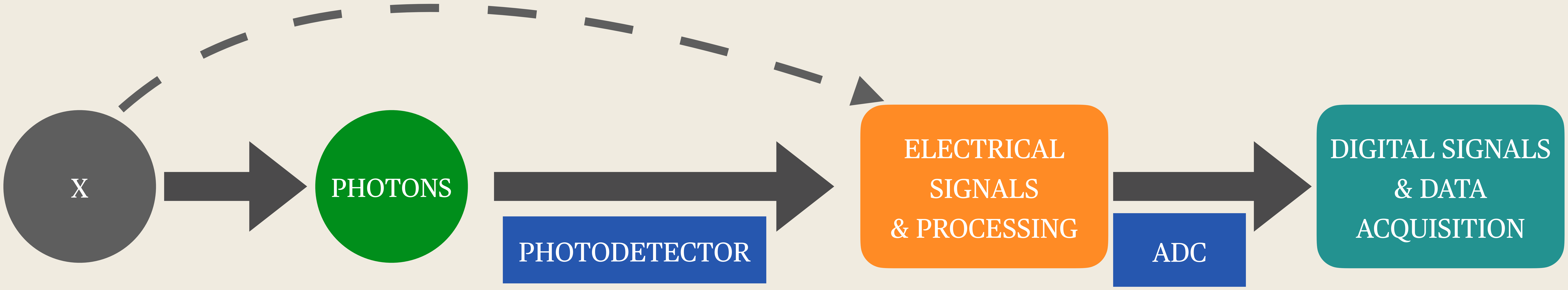
A brief introduction to MPPC and its application

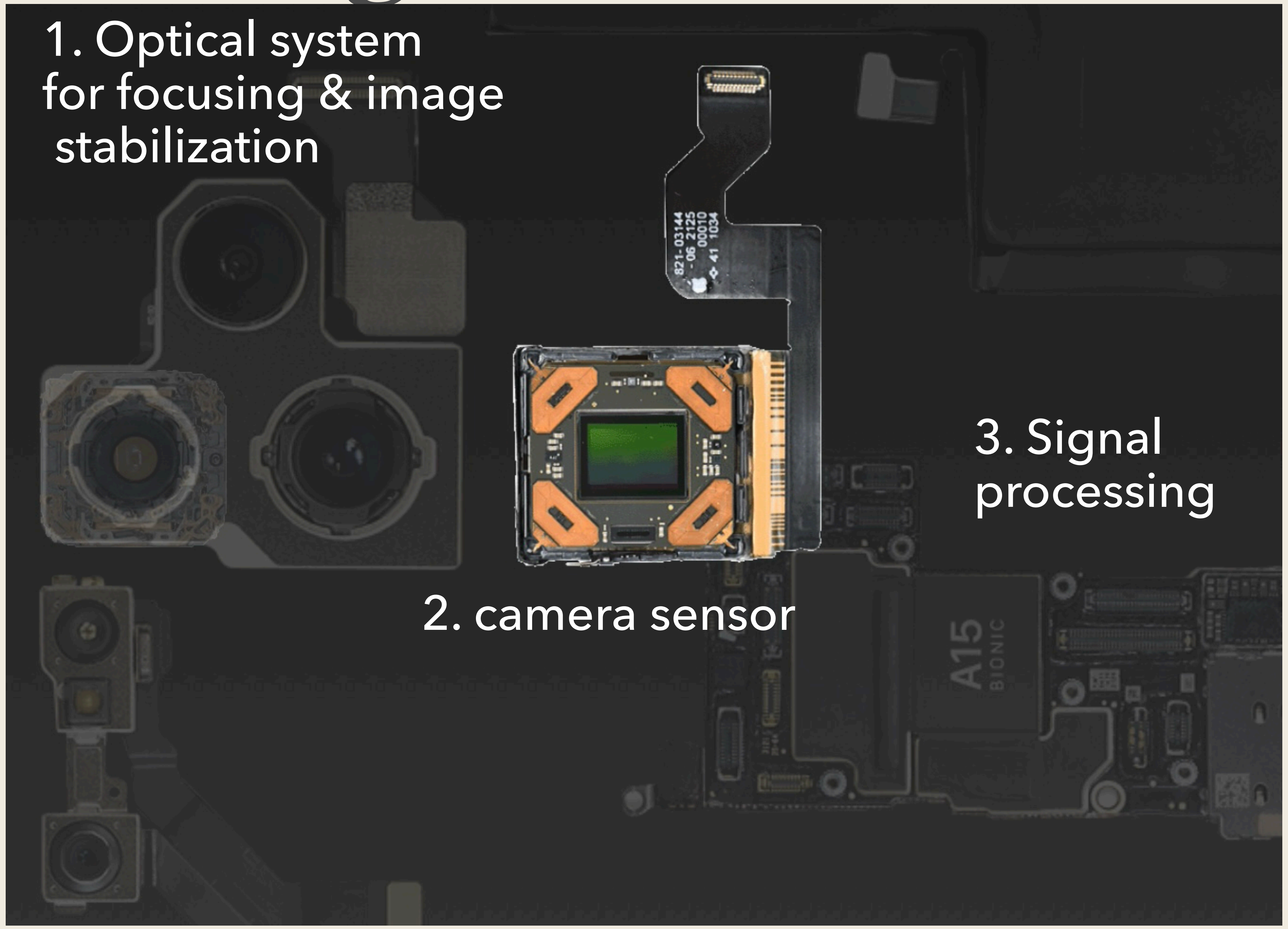
Son Cao (IFIRSE, ICISE)

General principle of modern PN detector

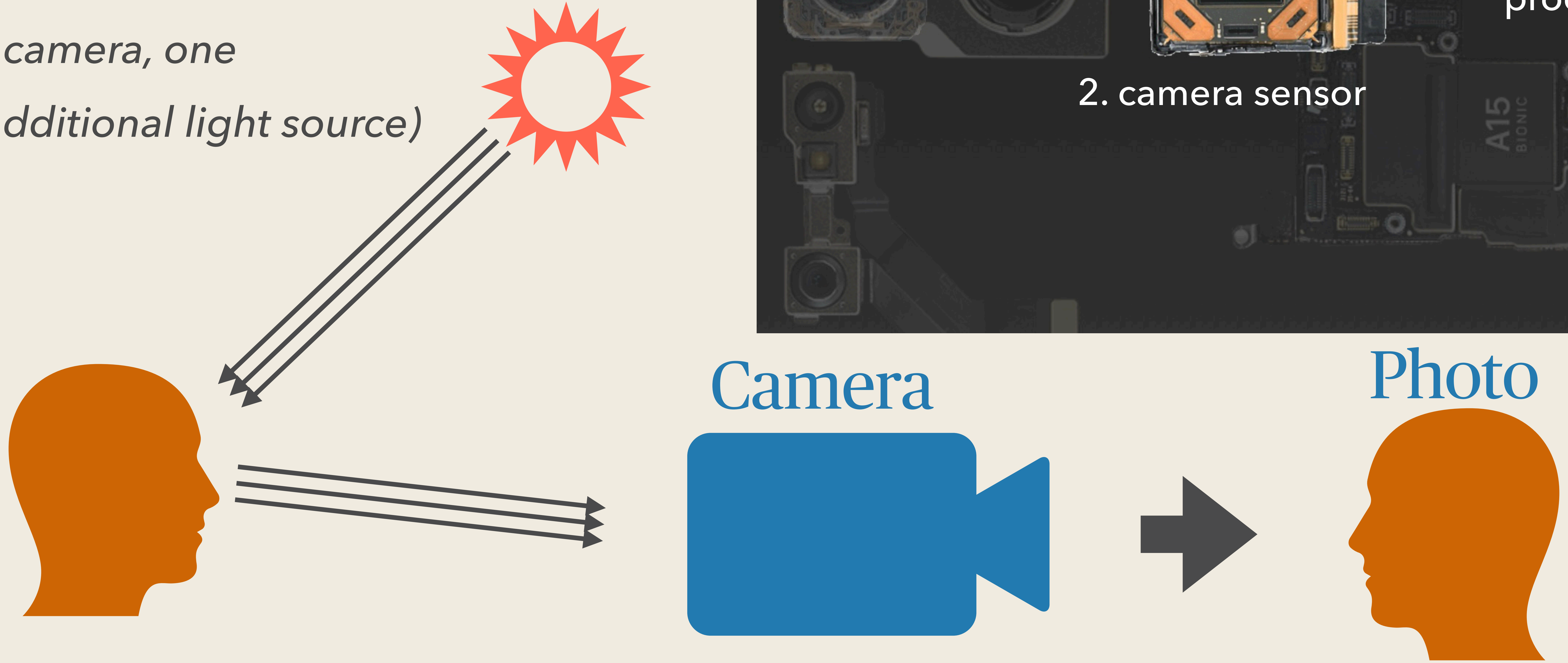


- Turn invisible things to visible things (*accessible to human perception*)
- (*Modern detector*) be **electrical** in nature, i.e at *some points the information is converted into electrical impulses and treated with electronic devices*
- NO detector can be sensitive to all types of radiations at all energies ➜ selection of the appropriate photosensor

Image sensor in Digital camera

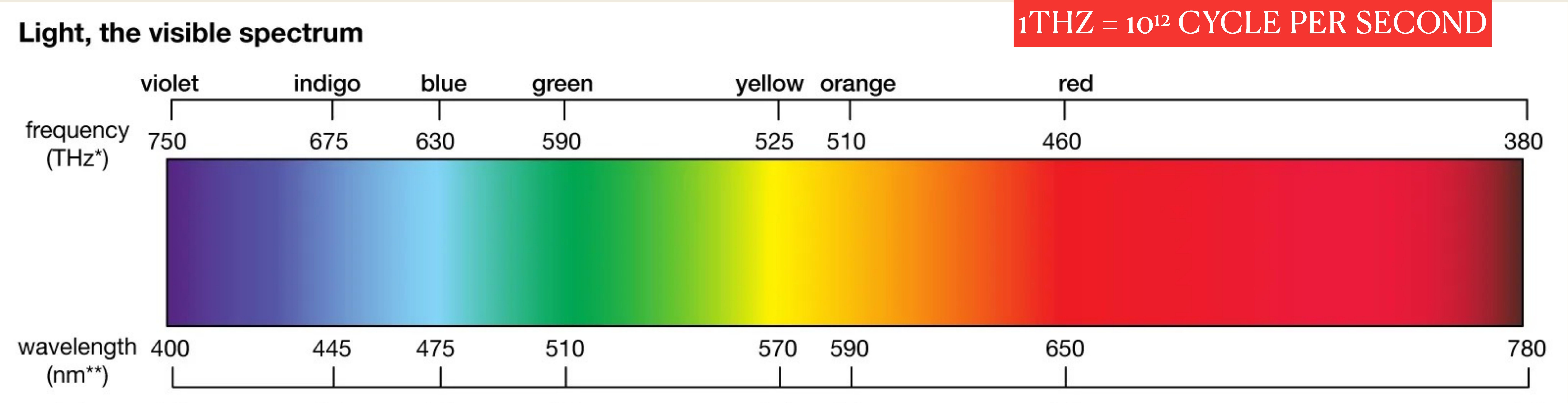


(For thermal camera, one
don't need additional light source)



1HZ = 1 CYCLE PER SECOND

1THZ = 10^{12} CYCLE PER SECOND



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

WAVELENGTH [M]

PERIOD [S]

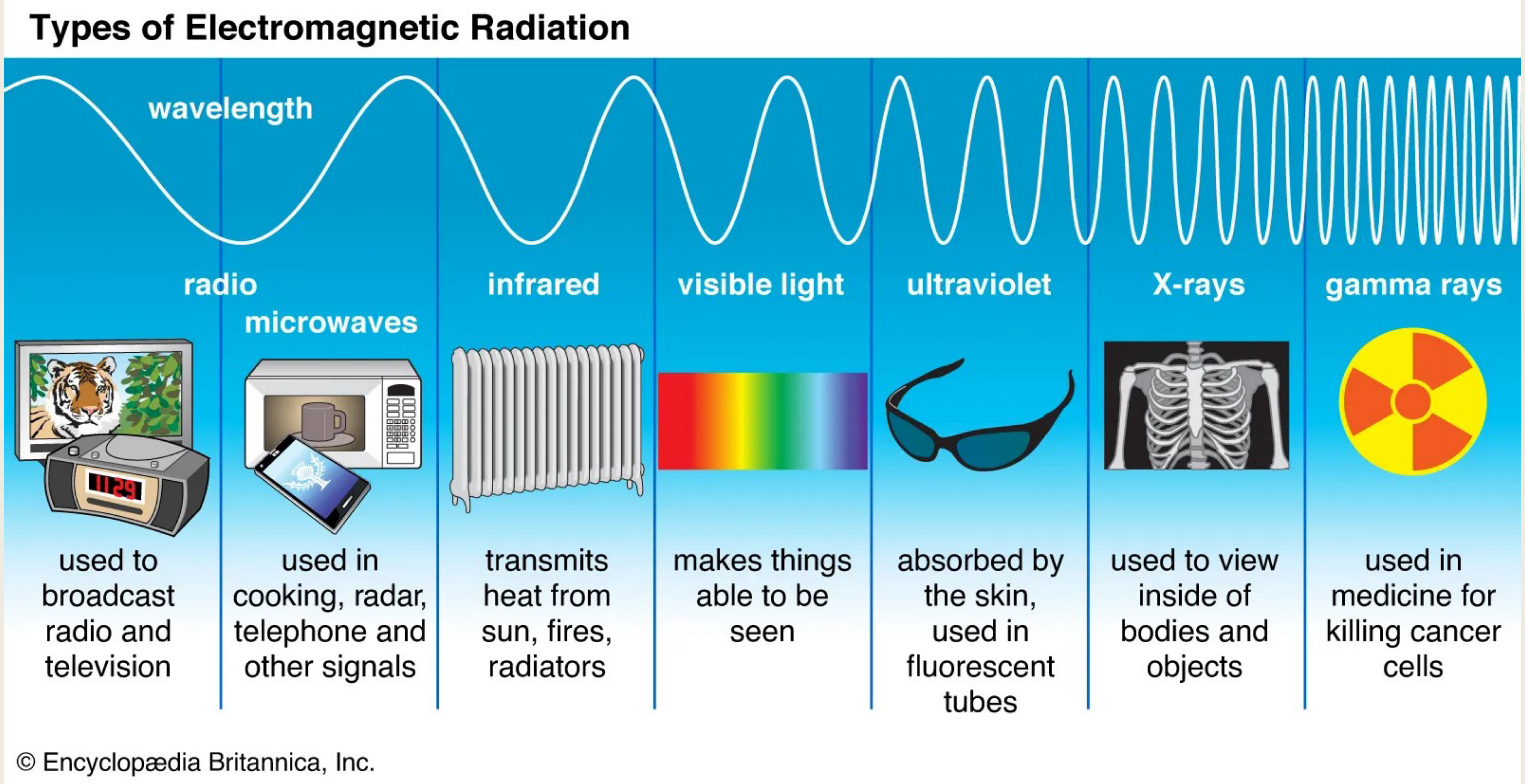
FREQUENCY [HZ]

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

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

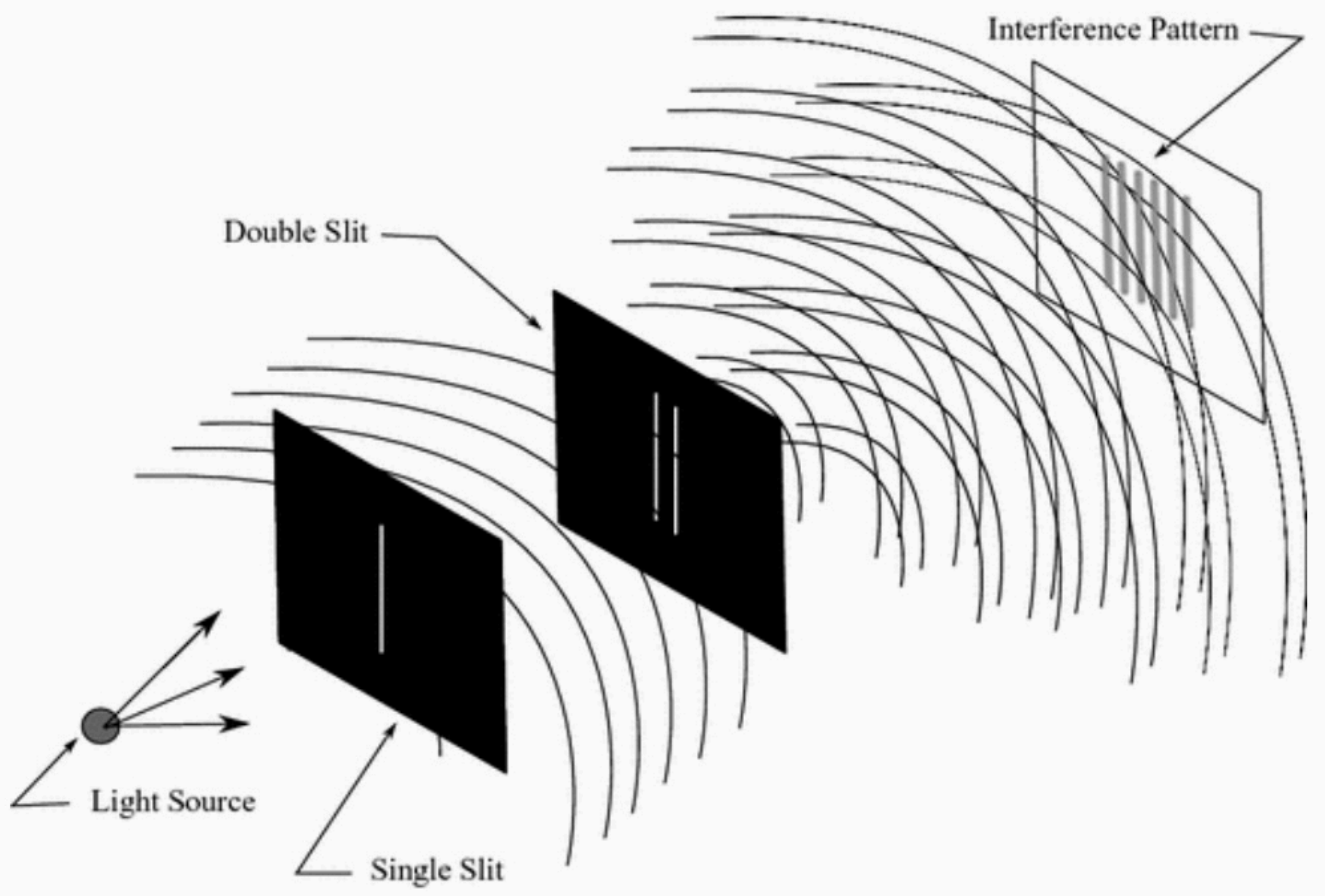


Higher energy (frequency), shorter wavelength

Nature of light: A brief reminder

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

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

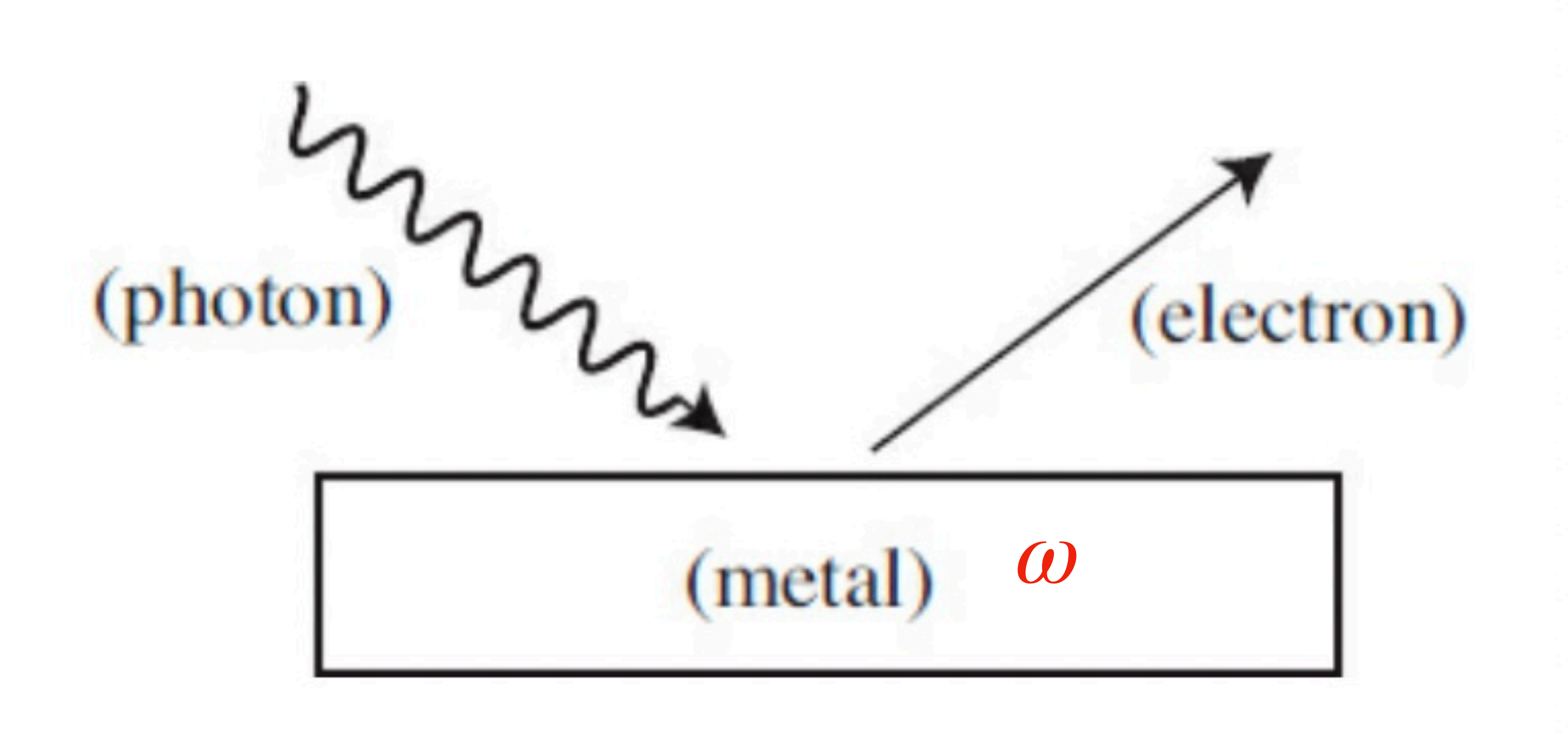


Young's double-slit interference experiment

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

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

- Also our eyes have some limitation in sensing the light
  - *Up to which light level (10 photons or 100 photons?) you can start seeing something in the dark?*
  - *How to set up such kind of experiment?*

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

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

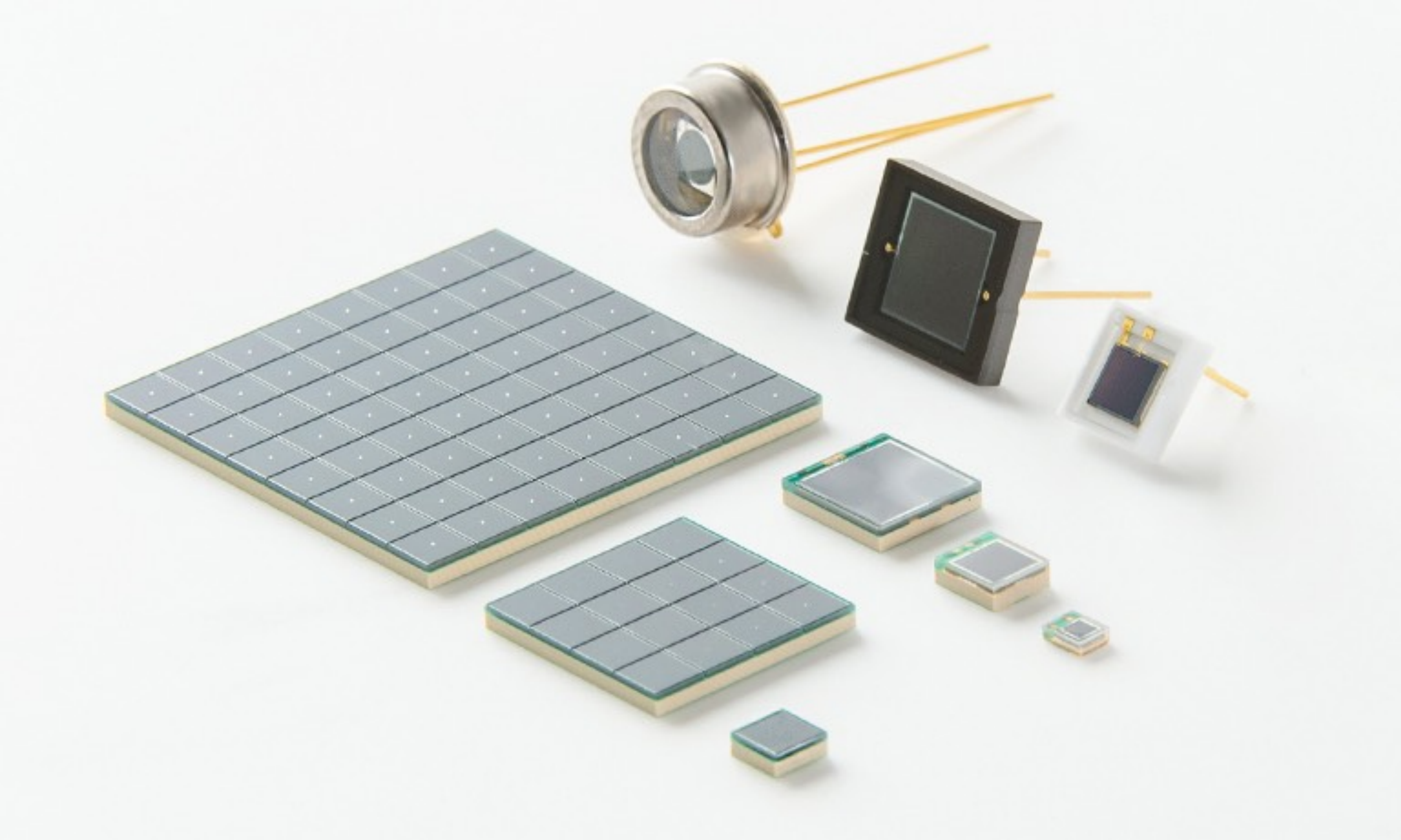
$$f = \frac{c}{\lambda} = \frac{3 \times 10^{8}[m/s]}{405 \times 10^{-9}[m]} = 7.4 \times 10^{14}[s^{-1}] = 7.4 \times 10^{14}[Hz]$$

Number of photons emitted per second

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

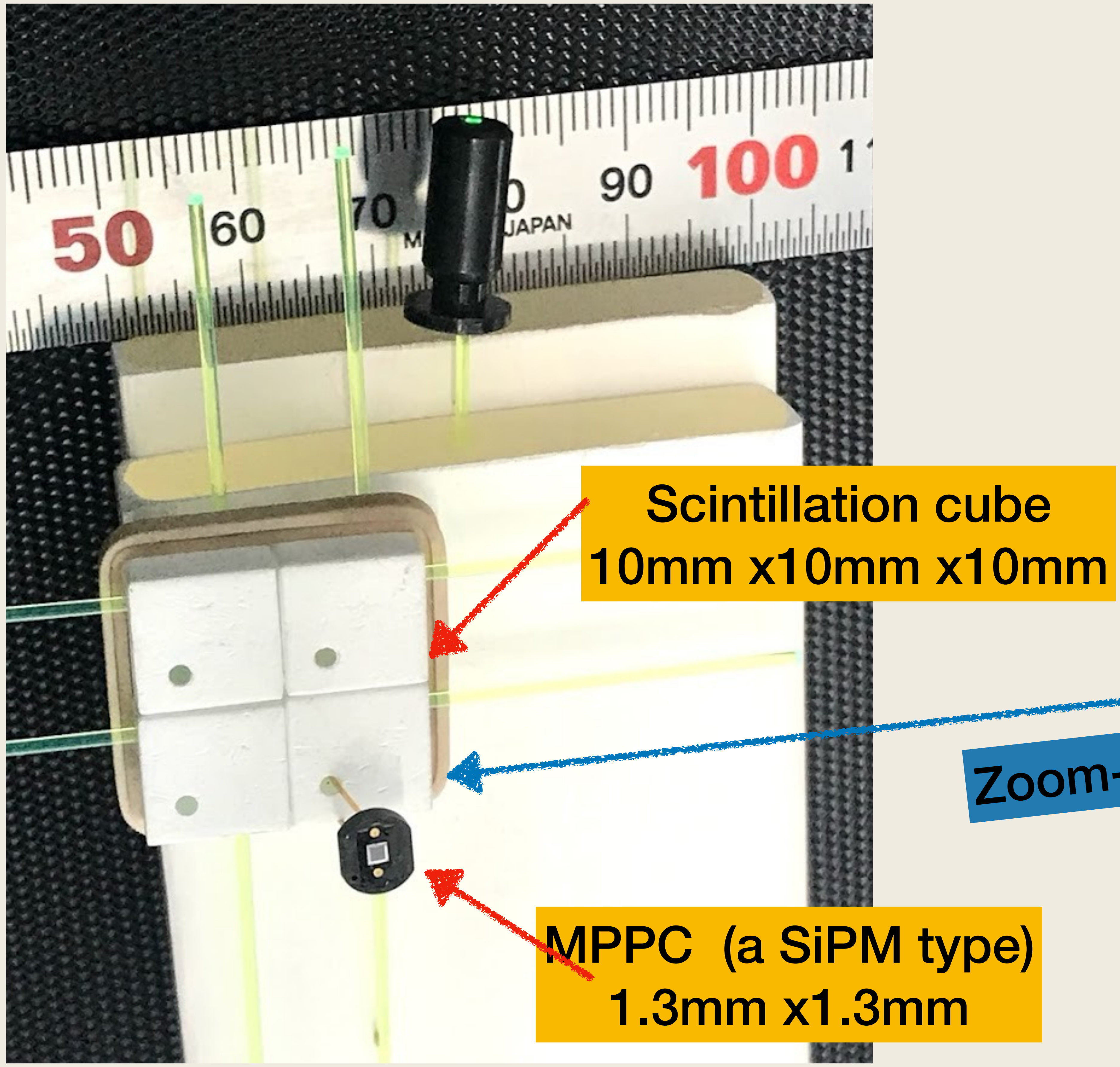
https://www.thorlabs.co.jp/newgrouppage9.cfm?objectgroup_id=2814

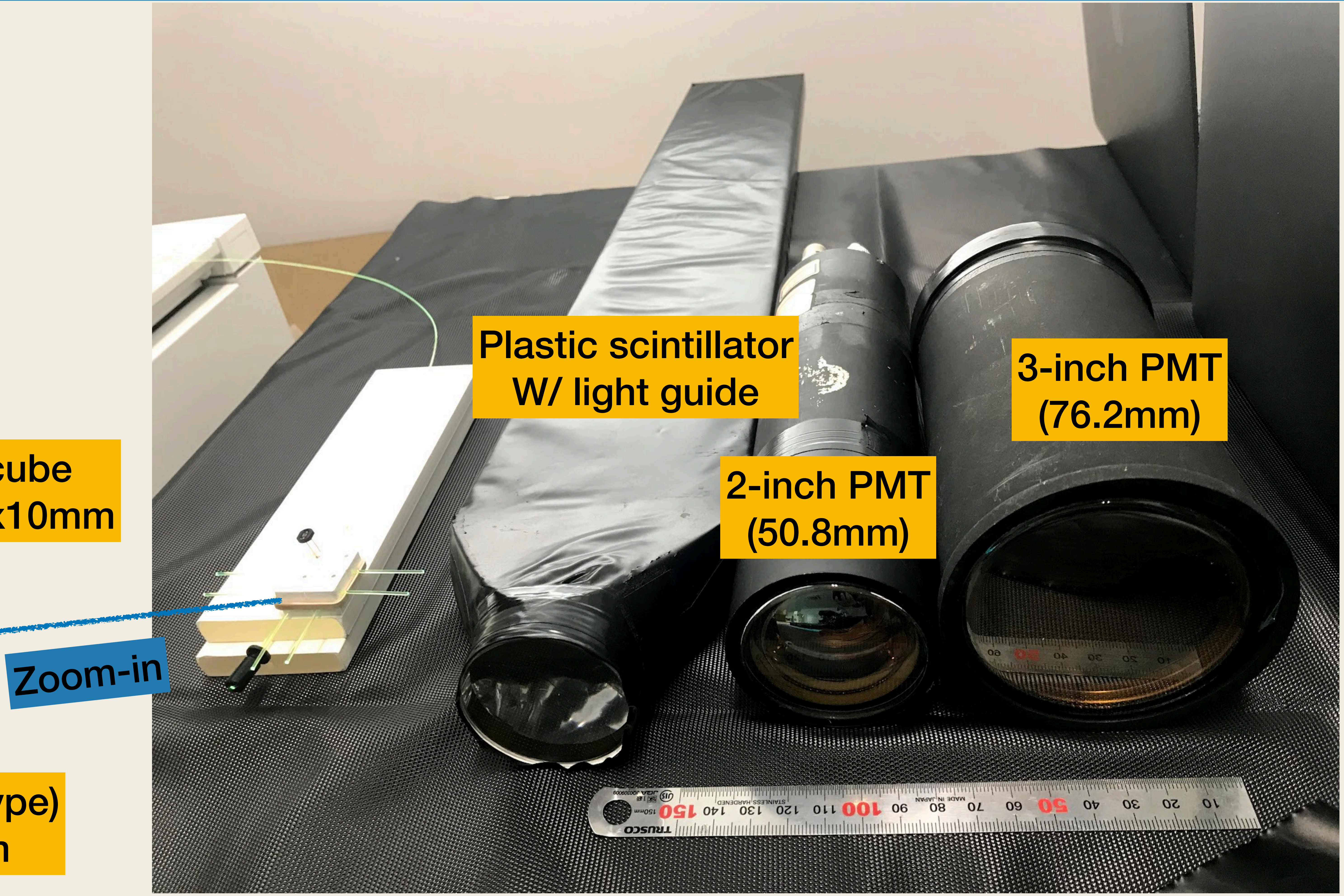
Multi-Pixel Photon Counter (MPPC)



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

Tracking the charged particle w/ scintillator

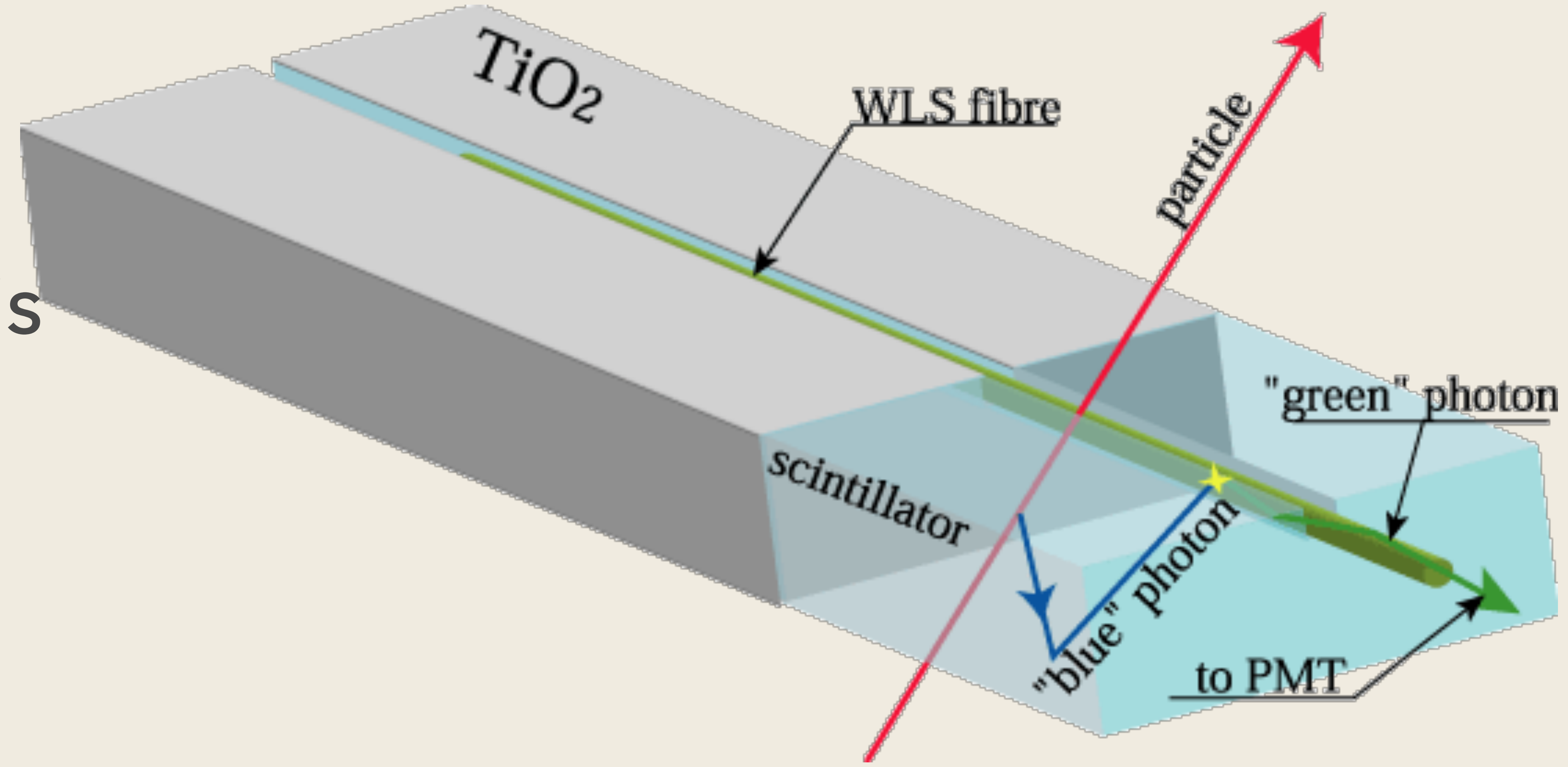




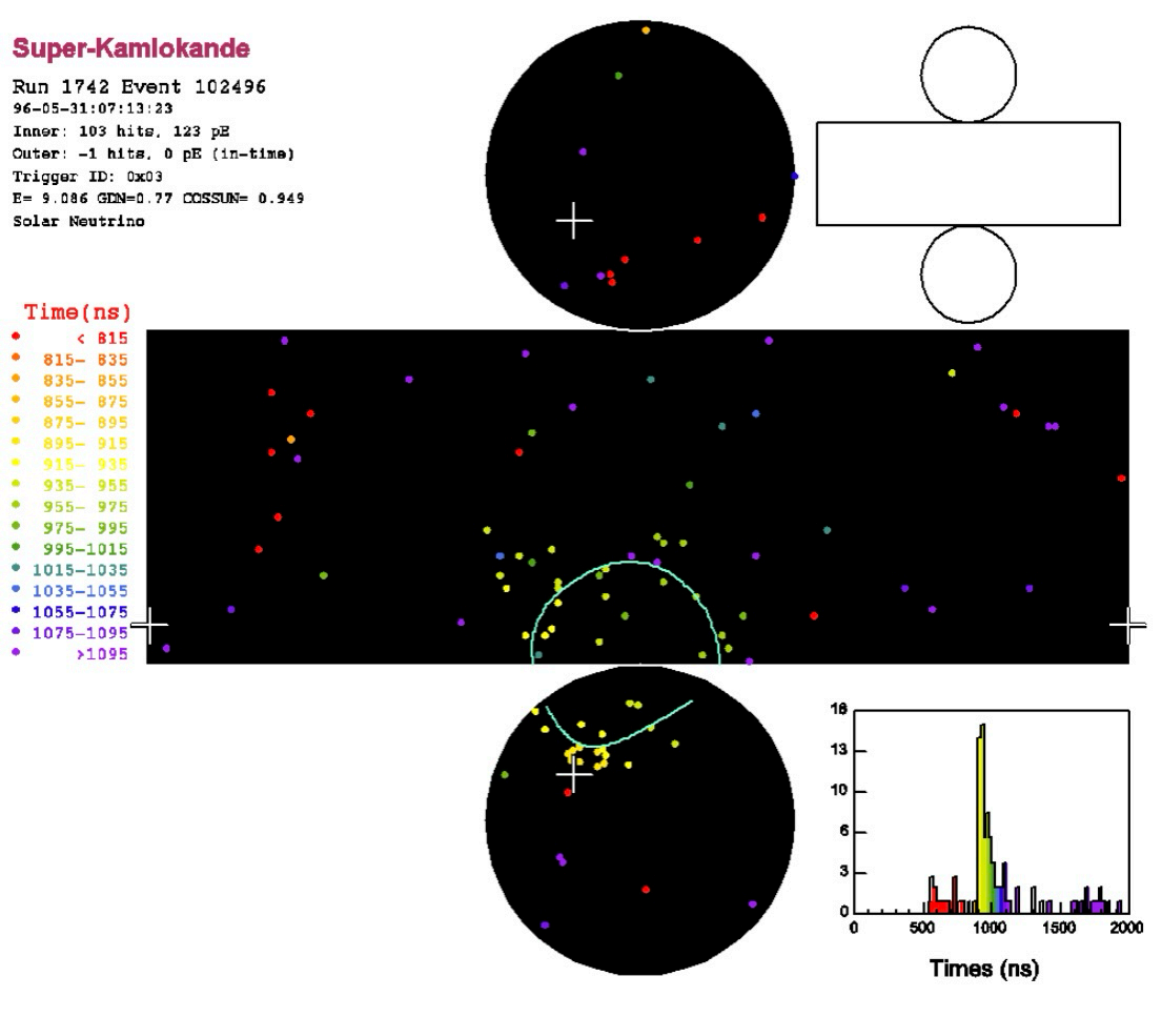
When passing through the scintillator, charged particles (μ, π, e,...) deposits energy and excite the scintillation photons, which are collected and guided to the photosensor for converting to the electrical signals (*more convenient for signal processing*) for data recording.

Tracking the charged particle w/ scintillator

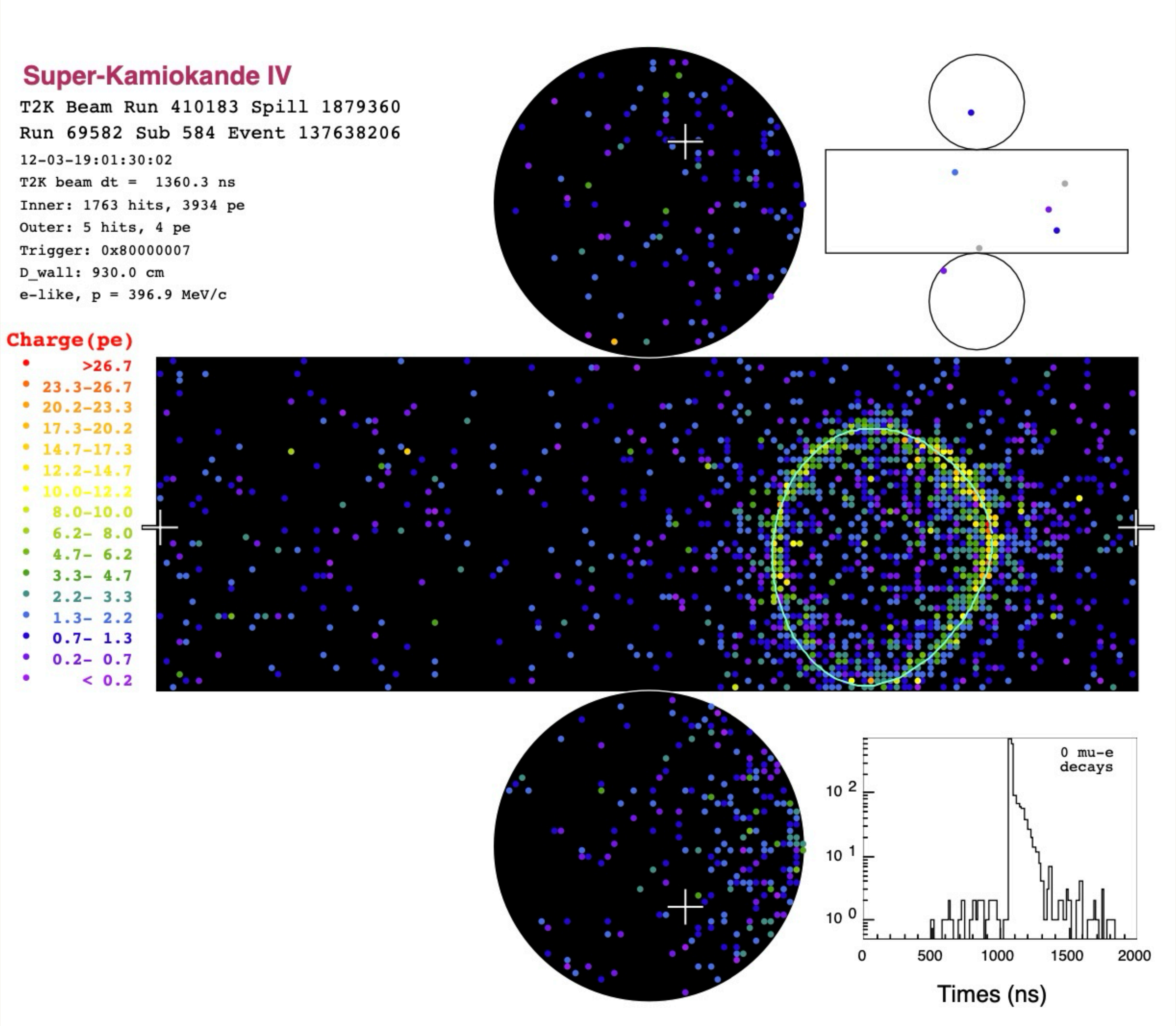
- Muon deposits ~ 2MeV per 1cm path in the plastic scintillator
- 2MeV deposit energy will produce ~ 10,000 scintillation photons with plastic scintillator
- Assume the probability for WLS catching the photons is about 1%, then ~ 100 photons are captured and changed to green photons (*assuming perfect blue-to-green wavelength shifting*)
  - *Light can loss when transport inside of WLS*
- 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*



Trace of neutrinos: (typically) very 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

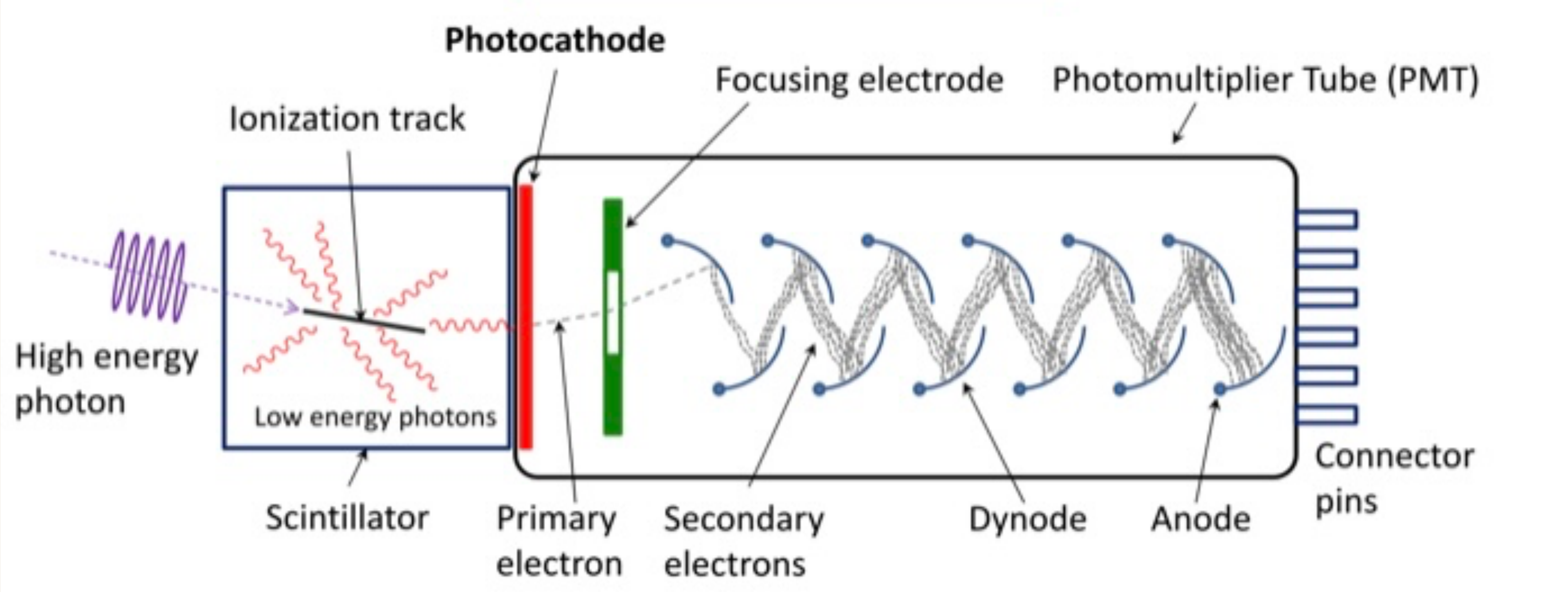
- ....~10^{15} photons are generated

Photodetectors

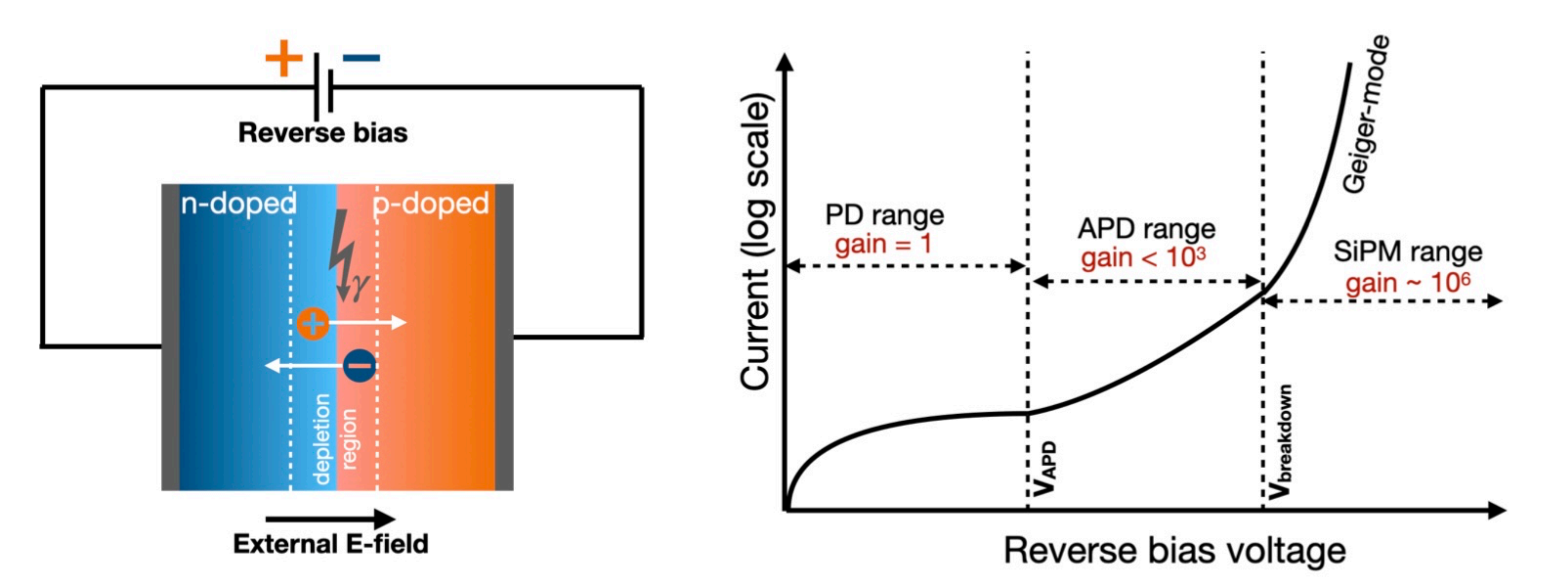
Extremely important to extend particle frontiers (precision, sensitivity, intensity...)

More in Prof. Tsuyoshi Nakaya's lecture

Characteristic	PMT	PD	APD	SiPM
Spectral coverage [nm]	115-1,700	190-13,000	190-1,700	320-900
Peak QE (η) [%]	< 40	< 90	< 90	< 40 (*PDE*)
Active area [mm^2]	< 12,000	< 100	< 100	< 10
Gain (μ)	10^5-10^6	1	< 100	10^5-10^6
NEP [W/√Hz]	> $2x10^{-17}$	> $6x10^{-16}$	> $1x10^{-15}$	> $6x10^{-16}$
Rise time [ns]	> 0.15	> 0.23	> 0.35	> 1
Bandwidth [Hz]	< $2x10^9$	< $1.5x10^9$	< $1x10^9$	NA
Time jitter [ns]	> 0.05	NA	> 0.2	> 0.2



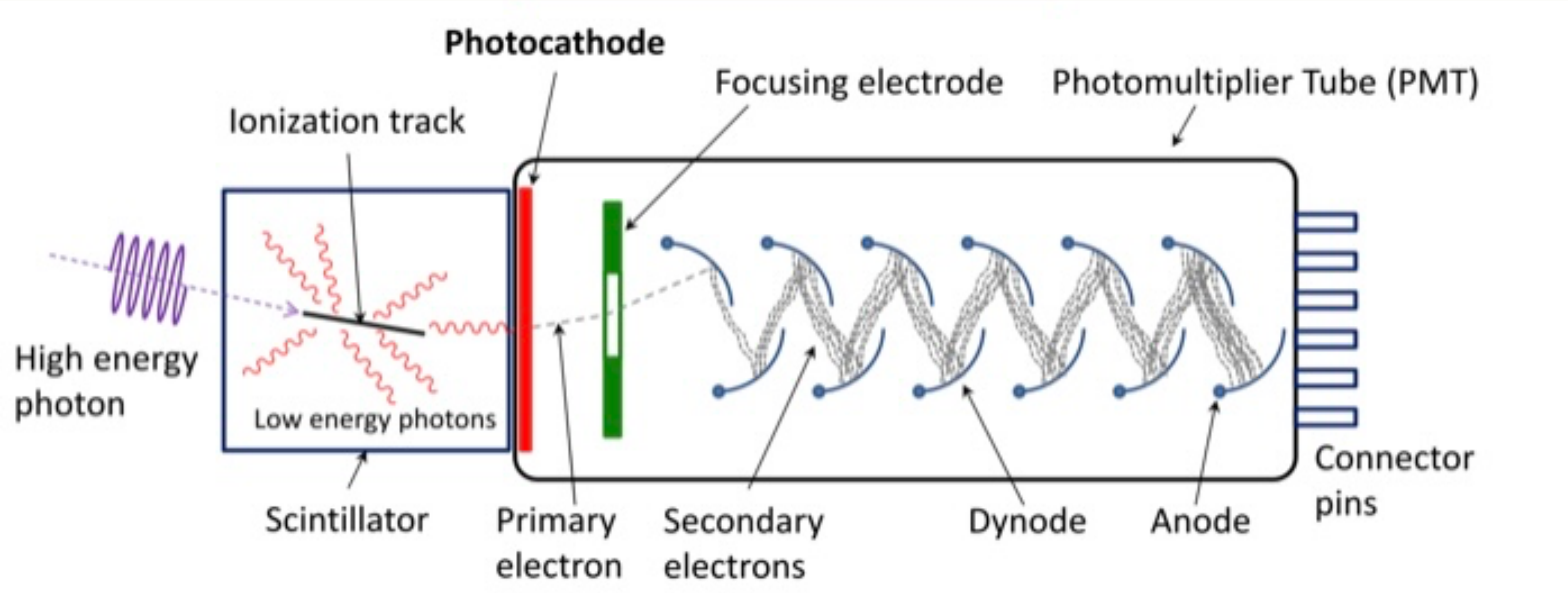
Based on "External" photoelectric effect



Based on "Internal" photoelectric effect

Other photodetectors are thermal type (*light-induced temperature rises*), e.g fire alarm.

PMT



Multiplication factor, or called electric gain

$$G = \delta^{n}$$

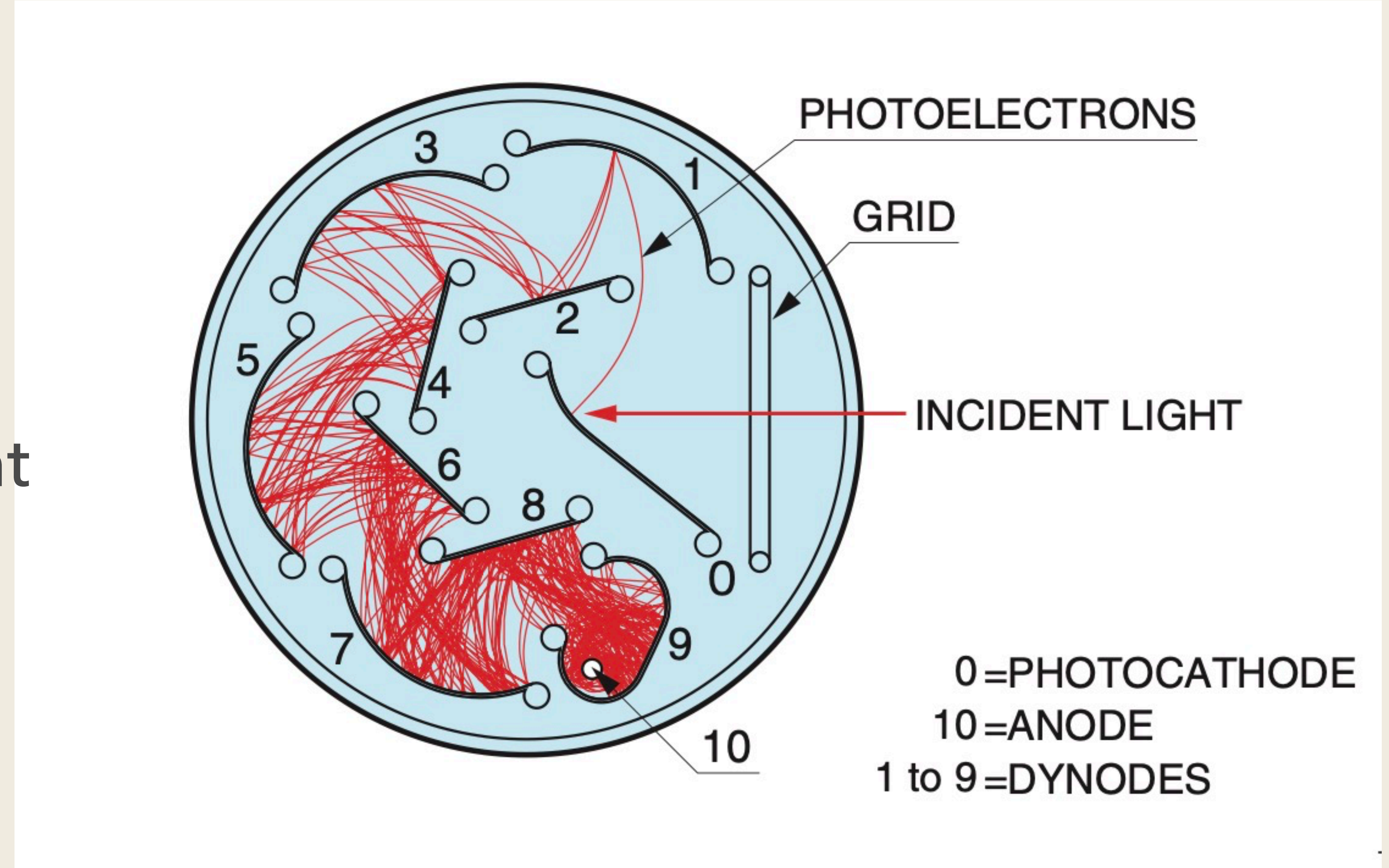
No. of dynodes

Emission ratio of secondary electron

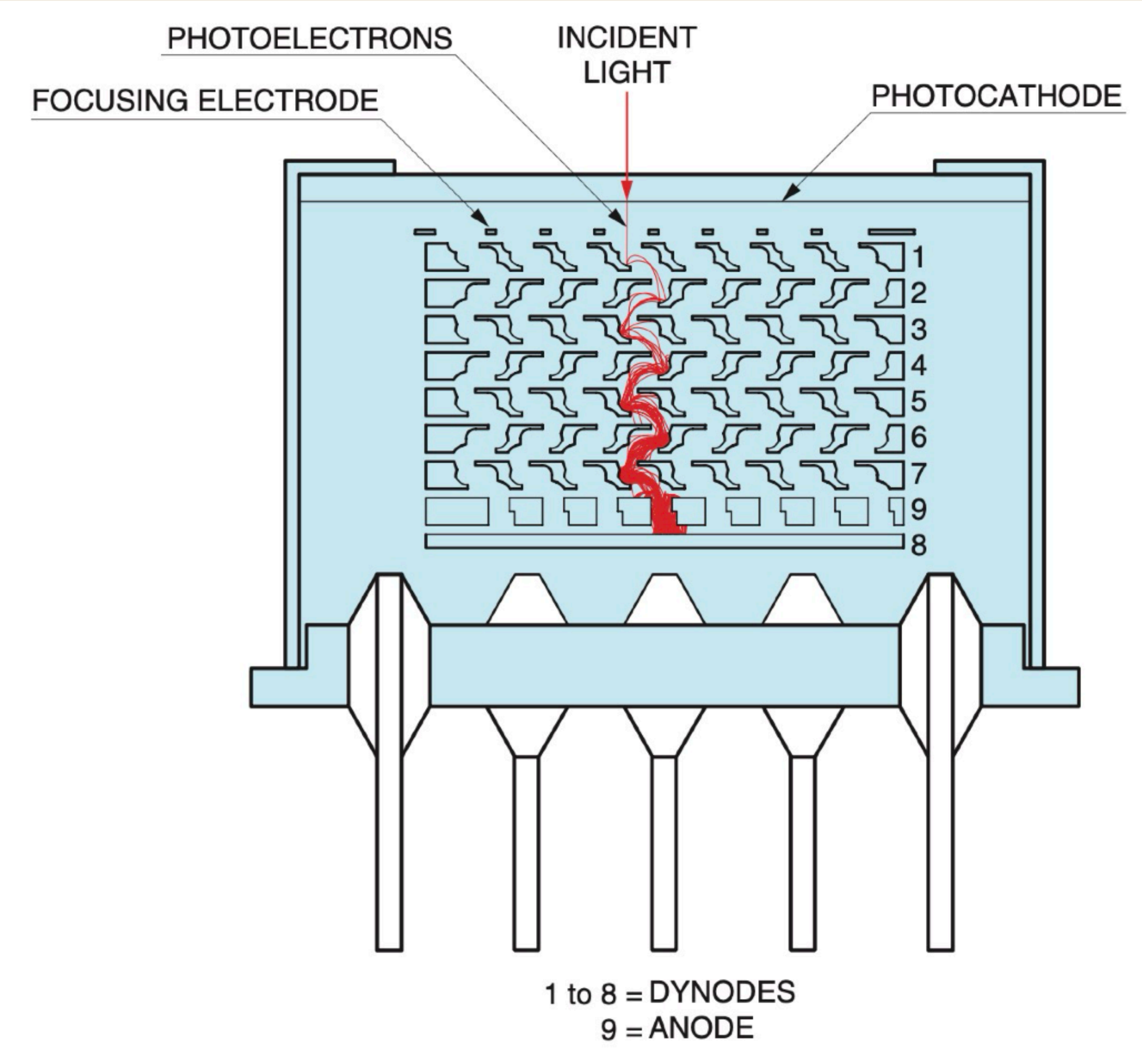
Based on "External" photoelectric effect

Also called vacuum-based PMT

Trajectory of secondary electrons determined by the dynode arrangement

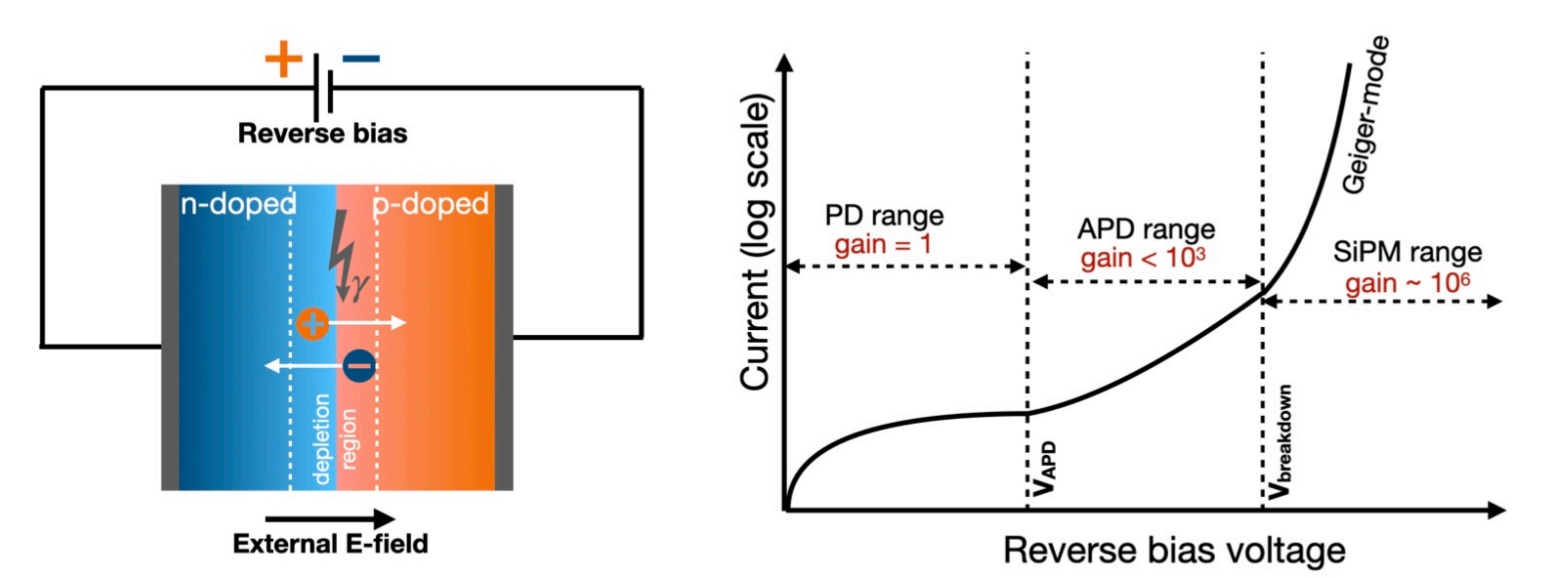


Circular-cage type



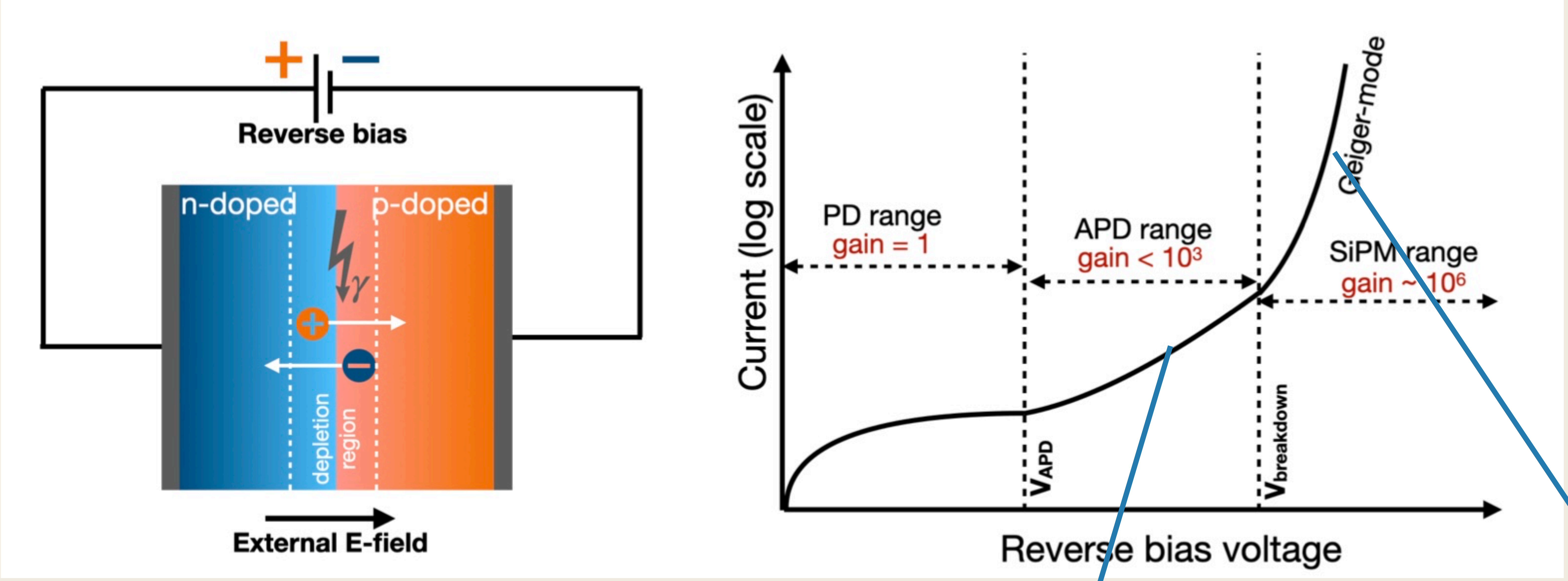
Metal-cage type

Photon detection principle w/ Silicon photomultiplier (SiPM)



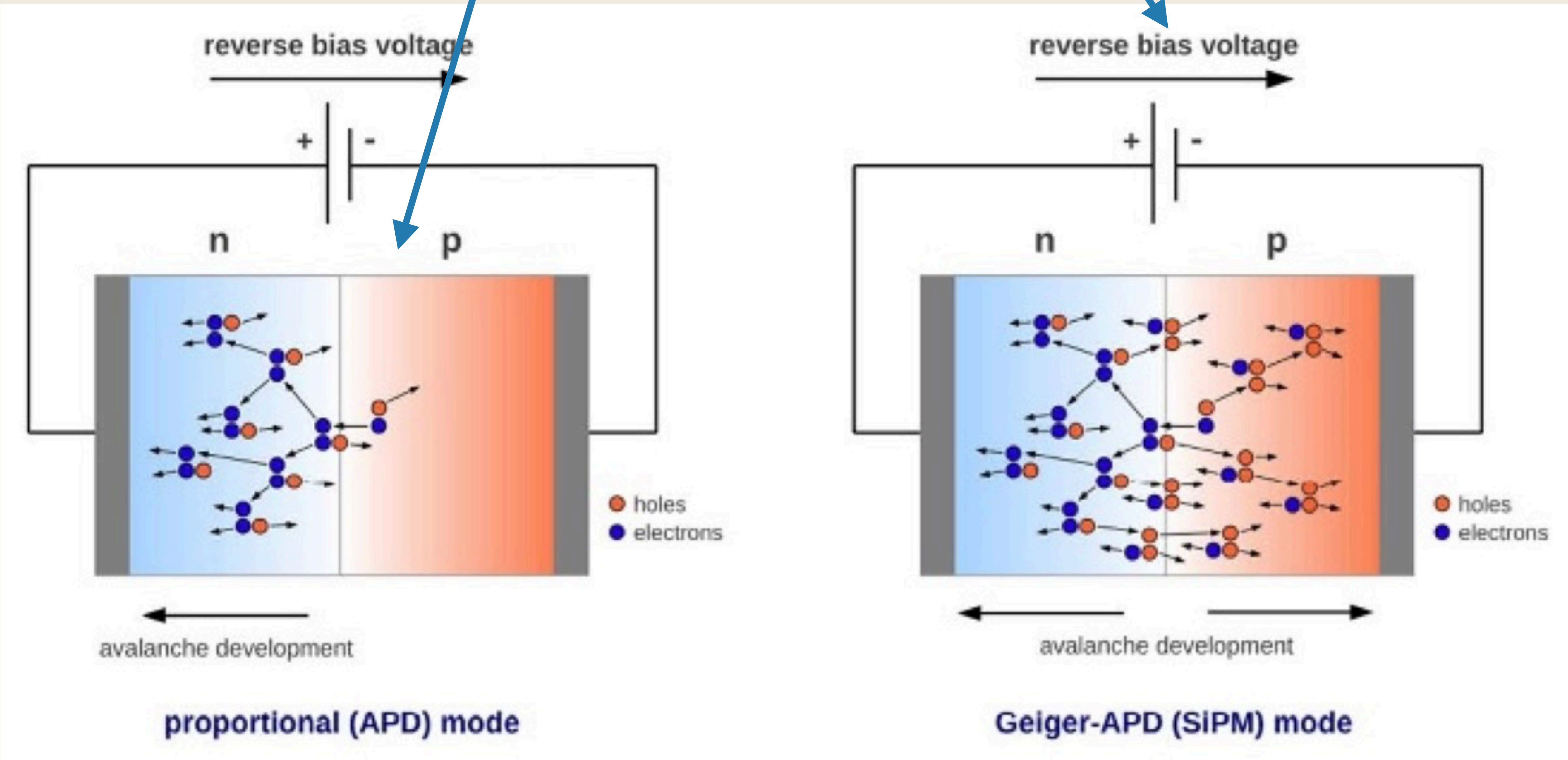
- Based on “internal” photoelectric effect: photon strikes in the depletion region and produce a pair of electron/hole
- Under external E-field, induced carrier can form a current when the circuit is closed.
- When the E-field is small, one coming photon induces one electron -> gain =1, called Photodiode (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

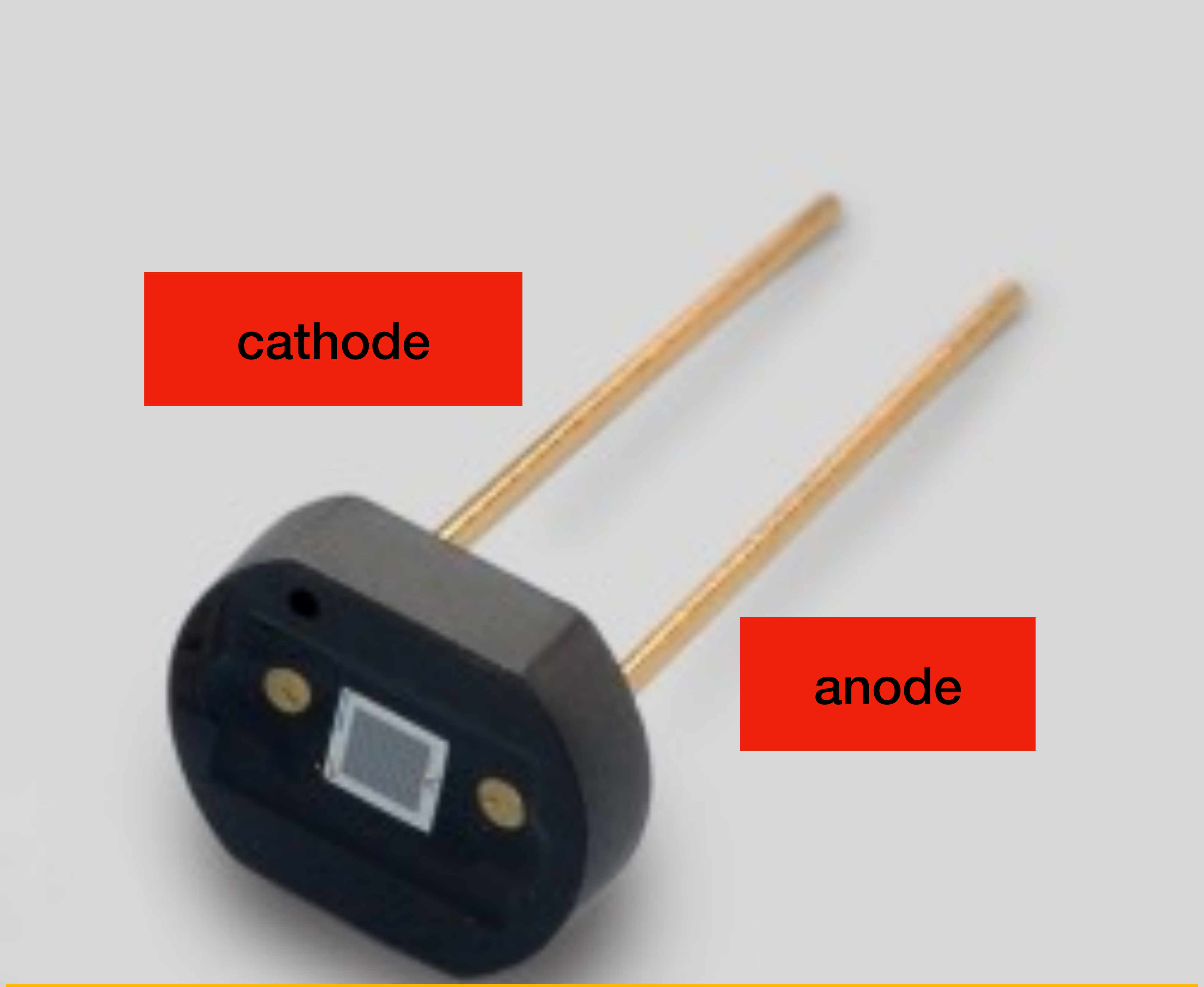
- (0) No signal = no photoelectron
- (1) same-size signal for **any number (>1)** of arriving photons



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?

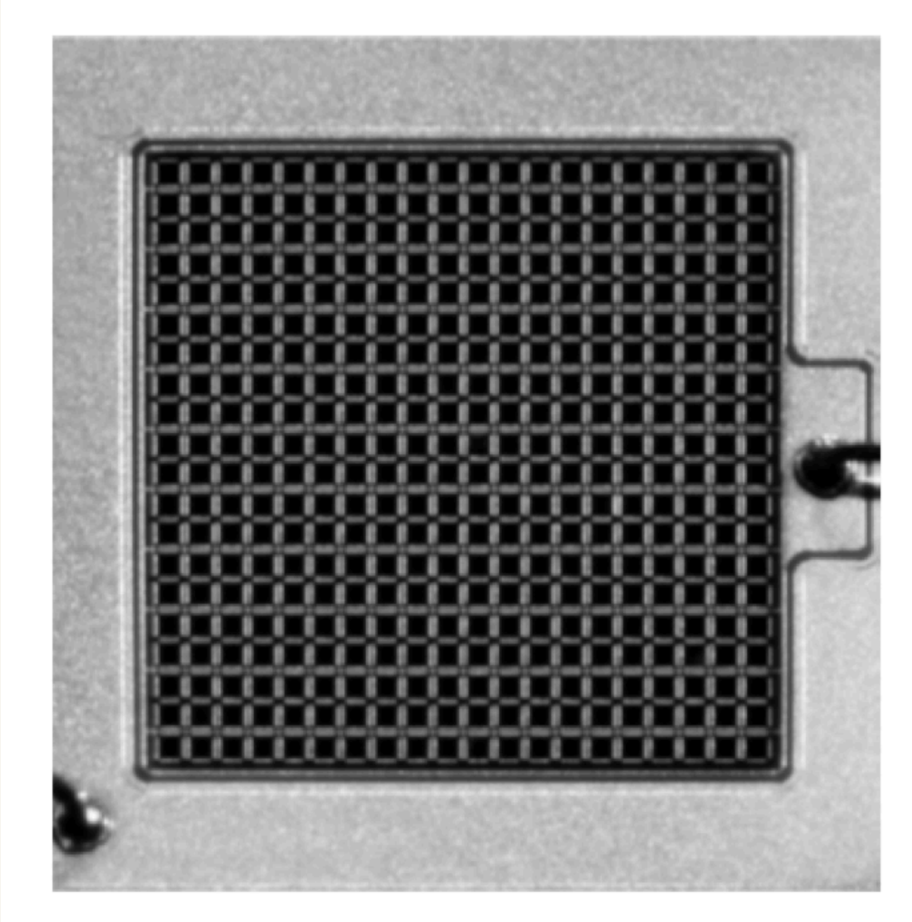
(Keep in mind, in the faint light sources, having photon arrived at the same time and same place is very rare.)

MPPC: a type of SiPM, developed by Hamamatsu

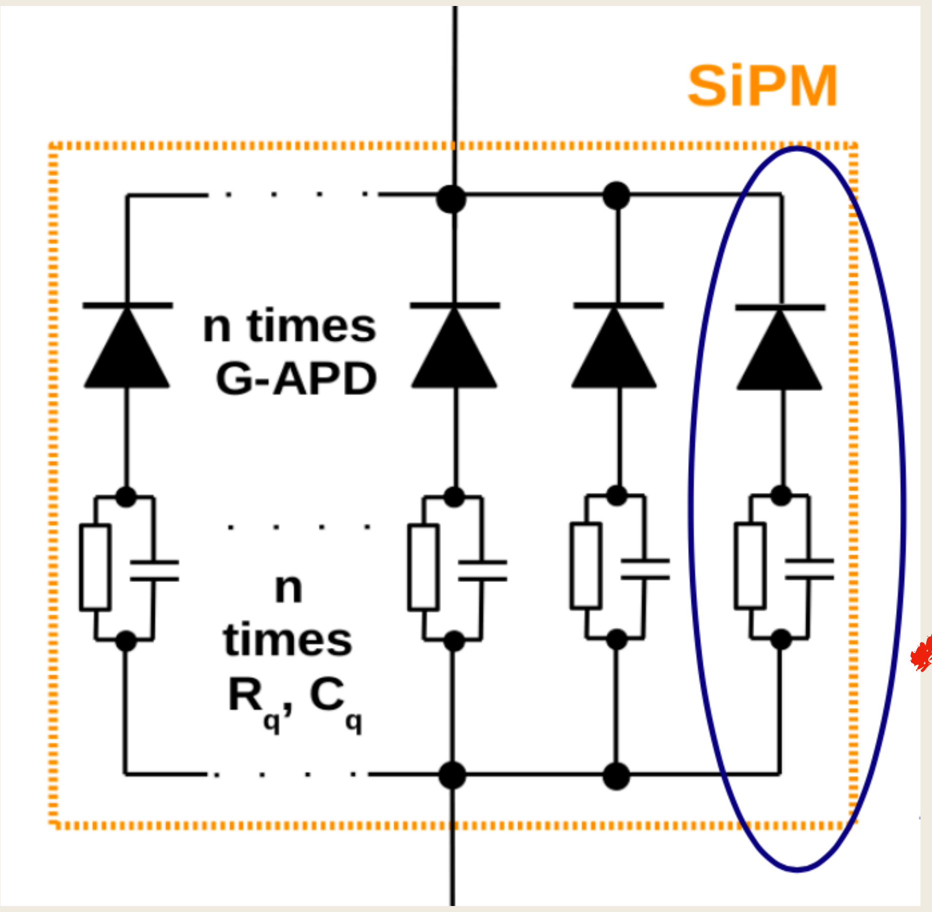


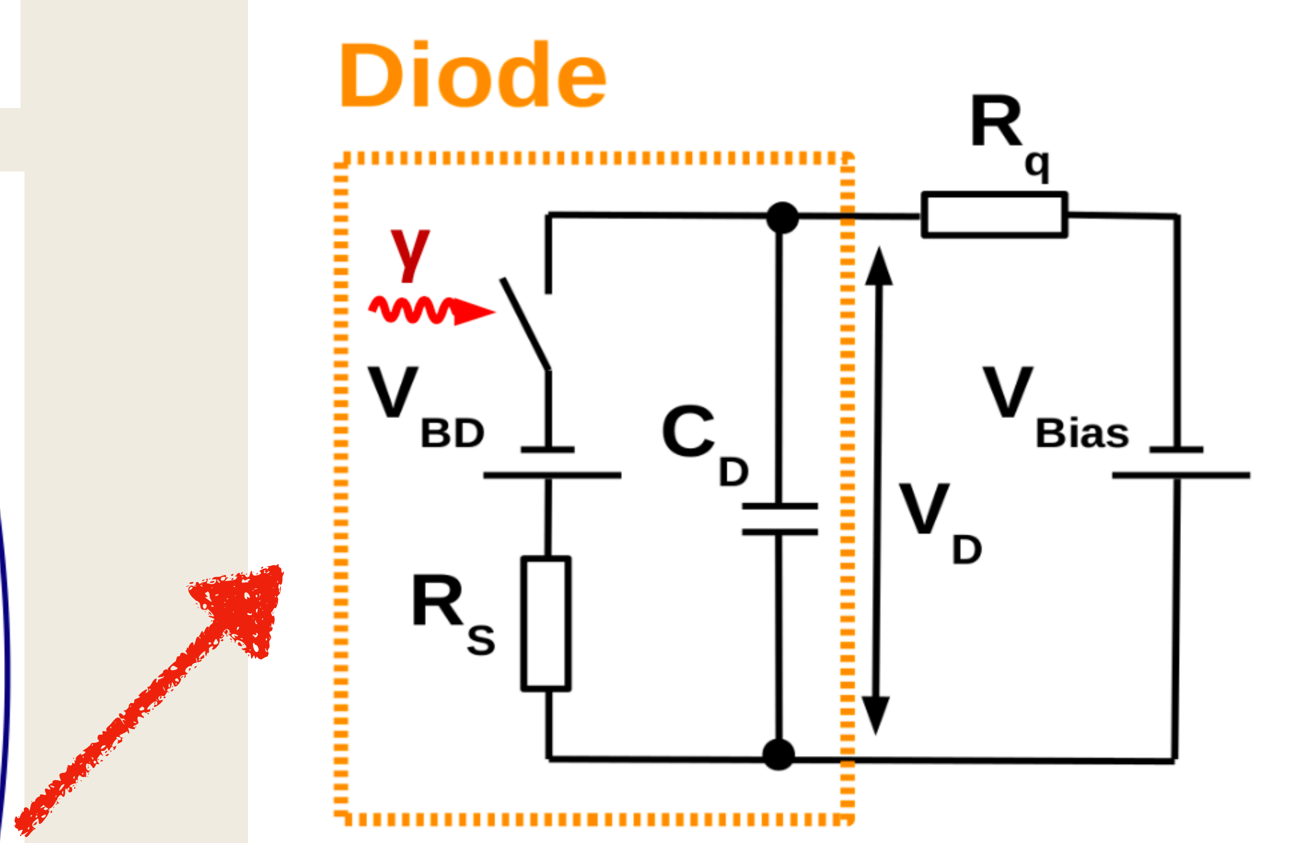
Sensor area: 1.3cm x1.3cm
Pixel pitch: 25um

An example

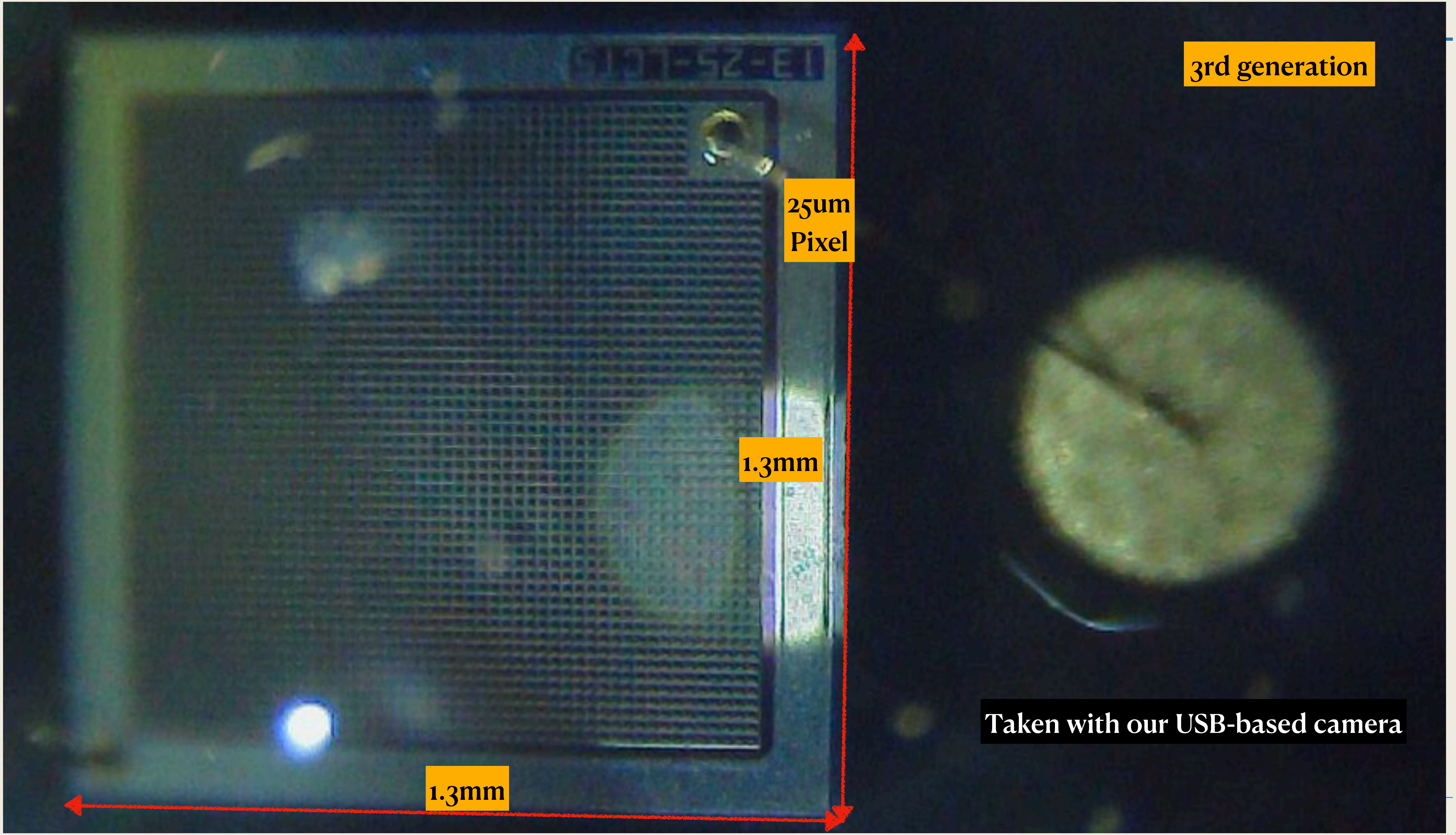


Array of pixels





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

MPPC: various lines of products

Type no.	Pixel pitch (µm)	Effective photosensitive area (mm)	Number of pixels	Package	Fill factor (%)
S13360-1325PE	25	1.3 × 1.3	2668	Glass epoxy	47
S13360-3025CS		3.0 × 3.0	14400	Ceramic	
S13360-3025PE				Glass epoxy	
S13360-6025CS		6.0 × 6.0	57600	Ceramic	
S13360-6025PE				Glass epoxy	
S13360-1350PE	50	1.3 × 1.3	667	Glass epoxy	74
S13360-3050CS		3.0 × 3.0	3600	Ceramic	
S13360-3050PE				Glass epoxy	
S13360-6050CS		6.0 × 6.0	14400	Ceramic	
S13360-6050PE				Glass epoxy	
S13360-1375PE	75	1.3 × 1.3	285	Glass epoxy	82
S13360-3075CS		3.0 × 3.0	1600	Ceramic	
S13360-3075PE				Glass epoxy	
S13360-6075CS		6.0 × 6.0	6400	Ceramic	
S13360-6075PE				Glass epoxy	

Some tradeoff

- More pixels (smaller pixel pitch) give more dynamic range in detecting photon, but lower fill factor -> reduce the detection efficiency (note: detection efficiency and quantum efficiency are not the same)
- Larger sensor will give more dark noise (or dark current)
- *(Most of what we have in the lab is with ceramic package. It's convenience for plug-in plug-out but more expensive)*

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 wide dynamic range S14160 series	For PET scanners S14160/S14161 series	
VIS	For precision measurement S13360/S13362 series	For precision measurement S13360/S13362 series		
VIS	For precision measurement (TSV type) S13360/S13361/S13363 series	For precision measurement (TSV type) S13360/S13361/S13363 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 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)

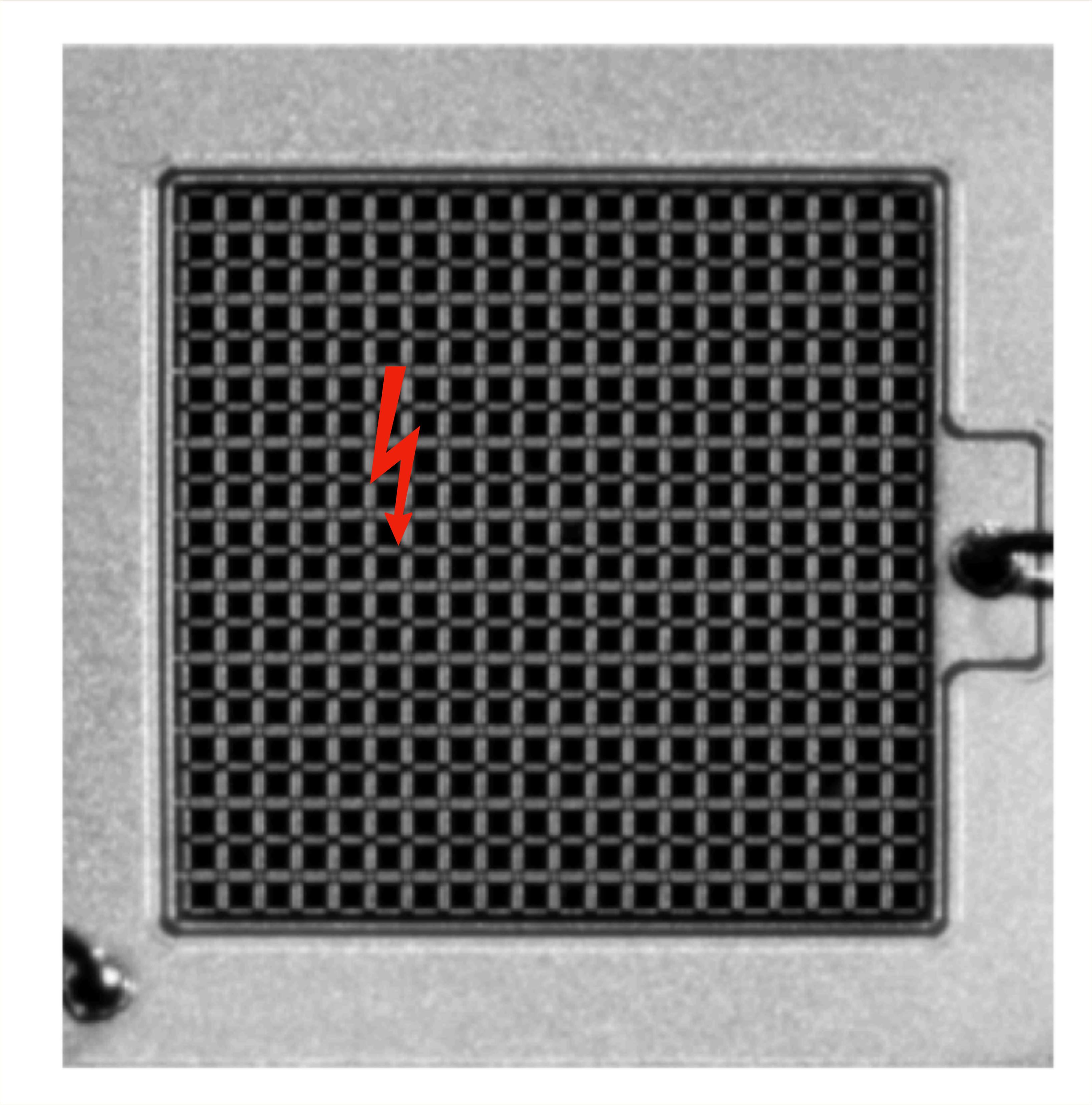
Applications

- 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

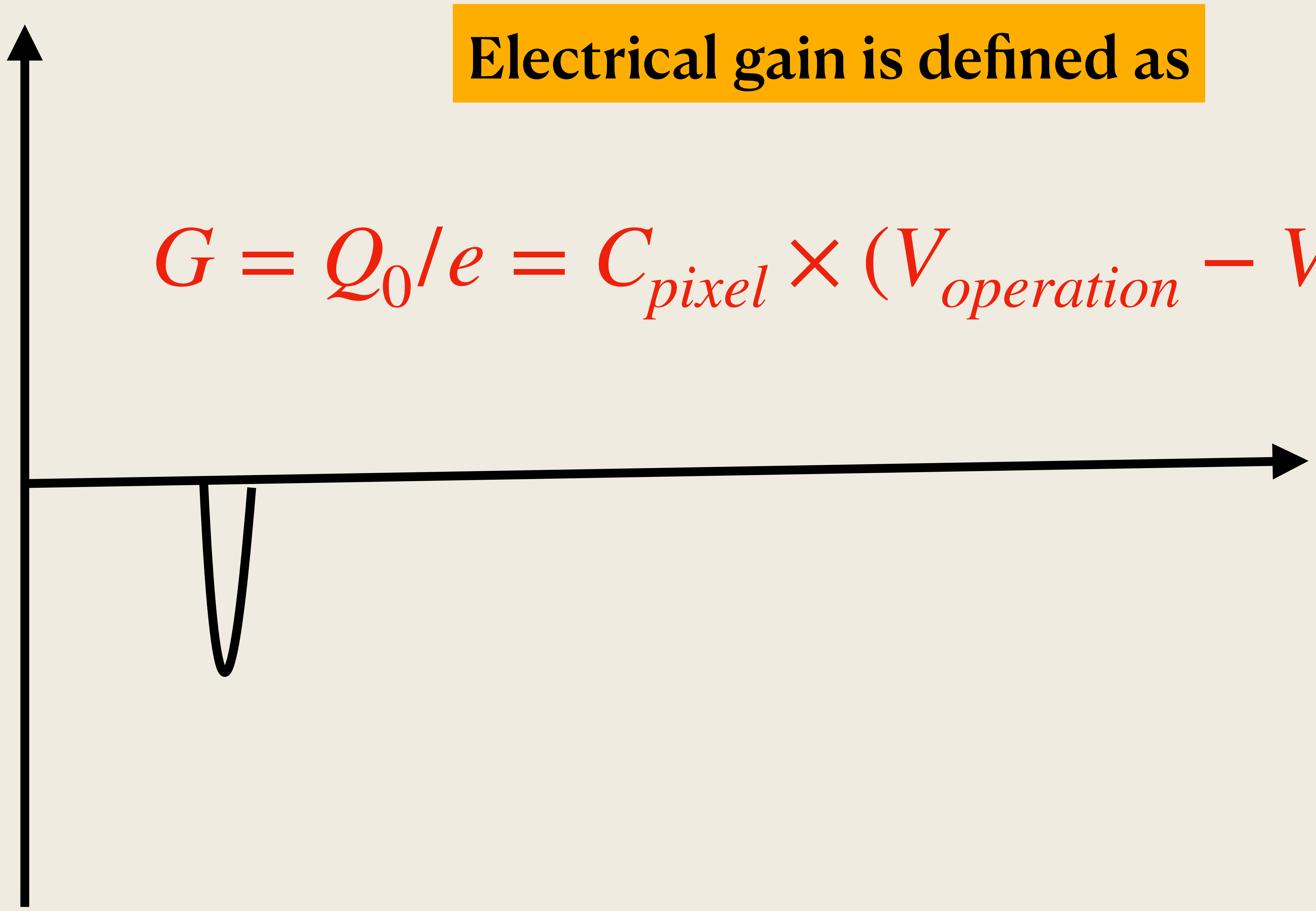
Basic principle of photon counting

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



Electrical gain is defined as

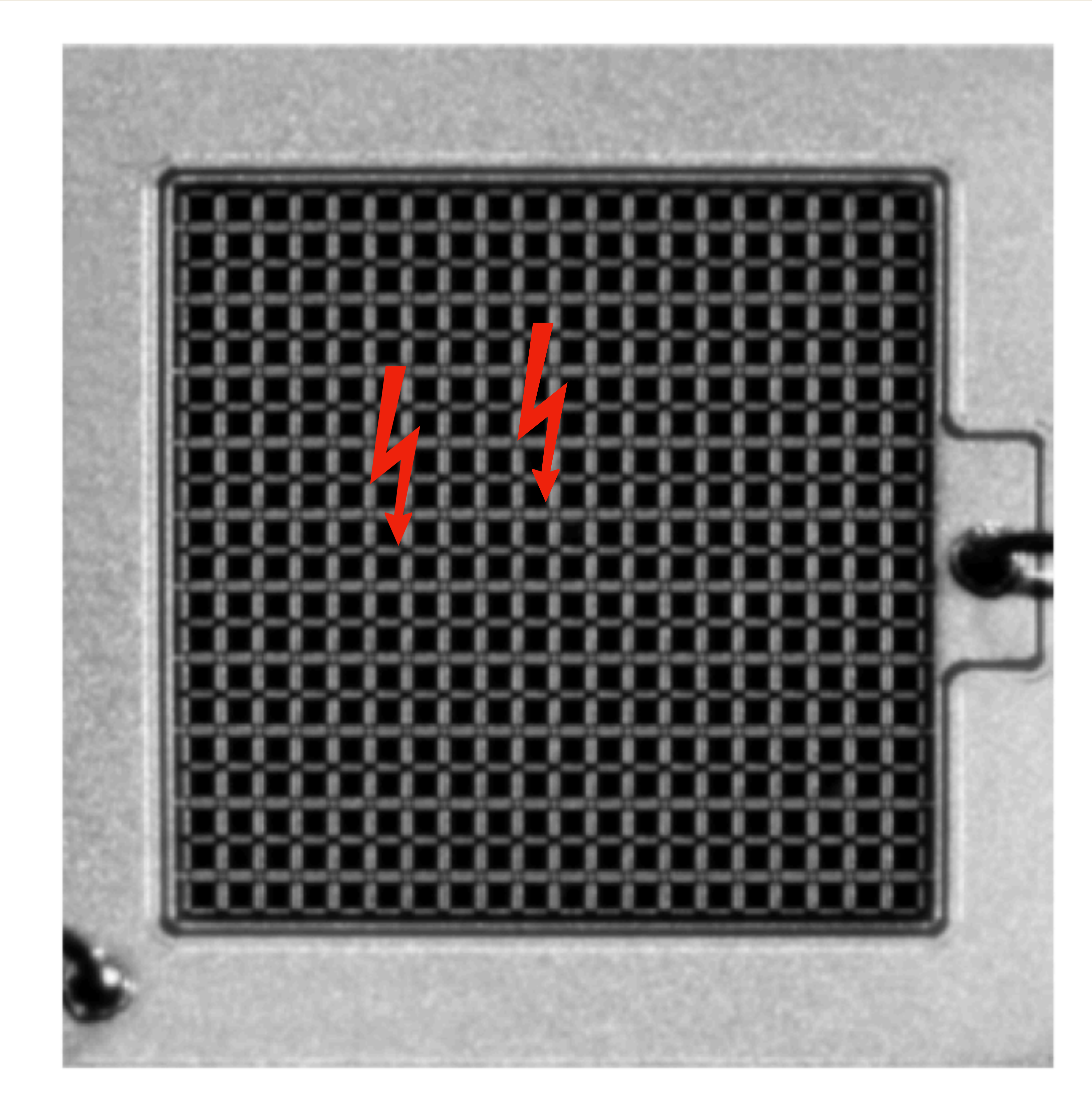
$$G = Q_0/e = C_{pixel} \times (V_{operation} - V_{breakdown.})$$

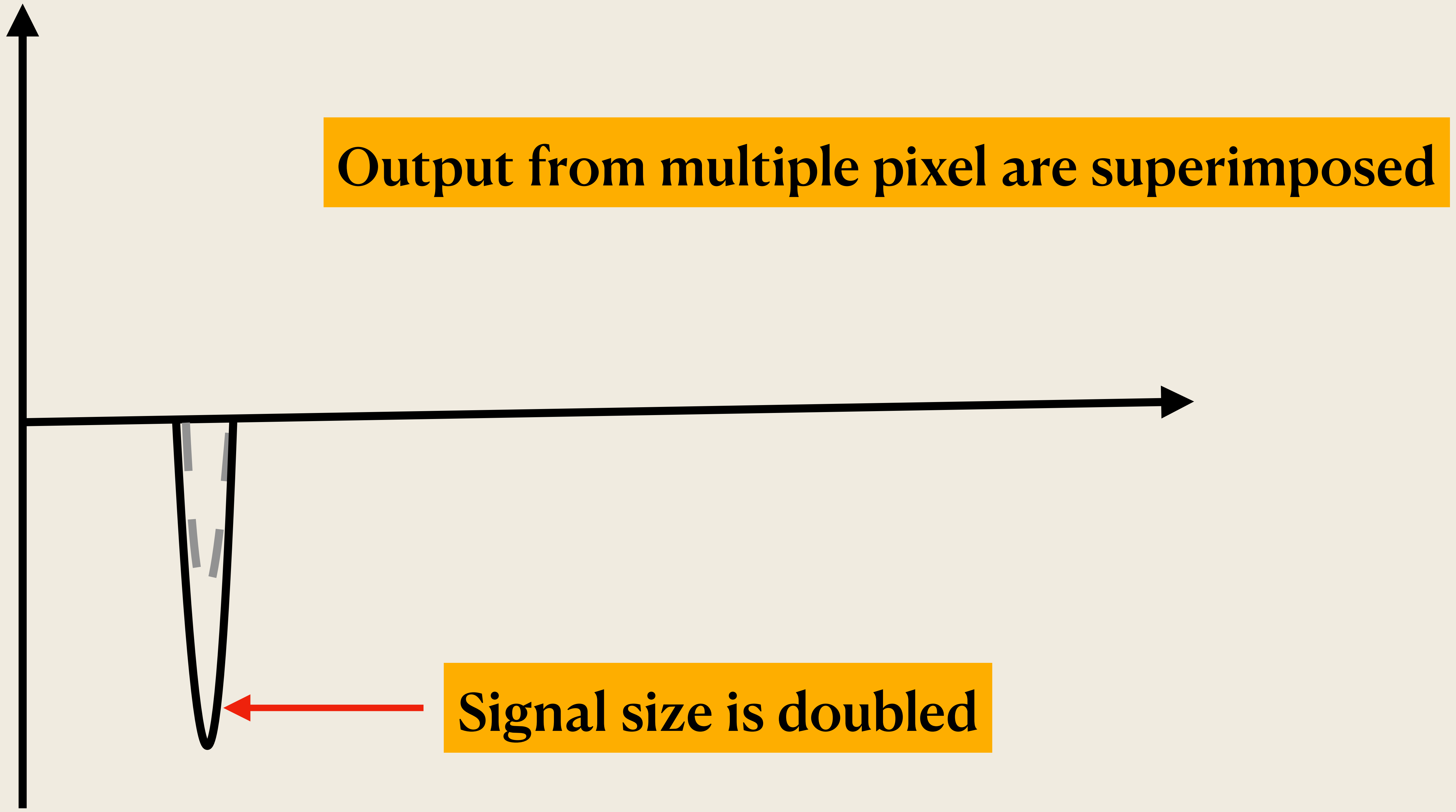


Pixel works independently but give out pulses with the same amplitude

Basic principle of photon counting

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

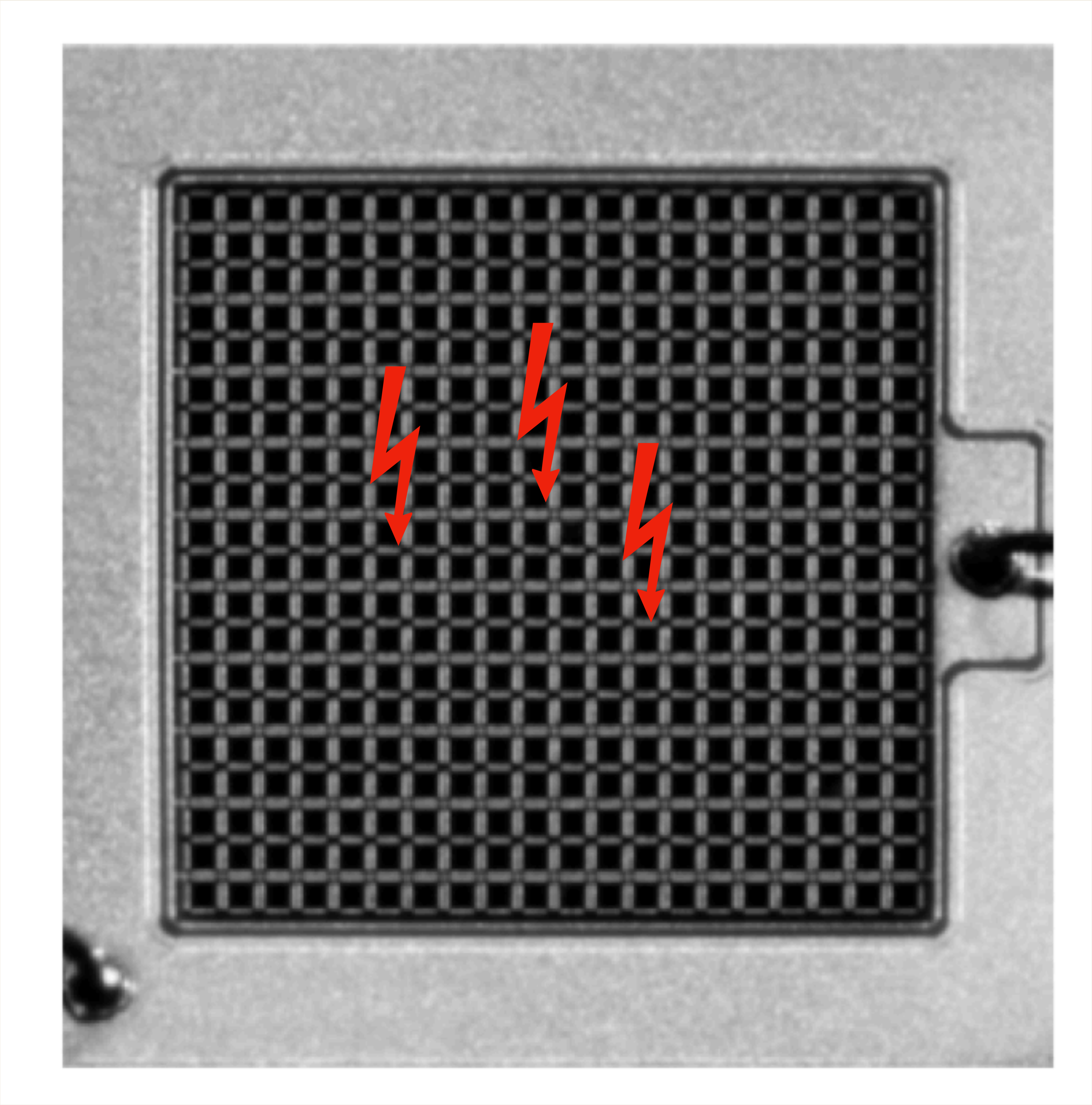


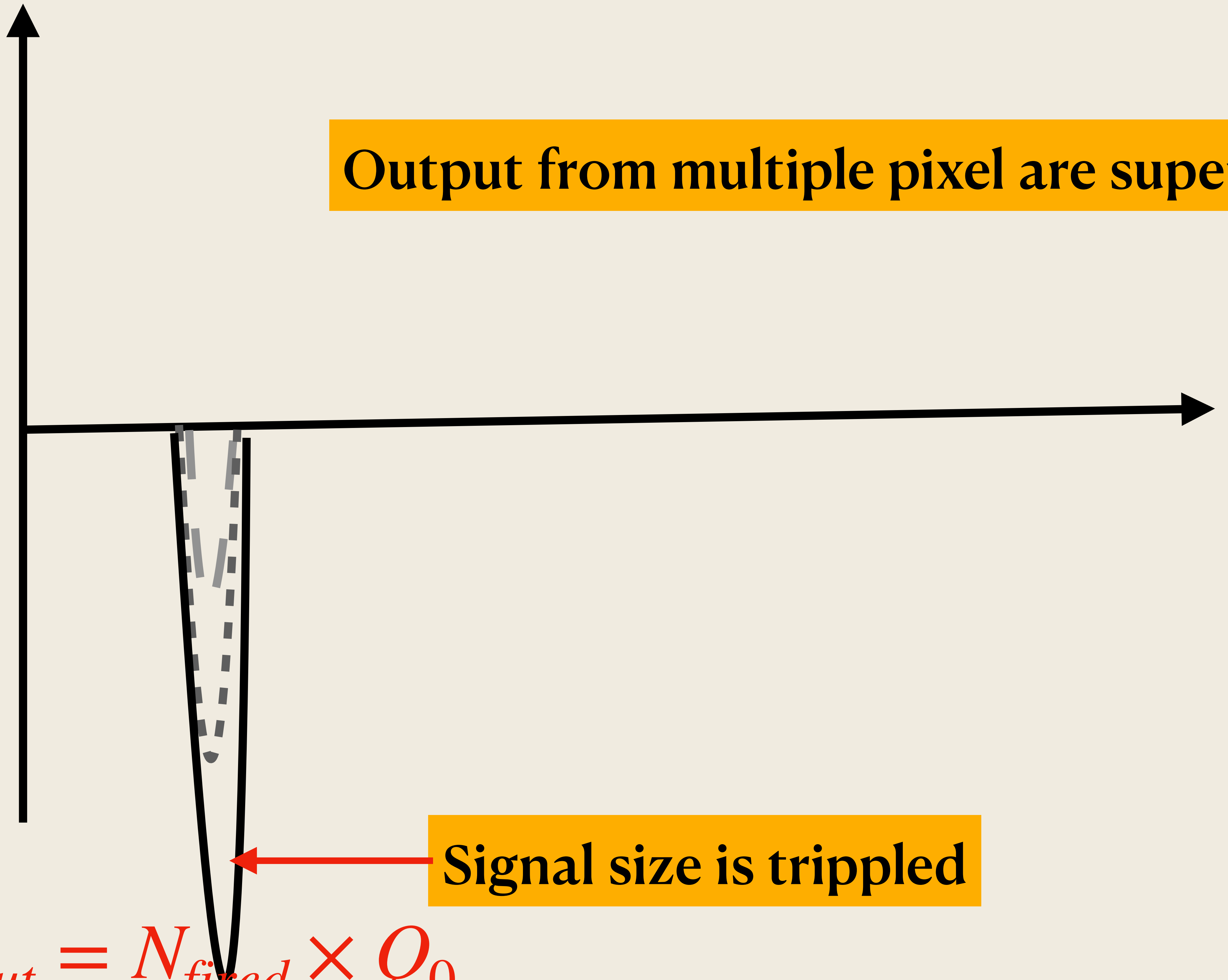


$$Q_{out} = N_{fired} \times Q_0$$
$$= N_{fired} \times C_{pixel} \times (V_{operation} - V_{breakdown.})$$

Basic principle of photon counting

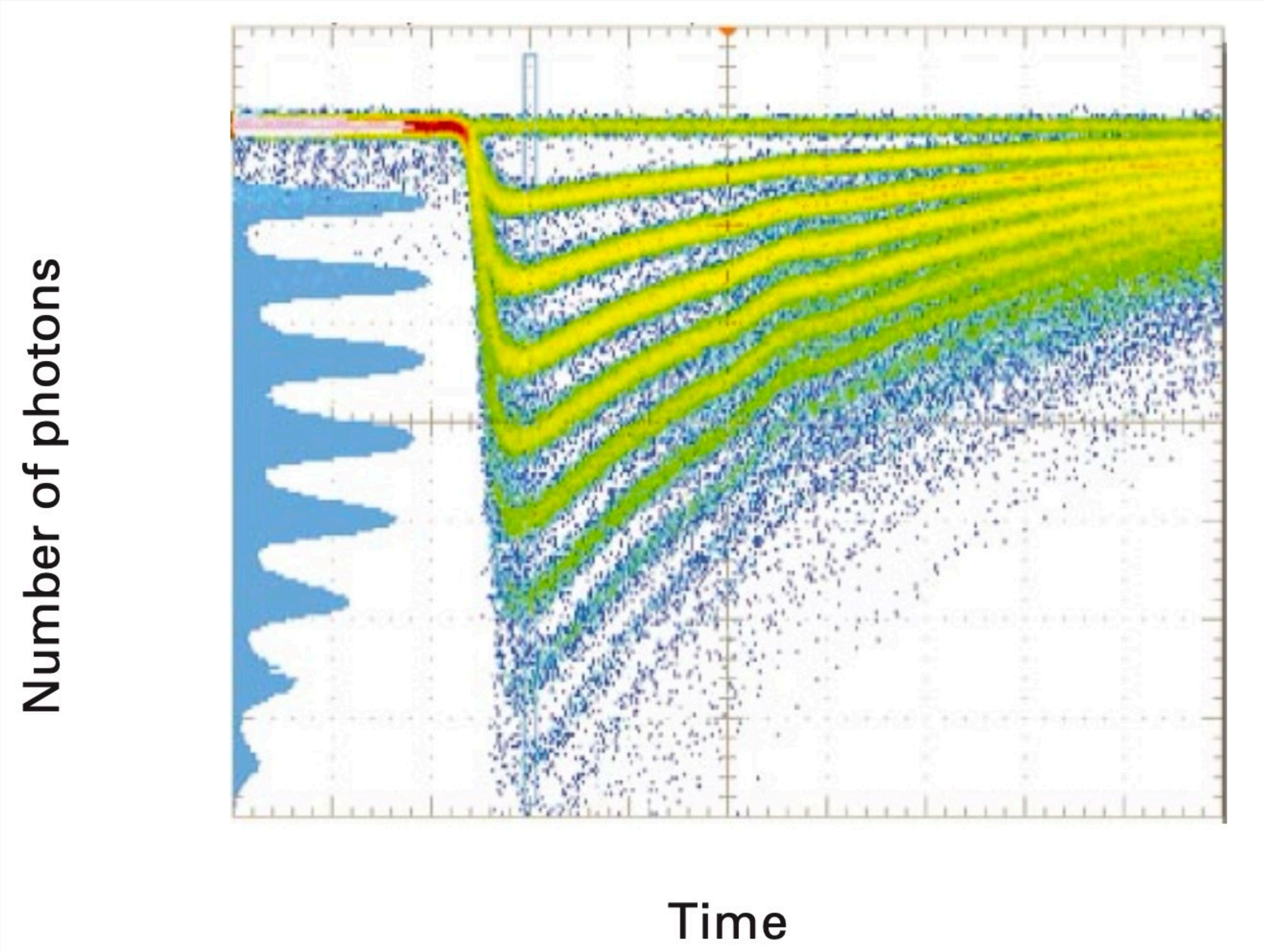
When a photon fires a pixel, a signal with charge Q_0 is generated and observed in macroscopic scale



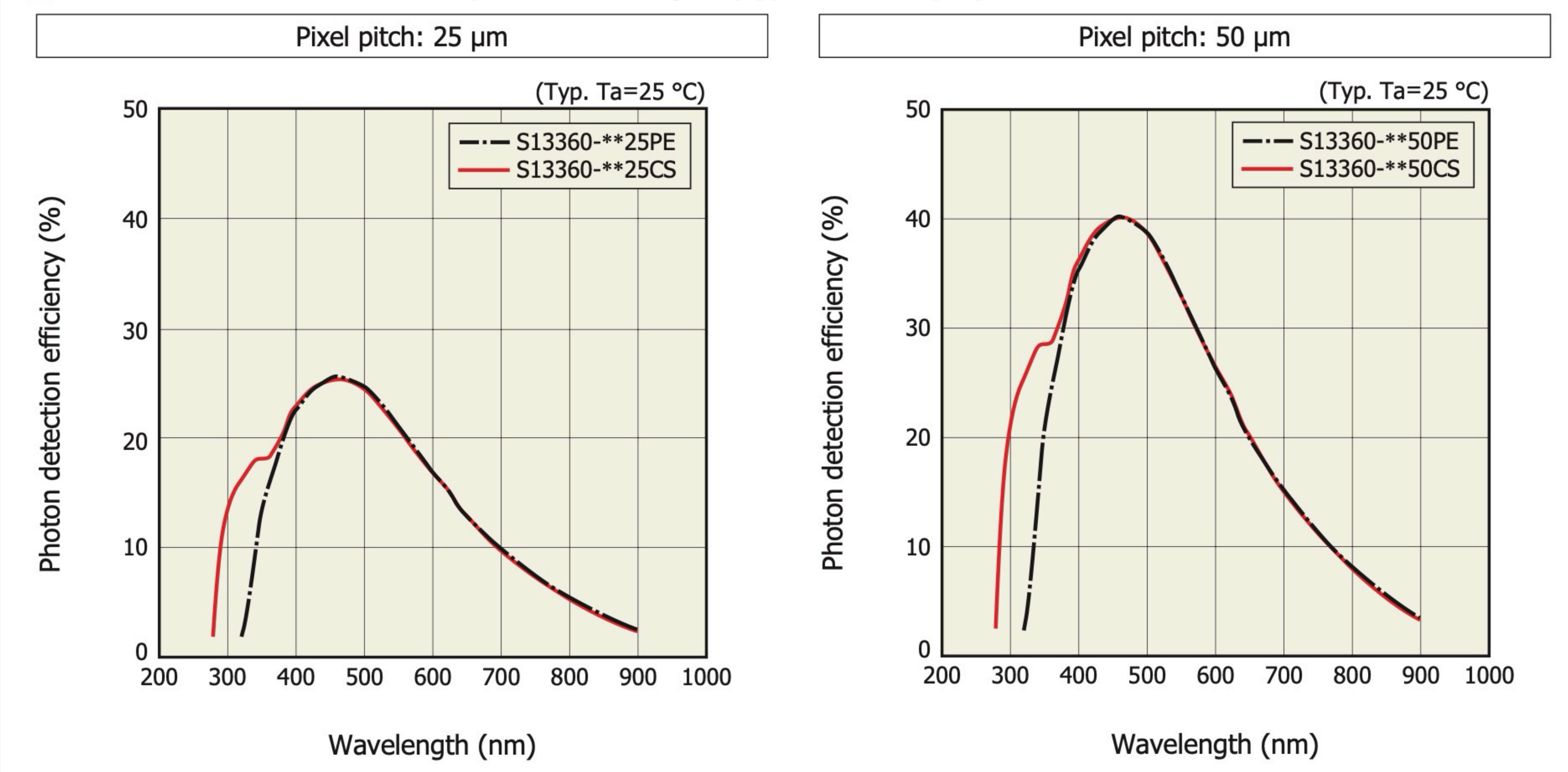


$$Q_{out} = N_{fired} \times Q_0$$
$$= N_{fired} \times C_{pixel} \times (V_{operation} - V_{breakdown.})$$

MPPC overlayed signals

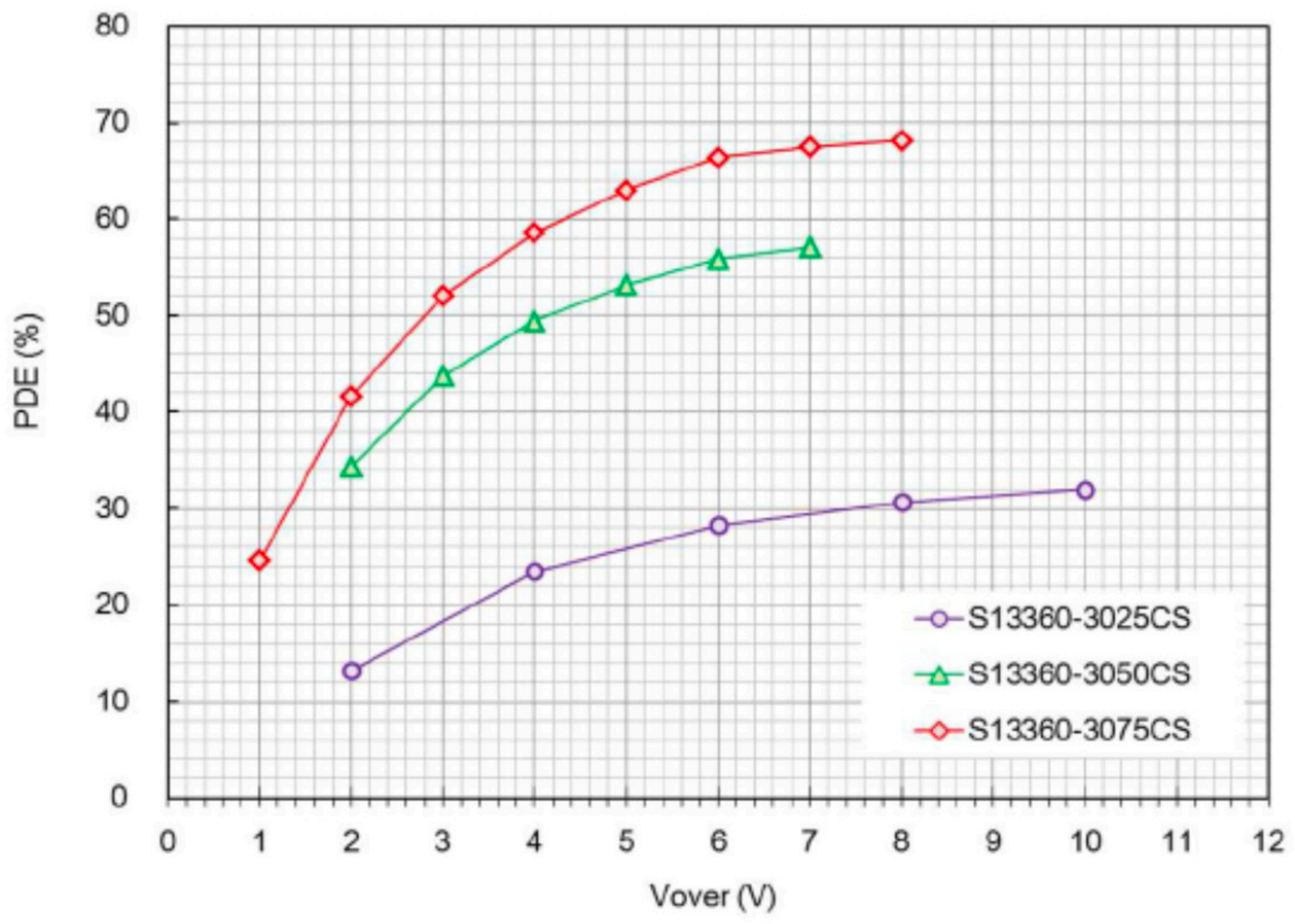


Photon detection efficiency



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

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

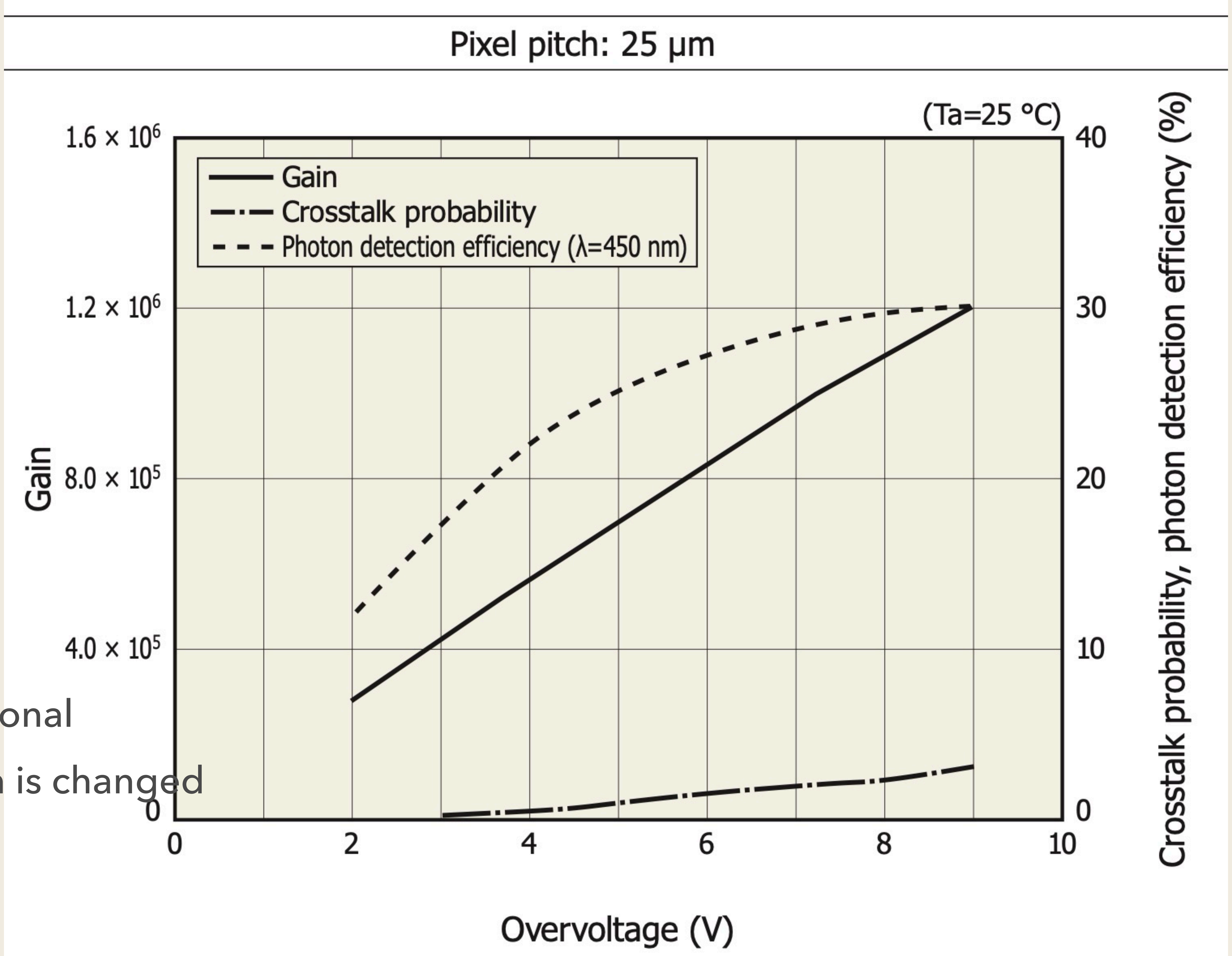
Electrical gain

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

Depend on overvoltage, defined as

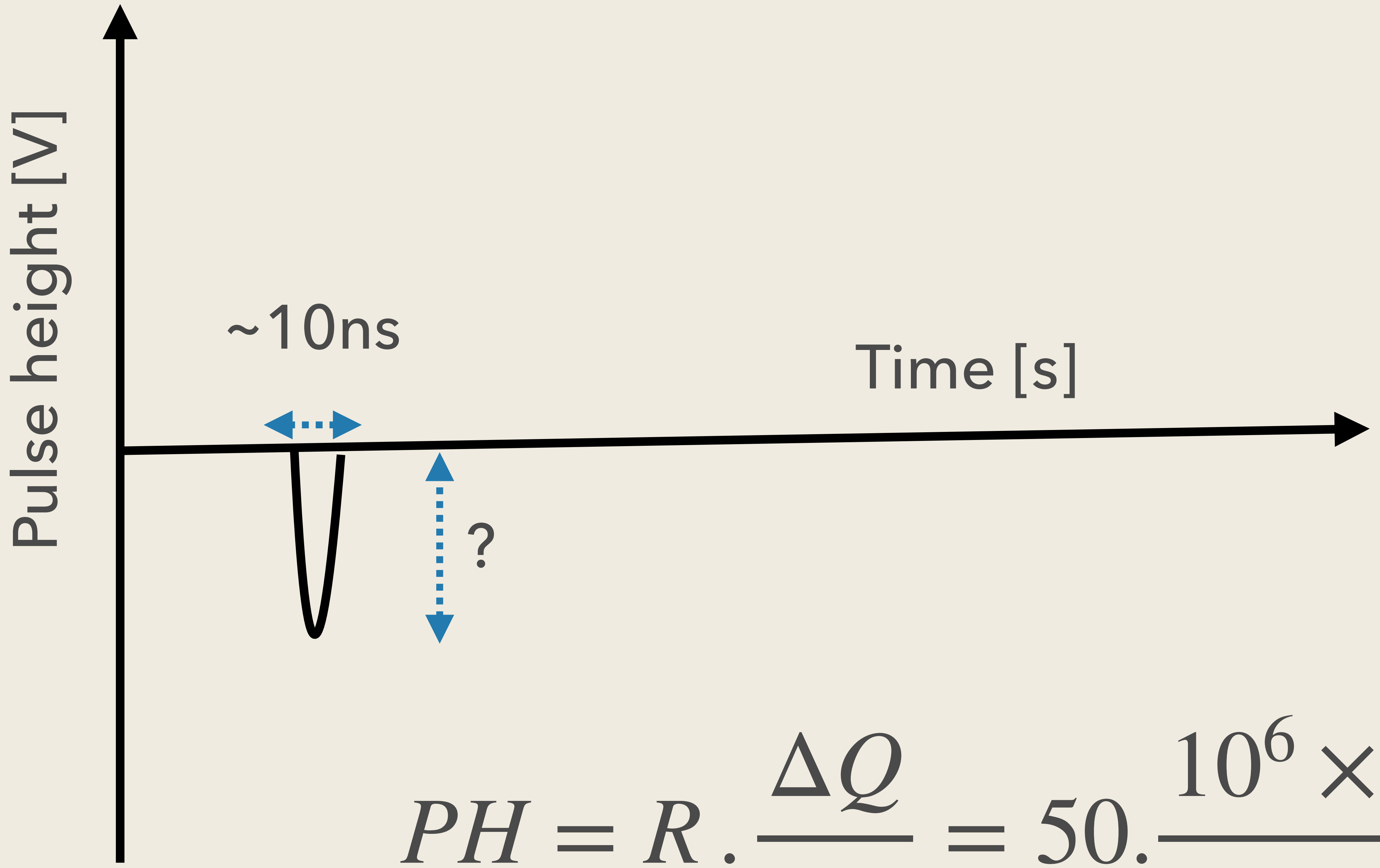
$$\Delta V_{op.} = V_{op.} - V_{breakdown}$$

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



Signal size of one photon?

Assume you have a electric gain of 10^6, what the size of the signal you expect if no amplification is applied?. *Assume the pulse width is about 10-ns and terminated by 50 ohm resistor.*



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

$$V = R \times I$$

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

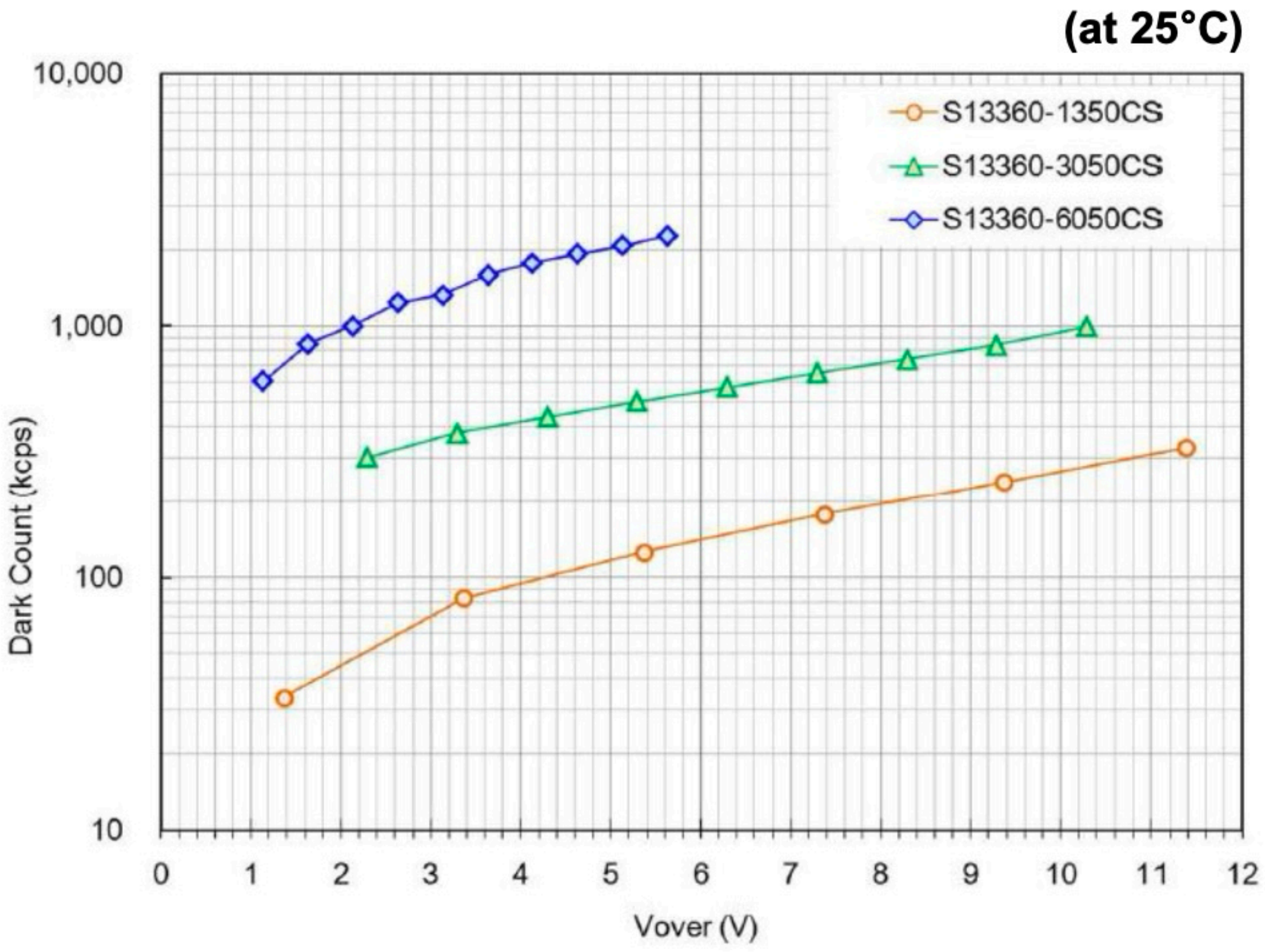
Signal size for a single photon (without amplifier) is less than 1mV

Dark count (or dark current) mainly due to thermal radiation

The **Dark Count Rate** is the rate at which a Geiger avalanche is randomly initiated by thermal emission.
For Hamamatsu MPPCs the DCR is defined as the number of pulses, which are generated in dark state and exceed the threshold of 0.5 p.e.

$$N_{0.5\,\text{p.e.}}(T) \approx A T^{\frac{3}{2}} \exp\left[\frac{Eg}{2kT}\right]$$

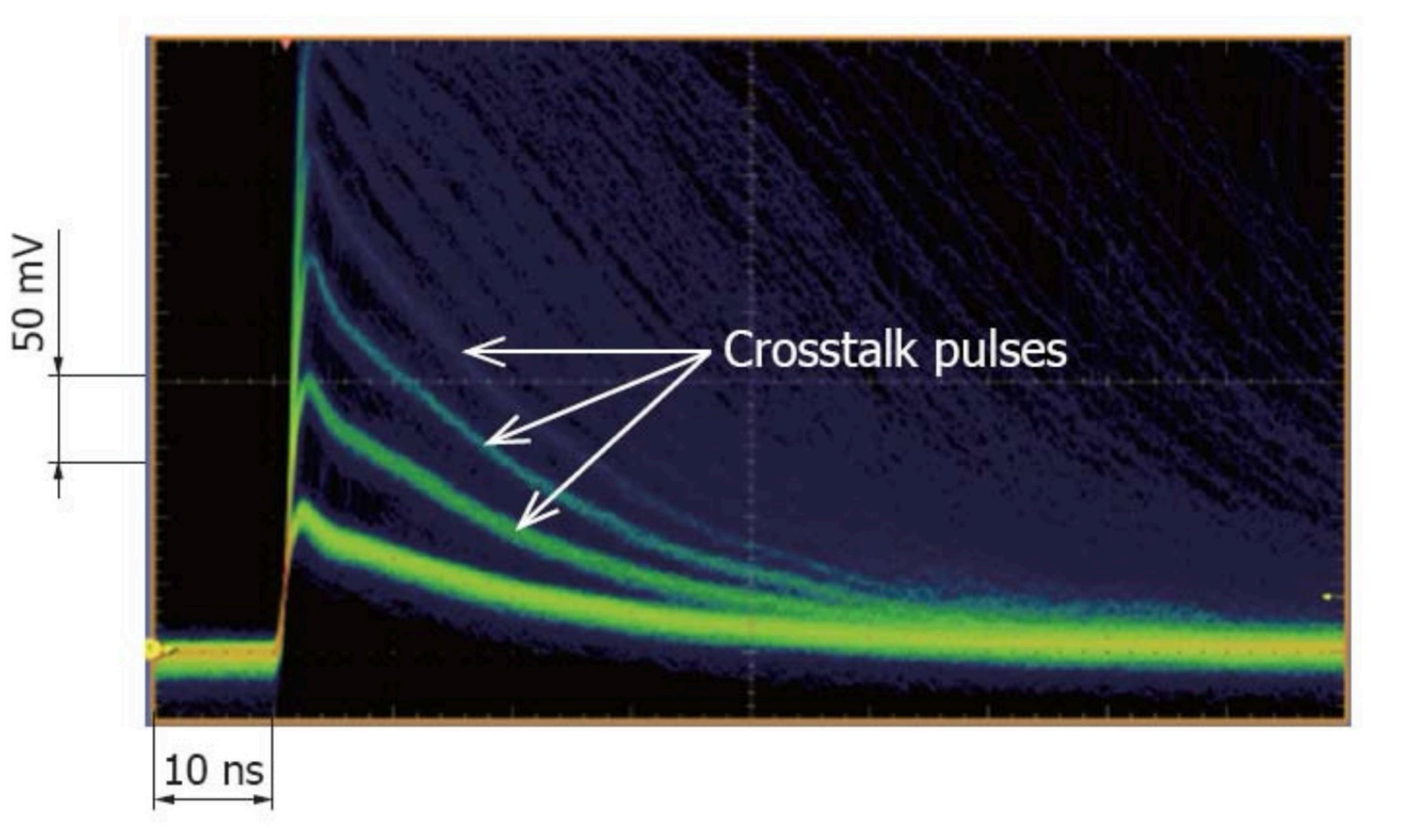
A: arbitrary constant
Eg: band gap energy [eV]
T: absolute temperature [K]
k: boltzmann's constant [eV/K]

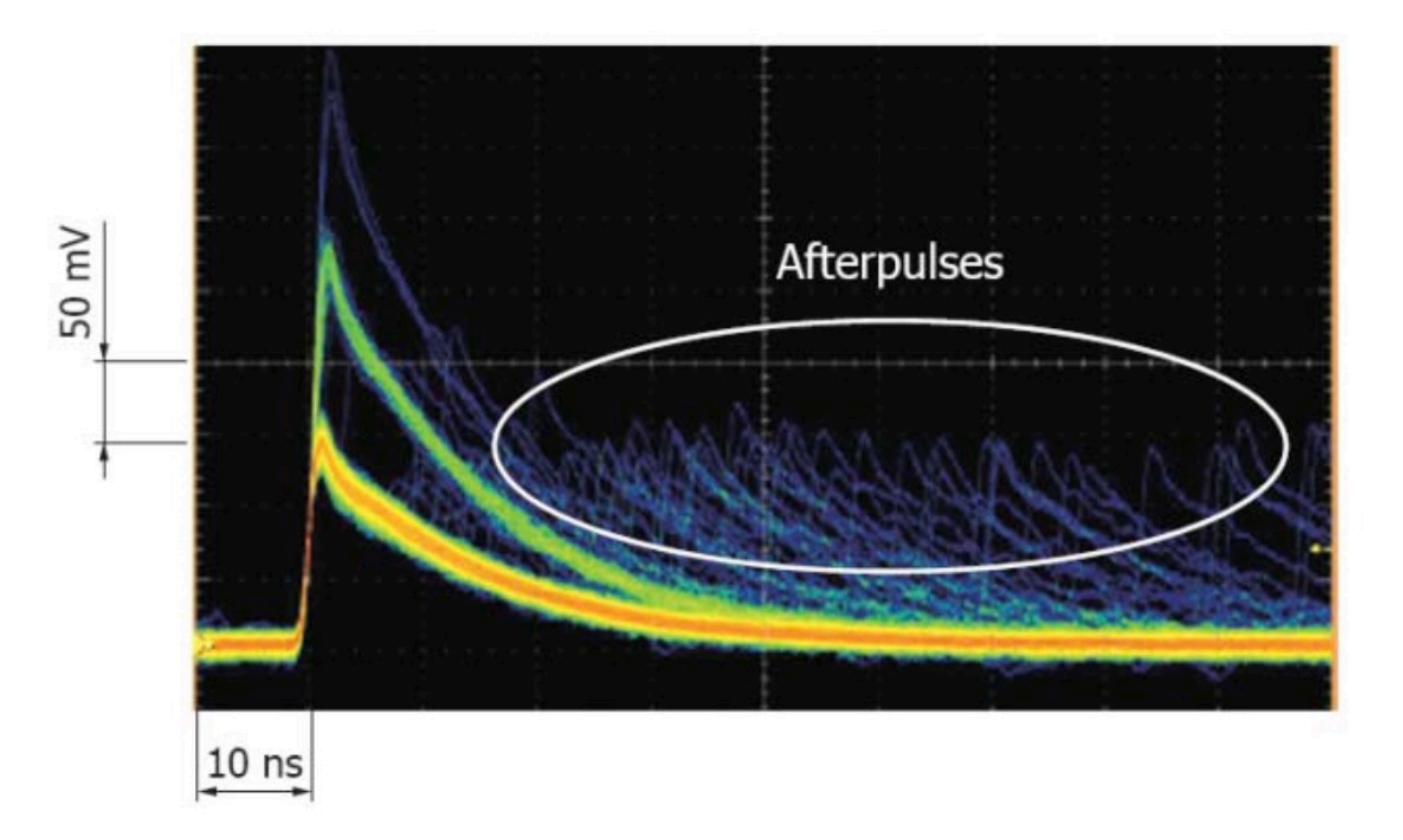


	Dark Count Vover = 3 V	Capacitance Ct
1.3x1.3 mm	90 kcps	60 pF
3x3 mm	500 kcps	320 pF
6x6 mm	2 M cps	1280 pF

It's very important to check temperature during measurement

Part of dark noise: Cross-talk and after-pulse

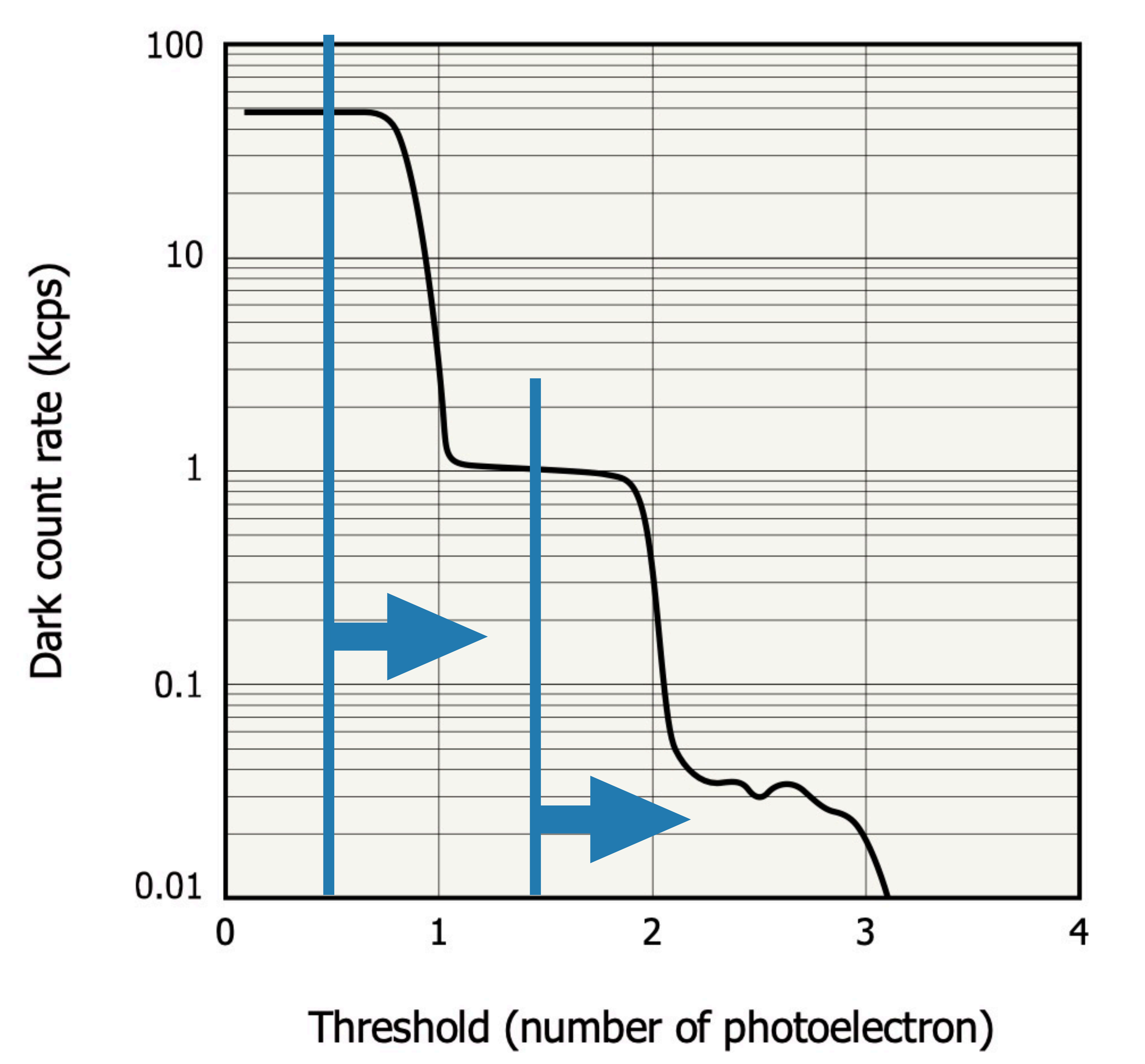


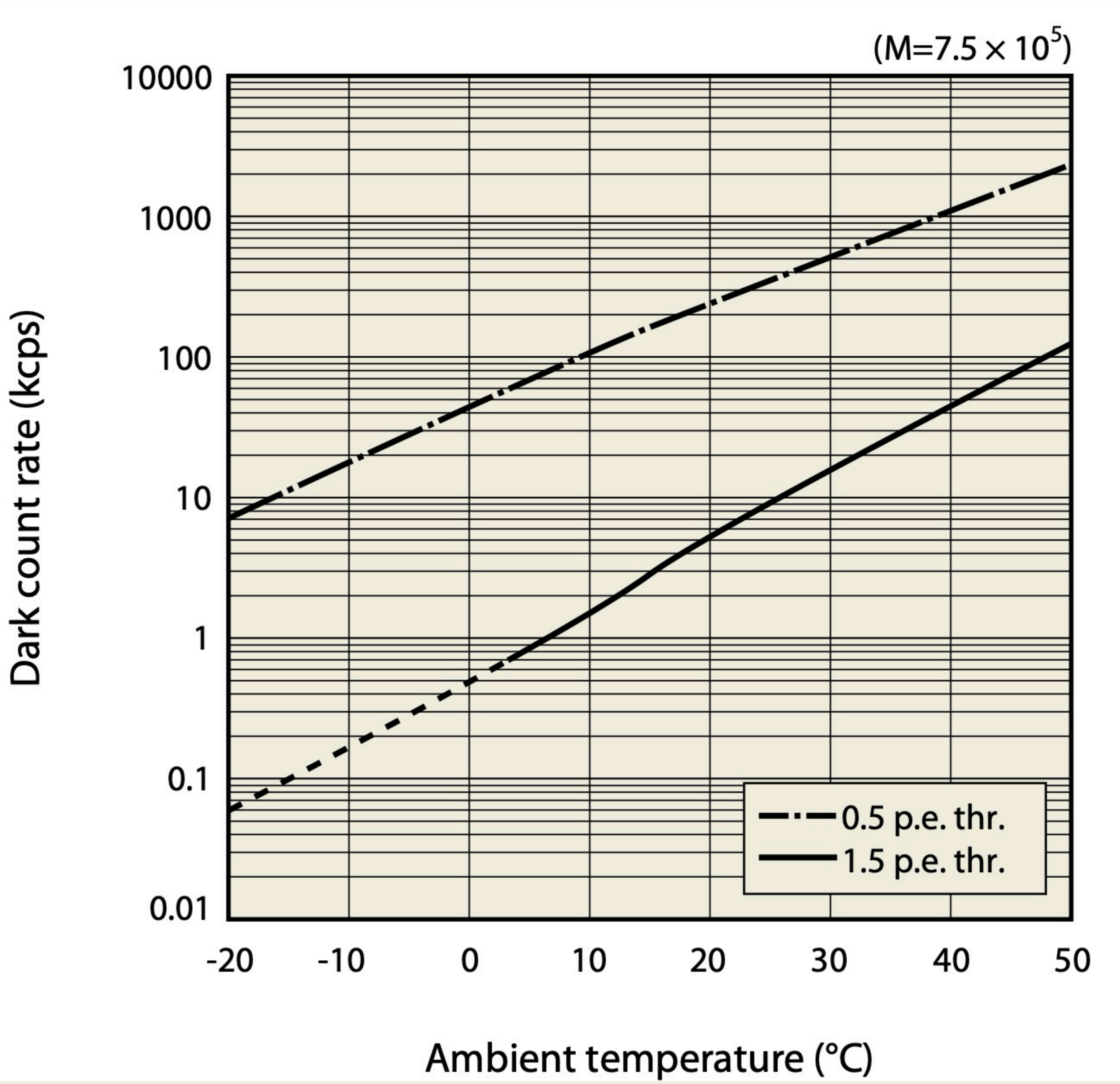


Additional photon(s) is created in another pixel due
To the energy deposit by energized charge carrier
Distinguished by signal amplitude

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

Dark noise rate



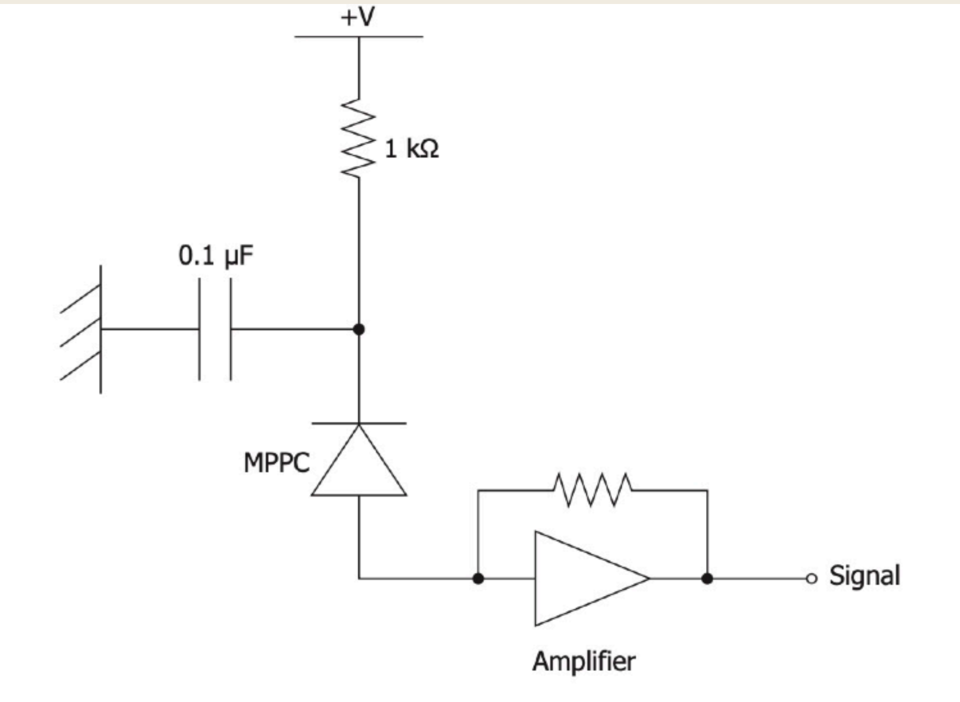


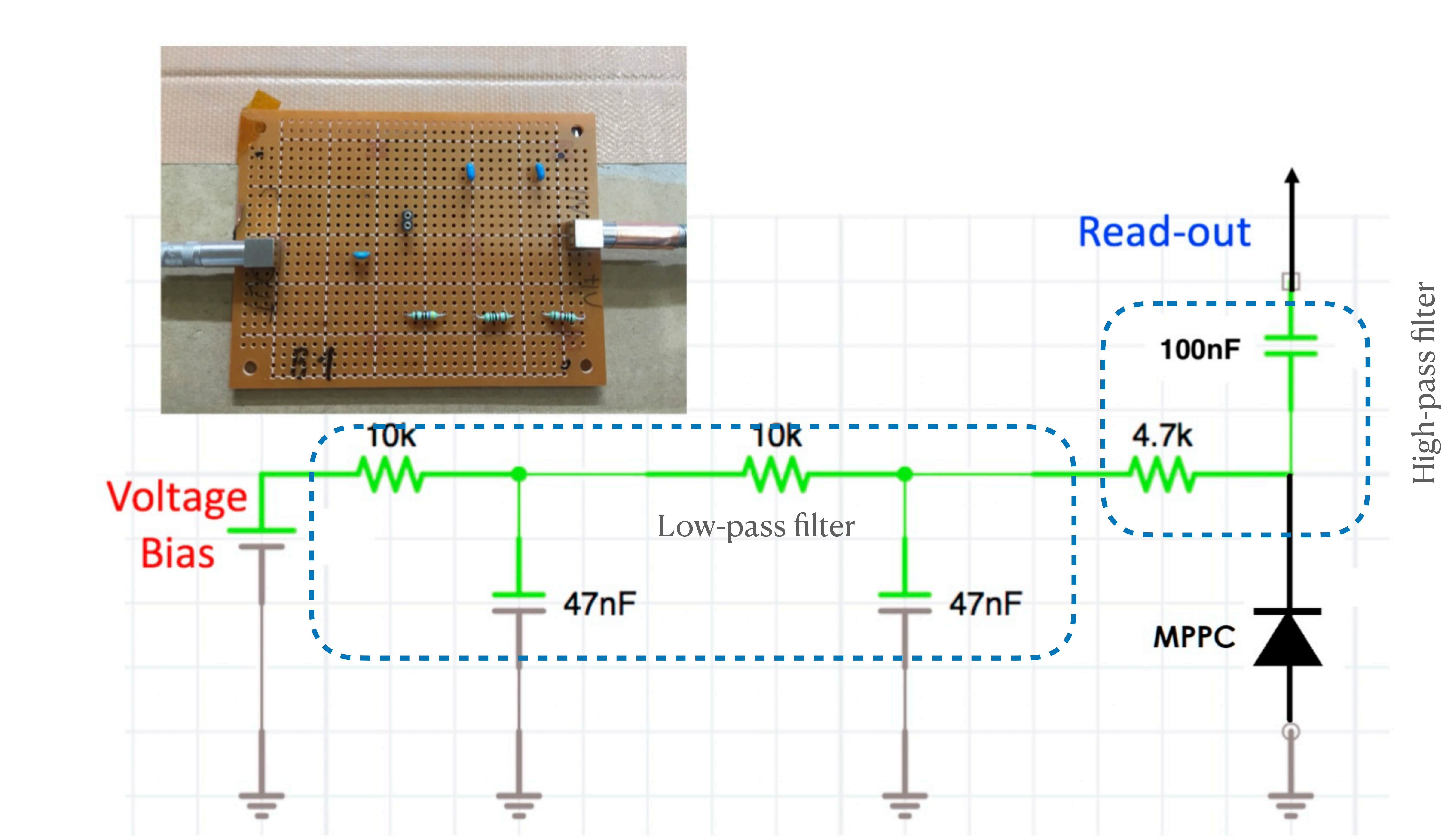
★Higher threshold can help to reduce the dark noise but also it will skip signals with few photons (not good for some low-energy experiment.)

★Other methods to suppress noise: coincidence technique and reference timing

★(It's very important to check temperature during measurement)

MPPC circuit example

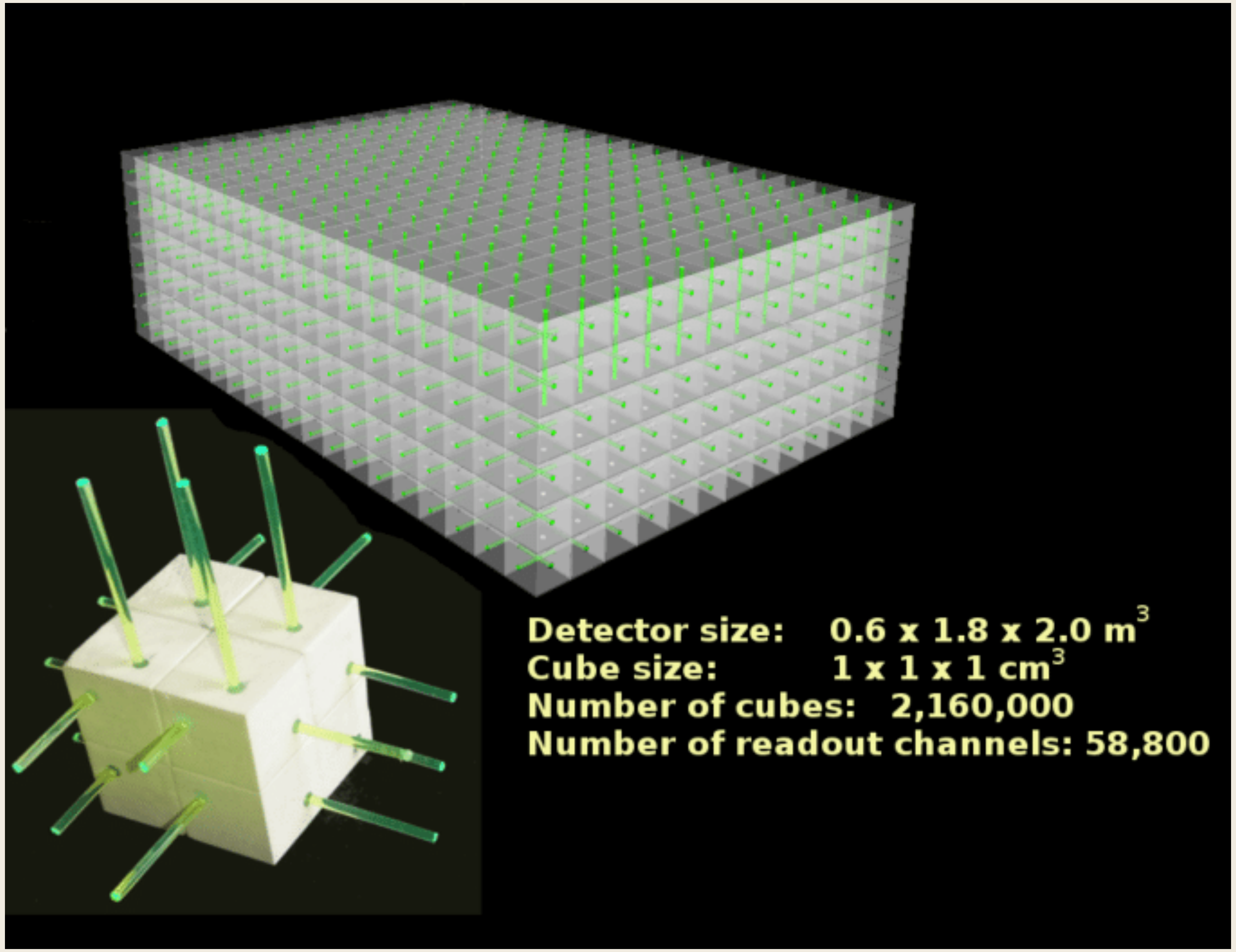




Circuit to operate SiPM is relatively simple! If you have a good power supply, low-pass filter is not needed. You do not need amplifier if your circuit have low electric fluctuation and your signal processing modules (eg. discriminator, coincidence, ADC) can handle ~ mV -pulse height/ ns - duration signals.

MPPC applications

For particle detector: tracking and calorimetry



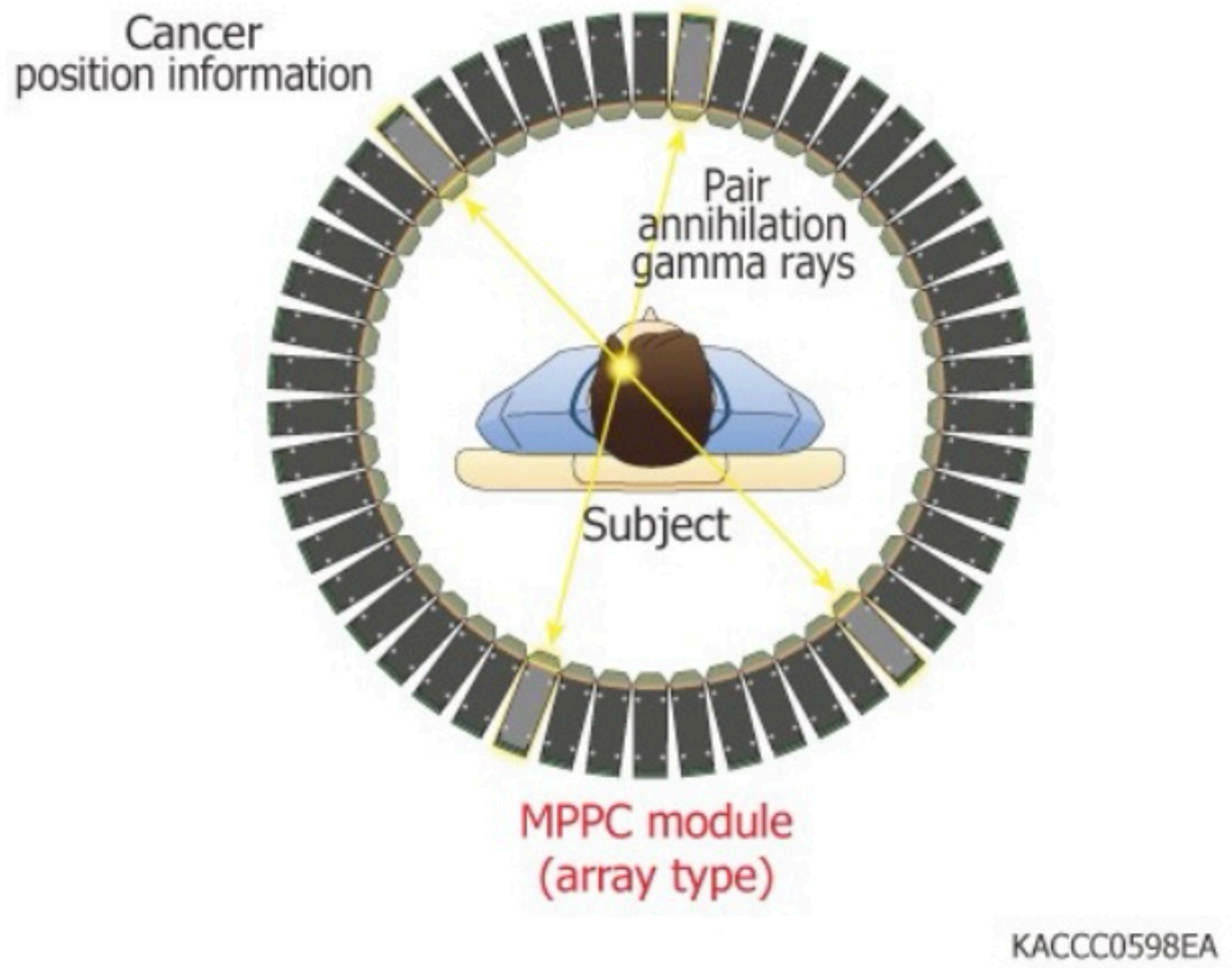
~60,000 MPPCs used to sense the faint light induced by neutrino interaction from > 2 million lego-size cubes of plastic scintillator

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

MPPC applications

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

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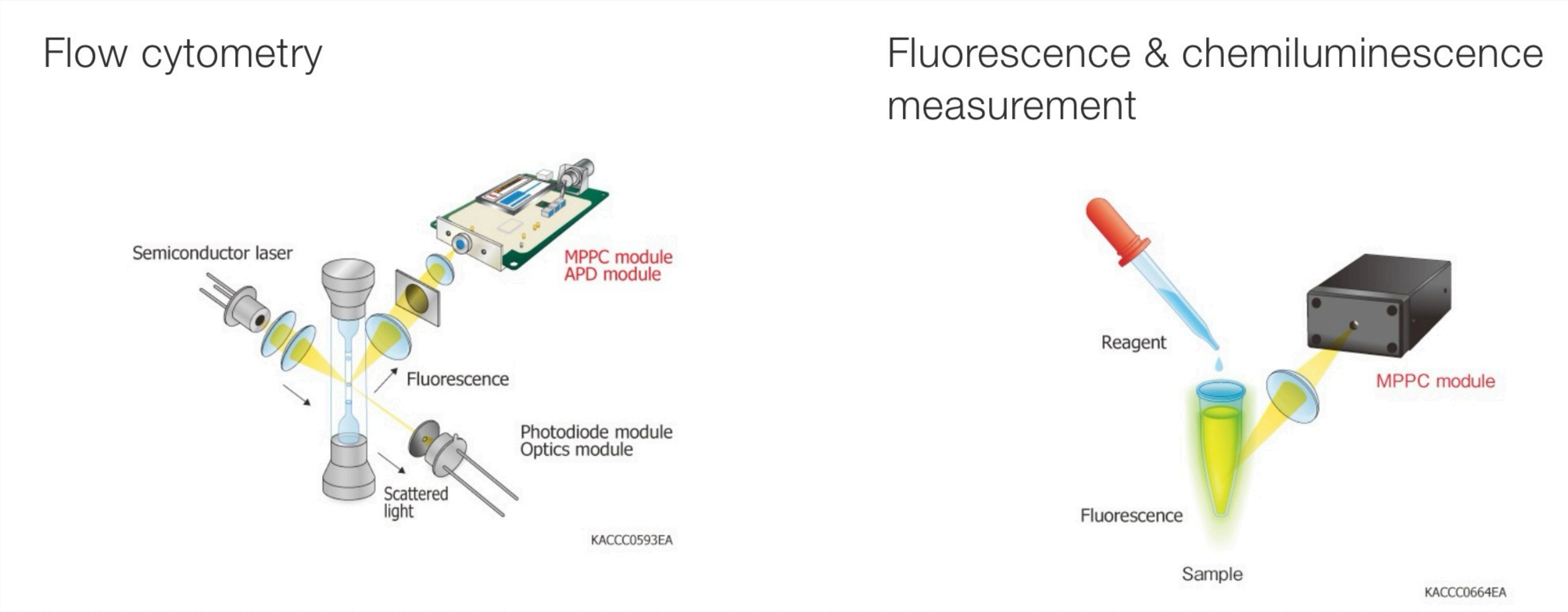
MPPC applications



- 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

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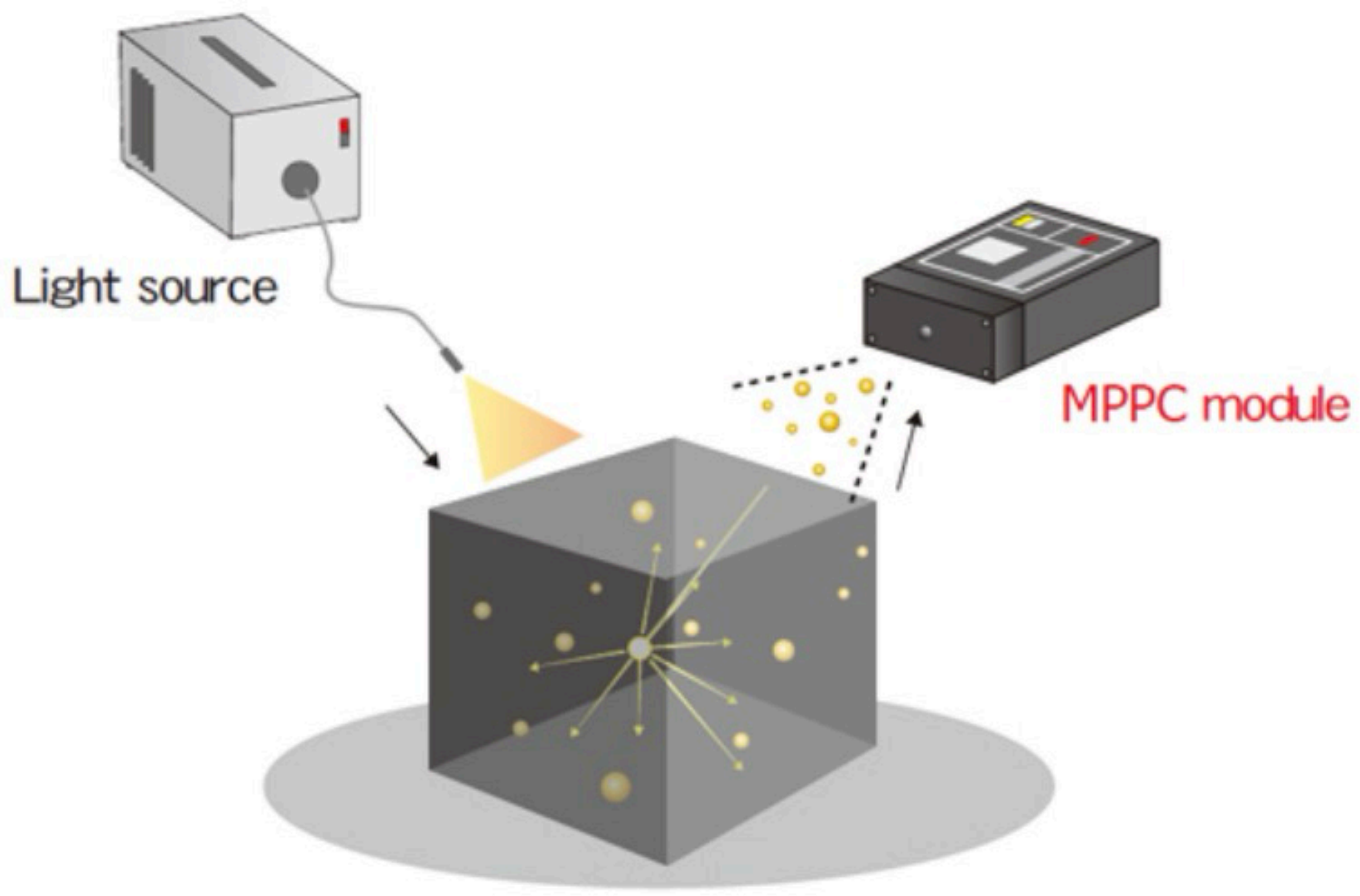
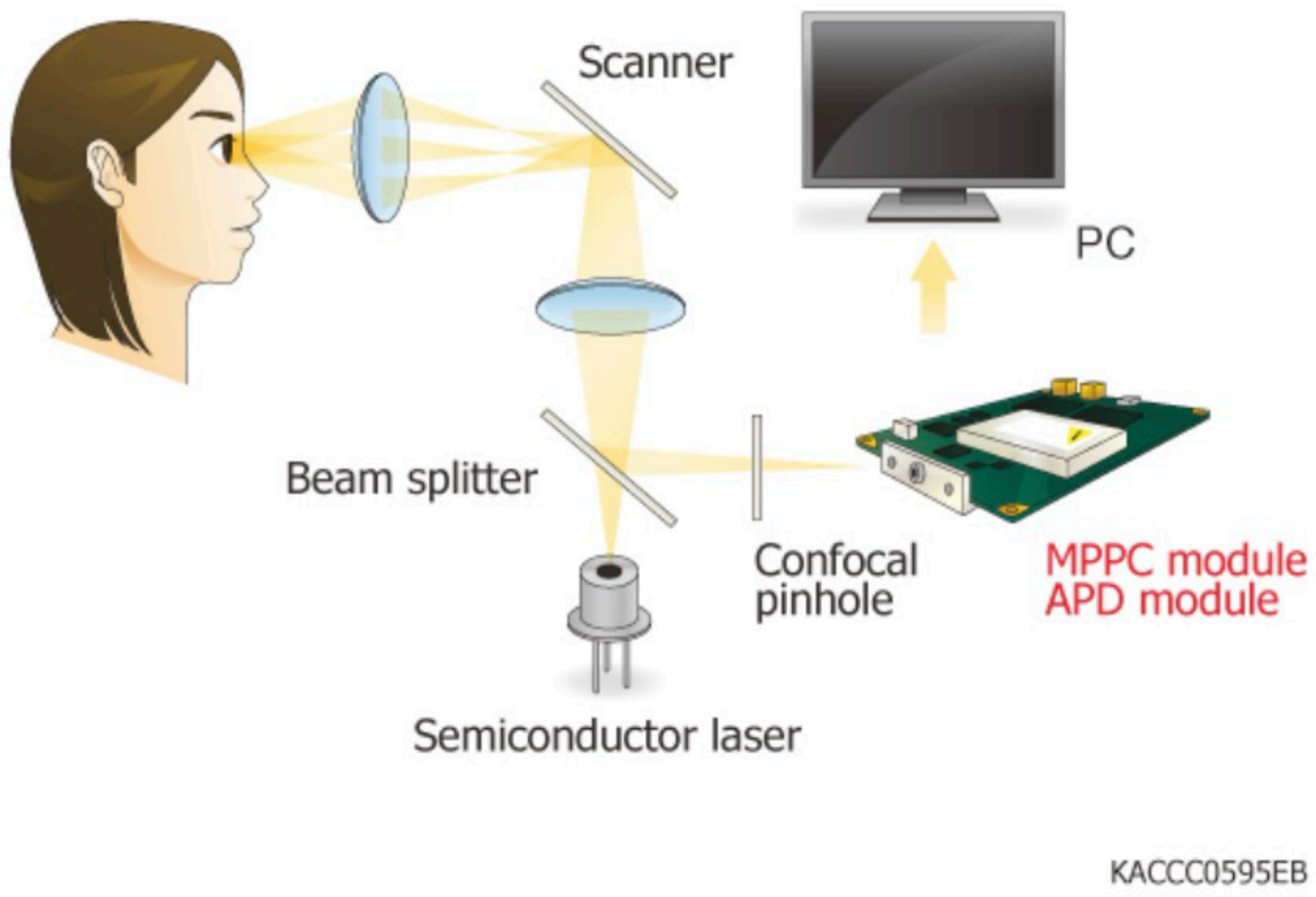
MPPC applications





MPPCs (SiPMs) modules are often used in optical particle counters to count and measure the size of particles. Particle counting is helpful in characterizing cleanrooms, analyzing contaminated areas, counting particles in liquids, and other situations. To detect the low intensity scatter from particles, a photodetector with gain, such as a silicon photomultiplier, is highly recommended. When a laser passes through a chamber that contains a gas or liquid, the high gain photodetector measures the scattered light, and the intensity and frequency of these events indicate the size and quantities of these particles.

In ophthalmoscopy or funduscopy, the light that is irradiated into the eyeball must be of low intensity for safety reasons. MPPC (SiPM) and APD modules can be used to detect with superior resolution and contrast the faint light reflected from the eye.

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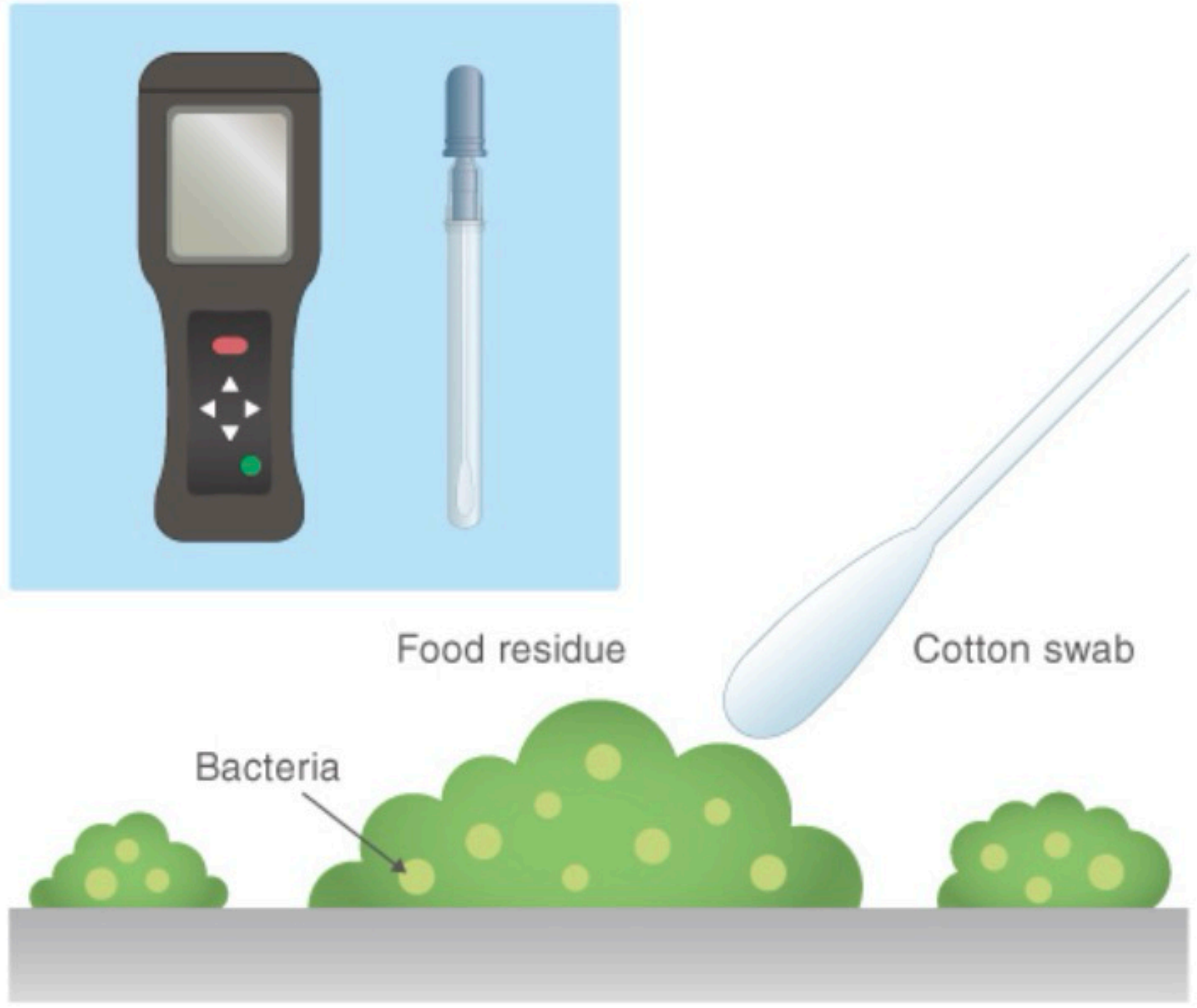
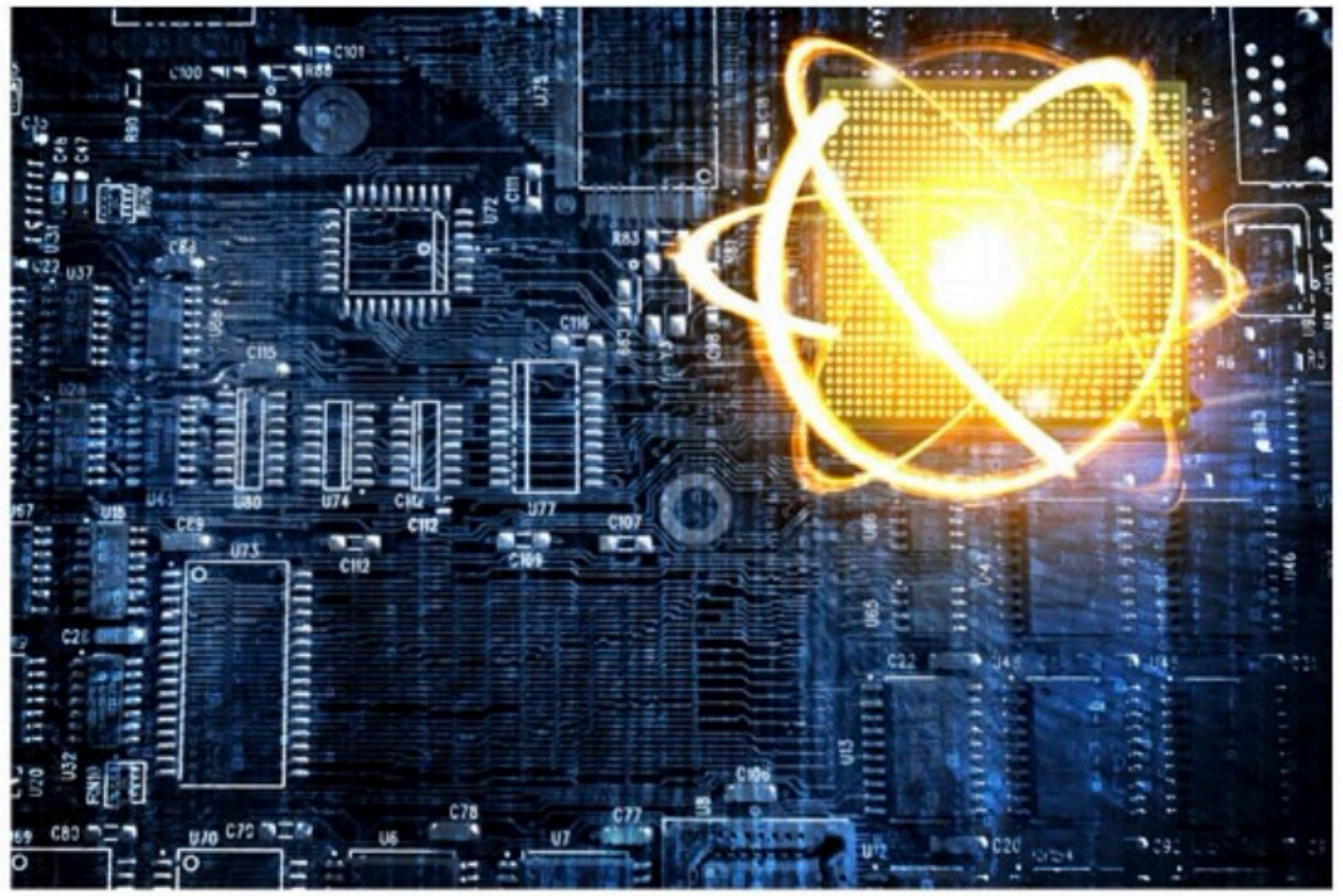
MPPC applications

Hygiene Monitor



Hygiene monitoring devices measure the amount of light emitted by the chemiluminescence reaction of adenosine triphosphate (ATP) with a reagent. The amount of light emitted by the sample is proportional to the amount of ATP present. The high gain and photosensitivity of MPPCs (SiPMs) enable the design of highly sensitive hygiene monitoring systems for use in challenging applications such as food safety to verify cleanliness of food production facilities, and industrial hygiene to detect the presence of dangerous microorganisms.

Quantum Computing & Cryptography



Optical detectors are utilized in certain quantum computation platforms to investigate quantum phenomenon such as entanglement and coherence that are much needed for the realization of quantum computation. An optical detector such as single pixel photon counter (SPPC), also known as SPAD, with very high photosensitivity and low dark count can be used for single photon counting. This type of detector is often used in quantum communication and quantum key distribution.

Excellent counting of SiPM may provide some very interesting feature for quantum computing (eg. *true* quantum random number)

Let’s harness the power of MPPC together !

Backup

Reference

- Hamamatsu's MPPC technical note https://hub.hamamatsu.com/content/dam/hamamatsu-photonics/sites/static/hc/resources/TN0014/mppc_kapd9005e.pdf
- Our work on MPPC http://arxiv.org/abs/2106.08603

MPPC technical note

- On MPPC quantum efficiency
  - Silicon's narrow bandgap of 1.14V
  - Higher probability of photoelectron from a silicon's valence band to its conduction band -> silicon PD can have higher quantum efficiencies over a wider range of wavelengths (UV-VIS-NIR) than the PMT
- Depletion region (of charge carriers) in presence of an Electric field -> diminishing carrier combination -> higher collection efficiency than the probability of creating secondary electron on the first dynode
  -

PN juction and unity-gain Si Photodiodes

- Pure silicon is steady equilibrium of negative and positive charge carriers -> unsuitable for charge collection
- PN junction
  - Doping with electron-donor atom to form N-region
  - Doping with electron-acceptor atom to form P-region