VO 260 066

Detector and detector systems for particle and nuclear physics I

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Part 2

Friday 16.1.2015

Scintillation principle

Inorganic scintillators

Organic scintillators

Light guide

Light detection

Applications

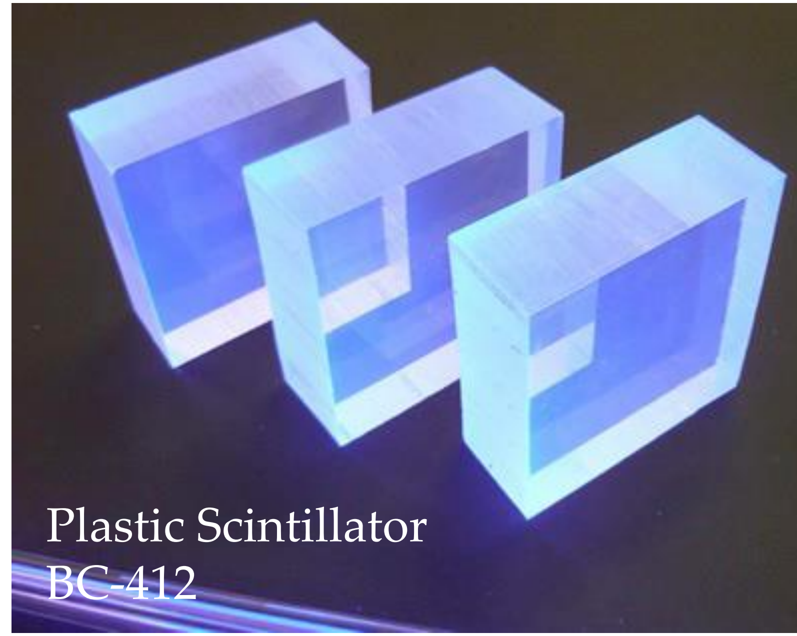
SCINTILLATION DETECTORS

Scintillators – General characteristics

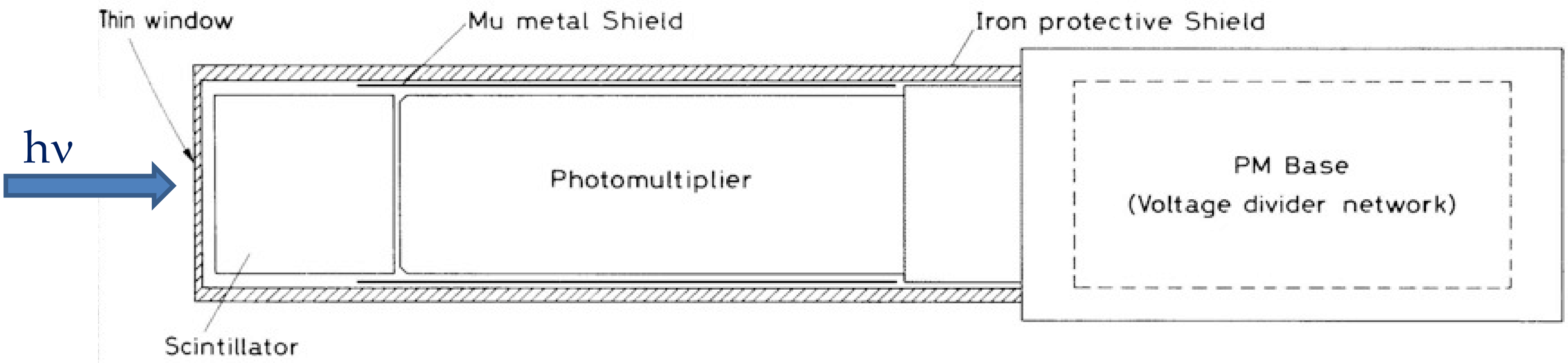
Principle:
- dE/dx converted into visible light
- detection via photo sensors
  [e.g. photomultiplier, human eye ...]

Features:
- sensitive to energy
- fast time response
- pulse shape discrimination

Requirements:
- high efficiency for conversion of excitation energy to fluorescent radiation
- transparency to its fluorescent radiation to allow transmission of light
- emission of light in a spectral range detectable for photo sensors
- short decay time to allow fast response



Scintillators – basic counter setup

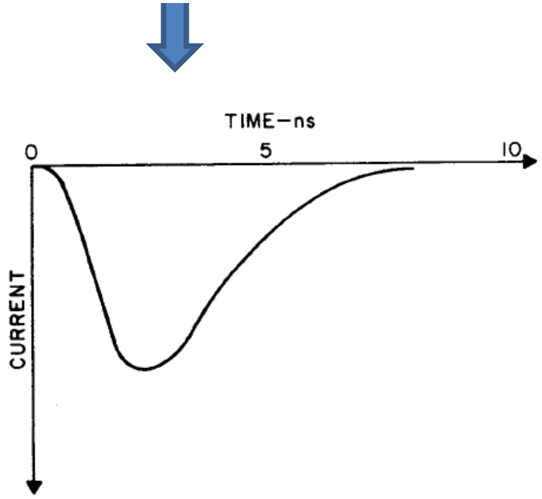


Scintillator Types:

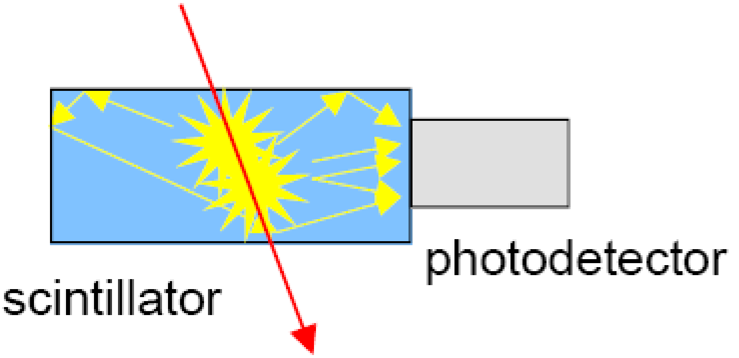
- organic scintillators
- inorganic crystals
- gases

Photo sensors:

- photomultipliers
- micro-channel plates
- hybrid photo diodes
- silicon photomultipliers (SiPMs)



Scintillation Detectors



Energy deposition by a ionizing particle
→ generation
→ transmission of scintillation light
→ detection

Inorganic (crystalline structure)
Up to 40000 photons per MeV
High Z
Large variety of Z and ρ
Un-doped and doped
ns to μs decay times
Expensive

E.m. calorimetry (e, γ)
medical imaging
radiation hard (100 kGy/year)

Organic (plastics or liquid solutions)
Up to 10000 photons per MeV
Low Z
$\rho \sim 1 g/cm^3$
Doped, choice of emission wavelength
ns decay times
Relatively inexpensive

Tracking, TOF, trigger, veto counters, sampling calorimeters.
medium rad. hard (10 kGy/year)

Inorganic scintillators

Some crystals are intrinsic scintillators in which the luminescence is produced by a part of the crystal lattice itself. However, other crystals require the addition of a dopant, typically fluorescent ions such as thallium (Tl) or cerium (Ce) which is responsible for producing the scintillation light (in both cases is the scintillation mechanism the same):

- The energy is transferred to the luminescent centres which then radiate scintillation photons.

For example, in the case of thallium doped sodium iodide (NaI(Tl)), the light output is ~40,000 photons per MeV deposited energy.
This high light output is largely due to the high quantum efficiency of the thallium ion, disadvantage rather slow (250 ns) decay time.

Inorganic scintillators

Inorganic crystals form a class of scintillating materials with much higher densities than organic plastic scintillators (typically 4-8 g/cm^3) with a variety of different properties for use as scintillation detectors.

Due to their high density and high effective atomic number, they can be used in applications where high stopping power or a high conversion efficiency for electrons or photons is required.

- total absorption electromagnetic calorimeters, which consist of a totally active absorber (as opposed to a sampling calorimeter)
- as well as serving as gamma ray detectors over a wide range of energies.

Many of these crystals also have very high light output, and can therefore provide excellent energy resolution down to very low energies (few hundred keV).

Organic scintillators

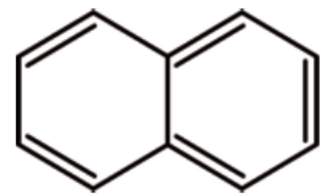
are aromatic hydrocarbon compounds containing linked or condensed benzene-ring structures.
Scintillation light arises from transitions made by “free” valence electrons of the molecule → very rapid decay time ~ ns

Aromatic hydrocarbon compounds:

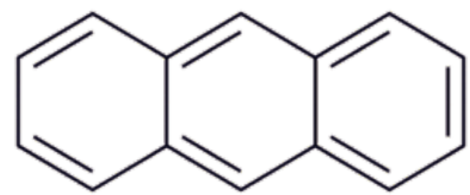
e.g. Naphtalene [$C_{10}H_8$]
Antracene [$C_{14}H_{10}$]
Stilbene [$C_{14}H_{12}$]

Very fast!
[Decay times of O(ns)]

Naphtalene

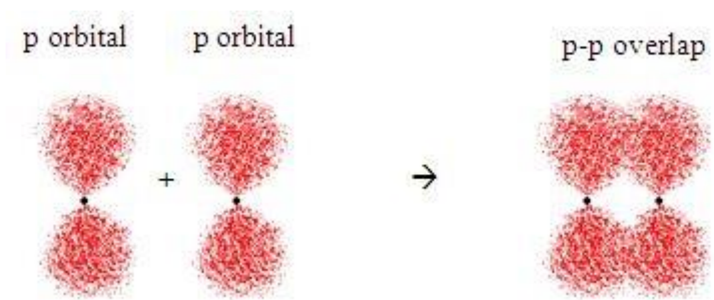


Antracene

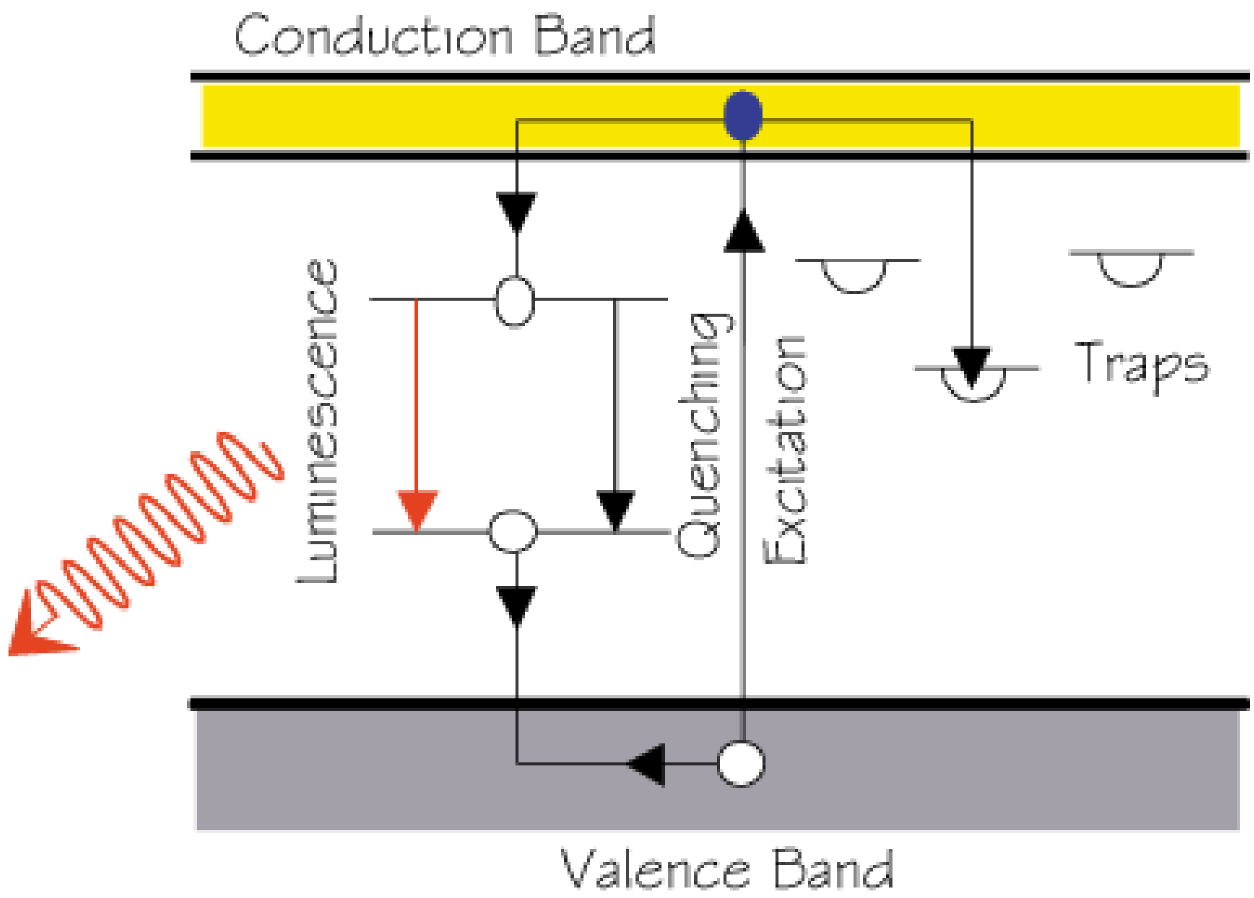


Scintillation is based on electrons of the C=C bond → π-bond

Scintillation light arises from
delocalized electrons in π-orbitals ...

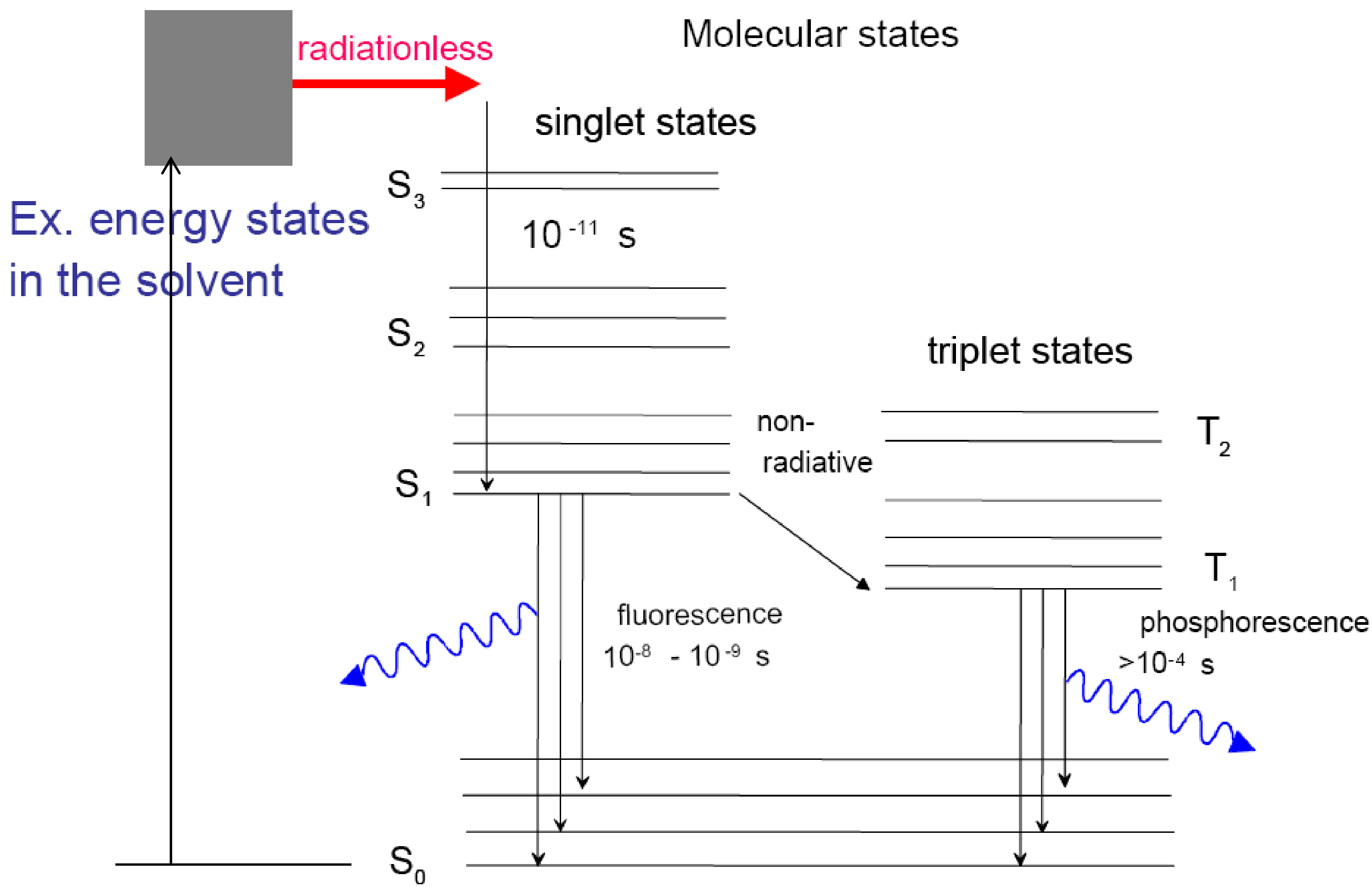


Scintillation principle



Material with special colour centres

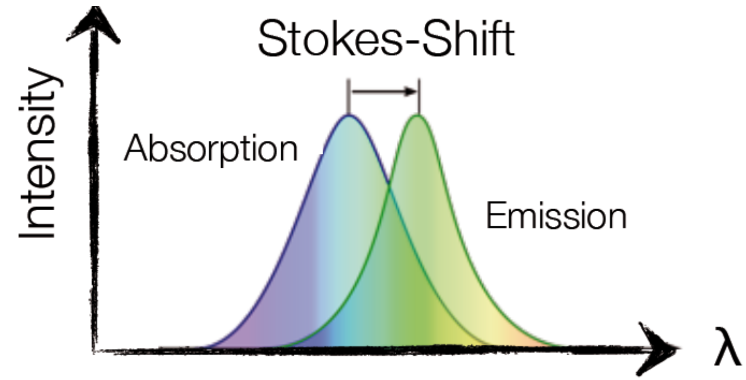
Organic scintillators – scintillation mechanism



Organic scintillators – transparency

Transparency requires:

Shift of absorption
and emission spectra ...

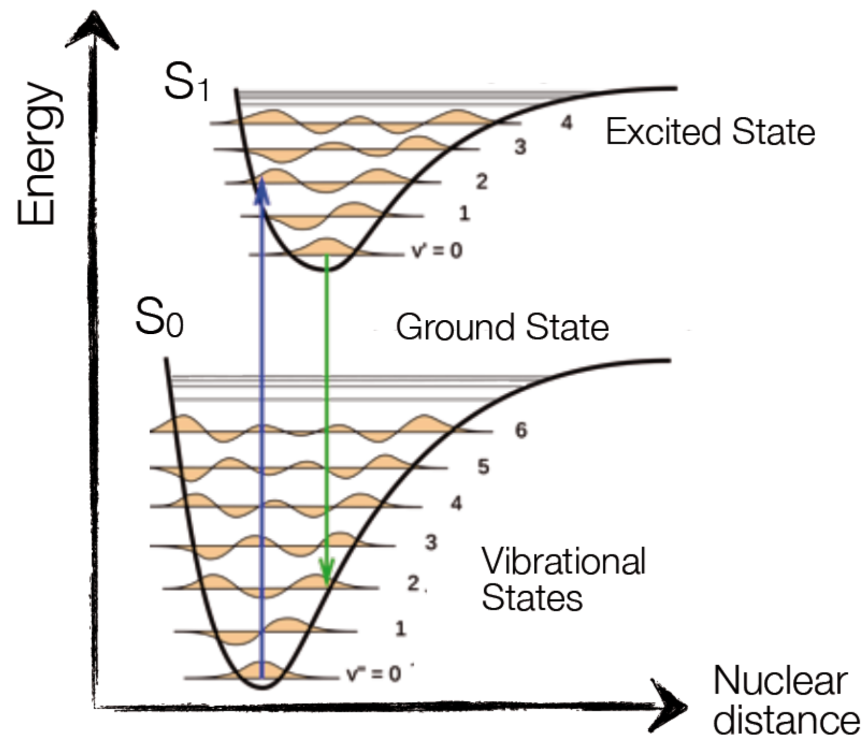


Shift due to

Franck-Condon Principle

Excitation into higher vibrational states
De-excitation from lowest vibrational state

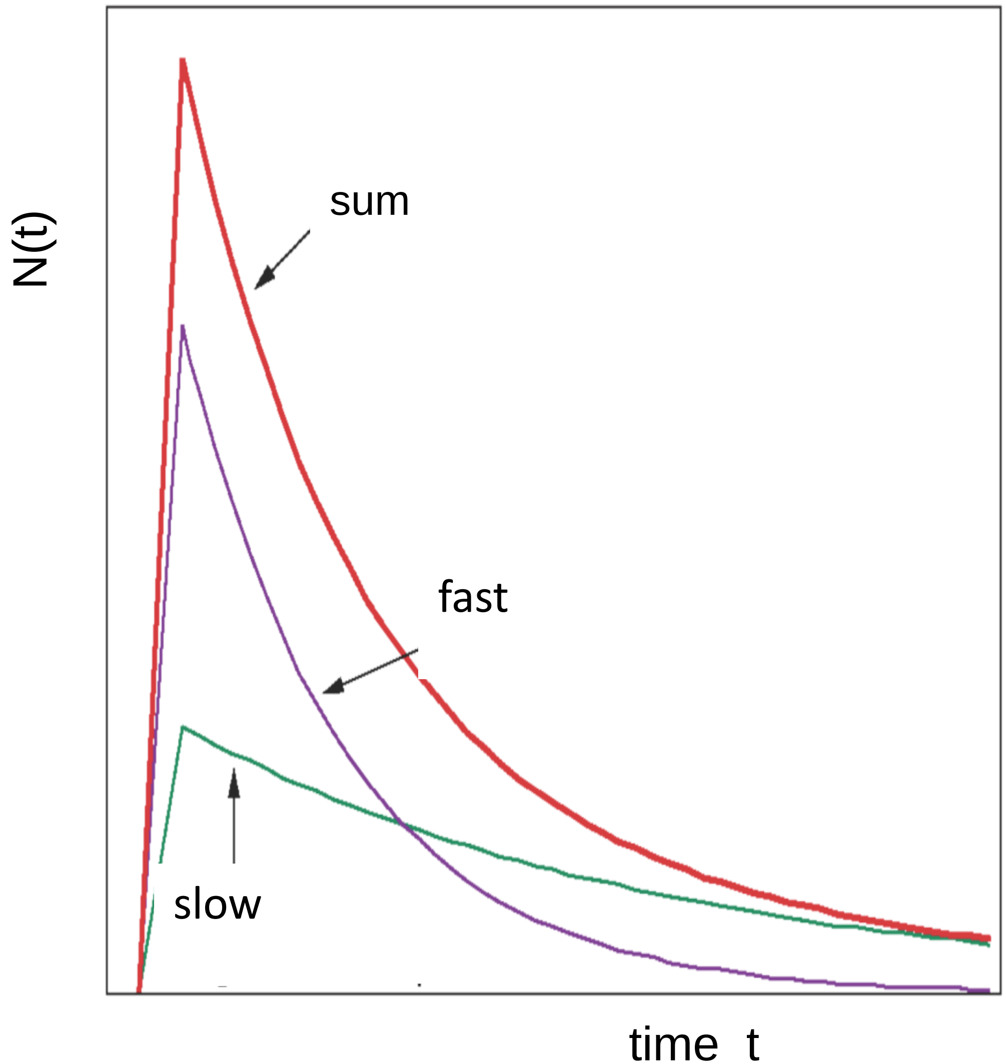
Excitation time scale : 10^{-14} s
Vibrational time scale : 10^{-12} s
S_1 lifetime : 10^{-8} s



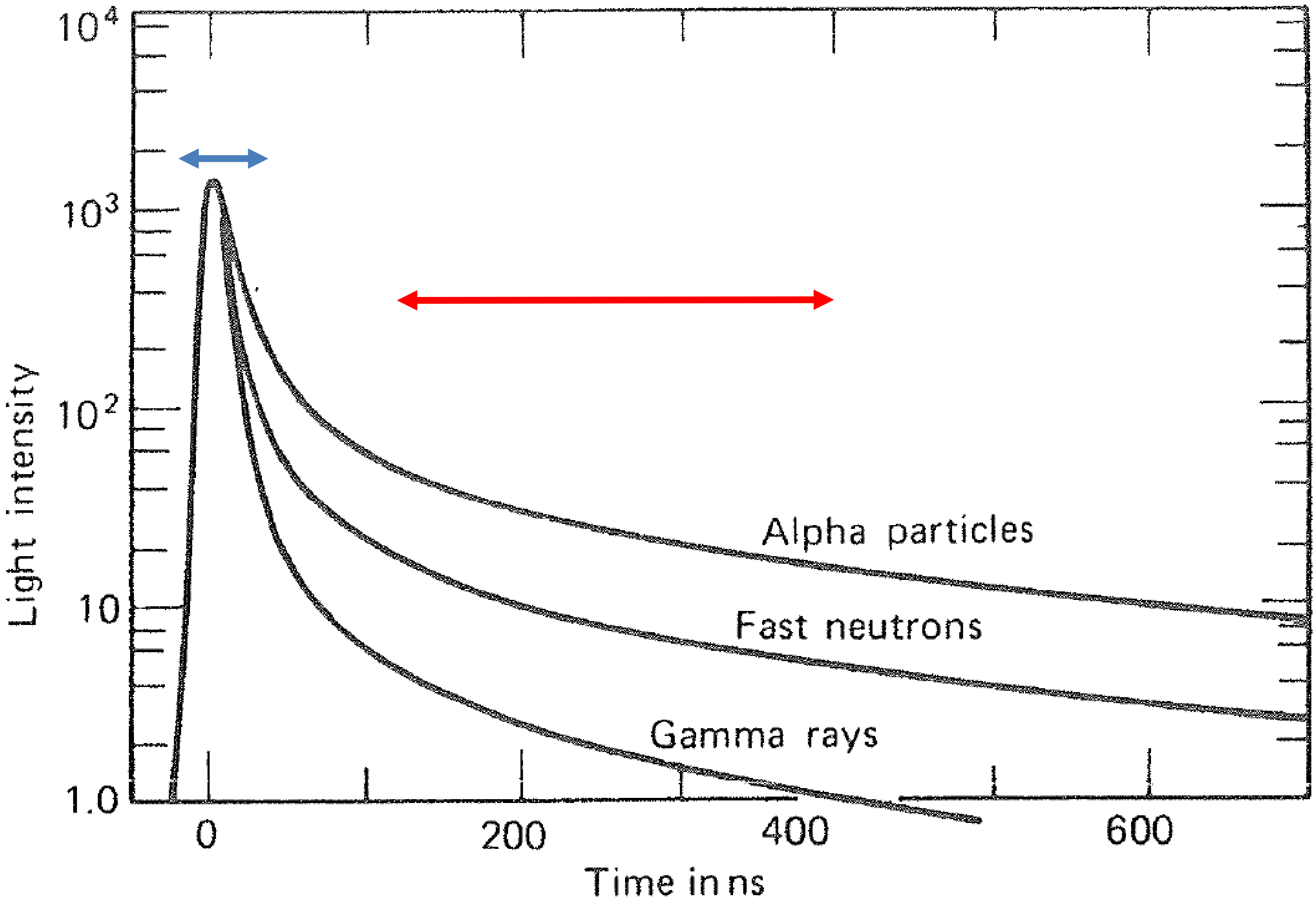
Decay times

$$N(t) = A\exp(-\frac{t}{\tau_f}) + B\exp(-\frac{t}{\tau_s})$$

N(t)...number of emitted photons
A,B....weight factors
τ........decay time (fast, slow)



Time dependence of scintillation pulses
(equal intensity at time zero)

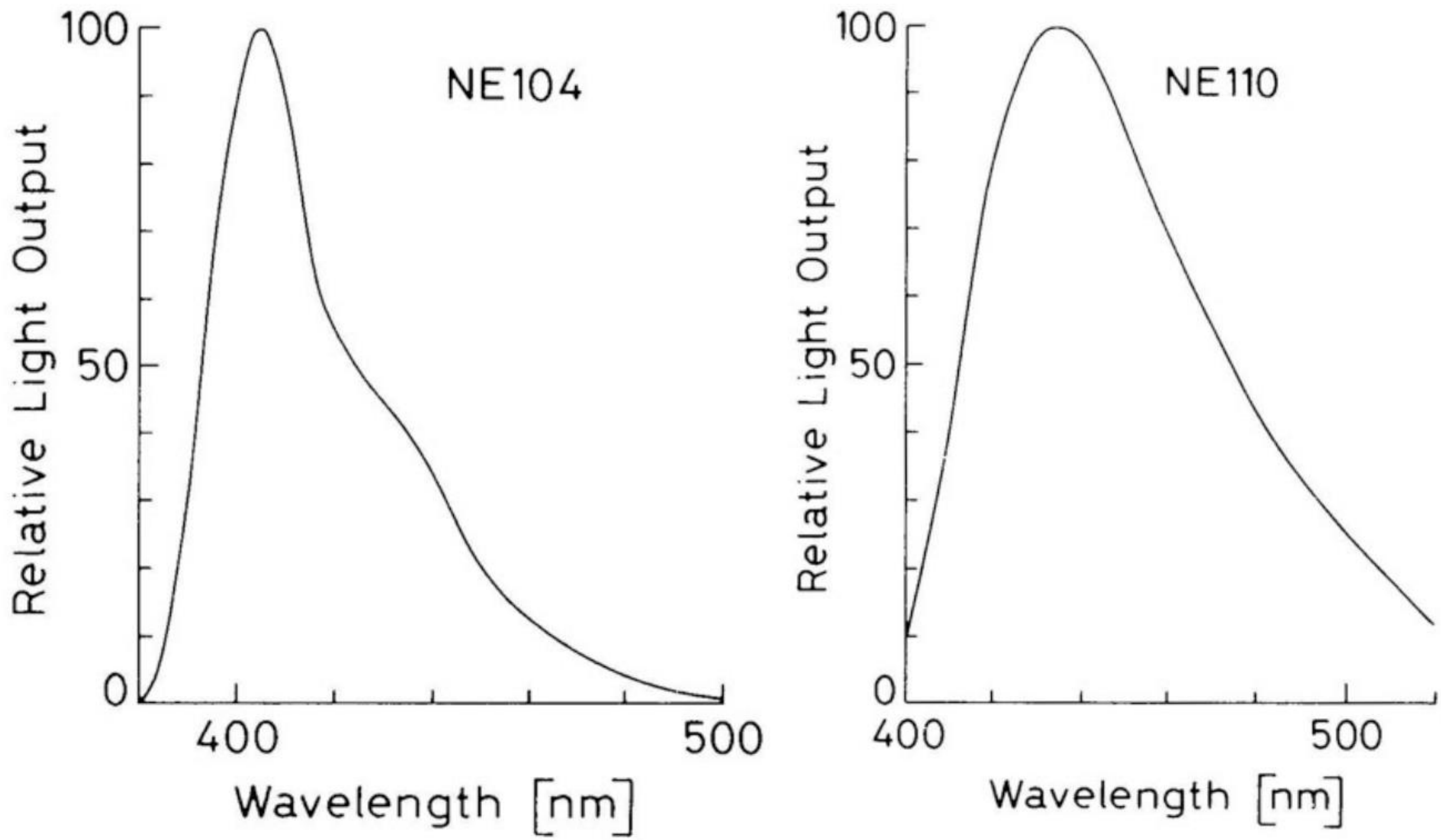


Organic scintillators – properties

Scintillator material	Density [g/cm^3]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [ns]	Photons/MeV
Naphtalene	1.15	1.58	348	11	$4 \cdot 10^3$
Antracene	1.25	1.59	448	30	$4 \cdot 10^4$
p-Terphenyl	1.23	1.65	391	6-12	$1.2 \cdot 10^4$
NE102*	1.03	1.58	425	2.5	$2.5 \cdot 10^4$
NE104*	1.03	1.58	405	1.8	$2.4 \cdot 10^4$
NE110*	1.03	1.58	437	3.3	$2.4 \cdot 10^4$
NE111*	1.03	1.58	370	1.7	$2.3 \cdot 10^4$
BC400**	1.03	1.58	423	2.4	$2.5 \cdot 10^2$
BC428**	1.03	1.58	480	12.5	$2.2 \cdot 10^4$
BC443**	1.05	1.58	425	2.2	$2.4 \cdot 10^4$

* Nuclear Enterprises, U.K.
** Bicron Corporation, USA

Organic scintillators – properties



Organic scintillators – properties

Light yield
(in absence of quenching)

$$\frac{dL}{dx} = S\frac{dE}{dx}$$

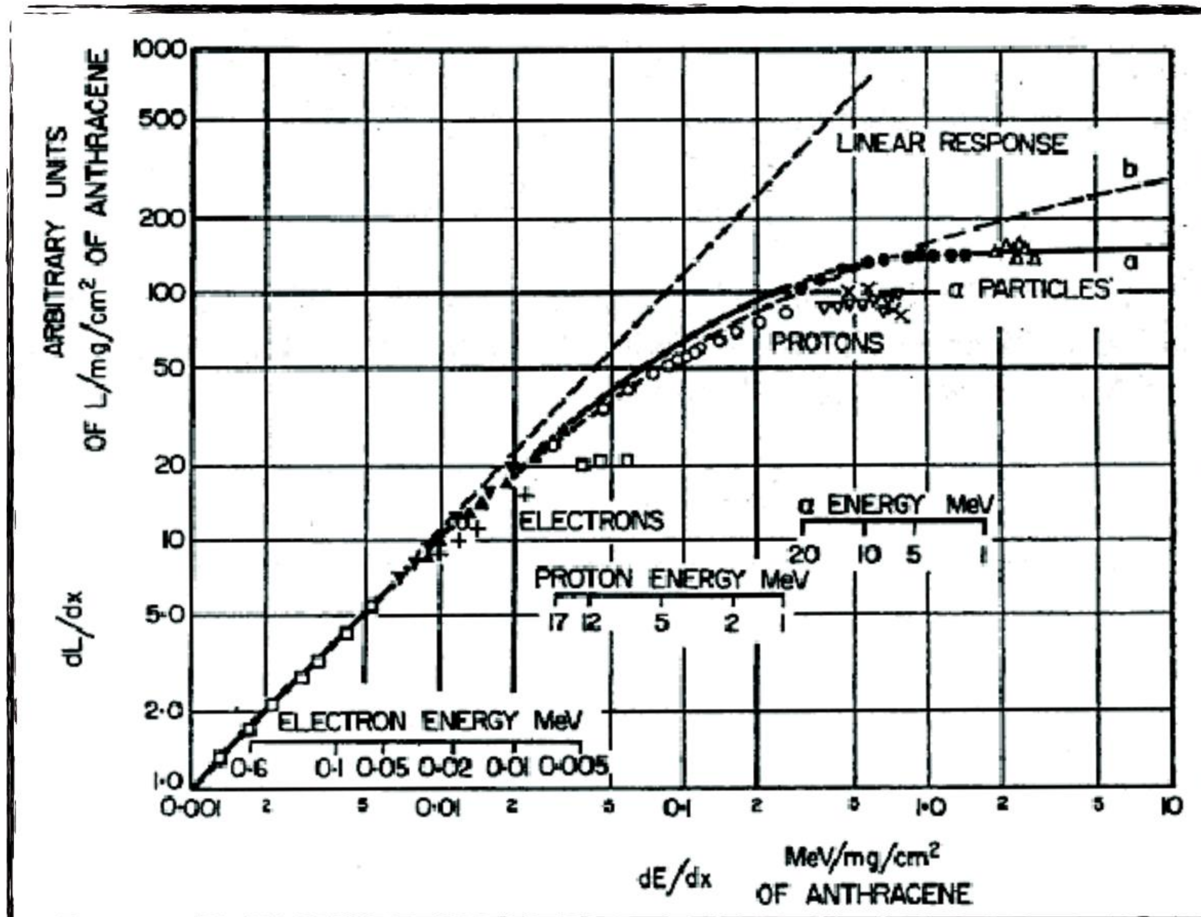
S…scintillation efficiency

Quenching → non-linear response due to saturation of available states

- Birks´ formula accounts for the probability of quenching

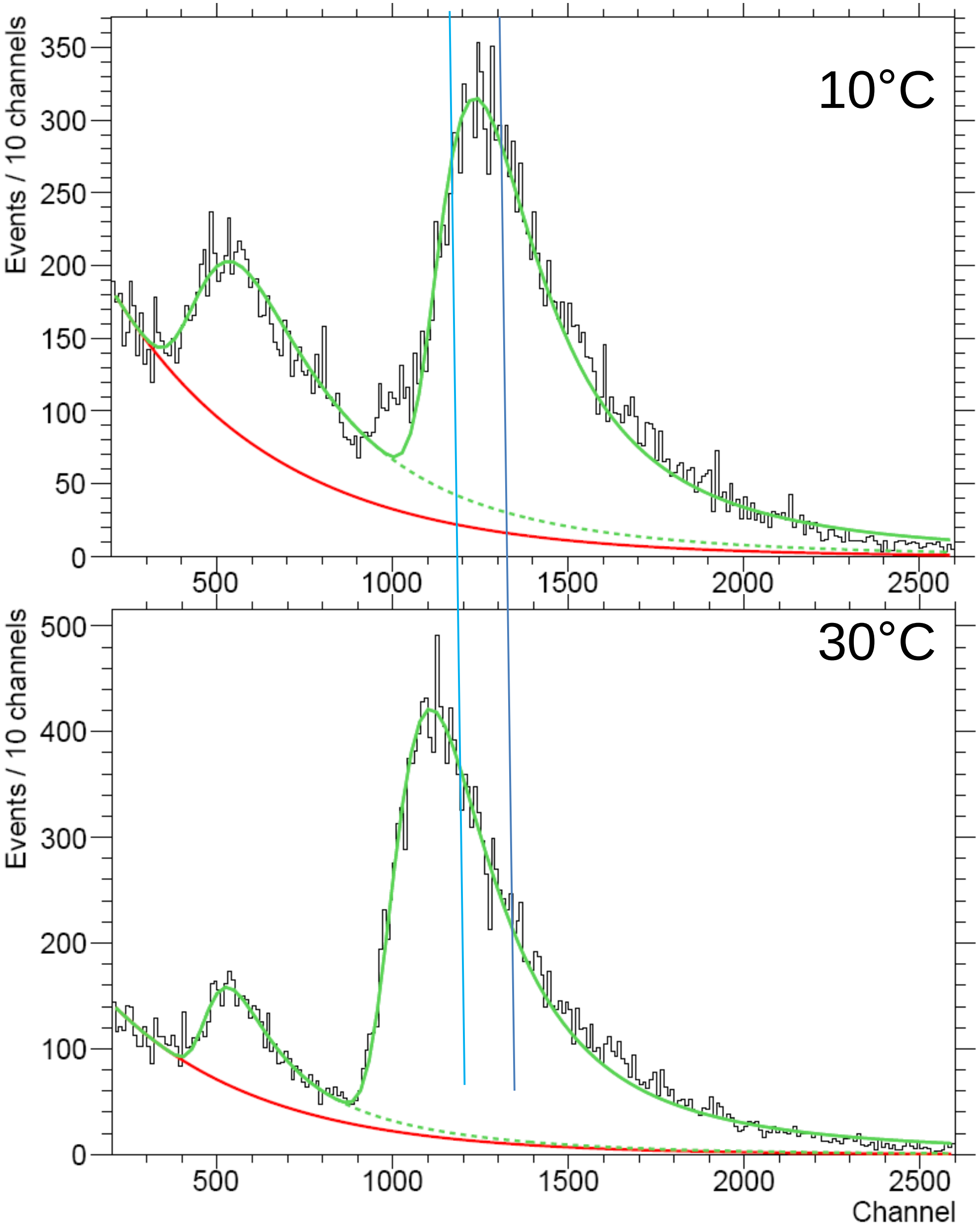
$$\frac{dL}{dx} = \frac{S\frac{dE}{dx}}{1 + k_B\frac{dE}{dx}}$$

k_B….Birks´ constant



Temperature dependence

of the Scintillator Bicron BC-400



$T/°C$	MPV/ch
10	1260.82
14	1288.23
18	1298.69
22	1298.99
26	1291.06
30	1128.95

UPPSALA UNIVERSITY,
internal report

Some remarks

Aging and Handling:
Plastic scintillators are subject to aging which diminishes the light yield. Exposure to solvent vapors, high temperatures, mechanical flexing, irradiation, or rough handling will aggravate the process.
A particularly fragile region is the surface which can “craze” - develop micro-cracks - which rapidly destroy the capability of plastic scintillators to transmit light by total internal reflection. Crazing is particularly likely where oils, solvents, or *fingerprints have contacted the surface.*

Attenuation length:
The Stokes' shift is not the only factor determining attenuation length. Others are the concentration of fluorines (the higher the concentration of a fluorine, the greater will be its self-absorption); the optical clarity and uniformity of the bulk material; the quality of the surface; and absorption by additives, such as stabilizers, which may be present.

Some remarks

Afterglow:
Plastic scintillators have a long-lived luminescence which does not follow a simple exponential decay. Intensities at the 10^{-4} *level of the initial fluorescence can* persist for hundreds of ns.

Radiation damage:
Irradiation of plastic scintillators creates coluor centres which absorb light more strongly in the UV and blue than at longer wavelengths. This poorly understood effect appears as a reduction both of light yield and attenuation length. Radiation damage depends not only on the integrated dose, but on the dose rate, atmosphere, and temperature, before, during and after irradiation, as well as the materials properties of the base such as glass transition temperature, polymer chain length, etc.

Inorganic Scintillators – Properties

Numerical examples:

NaI(Tl) λ_{max} = 410 nm; hν = 3 eV
photons/MeV = 40000
τ = 250 ns

$PBWO_4$ λ_{max} = 420 nm; hν = 3 eV
photons/MeV = 200
τ = 6 ns

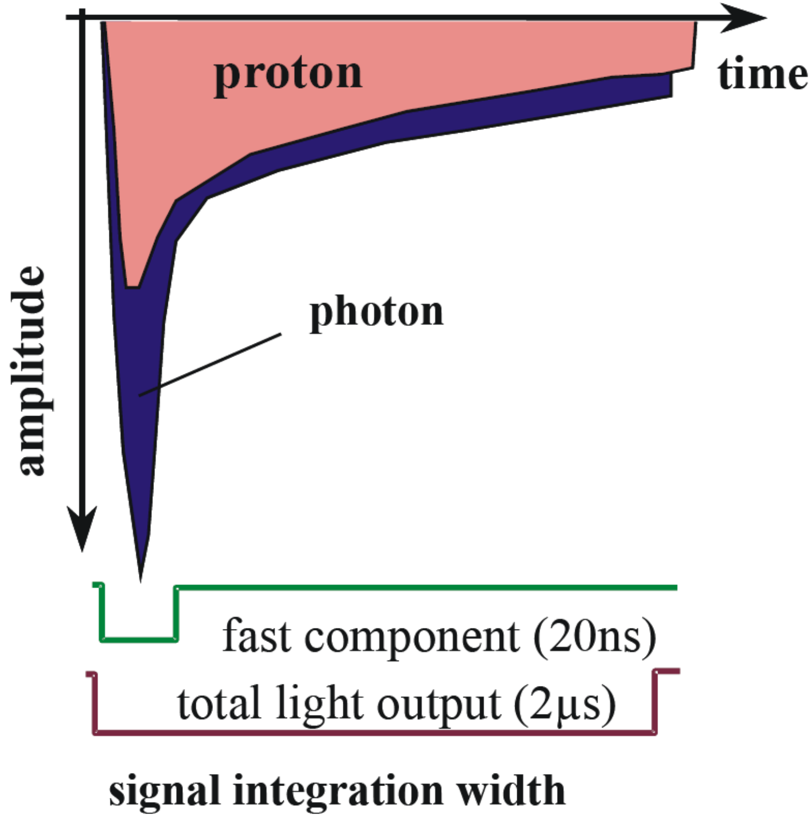
Scintillator quality:

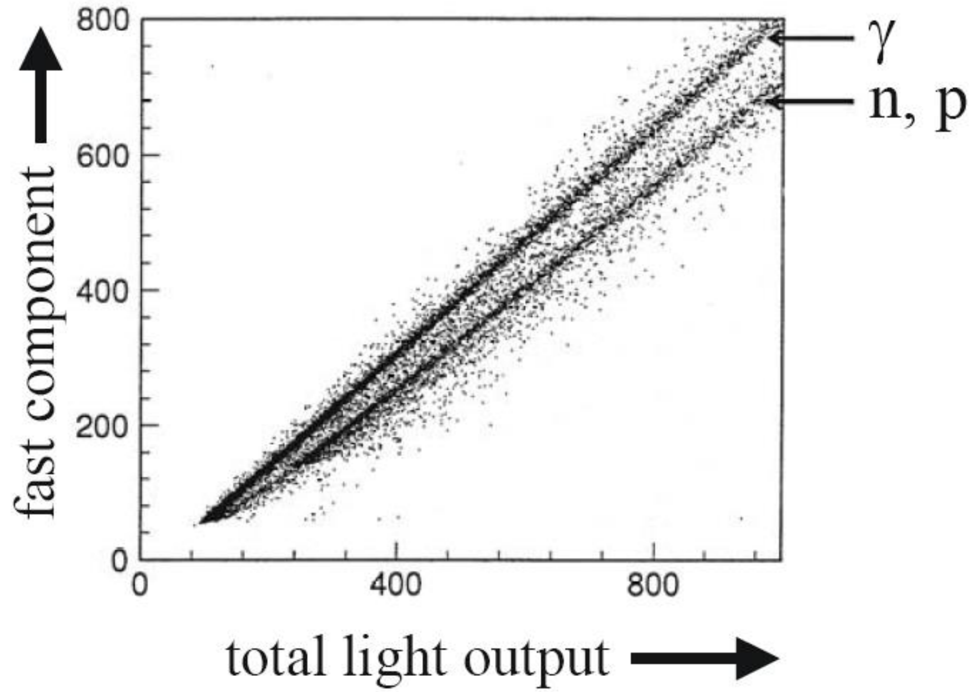
Light yield – ε_{sc} ≡ fraction of energy loss going into photons

e.g. NaI(Tl) : 40000 photons; 3 eV/photon ➛ $\varepsilon_{sc} = 4 \cdot 10^4 \cdot 3\ \mathrm{eV}/10^6\ \mathrm{eV} = 11.3\%$
$PBWO_4$: 200 photons; 3 eV/photon ➛ $\varepsilon_{sc} = 2 \cdot 10^2 \cdot 3\ \mathrm{eV}/10^6\ \mathrm{eV} = 0.06\%$
[for 1 MeV particle]

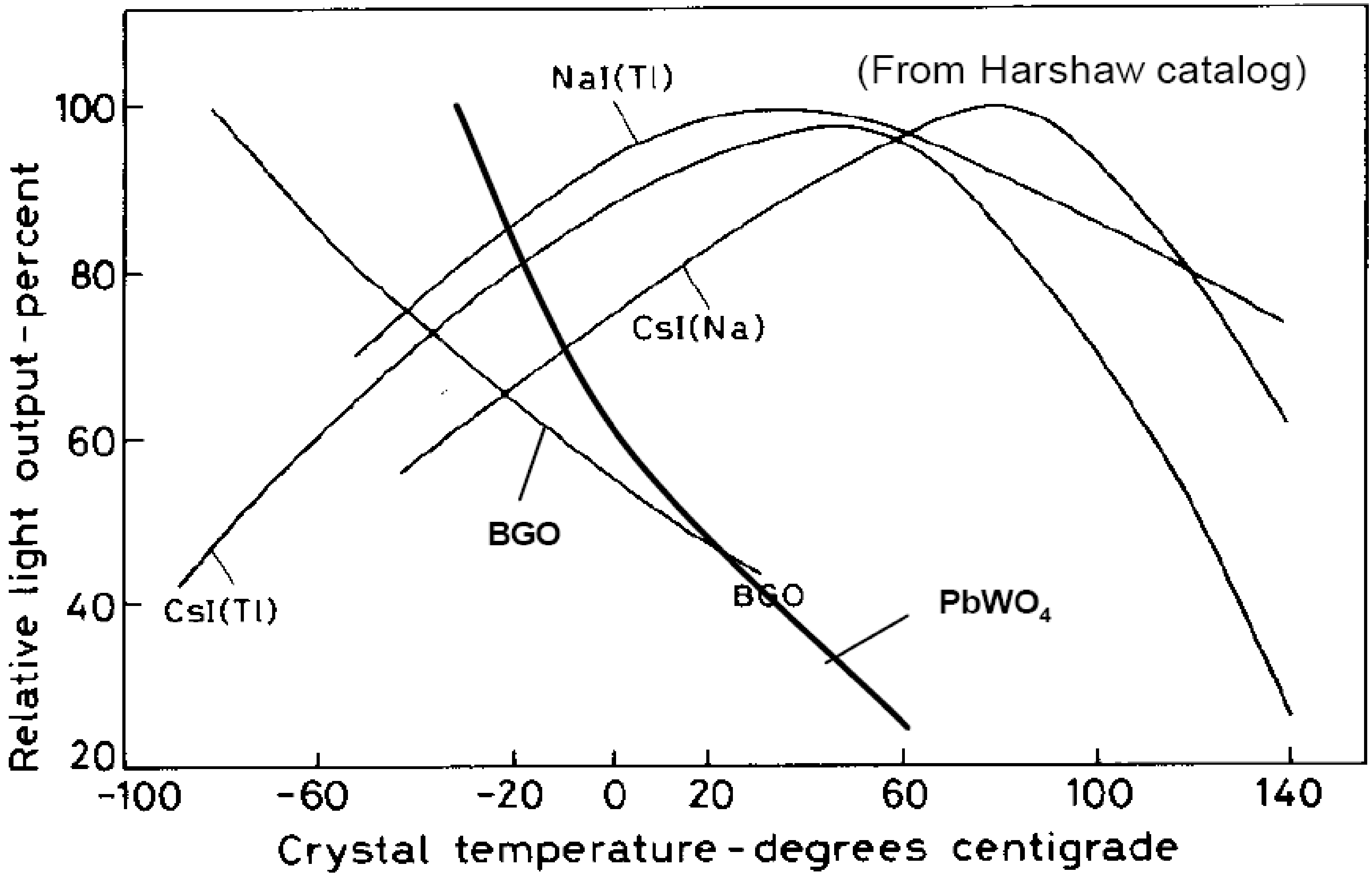
Pulse shape discrimination, e.g. BaF_2

Barium fluoride (BaF2) is presently one of the fastest scintillator.
It has an emission component with sub-nanosecond decay time.
Time resolutions of ~200 ps are possible.

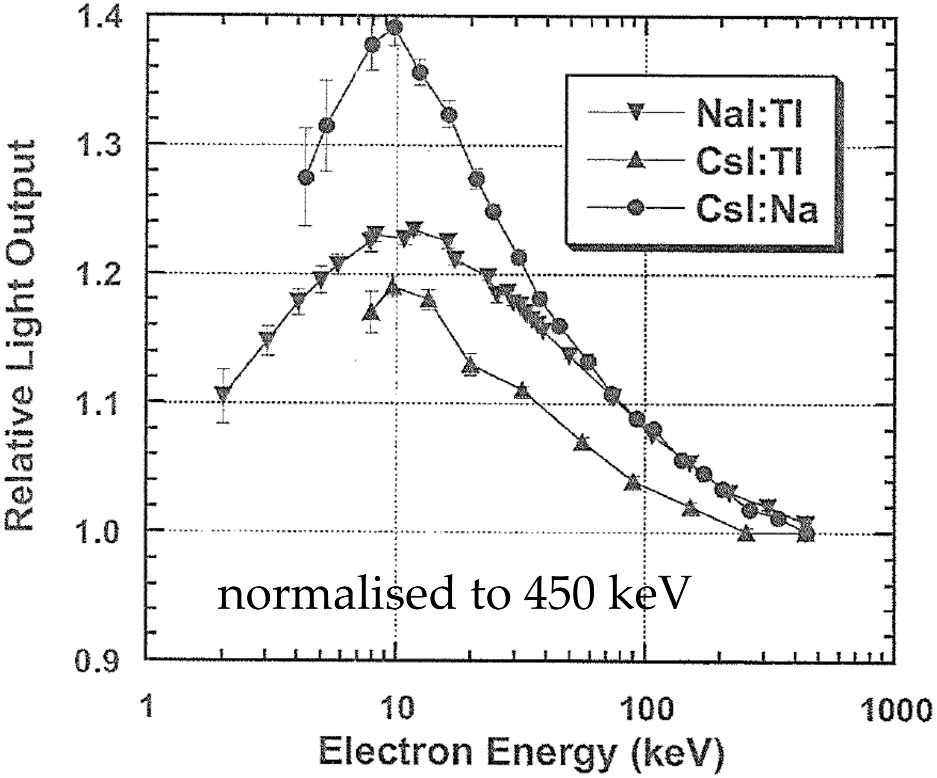


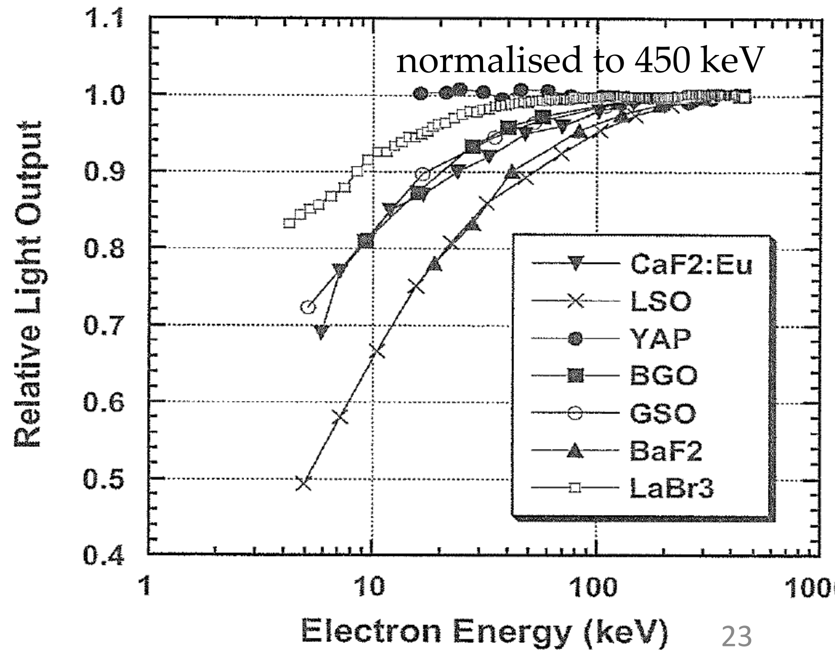


Light output of inorganic crystals shows strong temperature dependence



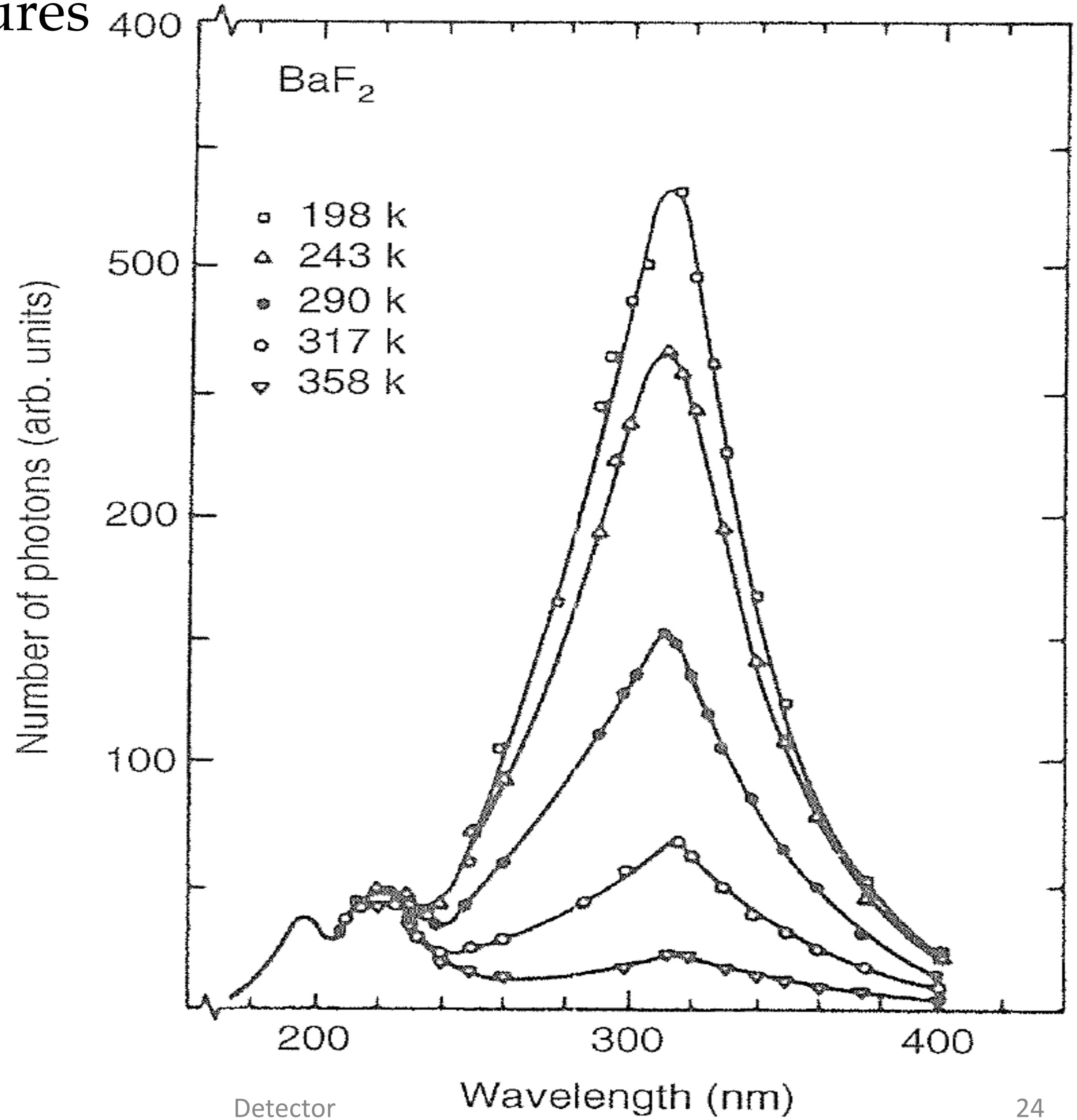
Energy dependence of the light output

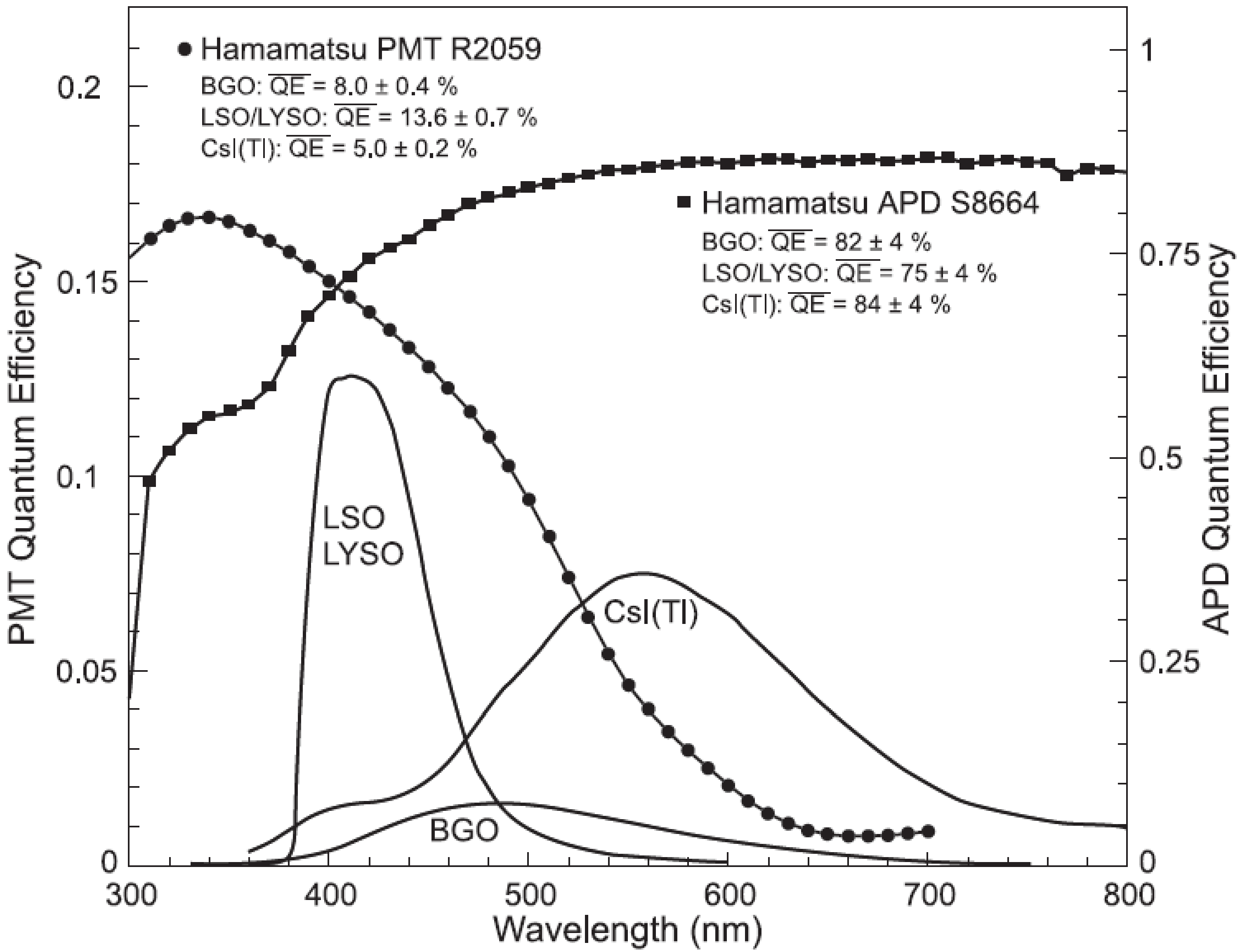




Scintillation emission spectra for BaF_2

at various temperatures





● Hamamatsu PMT R2059
BGO: $\overline{QE}$ = 8.0 ± 0.4 %
LSO/LYSO: $\overline{QE}$ = 13.6 ± 0.7 %
CsI(Tl): $\overline{QE}$ = 5.0 ± 0.2 %
■ Hamamatsu APD S8664
BGO: $\overline{QE}$ = 82 ± 4 %
LSO/LYSO: $\overline{QE}$ = 75 ± 4 %
CsI(Tl): $\overline{QE}$ = 84 ± 4 %
LSO
LYSO
CsI(Tl)
BGO
PMT Quantum Efficiency
APD Quantum Efficiency
Wavelength (nm)
0
0.05
0.1
0.15
0.2
0.25
0.5
0.75
1
300
400
500
600
700
800

Scintillator composition	Density (g/cm^3)	Index of refraction	Wavelength of max.Em. (nm)	Decay time Constant (μs)	Scinti Pulse height[1)]	Notes
NaI(Tl)	3.67	1.9	410	0.25	100	2)
CsI	4.51	1.8	310	0.01	6	3)
CsI(Tl)	4.51	1.8	565	1.0	45	3)
CaF_2(Eu)	3.19	1.4	435	0.9	50	
BaF_2	4.88	1.5	190/220 310	0,0006 0.63	5 15	
BGO	7.13	2.2	480	0.30	10	
$CdW0_4$	7.90	2.3	540	5.0	40	
$PbWO_4$	8.28	2.1	440	0.020	0.1	
CeF_3	6.16	1.7	300 340	0.005 0.020	5	
GSO	6.71	1.9	430	0.060	40	
LSO	7	1.8	420	0.040	75	
YAP	5.50	1.9	370	0.030	70	

1) Relative to NaI(Tl) in %; 2) Hygroscopic; 3) Water soluble

Inorganic Scintillators → expensive

Advantages

high light yield [typical $\varepsilon \sim 0.13$]
high density [e.g. PWO ~ 8.3 g/cm^3]
good energy resolution

Disadvantages

complicated crystal growth
large temperature dependence

Organic Scintillators → cheap

Advantages

very fast
easily shaped
small temperature dependence

Disadvantages

lower light yield [typical $\varepsilon \sim 0.03$]
radiation damage

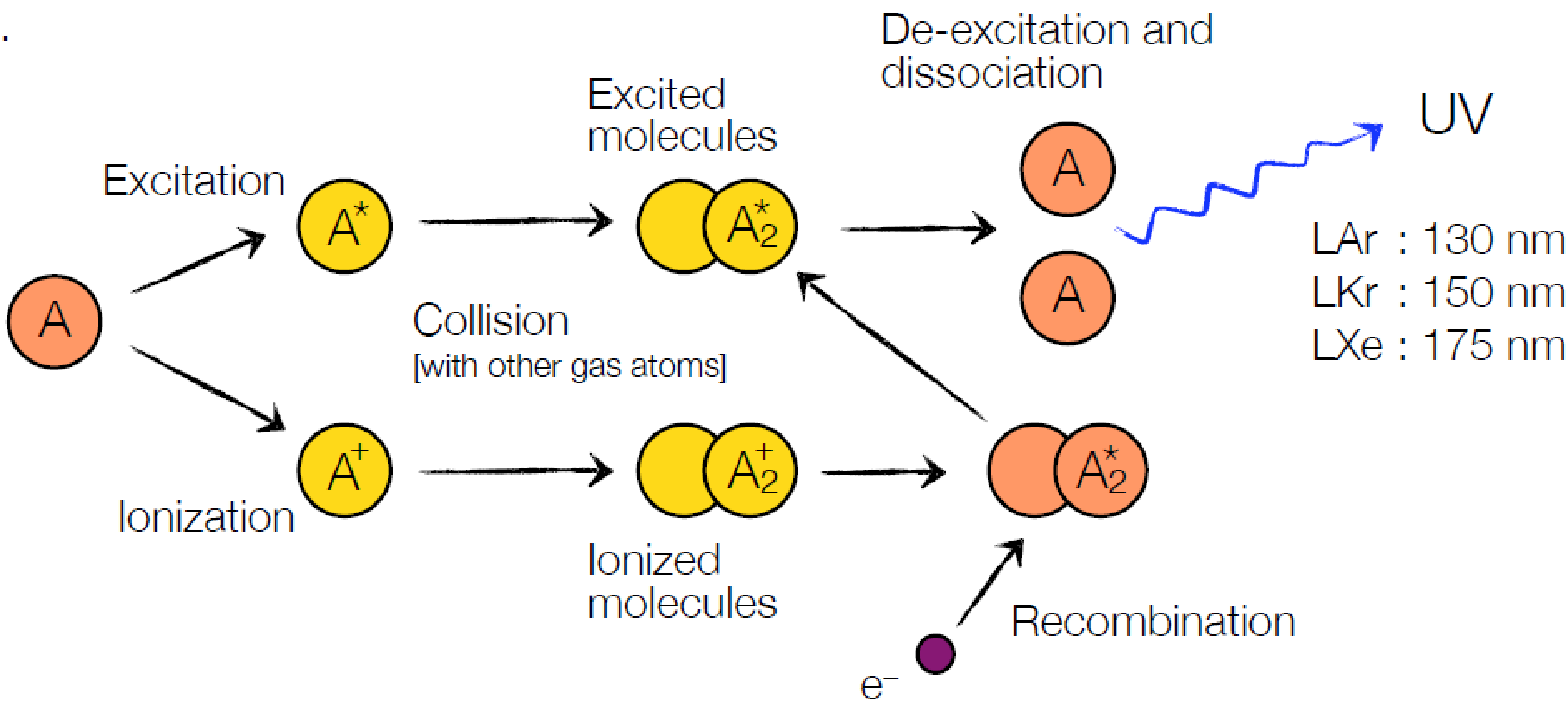
Scintillation in liquid Nobel gases

Materials:

Helium (He)
Liquid Argon (LAr)
Liquid Xenon (LXe)
...

Decay time constants:

Helium : τ_1 = .02 μs, τ_2 = 3 μs
Argon : $\tau_1 \leq$ .02 μs



Light transmission through light guides

In coupling a scintillator to a photodetector through a light guide, it is tempting to couple a large area scintillator to a small area detector.

- This could save money and also small photodiodes could be used

BUT, the efficiency of light transmission through a light guide is limited by

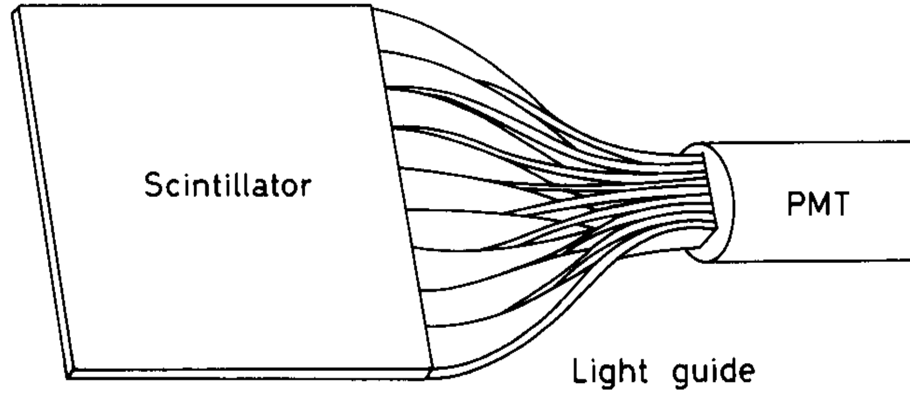
- the angle of total reflection
- conservation of phase space (Liouville's theorem)

$$\boxed{\frac{I_{out}}{I_{in}} \leq \frac{A_{out}}{A_{in}}} \qquad (A_{out} \leq A_{in})$$

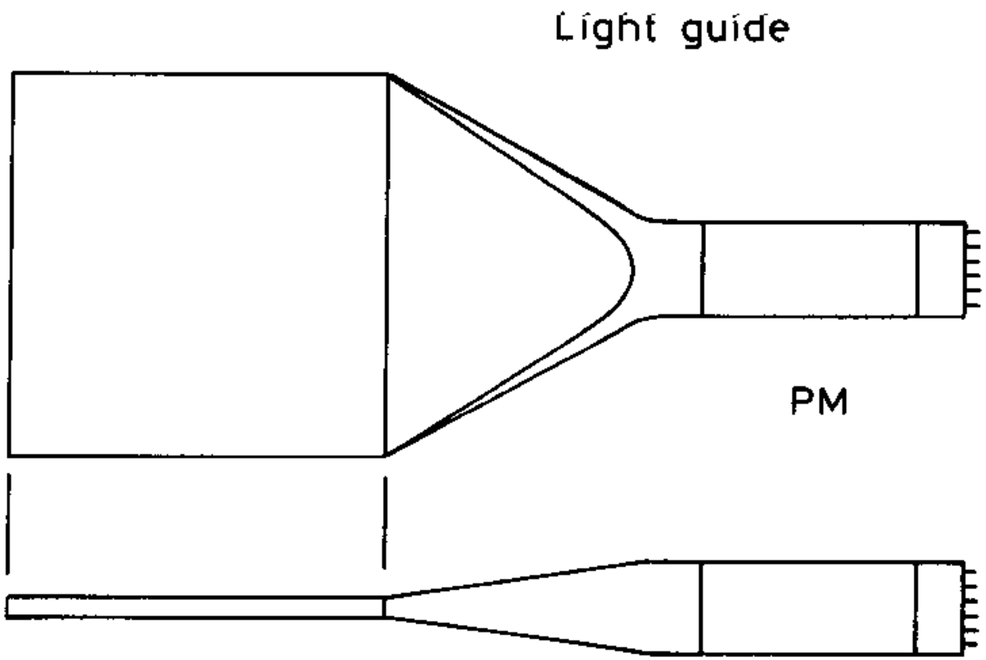
A_{in} … Querschnittsfläche am Übergang zum Szintillator
A_{out} … Querschnittsfläche am Übergang zum Photodetektor
I_{in} … gesamte Lichtintensität bei Eintritt in den Lichtleiter
I_{out} … gesamte Lichtintensität bei nach Übertragung durch den Lichtleiter

Light guide – different geometries

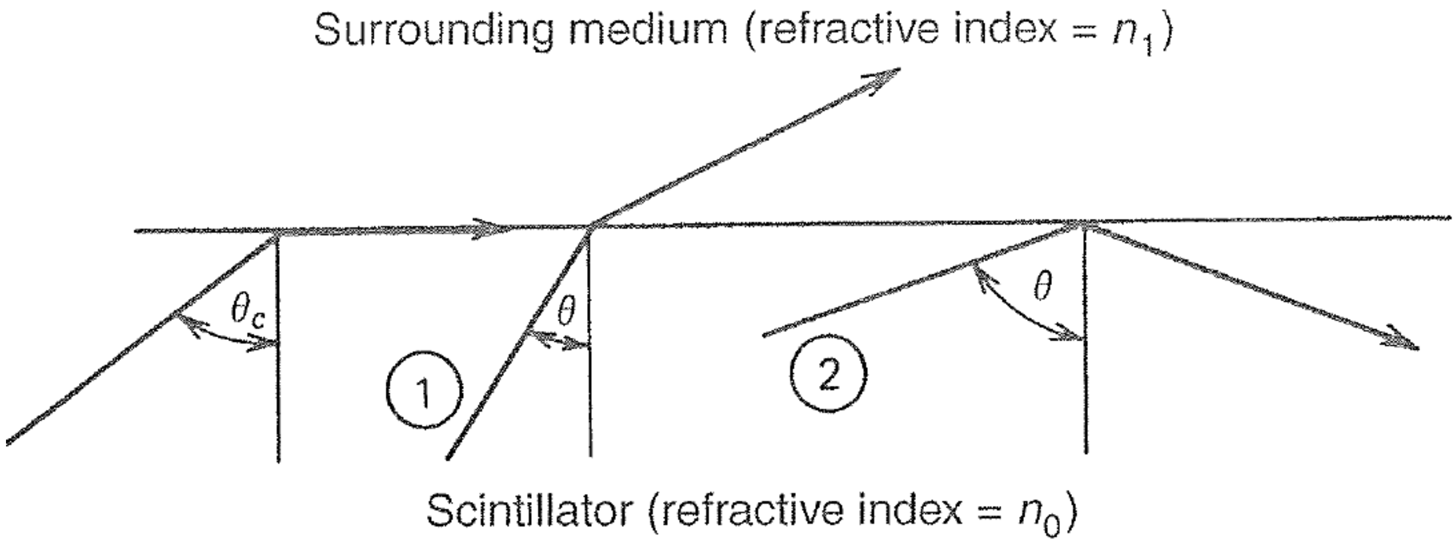
“fish tail”



“adiabatic”

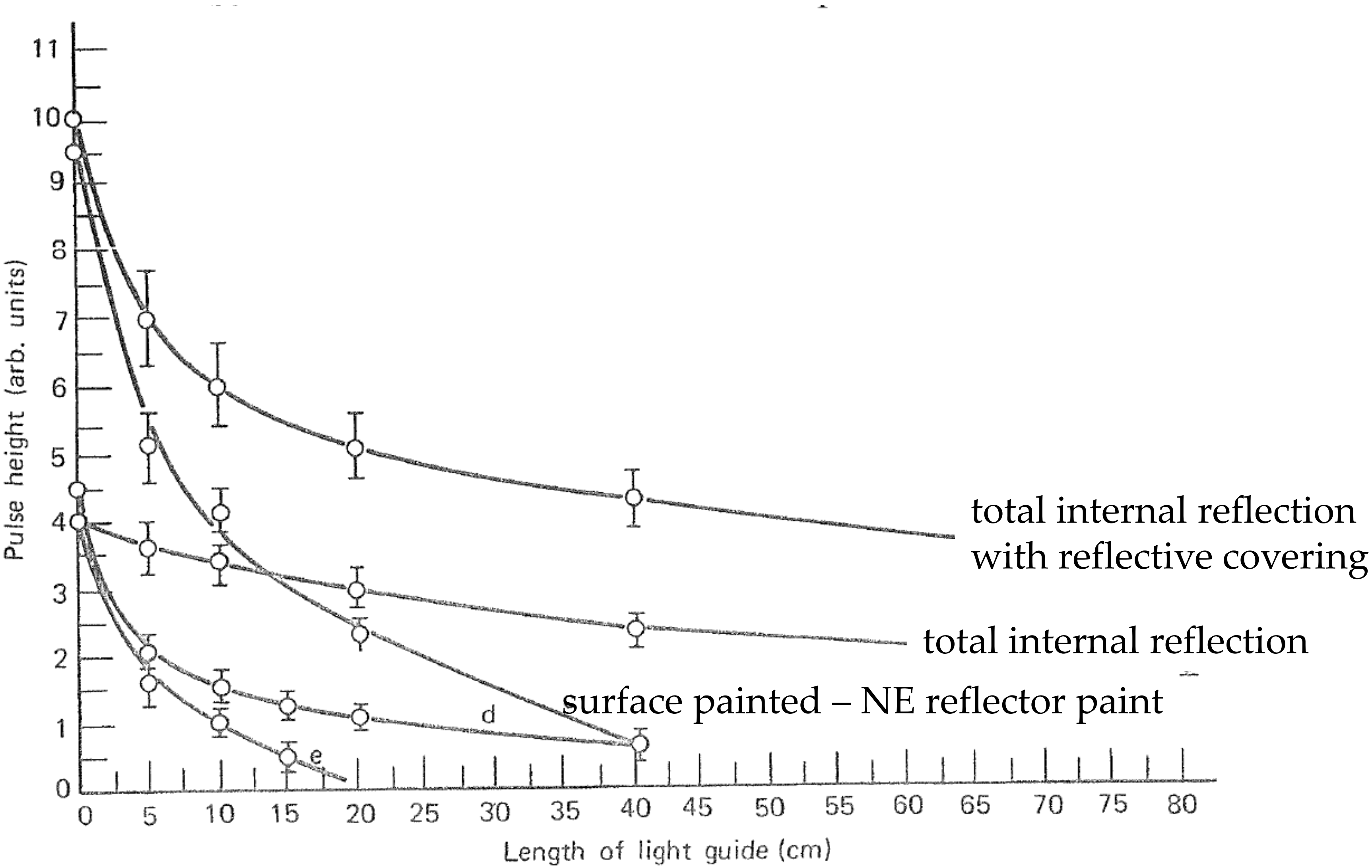


Light guide – conditions at the interface of dissimilar optical media ($n_0 > n_1$)



$$\theta_c = \arcsin \frac{n_1}{n_0}$$

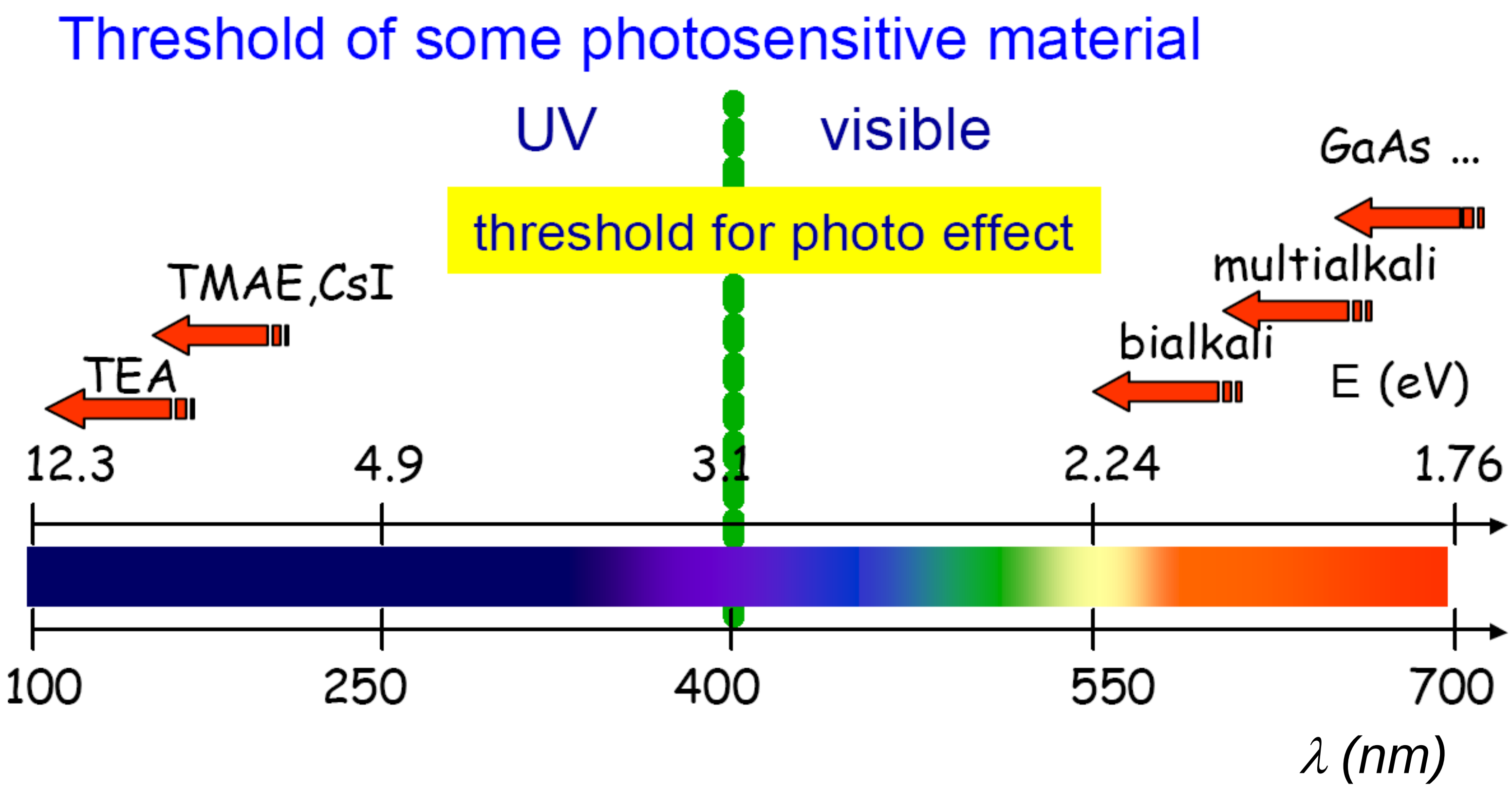
Light guide – variation of pulse height with length



d…..specular reflector, wo. light guide e…..diffuse reflector, e.g. Teflon

Photo detectors

Purpose: Convert light into detectable electronics signal – usually we are interested in the visible and UV region



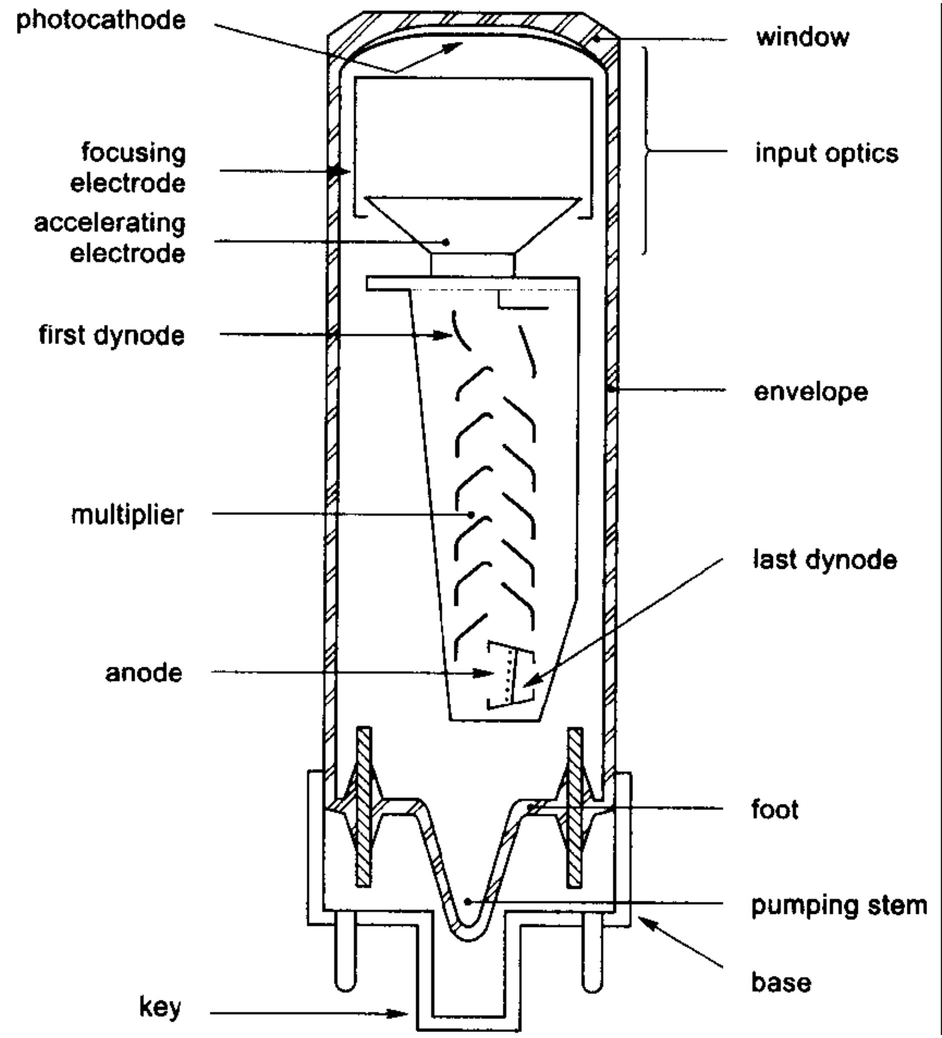
standard requirement
high sensitivity, usually expressed as quantum efficiency

$$QE = \frac{N_{photoelectrons}}{N_{photons}}$$

Photon detectors - Photo Multiplier Tube

Purpose:

- Convert light into detectable (electronic) signal

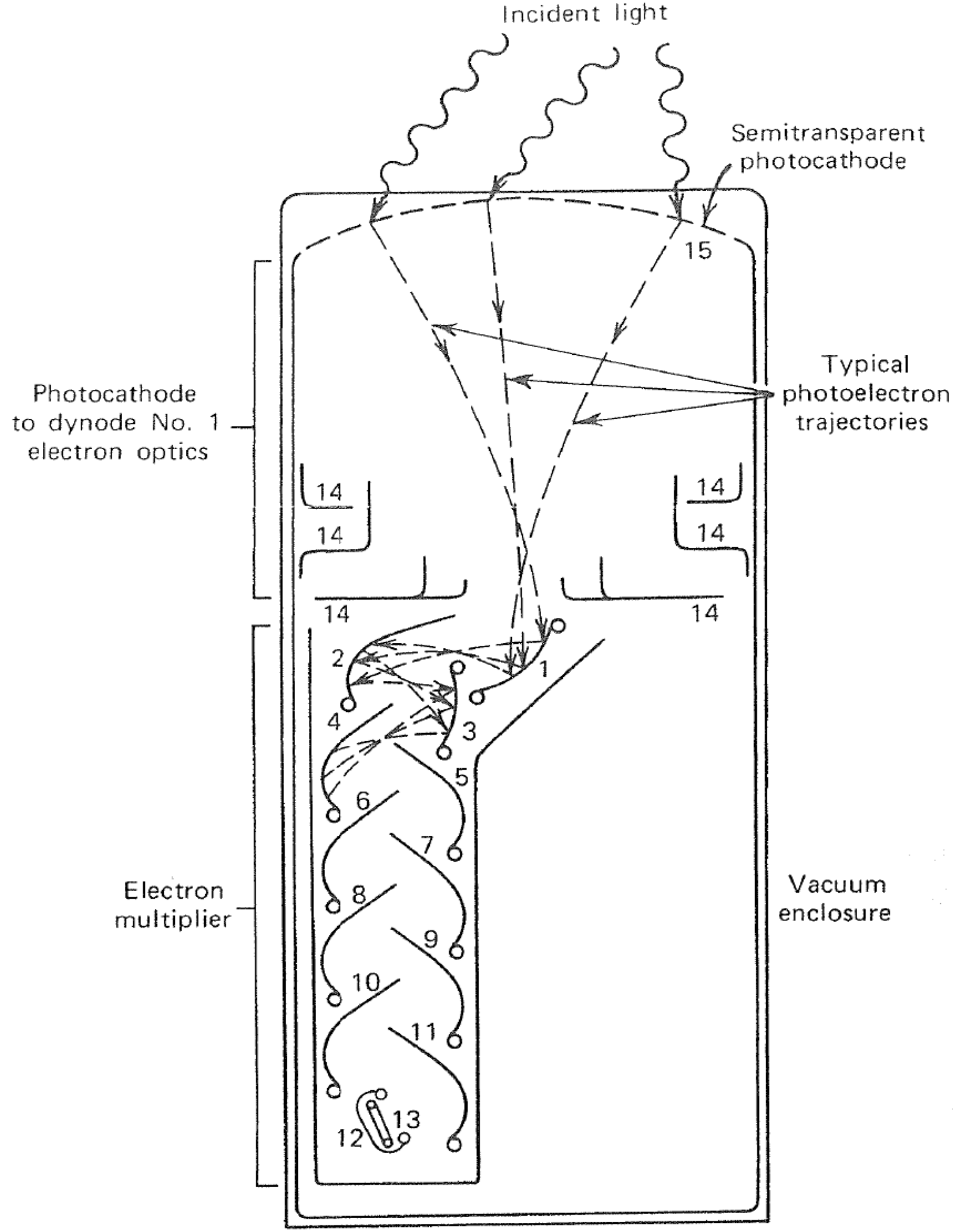


main phenomena:

- photo emission from photo cathode
- secondary emission from dynodes. dynode gain $g=3\text{-}50$

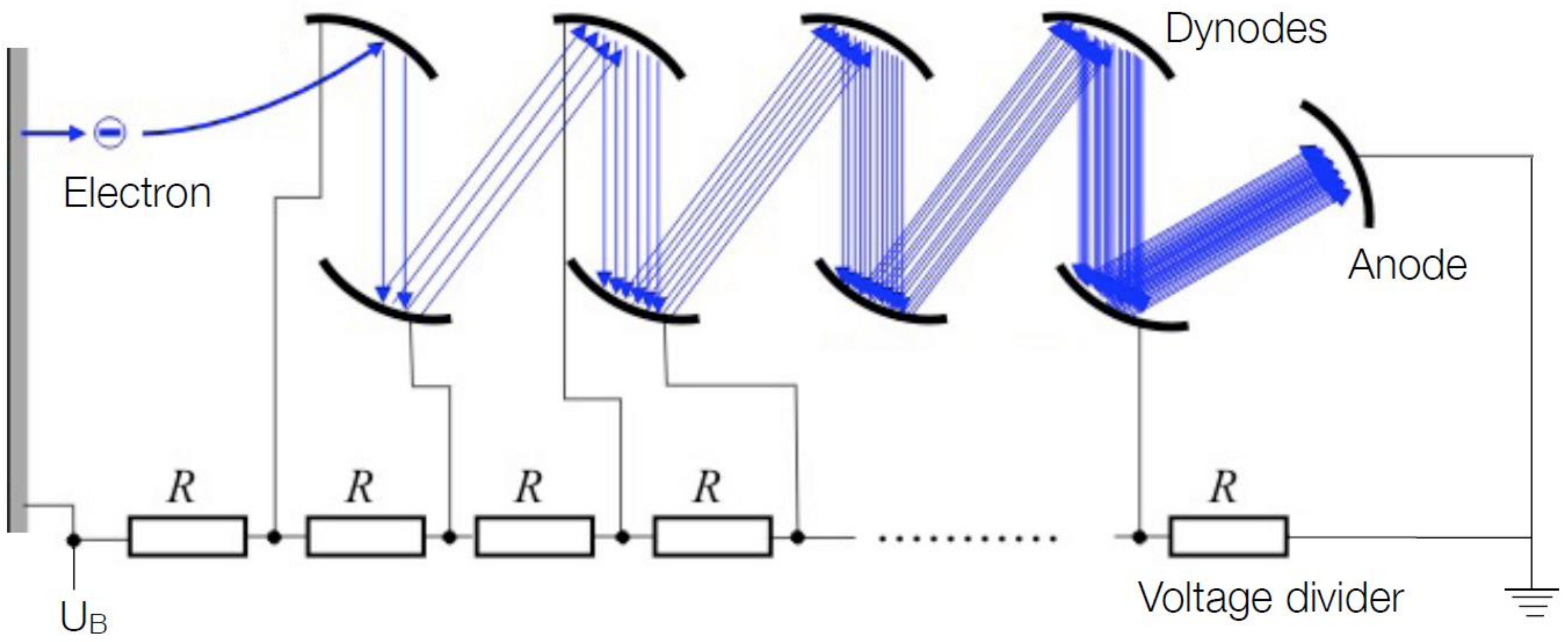
e.g. total gain for 10 dynodes, with g=4
$G = 4^{10} \sim 10^{6}$

PM Tube



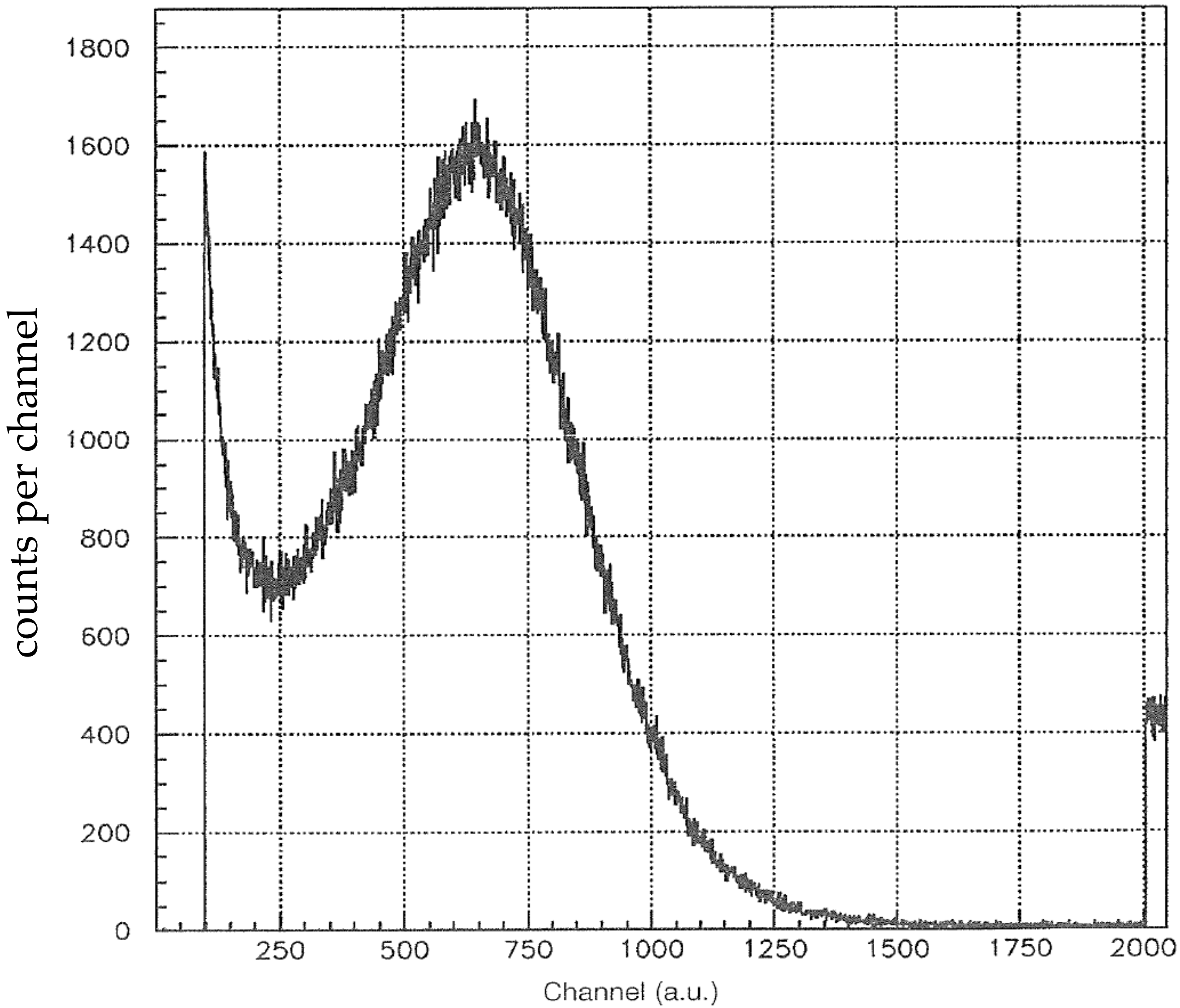
1–12: Dynodes 14: Focusing electrodes
13: Anode 15: Photocathode

Photo Multiplier Tube - Dynode chain



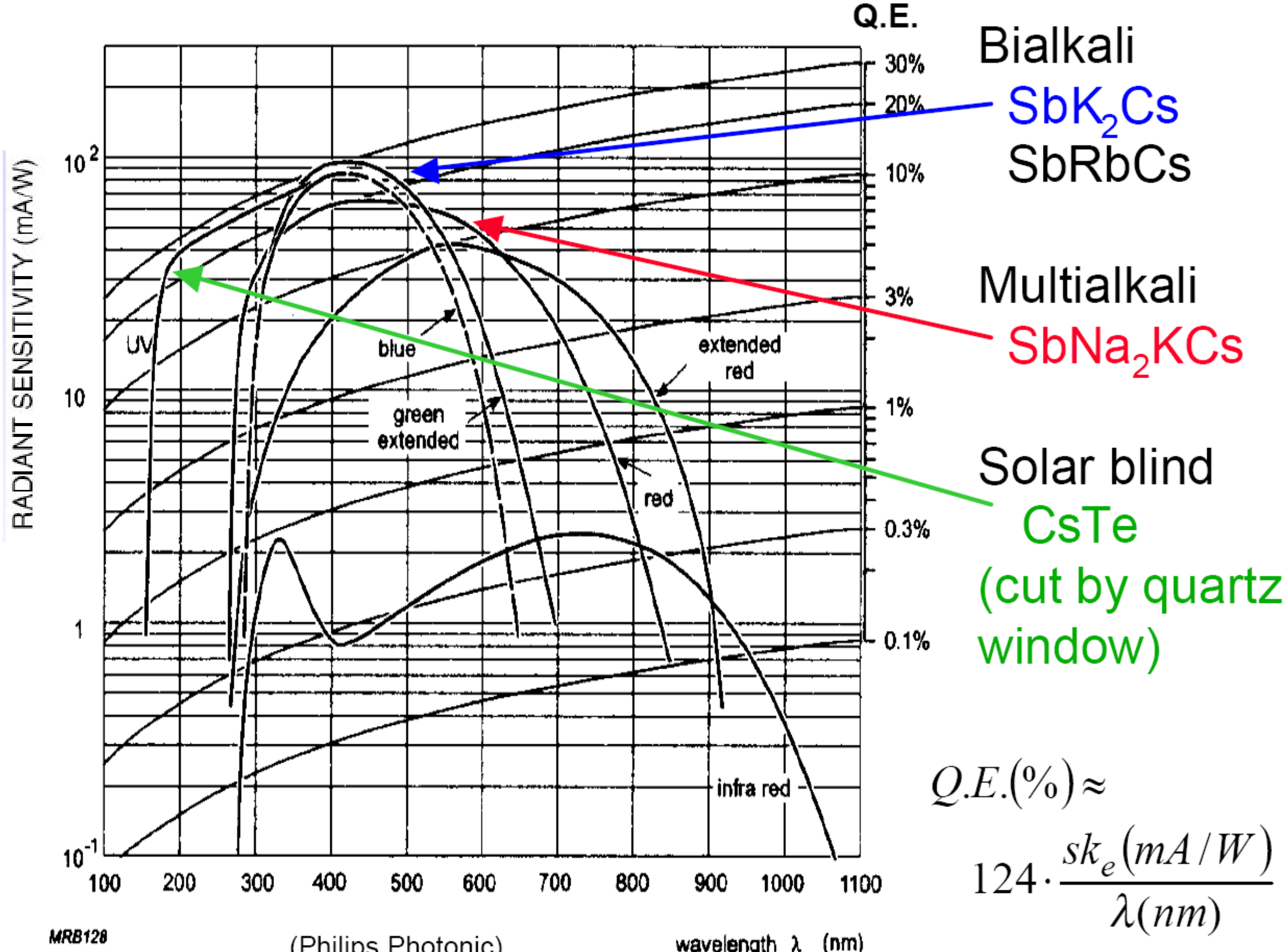
e.g. total gain for 10 dynodes,
with g=4
$G = 4^{10} \sim 10^{6}$

Noise, measured "dark spectrum"



Pulse height spectrum measured with Hamamatsu PMT R5912
due to a single electron emitted spontaneously

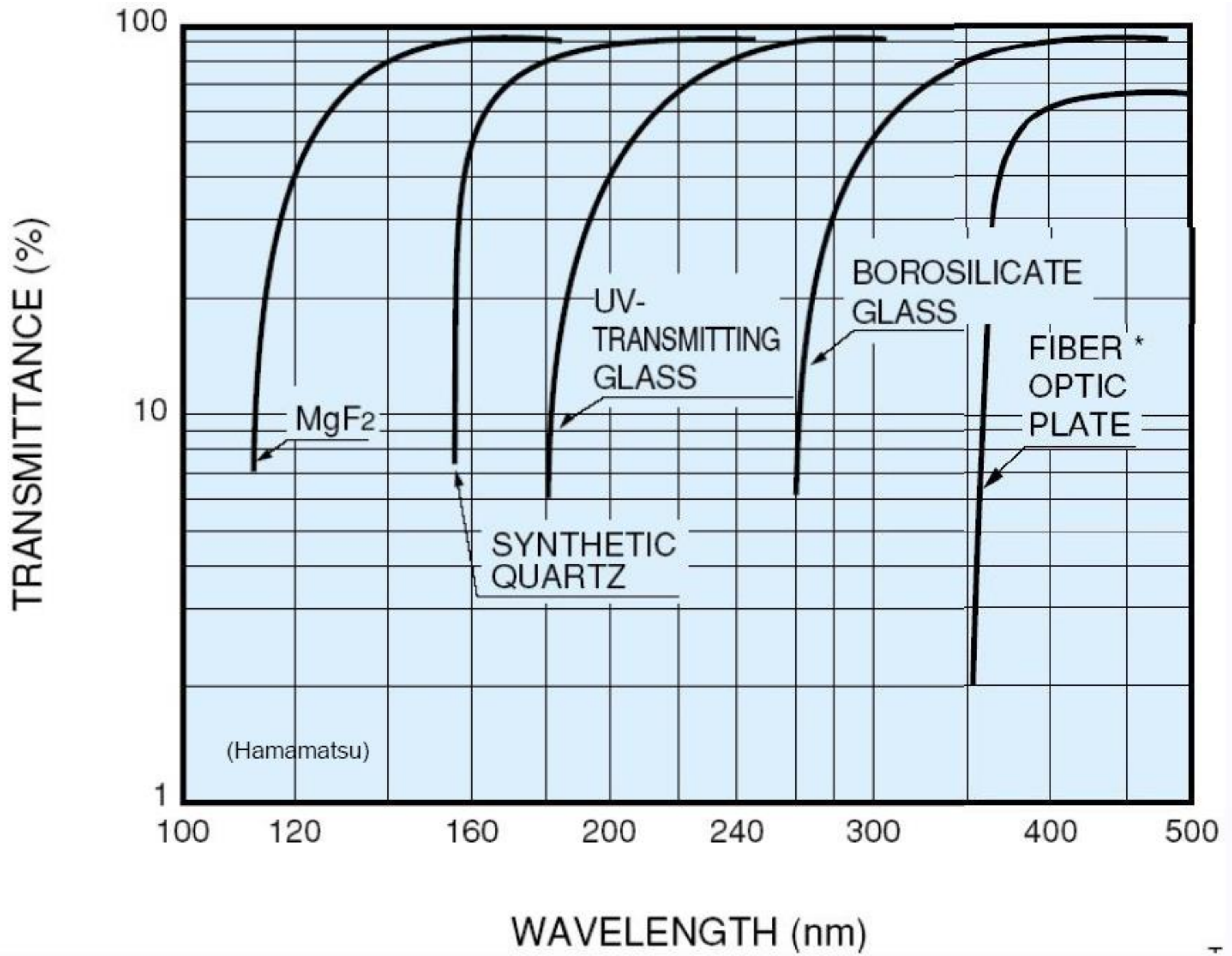
QE's of typical photo-cathodes



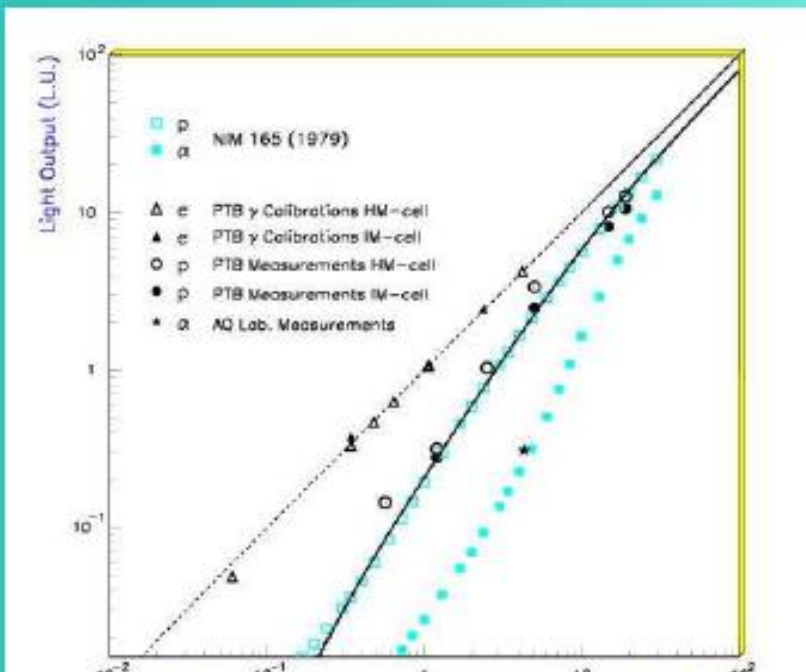
(Philips Photonic)

$$Q.E.(\%) \approx 124 \cdot \frac{sk_e(mA/W)}{\lambda(nm)}$$

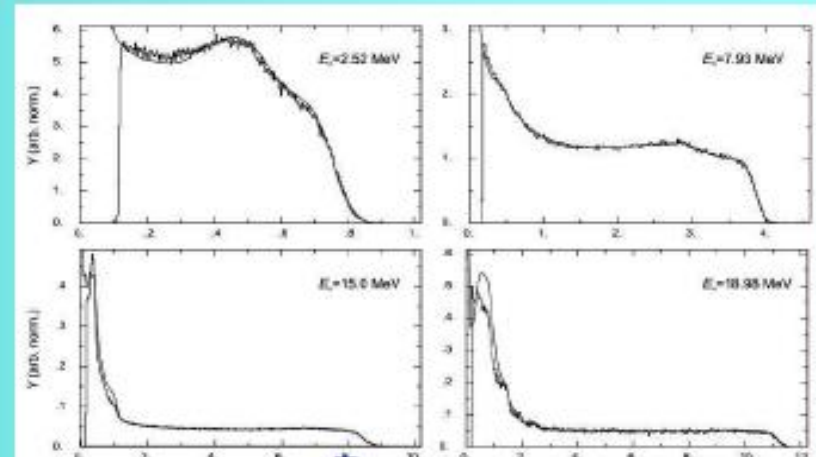
Transmission of optical windows



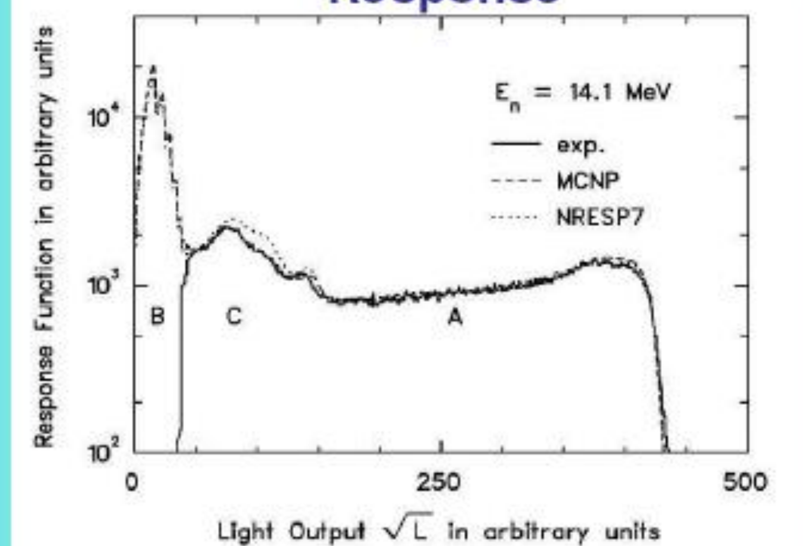
BC501/NE213 liquid scintillators



Light-output particle dependence

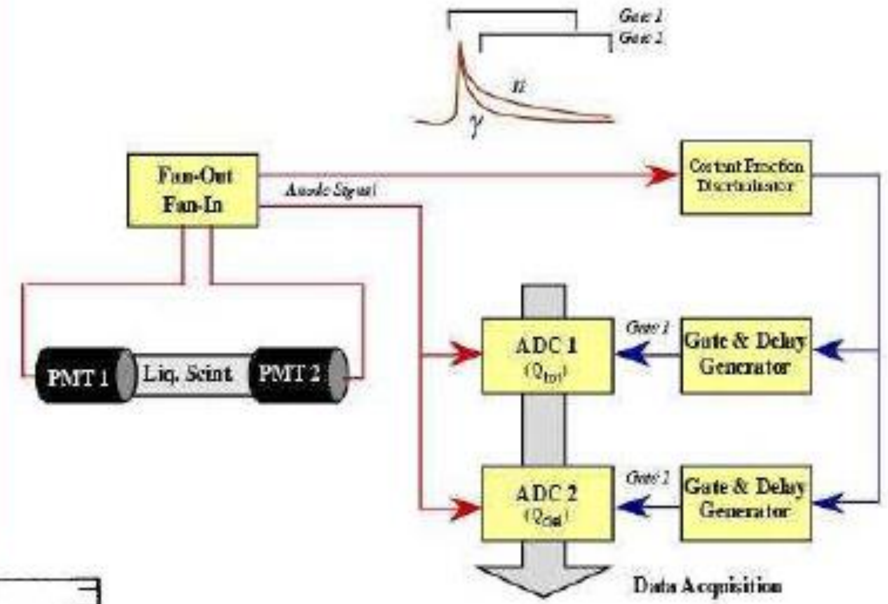


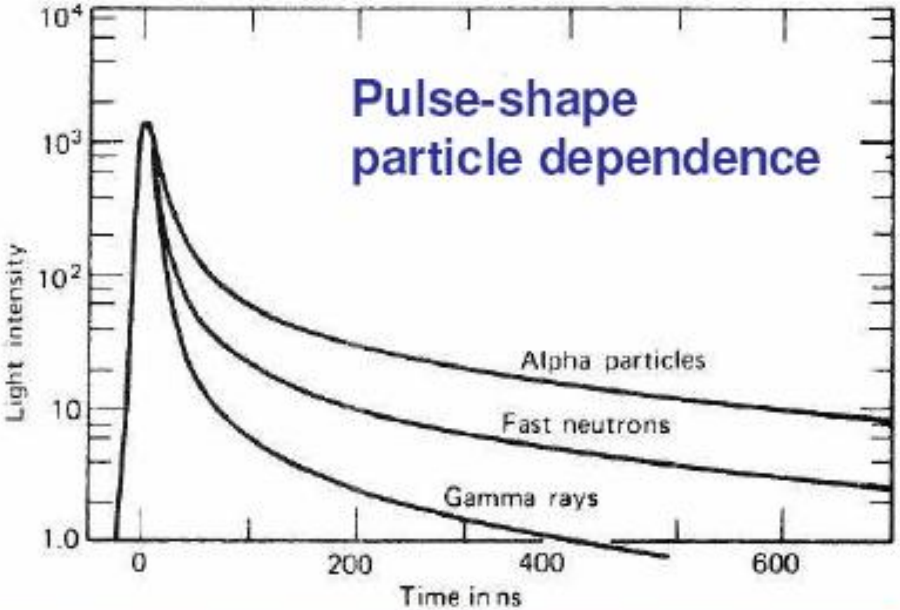
Response

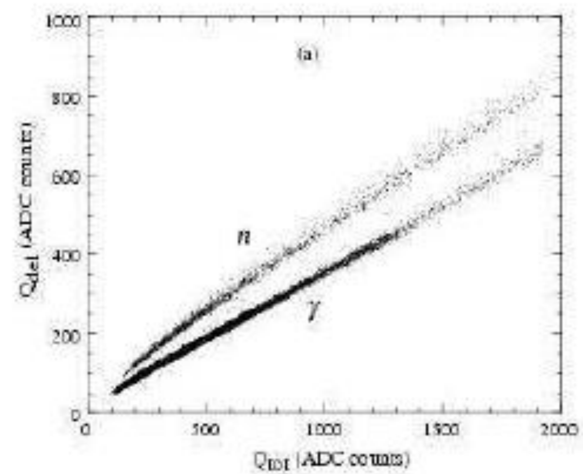


BC501/NE213

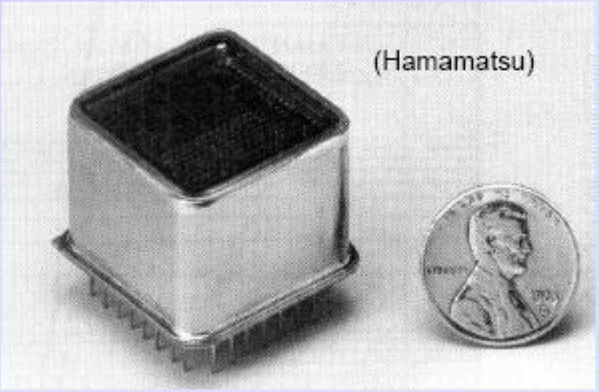
Pulse Shape Discrimination







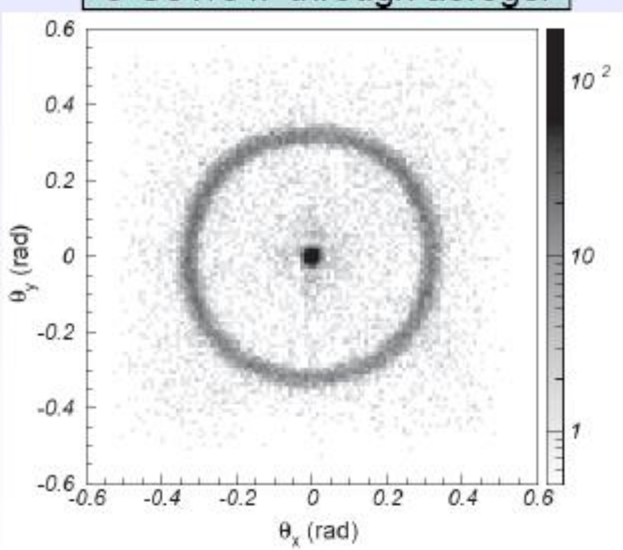
Multi-anode and flat-panel PMT's



Multi-anode (Hamamatsu H7546)

- Up to 8×8 channels (2×2 mm^2 each);
- Size: 28×28 mm^2;
- Active area 18.1×18.1 mm^2 (41%);
- Bialkali PC: QE $\approx$ 20% @ λ_{max} = 400 nm;
- Gain $\approx 3\ 10^5$;
- Gain uniformity typ. 1 : 2.5;
- Cross-talk typ. 2%

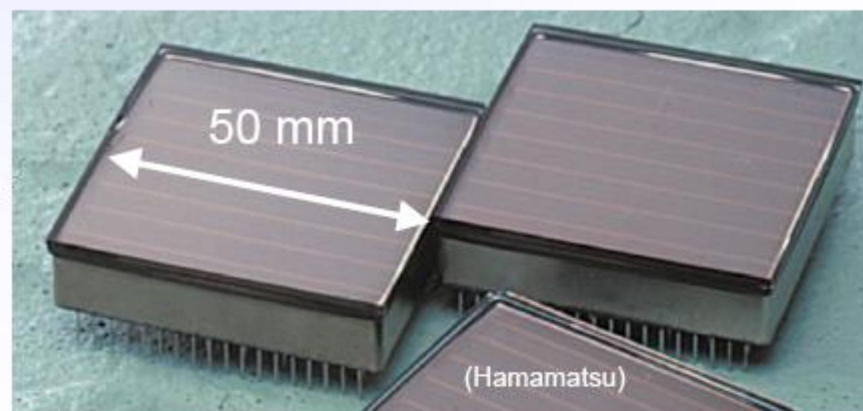
Cherenkov rings from 3 GeV/c π^- through aerogel



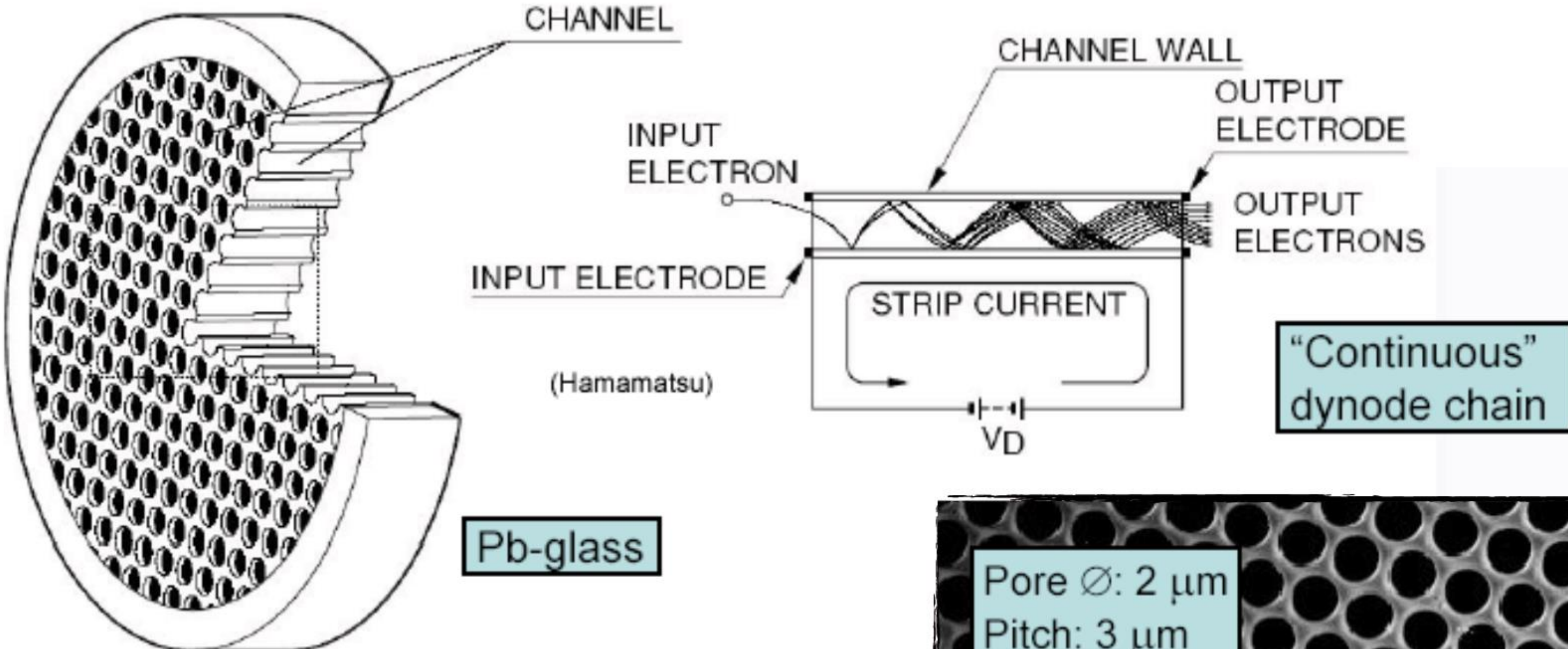
(T. Matsumoto et al., NIMA **521** (2004) 367)

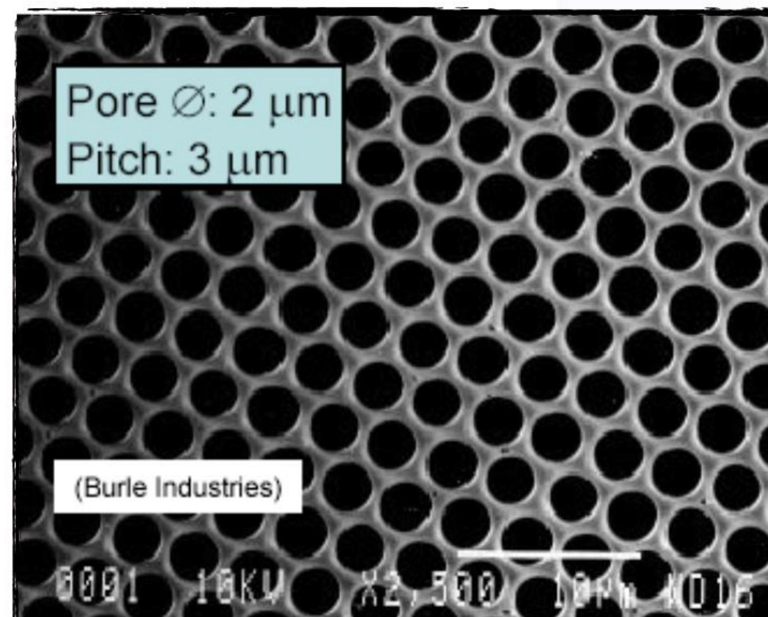
Flat-panel (Hamamatsu H8500):

- 8 x 8 channels (5.8 x 5.8 mm^2 each);
- Excellent surface coverage (89%)



Microchannel plate



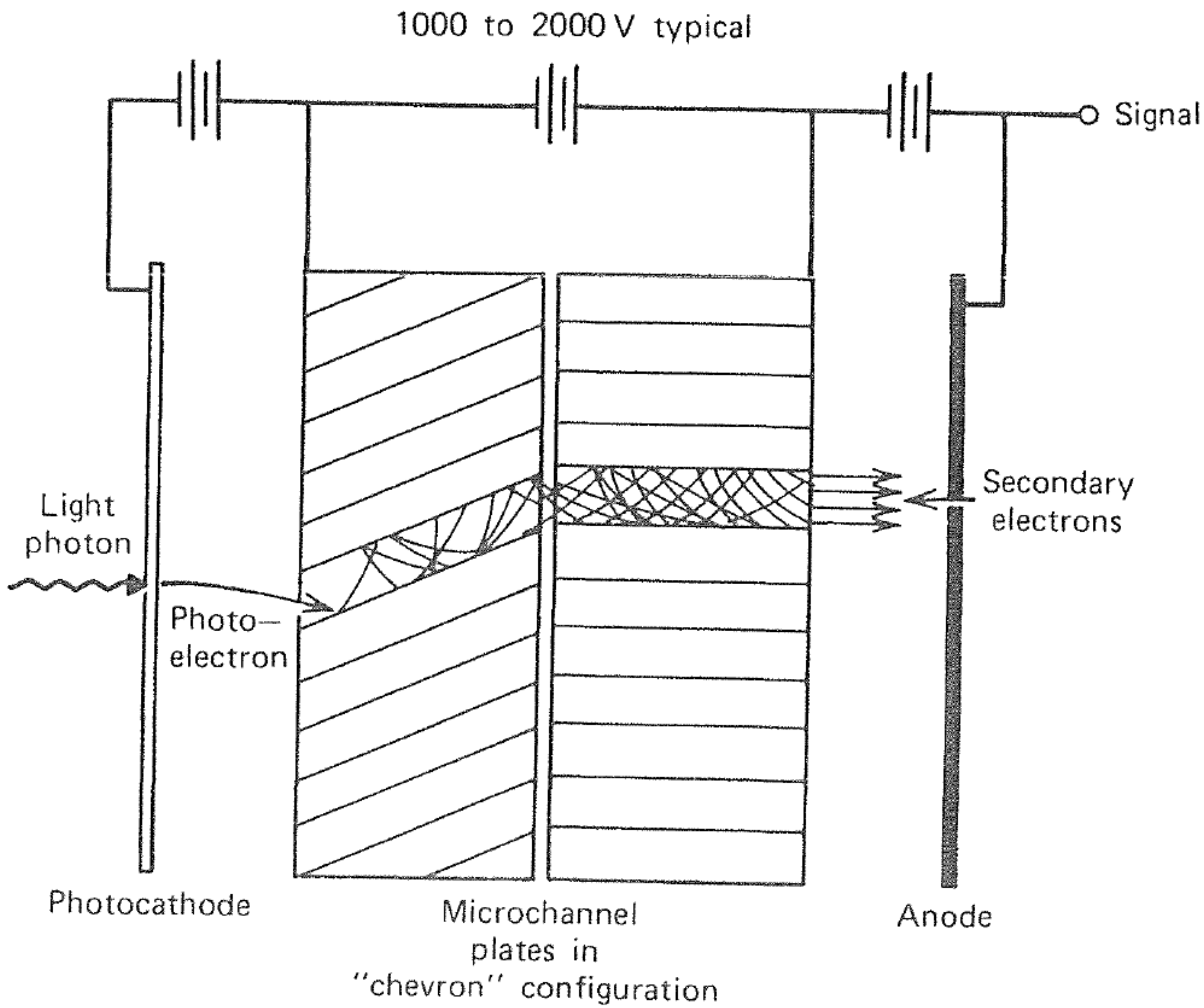


"2D Photomultiplier"

Gain: $5 \cdot 10^4$
Fast signal [time spread ~ 50 ps]
B-Field tolerant [up to 0.1T]

But: limited life time/rate capability

Microchannel plate – chevron configuration



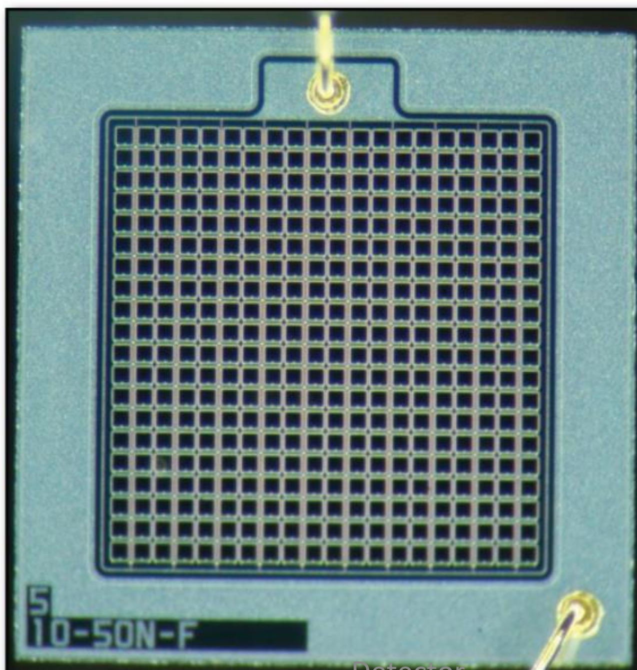
Silicon Photomultipliers (SiPMs)

Silicon Photomultipliers (SiPMs) are novel, solid state based low level light detectors.

Due to their distinguished properties,

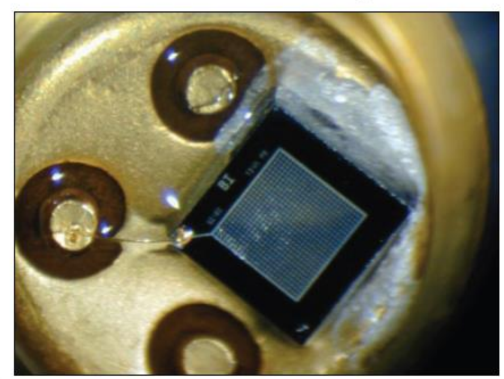
- very high quantum efficiency compared to PMTs
- much higher gain compared to APDs,

they are able to replace PMTs and APDs in many applications.



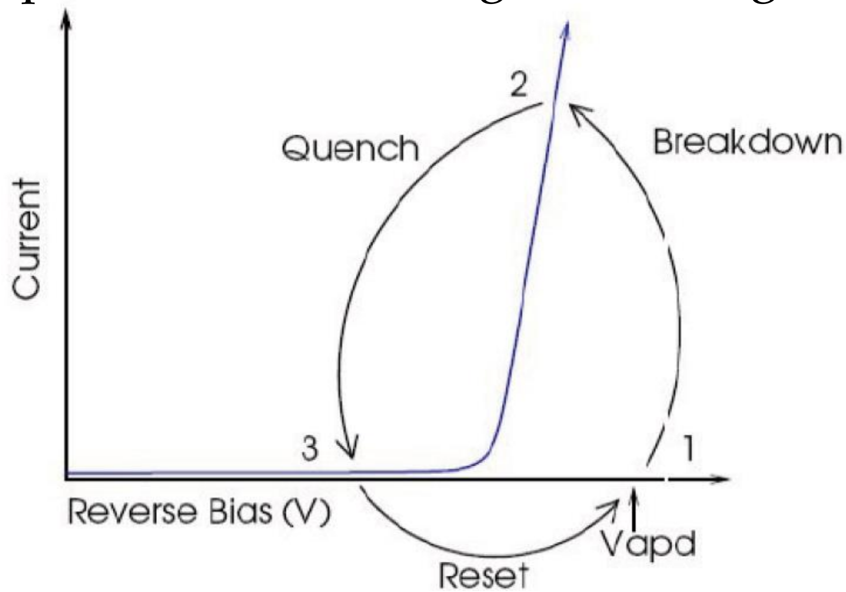
HAMAMATSU
MPPC 400Pixels

One of the first SiPM
Pulsar, Moscow

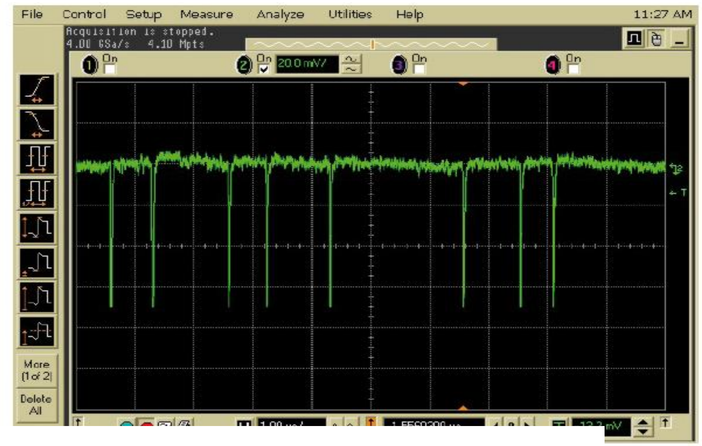


Silicon Photomultiplier – operated in Geiger mode

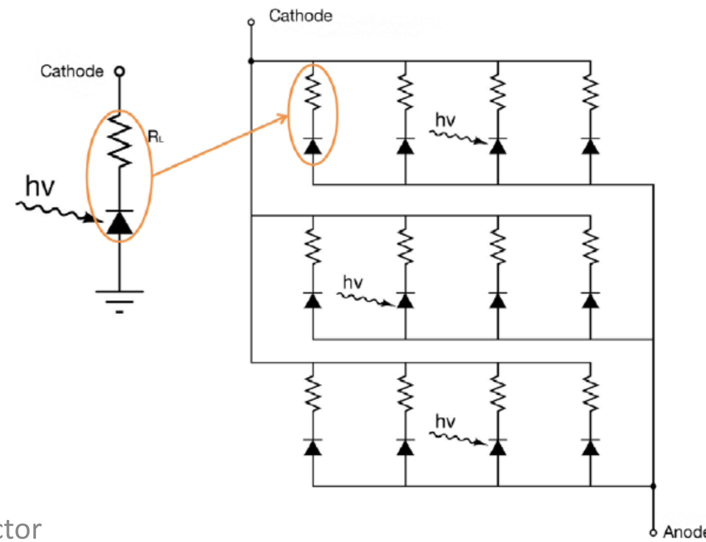
Breakdown, quench and reset cycle of a photodiode working in the Geiger mode



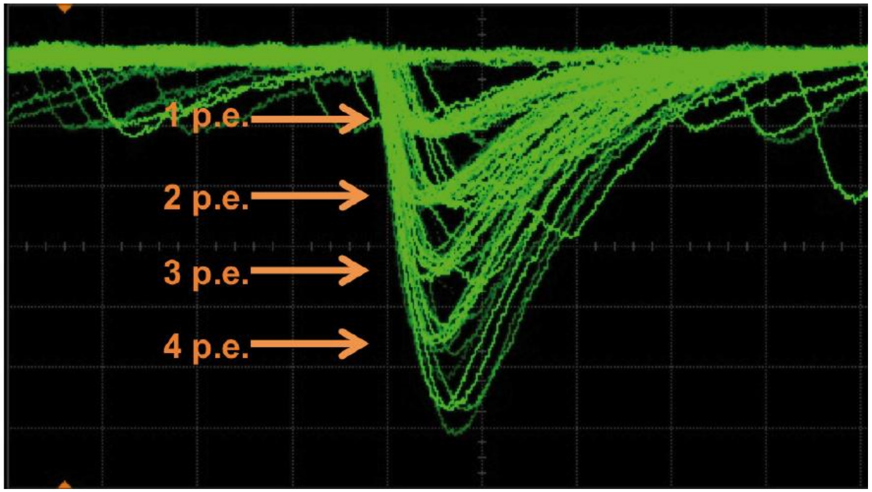
“digital” pulse output from a photodiode working in Geiger mode



An array of microcells (photodiode plus quench resistor) with summed output

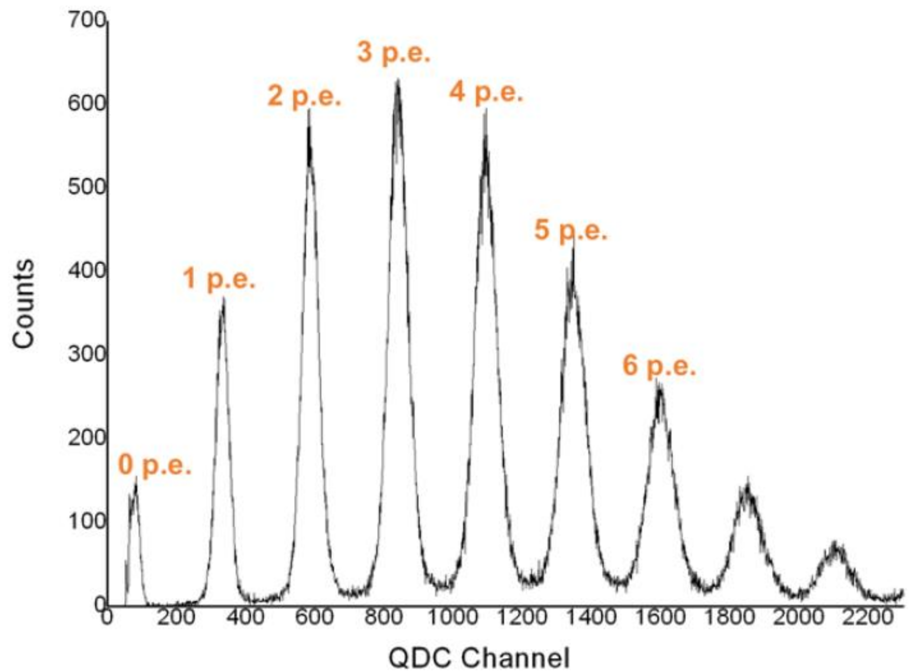


Silicon Photomultiplier – single photon counting



Oscilloscope shot showing the discrete nature of SiPM output when illuminated by brief pulses of low-level light

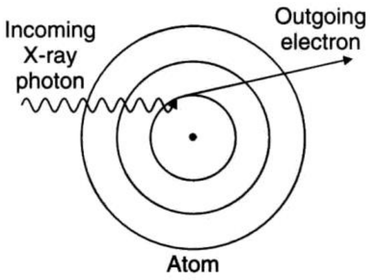
Photoelectron spectrum of a SiPM, using brief, low-level light pulses



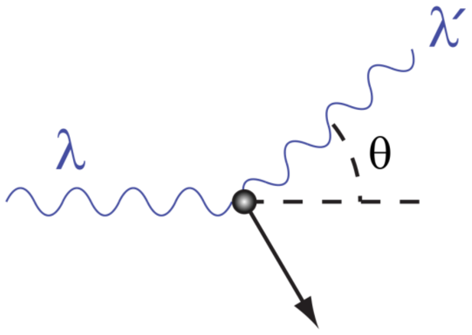
Radiation spectroscopy with scintillators

The main interactions of X-rays and γ-rays in matter are:

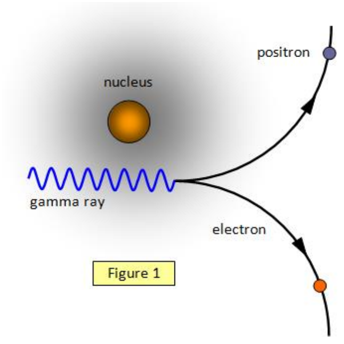
- photoelectric effect



- Compton scattering



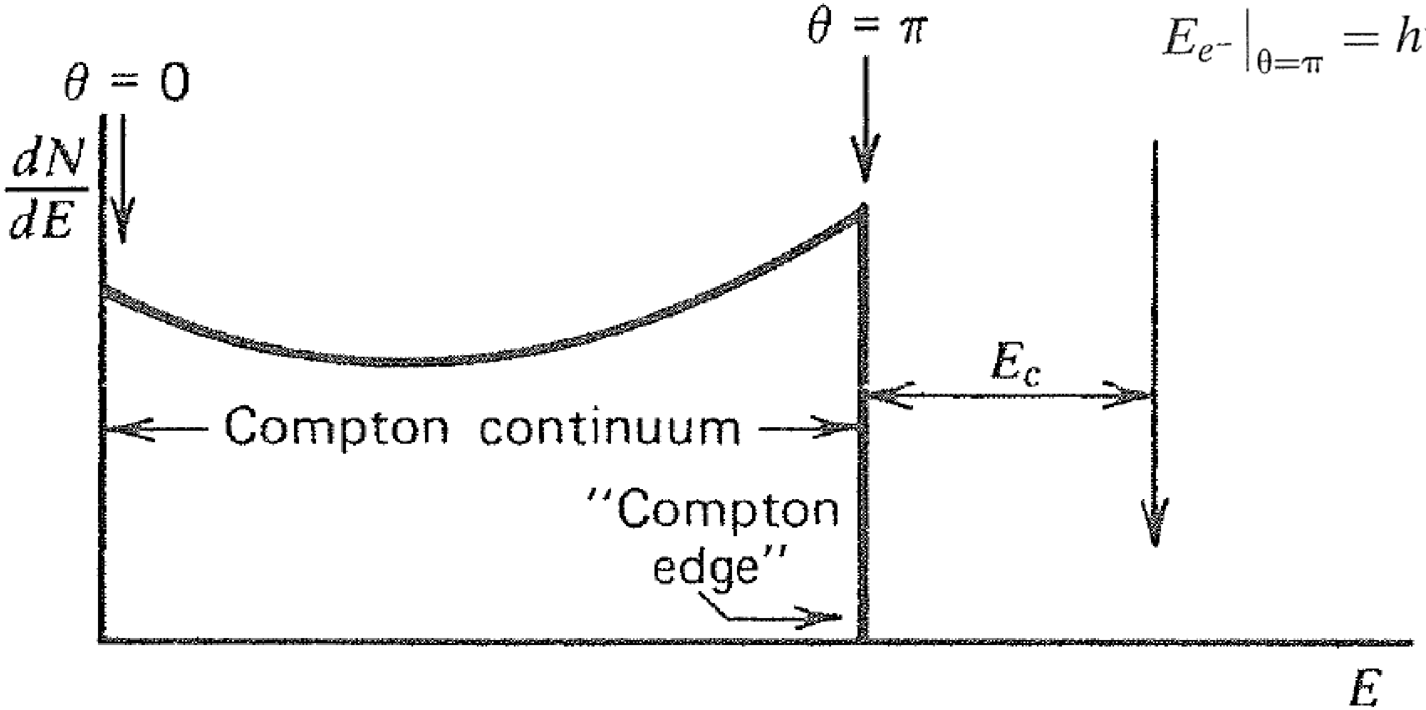
- pair production



Compton scattering

$$h\nu'\big|_{\theta=\pi} = \frac{h\nu}{1+2h\nu/m_0c^2}$$

$$E_{e^-}\big|_{\theta=\pi} = h\nu\left(\frac{2h\nu/m_0c^2}{1+2h\nu/m_0c^2}\right)$$

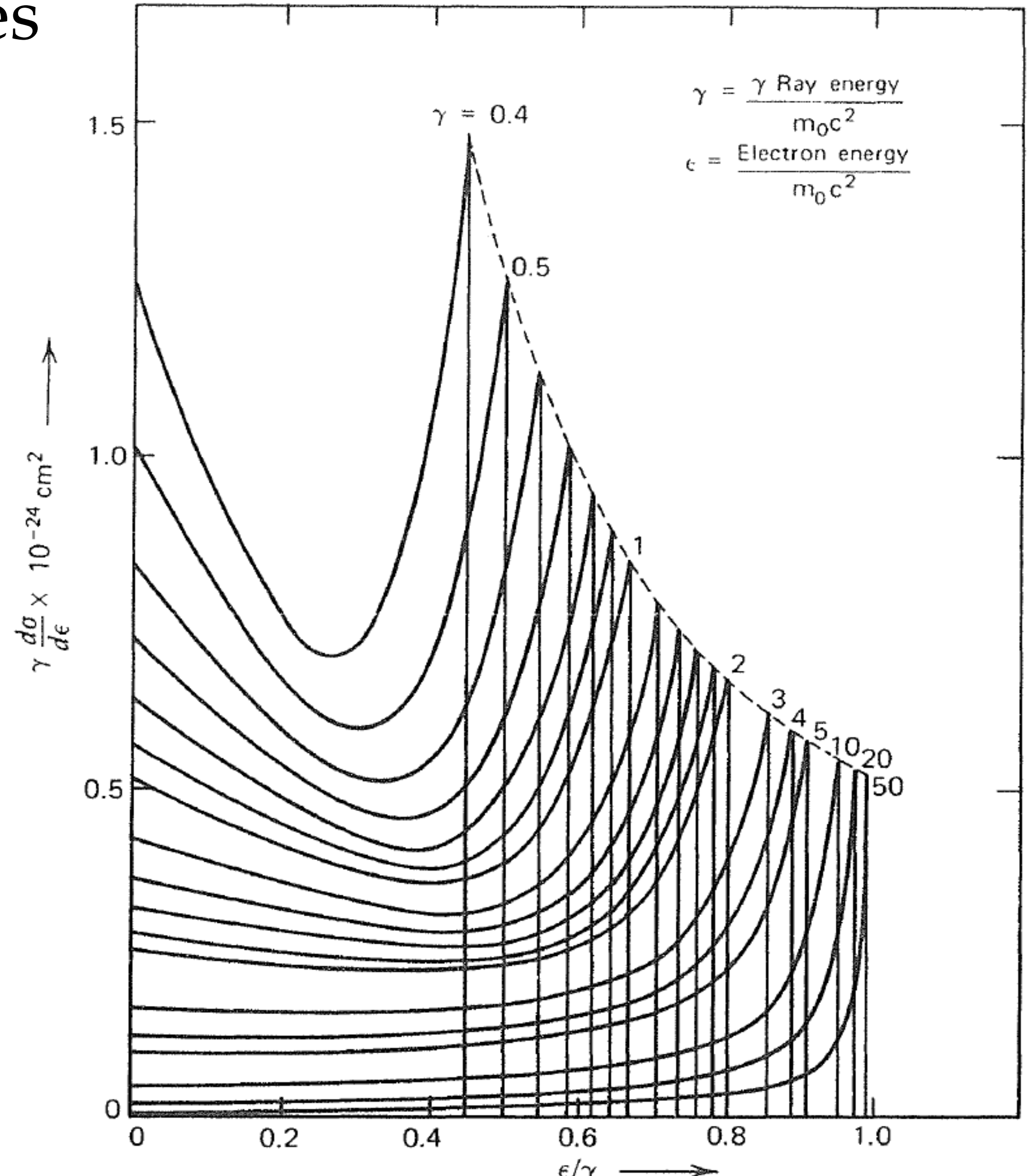


head-on collision:

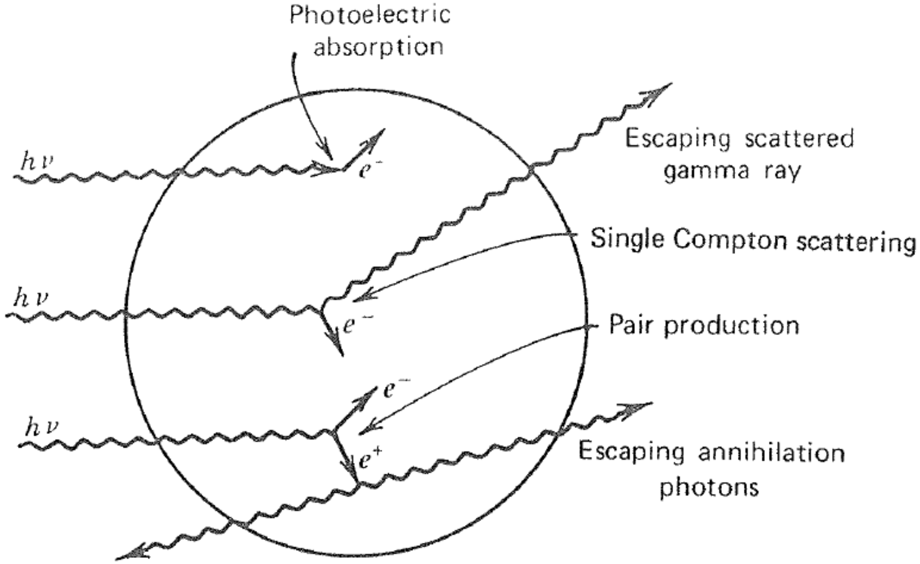
$$E_C \equiv h\nu - E_{e^-}\big|_{\theta=\pi} = \frac{h\nu}{1+2h\nu/m_0c^2}$$

for $h\nu \gg m_0c^2$ $\qquad E_C \cong \frac{m_0c^2}{2} (= 0.256\,\mathrm{MeV})$

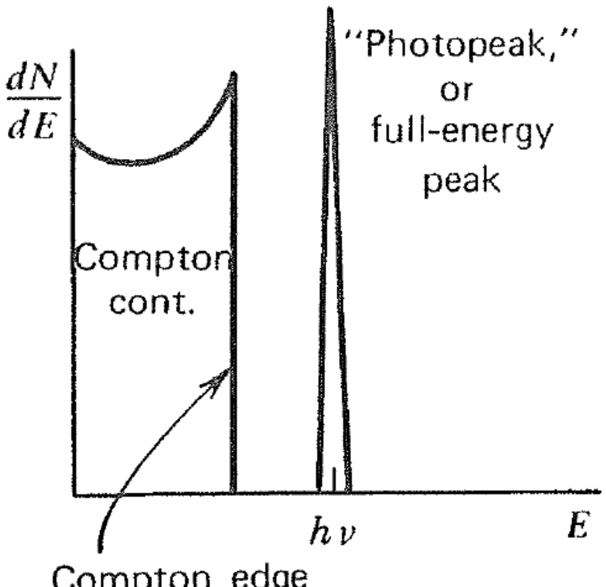
Shape of the Compton continuum for various gamma-ray energies



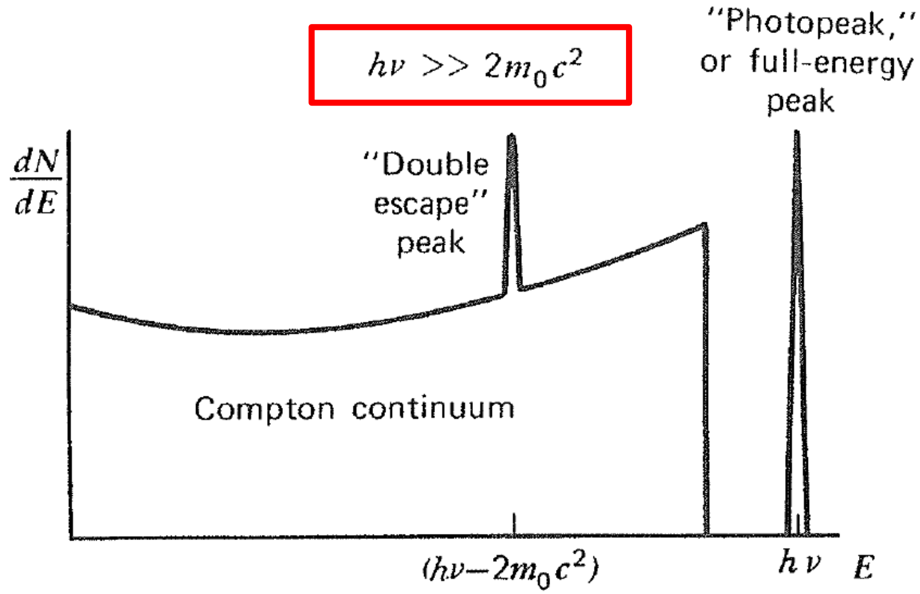
"Small" detectors – response function



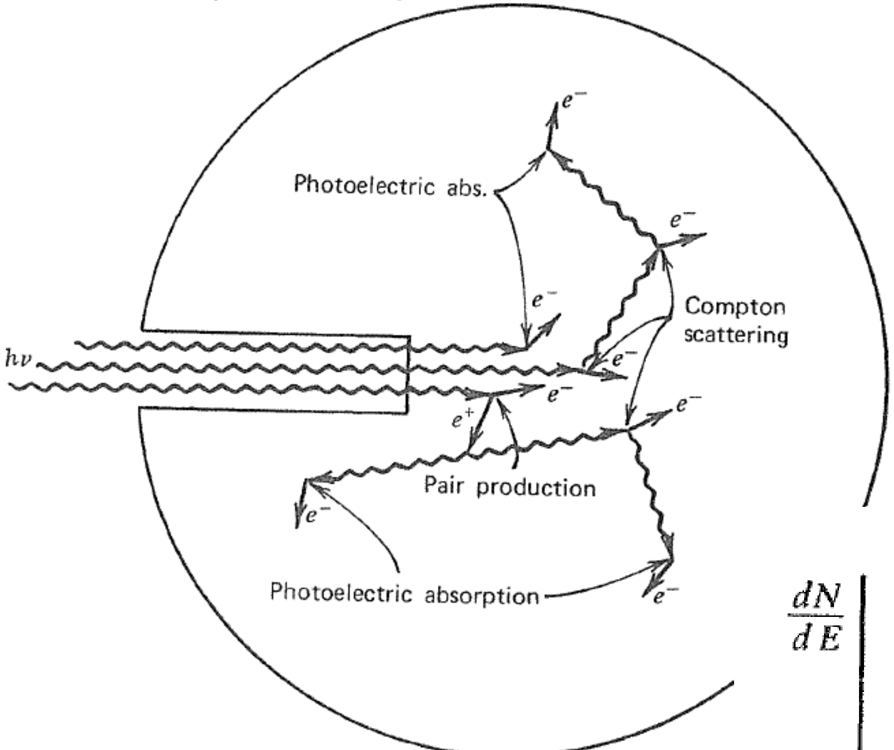
$h\nu < 2m_0c^2$

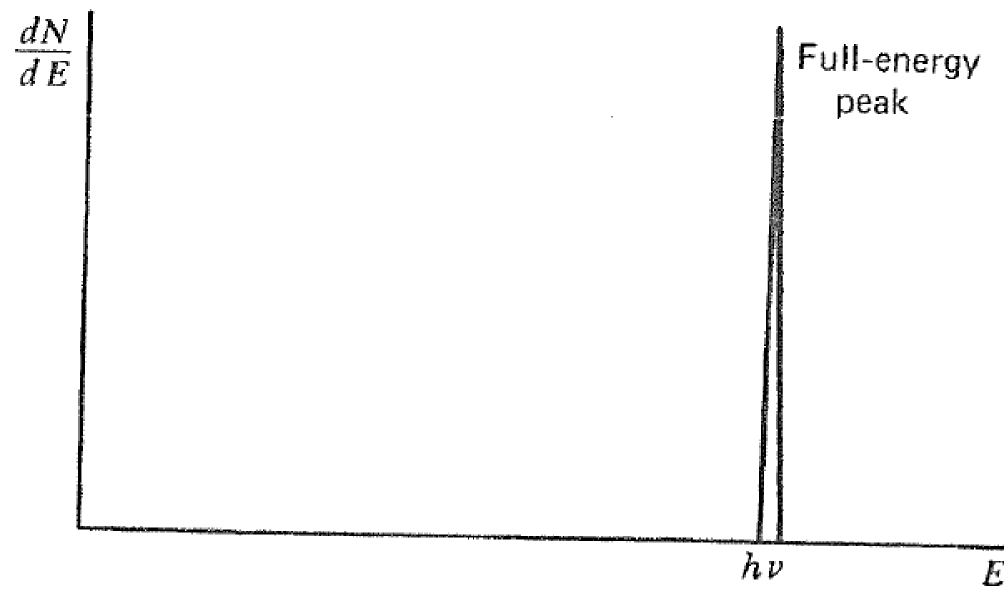


$h\nu >> 2m_0c^2$

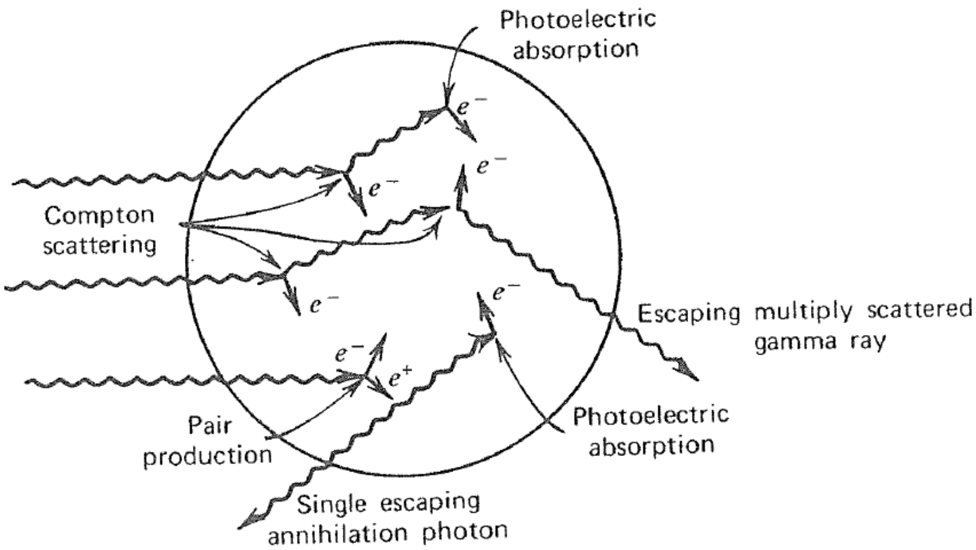


“Very large” detectors – response function



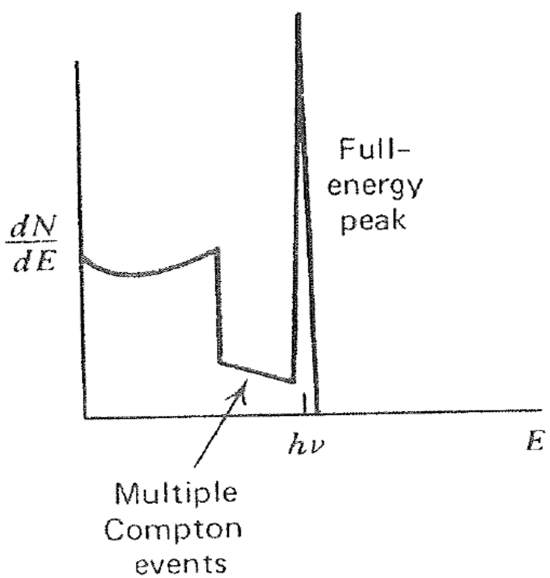


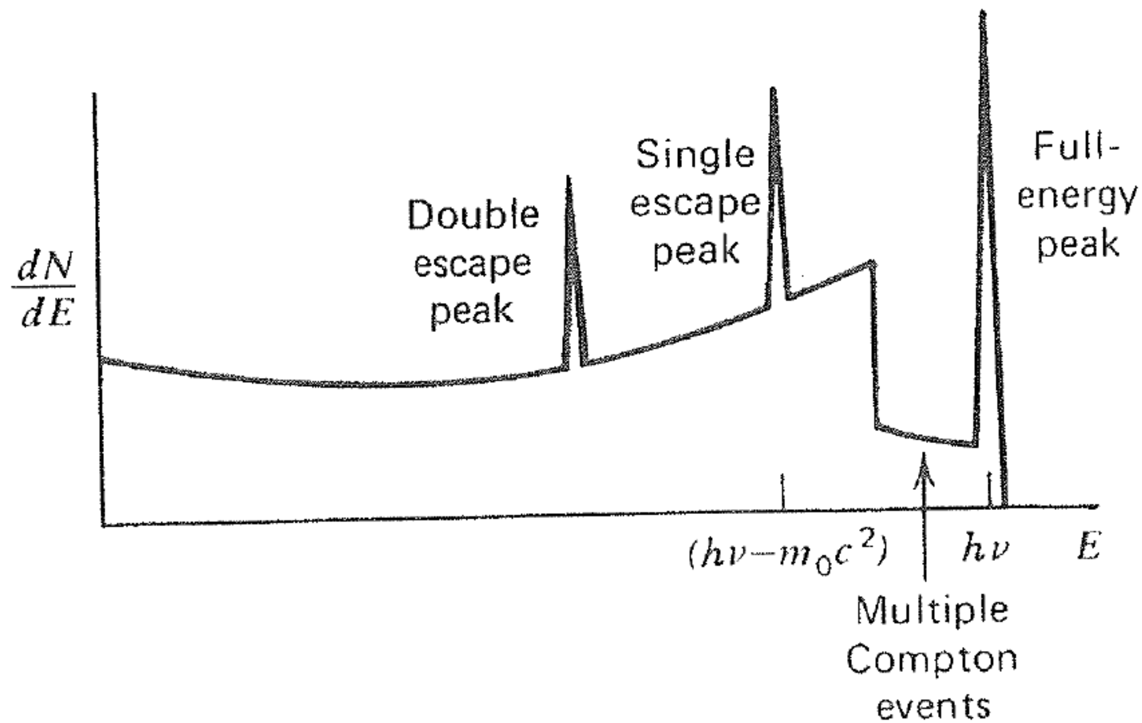
Intermediate size detectors – response function



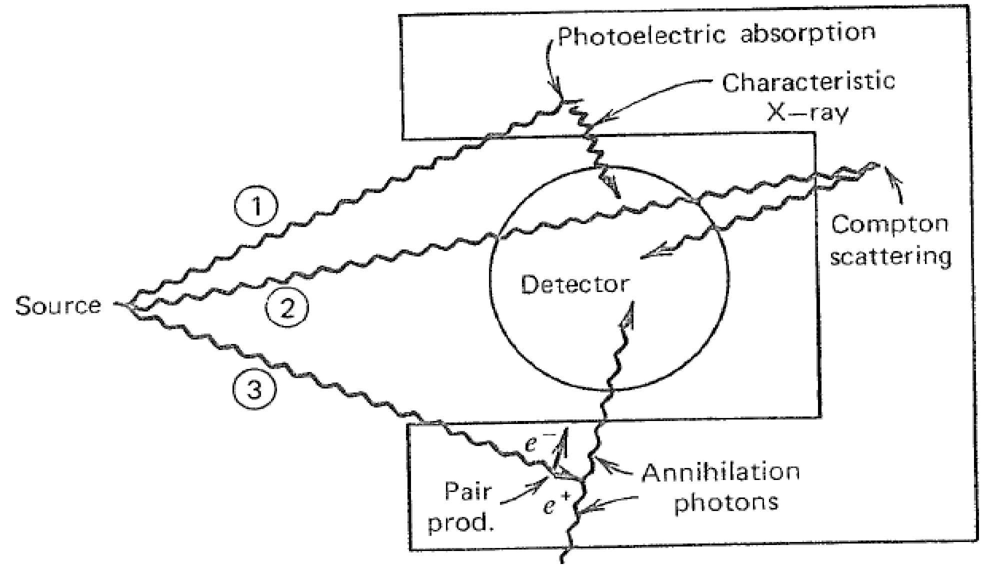
$h\nu >> 2m_0c^2$

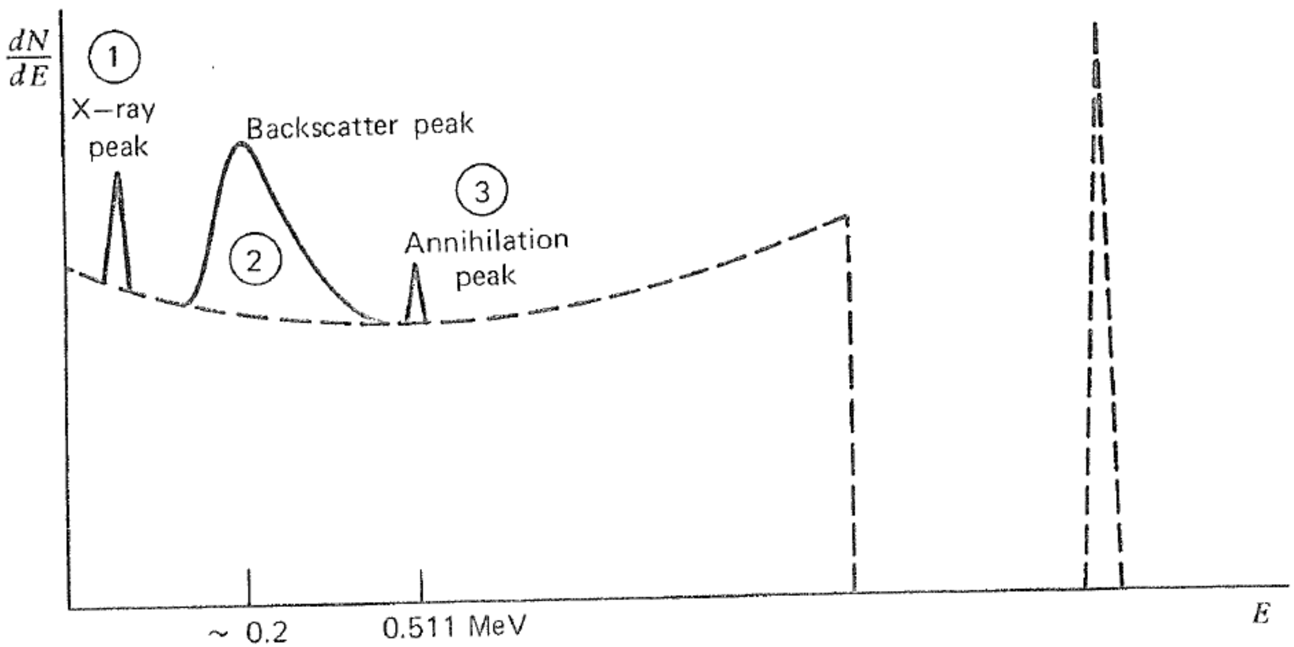
$h\nu < 2m_0c^2$



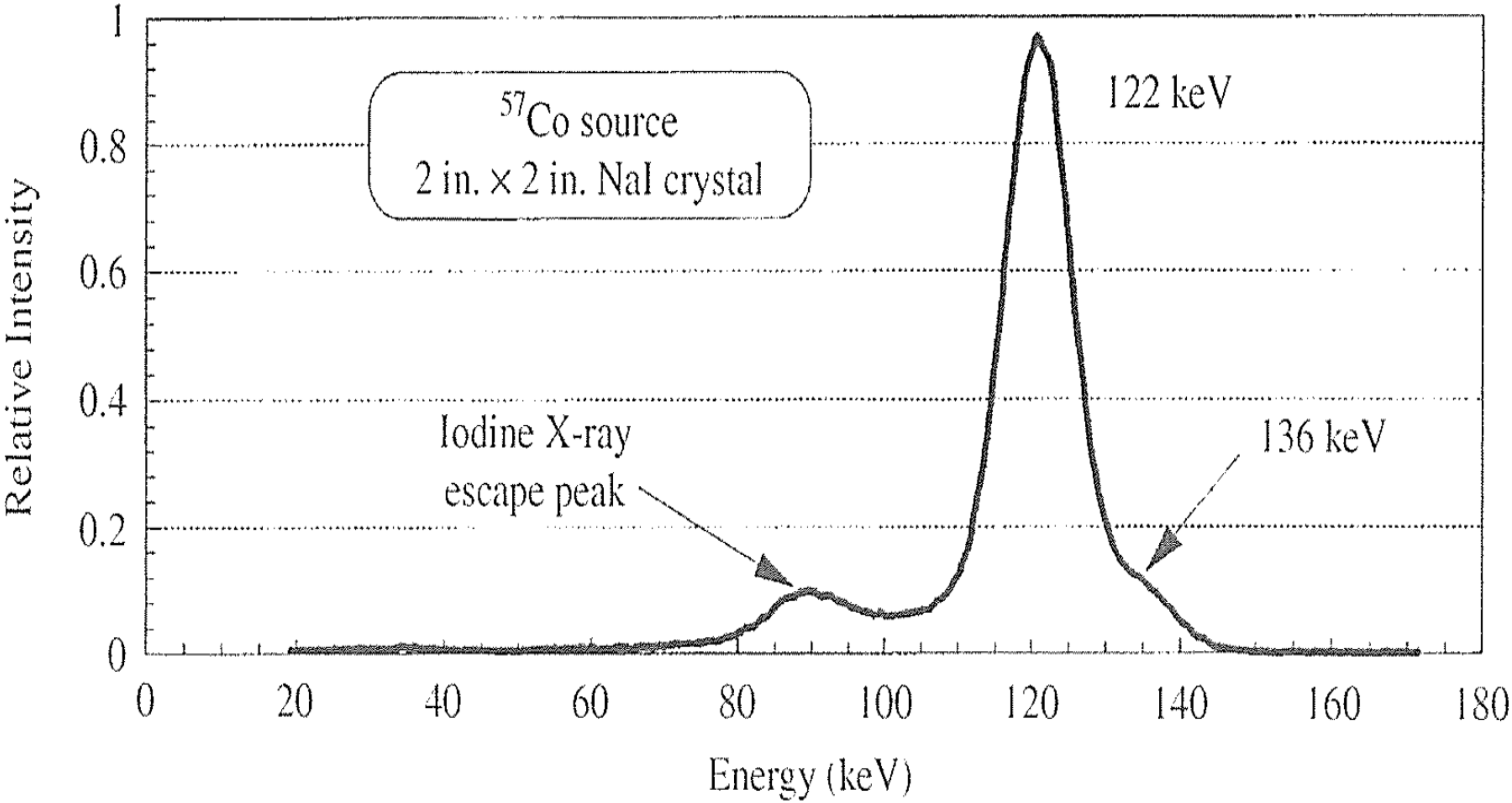


Effects of surrounding materials - shielding

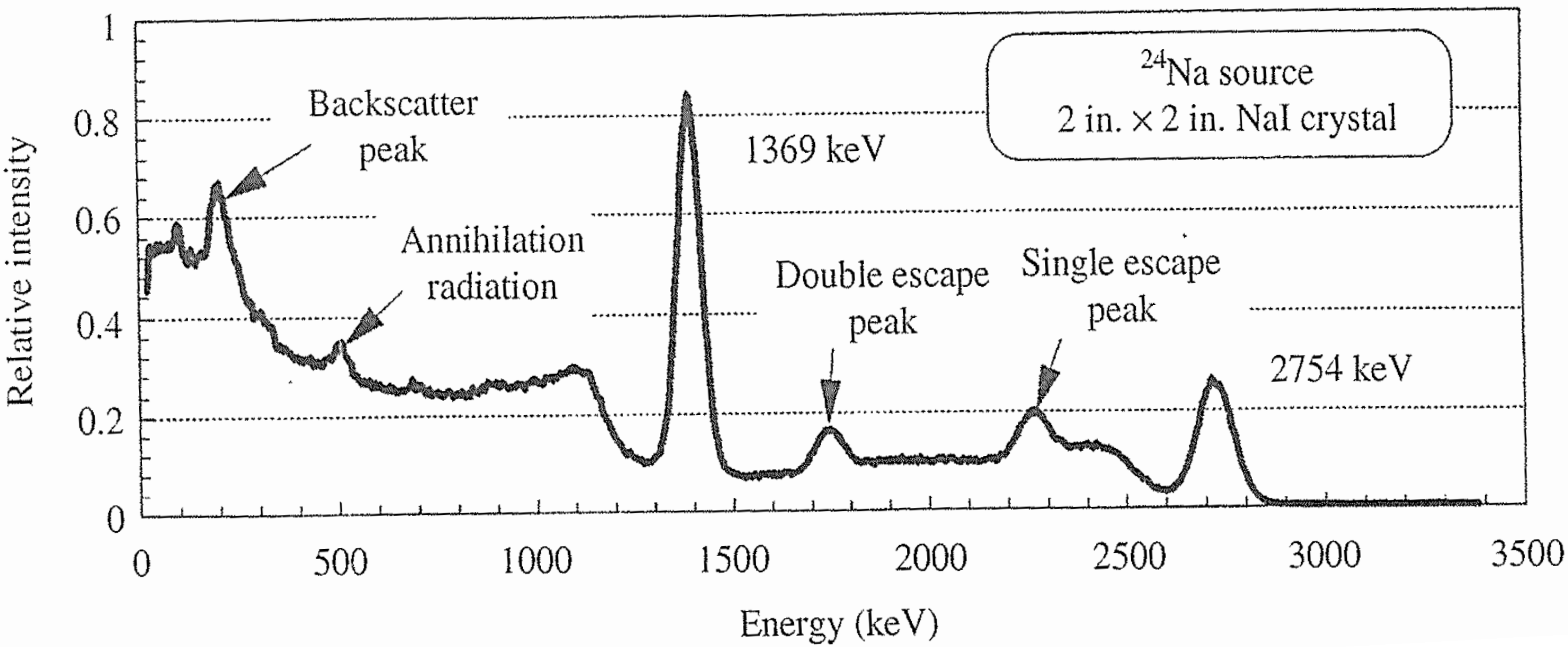




Response function – NaI(Tl)

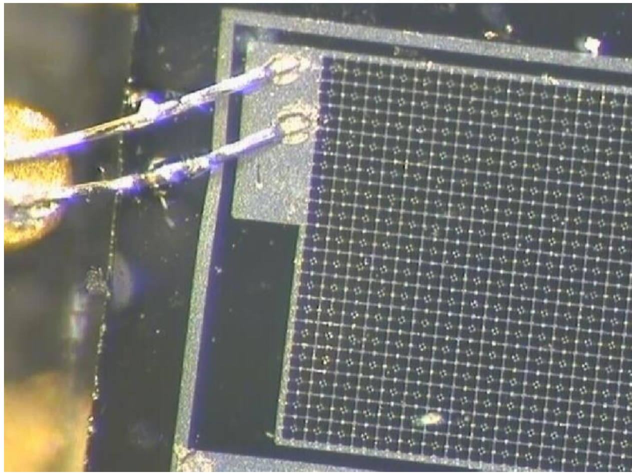


Response function – NaI(Tl)



SiPM – Silicion photo multiplier (Avalanche Photodiodes)

Test of different types of SiPM:
SiPM Photonique, KETEK, FBK Trento
MPPC Hamamatsu
(Multi-pixel Photo Counter)



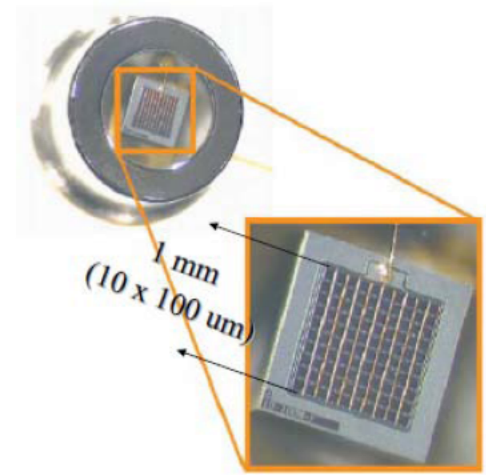
Basic performance of SiPMs, like:
timing, amplification, stability

FOPI
SIDDHARTA-2
PANDA
AMADEUS

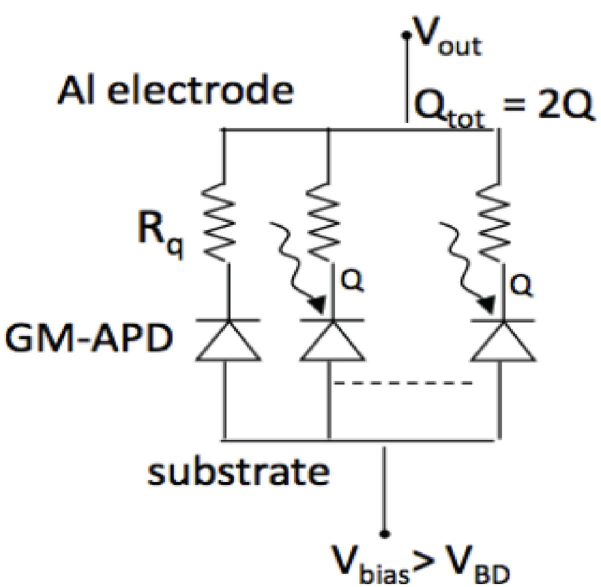
- **EU-FP7 HP2: WP28 – SiPM**
- **EU-FP7 HP3: WP28 - SiPM**

SiPM – Silicion Photo Multiplier

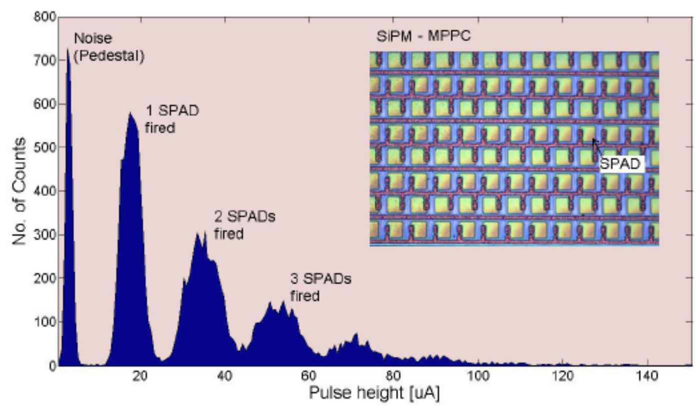
		PMT	MCP-PMT	SiPM
PDE	Blue	20%	20%	50%
	Green - Yellow	40%	40%	40%
	Red	≤ 6 %	6%	30%
Time precision		100 ps	≤ 100 ps	130 ps
Gain		10^6	10^6	10^5 - 10^6
Threshold sensitivity		1 p.e.	1 p.e.	1 p.e.
Dark count rate		Hz - kHz	Hz/cm²	MHz/cm²
Operation in magnetic fields		< 10^{-3} T	< 2 T	Yes
Operation voltage		1 kV	3 kV	< 100 V



Hamamatsu S10362-11-100U

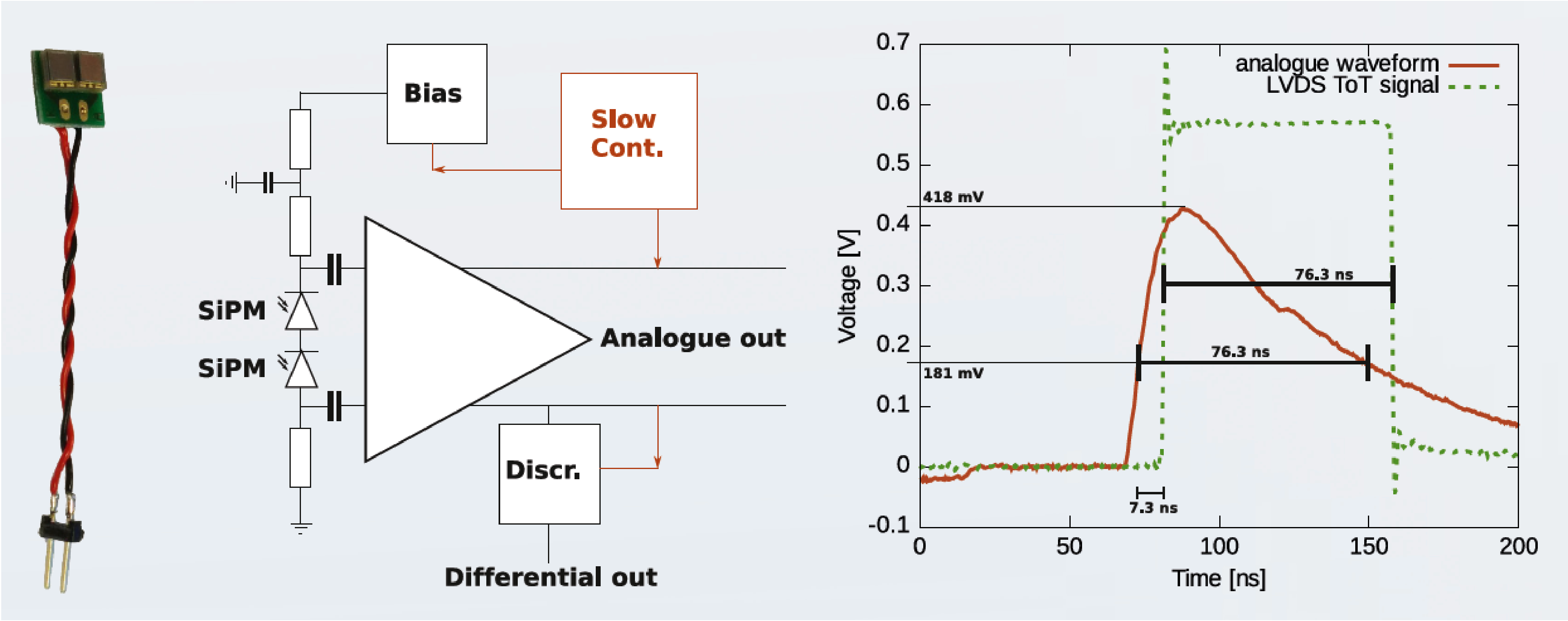


photon counting with SiPMs



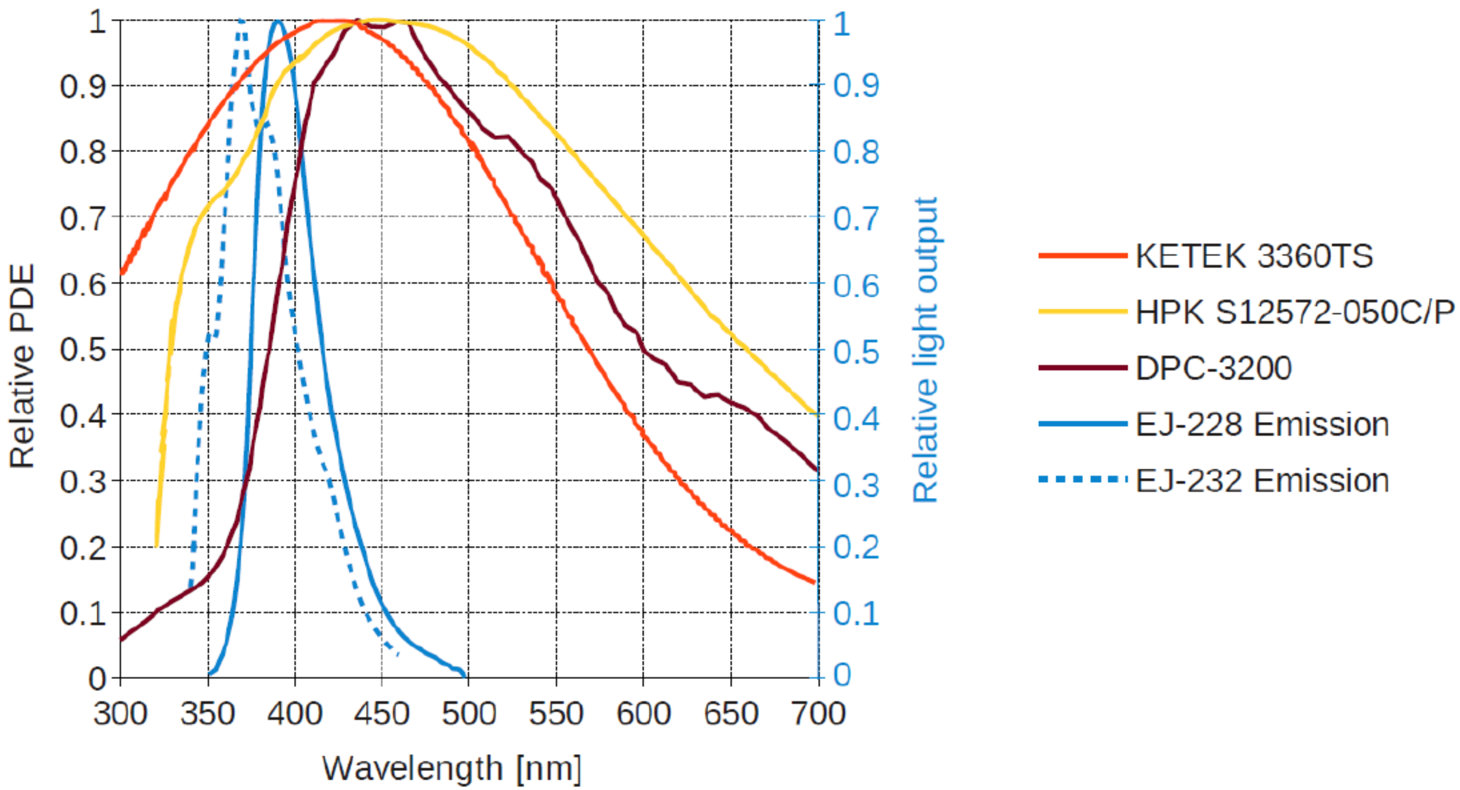
SiPM frontend electronics

- differential diode readout
- accurate bias control
- on-board discriminator
- differential signal output: balanced analogue signal and LVDS trigger
- remote slow control



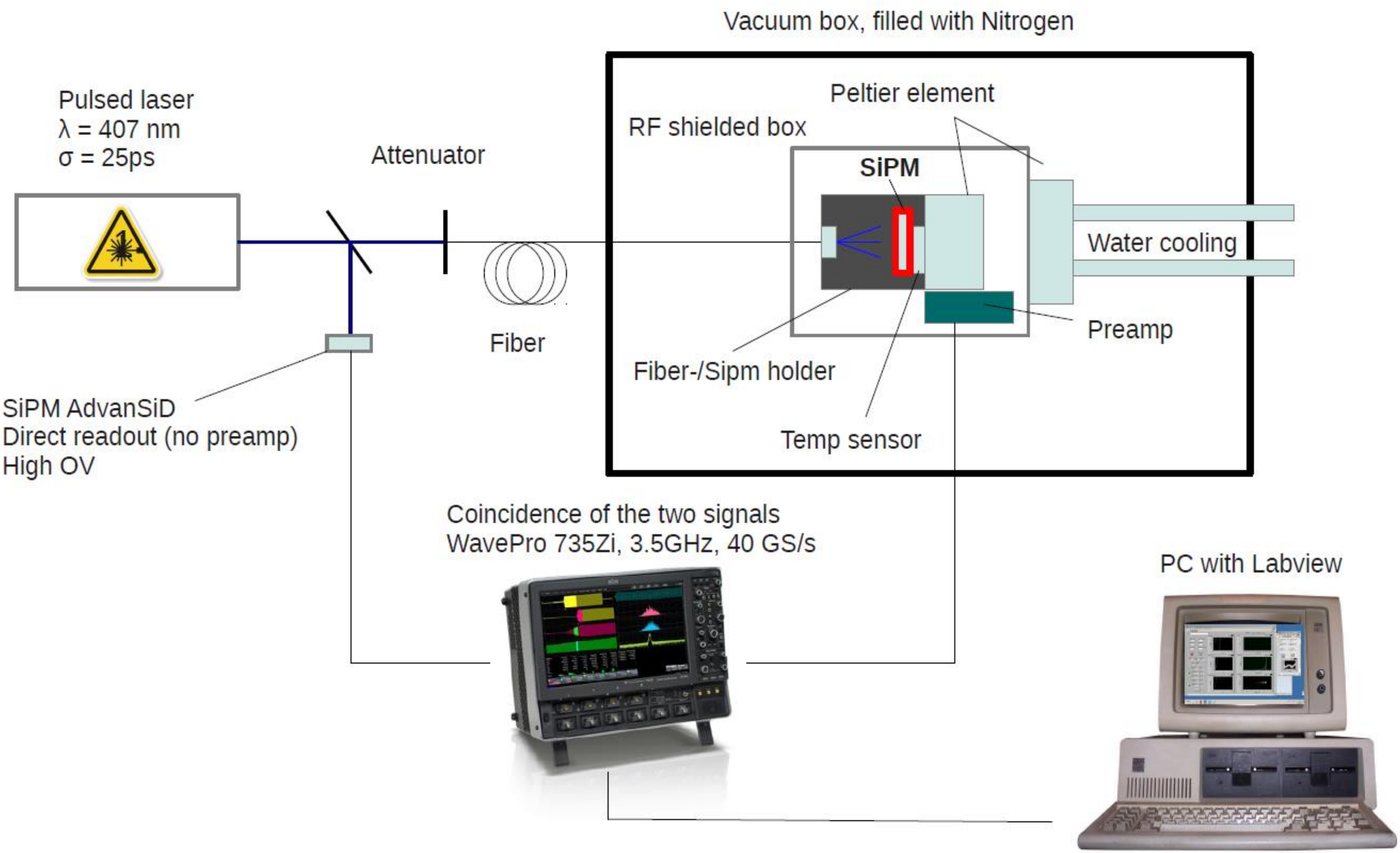
Photodetector

- **Photon detection efficiency should match the emission spectrum of the scintillator**

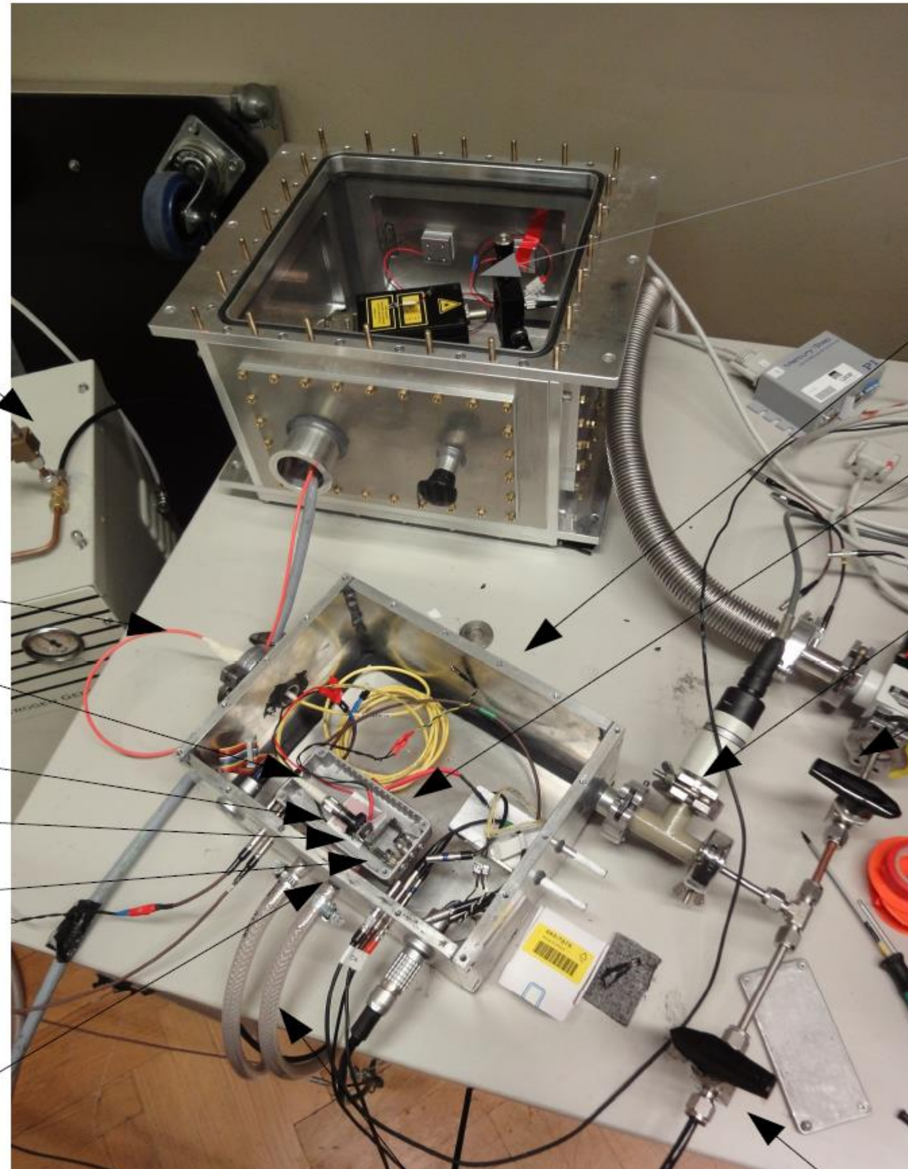


The Ketek SiPM seems to fit best.

SiPM - time resolution measurement



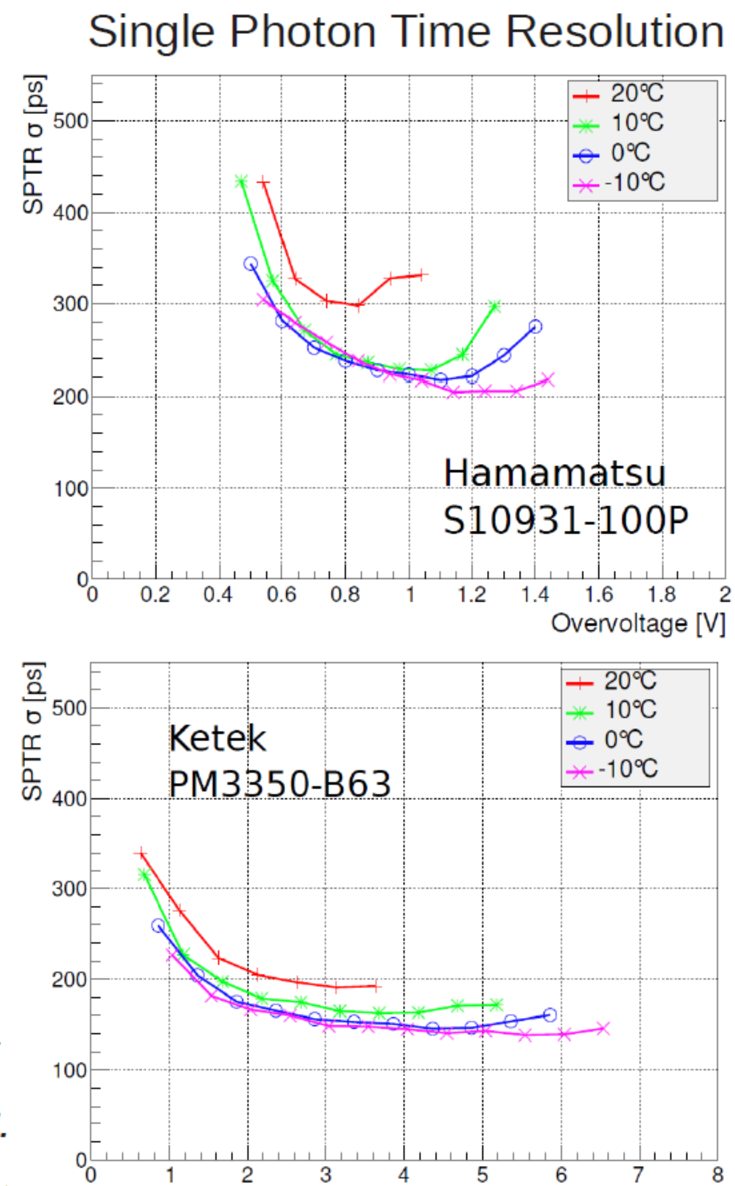
Setup - time resolution measurement



Photodetector - SiPM

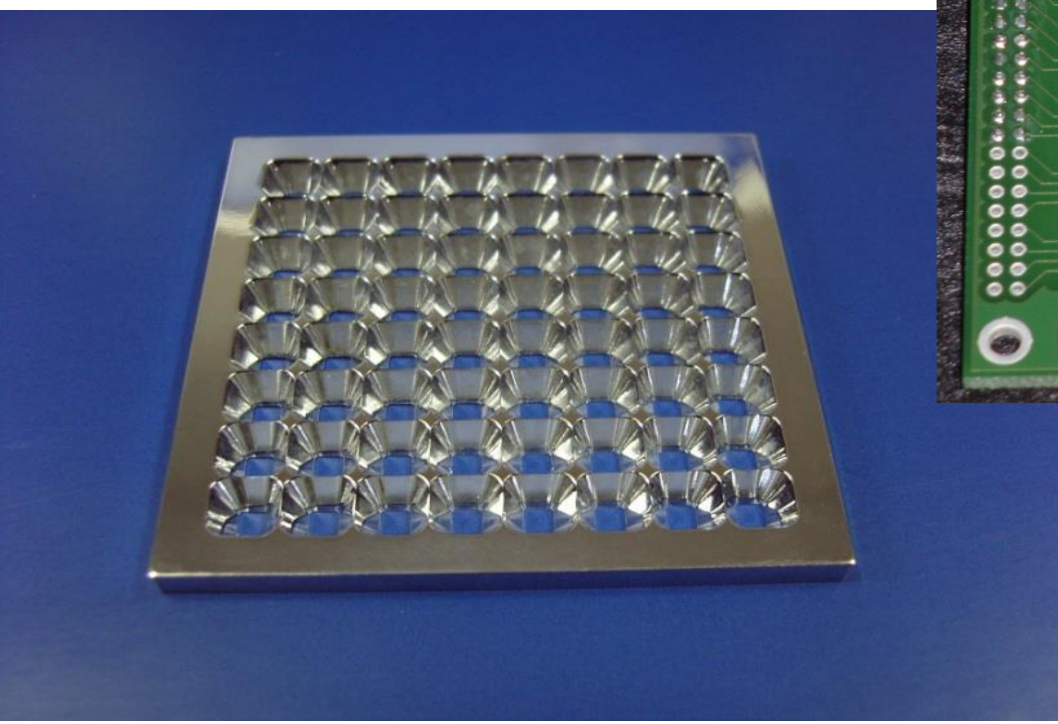
- **SiPM time resolution studies with picosecond pulsed laser (400 nm)**
- **2 options: Hamamatsu or Ketek (3x3 mm²)**
- **AdvanSiD: worse timing, low PDE**
- **SensL: also lower PDE**
- **Ketek with optical trenches showed best results**

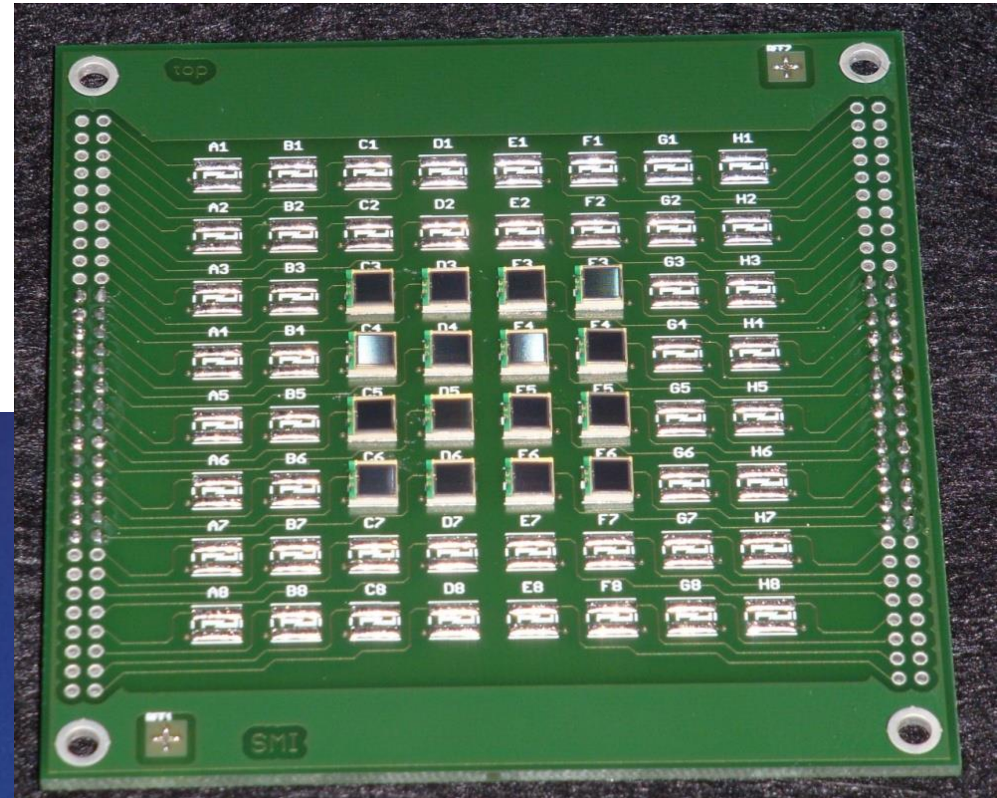
Time resolution follows 1/sqrt(Nb of photons)
We expect ~ 60 photons per SiPM:
- Hamamatsu 100P → σ ~ 40 ps
- Ketek PM3350 → σ ~ 25 ps



"Time resolution below 100 ps for the SciTil detector of PANDA employing SiPM"
S.E. Brunner, L. Gruber, J. Marton, H. Orth, K. Suzuki.

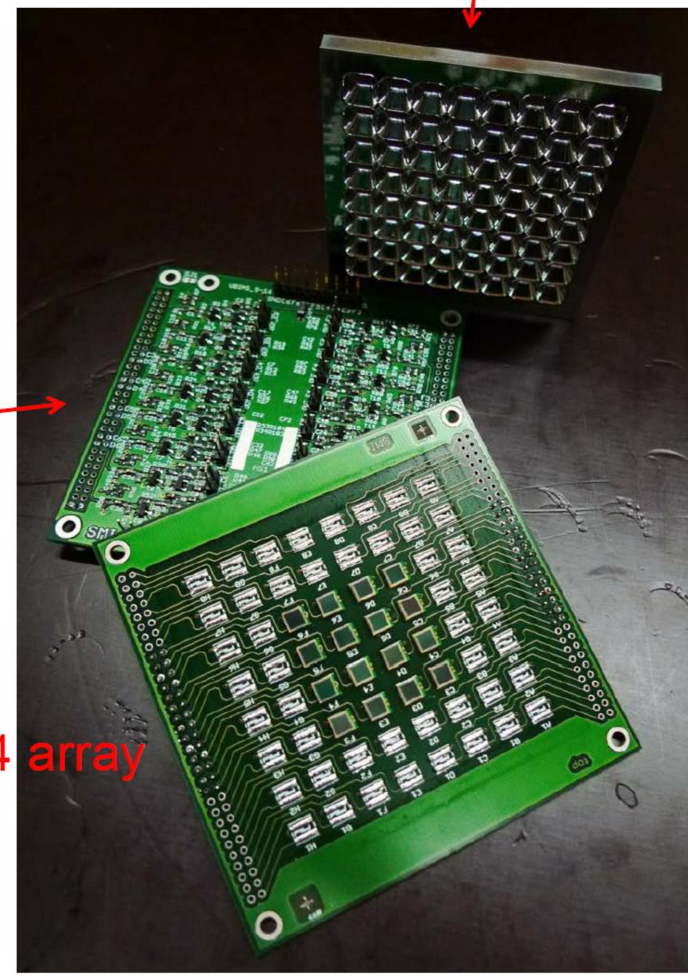
Application of SiPM:
position-sensitive detectors



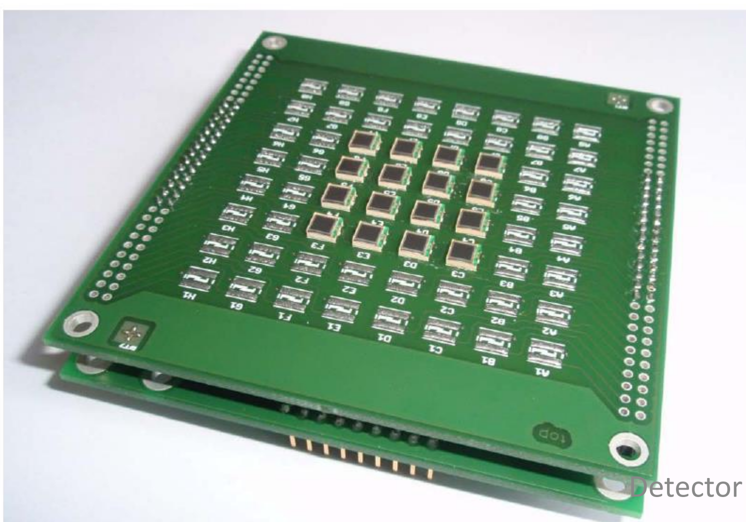


SiPM array

- The prototype photo detector consists of 64 3x3 mm² Hamamatsu SiPMs (MPPC S10931-100P) arranged in a 8x8 array with suitable light guides on top.
- Each detector is readout separately
  → 64 readout channels
- First, an array of 4x4 SiPMs is tested.
- The photo sensors are readout by a 16 channel preamplifier board.

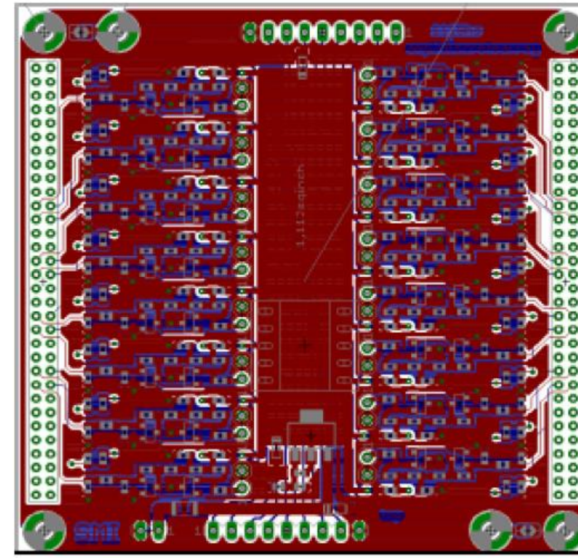


4x4 array

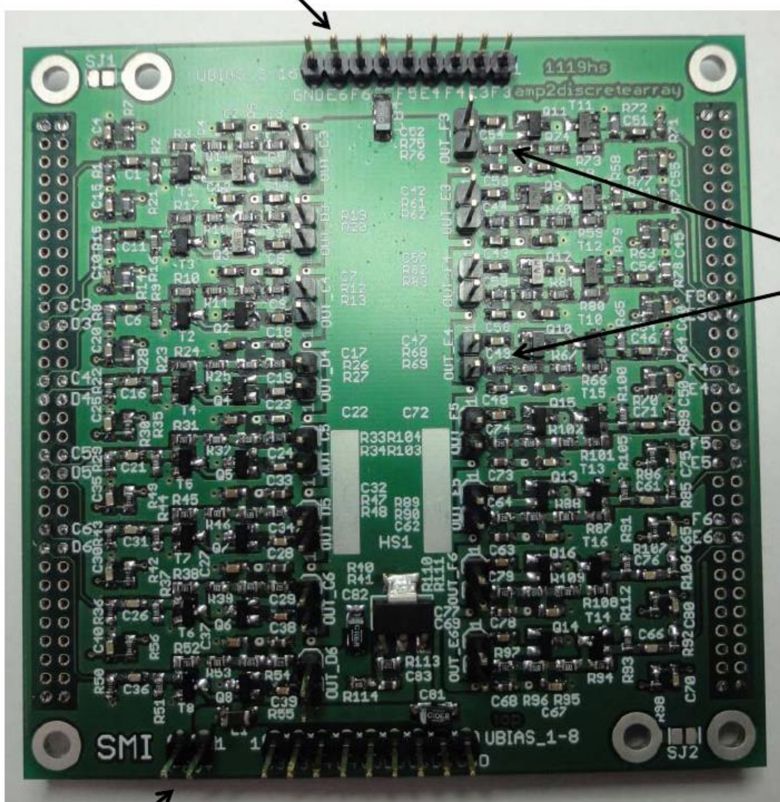


16-channel pre-amplifier board

- The SiPM module is readout by a 16 channel preamplifier board, developed at SMI



SiPM bias

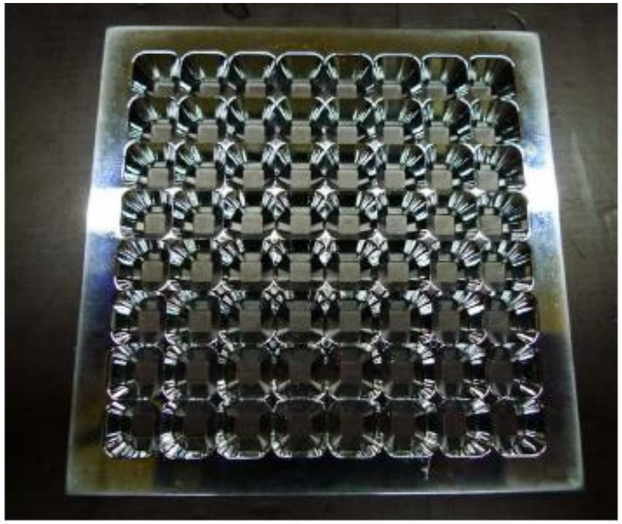


Signal out

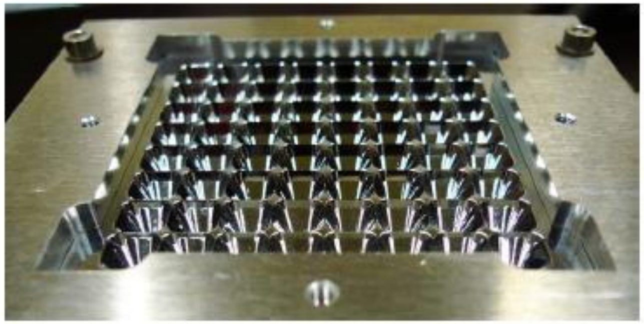
The preamplifier is basically a copy of Photonique AMP_0611

Preamp supply

Light concentrator



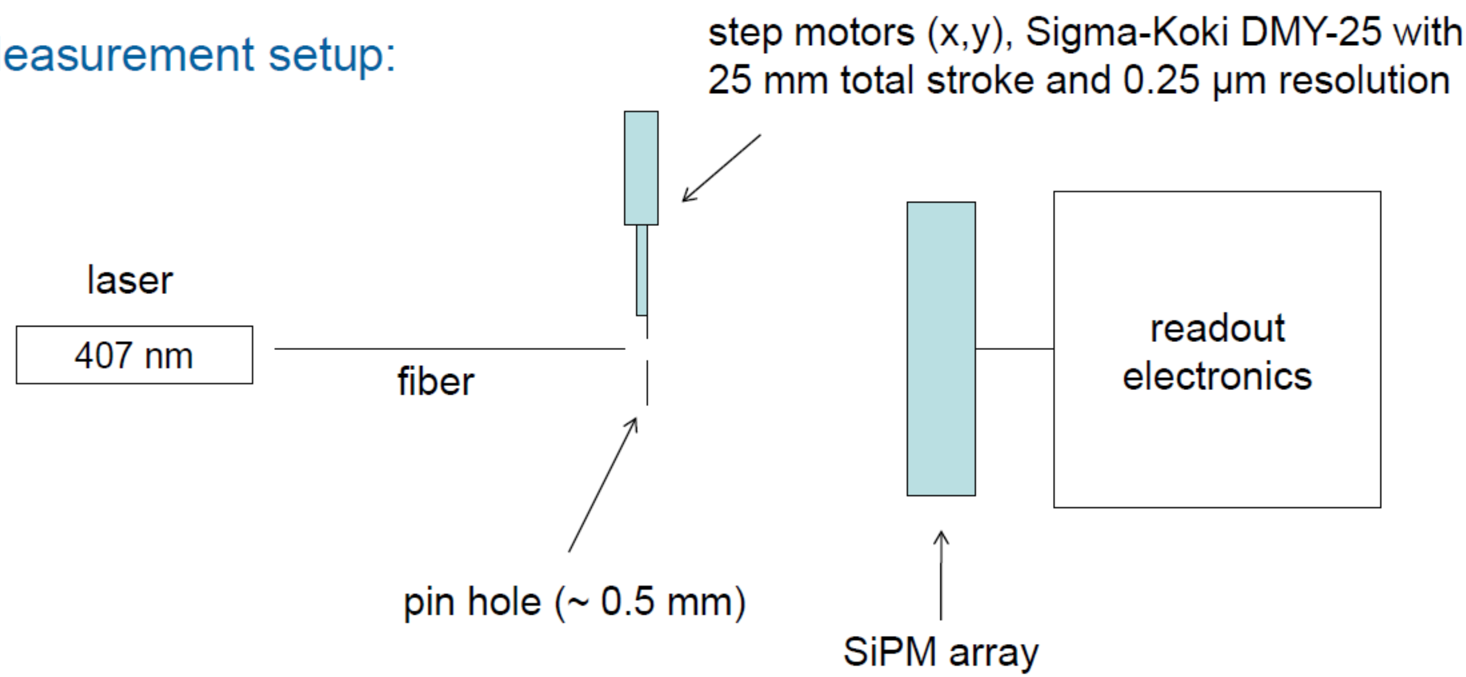
- An array of suitable light guides placed on top of the detectors leads to
  → increased geometric acceptance
  → increased signal to noise ratio
  (dark count not affected by light guides)
- The light concentrator is made out of brass, the funnels were produced by electro-erosion. Then the plate has been chrome-plated.
- It consists of 64 regularly arranged pyramid-shaped funnels with round edges and has been designed to be used with an array of 3x3 mm² SiPMs.
- The dimensions are:
  Total: 65 mm x 65 mm x 4.5 mm
  Entrance window: 7 mm x 7 mm
  Exit aperture: 3 mm x 3mm



- Simple geometry, robust, easy to fabricate

Efficiency measurements

- Measurement setup:



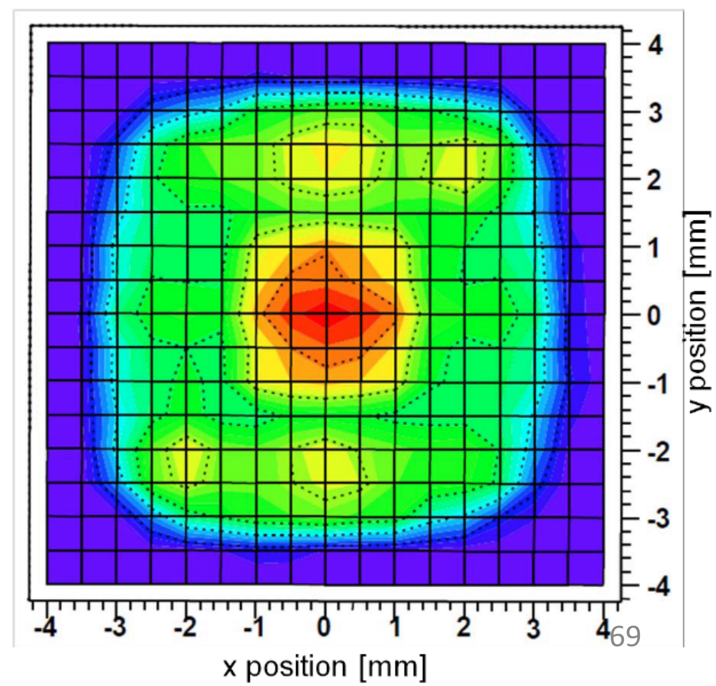
- The measurements were done inside a dark box
- Laser light was coupled into an optical fiber as a first collimator (single mode, 3.2 μm core diameter, angular acceptance ± 7°)
- We used an additional pin hole collimator to restrict the angle further
- The fiber and collimator can be moved in 2 dimensions in order to scan the light concentrator
- The distance between fiber and detector is ~ 1.5 mm
- The beam diameter at the detector is ~ 1 mm
- The setup was kept at a stable temperature of 15°C

Conclusions

- Basically the SiPM array is working very well
- The light concentrator is behaving more or less as expected

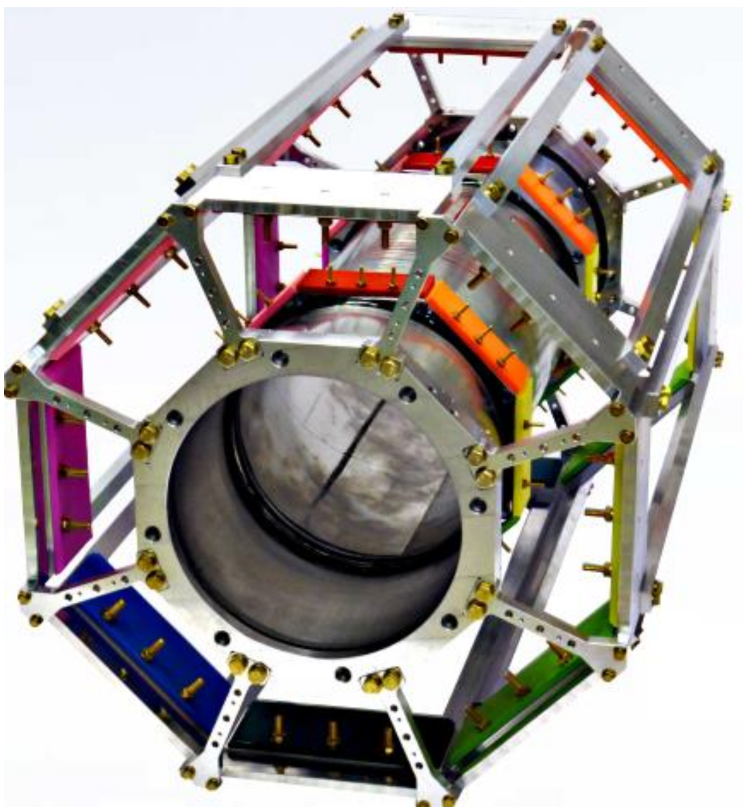
- Explanations for unexpected behavior:
  - no plateau: beam size (1 mm)
  - "hot spots": fabrication defects, inhomogeneous surface, oval beam profile (asymmetry of "hot spots")
  - minima at transitions: defects, oxidation or dust at the edges, no perfect matching between light guide and SiPM, incident angles not exactly 0°

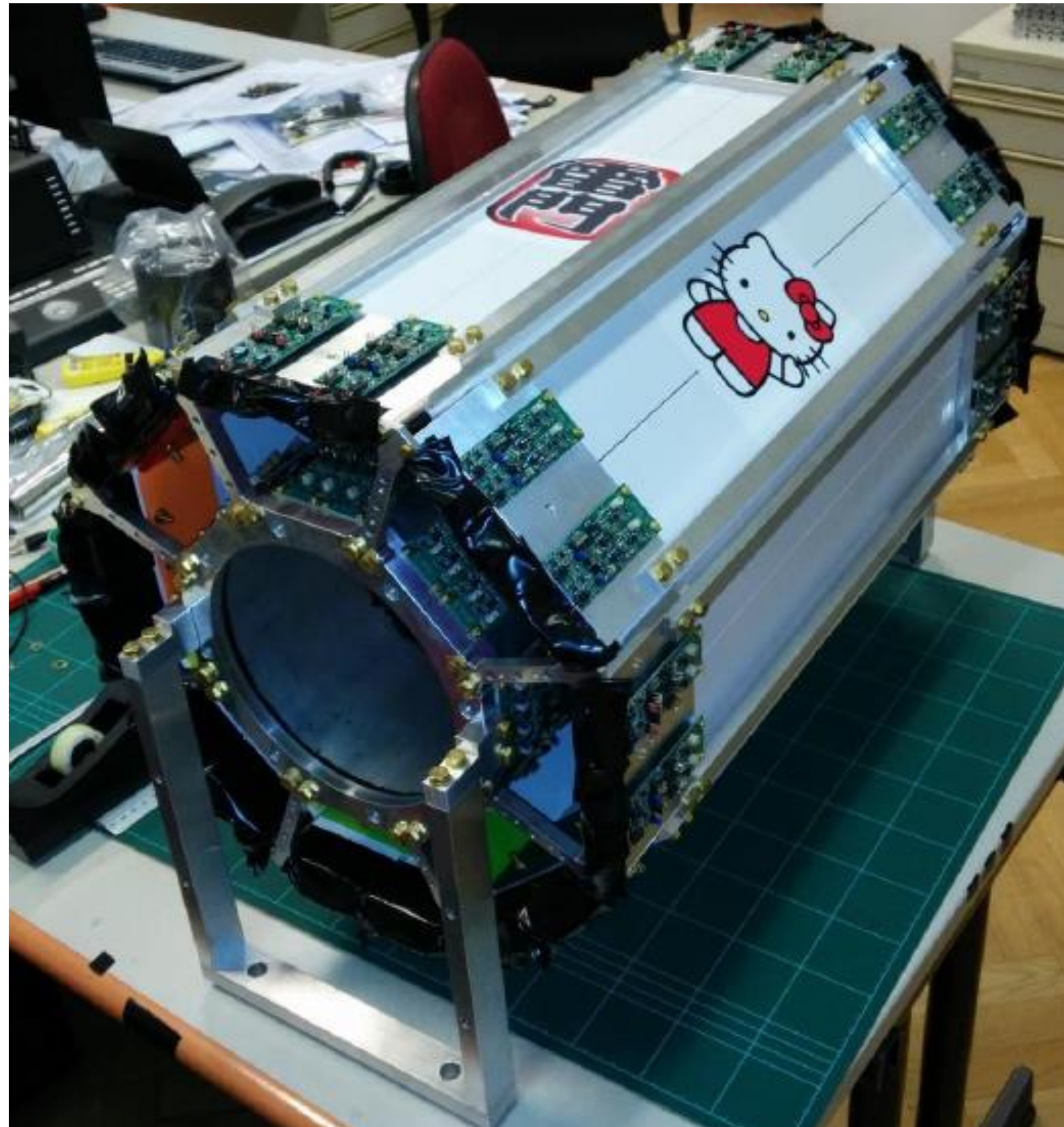
- Comparison with simulations:
  From the measurements we find an average light collection efficiency of 3.1 (57%), which is in very good agreement with the simulated value of 2.8 (52%).
  This is a first and rough estimation but shows that the light concentrator is working very well.



Application of SiPMs – H^{bar}-Hodoscope

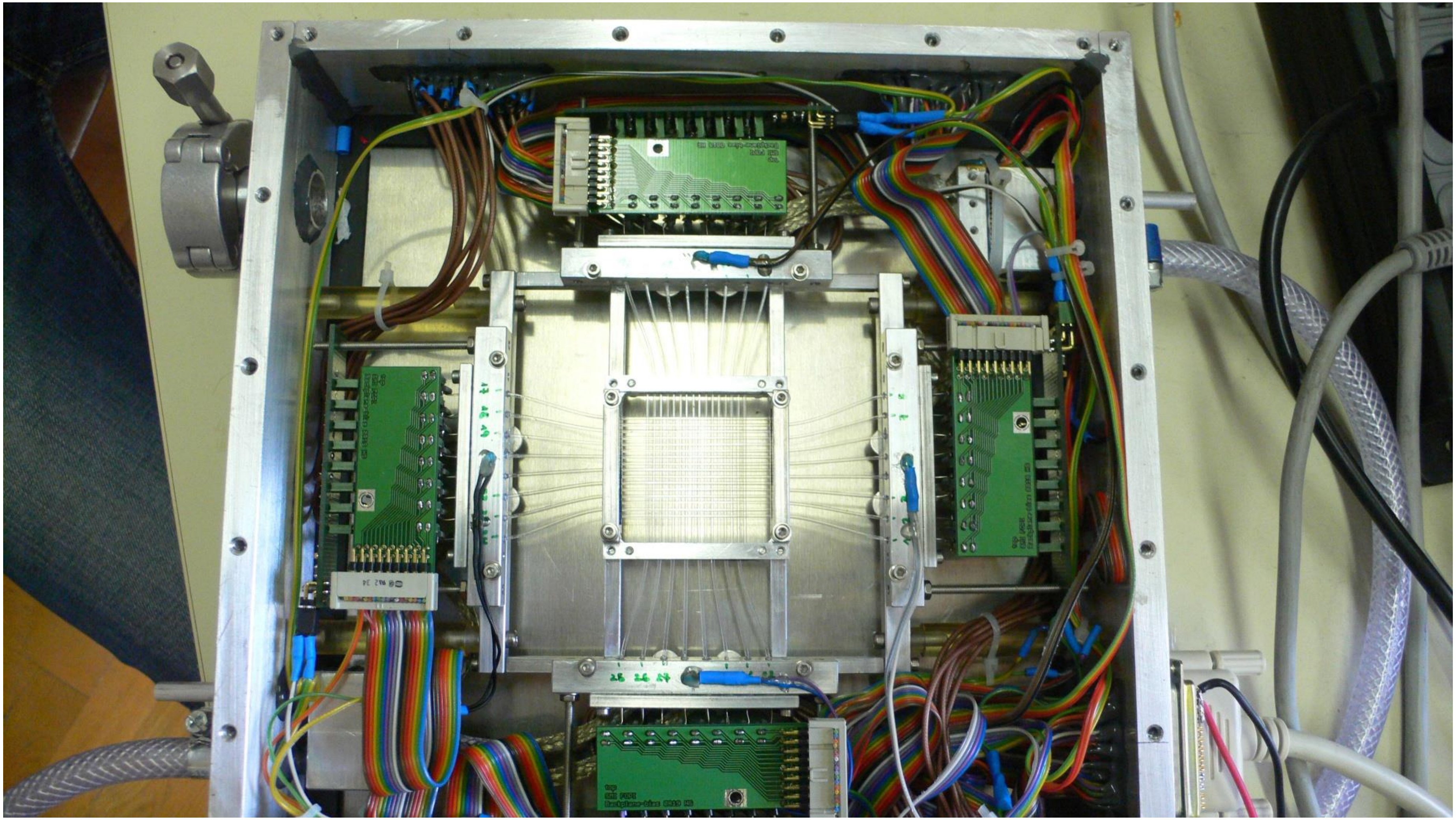
octagonal hodoscope
2 layers, composed of
32 scintillating bars



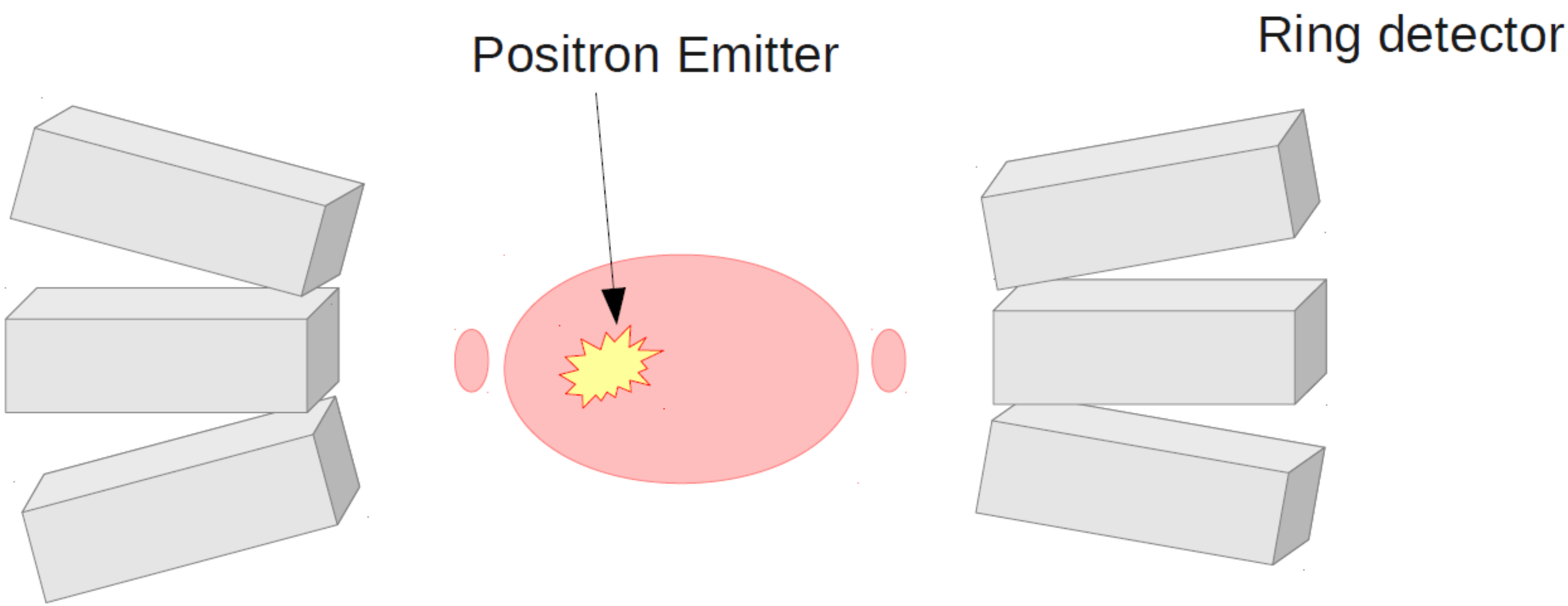


Application of SiPM

Beam profile monitor for FOPI (3 GeV/c protons)

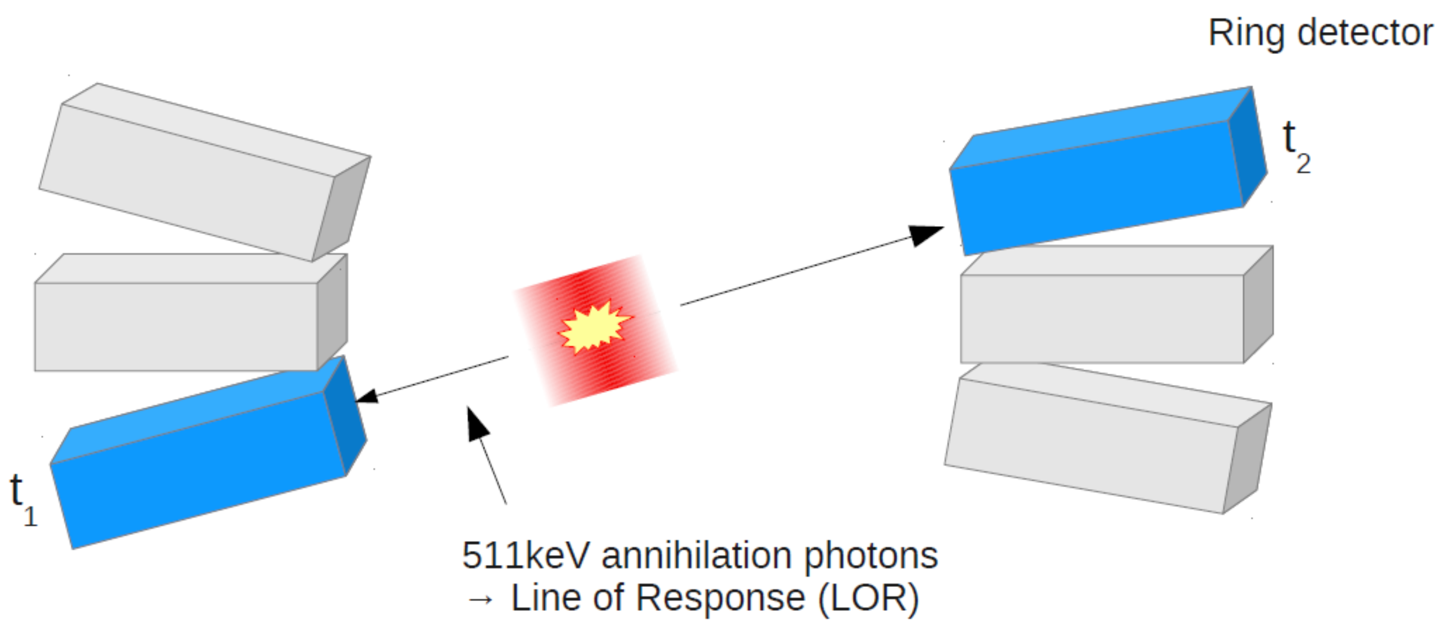


Positron Emission Tomography - PET
Improvements due to Time-of-Flight measurement



- Tracer (positron emitter) is injected into patient
- Accumulates in region of interest (e.g. High metabolism)
- Emitted positrons annihilate with electrons of tissue

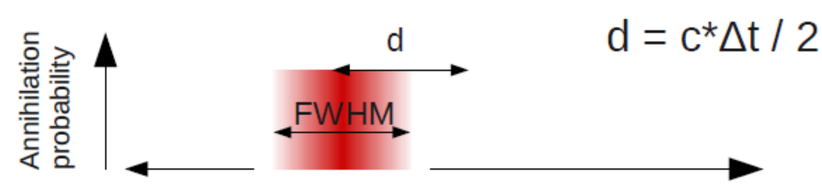
Time-of-Flight for PET



PET

Annihilation Probability equally distributed over LOR

TOF-PET

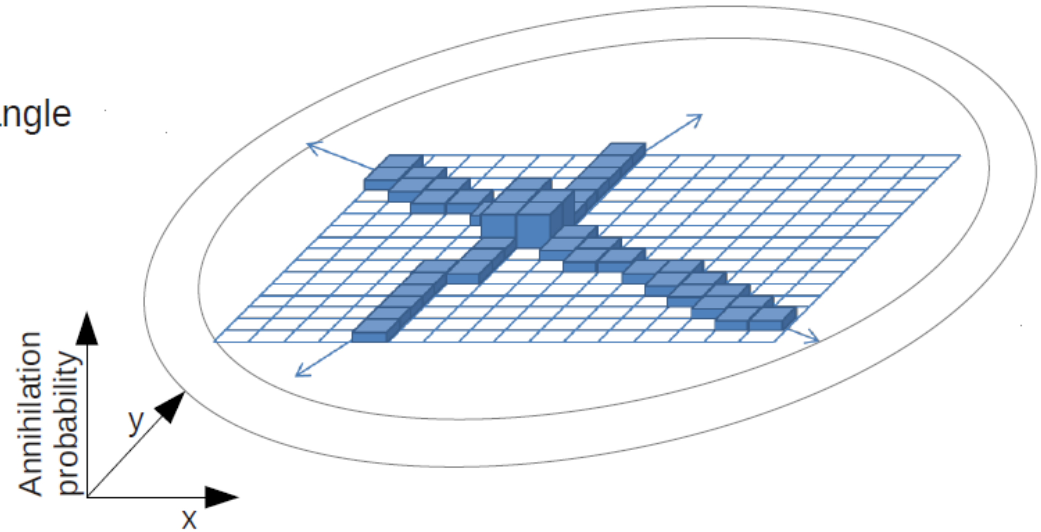


Annihilation can be localized on LOR

Motivation: PET + Time of flight
Positron Emission Tomography

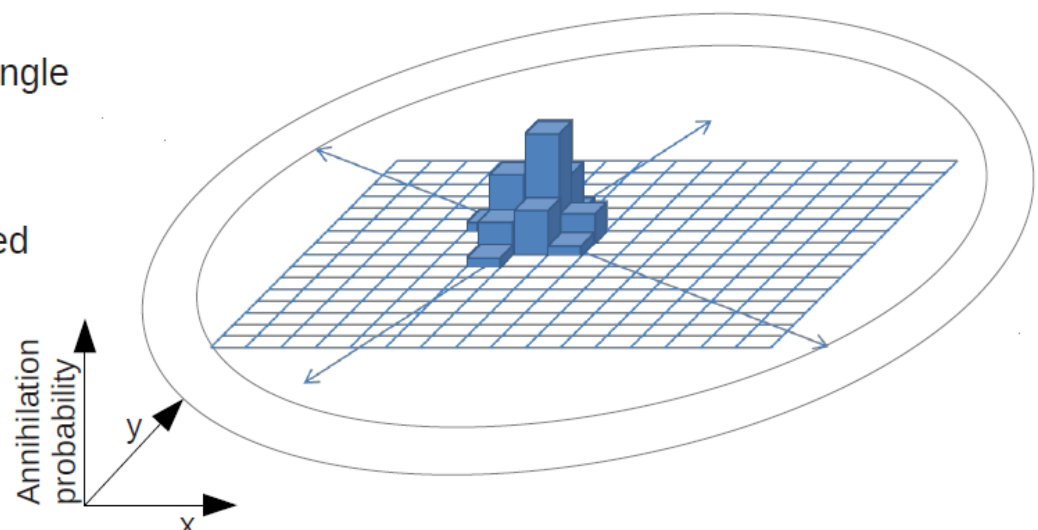
PET

- Electron – positron annihilation
- Emission of two photons with 511keV at rel. angle of 180°
- The two photons are detected by a ring of detectors (within coinc. time window)
- A LOR is drawn between the responding detectors
- Statistics → Image reconstruction



TOF - PET

- Electron – positron annihilation
- Emission of two photons with 511keV at rel. angle of 180°
- The two photons are detected by a ring of detectors
- Arrival time of the 511keV photons is measured
- LOR between responding detectors with a probability distribution determined by the time difference of the photon detection
  → **Need less statistics**
  → **Faster image reconstruction**
  → **Less artifacts**



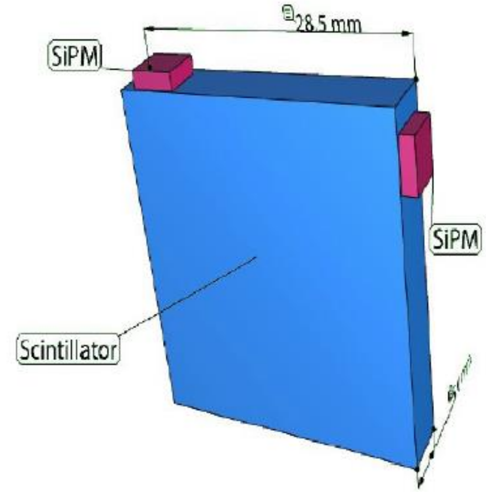
SciTil R&D for PANDA

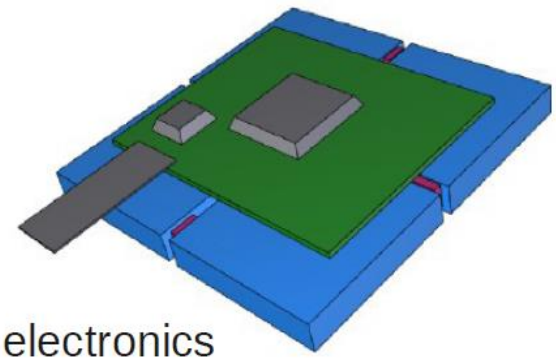
- **Minimum material:**
  - 2% of a radiation length
  - 2 cm radial thickness (including readout and support)

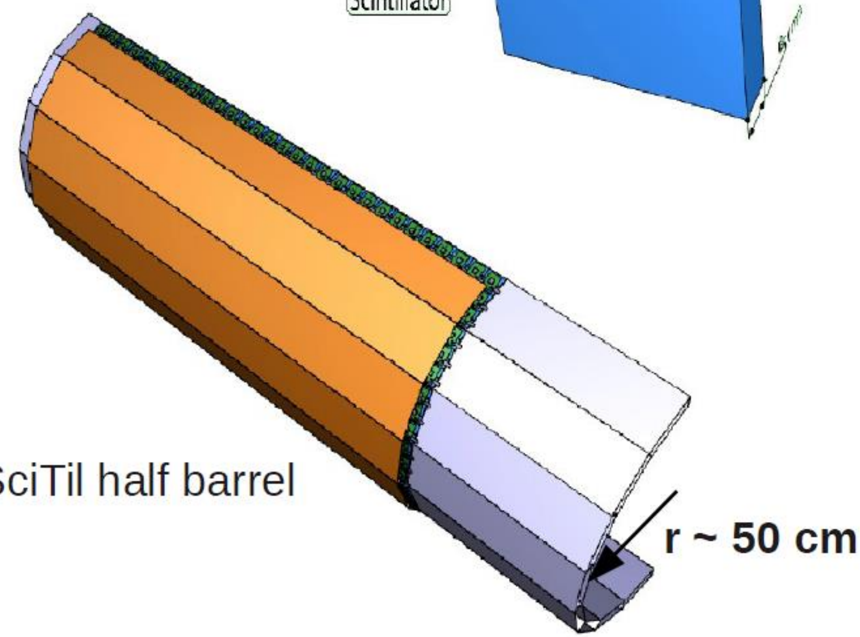
- **Excellent time resolution:**
  - $\sigma_t \approx 100$ ps

SciTil detector layout

- **Small plastic scintillator tiles (~ 30 x 30 x 5 mm³)**
- **Detect photons with directly attached Silicon Photomultipliers (SiPMs)**
- **In total about 6000 tiles and 12000 SiPMs**




4 tiles with electronics



SciTil half barrel

R&D to optimize sensor/scintillator geometry and configuration (incl. feasibility study)

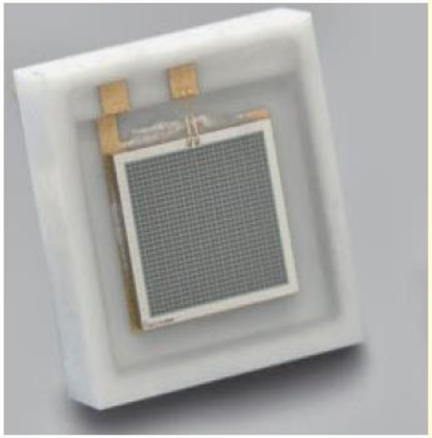
Plastic scintillators for fast timing applications

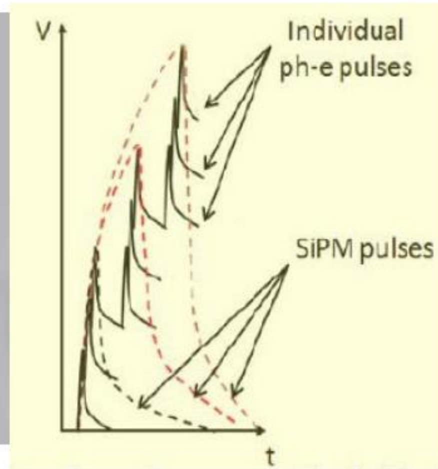
	EJ-232* **NE-111A/BC-422****	**EJ-228** **Pilot-U/BC-418**	**EJ-204** **NE-104/BC-404**	**EJ-200** **Pilot-F/BC-408**
Light yield [% Anthracene]	55	67	68	64
Light yield [photons/MeV]	8,400	10,200	10,400	10,000
Rise time [ns]	0.35	0.5	0.7	0.9
Decay time [ns]	1.6	1.4	1.8	2.1
Wavelen. of Max. Emission [nm]	370	391	408	425
Prize per piece*** (28.5 x 28.5 polished) [EUR]	80	75	65	65

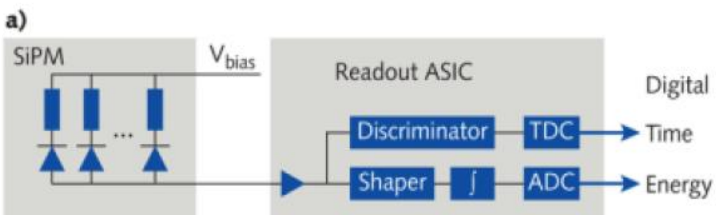
* *Eljen Technology, http://www.eljentechnology.com/*
** *Saint-Gobain Crystals, http://www.crystals.saint-gobain.com/*
*** *Scionix Netherlands, http://www.scionix.nl/*

Analog and digital SiPM

Analog:

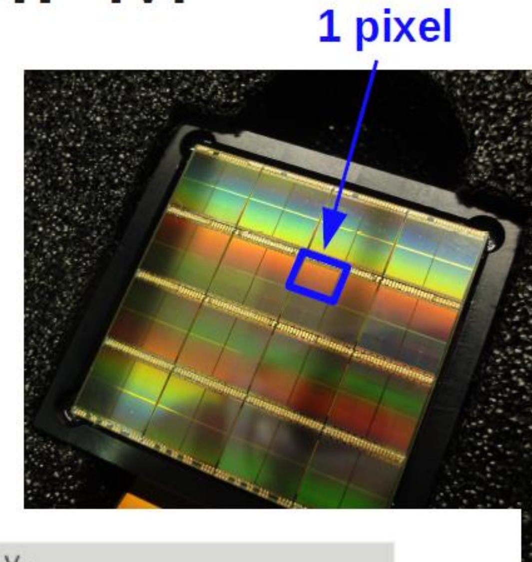


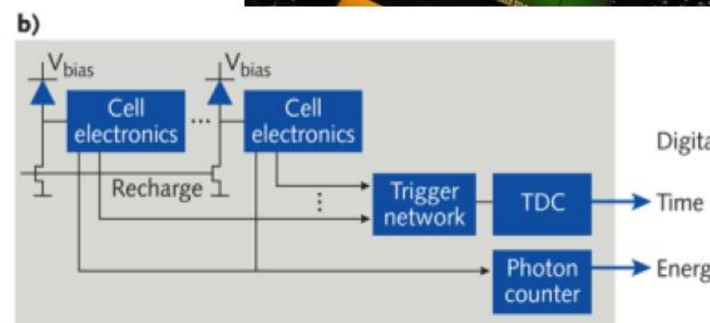




- Array of SPADs (Single Photon Avalanche Diode)
- Few 100 – few 1000 SPADs
- Signal: analog sum of individual pulses
- Pulse amplitude depend on gain/temperature
- **<u>Hamamatsu, Ketek, AdvanSiD, SensL,...</u>**

Digital:

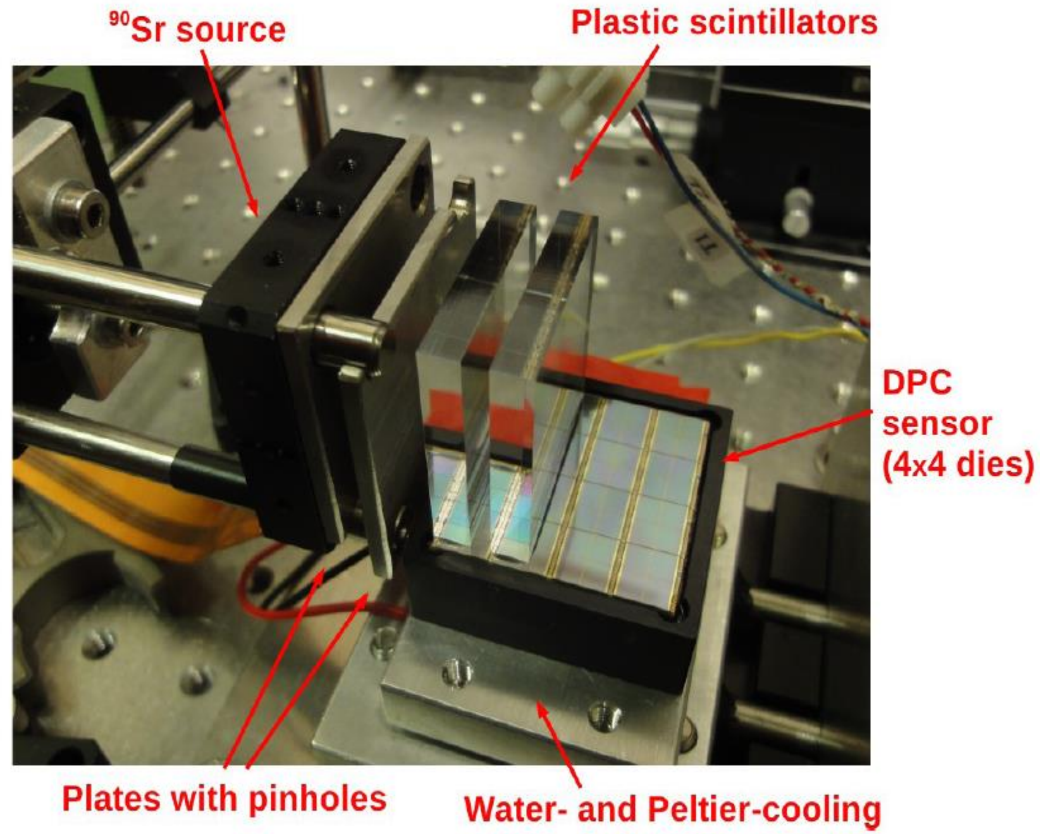


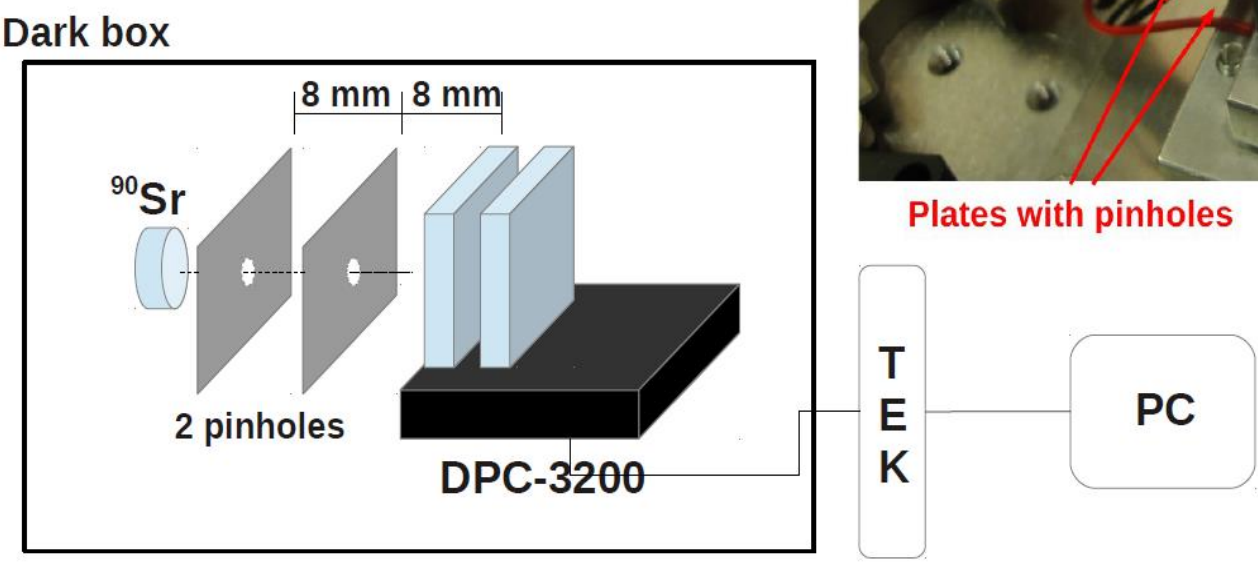


- Array of SPADs
- 3200/6400 SPADs per pixel
- Signal: digital sum of trigger bins (breakdowns) & digital time stamp from TDC
- Pulse amplitude is not relevant
- **<u>Philips</u>**

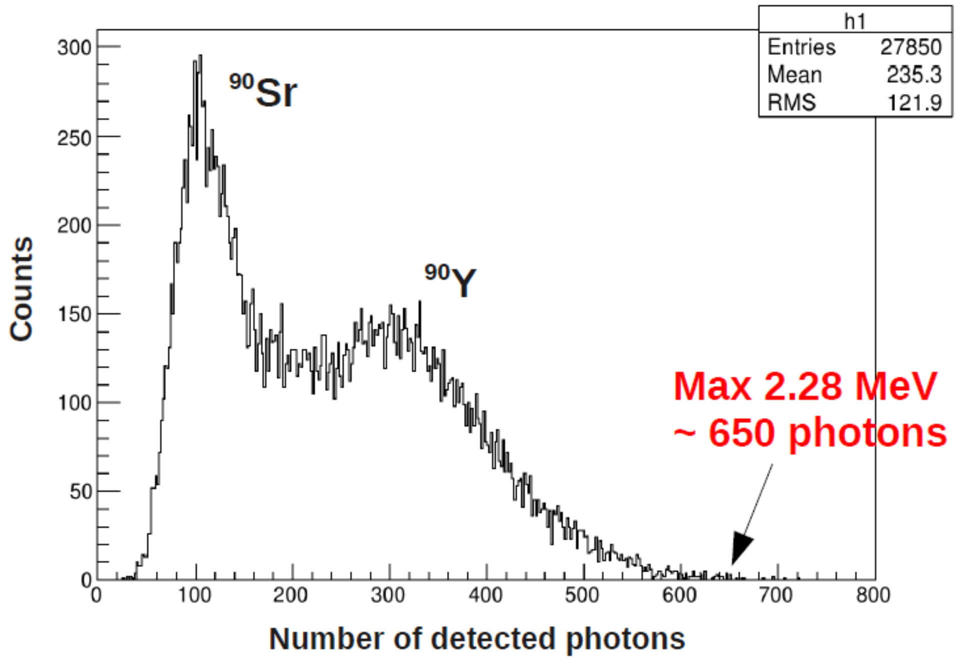
R&D with digital SiPM (DPC) – experimental setup

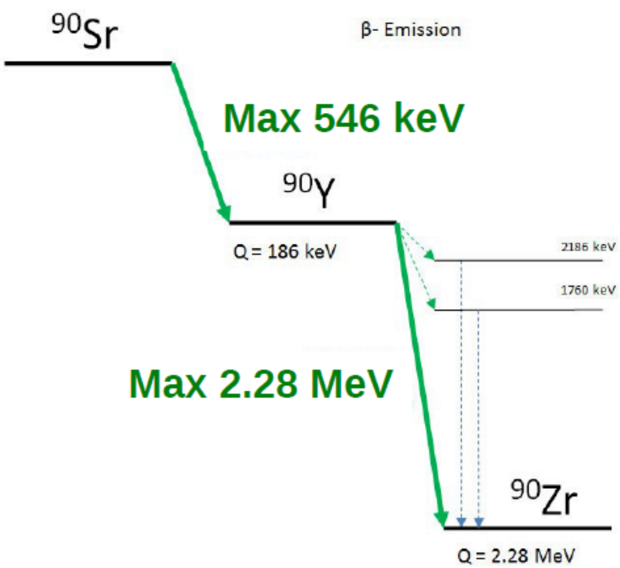
- **Coincidence using two scintillator tiles**
- **e^- from ^{90}Sr source**
- **Pinholes (Al) to define beam direction**
- **Philips digital SiPM (Digital Photon Counter – DPC) as detector**





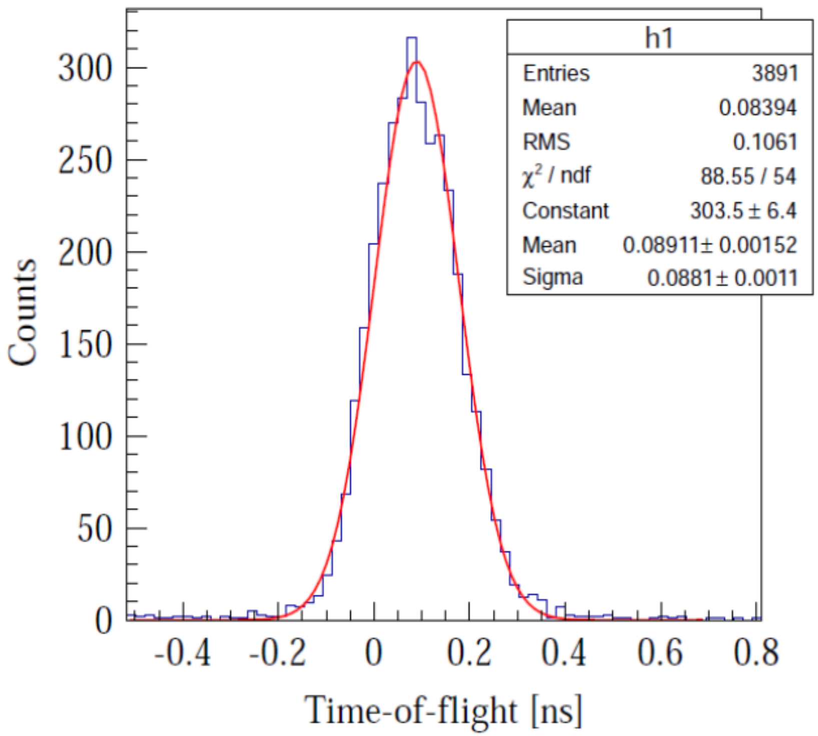
Photon spectrum





- **Strontium spectrum as expected using a plastic scintillator from Eljen (EJ-228) with a size of 30 mm x 30 mm x 5 mm and the DPC**
- **For further measurements: cut on the spectrum (ΔE > 0.8 MeV)**
- **A minimum ionizing particle (MIP) in PANDA will deposit about 1 MeV in the SciTil detector**

Time resolution



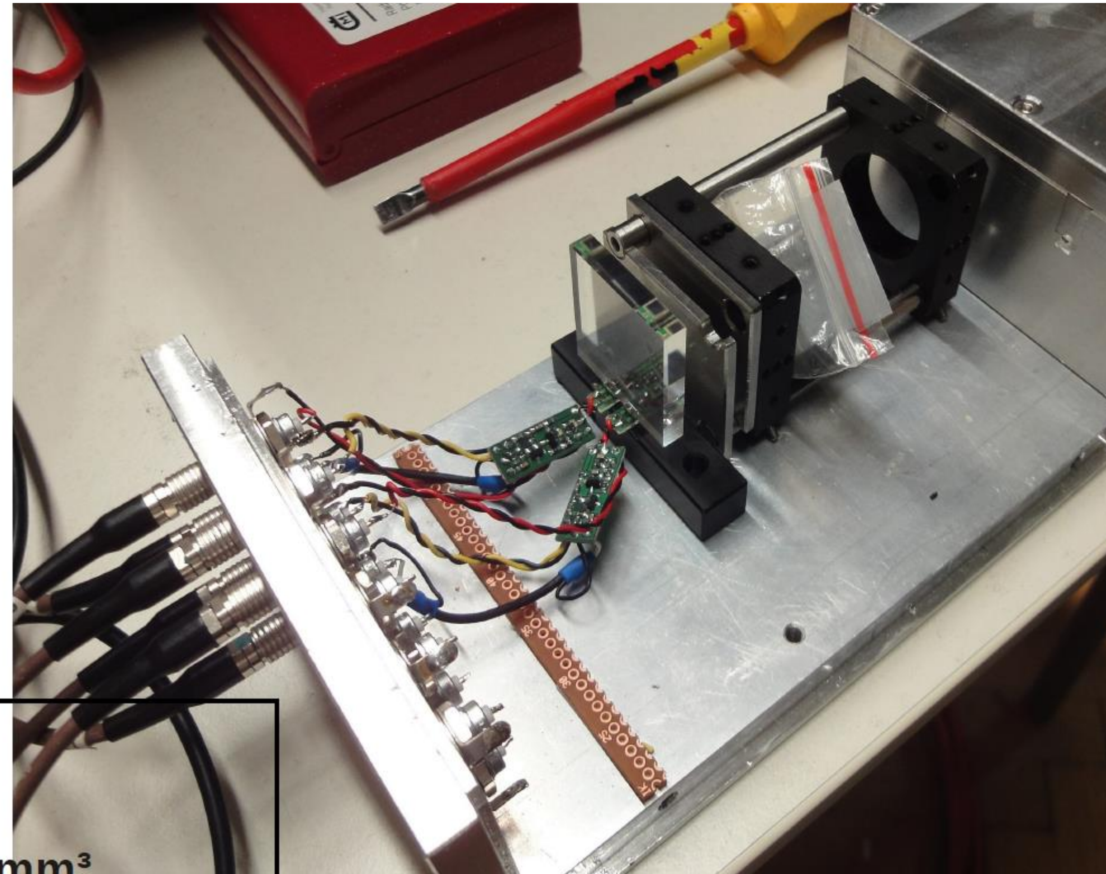
Since we have two identical scintillator tiles we can estimate the time resolution of a single tile by using the time-of-flight (TOF) resolution.

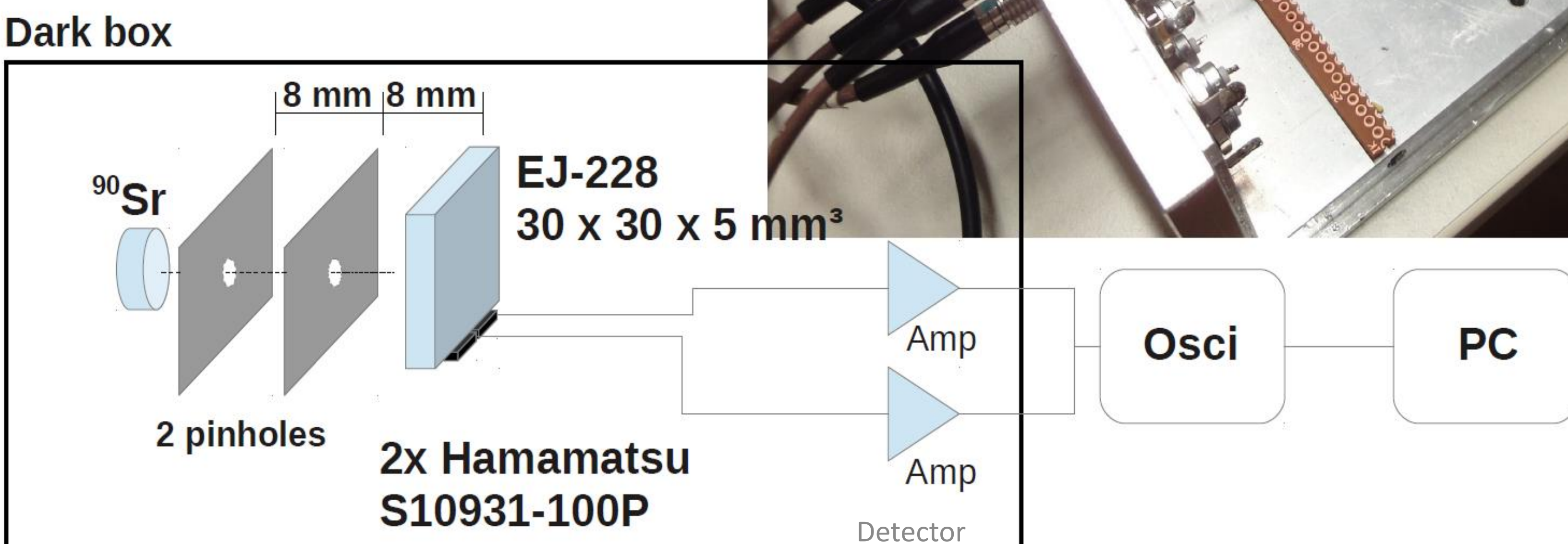
$\sigma_{tile} \sim \sigma_{TOF}/\sqrt{2} \sim 62$ ps

Time resolution with DPC about 60 ps.

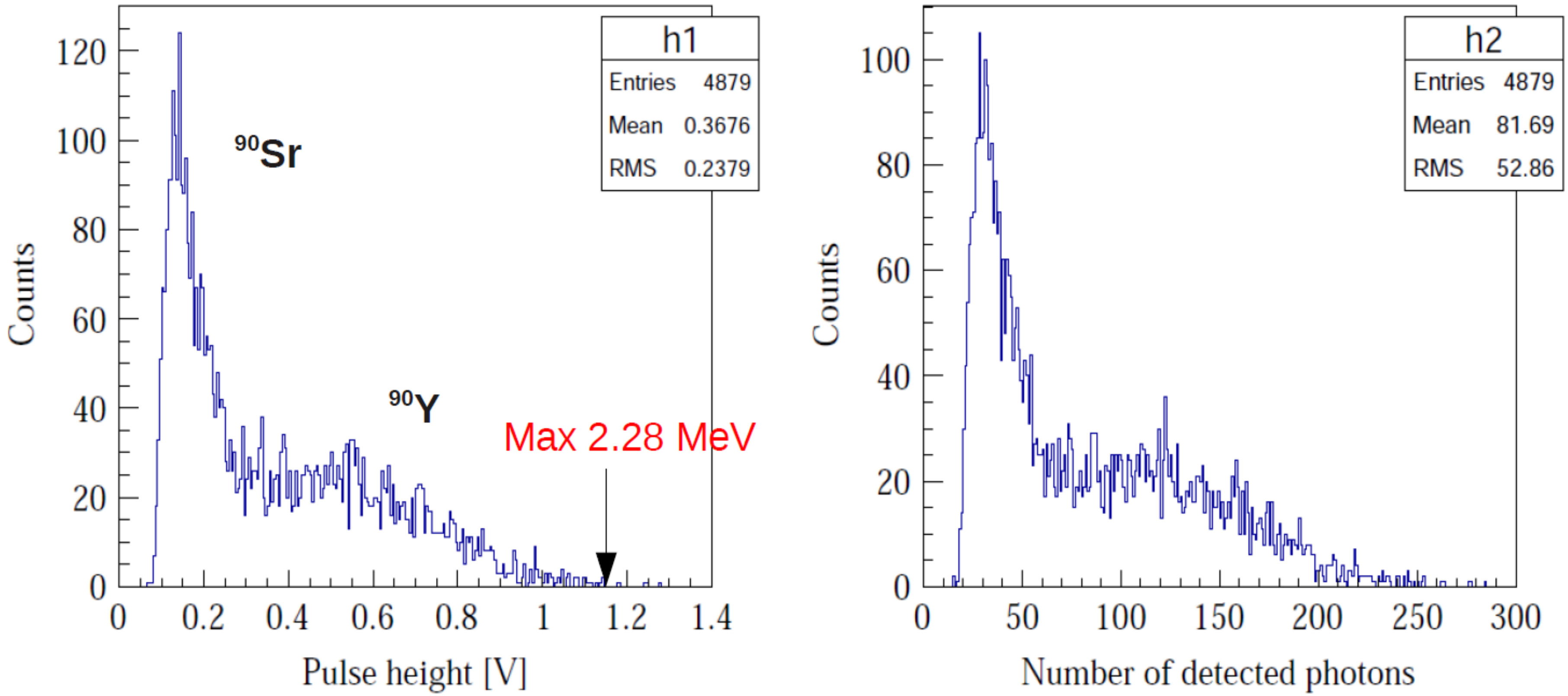
R&D with conventional SiPM – experimental setup

- Now only one scintillator tile
- e^- from ^{90}Sr source
- Pinholes (Al) to define beam direction
- Hamamatsu 100P as detector



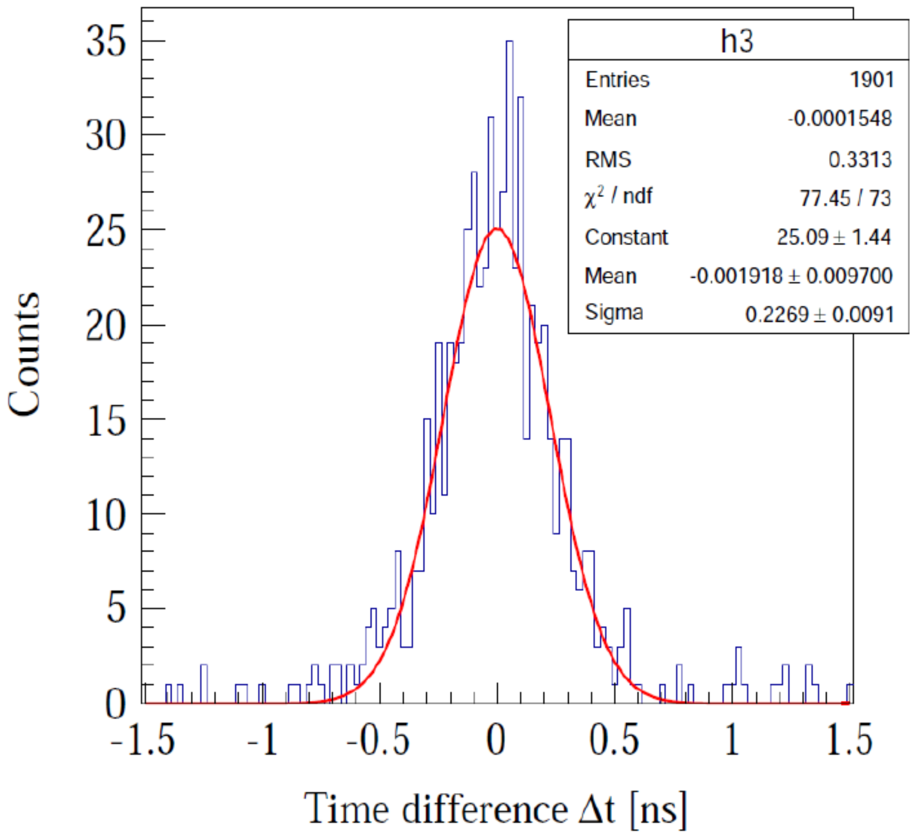


Conventional SiPM – pulse height spectrum



- **^{90}Sr spectrum as expected using a plastic scintillator from Eljen (EJ-228) with a size of 30 mm x 30 mm x 5 mm and SiPM from Hamamatsu**
- **Factor 3 less photons compared to DPC due to smaller sensitive area**
- **For further measurements: cut on the spectrum (ΔE > 0.8 MeV)**

Time resolution



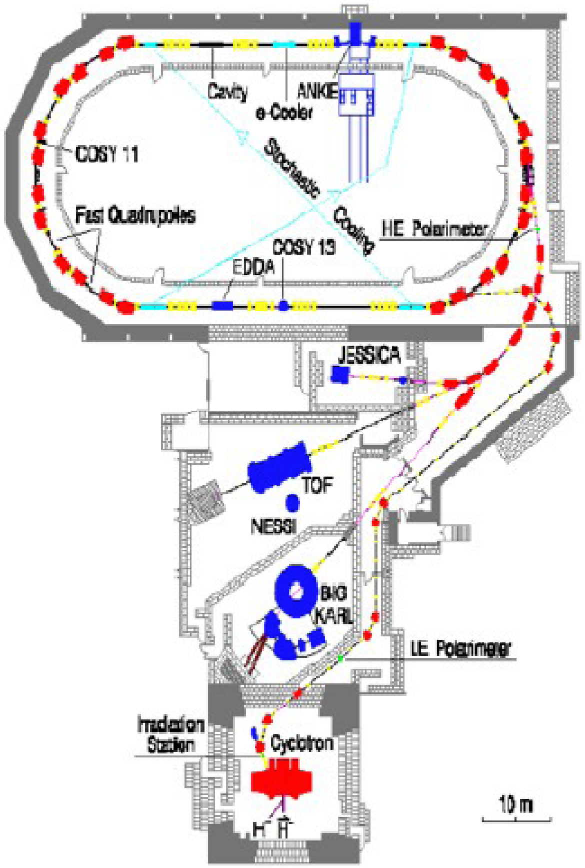
- **Data taking with oscilloscope**
- **Offline waveform analysis**
- **Software threshold: best results at 6% of the amplitude (CFD)**
- **Energy cut: ΔE > 0.8 MeV (MIP) (Amplitude > 0.2 V)**

- **Estimation of the time resolution of single tile readout with two SiPM from time difference:**

$$\sigma_{tile} \sim \sigma_{diff}/2 \sim 113 \text{ ps}$$

Time resolution with conventional SiPM about 110 ps.
Potential for improvement (SiPM type, operating conditions, …)

Test beam at COSY (FZ Jülich)



Facts:

- FZ-Jülich, COSY-JESSICA external beam line
- Week no. 5 and 6, 2014 (Jan 27 to Feb 9, 2014)
- During week: beam during night (9 p.m. - 8 a.m.)
- On weekends: 24 hours
- Beam: 2.7 GeV/c and 1.5 GeV/c protons
- Intensity: ~ 10^4 – 10^5 Hz
- Defocused beam: ~ 5 cm x 5 cm

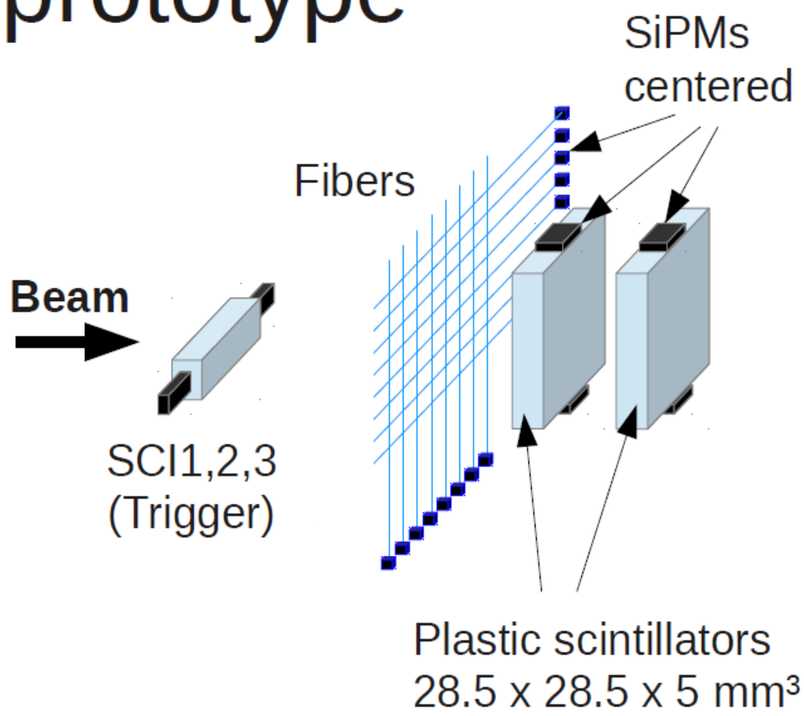
Activities:

- EtaPrime Experiment (GSI):
  - Cherenkov counters (mini-HIRAC, HIRAC, TORCH)
  - Multi-wire drift chambers (MWDC)
  - Time-projection chambers (TPC)
  - Plastic scintillators (SCIs)

- 3 SciTil prototypes:
  - SMI prototype: SciTil + SiPM
  - SMI + Philips prototype: SciTil + DPC (Digital Photon Counter)
  - Erlangen prototype: SciRod + SiPM

The SciTil-SiPM prototype

Setup:
- **Scintillating fiber grid for position resolution in x and y: 8 + 8 fibers, 4 mm pitch**
- **Fibers are readout with 1 x 1 mm² SiPMs**
- **2 SciTil layers: plastic scintillators readout with two 3 x 3 mm² SiPMs each**
- **No cooling: room temperature ~ 15 °C**



SiPMs tested (most promising):

HPK MPPC S12572-33-050P (low afterpulse)
HPK MPPC S12572-33-025C (low afterpulse)
Ketek PM3350TS (low crosstalk)
Ketek PM3360TS (low crosstalk)

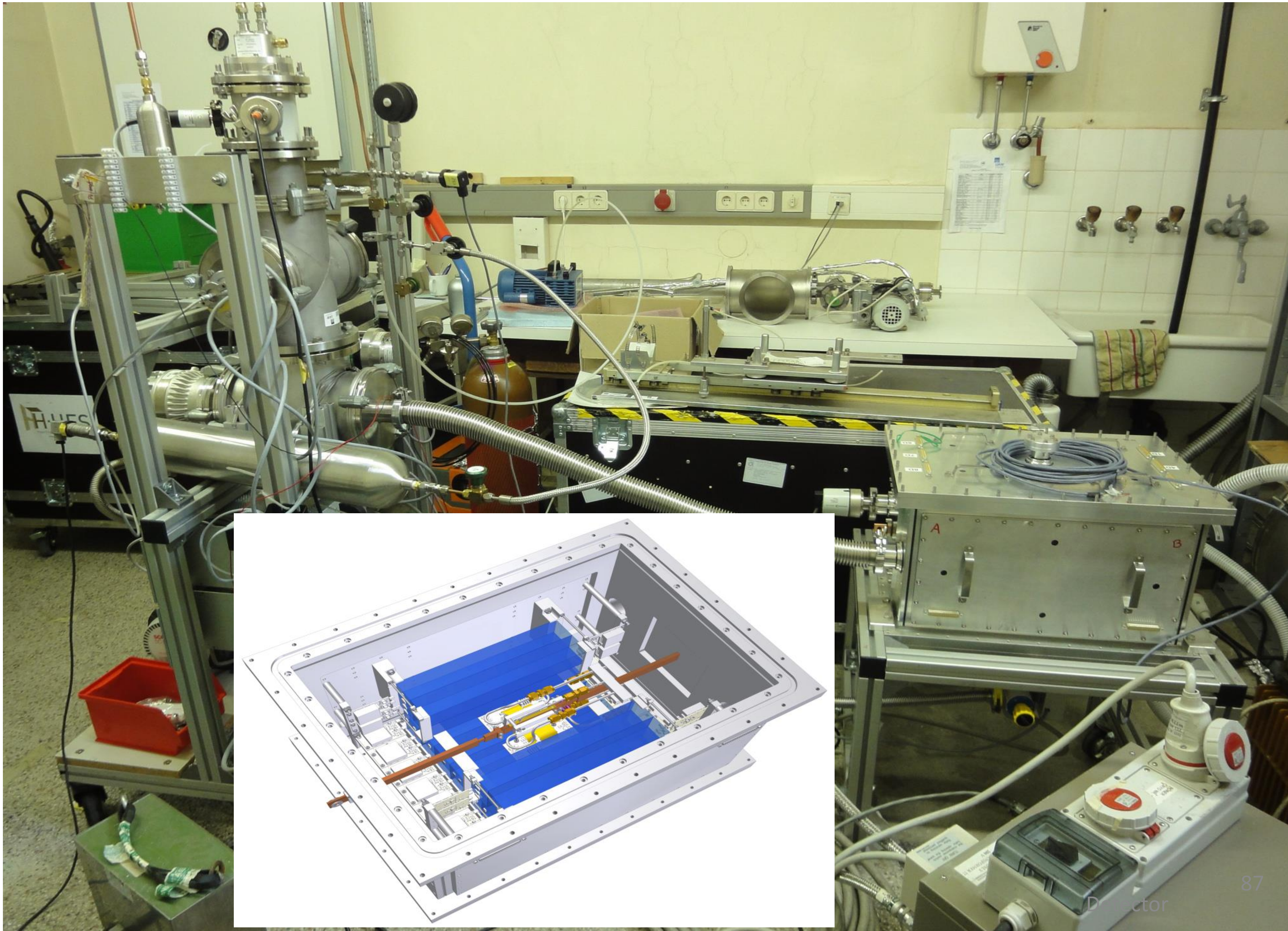
Scintillators tested (most promising):

	EJ-228 Pilot-U/BC-418	EJ-232 NE-111A/BC-422
Light yield [photons/MeV]	10,200	8,400
Rise time [ns]	0.5	0.35
Decay time [ns]	1.4	1.6
Wavelen. of Max. Emission [nm]	391	370

Goal:

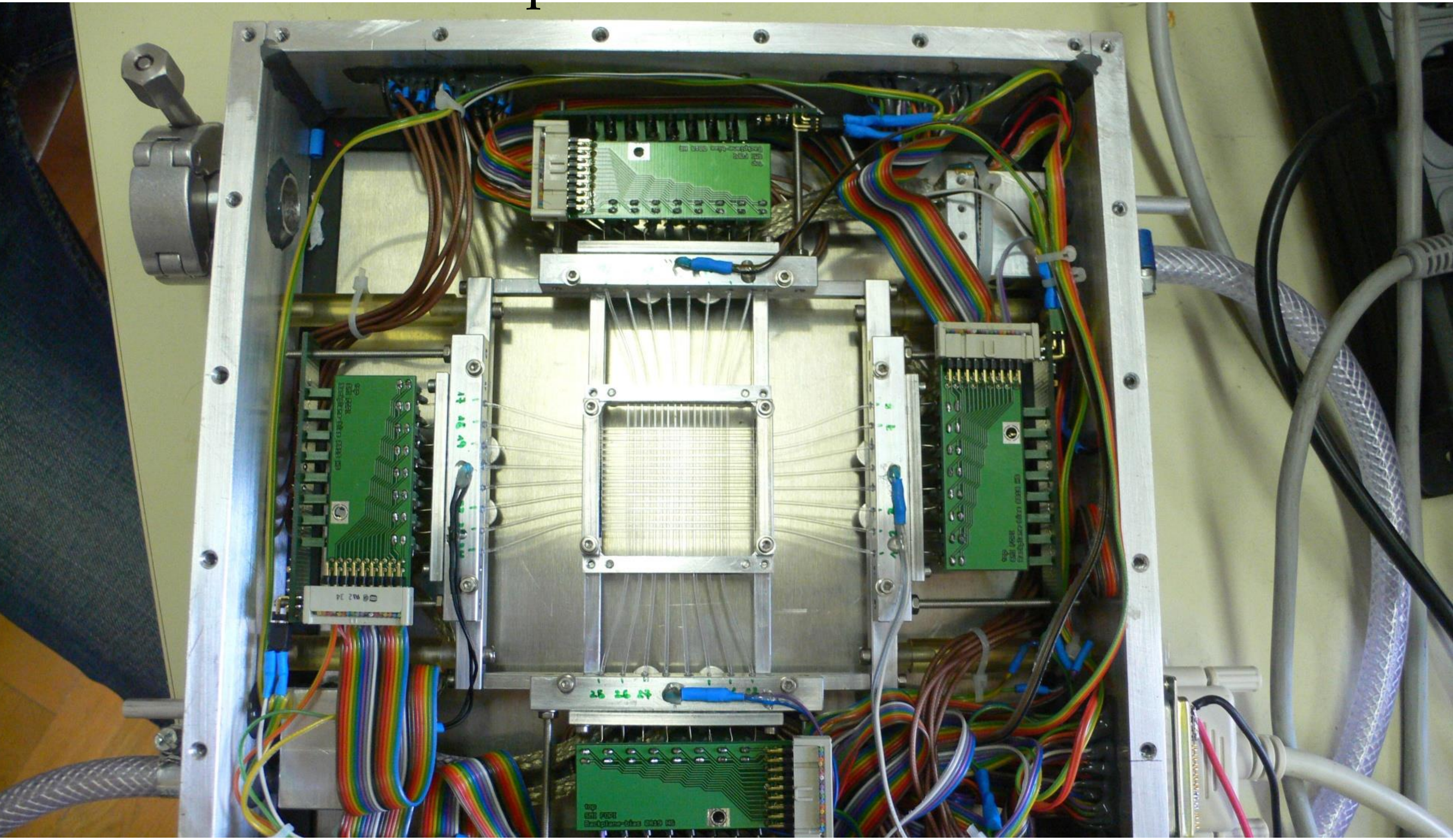
Time resolution of SciTil prototype: σ < 100 ps

VIP-2 apparatus – SiPMs/SDDs



Application of SiPMs

→ π beam profile monitor for FOPI



Radiation protection

Recommended units SI units given by **International Commission on Radiation Units and Measurements (ICRU),** other common units in parentheses:

Unit of activity = becquerel (curie):

1 Bq = 1 disintegration per second [s^{-1}] (= $1/3.7 \times 10^{10}$ [Ci])

Unit of absorbed dose in any material = gray (rad):

1 Gy = 1 joule kg^{-1} (= 10^4 erg g^{-1} = 100 rad)

= 6.24×10^{12} MeV kg^{-1} deposited energy

***Unit of equivalent dose (for biological damage) = sievert (= 100 rem, roentgen* equivalent for man):**

Equivalent dose H_T *[Sv] in an organ T is equal to the absorbed* dose in the organ D_R [Gy] times the radiation weighting factor w_R *(formerly the quality* factor *Q, but* w_R *is "new" defined for the radiation incident on the body).*

$$H_T = w_R \cdot D_R$$

Radiation protection

Radiation weighting factors

Radiation	w_R
X- and γ-rays, all energies	1
Electrons and muons, all energies	1
Neutrons < 10 keV	5
10–100 keV	10
> 100 keV to 2 MeV	20
2–20 MeV	10
> 20 MeV	5
Protons (other than recoils) > 2 MeV	5
Alphas, fission fragments, & heavy nuclei	20

Radiation protection

If there is more than one radiation type present, the sum of the absorbed dose has to be summed up:

$$H_T = \sum_R w_R \cdot D_{T,R}$$

Tissue or organ	Tissue weighting factor, w_T
Gonads	0.20
Bone marrow	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01

The sum of the equivalent doses, weighted by the tissue weighting factors w_T of several organs and tissues of the body that are considered to be most sensitive, is called ***"effective dose" E****:*

$$E = \sum_T w_T \cdot H_T$$

Natural radiation background

Natural annual background, all sources:
Most world areas, whole-body equivalent dose rate ~(0.4 - 4) mSv (40 - 400 mrem), can range up to 50 mSv (5 rem) in certain areas.

U.S. average 3.6 mSv, including 2 mSv from inhaled natural radioactivity, mostly radon and radon daughters.
(Average is for a typical house and varies by more than an order of magnitude. It can be more than two orders of magnitude higher in poorly ventilated mines. 0.1 - 0.2 mSv in open areas).

Cosmic ray background in counters (sea level, mostly muons):
1 $\text{min}^{-1}\,\text{cm}^{-2}$

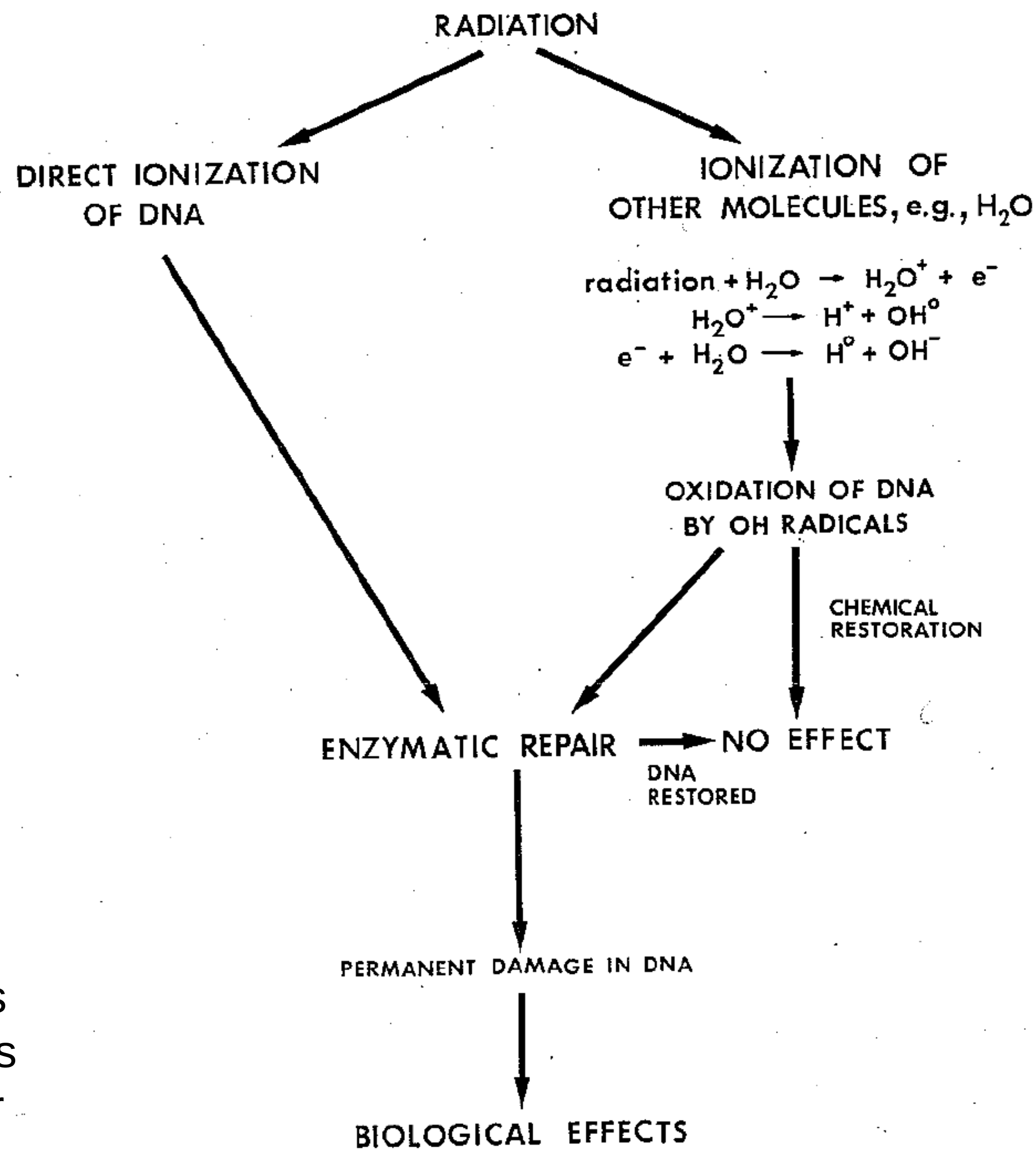
Recommended limits to exposure of radiation workers (whole-body dose):
EU: 20 mSv yr^{-1}
U.S.: 50 mSv yr^{-1} (5 rem yr^{-1})

Average dose per person

Source	Average dose per person (mSv/yr)		
	World population [3.3]	USA [3.4]	Germany [3.5]
Natural sources			
Overall	2.4	2.95	2 – 2.5
Cosmic rays	0.37	0.27	
Terrestial		0.28	≈ 0.1
Inhaled radon		2.0	0.8 – 1.6
Environmental sources			
Nuclear power	0.002		
Baggage check at airport		7 nSv/trip	
Subsonic airplane flight at 8000 m		2 μSv/hr	
Medical exposures			
Diagnosis	0.4 – 1	0.53	0.5 – 1.5
(e.g. 1 chest x-ray)		0.1 mSv/x-ray	
Occupational	0.002	0.1 – 3	

Biological effects

Sequence of events occurring in living matter due to radiation



- genetic effects
- somatic effects
  - cancer
  - sterility

Prompt neutrons at accelerators

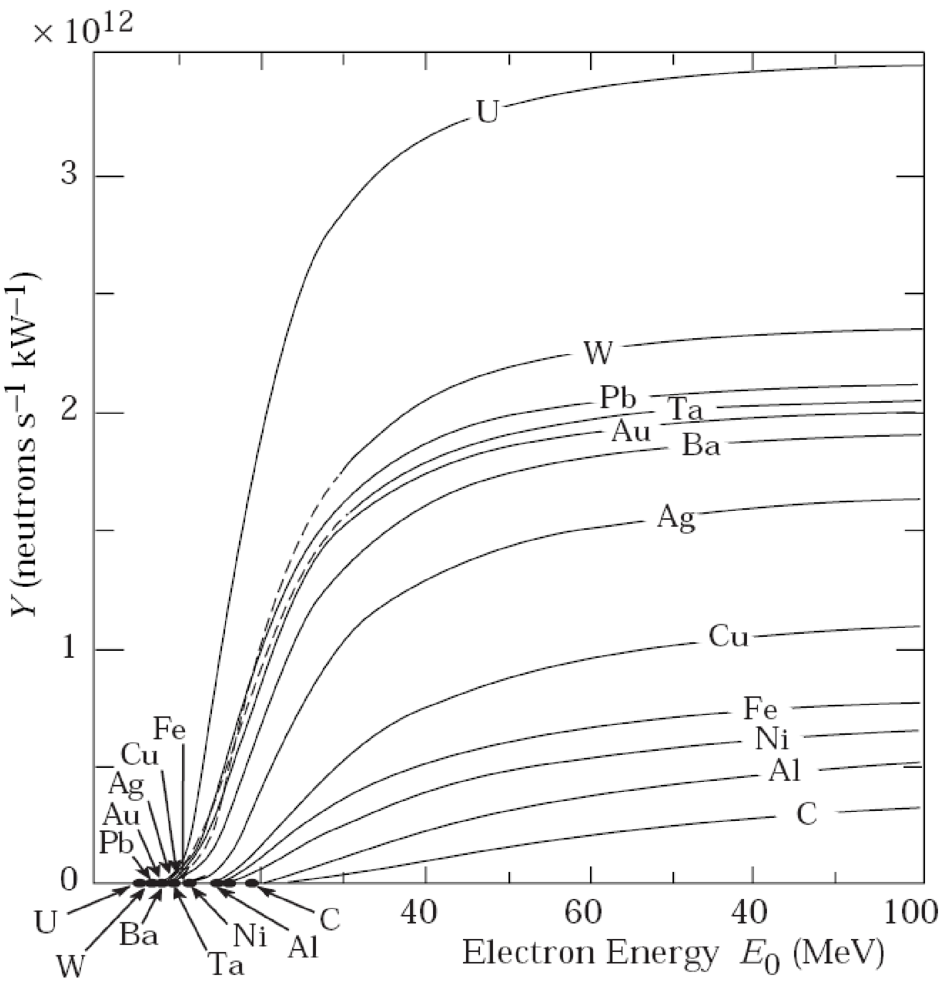
Neutrons dominate the particle environment outside thick shielding (> *1 m) for high* energy (> *a few hundred MeV) electron and hadron accelerators.*

Electron beams:
At electron accelerators neutrons are generated via photo-nuclear reactions from bremsstrahlung photons.

Neutron yields from semi-infinite targets per unit electron beam power, as a function of electron beam energy.

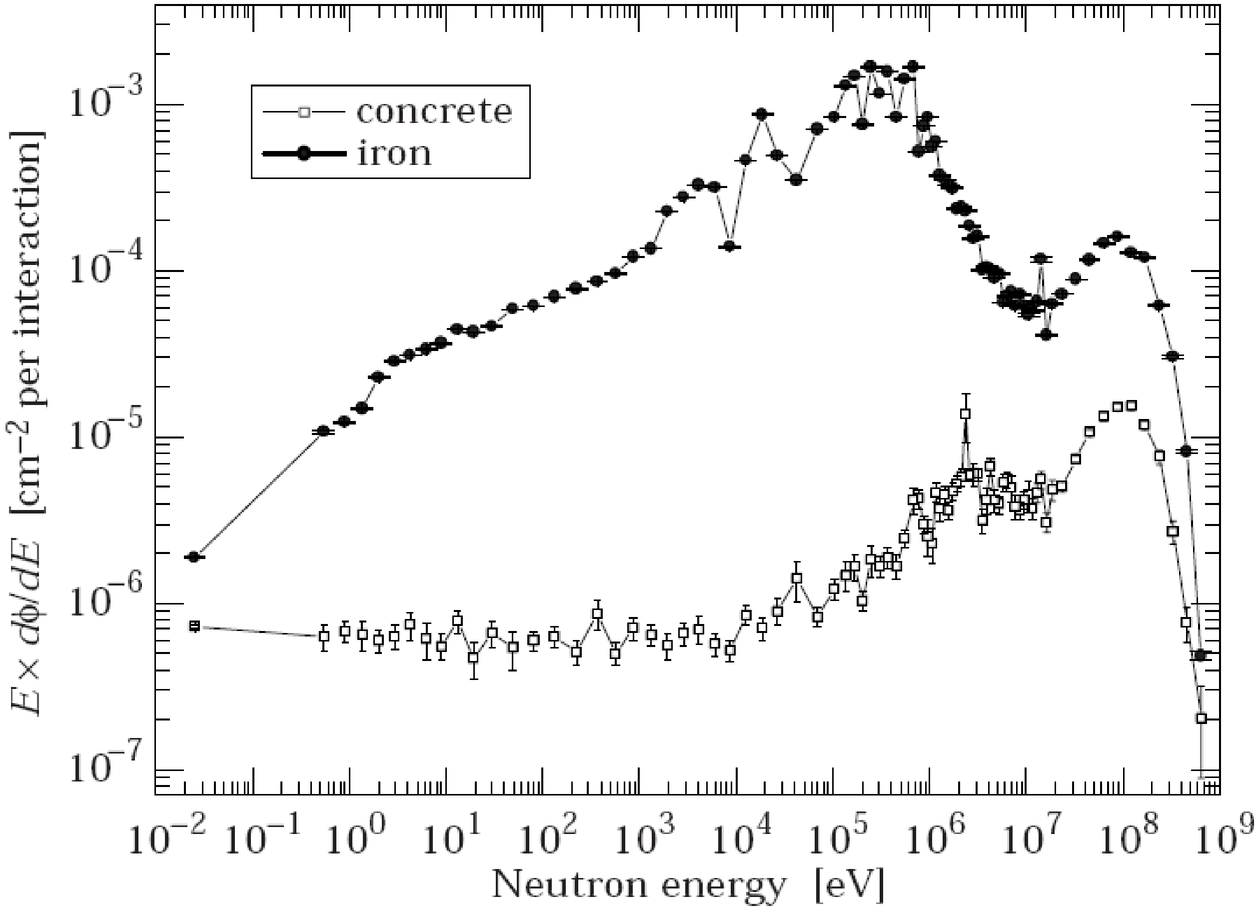
Energy distribution of produced neutrons:

$$\frac{dN}{dE_n} = \frac{E_n}{T^2} e^{-E_n/T}$$

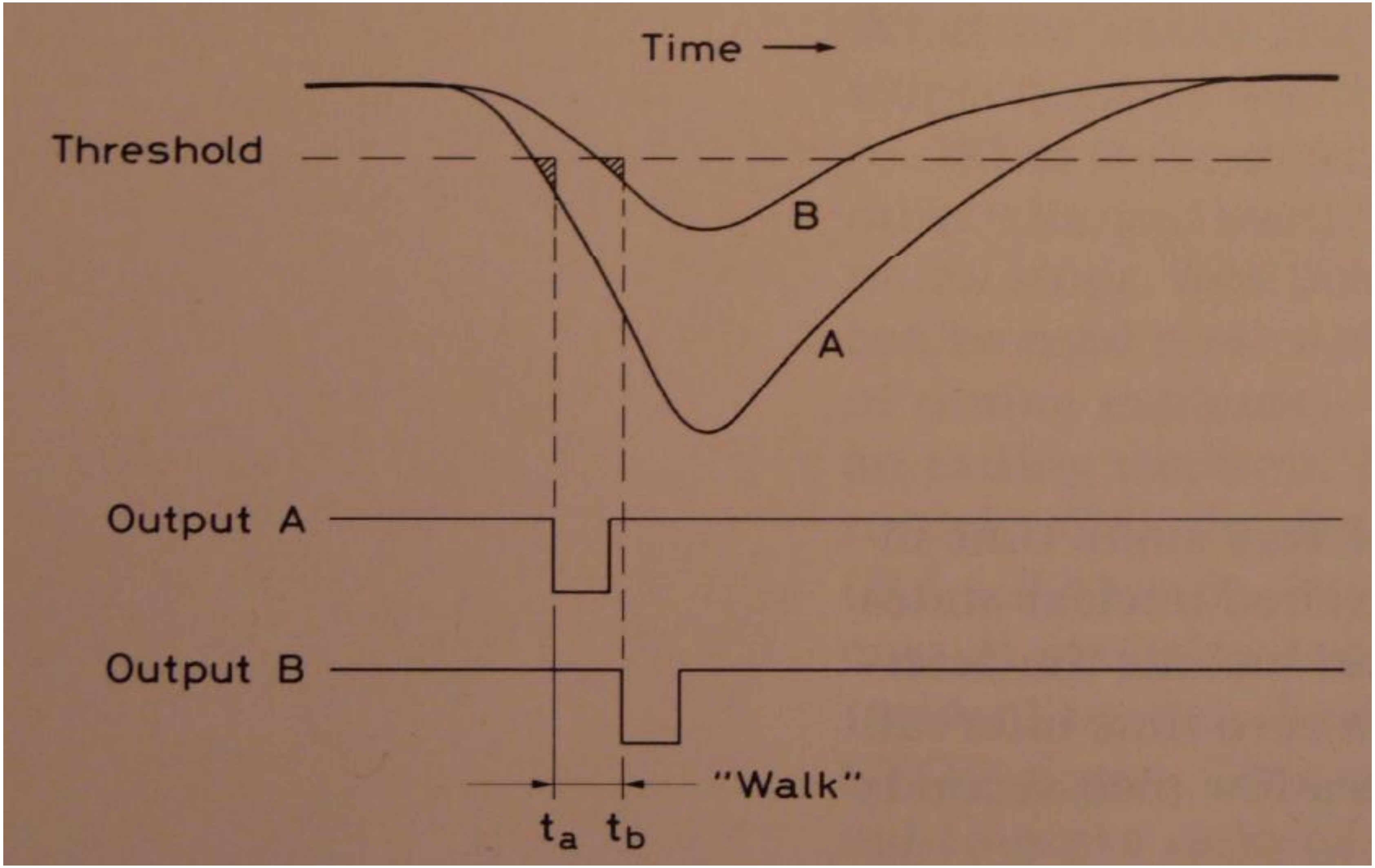


Prompt neutrons at accelerators

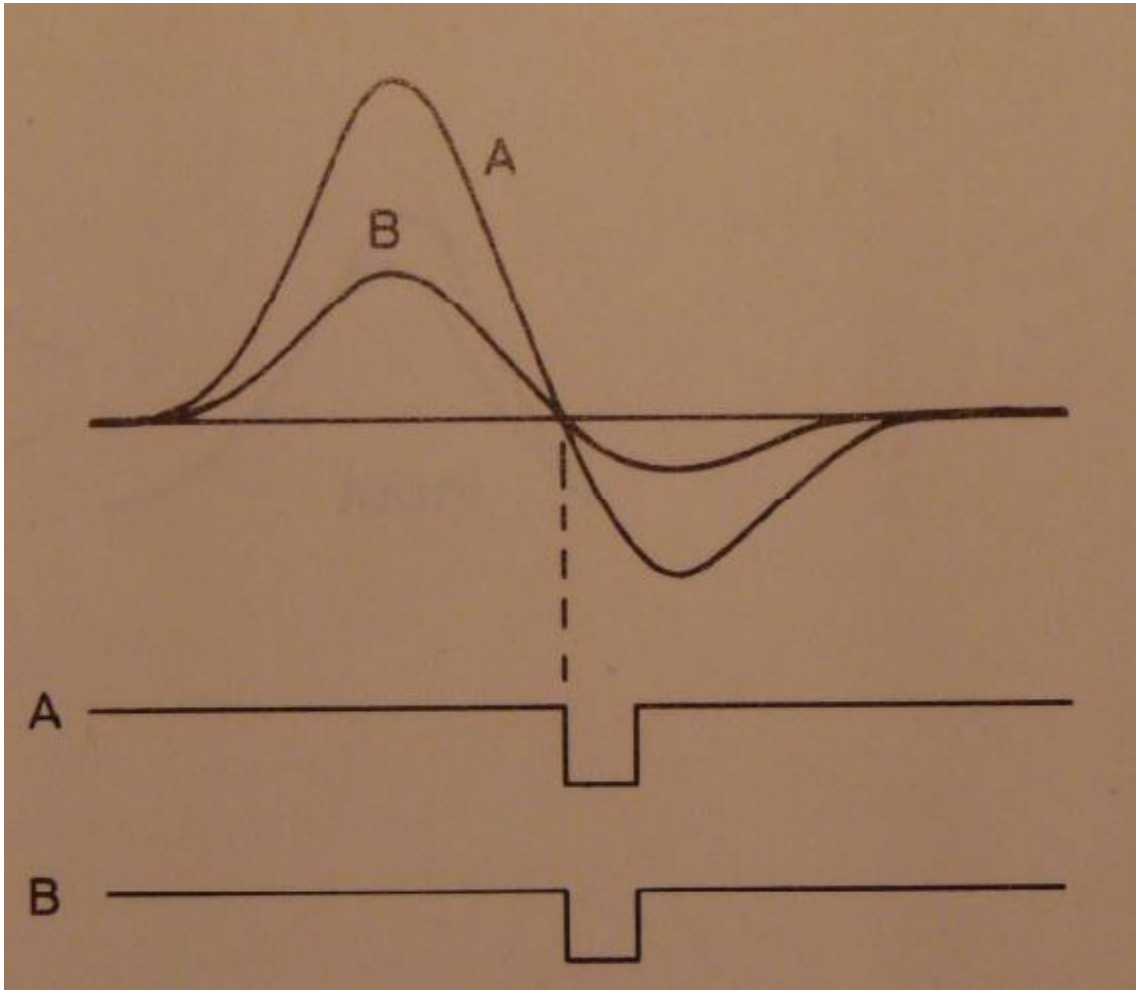
Proton beams: At proton accelerators the emitted neutron yields per incident proton for different target materials are roughly independent of proton energy between 20 MeV and 1 GeV, and given by the ratio **C:Al:Cu-Fe:Sn:Ta-Pb = 0:3 : 0:6 : 1:0 : 1:5 : 1:7**.
Above 1 GeV the neutron yield is proportional to E^m ($0.80 < m < 0.85$).



Leading Edge Triggering



Zero-Crossing Triggering



Constant Fraction Triggering