Silicon detectors for photo-detection

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September 26 – 30, 2010

3rd MC-PAD Network Training Event,
Ljubljana

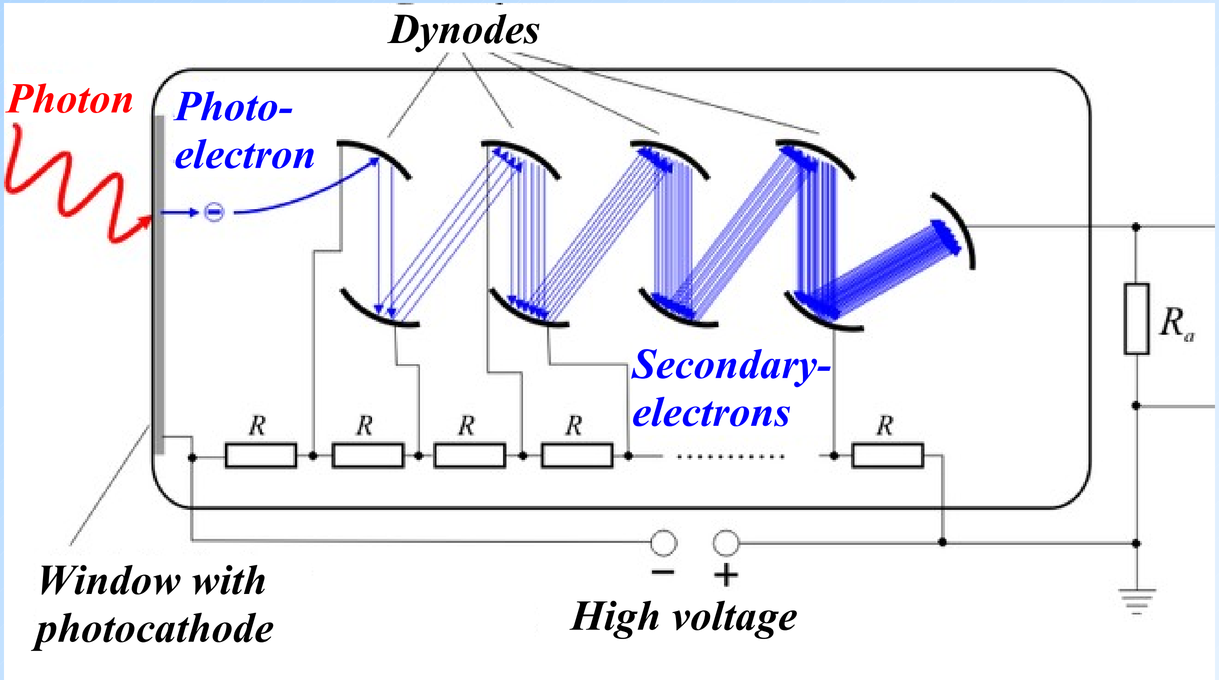
Outline

- Introduction
- Detection of light with solid state sensors
  - photo diode
  - avalanche photo diode (APD)
  - hybrid photo detectors (HPD, HAPD)
  - APD operated in Geiger mode
  - Silicon photomultiplier
- Applications (SiPM):
  - aerogel RICH development for Belle II
  - astrophysics Cherenkov telescopes
  - CALICE and T2K large system experience

Detection of photons (light)

Photomultiplier:

- conversion: photon produces photo-electron
- amplification: photo-electron is accelerated toward the first dynode where it starts the amplification process, secondary electrons continue the amplification process throughout the dynode structure
- signal: at the end the charge is collected by the anode
- bulky, sensitive to magnetic field, high voltage, lower QE



Application examples

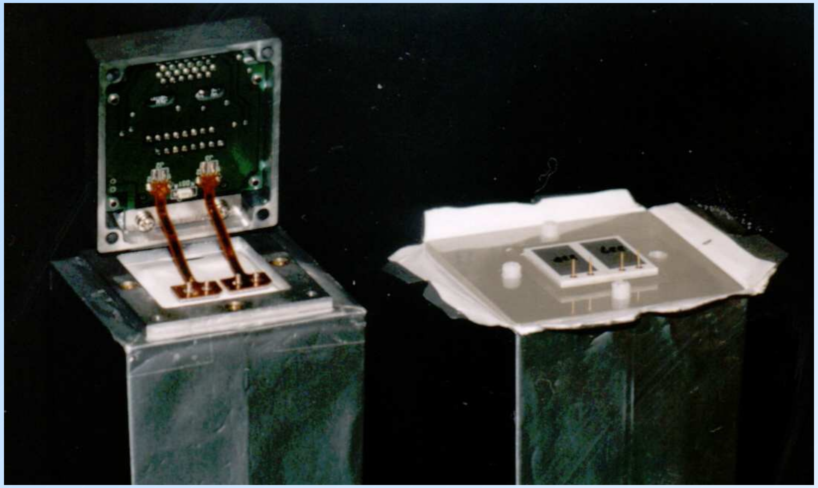
Calorimeters:

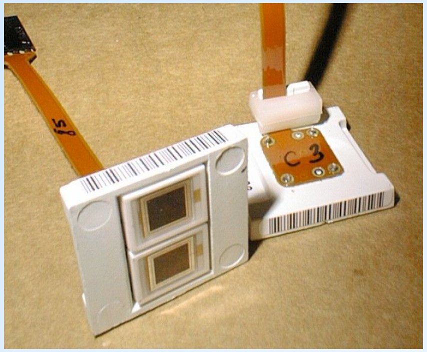
- Belle calorimeter with PIN photodiodes

~ 50000 photons/MeV

- CMS calorimeter with APDs

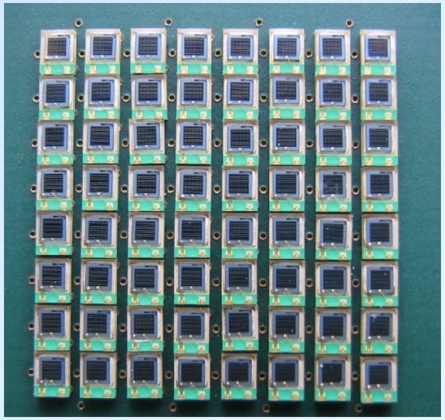
~ 100 photons/MeV

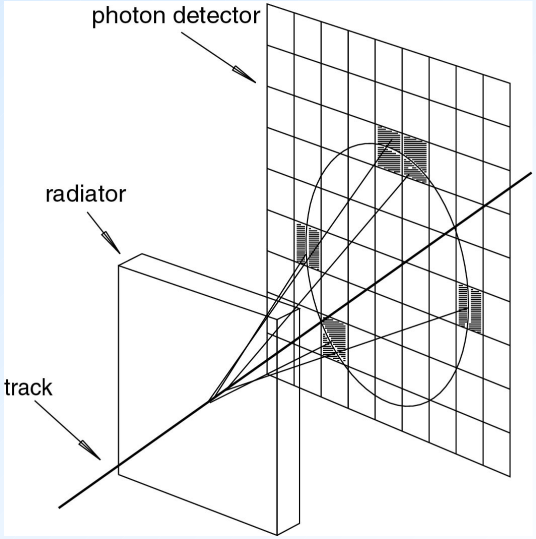




Cherenkov light detection:

- Belle-II aerogel RICH prototype module with SiPMs – detection of single photons

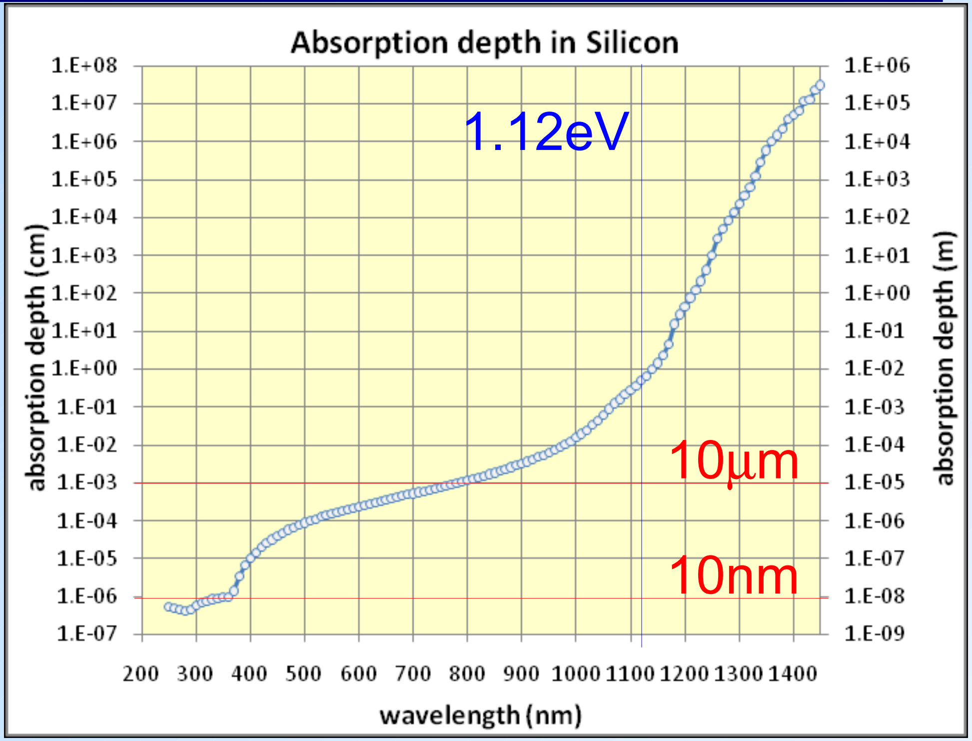


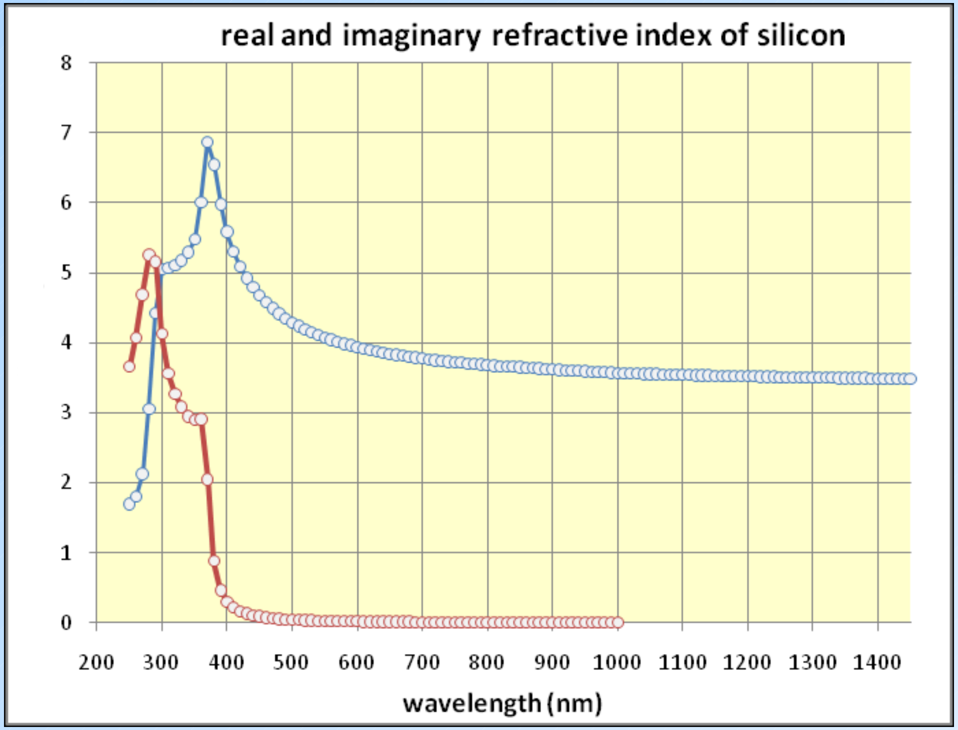


Fiber trackers, medical imaging (PET), TOF ...

Si optical properties

- large variation of absorption length (10nm-10μm) → limits QE for short and long wavelengths
- high refractive index → high reflectivity → anti-reflecting coating is used





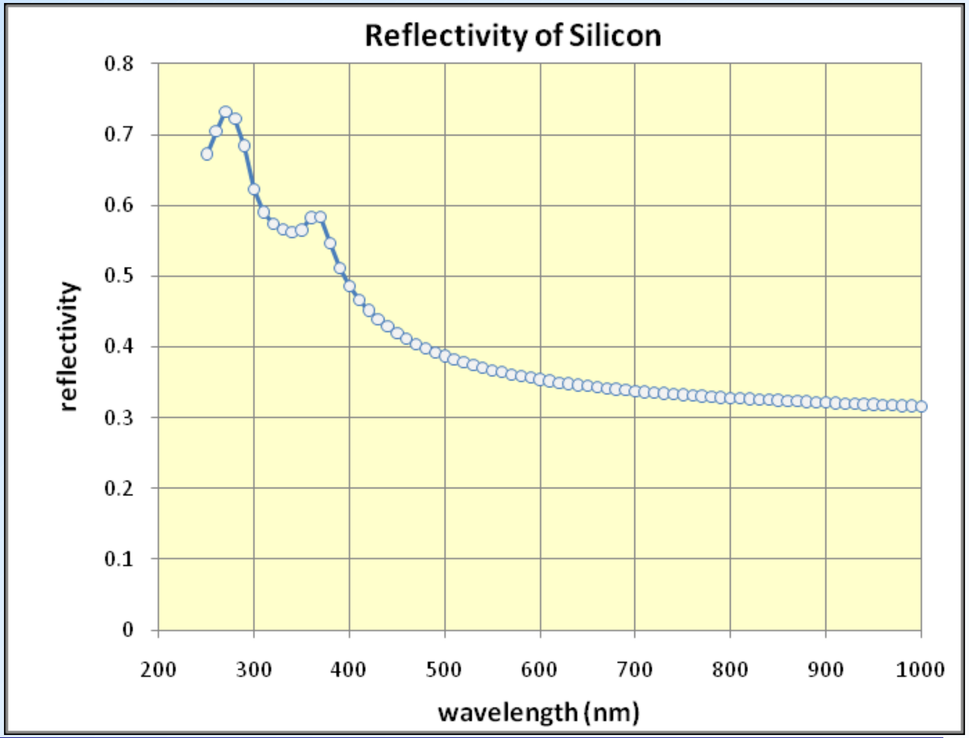
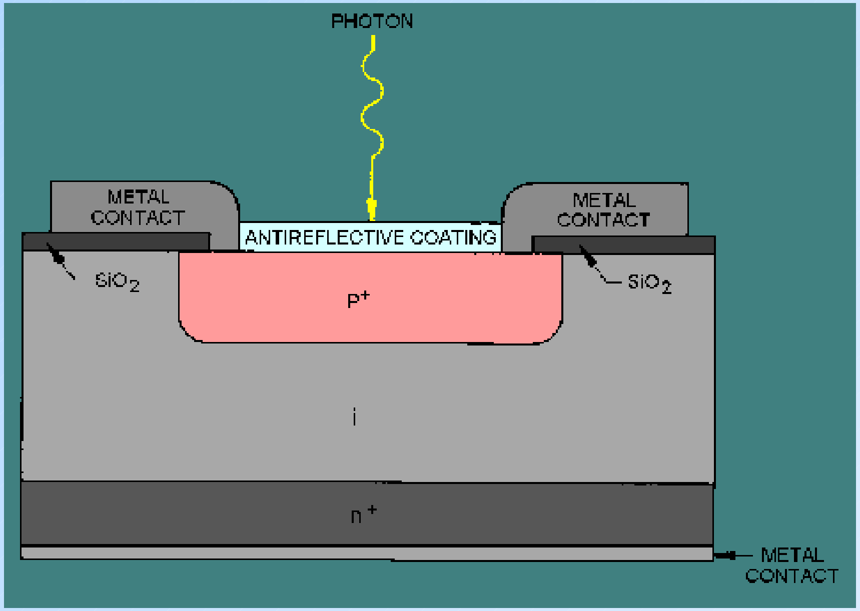
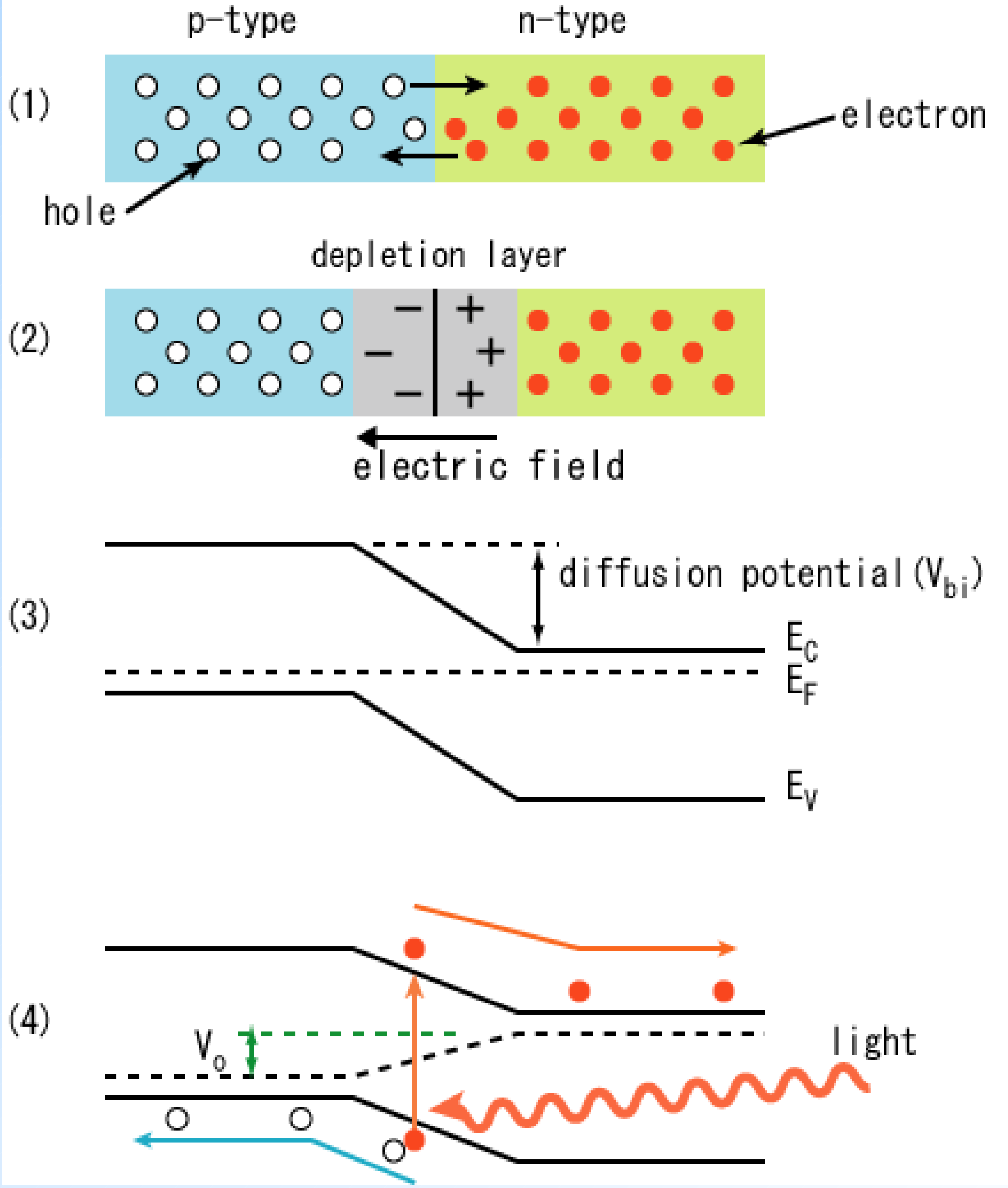


Photo diode (p-n, p-i-n)

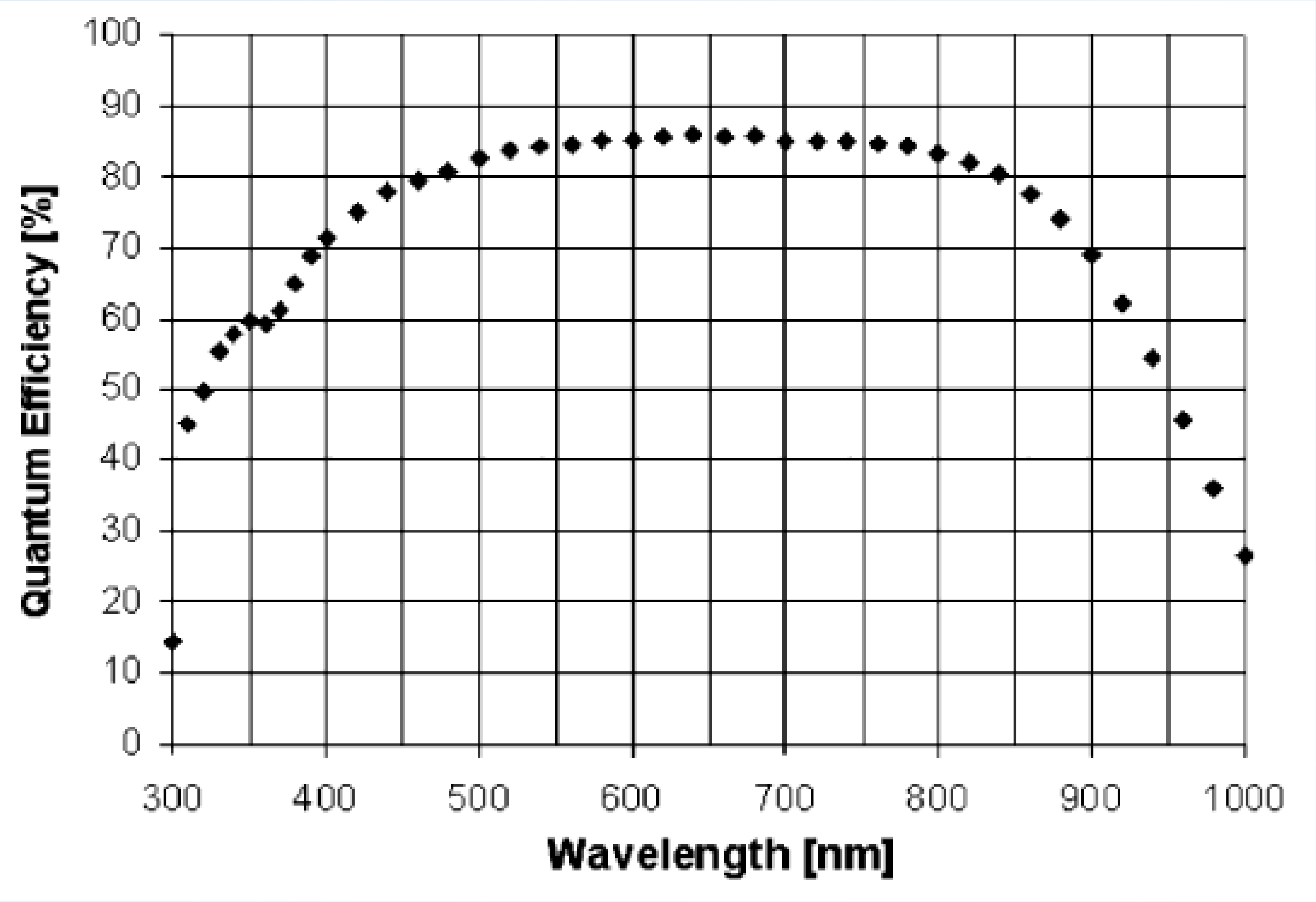
- photons absorbed in the depleted region generate photo-current
- no amplification – can detect light pulses with large number of photons (> ~10^4)
- Si band gap energy 1.12eV (wavelength 1100nm)
- p-i-n → lower V_{bias} and C



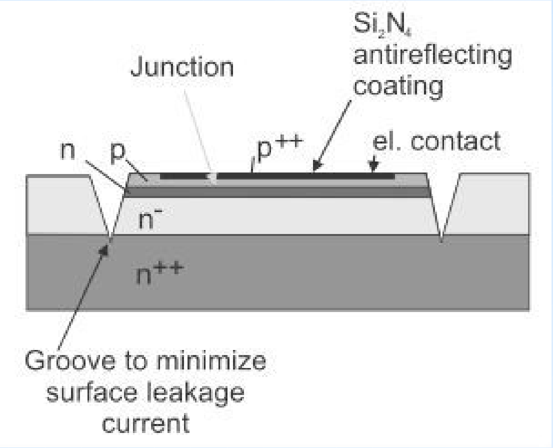


p-i-n diode Q.E.

- depleted region ~100 μm thick

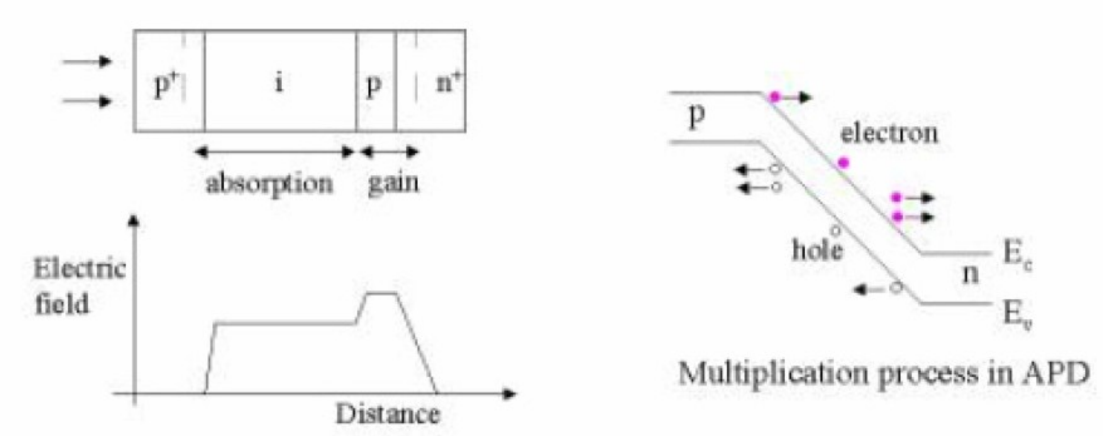


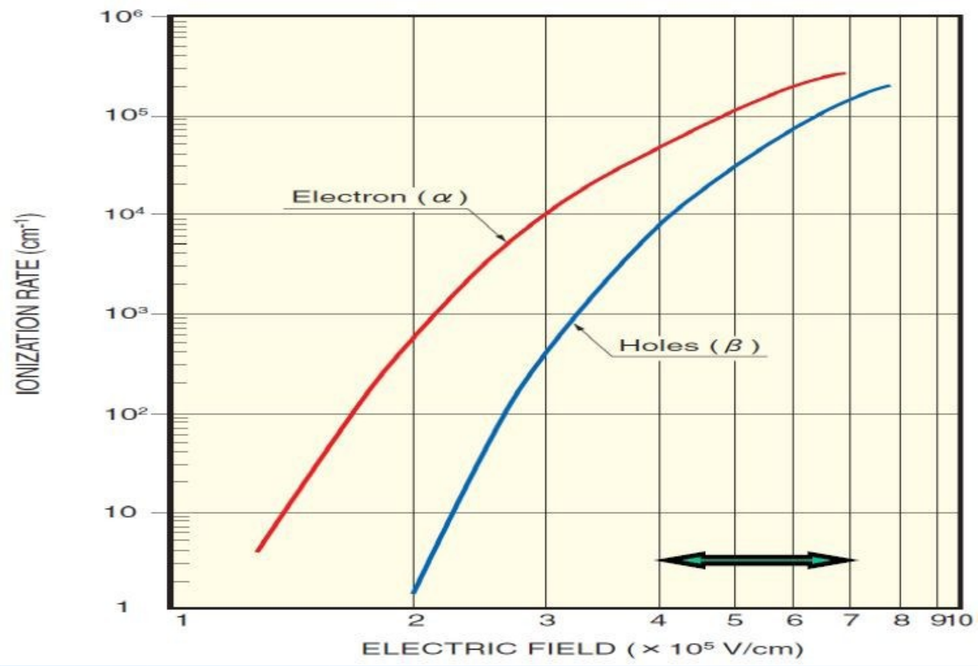
Avalanche photodiode



Photodiode with high field amplification region:

- both carriers can participate in amplification
- modest amplification up to 1000 limited by start of pair production by holes → leads to avalanche breakdown.
- not capable of single photon detection



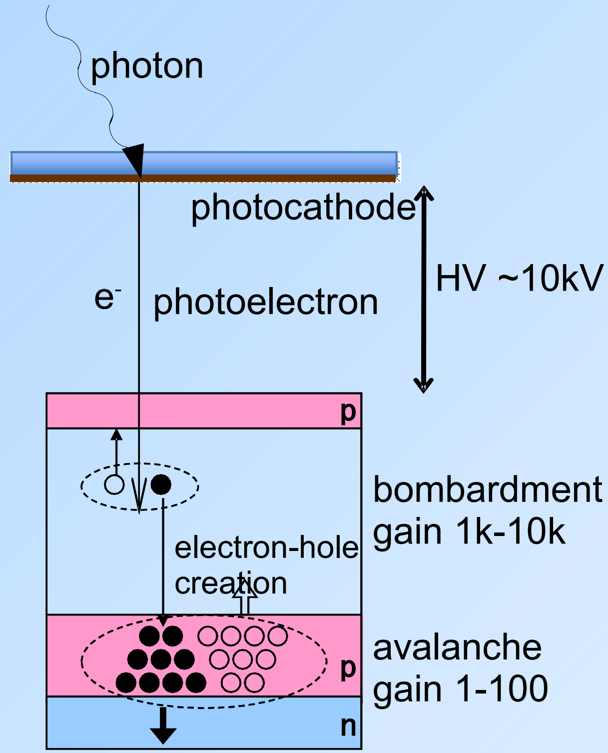


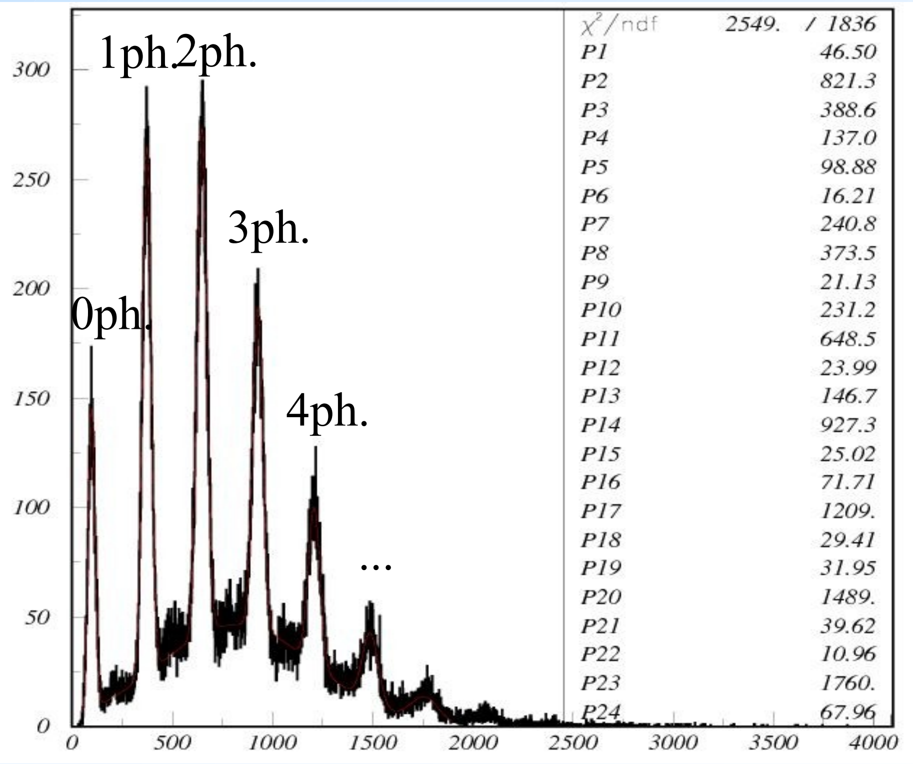
VLPC (Visual Light Photon Counter) is impurity band conduction silicon diode capable of detecting single photons. Band gap energy ~50meV → operation at cryogenic temperature (6.5K). Used for D0 fiber tracker.

Hybrid photo detectors

Single photon detection can be achieved by using PD or APD in vacuum device (replacing dinode structure):

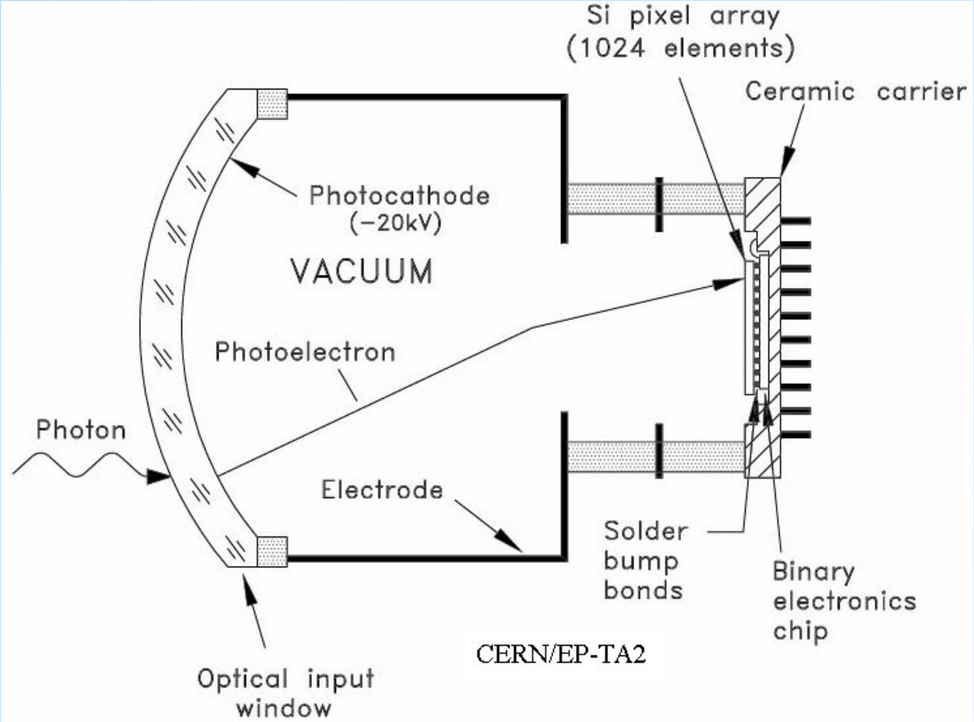
- photon interacts in photocathode and produces photoelectron
- high electric field accelerates photoelectron
- on impact electron-hole pairs are generated (bombardment gain)
- in APD signal is further amplified → lower HV and higher gain
- photon counting

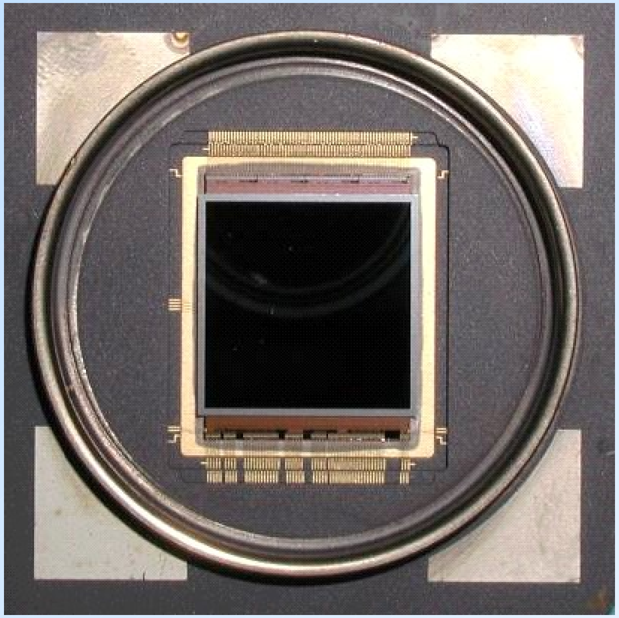


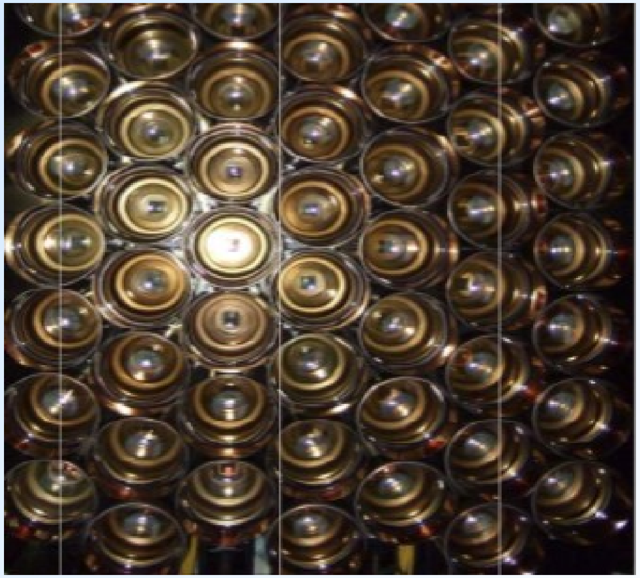


LHCb RICH HPD:

- electron optics → 5x demagnification
- sensitive to magnetic field
- HV ~20kV, gain ~5k
- detector in operation
- CERN+DEP-Photonis

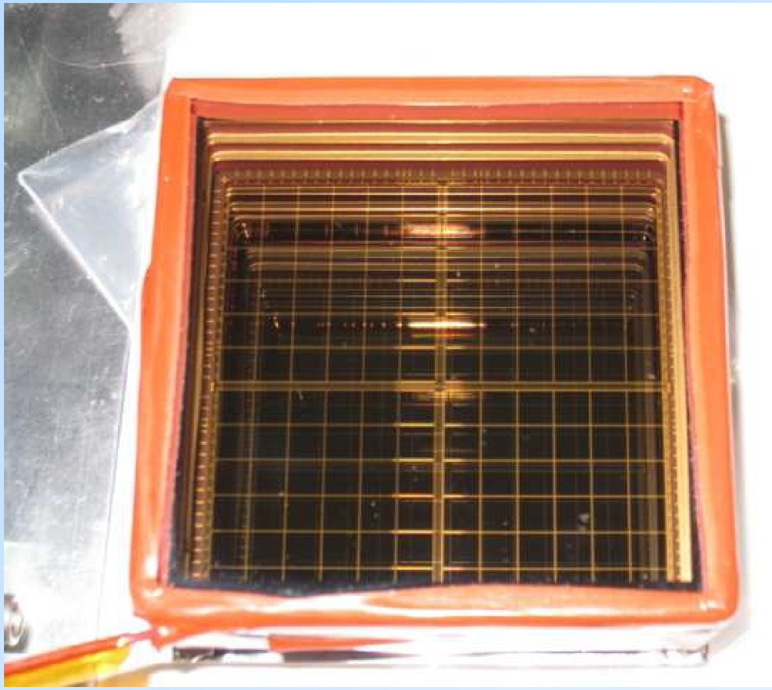


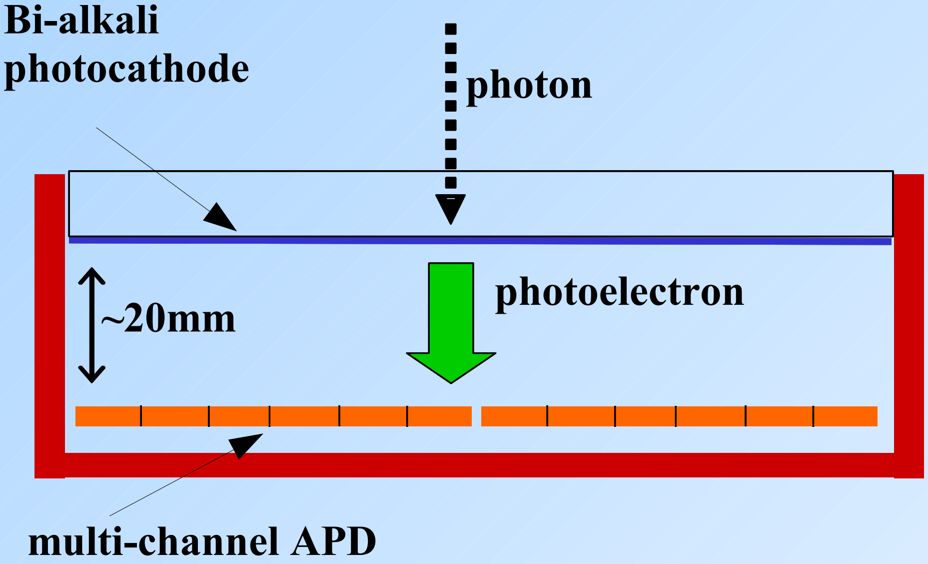


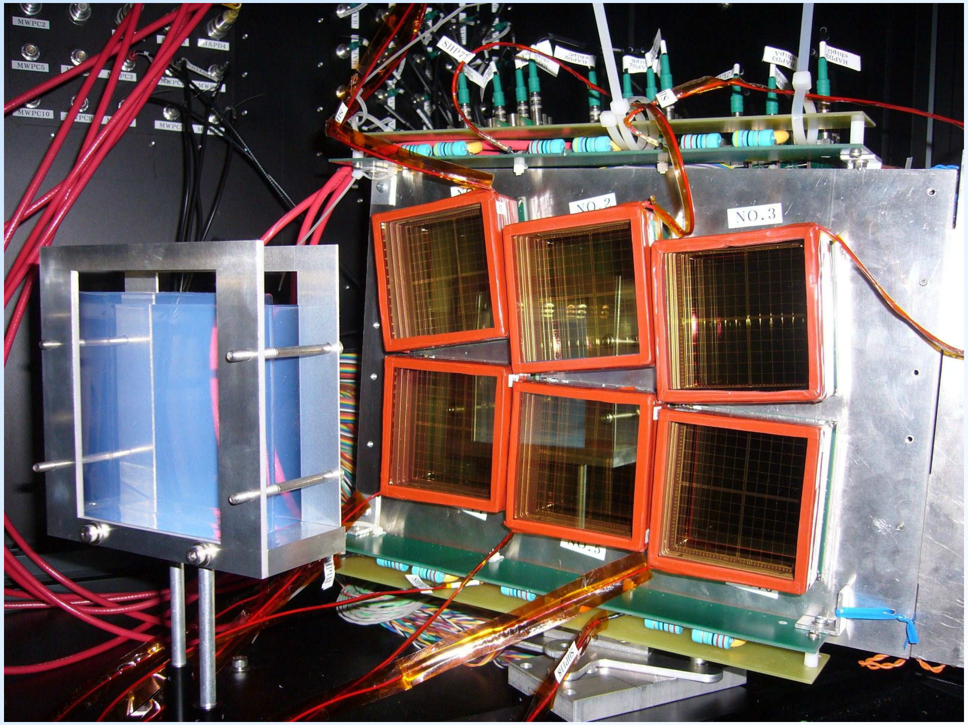


Belle II aerogel RICH HAPD

- proximity focusing configuration
- operation in magnetic field
- HV ~8kV, gain ~100k
- Belle + Hamamatsu



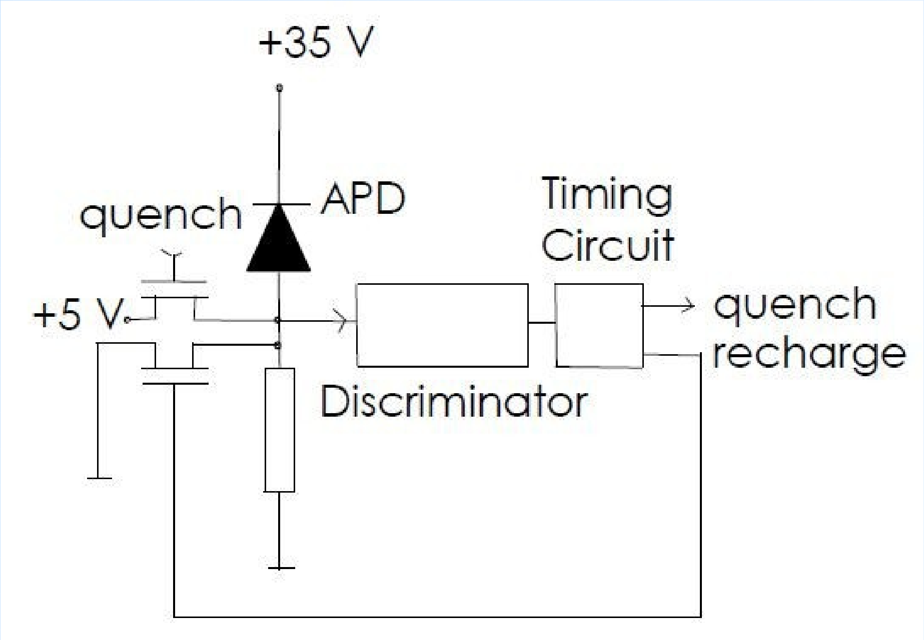




APDs operated in Geiger mode

Another option is to operate the APD in Geiger mode.
Bias voltage is increased above the breakdown voltage and avalanche must be stopped by:

- active bias control or
- quenching resistor

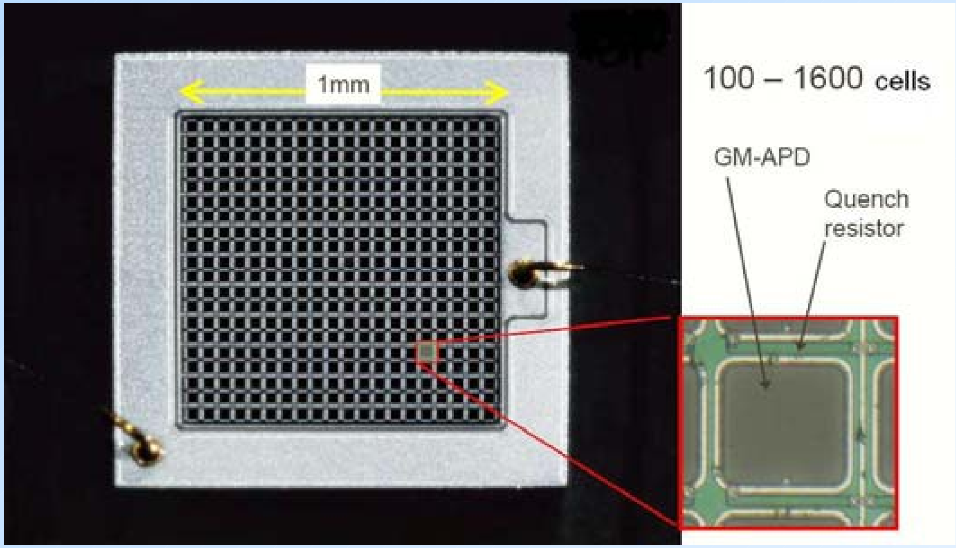


Large are APD operating in Geiger mode would be most of the time in the recovery state due to the large number of dark counts.
Solution: localization of quenching, division of large area APD in an array of smaller ones → SiPM (1990's: Golovin, Sadygov)

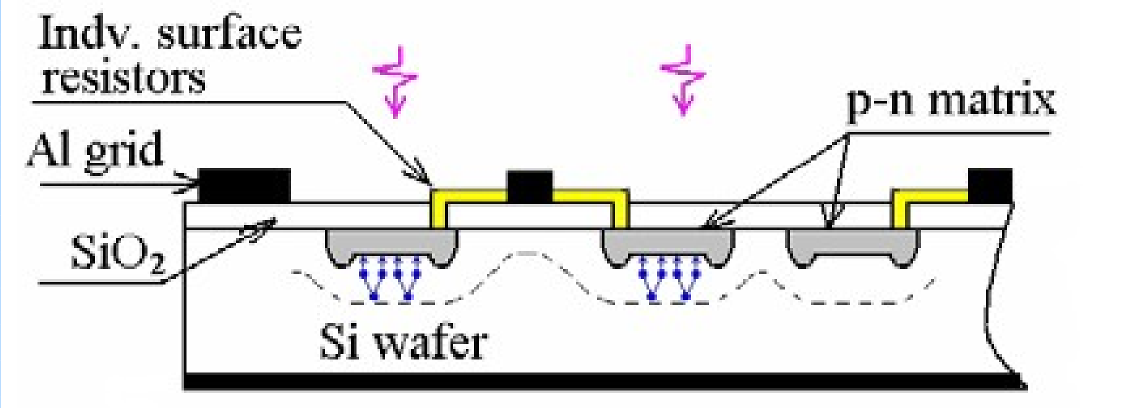
SiPM – Structure

SiPM is an array of Geiger mode APDs (micro cells) each consisting of:

- p-n structure with high field region
- quenching resistor connected to common electrode by metal strips



Hamamatsu MPPC with 50um cells

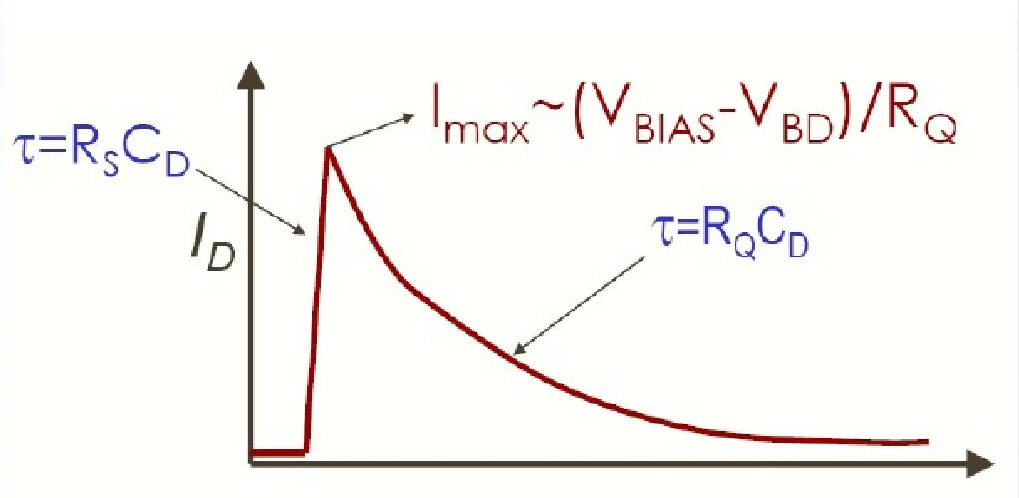


Manny producers: Photonique/CPTA, MEPhI/PULSAR, Hamamatsu, MPI, FBK-irst, STMicroelectronics, SensL, Philips (dSiPM), Zecotec ...
using different names: SiPM, MRS APD, MAPD, SSPM, MPPC, PPD ...

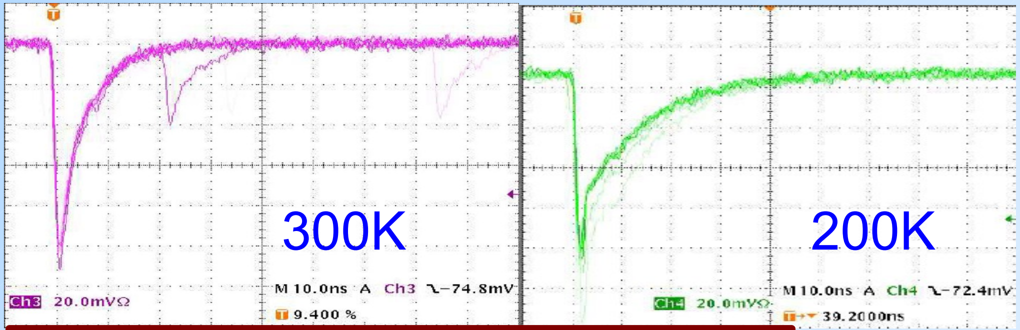
SiPM – Signal

SiPM signal sequence:

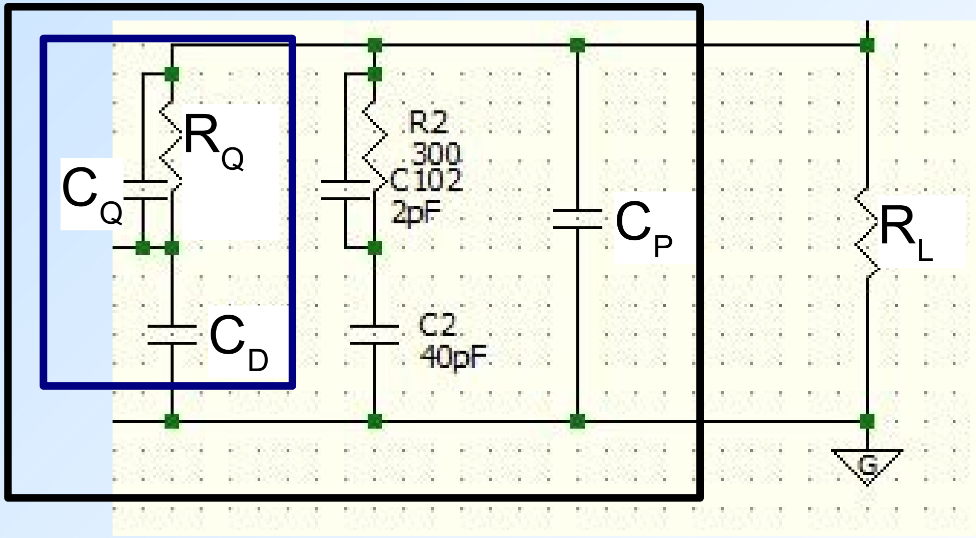
- charged to V_{bias}
- carrier enters breakdown region and initiates the avalanche
- micro cell is discharged to $V_{breakdown}$ and avalanche process stops
- micro cell is recharged to V_{bias} – during this time a new avalanche process in the same micro cell will result in a reduced signal



Simplified explanation of output signal (C_D~20fF, R_S~1kΩ, R_Q~100kΩ). Parasitic capacitances C_Q and C_P also influence the output signal.

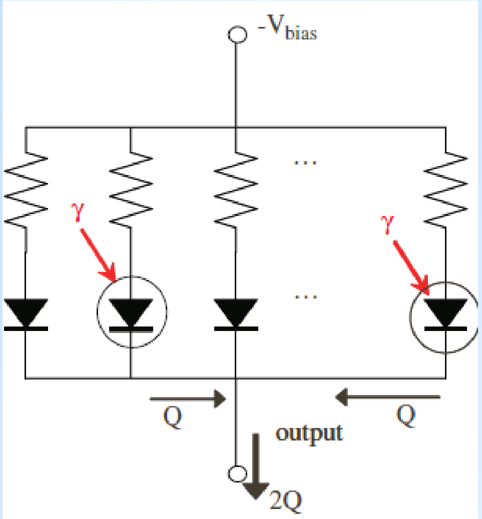


H. Otono (U. of Tokyo)@PD07



SiPM - Gain

Gain is determined by micro cell capacitance (~10 – 100 fF) and overvoltage – the difference between bias and breakdown voltage (typically few volts).



$$G = C_{m.c.} \times (V_{bias} - V_{breakdown}) / e_0$$

- large gains, typically $10^5 - 10^7$
- short signals (~10 ns) produce several mV on 50 Ohm
- total signal is the sum of signals from individual micro cells
- afterpulses and optical crosstalk also contribute to total charge produced by single photon

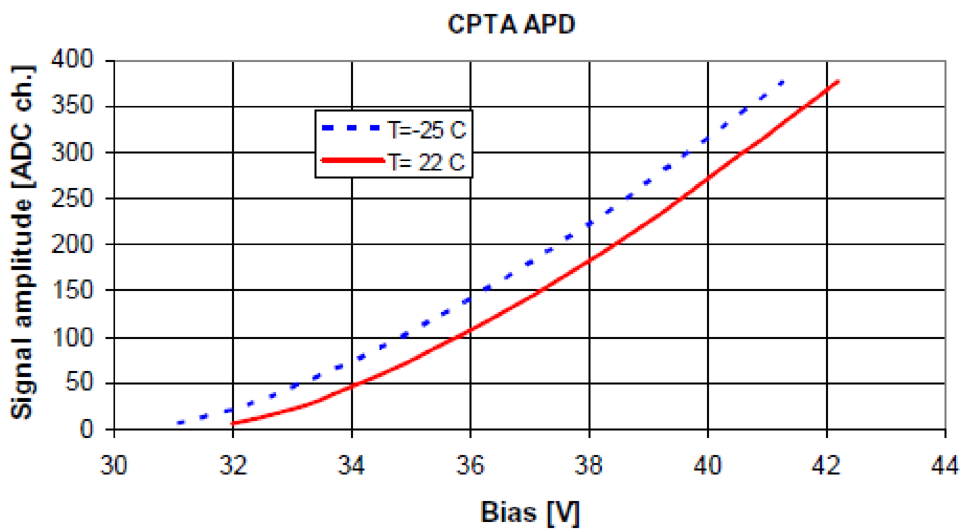
Photon counting(?)

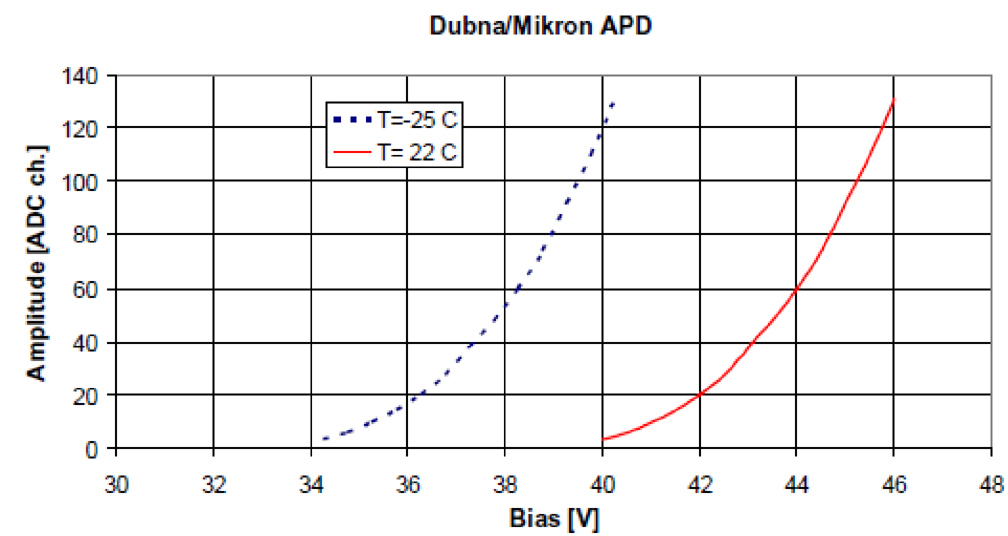
J. Musienko (INR/NU)@PD07

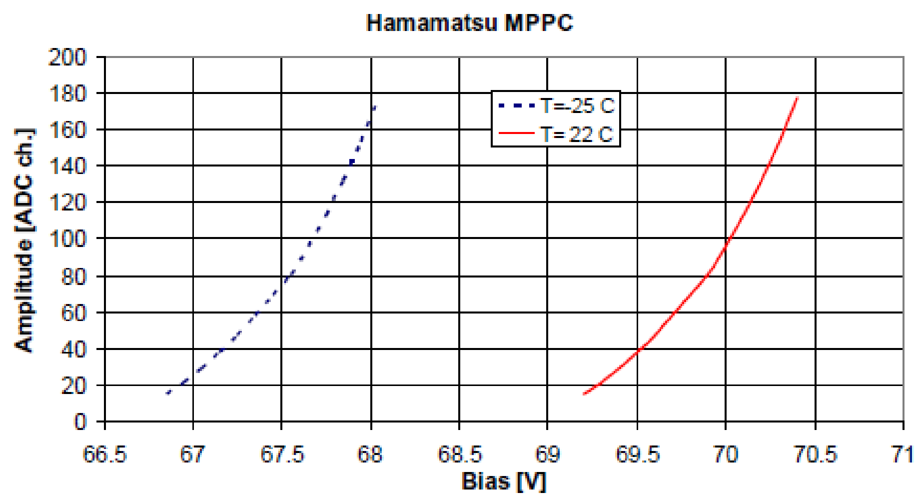
SiPM – Gain vs. temperature

Breakdown voltage changes with temperature → gain variation.

Not critical for single photon detection.







CPTA/Photnique:
dVB/dT=-20 mV/C

Dubna/Micron:
dVB/dT=-122 mV/C

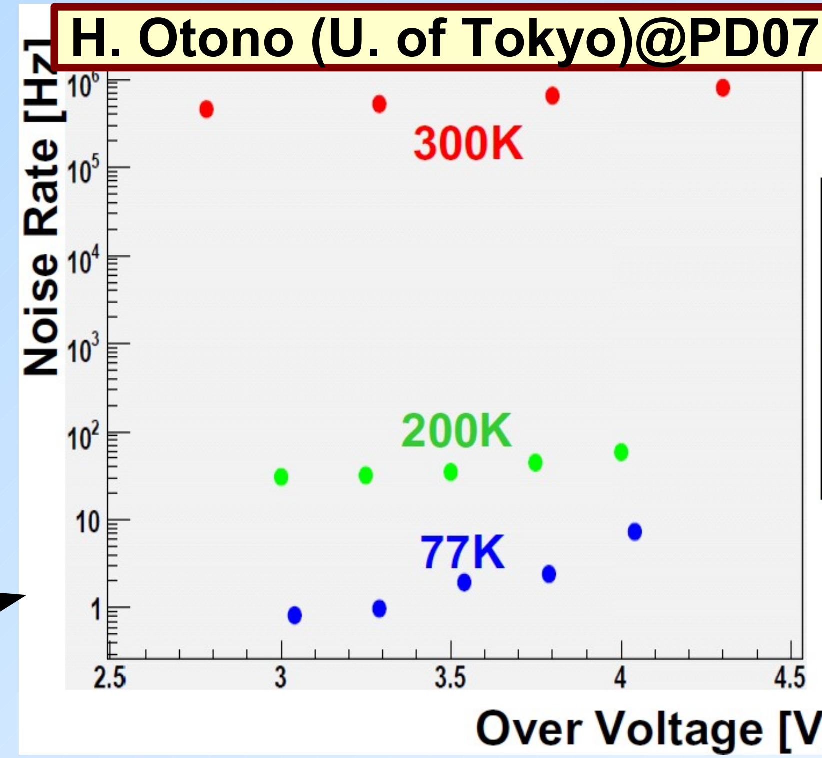
Hamamatsu:
dVB/dT=-50 mV/C

J. Musienko (INR/NU)@PD07

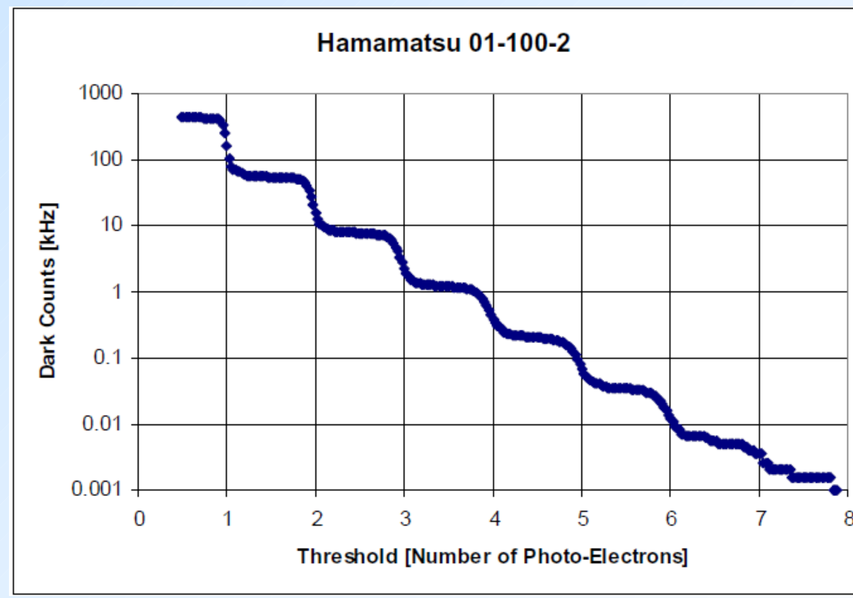
SiPM-Dark noise

Any free carrier entering breakdown region produces the same signal as single photon. The rate of breakdowns initiated by thermally generated carriers is in the range of 100 kHz to several MHz per mm^2 at room temperature. Thermal generation can be reduced by:

- cooling → factor 2 every 8°C
- smaller electric field (also reduces gain and PDE)
- small active volume (charge collection region)



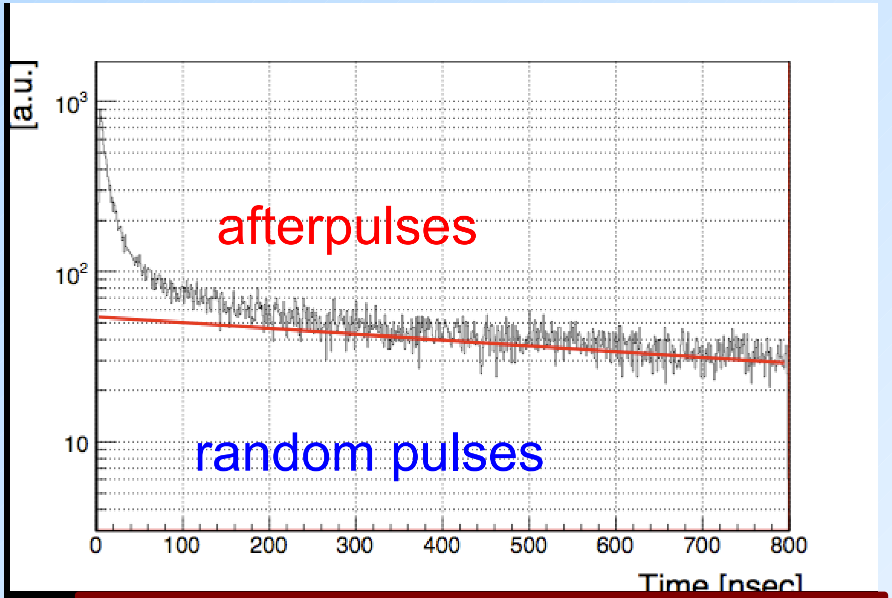
Signals are at the single micro cell level and can be effectively suppressed by threshold level at the signal of few micro cells (depends on optical cross talk level).



SiPM-Afterpulses

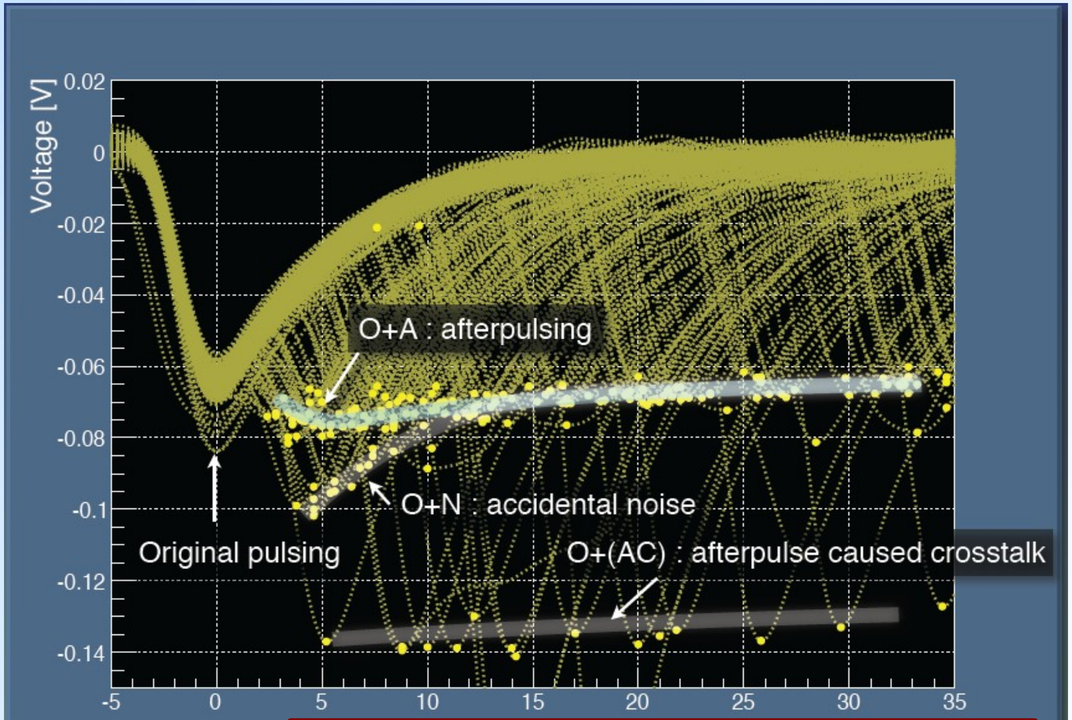
Deep traps are loaded during the avalanche processes and carriers that are subsequently released trigger afterpulses:

- afterpulses can occur several hundred ns after the primary pulse
- probability for afterpulses increases with overvoltage – higher gain



T. Murase (U. of Tokyo)@PD09

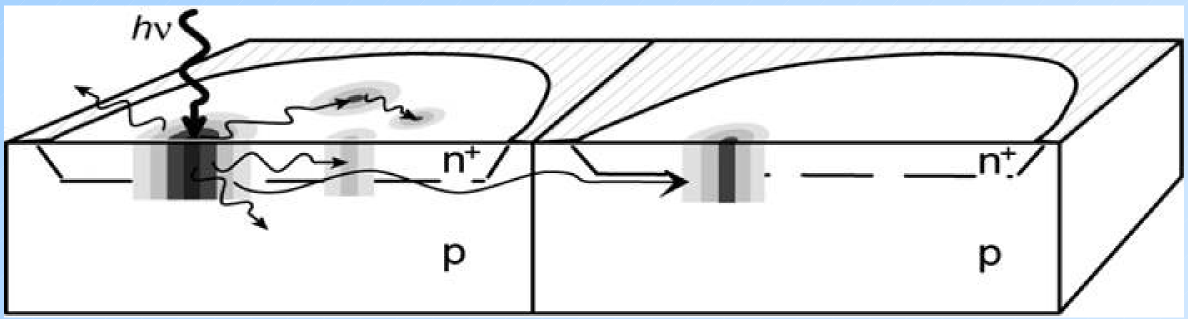
	40x40 px	20x20 px	10x10 px
Afterpulsing 1-1/e Recovery	~ 4 [ns]	~ 9 [ns]	~ 33 [ns]
Pulse Shape returning time (RC Time Const.)	~ 5 [ns]	~ 11 [ns]	~ 35 [ns]



H. Oide (U. of Tokyo)@PD07

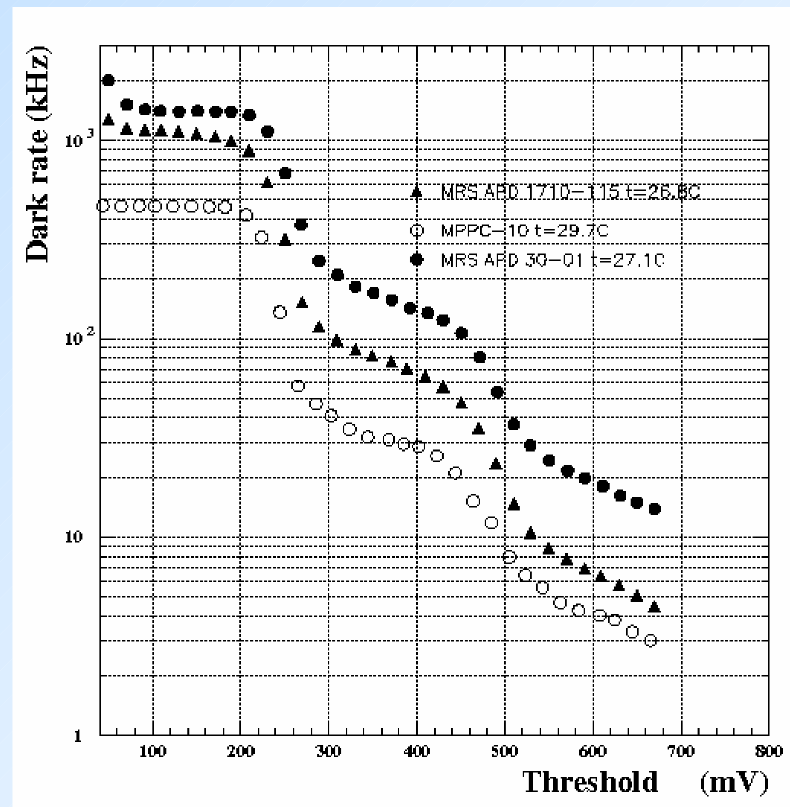
SiPM-Optical cross-talk

Optical cross-talk is generated when photon produced in the avalanche process escapes to the neighboring cell and initiates Geiger discharge → large excess noise factor.



It is the main cause of the larger number of fired micro cells in dark pulses than expected from accidental coincidences (Poisson probability).

Increases with overvoltage – higher gain.

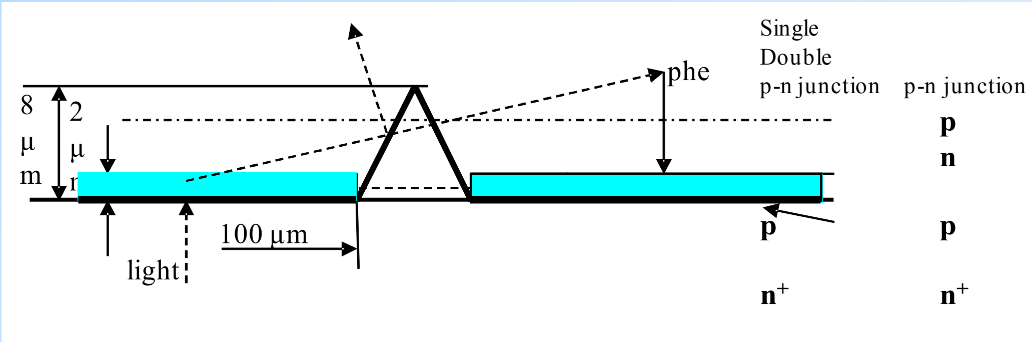


Y. Kudenko (INR Moscow)@PD07

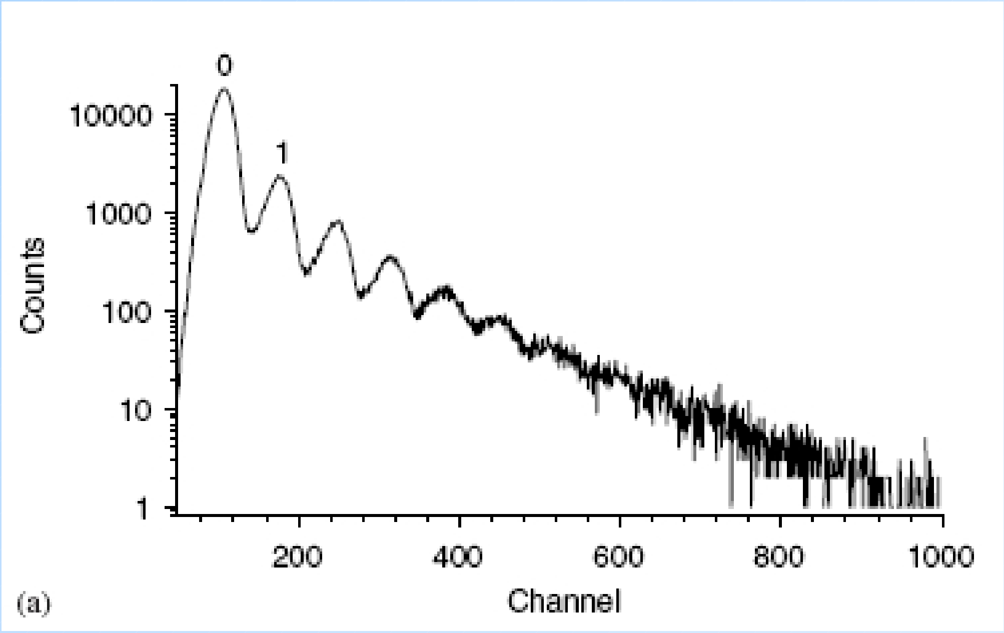
SiPM - Optical cross-talk suppresion

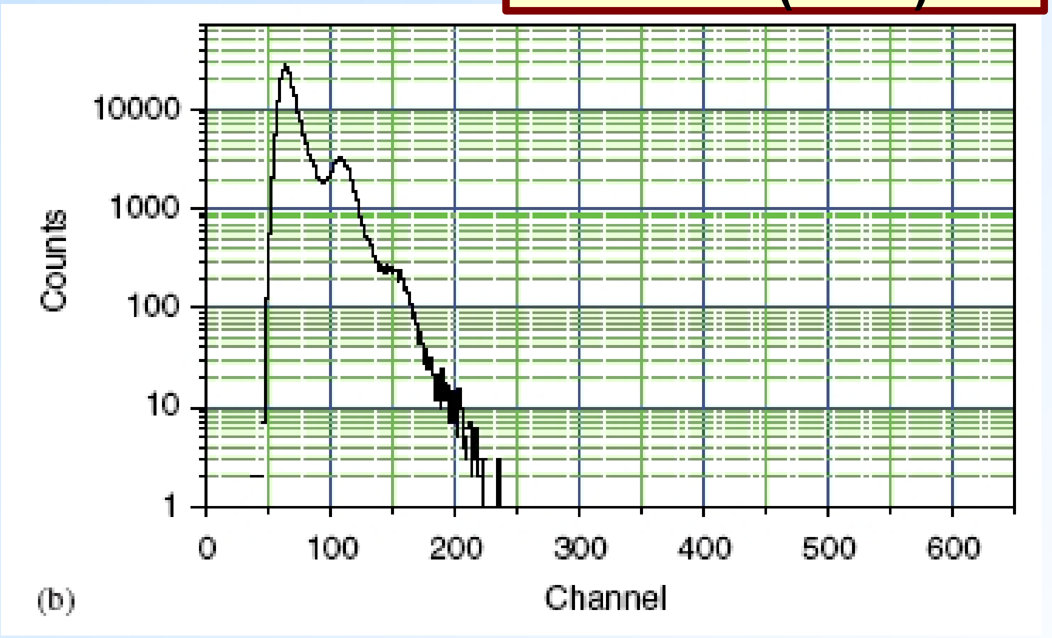
Optical crosstalk can be suppressed by shielding one micro cell from the other:

- tranches are introduced between the cells
- typically lower photon detection efficiency – more dead space



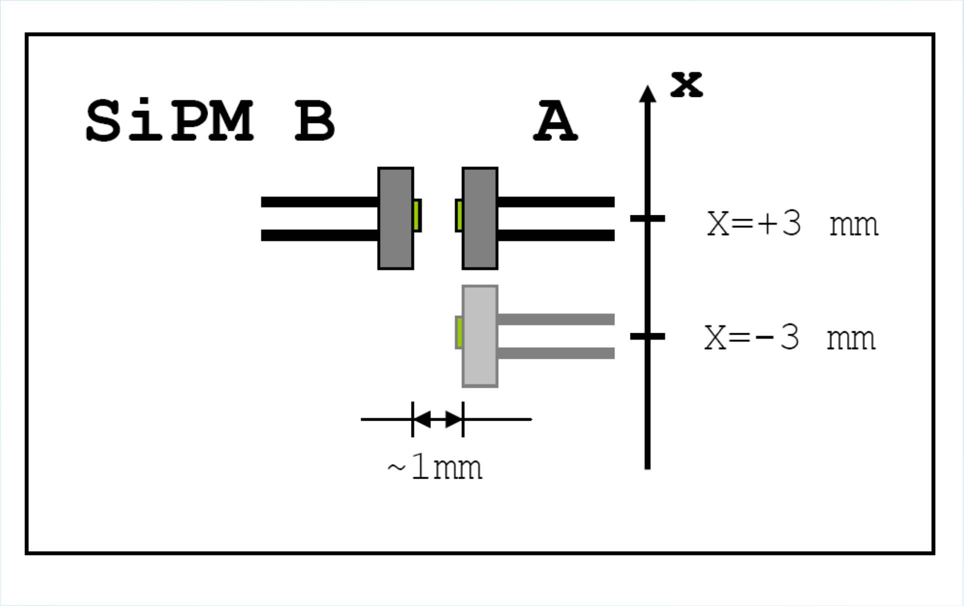
NIM A567 (2006) 78





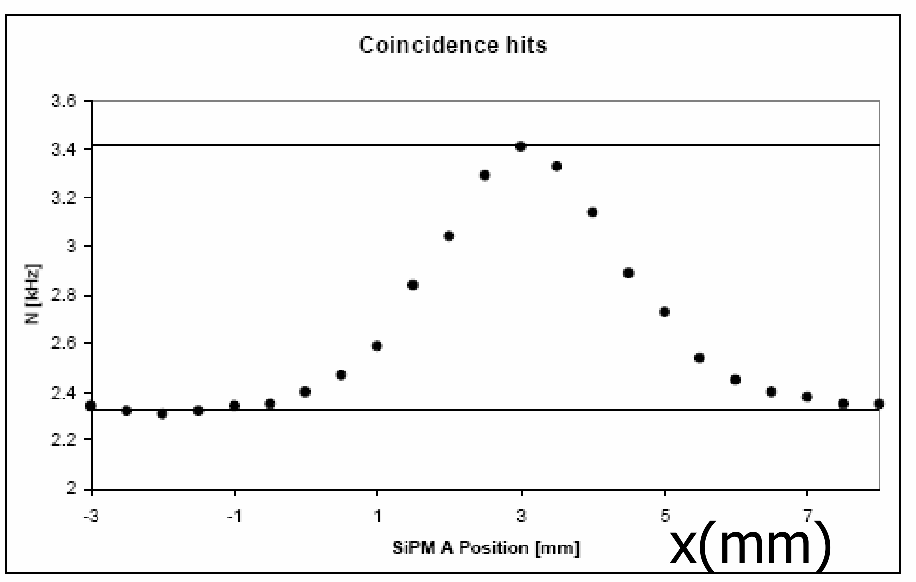
External secondary photon cross talk

Will SiPMs “communicate”?
Scan one SiPM in front of a second one and observe coincidence rate



- single sensor dark rate ~ 200 kHz
- coincidence background rate ~ 2.4 kHz
- coincidence rate increase when face to face ~ 1 kHz
- 1 mm active area 1 mm away
  → ~ 15% of 2π solid angle
- full (2π) solid angle:
  1kHz/(2x200kHz)/15% ~ 2%

→ OK, increase of background at % level

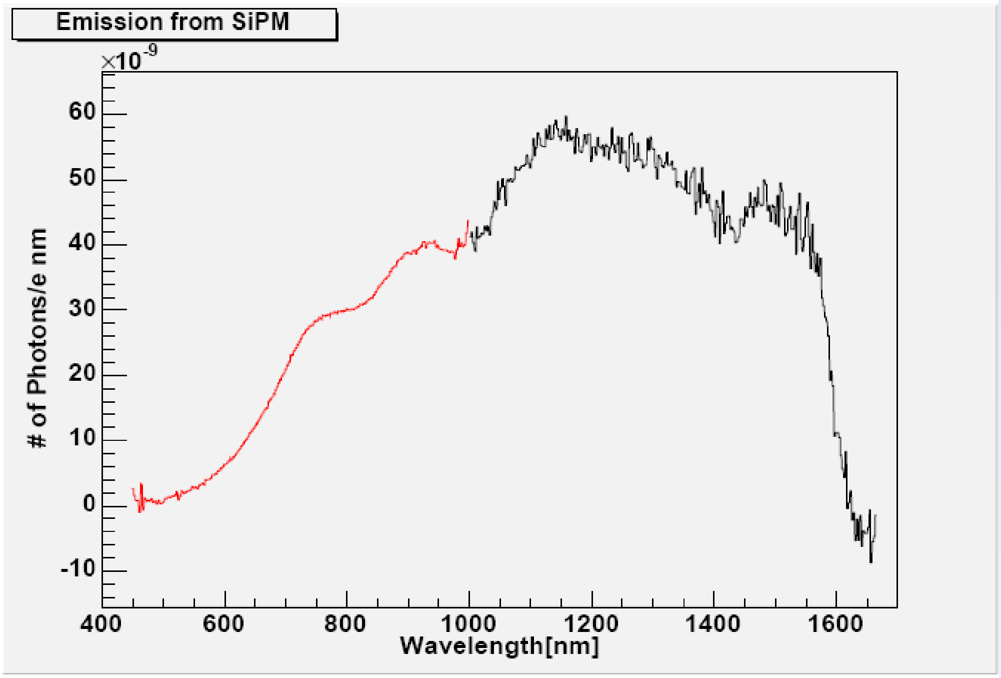


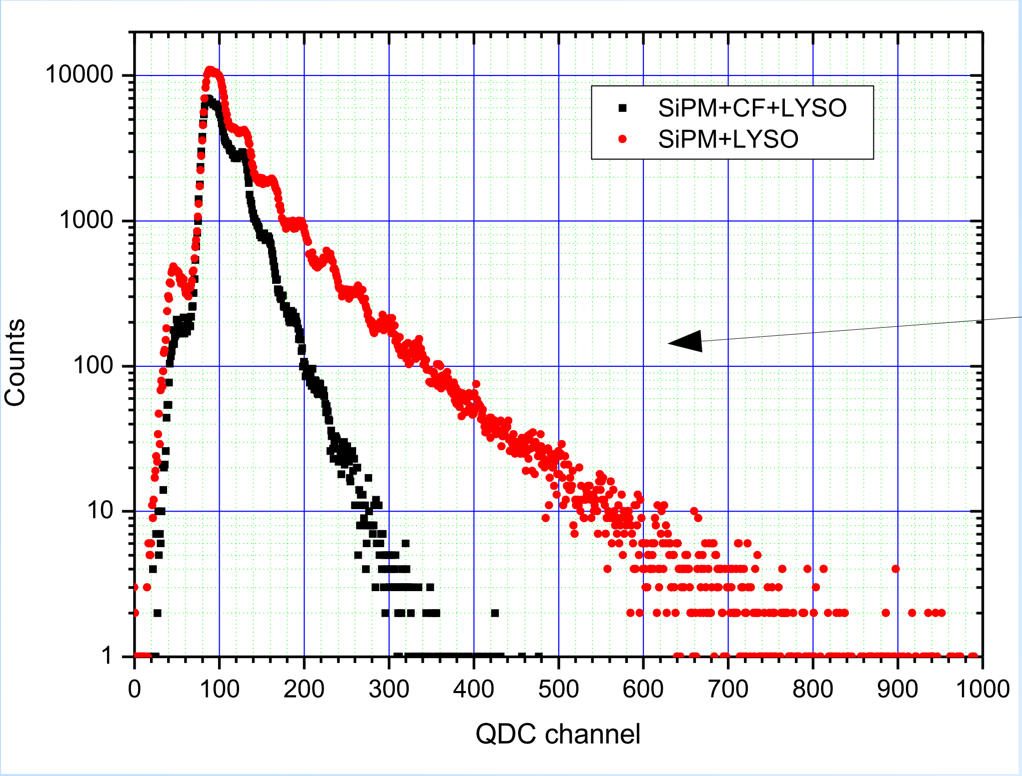
P. Križan (IJS)@LIGHT07

External secondary photon cross talk

Photons escaping SiPM can be reflected back when SiPM is coupled to crystal.

Wavelength distribution of light escaping from SiPM





Effect can be suppressed by use of color filter:

- 5x5 mm2 SiPM with OC suppr.
- operated at gain 107
- LYSO 4x4x20 mm3
- BGC20 color filter

R. Mirzoyan (MPI Munich) @ PD09

SiPM-Signal saturation

Output of SiPM is saturated if number of photons in the pulse is comparable to number of micro cells:

• photons hitting the same micro cell count as one for signal charge

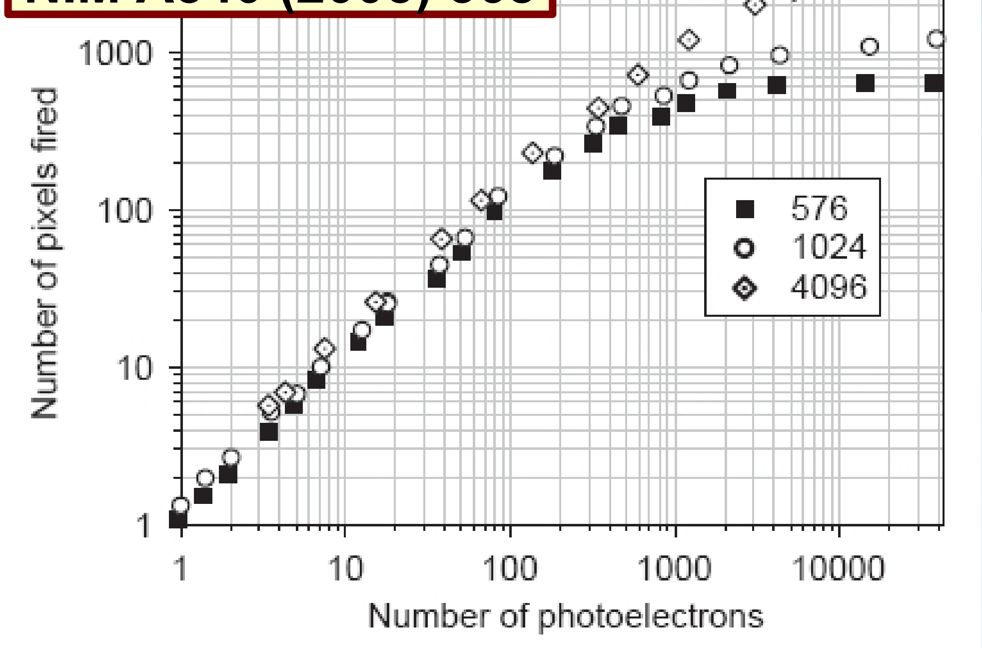
• if photons are simultaneous (Cherenkov light) signal limit is number of pixels (disregarding after-pulse contribution)

• saturation can be approximated by

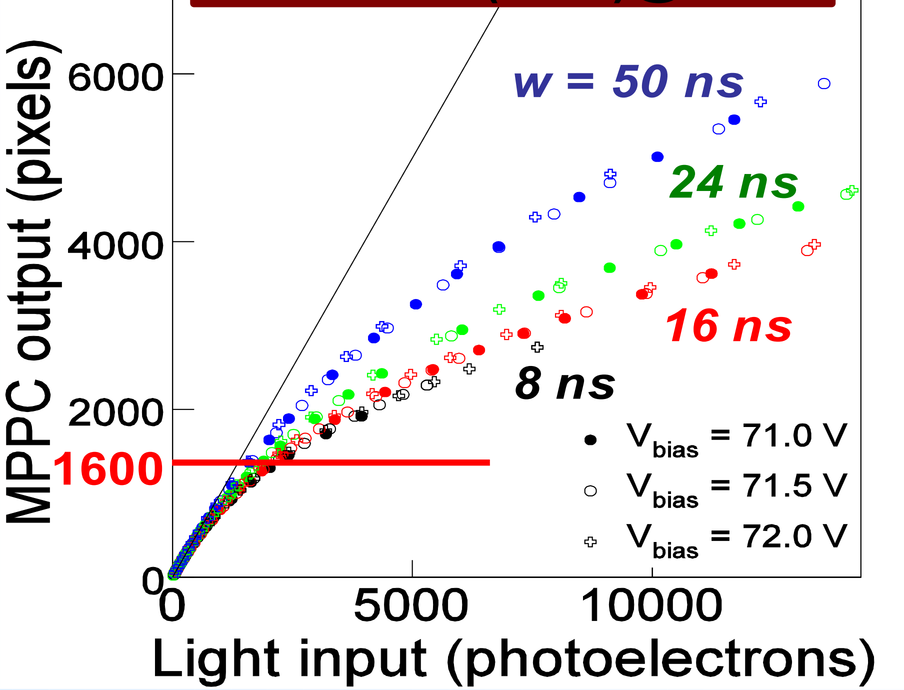
$$N_{sig.} = N_{all} \cdot \left(1 - e^{-\frac{PDE \cdot N_{ph.}}{N_{all}}}\right)$$

• pulses from scintillators with decay times longer than pixel recovery time can produce signals significantly exceeding number of micro cells

NIM A540 (2005) 368



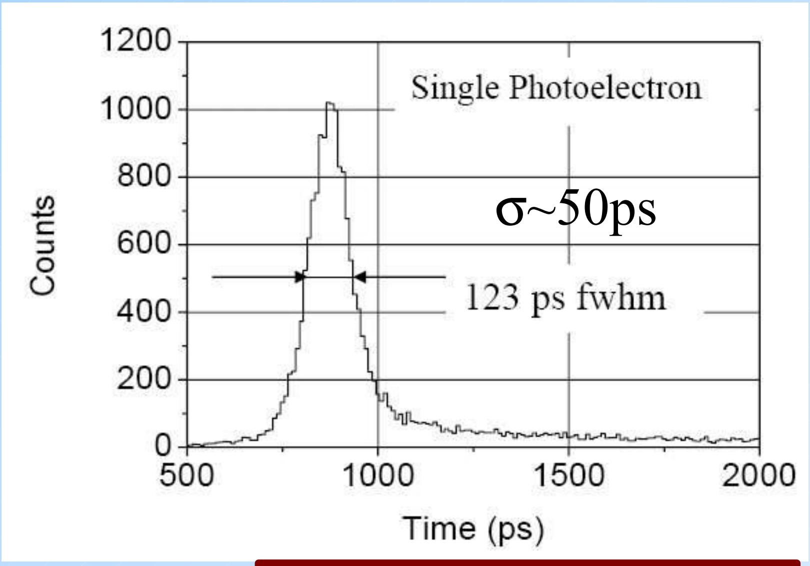
S. Uozumi (GLD)@PD07



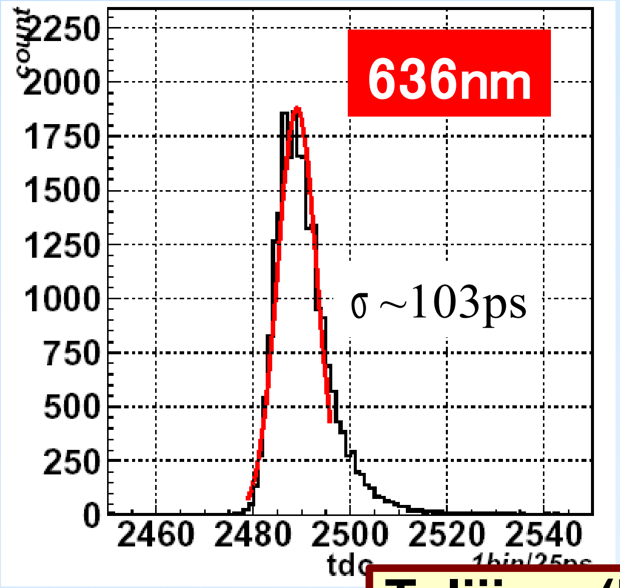
SiPM-Timing

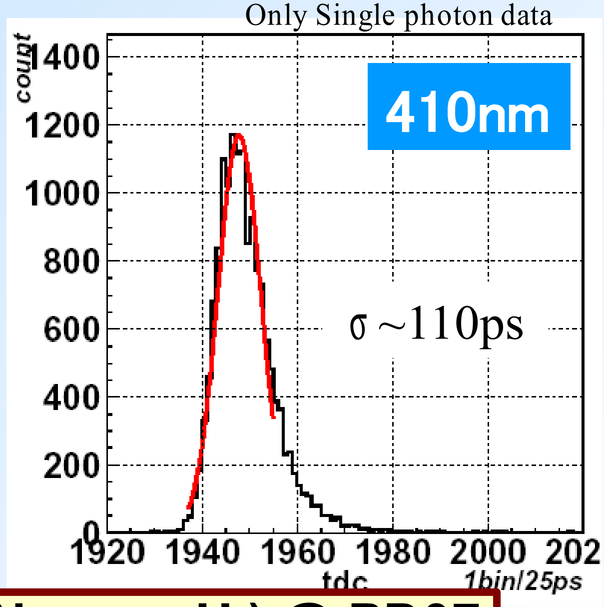
Fast rise time of the signal and high gain result in an excelent timing properties of SiPMs. Single photon timing resolution is on the order of 100ps. Applications to TOF, PET-TOF etc. are being investegated.

Sample MPPC
Bias -71.5V
Threshold 0.5pe
Only Single photon data



NIM A504 (2003) 48





T. Iijima (Nagoya U.) @ PD07

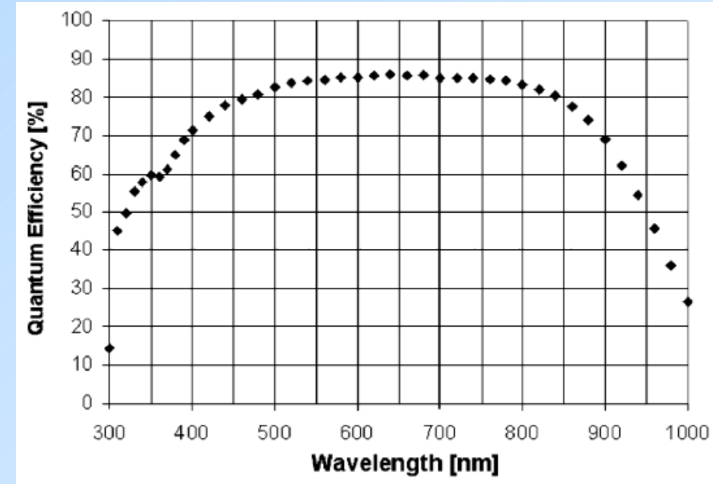
SiPM – Photon detection efficiency

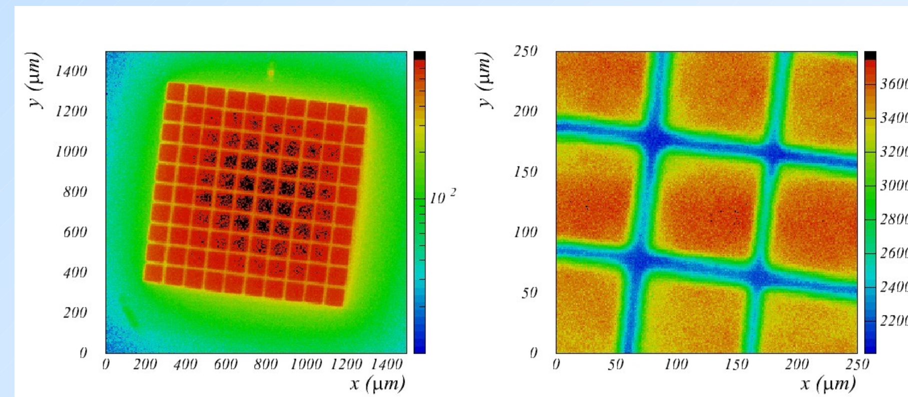
Photon detection efficiency (PDE) depends on three factors:

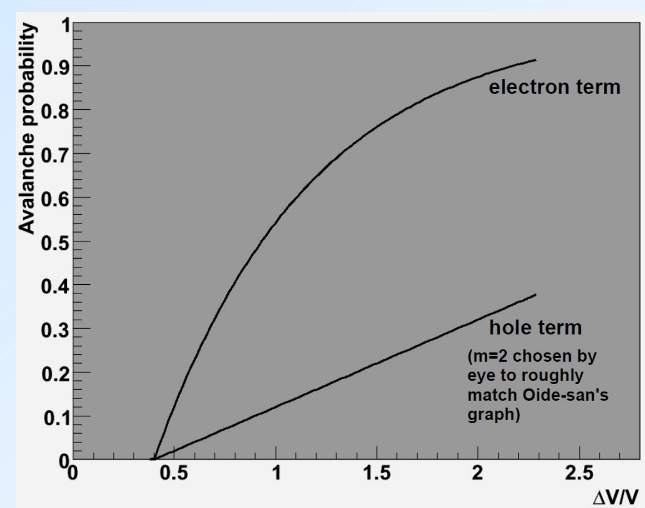
$$PDE = Q.E. \times \epsilon_{geom.} \times \epsilon_{Geiger}$$

- quantum efficiency (mainly absorption of photons in active volume)
- geometrical efficiency – ratio of active to total area
- probability for a carrier to initiate avalanche
  - depends on electric field
  - higher for electrons than holes

→ increases with overvoltage







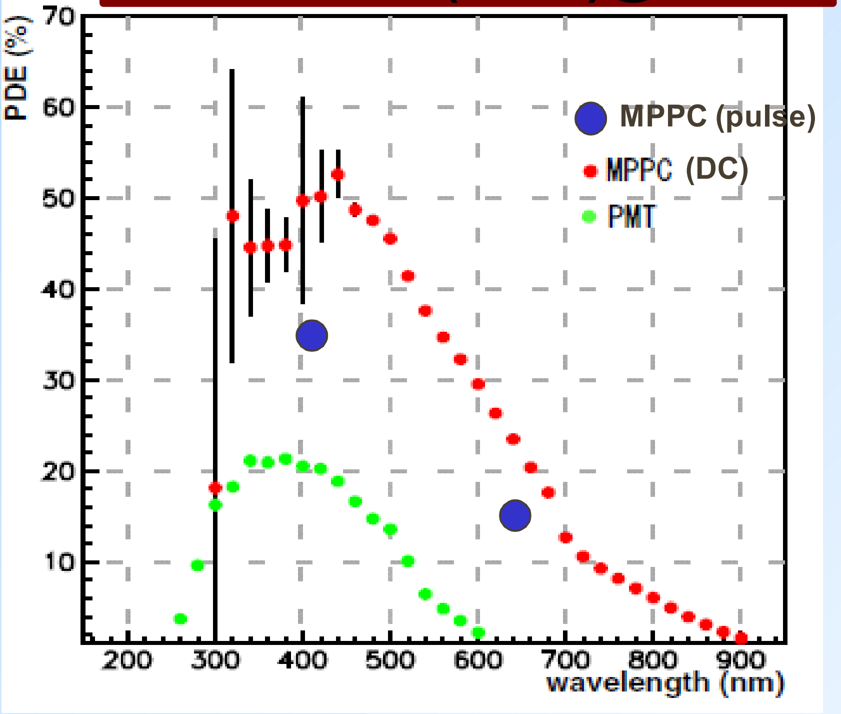
SiPM – PDE measurements

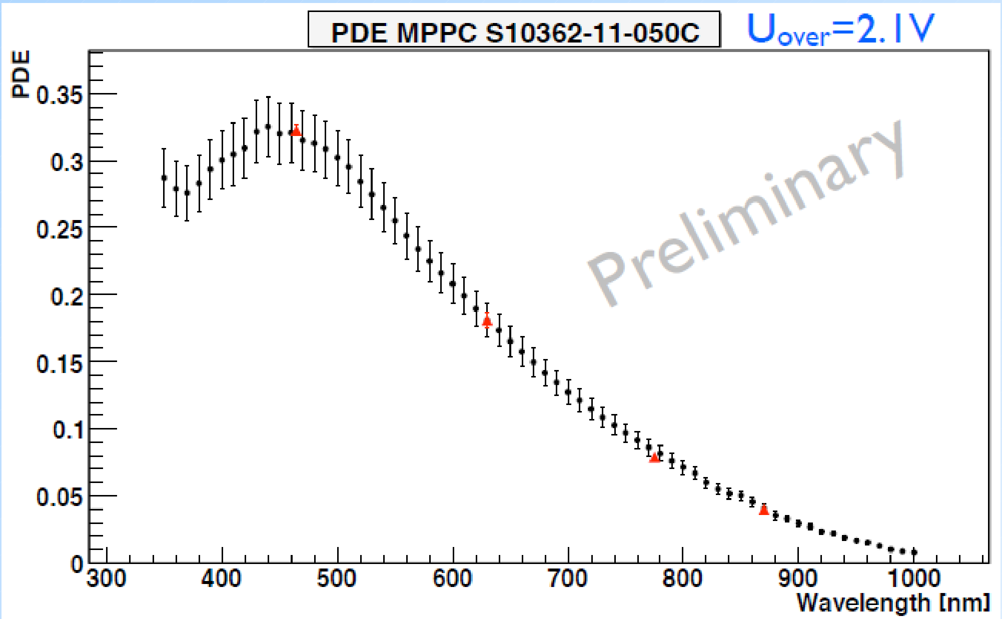
Standard measurement of QE by measuring photo current overestimates PDE by up to 30% due to the underestimation of the gain measured without including afterpulses.

More accurate results are obtained by pulse counting method.

Current measurement is renormalized to points measured by pulse counting.

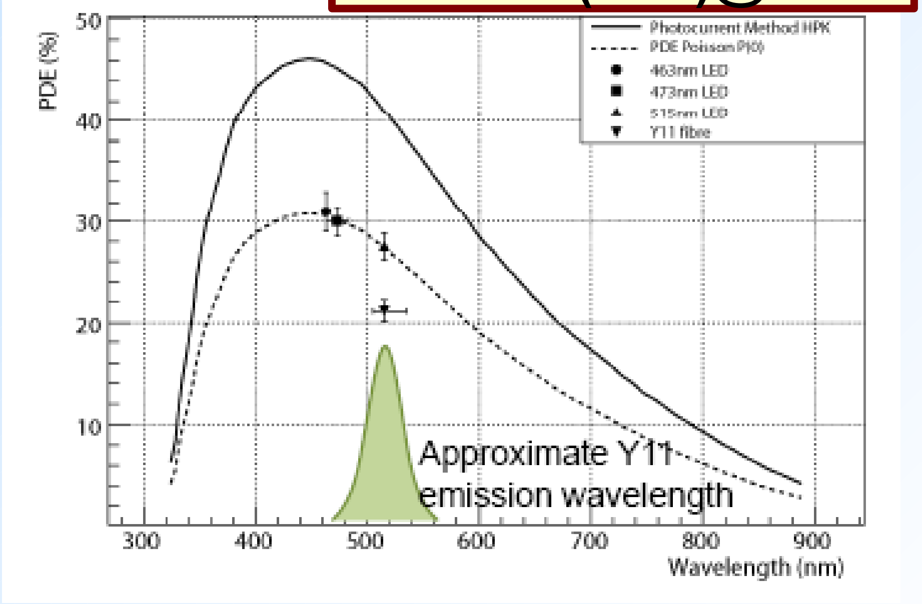
M. Yamaoka (Belle)@JPS07





A. Tadday (CALICE)@PD09

F. Retier (T2K)@PD09



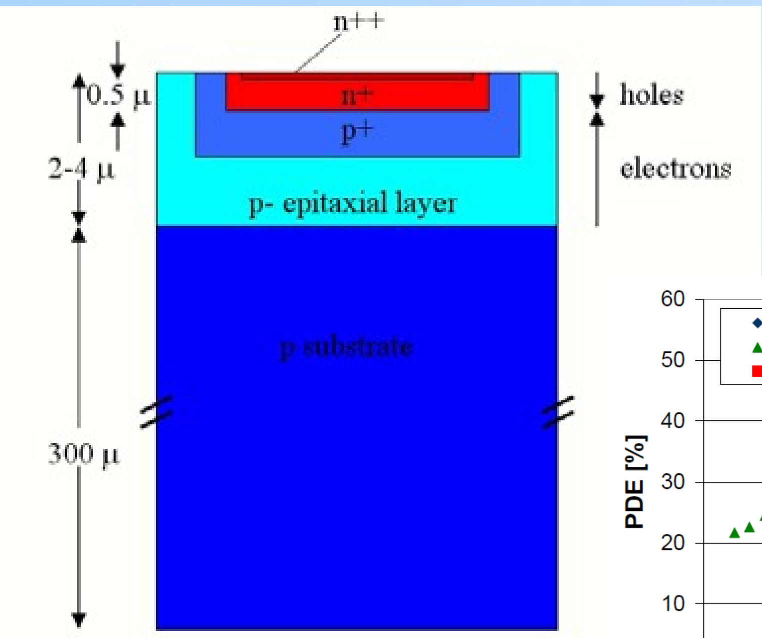
SiPM – p on n vs. n on p

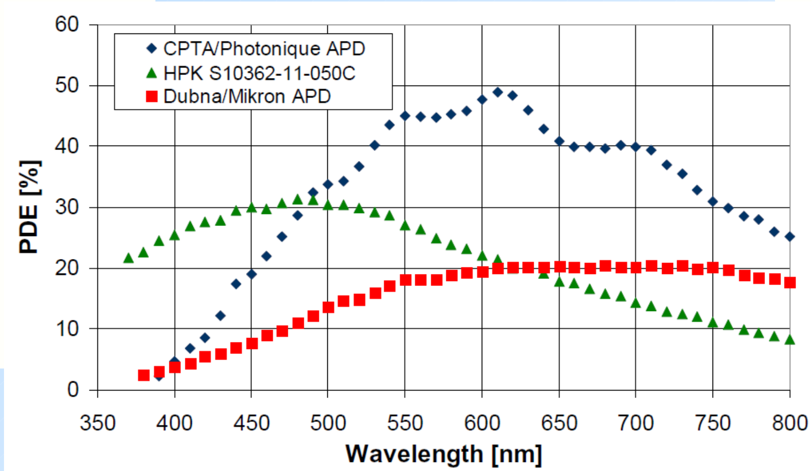
n on p - green/red light sensitive:

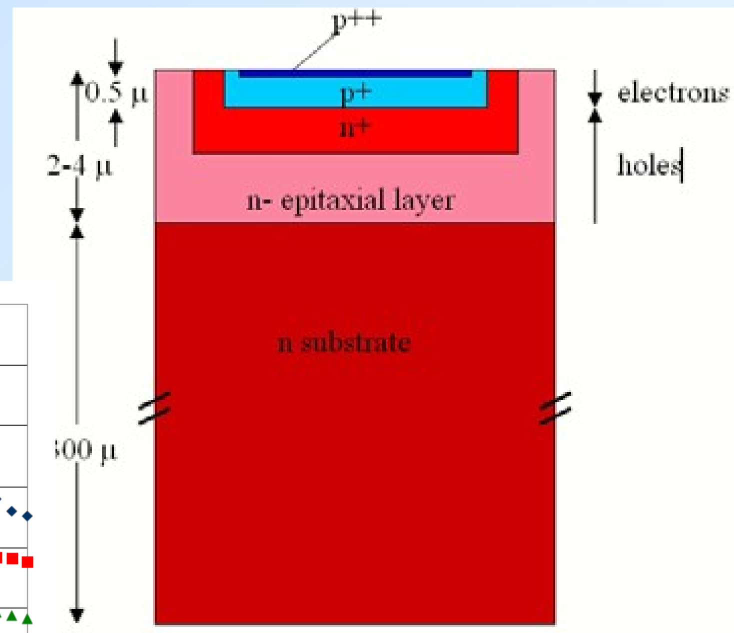
- electrons drift to Geiger region from substrate and holes from surface side
- higher dark count rate – most of the thermally generated carriers arriving to Geiger region are electrons

p on n - green/blue light sensitive:

- electrons drift to Geiger region from surface and holes from substrate side
- lover dark count rate – most of the thermally generated carriers arriving to Geiger region are electrons



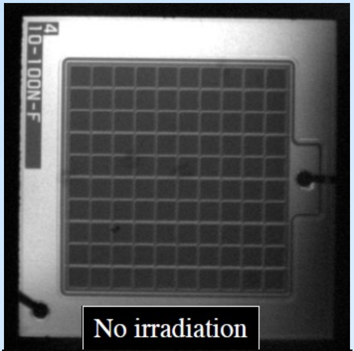


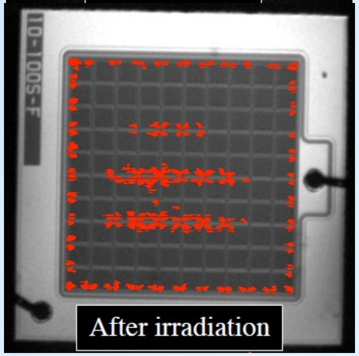


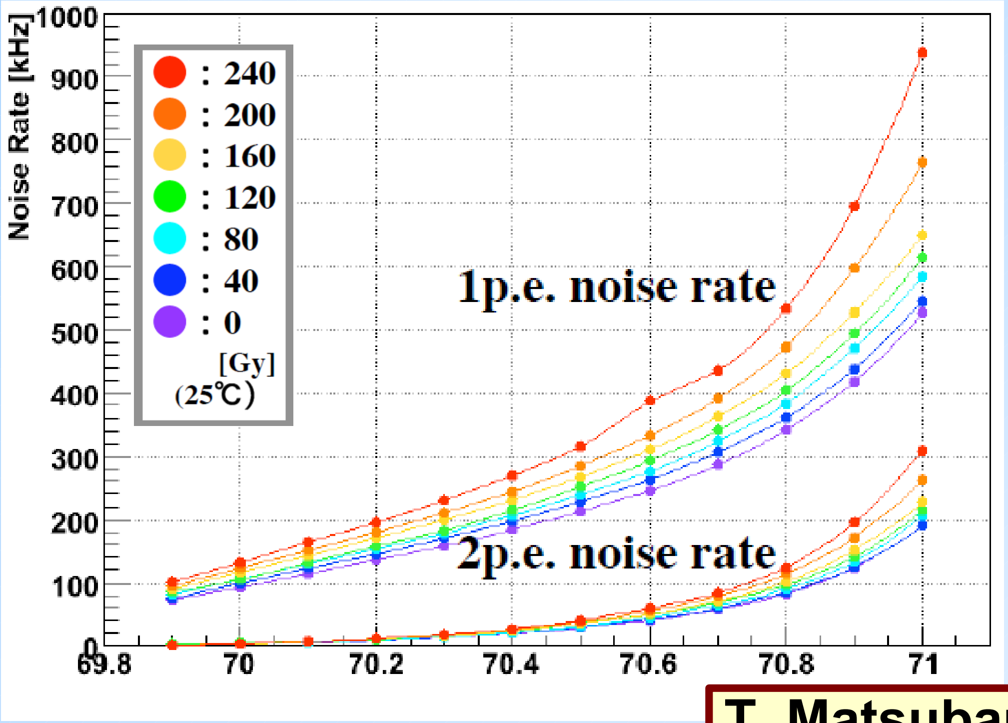
J. Musienko (INR/NU)@PD07

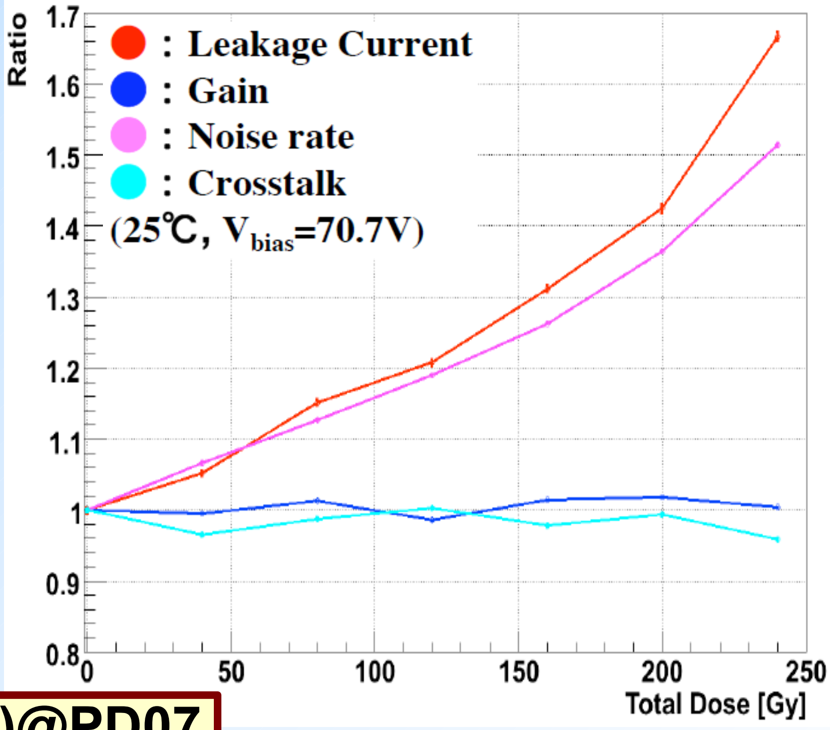
SiPM - Irradiation by γ rays from ^{60}Co

- moderate leakage current is observed and corresponding increase of dark counts
- functionality still OK after 240 Gy
- damage is produced mainly in SiO_2 layer – along the metal traces





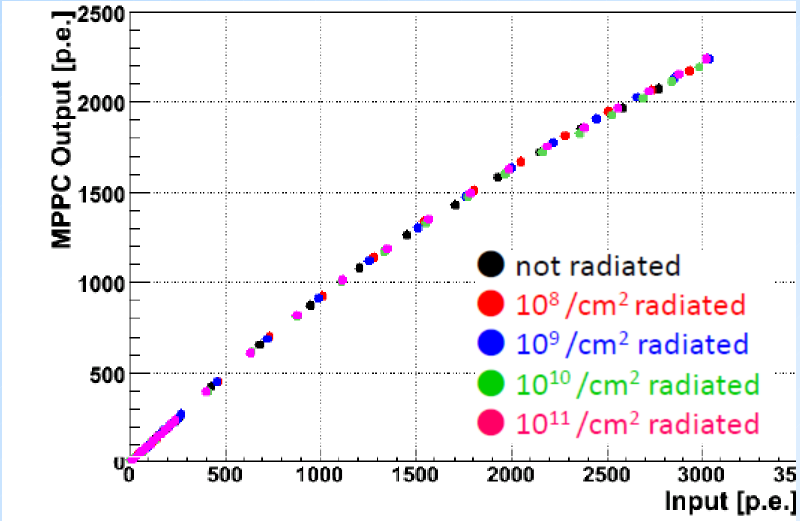


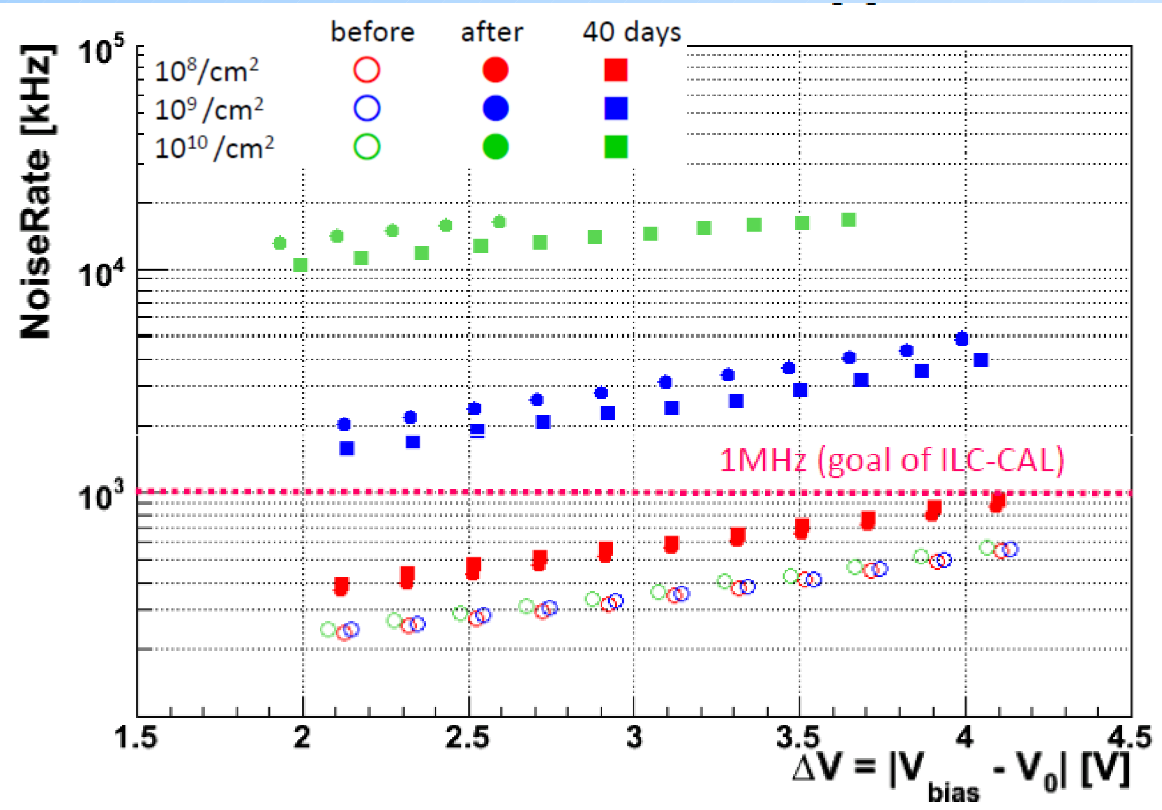


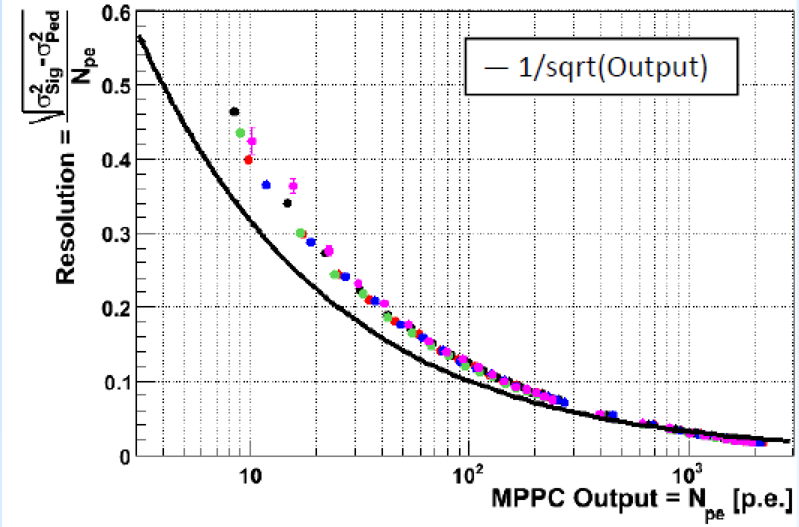
T. Matsubara (TIT)@PD07

SiPM – p,n irradiation

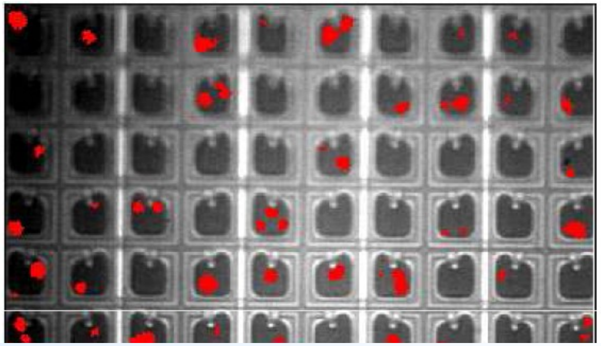
- non ionizing energy loss coses lattice defects where carriers are thermally generated → dark count rate increases as expected
- increase of afterpulses
- detection of many photon pulses still OK





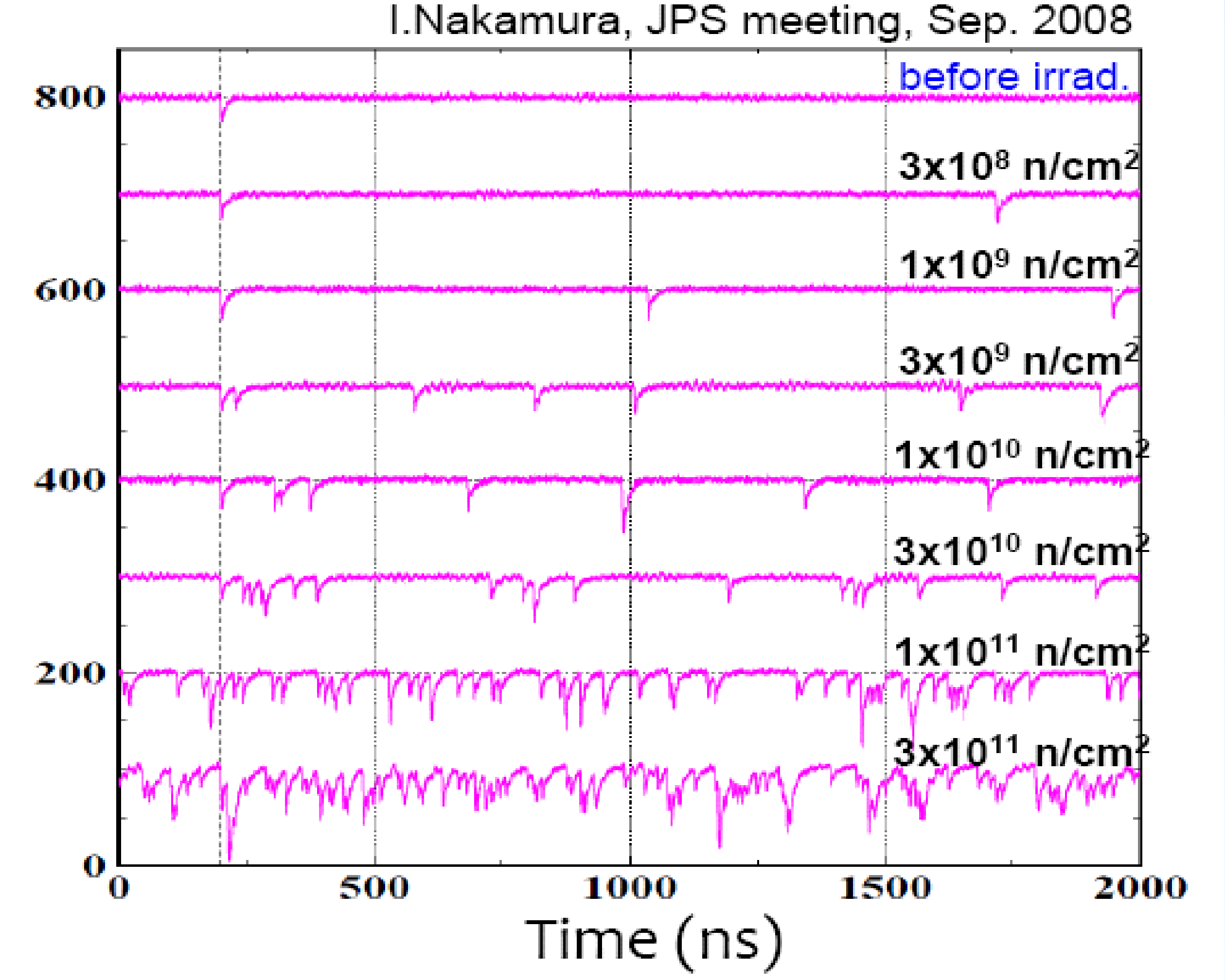


10^{11} /cm^2 irradiated (zoomed)



Y. Sudo (Tsukuba)@PD09

SiPM – p,n irradiation



→ Very hard to use present SiPMs as single photon detectors after fluence of 10^{11} n/cm^2 1MeV neutrons

SiPM – Summary of characteristics

In many ways SiPM behaves like an ordinary PMT and is a very promising photon detector for Cherenkov applications.

Advantages:

- high PDE
- low bias voltage (less than 100V)
- high gain – single photon detection
- excellent timing
- operation in magnetic field
- (potentially low cost?)

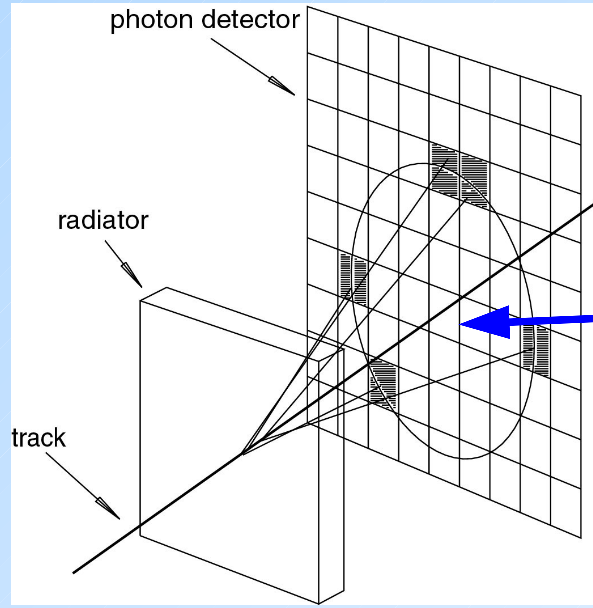
Disadvantages (low light intensity):

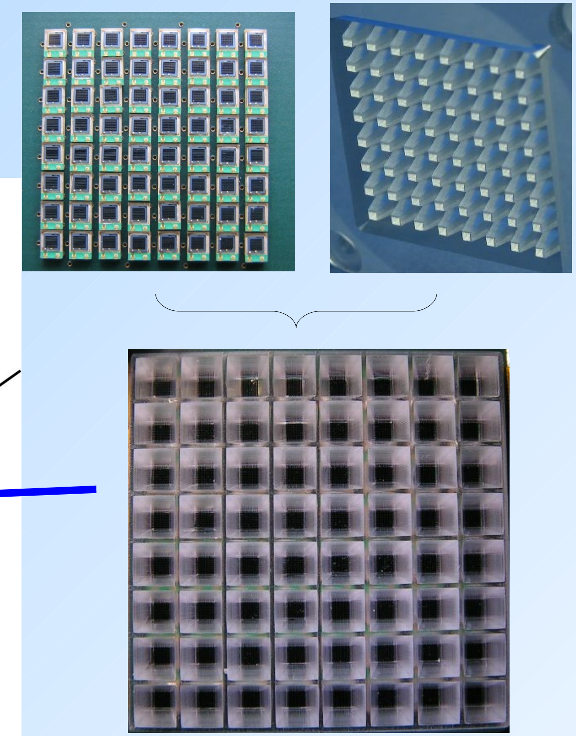
- high dark count rate
- sensitive to radiation damage (n,p)

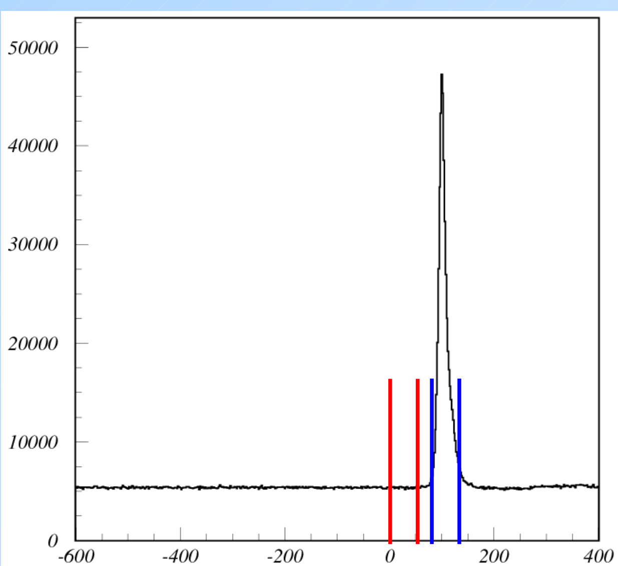
Belle II aerogel RICH development

SiPM based photon detector was considered for aerogel RICH.

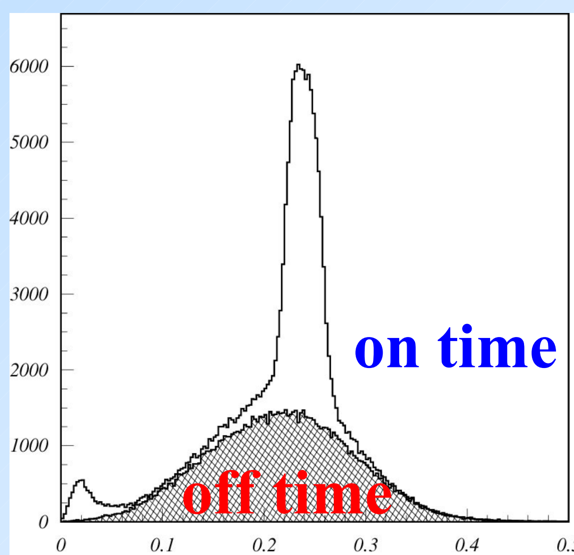
- 8x8 array of MPPCs + light guides was produced
- module was tested in the test beam with 1cm thick aerogel radiator and performed well



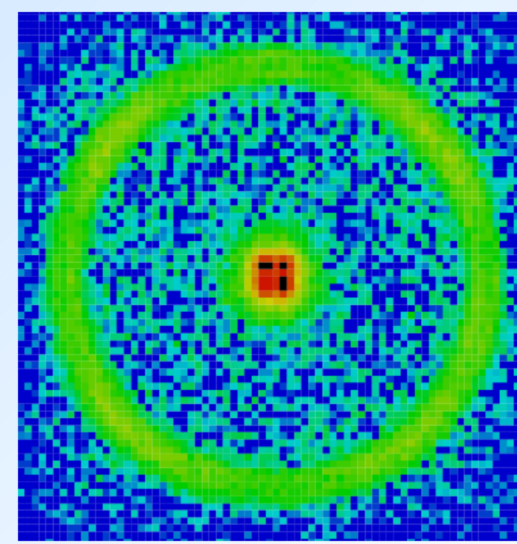




TDC [100ps/ch]

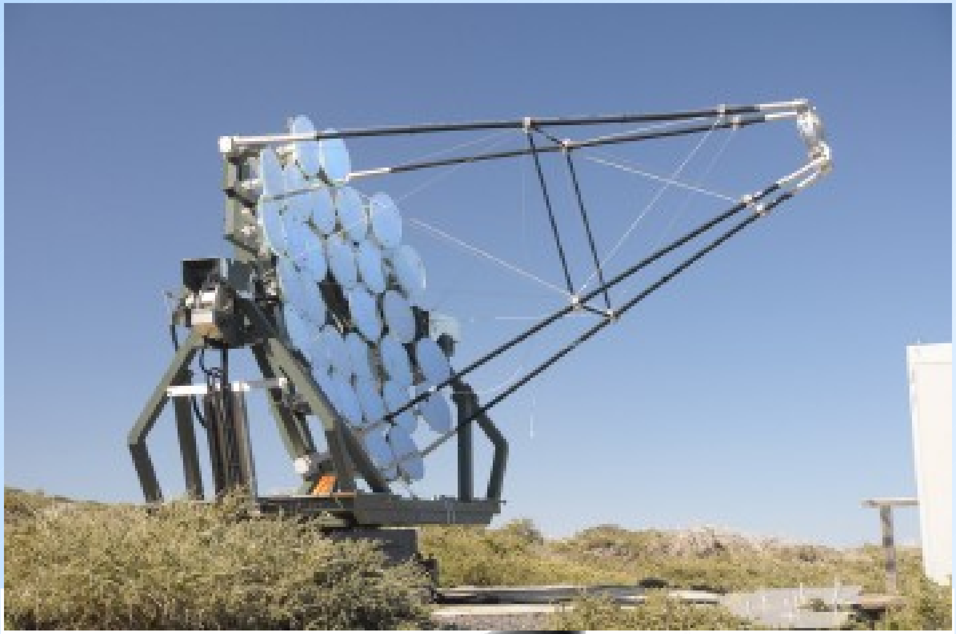


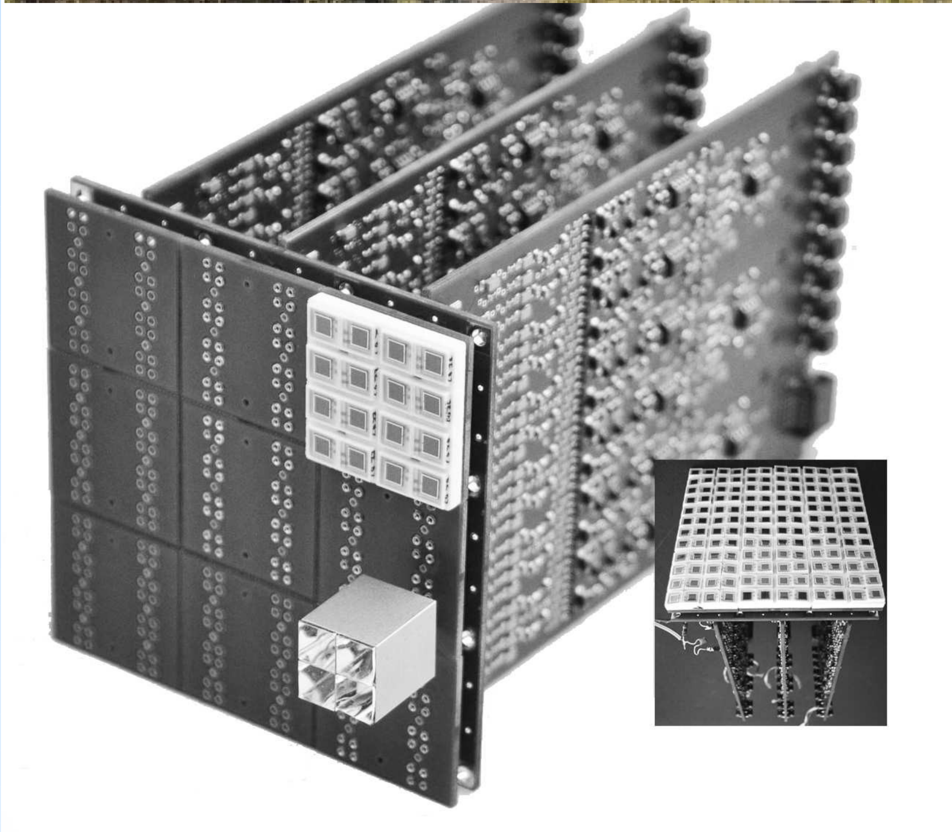
Cherenkov angle



FACT project

• SiPM based module for camera for a Cherenkov telescope (DWARF: Dedicated multi Wavelength AGN Research Facility)
• 144 SiPMs + Winston cones
• 36 electronic channels



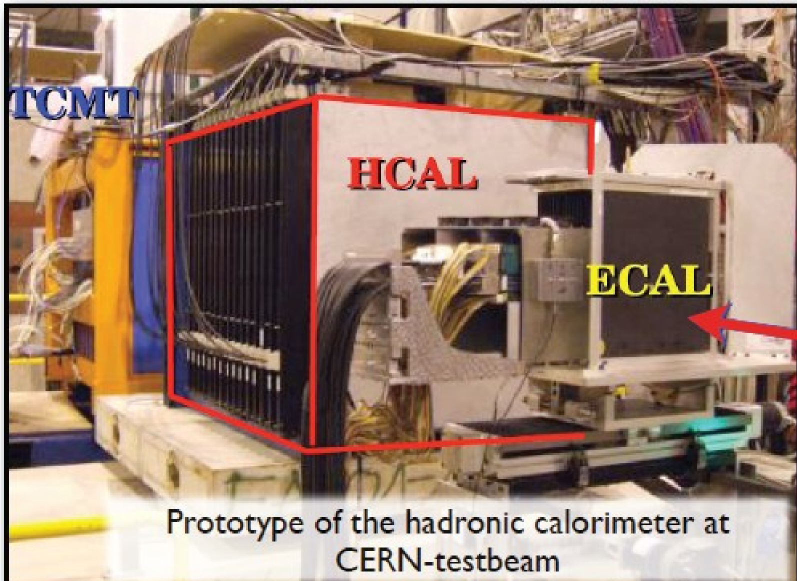


T. Krähenbühel (ETH Zurich) @ PD09

CALICE – first large system experience

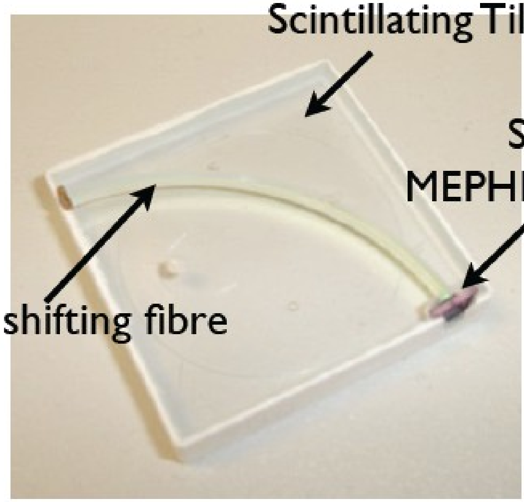
- only 8 bad channels in 3 years of testing – mostly mechanical problems

CALICE: Calorimeter for the Linear Collider Experiment



Prototype of the hadronic calorimeter at CERN-testbeam

~ 7600 SiPMs



Wavelength schifting fibre
blue → green (highest sensitivity of sensor)
+ response uniformity

- Several producers/sensor types
- Which sensor ist best for the application?
- Characterisation is needed

A. Tadday (CALICE)@PD09

BACKUP SLIDES

Main sources of information

Conferences:

- PD09, Matsumoto (http://www-conf.kek.jp/PD09/)
- TIPP09, Tsukuba (http://tipp09.kek.jp/)
- PD07, Kobe (http://www-conf.kek.jp/PD07/)
- RICH2010, Cassis (http://rich2010.in2p3.fr/)
- RICH2007, Trieste (http://rich2007.ts.infn.it/index.php)

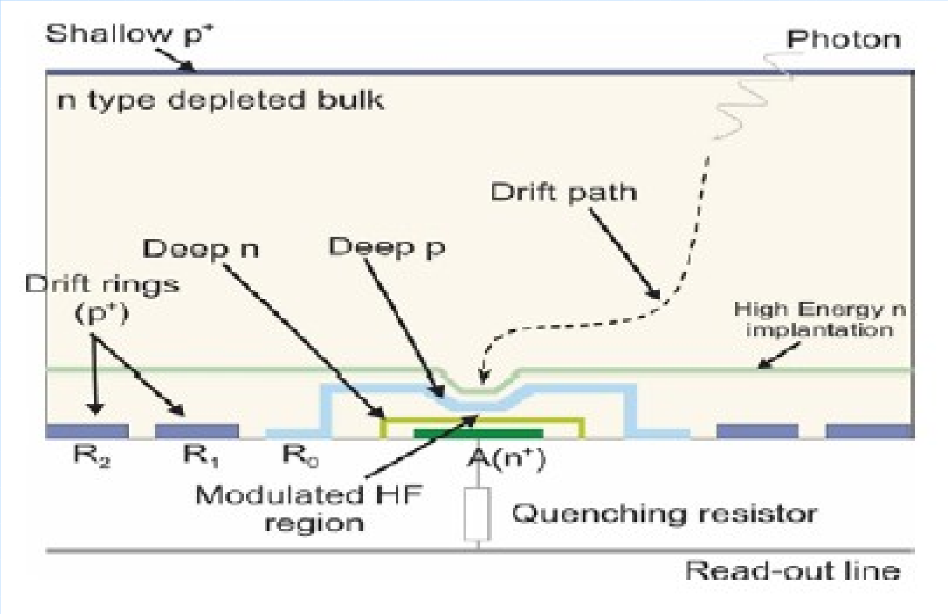
Overview papers:

- D. Renker and E. Lorenz (JINST-P04004)
- D. Renker (NIM A598 (2009) 207)
- J. Haba (NIM A595 (2008) 154)

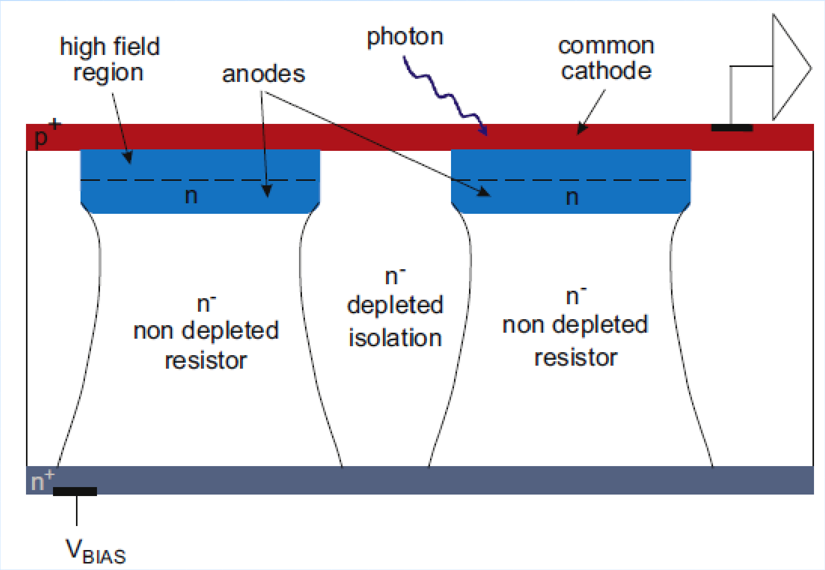
and other conferences and related papers …

SiPM – different types

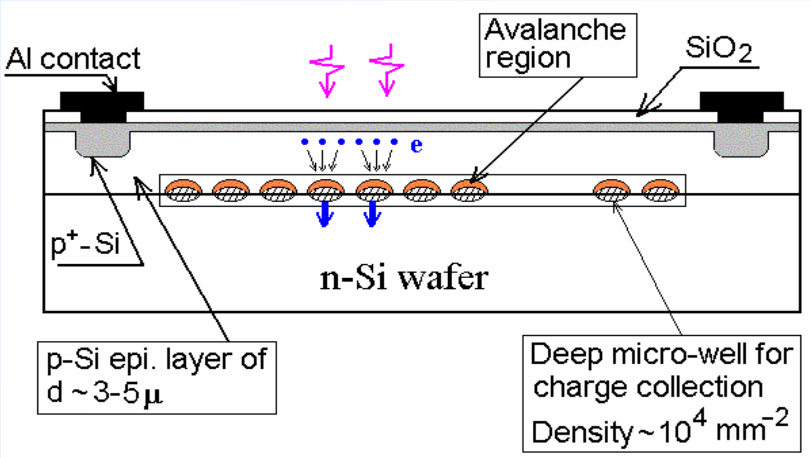
back illuminated:



bulk integrated resistor:



MAPD with deep micro-wells (MAPD-3):

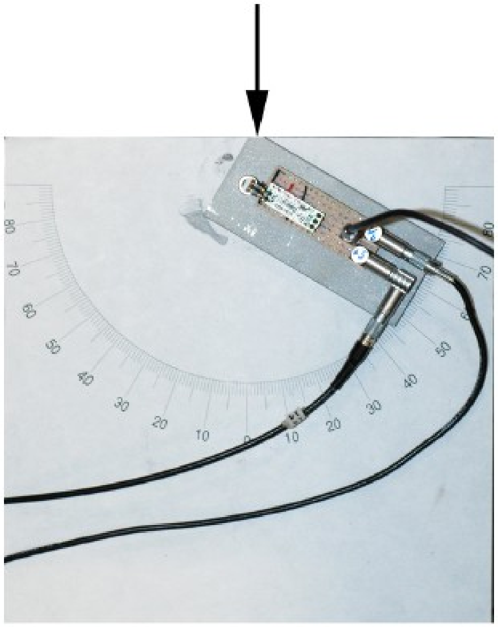


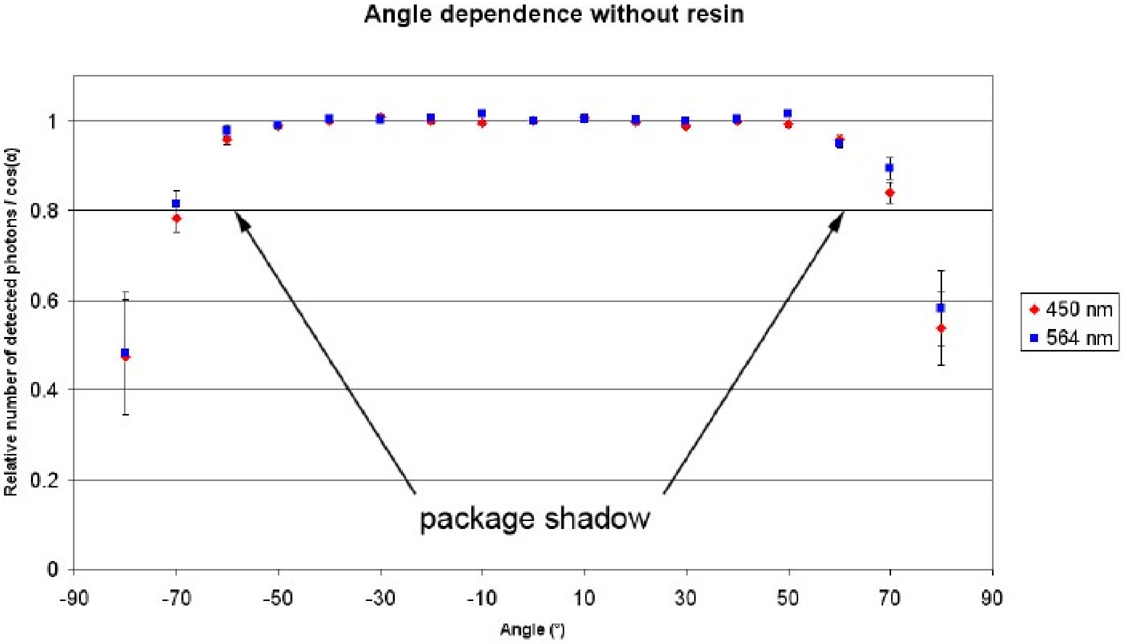
Samo Korpar
University of Maribor and Jožef Stefan Institute

SiPM – PDE vs. incidence angle

When light concentrators are used photon incidence angles on SiPM are increased. PDE shows no variation up to measured angle of 60°.

The epoxy resin was removed to get rid of refraction.





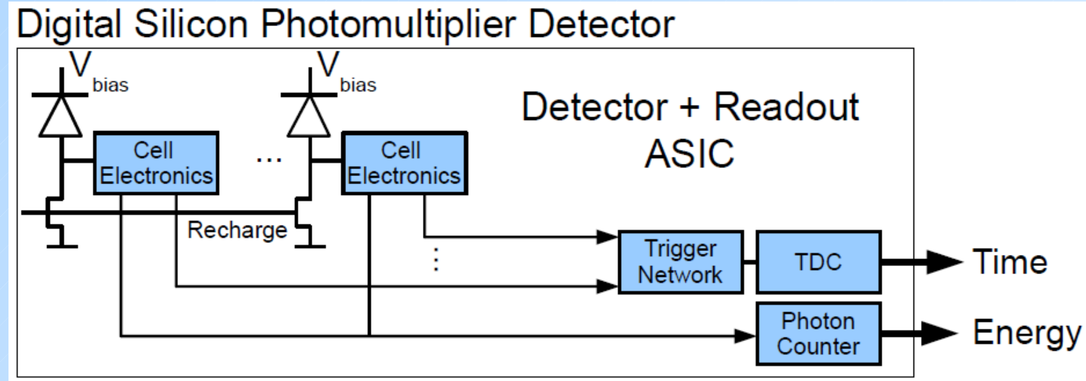
⇒ No angle dependence was found within the measurement error (approx. 1%) up to 60°.

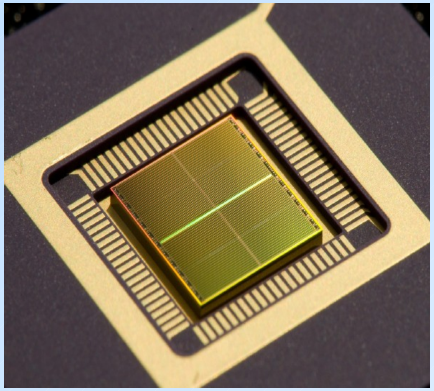
T. Krähenbühel (ETH Zurich) @ PD09

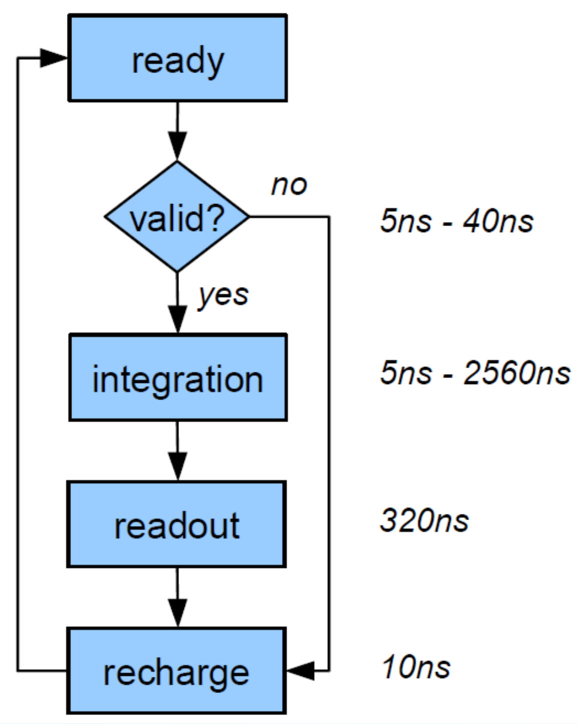
dSiPM-Digital SiPM (Philips)

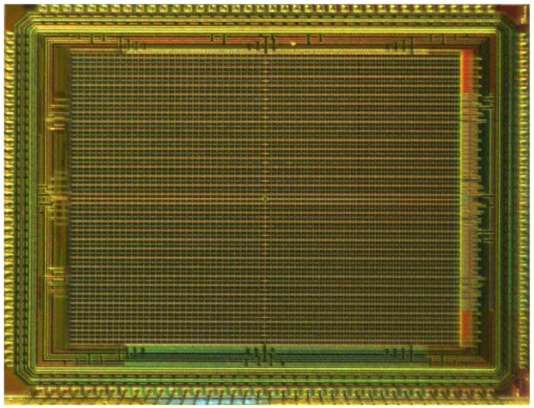
Signal from each pixel is is digitized and the information is processed on chip:

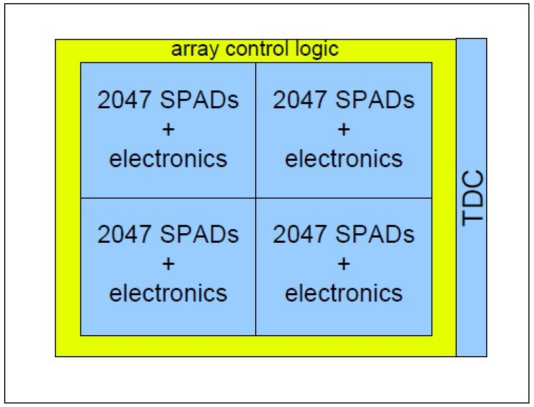
- time of first fired pixel is measured
- number of fired pixels is counted
- active control is used to recharge fired cells
- 4 x 2047 micro cells
- 50% fill factor including electronics
- integrated TDC with 8ps resolution





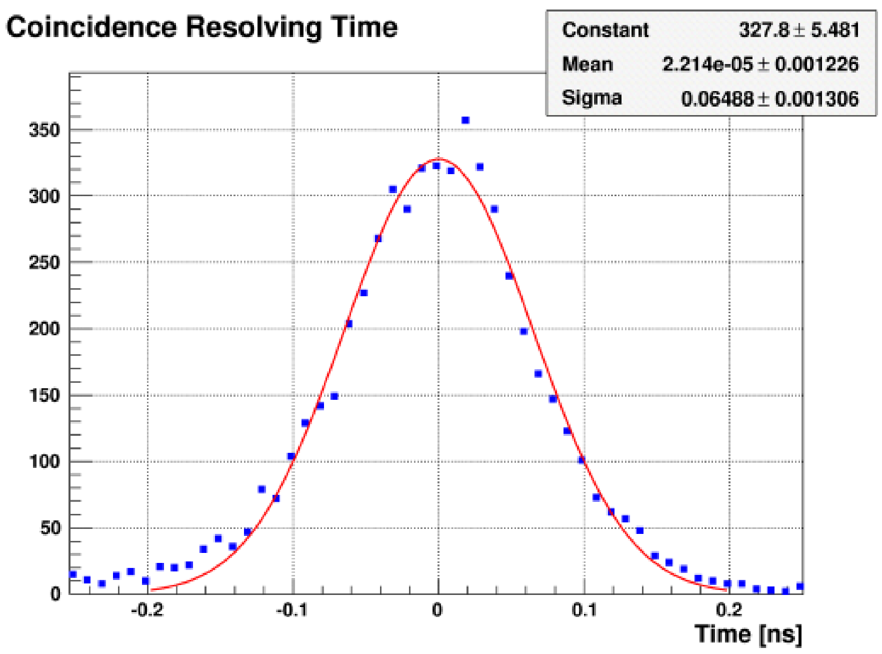


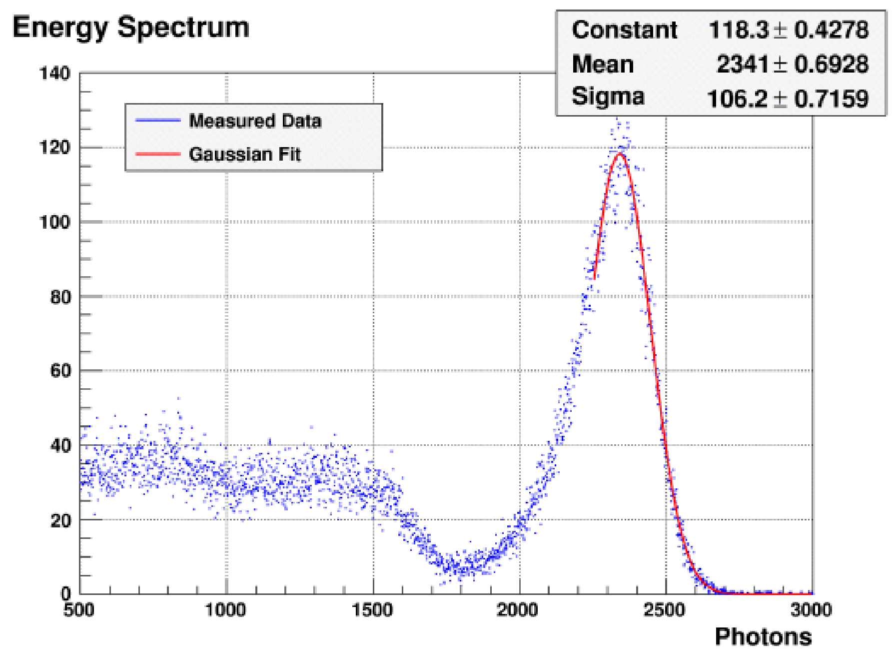




T. Frach (Philips) @ IEEE2009

dSiPM – TOF-PET application





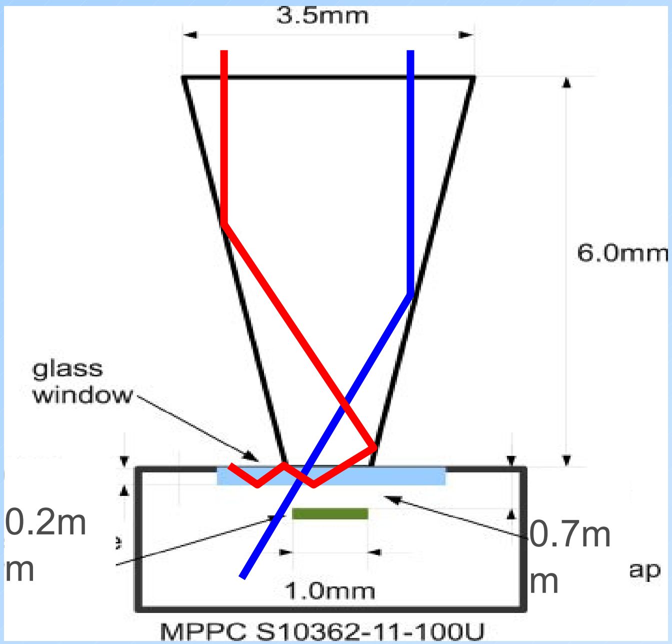
- 3X3x5 mm³ LYSO in coincidence, ^{22}Na source
- Time resolution in coincidence: **153ps** FWHM
- Energy resolution (excluding escape peak): **10.7%**
- Excess voltage 3.3V, 98.5% active cells
- Room temperature (31°C board temperature, not stabilized)

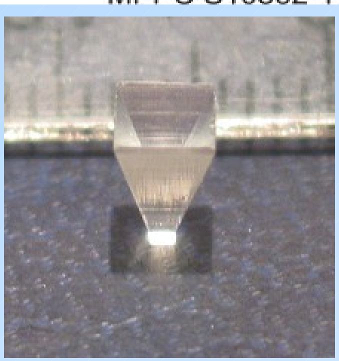
T. Frach (Philips) @ IEEE2009

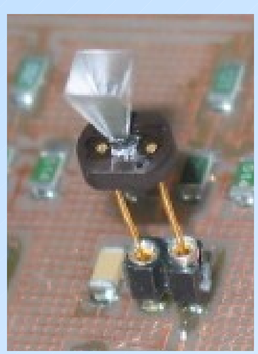
Light concentration

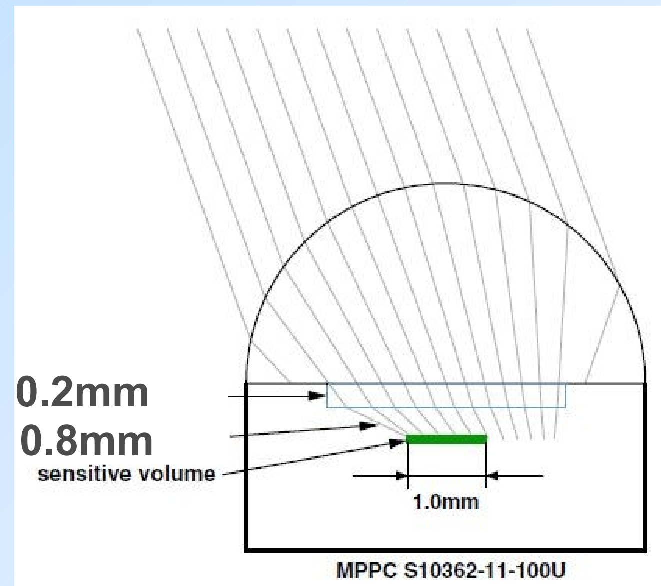
Can be used if light comes within the limited solid angle

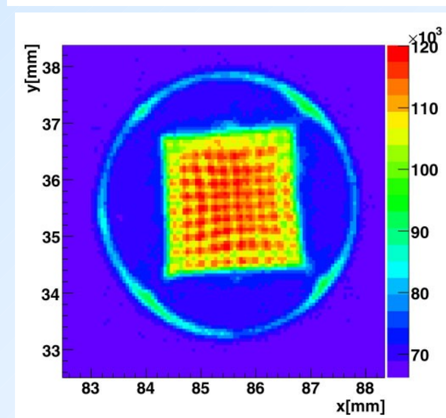
- Winston cones produce large angular spread at the exit surface – photons can miss the active area
- hemispherical light concentrators give better results with large spacing between concentrator and SiPM

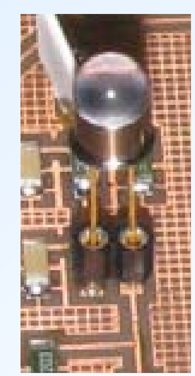






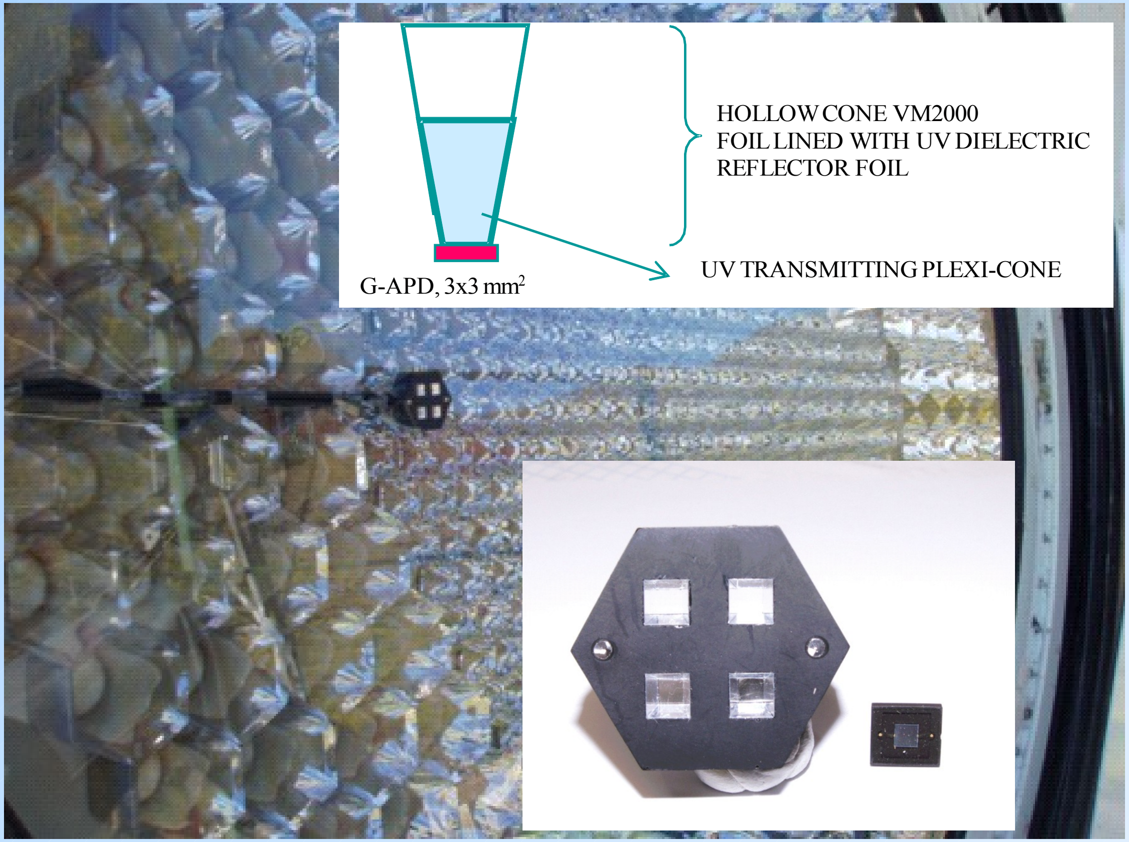


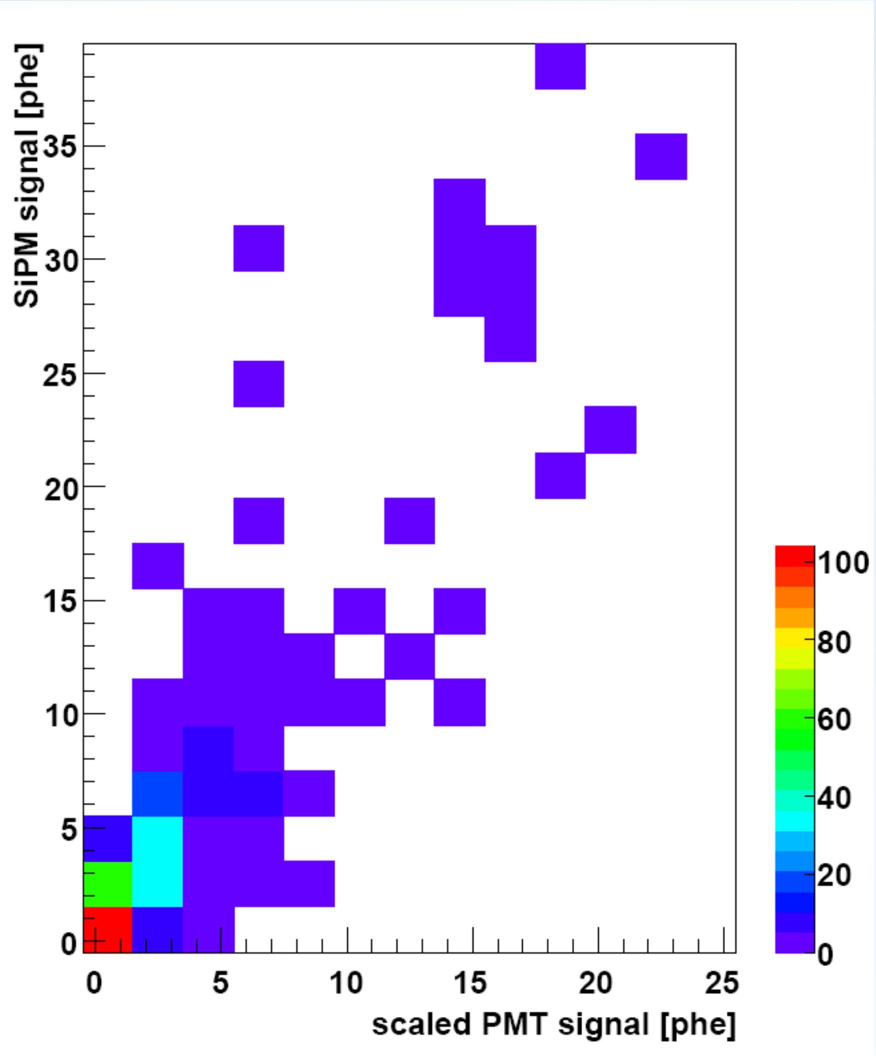




MAGIC project

First detection of air-shower Cherenkov light presented at RICH 2007.
On average larger signal in SiPM modules than in PMT modules.

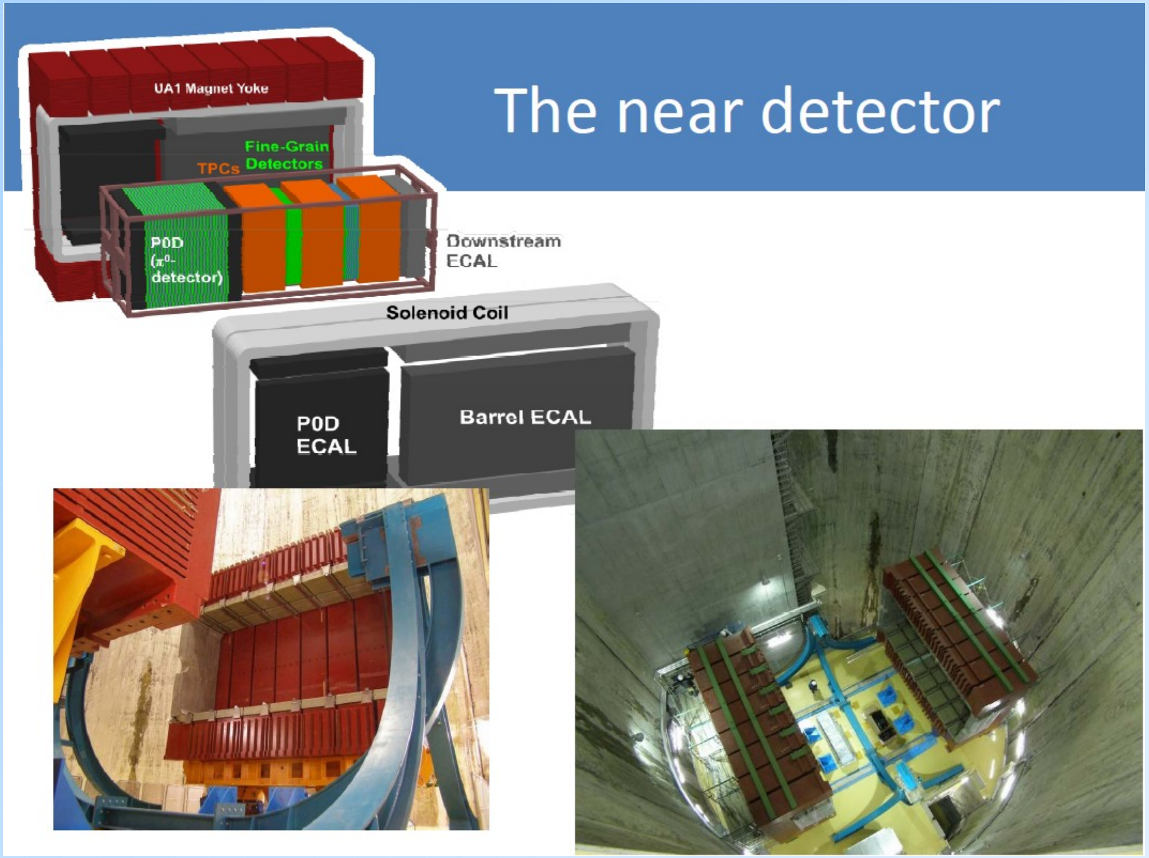




E. Lorenz (MPI,ETH) @ RICH2007

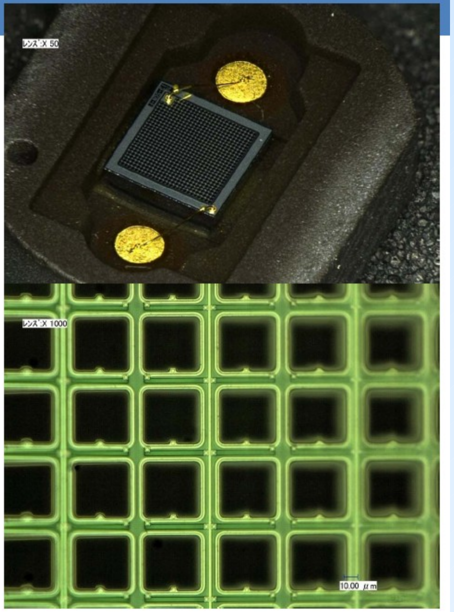
T2K – first experiment with SiPMs

- same type of SiPM used in many detectors in total more than 60000
- all have been tested → very low number of bad samples



Using the same MPPC

- 1.3x1.3 mm^2 specifically designed for T2K
  - Well suited for 1 mm diameter fiber
- 667 pixels
  - 26x26 50 μm pixels minus 9 in the corner for lead
- Dark noise < 1.2 MHz at nominal voltage (7.5 10^5 gain at 25C)



	Institution	tested	bad
FGD	Kyoto	9,559	5
ECAL	Imperial/warwick	4,000	0
INGRID	Kyoto	8,235	4
INGRID	Ecole Polytechnique	3,194	?
POD	Colorado State	11,500	80*
SMRD	Louisiana State	1,717	11*
SMRD	INR Moscow	600	1
SMRD	Warsaw University of Technology	1,202	4

* Conservatively removed

F. Retier (T2K)@PD09