Scintillators and photodetectors

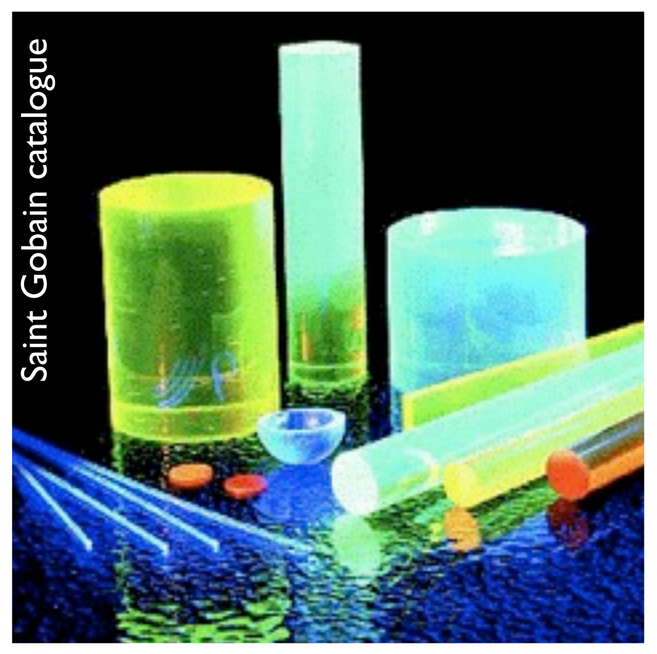
ESI School 2013

Outline:

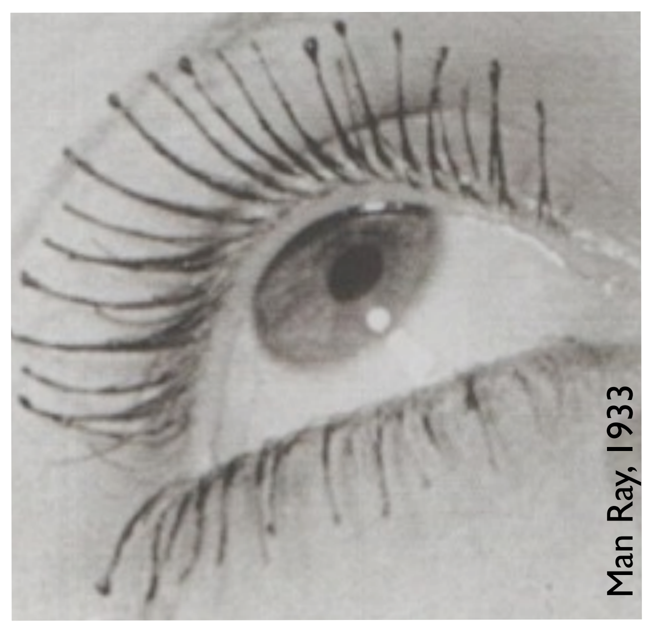
- **Scintillators**
  - mechanism and properties
  - organic and inorganic scintillators

- **Photodetectors**
  - Photomultipliers and its derivations (MA-PMT, MCP)
  - Solid state photodetectors (pin diodes, APD, SiPM)
  - Hybrid Photo Diodes (HPD)

30 mins impressions, slightly HEP oriented,
biased by my own experience



Saint Gobain catalogue



Man Ray, 1933

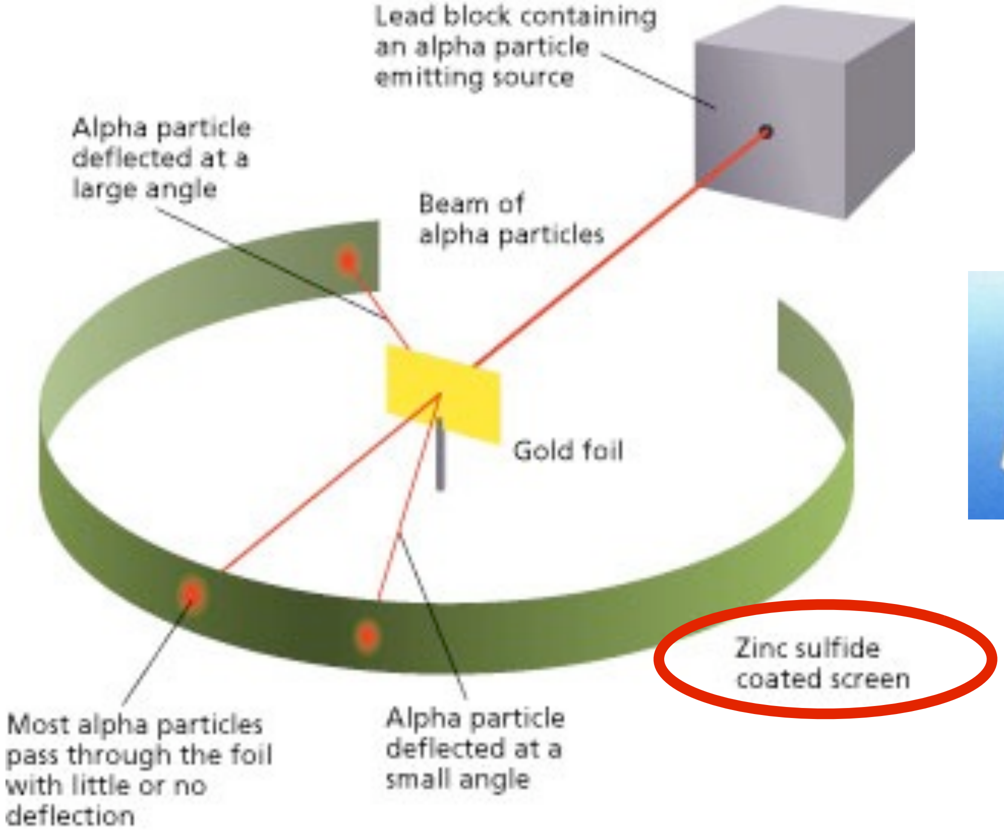
CERN, May 2013

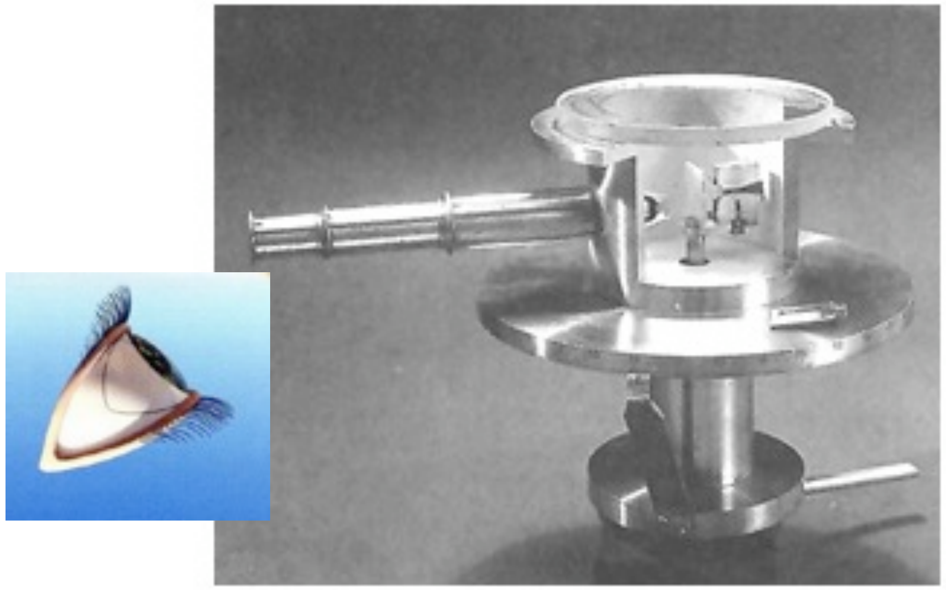
Chiara Casella, ETH Zurich

Usage of scintillators and photodetectors

from old times...

Ernest Rutherford (1871-1937)



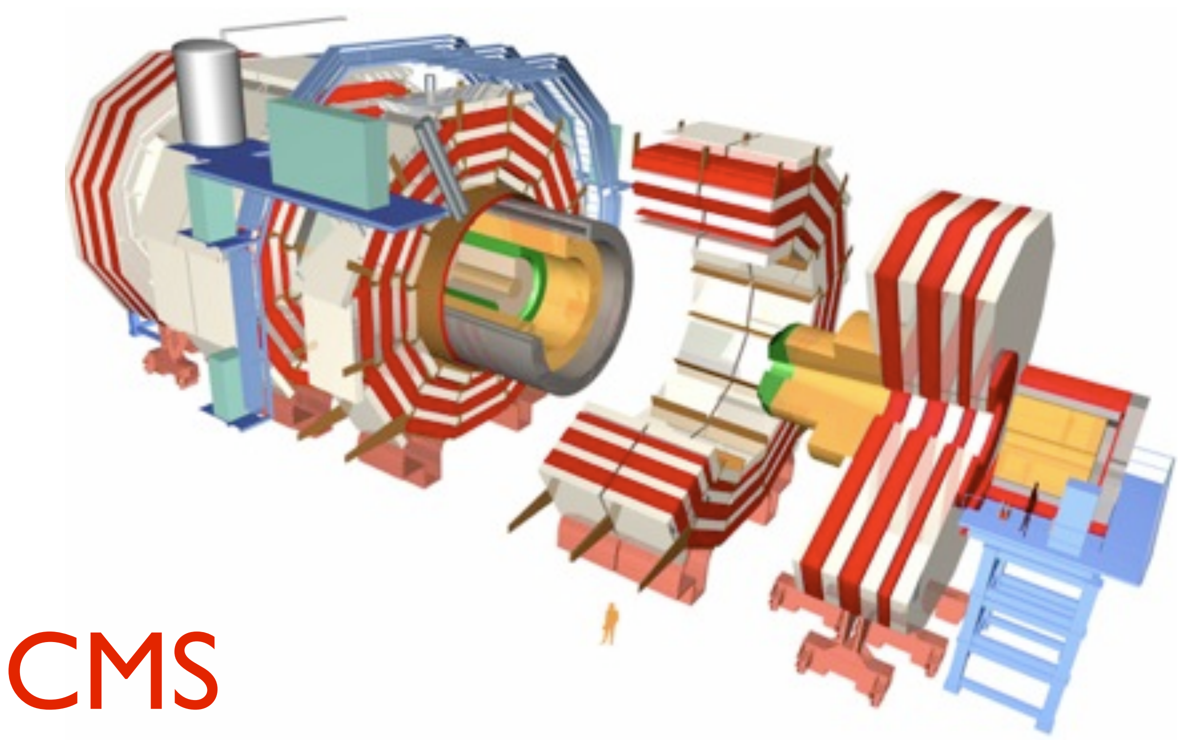


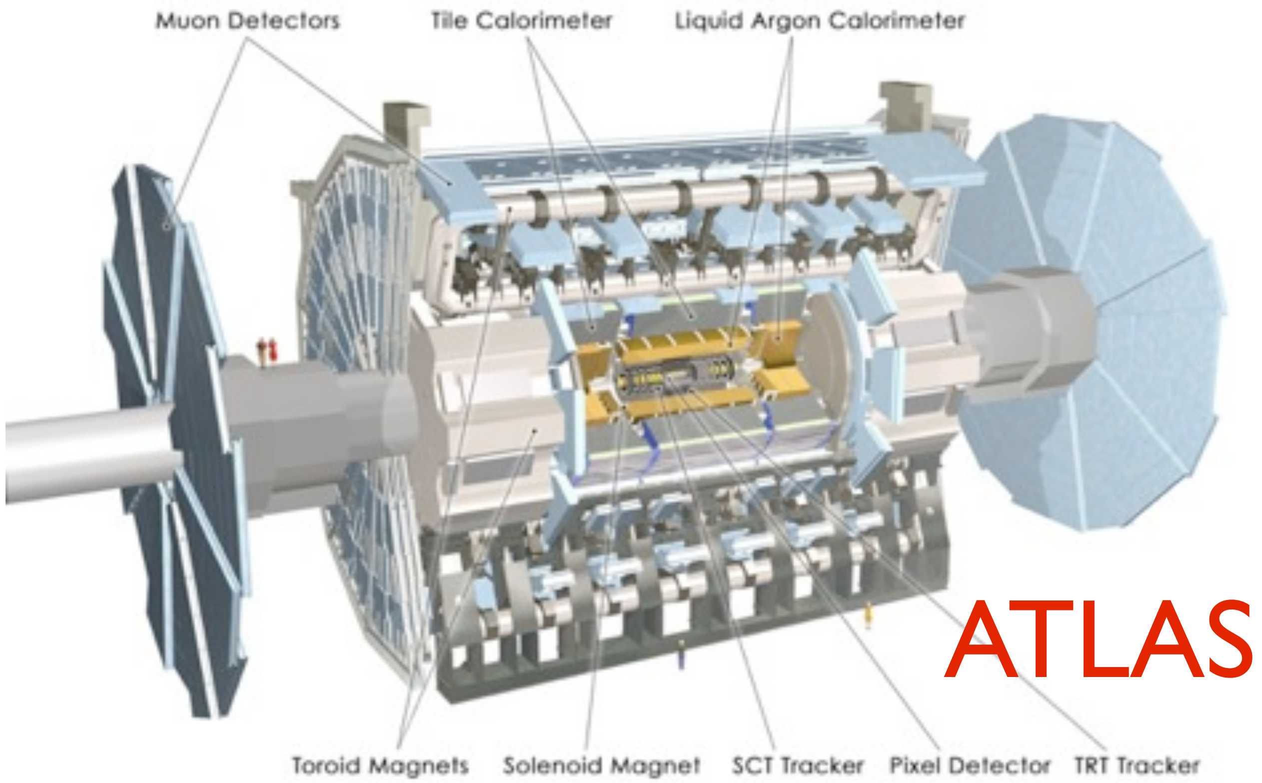
- PhD’s were selected according to their eyes capabilities...
- 40’s : invention of the PMT (light pulse => electrical signal)
- ~ 50 years of detector development, starting from MWPC - Charpak, 1968 - (revolution in electronics detection of particles)

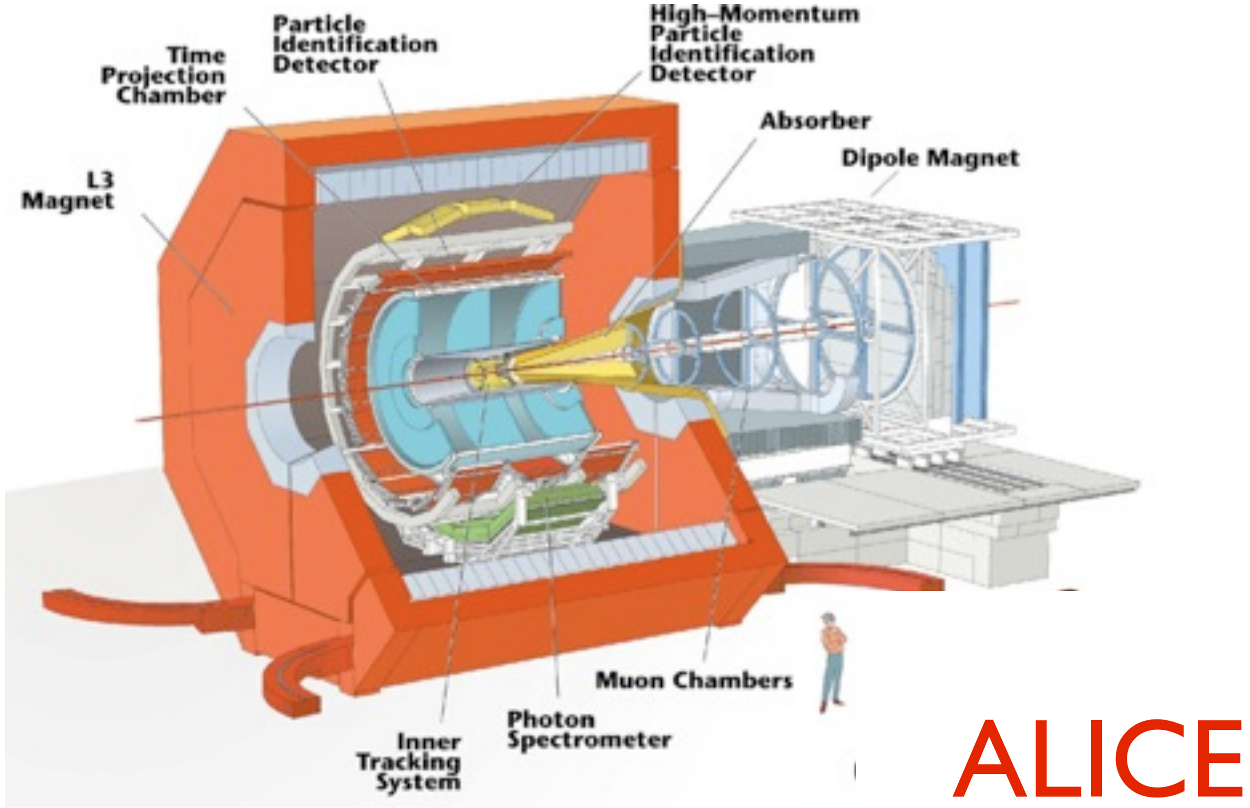
Usage of scintillators and photodetectors

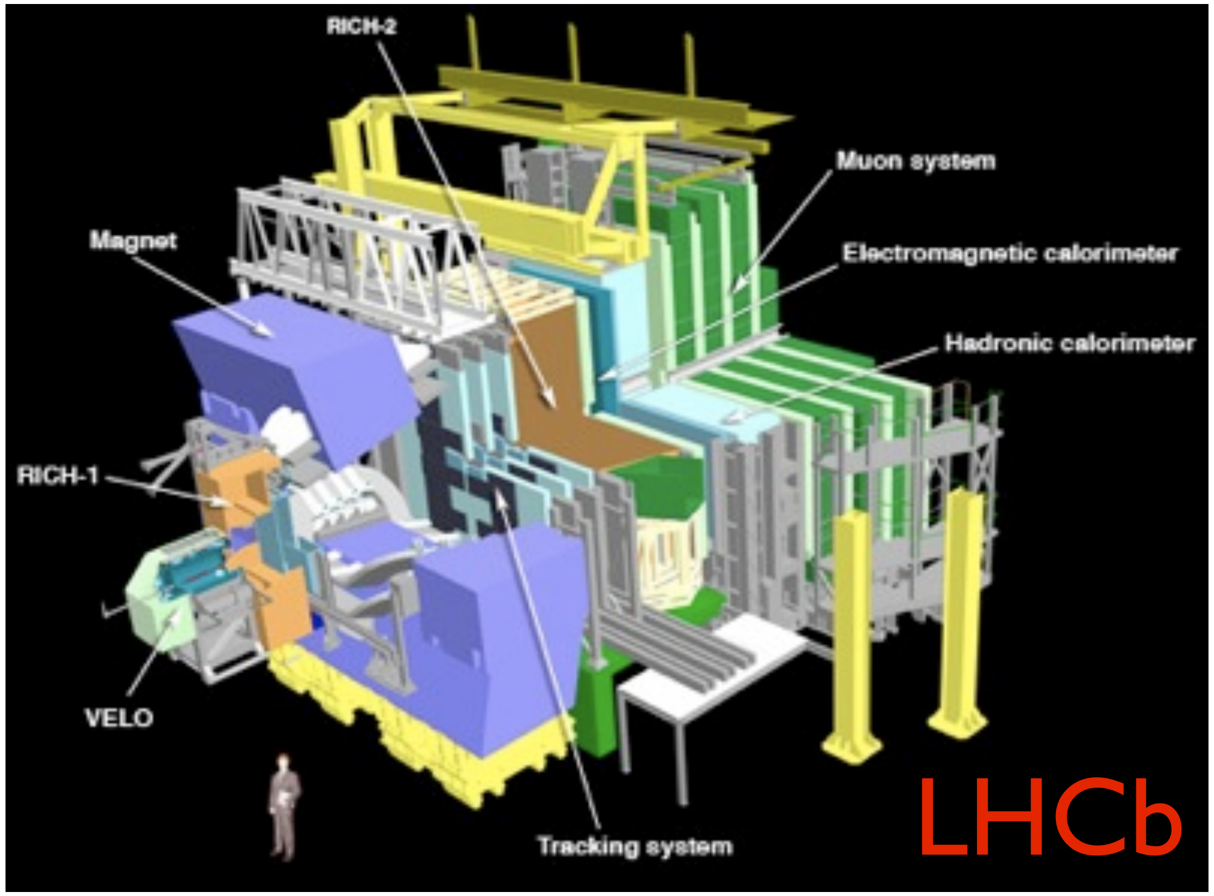
C.Joram, NIM A *695 (2012) 13-22*

... up to NOW and HERE !









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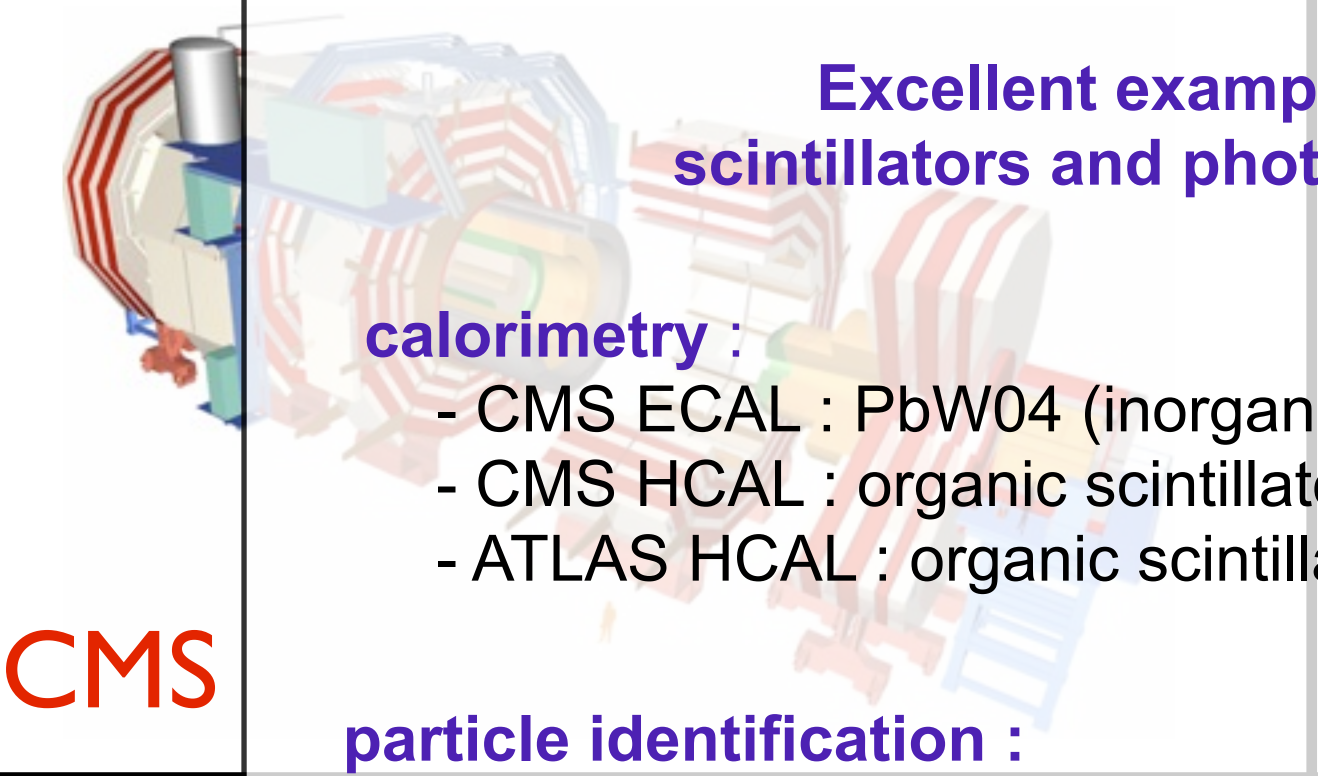
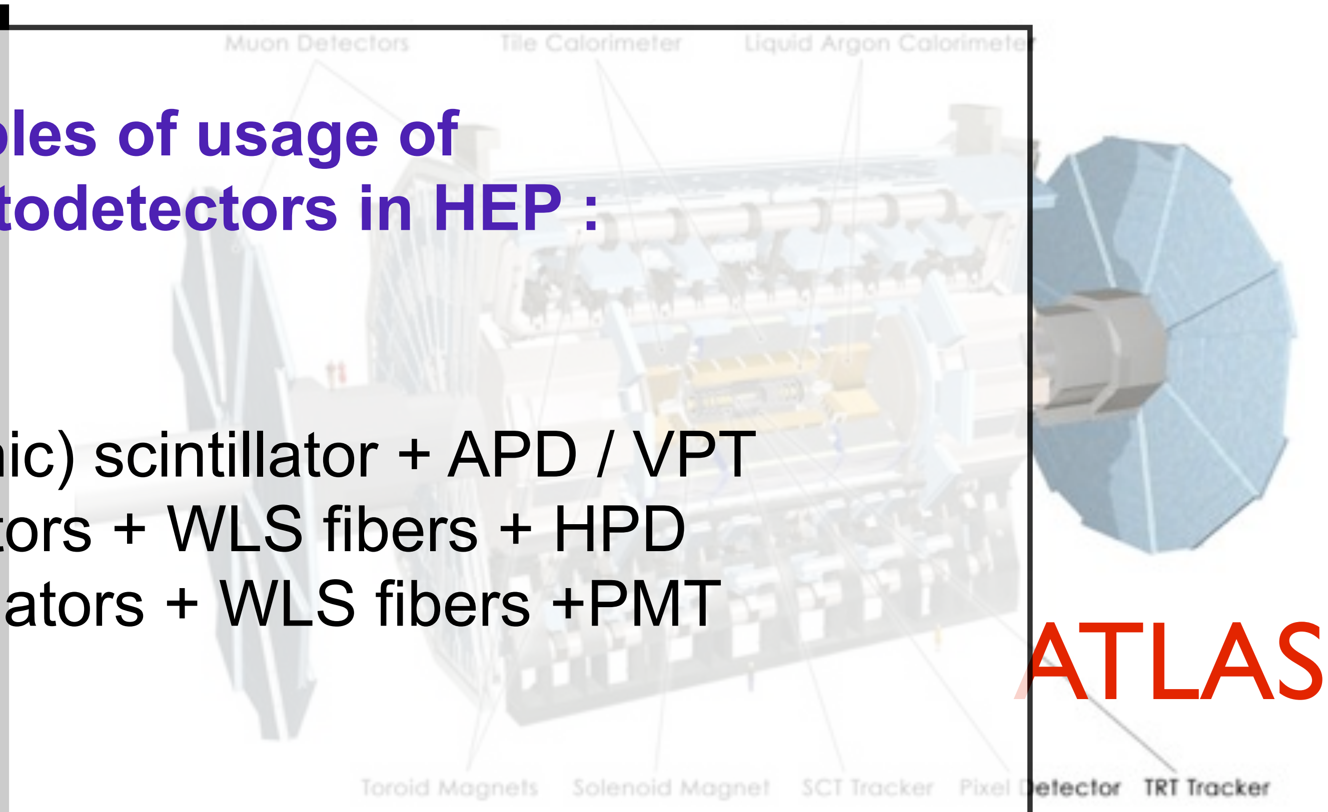
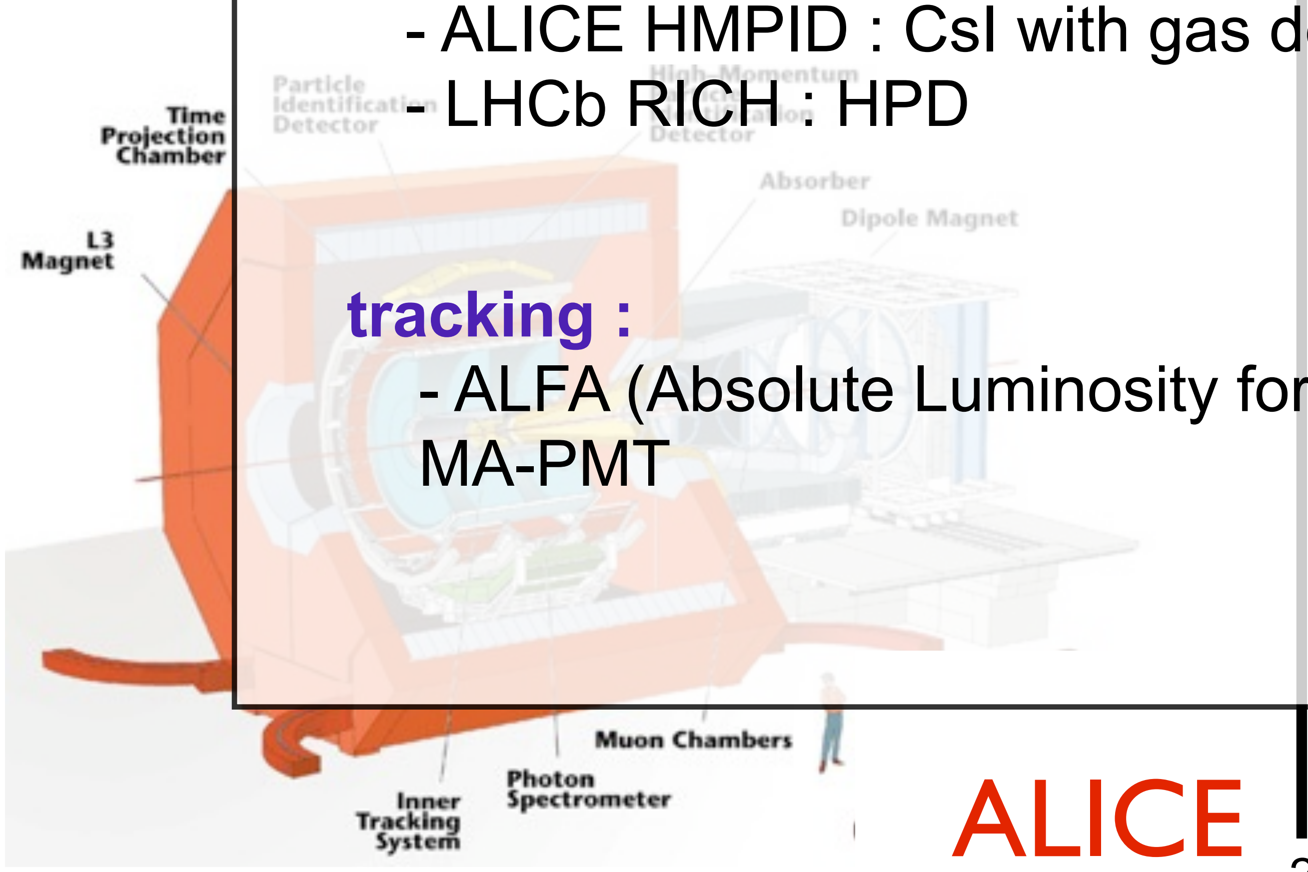
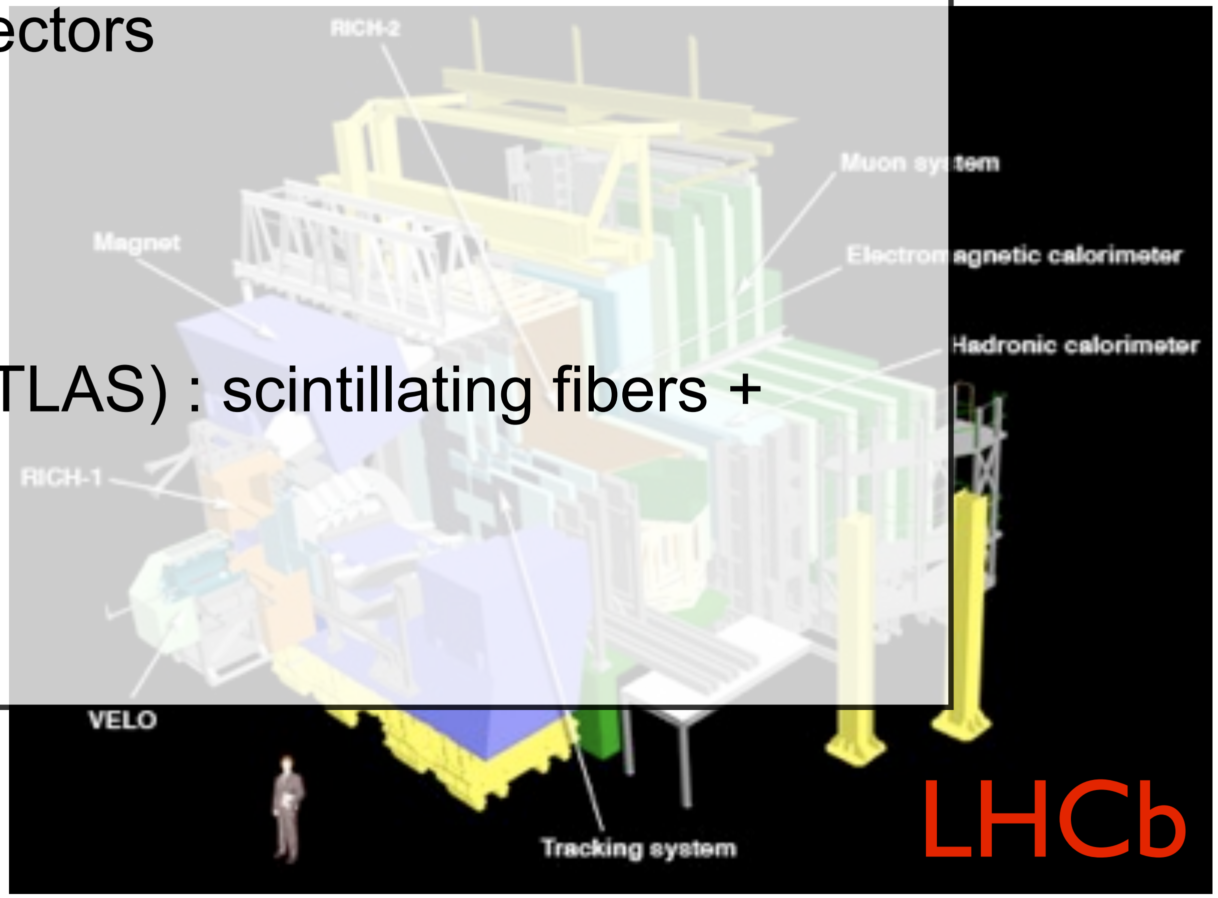








Excellent examples of usage of scintillators and photodetectors in HEP :

calorimetry :

- CMS ECAL : PbW04 (inorganic) scintillator + APD / VPT
- CMS HCAL : organic scintillators + WLS fibers + HPD
- ATLAS HCAL : organic scintillators + WLS fibers +PMT

particle identification :

- ALICE HMPID : CsI with gas detectors
- LHCb RICH : HPD

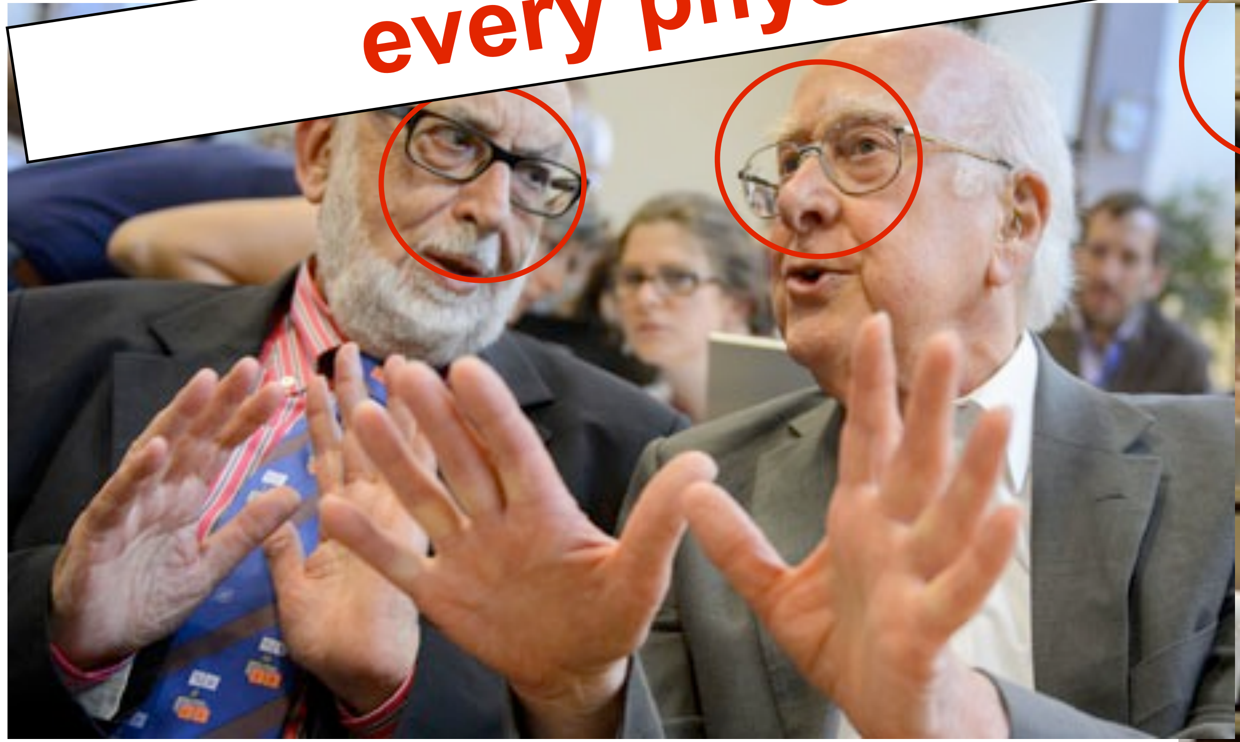
tracking :

- ALFA (Absolute Luminosity for ATLAS) : scintillating fibers + MA-PMT

LHC first beam, 10 Sept 2008

first high energy collisions, 30 March 2010

every physicist can happily wear glasses !

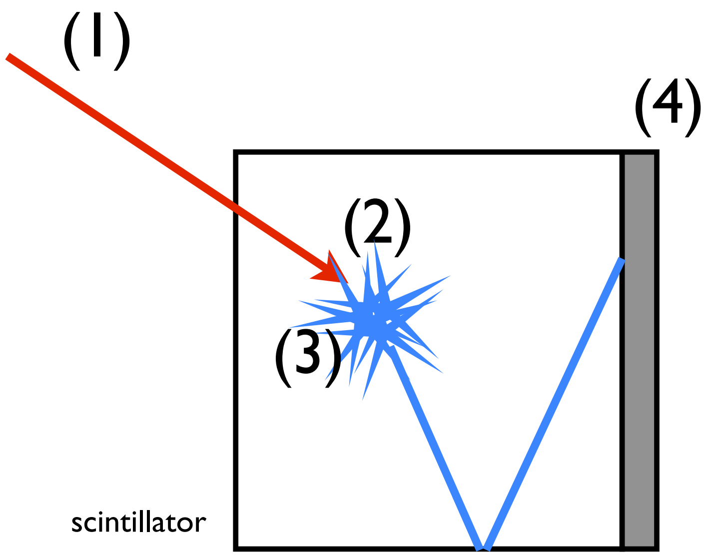


Higgs discovery announcement, 4 Jul 2012

Scintillators

Scintillators

Scintillators : class of materials which “scintillate” when excited by ionizing radiation



(1) ionizing radiation
(2) energy deposition
(3) SCINTILLATION : emission of photons (visible or near-visible)
(4) detection of the photons by a photodetector and conversion into an electrical pulse

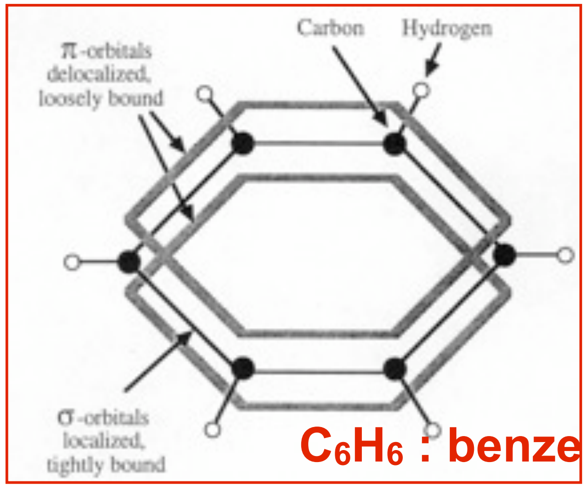
Basis of the scintillation : **energy loss from ionizing radiation i.e. IONIZATION and/or EXCITATION of the medium atoms / molecules**

Two main categories of scintillator materials
(details of the scintillation mechanism and properties)

ORGANIC	**INORGANIC**
e.g. plastics **scintillation is a molecular property**	e.g. NaI , BGO, LYSO... **scintillation is bound to the crystal lattice structure**

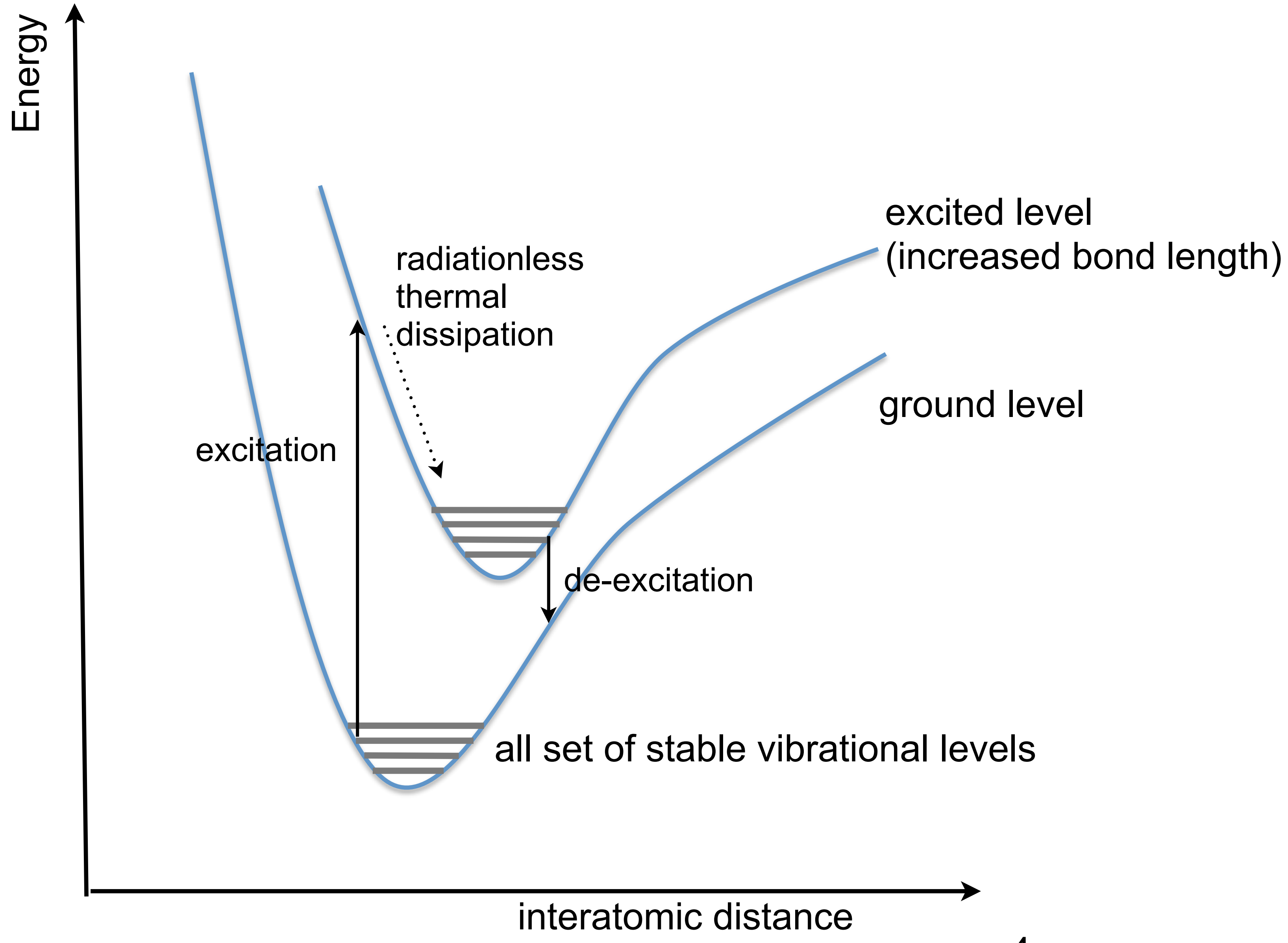
Organic scintillators

- inherent molecular property
- arises from the electronic structure of the molecules
- orbital arrangement of the electrons in organic compounds (tightly bound e in σ-orbitals ; <u>loosely bound e in π-orbitals</u>)



C_6H_6 : benzene

potential energy configuration of the molecule



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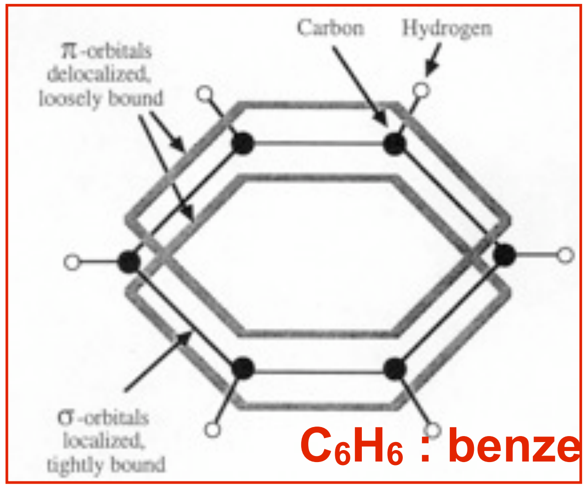

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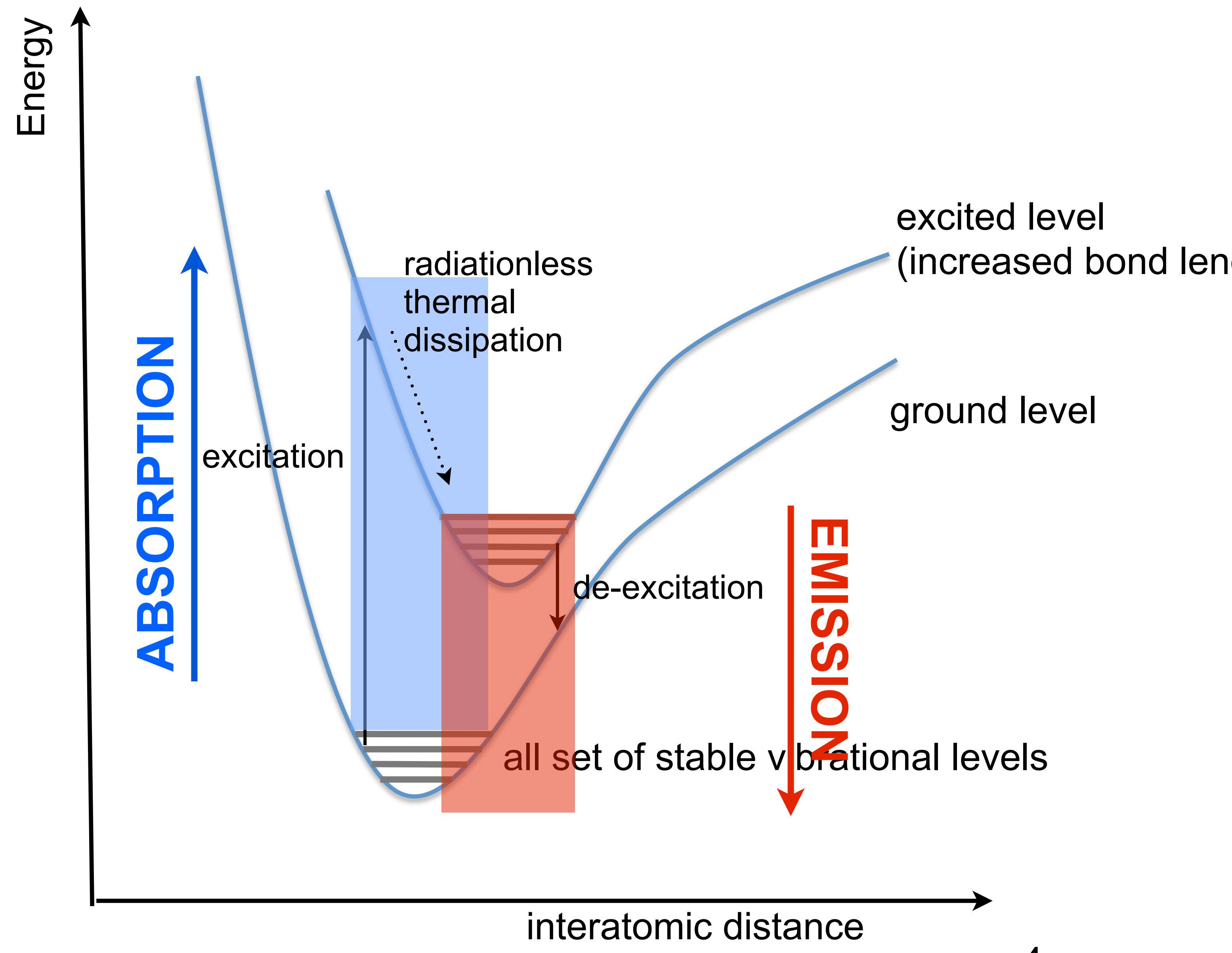
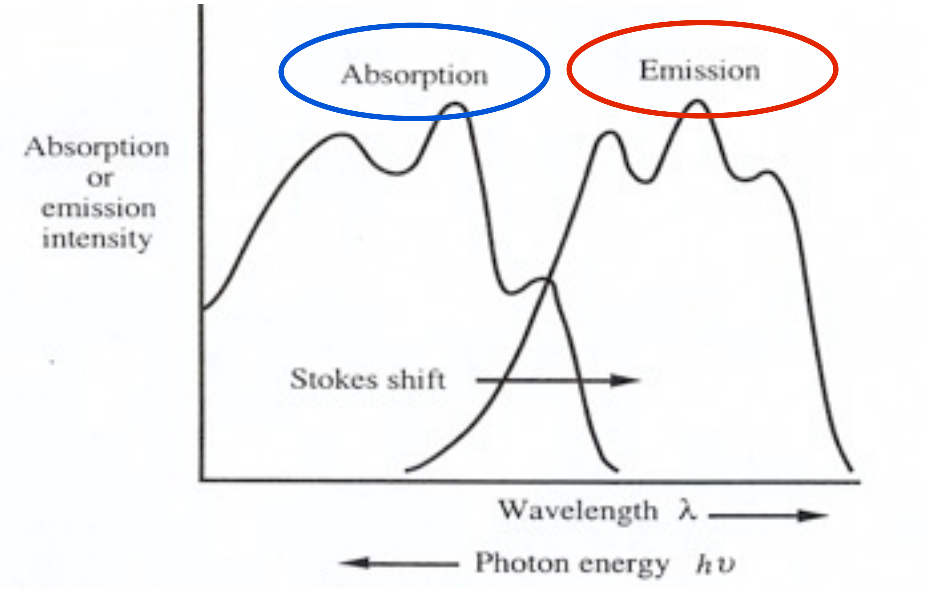


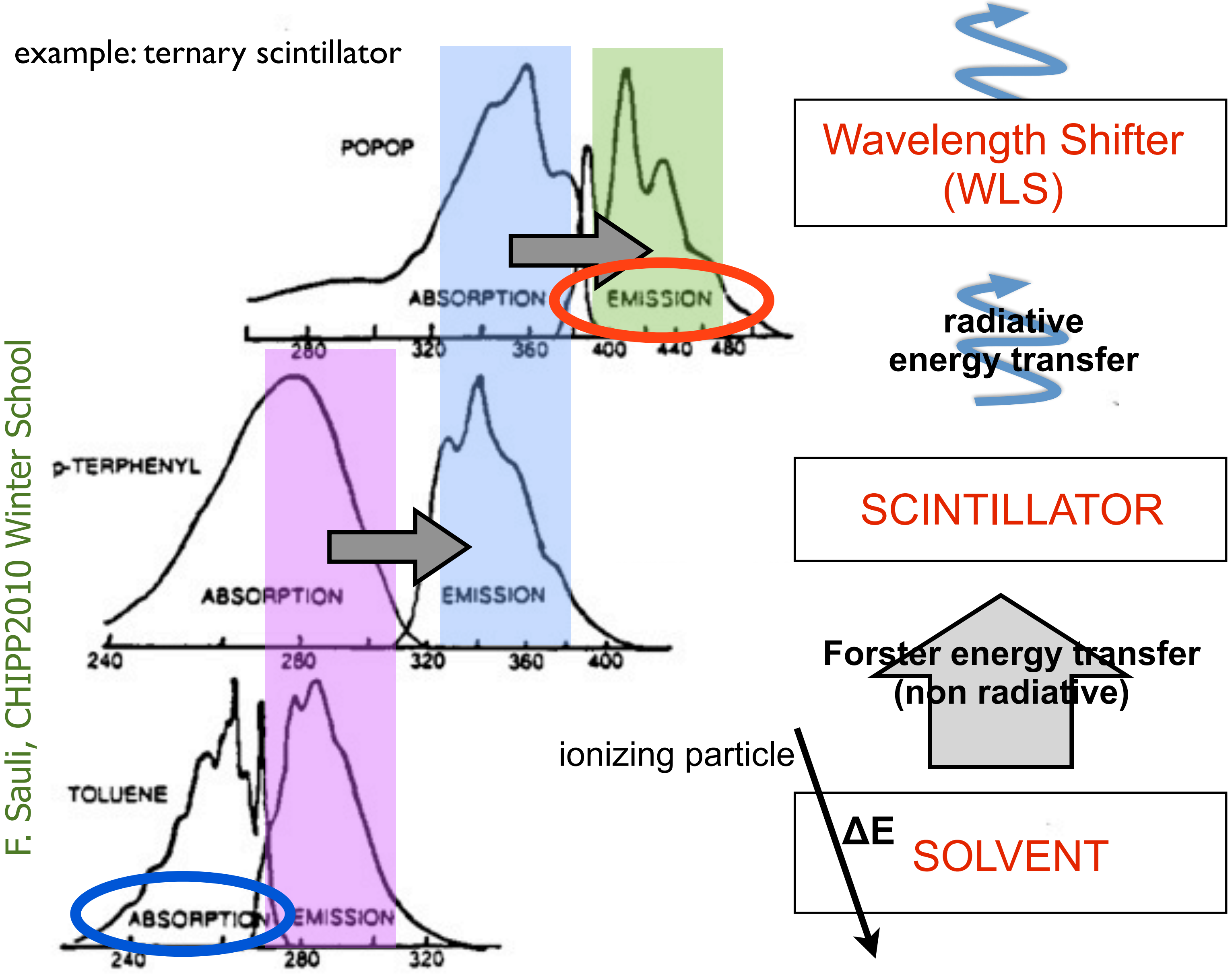


Efficient scintillator if :
(1) Large Stokes shift
(2) Emission spectrum matching the photodetector response

Organic scintillators (binary / ternary) solutions

Solutions of one or more organic scintillators in an organic solvent
- same scintillation mechanism as before
- different energy absorption mechanisms:
    non radiative dipole-dipole exchange (Forster transfer)
    [dominates over the radiative transfer for high concentration]

example: ternary scintillator



Wavelength Shifter (WLS)

radiative energy transfer

SCINTILLATOR

Forster energy transfer (non radiative)

ionizing particle

ΔE

SOLVENT

- secondary solute (scintillator)
- very small concentration => no direct energy transfer and negligible self-absorption

- primary solute (scintillator)
- high concentration (to optimize Forster transfer)
- scintillation process
- cannot prevent self-absorption (because of the high concentration) and often emission in UV

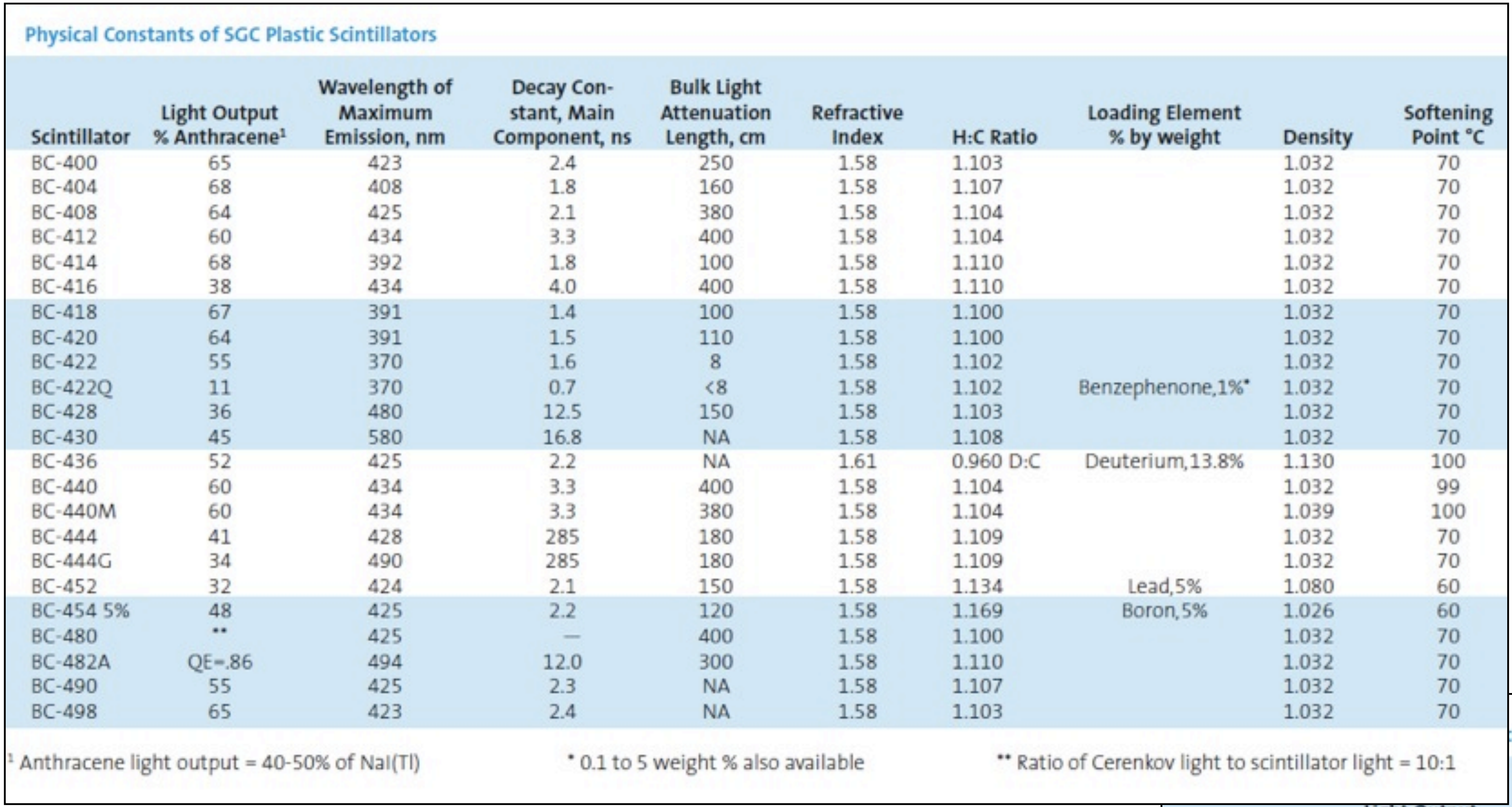
- main constituent (inefficient scintillator)
- energy dump ($\Delta E = dE/dx\ \Delta x$)
- responsible for the absorption spectrum

challenge: right choice of the elements and concentrations
result : great versatility (in emission wavelength, photodetector matching, fabrication...)

F. Sauli, CHIPP2010 Winter School

Organic scintillators

plastic scintillators



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		1.032	70
BC-418	67	391	1.4	100	1.58	1.100		1.032	70
BC-420	64	391	1.5	110	1.58	1.100		1.032	70
BC-422	55	370	1.6	8	1.58	1.102		1.032	70
BC-422Q	11	370	0.7	<8	1.58	1.102	Benzephenone,1%*	1.032	70
BC-428	36	480	12.5	150	1.58	1.103		1.032	70
BC-430	45	580	16.8	NA	1.58	1.108		1.032	70
BC-436	52	425	2.2	NA	1.61	0.960 D:C	Deuterium,13.8%	1.130	100
BC-440	60	434	3.3	400	1.58	1.104		1.032	99
BC-440M	60	434	3.3	380	1.58	1.104		1.039	100
BC-444	41	428	285	180	1.58	1.109		1.032	70
BC-444G	34	490	285	180	1.58	1.109		1.032	70
BC-452	32	424	2.1	150	1.58	1.134	Lead,5%	1.080	60
BC-454 5%	48	425	2.2	120	1.58	1.169	Boron,5%	1.026	60
BC-480	**	425	—	400	1.58	1.100		1.032	70
BC-482A	QE=.86	494	12.0	300	1.58	1.110		1.032	70
BC-490	55	425	2.3	NA	1.58	1.107		1.032	70
BC-498	65	423	2.4	NA	1.58	1.103		1.032	70

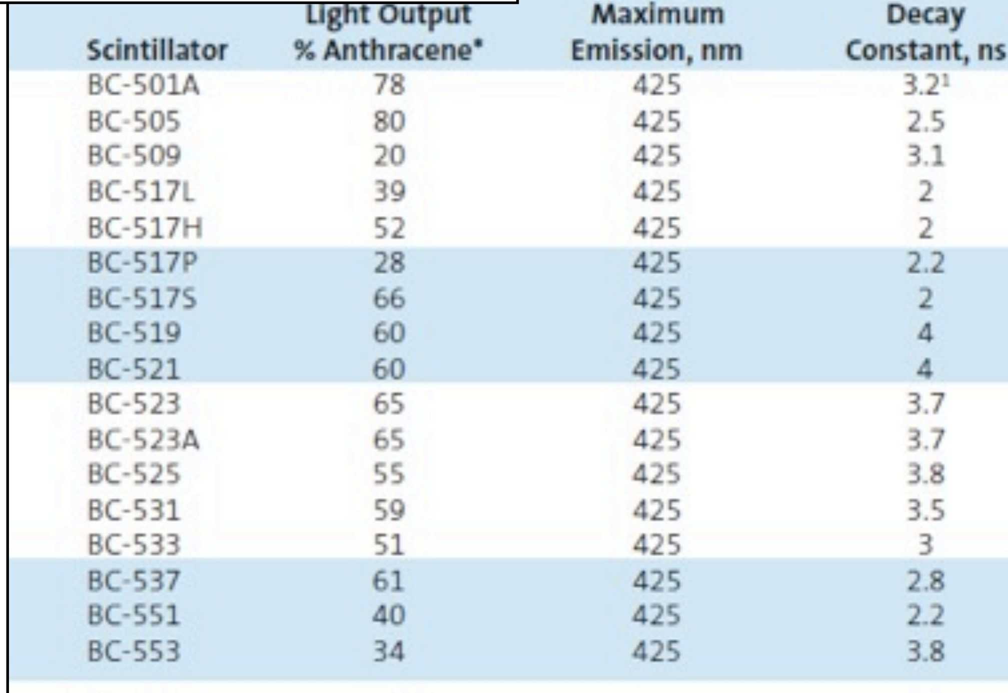
[1] Anthracene light output = 40-50% of NaI(Tl)

* 0.1 to 5 weight % also available

** Ratio of Cerenkov light to scintillator light = 10:1

liquid scintillators

intillators



Scintillator	Light Output % Anthracene*	Wavelength of Maximum Emission, nm	Decay Constant, ns
BC-501A	78	425	3.2[1]
BC-505	80	425	2.5
BC-509	20	425	3.1
BC-517L	39	425	2
BC-517H	52	425	2
BC-517P	28	425	2.2
BC-517S	66	425	2
BC-519	60	425	4
BC-521	60	425	4
BC-523	65	425	3.7
BC-523A	65	425	3.7
BC-525	55	425	3.8
BC-531	59	425	3.5
BC-533	51	425	3
BC-537	61	425	2.8
BC-551	40	425	2.2
BC-553	34	425	3.8

ORGANIC SCINTILLATORS :

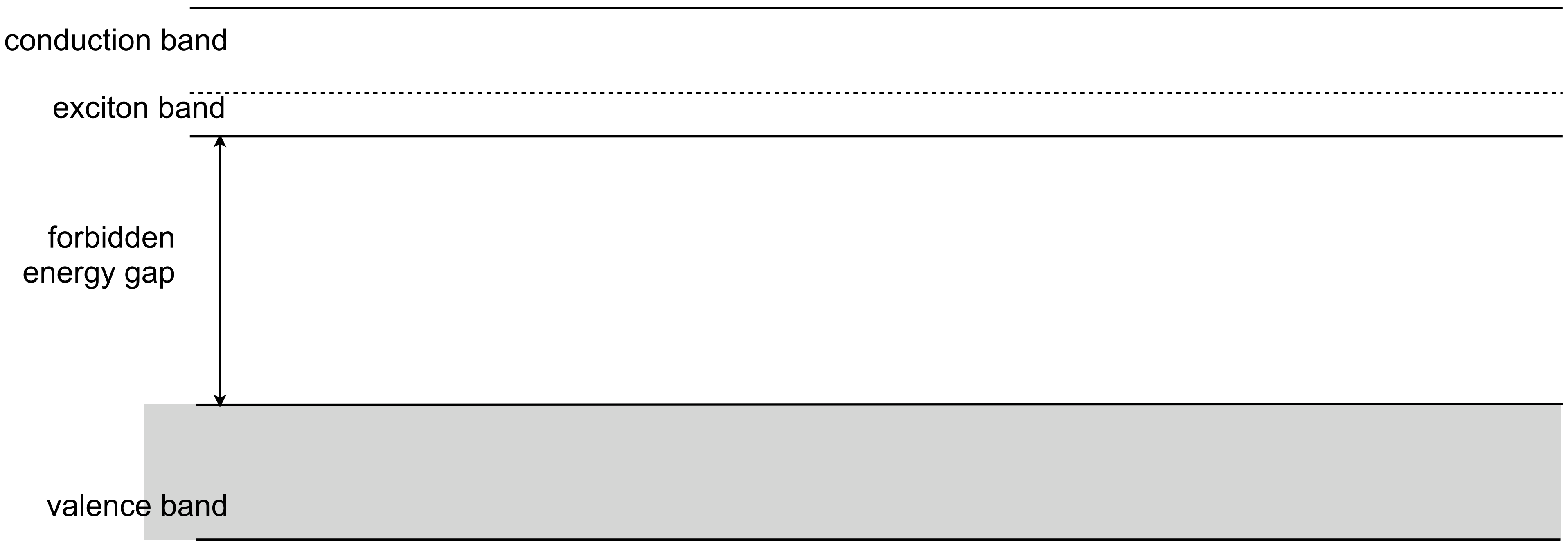
- large choice of emission wavelength
- short decay time (~ ns)
- long attenuation length (~ m) => large size possibilities
- ease of fabrication, flexibility in shape and dimensions, both solid and liquid scintillators

- modest light yield (because of small solute concentration)
  max 10000 γ/MeV

Inorganic scintillators

- crystalline property
- bound to the crystal lattice structure, and in particular to its ‘defects’

Energy band model



- typical energy gaps Eg ~ few eV (semiconductors)

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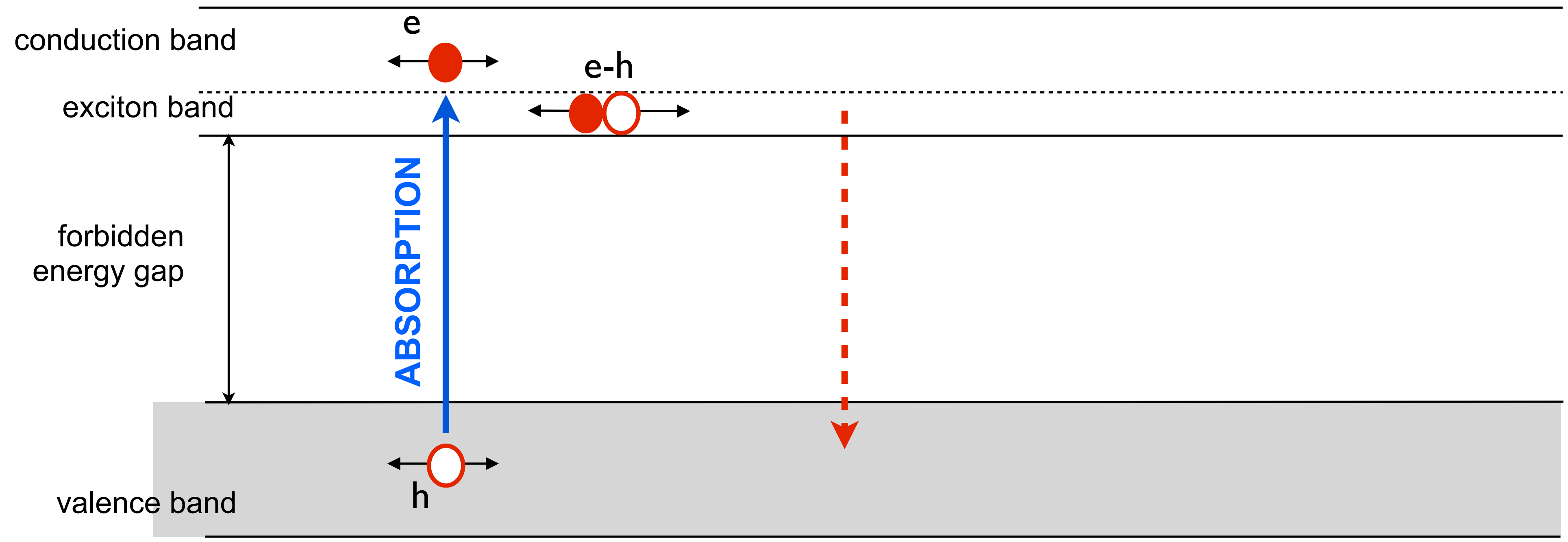

- typical energy gaps Eg ~ few eV (semiconductors)
- ionizing radiation => ΔE => ionization / excitation
- if <u>perfectly pure crystal</u> => de-excitation is a <u>completely inefficient</u> process

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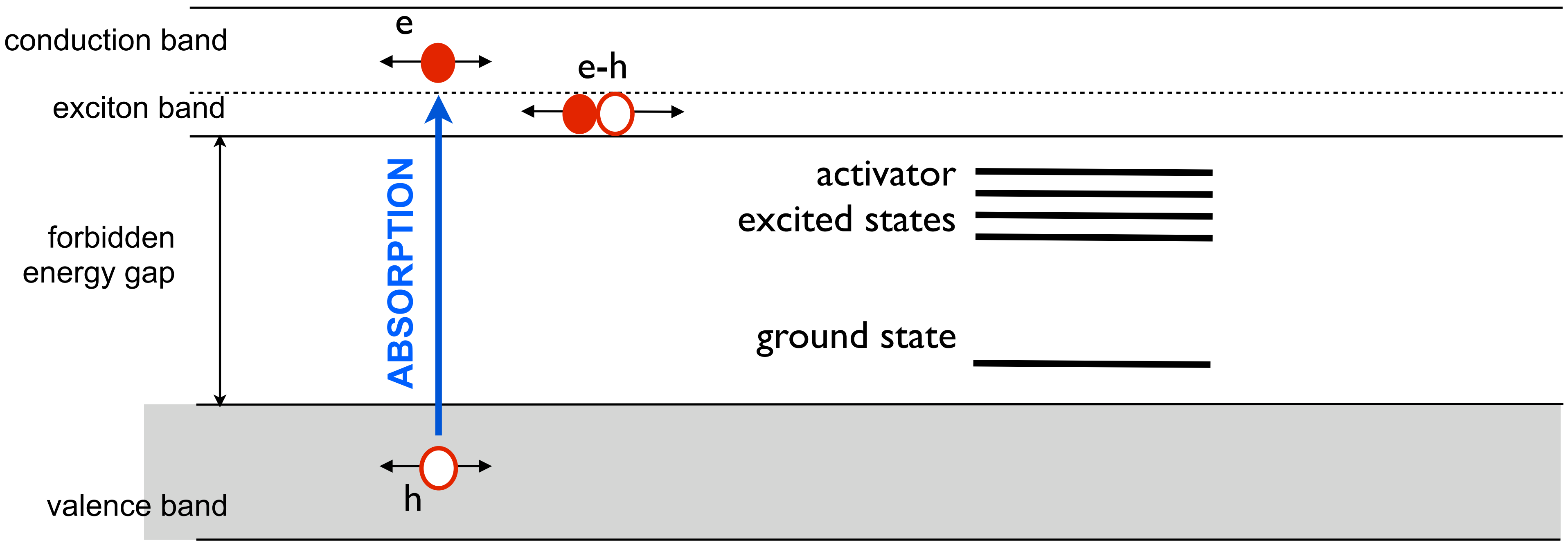

- typical energy gaps Eg ~ few eV (semiconductors)
- ionizing radiation => ΔE => ionization / excitation
- if perfectly pure crystal => de-excitation is a completely inefficient process
- if <u>impurities in the lattice</u> : energies allowed in the forbidden region
  - external activators doping (e.g. Tl in NaI => NaI(Tl))
  - defects in the structure
  - stechiometric excess of one component

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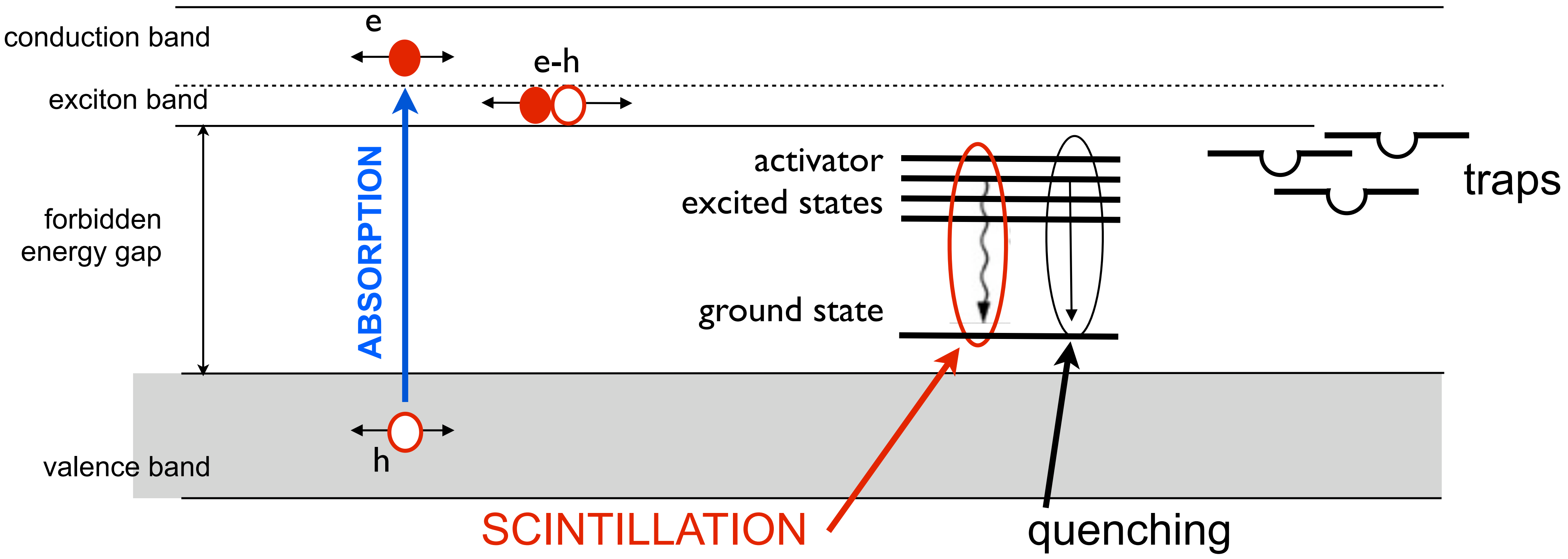

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=> de-excitation produces SCINTILLATION

Inorganic scintillators

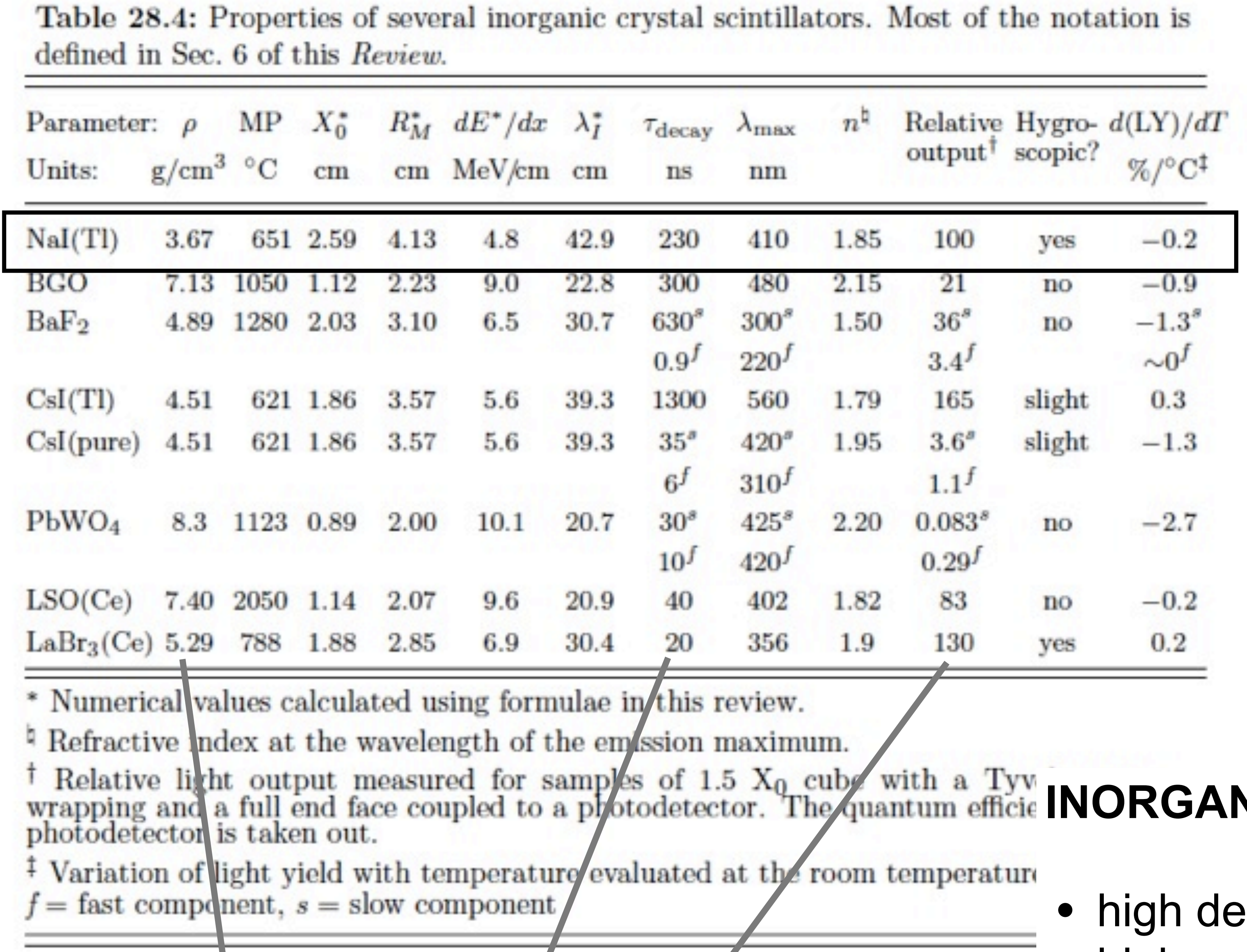


Table 28.4: Properties of several inorganic crystal scintillators. Most of the notation is defined in Sec. 6 of this *Review*.

Parameter:	ρ	MP	X_0^*	R_M^*	dE^*/dx	λ_I^*	$\tau_{\rm decay}$	$\lambda_{\rm max}$	$n^\natural$	Relative output†	Hygroscopic?	$d(LY)/dT$
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 0.9^f	300^s 220^f	1.50	36^s 3.4^f	no	-1.3^s $\sim 0^f$
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 6^f	420^s 310^f	1.95	3.6^s 1.1^f	slight	−1.3
$PbWO_4$	8.3	1123	0.89	2.00	10.1	20.7	30^s 10^f	425^s 420^f	2.20	0.083^s 0.29^f	no	−2.7
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

[*] Numerical values calculated using formulae in this review.

[♮] Refractive index at the wavelength of the emission maximum.

[†] Relative light output measured for samples of 1.5 X_0 cube with a Tyv wrapping and a full end face coupled to a photodetector. The quantum efficie photodetector is taken out.

[‡] Variation of light yield with temperature evaluated at the room temperatur

f = fast component, s = slow component

from Particle Data Group, Review of Particle Physics

Light yield ~ 40000 γ/MeV

high density

higher light yields

slower decay times

WRT ORGANIC SCINTILLATORS

INORGANIC SCINTILLATORS :

- high density, high Z => High stopping power, high conversion efficiency
- high light yields => Good energy resolution

- long decay times (few 10s - 100s ns)

- expensive (e.g. LYSO ~ 100 euro/cm3)
- no large sizes

inorganic

high density, high Z

high light yield

**γ-detectors
(e.g. medical imaging applications),**

HEP electromagnetic calorimeters (γ,e)

organic

fast

cheap

large flexibility

**timing
(e.g. TOF, trigger, veto...),**

large areas coverage

Photodetectors

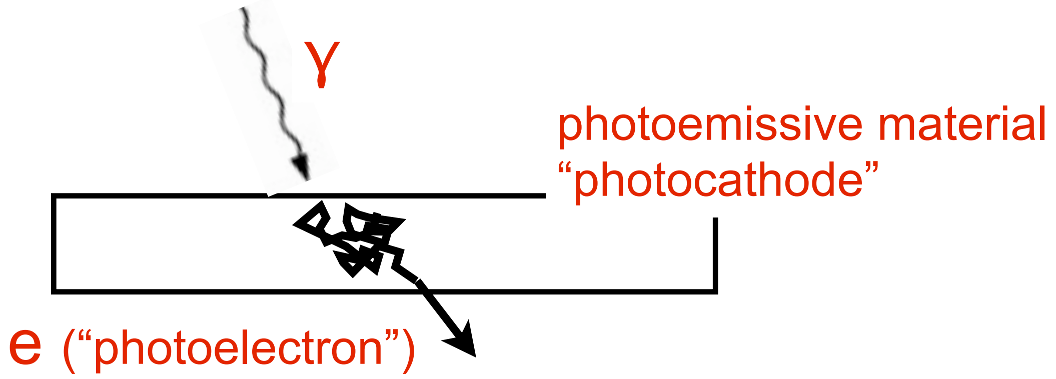
Basic principles of photodetection

GOAL : Detect photons in the visible / near-visible range and convert them into a detectable electric signal

photons
$\lambda \in [100, 1000]$ nm ;
E ~ few eV
from scintillation or Cherenkov effect

---

fundamental phenomenon : **photoemission**



1) optical absorption process $\gamma \Rightarrow e$ i.e. photoelectric effect

2) electron diffusion

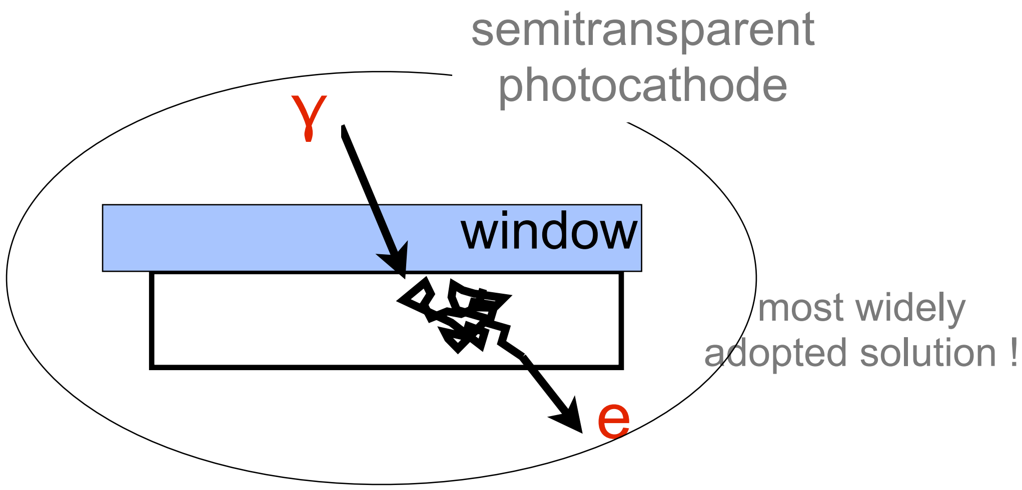
3) escape process

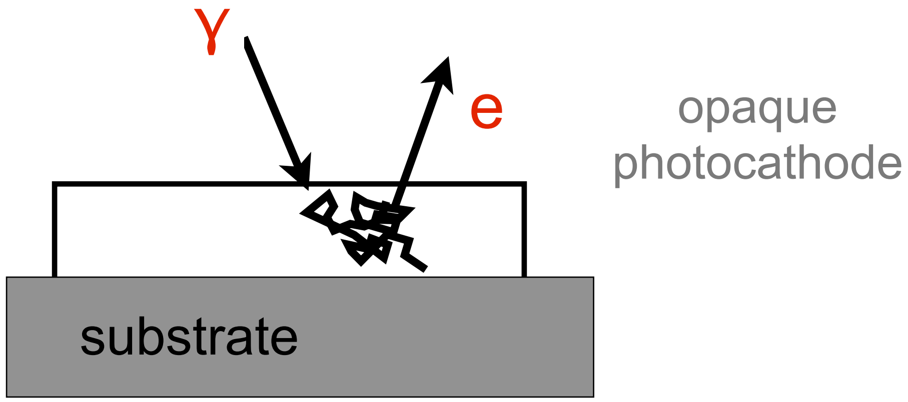
External photoelectric effect:

- photoelectrons extracted from the photocathode
- detection principle: amplification and collection of pe
  PHOTOMULTIPLIERS (PMTs)
  HYBRID PHOTO DIODES

Internal photoelectric effect:

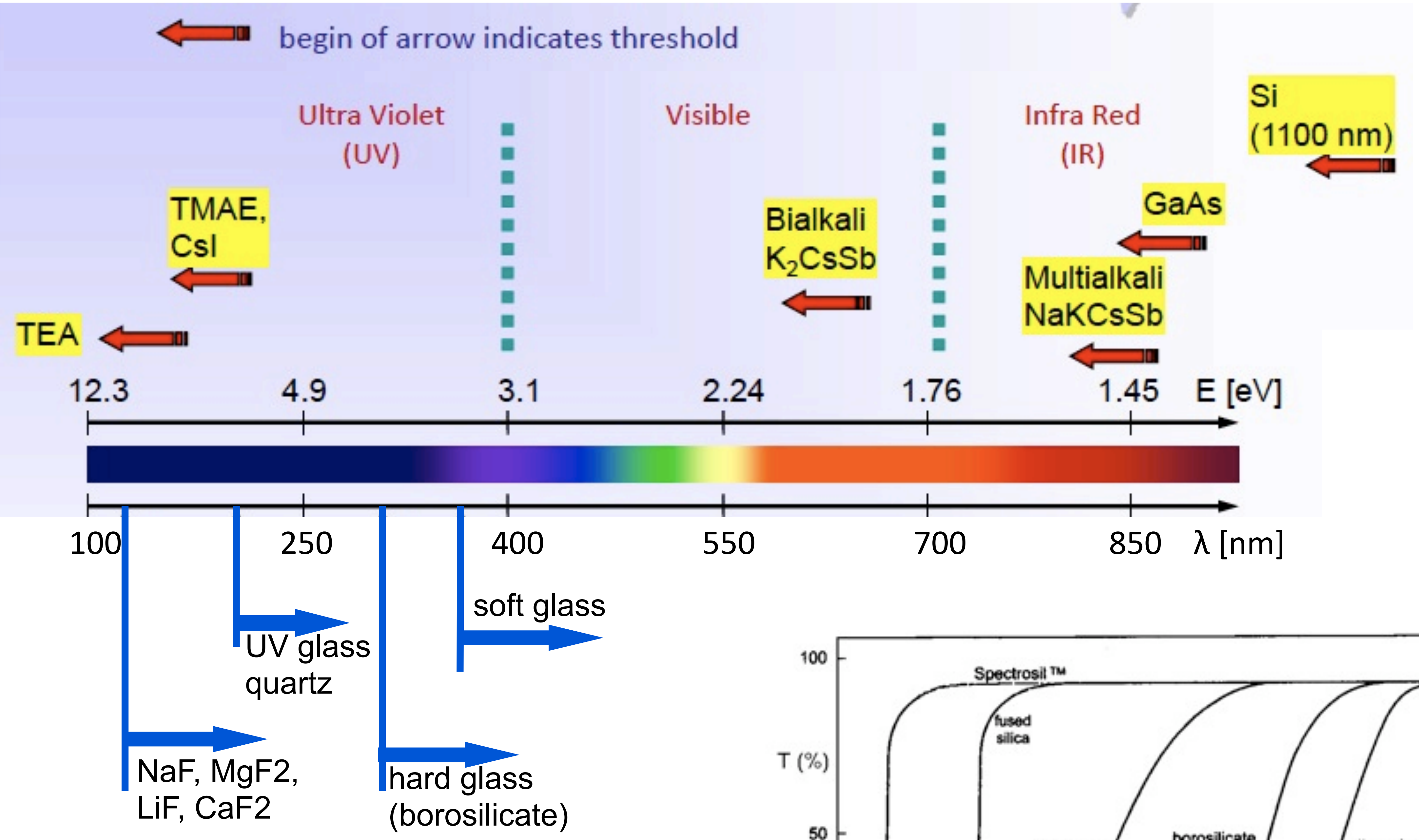
- photoelectrons not extracted
- detection principle: measurement of the photocurrent
  SILICON PHOTODETECTORS (pin, APD, SiPM)





Photoemission is a threshold phenomenon

a minimum photon energy is required to produce photoemission !
(depending on the photocathode)

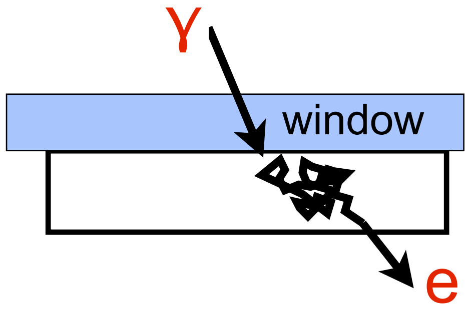


soft glass

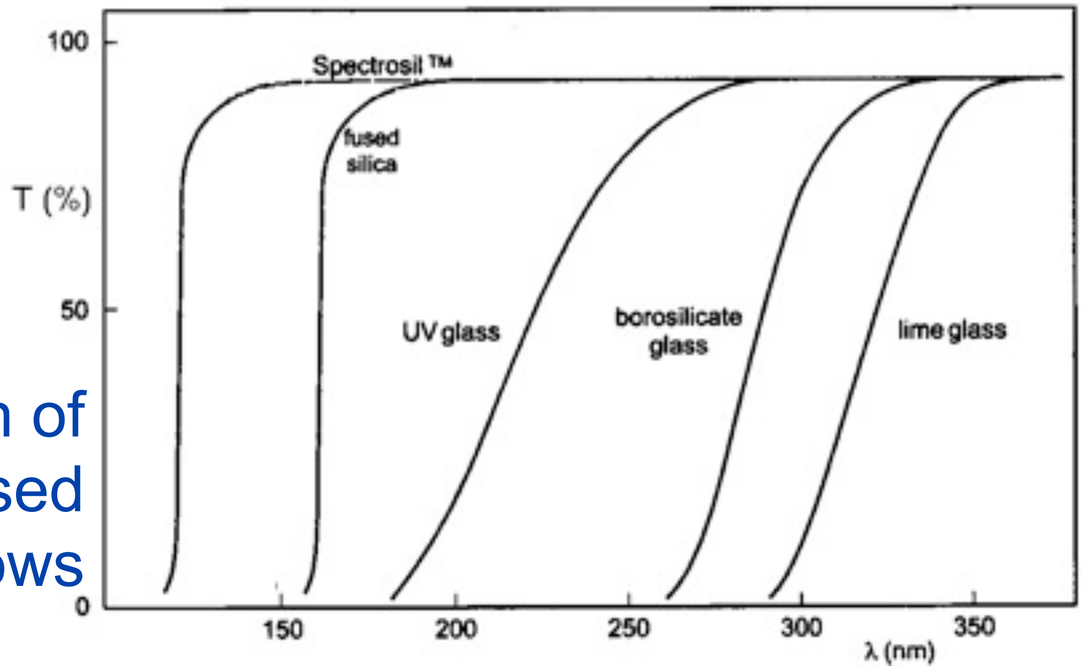
UV glass
quartz

NaF, MgF2,
LiF, CaF2

hard glass
(borosilicate)



transmission of frequently used windows



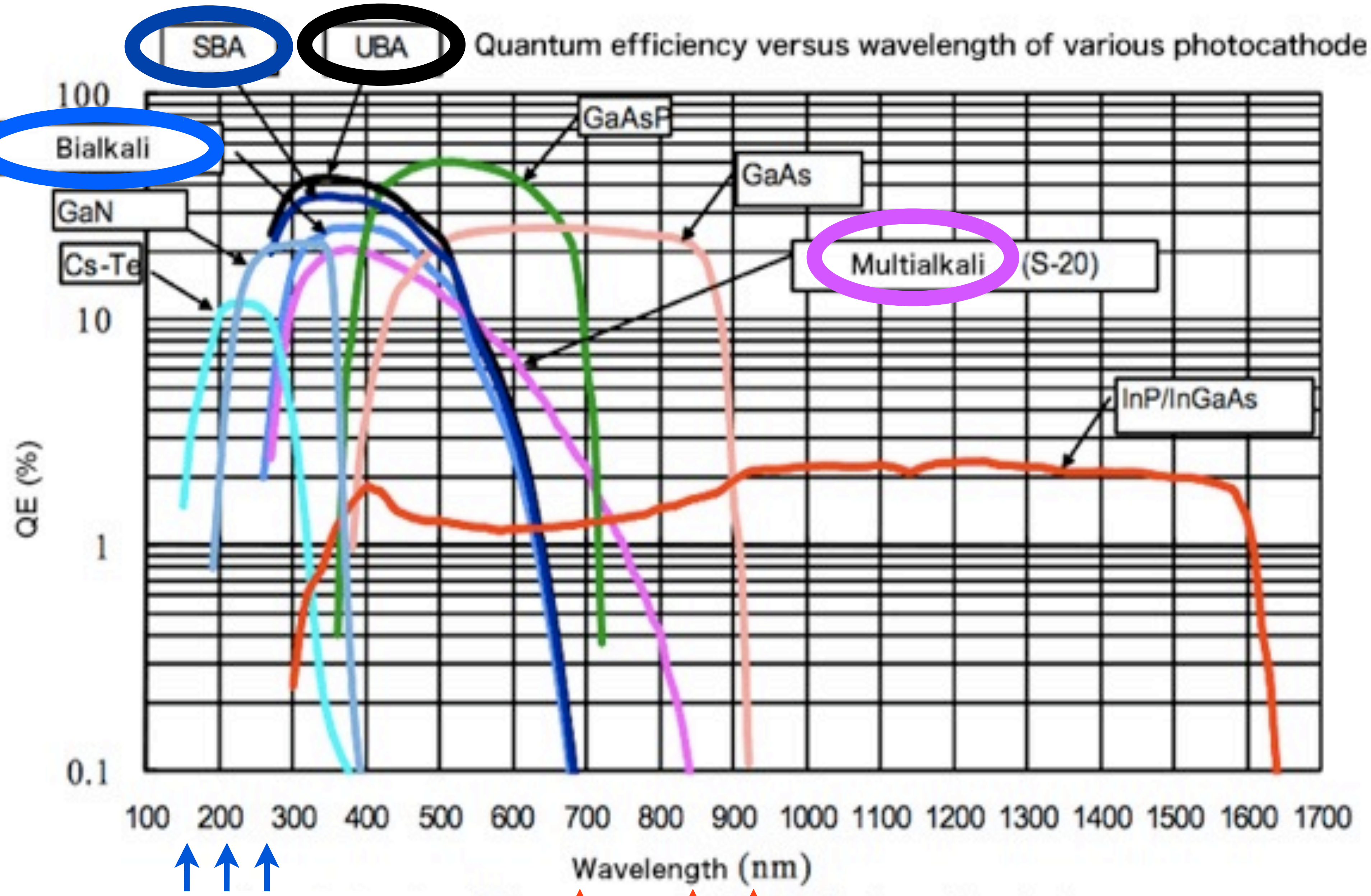
Quantum efficiency (QE)

not all photons incident on a photoemissive material will cause the emission of photoelectrons !
=> Sensitivity / Quantum efficiency

$$QE(\%) = \frac{N_{pe}}{N_\gamma}$$

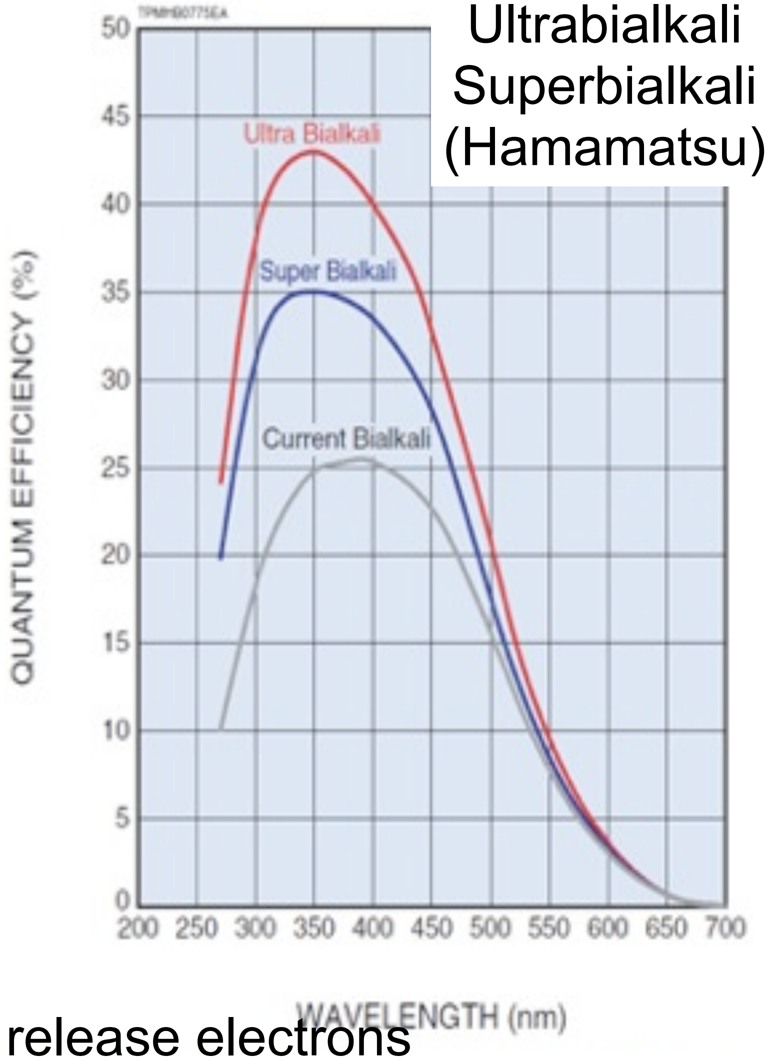
QE ~ 15% - 25%
(typical values)

QE ~ 40% in UBA



low λ cutoff
(window transmission)

↑ ↑ ↑
high λ cutoff
(material photoemission thr)



Ultrabialkali
Superbialkali
(Hamamatsu)

alkali (Li,Na,K,Rb,Cs): metals with low electronegativity i.e. high tendency to release electrons

Photodetectors

vacuum family:

Photomultipliers (PMT)

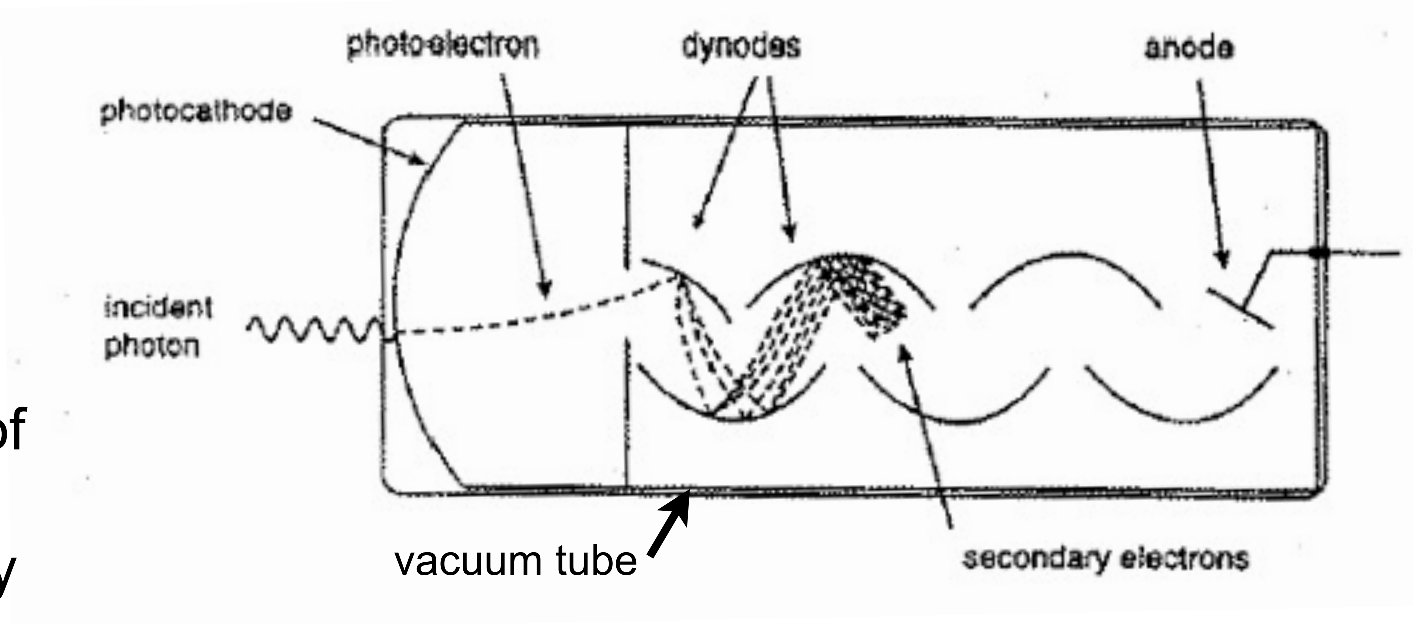
Multi anode photomultipliers (MA-PMT)

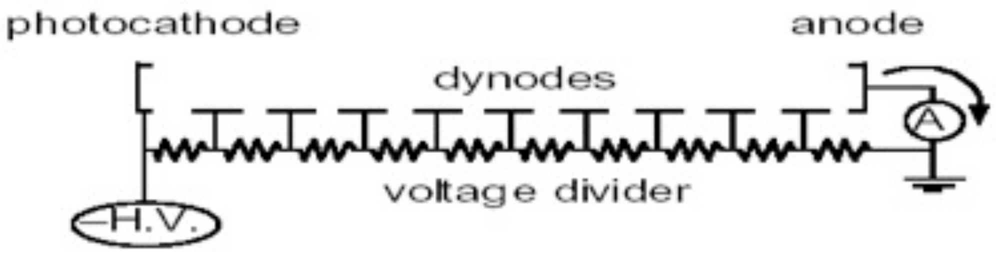
Micro Channel Plates (MCP)

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



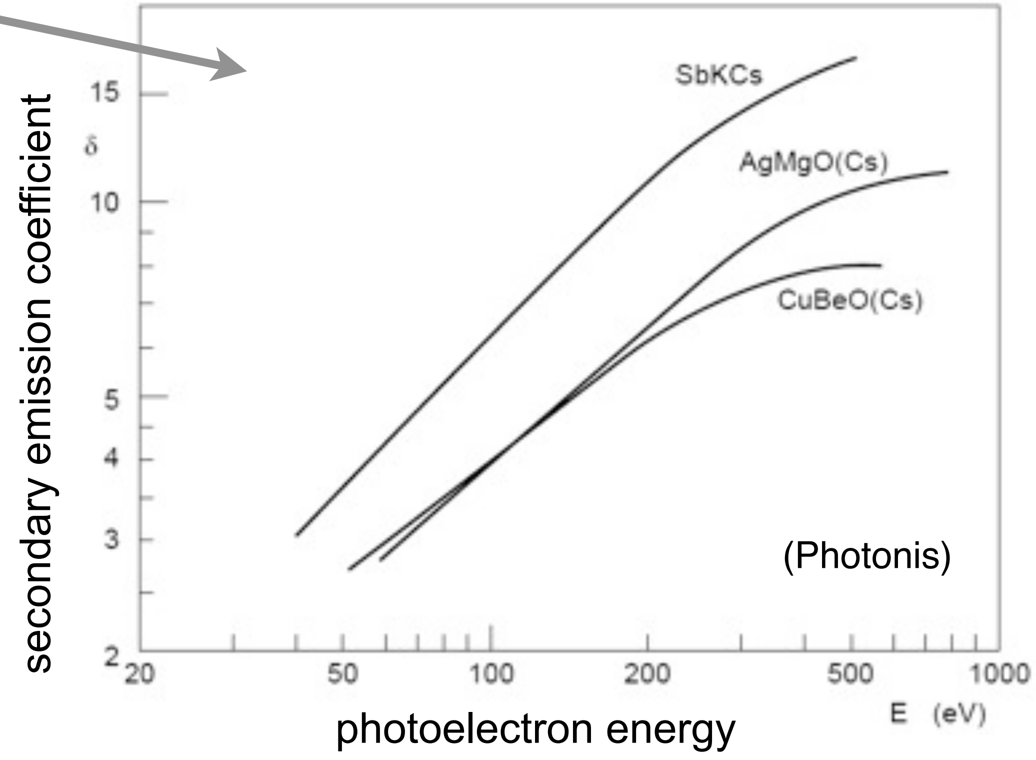


Gain : nr of dynodes

gain of each dynode $\delta = f(E_e)$

$$M = \delta^n$$

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



Vulnerable to magnetic field :

even with B_{Hearth} ~ 30-60μT
requires μ-metal shielding

PMT: Statistical fluctuations

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

statistical processes ⇨ statistical fluctuations

gain spread

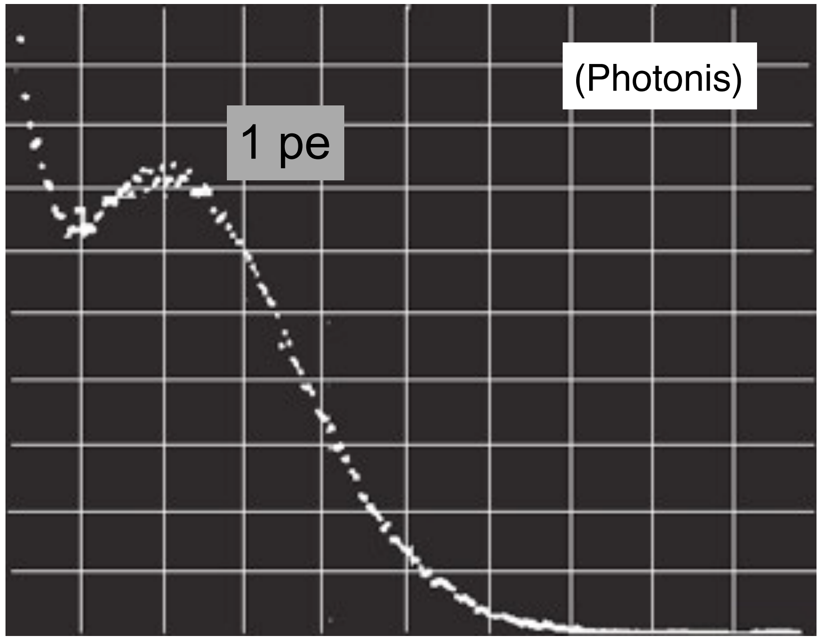
Poisson statistics: $$P_\mu(a) = e^{-\mu}\frac{\mu^a}{a!}$$ $$\sigma = \sqrt{\mu}$$

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

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

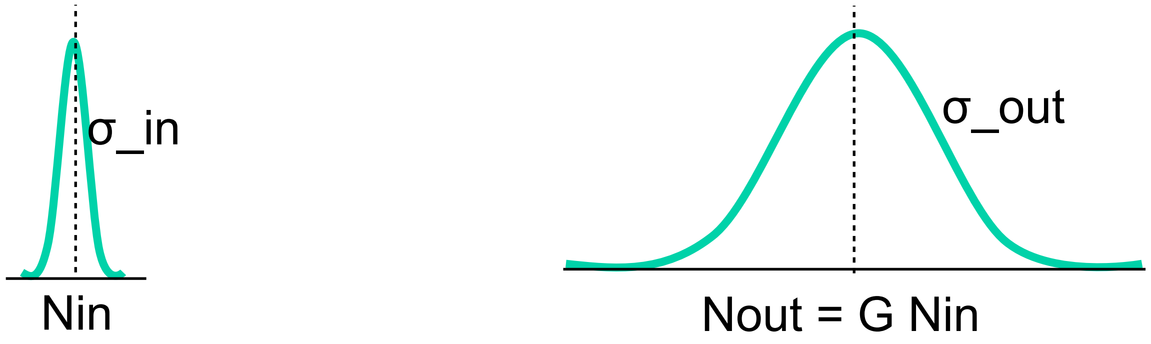
Biggest fluctuations when μ is small
=> Gain spread is essentially
dominated by the 1st 2nd dynodes

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



=> Single photon resolution : Statistically limited

Excess Noise Factor



$$\boxed{ENF \equiv \frac{\sigma^2_{Output}}{\sigma^2_{Input}}}$$

ENF : quantitative description of the statistical fluctuations

$$ENF = 1 + \frac{1}{\delta_1} + \frac{1}{\delta_1 \cdot \delta_2} + \cdots + \frac{1}{\delta_1 \cdot \delta_2 \cdots \delta_n}$$

PMT ~ 1 - 1.5

The photomultiplier tube (PMT)

PMT :

<u>commercial products since > 70 years</u>

- **high gain ~ 10^6 - 10^7**
- **high sensitivity** (low light pulse, single pe)
- **large** sensitive **areas** available
- large variety in windows/photocathodes, dynode design...


(Hamamatsu)

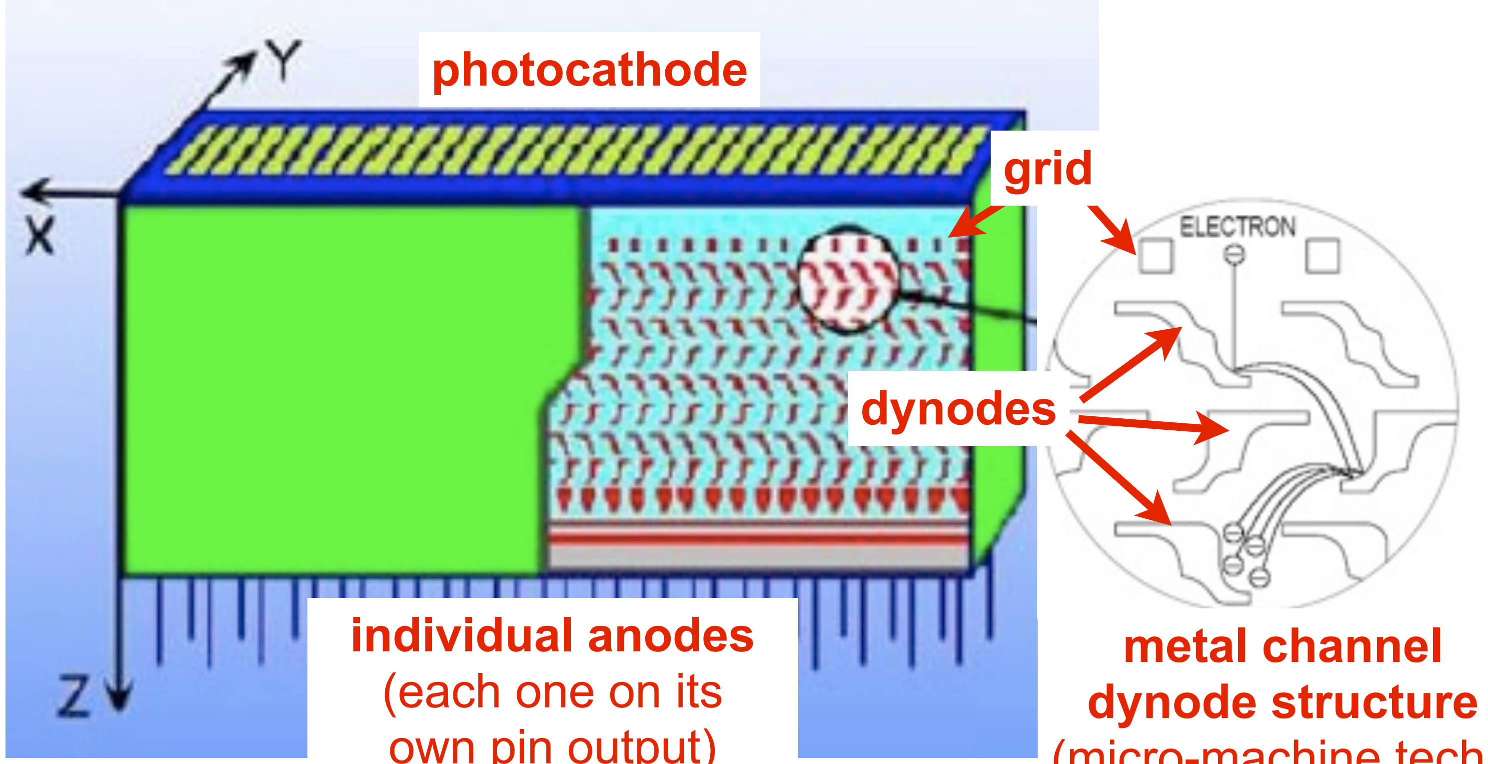
=> Why not (only) PMTs??

- 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

- you might want a small, pixelated light detector
- you might want even faster timing
- you might want improved p.e. resolution (less gain fluctuations)
- you might want higher quantum efficiency (especially at longer wavelengths)

...

Multi Anode PMT (MA-PMT)



metal channel dynode structure
(micro-machine tech.)

position sensitive PMT arrays
in a single vacuum envelope

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

Multi-anode (Hamamatsu H7546)

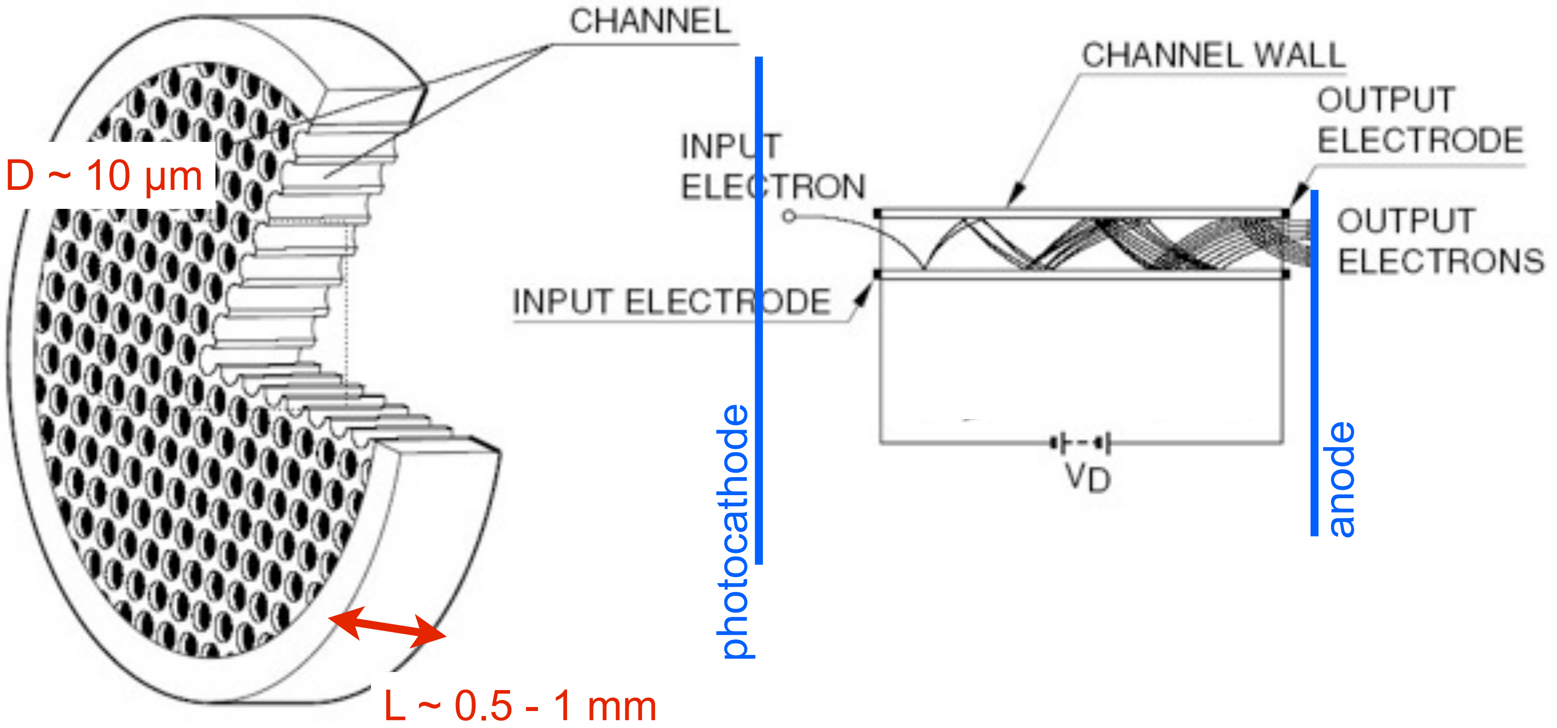
- Up to 8x8 channels (2x2 mm2 each);
- Size: 28x28 mm2
- Active area: 18.1x18.1 mm2 (41%)
- Bialkali PC : QE ~ 25-45% (λmax = 400 nm)
- Gain ~ 3x10^5
- Gain uniformity typ. 1:2.5
- Cross-talk typ. 2%

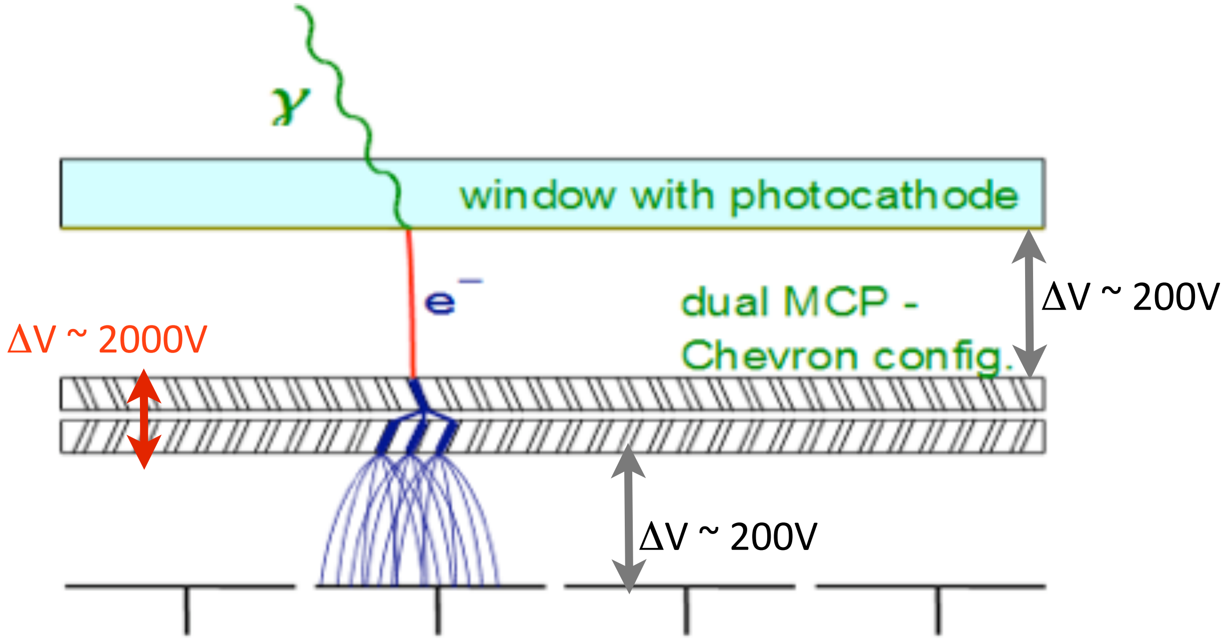
Advantages wrt PMT :
position sensitive
compact => better timing perfs
compact => B tolerant

Limitations :
non uniformity in the gain
(~ 30% differences among channels)
cross-talk
reduced single pe resolution

Micro channel plates (MCP) PMTs

- lead glass plate
- perforated by arrays of cylindrical holes ("micro-channels")
- inner surface of each channel = **continuous dynode**
- δ ~ 2 / strike
- Gain = f (Length/Diameter)
- typical L/D ~ 40 => ~ 10 strikes => **Gain** = 2^{10} **~ 10^3 (single plate)**





typical configuration: Chevron configuration.
- 2 MCP => **Gain ~ 10^6**
- segmented anode possible => position sensitive

Advantages wrt PMT :

excellent timing resolution (σ ~ 40 ps)
B tolerant (0.1 T random direction ; ~ 1T axial dir.)
position sensitive (if segmented anode)
better single pe (if operated in saturation mode)

Limitation :

severe aging effect (due to ion feedback)
limitation on count rate (long recovery time)

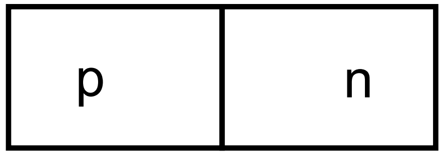
Photodetectors

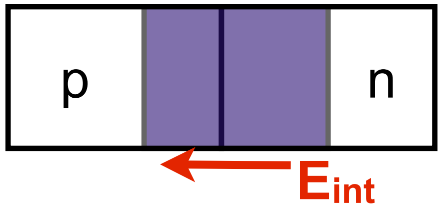
Solid state photodetectors:

pin diode
avalanche photo diode (APD)
silicon photomultiplier (SiPM, G-APD)

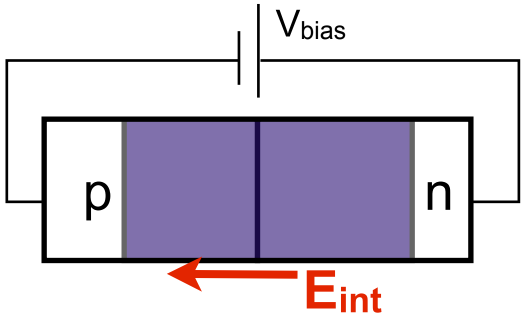
Si p-n junction as photodetector

Silicon p-n junction

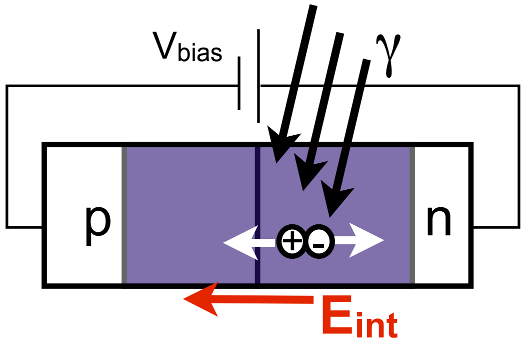




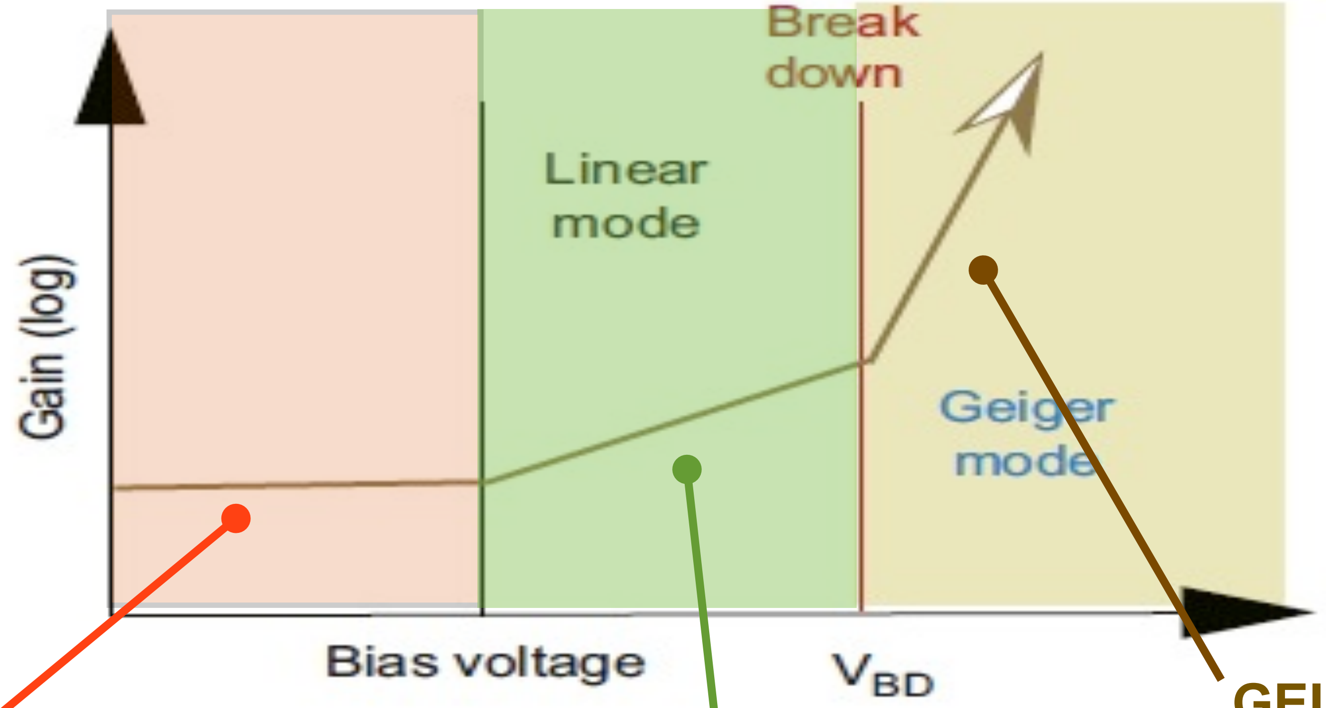
- charge diffusion => **depletion region**
- built-in **E_{int}** (which prevents further charge flow)



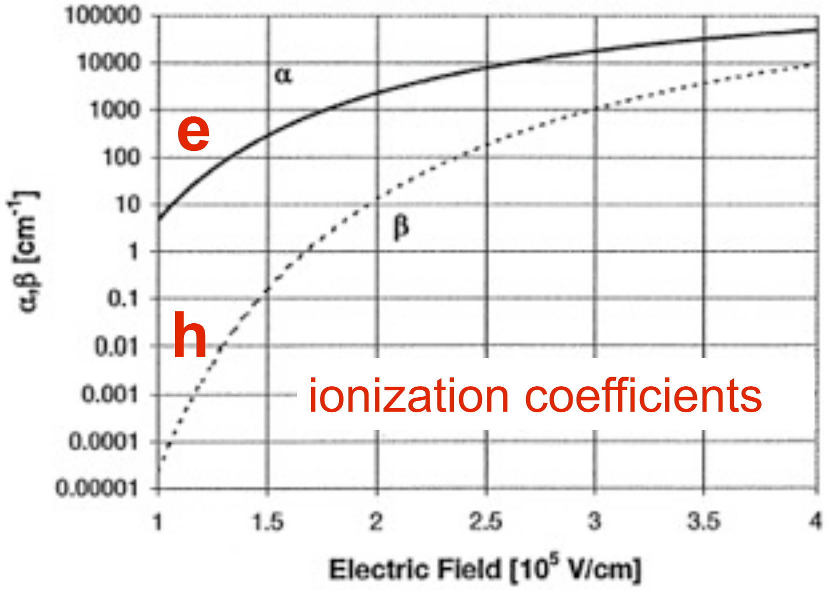
reversed biased
p-n junction
increased size for
the depl. region



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



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



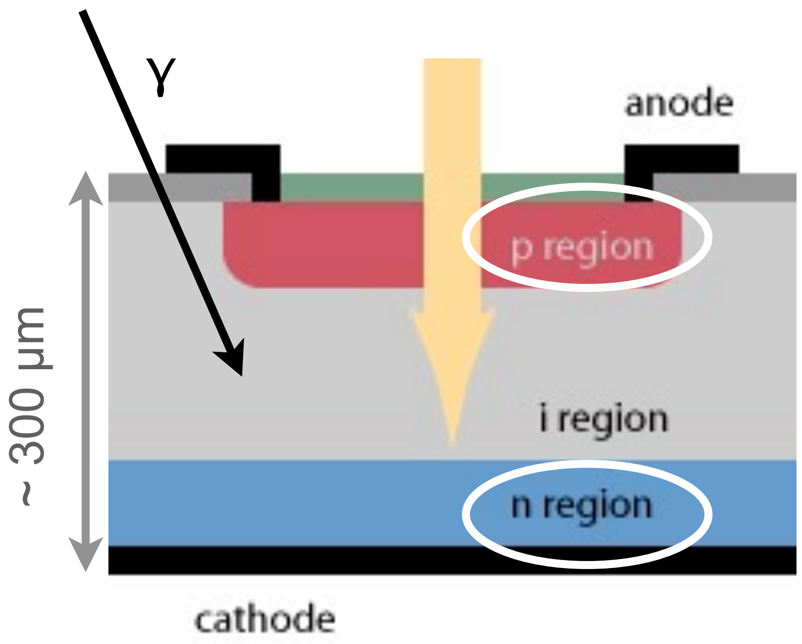
PIN Diode
- no bias
- no gain

p-n junction works as photodetector even without bias

AVALANCHE PHOTODIODE (APD)
- voltage
- secondary ionization <u>from electrons</u>
- avalanche
- linear regime

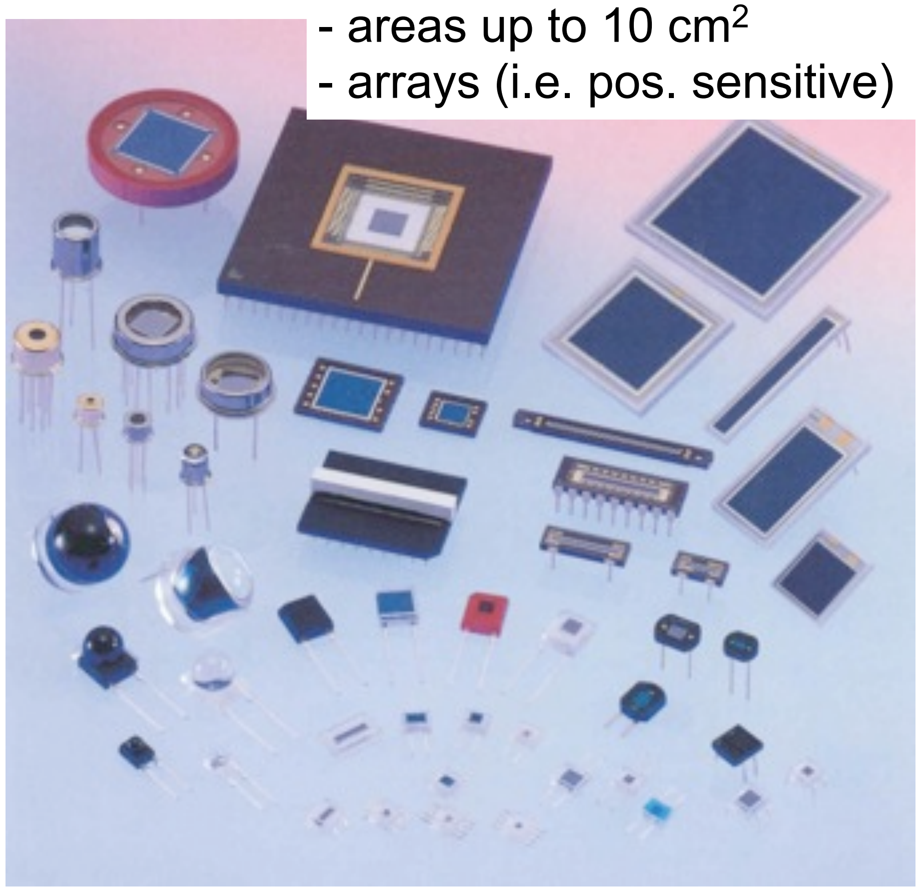
GEIGER MODE AVALANCHE (G-APD) or SILICON PHOTOMULTIPLIER (SiPM)
- V > V_breakdown
- secondary ionization <u>from electrons and holes</u>
- “broken” junction , avalanche
- Geiger regime, not linear anymore

PIN photodiode



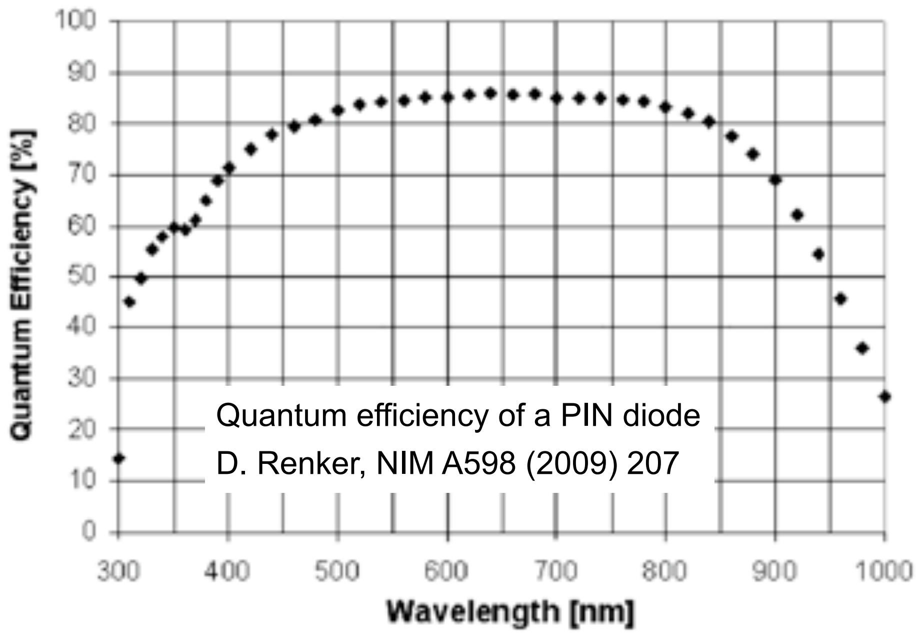
P-I-N junction

“i” : intrinsic (i.e. undoped)
- no free carriers
- conversion region
- acts as (thick) depletion region



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

- no bias required
- high sensitivity, large spectral response
- simple / reliable / successful
- widely used in HEP on large scale applications
  (small volume, insensitive to magnetic field, high QE)



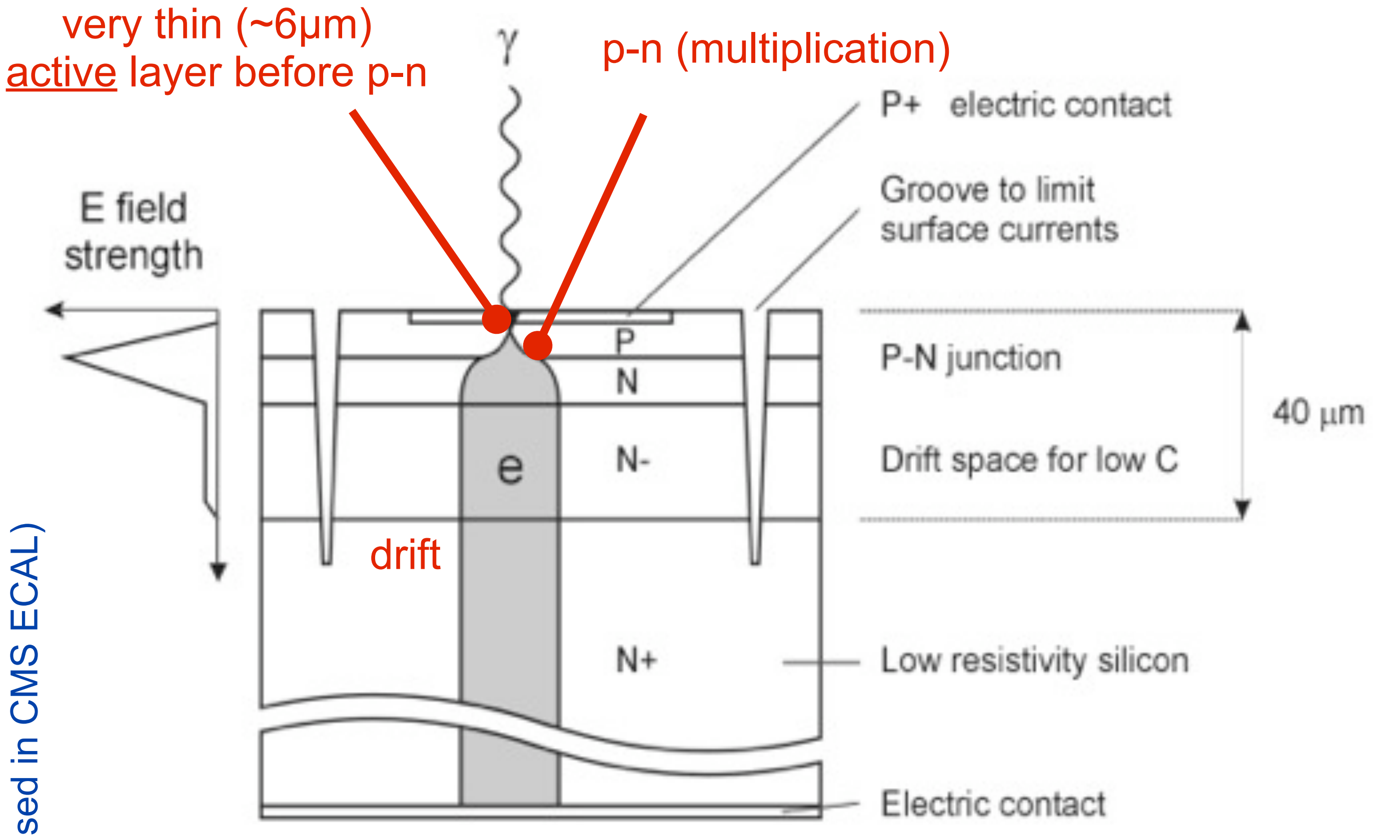
Quantum efficiency of a PIN diode
D. Renker, NIM A598 (2009) 207

- **QE ~ 80%** @ 500 - 800 nm

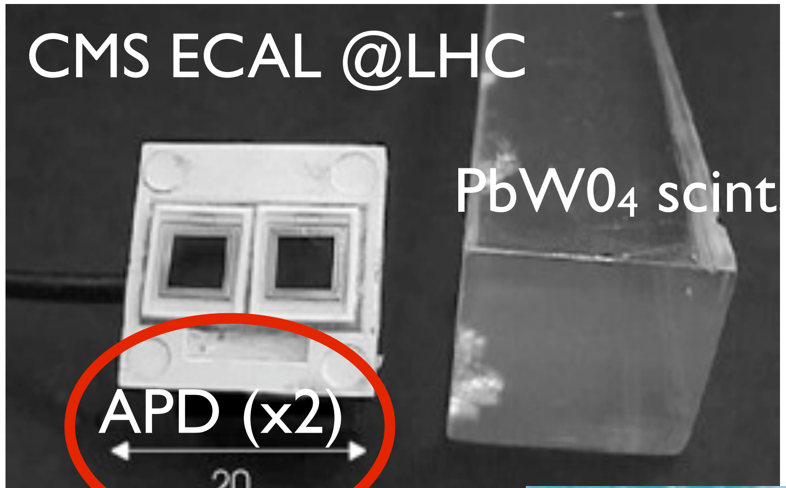
- the full thickness (~ 300 μm) is sensitive volume
- tick layer (~ 300 μm) :
  - sensitive red / infrared (long λ_abs is Si)
  - low noise (low C)

- no internal gain
  => no single photon detection
  => min ~ few 100 γ
  => requires external amplifier

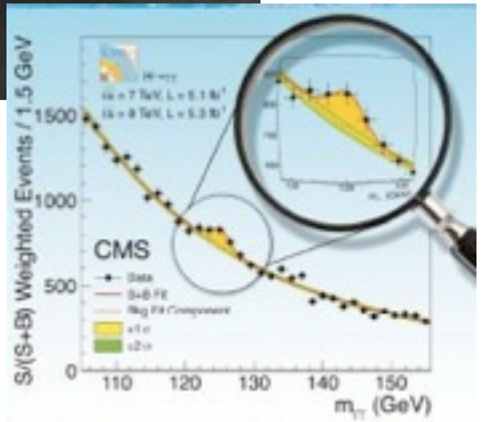
Avalanche PhotoDiode (APD)



reverse APD, Hamamatsu S8148 (used in CMS ECAL)



working gain ~ 50
Vbias ~70V



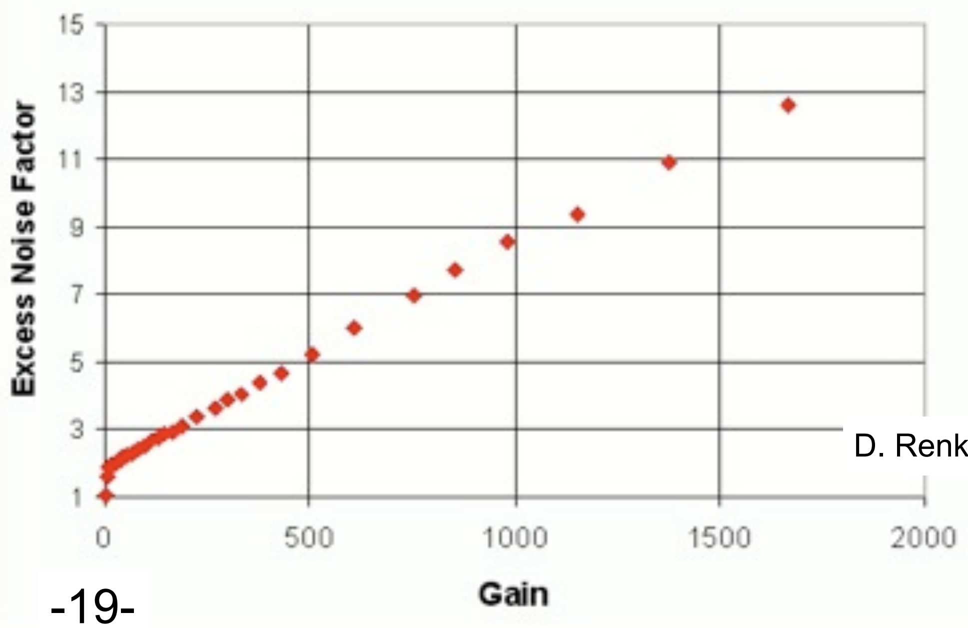
- p-n junction with increased electric field
- Vbias ~ 100 - 200 V

- internal gain, due to amplification of charge carriers with an avalanche development (only e start secondary ionization) - Linear regime
- Gains: M ~ 50 - 500 (f(Vbias))

- QE ~ 80% [same as for PIN diodes]
- peaked spectral response (because of the thin conversion region)

- Avalanche formation => statistical fluctuations
- ENF ≥ 2 (increases with gain)

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



D. Renker, 2009 JINST 4 P04004

Geiger mode APD (G-APD) / Silicon photomultiplier (SiPM)

array of several micro-cells APDs operated in Geiger mode

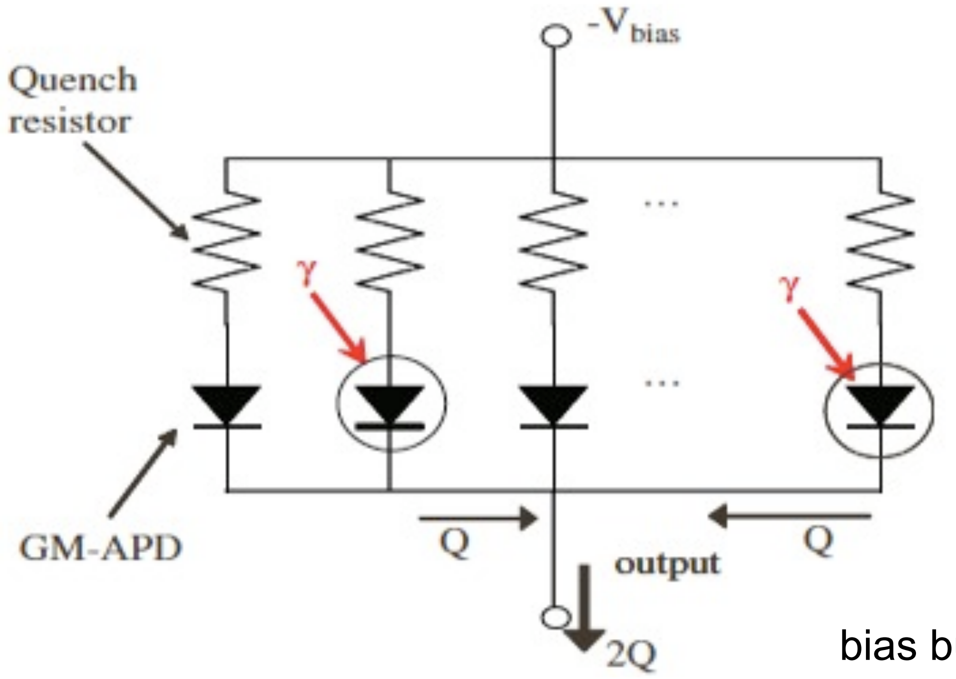
every single cell :

- Vbias > Vbd (Vovervoltage = Vov = Vbias - Vbd)
- Geiger regime: e and h participating to the avalanche
- Gains ~ 10^5 - 10^6

- when hit by one/n photon(s) => full discharge => released charge: $\mathbf{Q_i = C_D\,(V_{bias} - V_{bd}) = C_D\,V_{ov}}$

- no analogue info at the single cell level

All cells connected to a **common bias** through **independent quenching resistors**, all integrated within a sensor chip. The output is the **analogue sum of all cells**



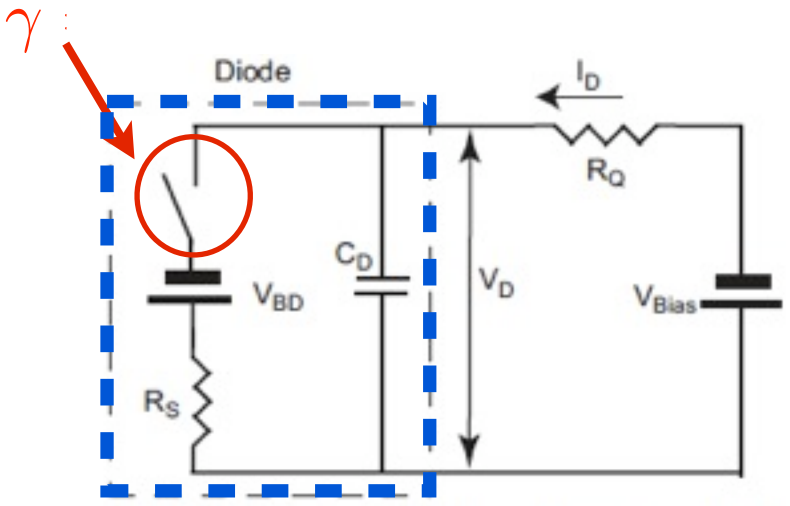
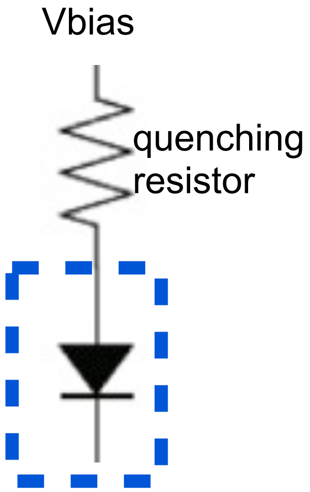
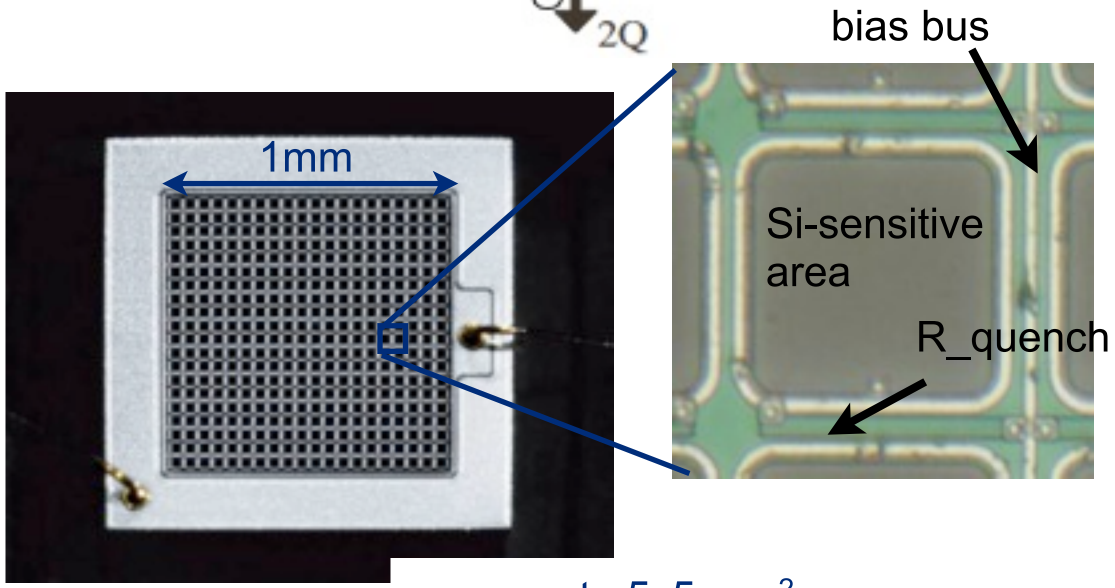


Fig. 4. Equivalent circuit of a single cell Geiger mode APD.

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

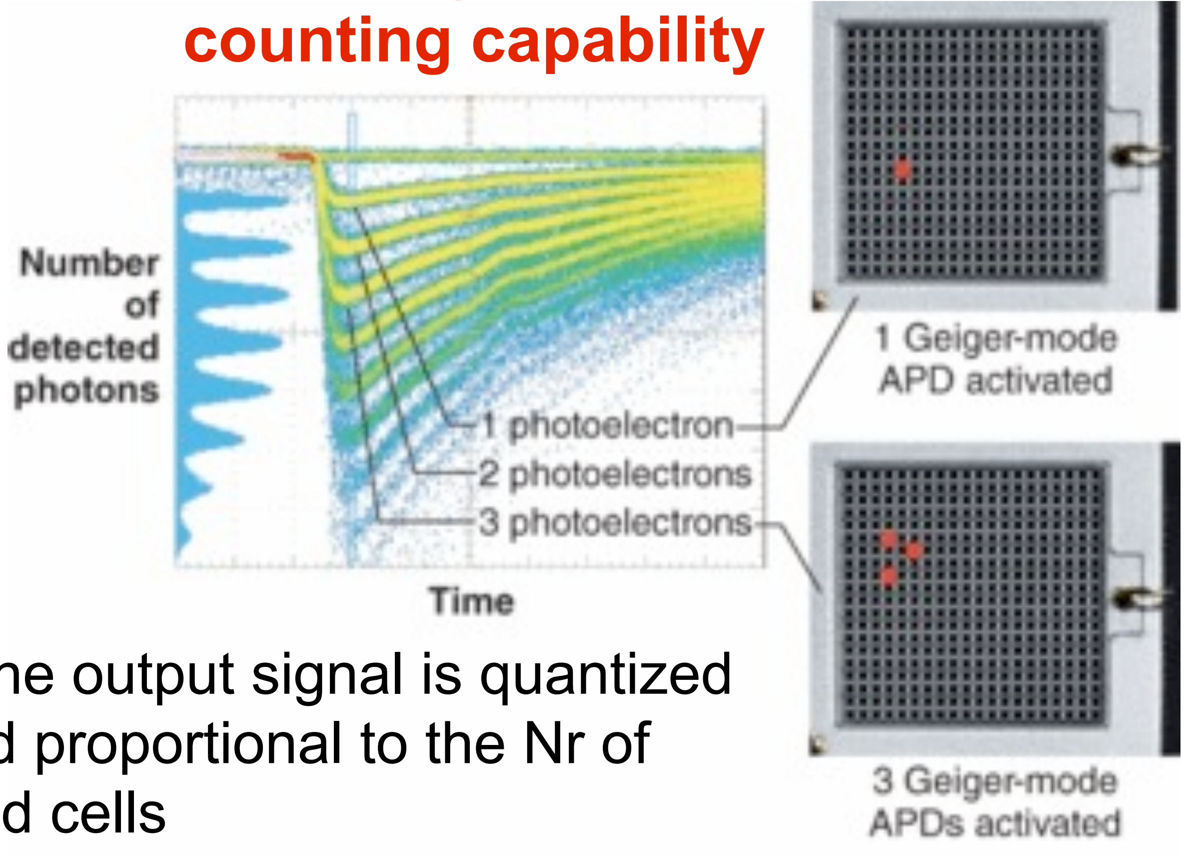




areas up to 5x5 mm^2
nr APD cells ~ 100 to 15000 / mm^2
typical cell size ~ 20 to 100 µm

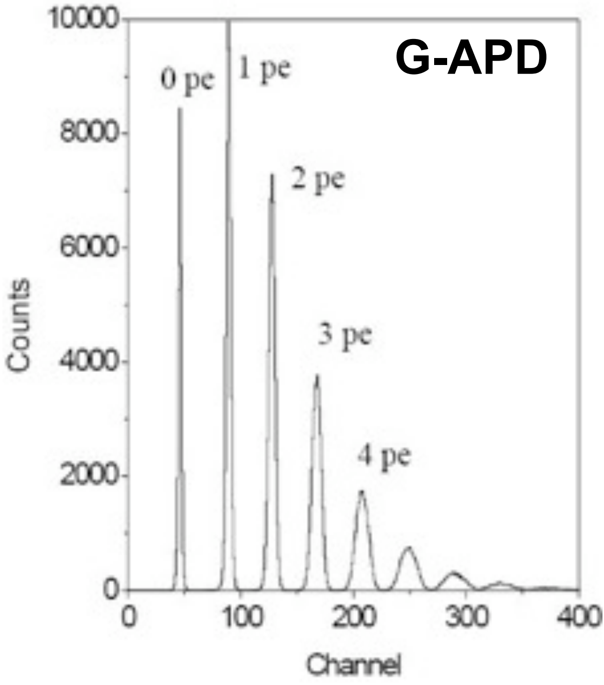
SiPM : photon counting

Excellent single photon counting capability



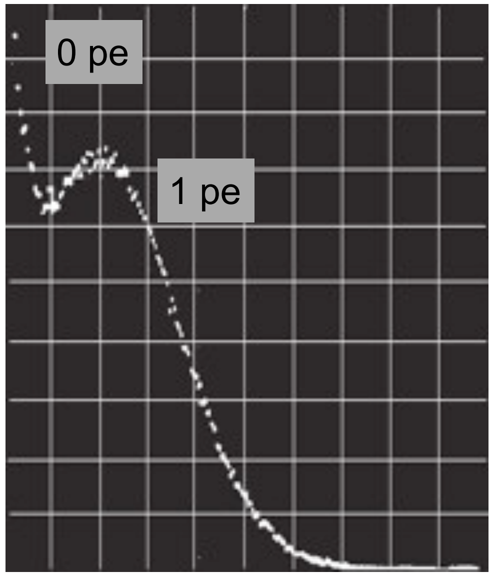
- The output signal is quantized and proportional to the Nr of fired cells

Pulse height spectra



D. Renker, 2009 JINST 4 P04004

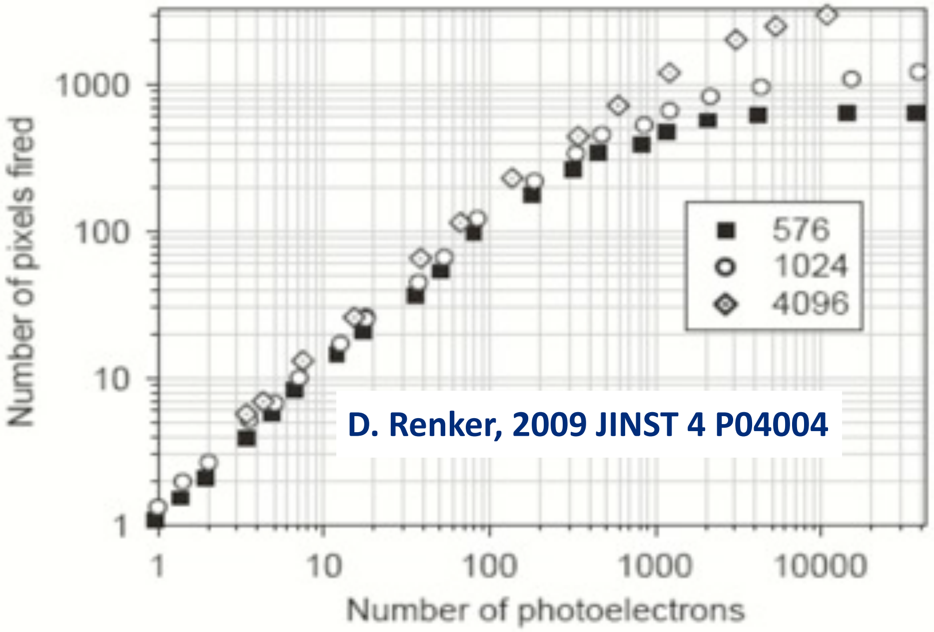
PMT (for comparison)



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

- Linearity as long as Nr_detected_photons < Nr_cells

$$N_{\gamma\_det} = N_{cells}(1 - e^{\frac{N_{\gamma\_inc}\cdot PDE}{N_{cells}}})$$



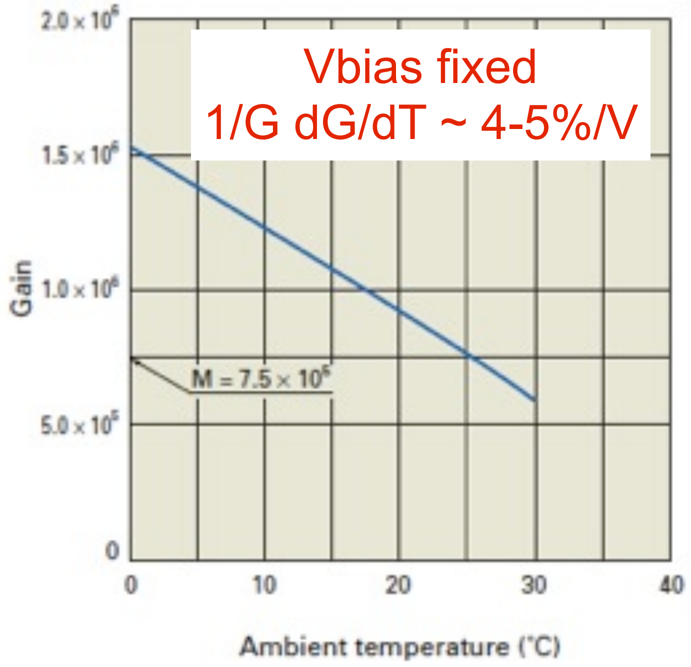
D. Renker, 2009 JINST 4 P04004

Gain and Photon detection efficiency of SiPM

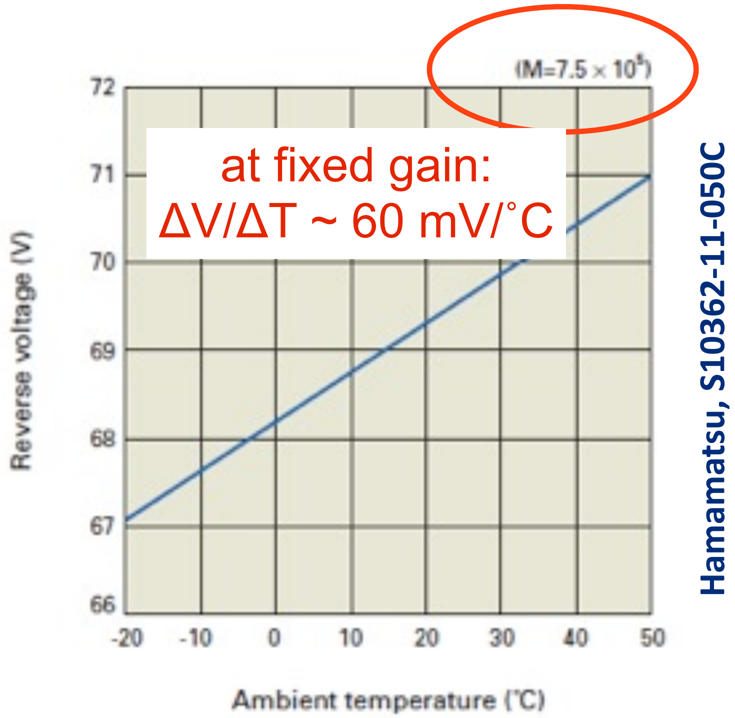
- excellent **linearity of gain with V_{bias}** [$Q_i = C\, V_{ov}$]
- typical gains : **10^5 - 10^6**
- typical V_{bias} **~ 70 - 100 V**
- gain strongly dependent on temperature
  - higher T => bigger lattice vibrations
  - carriers may strike the lattice before ionization
  - ionization becomes more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

  (the same is true for APD detectors!)

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



Vbias fixed
1/G dG/dT ~ 4-5%/V



at fixed gain:
ΔV/ΔT ~ 60 mV/°C

Hamamatsu, S10362-11-050C

- sensitivity : photon detection efficiency (PDE)

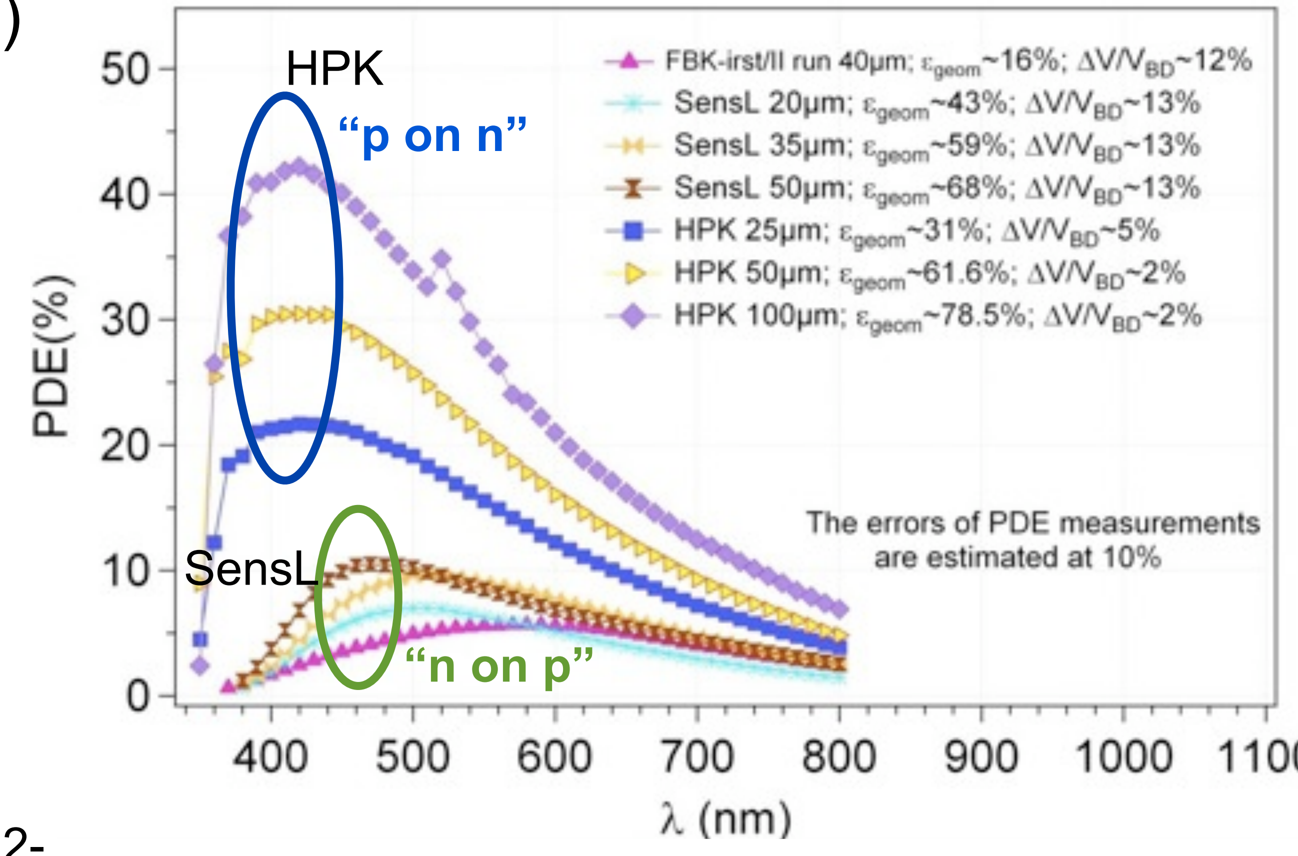
$$PDE = (QE)\ (\varepsilon_{geom})\ (P_{Geiger})$$

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})**

- **typical PDE ~ 30 %** (λ-peaked)



The errors of PDE measurements are estimated at 10%

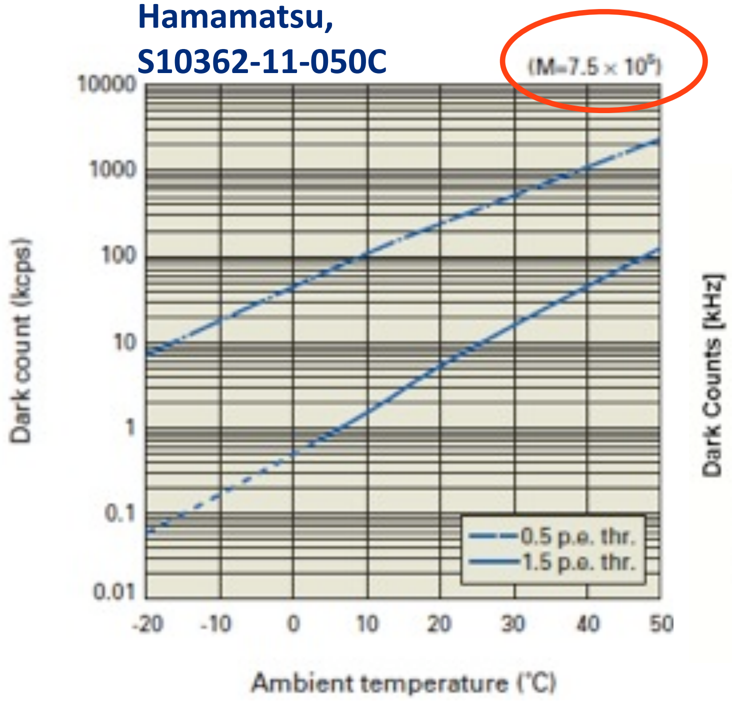
N. Dinu & al, NIM A 610 (2009) 423–426

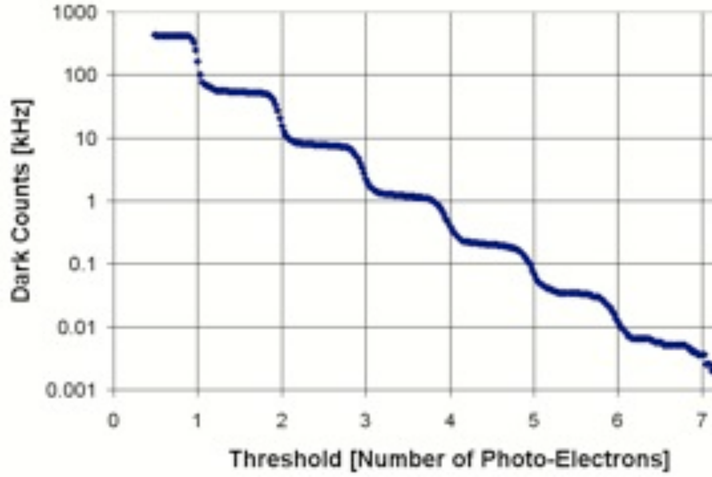
SiPM noise

Counts registered by SiPM in absence of light.
Three main sources:

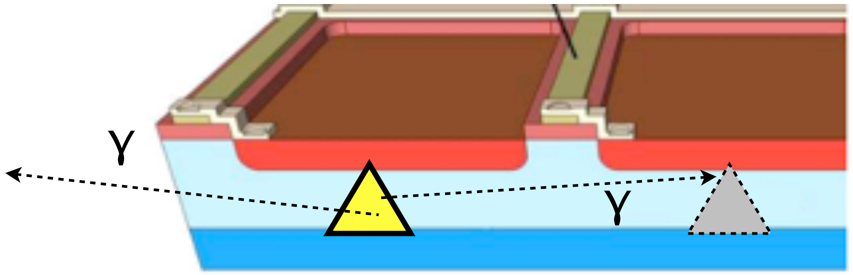
- **Dark counts:**
  mainly by thermal generation

  typical Dark Count Rates (DCR) :
  100 kHz - few MHz / mm^2 (@ 0.5 pe thr)
  => Cooling !
  (dark rate is halved every 8K)

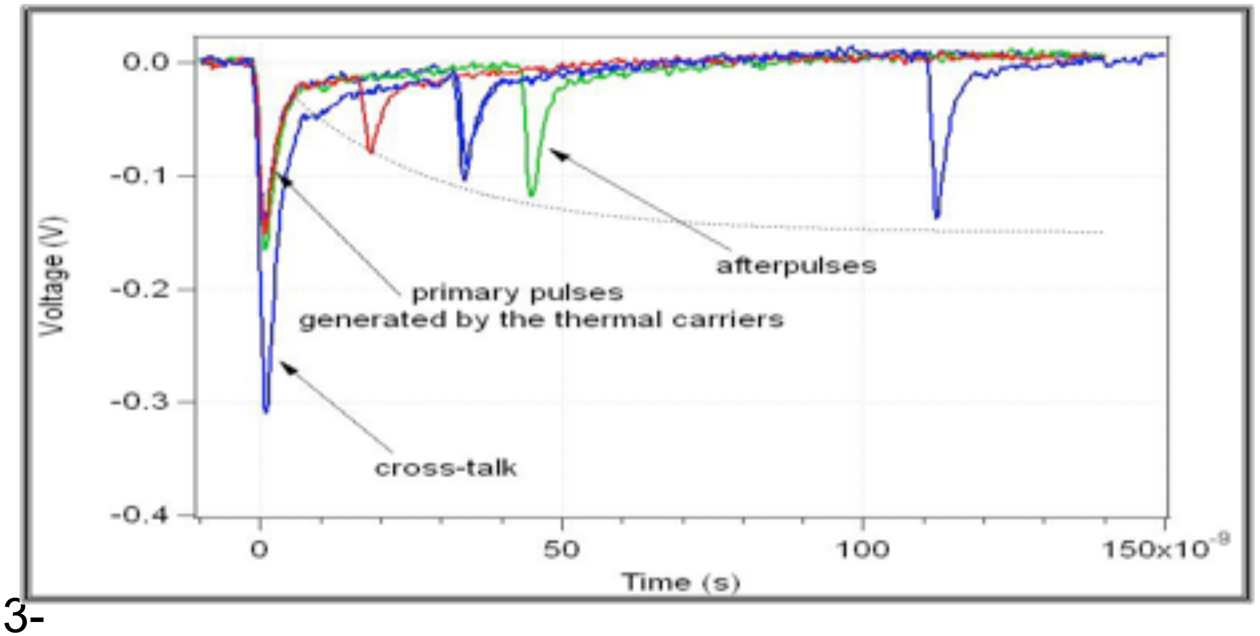

Hamamatsu, S10362-11-050C

D. Renker, 2009 JINST 4 P04004


- **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



SiPM on the market

- ~ 10-15 years development
- too new for LHC !
- strong impact on future detectors : LHC upgrades / medical imaging instrumentation (e.g. PET/ MRI)

- :-) **compact / high gain with low voltage / low power consumption / insensitive to magnetic fields / high QE / single photon counting**
- :-(**high dark count rates / cooling / stability issues (T,V) / small & not cheap!**

a few examples (EDIT school 2011)

- current trends of development : higher PDE / different λ matching / larger areas / lower noise / lower x-talk

- DIGITAL SiPM (Philips) => See Thomas Frach lecture tomorrow

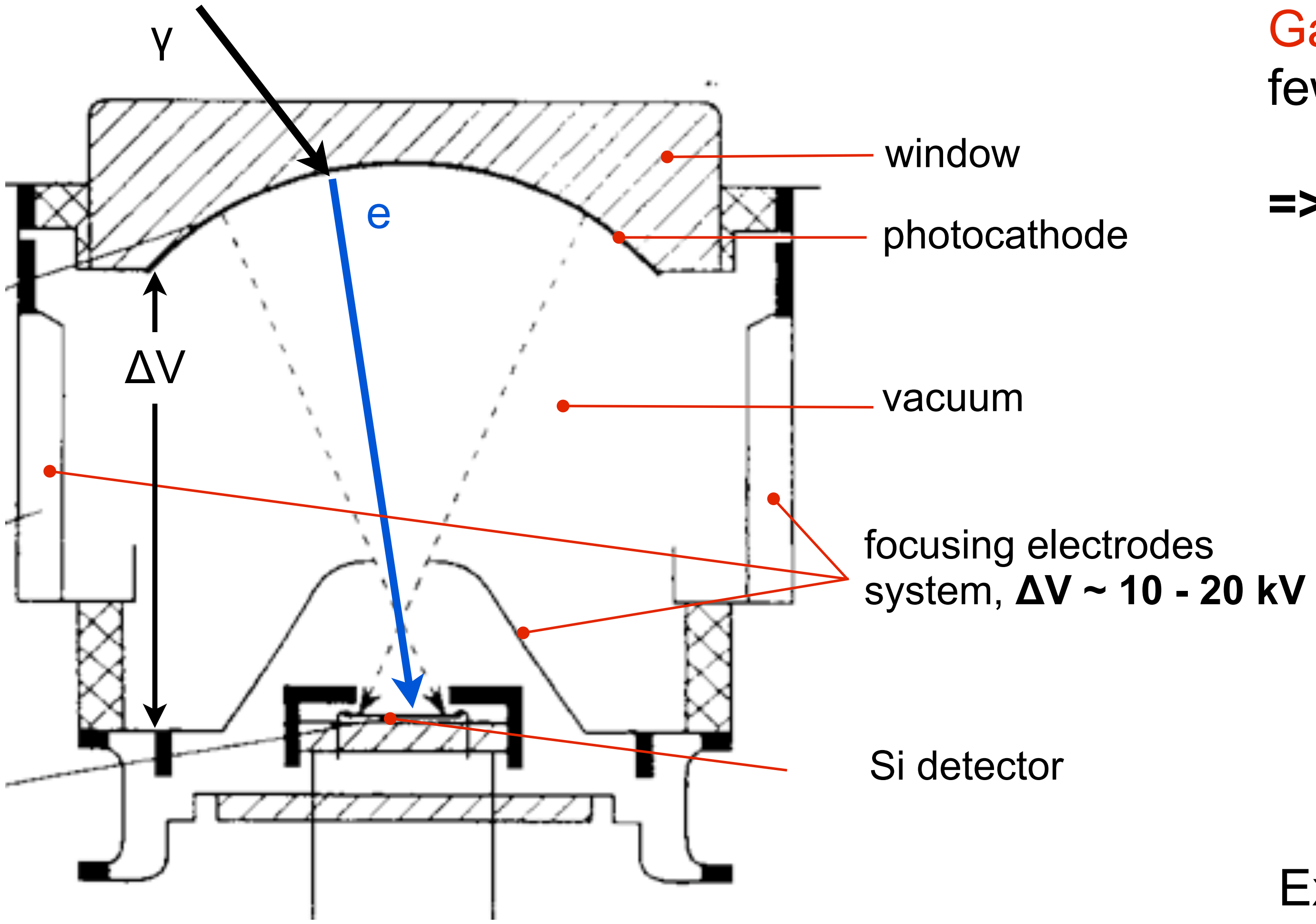
Photodetectors

Hybrid PhotoDiode

(HPD)

Hybrid Photodiodes: HPD

<u>hybrid</u> : **combination of vacuum photodetector and solid state technology**



Gain: achieved **in one step** (by energy dissipation of few keV pe's in solid state detector anode)

=> low gain fluctuations (Fano factor *F* ~ 0.12 in Si)

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

~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

$$\sigma_M = \sqrt{M F_{Si}}\ ;\ F_{Si} = 0.12$$

"Fano factor"

Example :

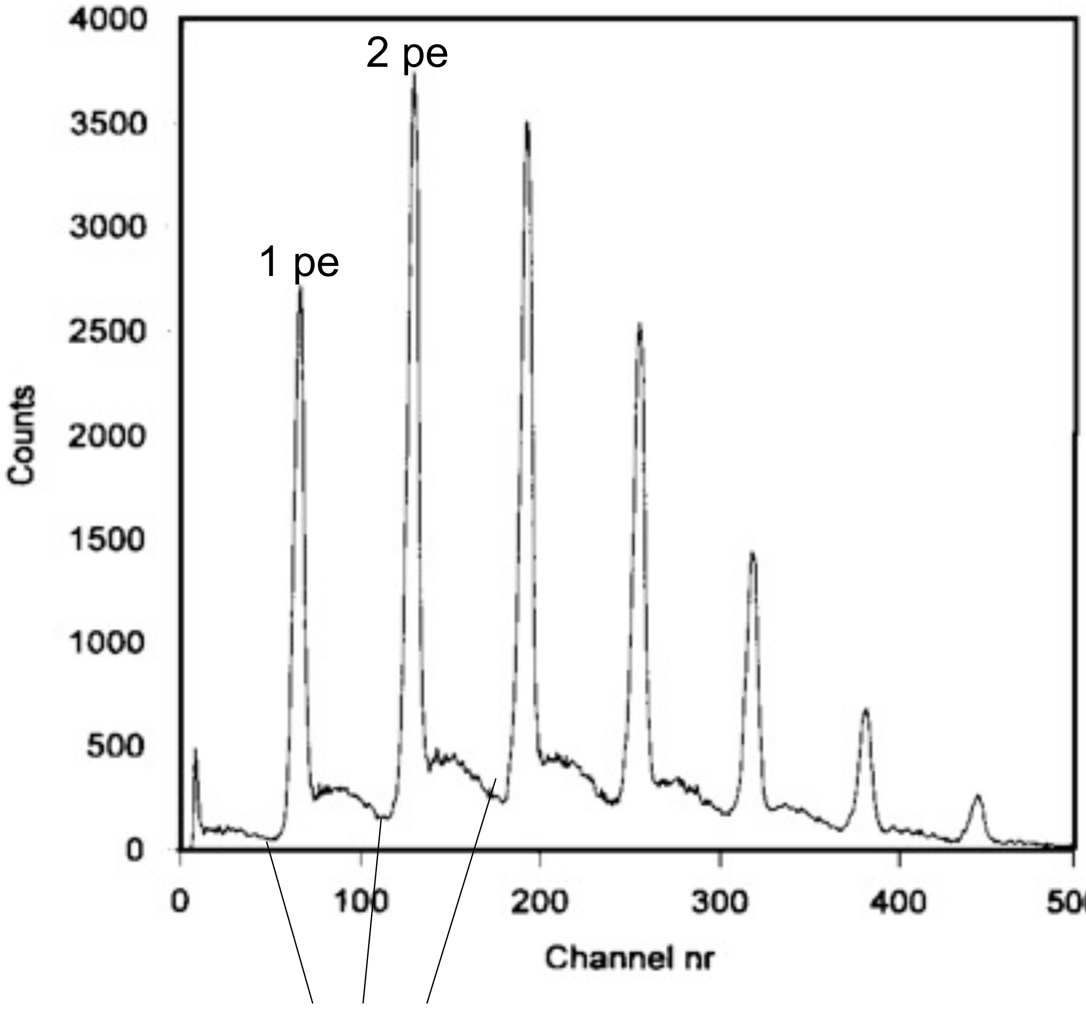
ΔV = 20 kV => **M ~ 5000, σ ~ 25**
=> overall noise dominated by electronics

- single photon sensitivity
- large areas coverage
- good spatial resolution (with segmented Si sensor)
- magnetic field operation (if proximity-focusing electrons optics)

HPD properties

Single photon counting

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



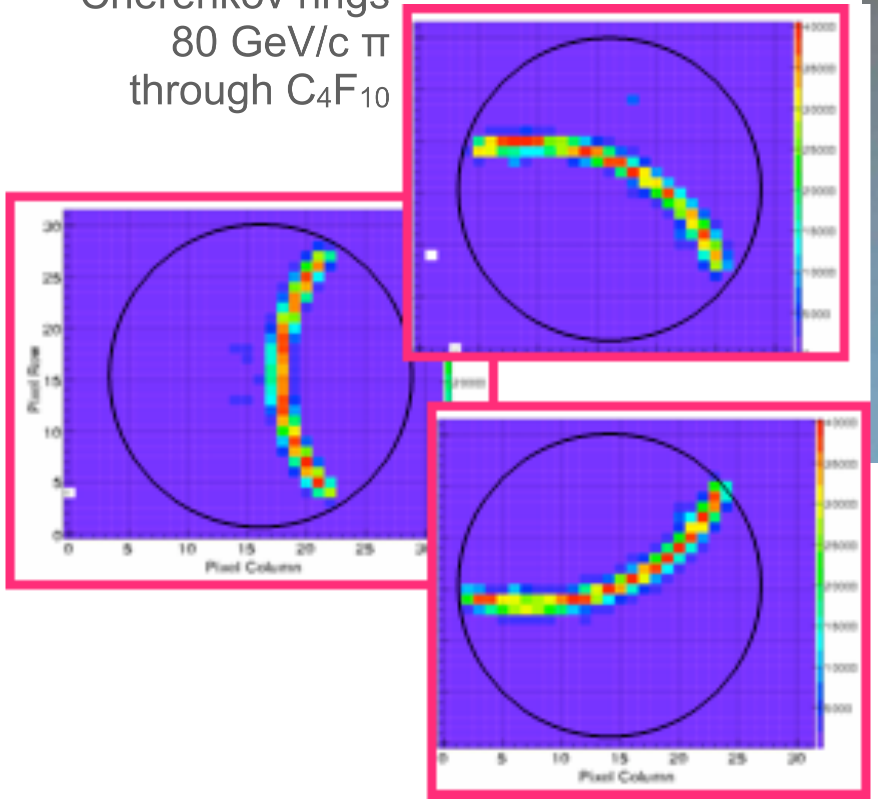
C.P. Datema et al., NIM A387 (1997) 100-103

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

Cherenkov rings
80 GeV/c π
through C_4F_{10}



M. Adinolfi et al., NIMA 603 (2009) 287-293

DEP Photonis /
LHCb development

The light image in the photocathode is projected into the Si sensor (pixel array).

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

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 photodetectors**
- **Photographic emulsions**
- **Liquid scintillators**
- **...**

Bibliography

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- 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

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- 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**

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