Silicon Photomultipliers

a new device
for frontier detectors
in
HEP, astroparticle physics, nuclear medical and industrial applications

Nepomuk Otte
MPI für Physik, Munich

Outline

- Motivation for new photon detectors
- APDs in proportional and Geiger mode
- From single APDs in Geiger mode to Silicon Photomultipliers
- SiPM characteristics
- Current status of development
- PET as one example of application of SiPM

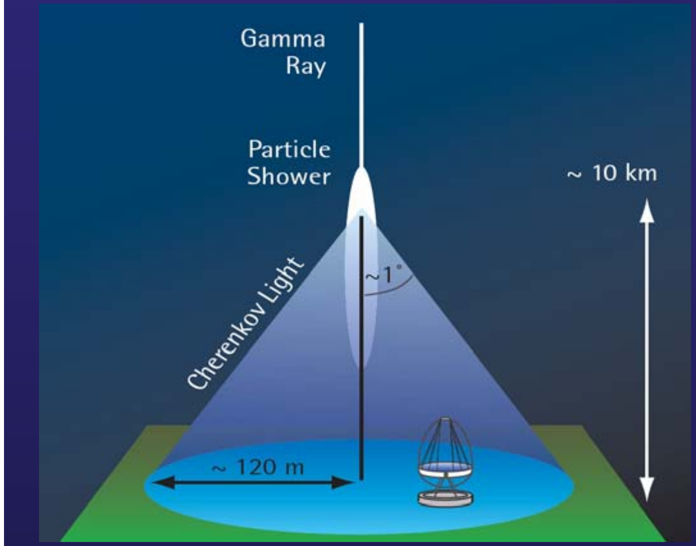
Many future experiments will use >> 100,000 photon detectors

Requirements to be fulfilled by the photon detector candidate:

- robust and stable
- easy to calibrate
- blue sensitive
- low cost (+ low peripheral costs)
- compact
- low power consumption
- …
- highest possible photon detection efficiency

Experiments that will use this photon detector

Ground based Gamma Ray Astronomy



Gamma Ray induces electromagnetic cascade

↳ relativistic particle shower in atmosphere

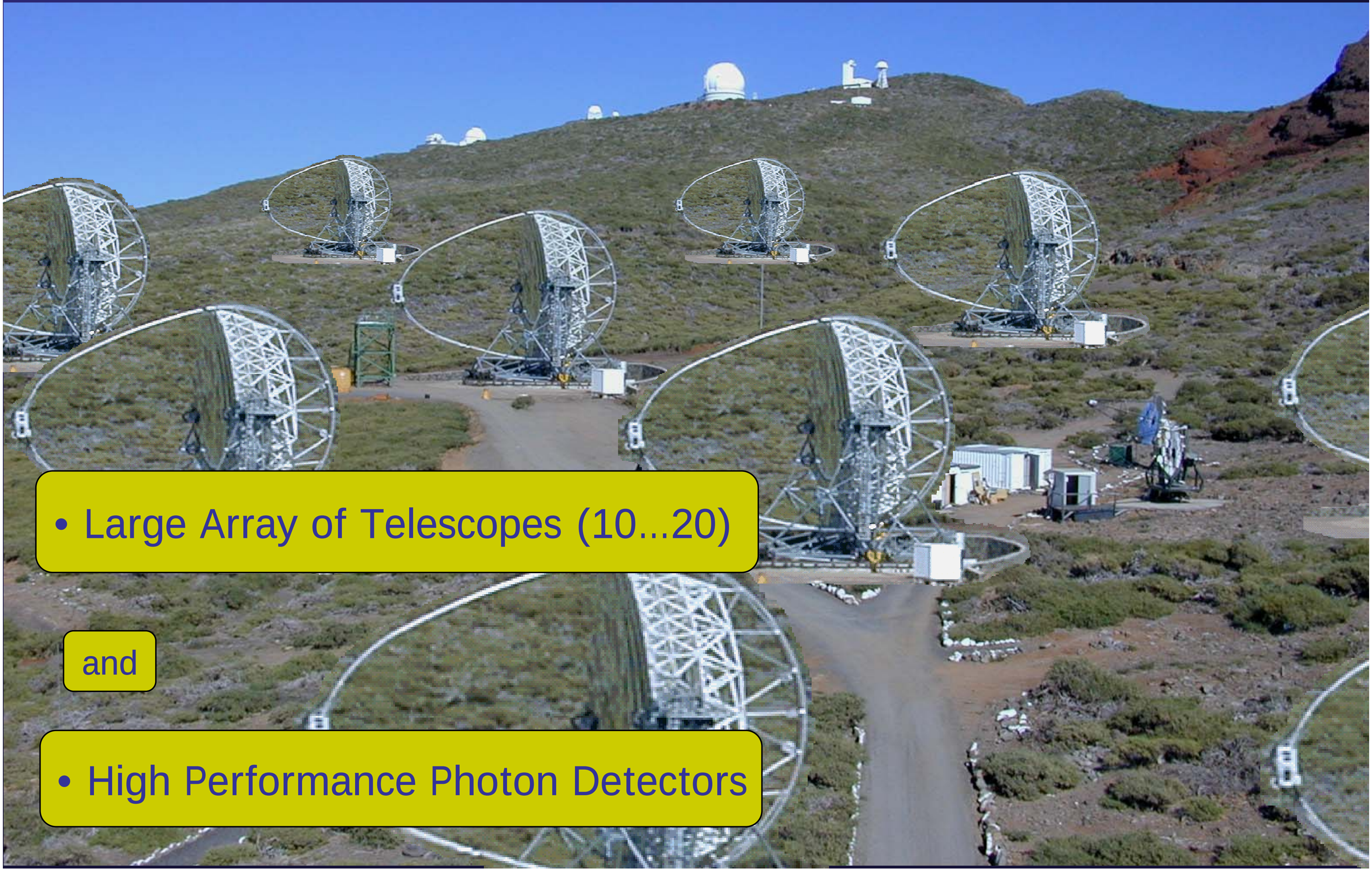
↳ Cherenkov light

fast light flash (nanoseconds)
100 photons per m² (1 TeV Gamma Ray)

MAGIC: world largest
air Cherenkov telescope

http://wwwmagic.mppmu.mpg.de/

Future Plans

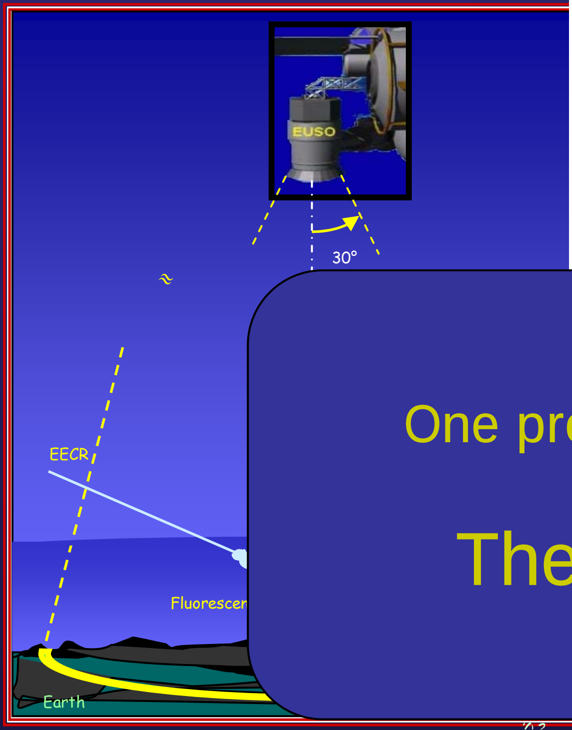


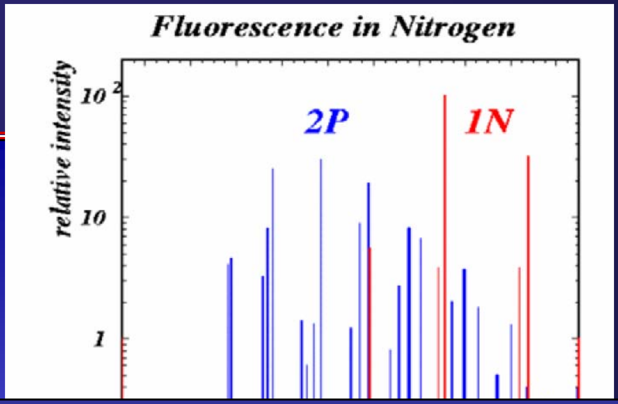
- Large Array of Telescopes (10...20)

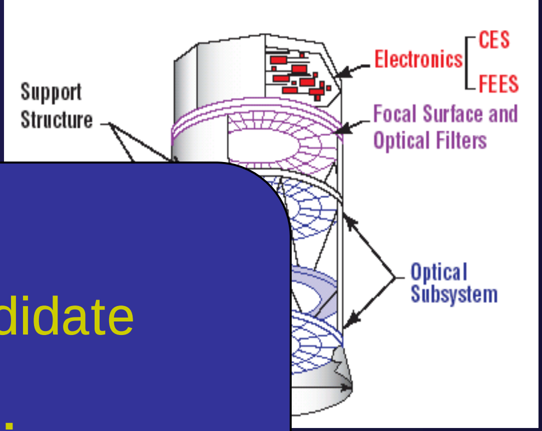
and

- High Performance Photon Detectors

Cosmic Ray Physics from Space







One promising photon detector candidate

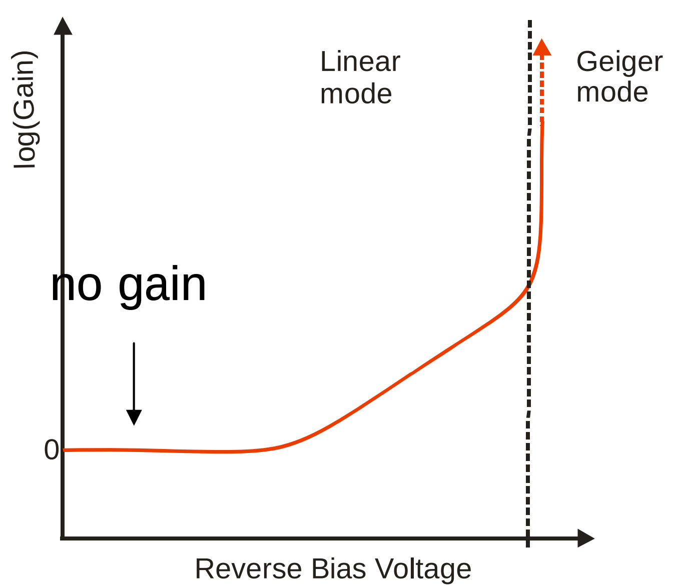
The Silicon Photomultiplier

> 10^{20} eV
- GZK mechanism
- sources of CR
- ...

http://www.euso-mission.org/

A look into basic operations
of
semiconductor photon detectors
with
internal amplification

Working modes of Avalanche Photodiodes



Linear/Proportional Mode

- Bias: slightly ***BELOW*** breakdown
- Linear-mode: it's an ***AMPLIFIER***
- Gain: limited < 300 (1000)
- High temperature/bias dependence
- No single photo electron resolution

Geiger Mode

- Bias: (10%-20%) ***ABOVE*** breakdown voltage
- Geiger-mode: it's a ***BINARY*** device!!
- Count rate limited
- Gain: "*infinite*" !!

Slide adapted from Cova et al. NIST 2003
Workshop on single photon detectors

Advantages of APDs in Geiger Mode
or
Single Photon Avalanche Diodes (SPADs)

- Large standardized output signal
  →high immunity against pickup
- High sensitivity for single photons
- Excellent timing even for single photo electrons (<<1ns)
- Good temperature stability
- Low sensitivity to bias voltage drifts
- Devices operate in general < 100 V
- Complete insensitive to magnetic fields
- No nuclear counter effect (due to standardized output)

The principal disadvantage for many applications:

It is a binary device

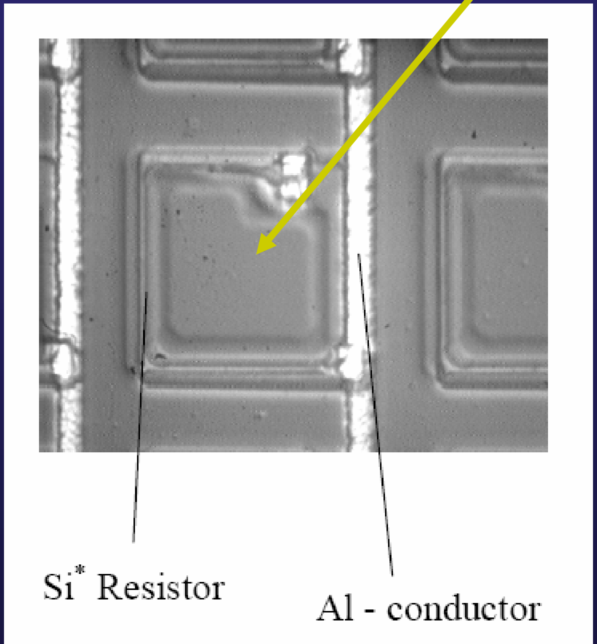
One knows: There was at least one electron/hole initiating the breakdown

but not

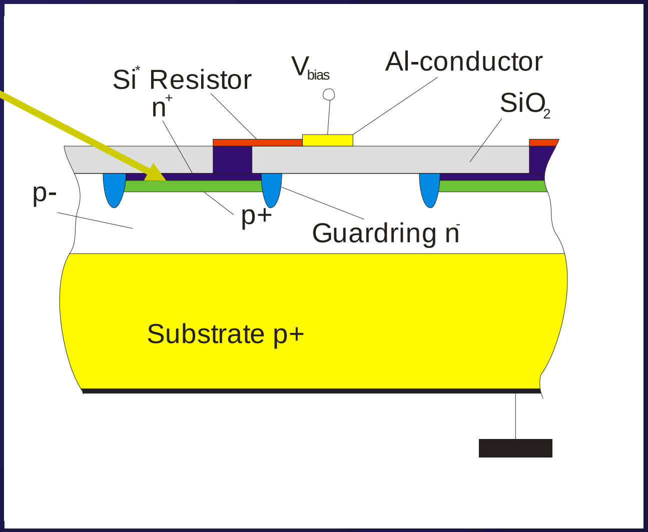
how many of them

solved in SiPM concept ⇨

Basic unit in a SiPM is a Single Photon Avalanche Diode (SPAD)

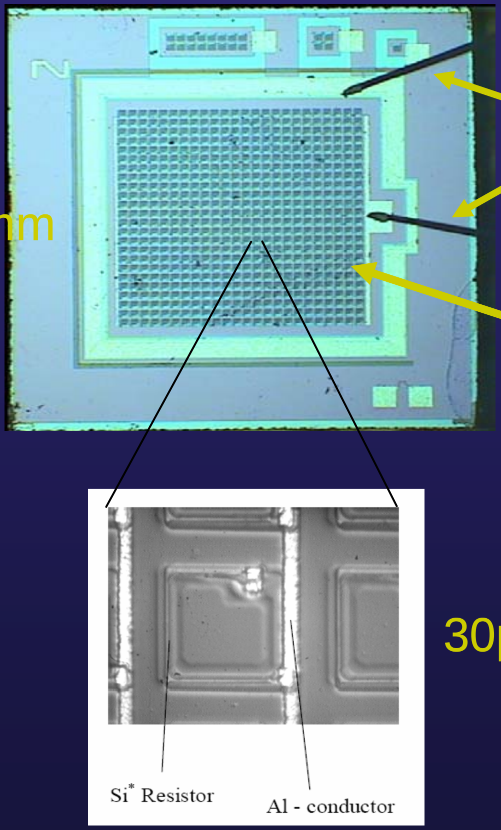


from B. Dolgoshein (ICFA 2001)
http://www.slac.stanford.edu/pubs/icfa/



Breakdown in SPAD is quenched by individual polysilicon resistor (passive quenching)

The Silicon Photomultiplier or Geiger-APD



1mm

30µm

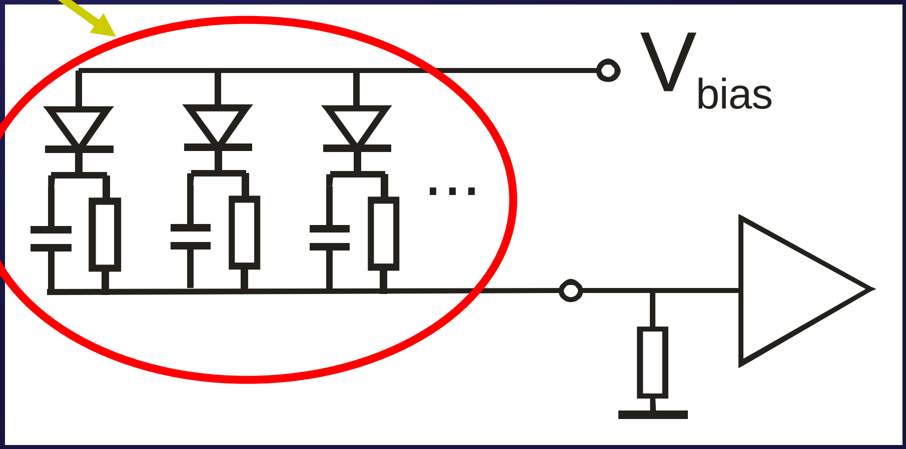
Bias and Output

SiPM

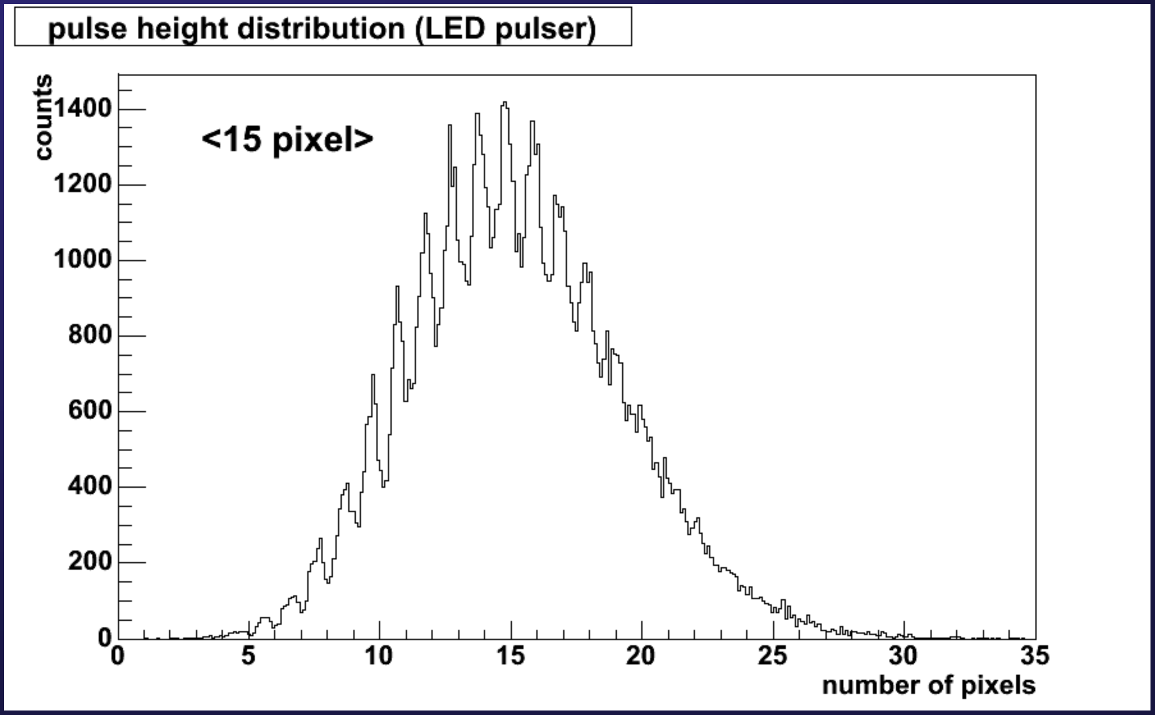
typically 100...2000 small SPADs / mm²

All SPADs connected in parallel

↳ Only one common signal line



SiPM output is the analog sum of all SPADs

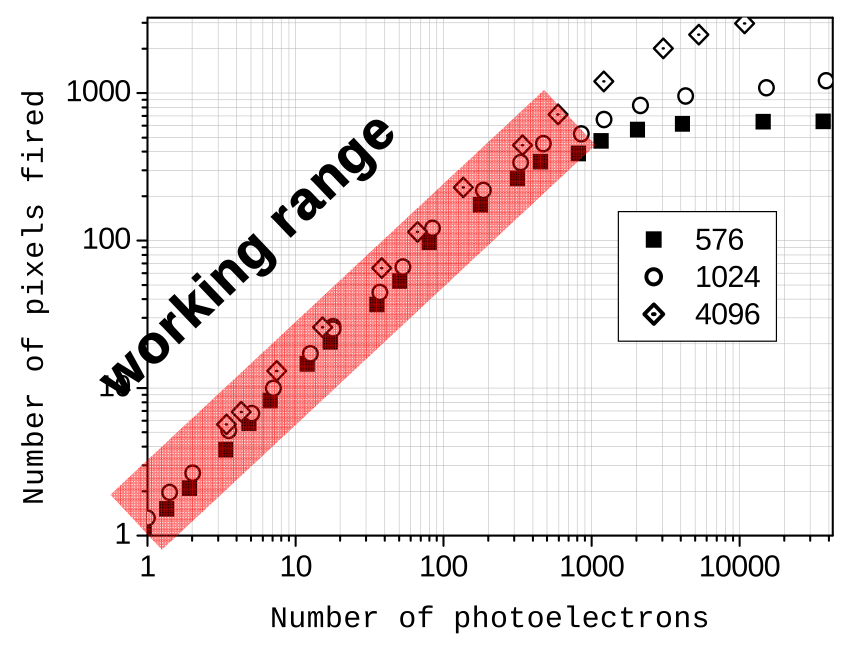


Well defined output signal per SPAD → multi pixel resolution

Dynamic Range

Dynamic range naturally limited by number of available SPADs

working condition:
Number of photo electrons < SPAD cells



from B. Dolgoshein Light06

From probability considerations:

$$N_{firedcells} = N_{available} \cdot \left[1 - e^{-\frac{N_{photon} \cdot PDE}{N_{available}}} \right]$$

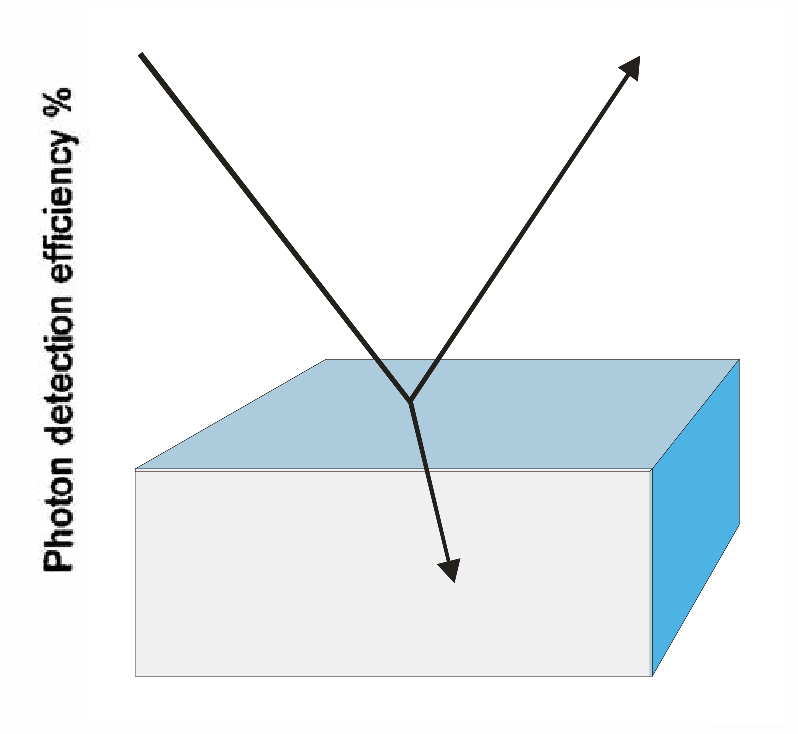
→ 20% deviation from linearity if 50% of cells respond

Photon Detection Efficiency (PDE) or Effective Quantum Efficiency

Most important parameter of a photon detector!!

limiting factors:

- Intrinsic quantum efficiency
- Fraction of sensitive area (20% - 80%)
- Surface reflection losses
- Probability for Geiger breakdown
  (depends on electric field)
- SPAD recovery time (passive quenching
- Active volume / absorption length



W.Oldham, P.Samuelson, P.Antognetti, IEEE Trans. ED (1972)

In total: Currently claimed best PDE values are ~40%   >60% seem feasible

Problems:

Optical Crosstalk

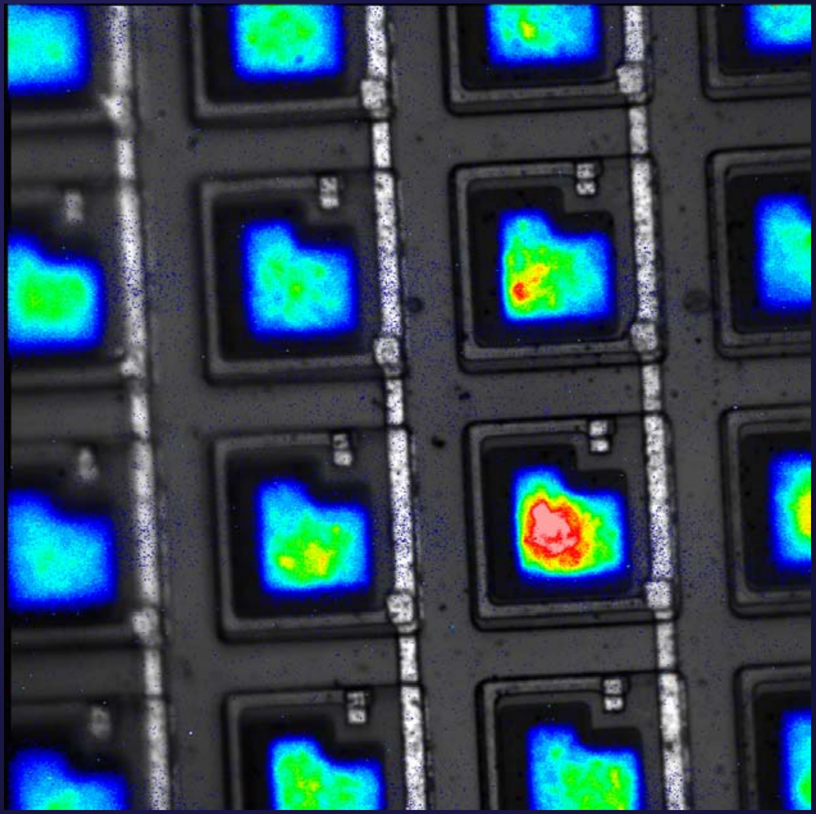
High Dark Count Rate

Optical Crosstalk

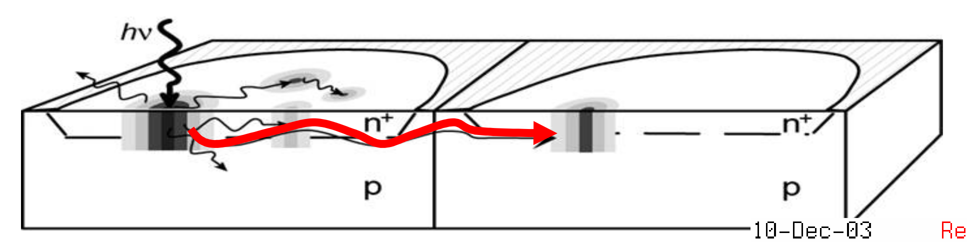
- SPADs not only detect photons they also emit photons during breakdown

- Hot-Carrier Luminescence **10^5** avalanche carriers → 3 emitted photon

e.g A. Lacaita et al, IEEE TED (1993)

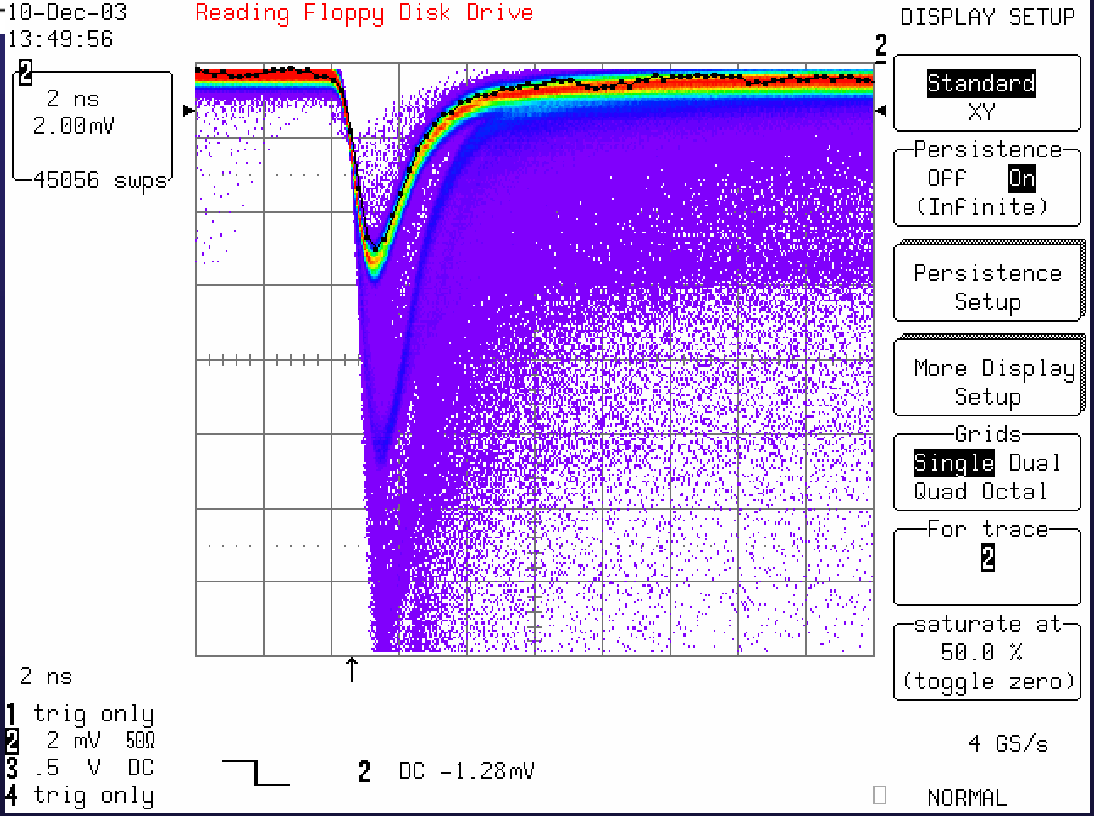


Emission microscopy picture of a prototype SiPM



Photons can trigger additional cells

Sketch from Cova et al. NIST 2003
Workshop on single photon detectors


10-Dec-03
13:49:56

Reading Floppy Disk Drive

DISPLAY SETUP

2
2 ns
2.00mV
45056 swps

2 ns
1 trig only
2 2 mV 50Ω
3 .5 V DC
4 trig only

2 DC -1.28mV

4 GS/s

NORMAL

- → Optical crosstalk
- →Artificial increase in signal
- → **E**xcess **N**oise **F**actor of SiPM

can be quite significant

How to suppress Optical Crosstalk?

Possible counter measures:

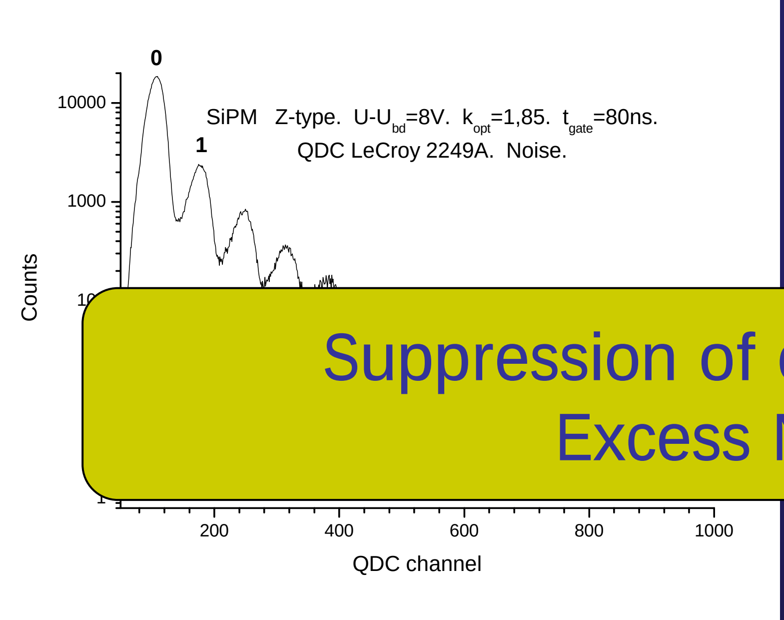
- Lowering bias voltage ←→ decrease in breakdown probability

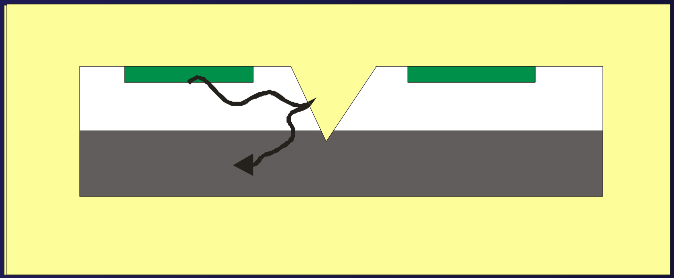
  (Price to pay: lower PDE)

- Lowering SPAD cell capacity

- Optical insulation between SPAD cells ➡

Blocking Photons with Grooves

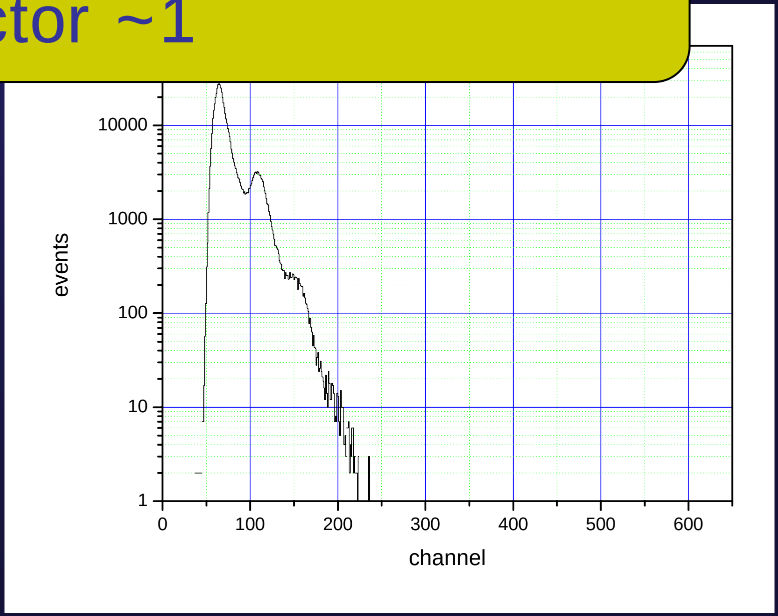




Suppression of crosstalk seems possible

Excess Noise Factor ~1

Gain: $3 \cdot 10^7$; with grooves →

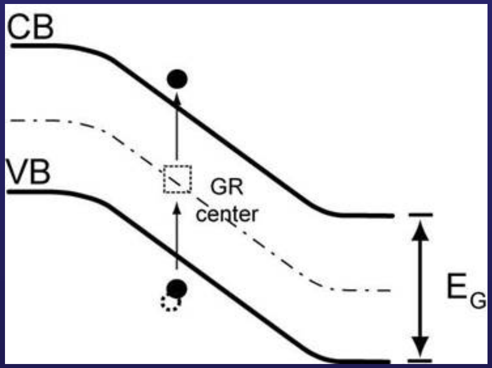


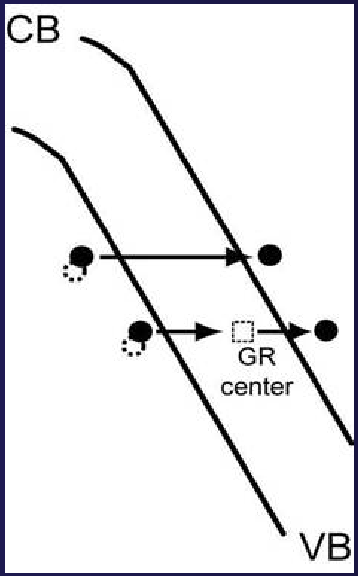
from B. Dolgoshein MEPhI

Dark Count Rate

It is a Complex Topic; here only the very basics:

Two main contributions:





Free Carrier Generation:

Depends on temperature
(Can be cooled away)

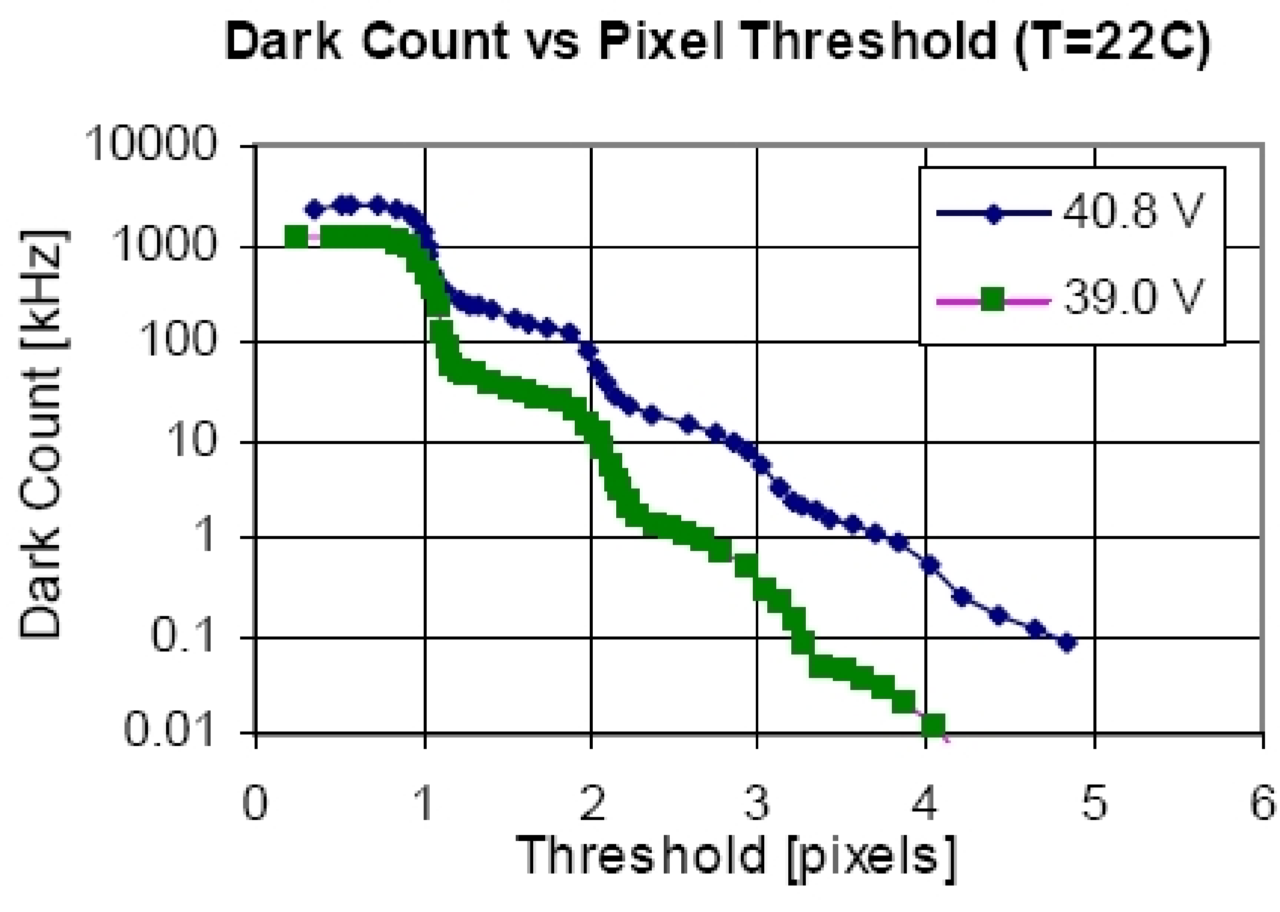
Tunneling:

Depends on operation voltage
Influenced by design of the device

Dark Count Rate

Silicon photomultipliers are sensitive to every single electron

→ hi mp.)



In r

re

(Factor two every 8°C)

Y. Musienko

Let’s go shopping

Various very intense developments ongoing in Industry (>4)
and Research Institutes:

- Center of Perspective Technology and Apparatus CPTA, Moscow
- MEPhI/Pulsar Enterprise, Moscow
- JINR(Dubna)/Micron Enterprise
- HAMAMATSU
- RMD (Abstract 218)
- SensL, Ireland
- Max-Planck Semiconductor Lab, Munich

In general devices are still in prototype stage

MEPhI/Pulsar/MPI

In collaboration with MPI for Physics (Munich)

Intended application:

Air Cherenkov Telescopes (MAGIC)

Cosmic Ray space missions (e. g. EUSO)

Development aimed at:

sensor area 10x10 mm²

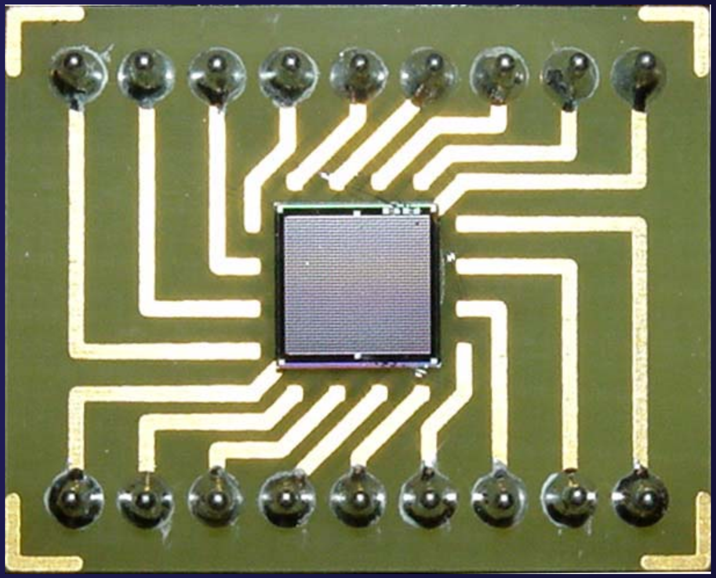
Photon Detection Efficiency >60%

Current device parameters @ 56V:

Dark rate: 500kHz at -60°C

Gain: 10^7

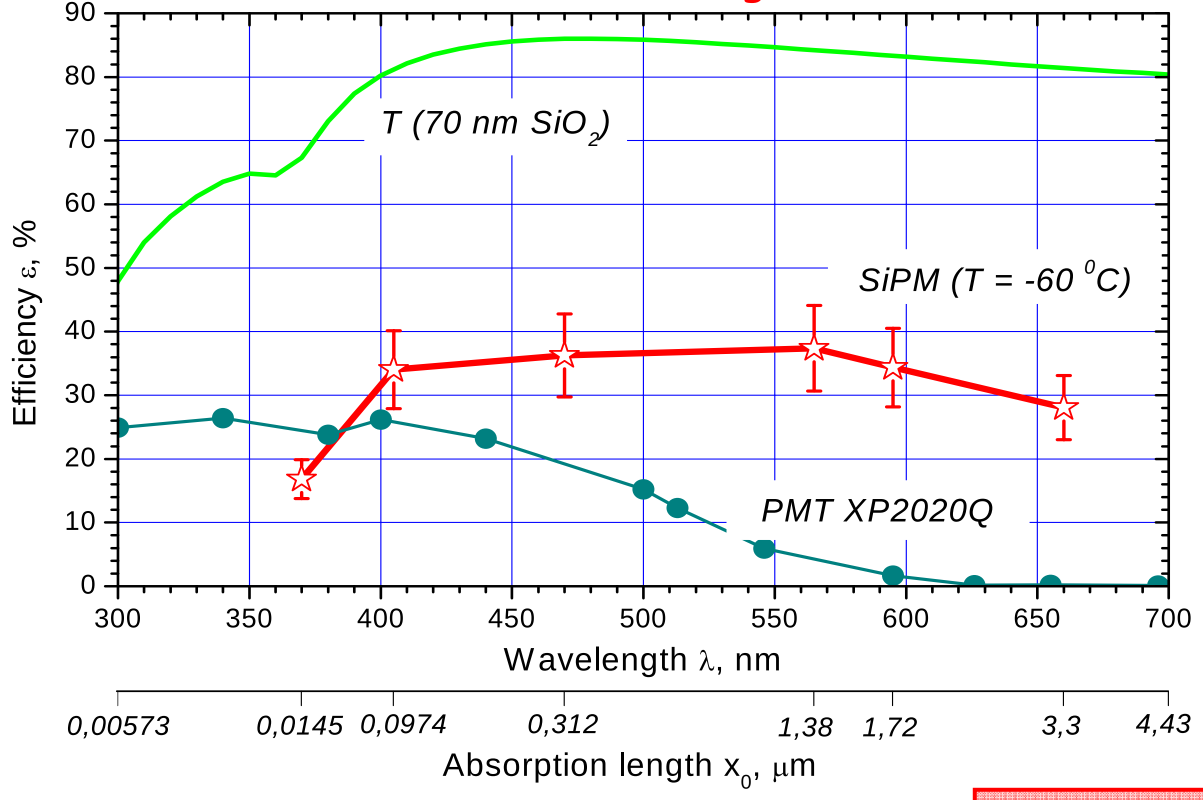
PDE: (see next slide)



Largest existing SiPM 5x5 mm²
2500 APD cells

5x5mm² SiPM: Photon Detection Efficiency

No antireflection coating of SiPM



$$PDE = T_{SiO_2} \cdot \varepsilon_{packing} \cdot \varepsilon_{Geiger} \cdot QE$$

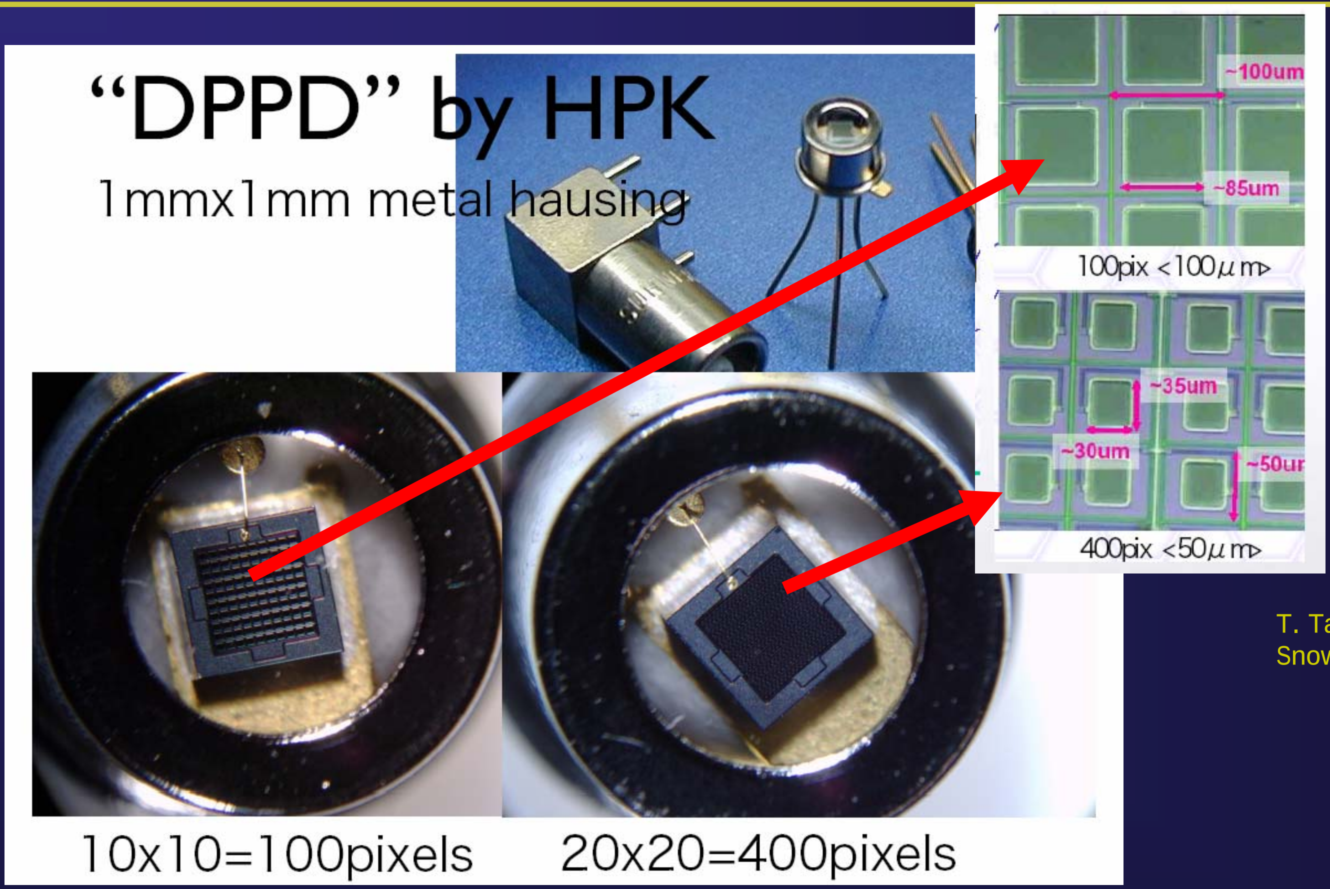
B.Dolgoshein,LIGHT06

$\varepsilon_{packing} = 0.5$

$\varepsilon_{Geiger} \approx 1$

limiting above 400nm

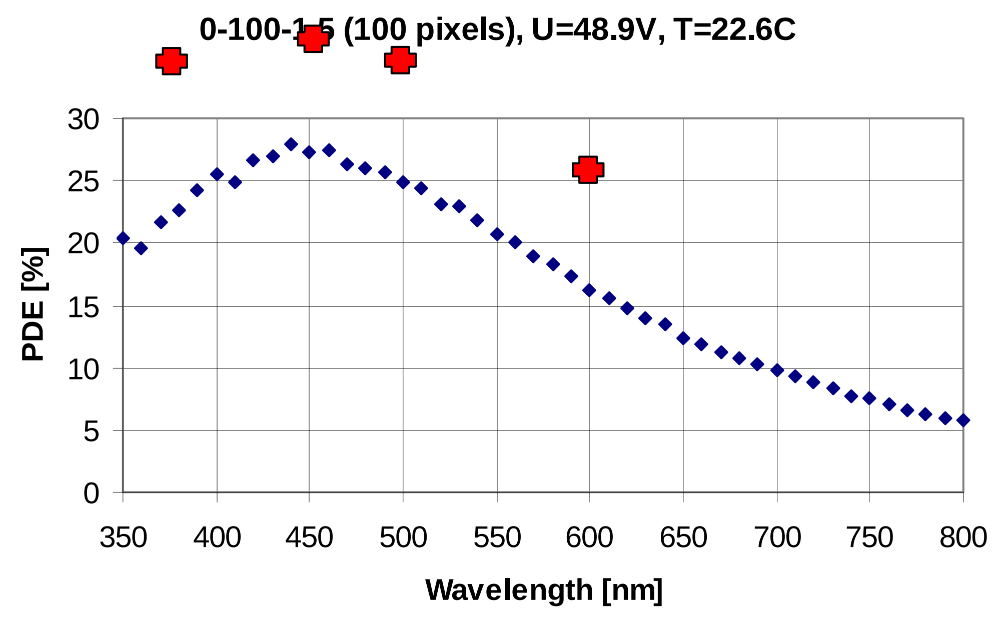
Hamamatsu: Digital Pixel Photon Detector



T. Takeshita
Snowmass 05

Device from early 2005

Hamamatsu

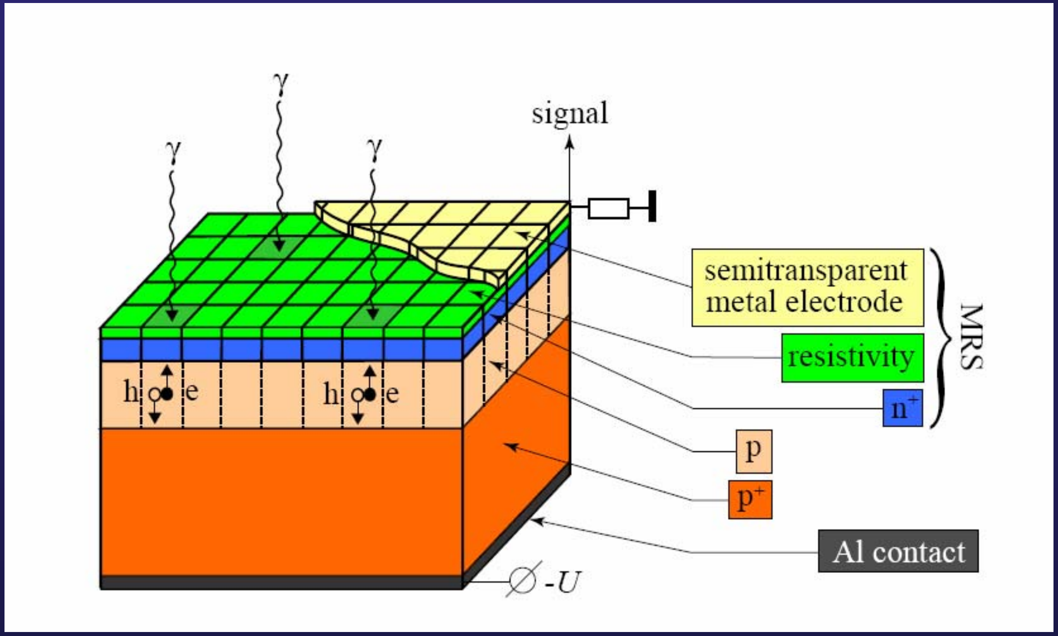


D. Renker (2005)

Latest devices achieve ~40% PDE @ 450nm (D. Renker)

Gain: 10^7
Dark noise: 550kHz @ room temperature
Crosstalk: 30%

Metal **R**esistive layer **S**emiconductor (MRS)



from K. Voloshin NIM A 539 (2005)

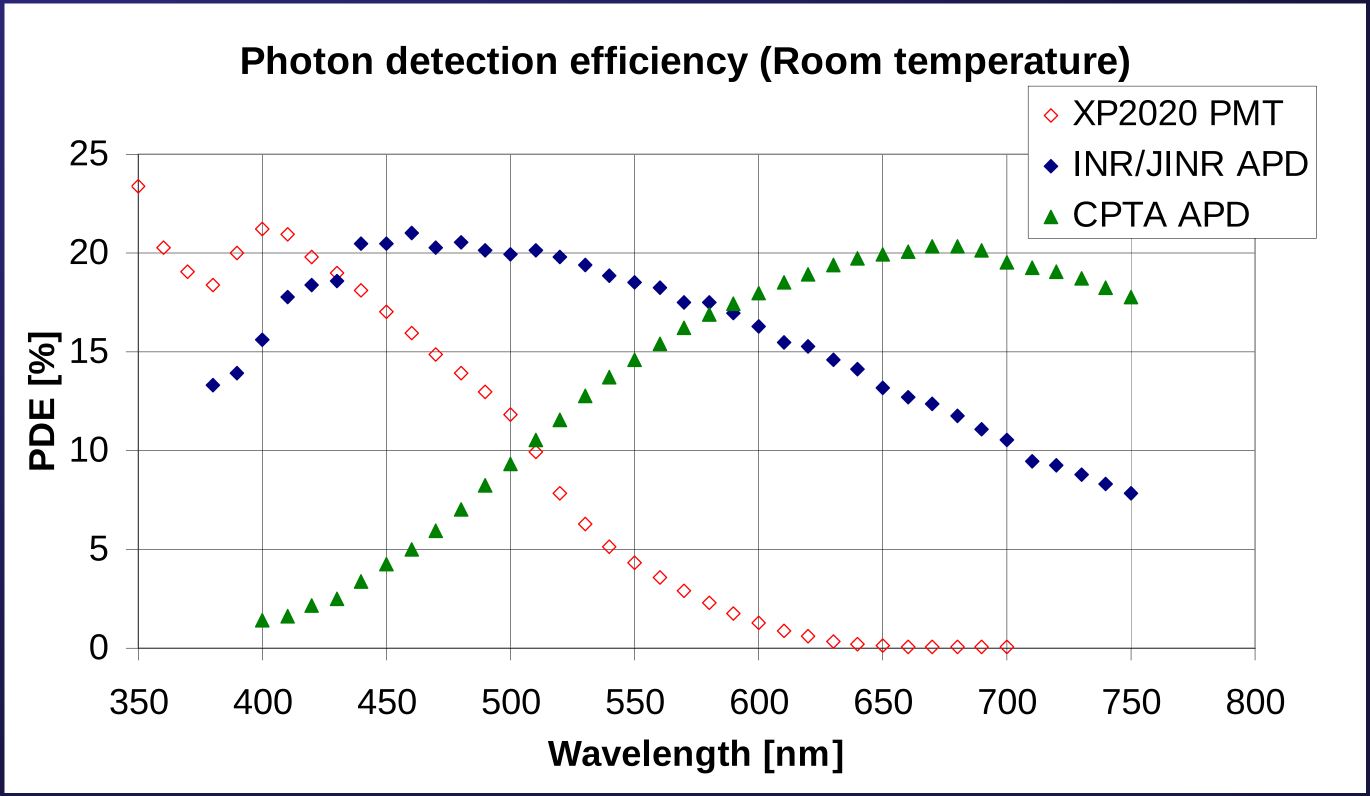
~100% Geometrical occupancy

PDE limited by semitransparent metal electrode

10,000 cells/mm² are possible with this technology

See results on PET later

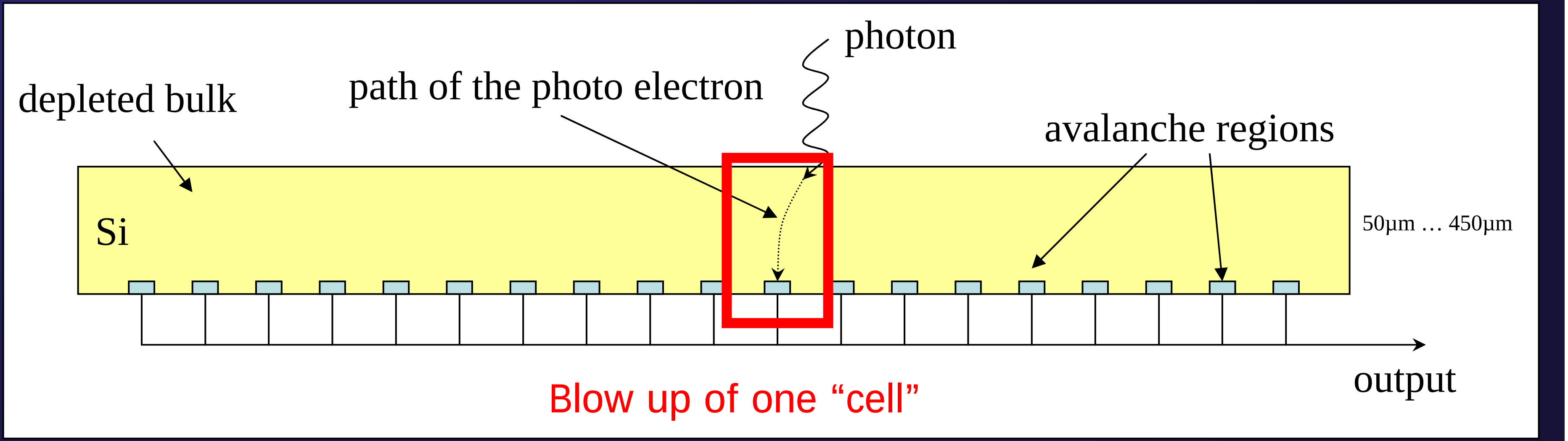
MRS: PDE



Y.Musienko (2005)

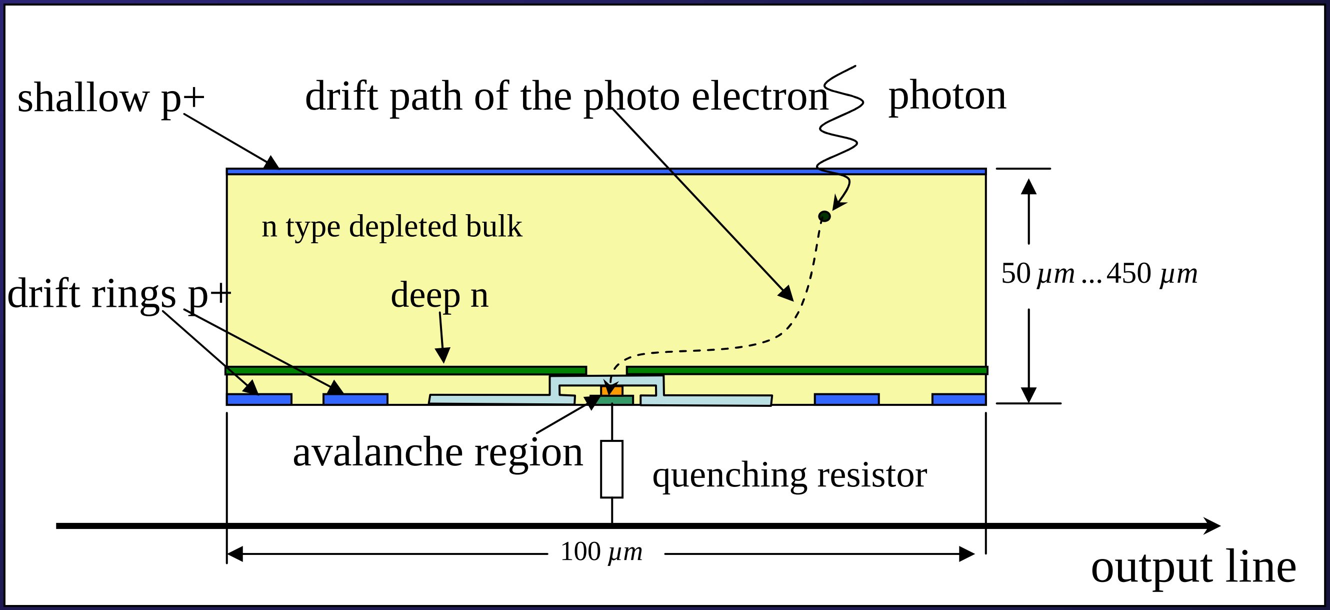
Ongoing Development: SiPM exploiting Backillumination

By the Semiconductor Laboratory
affiliated to the MPIs for Physics and Extraterrestrial Physics



predicted characteristics:

- PDE > 80%
- Single photo electron time jitter ~ nsec
- Cooling is mandatory



- test structures of novel avalanche structure will be finished next month
- After successful evaluation → prototypes end 2007

Crosstalk problem can be a showstopper!!

will be evaluated by dedicated structures

small cell capacitance is of advantage

Possible Applications of SiPM

The SiPM opens up a great variety of possible applications

- Calorimeter readout in magnetic fields (CALICE, ILC, …)
- Space applications (EUSO, …)
- Astroparticle experiments (MAGIC,…)
- Medical imaging (PET)
- Fast timing applications (<1nsec)
- time resolved X-Ray correlation spectroscopy
- Fiber trackers
- Large pixilated photon detectors
- …

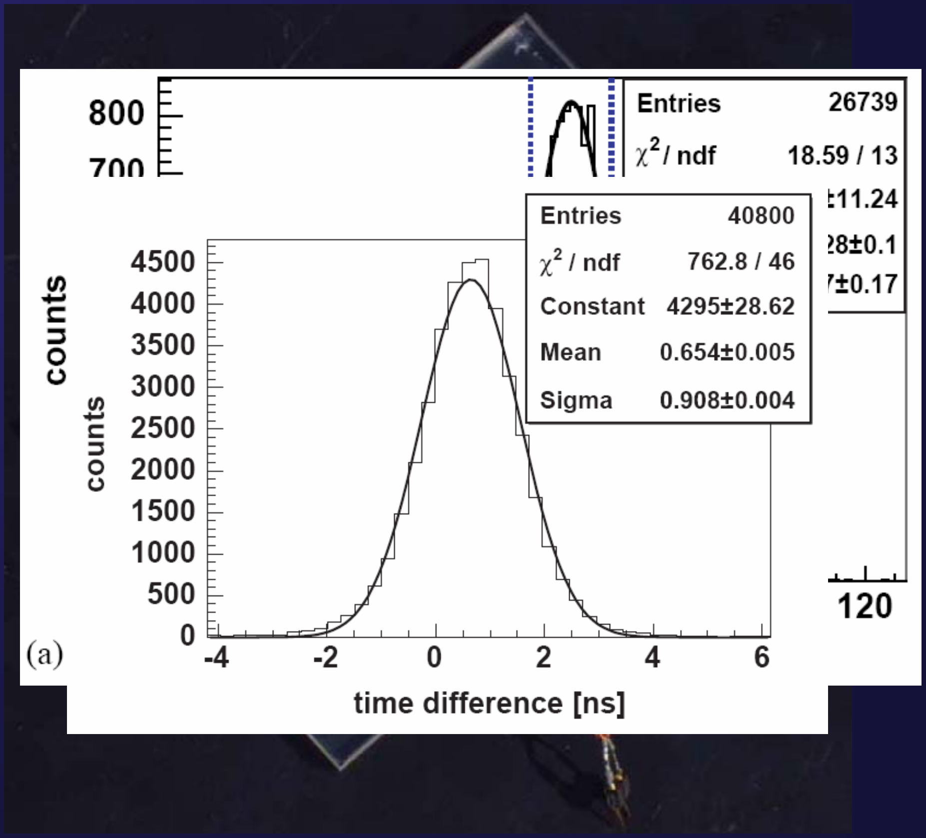
In some applications the SiPM is already superior to PMT's or APD's

Some examples ⇨

SiPMs in PET

Advantage: very compact, no sophisticated amplifier needed, ...

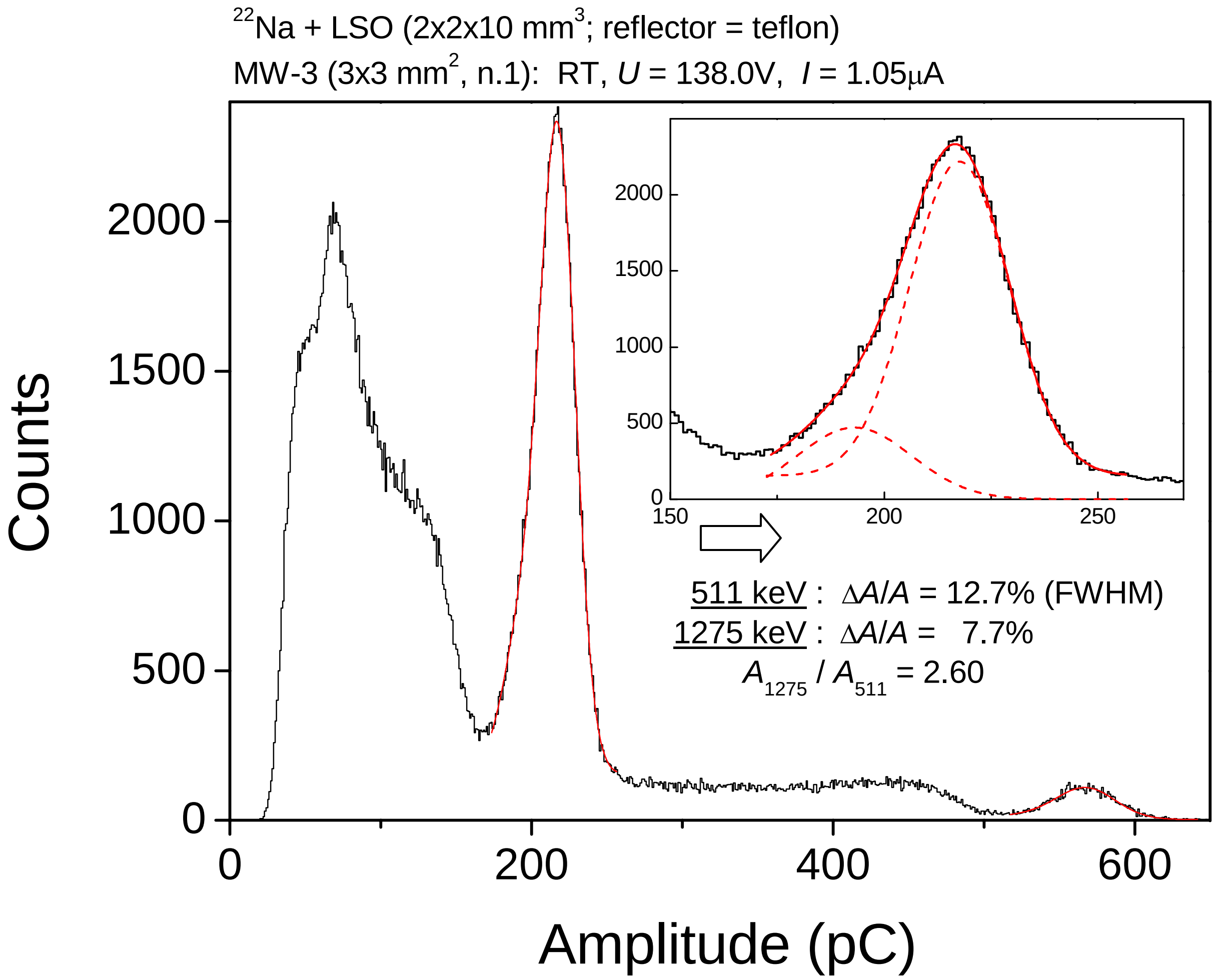
- direct coupling of SiPM to crystal
- no cooling
- Factor 4 area miss match between SiPM and crystal
- Energy resolution 22% FWHM on ^{22}Na coincidence spectrum
- Time resolution 1.5 nsec FWHM



Otte, et al. NIM A 545 (2005)

Things have quite improved since then ⇒

First result of measurments with MW-3 (3x3 mm^2) Geiger- mode APDs from Dubna (Z. Sadygov) + LYSO crystals (2x2x10 mm^3)



Energy Resolution:
12% FWHM

Time Resolution:
540ps

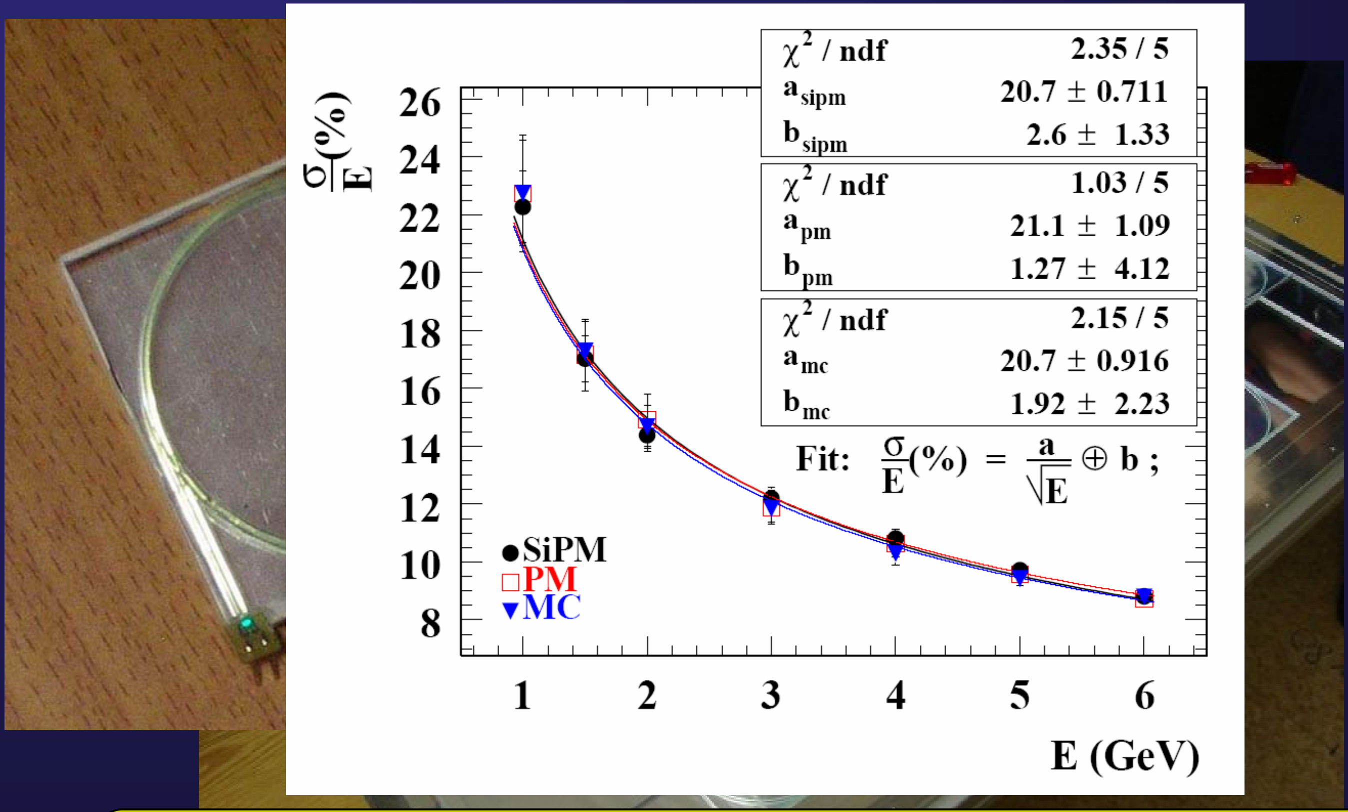
(limited by crystal)

MRS diode used

Alexey Stoykov,
Dieter Renker (PSI)

CAlorimeter for the LInear Collider Experiment

High granularity needed



see also:
Gerald Eigen
Abstract 211

Calice
collaboration

SiPM is equivalent to PMTs and APD (not shown)

Things not discussed

30 minutes are by far not enough to give an overview on SiPM

- Cell recovery
- Quenching mechanisms
- Importance of parasitic capacitances
- Afterpulsing
- ...

Summary

The silicon photomultiplier is a real breakthrough in photon detection!!

High photon detection efficiency (>60%)

Offers high internal amplification ($>10^5$)

Fast timing (<nsec)

Low power consumption (1...100µW/mm^2)

It can not be damaged by exposure to strong source of light

No aging

CMOS like technology → prospects for cheap mass production <10$ per mm^2

...

Summary

High dark count rate not a showstopper for most applications

Optical crosstalk is a problem but solvable

Current parameters of available prototypes:

Detector area: 5x5 mm²

Photon detection efficiency: ~40%

Dark rate at room temperature: 10^5-10^6 counts/sec/mm²