Photon Detectors

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- Introduction
- Basic Properties of Photo-detector
- Vacuum photo-detector
- Solid-state photo-detector
- Comparison
- Summary

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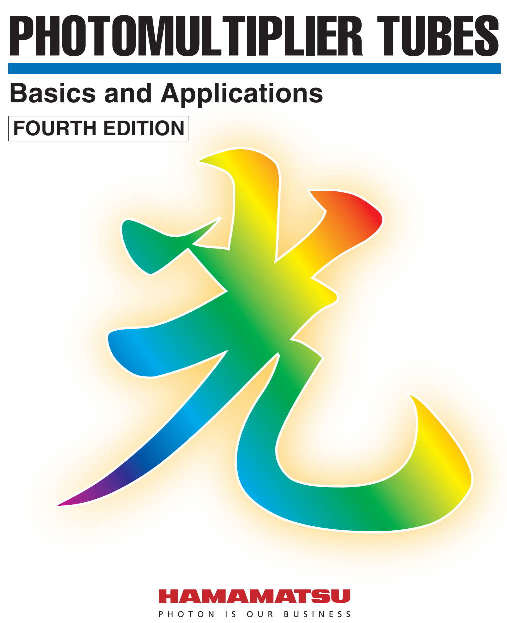
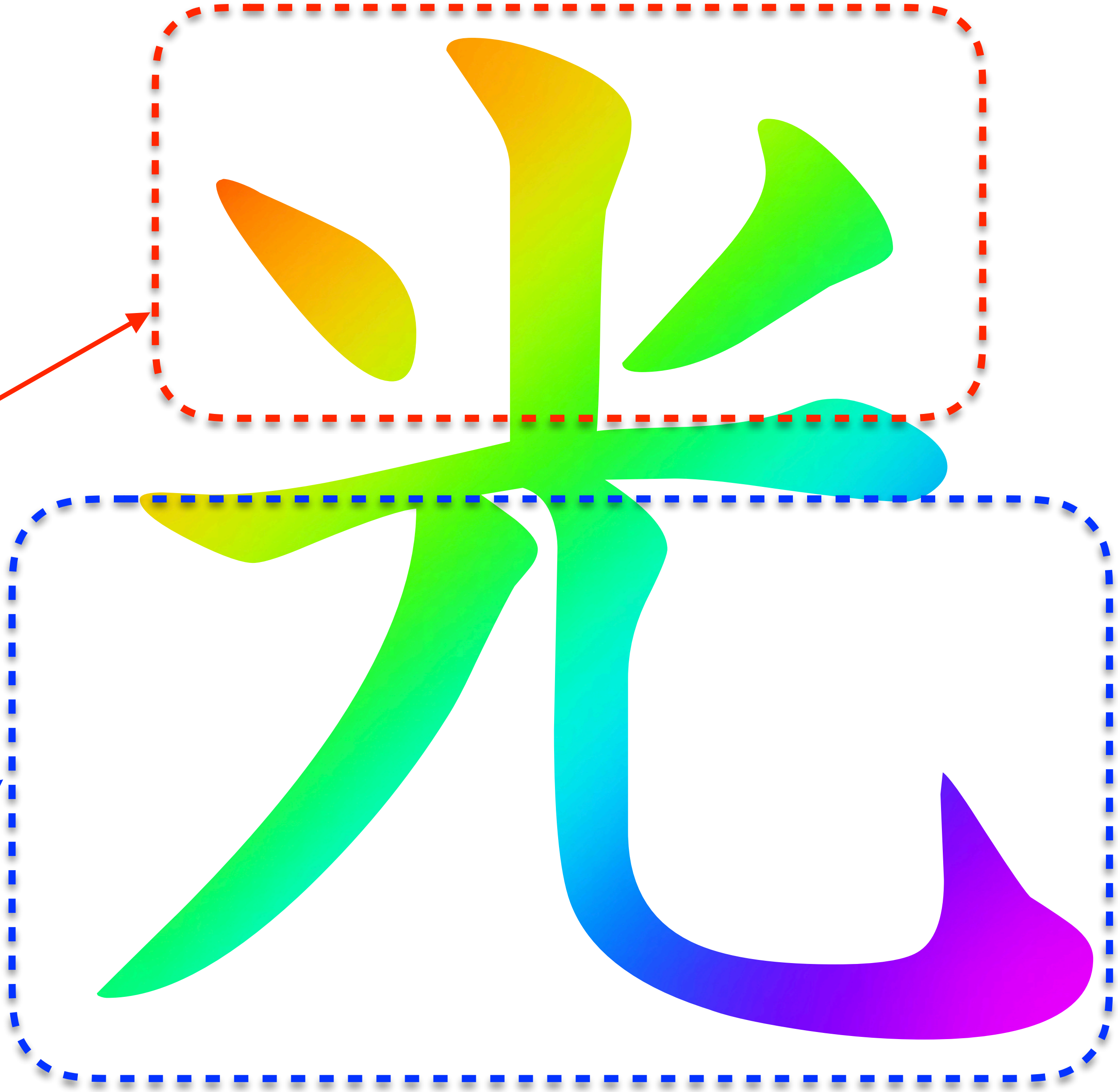
Hamamatsu Photonics, PMT handbook



“Light, Photon”



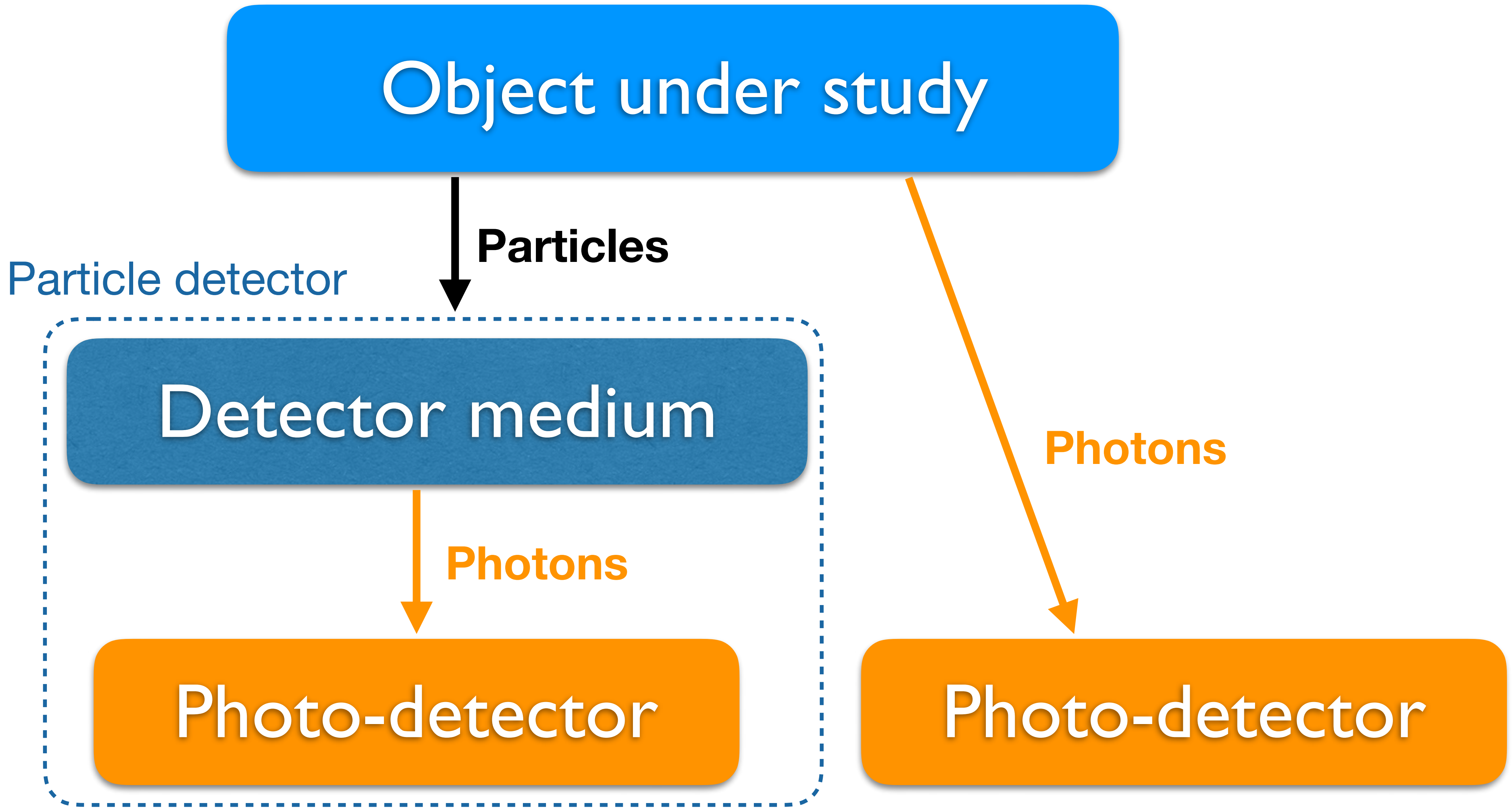
火= “Fire”

人= “Person”

= person performing religious ritual with fire, symbolising something precious and glorious

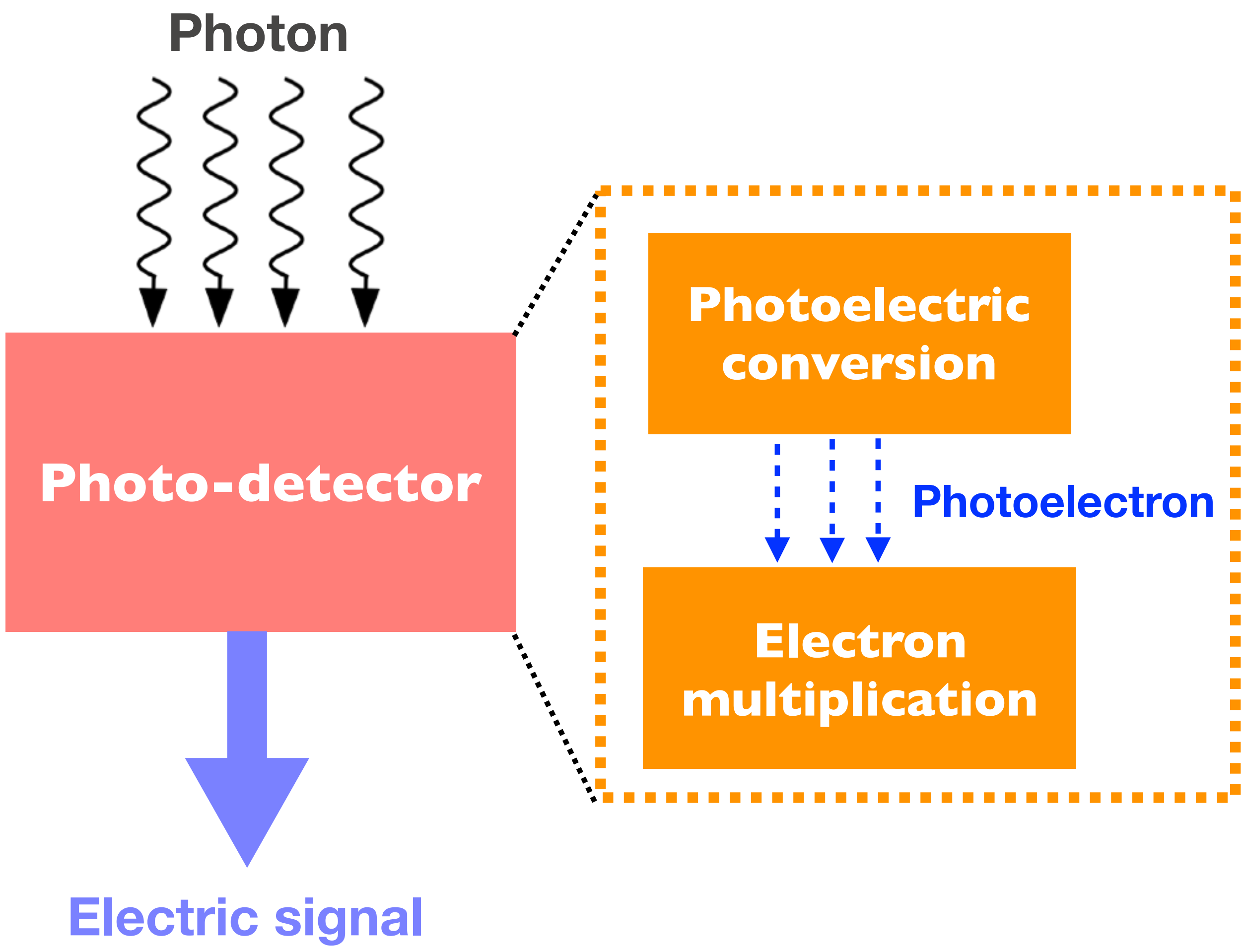
Why Does Photo-Detection Matter?

- **Photons to be detected**
  - Photons emitted from object under study
  - Photons generated in detector medium by particle interaction



How Does Photo-Detector Work?

- **Basic concept**
  - Covert light (photon) to electric signal
- **Detection process**
  - Photo-conversion (photoelectric effect)
  - Photoelectron collection
  - Electron multiplication
- **Building blocks**
  - Light window
  - Photocathode material
  - Electron multiplier



Brief History of Photo-detector

1873 Discovery of photoconductivity in Selenium (Se) by W. Smith

1905 A. Einstein paper to explain photoelectric effect as quantum effect

1913 First photoelectric tube by Elster and Geiter

1919 Invention of photomultiplier by J. Slepian

1950s First semiconductor photodiode (Ge)

1967 Invention of APD

1970 First CCD device

1990s Development of SiPM

Categories of Photo-detector

- **Vacuum photo-detector**
  - Discrete dynode: PMT, MaPMT,…
  - Continuous dynode: MCP-PMT
  - Silicon-based electron multiplier: HPD, HAPD
- **Solid-state photodetector**
  - Photodiode/PIN photodiode
  - APD
  - SiPM
  - CMOS
  - CCD
- **Gaseous photo-detector** ←**not covered today**
  - Photo-ionisation (TMAE, TEA, …)
  - Electron multiplier (GEM, MWPC,…)

Photoelectric Effect

- **Two types of photoelectric effect**
  - External photoelectric effect
    - **Photoelectric effect with emission to vacuum**
    - Electrons are excited to conduction band and diffuse to photocathode surface loosing some energy

      →If electrons still have energy above vacuum level, they can be emitted to vacuum

      →Collected to electron multiplier
    - Vacuum photo-detector, gaseous photo-detector
  - Internal photoelectric effect
    - **Photoelectric effect without emission to vacuum**
    - Electrons are excited to conduction band

      →Generate photocurrent

      →Electron multiplication in the same material
    - Solid-sate photo-detector

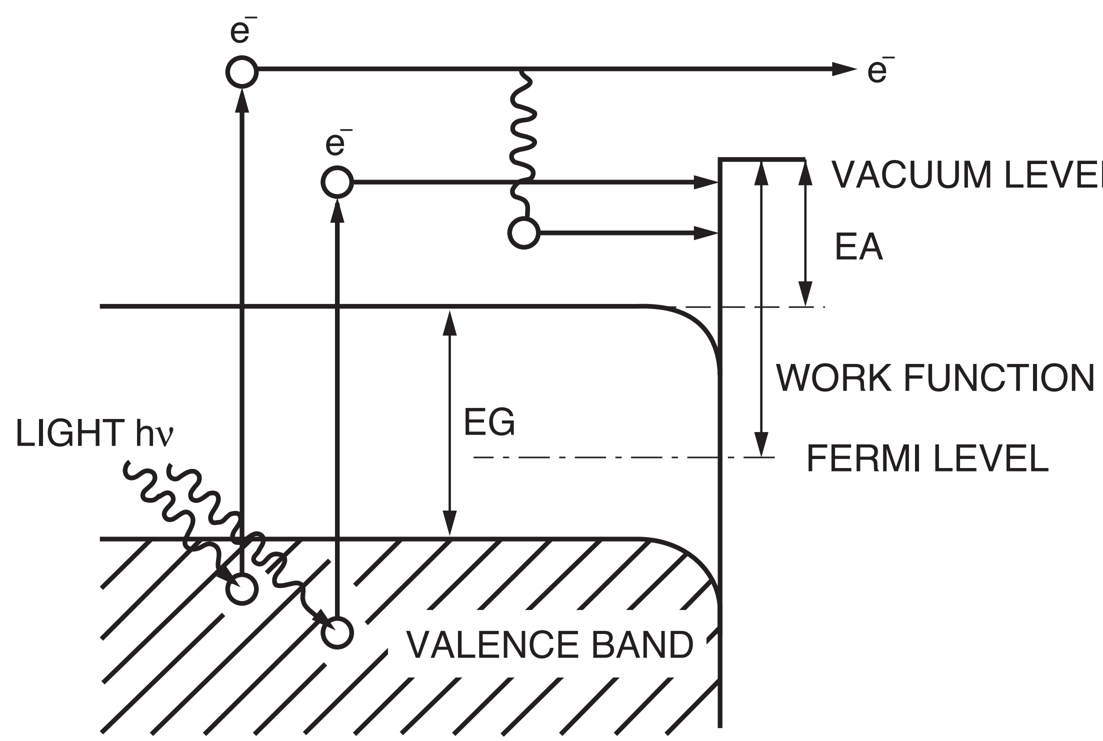
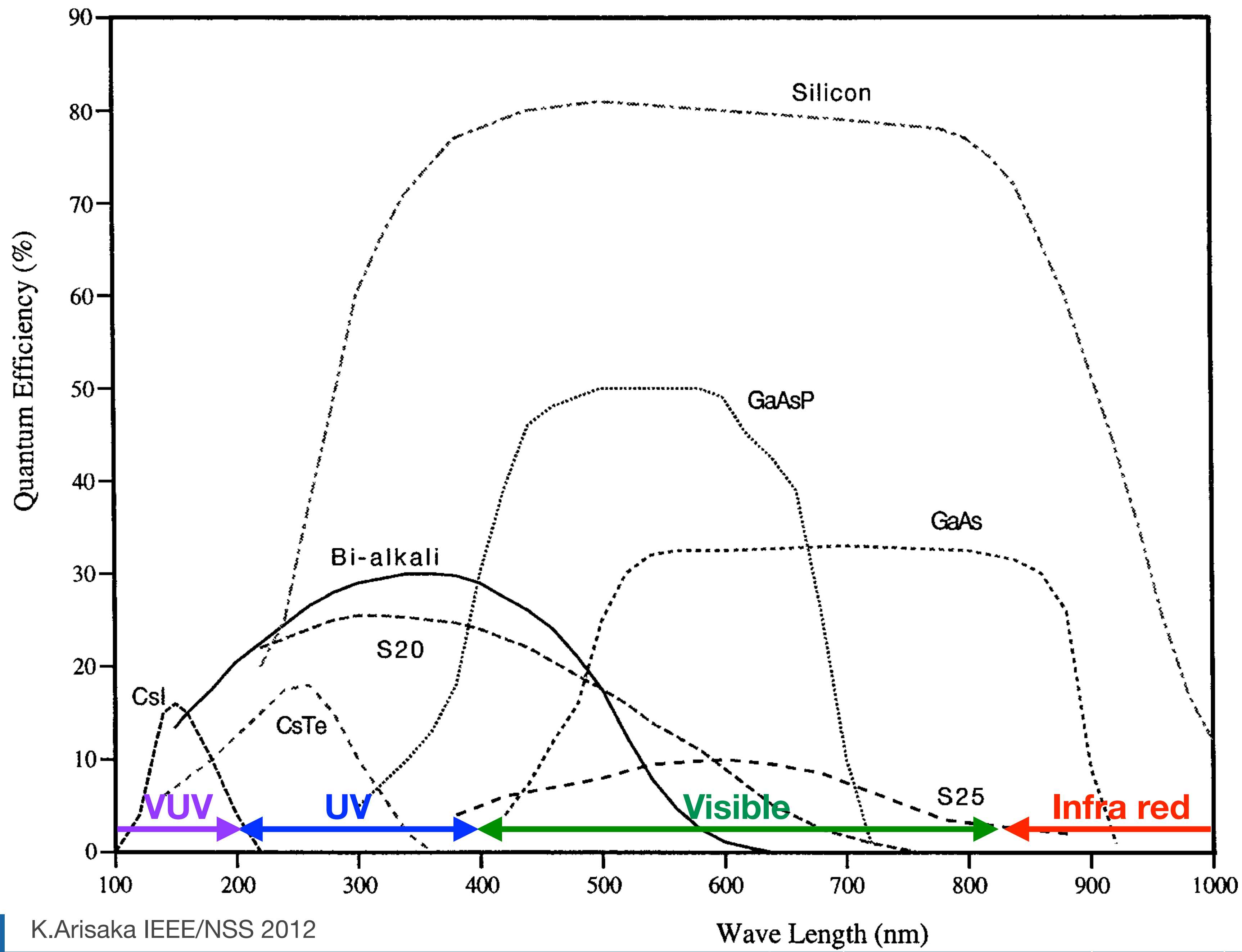


Photo-sensitive Materials

- **A wide range of wavelength to cover!**
  - Different types of photo-sensitive materials to be utilised
  - QE<50% for photocathode for vacuum photodetector
  - QE<80% for silicon



K.Arisaka IEEE/NSS 2012

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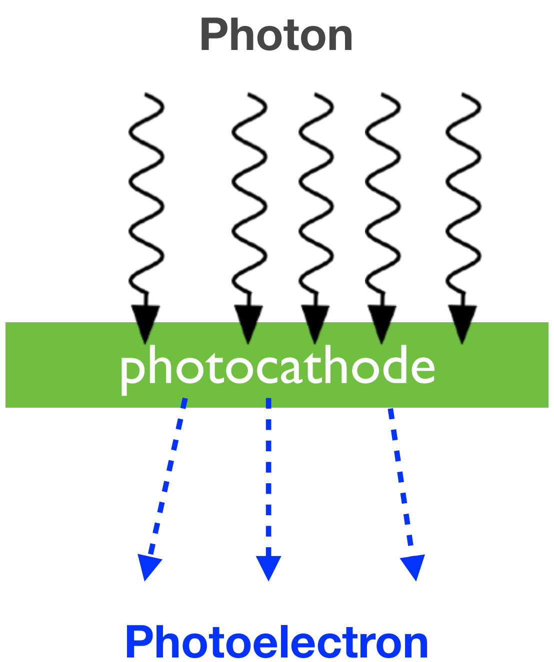
Crucial Properties

- **Crucial properties for photo-detector**
  - Sensitivity incl. spectral response
  - S/N (gain + noise)
  - Linearity
  - Signal fluctuation
  - Timing performance
  - Area (large or compact, depending on purpose)
  - Immunity to magnetic field
  - Radiation hardness
  - Ageing
  - …

Sensitivity

- **Different ways of measuring sensitivity**
- **Pulse operation**
  - Quantum Efficiency (QE) = Efficiency for photoelectric conversion [%]
  - Photon Detection Efficiency (PDE) [%]
- **Continuous (current) operation**
  - Radiant sensitivity (Responsivity)
    = output current / input power [A/W]



$$QE = \frac{N_{\text{photoelectron}}}{N_{\text{photon}}}$$

$$S = \frac{QE \cdot e}{E_{\text{photon}}} = \frac{QE \cdot e \cdot \lambda}{hc}$$

Collection eff. for photoelectrons from photocathode to electron multiplier

Efficiency of electron multiplication (~1)

PMT: $$PDE = QE \cdot CE \cdot \epsilon_{\text{mult}}$$

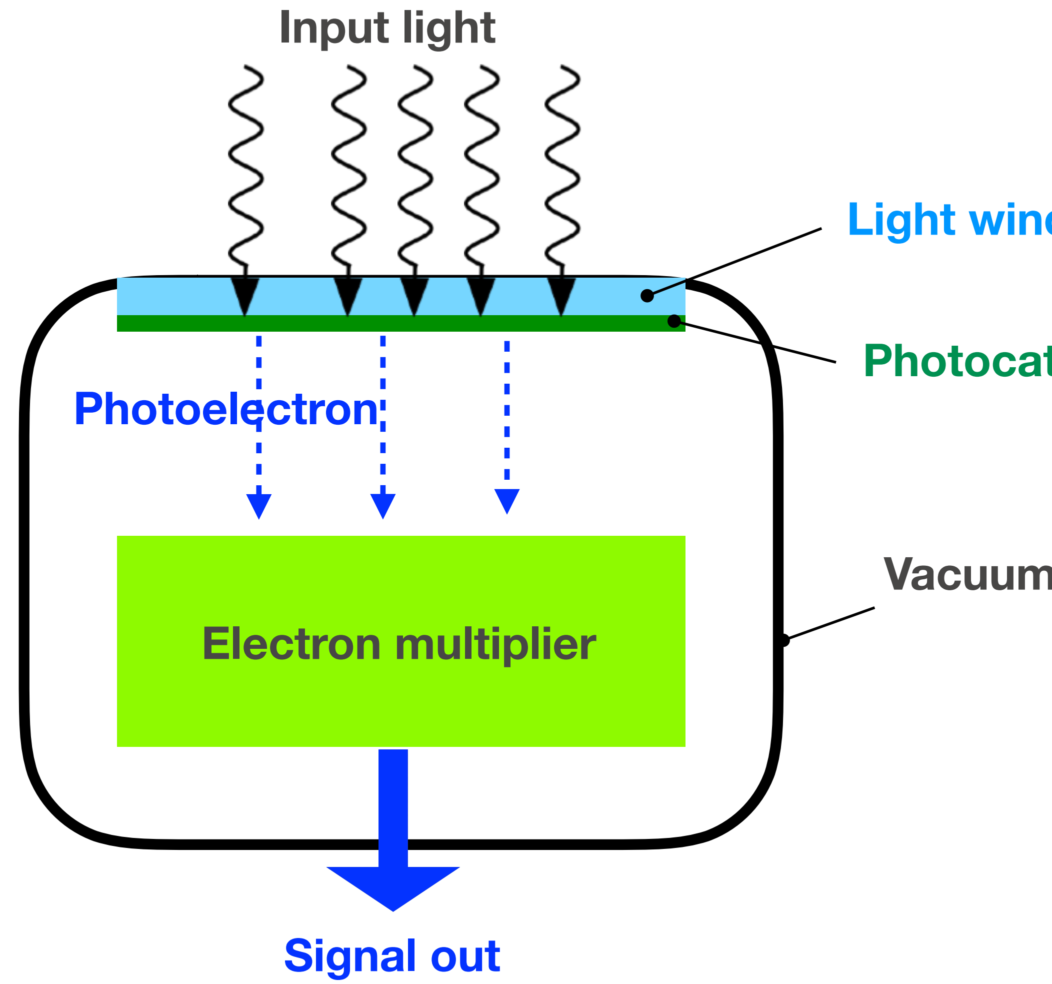
SiPM: $$PDE = \epsilon_{\text{FF}} \cdot QE \cdot \epsilon_{\text{trg}}$$

Geometrical fraction of active area

Efficiency of triggering Avalanche multiplication

Signal Fluctuation

- **Source of signal fluctuation**
  - Photoelectron statistics (Poisson distribution)
  - Additional statistical fluctuation in multiplication process
- **Signal fluctuation characterised by Excess Noise Factor (ENF)**
  - Large ENF worsens energy resolution



$$\boxed{ENF = \frac{\sigma^2_{\mathrm{OUT}}}{\sigma^2_{\mathrm{IN}}} = 1 + \frac{\sigma^2_{\mathrm{M}}}{M^2}}$$

M: multiplication gain

$$\boxed{\frac{\sigma}{E} = \sqrt{\frac{ENF}{N_{\mathrm{pe}}}}}$$

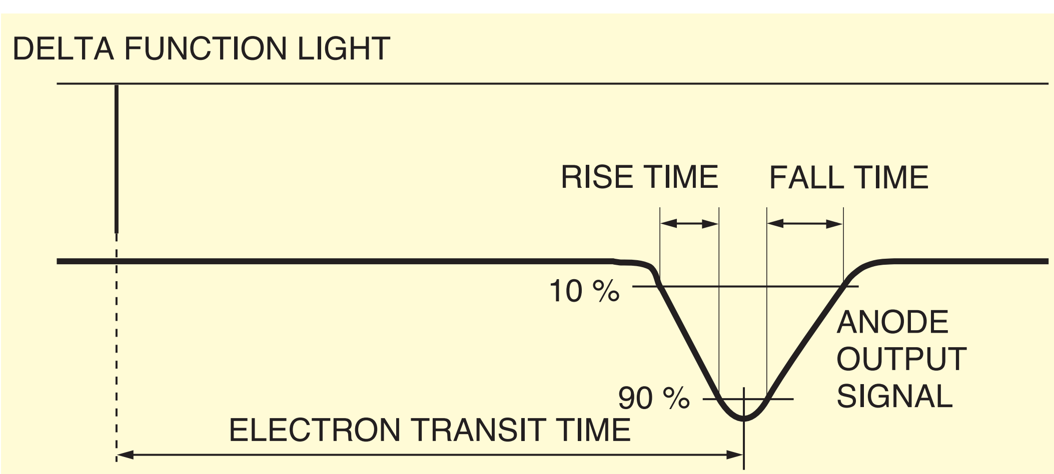
N_{pe} : # of photoelectrons

ENF for photo-detectors

	ENF
PMT	1.3
MCP-PMT	~1
HPD	~1
APD	2 (Gain=50)
SiPM	1.3

Timing Performance

- **Fast response of photodetector crucial for some applications**
- **What determines time response of photodetector?**
  - Signal shape
    - Rise time, fall time, duration
  - Transit time spread (T.T.S.)
  - Photoelectron statistics
  - S/N



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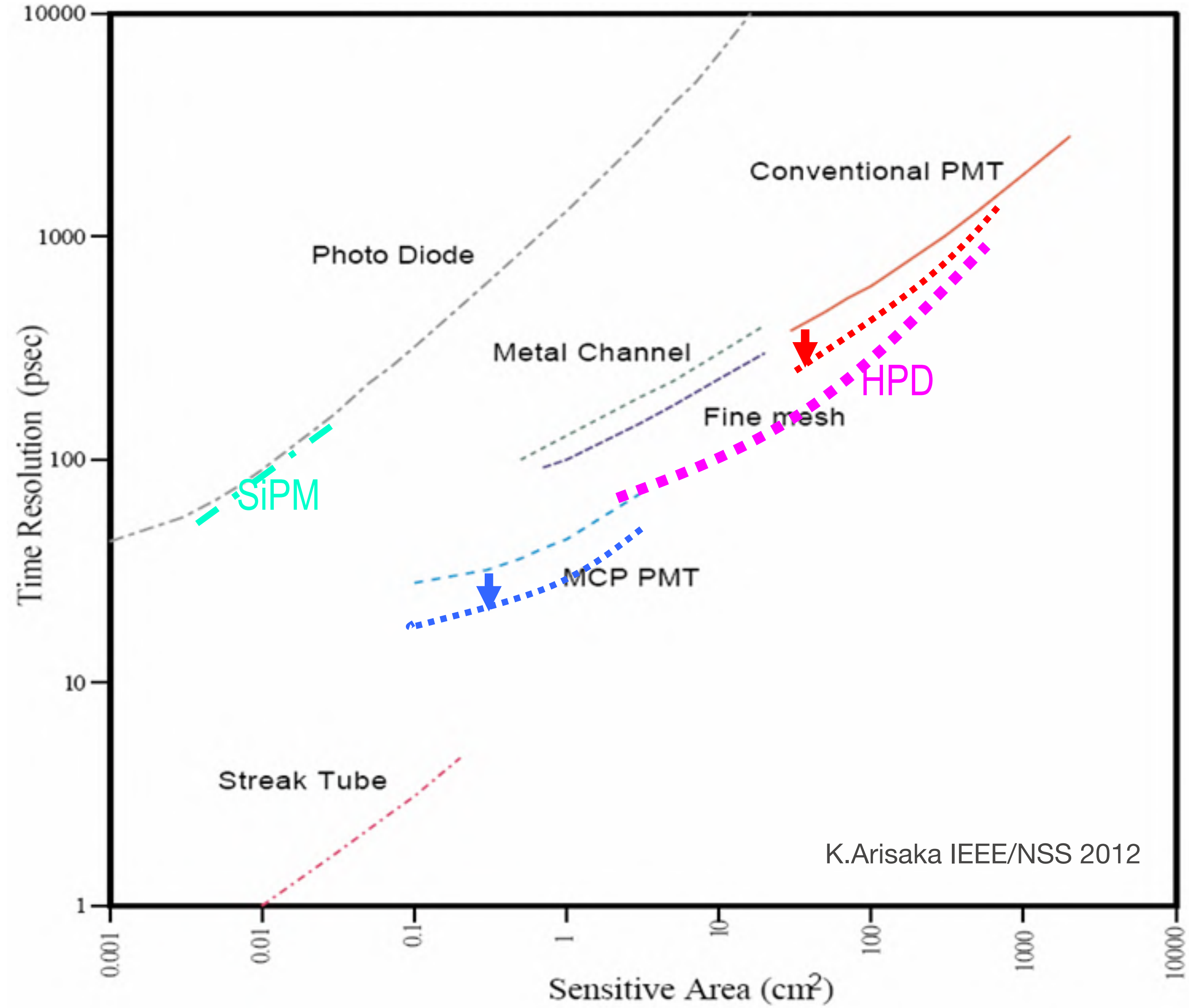
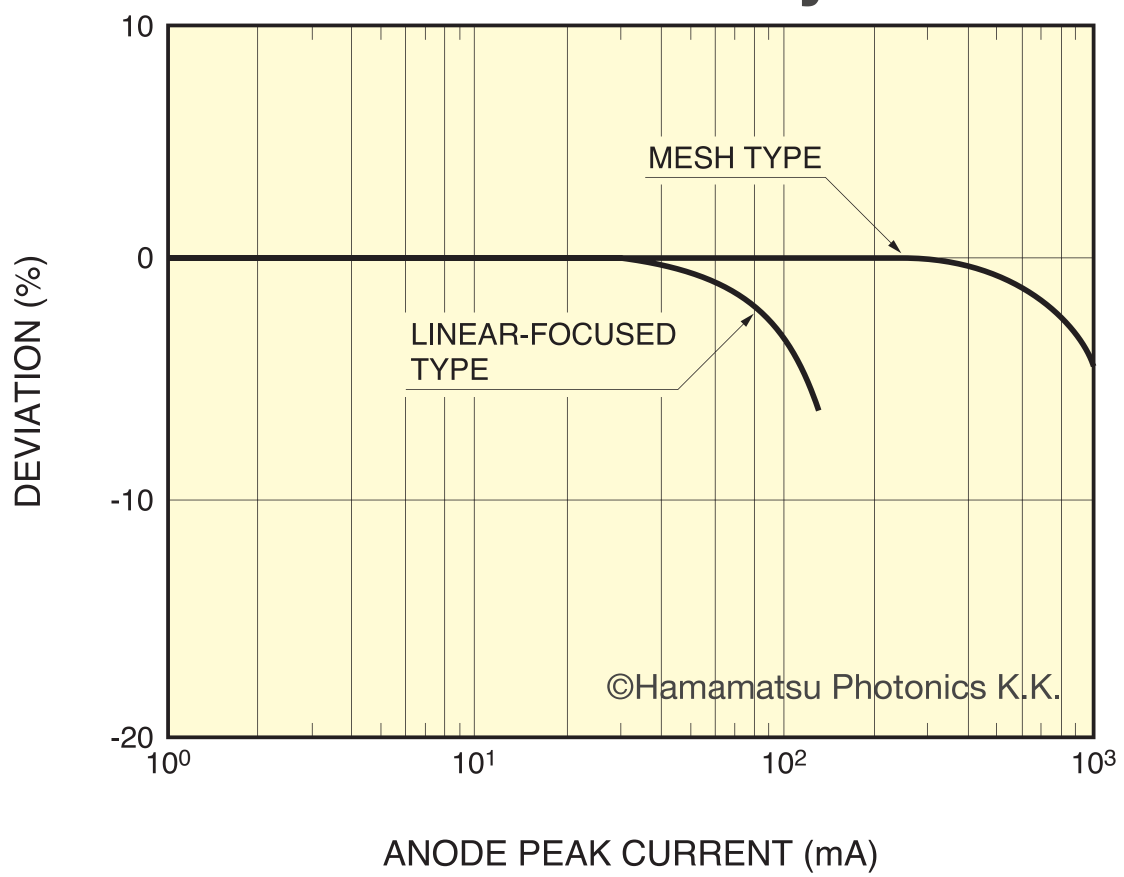


Linearity

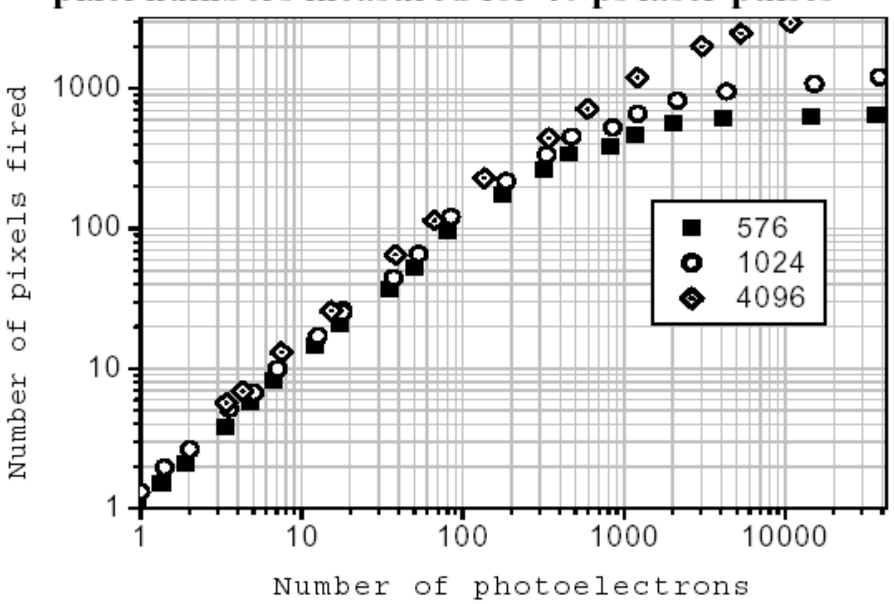
- **Linearity is crucial especially for energy measurement**
- **For ideal photon detector, signal output ∝ input #photon**

PMT linearity



SiPM linearity

Response functions for the SiPMs with different total pixel numbers measured for 40 ps laser pulses

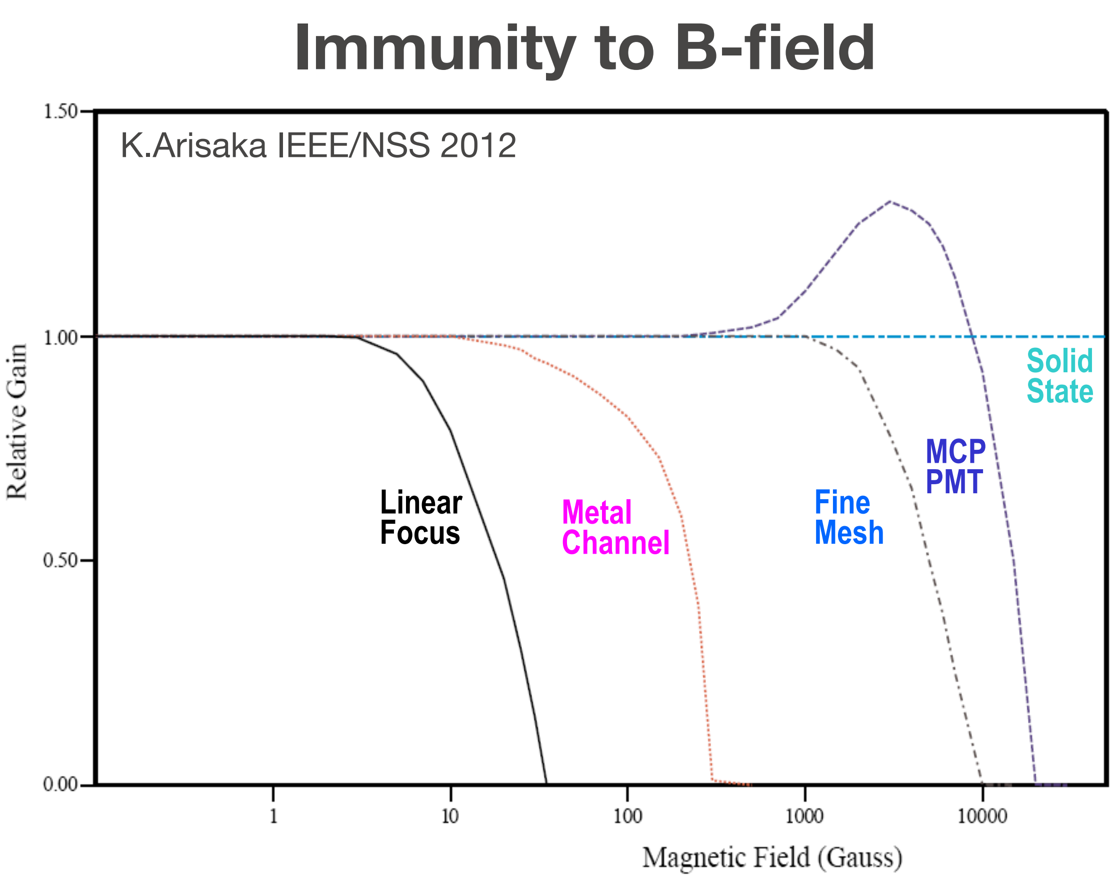


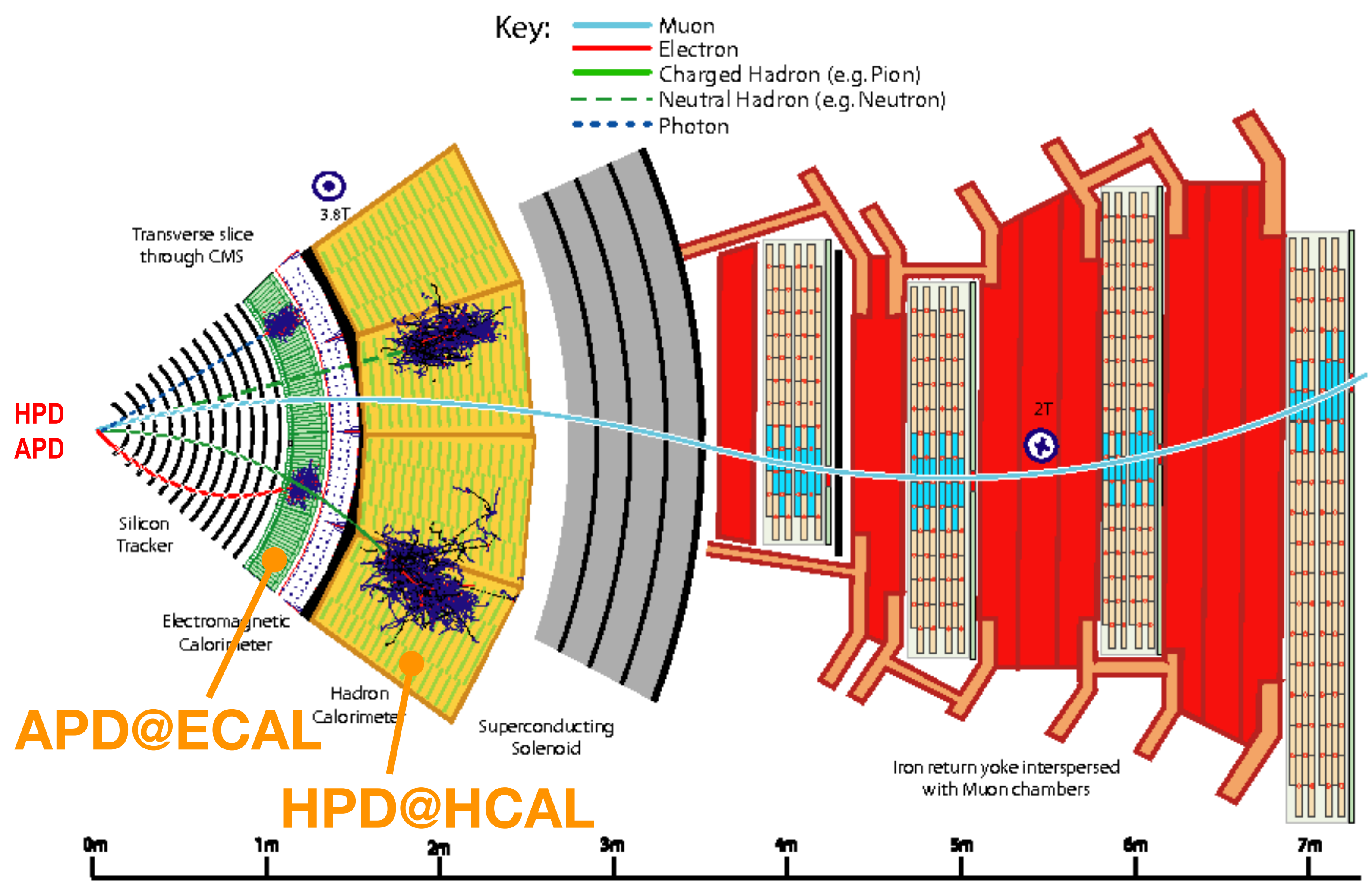
B. Dolgoshein, TRD2005

	PMT	MCP-PMT	HPD	APD	SiPM
Dynamic range (p.e.)	10^6	10^7	10^7	10^7	10^3

Immunity to Magnetic Field

- **Some particle detectors operated in magnetic field**
  - Tracking detector and other detectors in magnetic field at collider detectors
- **Immunity to magnetic field is required**
- **Otherwise light is transmitted via long optical fibre to photodetector placed outside without B-field**

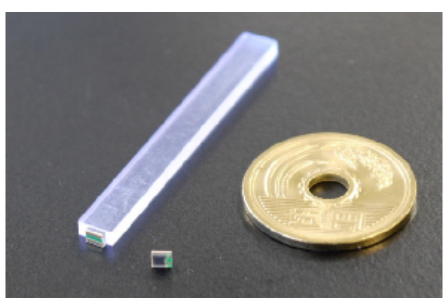


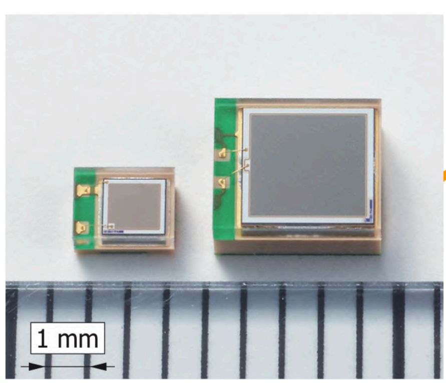


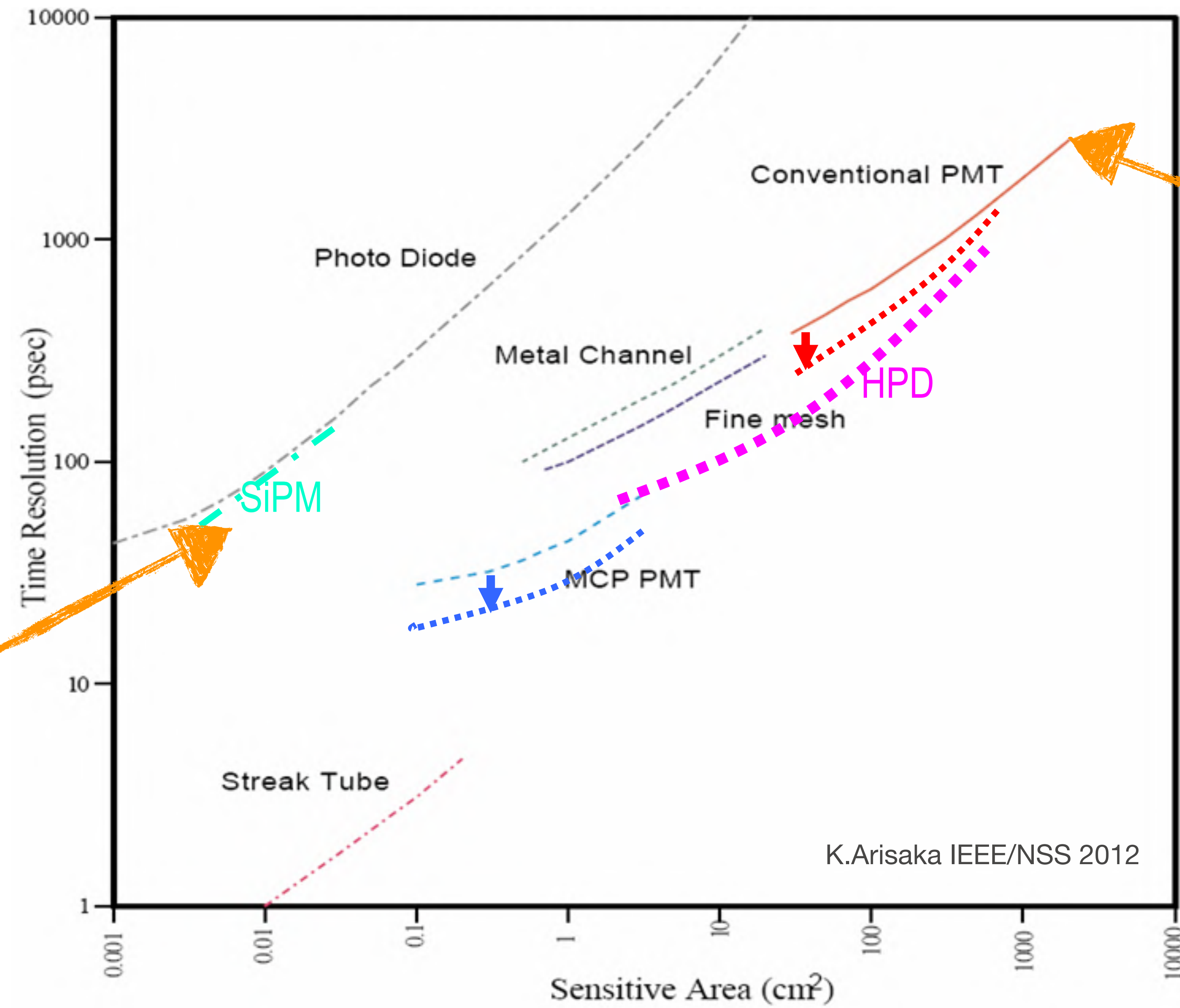
Area

- **Different requirements for sensor area**
  - Solid-state photodetector →Compact → High granularity
  - Vacuum-based and gaseous photodetectors →Large are coverage

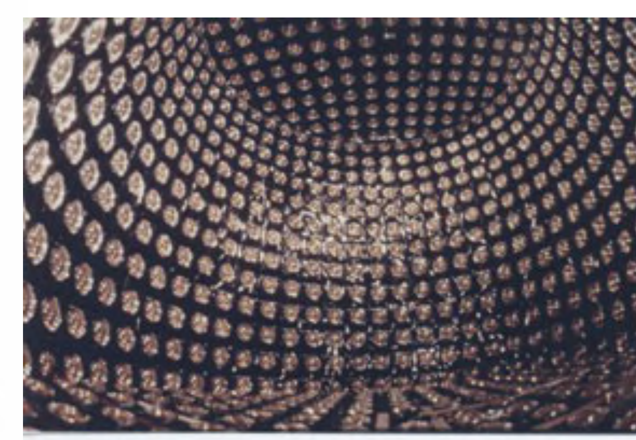
SiPM (1x1mm^2)







PMT (20"ϕ)



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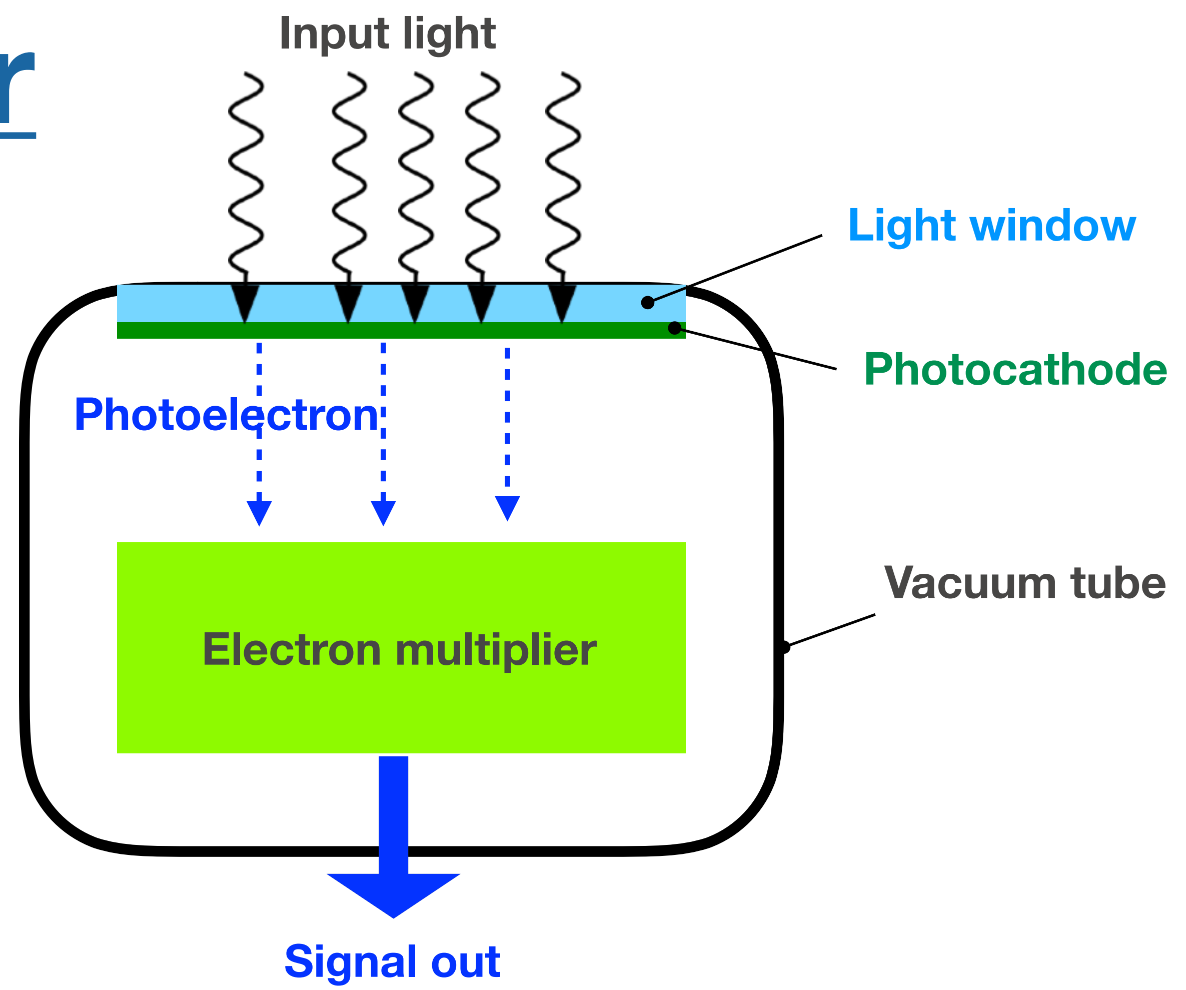
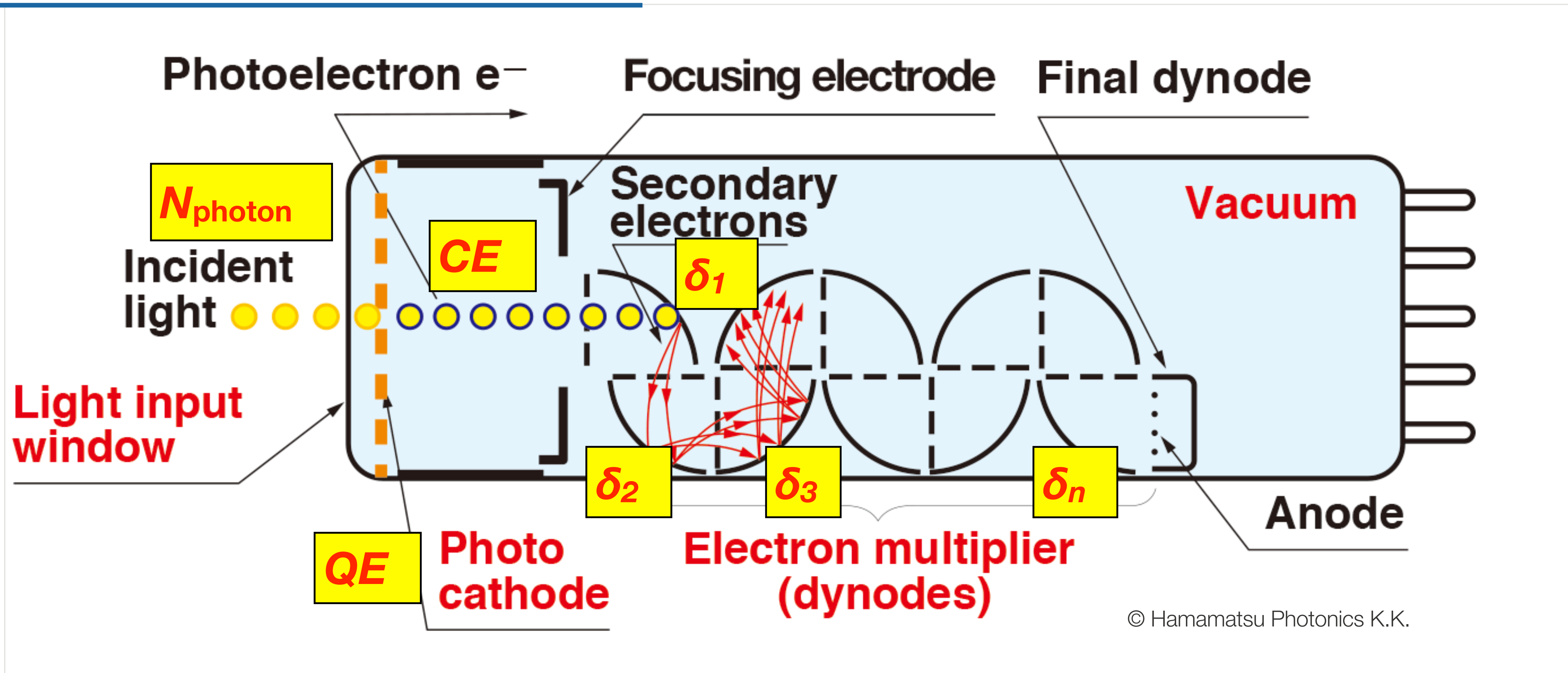
Vacuum Photo-detector

- **PhotoMultiplier Tube (PMT) and its variants**
- **Old device, but still used in many projects**
- **Concept**
  - External photoemission at photocathode in vacuum tube
  - Electron multiplier
  - Signal extraction at anode
- **Advantages**
  - High gain
  - Wide spectral range to cover
  - Large area
  - Low dark current
  - Excellent timing performance
  - Radiation hardness
  - Linearity, stability
- **Disadvantages**
  - Moderate QE
  - Non uniformity
  - Bulky
  - Expensive



Signal Generation



$$\boxed{Signal = N_{photon} \cdot QE \cdot CE \cdot G}$$

Quantum efficiency

Collection efficiency
(Photocathode → 1st dynode)

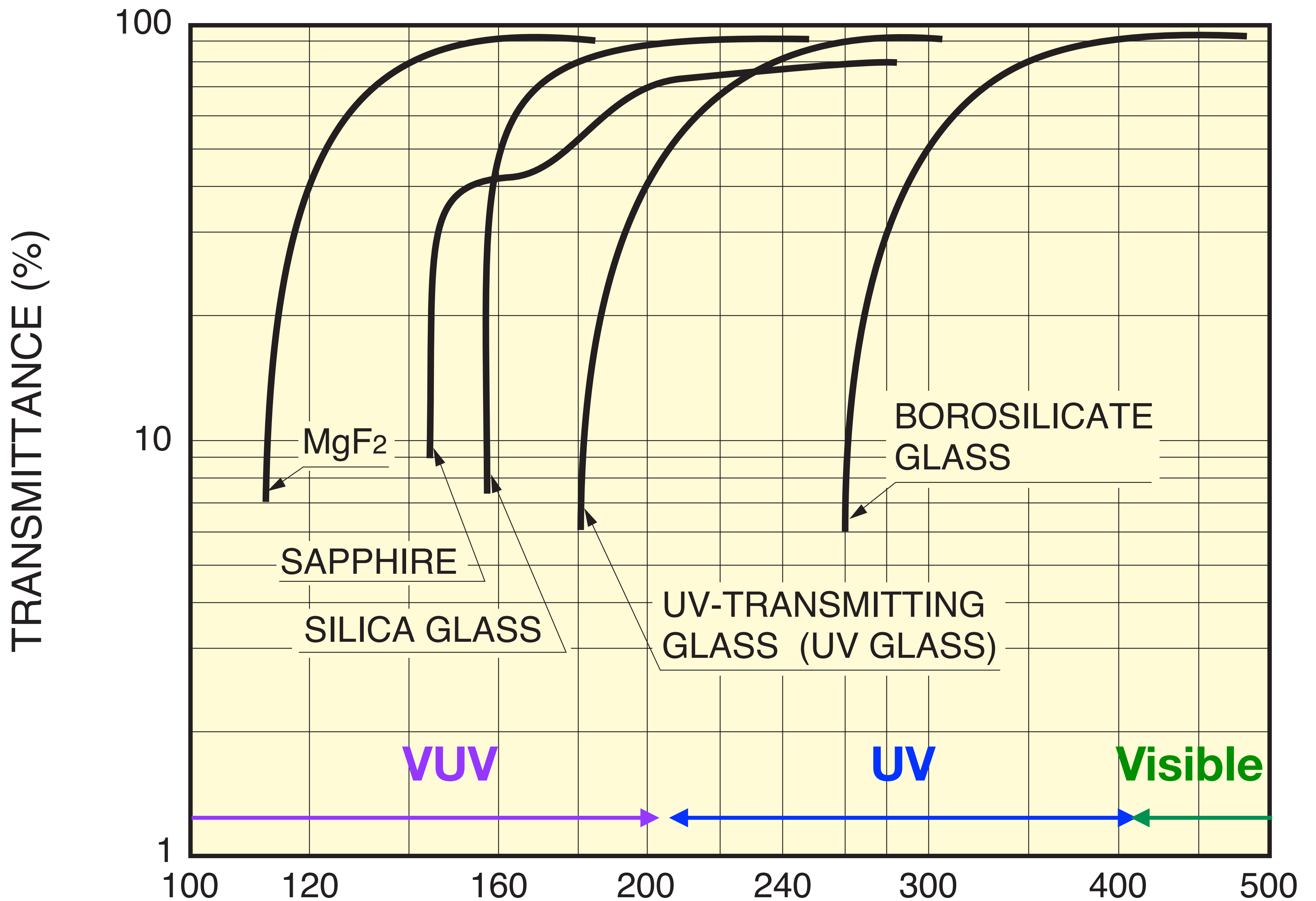
Gain

$$\boxed{G = \delta_1 \cdot \delta_2 \cdots \delta_n}$$

δ : Secondary emission rate at dynode

Light Window

- **Transmission in light window is crucial for shorter wavelength**
  - Need (expensive) UV-transmittng window for UV light



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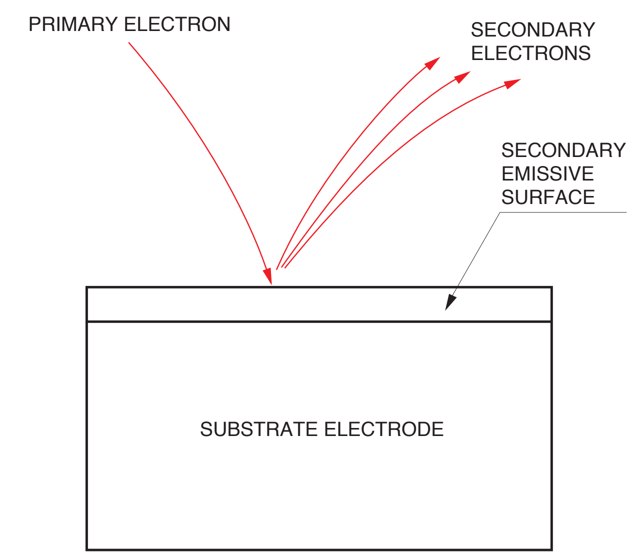
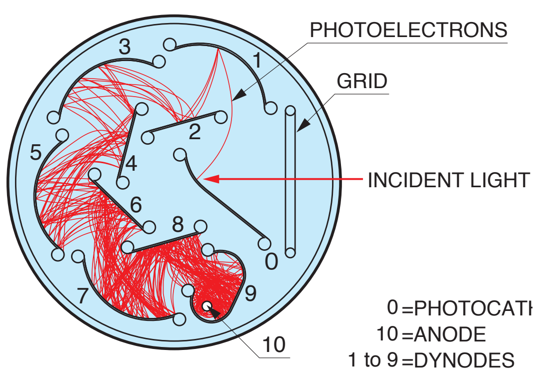
Dynode Discrete Type

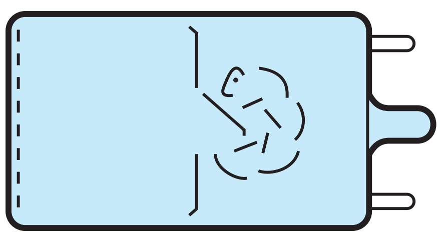
- **Multi-stage photoelectron multiplication**
- **Different dynode structures**

Secondary electron emission at dynode

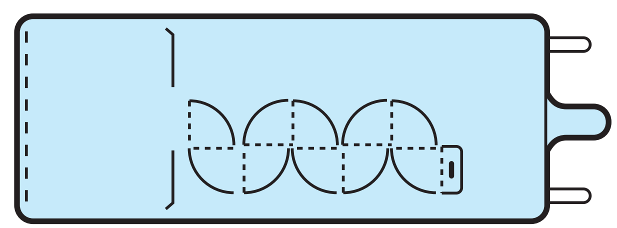


Circular cage
- Compact, high speed

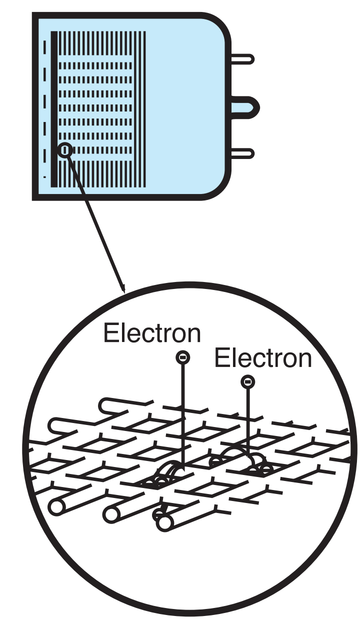




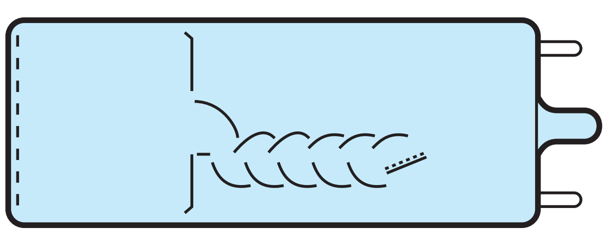
Box-and-grid
- High collection efficiency



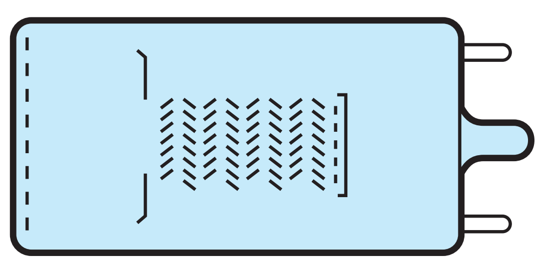
Fine mesh
- Good immunity to B-field



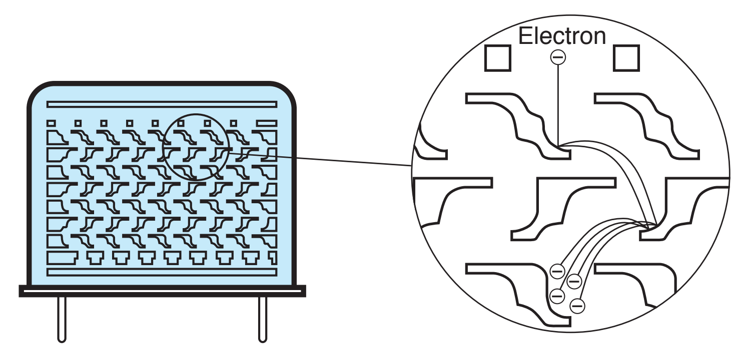
Linear focused
- Fast response, good linearity



Venetian blind
- Suitable for large diameter



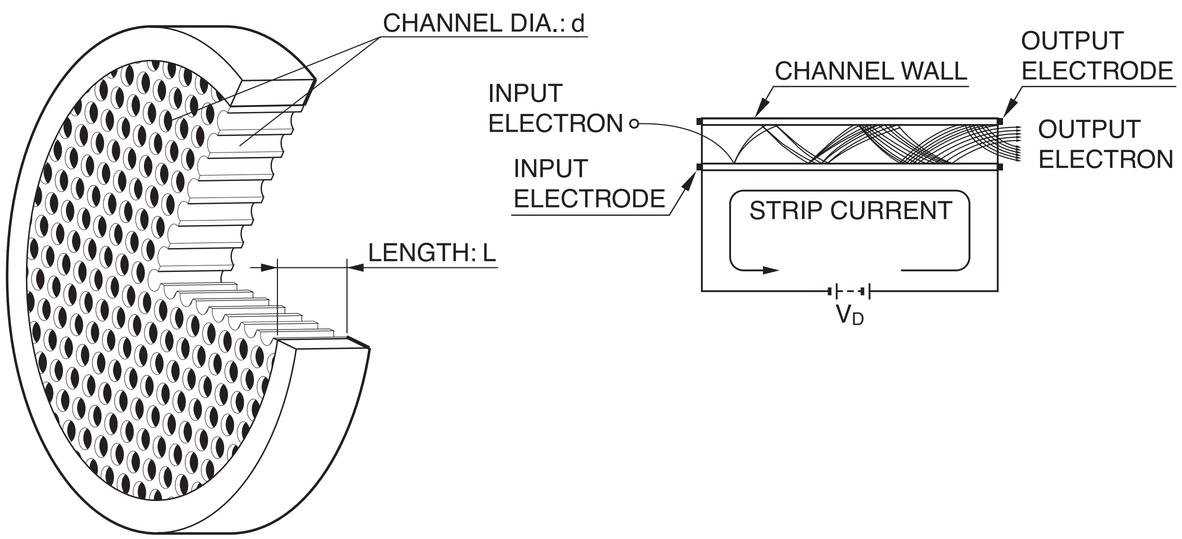
Metal channel
- Compact, high speed



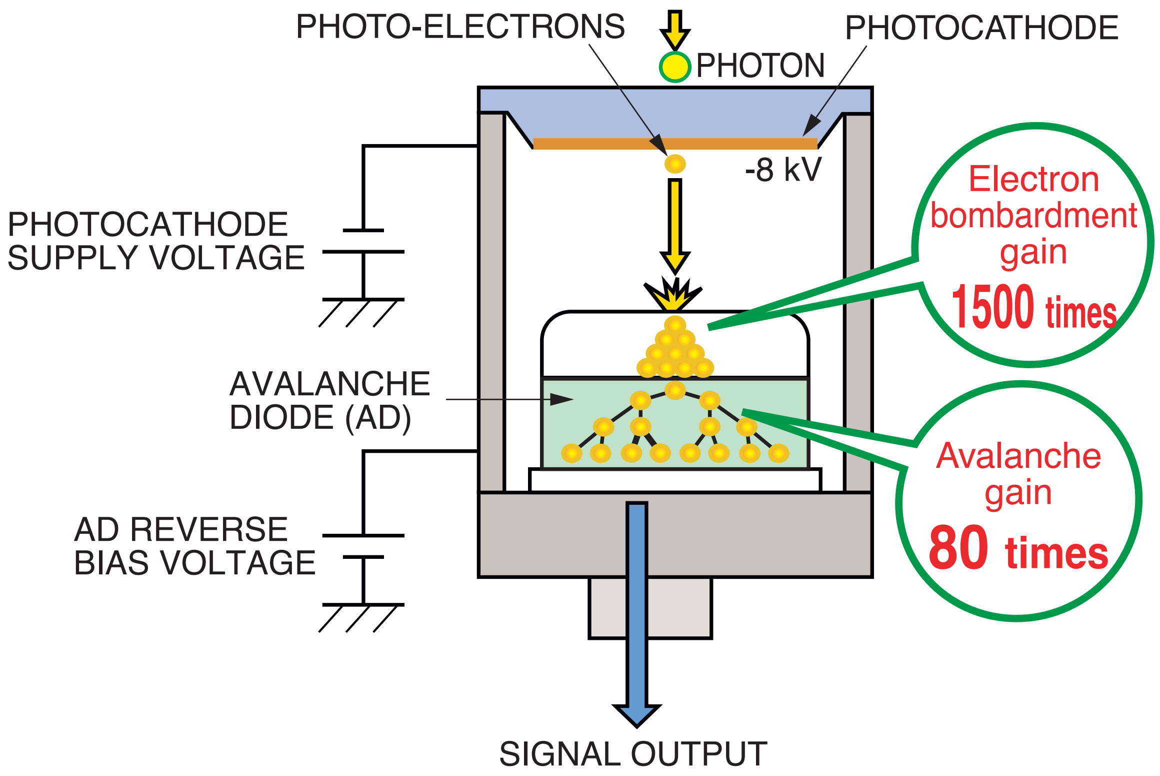
Dynode Non-discrete Type

- **Micro Channel Plate (MCP)**
  - Electron multiplication in micro glass capillaries (channels)
    →MCP-PMT
- **Silicon device as electron multiplier**
  - Photo-diode (PD), Avalanche photo-diode (APD)
  - Hybrid PMT
    →HPD, HAPD

MCP

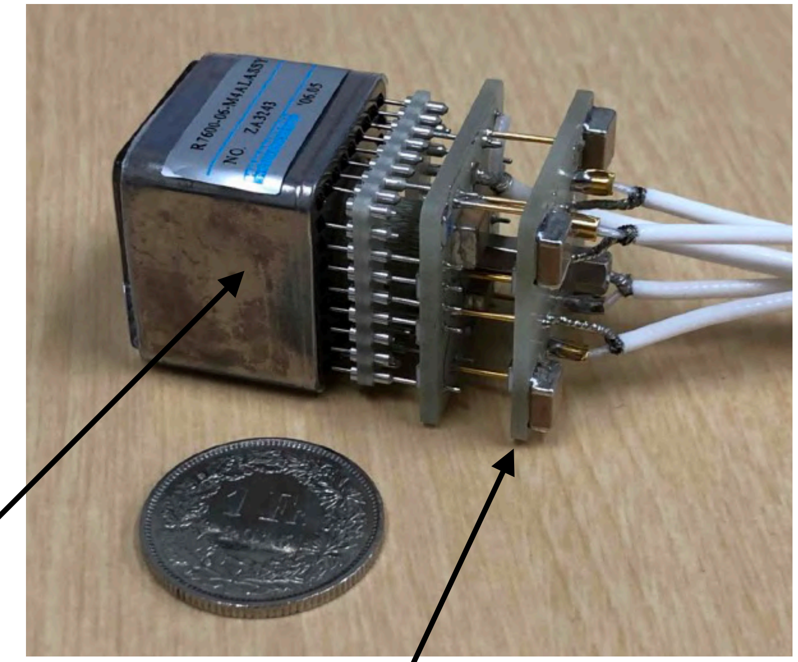


APD



Voltage Divider

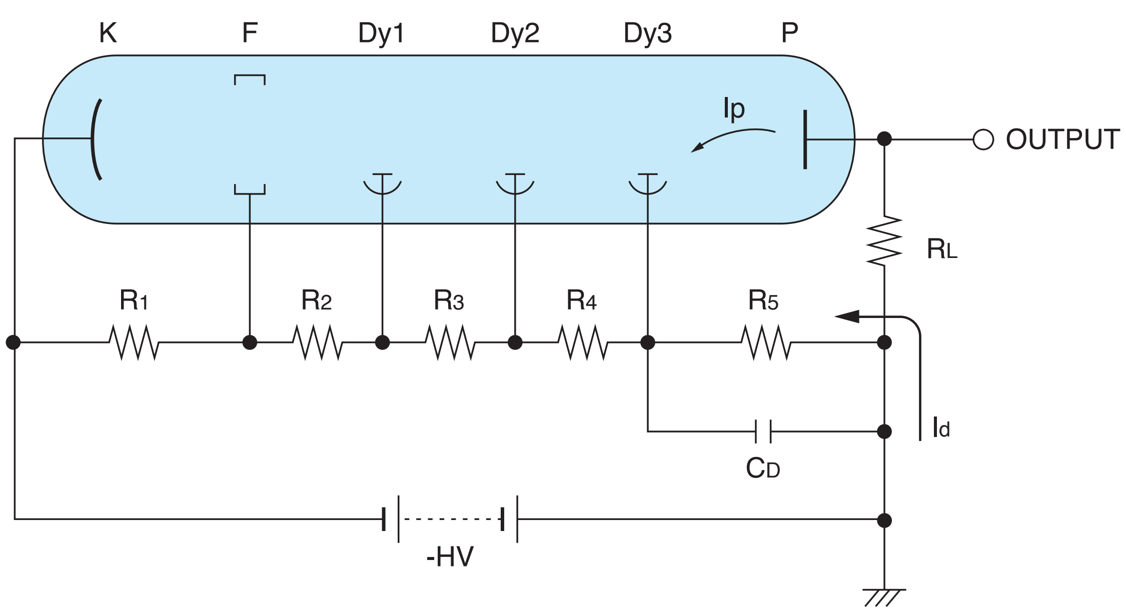
- **Electron multiplication at multistage dynodes**
  - Voltage divider circuit to provide proper voltage gradient over dynodes
  - Two types of grounding scheme: anode grounded & cathode grounded
  - **Anode grounded**
    - Both pulse and DC mode operations are possible
  - **Cathode grounded**
    - Only pulse mode is possible
    - Safer coupling between detector medium (scintillator) and PMT



PMT

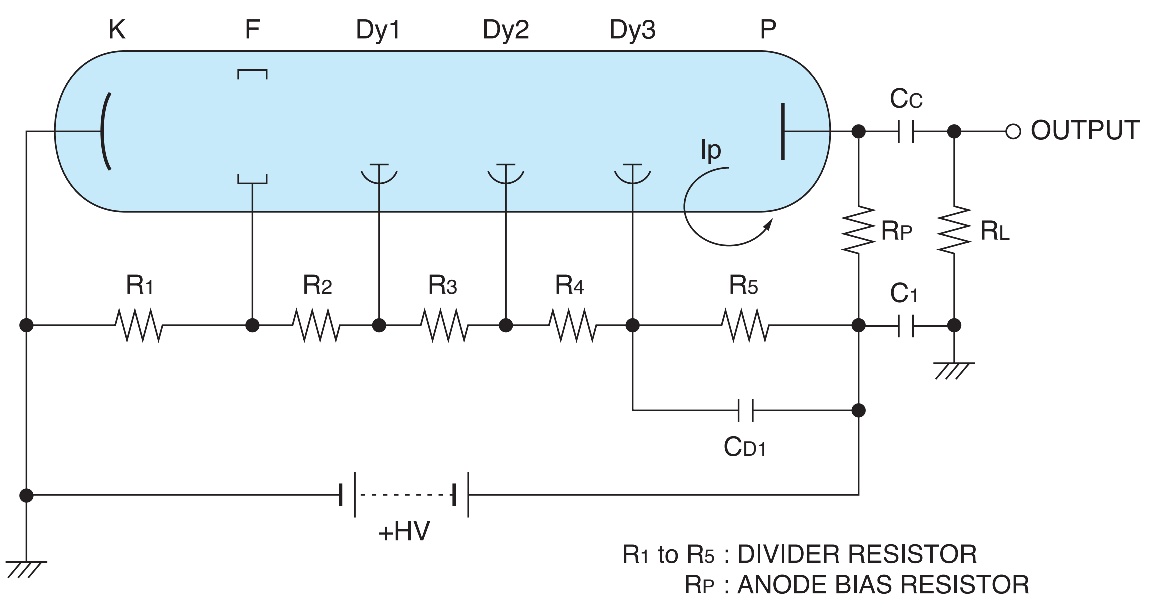
Voltage divider circuit

Anode grounded



R1 to R5 : DIVIDER RESISTOR
RL : LOAD RESISTOR
Ip : ANODE CURRENT
Id : DIVIDER CURRENT

Cathode grounded



R1 to R5 : DIVIDER RESISTOR
RP : ANODE BIAS RESISTOR
RL : LOAD RESISTOR
Ip : ANODE CURRENT
Cc : COUPLING CAPACITOR
CD1 : DECOUPLING CAPACITOR
C1 : BYPASS CAPACITOR

Gain

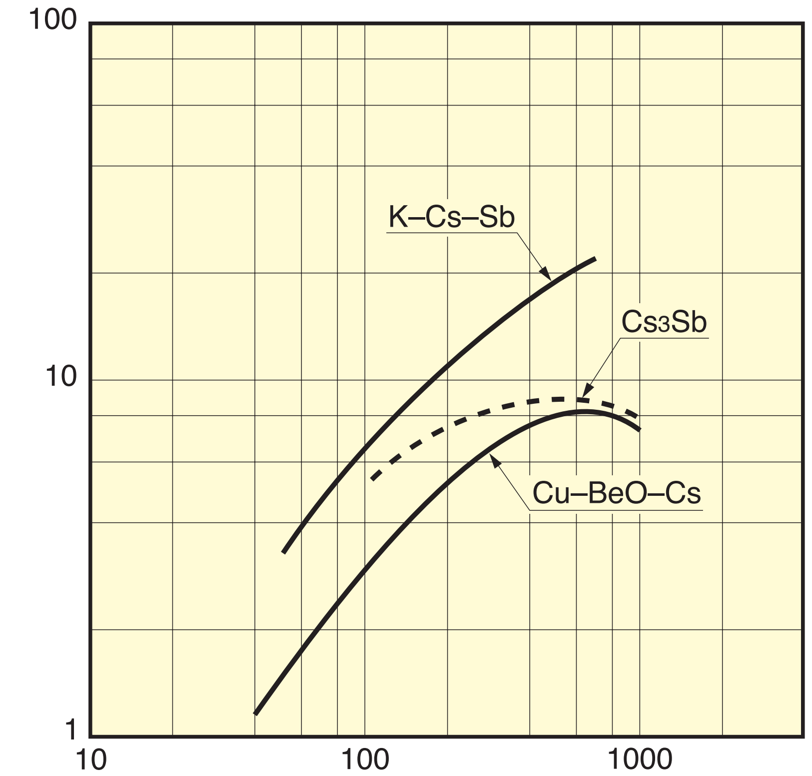
- **Secondary emission ratio δ**
  - Average # photoelectrons emitted per incident photoelectron at each dynode
  - Dependent on inter-dynode voltage ΔV (=HV/(n+1))
  - Poisson fluctuation of δ (√δ)→ main source of gain fluctuation

$$\delta_i \propto \Delta V^k \quad k = 0.7 - 0.8$$

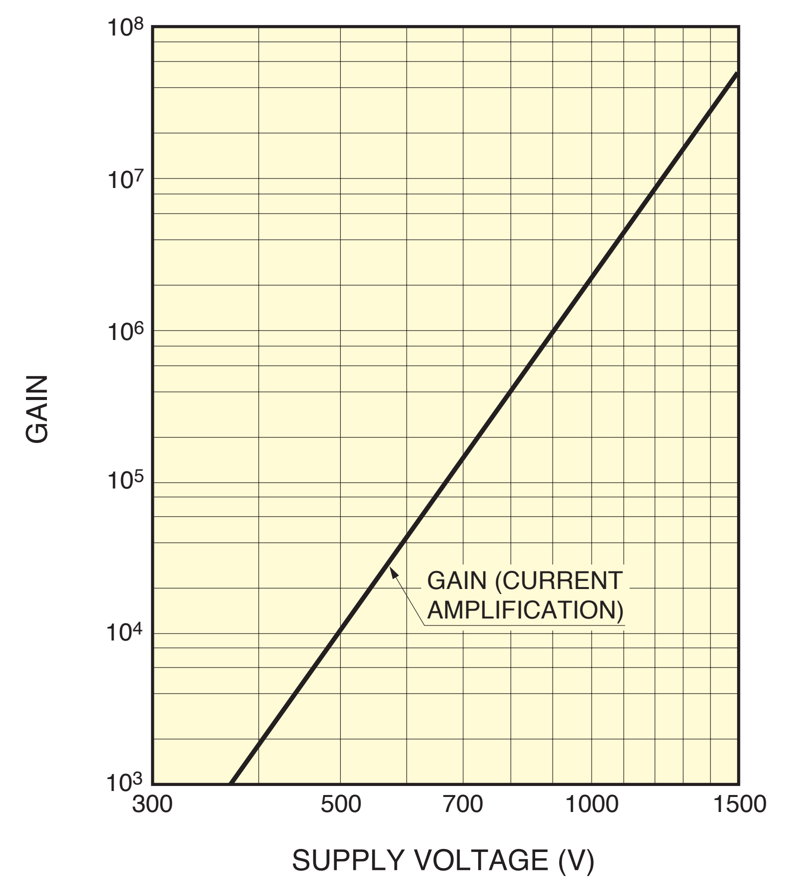
$$\boxed{G = \delta_1 \cdot \delta_2 \cdots \delta_n \propto HV^{kn}}$$

$$\boxed{ENF = \frac{\sigma_{\mathrm{OUT}}^2}{\sigma_{\mathrm{IN}}^2} = 1 + \frac{\sigma_{\mathrm{M}}^2}{M^2} = 1 + \frac{1}{\delta_1} + \frac{1}{\delta_1 \cdot \delta_2} + \cdots + \frac{1}{\delta_1 \cdot \delta_2 \cdots \delta_n}}$$

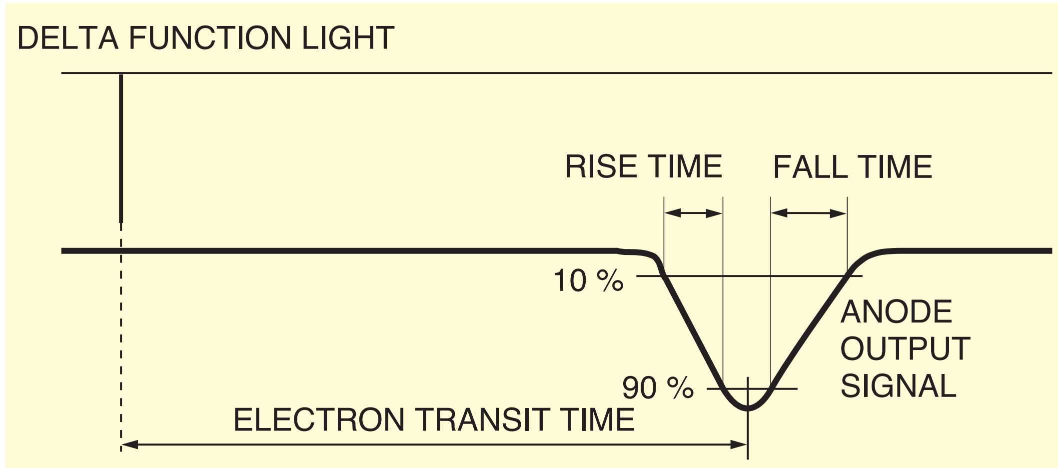
Secondary emission rate δ



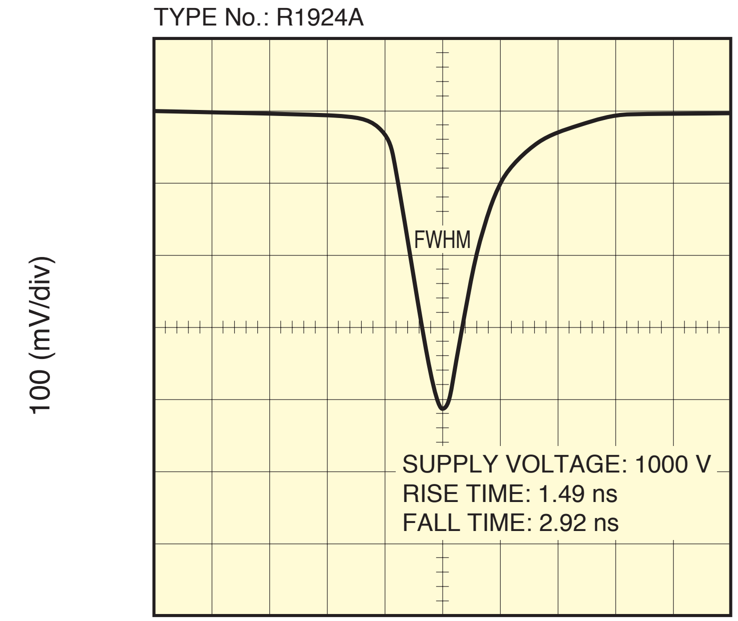
HV-dependence of gain



Time Response

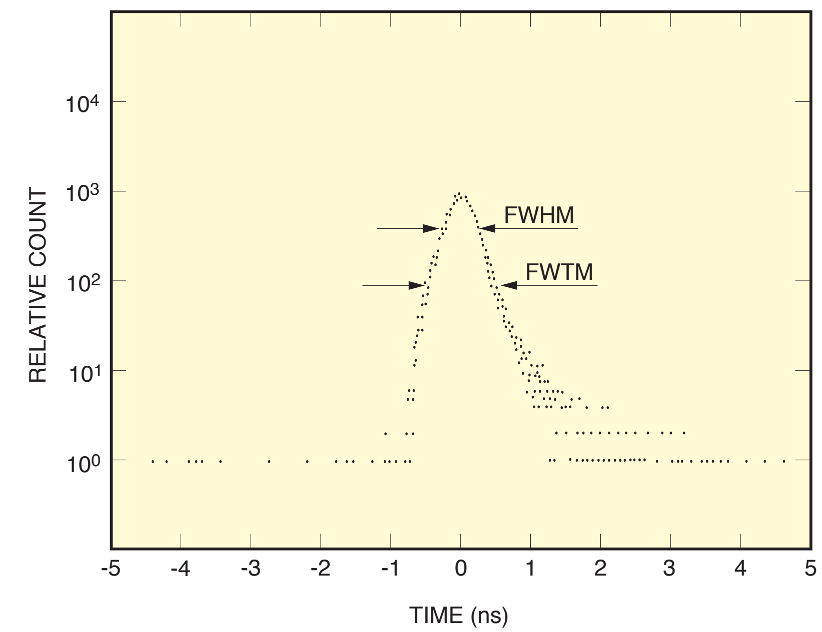


Typical PMT signal



- **Parameters for photo-detector time response**
  - Waveform (rise-time, fall-time, S/N)
  - Spread of electron transit time (Transit Time Spread, T.T.S.)
- **PMT is a fast photo-detector**
  - Carefully designed electron trajectories with minimum TTS
  - TTS < 1ns

Transit Time Spread (TTS)

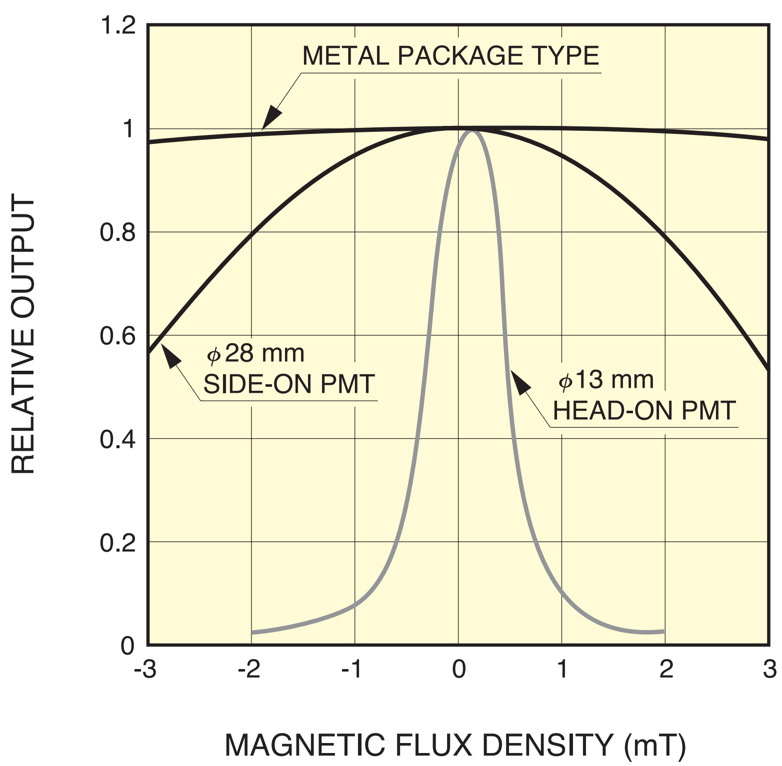


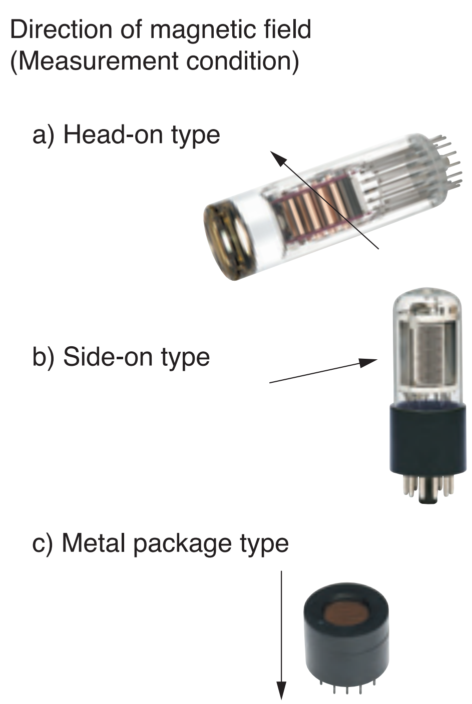
Unit: ns

Dynode type	Rise time	Fall time	Pulse width (FWHM)	Electron transit time	T.T.S.
Linear-focused	0.7 to 3	1 to 10	1.3 to 5	16 to 50	0.37 to 1.1
Circular-cage	3.4	10	7	31	3.6
Box-and-grid	to 7	25	13 to 20	57 to 70	Less than 10
Venetian blind	to 7	25	25	60	Less than 10
Mesh	2.5 to 2.7	4 to 6	5	15	Less than 0.45
Metal channel	0.65 to 1.5	1 to 3	1.5 to 3	4.7 to 8.8	0.4

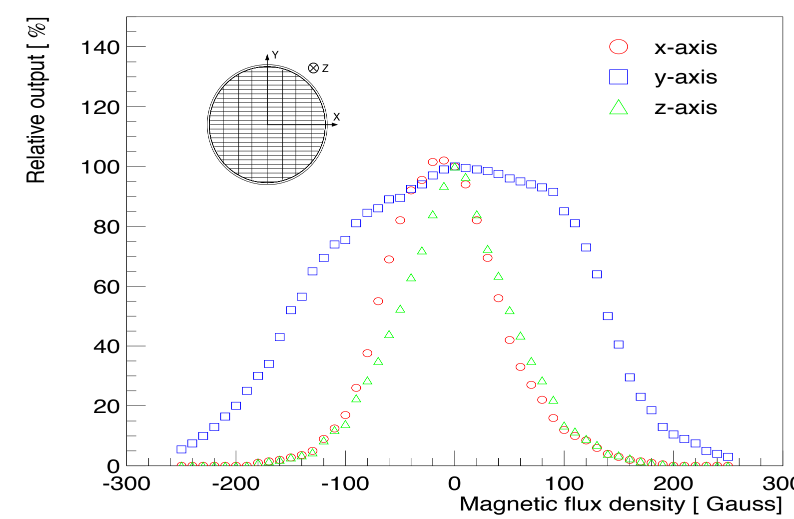
Effect of External Magnetic Field

- **PMT is quite sensitive to external magnetic field**
  - Electron trajectory can easily be modified
  - Somewhat dependent on dynode type
  - Easily affected even by earth magnetic field (~0.05mT) → need magnetic shield!
- **Some PMT type has moderate immunity, but strongly dependent on B-field direction**

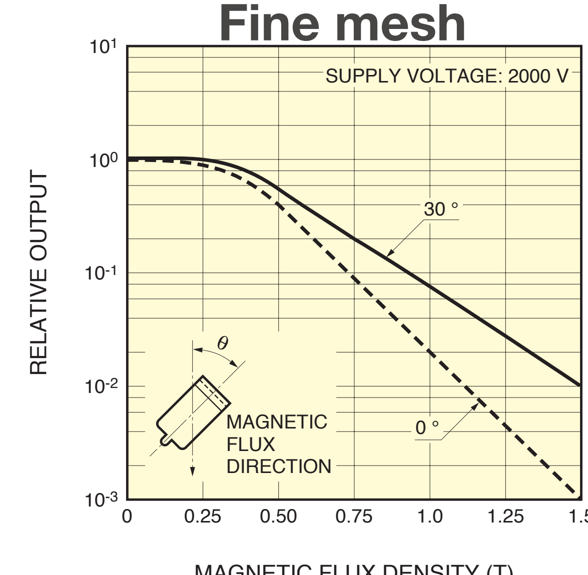




Metal channel

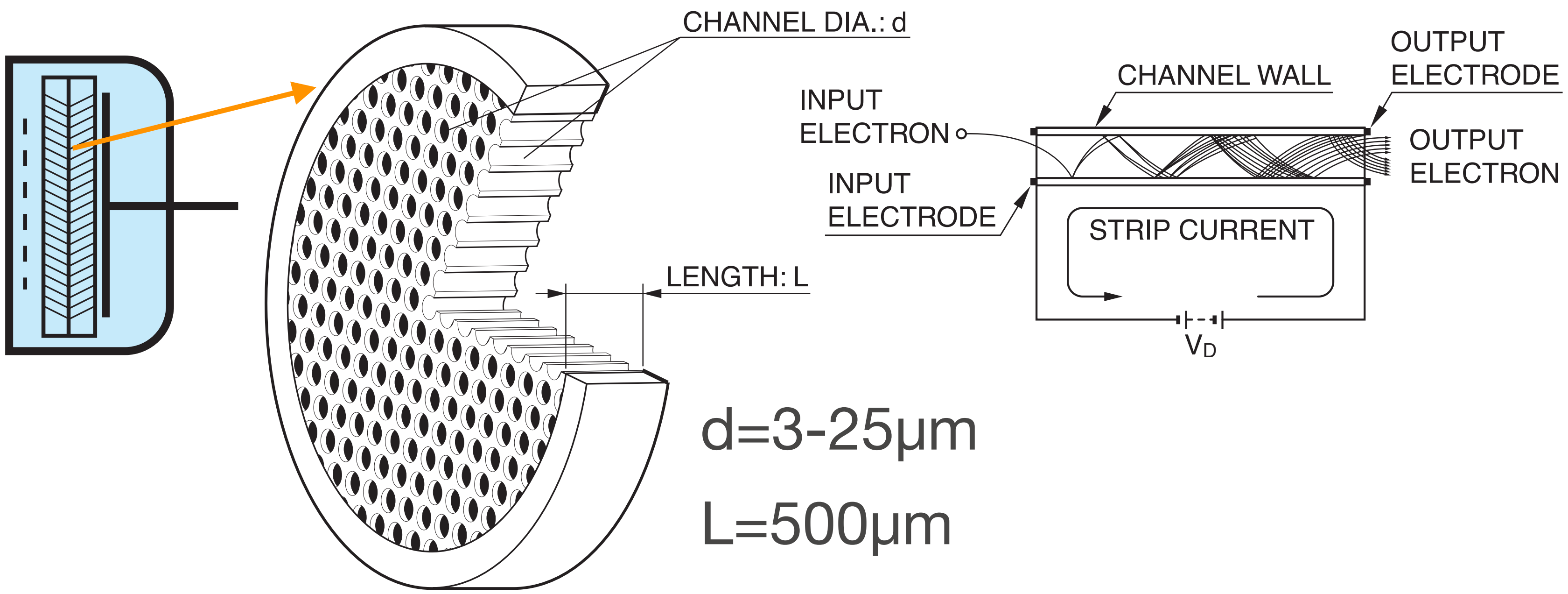


Fine mesh



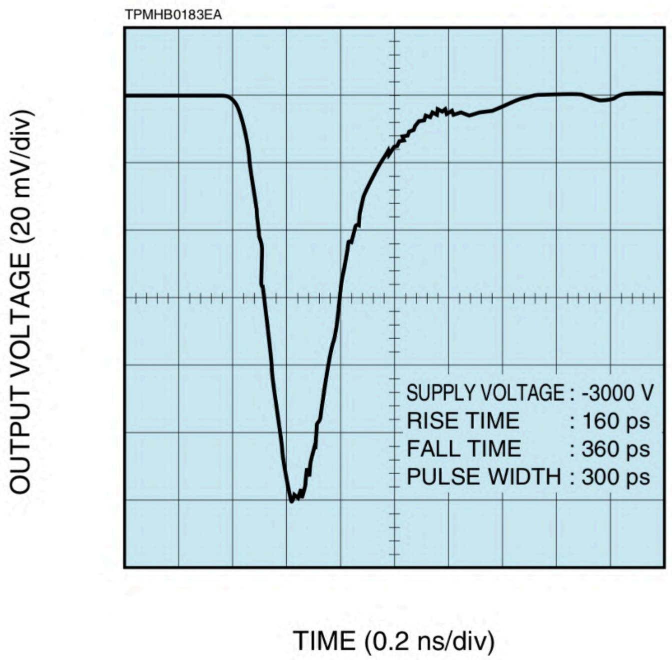
MCP-PMT

- **MCP**
  - Thin glass plate with many micro channels
- **Performance**
  - High gain of 10^6 with two stage MCP
  - Excellent time performance (TTS~50ps)
  - Operational in B-field
  - Position sensitive by segmented anode readout
- **Ageing issue**
  - Photocathode damaged by neutral gas and feedback ion from MCP



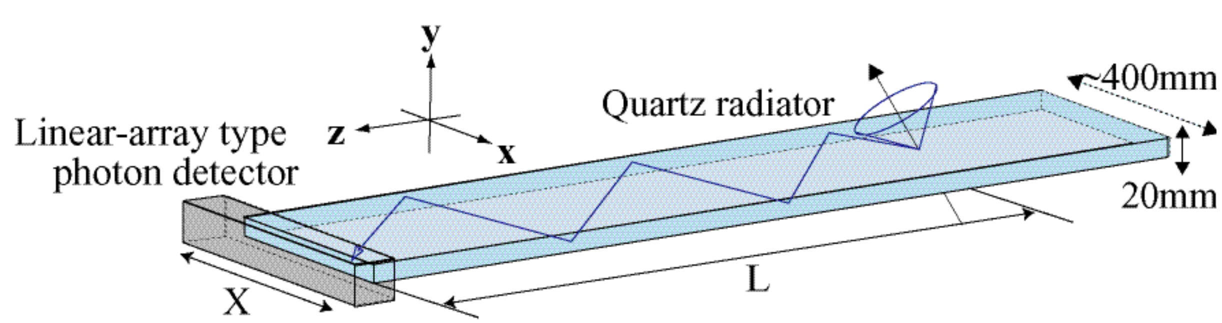
d=3-25μm

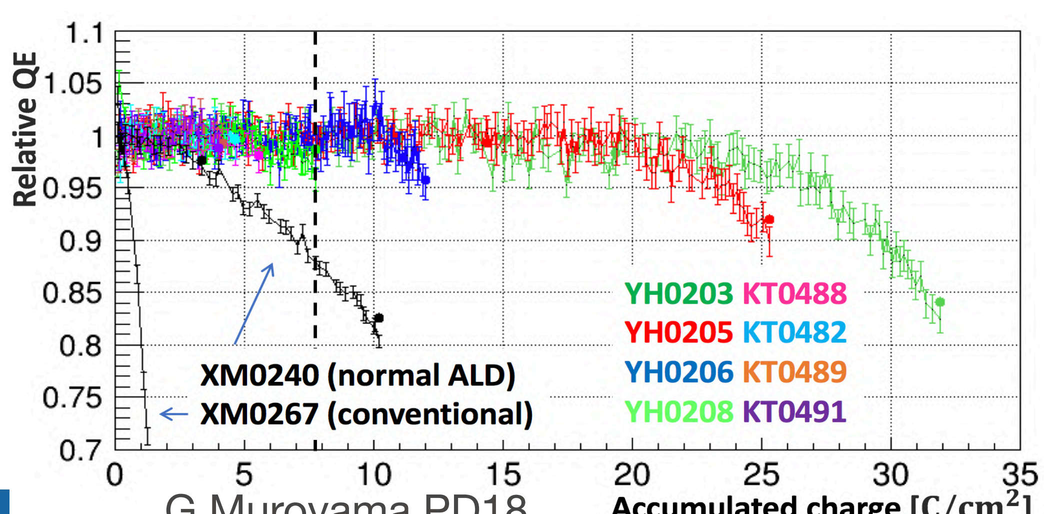
L=500μm

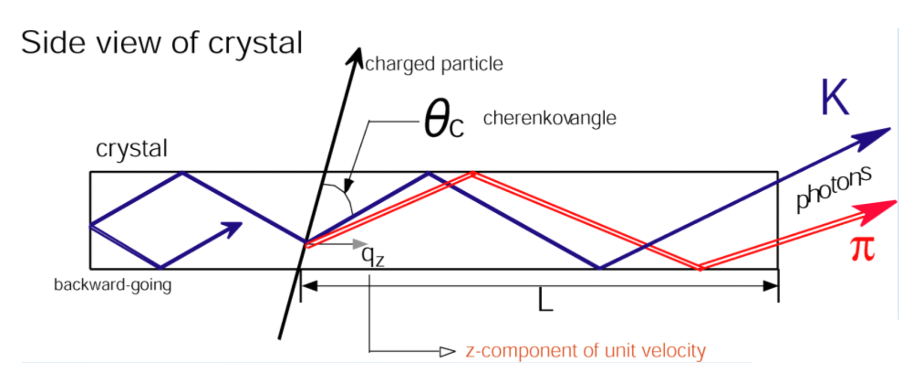


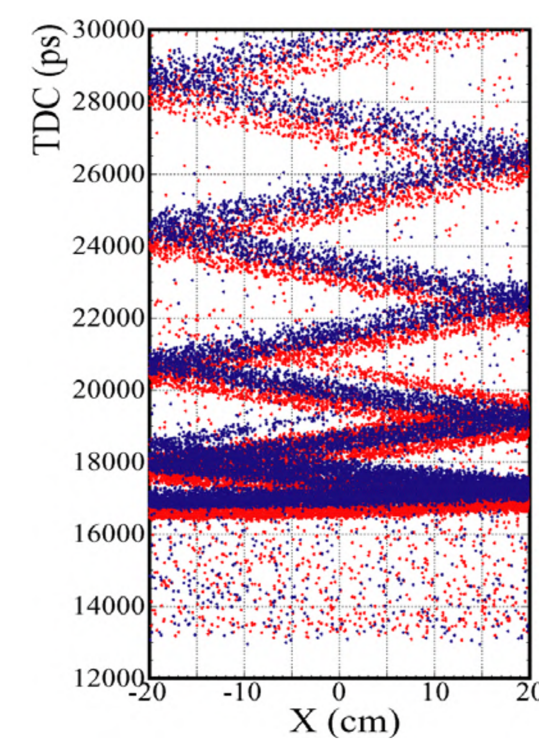
MCP-PMT for Belle II TOP Counter

- **Belle II Time-Of-Propagation (TOP) counter**
  - Based on DIRC (Detection of Internally Reflected Cherenkov light) concept
  - Linear array of MCP-PMT to measure one coordinate and time of propagation → 2D image reconstruction
  - Excellent K-π separation
- **Short lifetime issue**
  - Photocathode damaged by neutral gas and feedback ion from MCP
  - Extension of lifetime by ALD (atomic layer deposition) coating on MCP





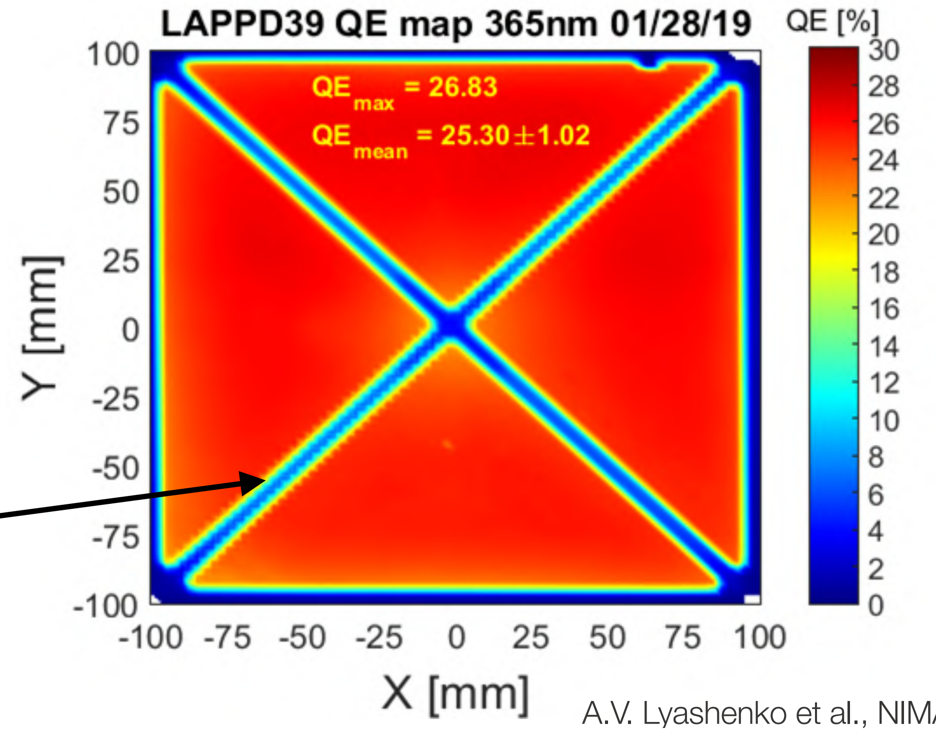


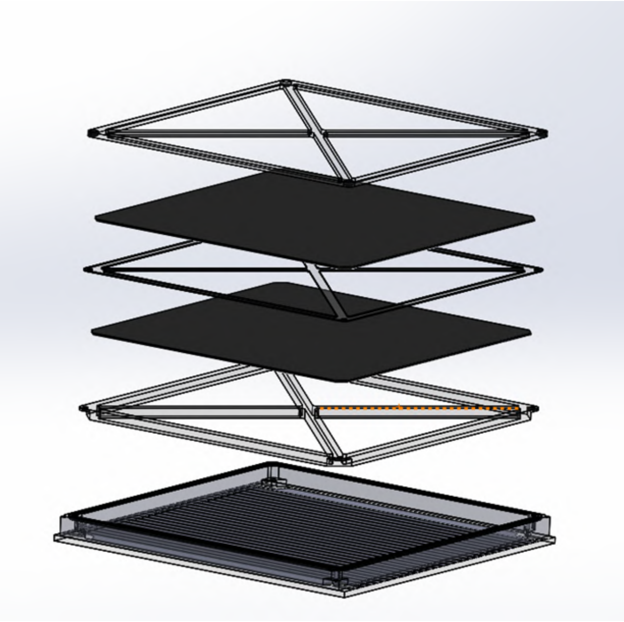


LAPPD

- **Large Area Picosecond Photo Detector (LAPPD™)**
  - MCP-based large area (and affordable) photodetector with picosecond timing
- **Performance**
  - Large area 20cm×20cm
  - High gain 10^7
  - Excellent uniformity
  - High photocathode QE
  - Low dark noise rate (100Hz/cm^2 @gain=6×10^6)
  - mm position resolution (electronics limited)
  - Timing resolution < 50ps (electronics limited)
- **Possible applications**
  - Neutrino experiments
  - Collider experiments
  - $0\nu\beta\beta$ experiments
  - Medical

dead area due to mechanical support!

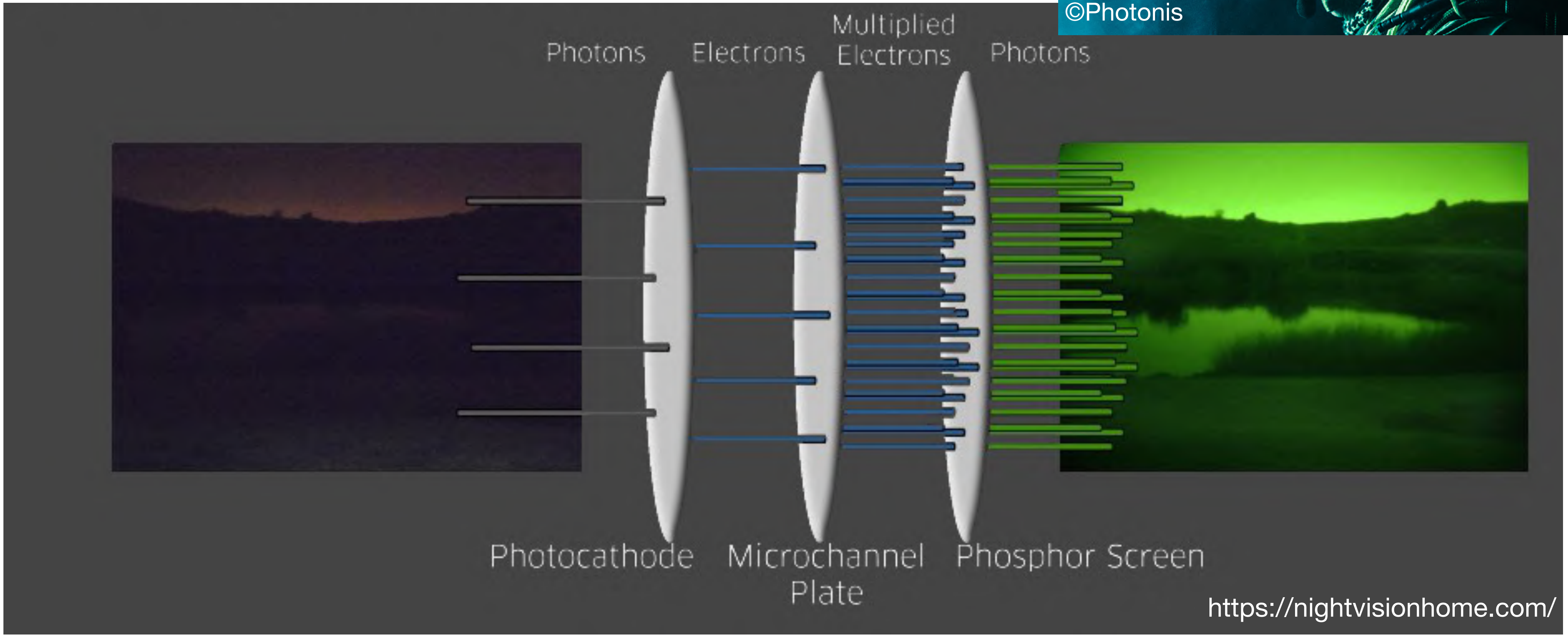




A.V. Lyashenko et al., NIMA958(2020)162834

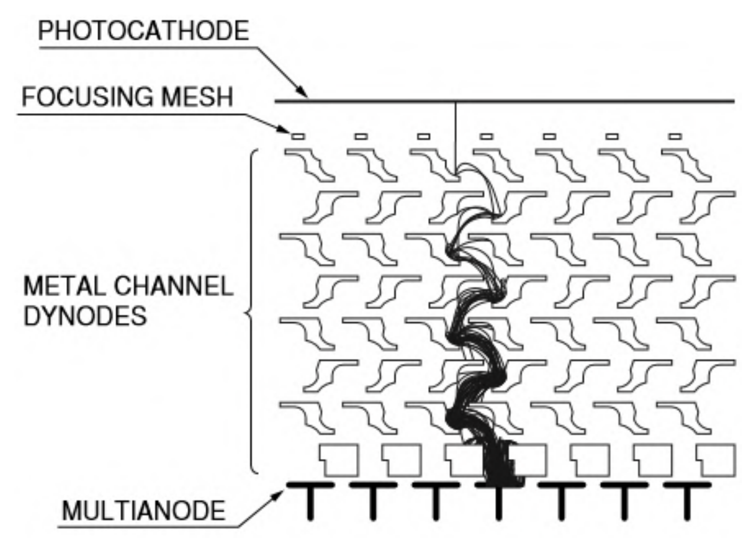
Image Intensifier Tube

- **Principle**
  - Photo-cathode + MCP + Phosphor screen
  - Low level light amplified to observable level
- **Night vision application**

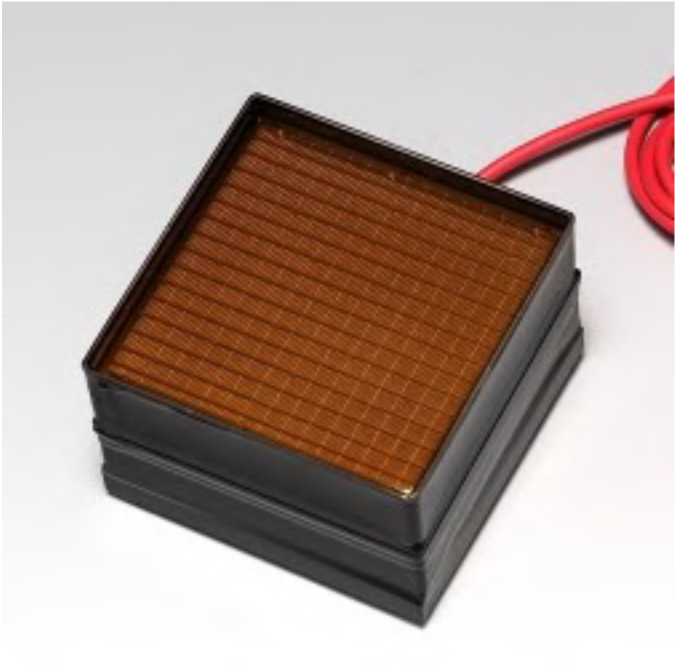


Metal Channel Dynode PMT

- **Metal channel dynode**
  - Electron multiplication confined in narrow channel
  - Fast response
  - Some immunity to magnetic field
- **Multi-anode PMT (MaPMT)**
  - Segmented anode readout →position sensitivity
  - Application to RICH detector
    - AMS, COMPASS, GlueX,…
- **Flat panel PMT**
  - Hamamatsu H9500
  - 50×50cm^2
  - Active area coverage 89%
  - 16×16 multi anode readout (pixel size 2.8×2.8mm^2)
  - Crosstalk ~5%(typ)

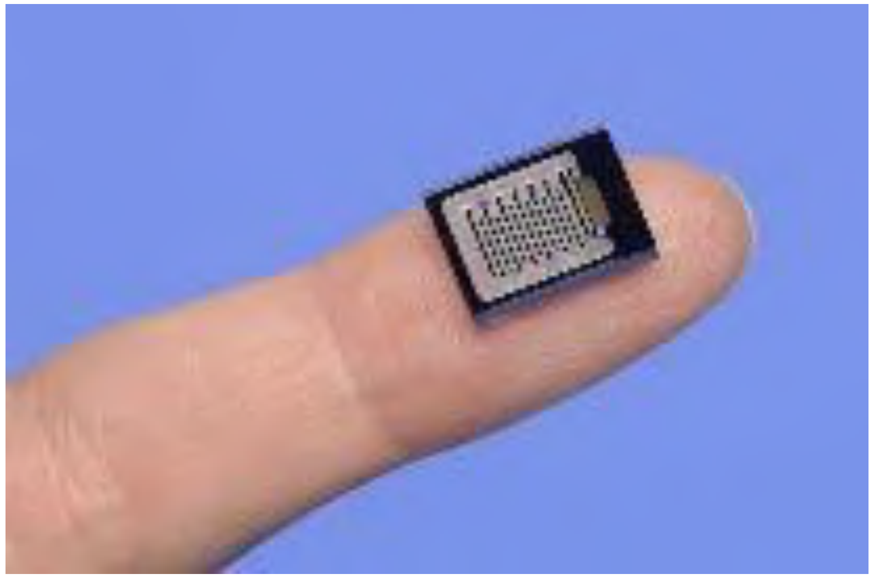


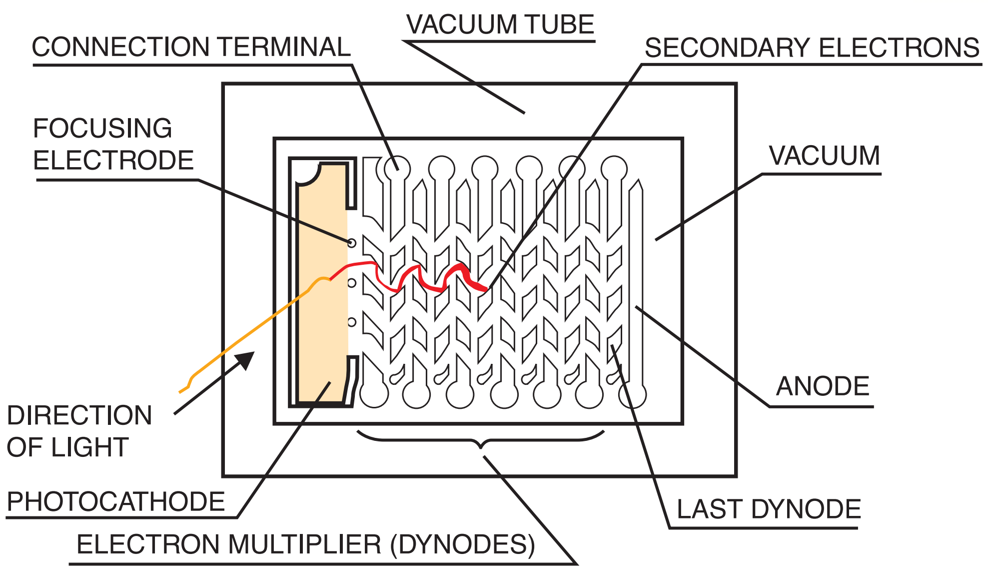
Hamamatsu H9500



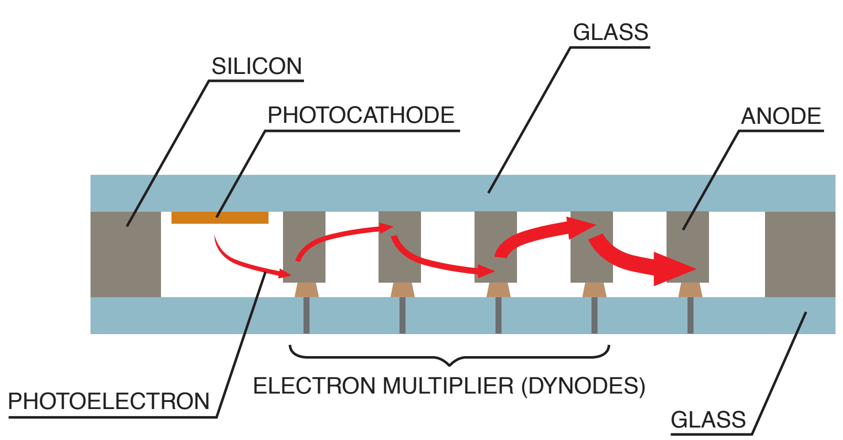
Micro-PMT

- **PMT is not necessarily bulky!**
- **µPMT™ from Hamamatsu Photonics K.K.**
    - Produced by Micro Electro Mechanical Systems (MEMS) technology
    - Tiny, easy to mass produce, high shock resistance



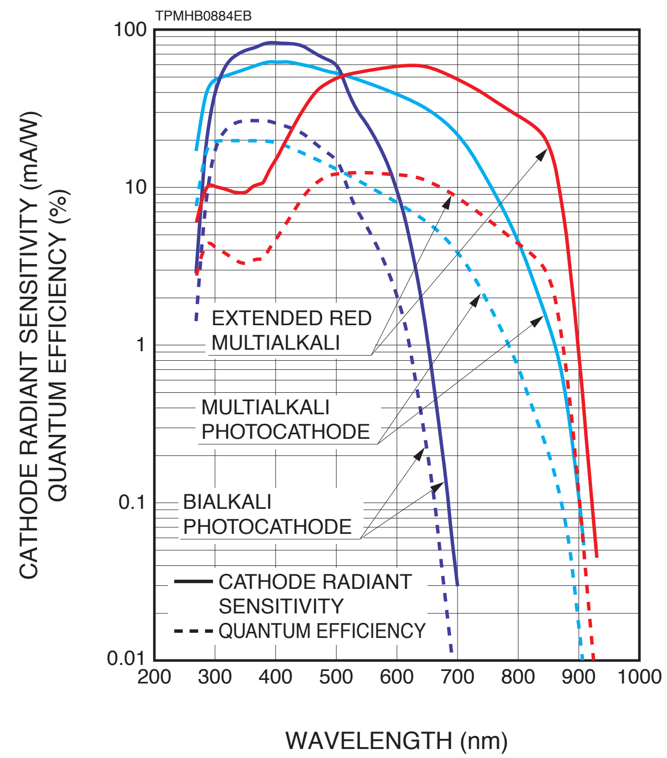


[TOP VIEW]

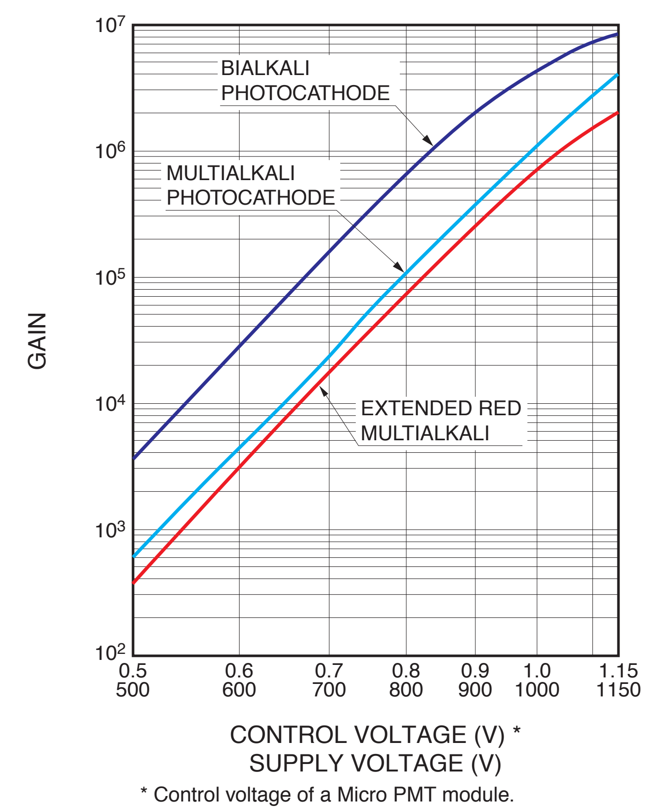


[SECTIONAL VIEW]

■ SPECTRAL RESPONSE

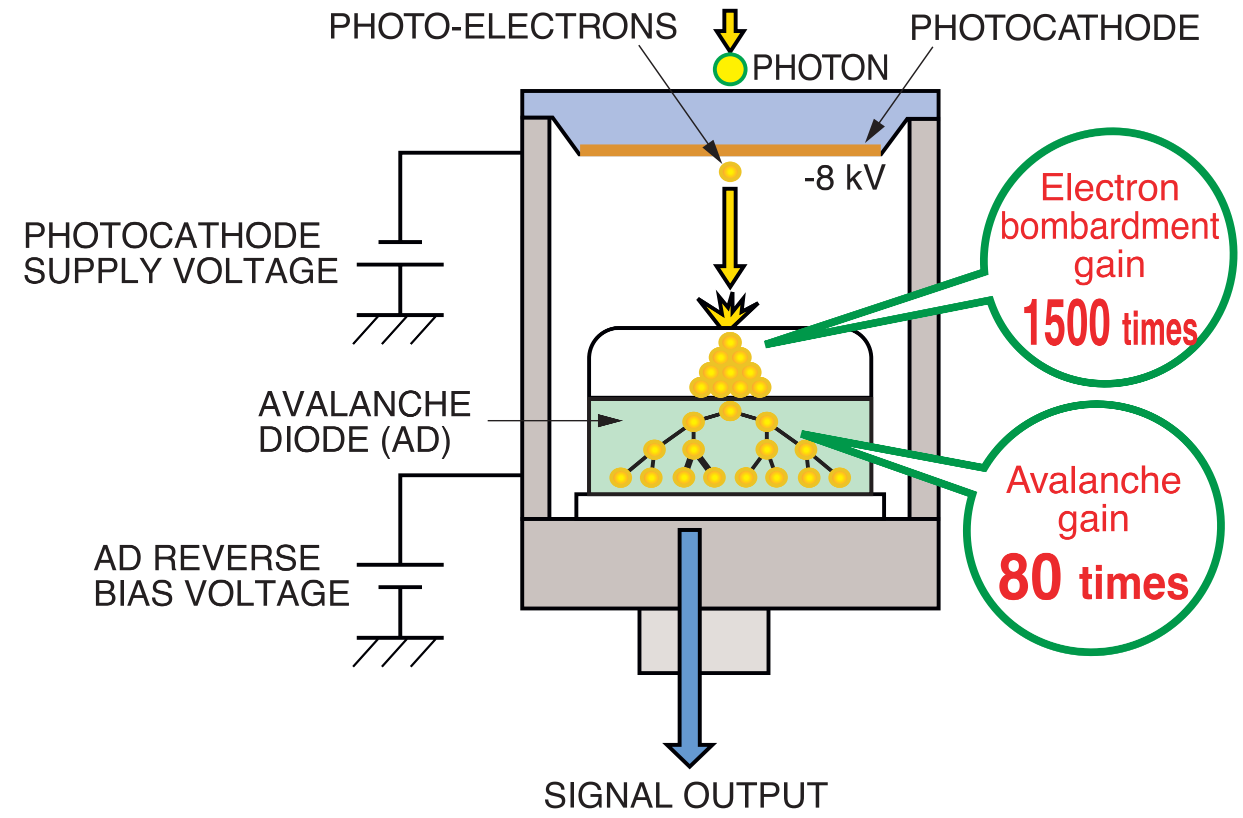


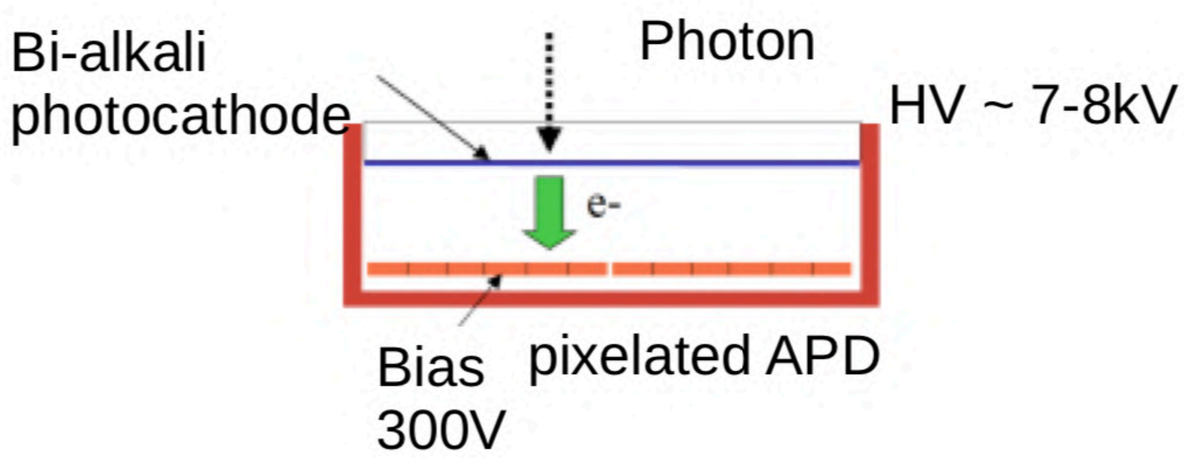
■ GAIN

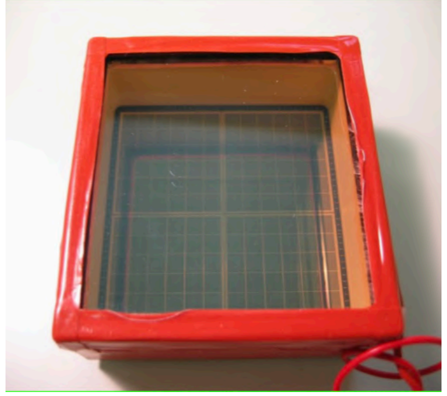


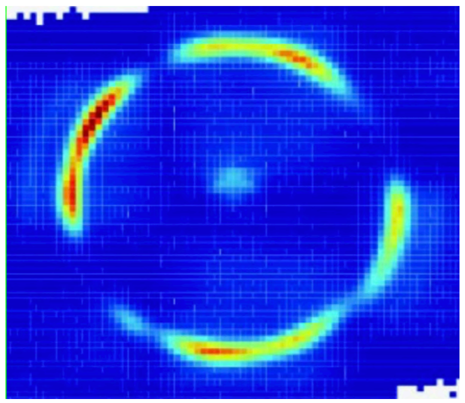
Hybrid Photo-detector (HPD)

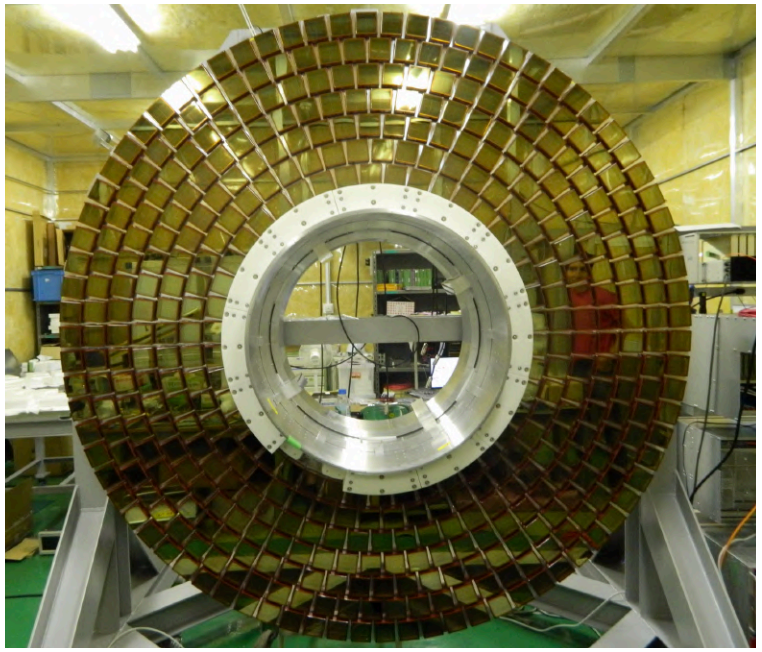
- **Combination of vacuum-tube + solid-state electron multiplier**
  - Conversion of photon to photoelectron at photocathode
  - Multiplication at solid-sate electron multiplier
- **Hybrid Avalanche Photo-detector (HAPD) at Aerogel RICH (ARICH) at Belle II**





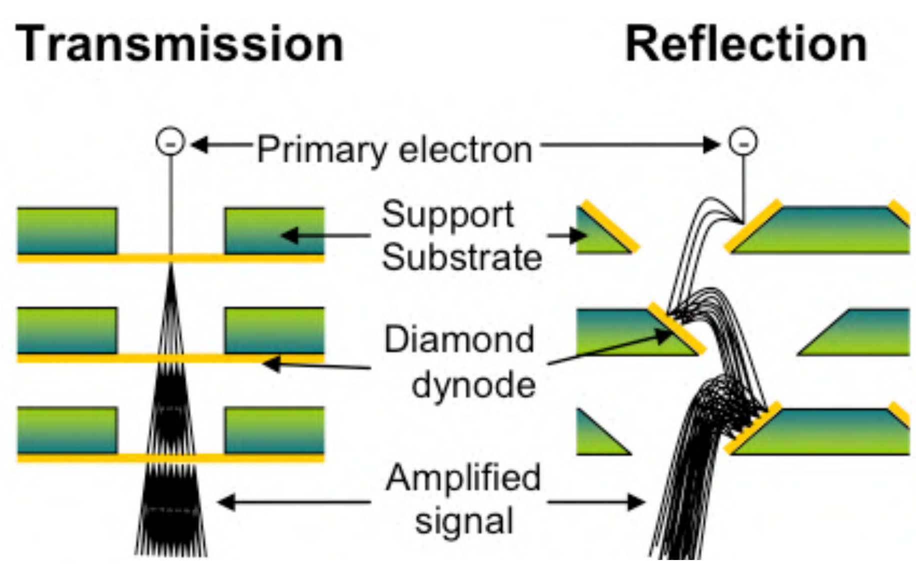


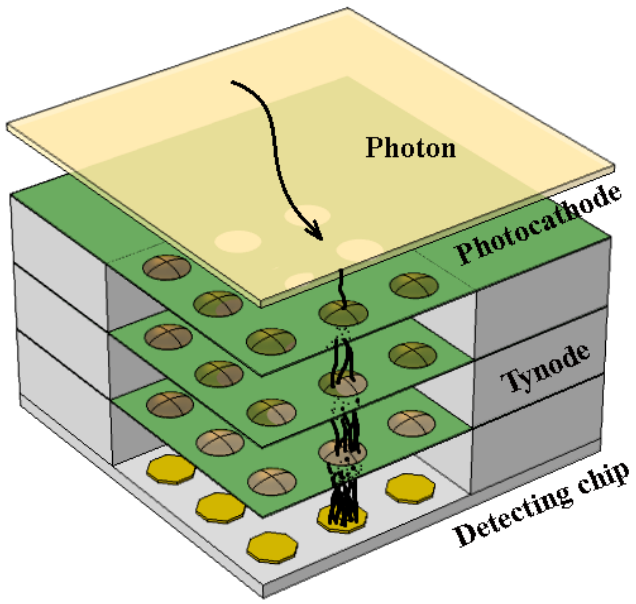


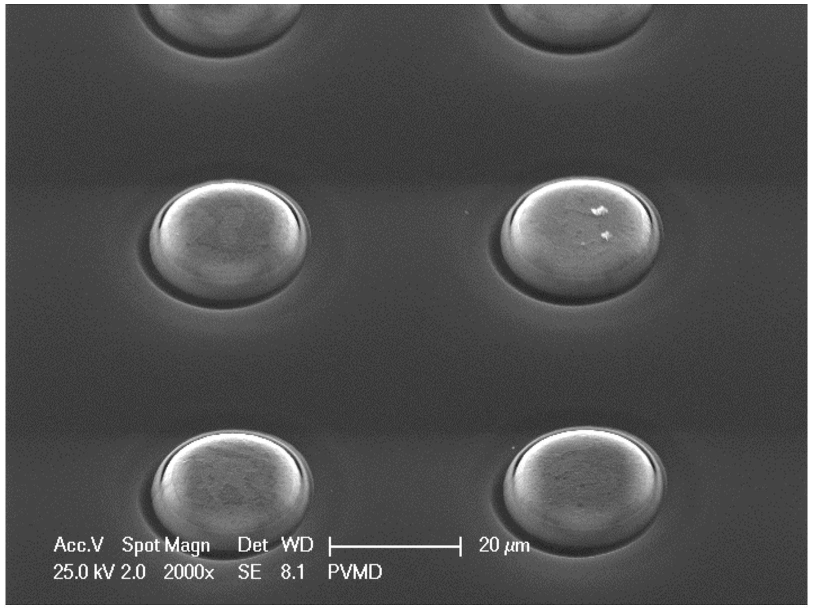


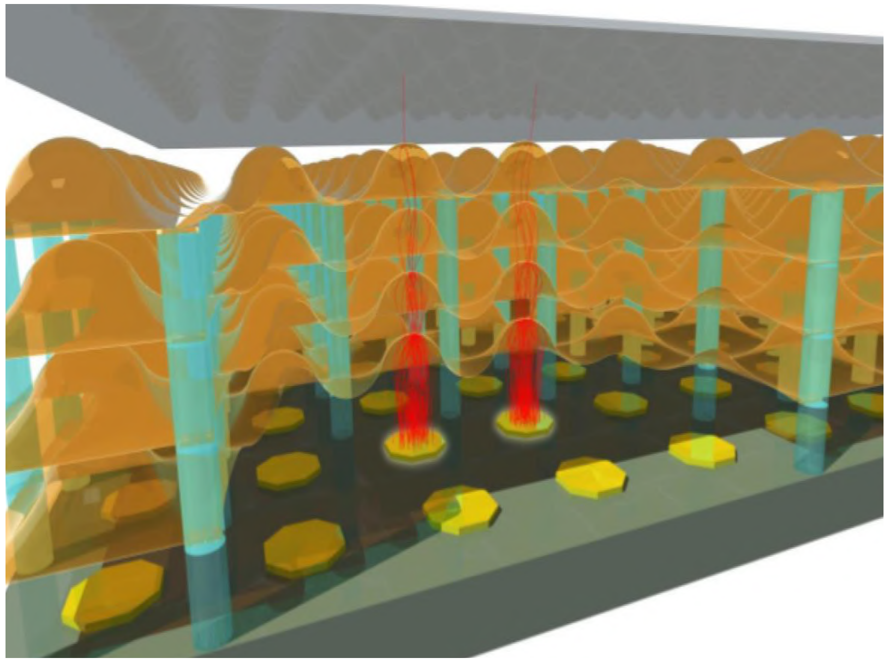
Tynode®

- **Transmission type dynode**
- **Developed for Timed Photon Counter (TipsyZero)**
  - Time resolution a few ps
  - Position resolution ~10μm
  - Compact
  - Operational in B-field
- **Recent Tynode prototype**
  - 5nm MgO membranes coated with 2.5nm TiN
  - Achieved transmission yields of 5.5





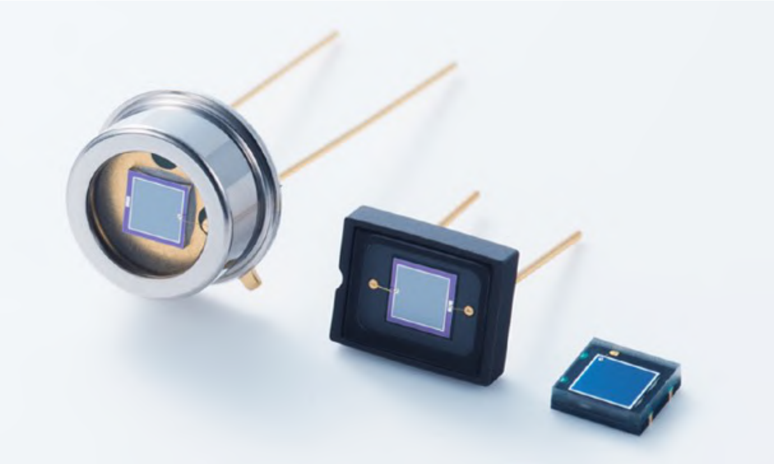


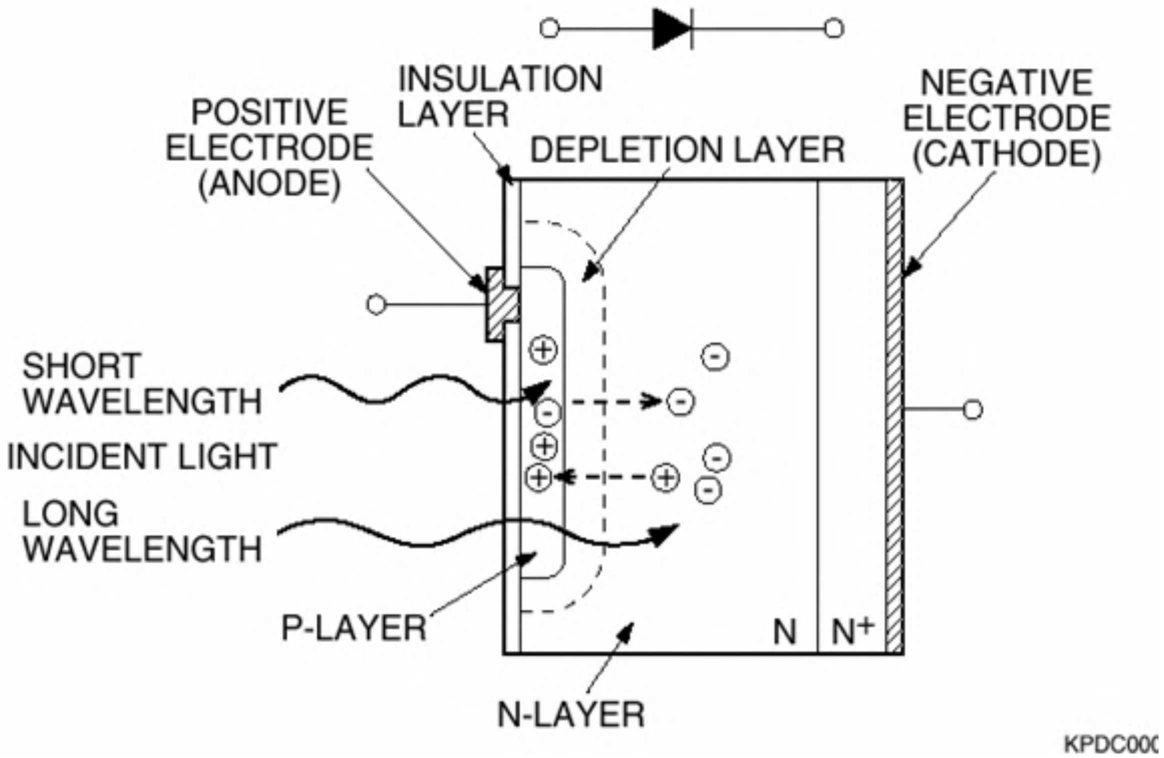


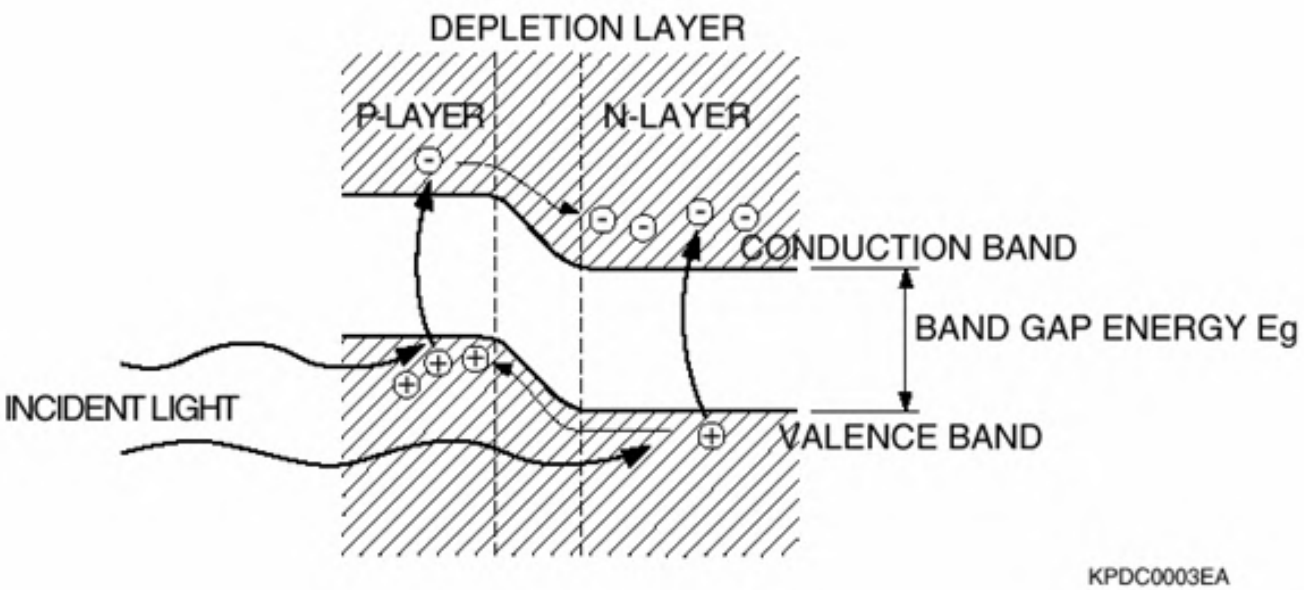
- Introduction
- Basic Properties of Photo-detector
- Vacuum photo-detector
- Solid-state photo-detector
- Comparison
- Summary

Solid-state Photodetector

- **Photodiode**
  - Simplest solid-state photodetector
  - Photovoltaic effect in semiconductor PN junction (Si, InGaAs,…)
    - Depletion layer with internal electric field around P and N layers
    - Incident photon generates e-h pair around depletion layer and thus current even without bias voltage
    - Same mechanism as solar battery
- **PIN photodiode**
  - Un-doped intrinsic semiconductor regions between P and N layers (p-i-n diode)
  - Higher field with external bias voltage
- **Performance**
  - QE~100%
  - Large dynamic range
  - Insensitive to B-field
  - Cheap!
  - but no internal gain (G~1)

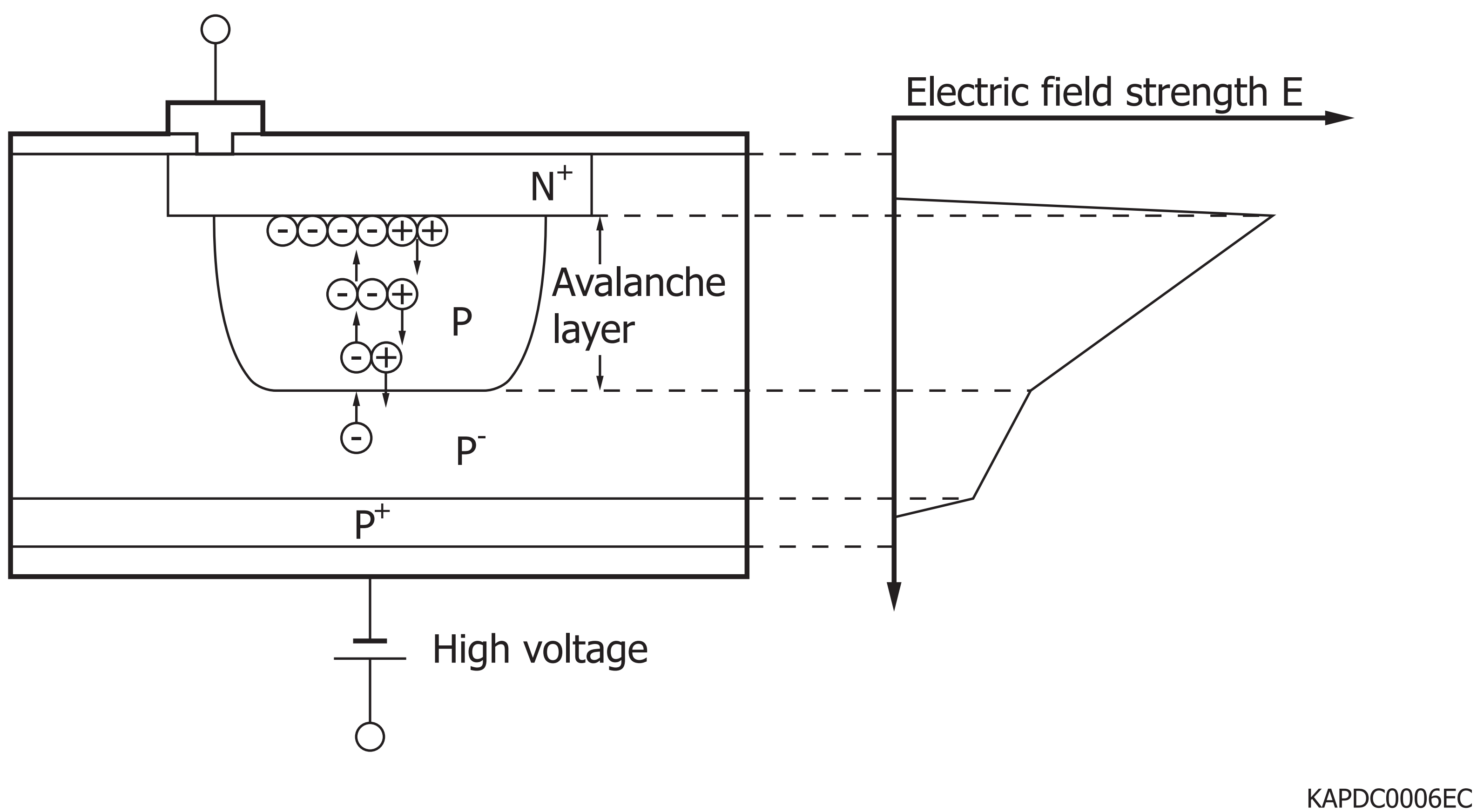




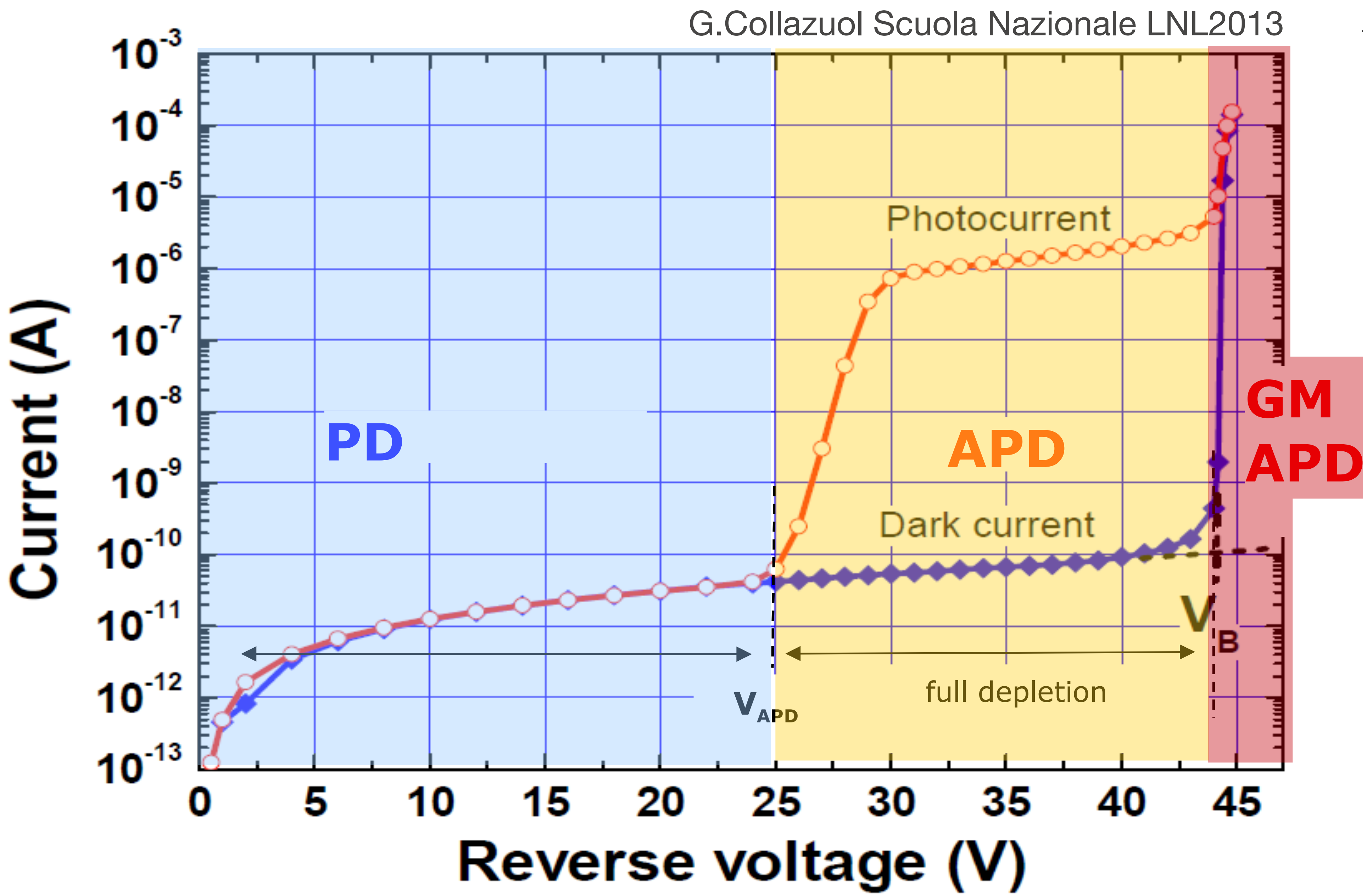


APD

- **Avalanche Photo-Diode (APD)**
  - Photodiode operated with higher reverse voltage
  - Avalanche multiplication in depletion layer
  - Main contribution from electron instead of hole because of its higher ionisation coeff.
  - Internal gain (50-500) @ linear mode



APD



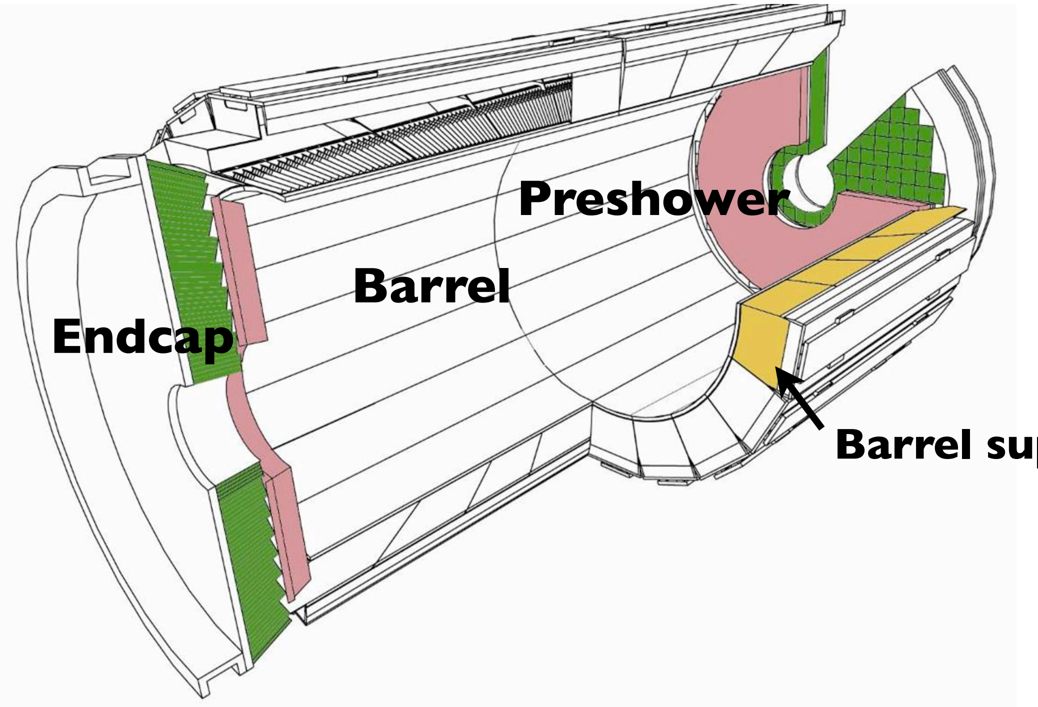
PD
- $V<V_{APD}$
- No internal gain (G=1)

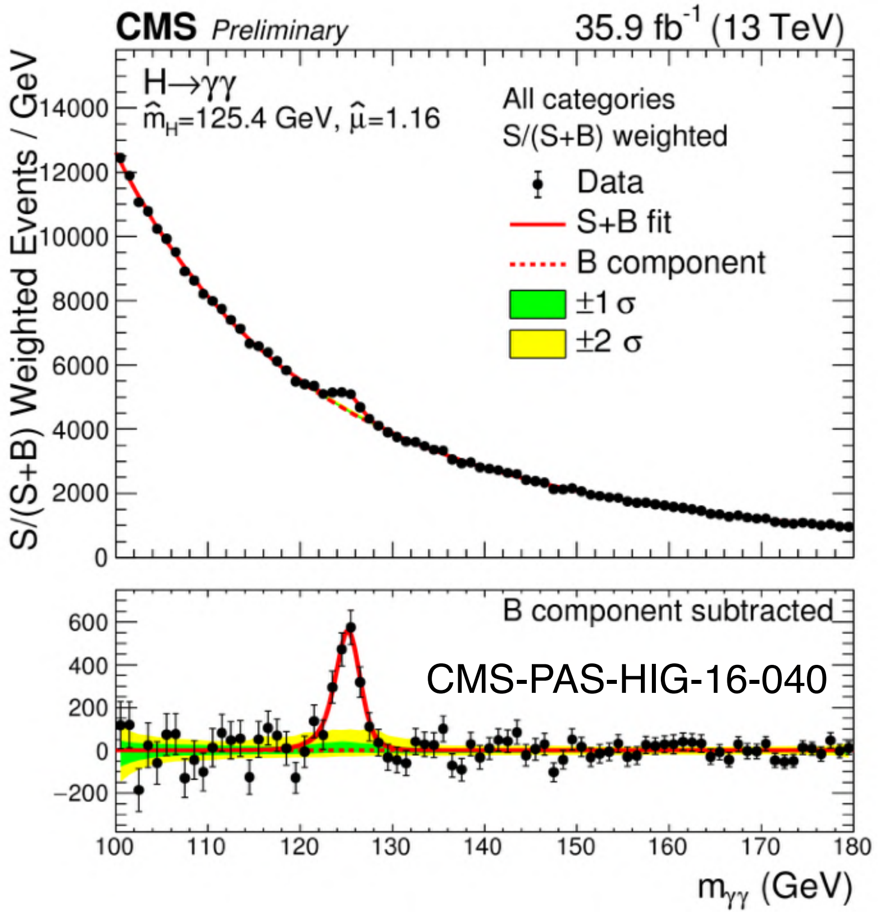
APD
- $V_{APD}<V<V_B$
- Liner mode operation
- Linear output w.r.t input light
- Internal gain (G=50-500)

GM APD
- $V_B<V$
- Geiger mode operation
- Internal gain ($G=10^5$)
  →**SiPM**

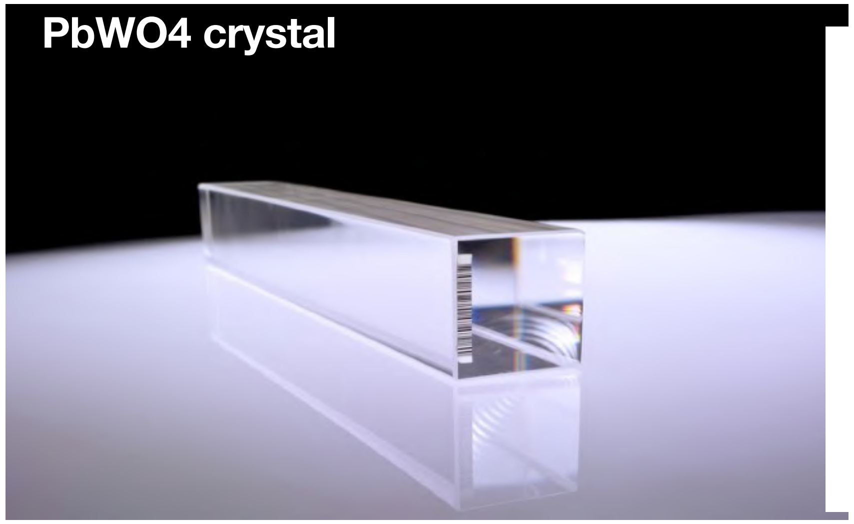
CMS ECAL

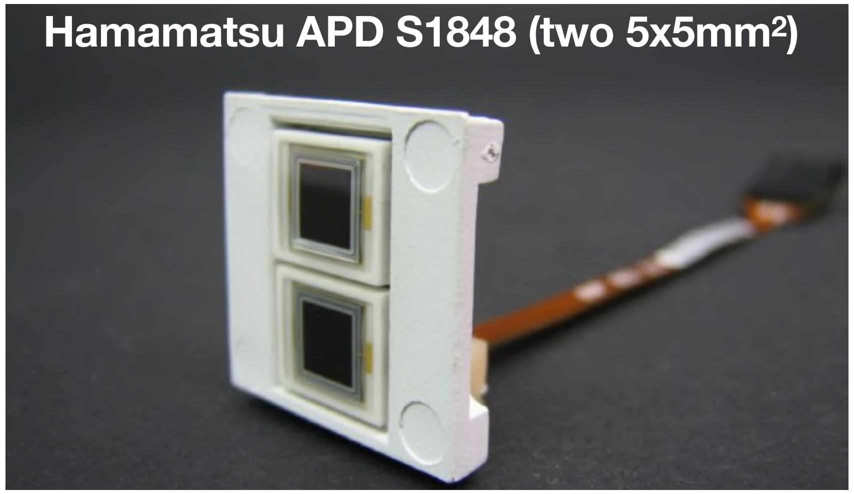
- **Successful operation of APD at CMS barrel ECAL**
  - $PbWO_4$ crystal + APD (Hamamatsu S1848)
  - Hamamatsu APD S1848
  - two 5×5mm^2
  - High QE ~75%
  - Gain ~50





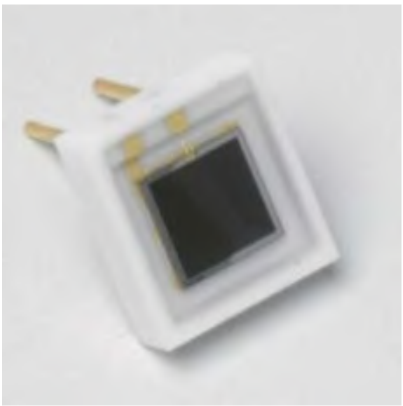
D.A.Petyt PANIC2017

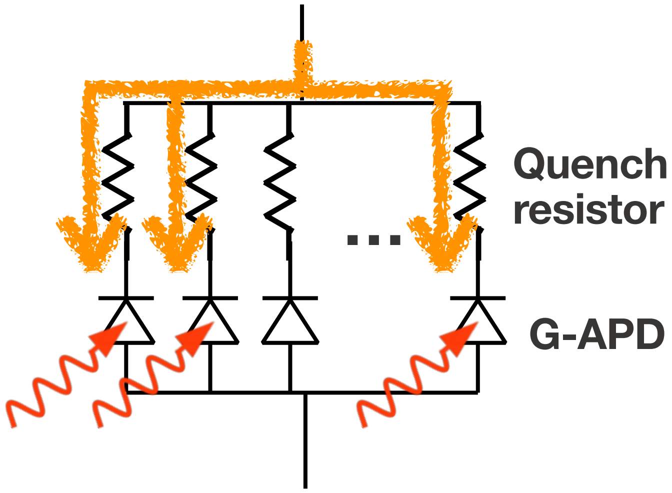


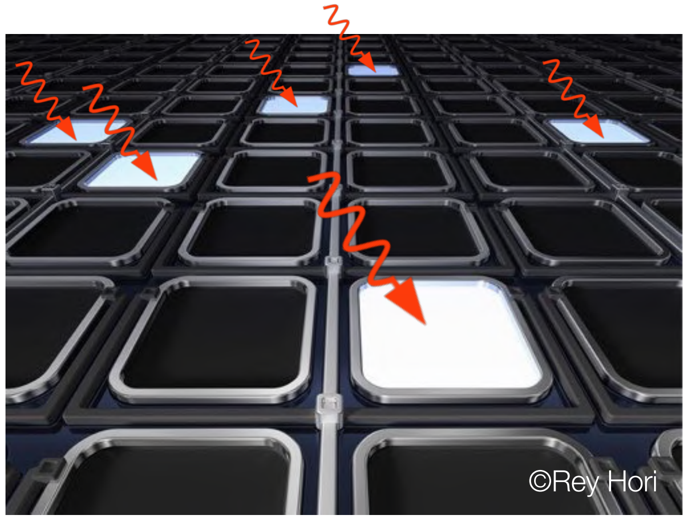


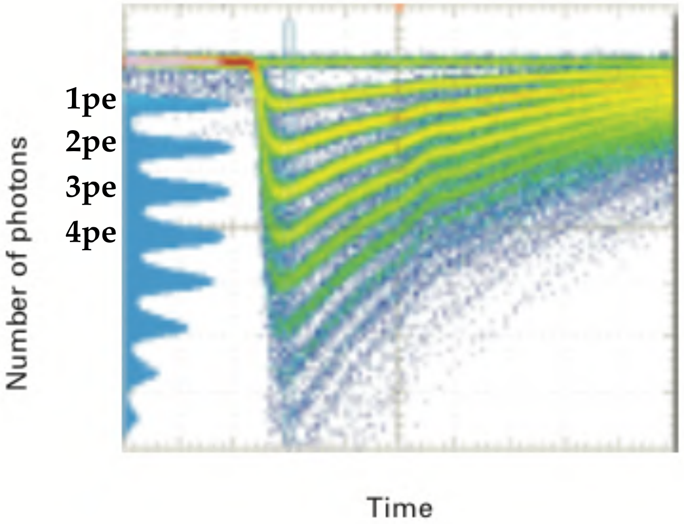
Silicon Photomultiplier (SiPM)

- **SiPM = Multi-pixelated Geiger-mode APD (G-APD)**
  - Tiny G-APD cells are connected in parallel together with resistor for self-quenching of avalanche
  - Each G-APD cell is a “binary” device. The same charge from each photon trigger
  - SiPM output is a sum of signals from triggered G-APD cells
- **SiPM output is proportional to # of impinging photons**
  - SiPM = “analogue” device
- **Pioneering works by Russian institutes in late 80s (Golovin, Dolgoshein, Sadygov)**

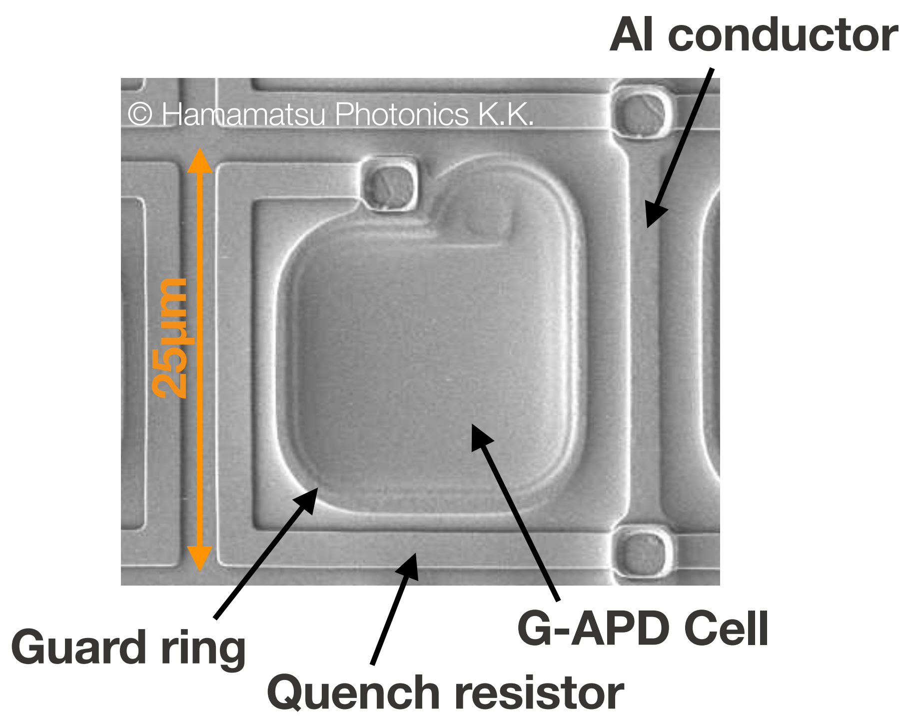


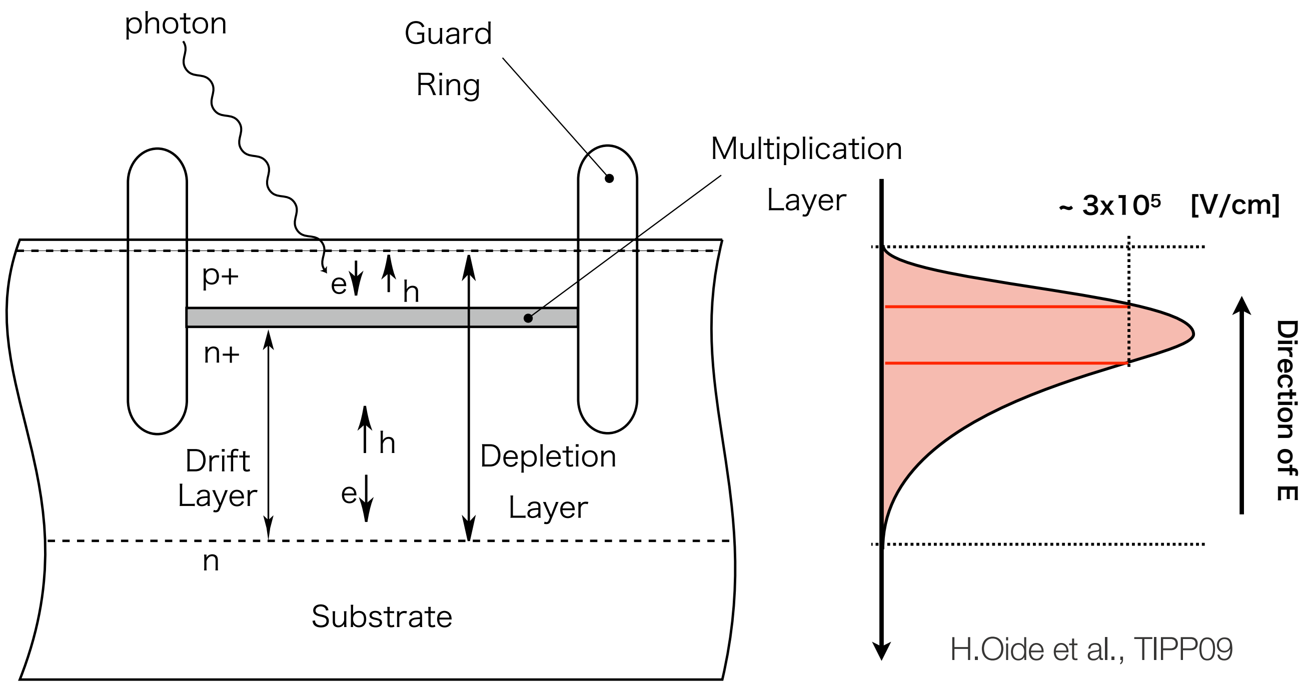


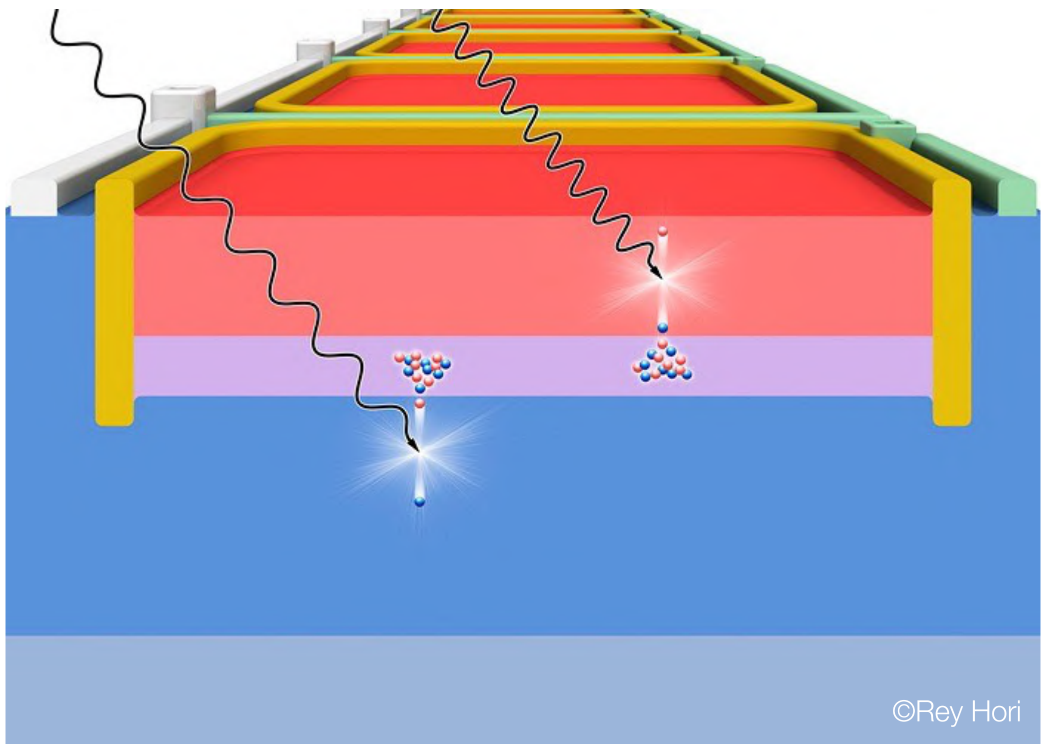




Closer Look at Cell







SiPM Advantages

- **Advantages**
  - High photon detection efficiency
  - High internal gain
  - Immunity to magnetic field
  - Single photoelectron resolution
  - Good timing resolution
  - Low bias voltage
  - Low power consumption
  - Compact
  - Low cost
- **Weak points**
  - Large area is difficult
  - Temperature dependence
  - Noise
  - Radiation hardness
  - Saturation

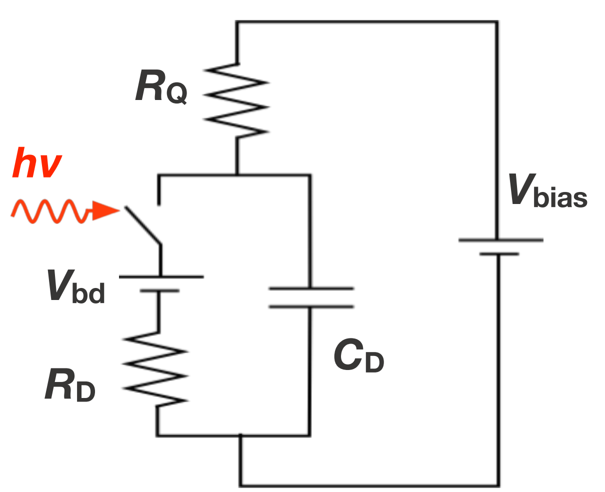
Sensor size (single)	1×1 - 6×6mm^2
Cell size (cell pitch)	10 - 100μm
Quench resistor	10k - 10MΩ
Internal gain	10^5 - 10^6
Photon detection efficiency (PDE)	20 - 50%
Time resolution (single photon)	O(100ps) (FWHM)
Dark noise rate	50k - 1M Hz/mm^2
Bias voltage	20 - 70 V

→Possible replacement with PMT!

SiPM Producers

Signal Generation

- **SiPM cell operation cycle (simplified model)**
  - ① Photo-generation of carrier ➔ avalanche (switch ON)
  - ② Self-quenching (switch OFF)
  - ③ Re-charge cell
- **Signal for light detection**
  - Convoluted with light emission time distribution



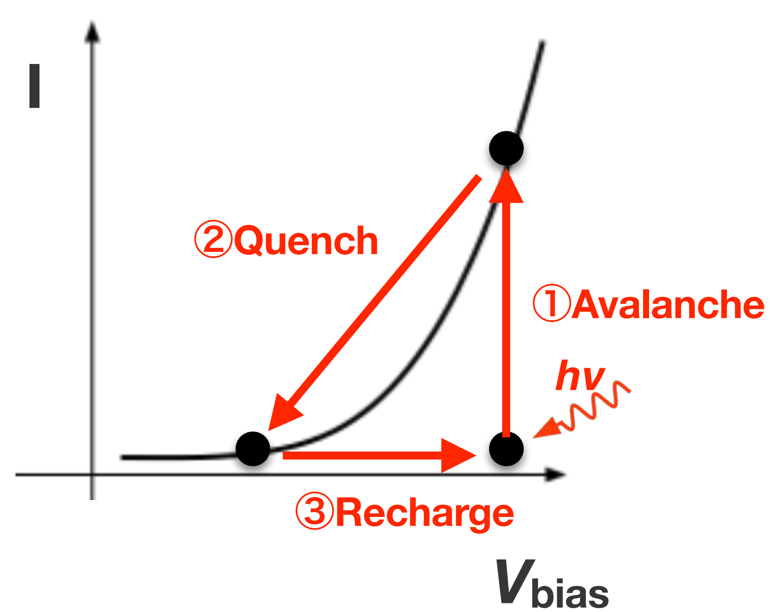
R_D: series resistance of micro-plasma in avalanche

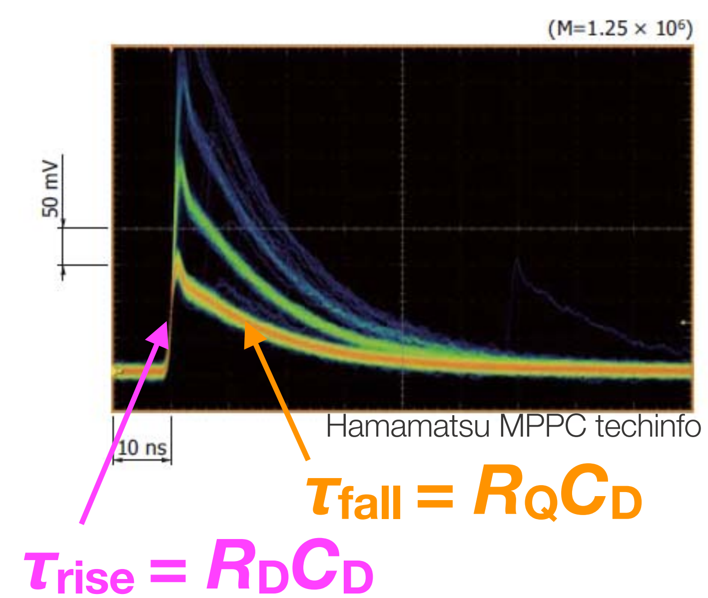
C_D: cell capacitance

V_{bd}: breakdown voltage

V_{bias}: bias voltage

R_Q: quench resistor

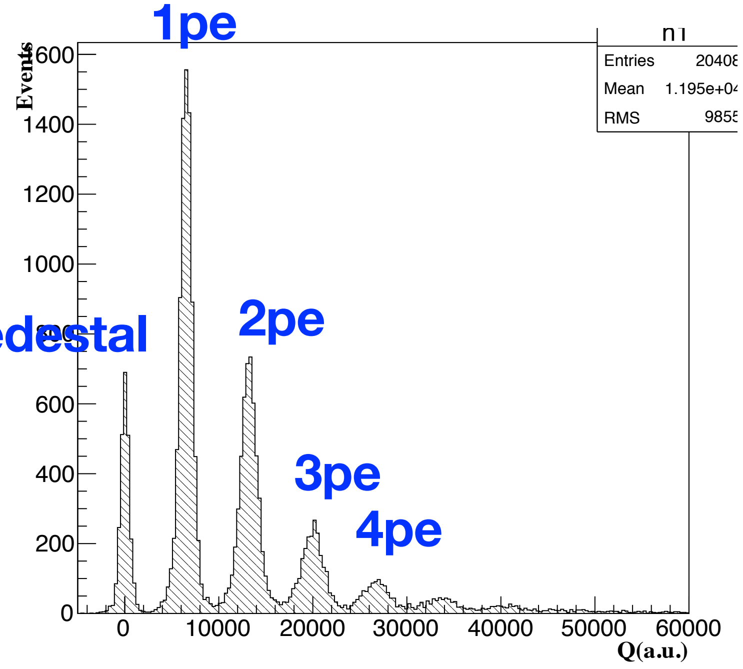




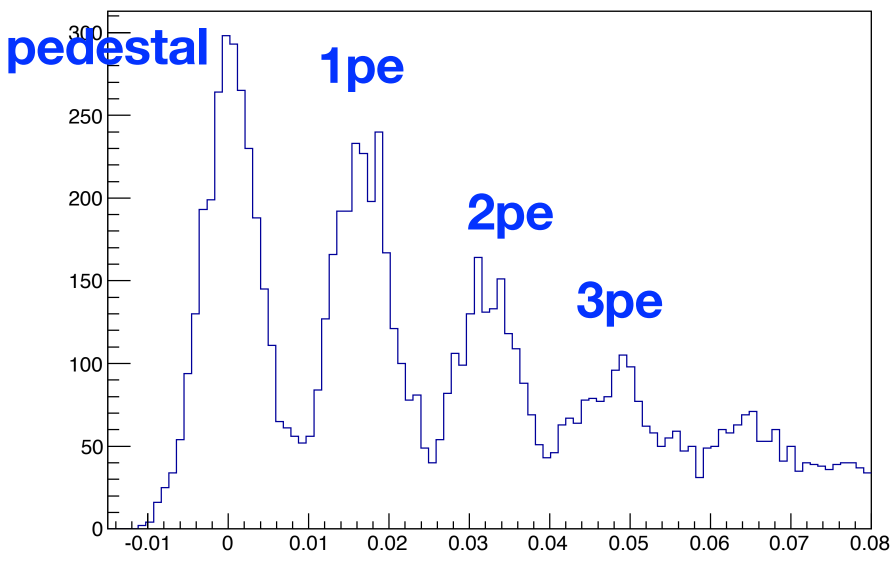
Single Photoelectron Resolution

- **Excellent single photoelectron resolution**
  - High internal gain
  - Good cell-to-cell gain uniformity
- **Can be worsened by electrical noise and pileup due to dark noise and after-pulsing**
- **Practically single photoelectron peak can not be resolved for >6×6mm² sensor area due to increasing dark noise**
  - Good photoelectron resolution still possible even for large area sensor at low temp.

3×3mm² MPPC at room temp



12×12mm² MPPC at 165K (for MEG II)

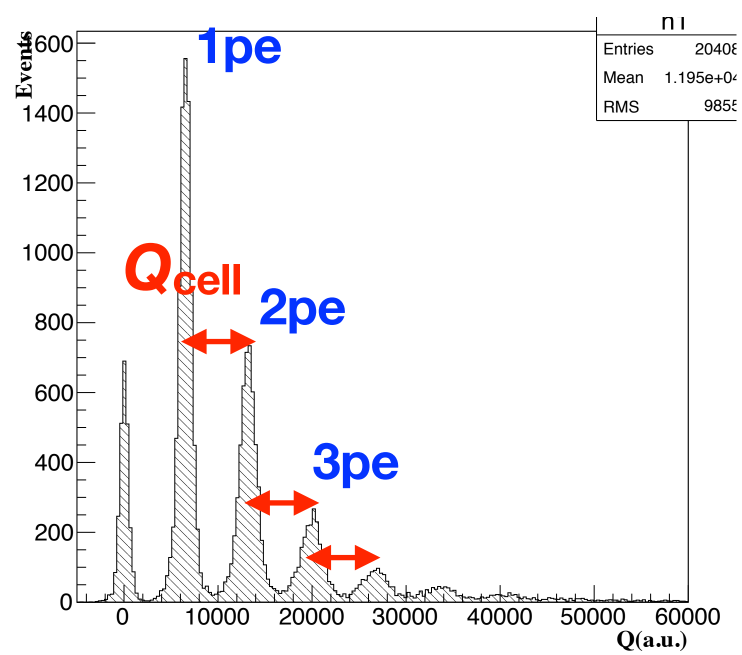


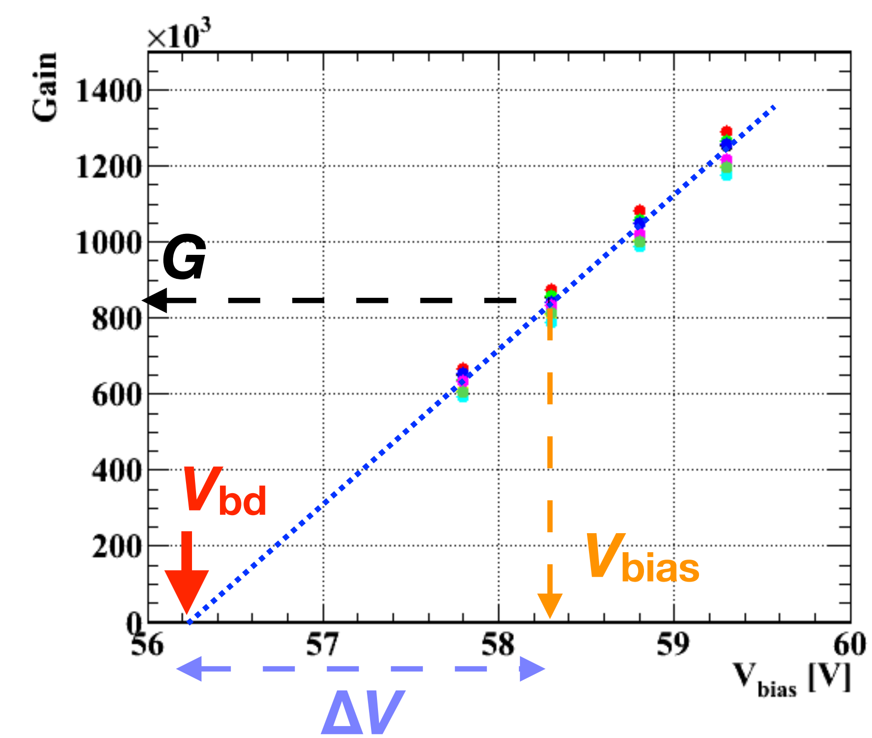
Gain

- **High internal gain of 10^5-10^6**
- **Proportional to over-voltage ($\Delta V = V_{bias} - V_{bd}$)**
- **Easily measured from single photoelectron charge**
- **Gain fluctuation is quite small**
  - Cell-to-cell uniformity on capacitance and V_{bd}
  - Small statistical fluctuation in avalanche multiplication (↔Poisson fluctuation in APD)

$$\boxed{G = \frac{Q_{\rm cell}}{e} = \frac{C_{\rm cell}\Delta V}{e}}$$

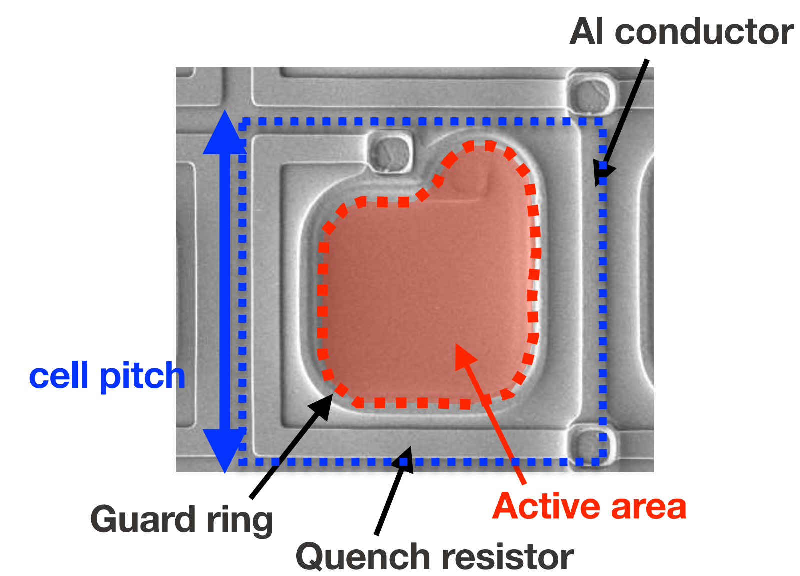
over-voltage $\Delta V = V_{\rm bias} - V_{\rm bd}$





Photon Detection Efficiency (PDE)

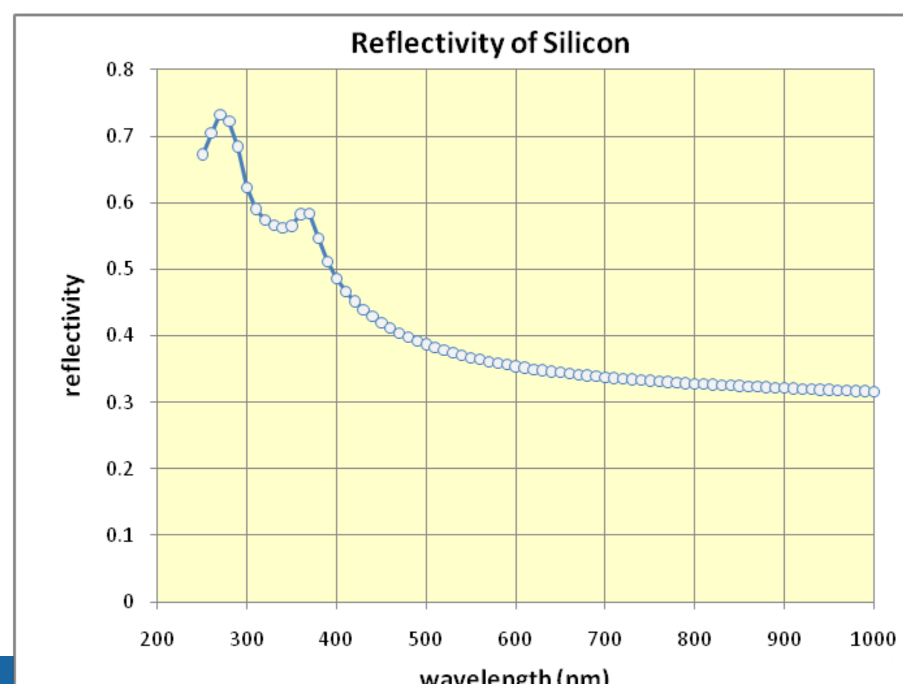
$$PDE = \epsilon_{\mathrm{FF}} \cdot QE \cdot \epsilon_{\mathrm{trg}}$$

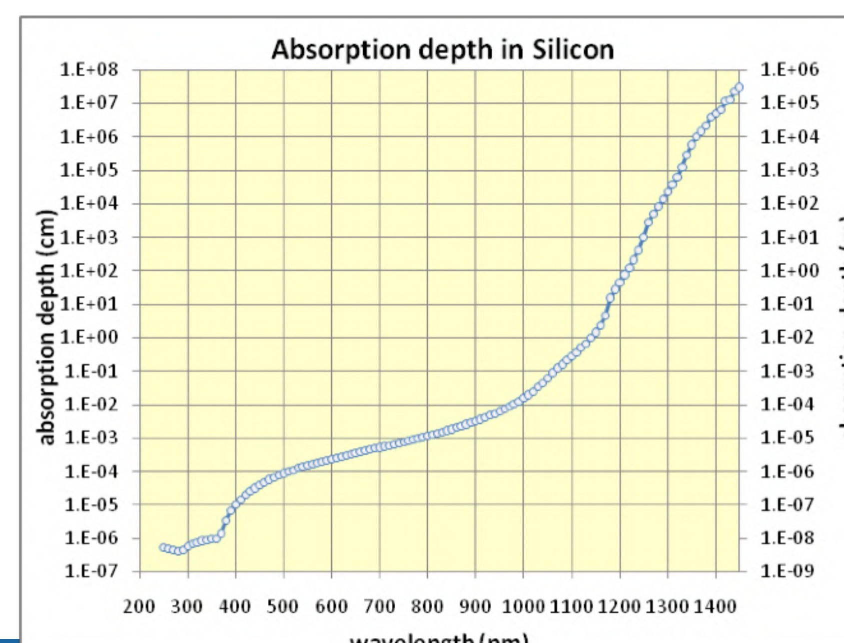


- **Fill factor ε_{FF}**
  - Fraction of active area, typically 50-70%
  - Dead area due to signal line, guard ring, trench,…
- **Quantum efficiency *QE***
  - Probability of photo-generation of carrier
  - Dependent on reflectivity on Si surface and absorption length in Si
- **ε_{trg}**
  - Probability for generated carrier to trigger avalanche

- **Dependence on**
  - Wavelength
  - Over-voltage
  - temperature

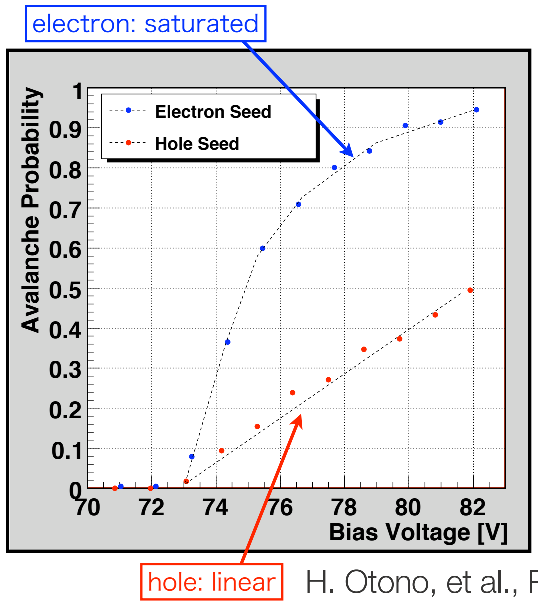
PV EDUCATION.ORG homepage



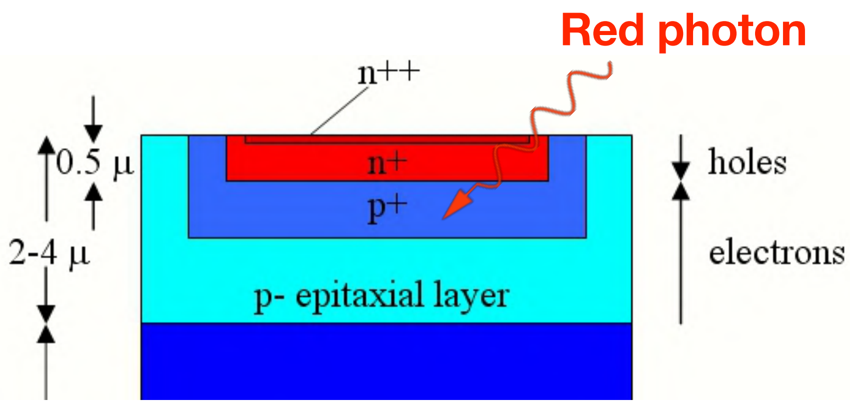


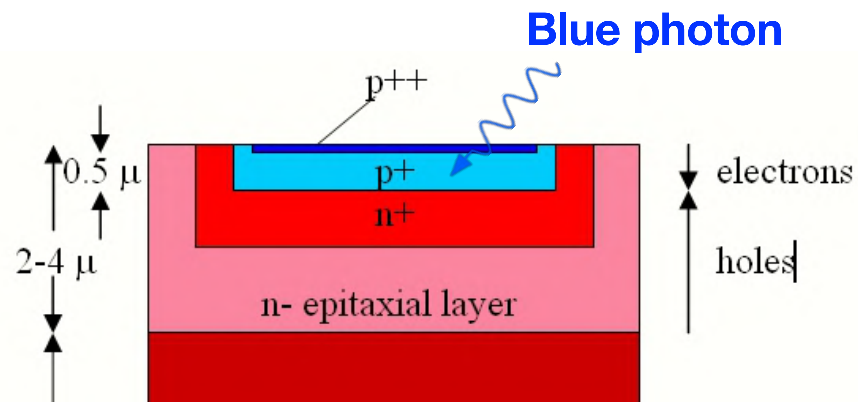
Photon Detection Efficiency (PDE)

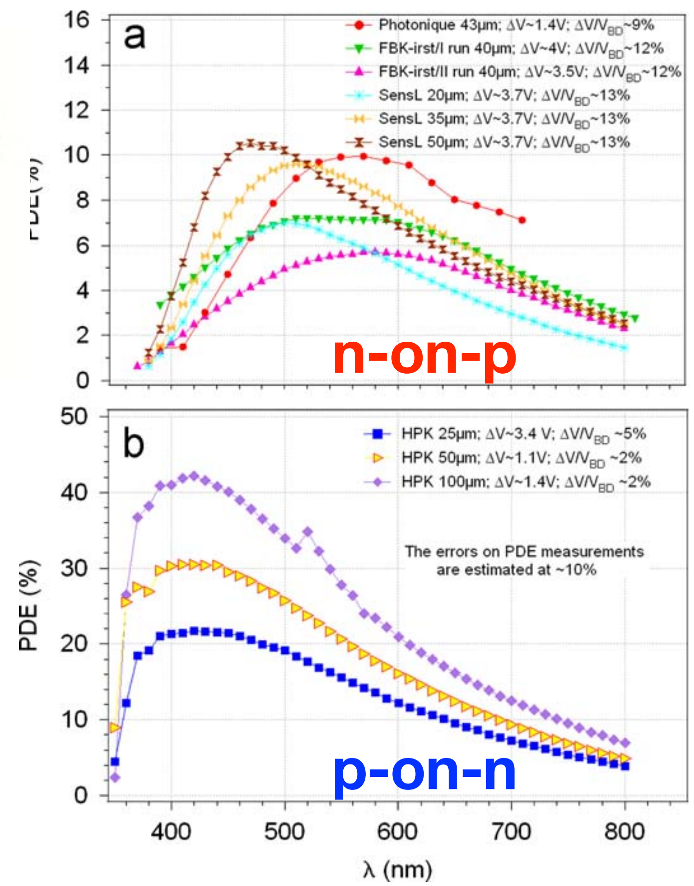
- $\varepsilon_{trigger}$ (electron) >> $\varepsilon_{trigger}$ (hole)
  ➔Higher PDE for carrier generated in p+ layer
- λ-dependence of absorption length in Si
  ➔Different λ-dependence of PDE depending on depth of p+ layer



H. Otono, et al., PANIC08







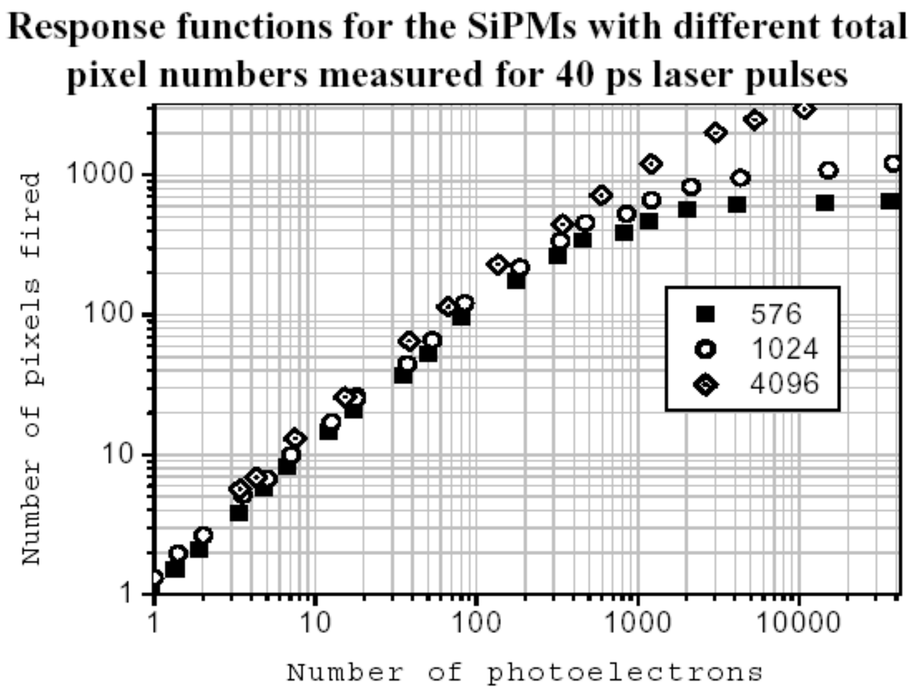
n-on-p structure
➔ Green/Red sensitive

p-on-n structure
➔ Blue sensitive

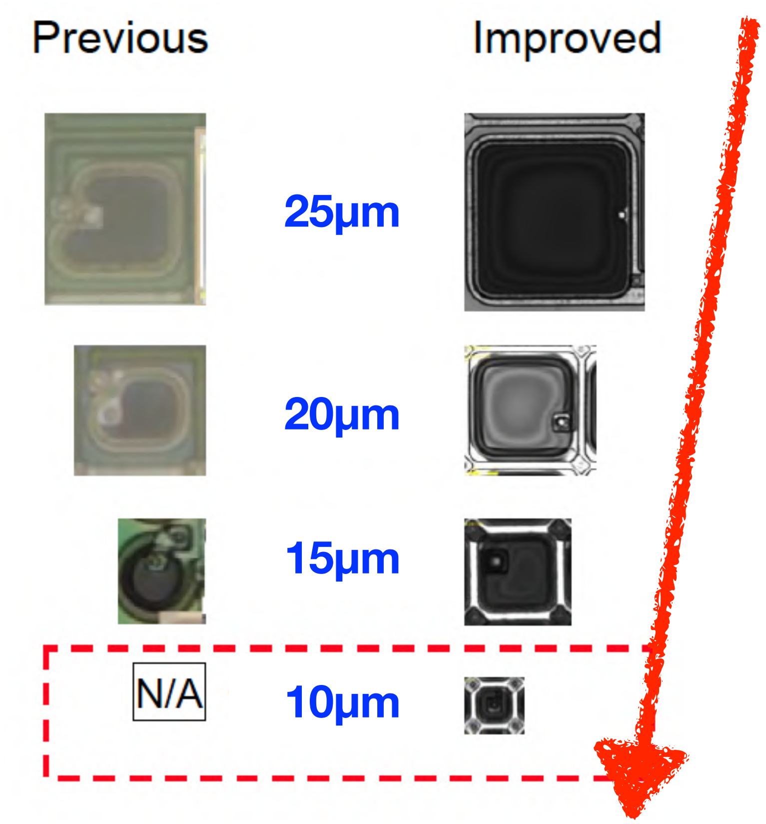
Linearity

- **Non-linearity (saturation) caused by finite number of cells**
- **Good linearity as long as $N_{pe} < N_{cell}$**
- **Limiting factors**
  - Incoming photon intensity
  - Cell size
  - Cell recovery time
- **Need careful calibration for many photons**
- **Smaller cell mitigates saturation**

$$N_{\mathrm{fired}} = N_{\mathrm{cell}}\left(1 - e^{\frac{-N_{\mathrm{photon}}PDE}{N_{\mathrm{cell}}}}\right)$$



B. Dolgoshein, TRD2005

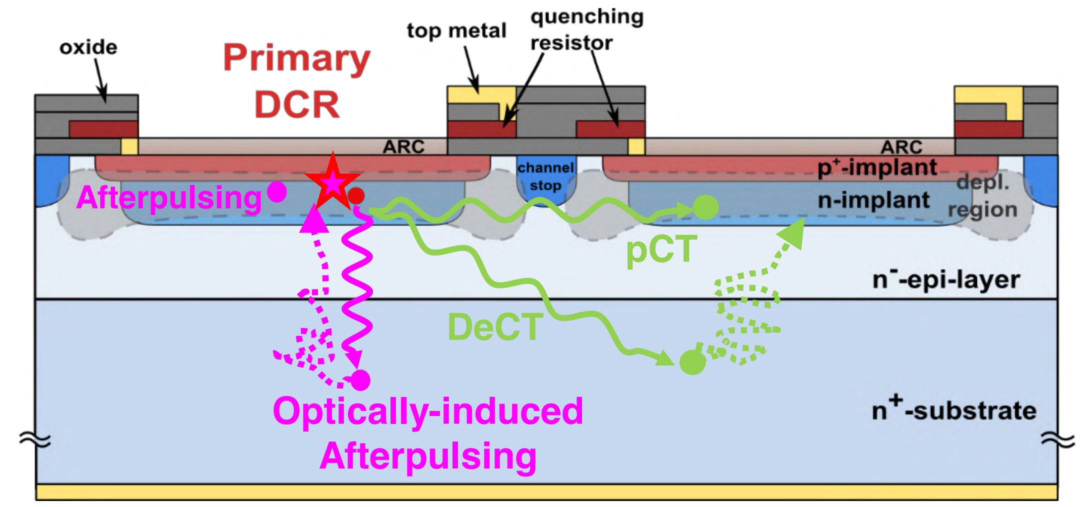


Noise

- **Dark noise**
  - Thermally generated carrier
  - Random
- **Correlated noise**
  - Direct optical cross-talk
  - Delayed optical cross-talk
  - After-pulsing

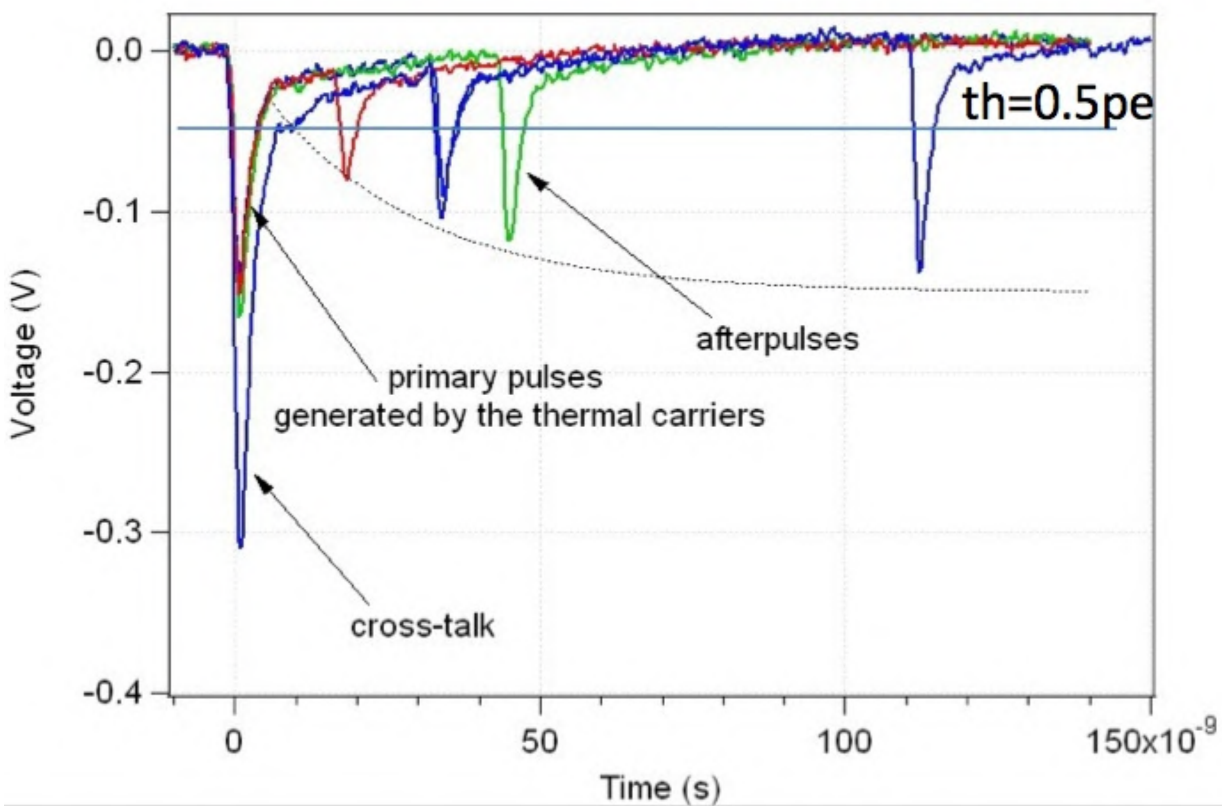
- **Correlated noise increases gain fluctuation and thus excess noise factor (ENF)**
  - Energy resolution is deteriorated with increased ENF

$$\boxed{ENF = 1 + \frac{\sigma_G^2}{G^2}}$$



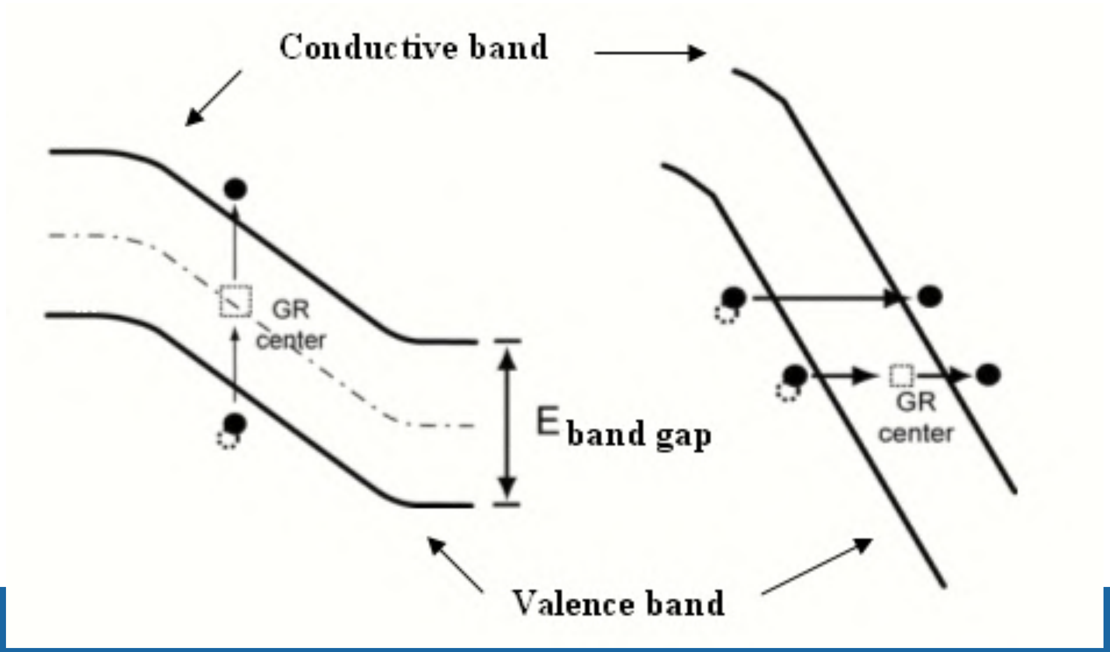
Cross-section of the SiPM microcells.

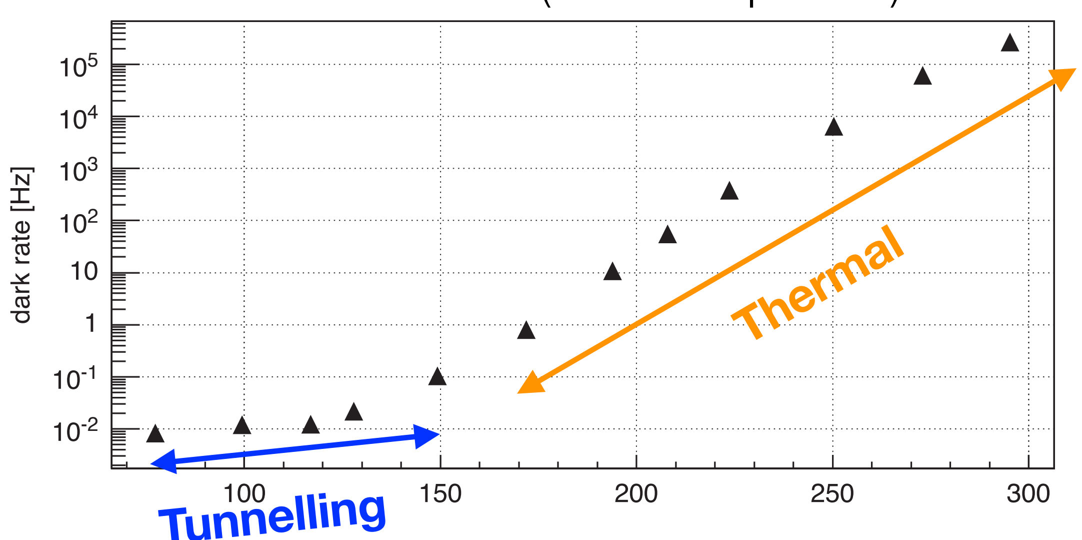
F. Acerbi, PD18



Dark Noise

- **Signal from avalanche triggered by randomly generated carrier**
  - Improved as <50kHz/mm² for recent devices
- **Two sources**
  - Thermally generated
    - Dominates at room temperature
    - Drastically reduced at low temperature
  - "Field-assisted" generation (Tunnelling)
    - Dominates below 200K
  - After-pulsing
- **Easy solution = Setting higher threshold (>1pe, 2pe, …)**

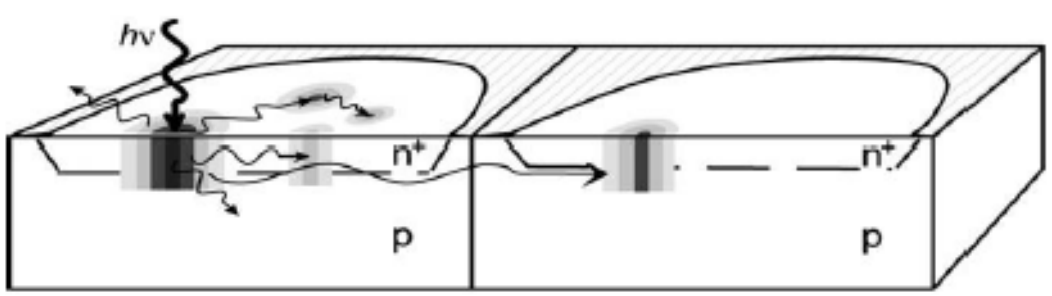




J. Csathy et al. NIMA 654 (2011) 225–232

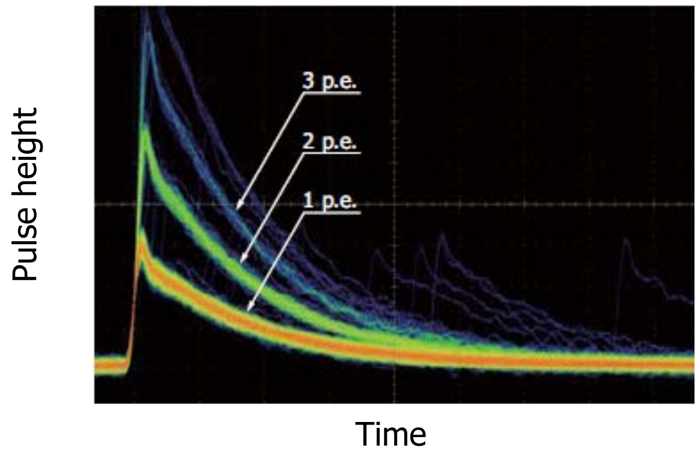
Optical Cross-talk

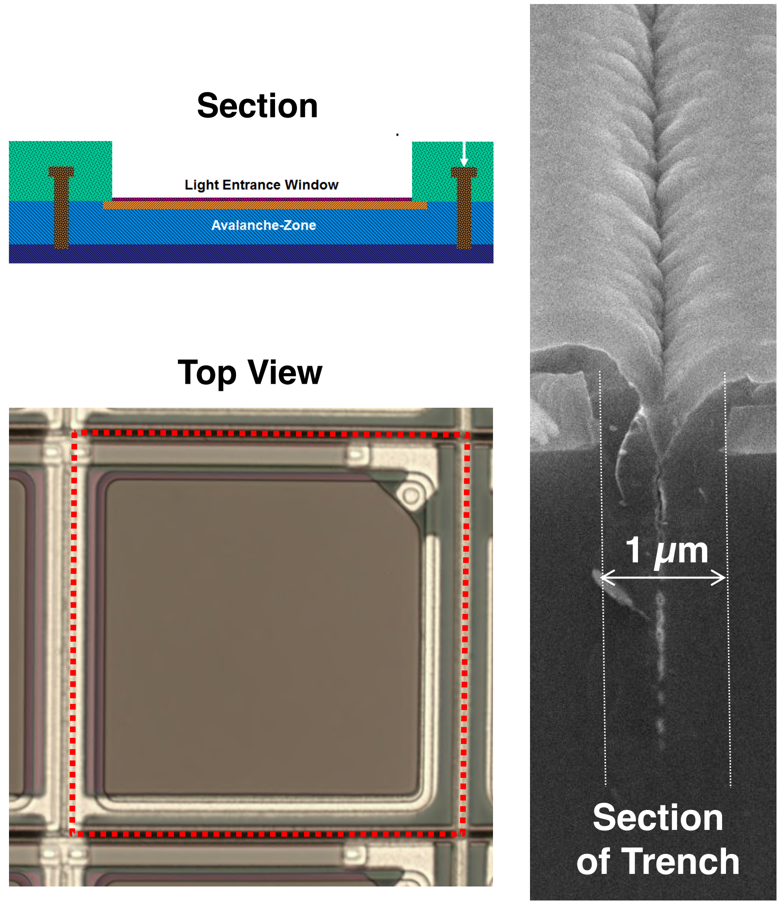
- **NIR luminescence during avalanche**
  - ~3 photons generated for 10^5 carriers (A. Lacaita et al.,IEEE TED 1993)
    →NIR photon can generate carrier in neighbouring cell and then induce another avalanche
- **Two types of cross-talk**
  - Direct (same timing as primary signal)
  - Delayed
- **Direct cross talk can be reduced by trench filled with opaque material**



A. Lacaita et al., IEEE TED 2013

Optical crosstalk superimposed on primary pulse

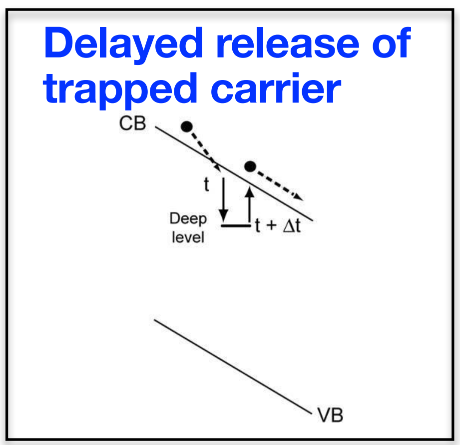


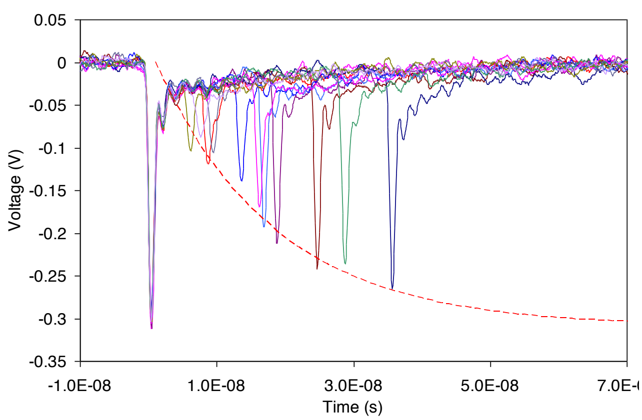


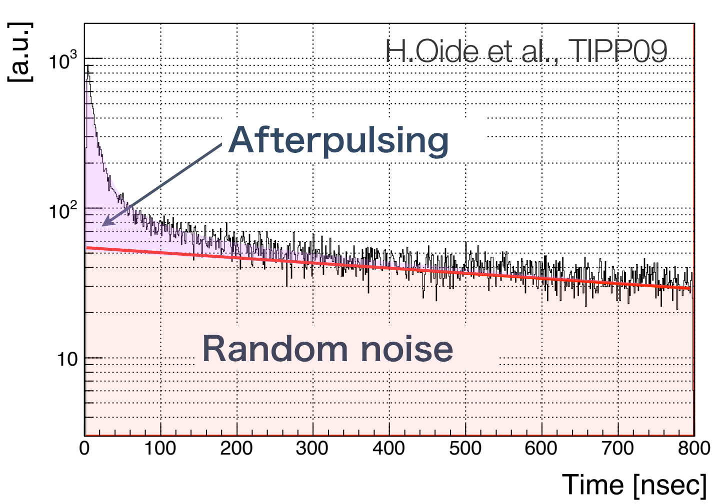
F. Wiest et al., PhotoDet2012

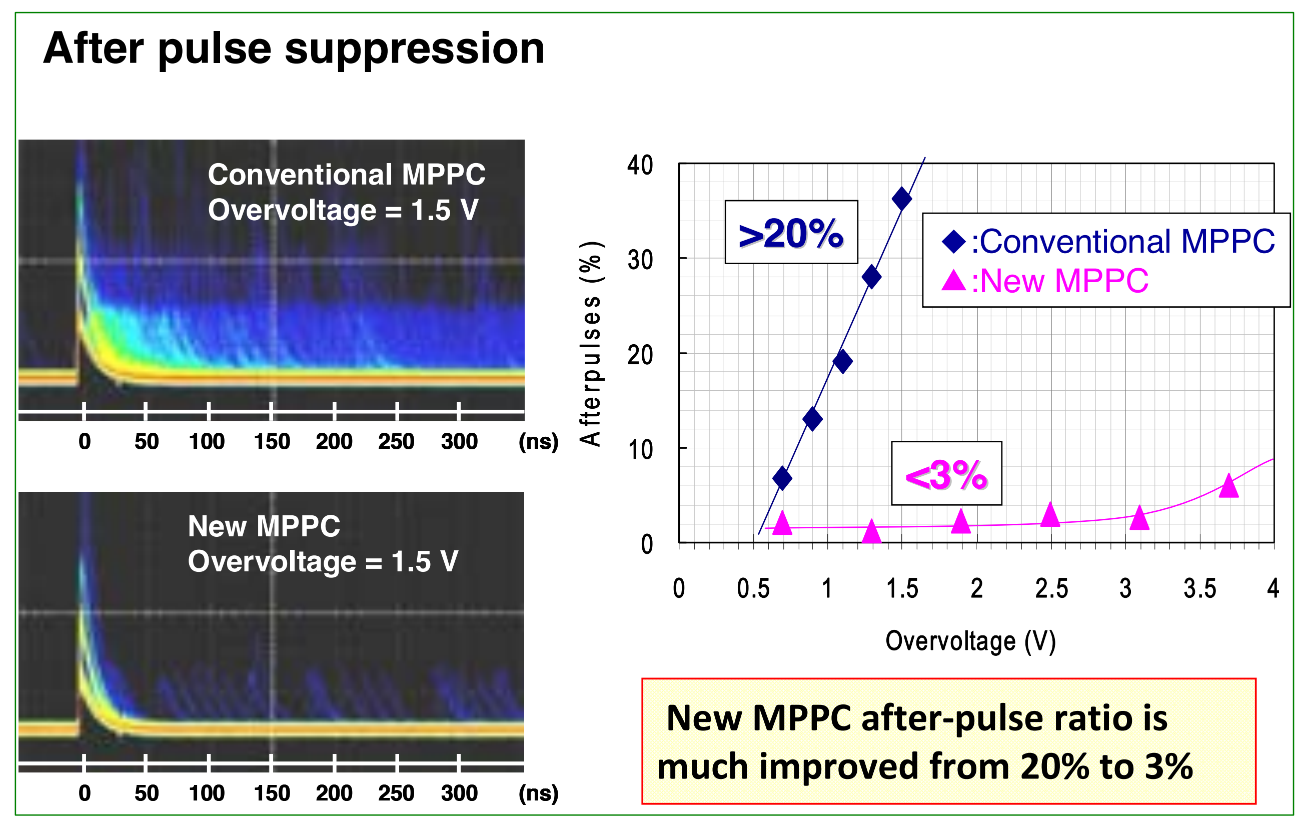
After-pulsing

- **Some of carriers are trapped in a deep trapping level in energy band gap → delayed release → trigger another avalanche**
- **Can be reduced by**
  - Better quality of wafer and epi. layer
  - Reduced gain





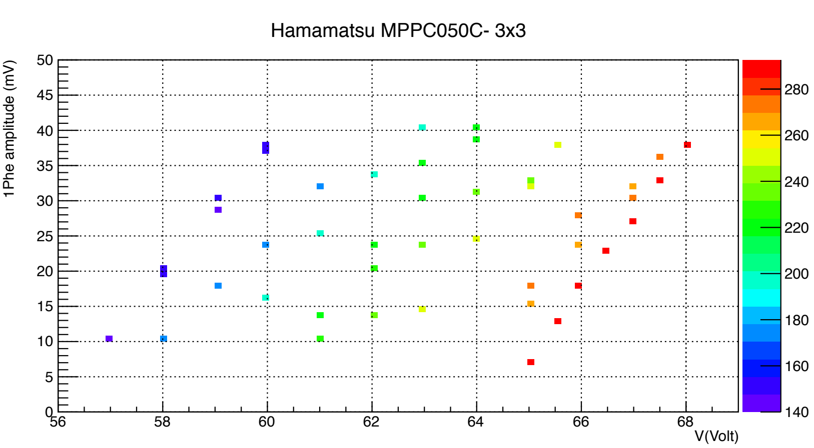




K. Sato, et al.,VCI2013

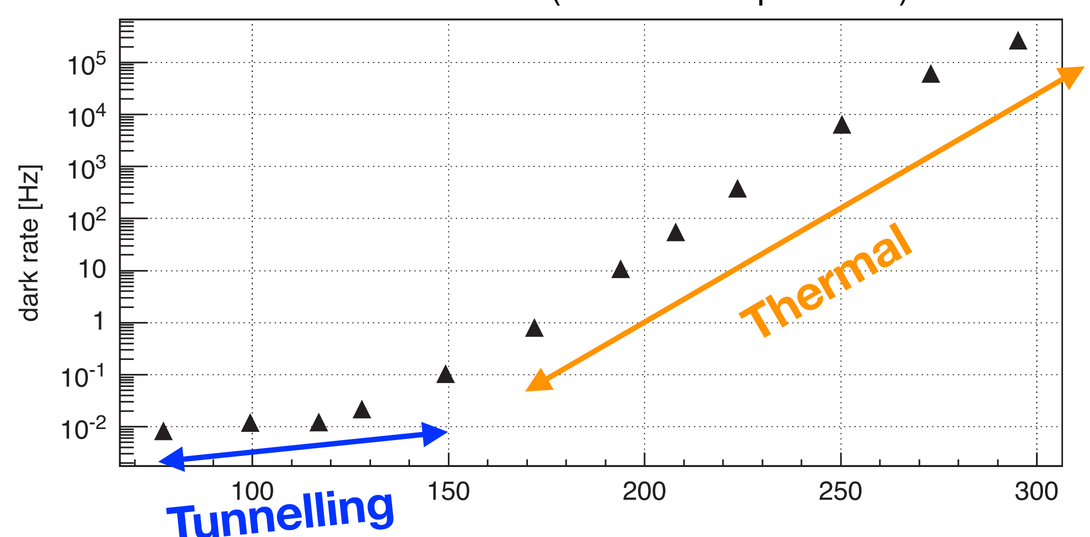
Temperature Dependence

- **In general, SiPM has to be operated at controlled temperature.** 🙁
- **Temperature dependence of SiPM**
  - Breakdown voltage
    - $\Delta V_{bd} / \Delta T$ = 55mV/deg (MPPC), 25mV/deg (AdvanSiD)
    - Gain can be drastically changed when temperature varies, if V_{bias} is not adjusted accordingly.
  - Dark noise rate
    - ×2 reduction every 8deg temp. reduction
  - Quench resistor
    - Signal shape can be changed.
    - Improved by using metal quench resistor instead of poly-Si (Hamamatsu MPPC)

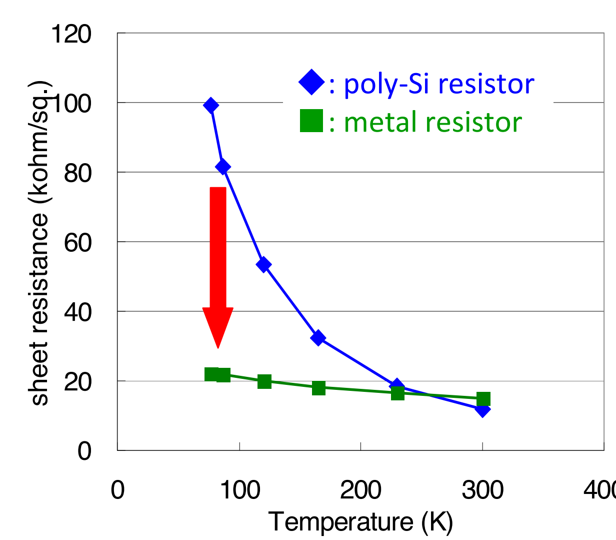


A. Papa

Dark count rate (MPPC 50μm cell)

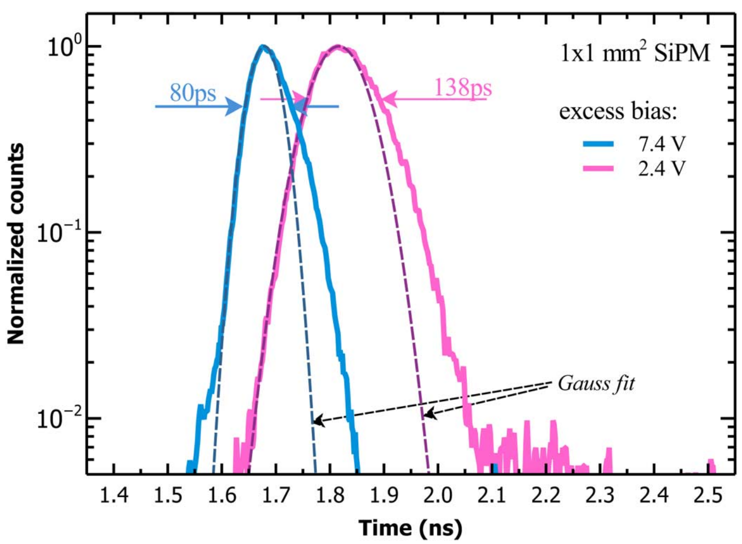


J. Csathy et al. NIMA 654 (2011) 225–232

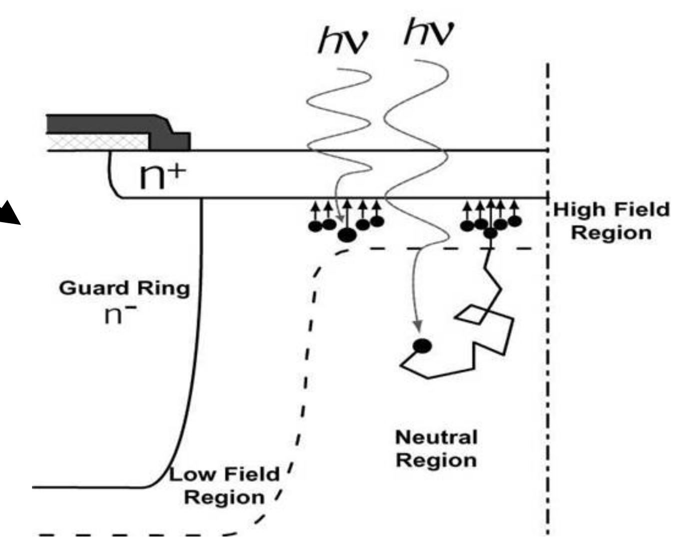


Time Resolution

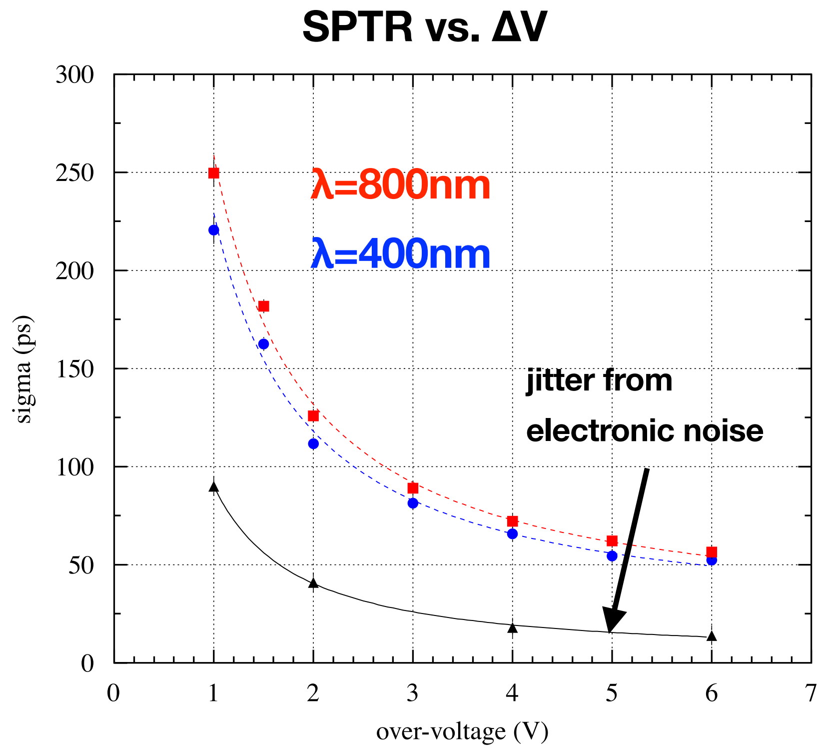
- **Excellent timing performance of SiPM**
  - Signal charge generated in very thin layer (< a few μm)
- **Single Photon Time Resolution (SPTR)**
  - Major component: Gaussian jitter ~O(100ps) (FWHM)
  - Minor slow tail (~O(ns)) from carrier drift from neutral region
- **Strong dependence on ΔV, weak dependence on λ**



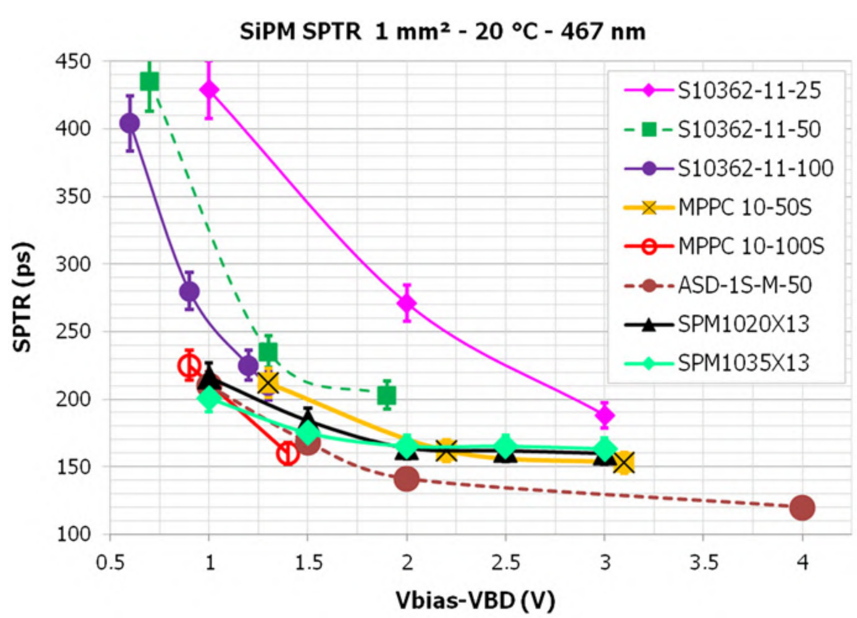
F. Acerbi et al., IEEE-TNS 61(2014)2678



S. Cova et al., NIST Workshop on Single Photon Detectors 2003



G. Collazuol et al., NIMA 581(2007)461

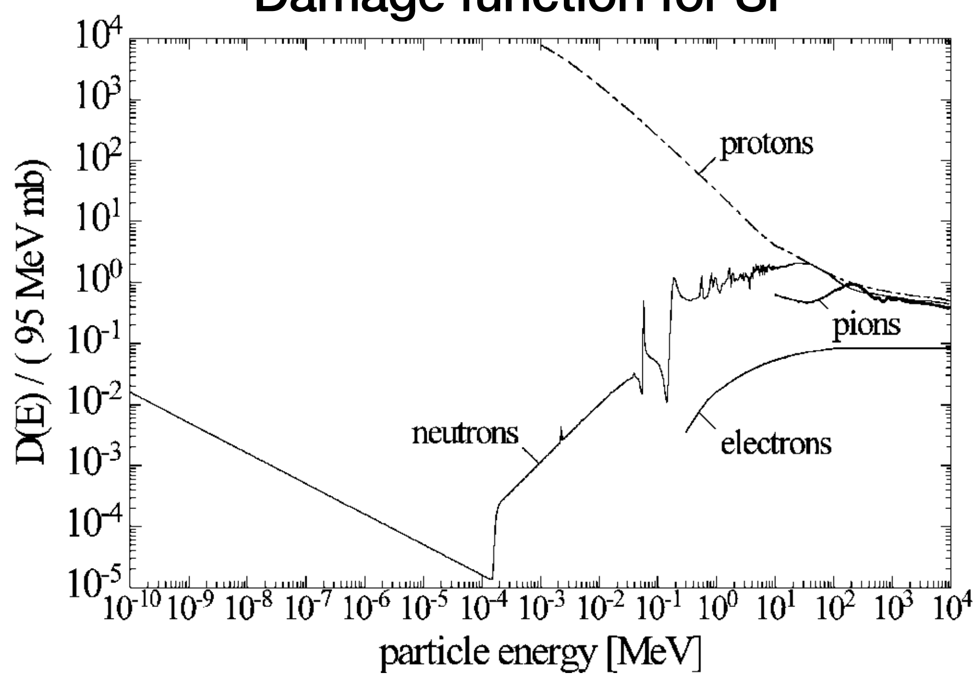


V. Puill et al., NIMA 695(2012)354

Radiation Hardness

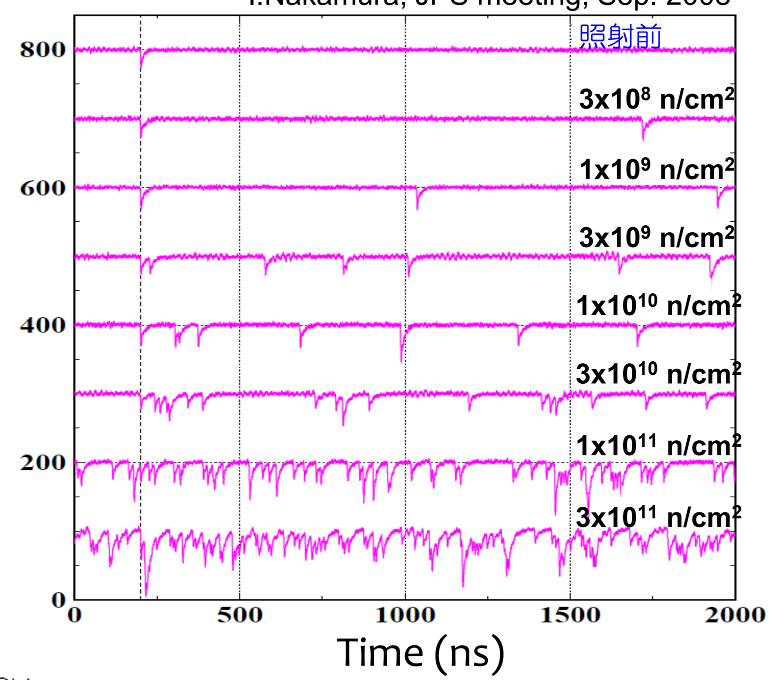
- **Radiation hardness → well-know issue of SiPM**
- **Radiation damage**
  - Neutron, proton →Bulk damage by Non-Ionizing Energy Loss (NIEL)
  - γ-ray, X-ray→Surface damage at Si-SiO_2 interface by ionising energy loss
- **Effect of radiation damage**
  - Mostly increase of dark noise
  - Change in breakdown voltage, gain and PDE for higher dose
- **Possible solutions**
  - Operation at lower temperature to reduce dark noise
  - Reduce volume to be damaged by thinning down epitaxial layer or substrate
  - Better insulator material to reduce surface damage
  - Other material than Si?

Damage function for Si

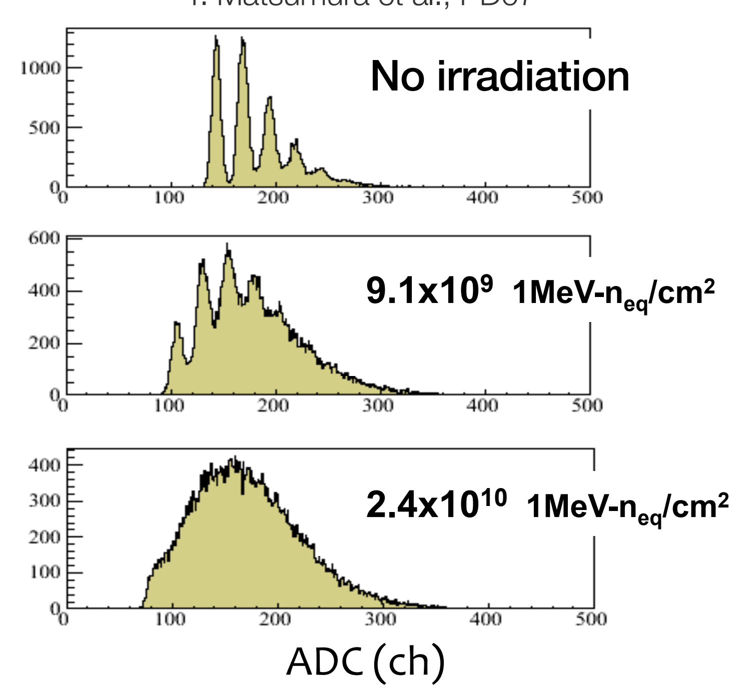


G. Lindstrom, et al., NIMA 426(1999)1

I.Nakamura, JPS meeting, Sep. 2008



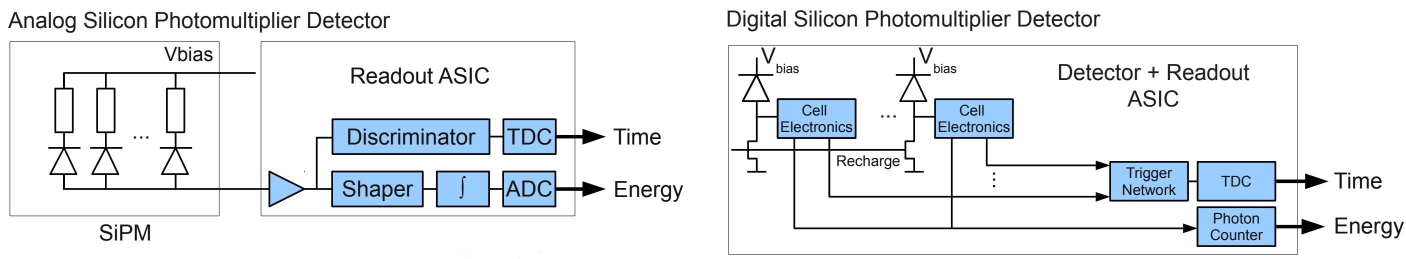
T. Matsumura et al., PD07

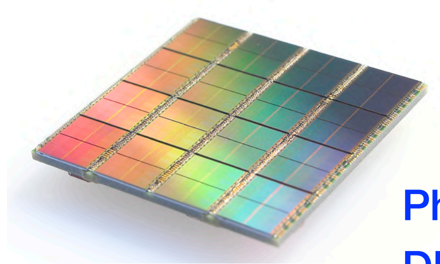


New Development

- **Digital SiPM**
  - SiPM arrays with integrated electronics
  - digital SiPM from Philips
  - 3D-dSiPM for LXe TPC of nEXO (low temp.)
- **Features**
  - Counting # of fired cells
  - Time stamp of first fired cell (per die)
  - Cell-by-cell active control ➔ disable hot cell
  - Active quenching

Concept of digital SiPM

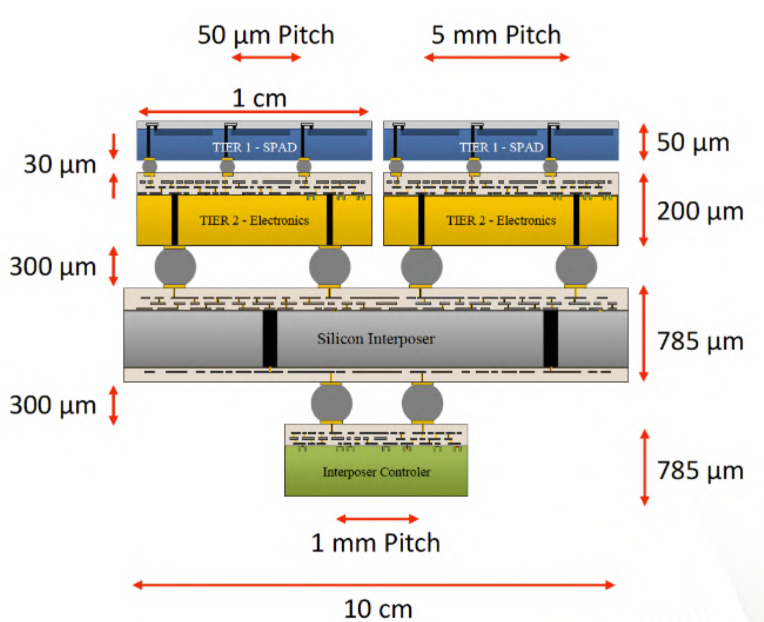


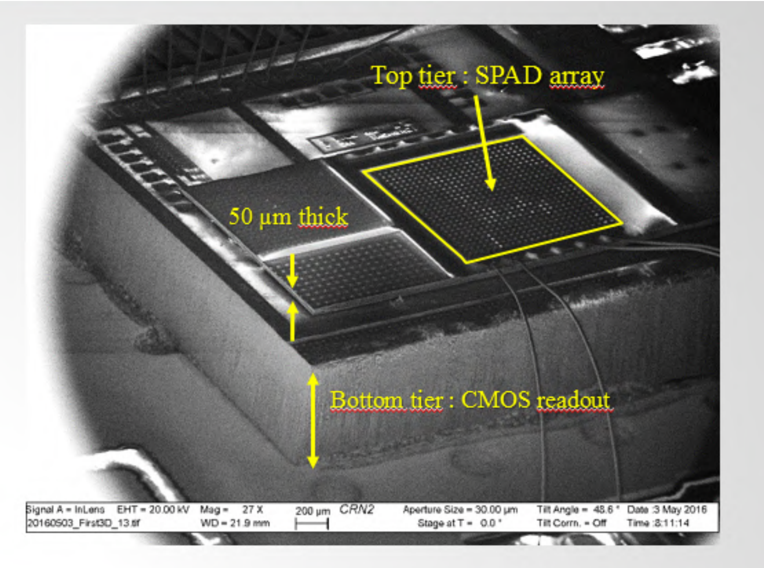


Philips digital SiPM
DPC6400-22-44 (DPC3200-22-44)

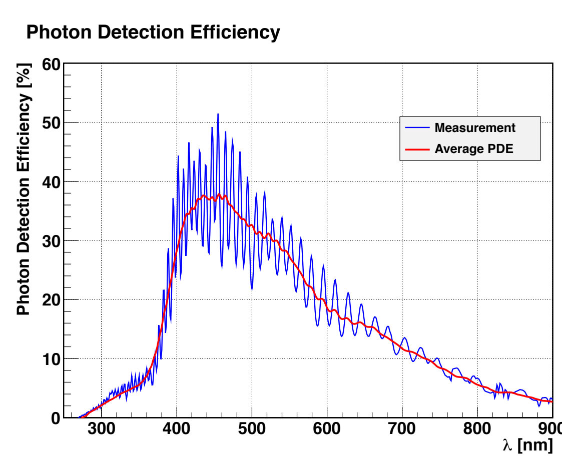
Outer dimensions	32.6×32.6 mm^2
Pixel pitch	4×4 mm^2
Pixel active area	3.9×3.2 mm^2
# of cells	6936(3200)
Cell size	59.4×32(64) mm^2
Pixel fill factor	54(74) %
Tile fill factor	75(55) %
Operational bias voltage	27±0.5 V

3D-dSiPM for nEXO

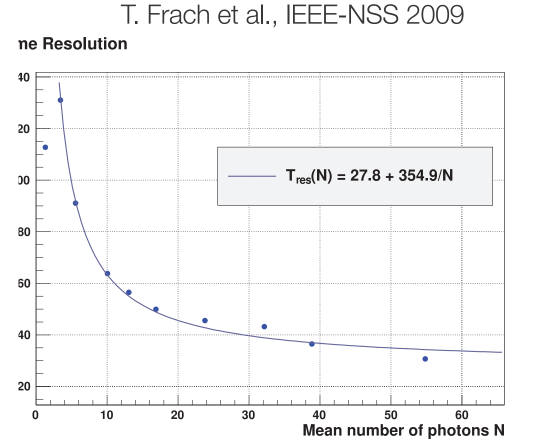




T. Frach, 2007 JINST 7 C01112



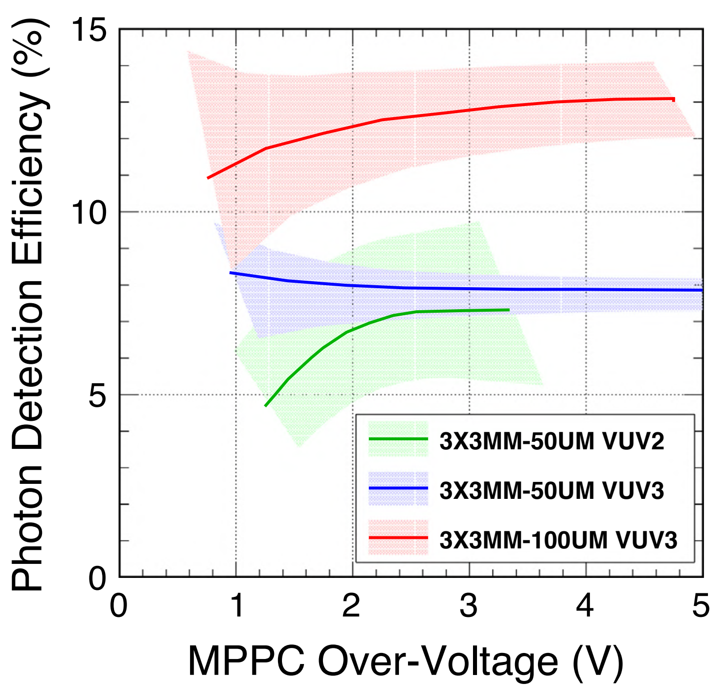
T. Frach et al., IEEE-NSS 2009



New Development

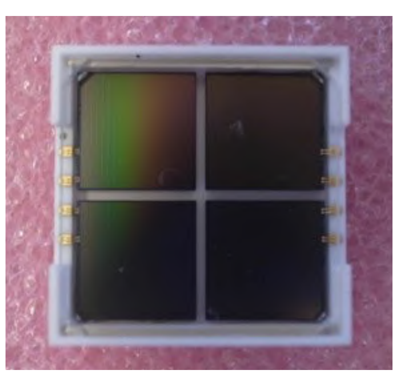
- **SiPM for deep UV light**
  - Detection for scintillation light from LXe (λ=175nm) and LAr (λ=128nm)
  - Recent development by Hamamatsu and FBK
- **VUV-MPPC for MEG II LXe detector**
  - Hamamatsu MPPC S10943-4372
  - PDE 15-20% at λ=175nm
  - 12×12mm^2 (discrete array of four 6×6mm^2 chip)
  - 50μm cell pitch
  - Metal quench resistor
  - Suppression of after-pulsing/cross-talk

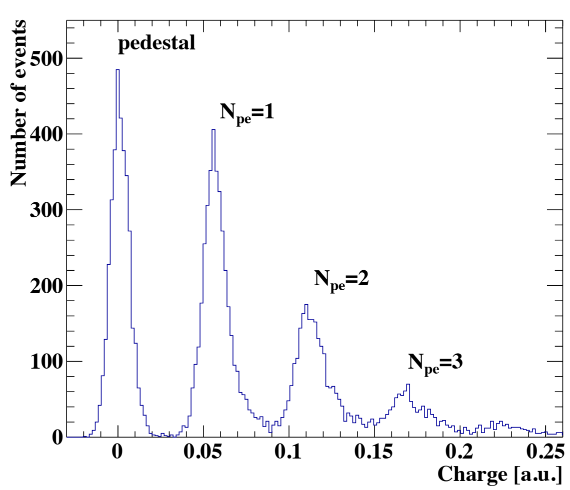
PDE for LAr scintillation light (λ=128nm)

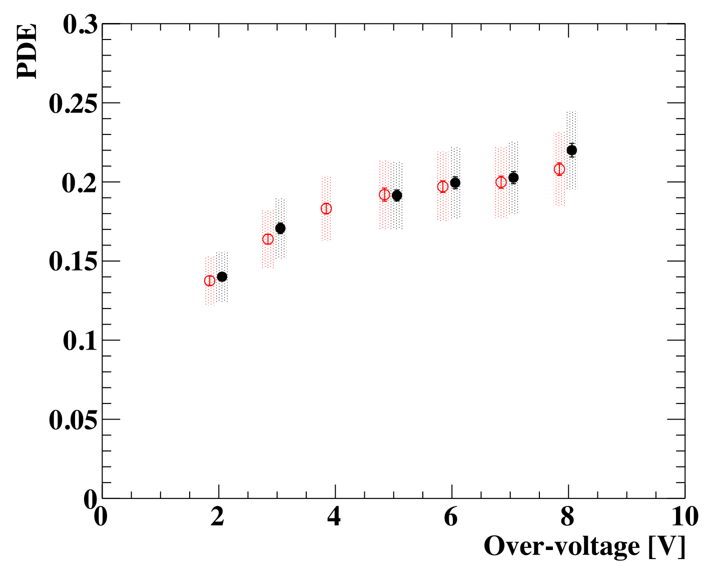


T. Igarashi et al., NIMA 833(2016)239-244

VUV-MPPC for MEG II LXe detector

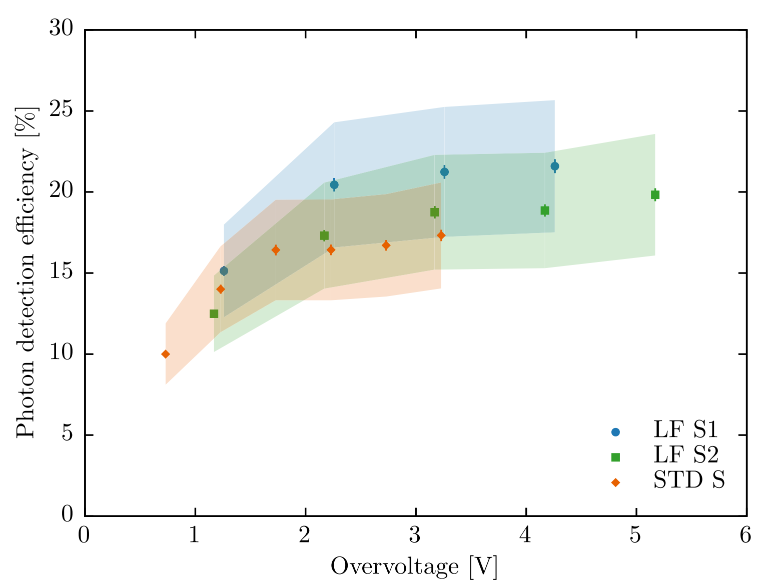






K. Ieki et al., NIMA 925(2019)148-155

VUV-SiPM from FBK



K. Ieki et al., NIMA 925(2019)148-155

- Introduction
- Basic Properties of Photo-detector
- Vacuum photo-detector
- Solid-state photo-detector
- Comparison
- Summary

Photo-detector Comparison

	PMT	PD/PIN	APD	SiPM
QE [%]	<40	<90	<90	<40 (PDE)
Gain	10^6	1	10^2	10^6
Operating voltage	~1kV	0-5V	100-1kV	20-70V
Temp. sensivitiy	Low	Low	High	Medium
Size	Bulky	Compact	Compact	Compact
Large area	Yes	No	No	No
Time jitter [ns]	>0.05	NA	>0.2	>0.1
Mechanical robustness	No	Yes	Yes	Yes
B-field immunity	No	Yes	Yes	Yes
Noise	Low	Low	Medium	High
Price	High	Low	Low	Low

- **Photo-detector choice depends on requirements for experiments!**
- **Recent trends = Replacement of PMT with SiPM**

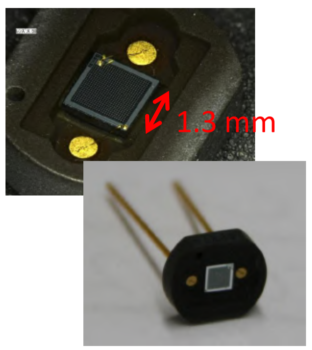
T2K

- **A large number of MPPCs totalling ~56,000 used in several detectors in T2K**
  - Working fine for ten years
  - # of bad channel < 0.28% incl. problem of readout electronics

A. Minamino, Next generation photosensor worksop 2010

Item	Spec
Active area	1.3 x 1.3 mm^2
Pixel size	50 x 50 μm^2
Num. of pixels	667
Operation voltage	70 V (typical)
PDE @ 550nm	~ 25 %
Dark count (Gain = 7.5 x 10^5)	< 1.35 Mcps @ 25 deg. (Thre. = 0.5 p.e.)
Num. of device	56,000

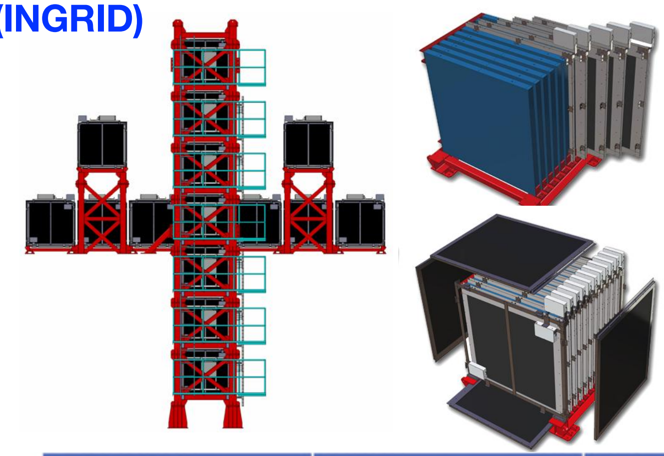
S10362-13-050C
Developed for T2K



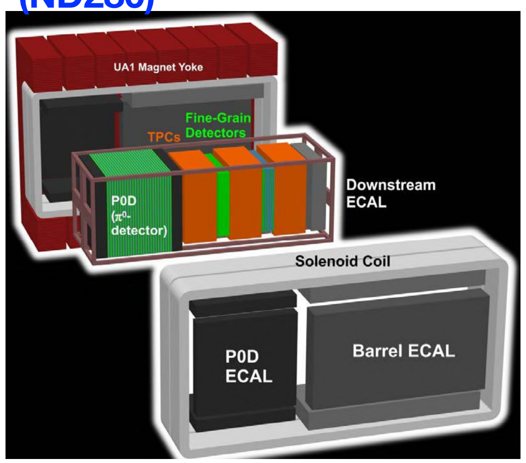
Produced by Hamamatsu Photonics

17

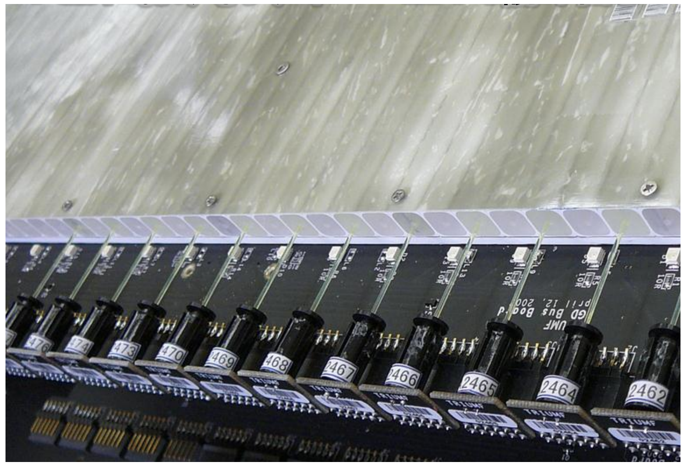
T2K on-axis near detectors (INGRID)



T2K off-axis near detectors (ND280)



MPPC readout (FGD)

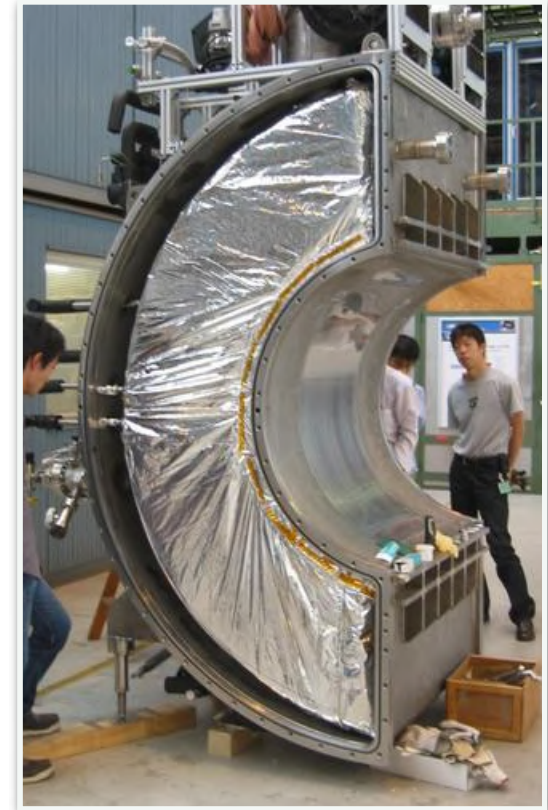


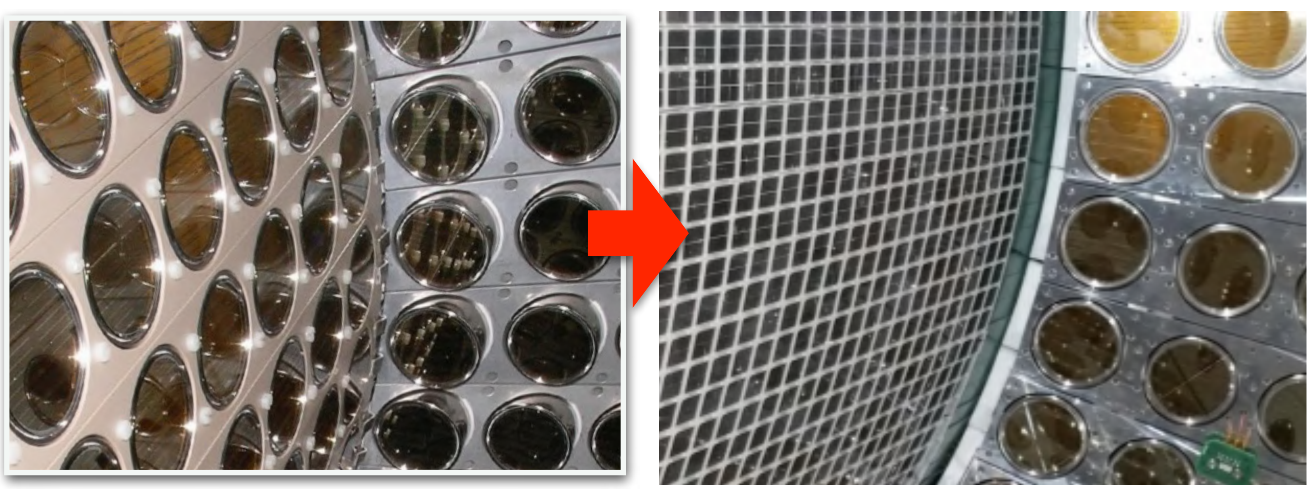
T. Kikawa, Next generation photosensor worksop 2012

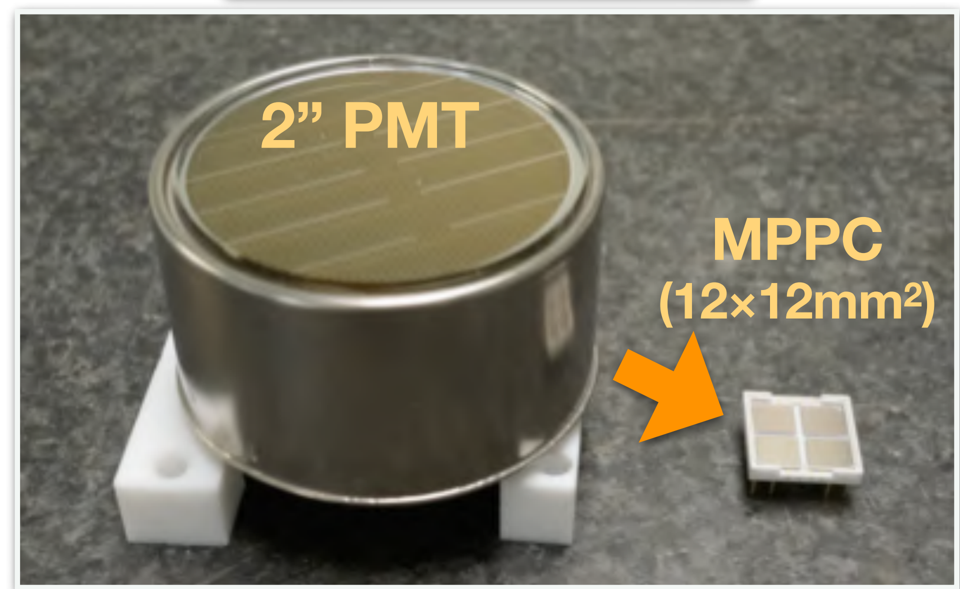
Detector	# of ch	# of bad ch		Fraction of bad ch	
		2010	2012	2010	2012
INGRID	10796	18	37	0.17%	0.34%
FGD	8448	20	20	0.24%	0.24%
ECAL	22336	35	58	0.16%	0.26%
P0D	10400	7	28	0.07%	0.27%
SMRD	4016	7	15	0.17%	0.37%
計	55996	87	158	0.16%	0.28%

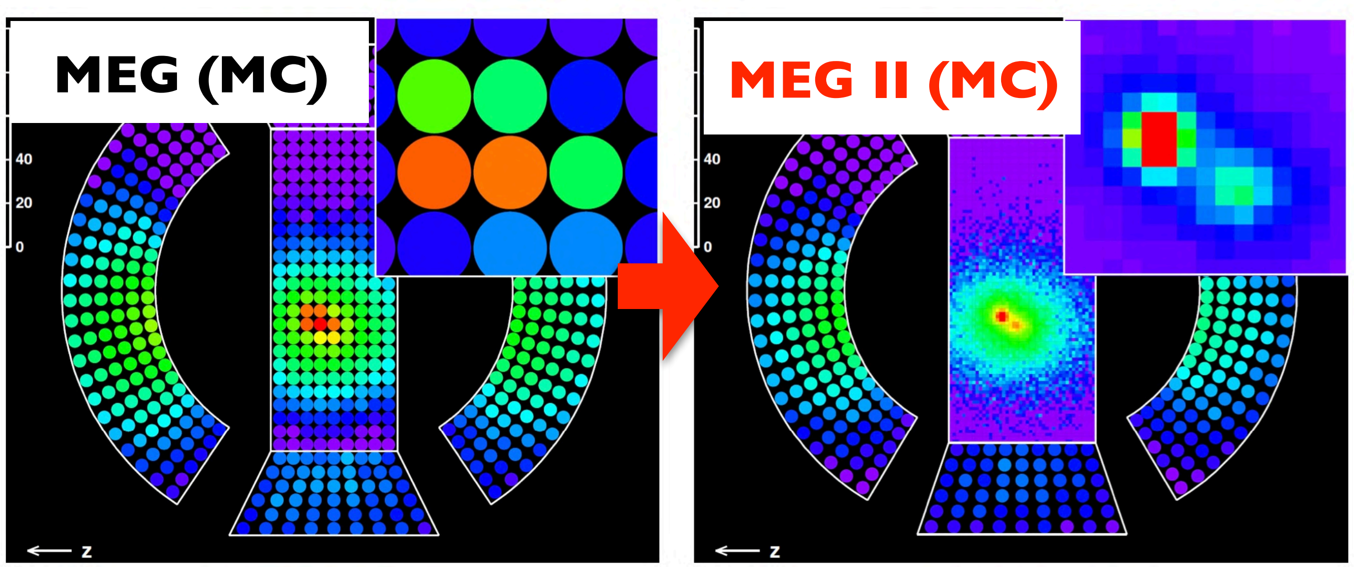
MEG II LXe Detector

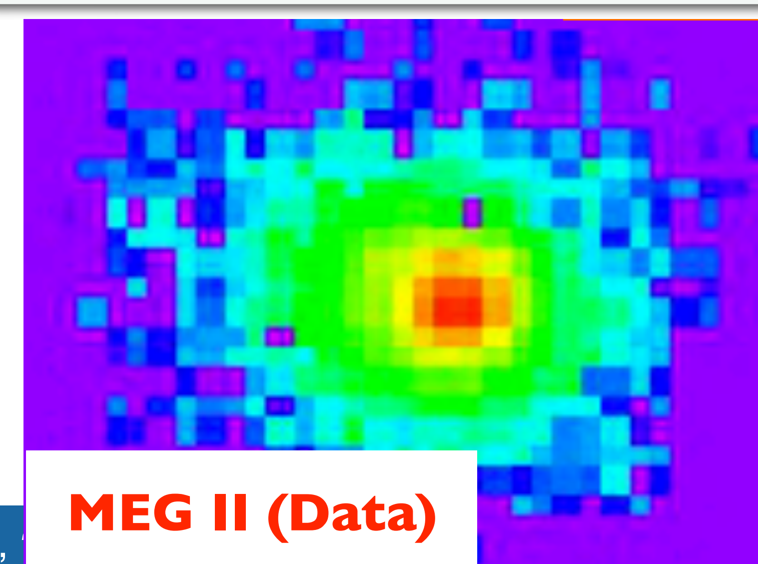
- **Highly granular scintillation readout**
  - 216 × PMTs(2-inch) on γ-entrance face are replaced with 4092 × VUV-MPPCs (139mm^2 each)
  - Energy and position resolutions will be improved by a factor of two.





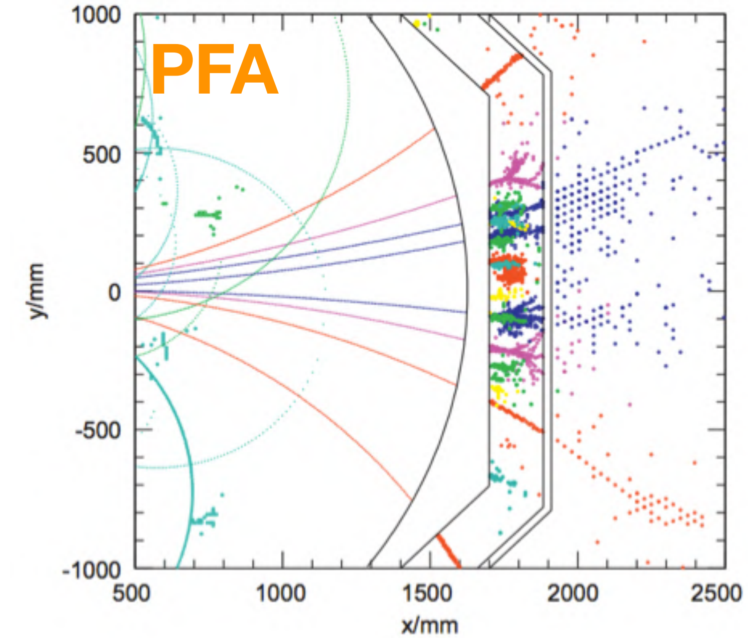




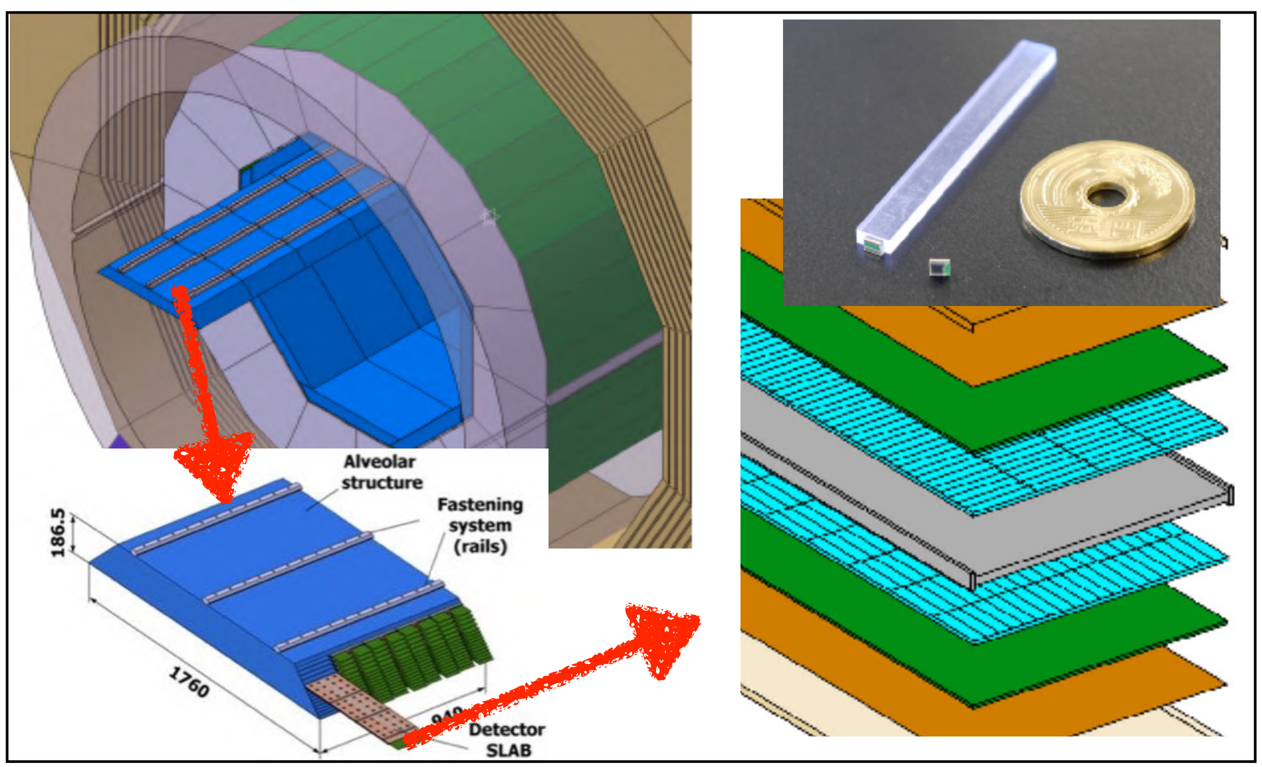


Calorimeters for ILC

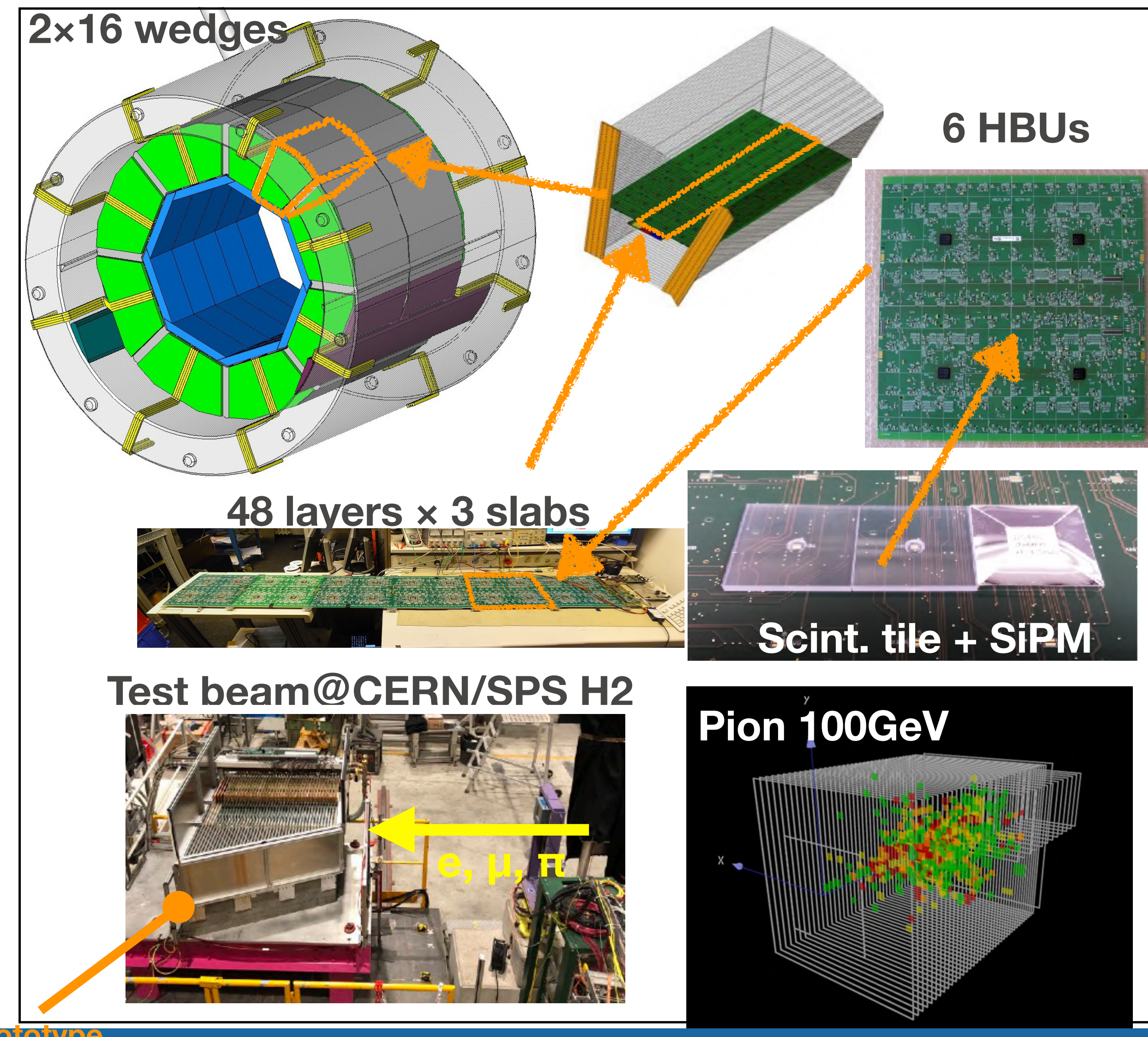
- **Highly granular calorimeter for ILC detector based on Particle Flow Algorithm (PFA)**
  - AHCAL: ~10^7 × (30×30×3mm² scinti. tile + SiPM)
  - ScECAL: ~10^7 × (5×45×2mm² scinti. strip + SiPM)
- **SiPM technology allows**
  - SiPM and readout electronics are integrated in active volume
  - Calorimeters in solenoid field of 4T



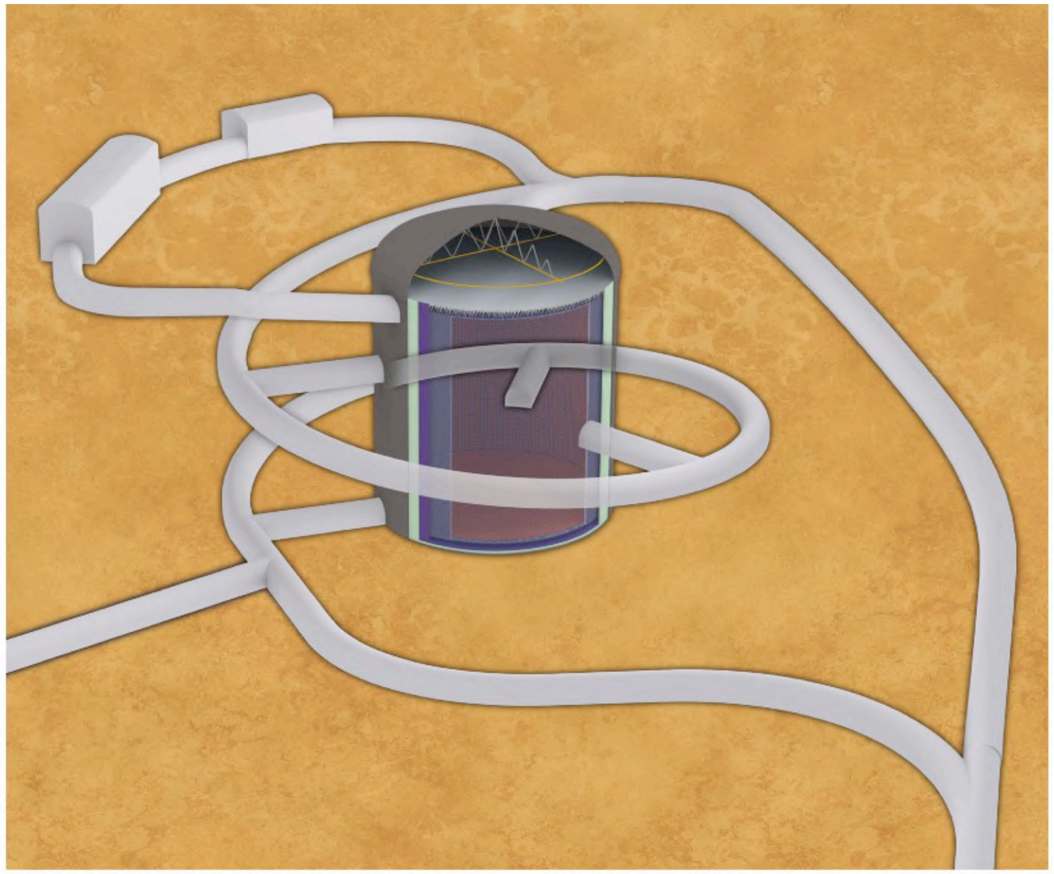
ScECAL

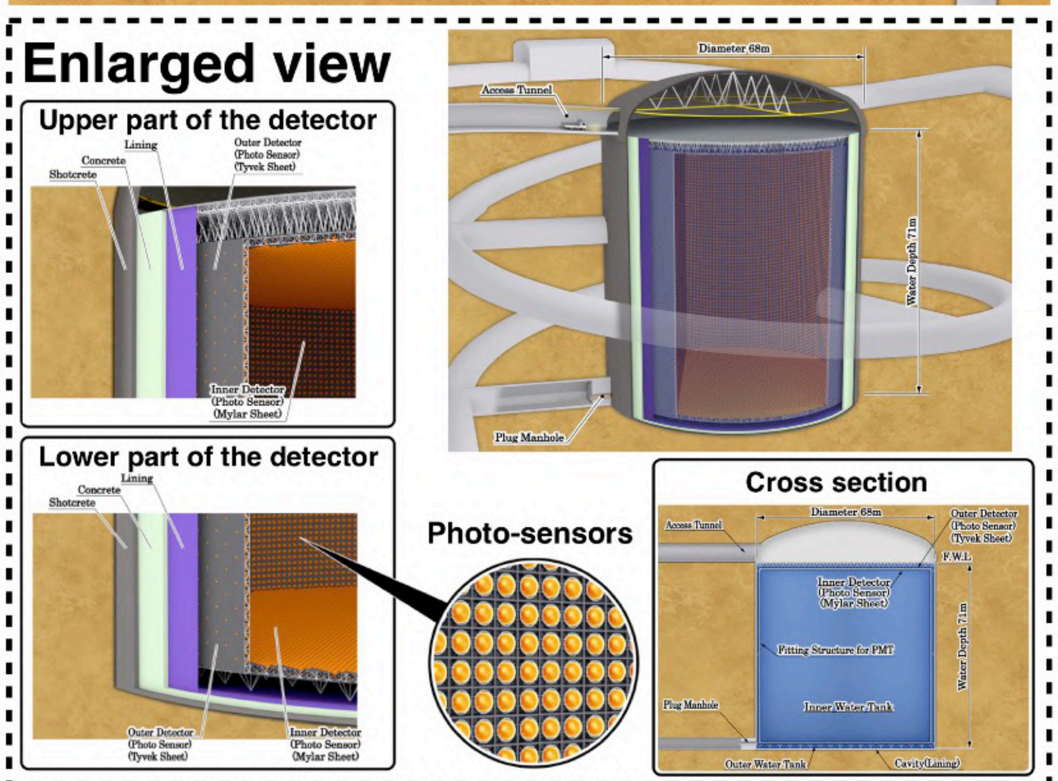


AHCAL

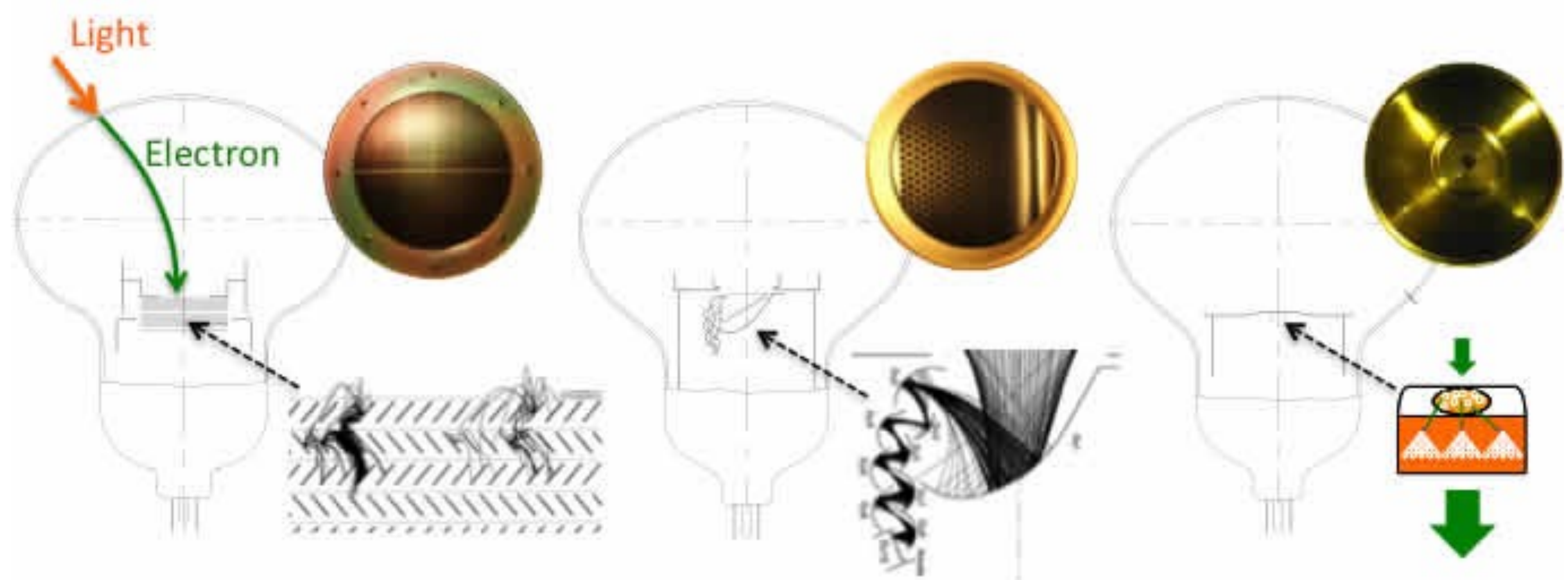


Still Only Possible with PMT!





- **Hyper-Kamiokande**
  - Next generation neutrino experiment
  - 10 times larger fiducial volume (190kton) than Super-Kamiokande (SK)
  - 40000 × new PMT with 2 × sensitivity than SK
- **Has been approved!**
  - Aiming at start-up in 2027



Summary

- **Photo-detector is one of the most crucial items in HEP experiment detectors**
- **Three types of photo-detector**
  - Vacuum photo-detector
  - Solid-state photo-detector
  - Gaseous photo-detector (not covered today)
- **Vacuum photo-detector**
  - ~100 years old!
  - Successful applications in many HEP projects
  - Still viable or even only possible solution for many projects
  - Still improving performance even with new ideas
- **Solid-state photo-detector**
  - PD and APD have been successfully used in many HEP experiments
  - Vast progress in development of SiPM technology since last two decades
  - More and more applications of SiPM because of many advantages

Useful References

- **Lectures in previous EDIT**
- **Vacuum photo-detector**
  - PMT Handbook (Hamamatsu Photonics K.K.)
  - K.Arisaka, “Vacuum Photon Detectors”, IEEE/NSS2012
- **Solid-state photo-detector**
  - Opt-semiconductor Handbook (Hamamatsu Photonics K.K.)
  - V. Puill, “Tutorial SiPMs”, NDIP2017
  - G. Collazuol, “Status and Perspectives of Solid State Photo-detector”, RICH2013
- **Gaseous photo-detector**
  - F. Sauli, “Photon detection and imaging with gaseous counters”, NDIP2017