Status and perspectives of solid state photon detectors

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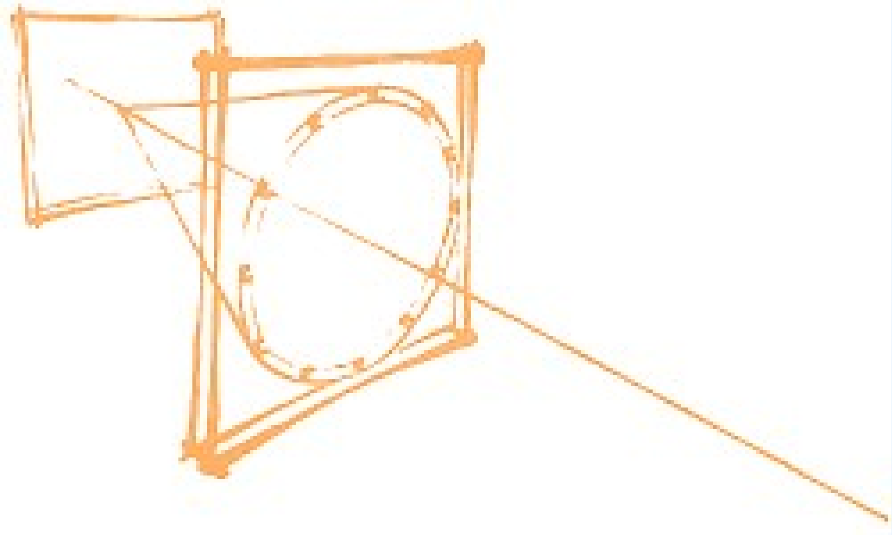


Outline

- 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:
  - aerogel RICH development for Belle II
  - astrophysics Cherenkov telescopes
  - CALICE and T2K large system experience
- Summary

Main sources of information

Conferences:

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

Overview papers:

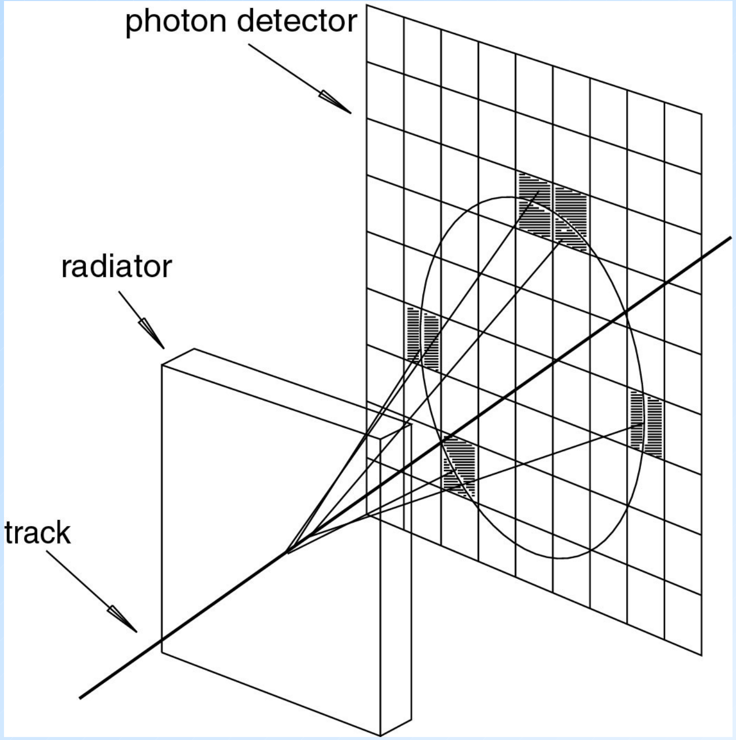
- D. Renker and E. Lorenz (JINST-P04004)
- D. Renker (NIM A598 (2009) 207)
- J. Haba (NIM A595 (2008) 154)

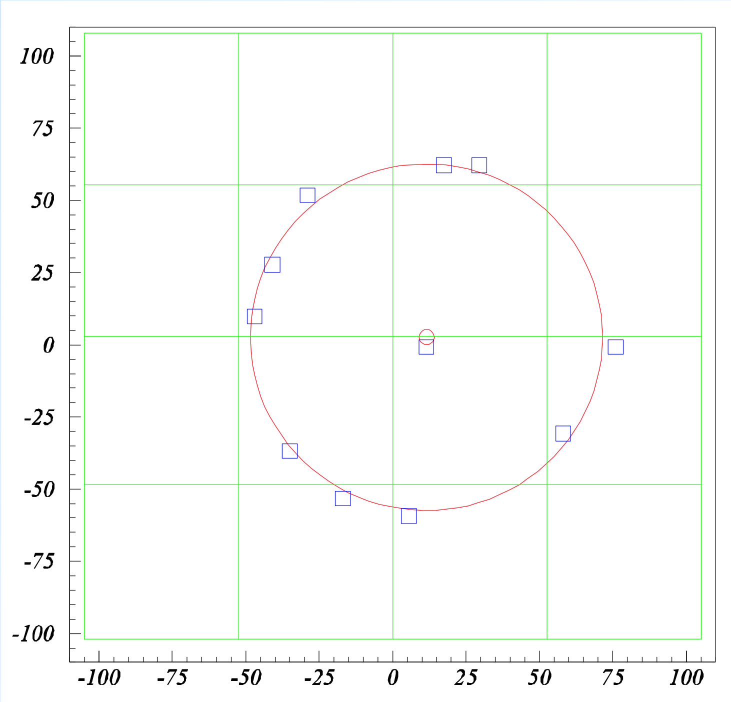
and other conferences and related papers …

Introduction

Photo sensor requirements for the detectors based on Cherenkov light (RICH, Cherenkov light TOF, cosmic ray Cherenkov telescopes):

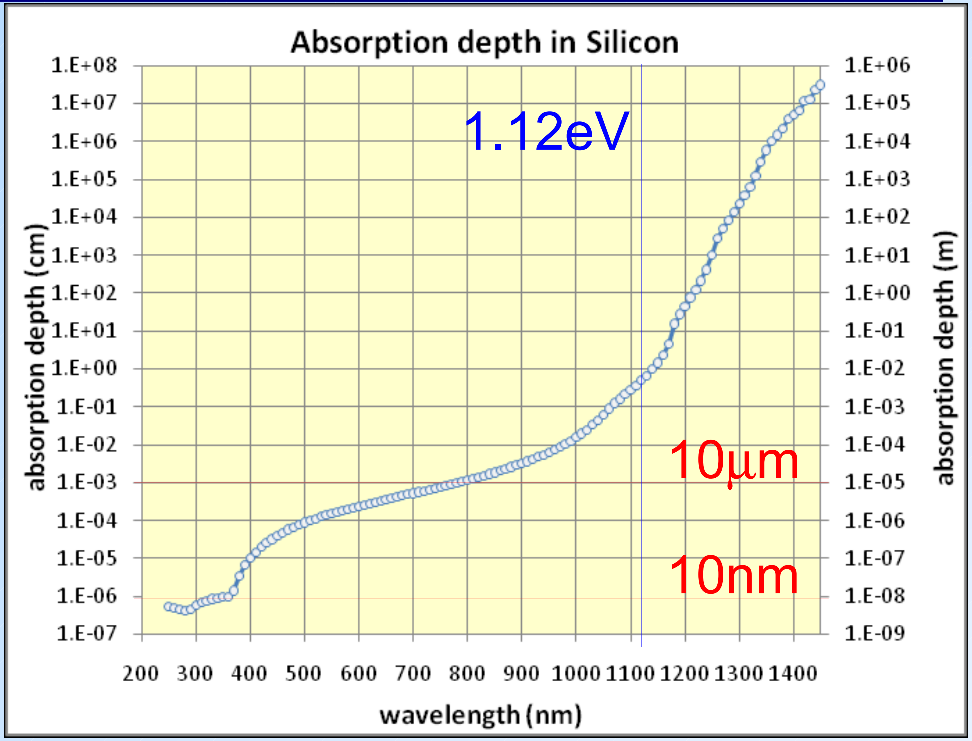
- single photon sensitivity (low intensity)
- high photon detection efficiency
- fast timing (background suppression and timing applications)
- low noise

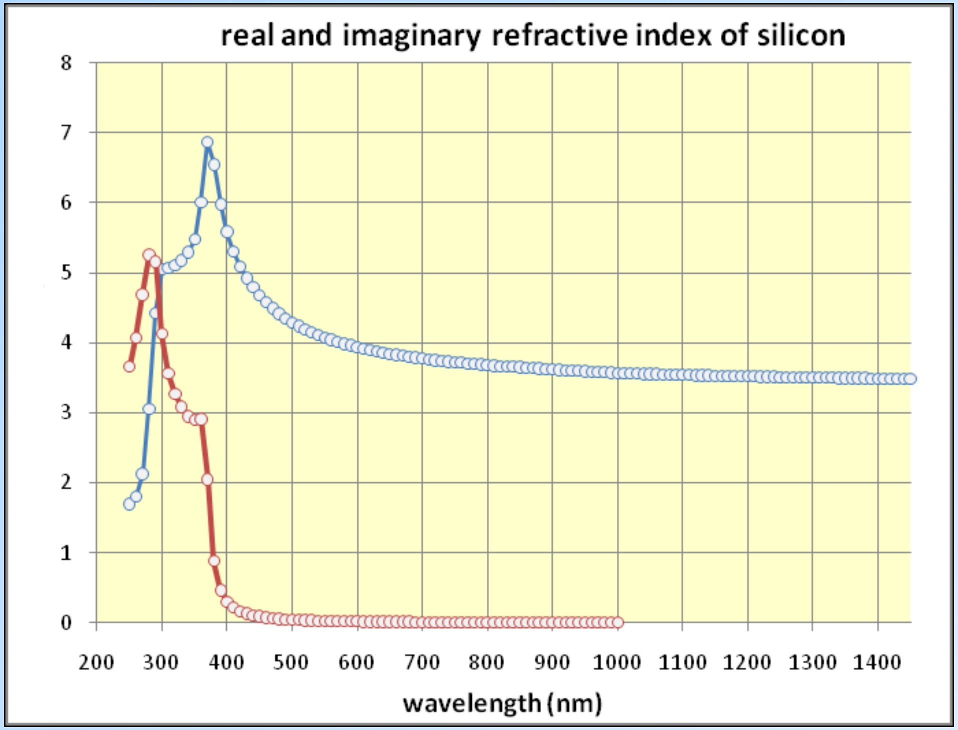




Si optical properties

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





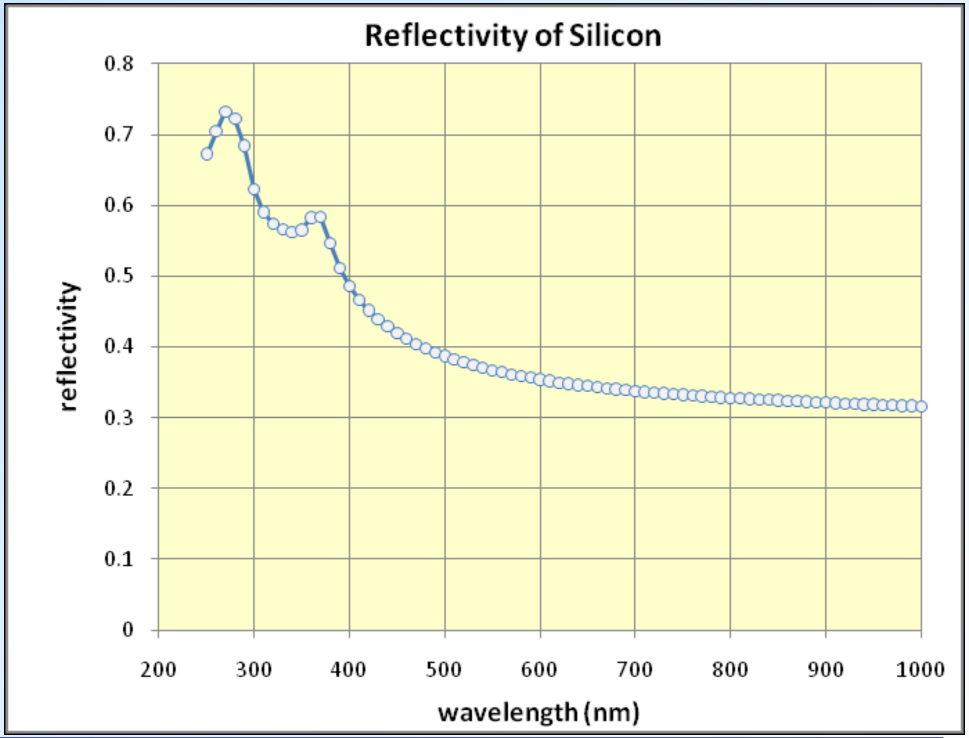
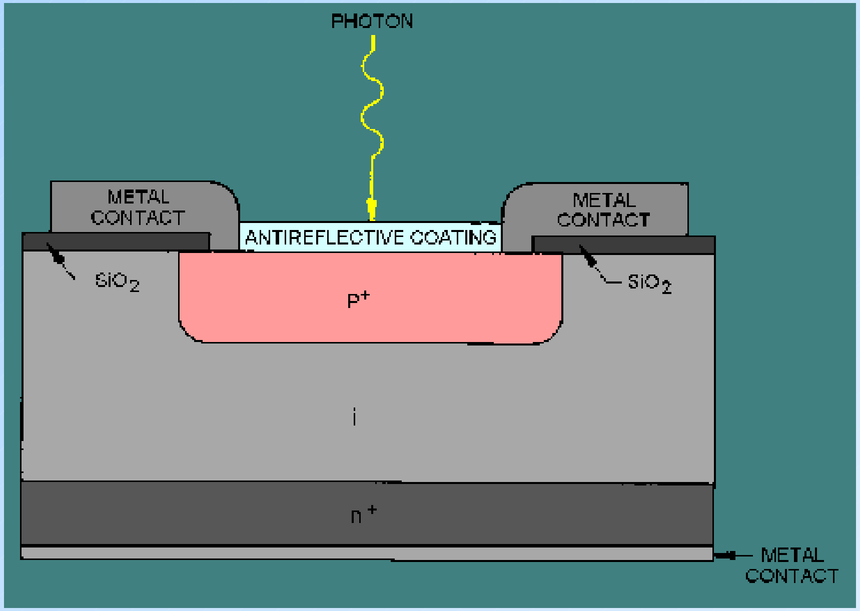
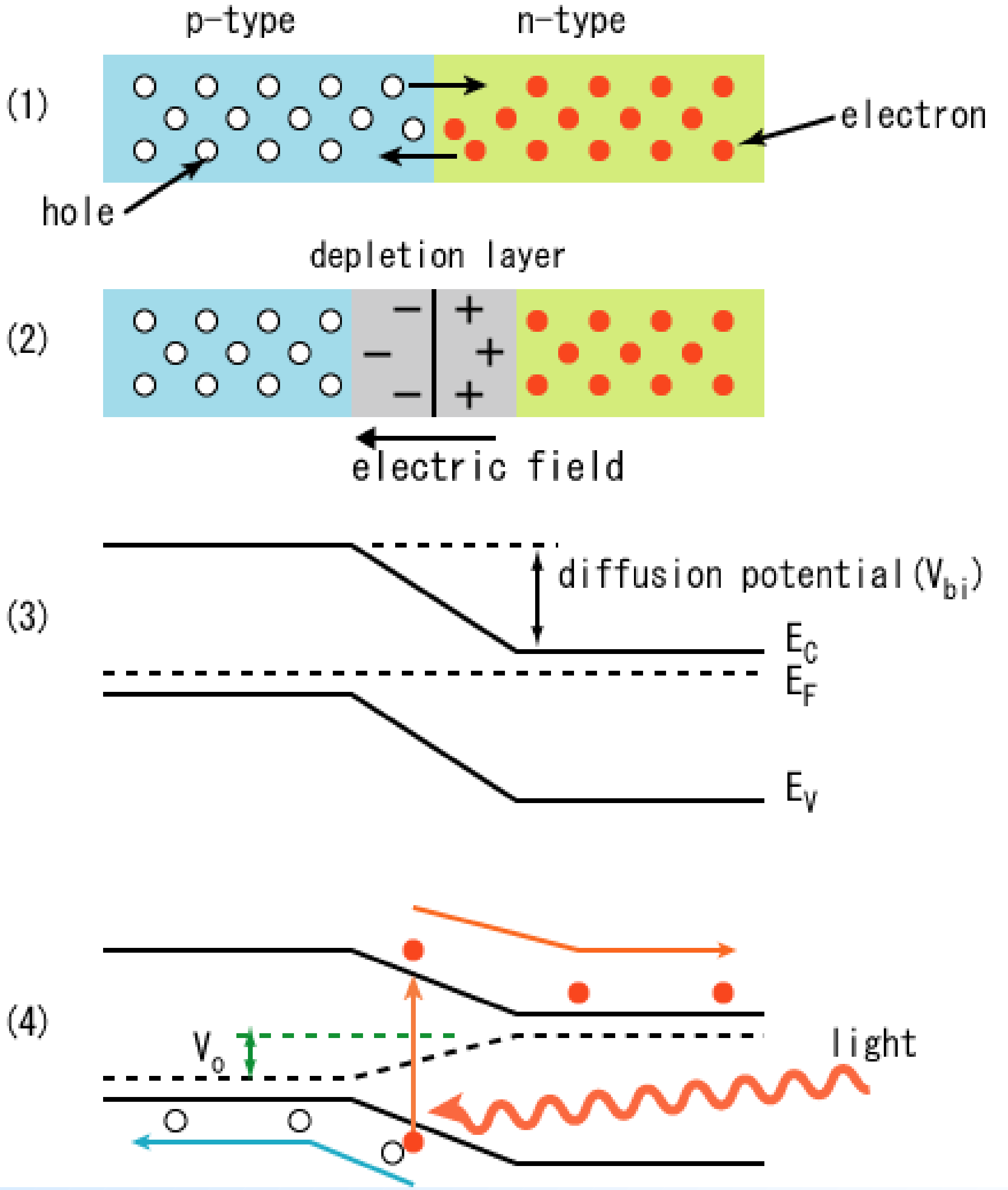


Photo diode (p-n, p-i-n)

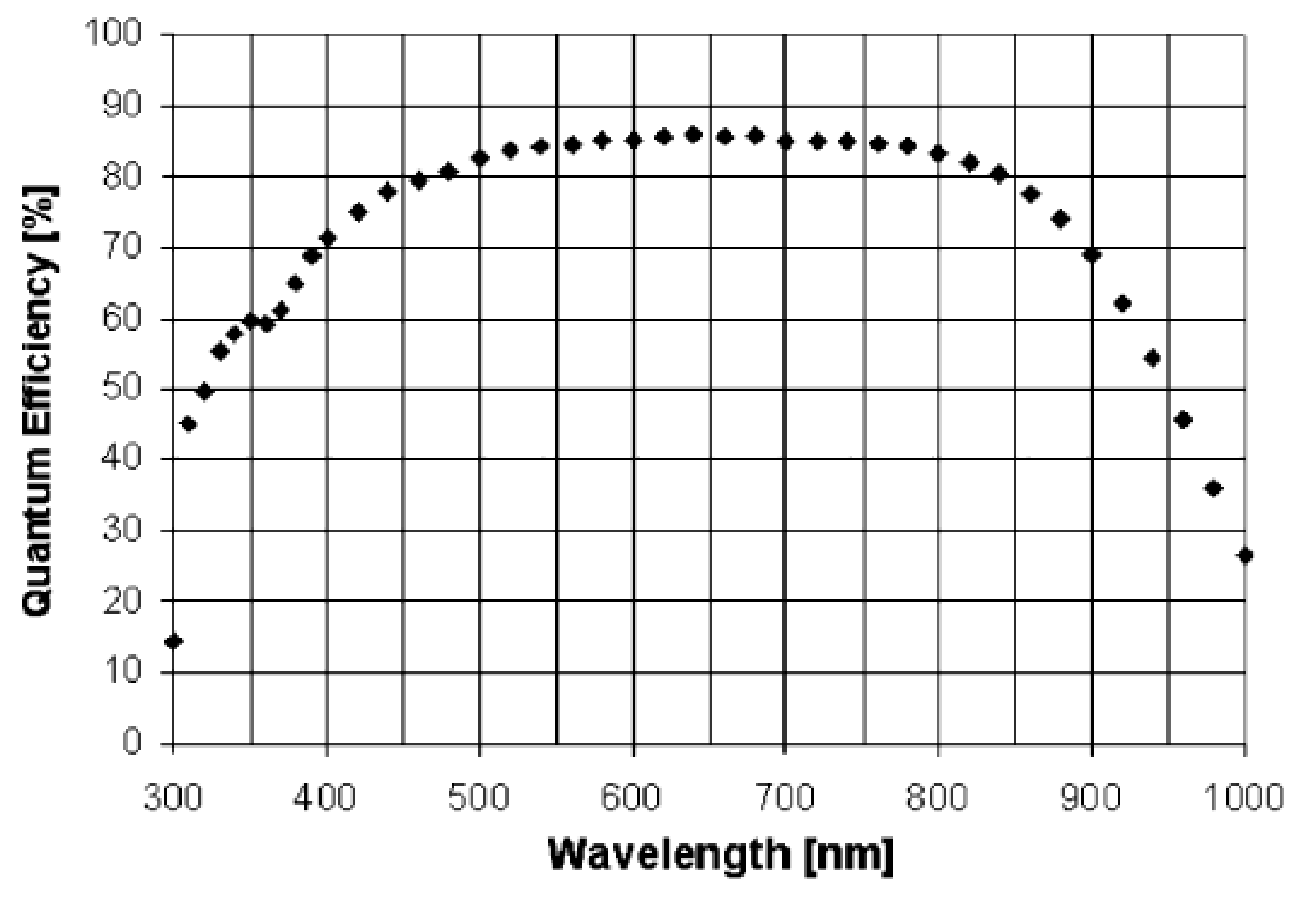
- photons absorbed in the depleted region generate photo-current
- no amplification – can detect light pulses with large number of photons (> ~10^4)
- Si band gap energy 1.12eV (wavelength 1100nm)
- p-i-n → lower V_{bias} and C





p-i-n diode Q.E.

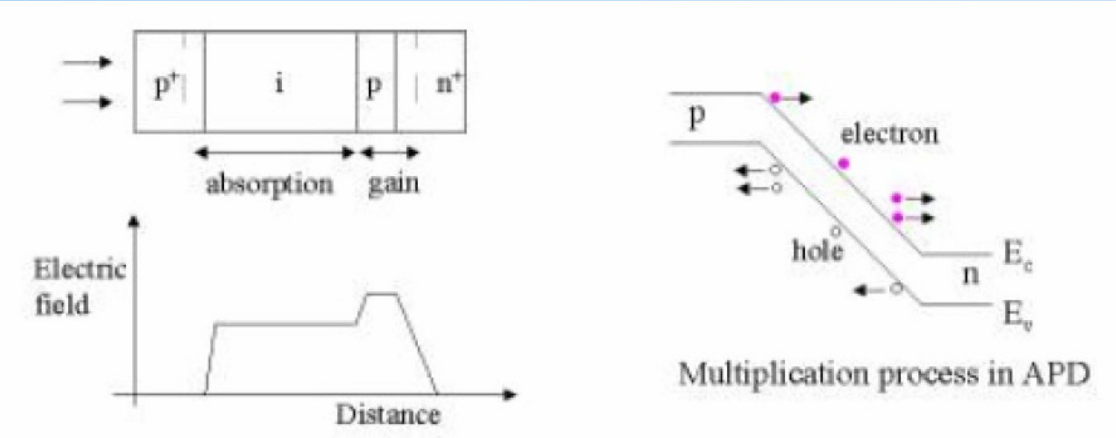
- depleted region ~100 μm thick

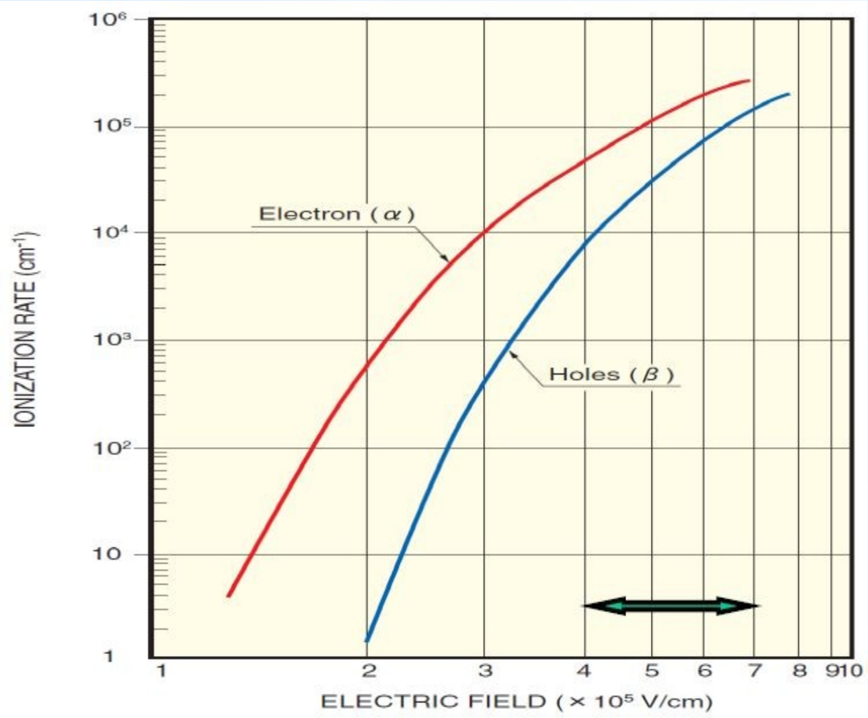


Avalanche photodiode

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



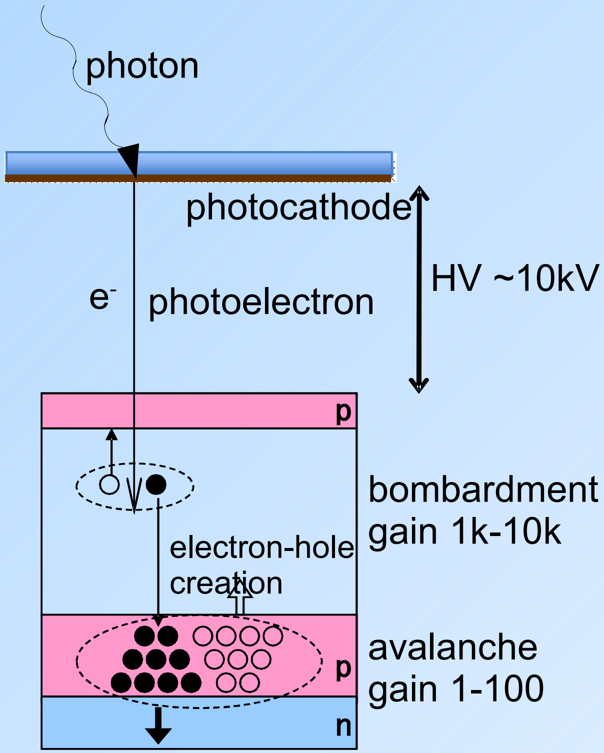


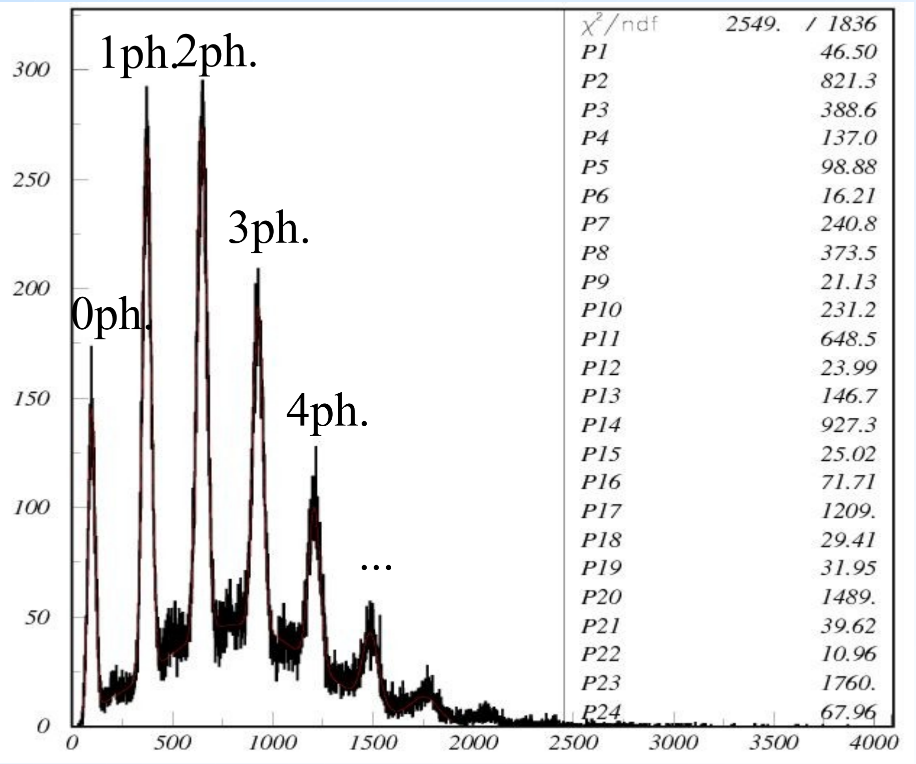
VLPC (Visual Light Photon Counter) is impurity band conduction silicon diode capable of detecting single photons. Band gap energy ~50meV → operation at cryogenic temperature (6.5K). Used for D0 fiber tracker.

Hybrid photo detectors

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

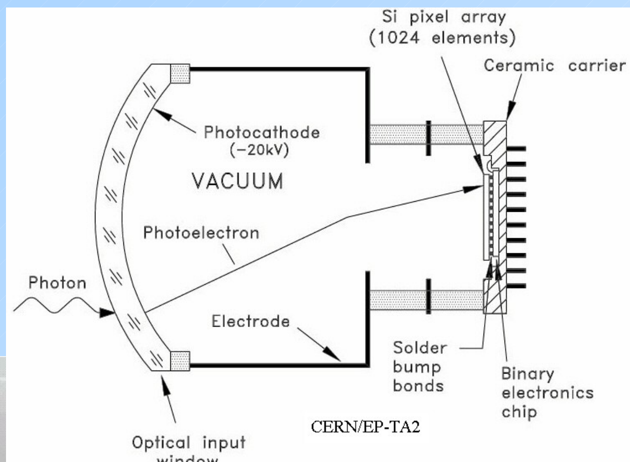
- photon interacts in photocathode and produces photoelectron
- high electric field accelerates photoelectron
- on impact electron-hole pairs are generated (bombardment gain)
- in APD signal is further amplified → lower HV and higher gain
- photon counting

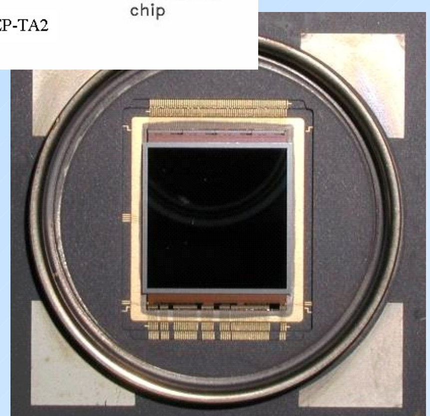




LHCb RICH HPD:

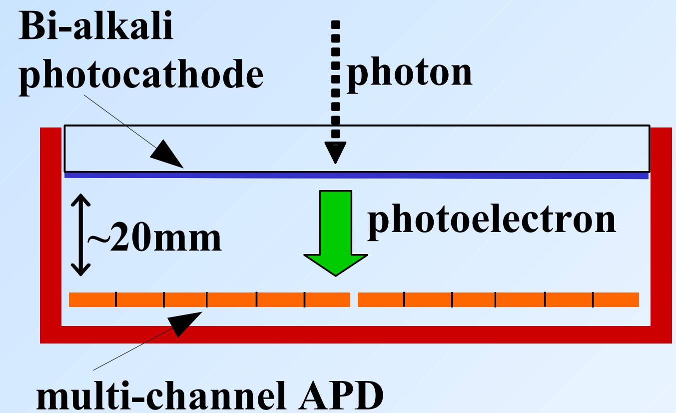
- electron optics → 5x demagnification
- sensitive to magnetic field
- HV ~20kV, gain ~5k
- detector in operation → R. Young (Edinburgh University), next talk
- CERN+DEP-Photonis

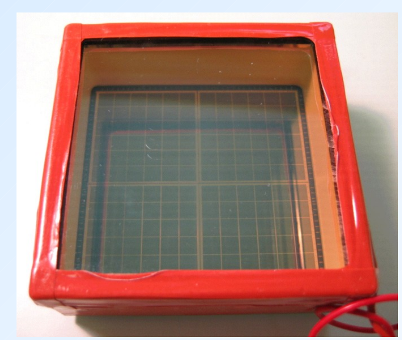




Belle II aerogel RICH HAPD

- proximity focusing configuration
- operation in magnetic field
- HV ~8kV, gain ~100k
- significant progress since RICH2007 → I. Adachi (KEK), tomorrow
- in collaboration with Hamamatsu



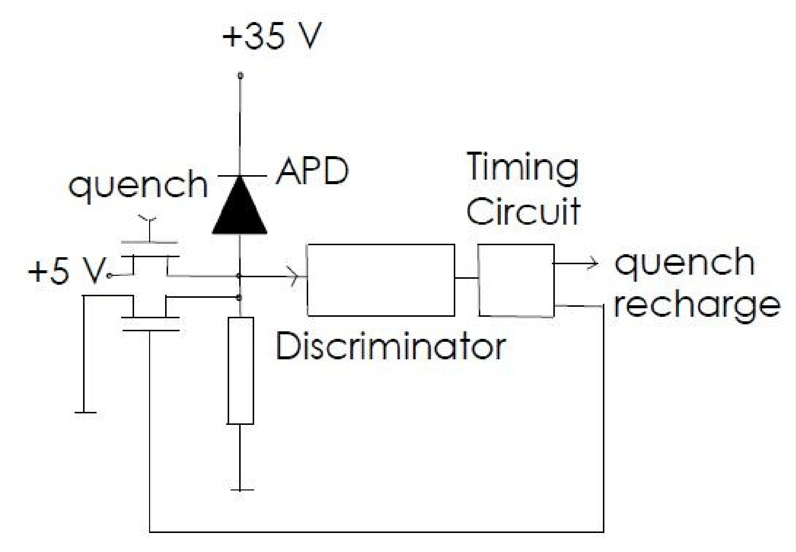


see also T. Iijima overview on vacuum devices

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

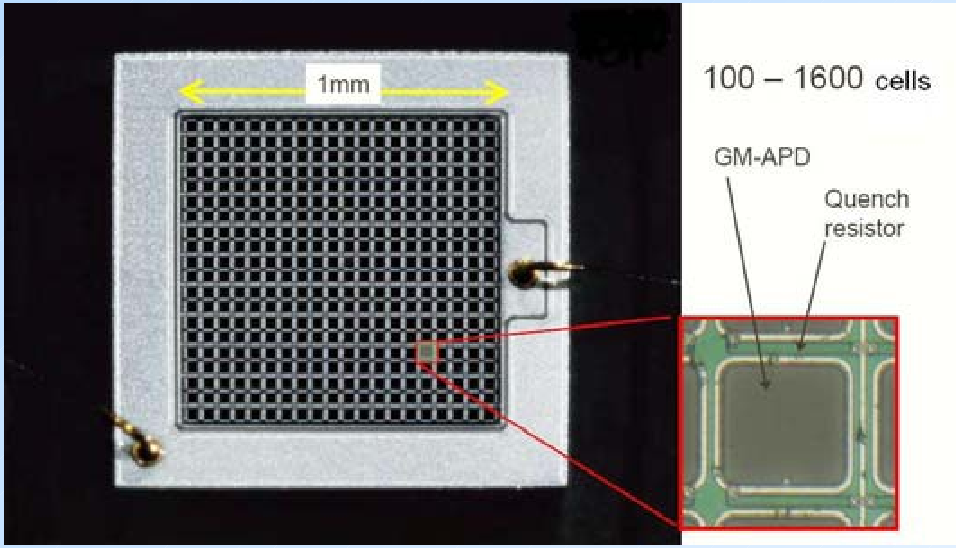


Large are APD operating in Geiger mode would be most of the time in the recovery state due to the large number of dark counts.
Solution: localization of quenching, division of large area APD in an array of smaller ones → SiPM (1990's: Golovin, Sadygov)

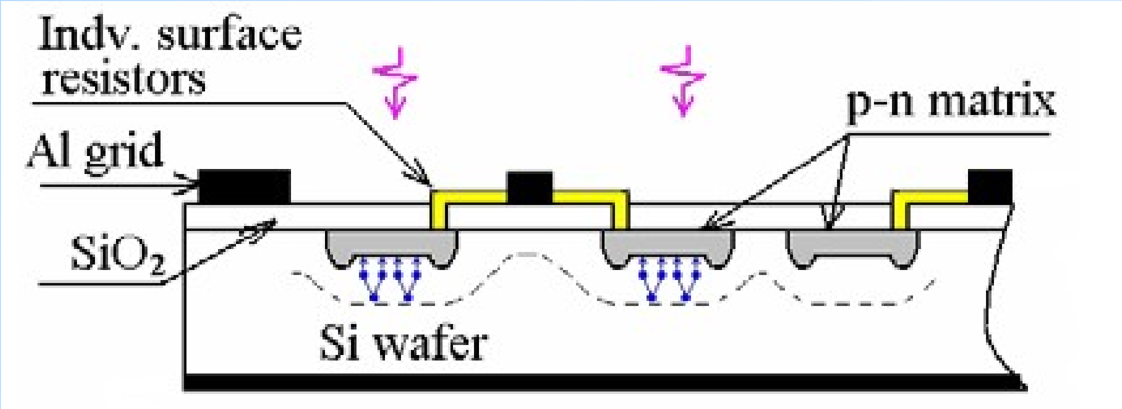
SiPM – Structure

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

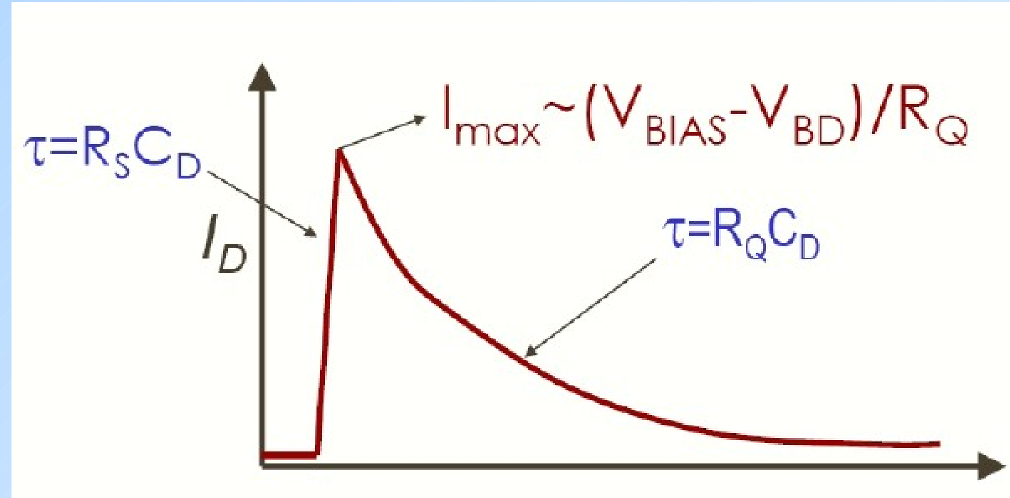


Manny producers: Photonique/CPTA, MEPhI/PULSAR, Hamamatsu, MPI, FBK-irst, STMicroelectronics, SensL, Philips (dSiPM), Zecotec ...
using different names: SiPM, MRS APD, MAPD, SSPM, MPPC, PPD ...

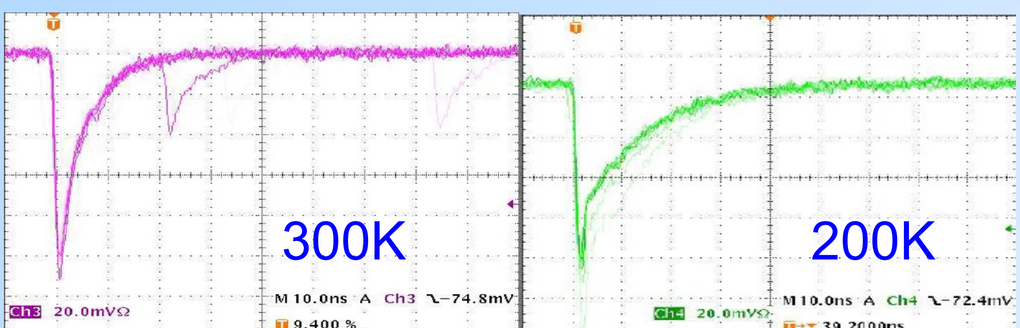
SiPM – Signal

SiPM signal sequence:

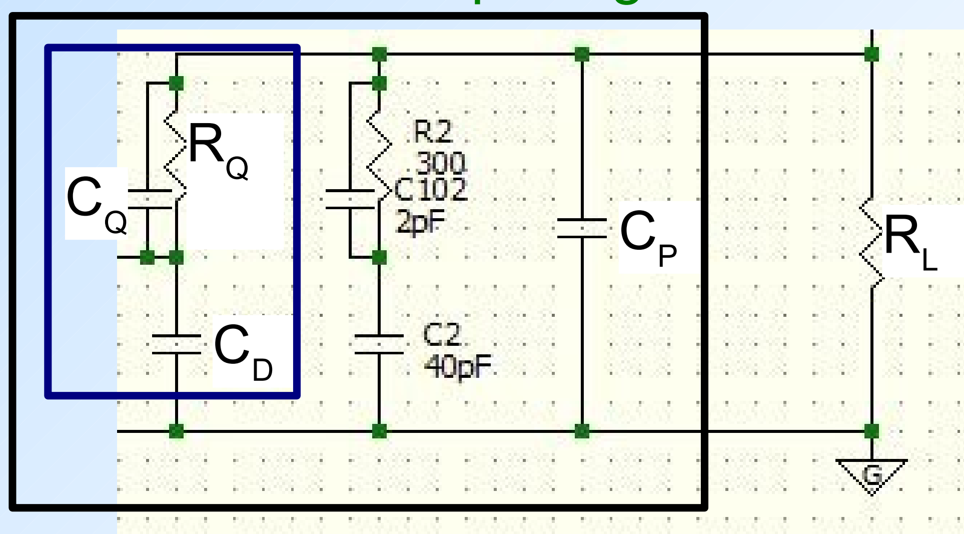
- charged to V_{bias}
- carrier enters breakdown region and initiates the avalanche
- micro cell is discharged to $V_{breakdown}$ and avalanche process stops
- micro cell is recharged to V_{bias} – during this time a new avalanche process in the same micro cell will result in a reduced signal



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.

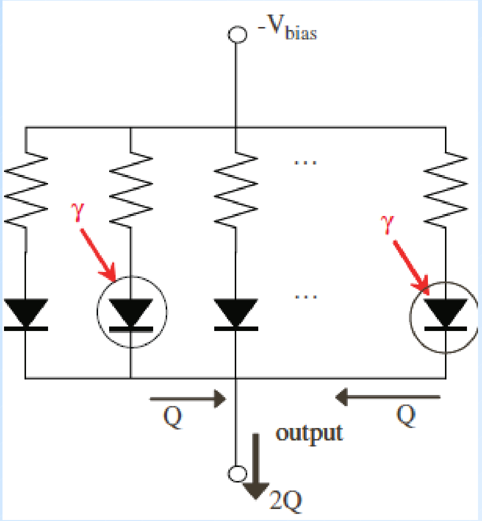


H. Otono (U. of Tokyo)@PD07



SiPM - Gain

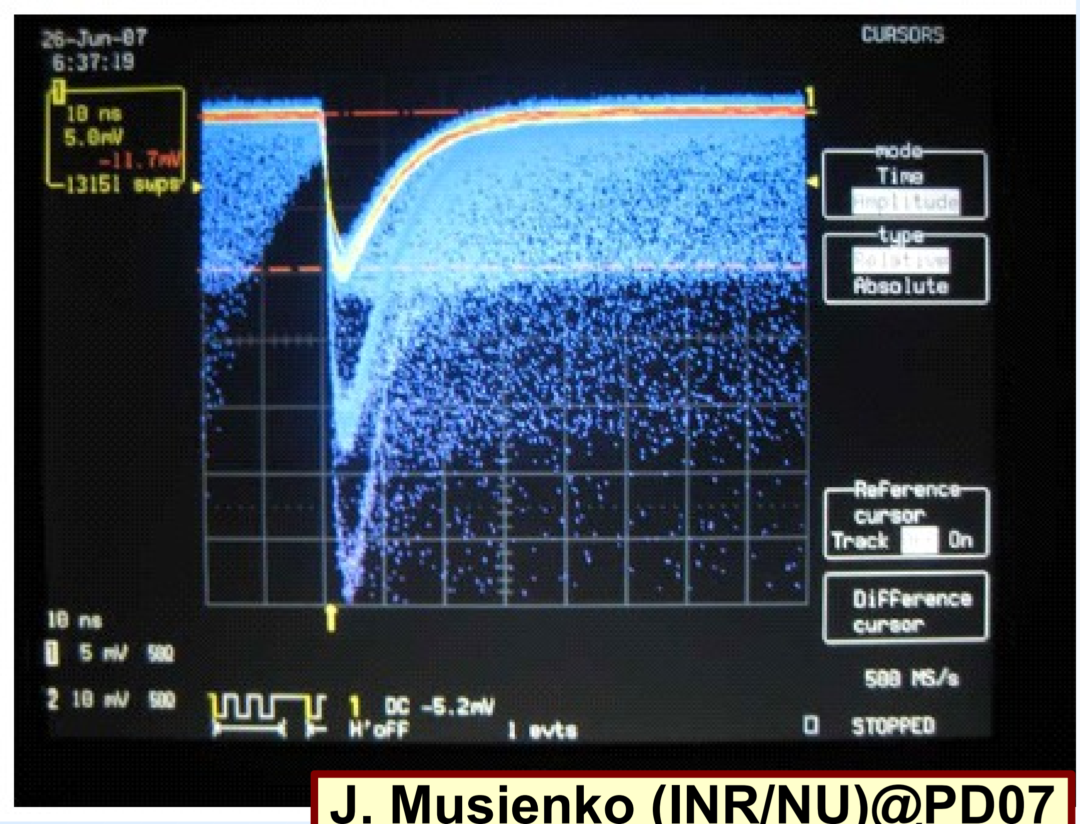
Gain is determined by micro cell capacitance (~10 – 100 fF) and overvoltage – the difference between bias and breakdown voltage (typically few volts).



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

- large gains, typically 10^5 – 10^7
- short signals (~10 ns) produce several mV signals 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

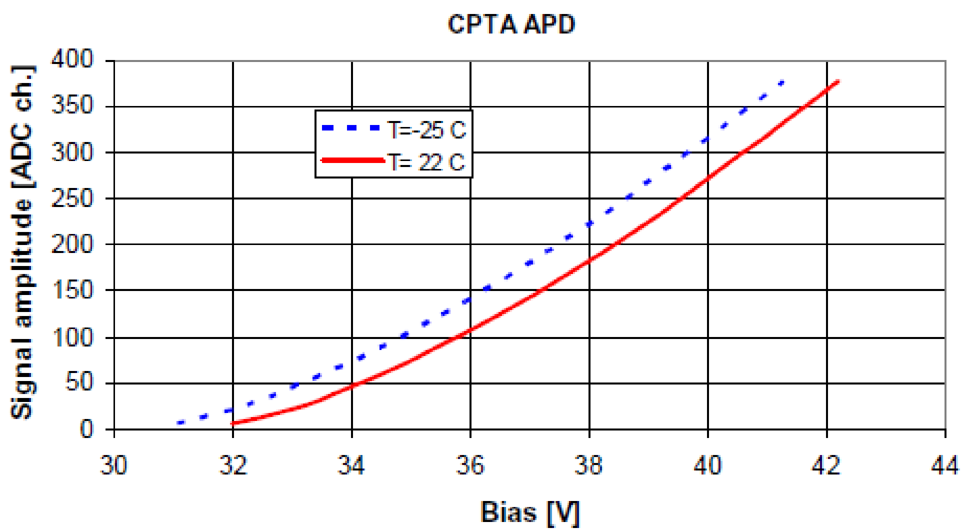
Photon counting(?)

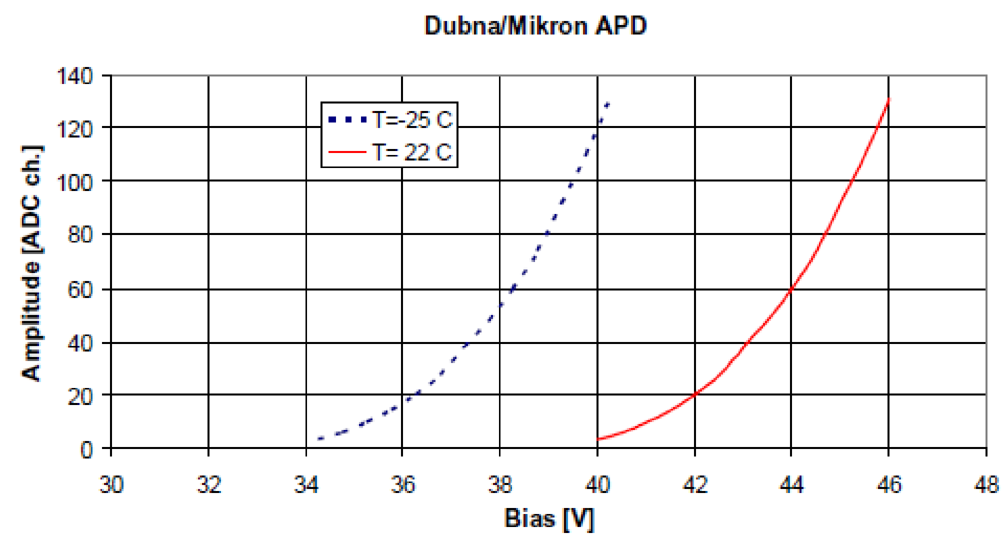


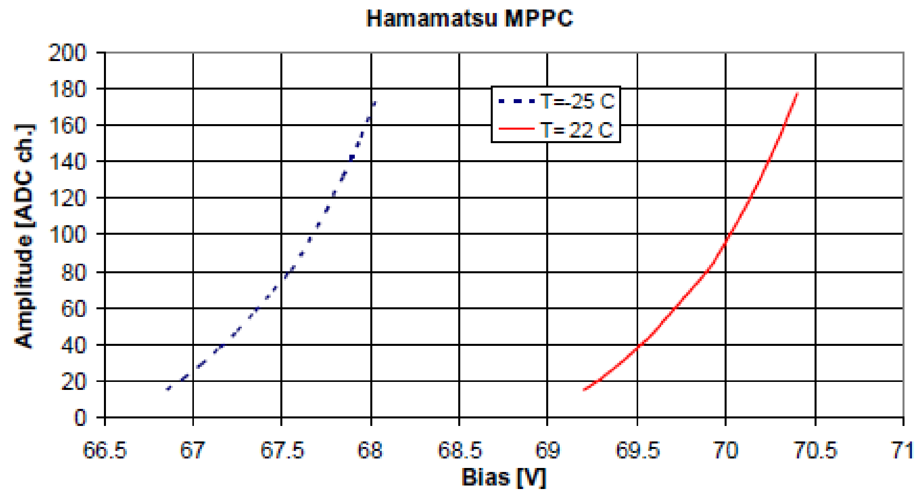
J. Musienko (INR/NU)@PD07

SiPM – Gain vs. temperature

Breakdown voltage changes with temperature → gain variation.
Not critical for single photon detection.







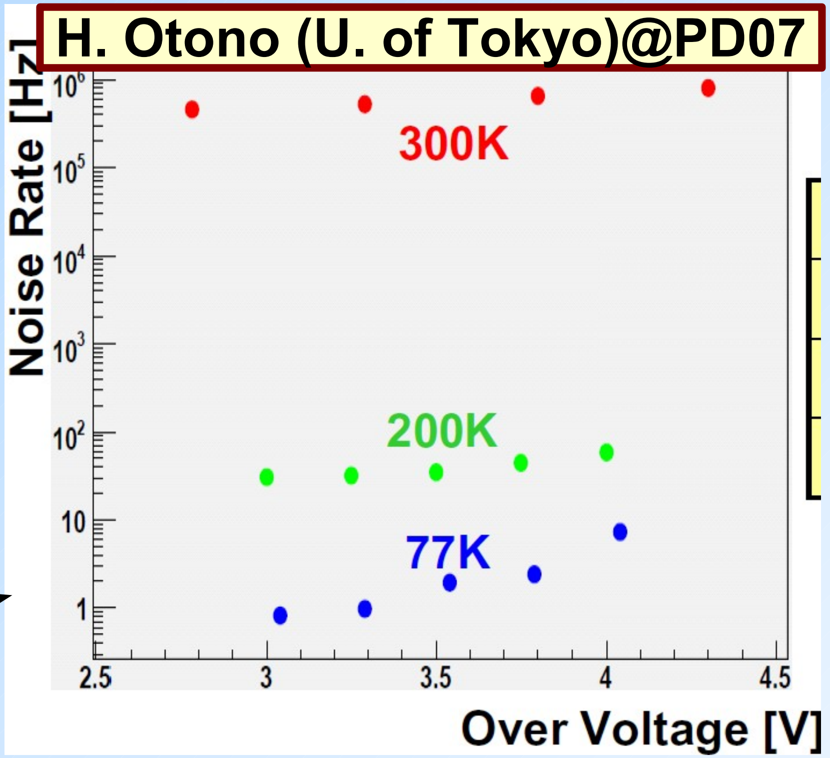
CPTA/Photnique:
dVB/dT=-20 mV/C
Dubna/Micron:
dVB/dT=-122 mV/C
Hamamatsu:
dVB/dT=-50 mV/C

J. Musienko (INR/NU)@PD07

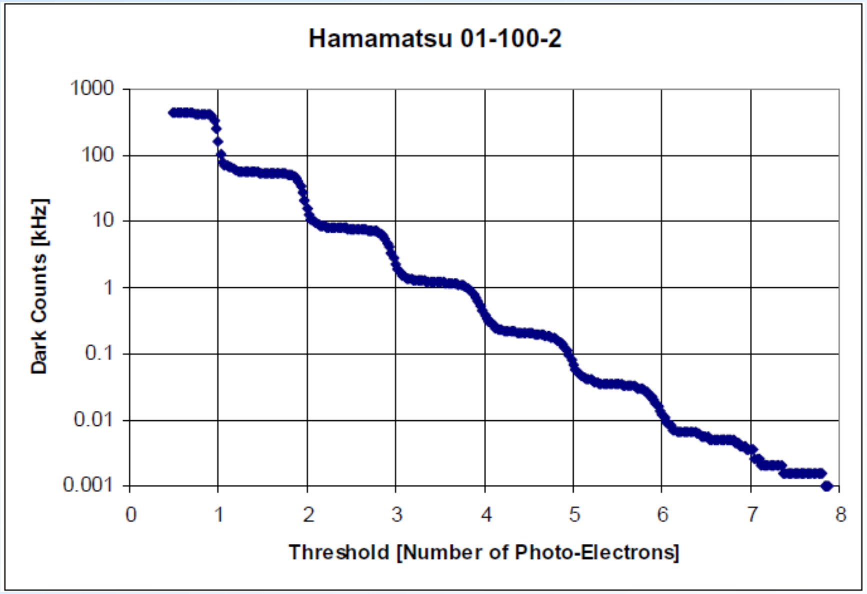
SiPM-Dark noise

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)



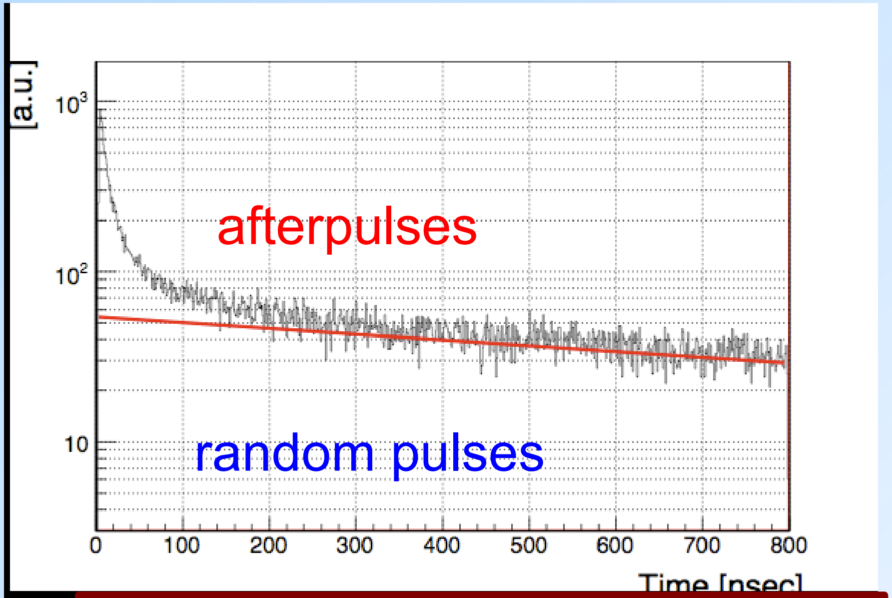
Signals are at the single micro cell level and can be effectively suppressed by threshold level at the signal of few micro cells (depends on optical cross talk level).



SiPM-Afterpulses

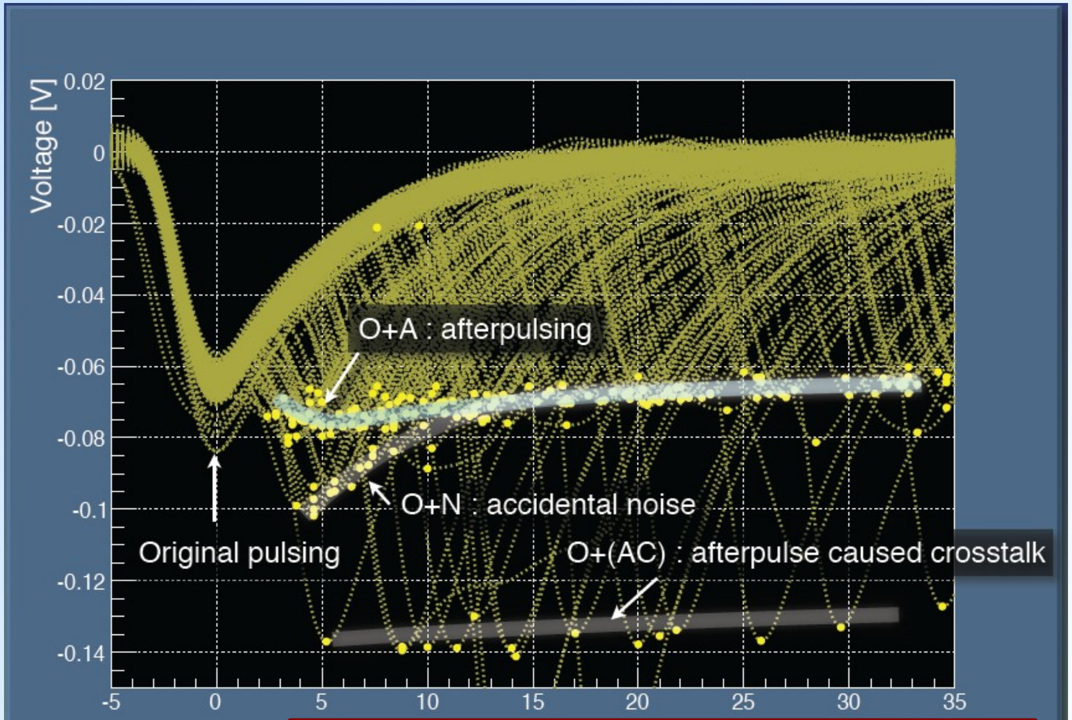
Deep traps are loaded during the avalanche processes and carriers that are subsequently released trigger afterpulses:

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



T. Murase (U. of Tokyo)@PD09

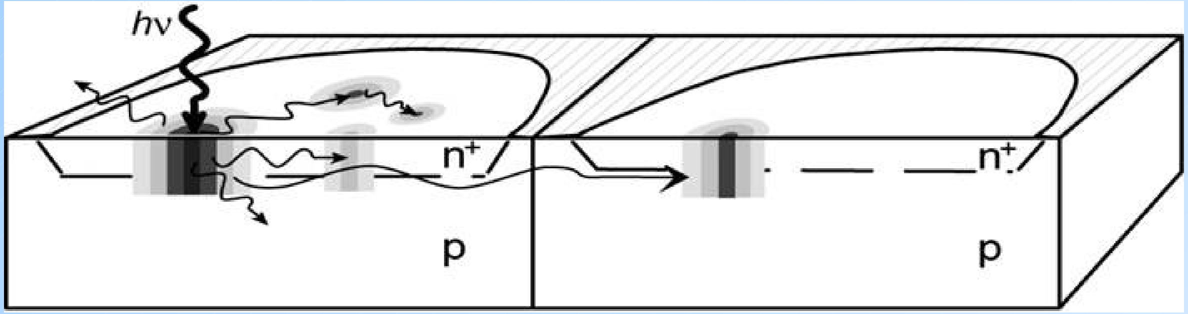
	40x40 px	20x20 px	10x10 px
Afterpulsing 1-1/e Recovery	~ 4 [ns]	~ 9 [ns]	~ 33 [ns]
Pulse Shape returning time (RC Time Const.)	~ 5 [ns]	~ 11 [ns]	~ 35 [ns]



H. Oide (U. of Tokyo)@PD07

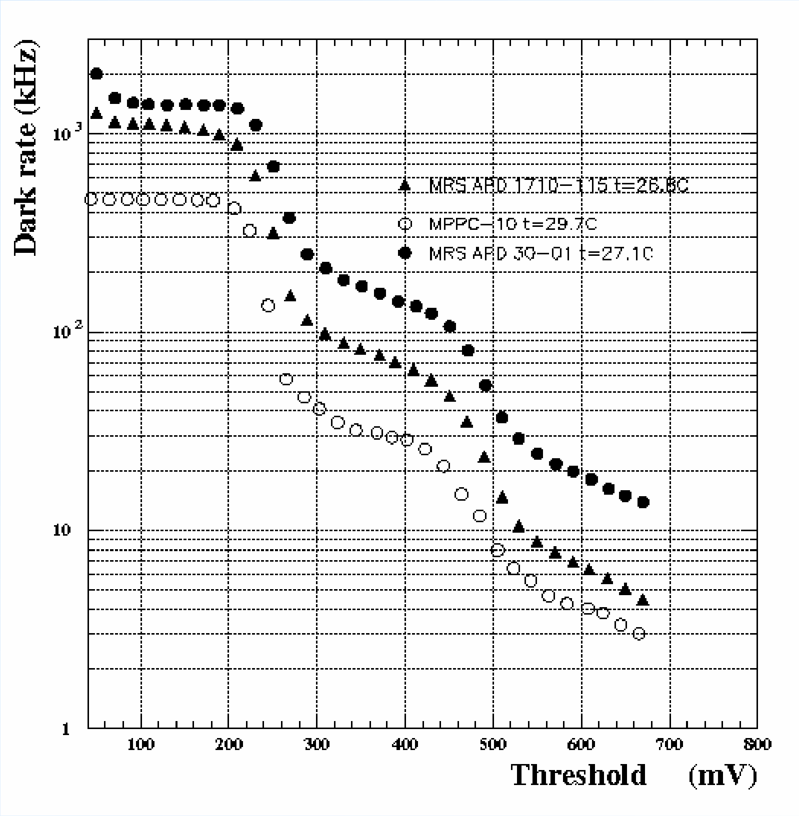
SiPM-Optical cross-talk

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.

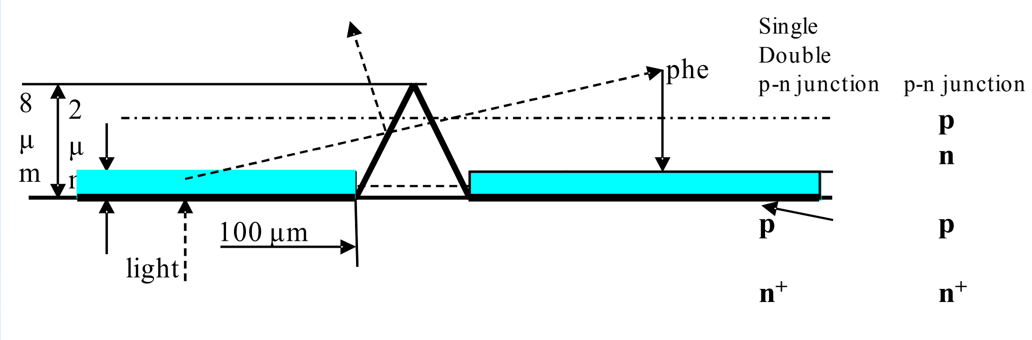


Y. Kudenko (INR Moscow)@PD07

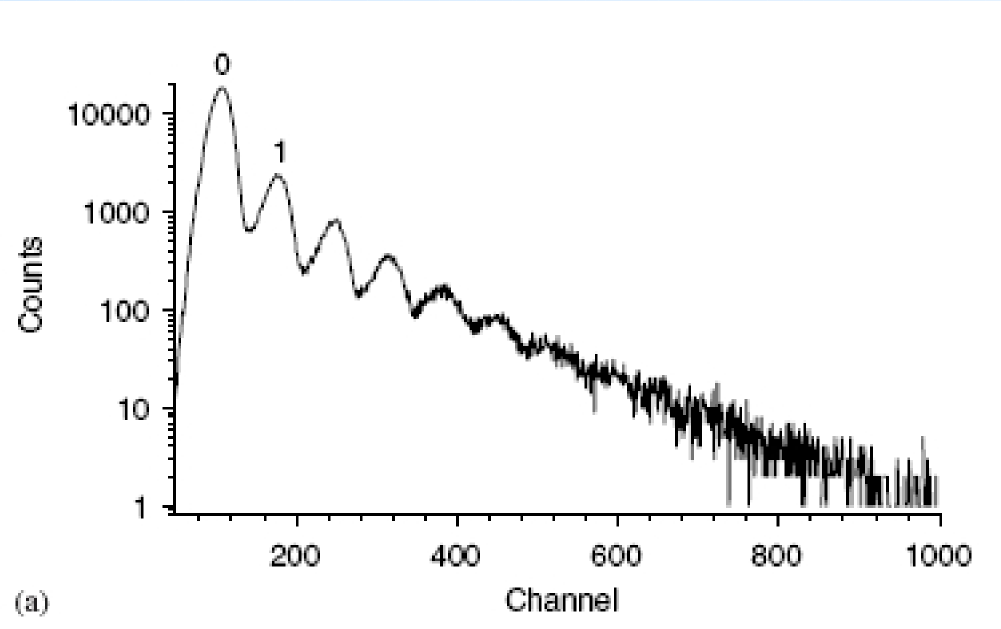
SiPM - Optical cross-talk suppresion

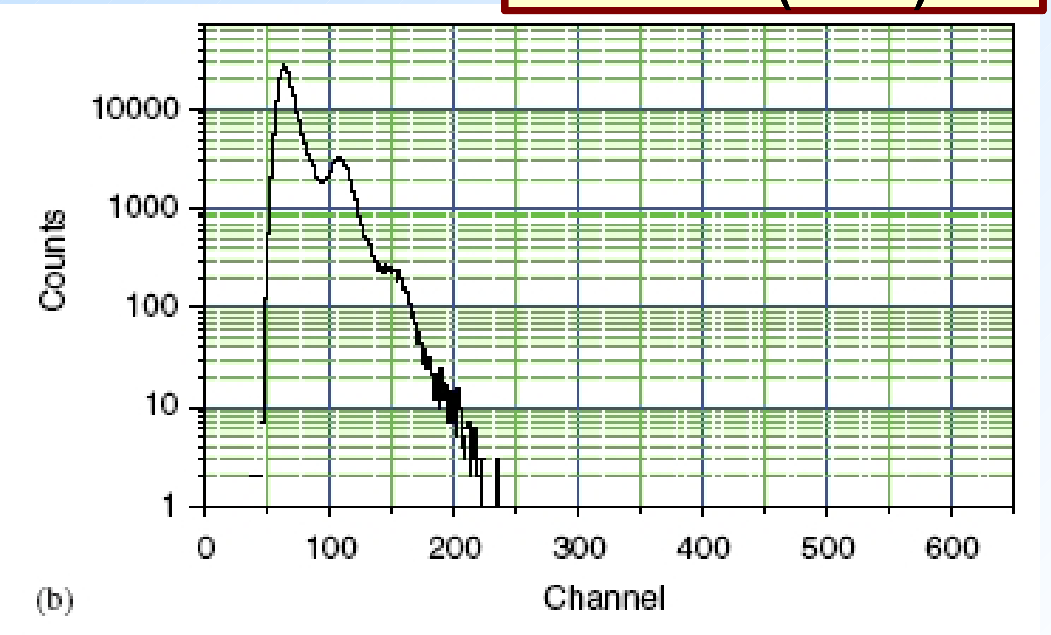
Optical crosstalk can be suppressed by shielding one micro cell from the other:

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



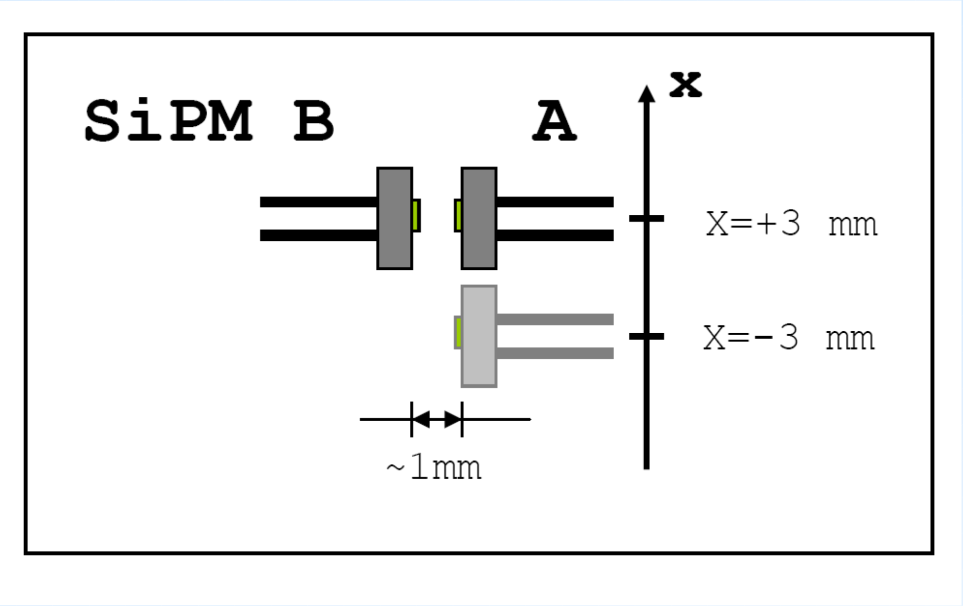
NIM A567 (2006) 78





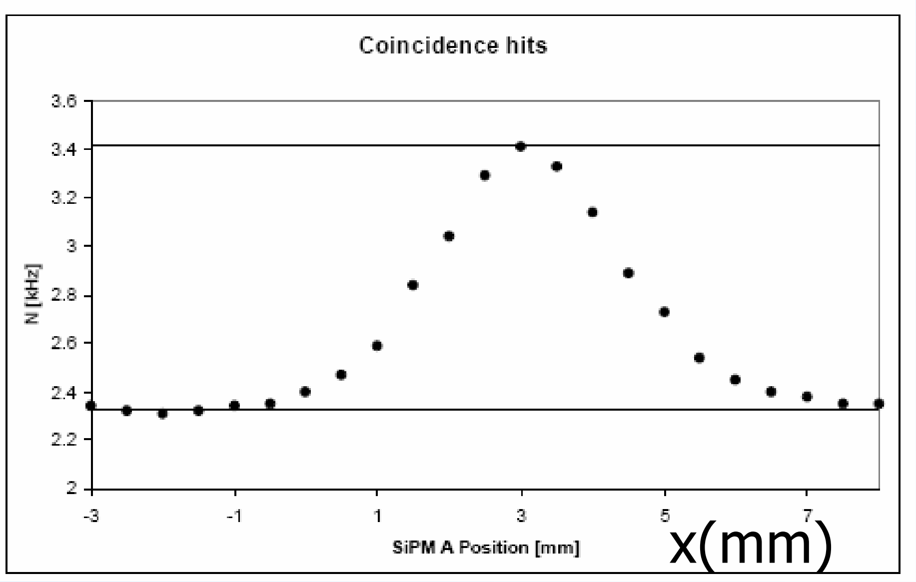
External secondary photon cross talk

Will G-APDs "communicate"?
Scan one G-APD 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%

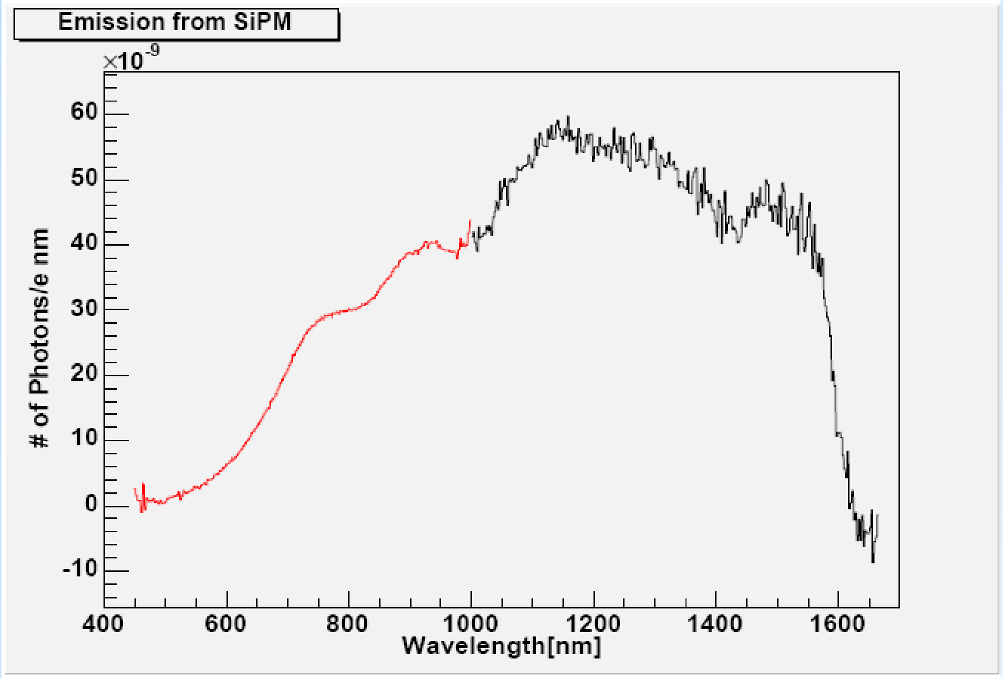
→ OK, increase of background at % level

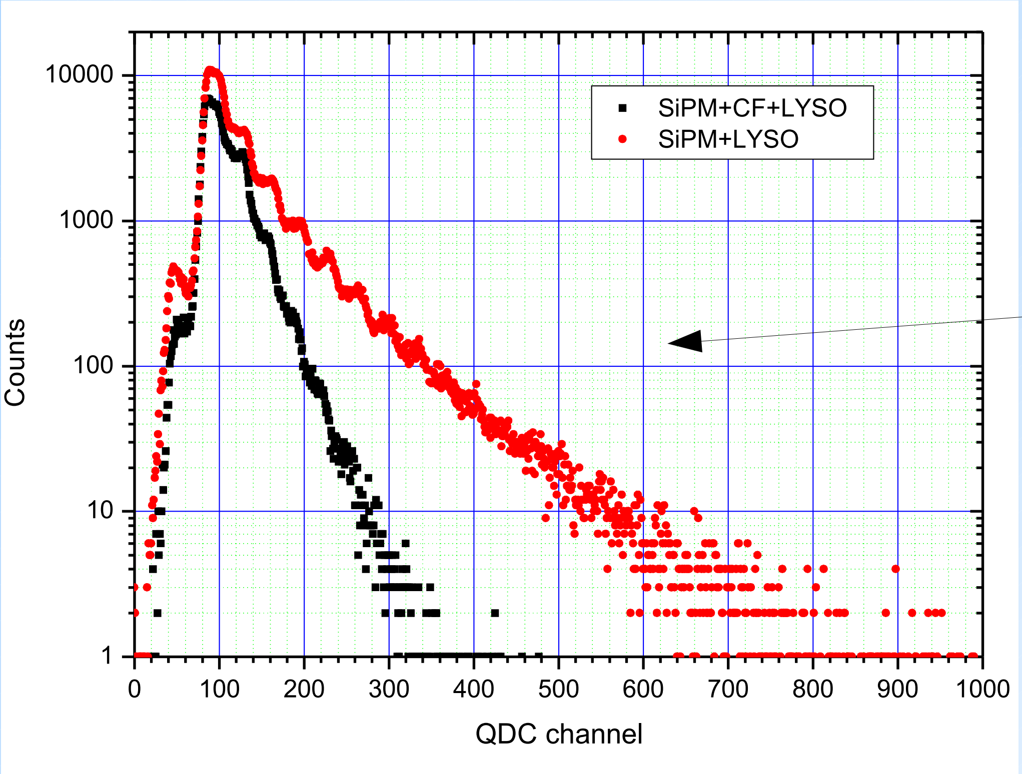


P. Križan (IJS)@LIGHT07

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

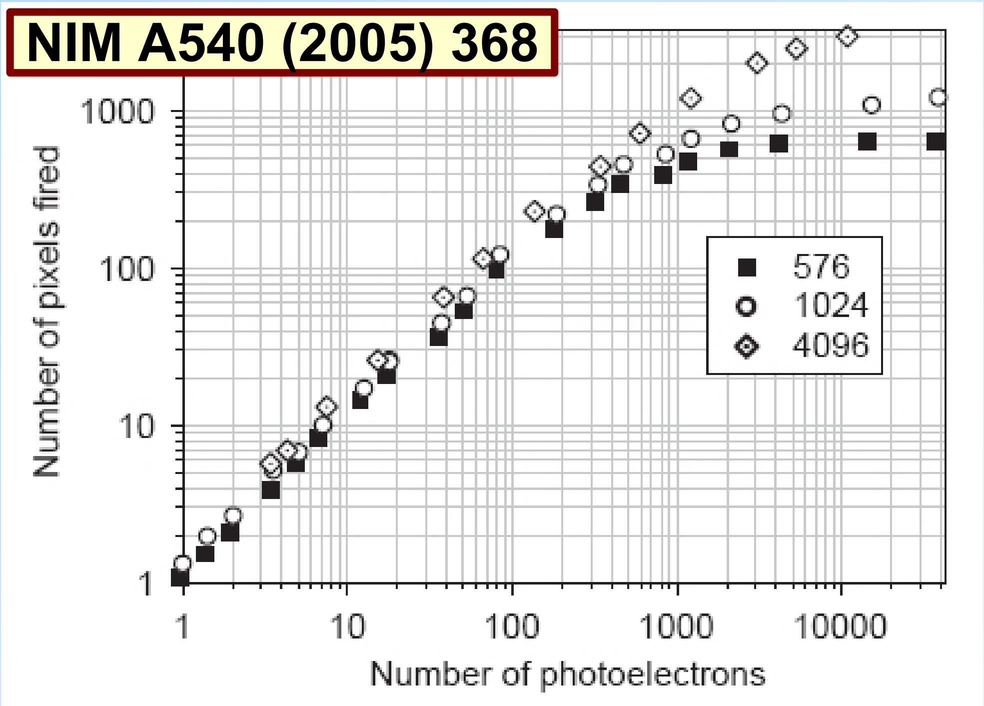
SiPM-Signal saturation

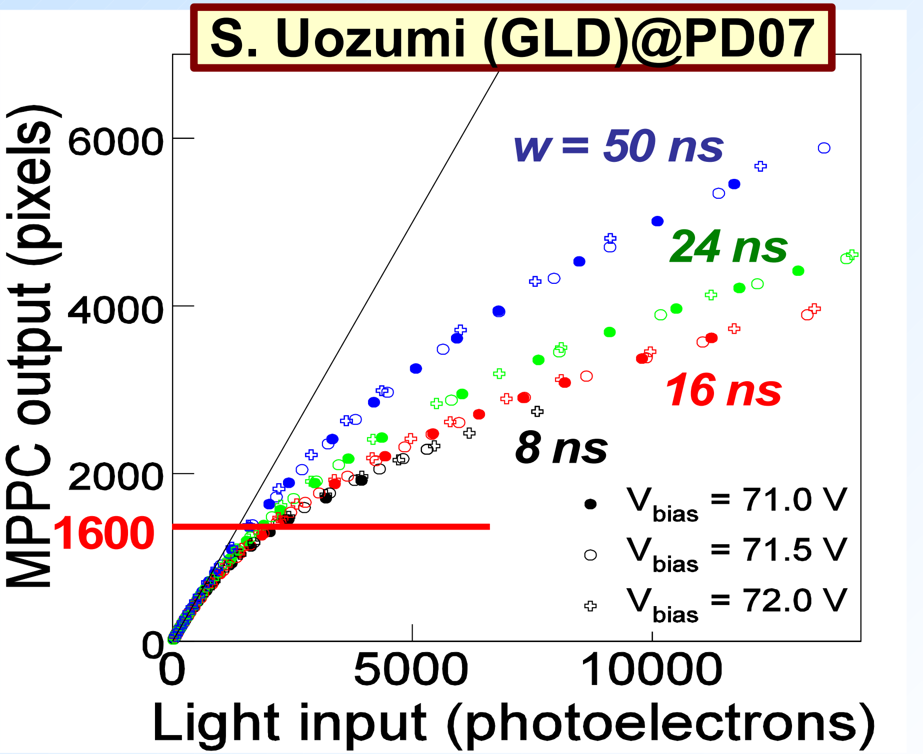
Output of SiPM is saturated if number of photons in the pulse is comparable to number of micro cells:

- 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

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

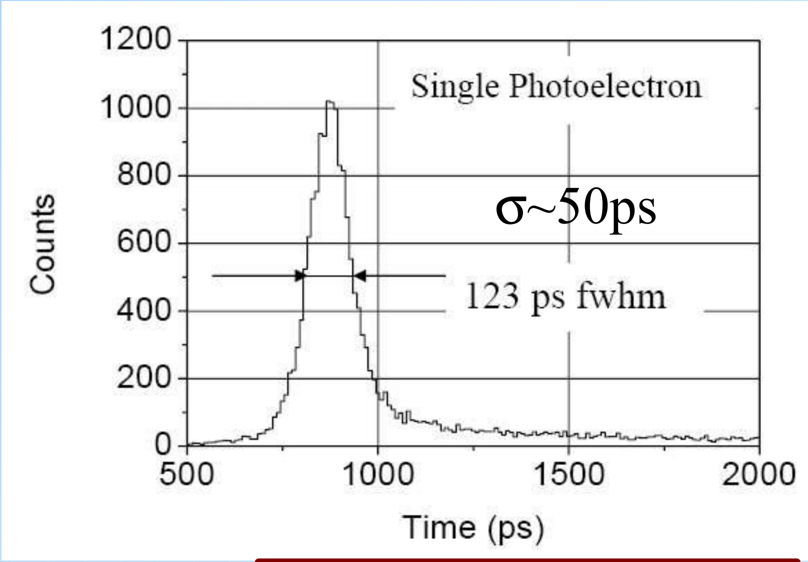
- pulses from scintillators with decay times longer than pixel recovery time can produce signals significantly exceeding number of micro cells





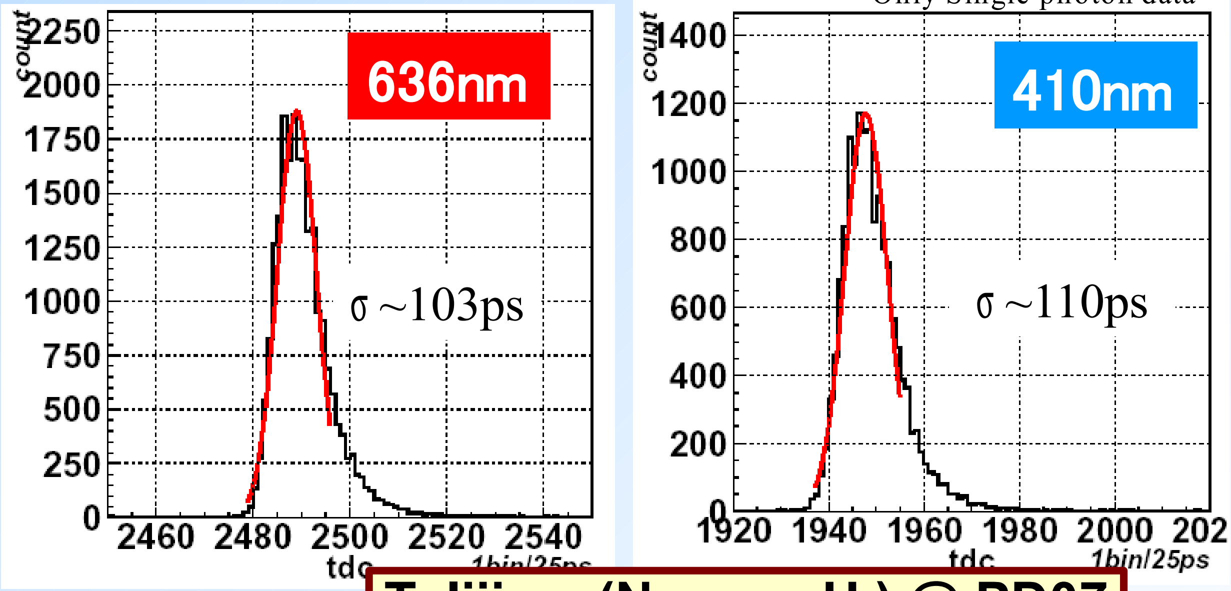
SiPM-Timing

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.



NIM A504 (2003) 48

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

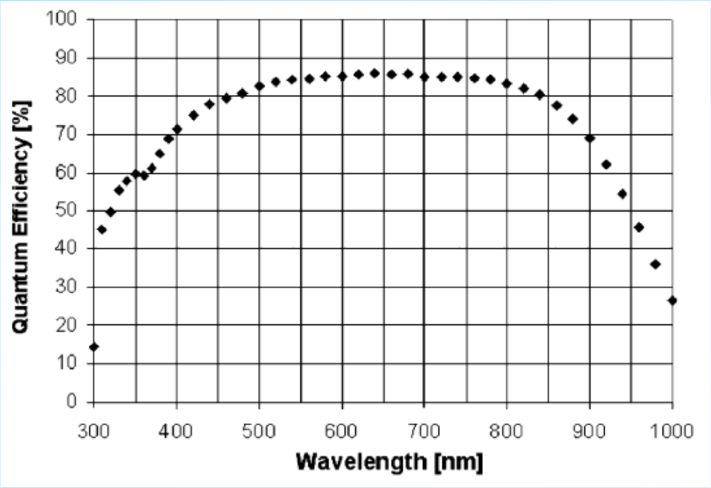


T. Iijima (Nagoya U.) @ PD07

SiPM – Photon detection efficiency

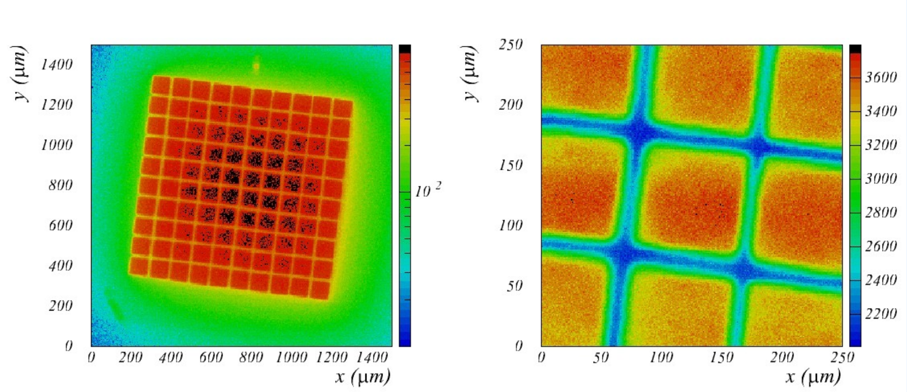
Photon detection efficiency (PDE) depends on three factors:

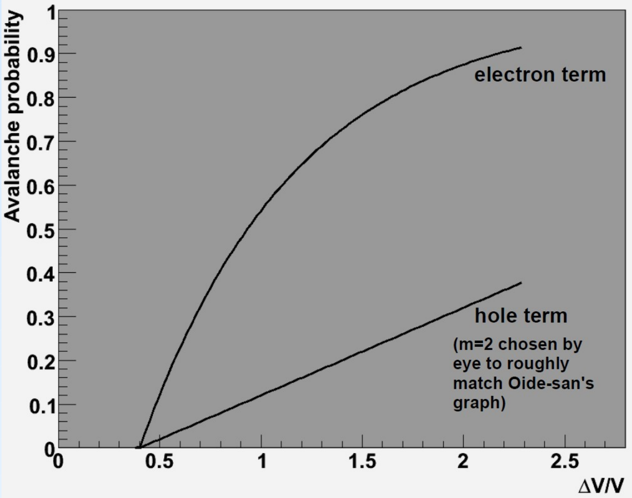
$$PDE = Q.E. \times \epsilon_{geom.} \times \epsilon_{Geiger}$$



- 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

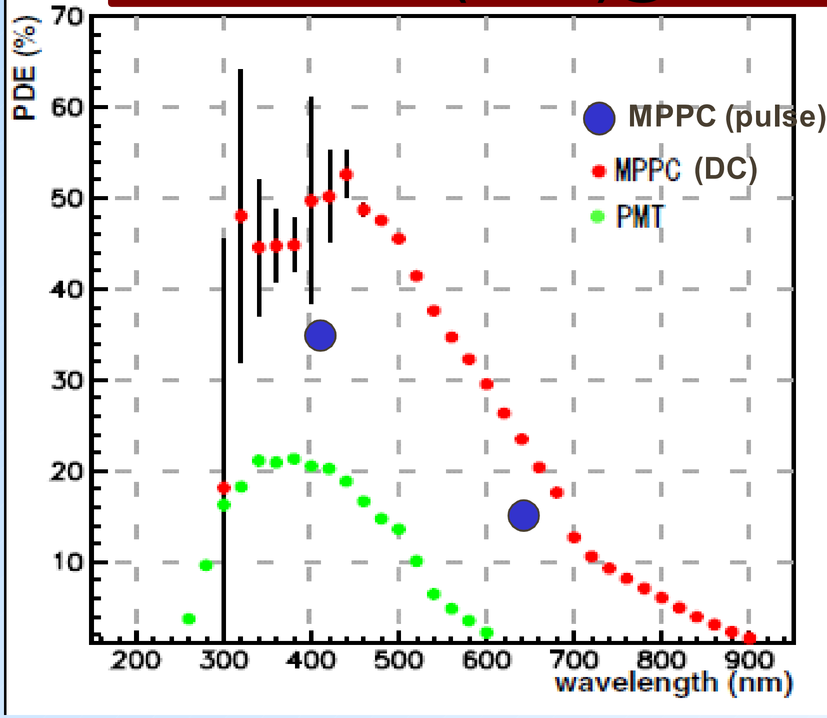


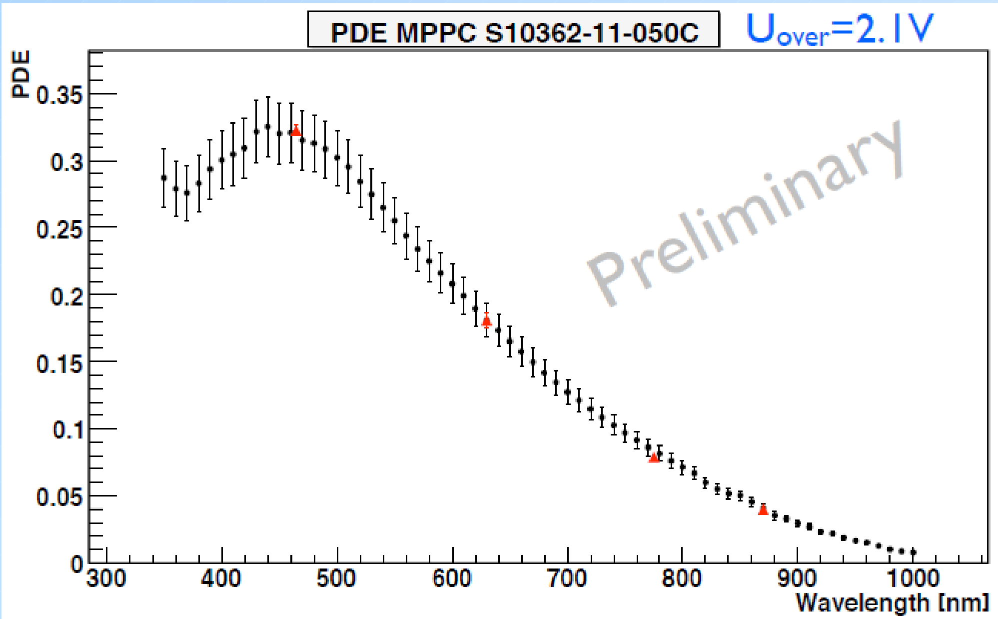


SiPM – PDE measurements

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.

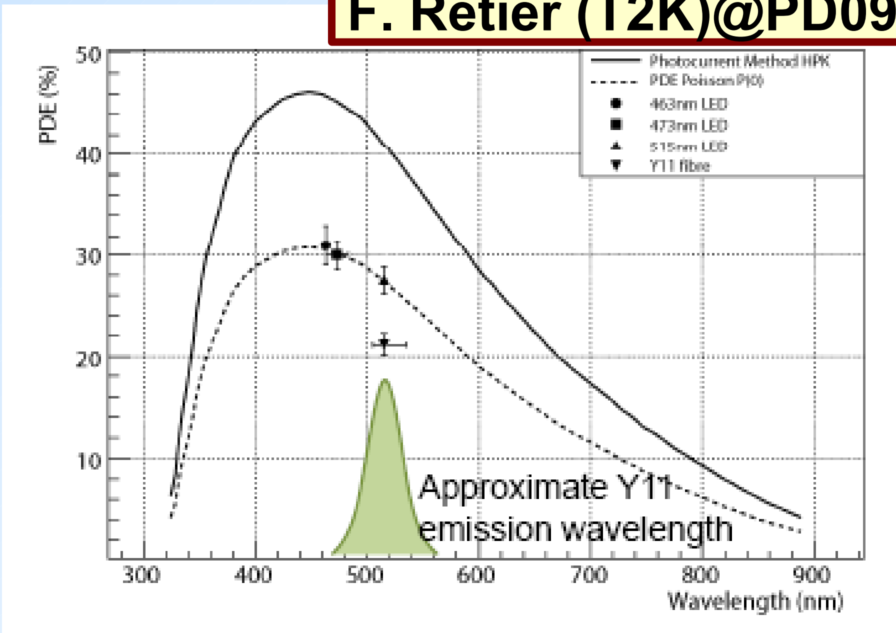
M. Yamaoka (Belle)@JPS07





A. Tadday (CALICE)@PD09

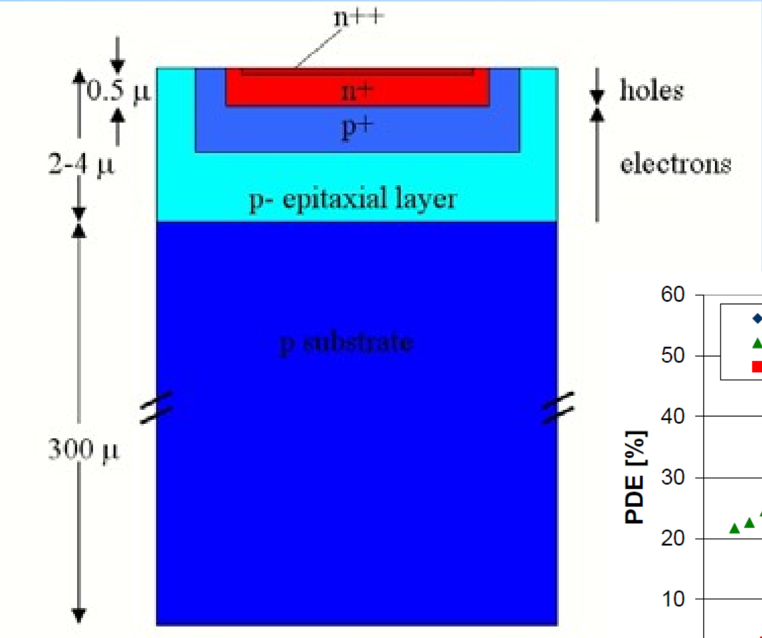
F. Retier (T2K)@PD09

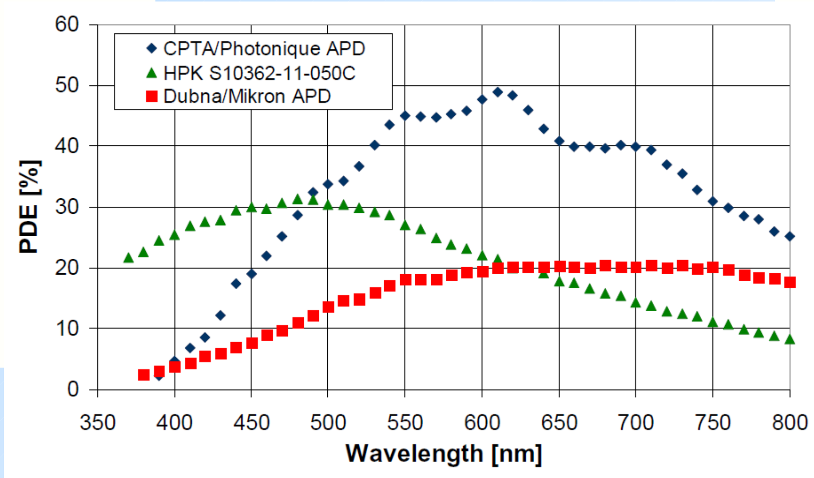


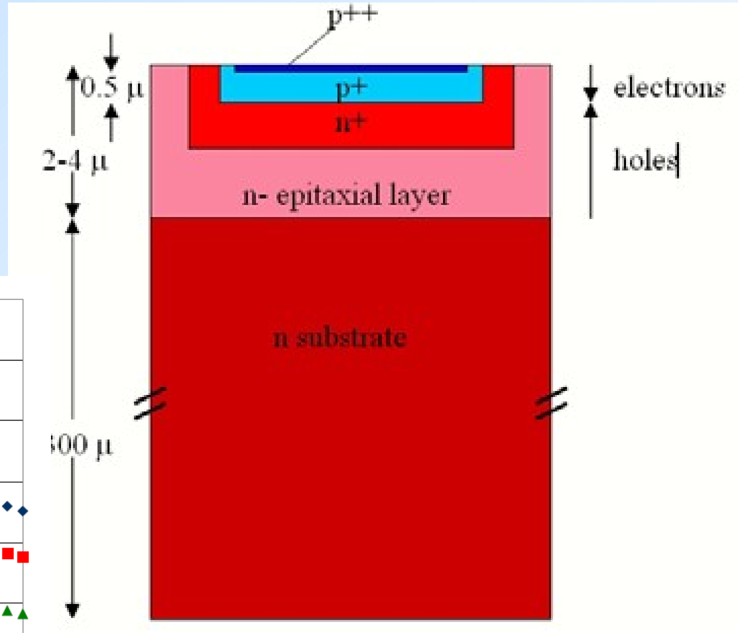
SiPM – p on n vs. n on p

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





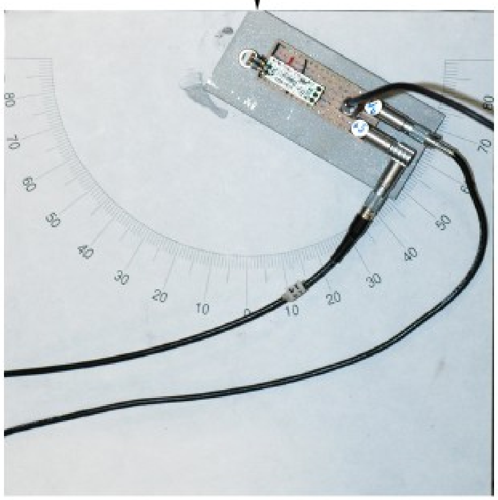


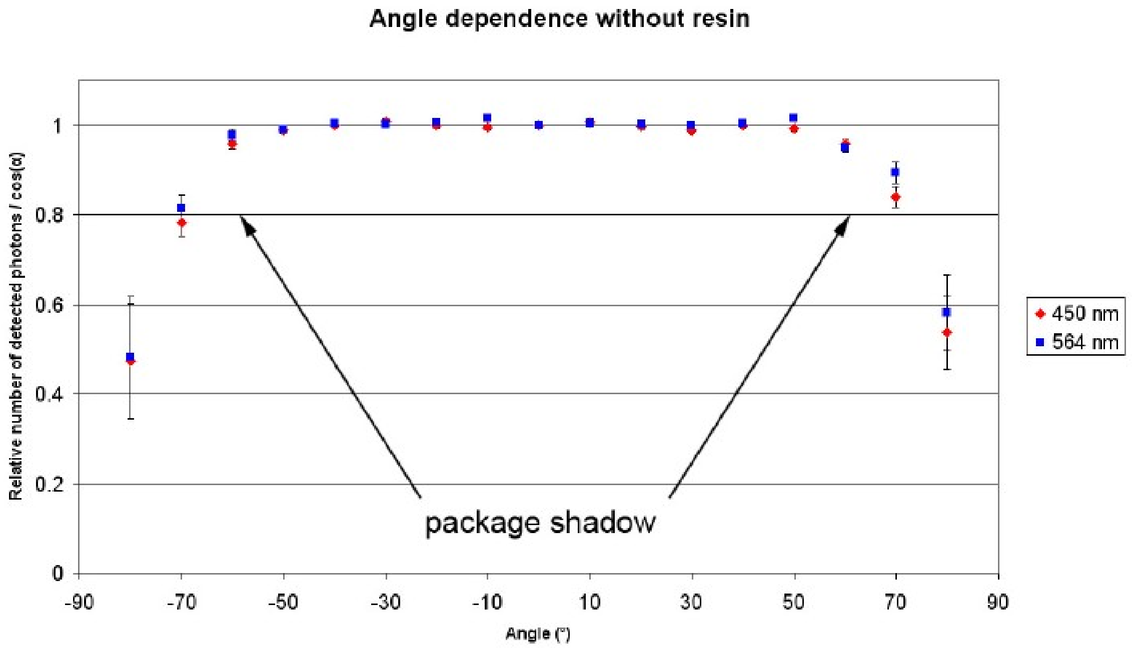
J. Musienko (INR/NU)@PD07

SiPM – 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.



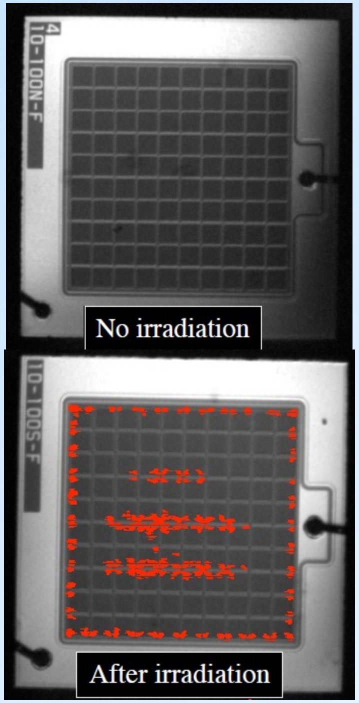


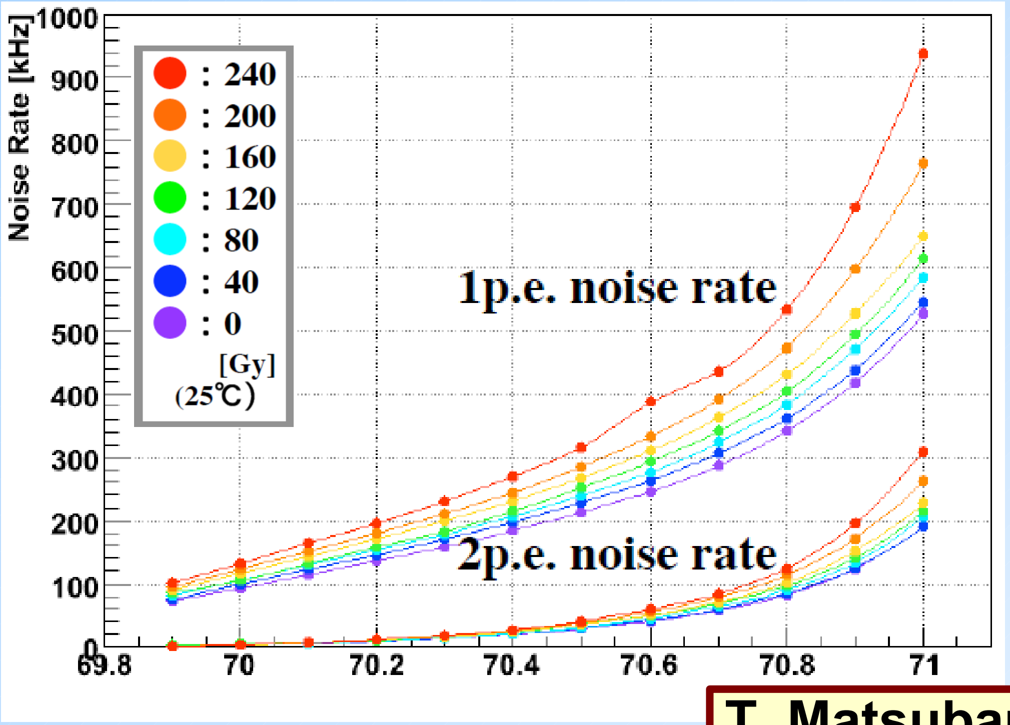
⇒ No angle dependence was found within the measurement error (approx. 1%) up to 60°.

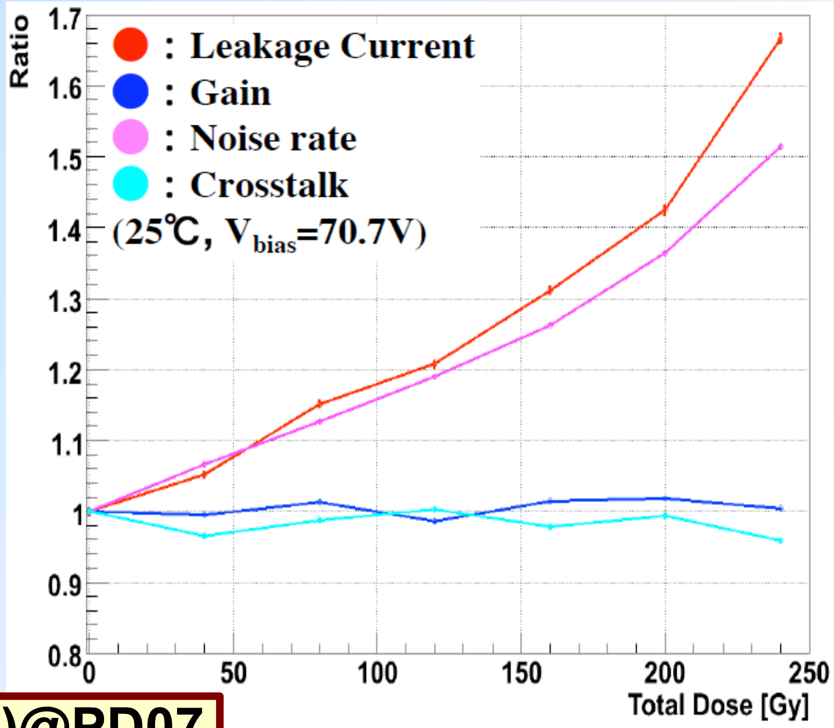
T. Krähenbühel (ETH Zurich) @ PD09

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



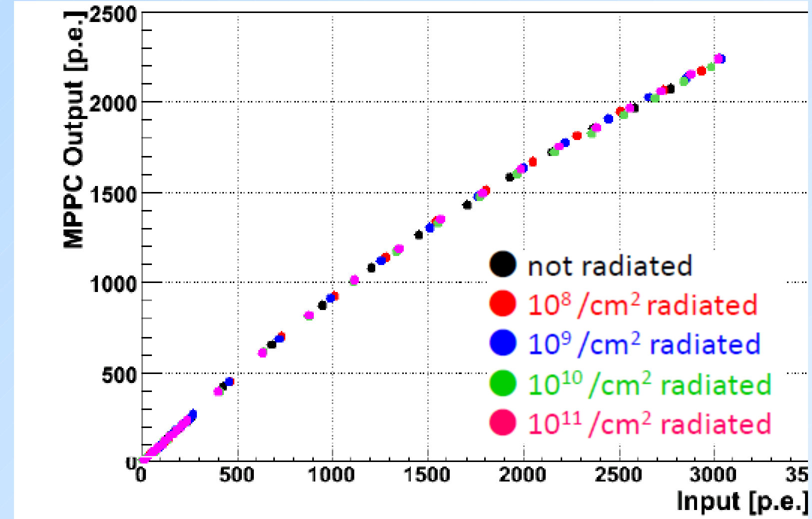


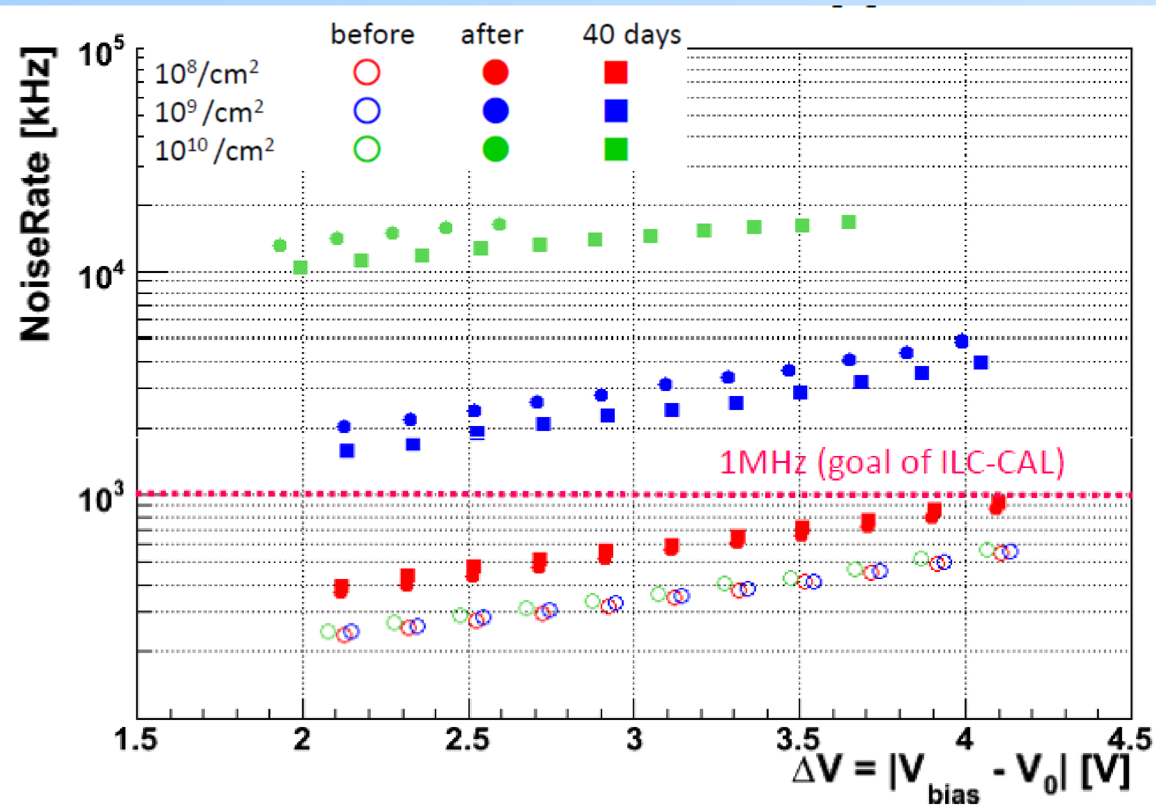


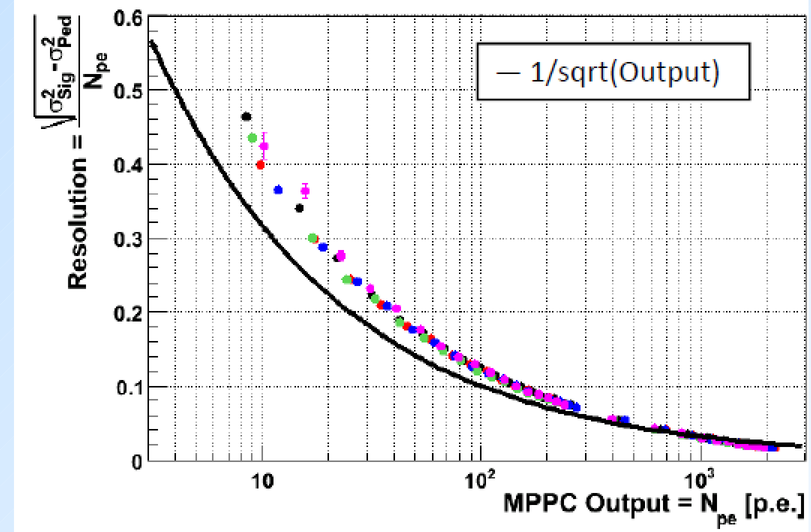
T. Matsubara (TIT)@PD07

SiPM – p,n irradiation

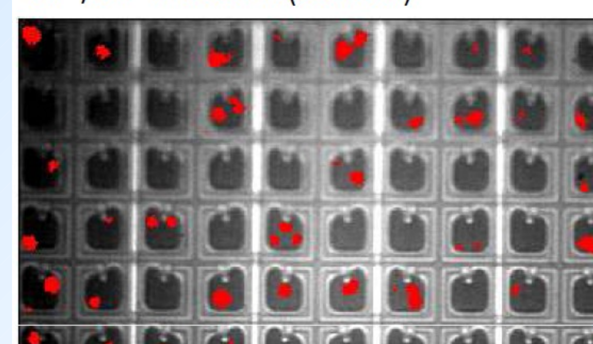
- non ionizing energy loss coses lattice defects where carriers are thermally generated → dark count rate increases as expected
- increase of afterpulses
- detection of many photon pulses still OK





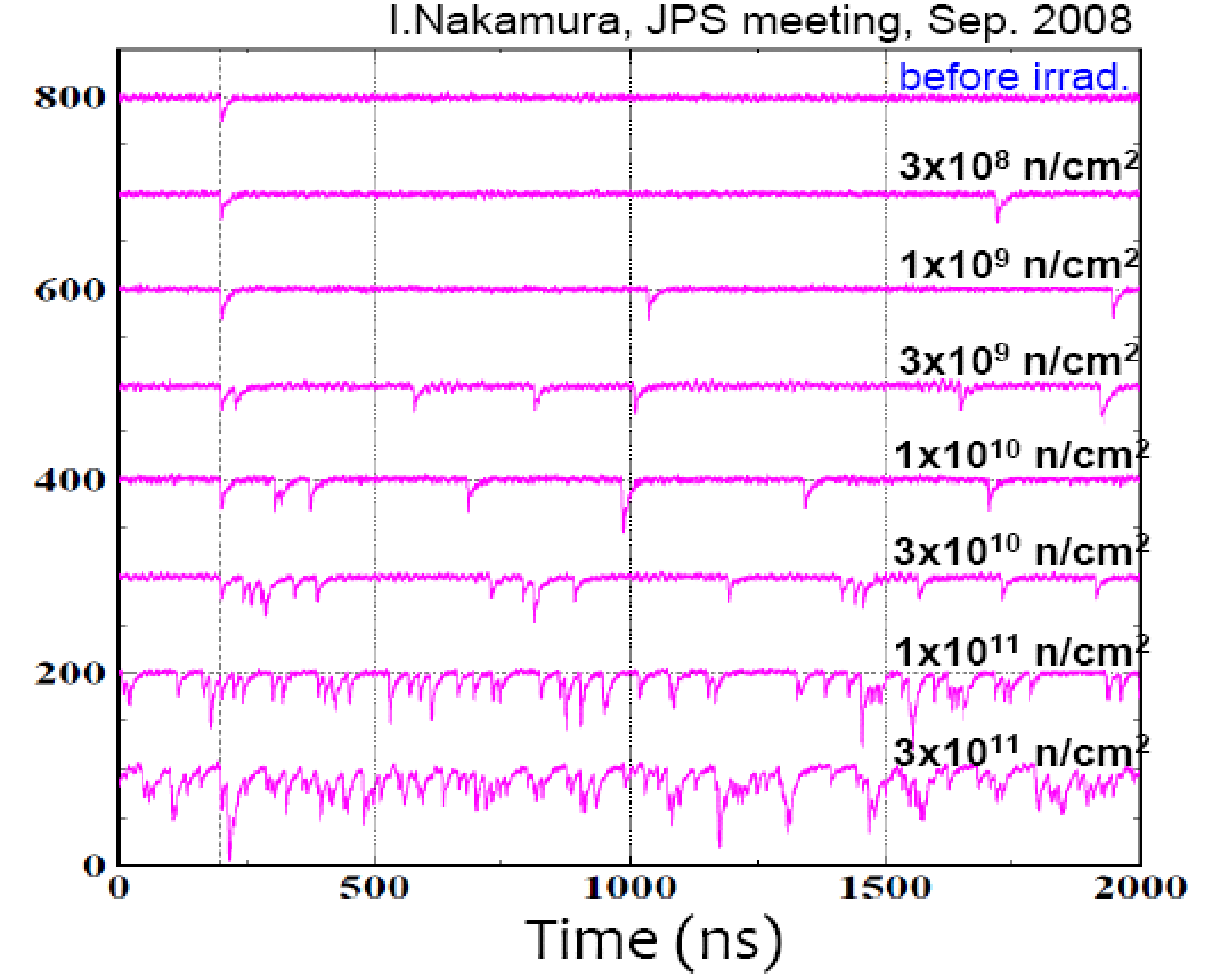


10^{11} /cm² irradiated (zoomed)



Y. Sudo (Tsukuba)@PD09

SiPM – p,n irradiation

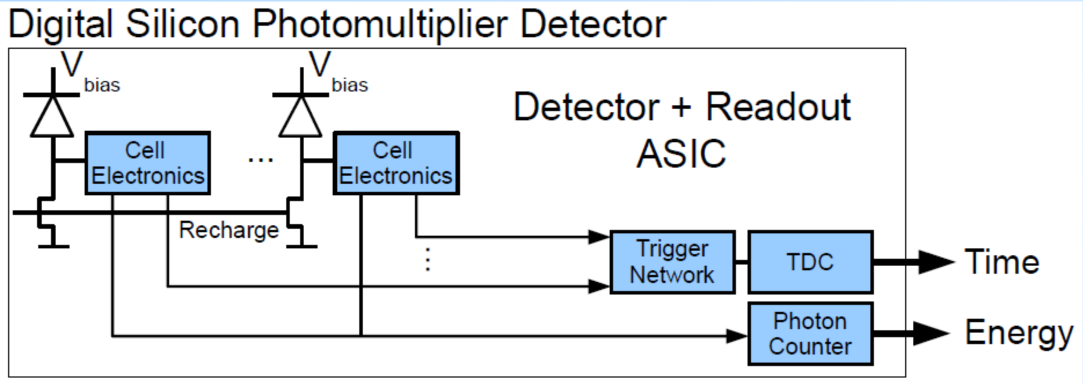


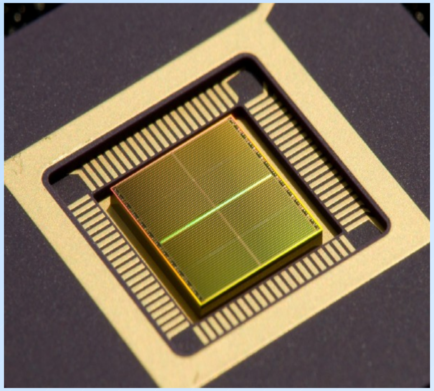
→ Very hard to use present SiPMs as single photon detectors after fluence of 10^{11} n/cm^2 1MeV neutrons

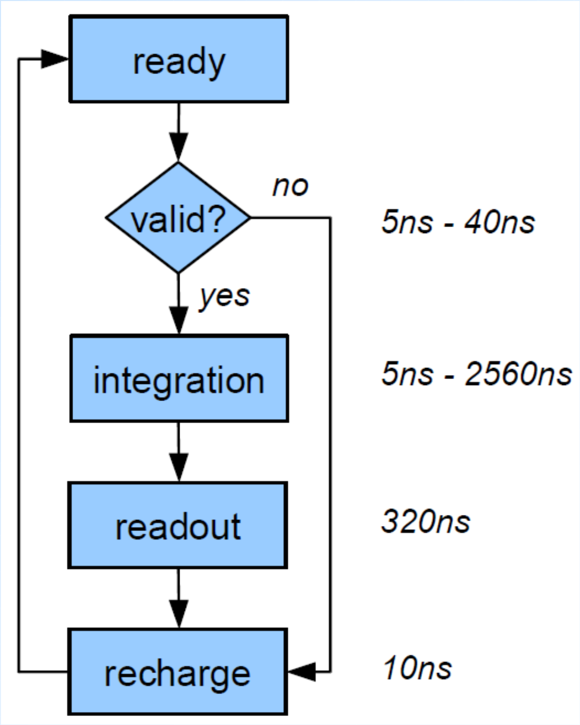
dSiPM-Digital SiPM (Philips)

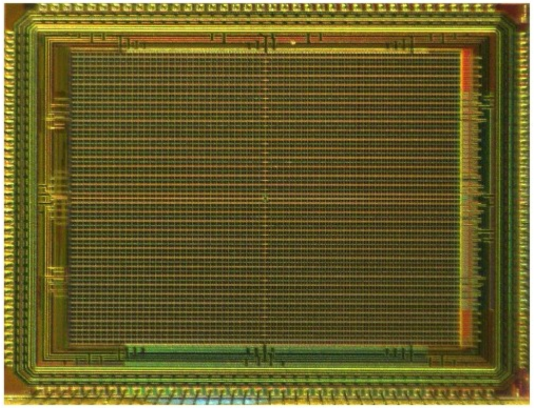
Signal from each pixel is is digitized and the information is processed on chip:

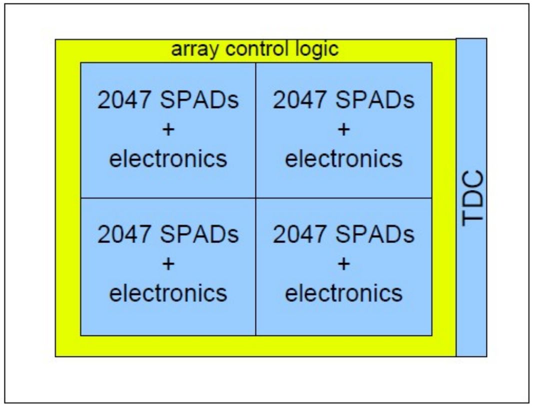
- time of first fired pixel is measured
- number of fired pixels is counted
- active control is used to recharge fired cells
- 4 x 2047 micro cells
- 50% fill factor including electronics
- integrated TDC with 8ps resolution





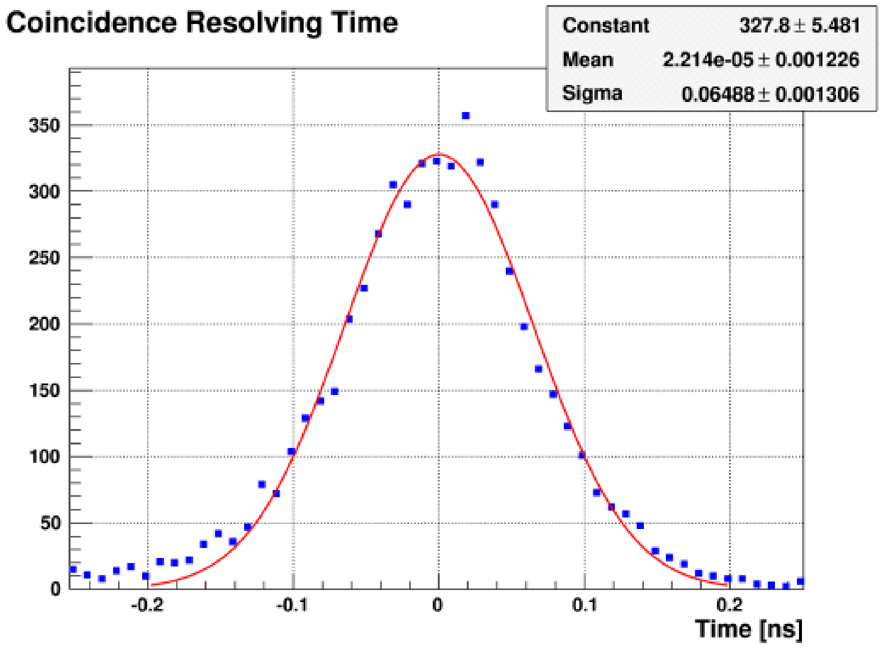


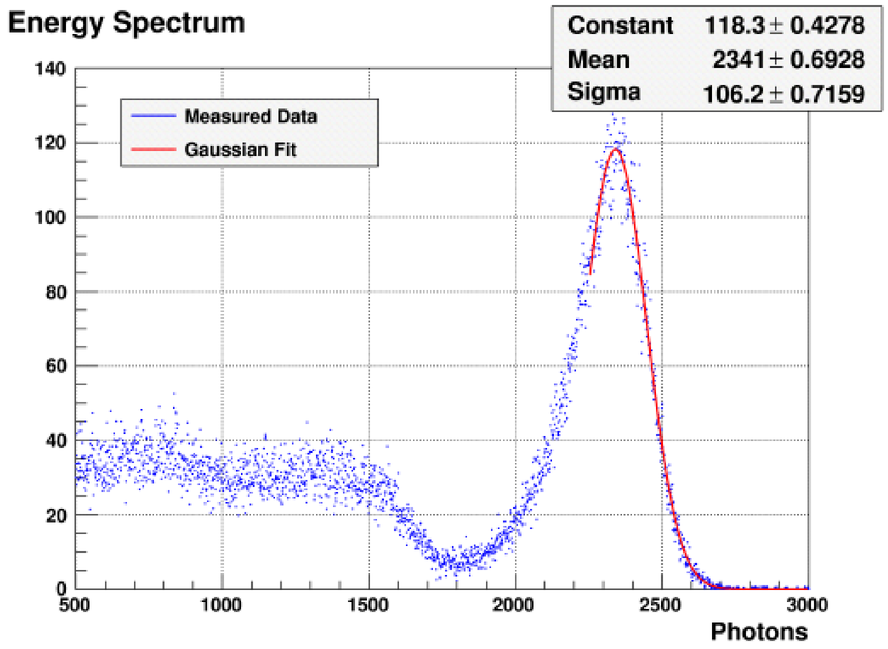




T. Frach (Philips) @ IEEE2009

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

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:

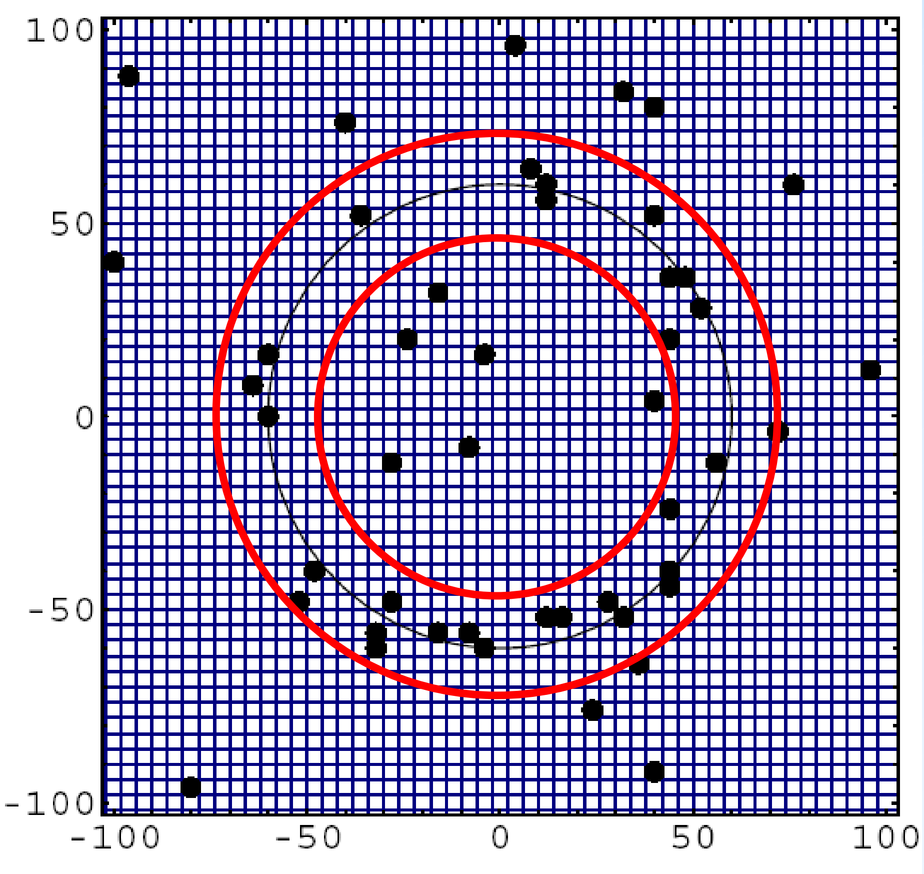
- high dark count rate
- sensitive to radiation damage (n,p)

Signal to background ratio

Expected number of background hits depends on:

- ring area ~ 2000 mm² (±3σ)
- dark count rate ~ 600kHz/mm²
- coincidence window ~ 5ns

$N_{dark} \sim 6 \quad \rightarrow \quad N_{ph}/N_{dark} \sim 3$



r = 60 mm

σ = 1mm

N_{ph} = 20

(typical parameters for proximity focusing aerogel RICH – Belle II)

Ratio can be increased by:

- **smaller ring image area → high Cherenkov photon density**
- **narrower time window**
- **use of light collection system (light concentrators) to increase effective area of the sensor**

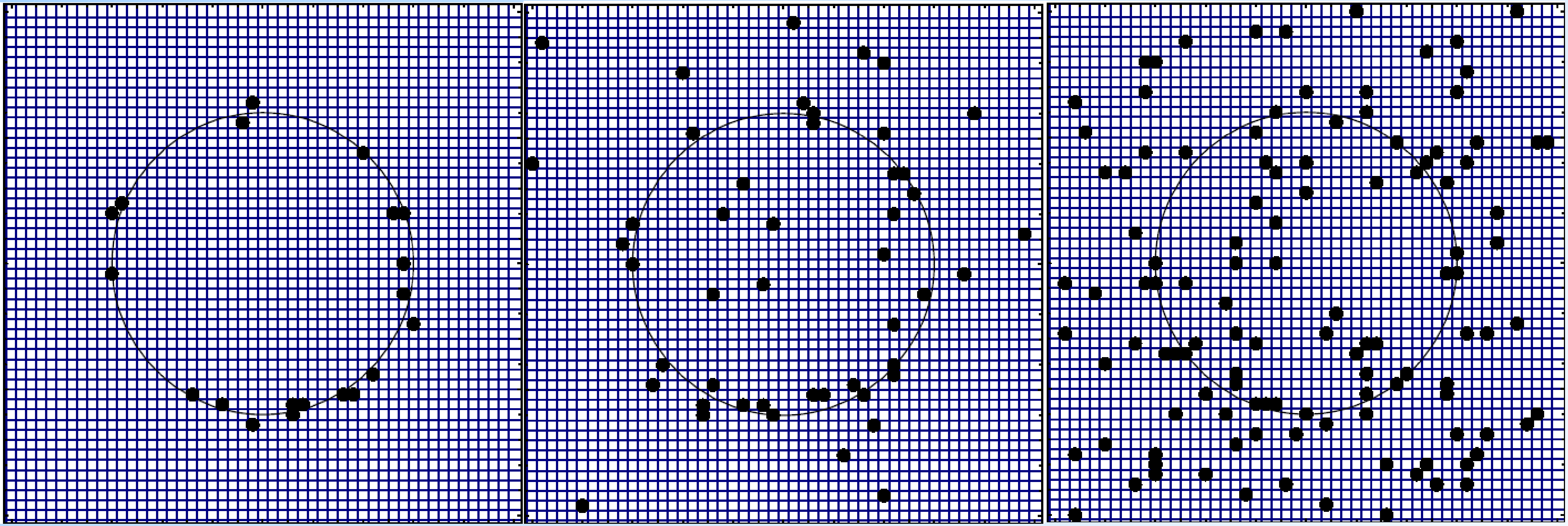
Can such a detector work?

RICH with SiPM - expected hit distribution

Ring on a uniform background:

- 20 ph./ring, ring radius 60mm, pad size 4mm
- dark count occupancy:

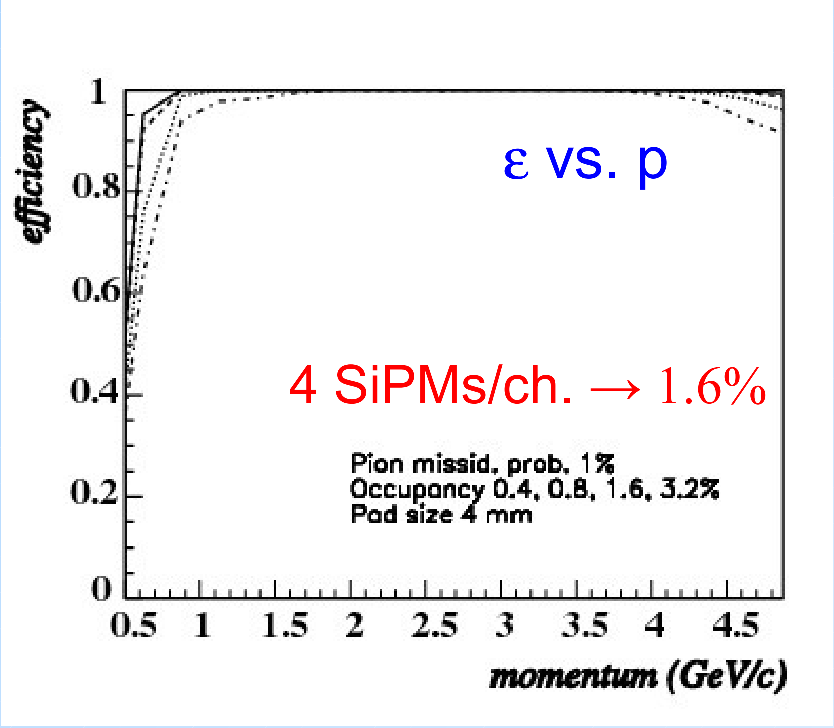
0% 1% 4%

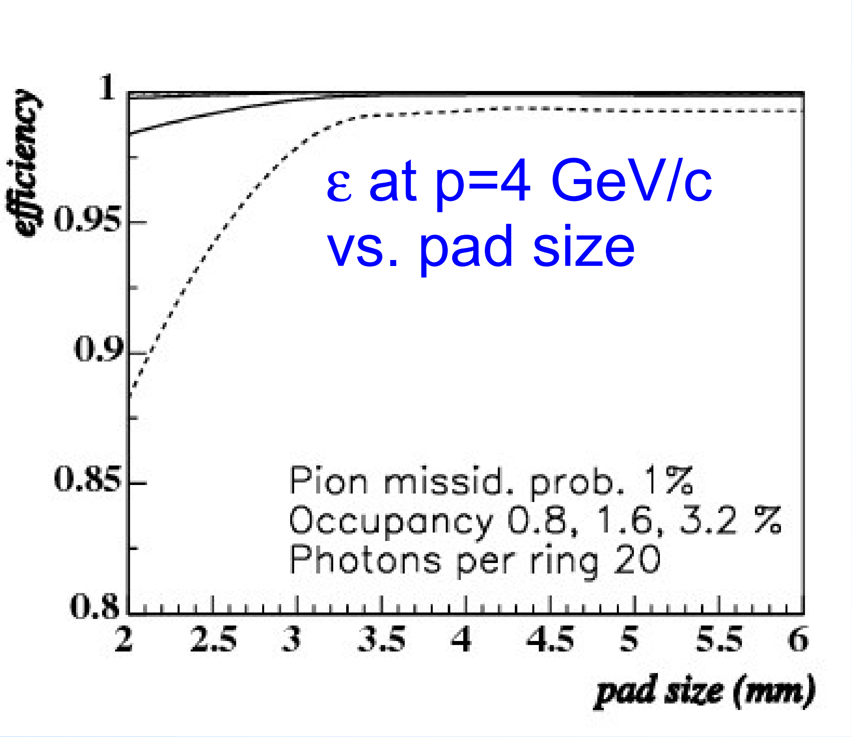


Can such a detector work?

MC simulation of the counter response: assume 1mm² – active area G-APDs with 0.8 MHz (1.6 MHz, 3.2 MHz, 6.4 MHz) dark count rate, 5 ns time window. Vary light collector demagnification (= pad size).

K identification efficiency at 1% π missid. probability



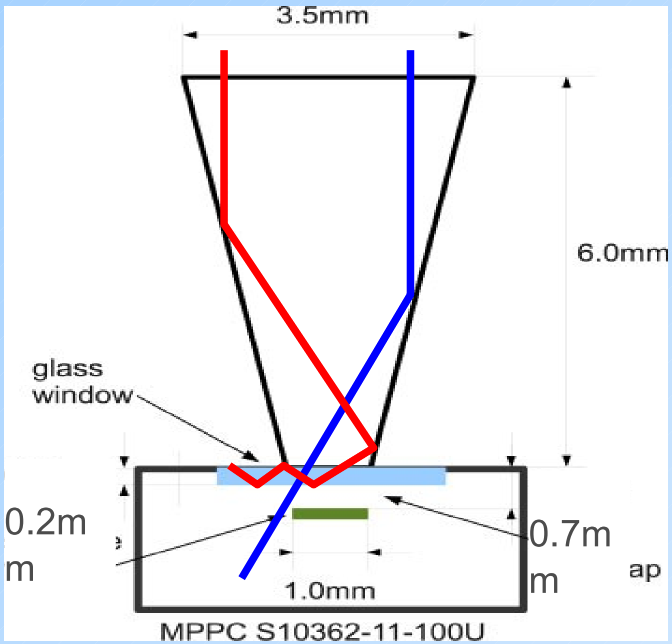


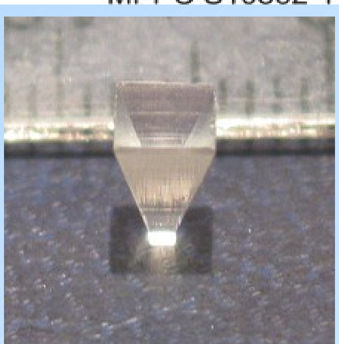
→ **Looks OK!**

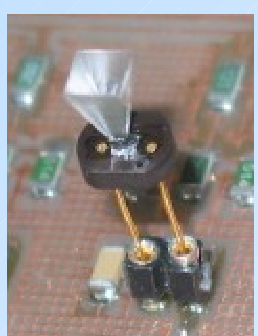
Light concentration

Can be used if light comes within the limited solid angle

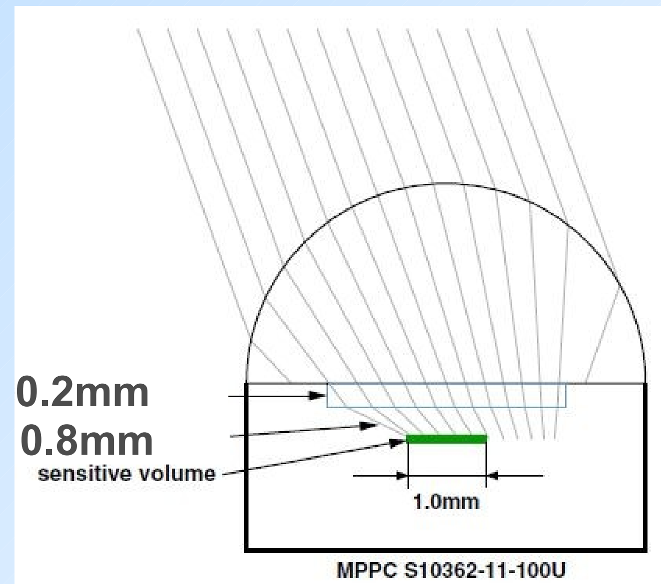
- Winston cones produce large angular spread at the exit surface – photons can miss the active area

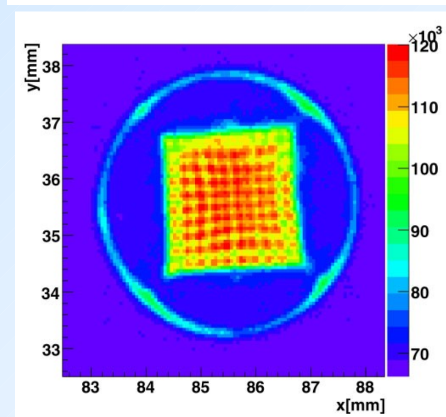


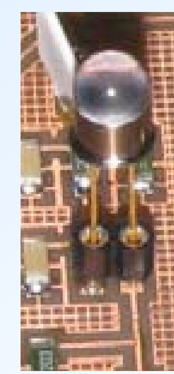




- hemispherical light concentrators give better results with large spacing between concentrator and SiPM

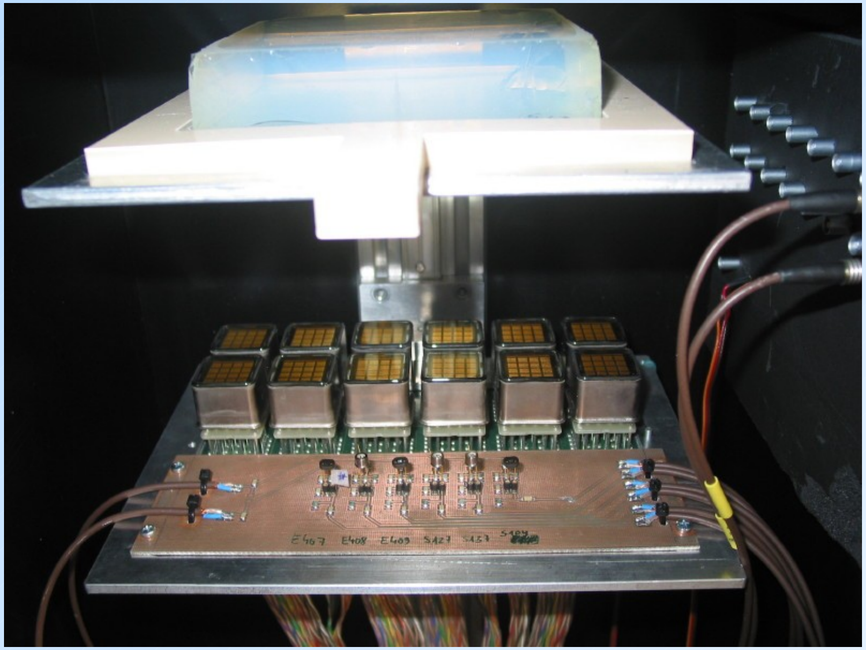


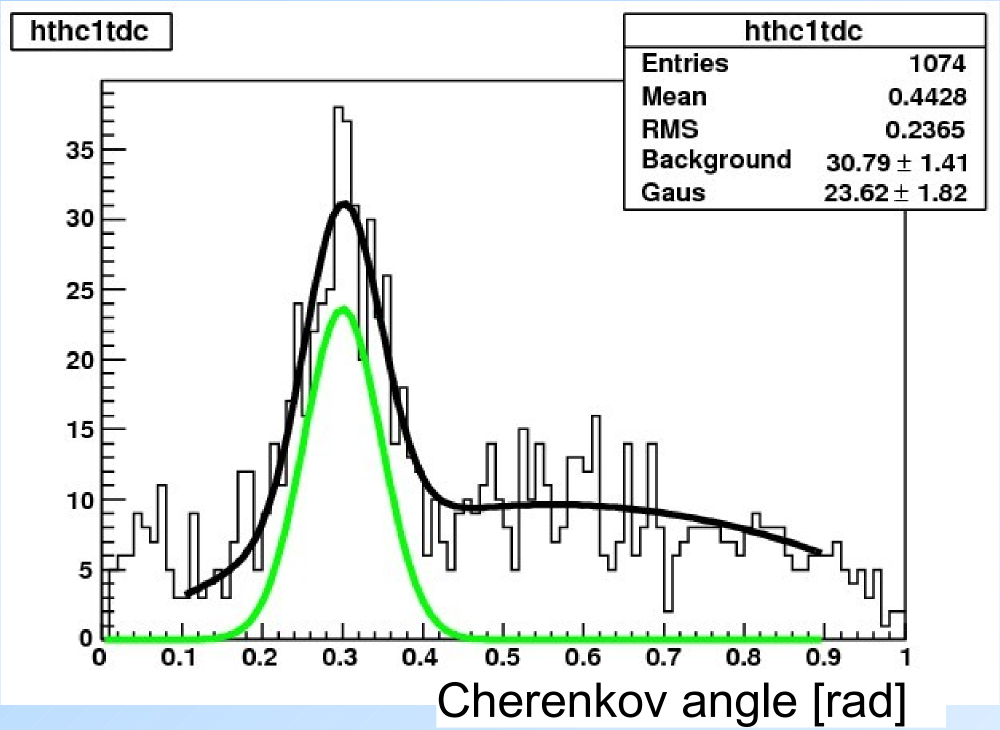


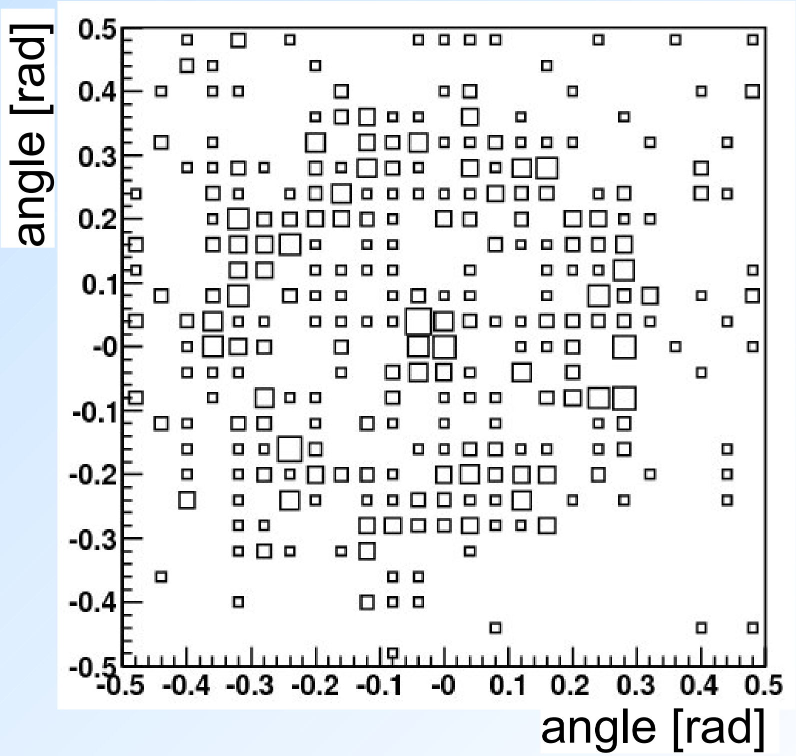


First ring @ RICH2007

First measurement of single Cherenkov photons in a cosmic ray setup was reported at RICH 2007.







S. Korpar (UM,IJS) @ RICH2007

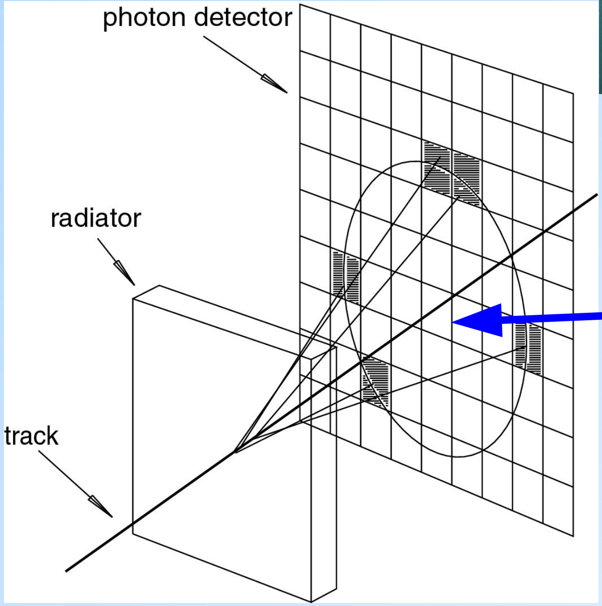
Belle II aerogel RICH development

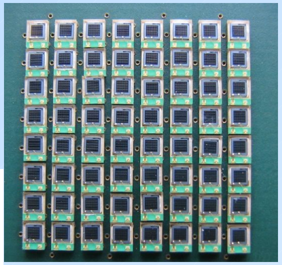
SiPM based photon detector was considered for aerogel RICH.

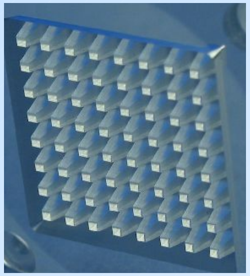
• 8x8 array of MPPCs + light guides was produced

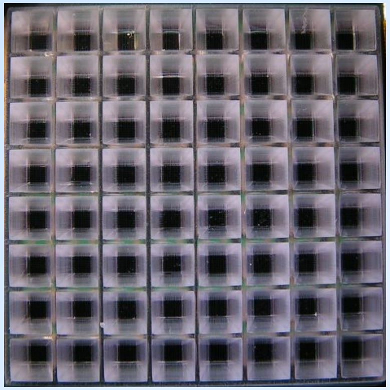
• module was tested in the test beam with 1cm thick aerogel radiator and performed well

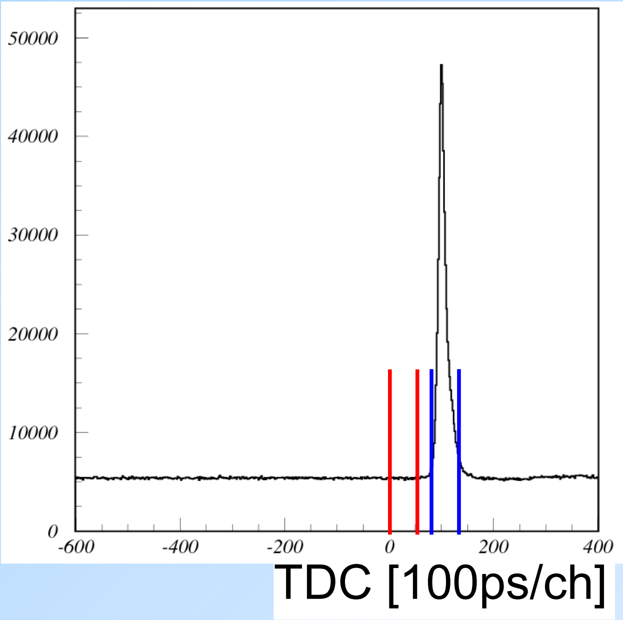
→ R. Pestotnik (IJS), this session

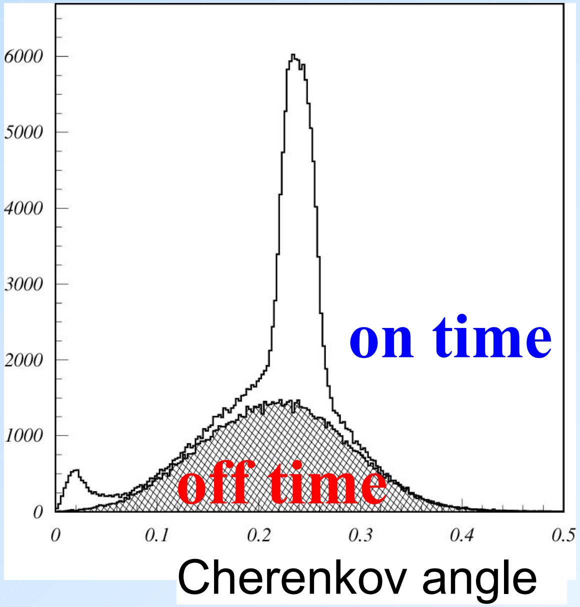


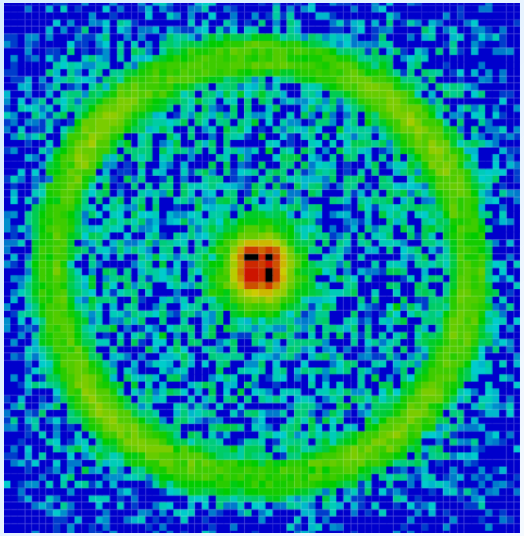






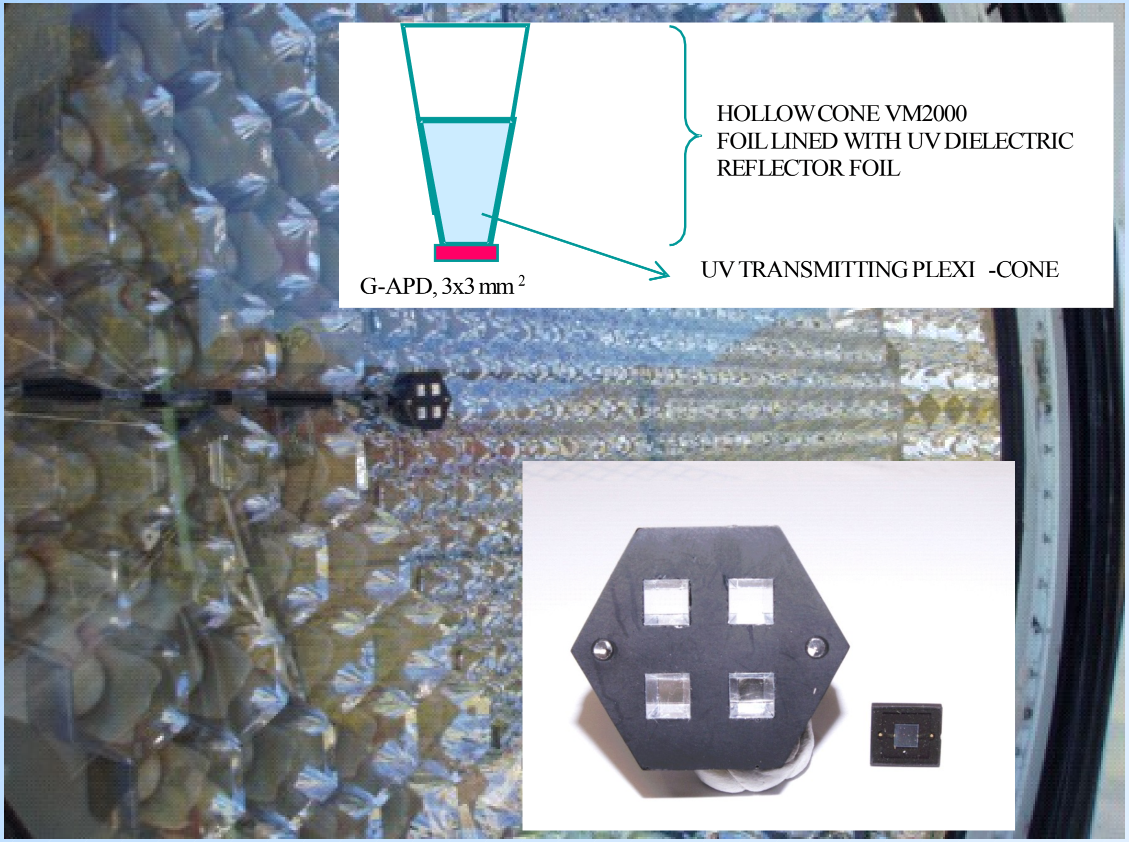


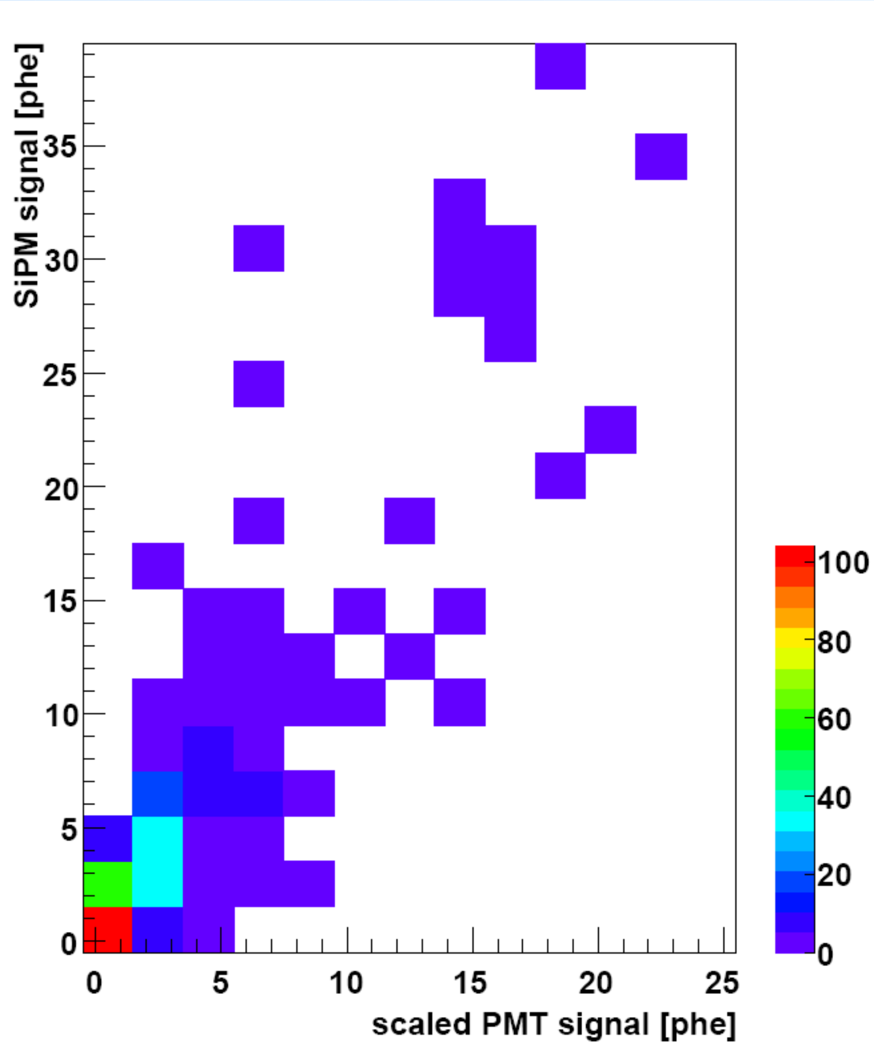




MAGIC project

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

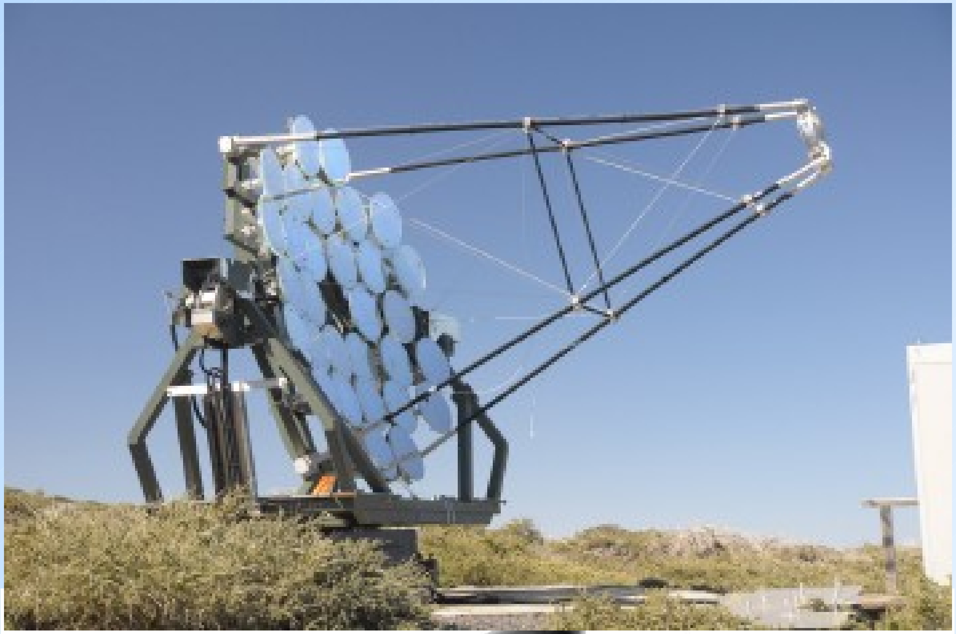


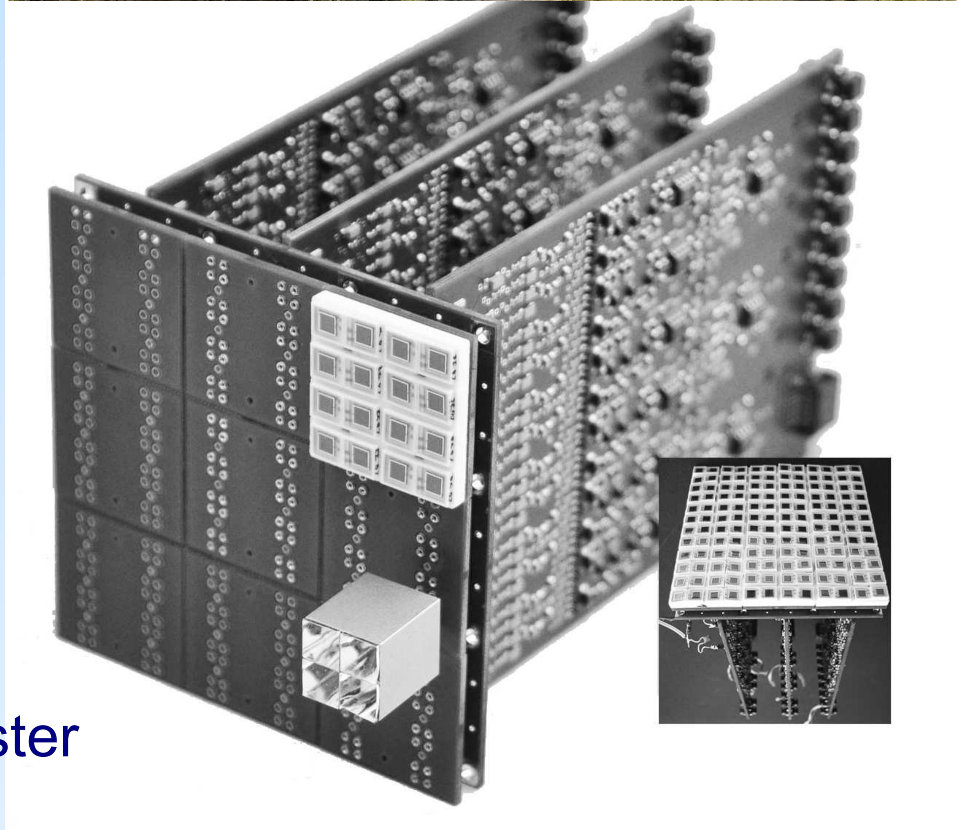


E. Lorenz (MPI,ETH) @ RICH2007

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





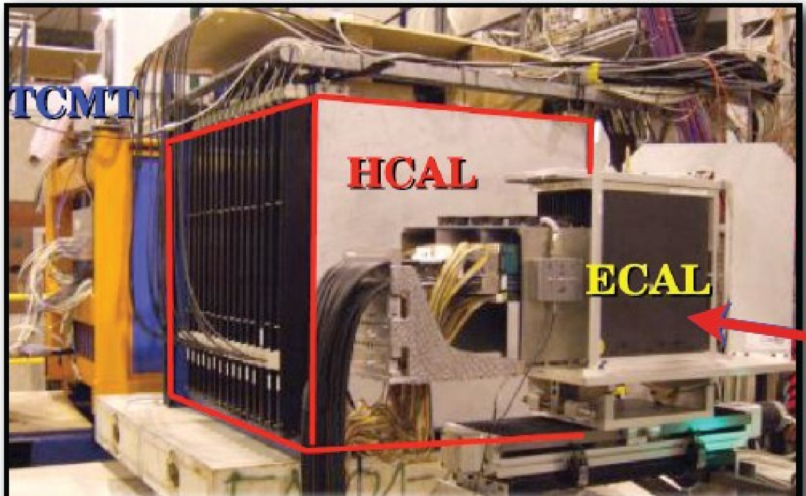
T. Krähenbühel (ETH Zurich) @ PD09

for update look at the previous talk and poster

CALICE – first large system experience

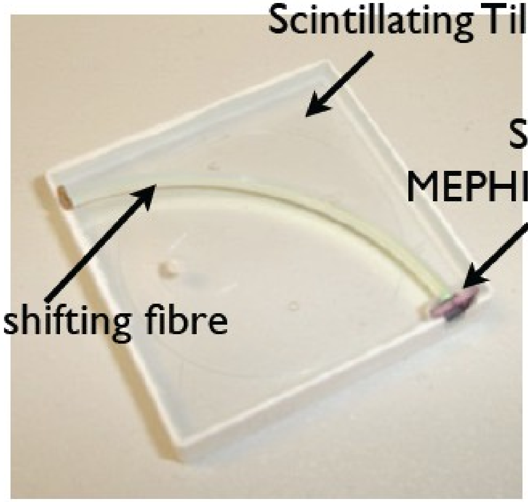
- only 20 bad channels in 3 years of testing – mostly mechanical problems

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

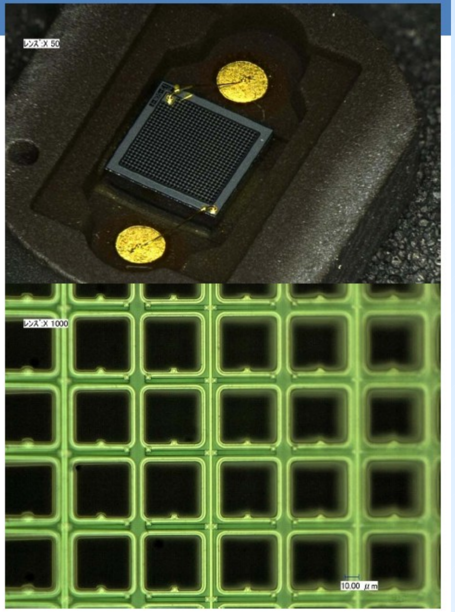
A. Tadday (CALICE)@PD09

T2K – first experiment with SiPMs

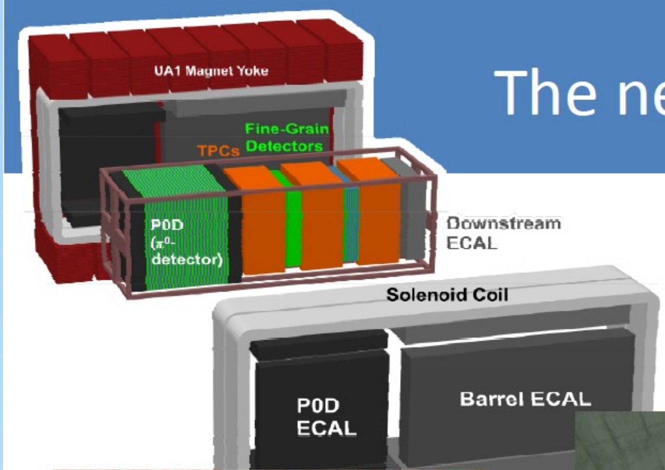
- same type of SiPM used in many detectors in total more than 60000
- all have been tested → very low number of bad samples

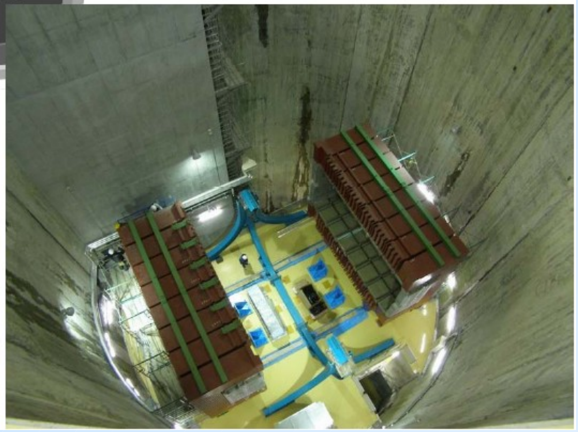
Using the same MPPC

- 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)



The near detector





	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

Summary

SiPM is a solid state device capable of single photon detection with many nice features and first tests show that it can be used as photon detector for RICH counters and Cherenkov telescopes.

Major draw back is high dark count rate that increases with radiation and hopefully this will be reduced in future (reduced active volume, different materials).

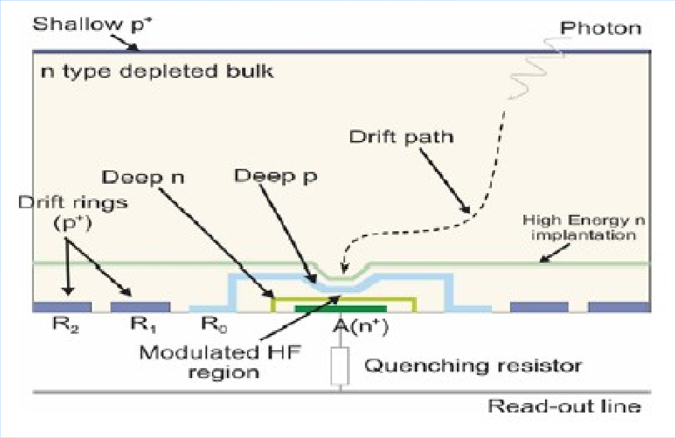
Use of SiPMs for calorimeters and fiber trackers is entering in mature stage. First large scale applications show reliable performance.

Hopefully Cherenkov light aplications will soon follow!

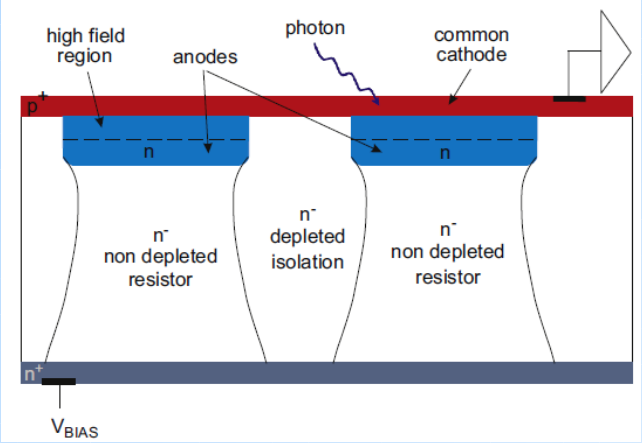
BACKUP SLIDES

SiPM – different types

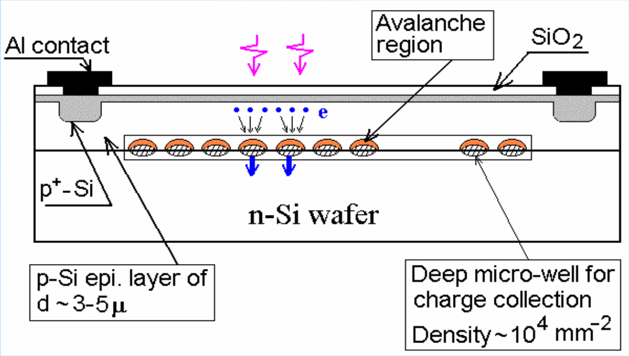
back illuminated:

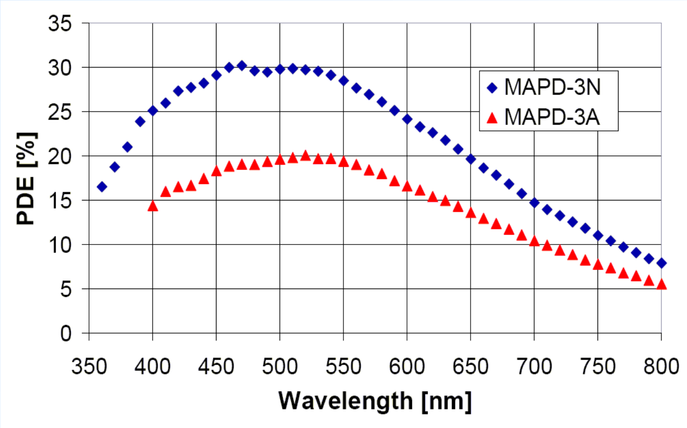


bulk integrated resistor:



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

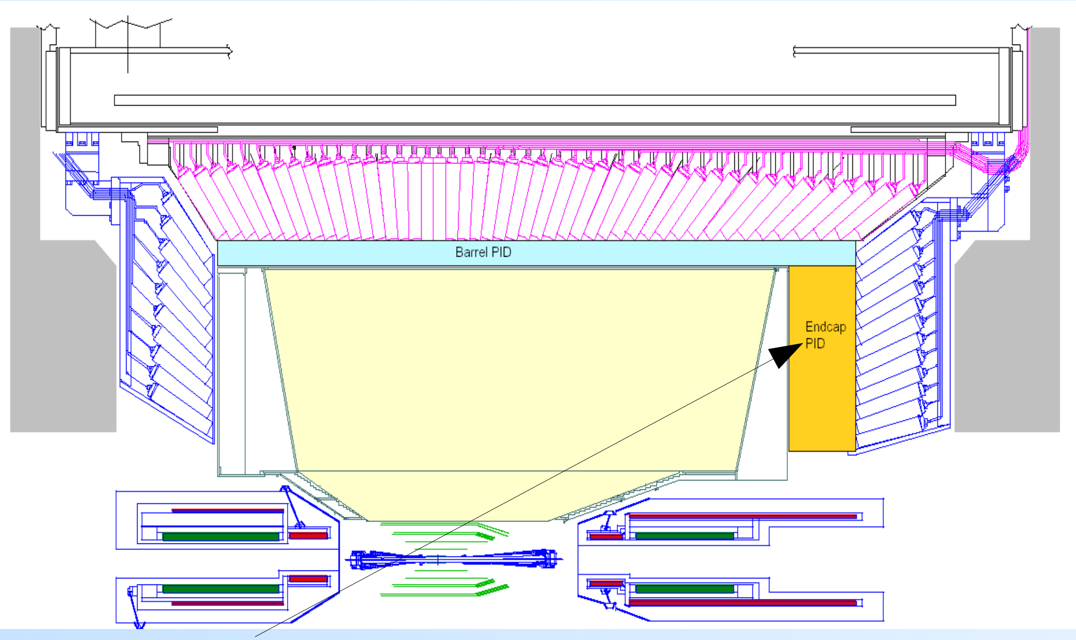




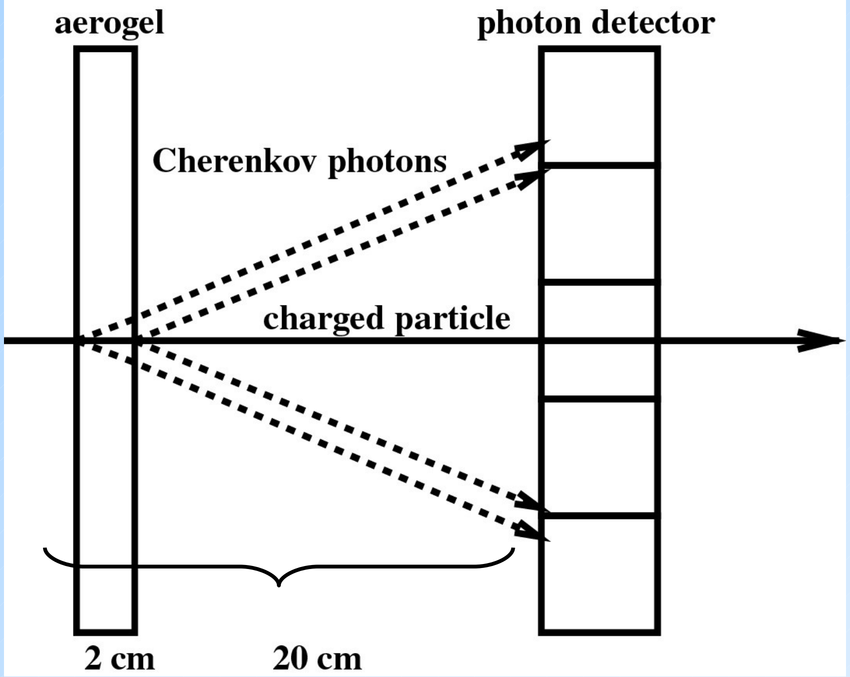
Forward PID for Belle II

Requirements and constraints:

- ~ 5 σ K/π separation @ 1-4 GeV/c
- limited available space ~ 250 mm
- operation in magnetic field 1.5T
- photon detector candidates: HAPD, MCP-PMT, **G-APD**



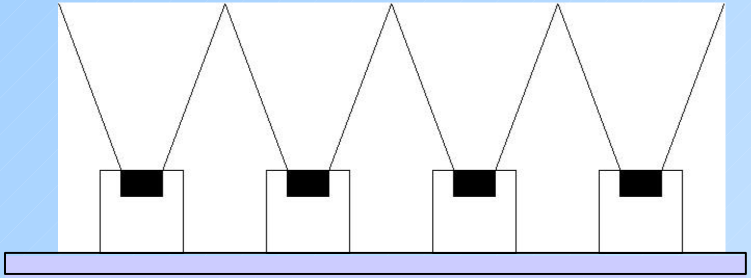
Selected type: proximity focusing aerogel RICH

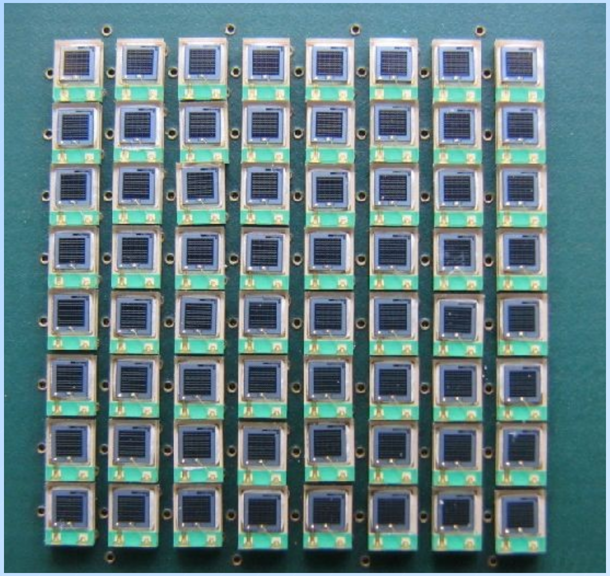


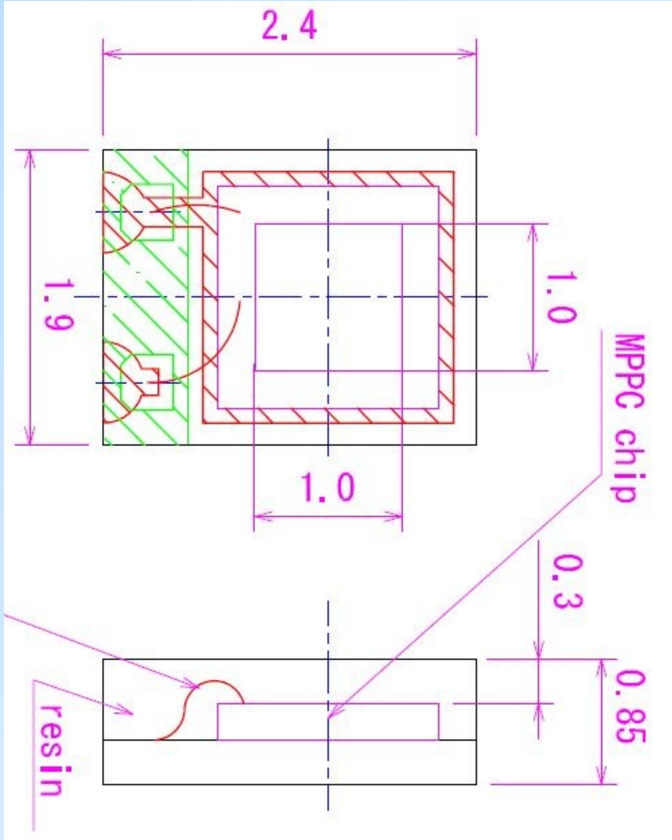
- <n> ~ 1.05 (focusing configuration)
- $\vartheta_c(\pi)$ = 308 mrad @ 4 GeV/c
- $\vartheta_c(\pi) - \vartheta_c(K)$ = 23 mrad @ 4 GeV/c
- pion threshold 0.44 GeV/c, kaon threshold 1.54 GeV/c
- time-of-flight difference (2m from IP): $t(\pi) - t(K)$ = 180(45) ps @ 2(4) GeV/c

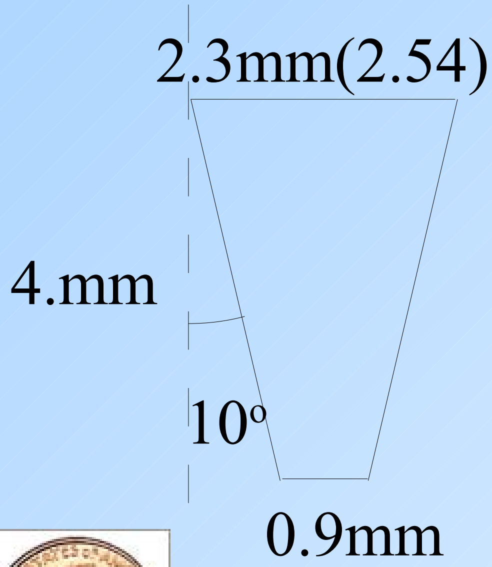
8x8 array of SMD-MPPCs

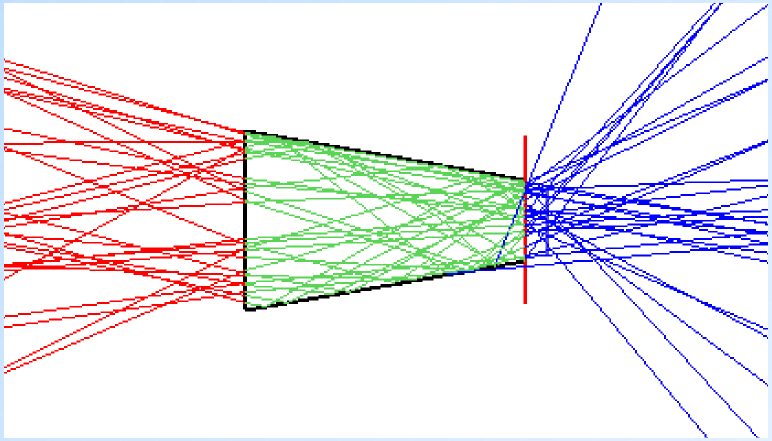
- Detector module with 8x8 array of SMD MPPCs at 2.54 mm pitch



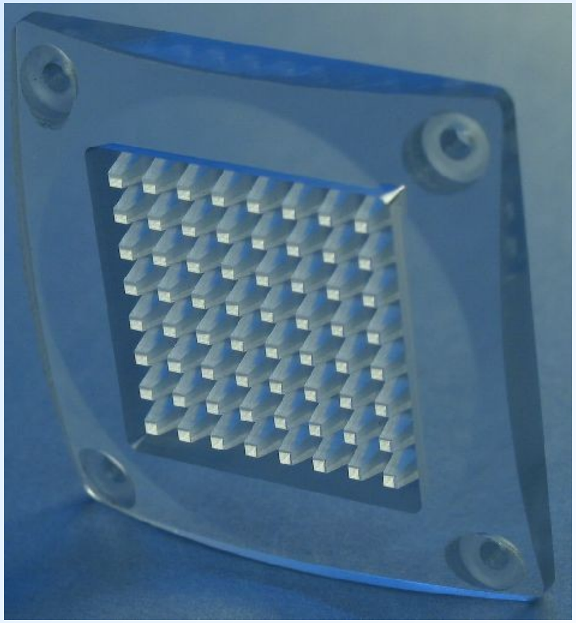






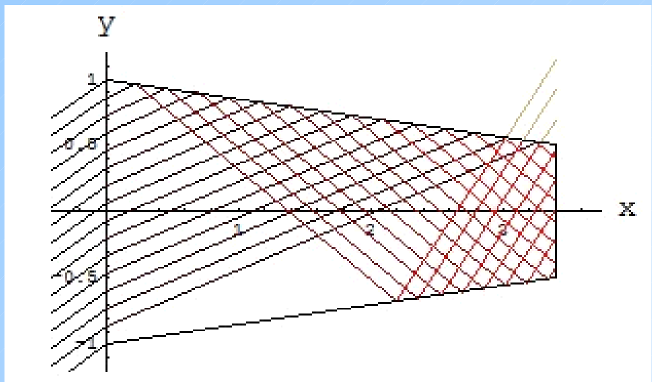


Light guides were machined from plastic (HERA-B lens material).

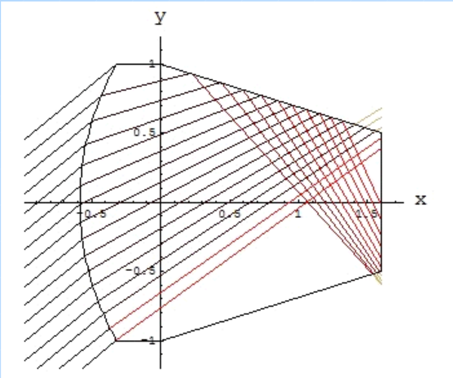


SiPM - Light guides

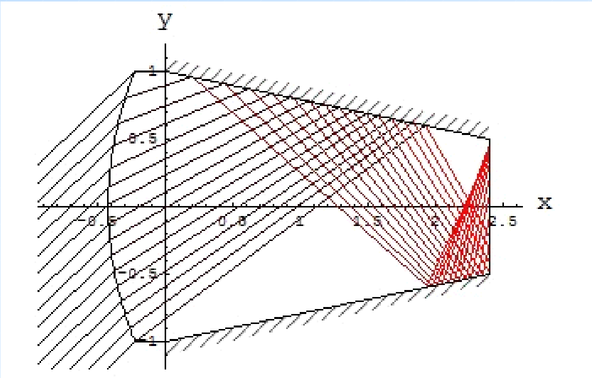
Planar entry window



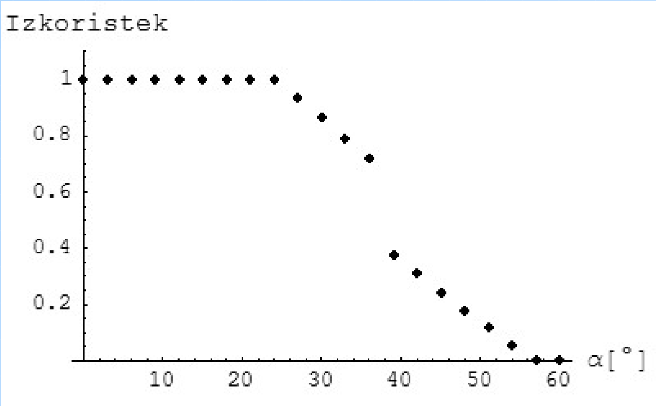
Spherical entry window

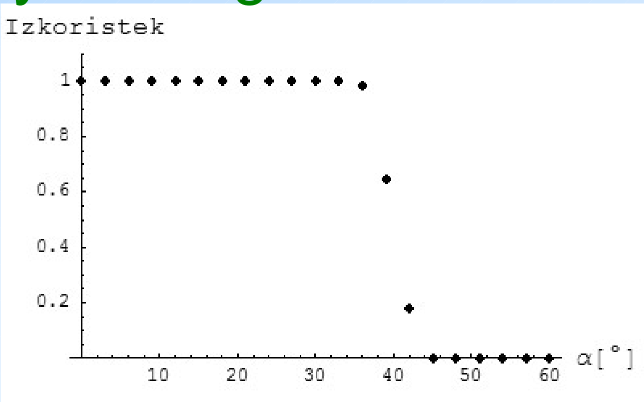


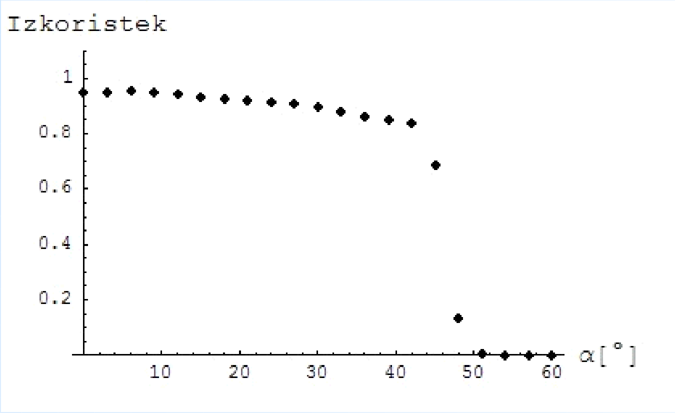
Spherical entry window, reflective sides



Efficiency vs. angle of incidence α



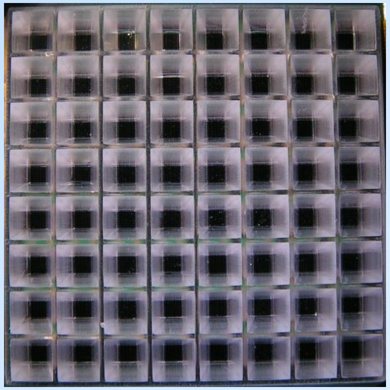


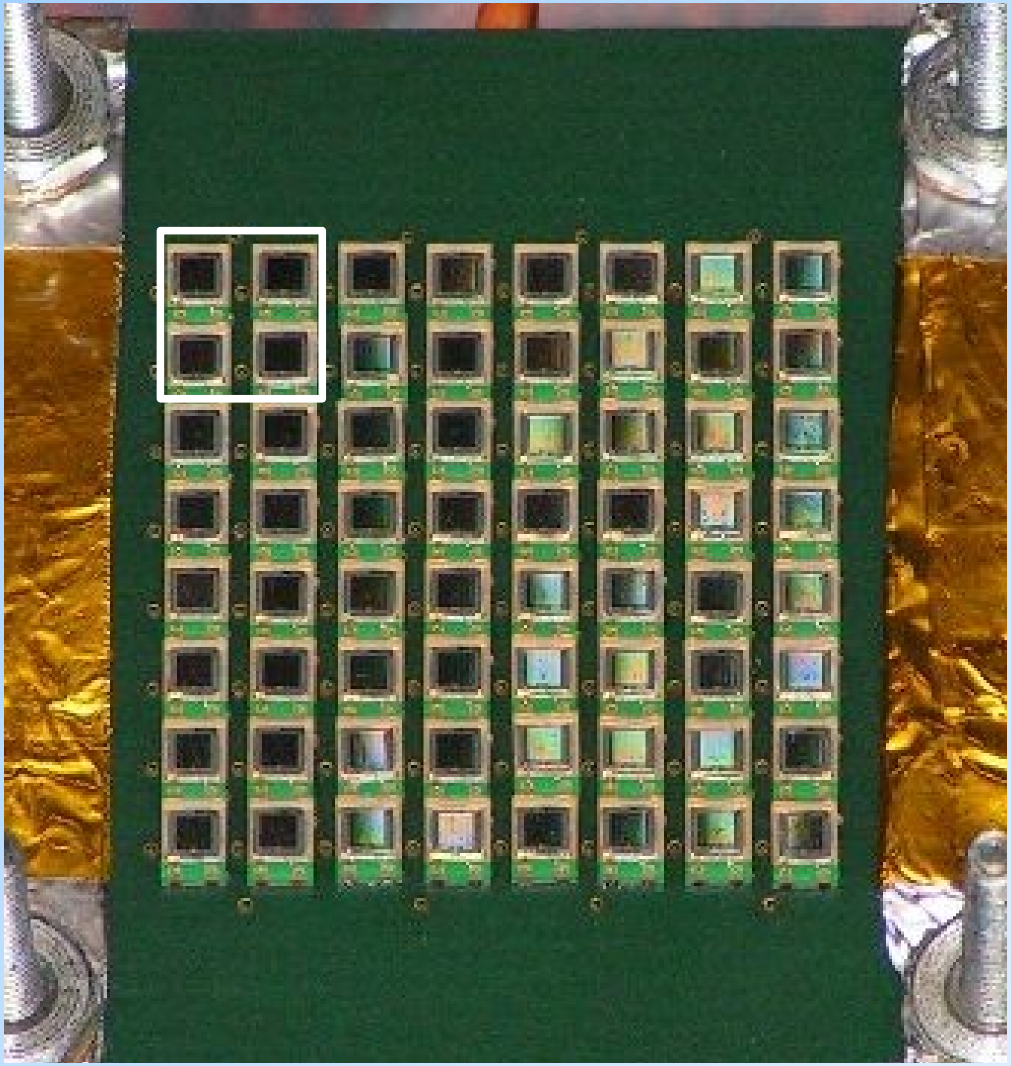


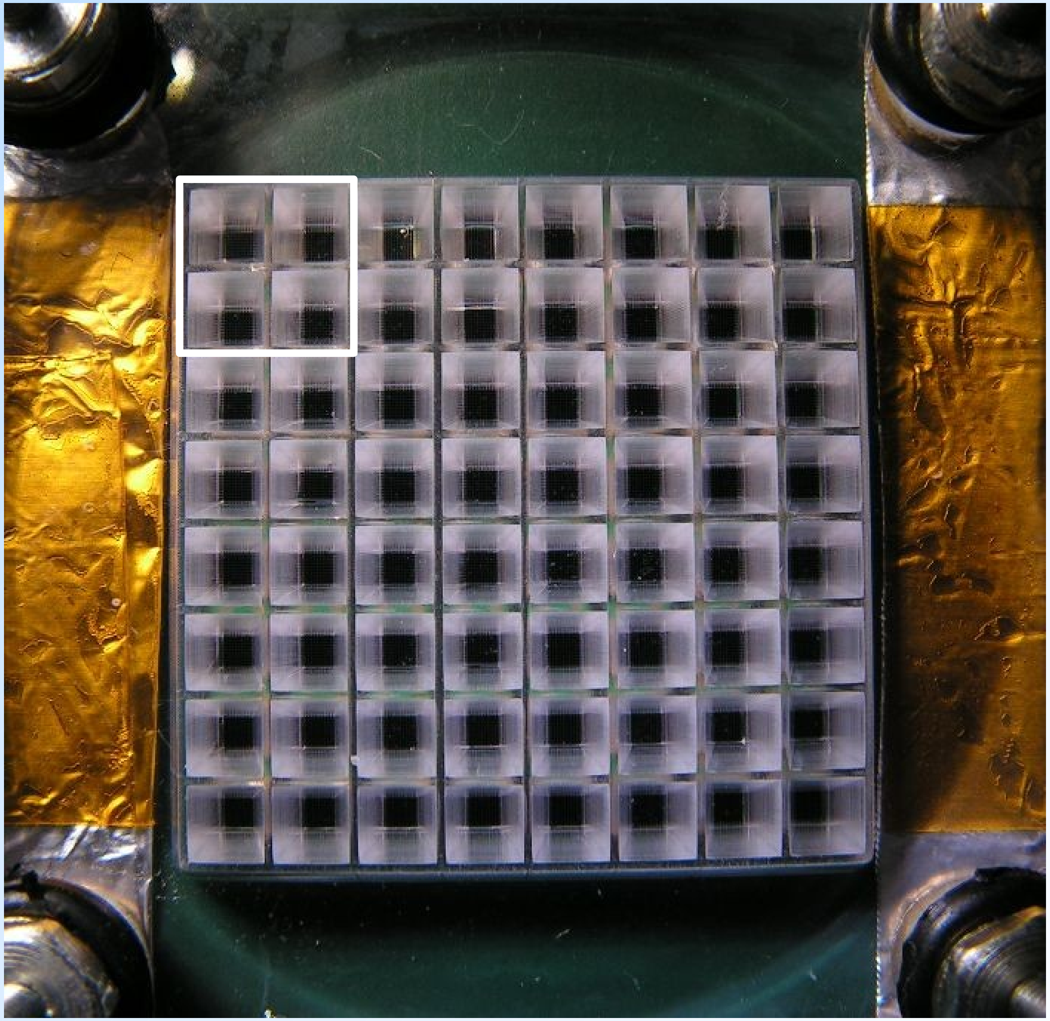
Light guide	d/a	R/a	α_{min}, α_{max}	I(-60°, 60°)
Planar entry	**3.4**	-	**-24°, 24°**	**64%**
Sph. entry	**1.6**	**2.0**	**-35°, 35°**	**66%**
Reflective sides	**2.4**	**2.6**	**-44°, 44°**	**69%**

MPPC module - 3

- pad size 5.08 mm, 4 mm^2 active (15.5% w/o LG)





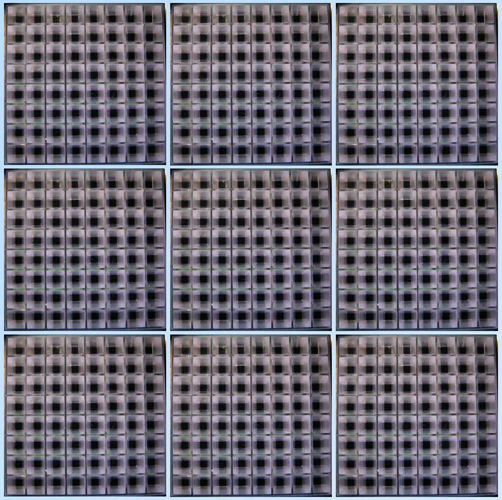


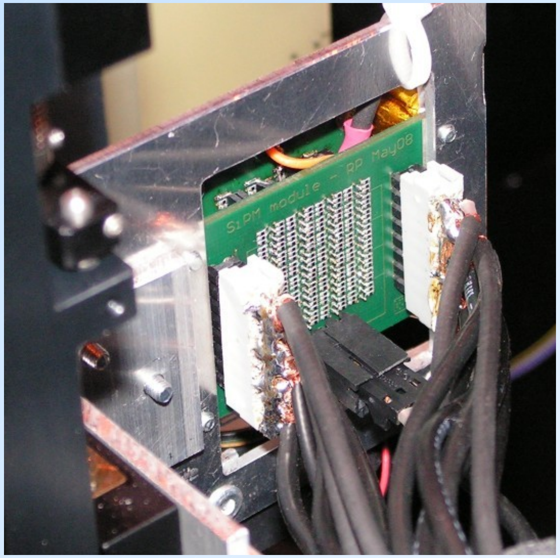
Beam test setup

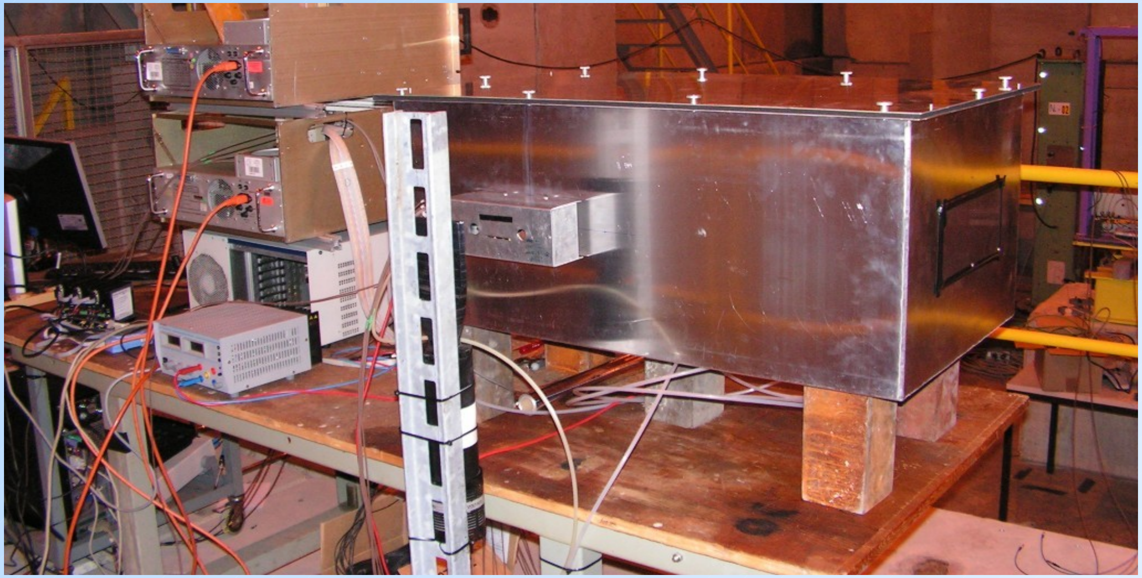
- MPPC array w/o or w/ light guide mounted on 3D stage

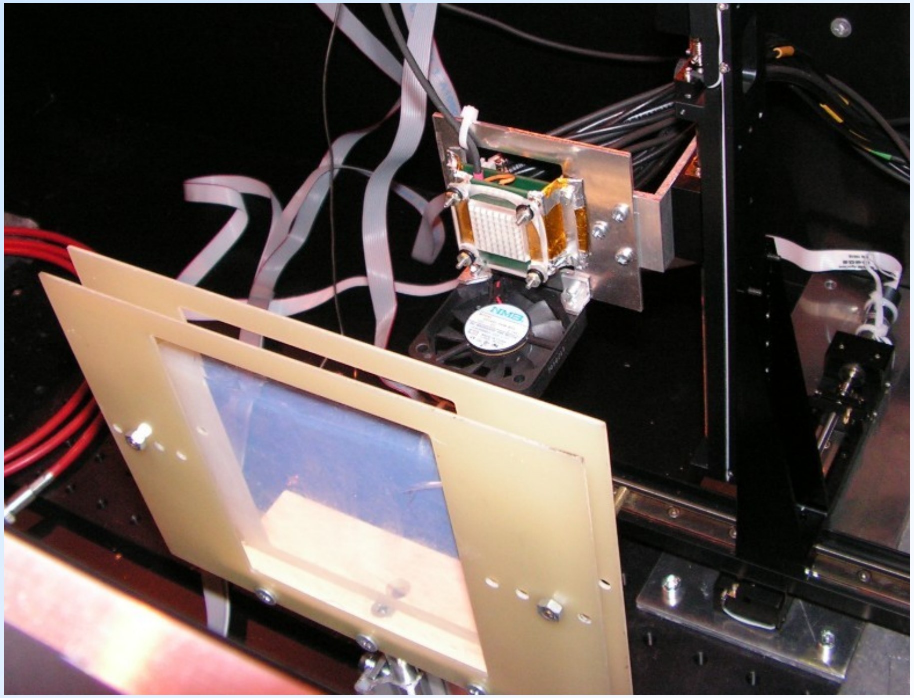
→ effective detector size 3x3

- aerogel n=1.03, d=10mm
  (distance 130mm)
- hits detected by multi-hit TDC
- +120 GeV/c pions, beam size ~1cm^2
- 2 MWPCs for tracking
- plastic scintillator for timing









Expected number of photons

Expected number of photons for aerogel RICH (beam test prototype):

- multianode PMTs (peak QE ~ 25%, collection eff. ~ 70%) or MPPCs (HC100)
- aerogel radiator: thickness 1 cm, n = 1.03 and transmission length 1.4 cm (@400nm)

$N_{SiPM}/N_{PMT} \sim 4$