1D Signals - the SiPM case

Lecture 2

Course of:

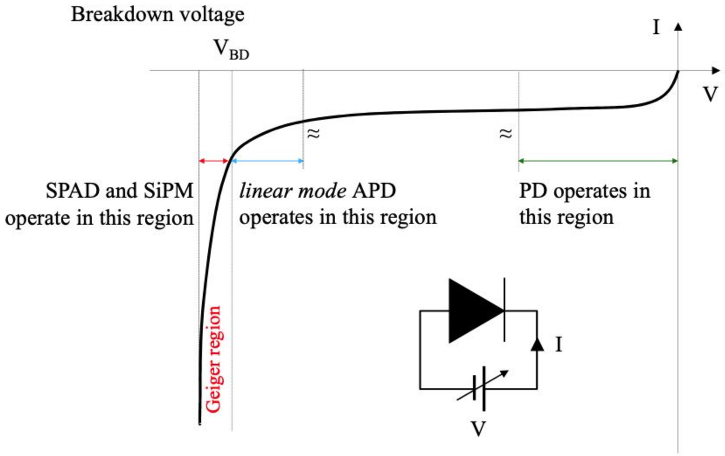
Signal and imaging acquisition and modelling in environment

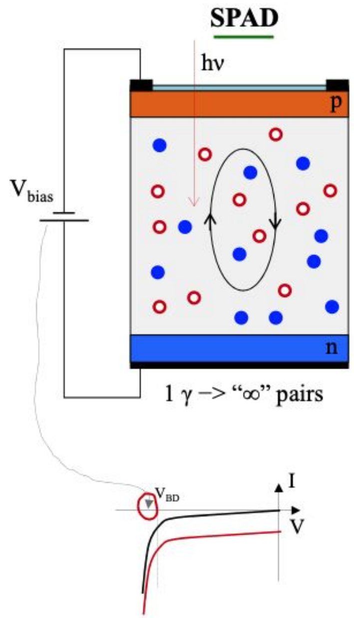
08/03/2024

Federico De Guio - Matteo Fossati

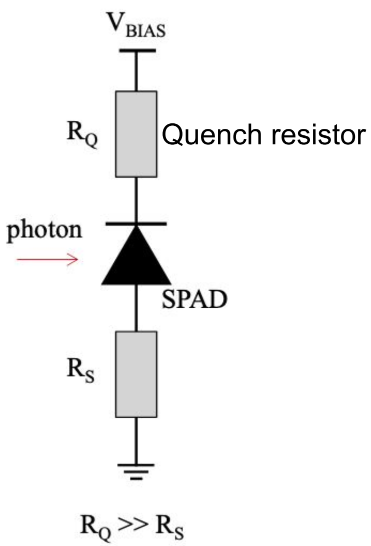
What is a PN junction and how it is operated

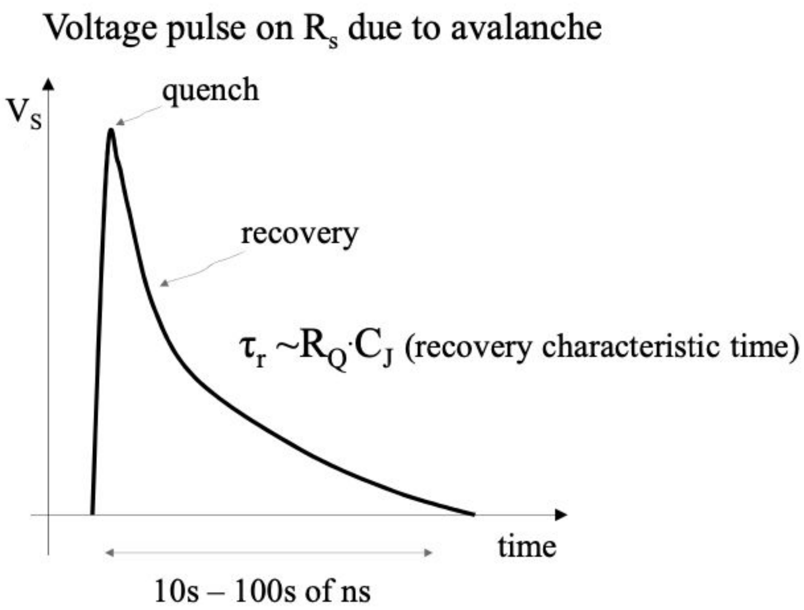
- A **PN junction** is an interface between a p-type and a n-type materials
  - PN junctions are created by doping the material with an excess or defect of electrons
  - Electrical current can flow through the junction in one direction only
  - At the junction, a **depletion layer** is created
  - When a **reverse bias** is applied, the depletion region is enlarged





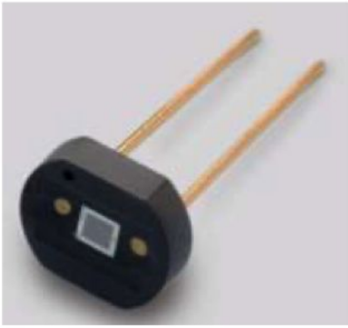
Operation of a Single-Photon Avalanche Diode (SPAD)

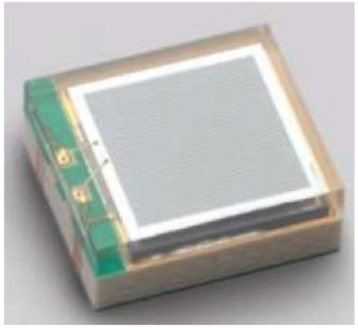


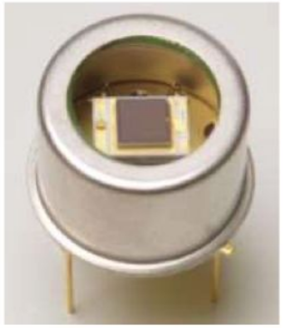


What is a Silicon Photo-Multiplier (SiPM)

- Gain: 10^5 - 10^6
- SPAD size: 10-100um^2
- nCells: from 100s to 10000s


Ceramic

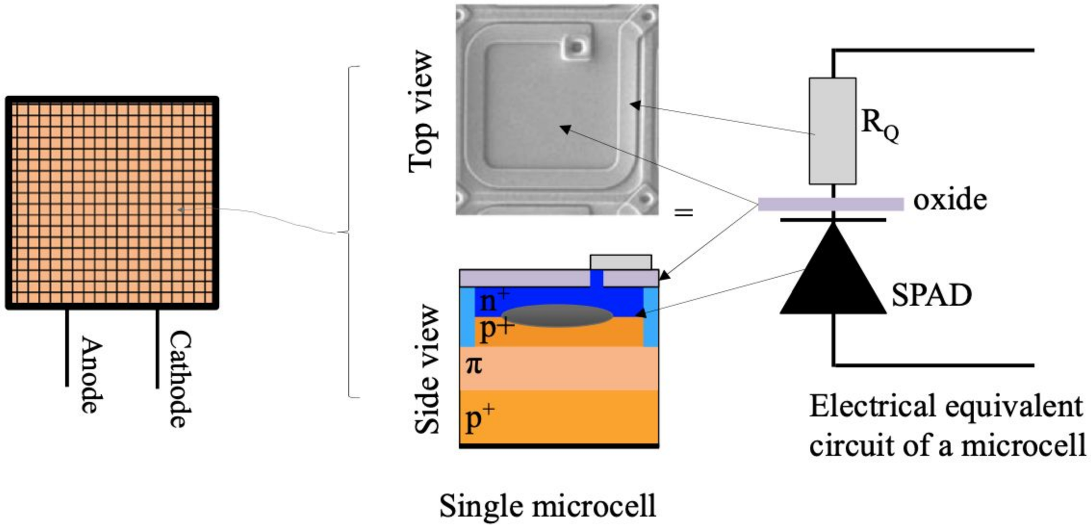

Surface mount


Metal, TE-cooled


Array of SiPMs

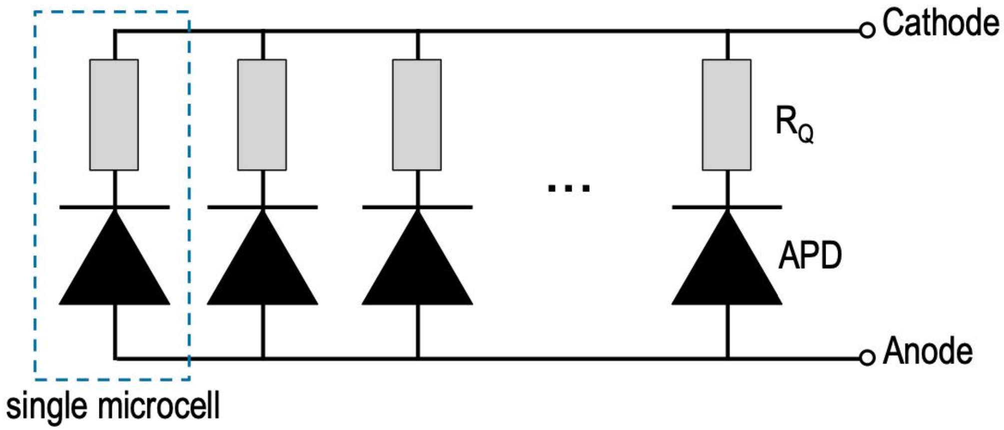
Images not to scale

SiPM structure



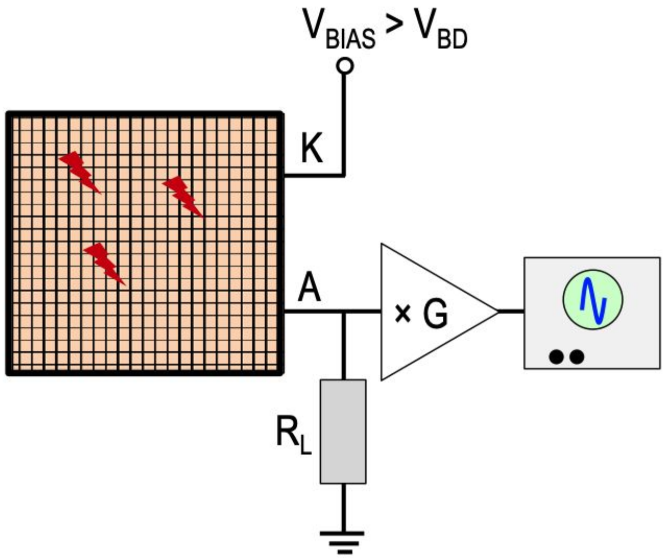
- Each microcell is a SPAD in series with a quench resistor

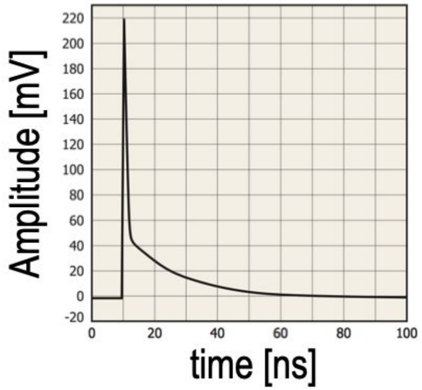
SiPM structure



- All microcells are connected in parallel → SiPMs are not imaging devices because all microcells share common anode and cathode

SiPM operation

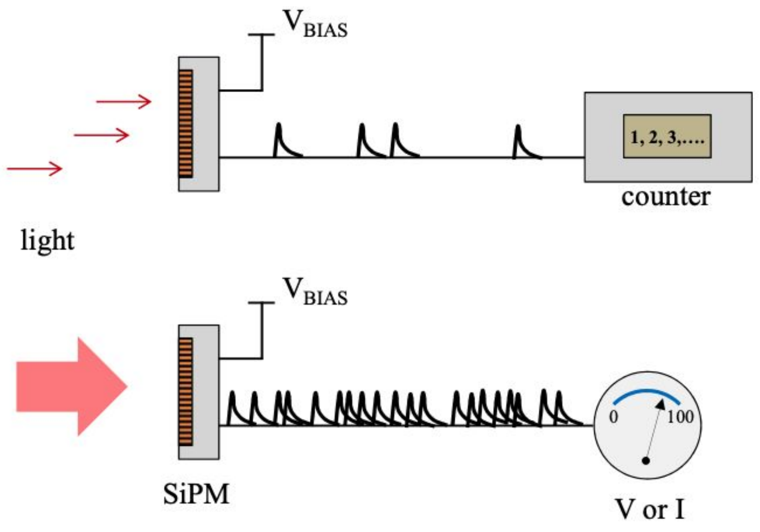




Example of single-photoelectron waveform (1 p.e.)

Gain = area under the curve in electrons

SiPM operation

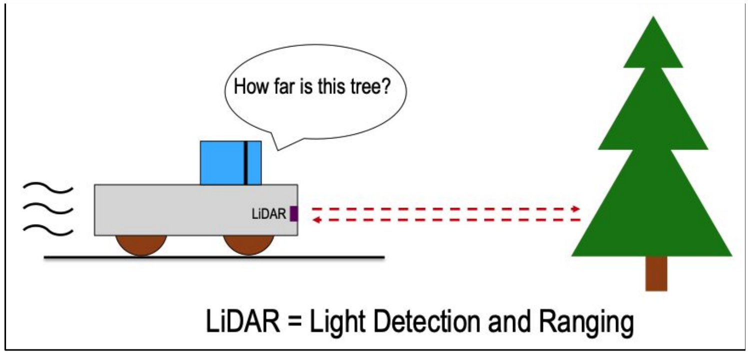


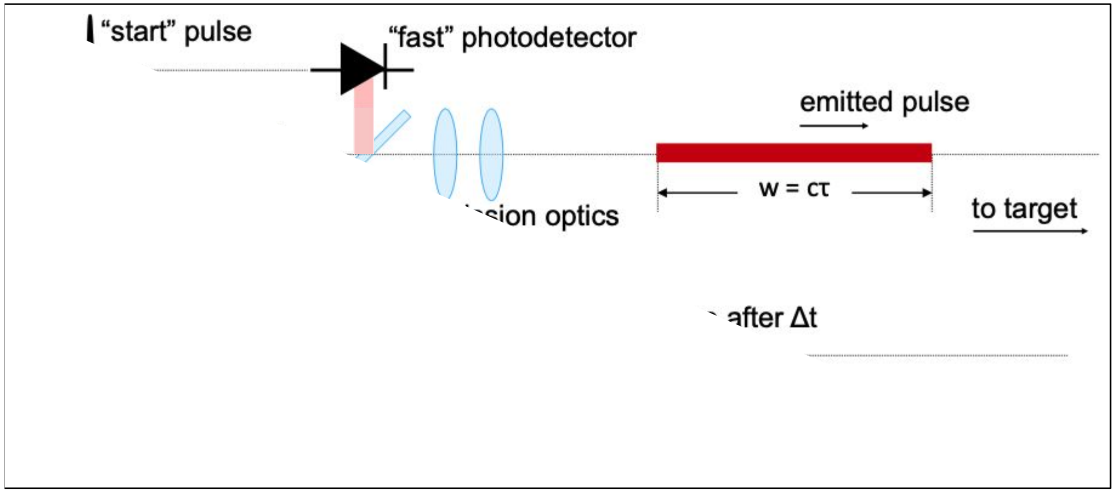
If the pulses are distinguishable, SiPM can be operated in a **photon counting** mode.

If the pulses overlap, the SiPM can be operated in an **analog mode**. The measured output is voltage or current.

Applications of SiPMs:
time-of-flight (TOF) LiDAR

- Measure the round trip time-of-flight Δt
- By scanning the surroundings, a 3D map can be constructed



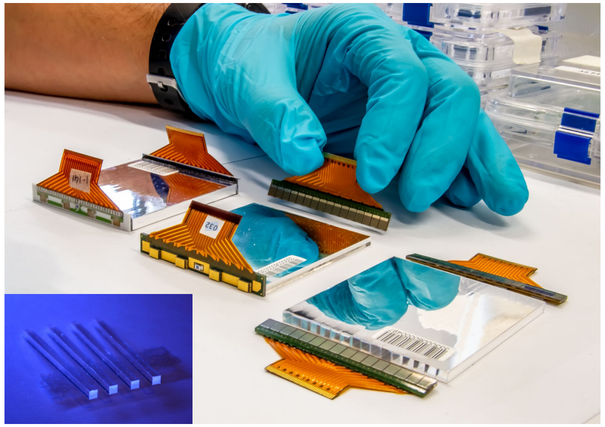


- Wavelength: 905 or 1550 nm
- Pulse duration: 2-5 ns
- N. of photons per returned pulse: 100's - 10,000's on detector's active area
- Repetition frequency: kHz - MHz

Applications of SiPMs: particle detectors

- SiPMs can be coupled to a **scintillator material**
  - In the case of the MTD detector, LYSO bars are glued to arrays of SiPMs

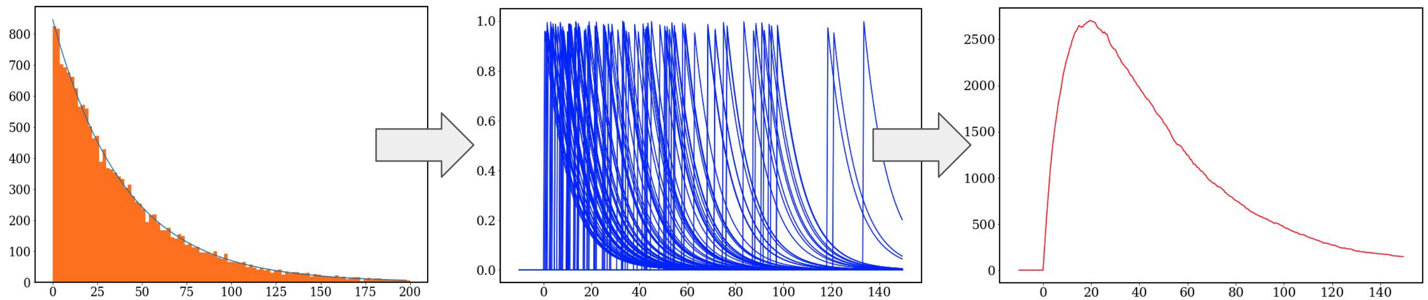
- The output signal is the **convolution of the scintillation pulse and the SiPM response**



Time distribution of the photons from scintillation (τ_1)

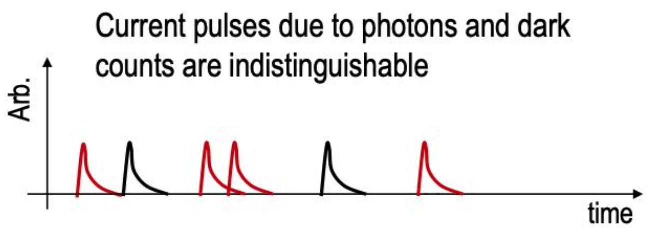
SiPM response associated to each photon (τ_2)

Integrated electronics pulse

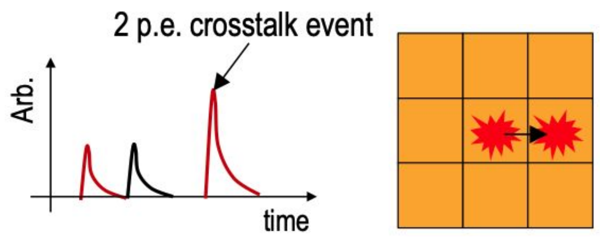


Spurious signals: dark current and cross talk

- **Dark counts** originate from the thermal motion of the charge carriers
  - A way of reducing the dark count rate is to lower the temperature of the detector

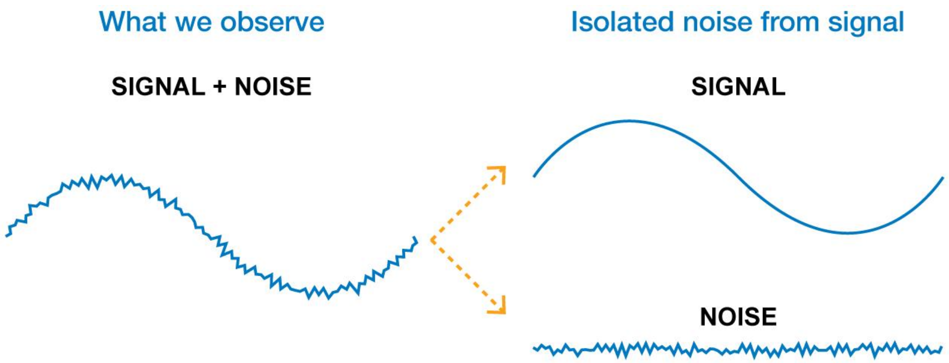


- **Cross talk:** the primary discharge can trigger a secondary discharge in neighbouring microcells



Impact of the electronics noise

- Electronic noise is an **unwanted disturbance** in an electrical signal
- Many different source of noise (e.g. electronics noise due to thermal motion of charge carriers)
- It is something that **can be reduced, but not eliminated completely**
- It impacts the observables that can be extracted from the pulses and **deteriorates the detector performance**

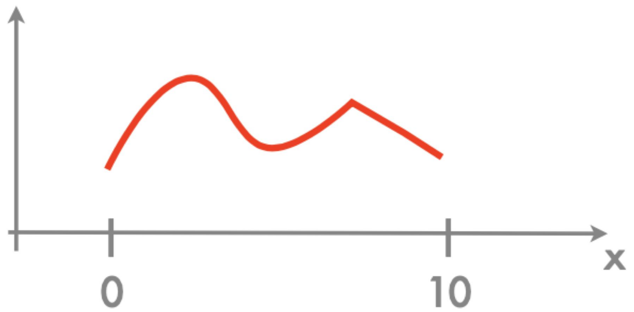


S/N ratio measures the impact of the noise in relation to the signal size

How to generate a pulse library using a MonteCarlo method

The hit or miss algorithm

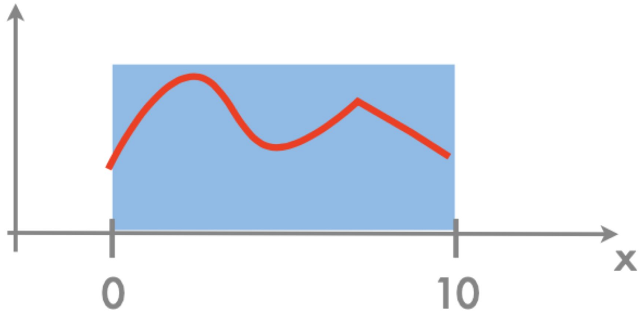
- The goal is to **generate events distributed according to a function f(x)**
  - In other words: generate observations from the distribution describing the physics phenomenon



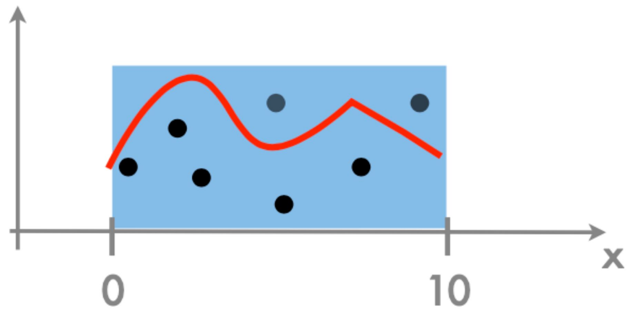
Generate events between
0 and 10

The hit or miss algorithm

- Define a box so that f(x) is always contained
    - Need to know the max and min of the function

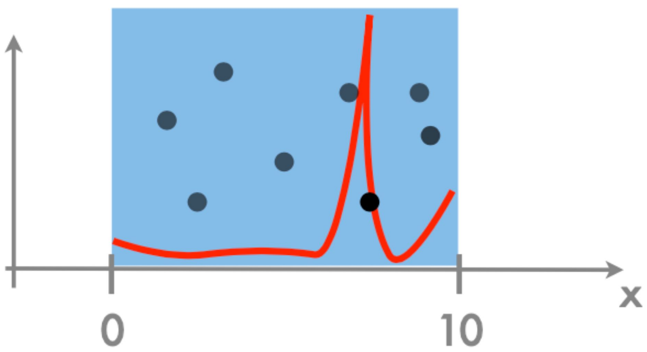


- Use a random number generator to extract (x, y) pairs and accept the ones that fall below the function



Efficiency

- The fraction of accepted events is proportional to the area below the curve
- It is the most efficient numerical integration method in many dimensions (>3)
  - Can be very inefficient for peaked distributions
  - It is ok if we want to generate O(10k) events



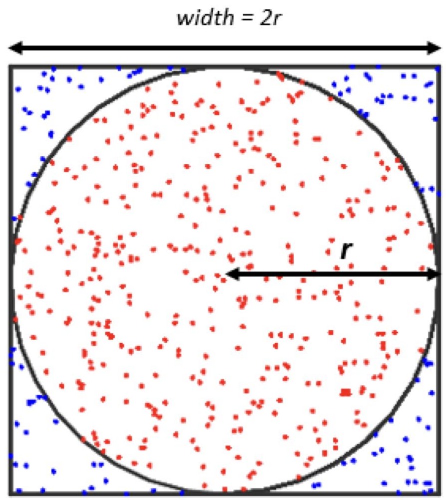
Classic example: calculate PI with a hit or miss method

- Consider a circle inside a square
- Generate "events" along x and y

$$\boxed{A_C / A_S = PI / 4}$$

- Question: how do I calculate the error on the measure of PI?

- See a generic implementation here



Today's exercise:

Generate a library of SiPM pulses
Simulate gaussian electronics noise

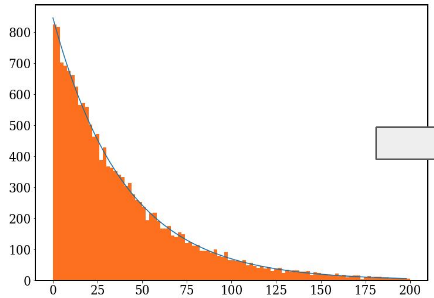
Next week:

Build a de-noising DNN
Apply it on the generated SiPM pulses

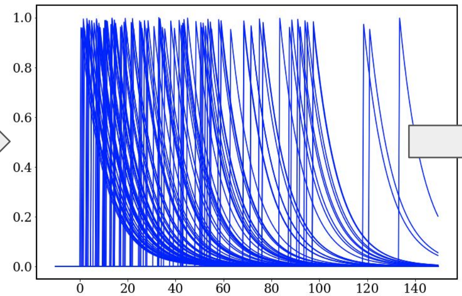
Simulation of the Scintillation+SiPM respose

- Generate one pulse reproducing the light collection and the SiPM response mechanism
  - Generate 10k events according to the scintillation process: **use τ_1 = 40ps**
  - Associate the SiPM response to each generated photon: **use τ_2 = 10ps**
  - Sum up all the SiPM pulses to get the final electronics responses

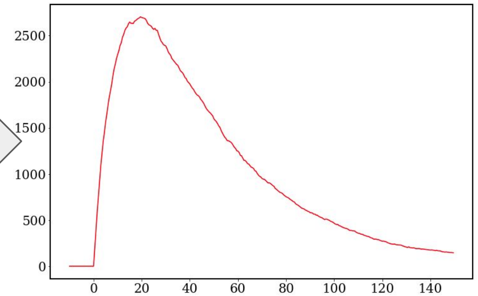
Time distribution of the photons from scintillation (τ_1)



SiPM response associated to each photon (τ_2)

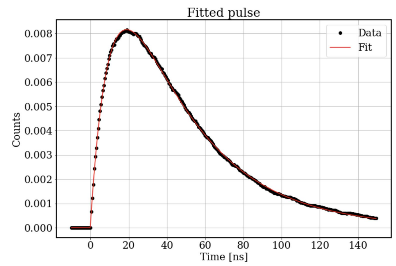


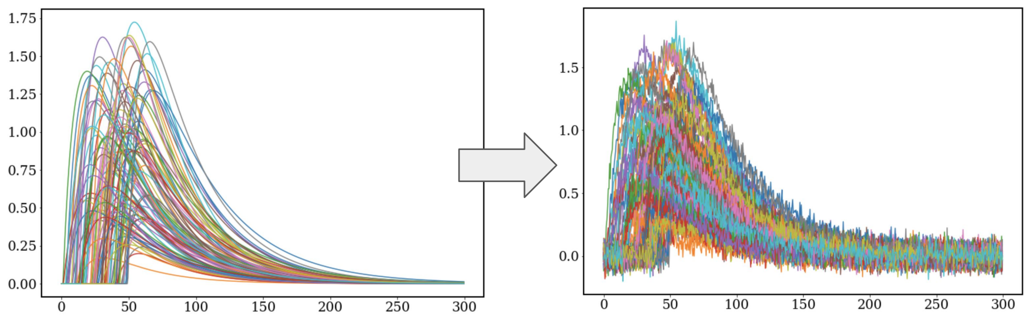
Integrated electronics pulse



Generate a library of pulses

- Fit the integrated pulse with a function which is the **convolution of the Scint and SiPM ones**
- Once confirmed that the function well describes the data, generate a library of pulses
    - `scint_tau_range = [30, 50]`
    - `sipm_tau_range = [8, 12]`
    - `ampli_range = [10, 100] #normalization`
    - `time_shift_range = [0, 50]`
- Generate a similar library where some gaussian noise is added
    - `noise_mean = 0`
    - `noise_sigma = 0.05`





Backup

Performance and characteristics of a SiPM