A brief introduction to photodetector and its application

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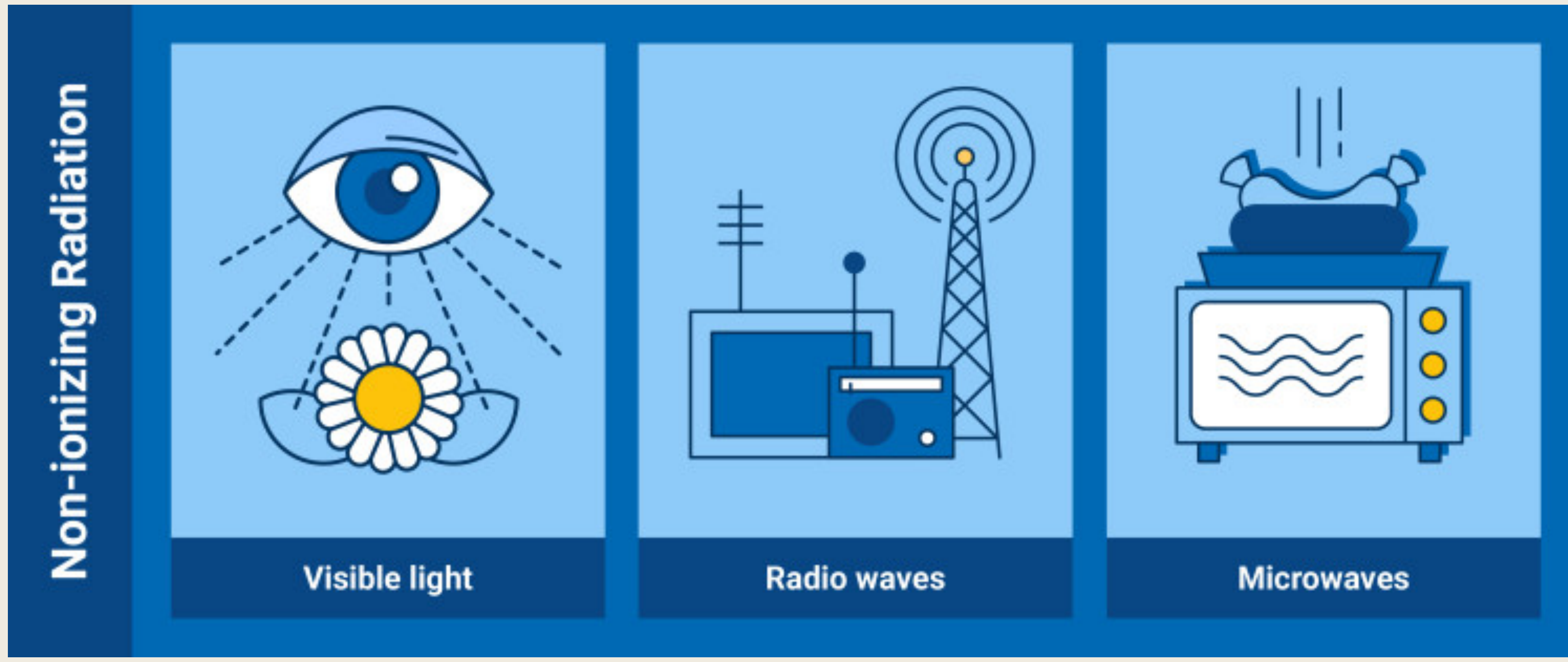
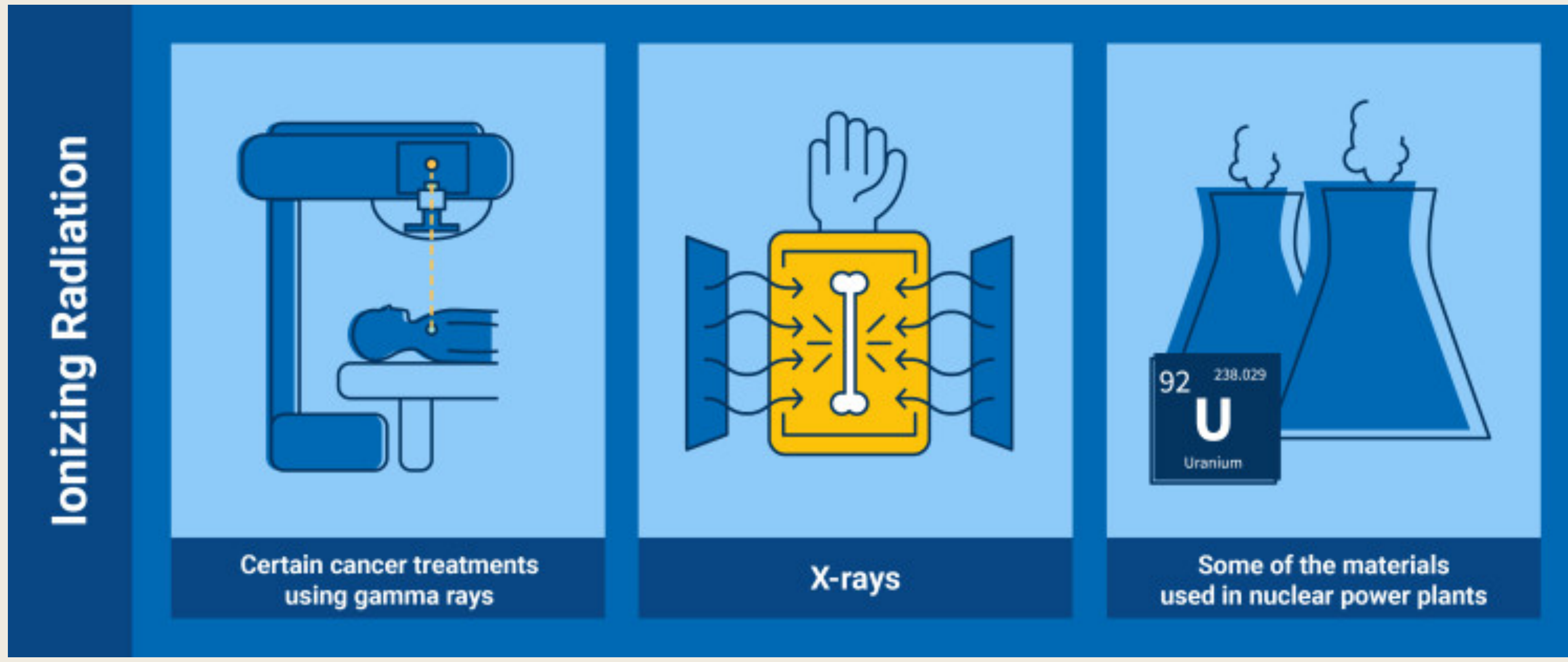
Radiation

- Radiation is energy that moves from one place to another in a form of EM waves or particles
  - **Non-ionizing** radiation (*eg. visible light, radio waves…*)
  - **Ionizing** radiation (*eg. x-rays, cosmic ray…*)
- Essential part of modern life, some beneficial to your health but some harmful ➜ must be monitored/controlled.

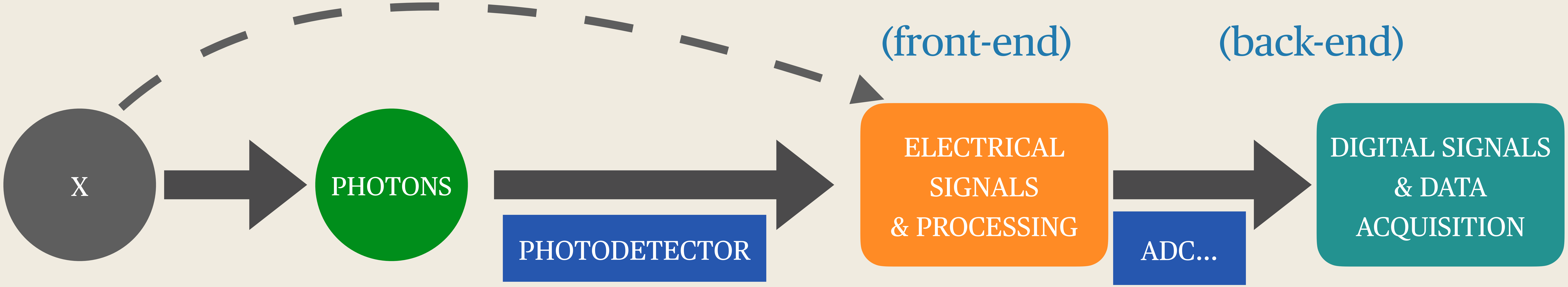




https://www.iaea.org/newscenter/news/what-is-radiation

Photodetector for the radiation detection

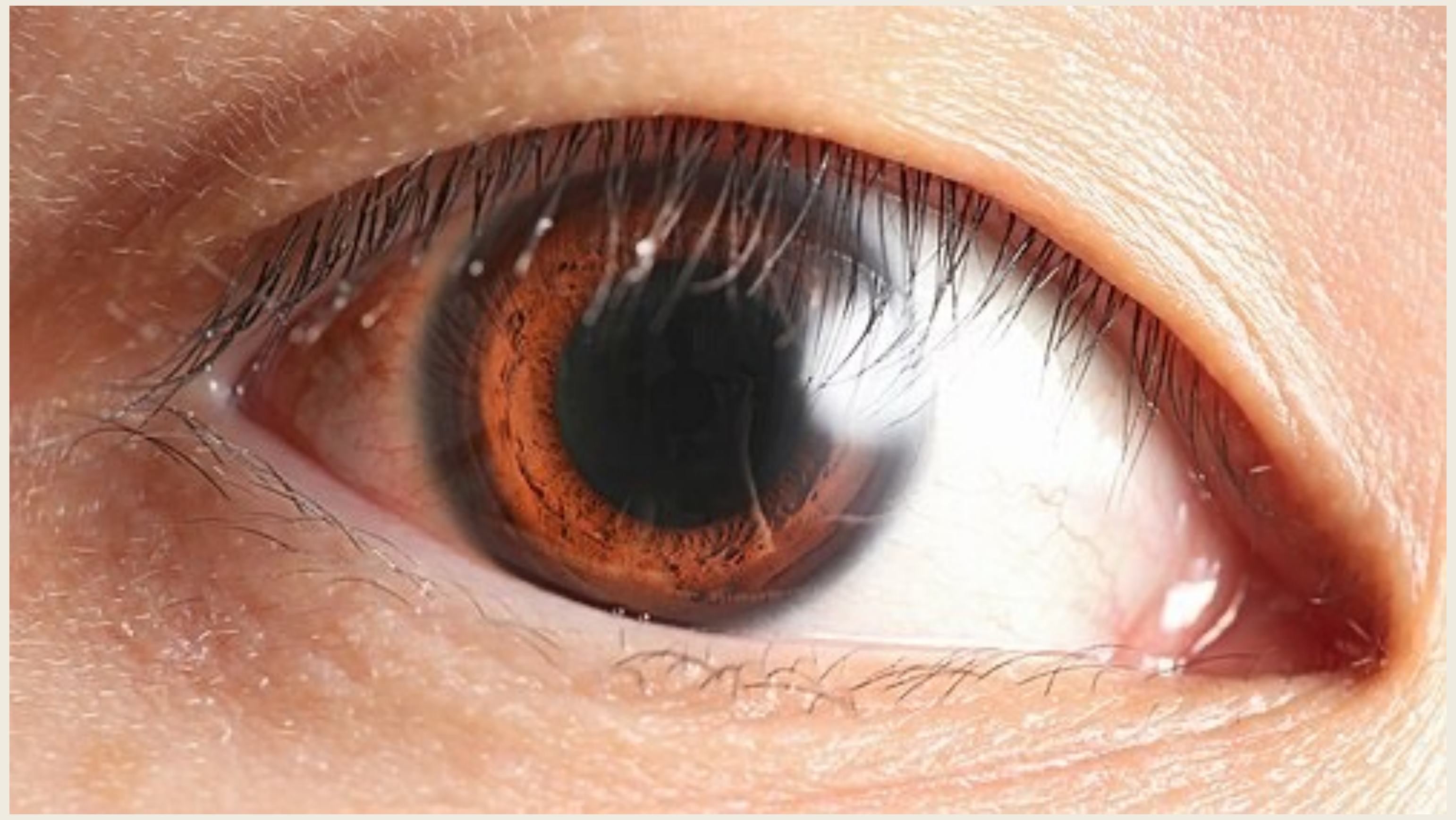
A long history of radiation detector development. Here, just focus on those with photodetector.



- (*Modern detector*) be **electrical** in nature, i.e at *some points the information is converted into electrical impulses and treated with electronic devices*
- Photodetector can *detect* both “non-ionizing” radiation and “ionizing” radiation. For later, it needs additional photon emission mechanism (*eg. scintillation, Cherenkov, optical transition*…)

Example: Human eyes as "biological" photodetector

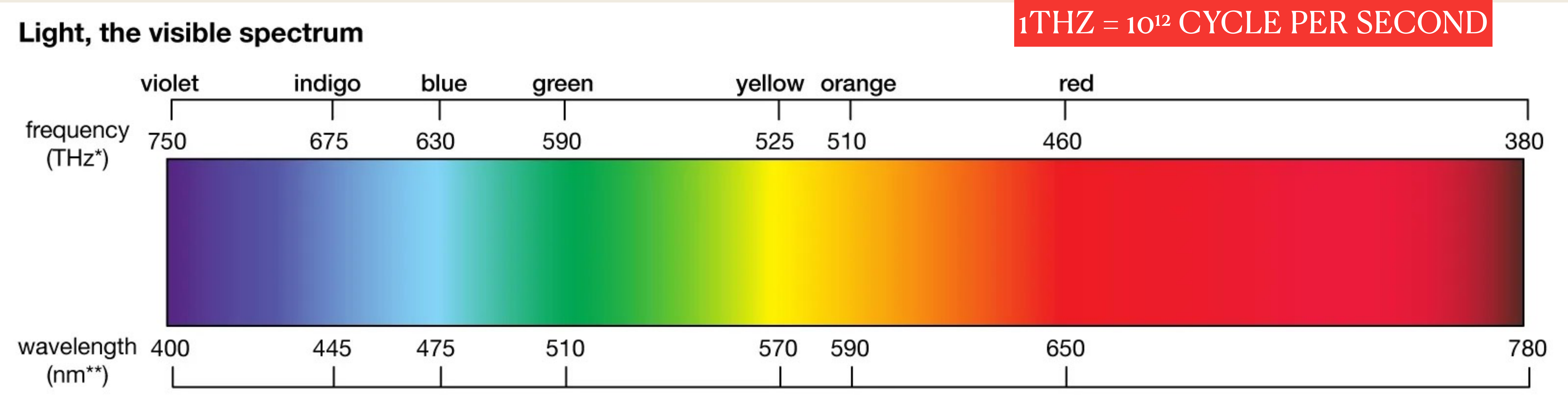
- Detect light in visible spectrum (*380-700nm*), peak around 555nm (*yellowish green*) in daylight
- Large dynamic range (~*1e6 time btw. the highest and lowest intensity can be seen*)
- Relatively slow response time (~ few tens of ms)
- Brains acts as an advanced image processor
- …



Visible spectrum of light

1HZ = 1 CYCLE PER SECOND

1THZ = 10^{12} CYCLE PER SECOND



$$\lambda = c \,.\, T = \frac{c}{f}$$

WAVELENGTH [M]

PERIOD [S]

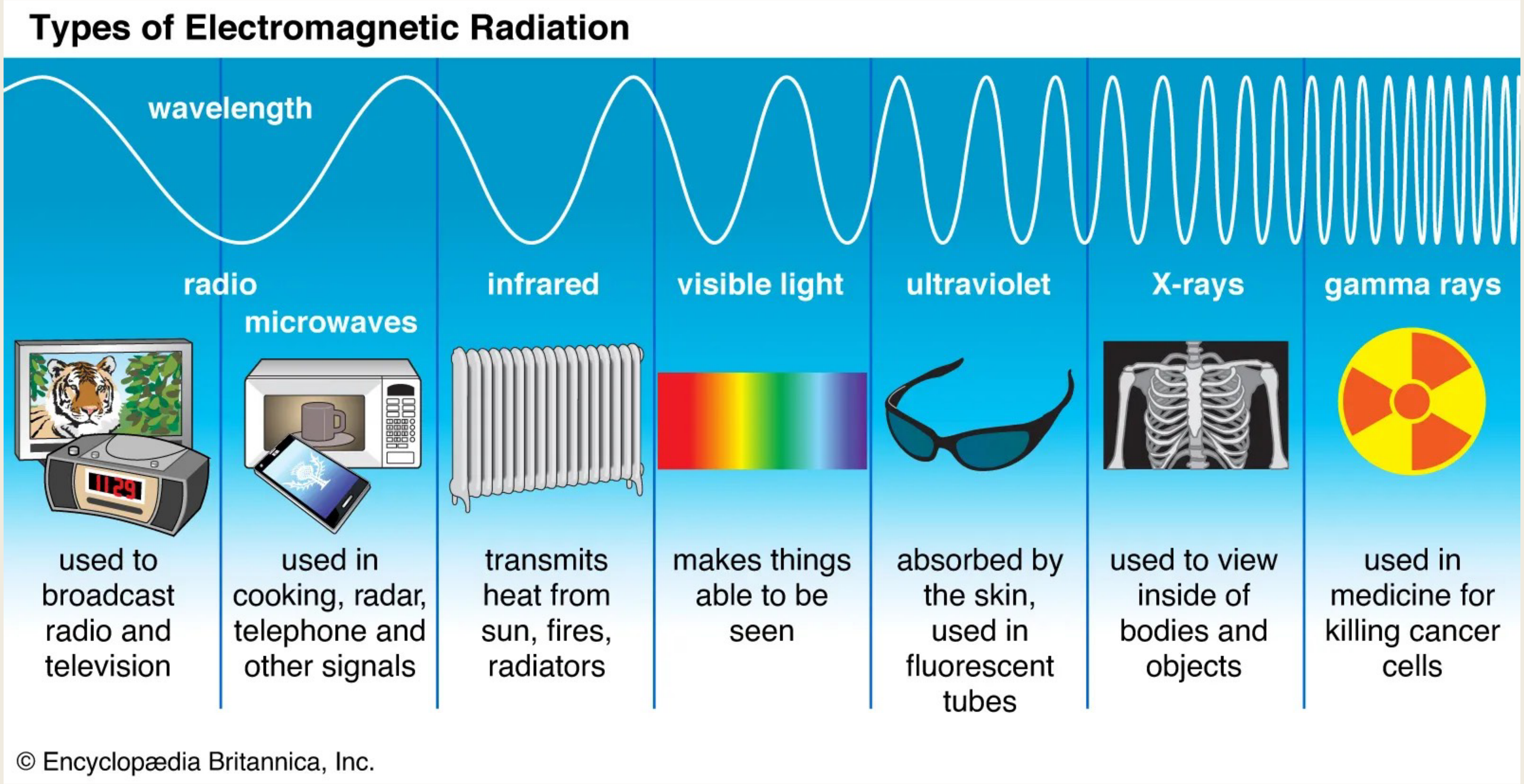
FREQUENCY [HZ]

$$c = 2.9979 \times 10^8 \text{ m/s}$$

SPEED OF LIGHT IN VACUUMS

This formula can also be applied for wave, sound wave, radio wave but with different velocity

Whole spectrum of light



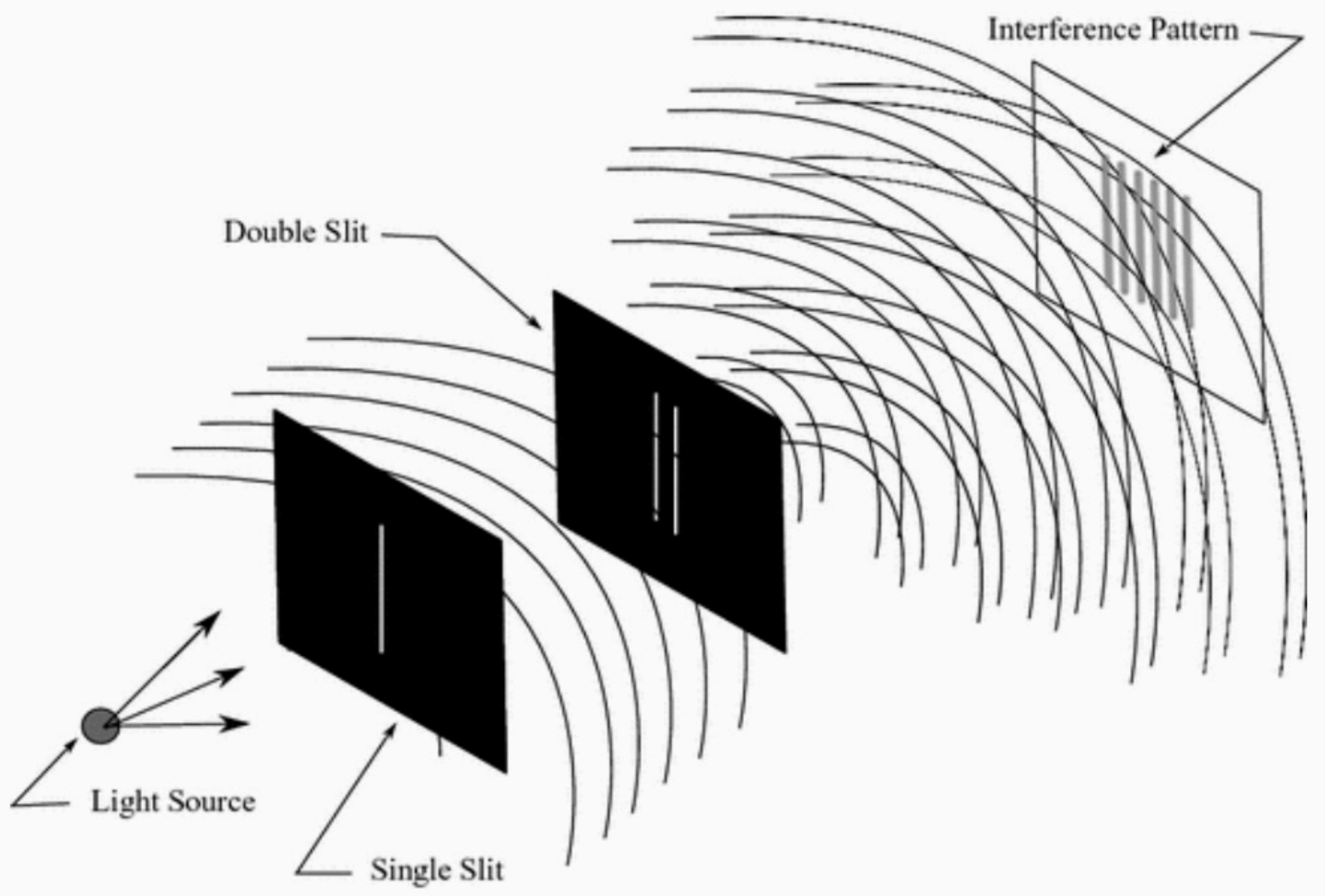
Higher energy (frequency), shorter wavelength

Nature of light: A brief reminder

Ref. Lectures by H. Van (IOP, VAST) and Chau Nguyen (Univ. Siegen)

Young's interference Exp. (~1803): Light is a EM wave

(Young originally used pinholes, conventionally educational experiment use narrow slit)

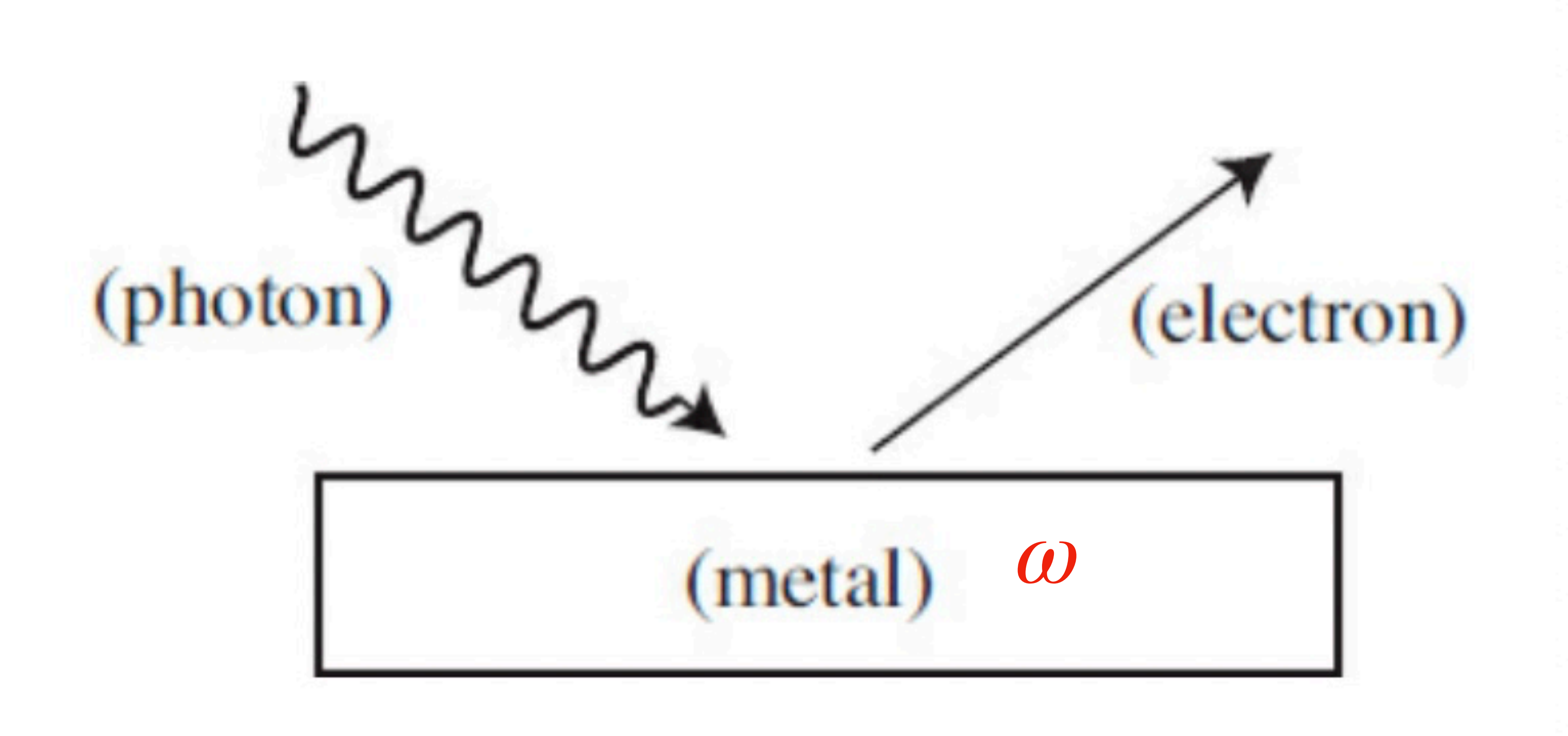


Young's double-slit interference experiment

Interference pattern:
bright and dark fringes

The photoelectric effect: Light is also particle

$$E_{photon} = hf \quad \Rightarrow \quad E_{electron} = hf - \omega$$



Observed by Hertz in 1887

Explained/Theoretical model

by Einstein in 1995

Electron is hod on the skin of the metal.
Some energy (or so-called work ω) needed to knock off electron

Three effects:

- Electron energy doesn't depend on light intensity (*no. of incoming photons*)
- Electron energy does depend on the wavelength of light
- No. of outgoing electron is proportional to the light intensity

Energy of photon: useful conversion

$$E_{photon} = hf \text{ where } h = 6.626 \times 10^{-34} Js$$

Energy of relativistic particle is expressed in eV, keV…

$$E_{photon} = hf = \frac{hc}{\lambda} = \frac{6.626 \times 10^{-34}[Js] \times 2.998 \times 10^{8}[m/s]}{10^{6}\lambda[\mu m]} = \frac{19.865 \times 10^{-20}[J]}{\lambda[\mu m]}$$

$$E_{photon} = \frac{19.865 \times 10^{-20}[eV]}{1.602 \times 10^{-19}\lambda[\mu m]} \approx \frac{1.24[eV]}{\lambda[\mu m]}$$

$$\lambda_{\text{blue}} = [0.45 - 0.50][\mu m]$$

↓

$$E_{\text{blue}} = [2.48 - 2.76][eV]$$

Photons in a blinking of LED

$$E_{photon} = hf \text{ where } h = 6.26 \times 10^{-34} Js$$

A 405nm LED has optical power of 6mW, how many photons emitted in a second ? (*Assume the light conversion efficiency is 100%*)

One hardly observes the particle nature of light since there are **a lot photons reach us even in a blinking of LED**

$$f = \frac{c}{\lambda} = \frac{3 \times 10^8 [m/s]}{405 \times 10^{-9} [m]} = 7.4 \times 10^{14} [s^{-1}] = 7.4 \times 10^{14} [Hz]$$

Number of photons emitted per second

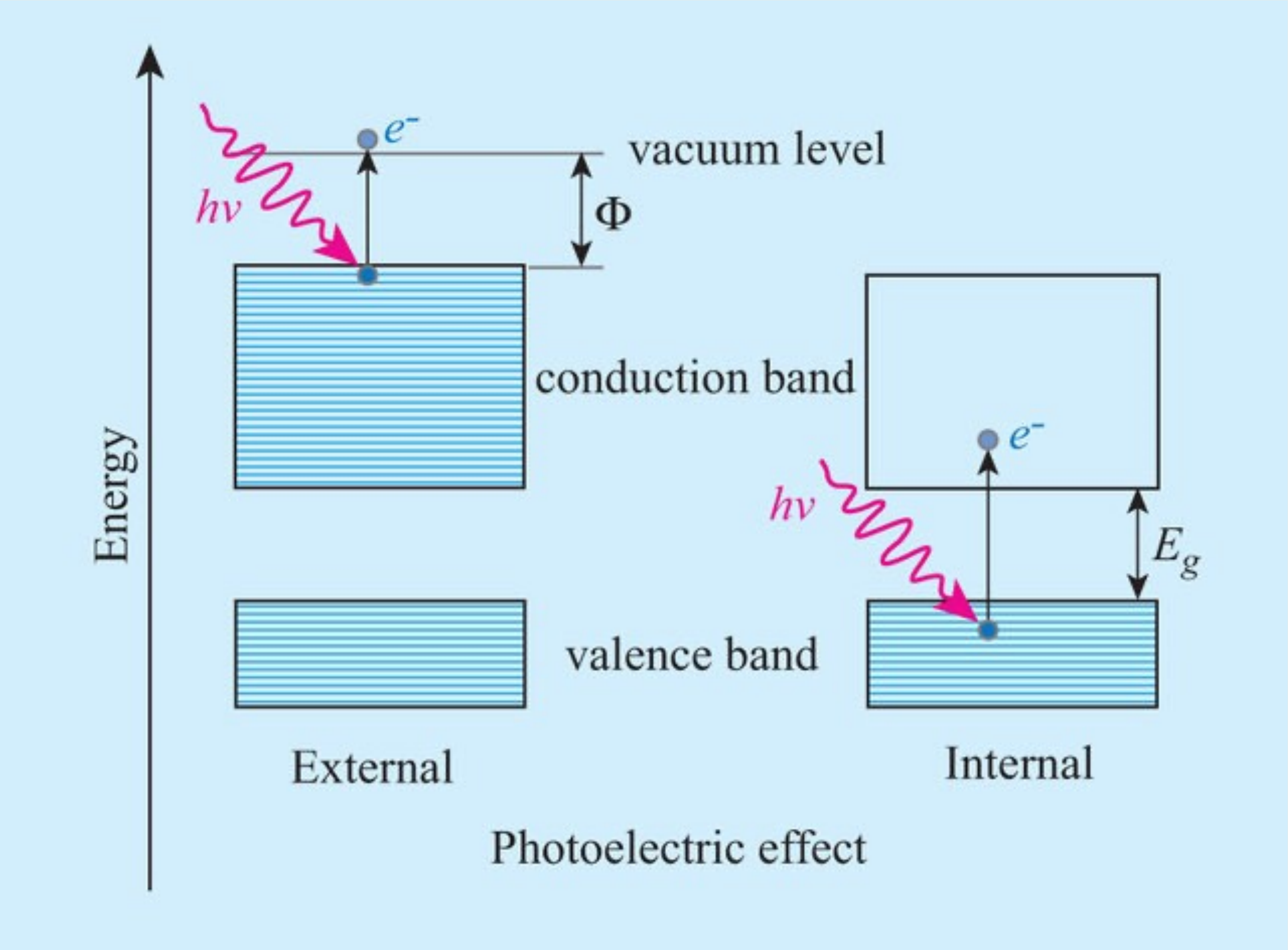
$$n_{photon} = \frac{6 \times 10^{-3} [W] \times 1 [s]}{6.626 \times 10^{-34} [Js] \times 7.4 \times 10^{14} [s^{-1}]} = 1.2 \times 10^{15}$$

https://www.thorlabs.co.jp/newgrouppage9.cfm?objectgroup_id=2814

Basic characteristics of photodetector

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

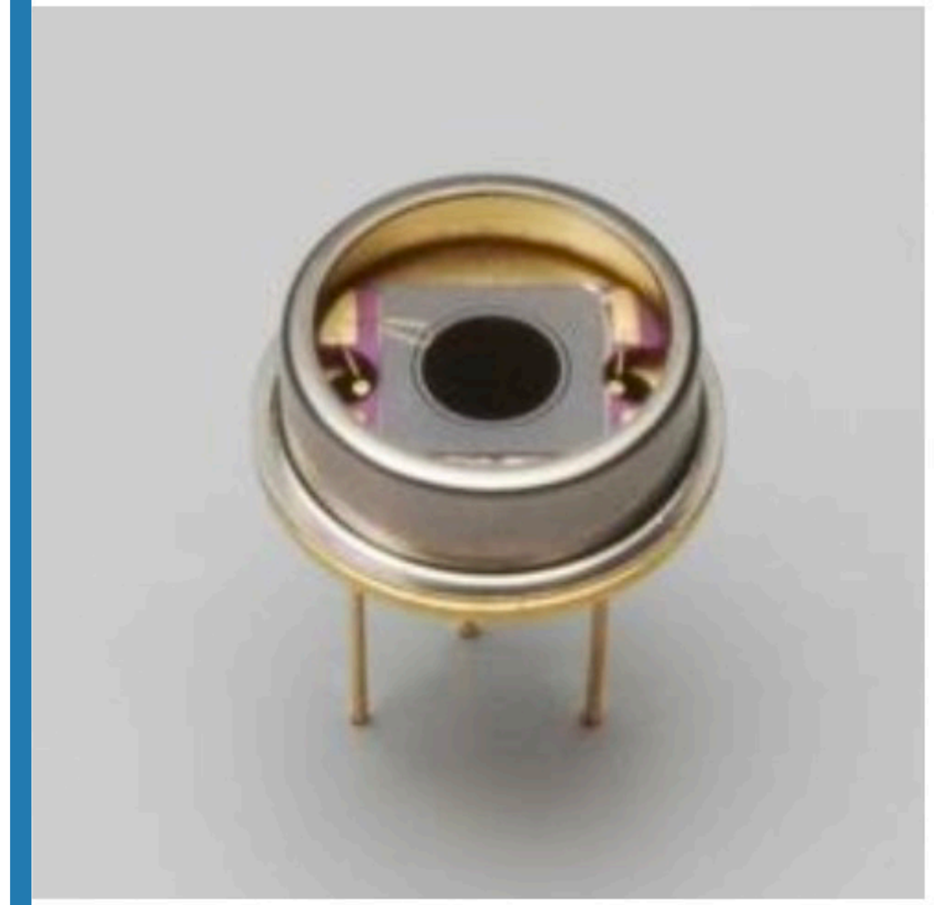
- Based on the **photoelectric effect**: **External** or **Internal**
- Need "*photosensitive*" materials (K, Na, Rb), which have high tendency to release electrons (or small *electronegativity*)
- Typically need to turn this *microscopic* "electron-emission" signal into the **macroscopic** level, eg.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

Different types of photodetectors

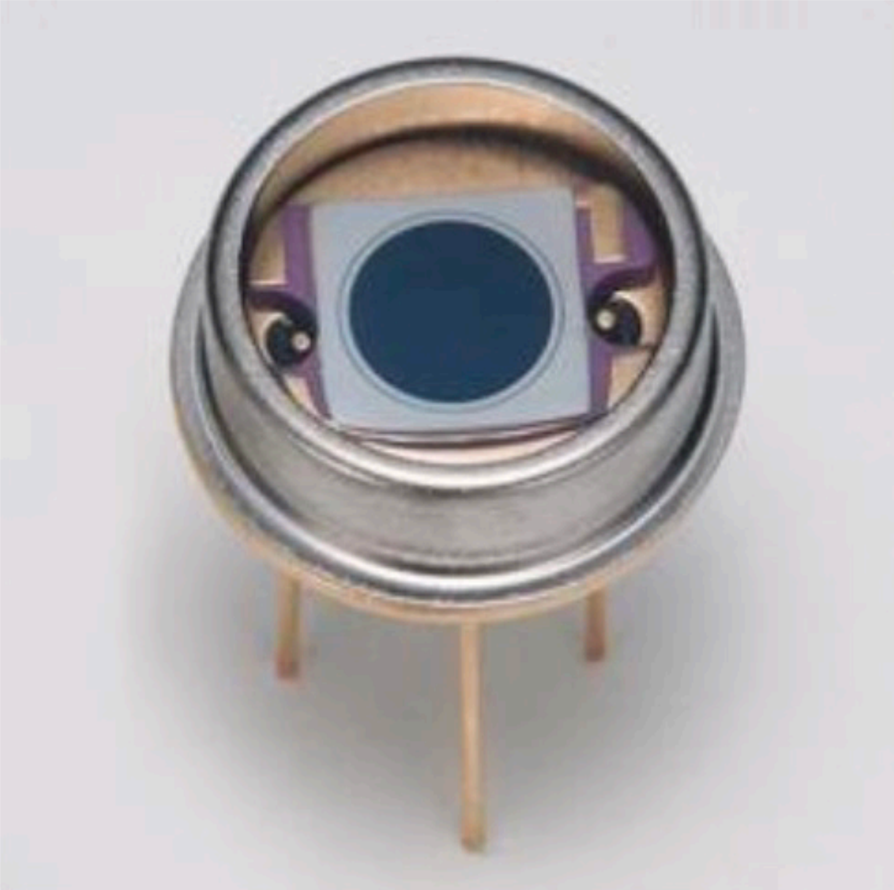
"EXTERNAL PHOTOELECTRIC"

"INTERNAL PHOTOELECTRIC"

PMT



PD



APD

SiPM

(Also called MPPC)

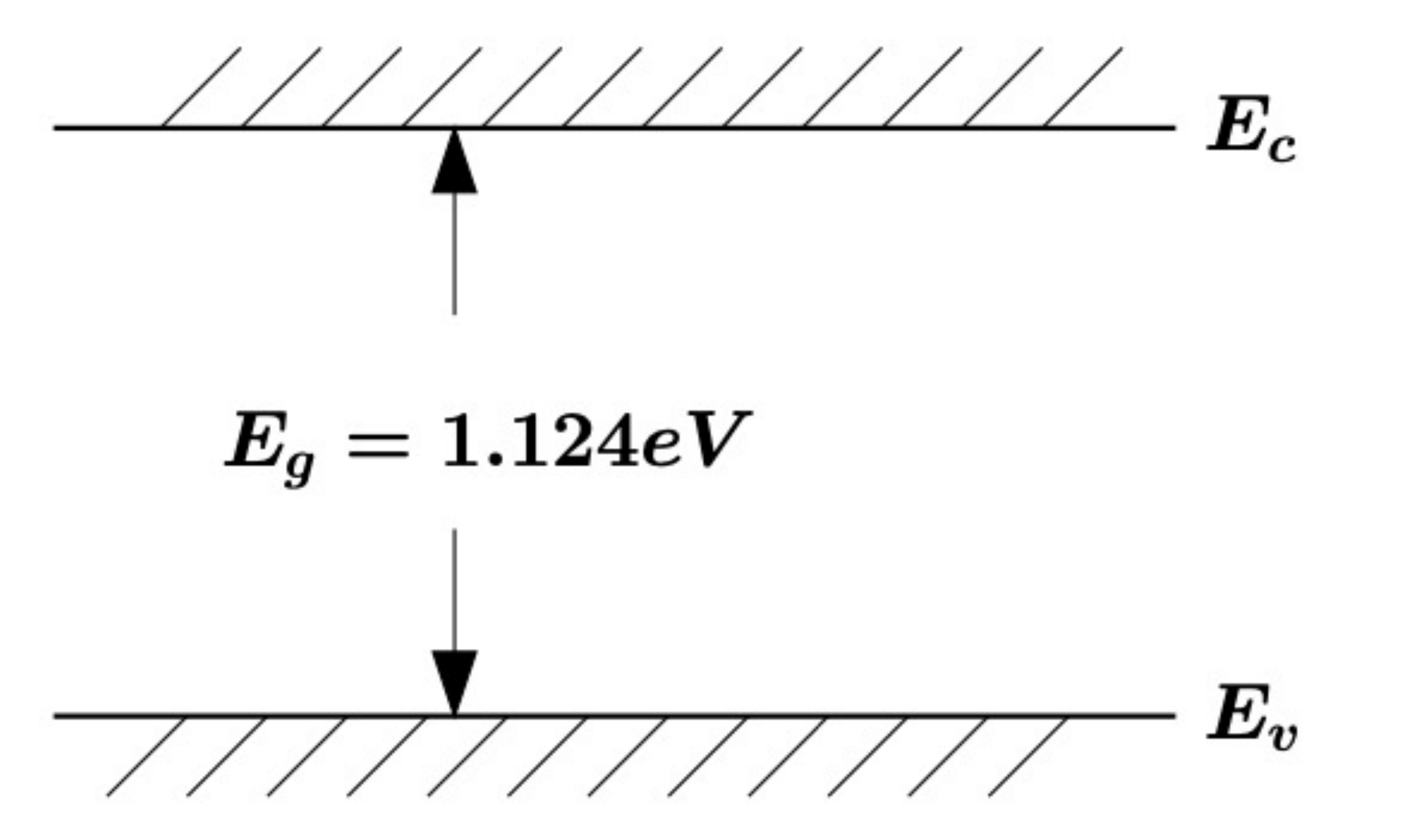
PMT – photomultiplier tube

PD – photodiode

APD – avalanche photodiode

SiPM – silicon photomultiplier

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

Basic characteristics of photodetector

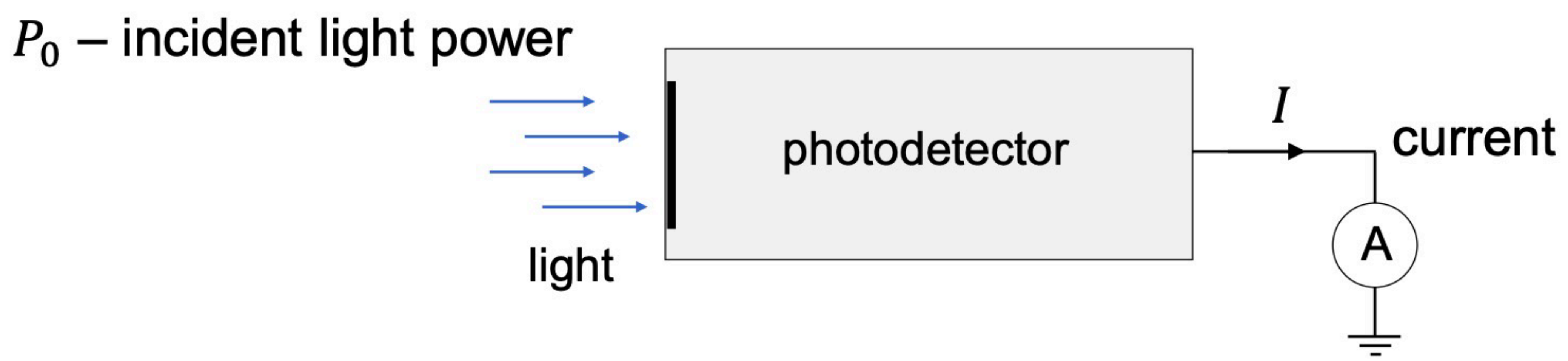
- **Spectral response:** *Range of wavelength can be detected *efficiently**
- ***Active* area:** *Part of detector is designed for producing photoelectron when light strikes on. PMT is typically larger than others*
- **Quantum efficiency (QE) and Photon detection efficiency (PDE)**:
  - QE: *probability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

σ – Spectral sensitivity; η – Quantum efficiency



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

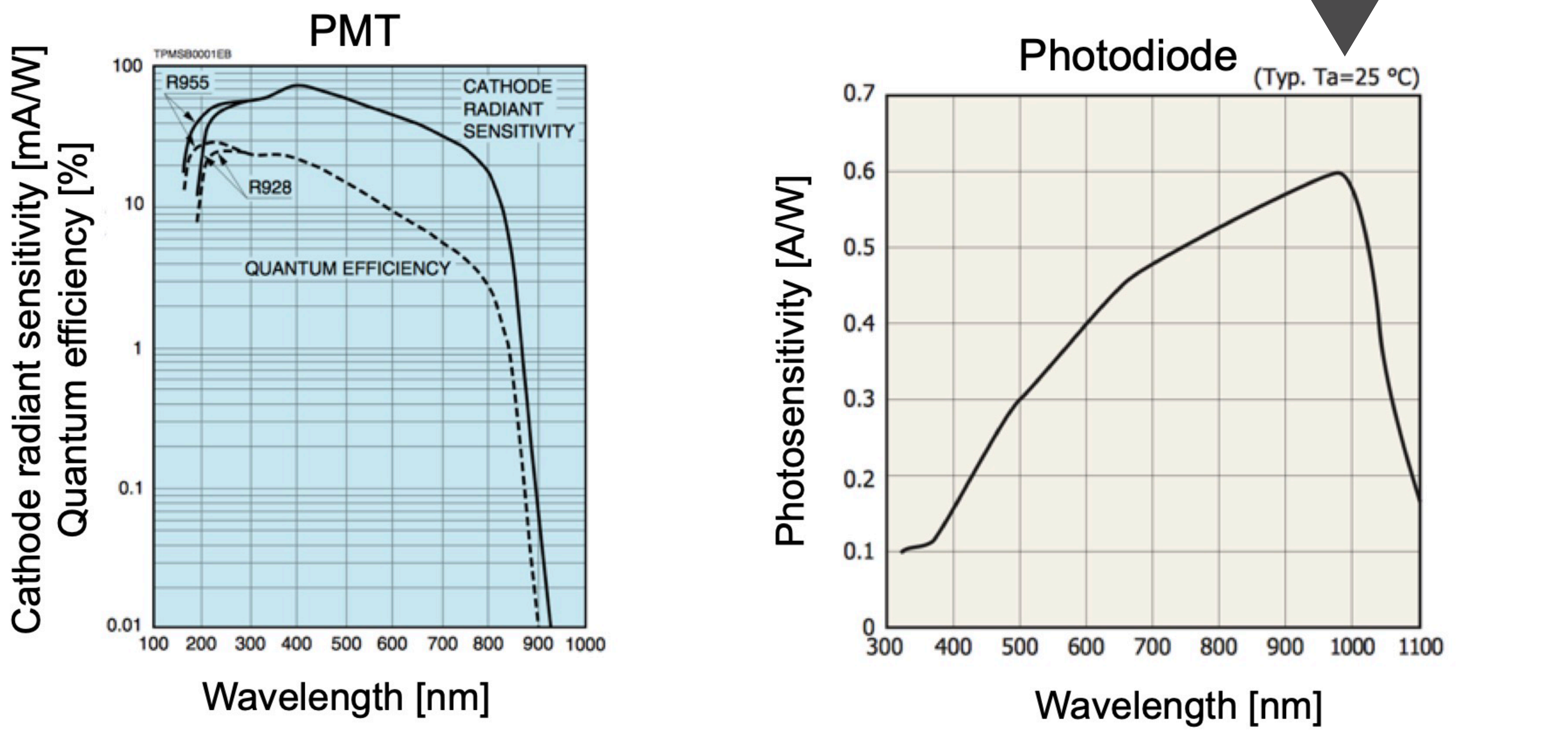
$$\eta = \frac{hc\sigma}{\lambda e} = \frac{1240\sigma}{\lambda[nm]} \quad \text{(monochromatic)}$$

(Suitable for Cherenkov/ Scintillation… light detection)

PEAK ~ 400NM

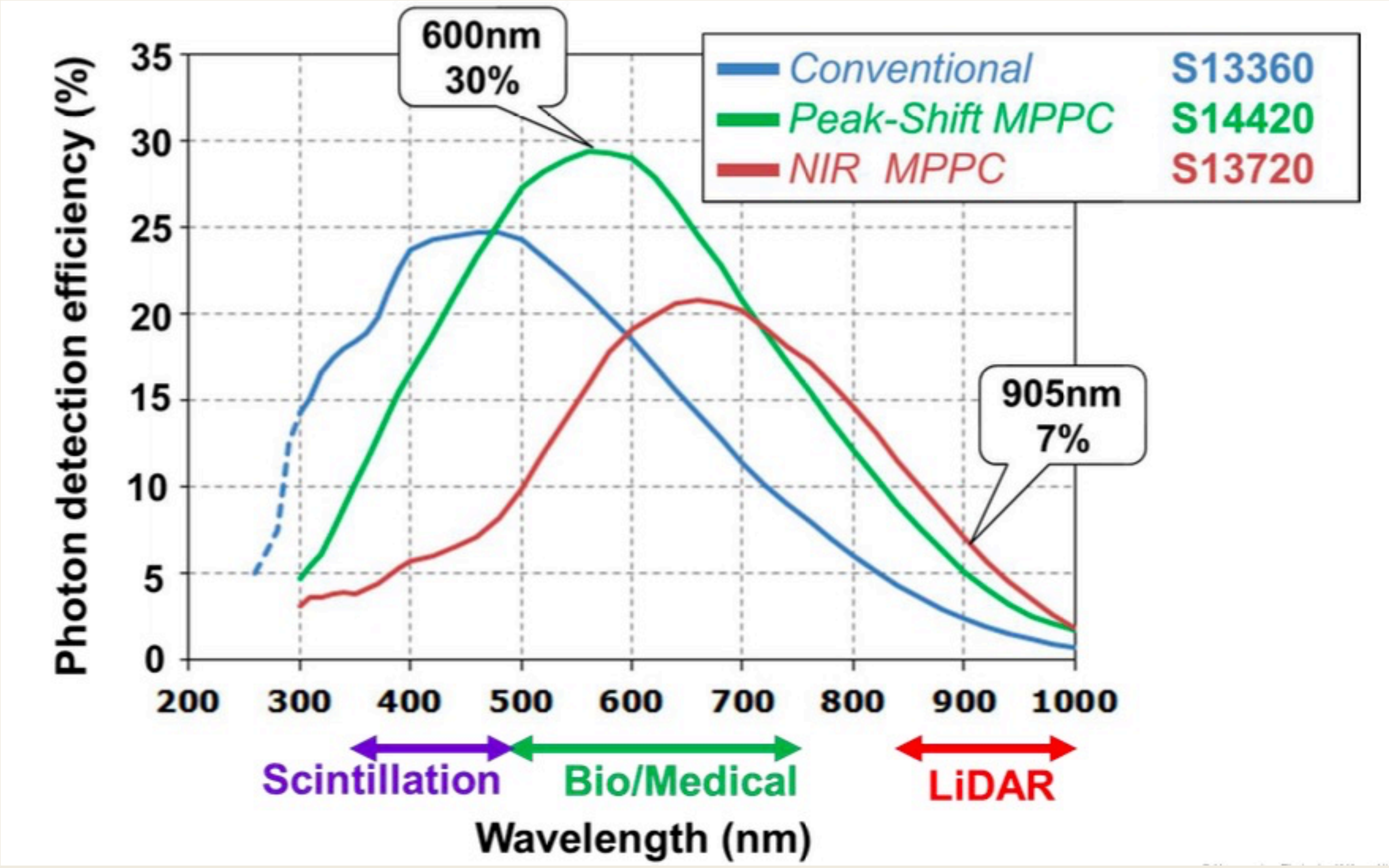
(Suitable for LiDAR)

PEAK ~ 1000NM



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

Quantum efficiency and spectral sensitivity



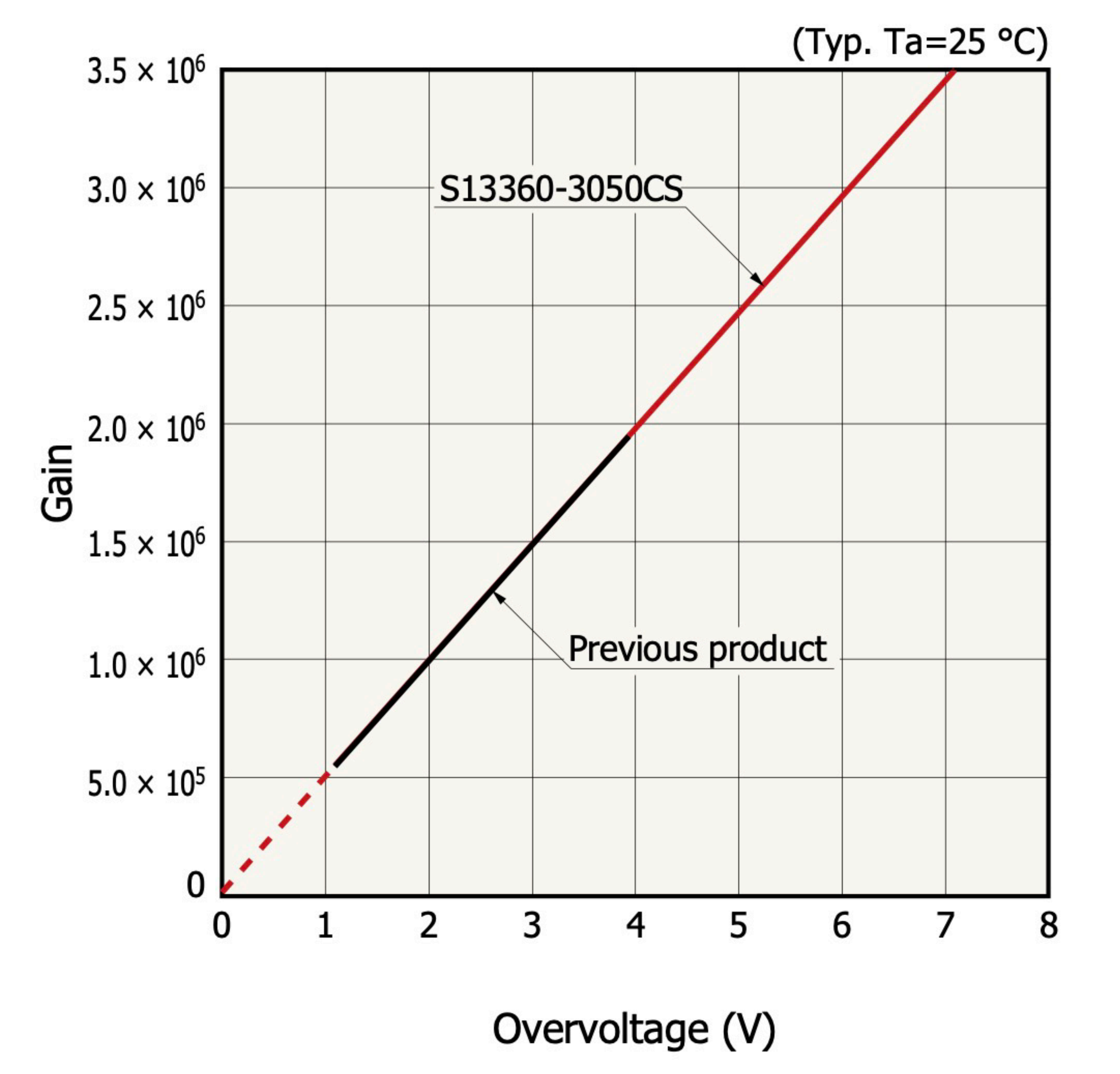
Each application utilizes different wavelength range. Choice of photodetector depends largely on high QE/PDE of photosensor at that range.

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

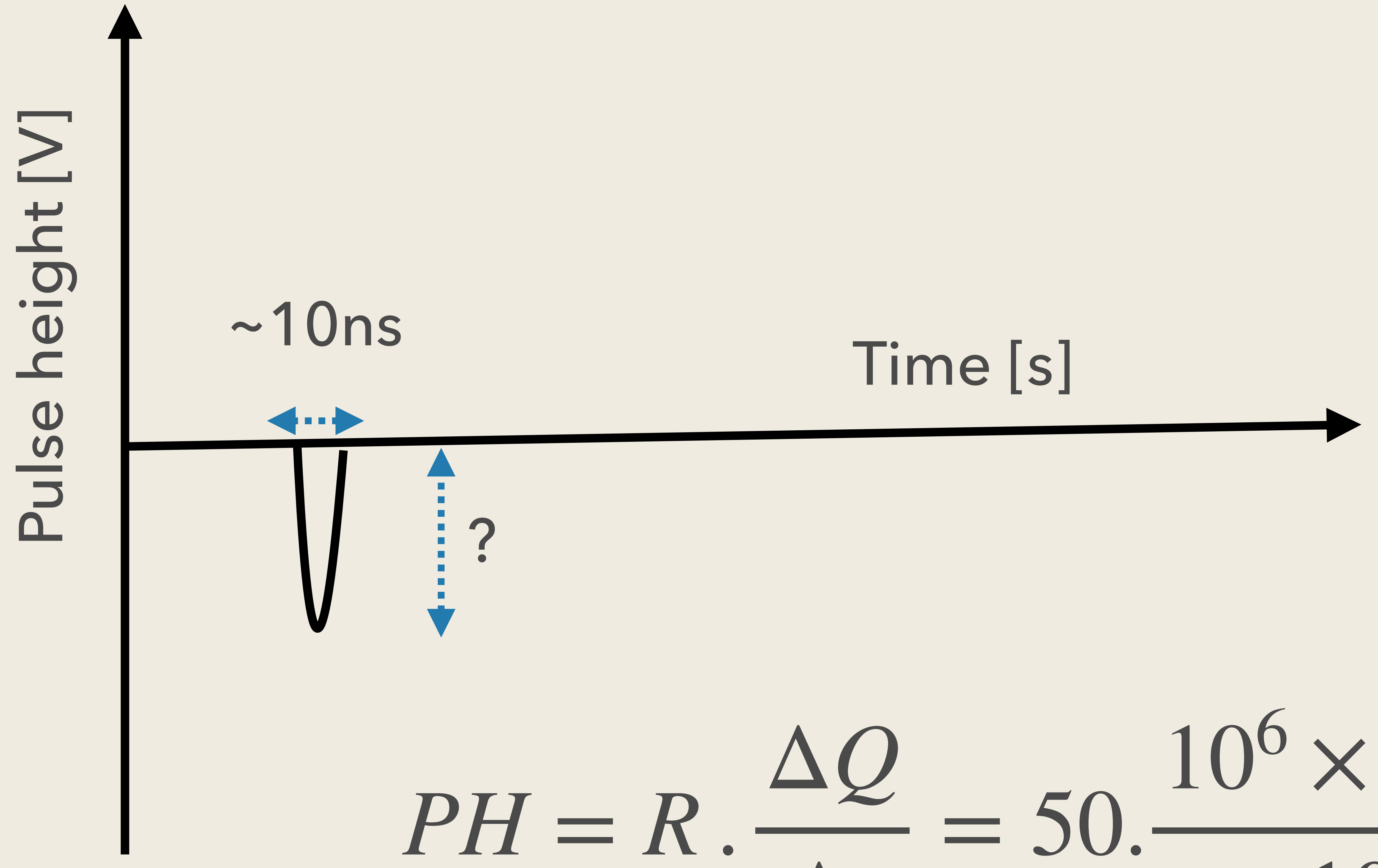
- Calibrate and monitor relevant factors for inferring the intrinsic gain is essential for $\Delta E \propto N_\gamma \propto N_{p.e.} = \frac{\int Idt}{G_i}$



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.



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

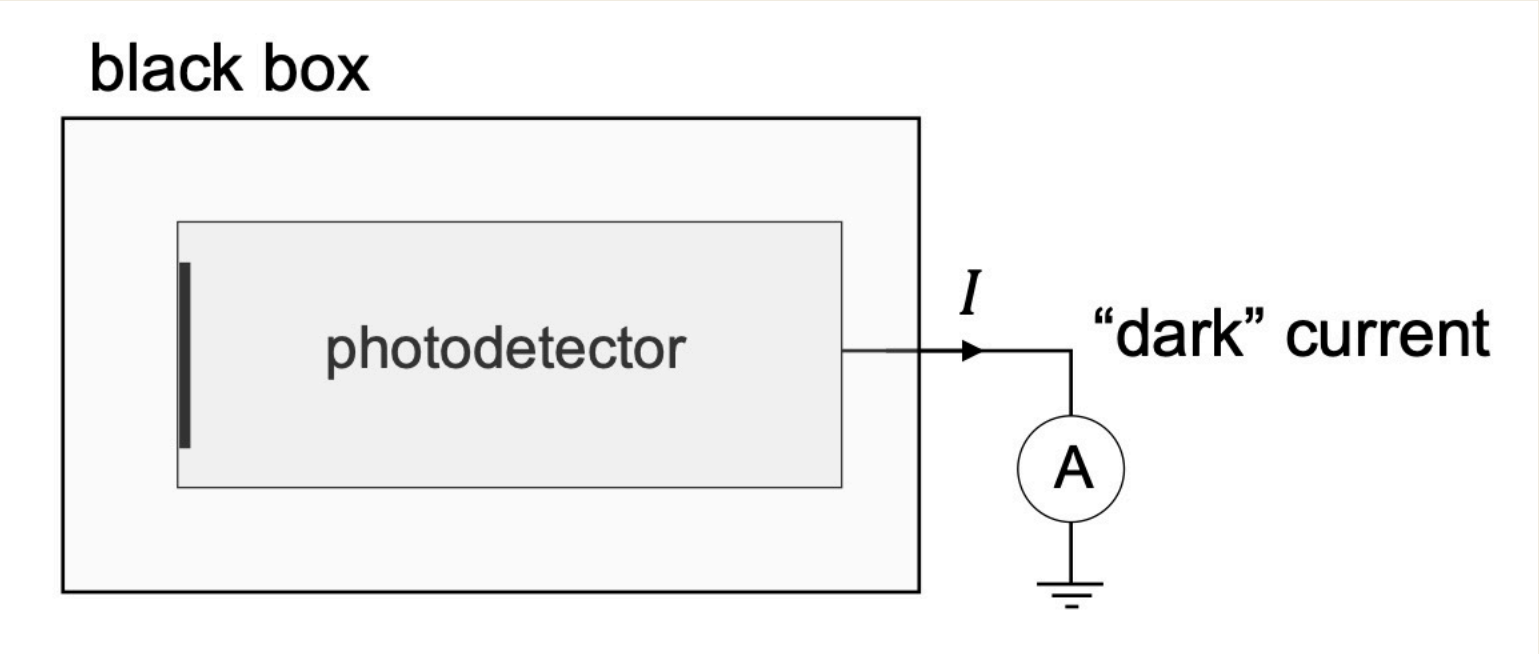
$$V = R \times I$$

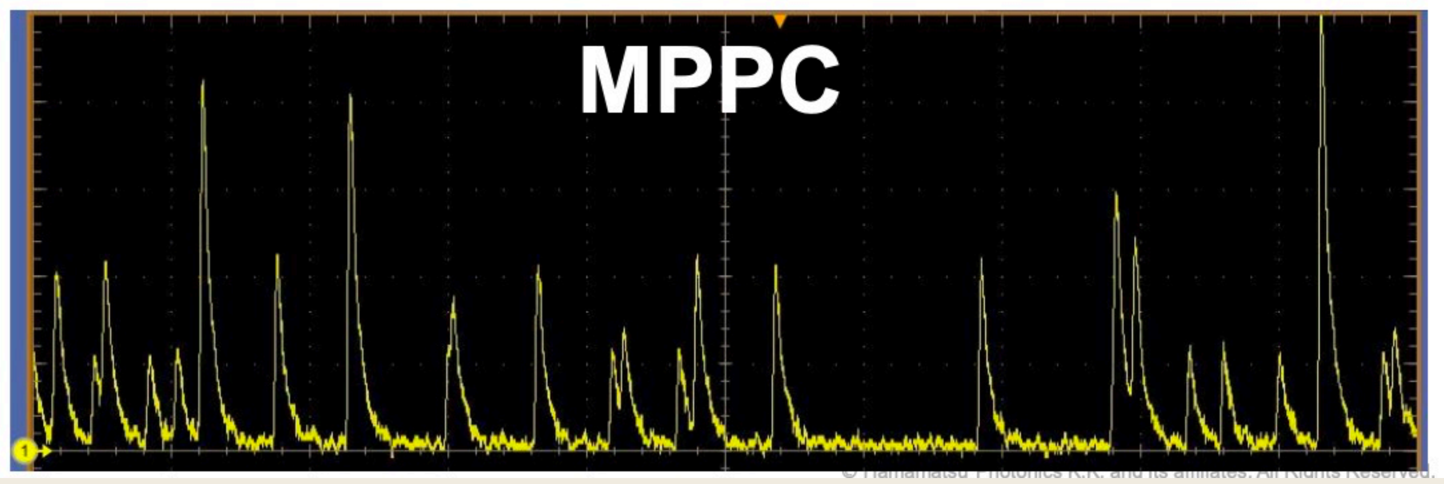
$$PH = R\,.\frac{\Delta Q}{\Delta t} = 50.\frac{10^6 \times 1.6 \times 10^{-19}}{10 \times 10^{-9}} = 8 \times 10^{-4}[V]$$

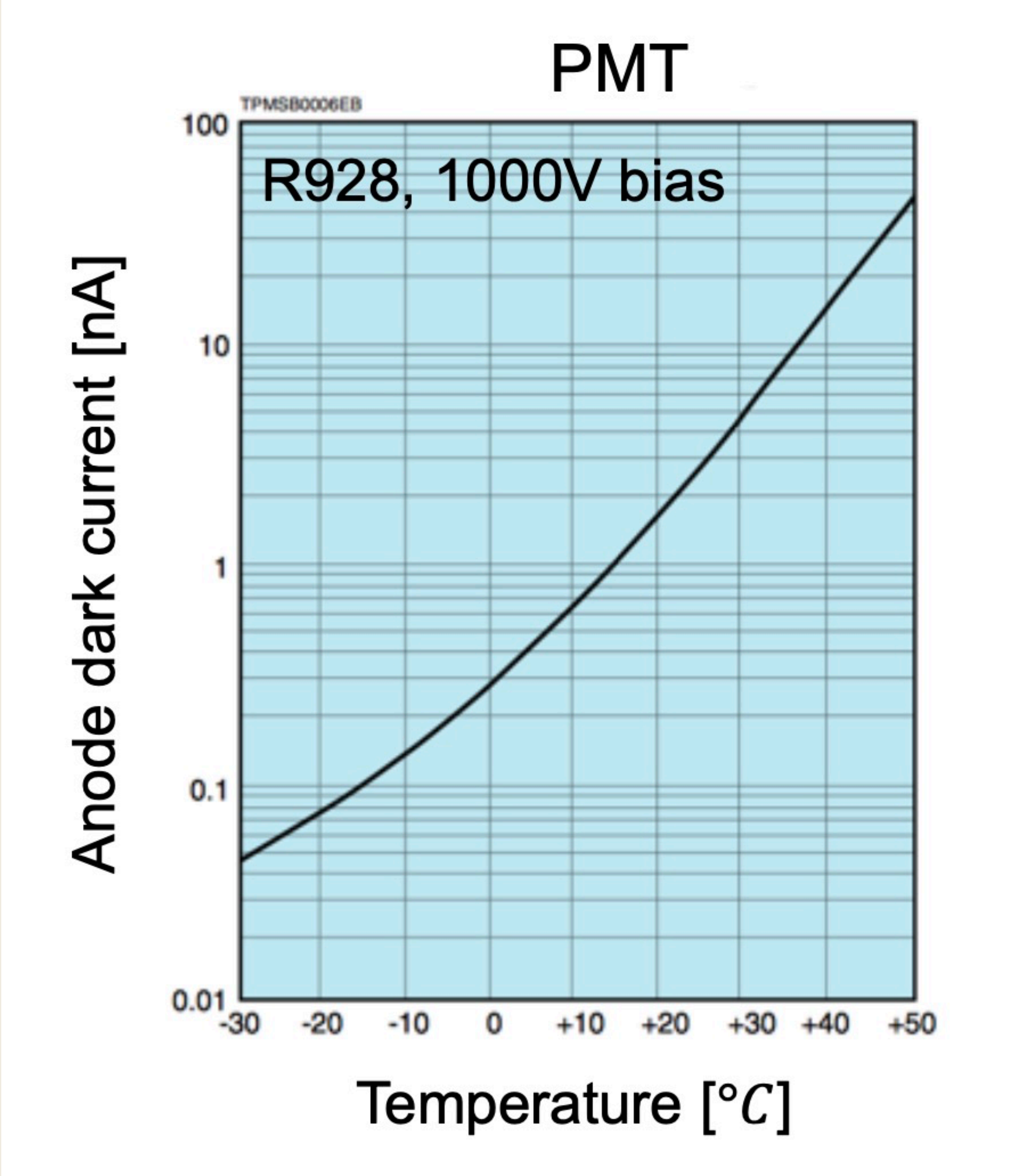
Signal size for a single photon (without amplifier) is less than 1mV

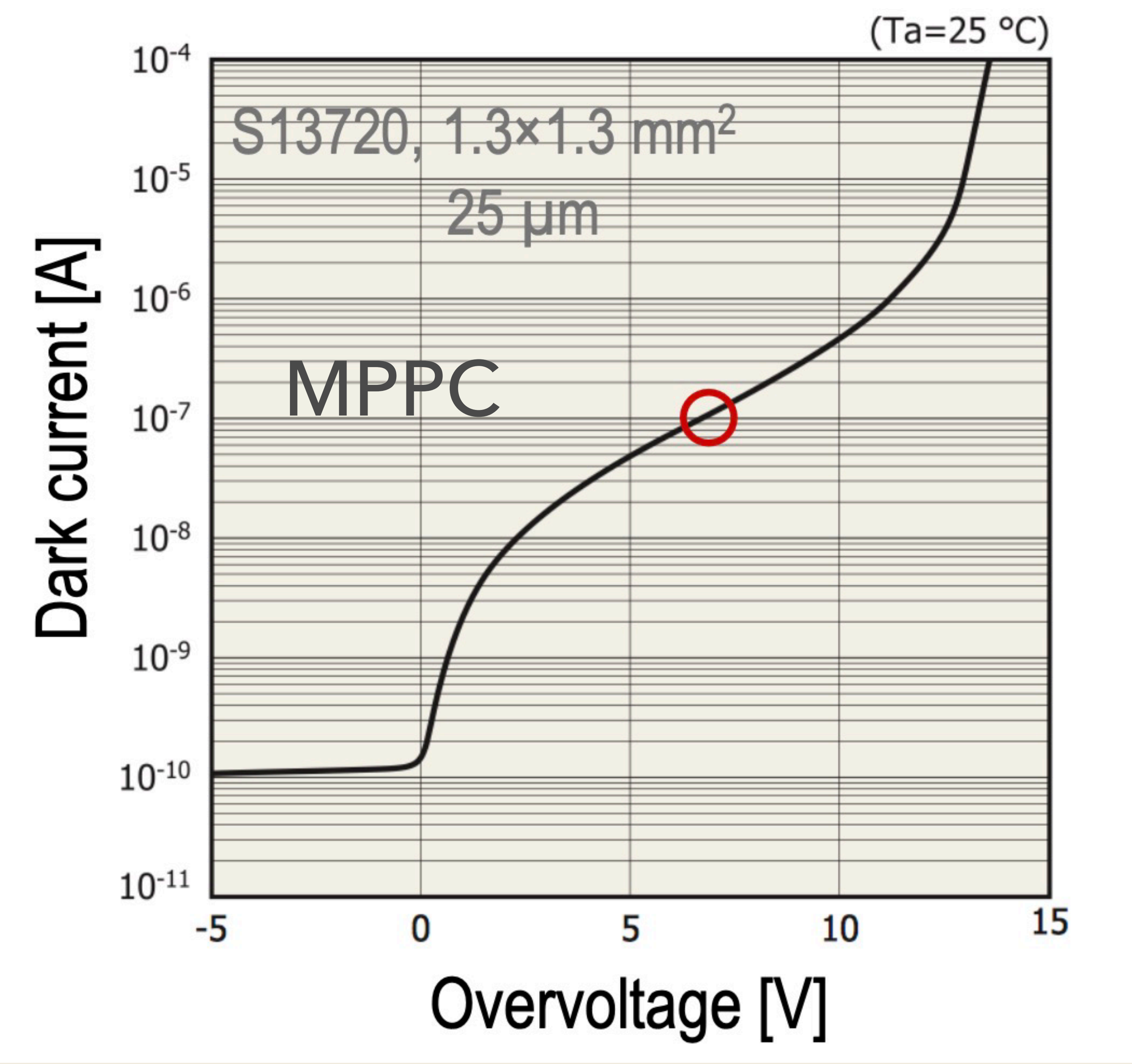
Dark current of photodetectors

- 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.





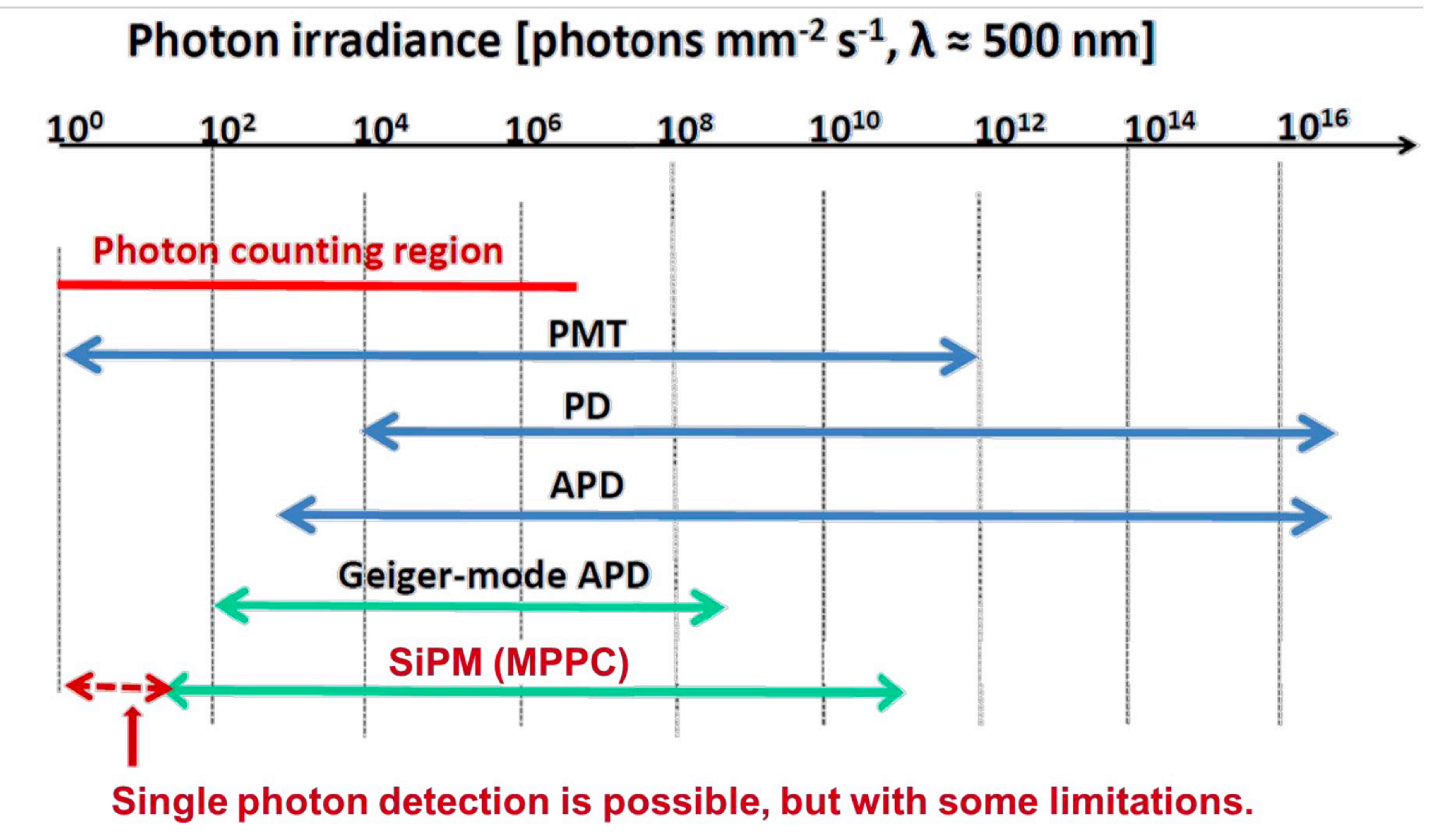


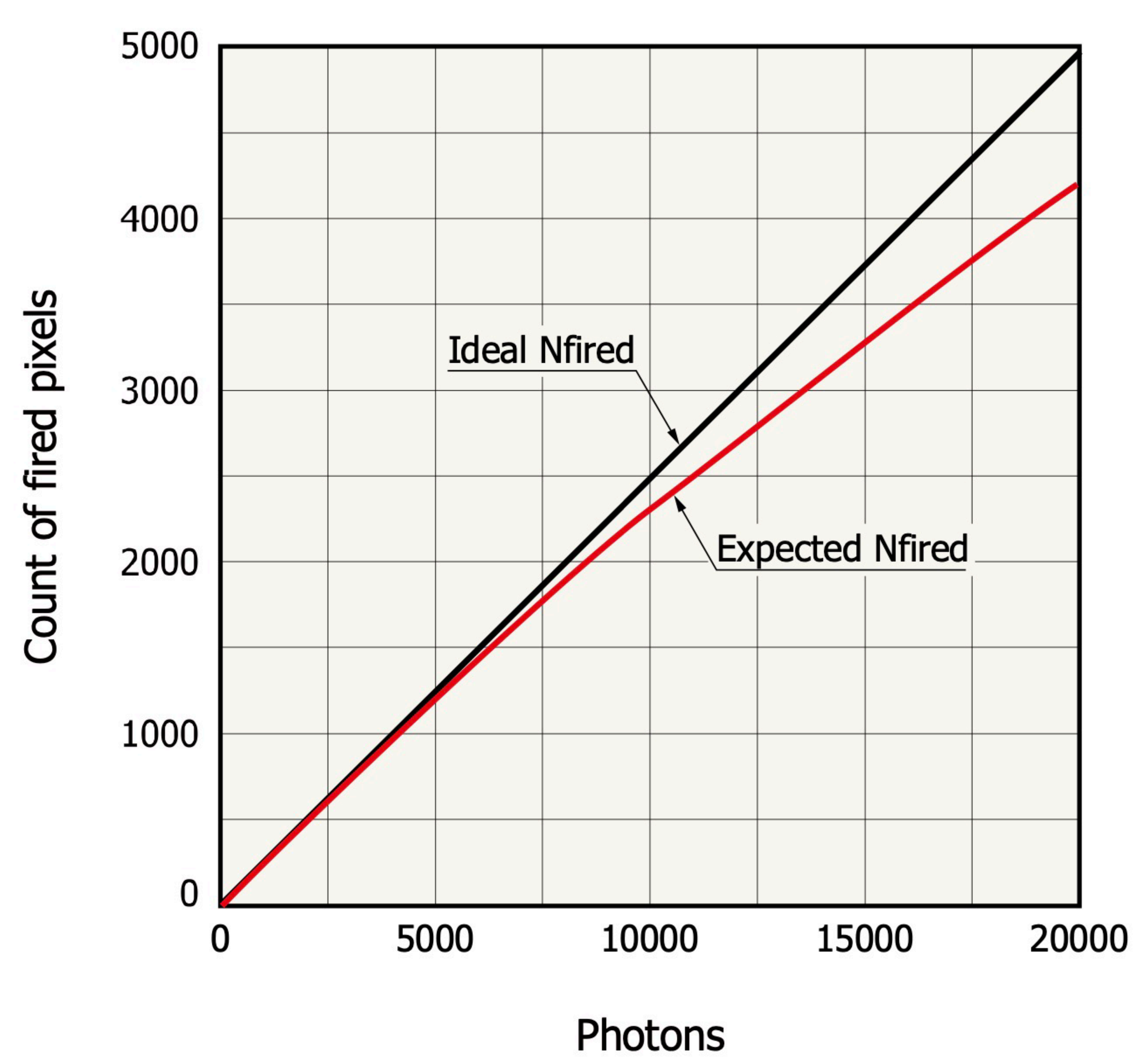


- Dark cout rate $R_{dark} = \frac{I_{dark}}{e \cdot g_i}$
- At 7V over-voltage operation, $I_{dark} = 10^{-7}A$, with $g_i = 10^6$, so $R_{dark} \approx 667kHz$
- Ref. Cosmic-ray muon rate at sea level is ~ $1/cm^2/min$.

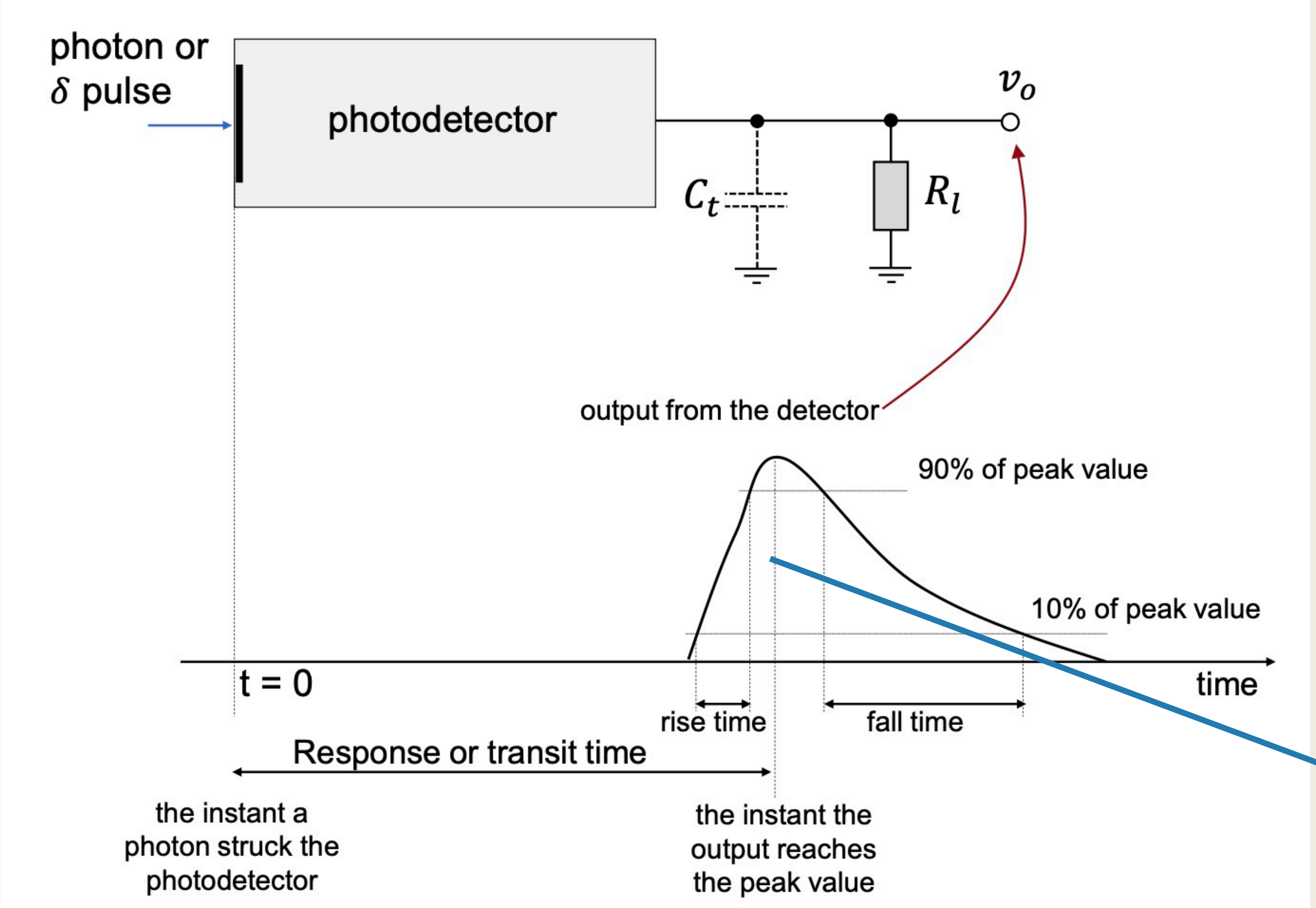
Linear response and Dynamic range

- 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

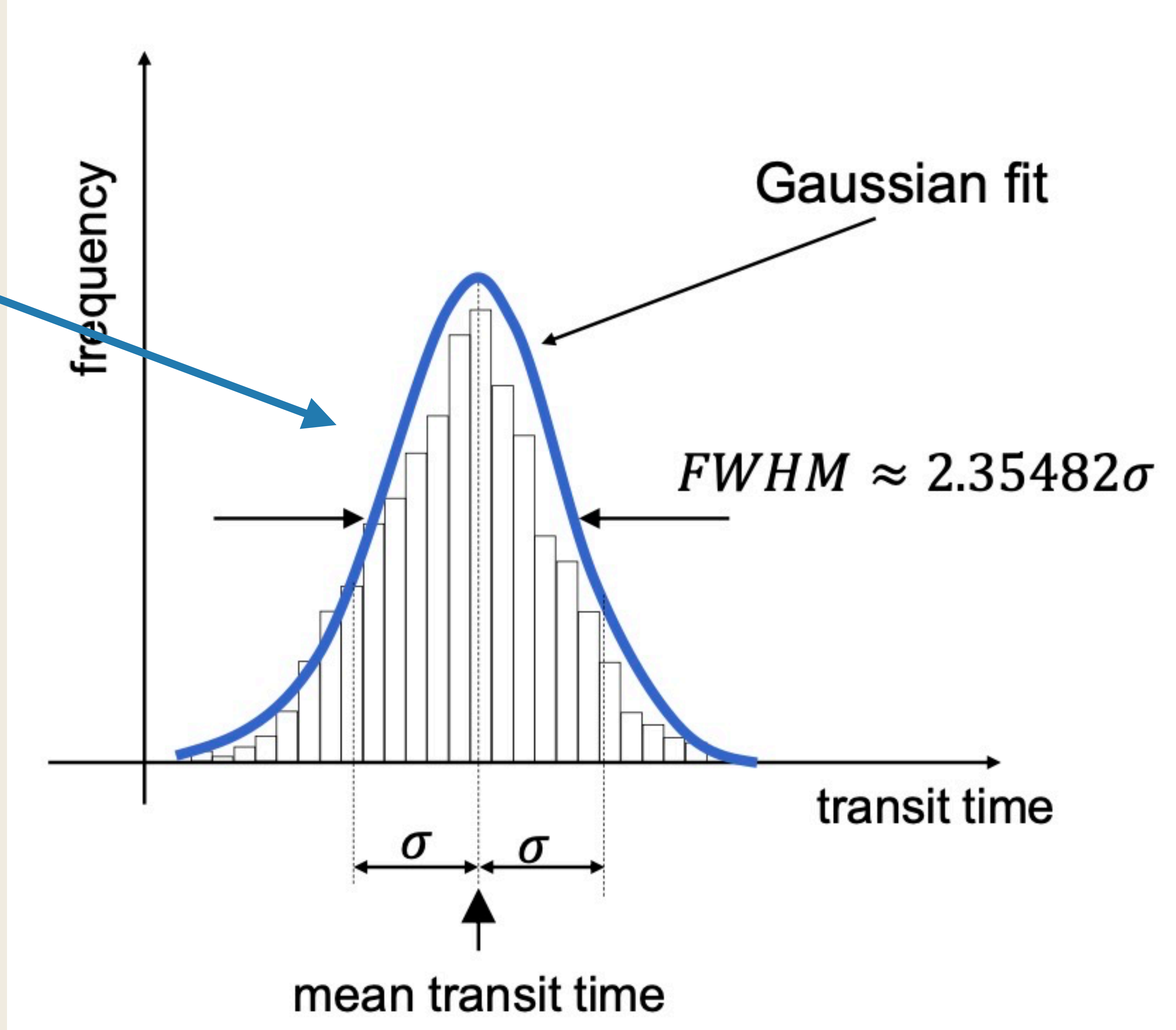




Time response of photodetector



- 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



https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/s13360_series_kapd1052e.pdf

A comparison of photodetectors' performance

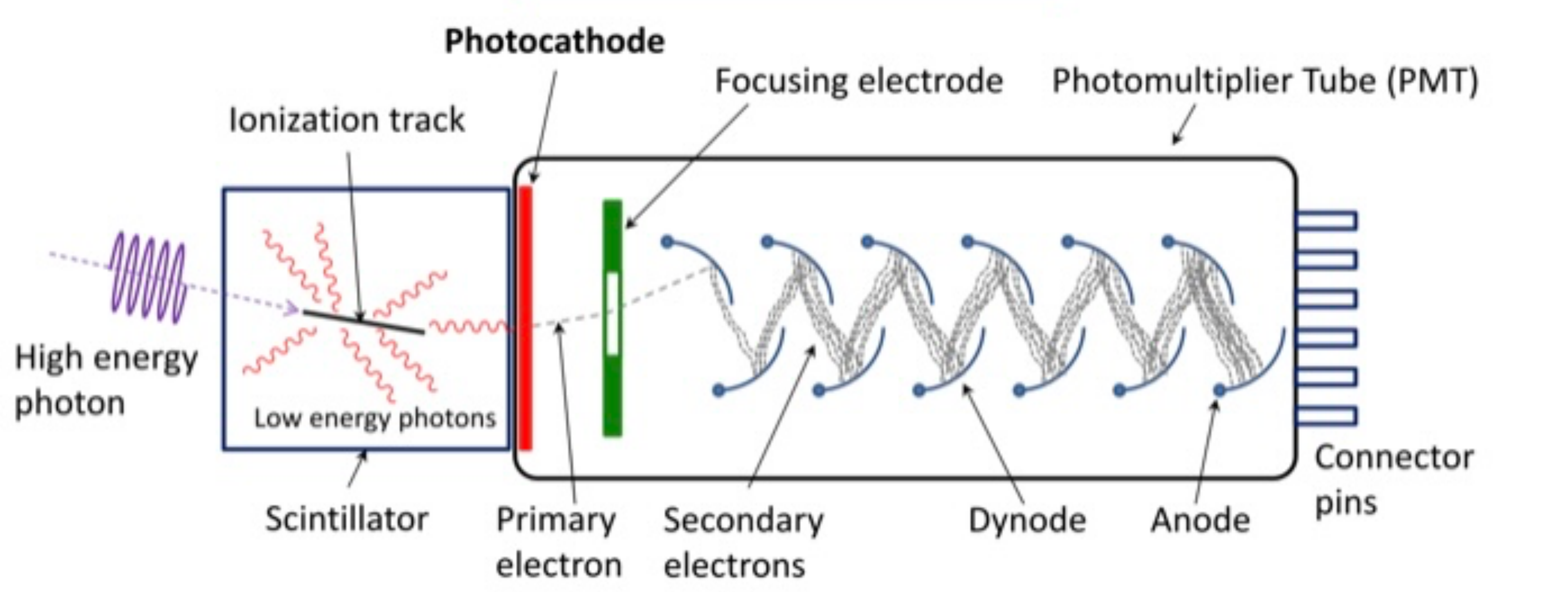
https://www.hamamatsu.com/us/en/product/optical-sensors/mppc/what_is_mppc.html

	PD	APD	MPPC	PMT
Gain	1	10^2	to 10^6	to 10^7
Quantum efficiency	Highest	High	Medium	Low
Operation voltage	5 V	100 to 500 V	30 to 60 V	800 to 1000 V
Large area	No	No	Medium	yes
Multi channel with narrow gap	Yes	Yes	Yes	No
Readout circuit	Complex	Complex	Simple	Simple
Noise	Low	Middle	Middle	Low
Uniformity	Excellent	Good	Excellent	Good
Energy resolution	High	Medium	High	High
Temperature sensitivity	Low	High	Medium	Low
Ambient light immunity	Yes	Yes	Yes	No
Magnetic resist	Yes	Yes	Yes	No
Compact & Weight	Yes	Yes	Yes	No

➜ DISCUSS MORE

Photomultipler tube (PMT)

PMT



Multiplication factor, or called electric gain

$$G = \delta^n$$

No. of dynodes (n)

Emission ratio of secondary electron (δ)

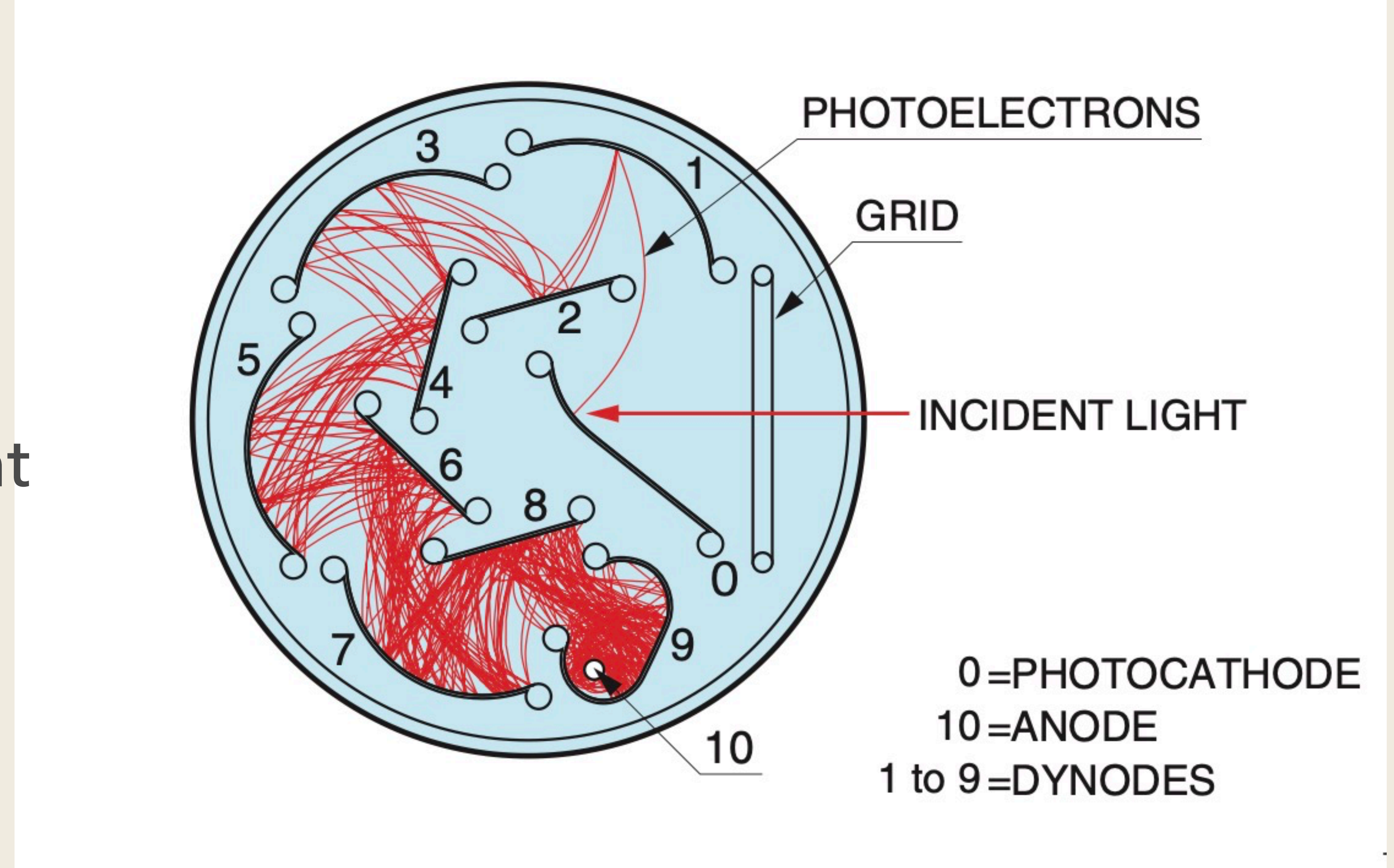
IF $\delta \approx 4$, $n = 10$ $\rightarrow G \approx 4^{10} = 10^6$

Based on "*External*" photoelectric effect

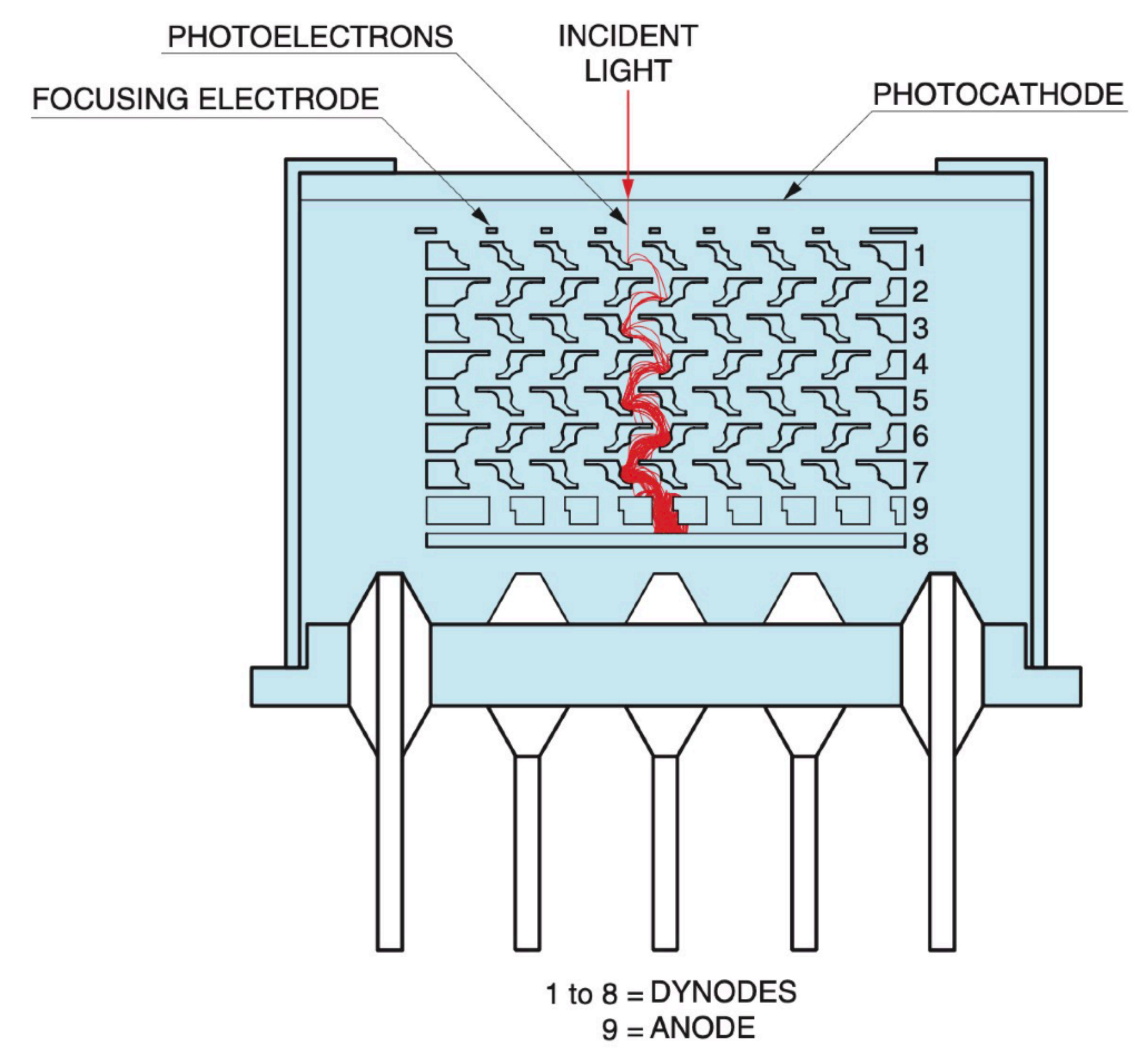
Also called vacuum-based PMT

Trajectory of *secondary electrons*

determined by the dynode arrangement

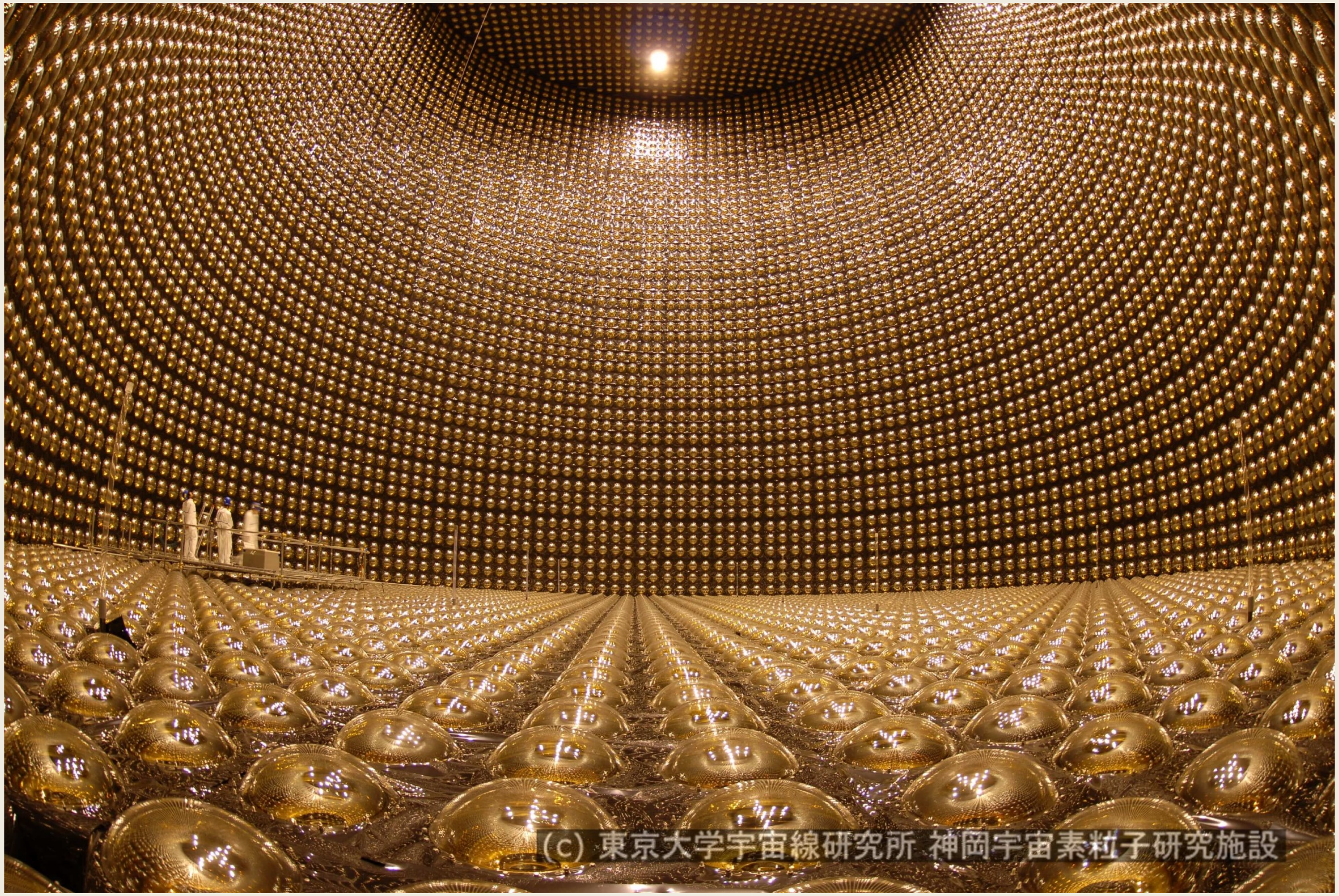


Circular-cage type



Metal-cage type

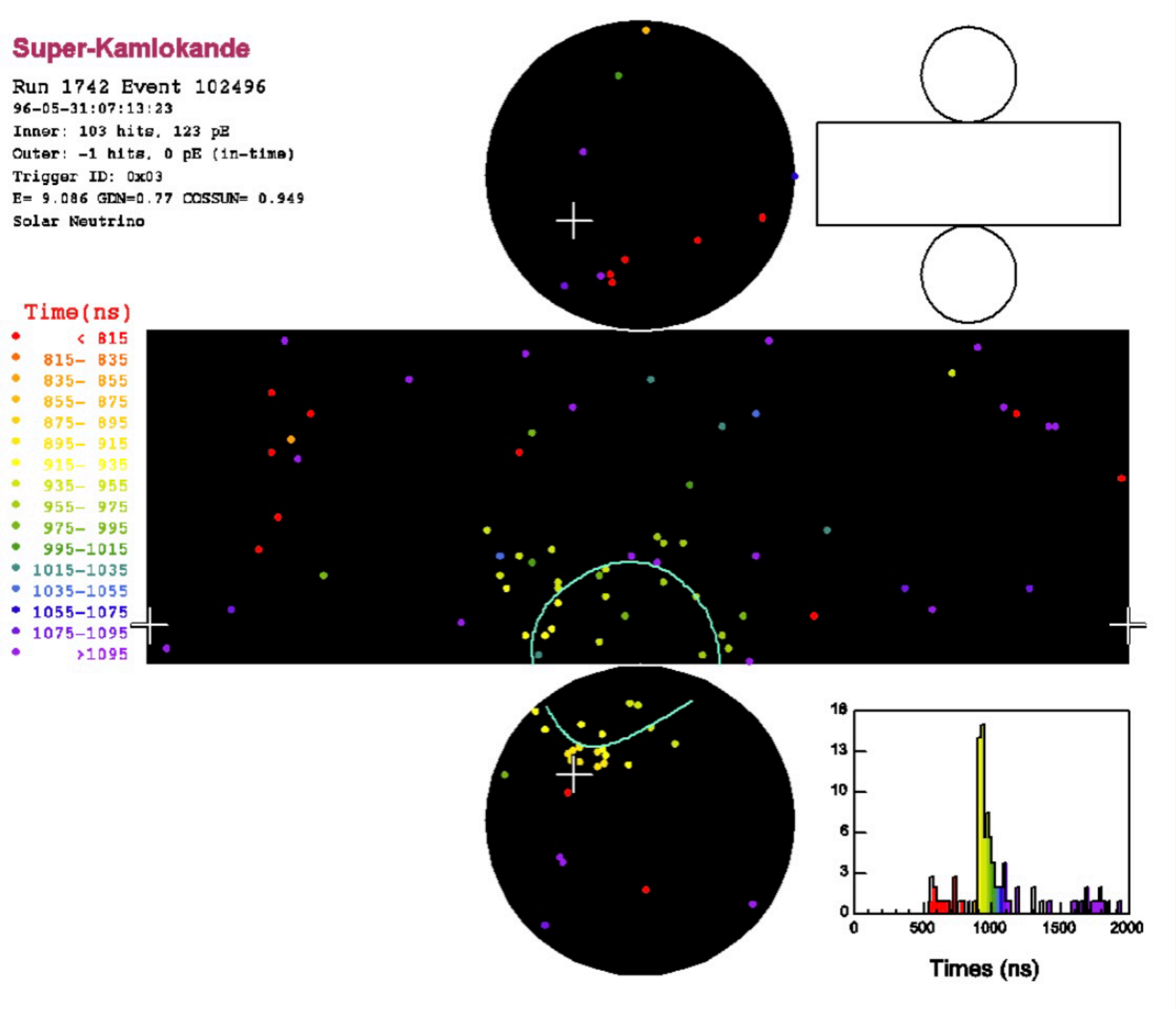
Super-Kamiokande: Wonder of 20-inch PMT



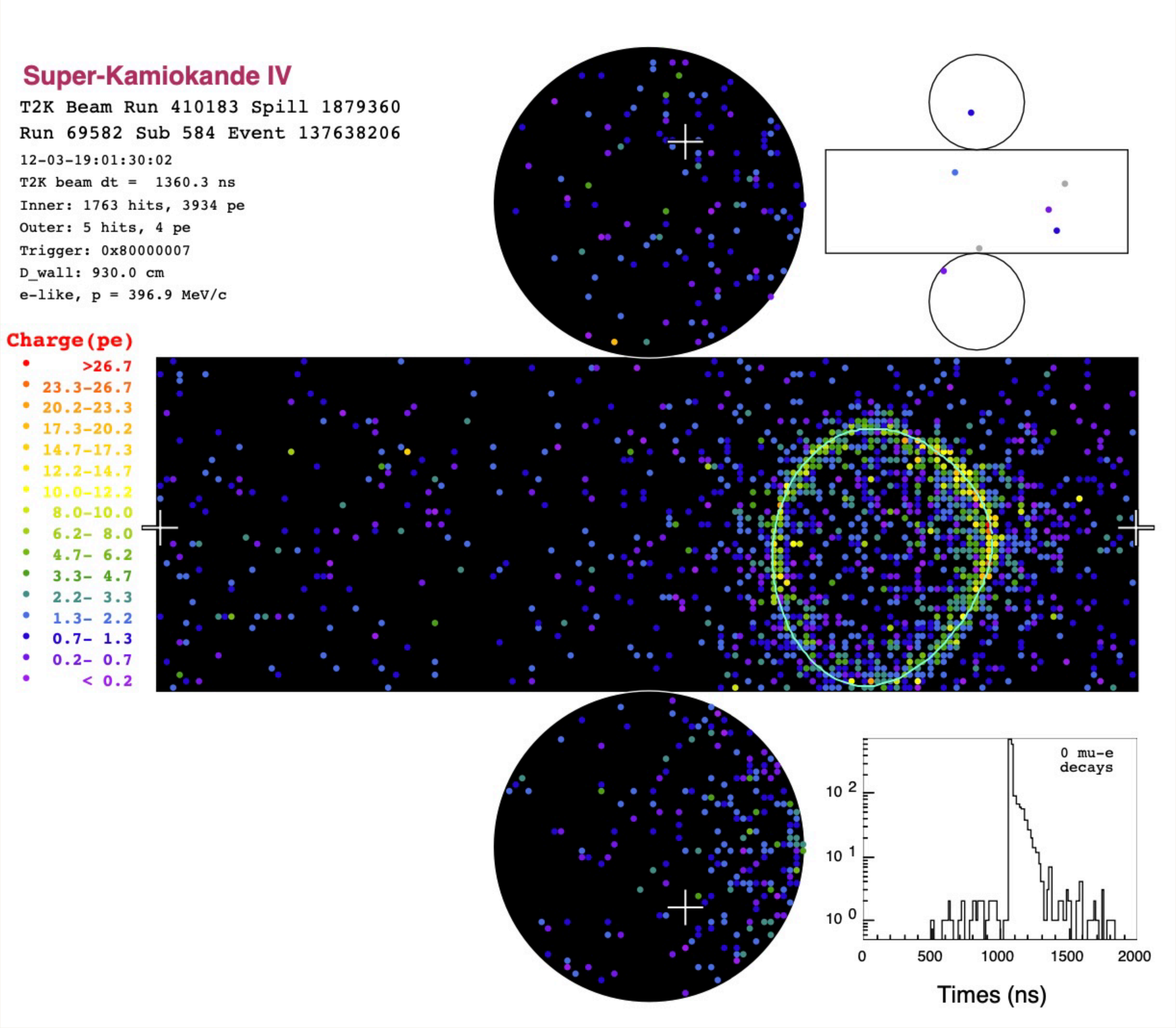
Super-Kamiokande

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

Fact: Big detector for tracking a faint flash of light



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

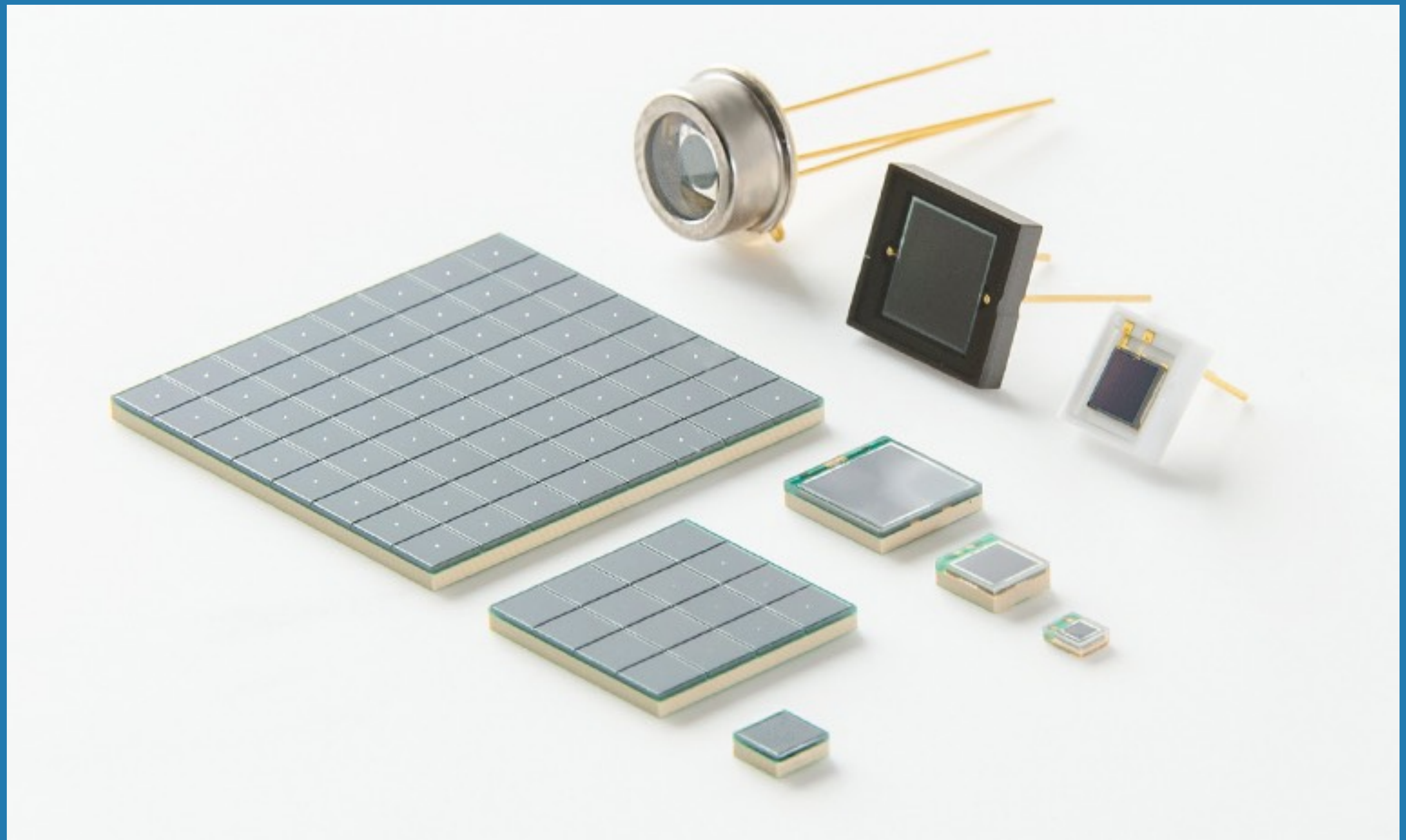


A ~400MeV ν_e candidate from T2K beam
3934 p.e. counted in 1763 hit PMT in few 100ns
~3-4 p.e. per hit PMT *in average*

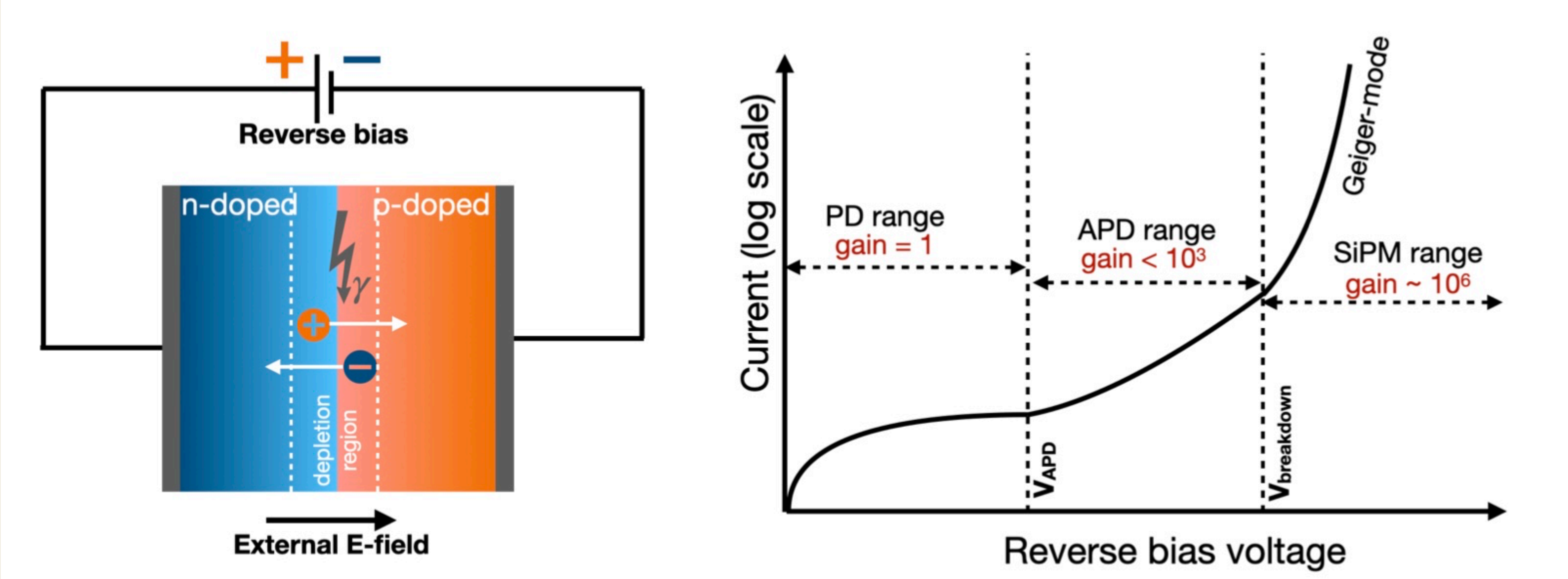
In a blinking of LED

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

Silicon Photomultiplier (SiPM)

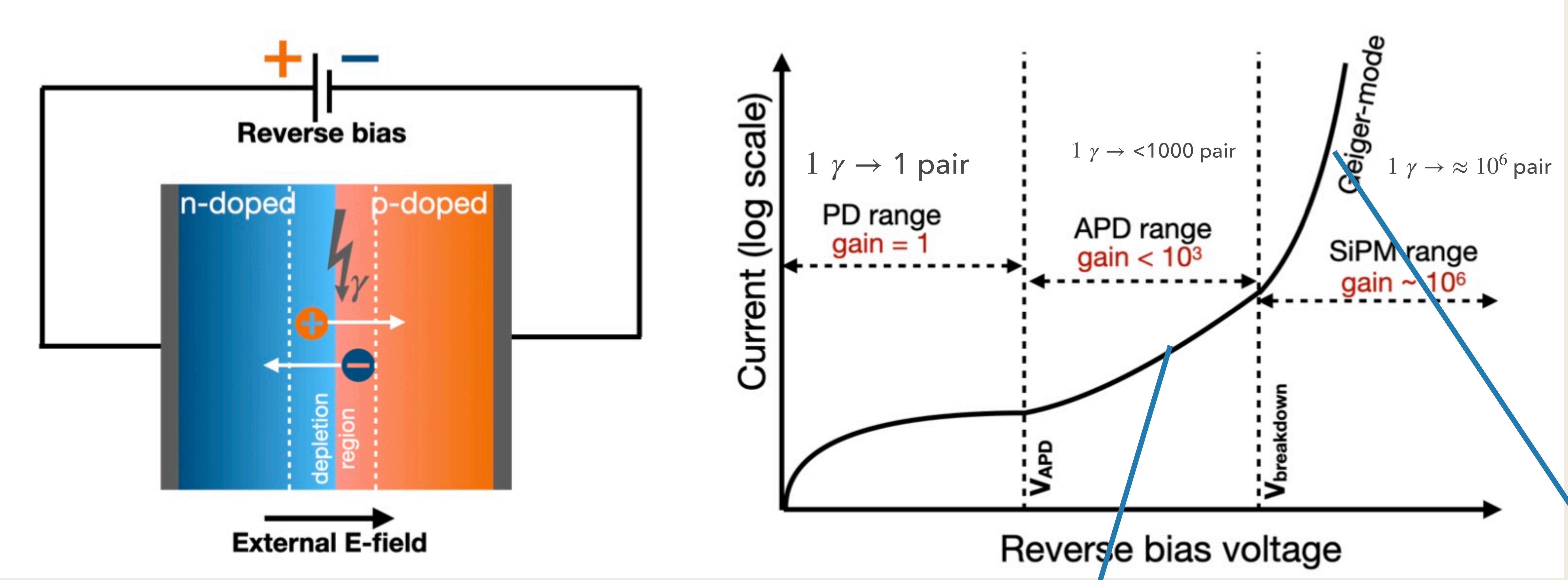


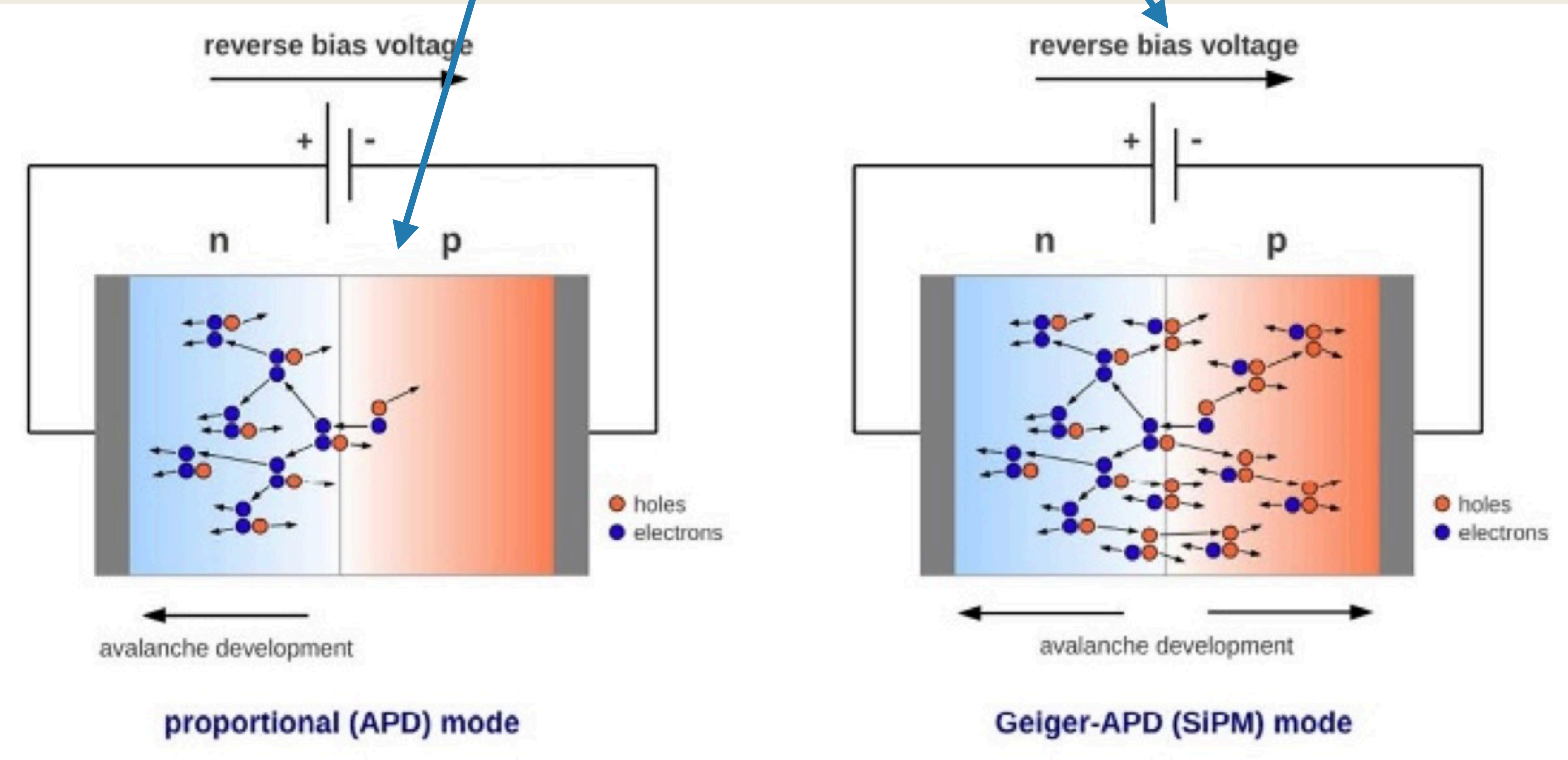
Photon detection principle w/ Silicon photomultiplier (SiPM)



- Based on "internal" photoelectric effect: photon strikes in the depletion region and produce a pair of electron/hole
- Under external E-field, induced carrier can form a current when the circuit is closed.
- When the E-field is small, one coming photon induces one electron -> gain =1, called Photodiode (PD)
- Higher E-field (*$V > V_{APD}$ but $< V_{breakdown}$*) will give higher energy (*more than the Silicon band gap energy*) to charged carriers which in turn ionize the lattice atoms and create other pairs of carriers. -> Avalanche process (*for electron carrier*) -> APD
- Even higher E-field ($V > V_{breakdown}$) will lead to the avalanche processes for both electron and hole carriers -> called Geiger-mode -> SiPM

Photon detection principle w/ Silicon photomultiplier (SiPM)





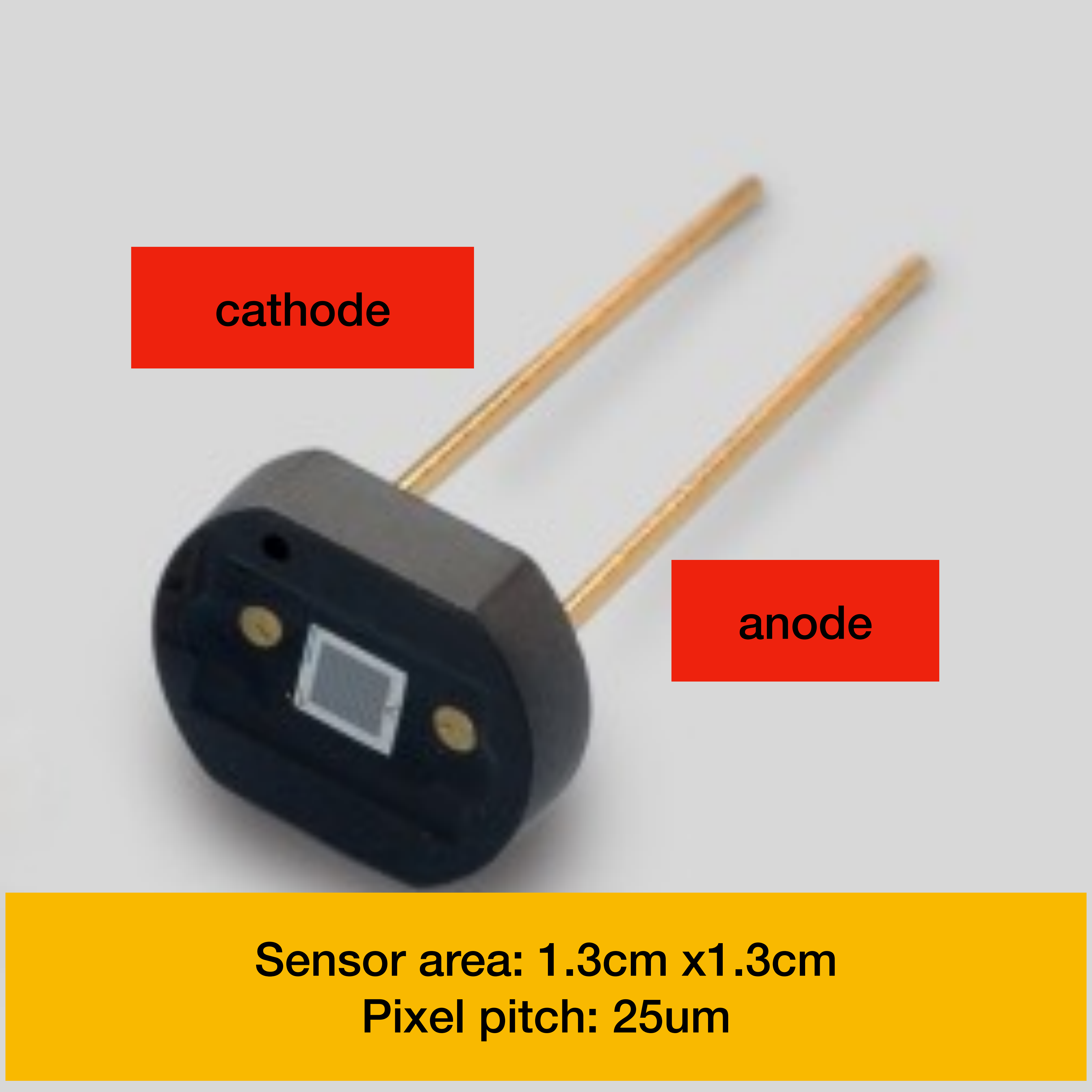
In Geiger mode, the detector has "binary" (or digital) response, which mean that

- (0) No signal = no photoelectron
- (1) same-size signal for **any number (>1)** of arriving photons

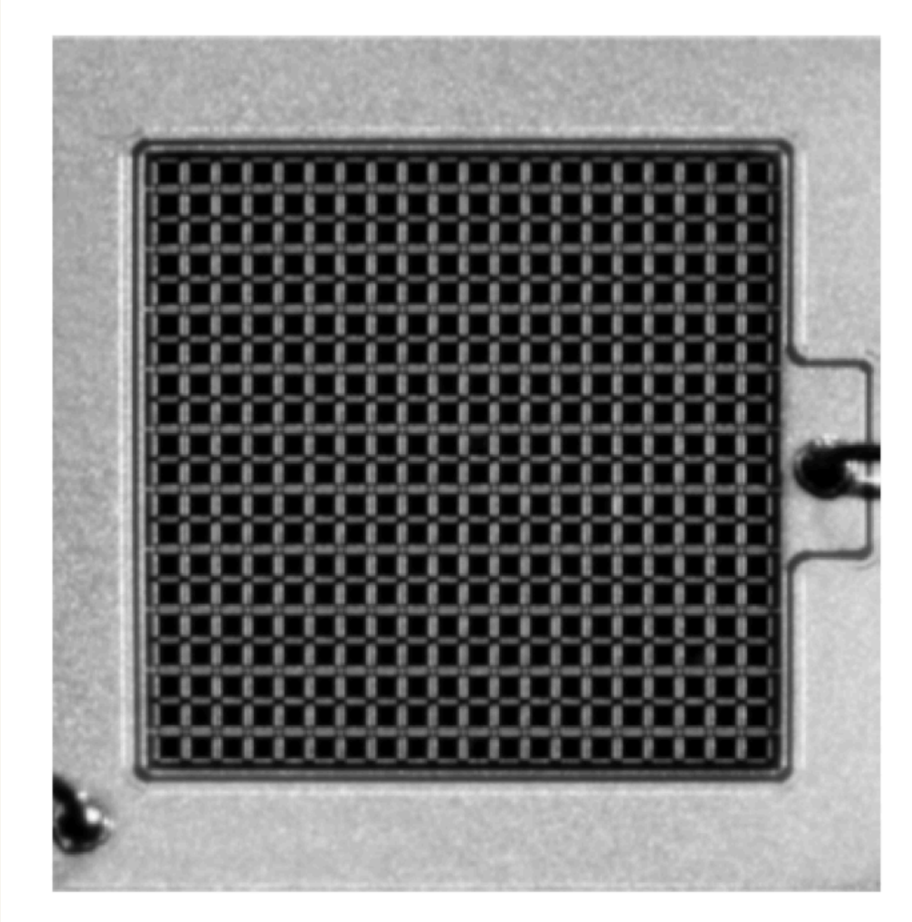
It's seem not much advance when operate in Geiger mode but...how about a matrix/or array of multiple pixels working in Geiger mode?

(Keep in mind, in the faint light sources, having photon arrived at the same time and same place is very rare.)

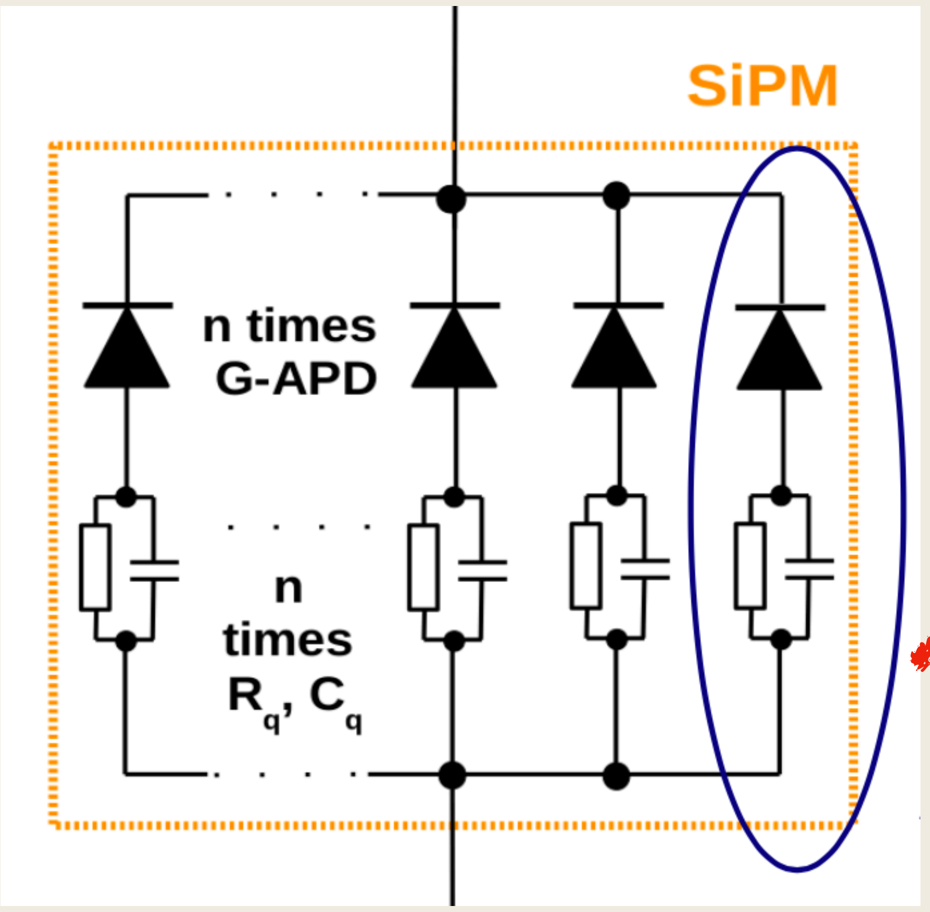
MPPC: a type of SiPM, developed by Hamamatsu

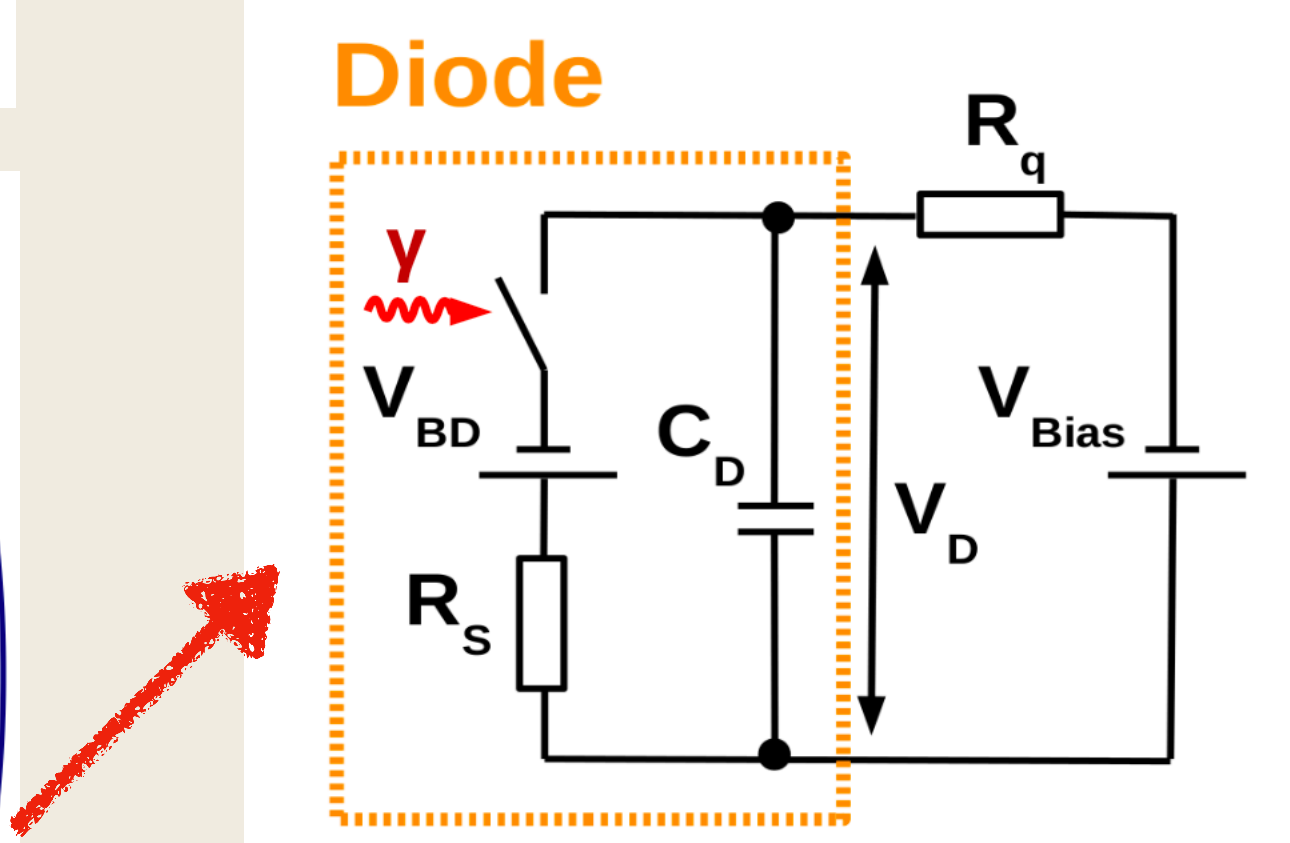


An example



Array of pixels

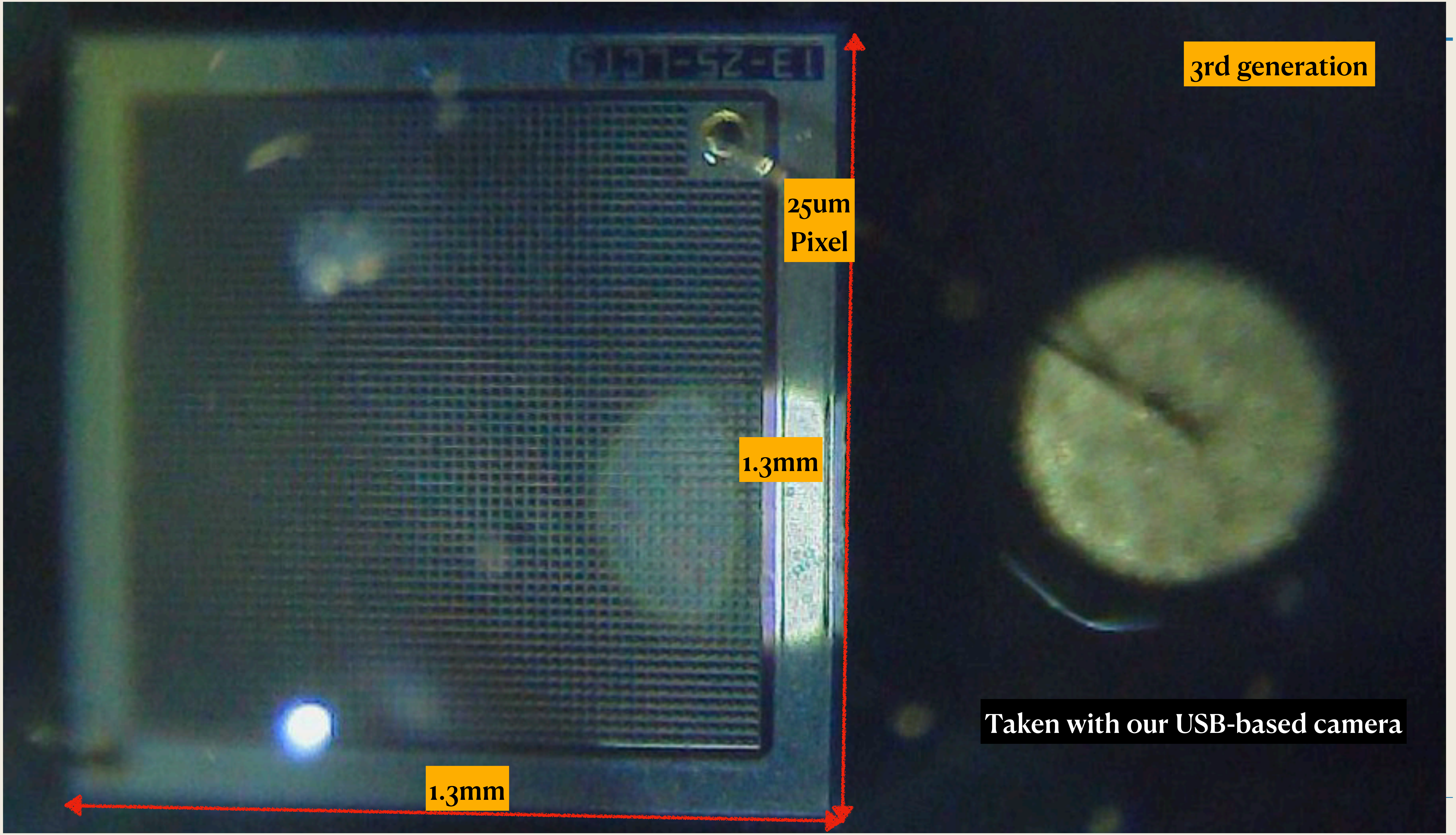




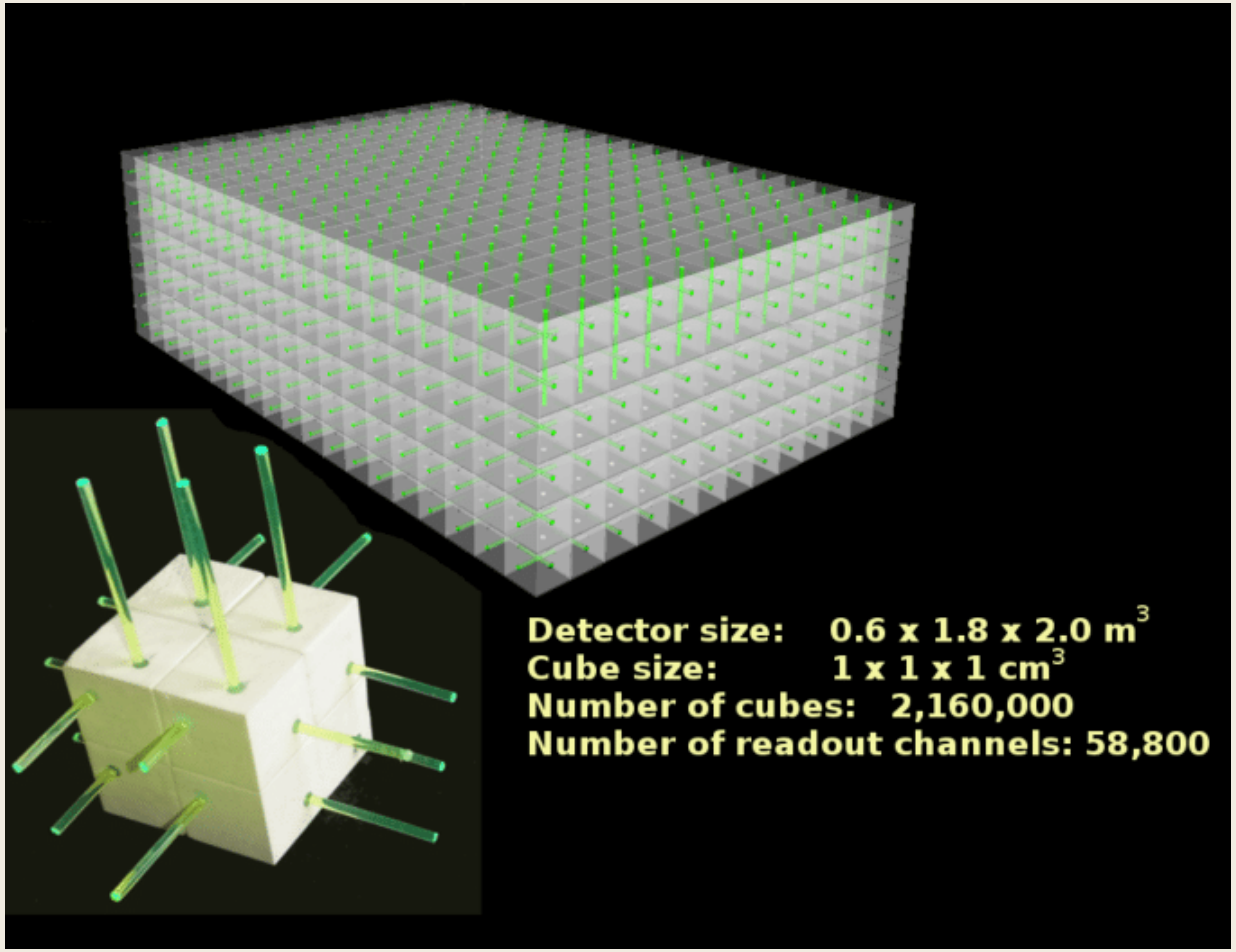
C_D: diode capacitance

R_S: silicon substrate serial resistor

V_{BD}: breakdown voltage


3rd generation
25um Pixel
1.3mm
1.3mm
Taken with our USB-based camera

For particle detector: tracking and calorimetry



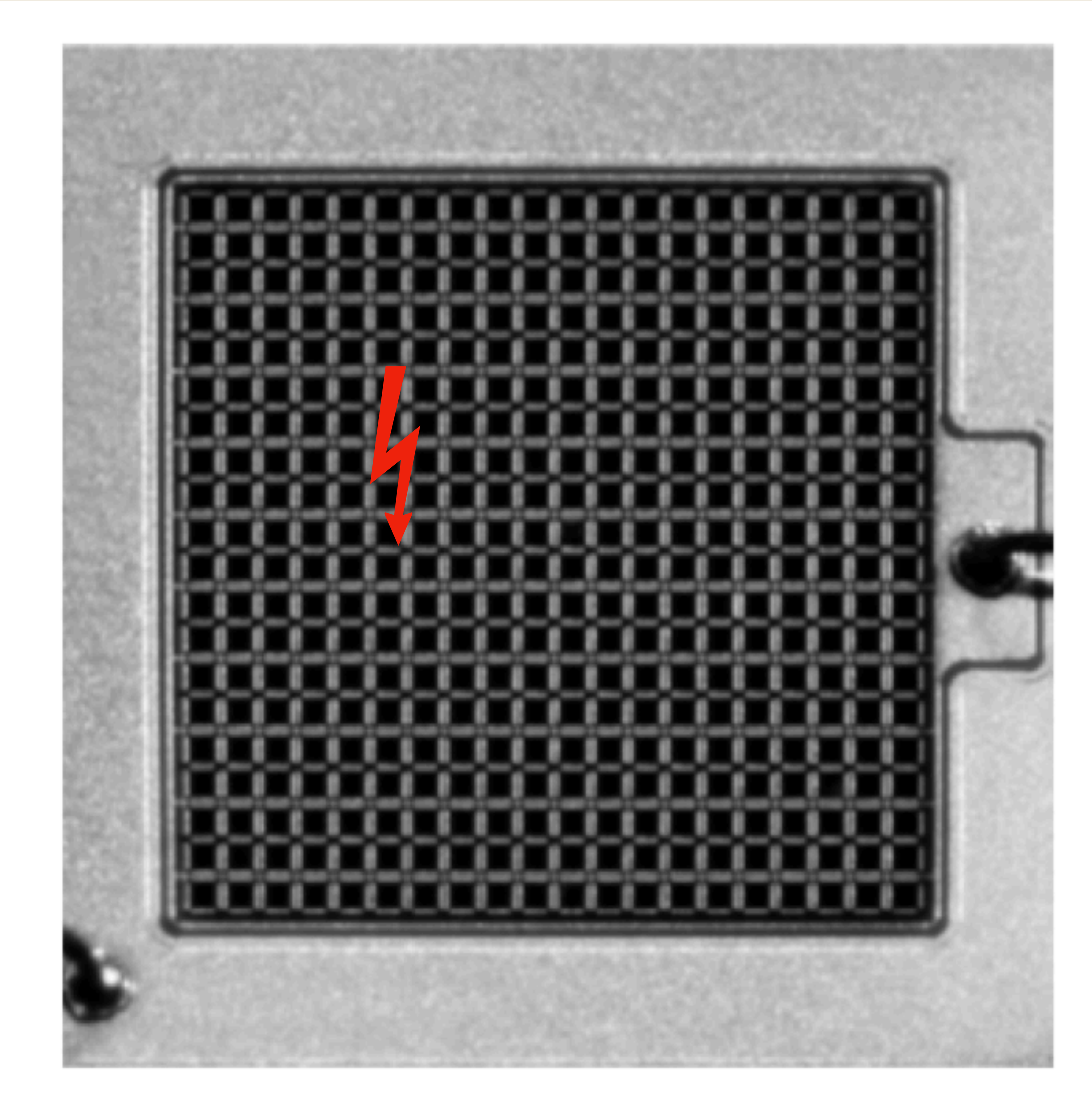
~60,000 MPPCs used to sense the faint light induced by neutrino interaction from > 2 million lego-size cubes of plastic scintillator

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

Photon-counting mode with SiPM

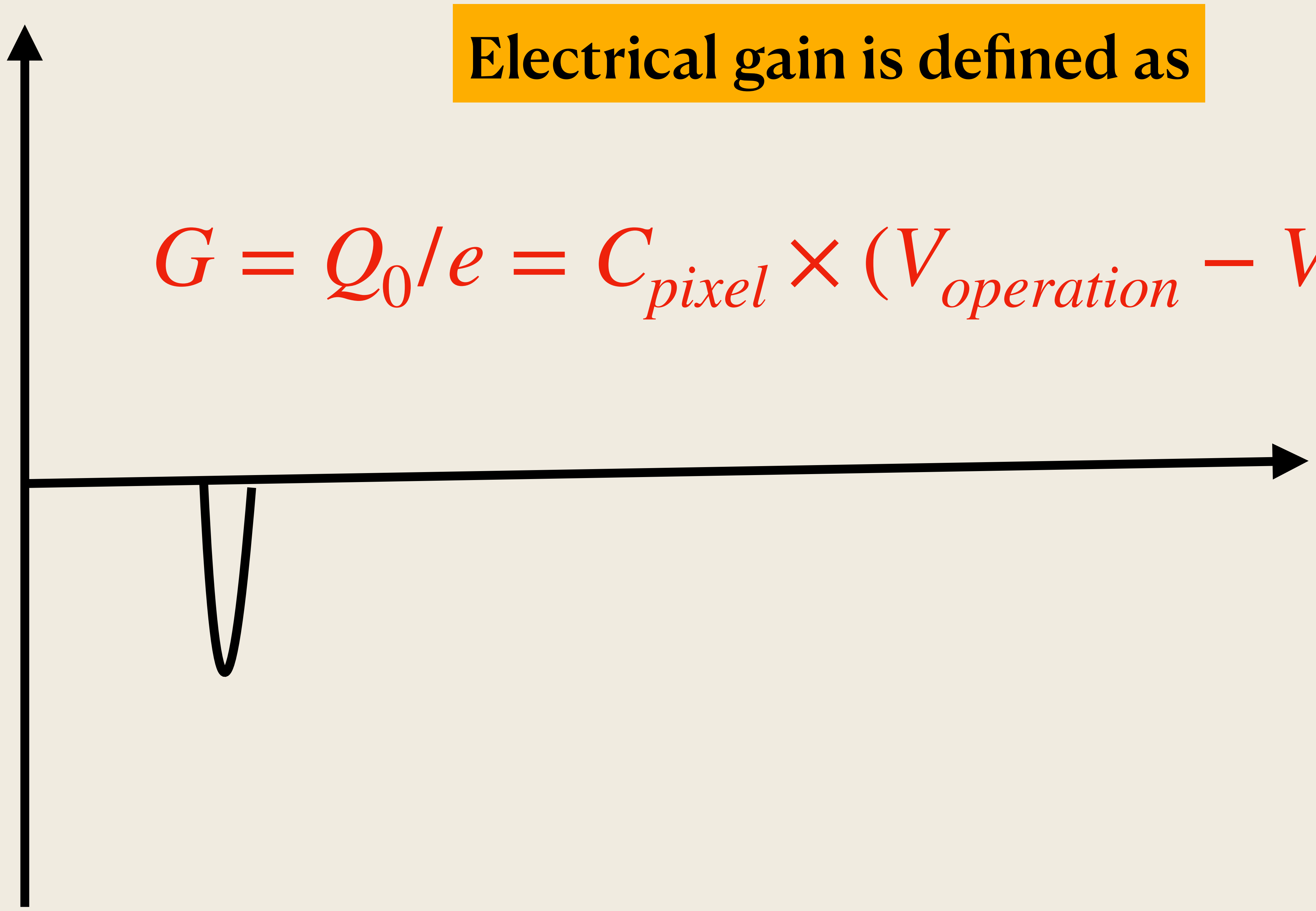
Basic principle of photon counting

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

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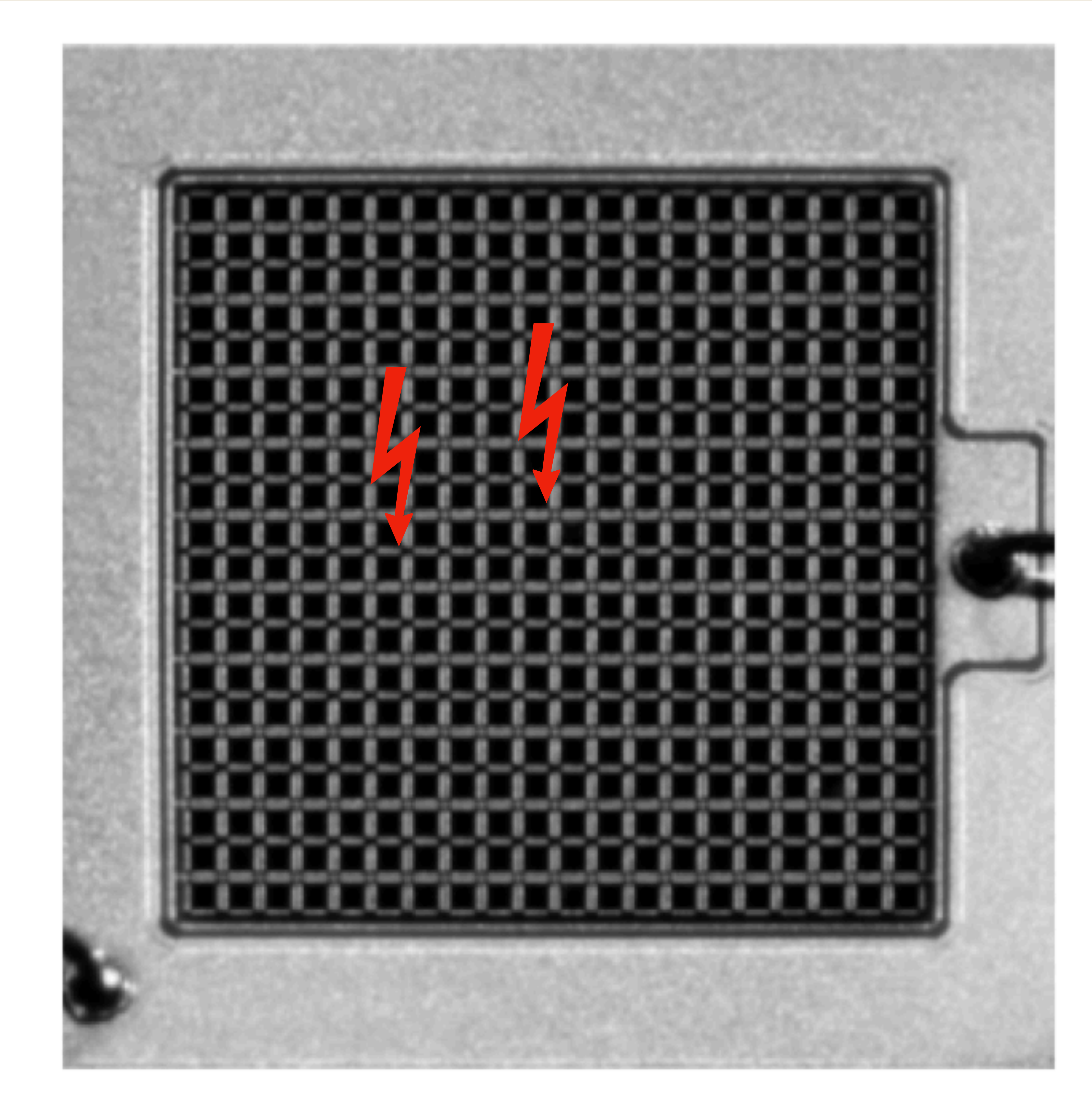
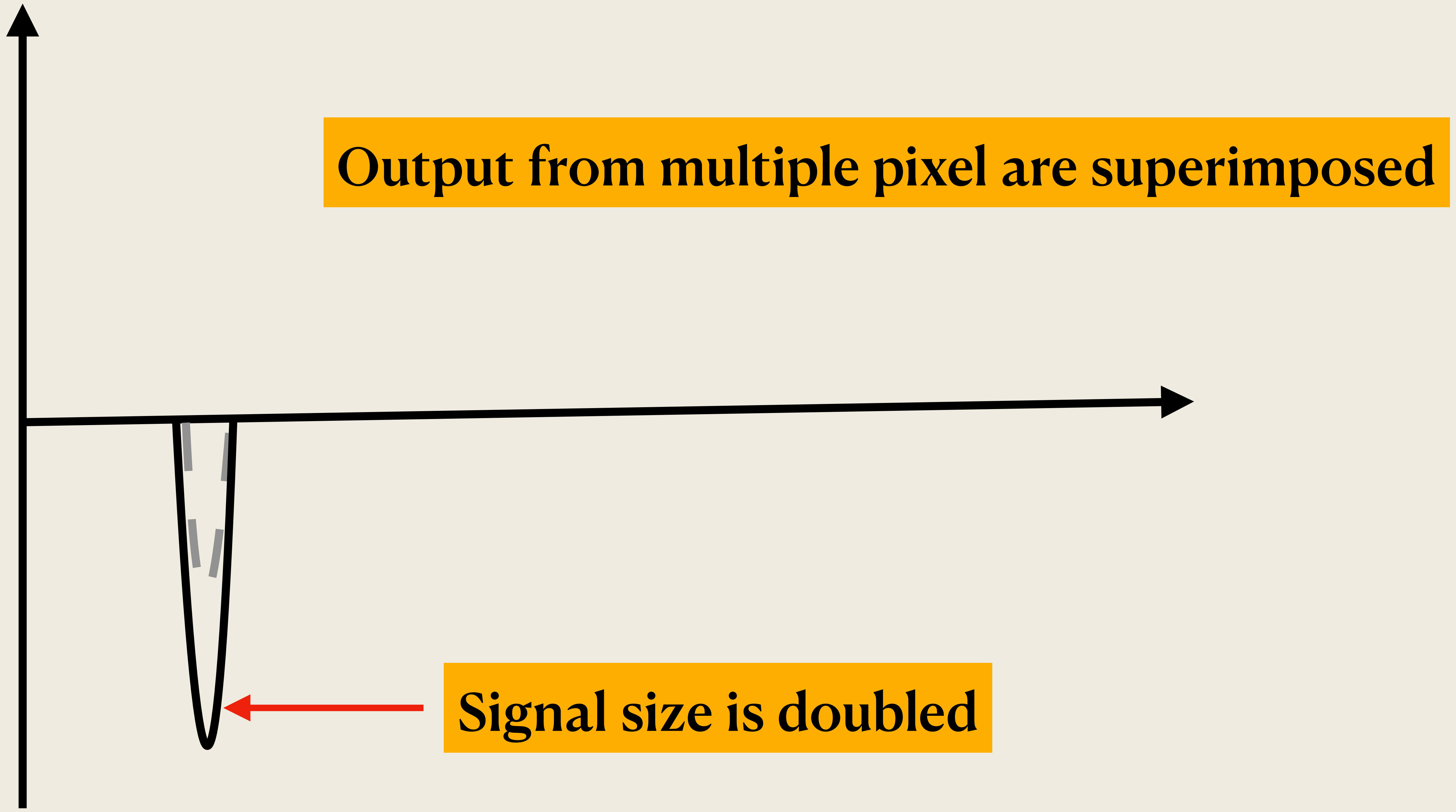
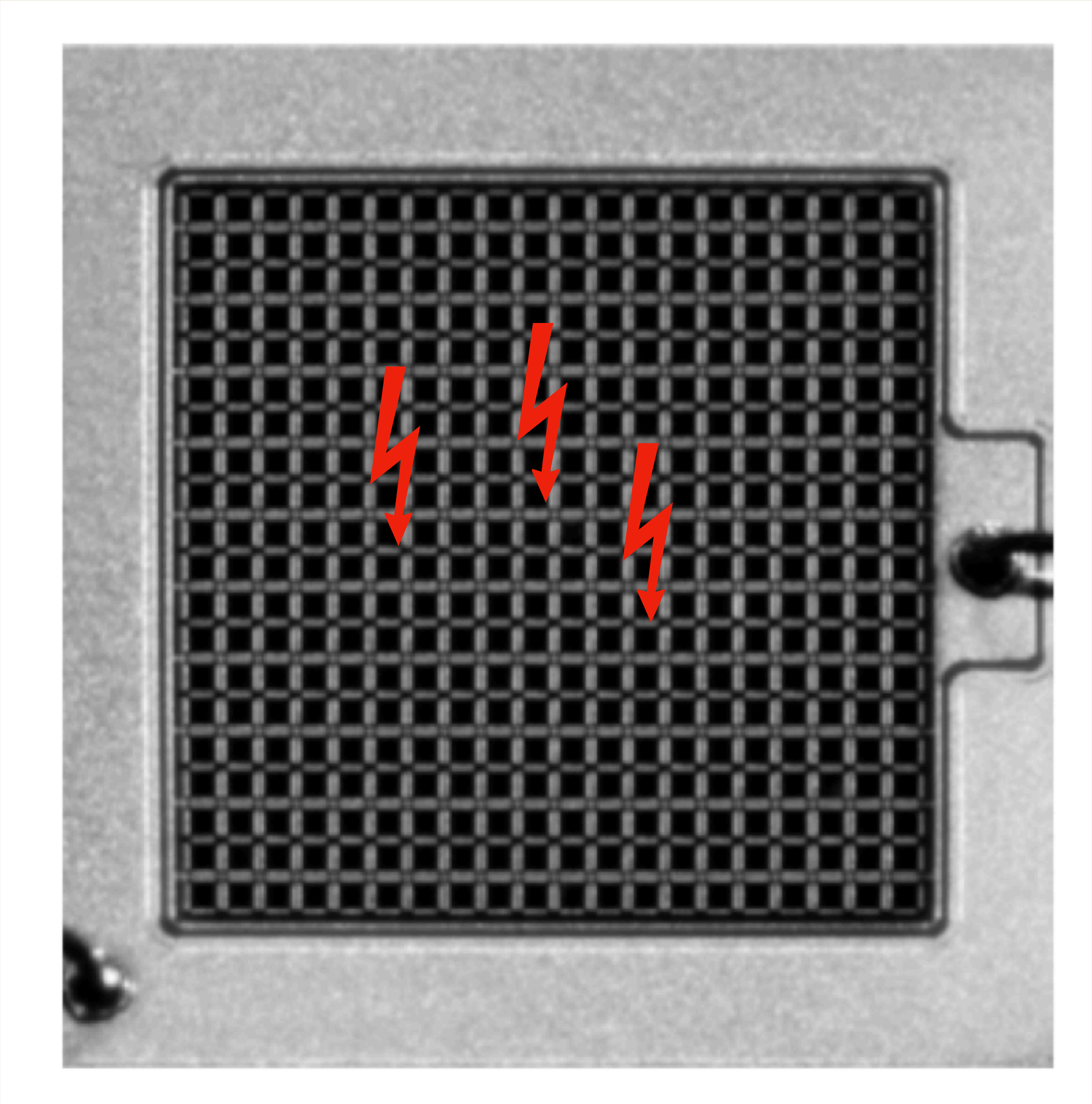




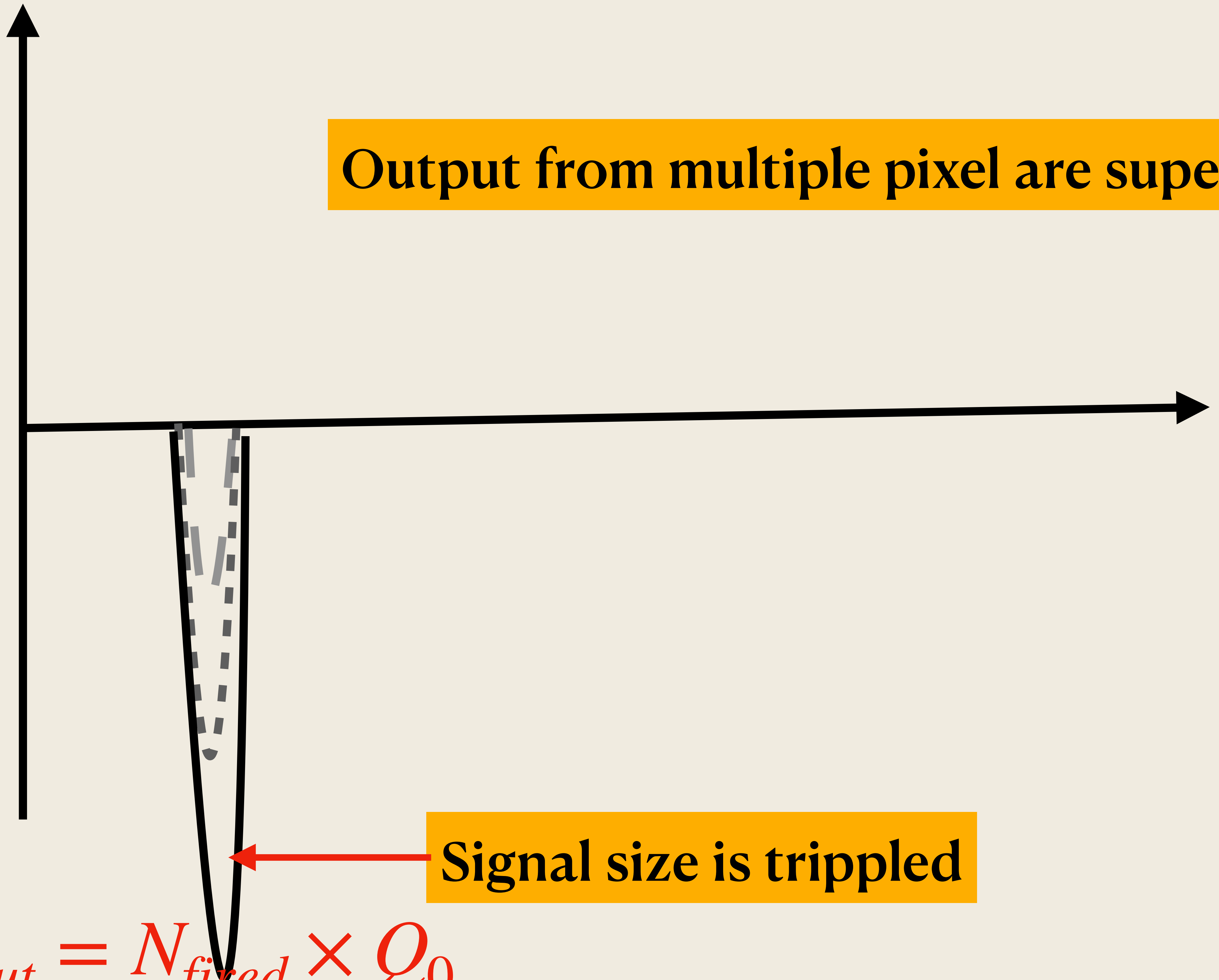
$$Q_{out} = N_{fired} \times Q_0$$
$$= N_{fired} \times C_{pixel} \times (V_{operation} - V_{breakdown.})$$

Basic principle of photon counting

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



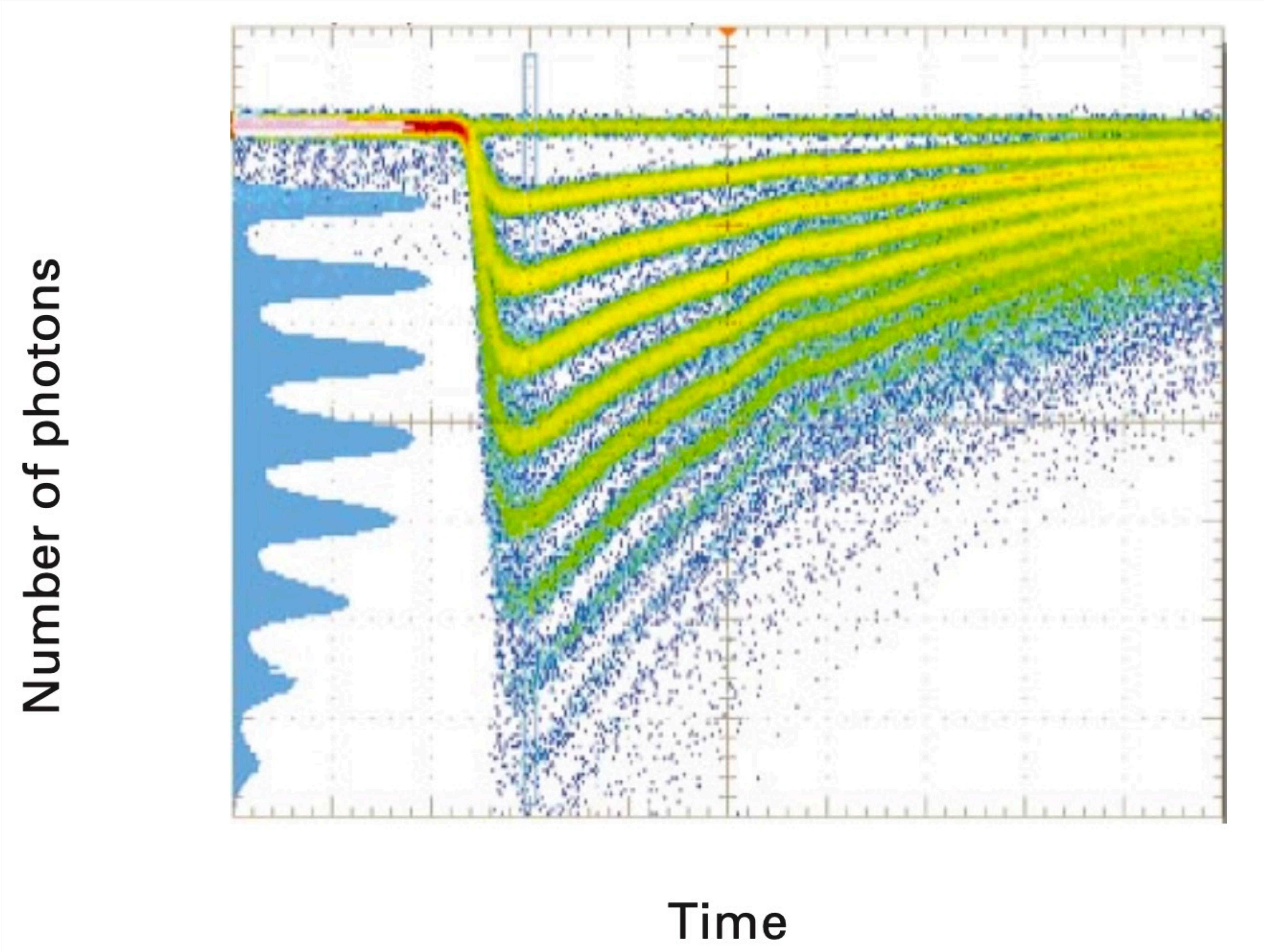
Output from multiple pixel are superimposed



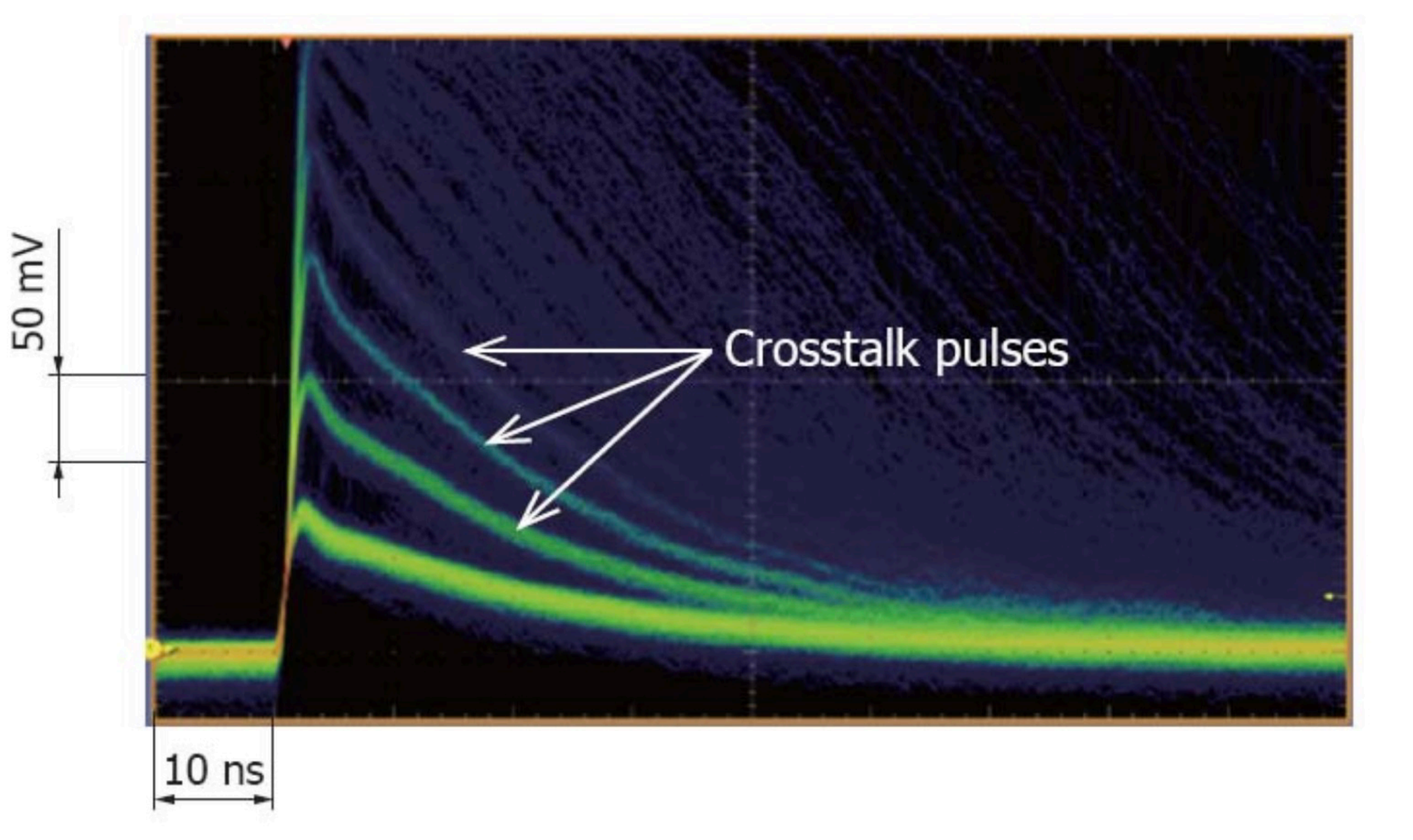
Signal size is trippled

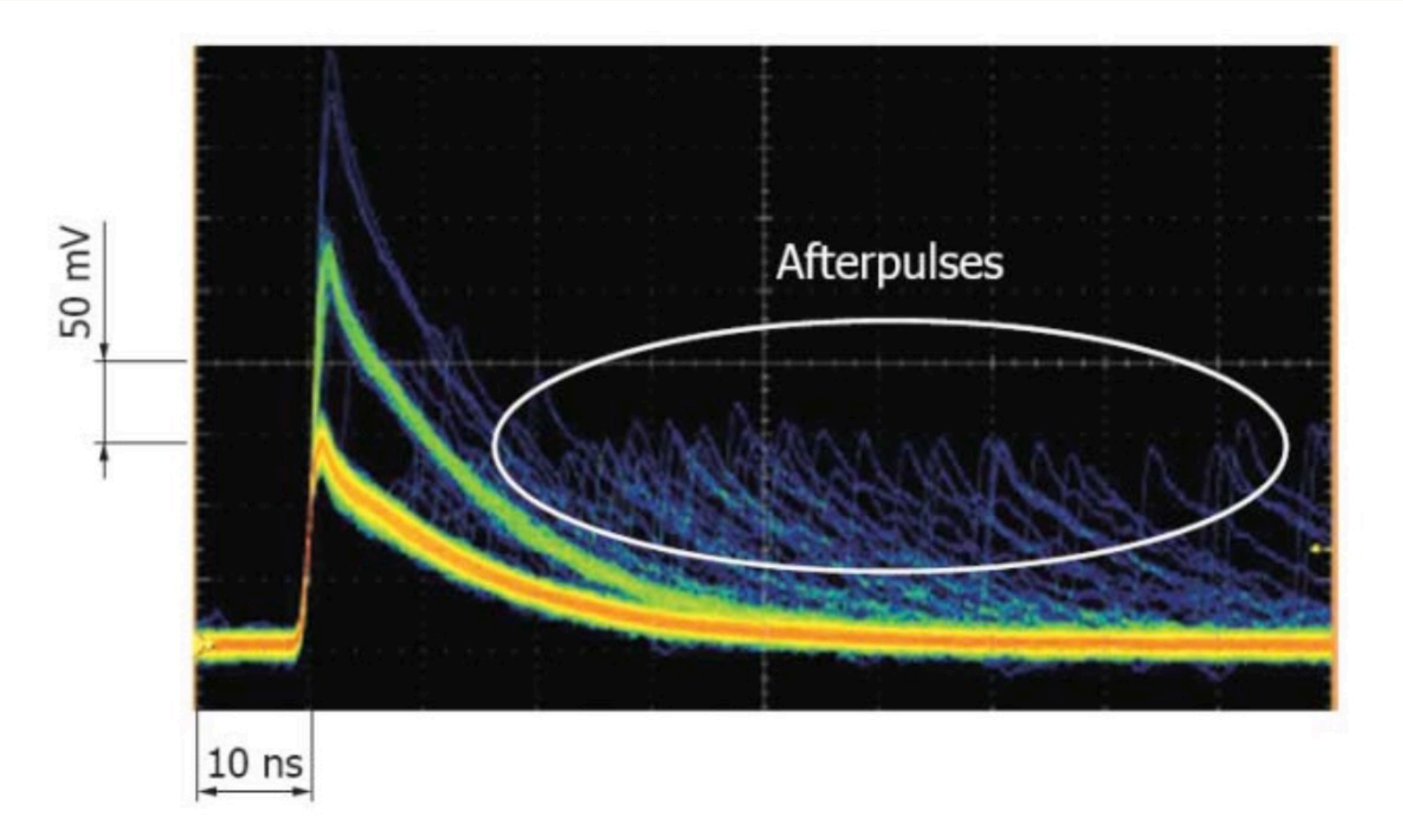
$$Q_{out} = N_{fired} \times Q_0$$
$$= N_{fired} \times C_{pixel} \times (V_{operation} - V_{breakdown.})$$

MPPC overlayed signals



SiPM *intrinsic* noise: Cross-talk and after-pulse





Additional photon(s) is created in another pixel due
To the energy deposit by energized charge carrier
Distinguished by signal amplitude

Charge carrier(s) from primary photon get trapped
and release later
Distinguished by timing information

Some technical terms

Features

- Reduced crosstalk and dark count (compared to previous products)
- Outstanding photon counting capability (outstanding photon detection efficiency versus numbers of incident photons)
- Compact
- Operates at room temperature
- Low voltage (V_{BR}=53 V typ.) operation
- High gain: 10^5 to 10^6
- Excellent time resolution
- Immune to the effects of magnetic fields
- Operates with simple readout circuit
- MPPC module also available (sold separately)

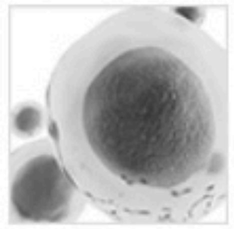
Applications

- Fluorescence measurement
- Laser microscopes
- Flow cytometry
- DNA sequencers
- Environmental analysis
- Various academic research

These characteristics will be elaborated further by mentors
Also please read the Hamamatsu document and specification

https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/s13360_series_kapd1052e.pdf

MPPC series selection

Measurement wavelength	 Academic research	 Measuring instruments (flow cytometers, microscope etc.)	 PET scanners	 LiDAR
VUV/UV	For academic research experiments			
VIS	For wide dynamic range S14160 series		For PET scanners S14160/S14161 series	
	For precision measurement S13360/S13362 series			
	For precision measurement (TSV type) S13360/S13361/S13363 series			
VIS to NIR		For visible light S14420/S14422 series		
NIR				For near infrared S15639-1325PS

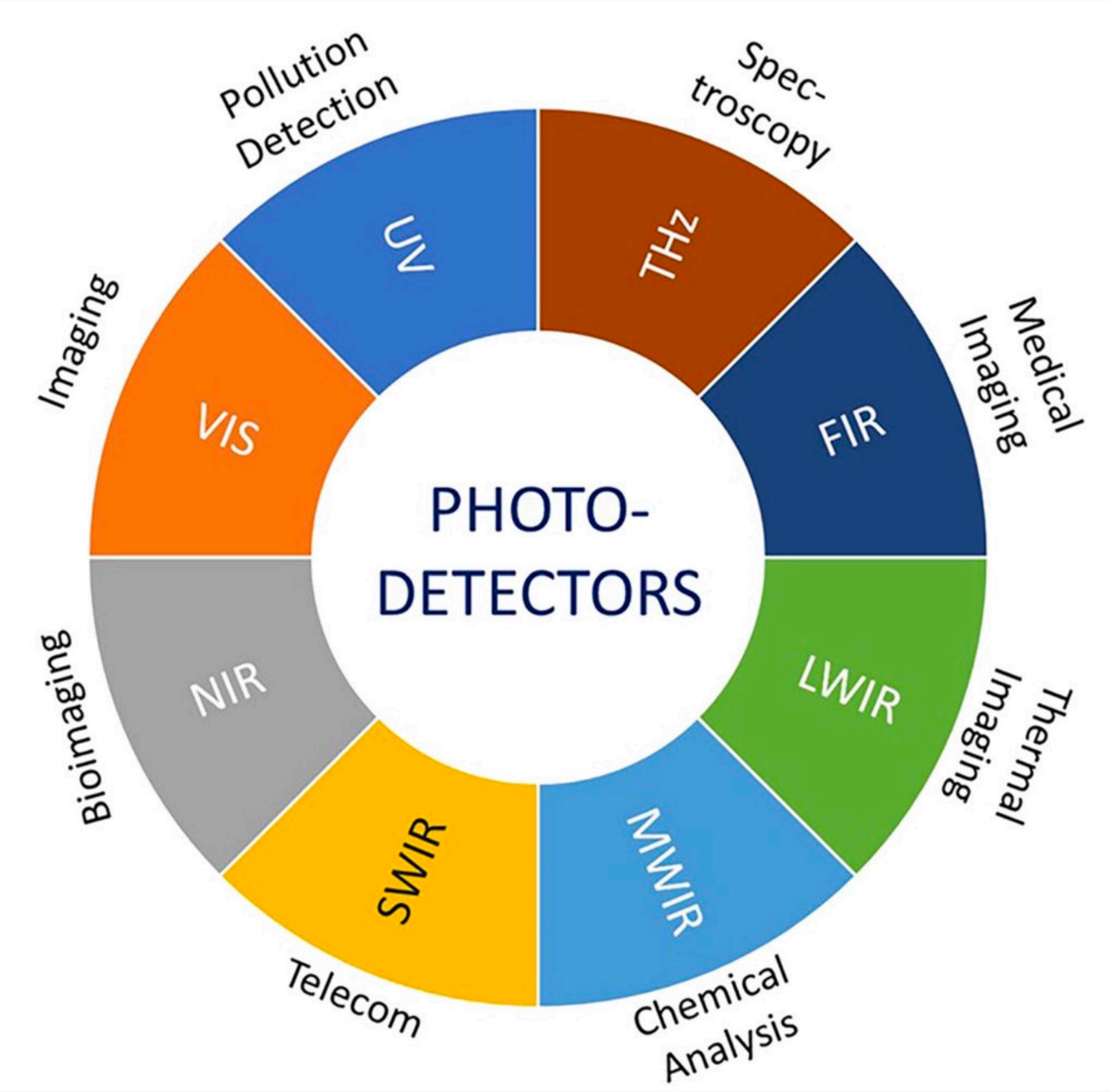
https://www.hamamatsu.com/eu/en/product/optical-sensors/mppc/mppc_mppc-array.html

Some applications

(Just give some for illustration. Please explore by yourself)

Application of photodetectors

- **Imaging and photography** (digital cameras, medical imaging devices, astronomical telescopes...)
- **Optical communication**: process signal in the fiber-optic network; high-speed internet infrastructure
- **Environmental monitoring**: detect pollutants, radiation, air quality
- **Food and beverage quality assessment**
- **Light detecting and ranging (LiDAR):** autonomous navigation, 3D mapping
- **Security and surveillance:** radiation detectors, night vision...
- **Scientific research:** particle and nuclear physics; astronomy; quantum computing ...
- ...

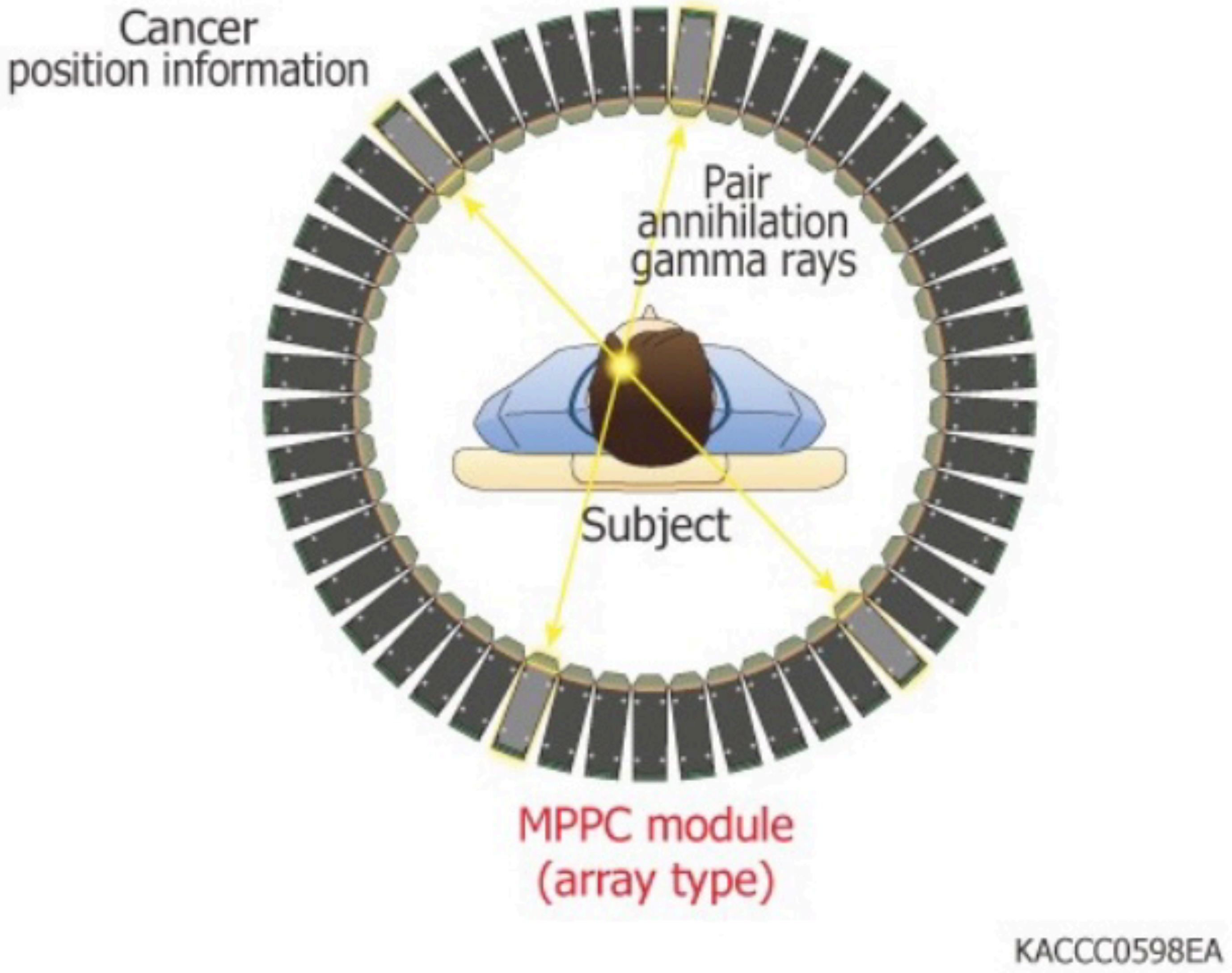


https://link.springer.com/article/10.1007/s10853-023-08876-8

Relevant to this hardware camp

Distance Measurement (LiDAR)

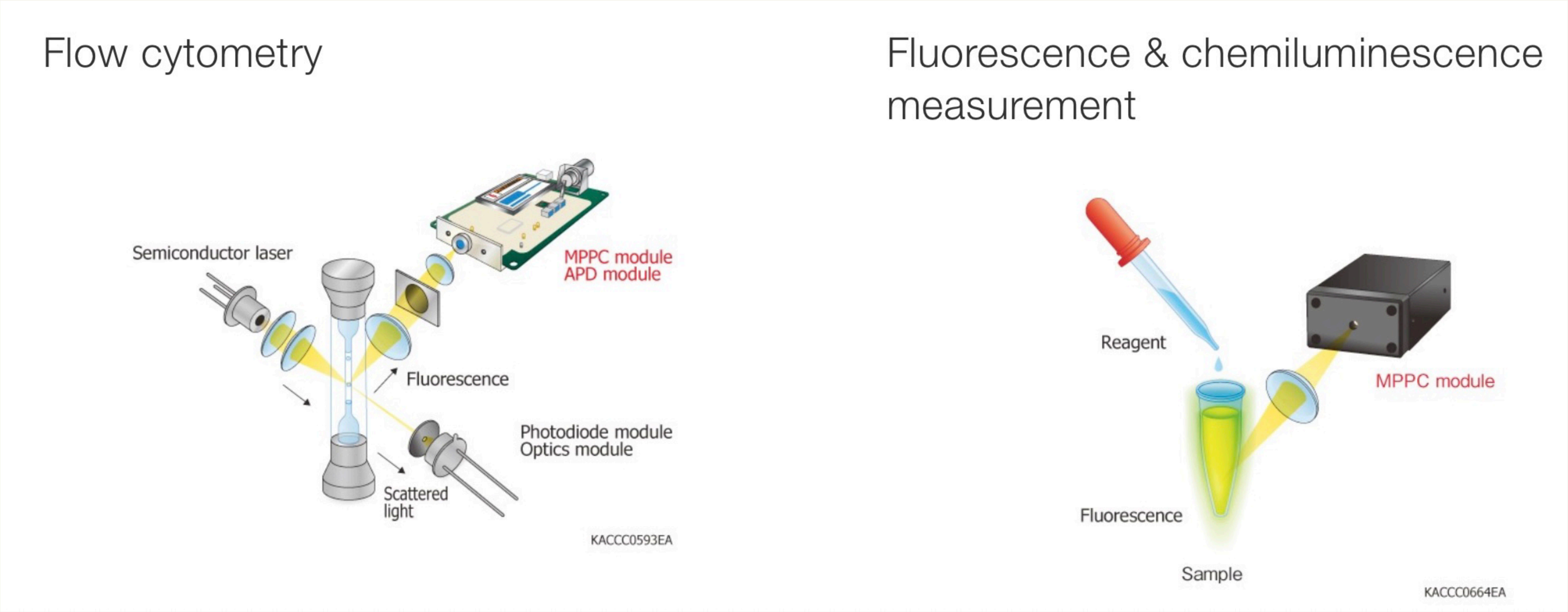
PET (Positron Emission Tomography)



Group A will try to measure the speed of photon in optical fiber, but in fact if you know the speed Already you can use the timing information to convert to length of fiber. Similar concept to LiDAR

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

Relevant to this hardware camp

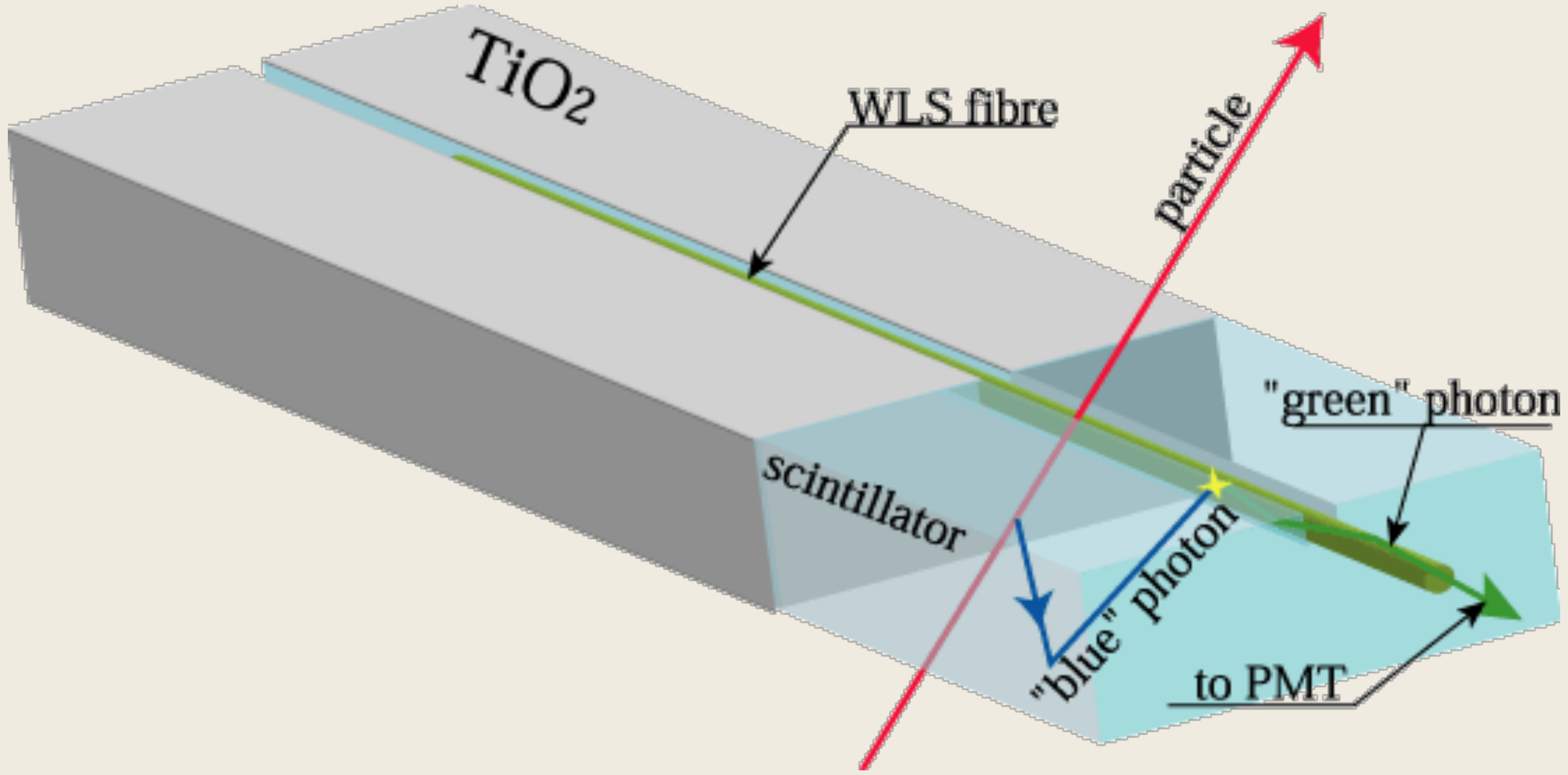


- Group B: measure the profile of the light out of optical fiber using MPPC array. It is important to understand of dedicated light source (spreading)
- Group C: measure the spectra of a light source. It is somewhat similar to the concept of the fast fluorescence/chemiluminescence spectrometer

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

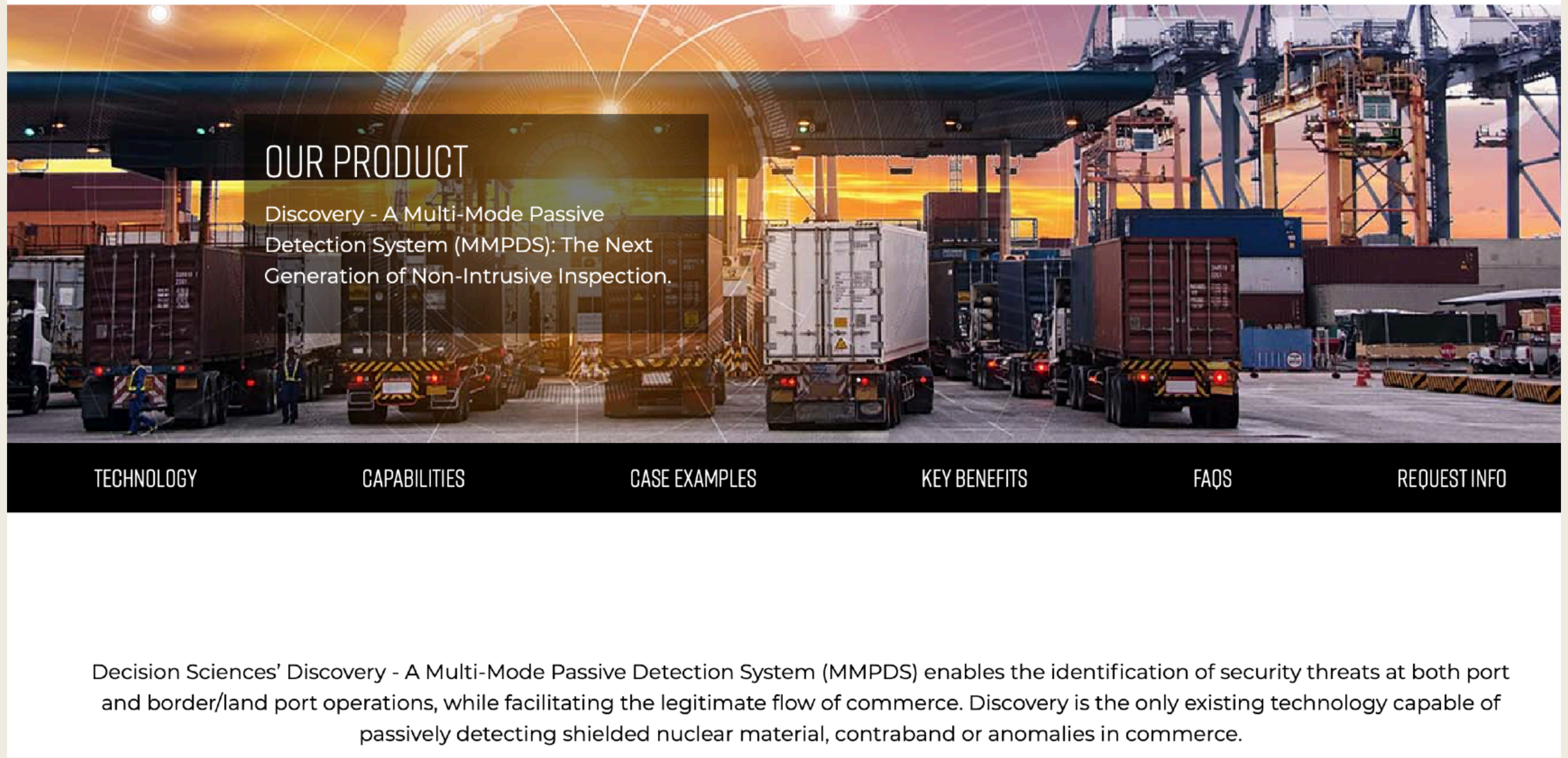
Relevant to this hardware camp

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



What's inside of pyramid (where you can't reach)?

All groups will try to observe the cosmic-ray muons - natural radiation



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

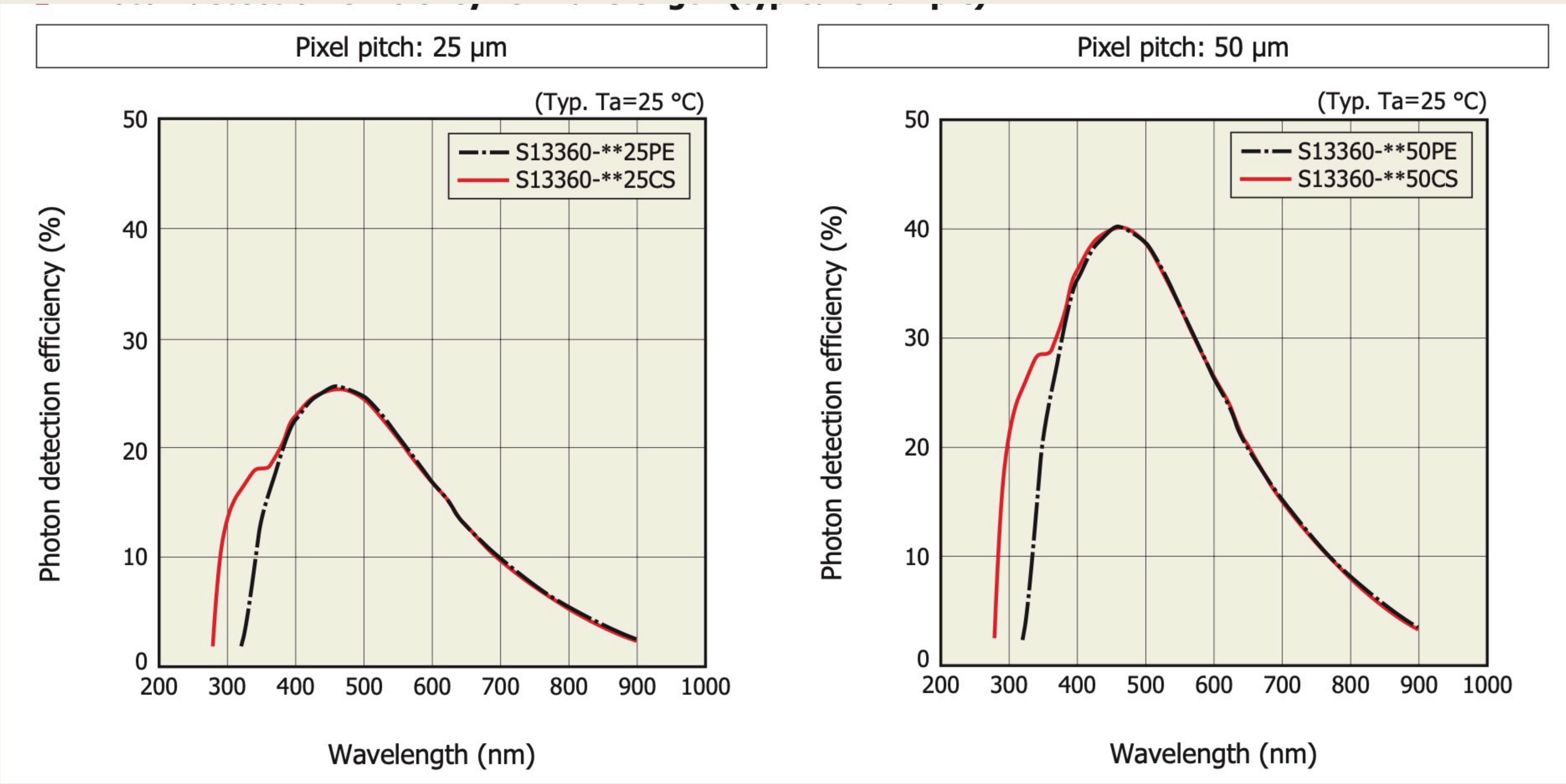
Let's harness the power of photodetectors together !

Reference

- *Hamamatsu's MPPC technical note* https://hub.hamamatsu.com/content/dam/hamamatsu-photonics/sites/static/hc/resources/TN0014/mppc_kapd9005e.pdf
- *Hamamatsu's PMT technical note* https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/etd/PMT_handbook_v4E.pdf
- …

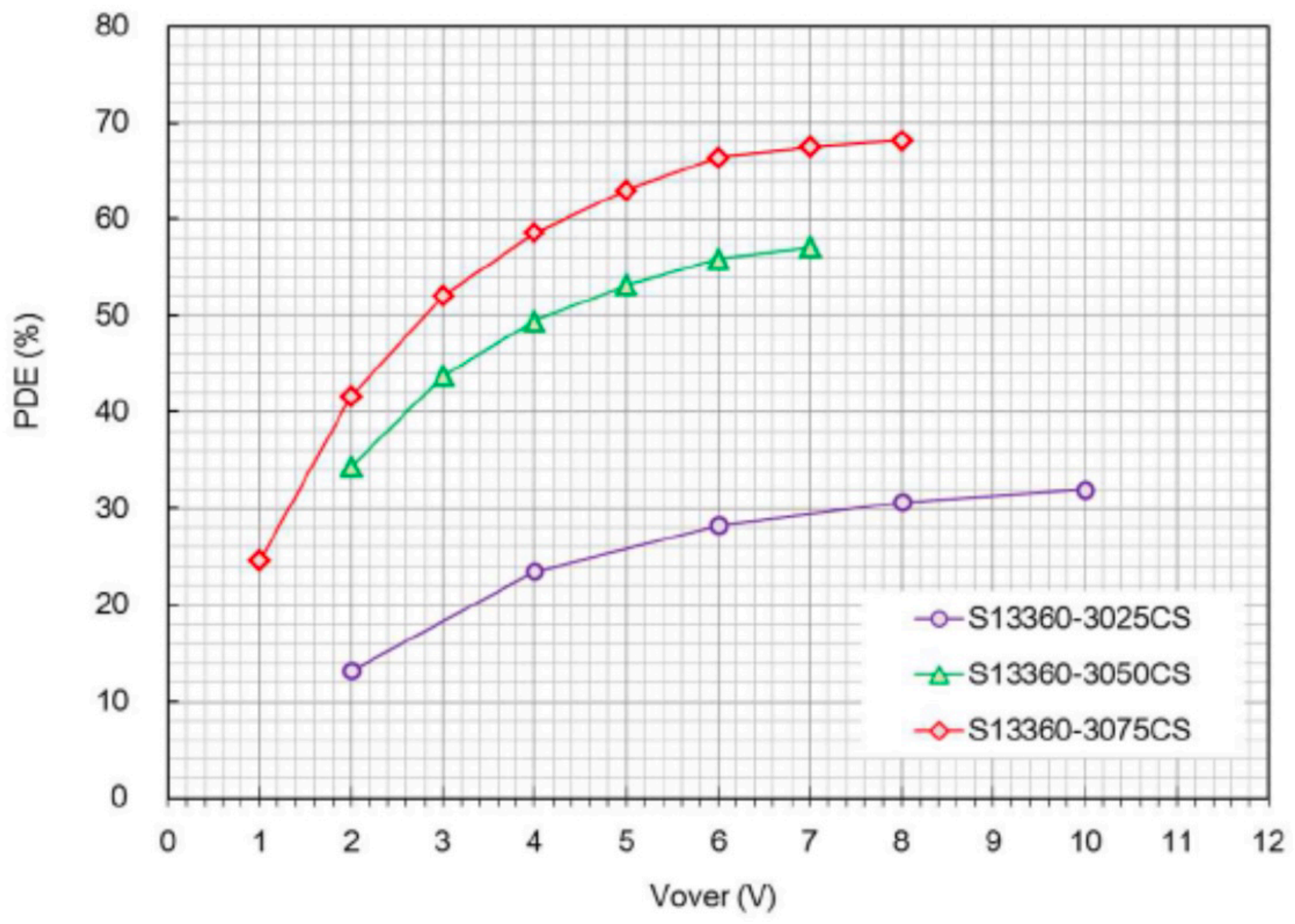
Backup

Photon detection efficiency



Depend on wavelength
Large pixel size will higher detection efficiency
(with higher dark noise)

◆ S1336x Series（25, 50, 75 μm）



PDE = FF x QE x AP
FF: Geometrical Fill Factor
QE: Quantum Efficiency
AP: Avalanche Probability

- High PDE achieved by the high fill factor and high overvoltage
- **Larger pixel has higher PDE**

Depend on operational voltage. Higher operation voltage give higher PDF but also more noise

In short, No. of photoelectron is always smaller than No. pf incoming photons. Good approximation

$$N_{fired} = N_{photon} \times PDE$$

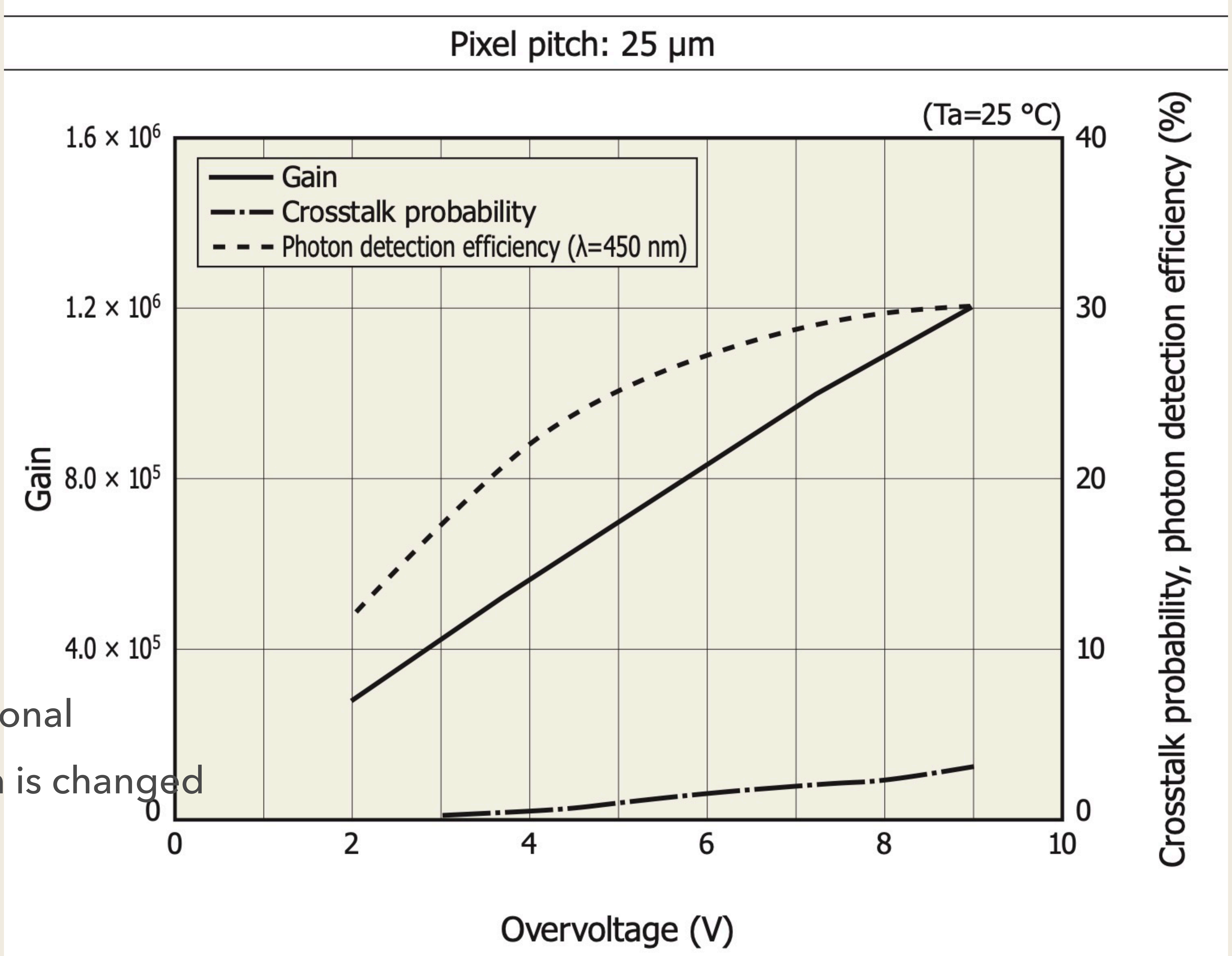
Electrical gain

Gain = No. of electrons produced
in the avalanche process
after a hit of photon

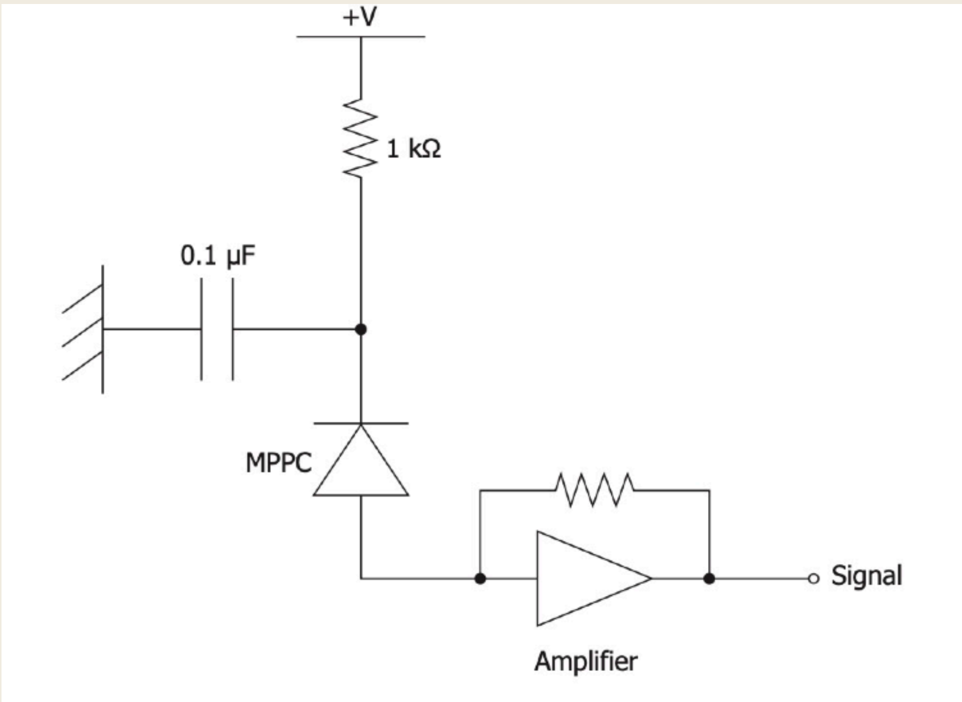
Depend on overvoltage, defined as

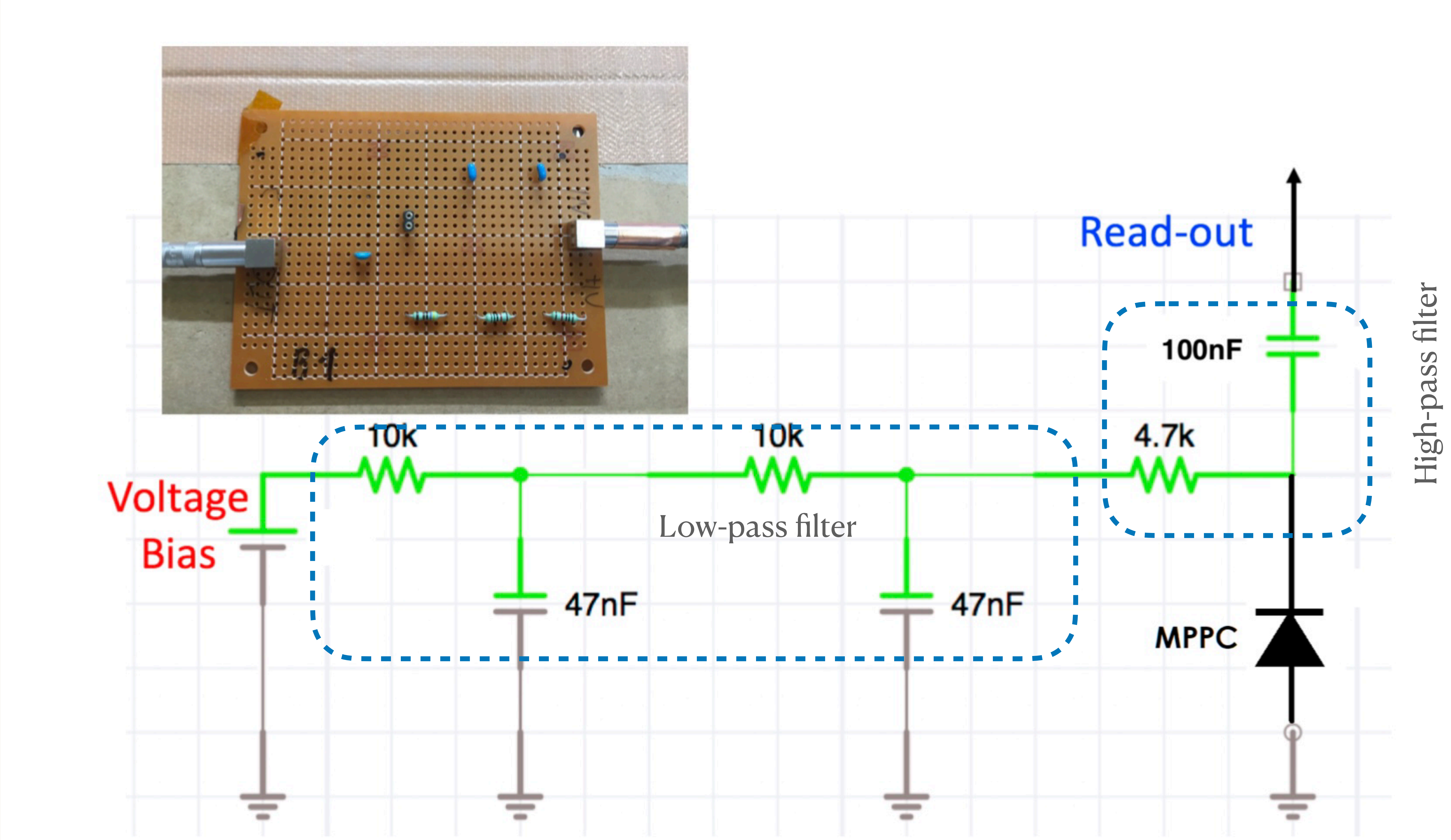
$$\Delta V_{op.} = V_{op.} - V_{breakdown}$$

(Note: breakdown voltage depends on temperature. So even with same operational voltage If the temp. changes, electrical gain is changed



MPPC circuit example





Circuit to operate SiPM is relatively simple! If you have a good power supply, low-pass filter is not needed. You do not need amplifier if your circuit have low electric fluctuation and your signal processing modules (eg. discriminator, coincidence, ADC) can handle ~ mV -pulse height/ ns - duration signals.