Modern Particle Physics Detectors I

Theory
Applications
Practice

Lesson 1: Photo-Detection

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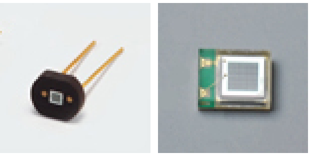
Commercial Si-PMs

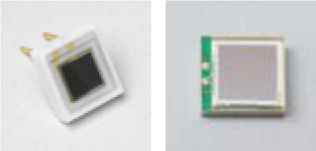
Hamamatsu HPK (http://jp.hamamatsu.com/)

25x25μm², 50x50μm², 75x75μm² pixel size

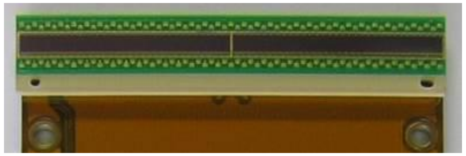
1.3x1.3mm²



3x3mm²

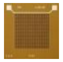


Si-PM Arrays

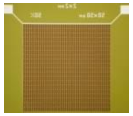


FBK-IRST

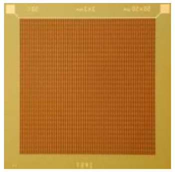
1x1mm²



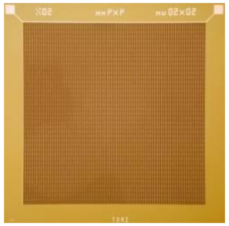
2x2mm²



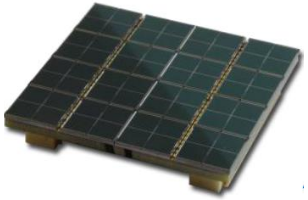
3x3mm²



4x4mm²



4x4mm²
2x2 channels



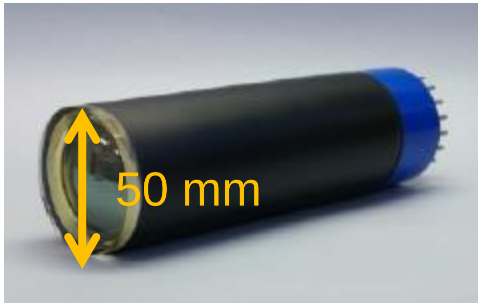
3x3 cm²
8x8 channels

SensL (http://sensl.com/)

3.16x3.16mm²
4x4 channels

3.16x3.16mm²
4x4 channels

Photo Multiplier Tube



Outline of the Course

Part 2

Photo-detection :

1. Introduction to photo-detection and various photo-detectors
2. Silicon photo-detectors
3. Theory of p-n junction
4. Si-PM “theory” and “applications”
5. Particle Identification; Cherenkov detectors

Calorimetry:

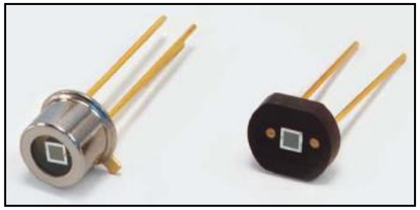
1. Generalities on calorimetry
2. Electromagnetic calorimeters
3. Hadronic calorimeters

Practicum

Practicum

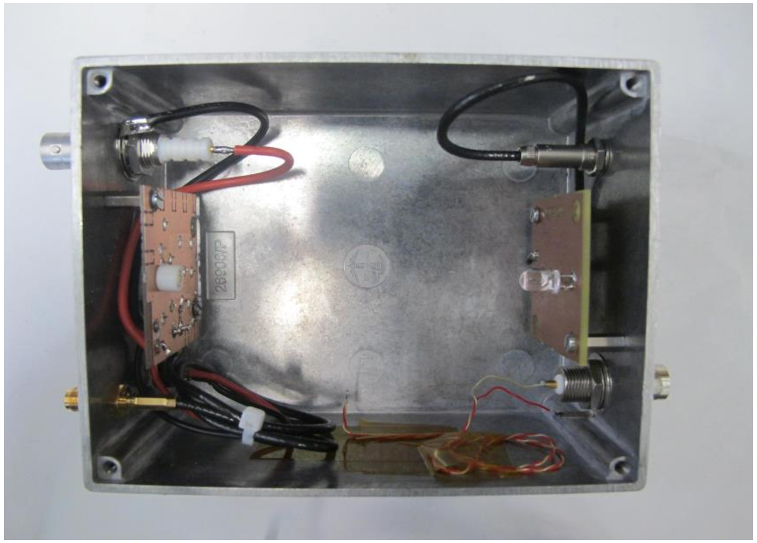
1) Introduction to the laboratory sessions

different laboratory equipment
the Si-PM
operation of Si-PMs



2) Characterization of Si-PMs

diode I-V curve
operation voltage
gain
noise
cross talk
after-pulsing
saturation
recovery time



3) Characterization of Si-PMs

compare different Si-PMs

4) Applications

Suggested Readings

For detectors in general, you can consult the textbooks of Leo or Knoll or Grupen

For a good understanding of semiconductor physics, best to consult a good solid state textbook like Ashcroft and Mermin

There is no specific (text)book on Si-PMs, but many on silicon technology and detectors
S. M. Sze and K. K. Ng
    Physics of Semiconductor Devices
C. Leroy and P.-G. Rancoita
    Silicon Solid State Devices and Radiation Detection
G. Lutz
    Semiconductor Radiation Detectors
H. Spieler
    Semiconductor Detector Systems
The field is evolving very rapidly, for recent developments best to search on the web :
    topical conference web sites and proceedings
    arXiv
    Si-PM manufacturers' sites : www.hamamatsu.com (Hamamatsu)
    www.ketek.net (KETEK)
    sensl.com (SensL)

For calorimetry you can consult the monography of Wigmans

Comment

The development of modern silicon detector systems , and Si-PMs in particular (e.g. trackers in HEP experiments, Si photo-detectors, or medical imaging systems) is a mix of many different competences in physics and engineering.

Designing, building, and operating such detectors is an interdisciplinary task with special knowledge of

Solid state physics
Semiconductor device physics and fabrication technology
Light emission processes
Scintillating materials
Light propagation
Analogue electronics, in particular low-noise front-end amplifiers
Digital electronics, in particular data coding and fast data transmission
Triggering
Data acquisition system
Cooling systems
Mechanics
…..

Photo-Detectors

Convert light into detectable (electronic) signal

Principle

Use photoelectric effect to convert photons (γ) to photoelectrons (pe)

Standard requirements

High sensitivity, usually expressed as

quantum efficiency $\boxed{QE = \frac{N_{pe}}{N_\gamma}}$

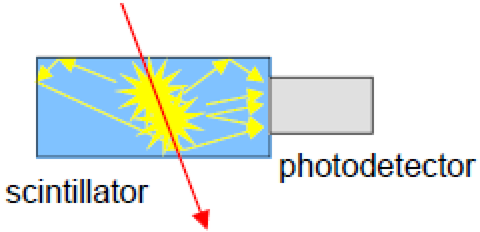
radiant sensitivity S(mA/W) with $\boxed{QE[\%] \approx 124 \frac{S[mA/W]}{\lambda[nm]}}$

Low intrinsic noise

Low gain fluctuations

High active area

Scintillators



Energy deposition by a ionizing particle

→ generation
→ transmission
→ detection

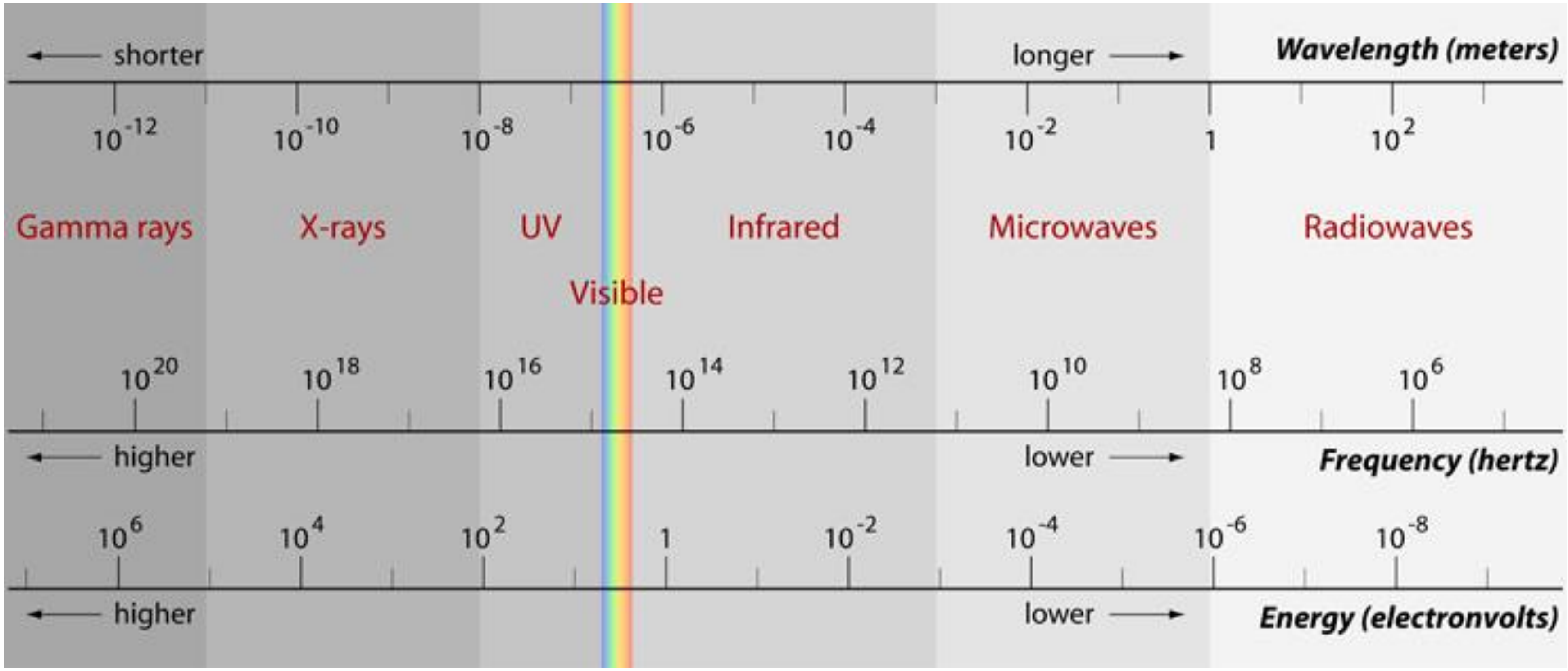
of scintillation light

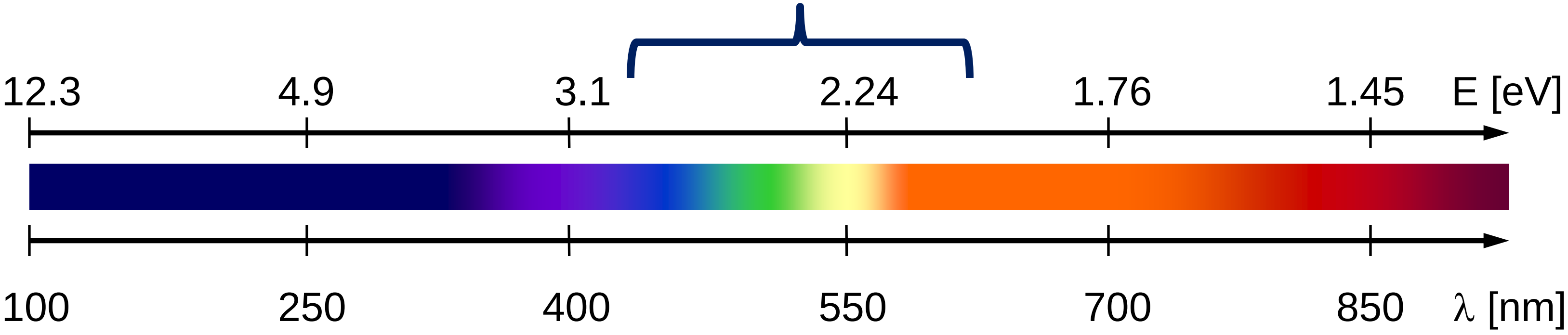
Two categories: Inorganic and organic scintillators

Inorganic (crystalline structure)	Organic (plastics or liquid solutions)
Up to 40000 photons per MeV	Up to 10000 photons per MeV
High Z	Low Z
Large variety of Z and ρ	ρ~1gr/cm3
Undoped and doped	Doped, large choice of emission wavelength
ns to μs decay times	ns decay times
Fairly Rad. Hard (100 kGy/year)	Medium Rad. Hard (10 kGy/year)
Expensive	Relatively inexpensive

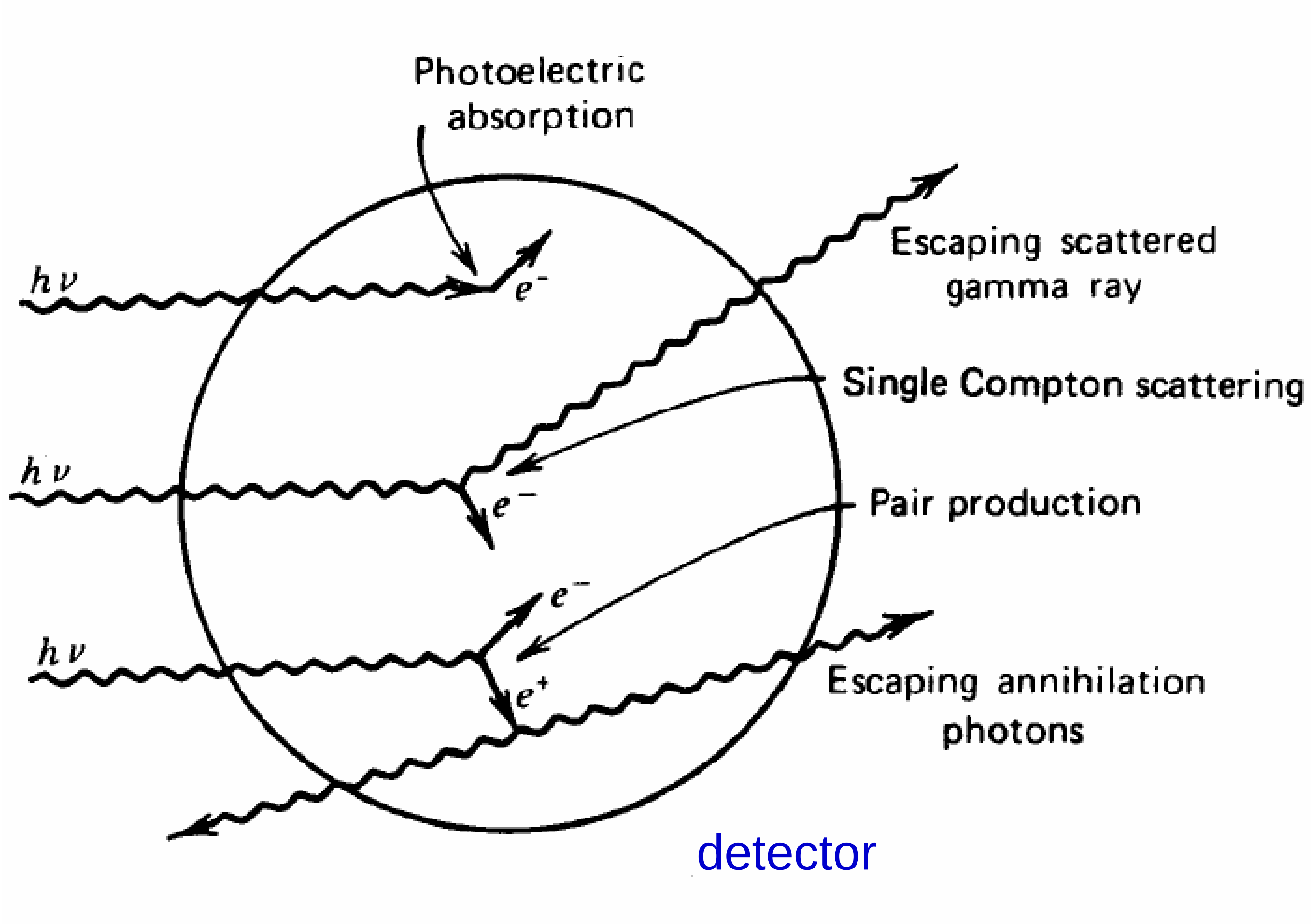
Electromagnetic Spectrum

$$E = h\,\nu = h\,c\,/\,\lambda \quad \rightarrow \quad E[\mathrm{eV}] = 1239\,/\,\lambda\,[\mathrm{nm}]$$





Photon Interactions



visible range – photo-electric effect dominates

Visible Light Emitters

Many “detectors” when excited by ionizing radiation emit light in the visible range.

Scintillators (organic and inorganic)

spectrum peaked around some characteristic wavelengths

emits typically blue light (440 nm)

Wavelength shifters

absorbs short wavelengths (blue, UV)

and re-emits at longer wavelengths (green, orange)

Cherenkov radiators

continuous spectrum (Frank-Tamm Eq.) for $v_p > c / n(\nu)$

intensity proportional to ν (that’s why it is blue)

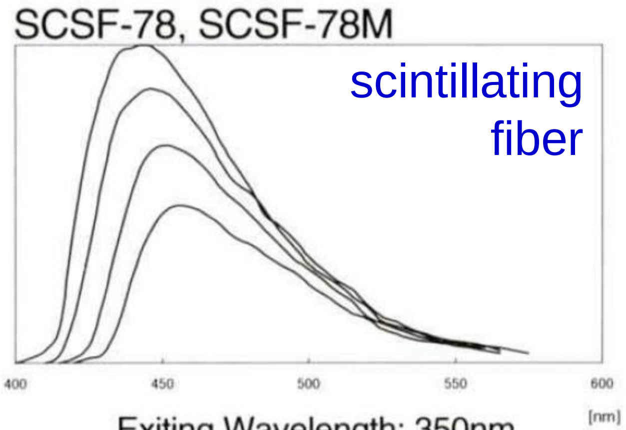
cutoff in the x-ray region, $n(\nu) < 1$!

Noble liquids

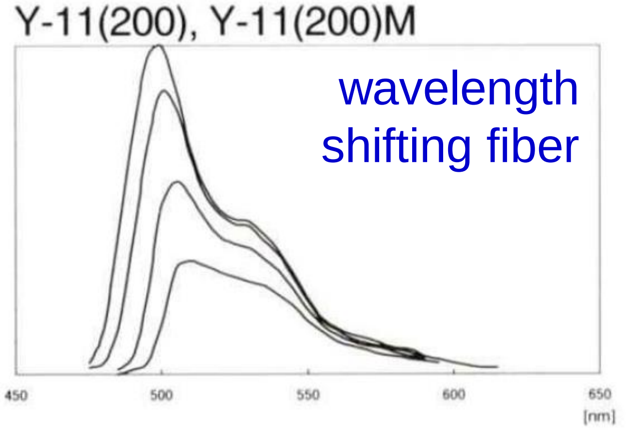
delayed de-excitation in the deep UV (100 – 200 nm)

Bioluminescence

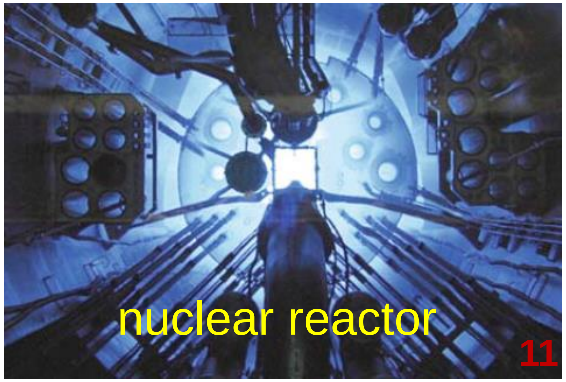
some insects, planktons emit yellow light (550 nm)



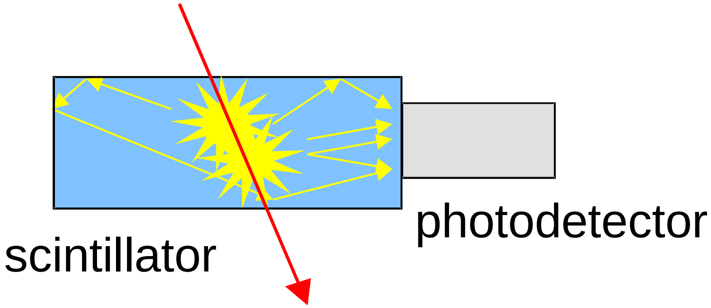
Exiting Wavelength: 350nm

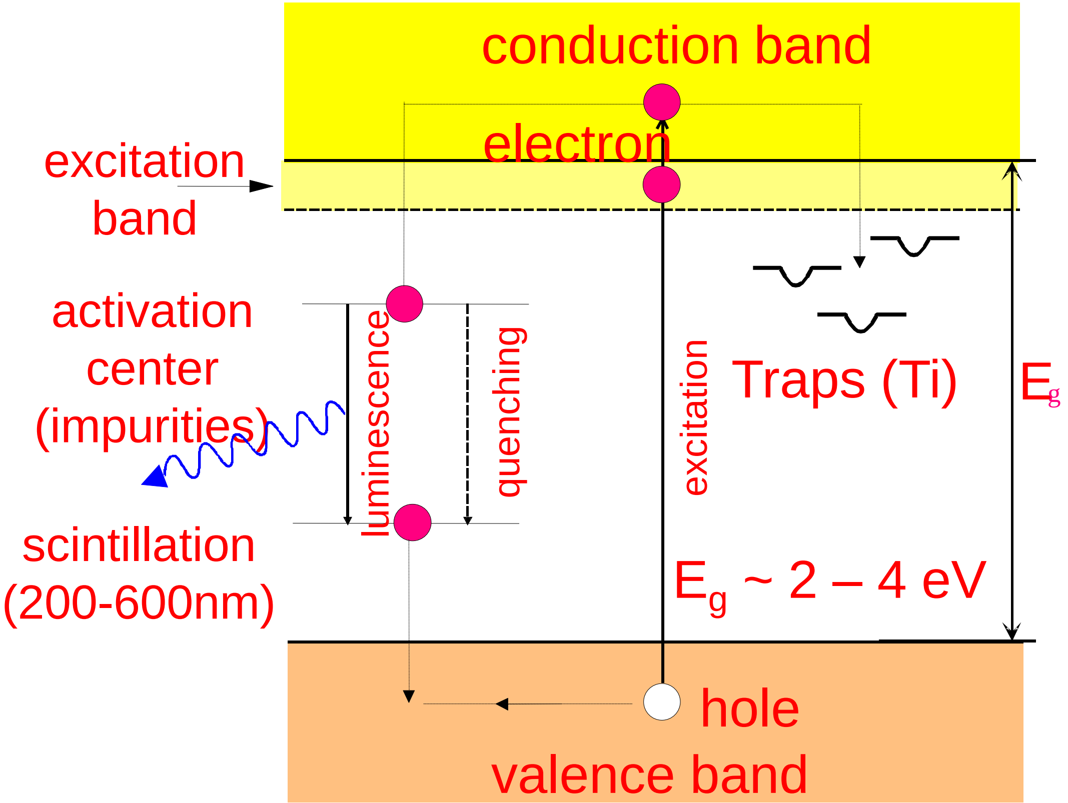


Exiting Wavelength: 430nm



Inorganic Scintillators

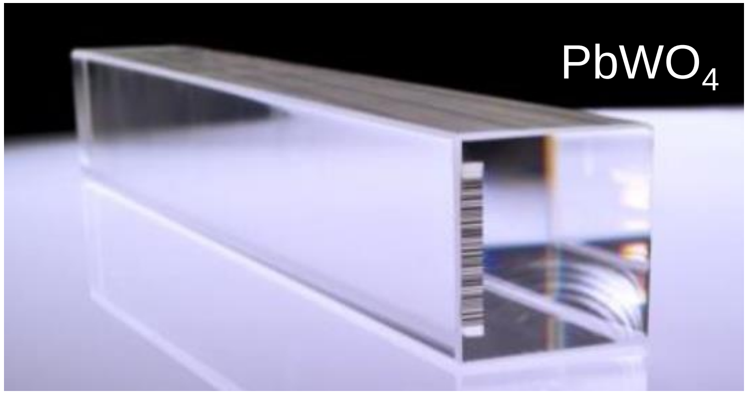




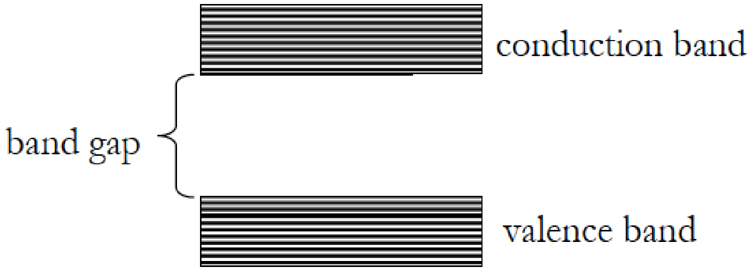
crystalline structure
NaI, CsI, BGO, LYSO, $PbWO_4$

up to 40000 photons per MeV
high Z
large variety of Z and ρ
undoped and doped
long decay times (from ns to μs)
fairly rad. hard (100 kGy/y)
expensive

E.M. calorimetry (e, γ)
medical imaging



Working Principles of Inorganic Scintillators



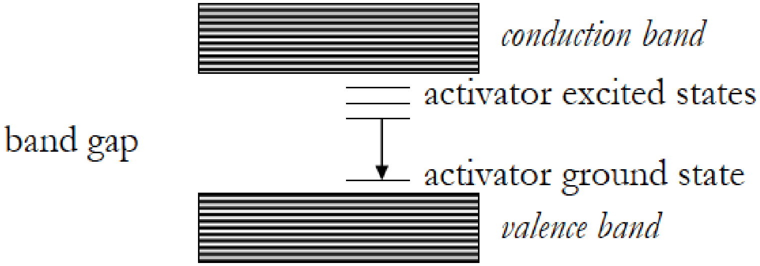
Inorganic scintillators are often crystals:

electrons are ordered into energy bands

bound electrons in valence band

free electrons in conduction band

band gap ("forbidden zone") separates bands



states in the forbidden zone caused by activators (dopants like Ti) or by defects of the lattice: luminescence centers

ionization tracks produce electron-hole pairs in conduction-valence band

→ photons produced by electron returning to valence band

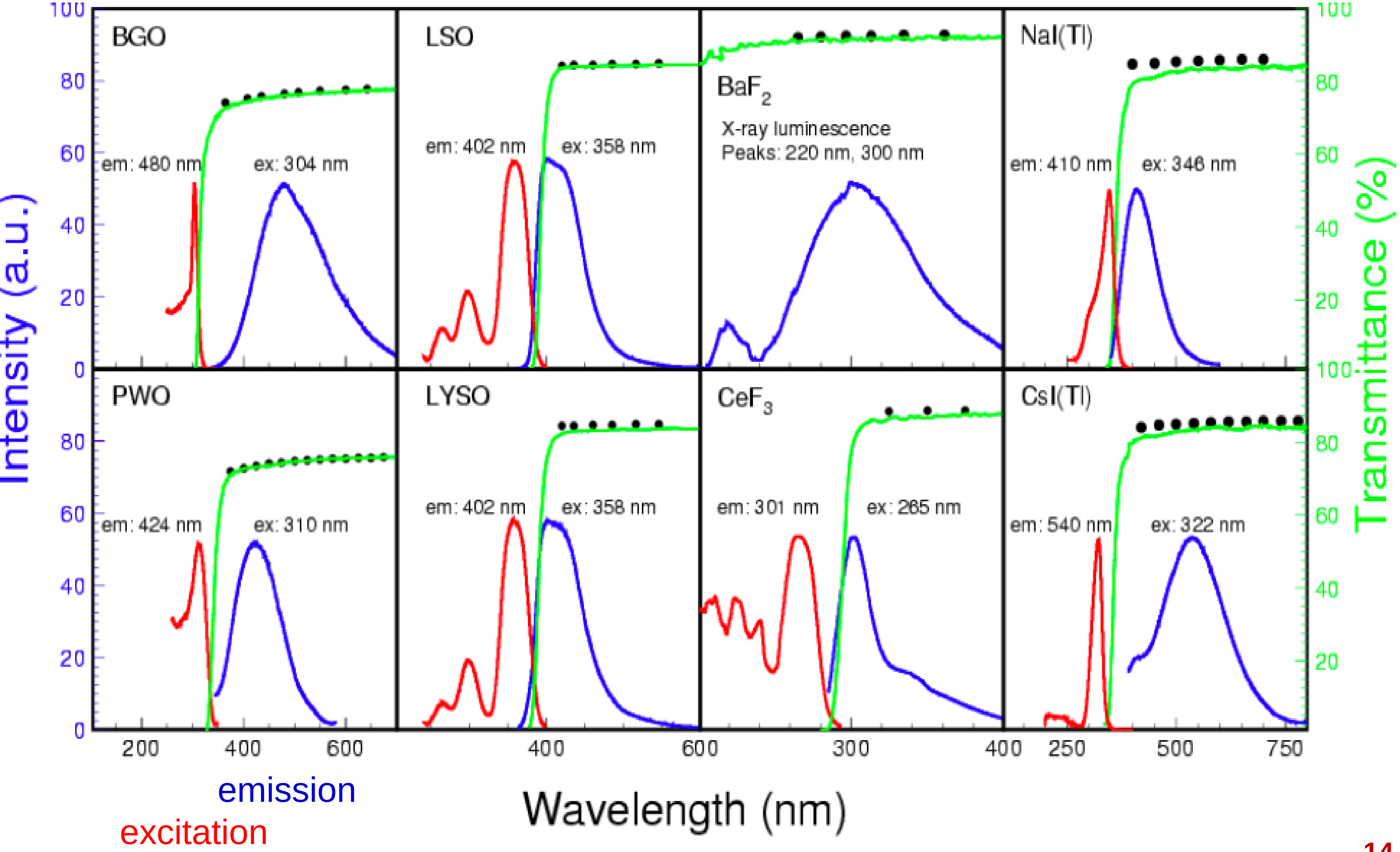
λ of emitted radiation and response time depend on lattice structure (e.g. gap valence-conduction band, electron migration in crystal, etc.)

usually doped with tiny amounts of impurities (e.g. Ti): create additional activation sites in the gap between conduction-valence band, which can be excited and de-excited

→ increase light yield and speed of response

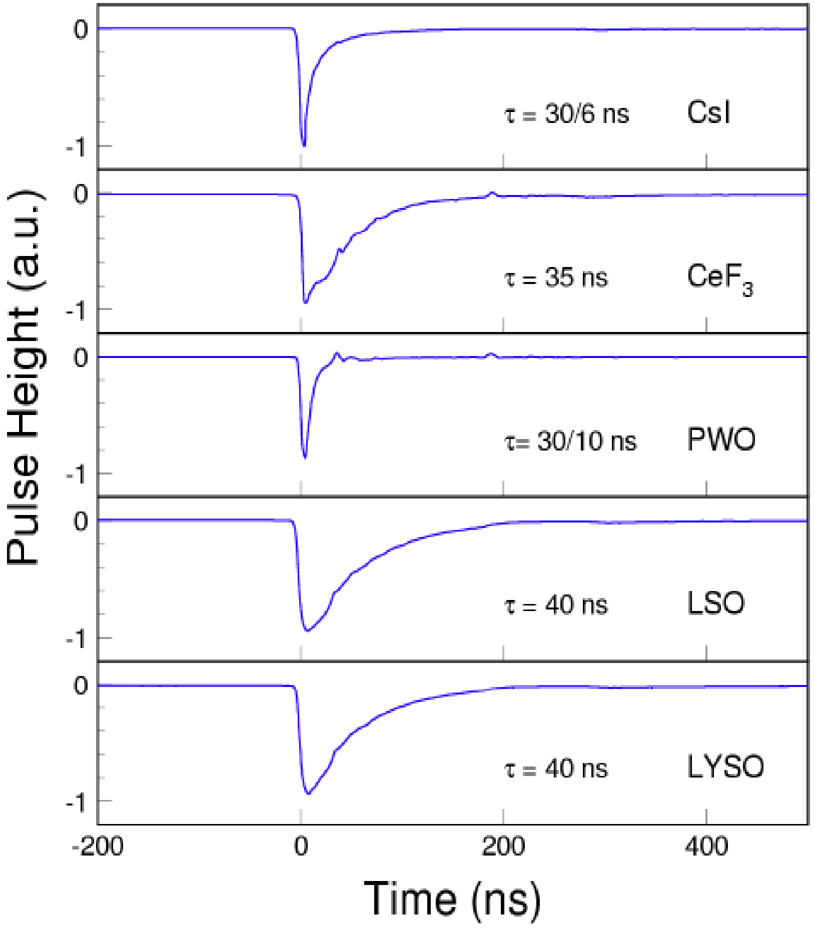
→ shift wavelength to match with photocathode sensitivity

Excitation, Emission and Transmission

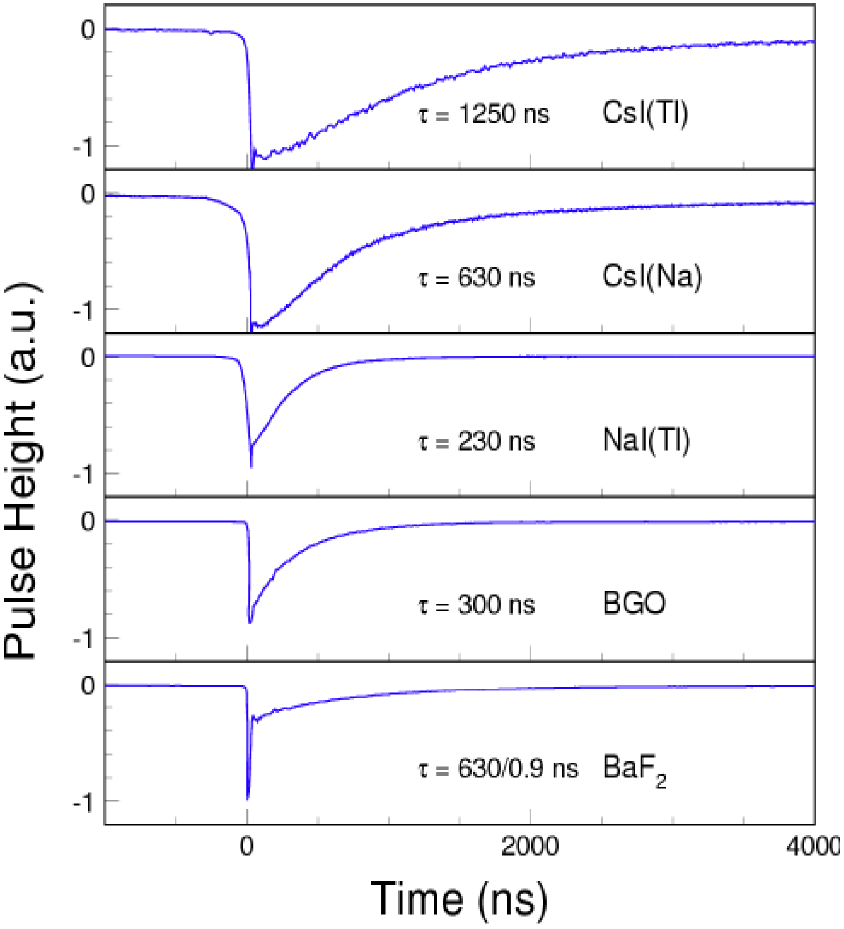


Intrinsic Speed of Inorganic Scintillators

Fast Scintillators



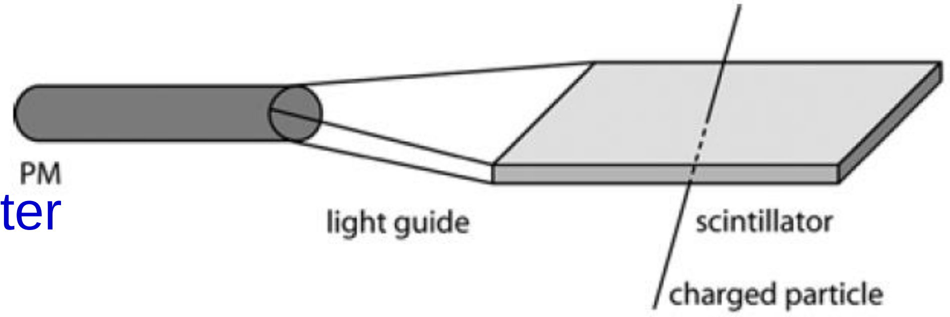
Slow Scintillators



Experiment: should try to observe the spread in time of single photons –
initially they are closer in time, while at later times they are sparser

will try with a LYSO crystal and Si-PM ☺

Organic Scintillators



plastics or liquid solutions
solvent + scintillator + wavelength shifter

up to 10000 photons per MeV

low Z (carbon)

$\rho \sim 1g / cm^3$

doped, large choice of wavelength shifters → emission wavelength
(typically blue, but also green or orange …)

fast excitation / emission process

→ fast response ~ few ns decay time

(however this limit the time resolution achievable with a scintillator!)

low light yield (low dopant concentration, too high concentration -> absorption)

relatively inexpensive

tracking, TOF, trigger, sampling calorimeters
medium rad. hard (10 kGy/y)

Working Principles of Organic Scintillators

plastics or liquid solutions : solvent + scintillator + wavelength shifter

1. A ionizing particle releases energy in the solvent.

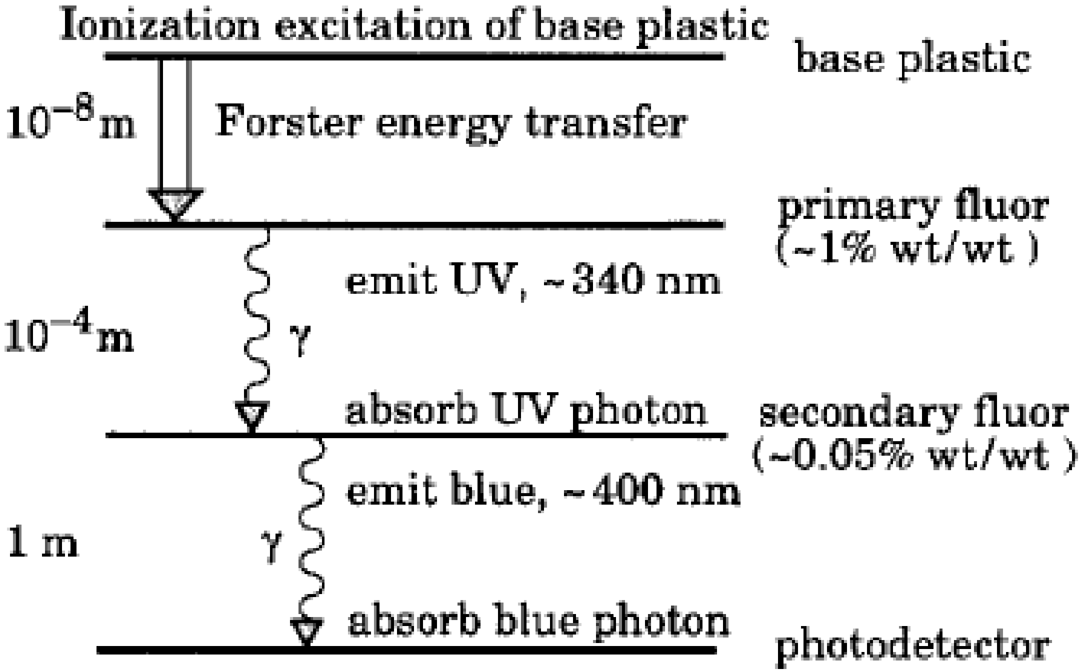
2. Energy flows to the scintillator by fast and local energy transfer via radiationless dipole-dipole interactions (Förster transfer) to the primary fluor.

3. Light emitted by the primary fluor (deep UV) is absorbed by the secondary fluor (radiative transfer) and re-emitted at a longer wavelength (~ 400 nm).
A fluor has its absorption and emission spectra slightly shifted (wavelength shifter).
The two peaks difference is called
Stokes shift

Förster transfer

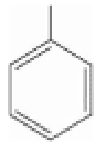
primary fluor

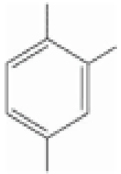
secondary fluor
Stokes shift

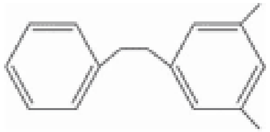


Organic Scintillator Molecules

solvent


Toluene


Pseudocumene


PXE (phenyl xylylethane)

and many other solvents :
- polystyrene
- mineral oils
- …

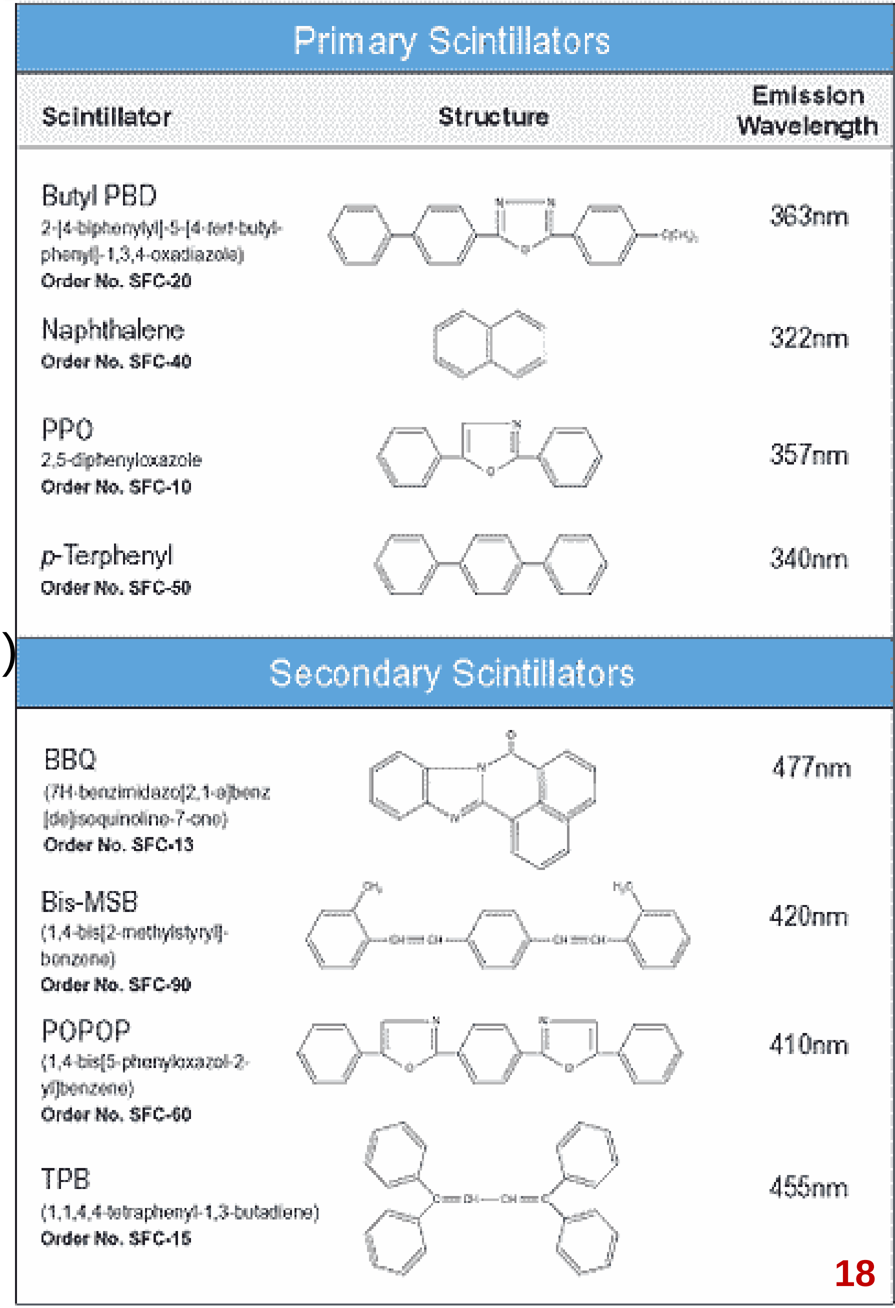
lately also water based liquid scintillators (R&D)

Challenges :

choose the right substrate
(with good λ transmission)

adjust “dopant” concentration,
i.e. primary and secondary flour

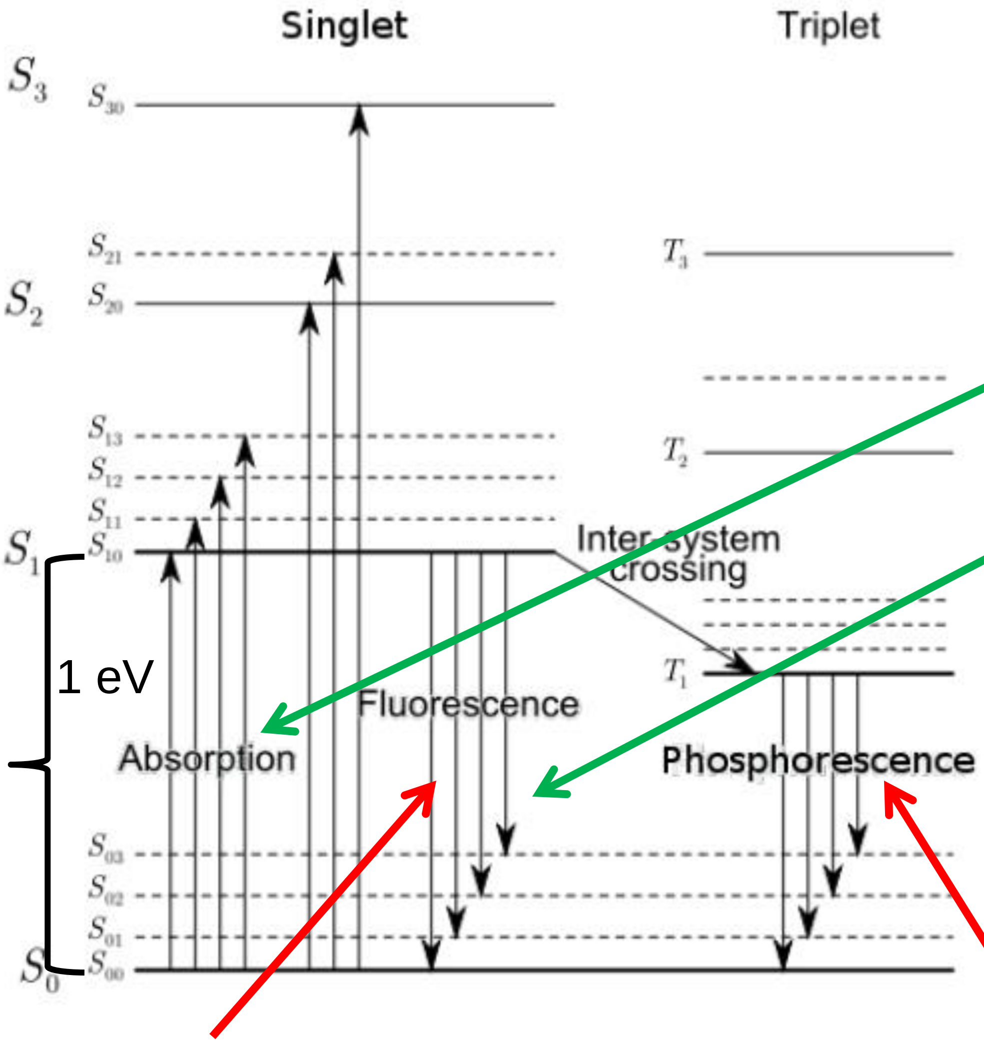
This will determine the performance of the scintillator.



Scintillator	Structure	Emission Wavelength
Primary Scintillators		
Butyl PBD 2-[4-biphenylyl]-5-[4-*tert*-butyl-phenyl]-1,3,4-oxadiazole) **Order No. SFC-20**		363nm
Naphthalene **Order No. SFC-40**		322nm
PPO 2,5-diphenyloxazole **Order No. SFC-10**		357nm
p-Terphenyl **Order No. SFC-50**		340nm
Secondary Scintillators		
BBQ (7H-benzimidazo[2,1-a]benz[de]isoquinoline-7-one) **Order No. SFC-13**		477nm
Bis-MSB (1,4-bis[2-methylstyryl]-benzene) **Order No. SFC-90**		420nm
POPOP (1,4-bis[5-phenyloxazol-2-yl]benzene) **Order No. SFC-60**		410nm
TPB (1,1,4,4-tetraphenyl-1,3-butadiene) **Order No. SFC-15**		455nm

Energy Levels of an Organic Scintillator

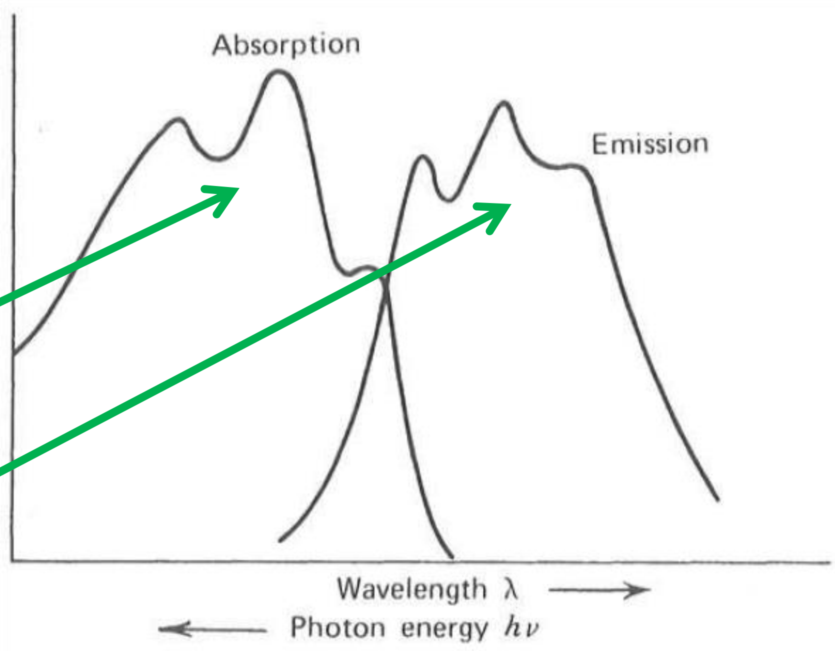
energy levels of an organic scintillator



fast component ~ few ns

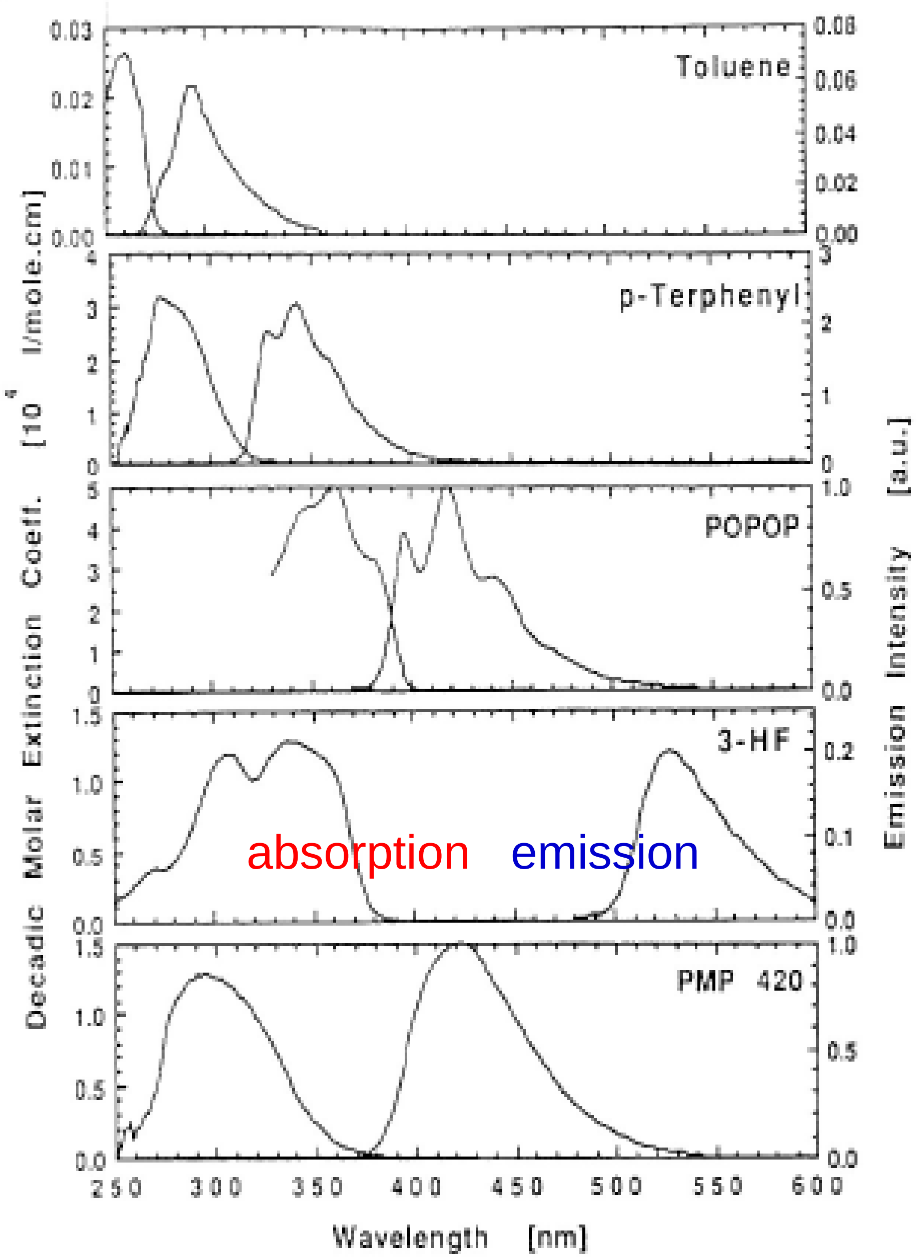
slow component

absorption and emission spectra of a *scintillating* molecule



note that the energy of the emitted photon is smaller than the energy of the exciting photon
→ wavelength shifter (Stokes shift)

Absorption / Emission Spectra



Saturation Effects in Scintillators

In general, the energy response of a scintillator is linear to the energy deposited. Only a small fraction of the deposited energy, however, is converted into fluorescent energy (light).

Light emitted per unit path: $$\boxed{\frac{\mathrm{d}L(\lambda)}{\mathrm{d}x} = S(\lambda)\frac{\mathrm{d}E}{\mathrm{d}x}}$$ (S $\equiv$ scintillation efficiency)

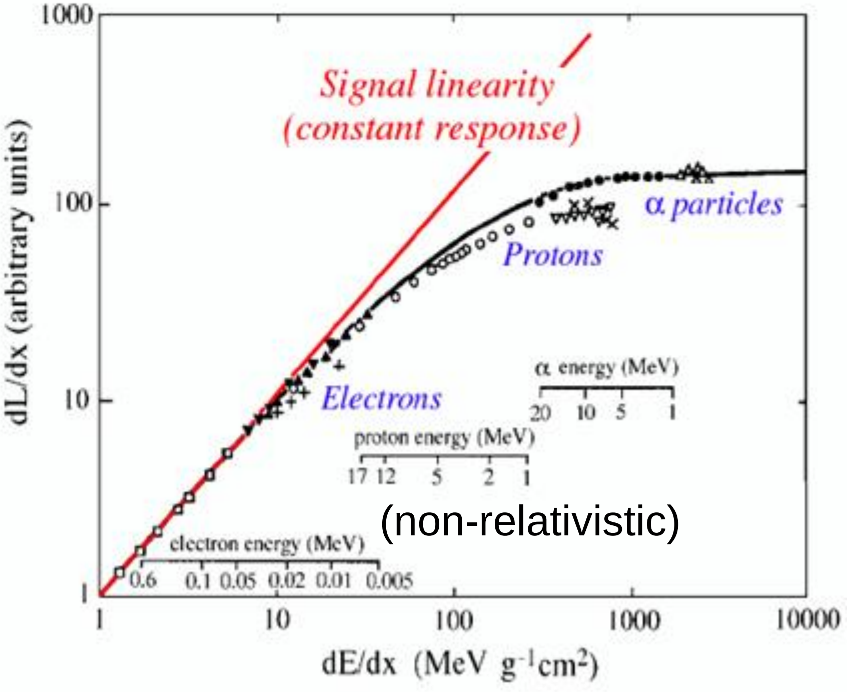
recall: dE/dx in plastics ~ 2 MeV g^{-1} cm^2 , 1 MeV “generates” around 5000 visible photons

In case of high ionization density along the track (stopping particles, nuclear fragments, ions, …) can saturate the response of the active medium.

Assuming that the “damage” is proportional to the ionization density, a fraction k of these “damaged” molecules will lead to quenching.

Birk’s law : $$\boxed{\frac{\mathrm{d}L}{\mathrm{d}x} = \frac{S \cdot \mathrm{d}E/\mathrm{d}x}{1 + kB \cdot \mathrm{d}E/\mathrm{d}x}}$$

k $\equiv$ fraction of quenching molecules
B $\equiv$ proportionality factor
kB ~ 0.01 – 0.02 cm / MeV



(non-relativistic)

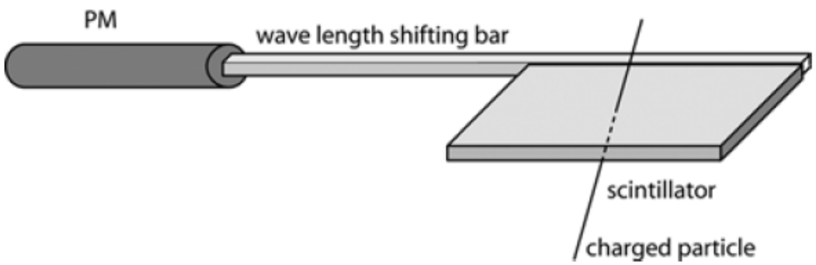
Wavelength Shifters

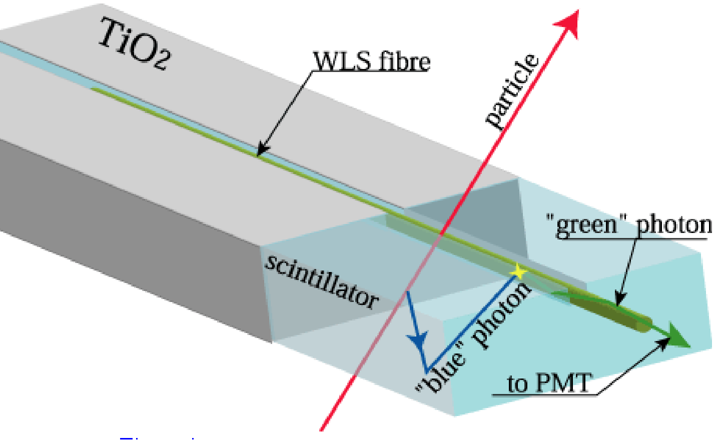
Often the geometry or environmental factors (i. e. B field) does not allow to couple the scintillator directly to the photo-detectors.

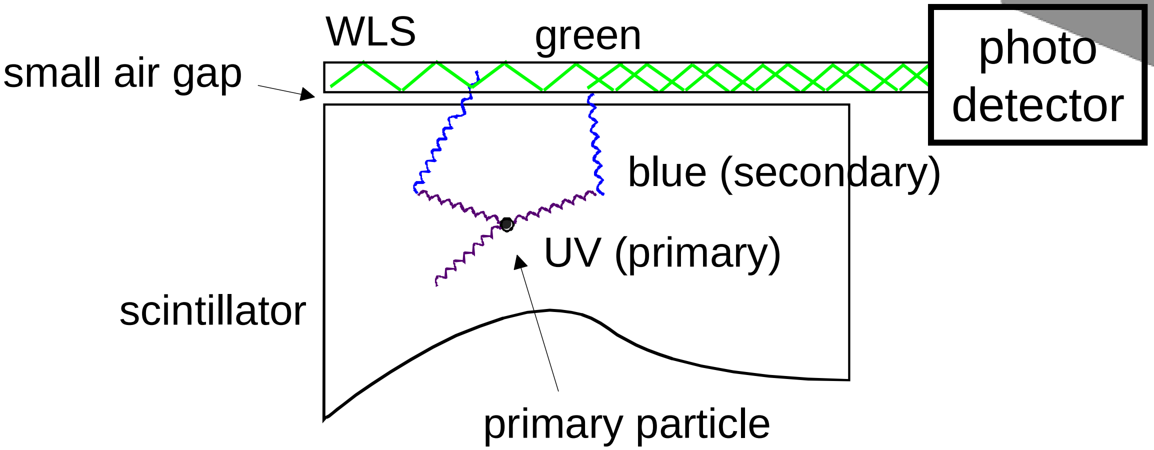
Use (some solutions)

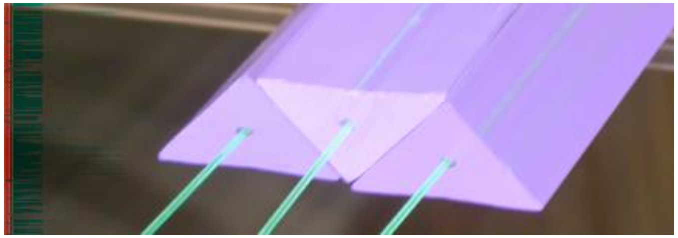
- light guides (PMMA – transparent plastic)
- optical fibers
- wavelength shifting bars
- wavelength shifting fibers

to couple the scintillator to the detectors.

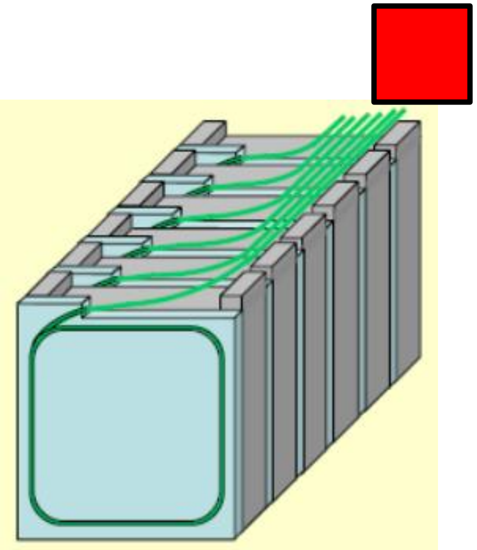








The wavelength shifter absorbs the scintillating light (~ 400nm) and (re-)emits the absorbed light at a longer wavelength (i.e. green ~ 550 nm).



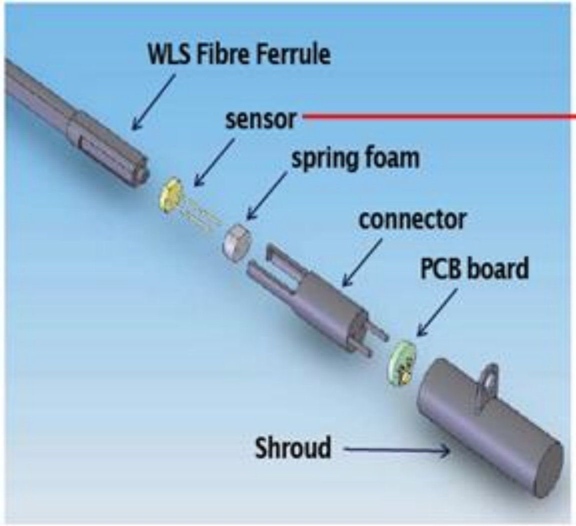
3 × 3 mm^2 Si-PM

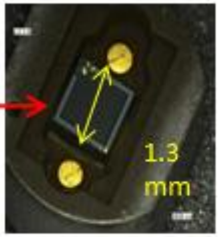
Calorimetry

readout of a calorimeter
with WLS (“green”) fibers
or WL shifters

“Tracking”

T2K Near Detector active target
readout of 1 cm scintillator bars with WLS fibers





1.3 × 1.3 mm^2 Si-PM

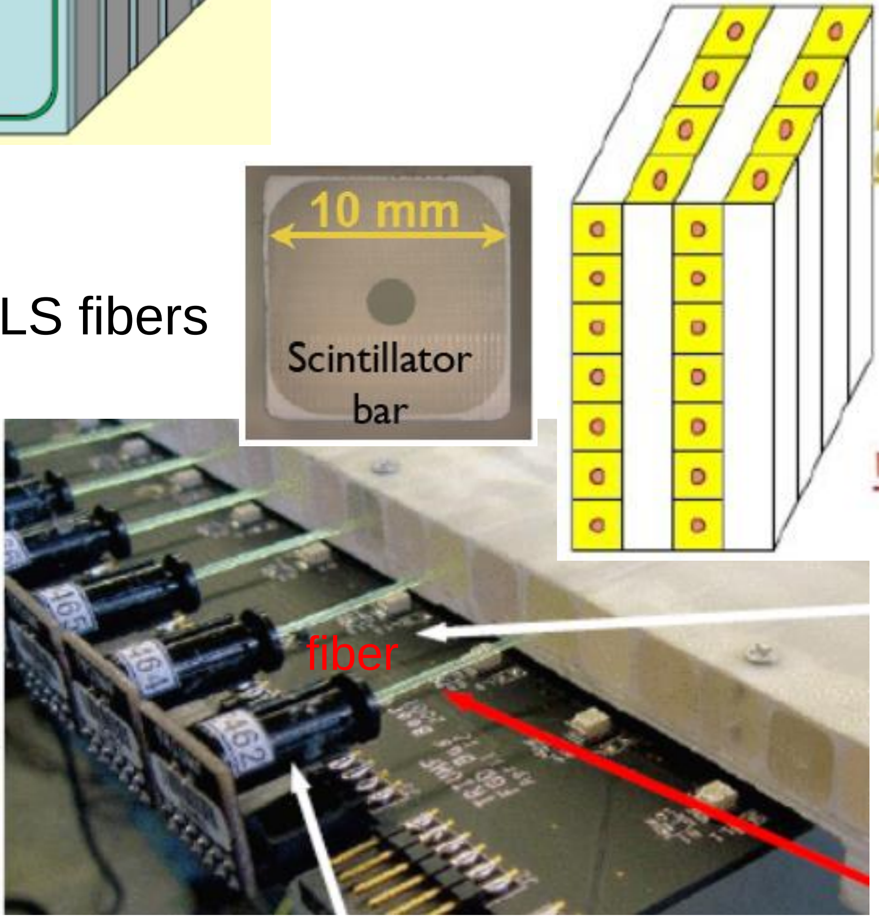


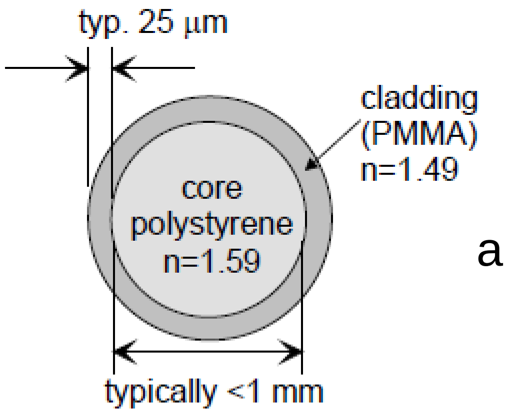
photo-sensor

Light Propagation in Fibers

working principle

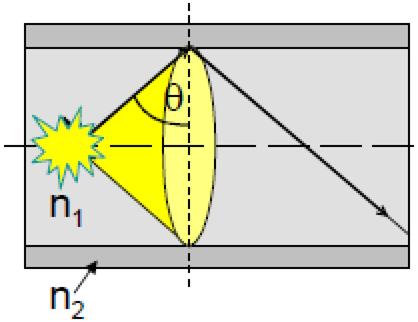
WLS excited by blue light

emitted light at longer wavelength transported by total internal reflection

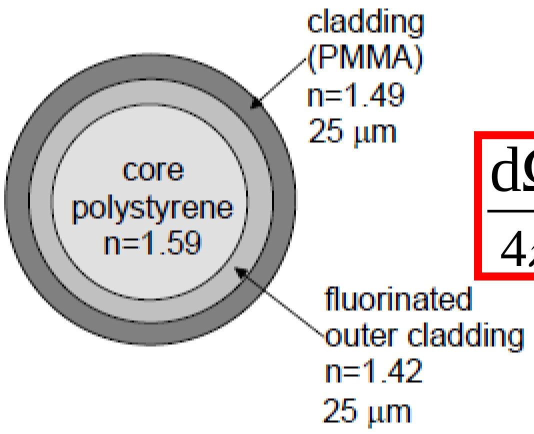


aperture $$\boxed{\frac{d\Omega}{4\pi} = \frac{1}{2}\left(1-\cos^2\vartheta\right) \approx 3.1\%}$$

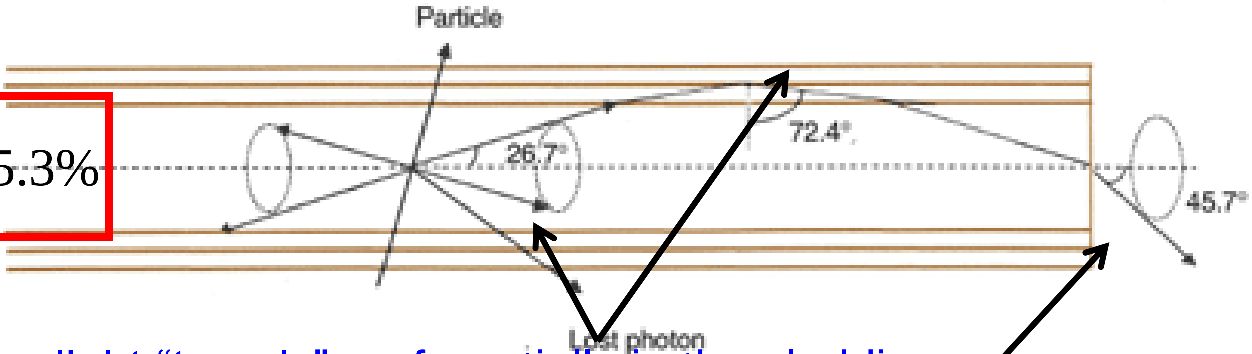
$$\vartheta \le \arccos\frac{n_1}{n_2} \approx 69.6^\circ$$



to improve on aperture (i.e. acceptance) double clad fibers

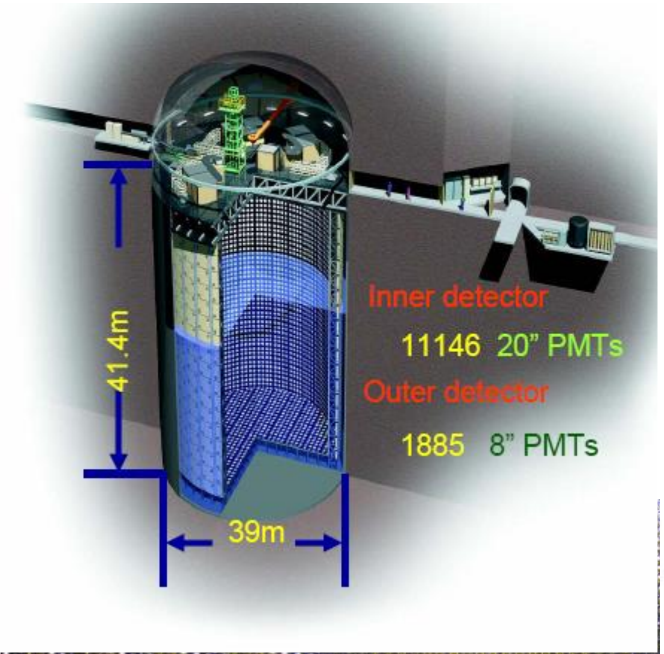


$$\boxed{\frac{d\Omega}{4\pi} = 5.3\%}$$

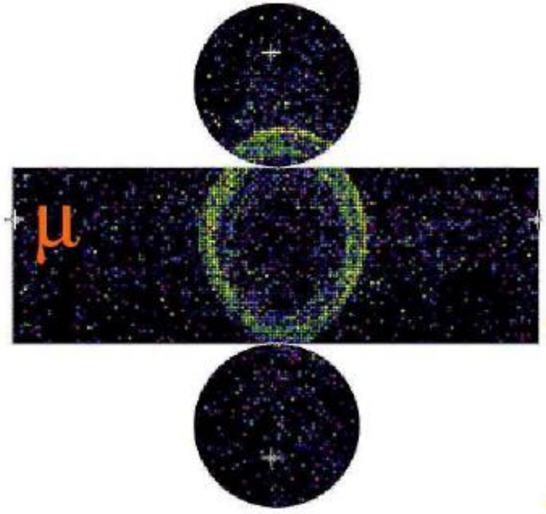


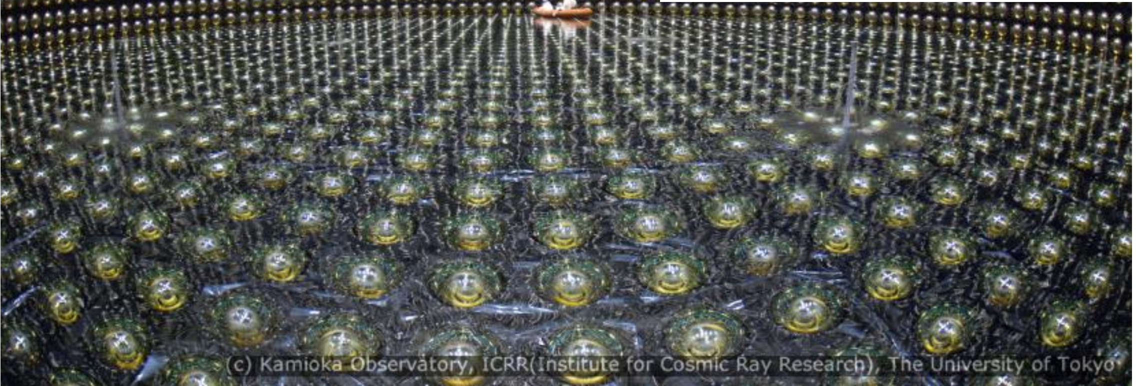
light “travels” preferentially in the cladding and exits the fiber at large angles

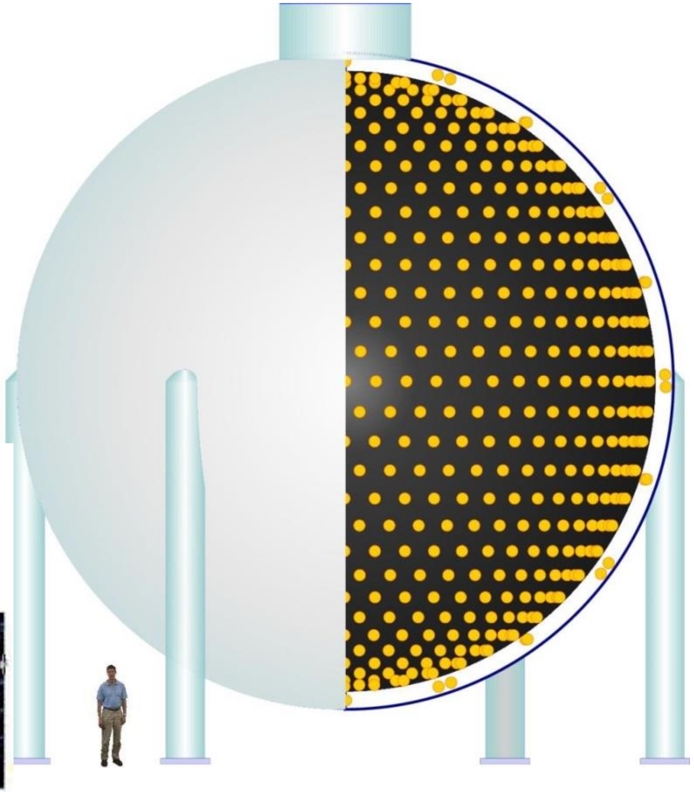
ν – Cherenkov Detectors



Super Kamiokande
Water Cherenkov

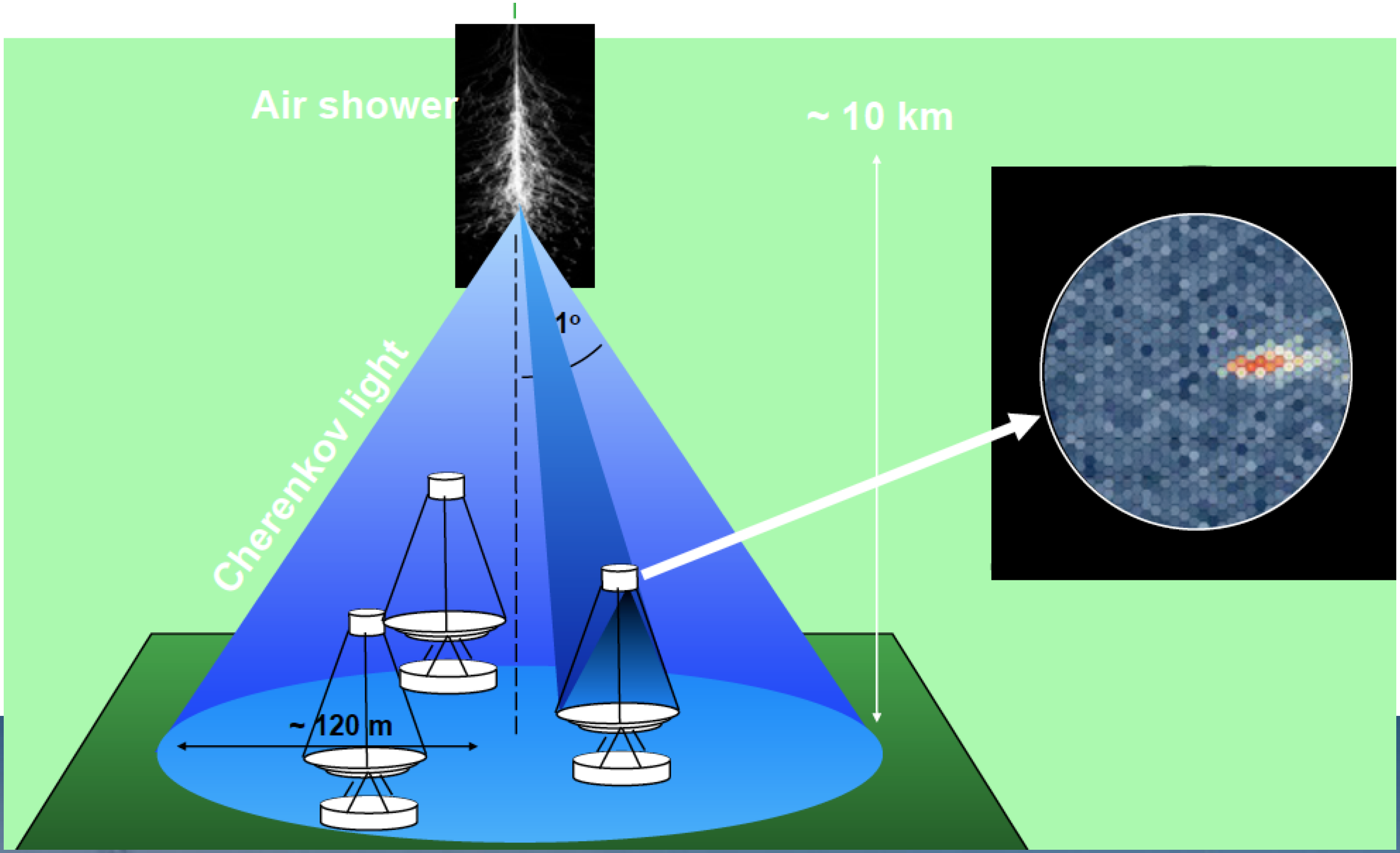



(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo



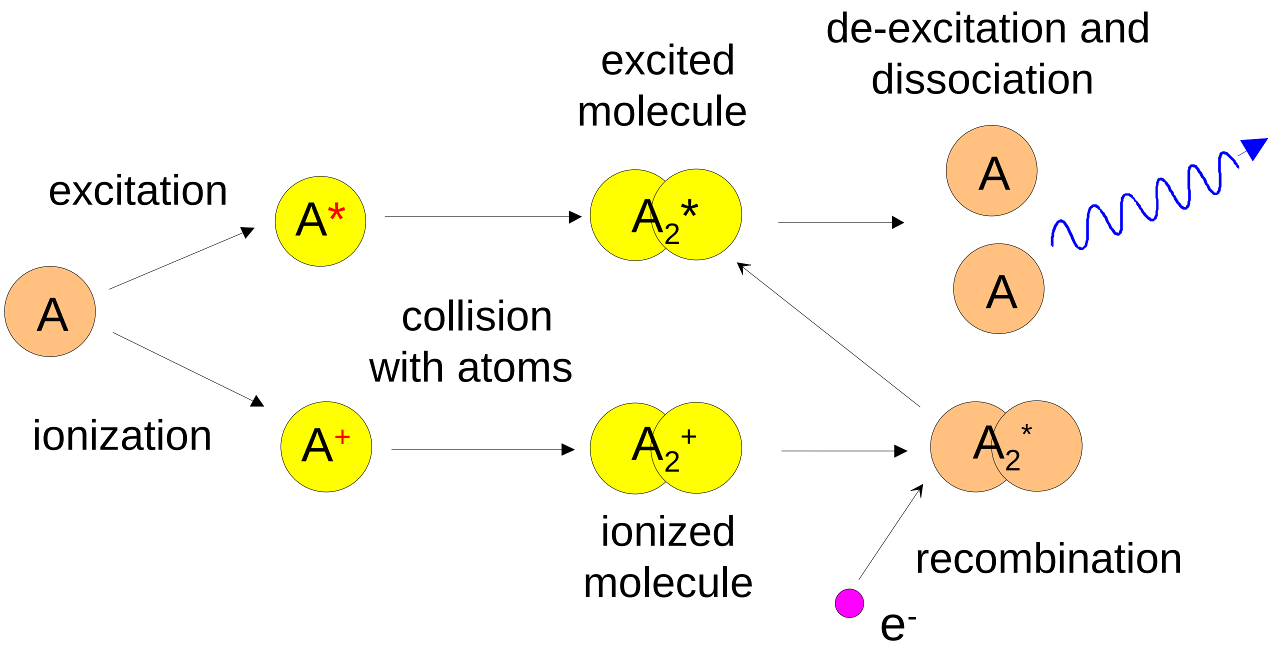
MiniBooNE @ FNAL
filled with liquid scintillator

Air Shower Cherenkov Detectors



Noble Liquids

Cryogenic Liquefied noble gases: LAr, LXe, LKr



excitation

ionization

collision with atoms

excited molecule

ionized molecule

de-excitation and dissociation

recombination

A

A^*

A^+

A_2^*

A_2^+

A_2^*

A

A

e^-

UV
130nm (Ar)
150nm (Kr)
175nm (Xe)

use a wavelength shifter to blue wavelengths to detect this light

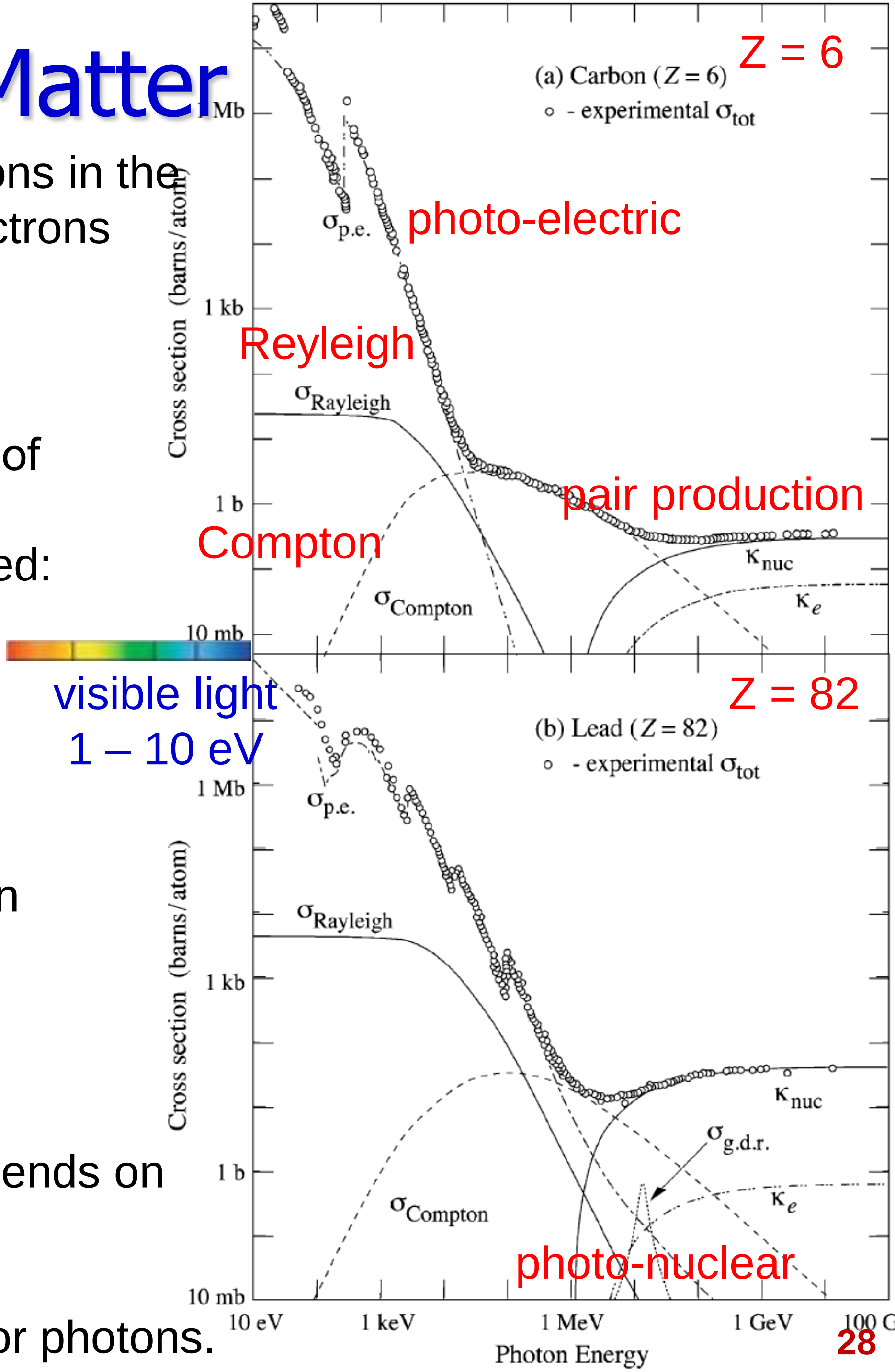
Also here one finds 2 time constants: from a few ns to 1 μs.

Interaction of γ with Matter

Photons are detected indirectly via interactions in the medium of the detector → production of electrons

convert light into detectable and quantifiable electronic signal

Contrary to "continuous" energy loss typical of charged particles
photon interactions are punctual and localized:
the photon is either completely absorbed (*photoelectric effect*, *pair production*)
or scattered with a shift in the wavelength (*Compton effect*).



A photon beam is attenuated exponentially in matter according to

$$\boxed{I(x,\lambda)=I_0 e^{-\mu(\lambda)\cdot x}}$$

μ (λ) – linear attenuation coefficient and depends on
the photon energy (or wavelength)
material properties

It is therefore impossible to define a range for photons.

Interaction of γ with Matter

5 major electromagnetic processes by which photons interact with matter

1) photo-electric effect ($E_e \leq$ few eV)

$$\gamma + A \rightarrow e^- + A^+$$

2) Reyleigh (coherent) scattering

$$\gamma + A \rightarrow \gamma + A$$

3) Compton scattering ($E_e \leq$ MeV)

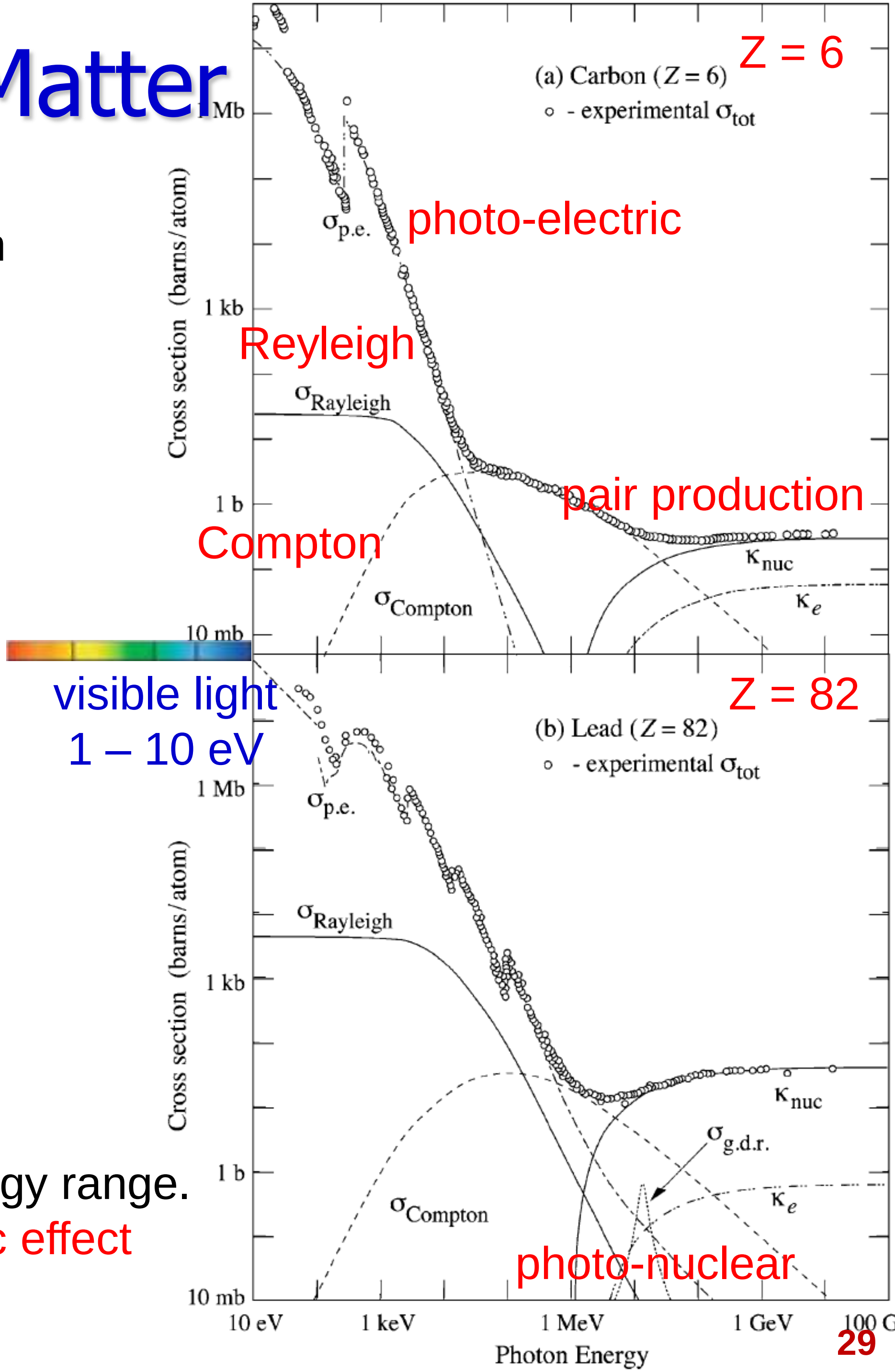
$$\gamma + e^- \rightarrow \gamma + e^-$$

4) pair production (also on electrons)

$$\gamma + N \rightarrow N + e^- + e^+$$

5) photo-nuclear reactions

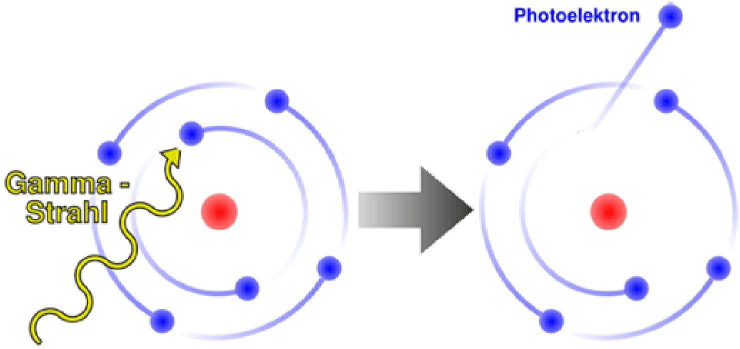
$$\gamma + N \rightarrow \text{nuclear fragments}$$

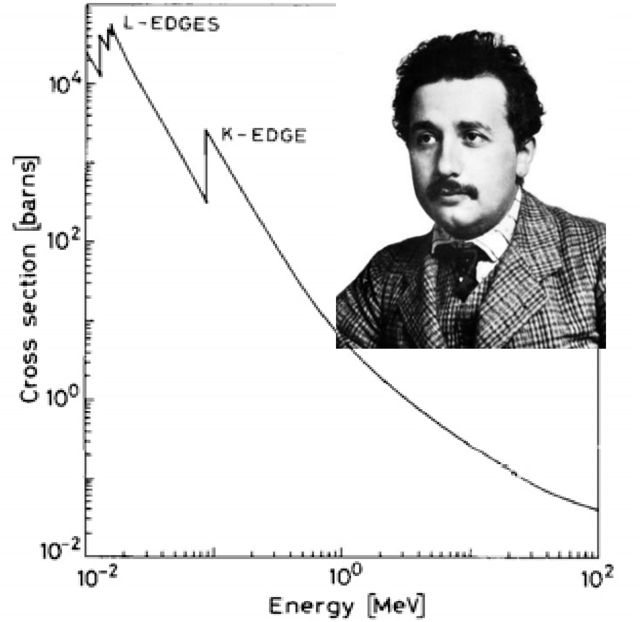


Each process dominates in a particular energy range.

In the visible energy range the photo-electric effect

The Photo-Electric Effect





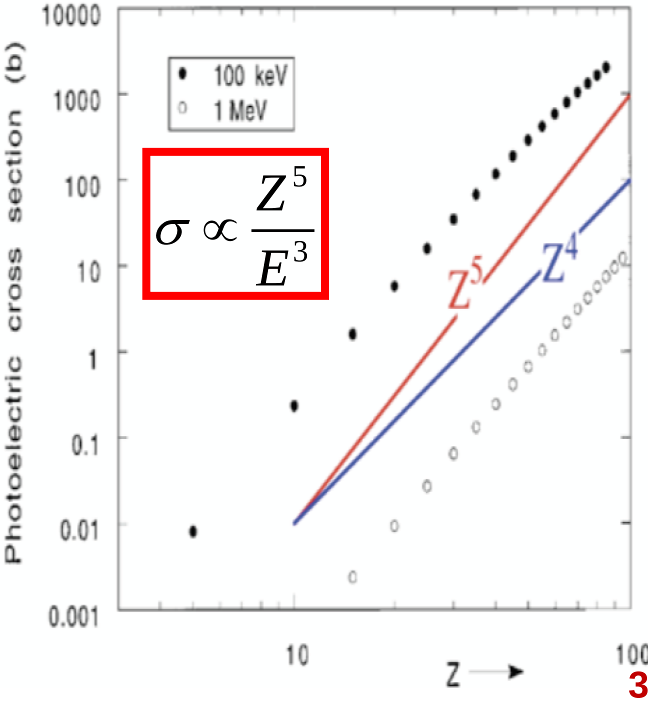
At low energies, electrons emitted near 90^0.
The total photoelectric cross section in the non-relativistic range away from the absorption edges
in the non-relativistic *Born approximation*

$$\sigma^K_{\text{photo}} = \left(\frac{32}{\varepsilon^7}\right)^{1/2} \cdot \alpha^4 \cdot Z^5 \cdot \sigma^e_{\text{Th}} \left\{\text{cm}^2 / \text{atom}\right\}$$

with ε the reduced γ energy and σ_{Th} the Thomson elastic γ – e cross section ($h\nu << m_e c^2$!)

$$\varepsilon = E_\gamma / m_e c^2 \qquad \sigma^e_{\text{Th}} = \frac{8\pi}{3} r_e^2 = 6.65 \times 10^{-25}\,\text{cm}^2$$

The cross section scales with Z^5 and $E^{-3.5}$
In reality much more complicated than this with
$Z^5 \rightarrow Z^{4.5}$ and $E^{-3.5} \rightarrow E^{-1}$



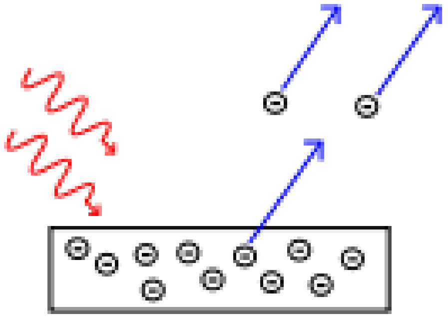
$$\sigma \propto \frac{Z^5}{E^3}$$

How to Detect this Light ?

At these wavelengths (~ 100 – 1000 nm)

convert incident photons into (photo)electrons via photoelectric effect

External photoelectric effect

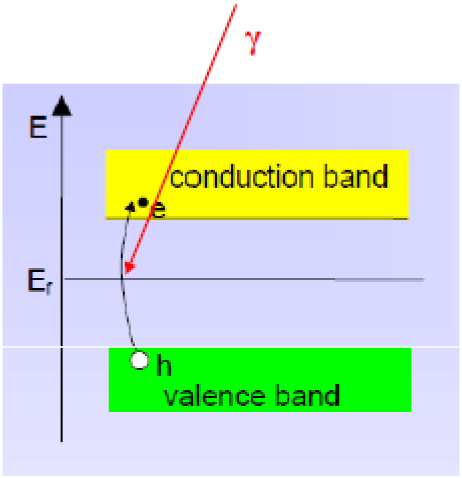


Electrons are extracted from the surface of a metal by the energy absorbed from an incident stream of photons :

$E_\gamma = h\nu > E_{pe} + E_W$

Examples : vacuum photodiode, photomultiplier

Internal photoelectric Effect



In a crystal or semi-conductor electrons are “lifted” from the valence band to the conduction band by absorption of incoming photons and a *hole* is left behind

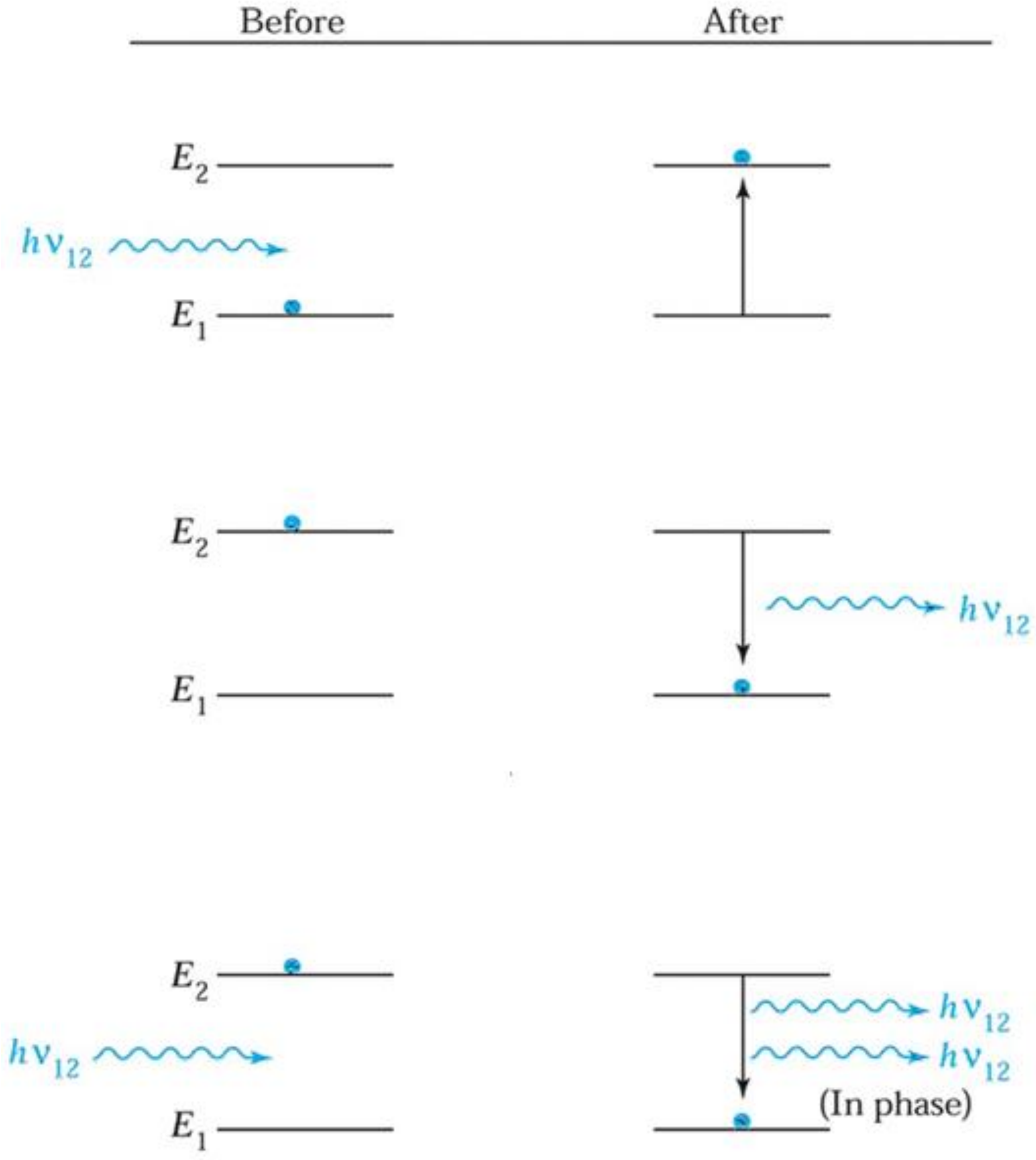
$E_\gamma > E_{gap}$

Examples: NaI, pn junction photodiode

competing process

Rayleigh scattering $\lambda >> d$ (that’s why the sky on Mars is red) with $\sigma \sim 1/\lambda^4$ (for instance limiting factor in light propagation in optical fibers)

Photon Absorption / Emission



absorption

spontaneous emission
τ – characteristic lifetime
of the excited state

stimulated emission
the emitted photon is in
phase with the incident one

Optical Absorption

Basic transitions in a semiconductor

when illuminated, photons are absorbed to create electron – hole pairs:

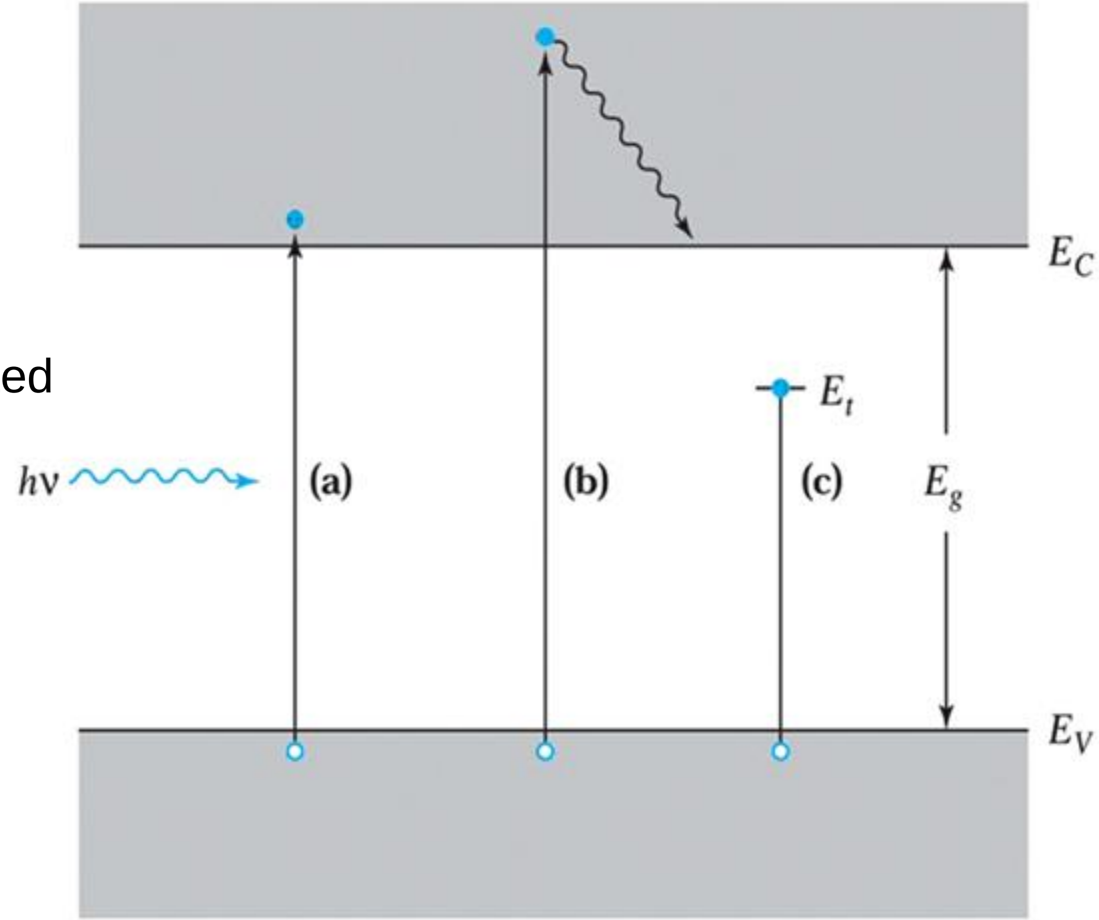
intrinsic transitions

a) hν = E_g
an electron – hole pair is created

b) hν > E_g
an electron – hole pair is created
and the excess energy is dissipated
in form of heat (phonons)

extrinsic transition

c) hν < E_g
this transition is possible, if there
are available energy states in the
the forbidden bandgap due to
chemical impurities or physical
defects.



Various Photo-Detectors

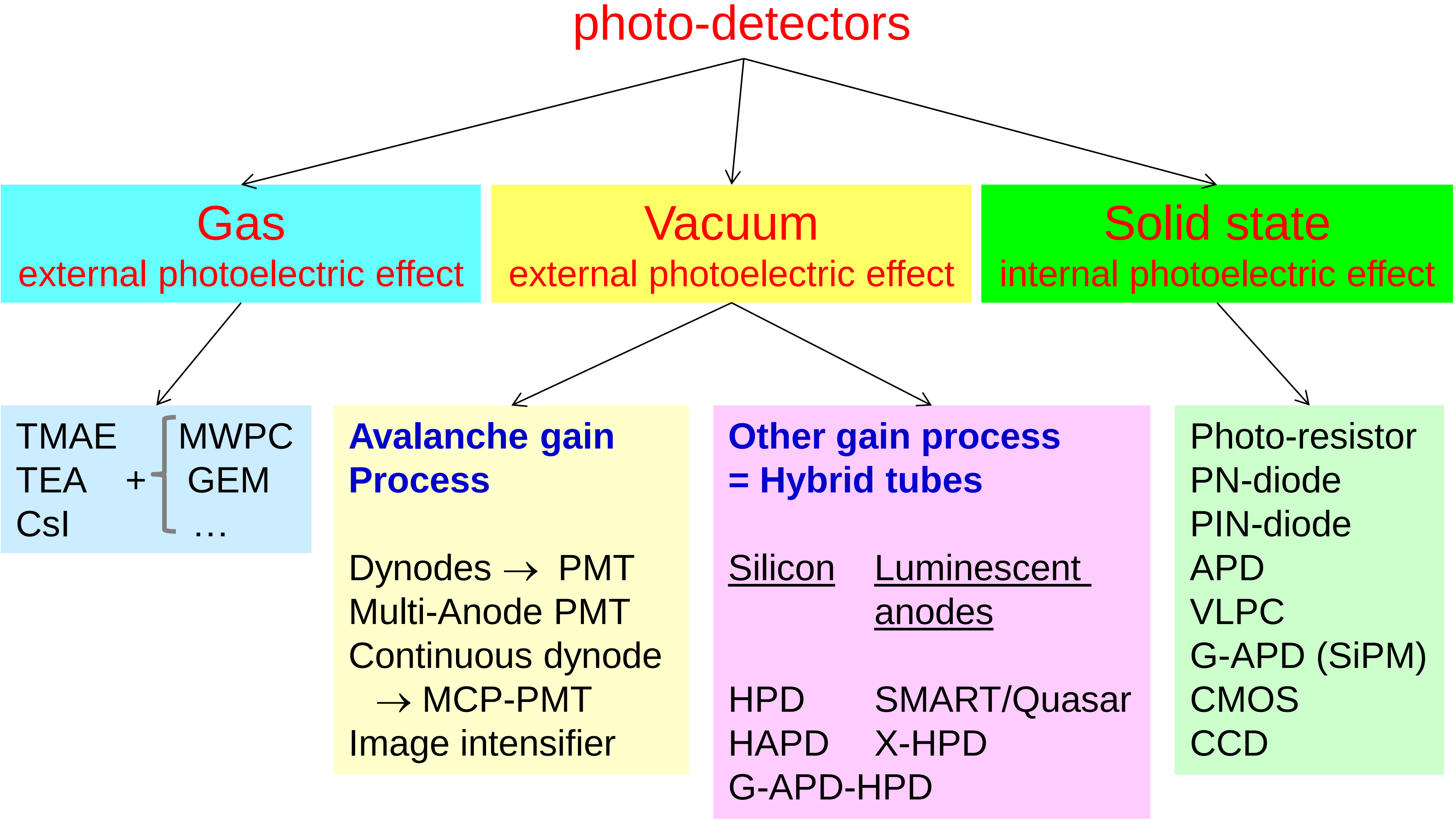


photo-detectors

Gas
external photoelectric effect

Vacuum
external photoelectric effect

Solid state
internal photoelectric effect

TMAE
TEA + { MWPC, GEM, … }
CsI

Avalanche gain Process

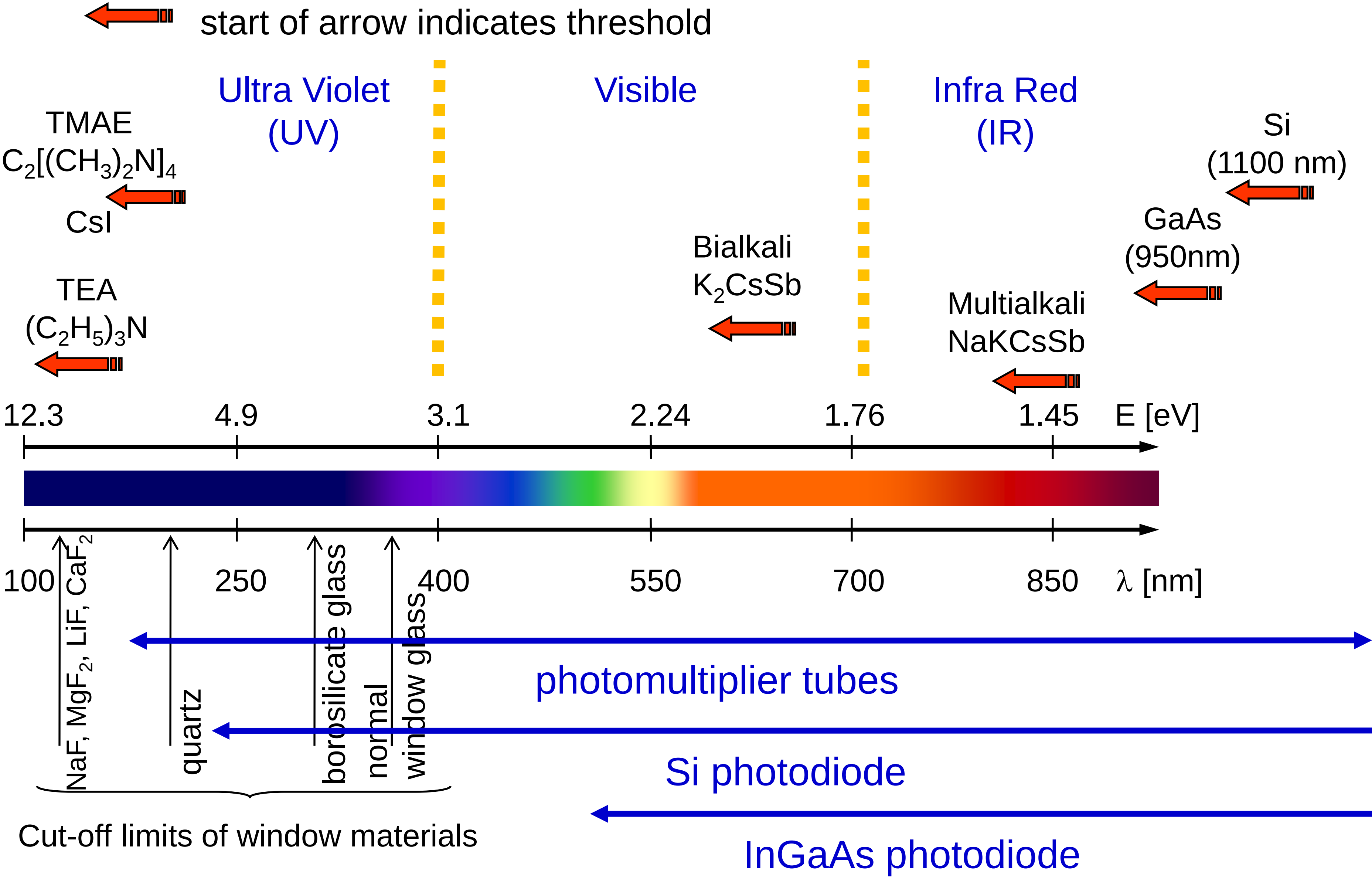
Dynodes → PMT
Multi-Anode PMT
Continuous dynode
→ MCP-PMT
Image intensifier

Other gain process = Hybrid tubes

Silicon	Luminescent anodes
HPD	SMART/Quasar
HAPD	X-HPD
G-APD-HPD	

Photo-resistor
PN-diode
PIN-diode
APD
VLPC
G-APD (SiPM)
CMOS
CCD

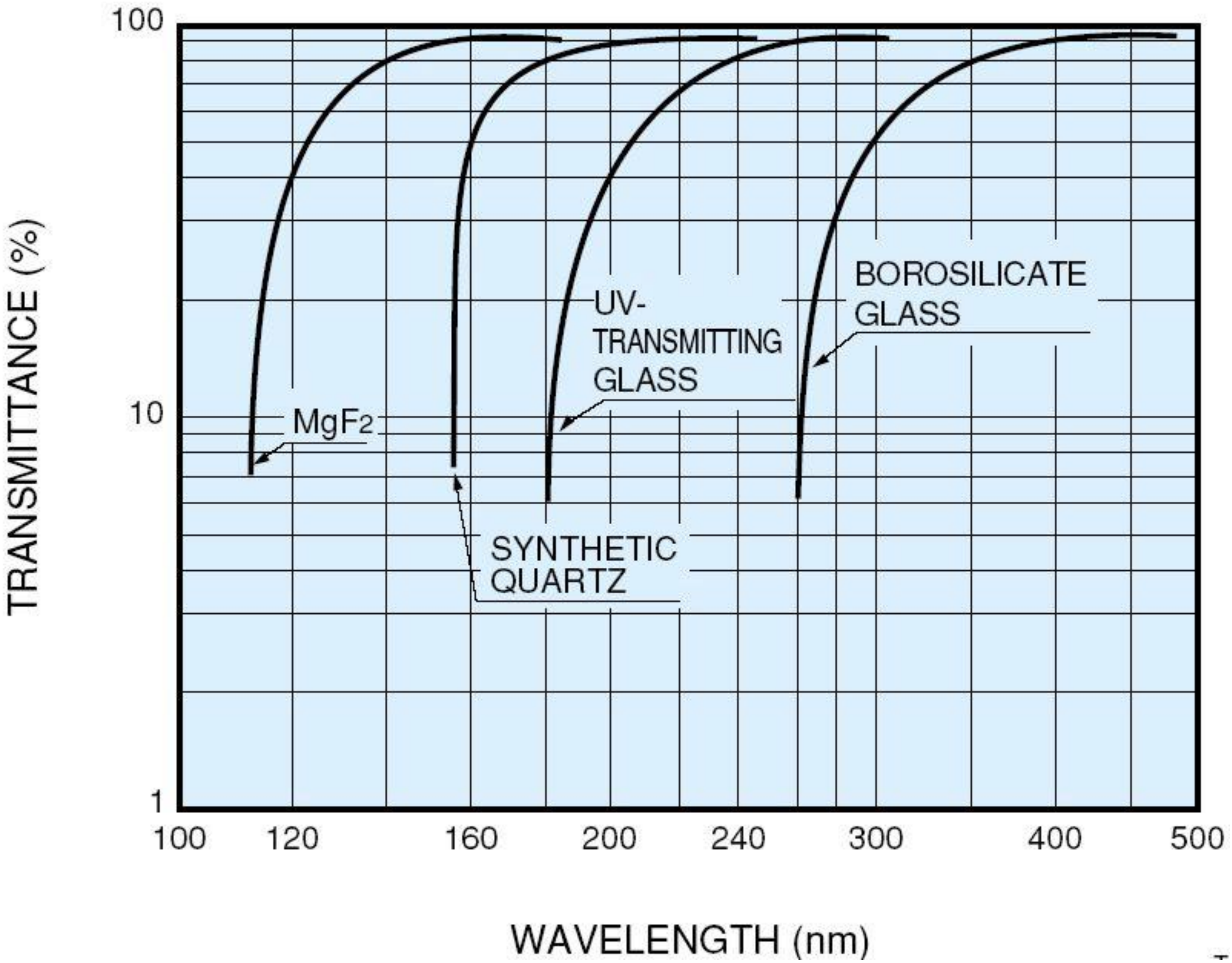
Wavelength Range of Photo-Sensors



start of arrow indicates threshold

Cut-off limits of window materials

Transmission of Optical Windows



Photometric Units

We often use macroscopic quantities, like coulomb or ampere, even when dealing with a handful of electrons.
Sometime it would make more sense to talk in terms: how many electrons?

Same with light, we don't talk often in terms of # of photons, but rather

radiant energy [J] = total energy emitted by the source

radiant flux [W] = total energy / time

irradiance [W/m^2] = radiant flux / unit surface

illuminance [lux] = radiant flux / unit surface in visible range (human eye response)

i.e. the energy transported by the electromagnetic radiation.

However, the response of many detectors depend on the # of photons.
(e. g. the power of FM radio systems is ~ fW while optical systems require μW)
Can easily convert to # of photons

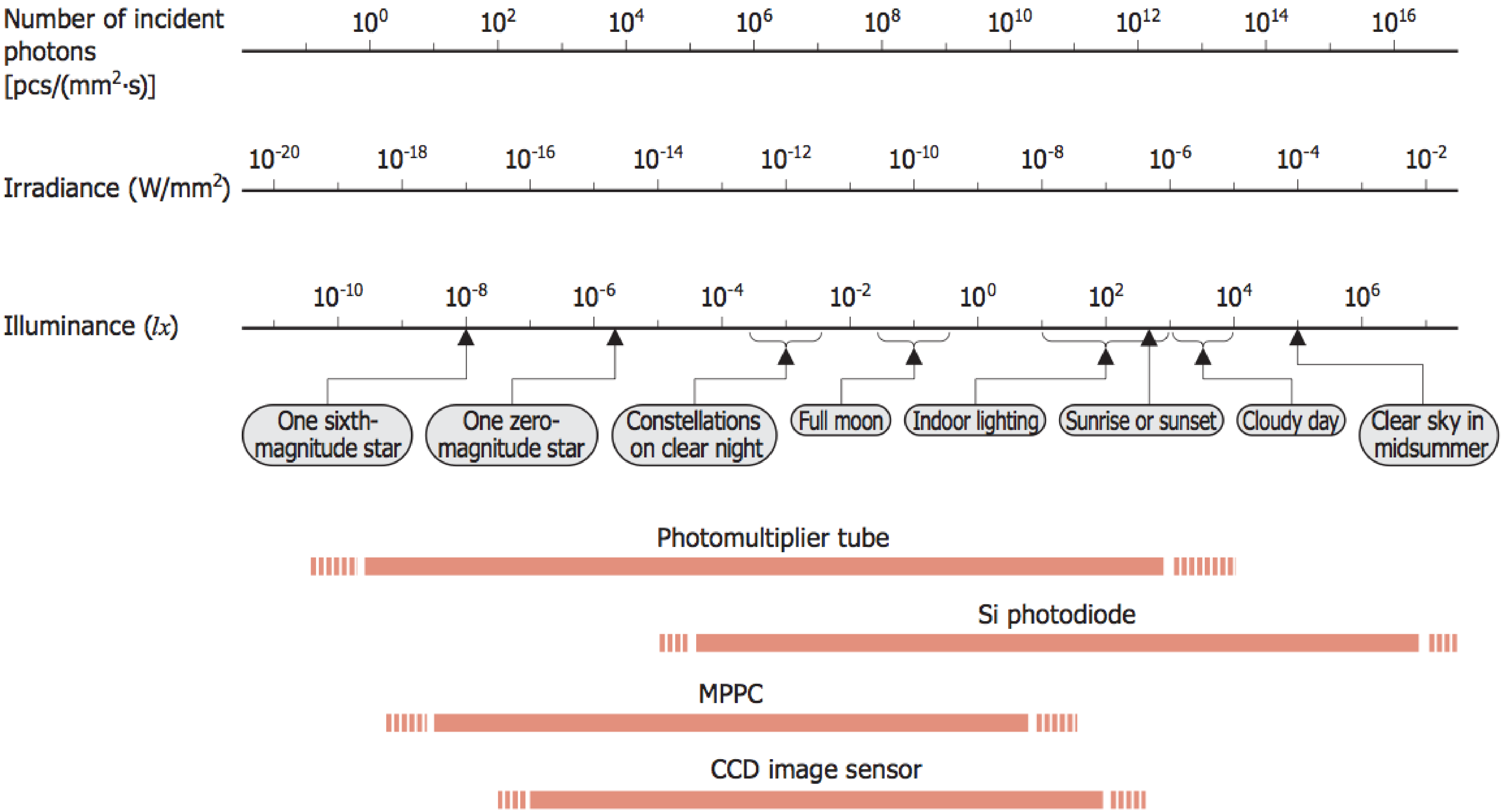
photons = radiant energy / hν

An important quantity is the responsivity (~ sensitivity): what current per optical watt?

$$r = \frac{I}{P} = \frac{\#\gamma \cdot q / t}{\#\gamma \cdot h\nu / t} = \frac{q \cdot \lambda}{hc} \approx 8.1 \times 10^{-4} \times \lambda[\mathrm{nm}] \frac{[\mathrm{A}]}{[\mathrm{W}]}$$

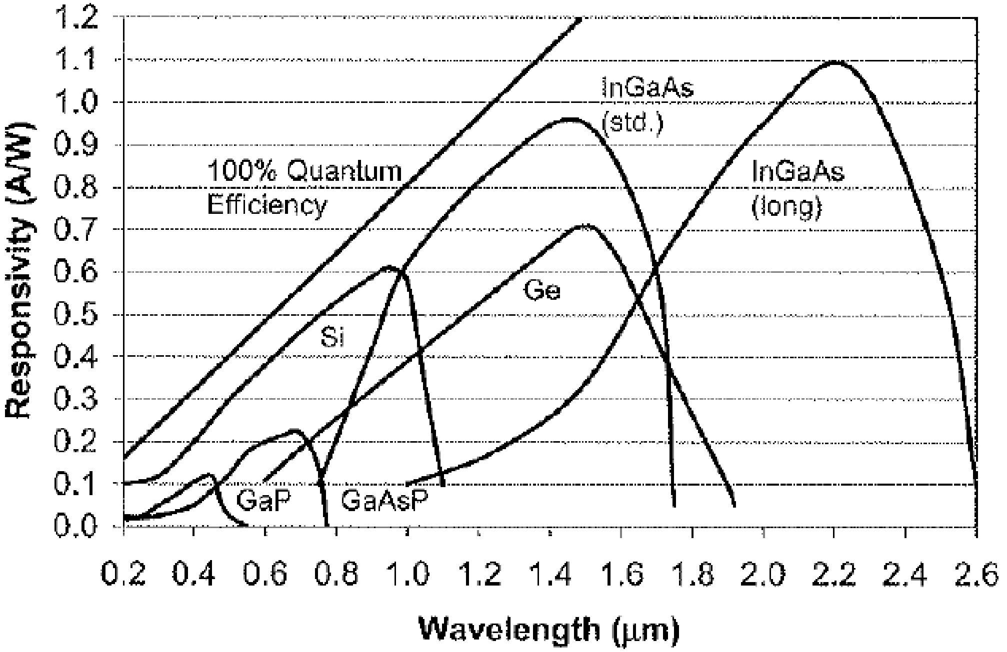
i.e. it depends on the photon wavelength only and not on the # of photons!

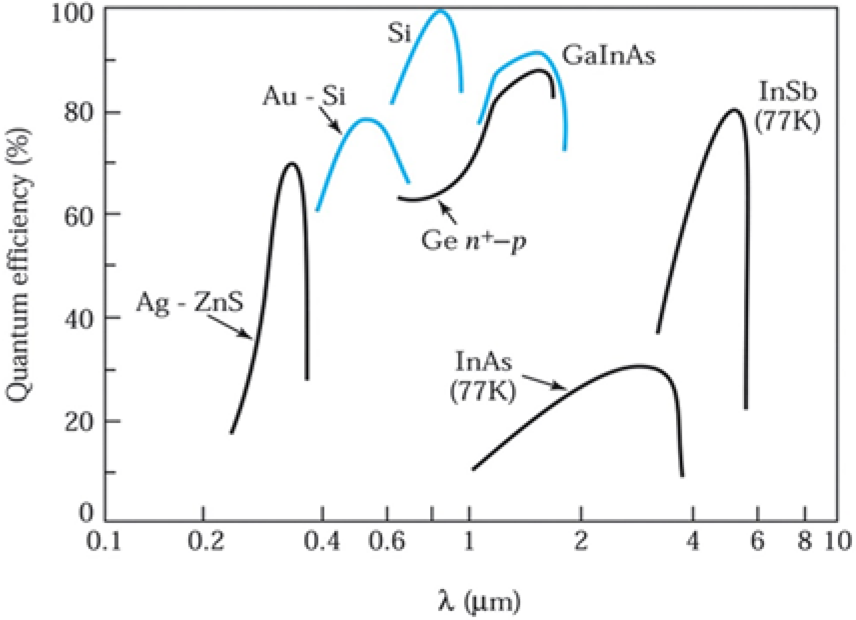
Light Level and Photo-Sensors



Correlations between # of incident photons, irradiance, and illuminance calculated for λ = 555 nm

Responsivity of Different Photo-Diodes



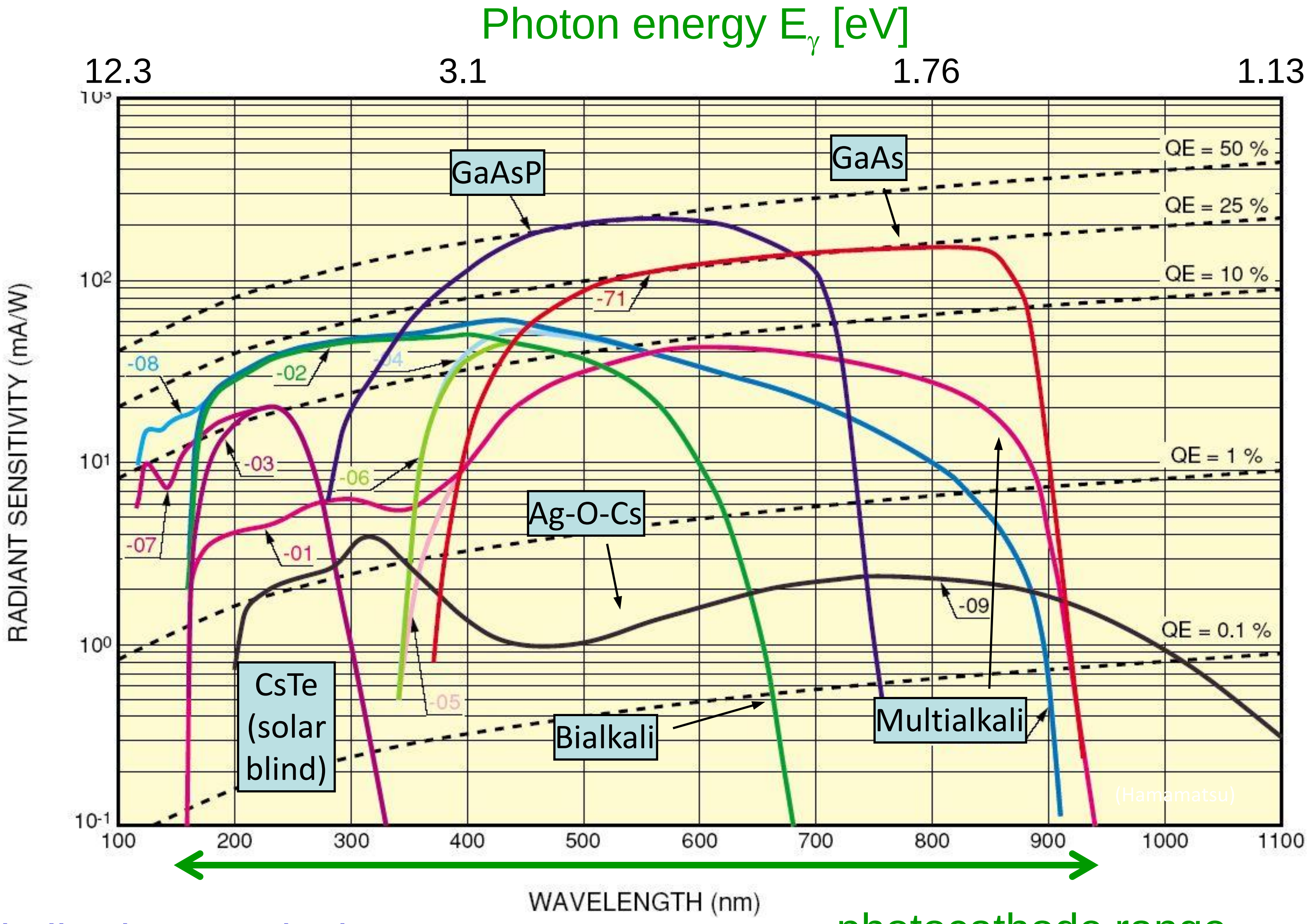


measure responsivity and compare to expected results

→ quantum efficiency

$$QE = R_{measured} / R_{expected} = I_{measured} / I_{expected}$$

Responsivity of Different Photo-Cathodes

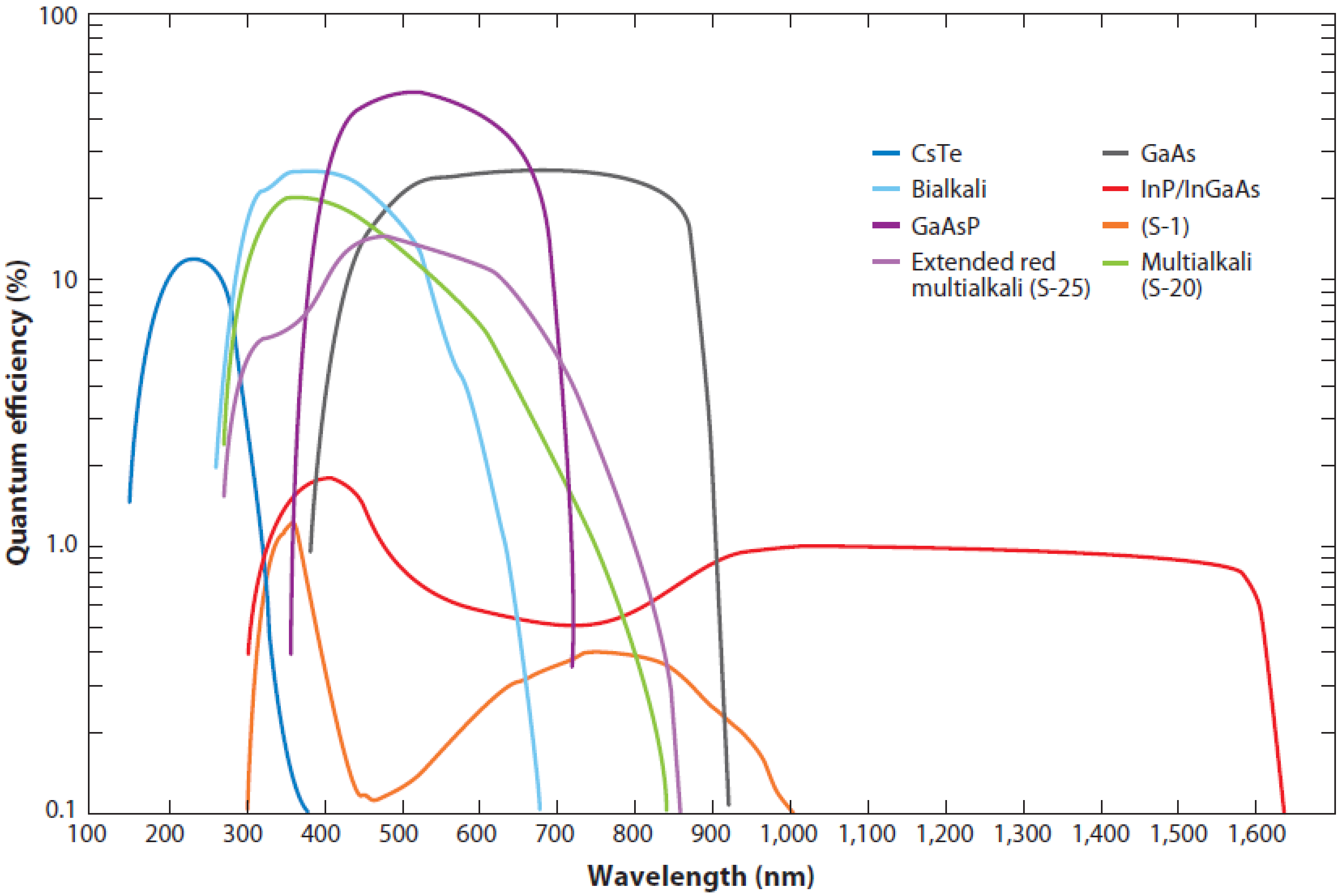


photocathode range

Bialkali: SbKCs, SbRbCs

Multialkali: $SbNa_2KCs$

Photo-Cathode Quantum Efficiency



An Example of a Photo-Detector
The (Human) Eye

First “eyes” evolved some 500 million years ago

Light passes through the cornea, …, lens ,…
before hitting the retina.

The iris controls the size of the pupil, and
therefore amount of light that enters the eye.

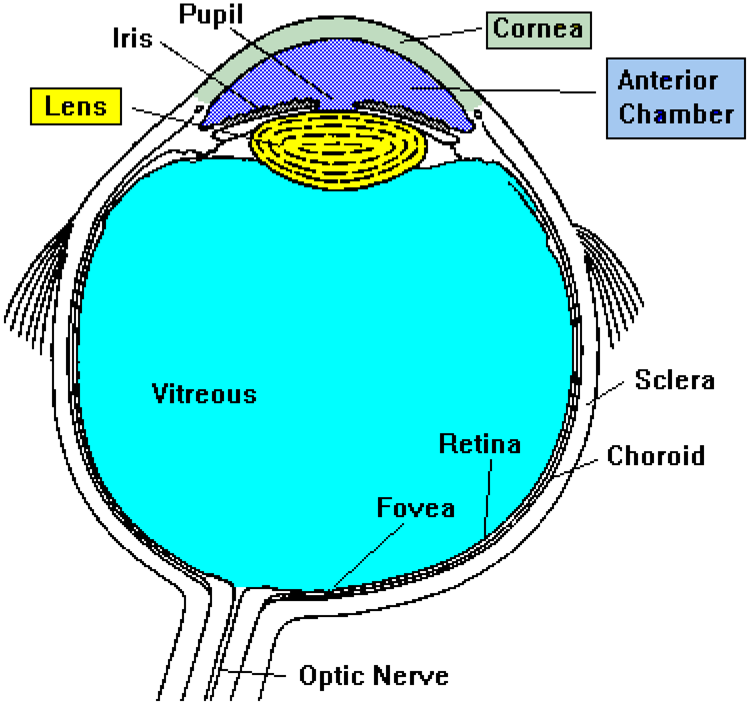
The retina contains ~10^8 photo-receptors
- rods : sensitive to low light contrast (B&W)
- cones : sensitive to colors

that respond to light.

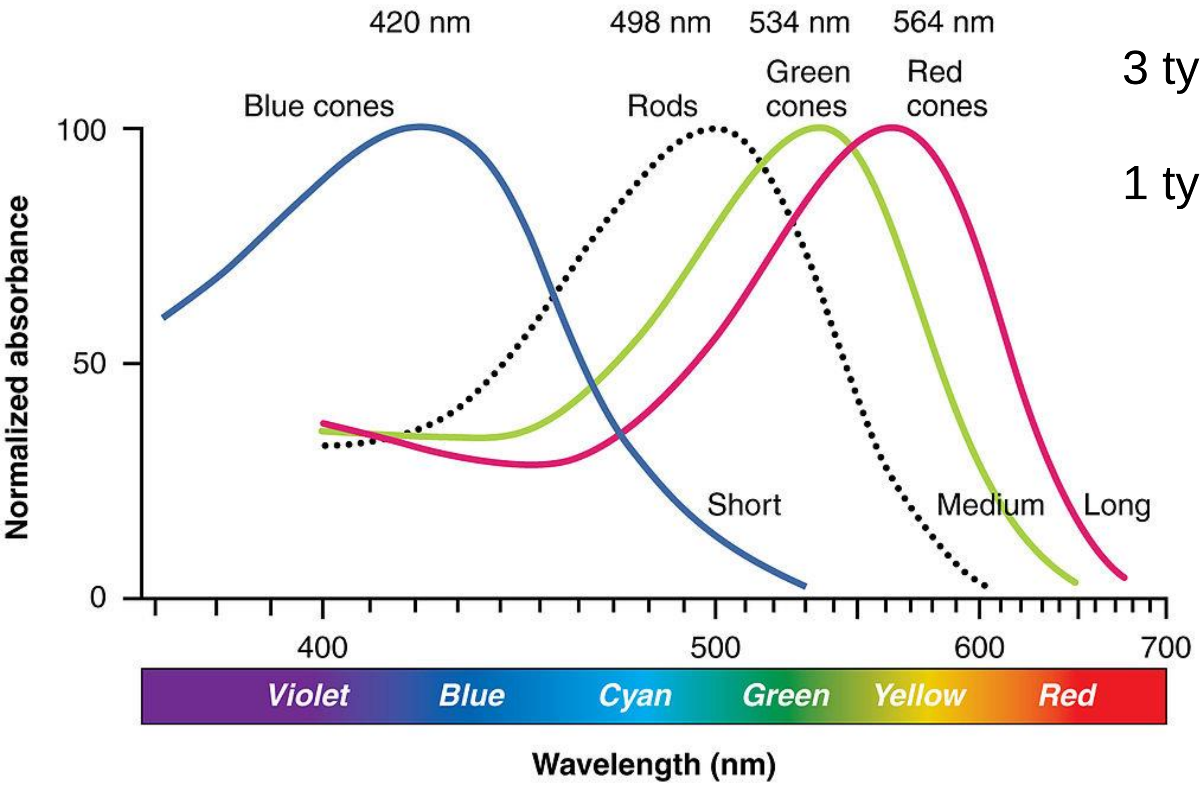
The receptors respond to light by generating
electrical impulses via photo-transduction
that travel through the optical nerve to the brain.

The optical nerve contains ~ 10^6 nerve fibers.

Brain: extremely sophisticated image processor

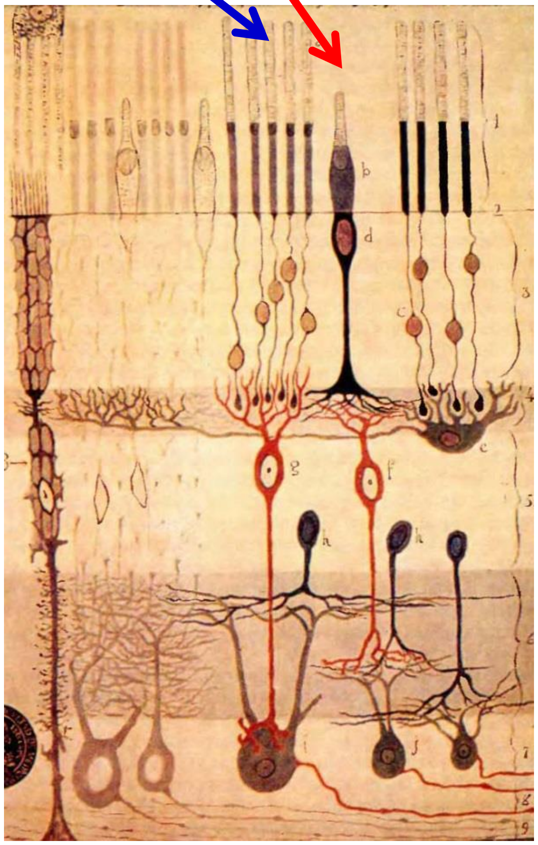


Spectral Sensitivity of the Eye



3 types of cone cells ~ 5×10^6 cells

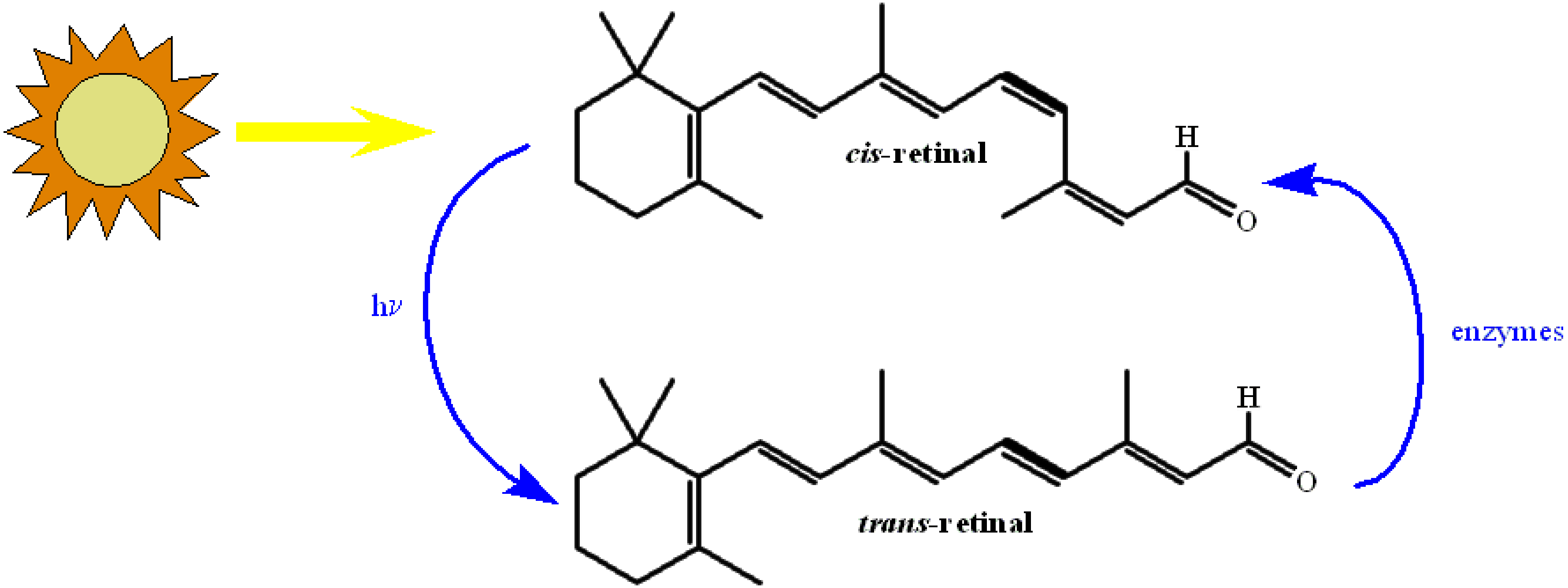
1 type of rod cells ~ 10^8 cells



The large abundance of rod cells over cone cells, explains why we can “see” colors only at high luminosities.

The eye can detect light pulses as low as 10 – 40 photons
- absorption in retina (P.D.E.) ~ 10 – 20 %
- eye transparency

Photo-Transduction



Light conversion into electro-chemical signal in rod and cone cells in the retina

Eye Performance as Photo-Detector

After nature having “built” it over and over again,
the eye can be considered as a very reliable photo-detector.

+’s

good spatial resolution < 1 mm (can be improved with “accessories”)

very large dynamic range from ~ 10^1 to 10^7 photons (6 orders of magnitude !)
with automatic threshold adaptation

good energy resolution, i.e. colors, however in a limited range (~ 400 – 650 nm)

long lifetime

-’s

modest sensitivity: requires between 500 and 1000 photons / second

modest speed: max 20 Hz including image processing

slow response > 0.1 s

Room for improvement ?

Photon-Detector Parameters

Sensitivity and Quantum efficiency $QE = \frac{N_{pe}}{N_{\gamma}}$

Responsivity (output current to input power)

Spectral range:

- infrared (not used in particle detectors)
- visible (450 – 600 nm) (scintillators, Cherenkov)
- ultra-violet (300 – 400 nm) (scintillators, Cherenkov)
- deep (vacuum) UV (scintillation in e.g. noble liquids)

Linearity

Gain and gain fluctuations

Dynamic range

Rate Capabilities (and dead time)

Time resolution

Dark count rate (noise)

Sensitivity to magnetic field

Lifetime and Radiation hardness

Susceptibility to environmental factors

and many others, just add to it

Sensitivity

Quantum Efficiency:

probability that the incident photon (N_γ) generates a photoelectron (N_{pe})

Radiant Sensitivity (responsivity):

output electrical current (I) per incident power (P)

N_γ

photo-detector

N_{pe}

P[W]

photo-detector

I [A]

$$\boxed{QE = \frac{N_{pe}}{N_\gamma}}$$

$$\boxed{S[mA/W] \approx \frac{QE[\%] \cdot \lambda[nm] \cdot e}{hc} = \frac{QE[\%] \cdot \lambda[nm]}{124}}$$

Photo-Detection Probability (P.D.E.) :

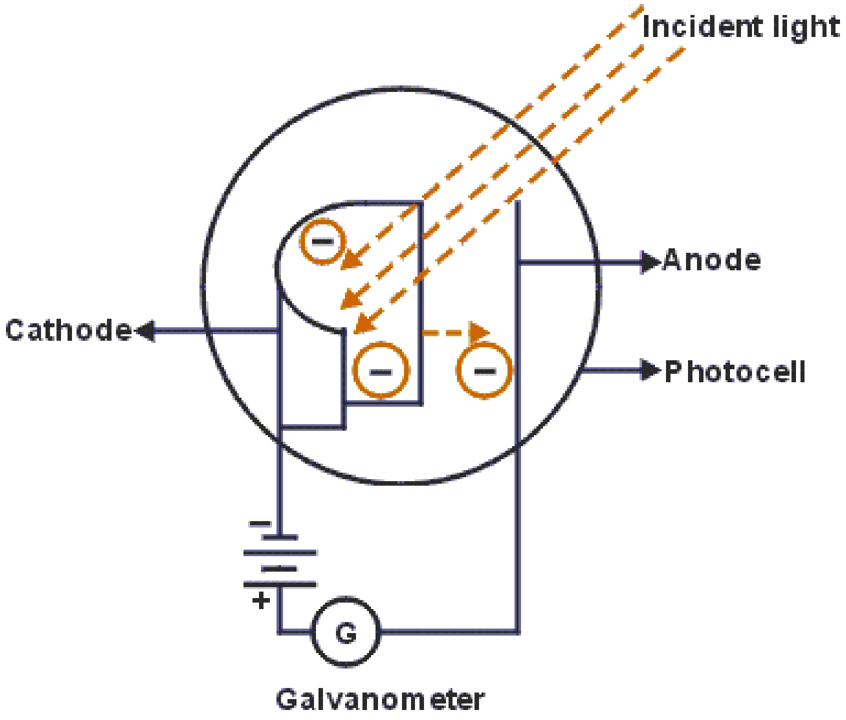
combined probability to produce a photoelectron and to detect it

$PDE[\%] = QE \cdot CE \cdot P_{mult}$ for a PMT (CE: collection eff., P_{mult}: multiplication prob.)

$PDE[\%] = \varepsilon_{geom} \cdot QE \cdot P_{trig}$ for a SiPM (ε_{geom}: geometrical factor, P_{trig}: triggering prob.)

Vacuum Photo Cell

Principle: convert incident photons into electrons via photoelectric effect

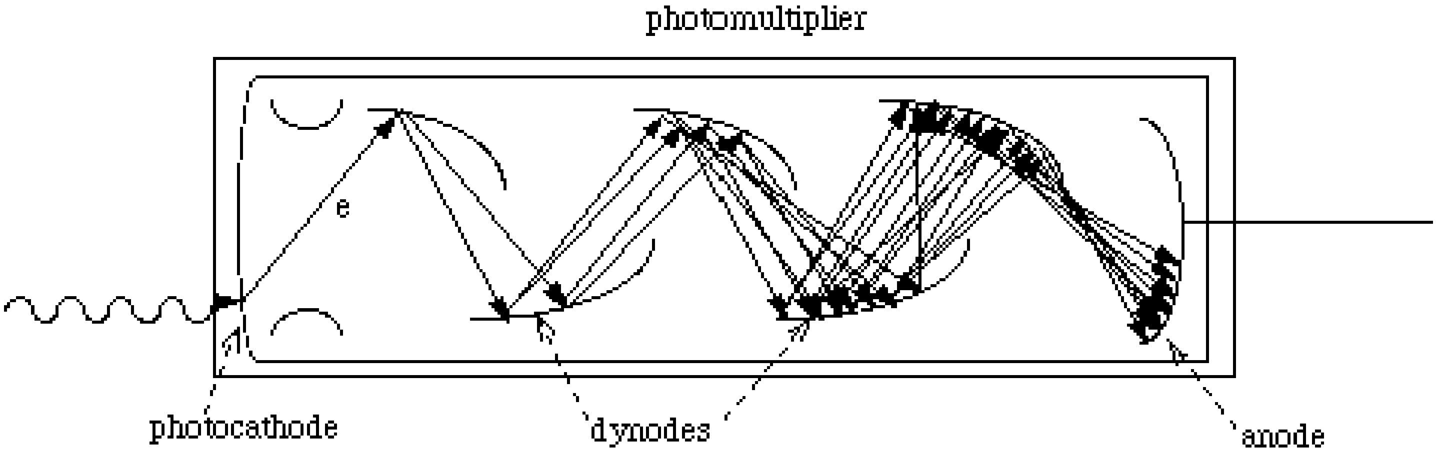


quantum efficiency $$QE(\%) = \frac{N_{pe}}{N_{\gamma}} \times 100$$

radiant sensitivity S (mA / W) $$QE(\%) \approx 124 \cdot \frac{S[mA/W]}{\lambda[nm]}$$

no gain! → lot of photons required to generate a detectable signal (exercise)

The Photo Multiplier Tube (PMT)




(Hamamatsu)

Many different types:
- shapes
- sizes
- gains
- sensitivities
- dynode structures
- applications

Basic Principle of a PMT

photo emission from photocathode
(photolectric effect Q.E. = $N_{p.e.} / N_{photons}$)

secondary emission from dynodes
(i.e. amplification)

single dynode gain g ~ 3 - 5 (f(E))

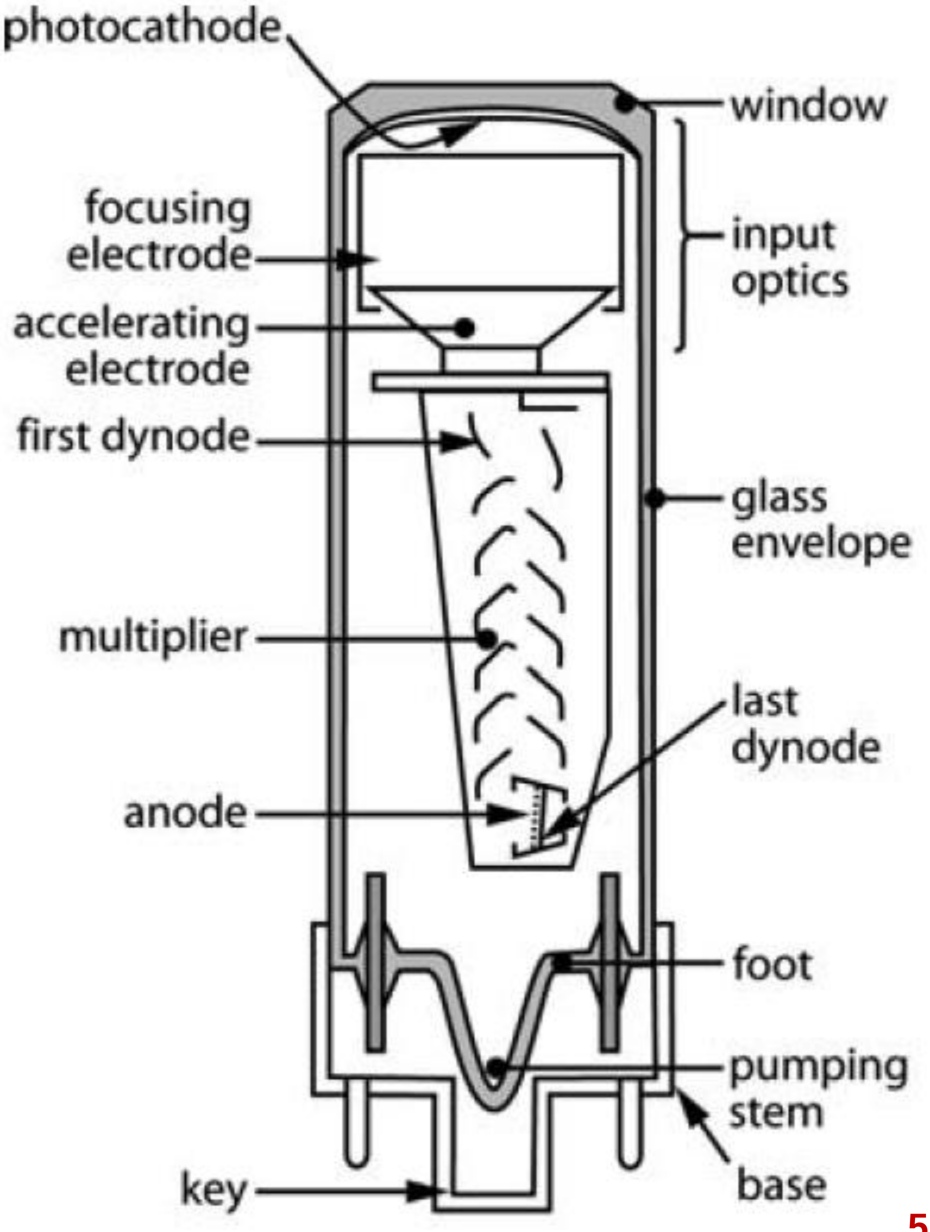
# of dynodes ~ 8 – 14

secondary electron collection at the anode
to form the electrical signal

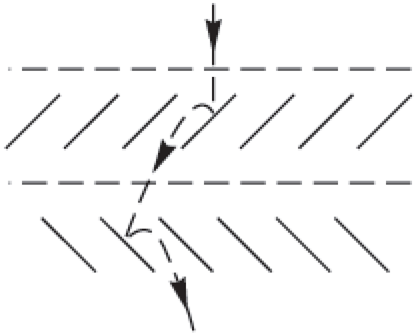
total gain M $$M = \prod_{i=1}^{N} g_i$$

(gain ~ 10^6 -10^8)

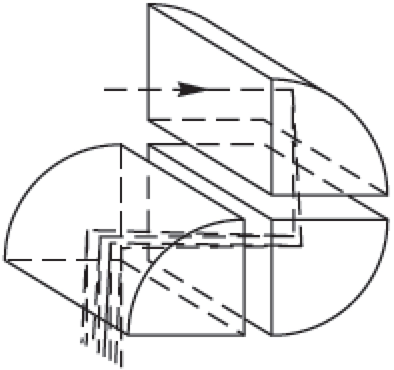
example :
10 dynodes with g = 4 → M = $4^{10} \sim 10^6$



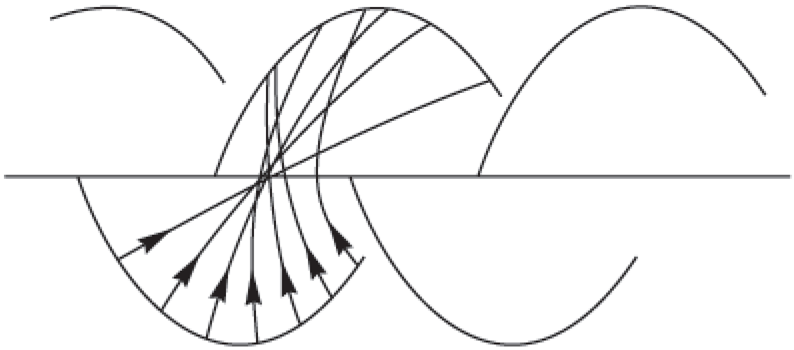
Dynode Structures



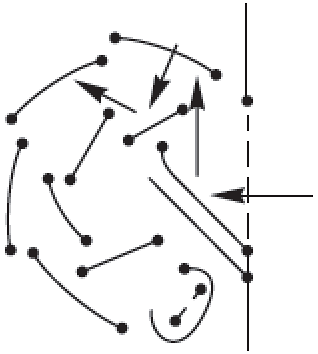
venetian blind



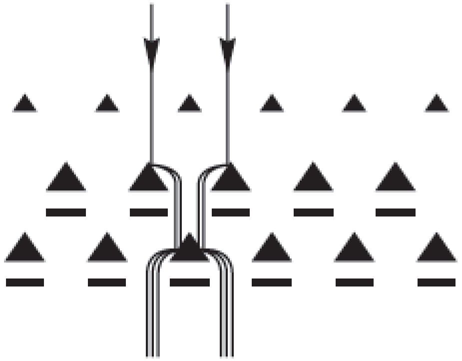
box



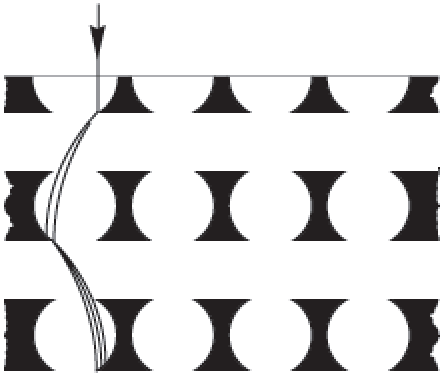
linear focussing



circular cage



mesh



foil

Design considerations

collection efficiency

gain

transit time and transit time spread

immunity to magnetic field

Voltage Dividers

Apply increasing voltages to successive dynodes

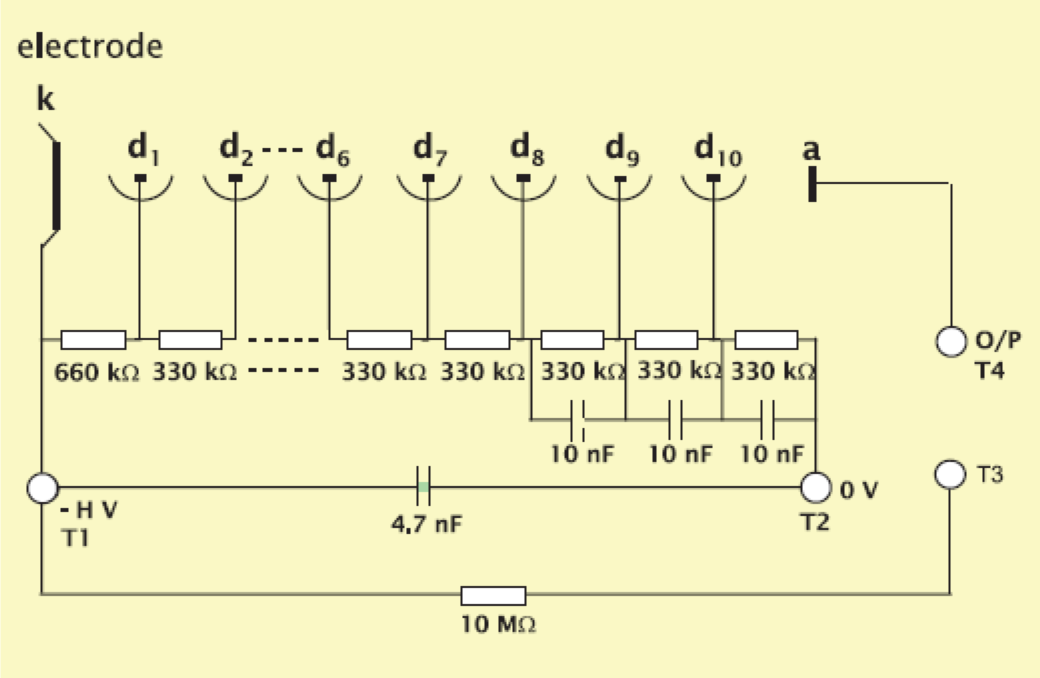
Overall resistance ~ MΩ
For a HV supply of –2000 V
and R = 4 MMΩ
a current of I = 0.5 mA will
flow through the divider

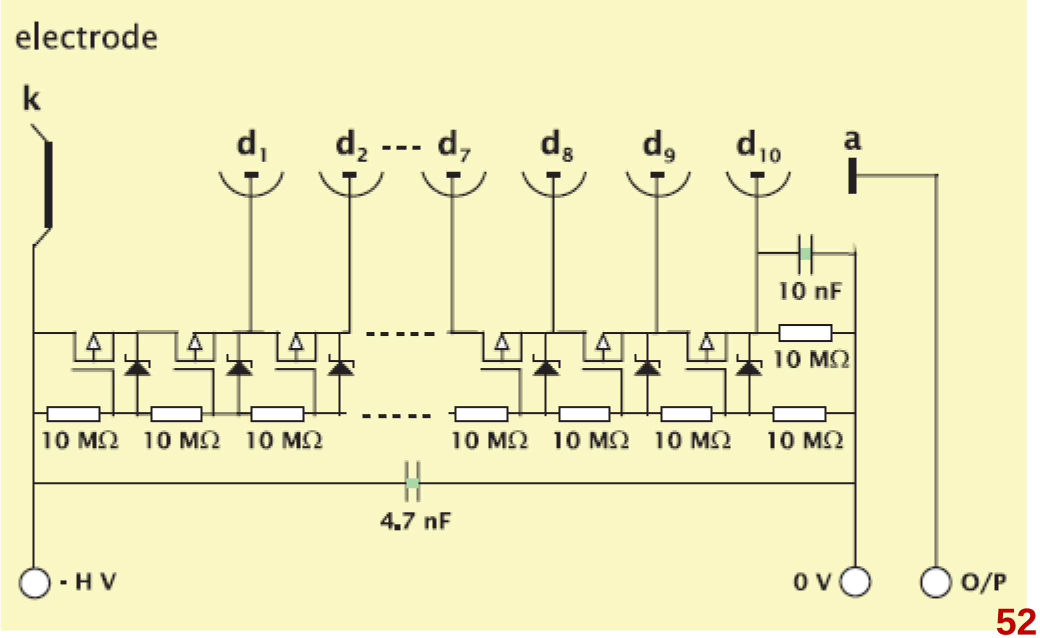
Gain $10^6 – 10^7$

Limitations:
  maximum rate and input light
  → sagging

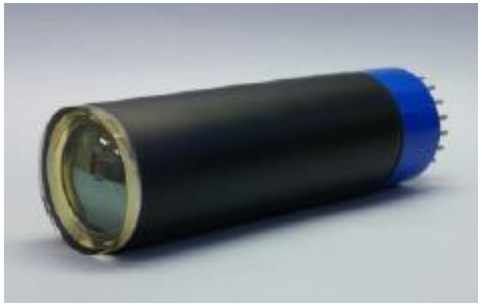
To improve PMT performance
use (transistor)
stabilized voltage dividers

Unfortunately the art of designing voltage dividers is fading away ☹

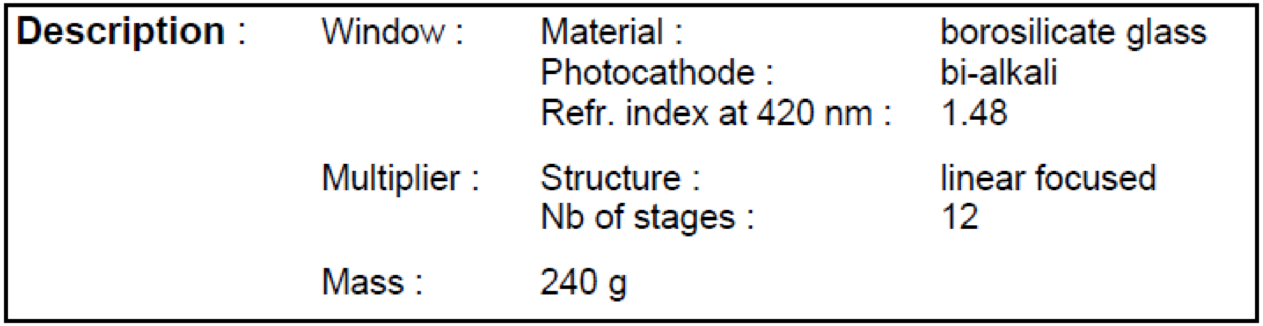




PMT Data Sheet (an Example XP2020)



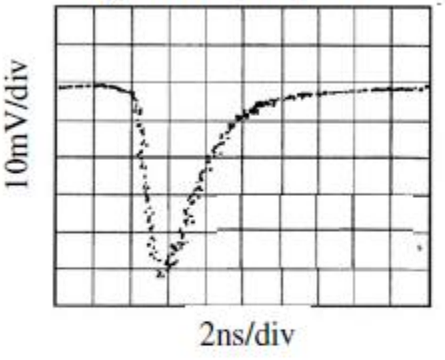
Standard, very fast, 12-stage, 51 mm (2”) round tube



Description :	Window :	Material :	borosilicate glass
		Photocathode :	bi-alkali
		Refr. index at 420 nm :	1.48
	Multiplier :	Structure :	linear focused
		Nb of stages :	12
	Mass :	240 g	

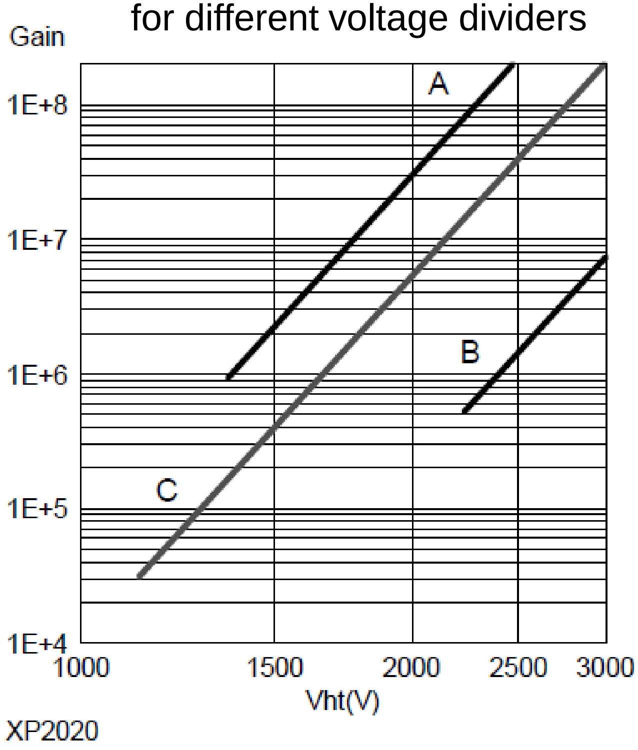
spectral range
sensitivity
gain
max. voltage
dark current
rise time
transit time

Typical output pulse:

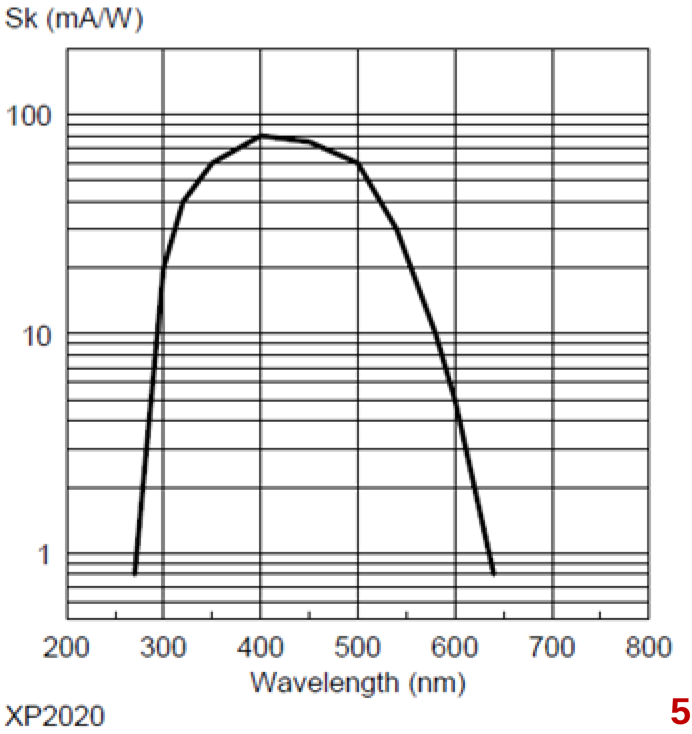


Typical gain curve

for different voltage dividers



Typical spectral characteristics



Gain Fluctuations in PMTs

Limits energy resolution and photon counting capabilities of PMTs

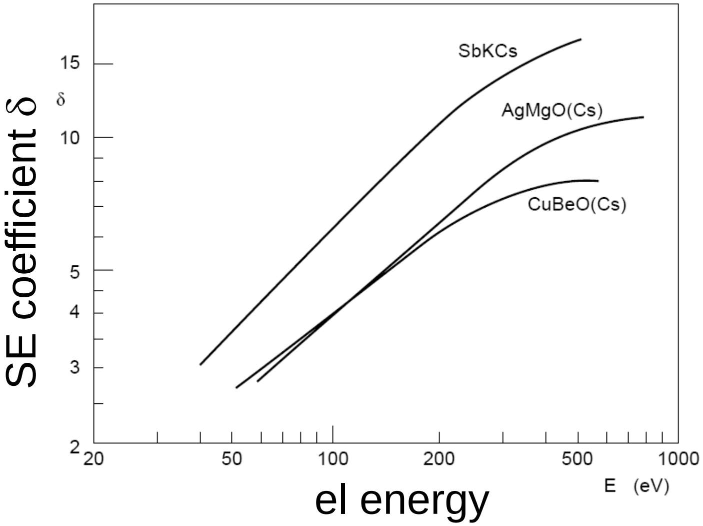
Mainly determined by the fluctuations of the number $m(\delta)$ of secondary electrons emitted from the dynodes

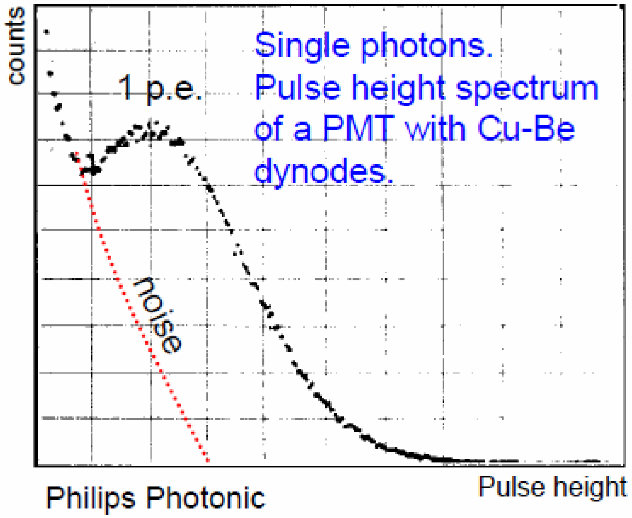
δ – secondary emission coefficient (# el. emitted / # primary el.)

from Poisson statistics $$P_\delta(m) = \frac{\delta^m e^{-\delta}}{m!}$$

the fluctuation (s) is $$\frac{\sigma_m}{\delta} = \frac{\sqrt{\delta}}{\delta} = \frac{1}{\sqrt{\delta}}$$

$\Rightarrow$ fluctuations dominated by 1st dynode gain





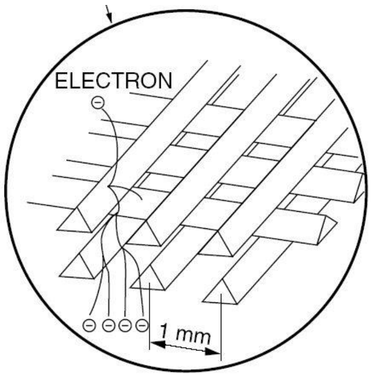
Single photons. Pulse height spectrum of a PMT with Cu-Be dynodes.

Philips Photonic

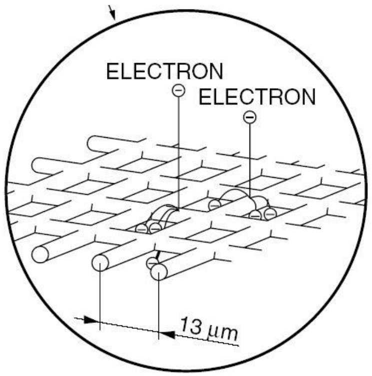
Multi Anode PMT

mesh type dynodes

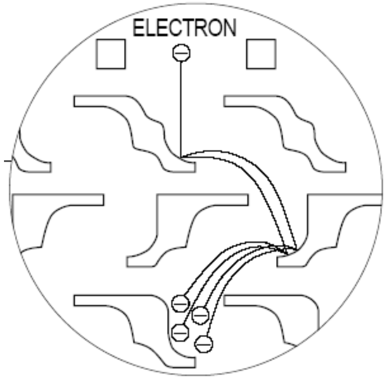
metal channel dynode



COARSE MESH TYPE



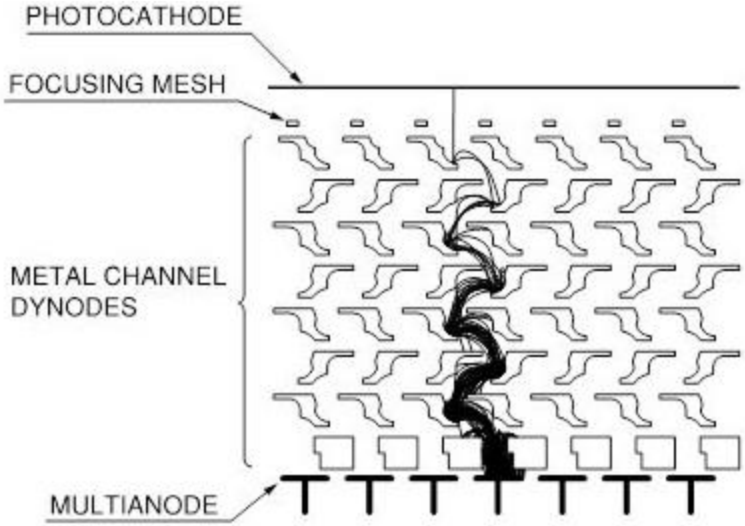
FINE-MESH TYPE



8 × 8 anode matrix

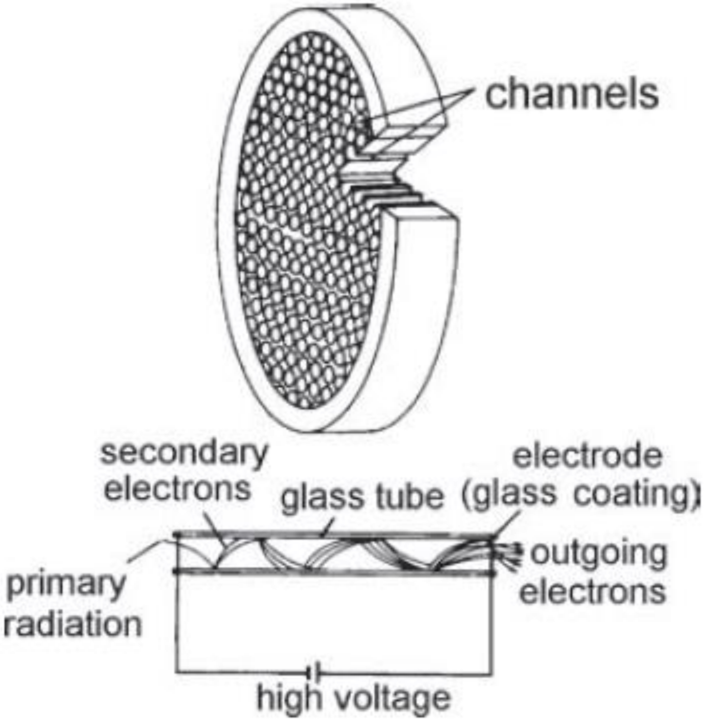
The electron shower evolution is localized and essentially aligned along an axis between the photocathode and anode.

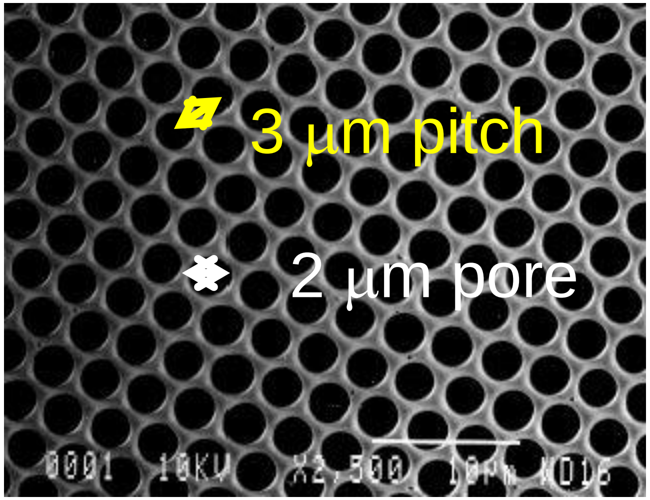
Using a segmented anode → multi-anode PMT can gain position sensitivity and reconstruct the impact position of the photon on the cathode. This configuration is also less sensitive to B.

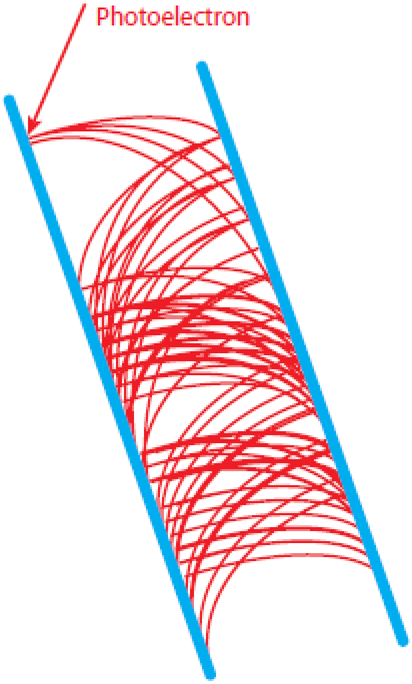


Used
- for scintillating fibers readout,
- bundles of wavelength shifting fibers
- RHIC detectors

Micro Channel Plate PMT







continuous dynode gain

high gain up to 5 × 10^4
fast signal (transit time spread ~ 50 ps)
excellent time resolution
less sensitive to magnetic field
limited lifetime (0.5 C/cm^2)
limited rate capability

Hybrid Photo Detectors (HPD's)

Combination of vacuum photon detectors and semiconductor technology

Photo-emission from cathode

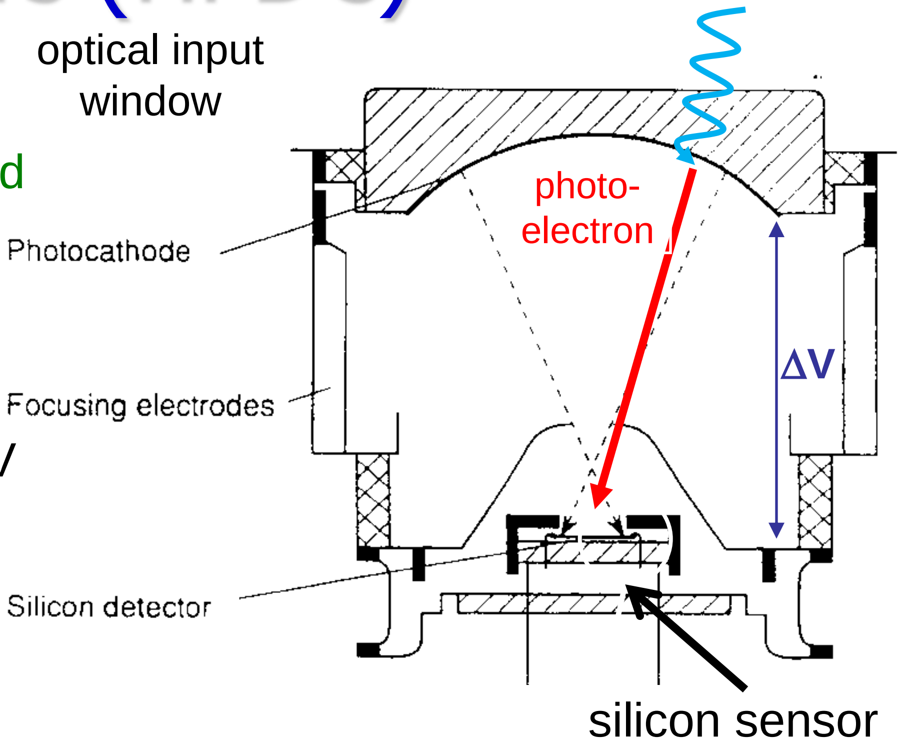
Photo-electron acceleration to ΔV ~ 10-20 kV

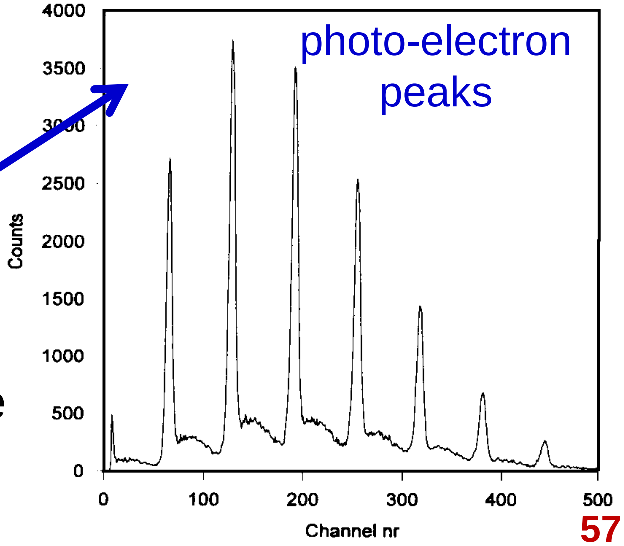
Gain achieved in one step by energy dissipation of keV photo-electrons in semiconductor detector.
This results in low gain fluctuations.

Output direct electronic signal

Suited for single photon detection with high resolution

Segmented (multipixel) silicon sensor
→ can reconstruct impact point of photon on photocathode





Gaseous Photo Detectors

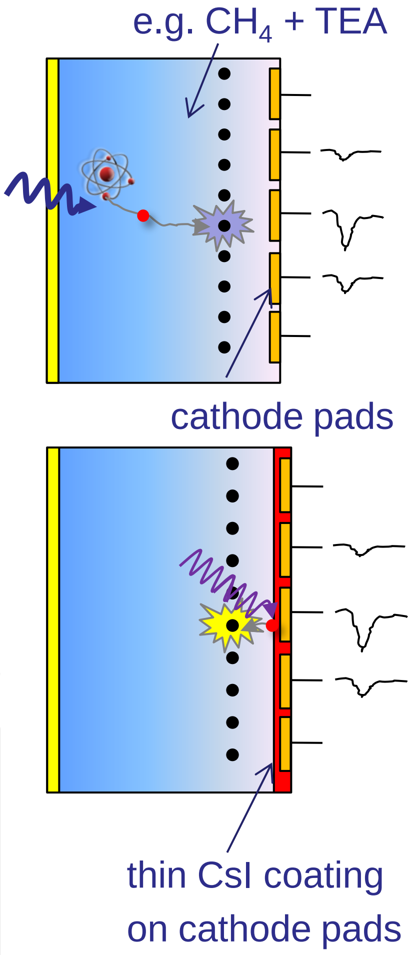
In general (visible) light does not produce any ionization in air;
on the other hand, x-rays do → Roentgen

There are two main principles of operation :

1. ionize photosensitive molecules,
   admixed to the counter gas (CH_4) like TMAE or TEA, or

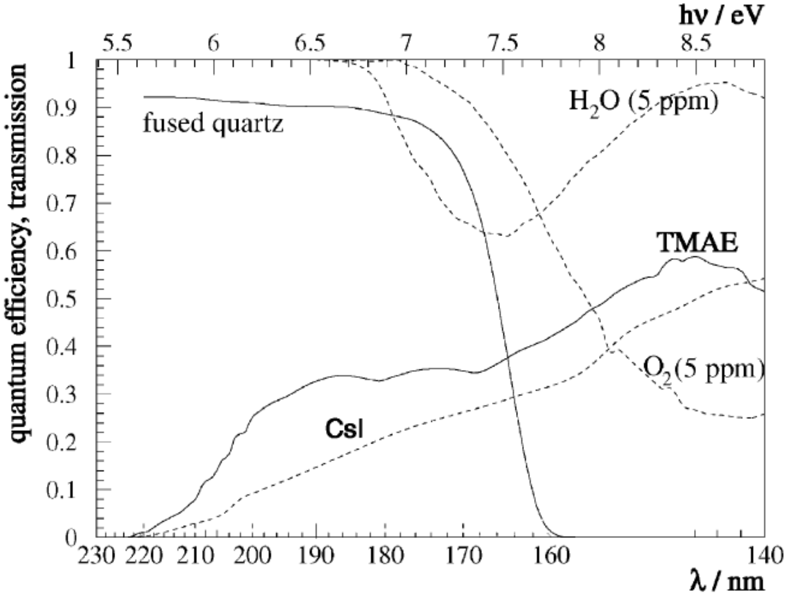
2. release photoelectrons from a solid photocathode (CsI, bialkali...);

Then use free ph.el. to trigger a Townsend avalanche → Gain



TEA, TMAE, CsI, …
work only in the deep UV region.

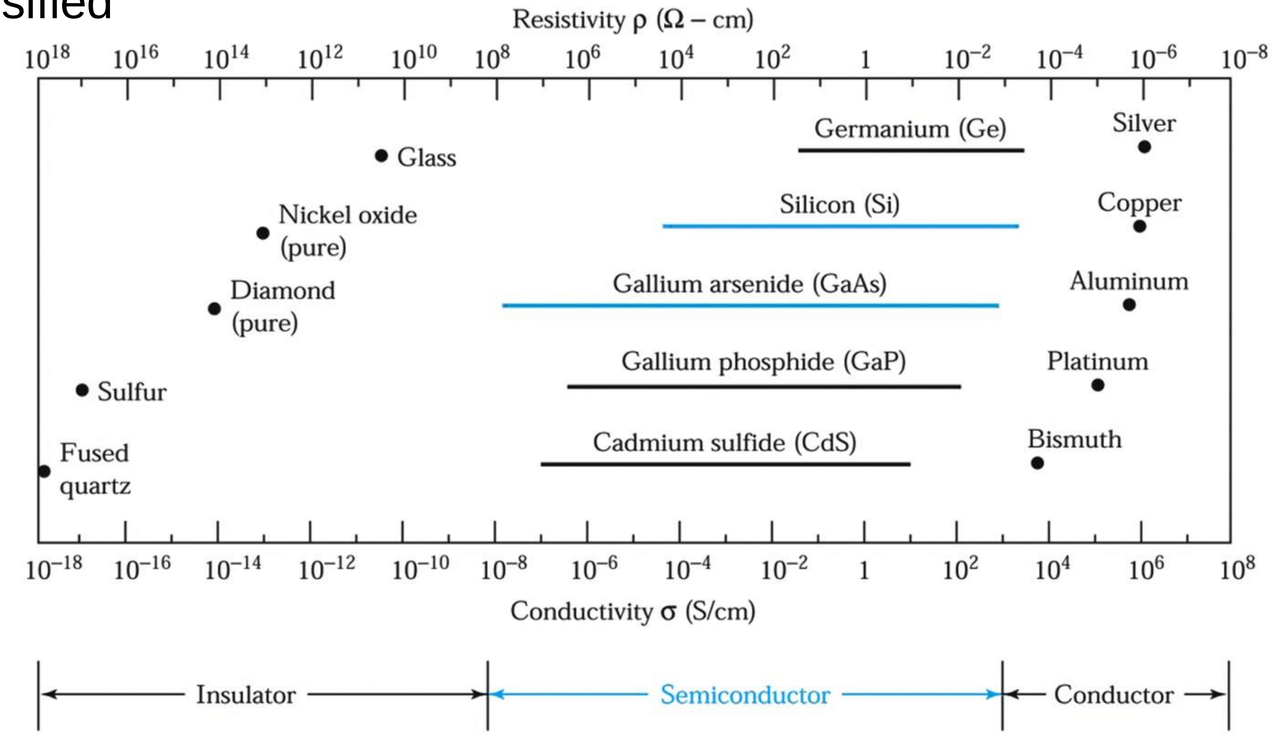
Bialkali works in visible domain,
however requires extremely
clean gases.
(not yet demonstrated)

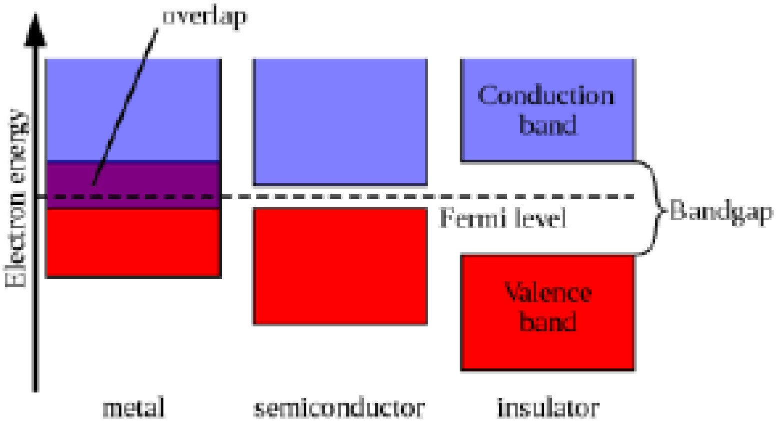


Conductors

Materials are generally classified into
- conductors
- semi-conductors
- insulators

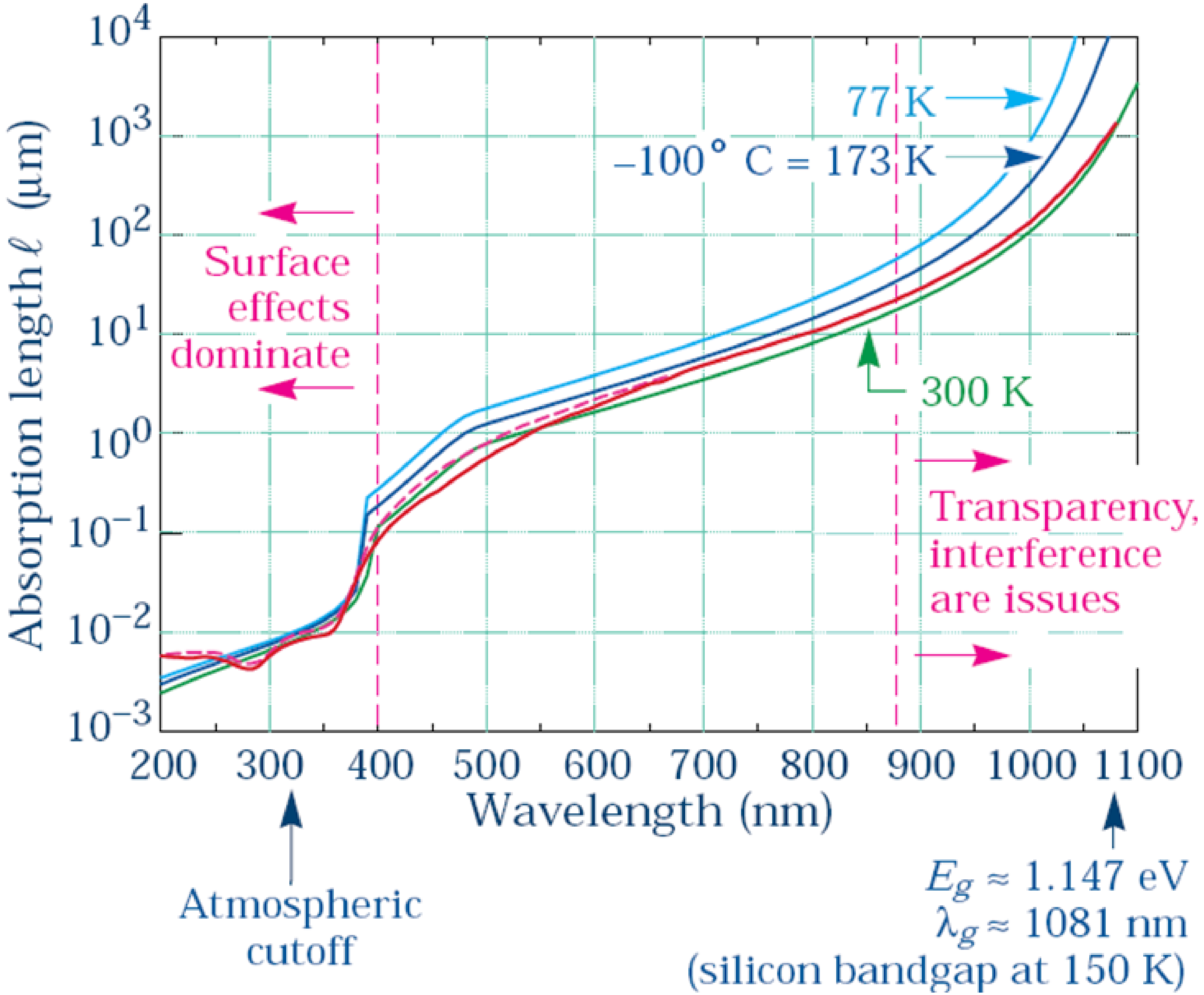
based e.g. on
their intrinsic resistivity
(not only)





or the energy band structure
i.e. the energy required to move one electron from the valence to the conduction band)
E_g ~ O[10 eV] in insulators
E_g ~ O[eV] in semiconductors
non-existing (overlap) in metals.

Light Absorption in Silicon



Optical Absorption Coefficient

photon flux attenuation

$$\boxed{\Phi(x)=\Phi_0 e^{-\alpha(\lambda)x}}$$

α – absorption coefficient which depends on hν

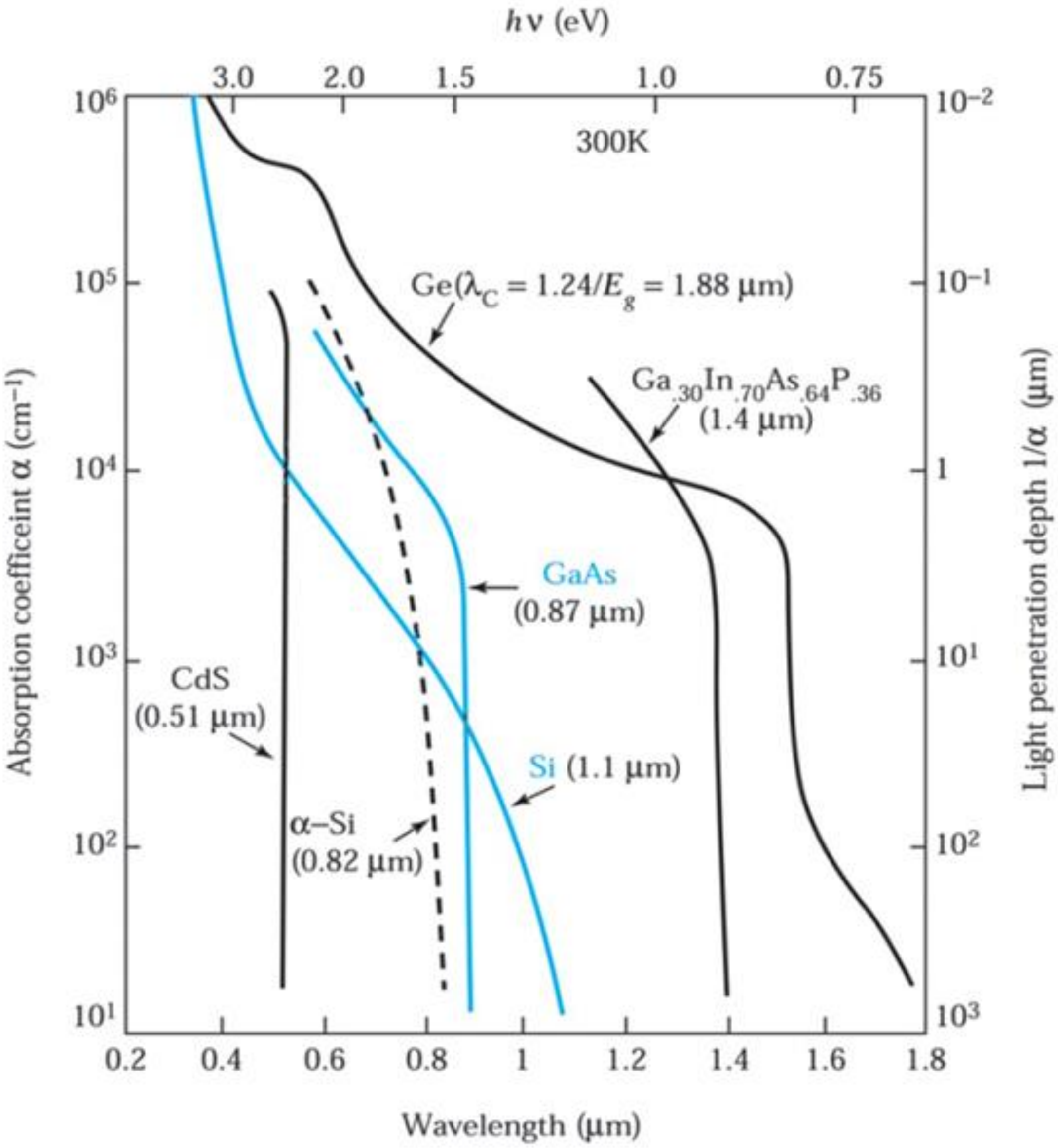
that has implications in the design of a photodetector :

1. the entrance window must be as thin as possible
2. to detect most photons the sensitive volume must be sufficiently thick

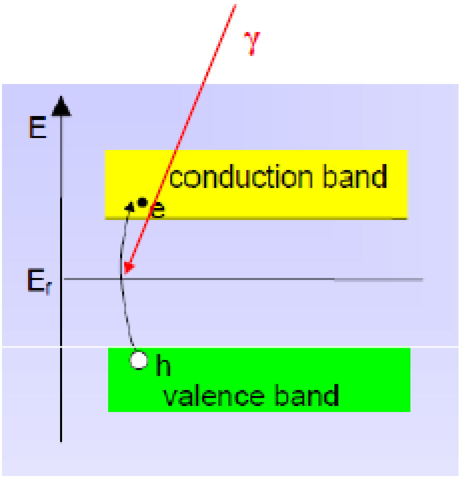
cutoff wavelength λ_c

$$\boxed{\lambda_c = \frac{1.24}{E_g}\,\mu\text{m}}$$

at longer wavelengths, the device becomes transparent



Si Photo-Detector (Example)



Imagine a photon hitting a small Si cube ($10\ \mu m \times 10\ \mu m \times 10\ \mu m$)
and freeing an electron to the conduction band
via the photo-electric effect.

In a pure semiconductor (undoped) semiconductor
the number of free electrons in the conduction band is

$$n_i = 9.65 \times 10^9\ cm^{-3} \times (10\ \mu m)^3 \sim 10$$

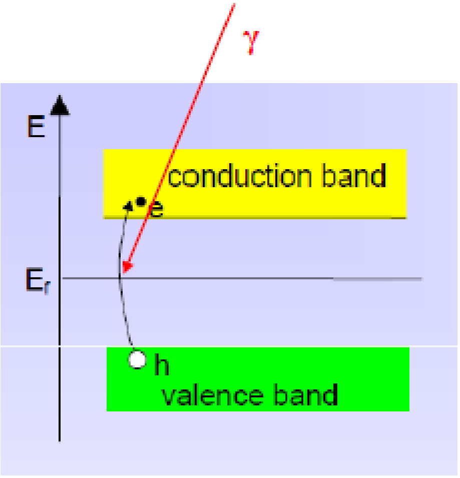
much larger compared to the single freed electron.
The signal is overwhelmed by the background
→ cannot do much about the signal (ionization detector)
→ must reduce the background

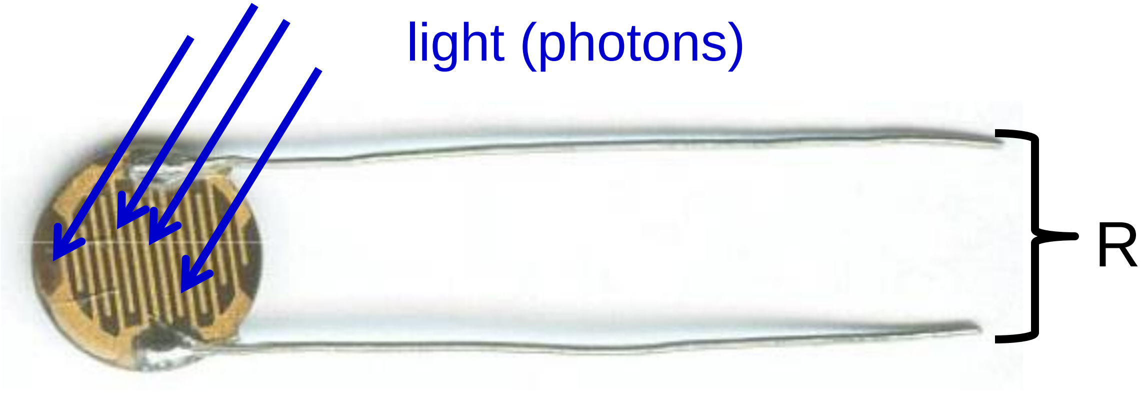
With a lot of light (i.e. a large number of photons > 1000) the effect becomes detectable,
e. g. as a change in the resistance of the Si cube.
This is the principle of operation of the photo–resistor.

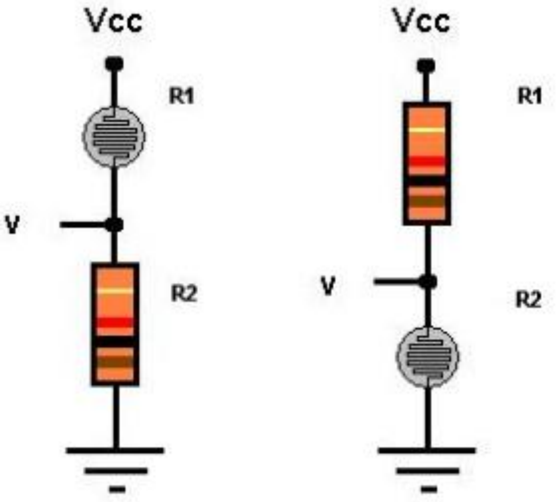
What can we do to improve the situation ?

1. empty (deplete) the Si cube of free charges → *pin* photo-diode
   still not enough to detect single photons (to small charge)
   it works with ~100 photons
2. add internal amplification → avalanche photo-diode

The Silicon Photo Resistor







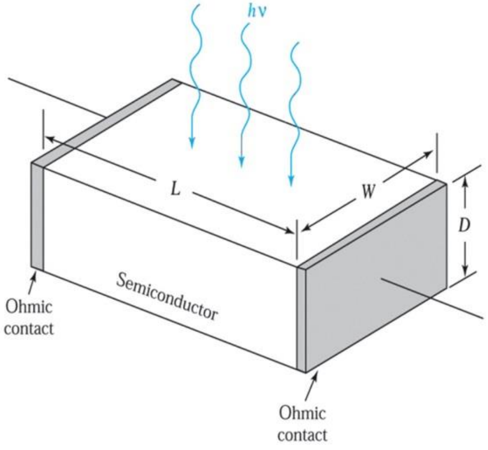


Figure 10.1a
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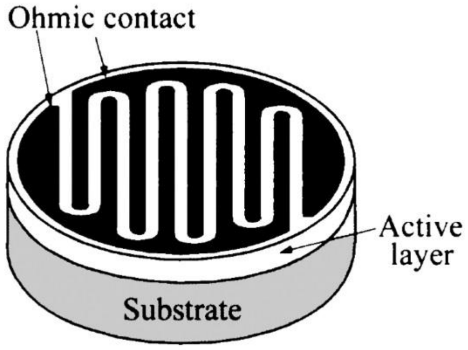

Figure 10.1b
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low sensitivity

low speed ~ O(1 ms)

used for exponometers, photo-relays, etc.

Photonic Devices

Photonic devices are devices in which the basic particle of light – the photon – plays a major role. The dominant photo-absorption process is the photoelectric effect.

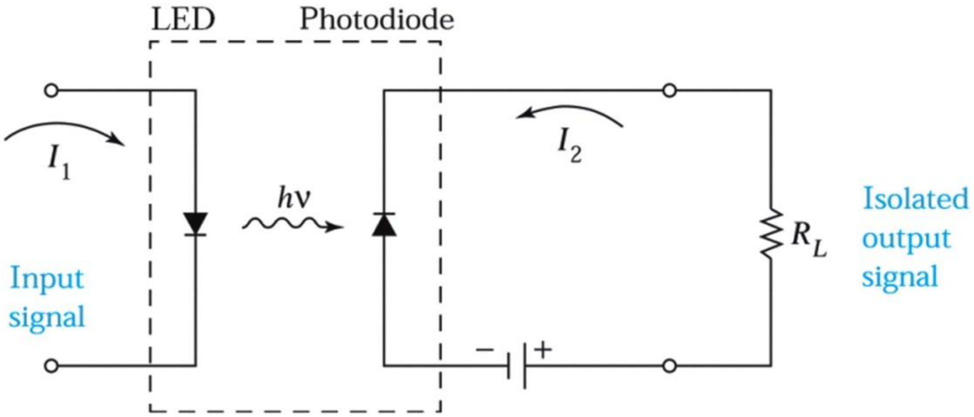
Photonic devices went through a tremendous development over the last 50 years thanks to the broad spectrum of applications. Today they represent an important fraction of industrial electronics development.
They are almost everywhere. Just to give some common examples : DVD players, optical fiber communication, solar panels, computer screens, LED TVs,
infra-red light detectors, barcode readers, range meters, lab instruments, …

Usually photonic devices are divided into four major groups

- light-emitting diodes (LED)
  - convert electrical energy into optical energy
- lasers
  - light amplification by stimulated emission, which converts electrical energy into optical energy
- photo-detectors
  - electrically detect optical signals
- solar cells
  - convert optical energy into electrical energy

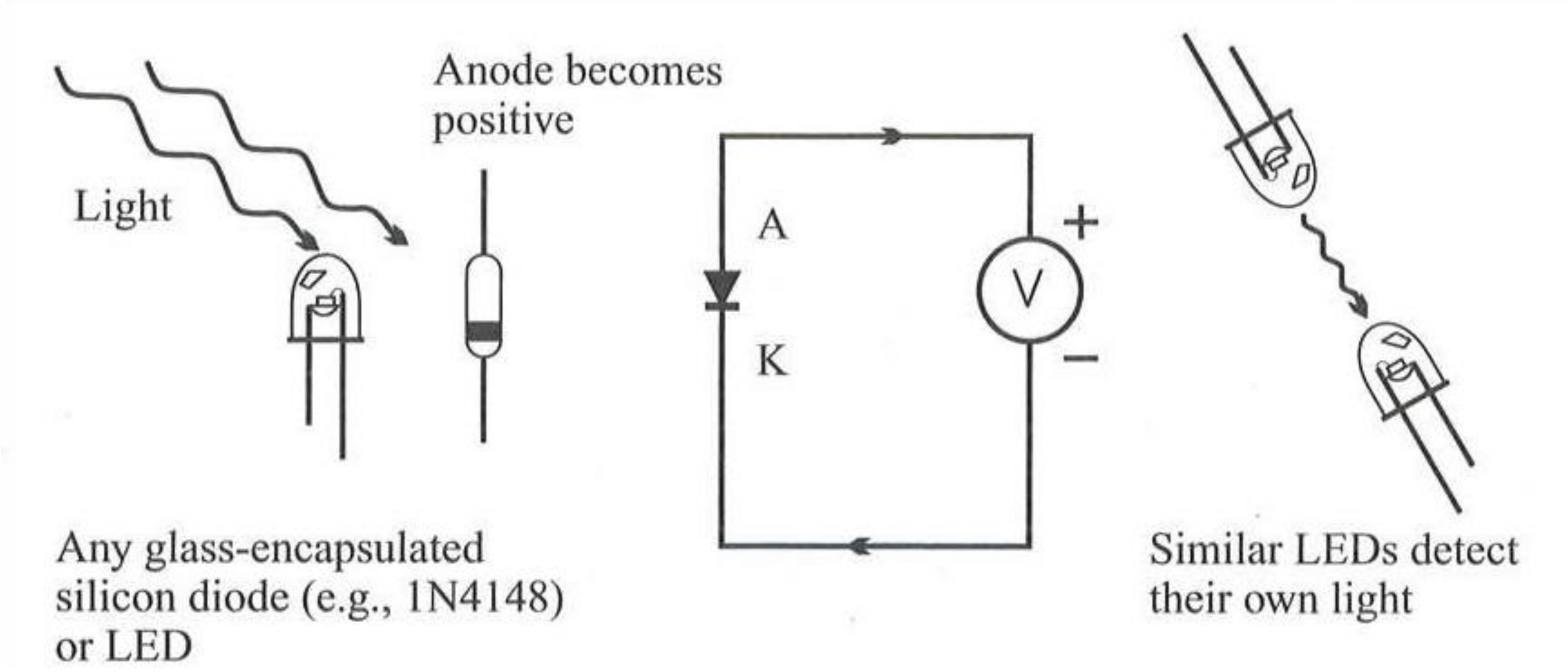
However, as they are, they are not suited for single photon detection.

A Small Experiment



Light emitting diodes (LEDs) are also excellent photo-diodes (photo-detectors)

Try to illuminate a “red” diode with
a “blue” diode and measure the voltage
across the “red” diode terminals.
Then repeat the experiment with a “blue” diode illuminating a “red” one.
What is the voltage on the “blue” diode terminals ?



Any glass-encapsulated silicon diode (e.g., 1N4148) or LED

Similar LEDs detect their own light

Various Solid State Photo-Detectors

Photo-Resistor

Semiconductor photo-diode (PN diode)

PIN diode

Avalanche PD (APD)

Visual light photon counters (VLPC)

Avalanche photo-diode operated in Geiger mode (G-APD) / Si-PM

Charged Coupled Devices (CCD)

CMOS Image Sensors (digital cameras)

....

HybridPD, HybridAPD