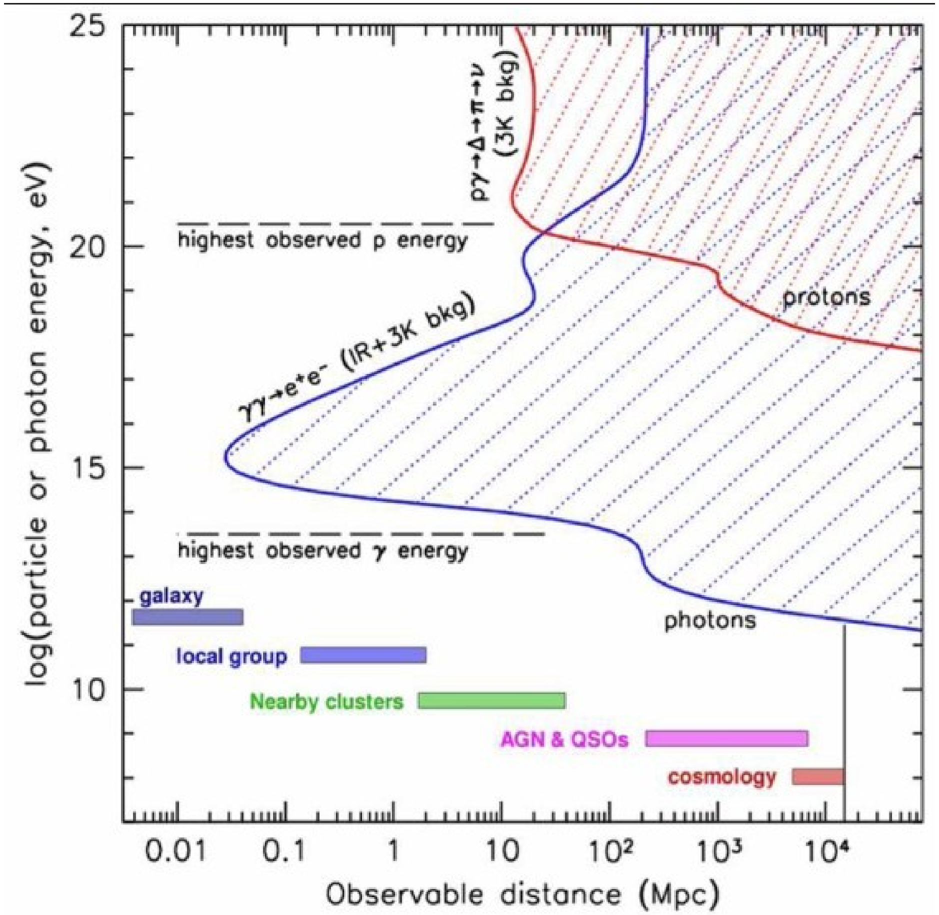
The optical sky – At very high energies



Cosmic Microwave Background (CMB)

$$\gamma_{PeV} + \gamma_{CMB} \rightarrow e^{+} + e^{-}$$

PeV Photons are interacting with CMB Photons (411/ cm³) before reaching our telescopes



→ **We need other "messengers"**

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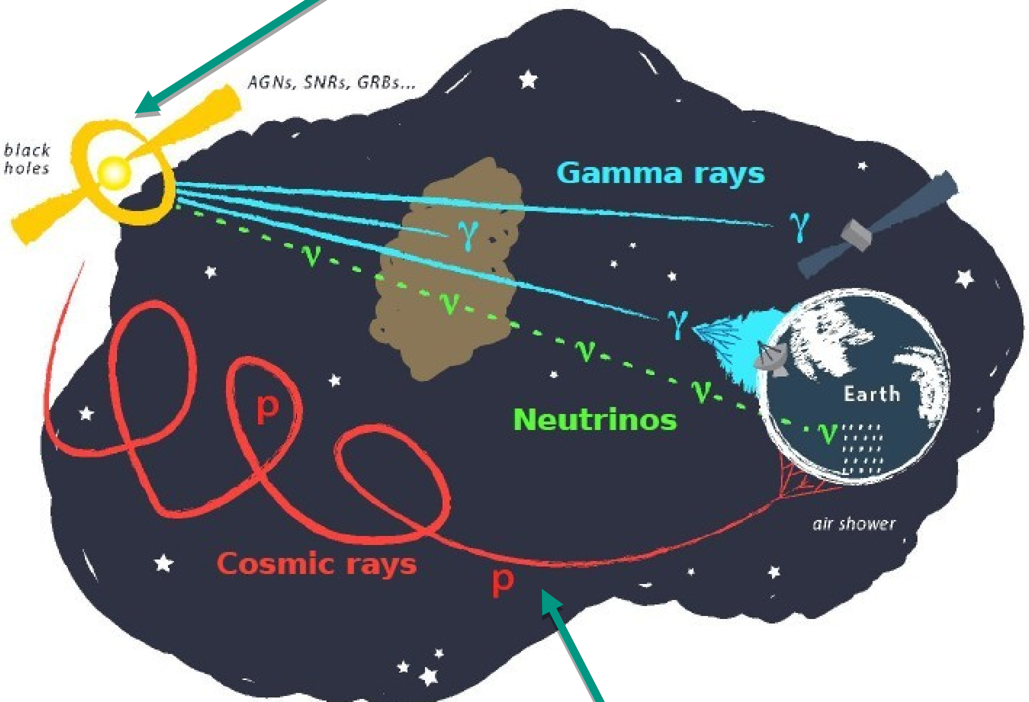
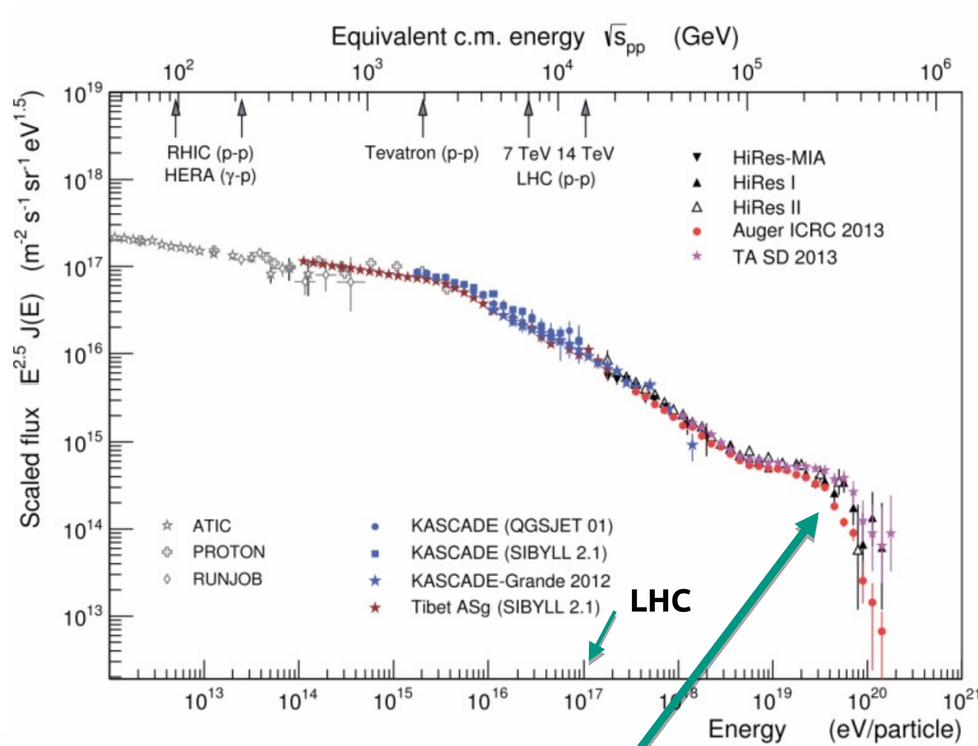
Astroparticle physics:
Another window into the universe: Cosmic Rays

Sources?
Accelerators?



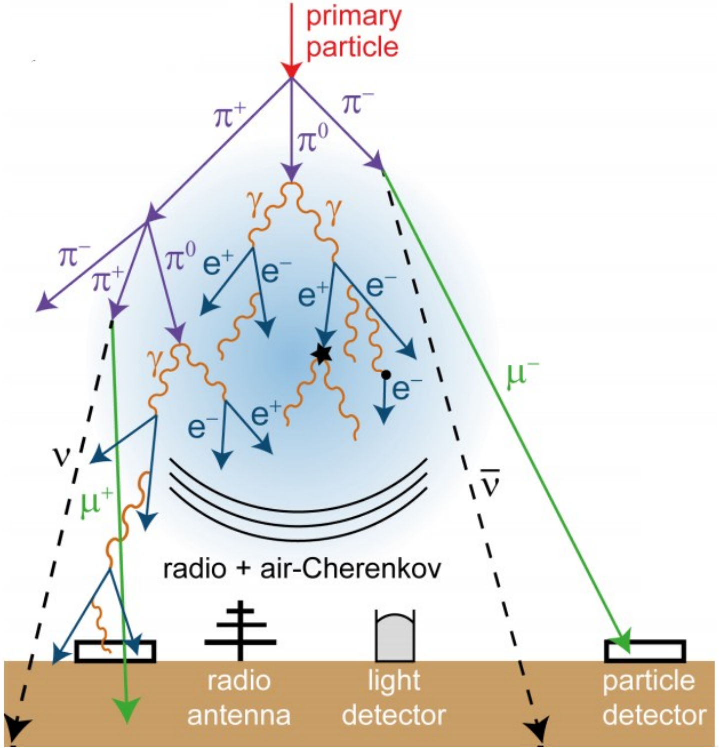
Cosmic rays:
Protons? Nucleons?
Composition?



$$1 \cdot \frac{1}{km^2 \cdot year}$$

Large instrumentation(s) needed!

Another window into the universe: Cosmic Rays: Extensive Air-Showers



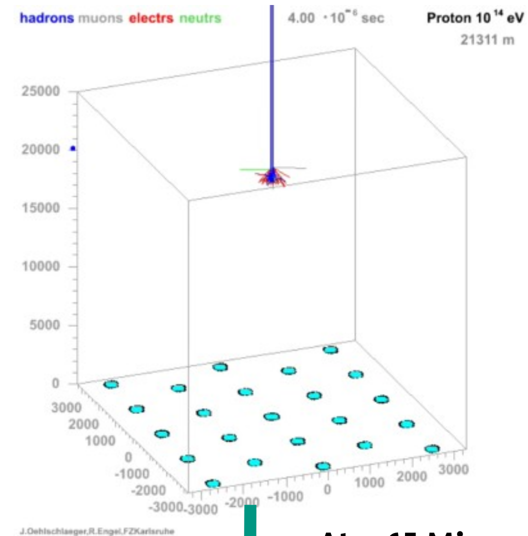
F. Schröder (KIT-IKP, Uni Delaware)

Extensive Air-Showers: Detectable!

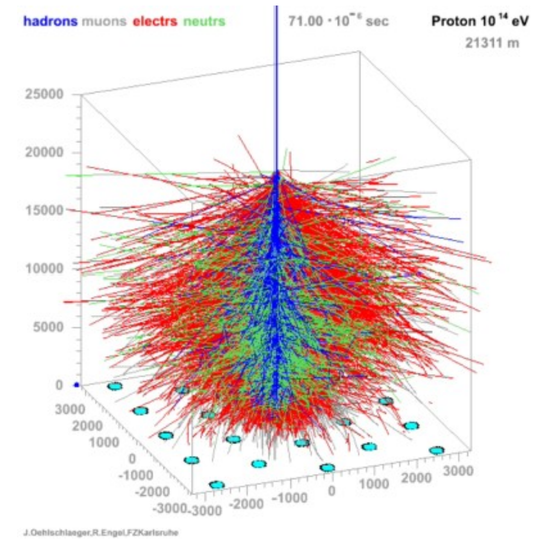
KASCADE

Pierre-Auger Observatory

IceCube : IceTop



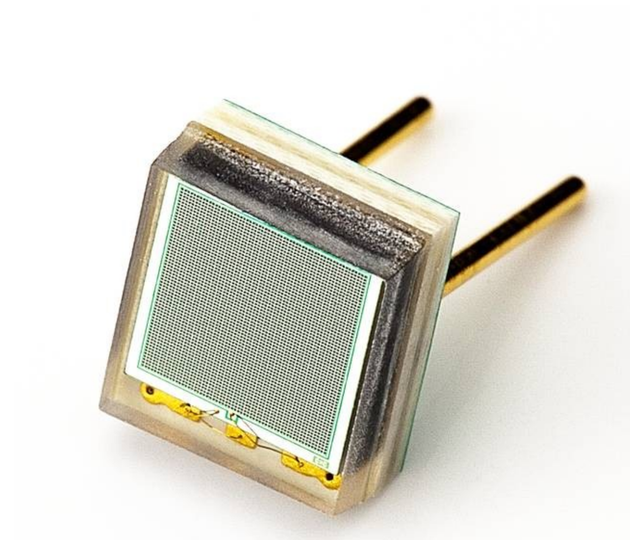
Δt ~ 65 Microseconds



J. Oehlschläger, R. Engel, (KIT-IKP)

How to read out the detectors.
Or: How to “transform“ Photons into a measurable voltage?

Photomultiplier (PMT)



Silicon Photomultiplier (SiPM)

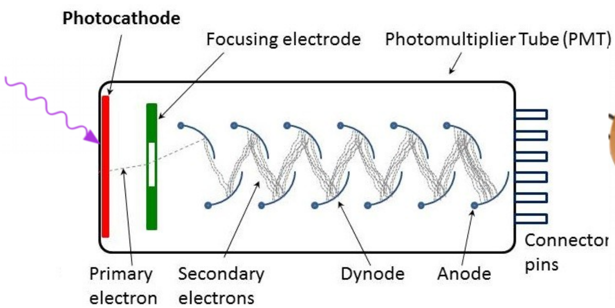
KASCADE

Pierre-Auger Observatory

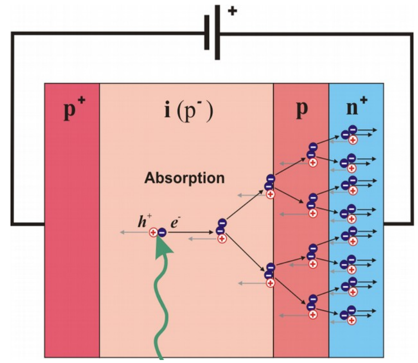
IceCube : IceTop

Silicon Photomultiplier (SiPM)

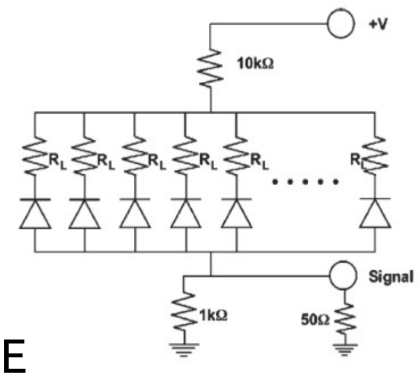
PMT



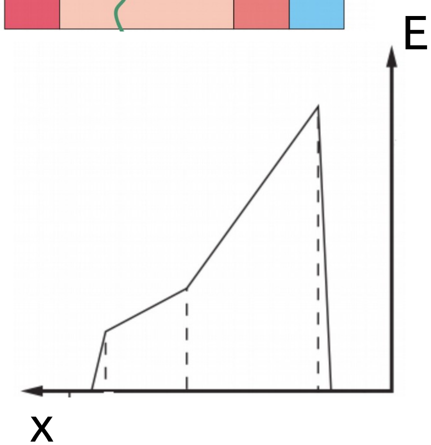
APD

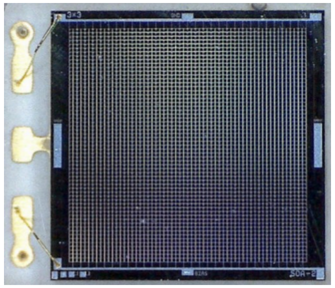


SiPM

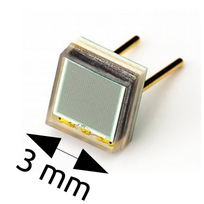


	PMT	SiPM
Photo Detection Efficiency PDE	20-40%	20-60%
Gain	10^6	10^6
TTS (Transit Time Spread)	~1 ns	~1 ns
Dynamic range	10^6	10^3
Dark noise rate	~Hz 🙂	~MHz 🙁
Behavior in magnetic fields	🙁	🙂
Operation Voltage	1000+ V 🙁	50-70 V 🙂
Temperature sensitivity	🙂	🙁
Robustness and compactness	🙁	🙂





$$PDE = \frac{\text{Number of detected photons}}{\text{Number of incident photons}}$$



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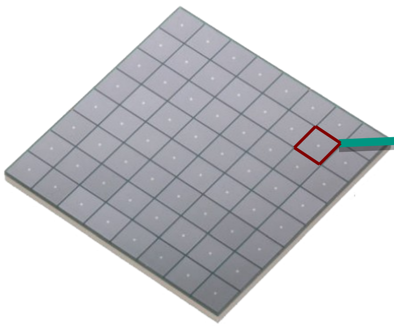
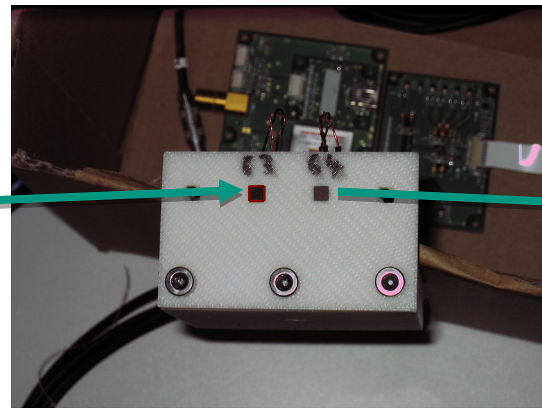
How they look like

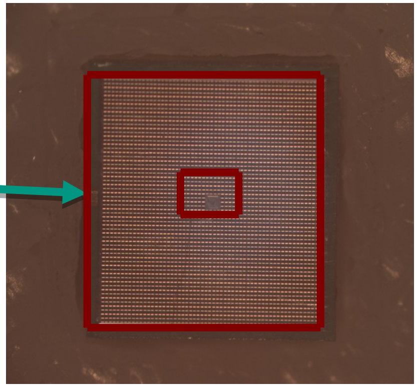
Candidate:
Hamamatsu
64 Pixel
SiPM TSV-Array



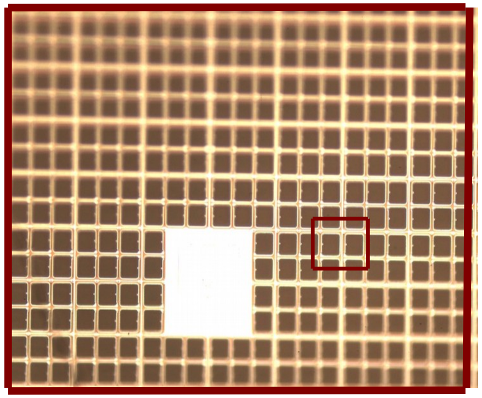
1 Pixel from the
TSV Array



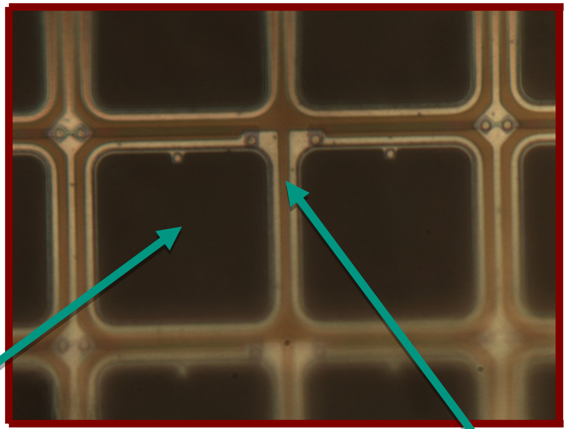
2.5x Zoom into 1 Pixel



10x Zoom



100x Zoom



1 Avalanche Photodiode
(of est. 3600 @ 1 pixel)

Crosstalk-reducing
Isolator

Hamamatsu S13361-3050

Gain:	~ 10^6
Low Bias Voltage:	~53V
Number of APDs:	~3600
Darkcountrate:	~1 Mcps

How to calibrate them?

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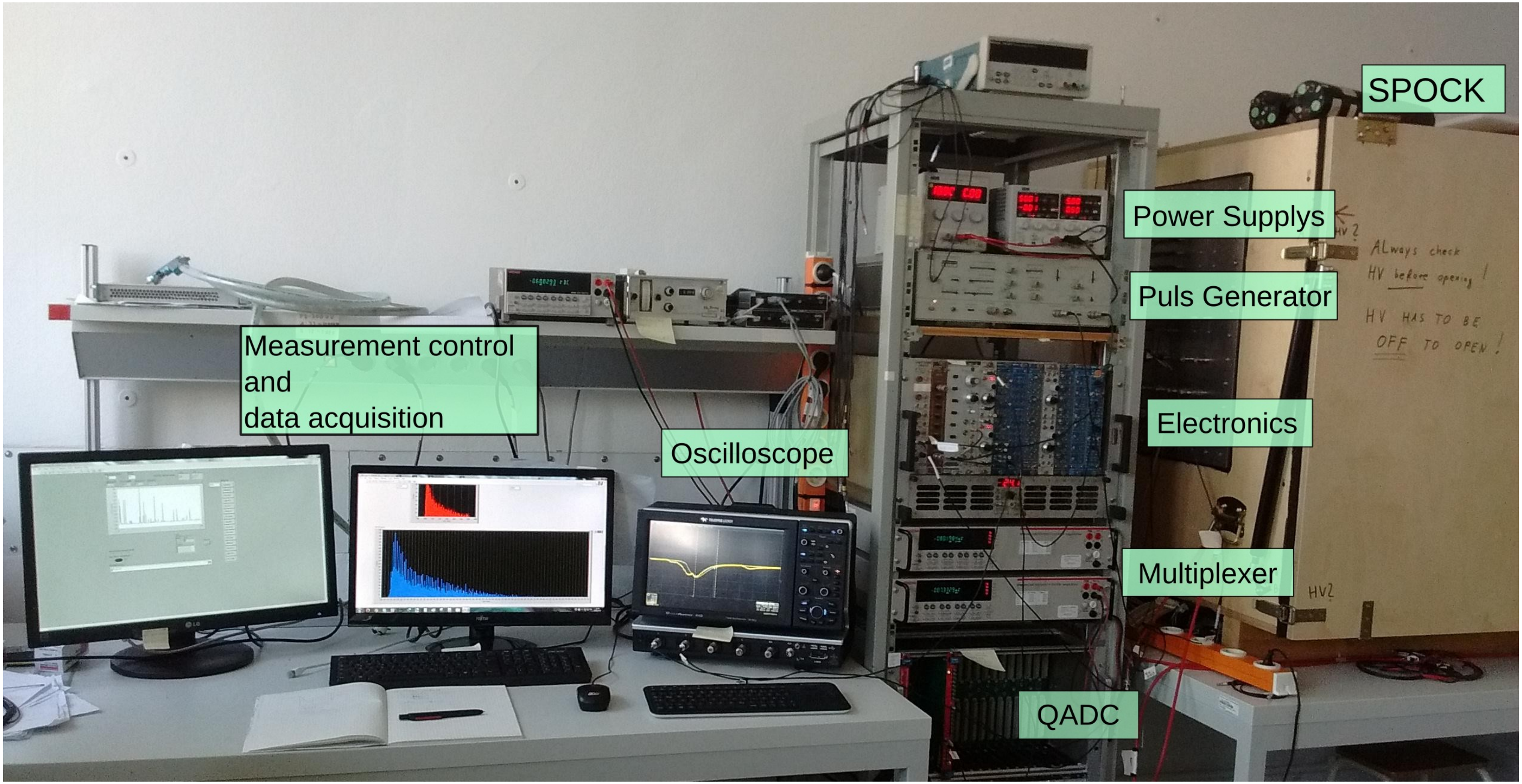
Characterising measurement setup (SPOCK)



SPOCK: Single PhOton Calibration stand at KIT

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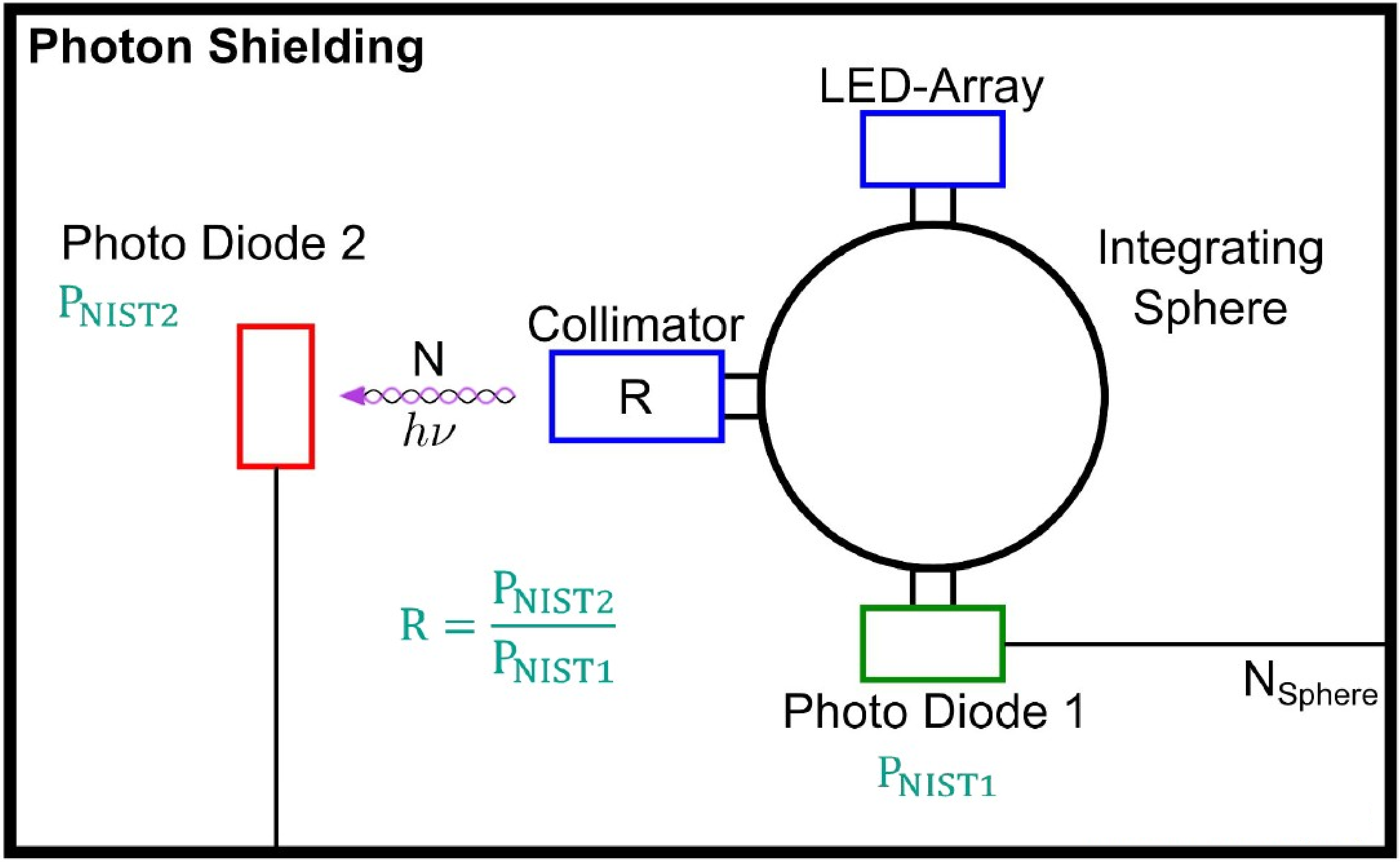
Simplified sketch of measurement method

1 st step: Calibrating the measurement setup:



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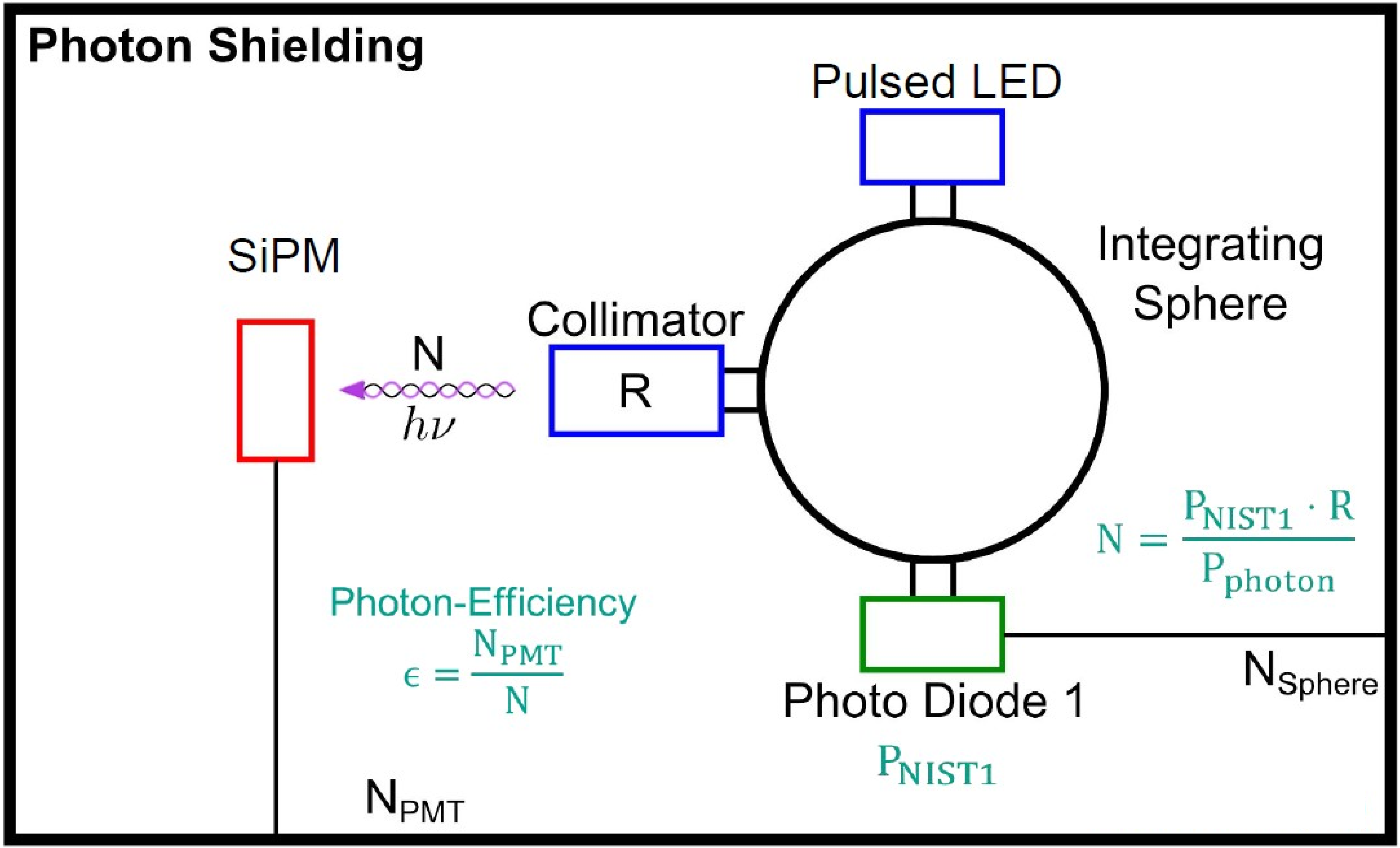
Simplified sketch of measurement method

2 nd step: Characterize the photo sensor (SiPM / PMT)



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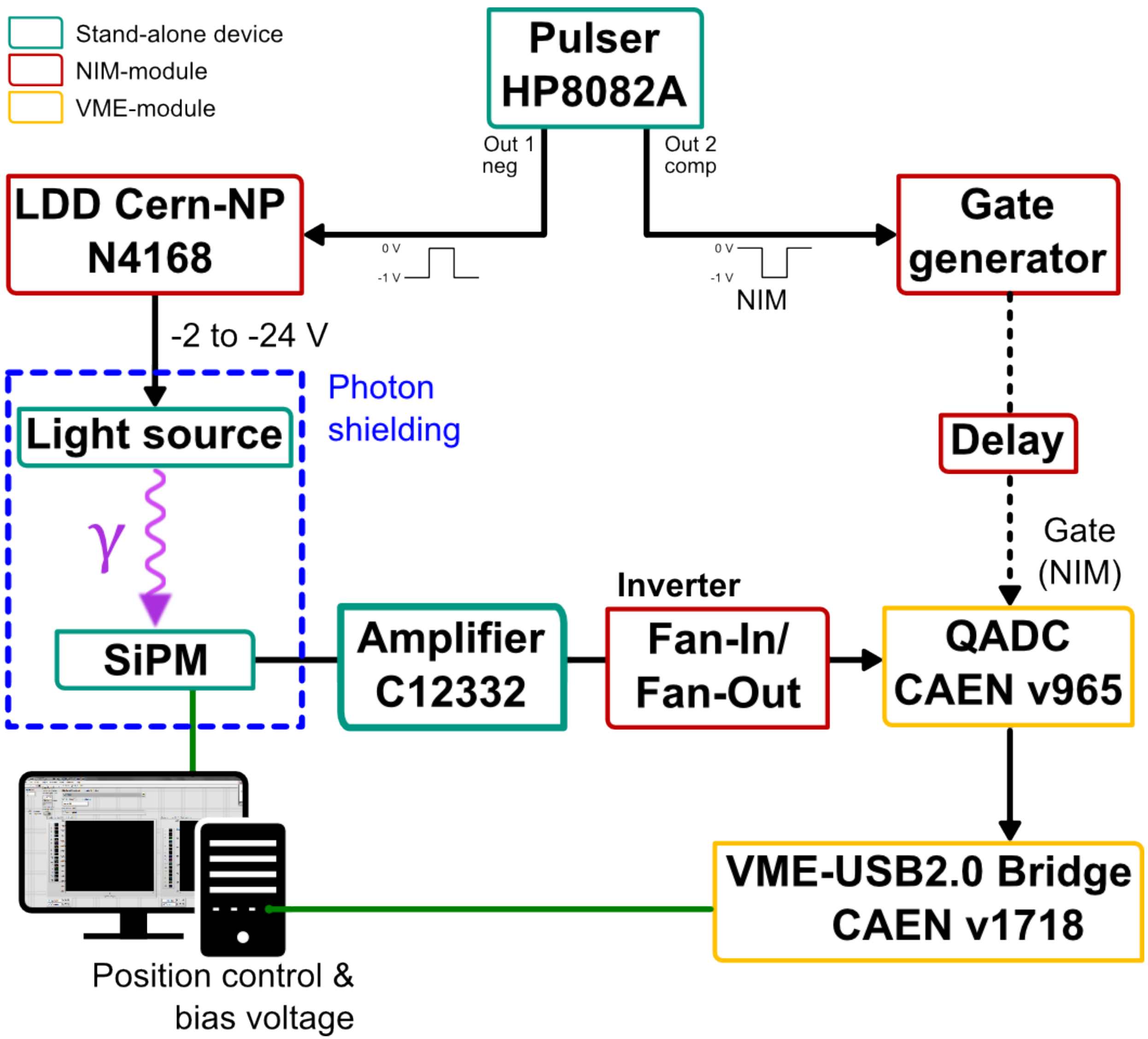
Characterizing SiPMs



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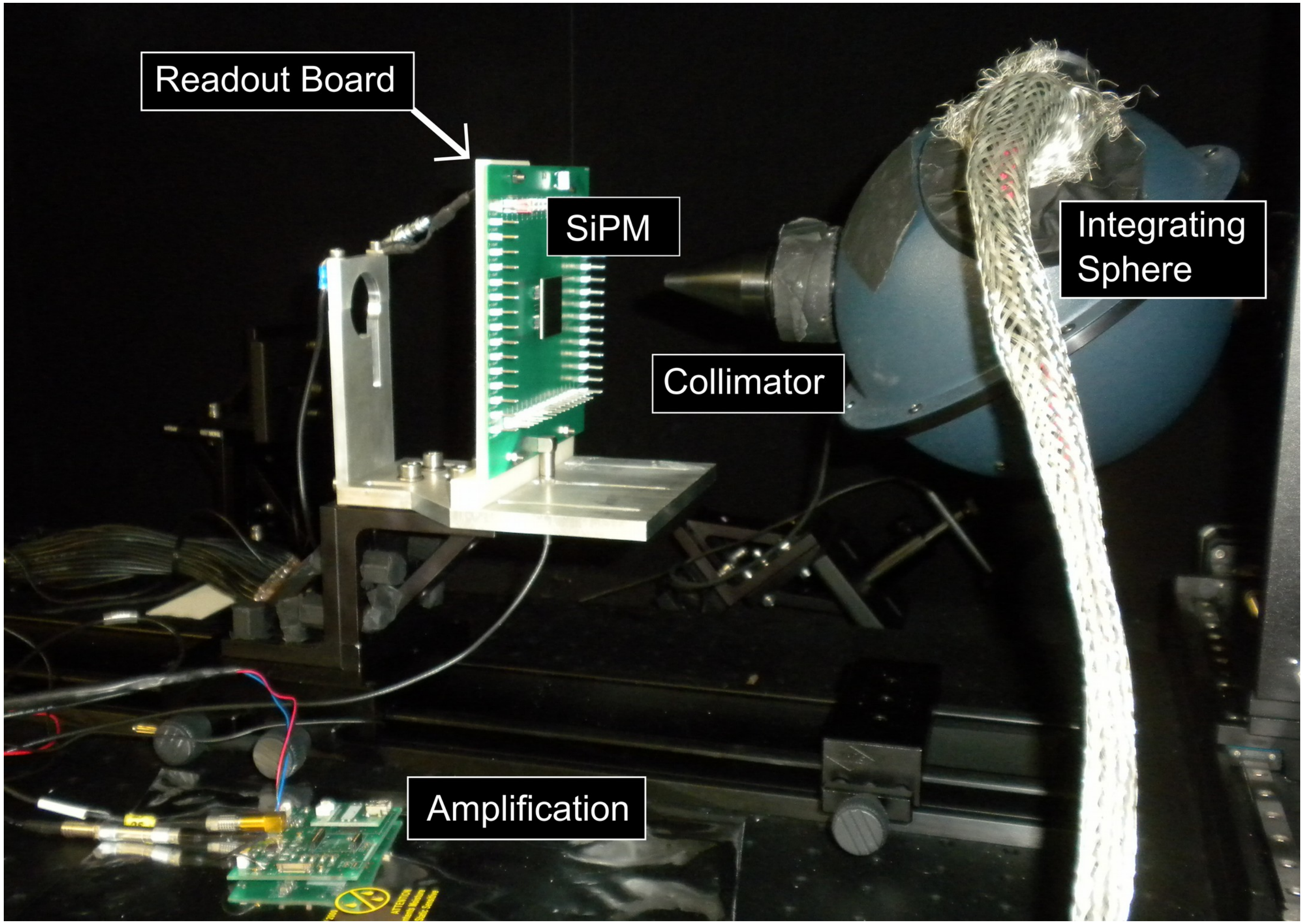
Inside of the calibration setup



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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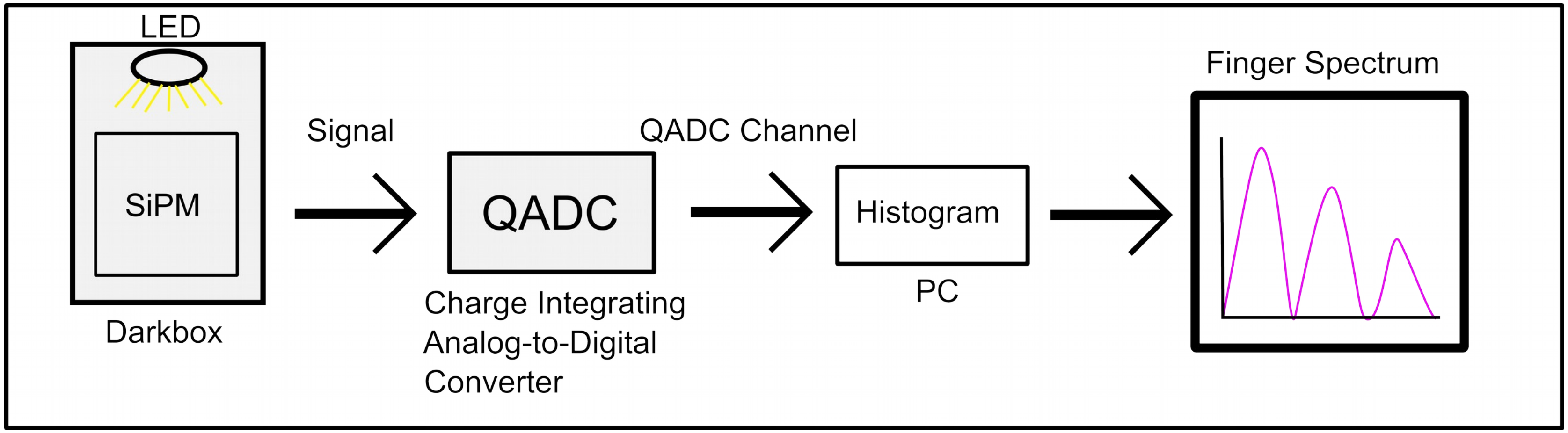
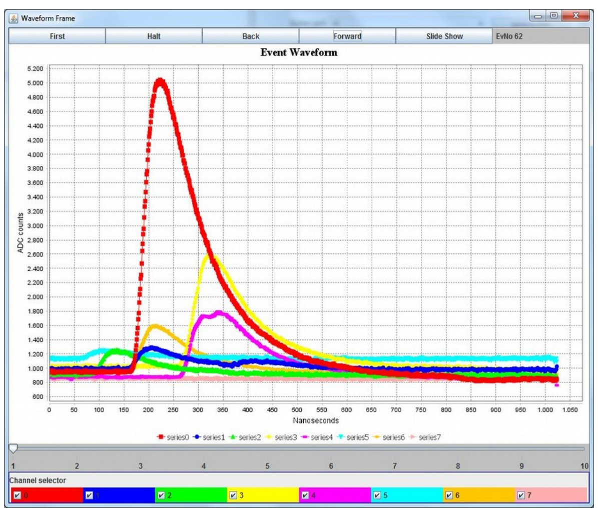
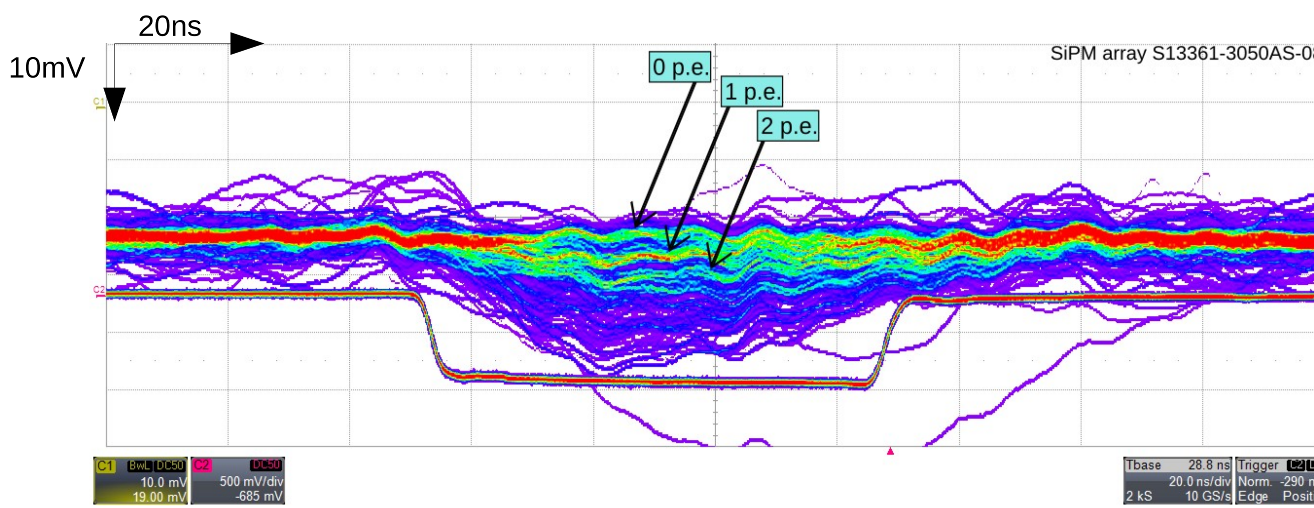
How the data looks like







Example of SiPM waveforms

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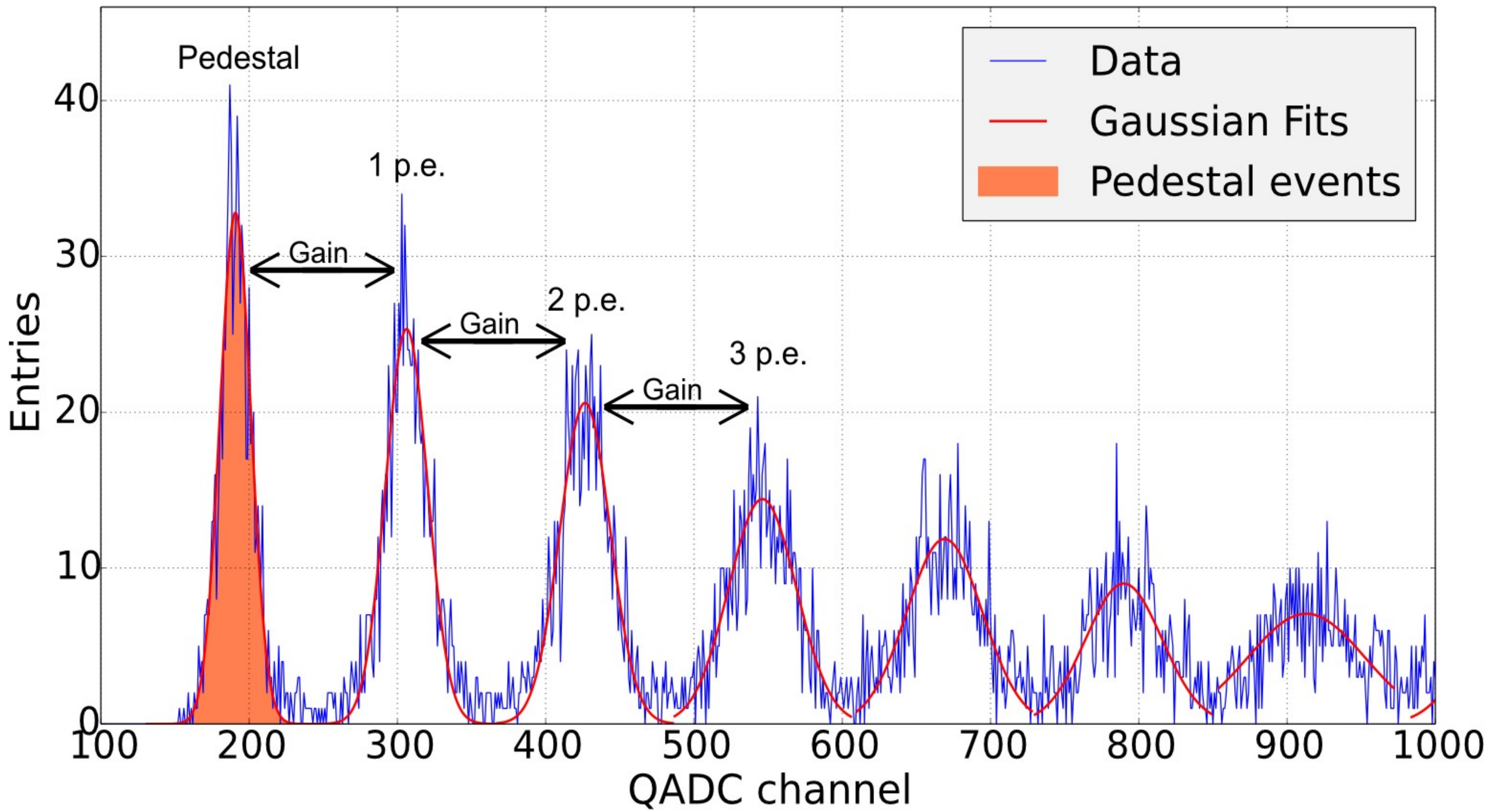
How the data looks like



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Okay…

Calibrated!

We know what we can measure with that

Using photo sensors in astroparticle physics for… what?

(“Backup” :
What is the story of the SiPM temperature dependcy ?)

Example #1
SiPMs for the surface extension at IceCube

Or:
Developing (and deploying) detectors as PhD thesis

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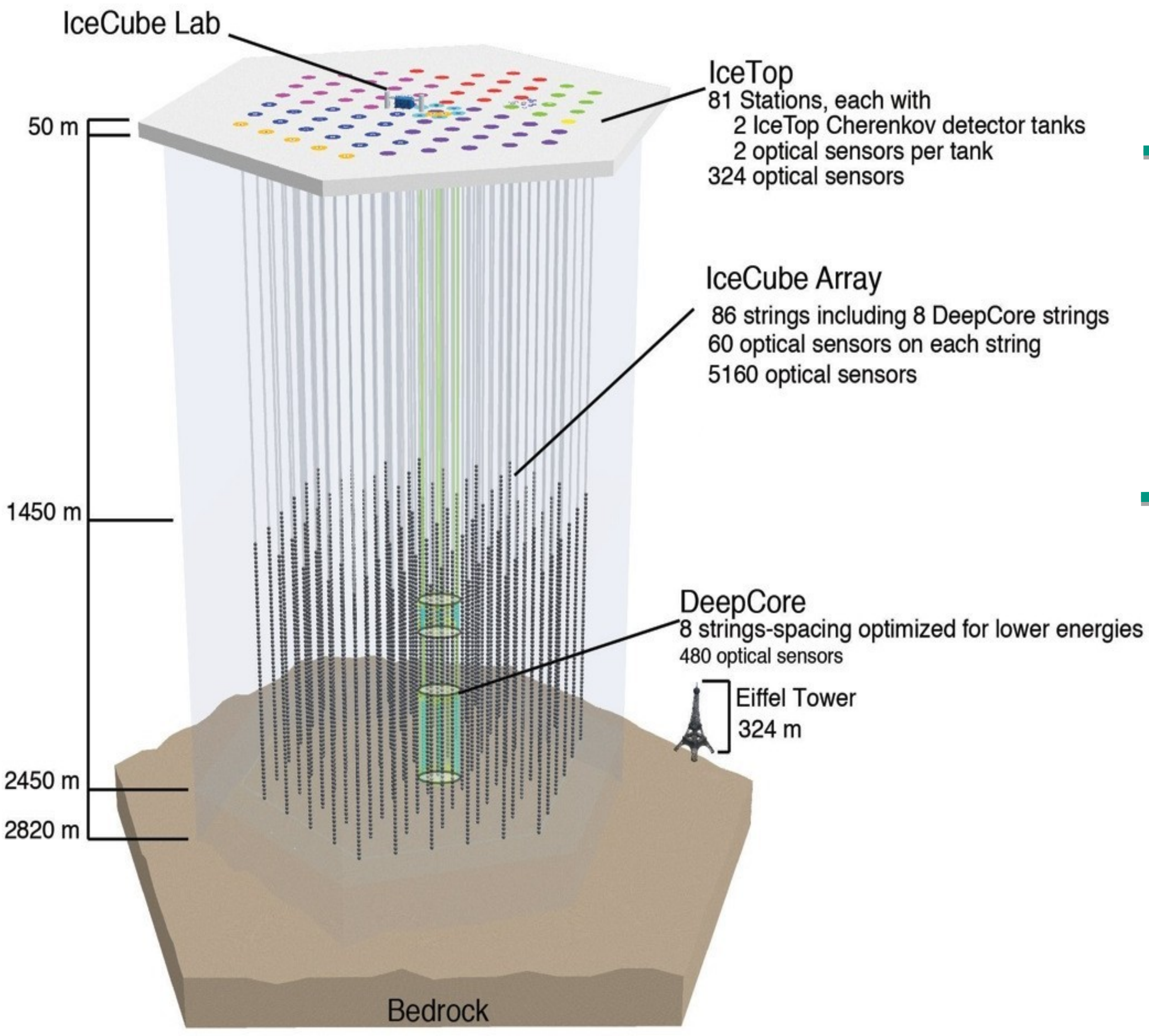
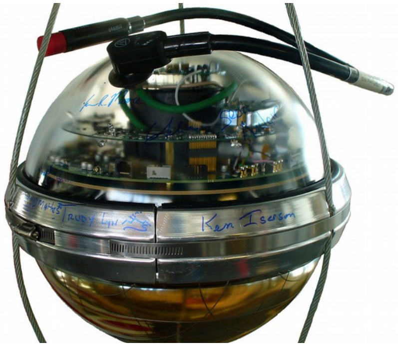
The IceCube Observatory



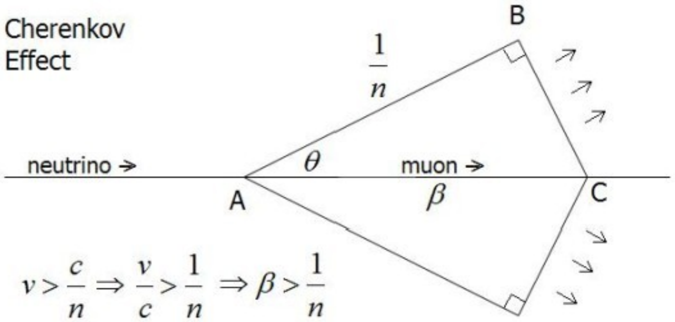
IceCube : IceTop

String with optical module



Optical Module (DOM)

How IceCube Signals looks like
– How you „see“ an astrophysical Neutrino

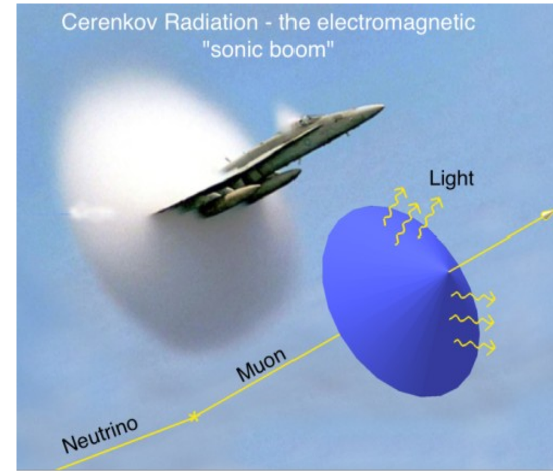


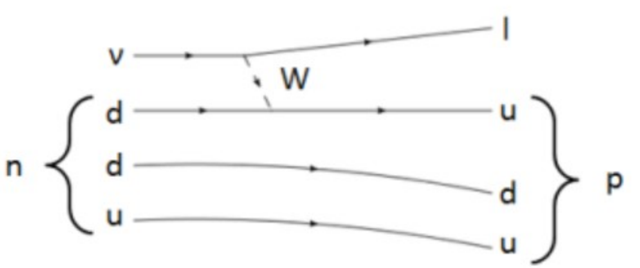
$$v > \frac{c}{n} \Rightarrow \frac{v}{c} > \frac{1}{n} \Rightarrow \beta > \frac{1}{n}$$

$$\cos\theta = \frac{AB}{AC} = \frac{1/n}{\beta} = \frac{1}{n\beta} = \frac{1}{n}$$

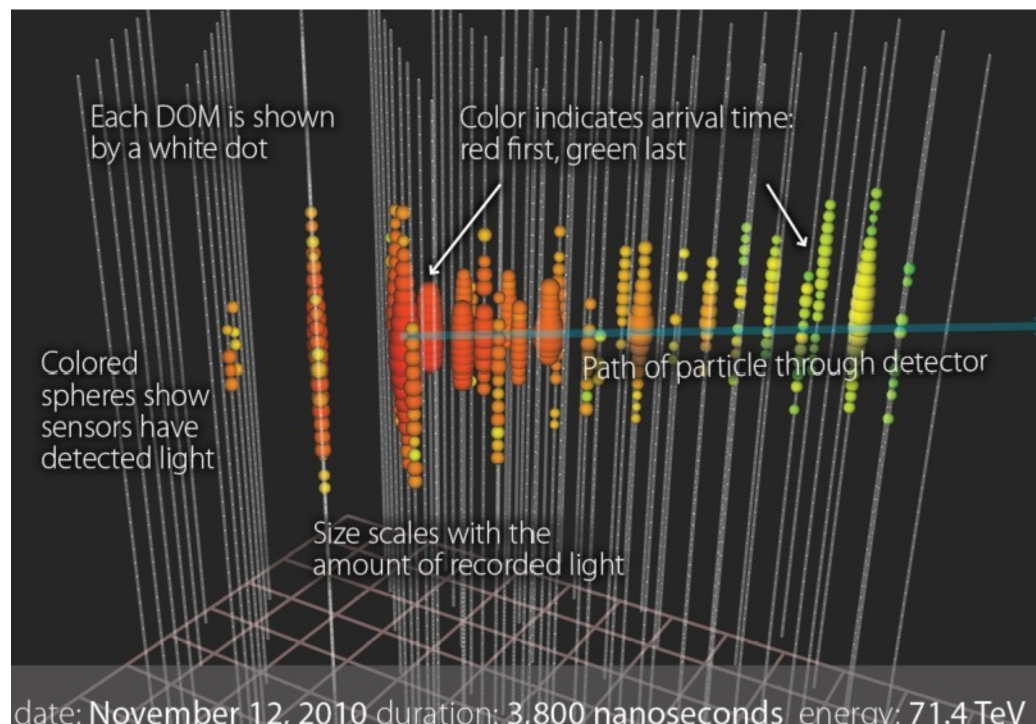
Neutrino detectable if it weakly interacts and creates a charged particle

(Muons, Electrons, Tauons)



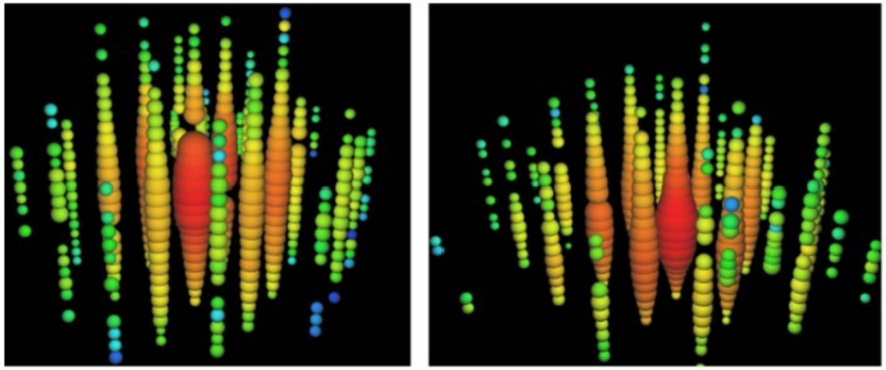


Weakly interaction



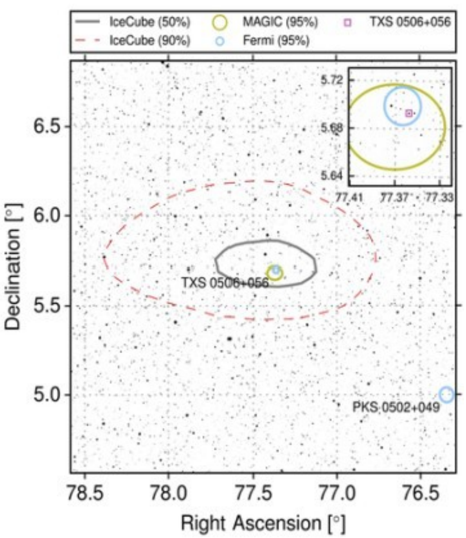
Is IceCube working? Seems like

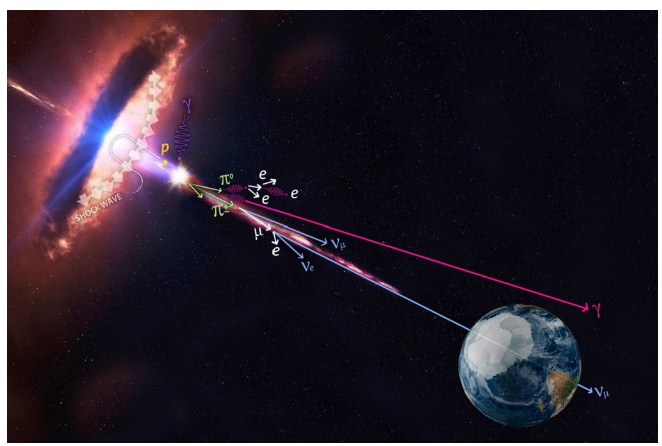
SENSE
Karlsruhe Institute of Technology
DESY.



2013: Signature of "Ernie" (1.1 PeV) and "Bert" (1.3 PeV)
→ The first observations of PeV Neutrinos of astrophysical origin

Blazar TXS 0506+056





2018: First time that a neutrino detector has been used to locate an object in space and that a source of cosmic rays has been identified → **Multi-Messenger astronomy**

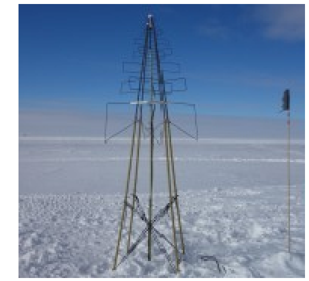
Towards IceCube-Gen2

Scintillators

Prototype stations deployed
2017/18

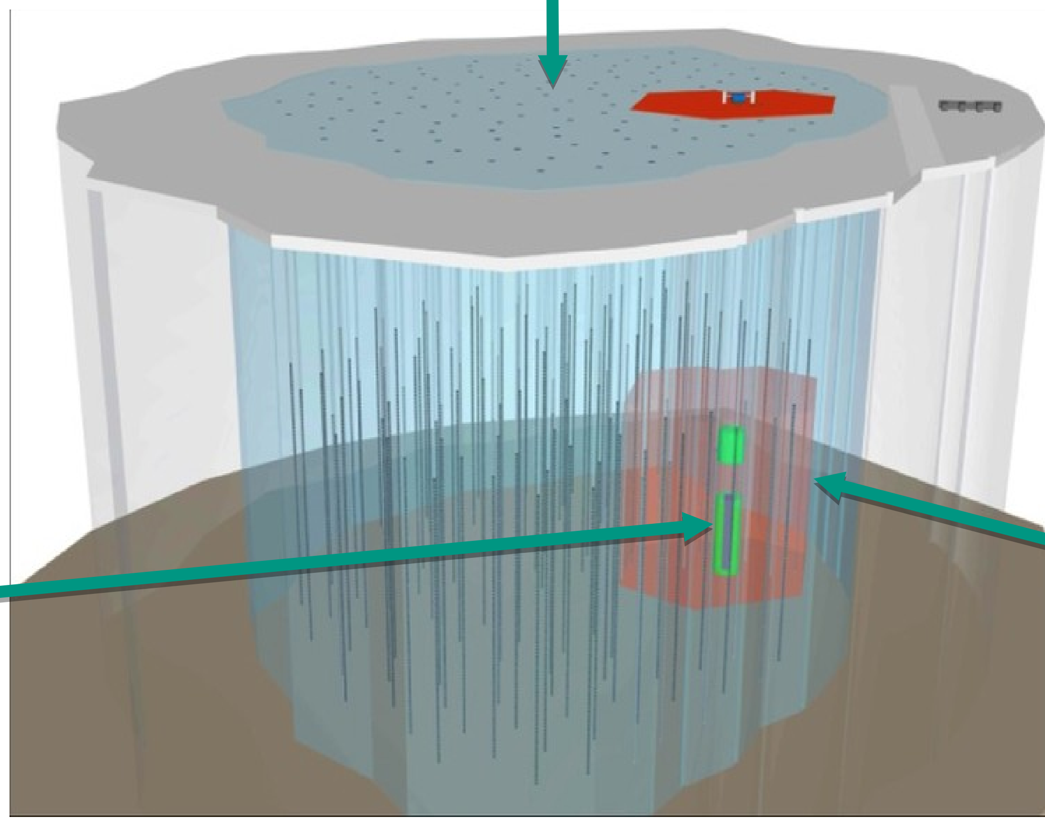
Next slides

Radio antennas

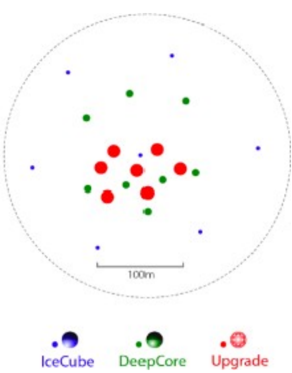


Prototype deployed
2018/19

Surface extension

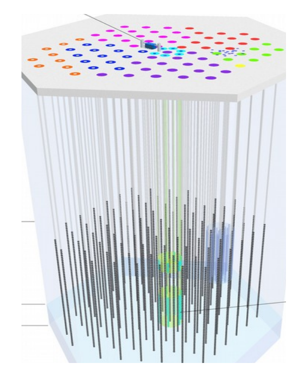


IceCube Upgrade



2021/22?

IceCube



Present

~ Possible IceCube-Gen2 facility

How to measure MIPs

Minimum Ionizing Particle (MIP)

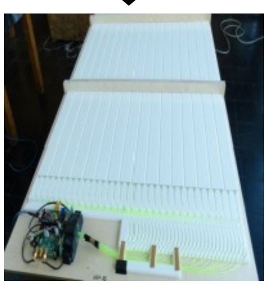
A new surface detector array for IceCube ☺

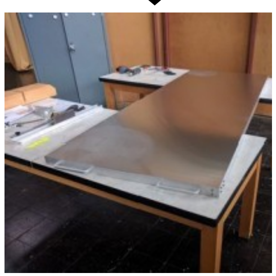
=

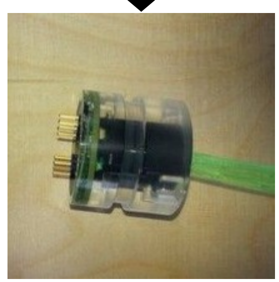
Synchronization with ICL, Trigger, Fieldhub connection

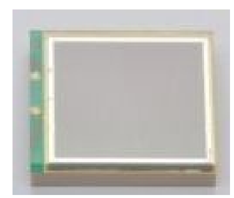
Datastream, Sat-Uplink, White Rabbit compatibility

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





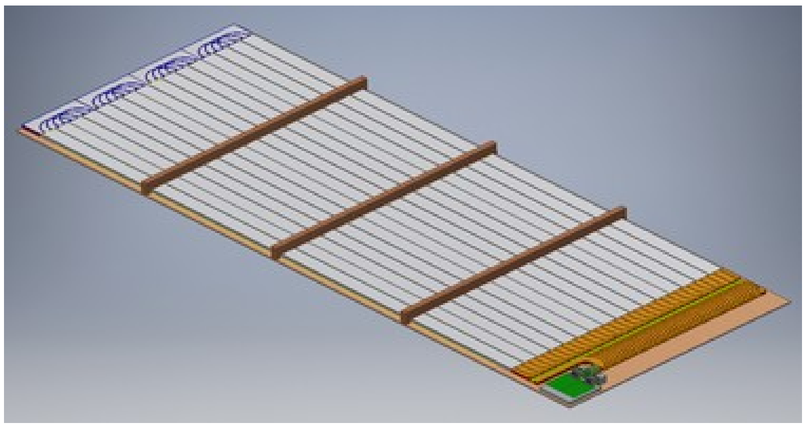




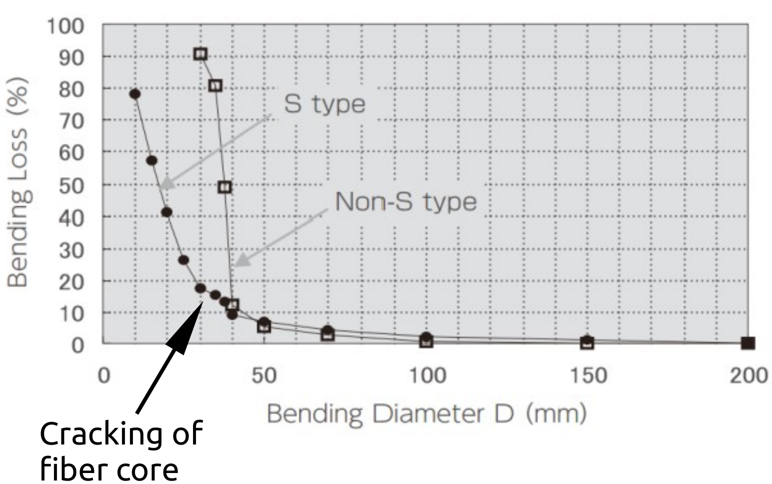
"Final result"

Used scintillator material and optical fibers

- **Scintillator material:**
  Fermilab scintillator bars
- **Wavelength shifting fibers:**
  “Kuraray Y-11” optical fibers

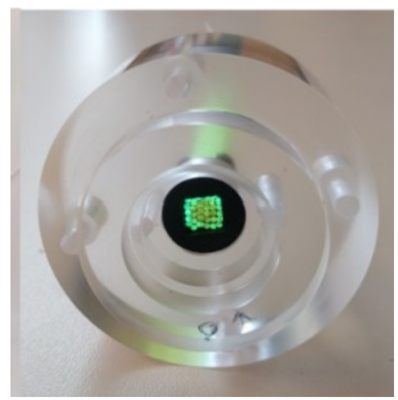


CAD of the detector



Sensitive scintillator area:
0.8m x 1.875m = 1.5m²

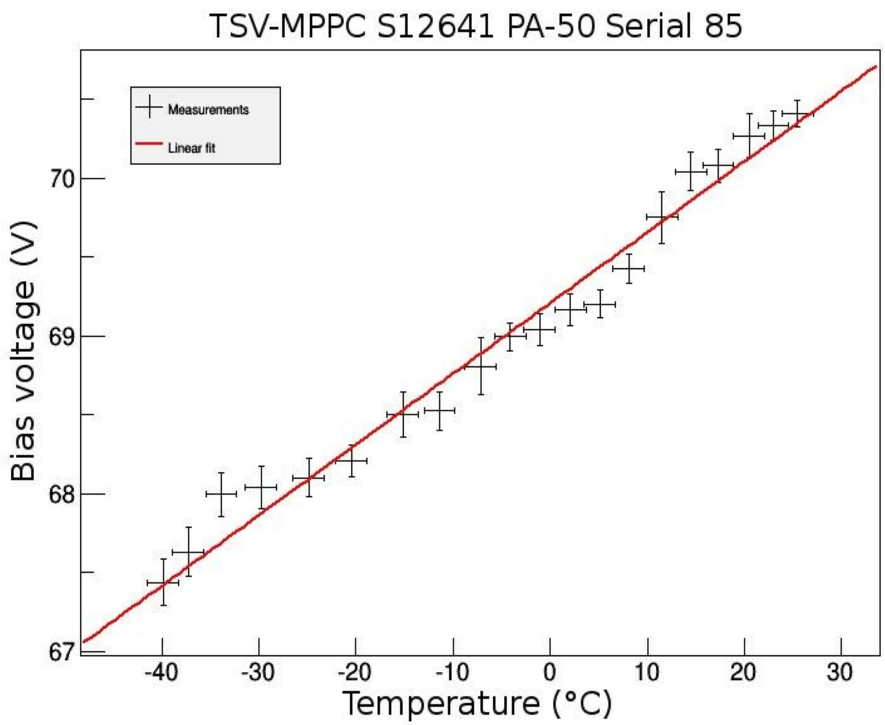
Routing of the fibers:
16 optical fibers = 32 fiber ends to the SiPM

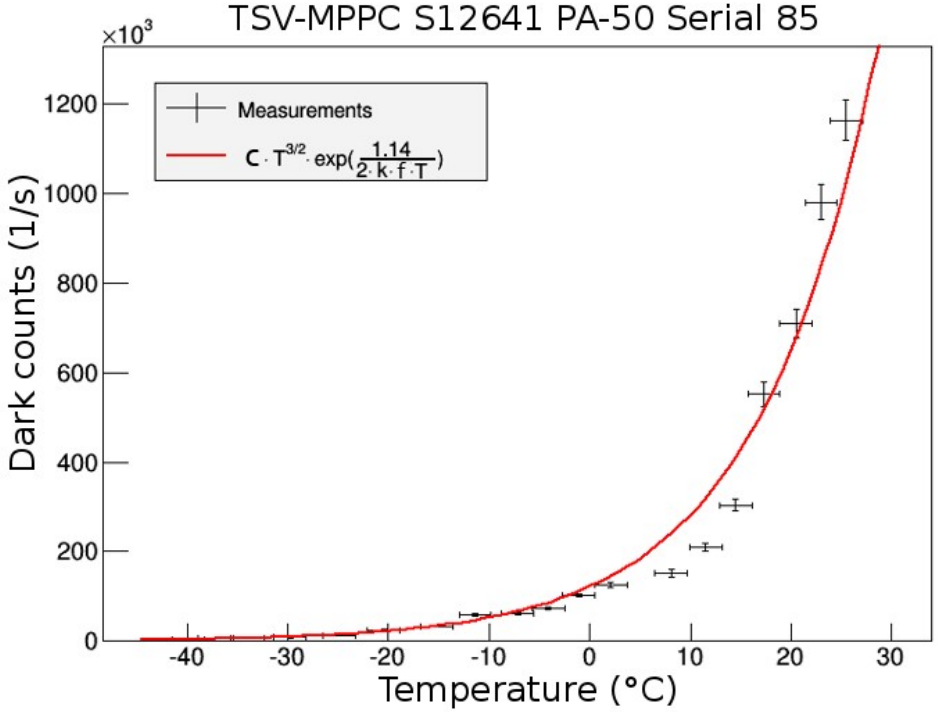


Optical coupling

Fixed routing of the optical fibers to ensure an uniform detector

Why SiPMs as photosensors?





Performance increases at low temperatures:

- Less dark counts
- Less bias voltage needed
- Higher PDE
- ...

No better place on Earth (beside the Lab) to operate SiPMs than:

At the South Pole

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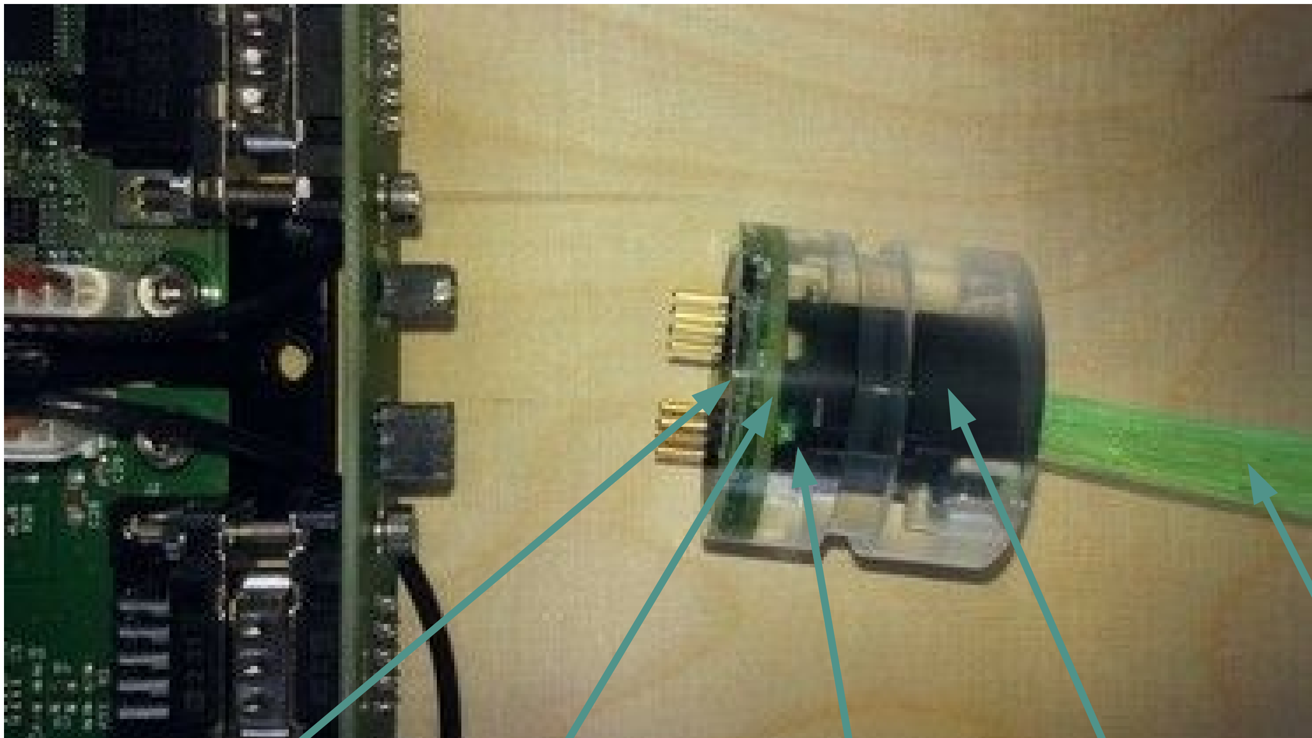
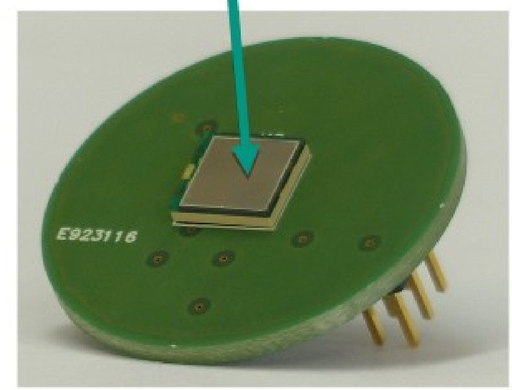
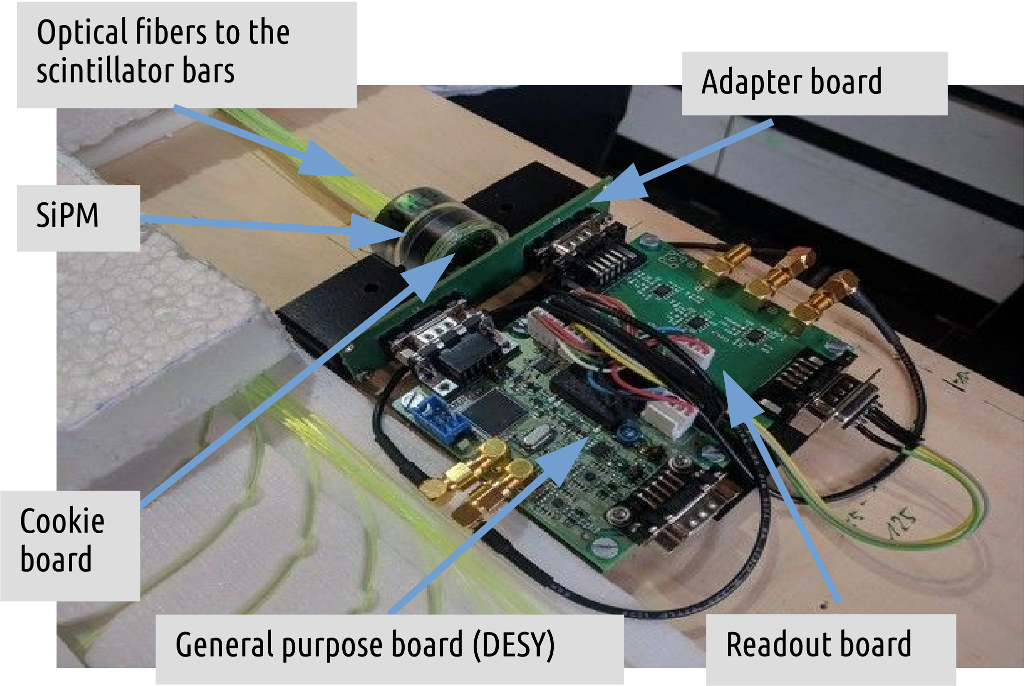
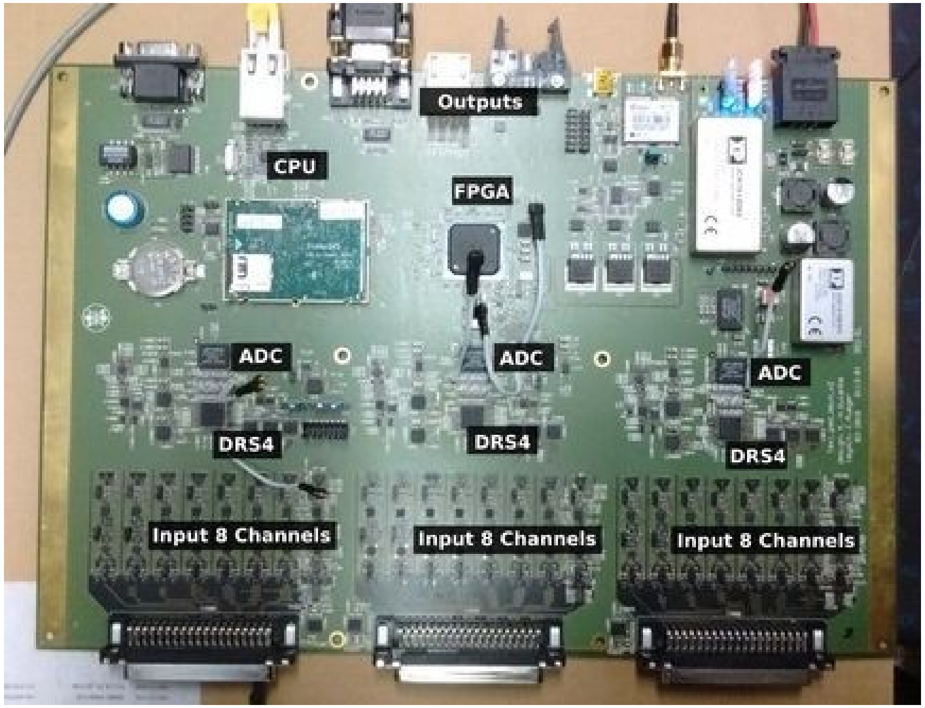
Optical coupling to the photosensor (SiPM)





Used DAQ electronics for the scint detector array





T. Karg, K-H. Sulanke, M. Kossatz (DESY)

IceARM (Analog Readout Modul) :

- Analog readout of the SiPM
- High-Gain / Low-Gain (10x / 1x)
- Hamamatsu Power supply for the SiPM
- Temperature sensor next to the SiPM

IceTAXI:

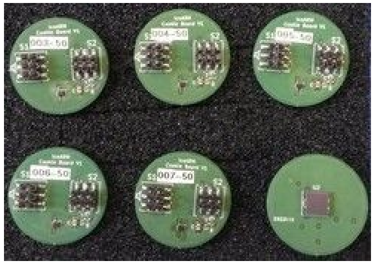
- Developed by DESY Zeuthen
- 1 or 3 DRS4 sampling chips, 8 input channels each
- Adjustable sampling rate up to 5 Gigasamples/s
- Triggered by signal-over-threshold

A lot of function tests + specifications + documentation

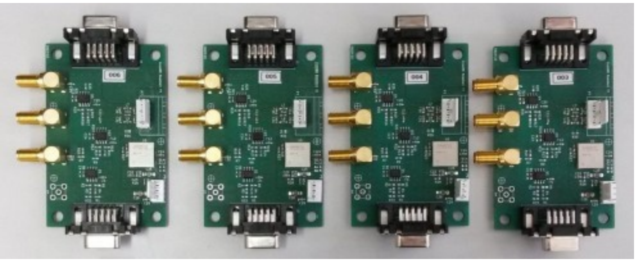
Tested, measured and documented: (**incomplete!**)

- **SiPM**:
  - Breakdown Voltage / Operation voltage
  - Photo Detection Efficiency, Gain, Crosstalk %, Darkcount rate
  - Breakdown Voltage at different low temperatures (ongoing)
- **Electronics**:
  - Cookie Board → SiPM connections, temperature sensor
  - Adapter board → Connection to readout board
  - Readout board:
    - Communication Hamamatsu power supply
    - Outgoing bias voltage to the SiPM
    - Amplification factors of the Op-Amps
    - Signal shape of high / low gain
    - …
  - GP-Board:
    - Function test
    - RS485 interface test
    - Amplification factor after 65m of cable

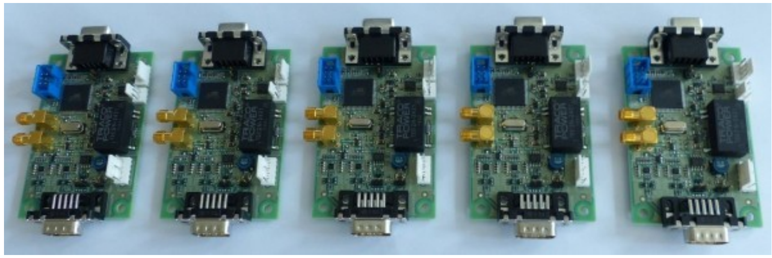
And a lot of tests…



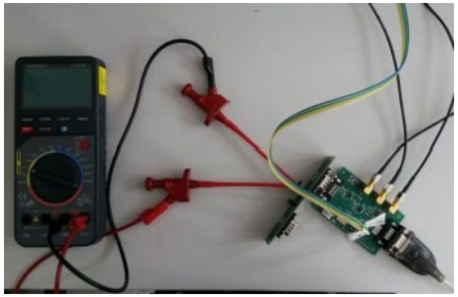
Cookie boards



Readout boards

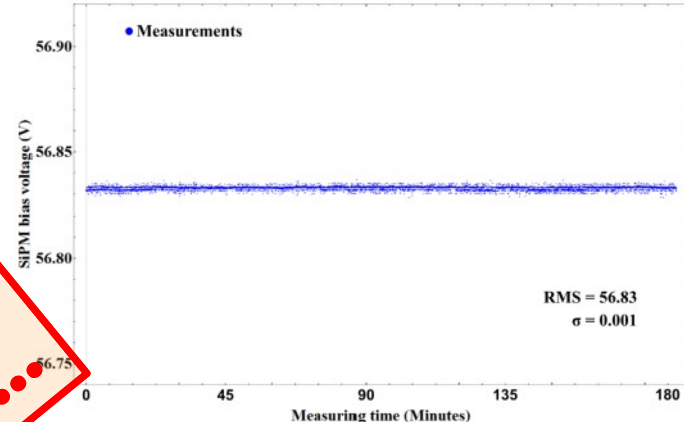


GP-boards (DESY)



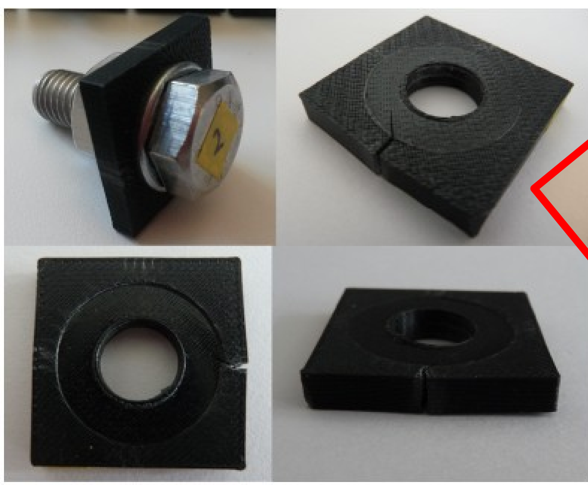
Testing of all components if they “survive” the South Pole

“Inverse Oven” at KIT-IKP



Test for T-Stability of the SiPM power supply at -70°C

And a lot of low temperature tests…

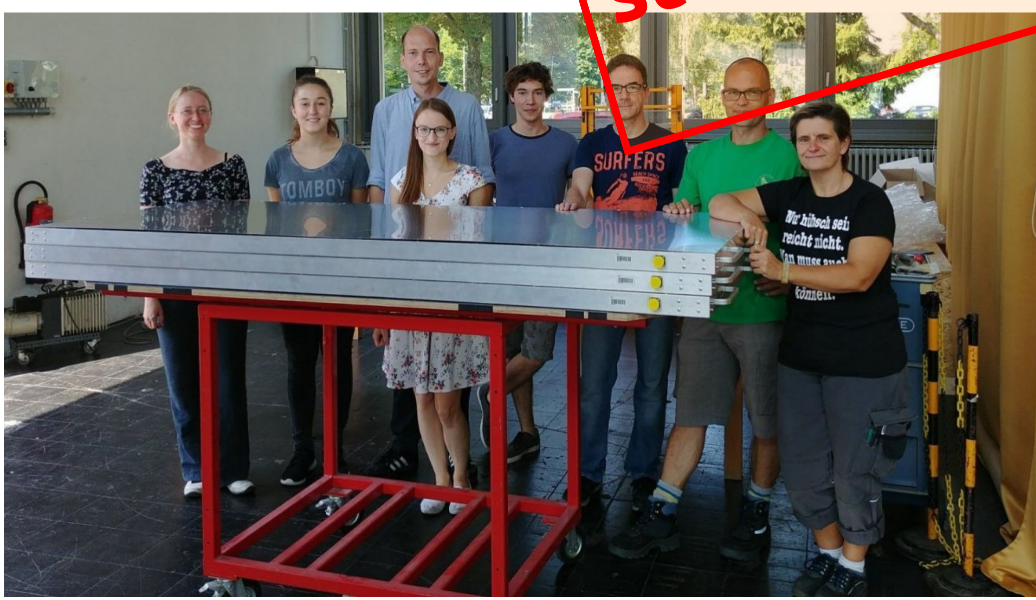


Low temperature stress tests of the used 3D printed material (A. Schmidt, KIT-IKP)

Full system tests a the IceCube cooling chambers with T. Karg (DESY) Madison, Physical Science Lab (PSL)

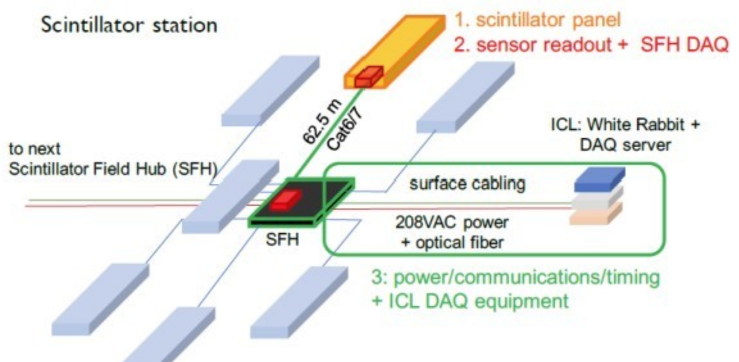
Production and testing of the scintillators

And a lot of production of three Scintillator stations...

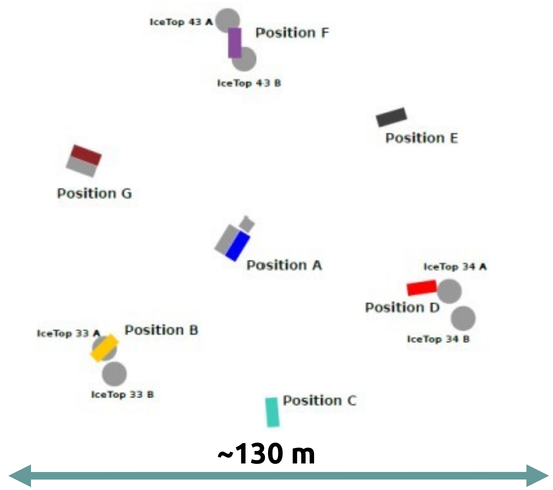


Deployment – Season 2017/18

- 2 different scintillator prototype stations
- Main difference:
    - Digital transfer of the detector signal to the DAQ (uDAQ, UW-Madison)
    - Differential analog signal transfer to the central DAQ and possibility to investigate the SiPM Waveforms (TAXI, KIT/DESY)

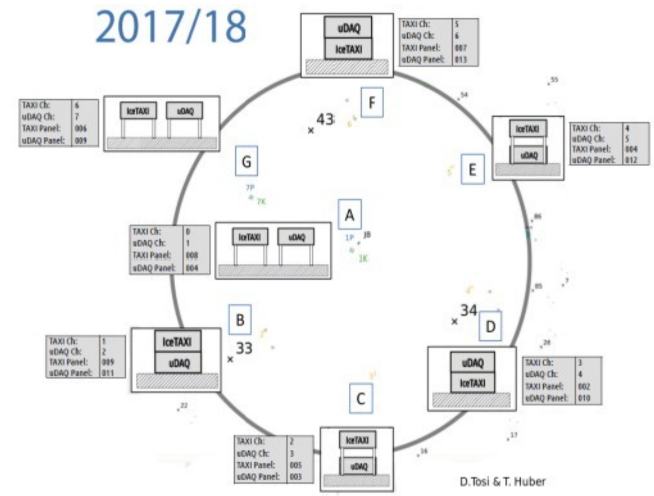


https://pos.sissa.it/301/401/pdf



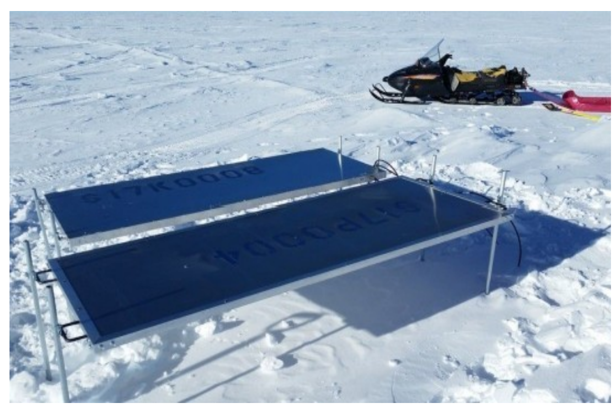
Scaled detector array positioning

(A. Schmidt, KIT-IKP)



Different alignments to compare both DAQ systems and the influence of snow covering

Detector "on the way"

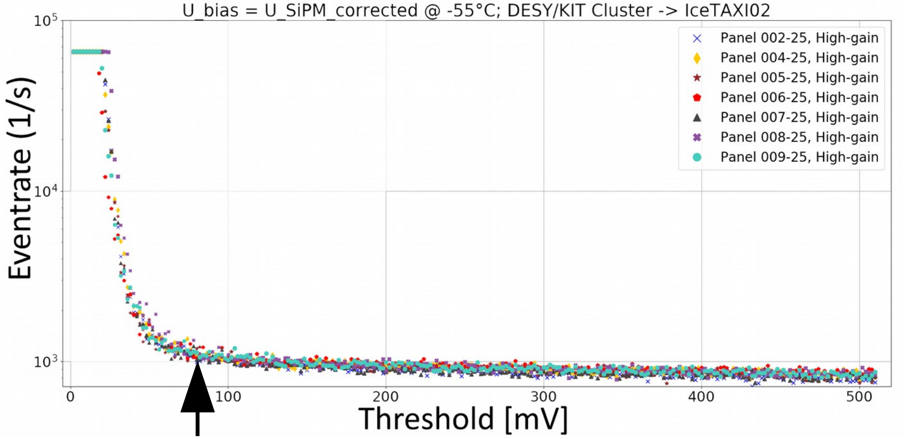


Deployed detectors

Data acquisition

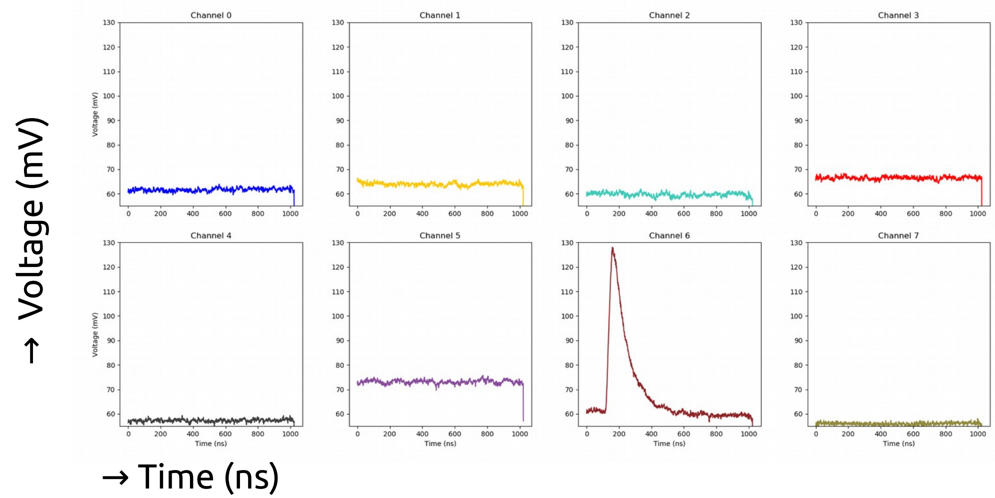
Is it working? How the scintillator signals look like

Threshold-Scan

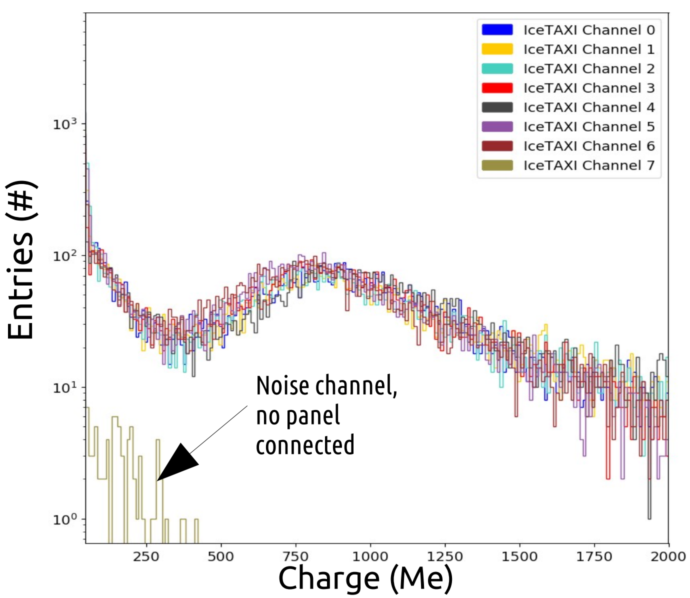


Threshold to start
processing MIP events only

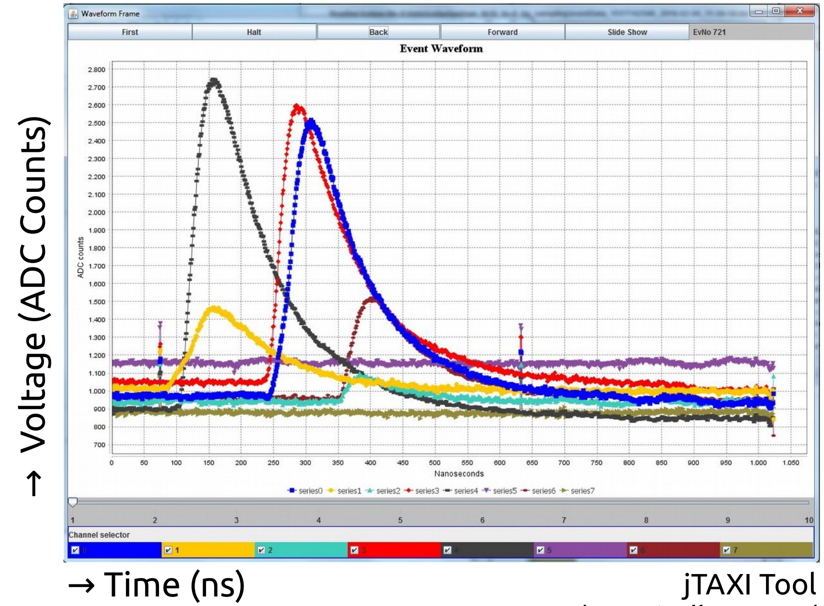
Signal-Over-Threshold SiPM Peak



Charge histogram

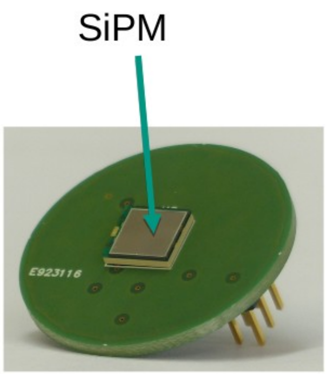


Waveforms Air-Shower event



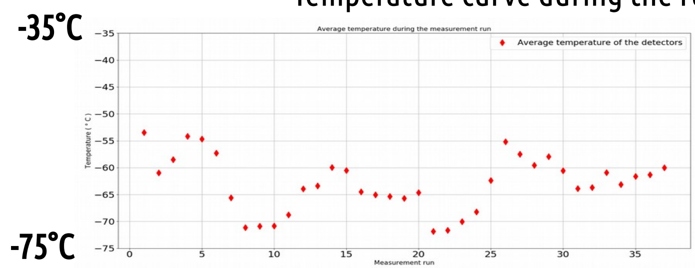
jTAXI Tool
(A.Weindl, KIT-IKP)

Is it working?
SiPM Bias-Voltage<->Temperature control loop



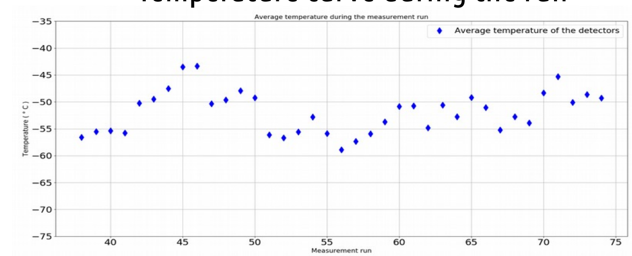
Gain of the SiPM is a function of the temperature

Temperature curve during the run

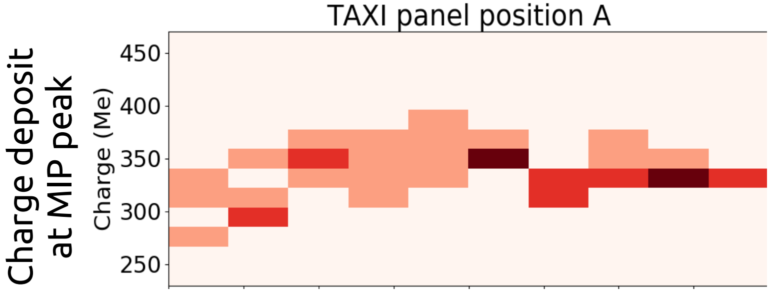


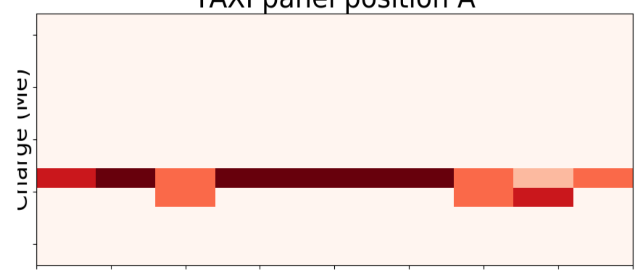
Disabled control loop

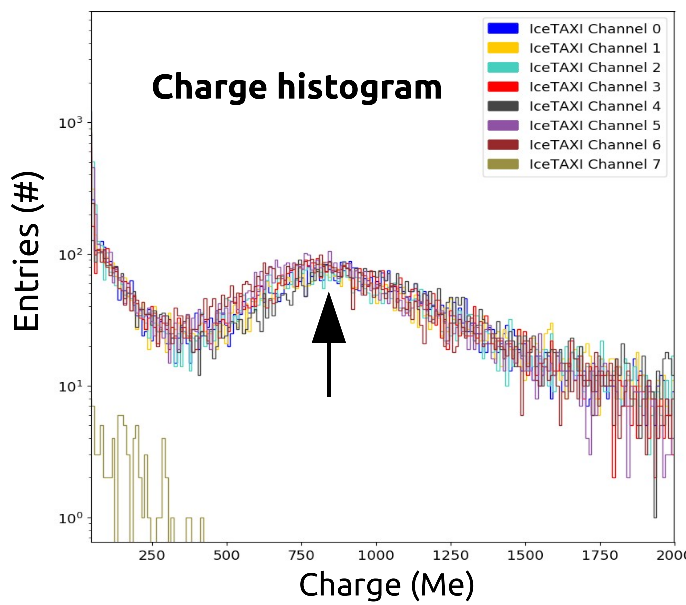
Temperature curve during the run



Enabled control loop

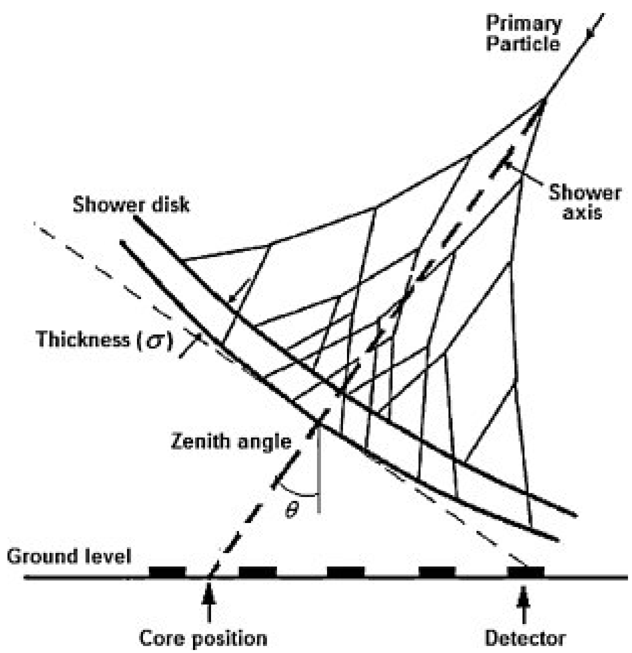




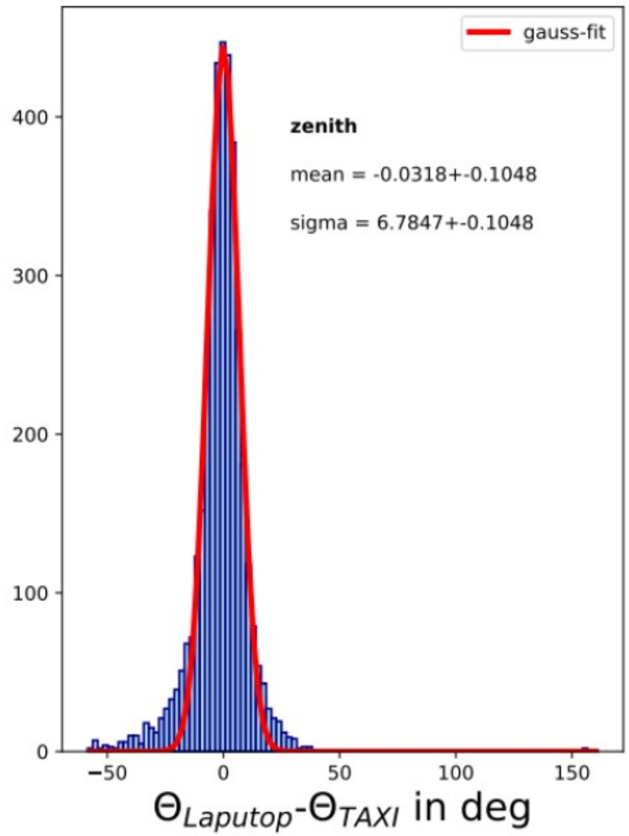


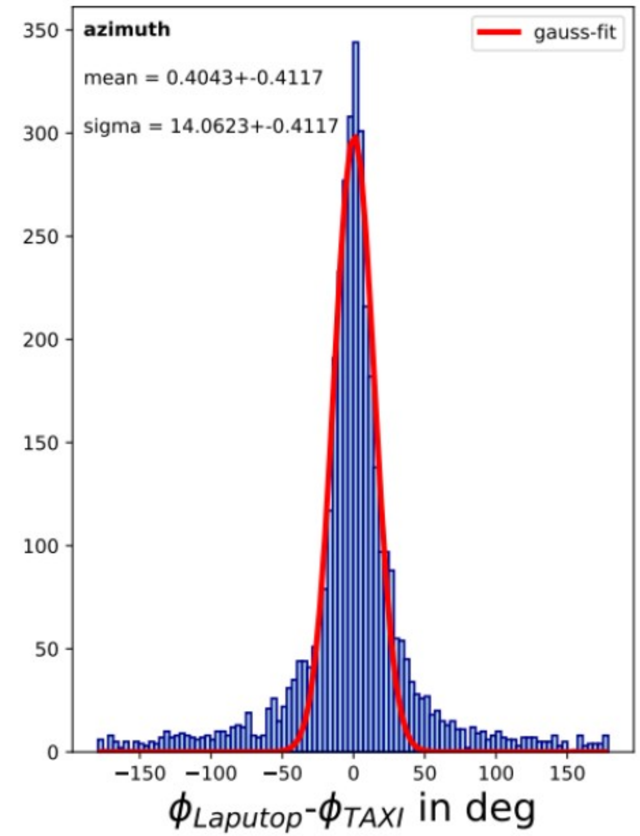
Uniform,
Gain stabilized,
detector array.

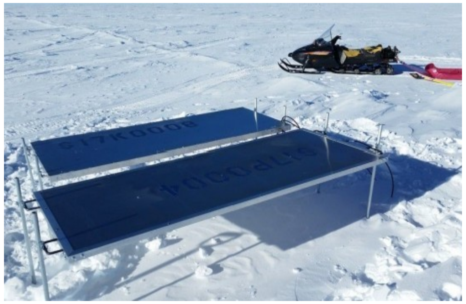
Is it working? Scintillators <-> IceTop reconstruction



Difference between scintillator station and IceCube: IceTop shower axis reconstruction (3834 events)







Summary: With a little of effort, you can really measure stuff with as example SiPMs :-)

Thanks for listening

If there is time you can choose

- Temperature dependency of SiPMs
- The space-based fluorescence telescope JEM-EUSO and the SiPM “Addon”
- What it is like to travel and work at the South Pole ?

Addition #1
- Temperature dependency of SiPMs

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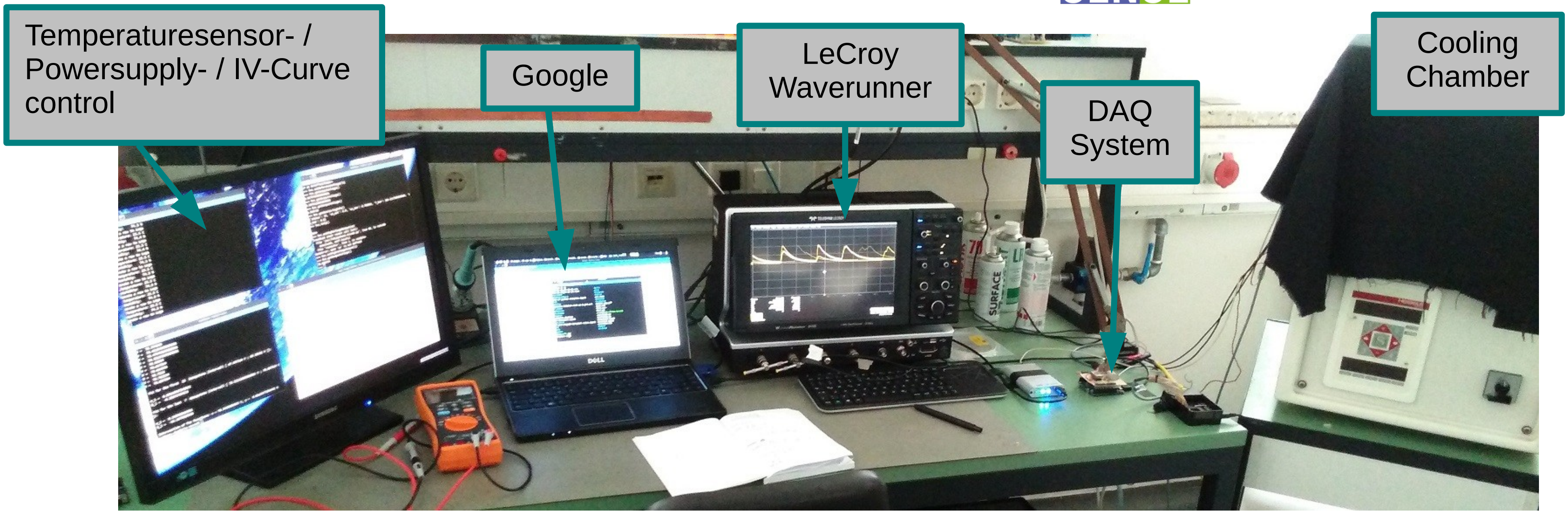
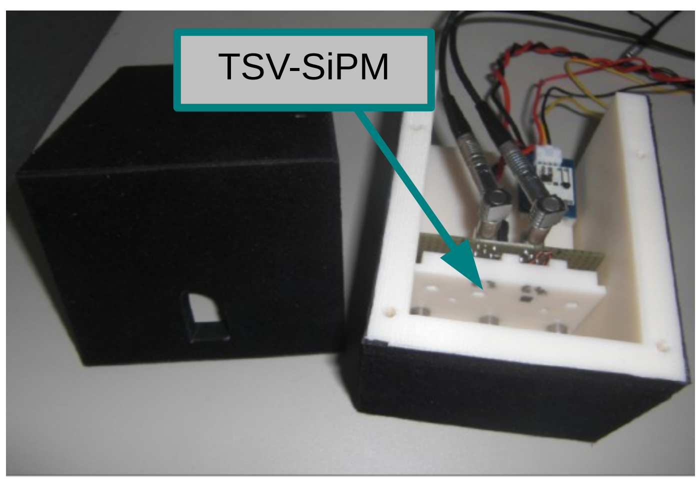
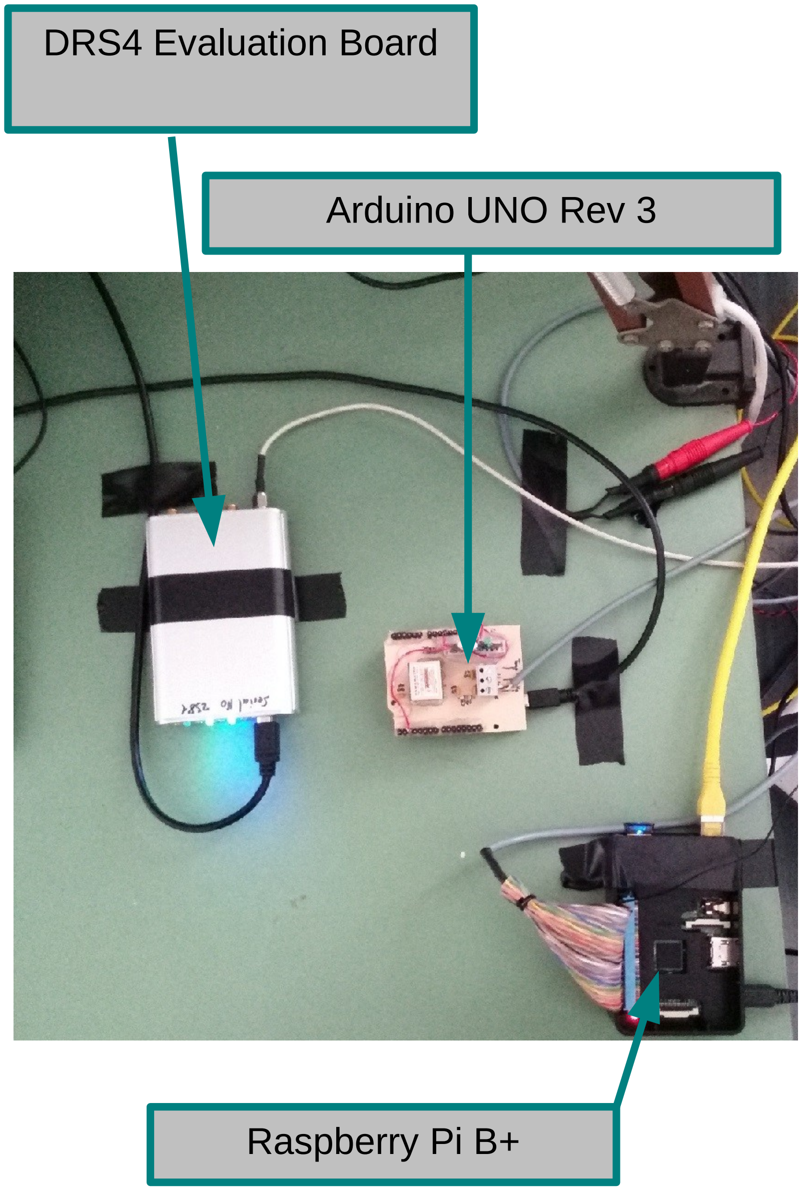
Experimental Setup for Bias-Voltage / Darkcounts



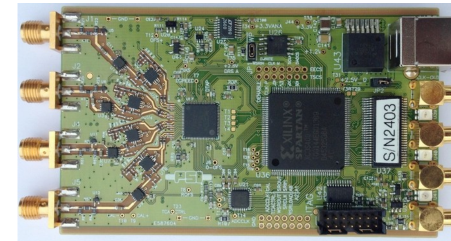


- TSV-SiPM testing device with attached temperature/humidity sensor and one part of the readout electronics
- 2x 3mm², 1x 2mm², 1x 6mm² TSV SiPM sockets to compare them simultaneously
- Photon shielding is overlapping the corners.

Experimental Setup for Bias-Voltage / Darkcounts



DRS4 Evaluation Board:
- Up to 5 GS/s
- DAQ SiPM Signals

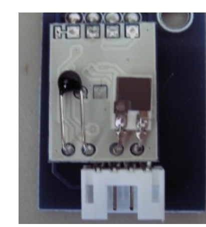


4 Channel ADC

Arduino UNO Rev 3:
- Mounted with Hamamatsu SiPM Power Supply
- Control of Bias voltage via Python interface
- Current Monitor

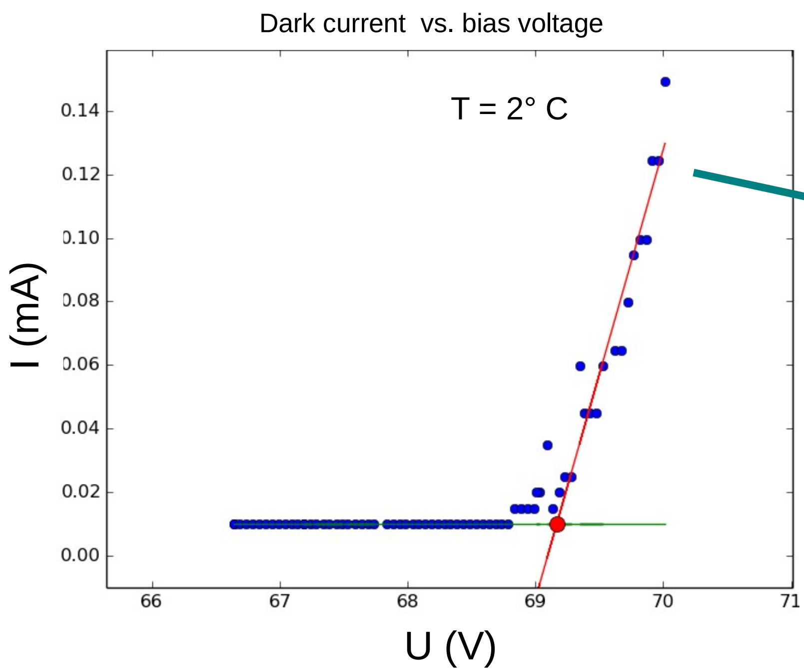
C11204-01
Output Voltage:
50V to 90V

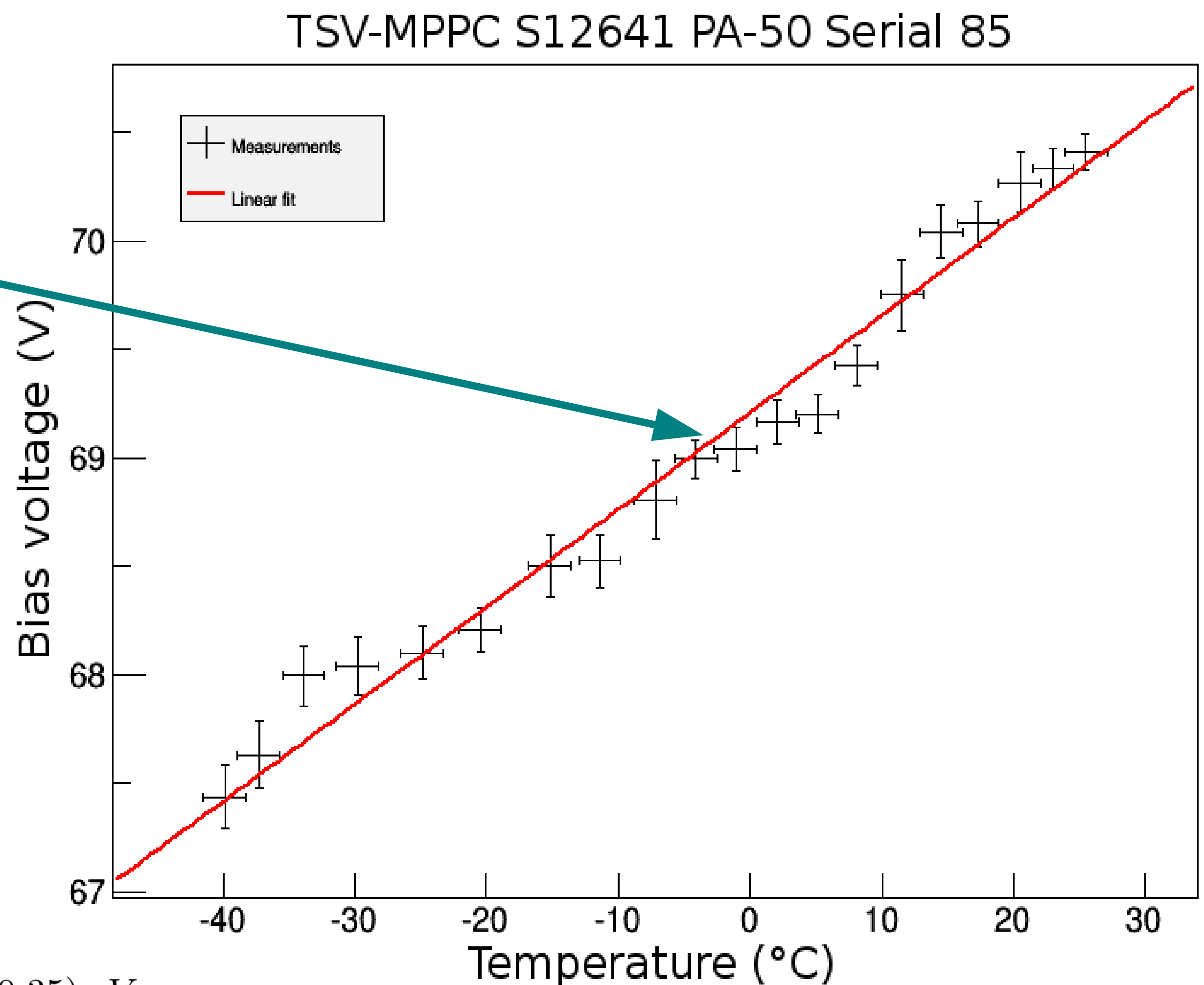
Raspberry Pi B+
- Connected via GPIO to temperature sensor
- Monitoring temperature. Written in Python; Controlled via SSH; Saving data via SQL to a local webserver



AM2303
± 2% of humidity level
± 0.3°C temperature

Temperature dependency of the bias voltage

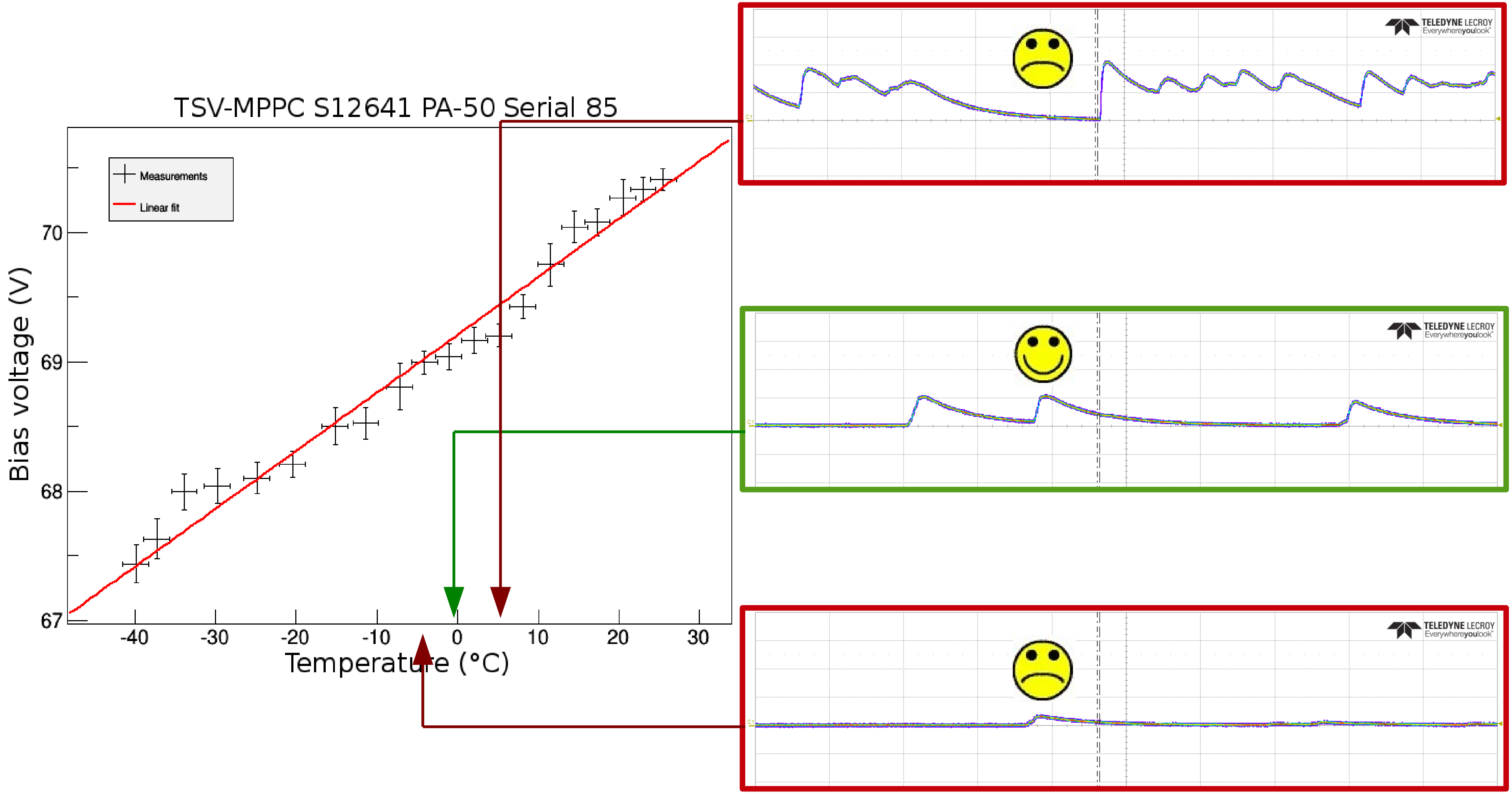




$$U_{Bias_{(T)}} = ((0.045 \pm 0.014)\frac{V}{T}) \cdot T + (69.20 \pm 0.35) \cdot V$$

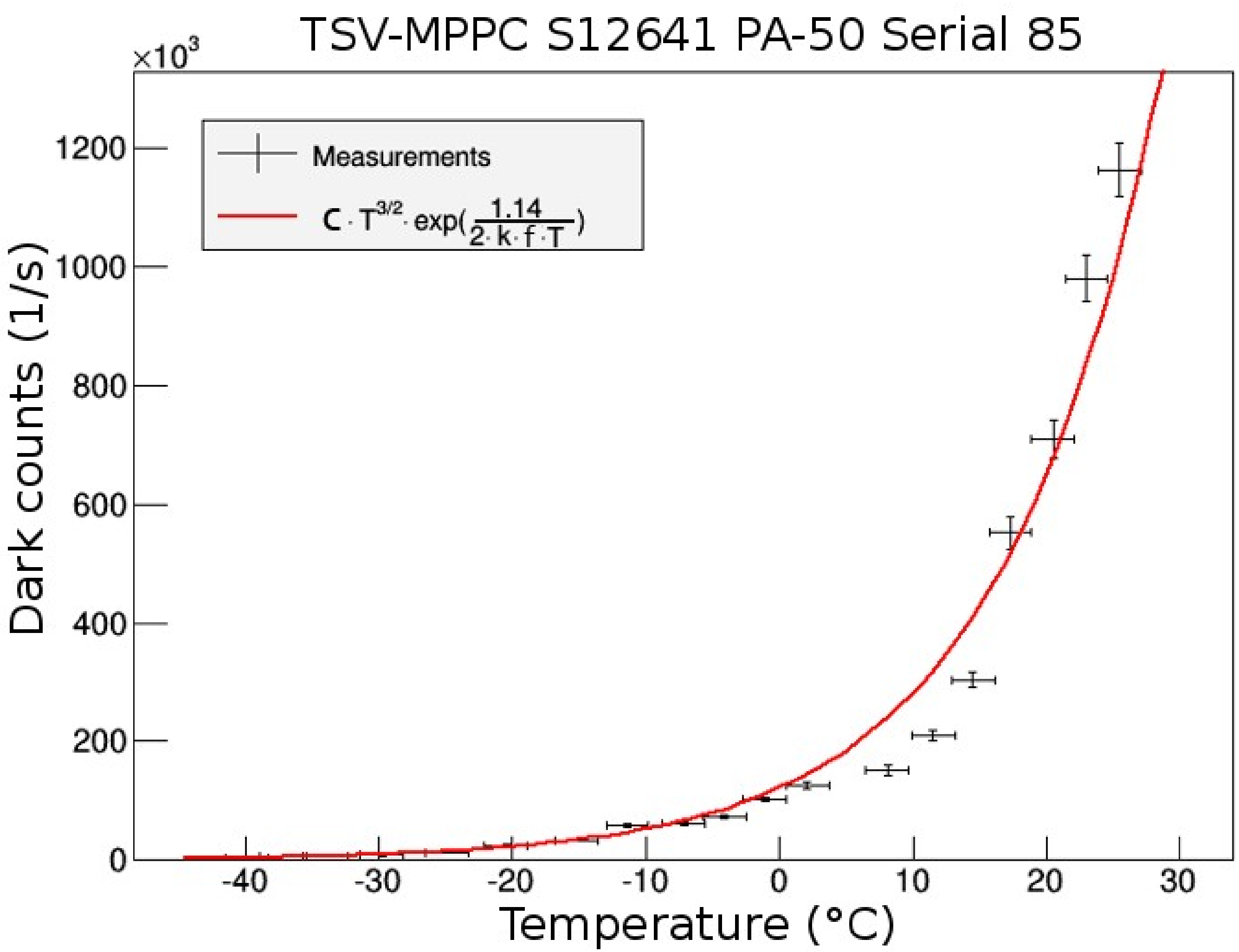
Consequence of not adjusting the bias voltage

With a constant bias voltage:



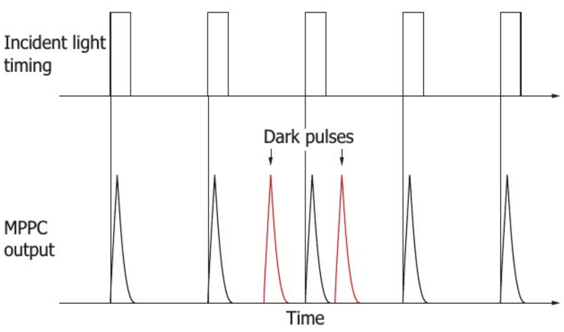
V: 50mV/div Timebase: 500ns/div

Dark counts of TSV-MPPCs



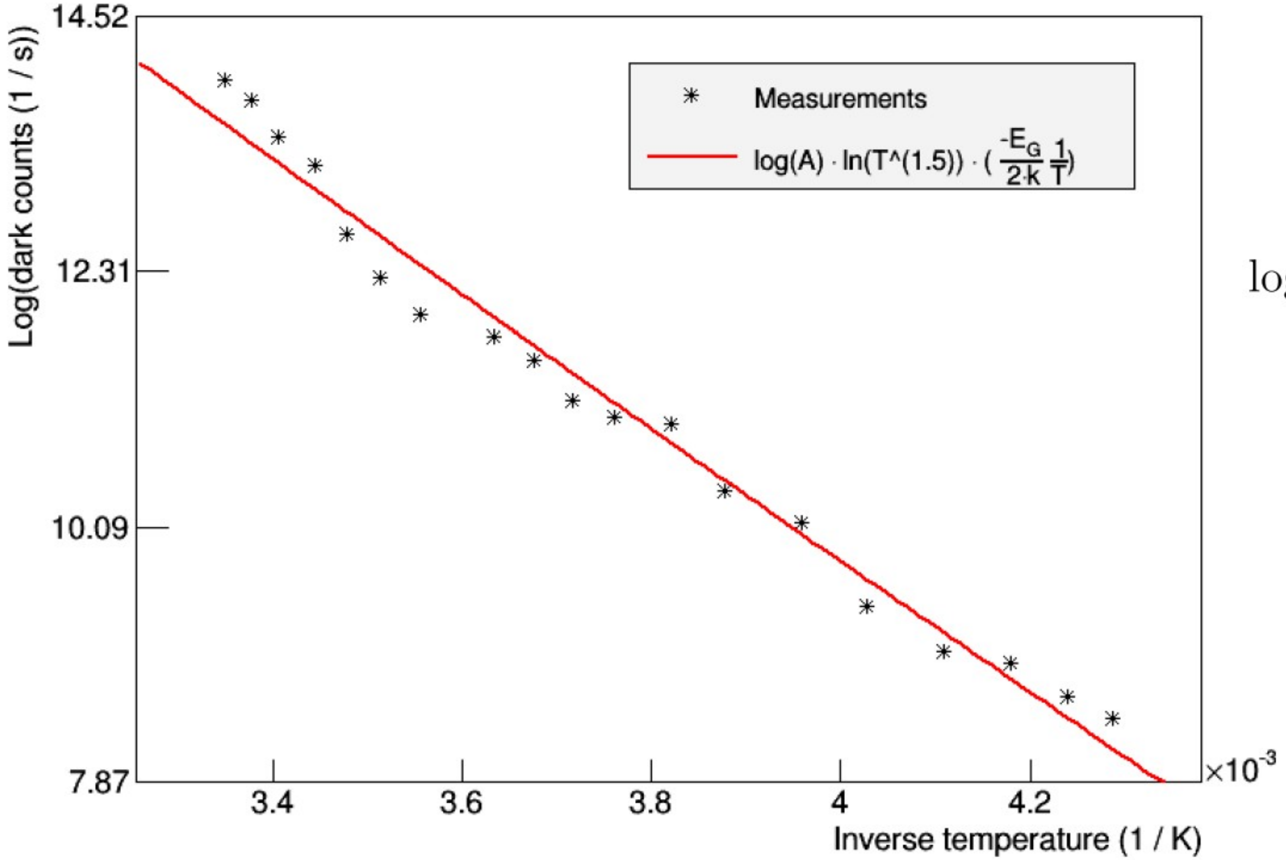
$$N_{0.5\,p.e.}(T) \approx AT^{\frac{3}{2}} \exp\left[\frac{Eg}{2k\,T}\right]$$

T : absolute temperature [K]
A : arbitrary constant
Eg: band gap energy [eV]
k : Boltzmann's constant [eV/K]



„Funny“: Estimation of the band gap energy of TSV-SiPMs

Arrhenius plot for estimating the band gap energy of the used TSV-MPPC (SiPM).



$$\xi = A \cdot T^{\frac{3}{2}} \cdot e^{\frac{E_g}{2 \cdot k_b \cdot T}}$$

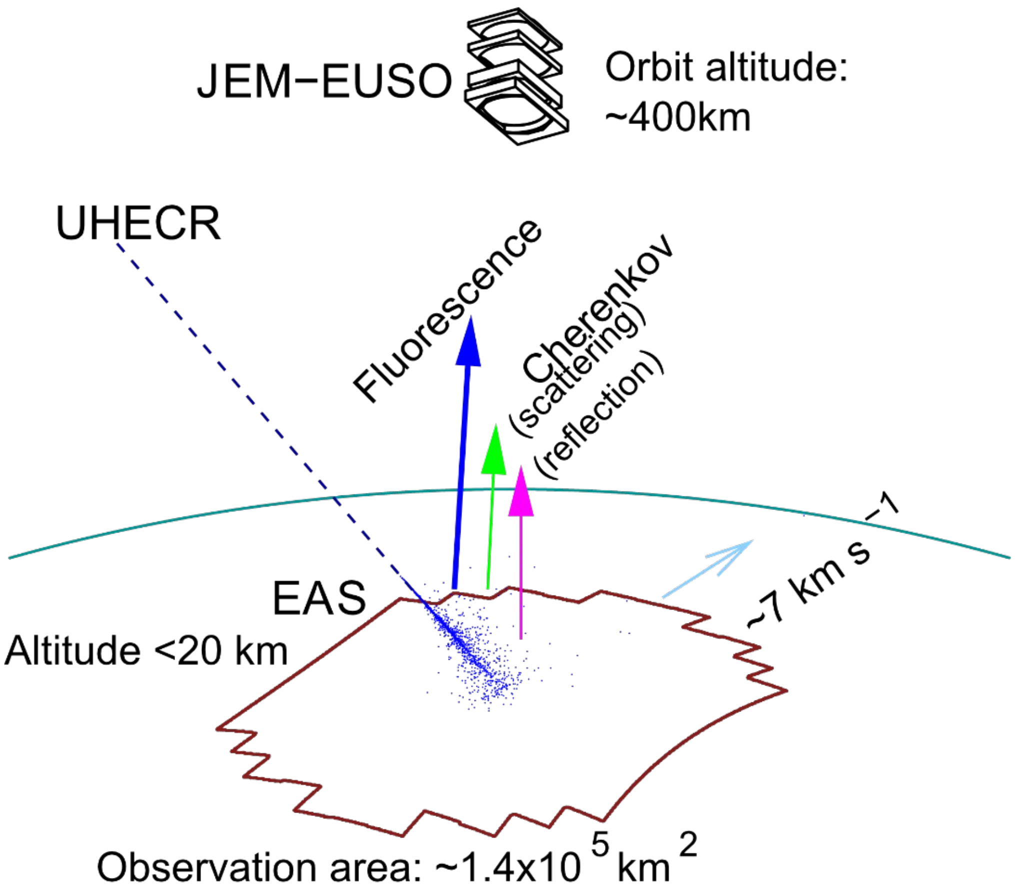
$$\log(\xi) = \log(A) + \log\left(T^{\frac{3}{2}}\right) - \frac{E_g}{2 \cdot k_b \cdot T}$$

$$E_{g\,(\text{TSV-MPPC})} \approx (0.99 \pm 0.05)\text{eV}$$

Institute for Experimental Nuclear Physics (IEKP)
thomas.huber@student.kit.edu

Addition #2
- The SiECA fluorescence camera
for JEM-EUSO

The (initial) 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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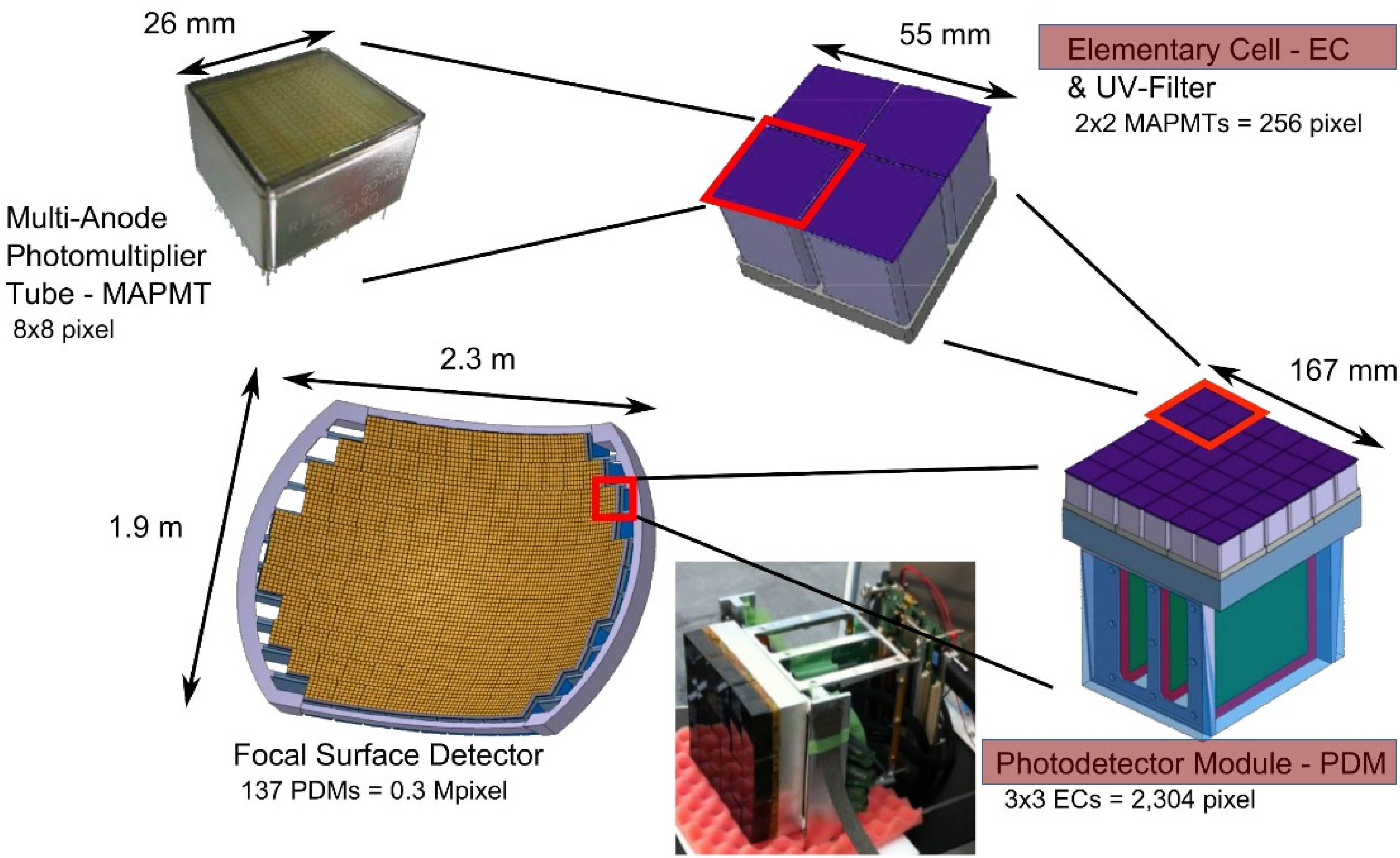
The (initial) JEM-EUSO program



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The (initial) JEM-EUSO program
One pathfinder: EUSO-SPB 2017

- Fluorescence camera with 265 SiPM channels

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

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

EUSO-SPB.

thomas.huber@kit.edu

EUSO-SPB 2017

Detector Basics

- 1 PDM, 2304 MAPMT channels
- 2 PMMA Fresnel Lenses
- Data storage and transmission

Mission

- Observe 10 UHECR Fluorescence and 2 Cherenkov events
- 60-100 days above 33 000 m

Plus the Silicon Photomultiplier Addon SiECA!

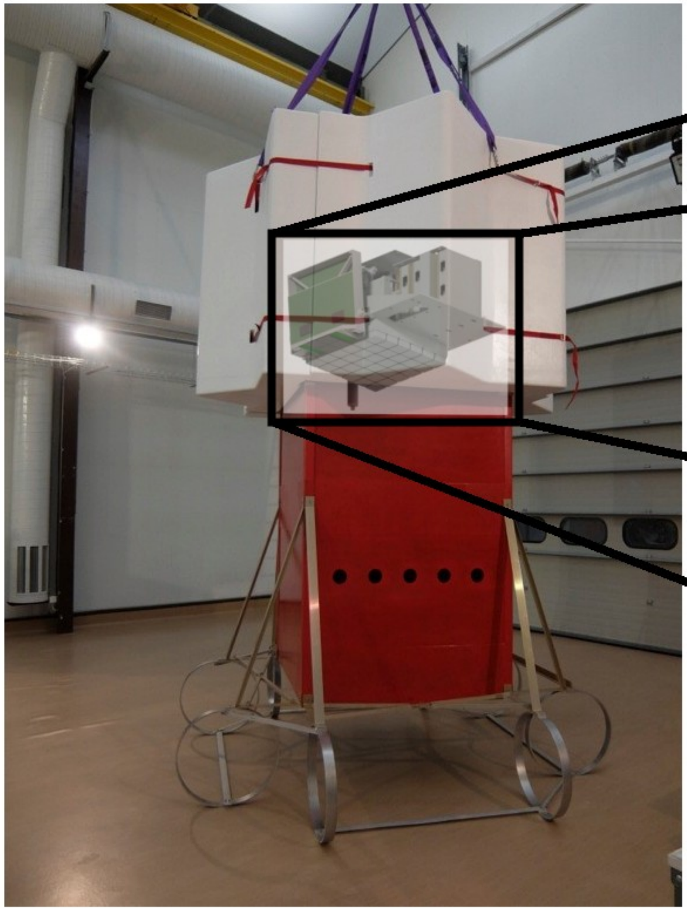
thomas.huber@kit.edu

The SiECA camera

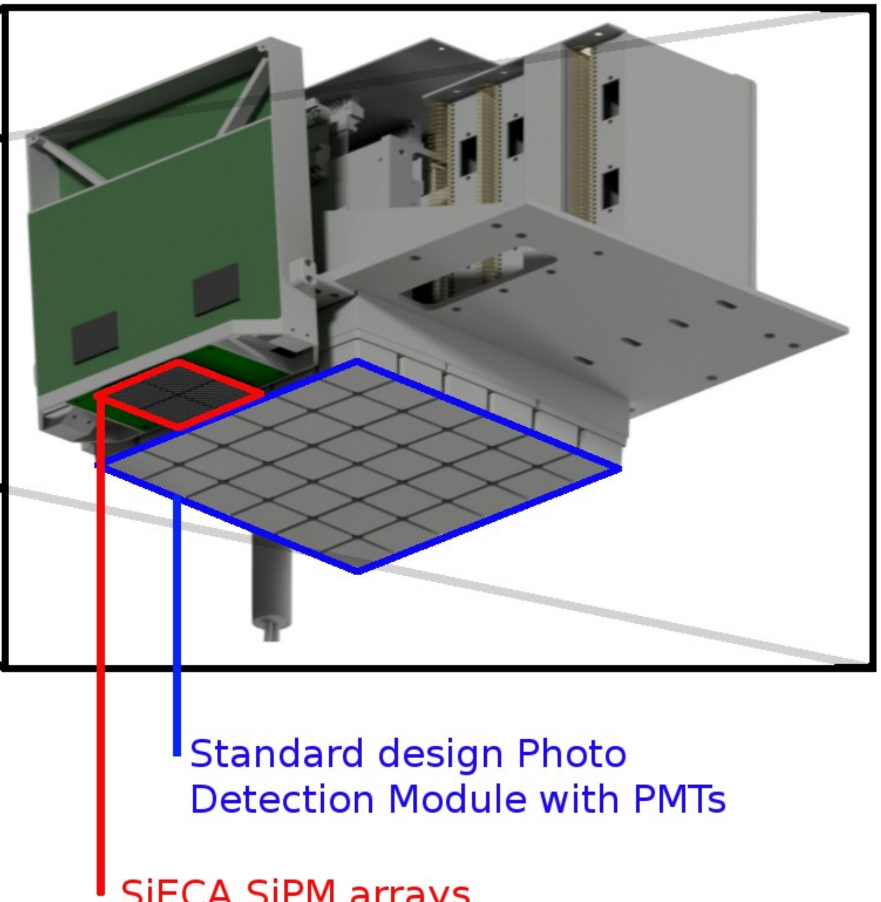
Silicon photomultiplier Elementary Cell Add-on camera

thomas.huber@kit.edu

SiECA integration in Super pressure balloon gondola



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



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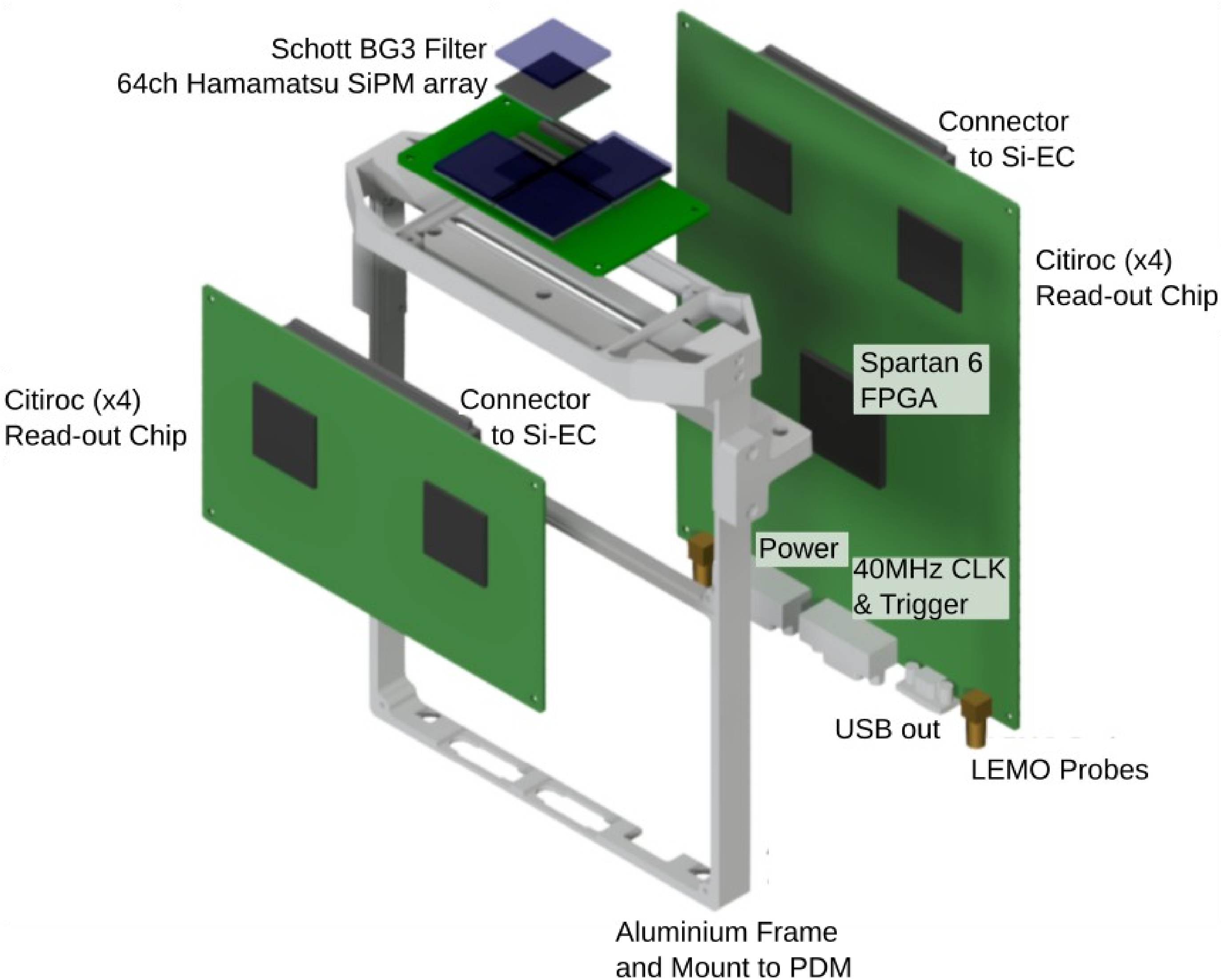
SiECA in detail



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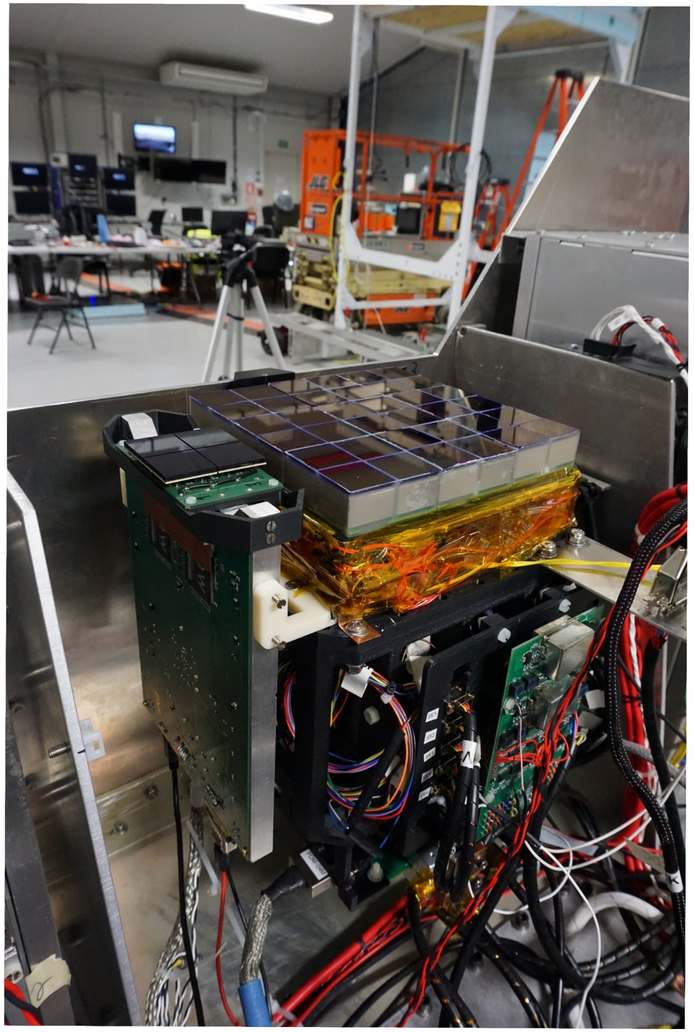
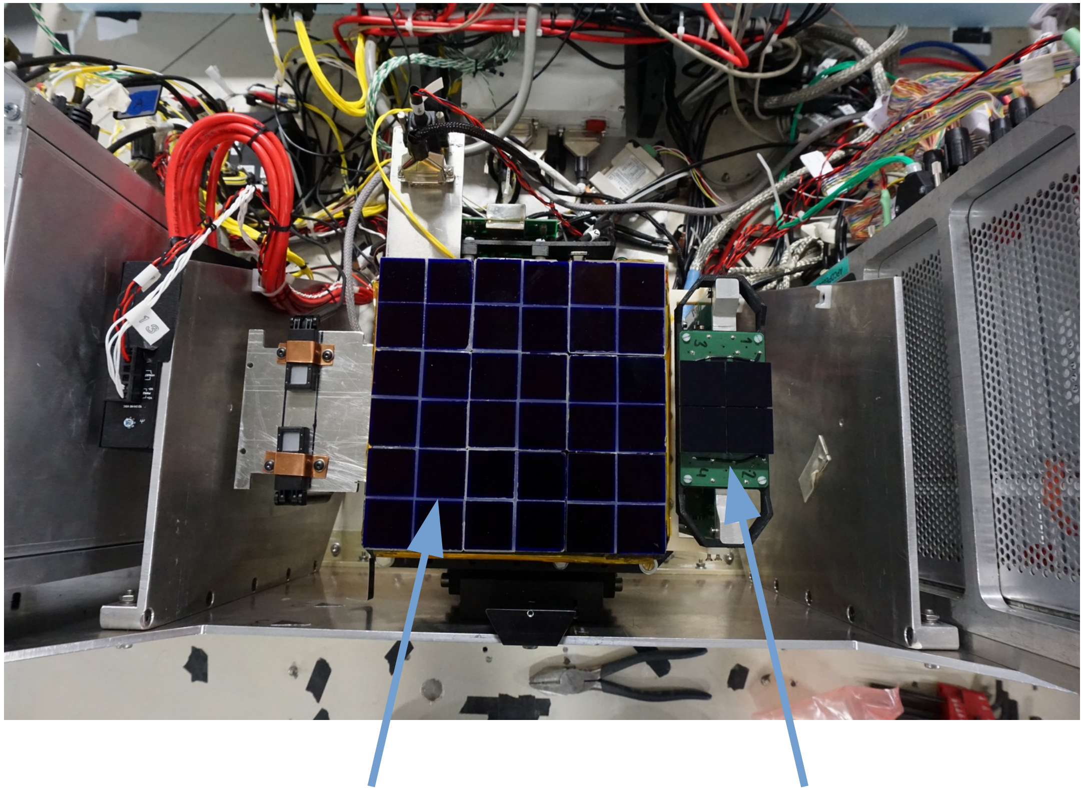
Euso-SPB with SiECA: ready to start





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First super pressure baloon flight 2015

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

- No scientific instrumentation
- But: Flight duration 32 days
  - → Proof of principle for the Super Pressure Baloon

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Disaster in the South Pacific

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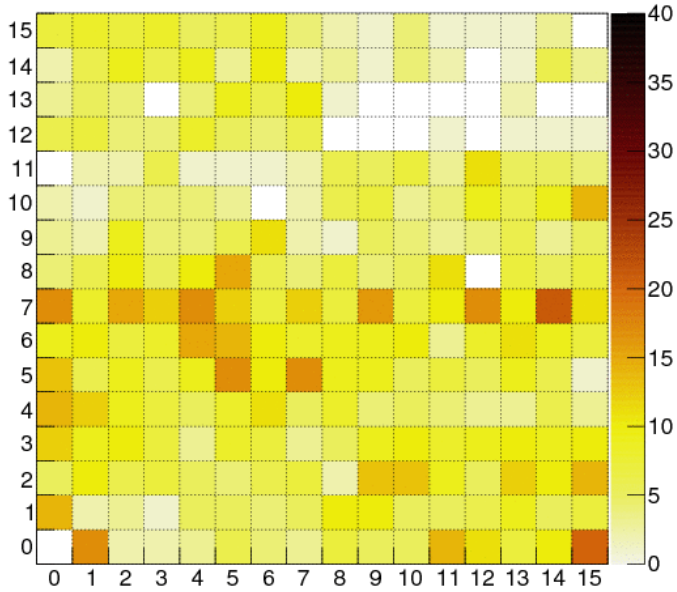
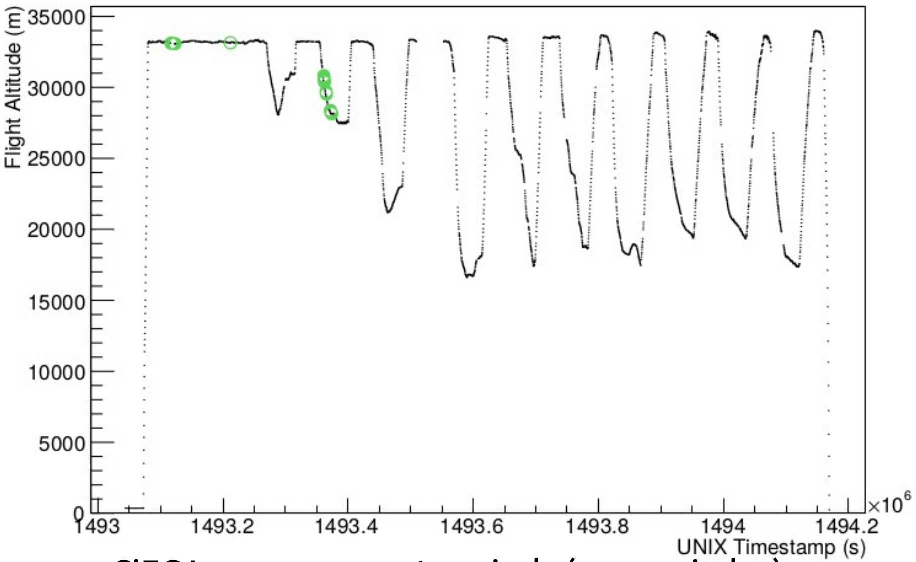
SiECA Results



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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Addition #3
- That was the physics.

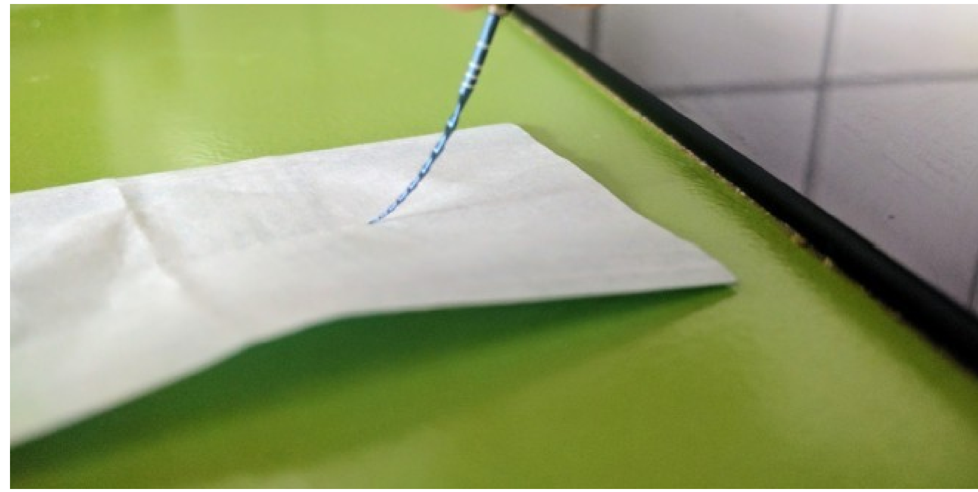
Lets switch to a “slide show” :-)

What's it like to travel to the South Pole?

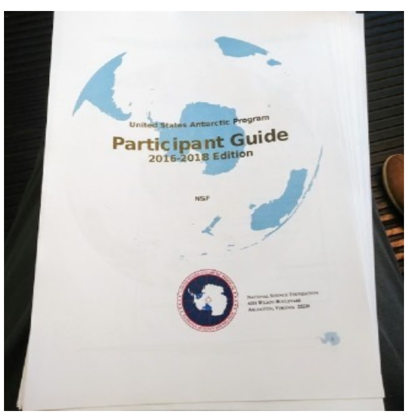
(...and how to get to the South Pole to work)

- **Tremendous** amount of paperwork
- A lot of medical and dental tests if you (and your teeth) survive at the South Pole
- Better do not have any wisdom teeth left

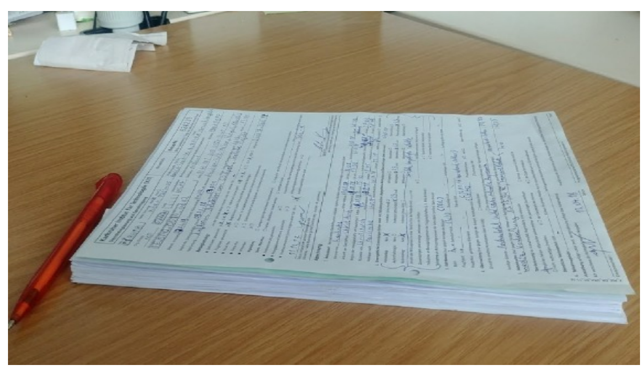
14 pages of blood count



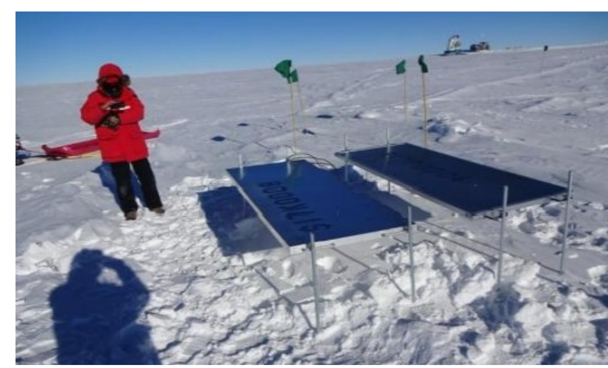
Dental “tests”...



How to survive



I guess that travel form (~100 pages) is a new KIT record



And you need some pretty good reason (= experiment) to go to the Pole

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(...and how to get to the South Pole to work)

SENSE
Karlsruhe Institute of Technology
DESY.

- And a **lot** of travel...

thomas.huber@kit.edu

(...and how to get to the South Pole to work)

- And a lot of **strange** travel...

Christchurch – USAP Terminal

Christchurch – USAP Terminal

Christchurch – Getting clothes

Inside of a LC-130 Hercules

Inside of a LC-130 Hercules

McMurdo Station - Runway

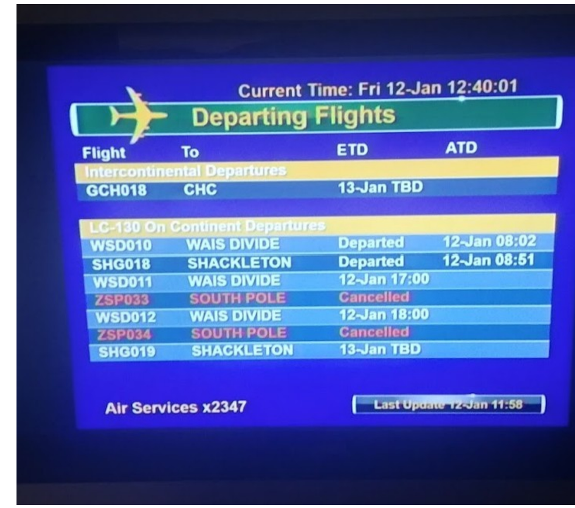
thomas.huber@kit.edu

(...and how to get to the South Pole to work)

- And a lot of **delay/waiting/** for good weather to travel to Mc Murdo Station and the South Pole Station (and back)

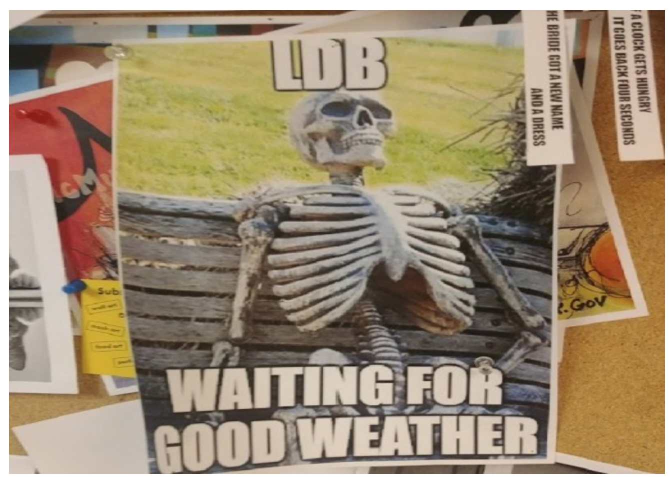
McMurdo Station

McMurdo Station

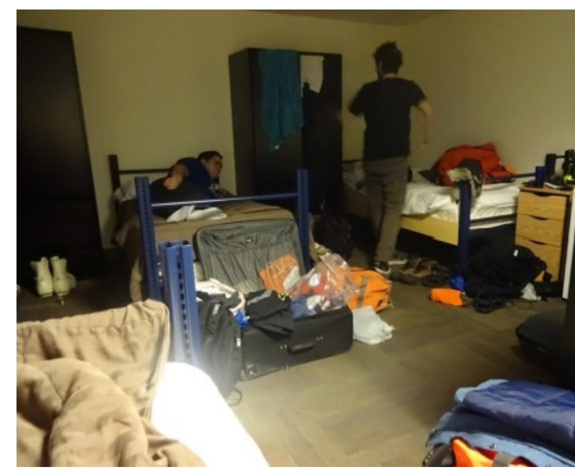


McMurdo Station

Christchurch - USAP



McMurdo Station



McMurdo Station

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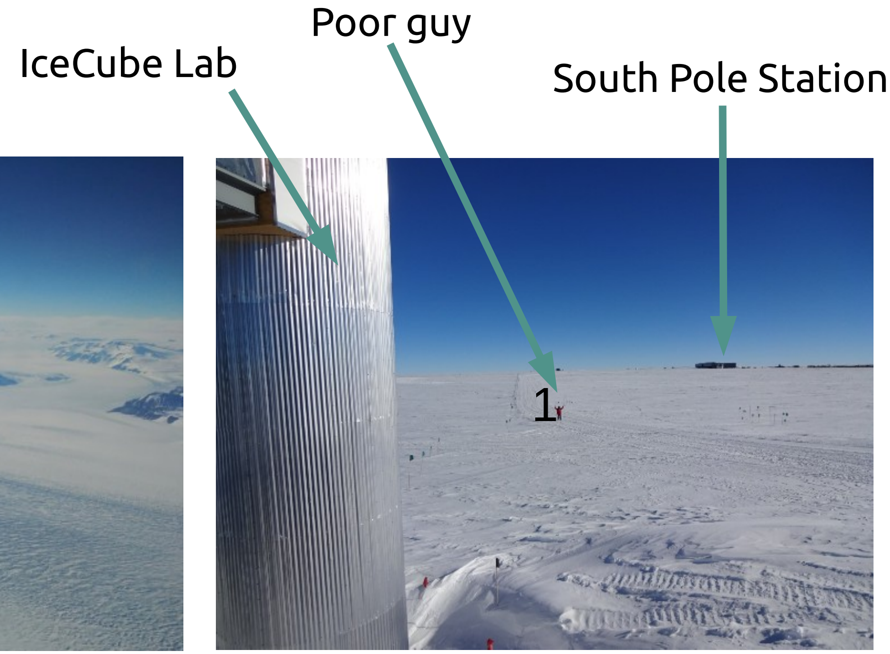
(...and how to get to the South Pole to work)

- But with **nice views**…

Towards South Pole

Towards Mc Murdo



View from ICL to South Pole Station

Hiking / Staying in shape / Waiting McMurdo

Hiking / Staying in shape / Waiting McMurdo

Hiking / Staying in shape / Waiting McMurdo

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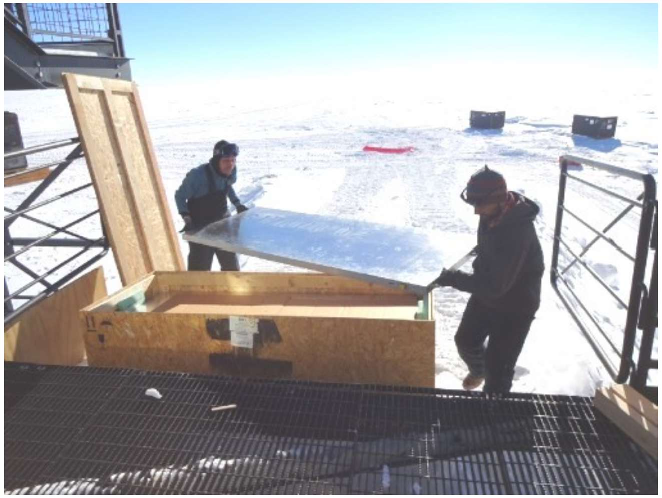
(...and how to get to the South Pole to work)

- But it is… **work** :-)



South Pole - ICL

South Pole - ICL

South Pole - ICL

South Pole – Somewhere nowhere

Digging out the DAQ

Recabling the DAQ

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(...and how to get to the South Pole to work)

- But: It is all not that **dead serious** :-)

South Pole Odyssey

Mc Murdo Station – M. Kauer, (UW Madison)

South Pole – T. Huber, M. Kauer, M. Kossatz (DESY)

Mc Murdo Station

ICL - South Pole -M. Kauer, (UW Madison)

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(...and how to get to the South Pole to work)

“Path” to the IceCube Lab and back to the South Pole Station

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Backup

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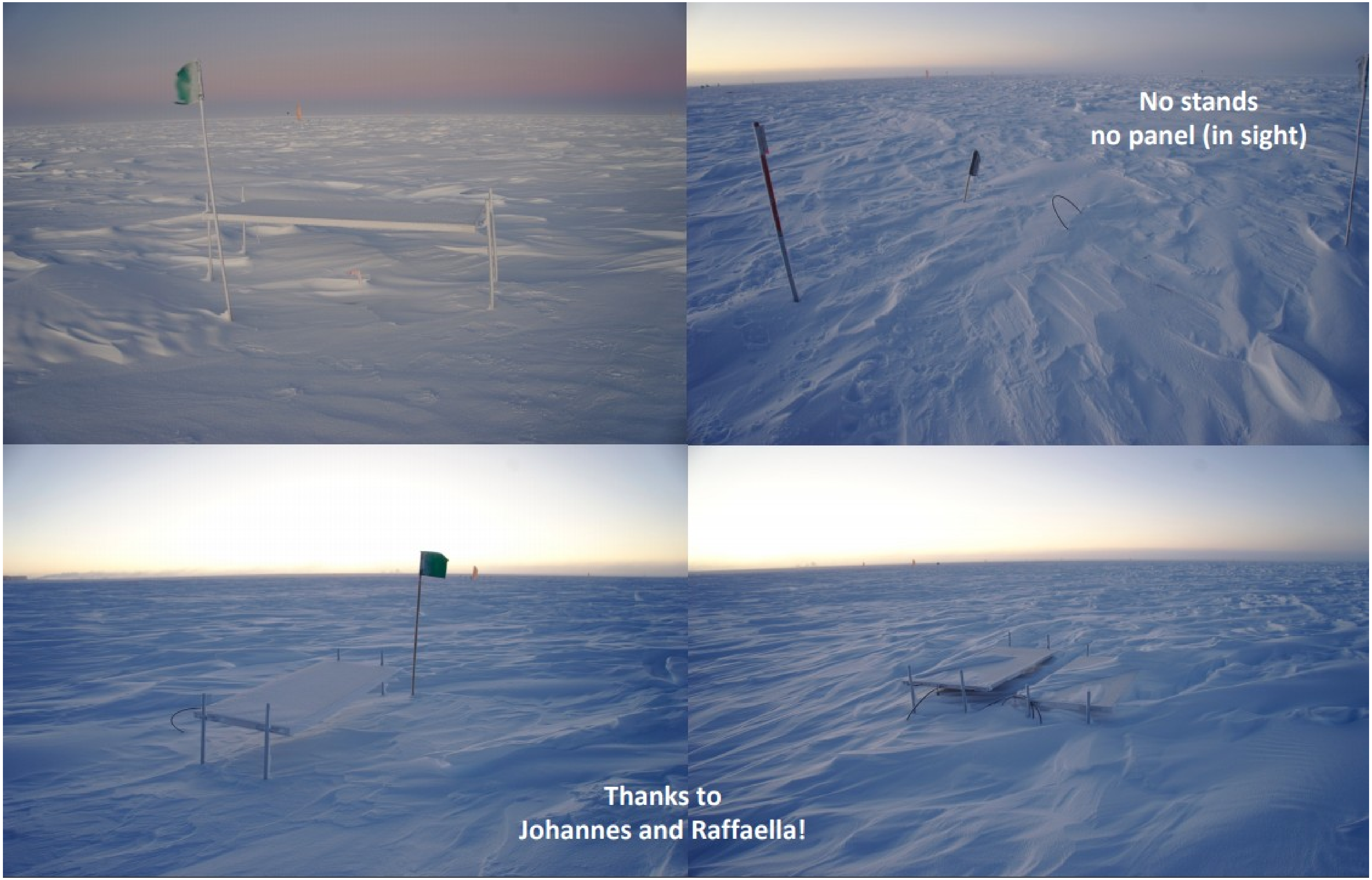
How the scint station looks like after one season



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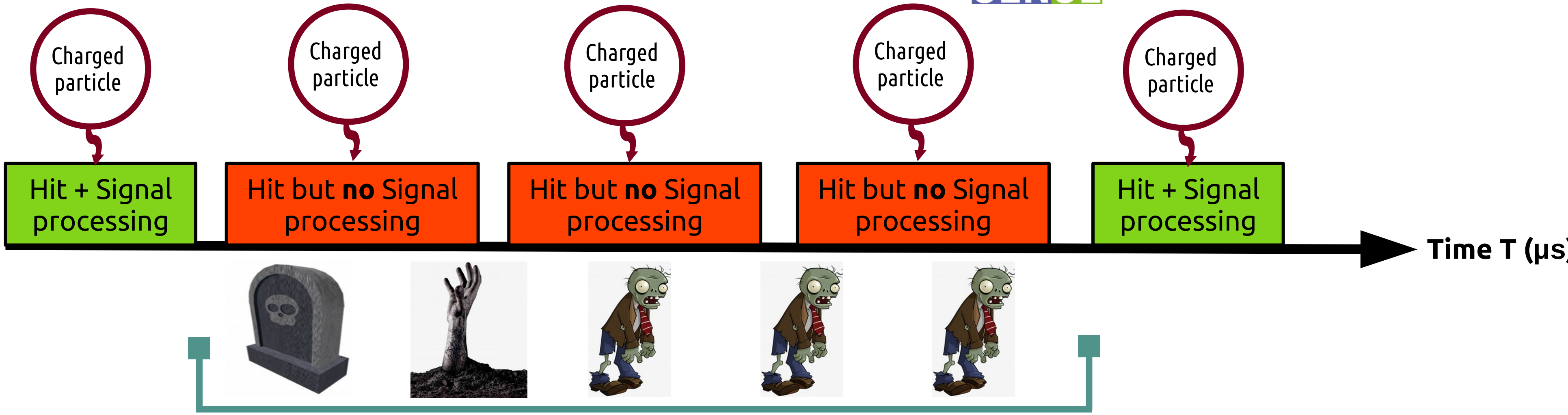
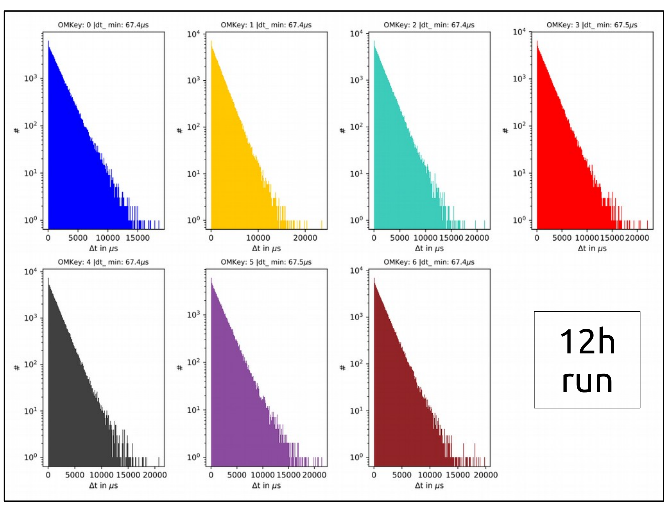
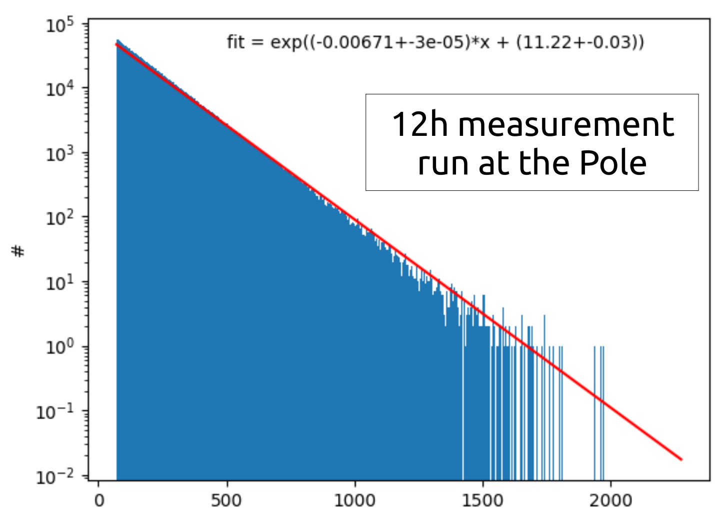
Example calibration: Dead time of the DESY/KIT System





Delta T (μs)

Time difference between two scintillator hits



Delta T (μs)

Time difference between two hits – All scintillators summed up

Dead time ≈ 67 μs

→ Fits to measurements in the lab with a pulser

Bachelor thesis F. Ellwanger (KIT-IKP)

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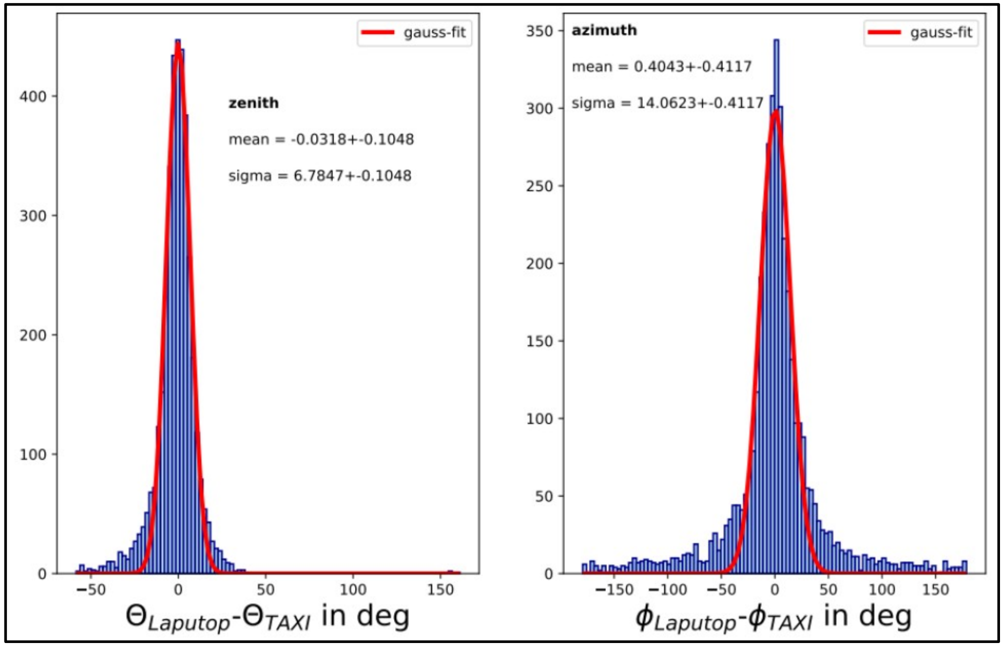
Summary / Outlook / What's next

Is the full DESY/KIT scintillator system capable to detect cosmic air-showers?

→ Comparison with IceTop reconstruction:



Zenith and Azimuth difference between DESY/KIT Scintillator Station and IceTop reconstruction

- IceARM<-> IceTAXI DAQ chain is meanwhile pretty good understood

- DAQ characterization still ongoing

- Air-Shower analysis starts
→ See next talk by Agnieszka

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