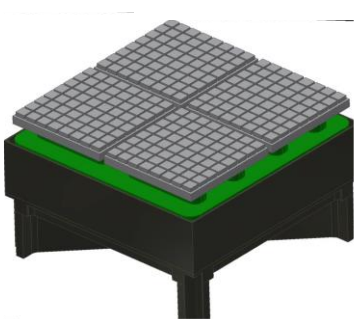
Karlsruhe Institute of Technology

HELMHOLTZ GEMEINSCHAFT
Allianz für Astroteilchenphysik

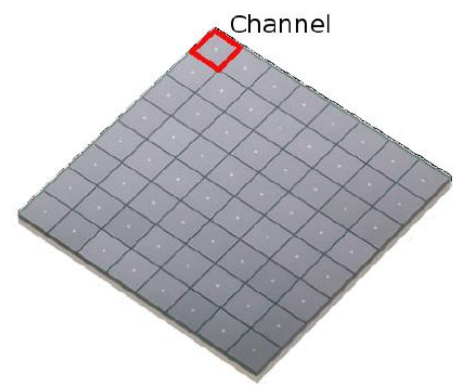
SiPMs in Astroparticle Physics:

KIT Activities
(presently “JEM-EUSO”, but R&D for broader application)

Andreas Haungs



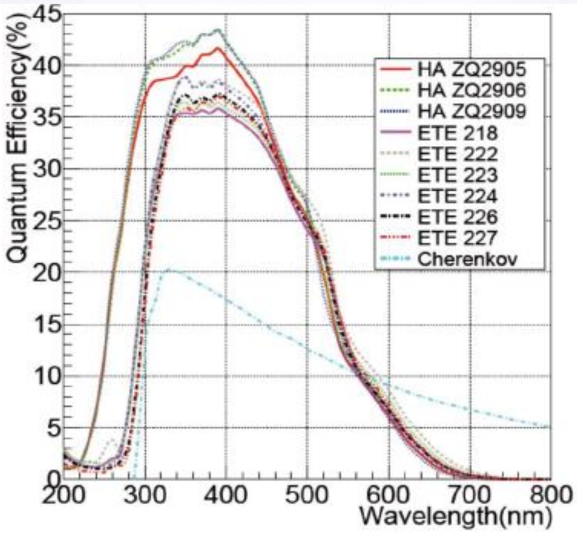
HELMHOLTZ ASSOCIATION
HAP
Helmholtz Alliance for Astroparticle Physics



Advanced Technologies

Standard PMT

Very small, mid & very large size PMTs



- **broad application**
- **good QE**

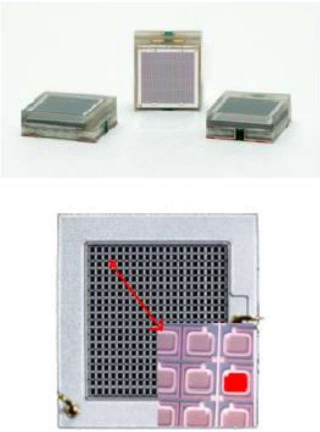
Still improvements possible

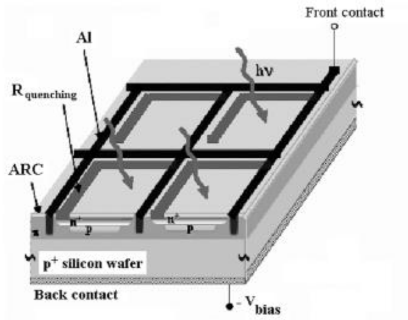
- **QE**
- **afterpulsing**
- **pulse width**
- **dynode coating**
- **various dynodes** **(intrinsic dynamic range)**
- **noise factor**
- **HV adjustment**
- **ageing**
- **more competition**

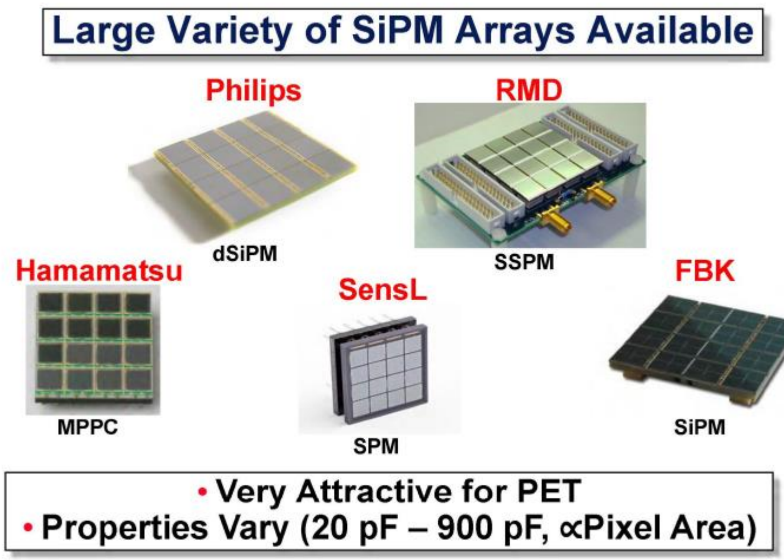
Though, okay for most applications

Conclusion:
Often no need to run behind newest SiPM developments

SiPM







- **fast development**
- **good PDE** (but PMT still better [Razmik])

Still improvements needed

- PDE (=QE?)
- crosstalk
- dark current
- fast readout
- large areas
- operation temperature
- wavelength range
- cost reduction
- .....

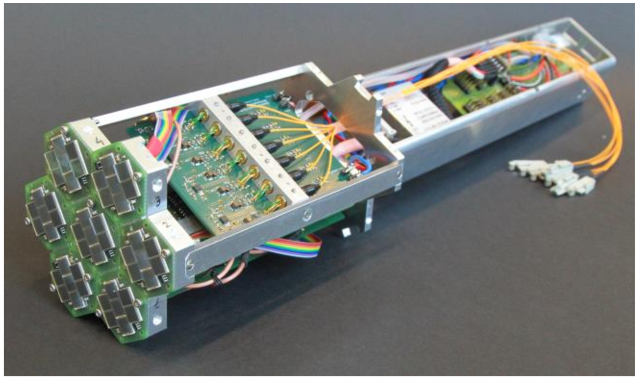
Conclusion:
Will be the future!
Need close cooperation between companies and experiments

PMT vs. SiPM

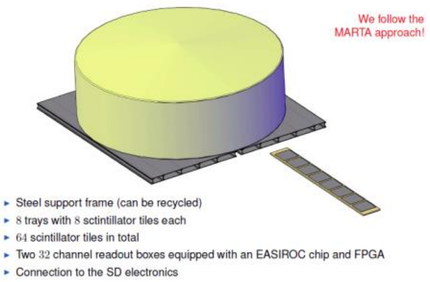
	PMT	SiPM
PDE	**20-45%**	**20-60%**
Gain	10^6	10^6
TTS (Transit Time Spread)	**~1 ns**	**~1 ns**
Dynamic range	10^6	10^3 🙁
Dark noise rate	**~kHz** 🙂	**~MHz** 🙁
Behavior in magnetic fields	🙁	🙂
Operation Voltage	**1000+ V** 🙁	**50-70 V** 🙂
Temperature sensitivity	🙂	🙁
Robustness and compactness	🙁	🙂

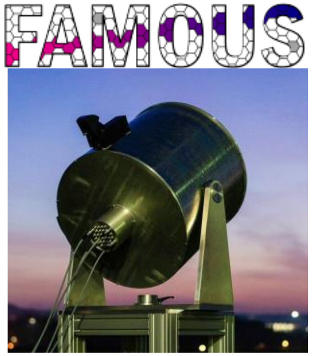
Examples of SiPM presently used in Astroparticle Physics

- **CTA**
  - **SST prototype with SiPM = ASTRI**
  - **Already existing: FACT**
  - **MAGIC started to replace**



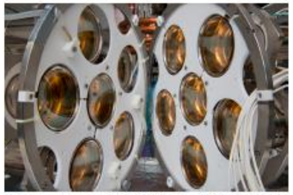
- **Pierre Auger Observatory**
  - **FAMOUS**
  - **AMD**
  - **SSD (AugerPrime)?**

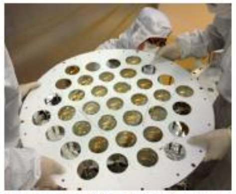




- **Dark Matter**
  - **Low radioactivity**
  - **Low dark current**

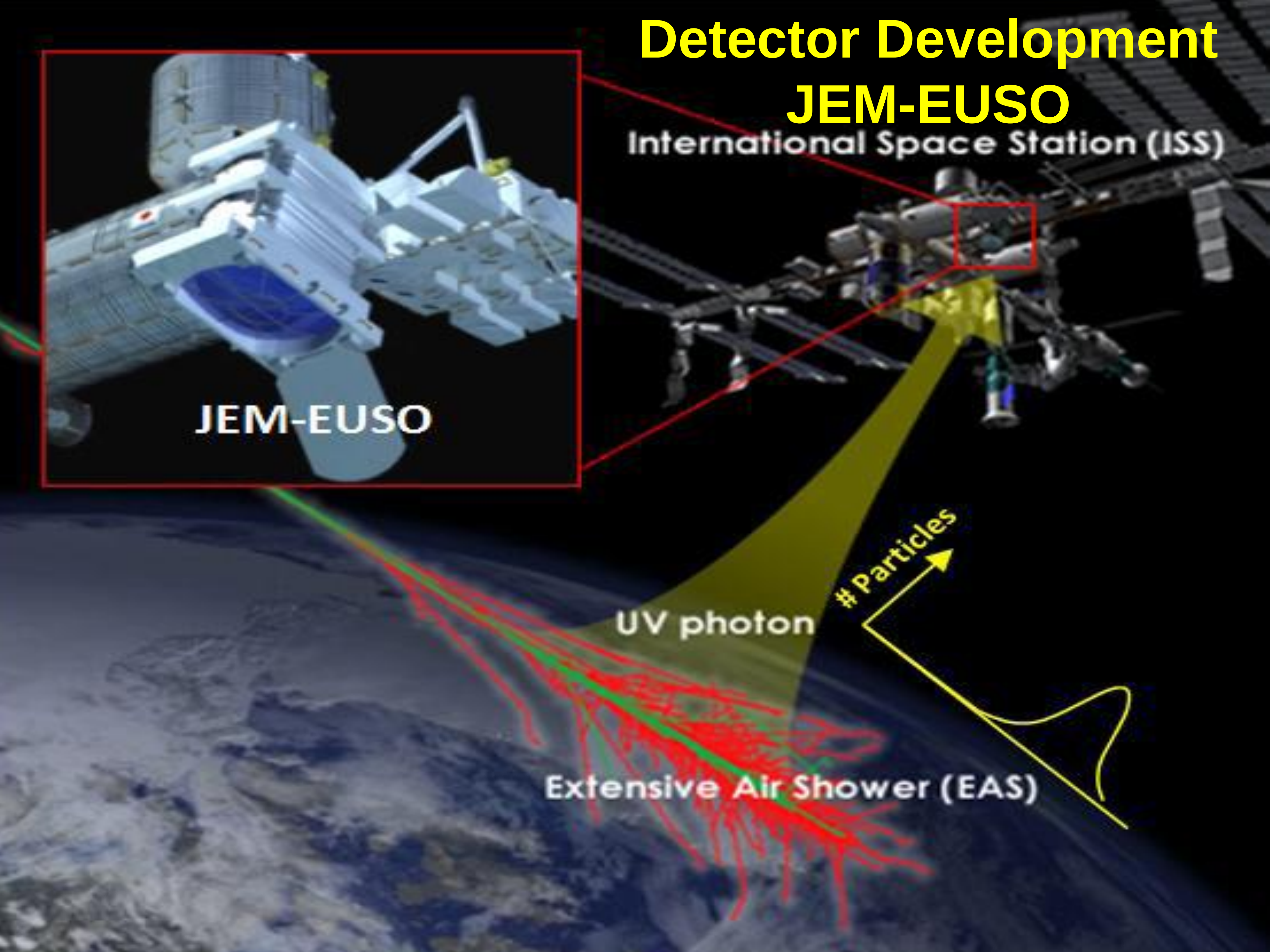

Bottom view of the DarkSide TPC


Setup to test 250 PMTs for XENON1T

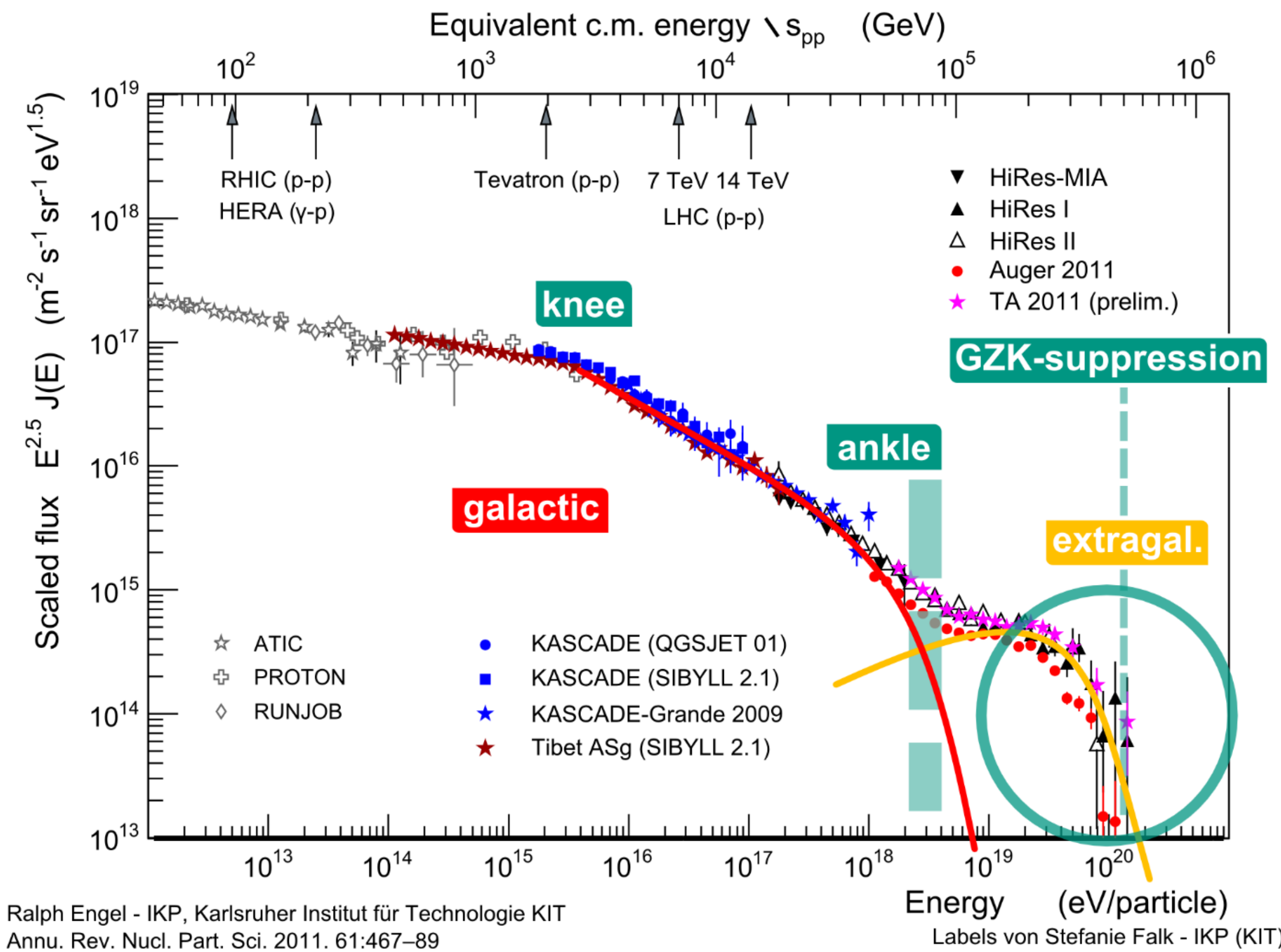

Bottom array of the PandaX detector

- **JEM-EUSO**

Detector Development
JEM-EUSO

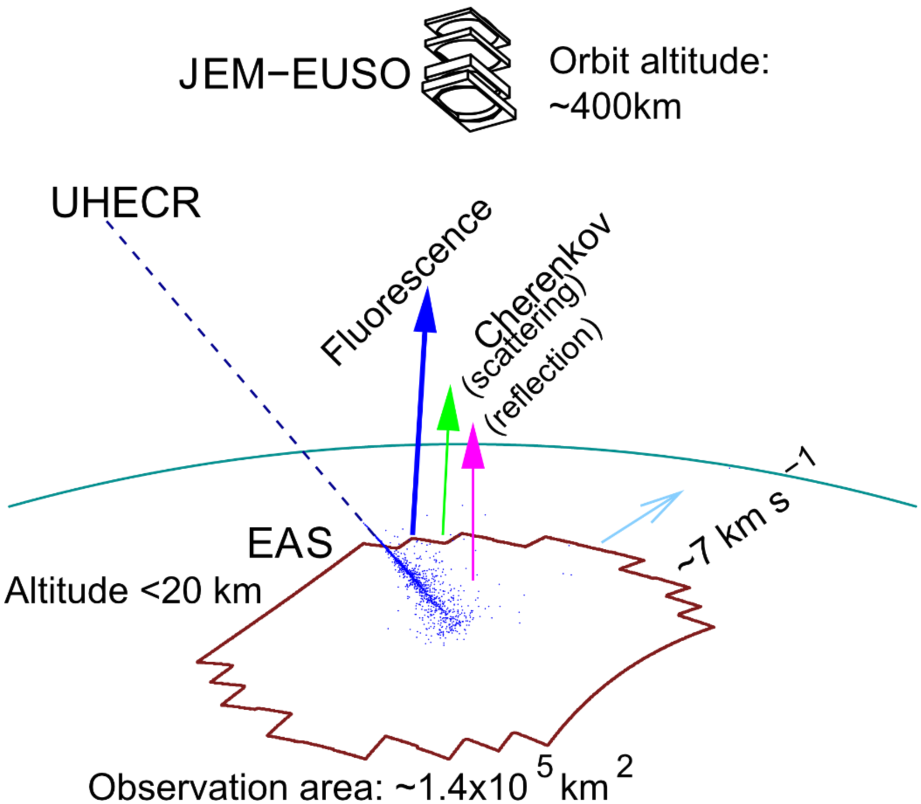


Main Physics Objective



- **Measurement of Extreme Energy Cosmic Rays (EECR)**

JEM-EUSO main features



Method:
fluorescence (full calorimetric)

Large field of view:
± 30° by double sided spherical Fresnel lenses

At 400 km (ISS):
$2 \cdot 10^5$ km^2 (nadir mode)
up to 10^6 km^2 (tilted mode)

No need for stereo:
400 km >> shower length
(TPC with a drift velocity = c)

Exploratory Scientific Objectives

- **Astronomy and Astrophysics through the particle channel**

  = Physics and Astrophysics at $E > 5.\times 10^{19}$eV

- **Exploratory Objectives:**

  new messengers

  – Discovery of UHE neutrinos

  discrimination and identification via X_0 and X_{max}

  – Discovery of UHE Gammas

  discrimination of X_{max}

  due to geomagnetic and LPM effect

- **Exploratory Objectives:**

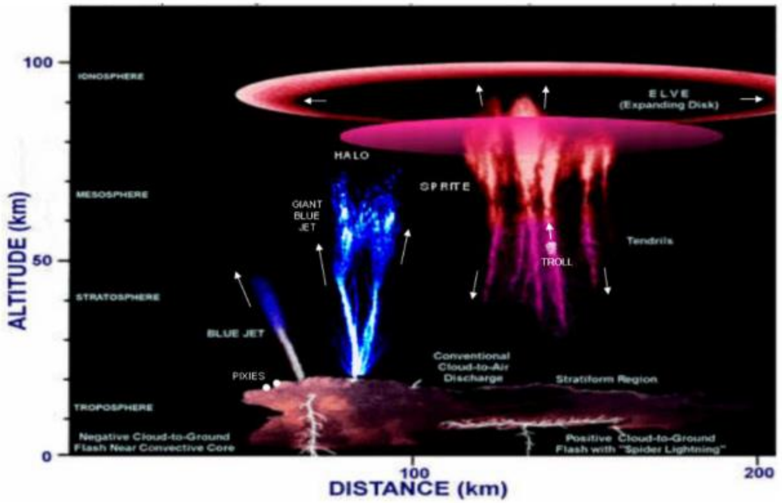
  magnetic fields

- **Exploratory Objectives:**

  Atmospheric science

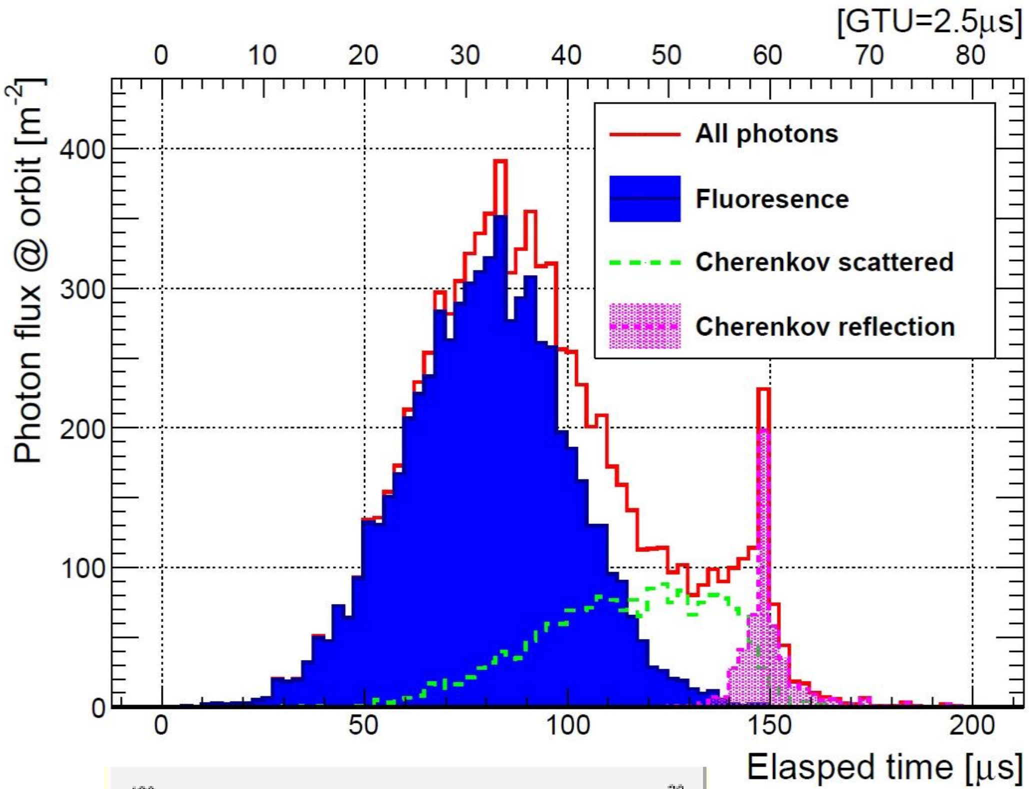
  - Nightglow
  - Transient luminous events
  - Space-atmosphere interactions
  - climate change

  🡐 with the fast UV monitoring of the Atmosphere



(Elaboration of figure by Lyons et al. 2000)

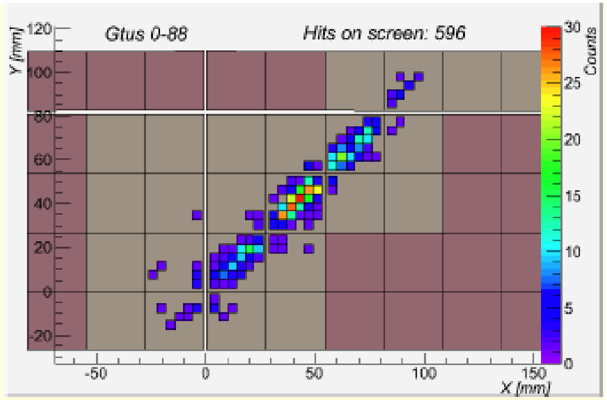
The observation technique



1 GTU = 2.5μs

Background
= 500 ph / m^2 sr ns
(from Tatiana satellite)

Fast signal: ~50-150μs

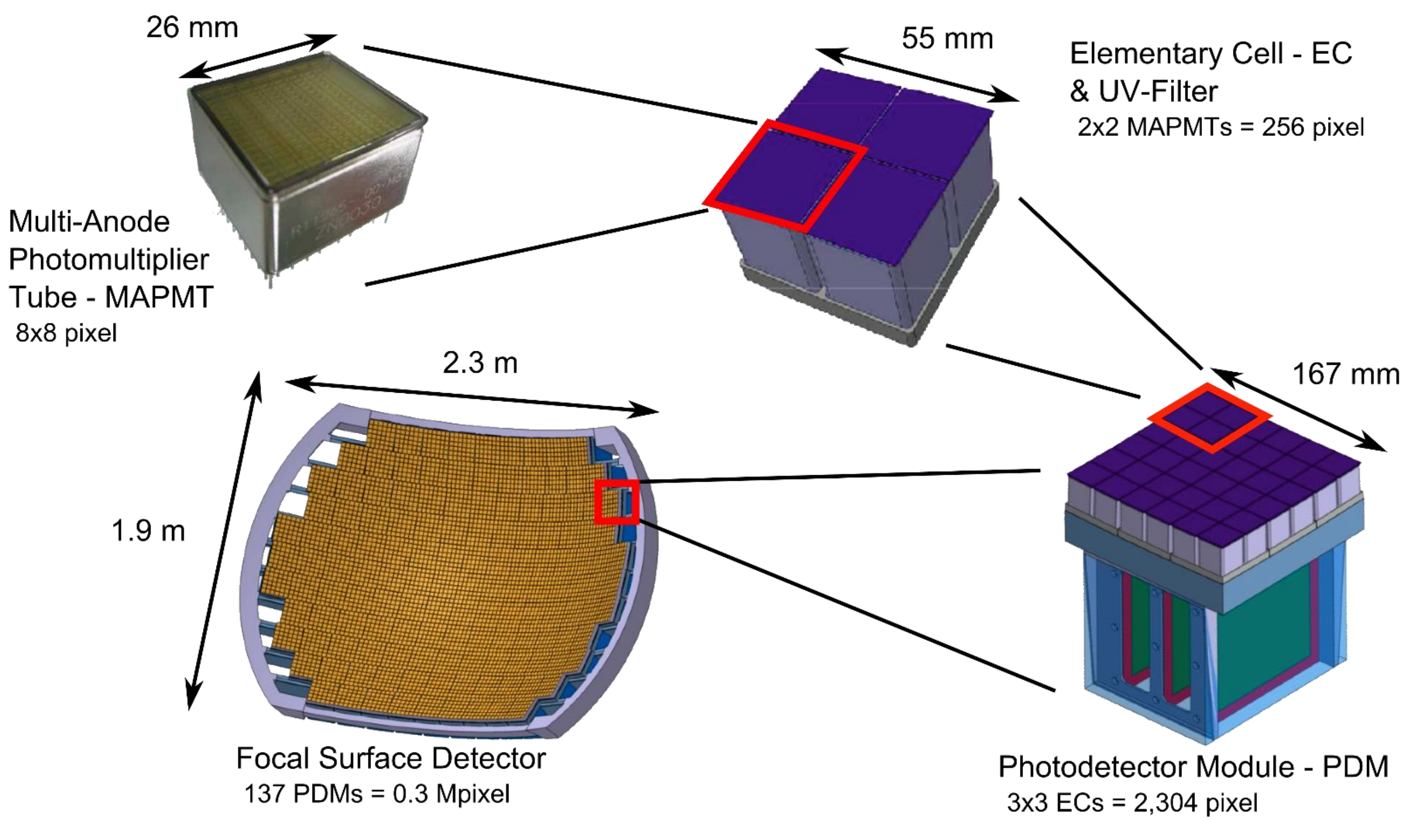


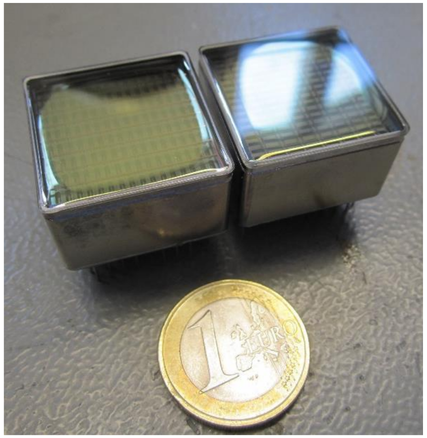
ΔE/E < 30% for ~90% of events

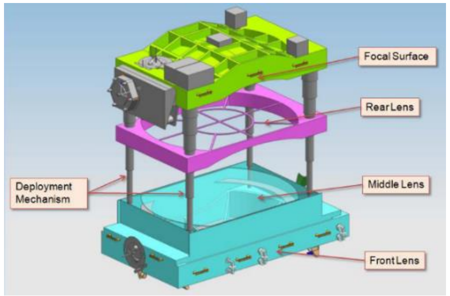
J.H. Adams Jr. et al. /
Astroparticle Physics 44 (2013) 76–90

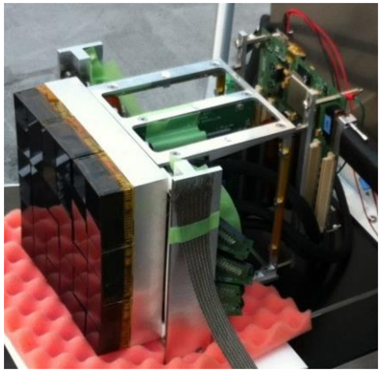
JEM-EUSO focal surface

Hamamatsu R11265-113-M64 MOD2







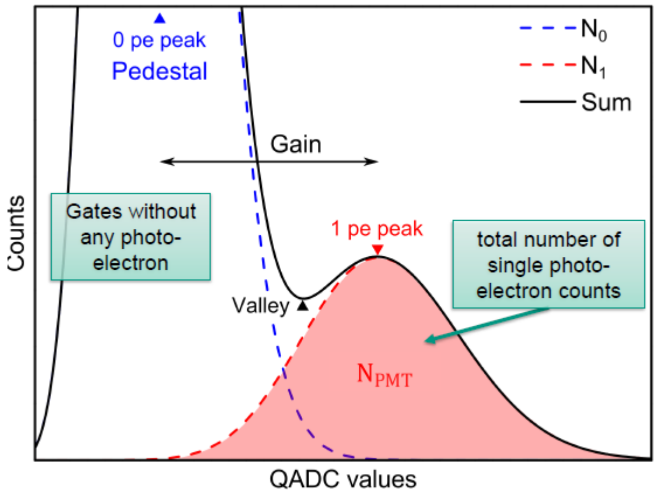


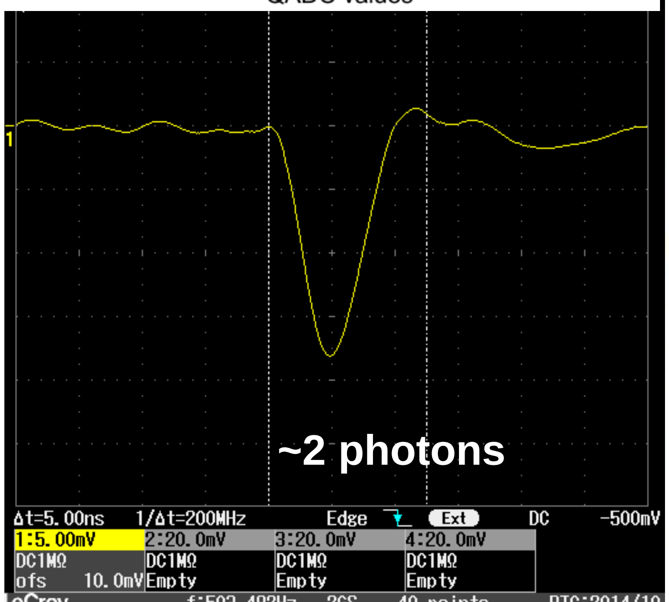
Focal surface:

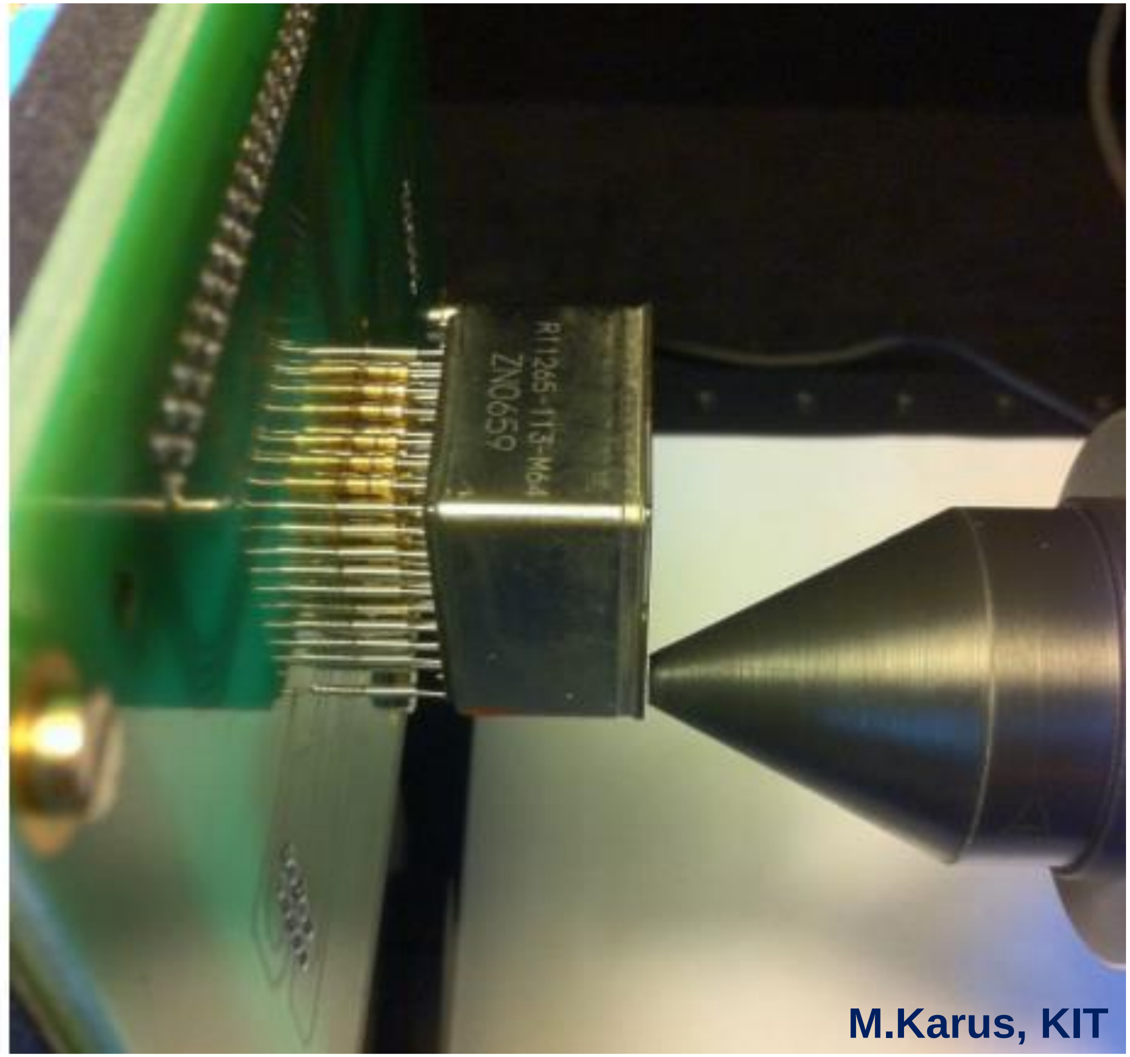
- prototypes of PDM available
- FoV of 1 PDM = 27 x 27 km^2

MAPMT: single photon Calibration

Single photoelectron spectrum







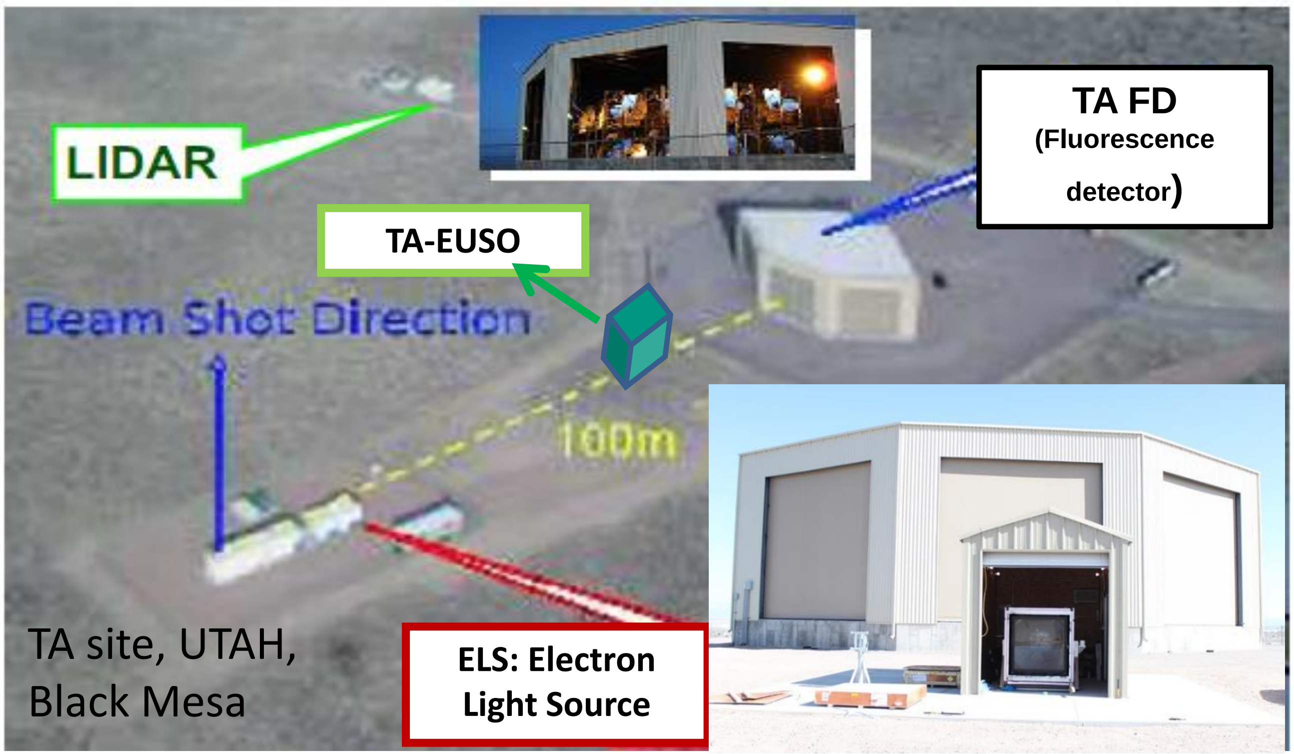
Andreas Haungs
IKP

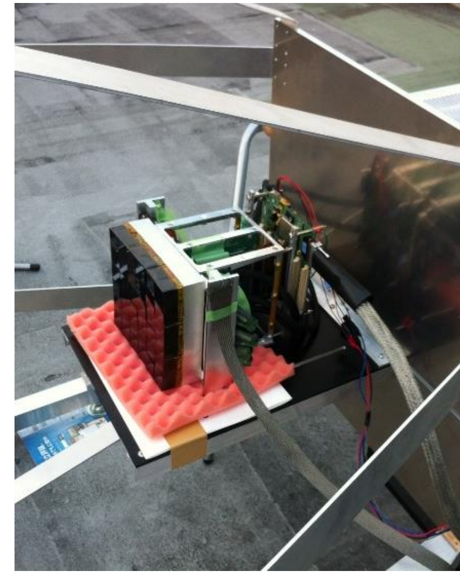
TA-EUSO: Cross-calibration tests at Telescope Array site, Utah

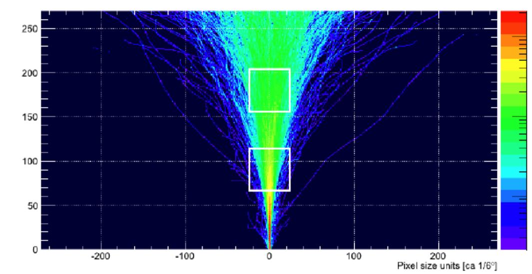
Main purpose: calibration using existing FD telescope

- Lidar and electron beam ➔ absolute calibration
- Few showers in coincidence with TA
- 2 (squared 1 m^2) Fresnel Lenses ➔ FoV = 8 degree
- focal surface: 1 PDM (36 MAPMT, 2304 pixels)

Operational since autumn 2014!







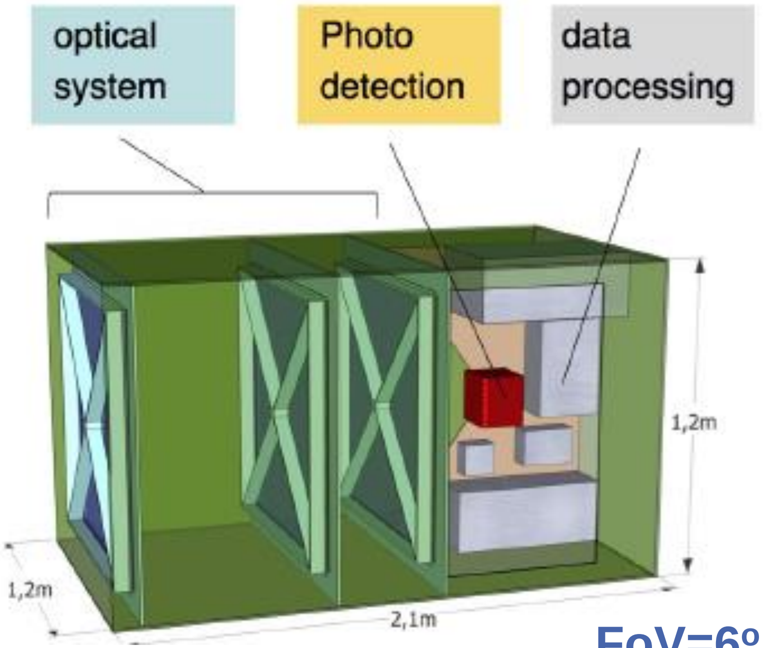
Simulation of UV photons of TA ELS
Squares: FoV of the TA-EUSO
N.Sakaki / F. Bisconti, KIT

EUSO-Balloon
JEM-EUSO prototype at 40km altitude

Main purpose: Background measurements and engineering tests

- Engineering test
- UV-Background measurement
- Laser tracks and flasher observations from helicopter

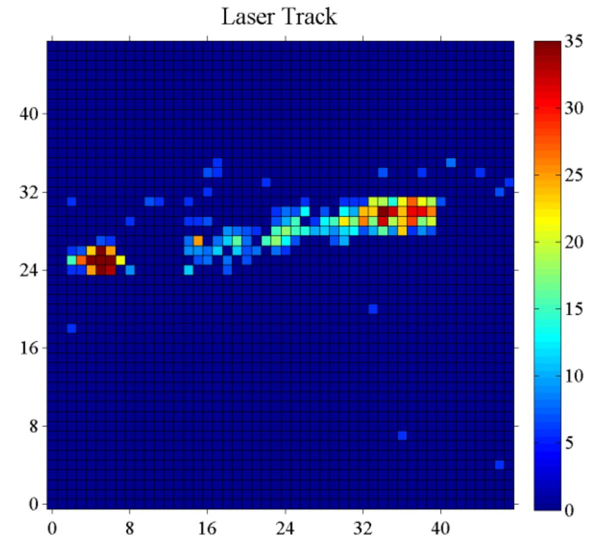
First flight: August 2014!



FoV=6º

EUSO-Balloon

First flight Timmins, Canada: 25th August 2014



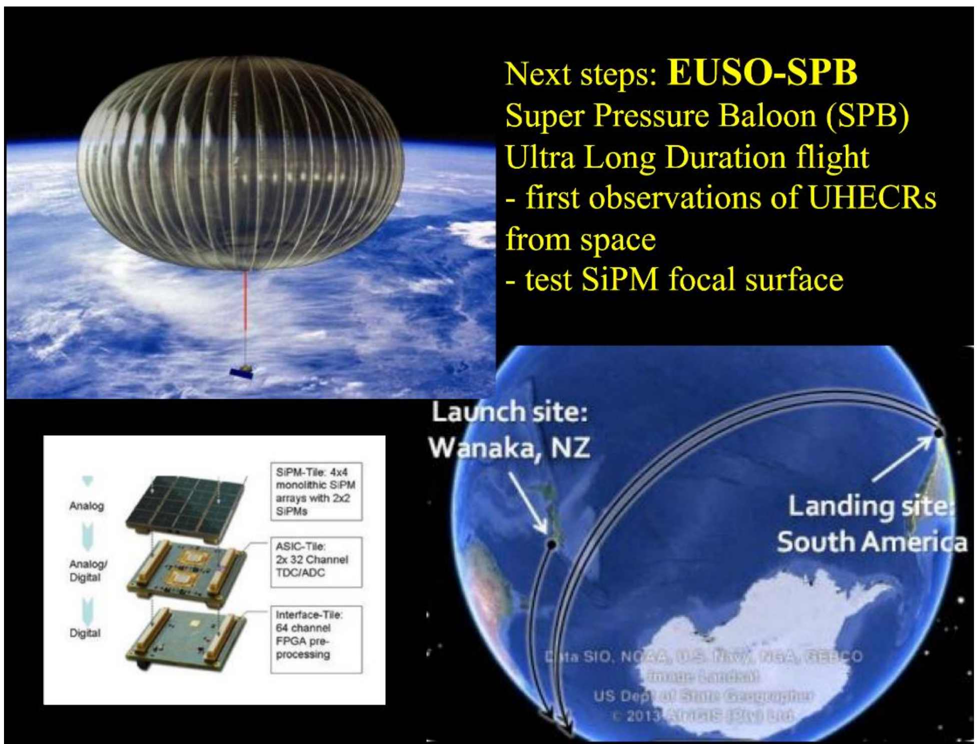
- **c. 5h data available**
- **incl. IR camera and laser (helicopter)**

EUSO-SPB
JEM-EUSO prototype at long duration balloon flight

Main purpose: first EAS maesurements from Space!!

- Engineering test
- UV-Background measurement
- Air shower observations

Launch: Spring 2017!



Columbia Scientific Balloon Facility
SPB - Flight 662NT -
32 days, 5 hours, 51 minutes

Mini-EUSO
Small (25 cm lenses + 1 PDM) prototype at ISS

<u>**Scientific objectives**</u>

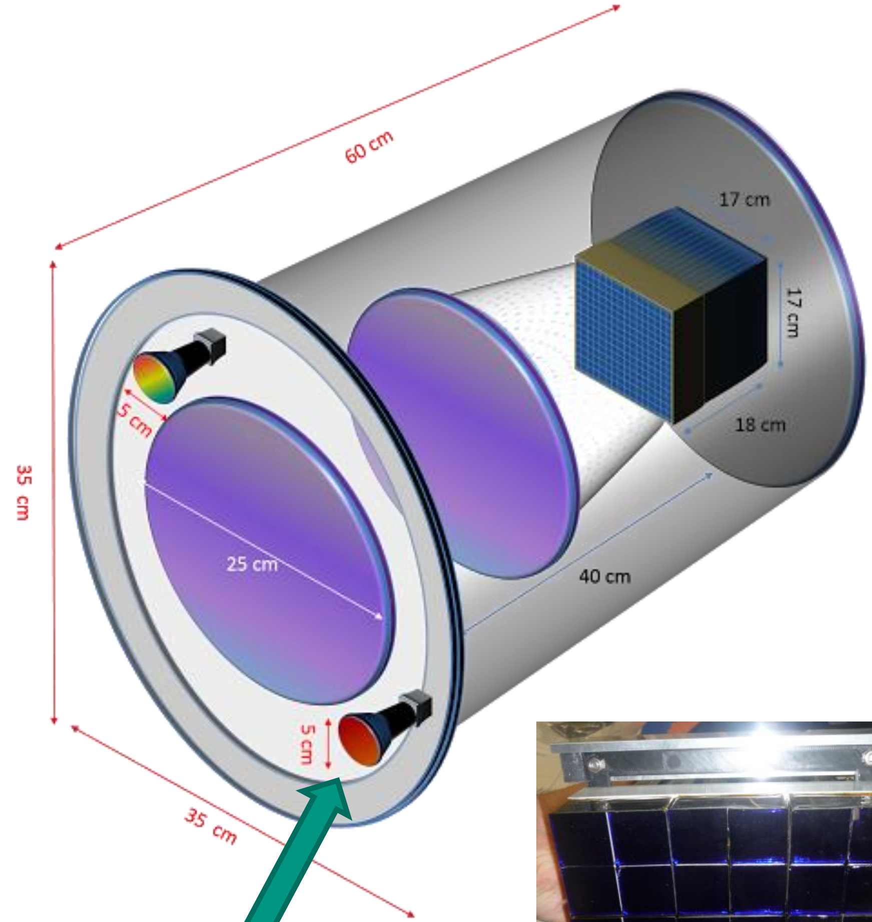
1) UV emissions from night-Earth;
   Map of the Earth in UV
2) Study of atmospheric phenomena
   and bioluminescence at Earth
3) Study of meteors

<u>**Technological objectives**</u>

1) First use of Fresnel lenses in space
2) Optimization of characteristics
   and performances of EUSO
3) Raise the technological readiness
   level of the Hardware

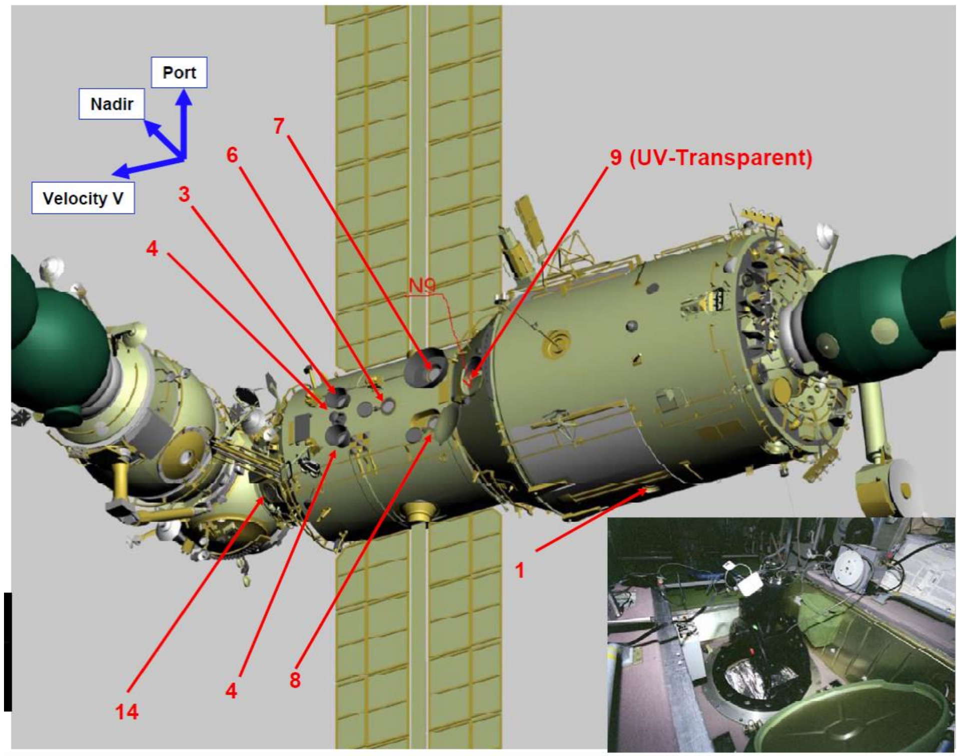
<u>**Operation approved**</u>

<u>**Launch 2017 or 2018 ?**</u>



CTA-ASTRI SiPM Module (passiv)? Temperature problem

Mini-EUSO at ISS
Russian Module Zvevna



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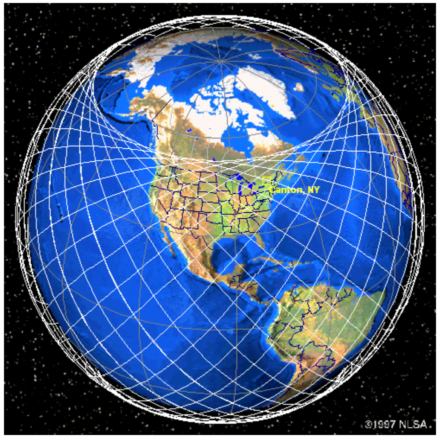
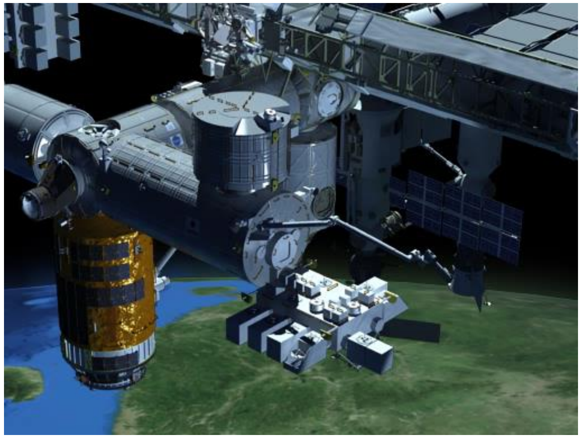
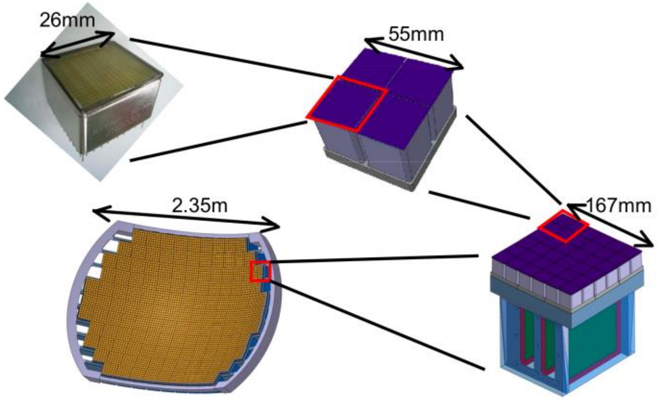
Karlsruhe Institute of Technology

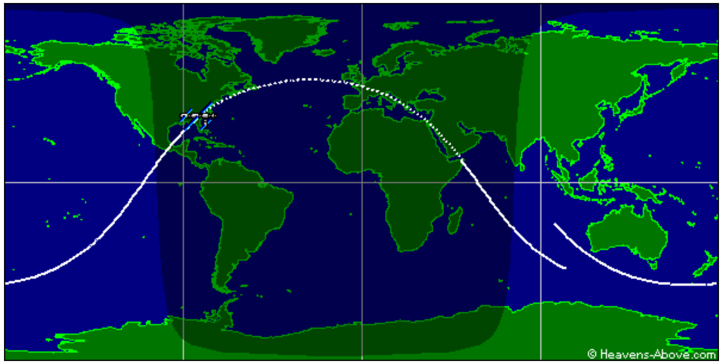
Future: later on ISS or free flyer (M5 mission)?

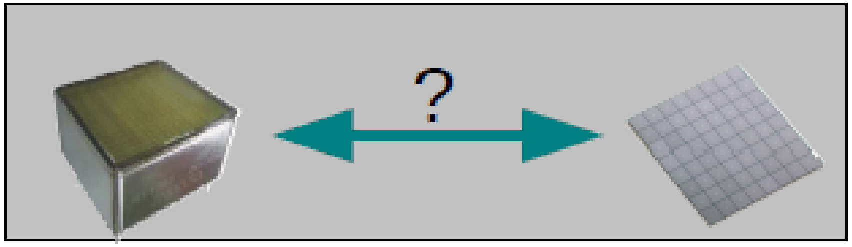






ISS: 1 orbit in 90min



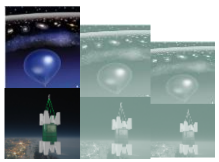


goal to replace MAPMT by SiPM !

Air Shower Observations from Space

2014 — 2017 — 2020 — 2023

TA-EUSO
Continuous operation

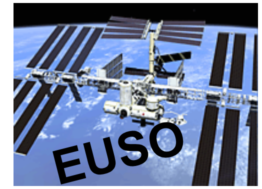


EUSO-Balloon
1st flight 2014

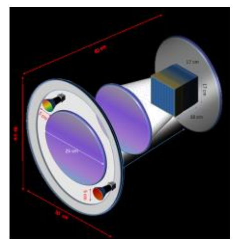
JEM-EUSO

Launch 2017 cancelled

?



AO from NASA in 2016?
for ISS 2021-24:
Probably not as too low exposure



Baseline design change to
SiPM-PDM?

M5 mission
Free flyer?

esa
European Space Agency

Proposal 2016?

EUSO-SPB (NASA)
Preparation in work
(including small SiPM-camera)
Launch spring 2017

Mini-EUSO on ISS
(approved for 2018)

TUS

“K-EUSO”

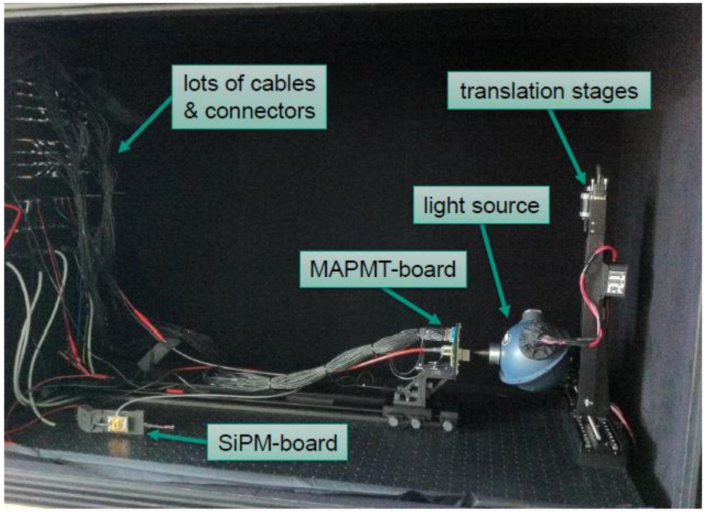
Andreas Haungs
IKP

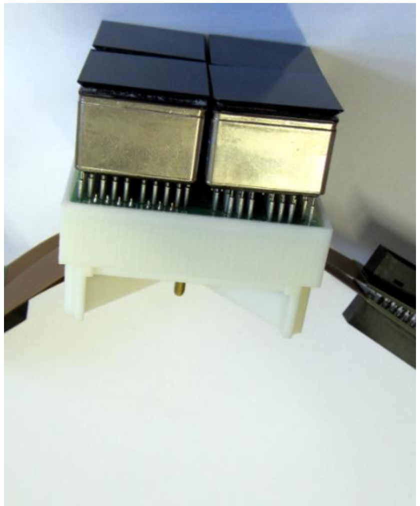
SiPM for x-EUSO-y

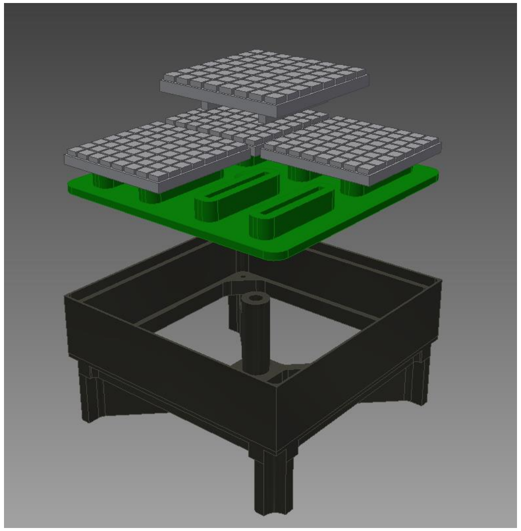
Goal: to have an EC based on SiPM within 1 to 2 years
to be able to design an alternative focal surface for the big mission and gaining experience and expertise for further SiPM applications

Main issues:

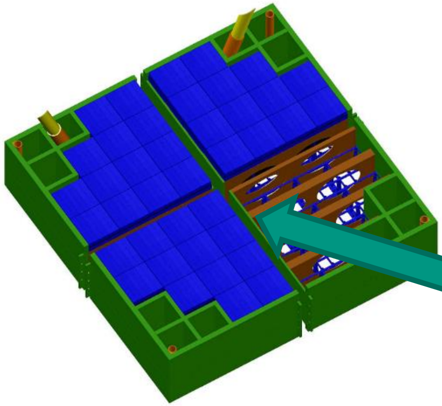
- **large sensitive area = high filling factor** (to avoid dead space and light cones)
- **sensitivity to fluorescence light** (UV-range 290-440 nm to cover full spectrum)
- **fast readout** (specific ASIC, digital SiPM, monolithic SiPM/ASIC readout)
- **characteristics and calibration** (single photon efficiency)
- **mechanical structure = integration** (to fit a focal surface)

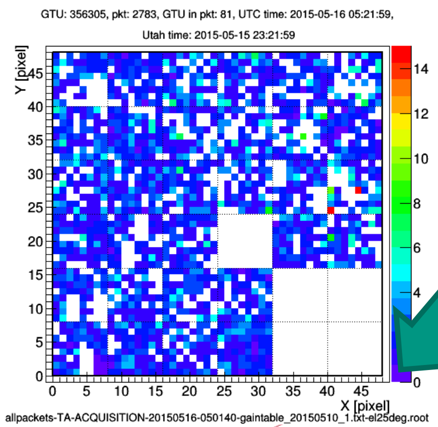


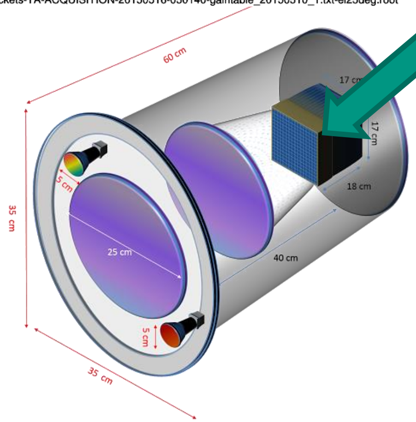


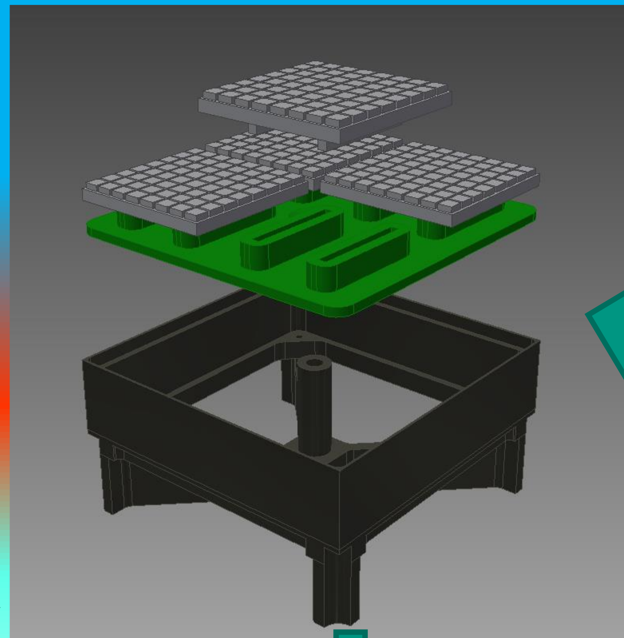


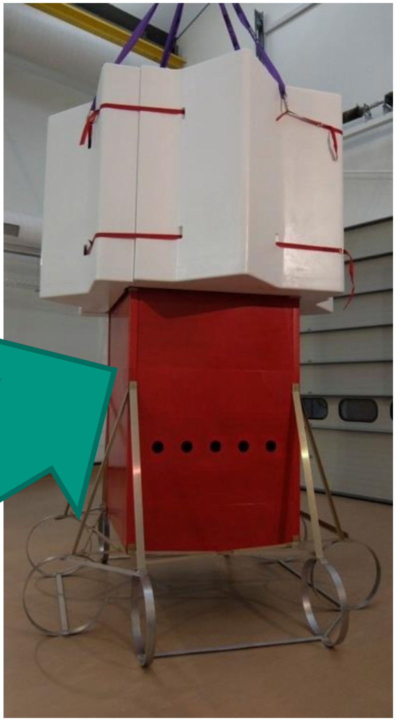
SiPM for x-EUSO-y





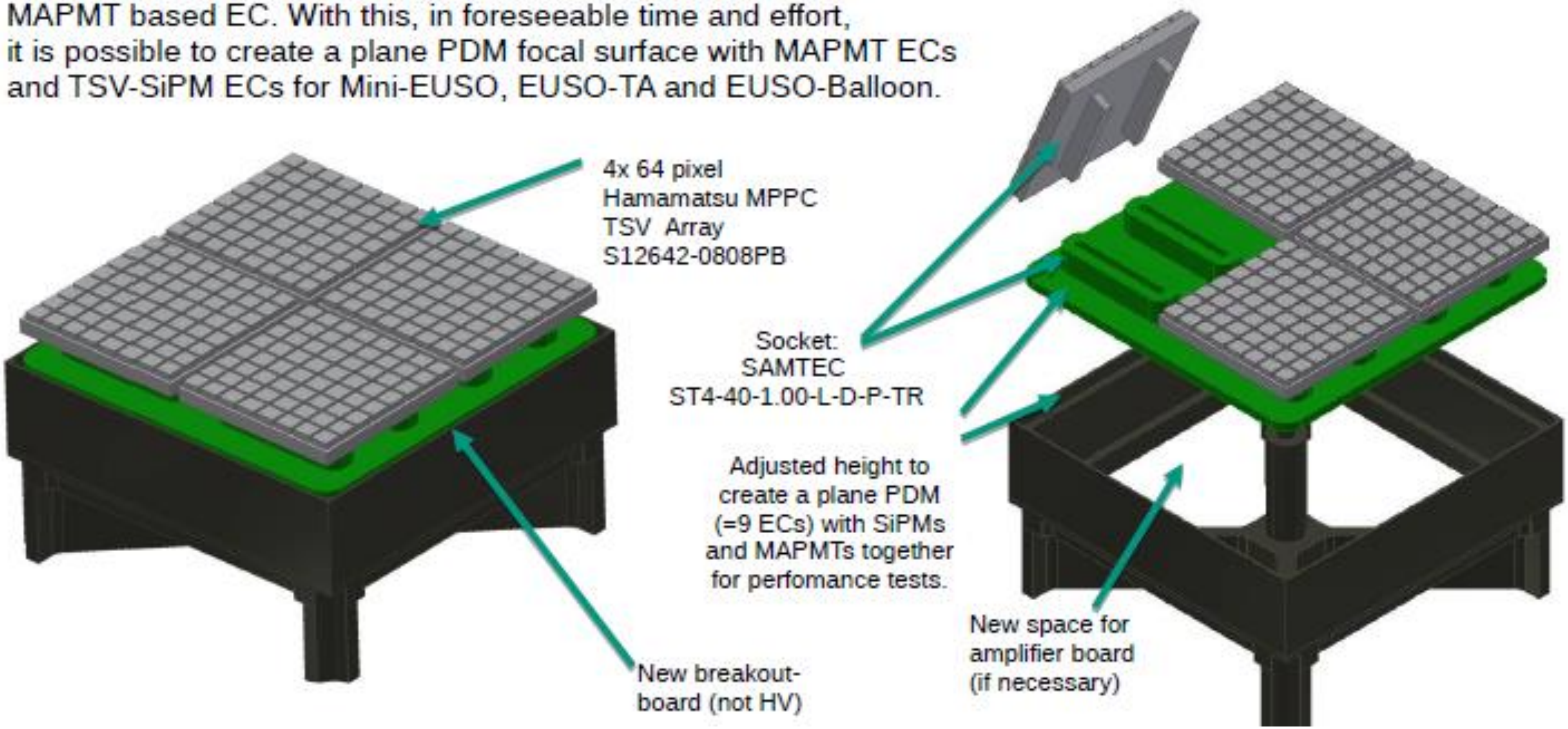






SiPMs as JEM-EUSO Elementary Cell?

The TSV-SiPM candidate fits into the former design of a MAPMT based EC. With this, in foreseeable time and effort, it is possible to create a plane PDM focal surface with MAPMT ECs and TSV-SiPM ECs for Mini-EUSO, EUSO-TA and EUSO-Balloon.

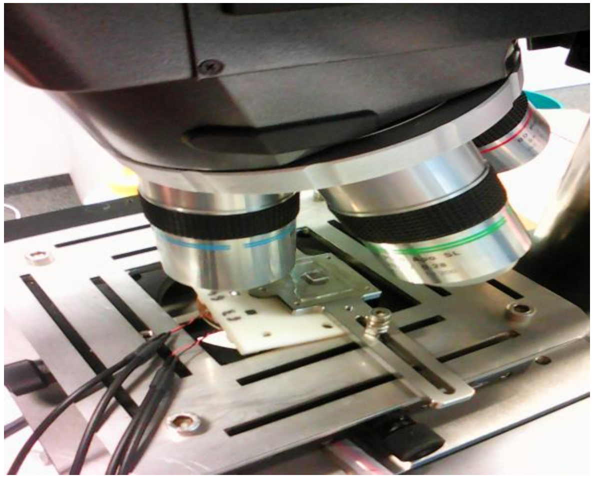


Filling factor higher than with MAPMTs

T. Huber, KIT

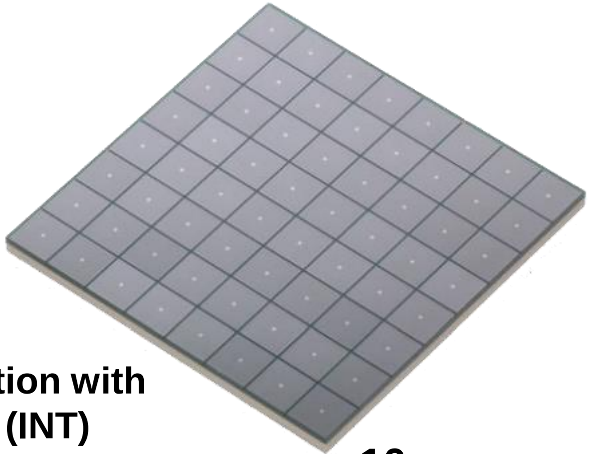
Hamamatsu TSV-Array

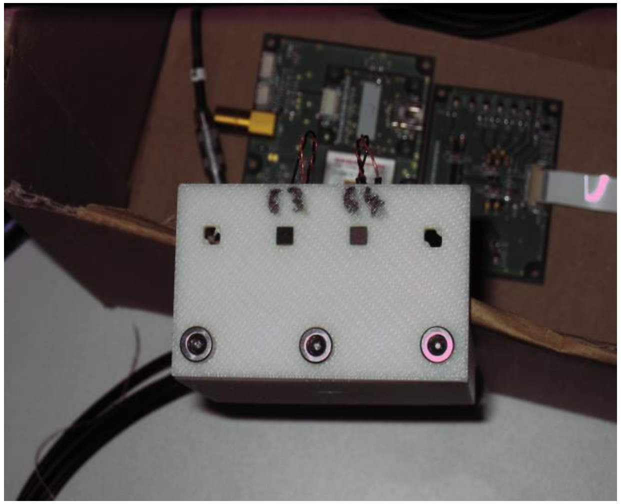
T. Huber, KIT



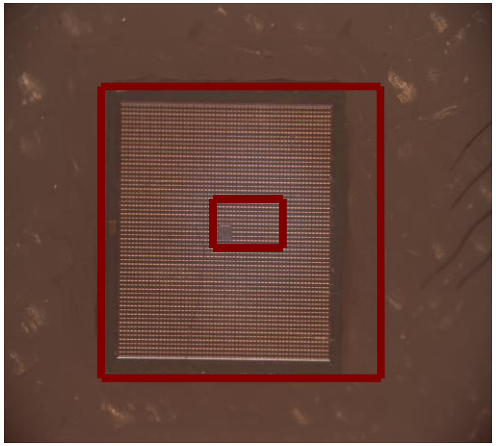
Microscope images made in cooperation with KIT - Institute for Nanotechnology (INT)

Candidate: Hamamatsu 64Pixel SiPM TSV-Array



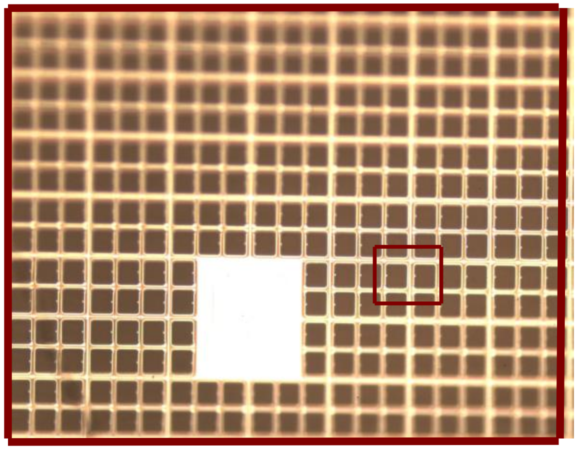


1 Pixel from the TSV Array



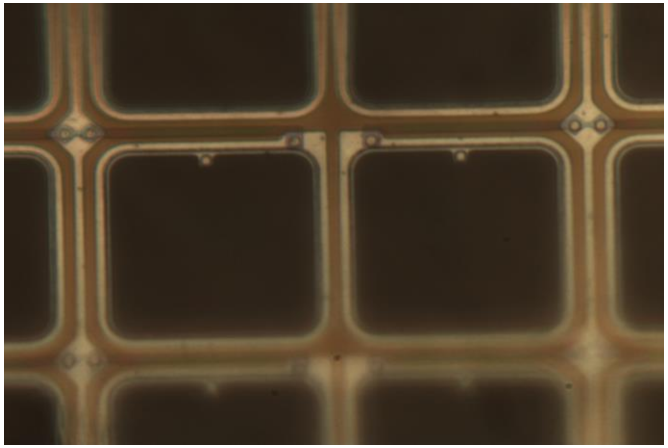
2.5x zoom into 1 Pixel

10x zoom



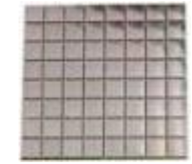
Crosstalk-reducing Isolator

100x zoom

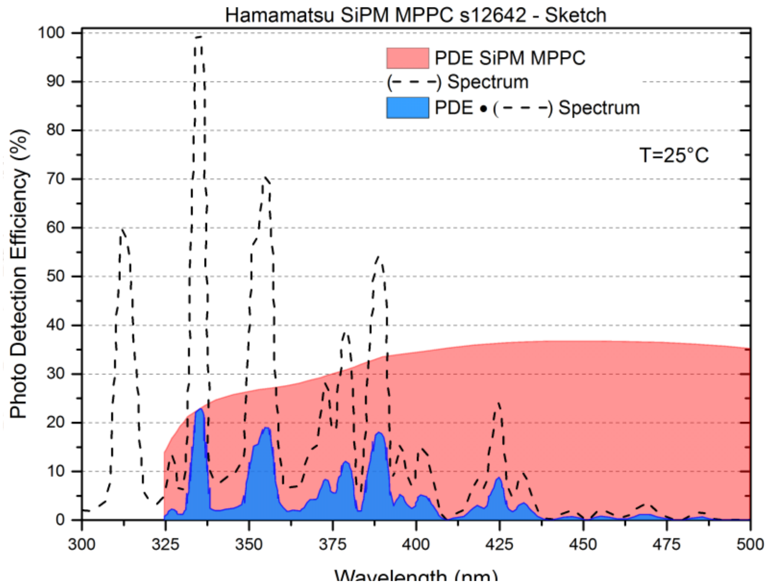


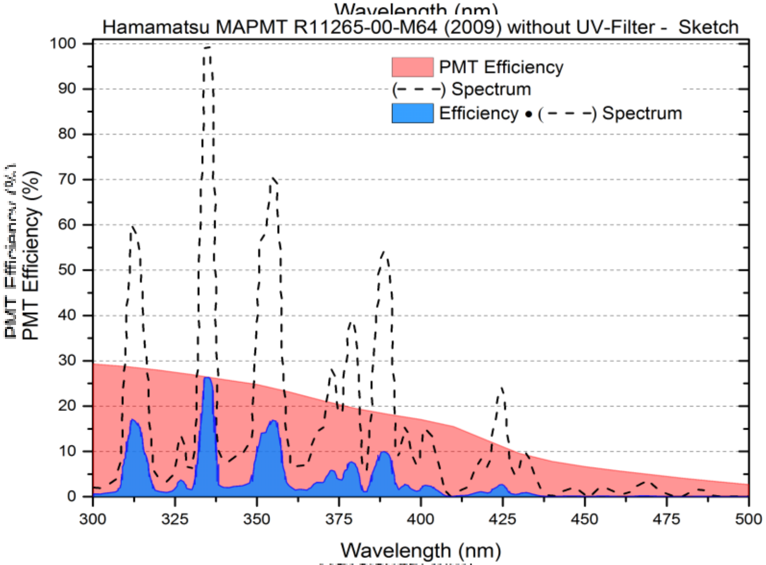
1 Avalanche Photodiode (of est. 1100@ 1 pixel)

SiPM vs MAPMT: Efficiency



An estimate for comparison





Now available: arrays available from Hamamatsu sensitive to UV light

Ratio of SiPM area and Nitrogen spectrum area ≈ 29 %

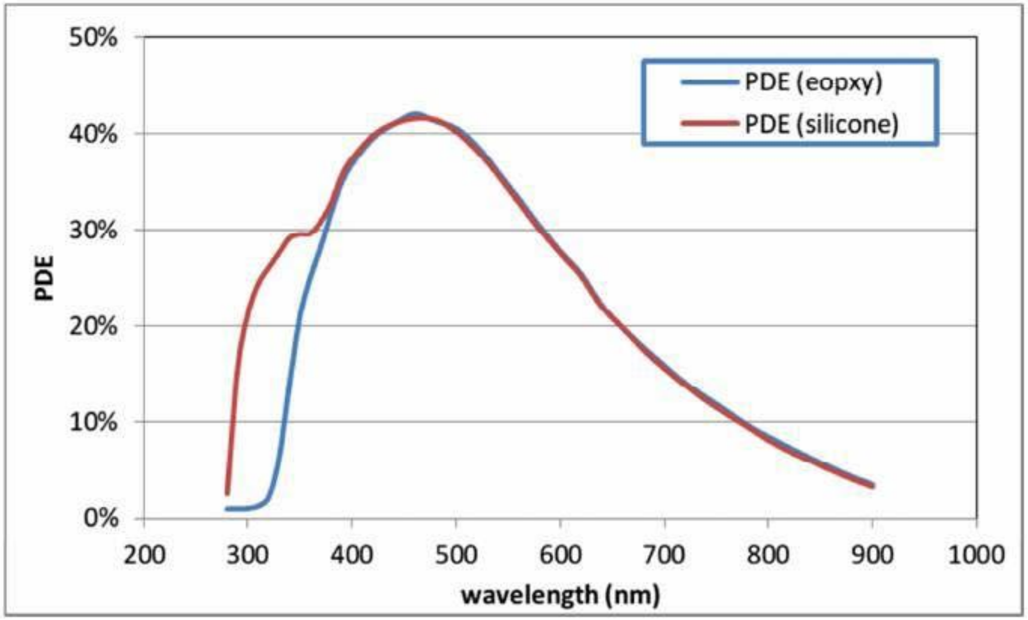
Be careful: Fluorescence spectrum depend on atmospheric height

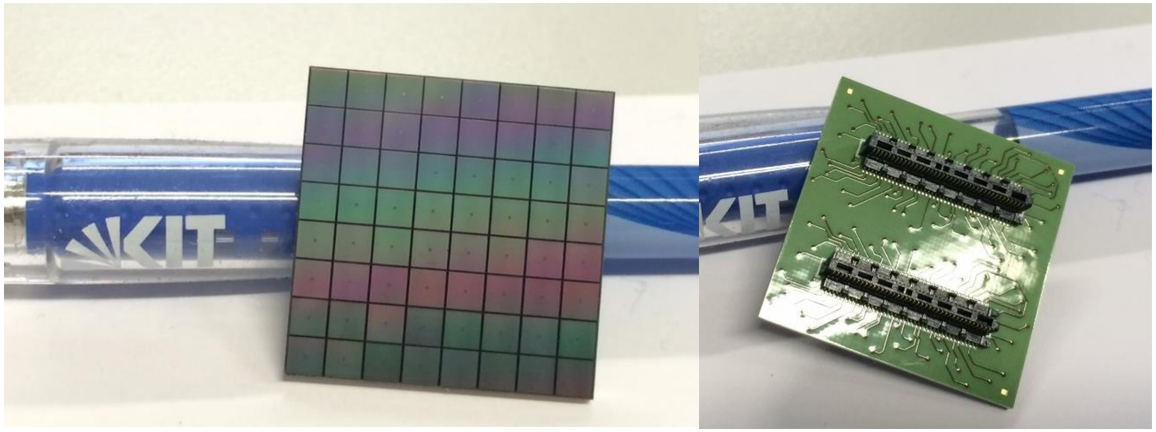
Ratio of MAPMT area and Nitrogen spectrum area ≈ 23 %

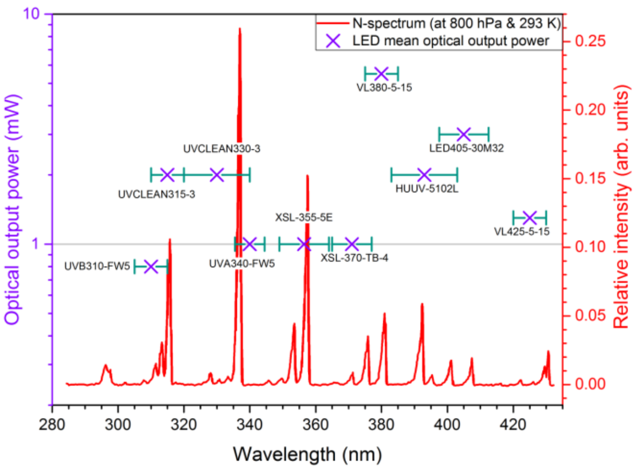
Thomas Huber (IKP)

SiPM vs MAPMT: Efficiency

Now available:
arrays from Hamamatsu
sensitive to UV light

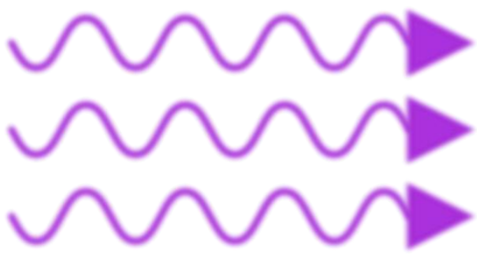




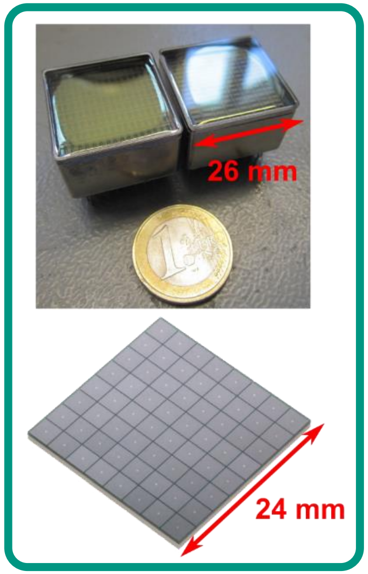


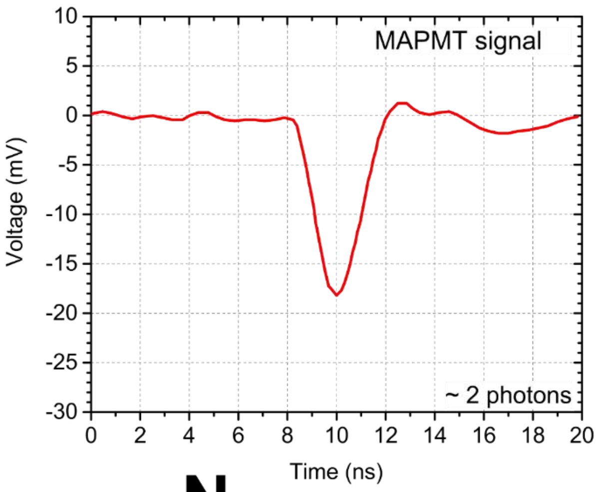
Andreas Haungs
IKP

Calibration Principle

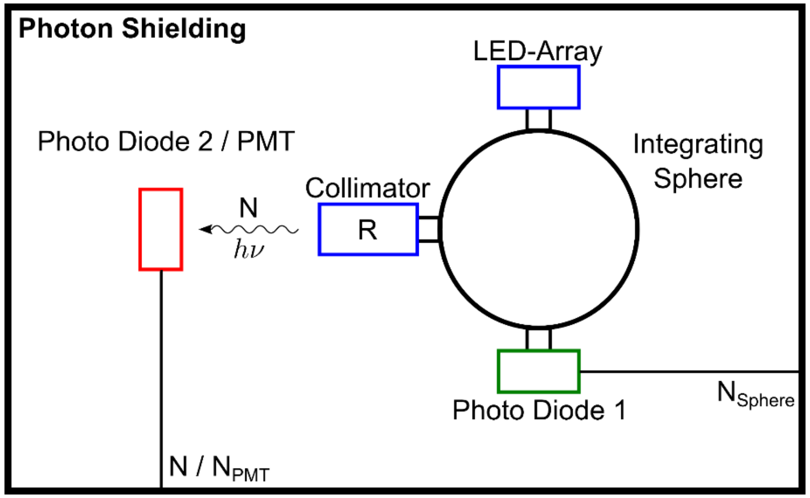


$N_{Photonen}$



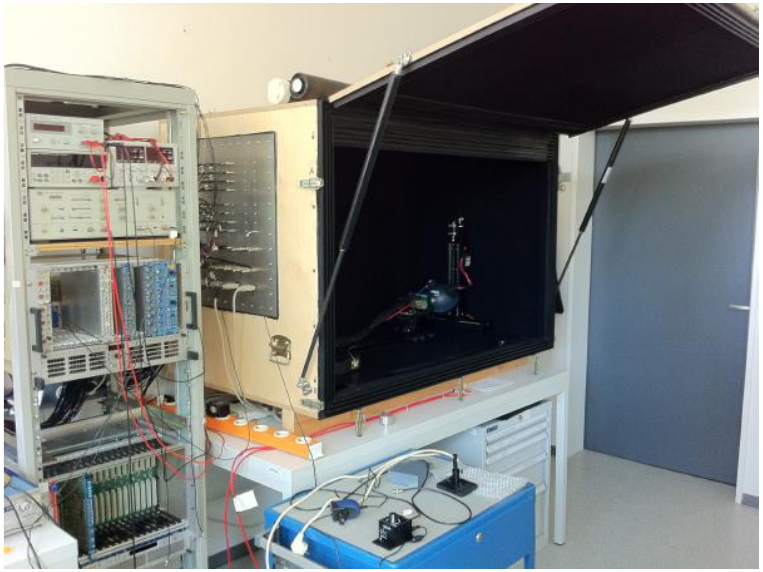


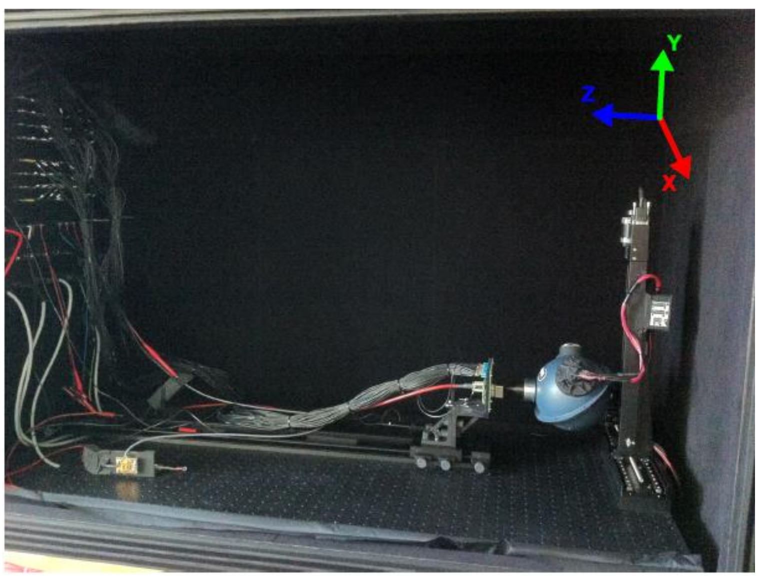
$N_{Detektor}$

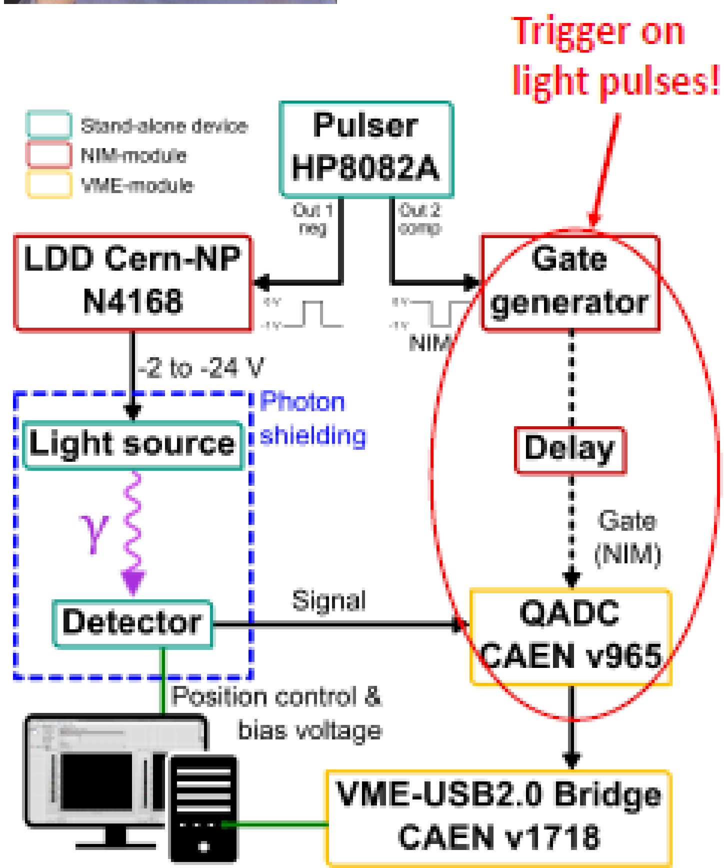


M.Karus, KIT

Single PhOton Calibration stand at KIT (SPOCK)







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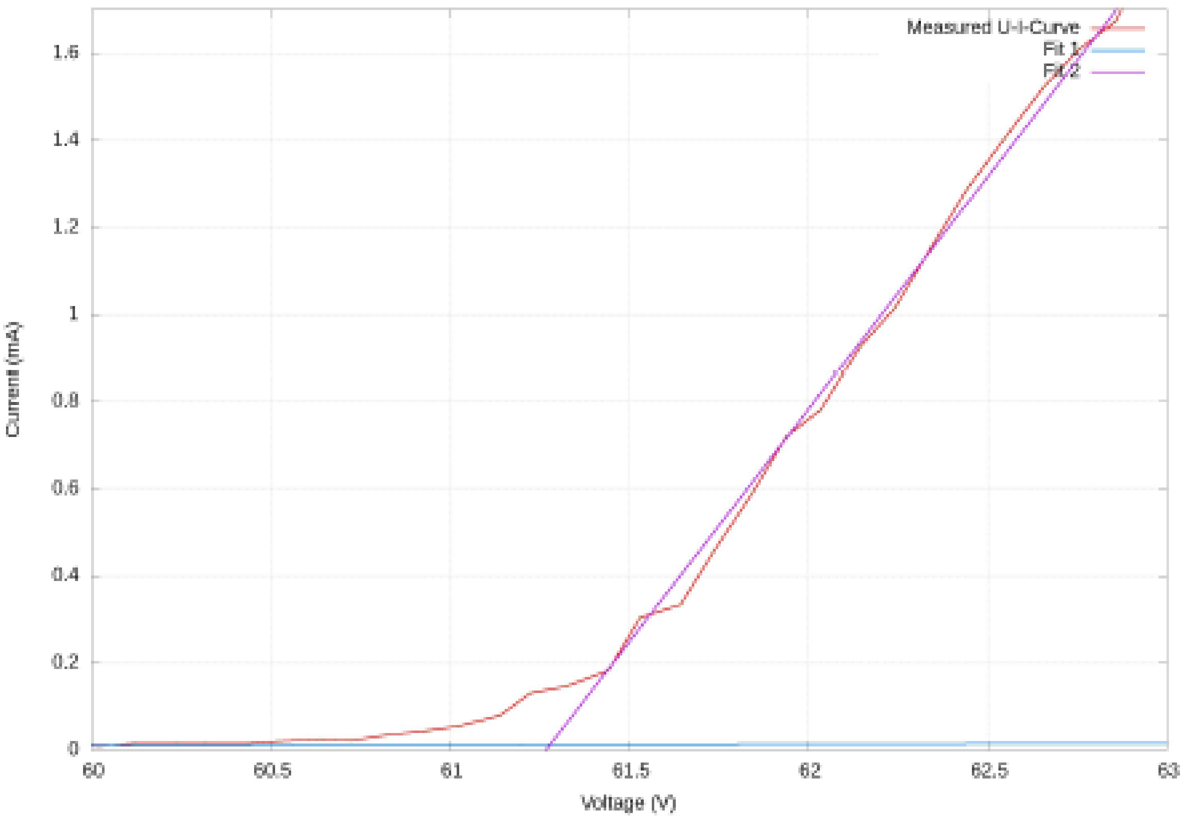
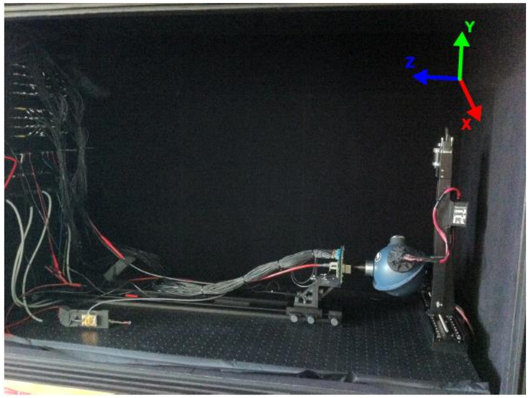
Determination of breakdown voltage

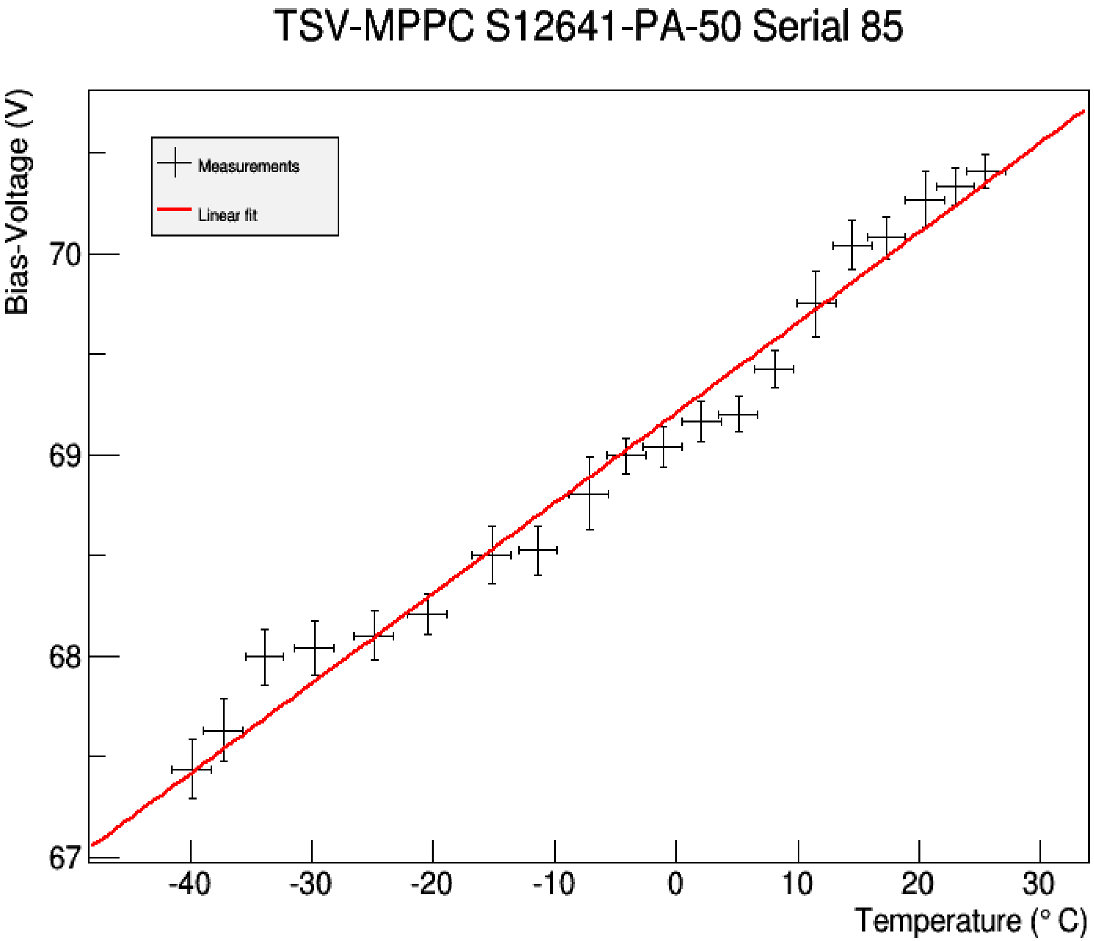


- U-I-Curve of one SiPM channel
- Linear Fits on the curve parts before and after Breakdown Voltage
- Crosspoint of the fits is approximate Breakdown Voltage

T. Huber, KIT

Temperature dependence of Bias Voltage

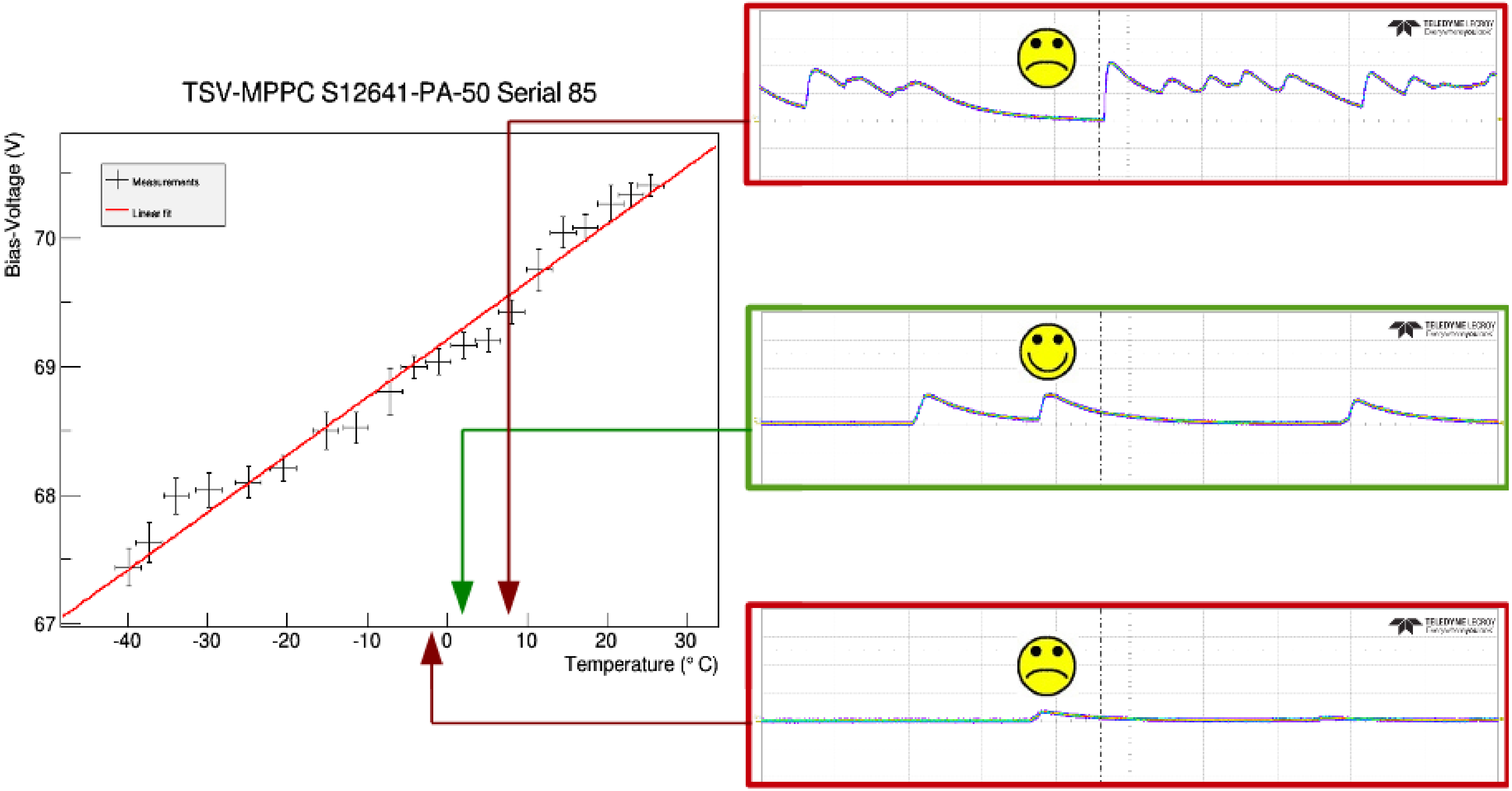




T. Huber, KIT

Correlation Bias Voltage and Temperature

With a constant Bias-Voltage:



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

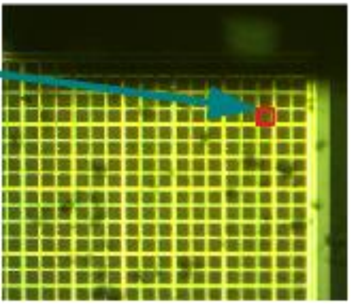
T. Huber, KIT

Investigation of TSV-SiPMs with an AFM before/after cooling

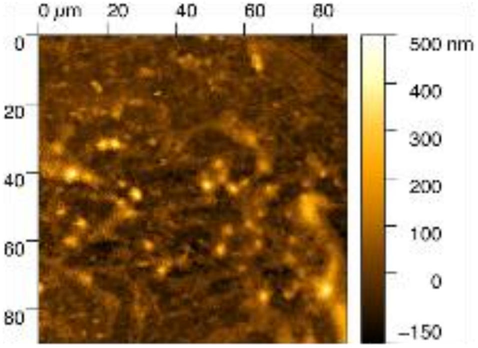
- No structural problems measured
- No grain boundary form cracks accured during cooling/heating process

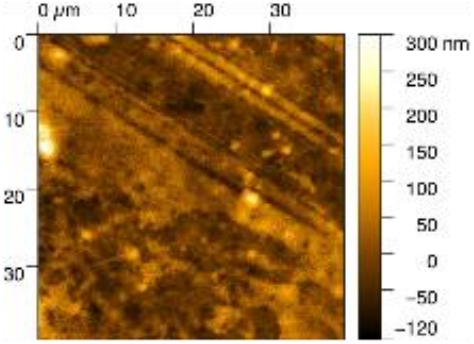
→ It seems that this kind of SiPMs are usable for operating in environmental conditions

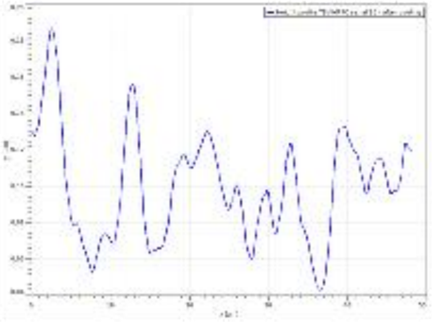
Screened APD Cell



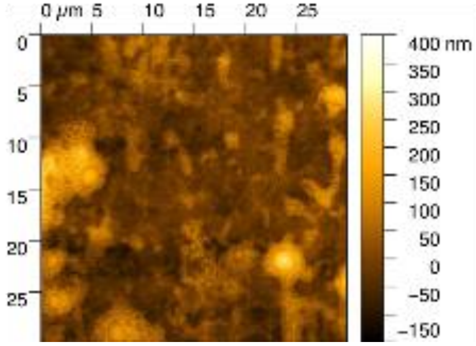
Before:

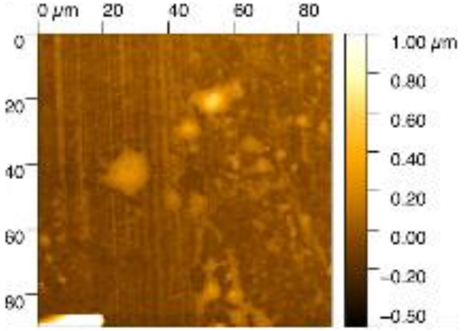


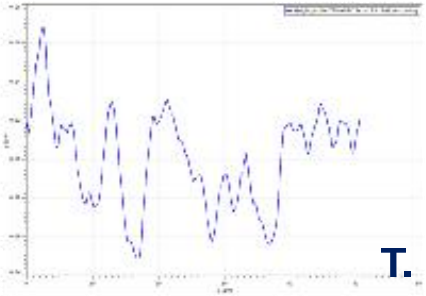




After:

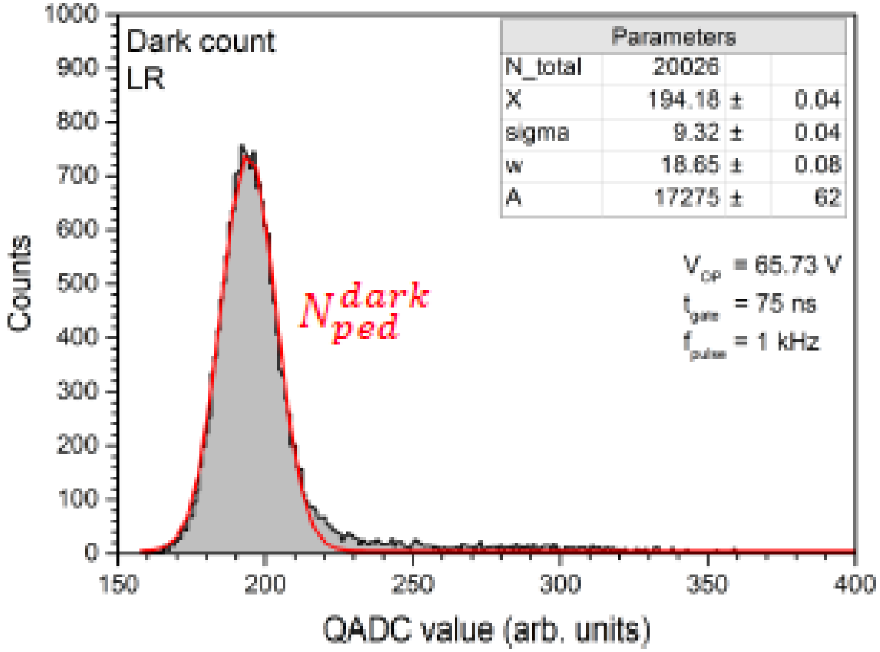


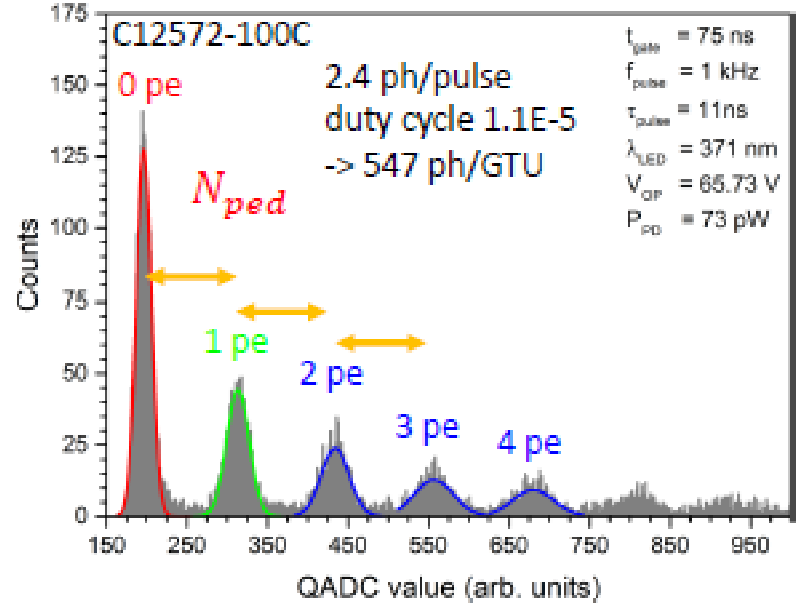




T. Huber, KIT

SiPM efficiency estimation with SPOCK





- Gauss fit: N_{ped}
- Total events (trigger): $N_{tot} = 10013$

- Gauss fit: N_{ped}^{dark}
- Total events (trigger): N_{tot}^{dark}
- Correction term for thermal noise

$$\epsilon = \frac{1}{N} \cdot \left\{ -\ln\left(\frac{N_{ped}}{N_{tot}}\right) + \ln\left(\frac{N_{ped}^{dark}}{N_{tot}^{dark}}\right) \right\}$$

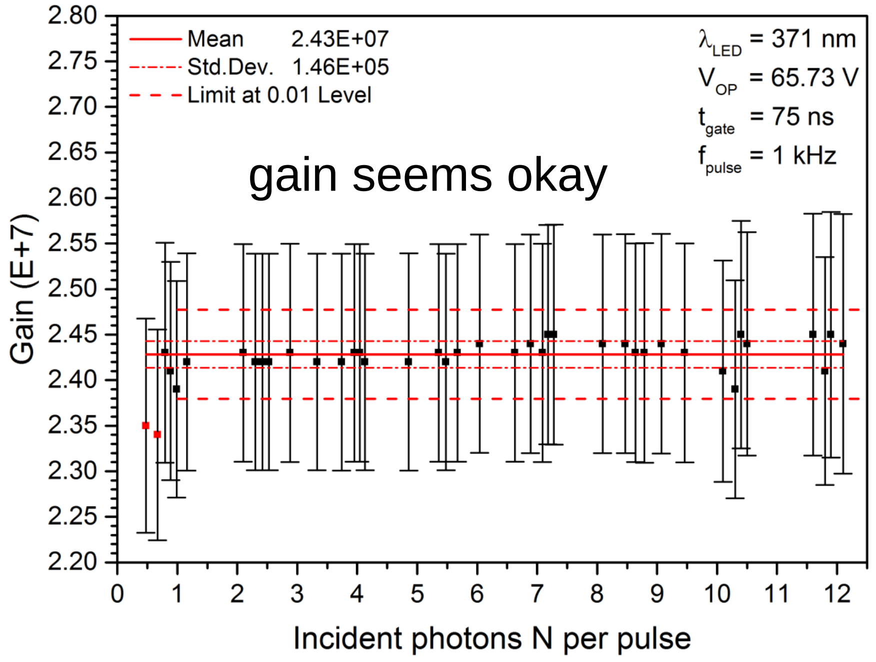
M.Karus, KIT

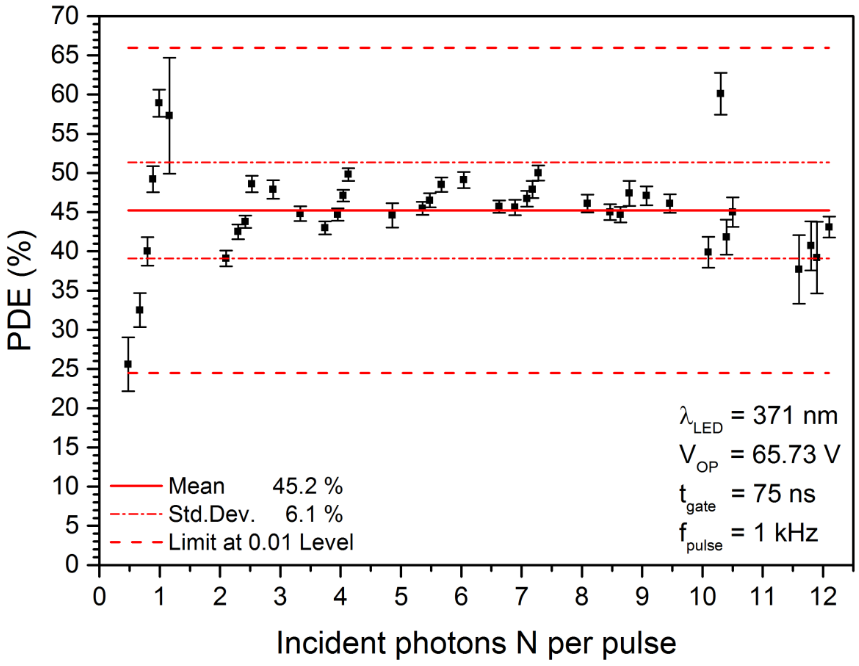
Andreas Haungs
IKP

SiPM efficiency estimation with SPOCK

1 single pixel (old) SiPM (due to misisng readout electronic for SiPM)

45% PDE @ 371 nm
This is most likely overestimated due to afterpulses and crosstalk





M.Karus, KIT

TSV-Epoxy vs TSV-Silicone Array from Hamamatsu

S12642 (old)

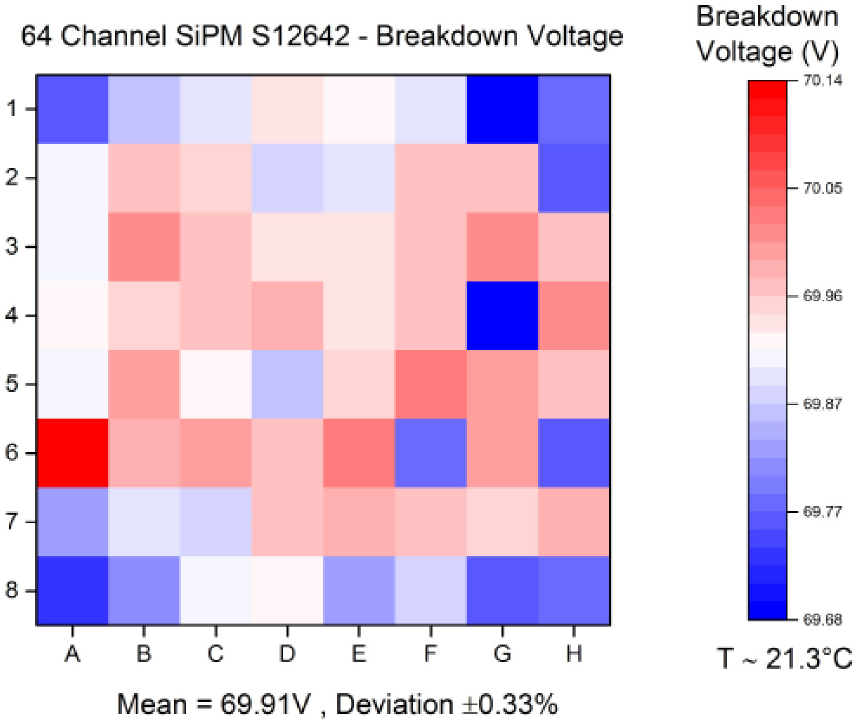
- 64 Channels
- SamTec Connectors
- Epoxy resin
- Specifications by Hamamatsu:
  - APDs: 3584 / channel
  - Breakdown Voltage: 65 ± 10 V
  - Darkcount: 2 - 3 M counts/s
  - Gain: 1.25 x 10^6
  - Photo Detection Efficiency: 35%

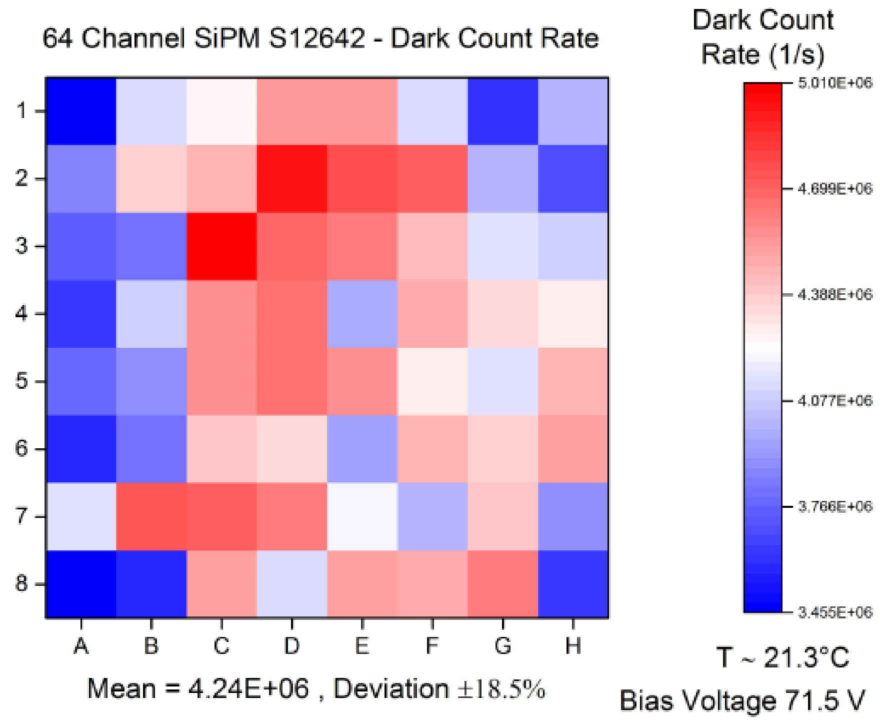
S13361 (new)

- 64 Channels
- SamTec Connectors
- Silicone resin
- Specifications by Hamamatsu:
  - APDs: 3584 / channel
  - Breakdown Voltage: 53 ± 5V
  - Darkcount: 0.5 – 1.5 M counts/s
  - Gain: 1.7 x 10^6
  - Photo Detection Efficiency: 40%

M.Renschler, KIT

TSV-Epoxy Array





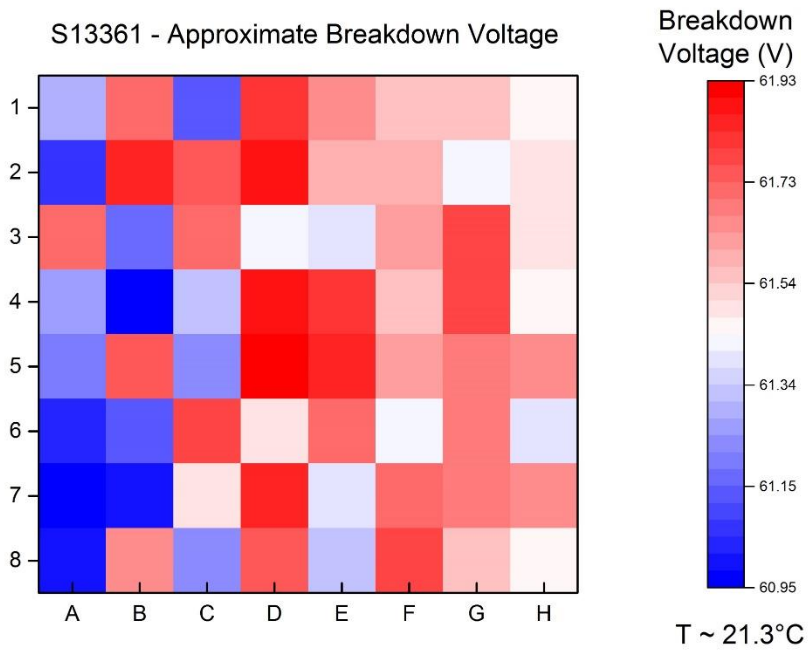
Next: Measurements of the 64 channel SiPM arrays with a QADC

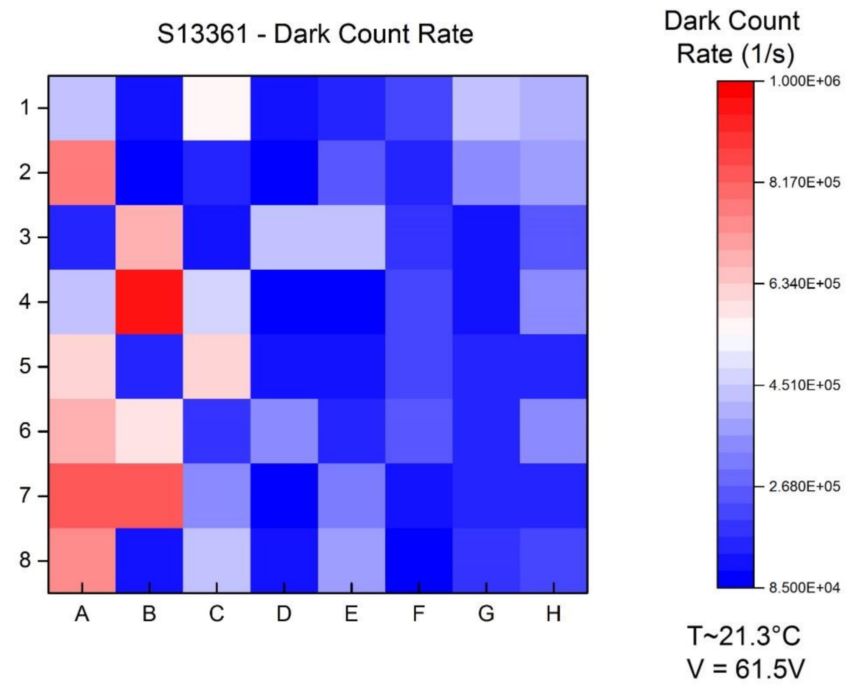
→ **Breakdown Voltage** → **PDE**

→ **Gain** → **Crosstalk Probability**

M.Renschler, KIT

TSV-Silicone Array





Next: Measurements of the 64 channel SiPM arrays with a QADC

→ Breakdown Voltage

→ Gain

→ PDE

→ Crosstalk Probability

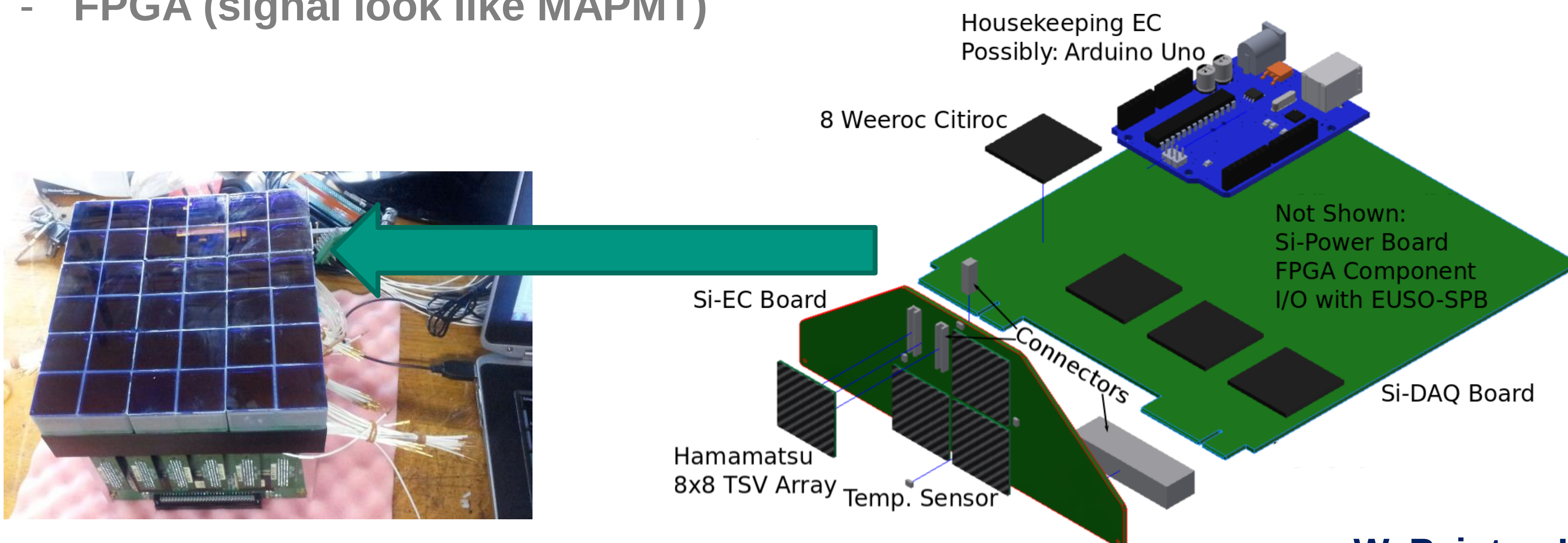
M.Renschler, KIT

EUSO-SPB Mission and SiECA

SiECA-Silicon EC Add-on for EUSO-SPB

Issues

- Si-DAQ Board
  - 256 SiPM channels
  - Clockand trigger from PDM
  - Power Supply
  - ASICs (8 citiroc?)
  - FPGA (signal look like MAPMT)
- SiECA mechanical frame
- UV-Filter
- Lab SiPM test system for SiECA (with Tübingen)



W. Painter, KIT

Requirements for the ASIC (in future)

KIT ASIC Development for EUSO-like devices

(This list is purely idealized and heavily based on currently available systems)

1) **Larger Channel input: Increasing the number of channels to 64, 128, 256 will greatly simplify board design**

2) **BGA package instead of QFP (More channels without increasing form factor)**

3) **5 ns timing resolution and pulse shaping**

4) **Low power consumption (2mW/ch or less)**

5) **Internal biasing for flat fielding/temperature control**

6) **Pulse counting within timing bin & current integration over entire timing bin; Bin length selectable from 250ns-5μs**

7) **Multiplexed output**

SiPM for JEM-EUSO….personal opinions

- Characteristics of different SiPMs (small ones, arrays)
  - worldwide effort….Hamamatsu seems to be leading (for us)
- Going for single photon calibration
  - hard job but possible
- Going for temperature
  - complex, but should be under control!
- Going for larger arrays
  - looks good!
- Going for UV sensitivity
  - looks promising - needs to be tested!
- Going for (fast) readout
  - crucial point
- Going for Simulations
  - needs to be done….
- Going for integration as EC
  - could be solvable
- Going for EC integration in PDM
  - slow progress! (at least for me)
- Going for space qualification
  - hmmm…..

All measurements shown are preliminary and need to be optimized and repeated in detail