Direct comparison of SiPM and PMT operation under bright background and perspectives of using truly digital sensors

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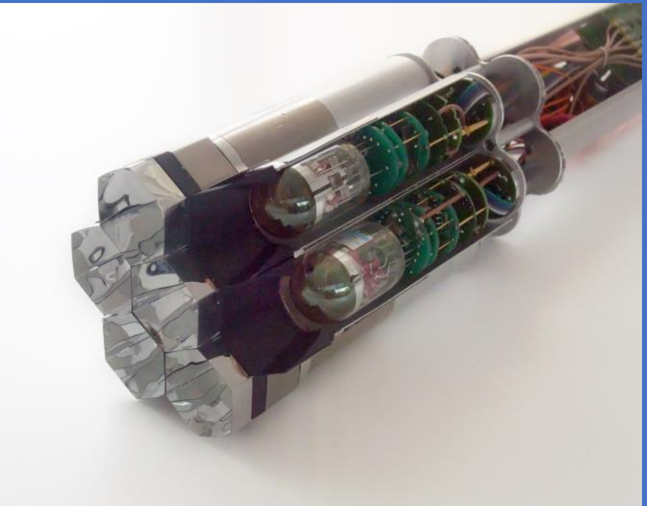
The MAGIC Imaging Cherenkov telescopes

- Two 17m diameter f/1 IACTs set 85m apart
- Canary island La Palma, 2200m a.s.l., Roque de los Muchachos obs.
- Imaging cameras with an aperture 3.5° are based on 1039 PMTs
- 169 modules, based on 7-PMT pixels
- PMT analog signals modulate light output of VCSEL diodes, coupled to 162m long multimode optical fibers
- 0.3mm ø PIN diodes at the end of the fibers demodulate fast signals
- No pulse deteoriation, 2.1 ns FWHM
- Readout in white experiment. house



AIM: Is it possible to benefit from the higher PDE of the SiPM compared to a PMT in an IACT?

- There exist **applications where SiPM are operated under strong background illumination**
- In IACTs such a strong illumination is due to the **Light of Night Sky (LoNS)**

- The PDE for recent generation SiPMs is ≥ than the PDE of PMTs
- SiPM advantages: compact, can be operated at ambient light, insensitive to magnetic fields, no ageing, low power,…
- SiPM drawbacks: size ≤ 7mm, X-talk, afterpulsing, T° -dependance
- Persistent speculations: soon SiPM will replace PMT in all applications

- **METHOD: Direct Comparison of SiPM and PMT, without making any assumption**

Much of information of this presentation is based on the below shown paper from 2024

Nuclear Instruments and Methods in Physics Research A 1064 (2024) 169350

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

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Full Length Article

Direct comparison of SiPM and PMT sensor performances in a large-size imaging air Cherenkov telescope

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ARTICLE INFO

Keywords:
SiPM
PMT
Low light level sensor
Multi-pixel avalanche photodiode
Calibration
IACT

ABSTRACT

The peak photon detection efficiency (PDE) of silicon photomultipliers (SiPMs) can be as good or better than the PDE of photomultiplier tubes (PMTs). There are experiments where the signal is measured in the presence of a strong, steady background light emission. In these, one needs to accurately evaluate the signal-to-noise ratio. Imaging Atmospheric Cherenkov Telescopes (IACT) observe in the presence of strong noise induced by the light of the night sky. It is certainly interesting to investigate the SiPM performance under operational conditions of IACTs and to compare it with that of the PMTs.

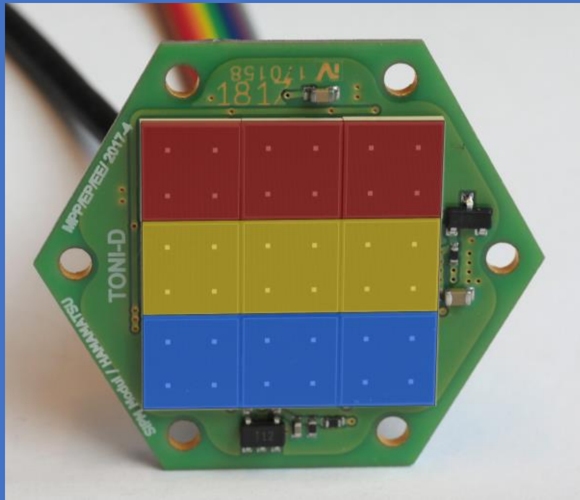
Composite SiPM Matrix With Large Area and Fast Timing

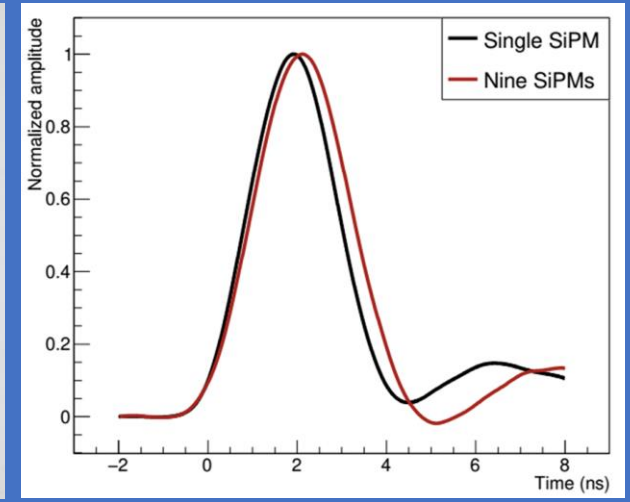
- A composite pixel is made of 3 groups of 3 SiPMs of similar parameters
- Common-base transistor circuit for signal amplification, SiPM output capacitances decoupling, summing-up

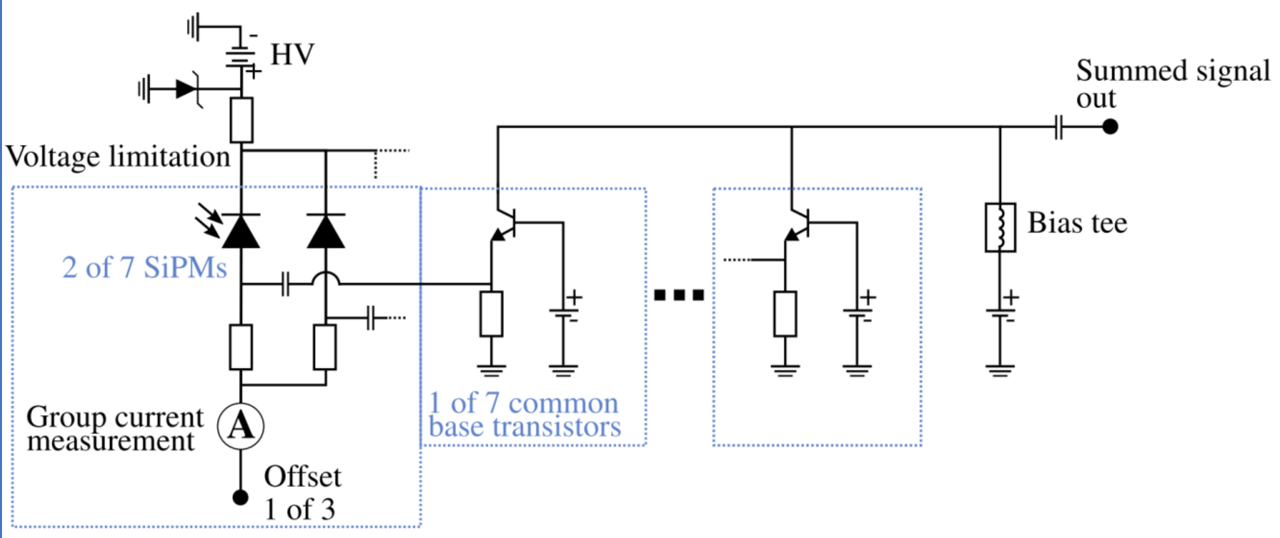
- FWHM of SiPM pixel ~ FWHM of PMT
- Linearity > 2000 ph.e.

- Adjust individual bias voltage at anode
- T° sensor next to SiPMs on front side
- Common power supply for all 7 or 9 pixels

Fink et al., 2016





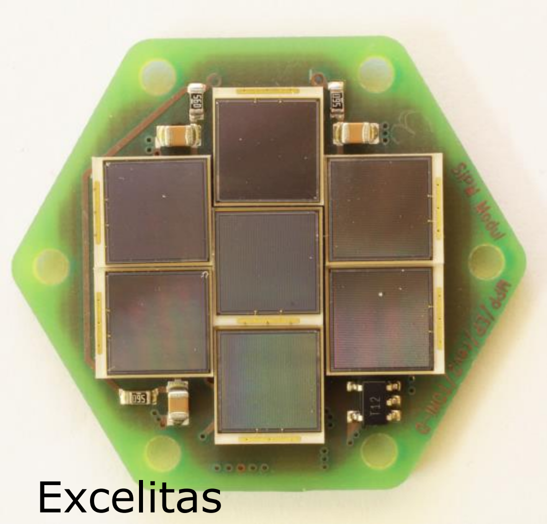


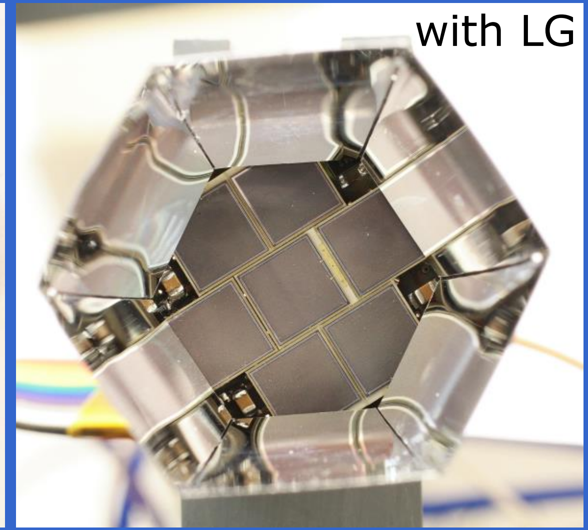
Tested Composite Large-Size SiPM Sensors

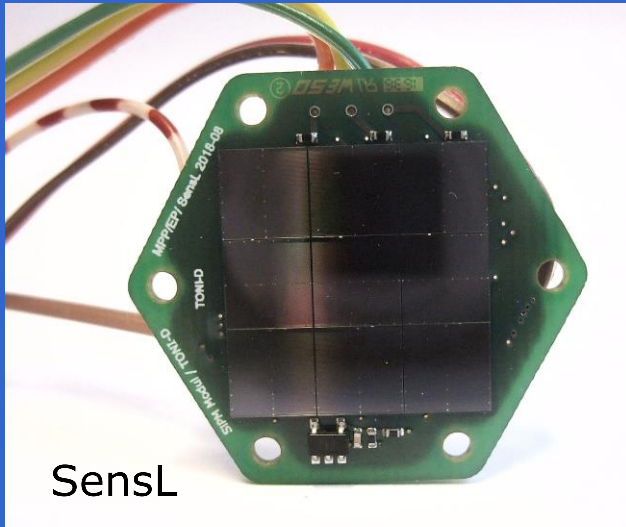
- Individual sensors: 6x6 mm²:

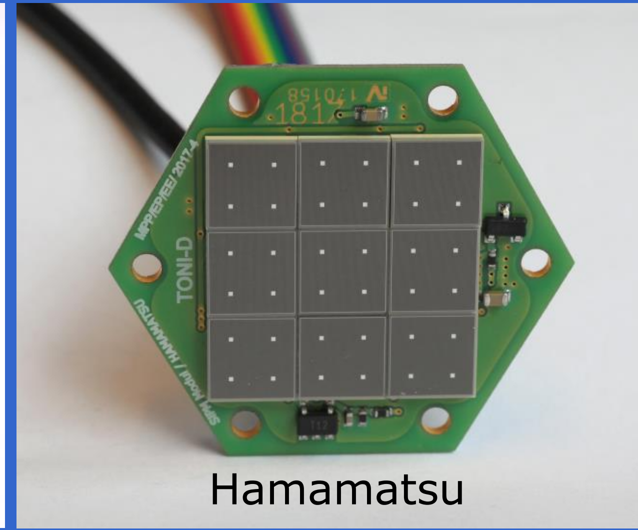
Excelitas	C30742-66-050-X
Hamamatsu	S13360-6075VS
SensL	MicroFJ-60035-TSV

- 1st generation: 7 SiPMs/pixel
- 2nd generation: 9 SiPMs/pixel
- Single sum output
- Optimized heat flow by using aluminum core PCBs
- Light guide to reduce dead area and albedo



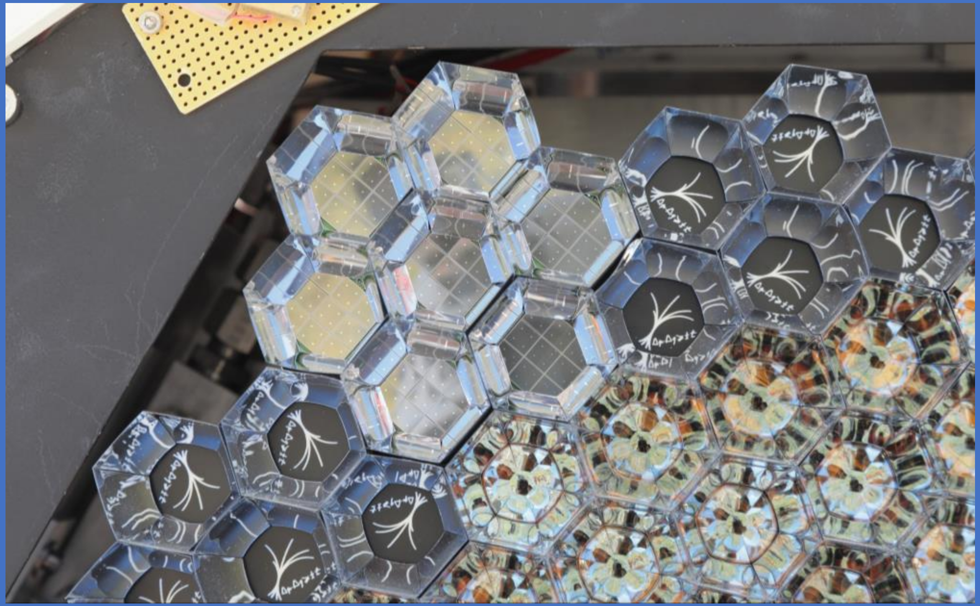




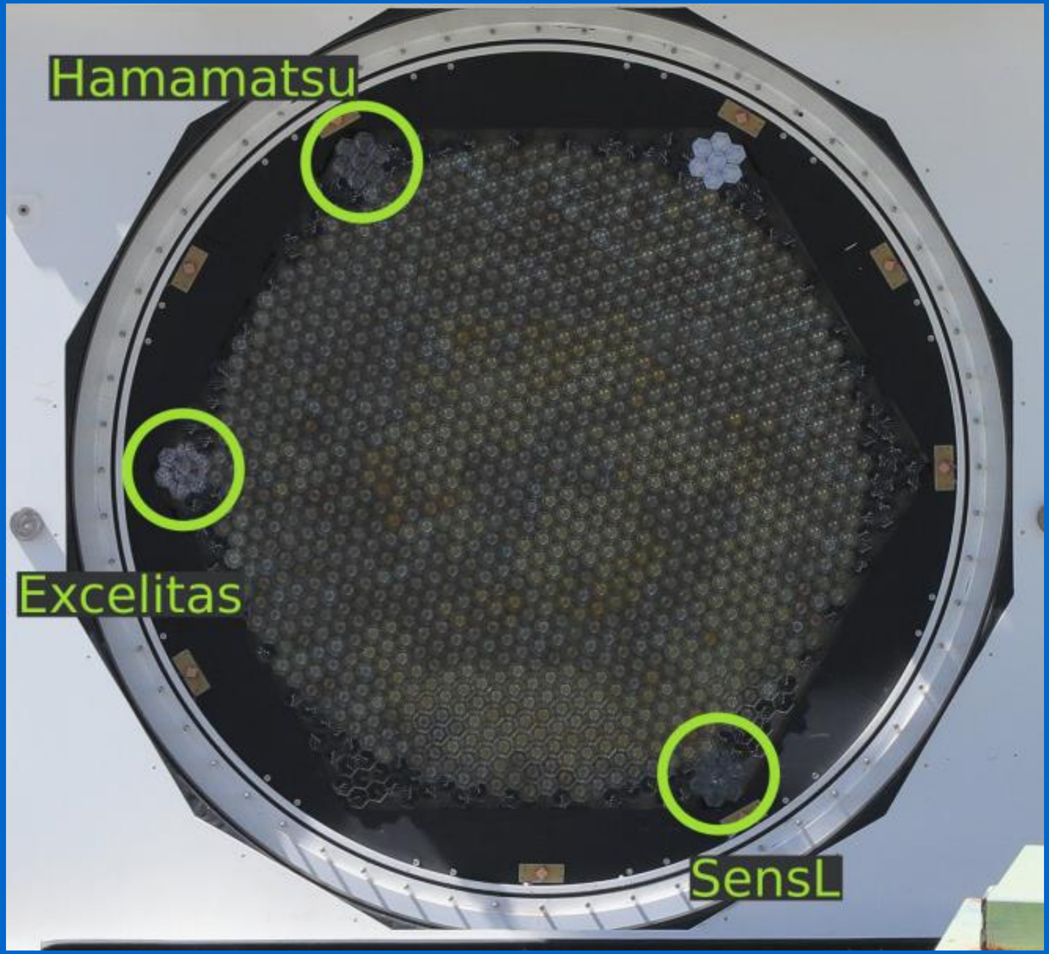


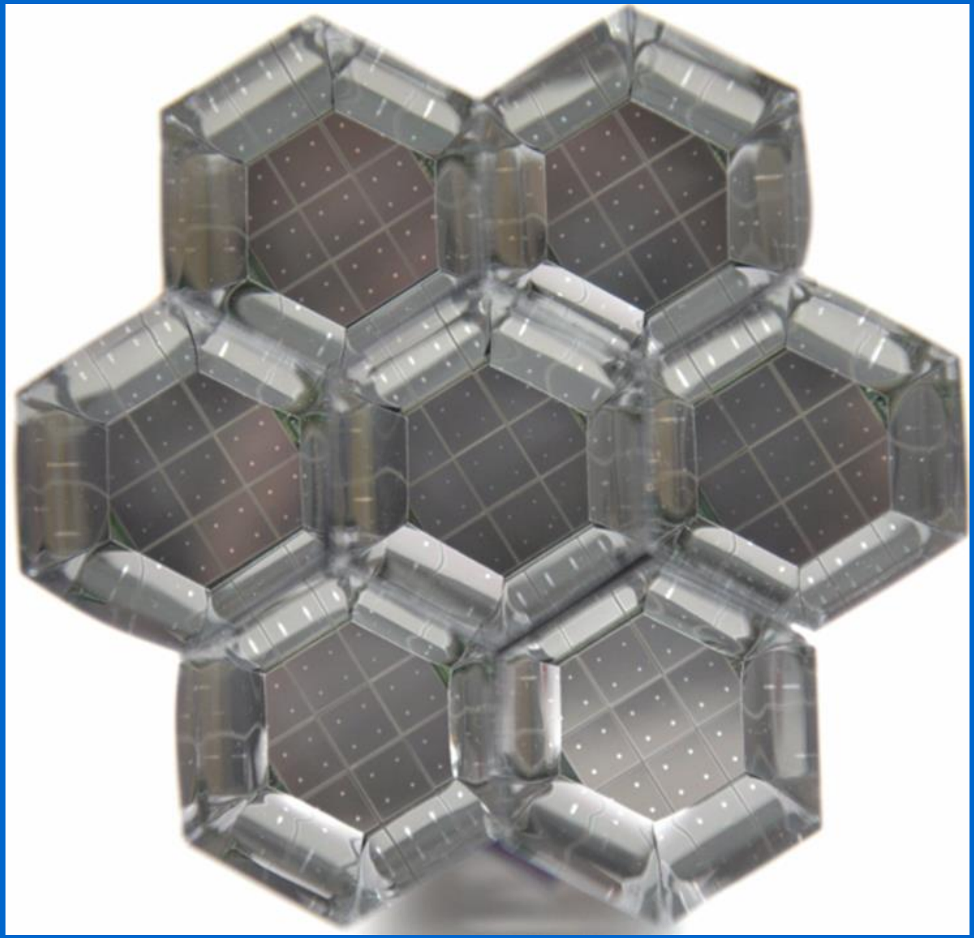
Installation/Operation

- EXCELITAS SiPM-module installed on May 8/9 2015
- Hamamatsu and SensL SiPM-modules installed in 2017
- Modules set in the free corners of the hexagonal-shape imaging camera
- Using the standard readout and data acquisition system
- Fully integrated into the slow control
- Operated simultaneously with PMTs



SiPM clusters in the MAGIC-I Imaging Camera

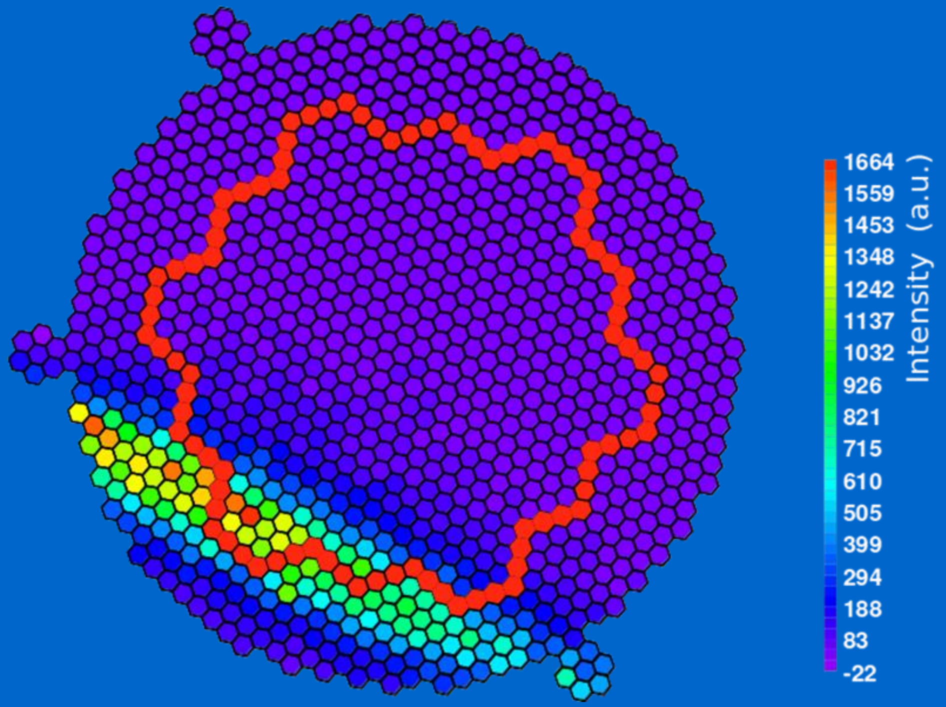




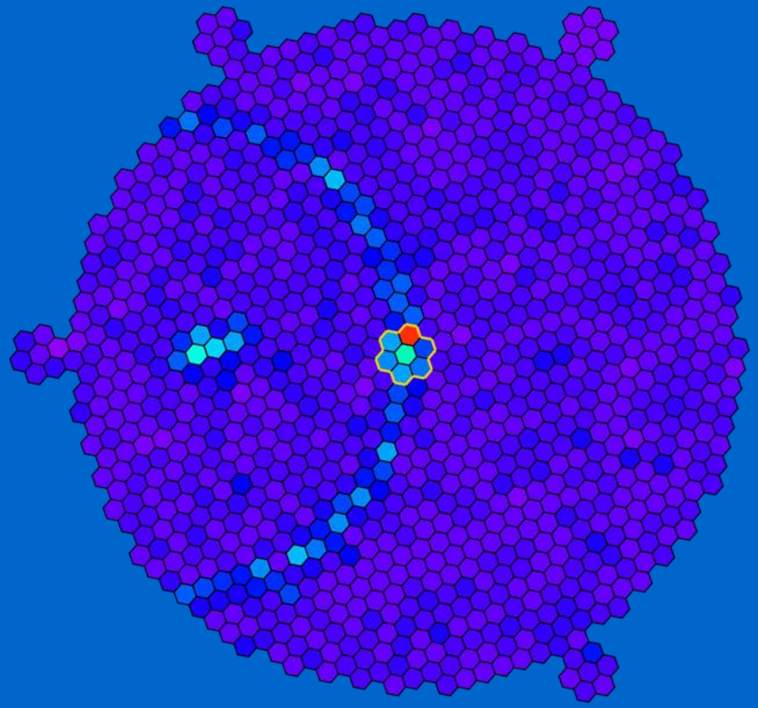
Hamamatsu SiPM module with LGs

SiPM modules in the MAGIC-I imaging camera tested over many years, under different conditions, calibration methods, etc.

A high energy cosmic-ray shower illuminates PMT and SiPM modules



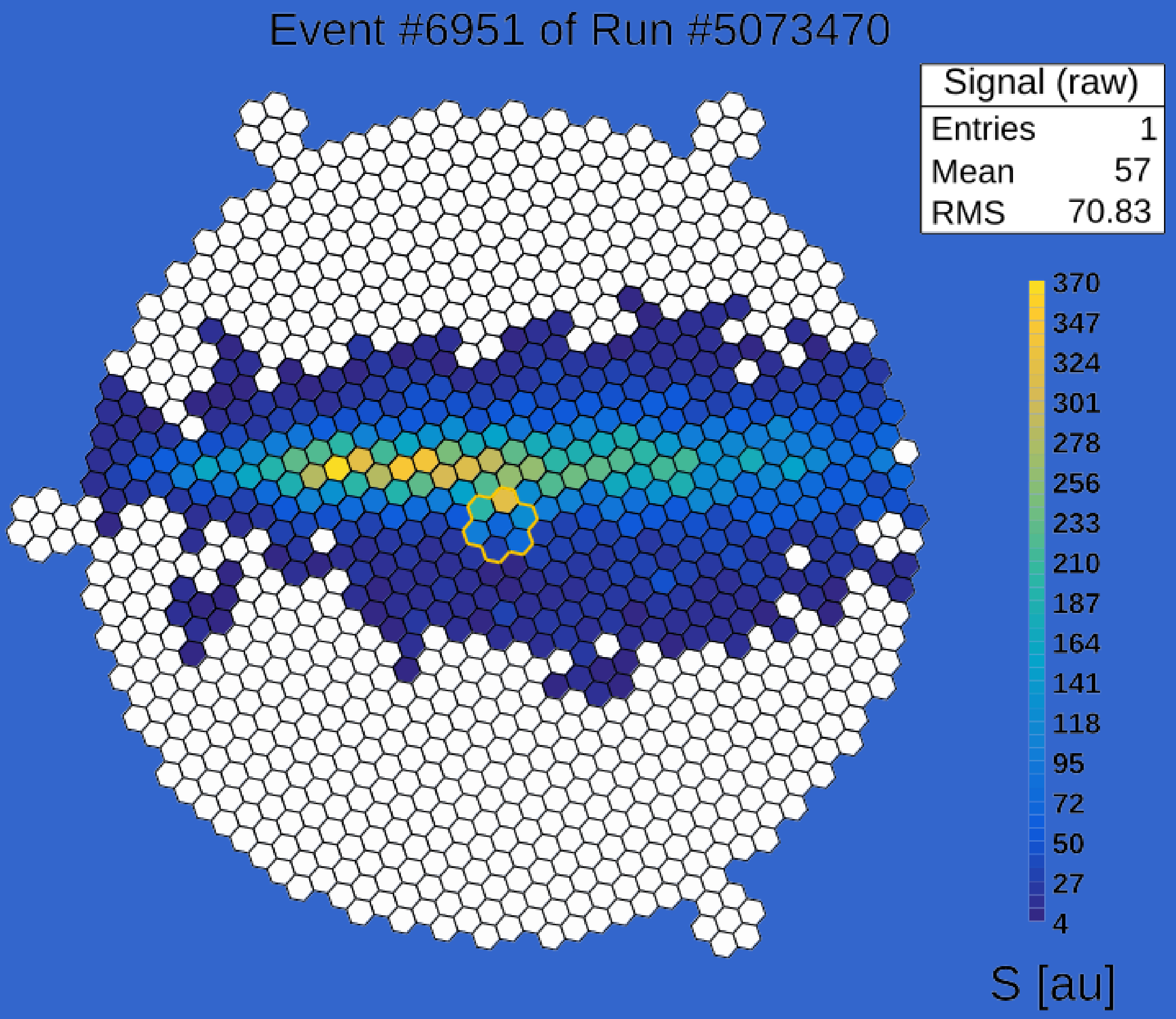
A single muon induced ring-shape arc illuminates both PMT and SiPM



Cherenkov light

- Simulation:
  - 5/50 TeV gamma-ray events

- Measurement:
  - Efficiency on extended air Cherenkov showers
  - For one night Hamamatsu SiPM module installed in the center region of the camera
  - Selecting very large events that illuminate both SiPMs and PMTs
  - Calibration with single ph.e. spectrum, X-checked with F-factor method



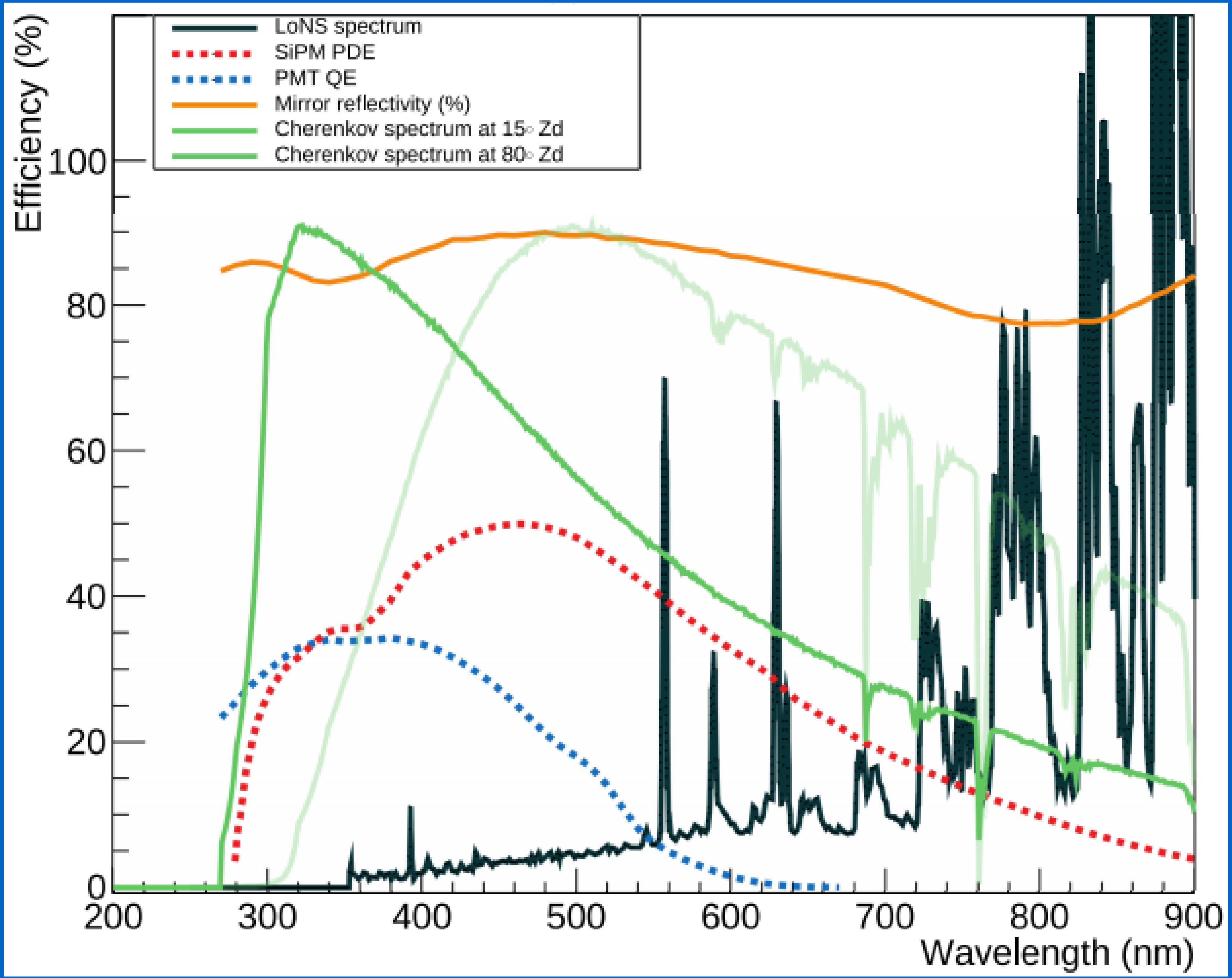
The LoNS spectrum at La Palma (black, from C. Benn)

PDE of Hamamatsu SiPM (red)

QE MAGIC PMT (blue)

Mirror reflectivity (orange)

Cherenkov spectrum of air showers from
15° - (green) and
80° (pale green)
zenith angles



Comparison of simulated and measured Cherenkov Light and LoNS for Hamamatsu SiPM and PMT

- LoNS intensity increases for longer wavelenghts
- Evaluate the expected performance of a SiPM compared to the used in MAGIC PMTs (type Hamamatsu R10408)

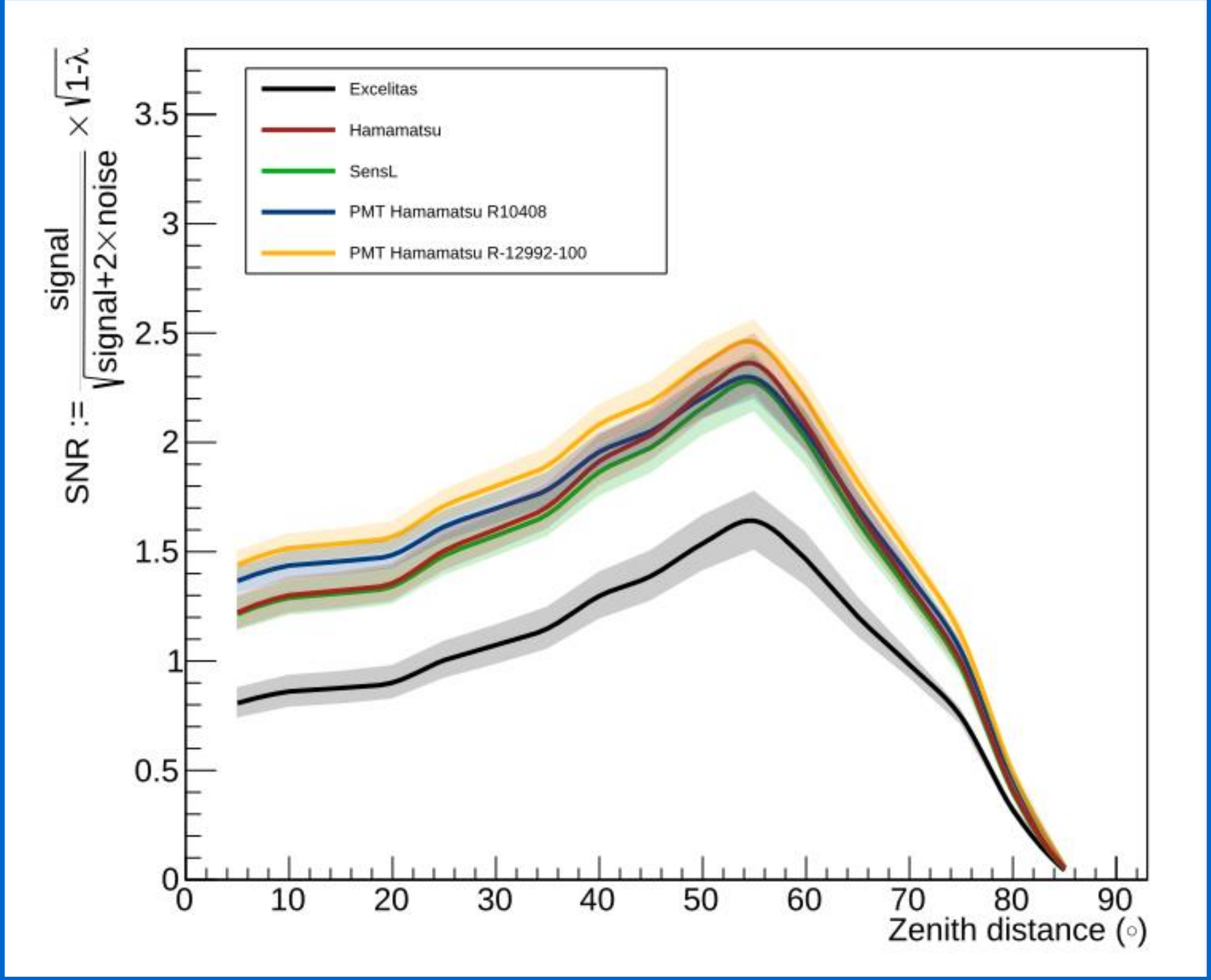
- **SIMULATIONS**: Hamamatsu SiPM output normalised to the used in MAGIC PMT:
- *Should measure:* 1.8 times higher Cherenkov signal and 4.9 times higher LoNS

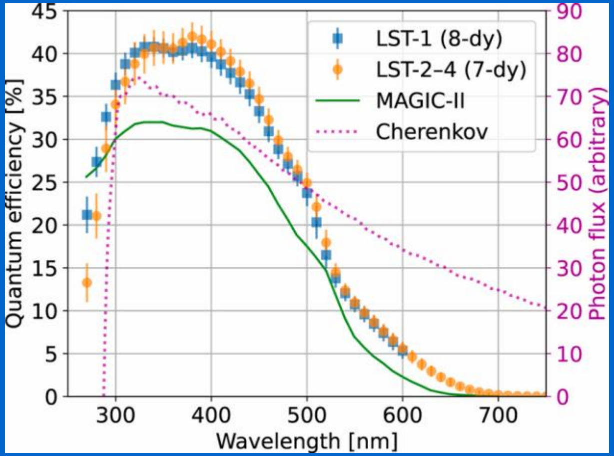
- **MEASUREMENT**:
- *Measured:* 1.9 times higher Cherenkov signal and 4.3 times higher LoNS
- The measurement is in agreement with the simulations, when taking into account the seasonal and diurnal variations of LoNS and the telescope performance as well as the chosen starfield

Signal to Noise Ratio (SNR) for SiPMs and PMTs

Hahn, et al, 2024

- A comparable performance of SiPM & PMTs for CTA-LST-MST
- Some advantage of SiPM compared to MAGIC (~15 years old) PMTs
- At large zentih angles SiPM is a bit better due to better match of Cherenkov spectrum to its PDE
- At very large zenith angles increased LoNS and lower amplitude signals reduce SNR differences





Intermediate Summary

- The goal was to compare SiPM versus PMT performance in IACTs, but <u>without making any assumption</u>

- 3 (sometimes 4) SiPM modules, each consisting of 7 pixels, based on 7 or 9 individual SiPM chips of 6x6 mm², were fully integrated and operating in the MAGIC-I image camera from 2015 (2017).

- Simulated and measured LoNS and Cherenkov spectra agreed within uncertainties

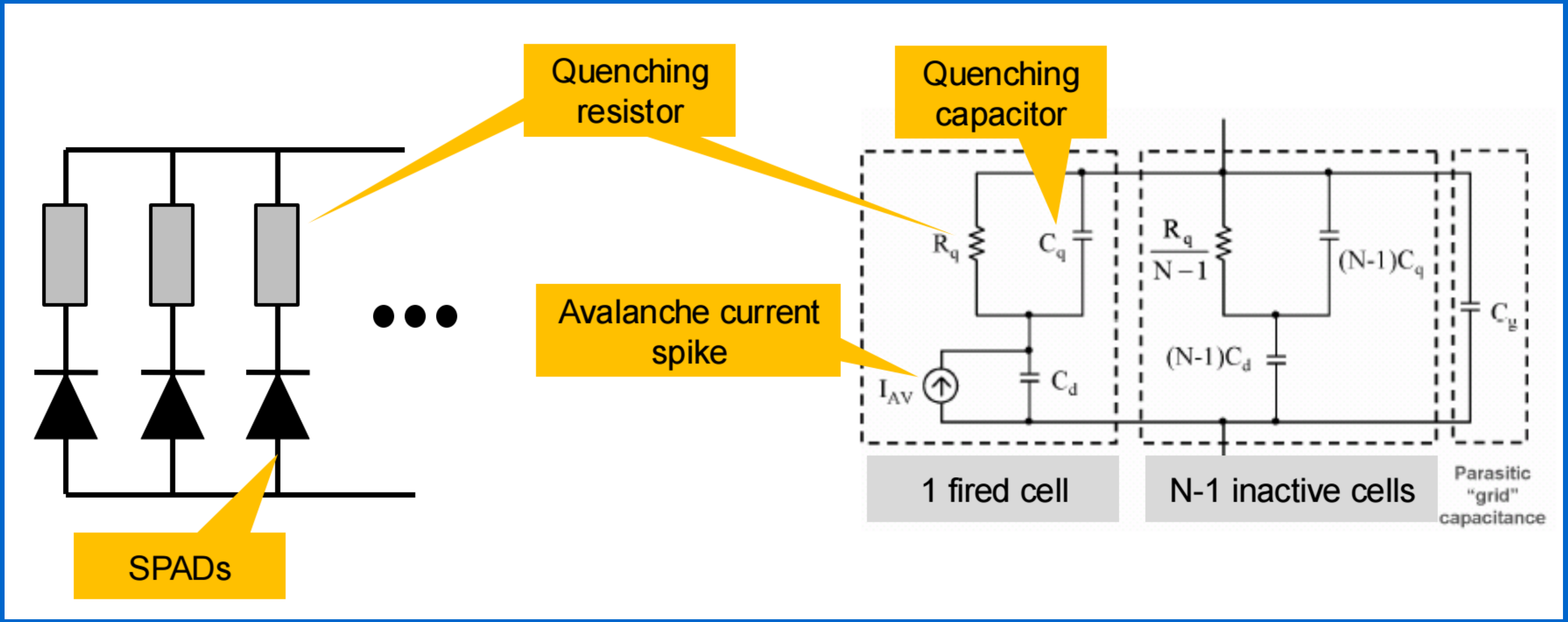
- SNR ratio:
  - For low zenith angle observations SiPM somewhat better than (old) MAGIC PMTs but no advantage over CTA/LST (CTA/MST) PMTs.
  - For large zenith angles SiPM is somewhat better than MAGIC PMTs but comparable to CTA/LST, CTA/MST PMTs.
  - For very large zenith angles SiPM observations comparable with the MAGIC PMTs

Silicon Photo Multiplier (SiPM)

- I was fortunate enough to work with Prof. Boris Dolgoshein (one of the "fathers" of SiPM) and his team at MEPhI from 2002 to 2010
- Multiple basic features of SiPM were developed during this time – already in 2011 we developed and demonstrated custom-made samples of SiPM with peak PDE of (50-60) % at a X-talk level of a 3-5 % (thanks to 4-fold X-talk suppression), T° sensitivity 0.5%/°C, see *Dolgoshein et al, 2012*
- I was next to B. Dolgoshein when he coined the term Silicon Photo Multiplier – SiPM
- But it took me almost 20 years to understand the real meaning of it. In fact, SiPMs are mostly used as a kind-of semiconductor substitute of classical PMTs. As with PMT, we typically amplify the few mV output signals, then discriminate them and finally use some kind of ADC system to digitize the amplitude. Because size of a SiPM << PMT, one uses many SiPMs to cover the same area, which can make it expensive
- Still one needs to calibrate the system by using some calibration method for deriving the number of measured ph.e.s

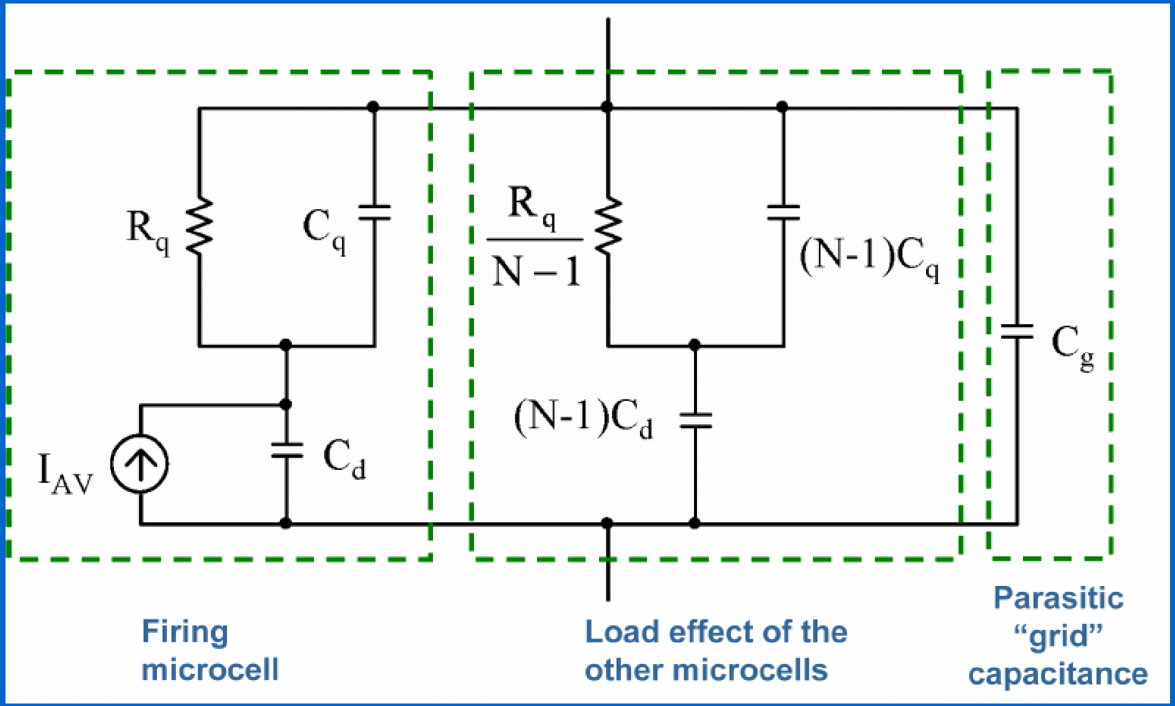
SiPM Operational Principle

SiPM is based on a plurality of SPADs, operated in Geiger mode
In a SiPM 1000’s of tipically 50µm x 50µm size SPADs are connected in parallel
Each SPAD has its own quenching resistor and operates in Geiger mode
The saturated avalanche signals are adding up at the common anode
The output analog signal is the momentary sum of the number of avalanches
This amplitude needs to be digitized, calibrated and converted back to ph.e.s



Silicon Photo Multiplier (SiPM)

- The original digital feature of SiPM (a Geiger avalanche produces the same, saturated amplitude, i.e. digital „1“) got lost „in the translation“
- A triggered SPAD is producing a relatively large amplitude of at least several hundreds of mV (for example, a 20µm x 20 µm SPAD will tipically produce an amplitude of 150-200 mV)
- This means that a SPAD is a noisless device

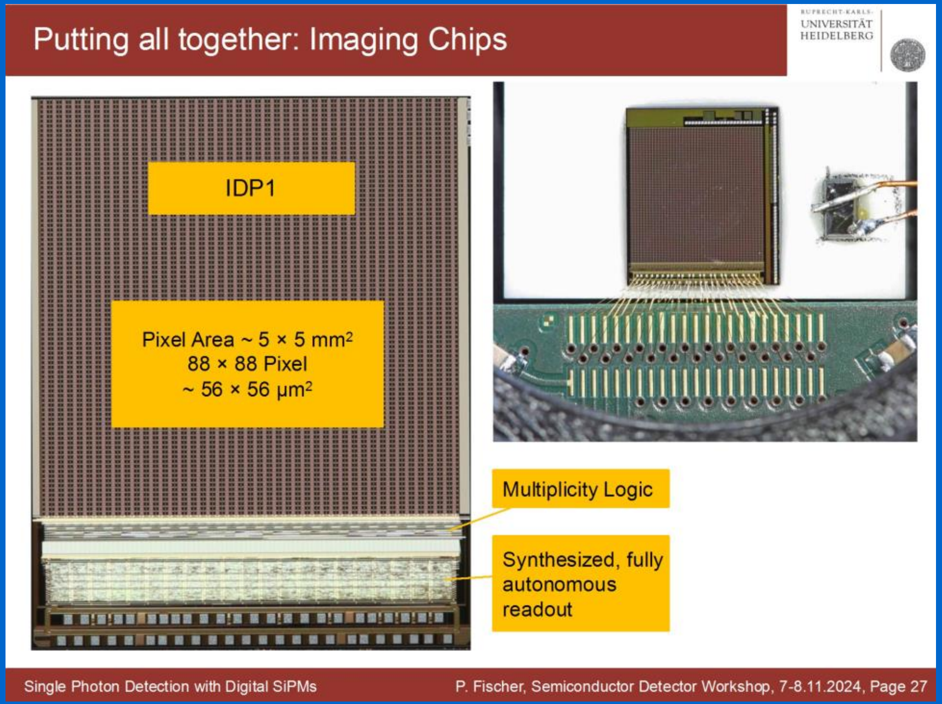


Use a plurality of SPADs to profit from their real digital feature

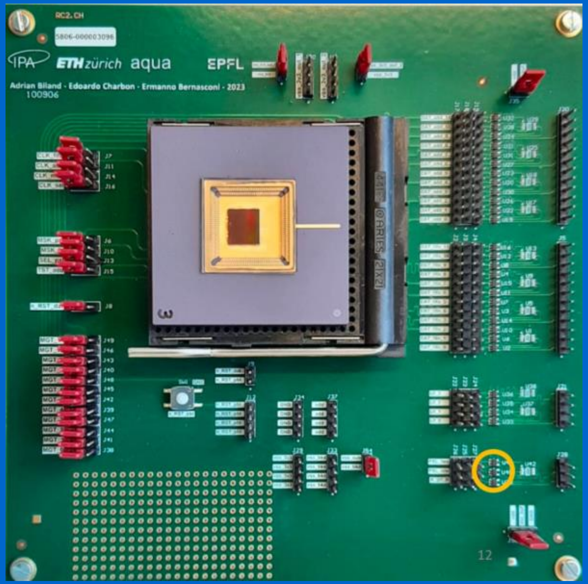
- Imagine an array of individual SPADS closely laid out on a semiconductor chip
- Each SPAD operates independent on others
- When a (Geiger mode) avalanche happens, a SPAD produces a „digital 1“
- An electronic scheme counts the number of fired SPADs
- This number shows the number of measured photons
- One needs no amplifier, no ADC, no X-talk of small amplitudes due to the electronic pick-up from closely-packed neighbouring readout channels
- Hence from the very first moment going digital
- Providing one can invent a very fast digital readout, this will be the „Non Plus Ultra“ light sensor of future – one can still improve the SPAD sensitivity (and eventually one may improve the counting speed of the electronics by moving from Si to „faster“ semiconductors)

The SPAD arrays with different readout principles are being intensively developed by many groups worldwide, to name just a few

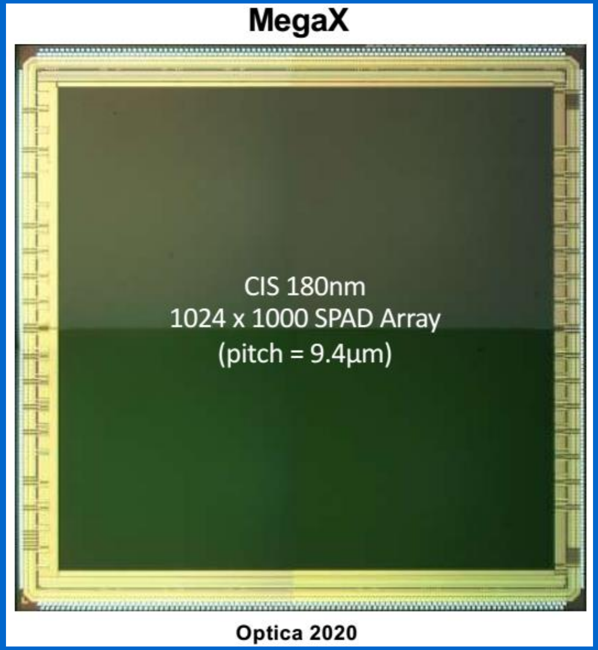
P. Fischer, U. Heidelberg, Semicond. Det. Work.



Digital Photon Counter – DiPC
Adrian Biland, CTAO Days in Switzerland, ETHZ, Oct.8, 2024

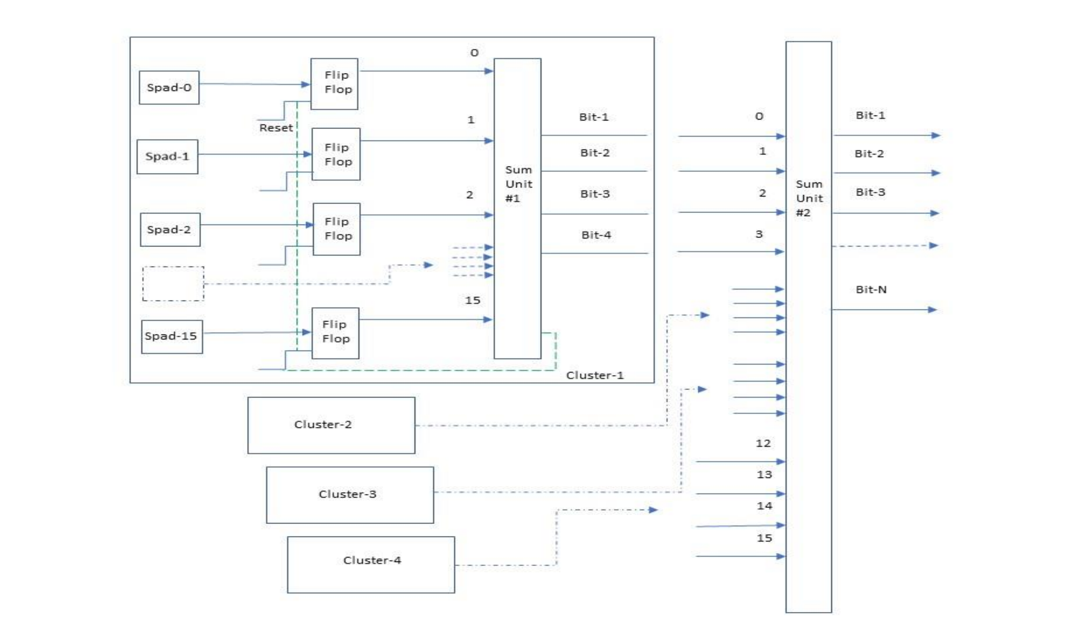


Multiple developments from Edoardo Charbon, SPAD Array, Swiss CTA Day, 2020



One may ask: and what is new, SPAD arrays have been intensively developed worldwide

- What's new is that we've also joined the "club" - we think that we have an interesting idea for how to readout a SPAD array very quickly and efficiently.
- We started developing an ASIC, initially a simple one, just for counting signals from a small matrix of SPADs, see a toy model-principle of summing up the signals



The SPAD arrays with different readout principles are being intensively developed by many groups worldwide

- We are hoping that the matching matrix of SPADs could be developed by the Semiconductor Laboratoray of the Max-Planck Society (HLL), who would integrate the ASIC with the sensor array
- Of course, as all the good things, also these will take time
- In the meantime, wonderful sensor developments are taking place elsewhere that benefit our entire community (and far beyond)
- I am afraid that these could soon send the SiPM into “retirement.” :-)

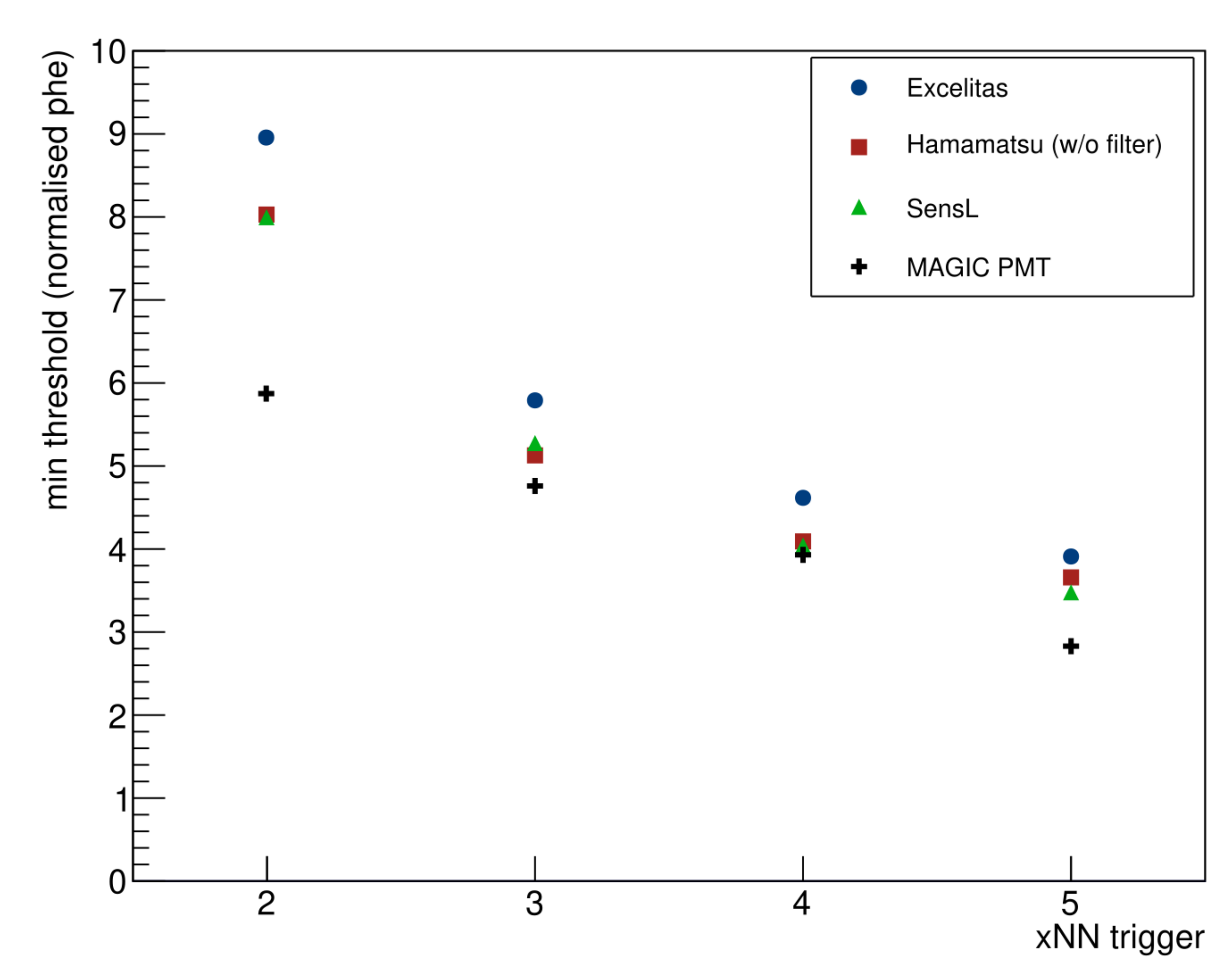
One can see the two 17m MAGIC IACTs on the left and 4 CTA/LSTs of 23m ø in the center and right

I took this photo on September 4th at the Roque de los Muchachos Observatory on La Palma

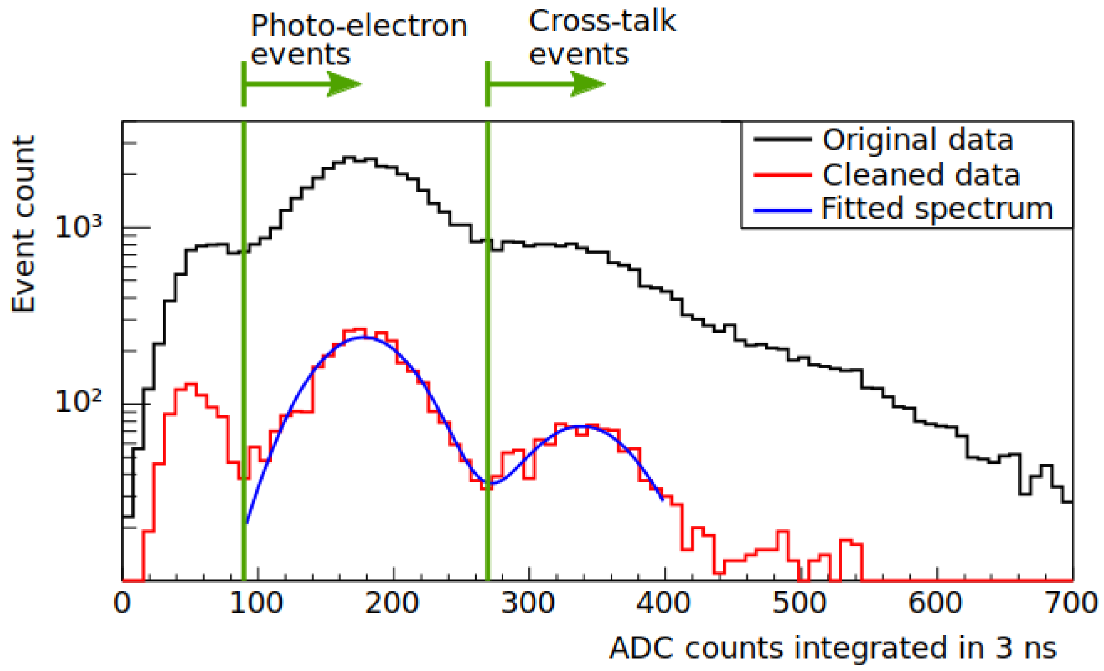
Back-up slides

Signal-to-noise ratio and the trigger threshold

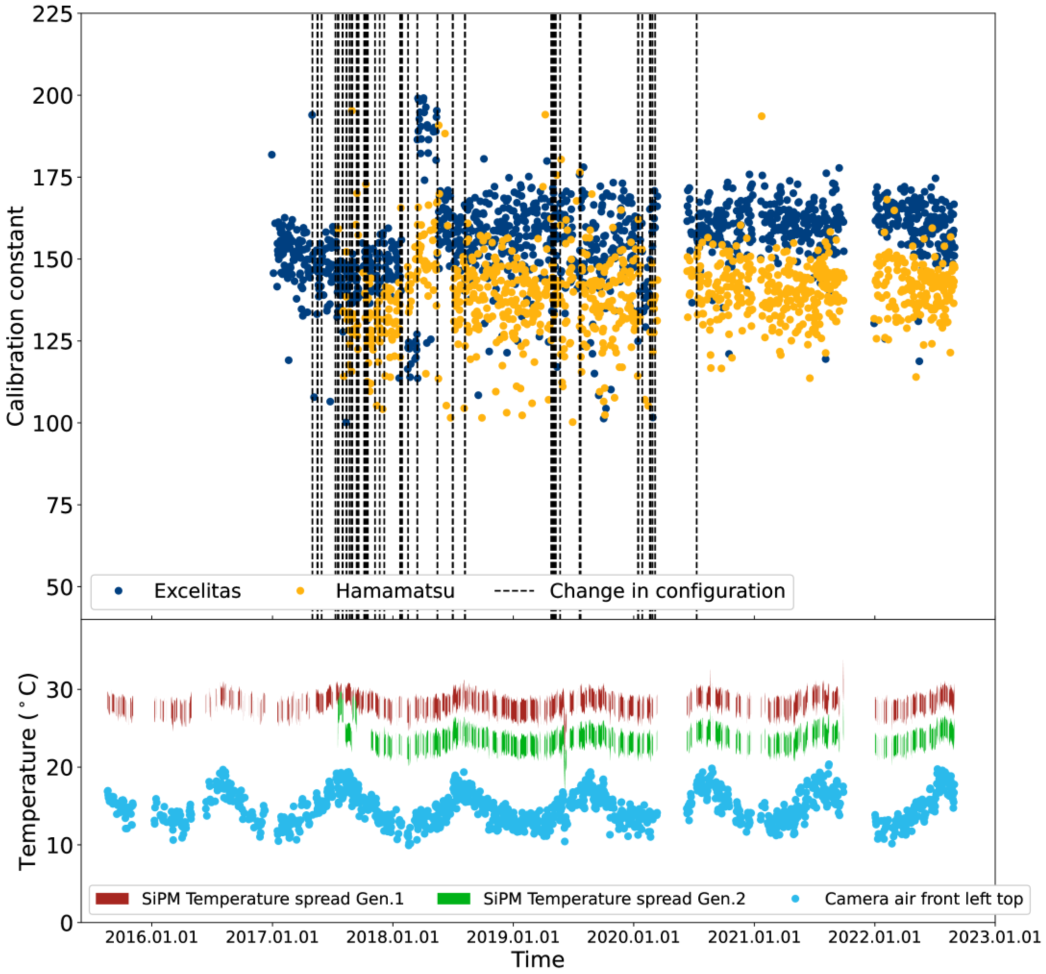
- Trigger threshold:
  - Four different next-neighbour pixel trigger configurations
  - Older EXCELITAS-based pixels perform worse
  - Hamamatsu and SensL pixels comparable to PMT
  - 3NN configuration directly comparable to SNR measurement ⇒ agreement within uncertainties



Calibration



Long-Term Stability



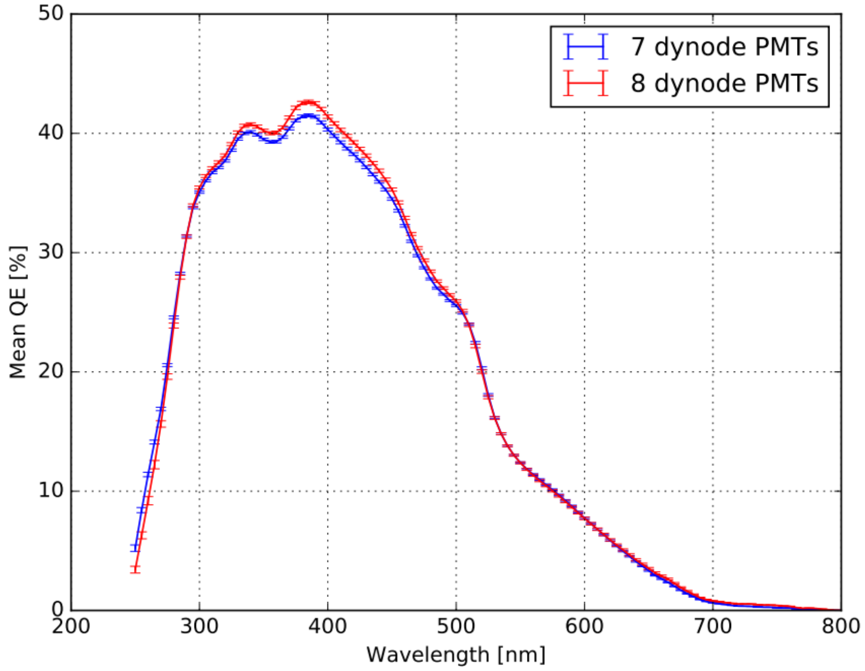


Figure 3.4: Mean measured QE as a function of the wavelength for 175 PMTs of each of the two PMT types respectively. The error bars indicate the error on the mean. The data points are connected to guide the eye. The 8 dynode PMTs feature a higher QE by about 1 %-point in the important wavelength range between 300 nm and 450 nm.