Characterization and modeling of SiPMs

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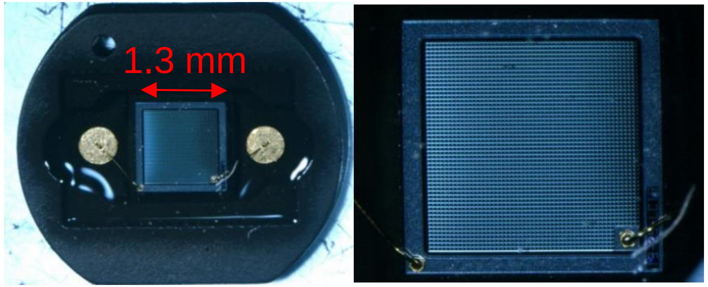
Silicon Photomultipliers (SiPMs)

- Photonsensor increasingly used in many applications, especially in scintillator detectors
- Array of reverse biased avalanche photodiodes (pixels) operating over the breaking voltage, “Geiger mode”
- Ideally, when any pixel is triggered by a photon, an avalanche of fixed charge is produced
- The amount of charge per avalanche is proportional to the overvoltage of the SiPM
- Many advantages compared with photomultipliers tubes.
  - Higher quantum efficiency, insensibility to magnetic fields, lower operating voltages,...
- Nevertheless, they have some problems:
  - Temperature dependence, **correlated noise, non-linear response**,...



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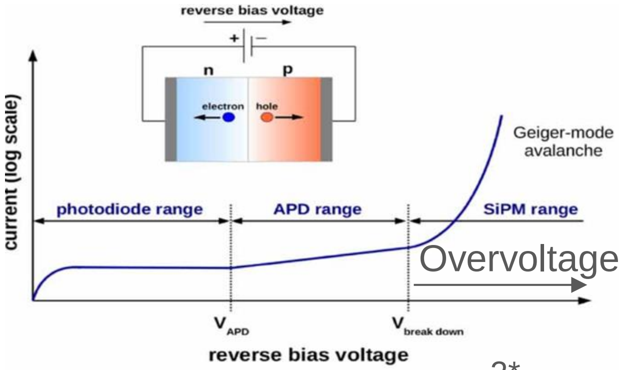

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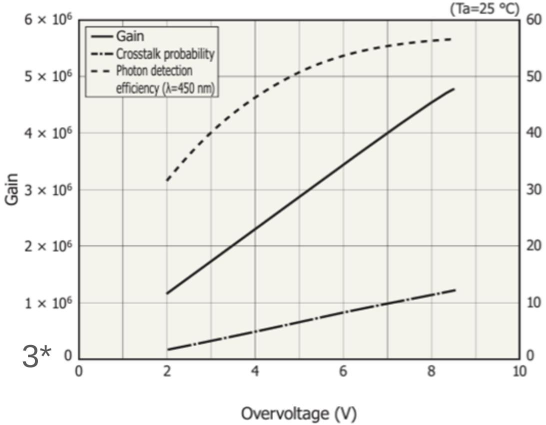

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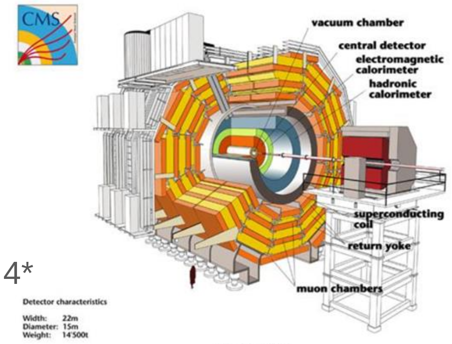
Applications of SiPMs

- High energy physics:
  - Compact Muon Solenoid (CMS)
  - Cherenkov Telescopes
- Medical applications:
  - Positron Emission Tomography (PET)
  - Compton Cameras
- Technology:
  - LIDAR
  - Flow Cytometry



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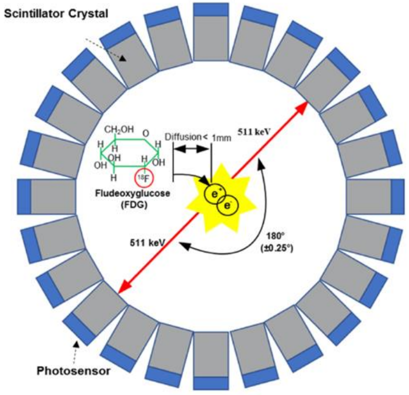

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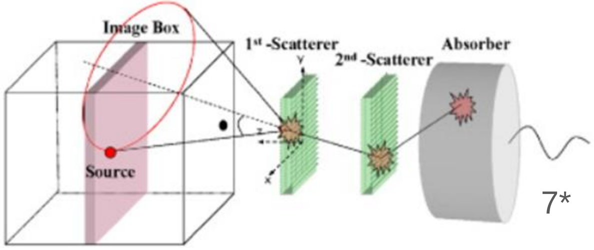

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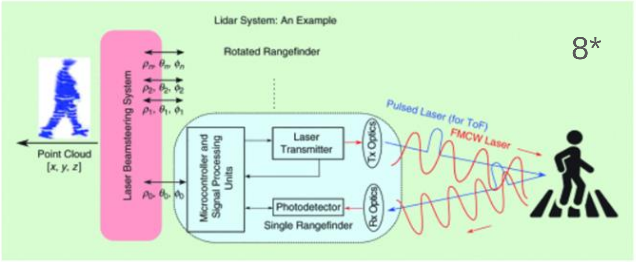

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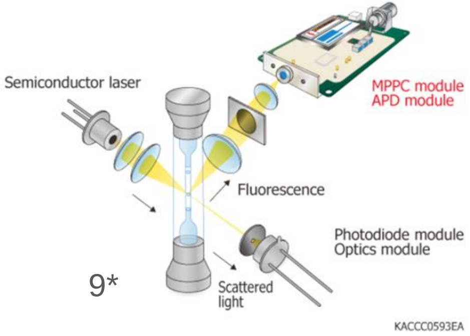

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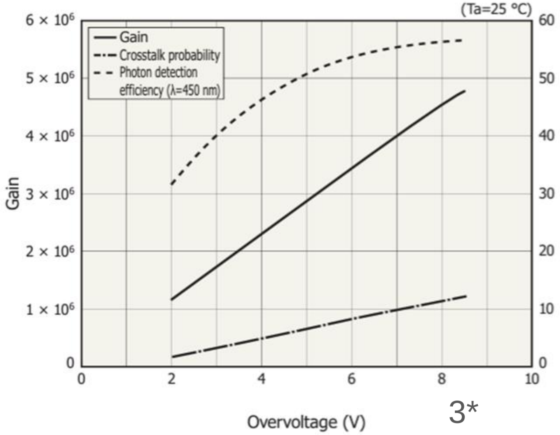
Intrinsic Noise in SiPMs

- Two kinds of intrinsic noise:
  - Uncorrelated noise: Dark counts
  - Correlated noise: Prompt crosstalk, Delayed crosstalk, Afterpulsing
- Both of them increase with overvoltage
- Dark counts have a strong temperature dependence



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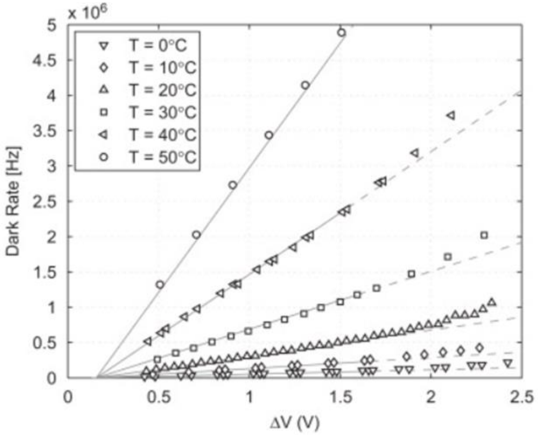

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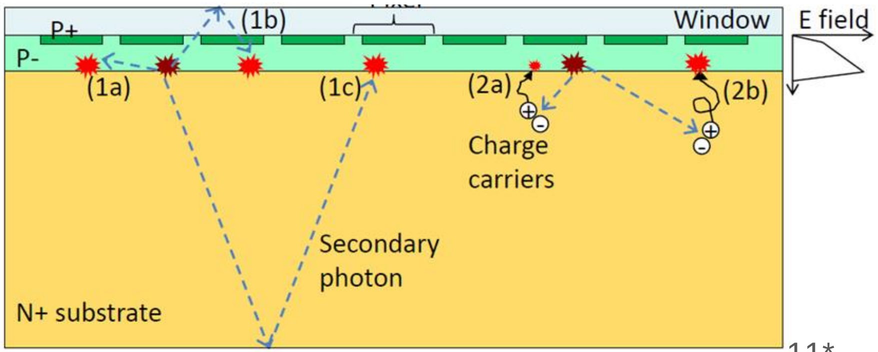

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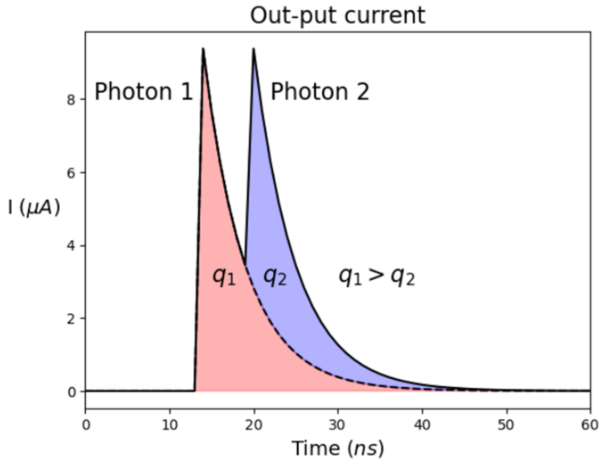
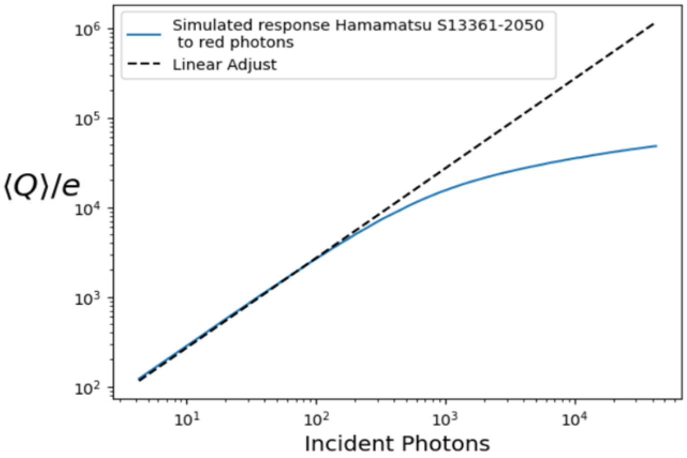
Non-linearity of SiPMs

- Ideally, each photon produces the same amount of charge, so there is a linear relation between the number of interacting photons and the output charge: $Q = q_{avalanche} \cdot n_{photons}$
- As the number of incident photons increases, the probability of two or more photons interacting in the same microcell increases
- After an avalanche each microcell spends some time restoring the charge
- If an avalanche is produced during this recovery the created charge will be lower than the fully-recovered charge





Experimental Set-Up

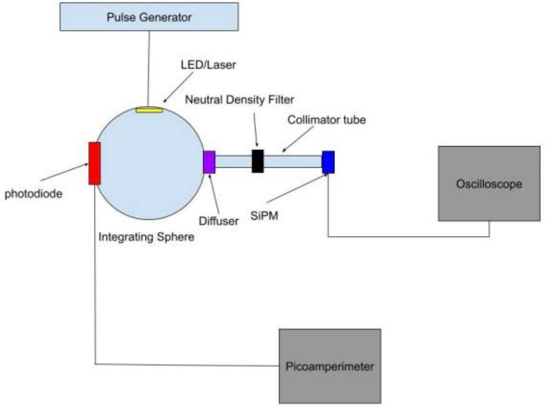
- Our optic set-up consists:
  - Laser/LED source
  - Integrating sphere
  - Photodiode + picoamperimeter
  - SiPM + control PCB (with BNC out-out)
  - Additional optics material: neutral density filters, collimator tubes, diffuser,...
- Readout by oscilloscope:
  - Detailed waveform analysis by dedicated software
- Characterization measurements:
  - PhotoDetection Efficiency (PDE)
  - Dark count rate
  - Correlated noise probability

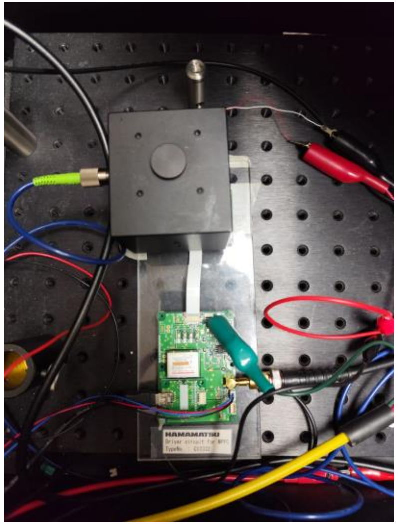
Dark box and control PC

LED/Laser sources

Oscilloscope

Voltage sources





Non-linear response for arbitrary light intensity

- We developed a simple fitting model based on the microcell recovery

$$y = \left(1 + c \cdot e^{-d \cdot x} + \frac{a \cdot x}{1 + b \cdot x} \right) \cdot \left(1 - e^{-x}\right)$$

Average charge of a triggered microcell

Probability of triggering a microcell

First avalanche

Noise contribution

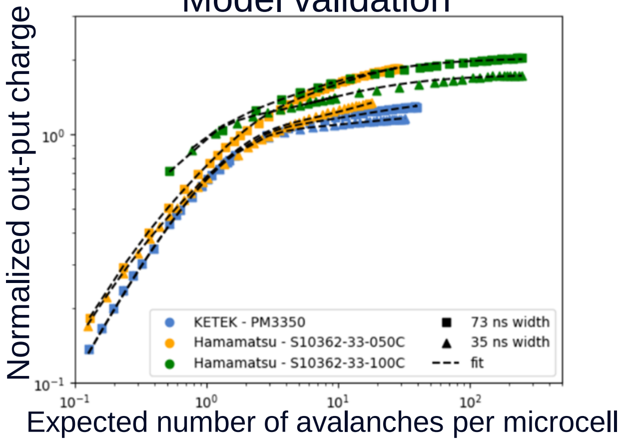
Successive avalanches

$$y = \frac{\langle Q \rangle}{q_{avalanche} \cdot N_{microcells}},$$ Normalized out-put charge

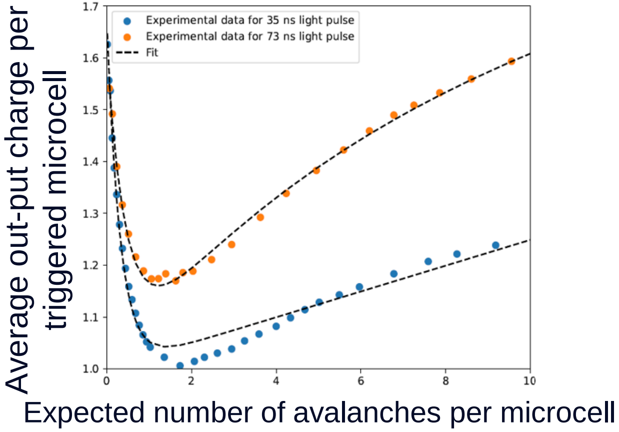
$$x = \frac{PDE \cdot N_{photons}}{N_{microcells}},$$ Expected number of avalanches per microcell

- The noise contribution of the first decreases with light intensity, as their neighbour microcells are already triggered
- Recovery term to model successive avalanches

Model validation



Noise decrease



Participation in astroparticle instruments

- SiPM characterization and development of analysis tools for:
  - LST-CTAO: Large Size Telescope in Cherenkov Telescope Array Observatory
  - Terzina: Cherenkov telescope on board of the NUSES mission, meant to detect Earth skimming high energy neutrinos

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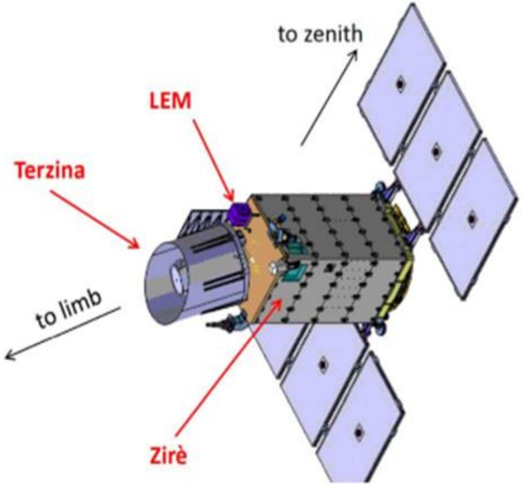

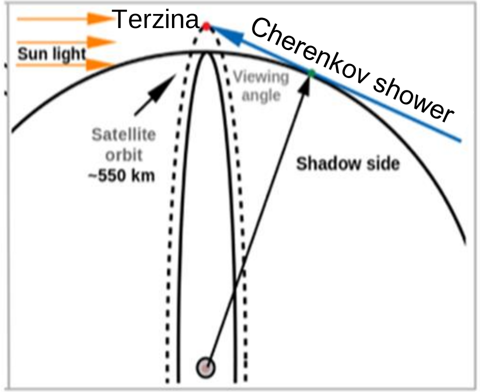

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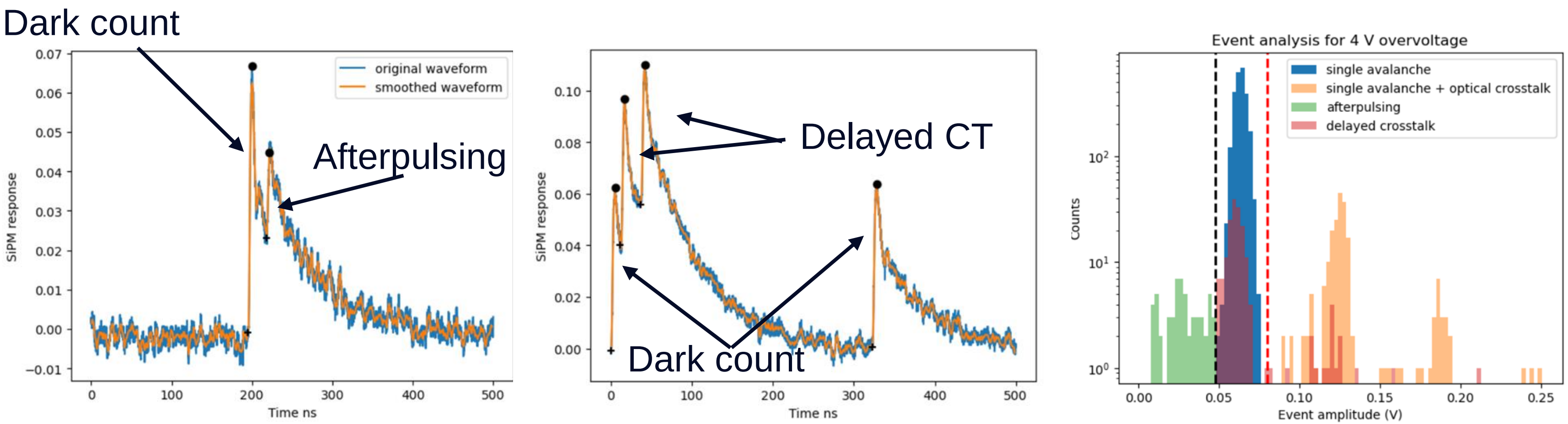
Participation in astroparticle instruments

- SiPM characterization and development of analysis tools for:
  - LST-CTAO: Large Size Telescope in Cherenkov Telescope Array Observatory
  - Terzina: Cherenkov telescope on board of the NUSES mission, meant to detect Earth skimming high energy neutrinos
- Detailed waveform analysis at dark conditions or single photon to identify different kinds of correlated noise
- Can identify different kinds of correlated noise



Conclusions

- SiPMs are becoming the detector of choice for many high energy physics experiments
- My thesis addresses the main problems of SiPMs: non-linearity and correlated noise
- I have contributed to characterization campaigns for astrophysical instruments.

References

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•5*: Credit: Moritz Huetten

•6*: Jiang, & Chalich, & Deen,. (2019). Sensors for Positron Emission Tomography Applications. Sensors. 19. 5019. 10.3390/s19225019.

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