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Massimiliano Antonello

SiDet R&D Meeting

Hamburg, 16.07.2024

SUM

SiPM Unified Model

A new project idea

Outline:

01.

Silicon Photo-Multipliers in a nutshell

Quick introduction:
basic principles,
advantages and disadvantages,
examples of their applications.

02.

Saturation and Non-linear response

The SiPM response to high intensity light is a major limitation for many applications and an easy and reliable method to **restore linearity** is required.

03.

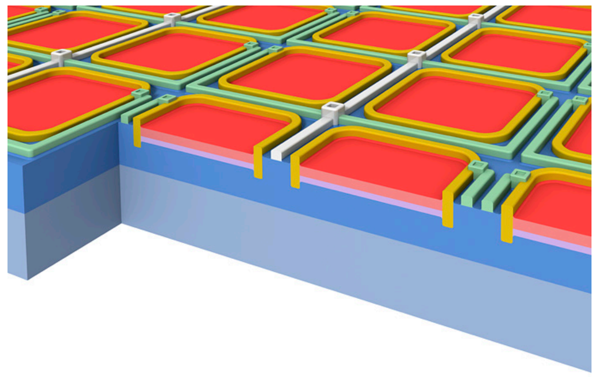
SUM model and framework

A comprehensive framework that includes a statistic model of SiPM operation, allowing simultaneously for **characterization, simulation**, and the **development** of new devices.

Silicon Photo-Multipliers in a nutshell

01

Introduction

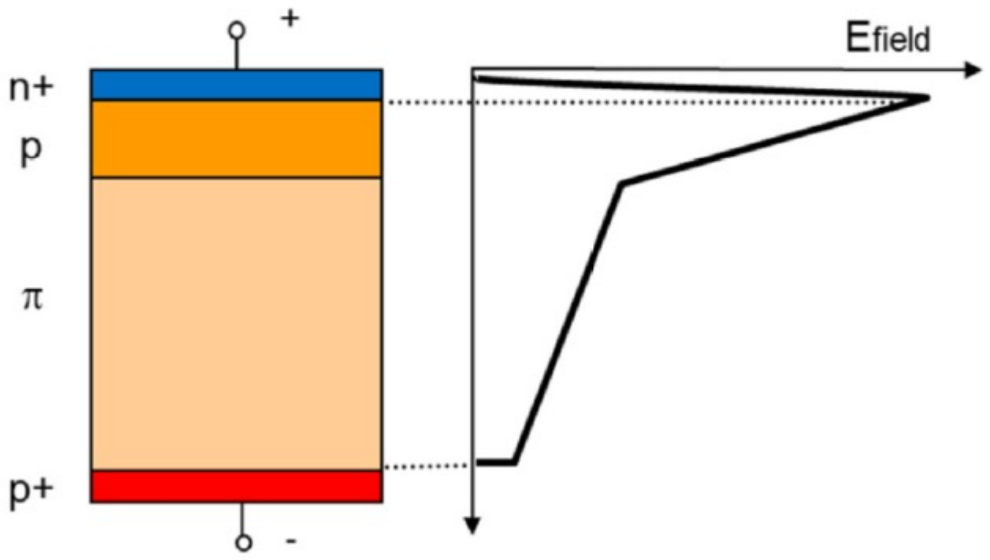


SiPM:

High density (~$10^4/mm^2$) **matrix** of independent **reverse biased** Single Photon Avalanche Diodes, called cells (or pixels).

SPADs:

p-n junctions, biased few Volts above V_{bd}, working in **Geiger-Müller regime** with ~ 10^6 gain.



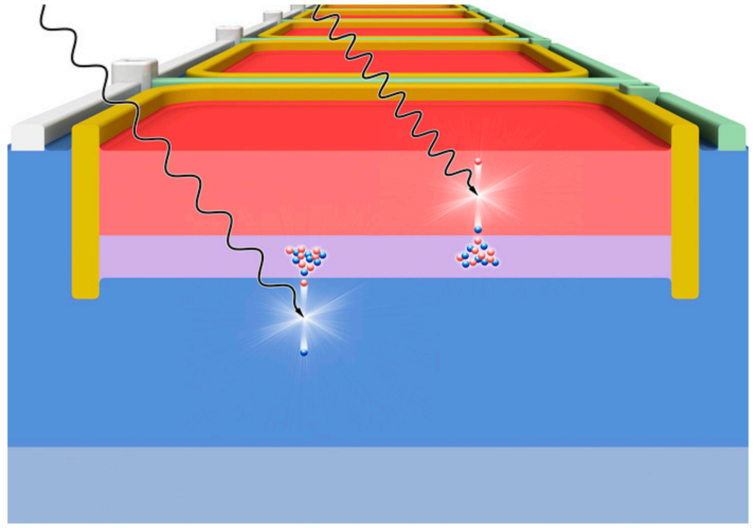
[1]

[1] C.Piemonte and A.Gola., **Overview on the main parameters and technology of modern Silicon Photomultipliers**, NIM A 926 2-15 (2019).

Operation principle

Single cell = binary information:

Initial charge carriers generated by an absorbed photon in the depletion region trigger a **self-sustaining avalanche** by impact ionitation.



The **Gain** of a SPAD represents the number of carriers flowing per triggered avalanche:

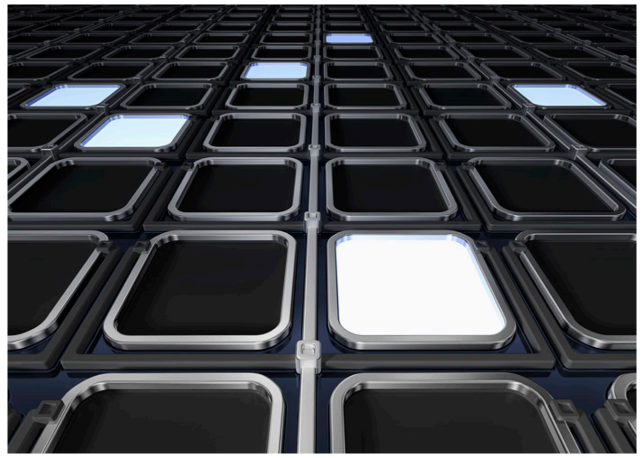
$$\text{Gain} = \frac{C_D \cdot (V_{bias} - V_{bd})}{q} = \frac{C_D \cdot V_{OV}}{q}$$

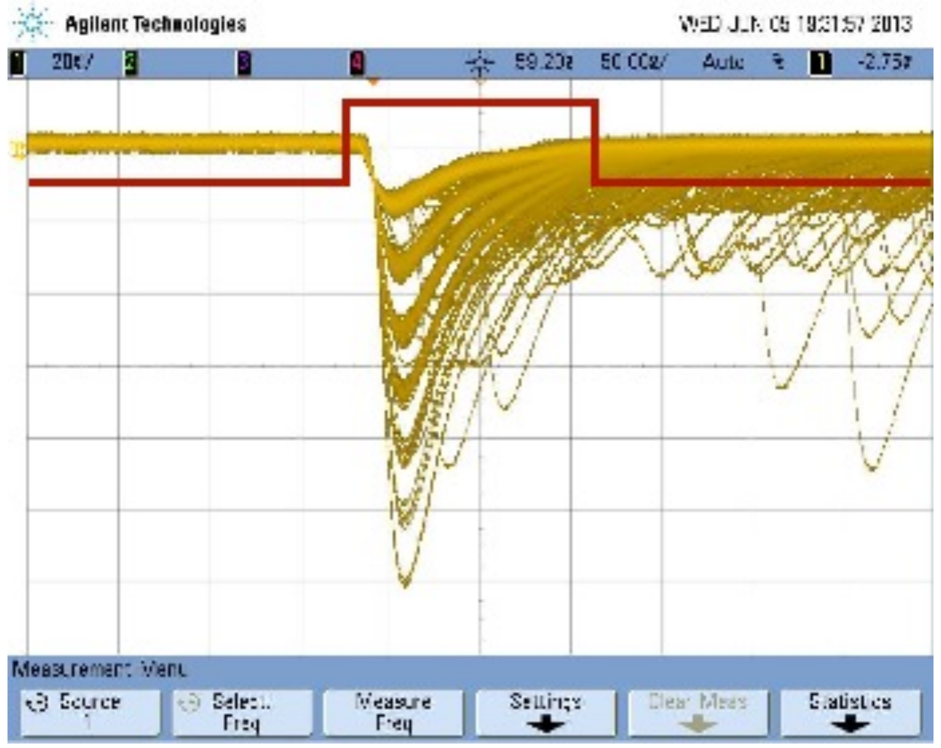
with C_D = capacitance of avalanche region.

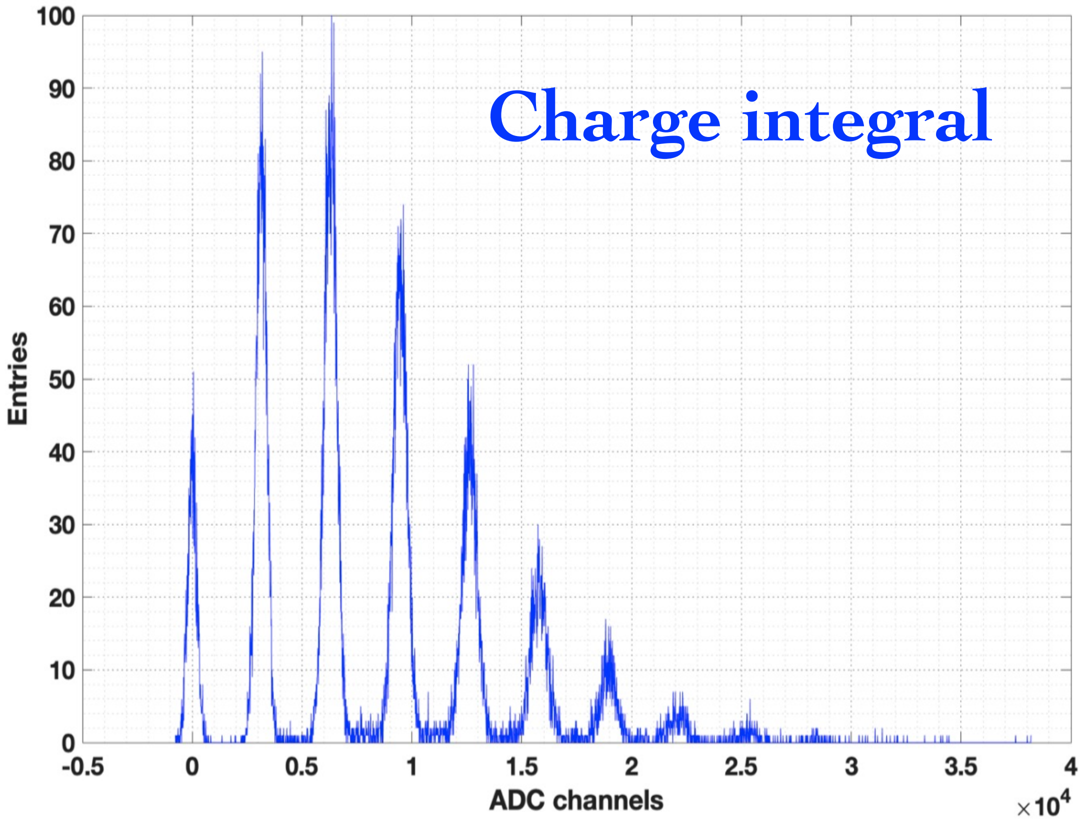
Operation principle

SiPM = analogue information:

SiPM may be seen as a collection of binary cells, fired when a photon is absorbed.
"Counting" cells provides an information about the intensity of the incoming light.





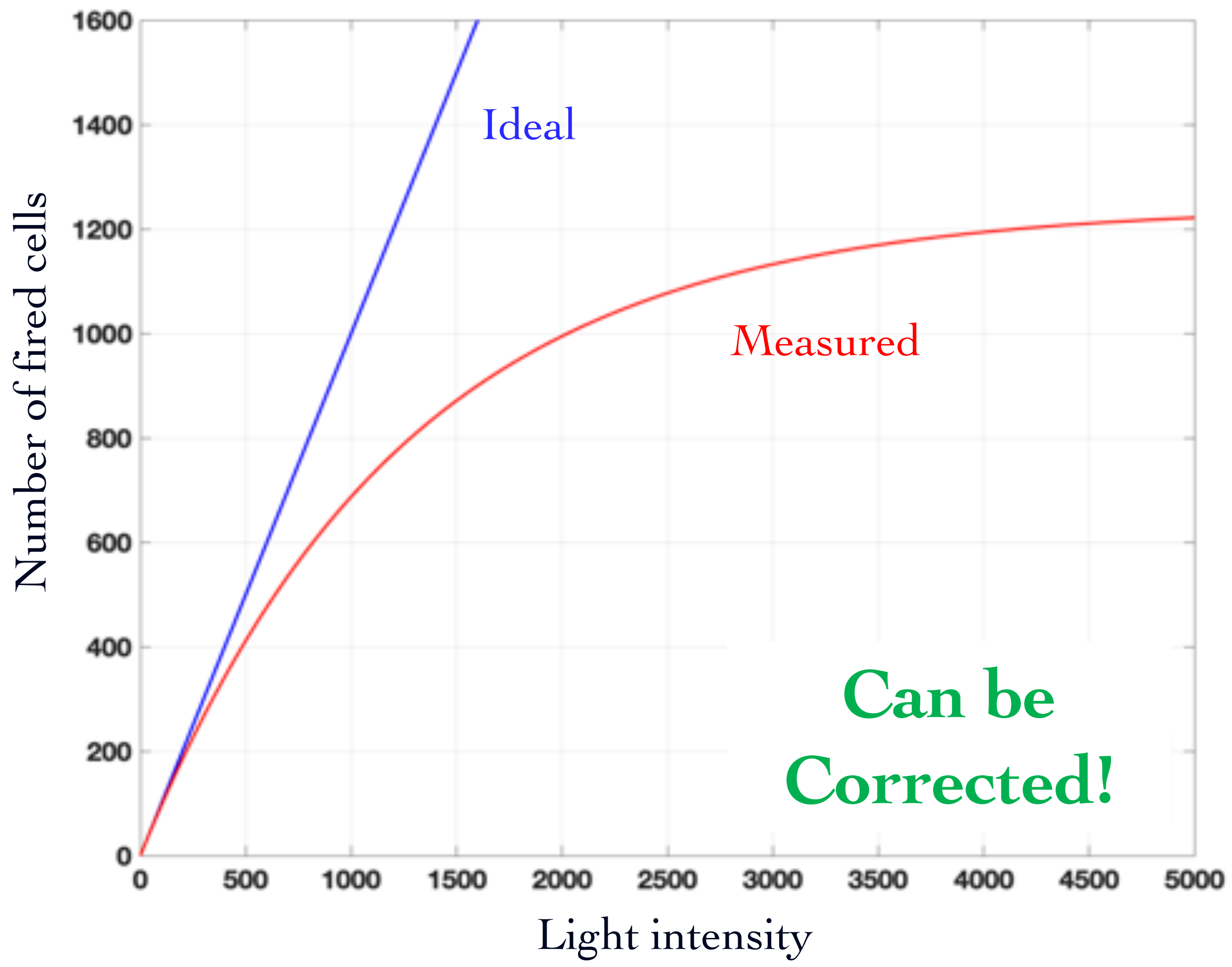


Saturation

Response linearity and dynamic range:

The **total number of cells** determines the SiPM dynamic range.

Non-linear response when the probability to have more than one photon per cell is not negligible.



Stochastic effects

Source of noise limiting the photon counting resolution and introducing response non-linearities.

DCR: Dark Count Rate

Spurious **random** avalanches triggered by free carriers **thermally generated** in the depletion region.

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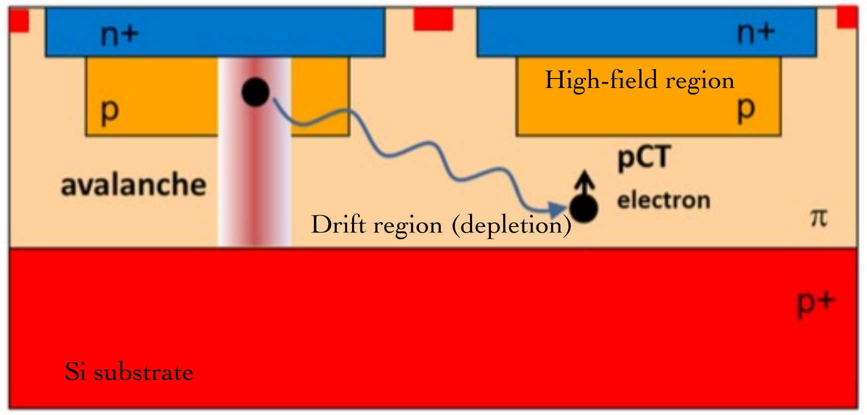
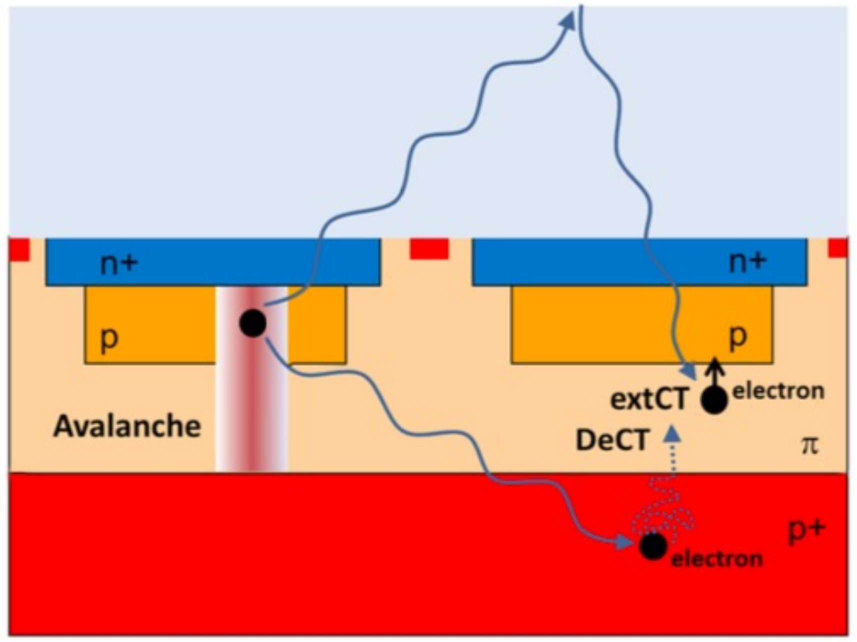
OCT: Optical Cross-Talk

Optical photons in a discharge can also trigger an avalanche in a **neighbouring** cell.



Prompt Cross-Talk (pCT) event.



Delayed Cross-Talk (DeCT) and External Cross-Talk (ExCT) events.

[1]

[1] C.Piemonte and A.Gola., **Overview on the main parameters and technology of modern Silicon Photomultipliers**, NIM A 926 2-15 (2019).

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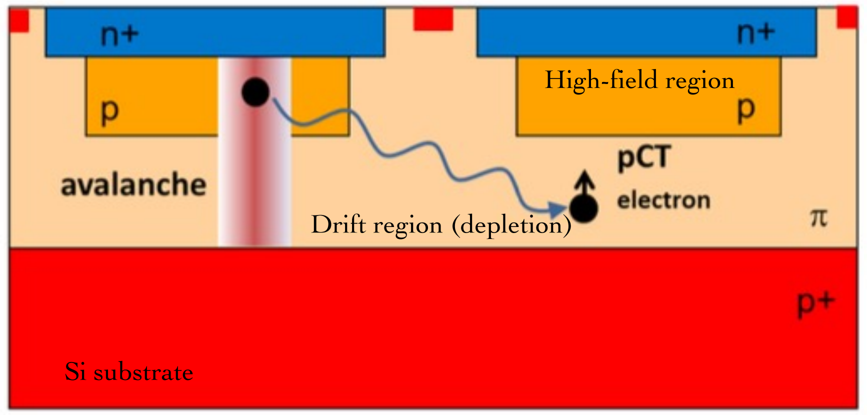
Optical photons in a discharge can also trigger an avalanche in a **neighbouring** cell.

AP: After-Pulsing

Carriers trapped in the high-field region by silicon **defects** can cause in the **same** cell a **delayed** avalanche (from ns up to μs).



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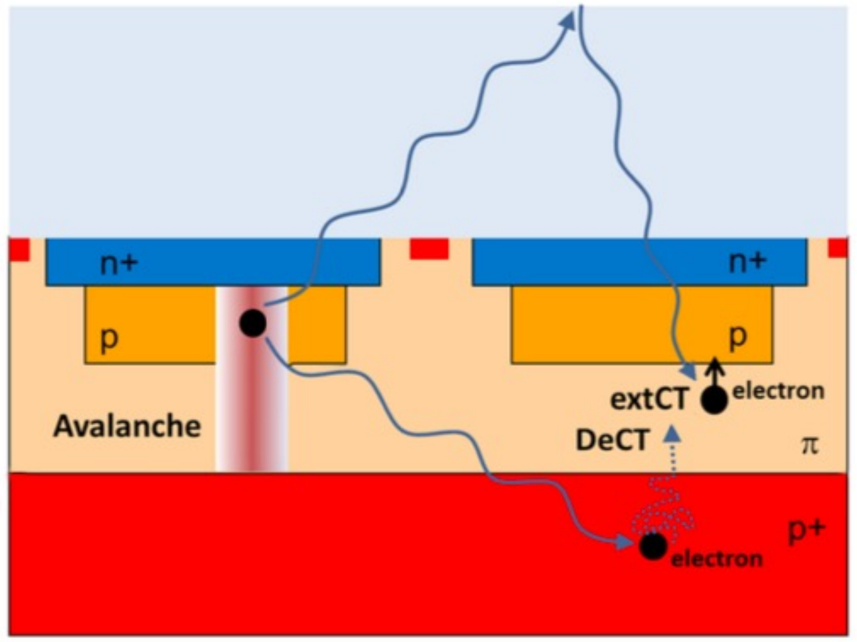

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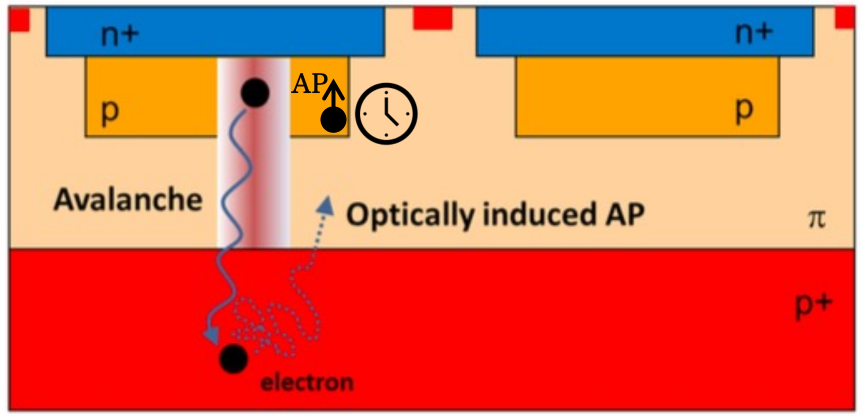


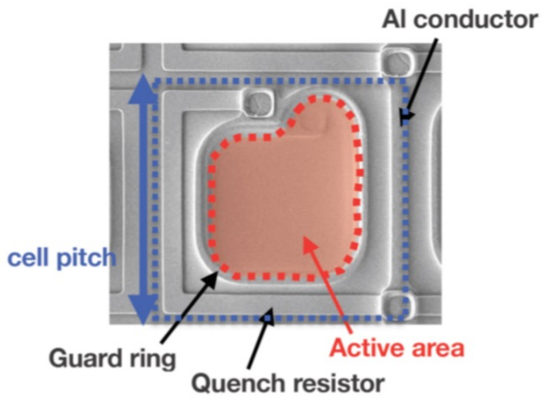
Optically induced after-pulsing (AP) event.

[1] C.Piemonte and A.Gola., **Overview on the main parameters and technology of modern Silicon Photomultipliers**, NIM A 926 2-15 (2019).

Photon Detection Efficiency

PDE quantifies the probability to detect an impinging photon.

Fill Factor:
Active/Total area.



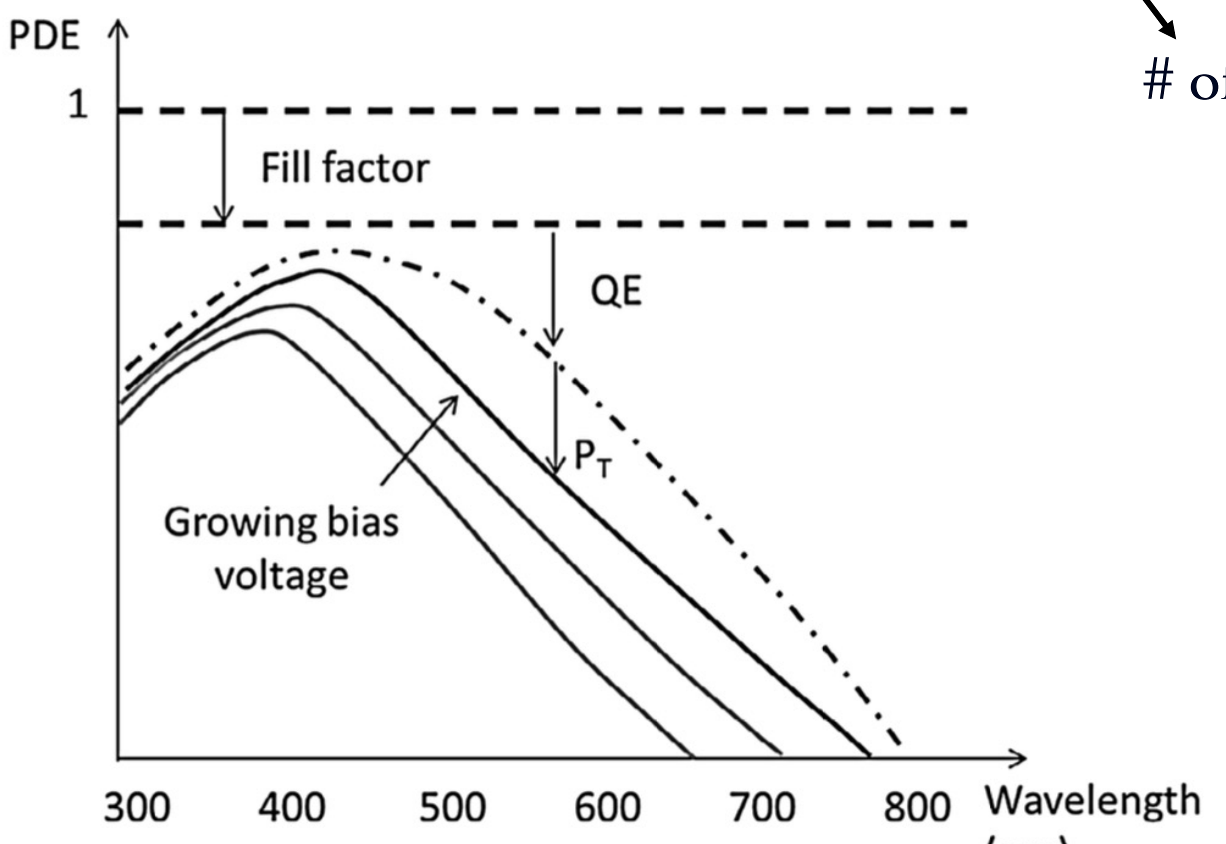
# of fired cells.

$$PDE = \frac{\langle N_{FC} \rangle}{\langle N_{\gamma} \rangle} = FF \cdot QE(\lambda) \cdot P_T(\lambda, V_{OV}, T)$$

# of impinging photons.

Avalanche breakdown triggering probability:
Probability that a carrier generates an avalanche.

Quantum Efficiency:
Probability that a photon creates a primary e/h pair.



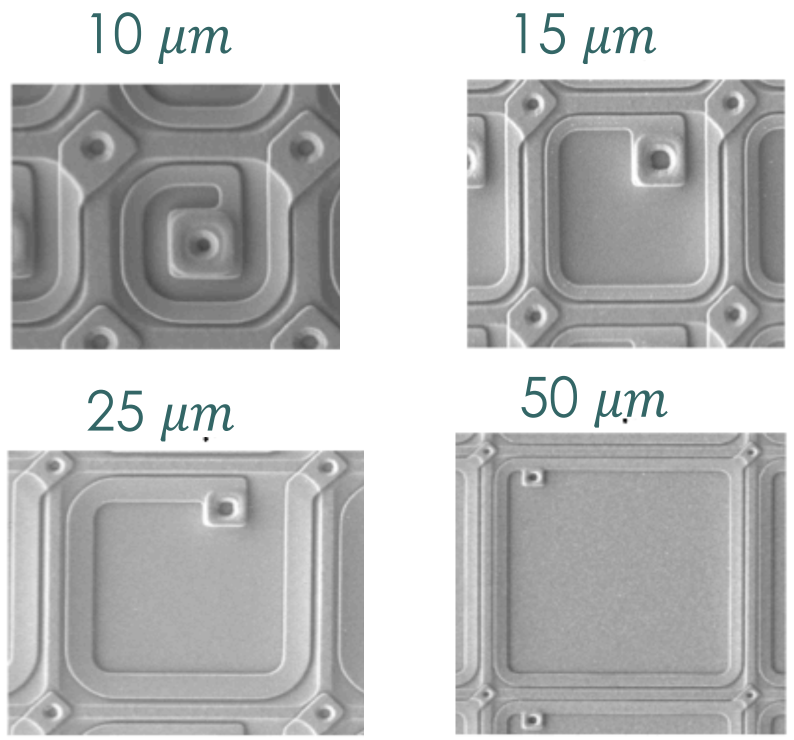
[1]

[1] C.Piemonte and A.Gola., **Overview on the main parameters and technology of modern Silicon Photomultipliers**, NIM A 926 2-15 (2019).

Many options available

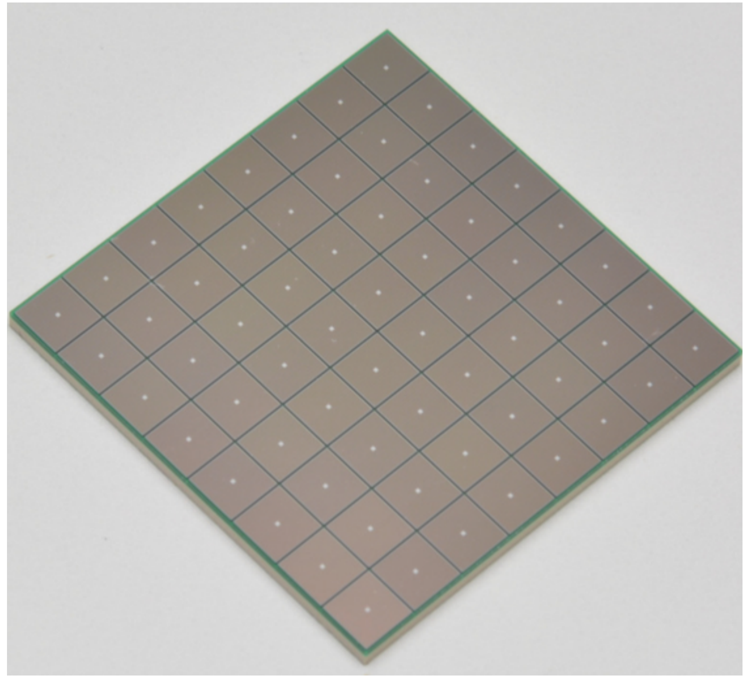
It is possible to choose the “best fit” device for each application in term of:

Pixel pitch



75 and 100 μm available as well.

Sensor area

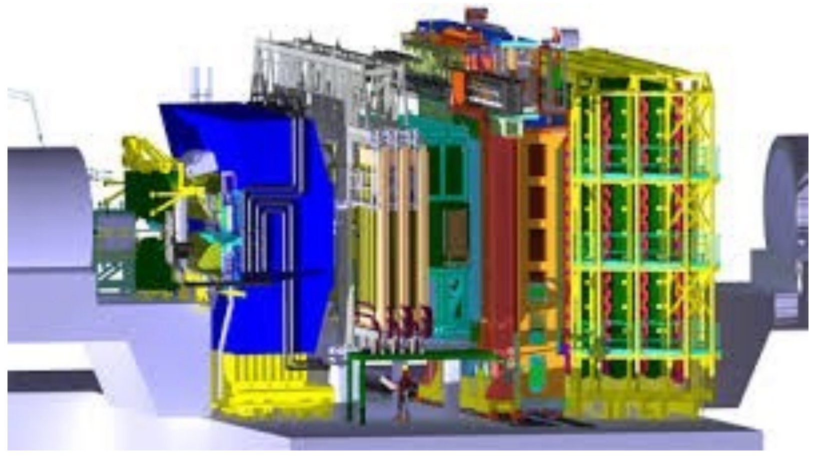


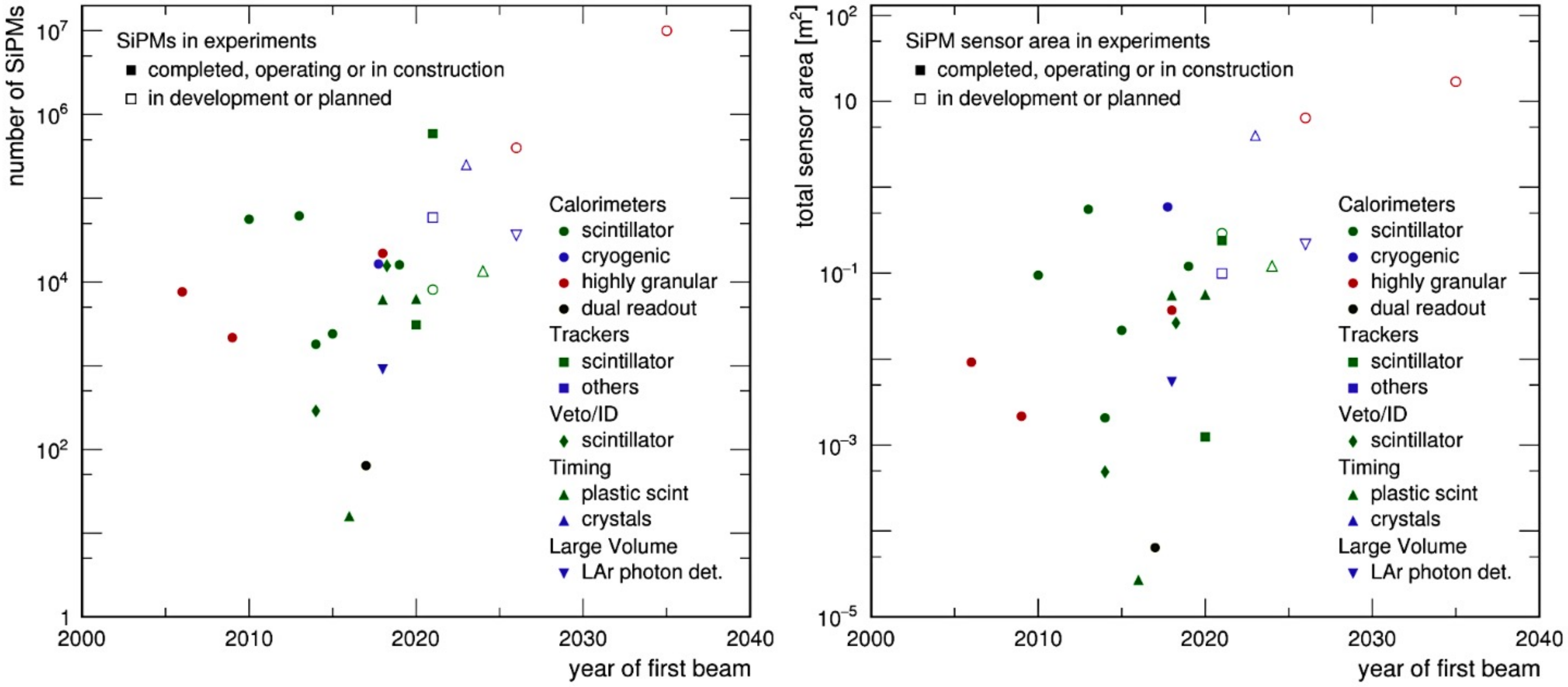
1x1 mm^2 up to 24x24 mm^2.

Not to mention the variety of available options for the front-end, the packaging and the integration with the read-out electronics.

One device, many applications

> **High Energy Physics**: blue/green light, scintillating tiles/fibers, linear response, radiation hardness.





[1]

[1] F.Simon, **Silicon photomultipliers in particle and nuclear physics**, NIMA 926 85-100 (2019).

One device, many applications

> **High Energy Physics**: blue/green light, scintillating tiles/fibers, linear response, radiation hardness.

> **Astrophysics:** near-IR/visible light, single-photon detection (low DCR), high PDE, T sensitivity, radiation hardness.

> **Medical imaging (PET scans):** blue/green light, inorganic crystals, time resolution.

> **Fluorescence spectroscopy:** wide emission spectrum (high PDE), wide intensity range (from single-photon to saturation), DCR.

> **LiDAR for autonomous vehicles:** pulsed red laser light, background light, all-weather operation (from -50°C to +100°C).

> **Quantum cryptography:** single-photon detection (ultra-low DCR), maximum possible PDE, near-IR sensitivity.

> Etc.

Main advantages

- Single-photon sensitivity.
- High photon number resolving capability (~40 ph. @ 25°C).
- High gain (~10^6).
- Low bias voltage (20-100 V).
- High PDE (20-50%).
- Good timing performance (~100-300 ps timing jitter).
- Magnetic field insensitivity.
- Compact and robust design.
- High-volume production capability and "low" cost.

Main advantages and drawbacks

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- Good timing performance (~100-300 ps timing jitter).
- Magnetic field insensitivity.
- Compact and robust design.
- High-volume production capability and “low” cost.

- Strong sensitivity to operational conditions such as temperature, fluence, light source, etc.
- High DCR (~10^5-10^6 Hz per mm^2).
- Stochastic effects as OCT, AP, etc.
- Limited large active area.
- Limited dynamic range.
- **Saturation and non-linear response.**

02

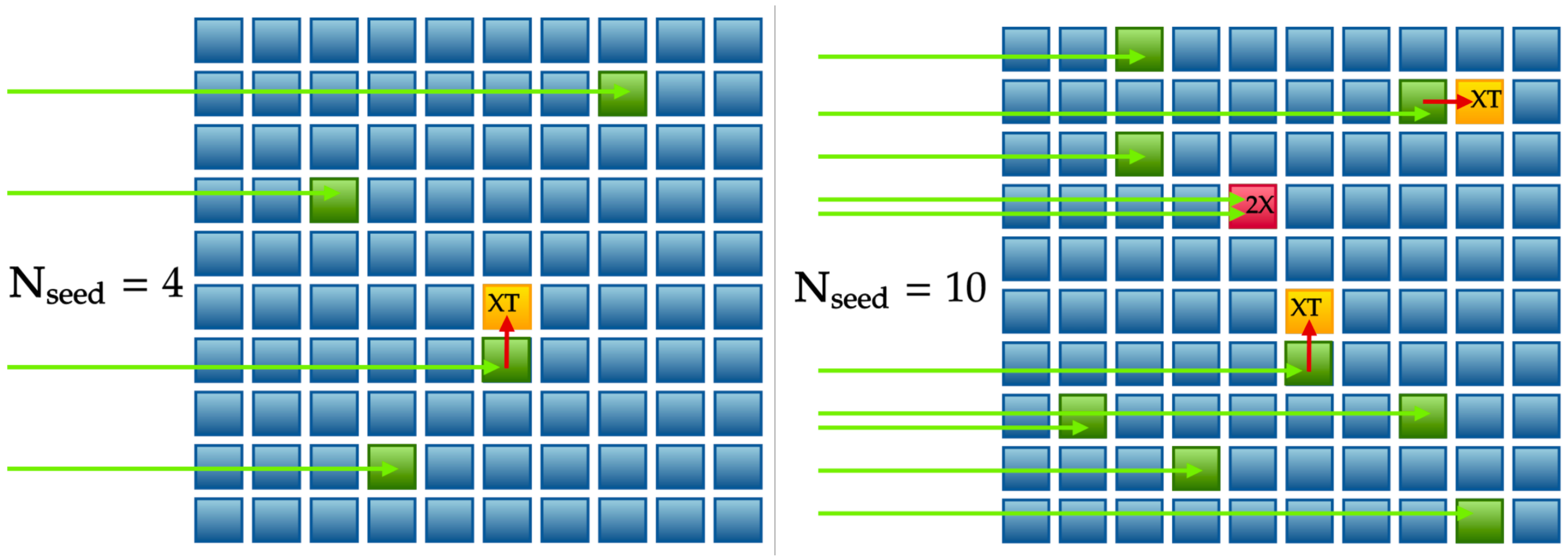
Saturation and non-linear response

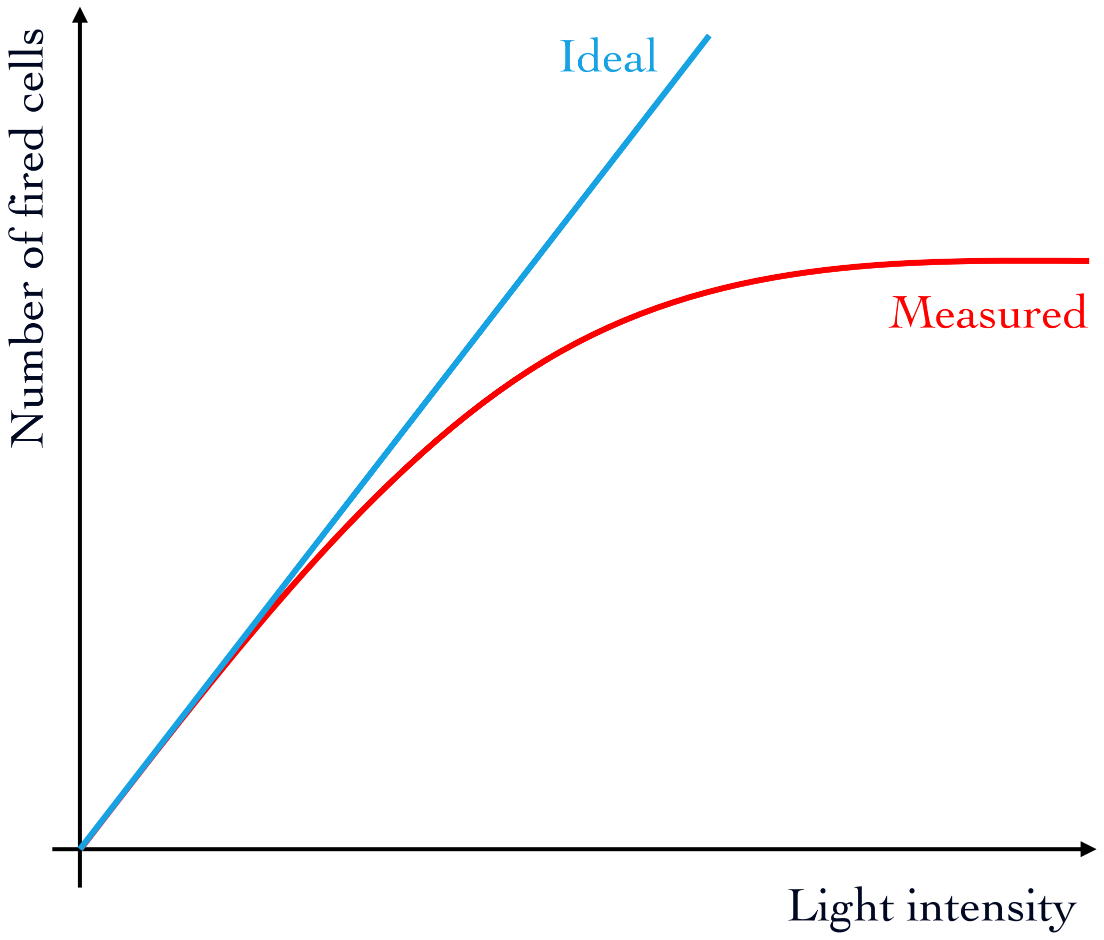
Non-linear response

SiPM response is linear when each incoming photon triggers a different cell.

The **non-linearity** depends on:

> Photon number.
> Photon time distribution (late arriving photons on partially recovered cells).
> SiPM noise and stochastic effects (XT, AP, DCR).





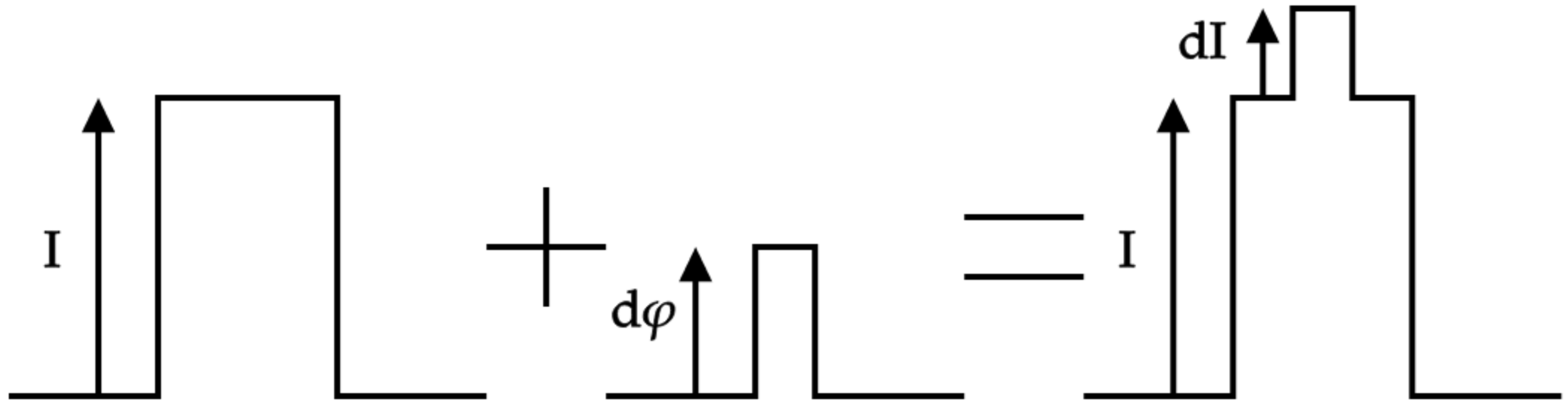
Can be measured and corrected

Some methods available, I will focus on "our" single step method…

The single step method

The method[1]:

Determine the SiPM non-linearity by measuring the change in amplitude (dI)
when a fixed, small **LED light pulse (dφ)** is added to a variable intensity base **laser pulse (I).**

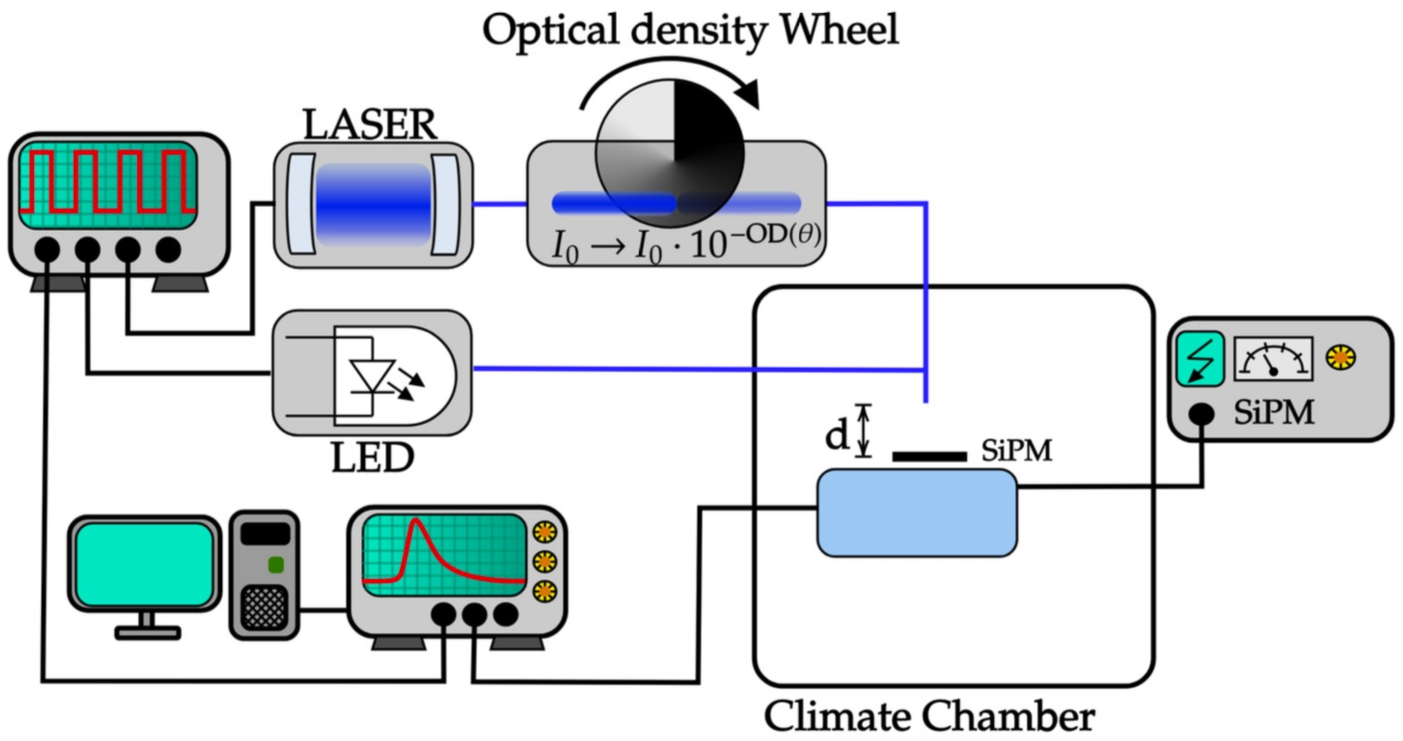


I : LASER, $\mathrm{d}\varphi$: LED, $\mathrm{d}I$: LED*(effective LED light)

[1]

[1] L. Brinkmann, E. Garutti, S. Martens, J. Schwandt, **Correcting the Non-Linear Response of Silicon Photomultipliers,** Sensors (2024), 24, 1671.

Setup and procedure



Parameter	Symbol	Value
Wavelength LASER	λ_{LASER}	451 nm
Wavelength LED	λ_{LED}	458 nm
Effective photosensitive area	-	1.3×1.3 mm
Pixel pitch	-	15 µm
Photon detection efficiency at λ_{LED}	PDE	32 %
Number of pixels	N_{pixel}	7296
Breakdown voltage	V_{br}	(37.270 ± 0.023) V

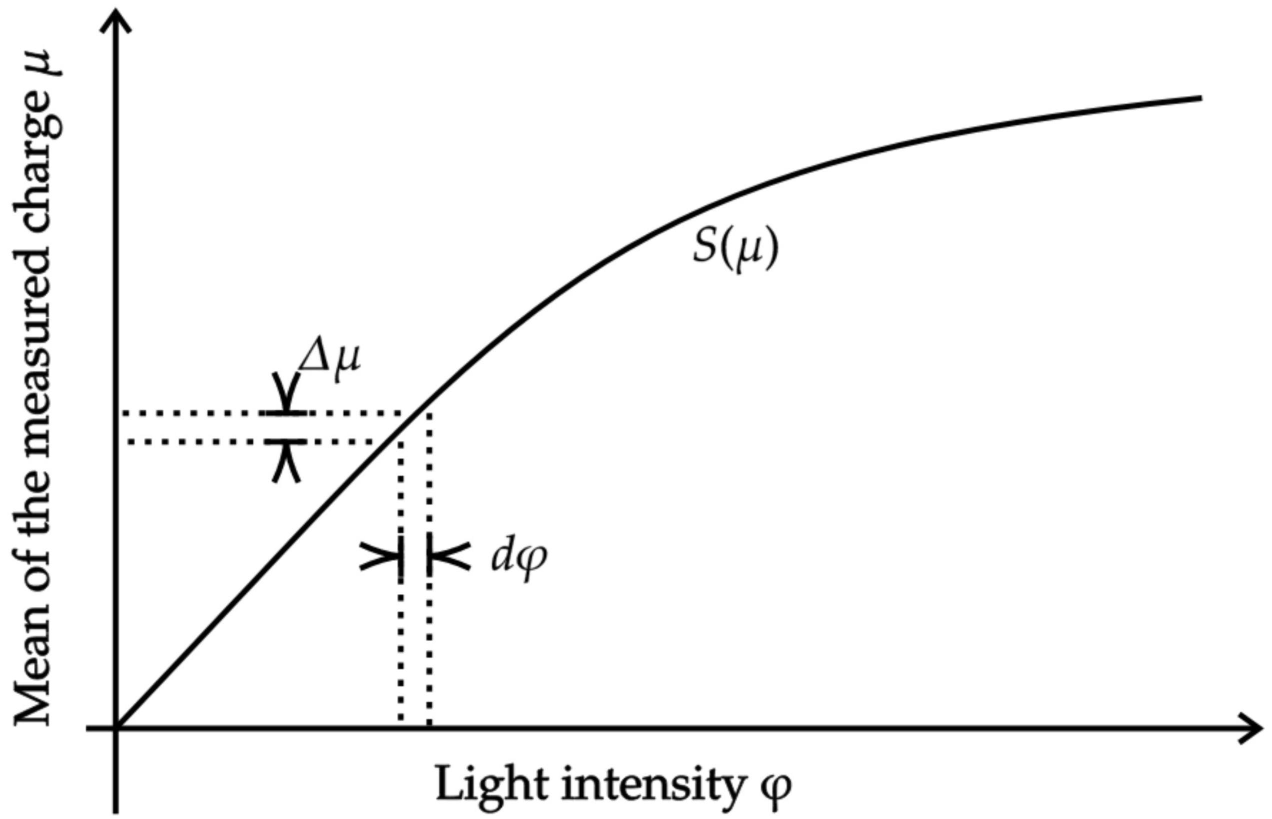
- Regulate the LASER intensity by setting the angle θ of the neutral density filter wheel.
  - Intensity(θ) = 100 . 10^{-OD} with OD = optical density.
- For every θ:
  - Acquire 50k waveforms with LASER only.
  - Acquire 50k waveforms with LASER + LED.

The single step method

The goal:

Correct the SiPM response function using **only measured quantities** (SiPM charge and gain).

- μ_L = mean LASER intensity
- μ_{LL} = mean LASER+LED intensity
- $dI = \Delta\mu = \mu_{LL} - \mu_L$
- $d\varphi$ = single step (LED only)



If linear response, for every single step:

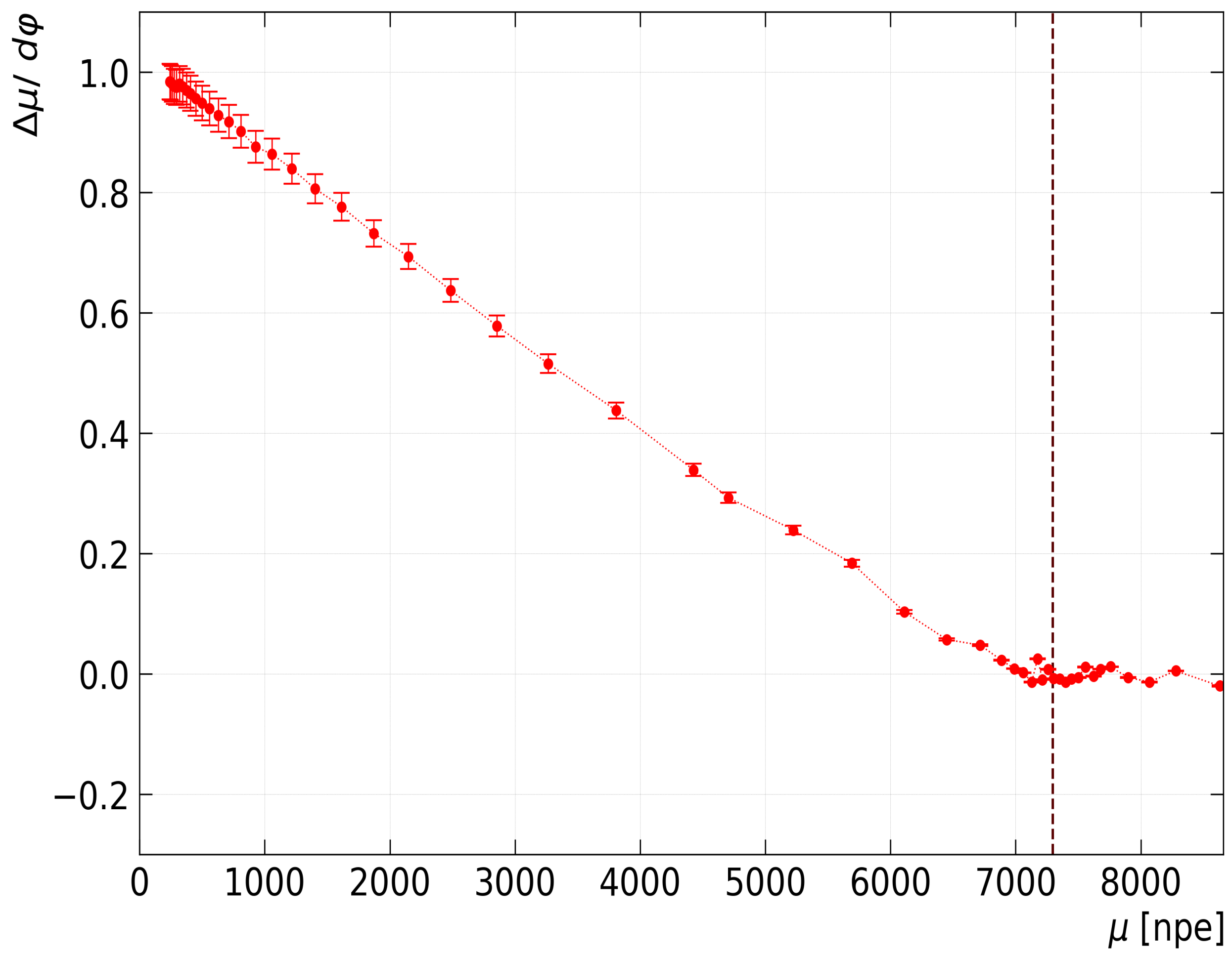
- $d\varphi = \Delta\mu$

The slope of the response function is:

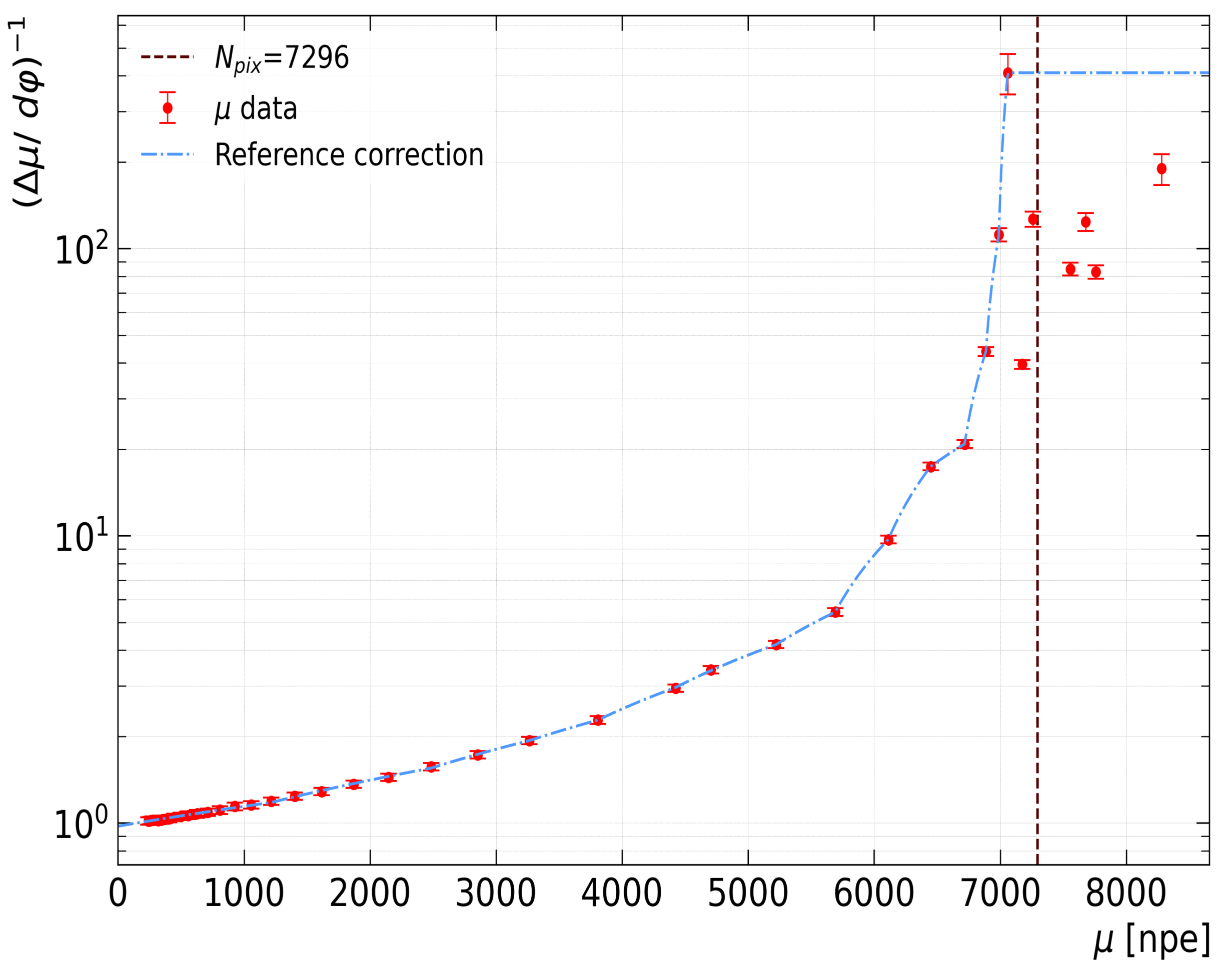
- $S(\mu) = \dfrac{\Delta\mu}{d\varphi}$

The Correction

Integral of the inverse of the normalized difference: $\varphi = \int_0^{\mu} \left(\frac{(\mu_{LL} - \mu_L)}{d\varphi} \right)^{-1} d\mu.$



$$S(\mu) = \frac{\Delta\mu}{d\varphi}$$

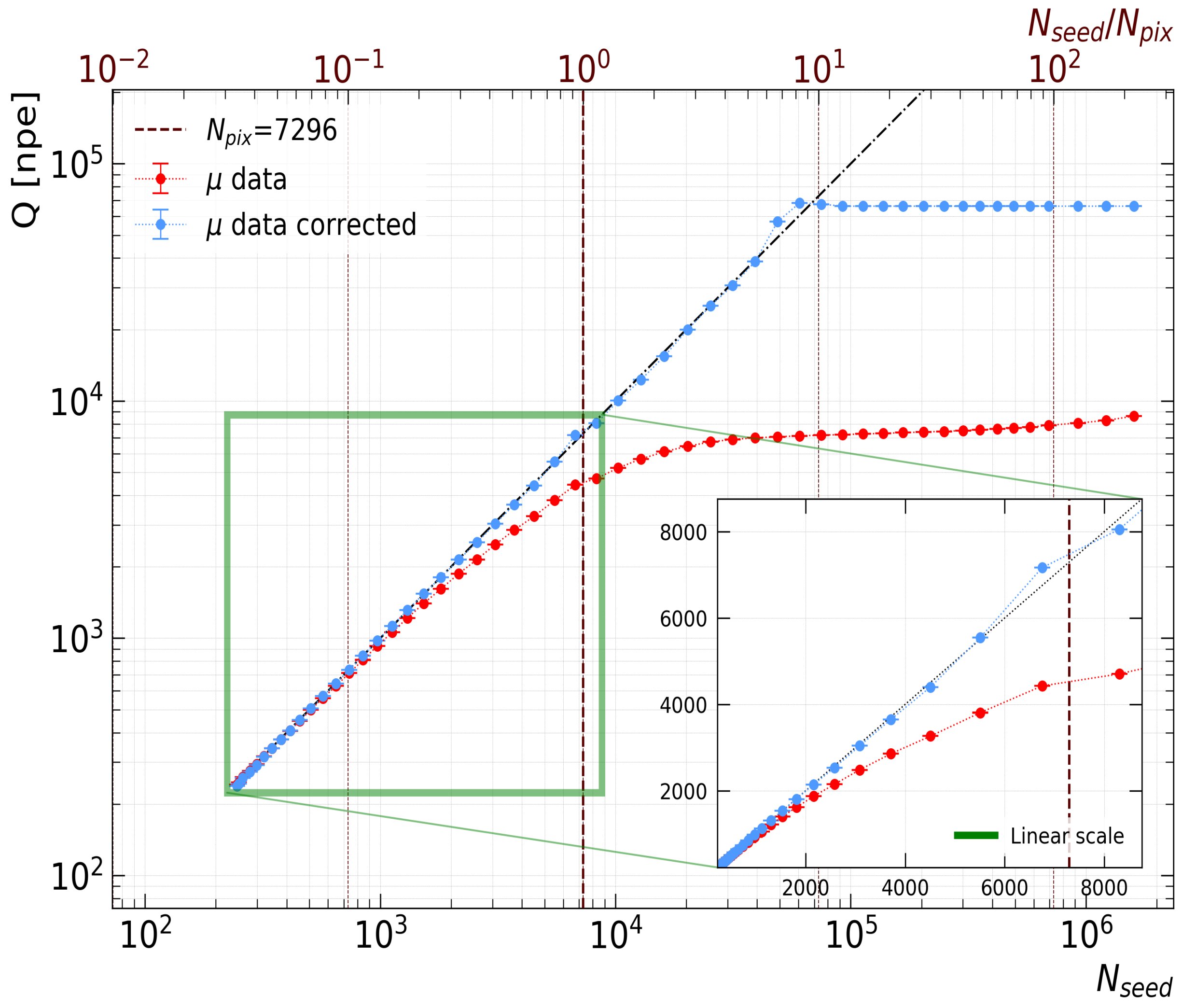


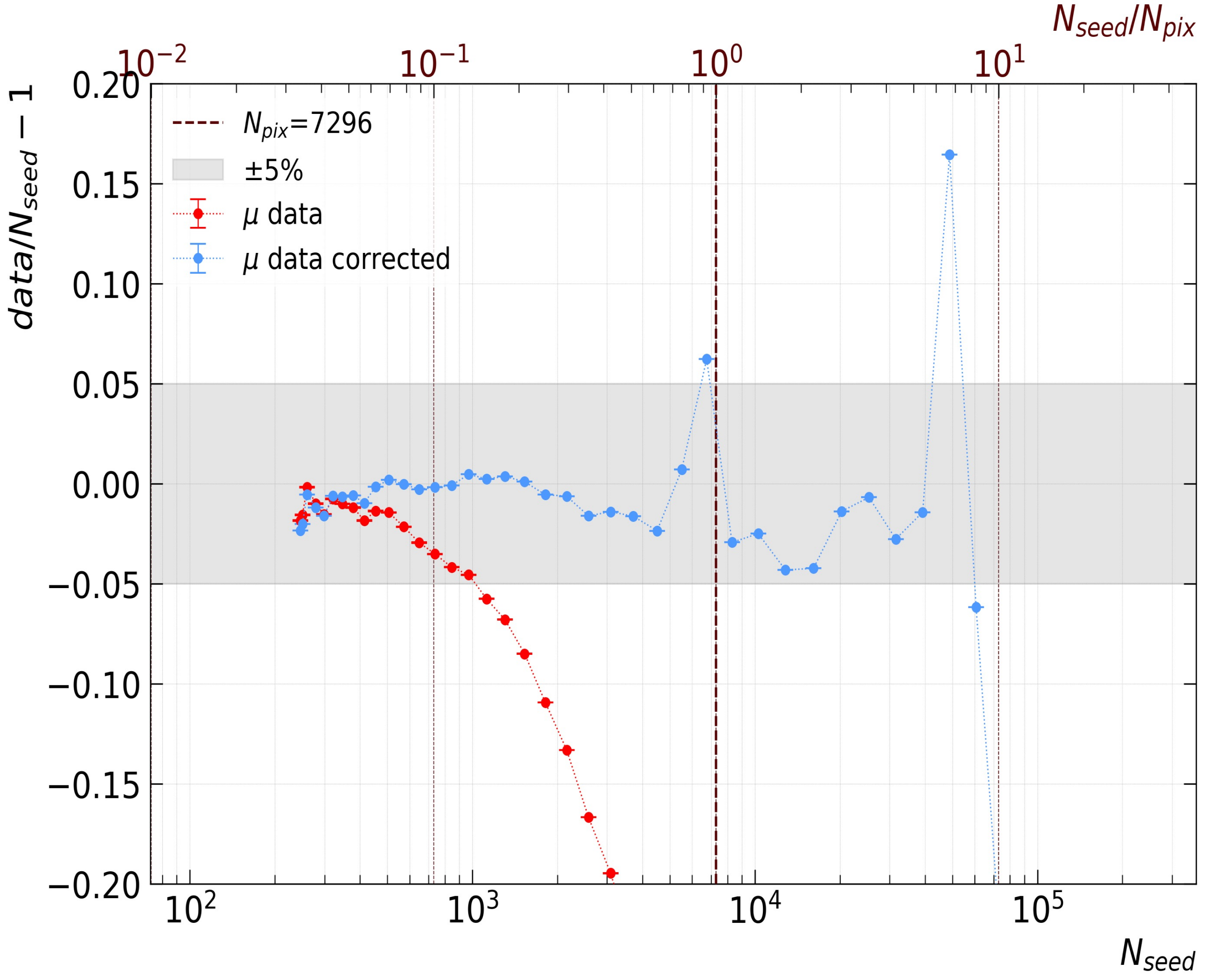
$$S(\mu)^{-1} = \frac{d\varphi}{\Delta\mu}$$

$$\mu = \frac{\mu_{LL} + \mu_L}{2}$$

The Correction

Integral of the inverse of the normalized difference: $$\varphi = \int_0^{\mu} \left(\frac{(\mu_{LL} - \mu_L)}{d\varphi} \right)^{-1} d\mu.$$





$$\mu = \frac{\mu_{LL} + \mu_L}{2}$$

N_{seed} : impinging light intensity expressed in number of seed photons.

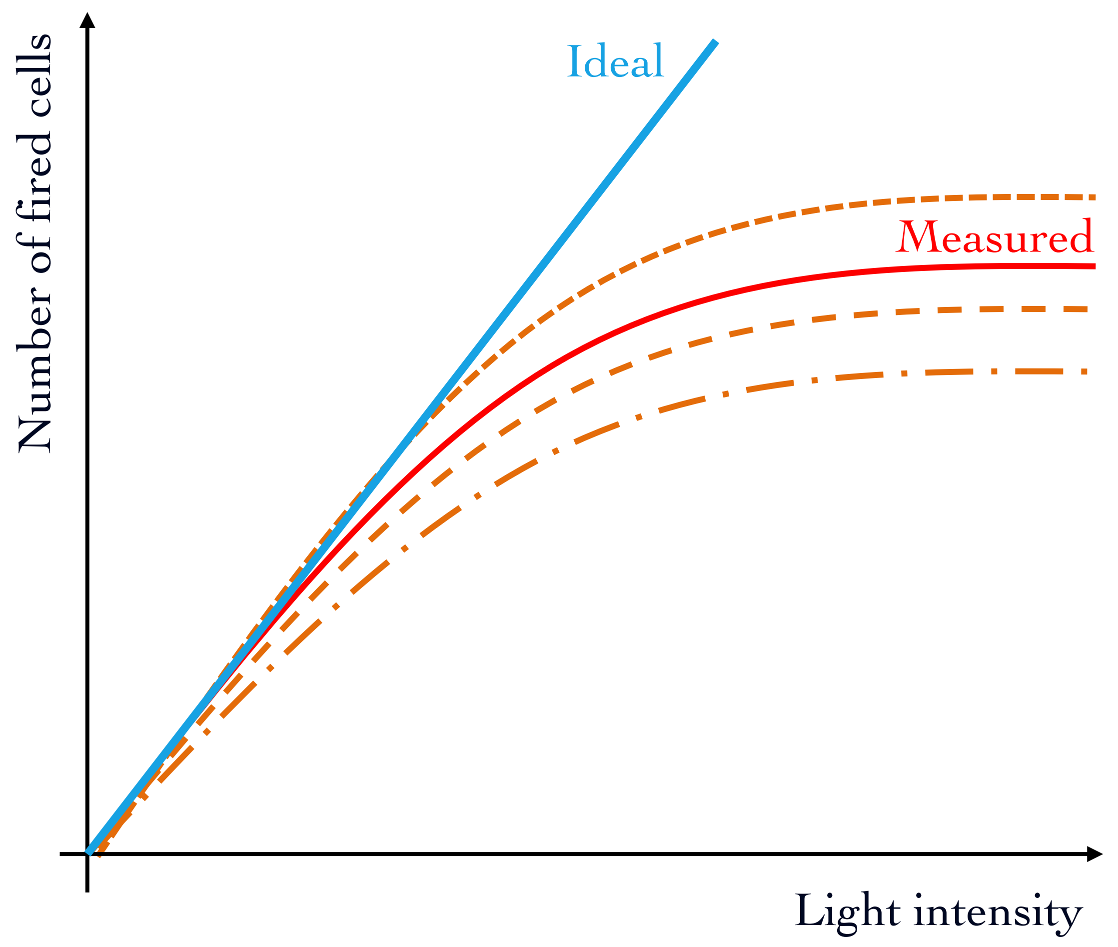
The "usable" SiPM range expanded by a factor of 10!

Negligible dependence on the operating voltage within 2-5 V_{OV} range!

Further in-depth studies ongoing.

Yes! But…

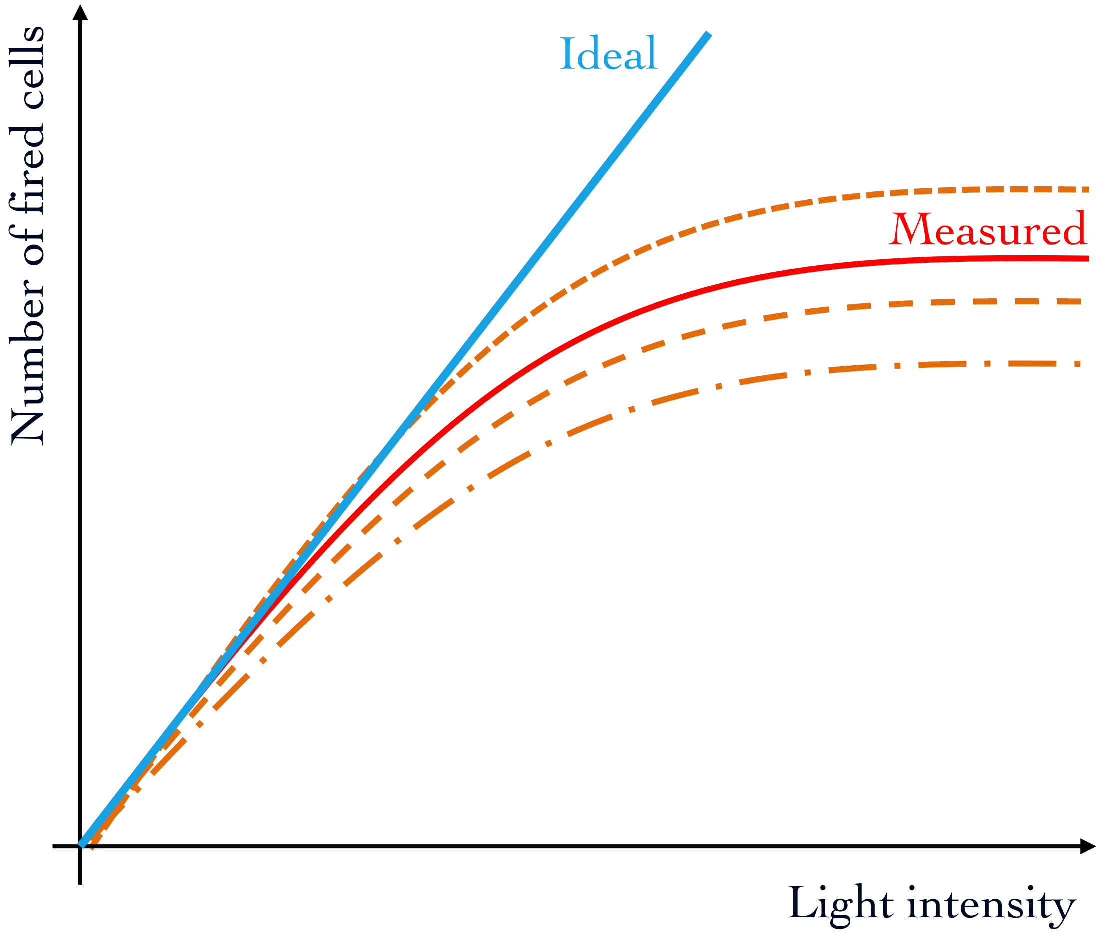
- **Many parameters** need to be considered, and the dependence of the SiPM response on each of them must be evaluated.
  - **Light source** type (laser, LED, scintillator, Cherenkov, etc.):
    - Spatial distribution (uniform, Gaussian, from tile, fiber, etc.)
    - Time spread (instantaneous, Gaussian, exponential, etc.)
    - Wavelength.
  - **SiPM** characteristics:
    - Geometry, V_{OV}, etc.
    - Stochastic effects (DCR, PDE, AP, OCT, etc.)
    - Fluence (DCR increase, trapping and SNR degradation, etc.)
  - **Environmental** conditions (temperature, fluence, etc.)
- In many cases, this could require a **new measurement** and a new correction function **for every new set of parameters**.



Yes! But...

- For many applications, **continuous variation** of some of these parameters is expected.
- In many cases, **direct measurement** of every possible "configuration" of these parameters is **not possible**.
- **A statistical (physical) model capable of providing such a response is currently lacking**.

SUM
SiPM Unified Model



03
SUM model and framework

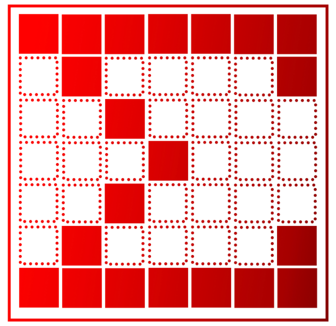
The basic idea

Three inputs, one output

01. Single cell signal

02. SiPM key parameters

03. Light source

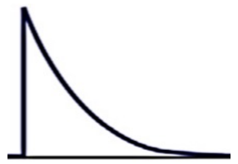


SiPM response

> The "Geiger Array" (GA).
For every event and Geiger discharge:
> Time of arrival.
> Signal amplitude.
> Cell ID.
> Type (light, DCR, OCT, AP).

> Transient for every event (from GA).

01. Single cell signal



Real data measurement:

- Average signal from a selected dataset with a single signal.
- Effect of the readout electronics already considered.
- Useful for experiments and research groups to test the "final" shape.

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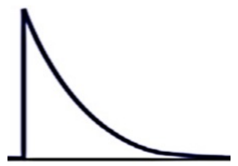

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Electric circuit simulation:

- Simulation results from TCAD, Spice, etc.
- All the different components can be modelled in detail.
- Useful for producers and companies with access to the schematics.

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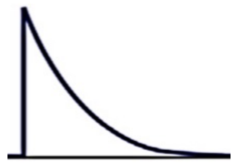

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Physical model simulation:

- Fast simulation results from SUM.
- Based on physical model (that can be changed by the user).
- Requires the “additional parameters” from 02.
- Useful to study new models, designs or basic assumptions.

02. SiPM key parameters

Specifications from datasheet:

- Shape and dimensions.
- Total N_{cells}.
- PDE.
- Etc.

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Key parameters from measurement:

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- τ_{OCT}, τ_{AP}.
- V_{bias}, V_{bd}, V_{OV}.
- Etc.

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- OCT and AP probabilities.
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- V_{bias}, V_{bd}, V_{OV}.
- Etc.

Additional parameters:

- Temperature (T).
- Fluence (ϕ).

- Integration length.
- τ_{rise}, τ_{fast}, τ_{slow}.
- Signal max.
- Electronic noise.

- dG/dV, dG/dT, dG/dϕ.

03. Light source

Source type and characteristics:

- Laser.
- Scintillator.
- LED.
- Fiber.
- λ.
- Etc.

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- Fiber.
- λ.
- Etc.

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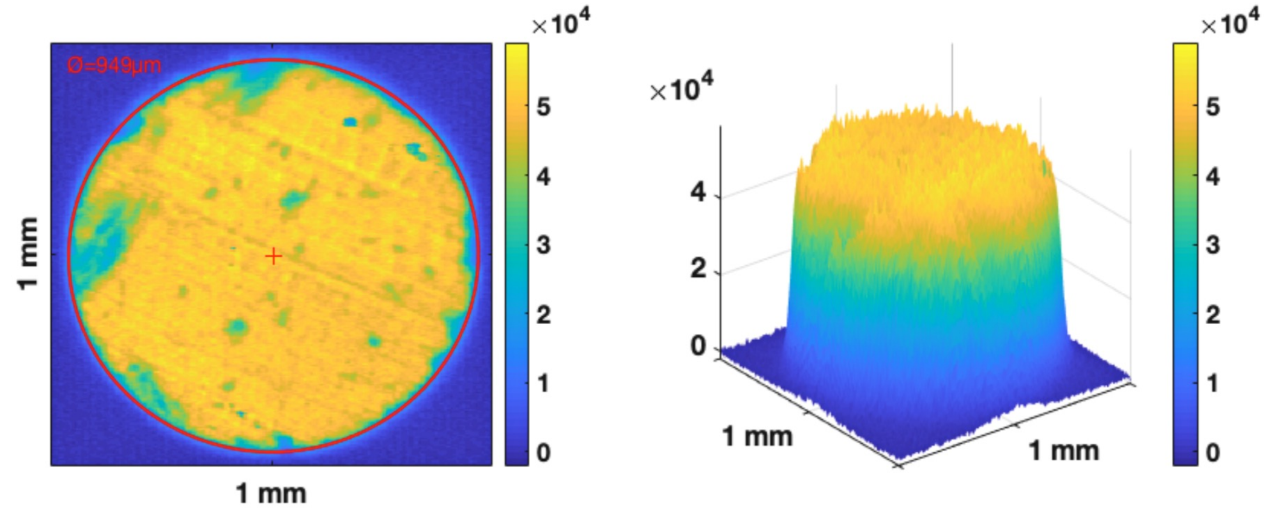
- Instantaneous.
- Exponential.
- Etc.

Photons spatial distribution:

- Uniform.
- Gaussian.
- Special shape.
- Etc.



The target

The primary development will be done starting from the specific needs of HEP, particularly in **calorimetry**.

SUM can help characterize and optimize the behavior of SiPMs in all their specific usage domains, such as **medical imaging, material science, automotive, and space exploration.**

It will be designed also for **companies and research groups** to facilitate the development of new solutions and devices, such as Digital SiPMs and Tip Avalanche Photodiodes (TAPDs).

From model to framework

The main structure

SW infrastructure and core:

The main part of the code including the GUI, the source, and the entire structure of the framework.

The core module is a **fast simulation** based on SUM, validated with real data for different regimes and systematic studies.

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Built-in utilities and modules:

The core module can interface with **various “modules”** developed from the group's know-how, which will complete and extend the simulation.

Each module will be designed to work **independently or in combination** with others.

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Extensibility and user's modules:

Each user will be able to implement and make available to the community their **own specific modules**.

Useful for adding other device designs such as Digital SiPMs or TAPDs, etc..

Many starting points

SUM core: Fast simulation

First approach with **LightSimtastic** (Python).
New development (Julia) based on:

- E.Garutti et al., **Simulation of the response of SiPMs; Part I: Without saturation effects**, NIM A 1019 (2021) 165853.
- R. Klanner, **Simulation of the response of SiPMs Part II: With saturation effects**, NIM A 1059 (2024) 169018**.**

CoNLis/DiSiPLin: Non-linearity correction

New development (Python) based on:

- L.Brinkmann et al., **Correcting the Non-Linear Response of Silicon Photomultipliers**, Sensors (2024) 24 1671.

PeakOTron: Characterization

Existing code (Python) based on:

- J.Rolph et al., **PeakOTron: A Python module for fitting charge spectra of Silicon Photomultipliers**, NIM A 1056 (2023) 168544.

Other ideas: Waveform analysis, ...

Modules for specific data analysis, including waveform studies, signal integration, MPPS generation, and fast analysis of parameters useful for our studies in basic physics and radiation hardness, with possible test beam implementation and corresponding analysis.

A parallel approach

Low light Intensity Regime (LIR) measurements:

1. Std SiPM, blue light.
2. Std SiPM, red light.
3. TAPD characterization.
4. Irradiated std SiPMs and TAPDs.

High light Intensity Regime (HIR) measurements:

1. Std SiPM, blue light (systematic studies).
2. Std SiPM, red light.
3. TAPD characterization.
4. Irradiated std SiPMs and TAPDs.

SUM code:

1. Initial implementation and validation with std. SiPM, blue light.
2. Validation with Std SiPM, red light.
3. Implementation of TAPD and validation.
4. Implementation of radiation effects and validation.

Thank you

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