# Orientation for Hardware Training

Son Cao (IFIRSE, ICISE)

Lab mentors: Alex Sells (UCL, UK); Sang Truong, Quyen Phan, Thanh Nguyen (IFIRSE, ICISE)

9th Vietnam School on Neutrinos, July 16, 2025

# Timetable for hardware training and mini-project

- We prepare **four independent setups** for hardware training. *They are not identical but similar concept (photodetector , scintillator, and relevant electronics )*
- Schedule for July 16th (Wed.)
  - 17:10 - 17:20 Student grouping and mini-project introduction
  - 17:20 - 17: 40 Orientation for hardware training
- Schedule for July 17th (Thu.)
  - 15:10 - 17: 10 (2h) Hands-on activities
  - Group must decide topics to work with before midnight of July 17th (local time)
- Schedule for July 18th (Fri.)
  - 13:20 - 15: 50(2.5h.) Hands-on activities
  - 16:00 - 17:30 (1h): mini-projects
- Time for mini-project next week: Tue(2.5h); Thu (2.5h); Fri (1.5h)

# VSON-2025 student grouping for hardware training

## Group 01

- Toma Abe, Institute of Science Tokyo, JP
- Shogo Horiuchi, Keio Univ., JP
- Seng Zong Yun, Univ. Malaya, MY
- (F)Anh Pham, USTH, VN
- Duc Luu, HUS-VNU, VN

Lab mentor: Alex Sells/ PMT

## Group 02

- Kotaro Indo, Kyoto Univ., JP
- Zhenhao Liang, Westlake Univ., CN
- Wi Han Ng., Univ. of Melbourne, AU
- Bruno Kovac,Rudjer Boskovic Inst., HR
- (F) Linh Ha, INST, VN
- Duong Hua, USTH, VN

Lab mentors: Sang Nguyen + Quyen Phan
MPPC array

## Group 03

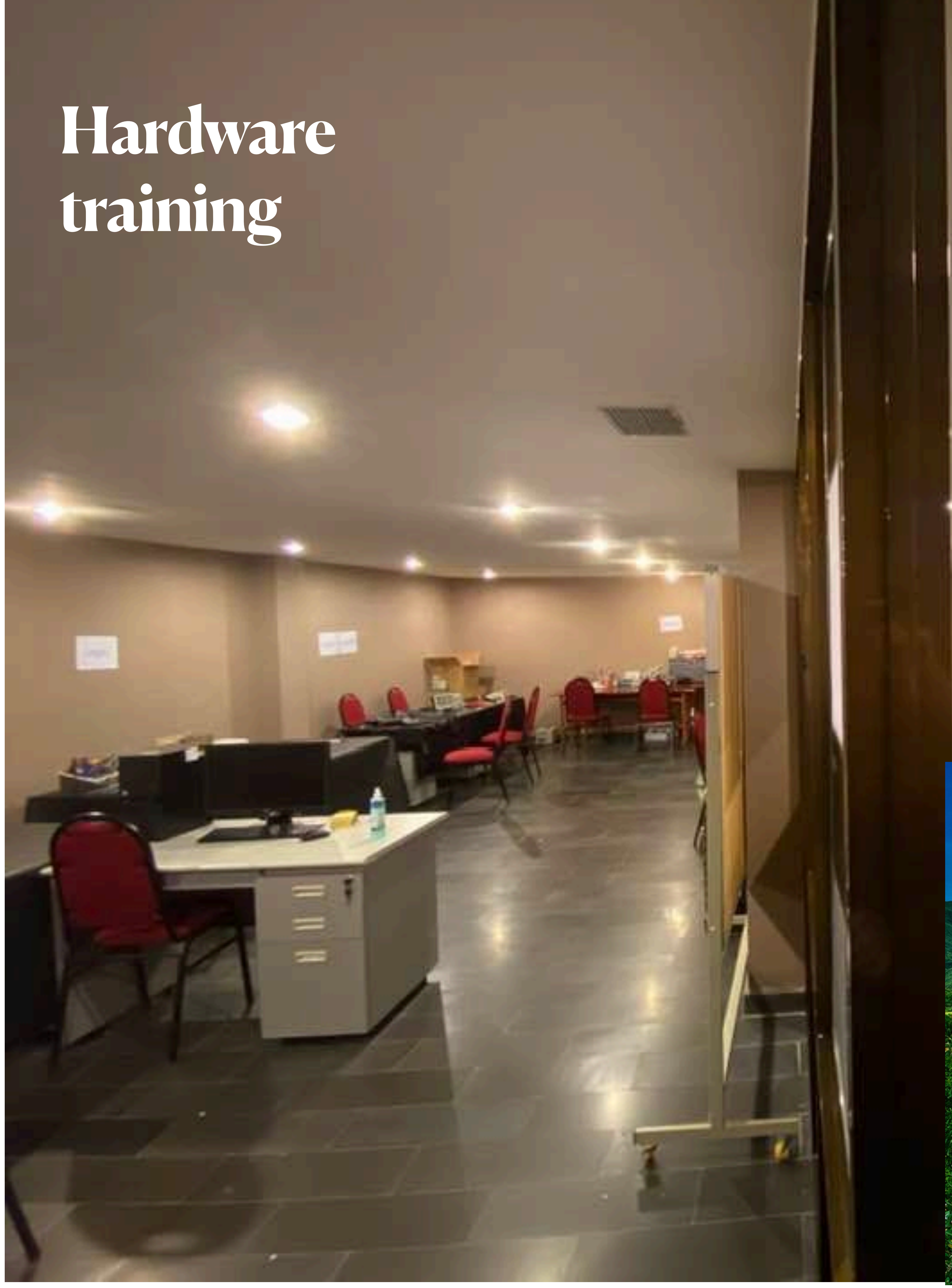
- SHINYA AOYAMA, Kobe Univ., JP
- Amal K. , Vellore Inst. of Tech. Chennai, IN
- Dang Nguyen, Univ. of Warsaw, PL
- Nam Pham, VNU-HCM, VN
- (F) Tien Le, USTH, VN

Lab mentor: Thanh Nguyen/ Single MPPC

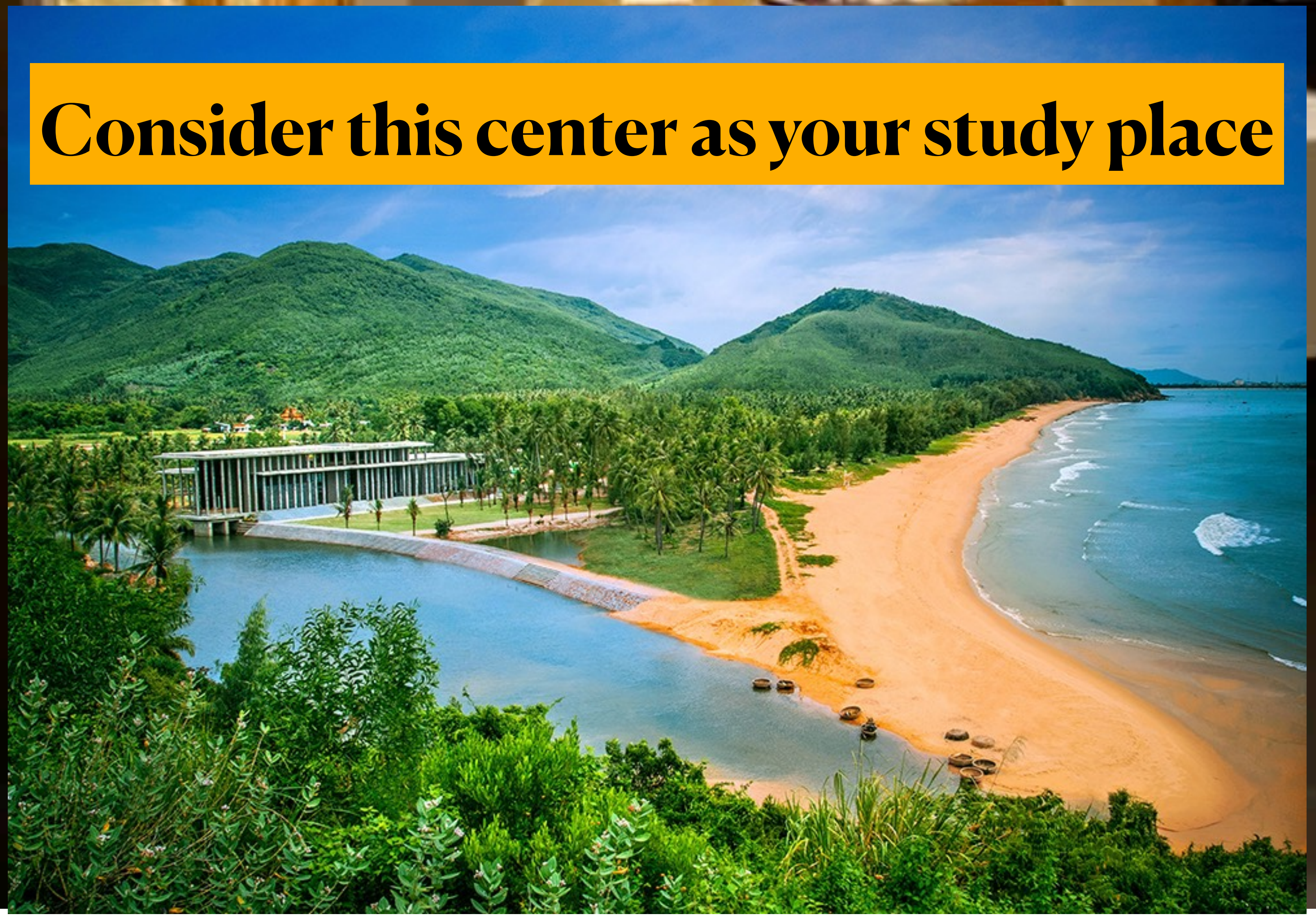
## Group 04

- Sota Kobayashi, Tohoku Univ., JP
- (F) Ayana Asai, Okayama Univ., JP
- Vexster Juali, Univ. Malaya, MY
- Tumurjav Lkhagvaja, Mongolian Academy of Sciences, MN
- Duc Quach, USTH, VN
- (F)Tuyen Le, QNU, VN

Lab mentor: Son Cao/ MPPC + PMT


Hardware
training


Study place
for mini-project


Consider this center as your study place


Hardware
training

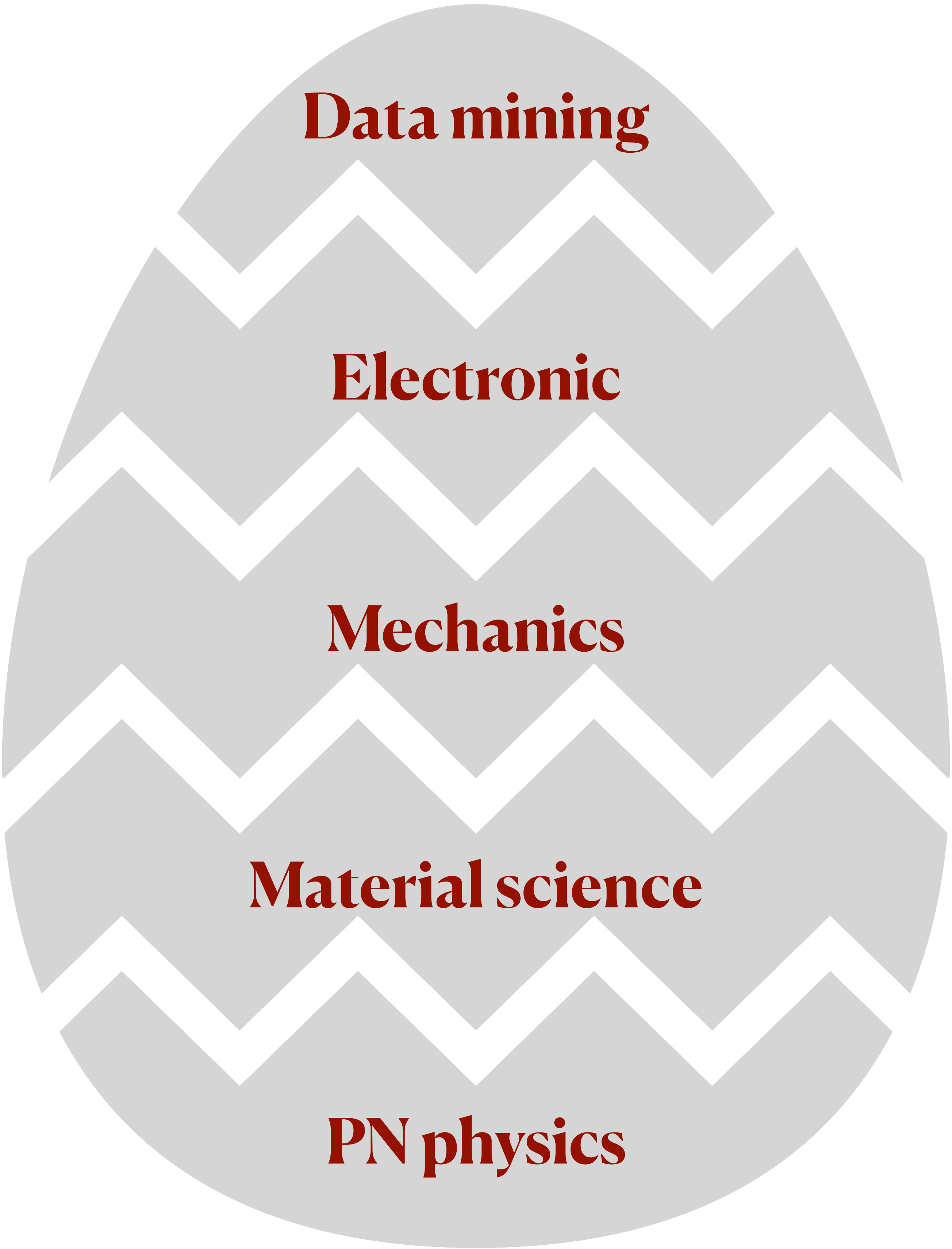
# Purpose:

**Provide some hands-on experience w/ hardwares used in real Neutrino Detector**

**Vietnamese students lack skills with hardware, especially in particle and nuclear physics**

- Did you use multimeter before?
- Did you use oscilloscope before?
- Did you use NIM modules before?
- Did you use photosensor (*not including smartphone's camera*) before?
- ....

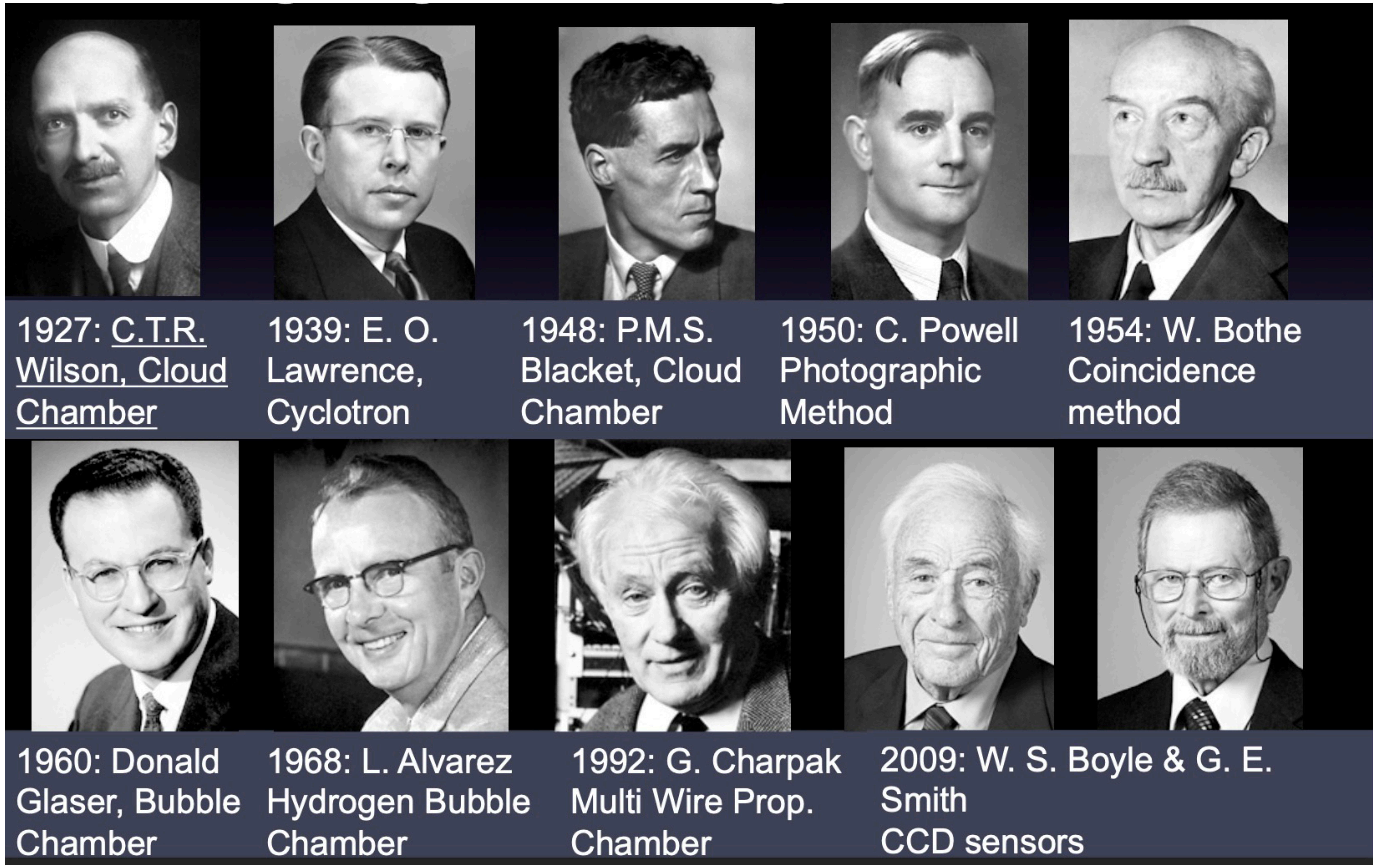
Particle detector is a *instrument (kind of classical device)* to detect, to track, and to identify the *particles (superposition of quantum states)*




**A complicate, interdisciplinary field**

Ref. Basics of Particle Radiation Detector and others

# Nobel prize for instrumentation




**“The real voyage of discovery consists, not in seeking new landscapes, but in having new eyes”**

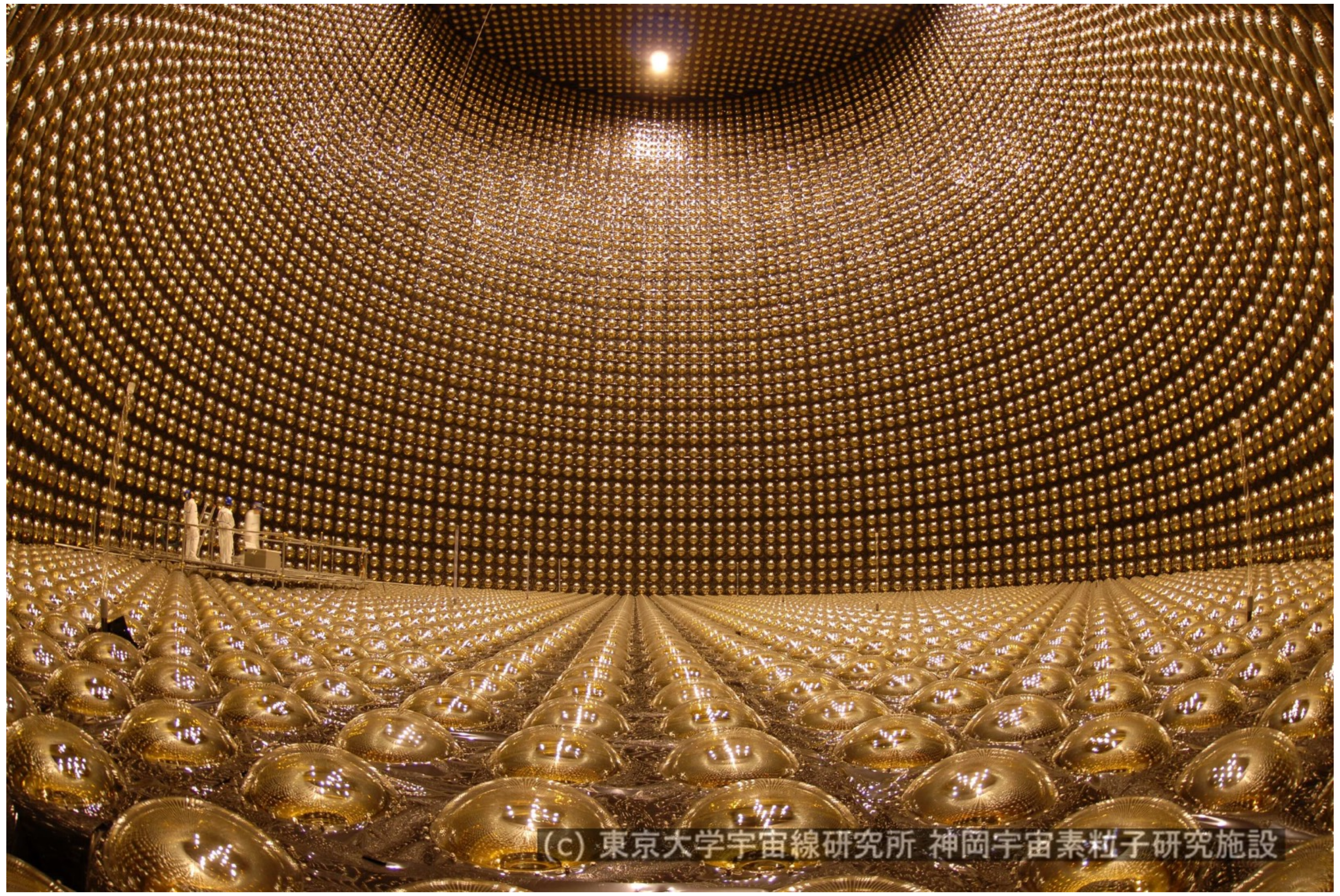
~Marcel Proust~

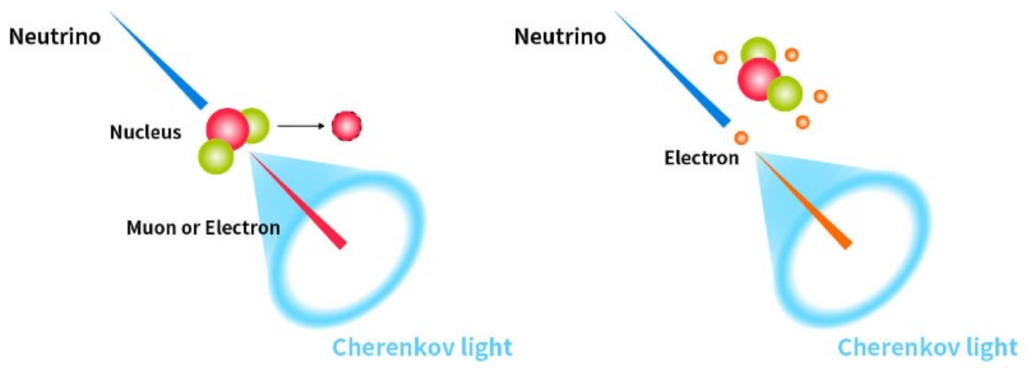
# Particle physics, a key driver for innovation

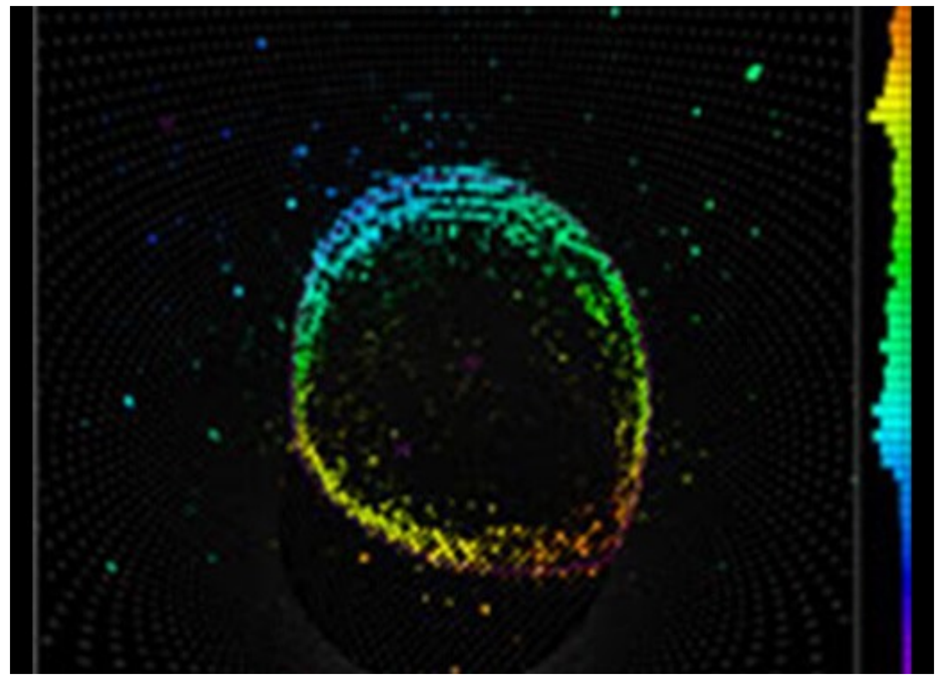
"The complex and sophisticated tools of particle physics are rich sources of new concepts, innovation and groundbreaking technologies, which benefit various applied research disciplines and eventually find their way into many applications that have a significant impact on the economy and society."

https://cds.cern.ch/record/1431474/files/ParticlePhysicsEurope-New.pdf

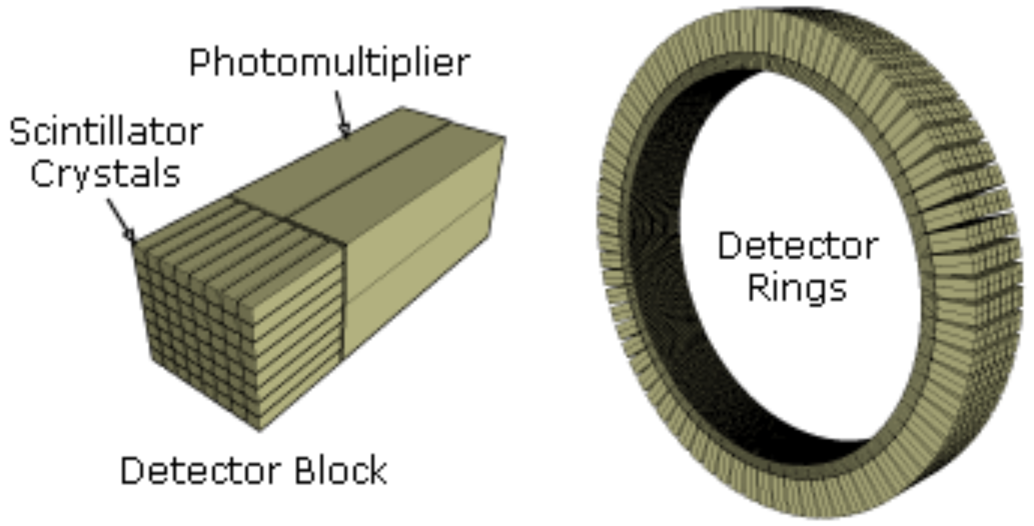
# Interplay btw. physics and technology

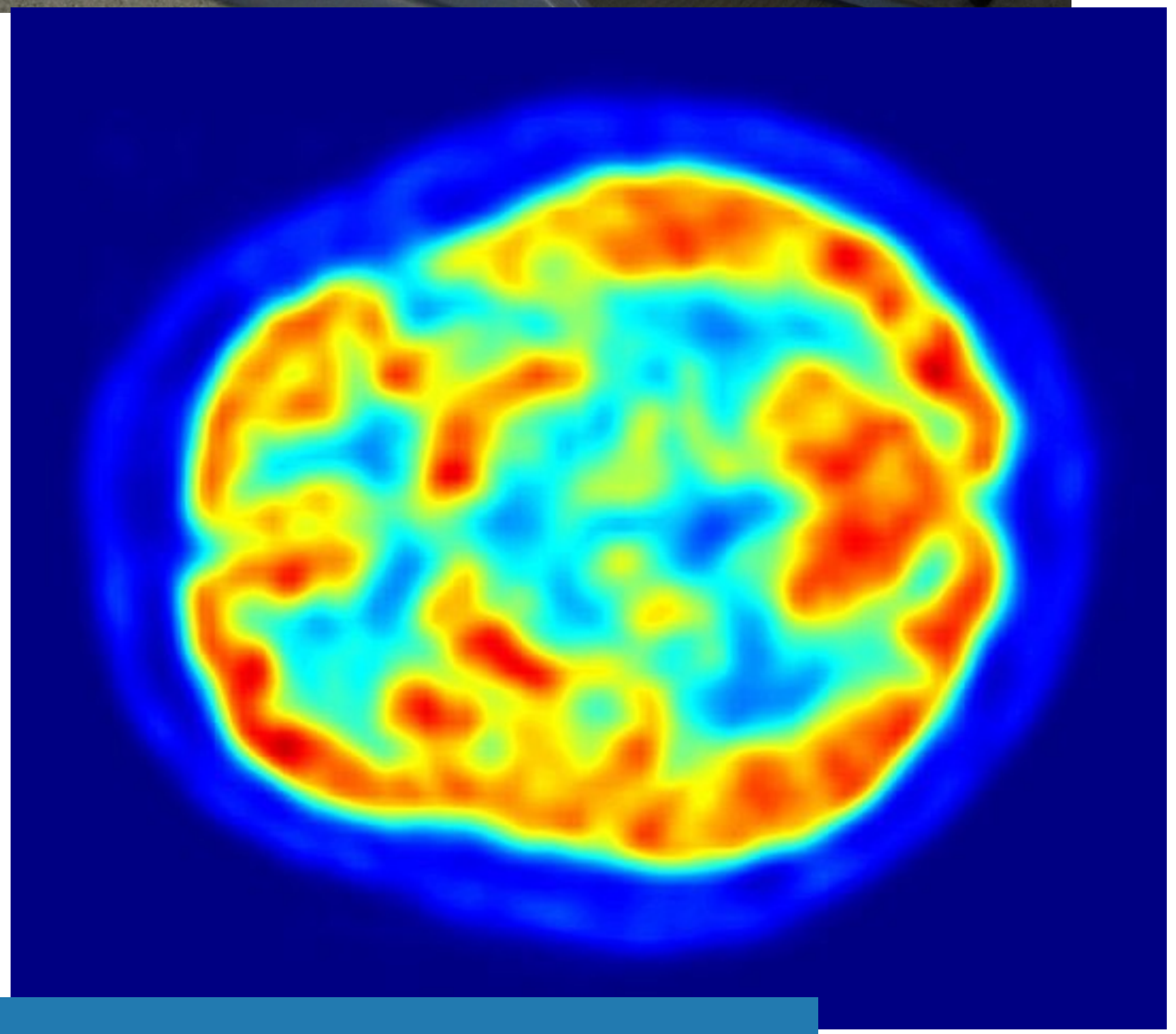


SUPER-KAMIOKANDE



POSITRON EMISSION TOMOGRAPHY

# Objectives of hardware-training

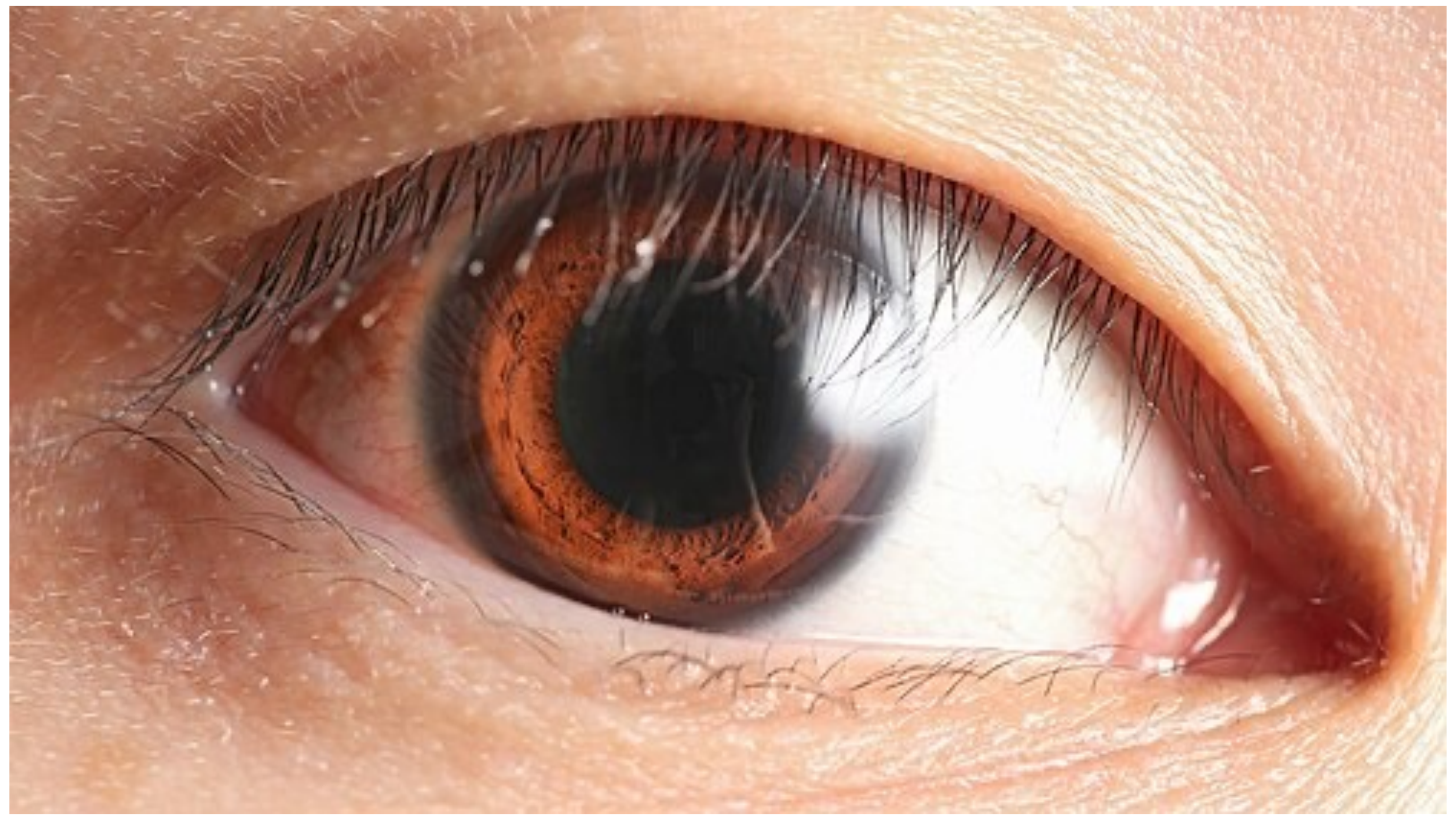
- Functionality and operation of photodetectors
- Observe the cosmic-ray muons

(Some electronics for signal processing)

# Photodetectors

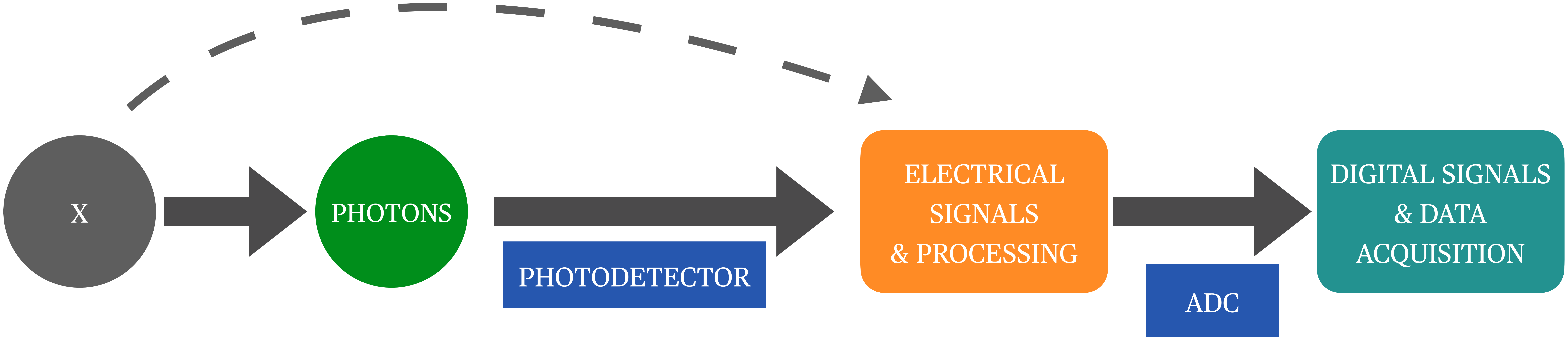
# Example: Human eyes as “biological” photodetector

- Detect light in visible spectrum (*380-700nm*), peak around 555nm (*yellowish green*) in daylight
- Large dynamic range (*~1e6 time btw. the highest and lowest intensity can be seen*)
- Relatively slow response time (~ few tens of ms)
- Brains acts as an advanced image processor
- …



# Role of photodetectors

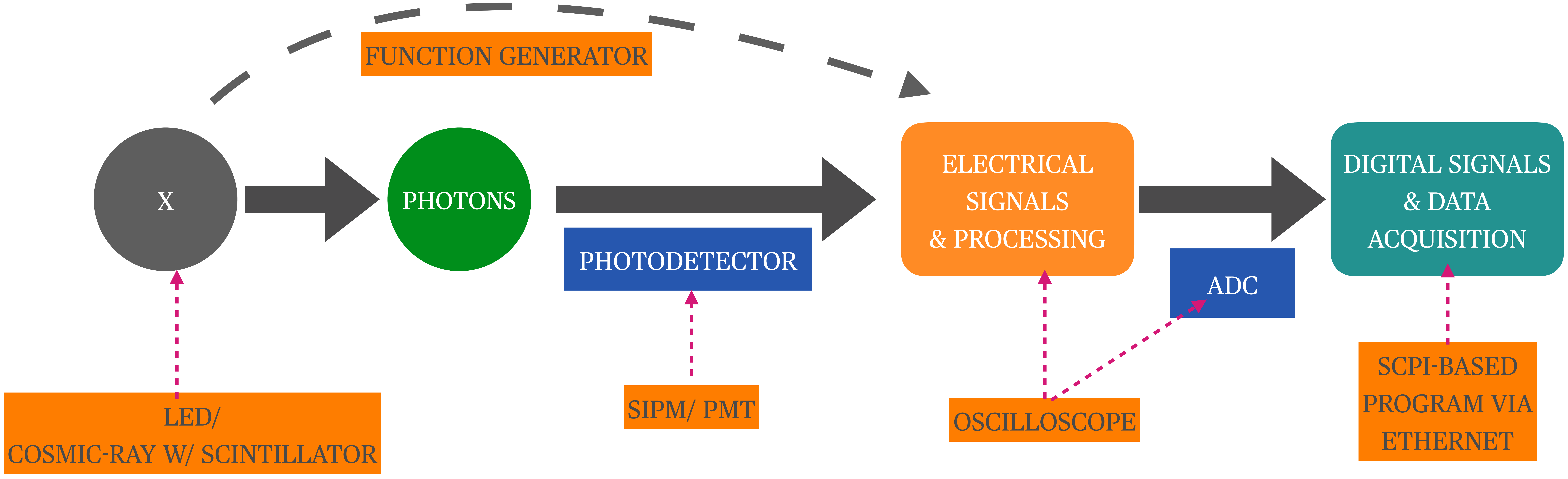
Typically, we sense/measure the things (*elementary particles, chemical elements…*) by converting them into the optical signals, which can subsequently be detected by the photodetectors




Signal processing and data acquisition are needed to obtain information from photosensor

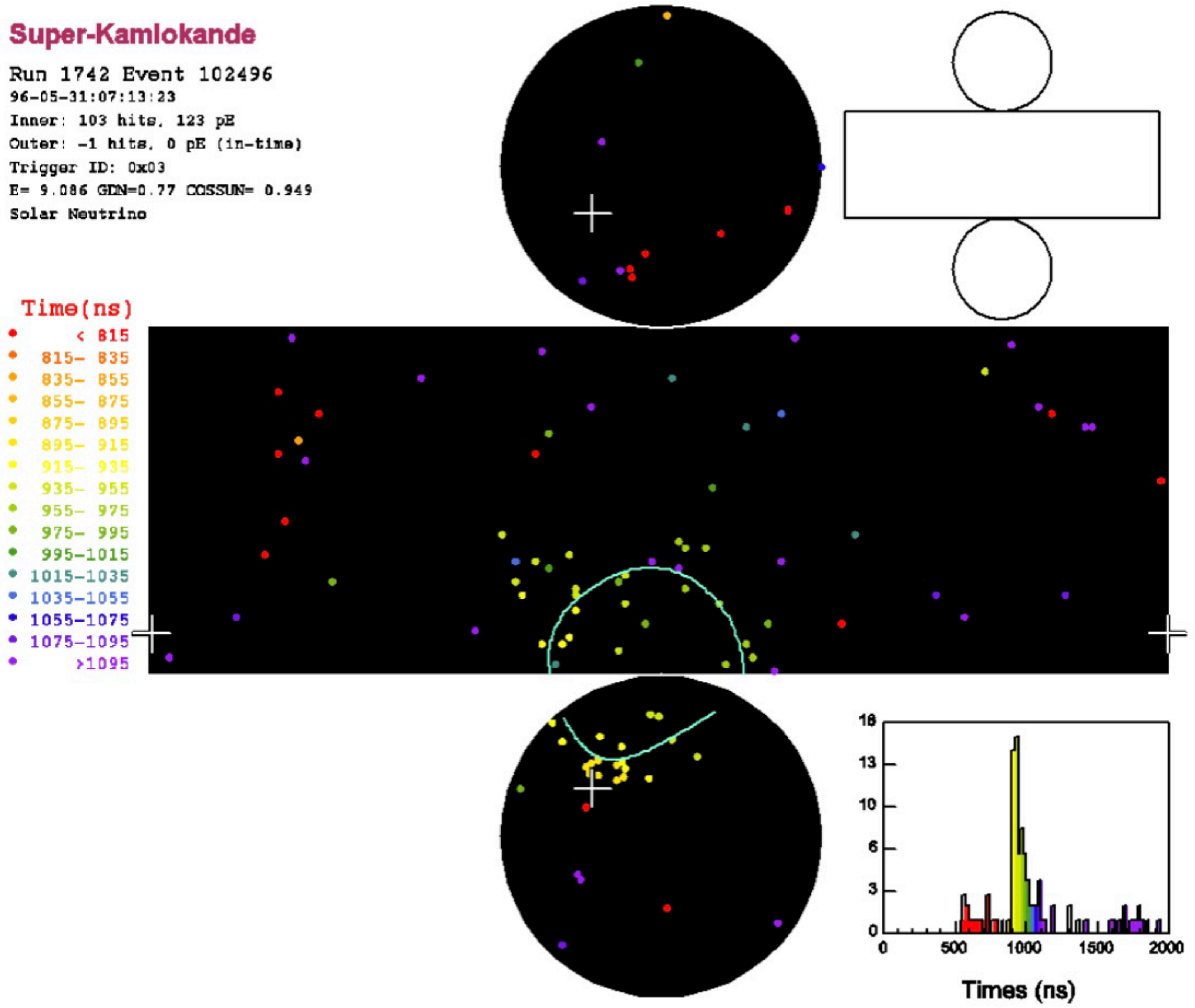
# Role of photodetectors

Typically, we sense/measure the things (*elementary particles, chemical elements…*) by converting them into the optical signals, which can subsequently be detected by the photodetectors

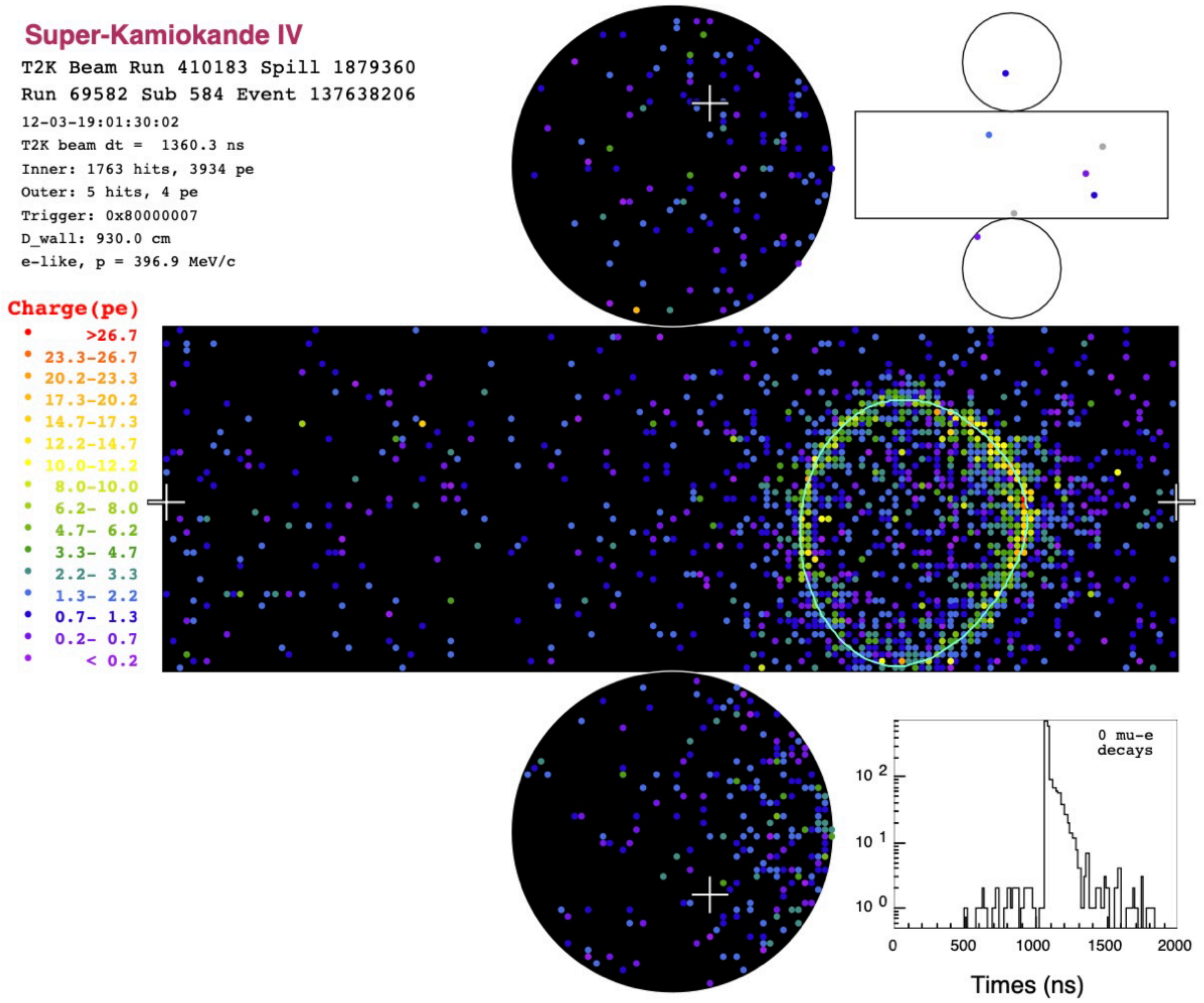


# Trace of neutrinos: (typically) very faint flash of light

"Experimental neutrino experiment in the nutshell"




A ~ 9MeV solar neutrino candidate
123 p.e. counted in 103 PMT in few 100ns;
~ 1 p.e. per hit PMT




A ~400MeV $\nu_e$ candidate from T2K beam
3934 p.e. counted in 1763 hit PMT in few 100ns
~3-4 p.e. per hit PMT

In a blinking of LED

....~$10^{15}$ photons are generated

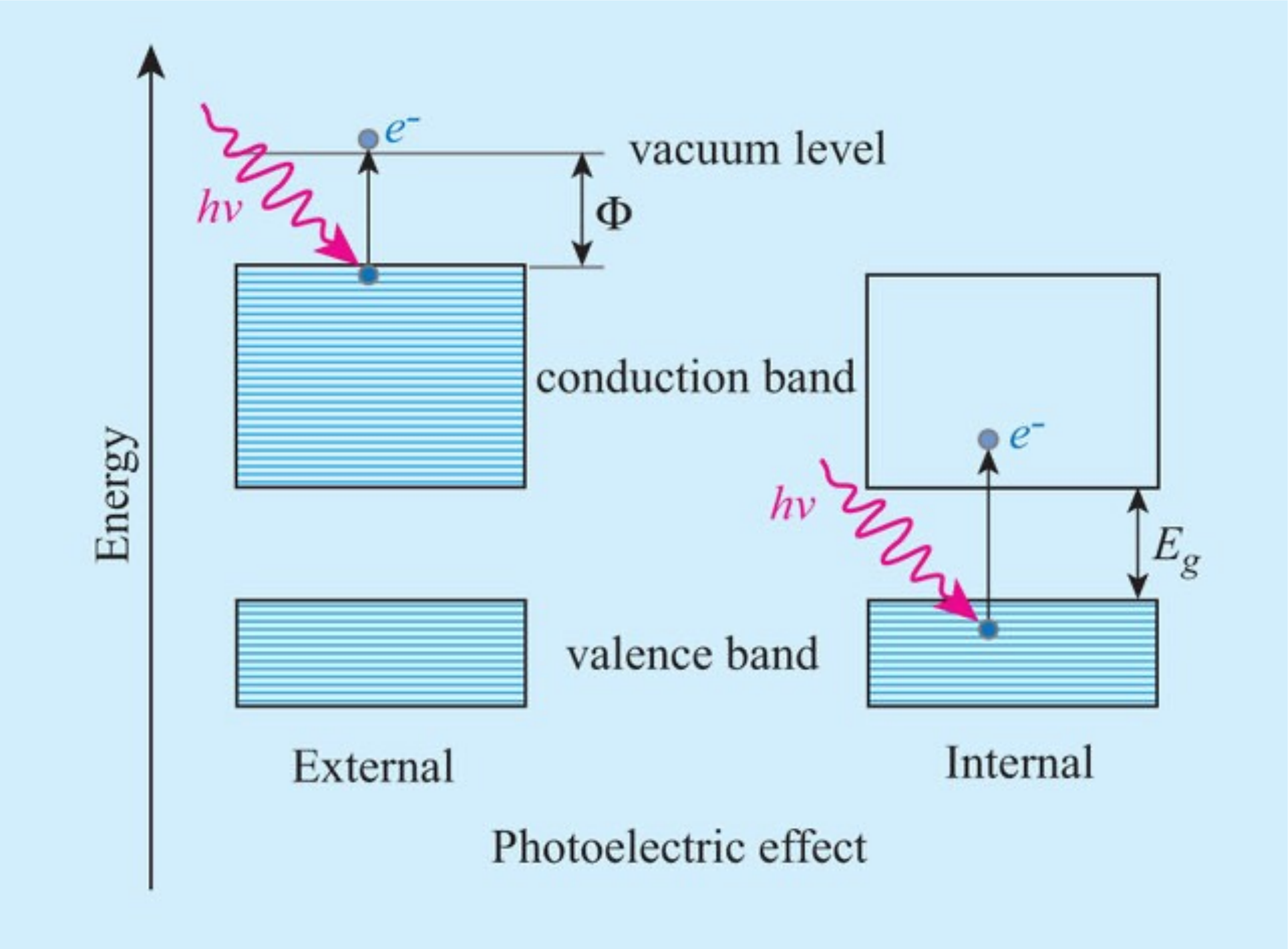
Typically, signature of the comic ray muons passing through detector is fast (ns or sub-ns) and faint (few 10s to 1000s photons)

↓

**We need a very good "Eyes" housed in light-shielding place**

# General working principle: external/ internal photoelectric effect

"**External**": photoelectron is ejected into free space (vacuum or air)




"**Internal**": photoelectron is moved from valence band into the conduction band

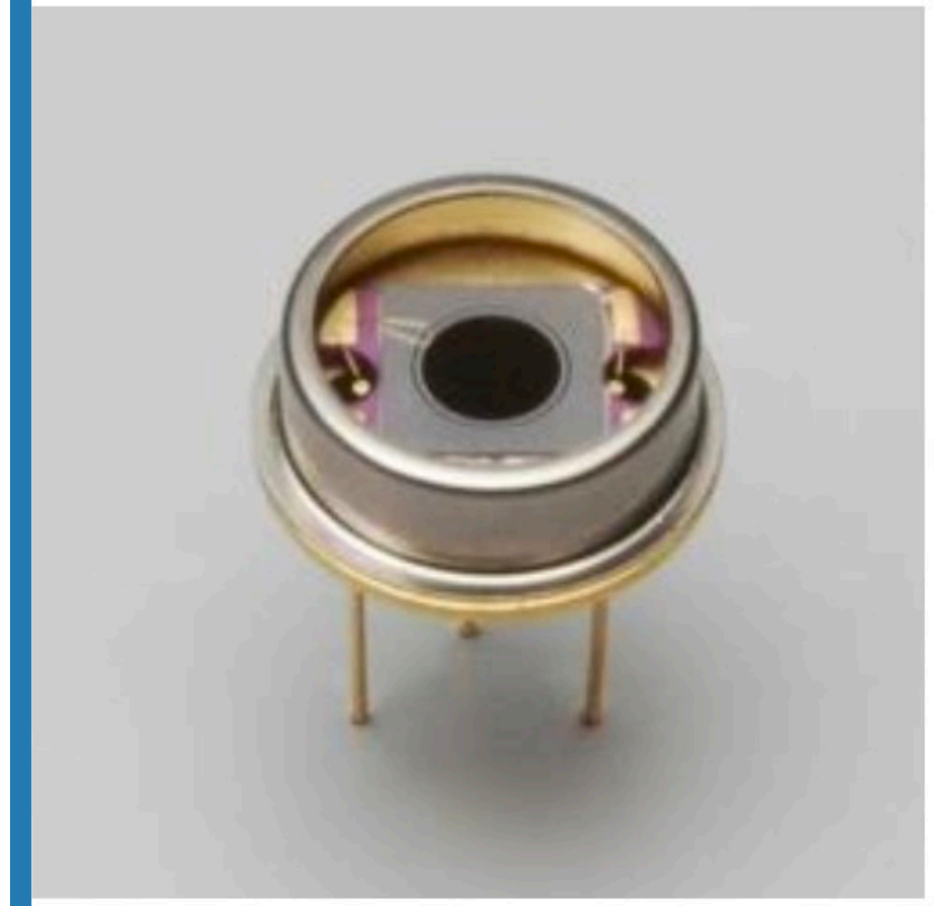
- Based on the **photoelectric effect**: **External** or **Internal**
- Need "*photosensitive*" materials (K, Na, Rb), which have high tendency to release electrons (or small *electronegativity*)
- Typically need to turn this *microscopic* "electron-emission" signal into the **macroscopic** level, eg. multiplication

# Different types of photodetectors

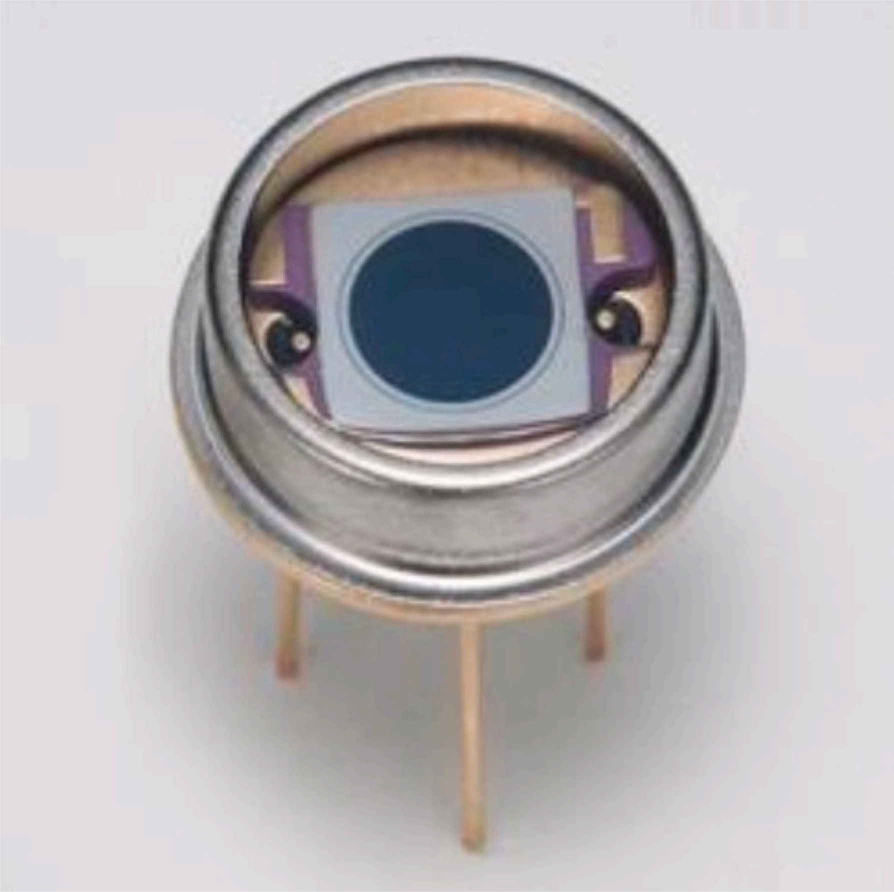
"EXTERNAL PHOTOELECTRIC "

"INTERNAL PHOTOELECTRIC "


PMT



PD



APD

SiPM

(Also called MPPC)

PMT – photomultiplier tube

PD – photodiode

APD – avalanche photodiode

SiPM – silicon photomultiplier

# Basic characteristics of photodetector

- **Spectral response:** *Range of wavelength can be detected *efficiently**
- ***Active* area:** *Part of detector is designed for producing photoelectron when light strikes on. PMT is typically larger than others*
- **Quantum efficiency (QE) and Photon detection efficiency (PDE)**:
  - QE: *probability for single photon coming into a "active" region and a photoelectron ejected.*

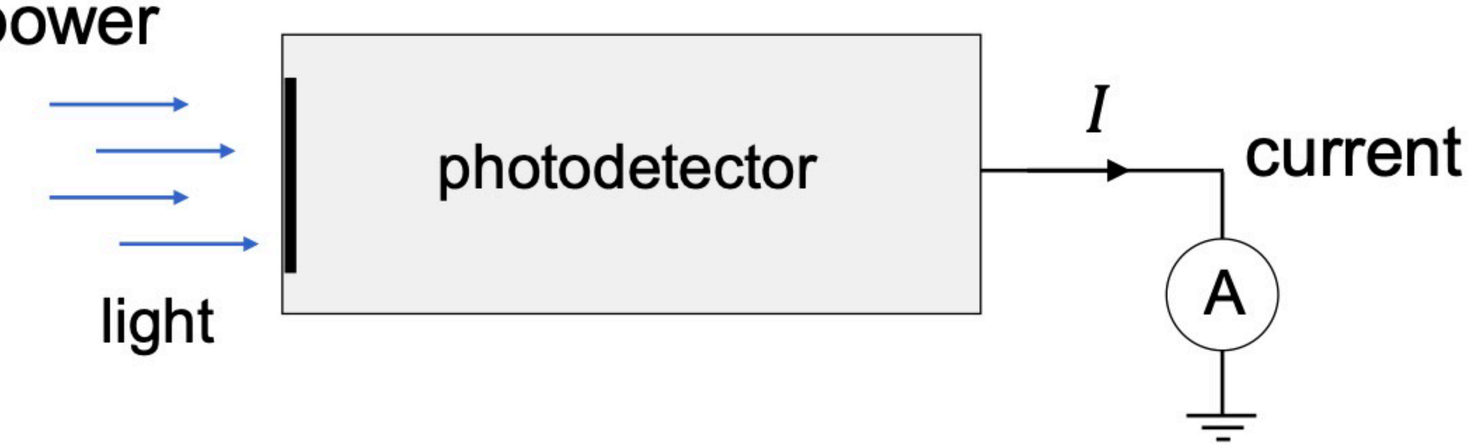
    $$QE = \frac{N_{p.e.}}{N_{\gamma}} \times 100\ \%$$

  - *PDE is probability for detectable output signal be generated by an incoming photon, normally smaller than* QE, *eg.* $PDE = QE \times R_{filling} \times P_{avalanche}$
- **Dark current:** *detectable output even in the completely dark (no light source )*
- **Intrinsic gain:** *No. of equivalent electron in the ouput given an incoming photon, PMT and SiPM are in order of* $10^6$
- **Dynamic range:** *ratio between the maximum and minimum detectable light intensities (with reasonably precise or good linearity)*
- **Response time:** *characterize how quickly it reacts to a strike of light (maybe confused from quantum point of view) and converts them into the electric signal.*
- …

# Quantum efficiency and spectral sensitivity

$\sigma$ – Spectral sensitivity; $\eta$ – Quantum efficiency

$P_0$ – incident light power

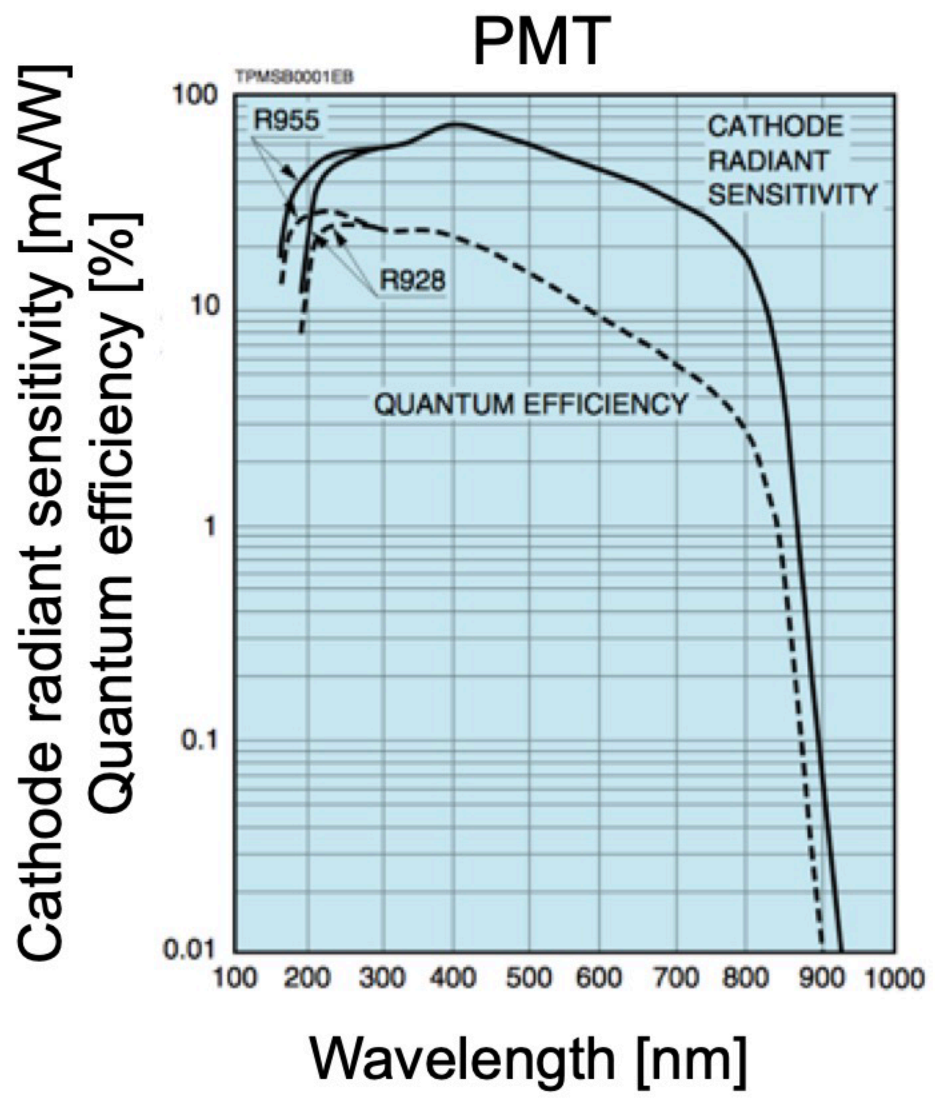



$$I = \sigma P_0 \qquad \text{(monochromatic)}$$

$$\eta = \frac{hc\sigma}{\lambda e} = \frac{1240\sigma}{\lambda[nm]} \qquad \text{(monochromatic)}$$

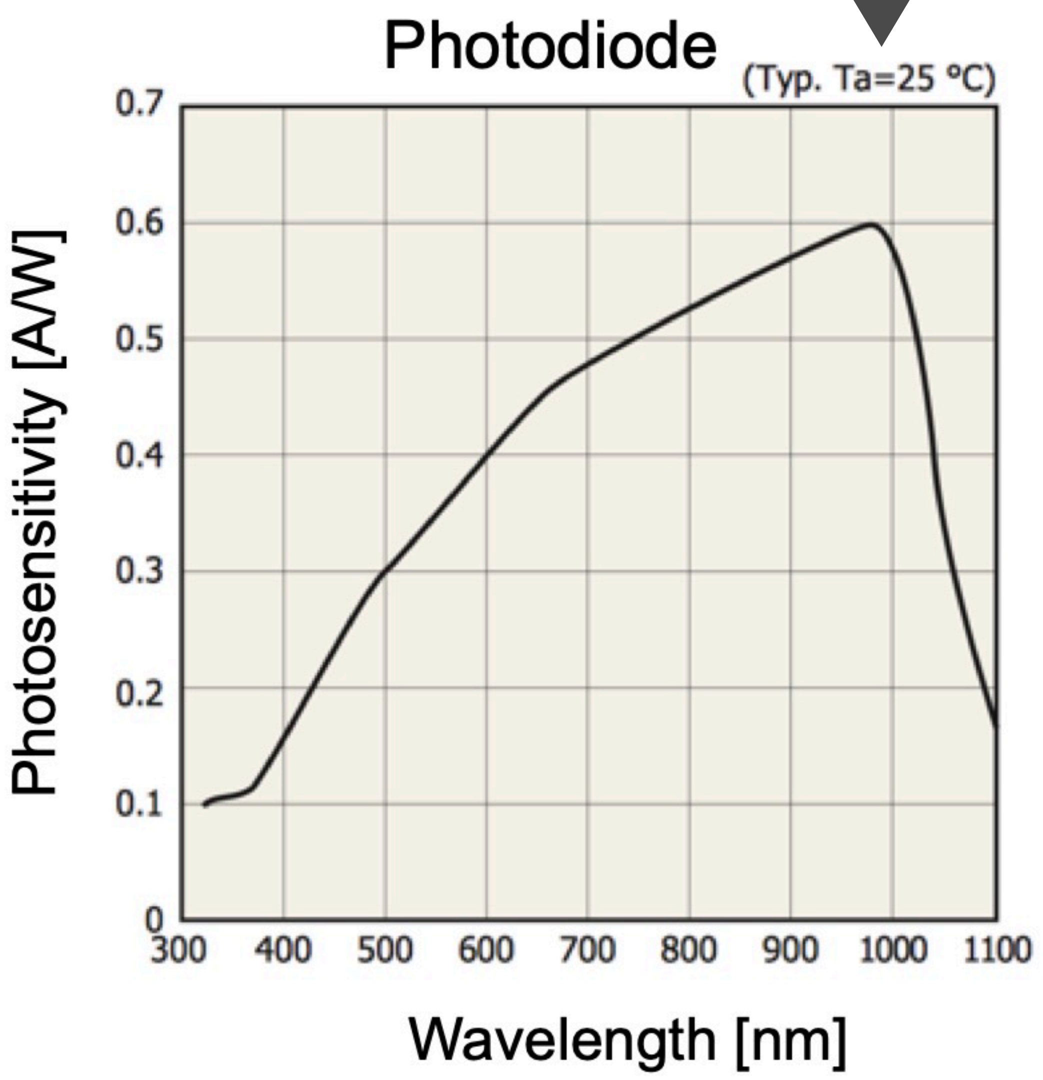
(Suitable for Cherenkov/ Scintillation… light detection)

PEAK ~ 400NM



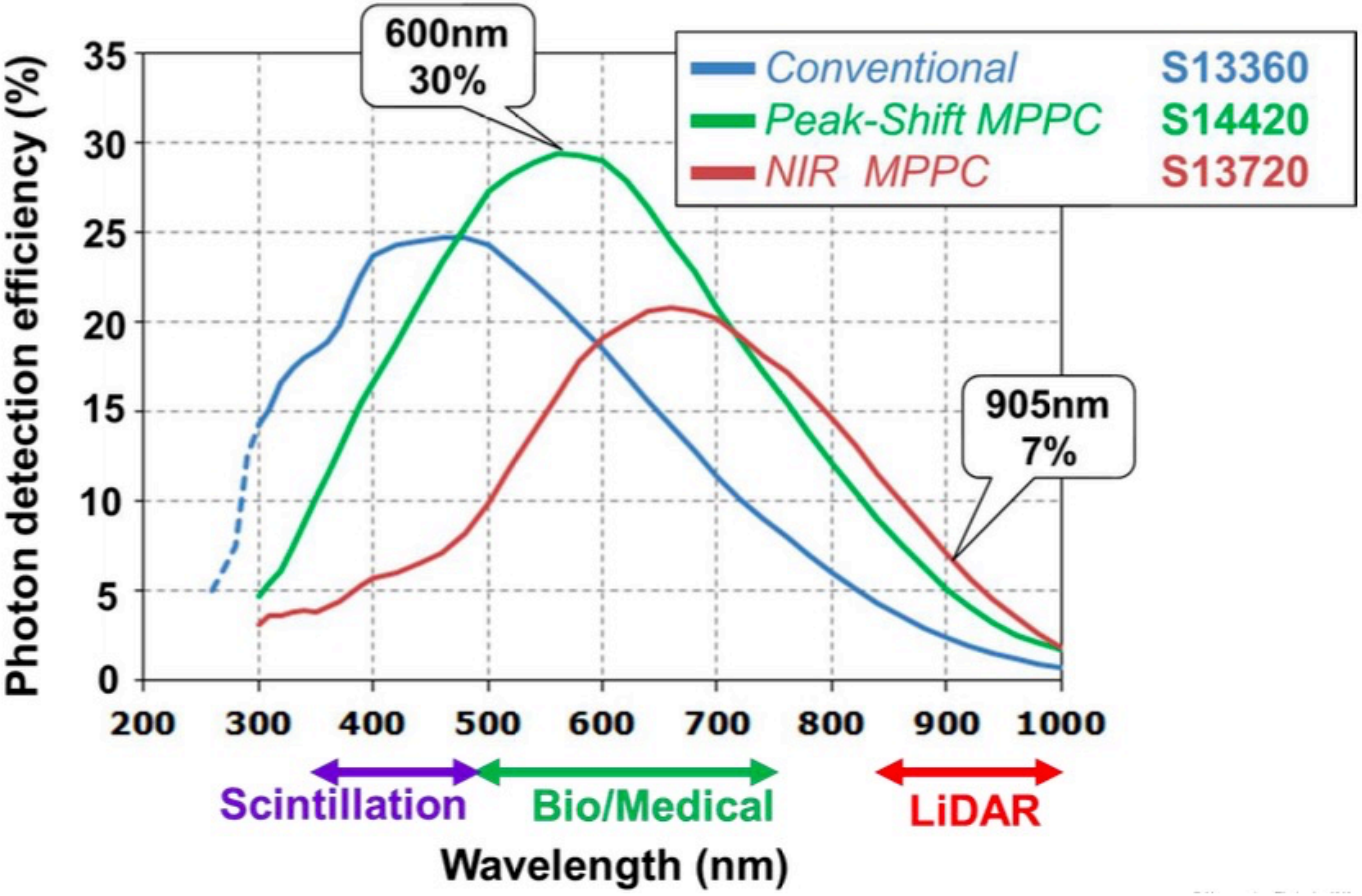

(Suitable for LiDAR)

PEAK ~ 1000NM




Examples of spectral sensitivity/quantum efficiency curves for a PMT and photodiode

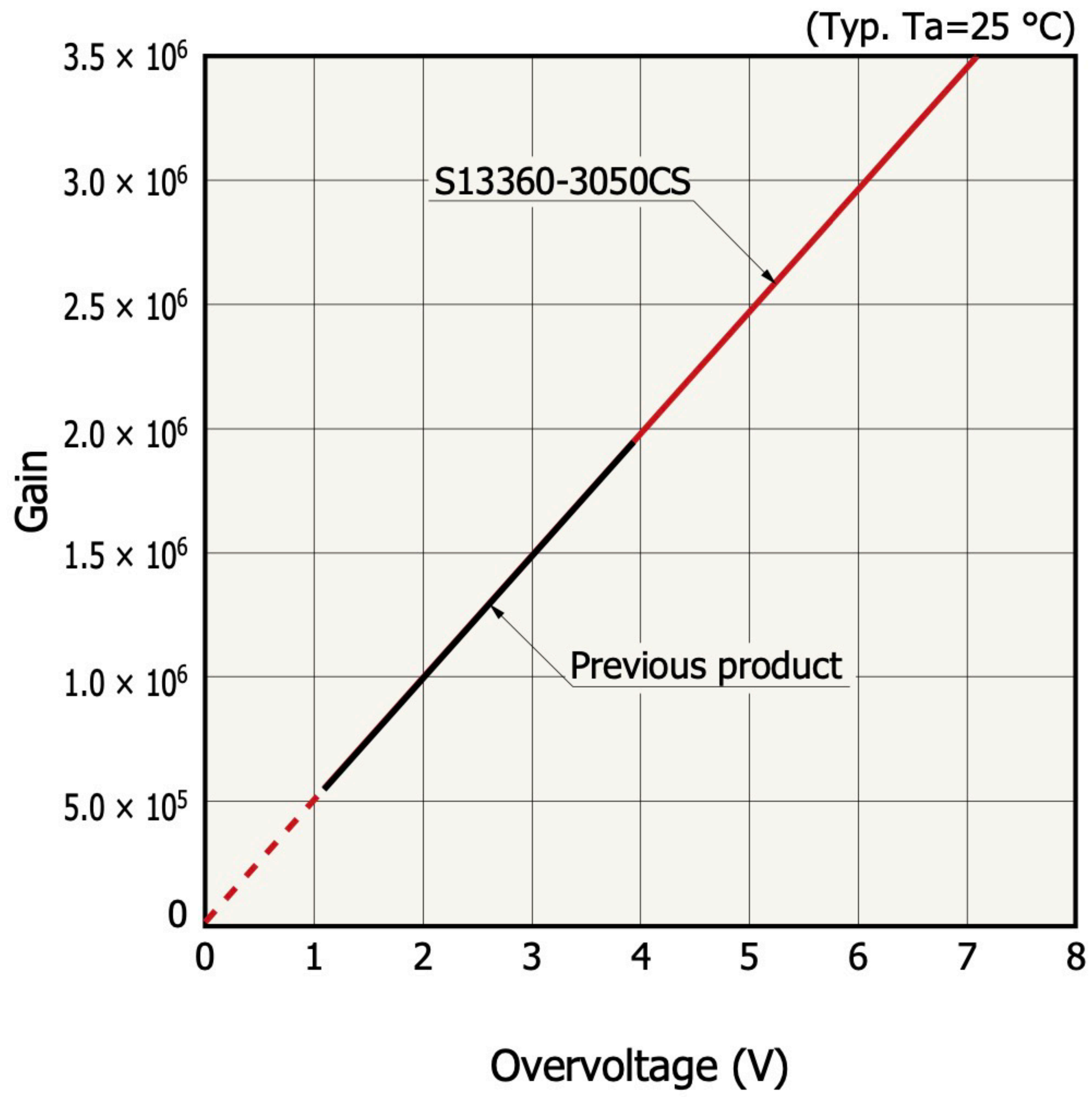
# Quantum efficiency and spectral sensitivity




Each application utilizes different wavelength range. Choice of photodetector depends largely on high QE/PDE of photosensor at that range.

# Intrinsic gain of photodetectors

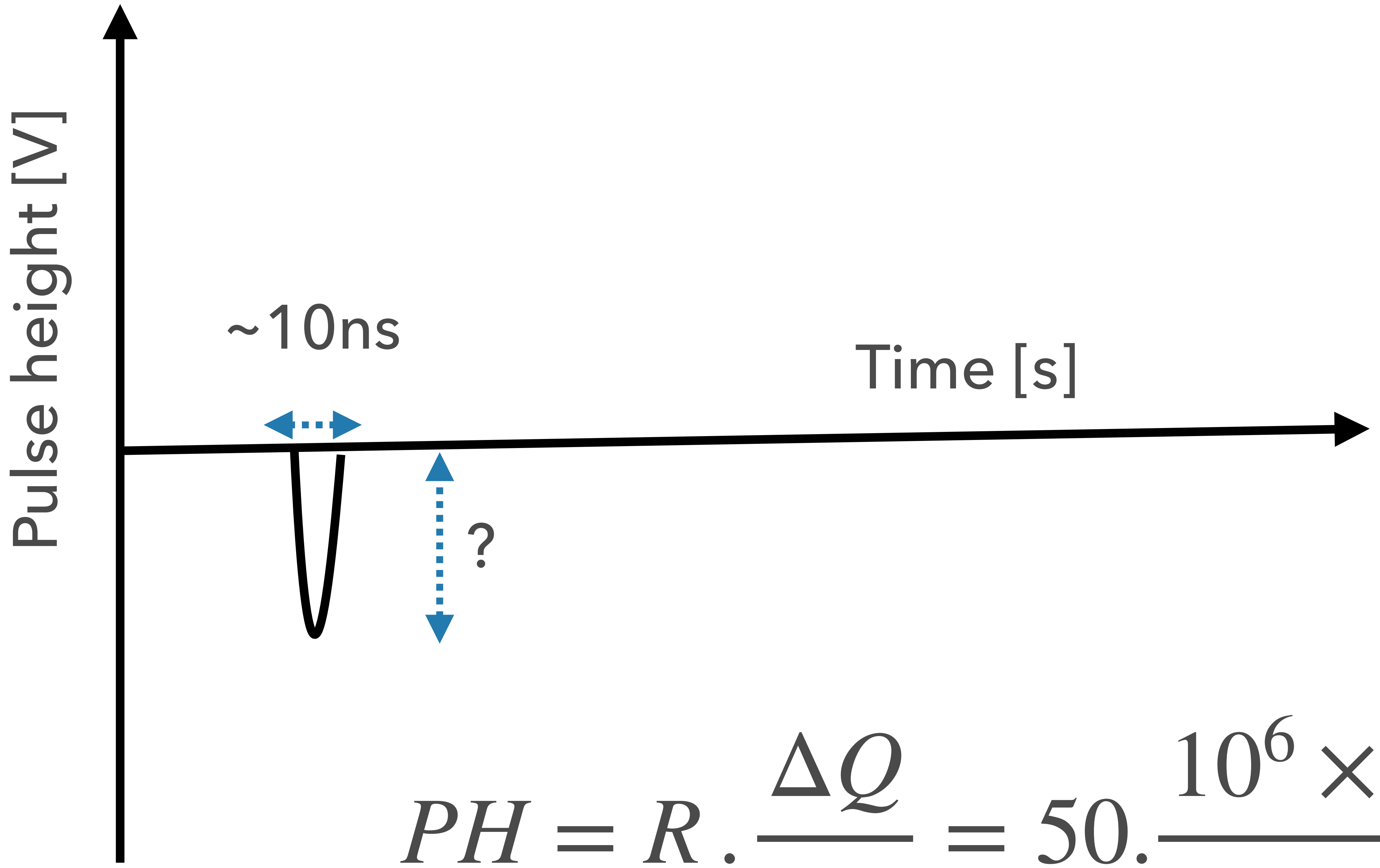
- Basically "multiply" the photoelectron current by a factor of $g_i$
  - For PMT and SiPM, gain is about $10^6 - 10^7$
  - For APD, gain is about $10 - 1000$
  - For PD, there is no intrinsic gain $g_i = 1$
- Depends ( linearly) on the supply voltage (PMT) or over-voltage (SiPM); also depends on the operational temperature
- Calibrate and monitor relevant factors for inferring the intrinsic gain is essential for $\Delta E \propto N_\gamma \propto N_{p.e.} = \frac{\int I dt}{G_i}$



# Signal size of one photon?

**Assume you have a electric gain of $10^6$, what the size of the signal you expect if no electronic amplification is applied?.**

*Assume the pulse width is about 10-ns and terminated by 50 ohm resistor.*




$$\Delta Q = I \Delta t$$

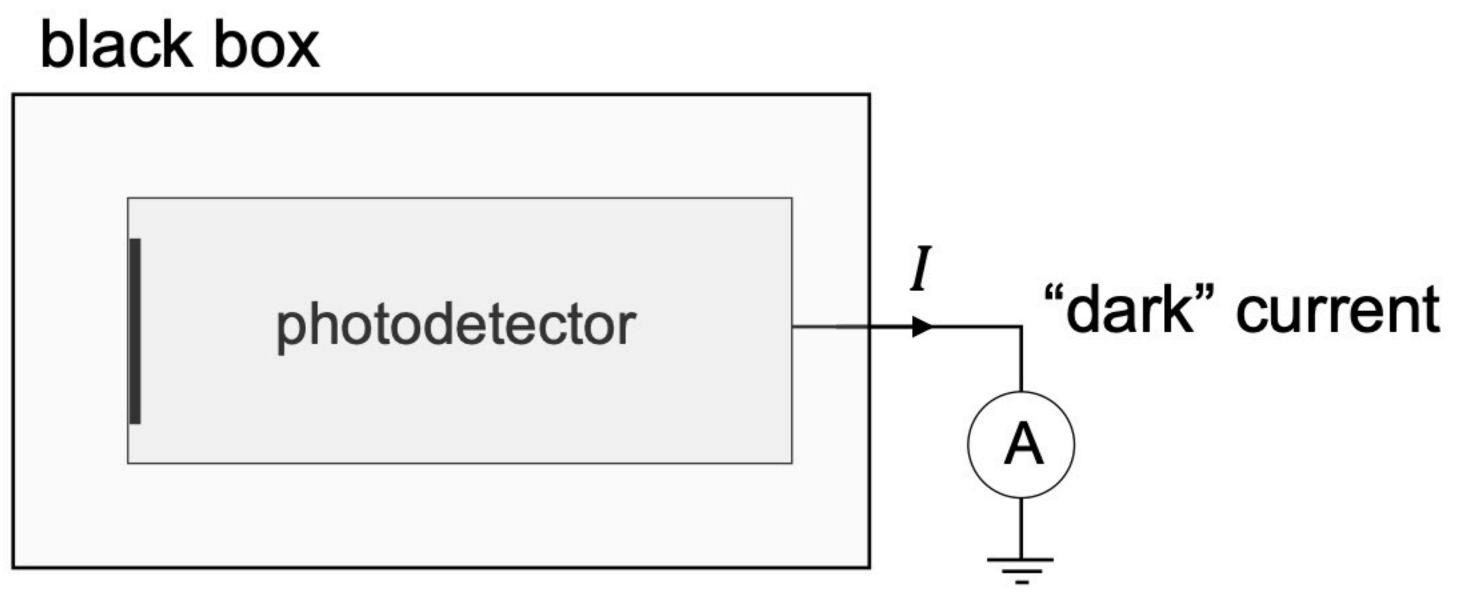
$$V = R \times I$$

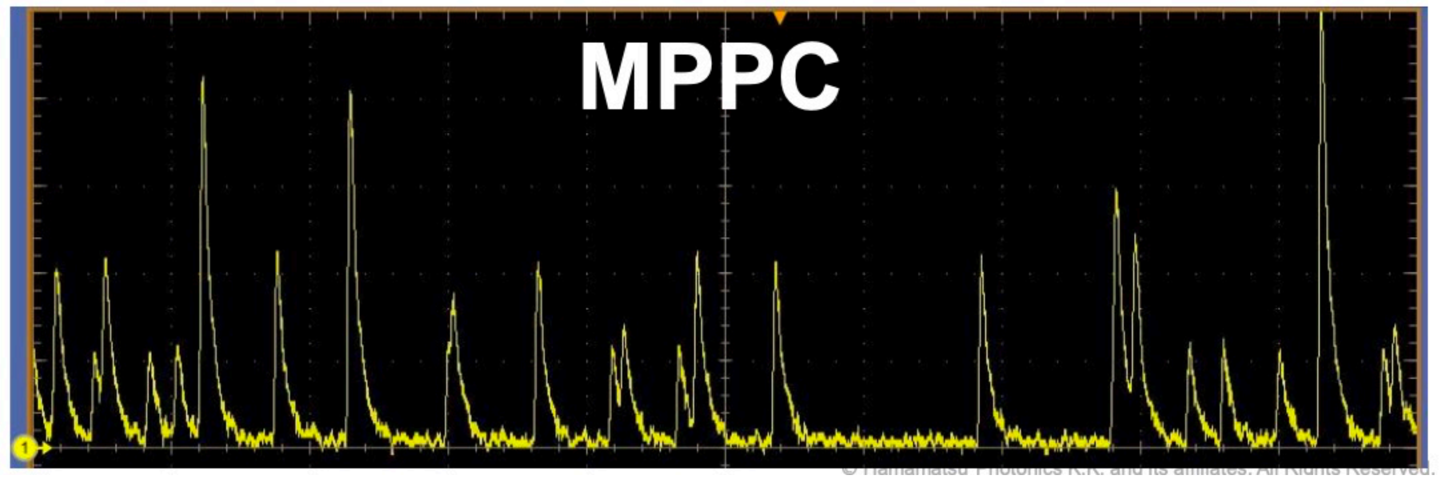
$$PH = R\,.\frac{\Delta Q}{\Delta t} = 50.\frac{10^6 \times 1.6 \times 10^{-19}}{10 \times 10^{-9}} = 8 \times 10^{-4} [V]$$

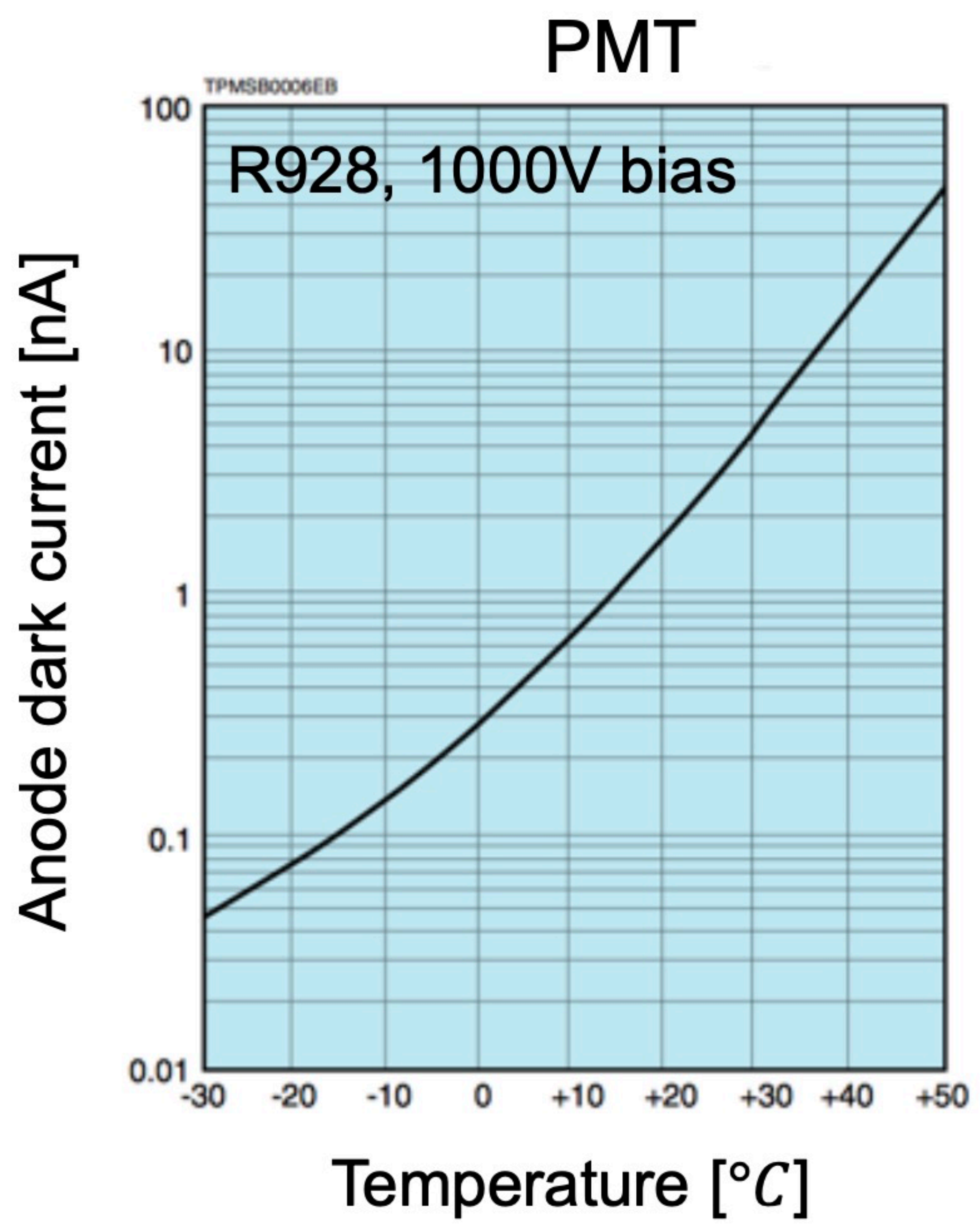
Signal size for a single photon (without amplifier) is less than 1mV

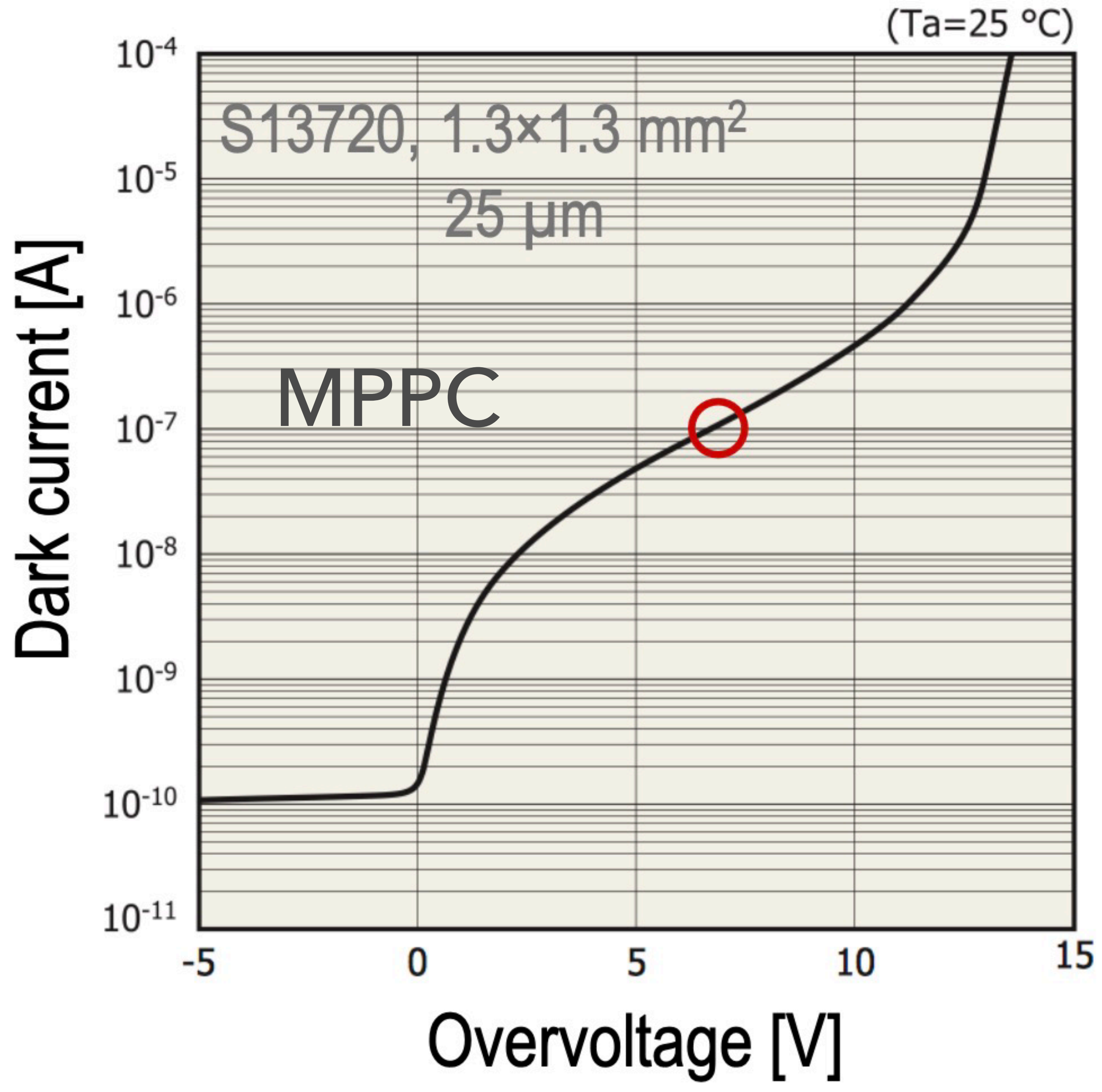
# Dark current of photodetectors

- Photodetector still can output current even in the black box without any incident light, so-called *dark current*
- Depends on operational temperature, type and size of the photosensitive material, applied voltage ...
- It's essential to estimate the noise, especially Signal-to-background ratio.



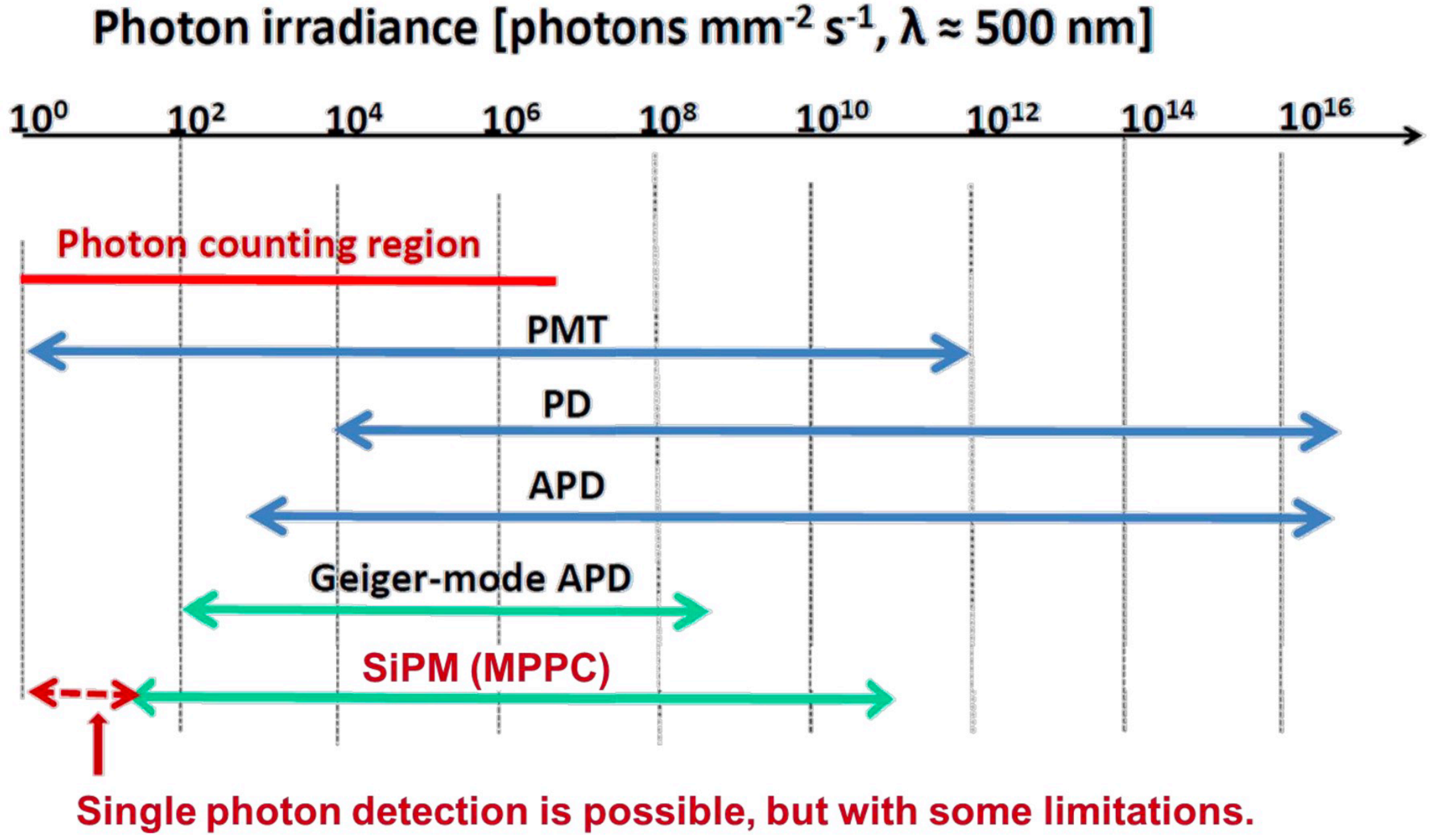



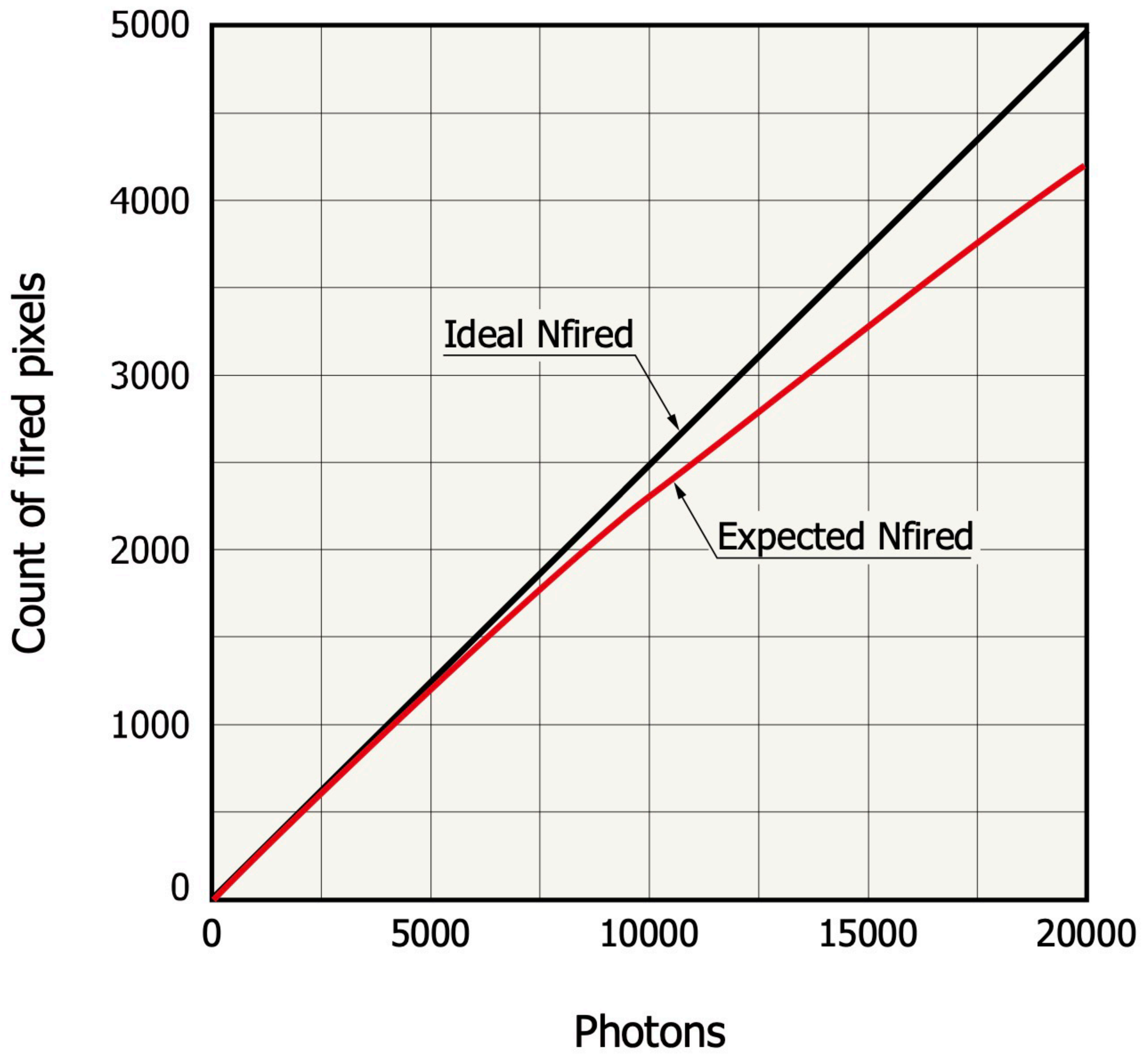




- Dark cout rate $R_{dark} = \dfrac{I_{dark}}{e \cdot g_i}$
- At 7V over-voltage operation, $I_{dark} = 10^{-7}A$, with $g_i = 10^6$, so $R_{dark} \approx 667kHz$
- Ref. Cosmic-ray muon rate at sea level is ~ $1/cm^2/min$ .

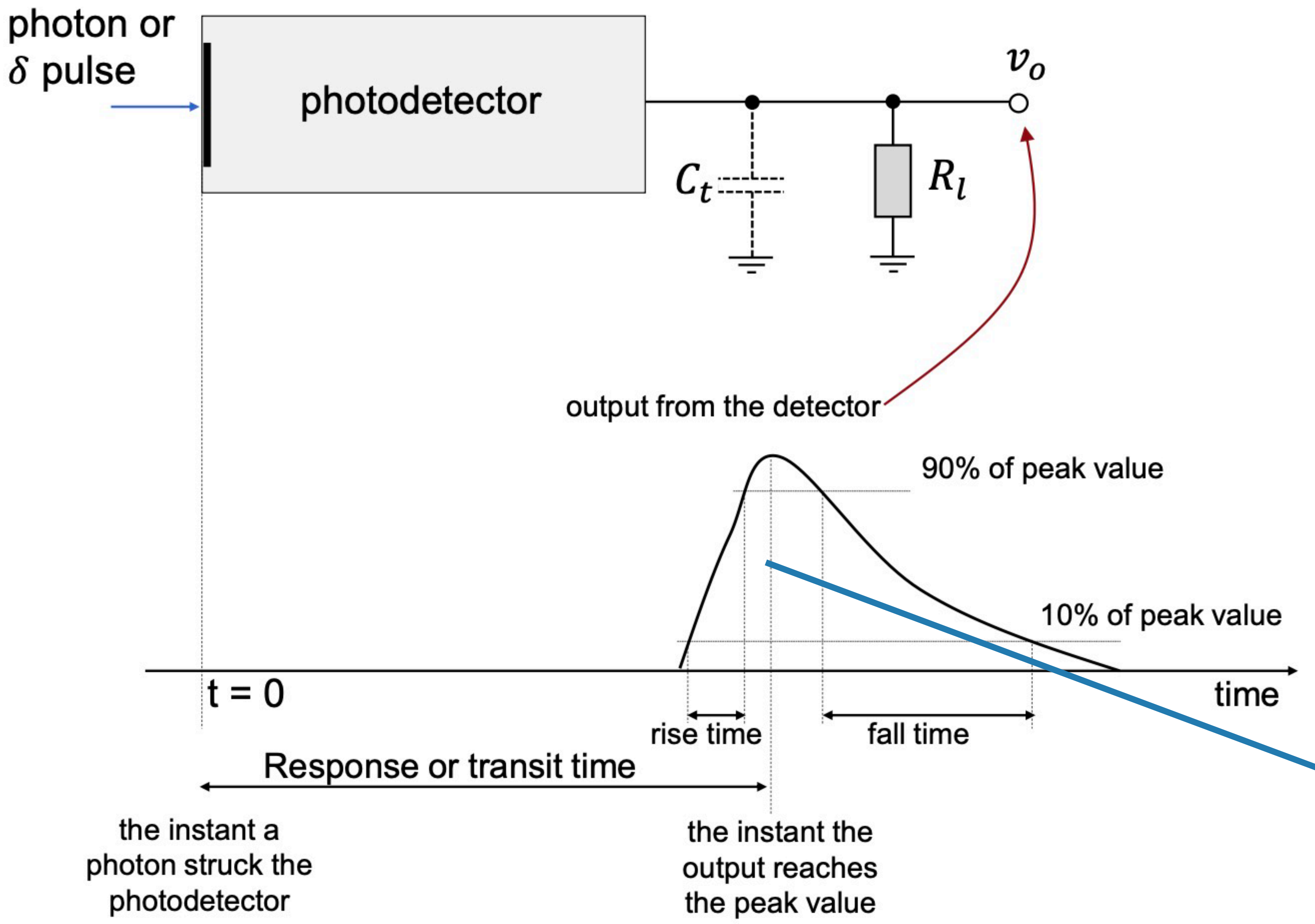
# Linear response and Dynamic range

- Ideally, we hope for a perfect linearity between number (*or intensity*) of incoming light with amplitude (*or current*) of the output
- However, normally this linearity is quantitatively excellent at a specific range of light intensity
- Non-linearity usually happens for large signal and must be taken into account for calibrating the signal

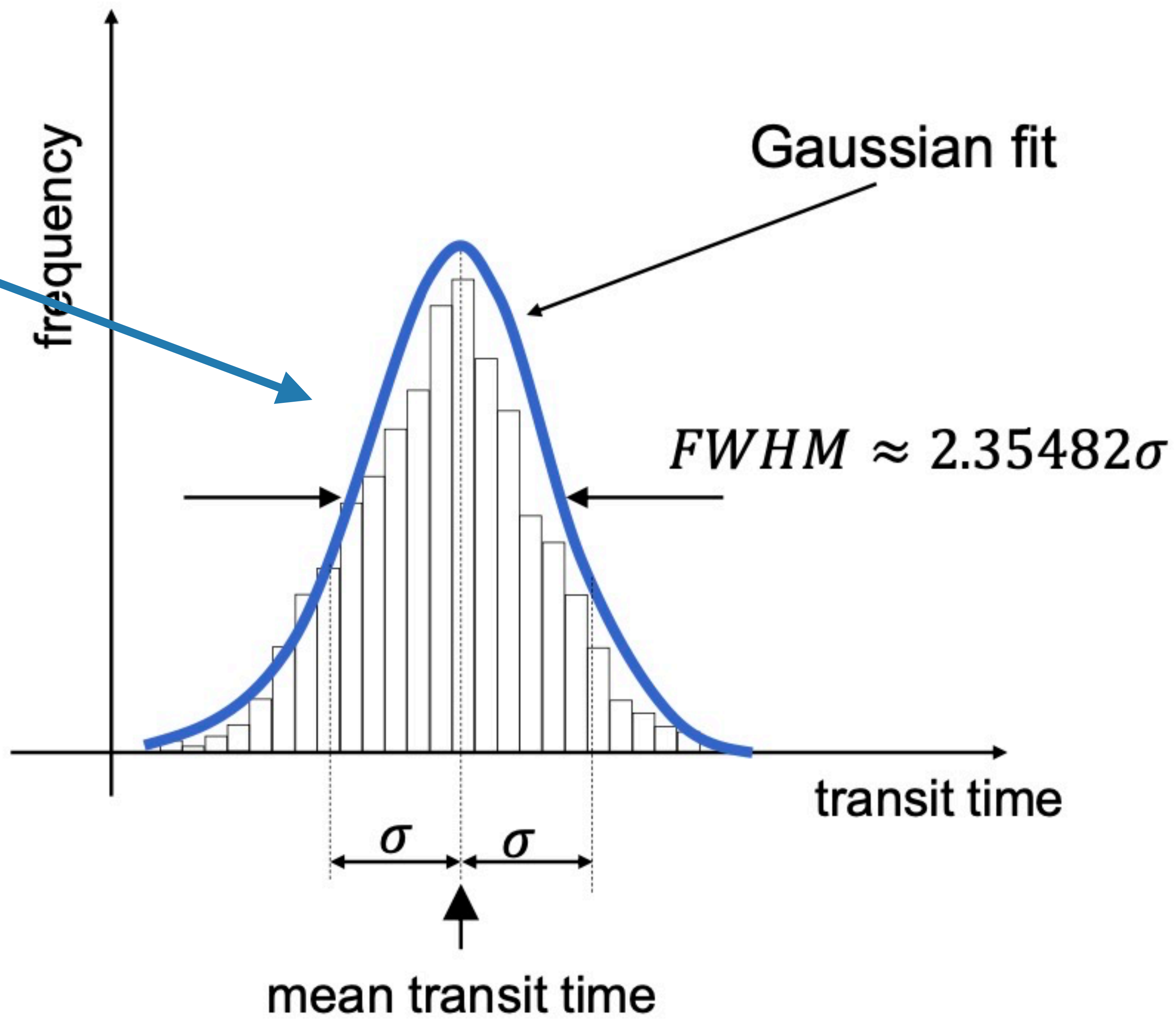


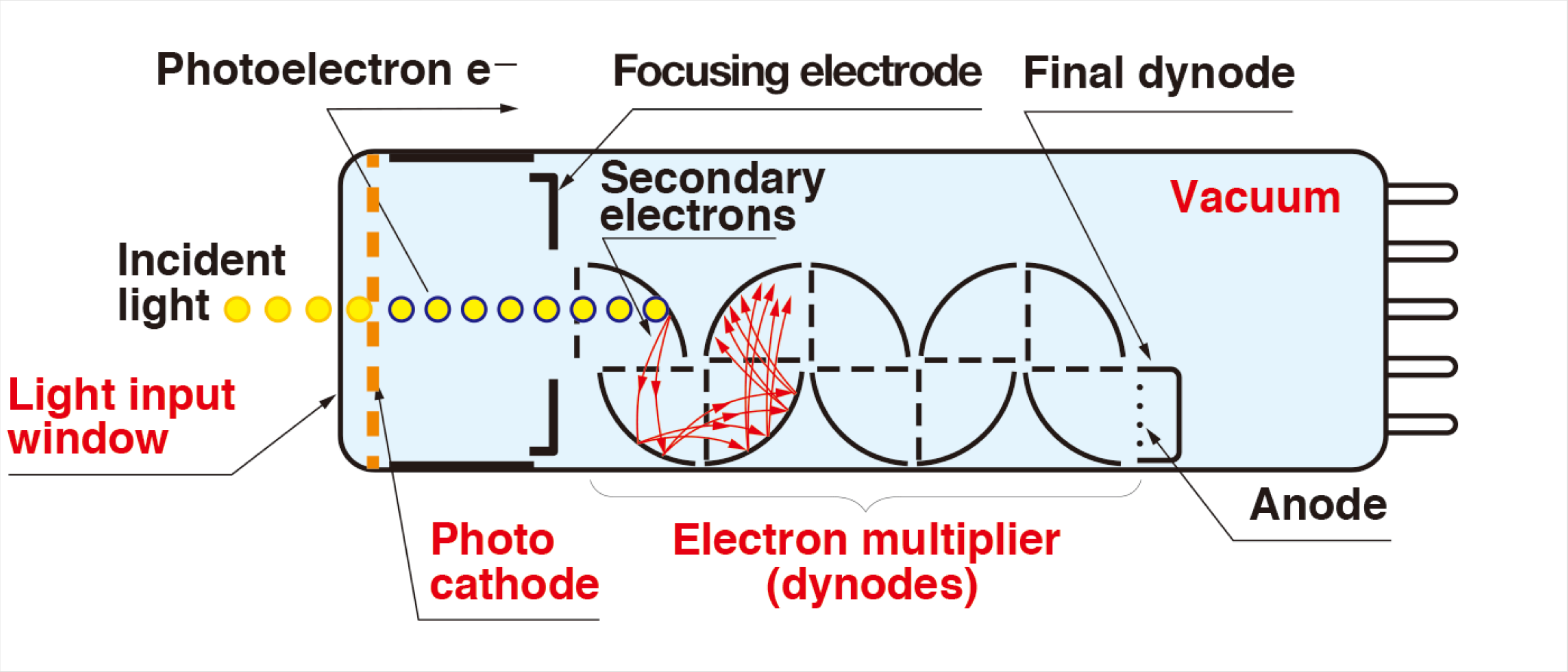
# Time response of photodetector




- This so-called "time jitter" is essential key for time-domain applications such as LiDAR / PET ...
  - (relates to "coincidence resolving time" )
- Order of few 100ps. Smaller is better



# A glance at PMT

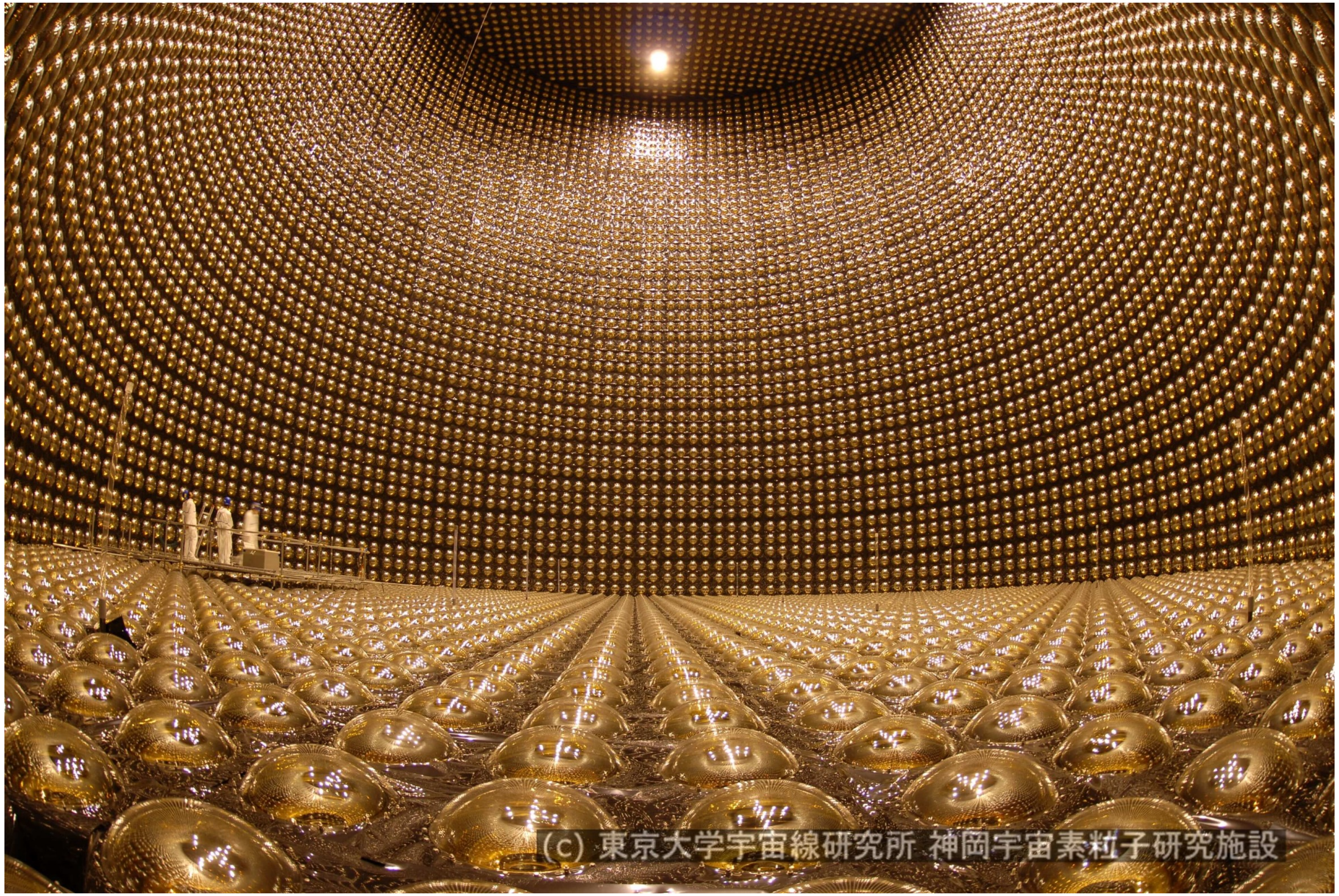



## 20-inch diameter PMT for research by Hamamatsu

| Facility name | Kamiokande (From 1983 to 1996) | SuperKamiokande (From 1996 to present) | HyperKamiokande (In planning stage) |
|---|---|---|---|
| Type No. | R1449 | R3600 | R12860 |
| Collection efficiency | 40 % to 50 % | 70 % | 90 % |
| Electron transit time spread | 4.4 ns | 2.2 ns | 1.0 ns |

https://www.hamamatsu.com/jp/en/product/optical-sensors/pmt/applications.html

# Super-Kamiokande: Wonder of 20-inch PMT



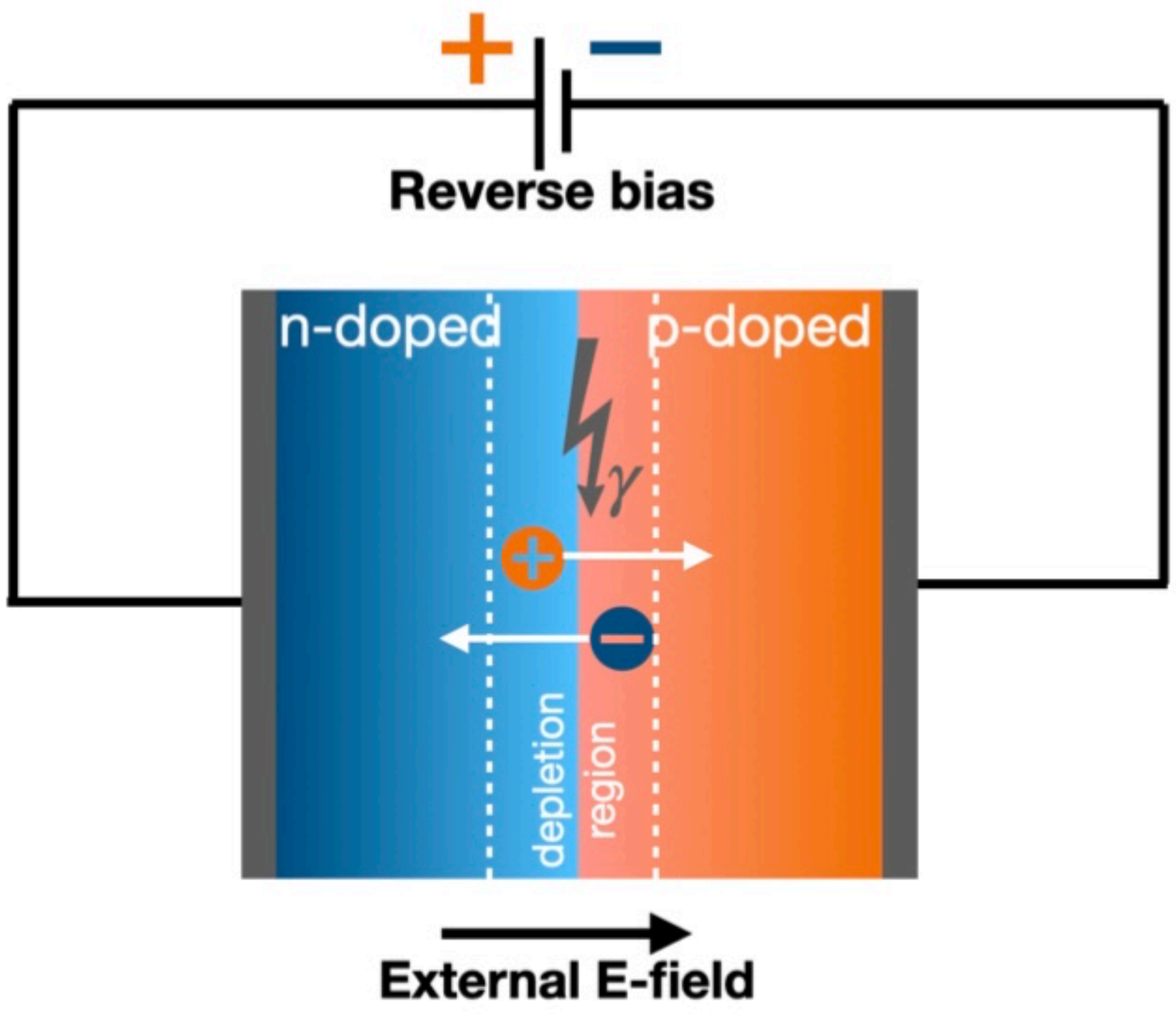


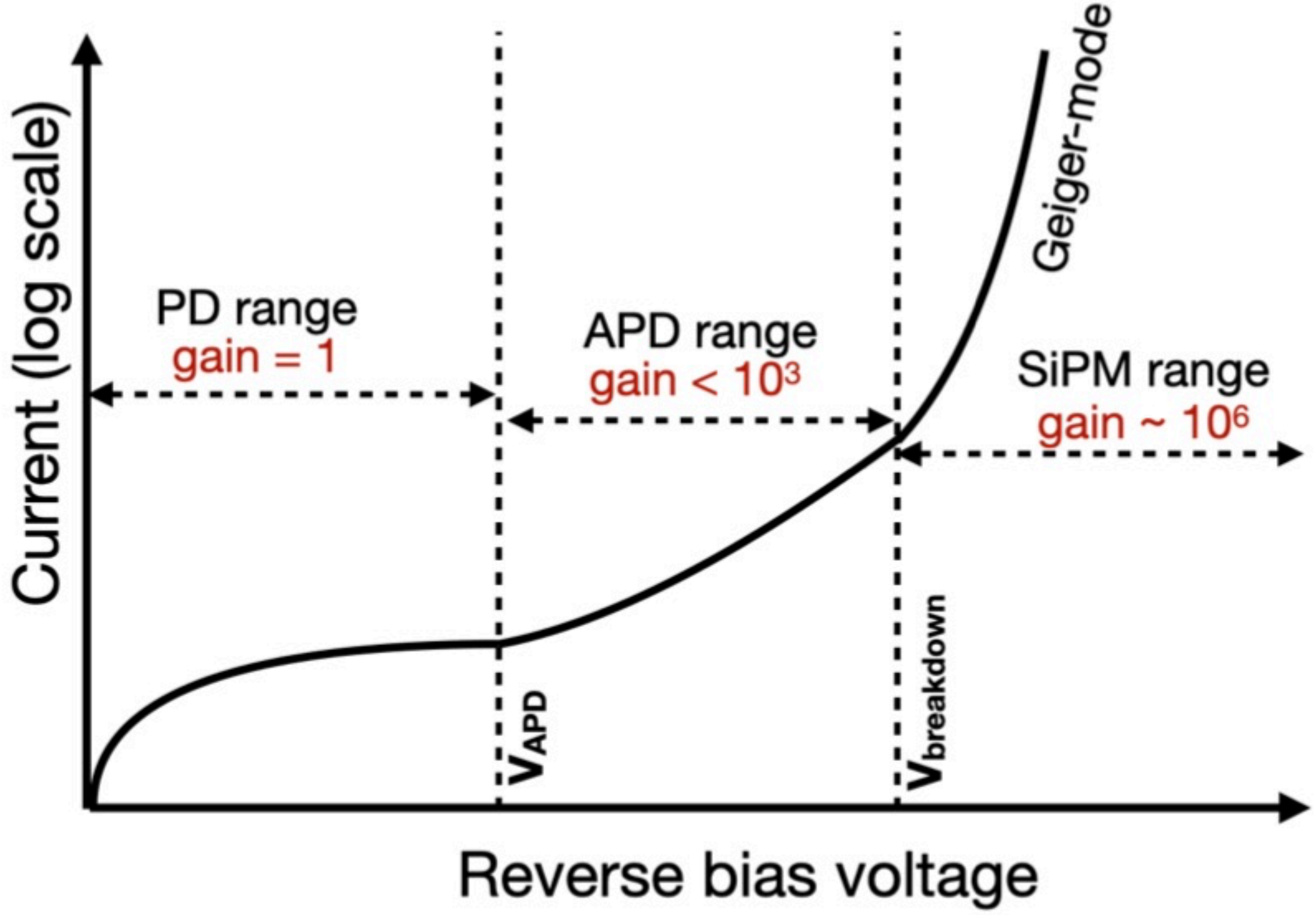
**Super-Kamiokande**



https://www.hamamatsu.com/us/en/why-hamamatsu/20inch-pmts.html

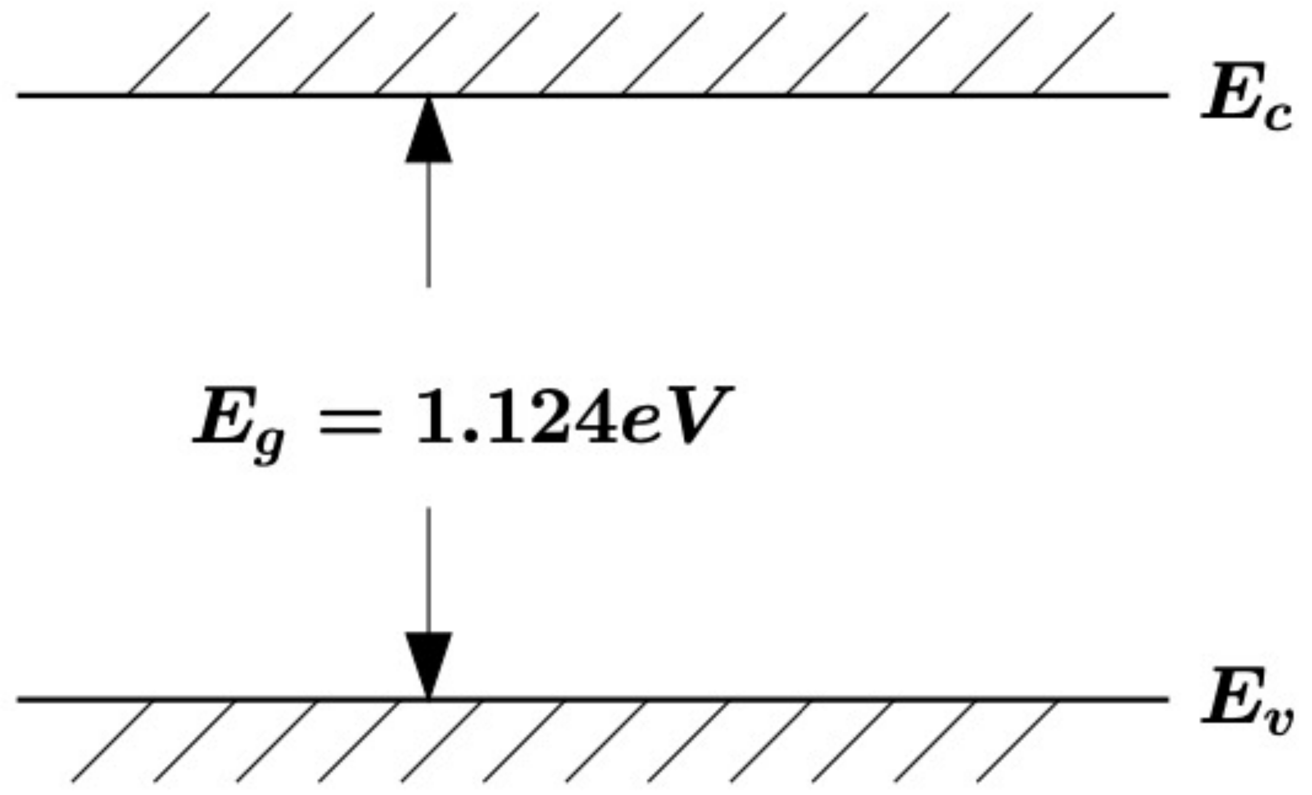
# Photon detection principle w/ Silicon photomultiplier (SiPM)



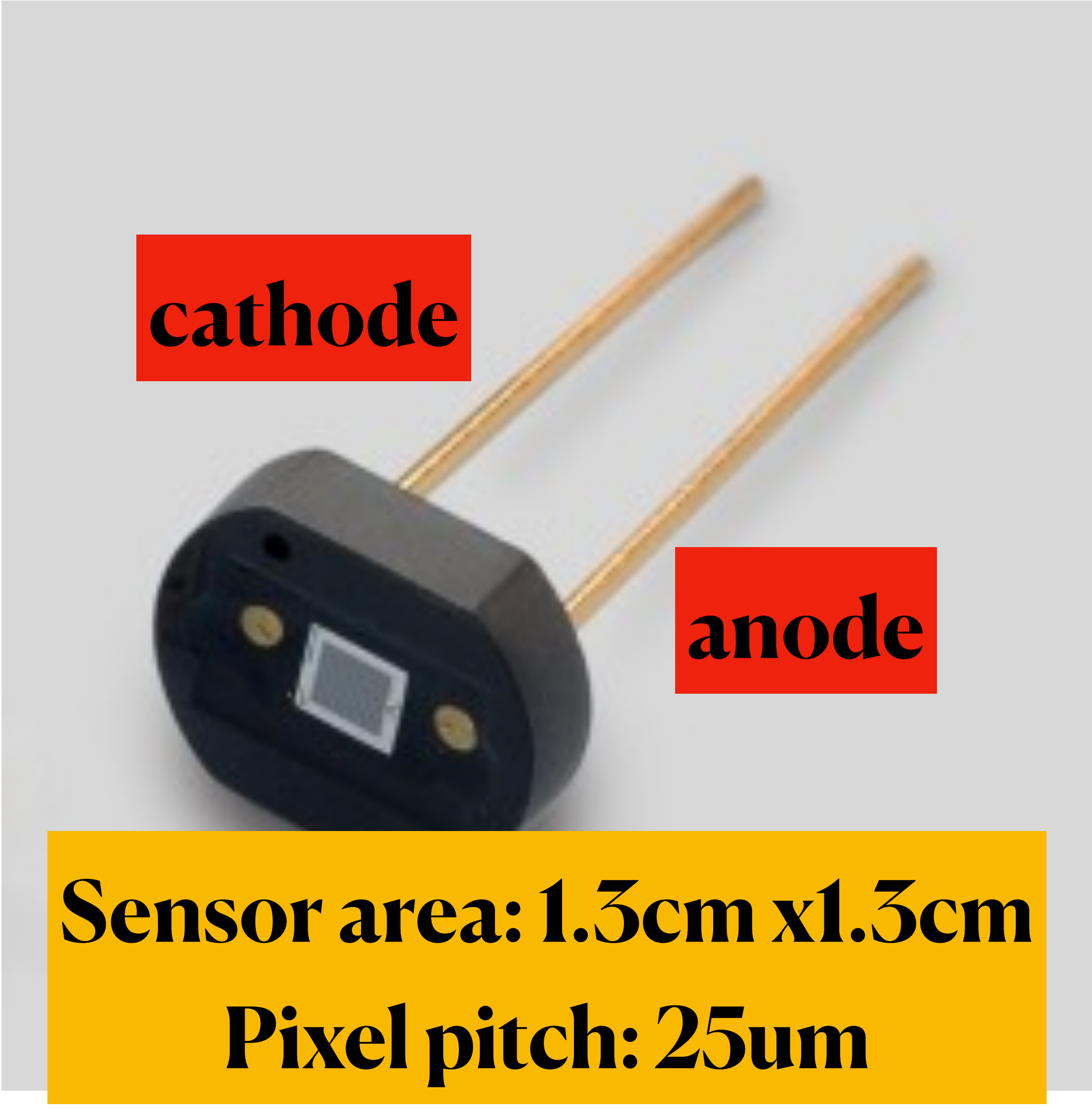

- Based on photoelectric effect: photon strikes and produce a pair of electron/hole
- Various types, selection depending on the measurement
- "Breakdown" here mean both hole and electron play roles in avalanche process

# Why Silicon?

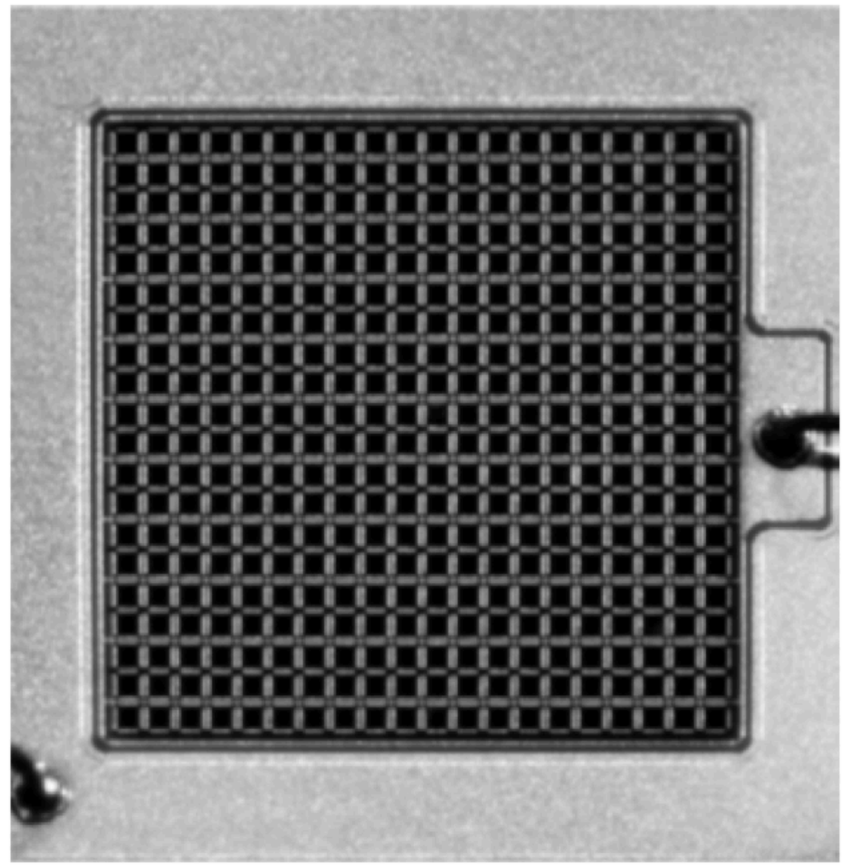



- Silicon has small bandgap ($E_g = 1.124eV$) so get excited by wider range wavelength of incident photon (*energy larger than $E_g$ to produce pair of electron and hole)*
- Very abundant (*the second after oxygen in mass* )
- Low Z so low multiple scattering
- High purity ➜long lifetime
- High mobility ➜ fast charge collection
- Good mechanical properties ➜ easily fabricated in small volume
- Industrial experience and commercial applications

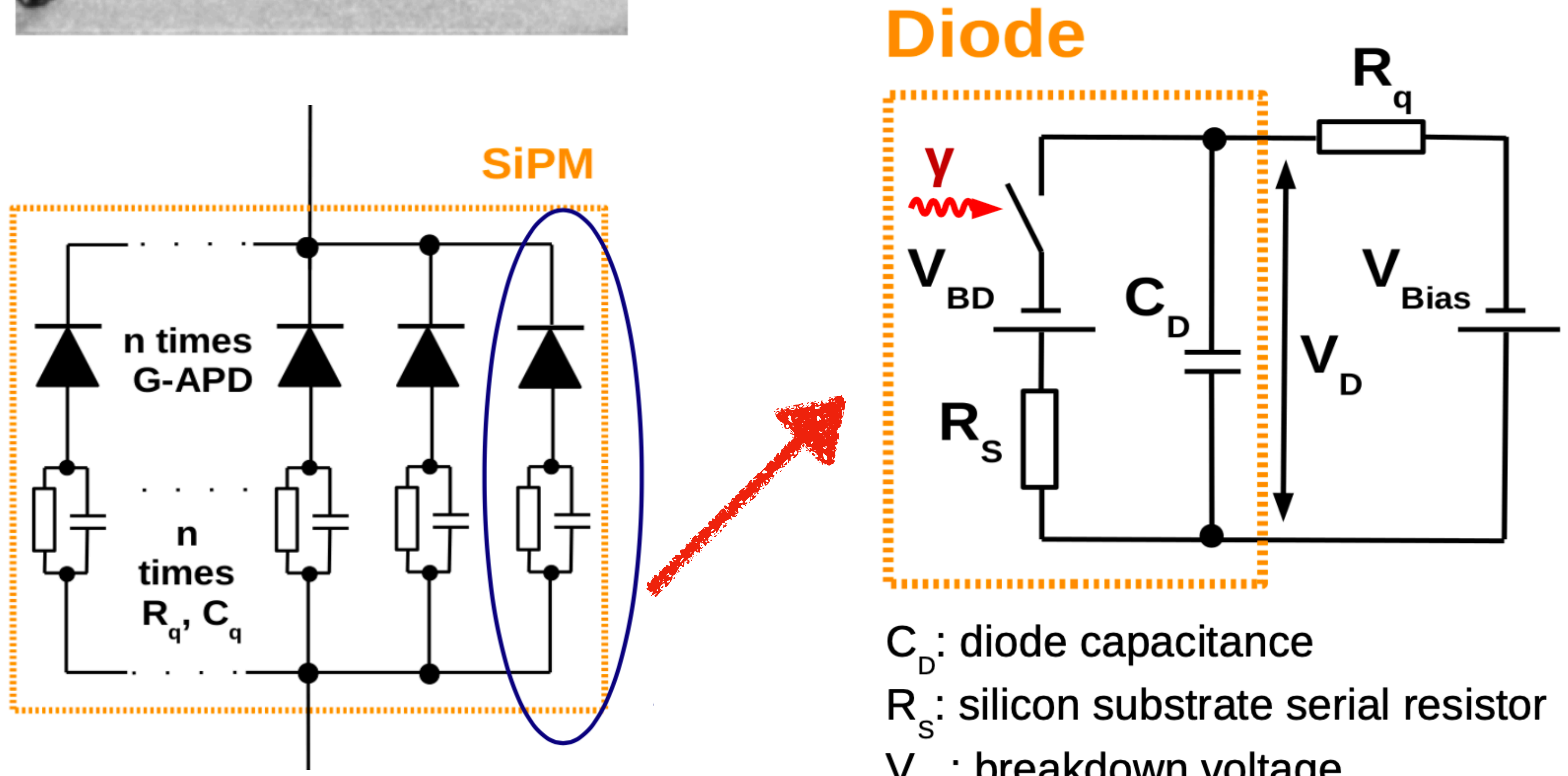
# MPPC: a type of SiPM, developed by Hamamatsu




Hamamatsu S13360-1325CS



Array of pixels




$C_D$: diode capacitance
$R_S$: silicon substrate serial resistor
$V_{BD}$: breakdown voltage

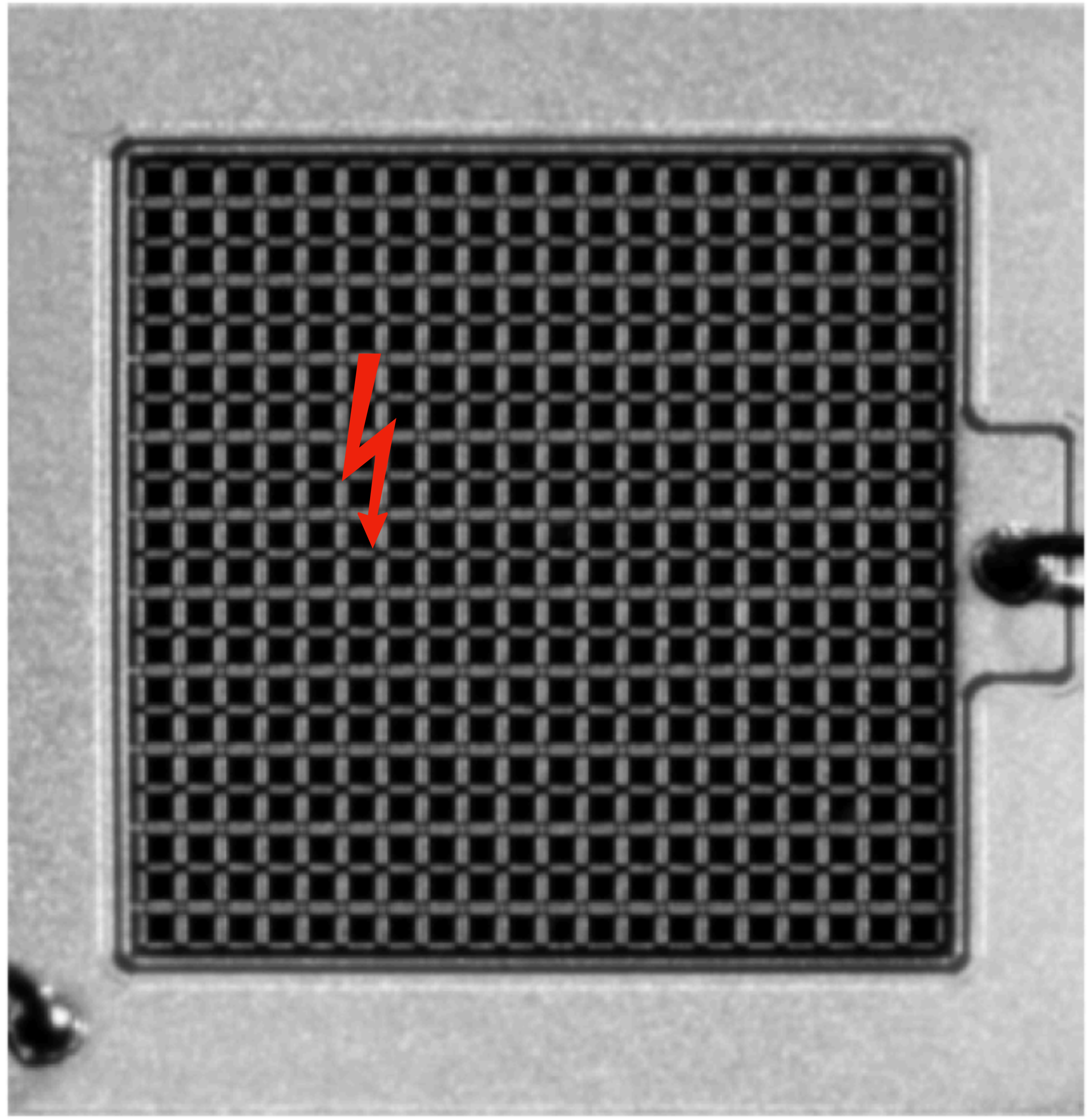
https://www.hamamatsu.com/jp/en/product/optical-sensors/mppc/mppc_mppc-array.html

# MPPC offers excellent capability of photon counting with high electric gain

Ref: *Hamamatsu's MPPC technical note* https://hub.hamamatsu.com/content/dam/hamamatsu-photonics/sites/static/hc/resources/TN0014/mppc_kapd9005e.pdf

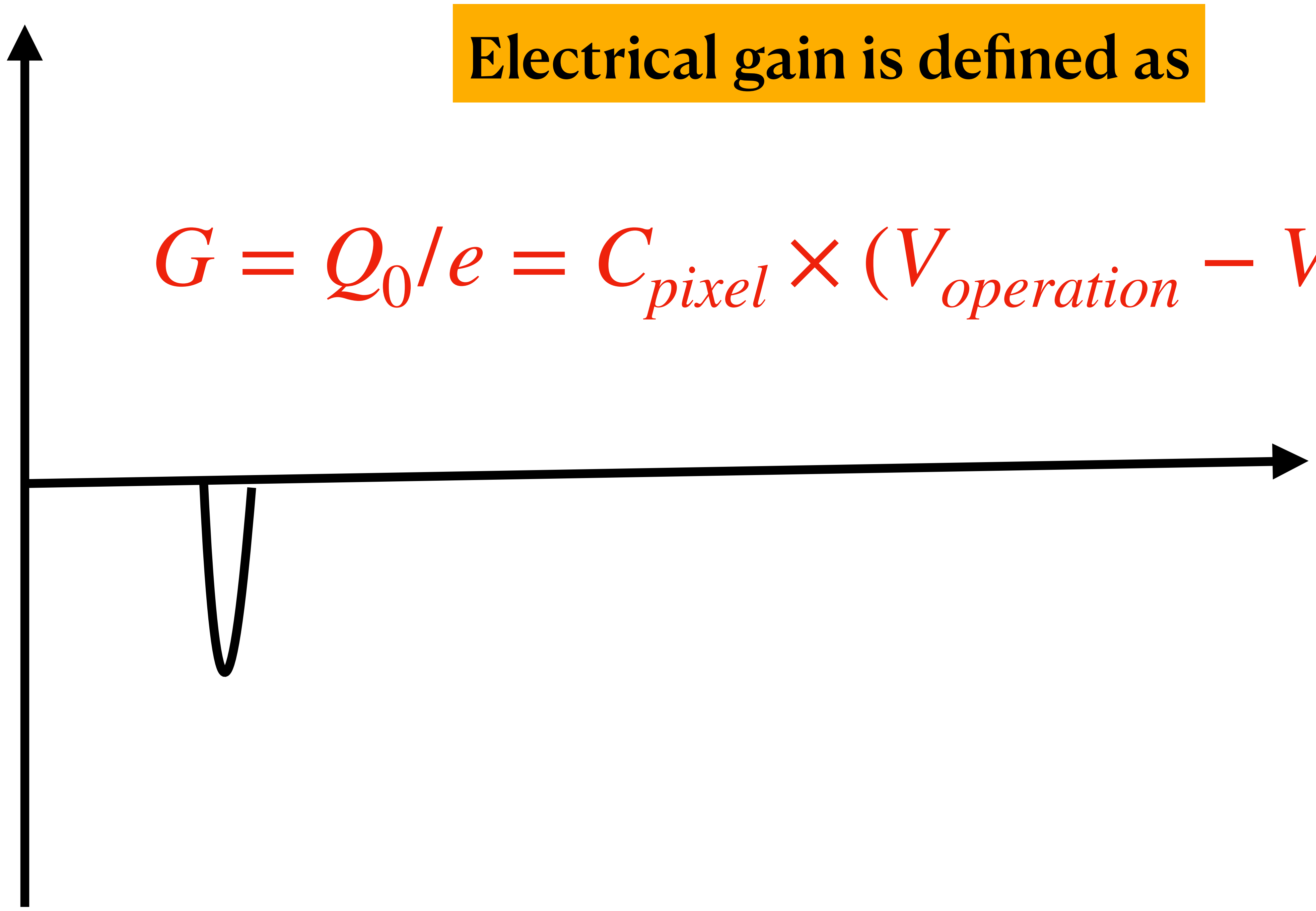
# Basic principle of photon counting

**When a photon fires a pixel, a signal with charge $Q_0$ is generated and observed in macroscopic scale**



**Electrical gain is defined as**

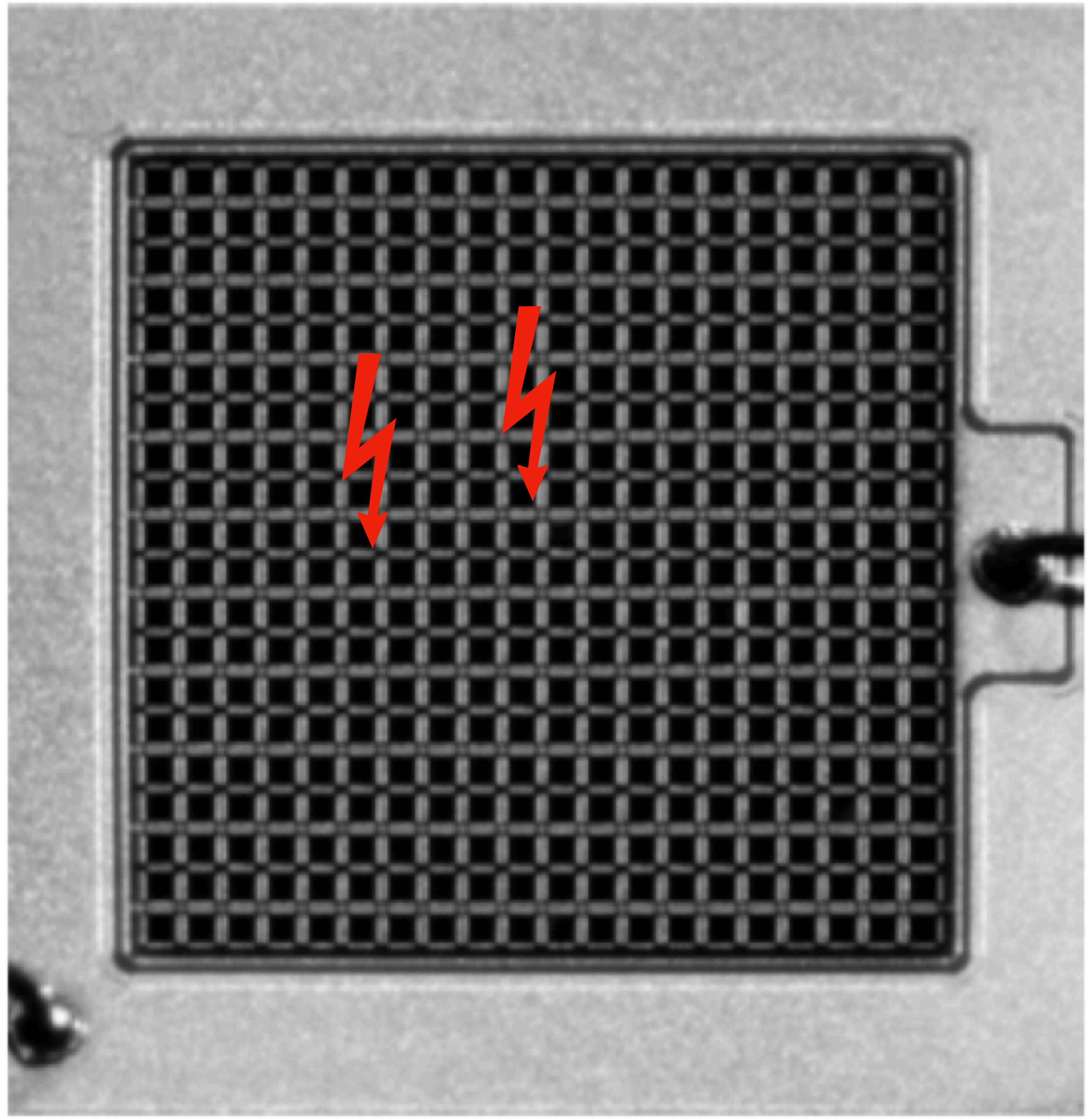
$$G = Q_0/e = C_{pixel} \times (V_{operation} - V_{breakdown.})$$

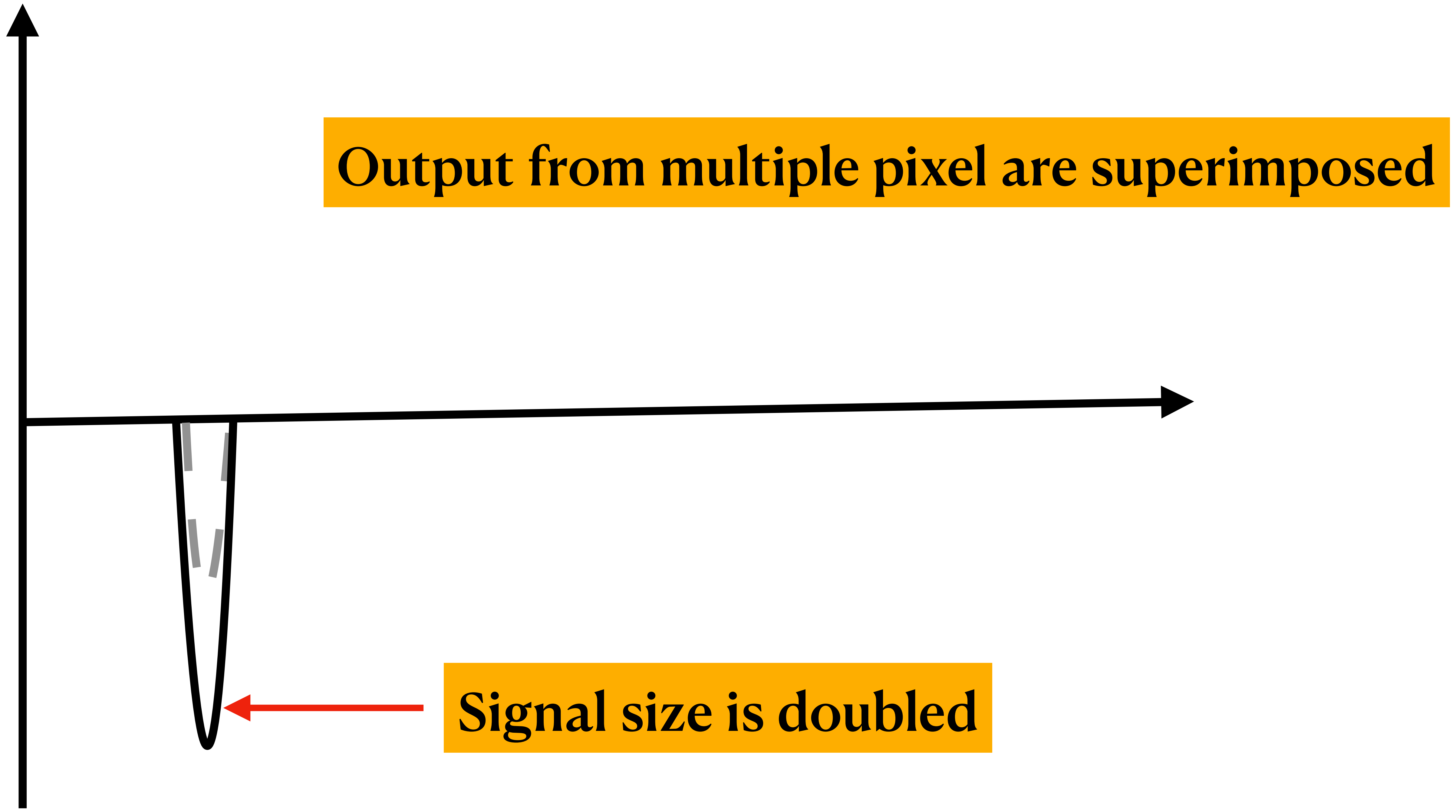


**Pixel works independently  but give out pulses with the same amplitude**

# Basic principle of photon counting

**When a photon fires a pixel, a signal with charge $Q_0$ is generated and observed in macroscopic scale**

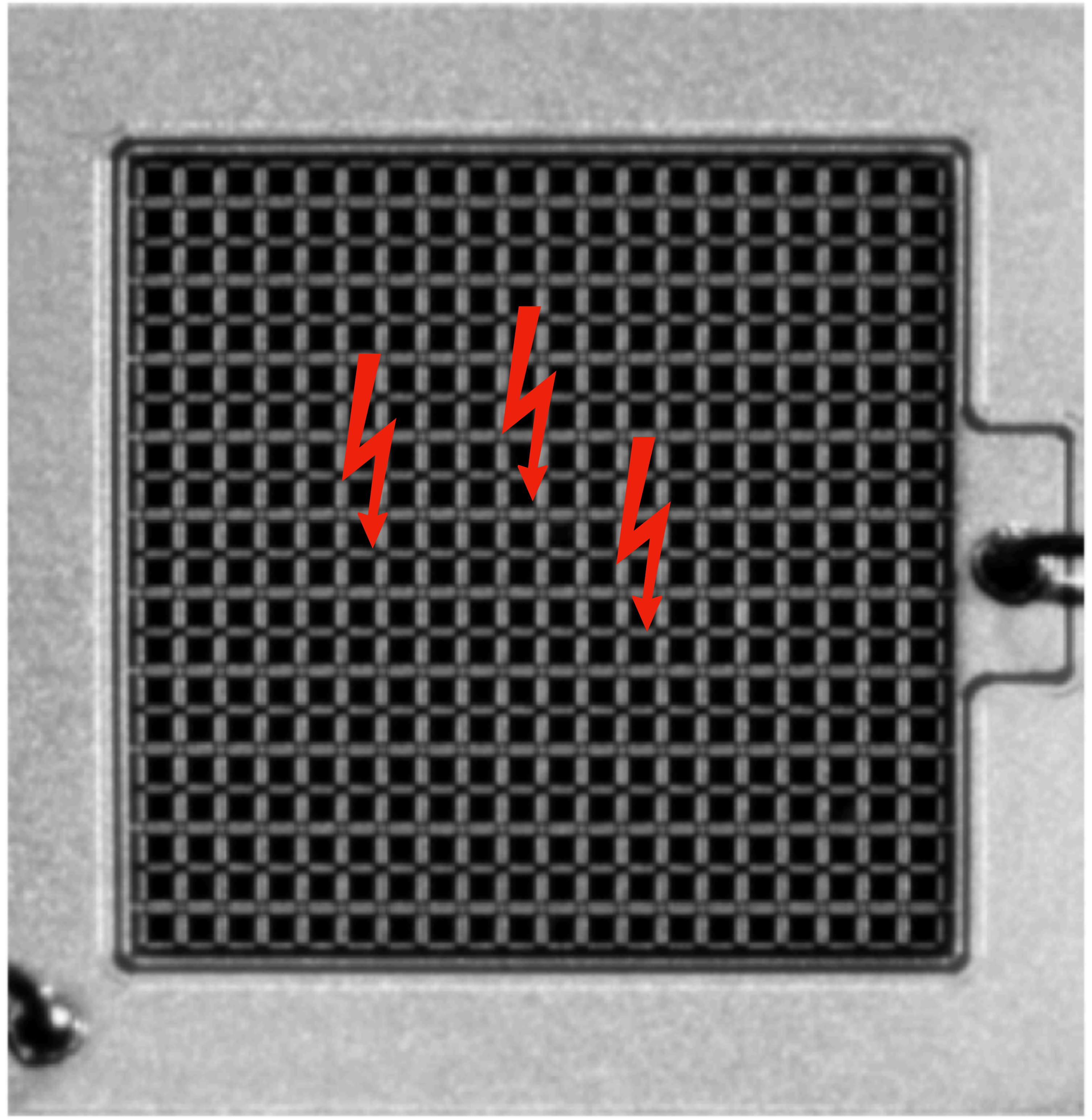


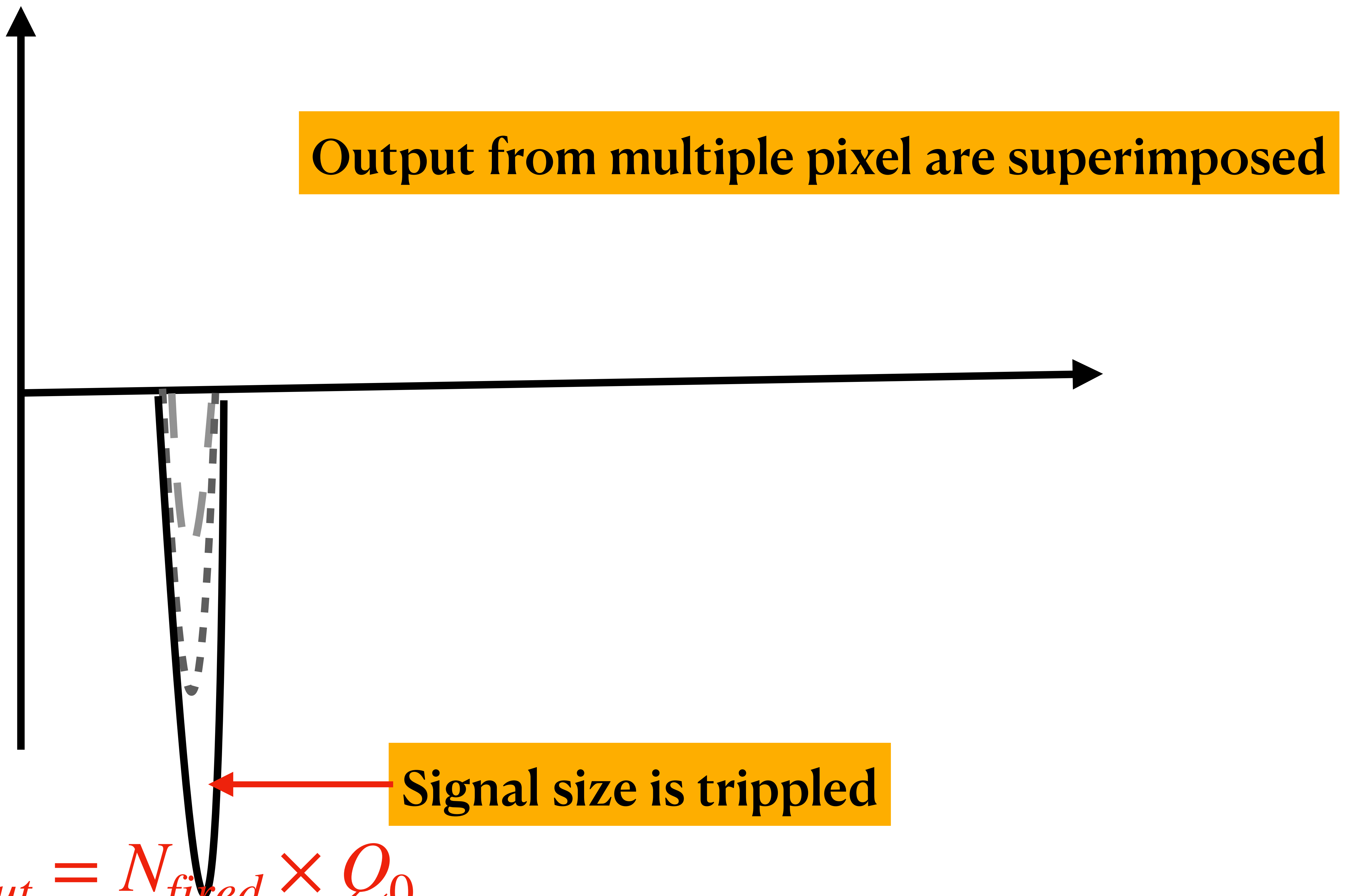



$$Q_{out} = N_{fired} \times Q_0$$
$$= N_{fired} \times C_{pixel} \times (V_{operation} - V_{breakdown.})$$

# Basic principle of photon counting

**When a photon fires a pixel, a signal with charge $Q_0$ is generated and observed in macroscopic scale**



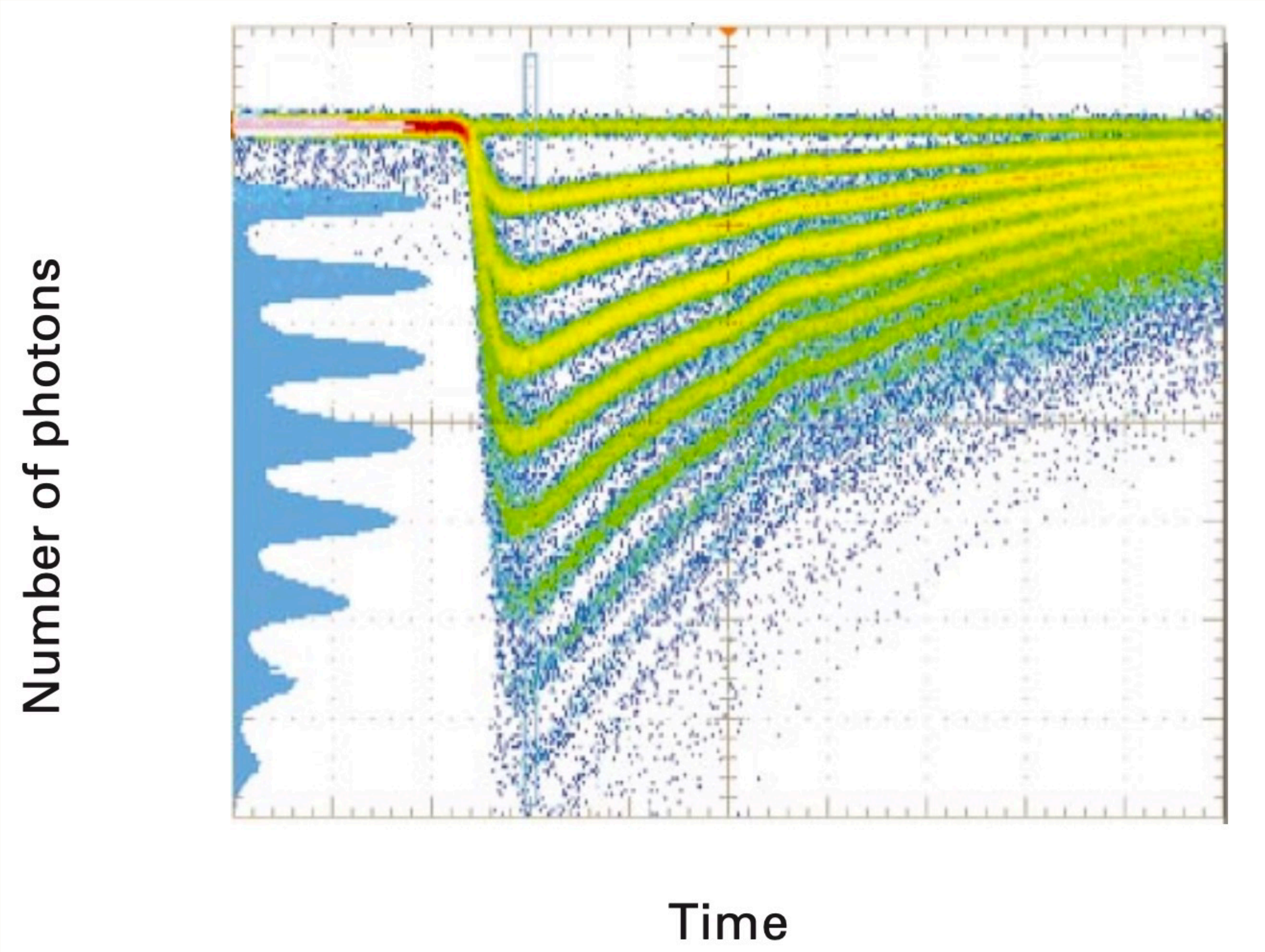



$$Q_{out} = N_{fired} \times Q_0$$
$$= N_{fired} \times C_{pixel} \times (V_{operation} - V_{breakdown.})$$

# MPPC overlayed signals

Let enjoy the light quanta with your observation

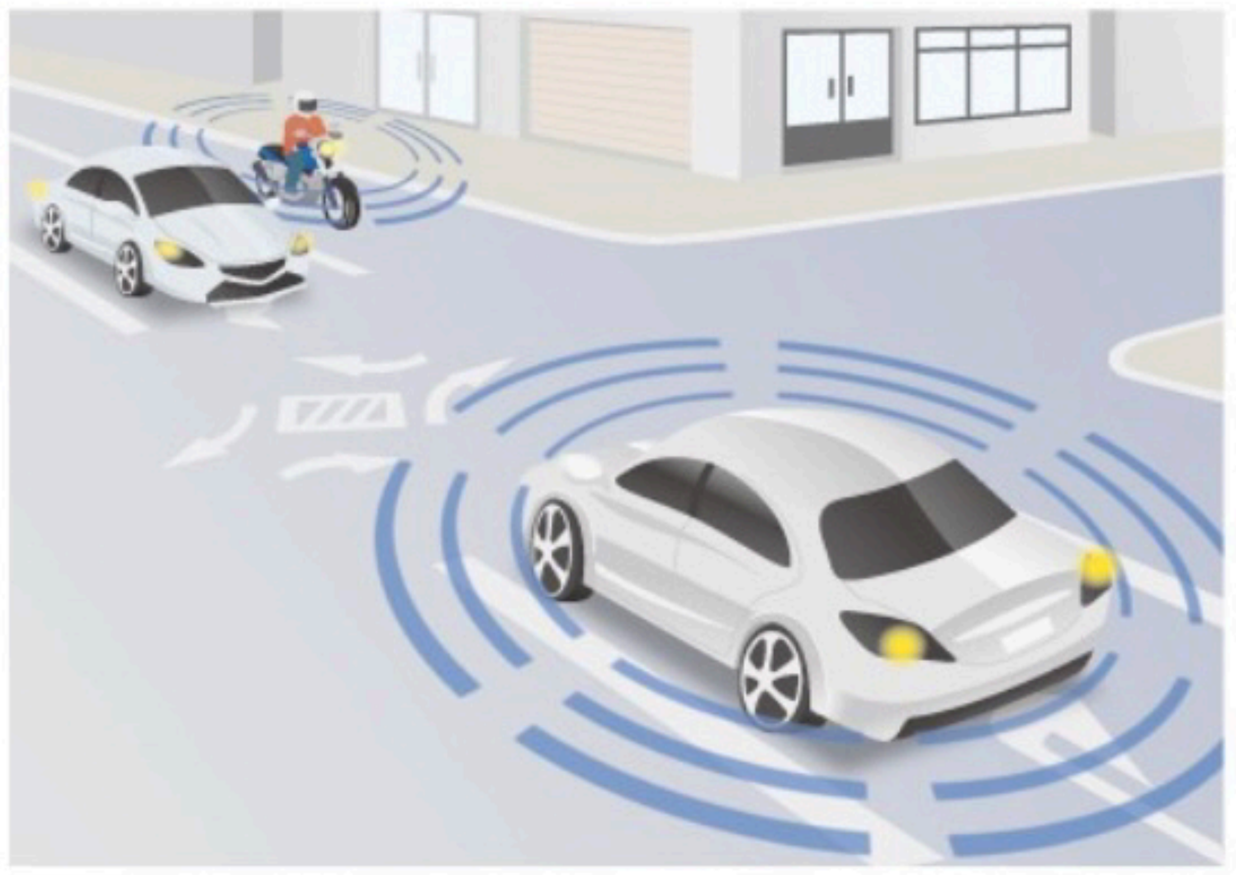
Lot of ambient in the lab, optical shielding (eg. Black sheet) is needed → give some ideas of low-light detection



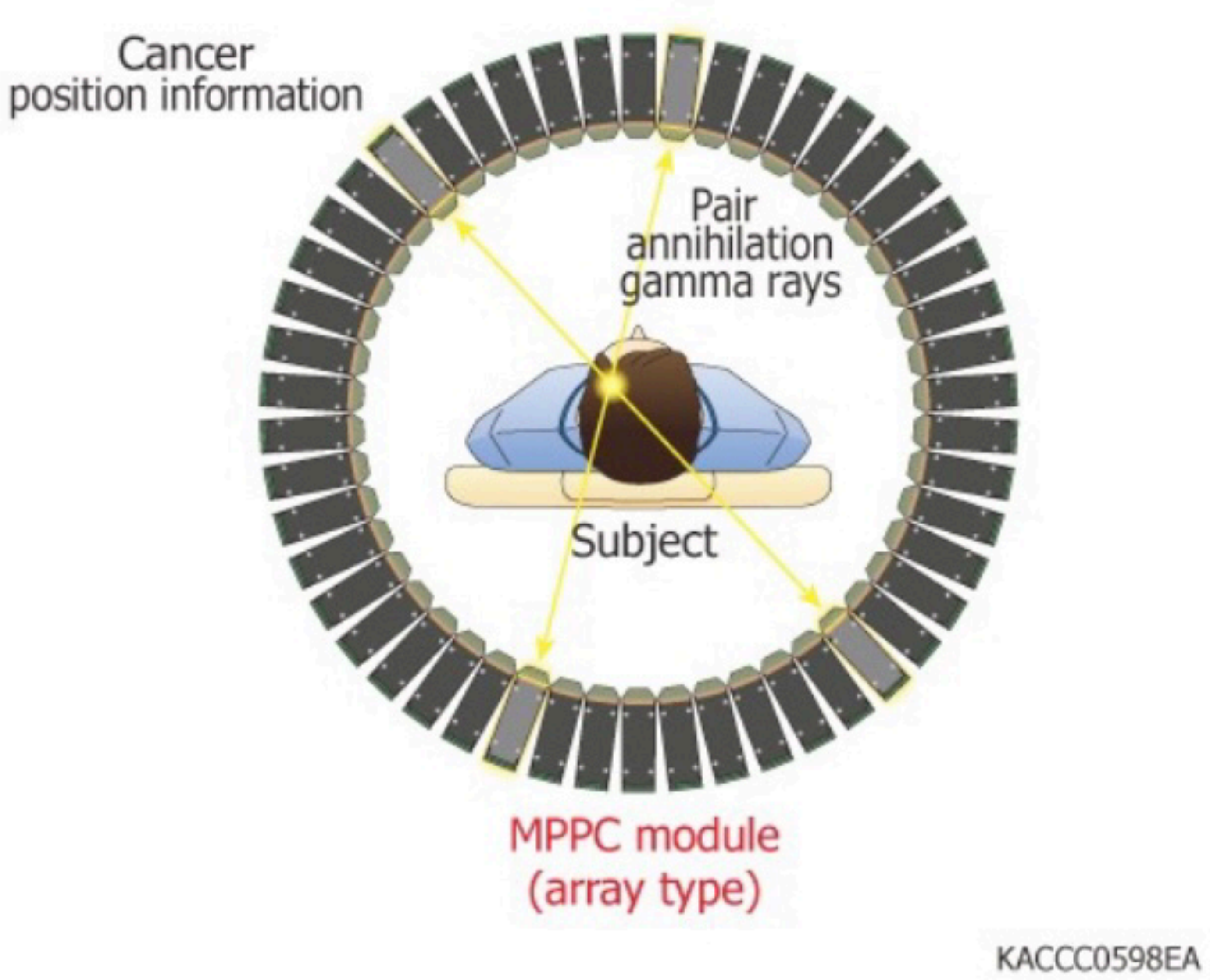
# MPPC/SiPM has wide-range of applications

https://www.hamamatsu.com/jp/en/product/optical-sensors/mppc/application.html

Distance Measurement (LiDAR)

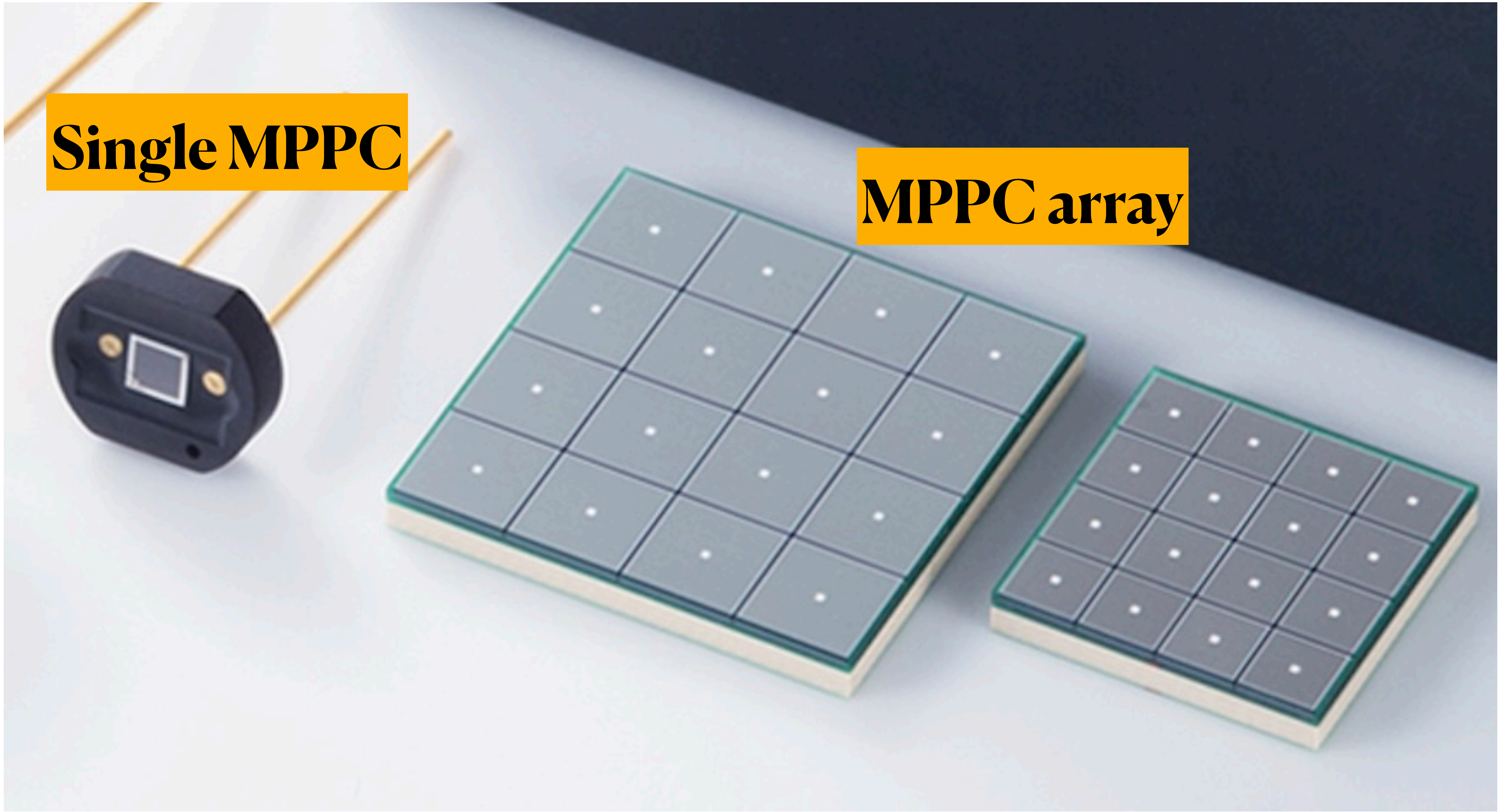


PET (Positron Emission Tomography)




**And many other applications**

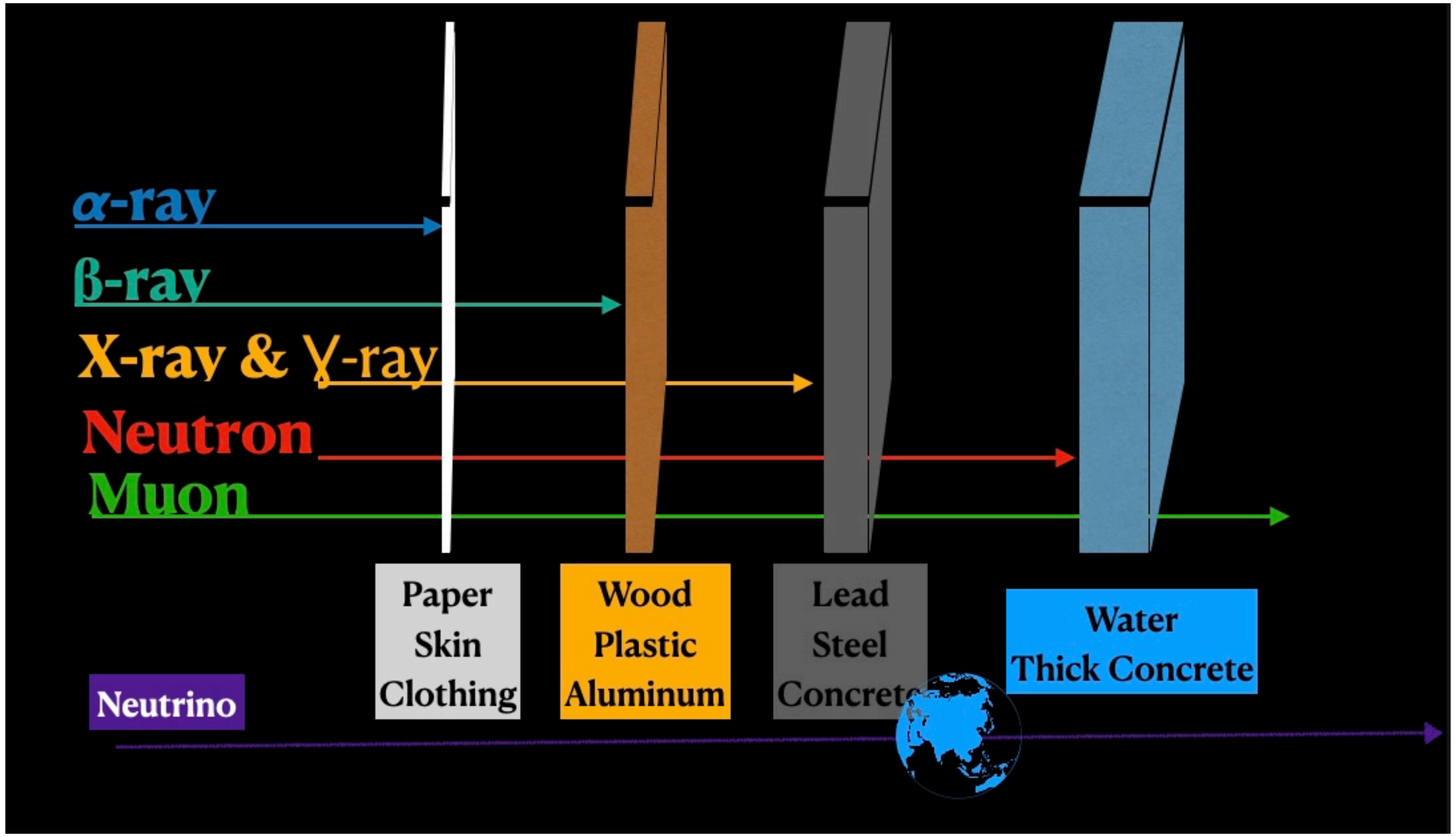
# We basically have both single MPPC and MPPC arrays



# Cosmic-ray muon detection

# Neutrino school but sorry, we can't observe neutrino here

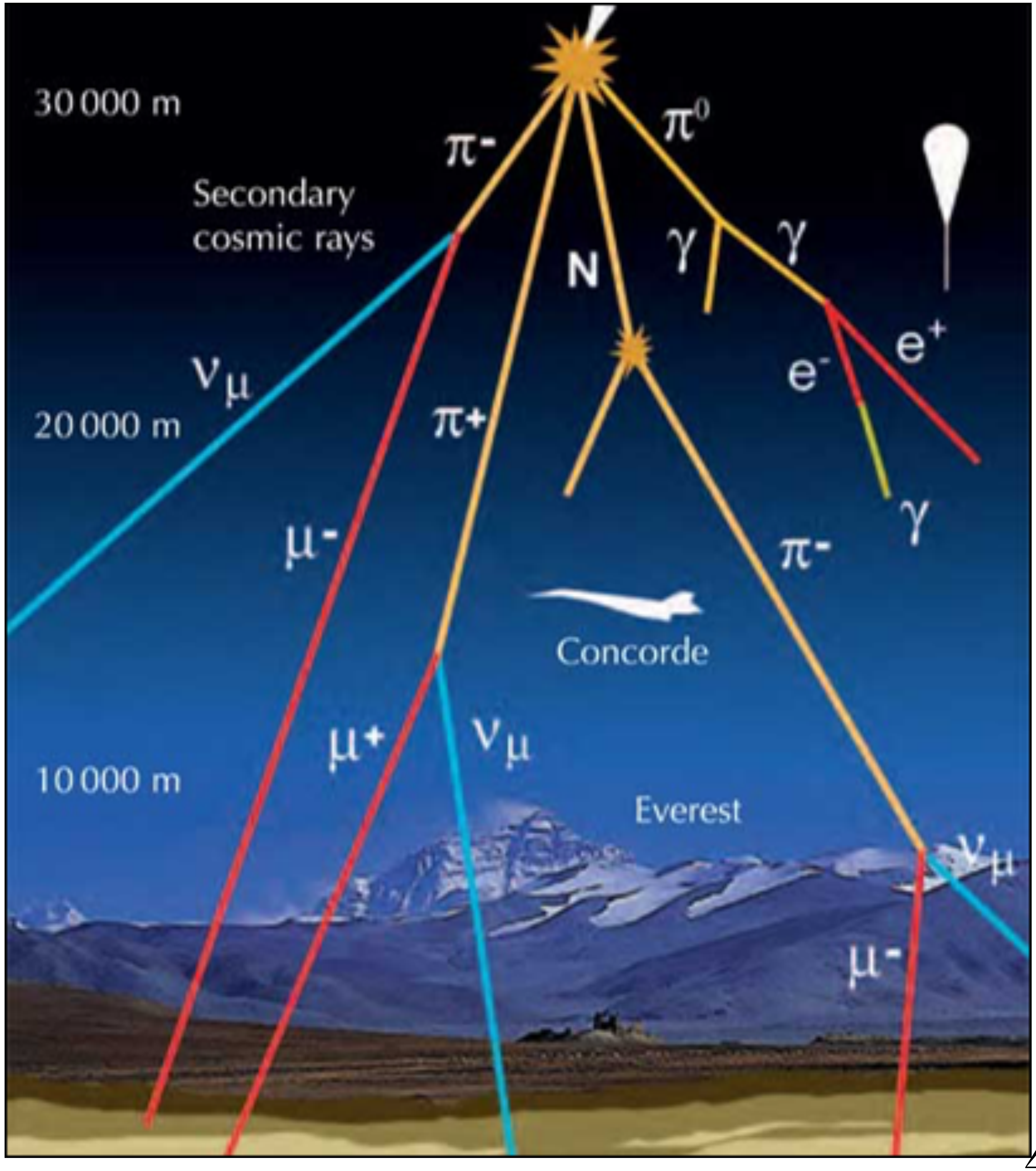
- To observe neutrino typically one *will need big detector and place near the huge source of neutrino or very sensitive detector utilising recoil energy from coherent neutrino-nucleus scattering*
- What we can observe in the lab is the ***cosmic ray* muon (big *brother/sister of neutrinos*)**



# High energy astrophysical particles (eg. hydrogen & helium from the Sun) interact with the Earth's atmosphere →produce vast amount of muons

## ~ 1 muon/cm²/minute

This number is important for particle detection



# Eg. What if Super-K places on the surface?

$A = 2.\pi.R.(R+h) \approx 2.3.40.80 = 9600\ m^2$

Note: flux of cosmic-ray muons depends on energy and the zenith angle

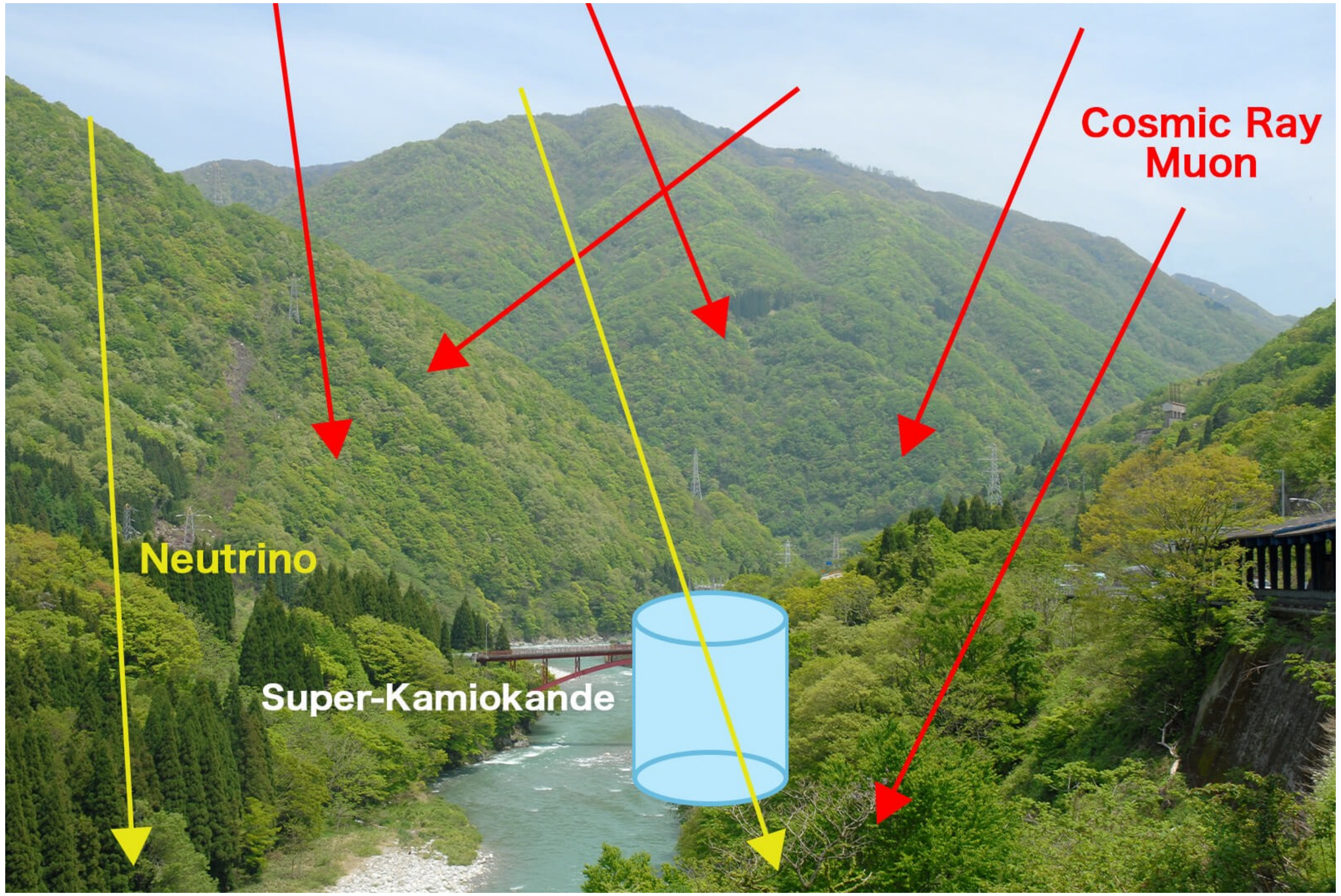
Simple calculation:

Cosmic ray rate ~ $10^6$ Hz

Neutrino rate is in Hz-level rate.

→ your detector is bombarded by cosmic ray muons (background) not neutrino (signal)

By putting detector 1000m underground, this cosmic ray rate is suppressed by factor of about $10^5$ and what we have actually observed in Super-K is about 2Hz of cosmic ray

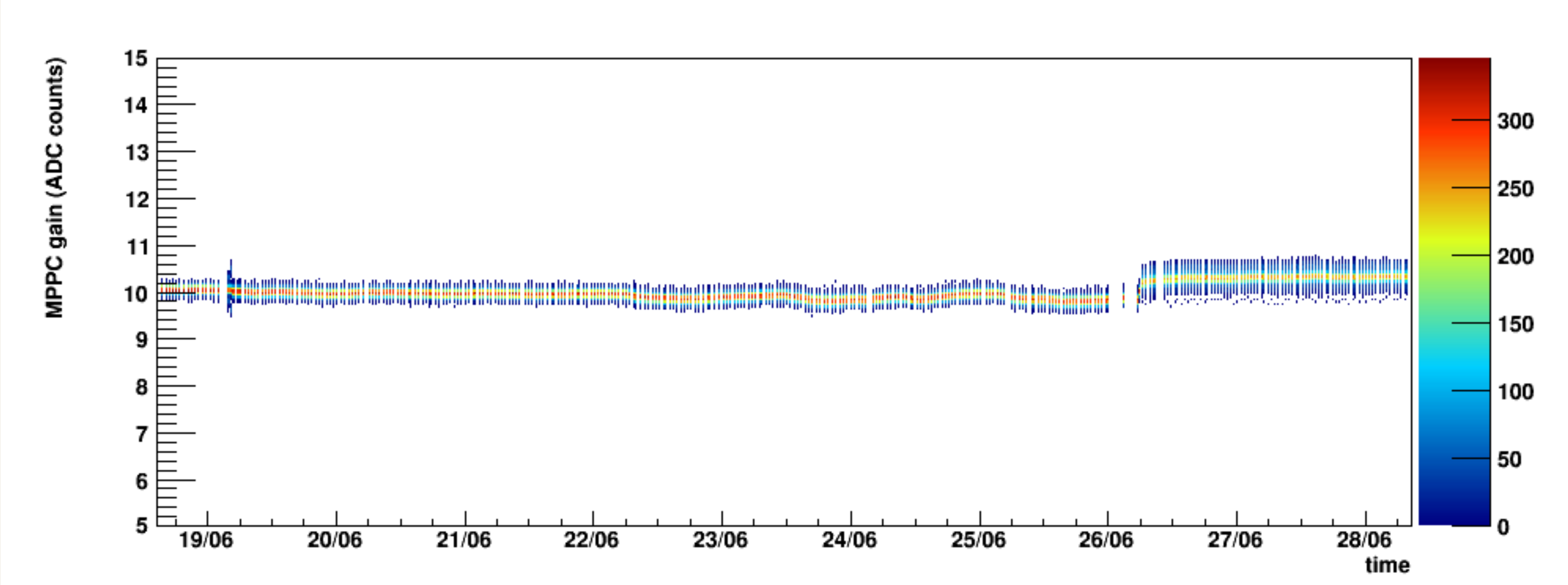


# Why is it interested?

- Will allow us to examine **the "time dilation" in special relativity**
  - **K**nowing 2.2us lifetime, if not taking relativistic effect, muon will travel ~ 600m before stopped
  - But we know most of muons produced in the upper atmospheric, ~ 10km (>>600m). So in classical mechanics, muons shouldn't reach the Earth surface
  - *If include the relativistic effect, range of 4GeV muons before decay is about 13.8 km.*
- Lifetime measurement will allow us to **estimate the Fermi coupling** constant which govern the weak interaction
- Allow to **test the Parity-violation** (*due to polarized nature of cosmic-ray muons and parity violation in the weak interaction*)
- Allow to verify that there are actually **two different kinds of neutrinos** are produced along with electron in muon decay

# Why is it interested? (cont'd)

- Deposited energy by muon is a standard "candle" for many energy calibration purpose in particle and nuclear experiment
  - Reminder: at particle level, you don't have old/young or fat/thin particles. They are all identical.



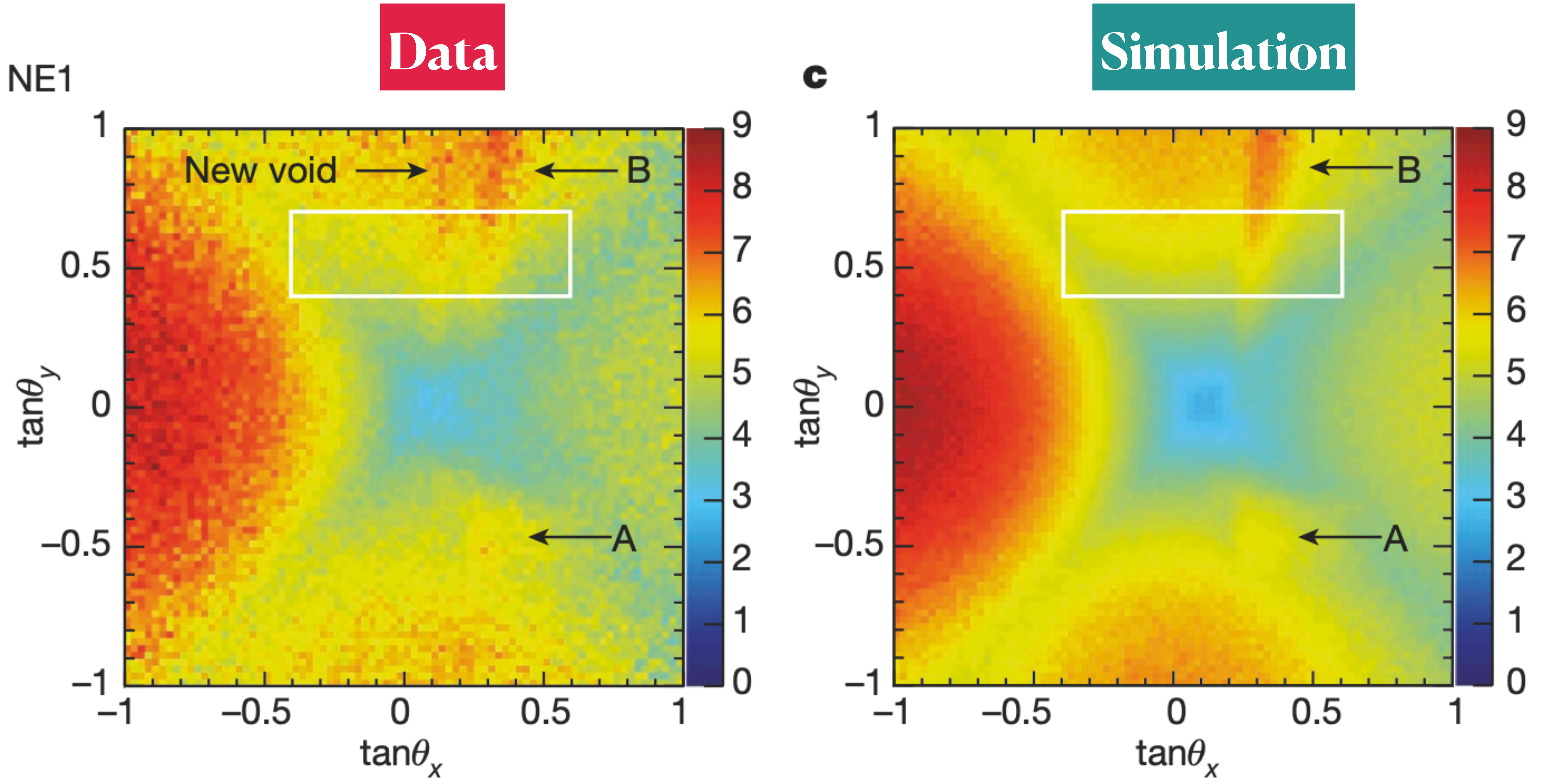

- Also wide-range of application for seeing the "inner" structure of big (or high-Z) structure, eg. Pyramid, volcano, reactor core…

https://www-he.scphys.kyoto-u.ac.jp/member/ingrid/ingrid_expert/

# Muon can be used for a practical application

https://www.nature.com/articles/nature24647

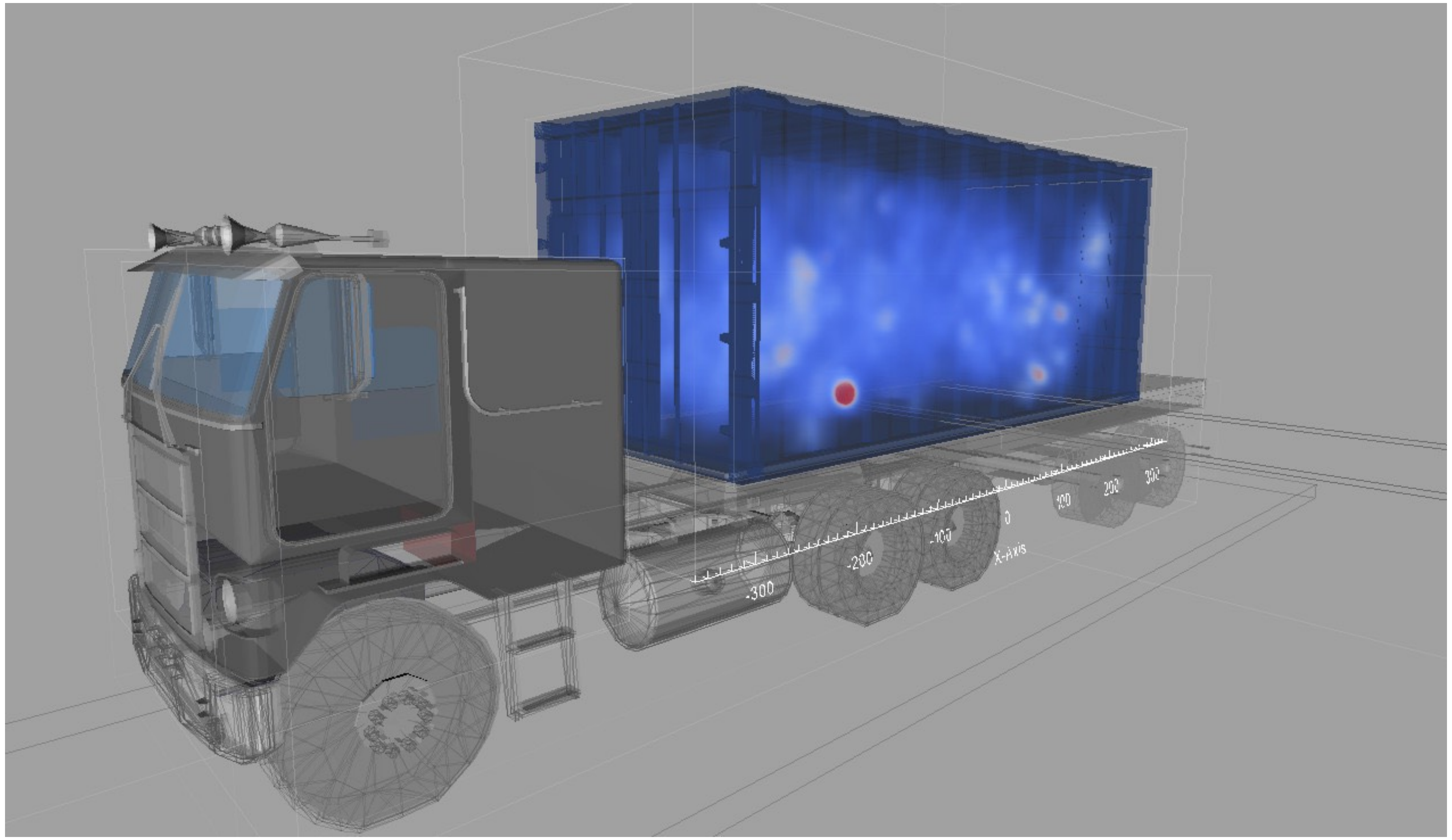
called: muon radiography technique




Color is corresponding to intensity of muons.
Red is with more muons detected

# Muon can be used for a practical application

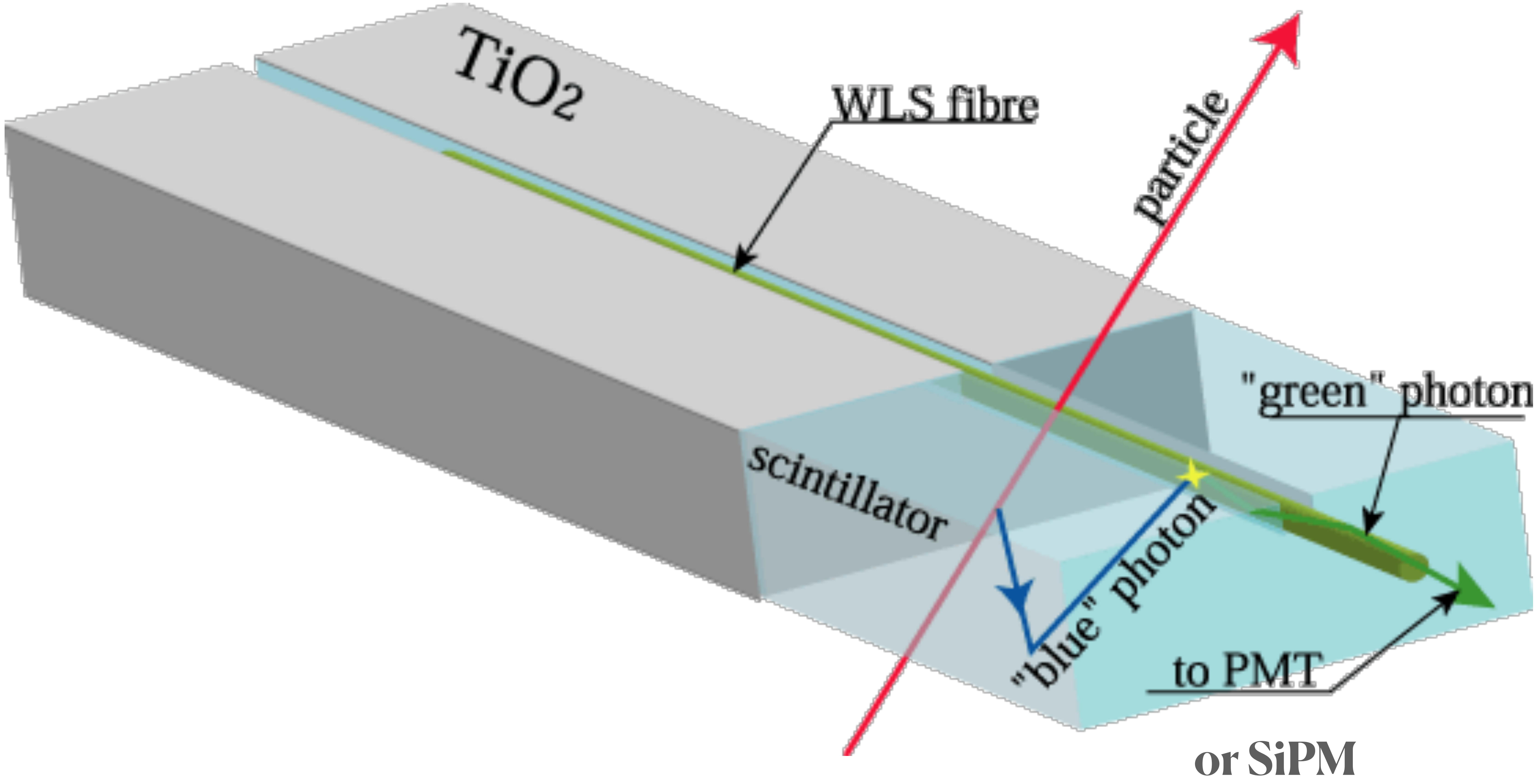
**For cross-bolder security**




https://cds.cern.ch/record/2281058

# How can we observe muons and measure their characteristics with *what we have in the lab?*

# Tracking the charged particle w/ scintillator

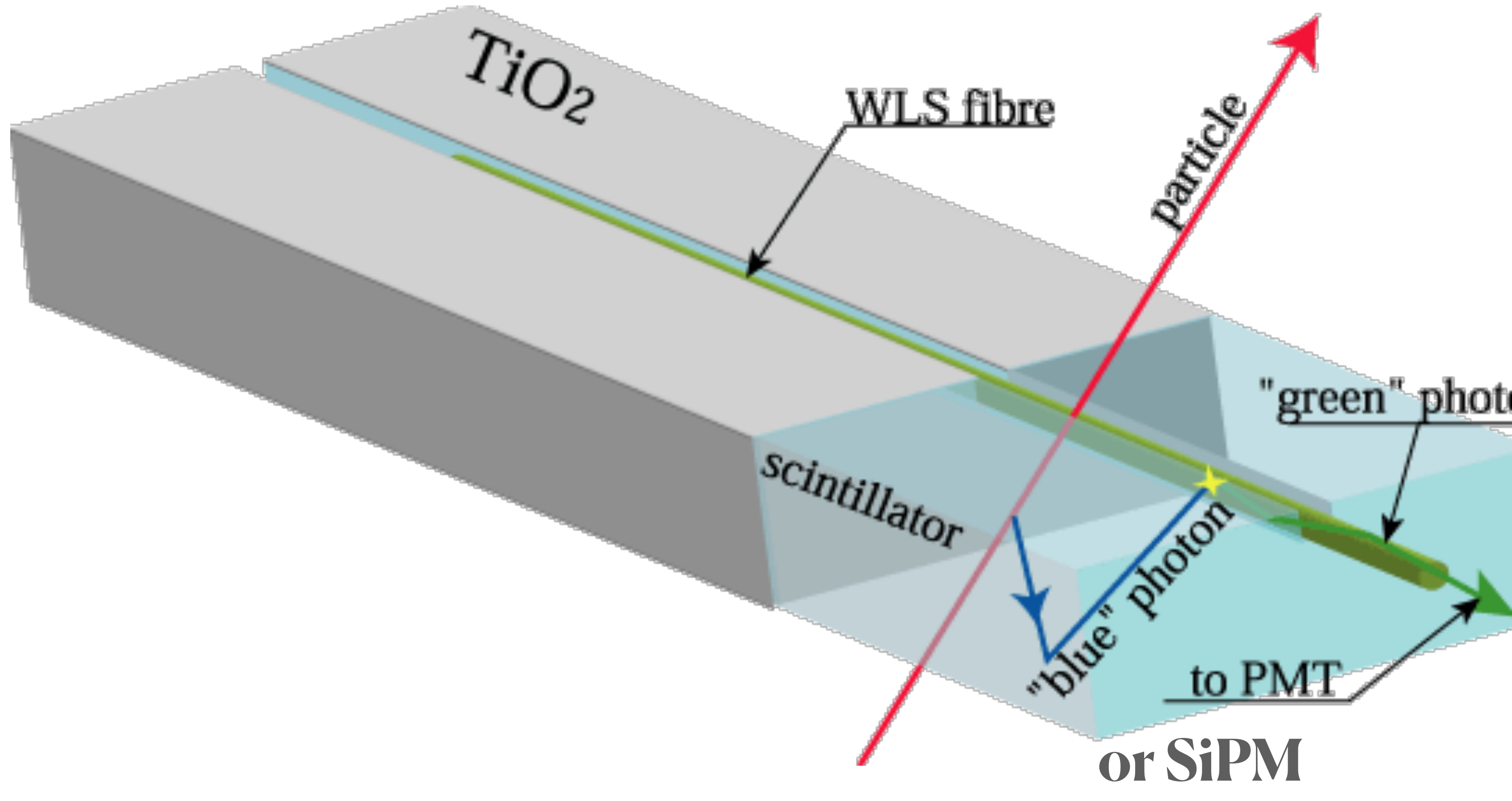



**When passing through the scintillator, charged particles ($\mu$, $\pi$, $e$,...) deposits energy and excite the scintillation photons, which are collected and guided to the photosensor for converting to the electrical signals (*more convenient to manipulate*) for data recording.**

Ref. Basics of Particle Radiation Detector and others

# Tracking the charged particle w/ scintillator

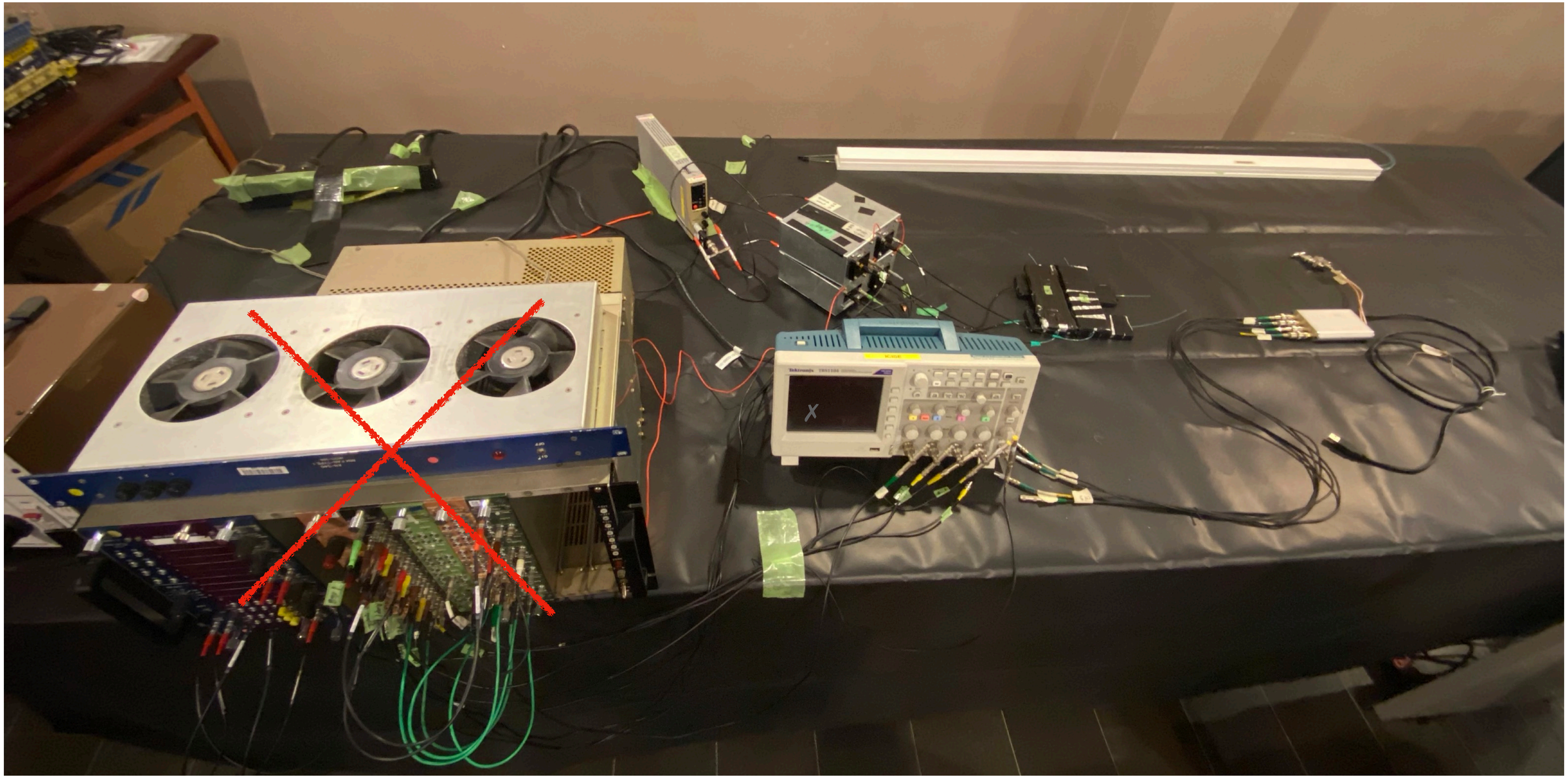
- Muon deposits ~ **2 MeV per 1cm-length** path in the plastic scintillator
- 2 MeV deposit energy will produce ~ **10,000 photons**
- Assume the probability for WLS catching the photons is about 1%, then ~ 100 photons are capture and change to green photons
- Detection of photosensor is about 20-40%, so will have about **20-40 photoelectrons observed**
  - Sometime you can get lower due to the aging of scintillator, attenuation in the WLS or light loss from imperfect coupling between the WLS and photosensor




**Why is light yield of scintillator important?**

# Experimental setup

# We get rid of the complicated setup with NIM modules



# And try to have out-of-box setup as much as possible

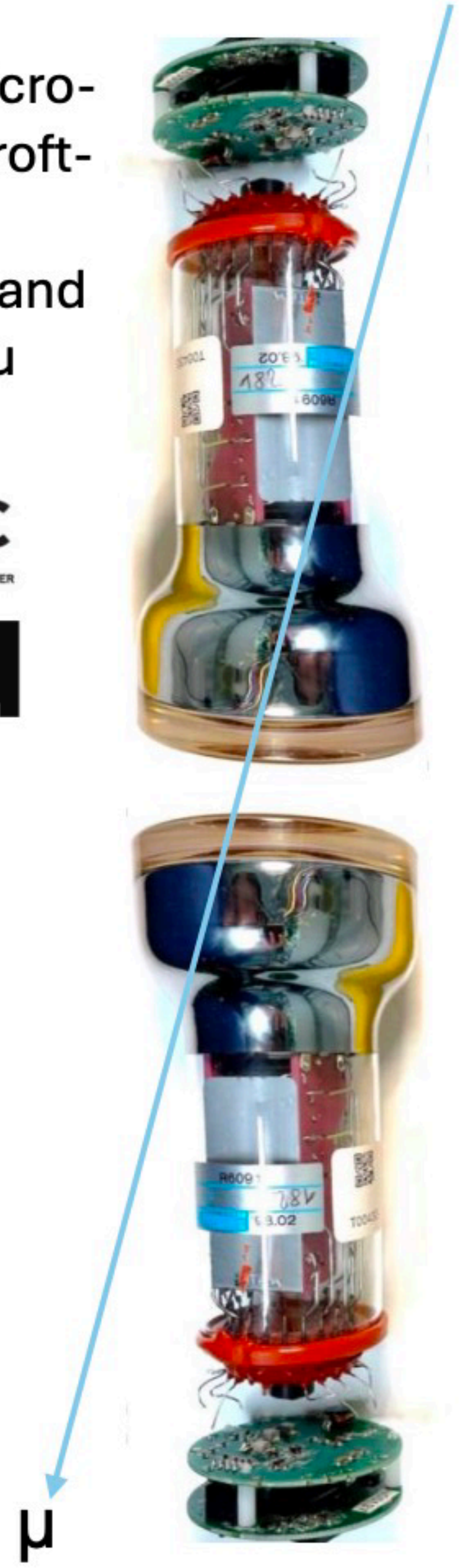
# Group 01 w/ relatively big PMT

## Muon counting with CHIPS photomultipliers

Stacked 'micro-DAQ', Cockroft-Walton powerbase and Hamamatsu R6091 PMT

WIPAC Wisconsin IceCube Particle Astrophysics Center

UCL




We will be using PMTs + scintillator to look for coincident signals (<1ns) caused by passing cosmic muons

Electronics setup includes PWM powered Cockroft Walton voltage multiplier and White Rabbit timing technology, resolution order 10ps

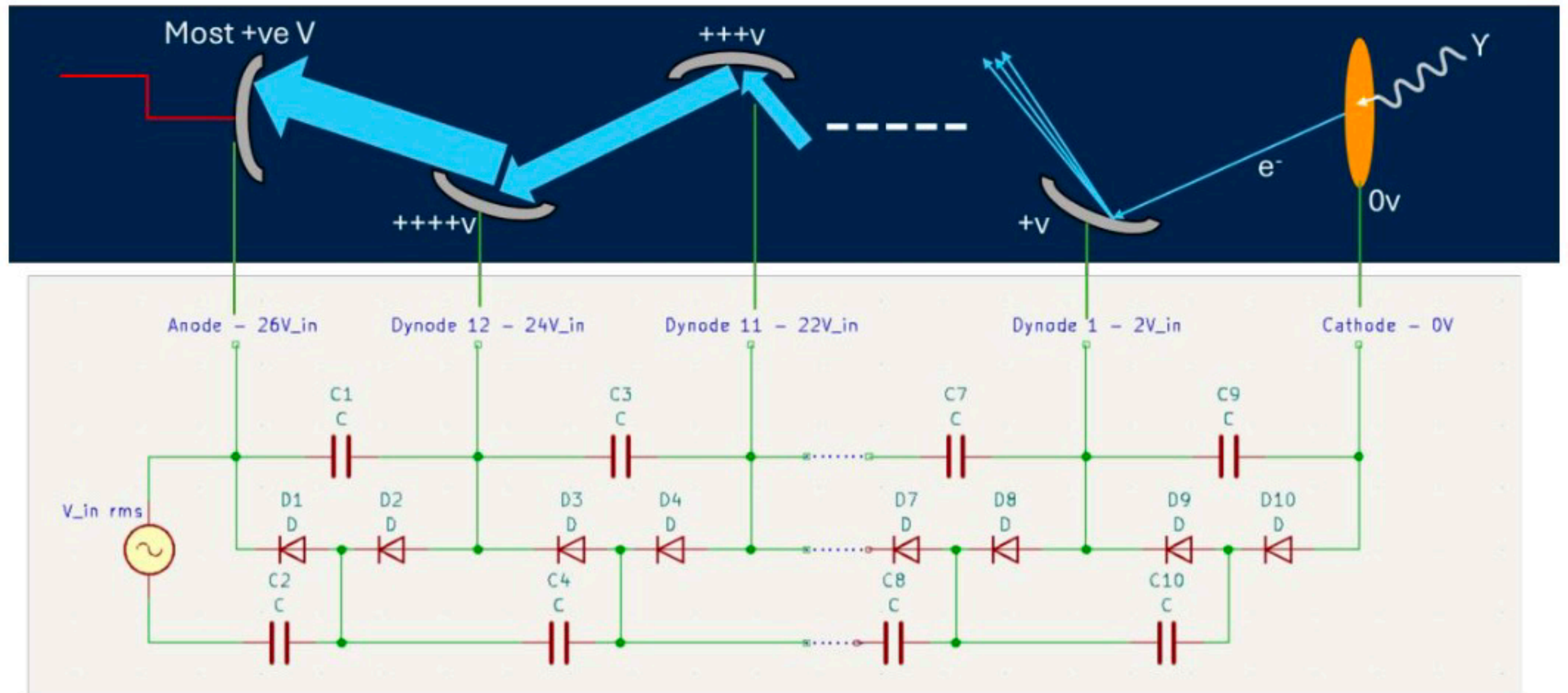
Electronics designed as part of Cherenkov In mine PitS (CHIPS) concept neutrino detector

**Mentor: Alex Sells (UCL, UK)**

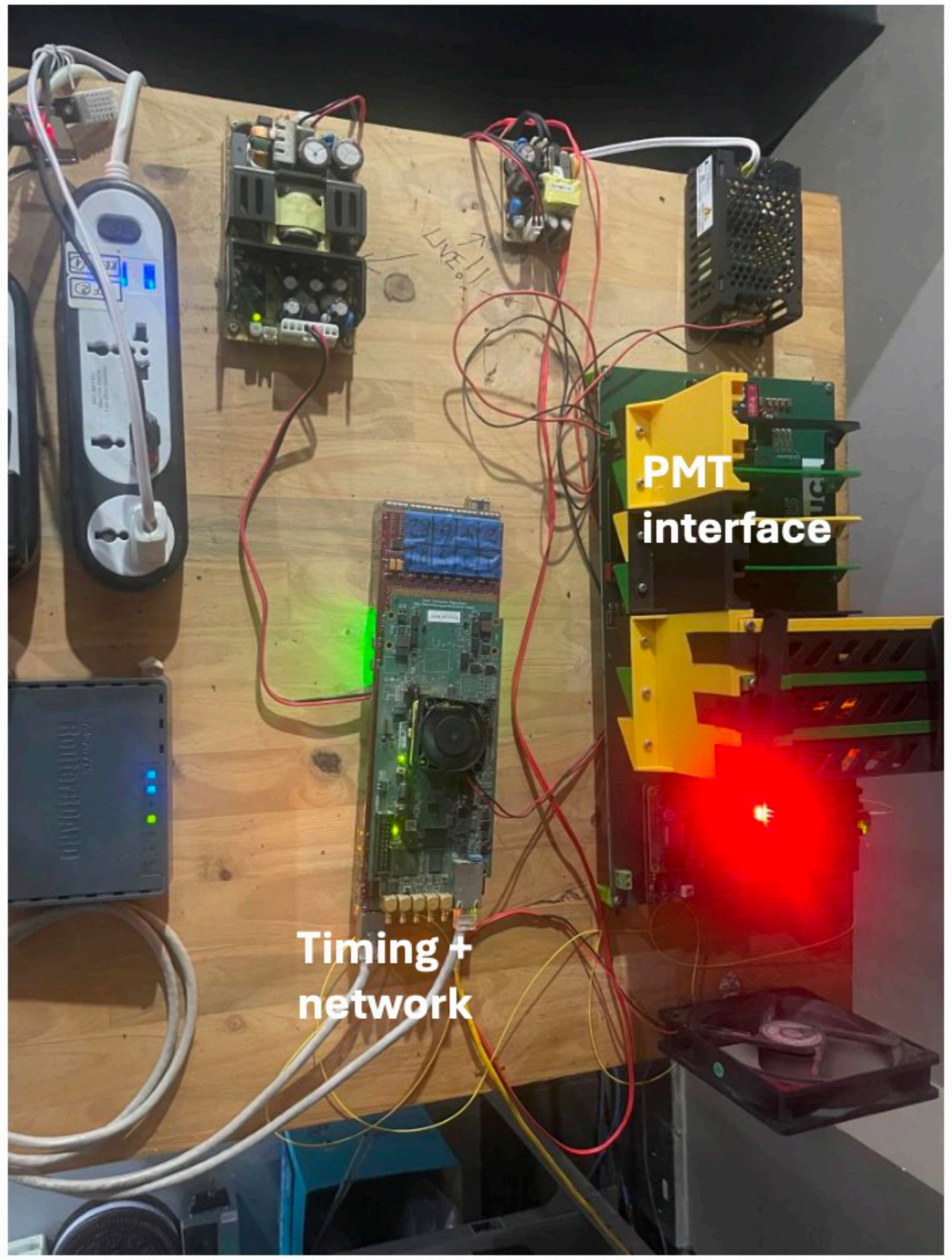
# Group 01 w/ relatively big PMT

## Program

- Test function of Cockroft-Walton Voltage Multiplier
- Measure photomultiplier high voltage vs PWM frequency
- Perform Muon coincidence experiment



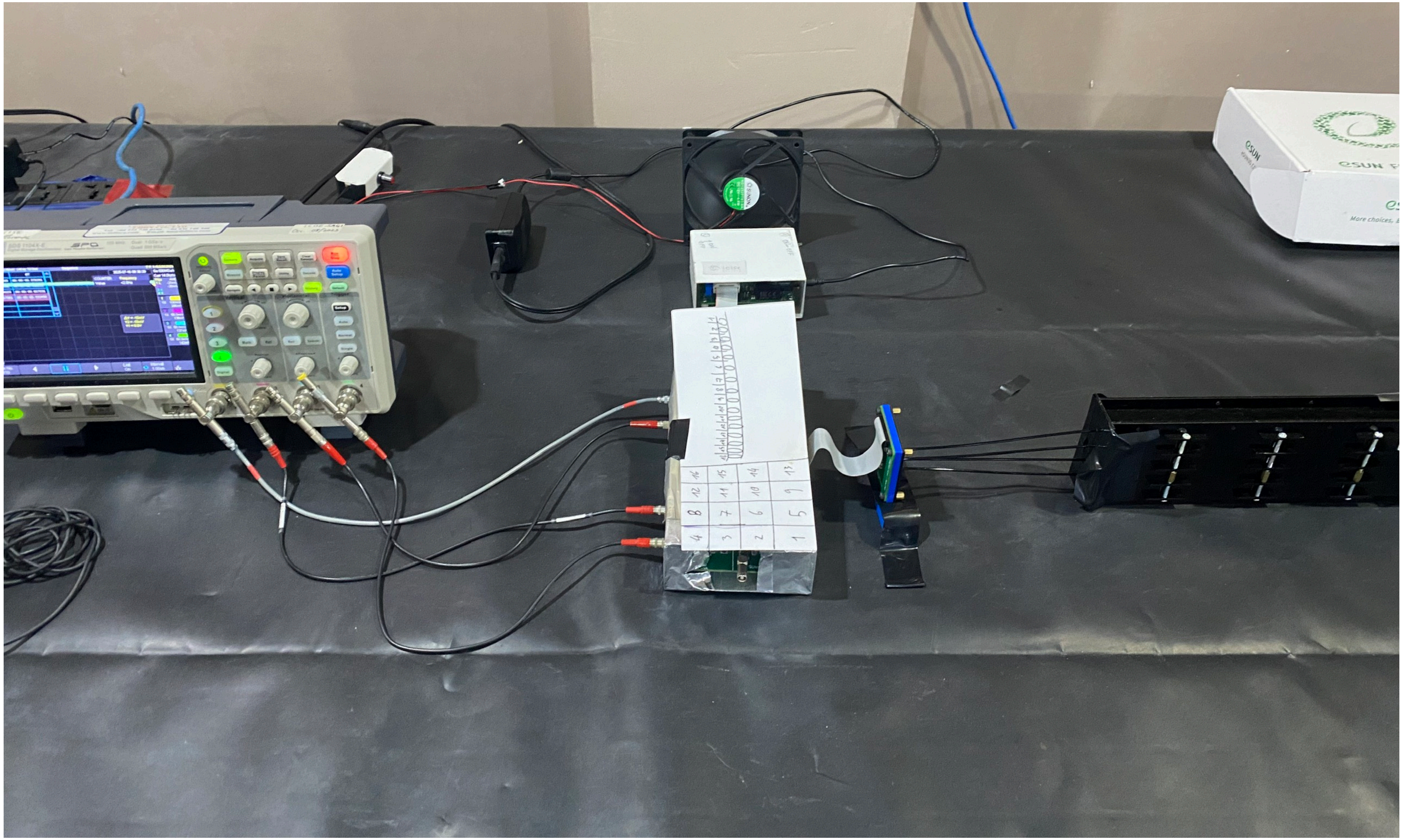

Schematic of Cockroft Walton circuit and photomultiplier tube interface




CHIPS PMT electronics setup Quy Nhon

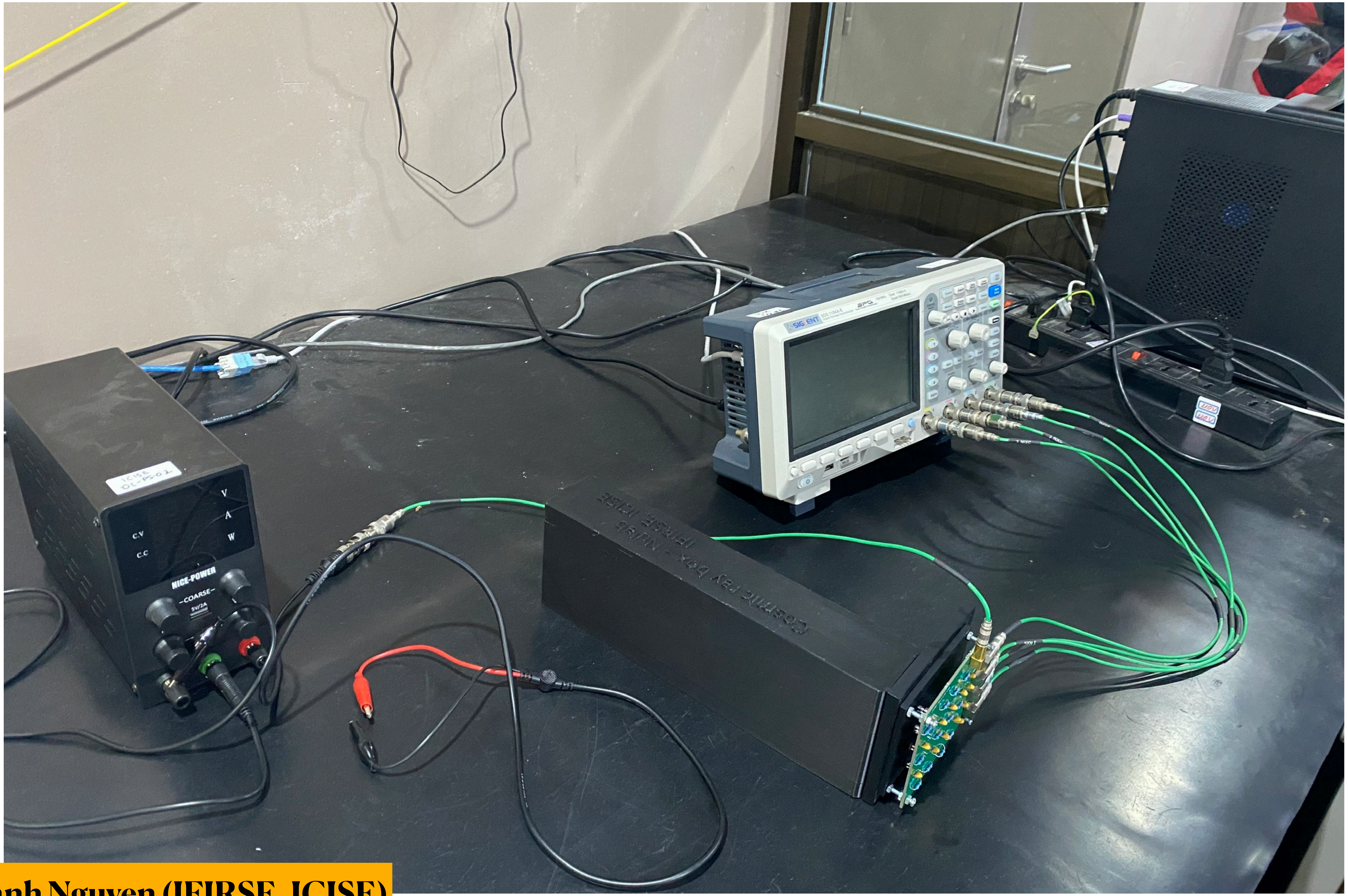
**Mentor: Alex Sells (UCL, UK)**

# Setup-02 with MPPC array (4x4)



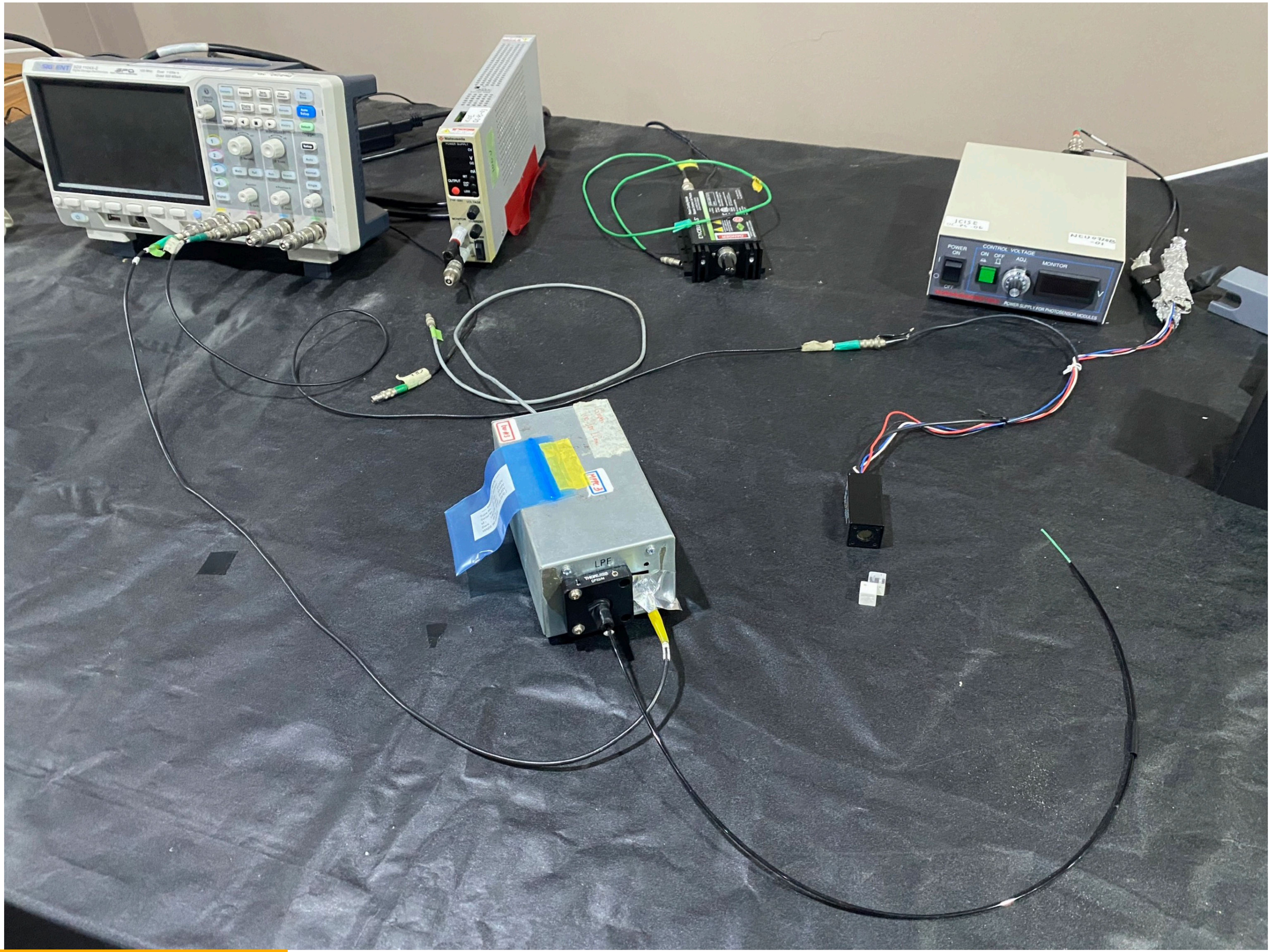
Mentor: Sang Truong + Quyen Phan (IFIRSE, ICISE)

# Setup-03 with four pieces of single MPPC



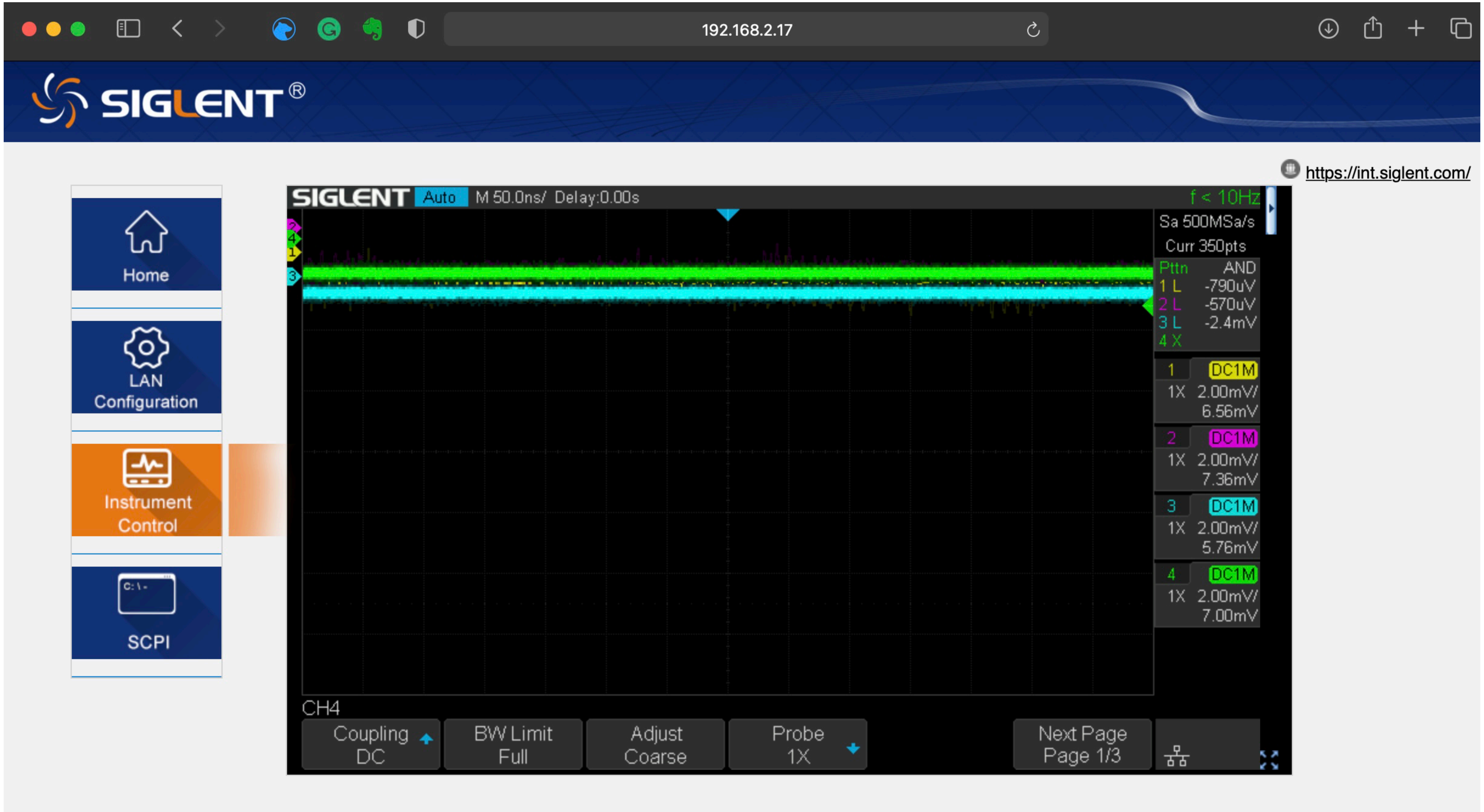

Mentor: Thanh Nguyen (IFIRSE, ICISE)

# Setup-04 with single MPPC and metal-package PMT and scintillation cube

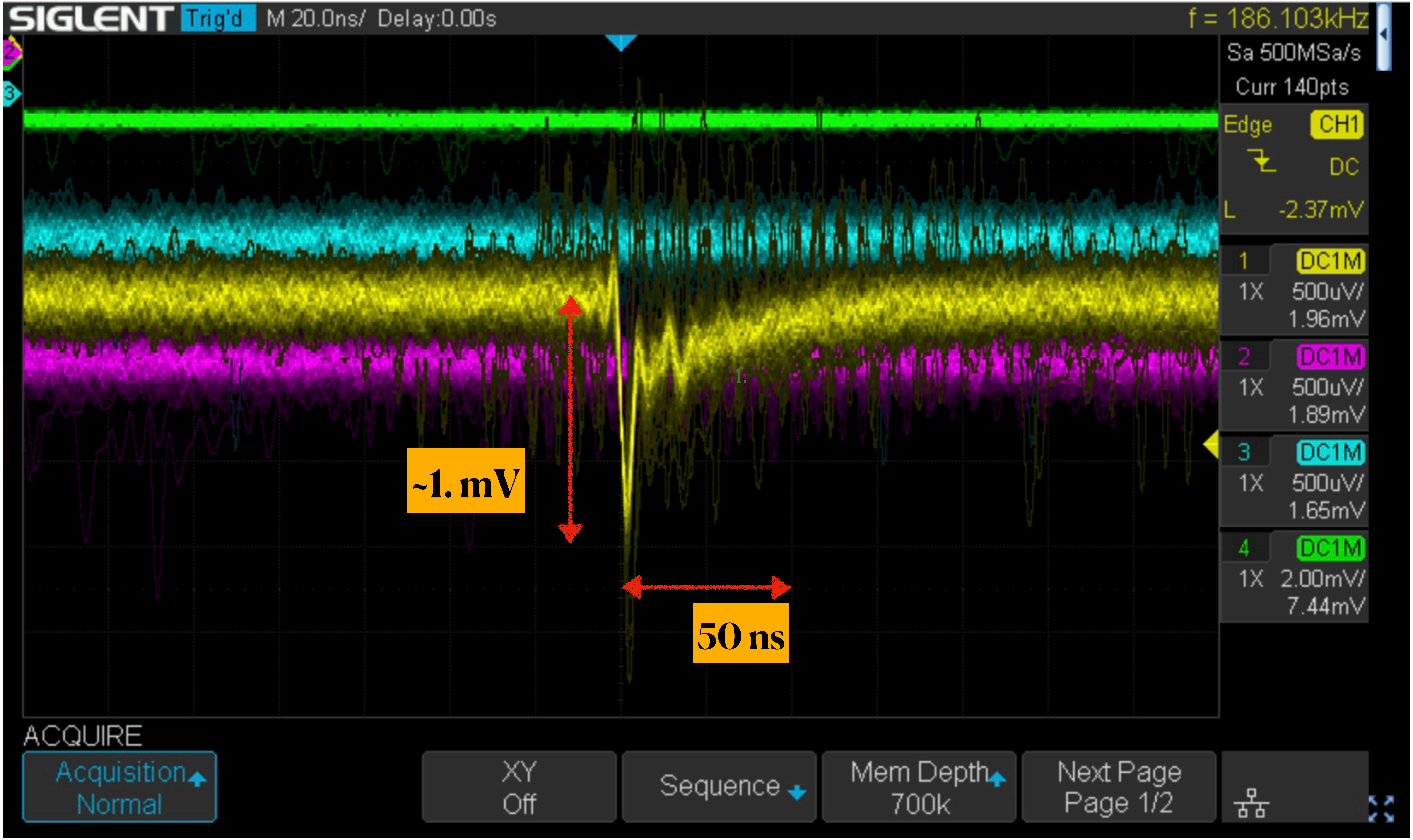


**Mentor: Son Cao (IFIRSE, ICISE)**

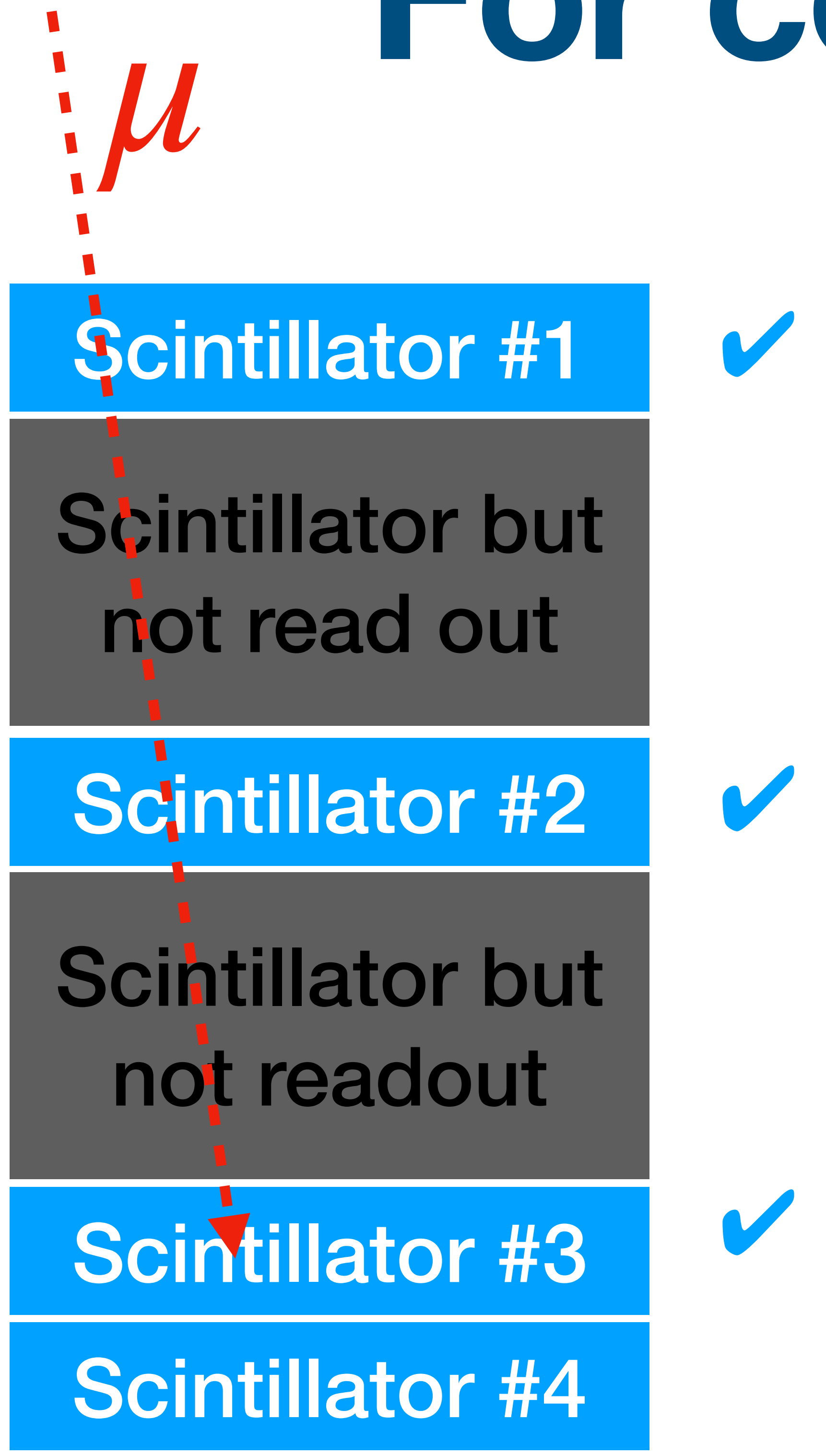
# The oscilloscope has web interface and can acquire data remotely via ethernet (and VXI)

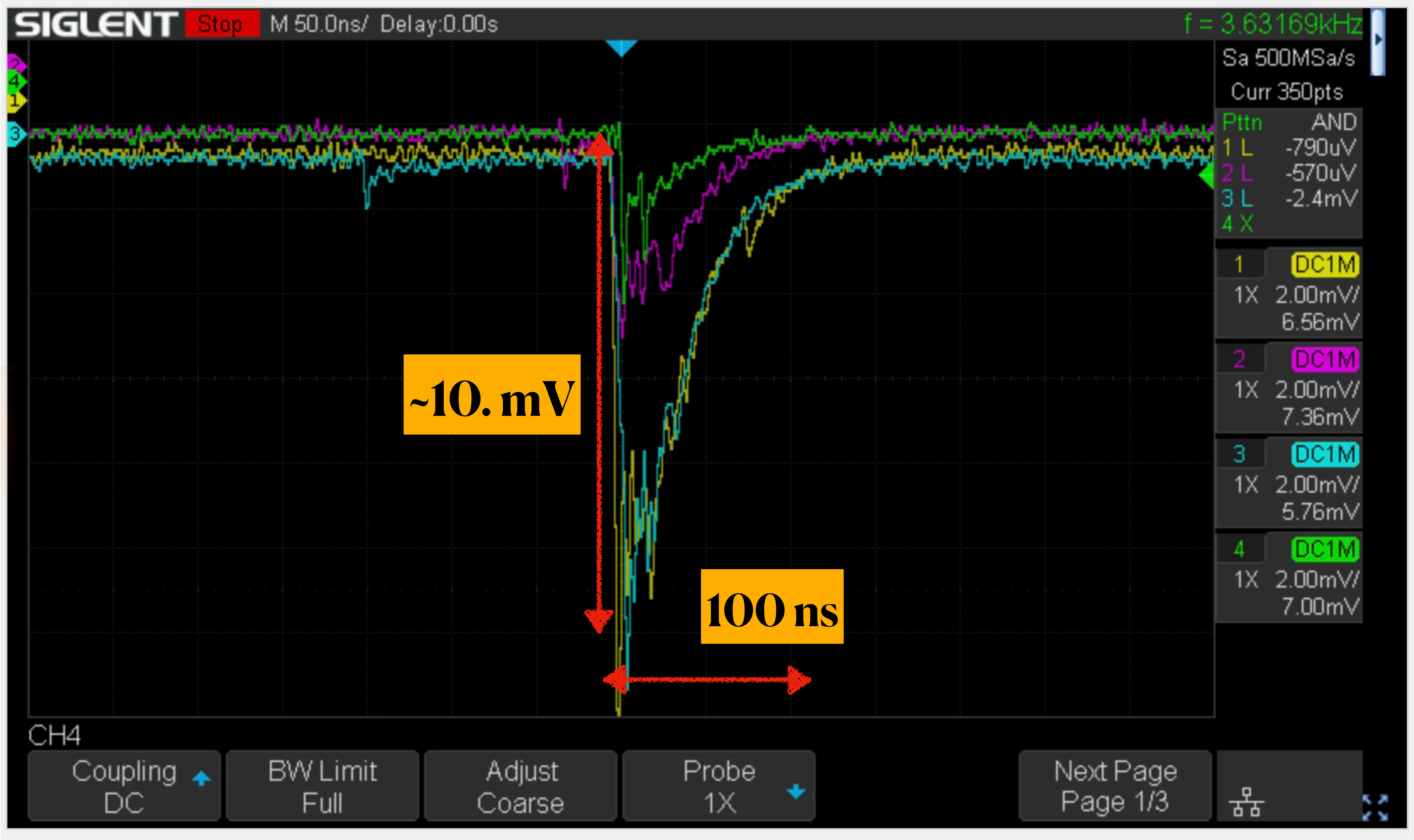


# The signal is very small, 1 pe ~ 1.0 mV

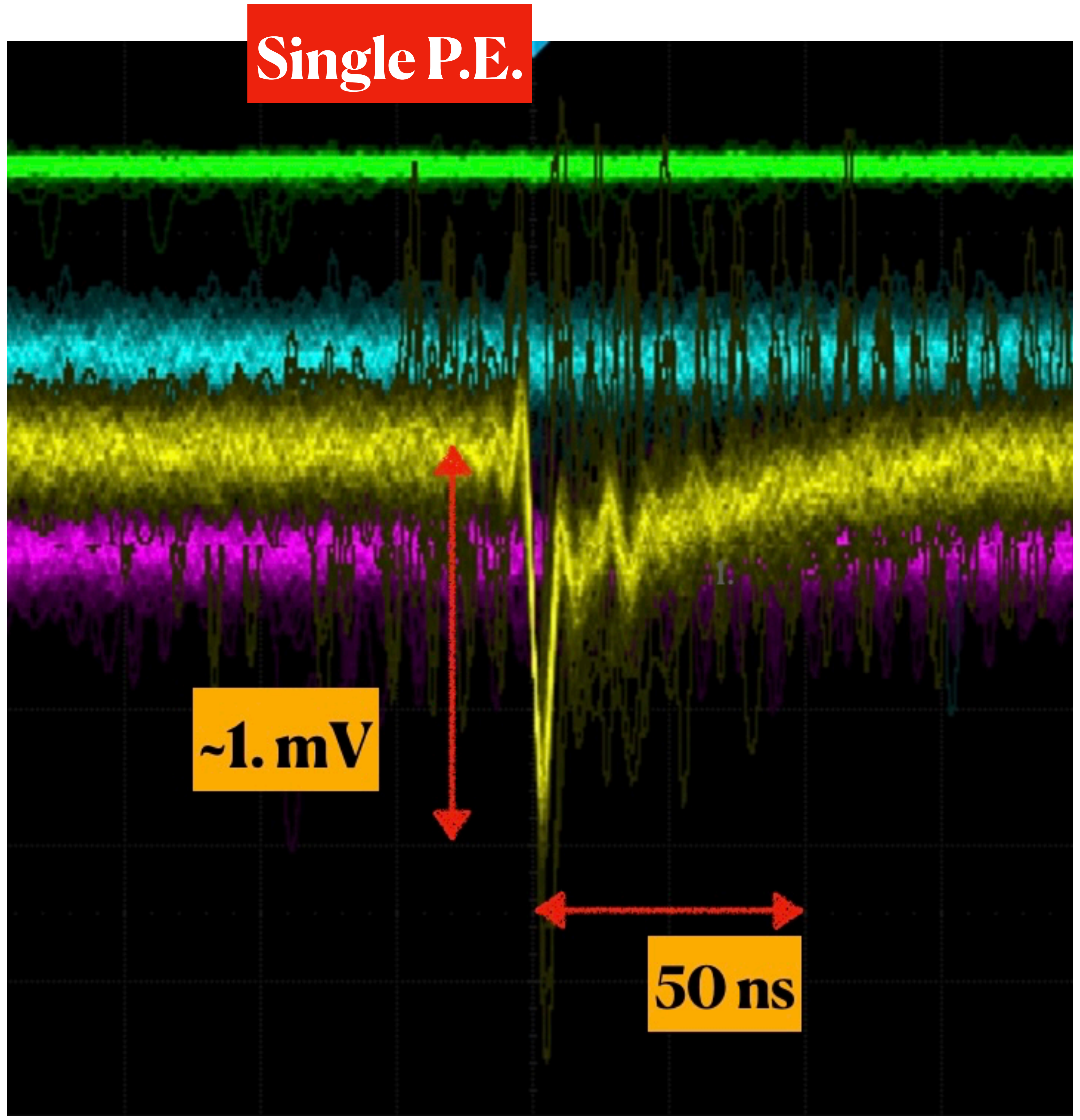


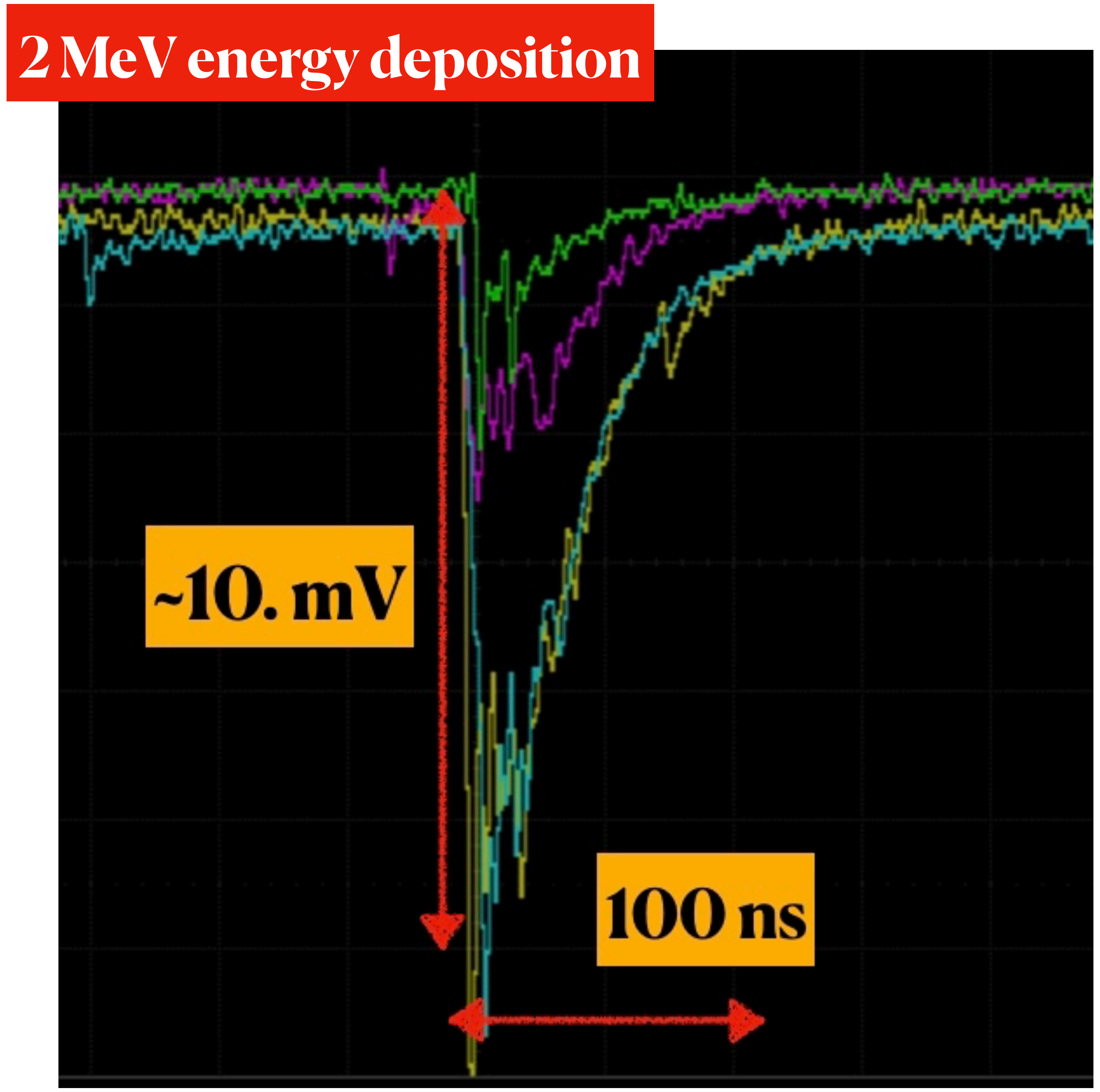
# For cosmic ray muon detection



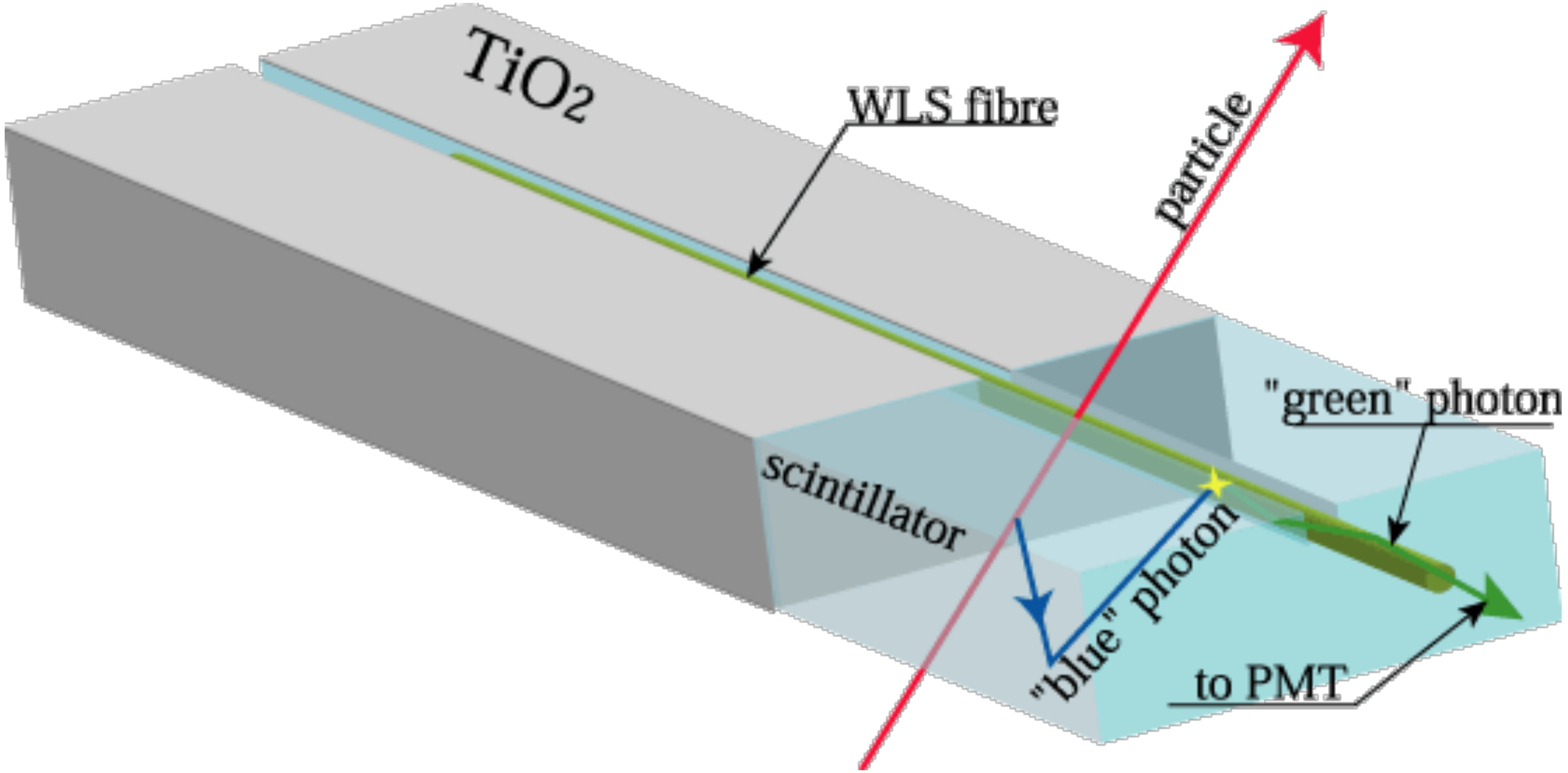
# Light yield of scintillator to MIP deposition



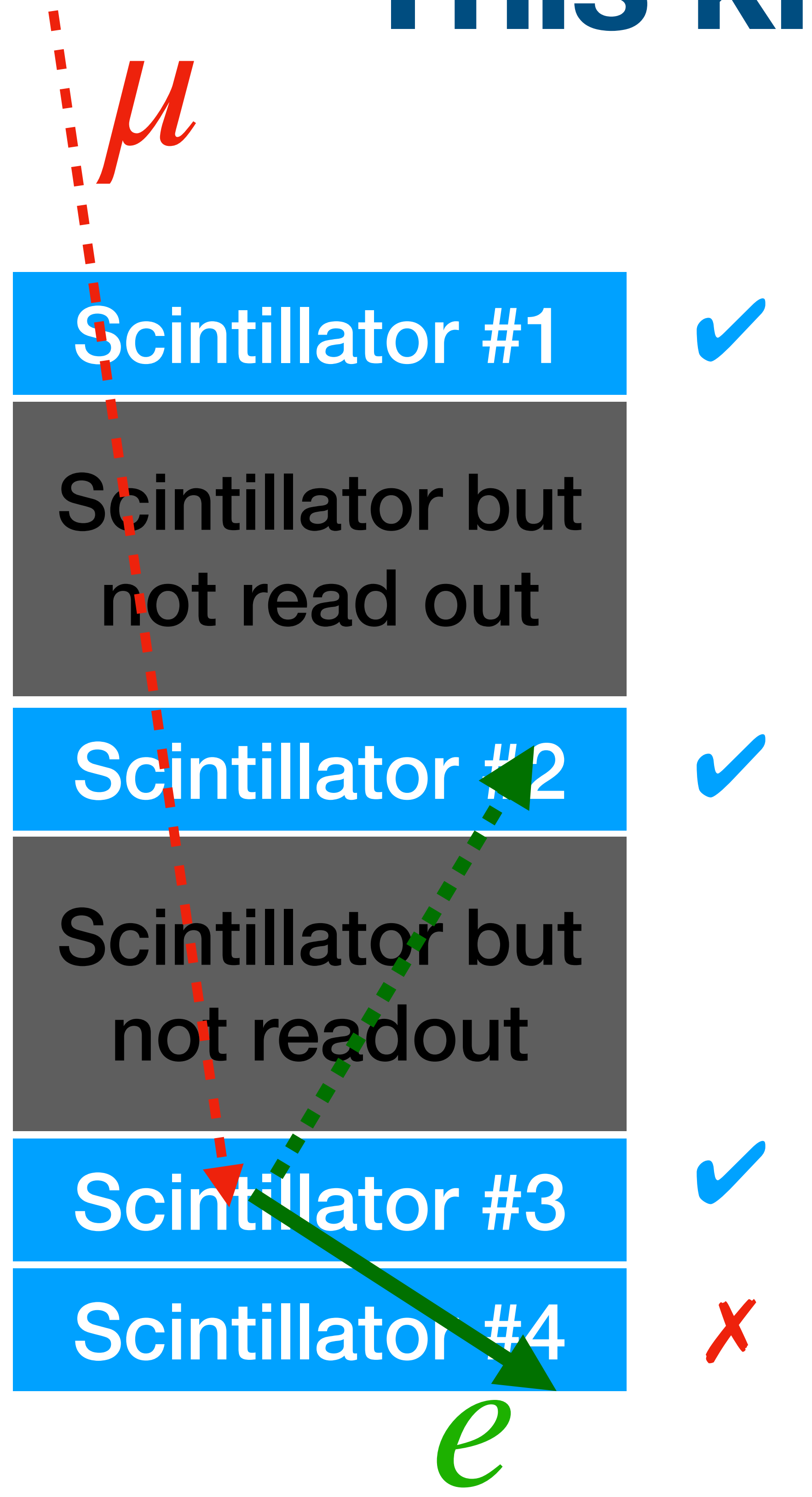

**By getting the ratio between these two signals, it allows to get the light yield of scintillator to MIP deposition , which is a basics for particle energy measurement.**

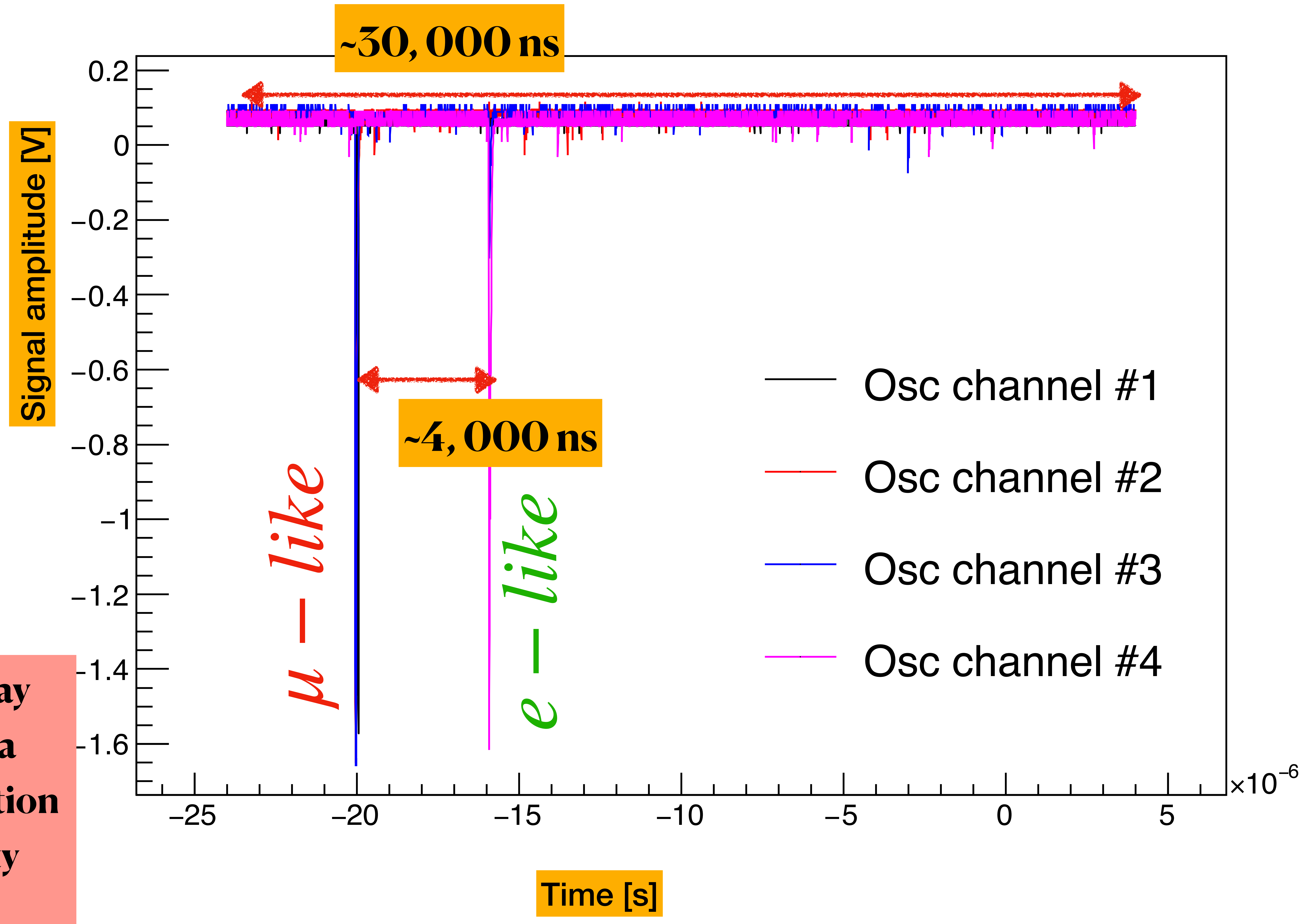
# To keep in mind: converting photons to energy depostion is a short cut




**Charged particle deposit and just few percents (~10%) are converted to scintillation light which needs to be captured by WLS and total reflection inside to guide to photosensor before experience the photoelectric effect and turn to the electric signal.**

# This kind of setup allow to see muon decay too




**Cosmic ray muon decay observed on Earth is a verification of time dilation in the special relativity theory**

# Mentoring

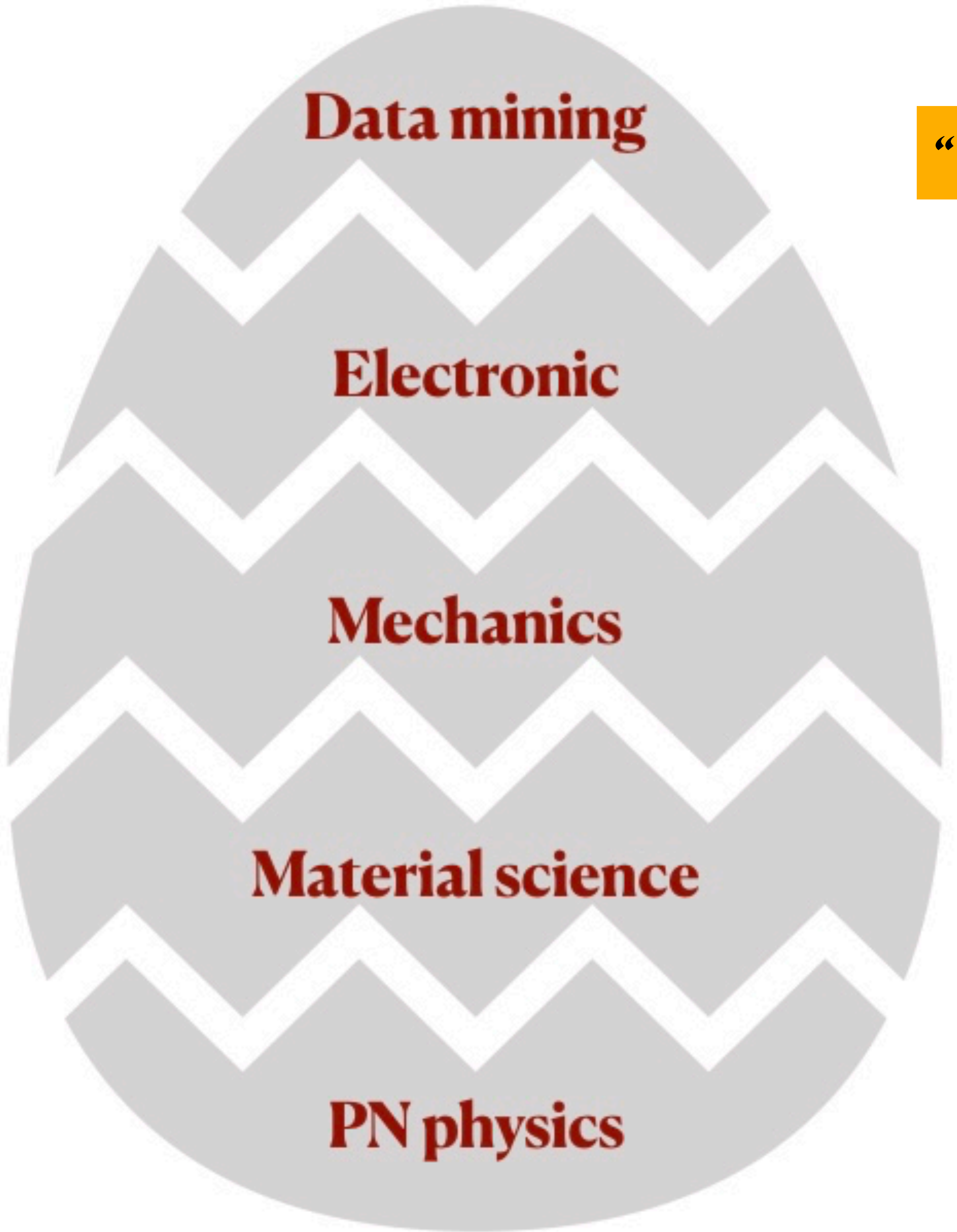
- Mentors: Son Cao, Alex Sells, Sang Truong, Quyen Phan, Thanh Nguyen
- Some students (eg. Japanese students) may be familiar with the setup. Please help members in your group

# Safety FIRST

# Safety note for handling the equipments

- Please be **gentle**! They are **fragile**
- High voltage for PMT (~1000V). For siPM, it use relatively high DC supply (50 - 80V). Please **use the slipper, no bare foot**, to avoid the electrostatic shock.
  - Don't try to adjust the HV larger the allowed (~56V for single MPPC and ~ 58V for MPPC array)
- **Don't bend the WLS** too much.
- **Aware of polarity.** Eg. Single MPPC has two legs, be aware of positive and negative. **Identify the right leg position before plug in.**
- **Ambient light**: Super-important for PMT. While the MPPC is not likely damaged if exposure to so much light in short time but it's good practice to make sure the light tightening enough
- **Turn on and off DC HV properly**: no touching the electronics when HV on. If you want to check PMT/ MPPC, HV must be turned off

**There are many practical things to follow for better use of the electronics. Please consult with me or other mentors. Don't try to do some weird things. We appreciate your cooperation.**




"Experimental neutrino experiment in the nutshell"

We will touch very small part of it.

# Neutrino detection is a complicate, interdisciplinary field

Time is very limited to play with hardware. You won't satisfy, I'm sure. If you want to play more, please work with us or apply internship or hardware camp (typically happen in Feb.-Mar. )

https://ifirse.icise.vn/nugroup/internship/index.html

https://ifirse.icise.vn/nugroup/hardwarecamp/index.html

# We thank for your donation

KEK

KYOTO UNIVERSITY

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**Without their generosity, this hardware training is impossible.**

# Rough schedule (details depend on specific setup/mentor)

## Day #1, July 16th (Wed.)

- Familiar with hardwares
- Safety instructions
- Overall plans
- Initial operation of photodetector

## Day #2, July 17th (Thu.)

- Explore photodetector characteristics (noise, gain, pedestal )
- Coincidence techniques

## Day #3, July 18th (Fri.)

- Observe cosmic-ray muon
- Measure rate/gain/ angu

# Backup

# Books and some technical note

If you want to take out, please put your name and remember to return