The application of SiPM for Cherenkov light detection in the atmosphere

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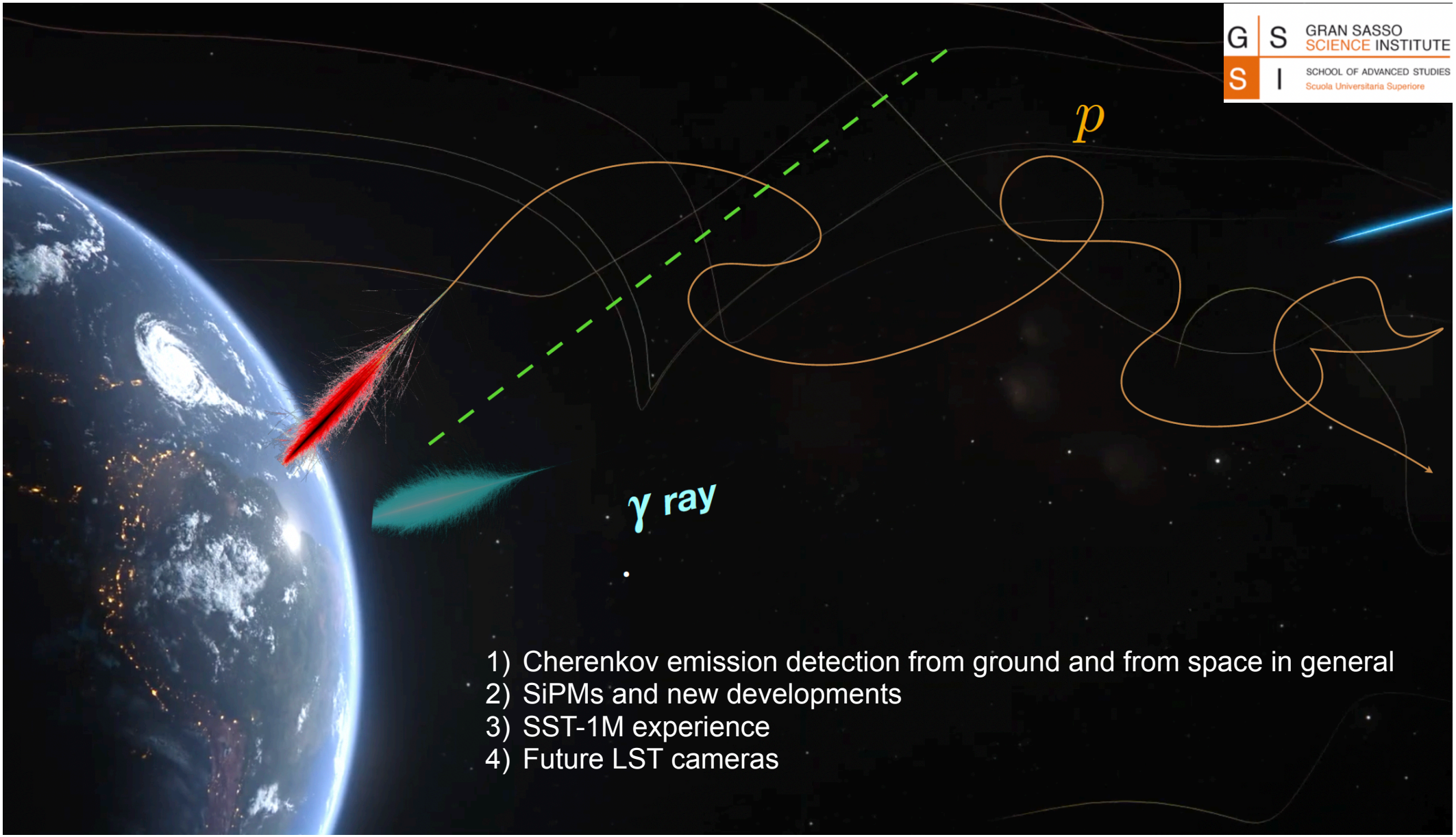

Thanks to A. Nagai, M. Heller, L. Burmistrov

The atmospheric calorimeter

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The atmosphere is a calorimeter of $\sim 27X_0$

The radiation length characterises radiative energy losses due to bremsstrahlung:

$X_0 \sim 37\mathrm{gcm}^{-2}$ (~300 m a.s.l., 1km at 10 km of altitude)

Pair production $L_{ee} = 9/7X_0$

For $E >> E_c \sim \alpha X_0 \sim 83\,\mathrm{MeV}$

$E \propto E_0 e^{(-X/X_0)}$ and $E = E_0/2$ in

$\ell = ln2\, X_0 \sim 25\mathrm{gcm}^{-2}$

Shower maximum: $N_{max} \propto \frac{E_0}{E_c}$ after n_{max}

interaction lengths $N_{max} = 2^{(n_{max})} \Rightarrow$

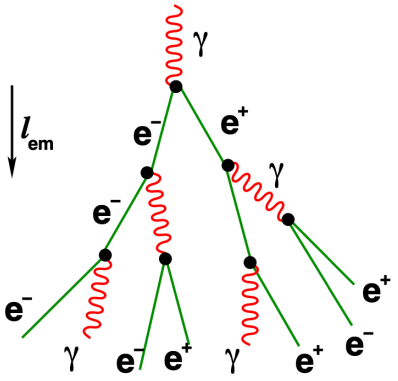
$$X_{max} \sim n_{max}\ell = X_0 ln\left(\frac{E_0}{E_c}\right)$$

Cherenkov light is emitted by electrons abo

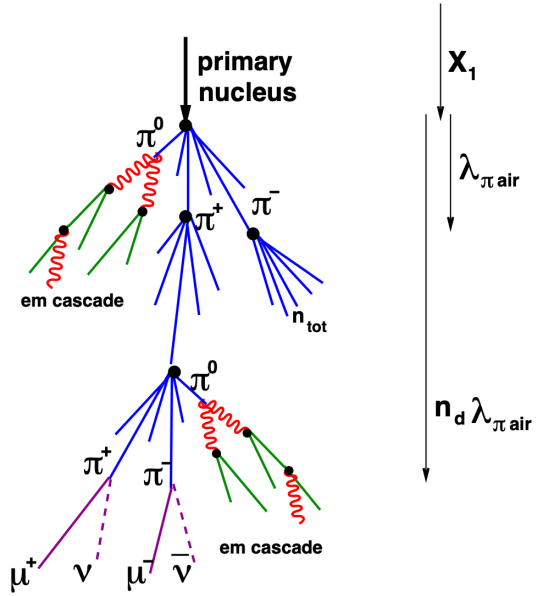
$$E_{th} = \frac{m_e c^2}{\sqrt{1 - 1/n^2}} \sim 40MeV$$ at 10 km in altitude in the atmosphere

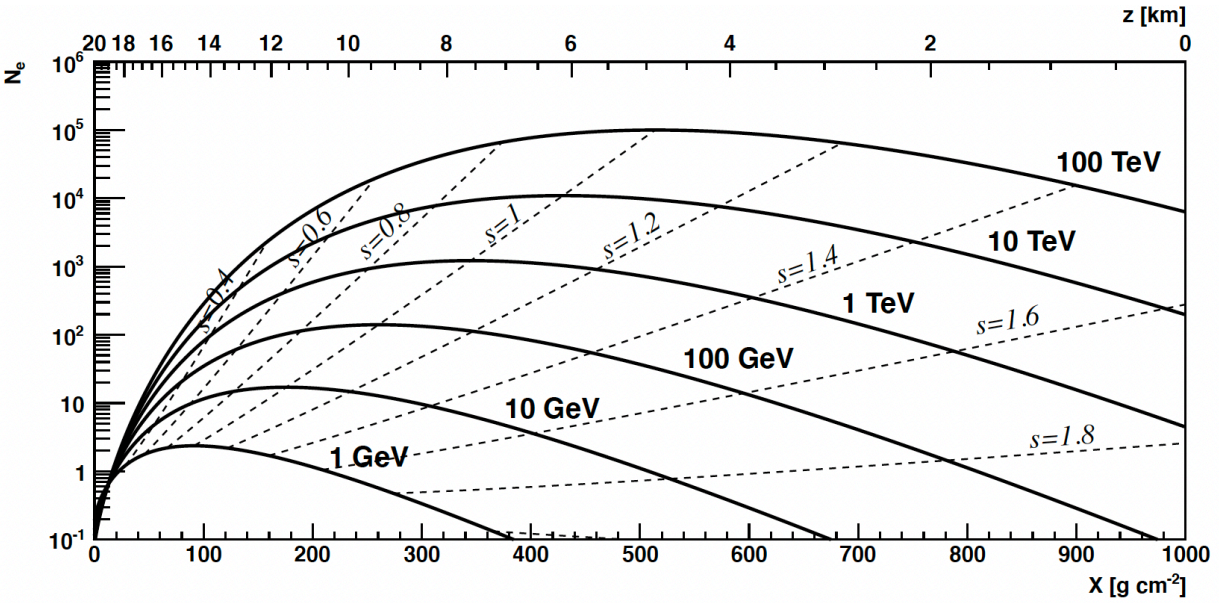
-

em cascade

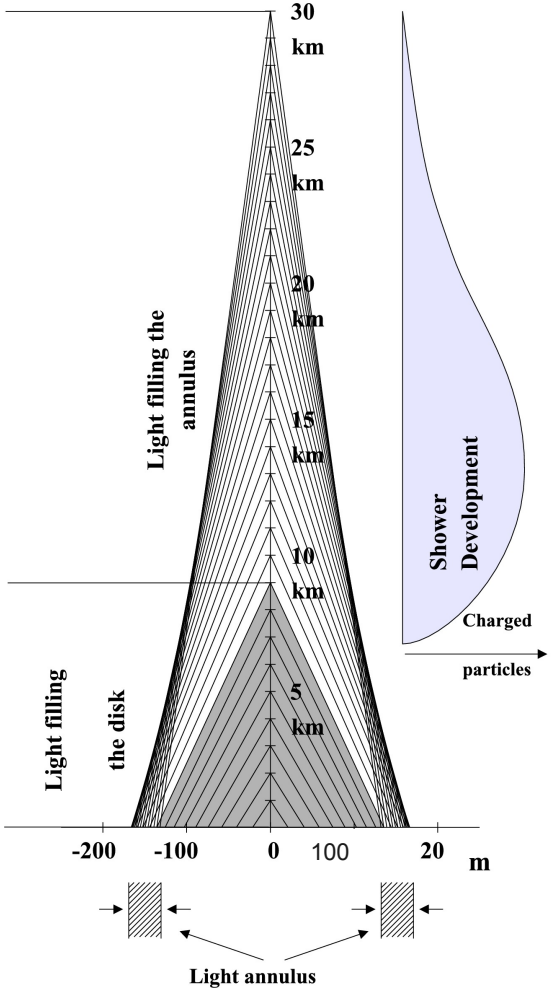


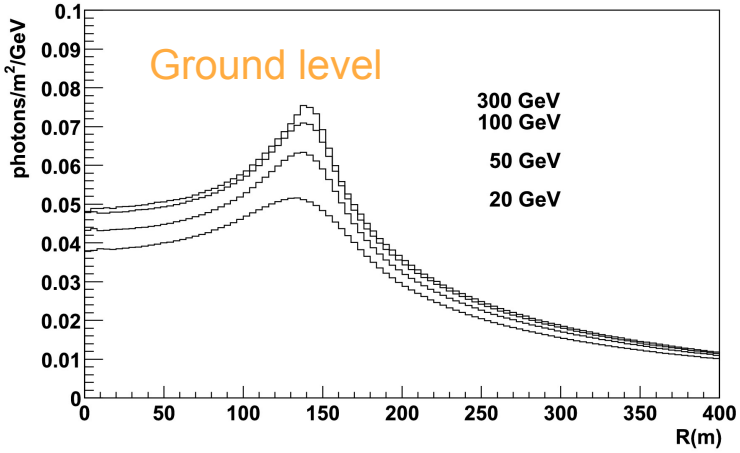
hadronic cascade

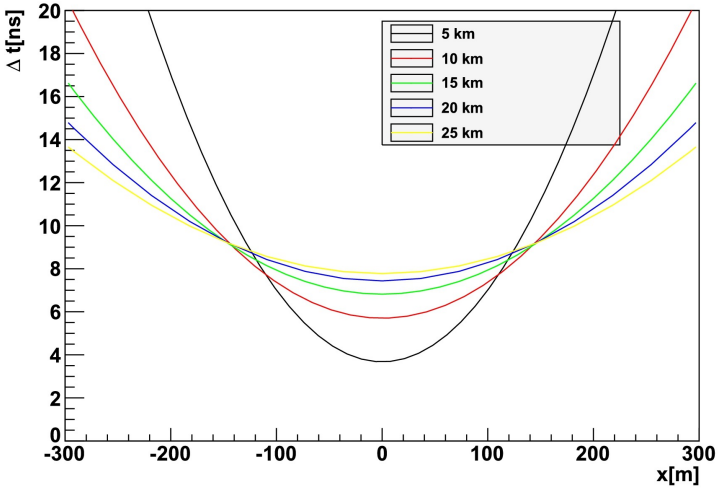




Cherenkov light detection principle from ground







altitudes of emission

The charged particles in the shower travel faster than light in air, so close to the shower axis the photons emitted at low altitude reach the detector before those emitted at high altitude. At large impact distance of the photons emitted at low altitude have a longer geometrical trajectory (track of charged particle to emission point + photon track). On axis time is ~5 ns.

1948 PMS Blackett (Nobel): ≈0.01% of the night light sky comes from Cherenkov light emitted by CRs and their secondaries as they traverse the atmosphere.

Experimental confirmation by C. Galbreith & J. Jelley, 1953

1989: Crab Nebula discovery by Whipple

E_0	X_{max} (g cm^{-2})	Altitude (m)	N_{max}
30 GeV	216	12000	50
1 TeV	345	8000	1200
1000 TeV	600	4400	$0,9 \times 10^6$
10^{19} eV	936	1200	$7,4 \times 10^9$

Photoelectrons in the camera

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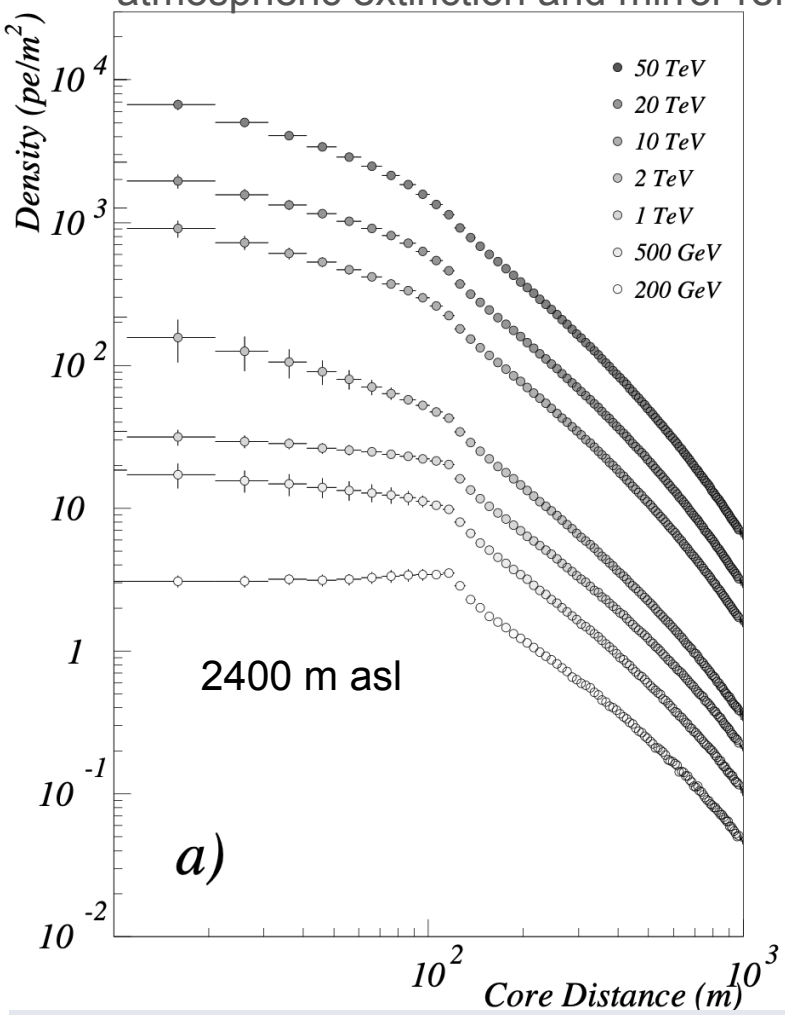
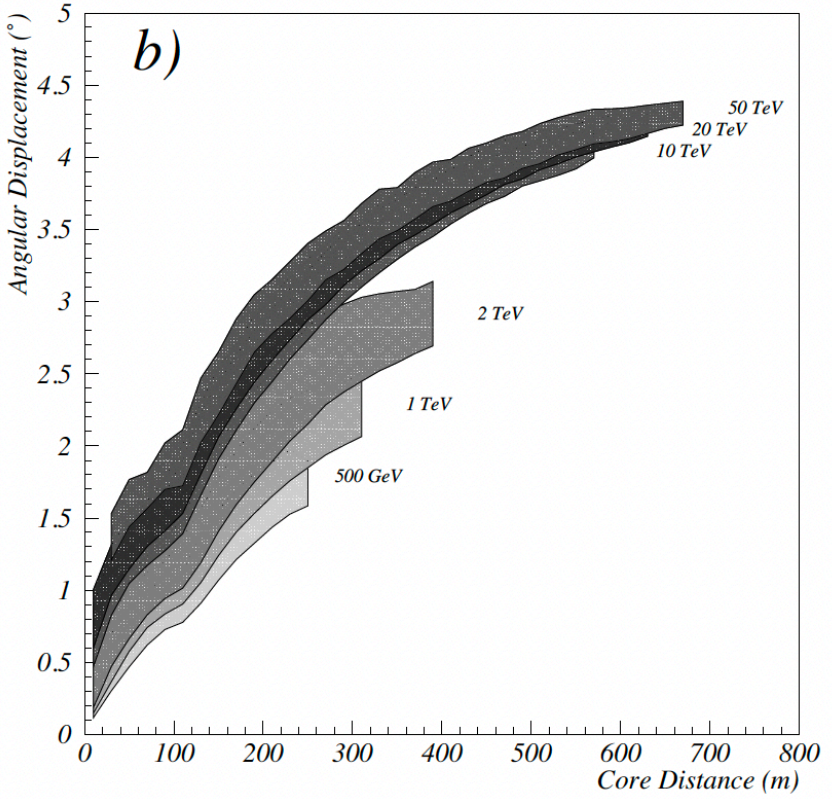
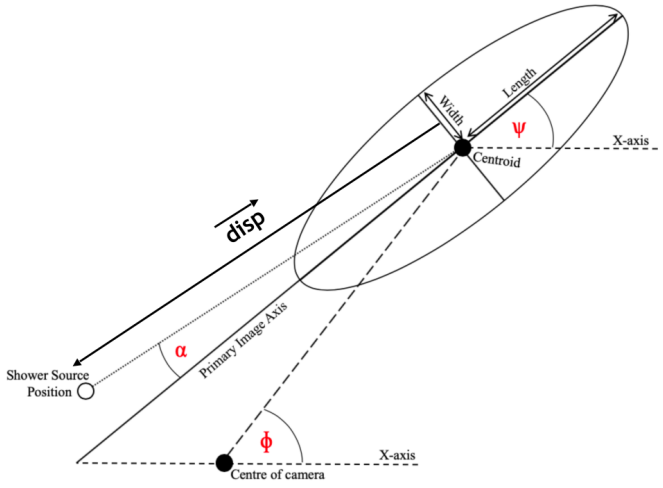
Photons after PDE of photosensor, atmospheric extinction and mirror reflectivity



Images from showers at larger core distances tend to have an average angle in the camera which is more displaced from the source position.





Centroid: image center of gravity (first moments of light distribution in camera)
Length and width of the ellipse (second moments)
Size (total charge of photo-electrons in the image
ϕ angular distance between the centre of the camera and the image centre of gravity
Ψ azimuthal angle of the image main axis (second moments)
α orientation angle of source from image axis

Cherenkov from space

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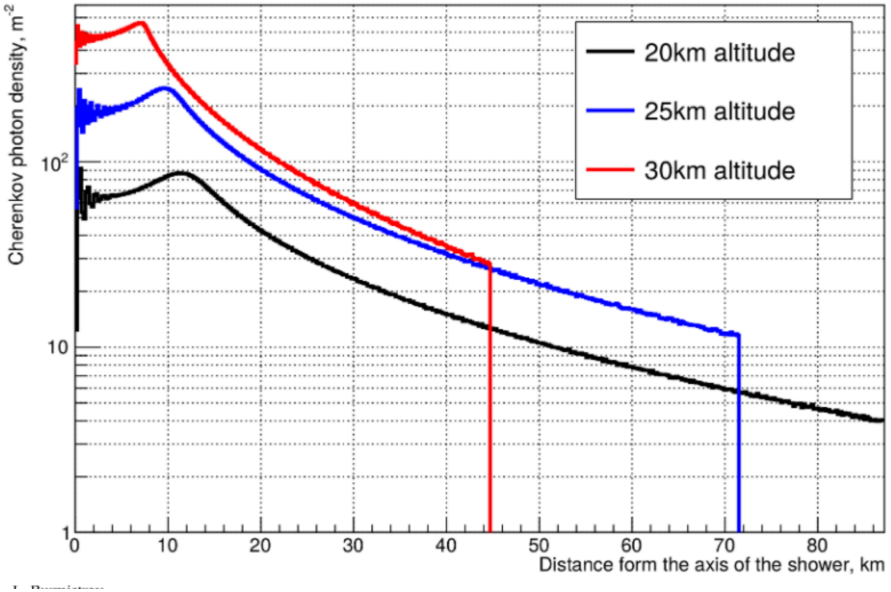
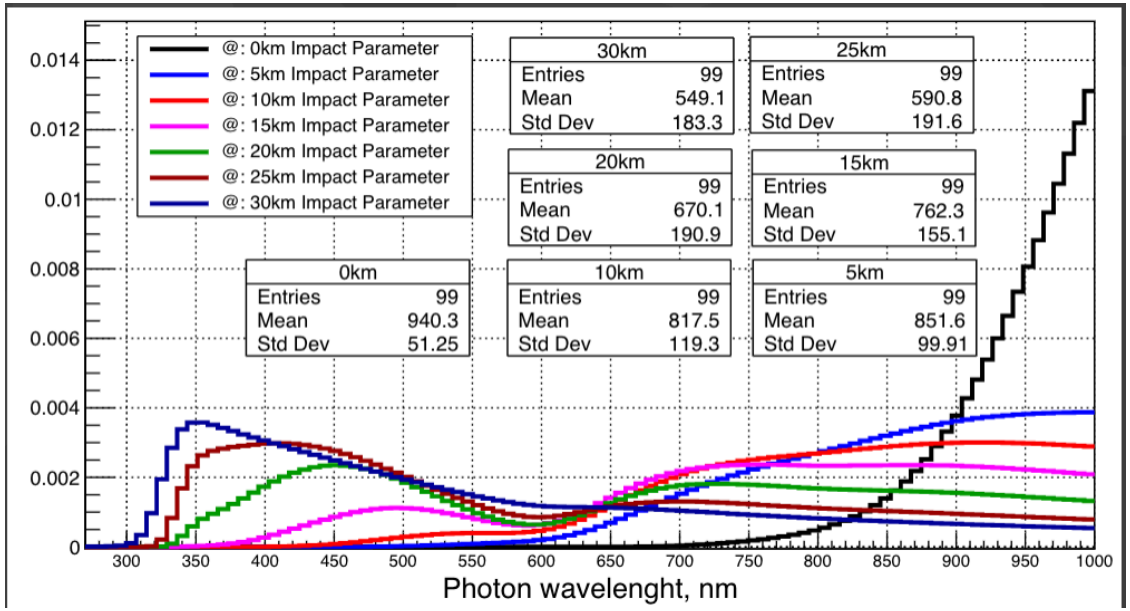
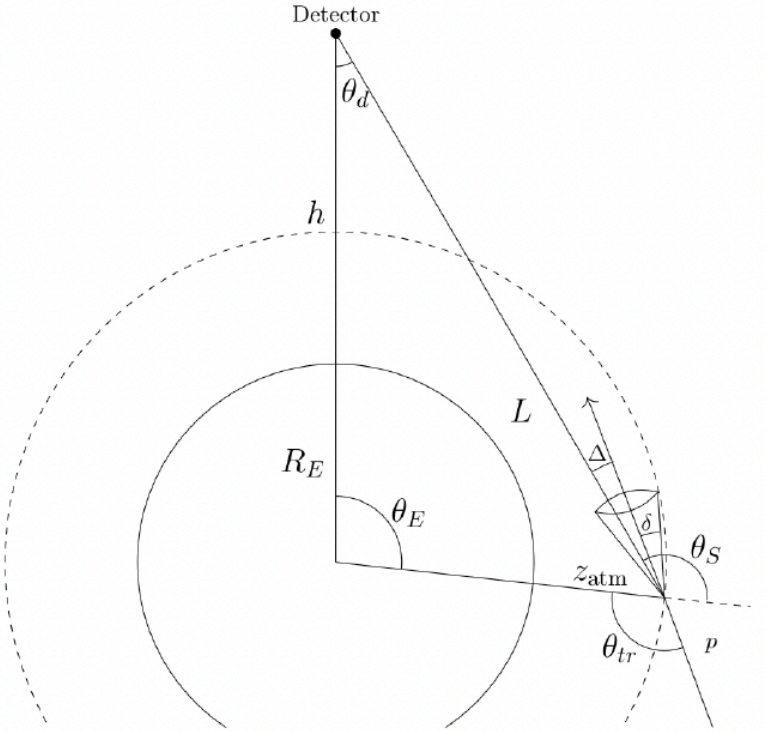
100 PeV UHECR showers in the limb as seen at different altitudes seen from 535 km orbit



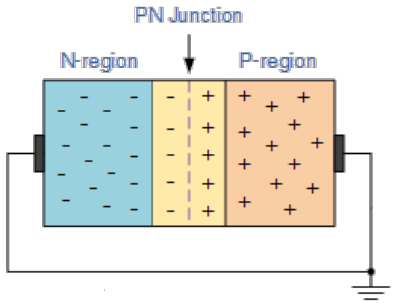
Simulation from Cummings, Aloisio, Eser, Krizmanic, 2021

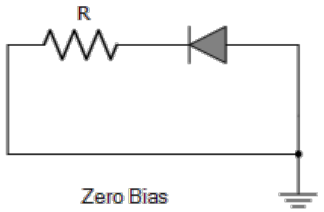


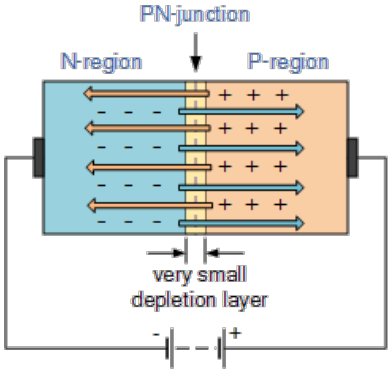


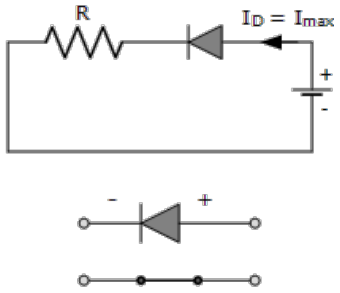
Cherenkov spectrum for UHECRs at different altitudes seen from 535 km

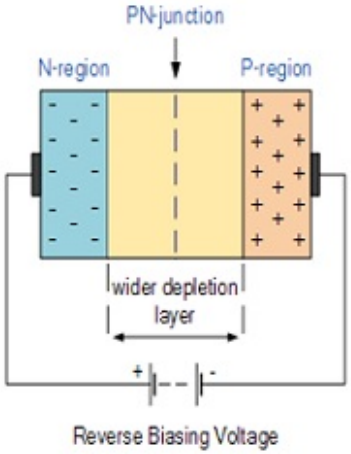
Diode : a pn junction

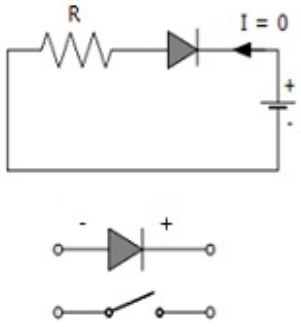




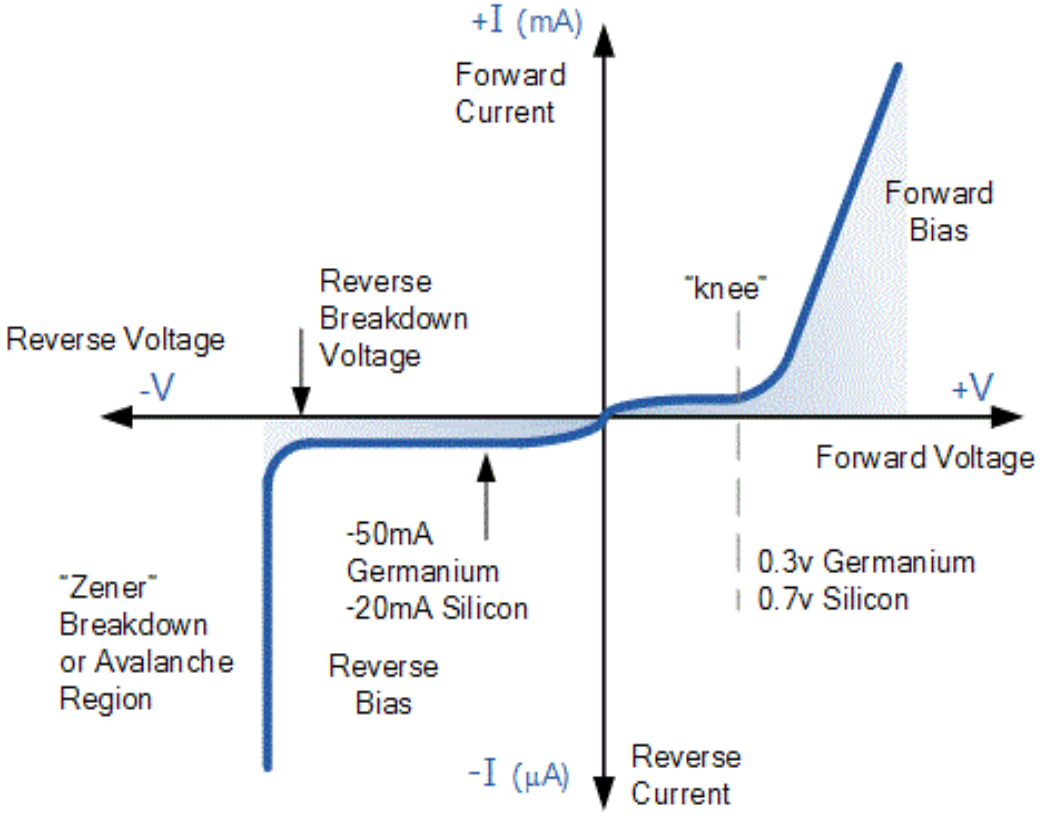






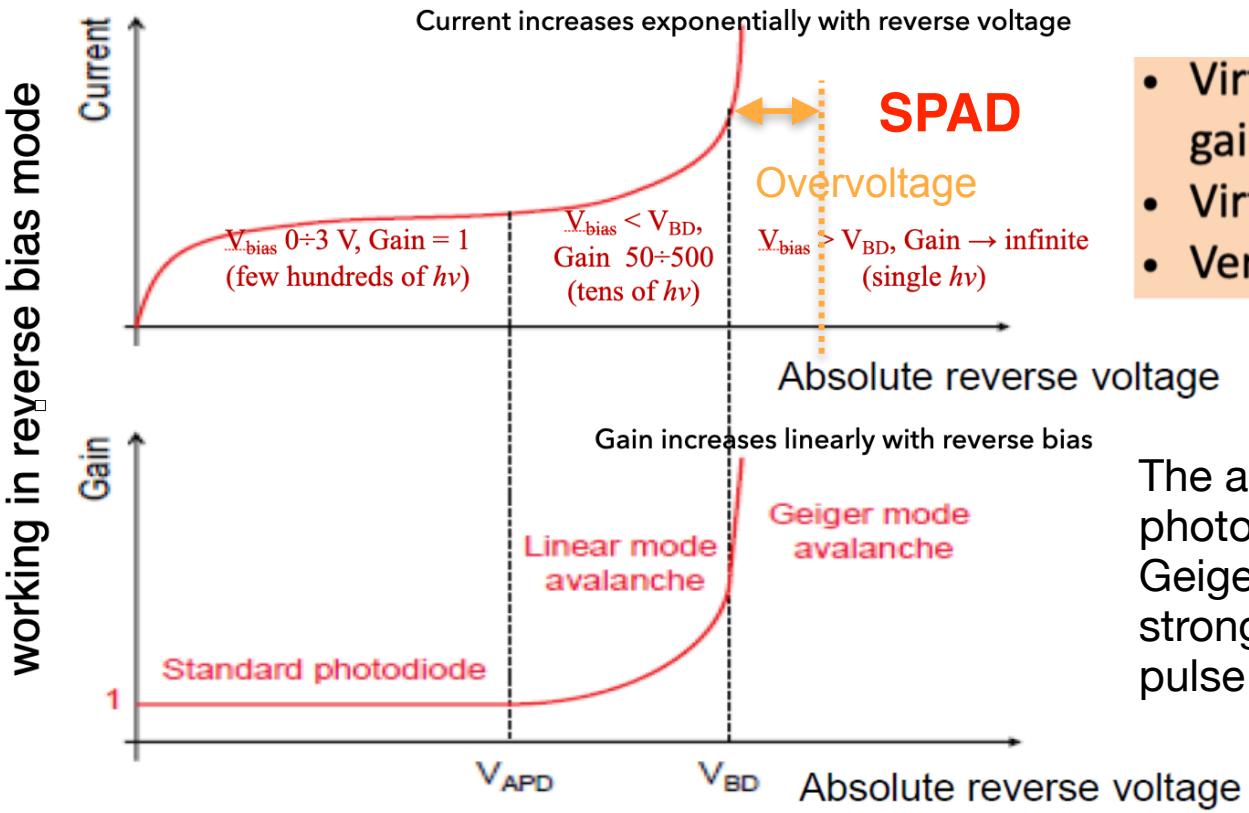


$$I = I_0\left(e^{-eV/kT} - 1\right)$$



Photons create e-h pairs in the depleted layer which can be used to detect light

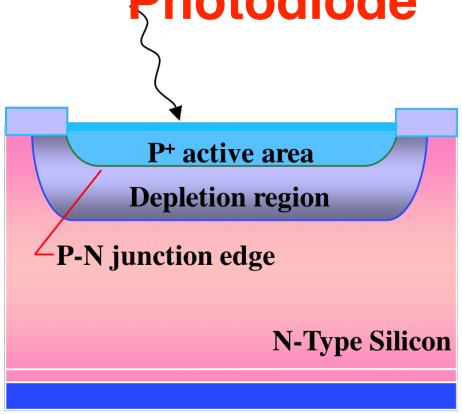
Photosensors



- Virtually infinite optical gain
- Virtually zero noise
- Very fast

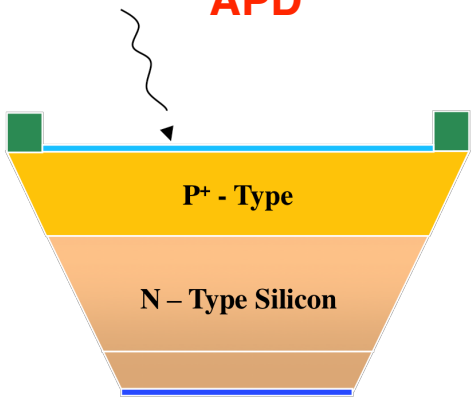
The absorption of single photon in photodiodes in Geiger mode can initiate a strong avalanche current pulse

Photodiode



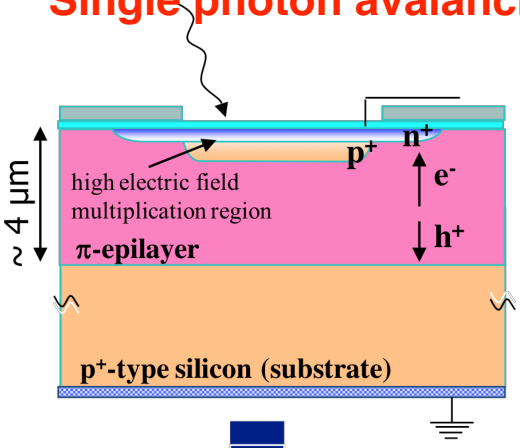
p-n junction,
reversed V_{bias} – 0-3 V

APD



p-n junction,
reversed $V_{bias} < V_{BD}$

Single photon avalanche diode



p-n junction,
reversed $V_{bias} > V_{BD}$

R.H. Haitz, J..A. Phys., Vol. 36, No. 10 (1965)

Single Photon Avalanche Diodes SPADs

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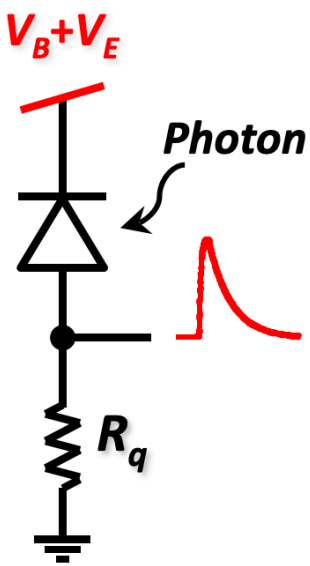
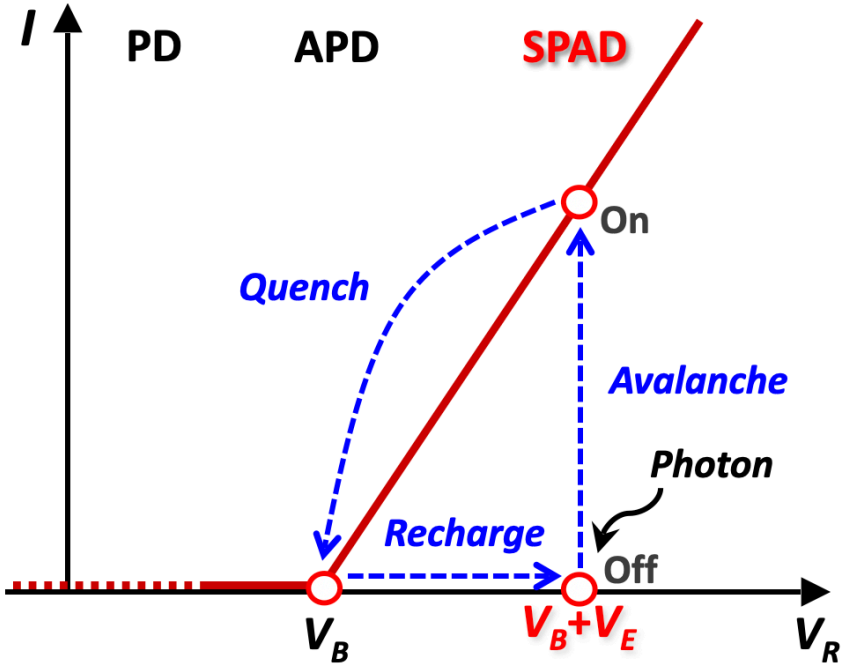
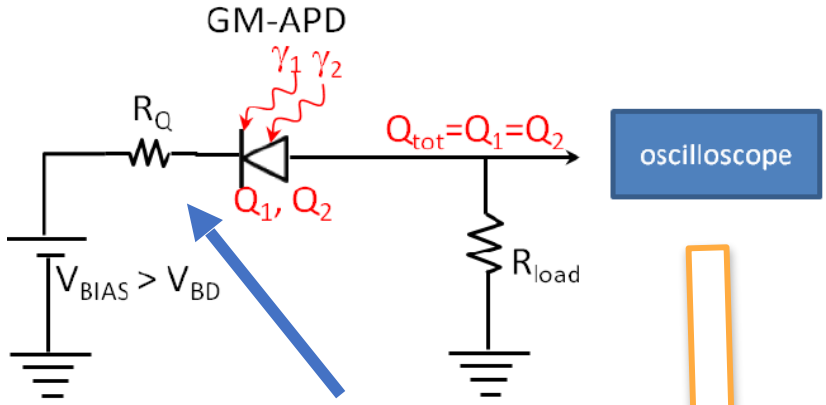
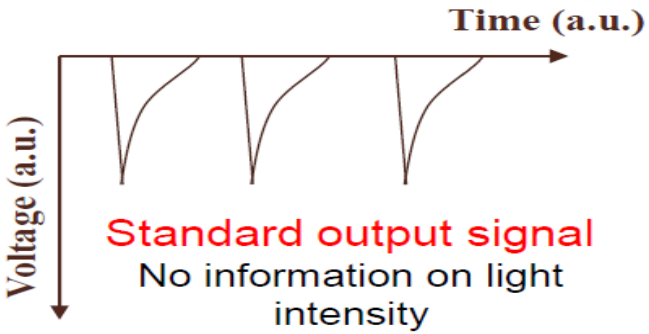
- The avalanche can be passively quenched



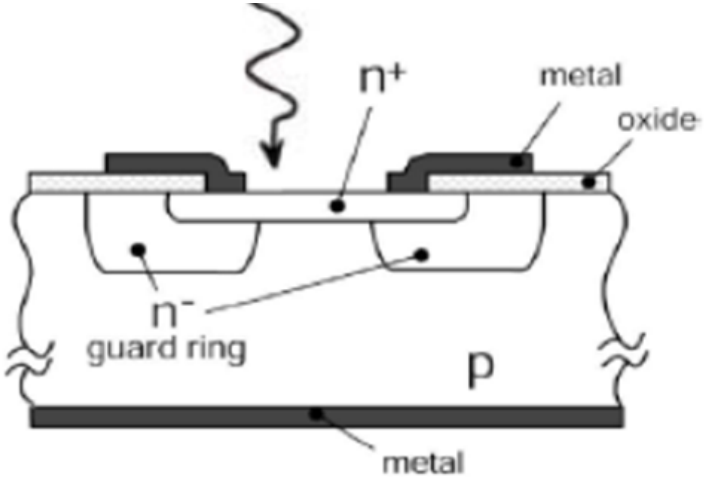




to quench avalanche



Standard output signal
No information on light intensity



Digital device

$Q = Q_1 = Q_2 = \ldots = Q_n$

G-APDs or SiPMs

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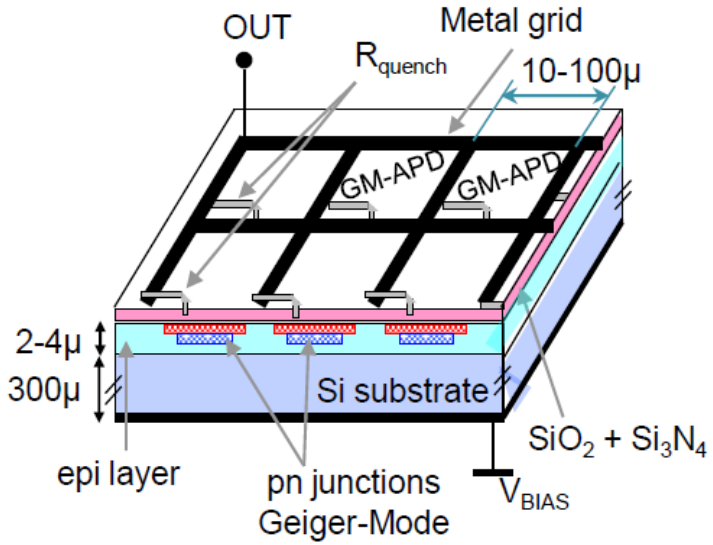
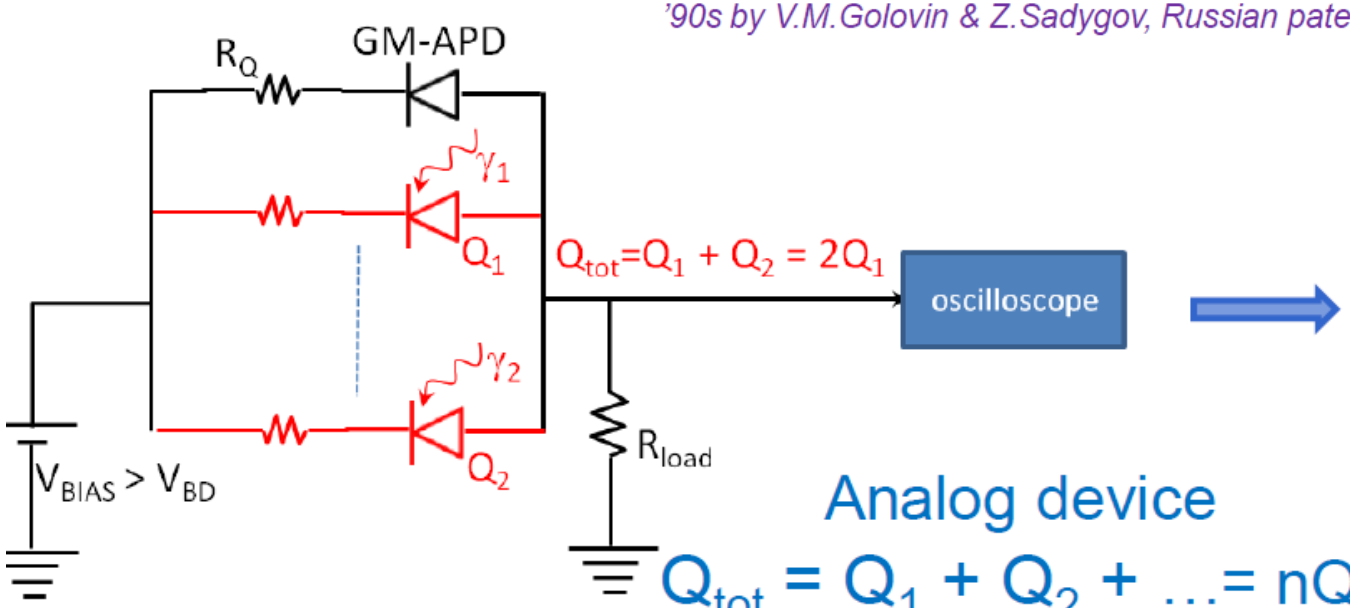
- Parallel array of SPADs or μcells on the same substrate and each SPAD in series with R_q

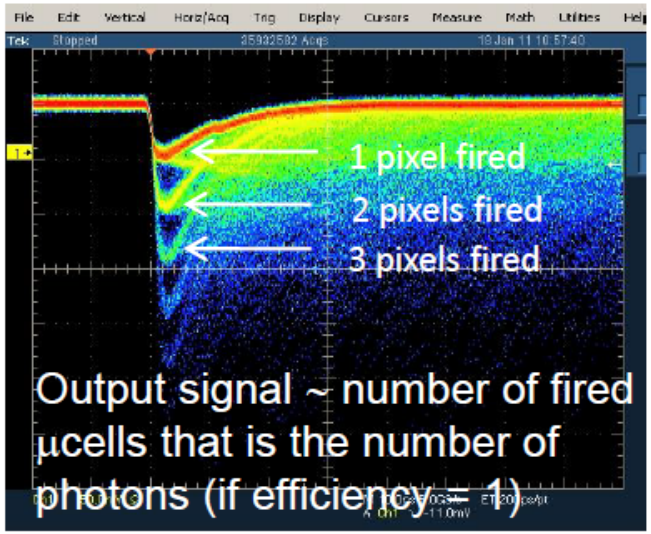


'90s by V.M.Golovin & Z.Sadygov, Russian patents



Analog device

$Q_{tot} = Q_1 + Q_2 + \ldots = nQ_1$



The quanta information from G-APDs

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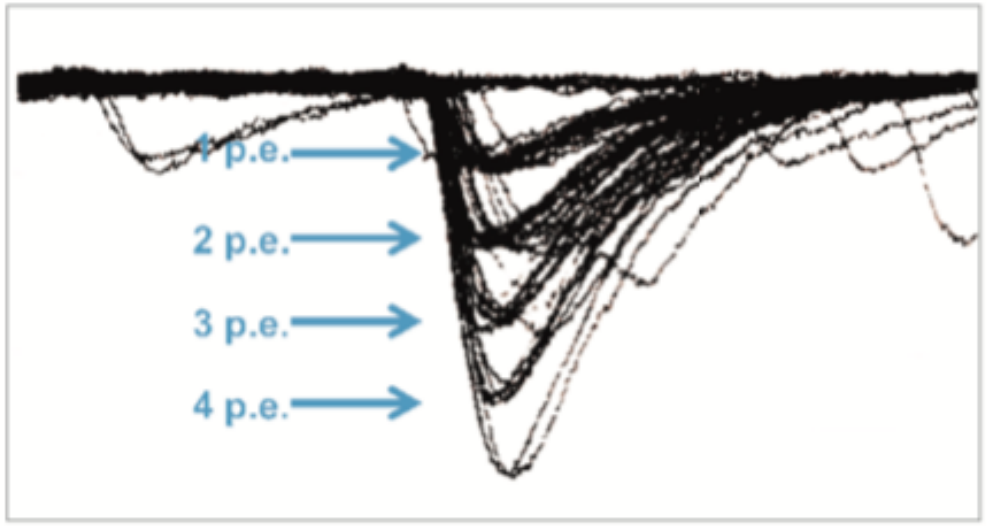

Figure 6, Oscilloscope shot showing the discrete nature of the SiPM output when illuminated by brief pulses of low-level light.

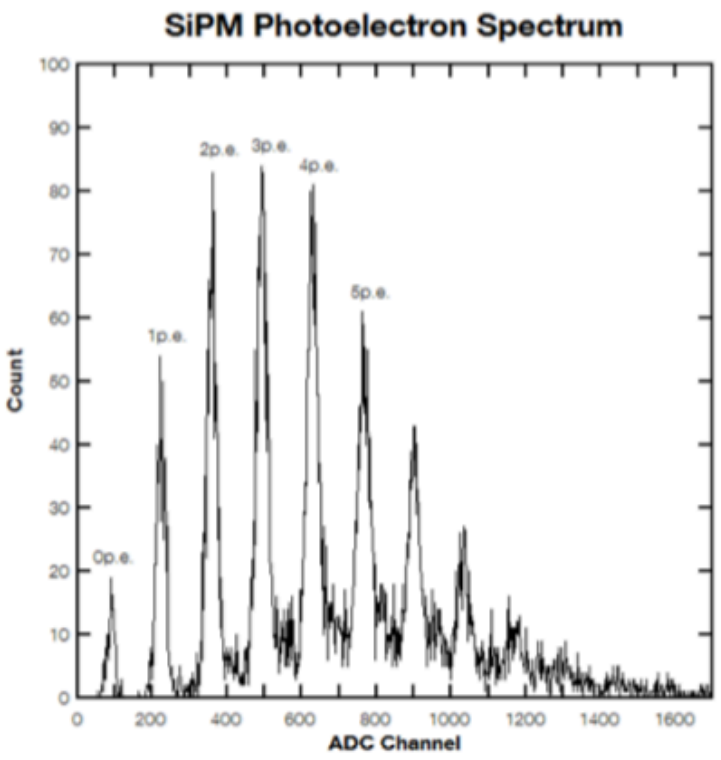

Figure 7, Photoelectron spectrum of the SiPM, achieved using brief, low-level light pulses, such as those from Fig. 6.

Gain and PhotoDetection Efficiency

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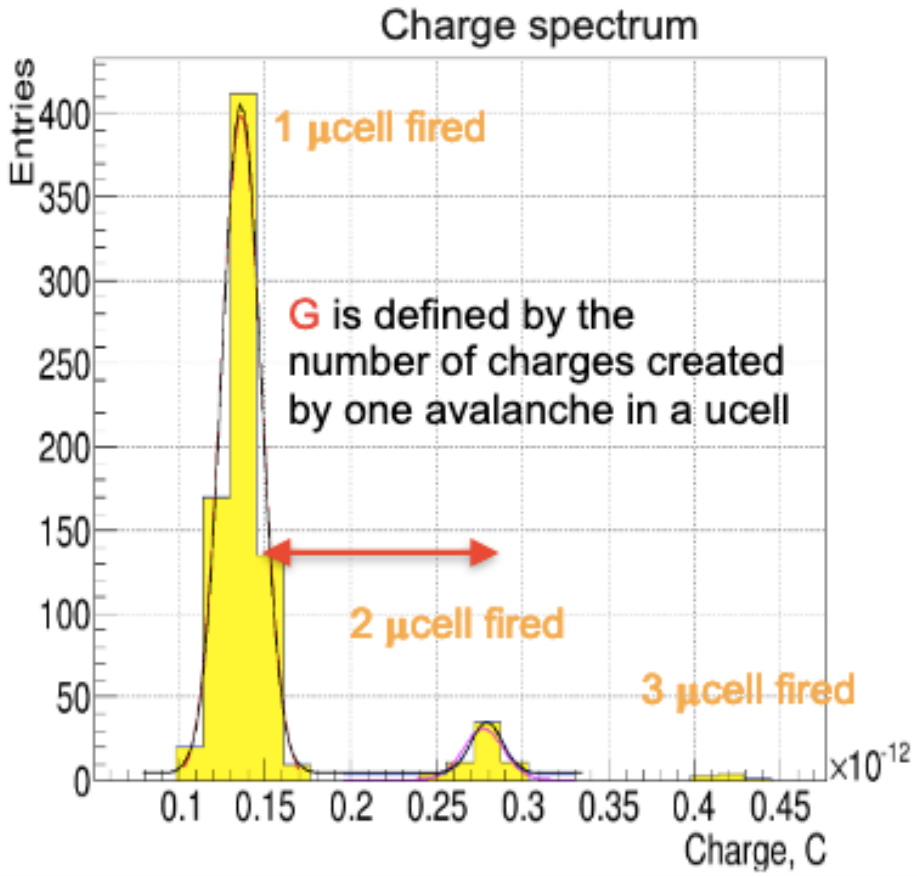
The sum of the photocurrents from each μcell combines to output the magnitude of the impinging photon flux. In practice, G is measured from integration of pulse - baseline.

$$G = \frac{Q}{e} = \frac{1}{G_{Amp} \cdot e} \cdot \frac{1}{R} \int (V(t) - BL)\, dt,$$

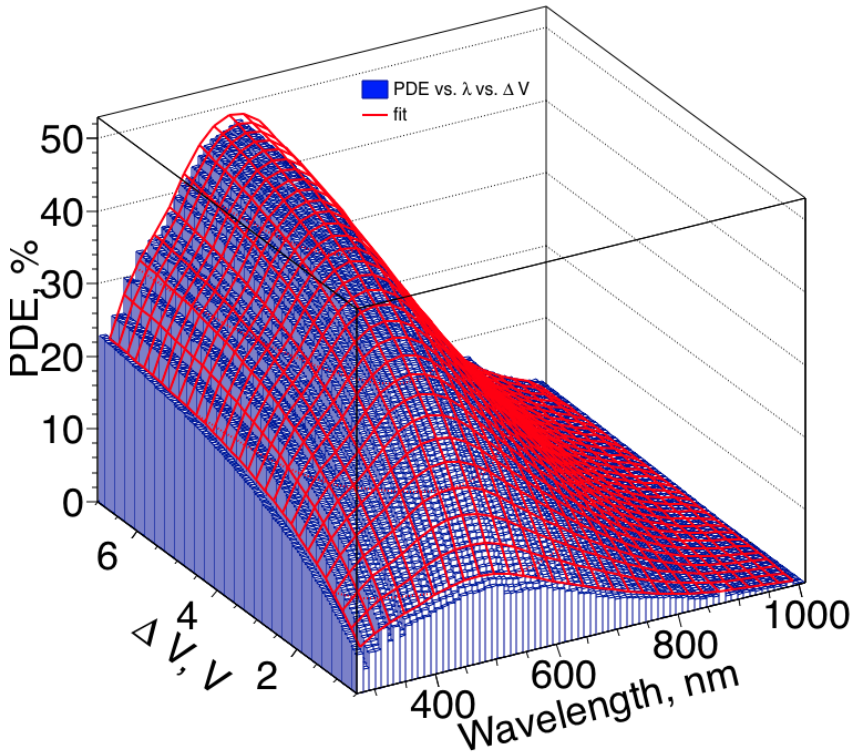
Amplifier input impedance



QE – probability to create an e/h pair

P_{Geiger} – probability that e/h triggers an avalanche

FF – ratio between active and total areas



SiPM in the gamma-ray astronomy

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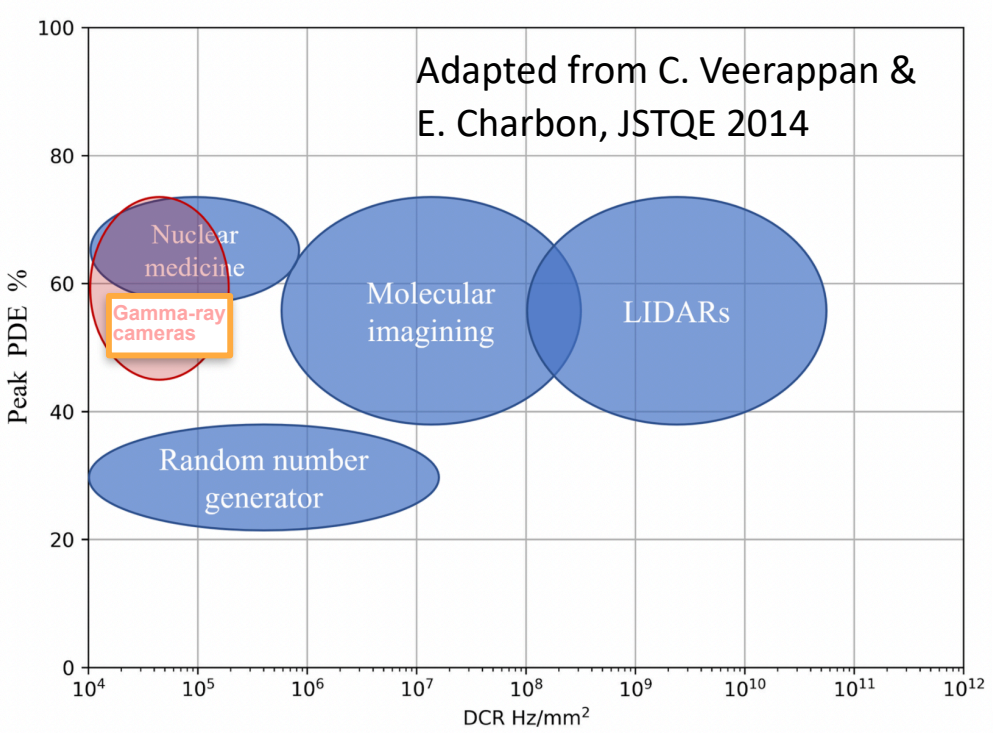
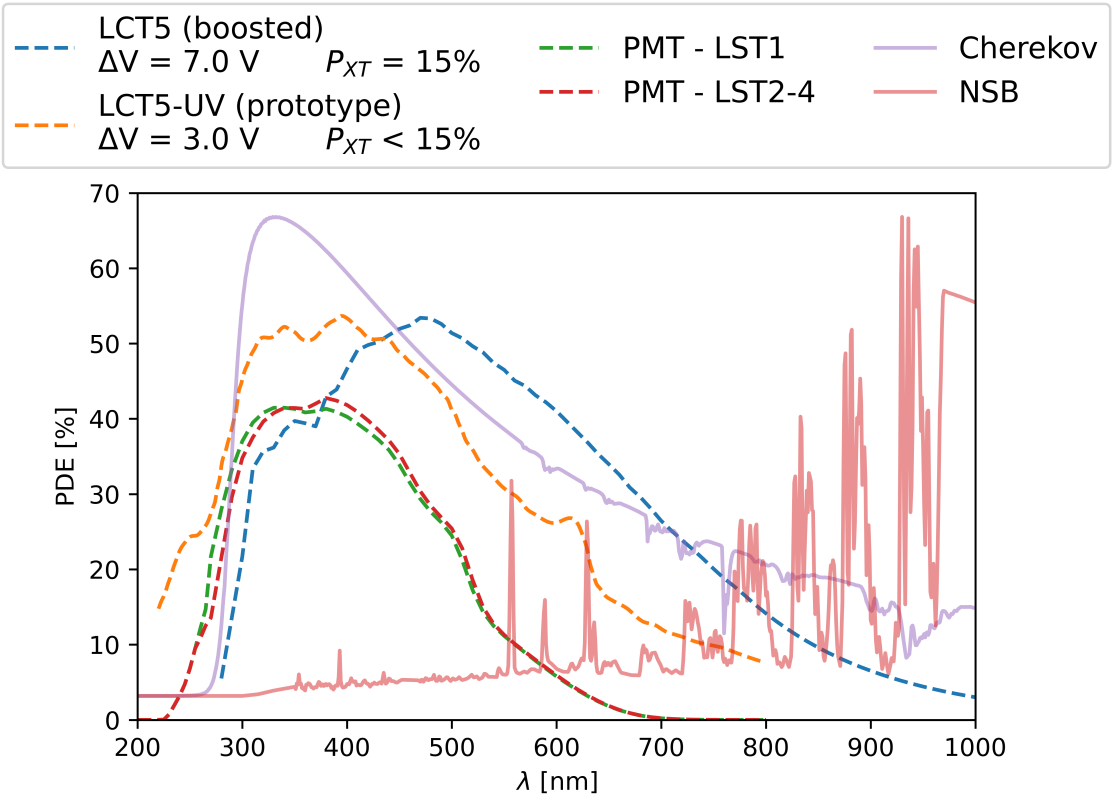
Advantages:

- robustness to light (~30% more observation time)
- Mass producibility, low power, cost
- Uniformity, negligible ageing

Challenges:

- high sensitivity in night sky background region > 500 nm
- PDE > 10% than PMTs but max at too high wavelength for Cherenkov spectrum; need to work at high over-voltage with consequent Xtalk increase and also Voltage drop effect
- Filters on entrance window (e.g. in borofloat) improve performance at high energy, at low energy it cuts more Cherenkov signal than PMMA window (on which coating cannot be applied)





G-APD developments

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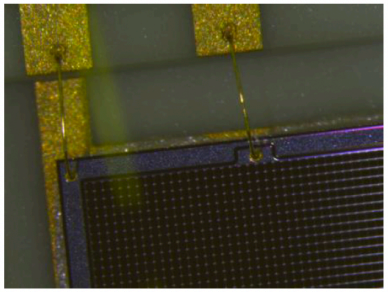
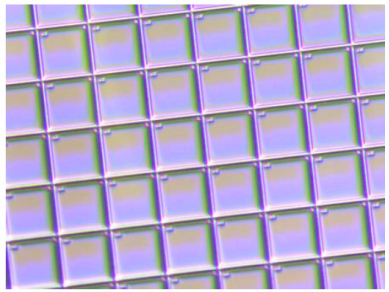
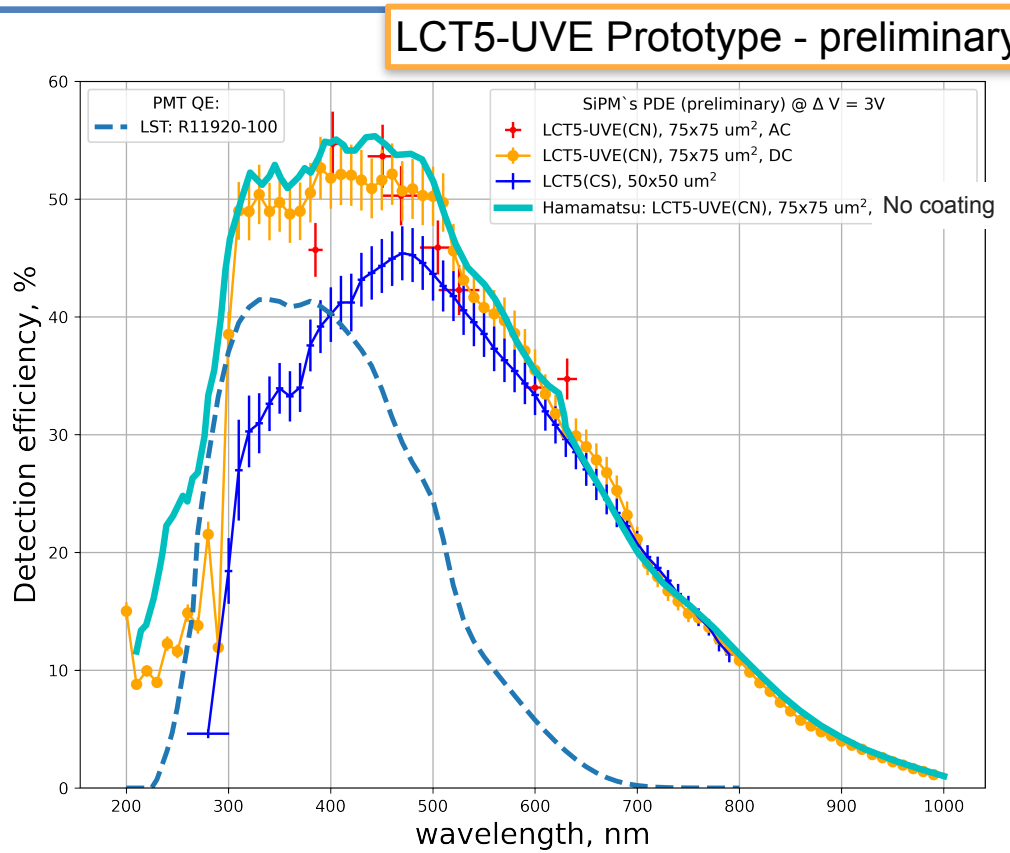
- Based on LCT5 (S13360) technology:
  - Improved UV sensitivity;
  - Reduced IR sensitivity;
- Size of 3×3 mm^2 ;
- Pixel size 75×75 um^2 ;
- Without Coating

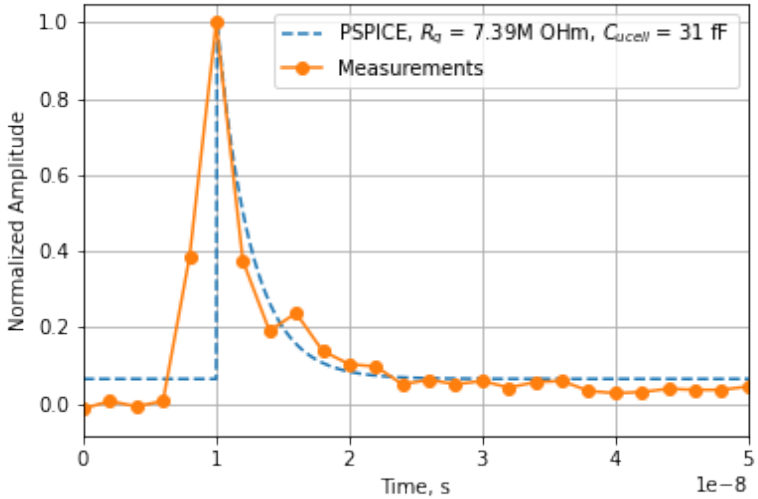
V_{BD}= 52.783 V



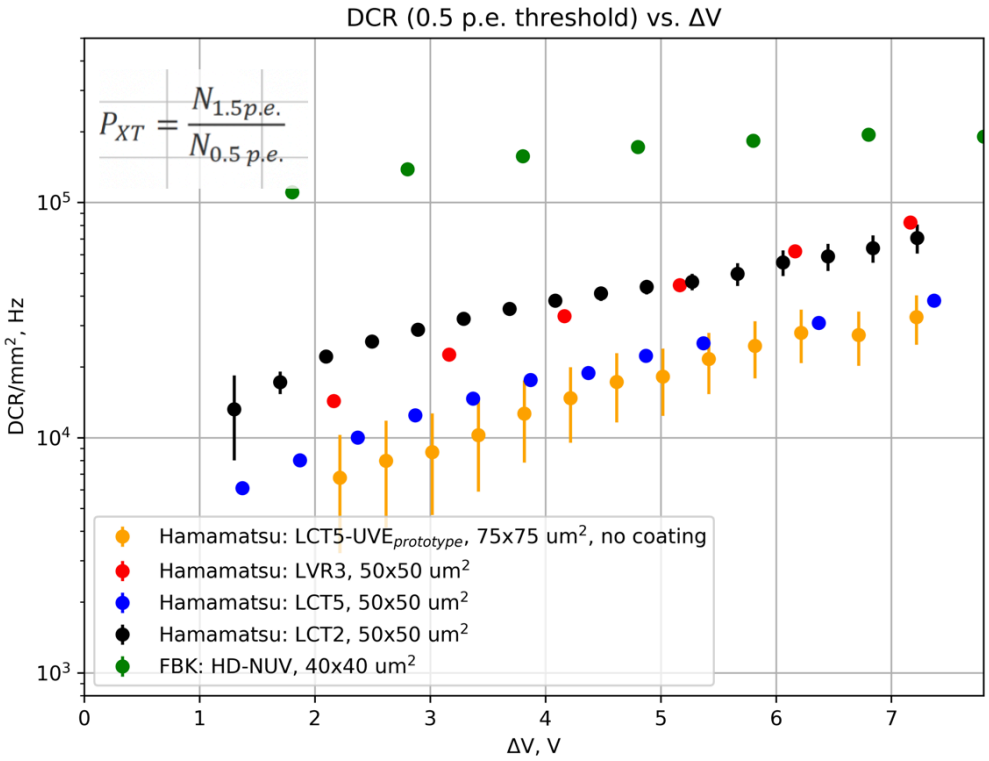


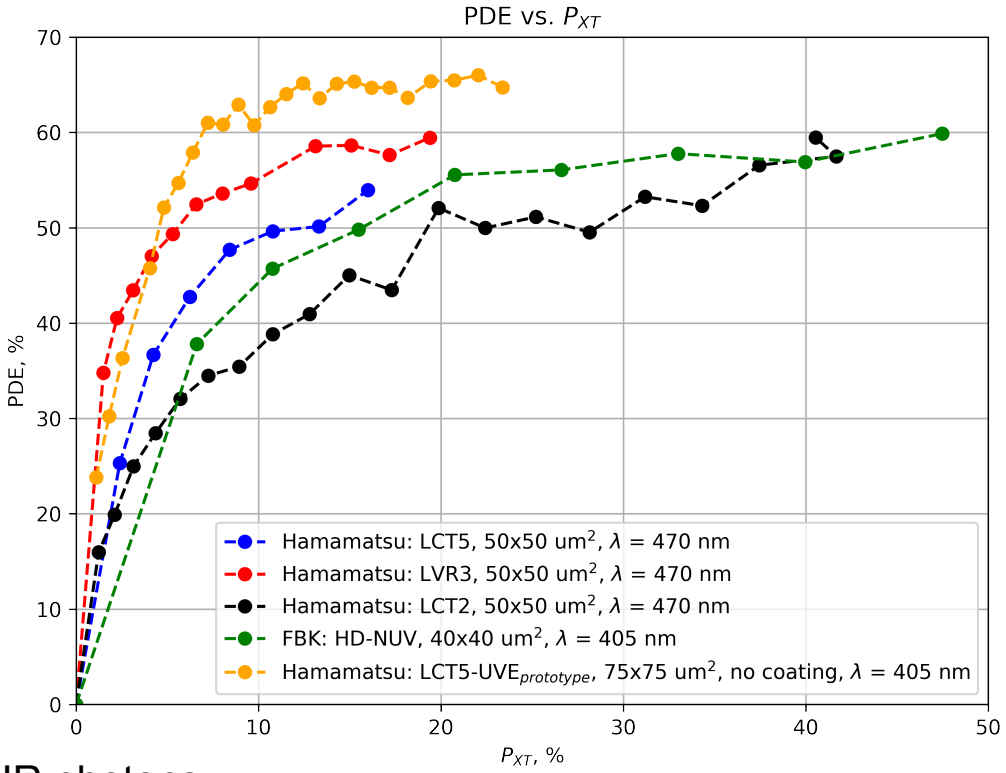


- Preliminary results from a new sensor by Hamamatsu:
  - ✦ Similar performance to former devices in term of noise
  - ✦ Large improvement in sensitivity in the UV compared to standard SiPM and PMTs
  - ✦ Remarkably short pulse (~3 ns FWHM) without specific shaping
- Possibly a coating to reduce IR contribution?

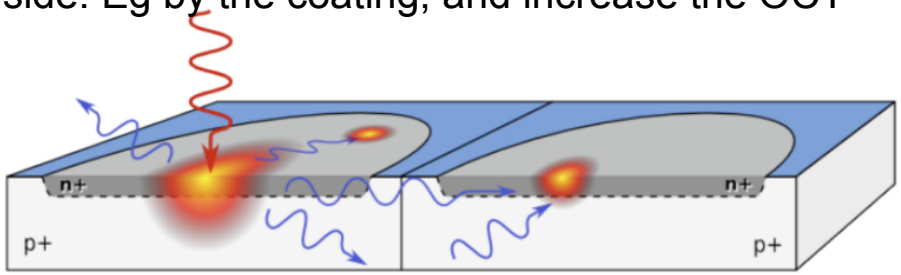


Uncorrelated and Correlated noise



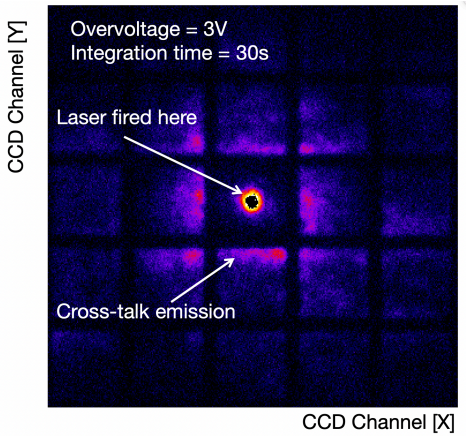


OXT : the avalanche process in a μcell emits secondary IR photons that are then detected by the surrounding μcells with a certain probability (P_{XT}). Some of the outgoing photons can be reflected inside. Eg by the coating, and increase the OCT



R. Mirzoyan et al., NIM A 610 (2009) 98-100
Bonanno et al, NIM A908 (2018) 117-12

D. Strom & R. Mirzoyan, PD18, Japan



Sensitivity range

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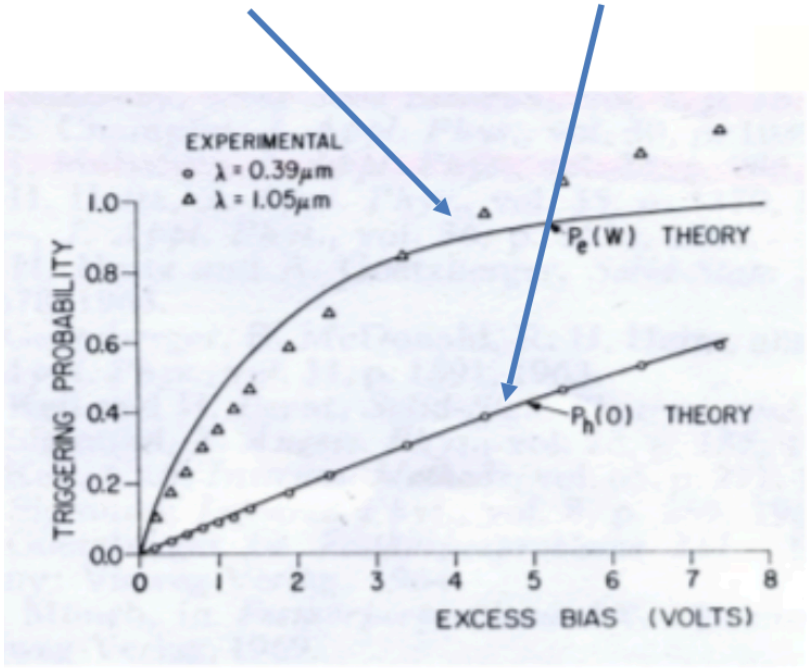
The PDE is given by : $PDE(\lambda, \Delta V) = QE \times CE = QE(\lambda) \times P_G(\Delta V) \times FF$

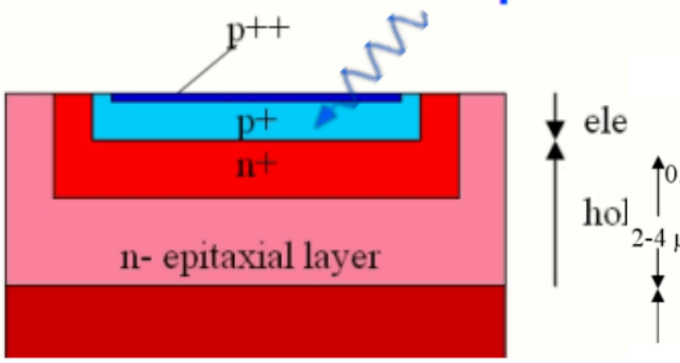
P_G (electron) >> P_G (hole) :

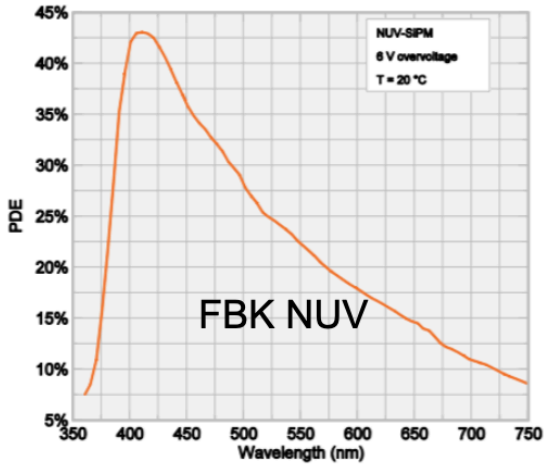


This plot was measured for the n-on-p junction where we need red ight to penetrate to p+ layer where electrons are produced. The lectron avalanche trigger probability has exponential behaviour

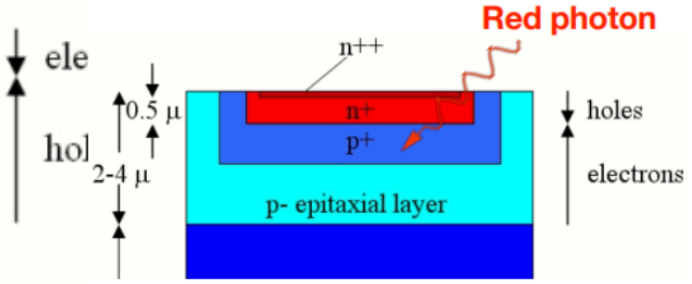
Two types of junction:

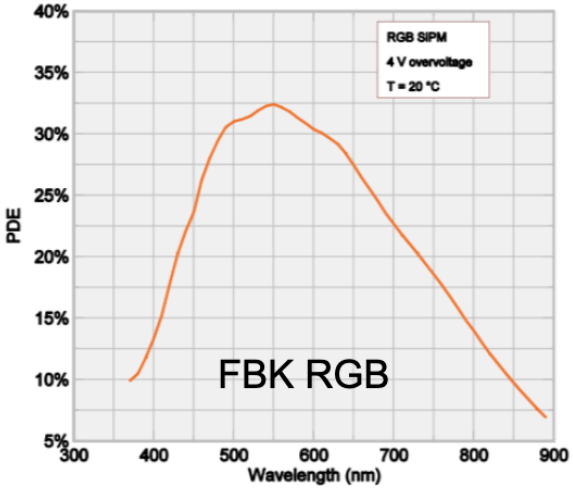
p-on-n:





n-on-p:
(green/red sensitive)





A. Gola, et all "NUV-Sensitive Silicon Photomultiplier Technologies Developed at Fondazione Bruno Kessler" doi: 10.3390/s19020308

What detectors for Cherenkov from space?

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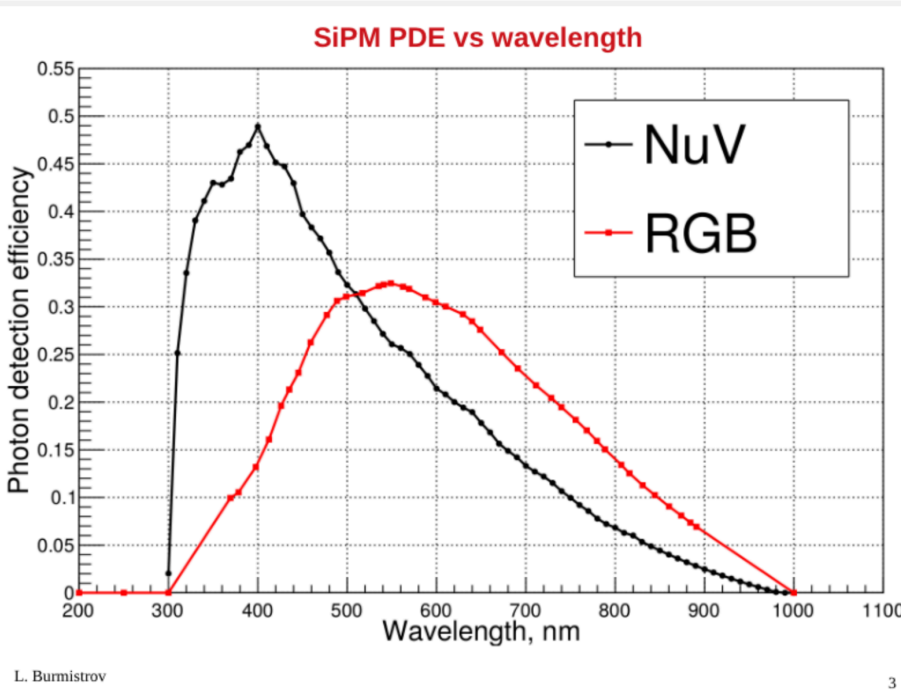
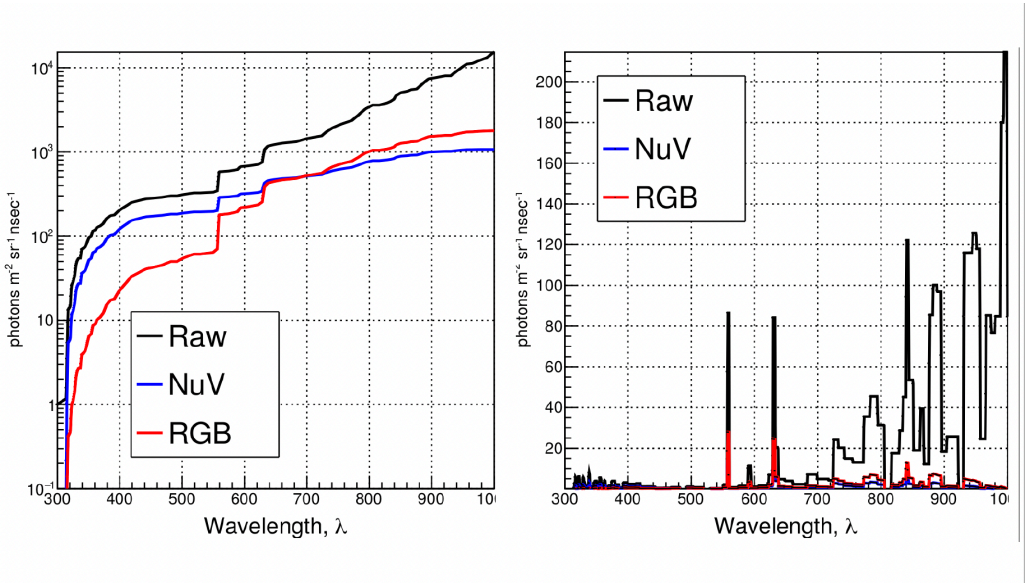
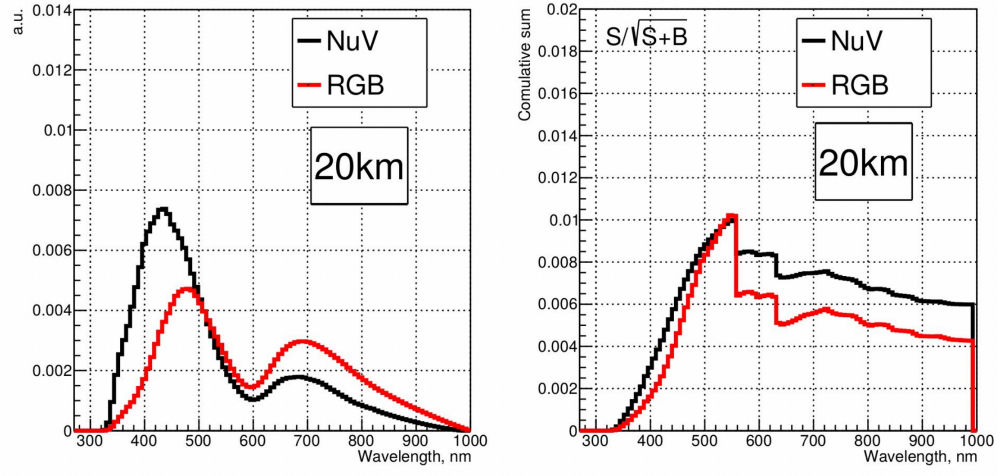
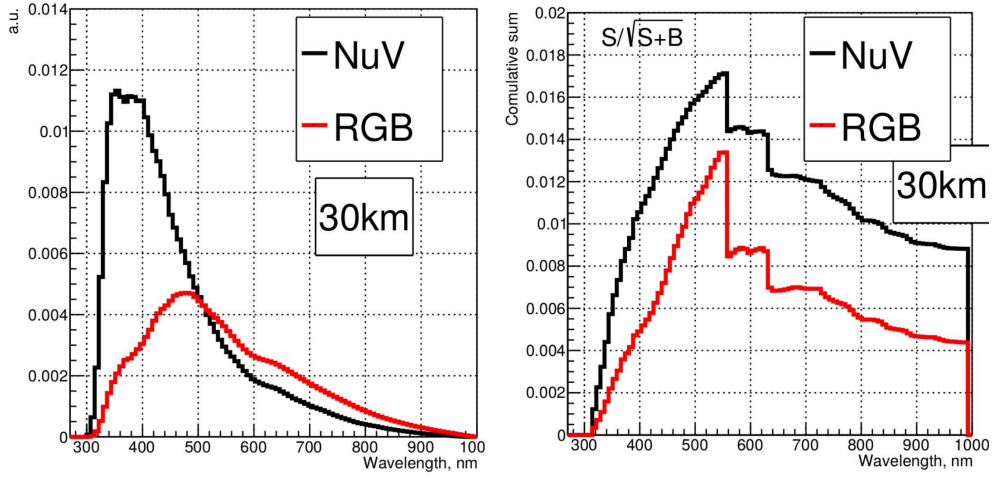


Convolved Night glow with PDE in log and Lin scale (arxiv:2008.04984):



Convolved Cherenkov signal with PDE





CMOS SPADs

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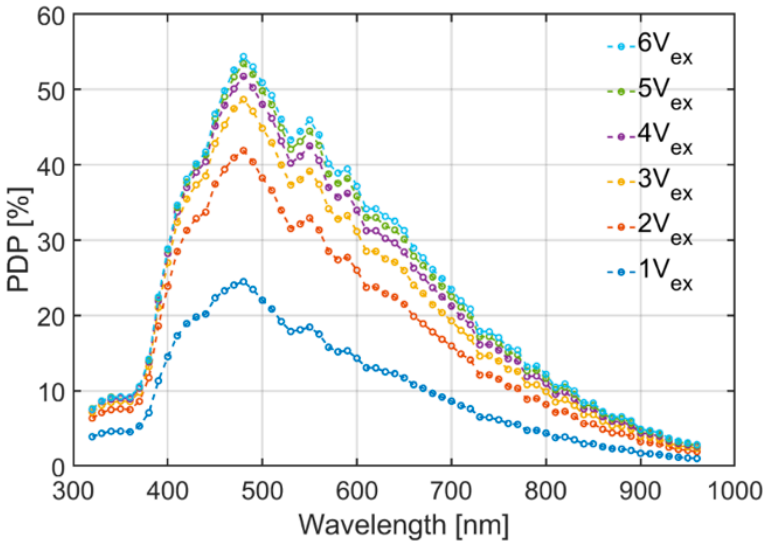
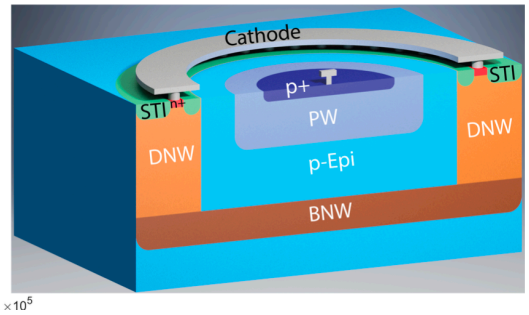


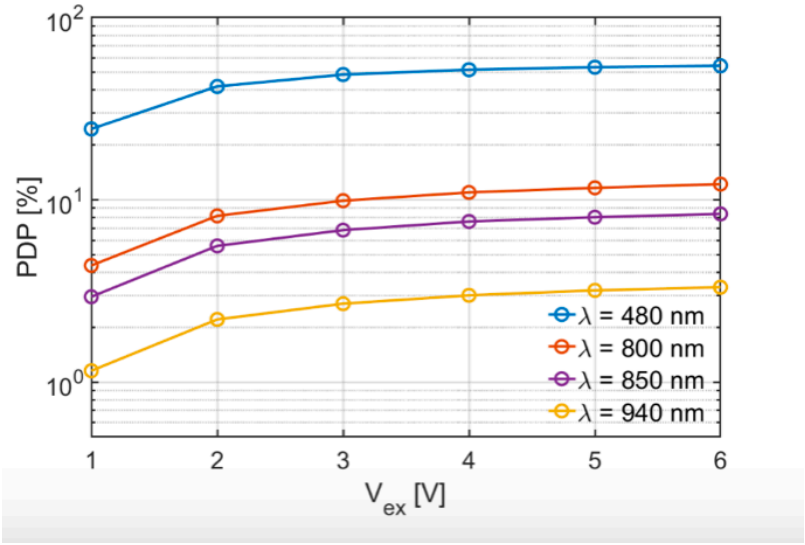
180 nm CMOS technology



State-of-the-art CMOS SPADs:

0.1~10Hz/µm²

Analog SiPM have 2-3 orders of magnitude lower DCR rate



PhotoDetection Probability does not account for Fill Factor. Solution with micro lenses on each SPAD allows to keep PDE high.

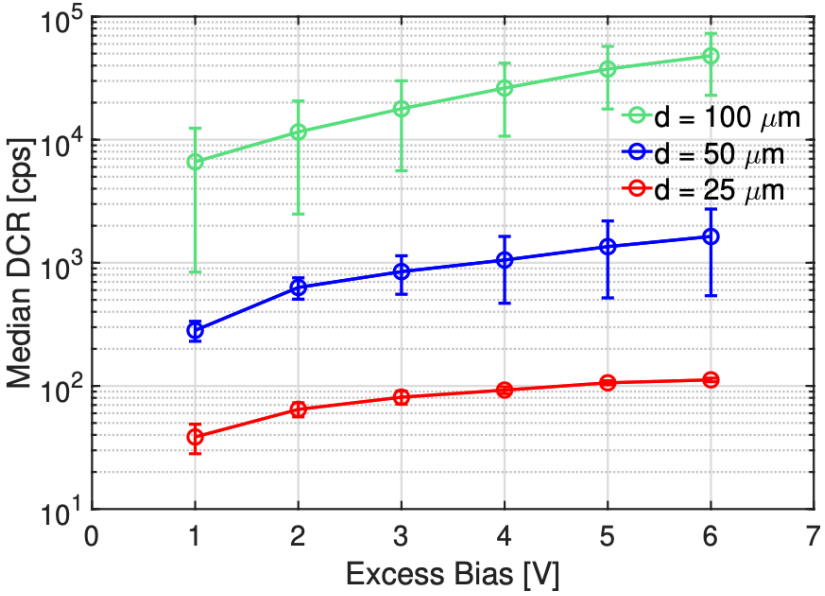
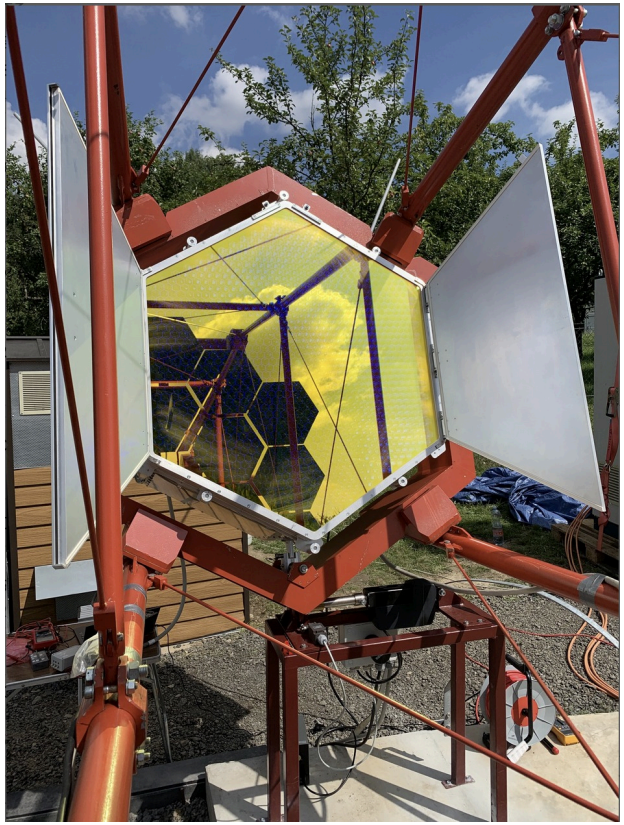


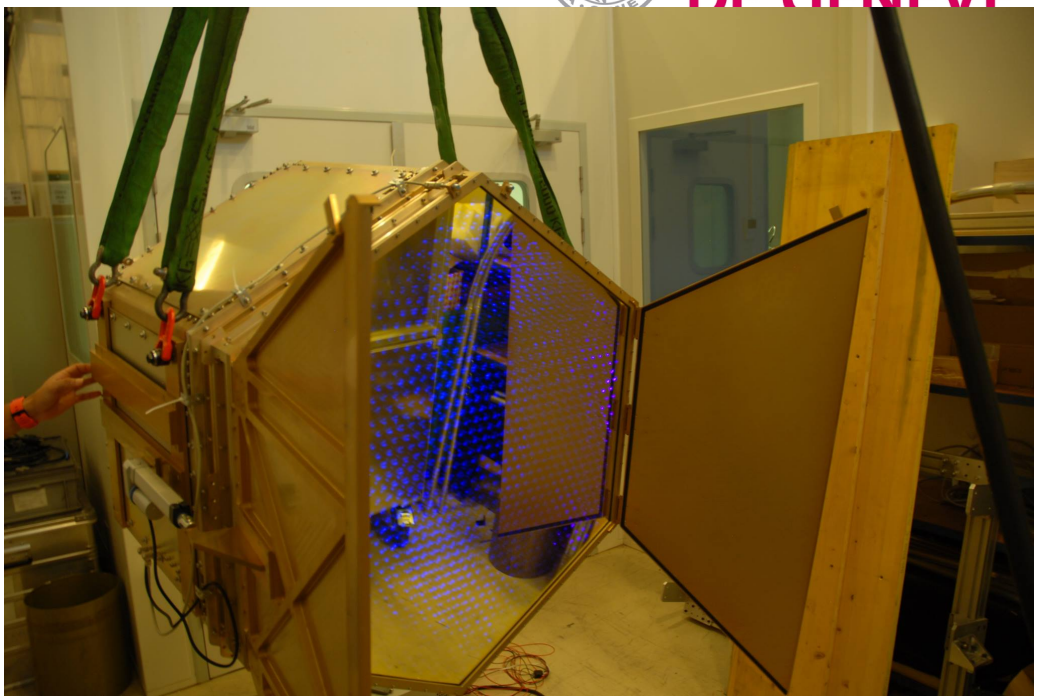
Fig. 5. DCR median value measured at several excess bias voltages for the different SPAD sizes. The results are obtained measuring 15 devices for each size.

Application : SST-1M camera

Initially developed for CTA as prototypes of SSTs
Was reviewed and satisfied all requirements
Now two SST-1Ms are installed at Ondrejov Observatory (CZ) for stereo tests and science commissioning



Camera design dependence on the optics



Dish = 4 m

FoV = 9°

f/D = 1.4

Davies-Cotton design

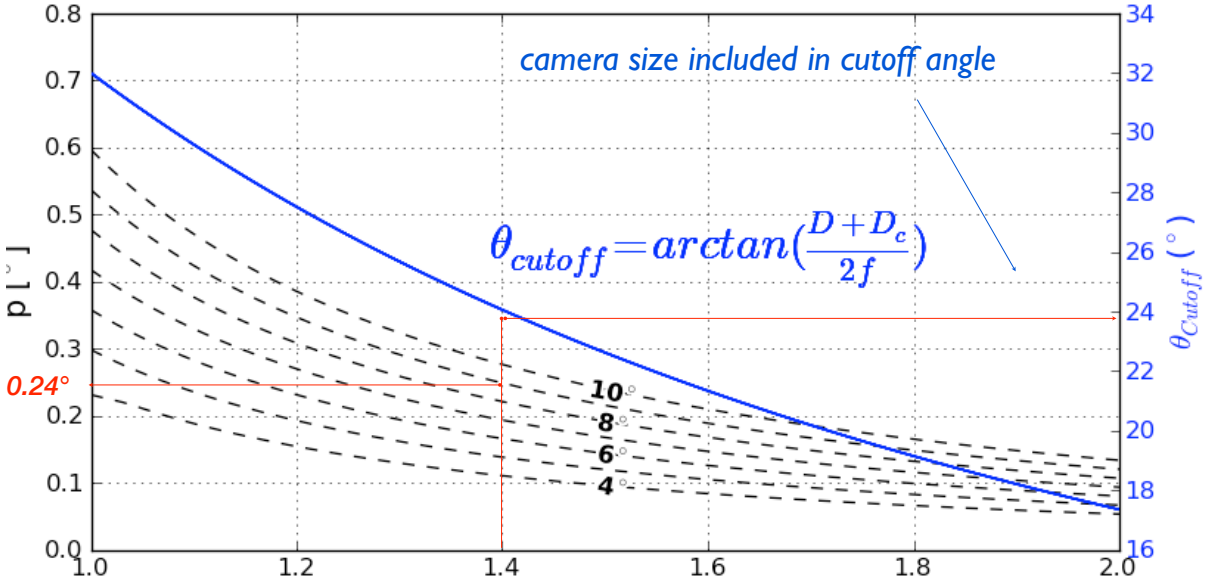
Pixel size = 4· min(σ_x, σ_y) = 0.24°

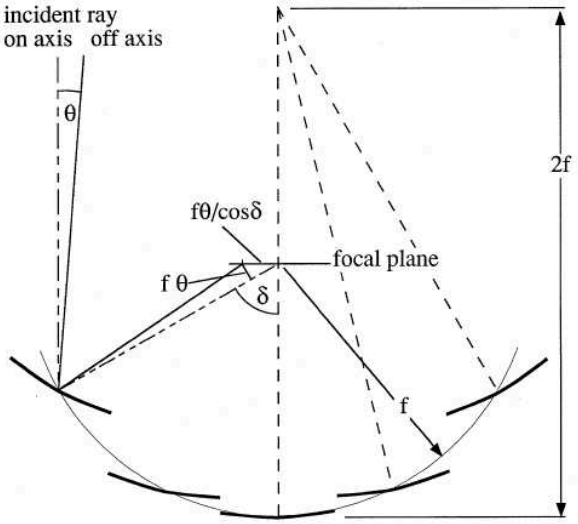
Camera size (D_c) = 88 cm

Pixel size (linear) = 2.32 cm

n_p = 1296 pixels

Watch us on Youtube:
Video 1 (HD) Video 2





SST-1M Camera

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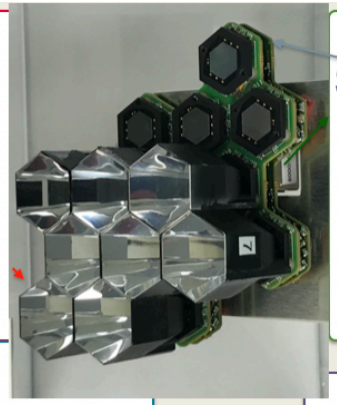
Hollow light guides:
- Cut-off at 24°
- 2.32 cm linear size
- Compression factor of ~6
- dichroic coating



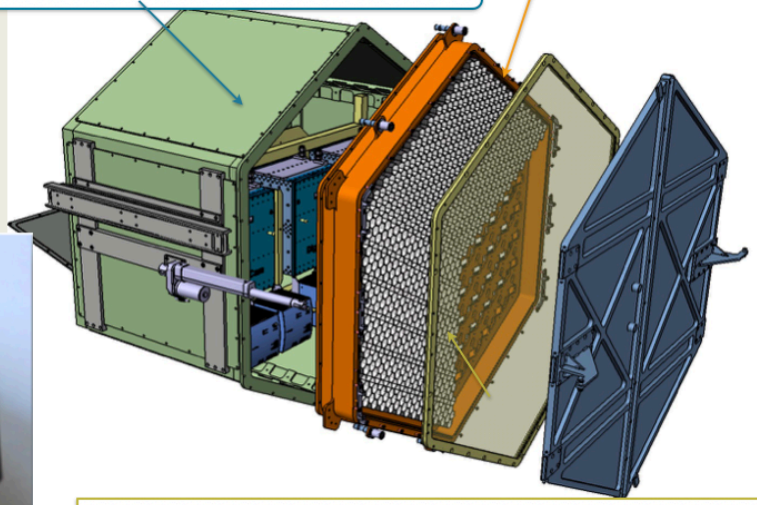
Slow control board:
- 108/camera
- Temperature compensation loop Hz
- HV generation

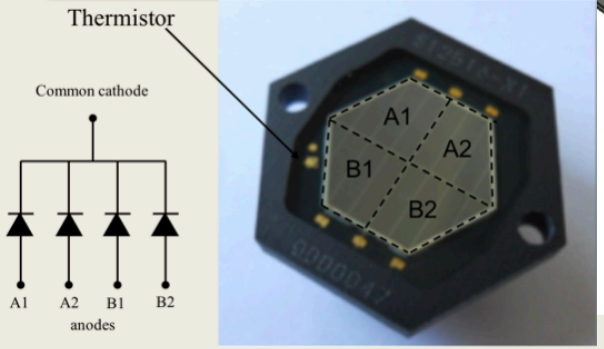
- 12 bits FADC @ 250 MS/s
- Fully digital trigger, reconfigurable and signal preprocessing
- Serial architecture based on multi-Gigabit links (both trigger and ADC data)
- Power consumption 1200 W

Photo detection plane:
- 1296 pixels
- 0.24° angular size
- Power consumption 500 W
- Analogue signals over CAT5/RJ45

Preamplifier board:
- 108 /camera
- discrete components
- Trans-impedance topology
- DC coupling

- Hamamatsu LCT2 50 um
- 4 anodes per pixel with one common cathode
- NTC temperature sensor





1 cm² sensitive area

$V_{over} = 2.8\,\mathrm{V} \Rightarrow C_{\mu cell} \sim 85\,\mathrm{nF}$

Entrance window:
- 3.3 mm Borofloat
- Cut-off filter at 540 nm for NSB rejection

Heller et al, Eur.Phys.J.C 77 (2017) 1, 47

DC coupling

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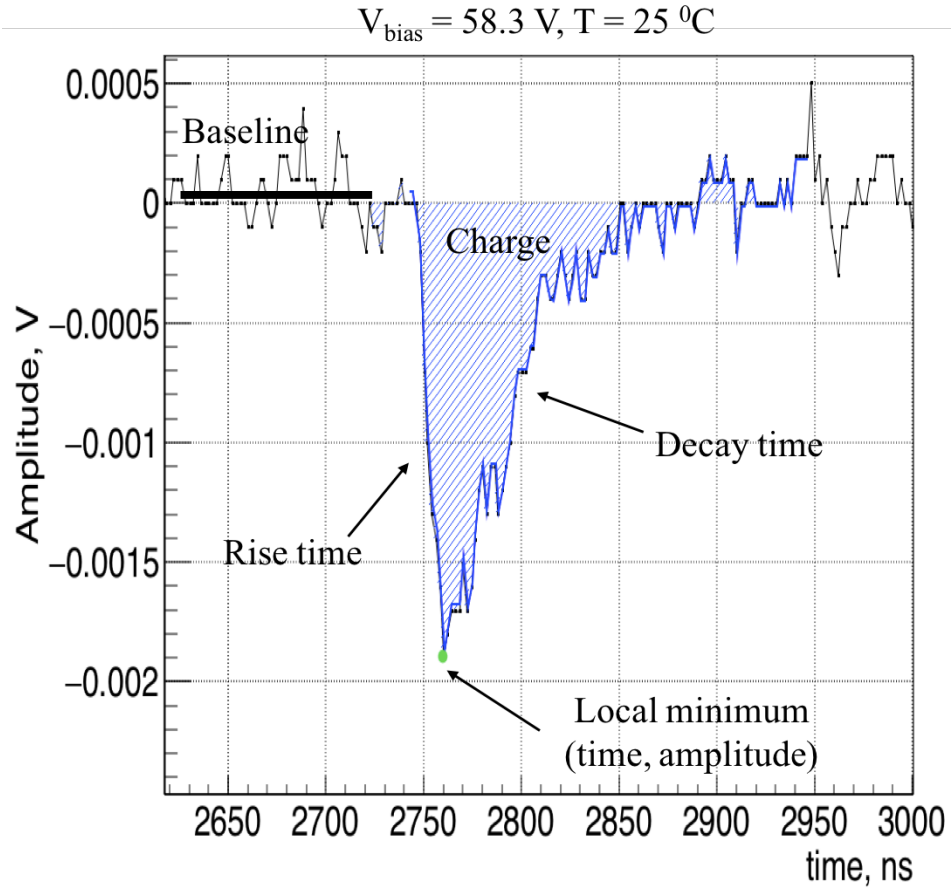
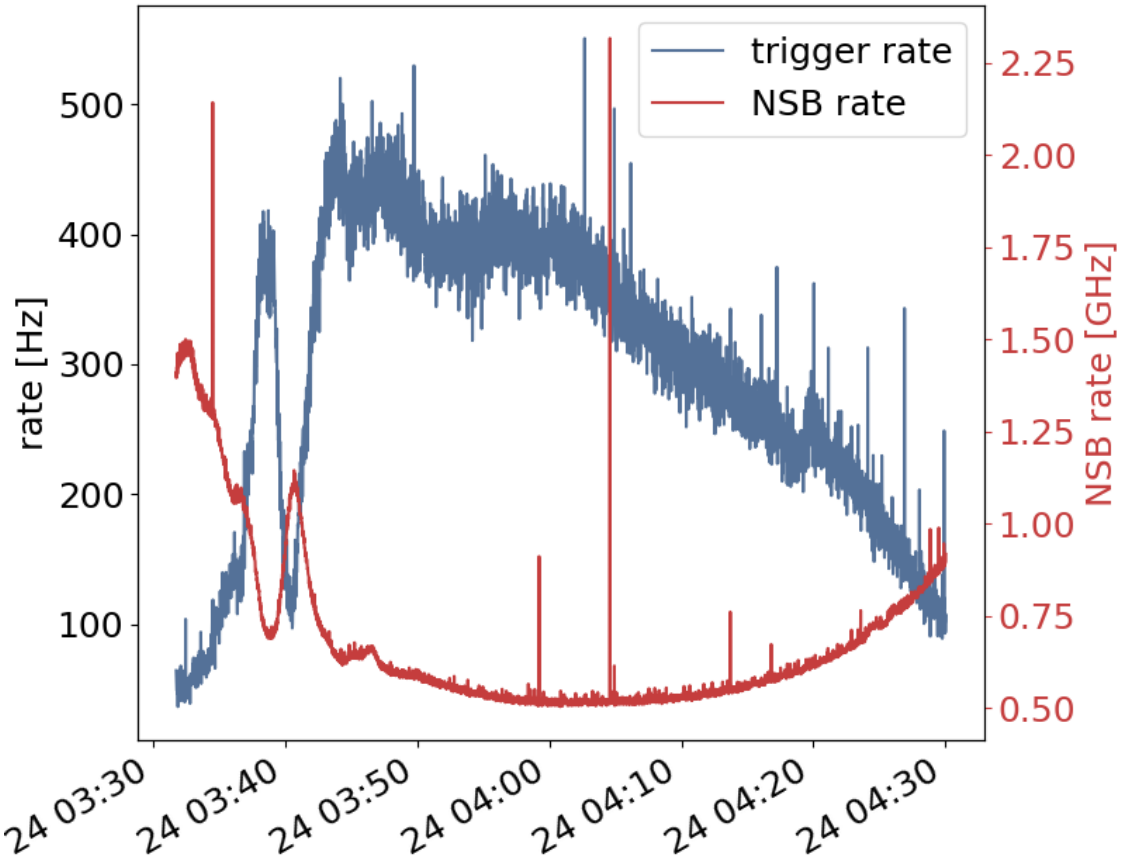
A DC coupled camera is NSB monitor!

The Digicam can measure the BL before each pulse.

Useful for correcting for changes of SIPM parameters



Rate of NSB in Krakow (including clouds and airplanes…)



Voltage drop

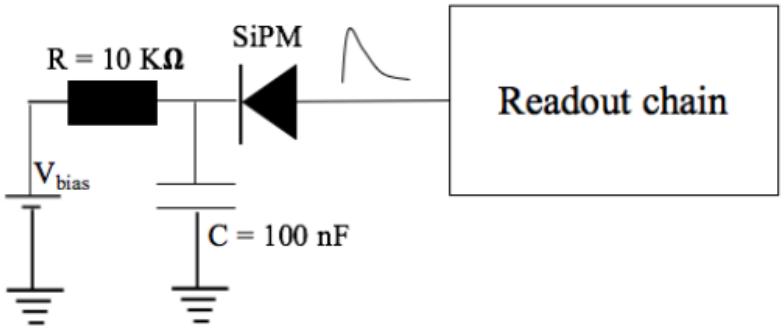
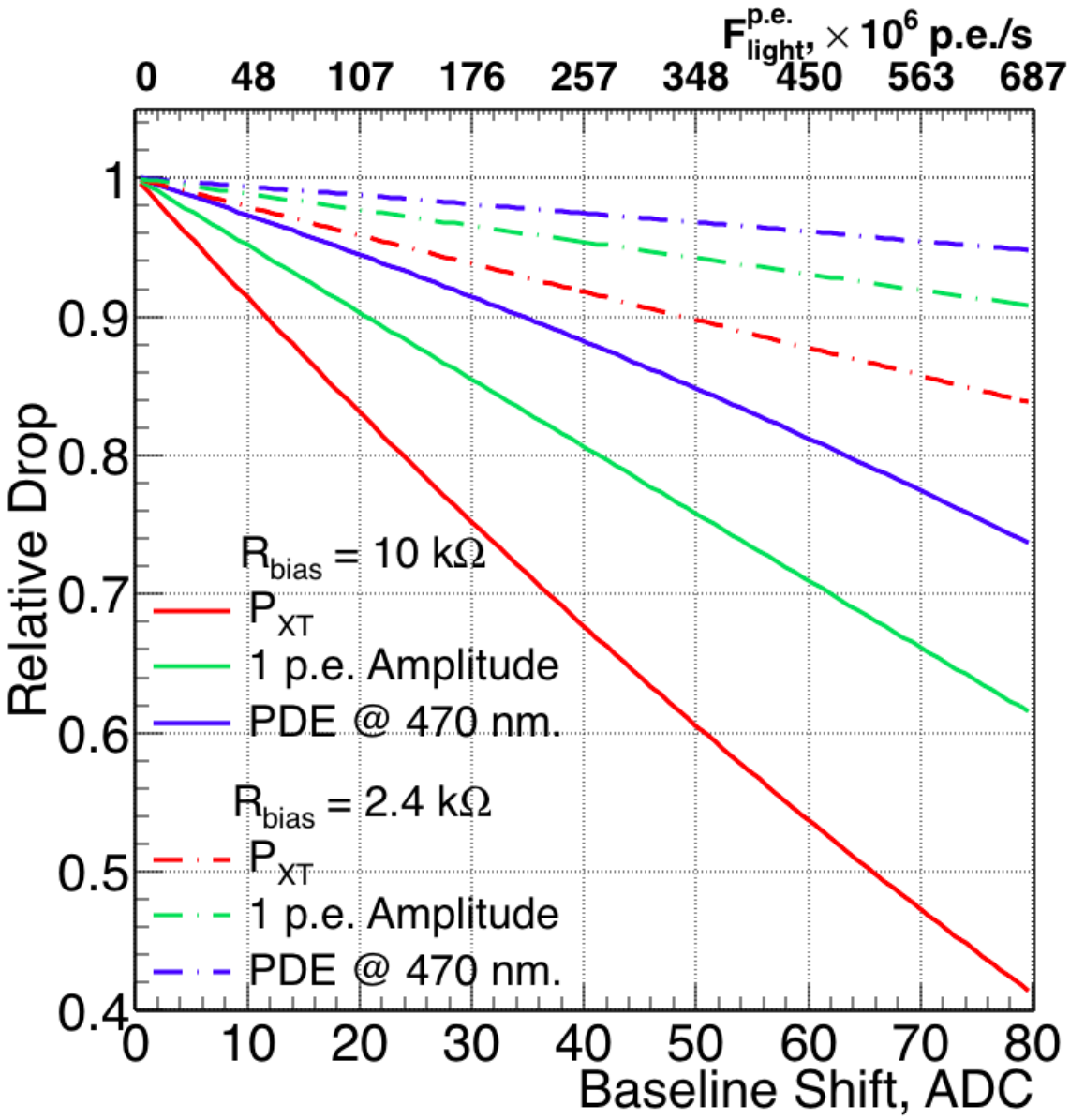


Figure 2: Typical schematics to bias SiPM device.

SiPM devices are usually biased through an RC filter to:

- filter high frequency electronic noise coming from the DC bias source
- limit the current to protect the sensor in case of intense illumination.
- Increase MTBF (mean time before failure) of sensor
- But this resistor induces a **voltage drop** at the sensor cathode in the presence of continuous light, which reduces the bias voltage and therefore changes its operation point



http://arxiv.org/pdf/1910.00348.pdf

An advanced large size telescope camera

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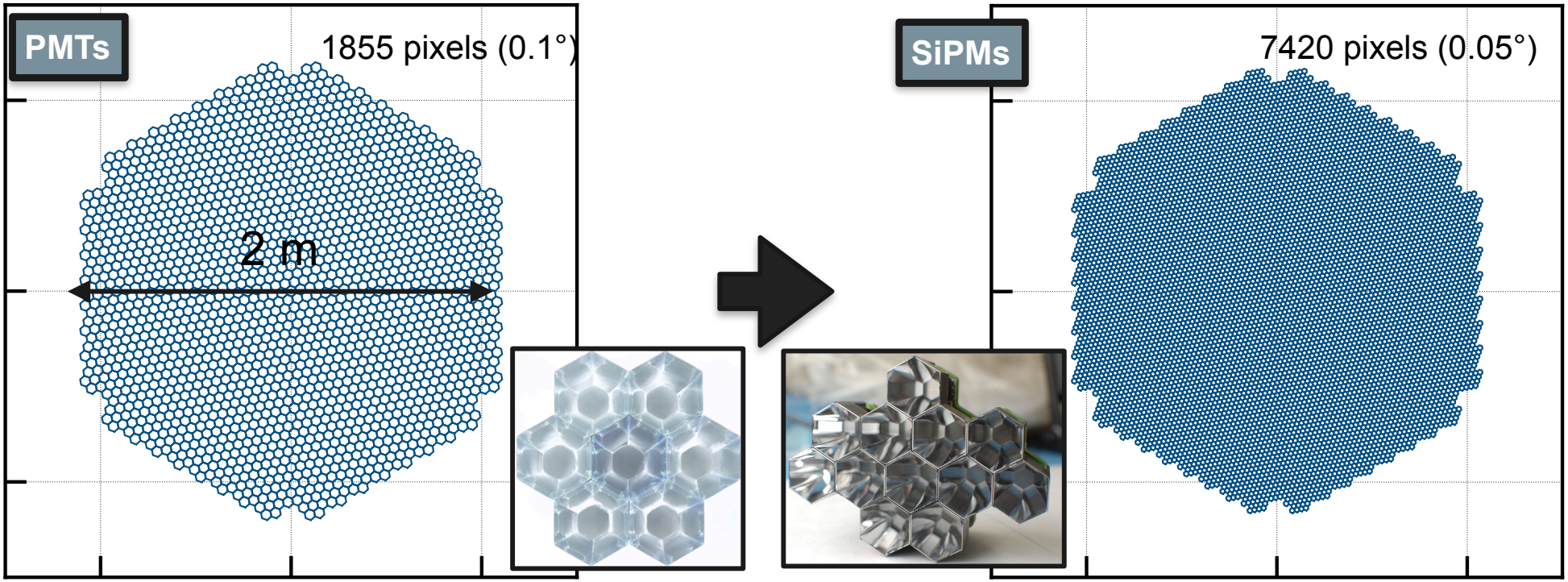
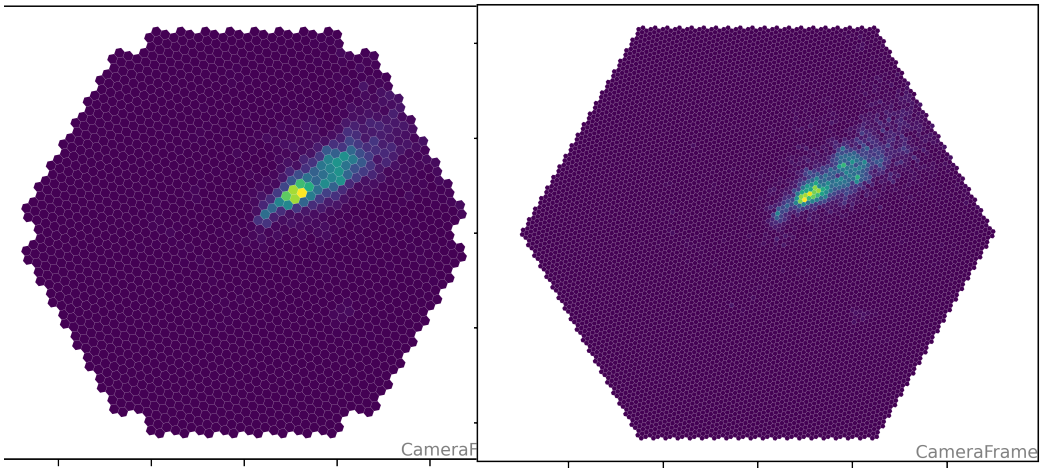
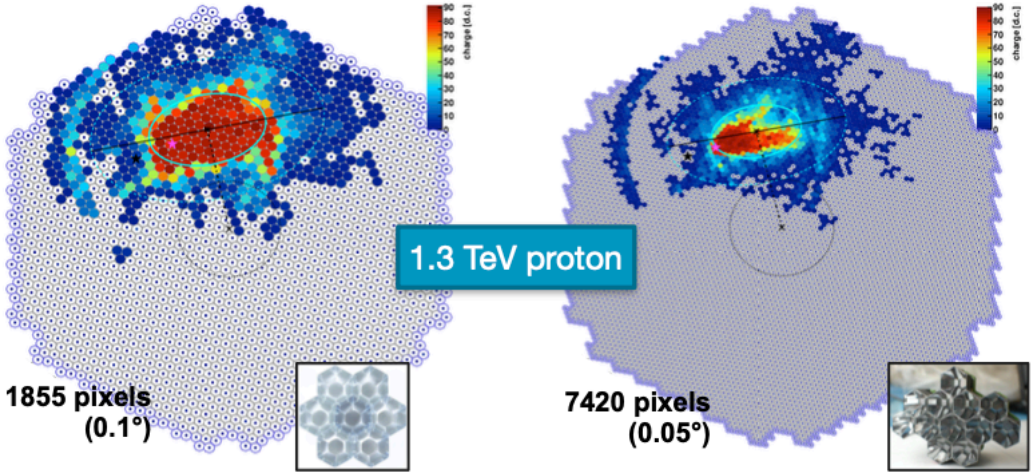


Gamma-ray event





Architecture

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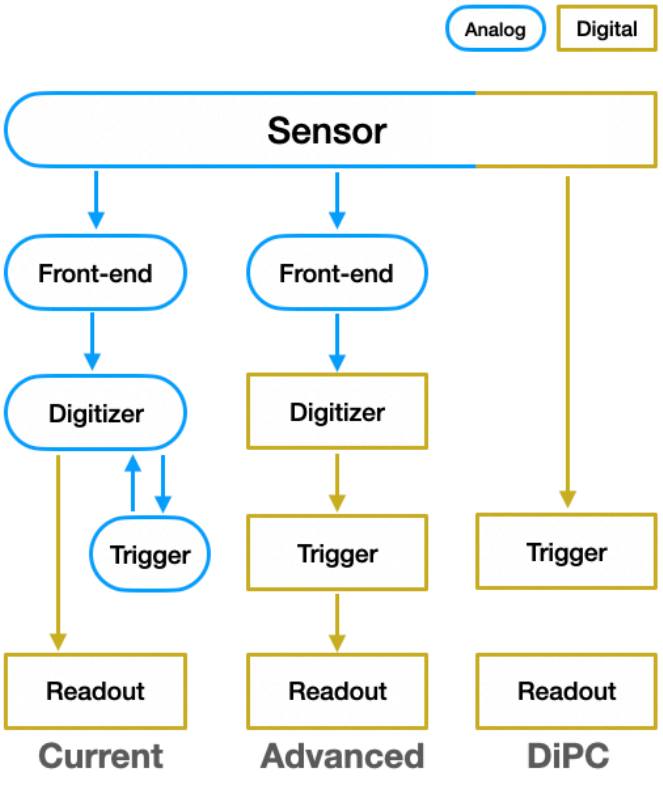
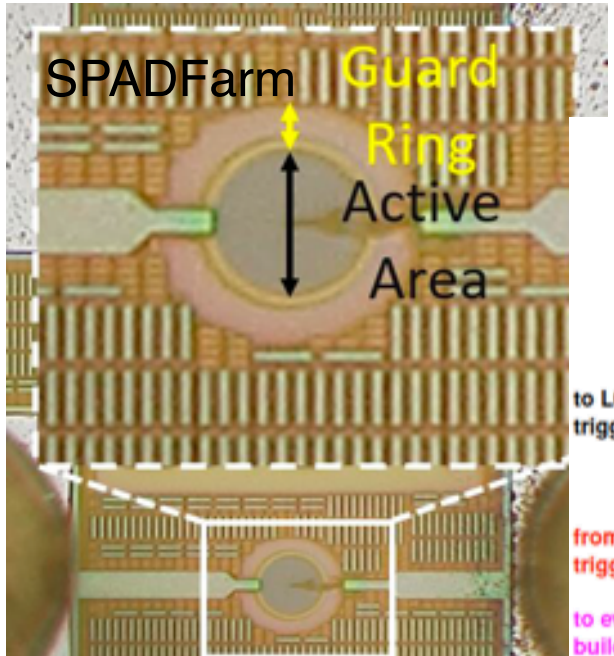
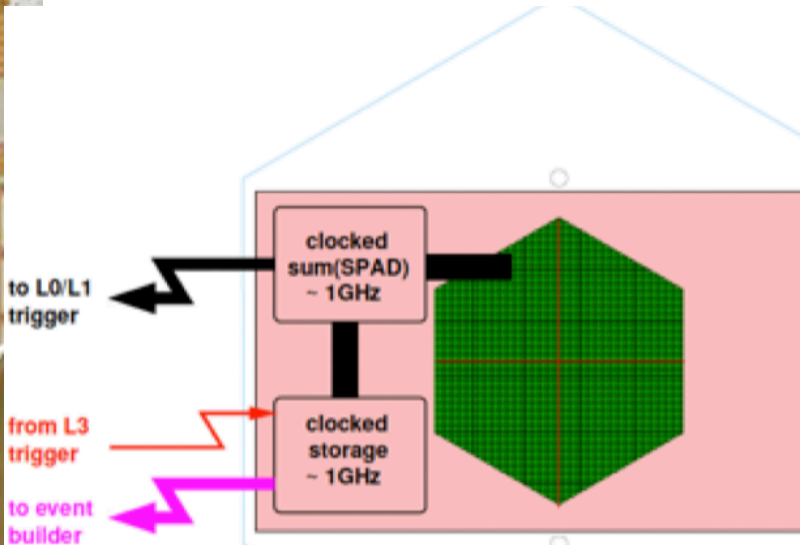
Frontend: Low power consumption amplification and shaping ASIC for improved SiPM technology
Readout: fully digital GHz readout in low power consuming ASIC.
With most of data out, real-time stereo smart triggers can be implemented. AI in ASIC or FPGAs for significant data volume reduction at raw data level as close to sensor as possible.
Upgradable and Reprogrammable!

Digital Photon Counters

- Instead of a waveform, provide a photon stream (photon count per time bin)
  - ✦ Compact and lower power photo-detection plane
- New developments based on existing SPAD technology:
  - ✦ LinoSPAD2 (CMOS 180 nm)
  - ✦ SPADFarm (CIS 110 nm)
- Data rate to output all photon information can be prohibitive, so trigger strategy on threshold+ coincidence among clusters of pixels







Conclusions

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- SiPM are robust and have at least comparable sensitivity than PMTs
- Low-power consuming + GHz digitising + integrated AI electronics suitable for new sensors needs developments
- Digital Photon Counters are challenging due to PDE in UV but many developers undertook the challenge
- NUV detectors work well for ground and space