Scintillation Detectors

J.L. Tain

Jose.Luis.Tain@ific.uv.es
http://ific.uv.es/gamma/

Instituto de Física Corpuscular

C.S.I.C - Univ. Valencia

Scintillation detector:

SCINTILLATION MATERIAL

LIGHT-GUIDE / WAVELENGTH-CONVERTER

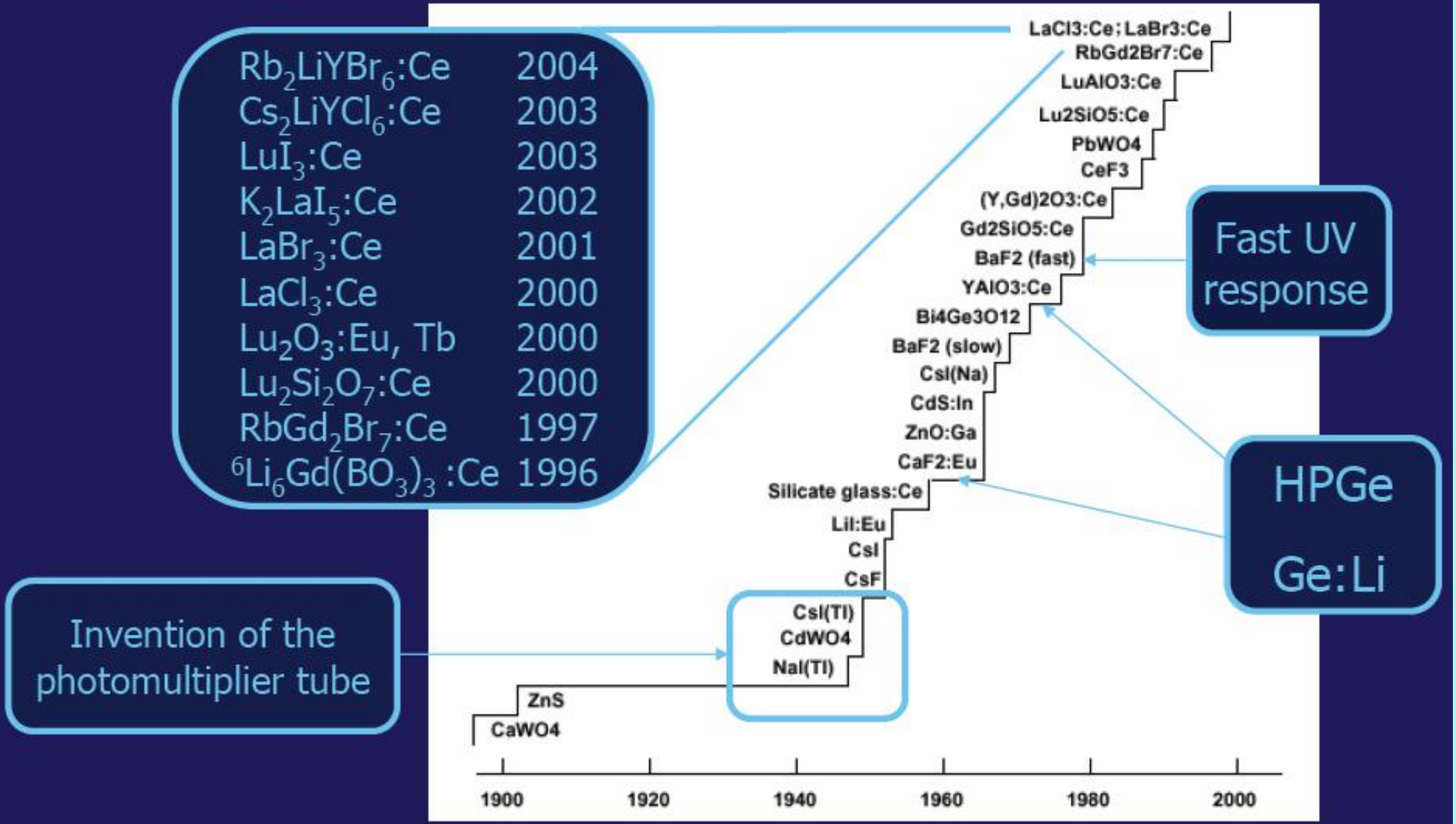
LIGHT TO ELECTRIC-PULSE TRANSDUCER

- Simple
- Versatile
- Rugged
- Cheap

History:

- Crookes (1903): ZnS screen + microscope
- Regener, Crookes (1908): nature of α-particles . + Rutherford, Geiger (gas counter)
- Geiger, Marsden (1909): angular distribution of scattered α-particles
- Rutherford (1911): discovery of atomic nucleus
- Rutherford (1919): discovery of nuclear reactions, $^{14}N(\alpha,p)^{17}O$
- Cockcroft, Walton (1932): coincidence experiment, $^{7}Li(p,\alpha)\alpha$
- Krebs (1941): photo-sensitive Geiger-Muller counter
- Curran, Baker (1944): use of photomultiplier + scintillator(ZnS)
- Kallman (1947): first organic scintillator (naphthalene)
- Hofstadter (1948): NaI(Tl)
- several (1980's): BGO
- Laval (1983): fast component of BaF_2
- several (1990's): many new scintillation materials

J. Lumin. 100 (2002) 35



Scintillation materials

Luminescent materials: reemit part of the absorbed energy in the form of light

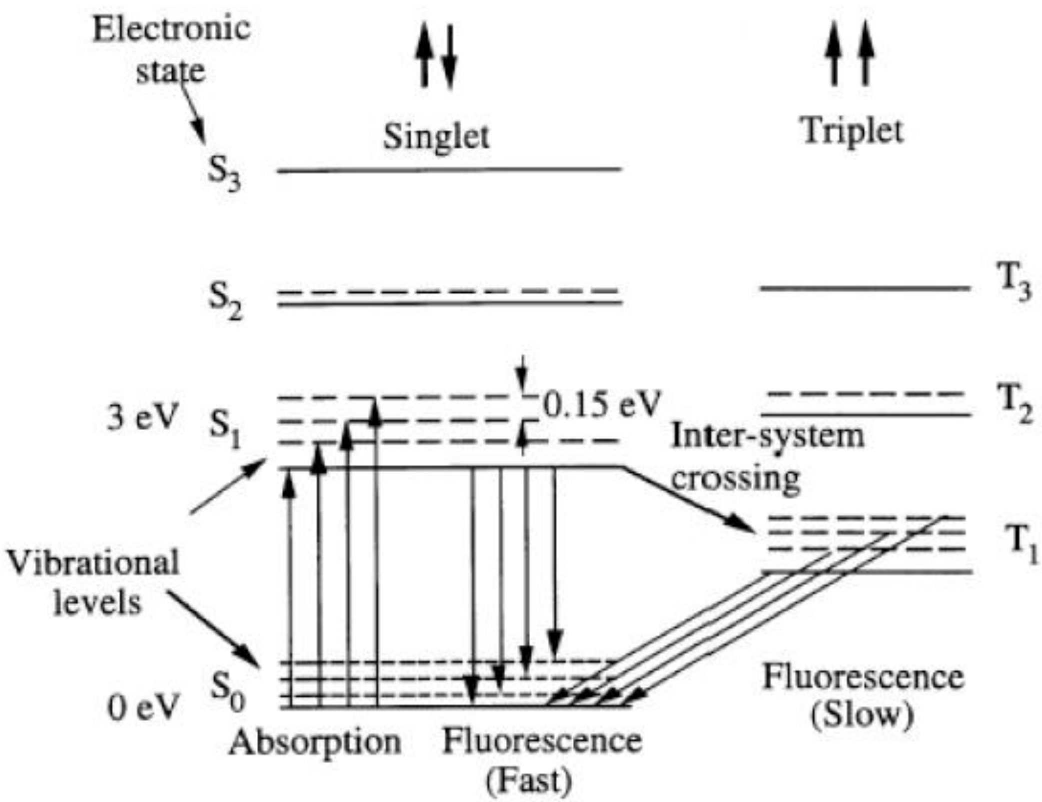
Emissions: fluorescence (prompt), delayed fluorescence and phosphorescence (delayed, different wavelength)

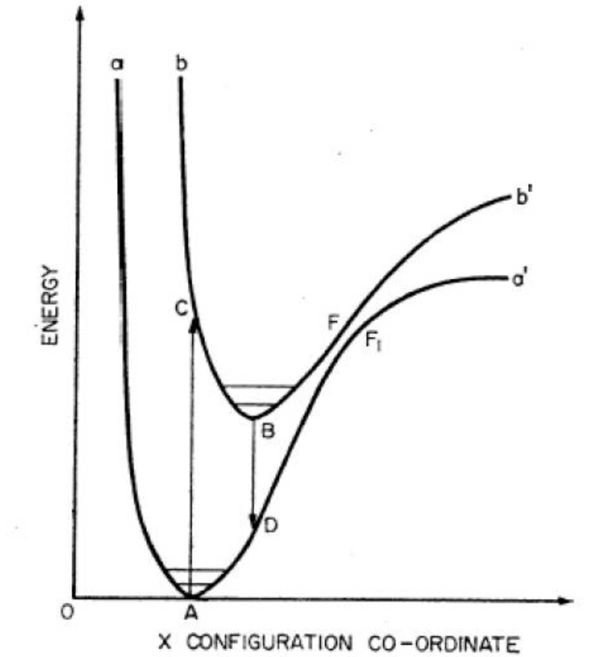
Scintillation material properties:

- transparency to its fluorescence
- luminous efficiency
- light spectral distribution
- light temporal distribution
- mechanical and chemical properties

- Organic materials:
    - Crystals
    - Liquids
    - Plastics
- Inorganic crystals
- Glasses
- Gasses

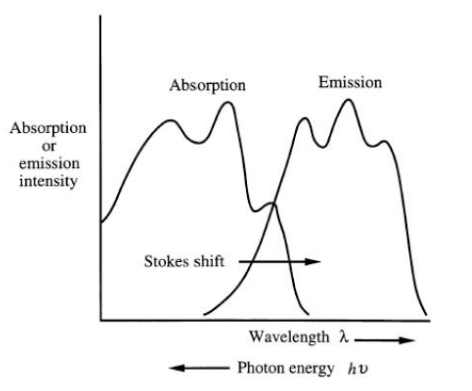
Luminescence in organic materials

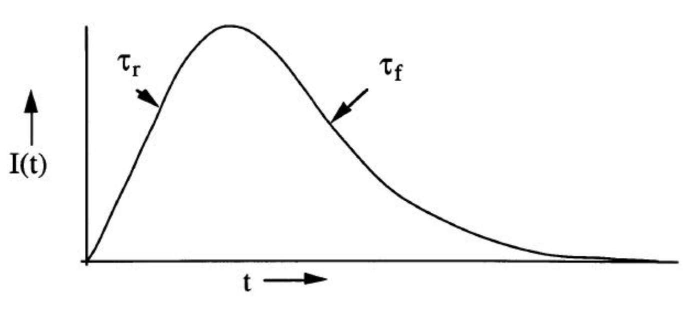




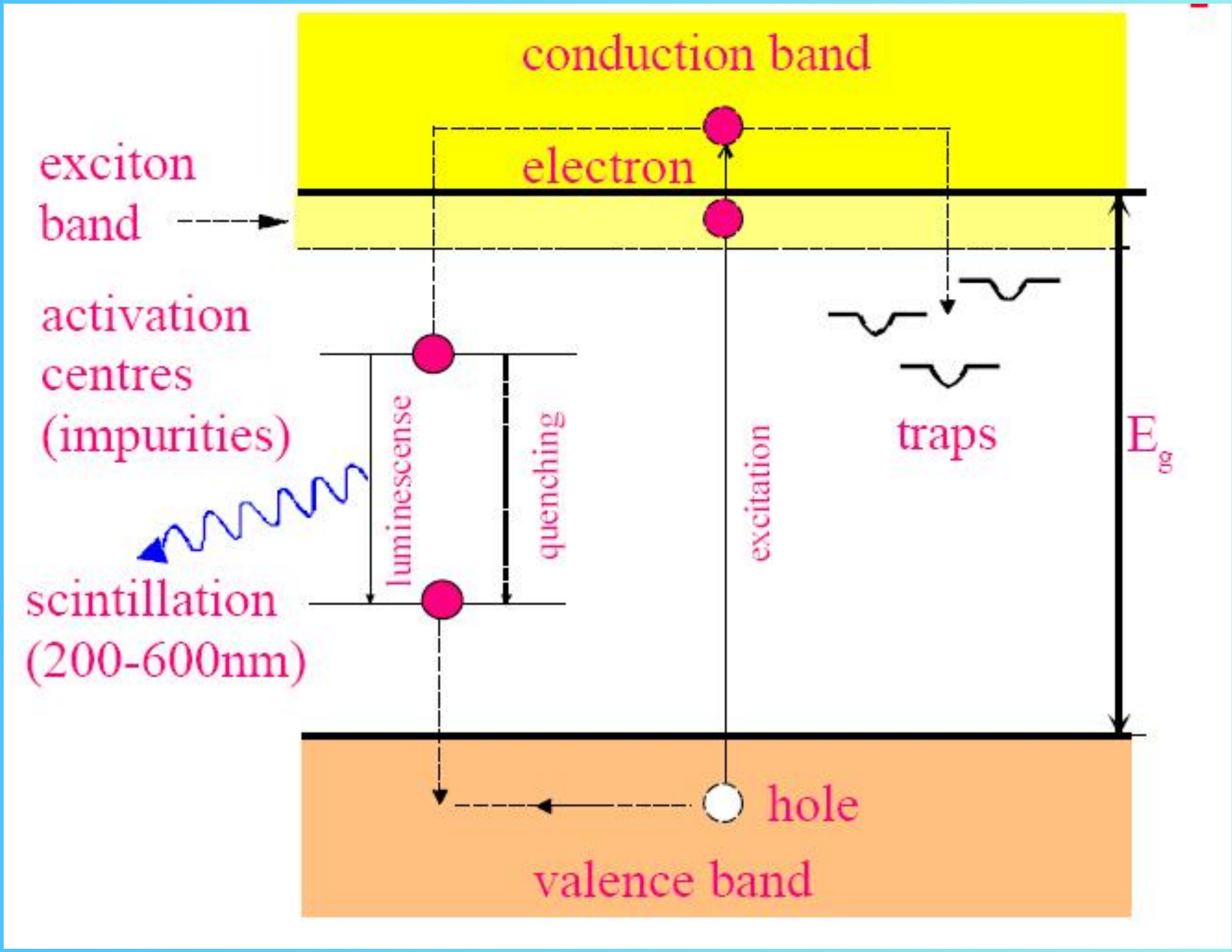
Several time components

Material transparent to its own light

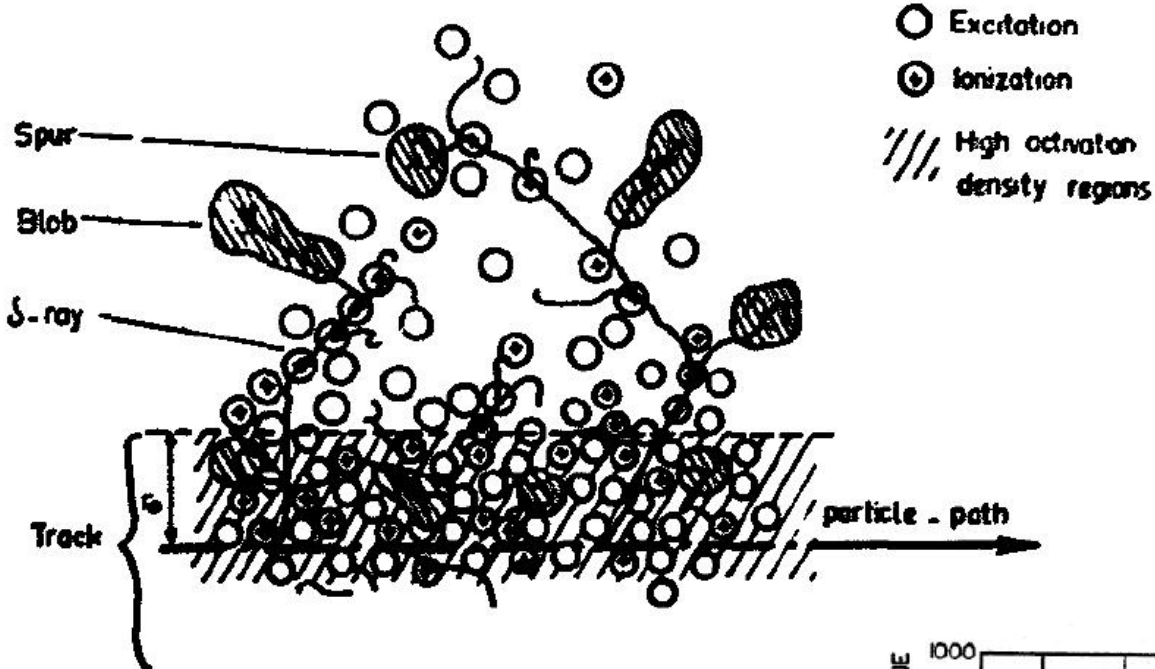




Luminescence in inorganic materials



Several mechanisms have been identified: luminescence of doping centers, self-activated luminescence and cross-luminescence

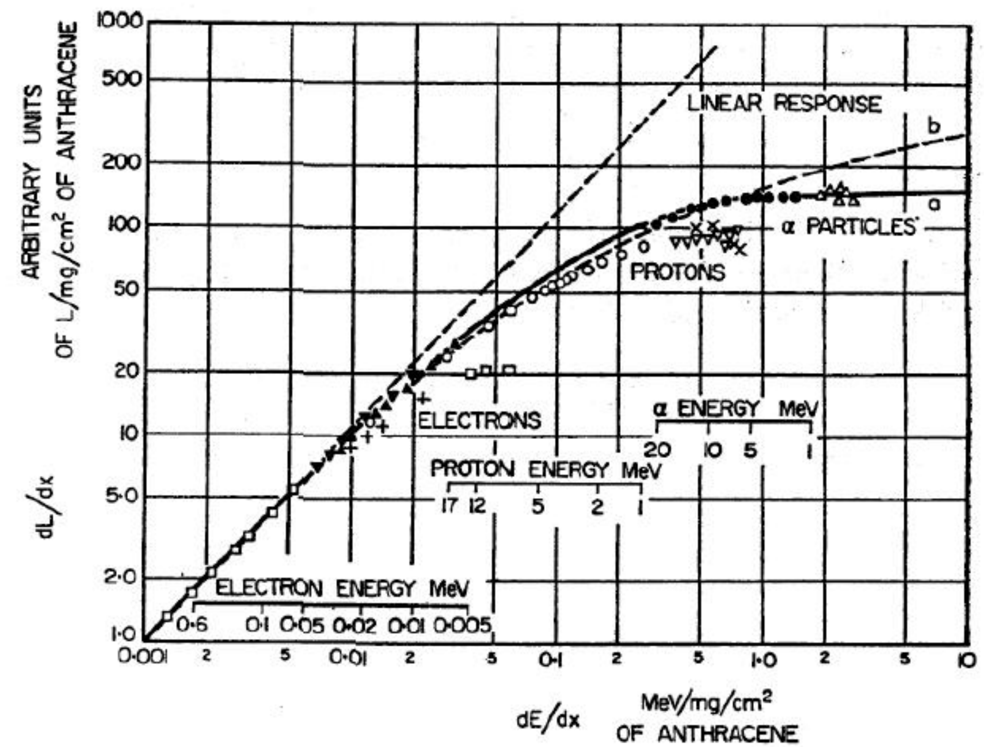


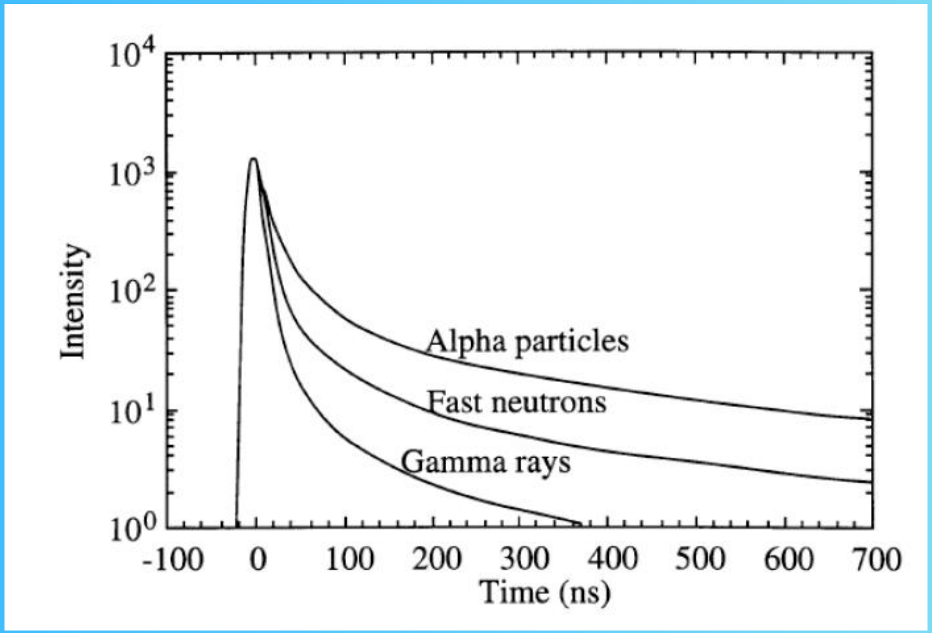
The non-radiative transfer mechanism between excited centers induces an energy-loss dependent light production

Simple parameterization:

$$\frac{dL}{dx} = \frac{A\frac{dE}{dx}}{1 + B\frac{dE}{dx}}$$

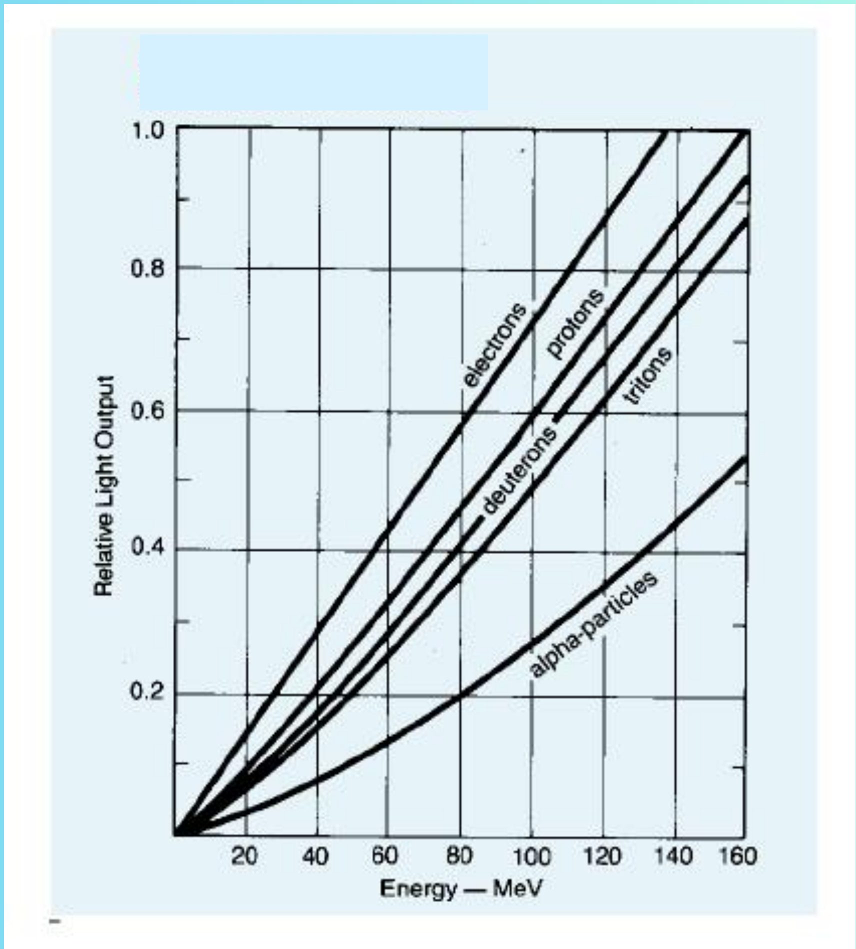
Birk´s formula

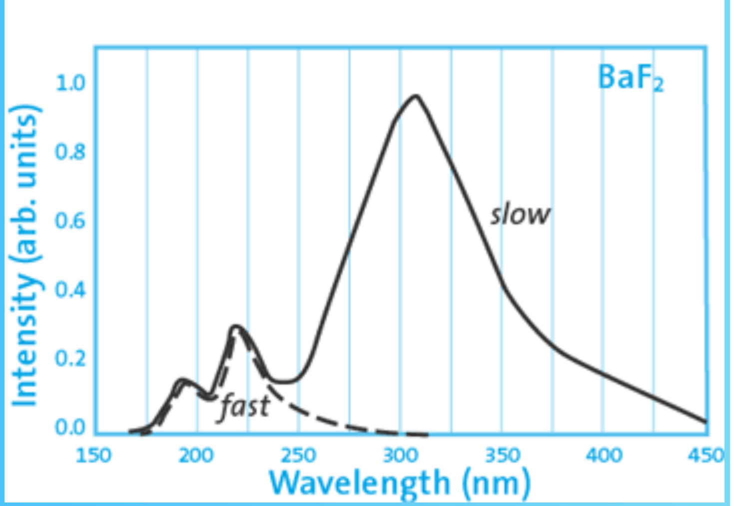


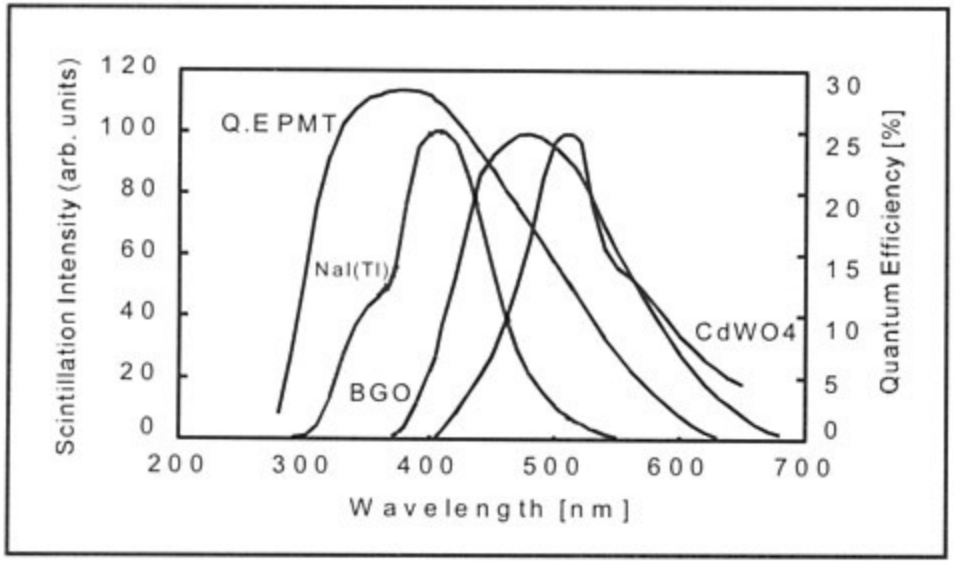


As a consequence there is a particle type and energy dependence of scintillation pulse shape and light output

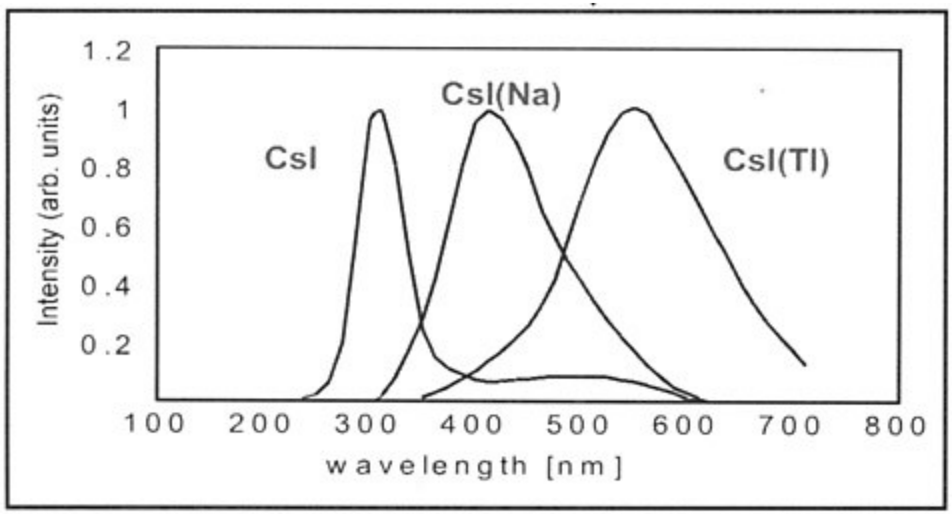
Both effects can be used to identify particles



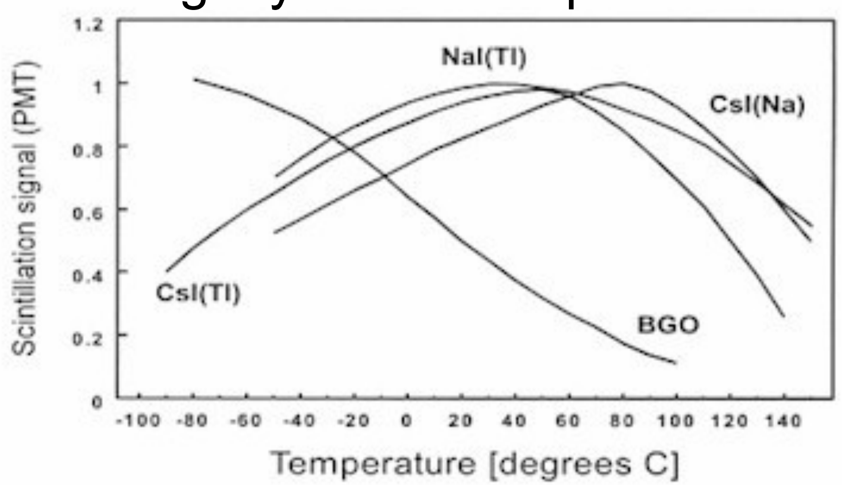




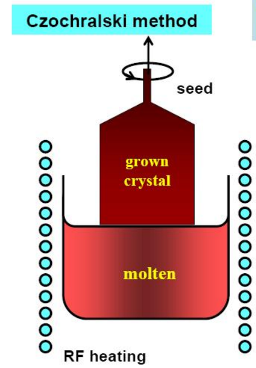
Emission spectra



Light yield vs. temperature



Properties of some inorganic scintillation crystals

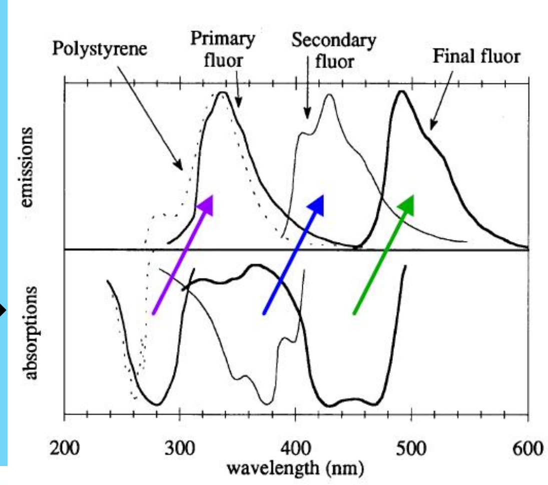


Optimization and equalization of crystals properties may take few years of efforts

	Density (g/cm^3)	Wavelength at max.(nm)	Refractive index	Decay time (ns)	Light yield (ph/MeV)
NaI(Tl)	3.67	415	1.85	230	38000
CsI(Tl)	4.51	540	1.80	680,3340	40000,25000
$Bi_4Ge_3O_{12}$	7.13	480	2.15	300	8200
BaF_2	4.89	220,310	1.56	0.6,630	1500,9500
CeF_3	6.16	310,340	1.68	5,27	4400
$YAlO_3$(Ce)	5.37	370	1.95	27	18000
Lu_2SiO_5(Ce)	7.4	420	1.82	47	25000
$LaBr_3$(Ce)	3.79	350	1.9	27	49000
Plastic BC-400	1.03	420	1.58	2.4	10000

Properties of some organic scintillation plastics

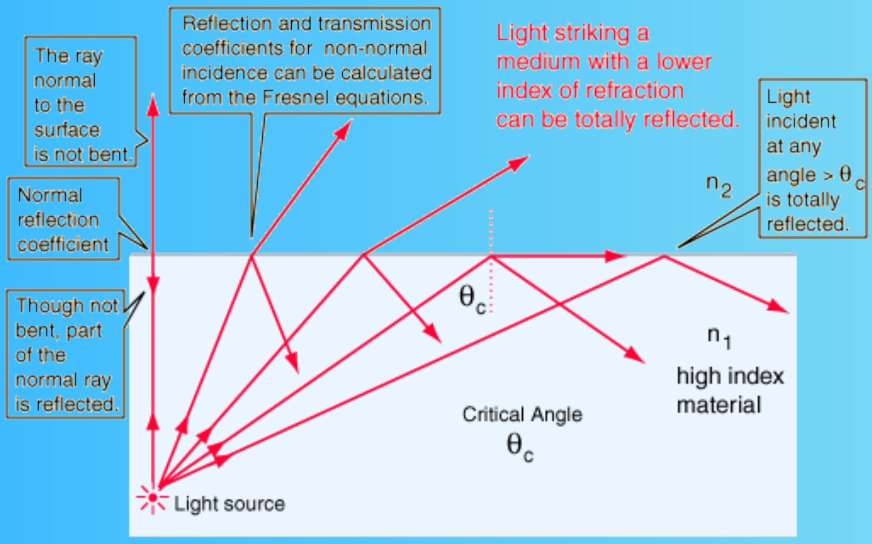
wavelength shifters ➔

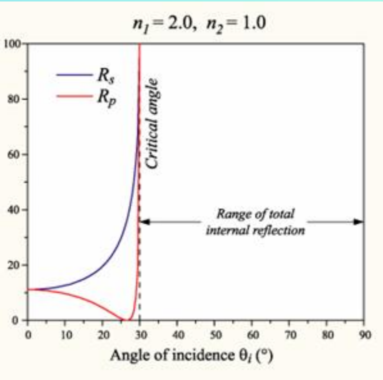


Scintillator	Light Output % Anthracene[1]	Wavelength of Maximum Emission, nm	Decay Constant, Main Component, ns	Bulk Light Attenuation Length, cm	Refractive Index	H/C Ratio	Loading Element % by weight	Density	Softening Point °C
BC-400	65	423	2.4	250	1.58	1.103		1.032	70
BC-404	68	408	1.8	160	1.58	1.107		1.032	70
BC-408	64	425	2.1	380	1.58	1.104		1.032	70
BC-412	60	434	3.3	400	1.58	1.104		1.032	70
BC-414	68	392	1.8	100	1.58	1.110		1.032	70
BC-416	38	434	4.0	400	1.58	1.110		1.032	70
BC-418	67	391	1.4	100	1.58	1.100		1.032	70
BC-420	64	391	1.5	110	1.58	1.100		1.032	70
BC-422	55	370	1.6	8	1.58	1.102		1.032	70
BC-422Q	11	370	0.7	<8	1.58	1.102	Benzephenone, 1%*	1.032	70
BC-428	36	480	12.5	150	1.58	1.103		1.032	70
BC-430	45	580	16.8	NA	1.58	1.108		1.032	70
BC-436	52	425	2.2	NA	1.61	0.960 D:C	Deuterium, 13.8%	1.130	100
BC-440	60	434	3.3	400	1.58	1.104		1.032	90
BC-440M	60	434	3.3	380	1.58	1.104		1.039	100
BC-444	41	428	285	180	1.58	1.109		1.032	70
BC-444G	34	490	285	180	1.58	1.109		1.032	70
BC-452	32	424	2.1	150	1.58	1.134	Lead, 5%	1.080	60
BC-454 5%	48	425	2.2	120	1.58	1.169	Boron, 5%	1.026	60
BC-480	**	425	—	400	1.58	1.100		1.032	70
BC-482A	QE=.86	494	12.0	300	1.58	1.110		1.032	70
BC-490	55	425	2.3	NA	1.58	1.107		1.030	70
BC-498	65	423	2.4	NA	1.58	1.103		1.032	70

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

Light collection and transmission



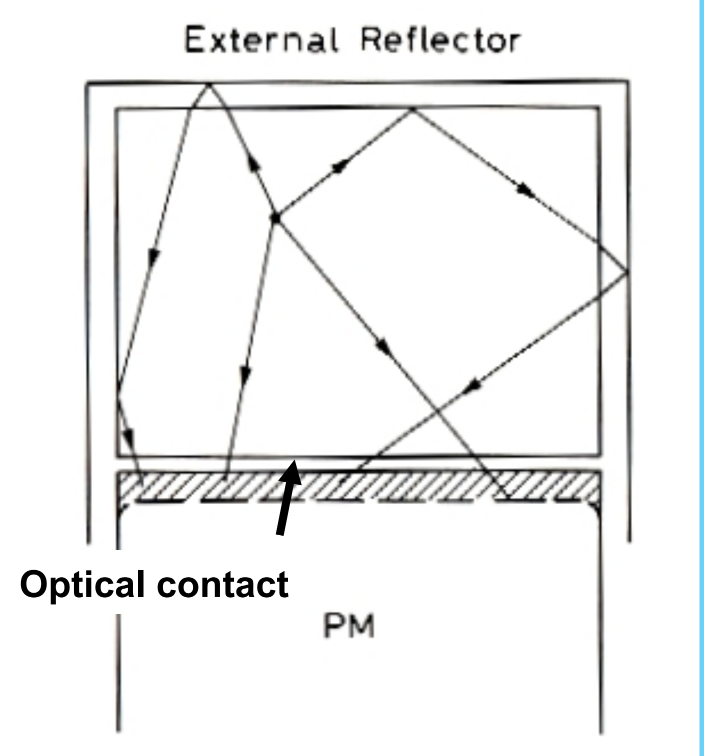


Snell law:

$$n_i \sin\theta_i = n_t \sin\theta_t$$

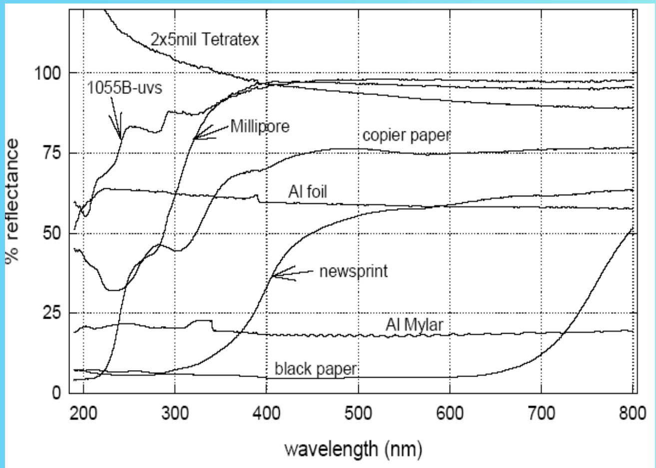
Fresnel formulae:

$$R_{para} = \frac{\tan^2(\theta_i - \theta_t)}{\tan^2(\theta_i + \theta_t)} \quad , \quad R_{perp} = \frac{\sin^2(\theta_i - \theta_t)}{\sin^2(\theta_i + \theta_t)}$$



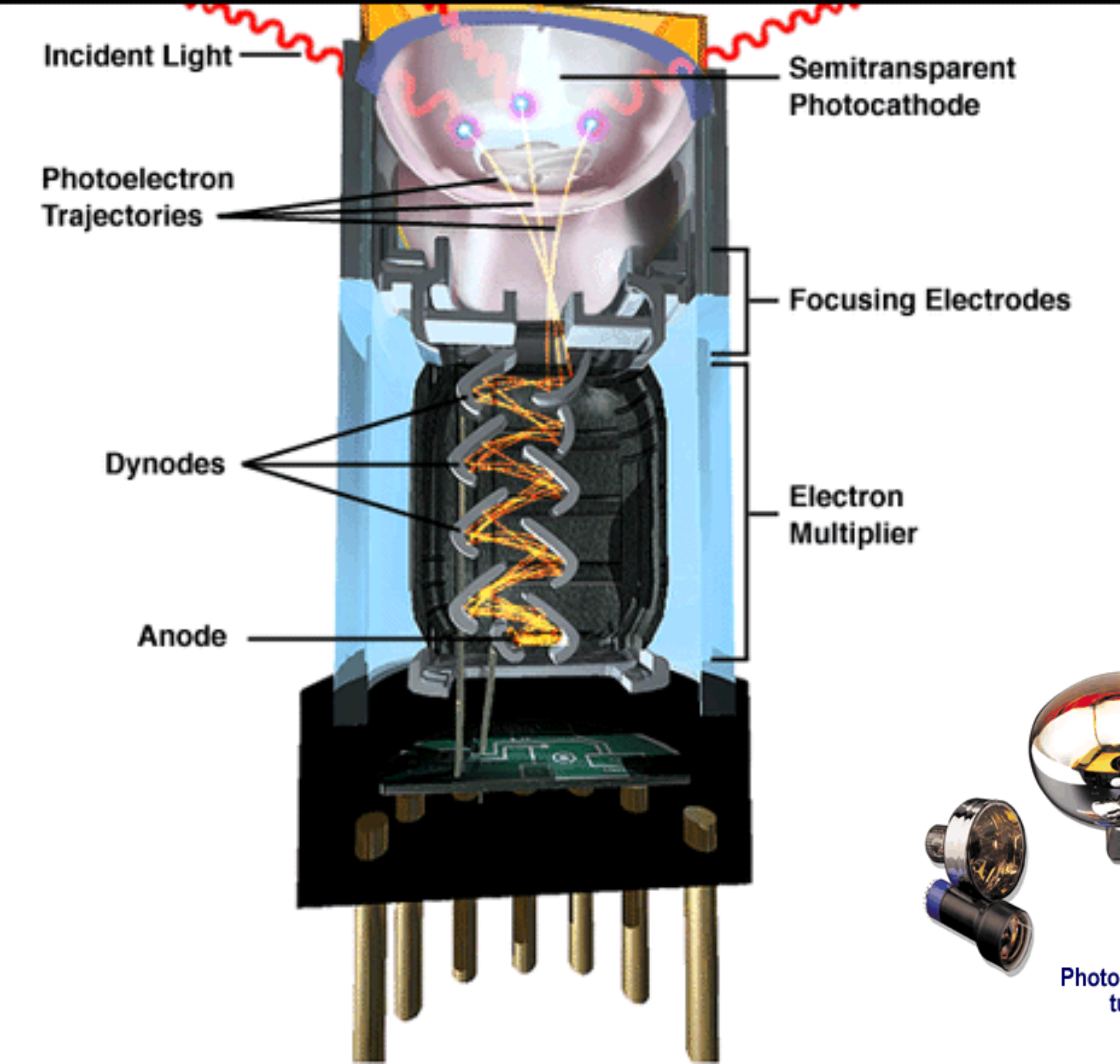
Reflector:

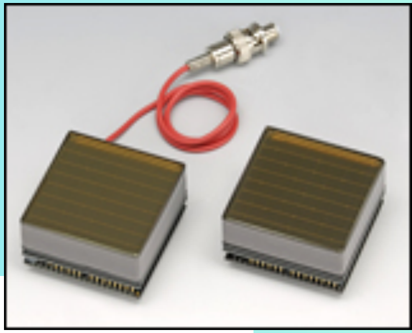
- mirror-like: $\theta_r = \theta_i$
- diffuse: θ_r random



Light-guide

The Photomultiplier Tube

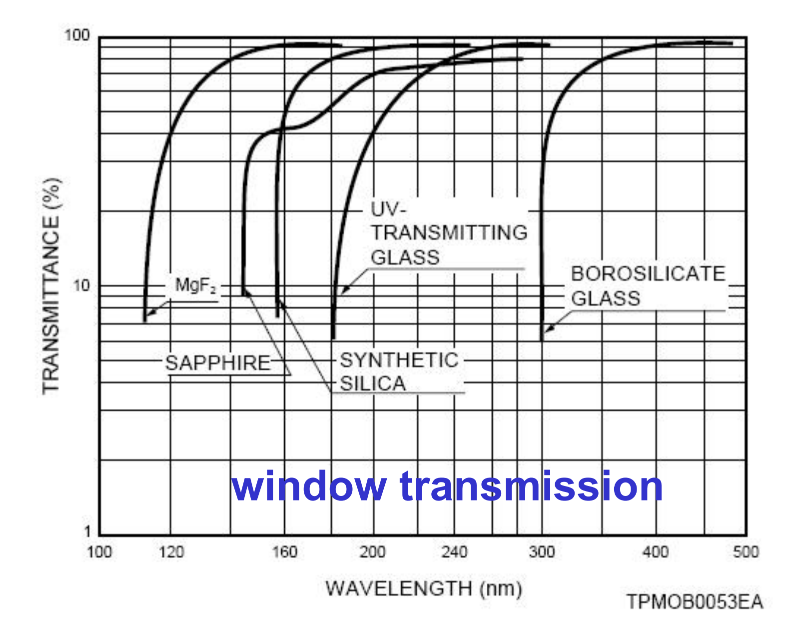


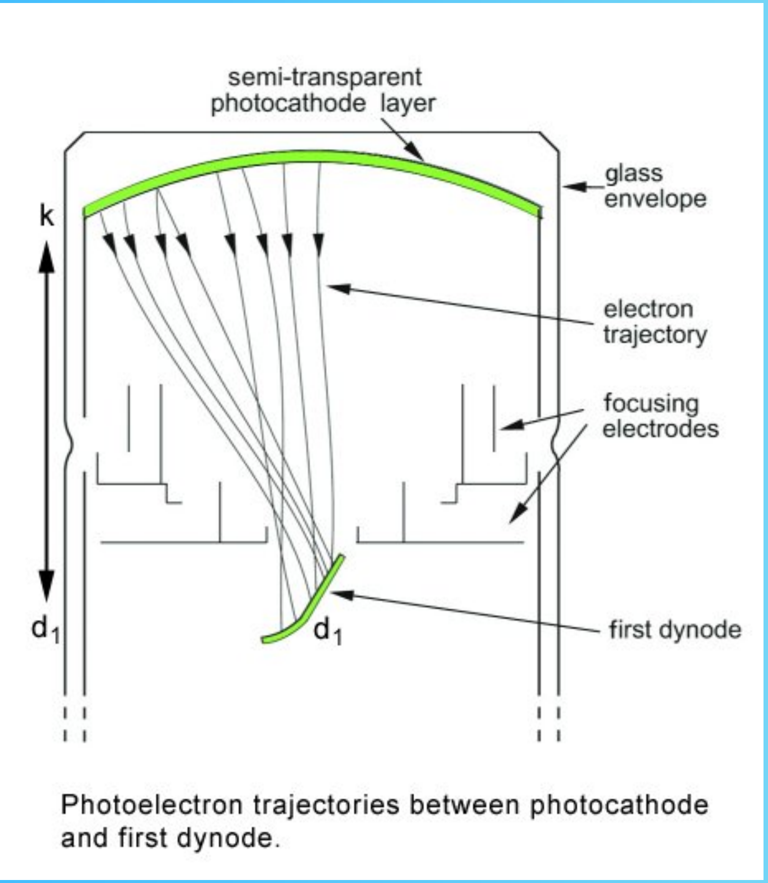


Photomultiplier tubes

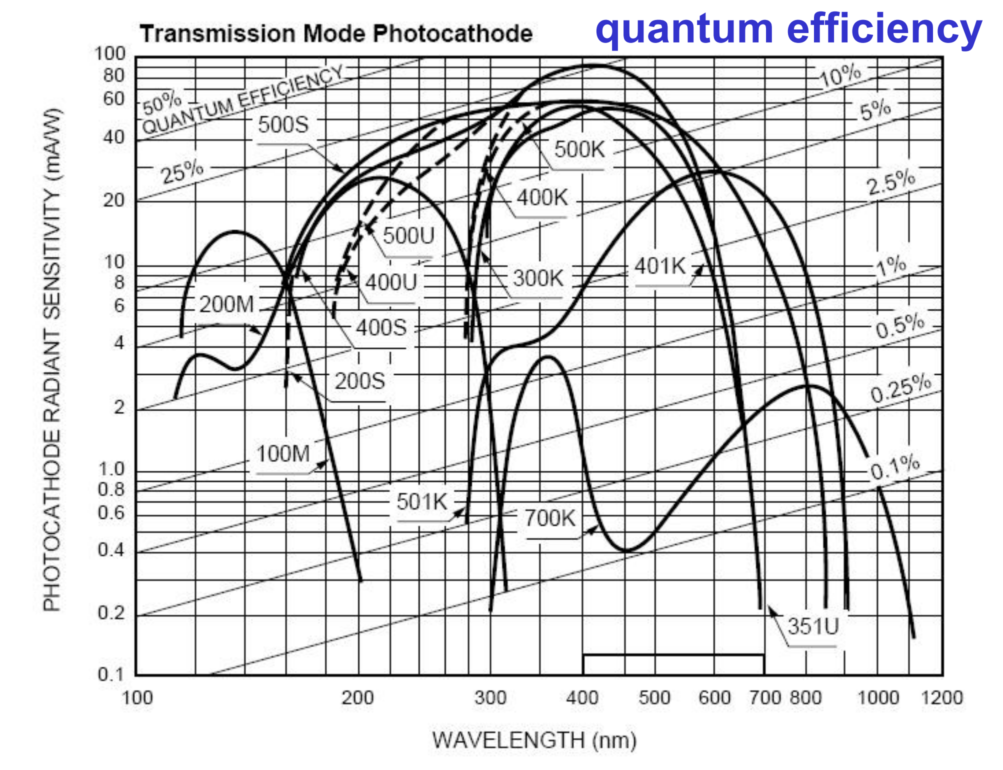
PMT window, photo-cathode and focusing electrodes:

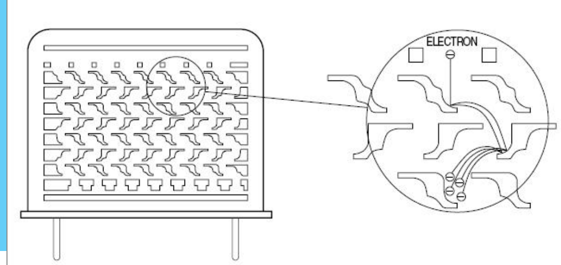
- spectral sensitivity, gain, energy resolution and time resolution





Photoelectron trajectories between photocathode and first dynode.





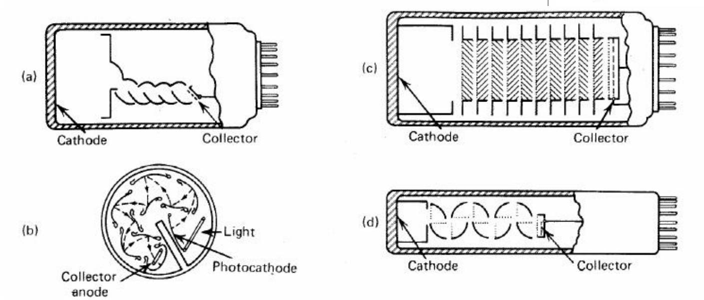
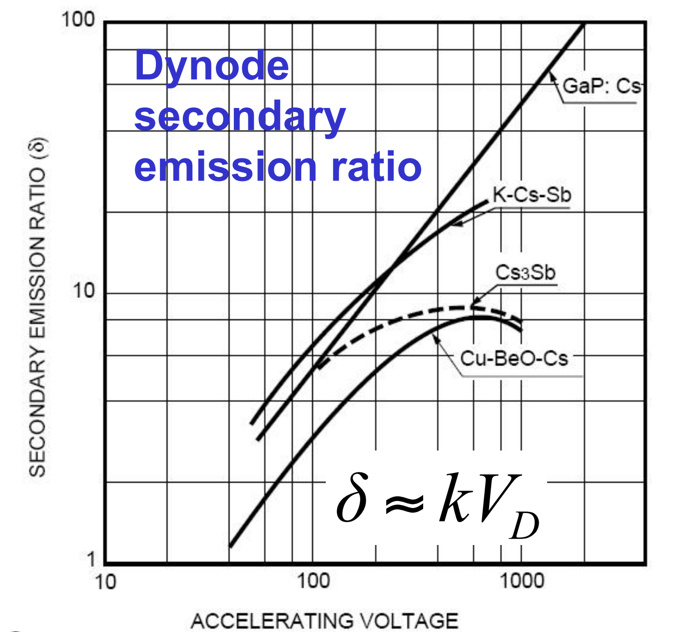


Fig. 4-8. Configurations of some common types of PM tubes. (a) Focused linear structure. (b) Circular grid. (c) Venetian blind. (d) Box-and-grid. (Courtesy of EMI GENCOM Inc., Plainview, NY.)

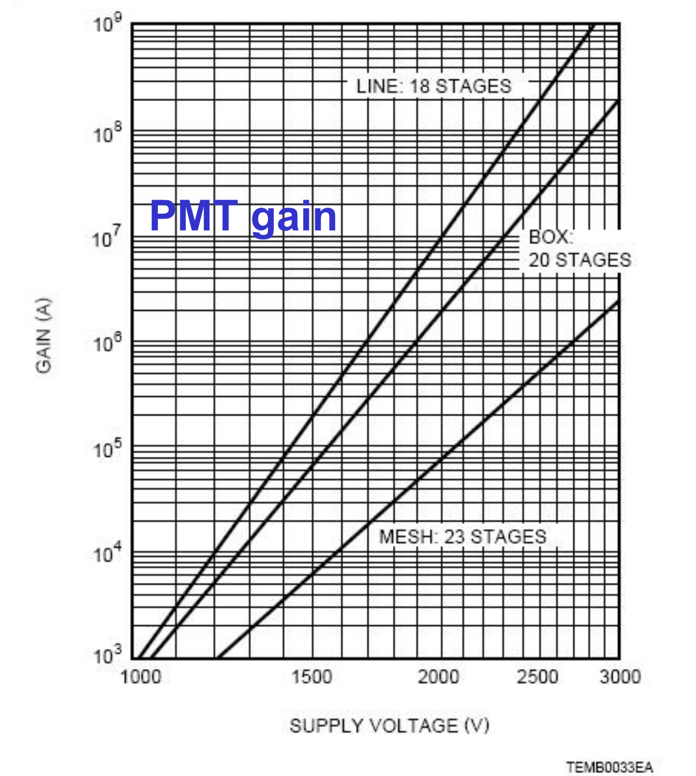


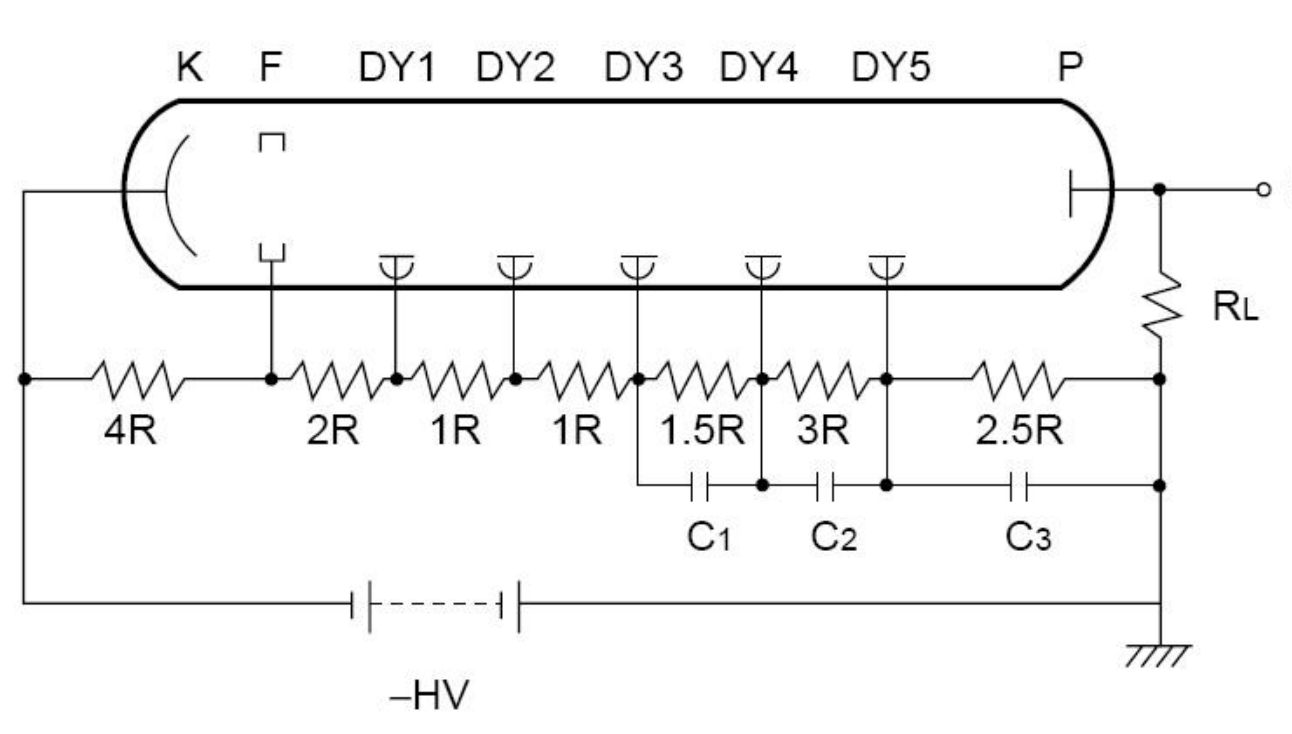
PMT dynode structure:

- gain & time resolution

$$G \approx \delta^n$$

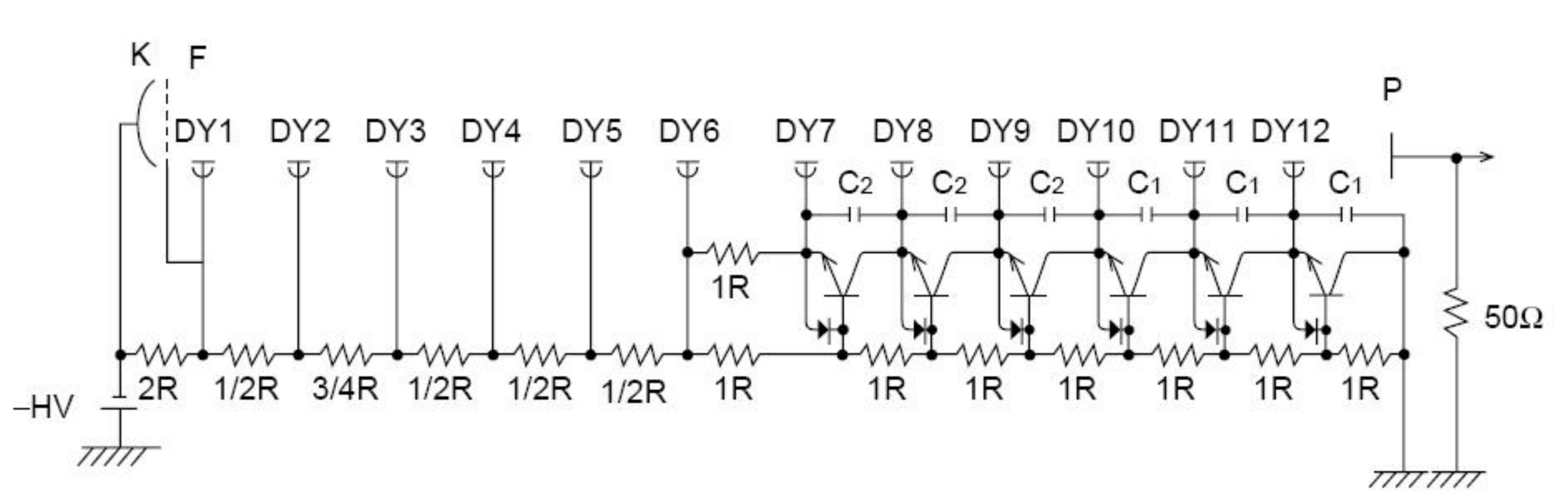
$$\frac{\Delta G}{G} \approx n \frac{\Delta V_D}{V_D}$$



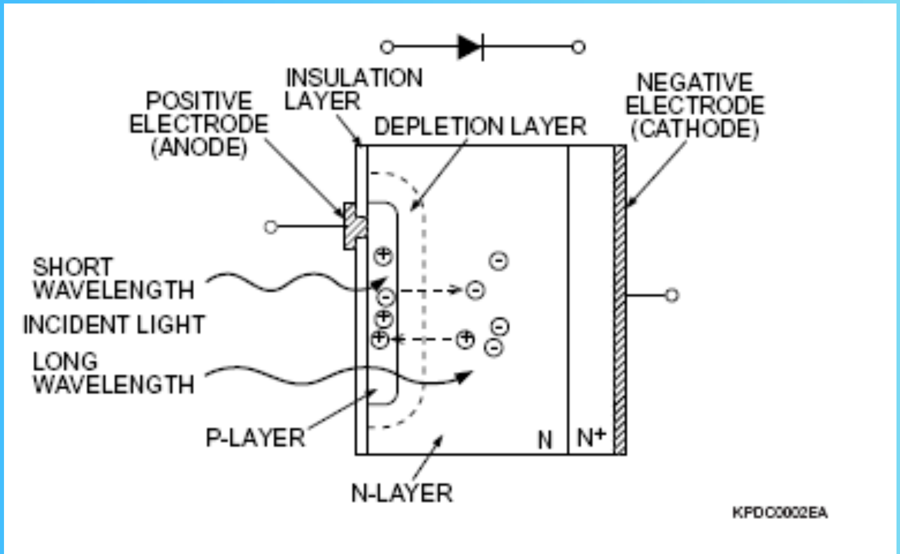


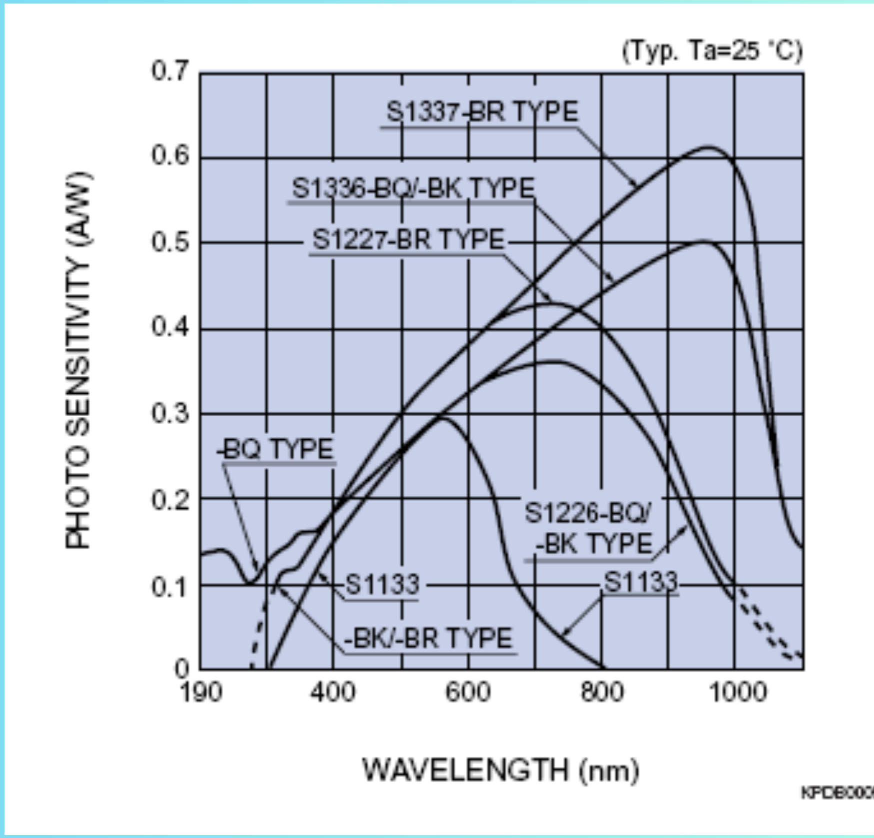
PMT base - voltage divider:

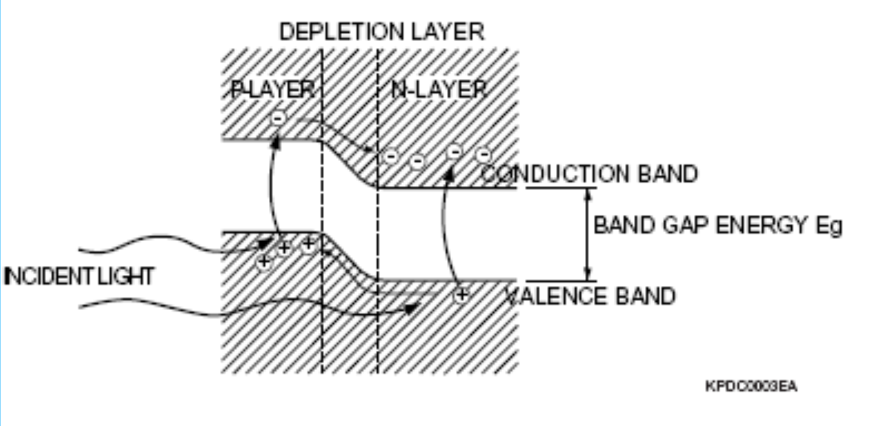
- linearity



Semiconductor photo-sensors

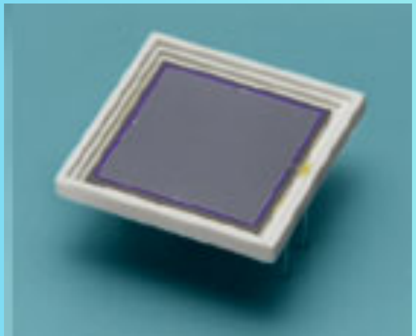


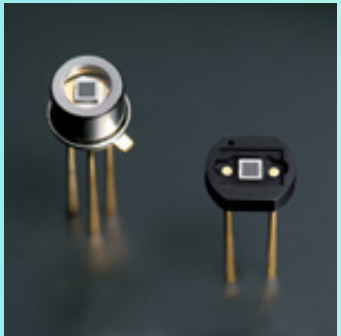


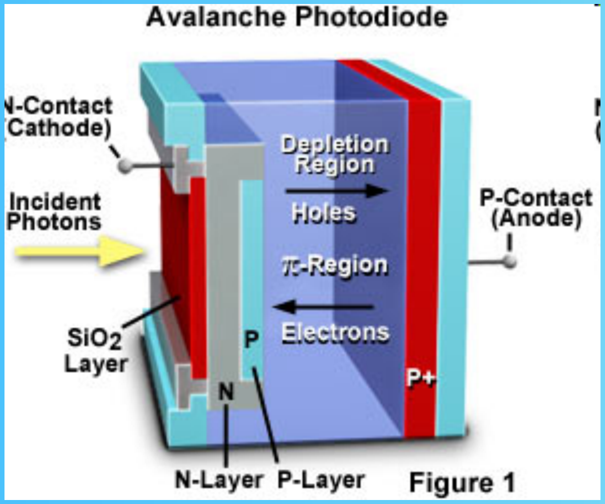


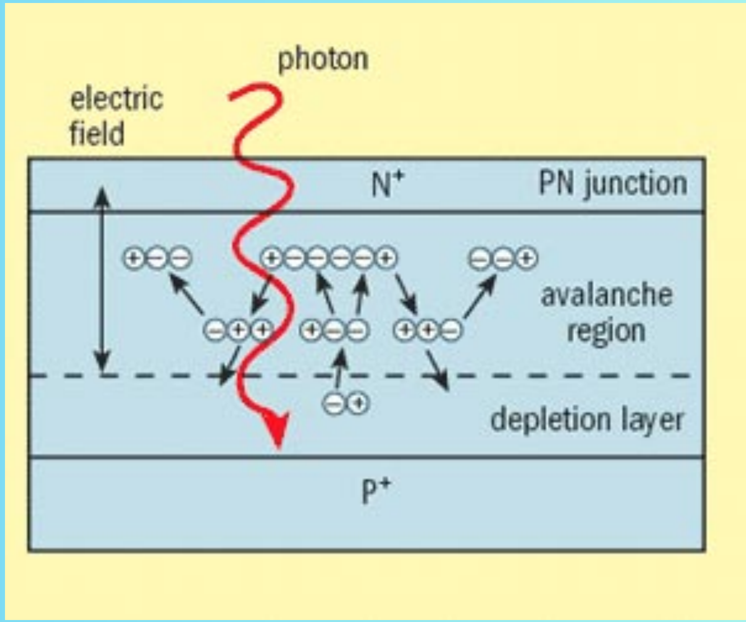
Si Photo-Diodes (PD):

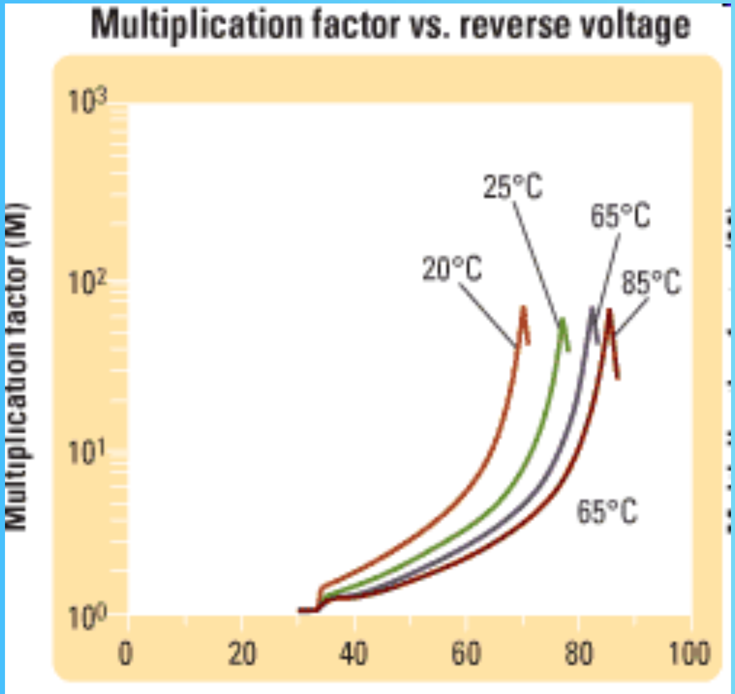
very small current proportional to photon intensity







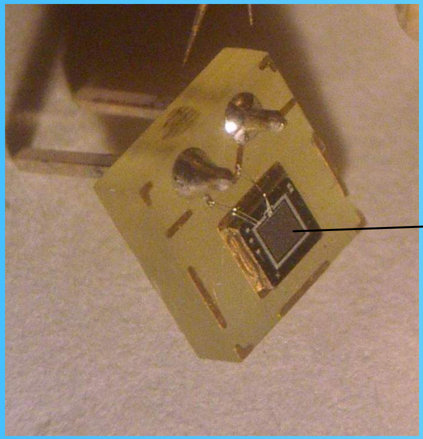




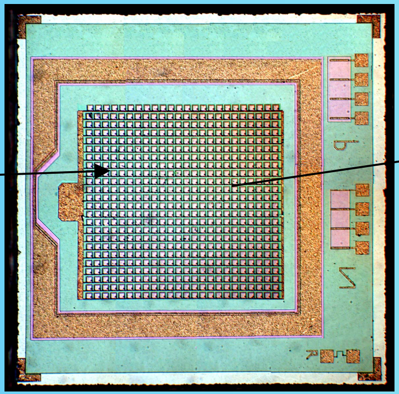
Avalanche Photo-Diodes (APD):
initial current amplified by avalanche process, still proportional to initial photon intensity

Silicon Photomultipliers (Si-PMT, SPM, MPPC, DAPD, …)

single photon counting

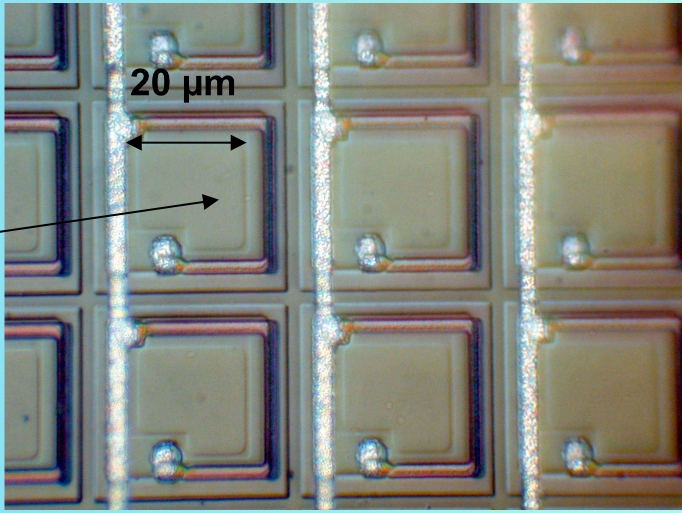


1 mm

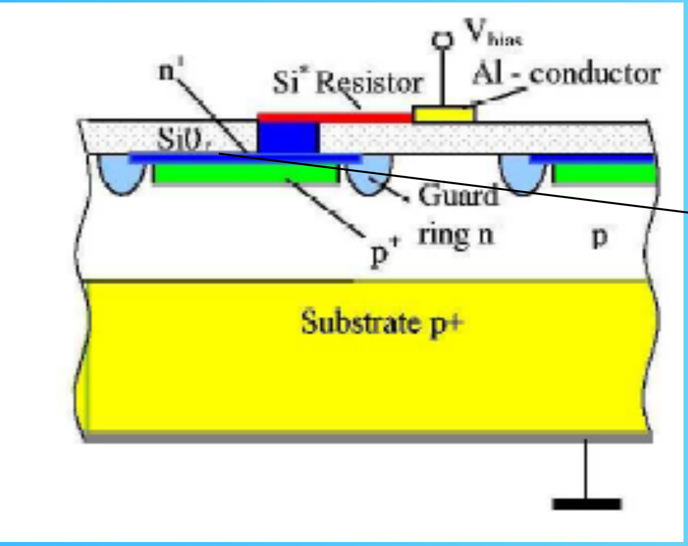


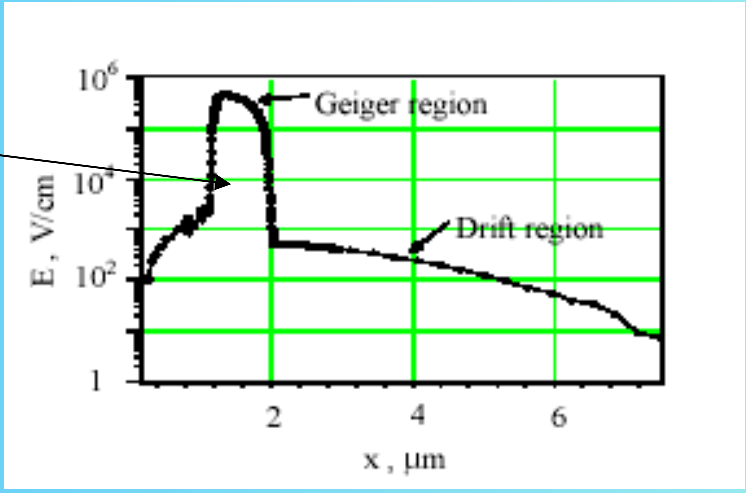
24*24=576 pixels

42 µm



$$N_{hits} = N_{cells} \times \left(1 - \left(1 - P_{cell}\right)^{N_{photons}}\right)$$





Very high amplification, current independent from initial photon intensity (Geiger mode)

Scintillation detector energy resolution:

1. Light yield variations of scintillation material: statistical (intrinsic) and non-proportionality of light production
2. Light collection variations: statistical, geometrical dependency
3. Light conversion variations: statistical (quantum efficiency), non-uniformity of photo cathode
4. Electron multiplication and collection variations (single photon response)
5. Read-out electronic noise

Scintillation detector linearity:

1. Light yield linearity
2. Electron multiplication linearity
3. Read-out electronic linearity

Scintillation detector noise:

1. Scintillation material activity and after-glow
2. Photo-multiplier dark current
3. Read-out electronic noise

Can we predict/influence the expected resolution?

The energy resolution in an scintillation detector for γ-rays will be given by the statistical fluctuations in:

1. the energy of secondaries generated (non-proportionality)
2. the number of scintillation photons per energy deposited (intrinsic)
3. the fraction of photons collected at the photocathode (transport, absorption)
4. the fraction of photo-electrons collected at the 1st dynode (quantum efficiency, collection)
5. the PMT gain (multiplication, collection)
6. the electronic noise

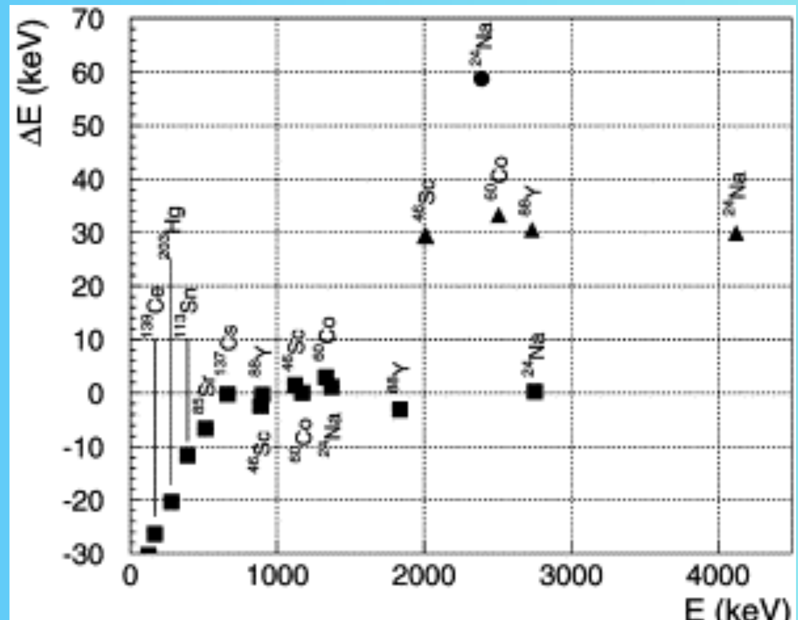
$$\frac{FWHM}{E} = \sqrt{\frac{\alpha_{2,3}}{E} + \beta_{4,5} + \chi_1(E)}$$

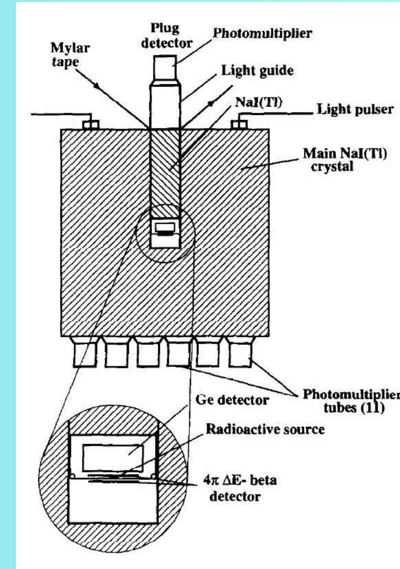
The case of the LBL-TAS @ GSI

D. Cano et al. NIMA430 (1999) 333

EXP: $$\left.\frac{FWHM}{E}\right|_{EXP} = \sqrt{\frac{2.655}{E} + 1.51\times10^{-3}}$$ **5.9%@1.33MeV**

Light yield non-proportionality



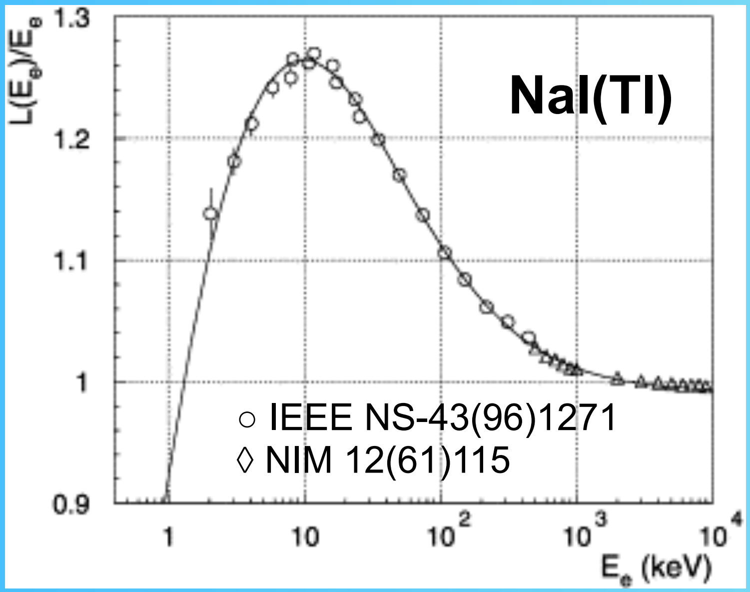


χ: $$\left.\frac{FWHM}{E}\right|_{non-prop} = \sqrt{\frac{1.373}{E} + 4.06\times10^{-5}}$$ **3.2%@1.33MeV**

β: $$\left.\frac{FWHM}{E}\right|_{multiplication} = 0.0383$$ **3.8%@1.33MeV**

α: $$\left.\frac{FWHM}{E}\right|_{photontransfer} = \sqrt{\frac{1.282}{E}}$$ **3.1%@1.33MeV**

Light yield non-proportionality



$LaBr_3$ negligible?

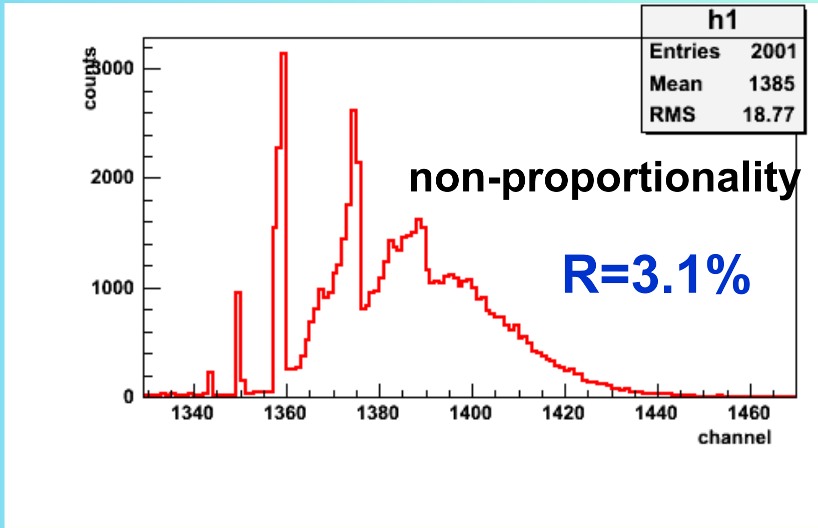
Light yield statistics

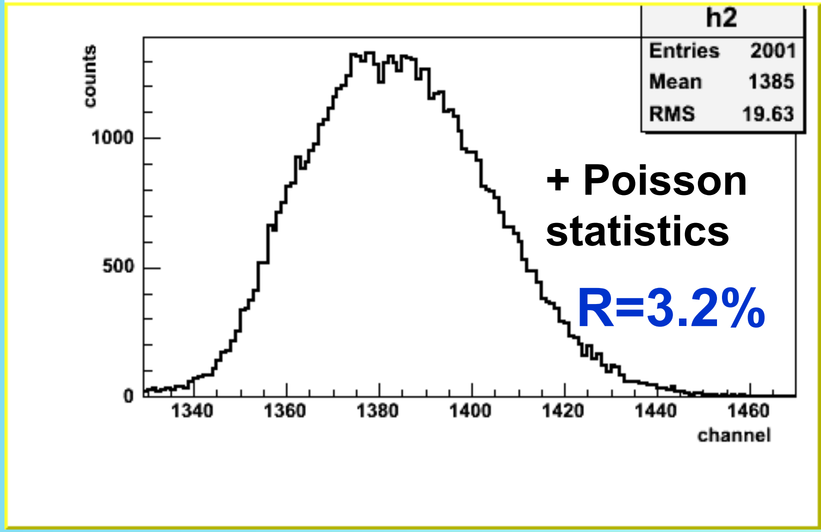
- assumed Poisson

$$Y_{NaI}^{scin} = 38\,ph/keV \quad \rightarrow 1.0\%$$

$$Y_{LaBr3}^{scin} = 63\,ph/keV \quad \rightarrow 0.8\%$$

GEANT3 MC simulation

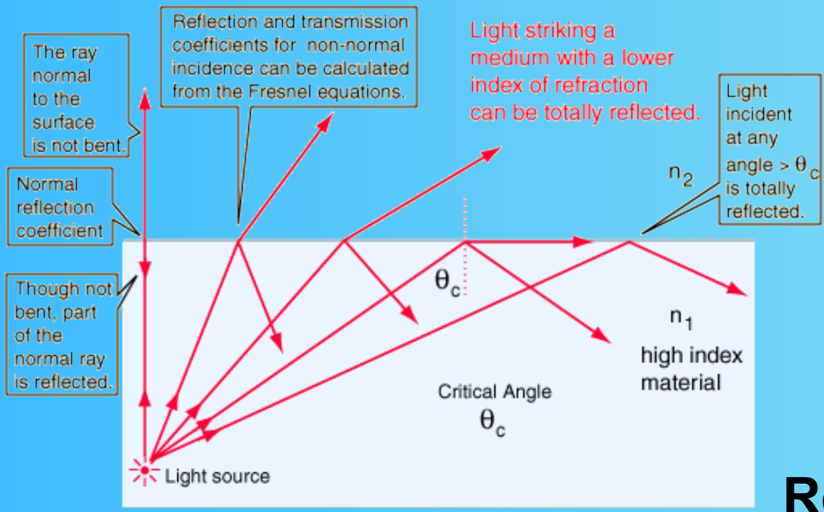




$$R = \frac{2.35}{\sqrt{E \times Y^{scin}}}$$

Simulation of light transport and collection with Geant4

- Influence of geometry, reflector type, surface treatment, refractive index matching, light-guide, …

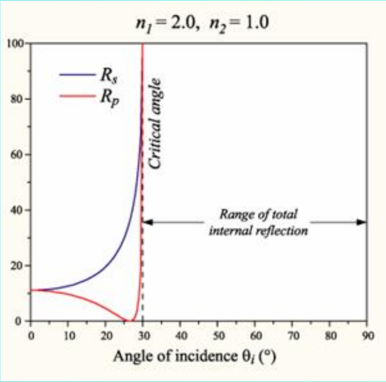


Snell law:

$$n_i \sin\theta_i = n_t \sin\theta_t$$

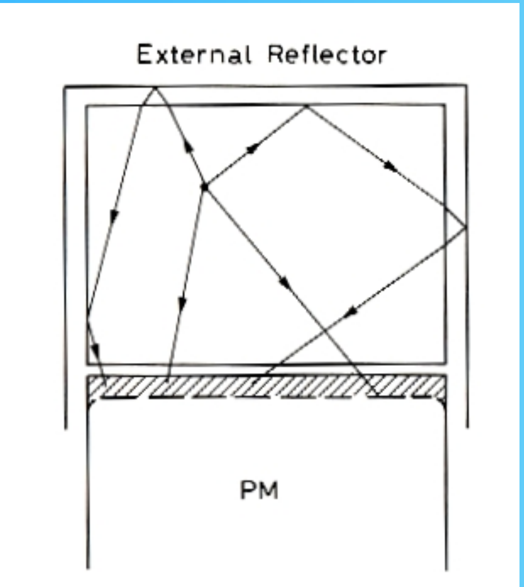
Fresnel formulae:

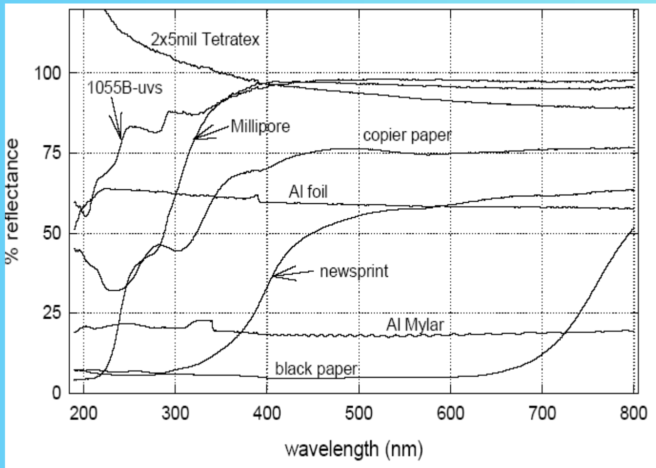
$$R_{\parallel} = \frac{\tan^2(\theta_i - \theta_t)}{\tan^2(\theta_i + \theta_t)} \quad , \quad R_{\perp} = \frac{\sin^2(\theta_i - \theta_t)}{\sin^2(\theta_i + \theta_t)}$$

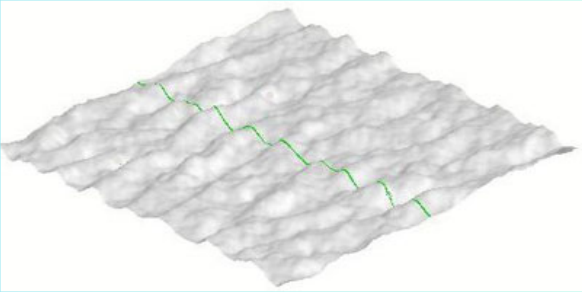


Reflector:
- mirror-like: $\theta_r = \theta_i$
- diffuse: θ_r random

Surface state:
- polished
- rough





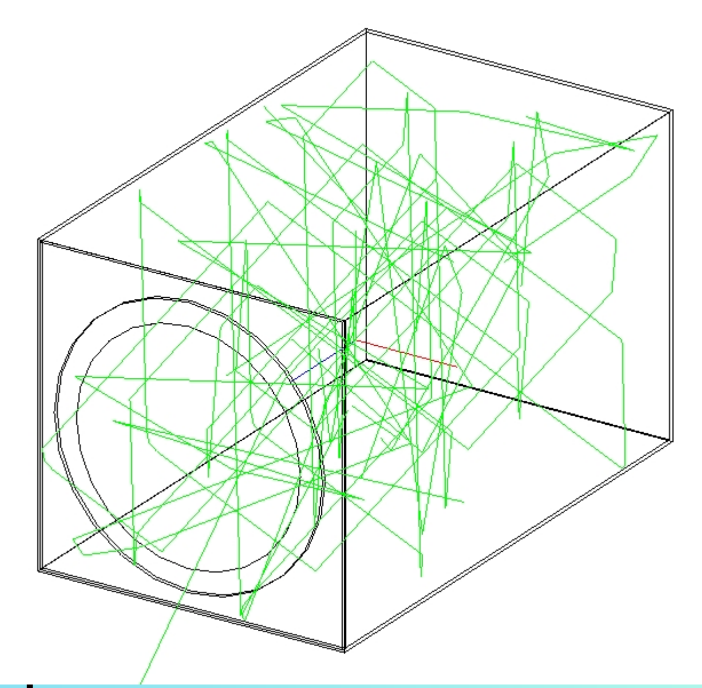


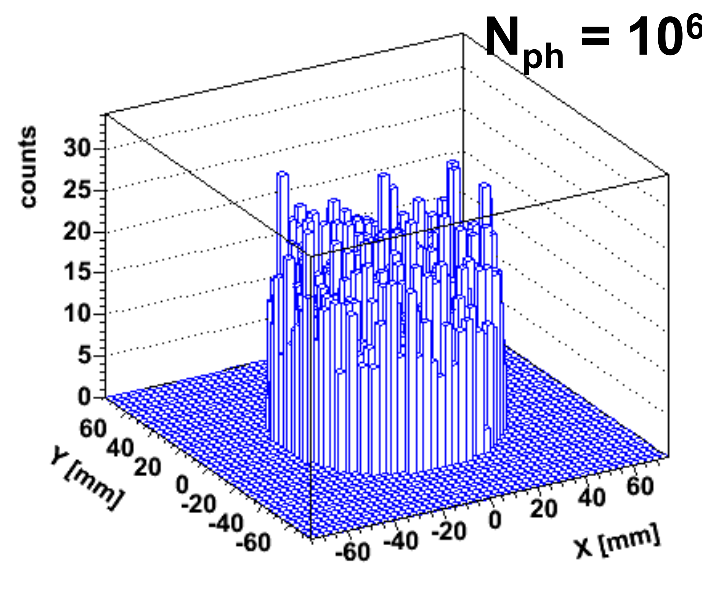
Geant4 MC simulations

NaI module

n_{NaI} = 1.85, n_{PMT}=1.47, n_{LG} = 1.60
λ_{NaI} = 1 m ?
Specular reflector: ρ=1
Diffusse reflector: ρ=1 (Lambertian)

	Specular reflector	Diffuse reflector
Point source λ_{abs}= 1 m	12.5%	16.3%
Extended source λ_{abs}= 1 m	12.1%	16.5%
Extended source λ_{abs}= 20 cm	4.4%	4.3%
Extended source λ_{abs}= 1 m Light guide n = 1.6	13.7%	18.0%





Geant4 MC simulation

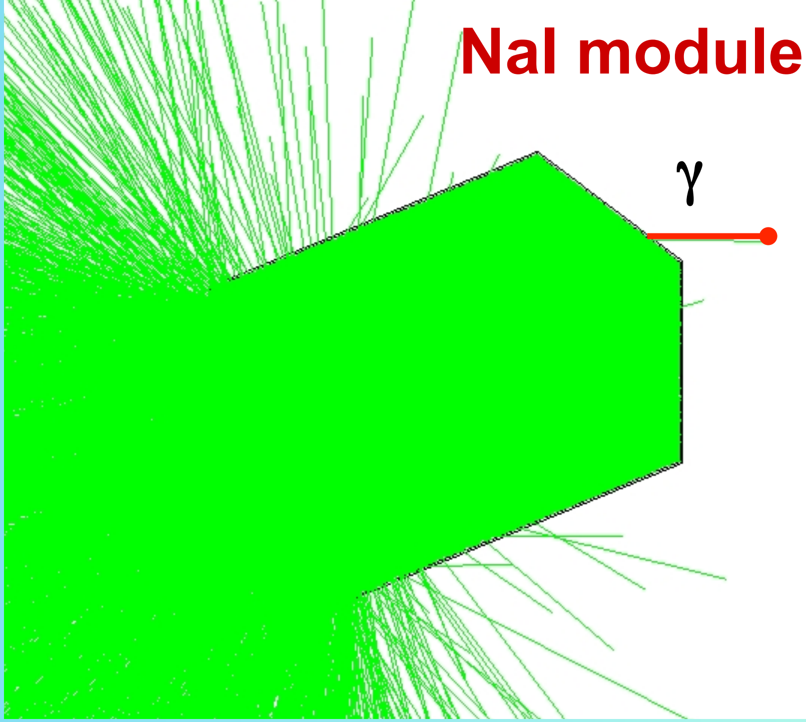
Light transport contribution to the energy resolution

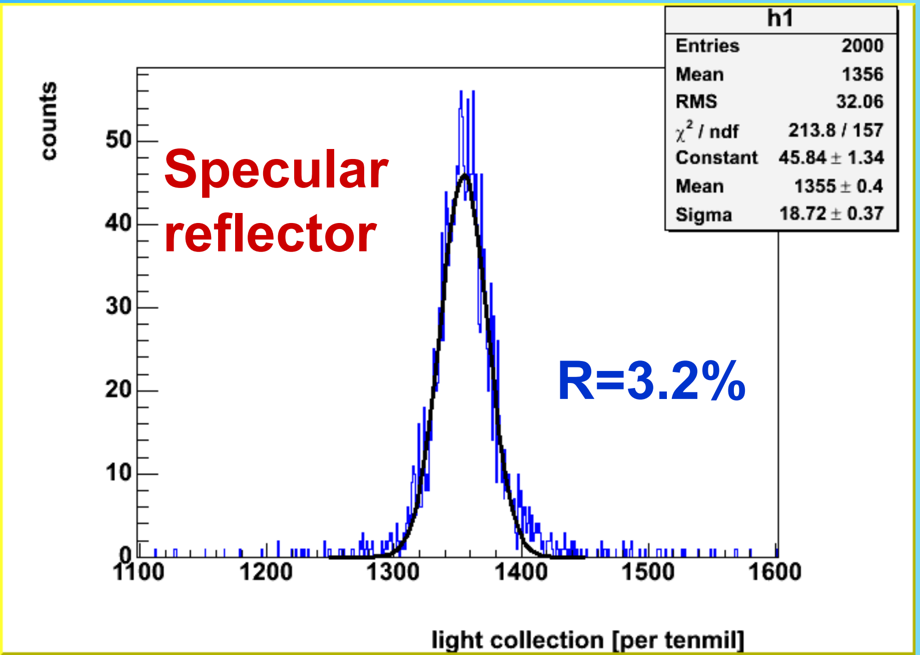
E_γ = 1.33 MeV, Y_{scint}= 38 ph/keV

No Poisson statistics,

no non-proportionality

$$LF = \frac{N^{cathode}}{E_\gamma \times Y^{scin}}$$





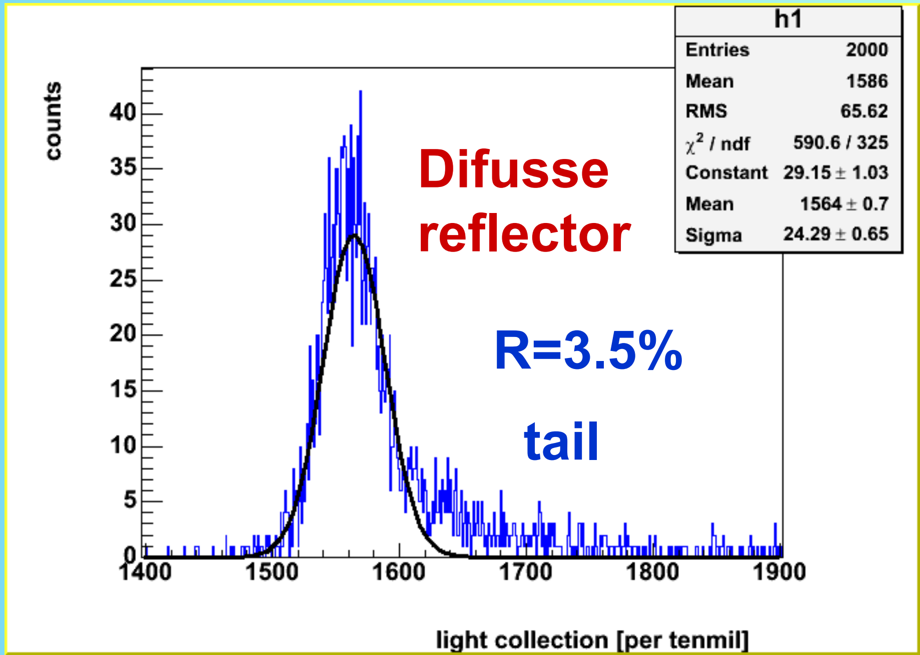
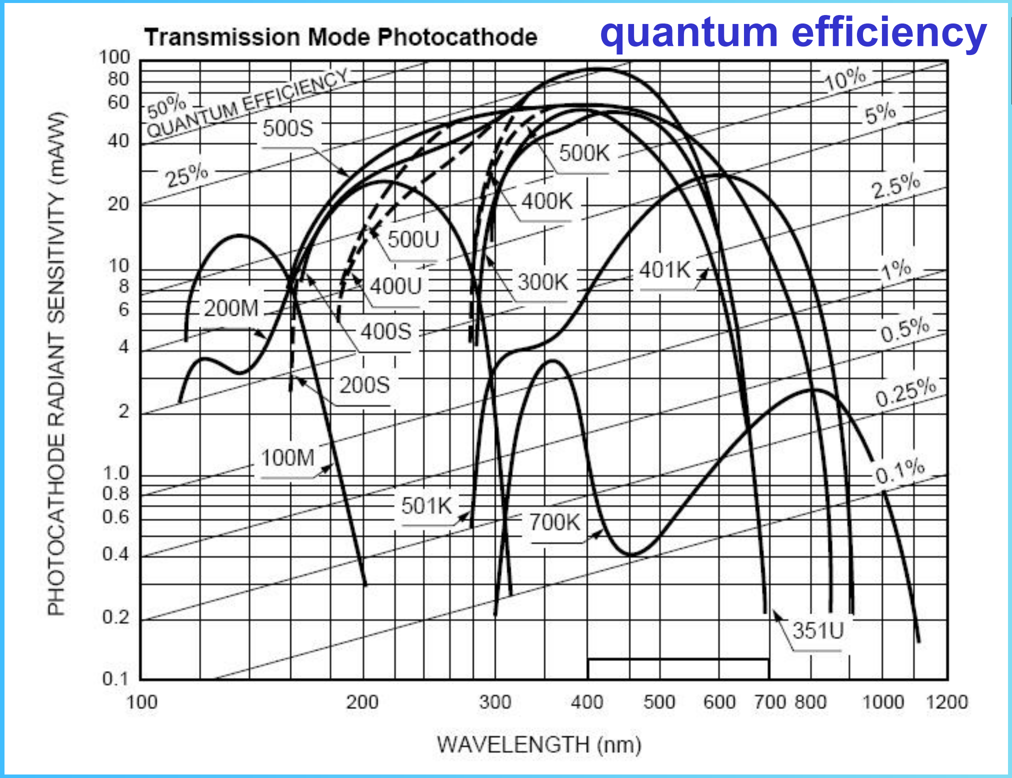


Photo-electron conversion



$$R = 2.35\sqrt{\frac{(1-QE)}{N_{ph}\times QE}}$$

Binomial distribution

x : success, N : trials, p : probability

$$P(x) = \frac{N!}{x!(N-x)!}p^x(1-p)^{N-x}$$

$$\bar{x} = Np$$

$$\sigma^2 = \bar{x}(1-p)$$