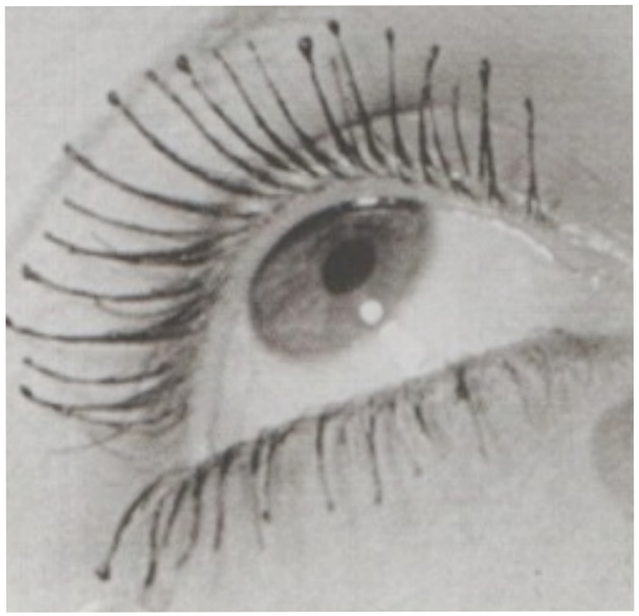
ETH Institute for Particle Physics

EIROforum

Scintillators and photodetectors



Man Ray, 1933

Chiara Casella, ETH Zurich

EIROforum School on Instrumentation (ESI 2011)

European Photon and Neutron Science Campus

Grenoble, 15 - 22 May 2011

Outline

- Scintillators

  scintillation mechanism and properties

  ✦ **organic**

  ✦ **inorganic**

- Photodetectors

  ✦ **vacuum** :

  ✤ PMT (Photomultiplier)

  ✤ MAPMT (Multi Anode PMT)

  ✤ MCP (Micro Channel Plate)

✦ **Si-detectors :**

✤ pin diode

✤ APD (Avalanche Photo Diode)

✤ G-APD (Geiger mode Avalanche Photo Diode)

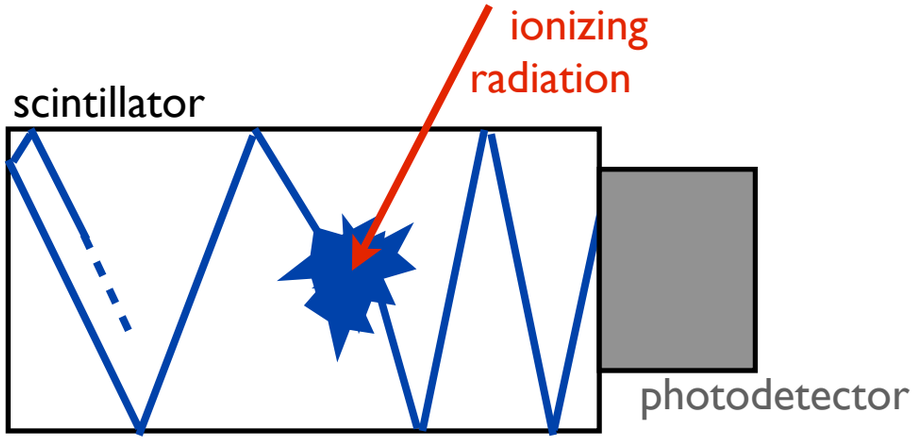
✦ **hybrid** :

✤HPD (Hybrid PhotoDetector)

Mainly high energy physics oriented choice

SCINTILLATORS

Scintillators : class of materials which “scintillate” (i.e. emit visible or near-visible photons) when excited by ionizing radiation



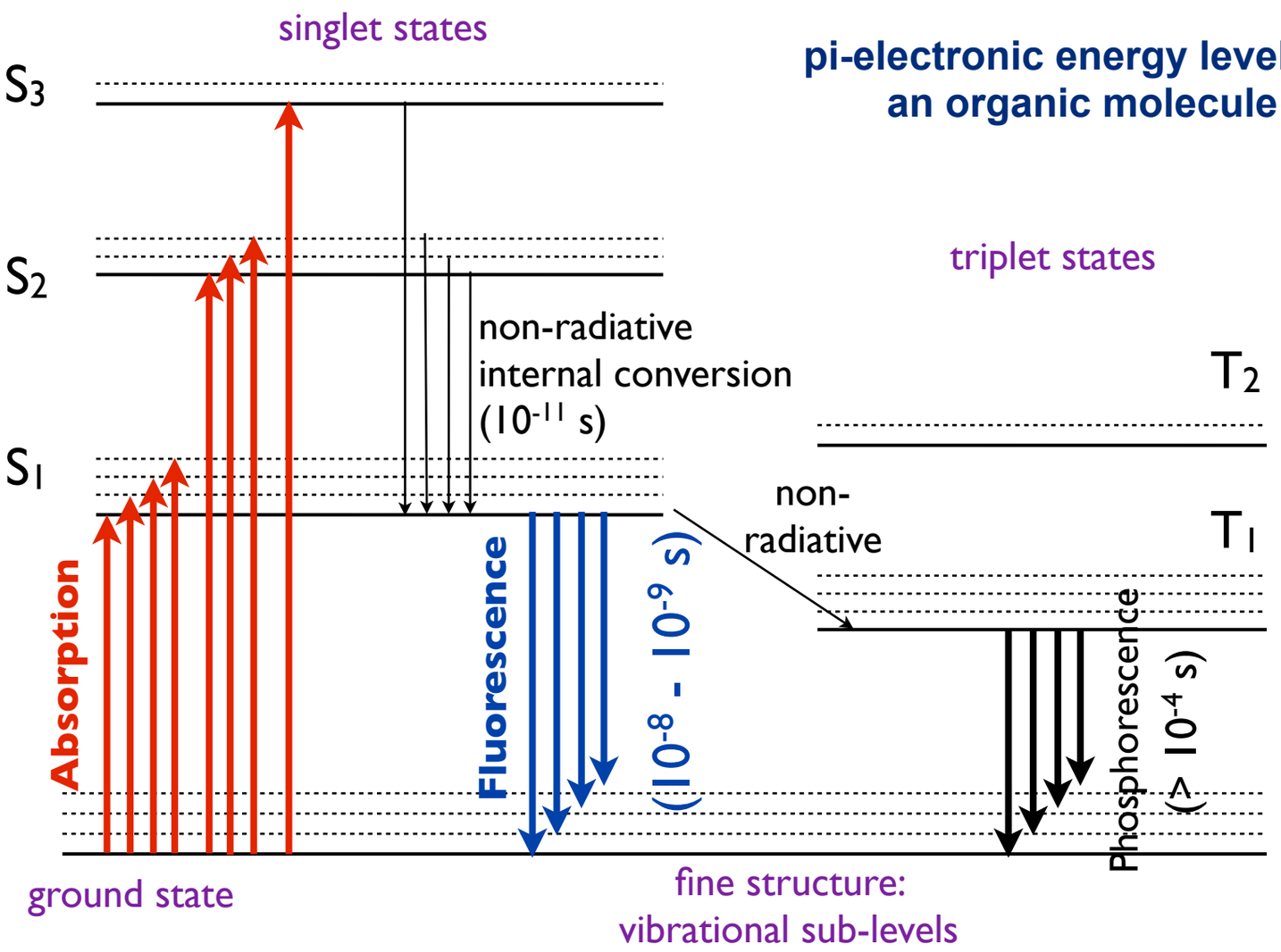
- **Energy loss from ionizing radiation** i.e. ionization and/or excitation of the atoms/molecules of the material
- **Scintillation** : emission of visible (or near-visible) light in the material
- **Transmission** of the scintillation light in the material (i.e. the material must be transparent to its own radiation)
- **Collection** by total internal reflection
- **Detection** of the scintillation light by the photodetector and conversion into an electrical pulse

Two different scintillator categories (scintillation mechanism and properties) :

- ORGANIC
- INORGANIC

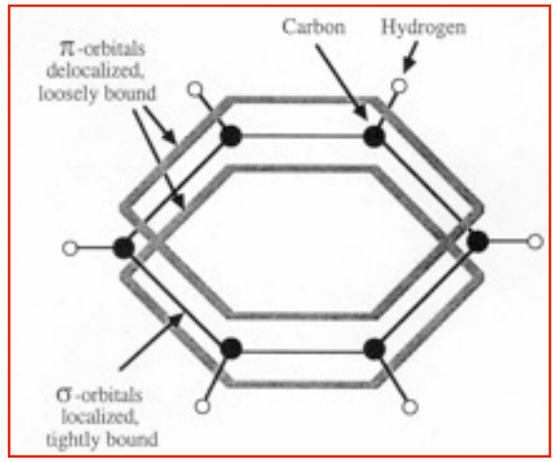
Organic scintillators : Scintillation mechanism

- aromatic hydrocarbon compounds containing benzene ring structures
- **scintillation** : based on **excitation** (and consequent de-excitation) **of molecular electronic levels**
- the electrons involved in the scintillation are the ones arranged in the π-orbitals

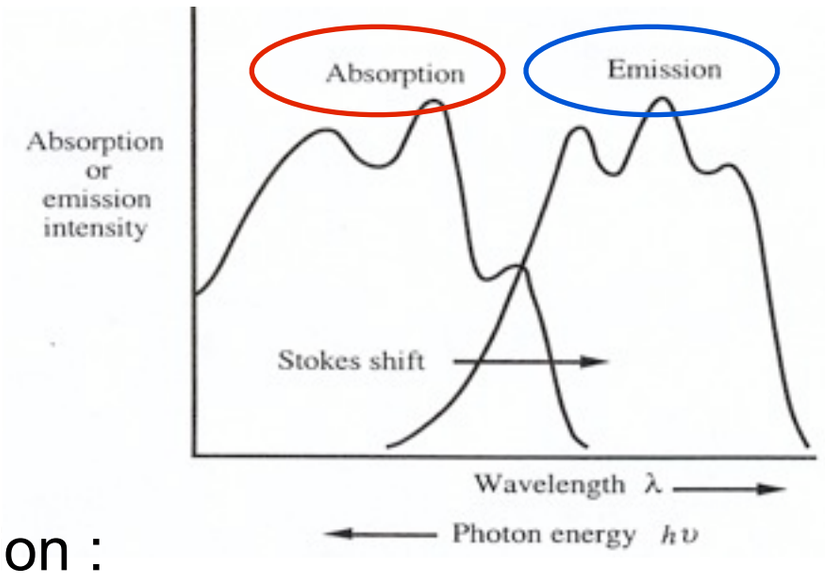


pi-electronic energy levels of an organic molecule

triplet states



C_6H_6 : benzene



- mechanism of photon emission following the energy deposition :
  - **fluorescence** (τ ~ 10^{-8} - 10^{-9} sec) : $\mathbf{I = I_0\, e^{-t/\tau}}$
  - phosphorescence (τ > 10^{-4} sec): delayed emission, at larger λ
  - delayed fluorescence (τ ~ sec): delayed emission, same emission spectrum as fluorescence.

Organic scintillators

- scintillation : **inherent molecular property** => independent on the physical state
  solid / liquid / vapors / solutions...
- organic scintillators exist as:

  unitary systems: crystals (very rarely used in HEP)

  binary / ternary systems : solvent + solute(s)

  - liquid solution
  - plastics (i.e. polymerized solutions) : widely used in HEP

  • proper choice of solute and solvents (including WLS)
  => excellent separation between emission and absorption spectra
  => long attenuation lengths => large sizes possibility

  • plastics : easy to fabricate ; flexible in shape

plastic scintillators - from Saint Gobain catalogue

Physical Constants of SGC Plastic Scintillators

Scintillator	Light Output % Anthracene[1]	Wavelength of Maximum Emission, nm	Decay Constant, Main Component, ns	Bulk Light Attenuation Length, cm	Refractive Index	H:C Ratio	Loading Element % by weight	Density	Softening Point °C
BC-400	65	423	2.4	250	1.58	1.103		1.032	70
BC-404	68	408	1.8	160	1.58	1.107		1.032	70
BC-408	64	425	2.1	380	1.58	1.104		1.032	70
BC-412	60	434	3.3	400	1.58	1.104		1.032	70
BC-414	68	392	1.8	100	1.58	1.110		1.032	70
BC-416	38	434	4.0	400	1.58	1.110		1	
BC-418	67	391	1.4	100	1.58	1.100		1	
BC-420	64	391	1.5	110	1.58	1.100		1	
BC-422	55	370	1.6	8	1.58	1.102		1	
BC-422Q	11	370	0.7	<8	1.58	1.102	Benzephenone,1%*	1	
BC-428	36	480	12.5	150	1.58	1.103		1	
BC-430	45	580	16.8	NA	1.58	1.108		1	
BC-436	52	425	2.2	NA	1.61	0.960 D:C	Deuterium,13.8%	1	
BC-440	60	434	3.3	400	1.58	1.104		1	
BC-440M	60	434	3.3	380	1.58	1.104		1	
BC-444	41	428	285	180	1.58	1.109		1	
BC-444G	34	490	285	180	1.58	1.109		1	
BC-452	32	424	2.1	150	1.58	1.134	Lead,5%	1	
BC-454 5%	48	425	2.2	120	1.58	1.169	Boron,5%	1	
BC-480	**	425	—	400	1.58	1.100		1	
BC-482A	QE=.86	494	12.0	300	1.58	1.110		1	
BC-490	55	425	2.3	NA	1.58	1.107		1	
BC-498	65	423	2.4	NA	1.58	1.103		1.032	70

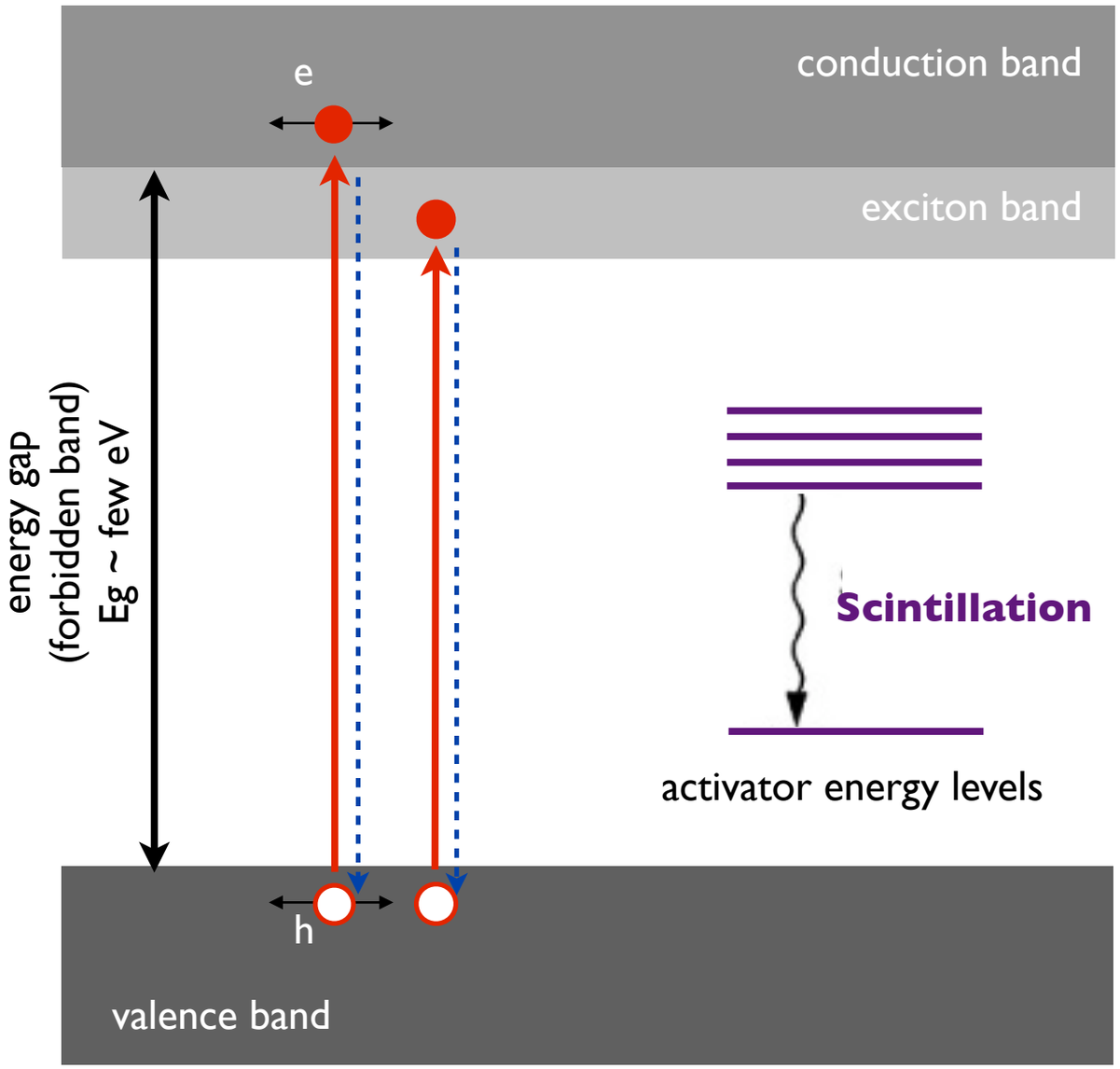
[1] Anthracene light output = 40-50% of NaI(Tl) * 0.1 to 5 weight % also available ** Ratio of Cerenkov light to scintillator light = 10:1

ORGANIC SCINTILLATORS :

- **short decay time (~ ns)**
- **long attenuation length (~ m)**
- **low density (~ 1g/cm^3)**
- **modest light yield (max 10000γ/MeV)**
- **cheap (< 1 euro/cm^3)**

Inorganic scintillators : Scintillation mechanism

- **scintillation**: due to the **electronic band structure in crystals**
- not molecular in nature [you cannot melt e.g. NaI(Tl) and still have a scintillator !!!]



- discrete energy bands available for electrons
- incoming radiation => **IONIZATION or EXCITATION**
  - ionization : free e (cond.) + free h (val.)
  - excitation : exciton (loosely coupled e-h pair in the exciton band); eh bound together but free to move inside the crystal

- if the crystal is perfectly pure => **de-excitation**, without possibility to produce light transparent to the crystal itself (self-absorption)

- if the crystal contains activators (e.g. dopants, defects)
  - e/h generation
  - h ionizes one activator site ($E_{ioniz_impurity} < E_{ioniz_lattice}$)
  - e encounters the ionized site => neutral impurity configuration, with all its own set of excited states

=> electronic levels in the forbidden gap are locally created => **de-excitation = SCINTILLATION LIGHT**

Inorganic scintillators

Table 28.4: Properties of several inorganic crystal scintillators. Most of the notation is defined in Sec. 6 of this *Review*.

Parameter:	ρ	MP	X_0^*	R_M^*	dE^*/dx	λ_I^*	τ_{decay}	λ_{max}	$n^\natural$	Relative output†	Hygro-scopic?	$d(\text{LY})/dT$
Units:	g/cm^3	°C	cm	cm	MeV/cm	cm	ns	nm				%/°C‡
NaI(Tl)	3.67	651	2.59	4.13	4.8	42.9	230	410	1.85	100	yes	−0.2
BGO	7.13	1050	1.12	2.23	9.0	22.8	300	480	2.15	21	no	−0.9
BaF_2	4.89	1280	2.03	3.10	6.5	30.7	630^s	300^s	1.50	36^s	no	−1.3^s
							0.9^f	220^f		3.4^f		∼0^f
CsI(Tl)	4.51	621	1.86	3.57	5.6	39.3	1300	560	1.79	165	slight	0.3
CsI(pure)	4.51	621	1.86	3.57	5.6	39.3	35^s	420^s	1.95	3.6^s	slight	−1.3
							6^f	310^f		1.1^f		
$PbWO_4$	8.3	1123	0.89	2.00	10.1	20.7	30^s	425^s	2.20	0.083^s	no	−2.7
							10^f	420^f		0.29^f		
LSO(Ce)	7.40	2050	1.14	2.07	9.6	20.9	40	402	1.82	83	no	−0.2
$LaBr_3$(Ce)	5.29	788	1.88	2.85	6.9	30.4	20	356	1.9	130	yes	0.2

NaI(Tl) light yield ~ 40000 γ/MeV

from Particle Data Group, Review of Particle Physics

INORGANIC SCINTILLATORS :

- slower decay time (wrt org. scint.)
- higher light yield (wrt org. scint.)
  => Good energy resolution
- high density, high Z
  => High stopping power
  => High conversion efficiency
- expensive (e.g LYSO ~ 100 euro / cm^3)
- Electromagnetic calorimetry in HEP, γ-rays detectors (e.g. PET)

PHOTO-DETECTION : Basic principles

GOAL : **convert photons (visible or near-visible range) into a detectable electronic signal**
- 100 nm < λ < 1000 nm
- E = hν ~ 1240/λ[nm] => few eV

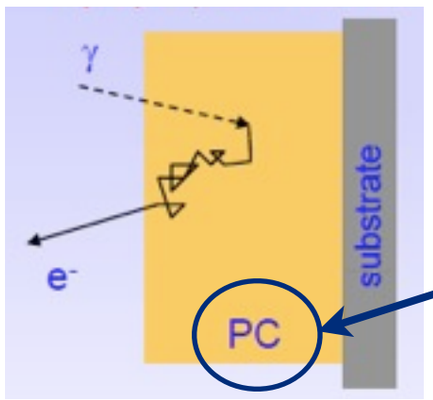
Where do these photons come from ?
- Scintillators
- Cherenkov radiation

(see C.Joram's lecture)

- Photons interact with matter via the photoelectric effect i.e. $\gamma \Rightarrow e$ *("photoelectron")*
- Two different branches of photo-detection methods, depending on the material properties :

1. External photoelectric effect :
- photon absorption
- e diffusion in the material (=> E losses)
- e liberated into the vacuum

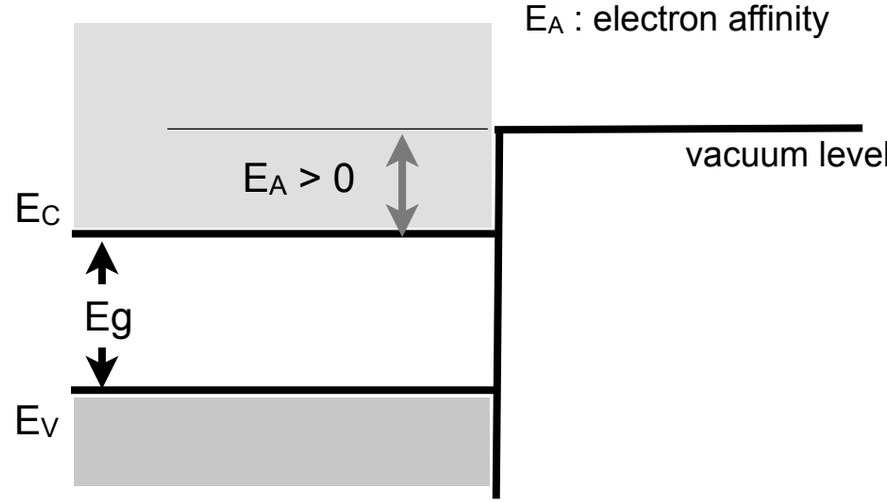
=> detection method: collection and multiplication of those e's (and secondary emissions e's)



photoemissive materials / photocathodes

PMT / HPD

Eg : band energy gap
E_A : electron affinity



In both cases : **threshold effect**

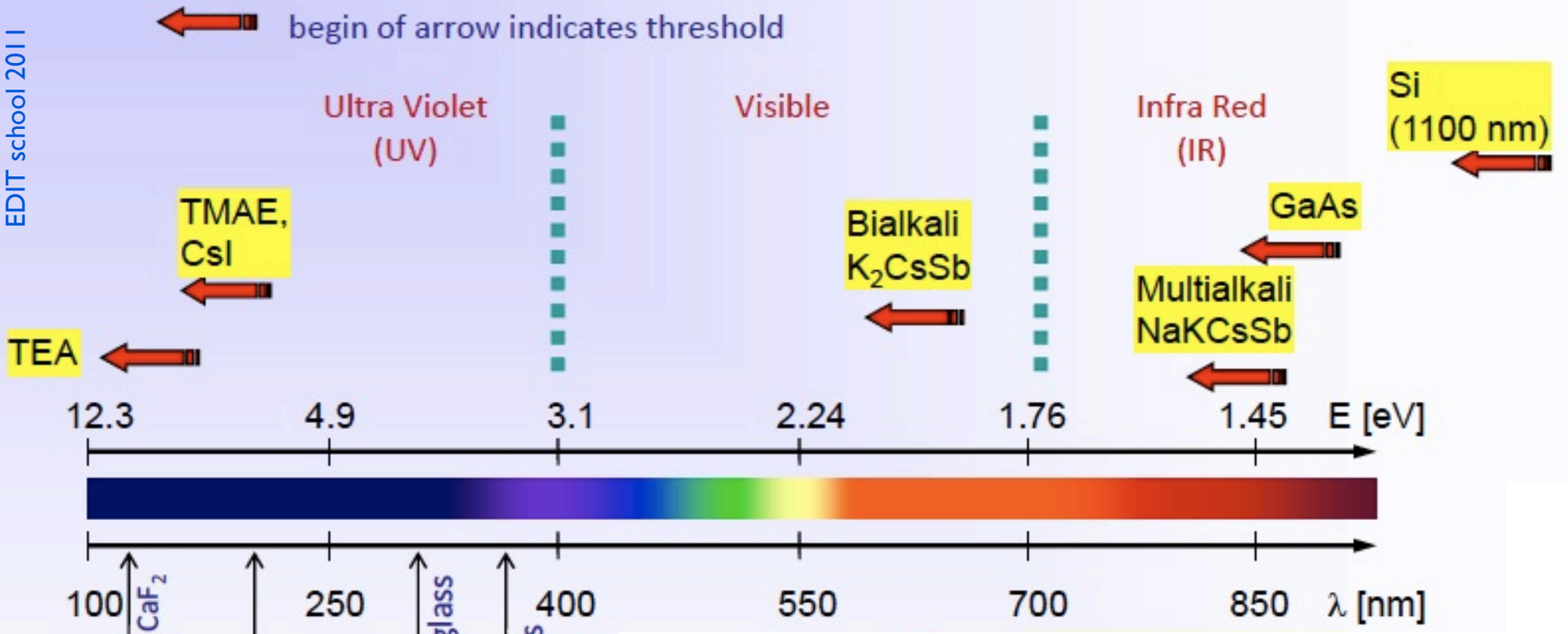
$$E_\gamma = h\nu > E_G + E_A [if\ (1)]$$
$$E_\gamma = h\nu > E_G \qquad [if\ (2)]$$

2. Internal photoelectric effect
- if Eγ = Ee > Eg => photocurrent

=> detection method: detection of the current. Does not require the e to be extracted !

Si detectors :
pin; APD; G-APD

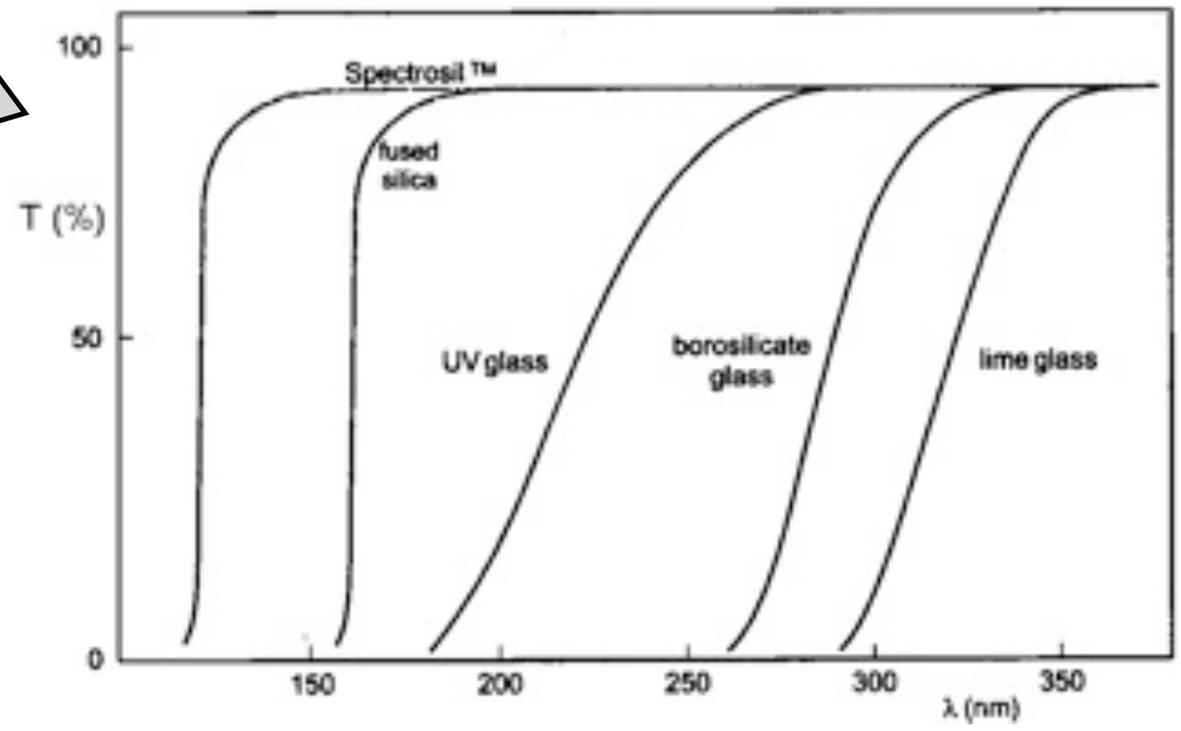
Photosensitive materials



Cut-off limits of window materials for semitransparent photocathodes

thr : minimum photon energy required for the photodetection to occurr

transmission of frequently used windows



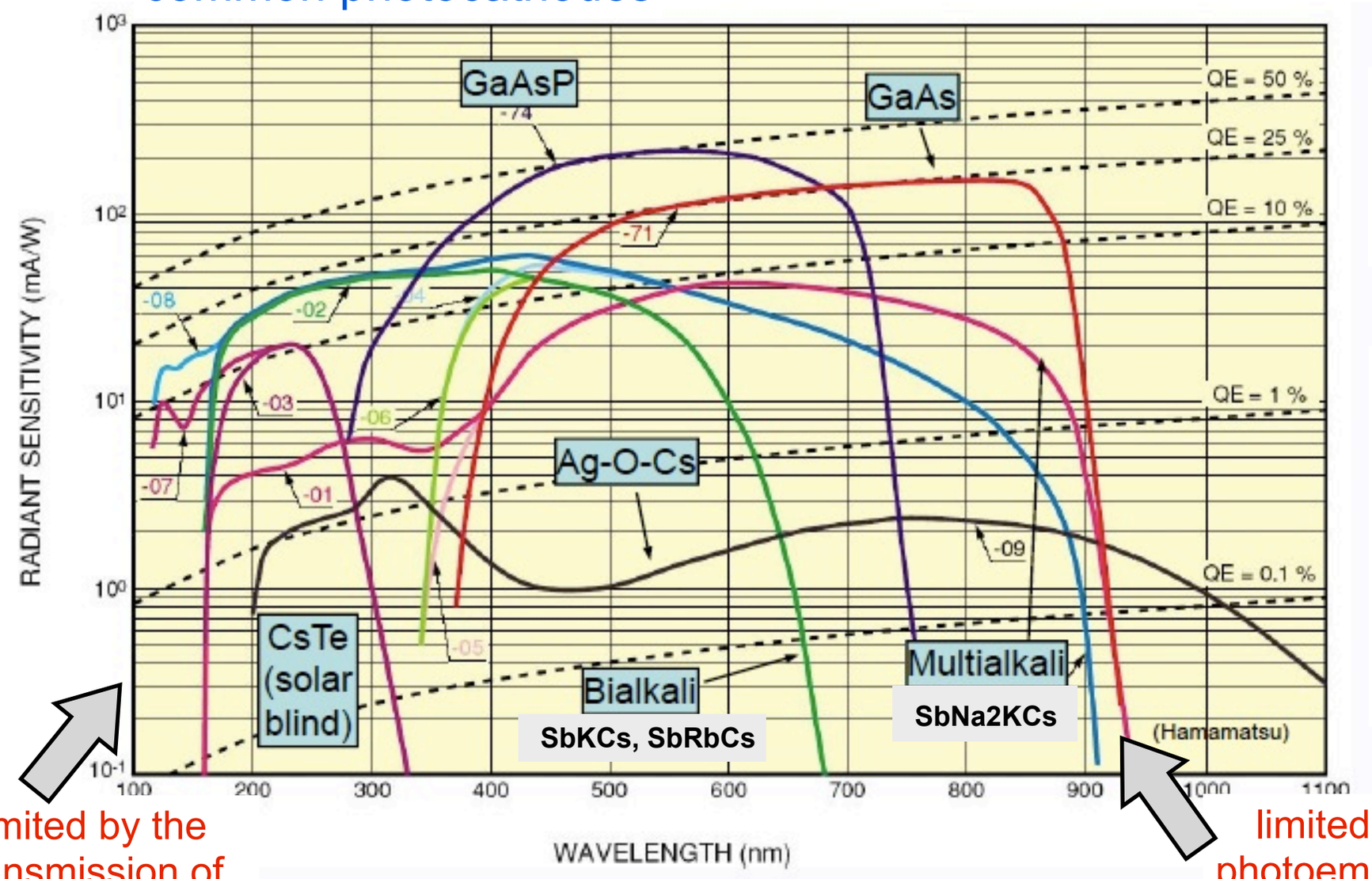
Almost all photosensitive materials are very reactive (alkali metals). Operation only in vacuum or extremely clean gas.
Exception : Silicon, CsI

Sensitivity of photocathodes

not all photons incident on a photoemissive material will cause the emission of photoelectrons !

- quantum efficiency $$QE(\%) = \frac{N_{pe}}{N_\gamma}$$ $$QE(\%) \sim 124 \frac{S_k(mA/W)}{\lambda(nm)}$$
- radiant sensitivity $$S_k = \frac{I_k(mA)}{\Phi_\gamma(W)}$$ I_k: cathode current; Φ_γ: incident flux

common photocathodes



limited by the transmission of the window

limited by the photoemission thr of the material

photocathodes QE ~ 15% - 25% (typical values)

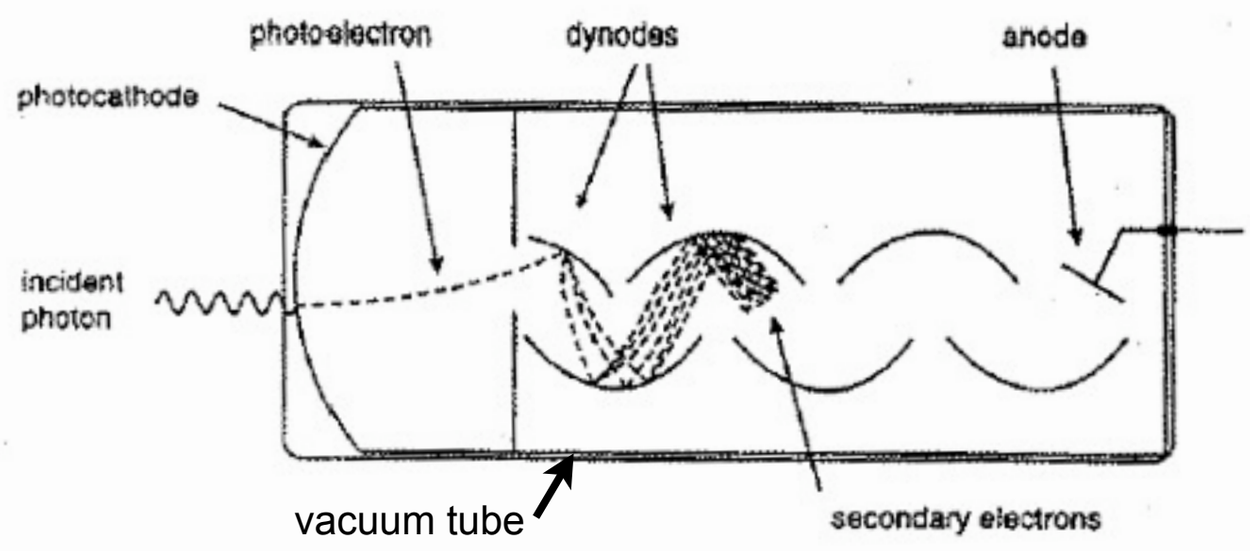
recently achieved: superbialkali (SBA) / ultrabialkali (UBA) **QE_max ~ 45%**

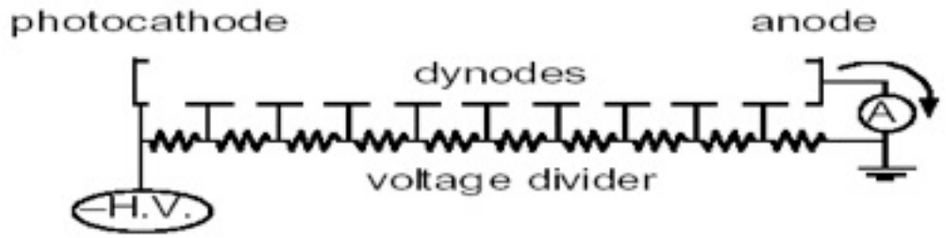
e.g. Hamamatsu
R7600-100 (SBA)
R7600-200 (UBA)

The photomultiplier tube (PMT)

PMT working principle :

- **photoemission** from the photocathode
- focusing / accelerating the photoelectrons with proper input optics
- electron multiplication: **secondary emission** of electrons by dynodes (gain δ_i)
  - resistive voltage divider across a HV supply
- collection of the total charge at the anode

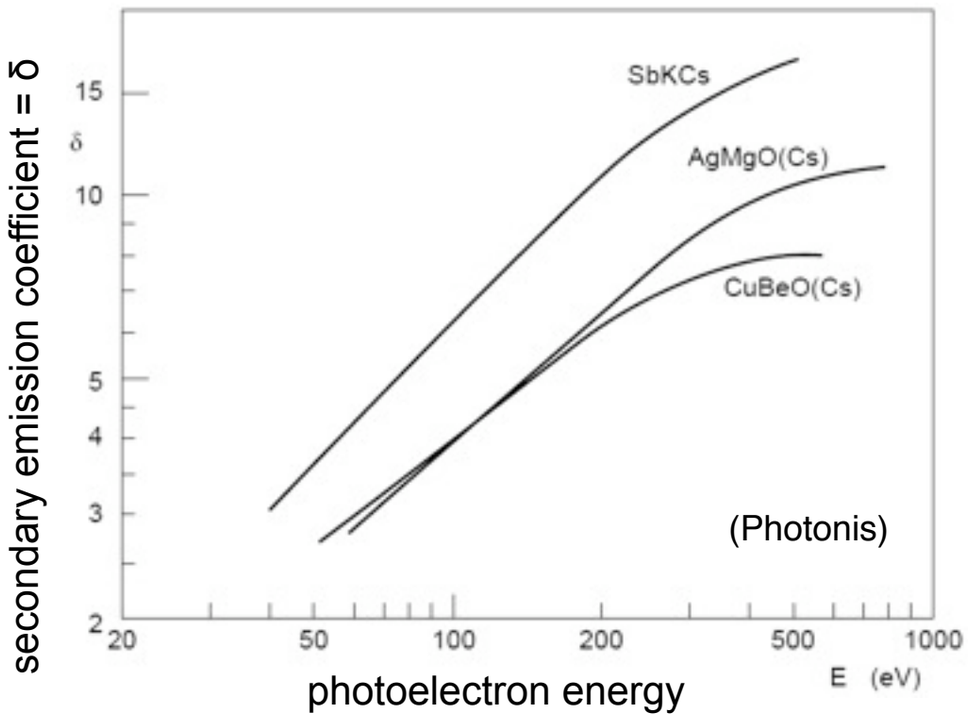




- **GAIN** : nr of dynodes
  gain of each dynode δ=f(E_e)

$$M = \delta^n$$

e.g. 10 dynodes, δ = 4 => $M = 4^{10} \simeq 10^6$



PMT: Statistical fluctuations

- **photoemission** from the photocathode
- **secondary emission** from the dynodes

statistical processes ⇒ statistical fluctuations, gain spread

Poisson statistics: $P_\mu(a) = e^{-\mu}\frac{\mu^a}{a!}$

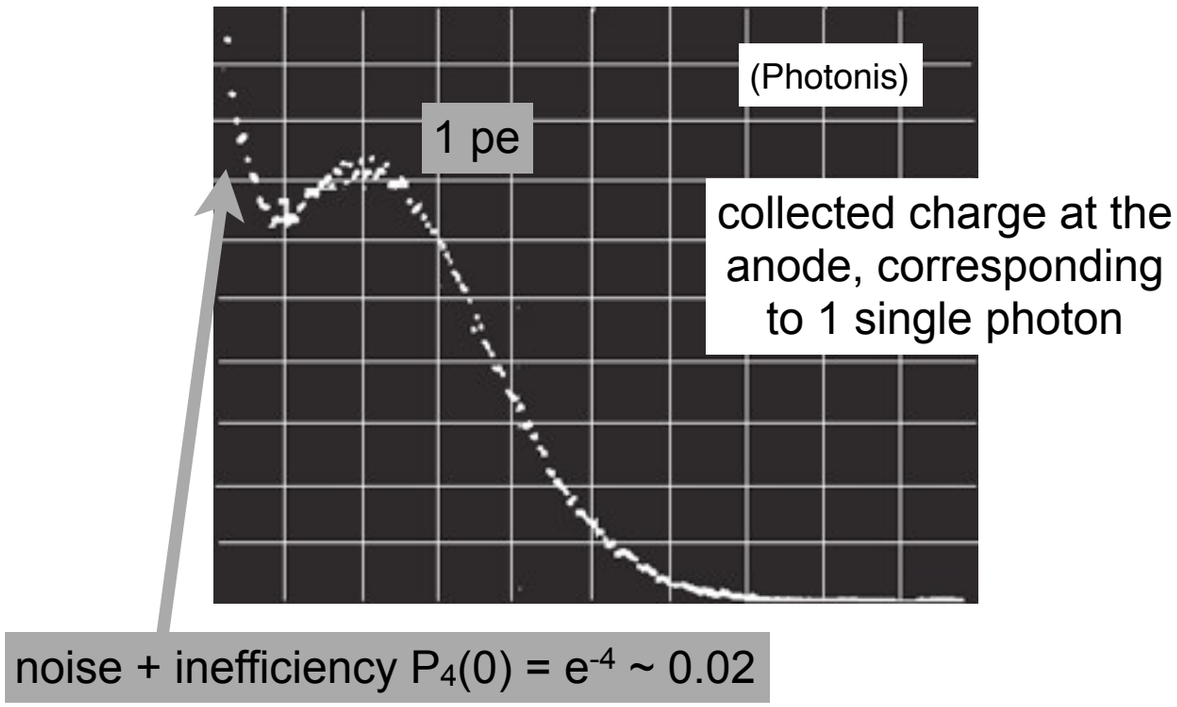
$\sigma = \sqrt{\mu}$

probability of *a* events, when the mean value is *μ*

Relative fluctuations: $R = \frac{\sigma}{\mu} = \frac{1}{\sqrt{\mu}}$

Biggest fluctuations when μ is small
=> Gain spread is essentially dominated by the 1st 2nd dynodes

Single photoelectron spectrum
typical dynodes : CuBe, δ ~ 4 (100-200eV)



=> Single photon resolution : Statistically limited

Why not PMT ?

PMT :

- high gain ~ 10^6 - 10^7
- high sensitivity
- large sensitive areas available
- various solutions windows/photocathodes, dynode design...

... commercial products since > 70 years

(Hamamatsu)

Why not (not only) PMT ?

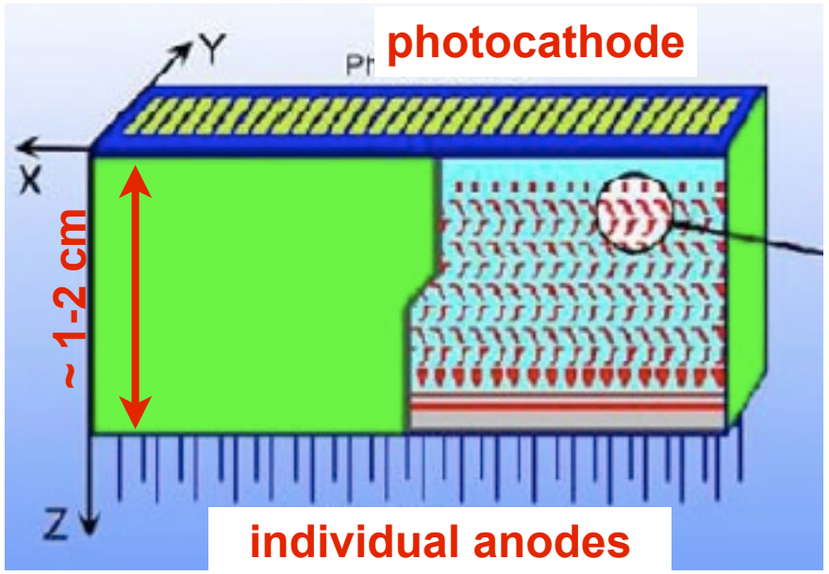
- large, bulky (now turning into flat design with good area coverage), fragile, costly
  - on the other hand, the cost per instrumented area is the lowest
- affected by magnetic fields
  - even B_{Hearth} ~ 30-60μT [0.3-0.6G]
  - μ-metal shielding
- sometimes you want a small, pixelated light detector
- you want even faster timing
- you want improved p.e. resolution (less gain fluctuations)
- you want higher quantum efficiency (especially at longer wavelengths)

...

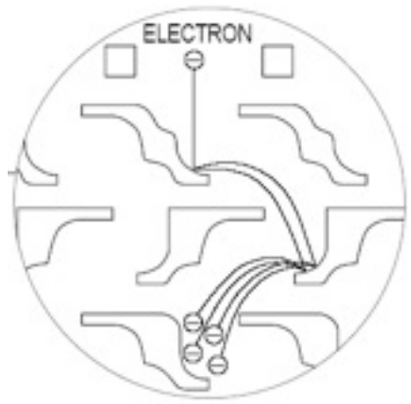
Multi Anode PMT (MAPMT)

Conventional PMT => No spatial information about the light incident at the photocathode

With a **special cathode configuration** and **special dynodes** that retain spatial information
=> position sensitive PMT arrays in a single vacuum envelope : MA-PMT



individual anodes
(each one on its
own pin output)



metal channel
dynode structure
(micro-machine tech.)

Multi-anode (Hamamatsu H7546)

- Up to 8x8 channels (2x2 mm2 each);
- Size: 28x28 mm2
- Active area: 18.1x18.1 mm2 (41%)
- Bialkali PC : QE ~ 25-45% (λmax = 400 nm)
- Gain ~ 10^6
- Gain uniformity typ. 1:2.5
- Cross-talk typ. 2%

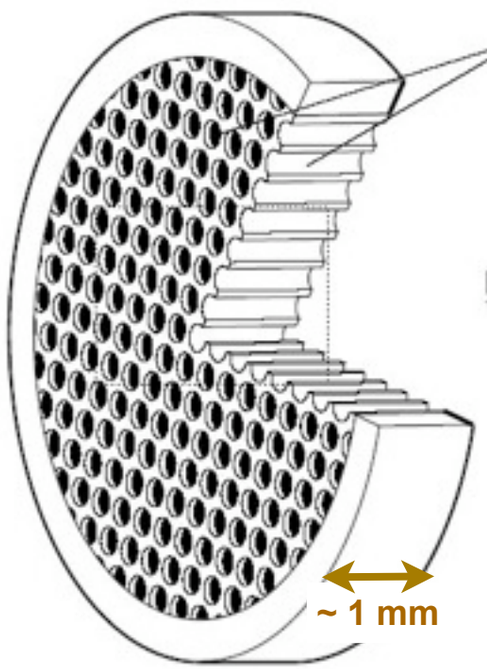
- multiple PMTs within the same vacuum housing
- one photocathode (common to all channels)
- charge multiplication in the dynode preserving the spatial information of the hit position at the photocathode

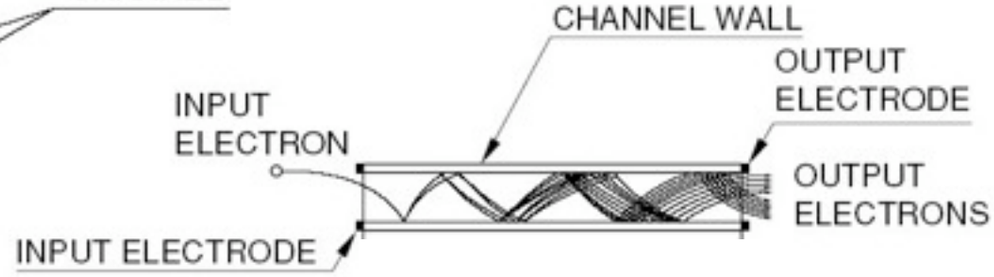
Position sensitive device
Compact => improved timing performance ; better B compatibility

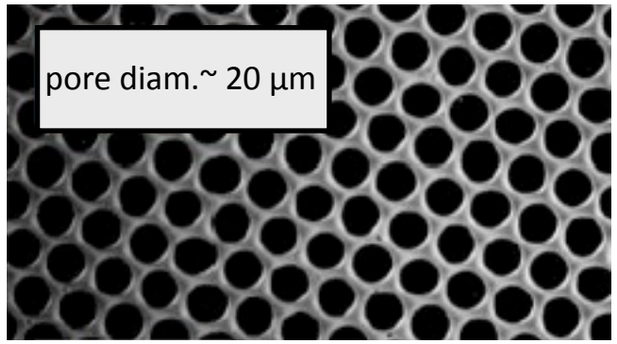
Cross talk ; non uniformity across the channels

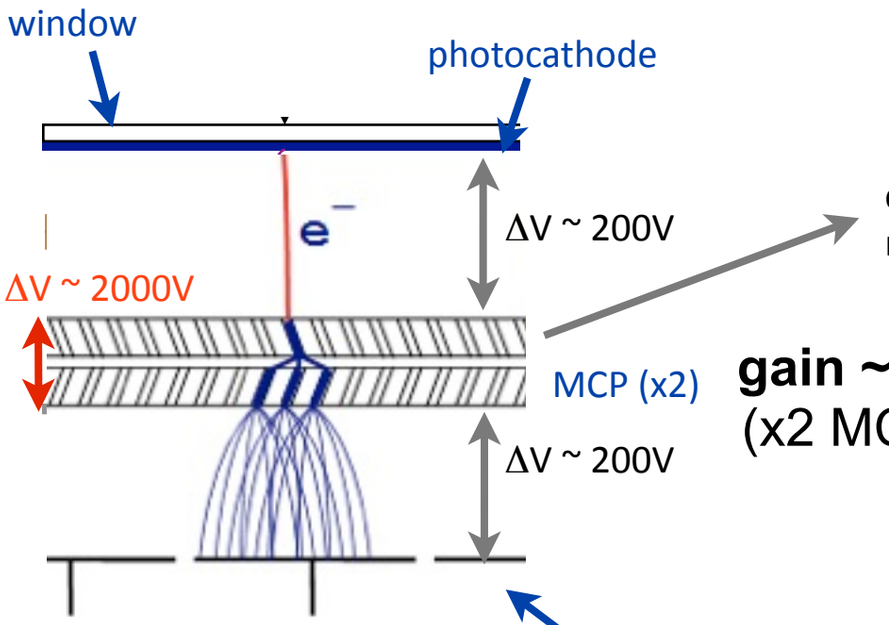
Micro channel plates (MCP) PMTs

- lead glass plate perforated by an array of cylindrical holes (few μm diam.) (channels), placed between PC and anode
- inner surface of each channel : continuous dynode









chevron configuration
reduces the positive ion feedback

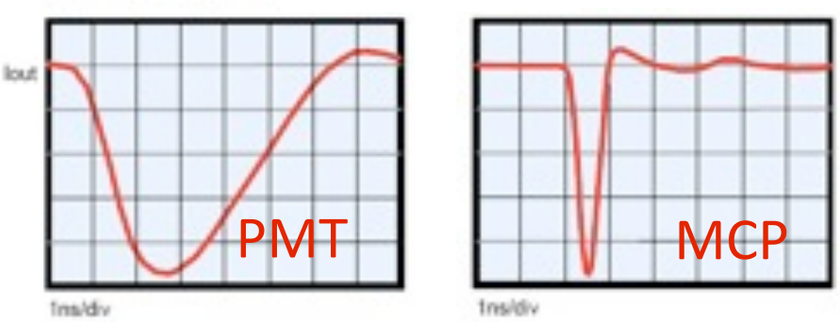
gain ~ 10^6
(x2 MCP)

- secondary emission gain (per strike) δ~ 2
- **gain = f (Length/Diameter , δ)**
- if L/D = 40 => typically 10 strikes
  => **gain** = 2^{10} **~ 10^3 (single plate)**

very fast response
excellent time resolution (δ ~ 20 ps)
tolerates magnetic field
up to 0.1 T random direction ; ~ 1T axial dir.
good spatial resolution (if segmented anode)

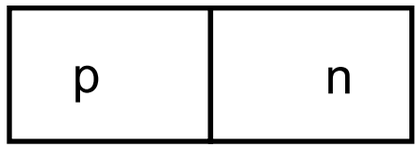
long recovery time per channel ; suffer from aging

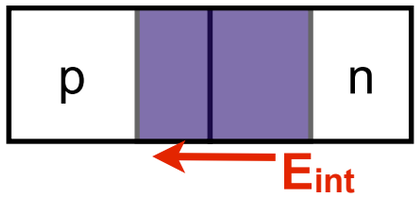
1 ns/div



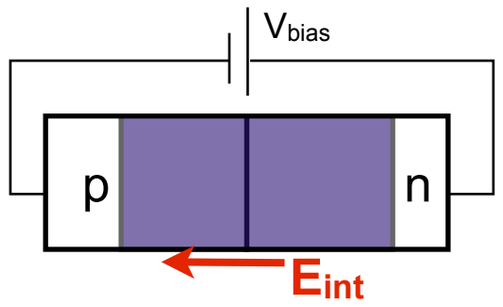
Si p-n junction as photodetector

Silicon p-n junction

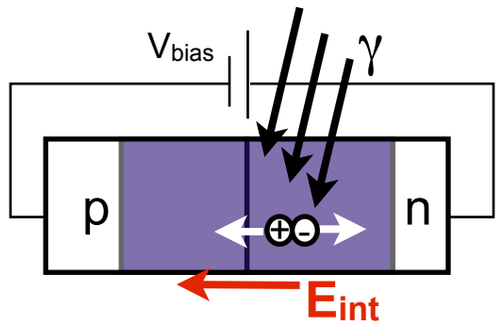




- charge diffusion => **depletion region**
- built-in E_{int} (which prevents further charge flow)

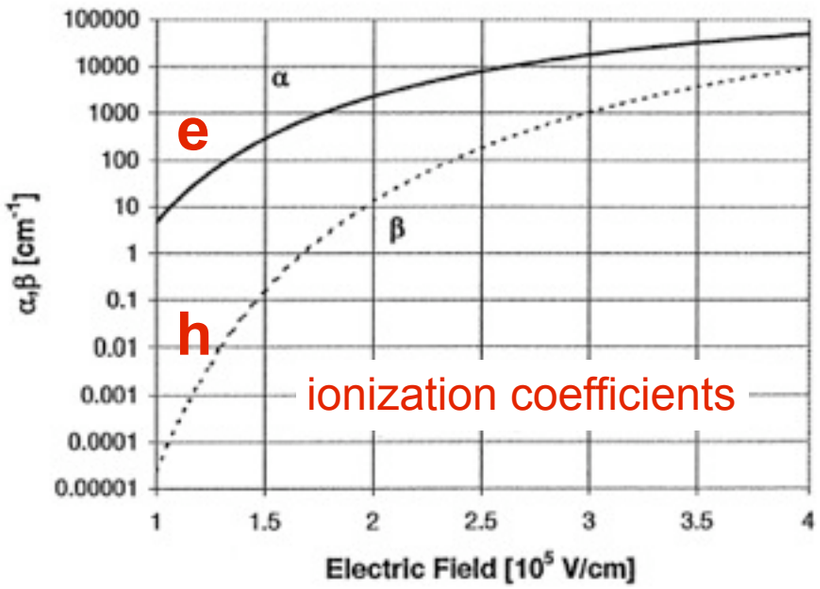


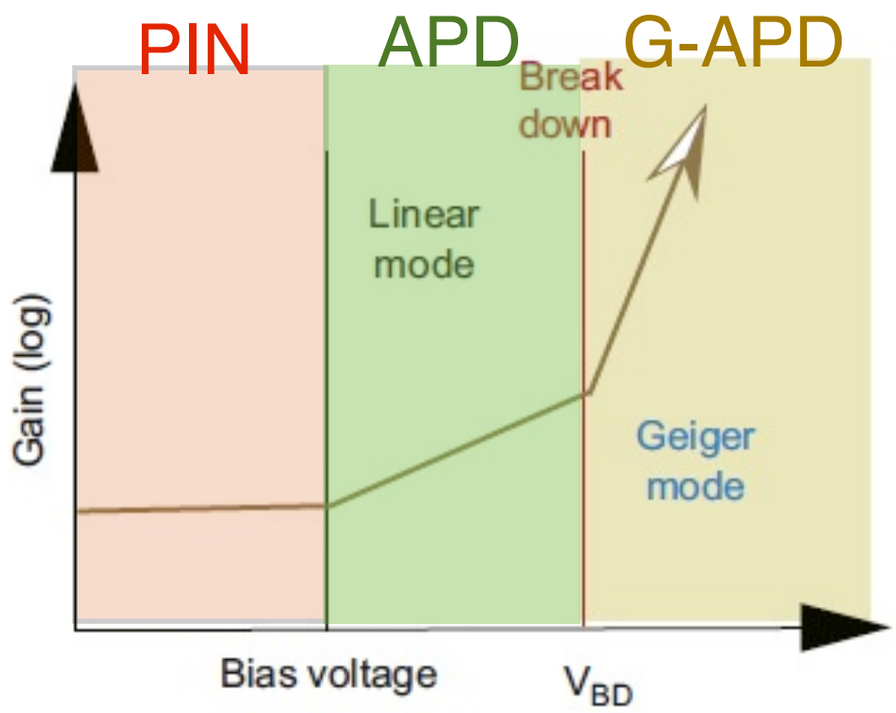
reversed biased p-n juction
increased size for the depl. region



- photon absorption in the depletion region => **eh pairs**
- charge separation in E_{int}
- **photocurrent**

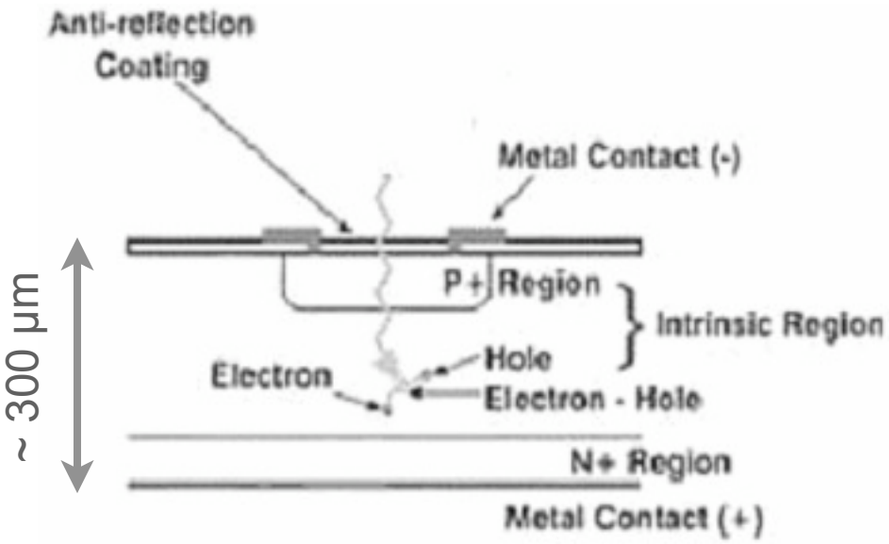
- p-n junction: works as photodetector even without bias
- bias => increase the depletion region
- increased bias => charge multiplication by impact ionization => Avalanche !
  - Vbias < Vbd : linearity mode (ionization by e, not h !)
  - Vbias > Vbd : Geiger regime (both e and h !)



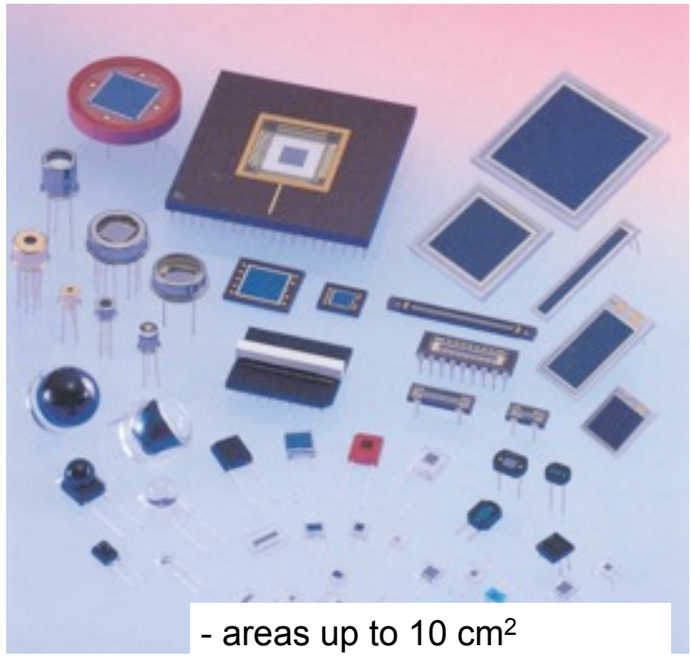


J. Haba, NIM A 595(2008) 154-160

PIN photodiode

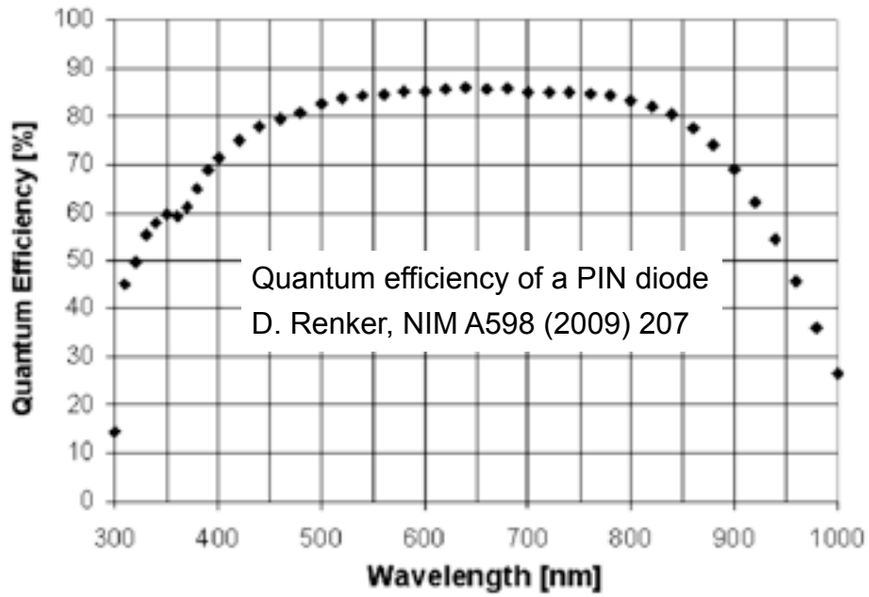


•**p-n junction** : intrinsic piece (i) of semiconductor sandwiched btw heavily doped p and n regions [p-i-n]



- areas up to 10 cm^2
- arrays (i.e. pos. sensitive)

- no bias required, or very little **(0 < V_{bias} < few Volts)**
- **no internal gain**
  - **no single photon detection**
  - min. detectable light flash ~ few 100's photons
  - external amplifier needed (noise , time)
- **QE ~ 80%** @ 500 - 800 nm

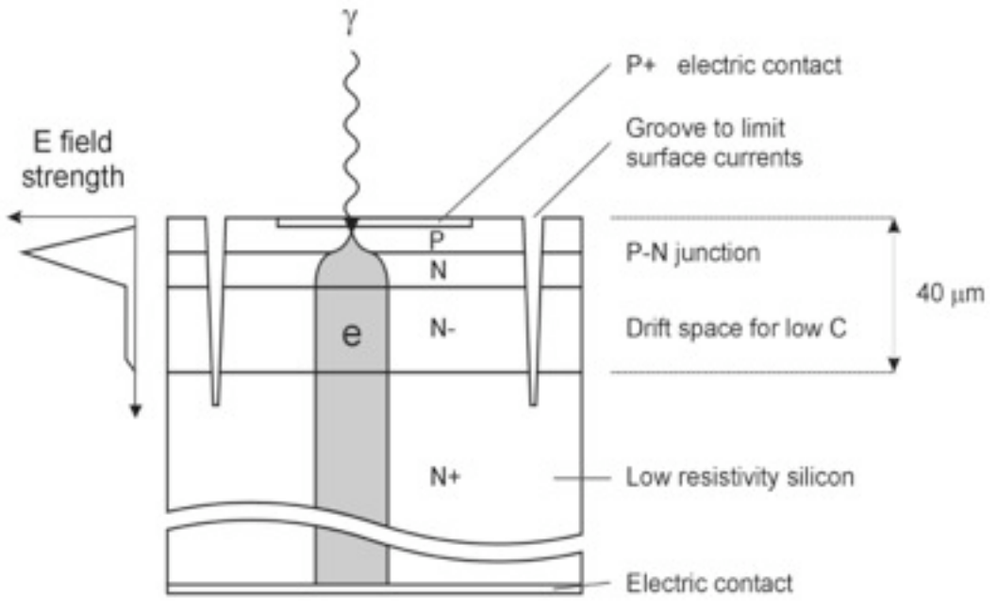


- simple / reliable / very successful device, widely used in HEP on large scale applications (small volume, insensitive to magnetic field, high QE)

Avalanche PhotoDiode (APD)

combine the advantages of Si detector (high QE, insensitivity to magnetic field, compactness)
with those of PMT (internal multiplication, gain)

reverse APD, Hamamatsu S8148
used in CMS ECAL

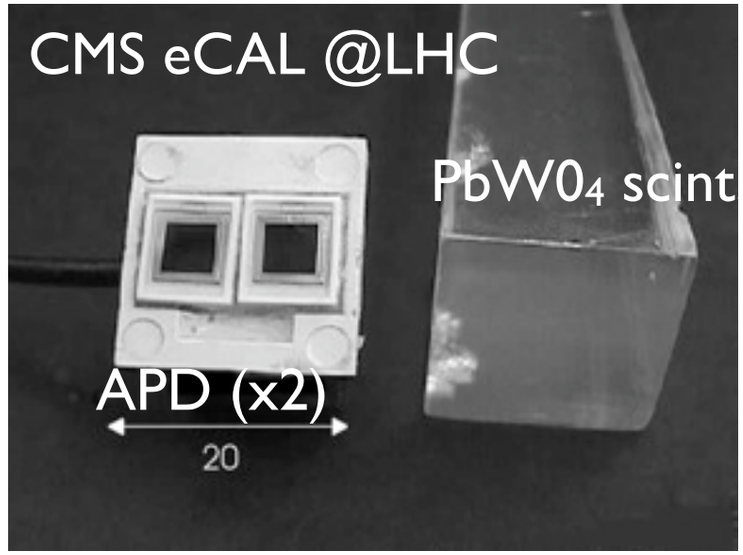


APD, Hamamatsu S8148:

very thin (<5μm) active layer before p-n (multiplication region)

30-40μm n-drift region (low C => low noise)

working gain ~ 50 (V~70V)



- external bias required
- avalanche multiplication of carriers, due to the **high internal field**
  - avalanche dominated by the e
  - develops in one direction (p to n) and multiplication stops when low field region reached
  - in linear regime (far from saturation i.e. very high Vbd [n-resistivity])

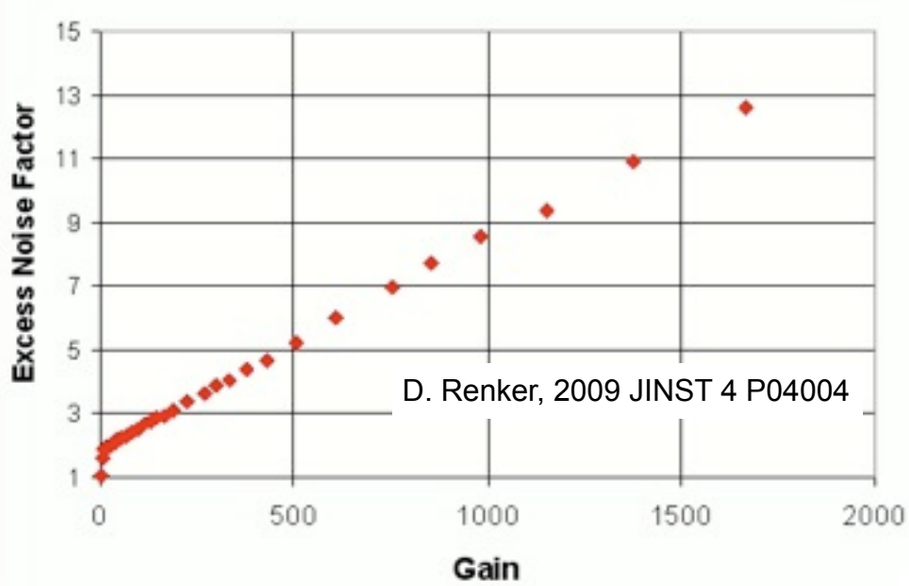
- **QE ~ 80%** [same as for PIN diodes]
- **gain: M ~ 50 - 500** M=f(V_{bias}), exponentially
- **V_{bias} ~ 100 - 200 V**

- avalanche multiplication => statistical fluctuations
  mostly due to h contribution to the avalanche

excess noise factor ENF

$$ENF \simeq 2 + \frac{\beta_{(holes)}}{\alpha_{(el)}} M$$

(increase in the noise wrt ideal - noiseless - multiplication)

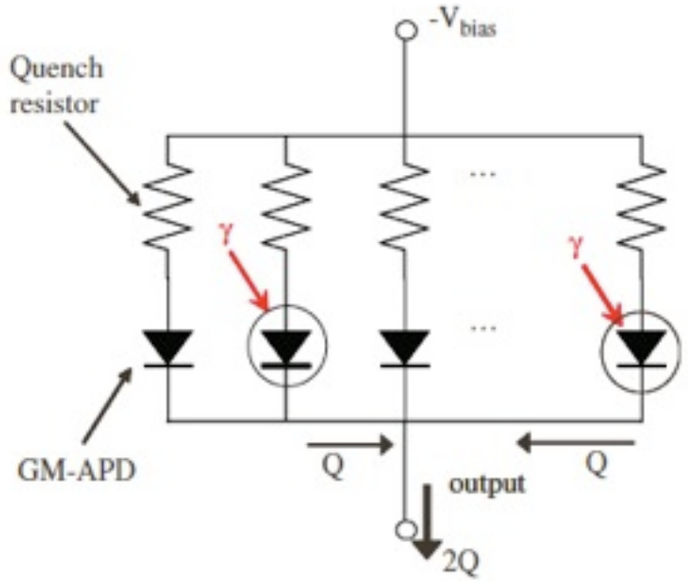


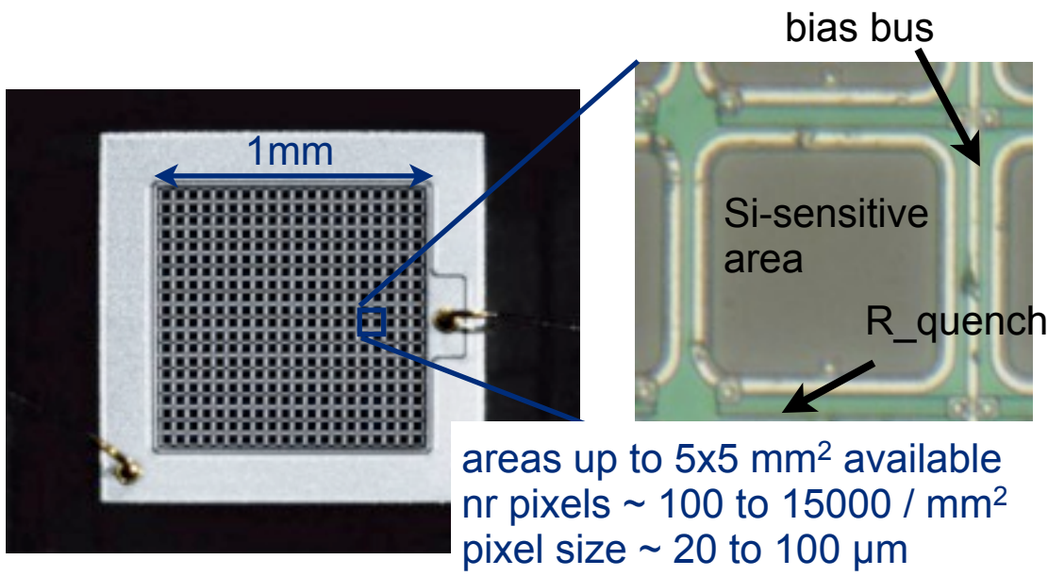
G-APD : Geiger mode APD

newest development in photo-detectors !!!

G-APD : array of micro-cells APD operated in Geiger mode ($V_{bias} > V_{bd}$)

All cells connected to a **common bias** through an **independent quenching resistor**, integrated within a sensor chip





areas up to 5x5 mm^2 available
nr pixels ~ 100 to 15000 / mm^2
pixel size ~ 20 to 100 µm

When hit by a photon, **each cell** releases a charge Qi (in the Geiger discharge):

$$Q_i = C\,(V_{bias} - V_{breakdown}) = C\,V_{ov}$$

- Geiger mode operation
  => no analogue info at the single cell level
- **G-APD output : analogue sum of the currents from all the activated cells**

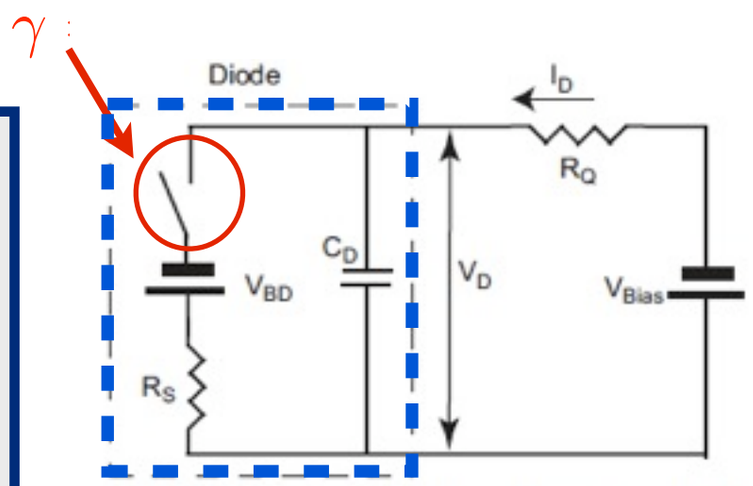


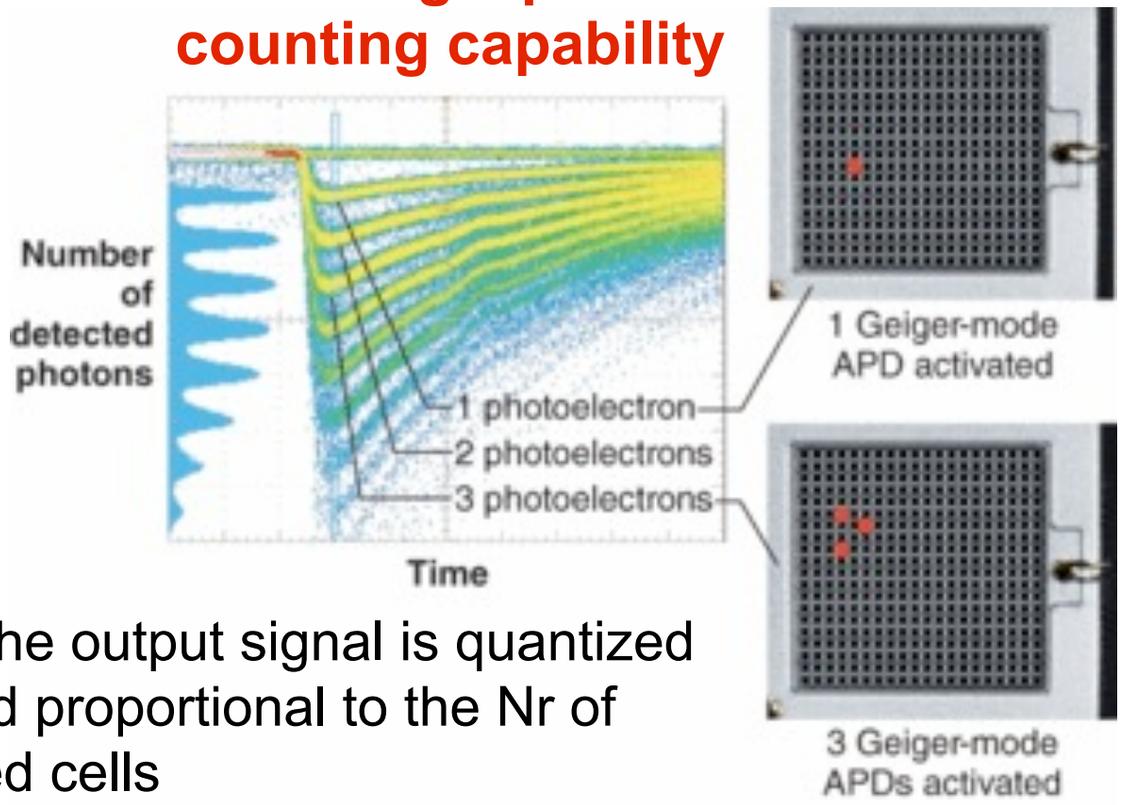
Fig. 4. Equivalent circuit of a single cell Geiger mode APD.

J. Haba, NIM A 595(2008) 154-160

very interesting BRAND NEW DEVELOPMENT : **digital G-APD** (which cells have been hit + time)

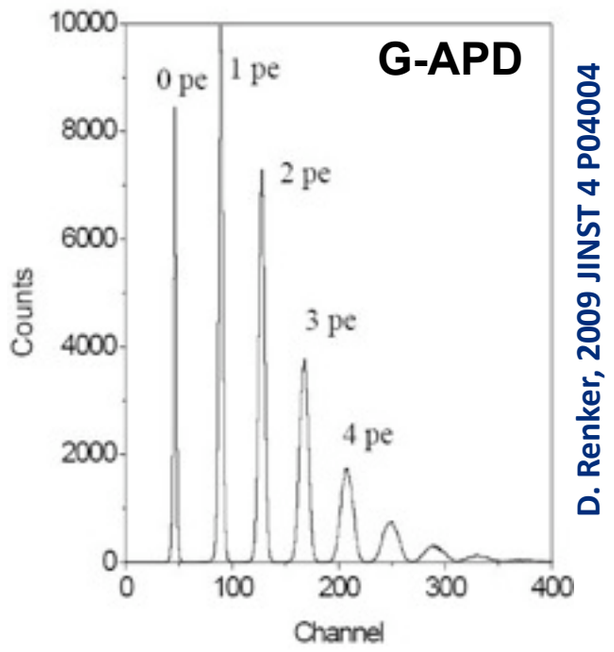
G-APD : photon counting

Excellent single photon counting capability

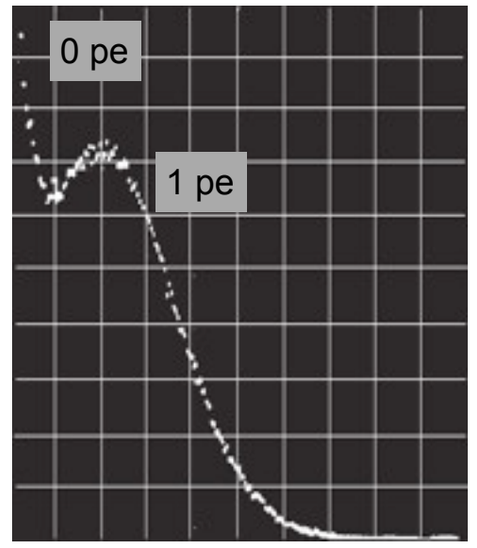


- The output signal is quantized and proportional to the Nr of fired cells

Pulse height spectra



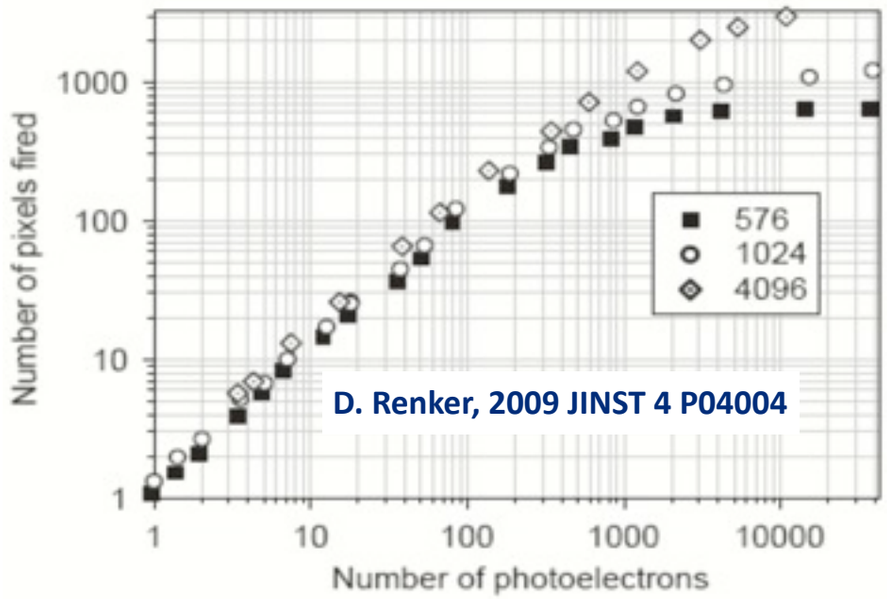
PMT (for comparison)



Intrinsic non-linearity in the response to high Nr incident photons

- Linearity as long as Nr_detected_photons < Nr_cells

$$N_{\gamma_det} = N_{cells}\left(1 - e^{\frac{N_{\gamma_inc} \cdot PDE}{N_{cells}}}\right)$$

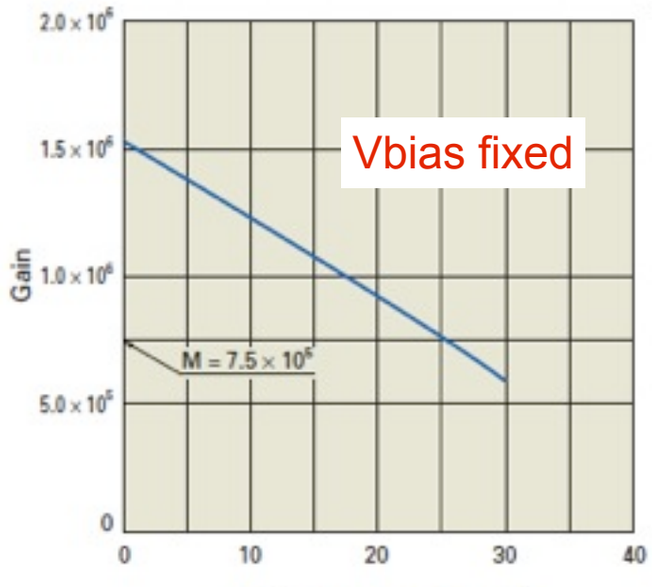


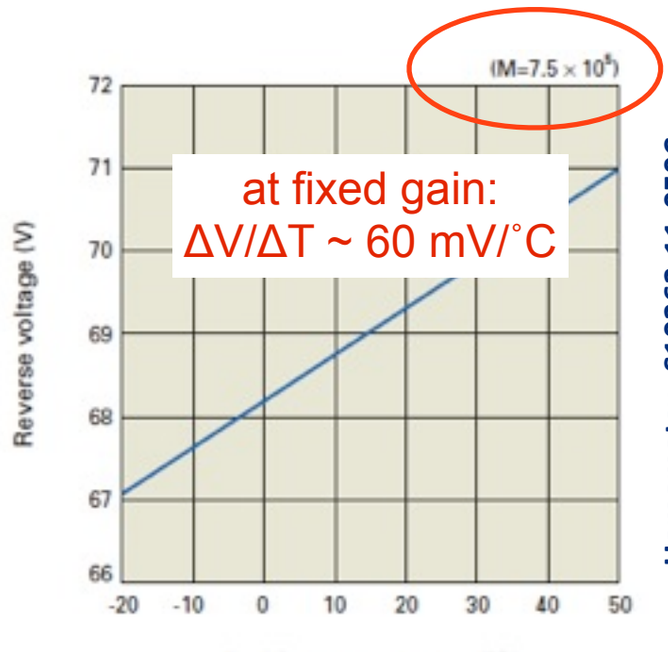
Gain and Photon detection efficiency of G-APD

- excellent **linearity of gain with V_{bias}** [$Q_i = C\ V_{ov}$]
- typical gains : **10^5 - 10^6**
- typical V_{bias} **~ 70 - 100 V**
- gain strongly dependent on temperature
  - higher T => bigger lattice vibrations
  - carriers may strike the lattice before ionization
  - ionization becomes more difficult

  (the same is true for APD detectors!)

T, V_{bias} must be precisely controlled!!!





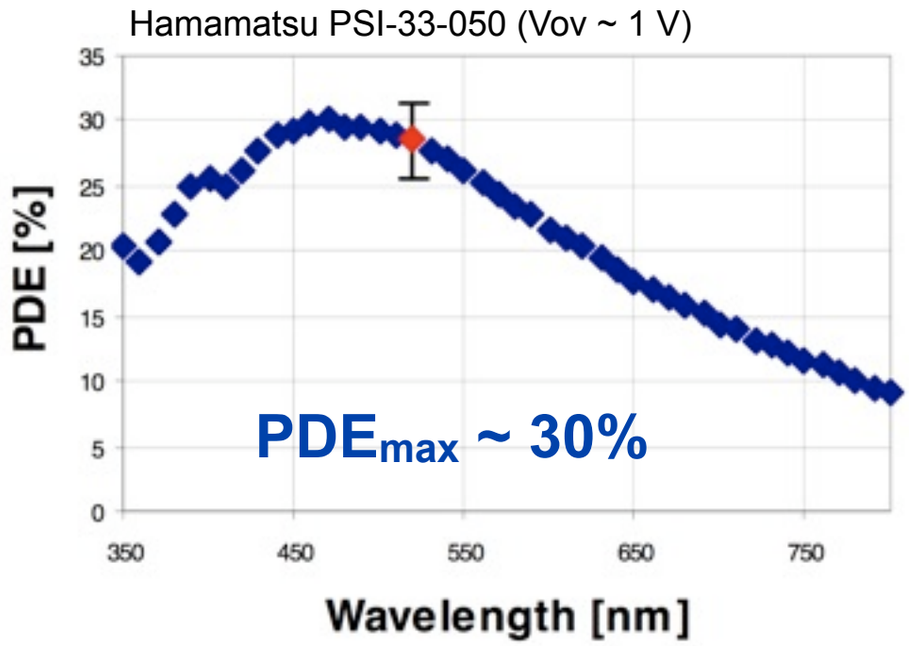
Hamamatsu, S10362-11-050C

$$PDE = (QE)\ (\varepsilon_{geom})\ (P_{Geiger})$$

QE = f(λ)

geometrical factor / fill factor
only part of the surface is photosensitive
f (Ncells) ~ 40% - 80%

probability to trigger a Geiger discharge ,
$f(V_{ov})$



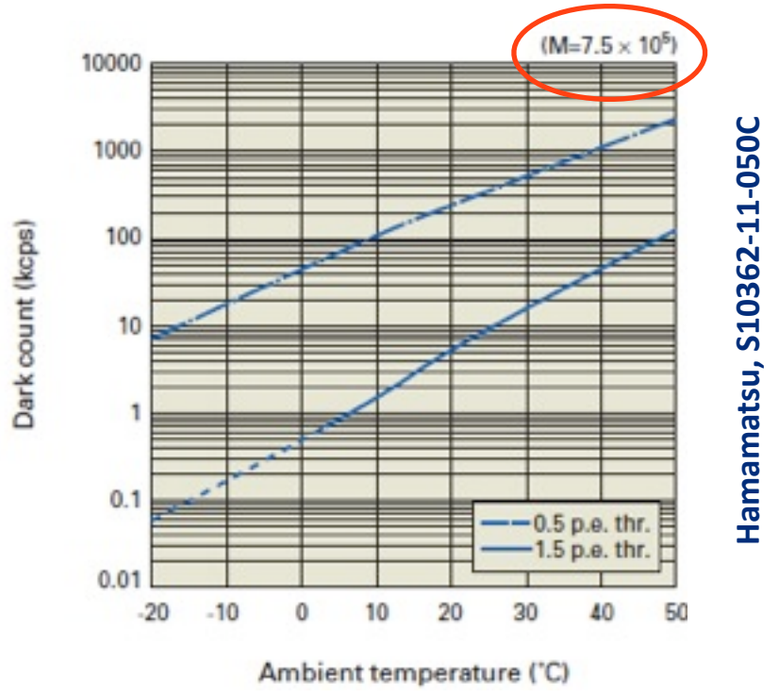
D. Renker, 2009 JINST 4 P04004

very thin sensitive layer
=> QE / PDE peaks at relatively narrow range

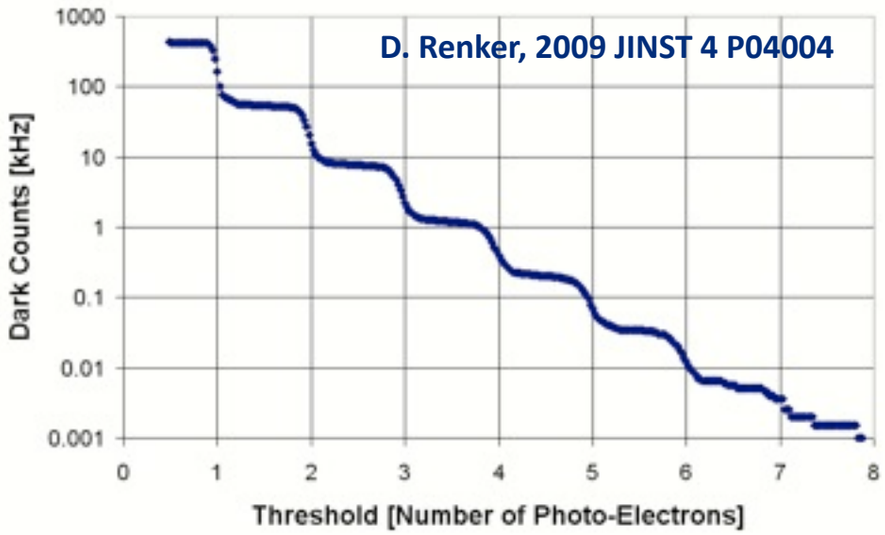
G-APD noise

- **Dark counts:**
  mainly by thermal generation

  typical Dark Count Rates (DCR) :
  100 kHz - few MHz (@ 0.5 pe thr)



Hamamatsu, S10362-11-050C



- **Optical cross-talk:**
  - due to photons generated in the avalanche process ($3\gamma/10^5$ carriers, A. Lacaita et al. IEEE TED 1993), being detected by neighbor cells
  - contribution added to the real signal
  - stochastic process => contribute to ENF

- **Afterpulses:**
  - charge carriers trapped in the lattice defects
  - then released with a certain time constant

G-APDs on the market

a few examples...

several names adopted for **G-APDs** :

SiPM (Si photomultiplier),
PPD (pixelated photodetector),
MPPC (for Hamamatsu),
MAPD (for Zecotek)
...

several producers, all aiming at : higher PDE , larger areas, lower noise, lower X-talk...

heavy impact on the design of future detectors

Advantages

- ✦ high gain (10^5-10^6) with low voltage (<100V)
- ✦ low power consumption (<50mW/mm²)
- ✦ fast (timing resolution ~ 50 ps RMS for single photons)
- ✦ insensitive to magnetic field (tested up to 7 T)
- ✦ high photon detection efficiency (30-40% blue-green)

Possible drawbacks

- ✦ high dark count rate (DCR) at room temperature
  - 100 kHz – 1MHz/mm2
  - thermal carriers, cross-talk, after-pulses
- ✦ temperature dependence
  - VBD, G, Rq, DCR

Hybrid Photodiodes: HPD

combines **high sensitivity cathodes** of **PMT tubes** with **high resolution (spatial / energy)** of **Si sensors**

HPD working principle :

- Photo-emission from photo-cathode
- Photo-electron acceleration (ΔV ~10-20kV) up to a Si-sensor (for pe detection)
- Gain mechanism: No electron multiplication but **energy dissipation** in one step (through ionization and phonon excitation) of keV pe's in solid state detector anode
  => low gain fluctuations (Fano factor $F \sim 0.12$ in Si);
- Gain M:

$$M = \frac{e\Delta V - E_{thr}}{W_{Si}}$$

~1-2 keV : Energy loss in the non active Si material (Al contacts, n layer)

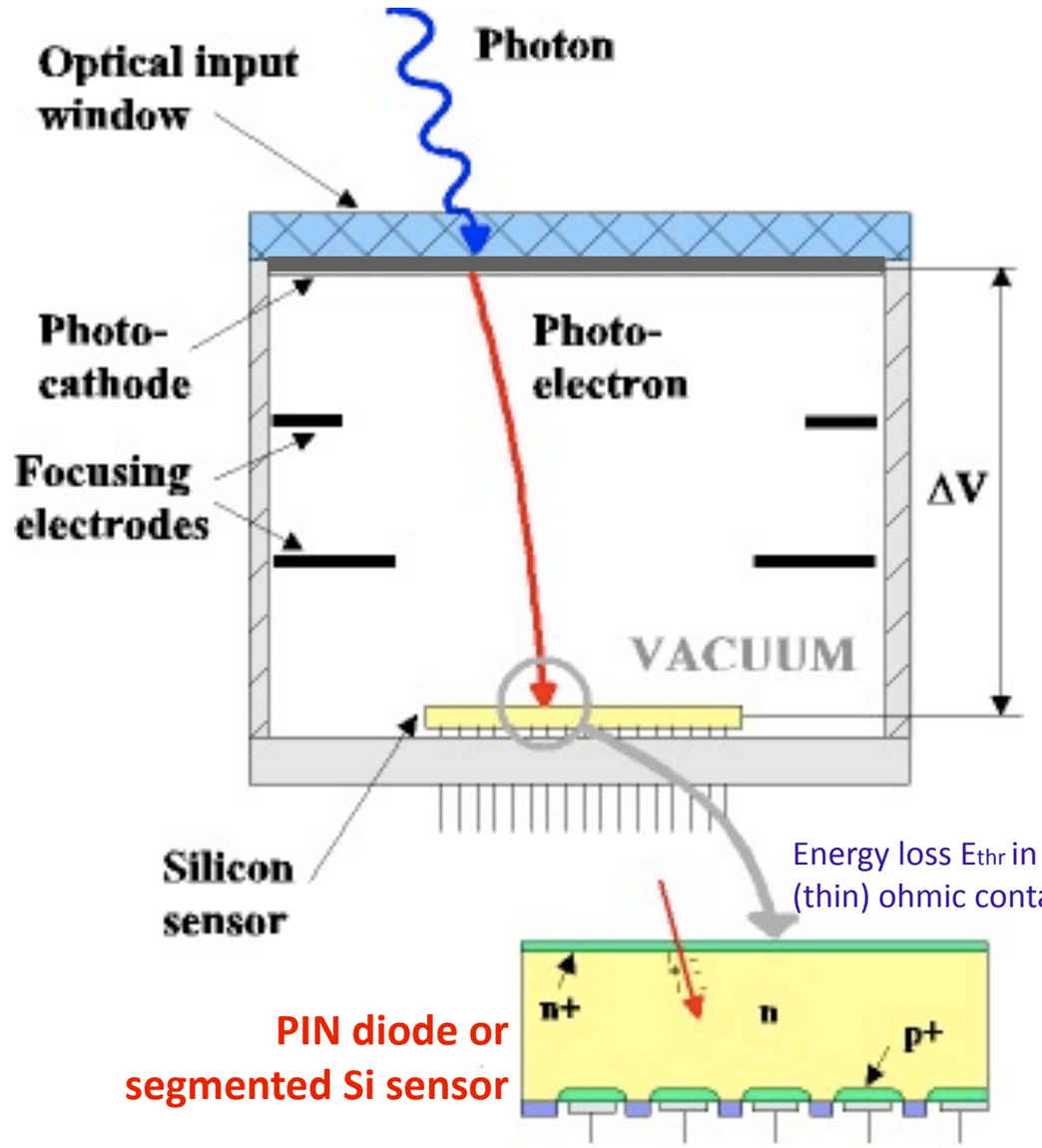
3.6 eV: Energy needed to create 1 e/h pair

- Intrinsic gain fluctuations σ_M :

$$\sigma_M = \sqrt{MF}\ ;\ F_{Si} \sim 0.12$$

- Example :

  ΔV = 20 kV => M ~ 5000, σ ~ 25
  => overall noise dominated by electronics

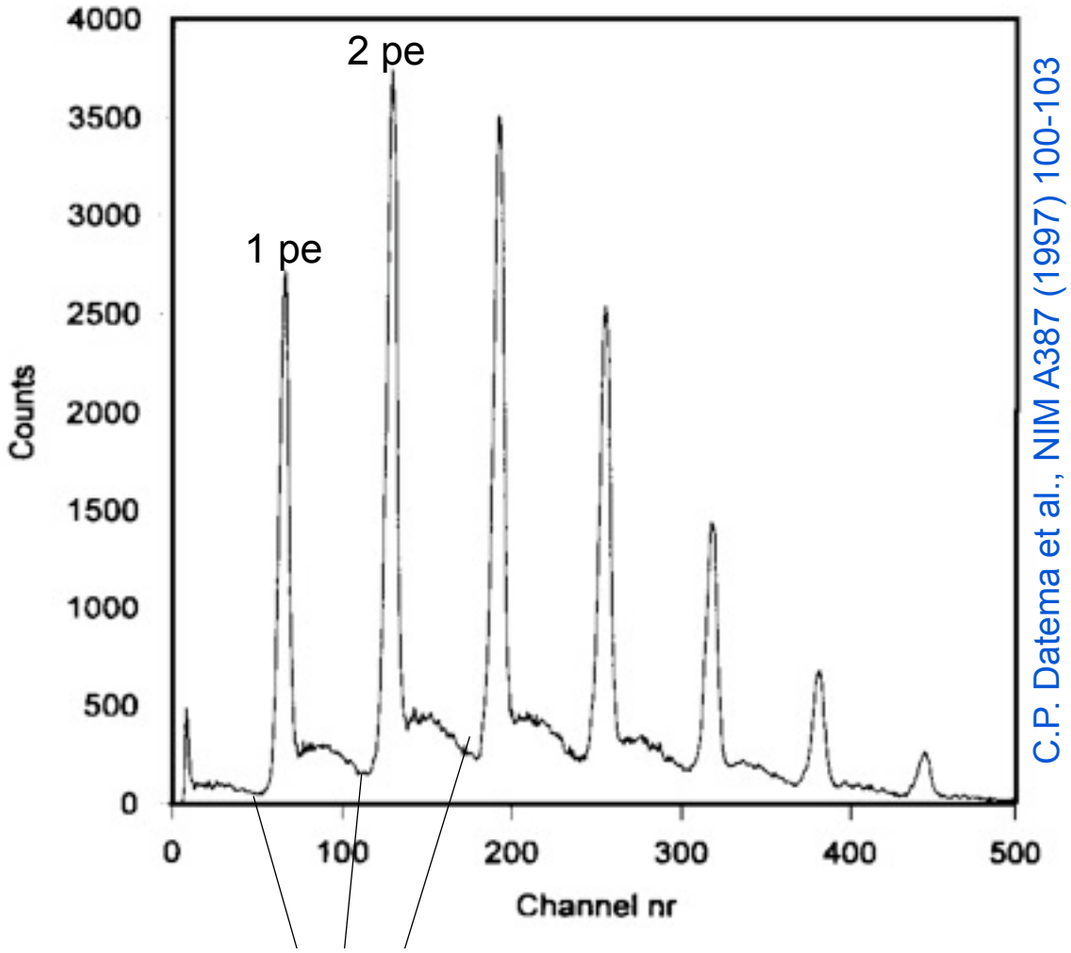


C. Joram, Nuclear Physics B (Proc. Suppl.) 78 (1999) 407-415

HPD properties

Single photon counting

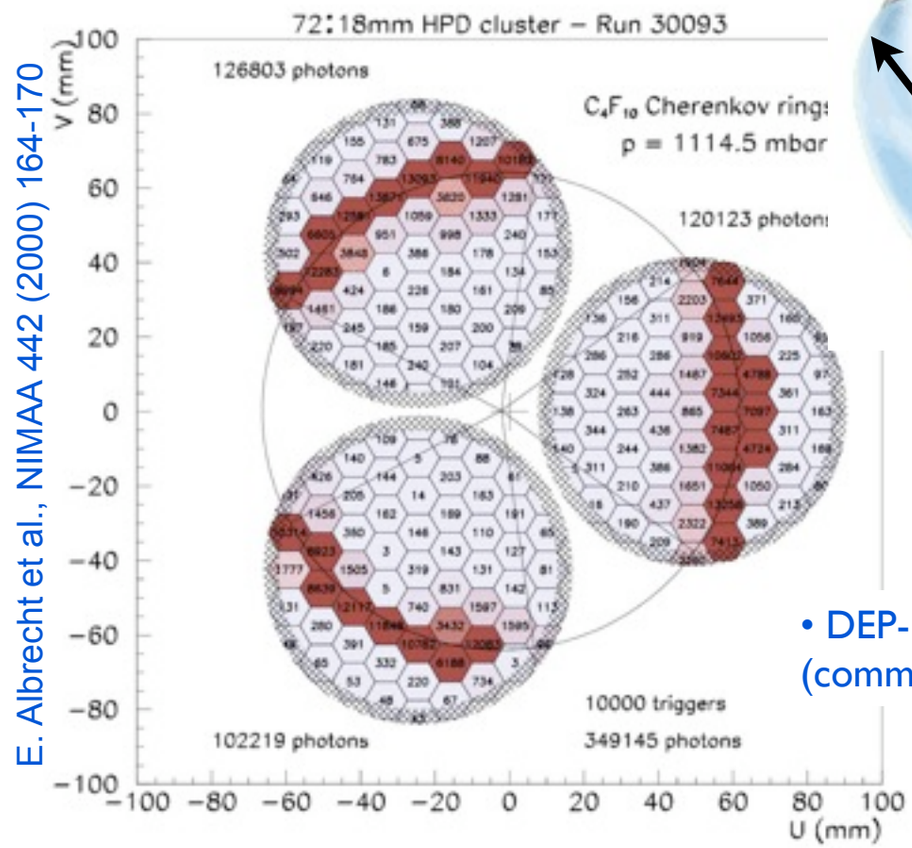
High gain, low fluctuations
=> Suited for single photon detection with high resolution

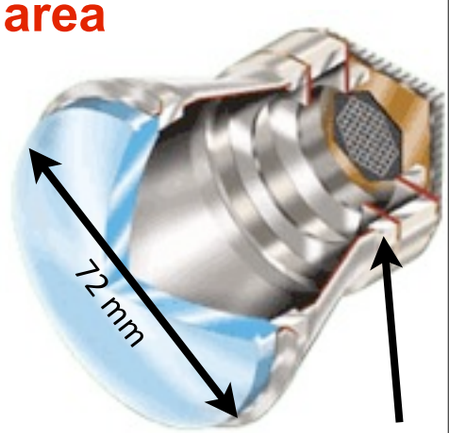


back-scattering of photoelectrons at Si surface
(α ~ 0.2 @ ΔV = 20 kV)
=> only a fraction of the total energy is deposited in Si
=> continuum background on the low En side of each peak

Spatial resolution

With a segmented Si sensor
=> HPD : position sensitive photodetector with high spatial resolution in a large area





segmented multi-pixel anode

- DEP-LHCb development (commercial anode)

The light image in the photocathode is projected into the Si sensor.

High spatial resolution determined by:
a) granularity of the Si sensor
b) focusing electron-optical properties

HPD on the market

a few examples...

- **High sensitivity cathodes** (as wells as PMTs)
- Dissipative / non multiplicative gain mechanism : **low gain fluctuations**
- **Segmented Si sensor**

fast detector
very good spatial resolution
very good energy resolution
photon counting capability
large areas coverage

standard commercial HPD configurations (from Photonis catalogue)

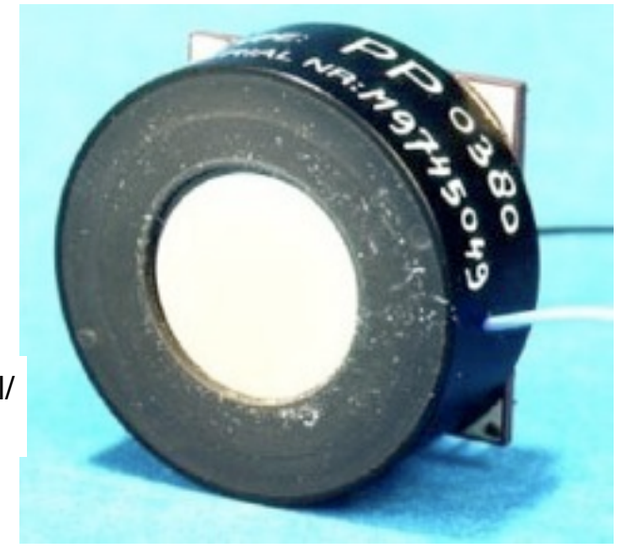
HPD Focus	Size	Number of pixels	Pixel size (mm)	Pixel configuration	Operating voltage (kV)	Entry window
Electrostatic	18	1	2	Single	15	Quartz
Electrostatic	40	1	2	Single	15	Quartz
Electrostatic	72	1	2	Single	20	Quartz
Electrostatic	72	61	2	Hexagonal	20	Quartz
Electrostatic	72	163	1.4	Hexagonal	20	Quartz
Proximity	18	32		In 2 circles	12	Quartz / F.O
Proximity	18	61	2	Hexagonal	12	Quartz / F.O
Proximity	18	163	1	Hexagonal	12	Quartz / F.O
Proximity	25	19	5.4	Hexagonal	12	Quartz / F.O
Proximity	25	73	2.7	Hexagonal	12	Quartz / F.O

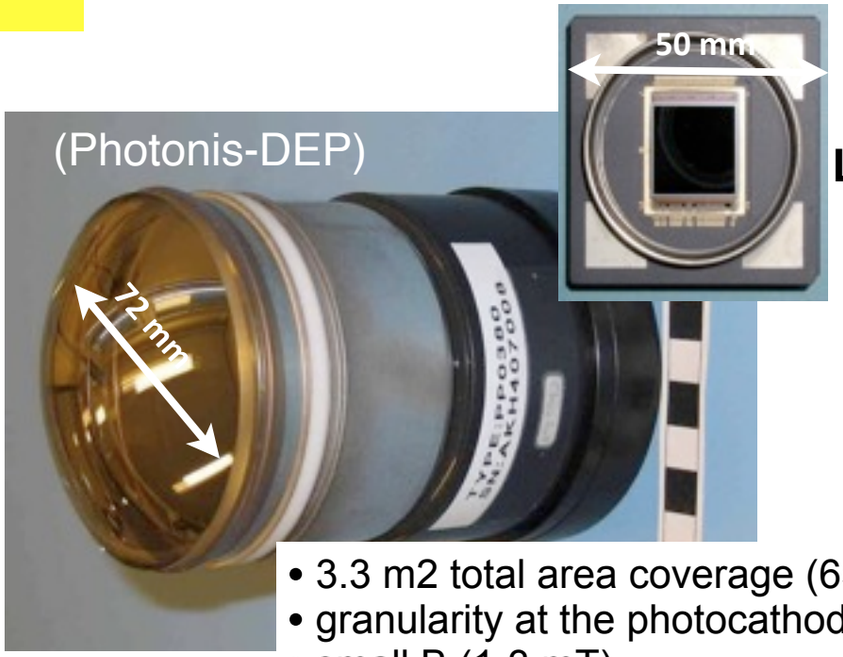
semi-commercial
for large scale applications at LHC

proximity focusing
CMS HCAL

- B=4T
- no demagnification
- 3.35mm gap
- HV=10kV

(http://cmsinfo.cern.ch/Welcome.html/CMSdetectorInfo/CMShcal.html)





cross focusing
LHCb RICH detector

(M. Moritz et al., IEEE TNS Vol. 51, No. 3, June 2004, 1060-1066)

- 3.3 m2 total area coverage (65% active; 484 HPD)
- granularity at the photocathode : 2.5 x 2.5 mm^2
- small B (1-3 mT)
- custom made anode
- x5 demagnification

Photodetectors: SUMMARY

There is a large variety of photodetectors and “the perfect one” does not exist.
But you can choose the best match with your application !

only approximate and indicative summary table

		QE	gain	V_bias	single photon counting	Spatial resolution	Time resolution	ENF	Photo-effect
vacuum	**PMT**	~25%	10^6 to 10^8	0.5 - 3 KV	limited	no	~ 1ns	1 - 1.5	external
	MAPMT	~25%	~ 10^6	~ 1 kV	limited	yes	~ 0.1 ns	1 - 1.5	external
	MCP	~25%	~ 10^6	~ 2 kV	reasonable(*)	yes	~ 20 ps	~ 1 (*)	external
Si-detector	**pin**	~80%	1	0 < V < few V	no	no	(**)	1	internal
	APD	~80%	50-500	~ 100 - 200 V	no	no	(**)	2 (@G=50)	internal
	G-APD	max 80% (λ dep) PDE ~ 30%	10^5 to 10^6	< 100 V	yes	no	< 0.1 ns	≥ 1(***)	internal
hybrid	**HPD**	~25%	~ 10^3	10 - 20 kV	yes	yes	~ 1ns	~ 1	external

(*) = for MCP used in saturation regime
(**) = cannot be quoted, because device is not looking to single photons
(***) = ENF ~ 1, but for the cross talk contribution

not covered at all in this lecture :

- **Gas detectors**
- **Photographic emulsions**

- W.R. Leo, “Techniques for Nuclear and Particle Physics Experiments”, Springer-Verlag
- G. Knoll, “Radiation Detection and Measurements”, John Wiley & Sons
- J.B. Birks, “The Theory and Practice of Scintillation Counting”, Pergamon Press
- Photonis, “Photomultiplier tubes. Principles and applications”

particle detectors books

- PDG K. Nakamura et al. (Particle Data Group), **J. Phys. G 37, 075021 (2010)** http://pdg.lbl.gov/

PDG

- D. Renker, “New developments on photosensors for particle physics”, **NIM A 598 (2009) 207-212**
- D. Renker, E. Lorentz, “Advances in solid state photon detectors” , **2009 JINST 4 P04004**
- J. Haba, “Status and perspectives of Pixelated Photon Detector (PPD)”, **NIM A 595 (2008) 154-160**
- C. Joram, “Large area hybrid photodiodes”, **Nuclear Physics B (Proc. Suppl.) 78 (1999) 407-415**

inspiring papers

Bibliography

slides from past detector schools (available on the web) :

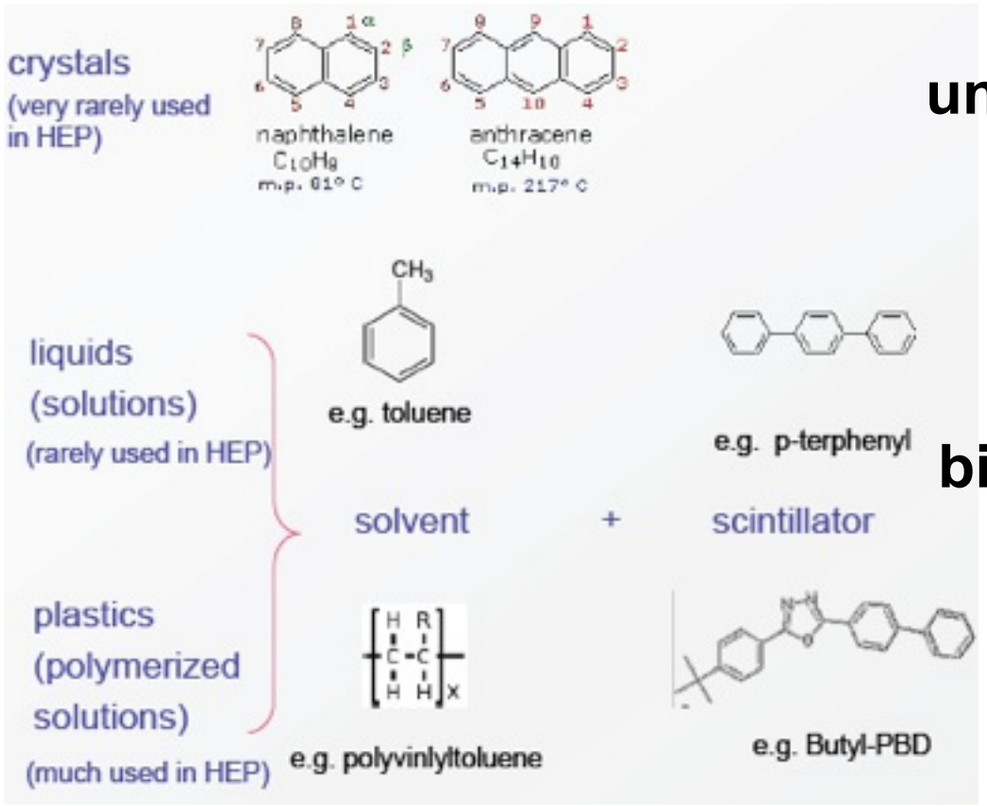
- Dinu, Gys, Joram, Korpar, Musienko, Puill, Renker - **EDIT School, 2011**
- C.Joram - **XI ICFA School 2010**
- F. Sauli - **CHIPP Winter School 2010**
- C.Joram - **ESI 2009**
- Gys, D’Ambrosio, Joram, Moll, Ropelewski - **CERN Academic training 2004/2005**

(Many thanks to the authors for the material re-used for these slides)

extra slides

Organic scintillators

- scintillation : **inherent molecular property** => independent on the physical state
  solid / liquid / vapors / solutions...
- organic scintillators exist as:



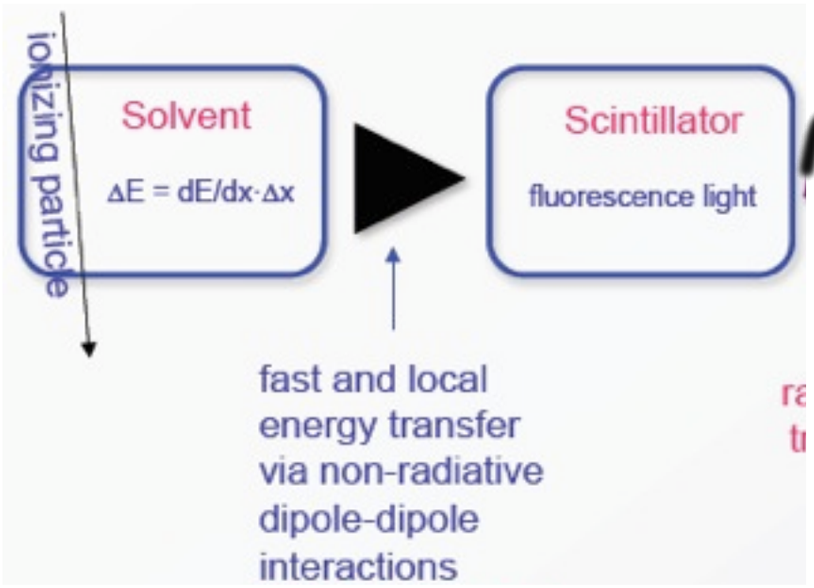
unitary systems

binary / ternary systems

in organic materials: before the de-excitation occurs, there is a substantial transfer of the excitation energy from molecule to molecule (dipole-dipole interaction, **Forster transfer**)

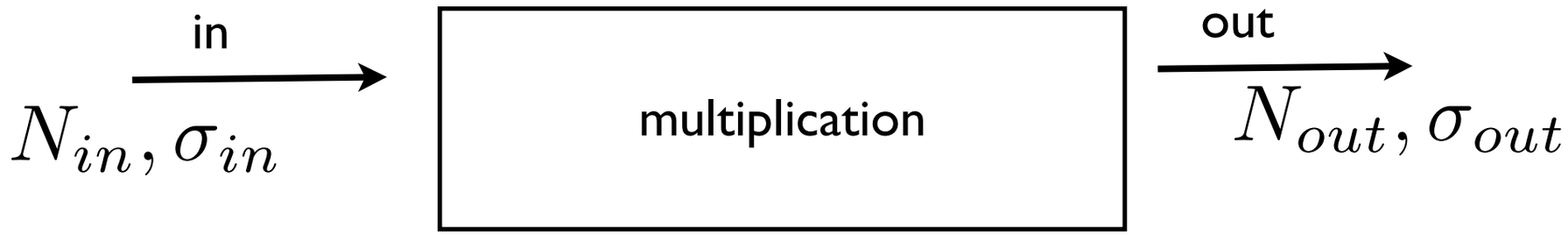
Solutions (liquid or plastic)

- solvent + solute(s) in small concentrations (<1%)
- the **solvent** molecules are excited by the incident particle: $\mathbf{(dE/dx)_{ion}}$**.** => energy absorption into **excitation**
- excitation transfered to the solute (**Forster transfer**)
- the **solute scintillates** (i.e. fluorescence light emission) at its own wavelength



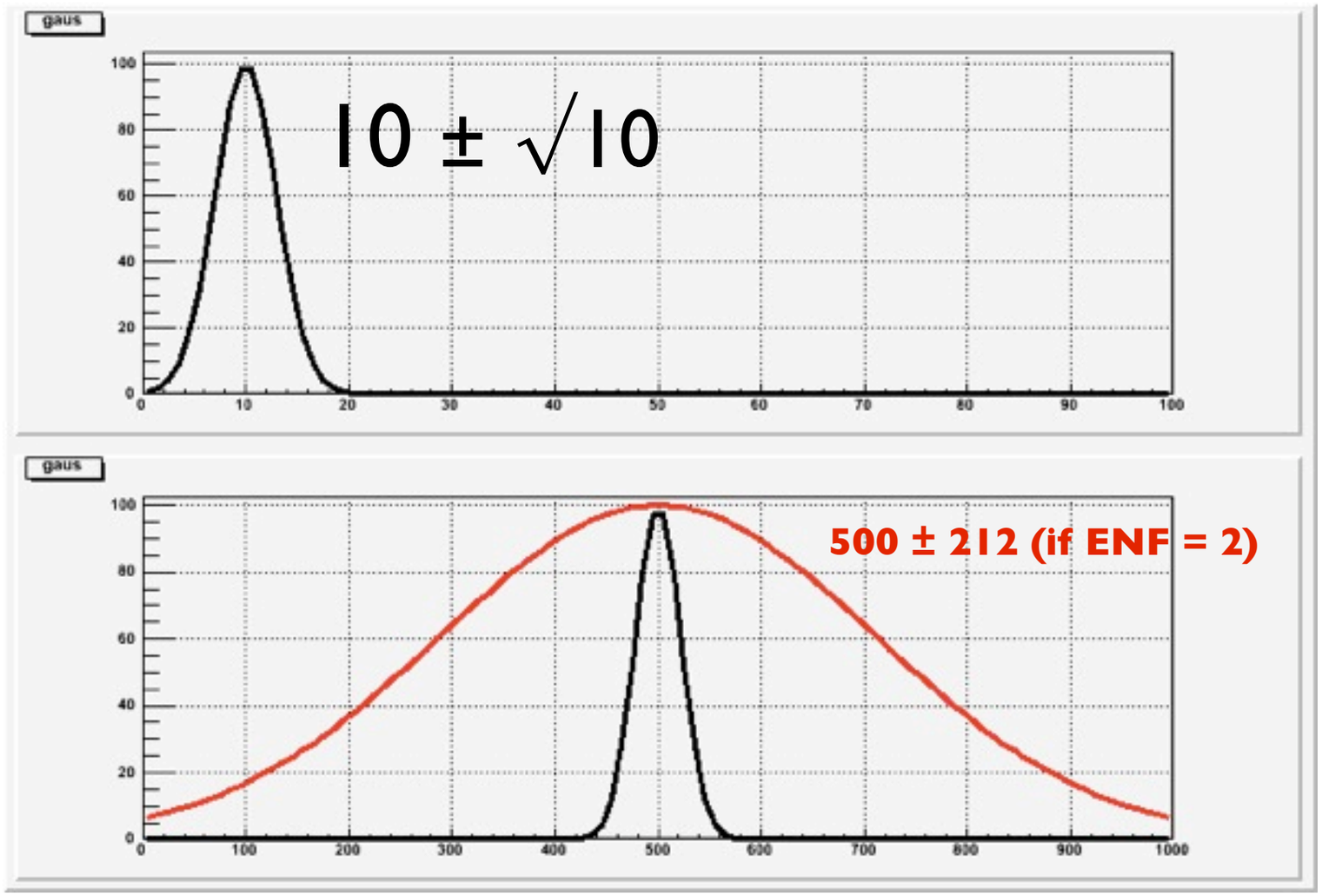
“Forster transfer”

EXCESS NOISE FACTOR (ENF)



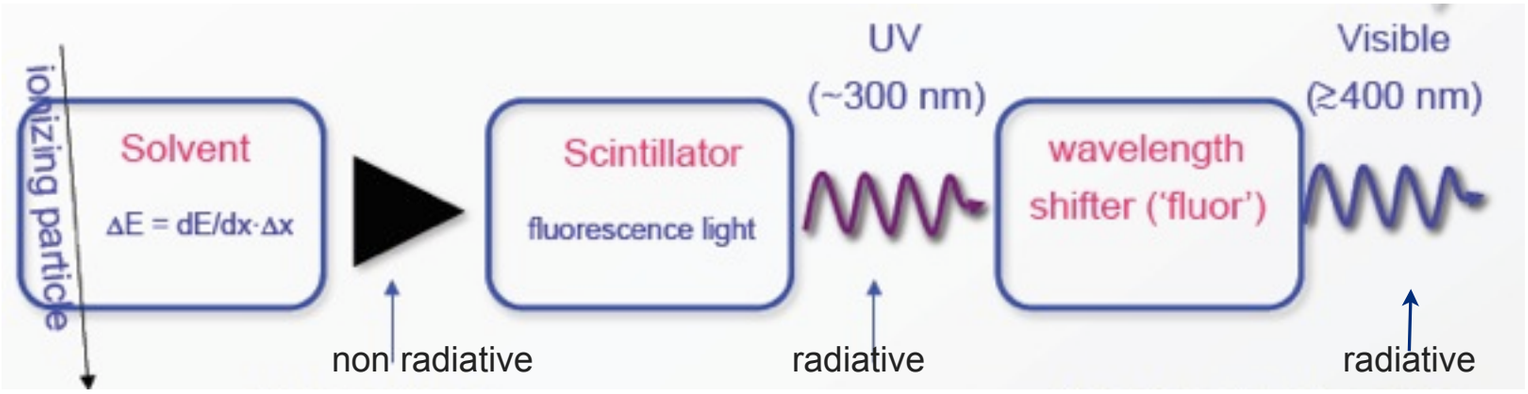
$$ENF = \frac{(\sigma_{out}/N_{out})^2}{(\sigma_{in}/N_{in})^2}$$

$$= \frac{\sigma_{out}^2}{G^2 \times \sigma_{in}^2}$$



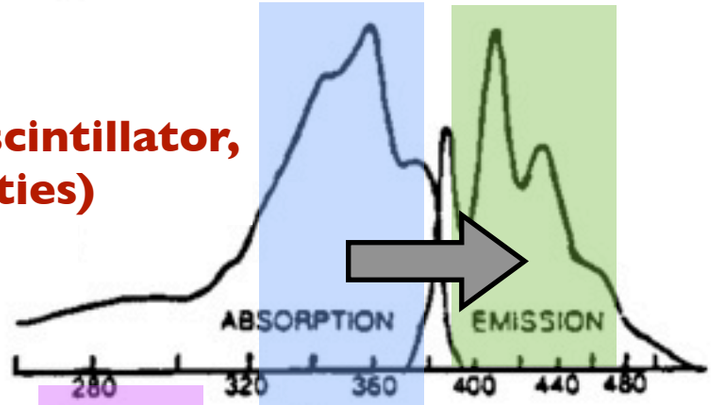
500 ± √500 ~ 500 ± 22

Organic scintillators and WLS

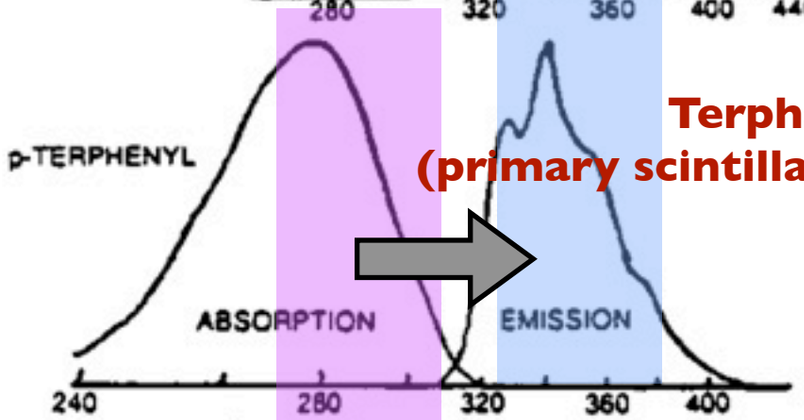


very common: addition of a second solute, which acts as a **wave length shifter (WLS)**

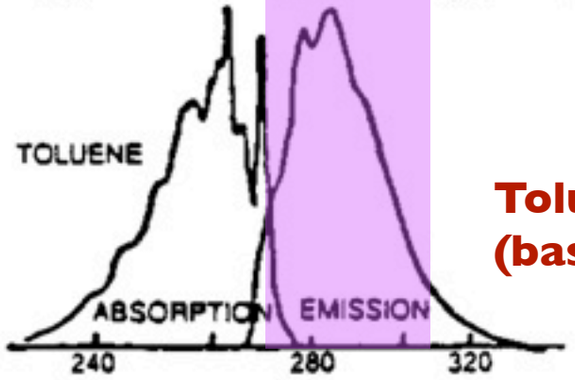
POPOP
(secondary scintillator, WLS properties)



Terphenyl
(primary scintillator)



Toluene
(base solvent)



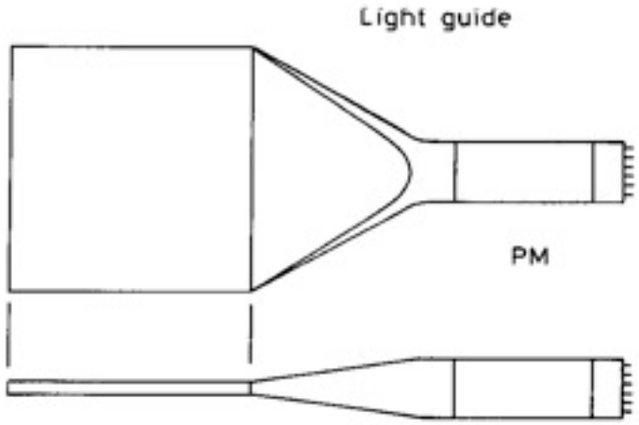
- **challenge** : **choose of the right substrate and adjust molecules concentration**
- very good matching with the spectral response of the photodetector
- large choice of emission wavelength
- **high transparency**: separation between the emission and absorption spectra
- **long attenuation lengths** (~ m) => large sizes possibilities
- plastic scintillators : **ease of fabrication**, flexibility in shape and dimensions
- **Small light output** (because of small solute concentrations)

Scintillator readout

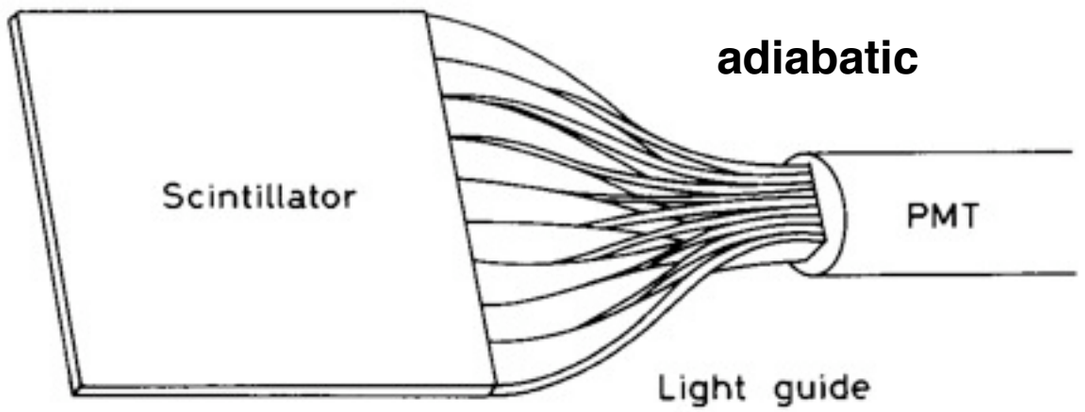
Readout has to be adapted to geometry, granularity and emission spectrum of scintillator.

Geometrical adaptation:

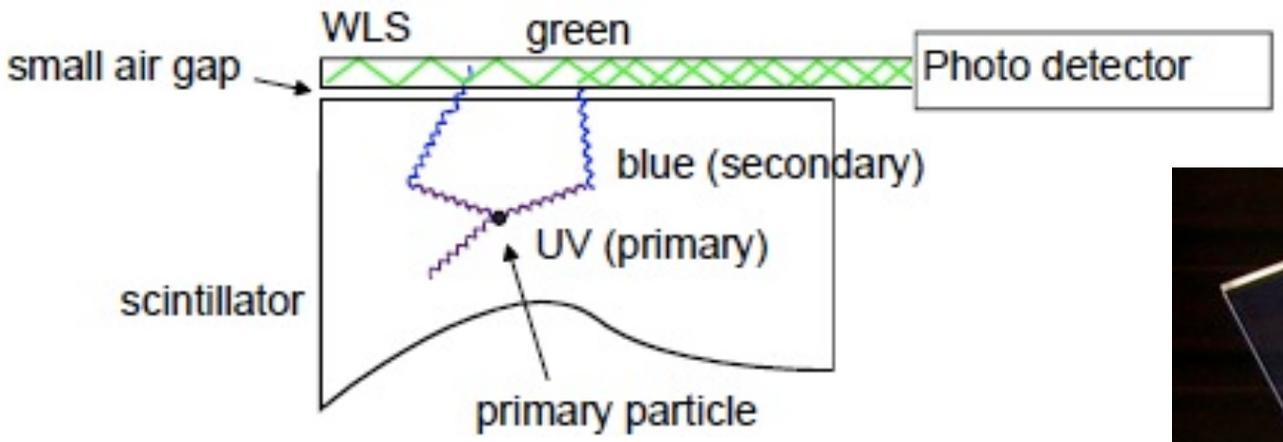
- **Light guides**: transfer by total internal reflection (+outer reflector)

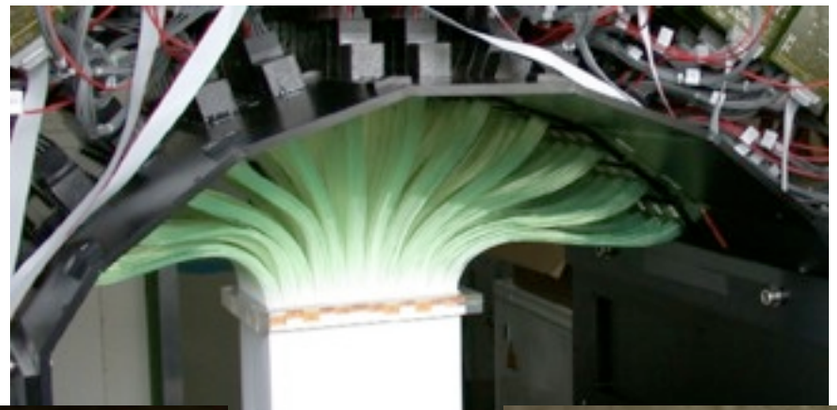


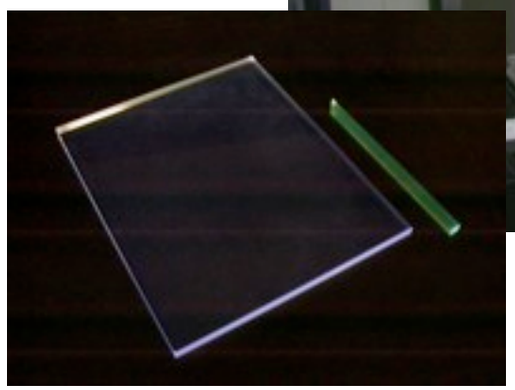
“fish tail”

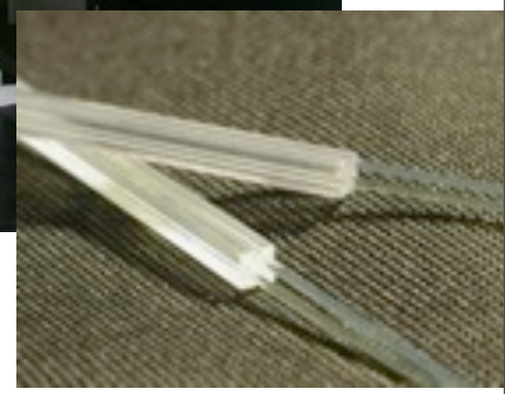


- **Wavelength shifter** (WLS) bars / fibers

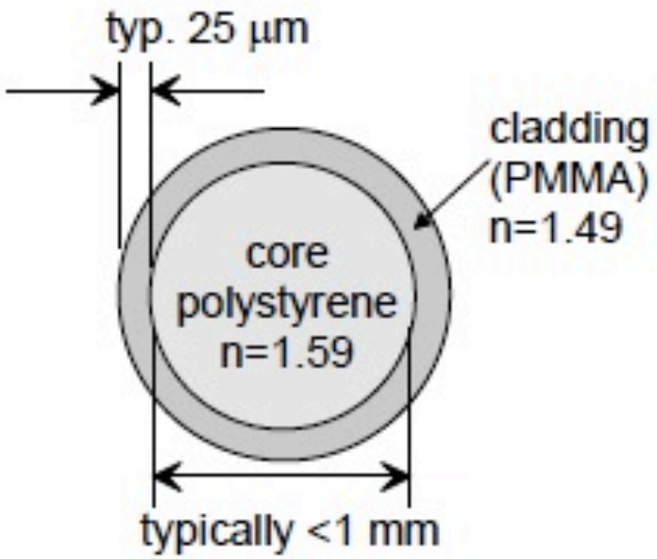




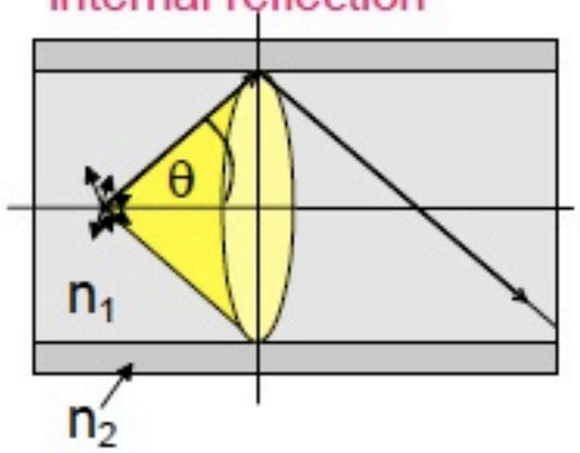




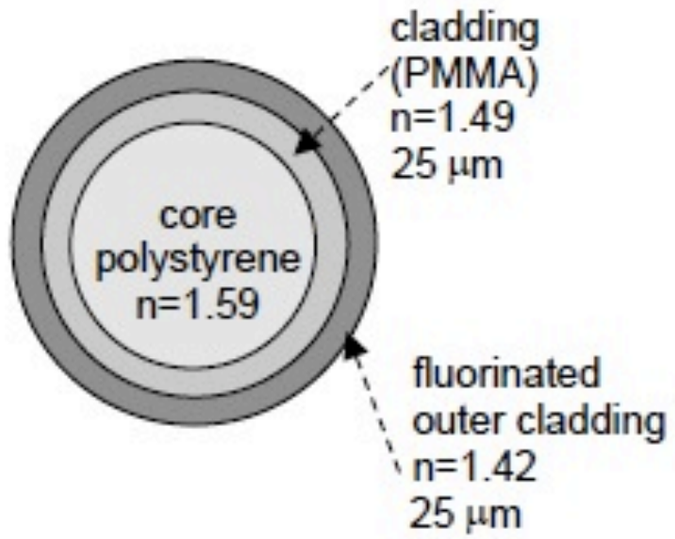
Scintillating fibers



light transport by total internal reflection



Double cladding system
(developed by RD7)

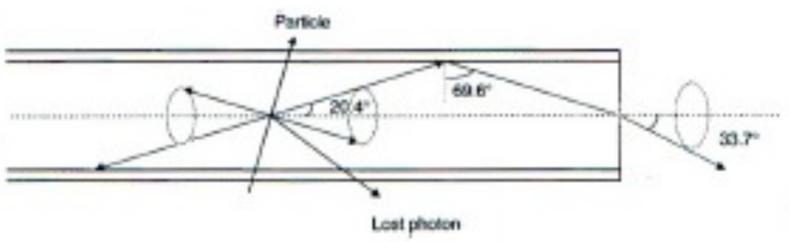


$$\frac{d\Omega}{4\pi} = 0.5\,(1-\cos^2\theta) = 3\%$$

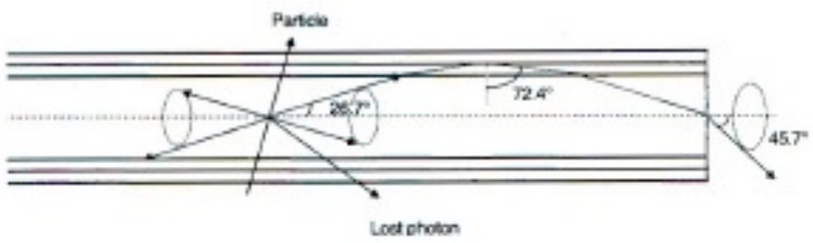
$$\theta \le \arccos\frac{n_2}{n_1} \approx 69.6^\circ$$

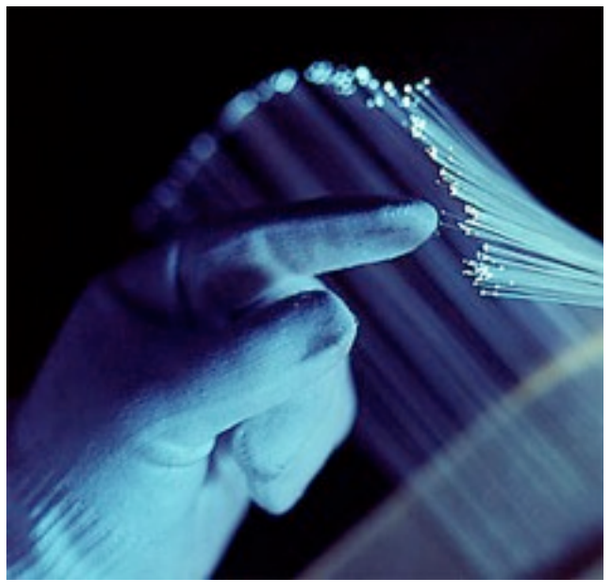
$$\frac{d\Omega}{4\pi} = 0.5\,(1-\cos^2\theta) \approx 5.3\%$$

SINGLE CLADDING



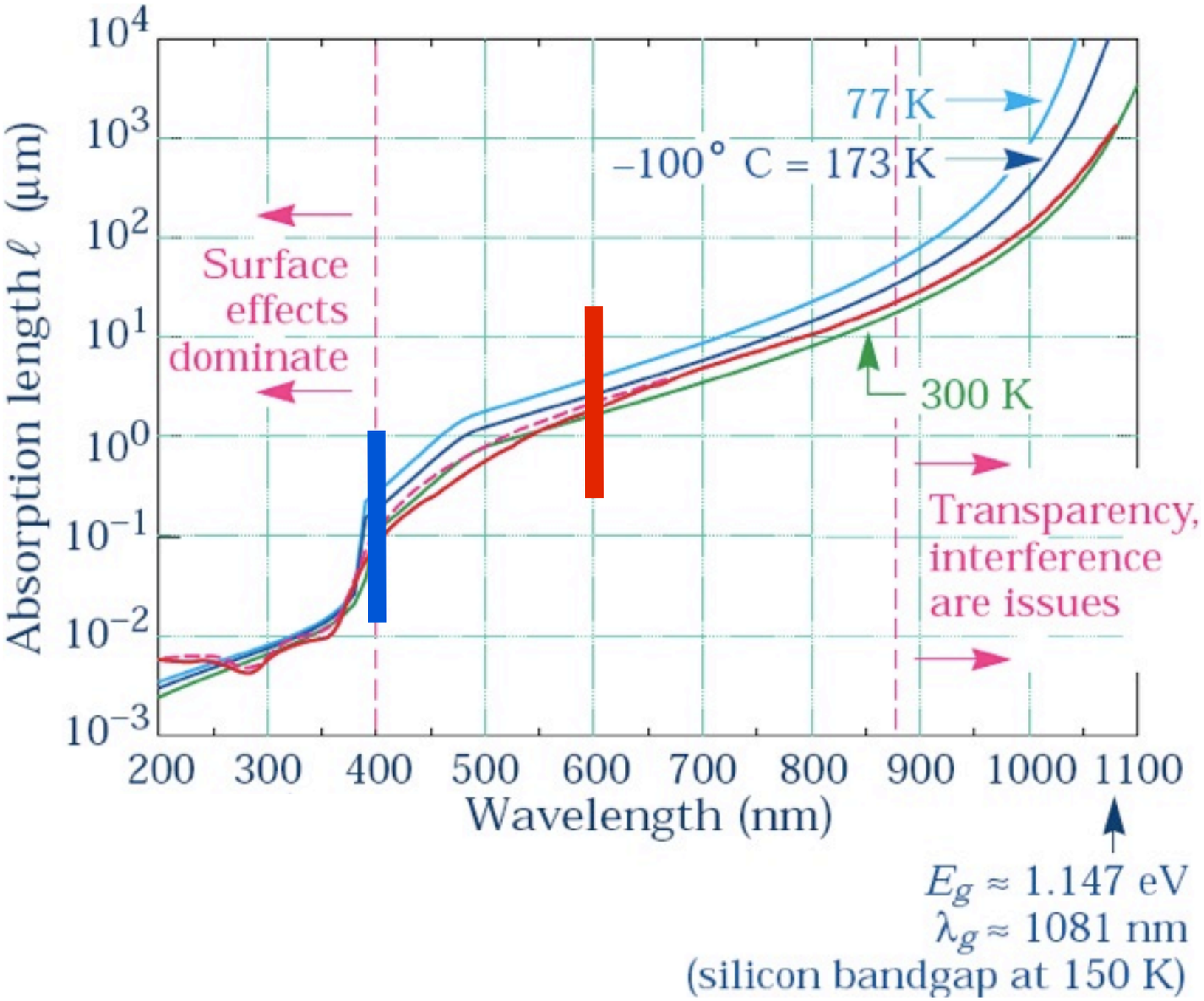
MULTIPLE CLADDNG





Fiber tracking system in HEP

Light absorption in Silicon



red light (λ ~ 600 nm)
=> ℓ ~ few μm

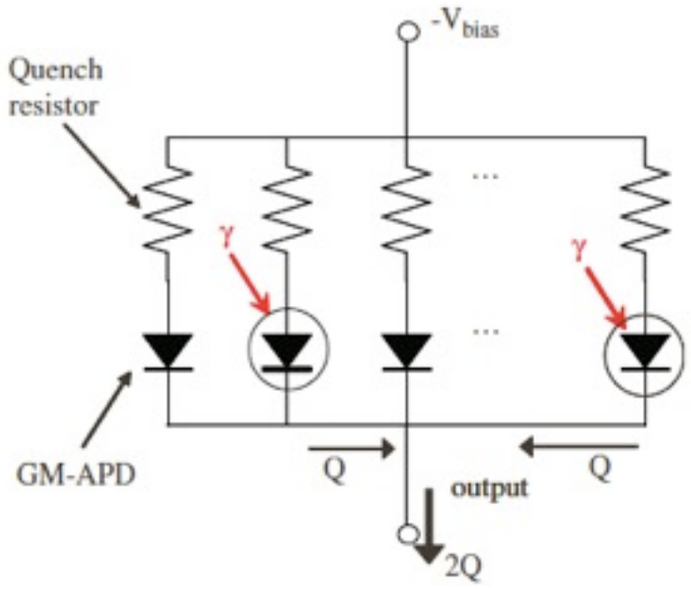
blue light (λ ~ 400 nm)
=> ℓ ~ 0.1 μm

red light penetrates deeper than blue !!

G-APD : Geiger mode APD

G-APD : array of micro-cells APD operated in Geiger mode ($V_{bias} > V_{bd}$)

All cells connected to a **common bias** through an **independent quenching resistor**, integrated within a sensor chip



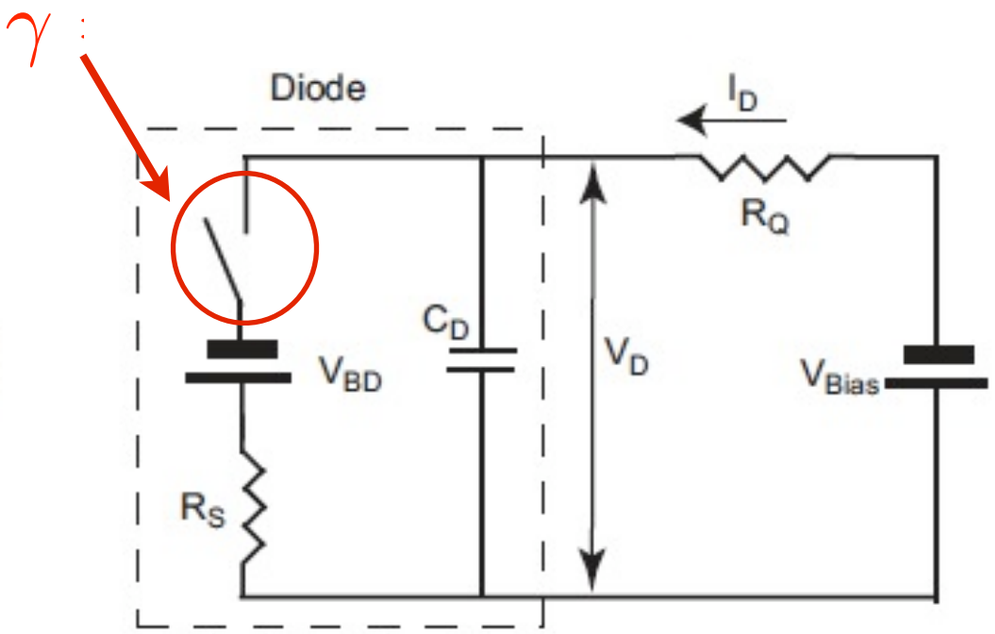


Fig. 4. Equivalent circuit of a single cell Geiger mode APD.

J. Haba, NIM A 595(2008) 154-160

➡ **each cell = capacitor (C)**

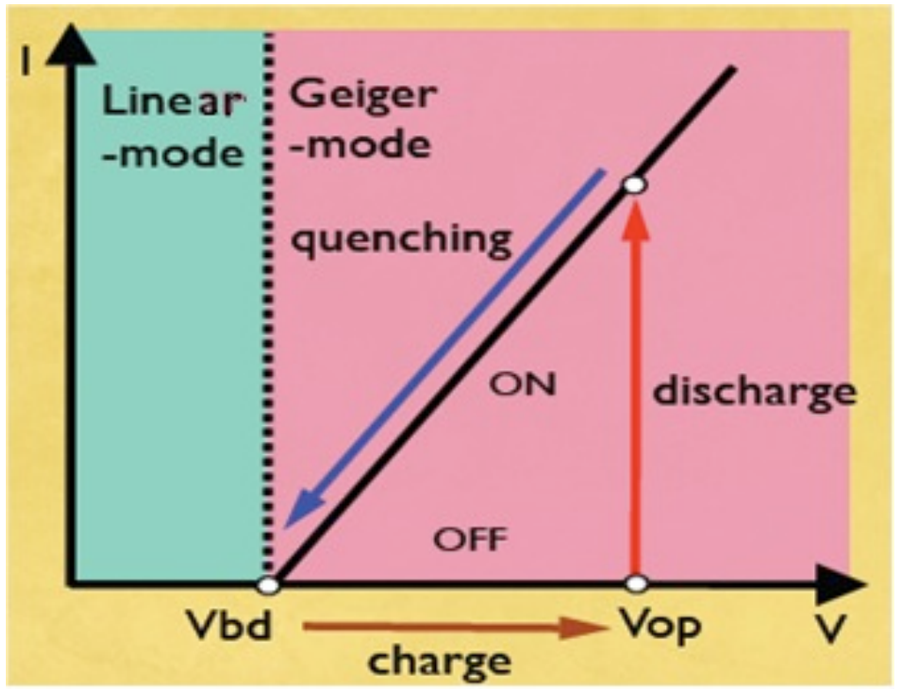
- V_{bias} => **charge**
- Photon conversion => **discharge**
- Charge released in a single Geiger discharge

  $Qi = C (V_{bias} - V_{bd}) = C V_{ov}$

- Current flows through R_Q

  => Avalanche **quenching**

  => Cell ready for the next discharge



➡ **G-APD output : analogue sum** of the currents from all individual cells

PDE : Photon Detection Efficiency

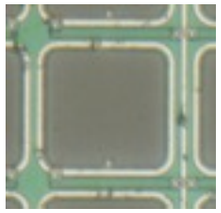
(PDE_{PMT} = (QE) (ε_collection) (P_multiplication))

$$PDE = (QE)\ (\varepsilon_{geom})\ (P_{Geiger})$$

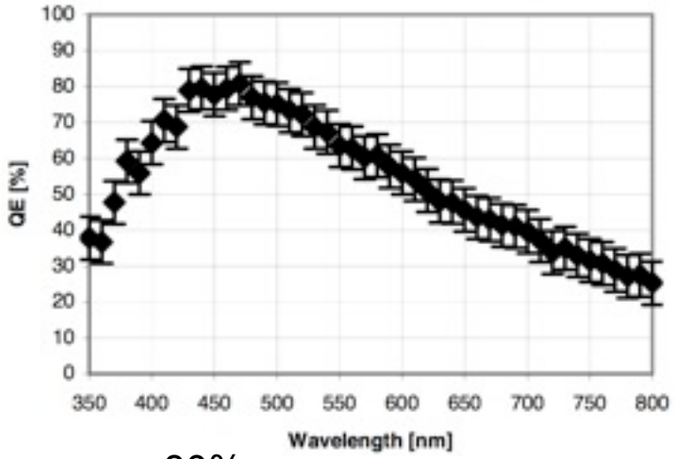
QE = f(λ)

probability to trigger a Geiger discharge , $f(\lambda, V_{ov})$

geometrical factor / fill factor
only part of the surface is photosensitive
f (Ncells) ~ 40% - 80%

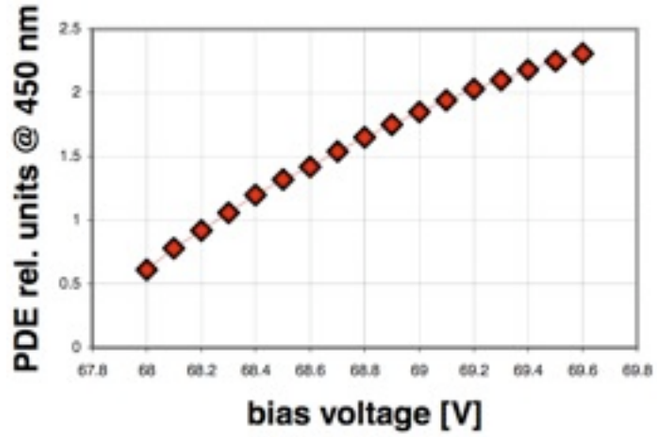


D. Renker, 2009 JINST 4 P04004



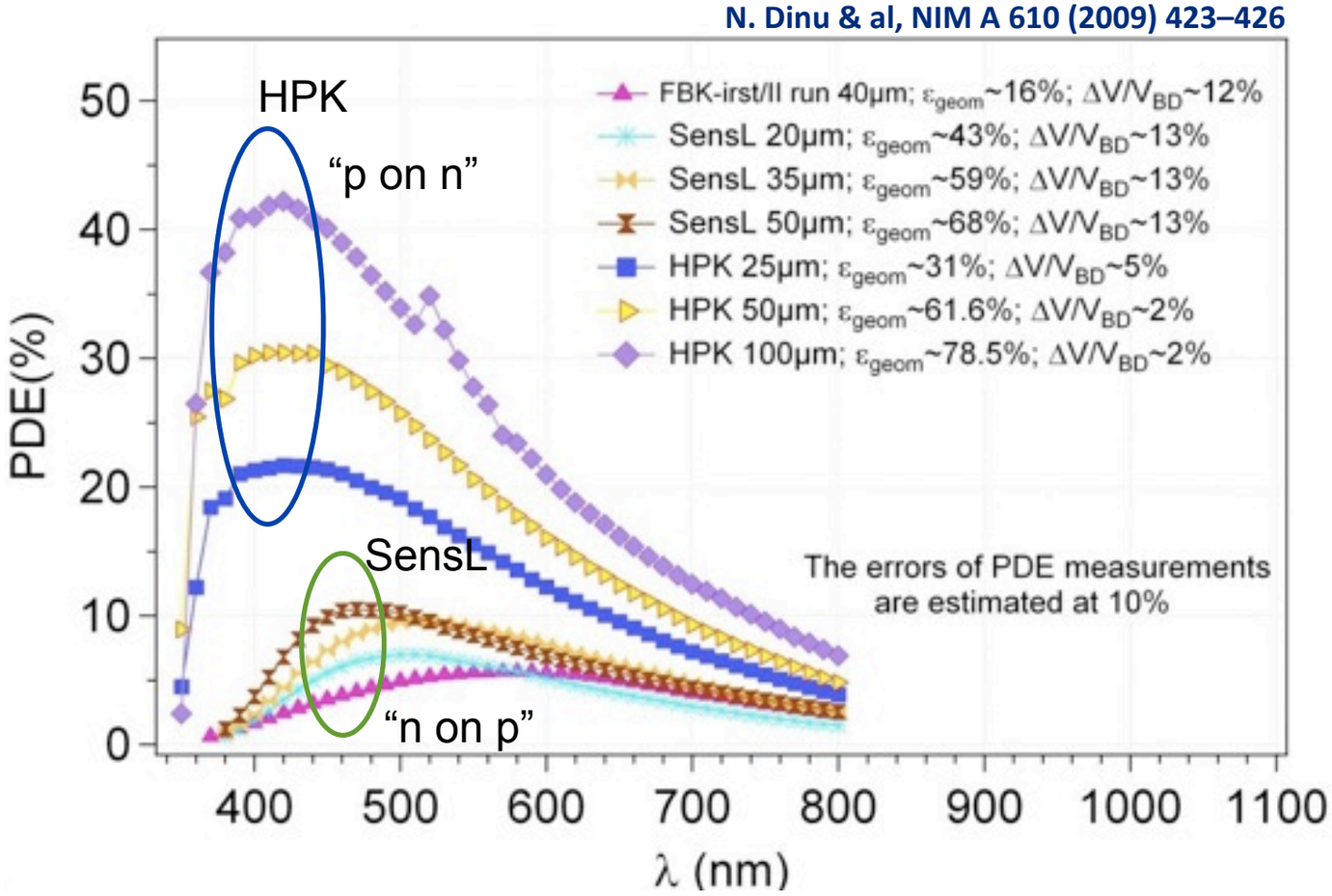
- max ~ 80%
- peaked distribution, because very thin sensitive layer (< 5μm)

D. Renker, 2009 JINST 4 P04004

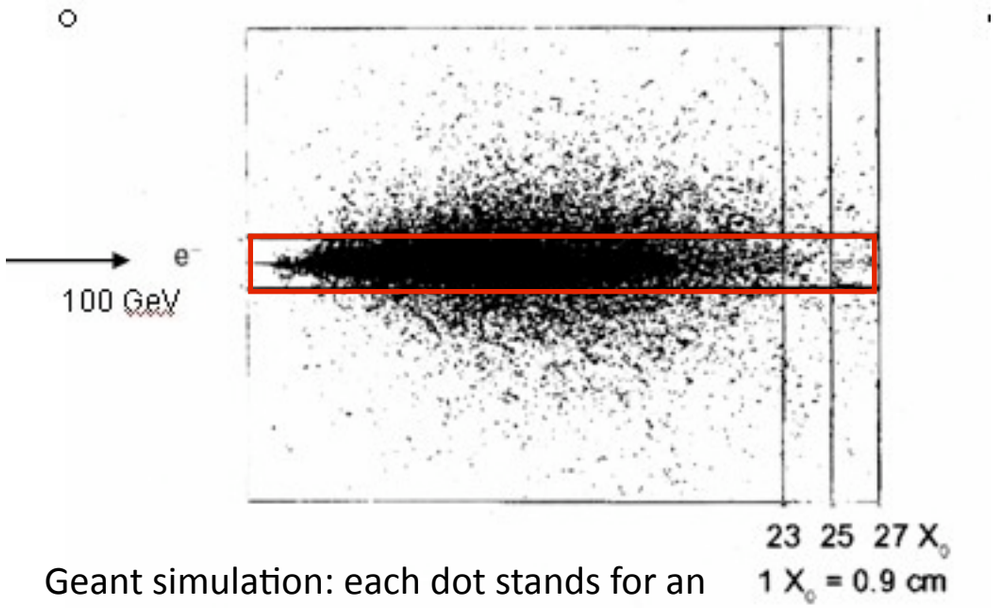


- PDE depends on the G-APD structure
  - highest probability to trigger a breakdown: when conversion of photon is in the p layer
  - "p-on-n" is more blue sensitive than "n-on-p"

N. Dinu & al, NIM A 610 (2009) 423–426



Nuclear counter effect (NCE) in Si-photodetectors



Geant simulation: each dot stands for an energy deposition of more than 10 keV

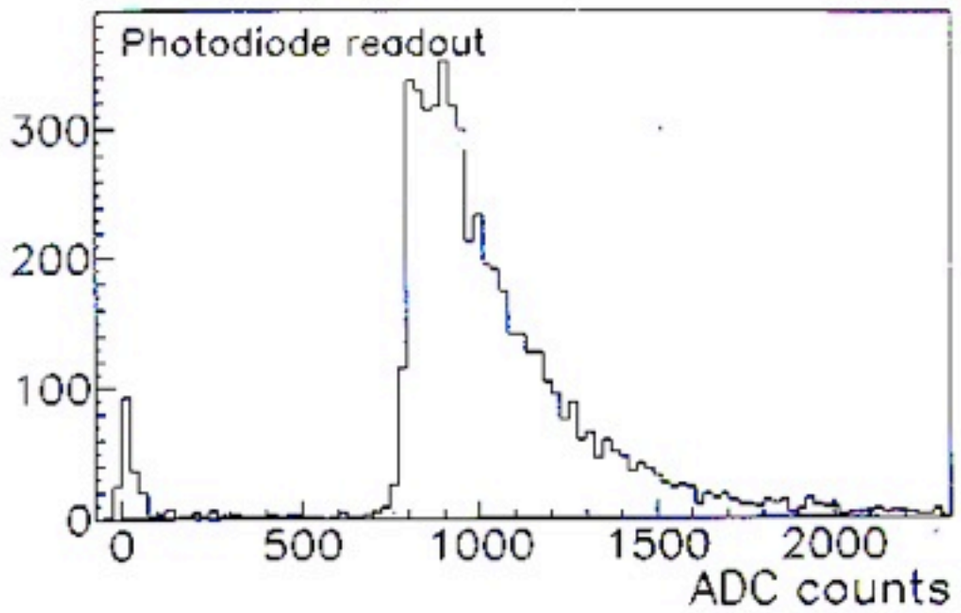
- charged particle (instead of photons) interacting in the depletion region

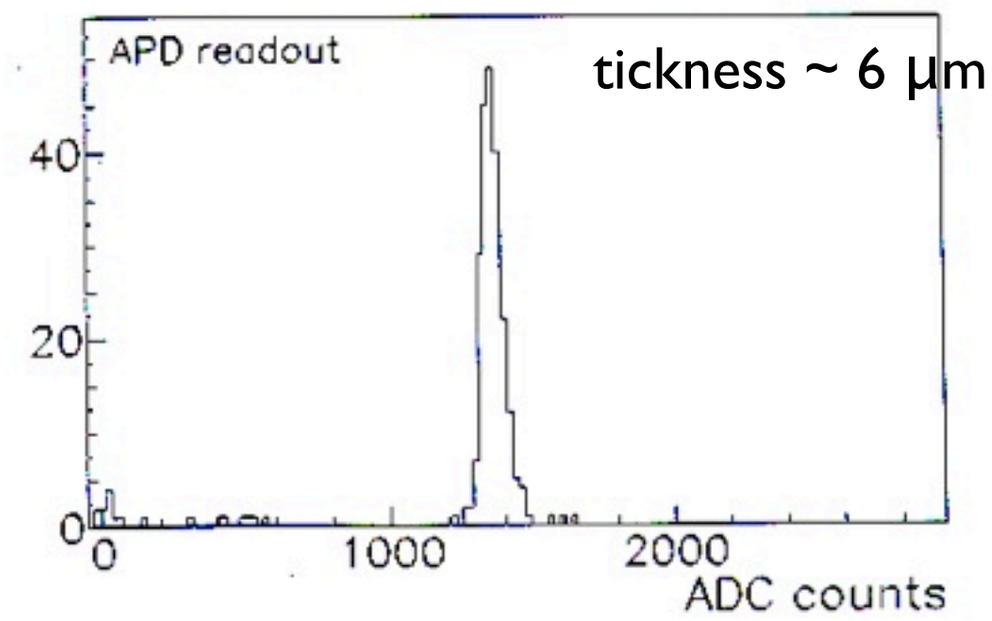
- unwanted addition to the signal

  - mip in Si: ~ 100 e-h/μm
  - PIN diode: t ~ 300 μm => 30000 e-h pairs
  - e.g. in PbW04 : 30000 eh pairs equivalent to a photon of 7 GeV

80 GeV e- beam in a 18 cm long PbWO4 crystal

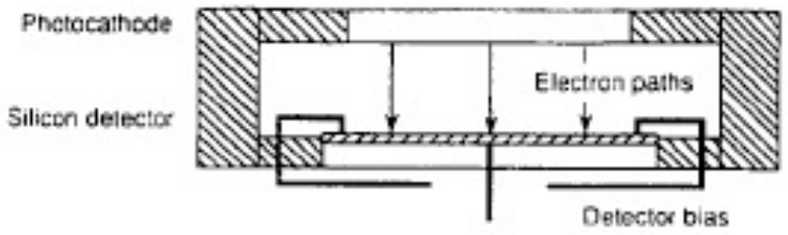
tickness ~ 300 μm





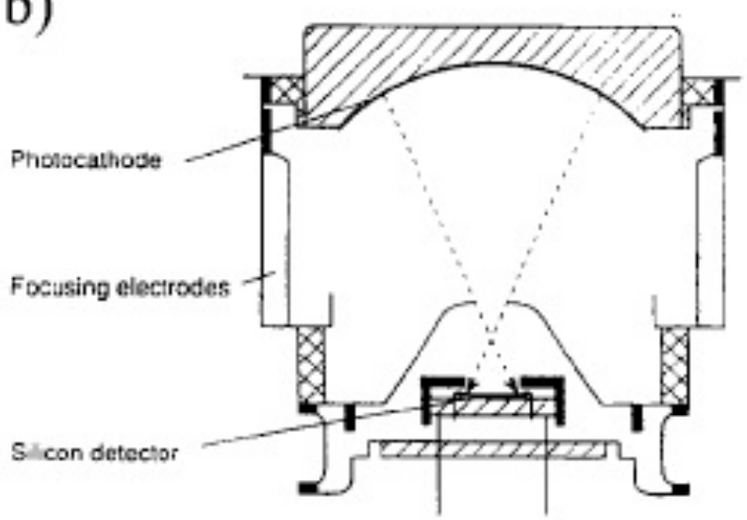
HPD : different design types

a)



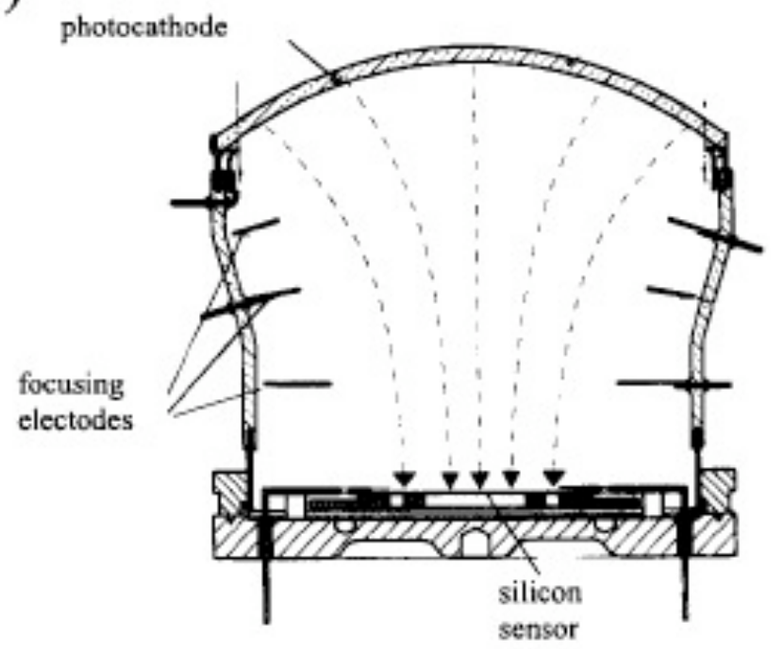
proximity focusing
- small gap btw photocathode and Si
- insensitive to magnetic field
- no demagnification
- small photosensitive area (A_PK = A_Si)

b)



cross focusing
- electrostatic lens effect compensating for the spread in the velocity and angular emission at the PK => high resolution imaging
- high demagnification
- long distance PK-Si => B-sensitive

c)



fountain focusing
- optics not correcting for the emission angle distribution => reduced spatial resolution wrt cross-focusing
- simple / compact
- B-sensitive

C. Joram, Nuclear Physics B (Proc. Suppl.) 78 (1999) 407-415