University of Ljubljana, Faculty of Mathematics and Physics

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Ultrafast detection of photons

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Outline

Photon detection technologies
Measurement of timing properties
Applications of ultrafast timing

Photon detector

A device that can detect photons

- Convert light into a detectable electronic signal

- *Requirements*:
  - Single photon sensitivity
  - High efficiency
  - Good spatial granularity
  - Linearity
  - **Good Time response**
  - Rate capability/ageing
  - Dark count rate
  - Operation in magnetic fields
  - Radiation tolerance

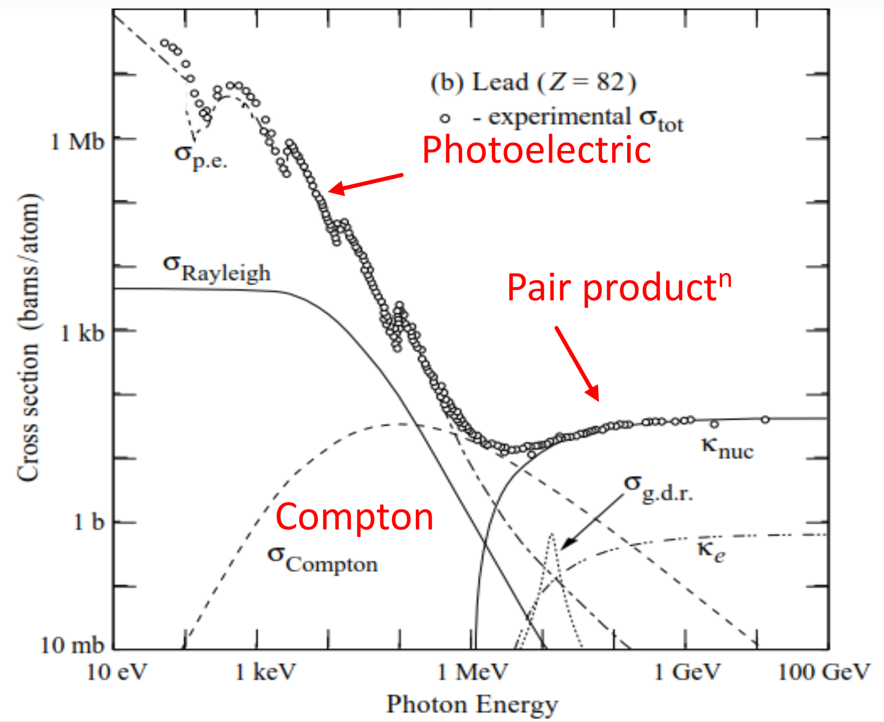
Detection mechanism:
Photoelectric effect

Photo-effect

Photoelectric effect: ‘conversion’ of photons (γ) to photoelectrons (pe)

- External – emission of free electrons from the metal surface due to energy absorption
- Internal – free charge carriers are generated by the absorption of incident photons in the semiconductor junction detector
- Visible photo detection

Interactions of gammas with matter



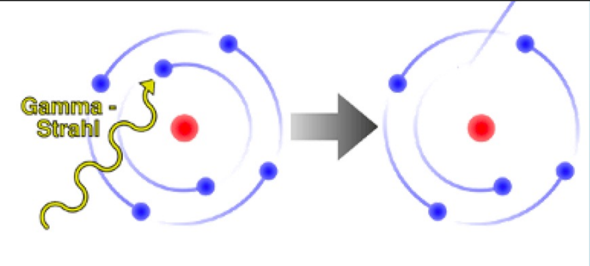


Photo sensor types

Almost all photosensitive materials are very reactive (alkali metals). Operation only in a vacuum or extremely clean gas.

Vacuum

- Photomultiplier tubes (PMT)
- Microchannel plate photomultiplier tubes

Solid-state photon detectors

- Silicon photomultipliers

Hybrid detectors

- HPDs and HAPDs
- Other hybrid photosensors

Gaseous photon detectors

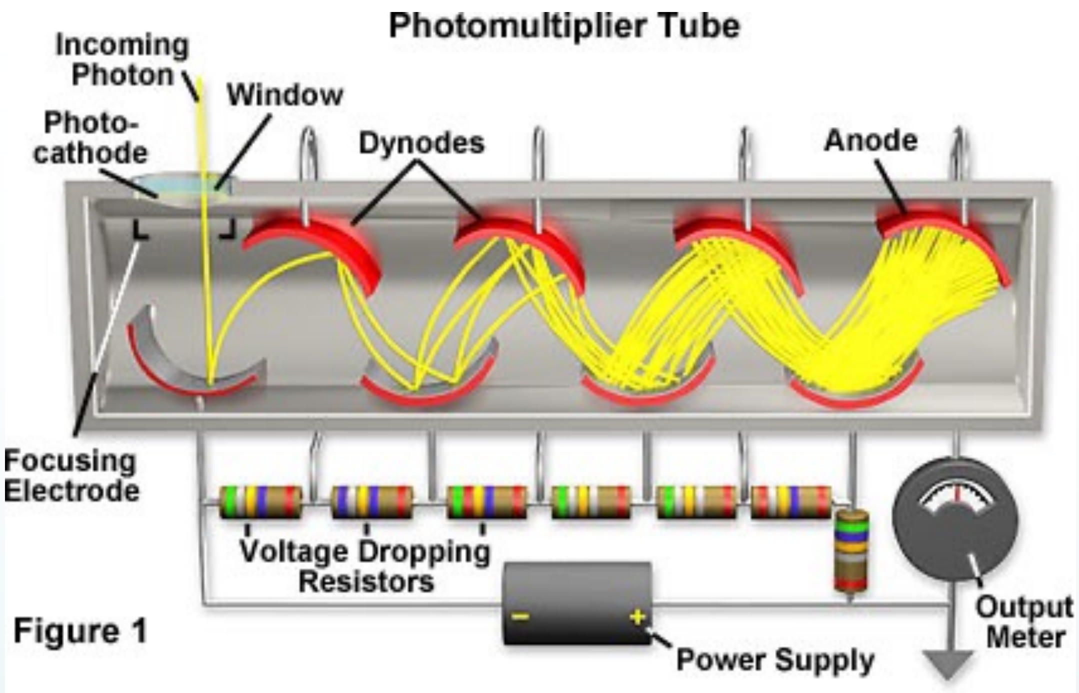
We will not focus on the hybrid and gaseous detectors today

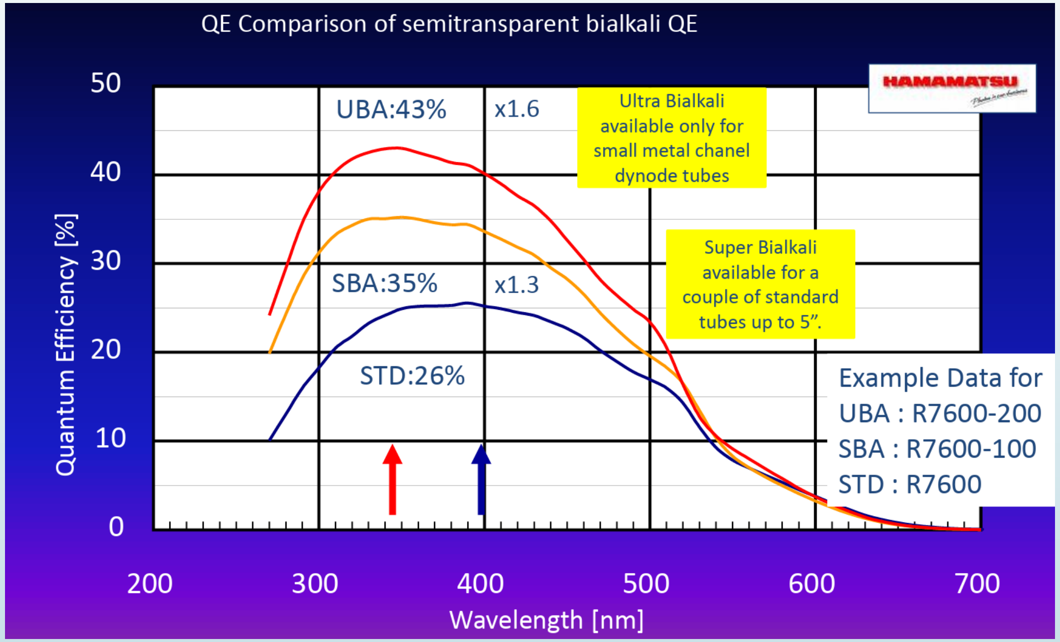
Photon multiplier tube

- After the photoelectric conversion, the photoelectron signal needs to be amplified to give a measurable electronic pulse.
- Achieved in a traditional photomultiplier by dynode chain
  - exponential multiplication of the charge at each dynode: e.g. if the number of electrons is tripled on each stage of a 12 - dynode chain
  - Gain = $3^{12} \sim 10^6$

$$G = \delta^n = (k\,V_d)^n$$

  - Quantum efficiency QE: $N_{detected} / N_{all}$



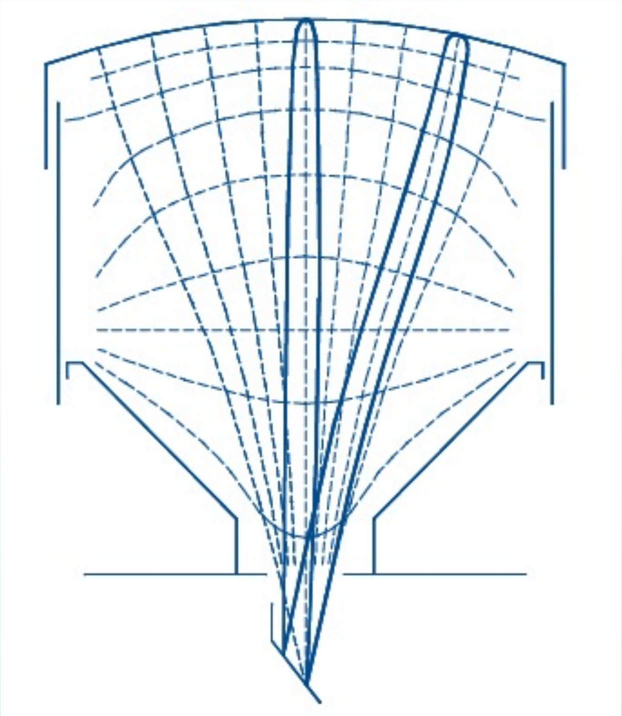


Collection of photo-electrons

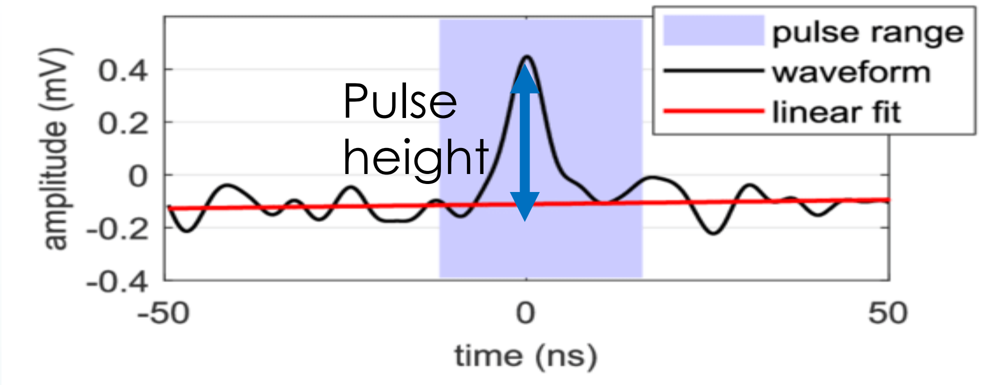
Use a suitably formed electric filed between the photocathode and the first dynode

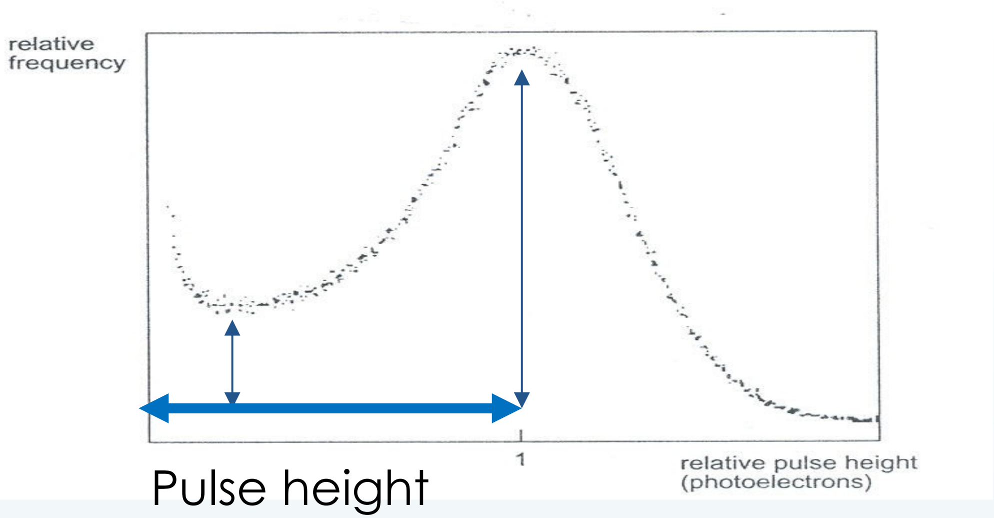
Requirements:

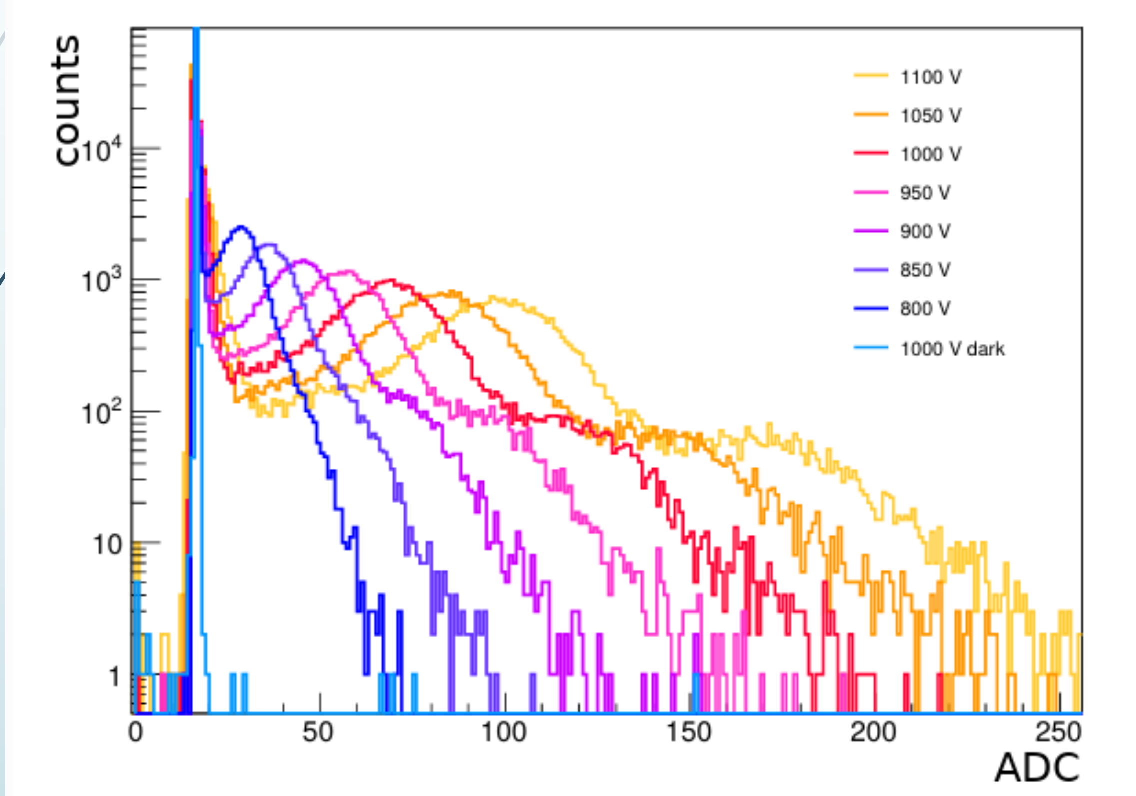
- High efficiency for the photo-electron collection (for different paths, exit energies, directions).
- The collection efficiency should not depend on the photoelectron exit point.
- Different travel times of the first photo electron from the exit point to the first dynode limit the time resolution.
- Larger sensors -> worse resolution



Pulse height distributions for single photoelectrons





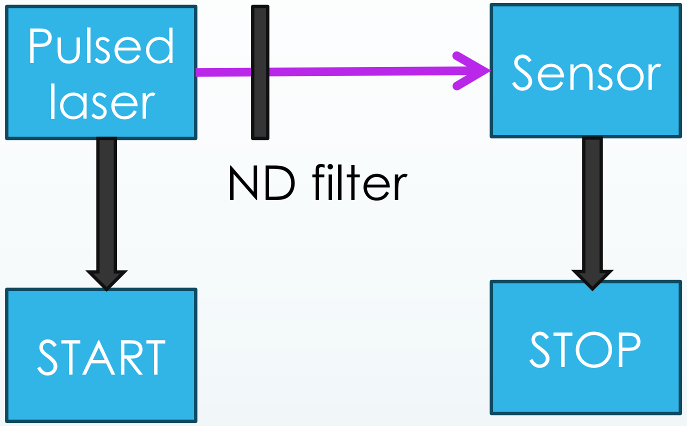


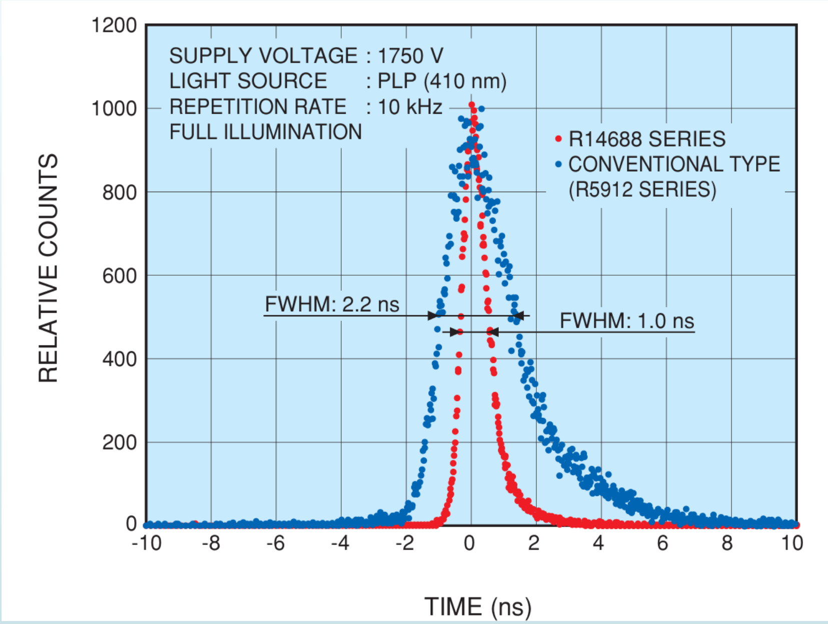
* multiple photons: convolution

How to measure transit time spread

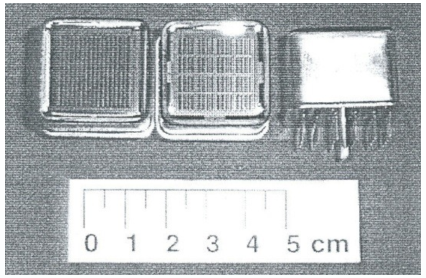
Use a pulsed laser light source with a very short light pulse (~10 ps or less)

- attenuate light to low intensity → single photon level
  - Poisson's statistics if the P(γ) = 5%, P(2γ) ~ 0.1%.
- Measure a transit time - the delay between the laser trigger pulse and the signal from the photosensor. 3 mm in 10 ps (vacuum)
- **Transit time spread (TTS)**: transit time variation between different events
  - →timing resolution

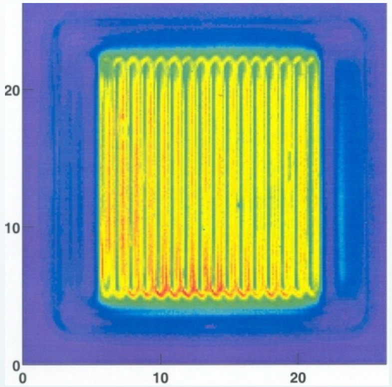


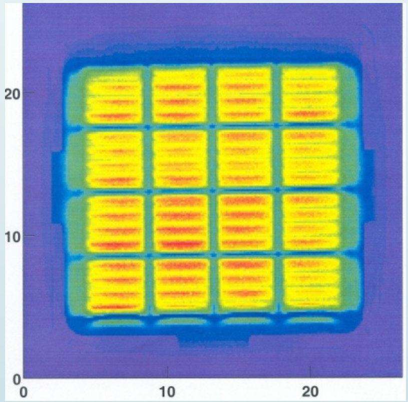


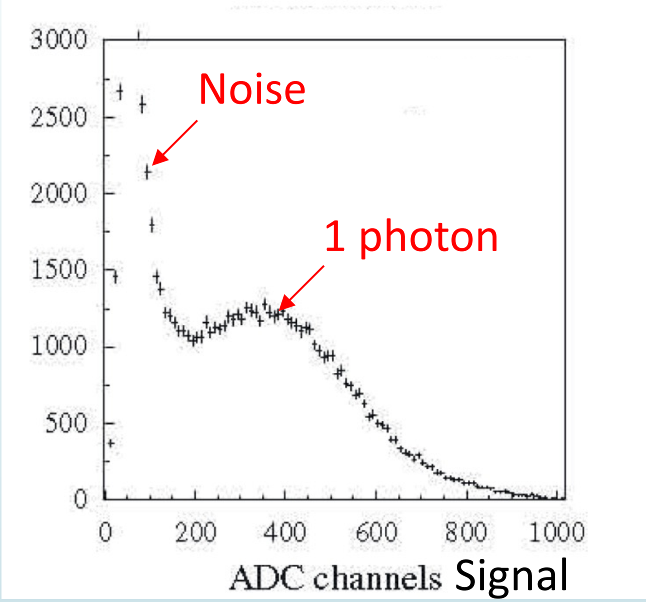
Multi-anode photo-multipliers

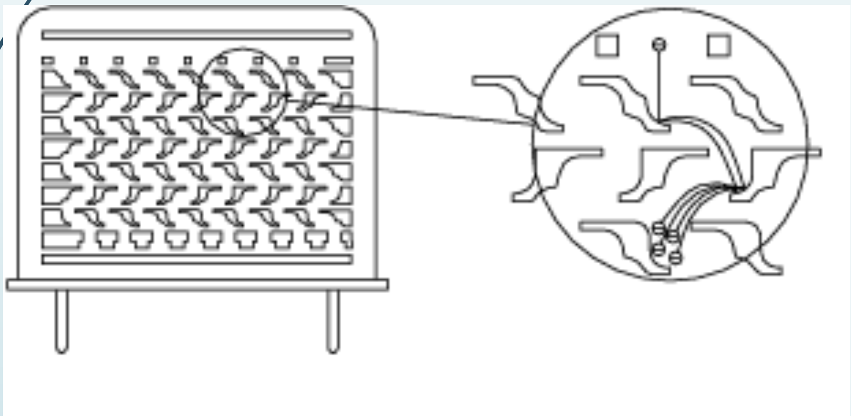


- Single photomultiplier tubes: limited spatial resolution
- The **multi-anode** photomultiplier / miniaturisation of a PMT tube → up to 64 pixels in a single tube, each with size ~ 2×2 mm^2
- Dynode structure formed from a stack of perforated metal foils
- **Signal width dominated by fluctuations in the charge multiplication of the first dynodes**









Multi-anode PM (Hamamatsu R5900)

metal foil dynodes

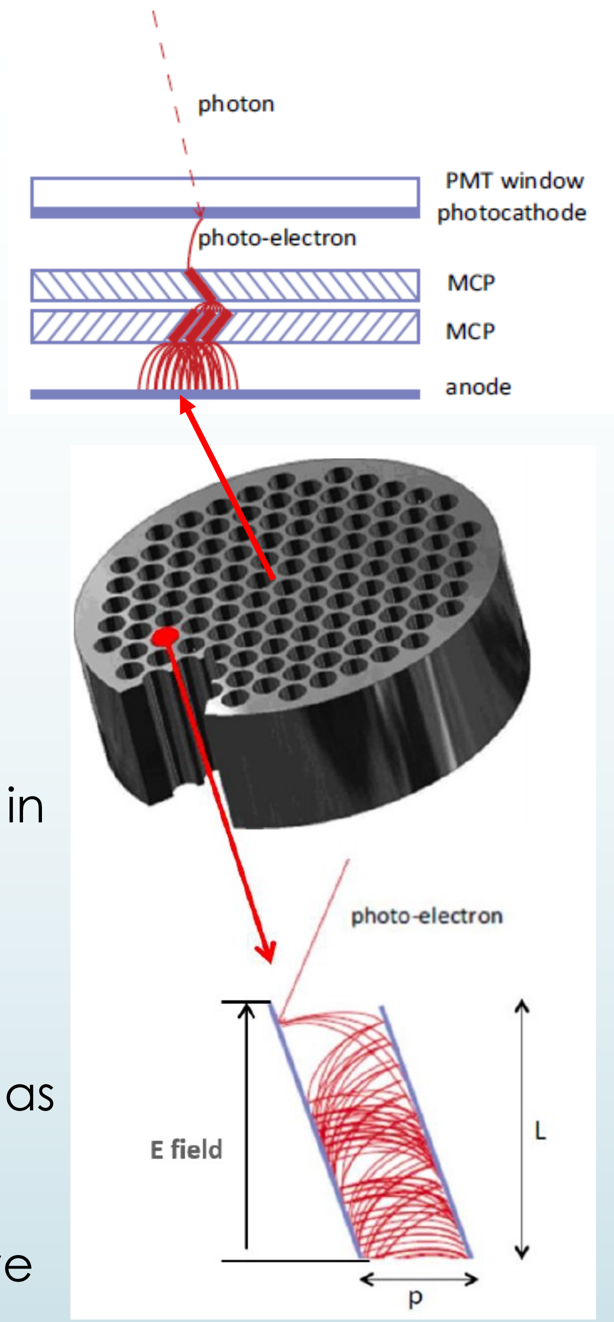
Micro-Channel Plate PMTs

MCP detector
(Photonis)
6 cm width
Up to 1024
anode pads

- Time-of-flight detectors would like timing precision at the *picosecond* (10^{-12} s) level
- 1 ps ≈ 0.3 mm for a relativistic particle
  → requires small feature sizes
- **Micro-channel plate** (MCP) photon detectors employ electron multiplication in small (~ 10 μm) pores, used in image intensifiers
- Timing precision of ~ 10 ps achieved

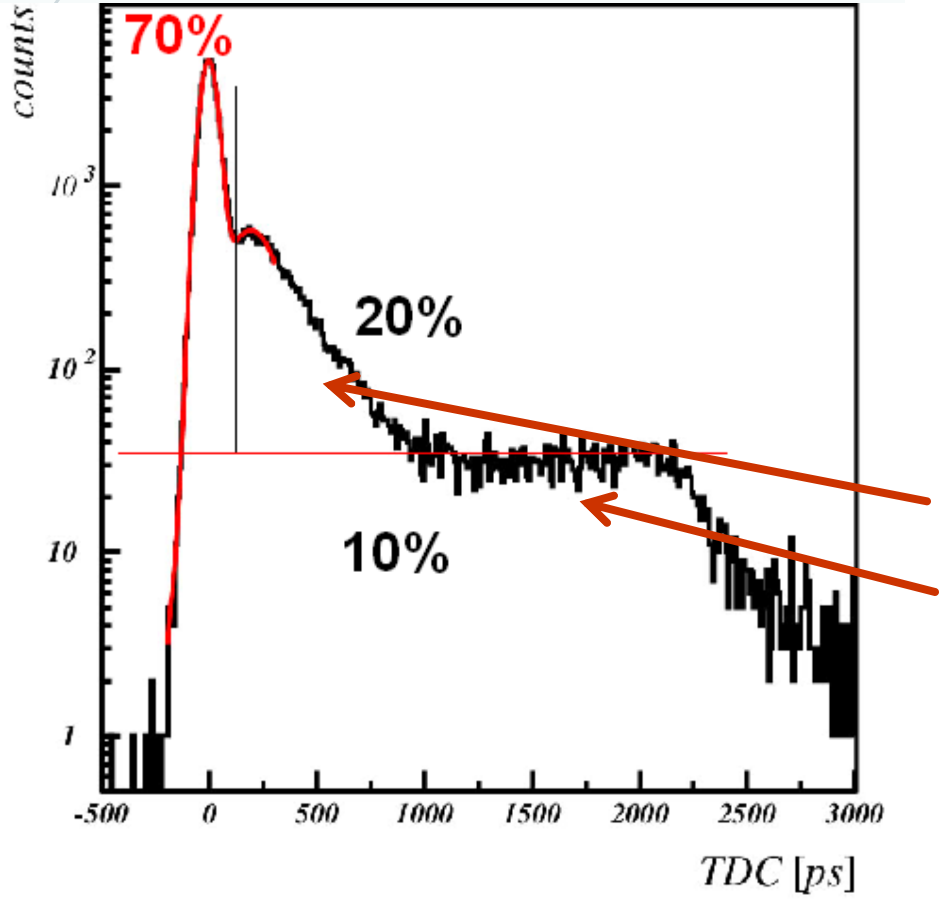
- MCP is an array of millions of capillaries (~10 um diameter) in a glass plate (d=1mm).
- Made by pulling millions of **tiny core/cladding glass fibers**.
- Bundling, slicing, and acid etching out the cores to make channels.
- Both faces of the plate are coated by thin metal, and act as electrodes.

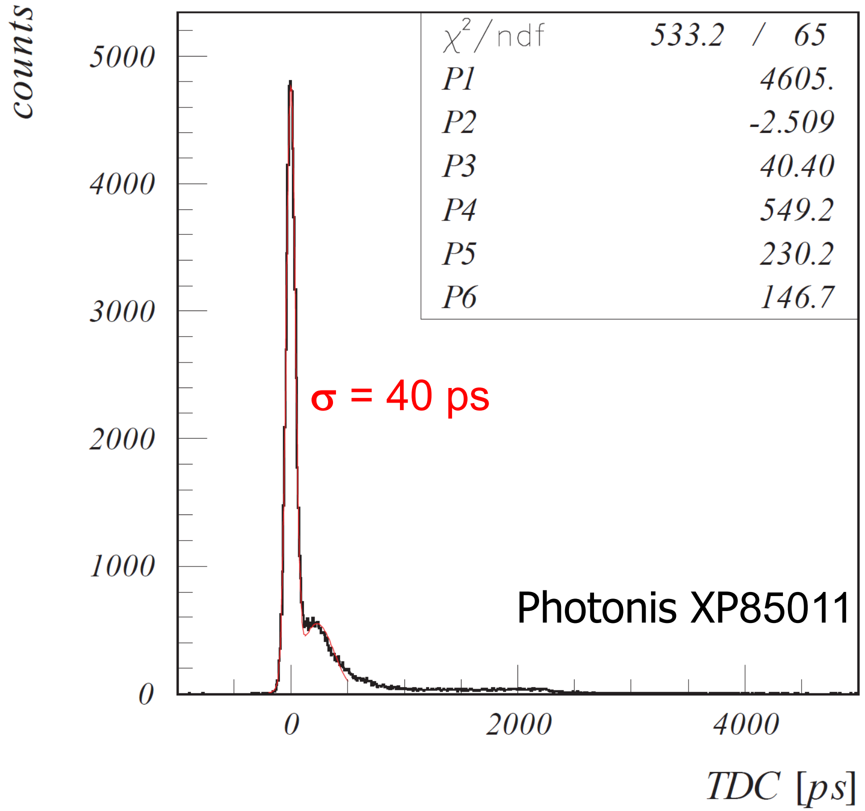
- The inner side of each tube is coated with electron-emissive material.



MCP PMT timing

MCP PMTs: main peak with excellent timing accompanied with a tail



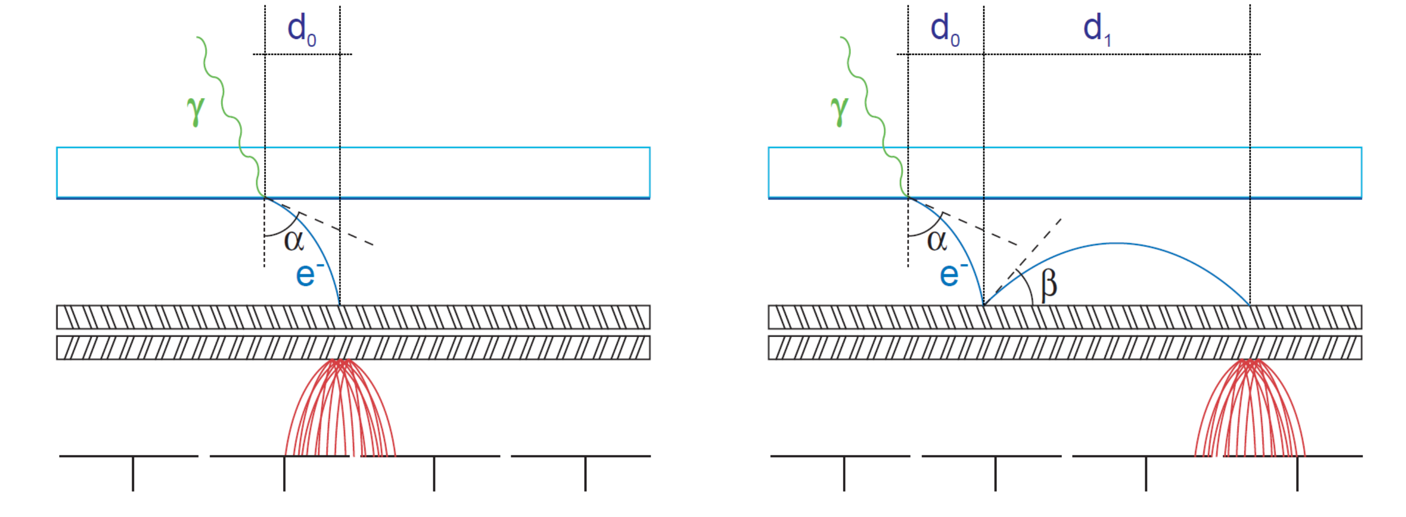


- Inelastic back-scattering
- Elastic back-scattering

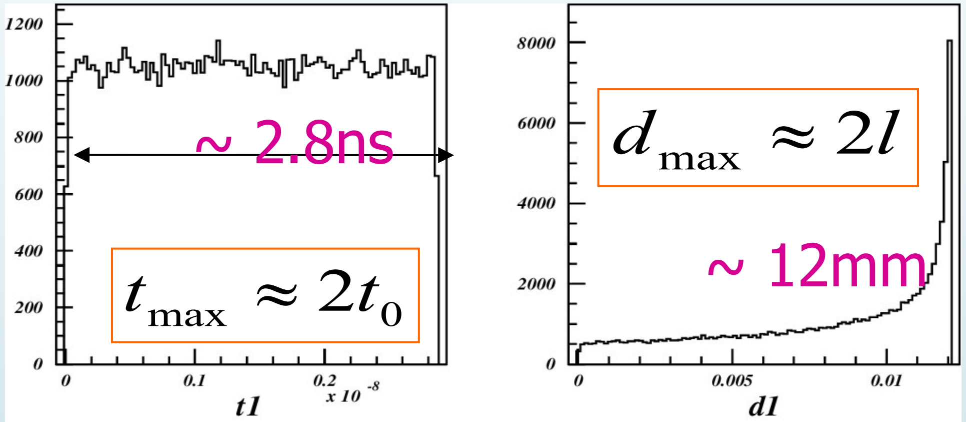
→good agreement with a simple model

Elastically backscattered photoelectrons

Simple model:
Assume uniform photoelectron back-scattering over the solid angle.



time required for the photoelectron to return to the MCP

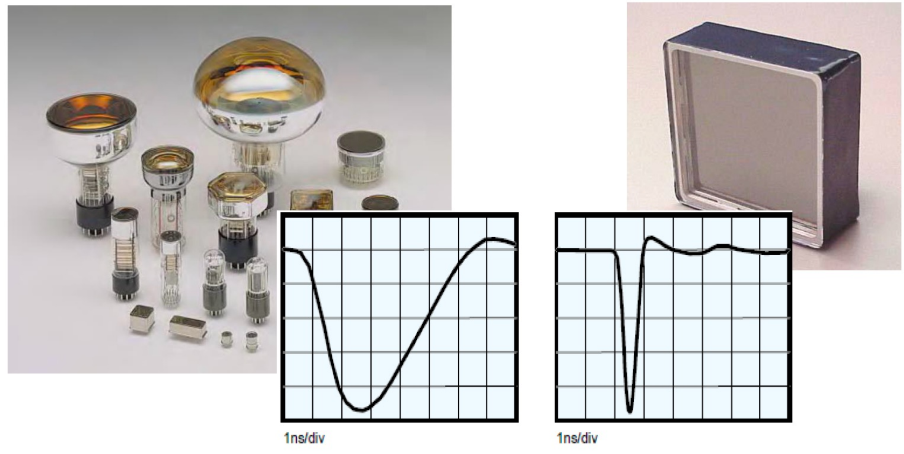


lateral distance travelled between point of backscattering and point where charge multiplication in the MCP begins

Tails can be significantly reduced by:

- decreased photocathode-MCP distance and
- increased voltage difference

PMT vs MCP-PMT



Standard photomultipliers

- Successful technology over the decades
- Large area available at low cost
- Rather fast: ns timing
- But……
  - Bulky
  - Limited position resolution
  - Low magnetic field tolerance

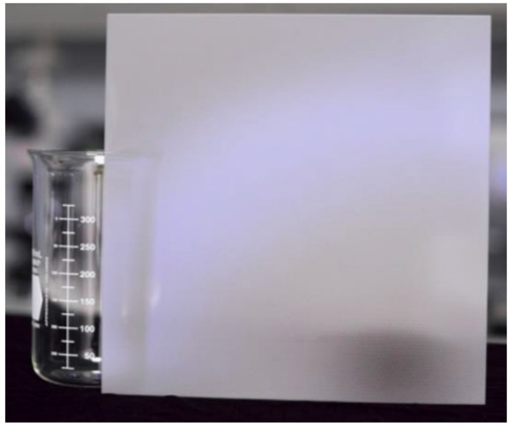
MCP photomultipliers

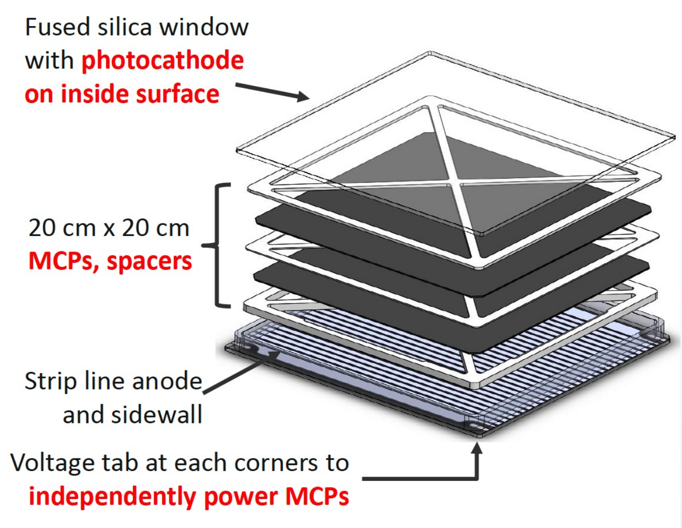
- Compact design
- Picosecond-level time resolution
- Micron-level spatial resolution
- Good magnetic field tolerance
- But……
  - Few vendors, high cost
  - Limited sizes

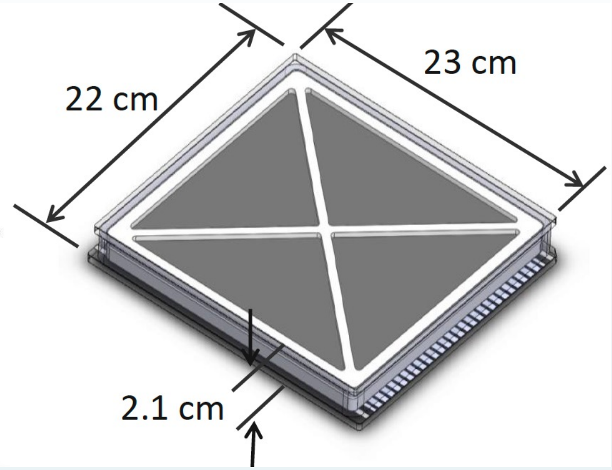
Large area picosecond photo-detector - LAPPD

Completely different MCP manufacture technology, eliminated the etching and firing processes in old technology, making low-cost, large area (20cmx20cm) MCPs possible.

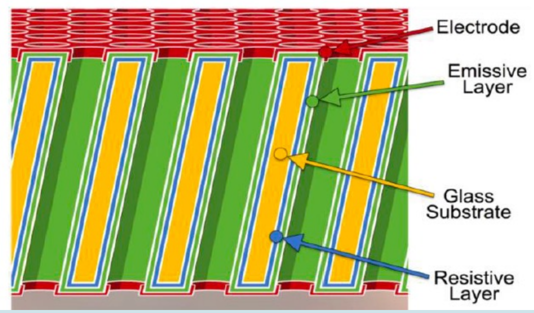
Glass capillary array (GCA)

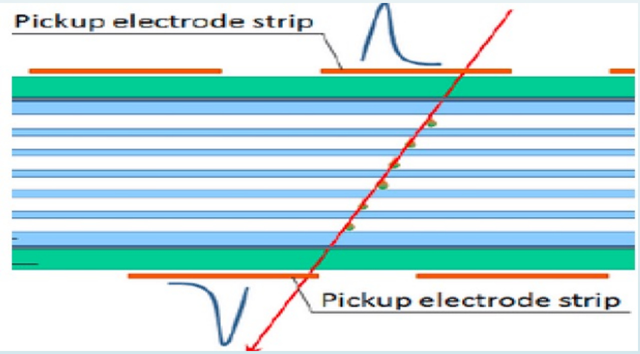






ALD coating





capacitive coupled electrode

Light detection in silicon

Two main obstacles:

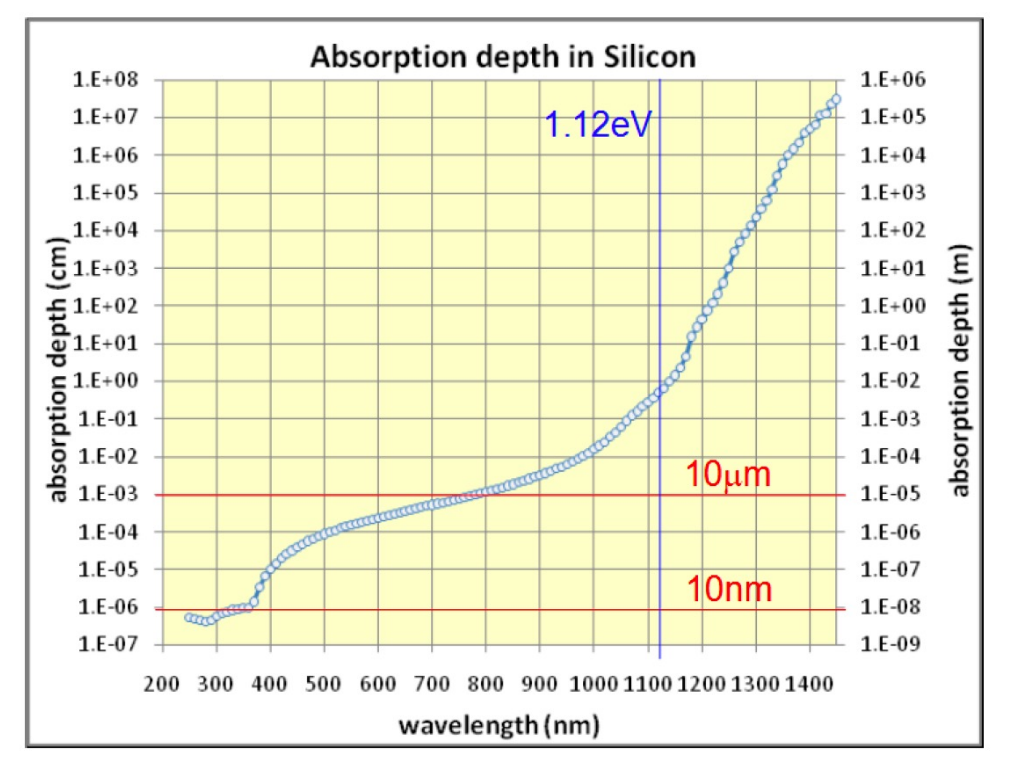
- Reflection at the entry surface due to high refractive index $n \approx 5$:

→ anti-reflective coating

- Large variation in absorption length

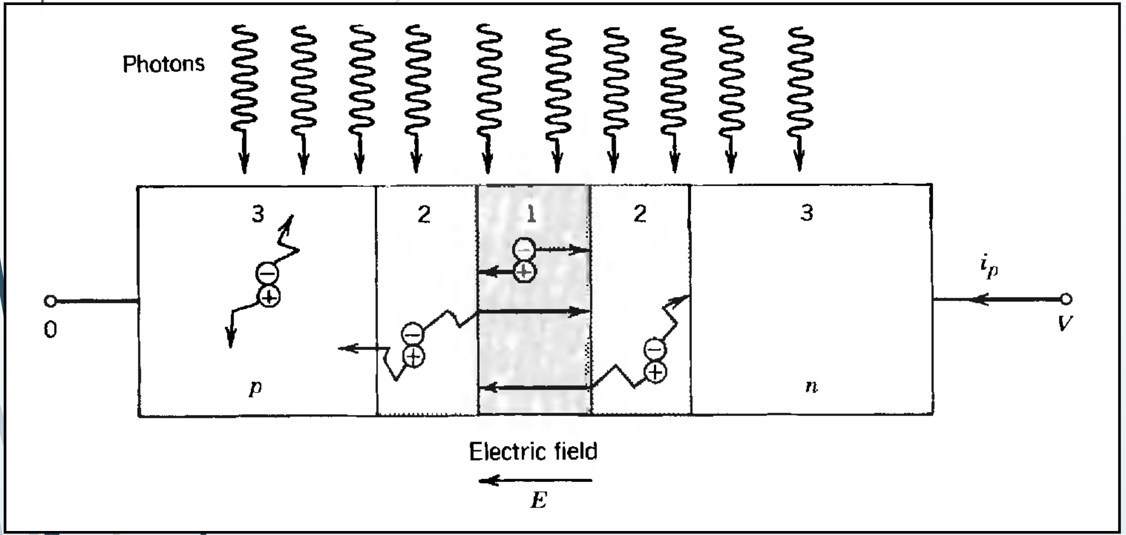
→ loss of efficiency:

- absorption at the surface for short λ
- transparent for long λ



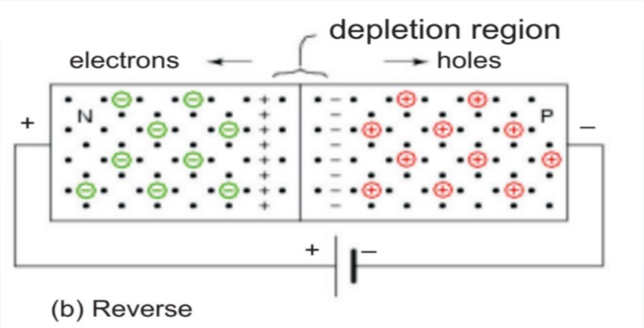
The P-N photodiode during illumination

- Electrons and holes generated in the depletion area due to photon absorption are drifted outwards by the electric field



<u>Reverse biasing:</u>

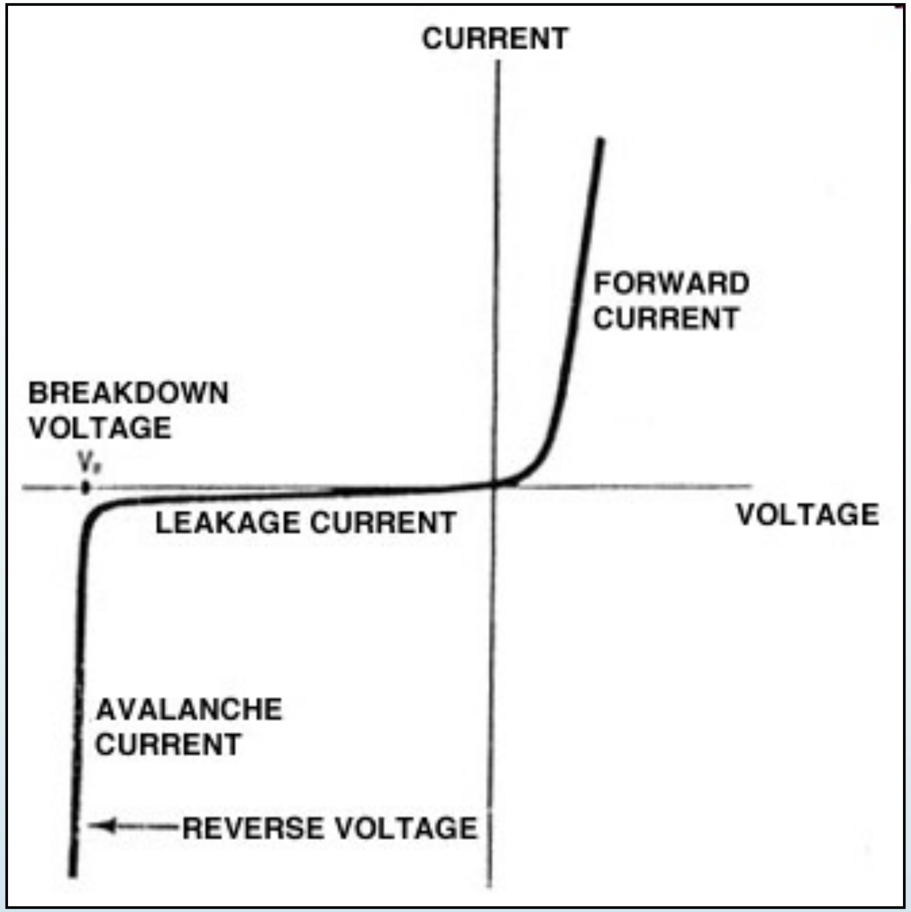
- The electric field in the junction increases quantum efficiency
- Larger depletion layer
- Better signal



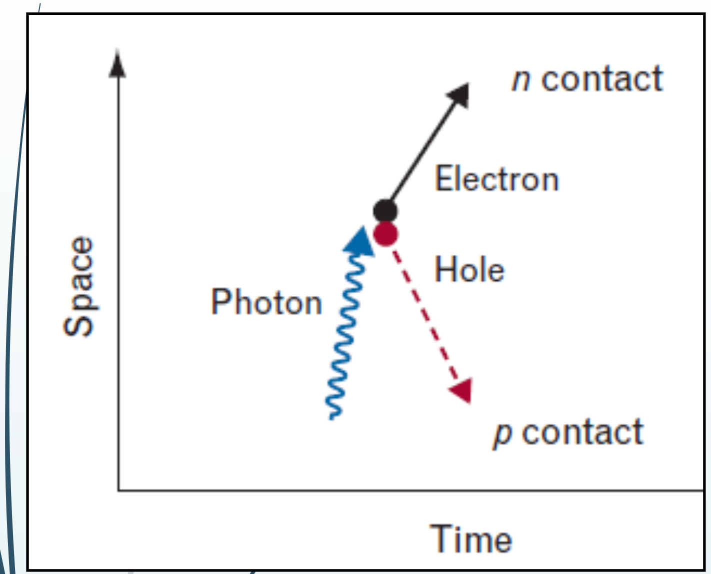
- No multiplication - No internal gain, linear response
- Noise ("dark" current) is at the level of several hundred electrons, and consequently, the smallest detectable light needs to consist of even more photons
- Can be used in cases with large light yields

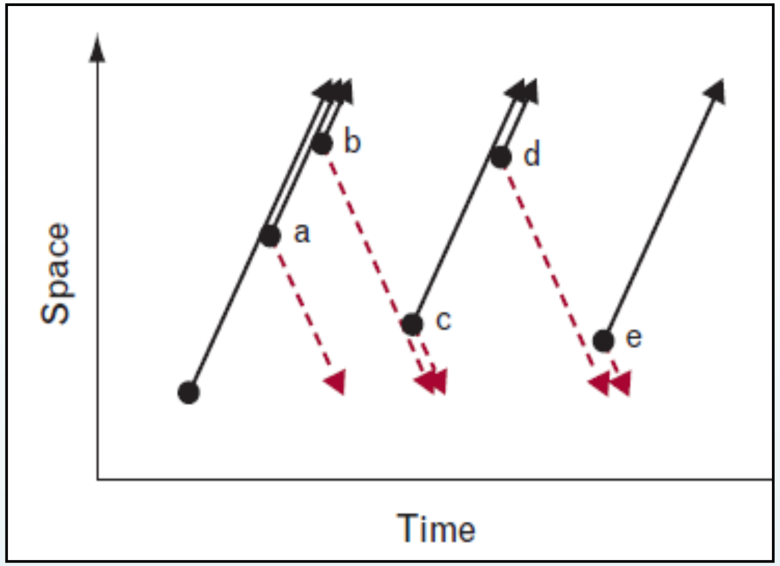
IV Characteristics of a P-N junction

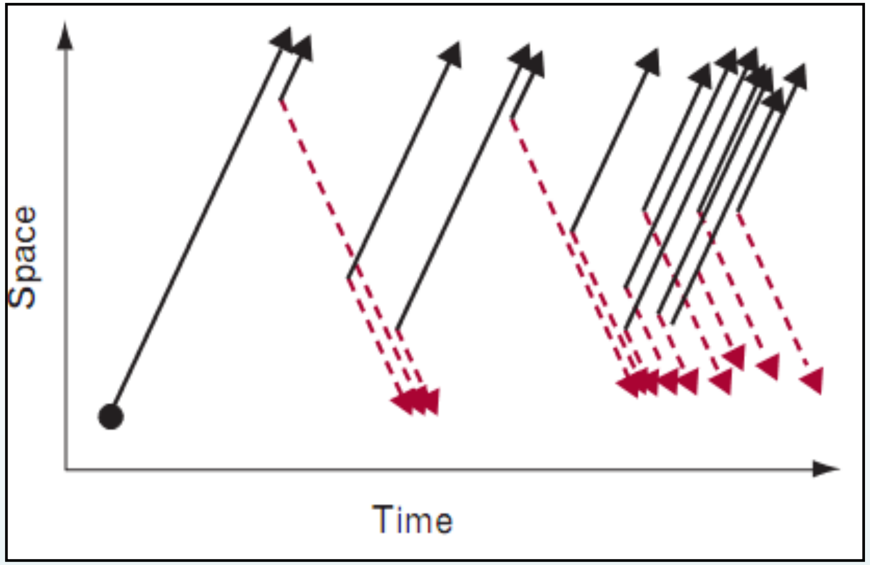
- When connected to a voltage source, the I-V curve of a P-N junction is given by:



From photodiode to Geiger-mode Avalanche photo-diode







P-N photodiode

The absorption of the photon:

creates an electron-hole pair,

.

Avalanche photodiode (APD)

Primary electron starts a chain of impact ionization events.

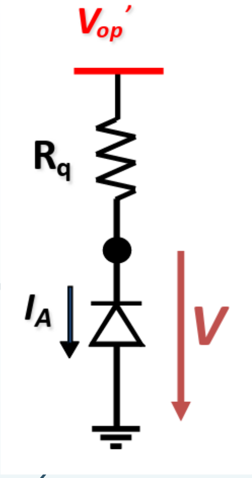
Geiger mode, APD

Electrons and holes multiply by impact ionisation faster than they can be collected,

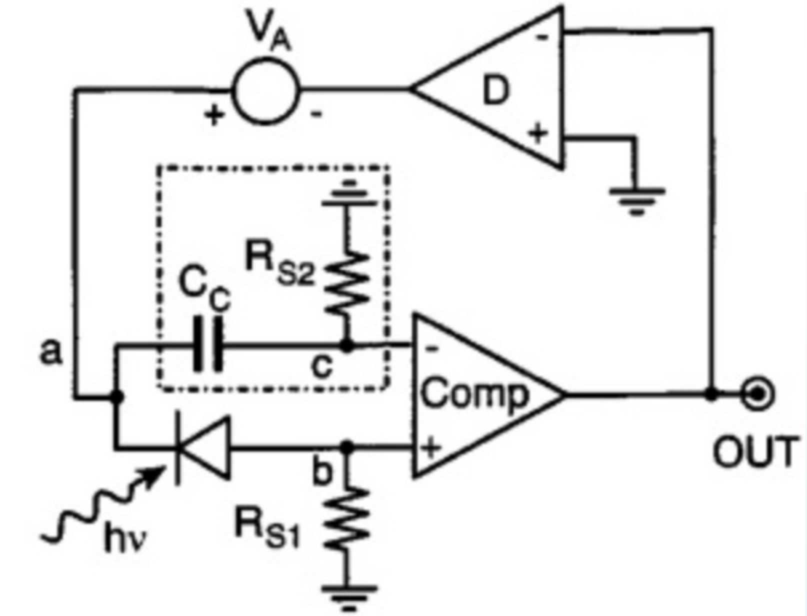
Exponential growth of the current

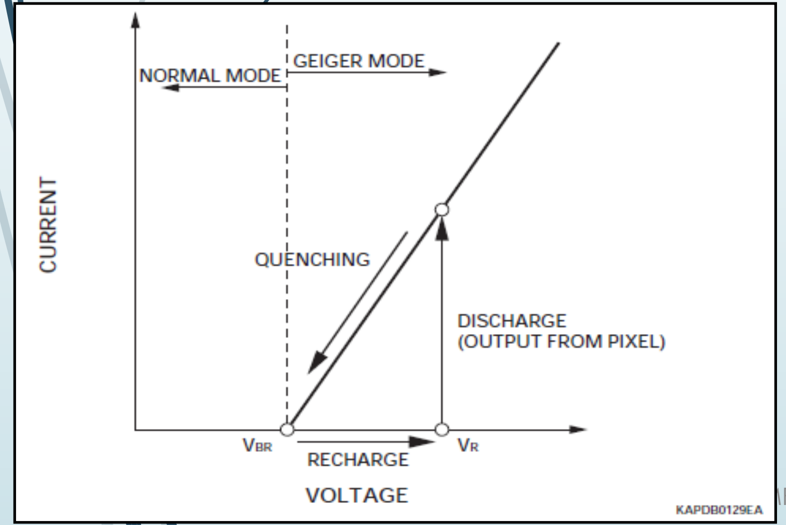
Allows Individual photon counting

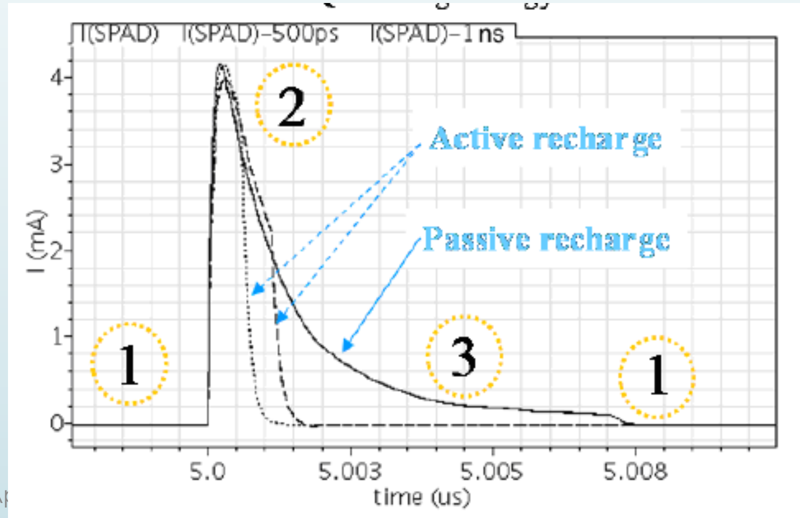
Geiger mode – quenching

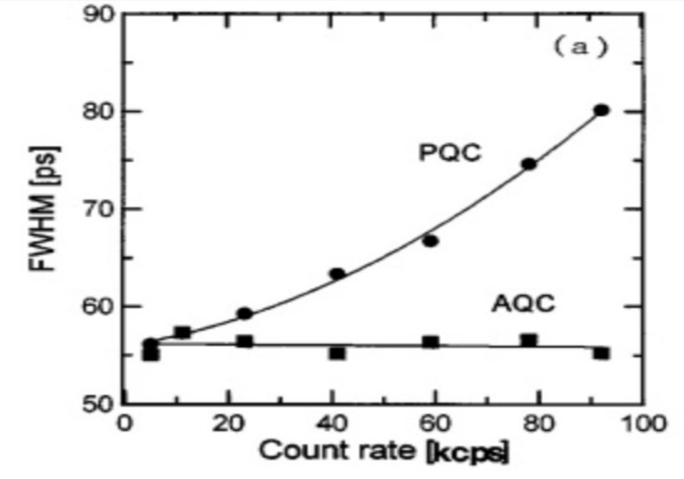


- Shutting off an avalanche current is called quenching
- Passive quenching
  - slower, ~10ns dead time
- Active quenching
  - faster



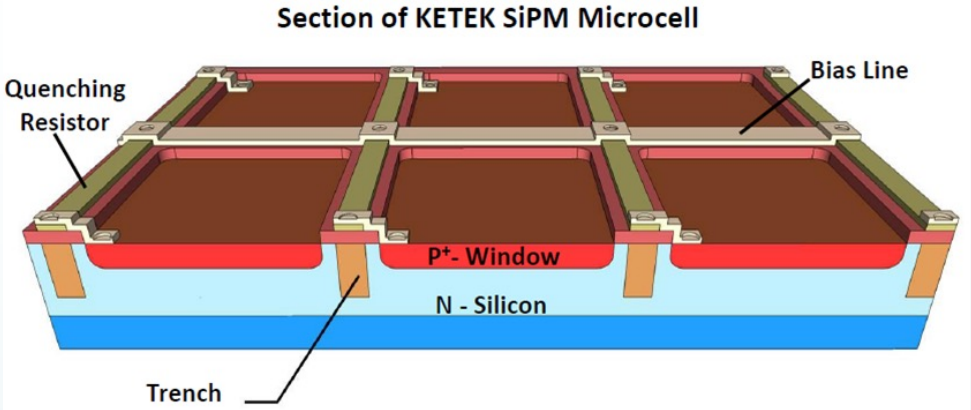






Silicon Photomultipliers

- Array of Geiger mode APDs (above the breakdown voltage) → large gain, binary signal, long recovery
- Microcell = GAPD (~20um)
- made on a silicon substrate, with 100-5000 pixels/mm^2. Total area 1-40mm^2.
- The independently operating pixels are connected to the same readout line



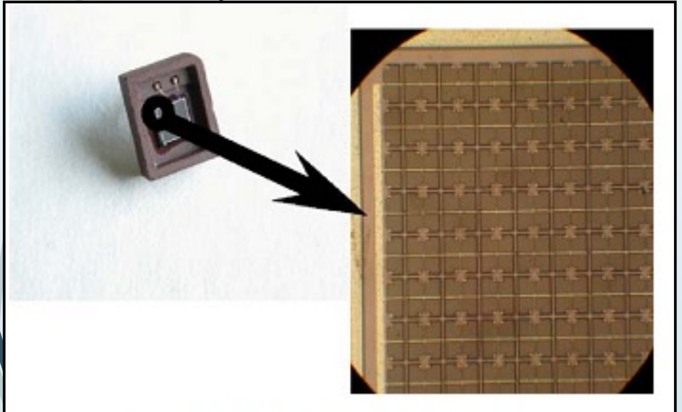
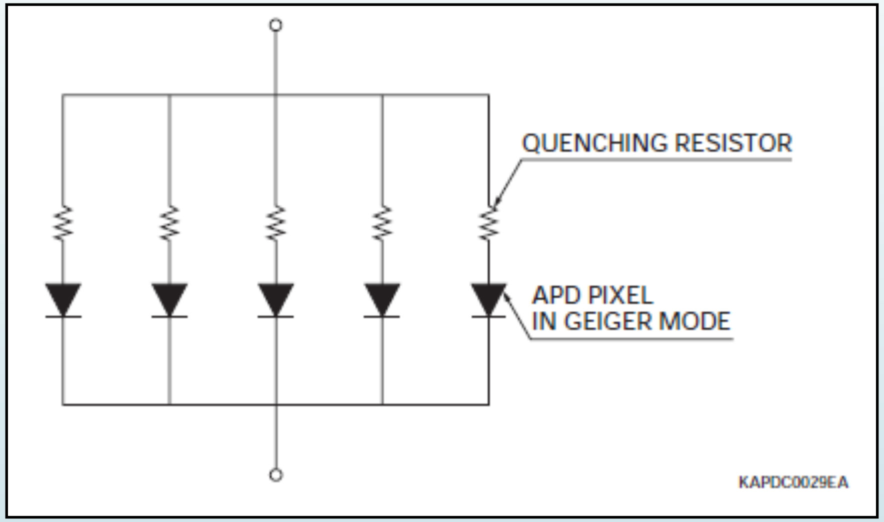
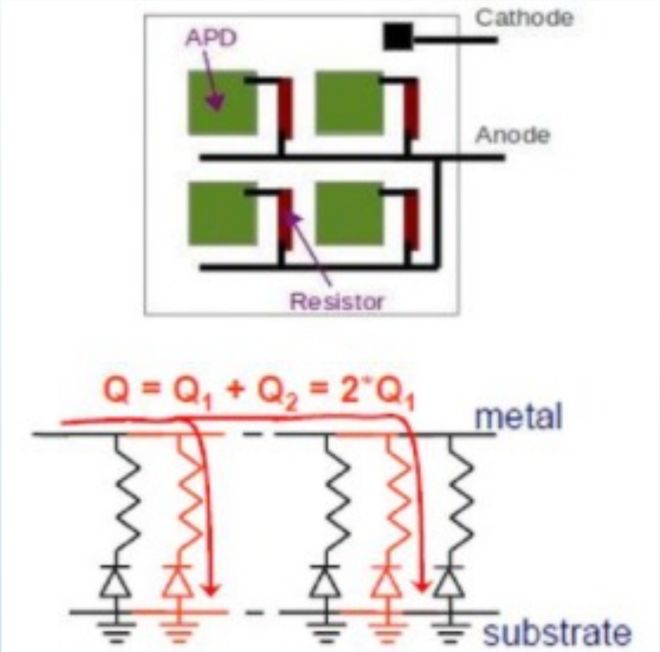


Fig. 9. SiPM 3 × 3 mm^2, 5625 pixels.



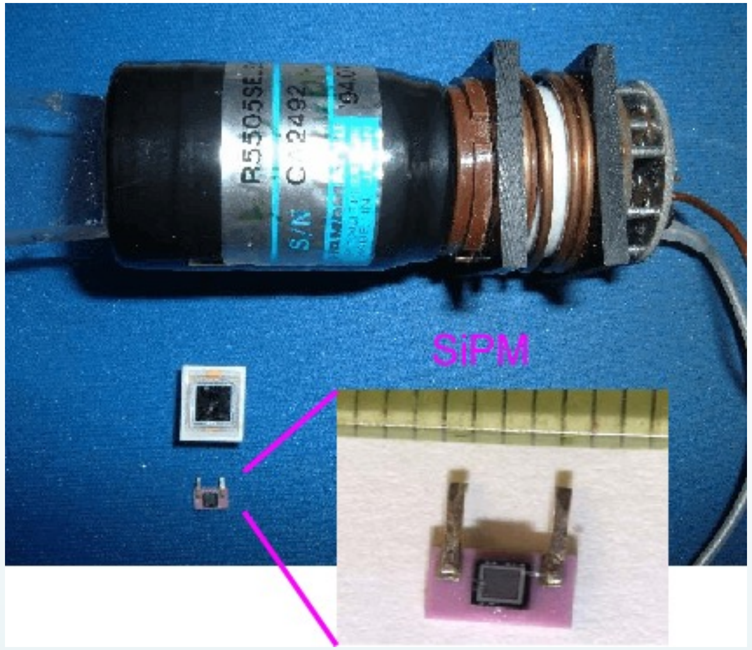


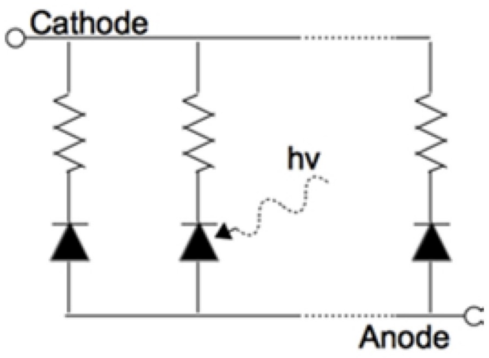
Characteristics of SiPM

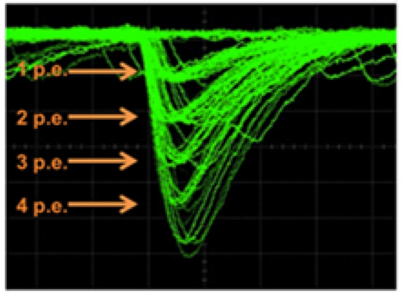
- low operation voltage ~ 10-100 V
- gain ~ 10^6
- peak PDE up to 65%(@400nm)

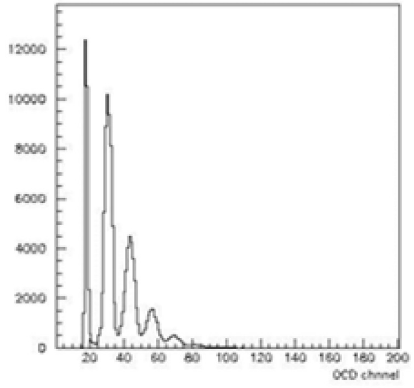
  PDE = QE x ε_{geiger} x ε_{geo} (up to 5x PMT!)
- ε_{geo} – dead space between the cells
- time resolution ~ 100 ps
- works in a high magnetic field
- dark counts ~ a few 100 kHz/mm^2
- radiation damage (p,n)
- G = k (V - V_{br})

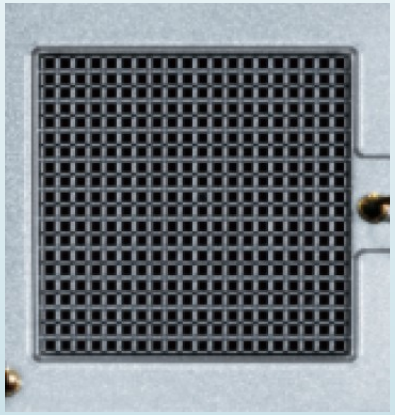
Traditional PM



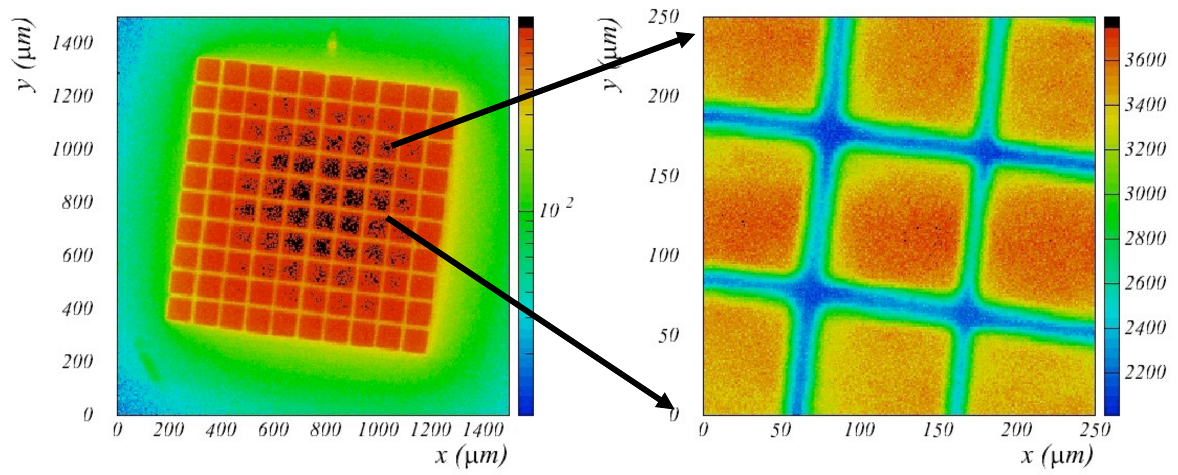


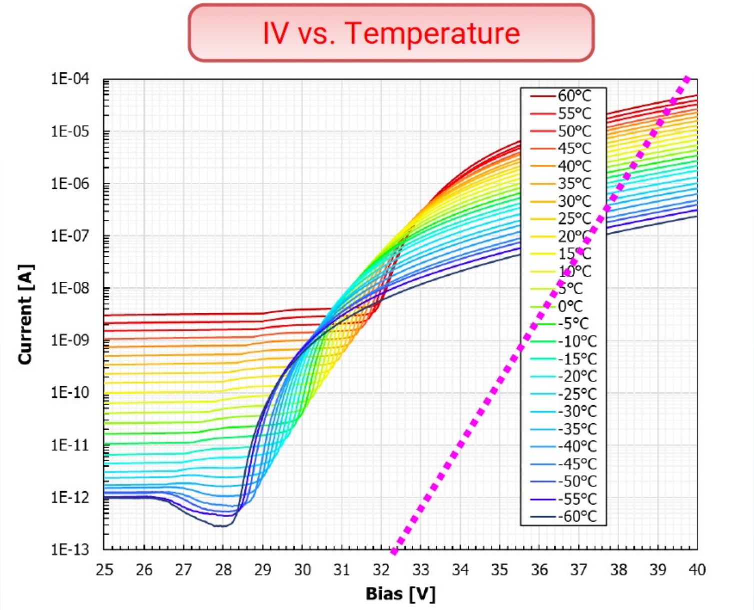


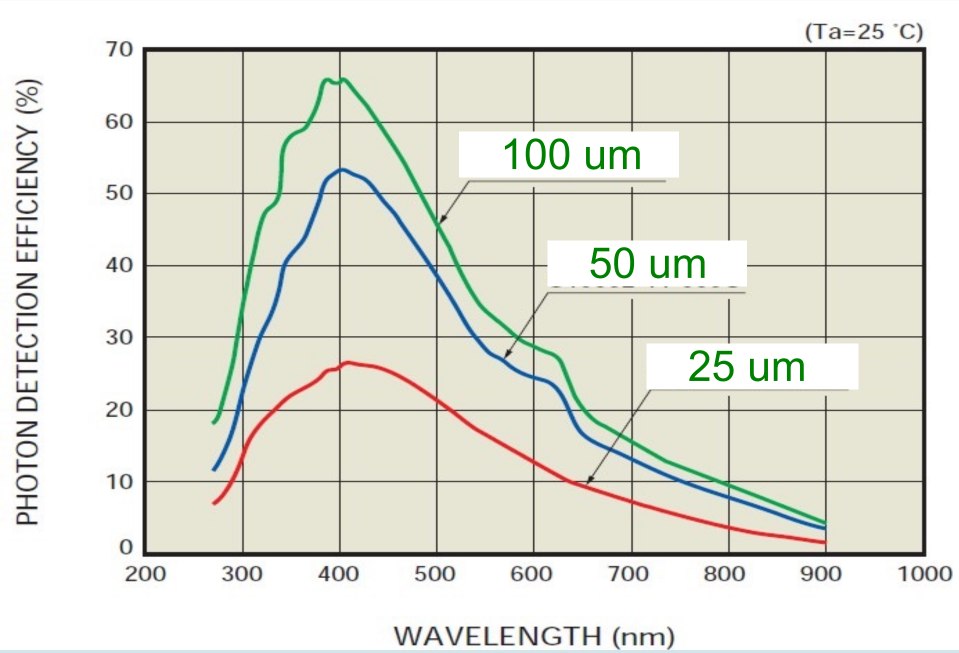


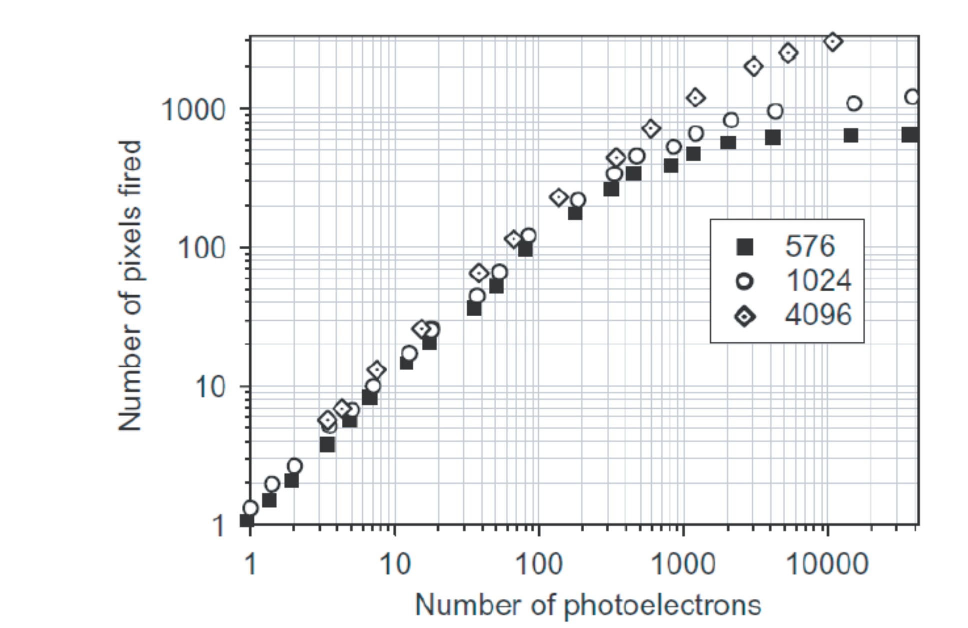


SiPMs as photon detectors



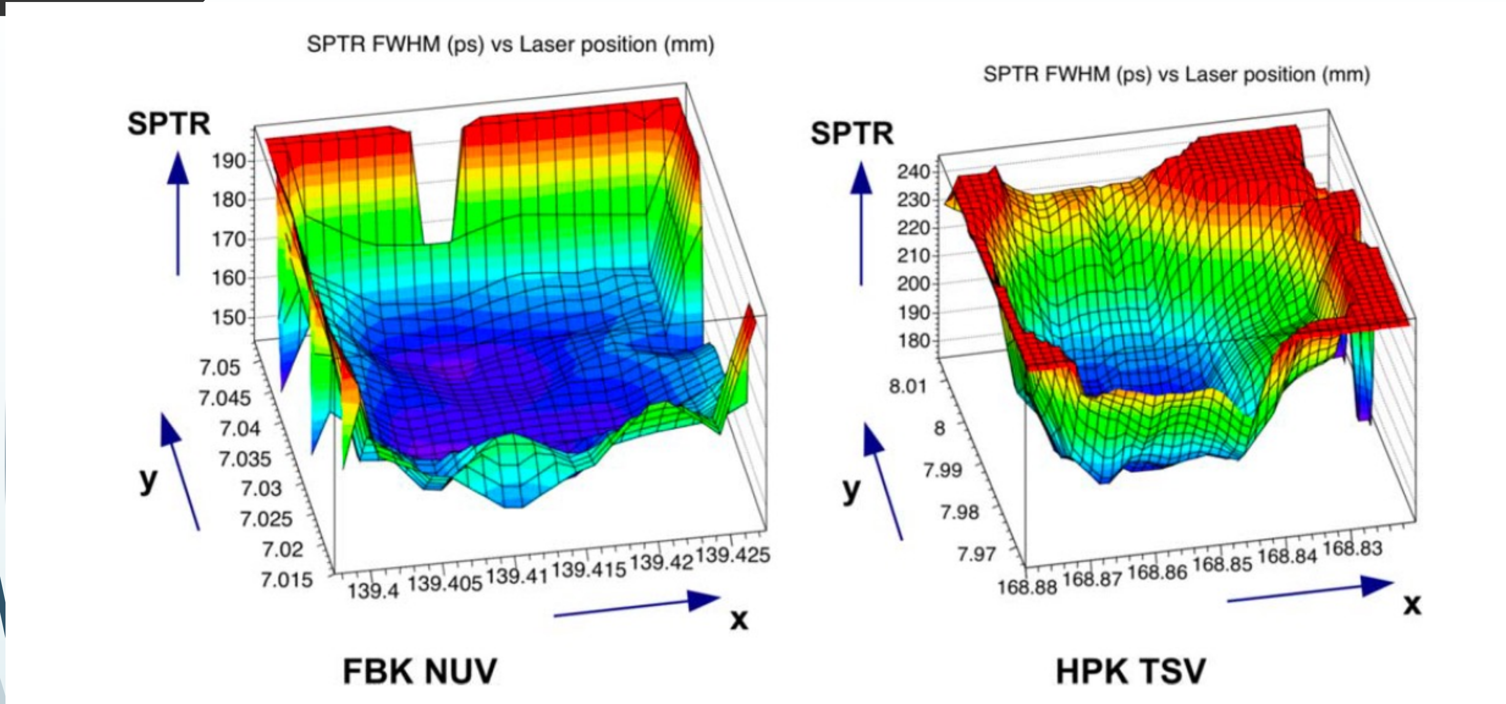


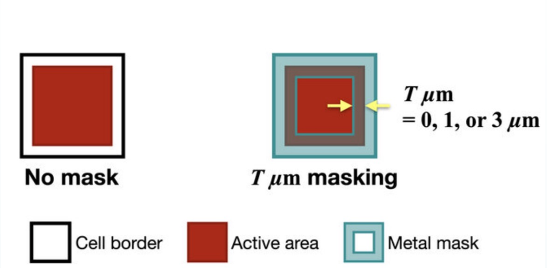


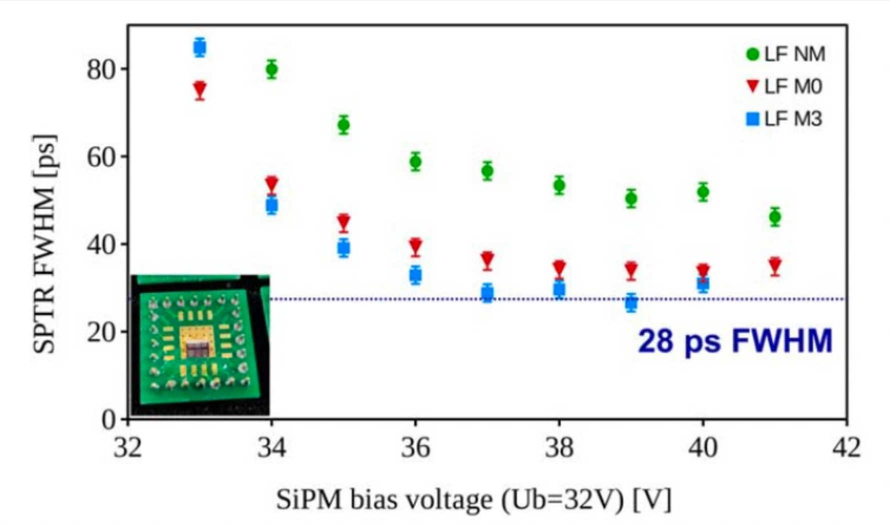


Optimization of SPTR with masking

1x1 mm2 low field FBK NUV-HD-CHK





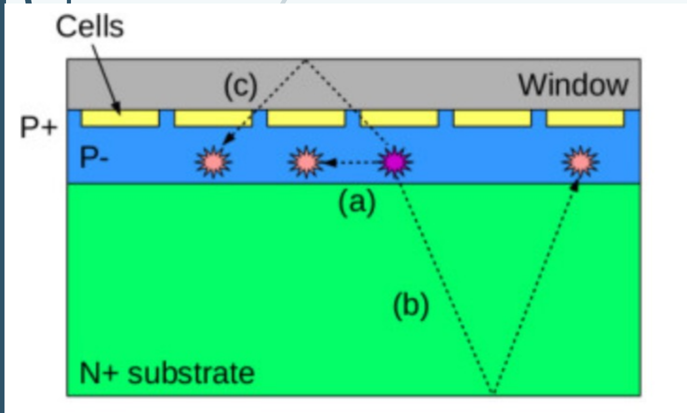


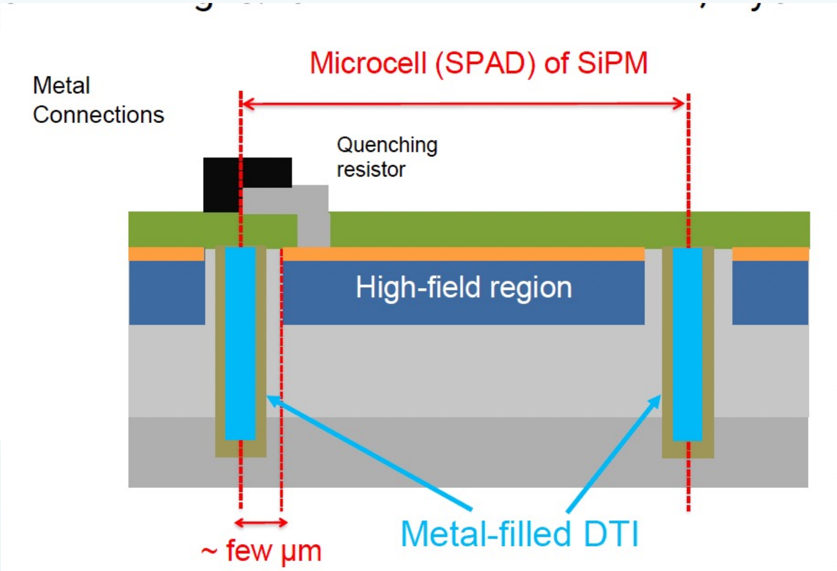
Masking of outer regions of SPAD: Improve signal peaking and mask areas of SPAD with worse SPTR

Phys. Med. Biol. 68 (2023) 165016

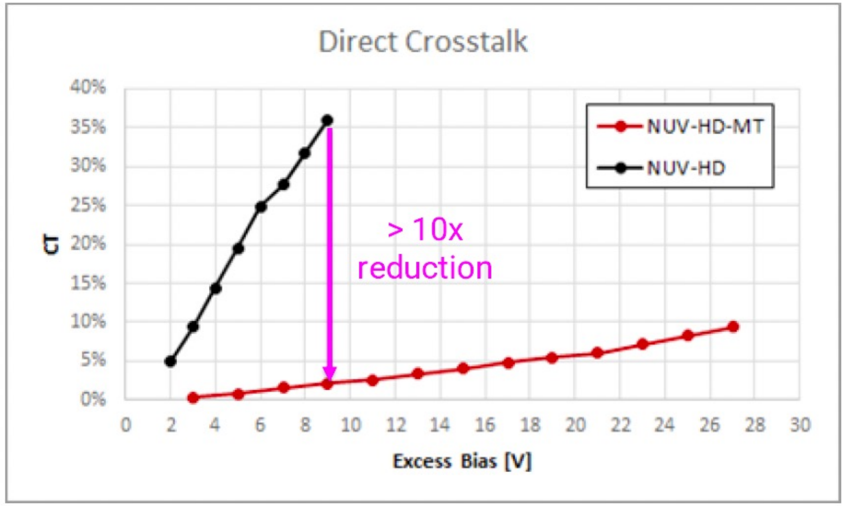
Reduction of optical crosstalk

- A single photon triggers multiple cells to fire artificially, even though only one photon has arrived.
- Impacts timing
- Metal-filled Deep Trench Isolation strongly suppresses optical crosstalk





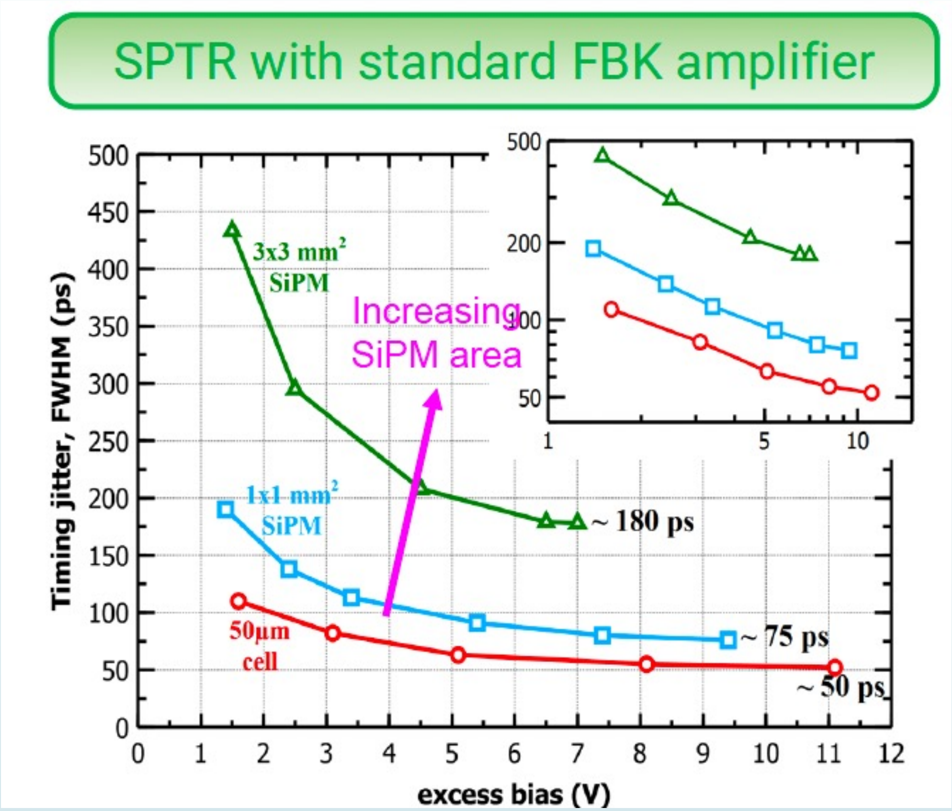
Conceptual drawing of the NUV-HD-MT, with the addition of metal-filled Deep Trench Isolation.



Reduction of optical crosstalk probability in NUV-HD-MT, compared to the "standard" NUV-HD. Measurement without encapsulation resin, i.e. *only considering internal crosstalk probability*.

Effect of SiPM area on SPTR

- SPTR and CRT performance is degraded when reading out SiPMs with large areas

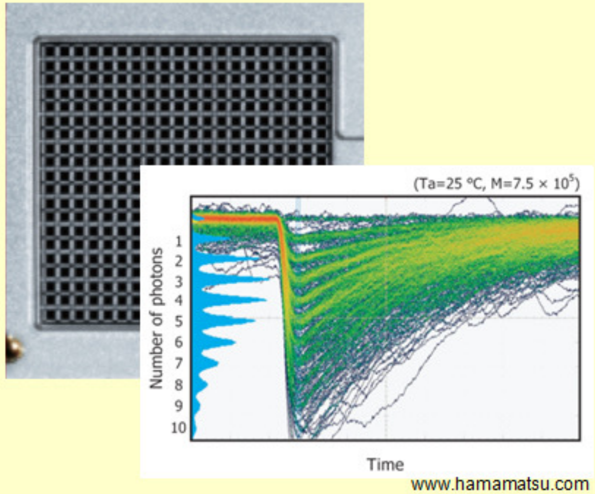


Alberto Gola - Status and perspectives of SiPMs at FBK

Digital SiPM

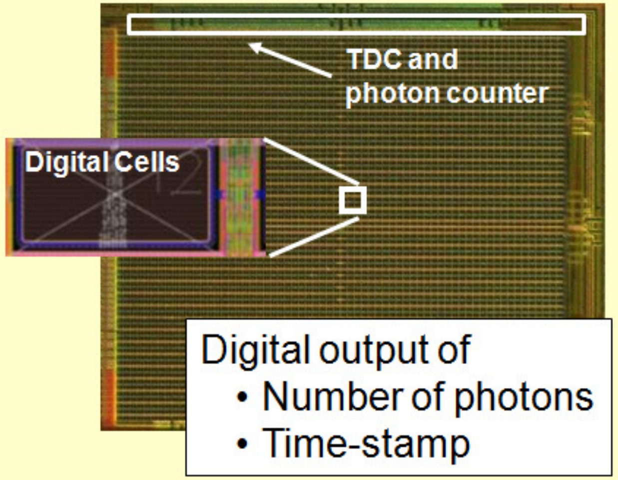
DPC: Front-end Digitization by Integration of SPAD & CMOS Electronics

analog SiPM

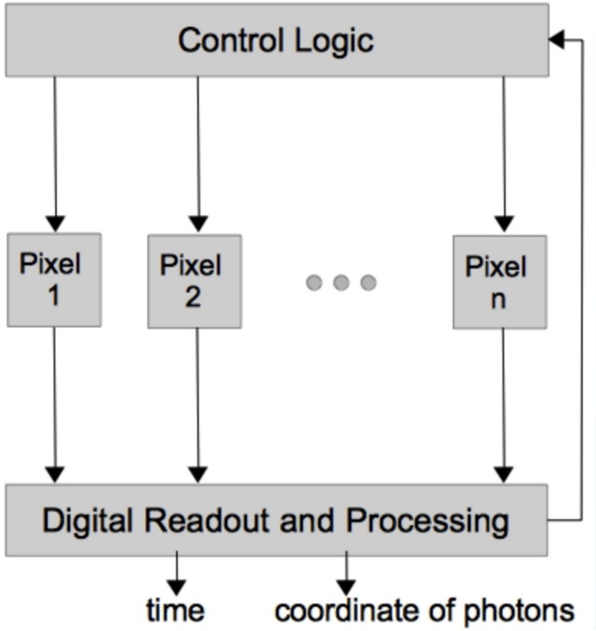


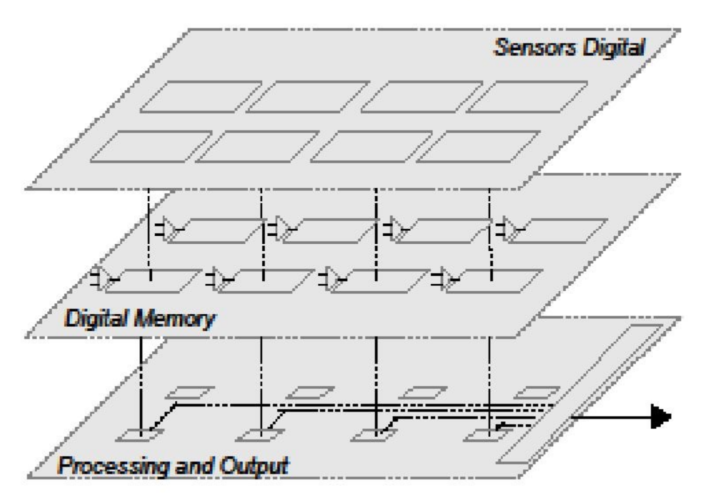
Summing all cell outputs leads to an analog output signal and limited performance

digital SiPM (dSiPM)



Integrated readout electronics is the key element to superior detector performance

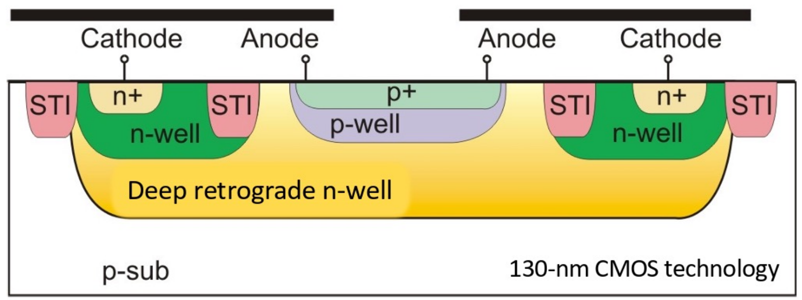




- New perspectives: 3D integration
- advanced photon-detection structures,
  - improved detection efficiency

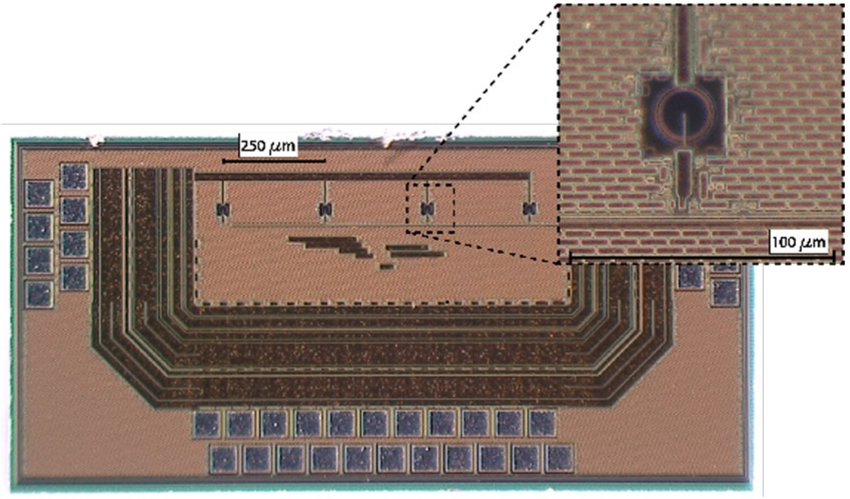
Ultrafast digital CMOS SPAD

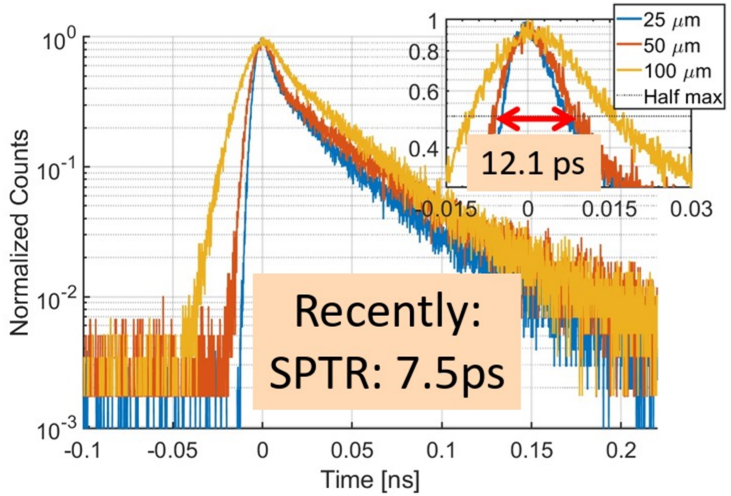
Frontside CMOS SPAD



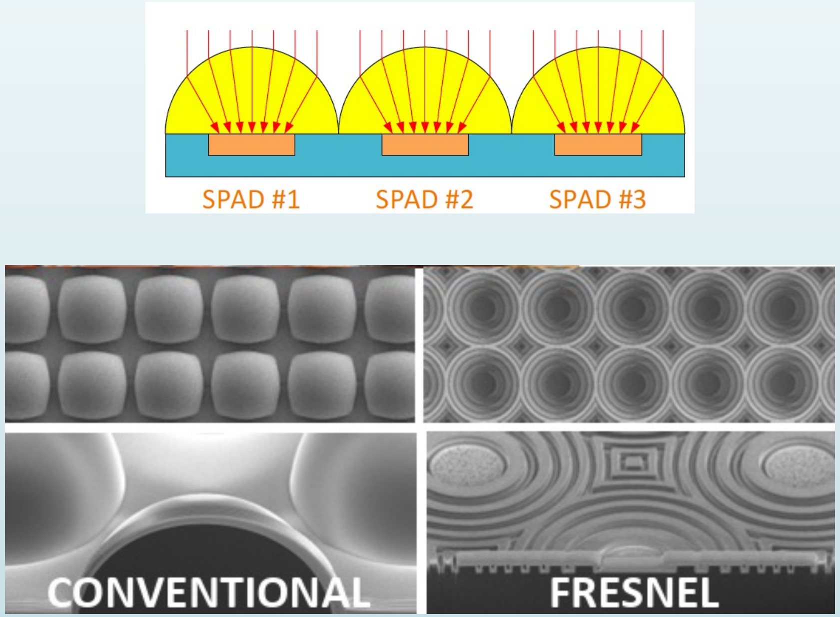
Niclass et al. 2007 – Richardson et al. – Pellegrini et al.

- SPADs implemented in CMOS technology
- Compatible with the electronics
- Combine SPAD with the electronics in a monolithic chip
- Reduced area coverage: compensate with microlenses

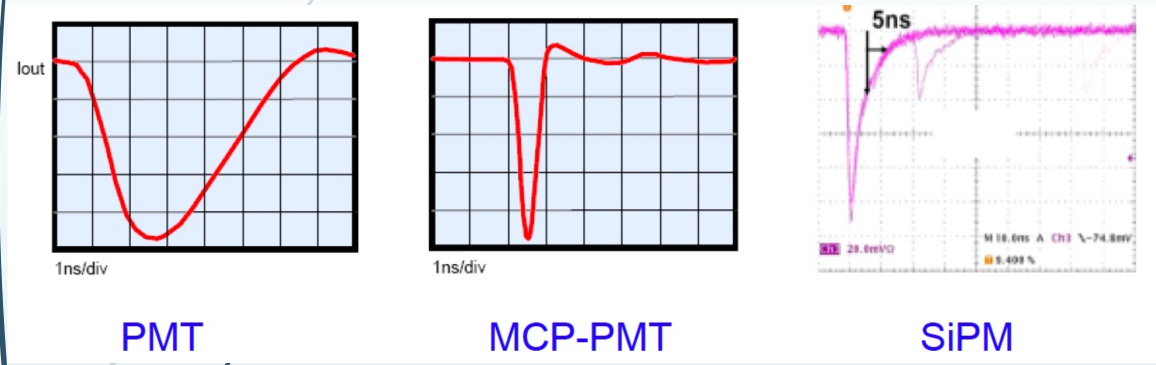


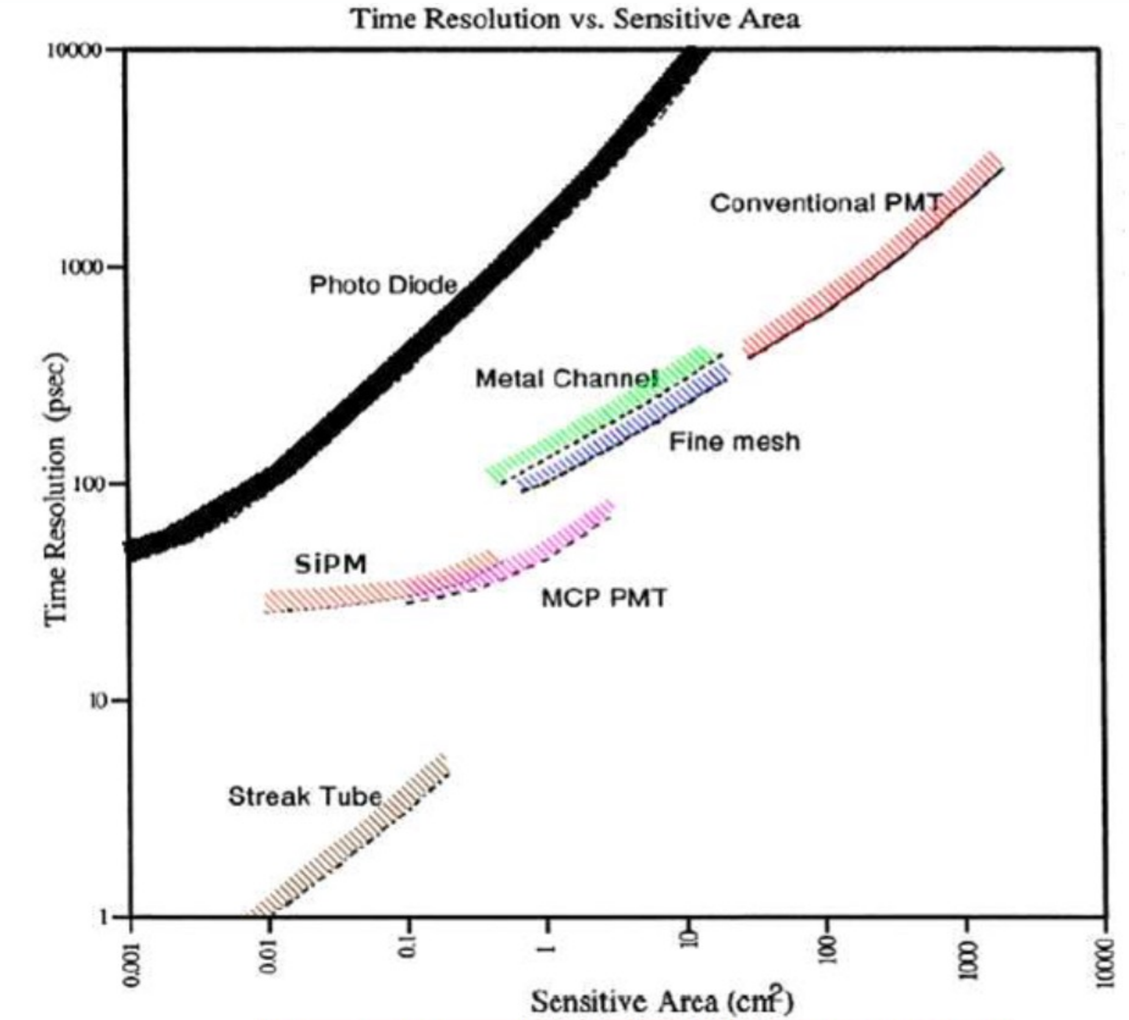


F. Gramuglia et al., JSTQE 2021
F. Gramuglia et al., Frontiers in Physics, 2022



Time response comparison





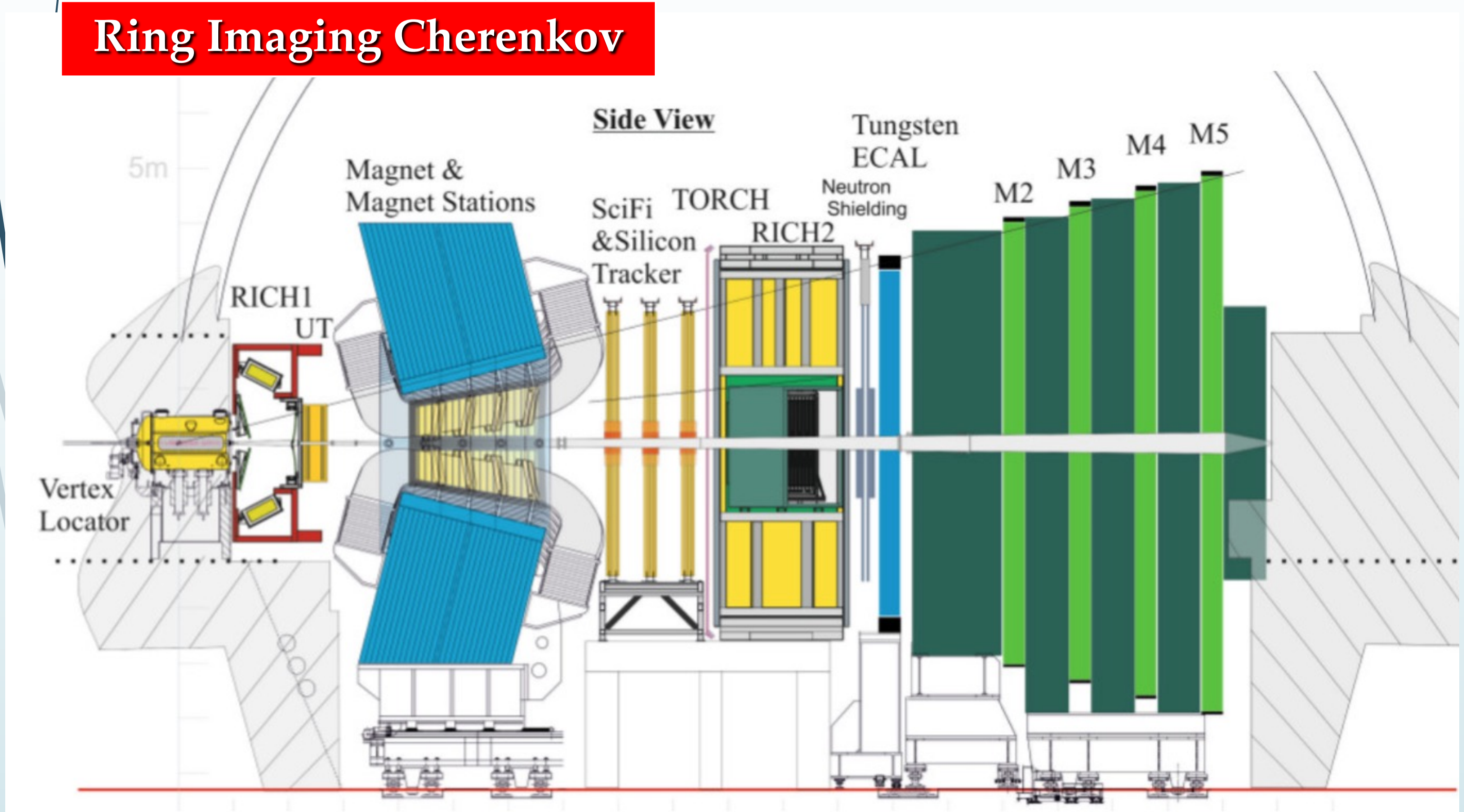
Adapted from K.Arisaka NIMA 442(2000)80

Application examples

- High energy physics:
  - LHCb
  - Belle II Time of propagation counter
- Medical physics
  - Time-Of-Flight PET
  - EIC Pathfinder - PetVision
  - ERC PoC - CherPET

LHCb Upgrade 2

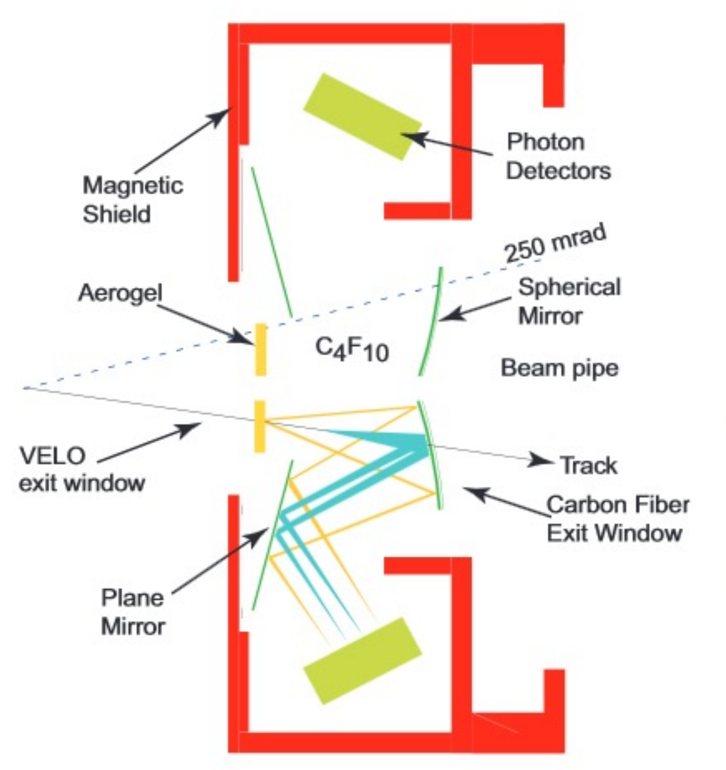
- LHCb – single-arm spectrometer, dedicated to precision studies of CP asymmetries and of rare decays in the B-meson system
- After the upgrade 2 40 **proton-proton collisions will happen at the same time** during a single bunch crossing, and their signals will overlap in the detector.

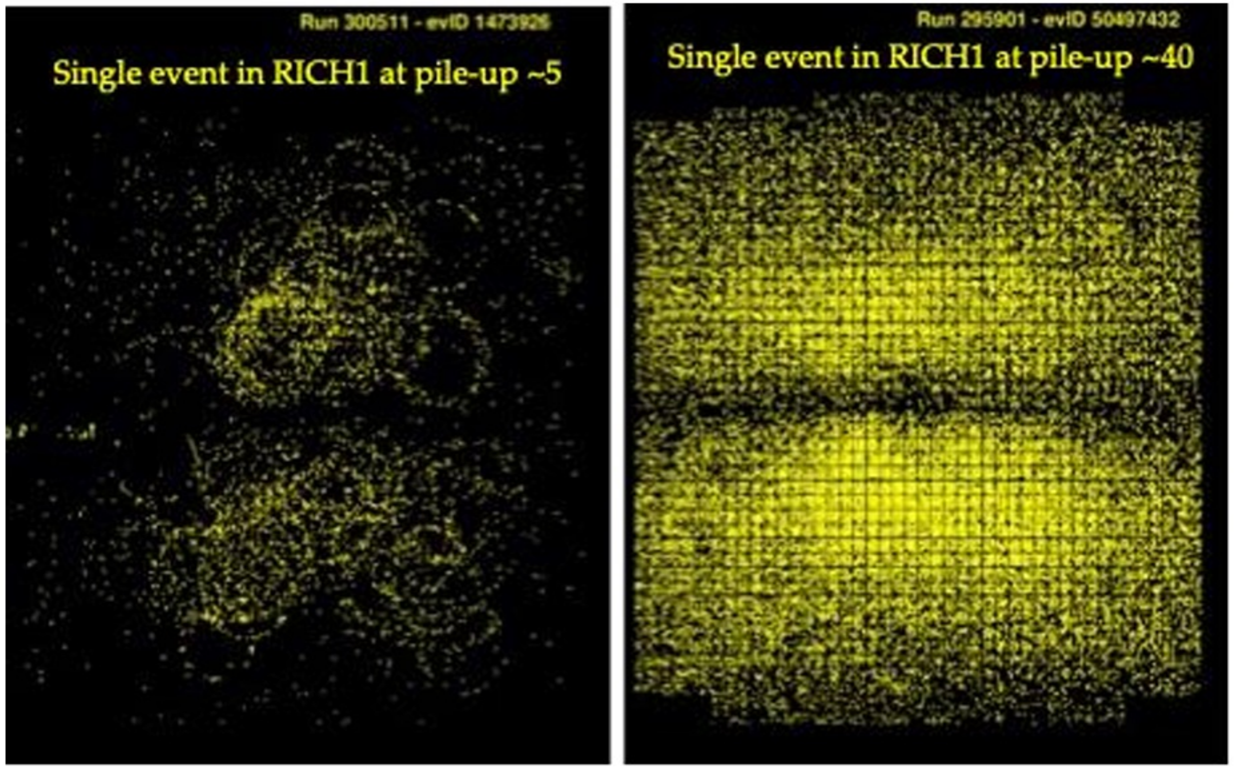


Run 3			LS3			Run 4				LS4		Run 5					
2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041
TDR phase			Construction phase							Installation		Exploitation					

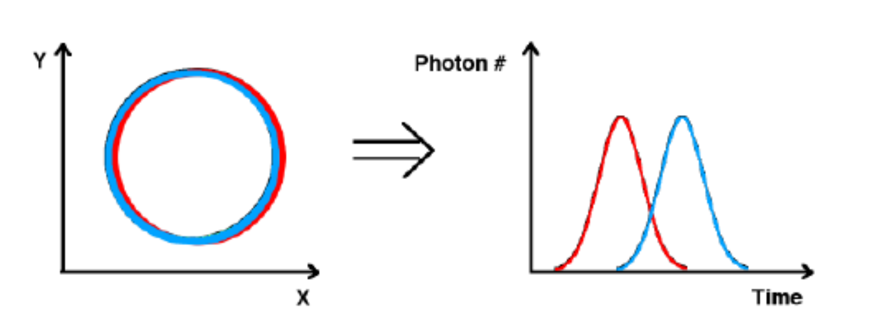
- Particle identification – separation of pions from kaons
- 2 Ring Imaging Cherenkov Counters – currently equipped with multianode photomultipliers
- Precise timing (~10 ps) and high granularity of sensors will be required
- Current MAPMTs do not fulfil the requirements

LHCb RICH



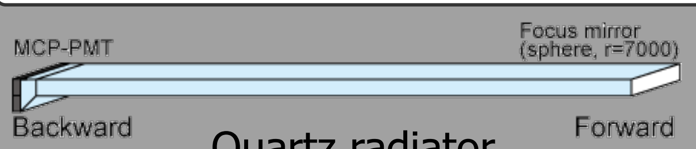


- High occupancy 10 MHz/mm2
- Current MAPMTS will be replaced by SiPMs of granularity about 1x1 mm2
- Requirement <100 ps r.m.s. for single photons
- In addition: expected neutron fluence ~3x10^{13} n/cm2



Belle II Cherenkov detectors

Barrel PID: Time of Propagation Counter (TOP)



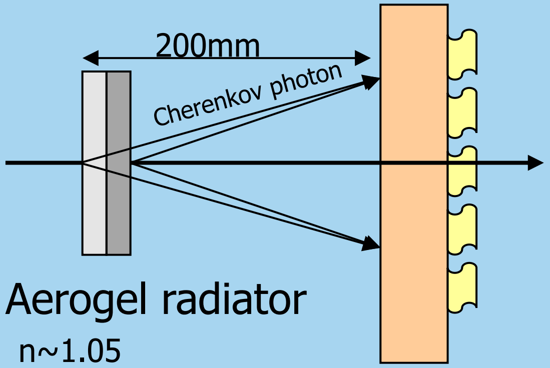
Quartz radiator

Focusing mirror

Small expansion block

Hamamatsu MCP-PMT (measure t, x and y)

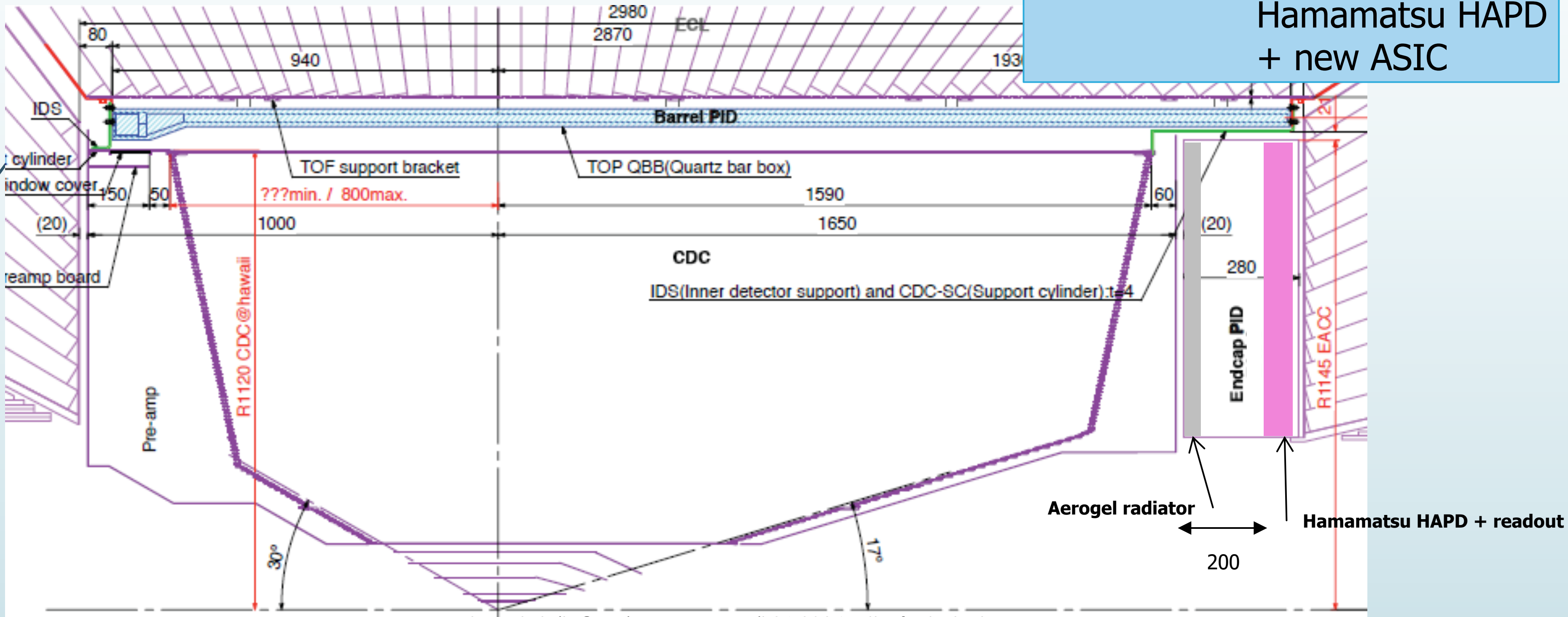
Endcap PID: Aerogel RICH (ARICH)



Aerogel radiator

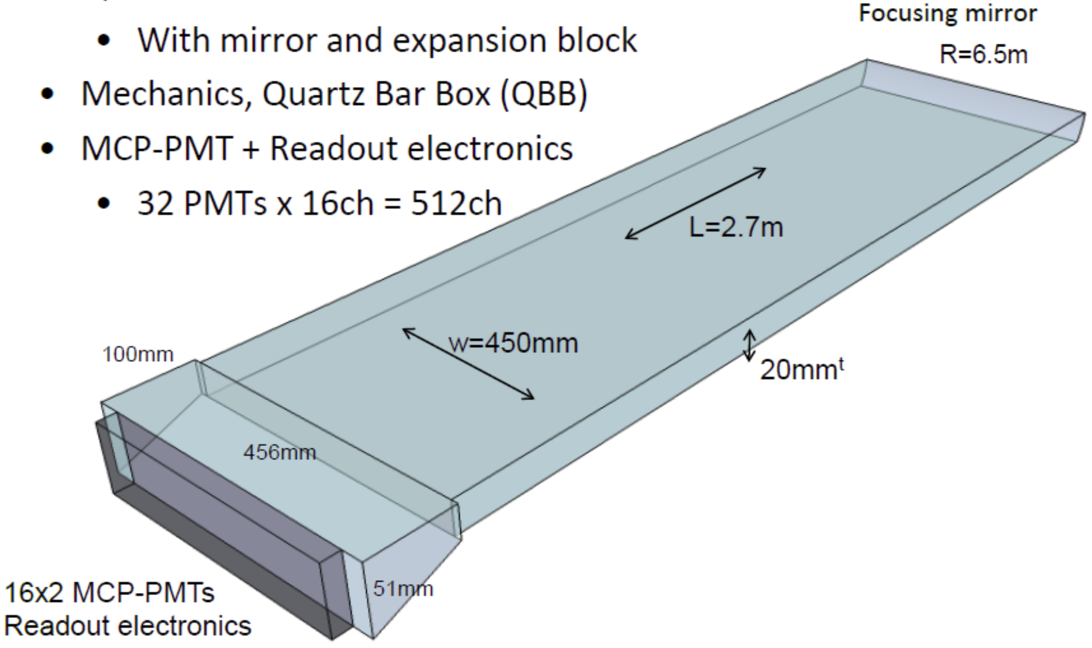
n~1.05

Hamamatsu HAPD
+ new ASIC

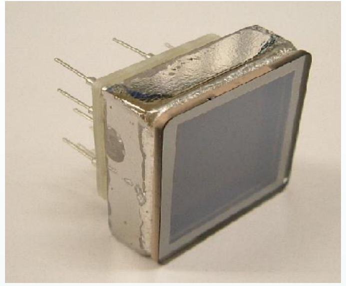


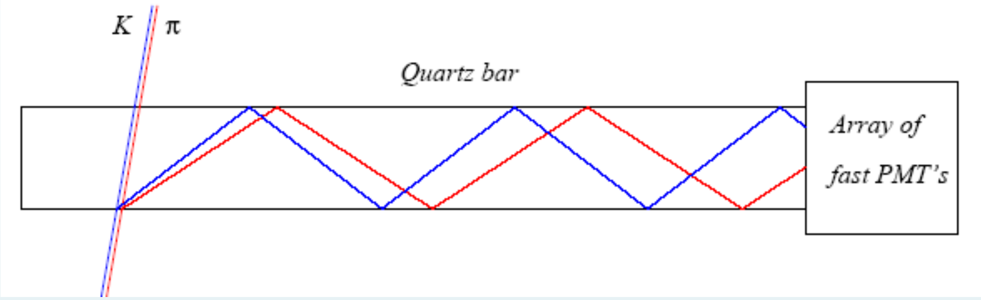
Time-Of-Propagation (TOP) counter

- Quartz radiator
  - With mirror and expansion block
- Mechanics, Quartz Bar Box (QBB)
- MCP-PMT + Readout electronics
  - 32 PMTs x 16ch = 512ch



Hamamatsu SL10 MCP-PMT



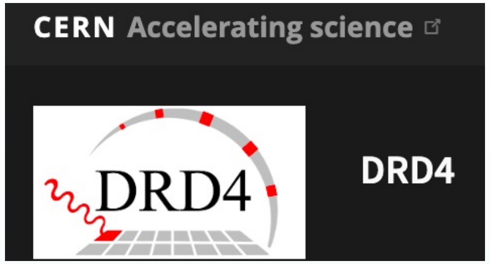


Instead of a 2D image in two coordinates ('ring') measure:

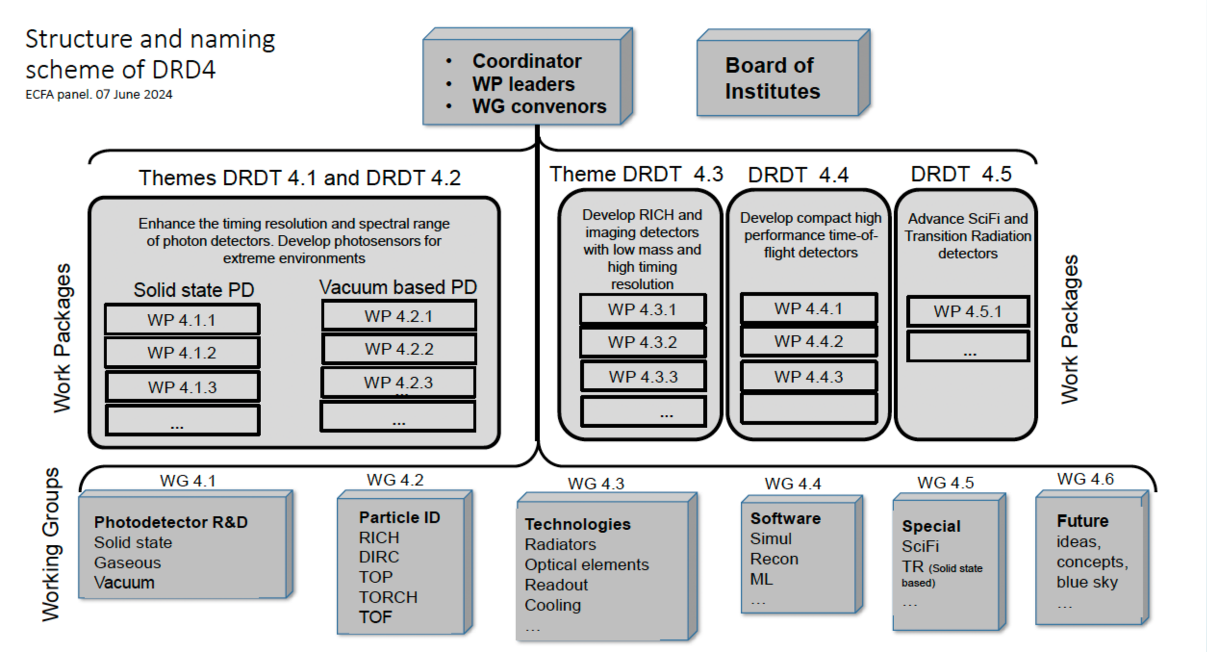
- One (or two coordinates) with a few mm precision
- Time-of-arrival

→ Excellent time resolution < 100ps (incl. read-out) required for single photons in 1.5T B field

R&D Development of Photon Detectors and Particle Identification Techniques



- International coordination and organisation of detector R&D activities
  - ECFA (European Committee for Future Accelerators) Detector R&D Roadmap
  - DRD4 R&D Collaboration, one of 8 DRD Collaborations, started working in 2024
  - 67 institutions
  - Work organized into
    - 5 work projects and
    - 6 workgroups



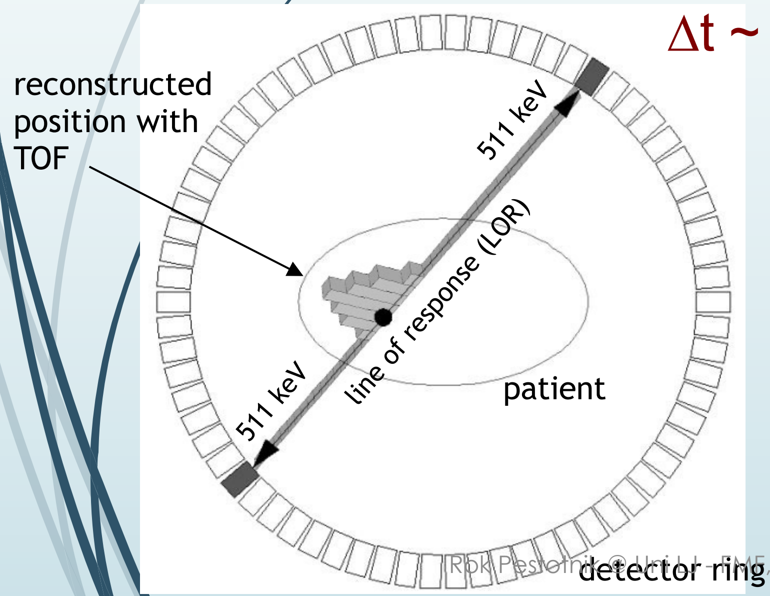
Medical applications
Time-of-flight Positron emission tomography

Positron emission tomography (PET)

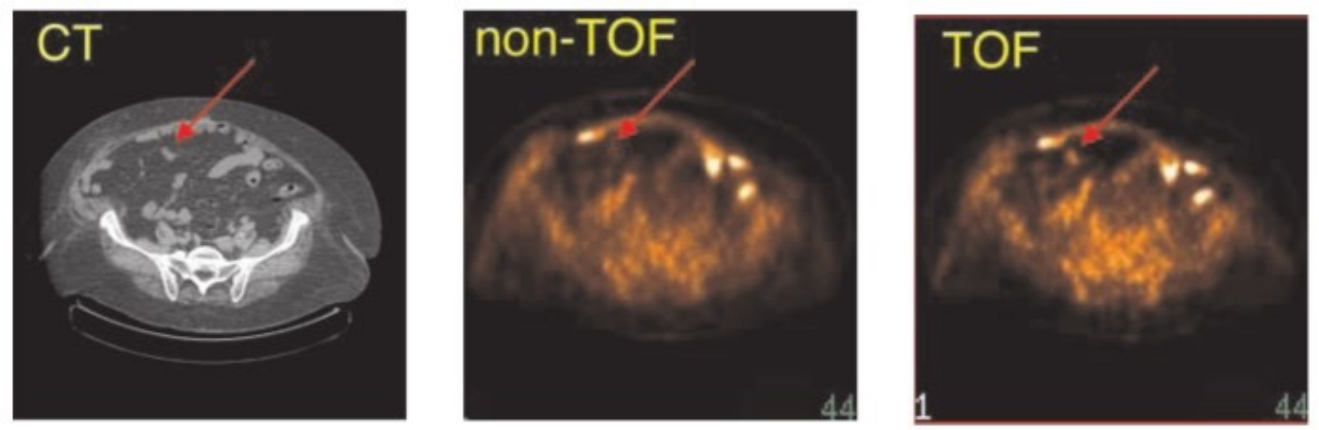
- in-vivo imaging of biological processes via detection of 511 keV annihilation γ rays

Time-of-flight (TOF)

- Limits the reconstructed position of annihilation by localizing source position along the LOR
- Improves the quality (contrast-to-noise ratio) of reconstructed images



$\Delta t \sim 66ps \rightarrow \Delta x = c_0 \Delta t/2 \sim 1cm$ Δt = coincidence resolving time, CRT

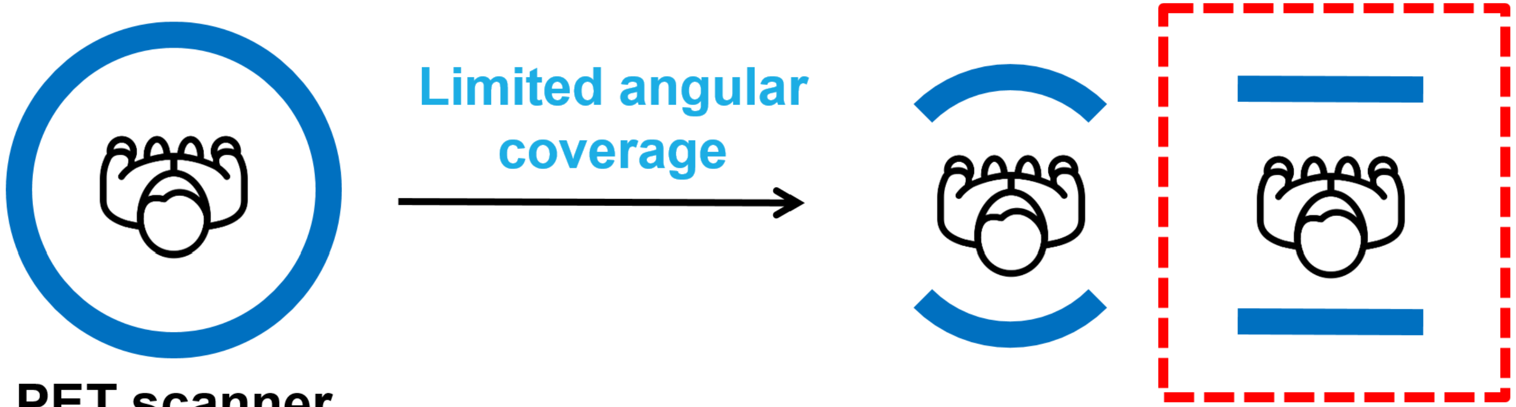


Philips Gemini TF PET/CT, TOF resolution of 600 ps
[PET Center of Excellence Newsletter, Vol.3 Issue 3 (2006)]

Next generation scalable time-of-flight PET

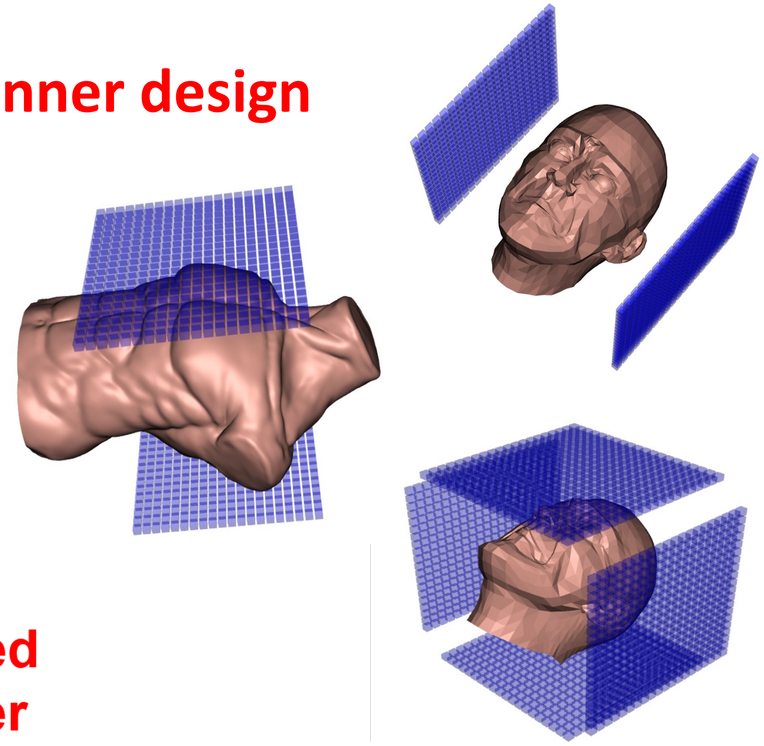
Institut "Jožef Stefan", Ljubljana, Slovenija

Superb time resolution enables simplifications in the scanner design



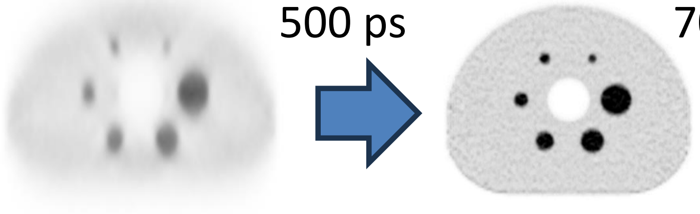
PET scanner

Panel-based limited angle PET scanner



Limited angle PET scanners will generally produce distorted images with artefacts unless they have good **time-of-flight** information

The angular sampling requirement to obtain distortion-free images decreases
S. Surti, J. S. Karp, Physica Medica 32 (2016) 12–22



G. Razdevšek *et al.*, "Multi-panel limited angle PET system with 50 ps FWHM coincidence time resolution: a simulation study," in *IEEE TRPMS*, doi: 10.1109/TRPMS.2021.3115704.

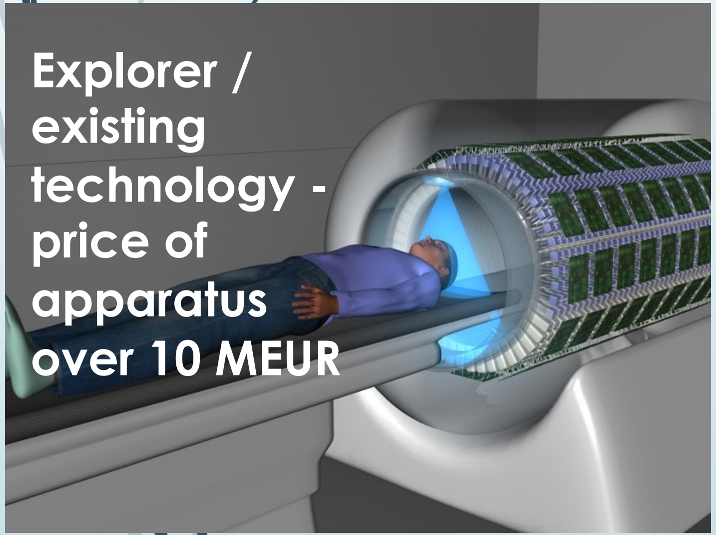
PetVision project

Funded by the European Union

Horizon Europe
European Innovation
Council Pathfinder

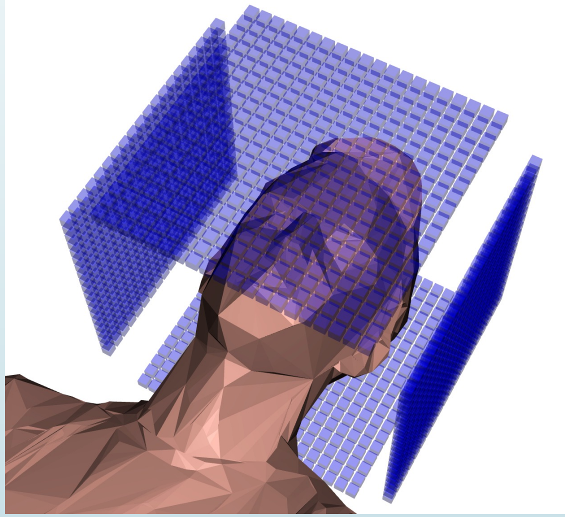
- Addresses improvements in diagnostics for functional imaging of biological processes
- Development of the next generation of fast time-of-flight positron tomography
- which will improve the mobility, flexibility, modularity and accessibility of the apparatus

- **Vision** - To develop breakthrough technology for more efficient and cheaper diagnosis and treatment of cancer and other diseases
- **Goal** - To prototype a limited field-of-view apparatus in a real-world test environment



PET VISION

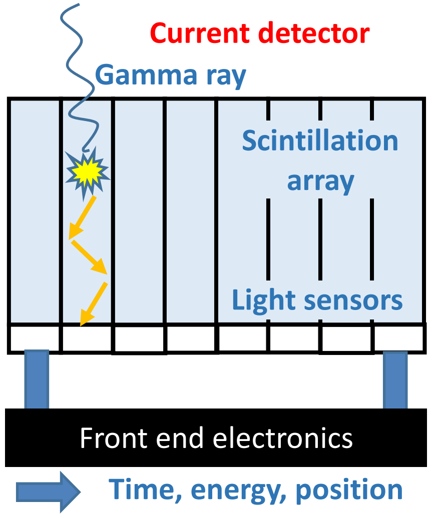
Price of apparatus below 0,5 MEUR

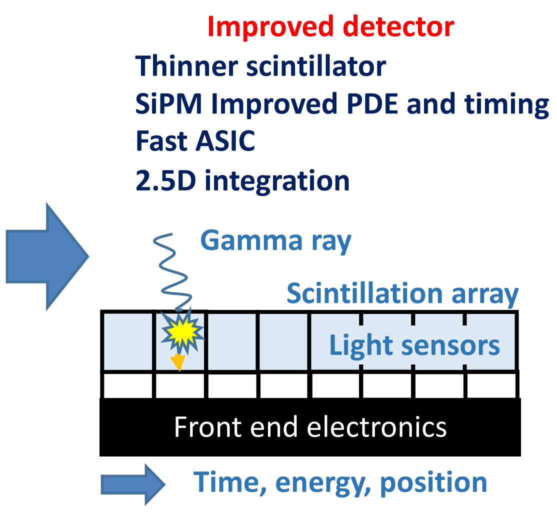


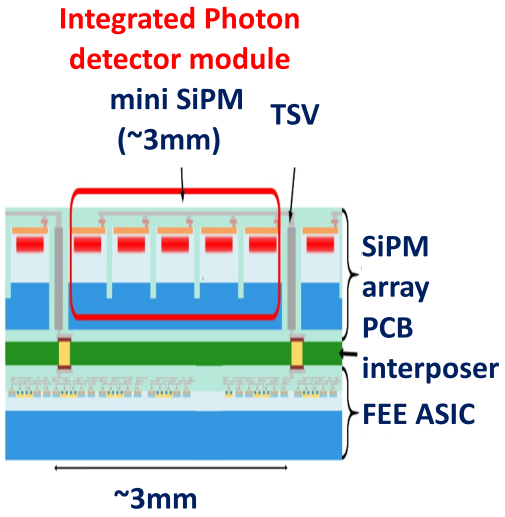
This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101099896 J7-50229

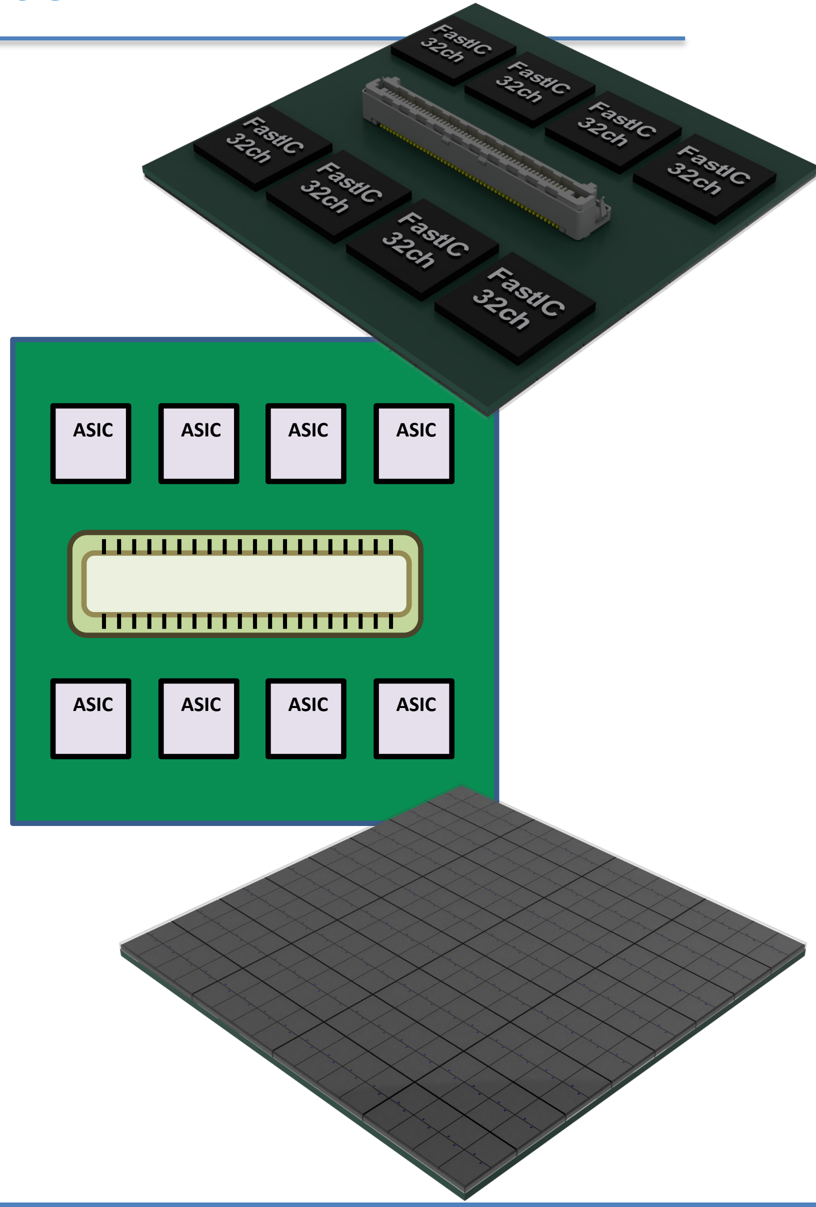
Development of ultrafast detector of annihilaton

How to achieve the required coincidence timing resolution?









Project partners

David Gascon

UNIVERSITAT DE BARCELONA

Chip design

Rok Pestotnik

Institut "Jožef Stefan" Ljubljana, Slovenija

Coordination
Design
Integration
Reconstruction

Alberto Gola

FONDAZIONE BRUNO KESSLER
FUTURE BUILT ON KNOWLEDGE

Photo sensors
2D integration

Jose Benlloch

i3M
Instituto de Instrumentación para Imagen Molecular

Readout Electronics
Data Acquisition

PET VISION

European Innovation Council
Funded by the European Union

Jorge Alamo

ONCO VISION

SME: Mechanics & Software

Georges El Fakhri

Yale

Associated P.
Hospital:
Design & Validation

Rafael Ballabriga

CERN

Associated P.
Chip design

Wolfgang Weber

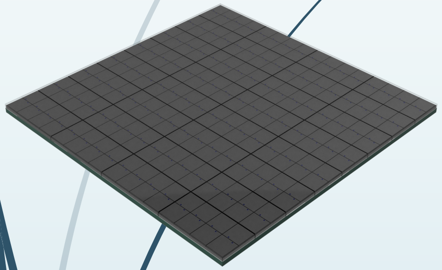
MRI TUM
Klinikum rechts der Isar
Technische Universität München

Hospital:
Validation

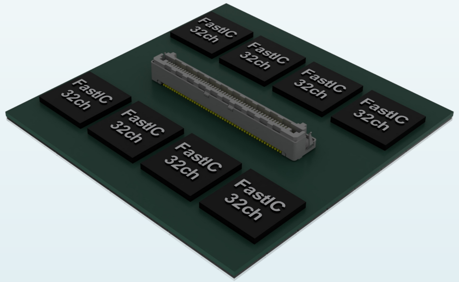
Project Timeline

PET VISION

Photo Sensor with improved performance



ASIC chip and integration into a digital module



Integration of the prototype

Validation in hospitals

Further developments & exploitation

2025 → 2026 → 2027 → 2028 → 2029-

TOF-PET with Cherenkov light

European Research Council
Established by the European Commission

One of the remaining problems:

TOF resolution is limited by the scintillation process

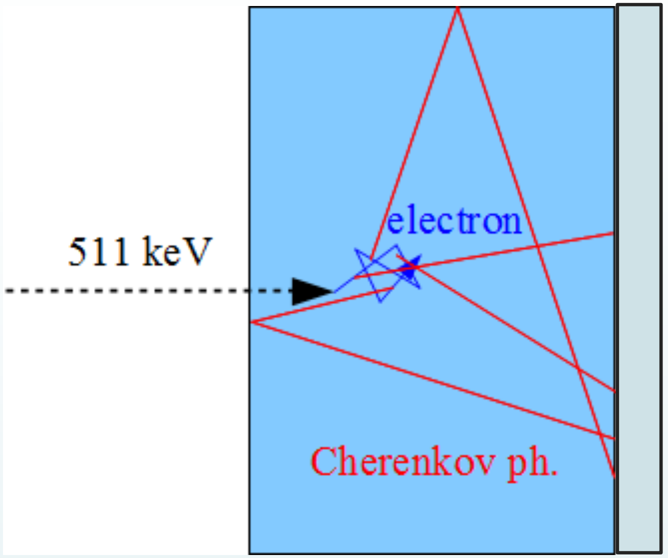
Solution

Use Cherenkov light promptly produced by a charged particle travelling through the medium with a velocity higher than the speed of light c_0/n. – pure Cherenkov radiators PbF_2

Disadvantage:

The number of Cherenkov photons is small compared to the number of scintillation photons (2-3 vs 1000)

- Detection of single photons is needed
- No energy information

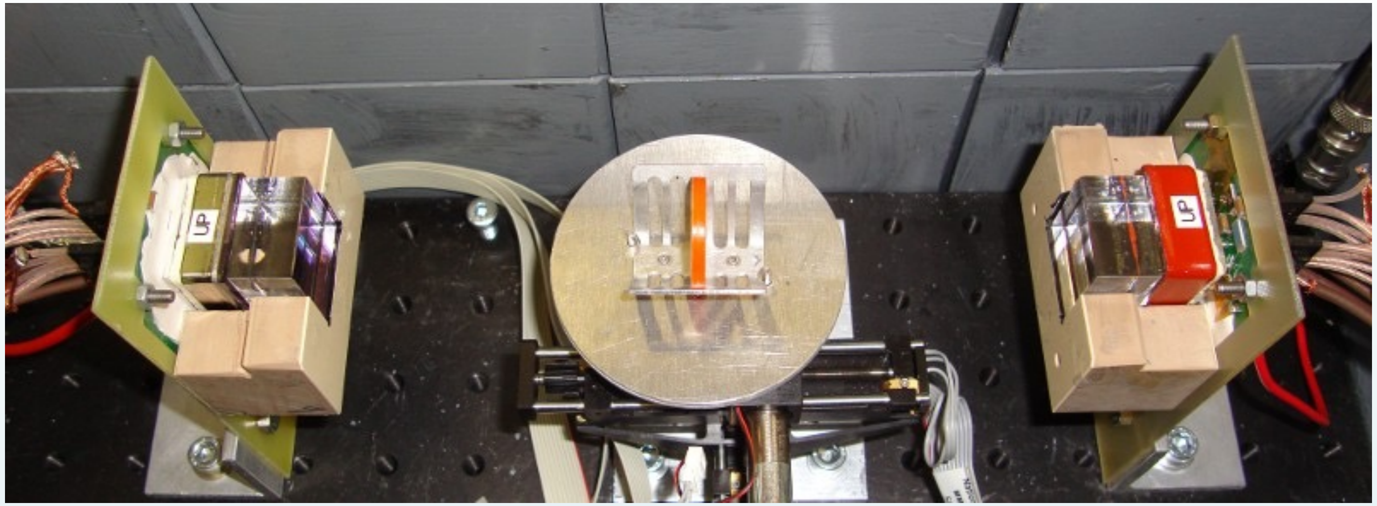


CherPET
ERC Proof of Concept Grant
P. Križan

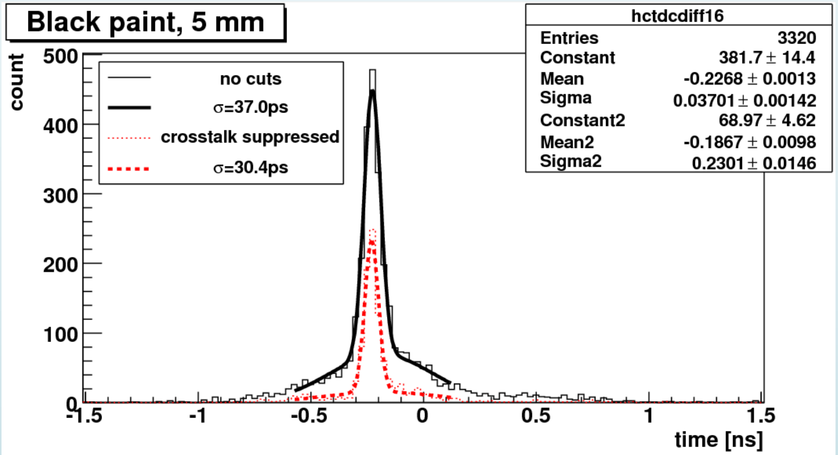
Panel detector from MCP PMTs and a PBF_2 radiator

TOF-PET with Cherenkov light

Two detectors in a back-to-back configuration with 25x25x15 mm^3 PbF_2 crystals coupled to MCP-PMT with optical grease.



5 mm long crystal:
→ FWHM ~ 70 ps



→ NIM A654(2011)532–538

Conclusion

- Low-light level detection is at the heart of different techniques for basic and applied science.
- New methods require very fast timing.
- Advances in different areas lead to new applications with extreme requirements.