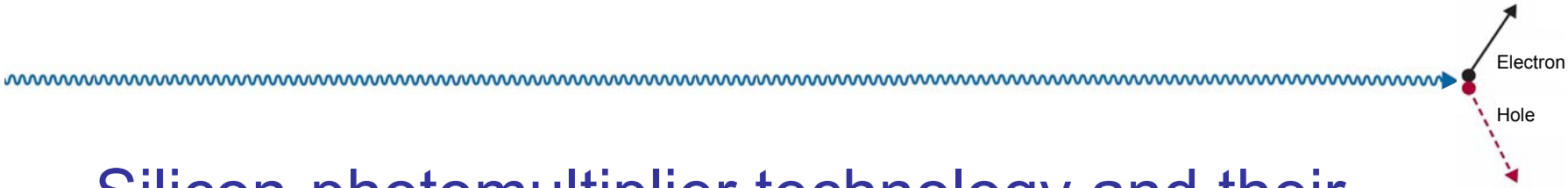
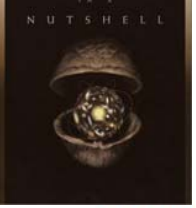


Silicon-photomultiplier technology and their application in high energy physics detectors

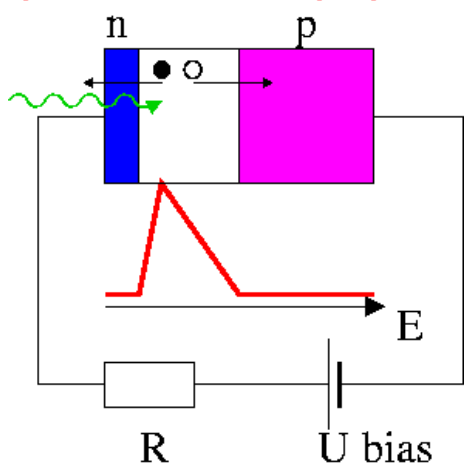
Erika Garutti (DESY)

Outline

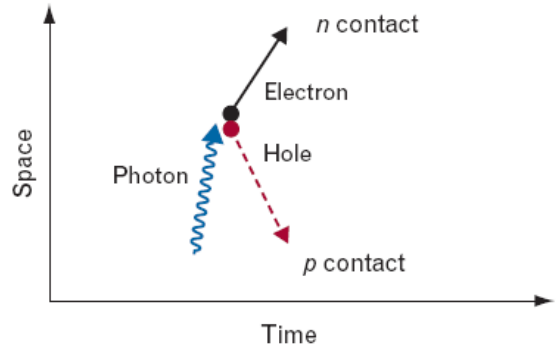
- Photo-detection in semiconductors: Basic principle
- Multi-pixel avalanche photo-diodes in Geiger mode (SiPM)
- Characterization of Silicon Photo-Multipliers
- Application of SiPM in detector development
- Conclusions: a bright future for photon detection



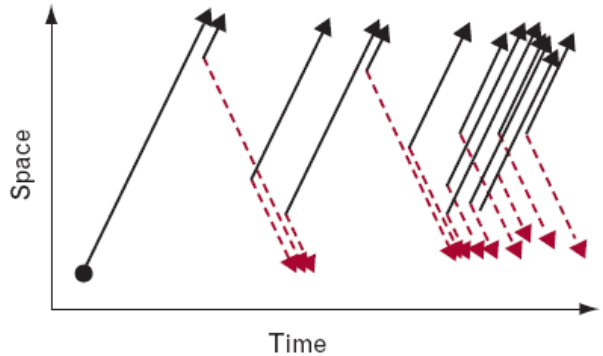
Photon detection in Semiconductors

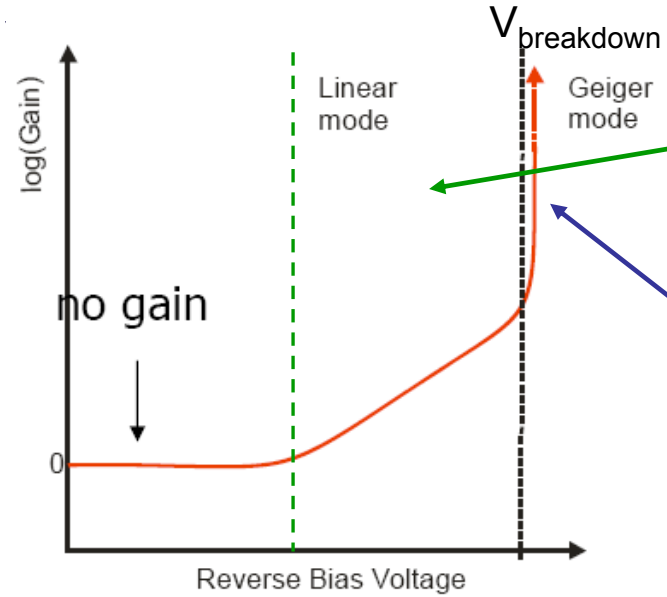


p-n junction



p-n junction + ($U_{bias} > U_{breakdown}$)

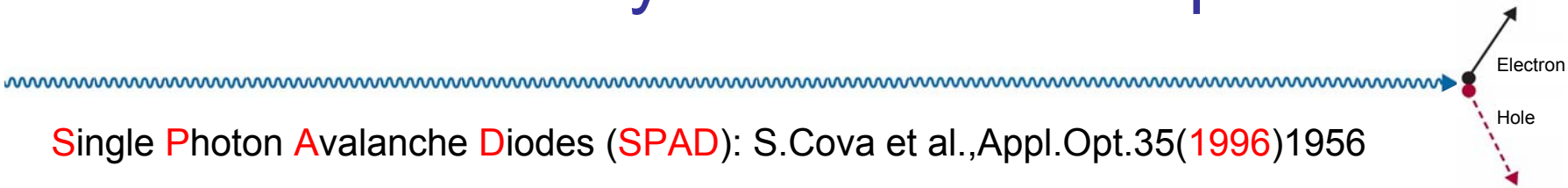




Avalanche Photo-Diode
operated in linear mode ~ AMPLIFIER (Gain ~ 50-500)
!! signal proportional to energy deposited
➔ used in CMS ECAL

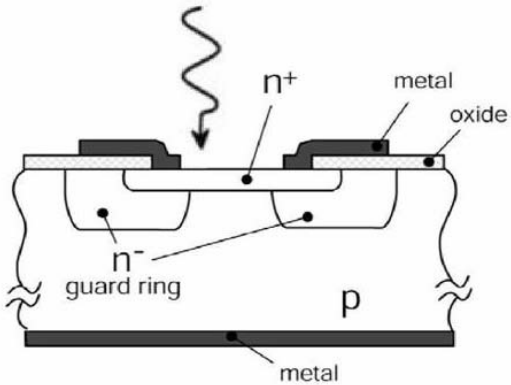
Geiger mode Avalanche Photo-Diode
operate above breakdown voltage (Gain ~$1*10^6$)
!! It's a BINARY device
➔for practical application use ARRAY of single Geiger mode Avalanche Photo-Diodes:
the Silicon Photo-Multiplier

A brief history of SiPM development

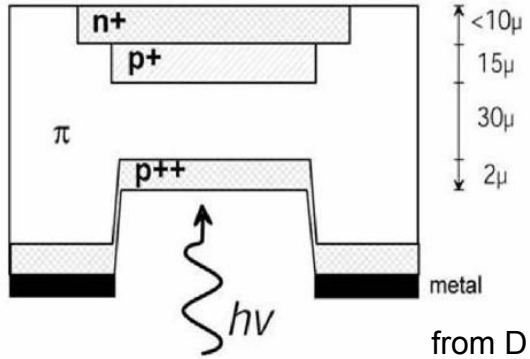


Single Photon Avalanche Diodes (SPAD): S.Cova et al.,Appl.Opt.35(1996)1956

The first 2 silicon single photon detectors fabricated by Haitz and by McIntyre. Both had to be operated in Geiger-mode, with a bias voltage several volts higher than the breakdown voltage.



planar diode (Haitz)



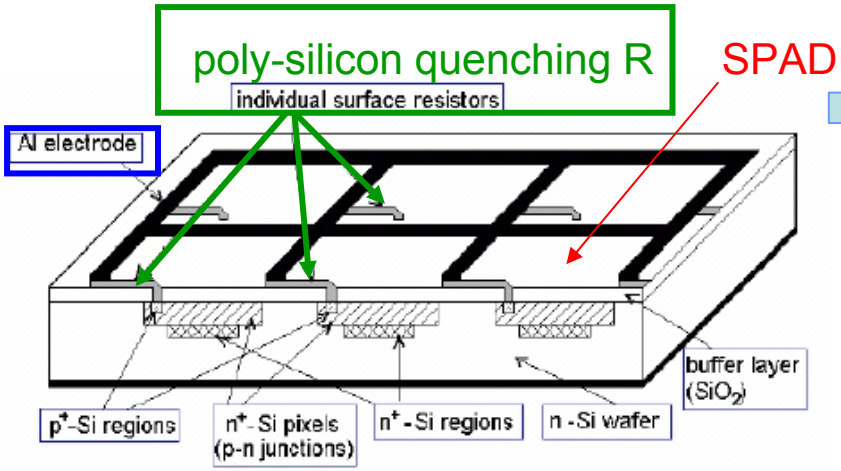
from D. Renker, PSI

reach-through diode (McIntyre)

after this single "photon counter" the play ground for development of Geiger mode silicon-based photo-detectors moves to Russia … " where the SiPM is born "

Main players: Center of Perspective Technology and Apparatus, CPTA,Moscow
MEPhI/Pulsar Enterprise,Moscow & DESY (R. Klanner)
JINR(Dubna)/Micron Enterprise

Array of Single Photon Avalanche Diodes



I will refer to one SPAD as pixel in the following

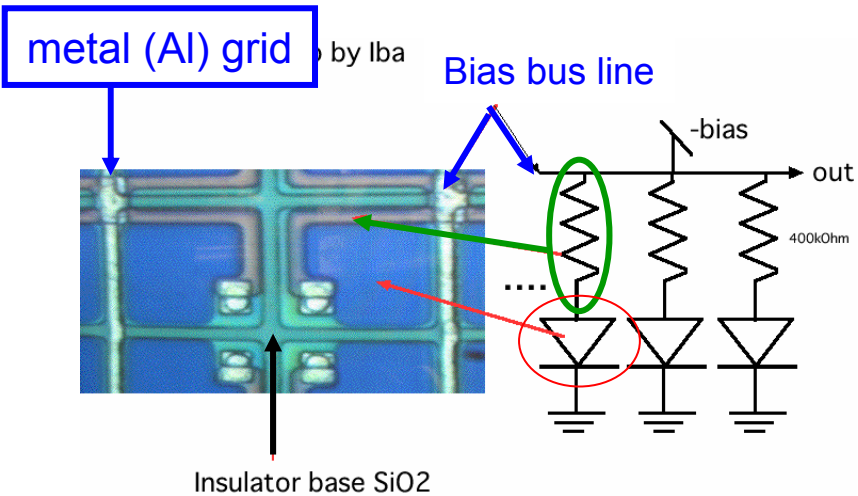
➔ typically 100-1000 pixels / mm²

Some typical pixel parameter:

-pixel size ~20-30μm

-pixel capacitance C_{pixel} ~ 50fmF

-quenching resistor R_{pixel} ~ 1-10 MΩ



all pixels connected in parallel

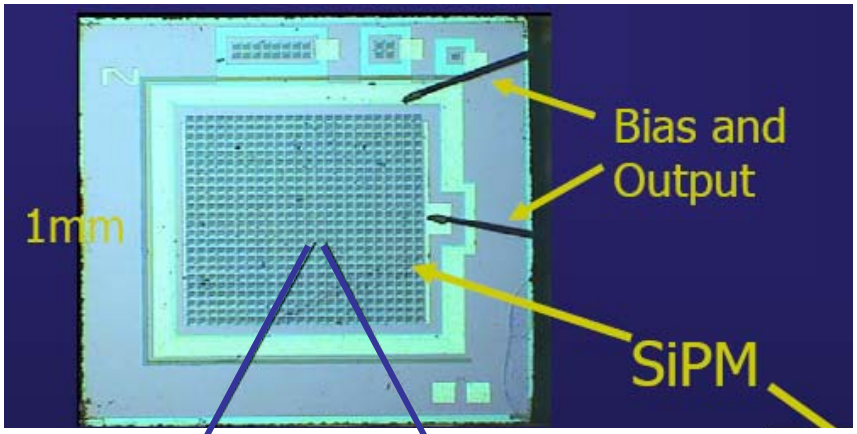
only one signal line

➔ output = Σ pixel signals

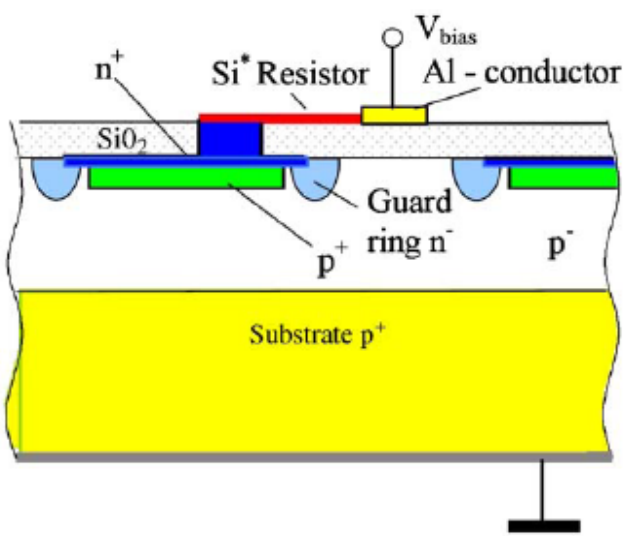
typical Bias voltage ~ 2 V above breakdown

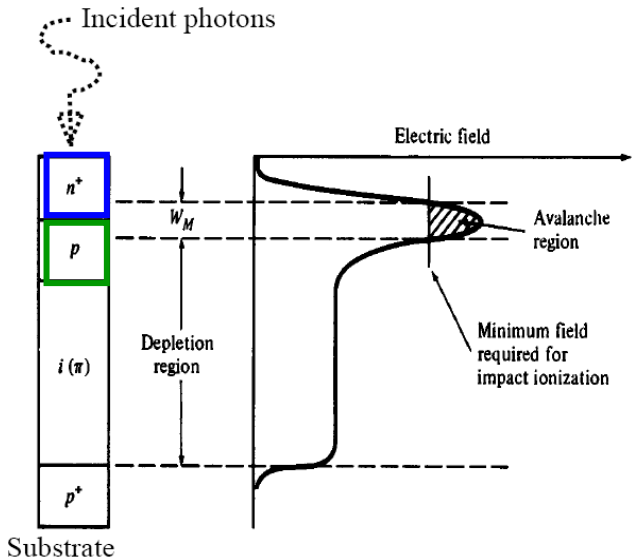
The Silicon Photo-Multiplier

Typical sensor area 1x1 mm² ➔ new developments 3x3, 5x5 mm²

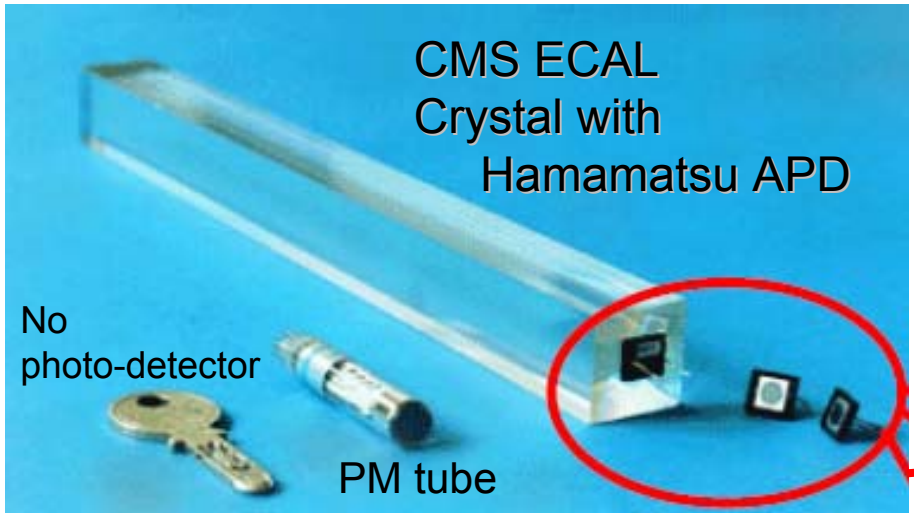


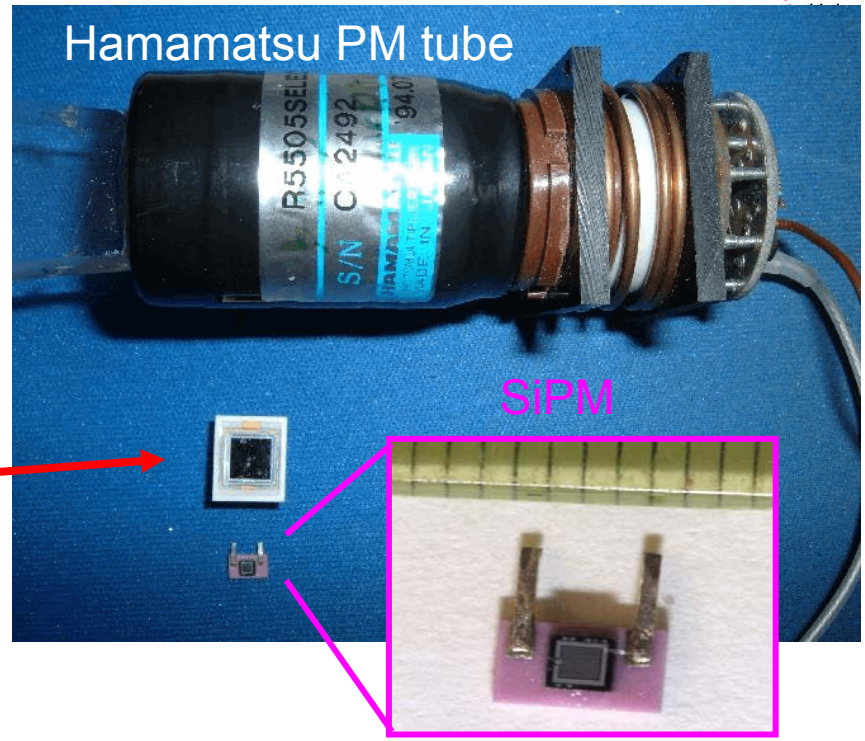
-small depletion region ~ 2μm
-strong electric field (2-3)x10^5 V/cm
-gain ~ 10^6
-carrier drift velocity ~ 10^7 cm/s
-very short Geiger discharge development < 500 ps





Semiconductor detector scale



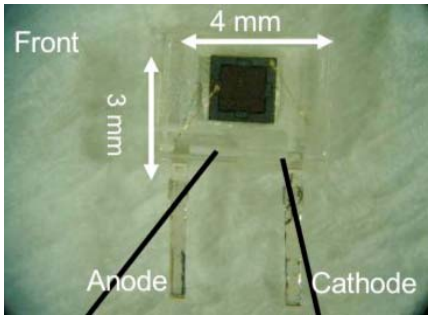


Advantages of semiconductor technique:

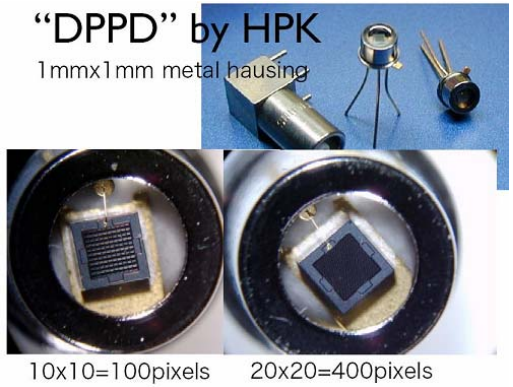
- reduced size
- low operation voltage ~ 100 V
- magnetic field insensitive !!!
- robust
- “cheap”

Many different names / and different products

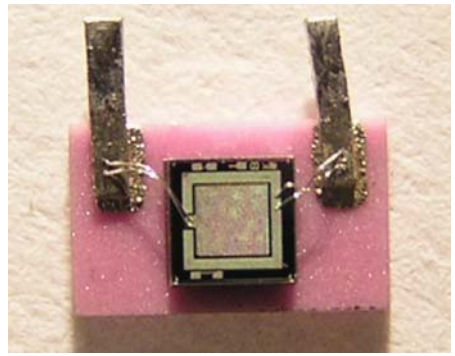
MPPC from Hamamatsu, Japan



Available on Hamamatsu catalogue

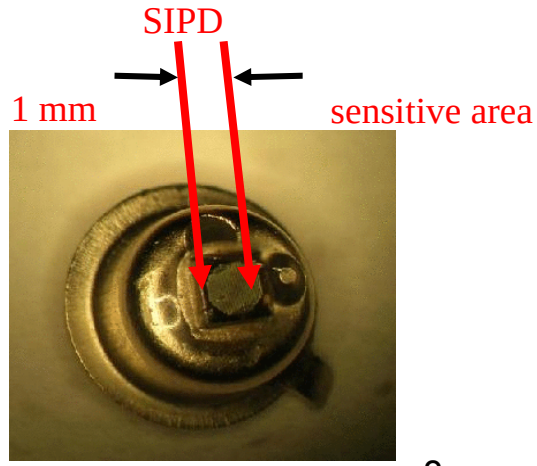


SiPM from MEPHI / PULSAR, Moskow



Short disclaim:
using the name SiPM I will refer to multi-pixel avalanche photo-diodes operated in Geiger mode

SiPM-CPTA from Photonique, Switzerland



AMPD from Z. Sadygov, Moskow

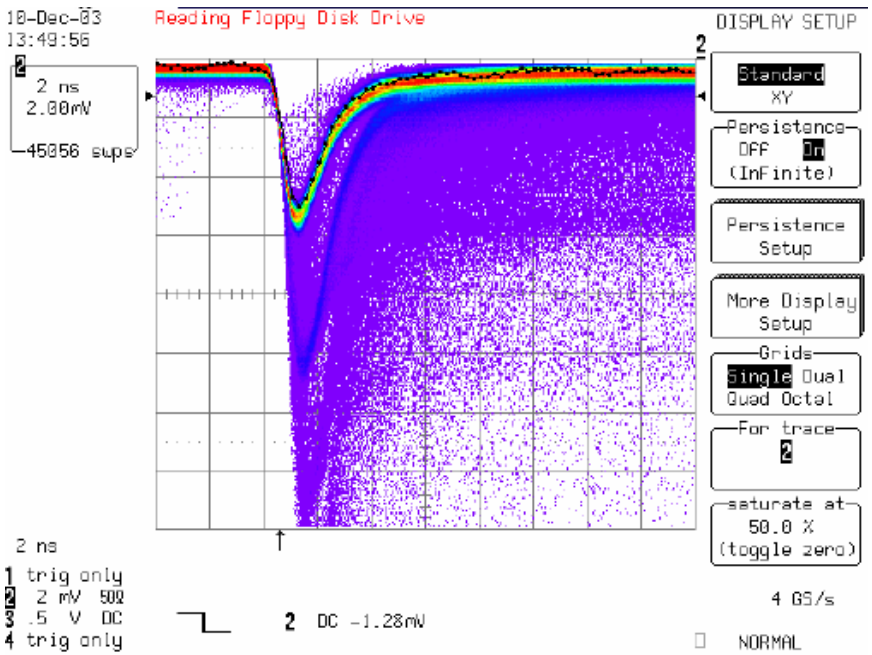
GMPD from INR/JINR, Moskow

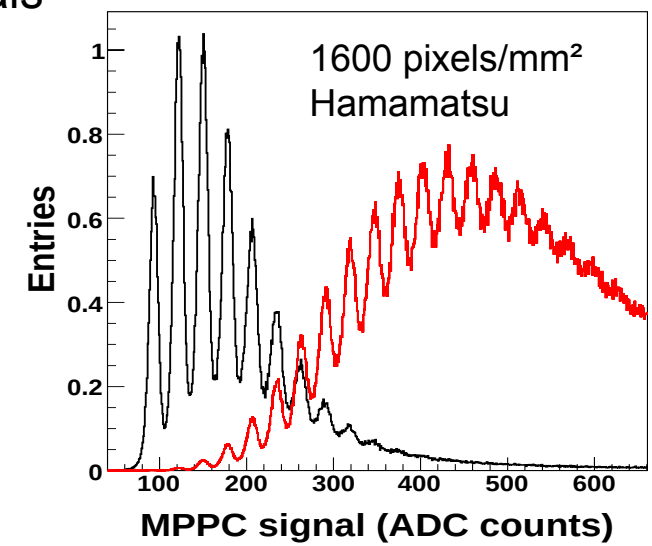
"SiPM" from SENSL, Irland is coming…

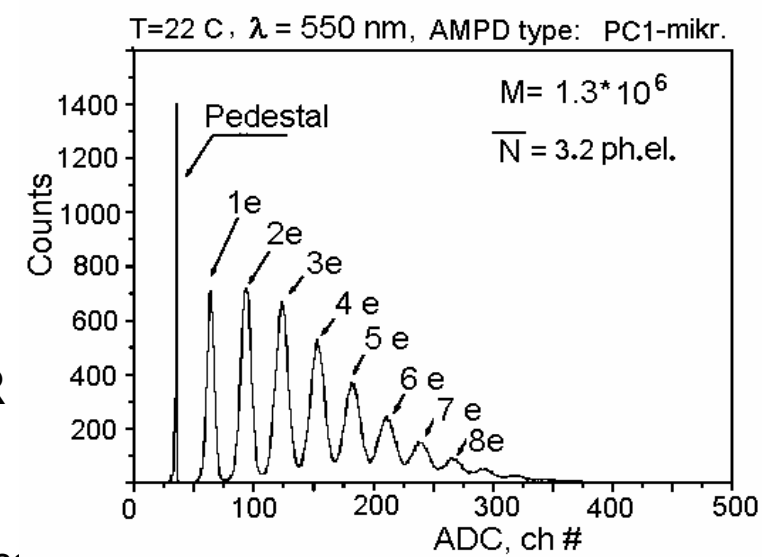
… and many others

SiPM properties: single pixel resolution

SiPM output is the analog sum of all pixel signals





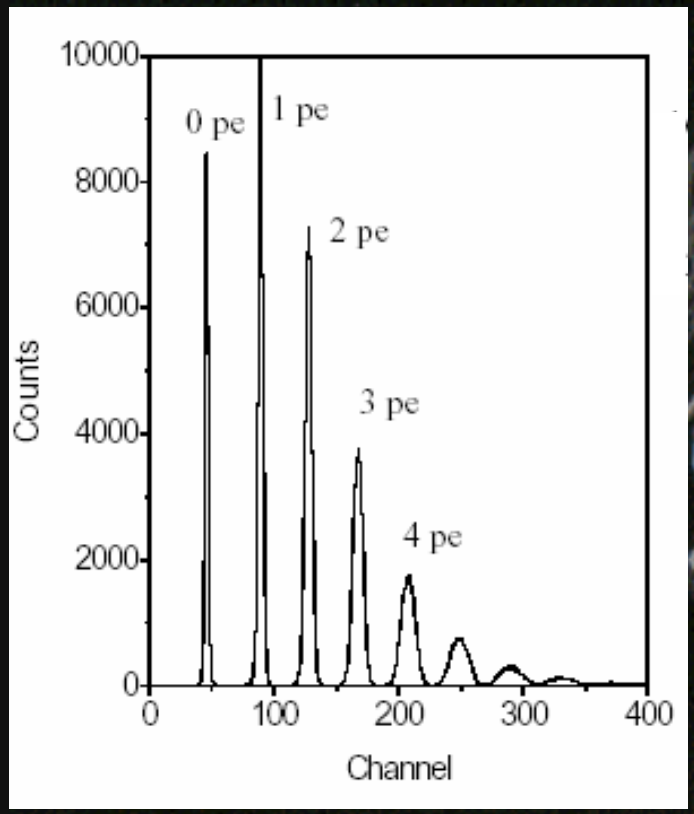


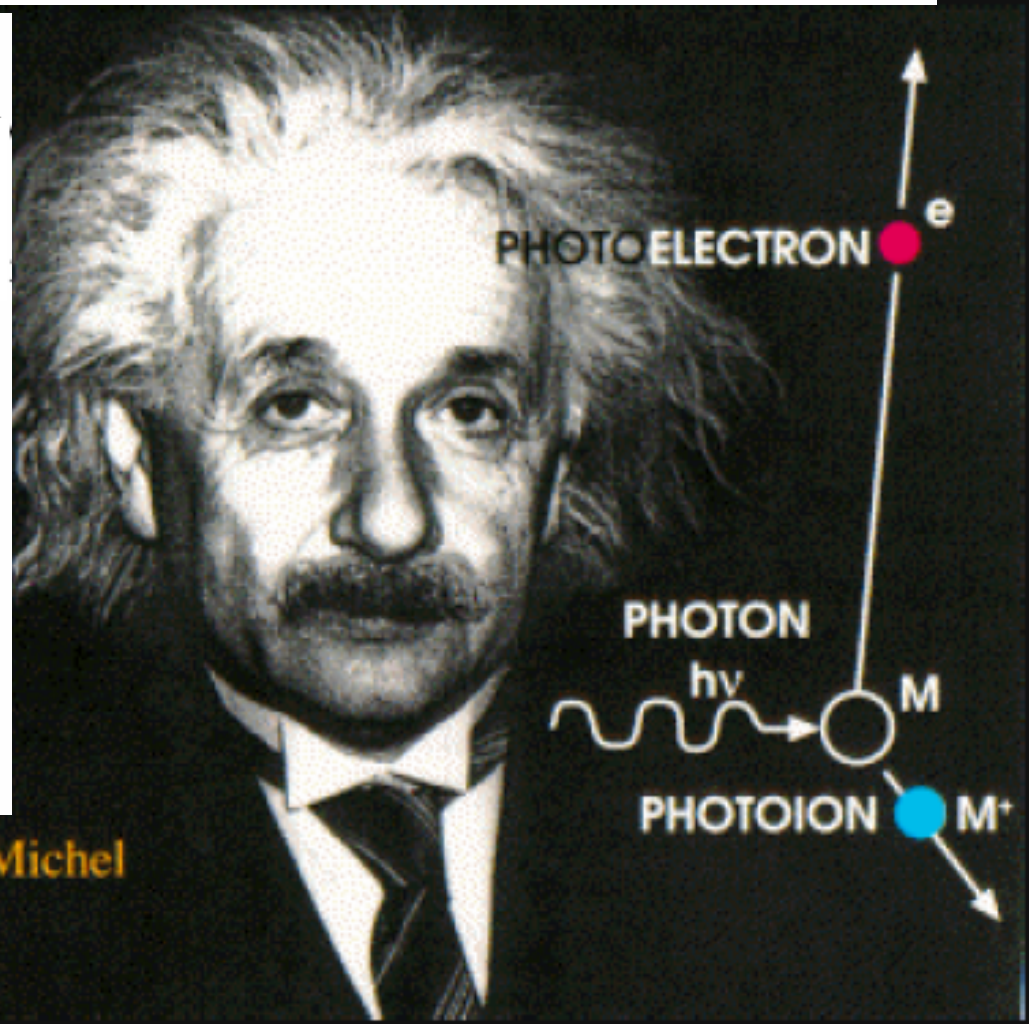
high gain ➔ pixel signal visible on scope
- signal rise time < 1 ns
- fast fall ~ 5-10 ns

recovery time tunable by choice of quenching R
$\tau \sim R_{pixel}C_{pixel} \sim 20 – 500$ ns

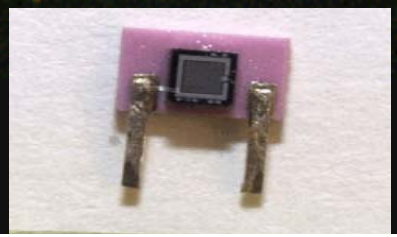
AMPD tested in LNP JINR and PSI

Single photoelectron spectrum recorded with silicon photodetector

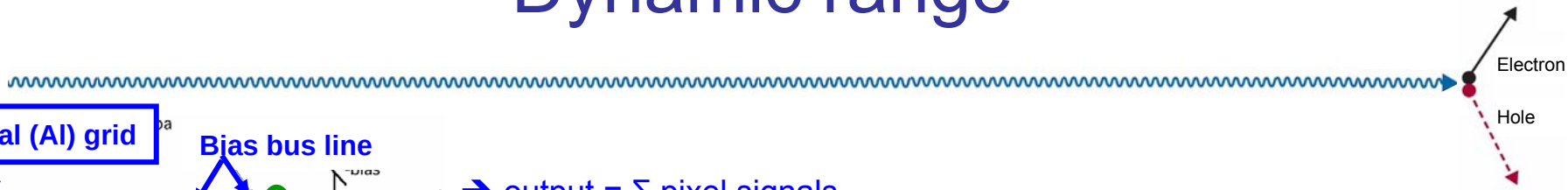


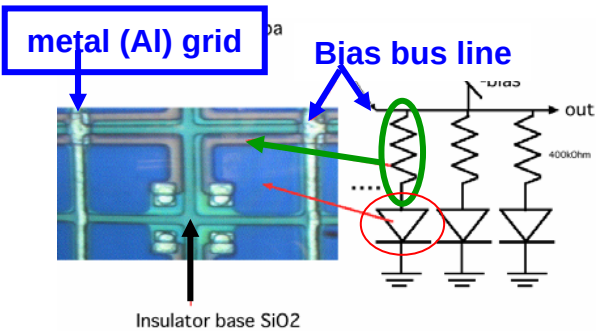


— Albert Einstein, letter to Michel Besso, 1951.



Dynamic range

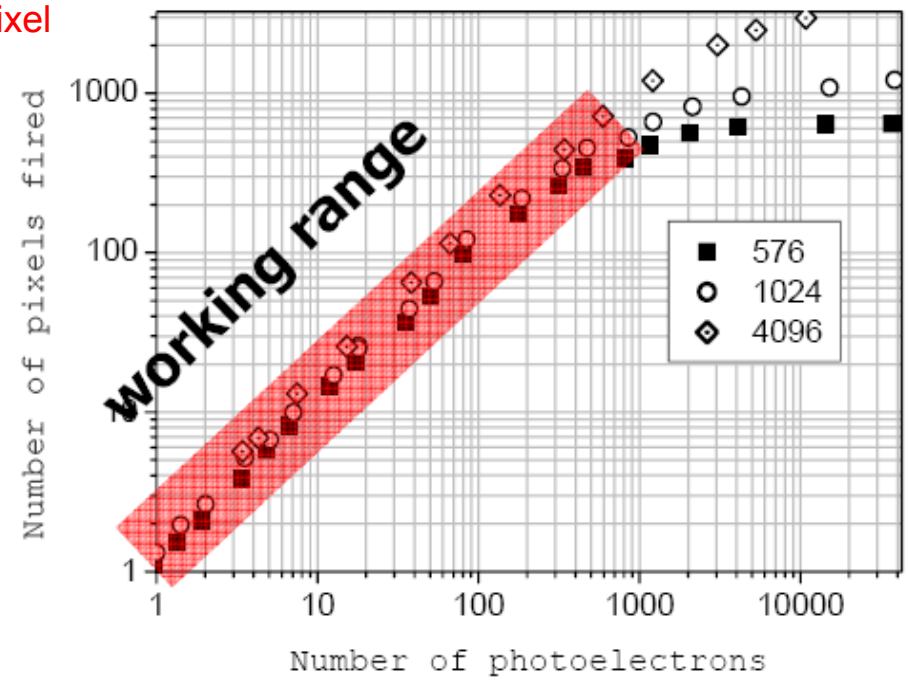




➔ output = Σ pixel signals

output ≤ total N pixel

Measured on SiPM MEPHI/Pulsar, from B. Dolgoshein



Dynamic range naturally limited by number of pixels

Optimal working condition:
number of photo-electrons < N pixels

from probability considerations:

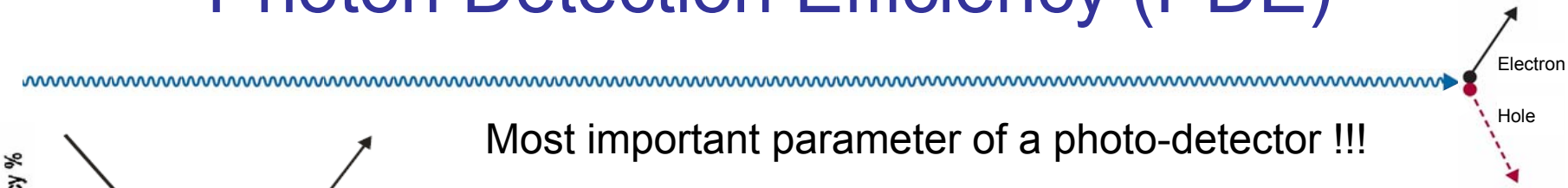
$$N_{pixels} = N_{available} \cdot \left[1 - e^{\frac{N_{photo\text{-}electrons}}{N_{available}}} \right]$$

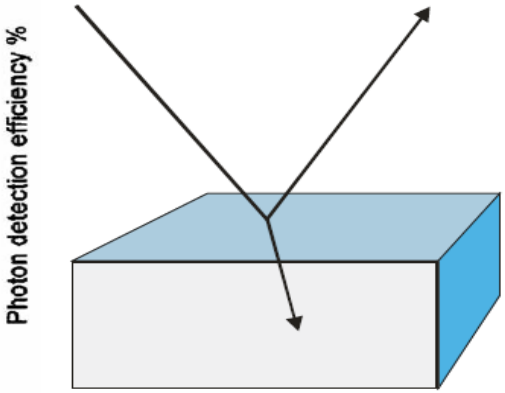
~20% deviation from linearity if 50% of pixels are fired

$N_{available}$ = total number of pixels in a SiPM

slide rearranged from Nepomuk Otte, MPI

Photon Detection Efficiency (PDE)



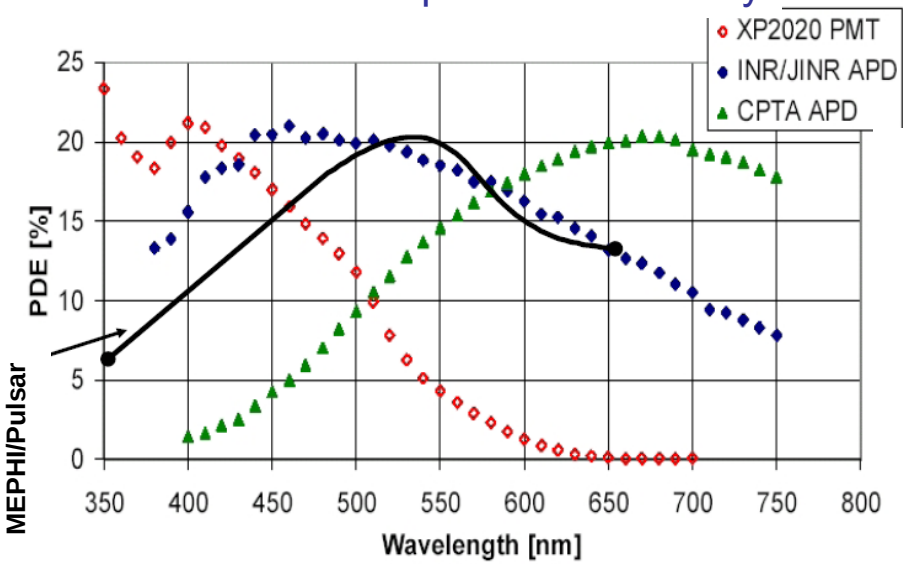


Most important parameter of a photo-detector !!!

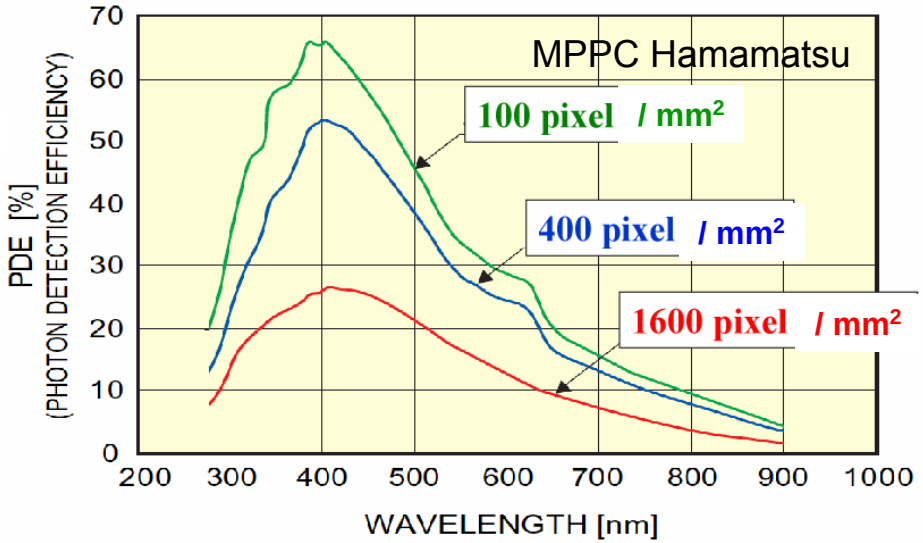
Limiting factors:

- intrinsic Quantum Efficiency (~80% for Si) ➔ λ dependent
- fraction of sensitive area (20-80%) ➔ technology
- surface reflection losses
- probability of Geiger breakdown (~100%) ➔ V_{Bias} (or E) dep.
- pixel recovery time (R_{pixel})

influence of quantum efficiency



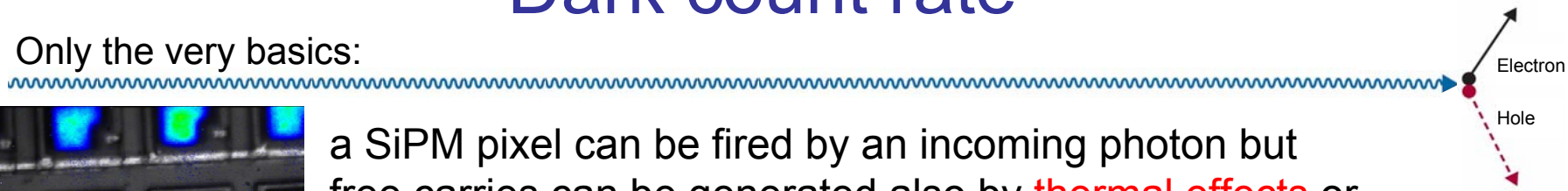
influence of sensitive area

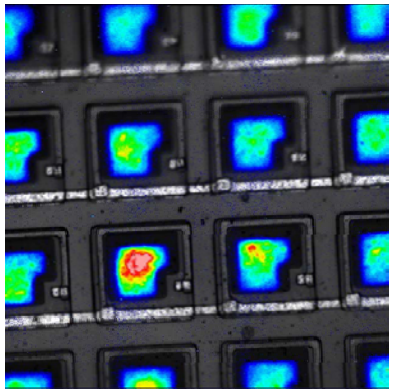


=400nm, including the cross-talk and after pulse

Dark count rate

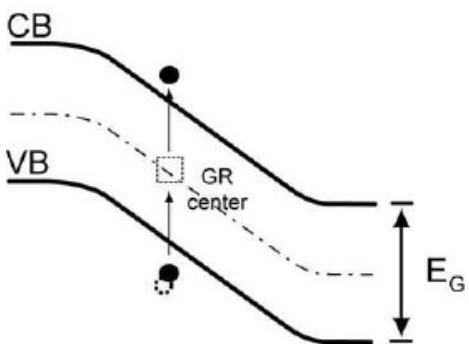
Only the very basics:





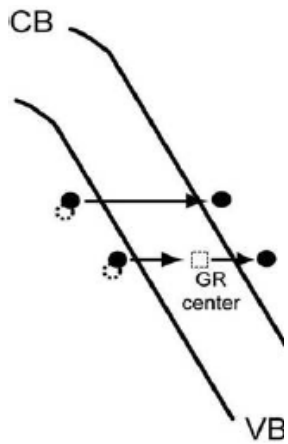
a SiPM pixel can be fired by an incoming photon but free carries can be generated also by thermal effects or tunneling (field-assisted generation)

these lead to a dark count rate of 100 kHz – 10 MHz / mm^2 (@25°C) with threshold at half of one photo-electron amplitude (~0.5x10^6)



Free carrier generation by thermal effects

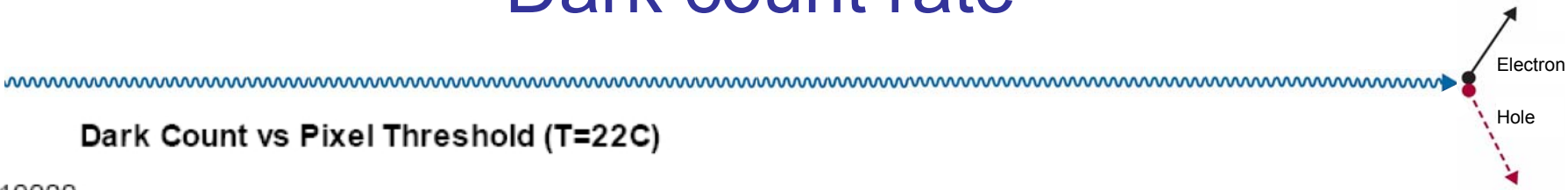
Depends on temperature (can be cooled away)

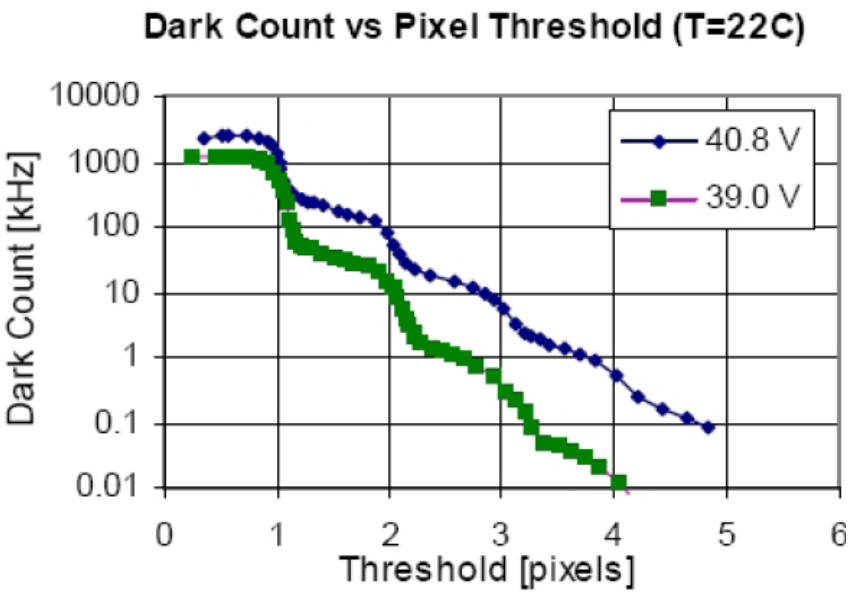


Tunneling

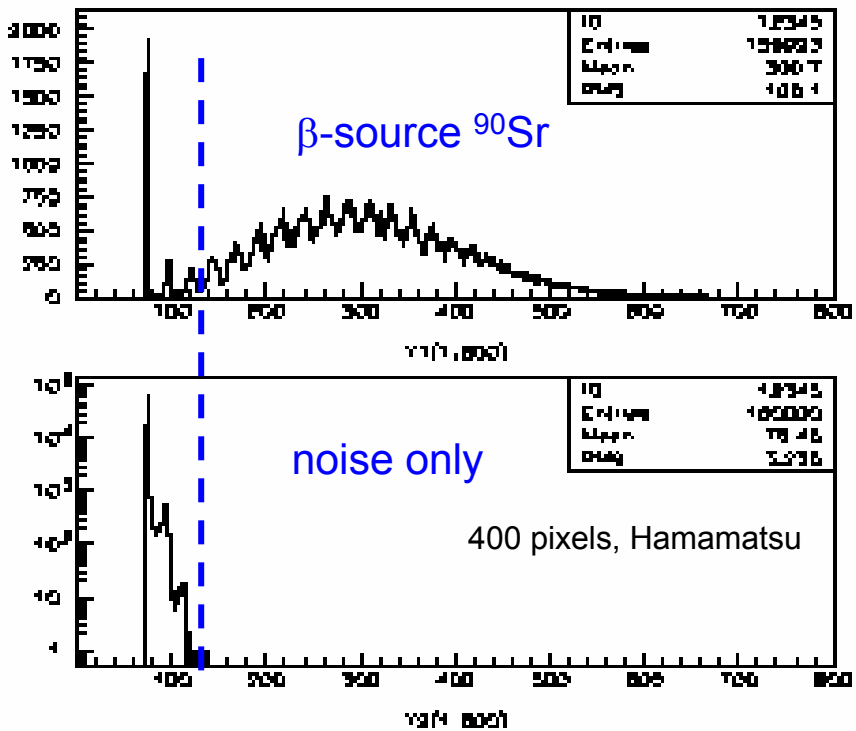
Depends on operation voltage (E field)
Influenced by technological design

Dark count rate





from N. D'Ascenzo, DESY

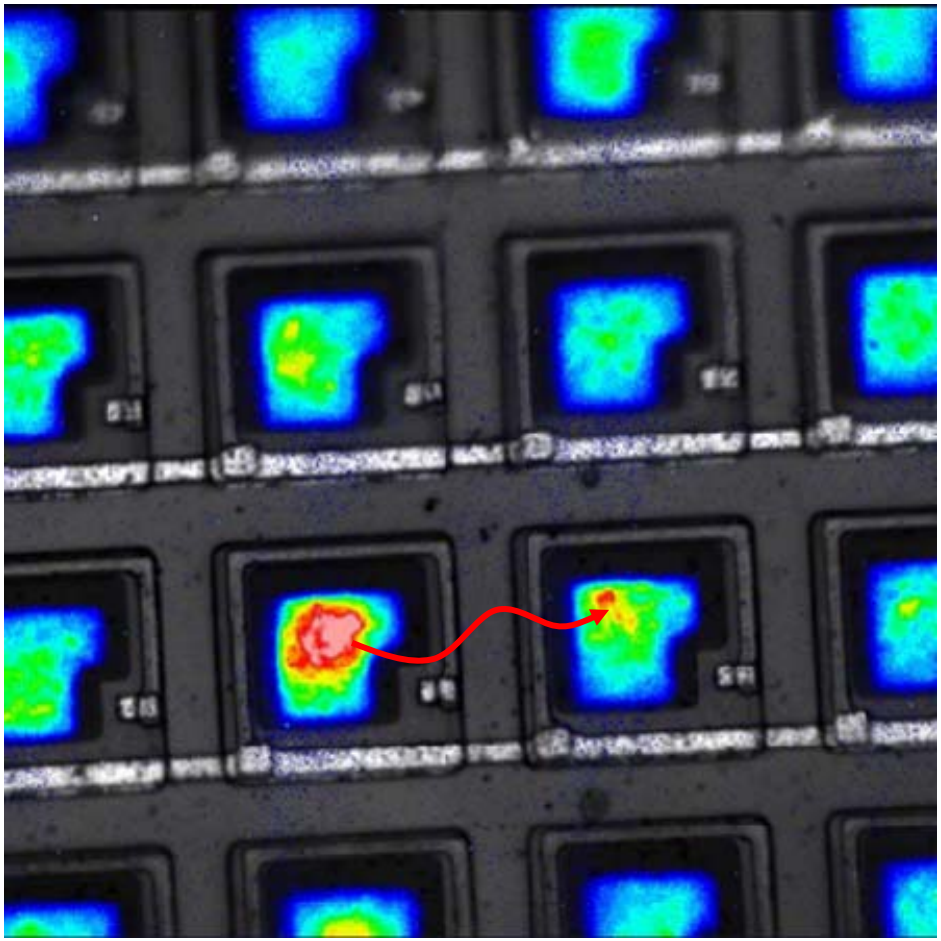


dark count rate > 0.5 pixel ~ MHz
decrease rapidly with threshold

➔ what is the relevant threshold for physics?

Blue sensitive SiPM directly coupled on 3x3x0.5 cm^3 scintillator tile

Pixel: a closer look

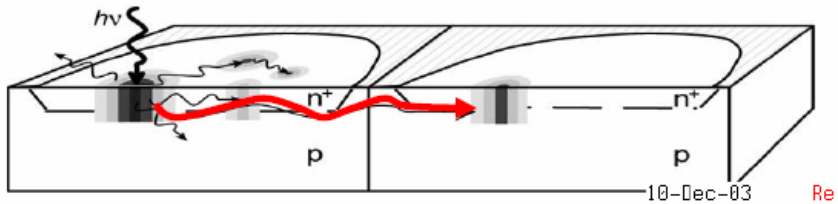


Emission microscopy picture, MPI

Optical inter-pixel cross talk:

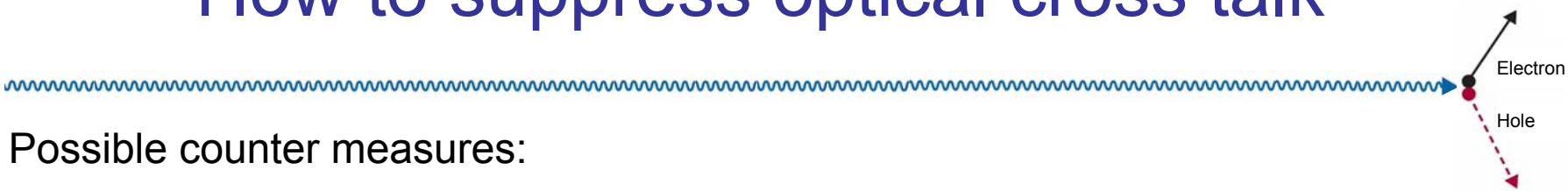
during Geiger avalanche
~3 emitted γ / 10^5 carriers
with $E\gamma > 1.14$ eV

A. Lacaita et al, IEEE TED (1993)



➔Leads to artificial increase of signal

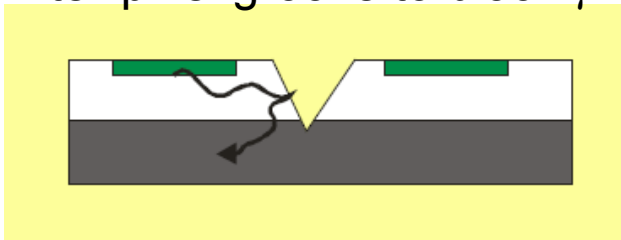
How to suppress optical cross talk



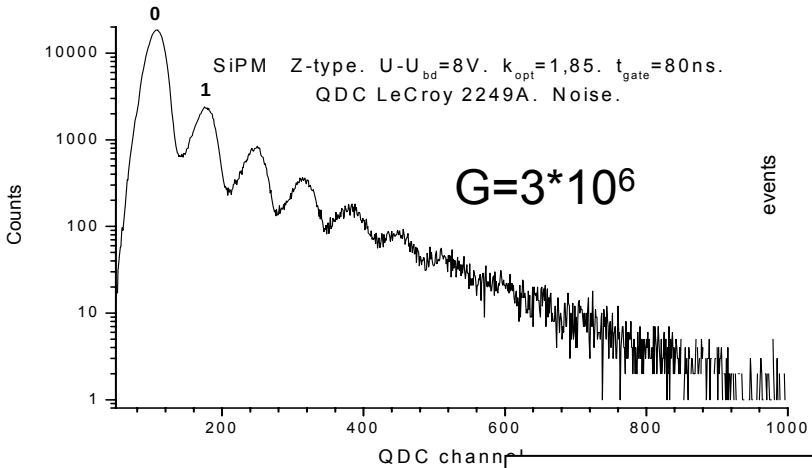
Possible counter measures:

- lower V_{Bias} → lower breakdown probability (lower PDE)
- optical insulation between pixels ➔
- technological modifications: i.e. smaller C_{pixel}

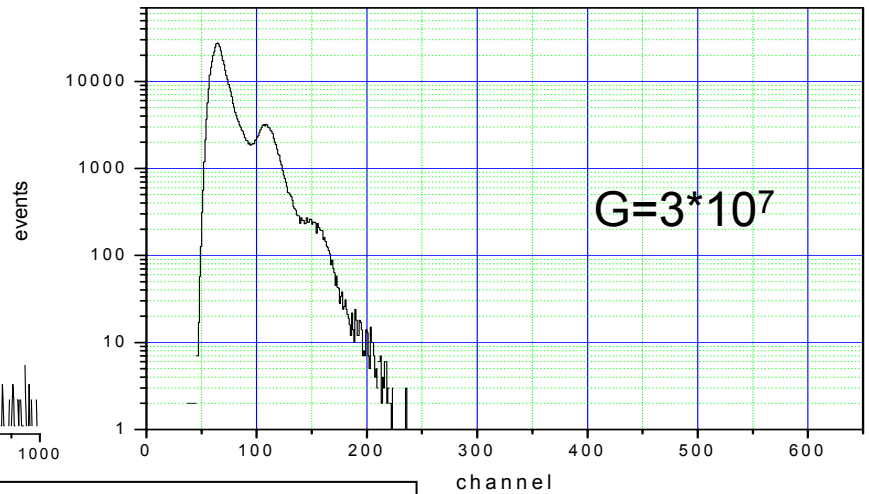
Inter-pixel groove to block γ



Before

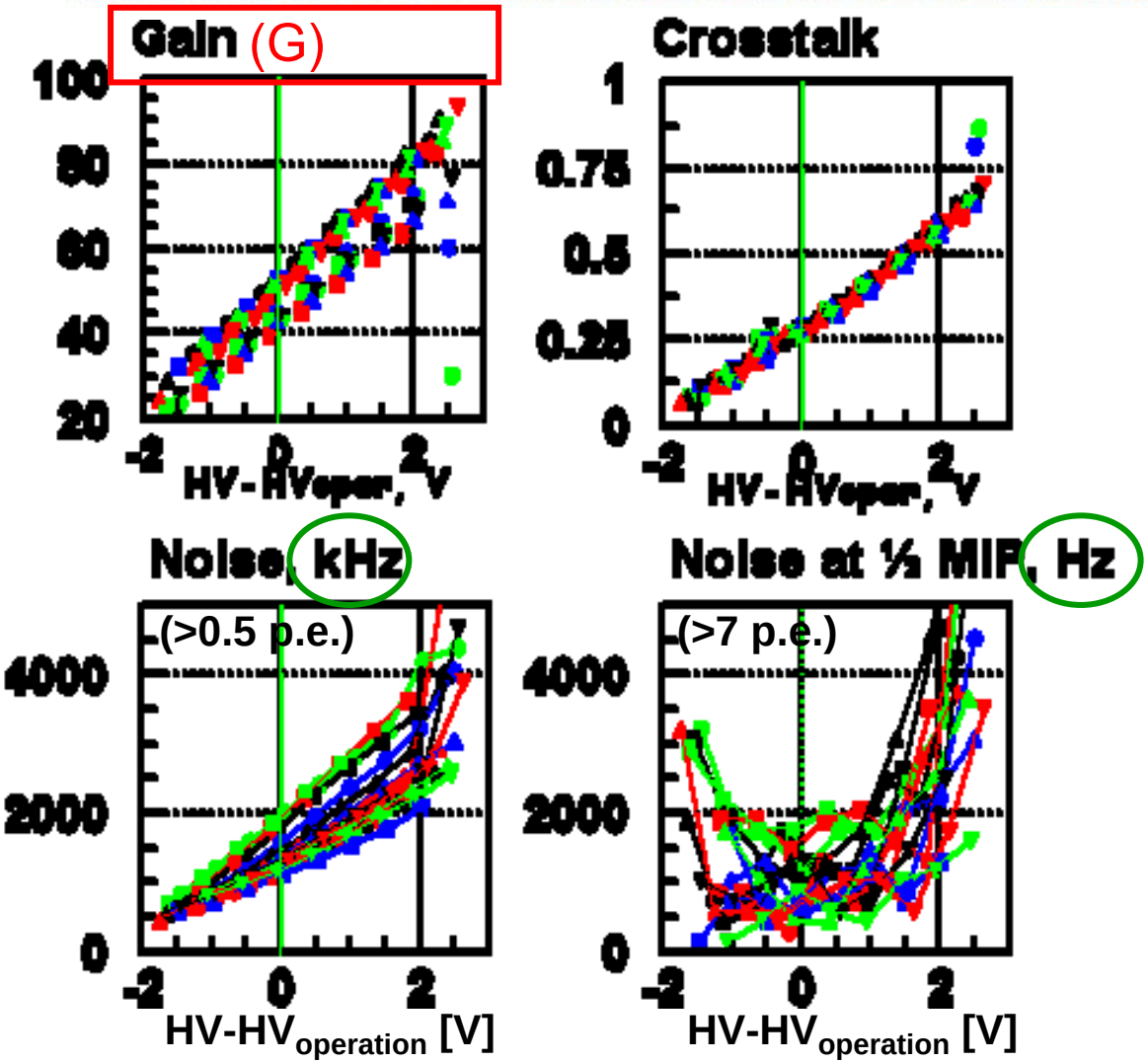


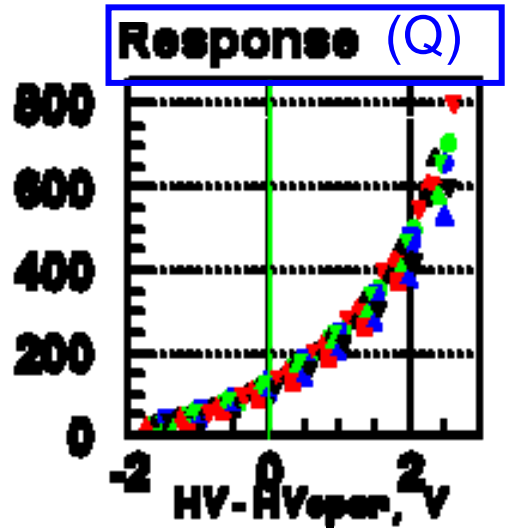
After



SiPM, MEPHI/Pulsar, PRELIMINARY

SiPM voltage dependence





Gain (G)

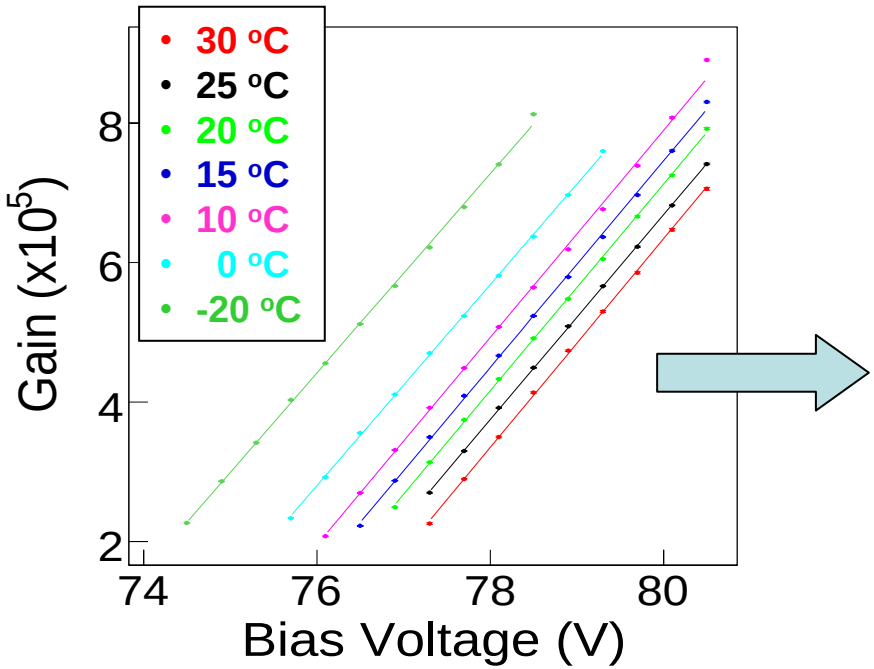
$$\frac{dG}{dV} \sim 2.5 \frac{\%}{0.1V}$$

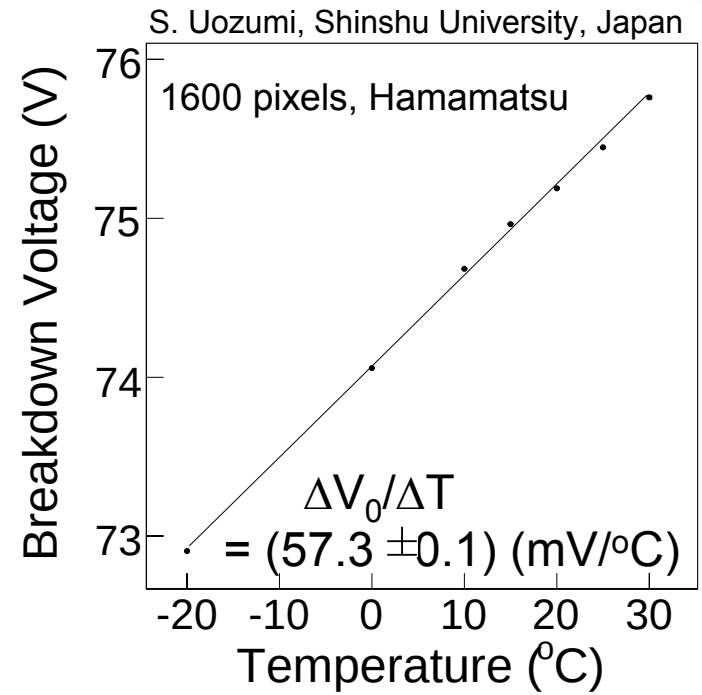
Total Charge (Q) = G*PDE

$$\frac{dQ}{dV} \sim 7.0 \frac{\%}{0.1V}$$

characterization of 4000 SiPM MEPHI/Pulsar, from E. Tarkovski, ITEP

SiPM temperature dependence





Gain = C (V_{bias}-V_0) / e
C : Pixel capacity
V_0 : Breakdown voltage

V_0 is linear to temperature.
➔temperature changes affect the over-voltage = V_{bias}-V_0(T)
→ therefore all SiPM properties

Gain (G)

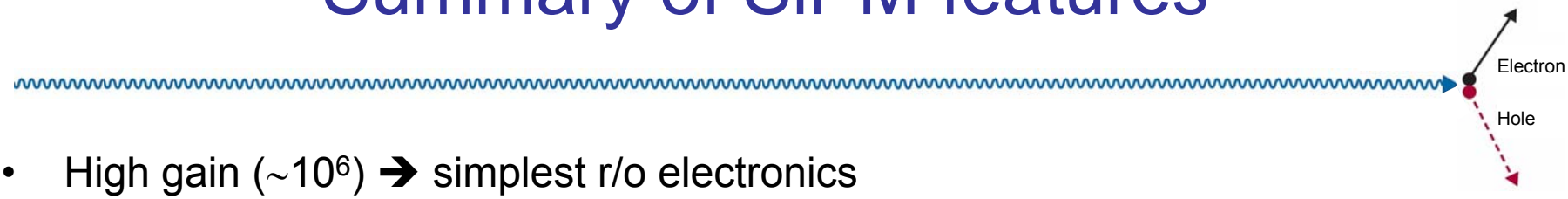
$$\frac{dG}{dT} \sim -1.7 \frac{\%}{K}$$

Total Charge (Q) = G*PDE

$$\frac{dQ}{dT} \sim -4.5 \frac{\%}{K}$$

← 1200 pixels, MEPHI/Pulsar

Summary of SiPM features



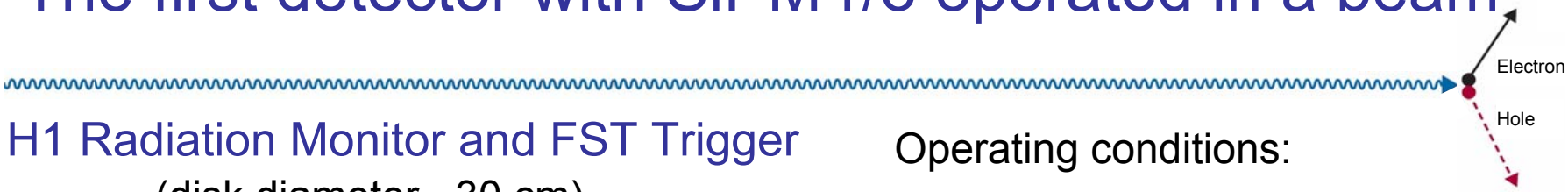
- High gain (~10^6) ➔ simplest r/o electronics
- Low electronics noise
- Low bias voltage (~50 V)
- Low power consumption (≤50 μW/mm^2)
- Insensitivity to magnetic field ➔ next generation of HEP detectors
- Compact and light ➔ direct couple to active material / space mission
- Excellent photon counting capability ➔ astro-particle physics
- Very low charge particle sensitivity (negligible nuclear counting effect)
- Very good timing (≤100 ps) ➔ medical applications
- Small recovery time
- Good temperature and voltage stability
- Room temperature operation
- Relatively low cost ➔ high number of channels possible

draw backs and limitations in the outlook ➔

SiPM application in detector development

- High energy physics
  - low light level detection
  - scintillation light readout
- astrophysics / “space” experiments
  - Cherenkov and Fluorescense light detection
  - Liquid Xenon detector
- medical applications
  - time resolution

The first detector with SiPM r/o operated in a beam



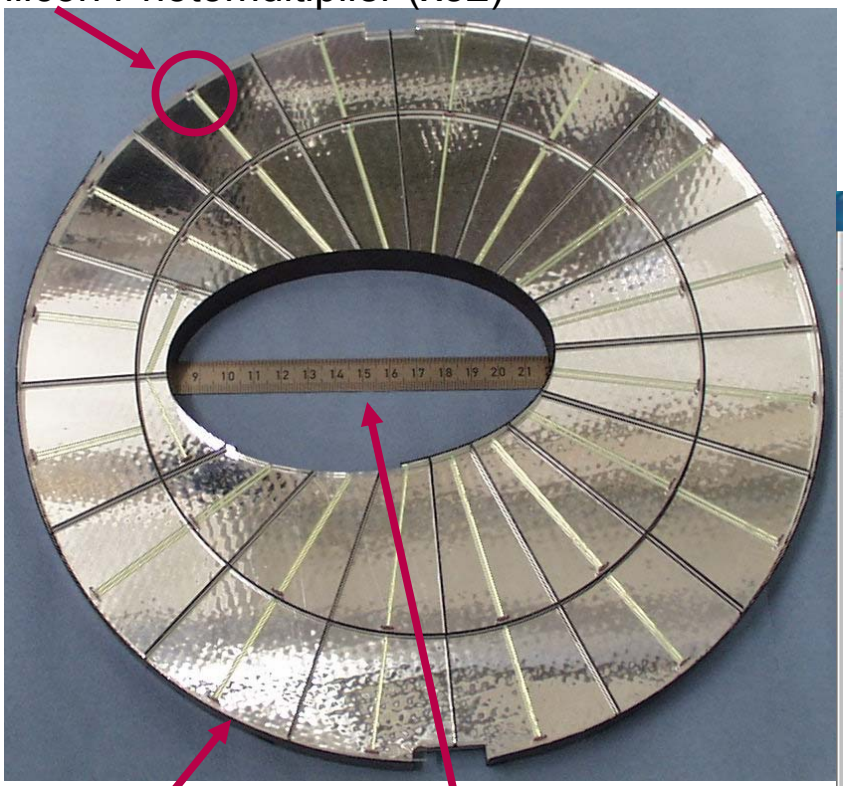
H1 Radiation Monitor and FST Trigger

(disk diameter ~30 cm)

Operating conditions:

- U – U_breakdown ~ 1.5 V
- Discriminator Threshold ~ 1 MIP

Silicon Photomultiplier (x32)



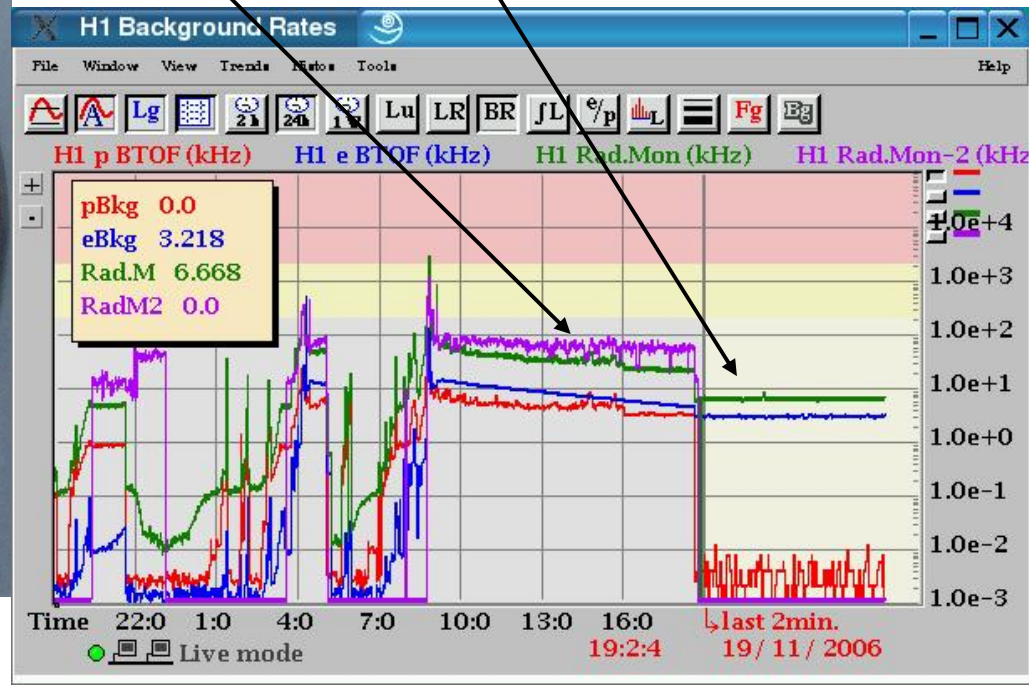
Organic Scintillator
(1 cm thickness)

HERA Beam-pipe

H1 shift tool (java applet):

Single SiPM count rate/bunch X-ng

count rate of whole detector / bunch X-ng

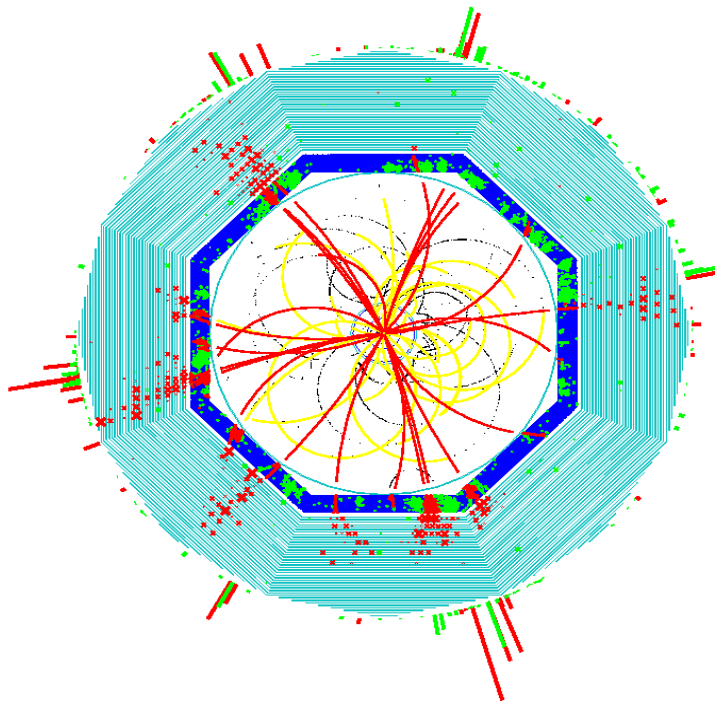


- On-line Measurement of the Dose rate and Total Ionization Dose
- Automatic Beam Dump by either Detector for too high Dose Rate

R&D for Calorimeters for the ILC

Key requirements for photo-detectors:

- ✓ couple to scintillator material
  - ➔ high sensitivity to blue or green (+WLF)
- ✓ operate in high magnetic field (~5T)
- ✓ high granularity = compact detector

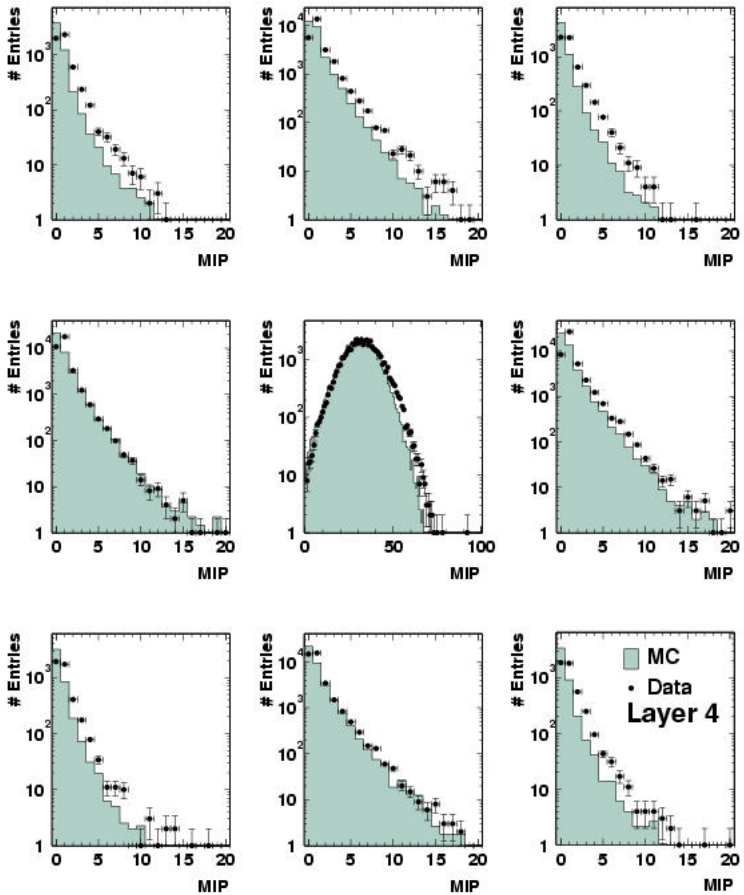


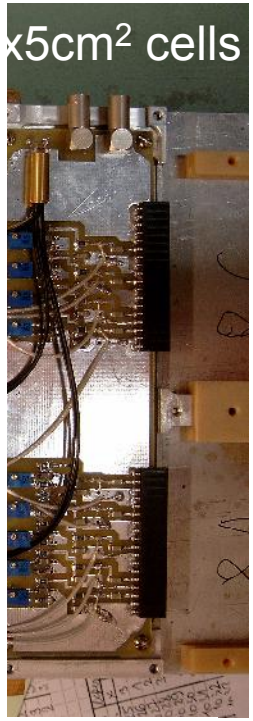
First prototype calorimeter with SiPM

Electron

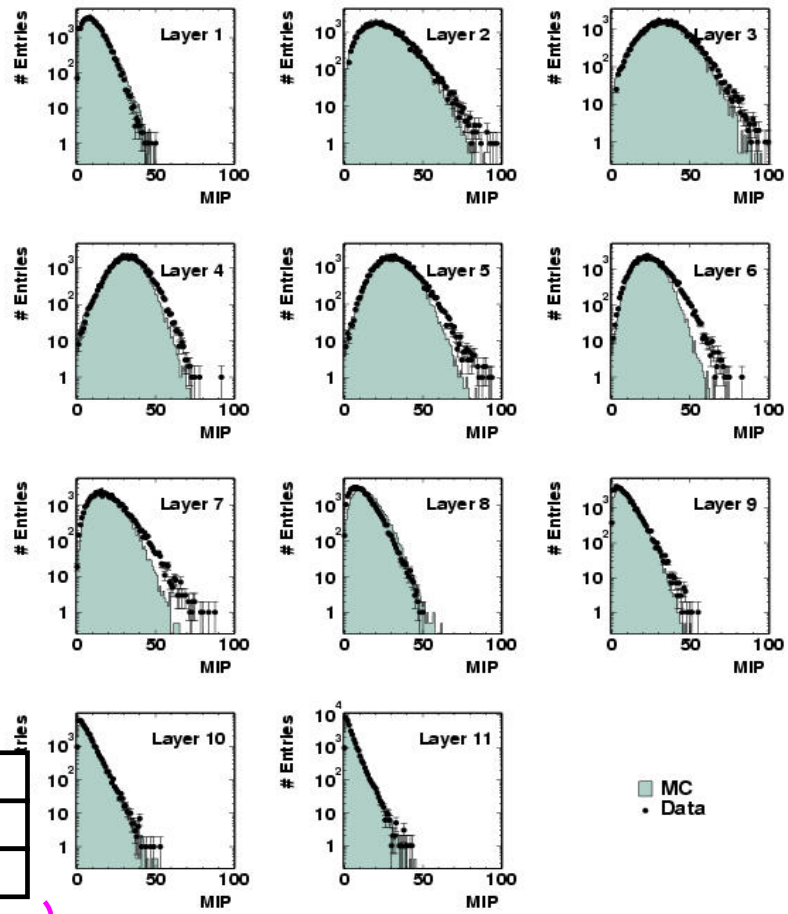
Hole

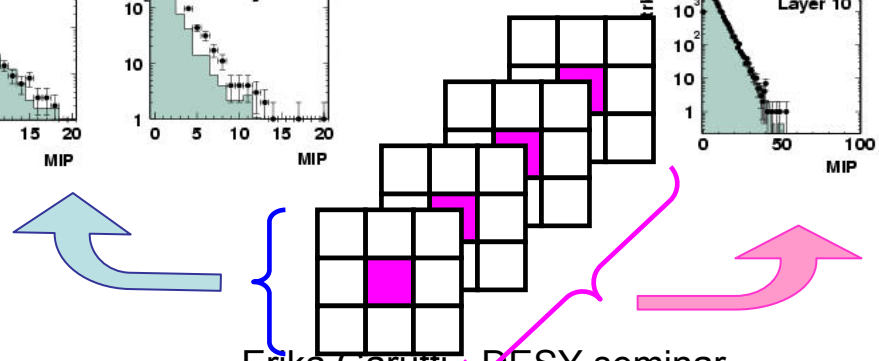
Lateral shower shape





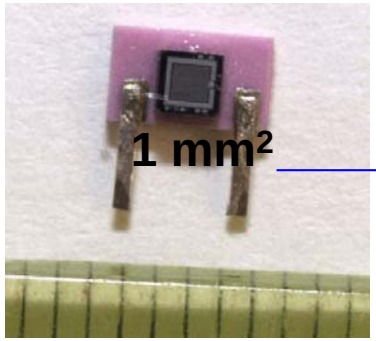
Longitudinal shower shape

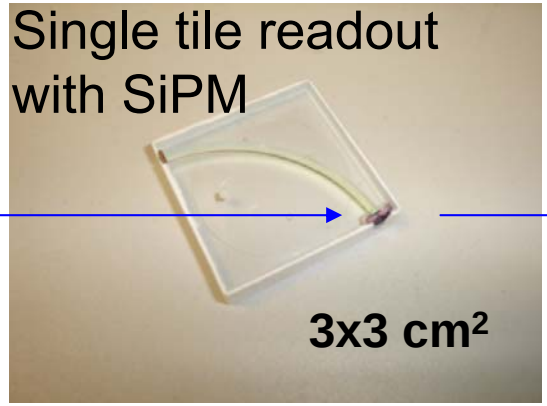


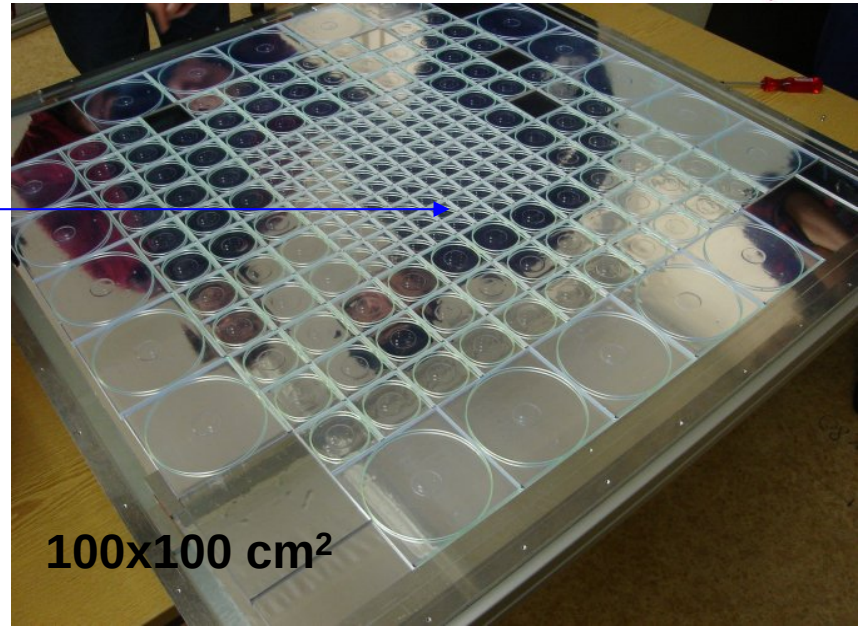


High granularity hadronic calorimeter

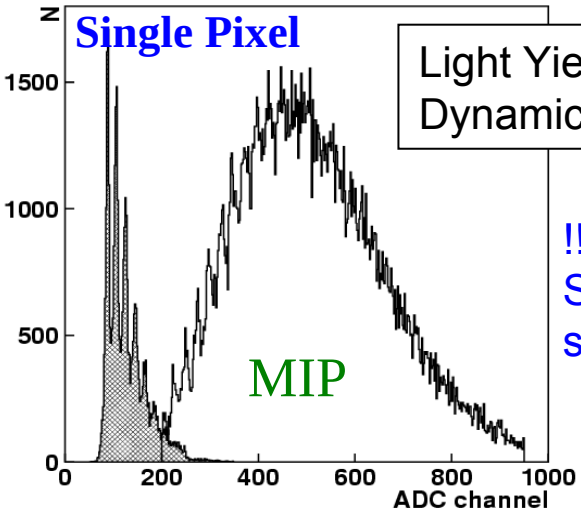
A crucial technology improvement to calorimetry







1x1m² prototype calorimeter with 8000 channels readout with SiPM (MePHI/Pulsar)



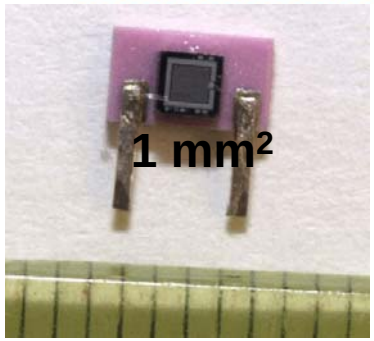
Light Yield = 15 pixels / MIP
Dynamic range ~ 100 MIPs

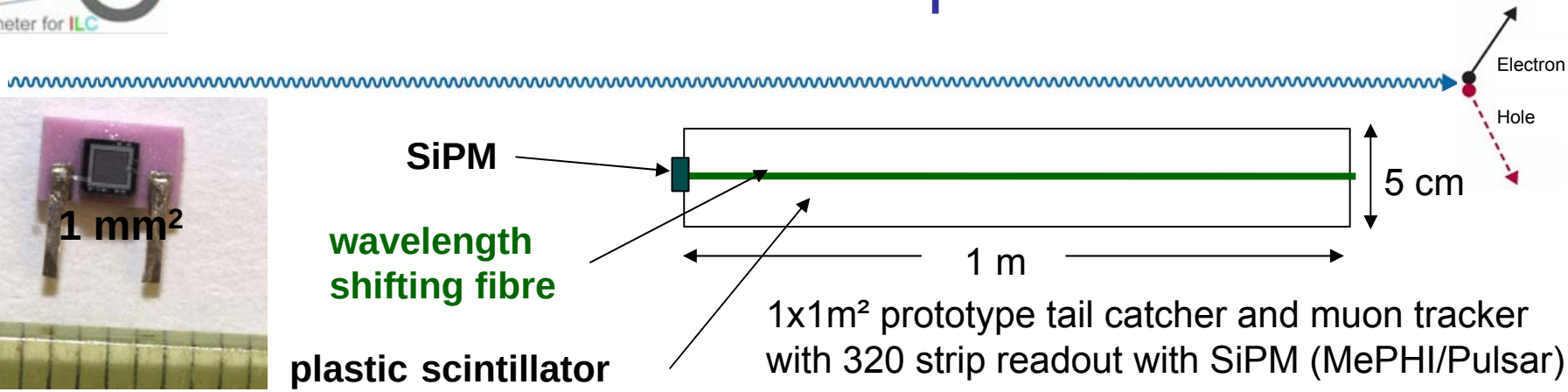
!! auto-calibration of SiPM gain from single-pixel spectra

Allows unprecedented high granularity

38 layers (~4.5 λ)
Scintillator – Steel sandwich structure (0.5:2cm)

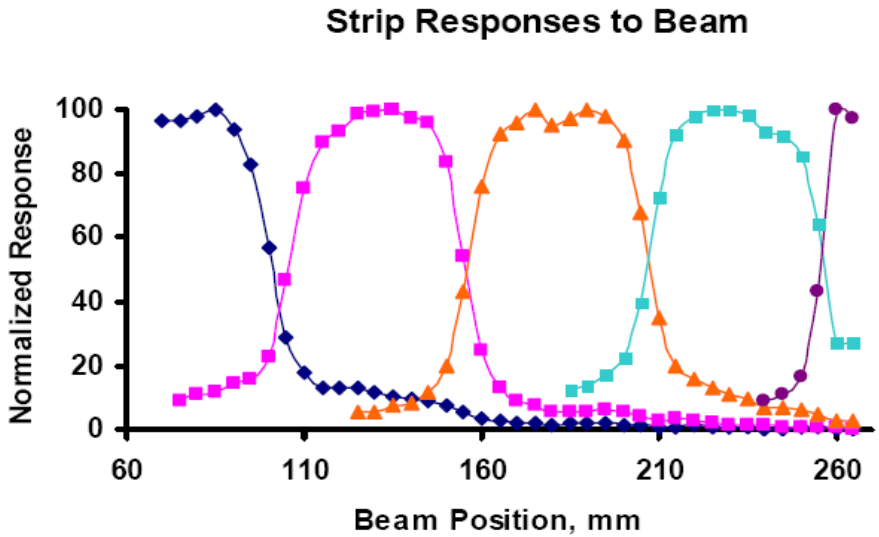
SiPM r/o for scint. strip: muon detector



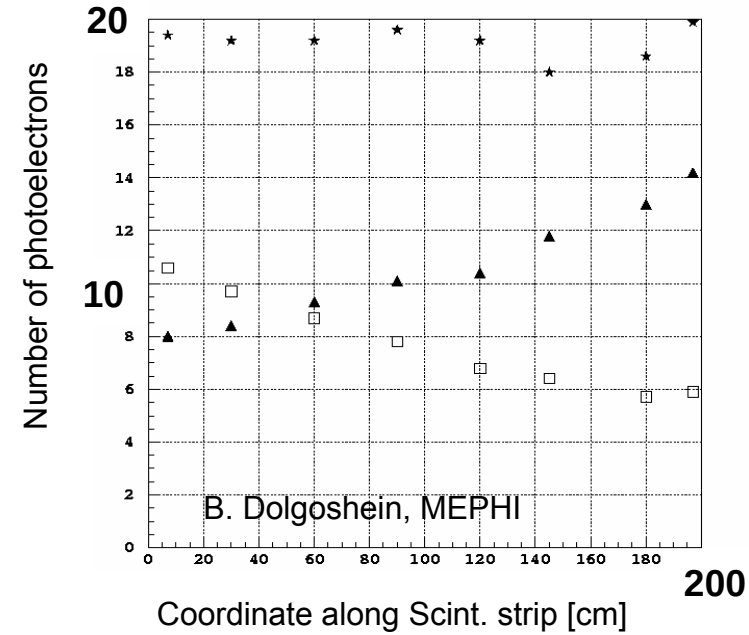


1x1m² prototype tail catcher and muon tracker with 320 strip readout with SiPM (MePHI/Pulsar)

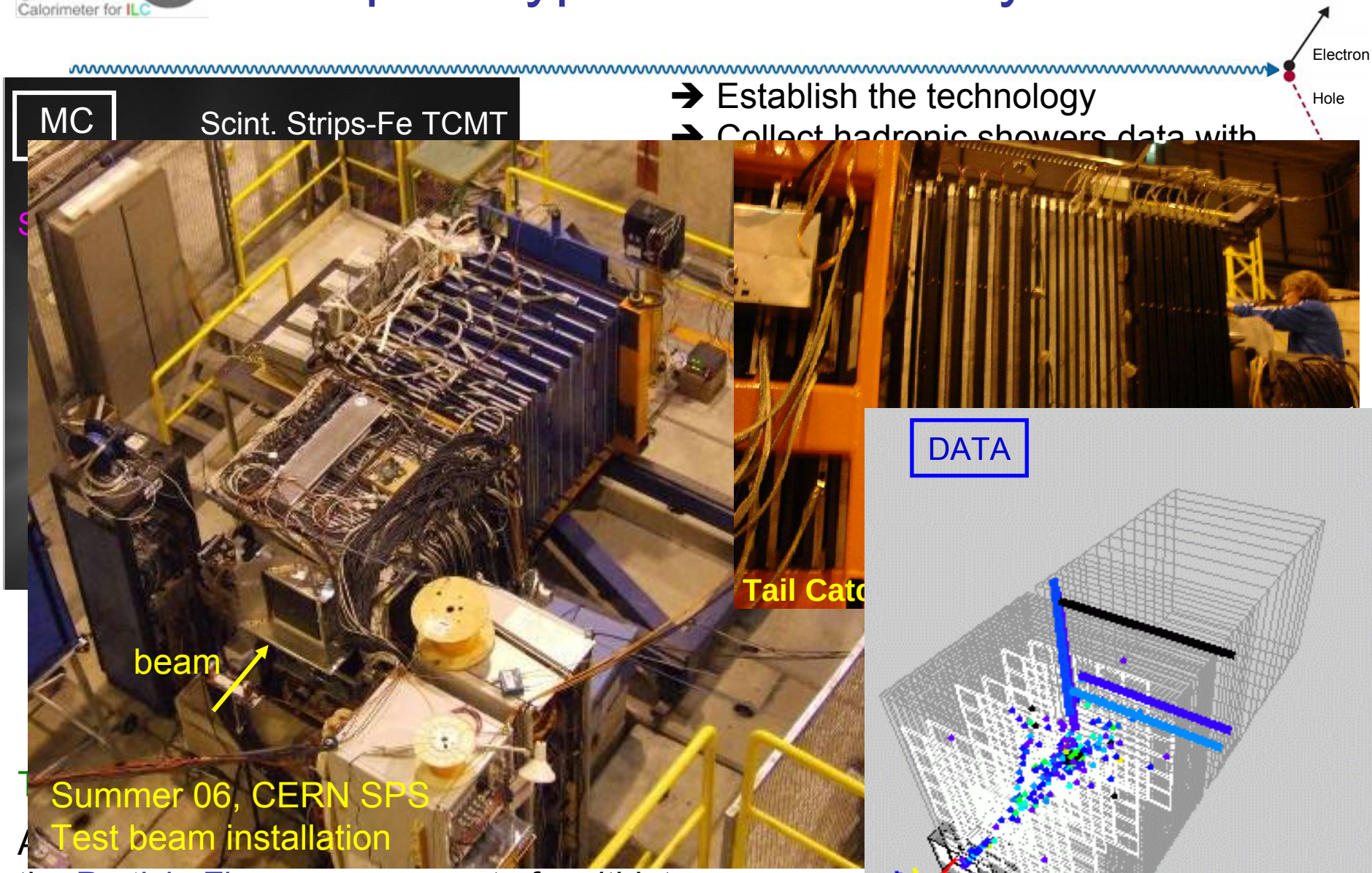
16 layers (~5.5 λ)
2 Scint. – Steel sandwich structure
8x(0.5:2)cm+8x(0.5:10)cm
tested at DESY electron test beam



Test on 2m scint. strip with double SiPM r/o



The prototype calorimeter system for ILC

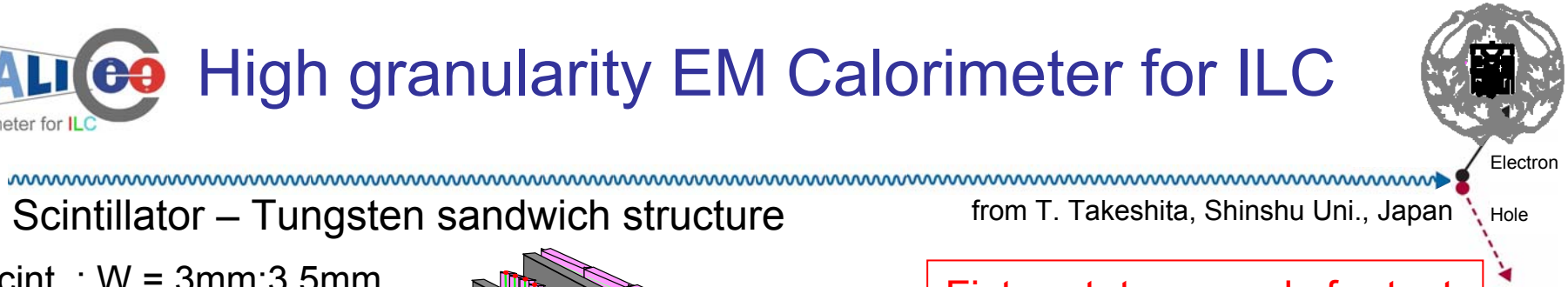


➔ Establish the technology

➔ Collect hadronic showers data with

the Particle Flow measurement of multi-jets final state at the International Linear Collider

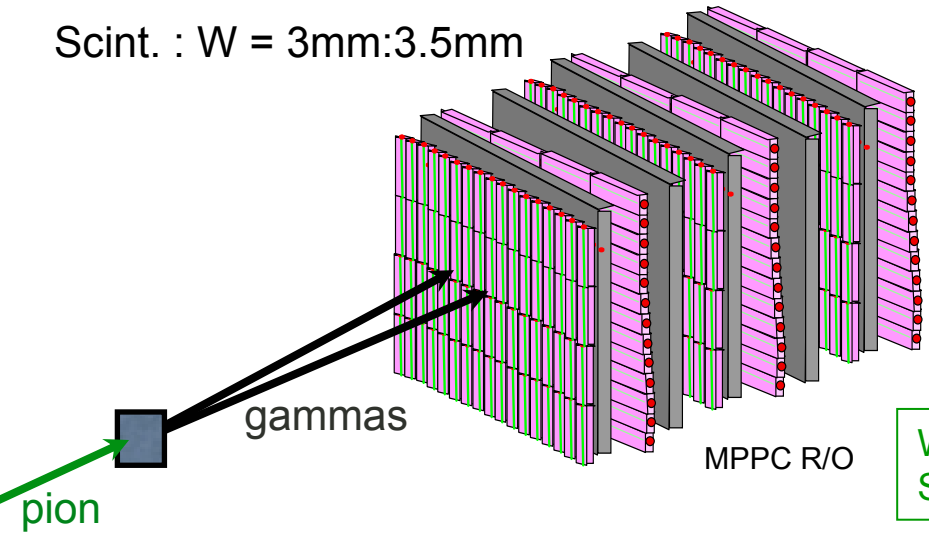
High granularity EM Calorimeter for ILC



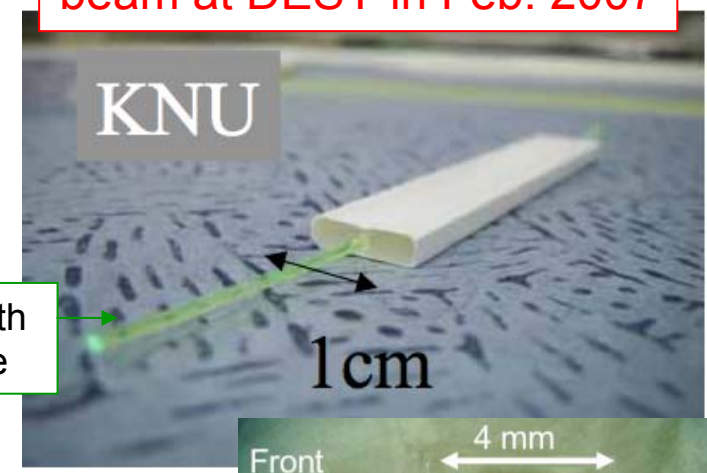
Scintillator – Tungsten sandwich structure

from T. Takeshita, Shinshu Uni., Japan

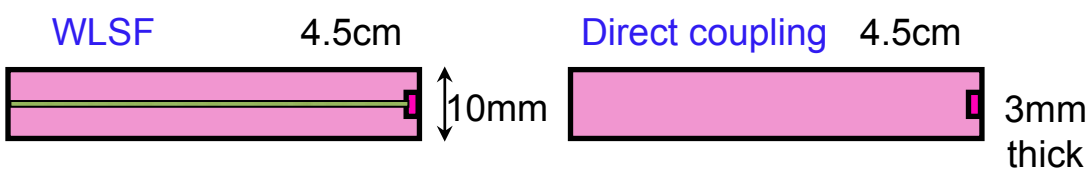
Scint. : W = 3mm:3.5mm

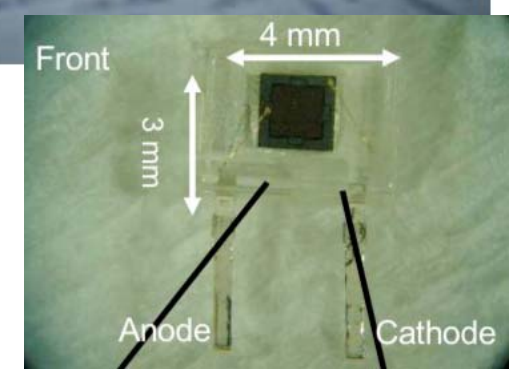


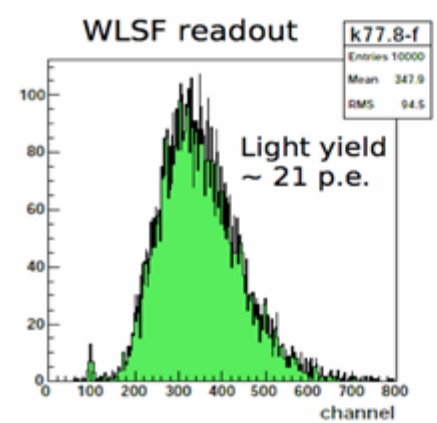
Fist prototype ready for test beam at DESY in Feb. 2007

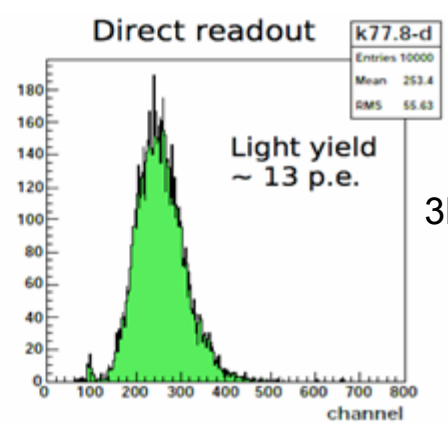


Wave-Length Shifter Fibre









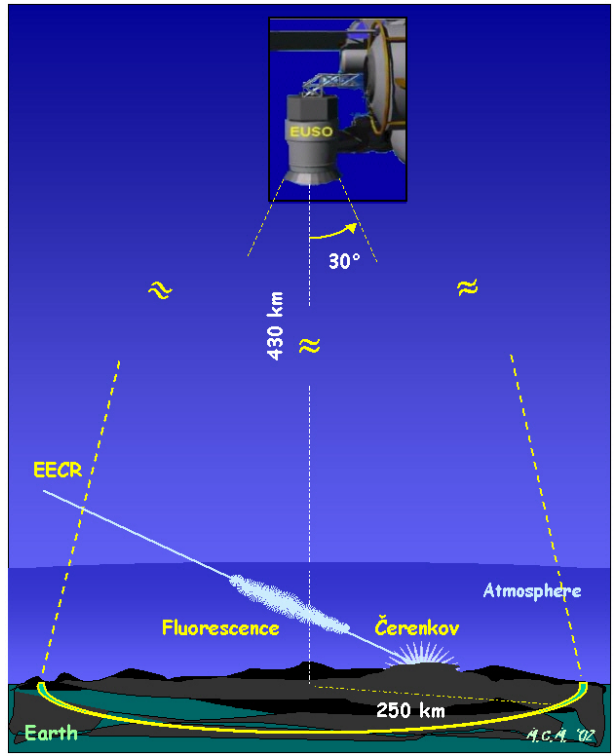
3M R.M.F.

Multi-Pixel Photon Counter from Hamamatsu

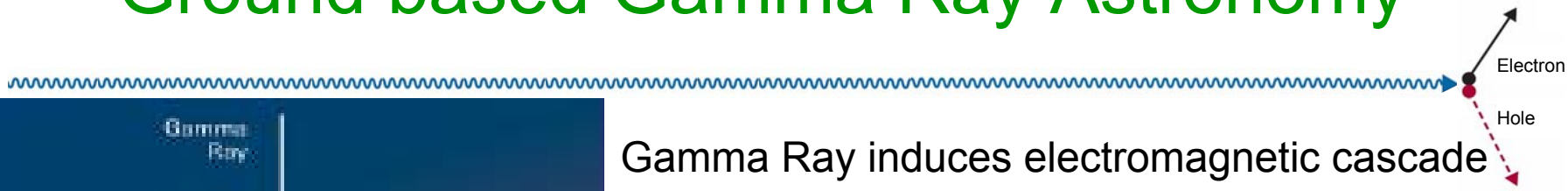
R&D for Astro-particle and space physics

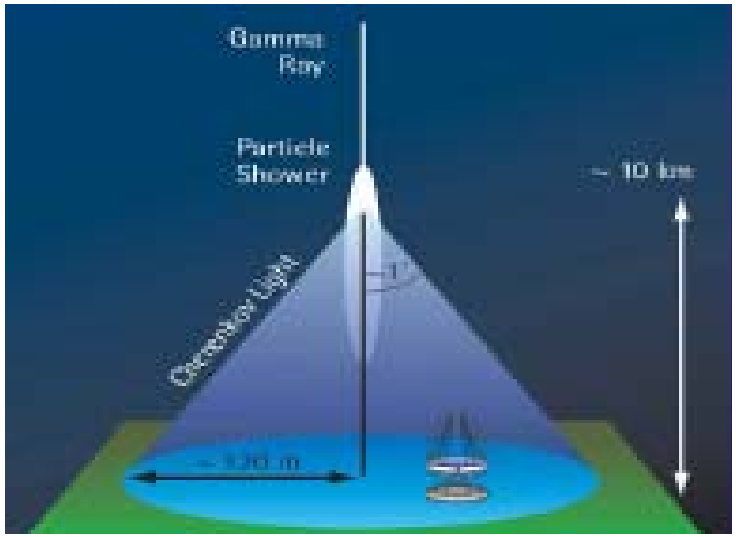
Key requirements for photo-detectors:

- ✓ detection of Cherenkov or fluorescent light
  - ➔ high sensitivity to UV (deep UV)
- ✓ good photon-counting capability
- ✓ rare events
  - ➔ highest possible Photo Detection Efficiency
- ✓ large detectors with small number of channels
  - ➔ larger area SiPM
- ✓ light and robust device
- ✓ time resolution



Ground based Gamma Ray Astronomy



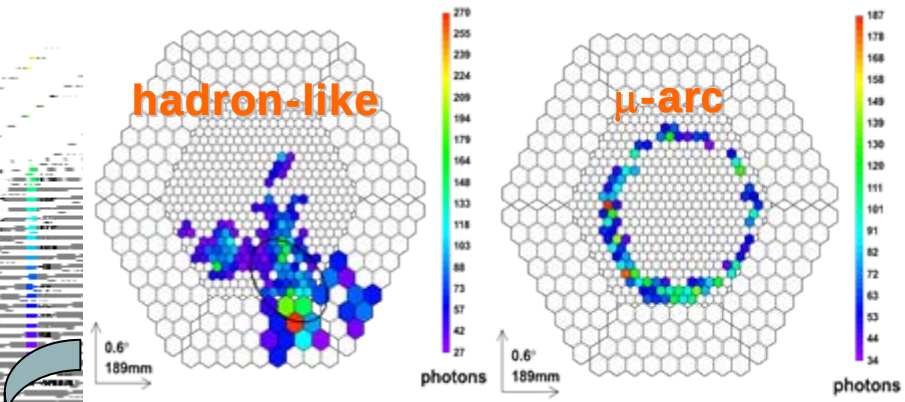


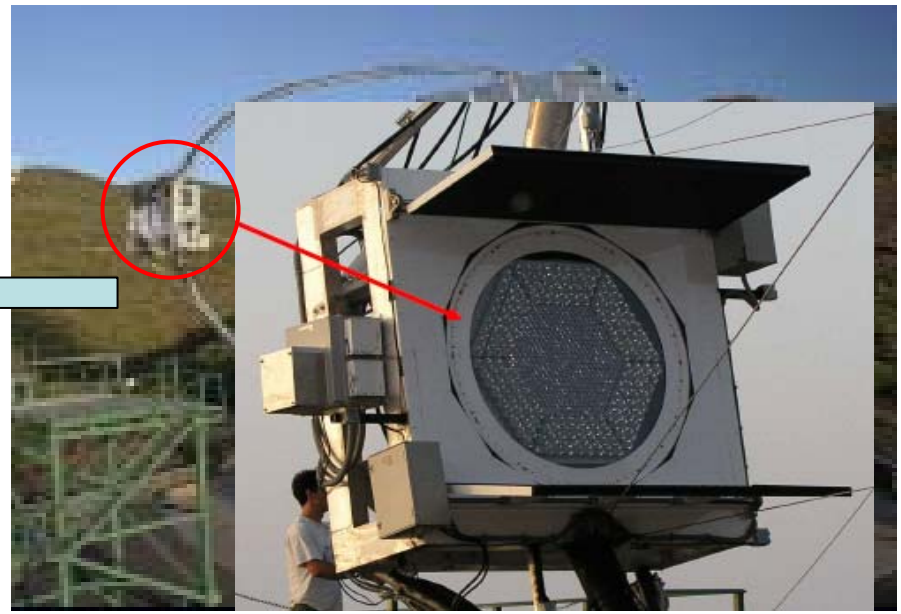
Gamma Ray induces electromagnetic cascade

➔ Relativistic particle shower in atmosphere

➔ Cherenkov light
fast light flash (~ns)
100 γ / m^2 (1 TeV Gamma Ray)

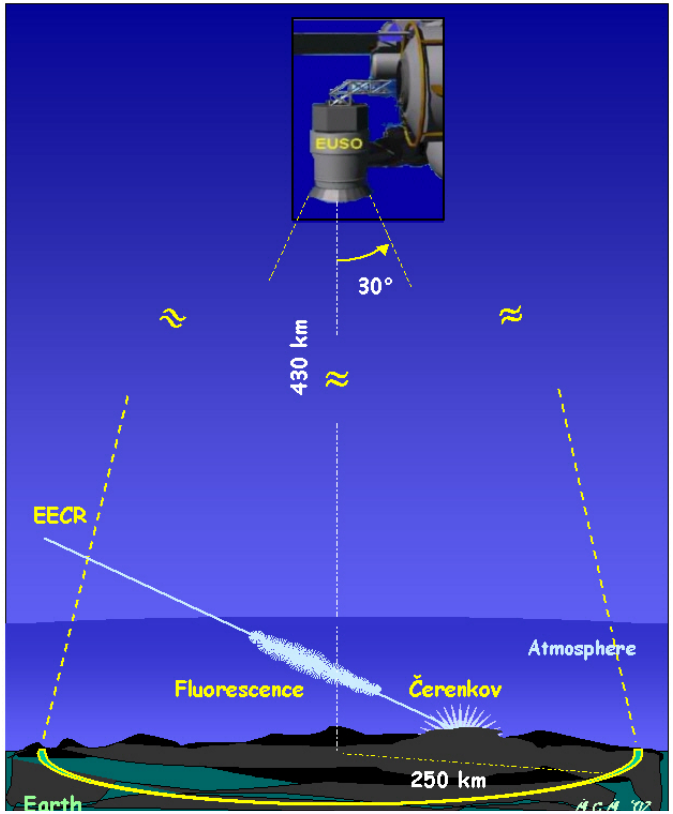
➔ MAGIC: world largest air Cherenkov telescope



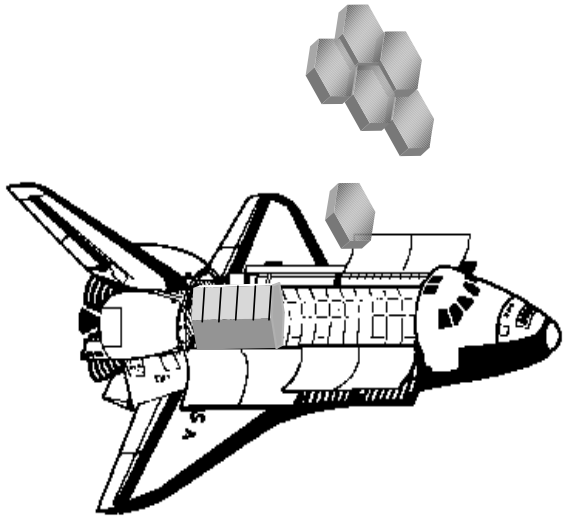


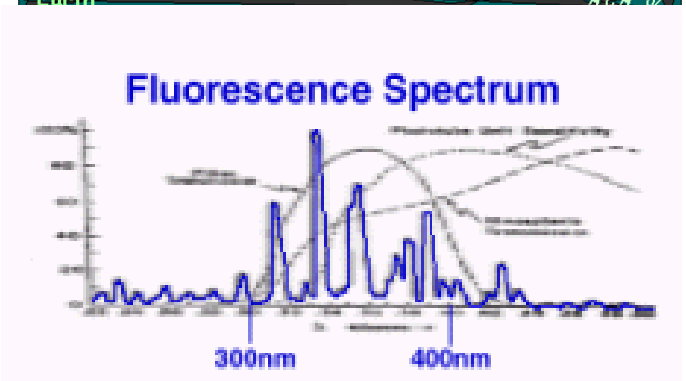
which photo-detector to use?!

Space-based High Energy Neutrino Astronomy



The Extreme Universe Space Observatory



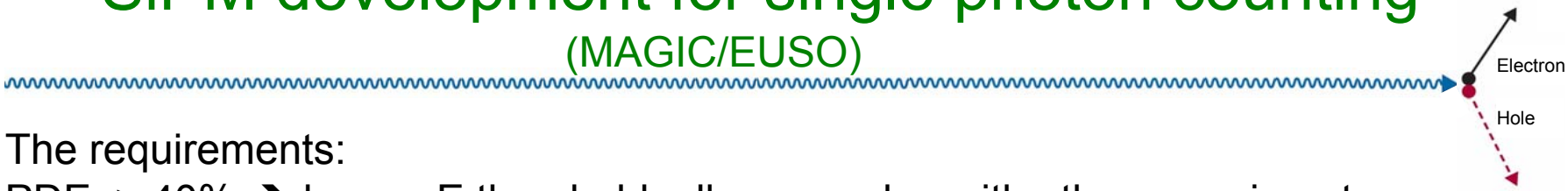


The detector requirements:

compact and light-weight (solid state ?)
high efficiency (>30-40%) photo-detectors (λ ~300-400nm)
good single photon counting capability
timing at the level of $\leq$10 ns (~few meters space resolution)
low single photoelectron dark rate (less than night sky rate)

SiPM development for single photon counting

(MAGIC/EUSO)



The requirements:

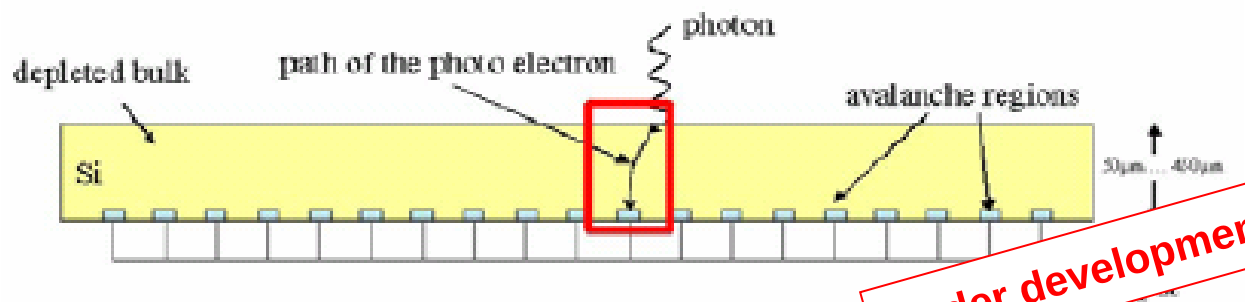
PDE > 40% ➔ lowers E threshold, allows overlap with other experiments

Larger size (up to 10x10mm^2 , 3x3 and 5x5 mm^2 under test)

➔ to cover large area detector

Alternative development: back-illuminated SiPM

Semiconductor laboratory (HLL), MPI and MEPHI, Moskow

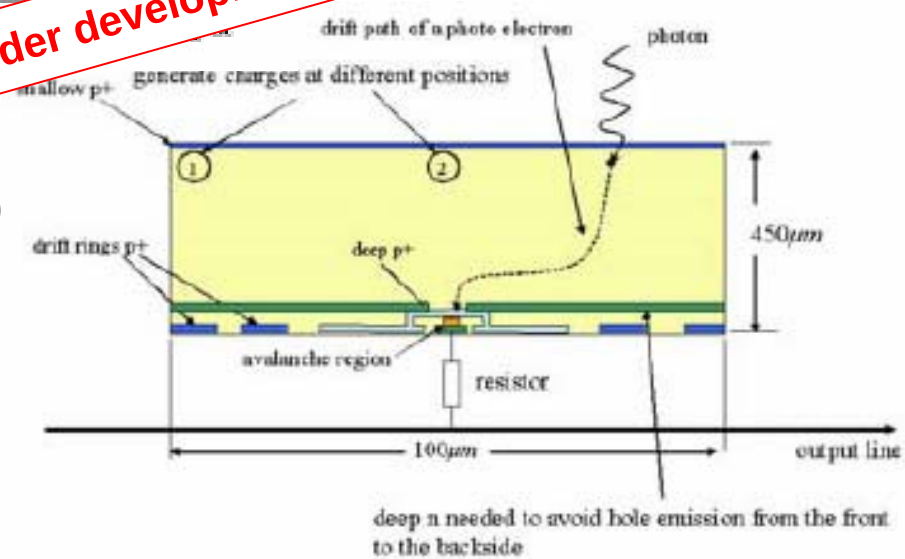


100μm Geiger drift cell:

-small C_{cell}

-full area efficiency

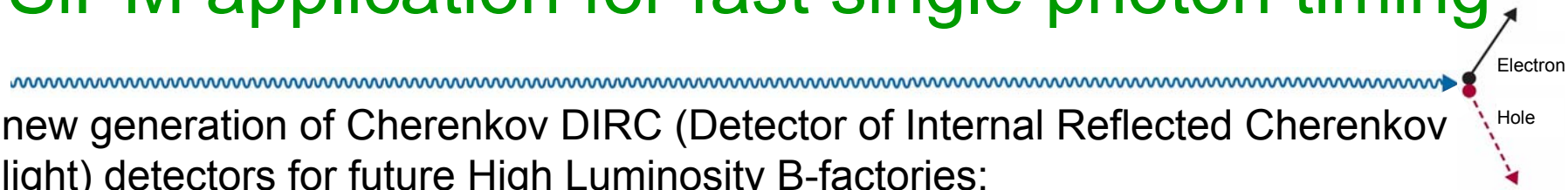
Under development



- Jitter of arrival of photo-electrons in the drift region < 3ns
- Dark rate (large drift volume ~ large noise?)
- Crosstalk should be kept one order of magnitude below physics

increase of PDE up to 70% possible

SiPM application for fast single photon timing

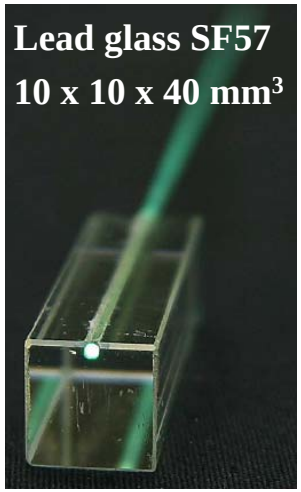


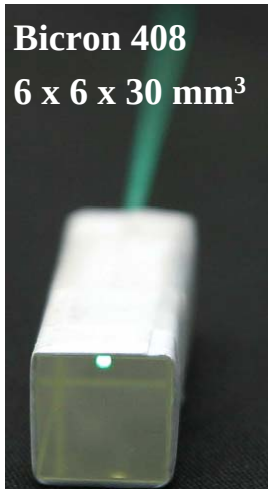
new generation of Cherenkov DIRC (Detector of Internal Reflected Cherenkov light) detectors for future High Luminosity B-factories:

- DIRC upgrade for BaBar
- Time of Propagation (TOP) detector for BELLE

The detector requirements:

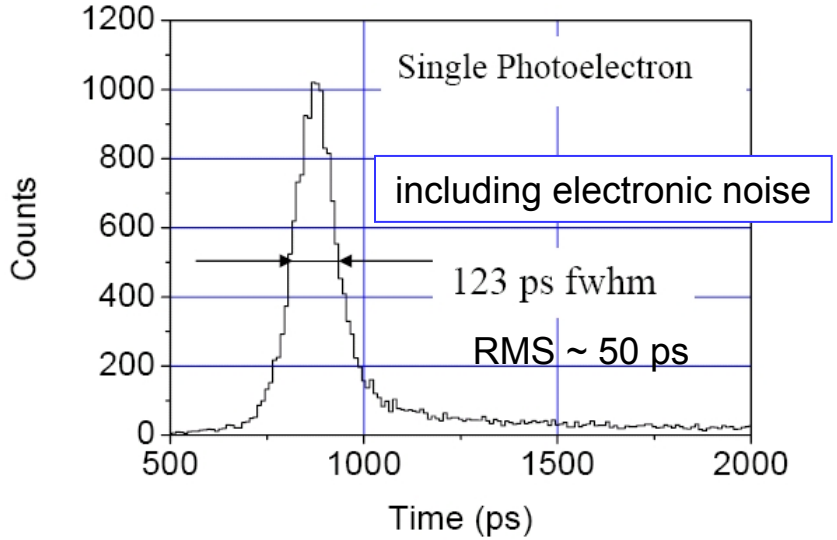
time resolution <100 ps
dark rate <300 kHz/few mm^2 size
photon detection efficiency > 30%





T. Zhao, University of Washington presentation at LCWS06 Bangalore, India

from B. Dolgoshein's presentation in Beaune 2002 (NIM A 504 (2003) 48)

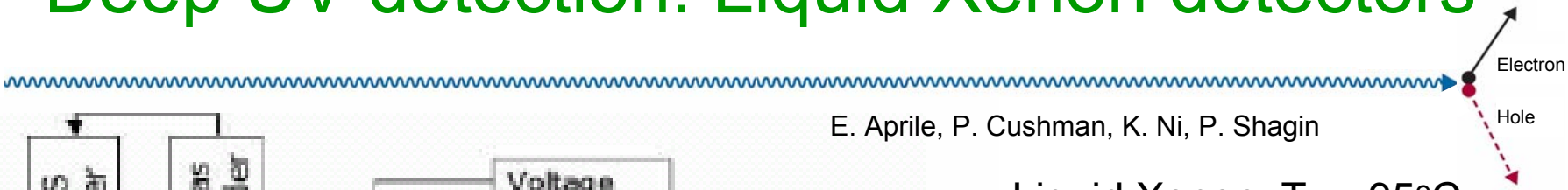


➔ Light Yield of Cherenkov light compared to Scint.

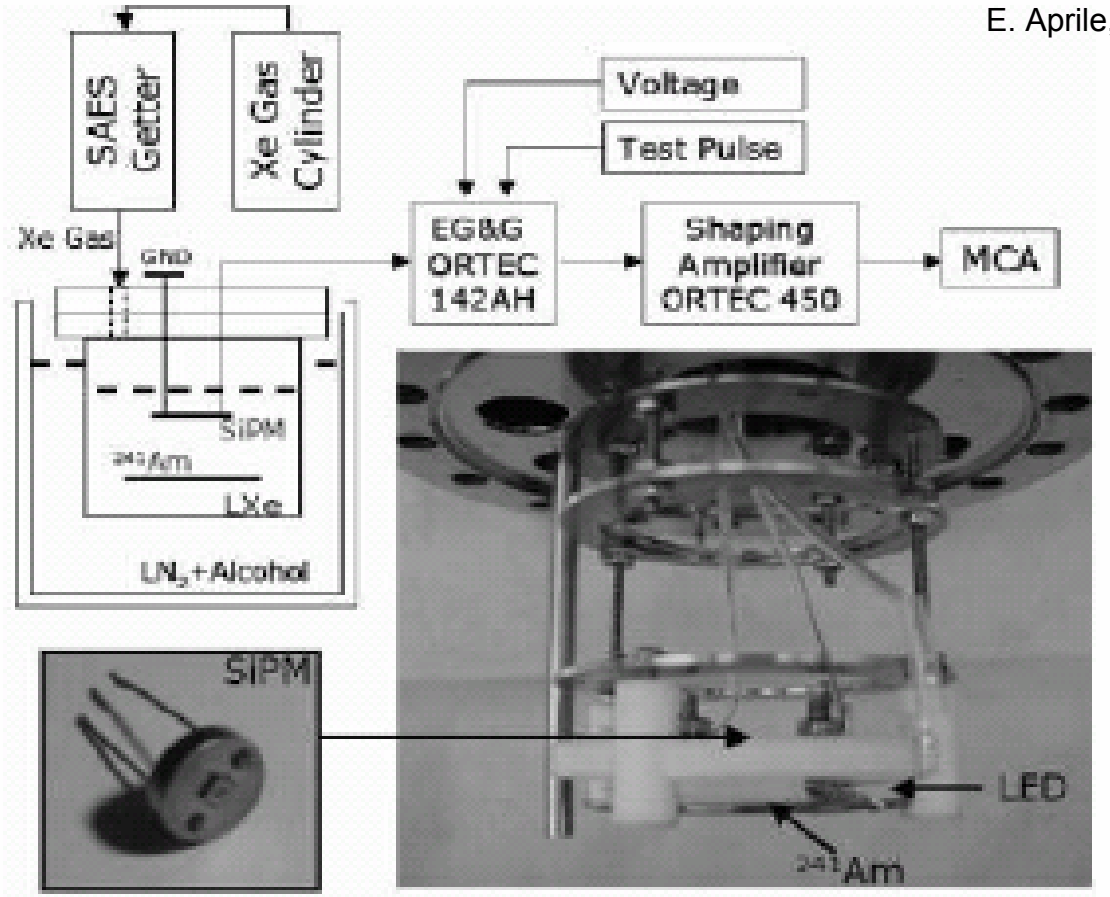
Lead glass: 2.4 ± 0.5 p.e. / Bicron 408: 27 ± 4 p.e.

(from cosmic ray measurement)

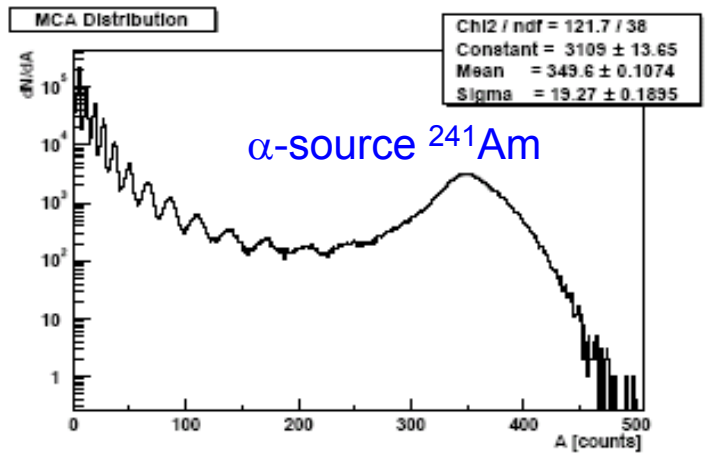
Deep UV detection: Liquid Xenon detectors



E. Aprile, P. Cushman, K. Ni, P. Shagin



Liquid Xenon: T = -95°C
λ = 178 nm



PDE ~ 5.5% (λ = 178 nm)

typical PMT applied in TPC for WIMP searches PDE ~20%

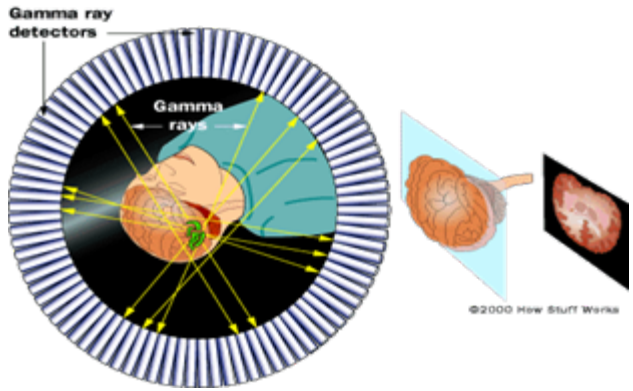
576 pixels SiPM, MePHI/Pulsar

➔Attractive alternative to PMT for UV photon detection at low energy detection threshold (i.e. neutralino dark matter searches)

R&D for medical field applications

Key requirements for photo-detectors:

- ✓ coupling to LSO, LYSO crystals
  - ➔ sensitivity to blue light
- ✓ high number of photons
  - ➔ dark rate and crosstalk are not an issue
- ✓ insensitivity to B field (inside NMR magnet)
- ✓ time resolution (TOF+PET)



Time Of Flight Positron Emission Tomography

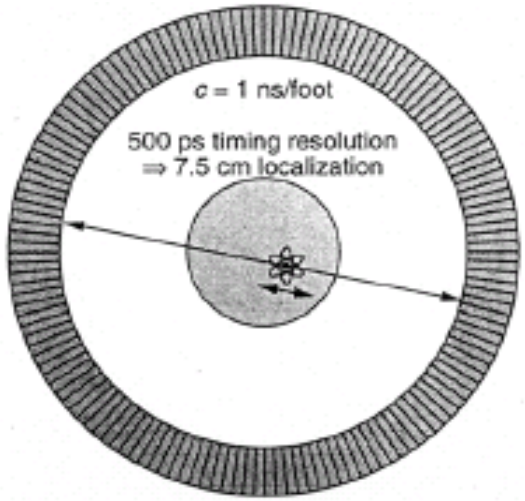
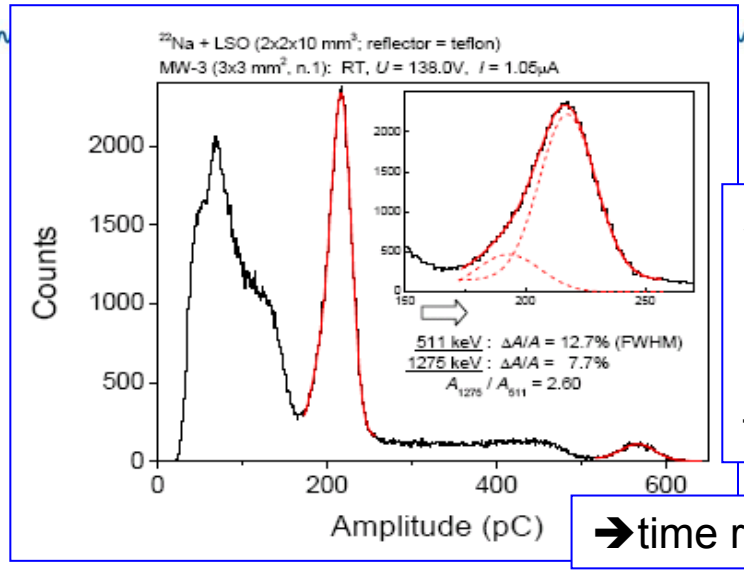
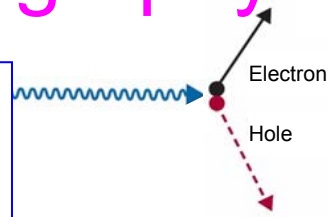


Figure 1. Time-of-Flight PET Camera. Annihilation pho detected by a ring of scintillation crystals. With a conv PET camera, this localizes the position of the positron to segment joining the two crystals. With a TOF PET cam arrival time difference is used to further restrict the positio

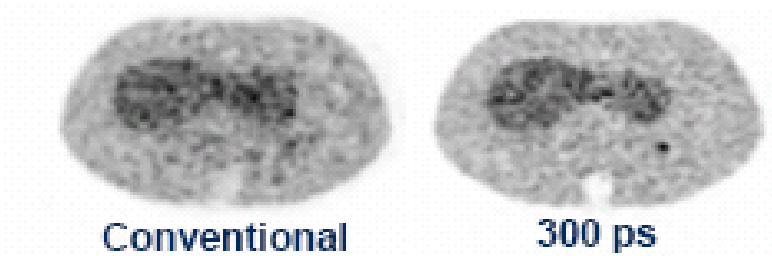




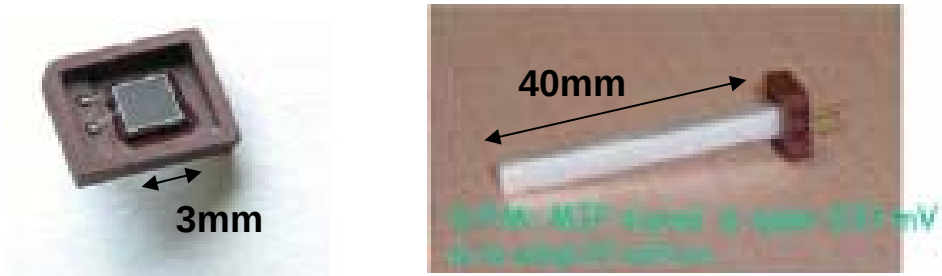
3x3mm^2 SiPM (Z. Sadigov) + LSO crystal (2x2x10mm^3) test with ^{22}Na

➔time resolution: 540 ps

PET + time information
➔ key for noise suppression



5625 pixels, MEPHI/Pulsar, B. Dolgoshein, Beaune 2005



large area 3x3mm^2 SiPM directly coupled to 3x3x40 mm^3 scintillator BC418
test with 3 GeV e- from DESY test beam
➔signal A ~ 2700 pixels
➔time resolution: σ(SiPM+BC418) = 33ps

SiPM summary

Advantages:

- High gain (~10^6) ➔ simplest r/o electronics
- Low electronics noise
- Low bias voltage (~50 V)
- Low power consumption (≤50 μW/mm2)
- Insensitivity to magnetic field
- Compact and light
- Excellent photon counting capability
- Very low charge particle sensitivity
- Very good timing (≤100 ps)
- Small recovery time
- Good temperature and voltage stability
- Room temperature operation
- Relatively low cost

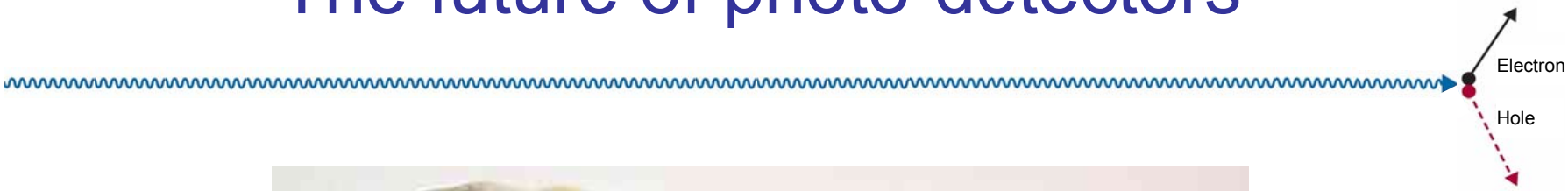
Drawbacks and limitations:

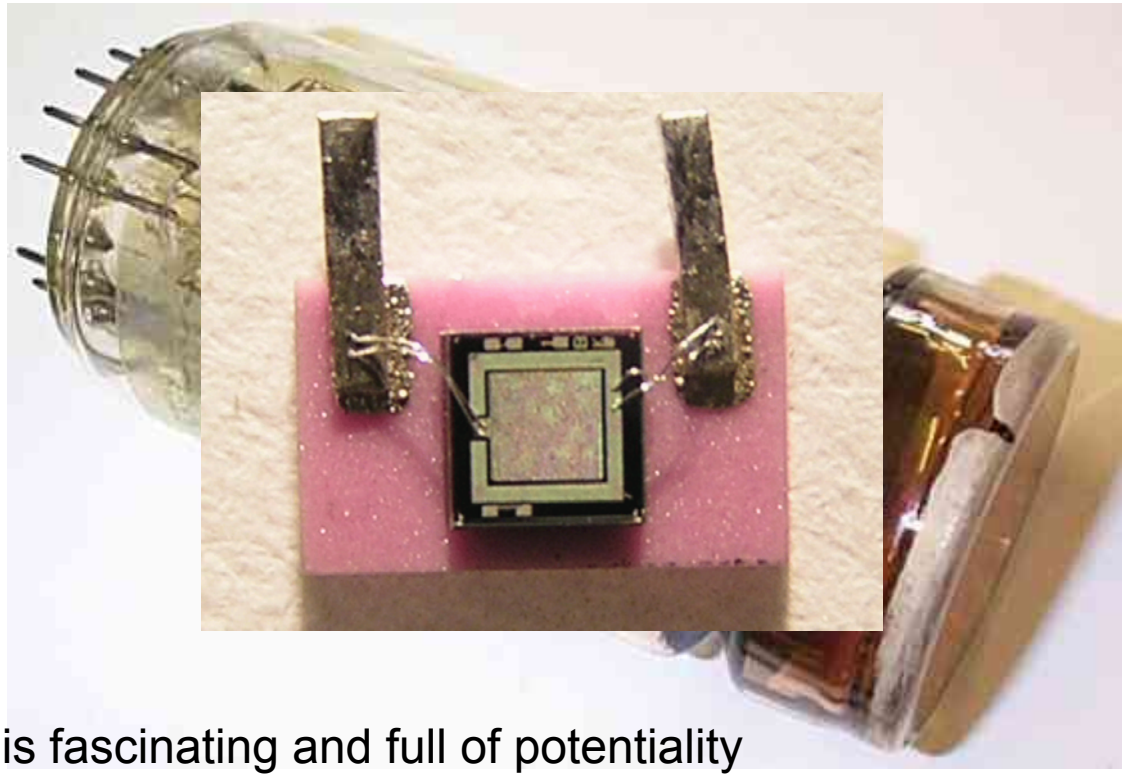
- Small size (established only 1x1mm²)
- Not enough PDE (~20%)
- High dark rate
- Limited dynamic range

- Optical crosstalk being reduced (<10%)
- Sensitivity to blue being established

Fast developing technology
Solutions to the remaining open issues are coming

The future of photo-detectors





Thank you !!

The SiPM field is fascinating and full of potentiality

The future is bright and efficient

Stay tuned on the developments !!!