Recent developments in photodetection for Astroparticle Physics

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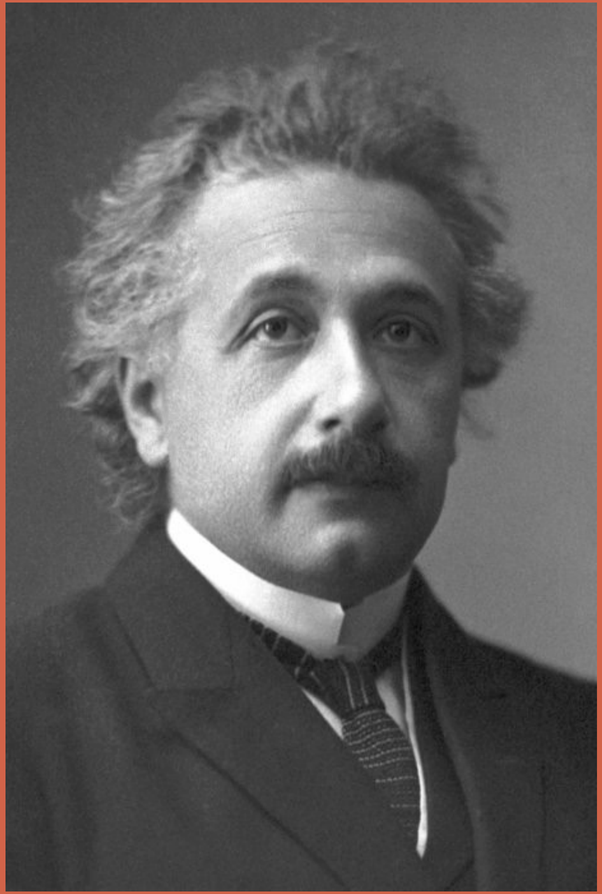
Outline

- The Physics behind silicon photomultipliers
- Geometry and principle of operation
- A SiPM for every need: from vacuum-ultra-violet to near-infrared, to extreme environments
- SiPMs for astroparticle physics

Pop quiz!!!

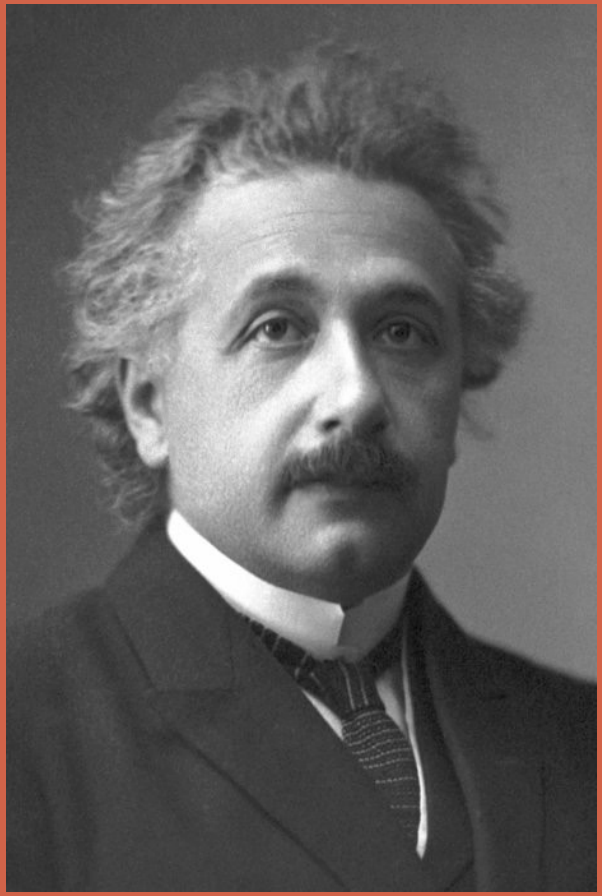


The Nobel Prize in Physics 1921 was awarded to Albert Einstein

a) «for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect»
b) «for his services to Theoretical Physics, and especially for his theory of special relativity, reconciling Newton's laws of motion with electromagnetism»
c) «for his services to Theoretical Physics, and especially for his theory of gravitation*»

*a.k.a.: «general relativity»

Pop quiz!!!

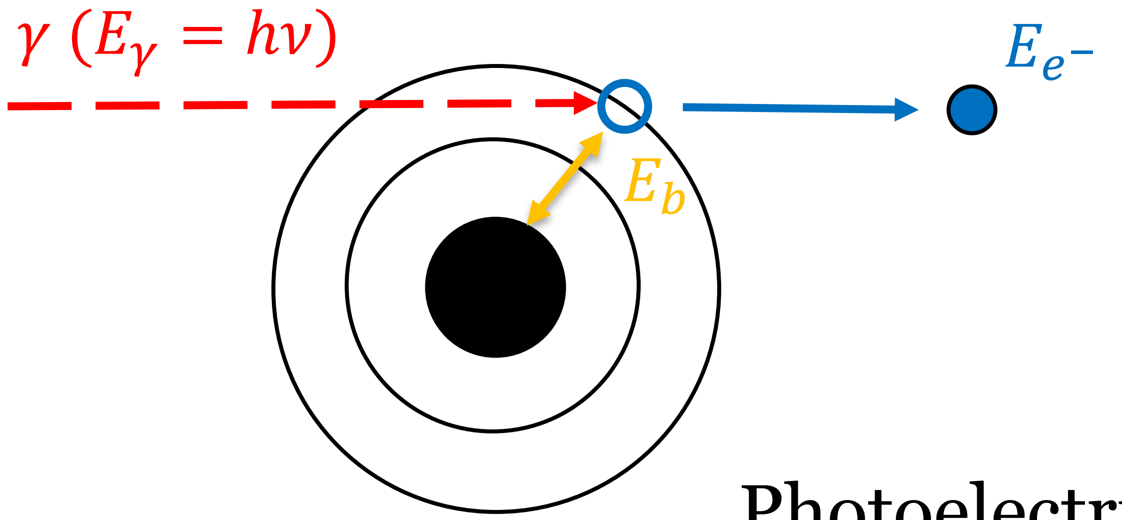


The Nobel Prize in Physics 1921 was awarded to Albert Einstein "for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect."

Albert Einstein received his Nobel Prize one year later, in 1922. During the selection process in 1921, the Nobel Committee for Physics decided that none of the year's nominations met the criteria as outlined in the will of Alfred Nobel. According to the Nobel Foundation's statutes, the Nobel Prize can in such a case be reserved until the following year, and this statute was then applied. Albert Einstein therefore received his Nobel Prize for 1921 one year later, in 1922.

https://www.nobelprize.org/prizes/physics/1921/summary/

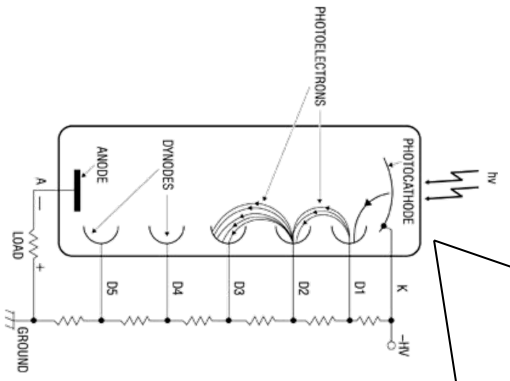
Photoelectric absorption

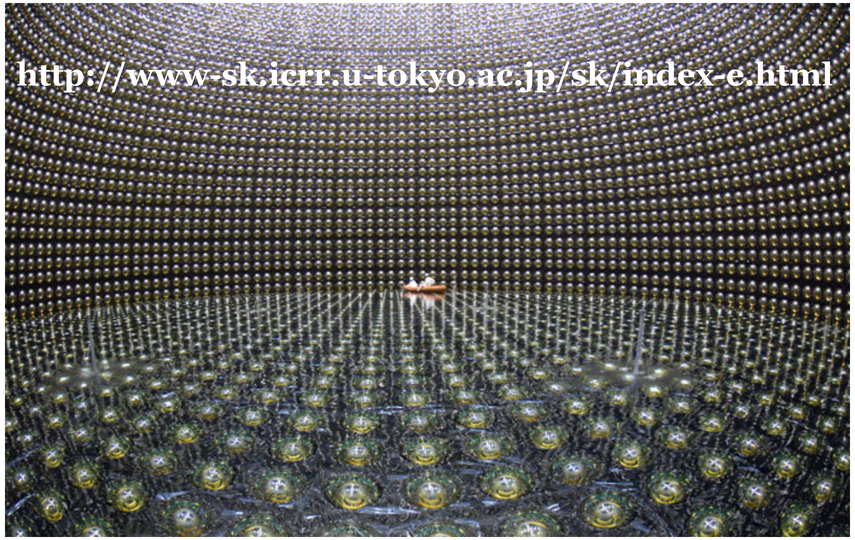


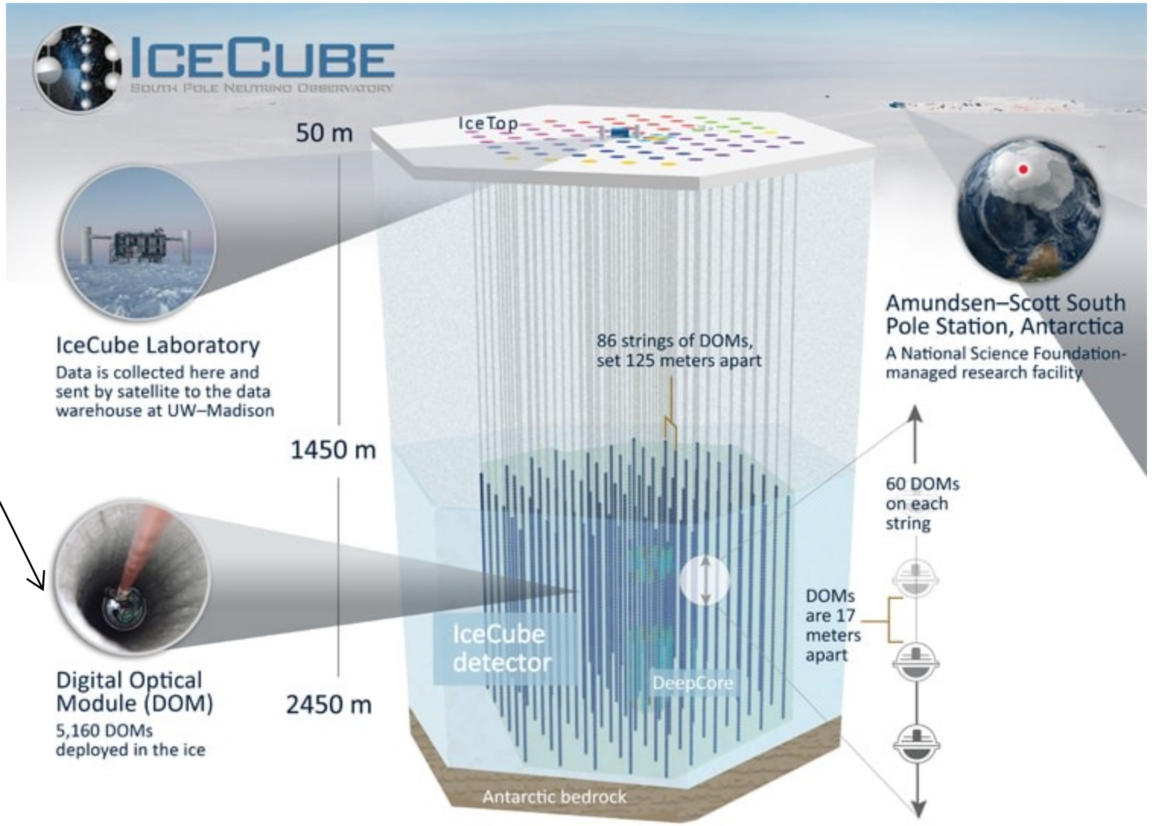
$$E_{e^-} = h\nu - E_b$$

Photoelectric absorption is a threshold process: E_b is the minimum amount of energy a photon must carry to extract the electron

Detectors that exploit the photoelectric effect: Photomultiplier tubes







https://icecube.wisc.edu/science/icecube/

Detectors that exploit the photoelectric effect: Solid-state sensors

Photodiodes

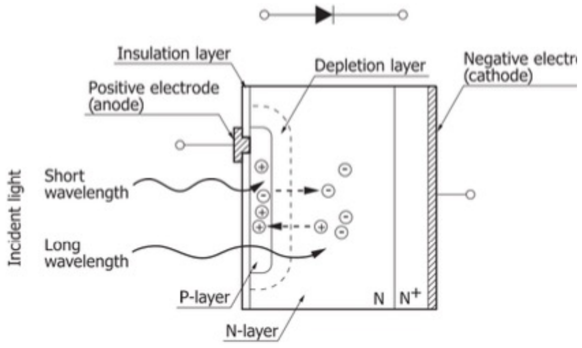


FIGURE 3.12: Schematic of a Si photodiode cross section

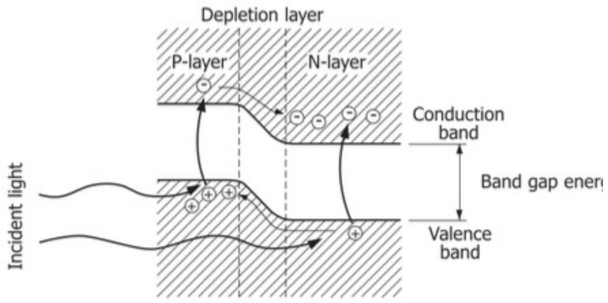
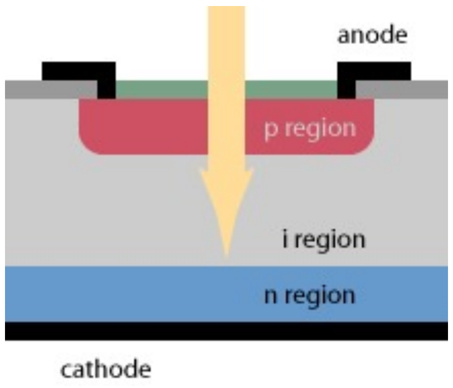
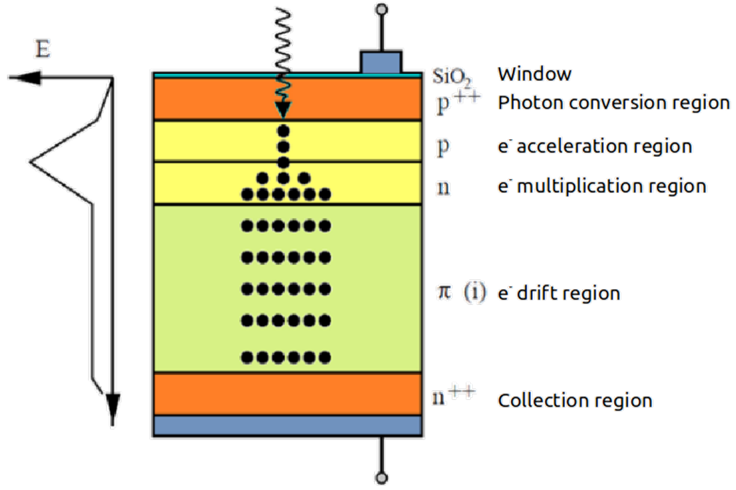


FIGURE 3.13: Effect of a photon impinging on a photodiode

Hamamatsu Photonics Handbook. Si Photodiodes

APD



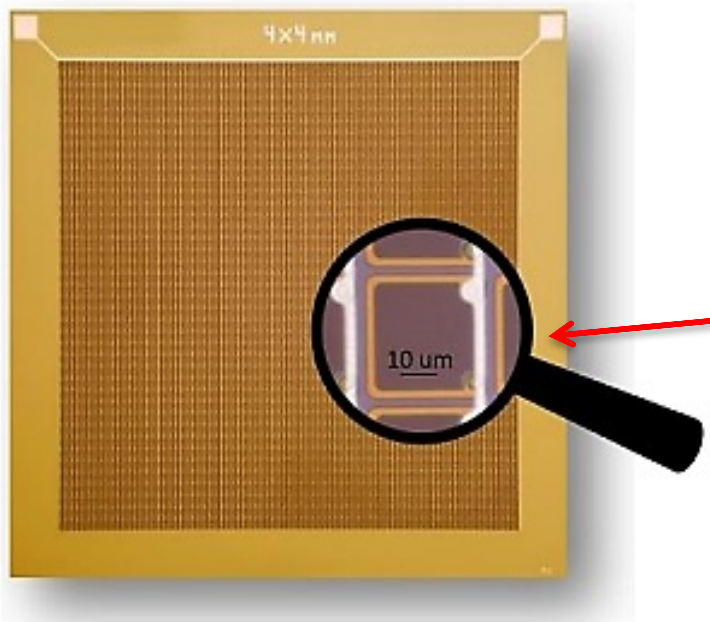


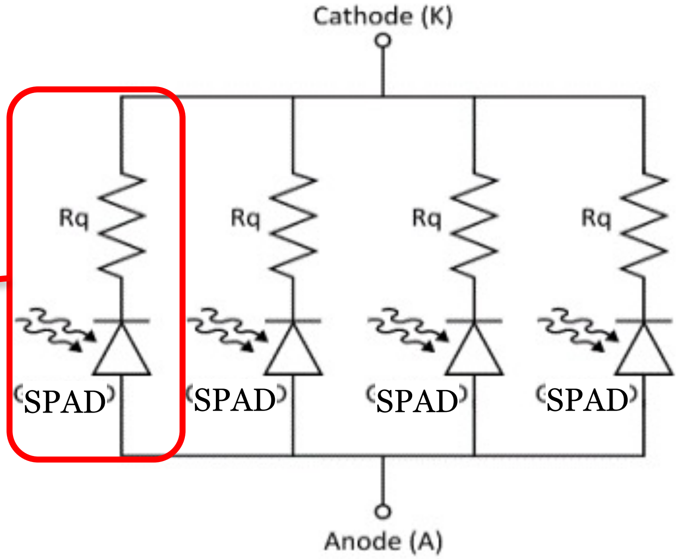
GM-APD

- p/n junction is biased above the breakdown voltage → <u>single hole-electron pair can trigger a self-sustaining avalanche</u>.
- <u>gain factor: 10^4-10^7</u>, even with relatively <u>low</u> applied <u>voltages</u> (few tens of volts).

Silicon photomultipliers (SiPMs): an array of GM-APDs

SiPMs: **array of reverse-biased Single Photon avalanche Diodes (SPADs)** connected in parallel, each with **integrated quenching resistor**



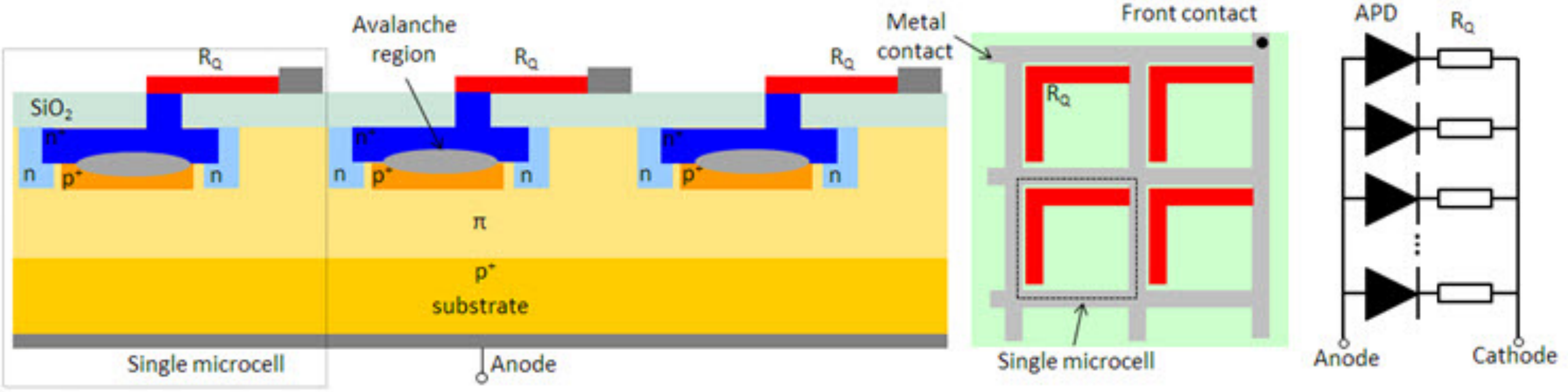


http://advansid.com/resources/the-silicon-photmultiplier

SiPM size: from 1x1mm² to 10x10mm²

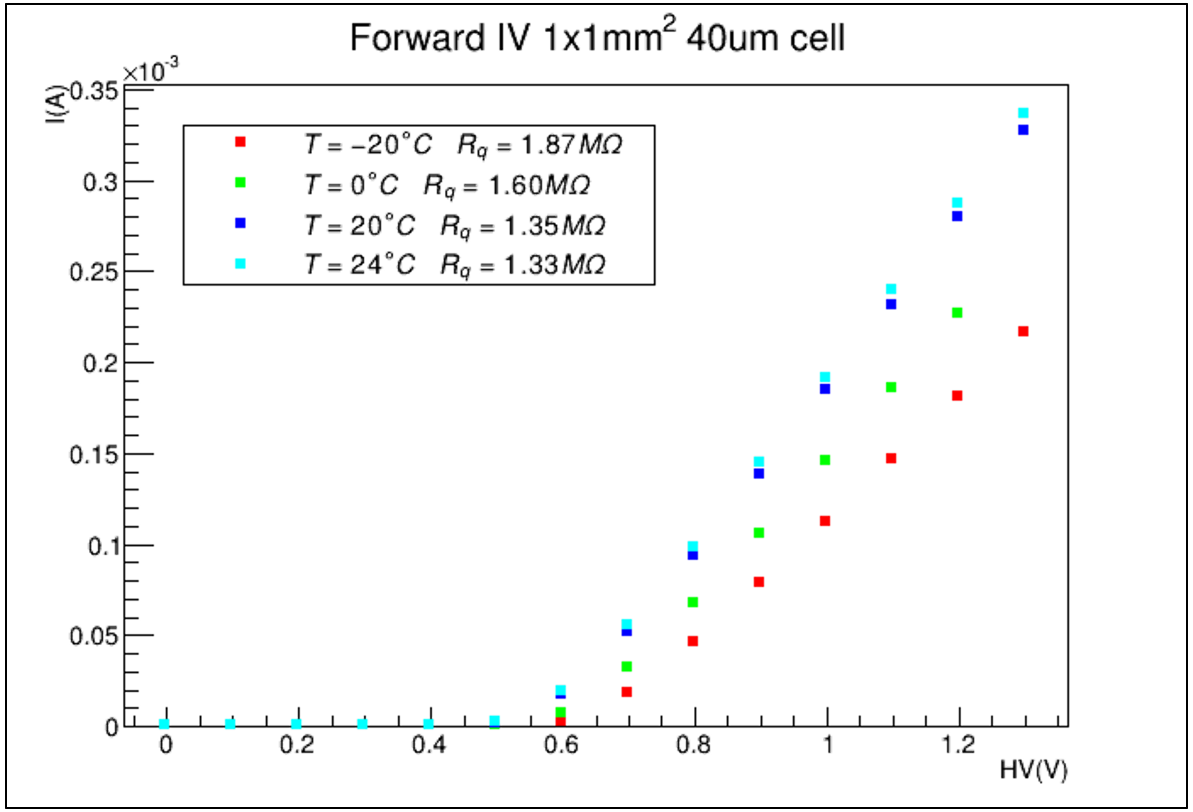
SPAD size: from 5µm to 40µm (typical)

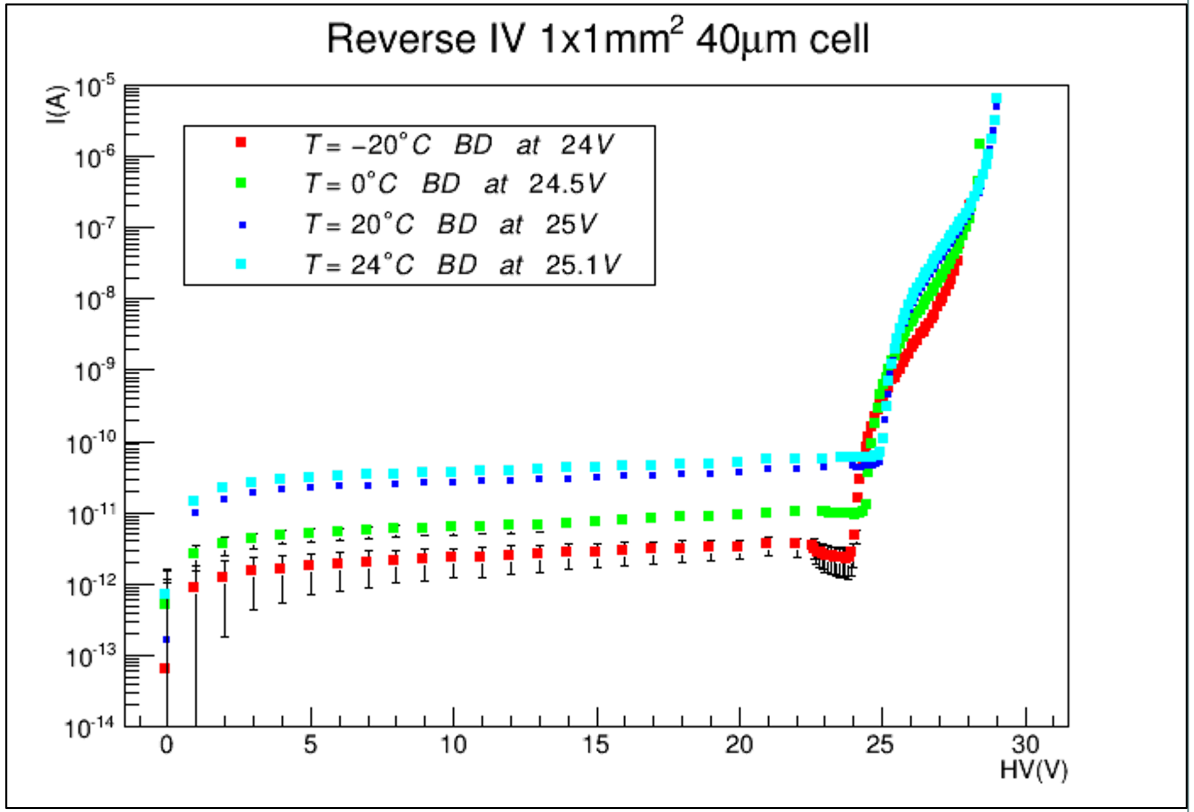
SiPMs: 3D view



https://hub.hamamatsu.com/jp/en/technical-note/how-sipm-works/index.html

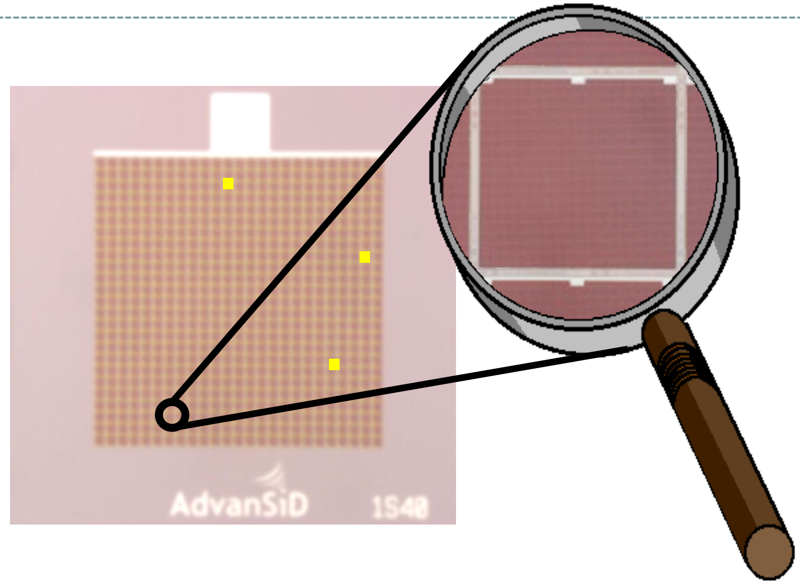
SiPMs I-V curves

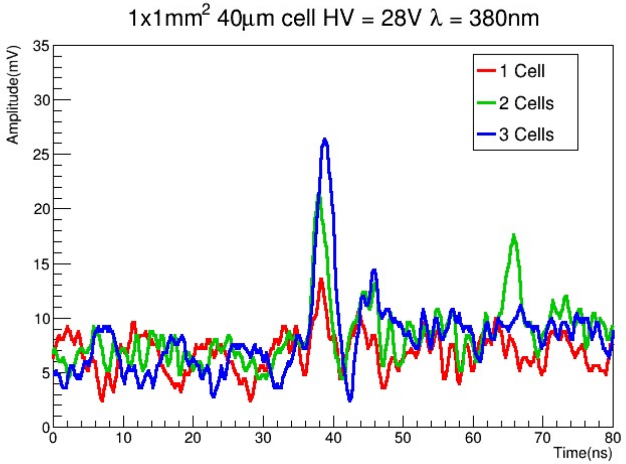


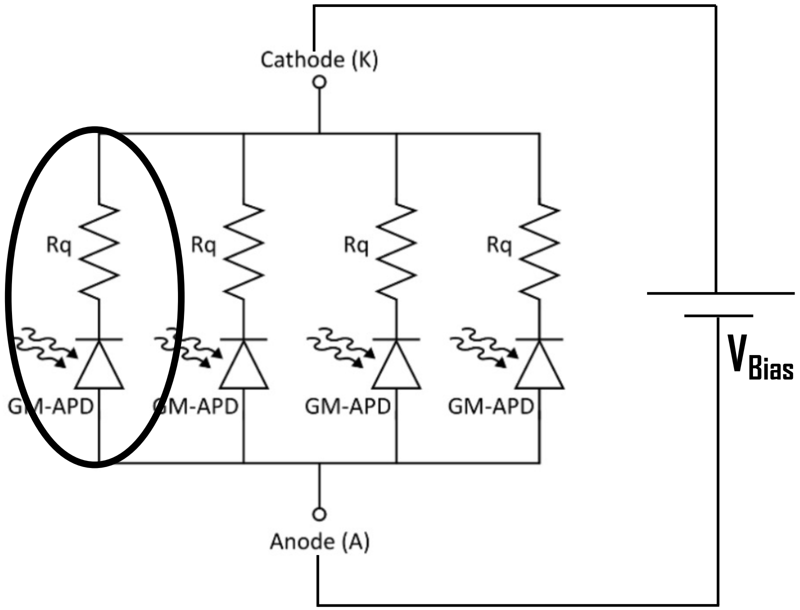


Forward and reverse I-V characteristics of a NUV 1x1mm² SiPM with 40μm cell at different temperatures. (M. Capasso, «Development of a NUV camera for Cherenkov telescopes applications»)

A single-photon counter in action







The output signal is proportional to the impinging number of photons (in the linear regime)

SiPMs: Fill Factor

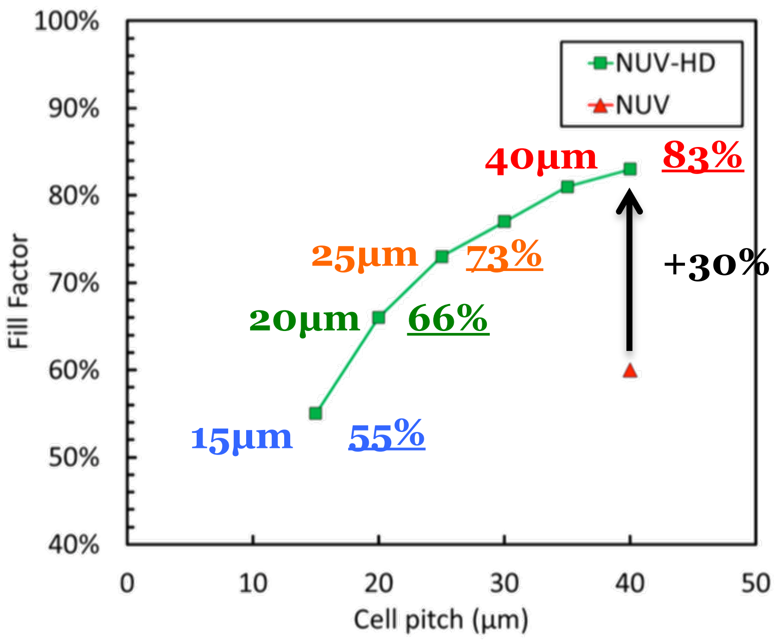
active area

SPAD size
(total area)

$$FF = \frac{A_{eff}}{A_{total}}$$

- All SiPMs belonging to a given technology lie on the same curve
- Smaller pixels → higher dynamic range and faster recovery
- Larger pixels → higher efficiency

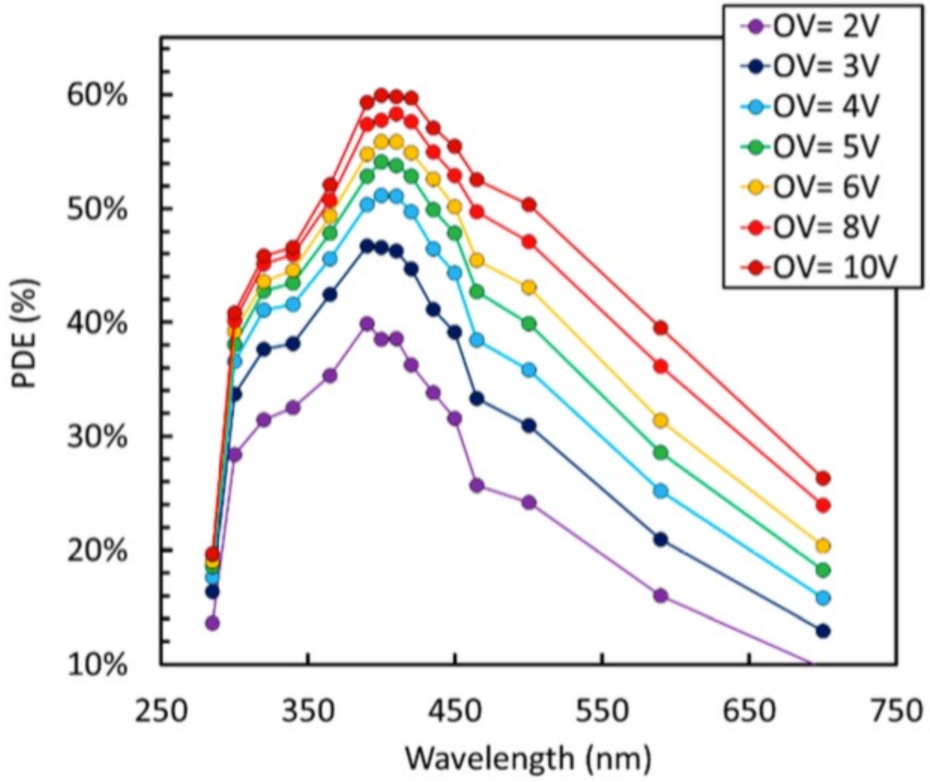
The optimal compromise varies from application to application (figure of merit)



A. Gola et al., https://doi.org/10.3390/s19020308

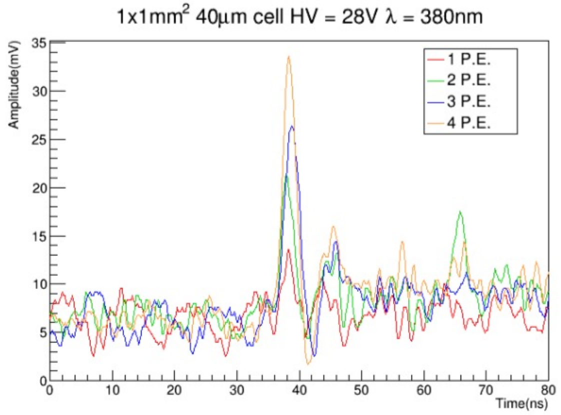
SiPMs in a snapshot: why we like them

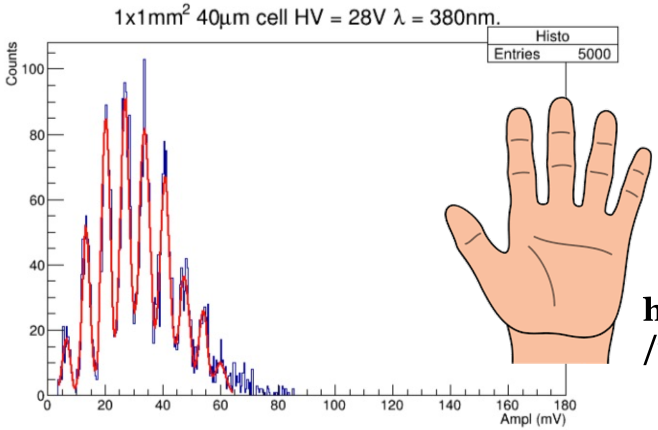
High PDE



Gola et. al. https://www.mdpi.com/1424-8220/19/2/308

Single p.e. resolution





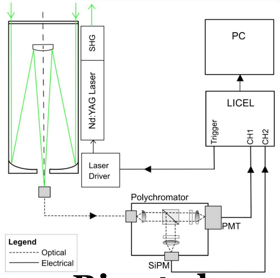
- Ruggedness
- Insensitivity to magnetic fields
- …

https://webstockreview.net/explore/thumb-clipart-hand/

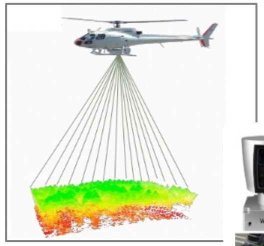
SiPMs: applications

<u>Compactness</u>, <u>ruggedness</u>, <u>insensitivity to magnetic fields</u>, <u>wide sensitivity spectrum</u>: a perfect mix for scientific and industrial applications!!!

LIDAR (light detection and ranging)

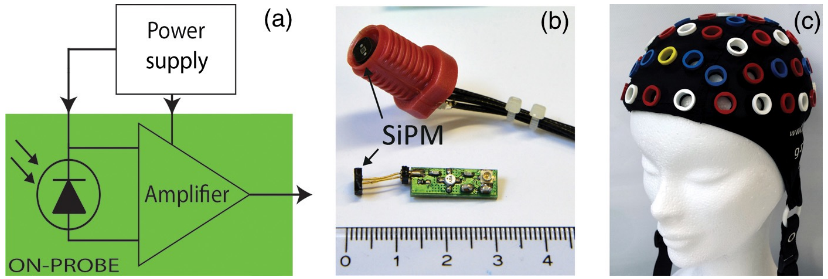


Riu et al.



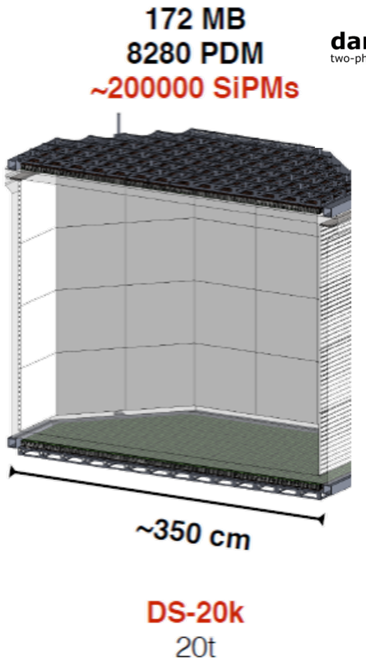
Kato et al.

fNIRS (functional NIR Spectroscopy)



Re et al. Neurophoton. 3(4), 045004 (2016)

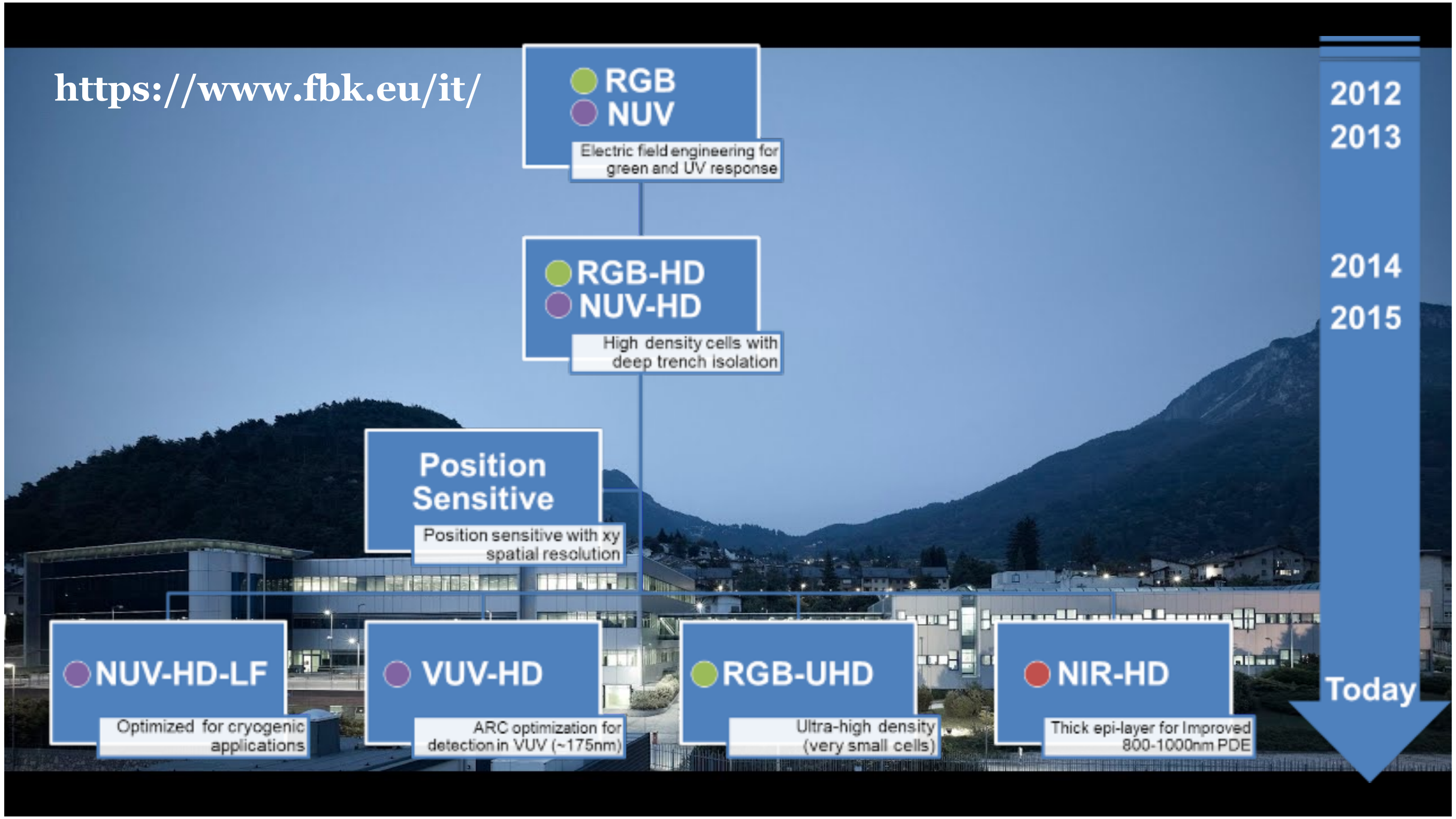
Rare-event experiments



Liquid Argon
emission, wavelength-shifted (~400-450nm)

2 light readout planes:
~20 m²

SiPMs at FBK: technological roadmap



INFN and FBK, a long, fruitful partnership (a.k.a.: an undergraduate story)

Università degli Studi di Bari "Aldo Moro"

Corso di laurea in Fisica

Tesi di laurea magistrale

Development of a NUV camera
for Cherenkov telescopes applications

Relatore:
Prof. Francesco Giordano
Correlatore:
Dott.ssa Elisabetta Bissaldi

Laureando:
Massimo Capasso

Anno Accademico 2013-2014

- 2012: F. Santoro "Studio di fotorivelatori al silicio per singolo foto-elettrone". Bachelor's thesis at Università degli Studi di Bari - Dipartimento Interateneo di Fisica Michelangelo Merlin.
- 2013-2014: M. Capasso first internship at FBK and Master's thesis on SiPM for Cherenkov telescopes applications
- …

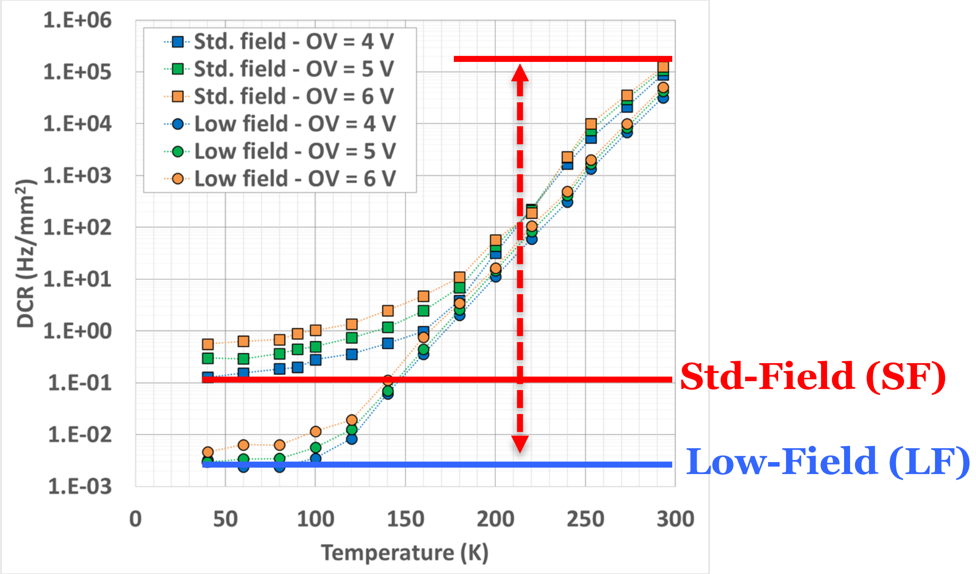
Some SiPM recent developments

SiPMs for «extreme» environments: cryogenic applications

SiPMs for short (VUV) or long (NIR) wavelengths

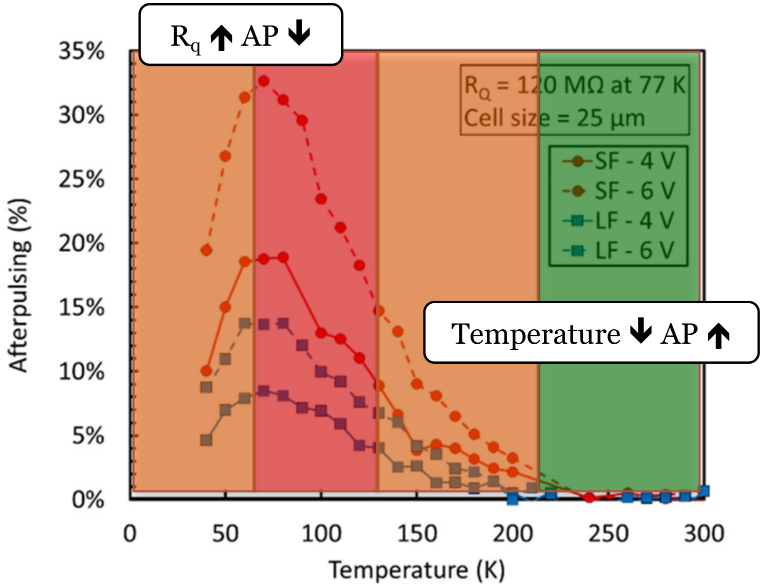
NUV-HD go "cool": cryogenic challenges

Tunneling is the primary DCR generation mechanism



F.Acerbi et al., *IEEE Trans. Electron Dev. 64, 2, (2017), 521-526*

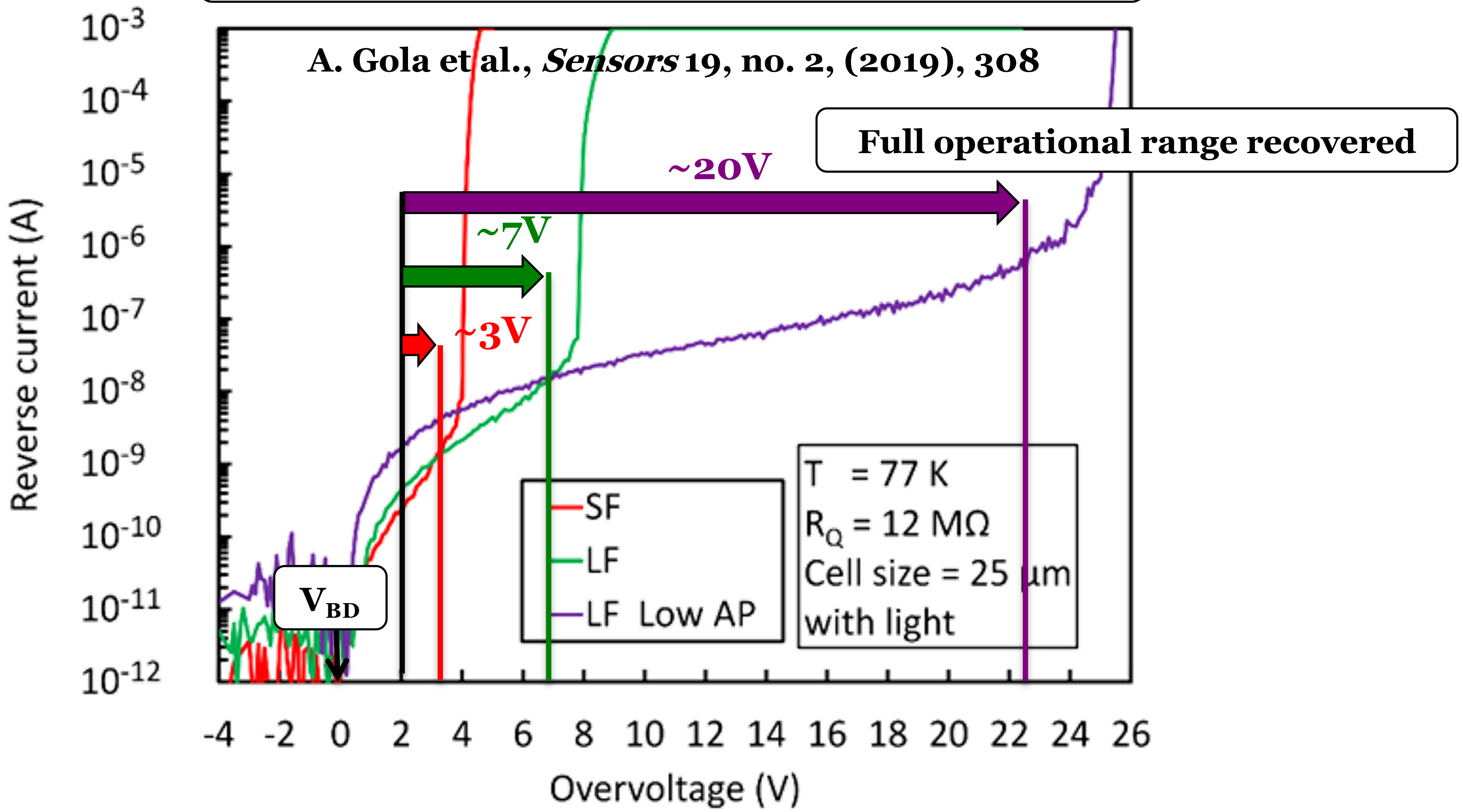
Increase of release time constant of trapping centers increases AP probability (LF is not enough).



A. Gola et al., *Sensors* 19, no. 2, (2019), 308

NUV-HD LowField+LowAP: NUV-HD-Cryo

Reverse IV curves at 77K (LN), under light



Vacuum ultra-violet detection with SiPMs

In some specific applications direct detection of VUV light is required → NUV-HD technologies have 2 main limiting factors

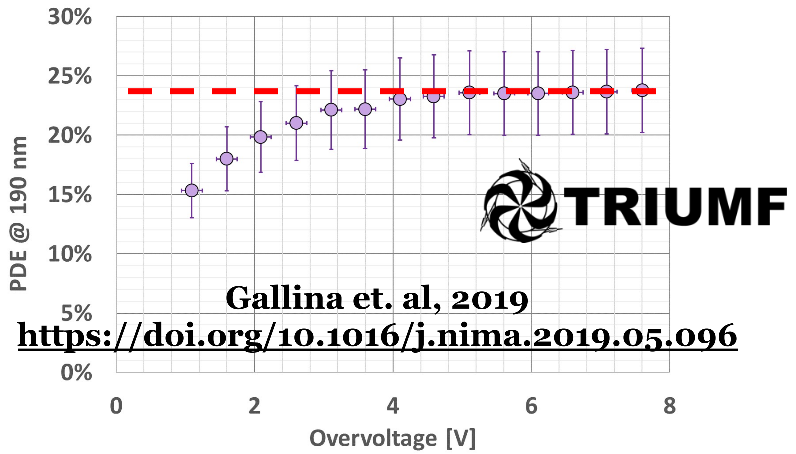
Typical ARC is a multi-layer stack of SiO_2(absorbs λ<150nm), Si_3N_4(absorbs λ<250nm) → external QE is affected

R&D focused on ARC optimization:

- Si_3N_4 removal
- Preservation of surface passivation quality

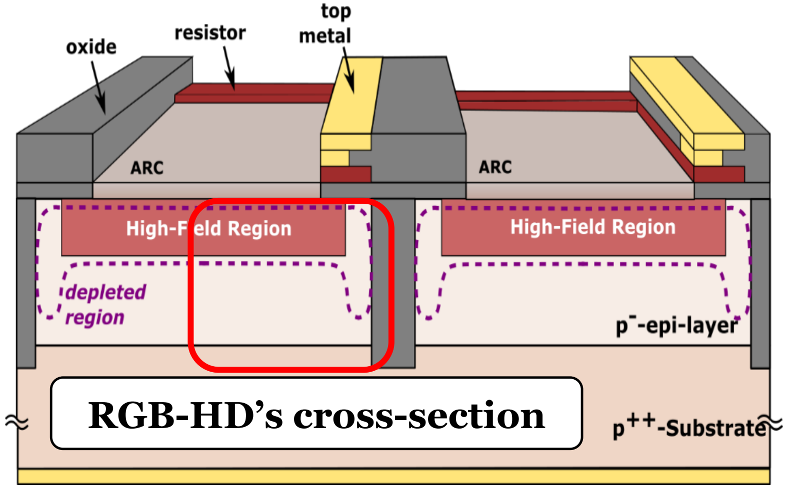
Current R&D has been conducted in collaboration with TRIUMF

Ultra-shallow absorption of UV light→ generated e-h pairs have high recombination probability → internal QE is affected



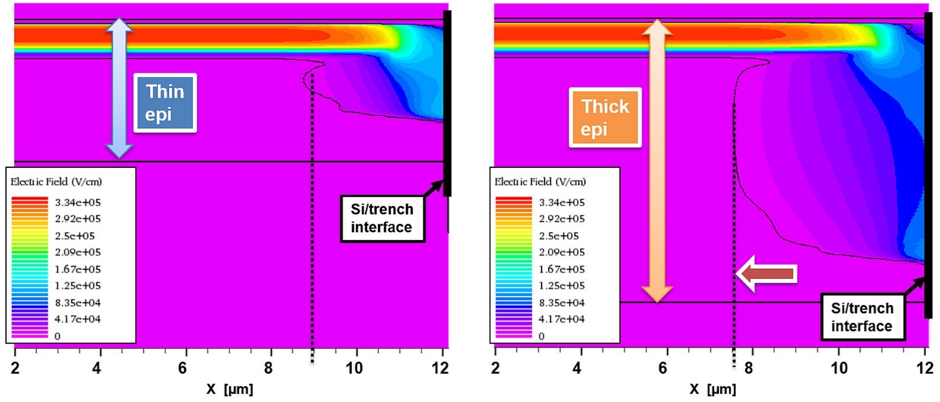
Gallina et. al, 2019
https://doi.org/10.1016/j.nima.2019.05.096

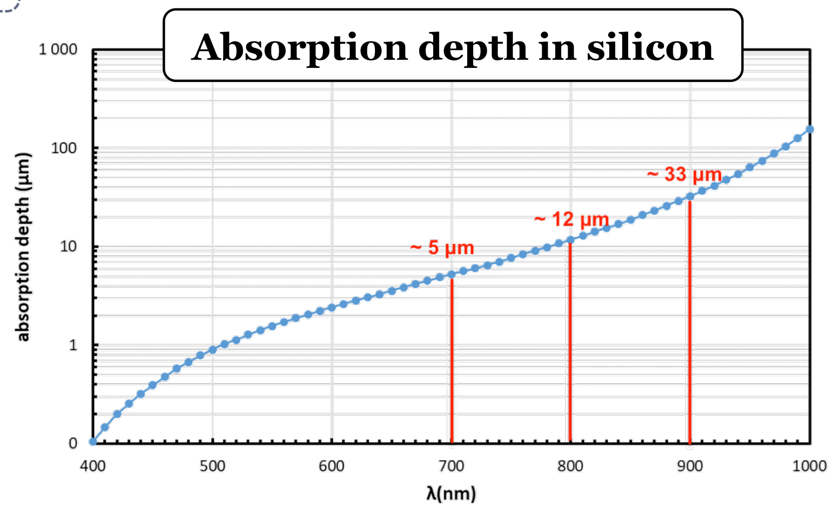
Near-infrared detection with SiPMs: technical challenges



Acerbi et al, 2018 10.1109/JQE.2018.2802542

TCAD simulation at BD





Longer absorption depth → thicker epitaxial layer

Border effects may limit the effective area, reducing the PDE despite the thicker epi

Dedicated electric-field engineering partially reduced lateral depletion and extended high-field region

Future challenges

- Go denser: some applications might require higher pixel density for higher dynamic range
  - Push pixel design to the limit in order to keep satisfactory fill-factor
- Go harder: required in high-energy-physics experiments and space applications
- Go longer: better performance in the NIR of interest for e.g.: LIDAR applications

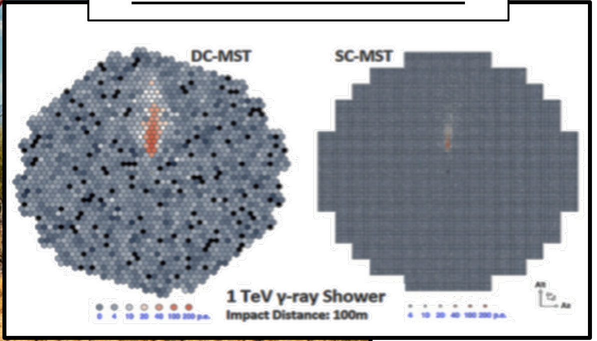
SiPMs for Cherenkov astronomy

The Schwarzschild-Couder Telescope at the Fred Lawrence Whipple Observatory (Arizona)

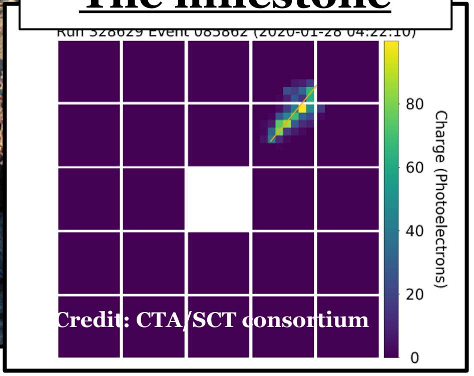
The Schwarzschild-Couder Telescope (SCT)

The inauguration

The motivation



The milestone



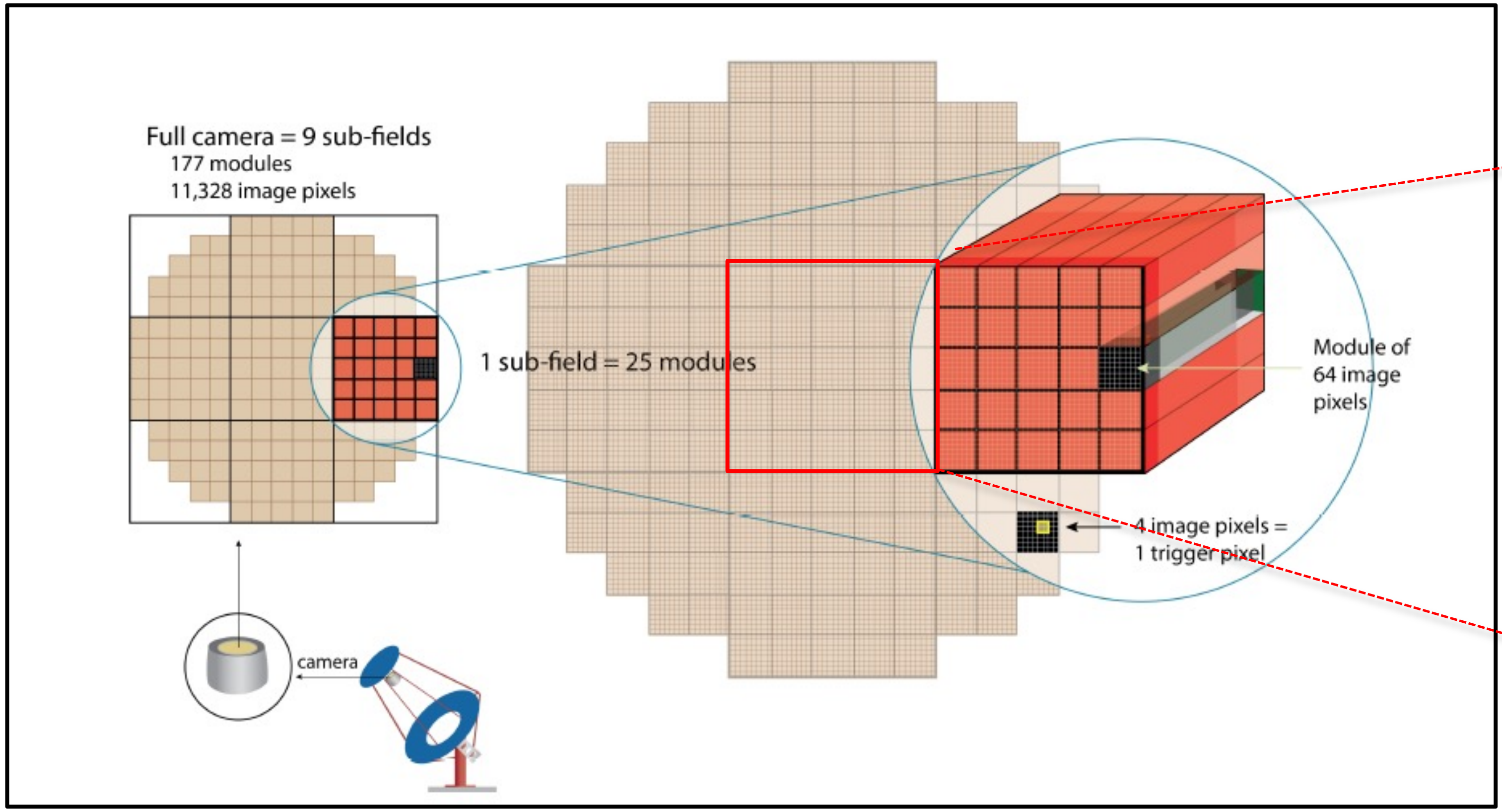
Credit: CTA/SCT consortium

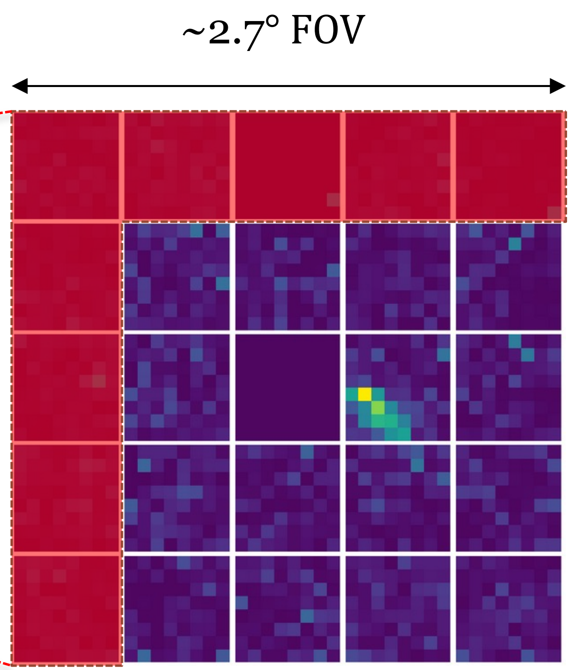
Photo: M. Capasso

The CTA SCT Project

- ~30 institutions https://cta-psct.physics.ucla.edu/institutions.html
- Milestones:
  - 1st construction: 06-23-2015
  - Inauguration: 01-17-2019
  - 1st light: 01-23-2019
  - December 2019: optical alignment achieving pre-construction estimated PSF
  - May 2020: significant detection of the Crab Nebula (presented at 236th AAS) – published paper
  - Endorsement by the CTA Consortium for supporting the development and construction of SCTs to add to the array and complement single-mirror MSTs
- Next steps:
  - Ongoing (funded MRI): population of the focal plane to ~11k channels with upgraded SiPMs and electronics

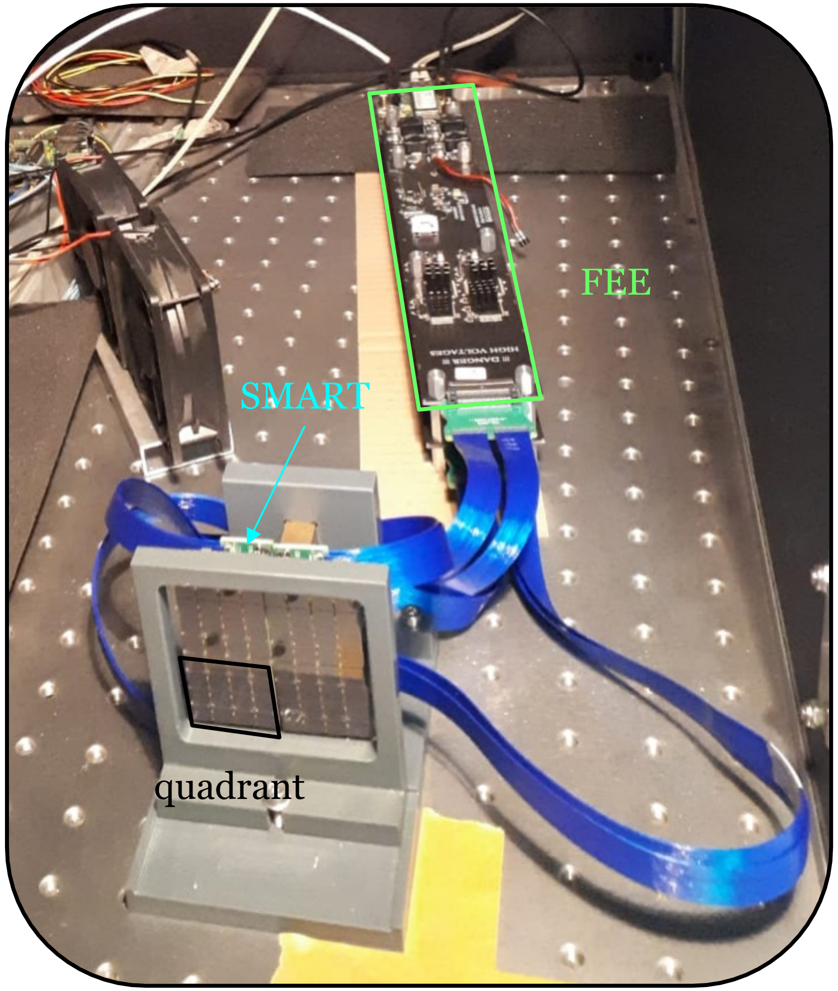
The SCT SiPM camera





INFN modules

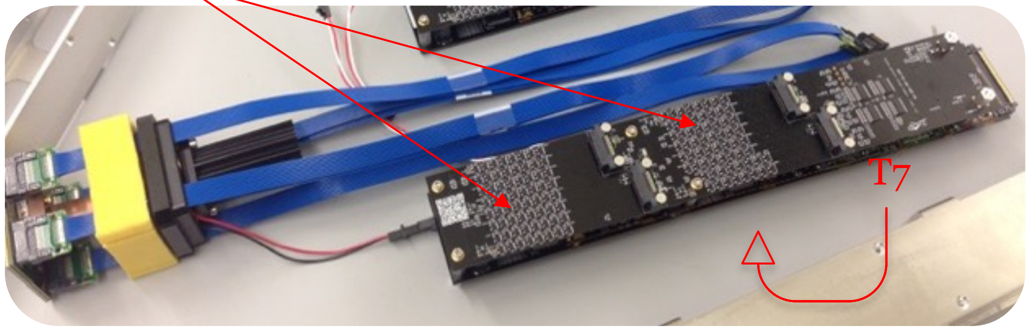
Preamplifier+FEE upgrade



- Testing Setup:
  - **Full chain** from SiPMs to FEE assembled
  - Laser source + moving stage to illuminate one pixel at a time

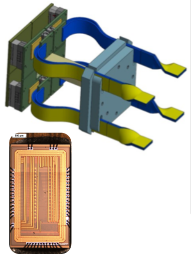
Full-chain testing : current vs. upgrade

Preamps and current sensors



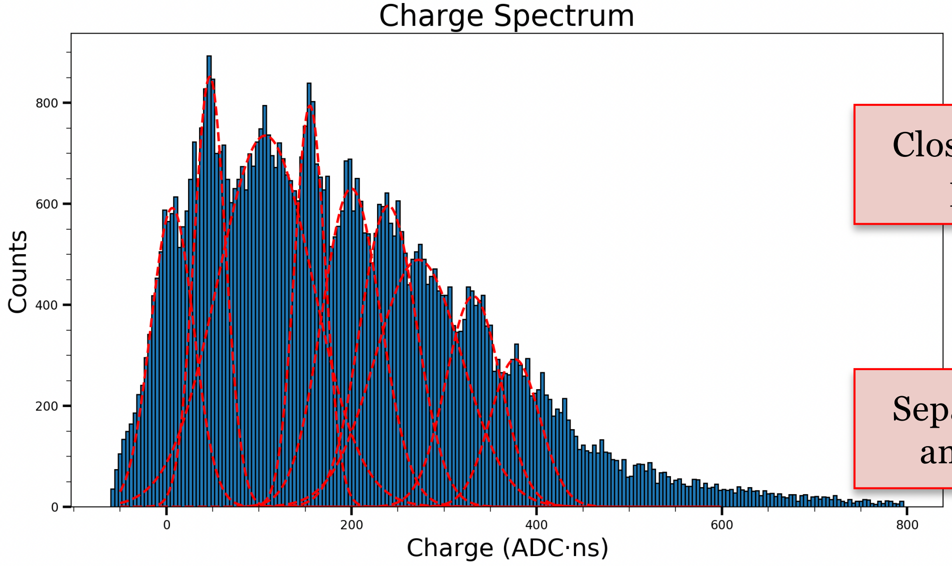
T7

FPM



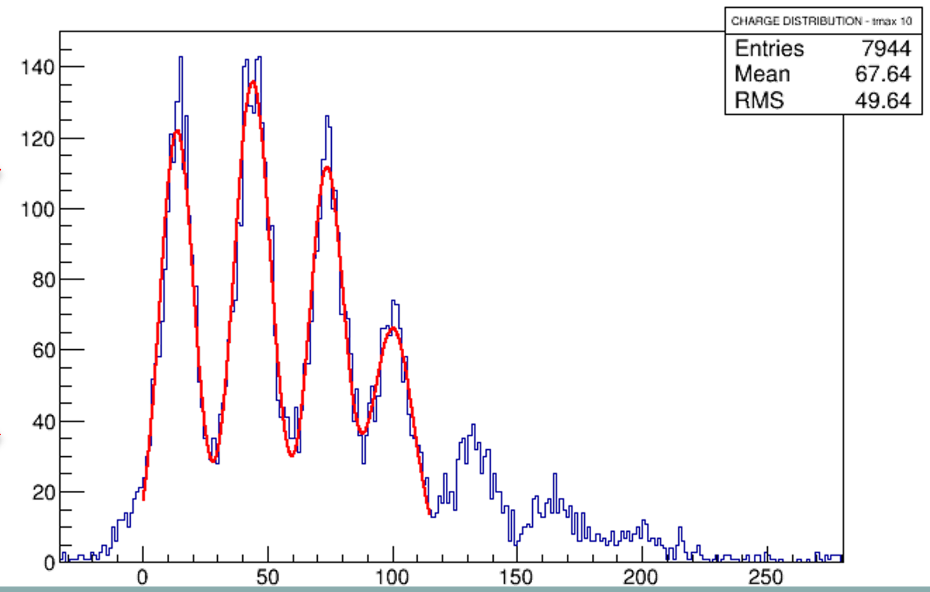
(C)T5TEA + (C)TC

FPM+preamps and current sensors (SMART)



Closer FPM and preamps

Separate trigger and digitizer



Summary and conclusions

- SiPMs are nowadays a mature technology that can replace PMTs in a wide variety of applications requiring single-photon sensitivity
  - There is a SiPM for every need and every spectral response from VUV to NIR
- SiPMs in ground-based Cherenkov astronomy: the SCT
  - A milestone pathfinder for dual-mirror telescope technology + solid-state sensors
  - New SiPMs, new electronics and a fully-populated focal plane to come! (The upgrade is ongoing)

STAY TUNED!!!