Application of Silicon-Photomultiplier in high energy astro-particle and medical physics detectors

Erika Garutti (DESY)

SiPM application in:

- 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

SiPM pioneering experience

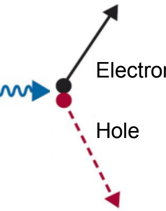
R&D for Calorimeters for the ILC

The history:

- After the LHC detectors (radiation hard / dense particle environment)
- The next generation HEP experiments ➔ precision experiments
- New paradigm for precision measurements in a jet environment

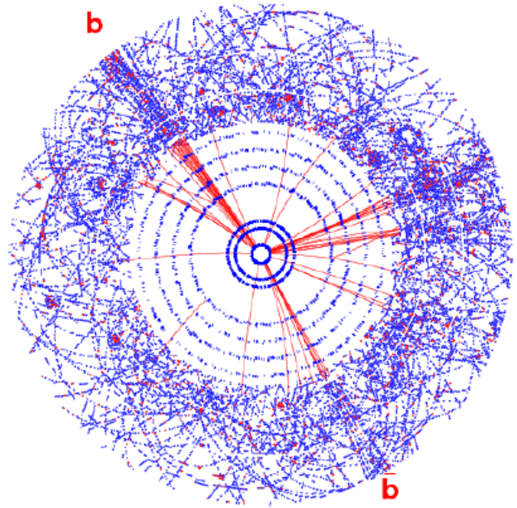
➔ Particle Flow

Calorimeter R&D for HEP detectors

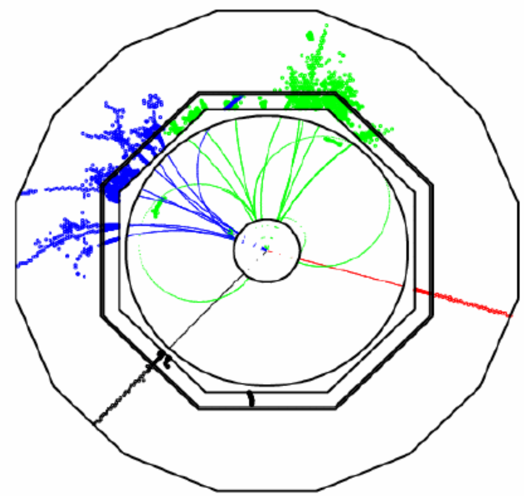


The largest scale HEP detectors at (s)LHC and the future LC

The LHC $pp \to H + X$



The ILC $e^+e^- \to HZ$



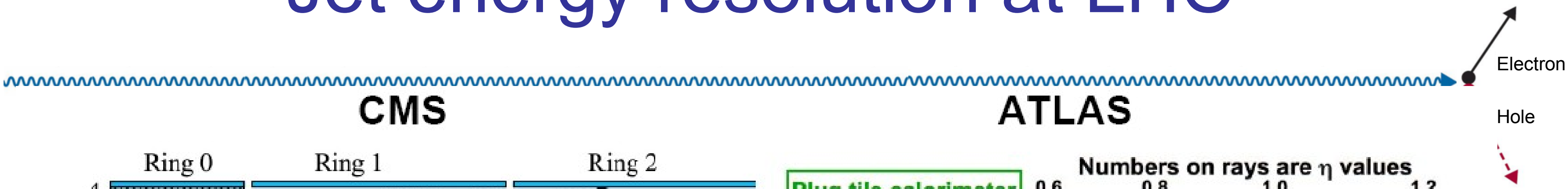
★ **At electron-positron the final state corresponds to the underlying physics interaction, e.g. above see** $H \to b\bar{b}$ **and** $Z \to \mu^+\mu^-$ **and nothing else…**

High precision LC physics demands a high precision detector:

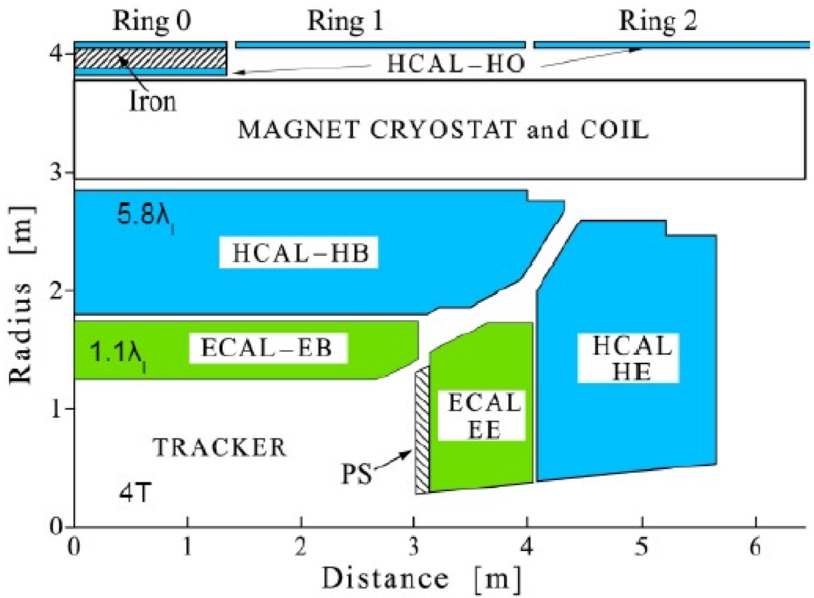
- high precision vertex (flavor tagging) and tracking (Higgs from di-lepton recoil mass)
- precision calorimetry (heavy bosons reconstruction from di-jet decay)

➔ significant improvements in the calo. system, in particular in the HCAL

Jet energy resolution at LHC



CMS

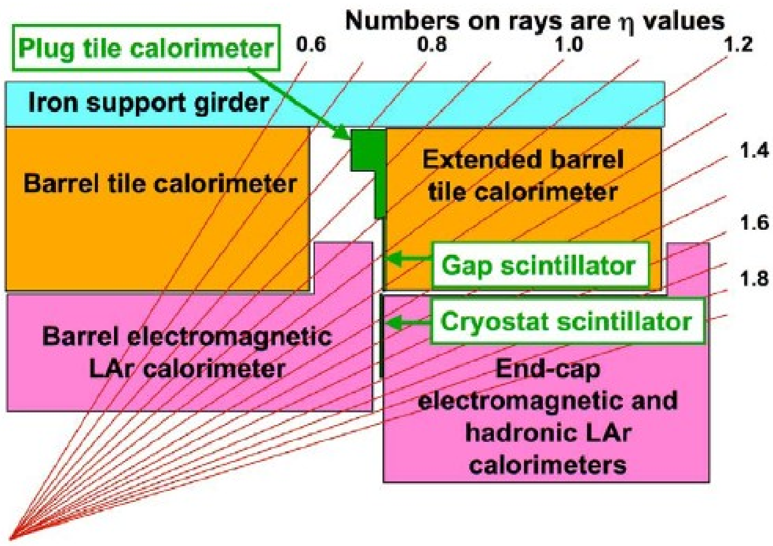


5 cm brass / 3.7 cm scint.
Embedded fibres, HPD readout

Expected jet resolution:

$$\frac{\sigma}{E} = \frac{125\%}{\sqrt{E}} \oplus \frac{5.6\ \mathrm{GeV}}{E} \oplus 3.3\%$$

ATLAS



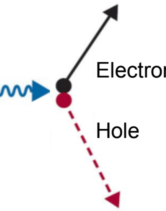
14 mm iron / 3 mm scint.
sci. fibres, read out by phototubes

Jet resolution with weighting:

$$\frac{\sigma}{E} = \frac{60\%}{\sqrt{E}} \oplus 3\%$$

Stochastic term for hadrons was ~93% and 42% respectively

SiPM pioneering experience



R&D for Calorimeters for the ILC

<u>The history:</u>

- After the LHC detectors (radiation hard / dense particle environment)
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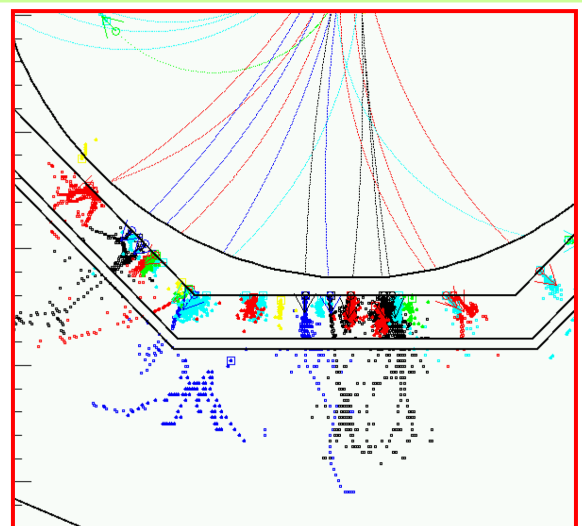
- New paradigm for precision measurements in a jet environment

➔ Particle Flow

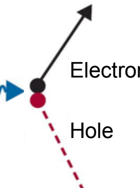
a concept to improve the jet energy resolution of a HEP detector based on:
proper detector design (high granular calorimeter!!!)
+ sophisticated reconstruction software

PFlow techniques have been shown to improve jet E resolution in existing detectors, but the full benefit can only be seen on the future generation of PFlow designed detectors

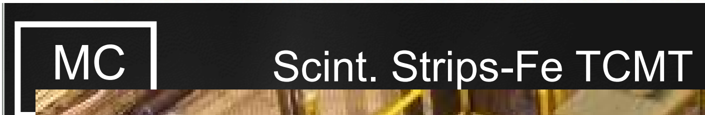
Requires the design of
- a highly granular calorimeter, O(1cm^2) cells
- dedicated electronics, O(20M channels)
- high level of integration

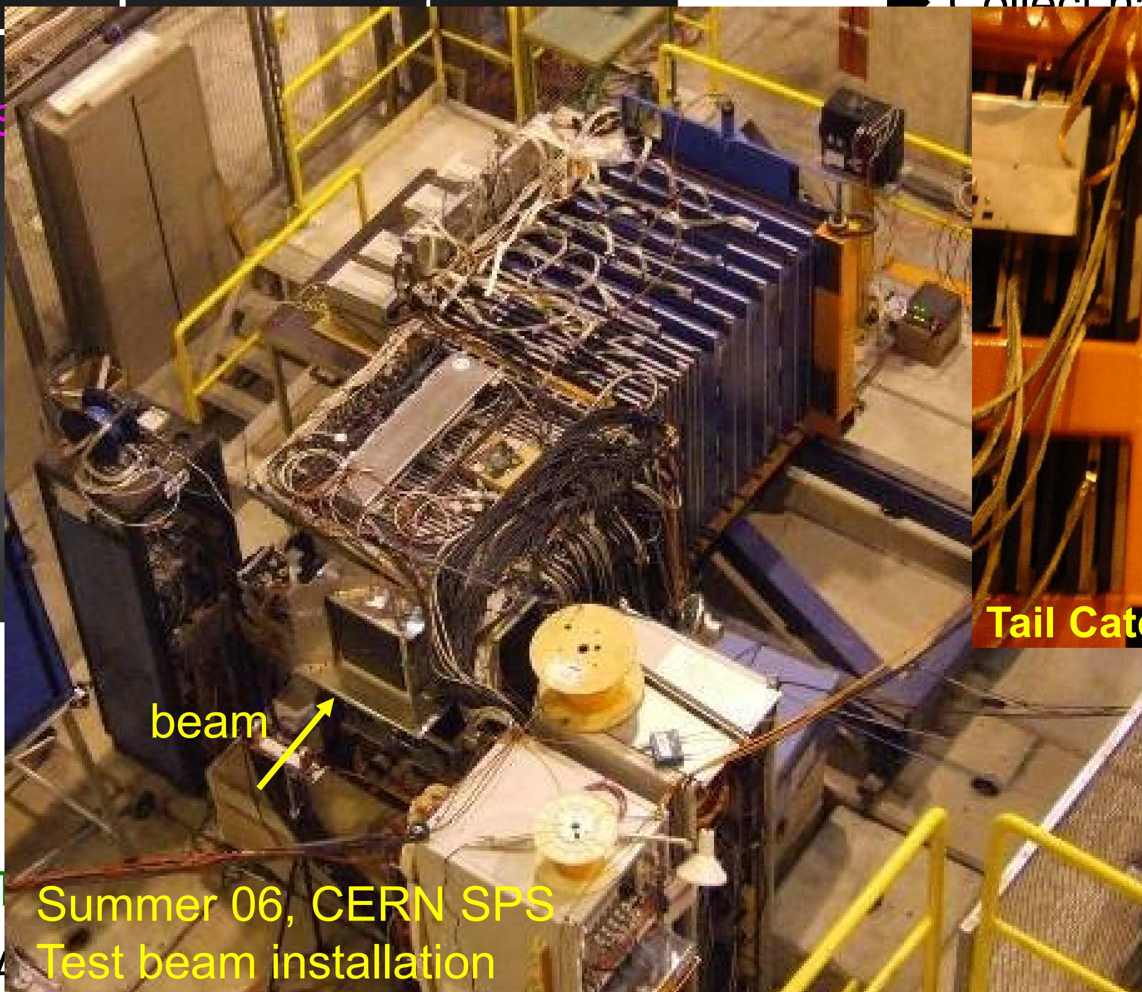


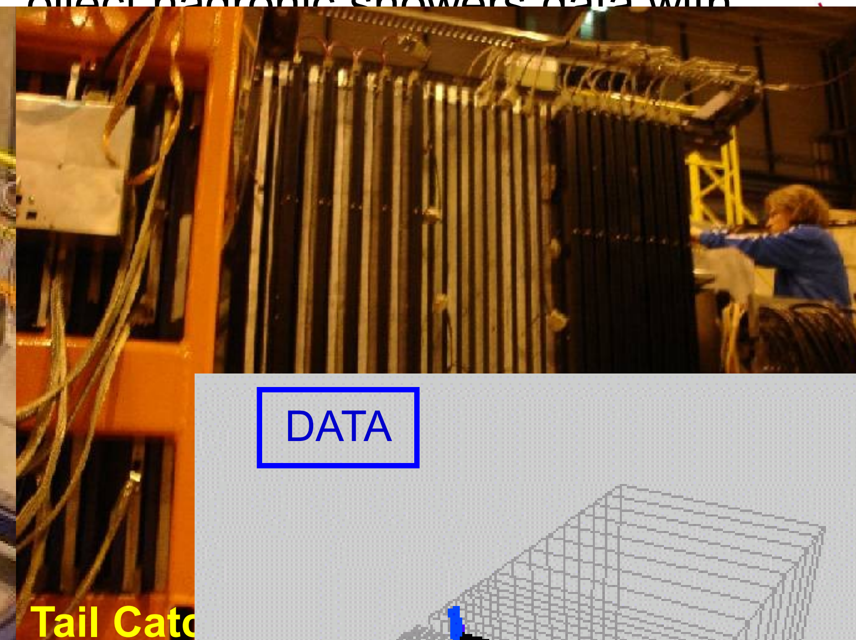
The prototype calorimeter system for ILC

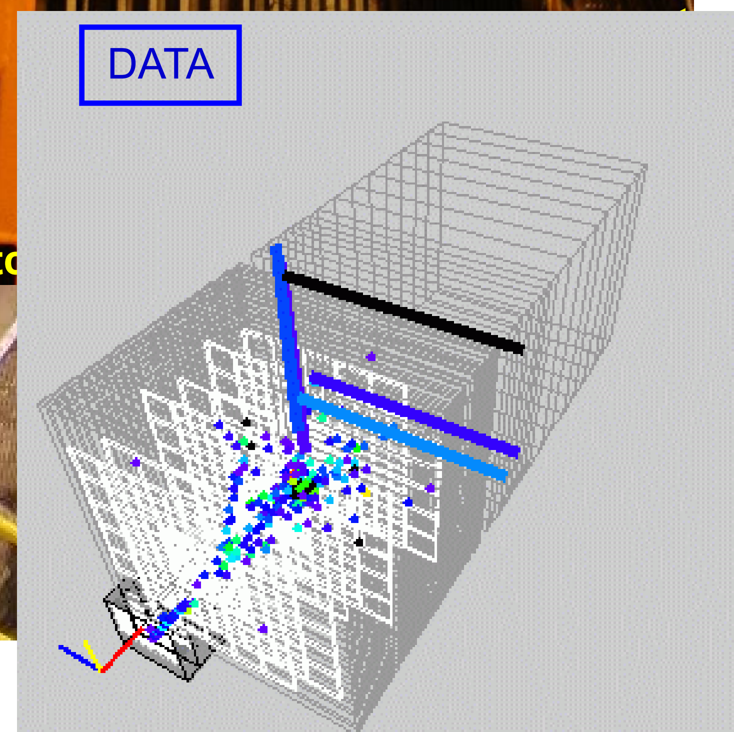


➔ Establish the technology
➔ Collect hadronic showers data with









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

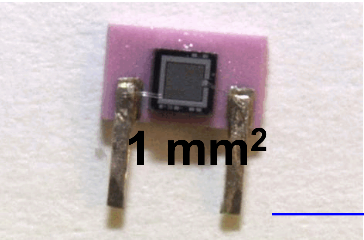
SiPM pioneering experience

Calorimeter for ILC

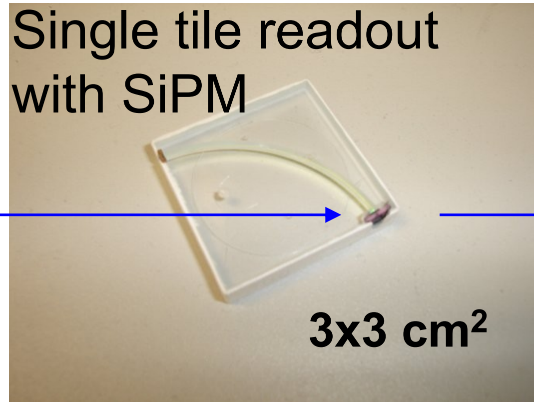
A crucial technology improvement to calorimetry

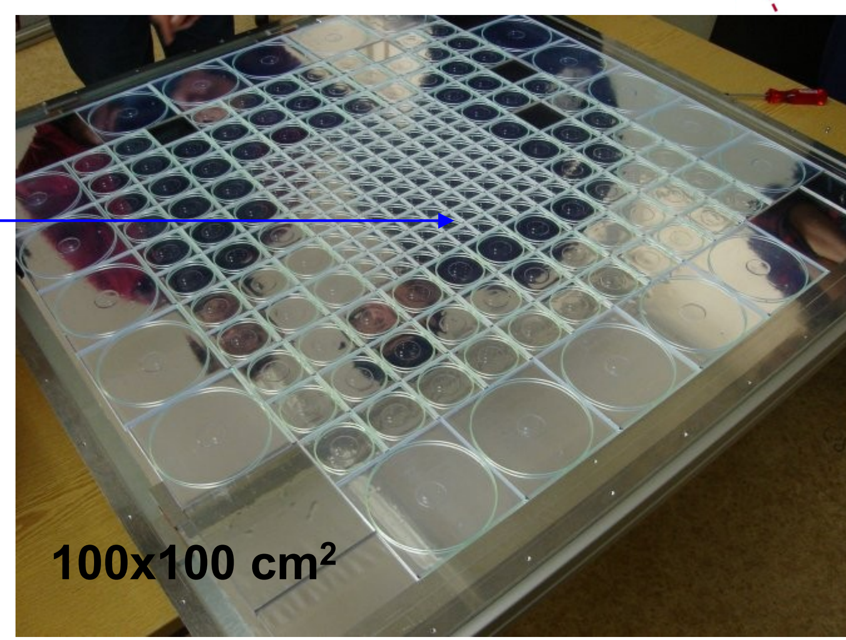
Electron

Hole

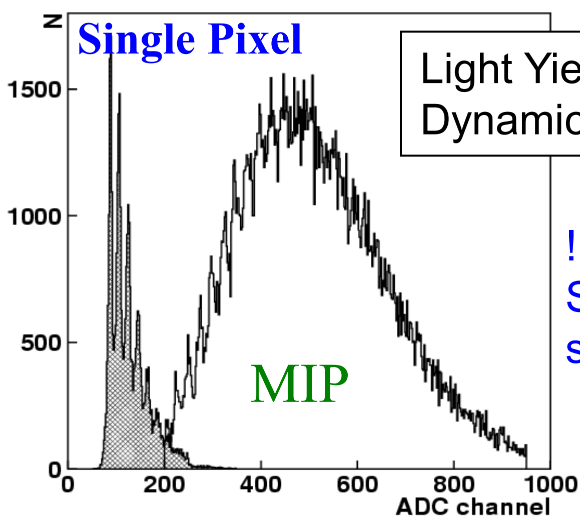


Si-based = insensitive to magnetic field!





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



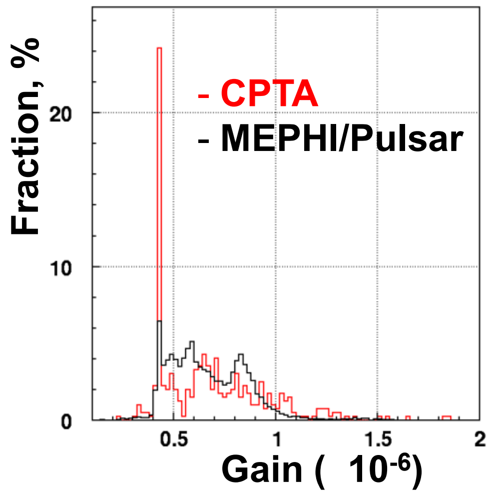
Light Yield = 15 pixels / MIP
Dynamic range ~ 100 MIPs

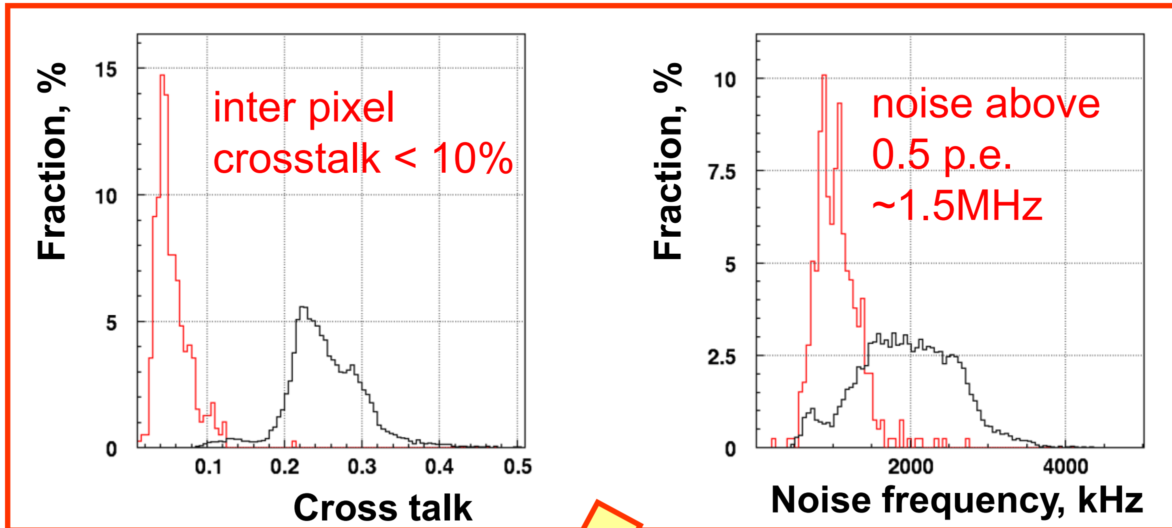
!! auto-calibration of SiPM gain from single-pixel spectra

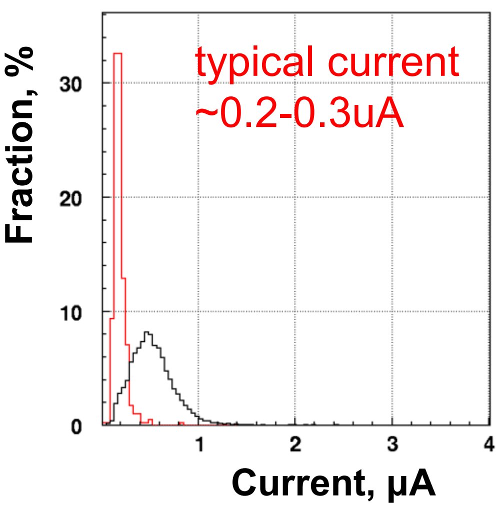
Allows unprecedented high granularity

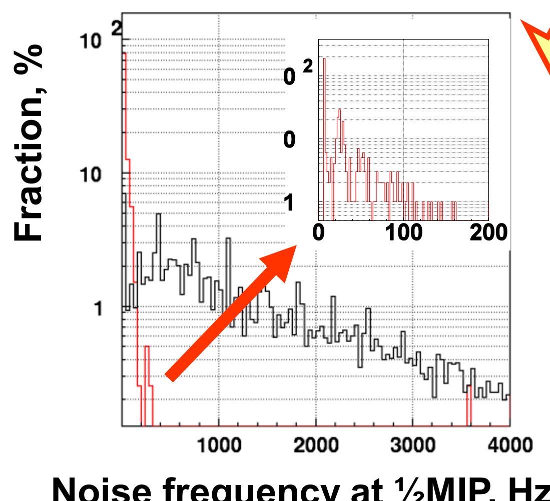
38 layers (~4.5 λ)
Scintillator – Steel sandwich structure (0.5:2cm)

Push for improved SiPM parameters

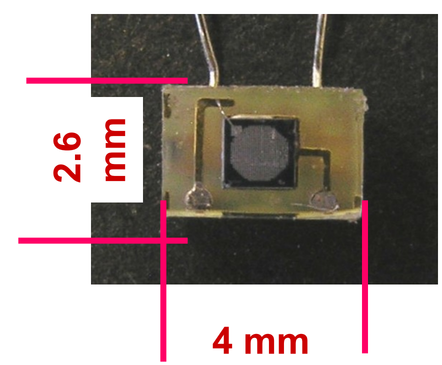




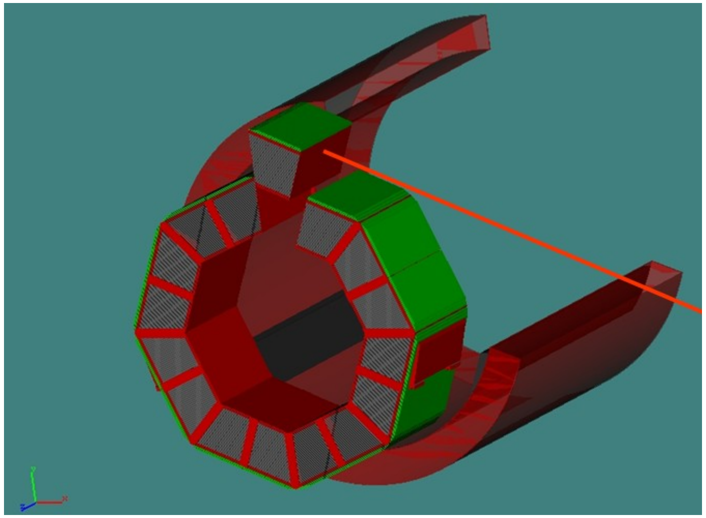


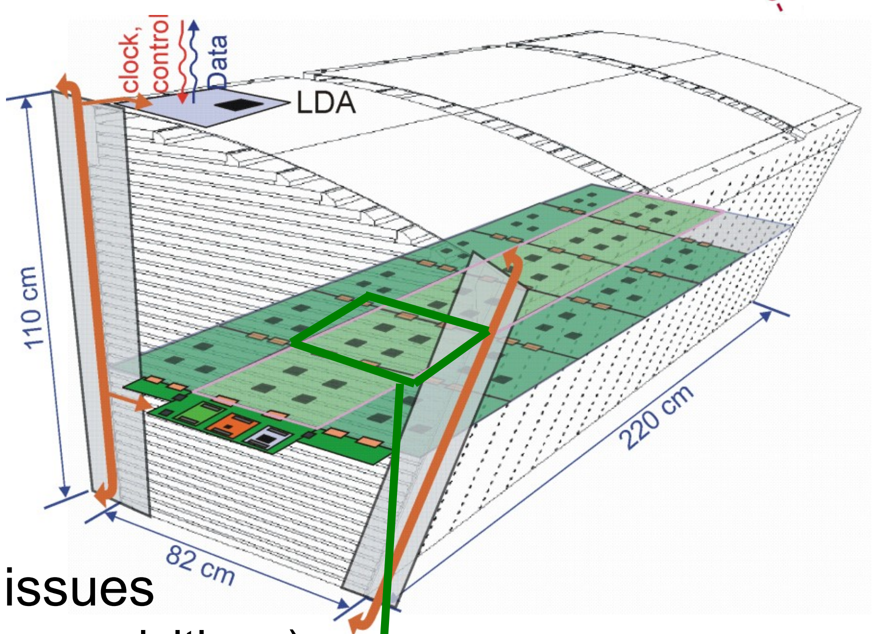


CPTA SiPM

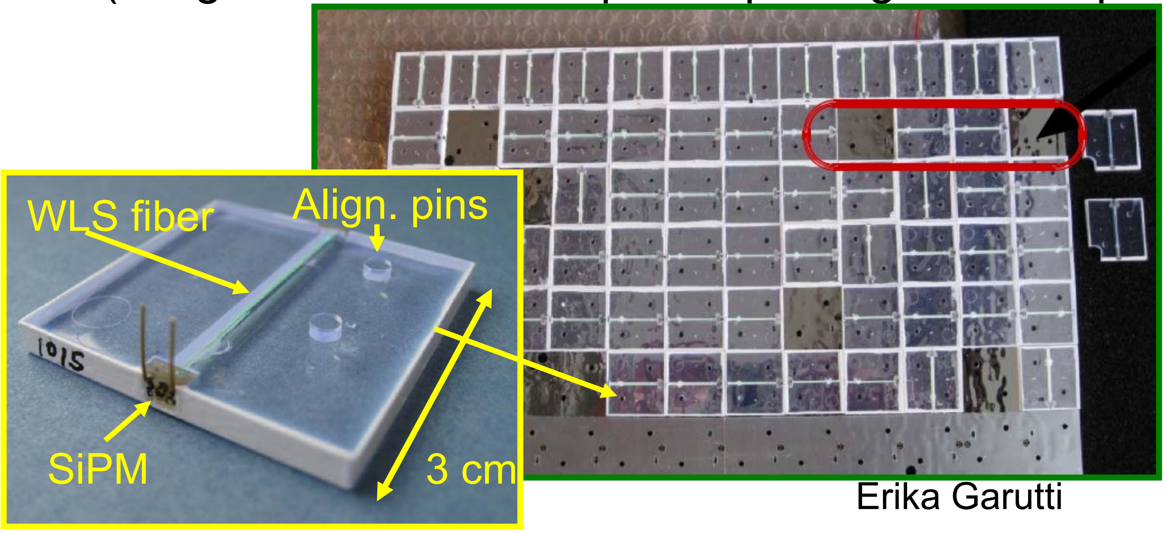


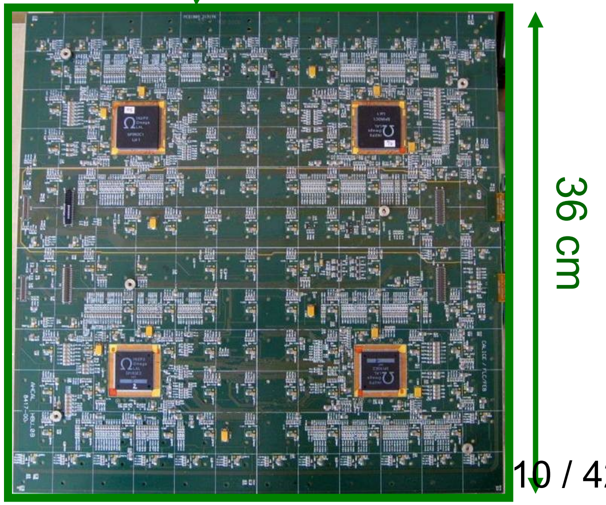
Next step towards a ILC detector



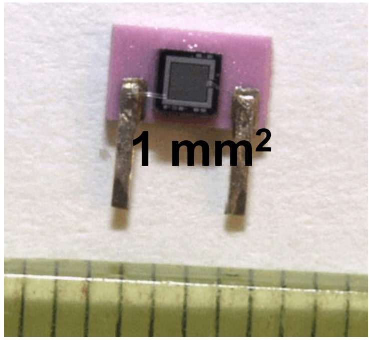


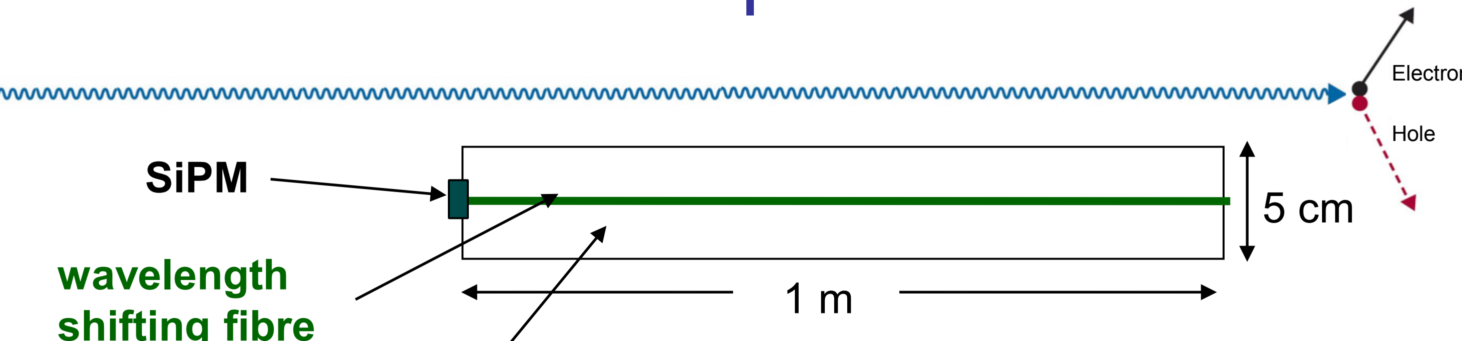
➔ Work on integration and scalability issues
(integrated electronics/ power pulsing/ data acquisition..)





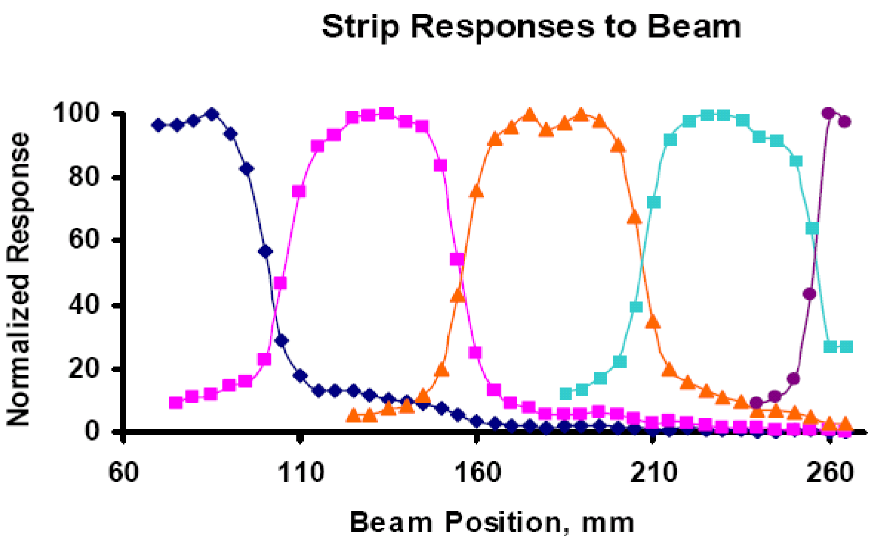
SiPM r/o for scint. strip: muon detector

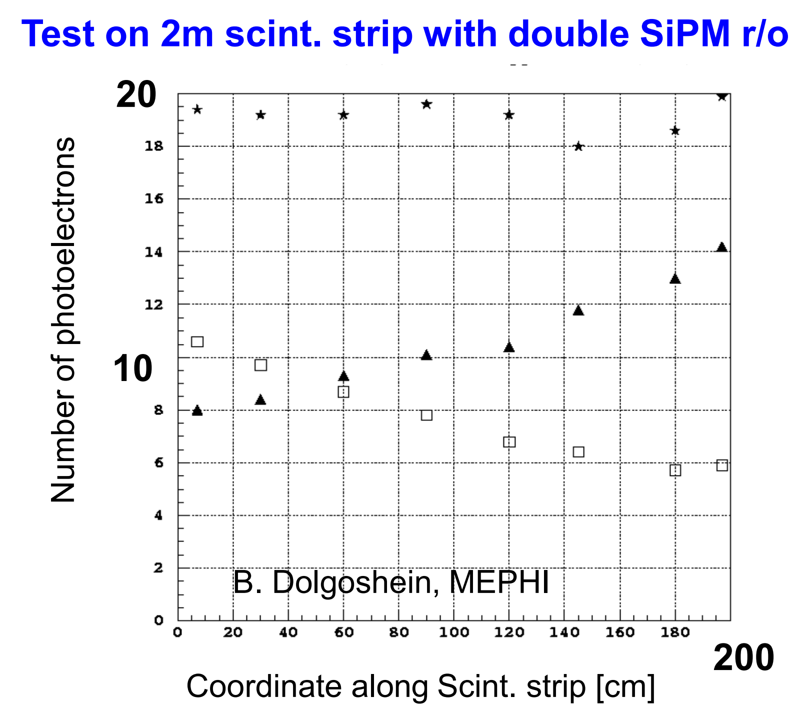




1x1m² prototype tail catcher and muon tracker with 320 strip readout with SiPM (MePHI/Pulsar)

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



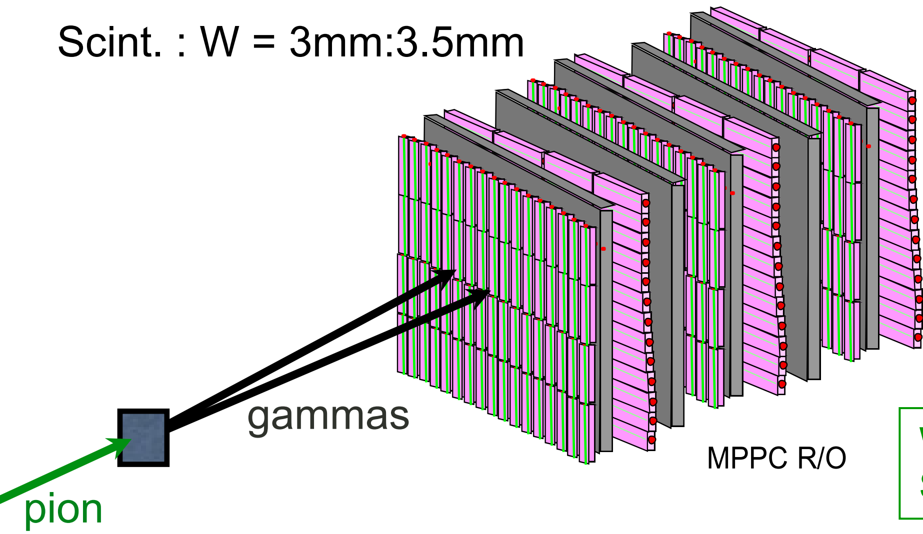


High granularity EM Calorimeter for ILC

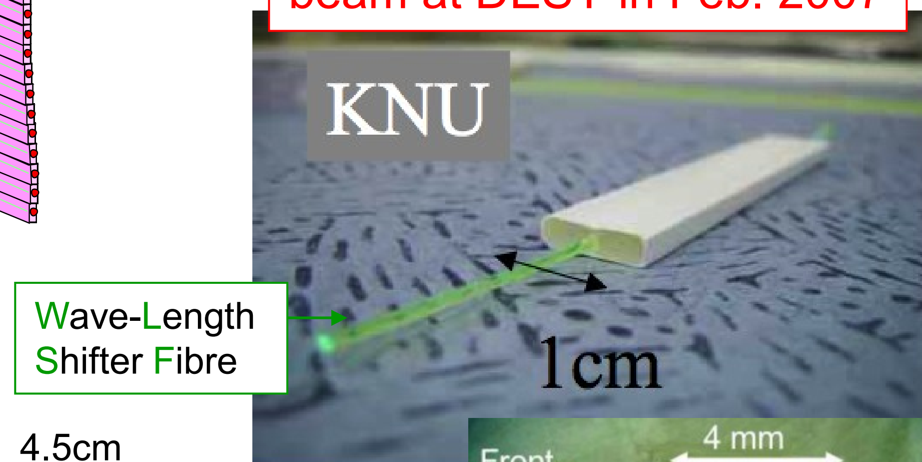
Scintillator – Tungsten sandwich structure

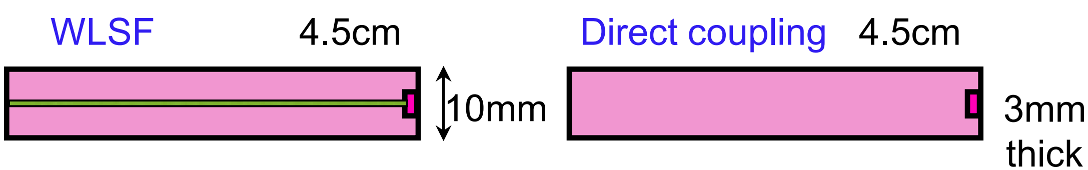
from T. Takeshita, Shinshu Uni., Japan

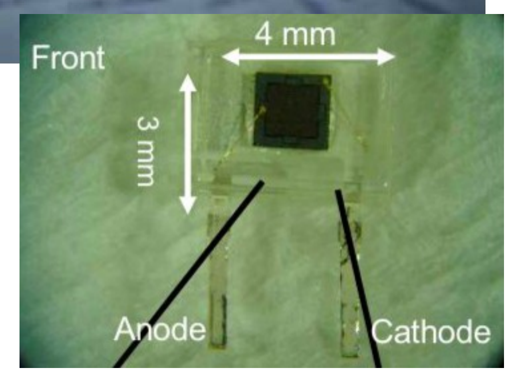
Scint. : W = 3mm:3.5mm

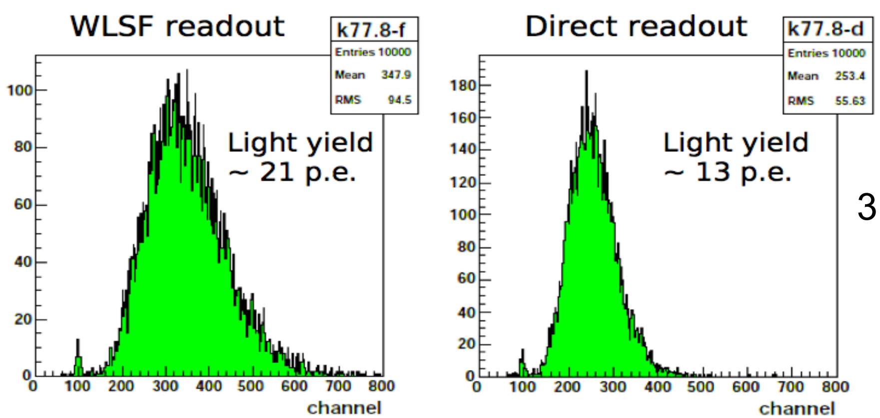


Fist prototype ready for test beam at DESY in Feb. 2007





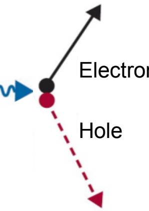




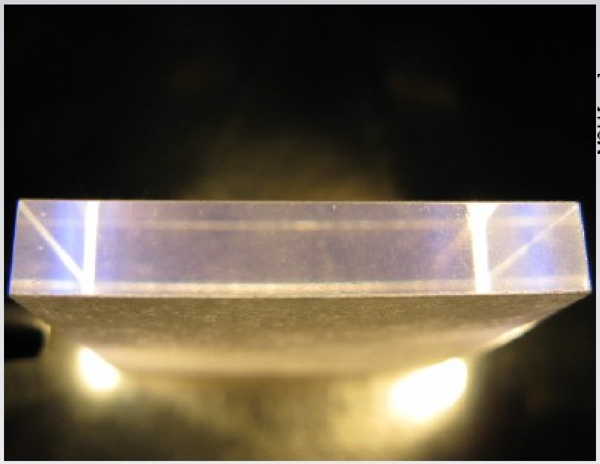
3M R.M.F.

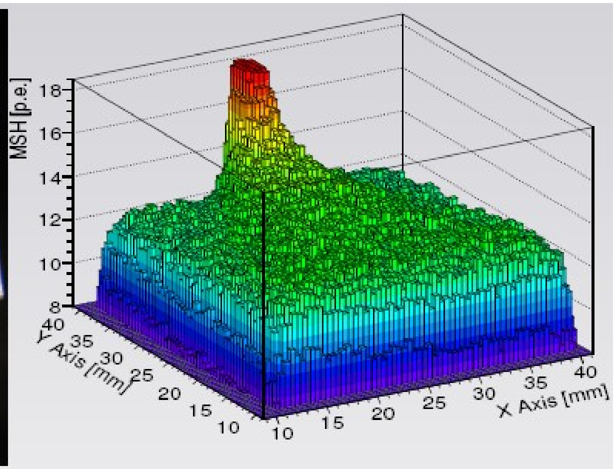
Multi-Pixel Photon Counter from Hamamatsu

Direct coupling of SiPM to scintillator



Coupling via WLS fiber has the advantage of higher uniformity:
- light from the whole tile is collected and guided to the SiPM

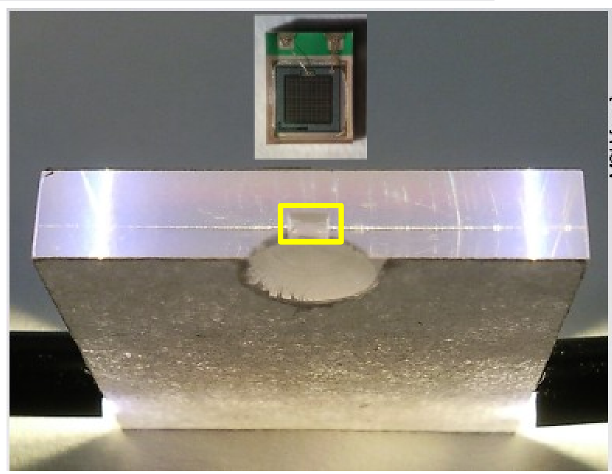


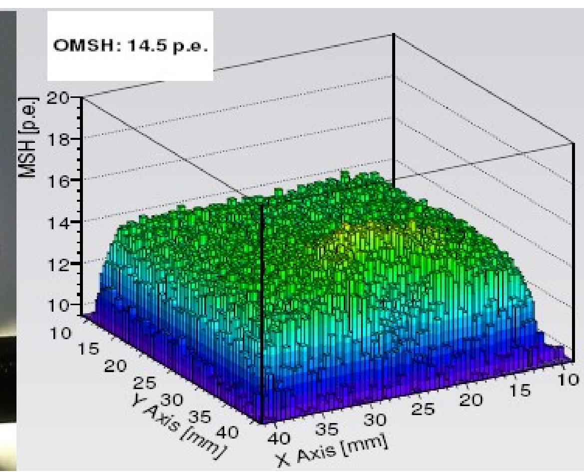


Direct coupling
➔ non-uniformity of light collection

Special optimization of SiPM coupling through a dimple in the scintillator allows to recover good uniformity

(study: MPI Munich)

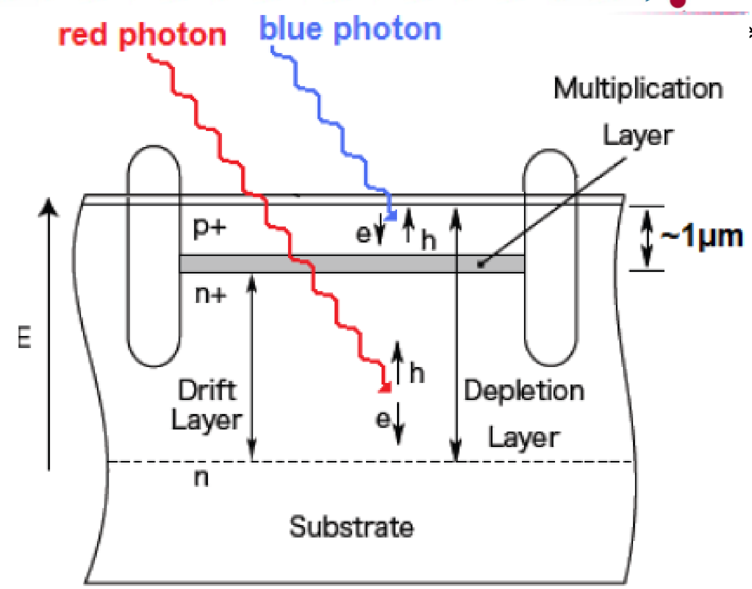




Photon Detection Efficiency (PDE)

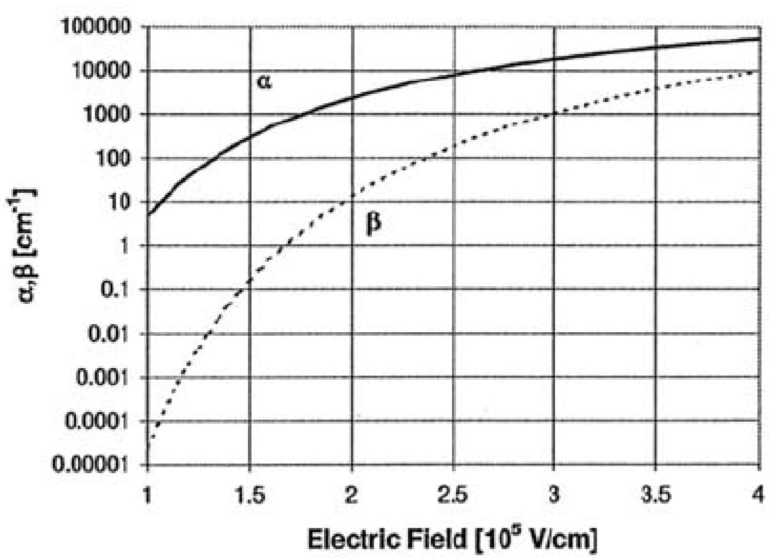
•The triggering probability depends on the position where the primary electron-hole pair is generated and it depends on the overvoltage.

•Electrons have in silicon a better chance to trigger a breakdown than holes. Therefore a conversion in the p+ layer has the highest probability to start a breakdown.



Wavelength dependence of PDE linked to depth of penetration of photon

Blue (470nm)	**0.6 µm**
Green (525nm)	**1.2 µm**
Yellow (590nm)	**2.2 µm**
Red (625nm)	**2.9 µm**



Ionization coefficients for electrons (α) and holes (β) in silicon

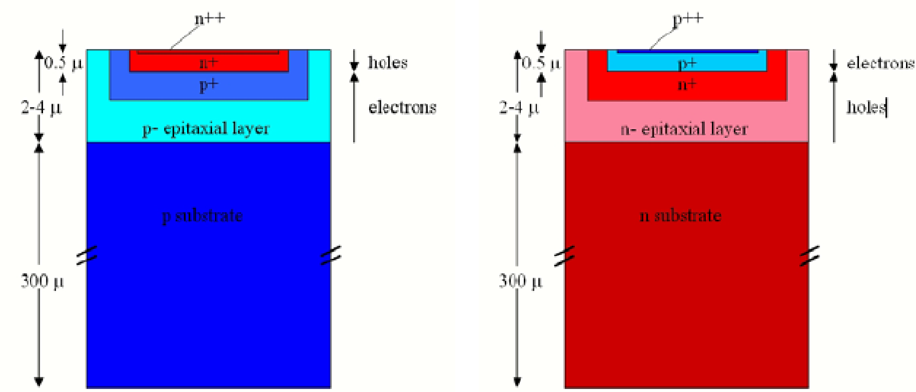
Photon Detection Efficiency (PDE)

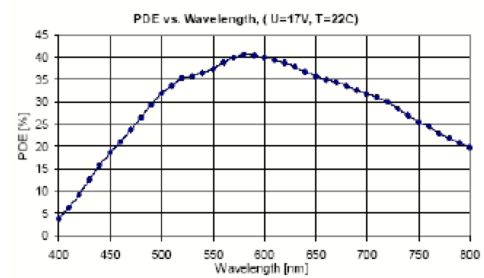
•Photons with short wavelengths will be absorbed in the very first layer of Si and create an electron-hole pair.

•In a structure with a n-type substrate (right) the electrons drift towards the high field of the p-n junction and trigger with high probability a breakdown.

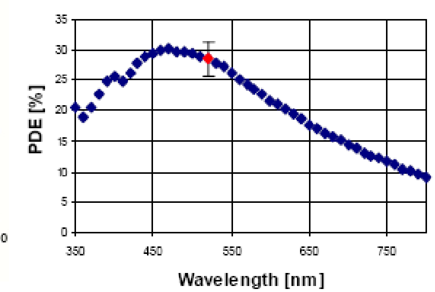
•A G-APD made on a n-type substrate will be preferential sensitive for blue light.

•A G-APD made on a p-type substrate (left) needs long wavelengths for the creation of electrons in the p-layer behind the junction and will have the peak sensitivity in the green/red.





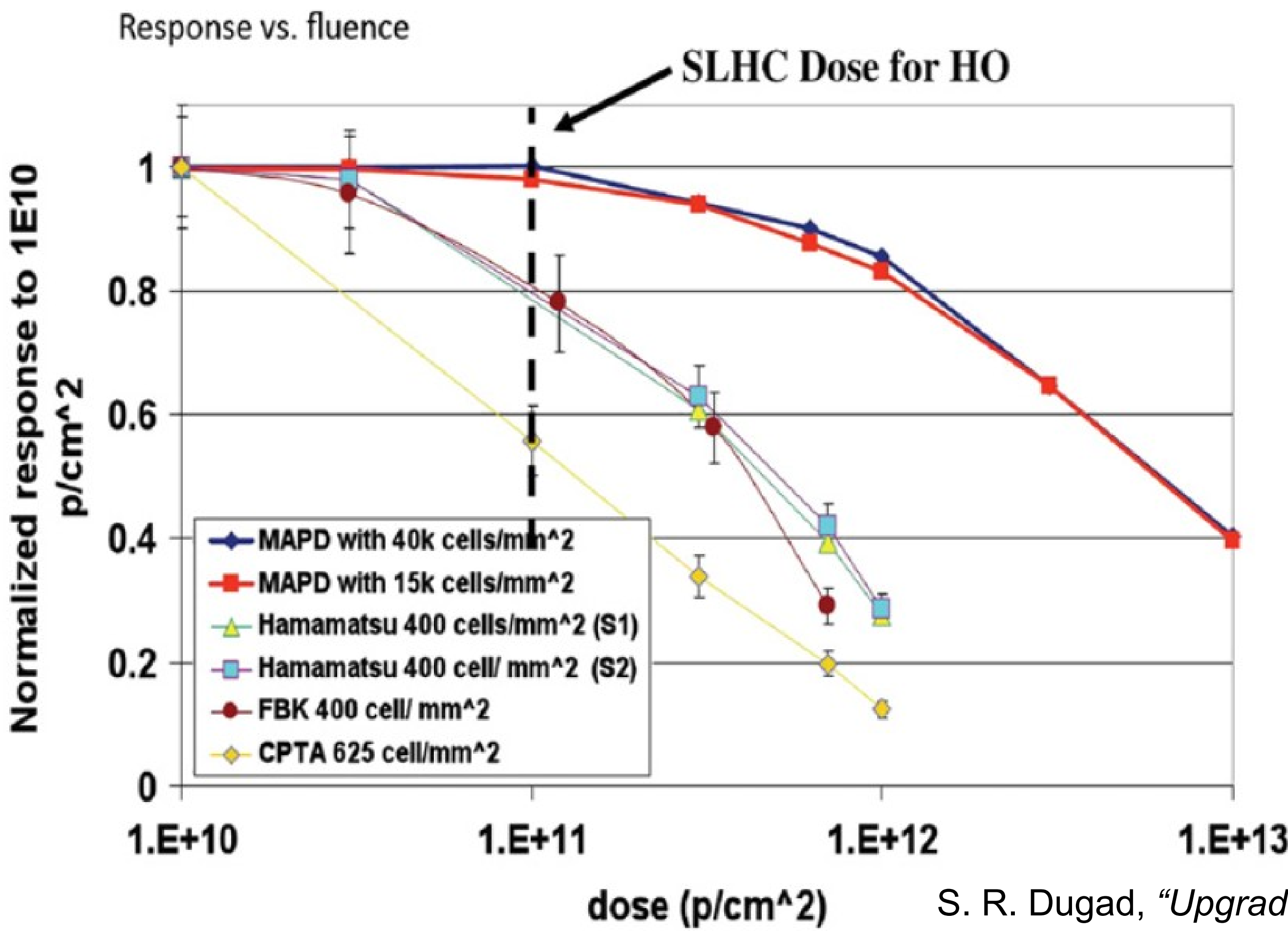
Photonique/CPTA
(SSPM_0710G9MM)



Hamamatsu
(PSI-33-050C)

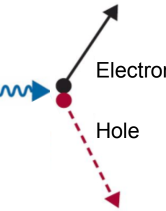
Radiation hardness issue

Relevant for applications in rad. hard environment: what is the SiPM tolerance

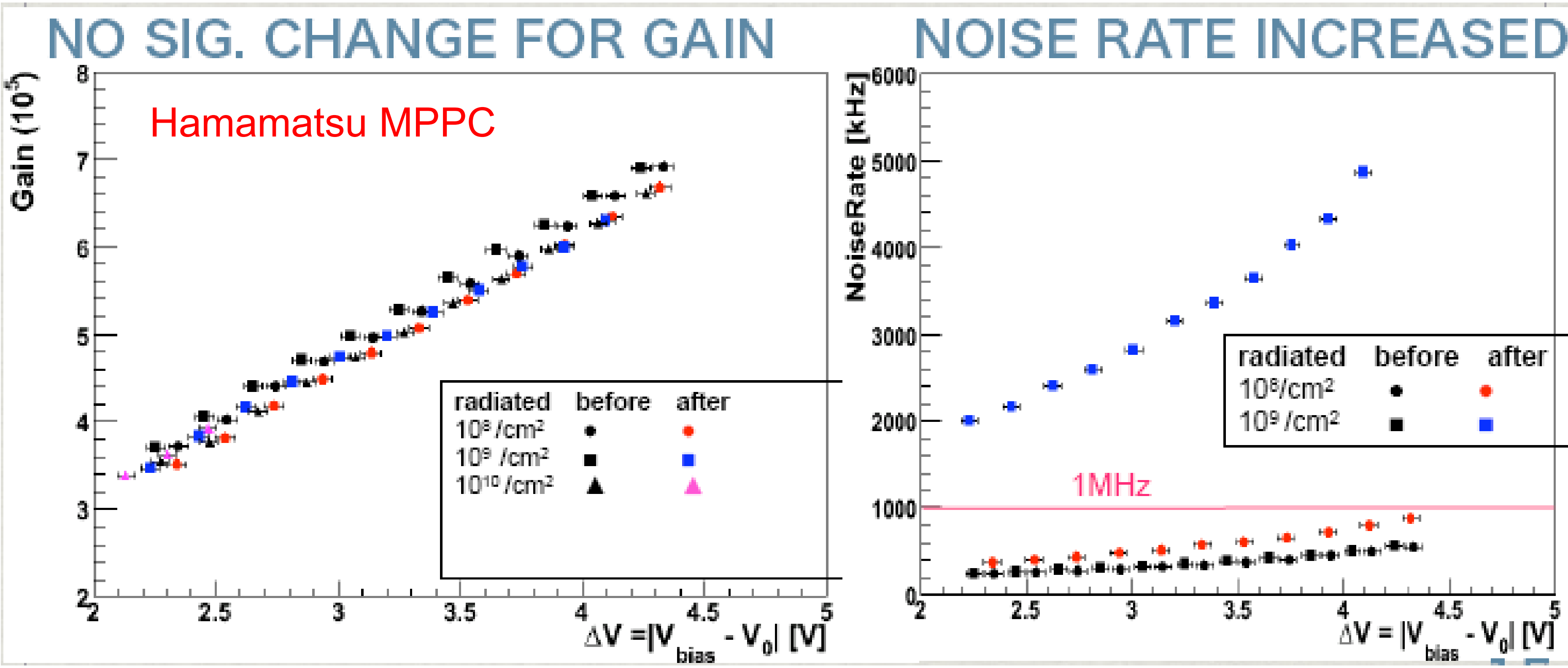


S. R. Dugad, *"Upgrade plans for hadron calorimeter in the CMS detector", Nucl. Inst. Meth. A (2010),* doi:10.1016/j.nima.2010.02.216

SiPM radiation hardness



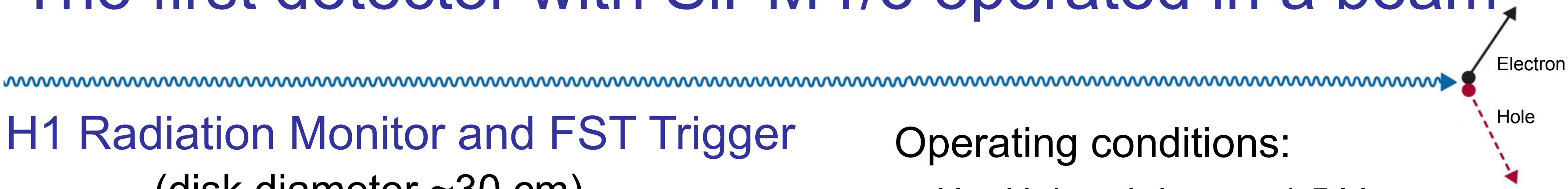
Neutron irradiation by reactor (E_n 0.8-1.2 MeV)



Only thermal noise increase after 10^9 n/cm², no other significant effects on Gain and response function

Gamma irradiation with ^{60}Co ➔ noise below MHz till 60Gy

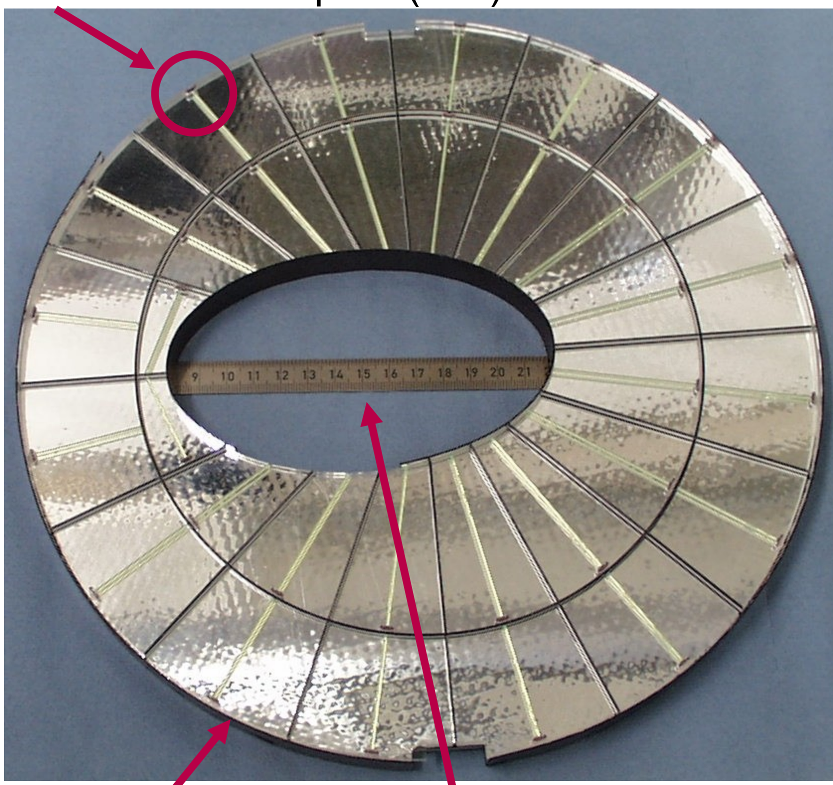
The first detector with SiPM r/o operated in a beam



H1 Radiation Monitor and FST Trigger

(disk diameter ~30 cm)

Silicon Photomultiplier (x32)



Organic Scintillator
(1 cm thickness)

HERA Beam-pipe

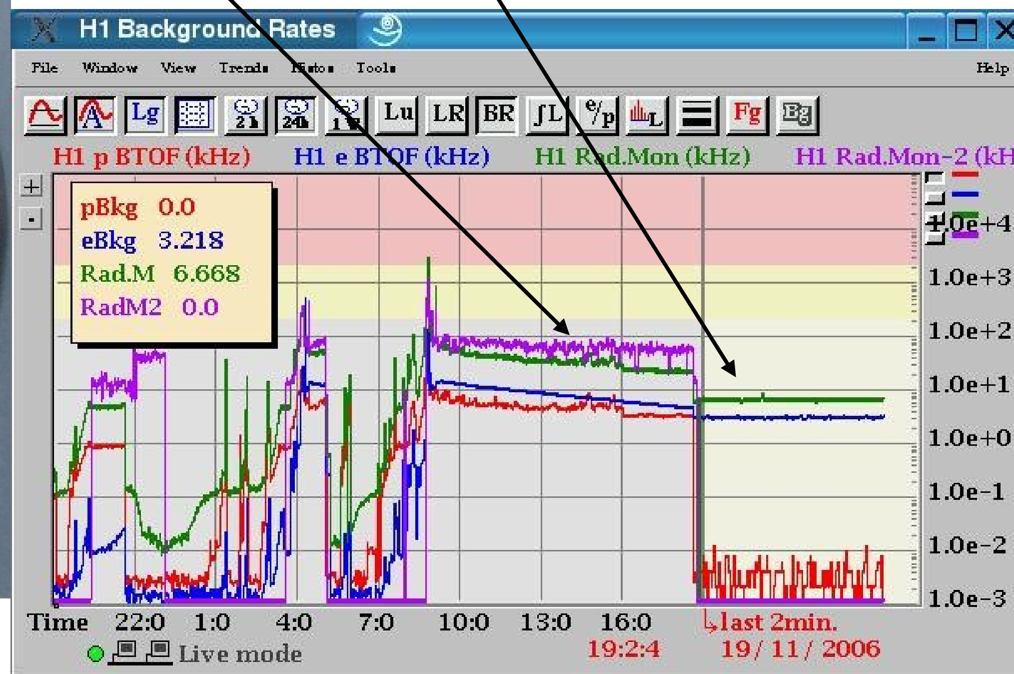
Operating conditions:

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

H1 shift tool (java applet):

Single SiPM count rate/bunch X-ng

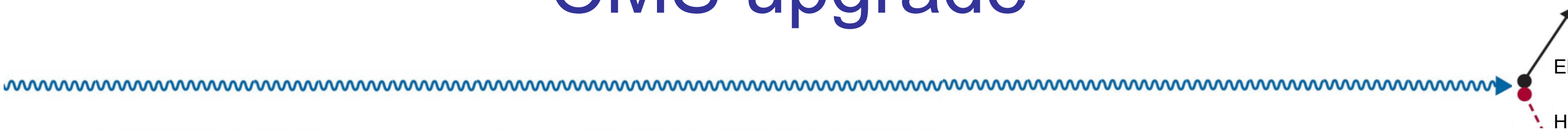
count rate of whole detector / bunch X-ng

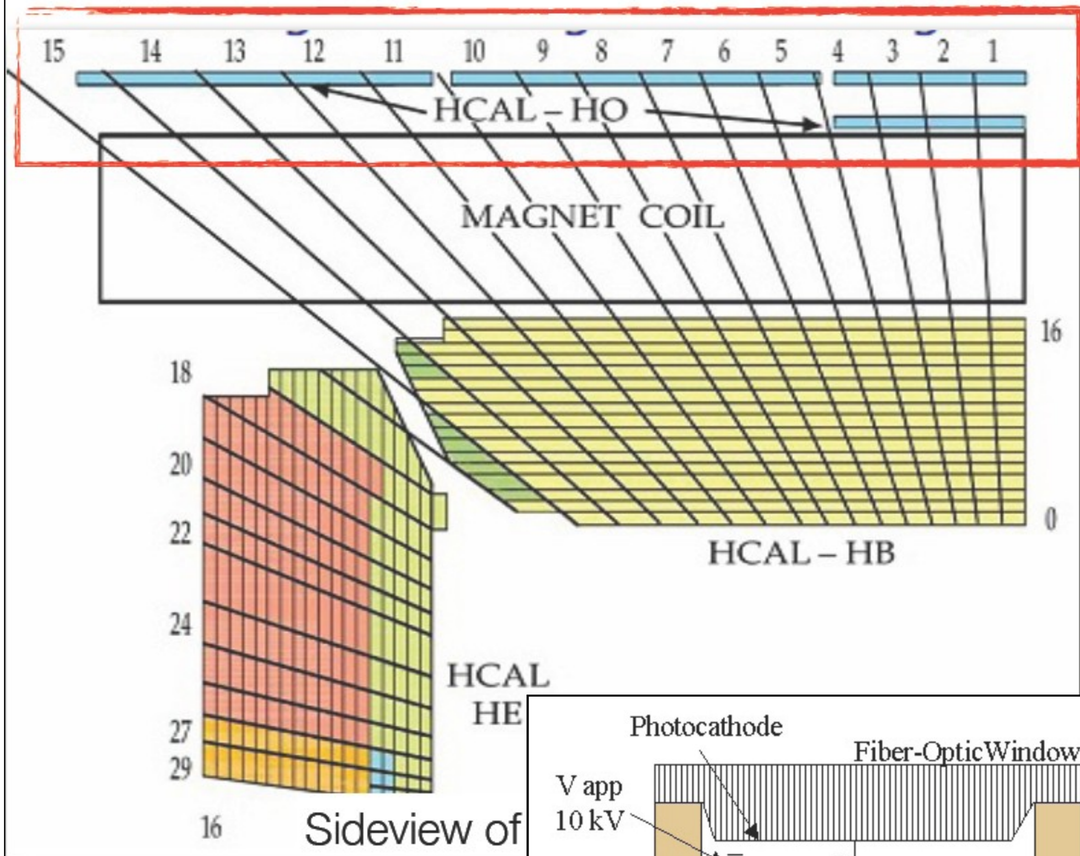


14-15 March 2011

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

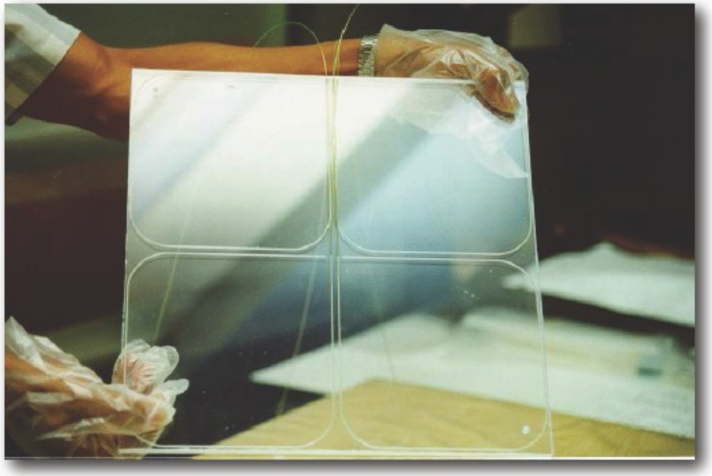
CMS upgrade

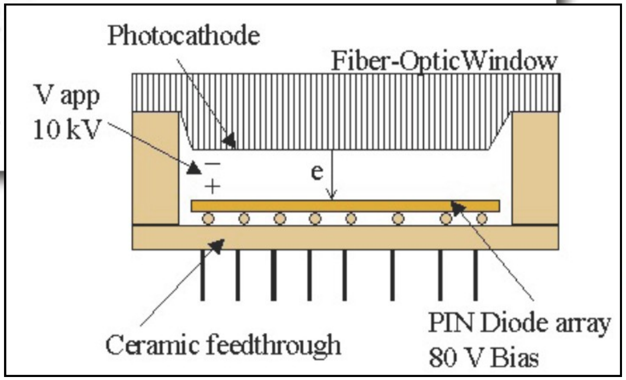




- **Outer hadron calorimeter** measure leakage for high energy particles
- Scintillation light collected and guided to **hybrid photo detector (HPD)**

H0 scintillator tile with wavelength shifter fiber

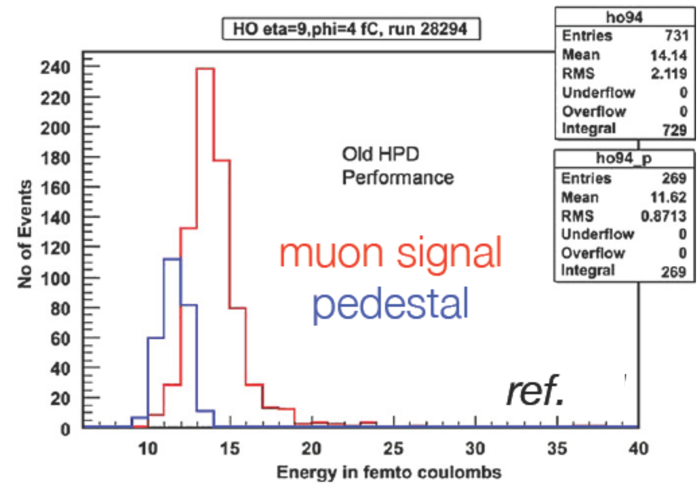


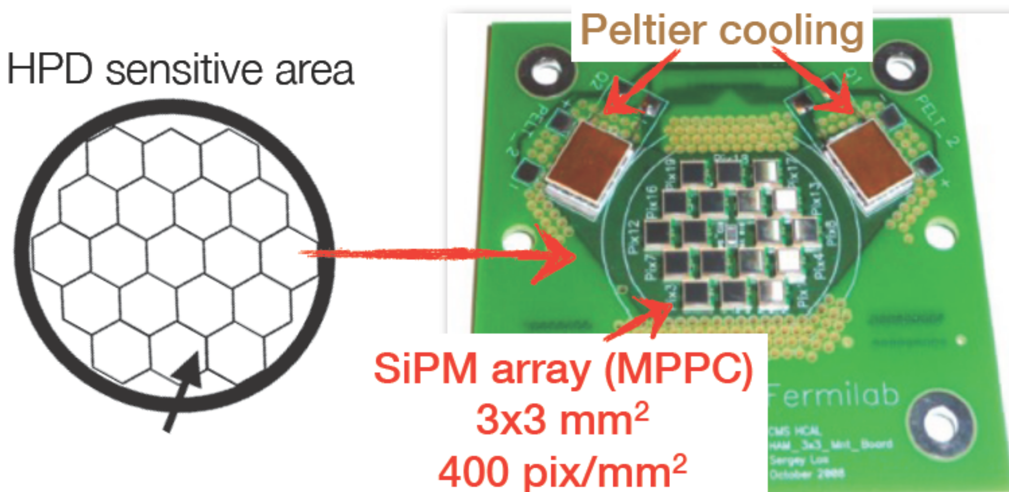


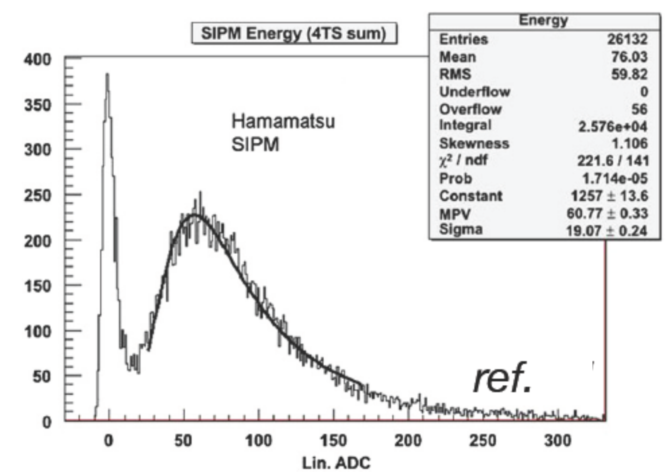
HPD: combination of phototube + photodiode → Gain ~ 2000-3000

H0 with SiPM readout

- ~ 2012 - **Exchange all HCAL outer HPDs with SiPMs**
  - 10x Improved signal to noise ratio in magnetic field
  - Better sensitivity to leakage
- ~ 2015 - **Exchange Barrel and Endcap HPDs with SiPM (~100K)**
  - Longitudinally segmented readout “High granularity” → Software compensation







Jim Freeman, *“Silicon Photomultipliers in the CMS calorimeter”*, Nucl. Inst. Meth. A 617 (2010) 393-395

Large scale application of SiPM

T2K experiment

ND280
off-axis near
detector

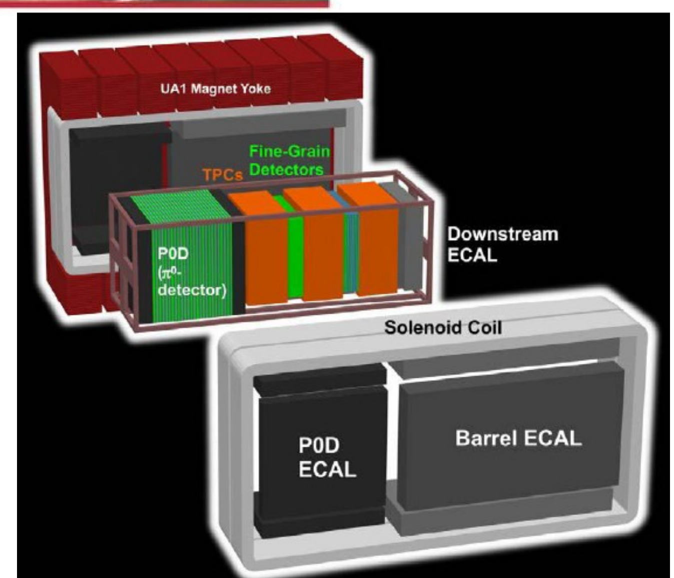
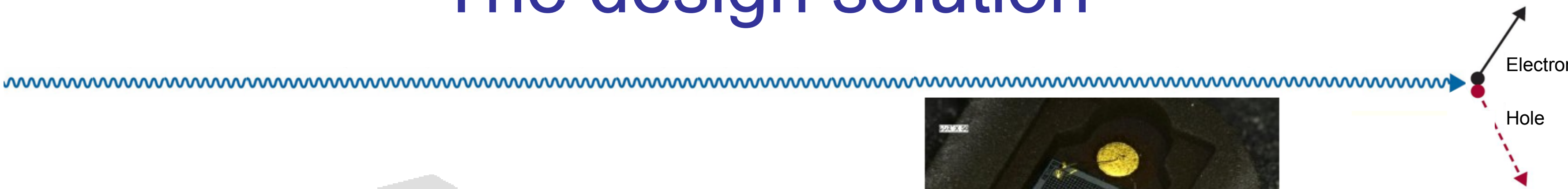
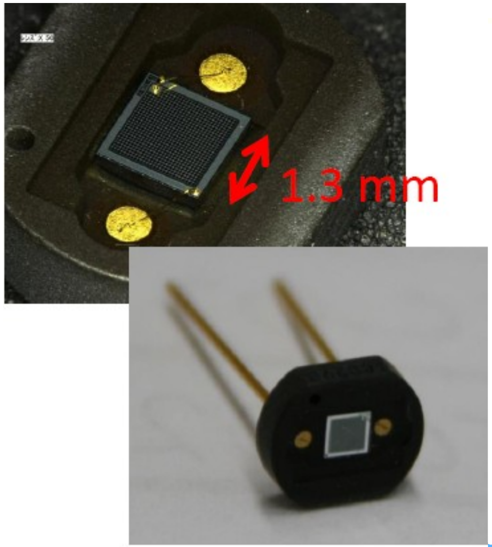


Photo-sensor requirements:

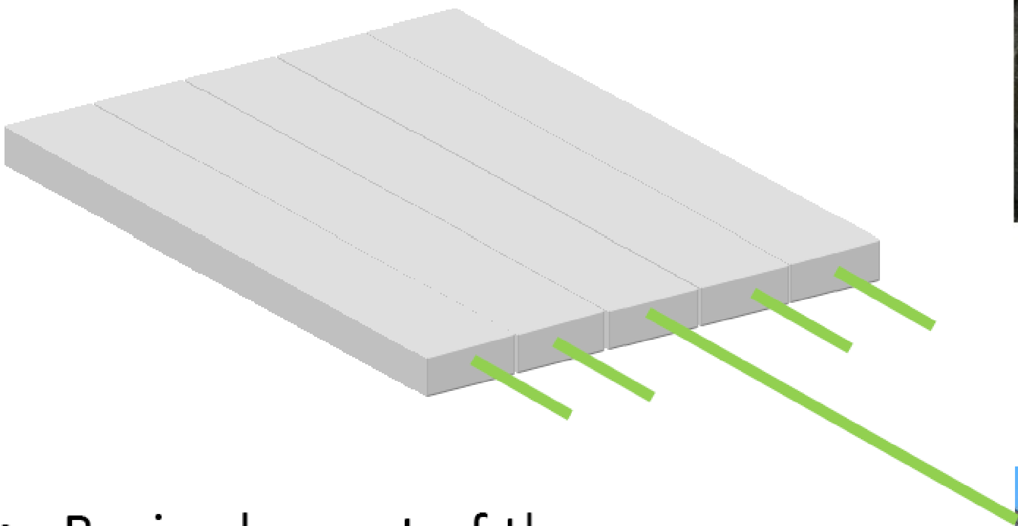
- Operational in magnetic field B=0.2T(UA1 magnet)
- Very tight space constraints ➔ compact
- Low light yield at the end of Y-11 fibre(λ_{att}= 3.5 m)
  ➔ PDE > PMT @ 550 nm
- Large number of channels (56000)

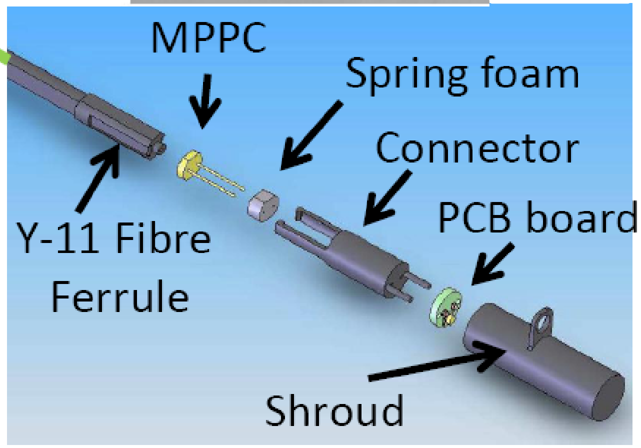
The design solution





MPPC

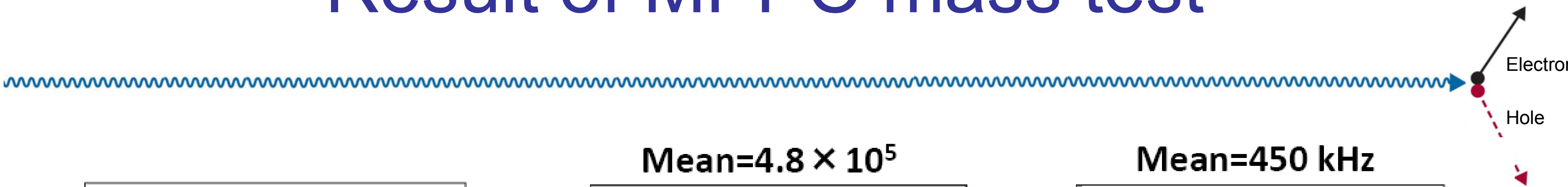


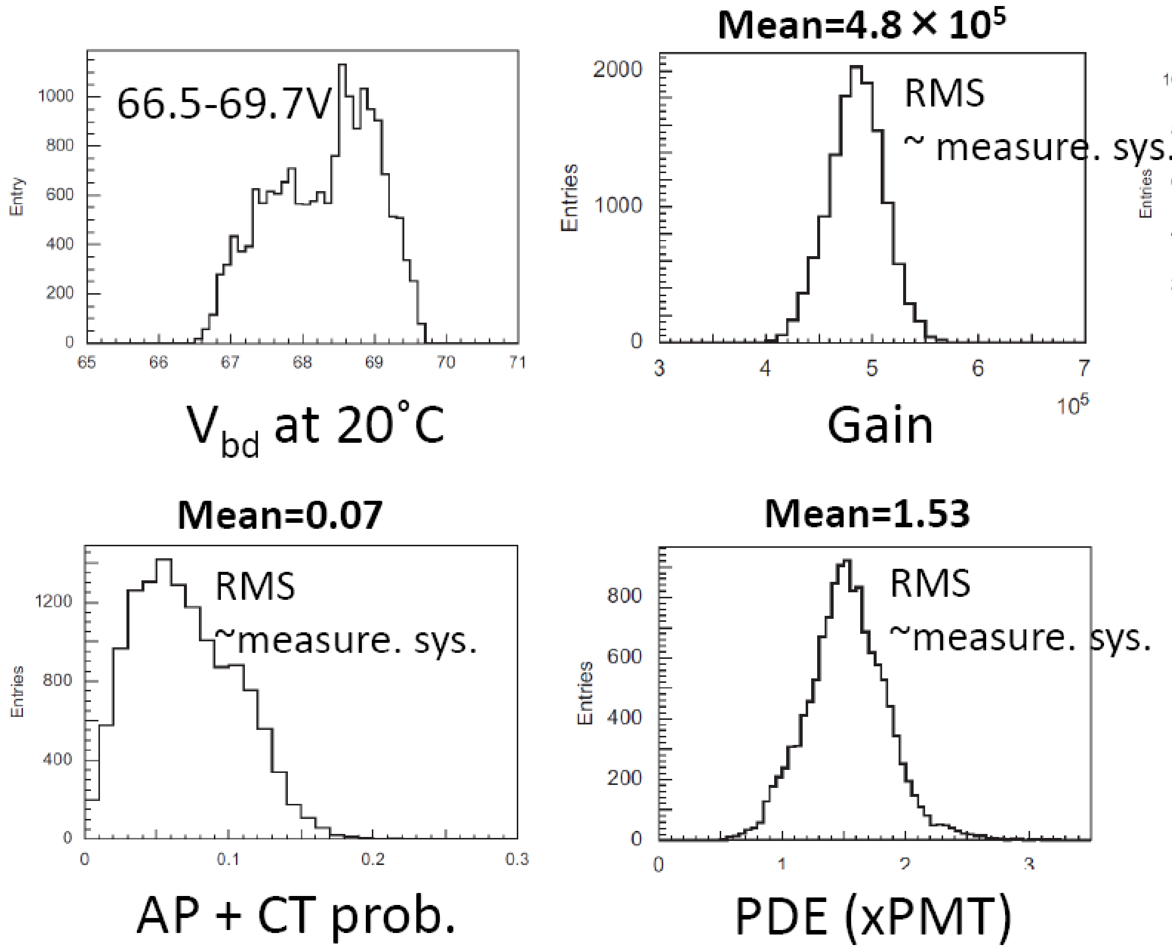


Connectors for P0D/ECAL/SMRD

- Basic element of the near detector scintillator subsystem (INGRID, P0D, FGD, ECAL, SMRD)
  - Extruded scintillator bar with embedded Y-11 fibre read out by individual MPPC in coupler
  - 56000 channels in total

Result of MPPC mass test





ΔV = 1.0V and 20˚C

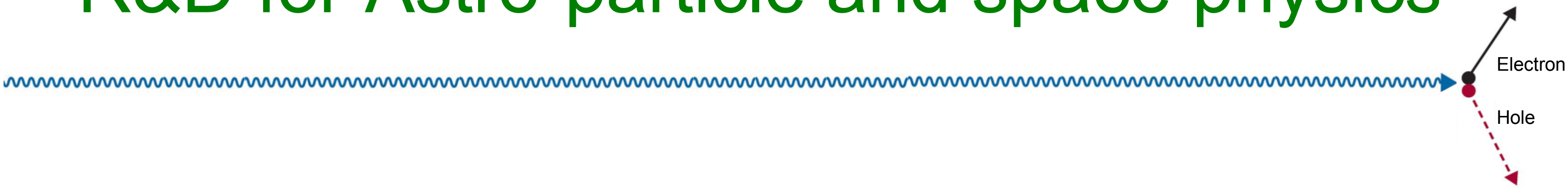
Failure rate < 0.05 %

M. Yokoyama et al.,
NIM A 622 (2010) 567-573

Device uniformity itself is considered to be much better.

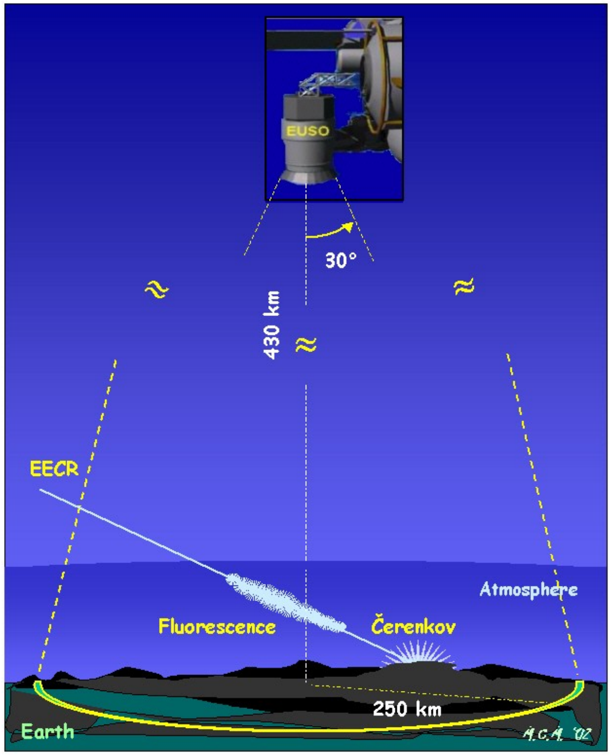
20

R&D for Astro-particle and space physics

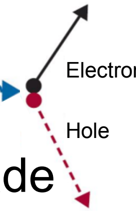


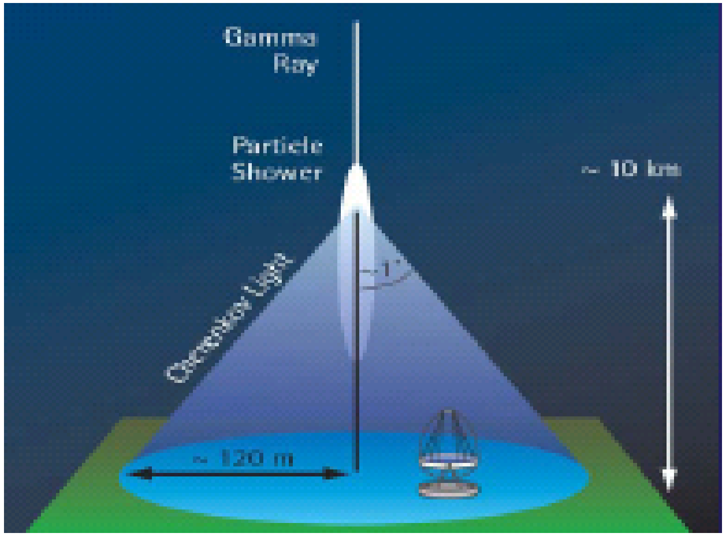
Key requirements for photo-detectors:

- ✓ 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

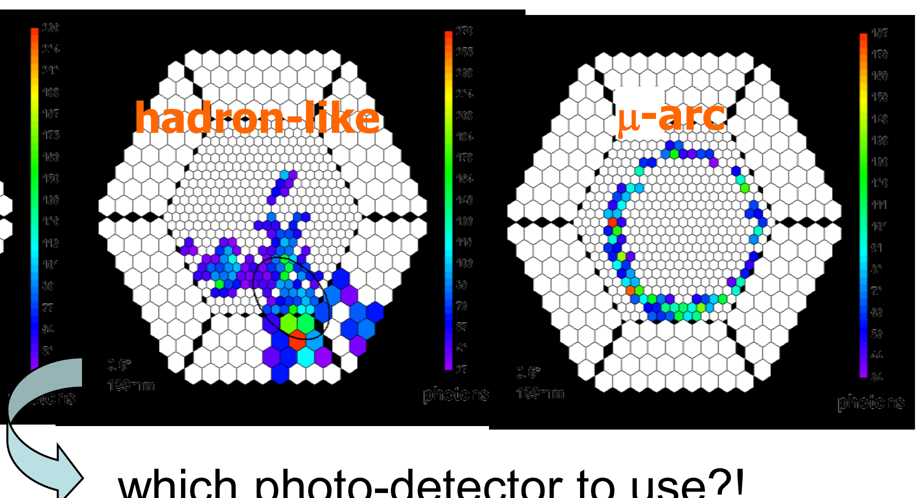


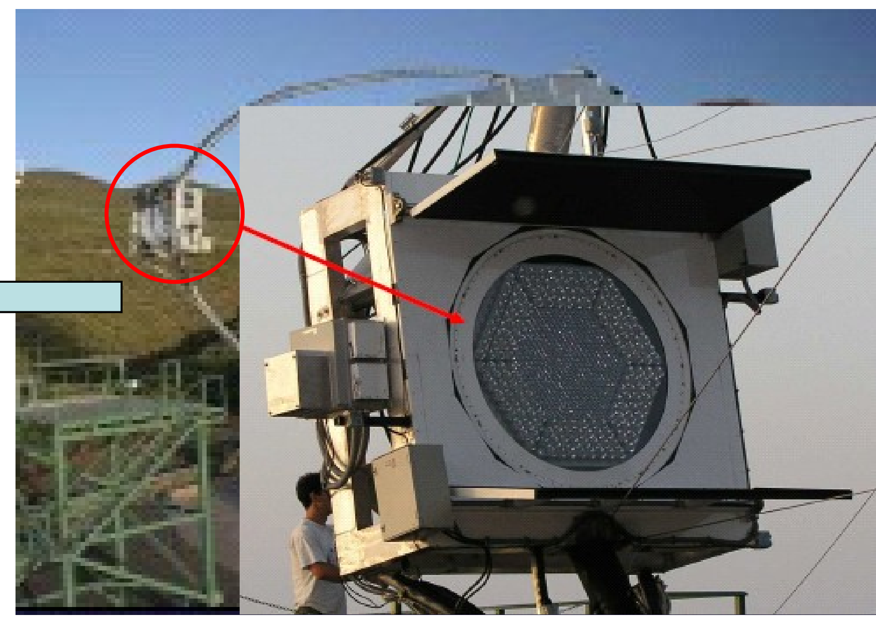


Gamma Ray induces electromagnetic cascade

➔ 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

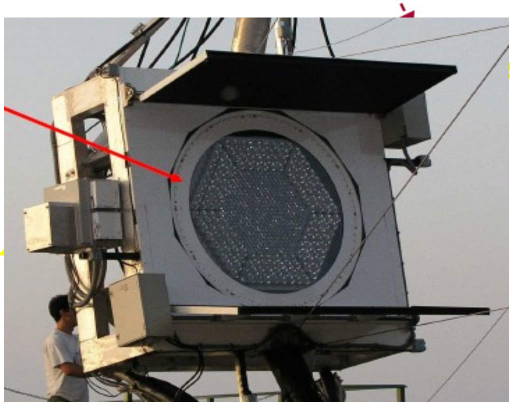




which photo-detector to use?!

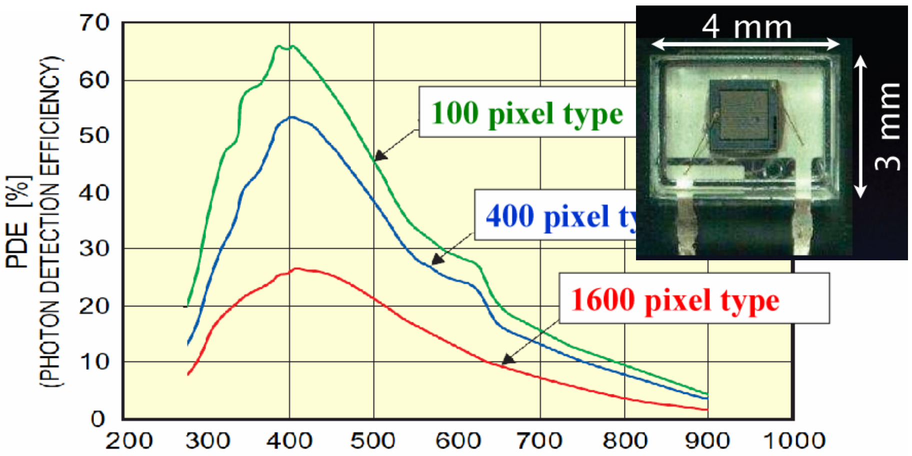
Ground based Gamma Ray Astronomy

Photo-detectors



CAMERA

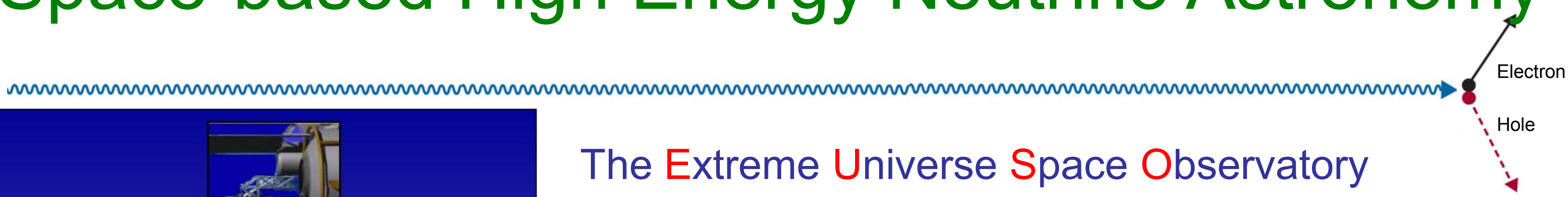
- Expensive
- Camera composed of 1000 – 2000 pixels ➔ use PMT for baseline (40% PDE)
- Fast timing response (~1ns) to cope with EAS Cherenkov flashes
- Electronics inside the camera
- Keep low weight

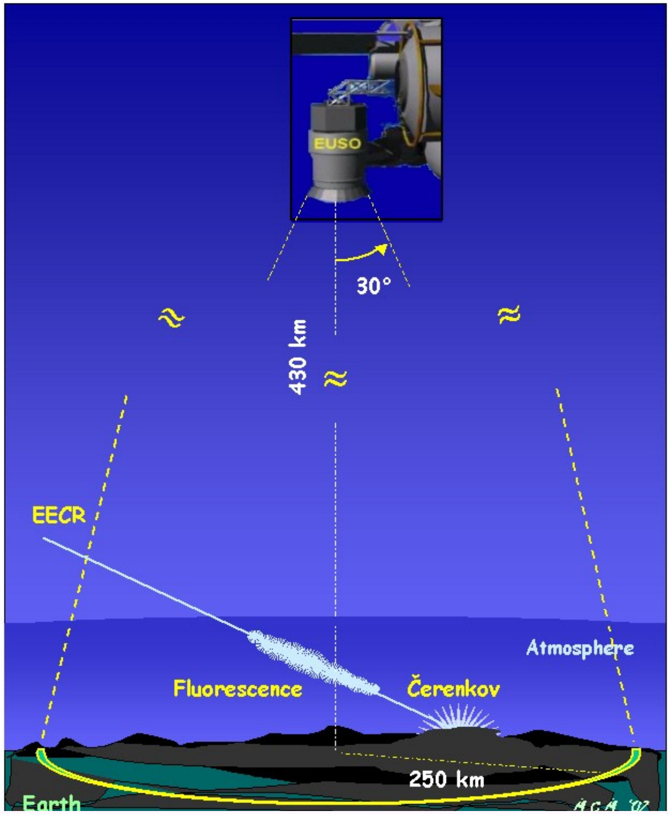


SiPM offer 60% PDE at 400nm
+ improvements with lower fill factor

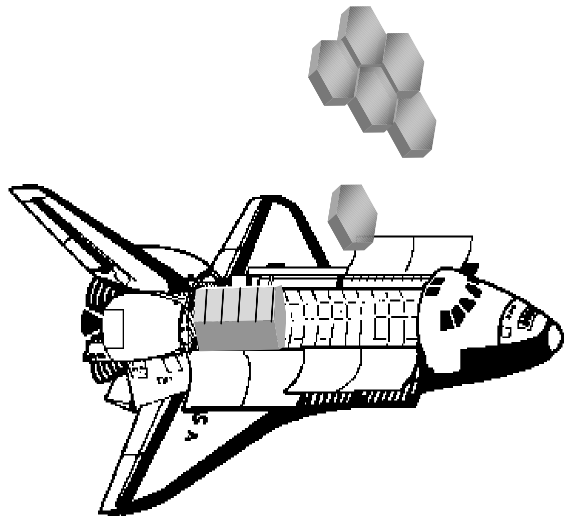
Next generation: **Cherenkov Array Telescope (CTA)**

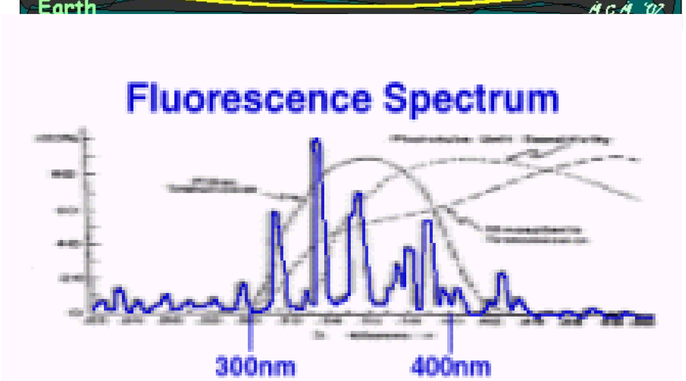
Space-based High Energy Neutrino Astronomy





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

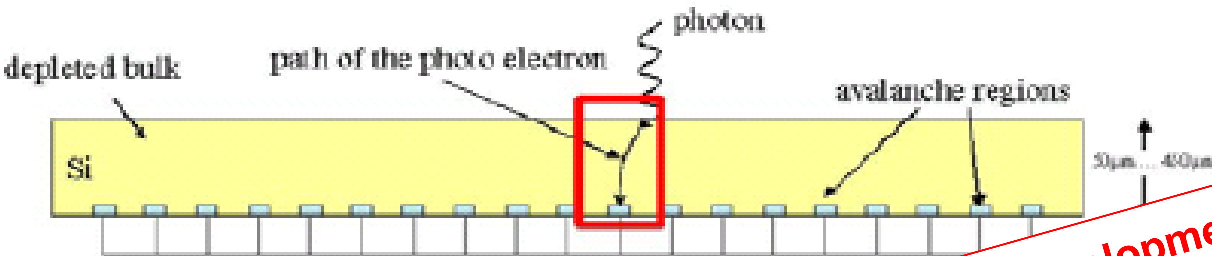
timing at the level of $\leq$10 ns (~few meters space resolution)

low single photoelectron dark rate (less than night sky rate)

SiPM for single photon counting
(MAGIC/EUSO)

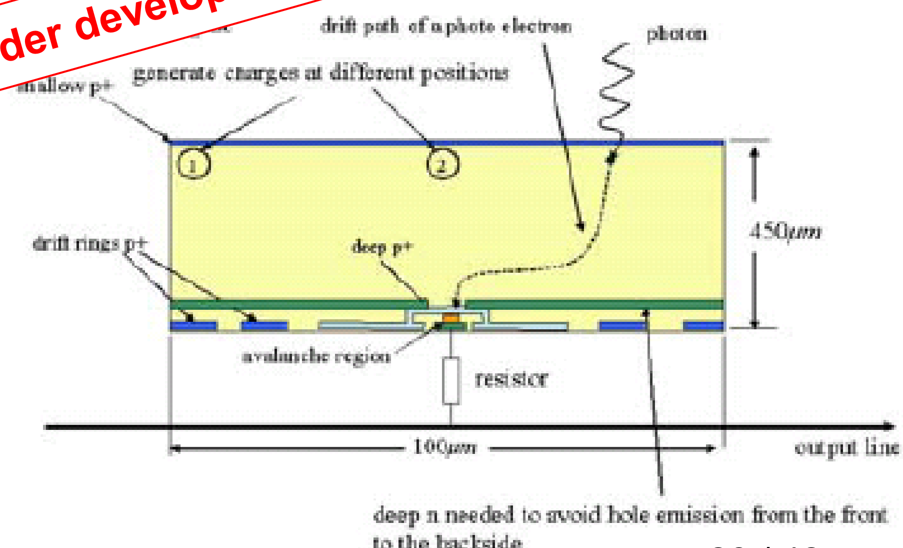
The requirements:
PDE > 40% ➔ lowers E threshold, allows overlap with other experiments
Larger size (up to 10x10mm^2 , 3x3 and 5x5 mm^2 under test)
➔ to cover large area detector
Alternative development: back-illuminated SiPM

Semiconductor laboratory (HLL), MPI and MEPHI, Moskow



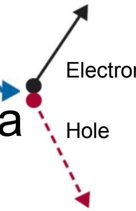
100μm Geiger drift cell:
-small C_{cell}
-full area efficiency

- 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

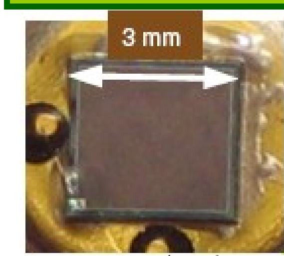
Positron Electron Balloon Spectrometer



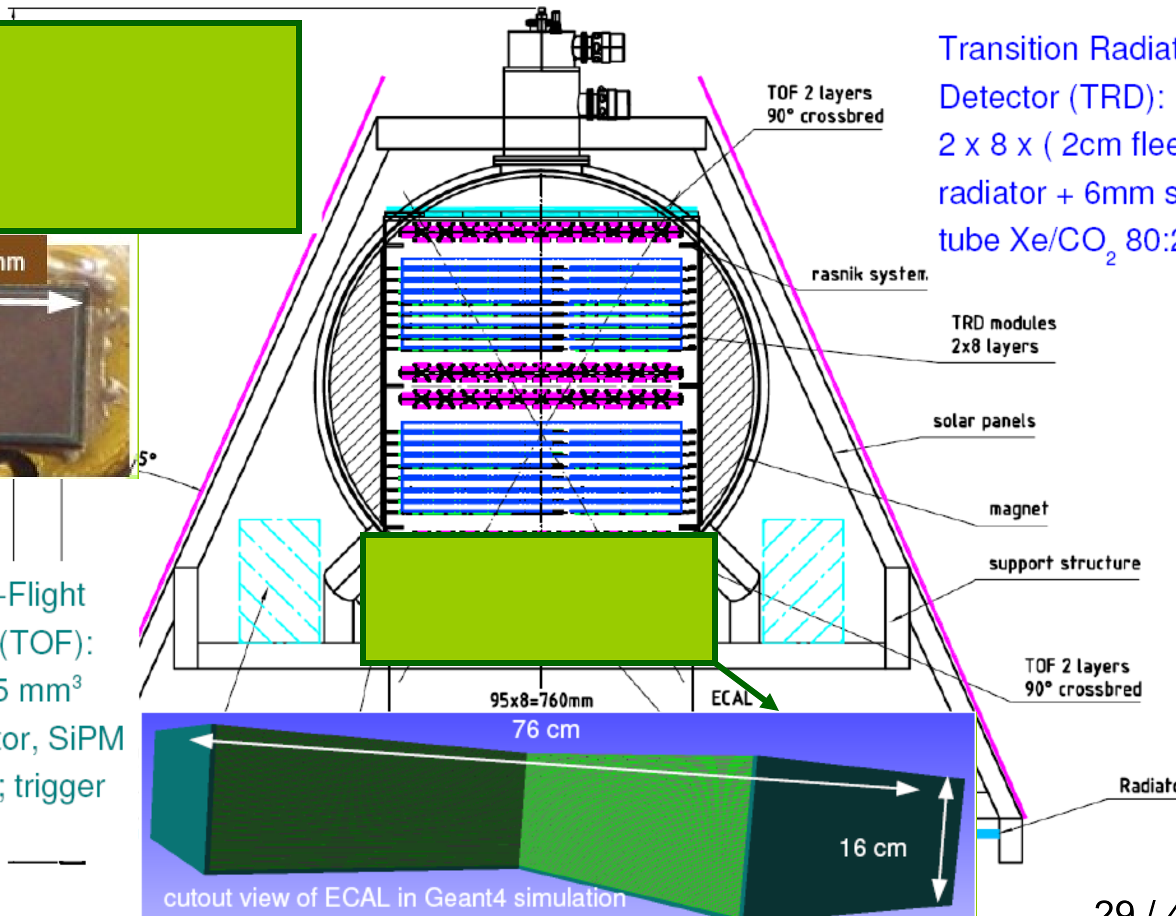
Goal: Measure the cosmic ray positron fraction with a balloon borne spectrometer

Motivation: Indirect search for dark matter

Requirements (calorimeter):
- Excellent proton suppression of O(10^6)
- Total payload weight < 2t
- Total power consumption < 1000W

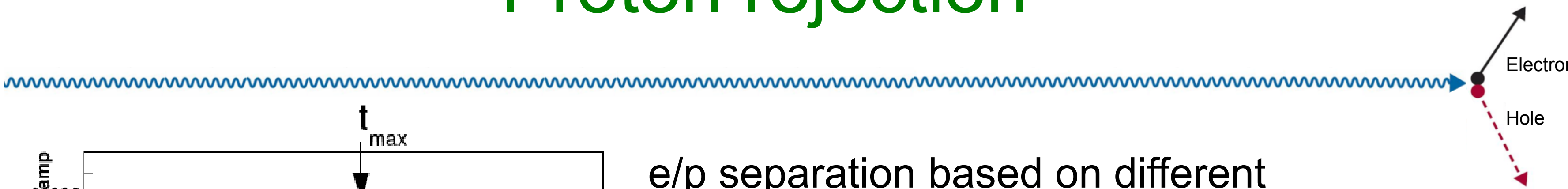


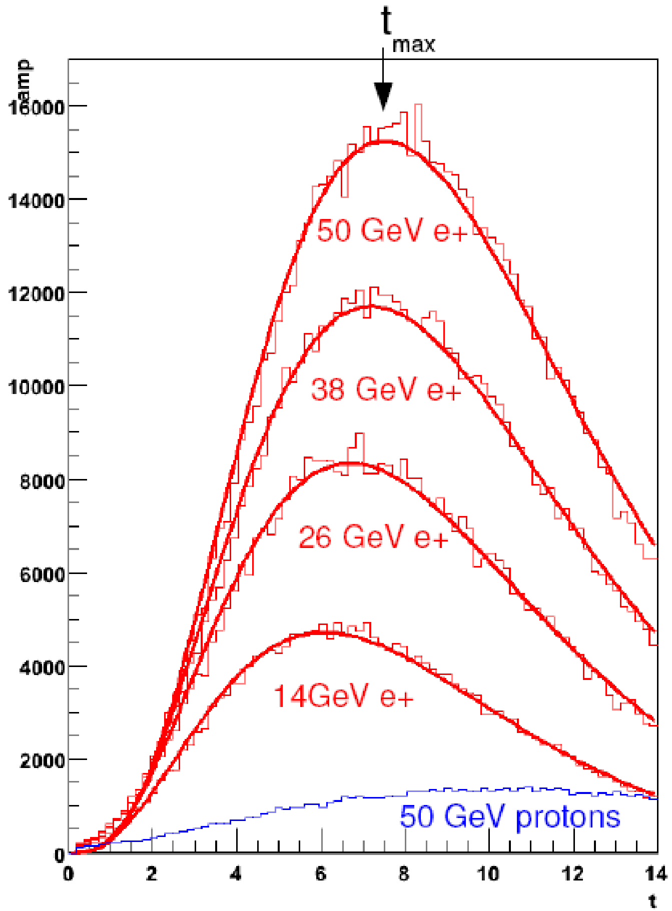
Time-of-Flight system (TOF): 2 x 2 x 5 mm^3 scintillator, SiPM readout; trigger system!



Transition Radiation Detector (TRD): 2 x 8 x (2cm fleece radiator + 6mm straw tube Xe/CO_2 80:20)

Proton rejection





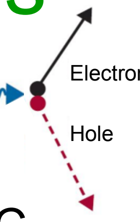
$$\frac{dE}{dt} = E_0 \frac{b^{\alpha+1}}{\Gamma(\alpha+1)} t^{\alpha} e^{-bt} \qquad t = x/X_0$$

longitudinal shower profiles

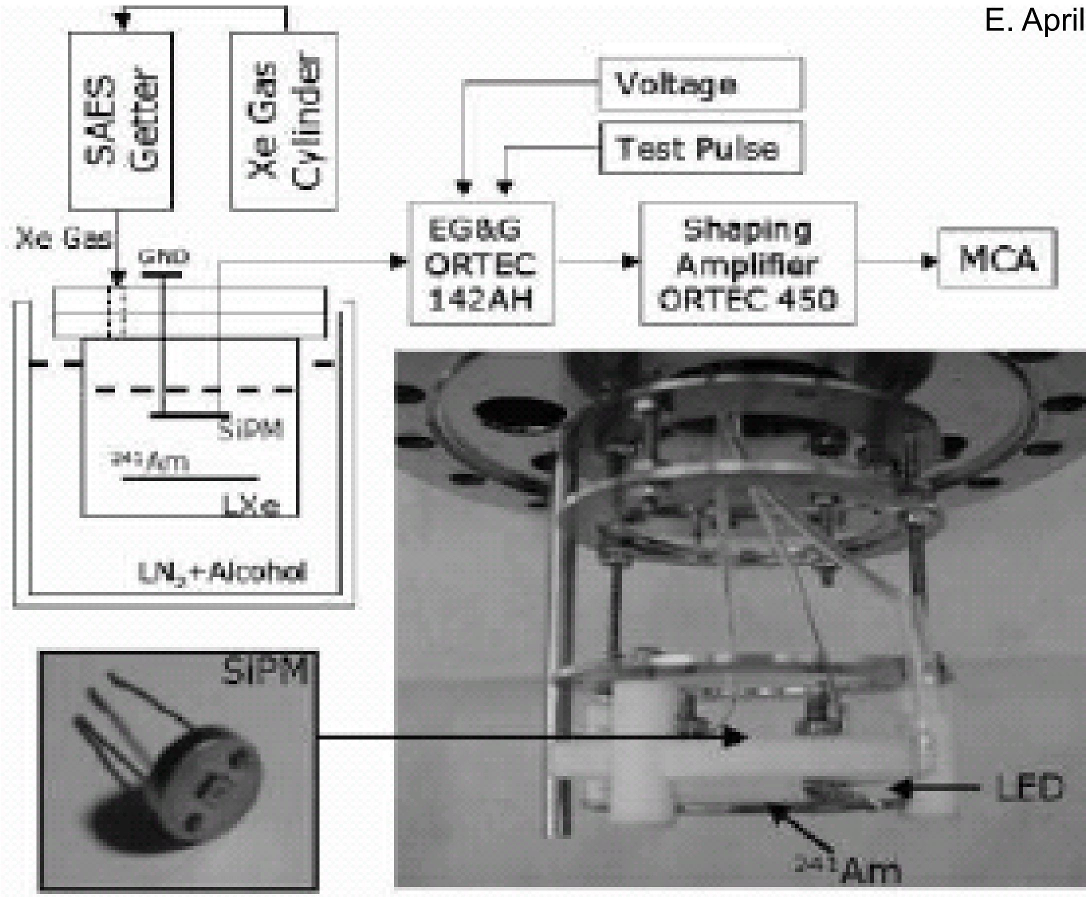
e/p separation based on different longitudinal shower shape at a given particle energy (spectrometer)

➔ extremely high granularity

Deep UV detection: Liquid Xenon detectors

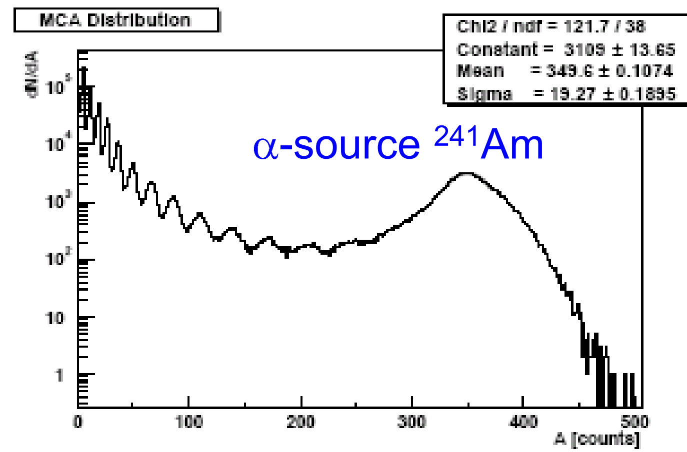



E. Aprile, P. Cushman, K. Ni, P. Shagin



Liquid Xenon: T = -95°C

λ = 178 nm



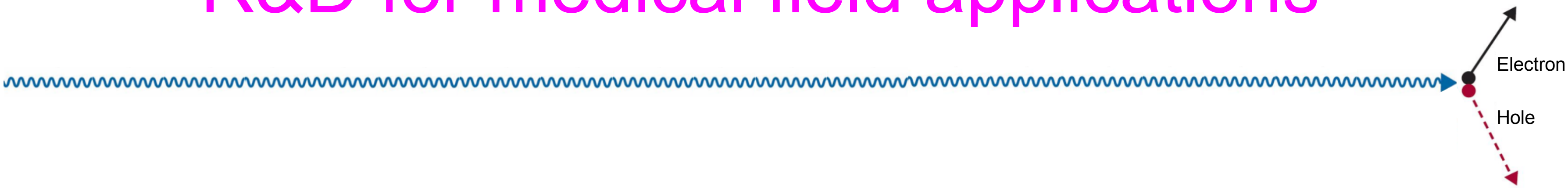
PDE ~ 5.5% (λ = 178 nm)

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

576 pixels SiPM, MePHI/Pulsar

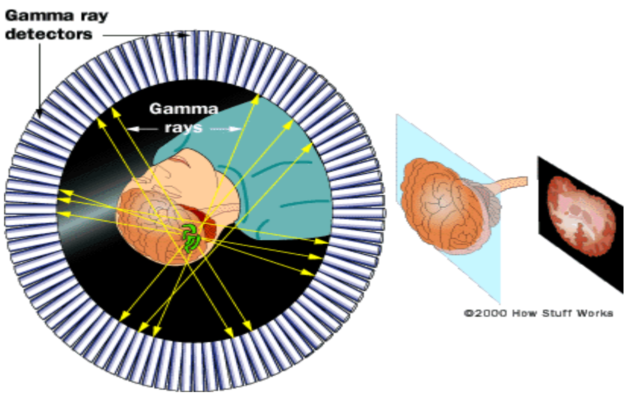
➔Attractive alternative to PMT for UV photon detection at low energy detection threshold (i.e. neutralino dark matter searches)

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

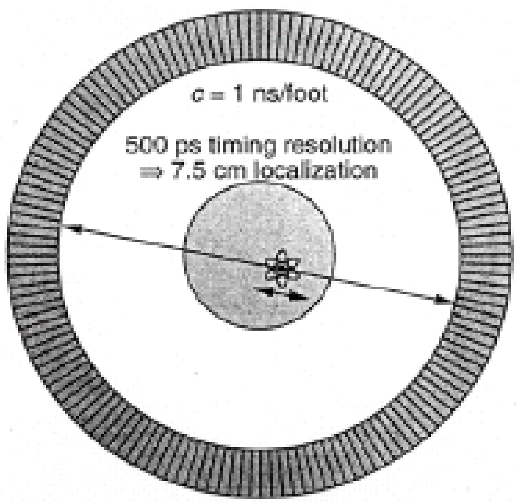
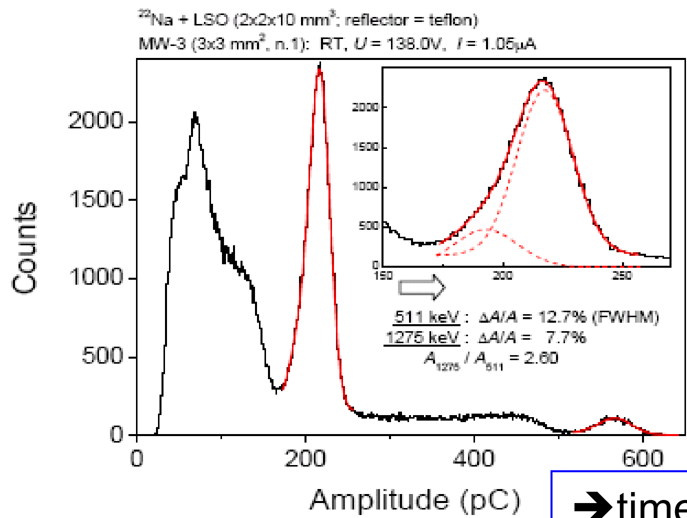
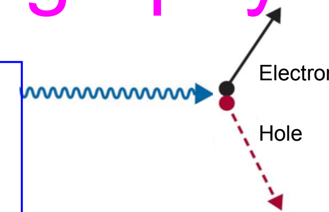


Figure 1. Time-of-Flight PET Camera. Annihilation pho
detected by a ring of scintillation crystals. With a conv
PET camera, this localizes the position of the positron to
segment joining the two crystals. With a TOF PET can
arrival time difference is used to further restrict the positio

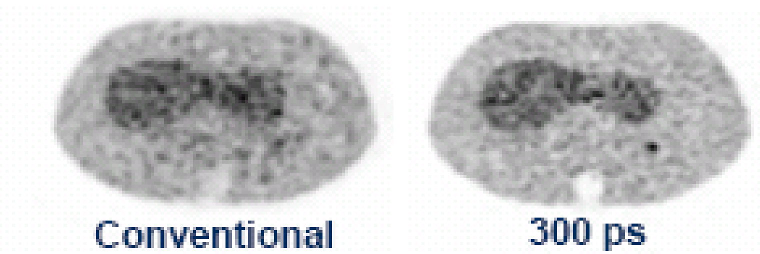




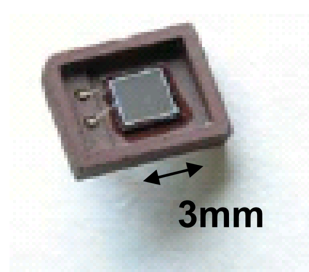
3x3mm^2 SiPM (Z. Sadigov) + LSO crystal (2x2x10mm^3) test with ^{22}Na

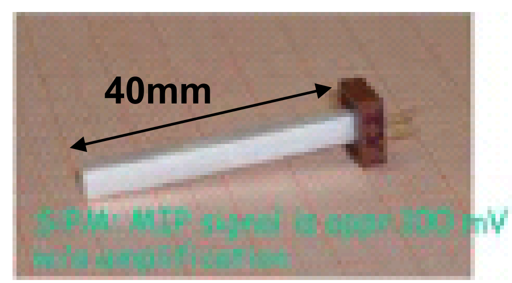
➔time resolution: 540 ps

PET + time information
➔ key for noise suppression



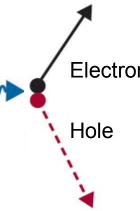
5625 pixels, MEPHI/Pulsar, B. Dolgoshein, Beaune 2005





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

New trends in PET calorimeters

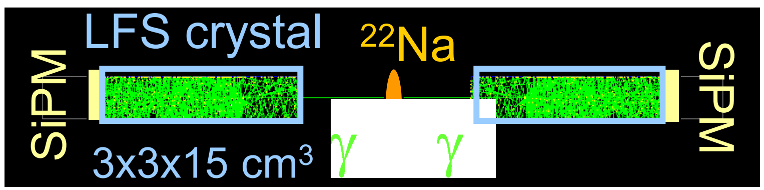


High granularity and small calorimeter cells improve space resolution

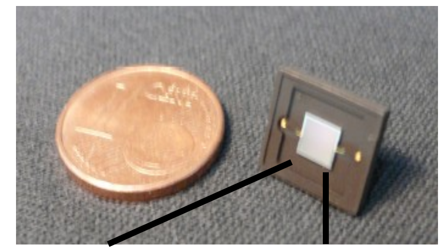
Advantages:
- Lower dose to patient
- Faster scan / larger hospital throughput

➔ Silicon Photomultiplier replace PMT

- compact system
- low HV & cost

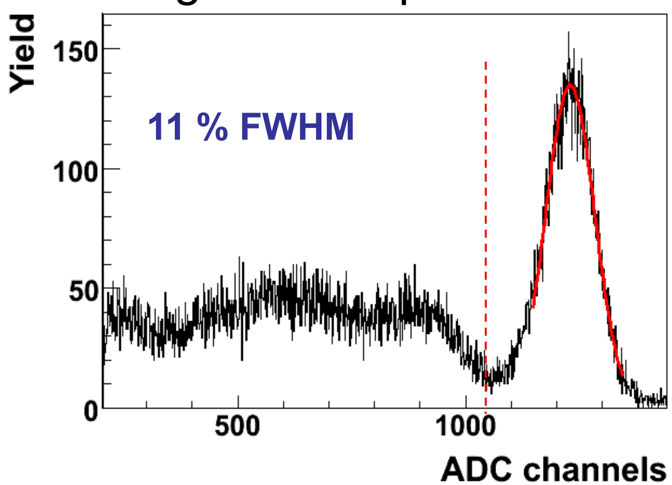


SiPM from Hamamatsu



3x3 mm^2 active area

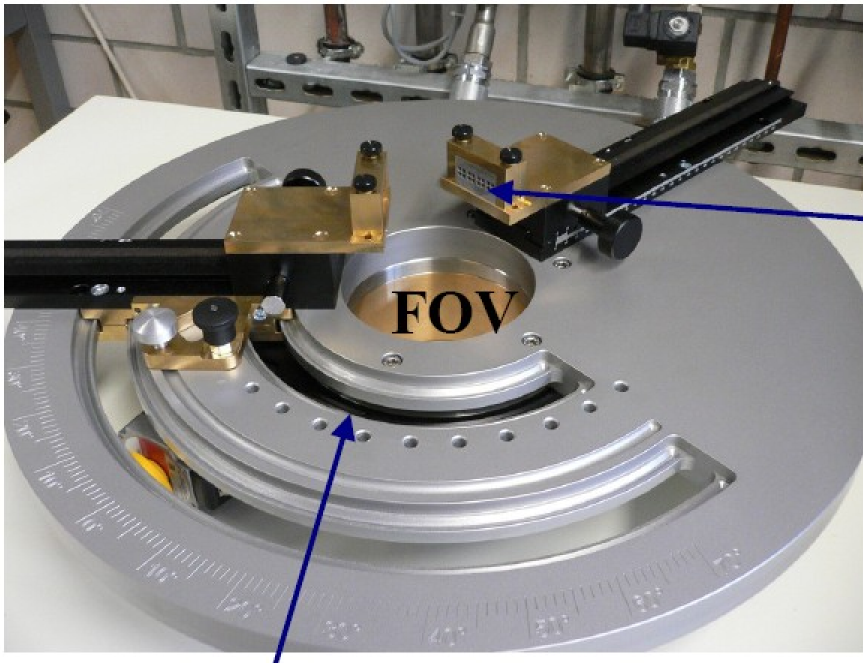
Single ch. E spectrum



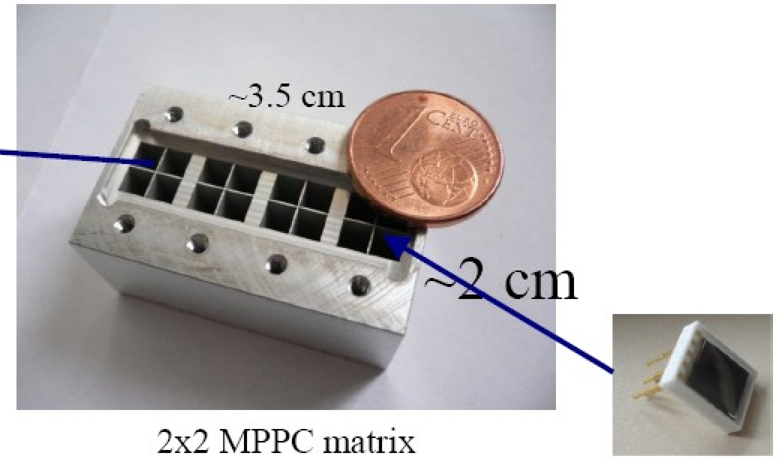
- Good E res. ➔ reduce Compton bg.
- Good t res. ➔ reduce combinatorial bg.

time resolution for coincidence of two channels ~250 ps using SiPM readout and dedicated electronics possible

Test prototype detector for PET



module(16 channels)



2x2 MPPC matrix

+ 4 LFS crystals

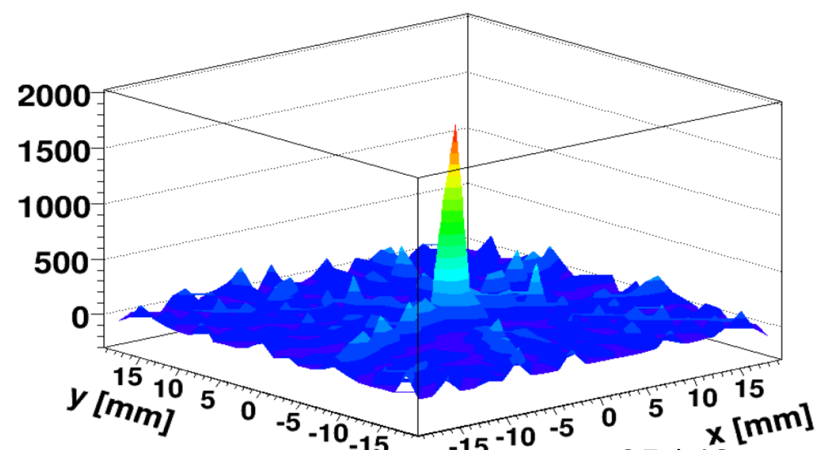
pixel size: 3x3 mm²

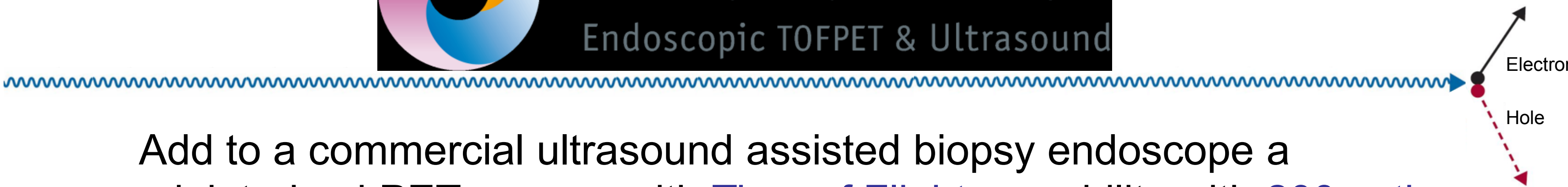
MPPC-33-2x2-50
(HAMAMATSU)

Two detector heads mounted on a movable support for rotation scans

Image reconstruction of a point like source

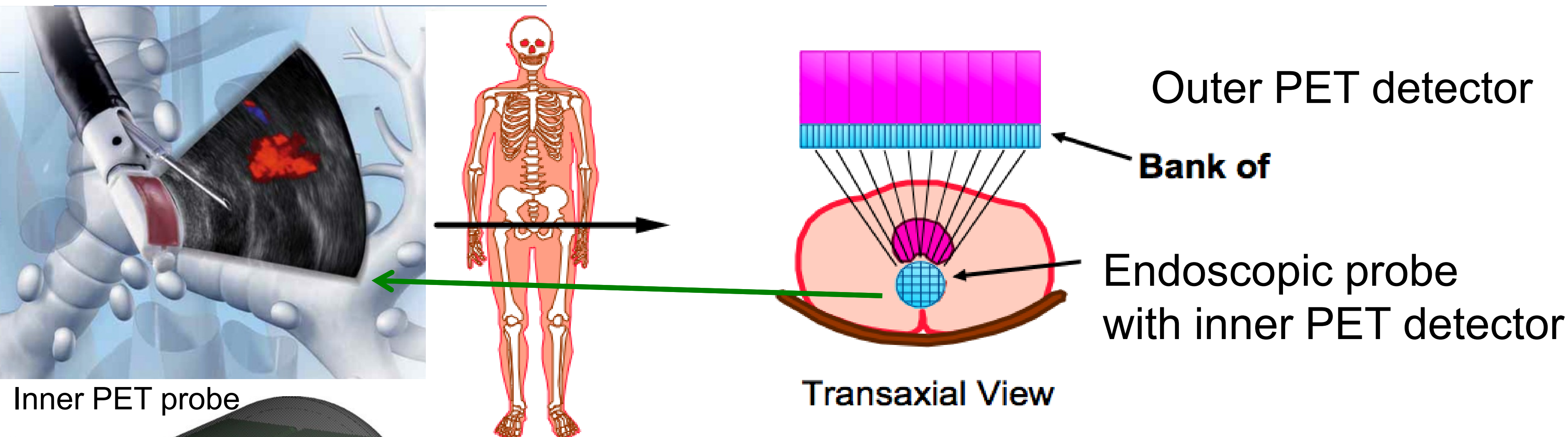
➔ resolution ~2 mm FWHM



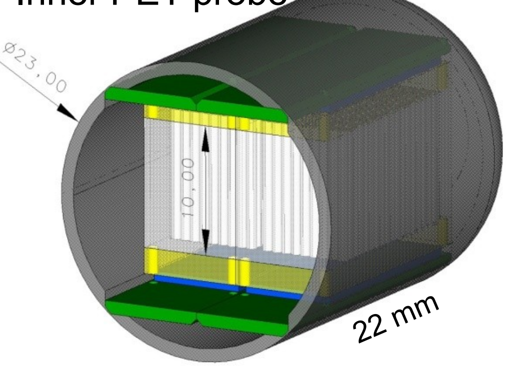


Add to a commercial ultrasound assisted biopsy endoscope a miniaturized PET camera with Time of Flight capability with 200ps time resolution

200ps = 3 cm along the Line of Response (LOR)



Inner PET probe

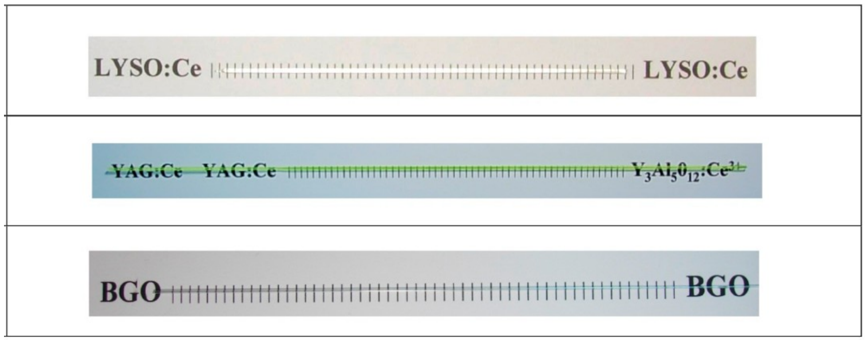


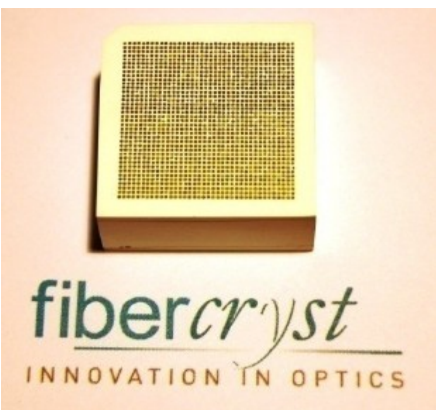
Envisioned Clinical Applications: prostate, pancreas and bile duct, digestive cancer

Technology frontier

Extreme granularity

Fiber crystals: ϕ 350um – 3mm





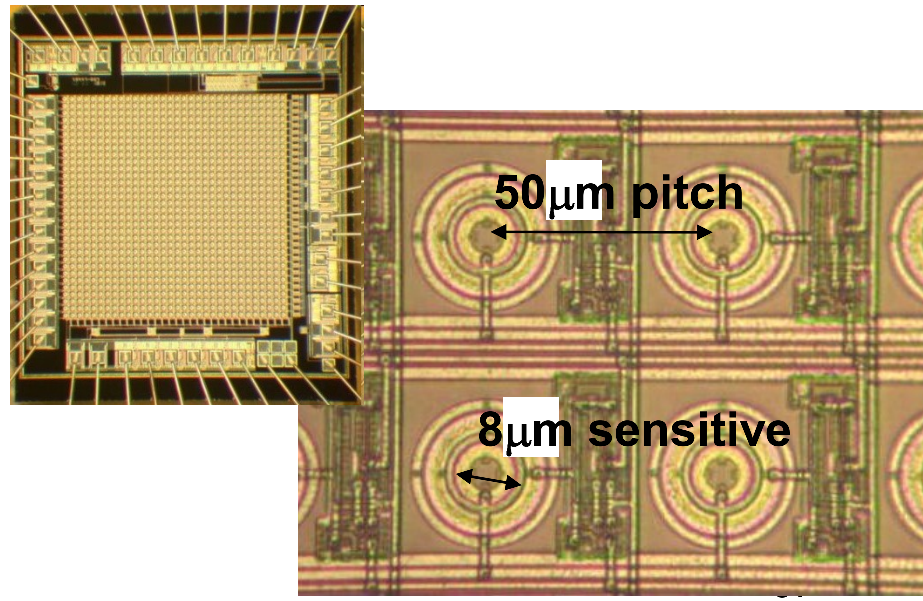
LuAG:Ce Array

light yield (~70000γ /511keV) and a very short rise (~30ps) and decay time (~20ns)

Improve space resolution using smallest crystals individually read out

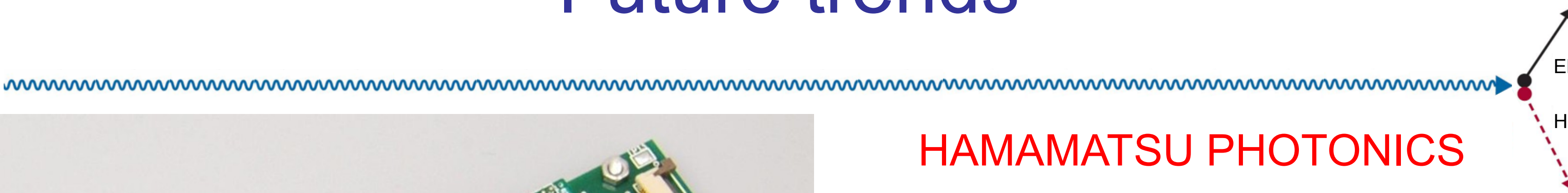
Extreme integration

new generation of Geiger-mode avalanche photo-detector: integrates SPAD on CMOS

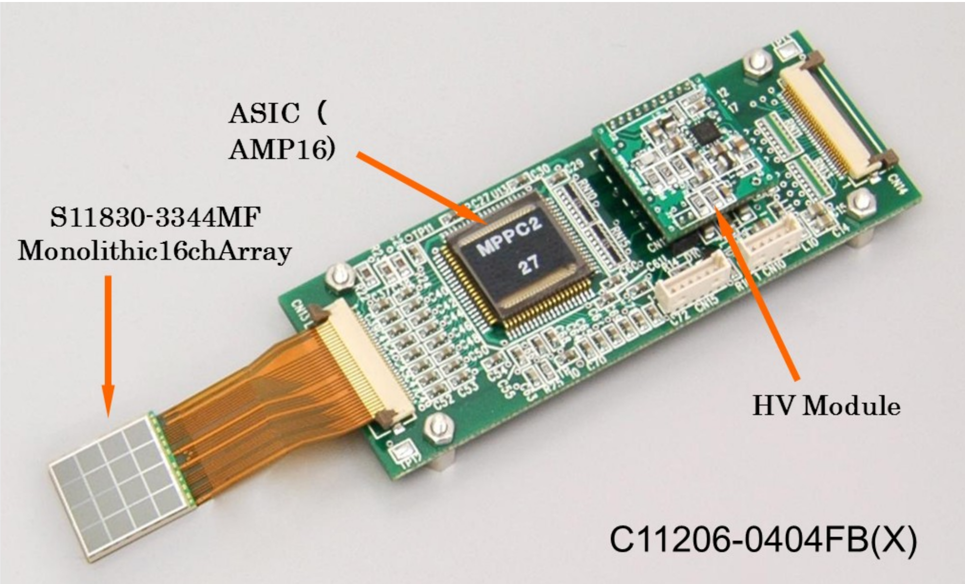


~50 μm pixel SPADs arranged in arrays with individual pixel readout
- O(100ps) time resolution on single photon
- dark count rate <100Hz

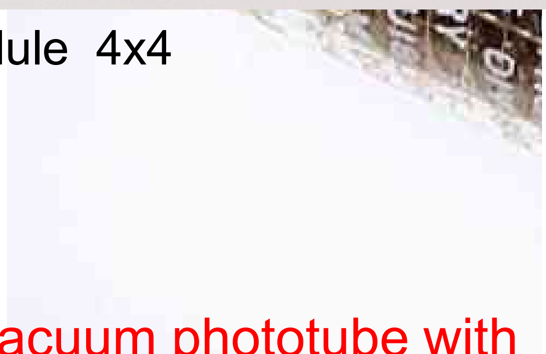
Future trends



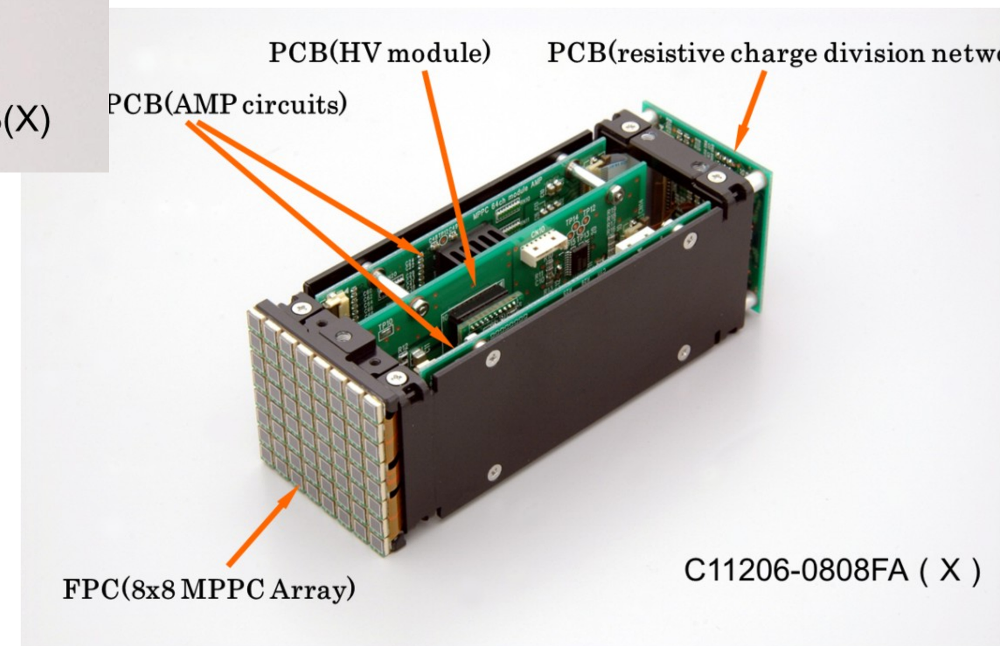
HAMAMATSU PHOTONICS



MPPC module 4x4



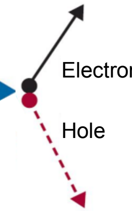
MPPC module 8x8 (prototype)



Including preamp and bias circuit for MPPC

Replace vacuum phototube with silicon-based photo-detectors for “any size and need”

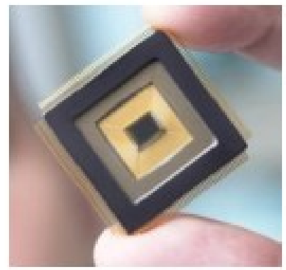
Future trends



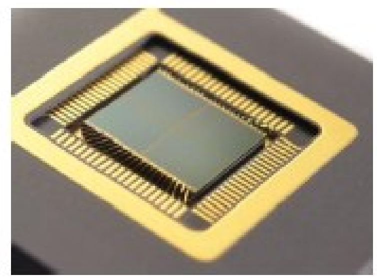
PHILIPS

How to replace old-fashioned PMT's?

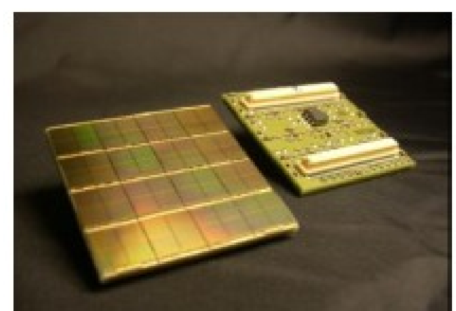
- Make the SiPM digital
  - 1 pixel



- Increase integration
  - 2 x 2 pixel on one chip (die)

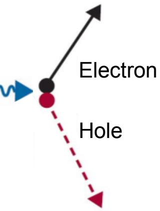


- Assemble arrays
  - 8 x 8 pixels on one PCB (tile)



Industry-academia matching event on SiPM and related technologies:
http://indico.cern.ch/internalPage.py?pageId=0&confId=117424

Future trends

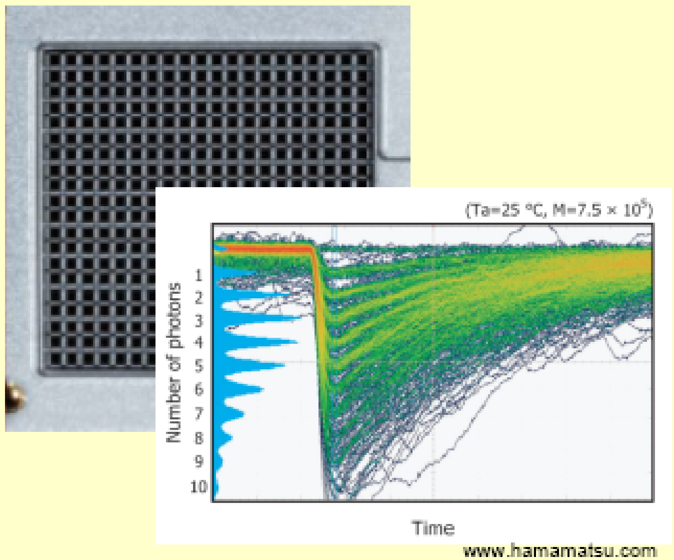


PHILIPS

Digital Photon Counting – The concept

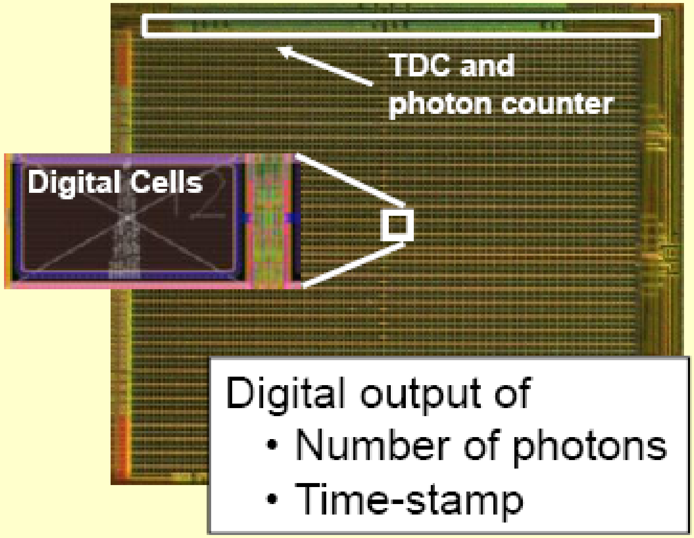
Intrinsically, the SiPM is a digital device: a single cell breaks down or not

analog SiPM



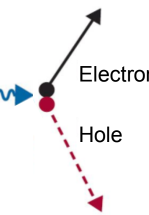
Summing all cell outputs leads to an analog output signal and limited performance

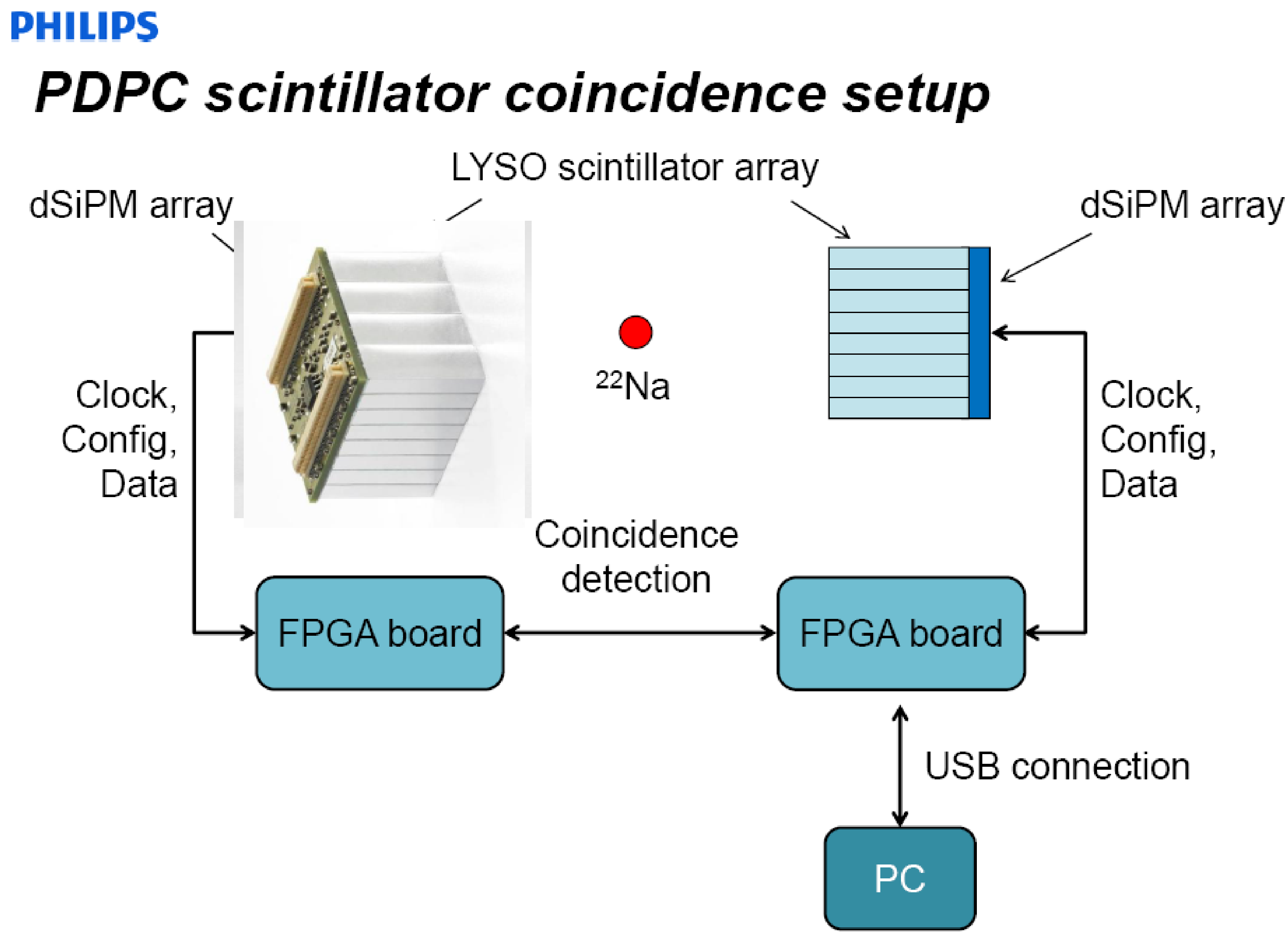
digital SiPM (dSiPM)



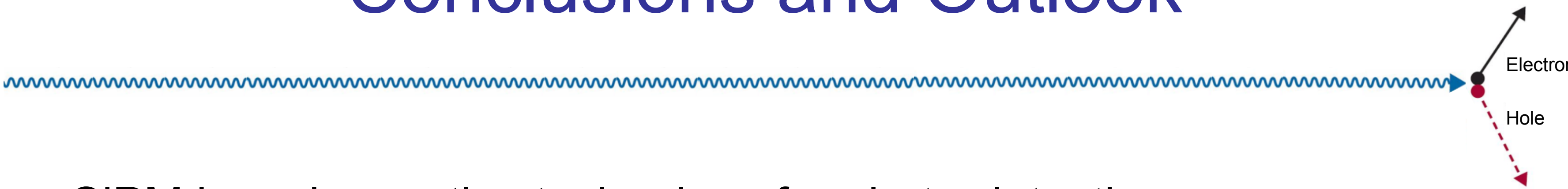
Integrated readout electronics is the key element to superior detector performance

Ready to buy PET module





Conclusions and Outlook



- SiPM is an innovative technology for photo-detection
- which opens revolutionary possibilities in detector development

- HEP has been the driving field for SiPM developments so far
- Medical detectors will probably be driving the future (cost issue)

- SiPMs may become the replacement of PMTs
- Digital readout is a further step in system simplifications
  - ➔ electronics, integration, low cost