# Scintillation Detectors

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# 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 $\alpha$-particles . + Rutherford, Geiger (gas counter)
- Geiger, Marsden (1909): angular distribution of scattered $\alpha$-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

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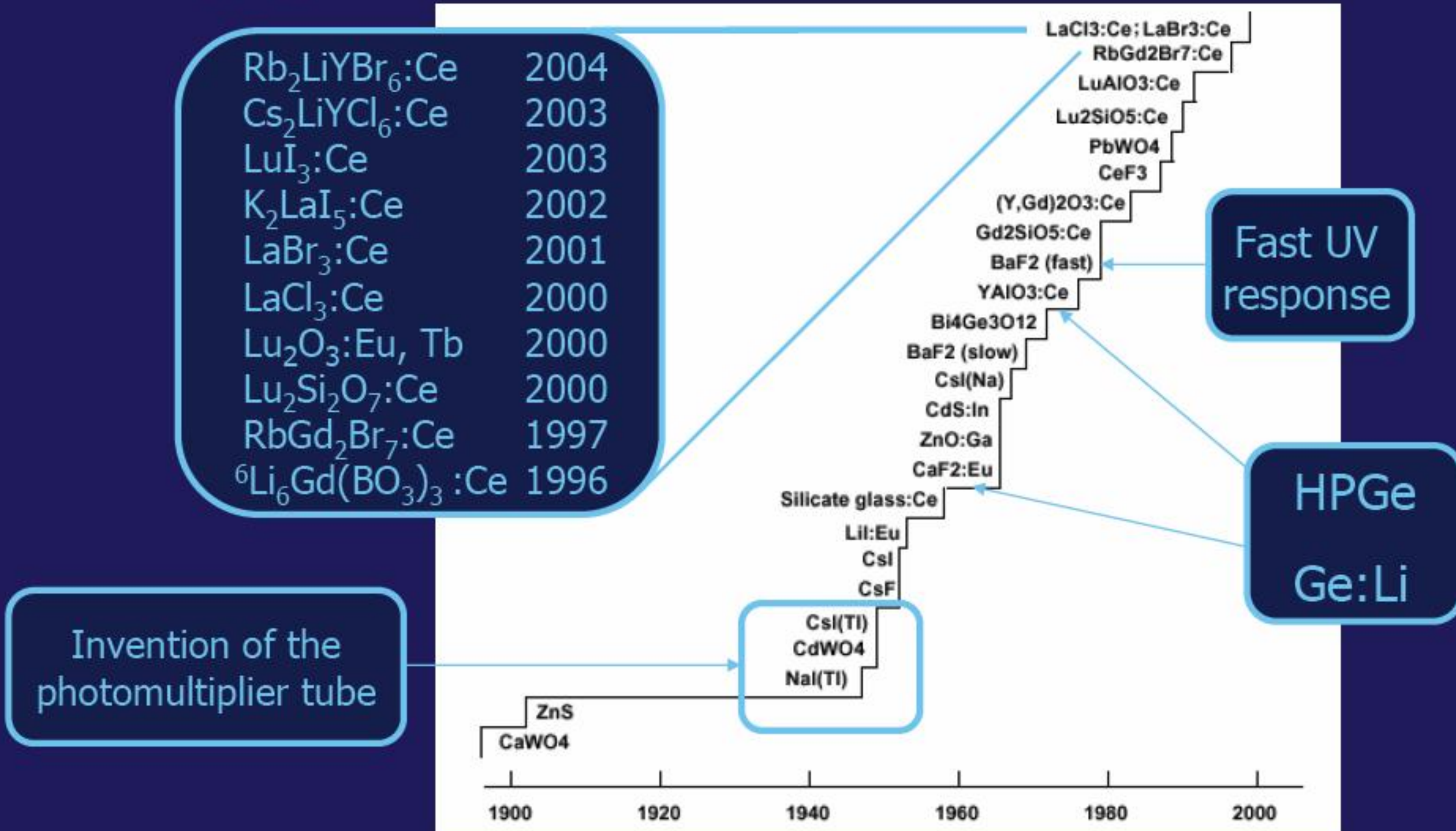


## Scintillation materials

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

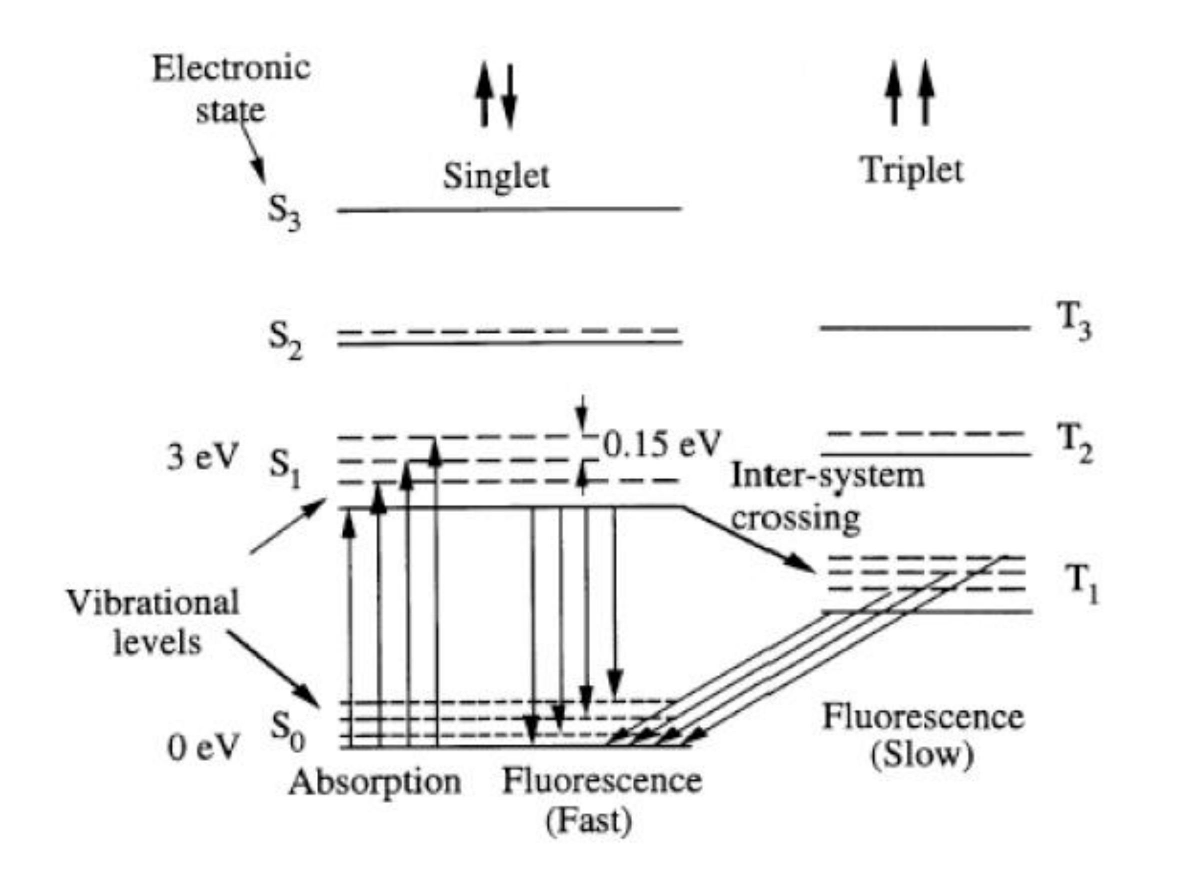
Emissions: fluorescence (prompt), delayed fluorescence and phosphorescence (delayed, different wavelength)

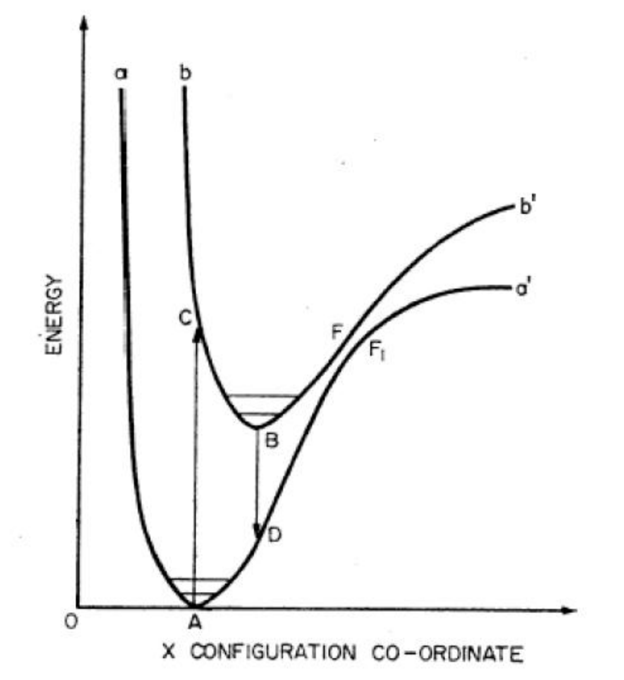
Scintillation material properties:

- 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

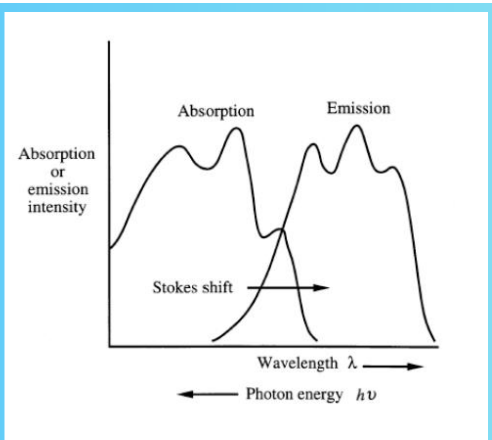
# Luminescence in organic materials

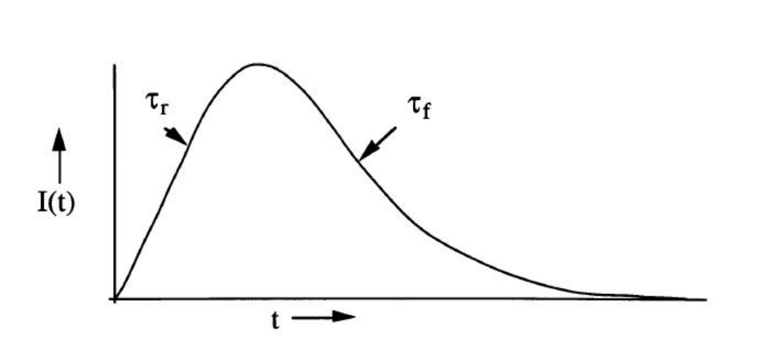


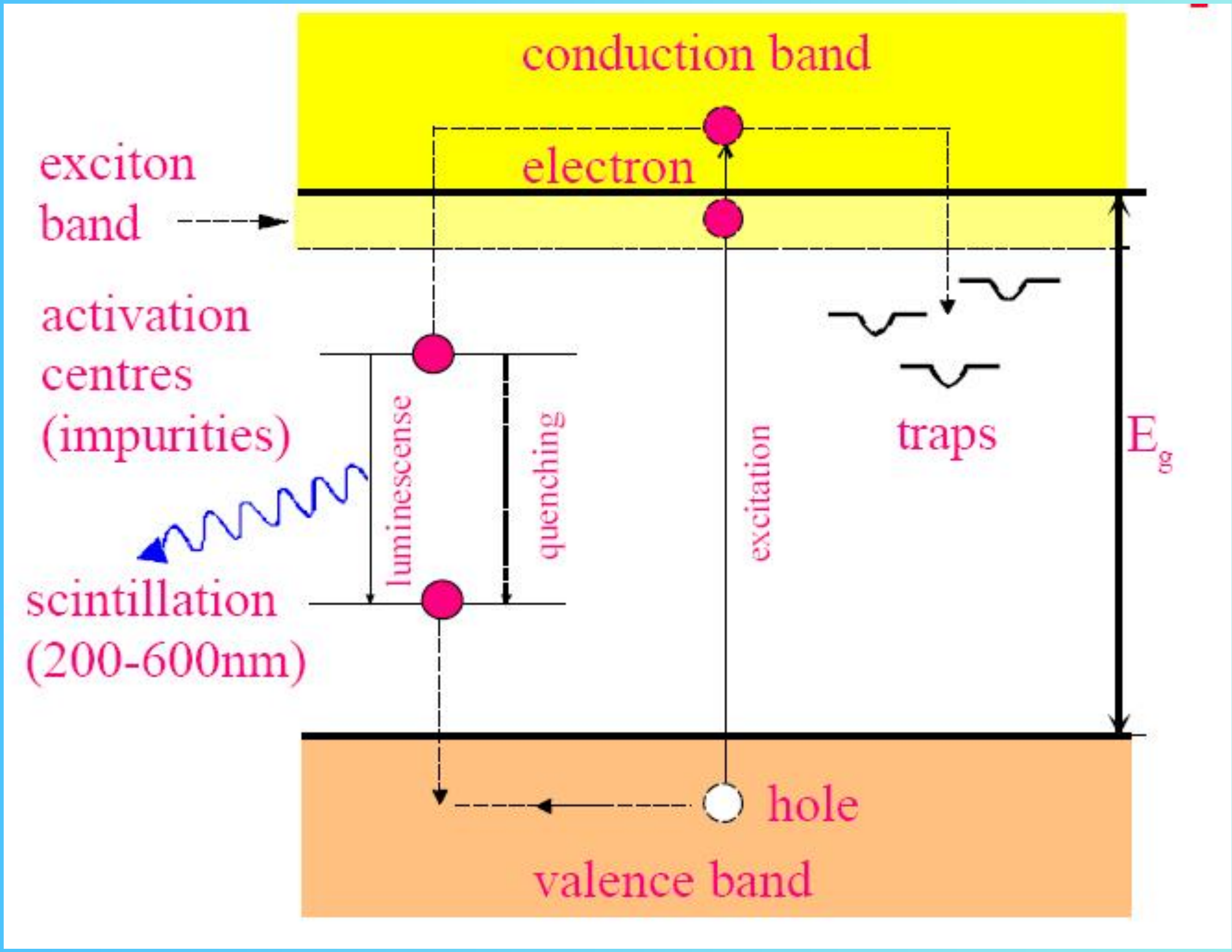

Several time components

Material transparent to its own light

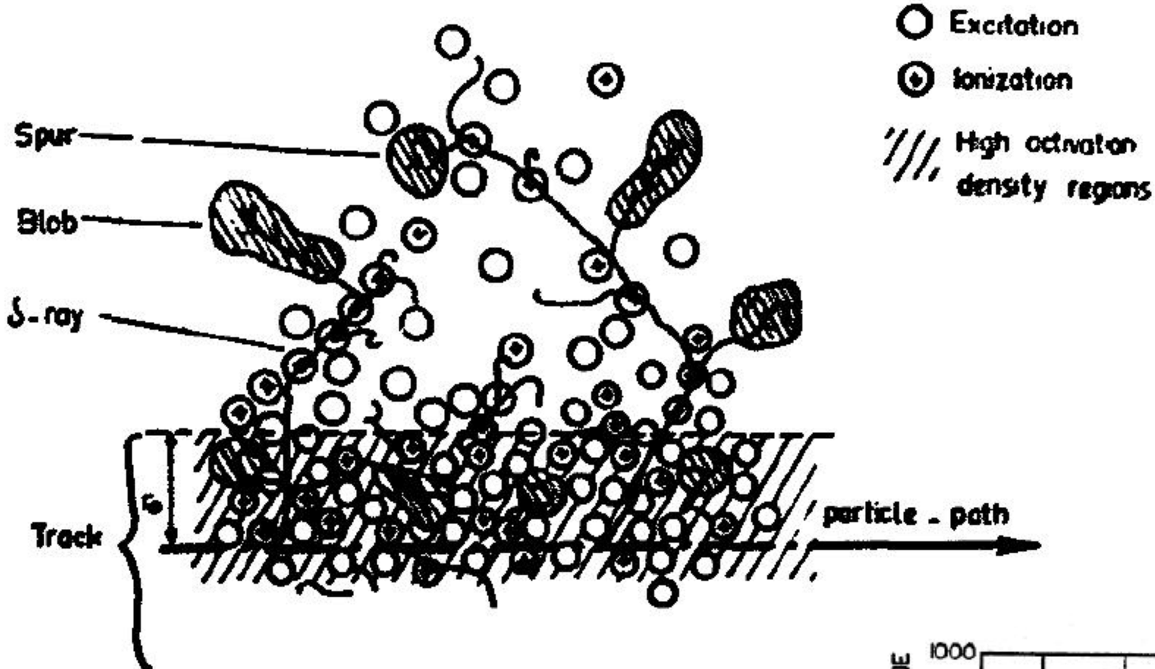


# Luminescence in inorganic materials




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

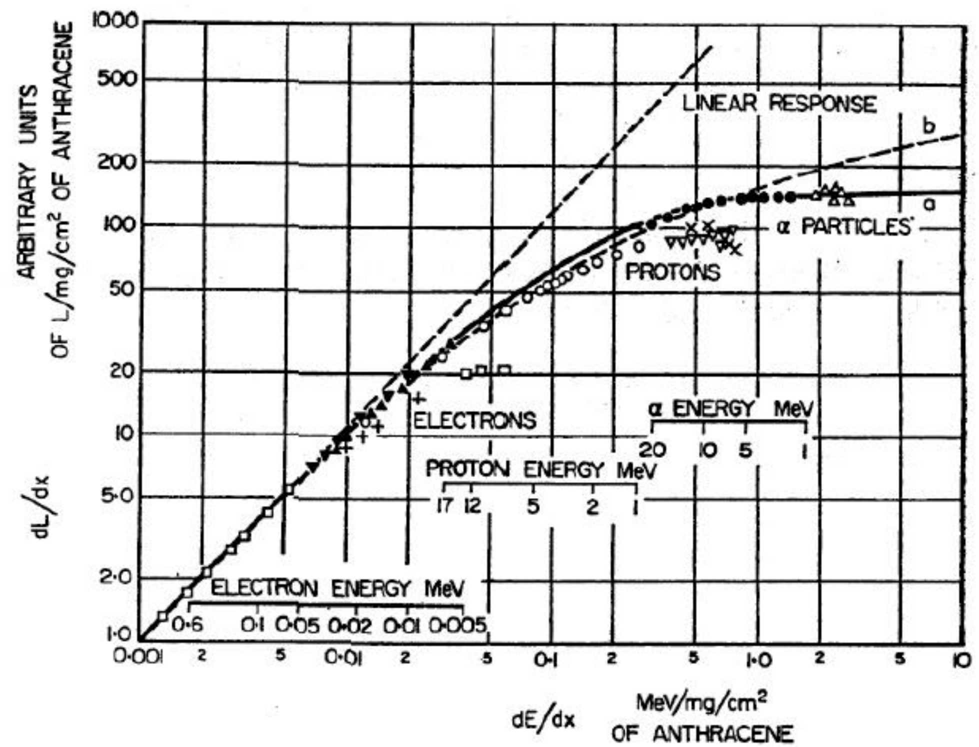


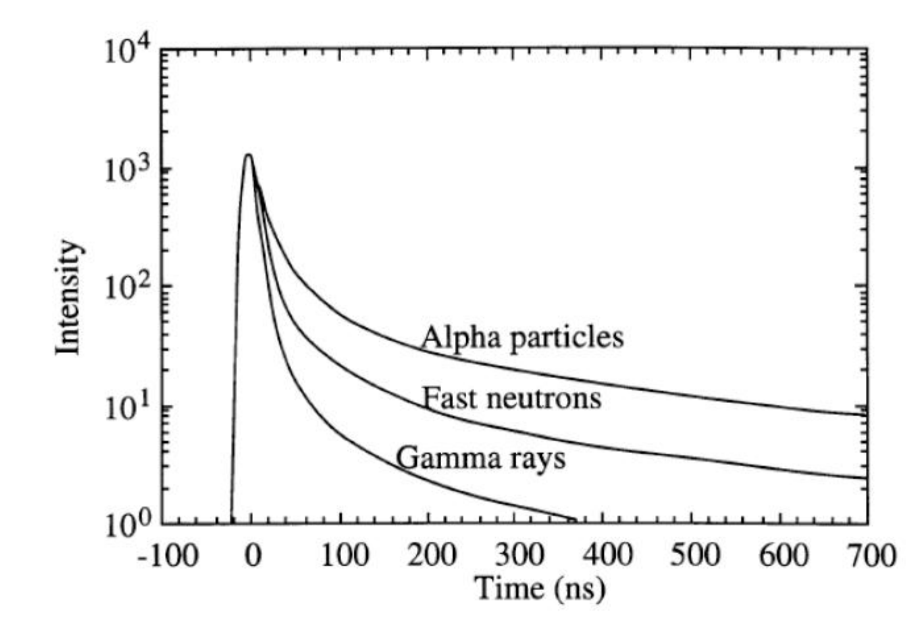

The non-radiative transfer mechanism between excited centers induces an energy-loss dependent light production

Simple parameterization:

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

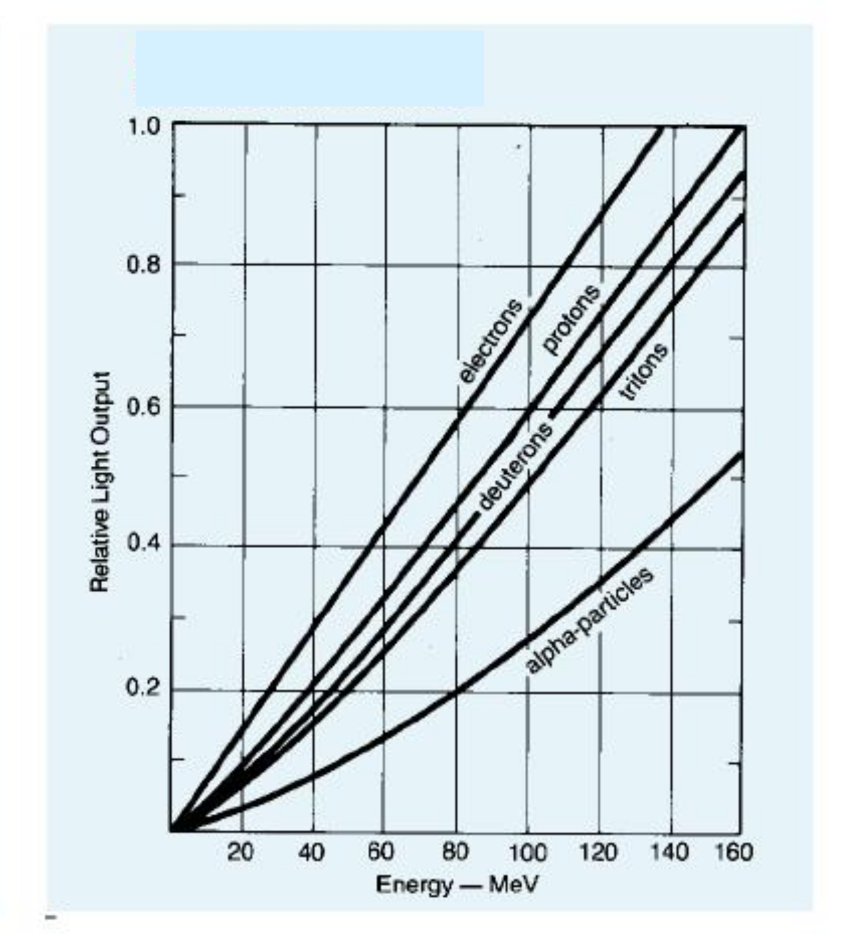
Birk´s formula

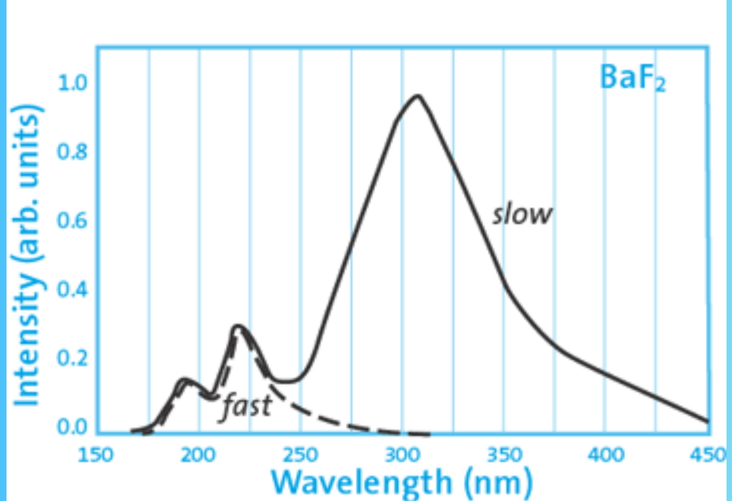


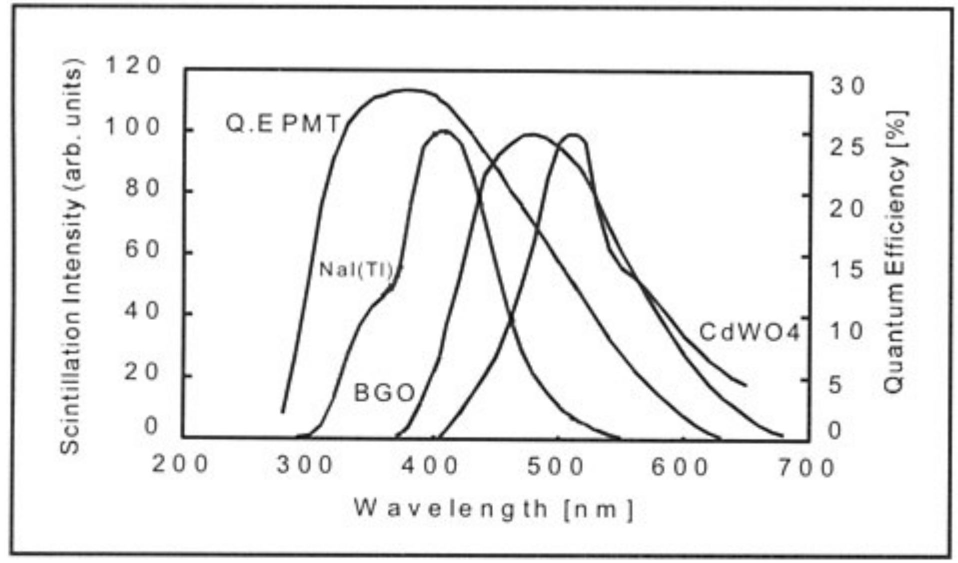



As a consequence there is a particle type and energy dependence of scintillation pulse shape and light output

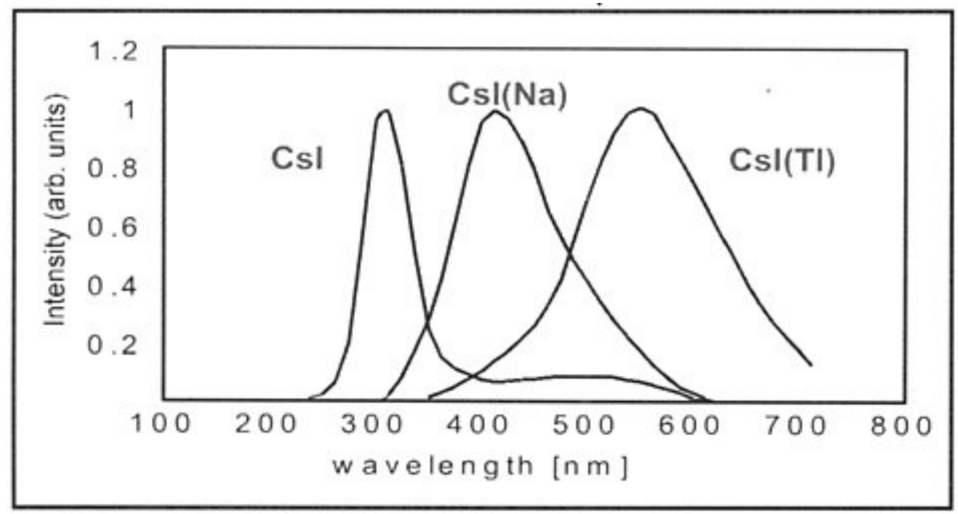
Both effects can be used to identify particles



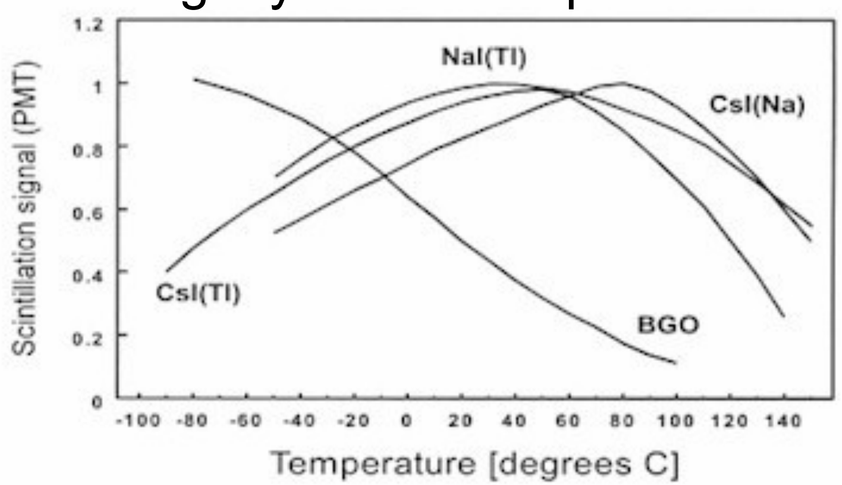


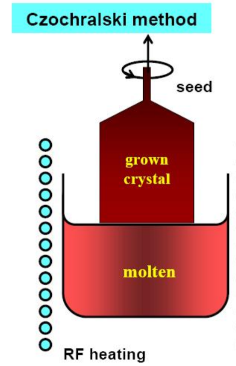

Emission spectra




Light yield vs. temperature



# Properties of some inorganic scintillation crystals




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

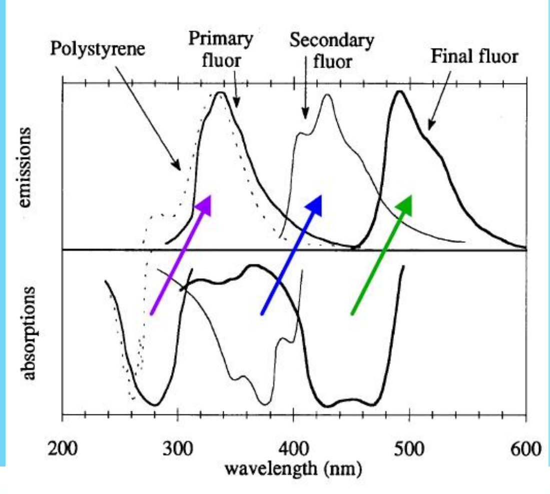
| | Density ($g/cm^3$) | Wavelength at max.(nm) | Refractive index | Decay time (ns) | Light yield (ph/MeV) |
|---|---|---|---|---|---|
| NaI(Tl) | 3.67 | 415 | 1.85 | 230 | 38000 |
| CsI(Tl) | 4.51 | 540 | 1.80 | 680,3340 | 40000,25000 |
| $Bi_4Ge_3O_{12}$ | 7.13 | 480 | 2.15 | 300 | 8200 |
| $BaF_2$ | 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 |

# Scintillation materials for PET

| Scintillator | Effective Z | Density (g/cc) | 1/*e* attenuation length at 511 keV (cm) | Relative light yield (%NaI) | Refractive index | Decay time (ns) | Peak emission wavelength (nm) | Rugged? |
|---|---|---|---|---|---|---|---|---|
| "BGO" $Bi_4(GeO_4)_3$ | 75 | 7.13 | 1.06 | 15 | 2.15 | 300 | 480 | Yes |
| "LSO" $Lu_2(SiO_4)O:Ce$ | 66 | 7.4 | 1.13 | 75 | 1.82 | 42 | 420 | Yes |
| "GSO" $Gd_2(SiO_4)O:Ce$ | 59 | 6.71 | 1.4 | 20 | 1.85 | 60 | 440 | Yes |
| "LYSO" $Lu_{1.8}Y_{0.2}(SiO_4)O:Ce$ | 65 | 7.1 | 1.2 | 107 | 1.81 | 40 | 420 | Yes |
| "Sodium Iodide" NaI(Tl) | 51 | 3.67 | 2.94 | 100 | 1.85 | 230 | 410 | No |

Properties of some organic scintillation plastics

✦ wavelength shifters



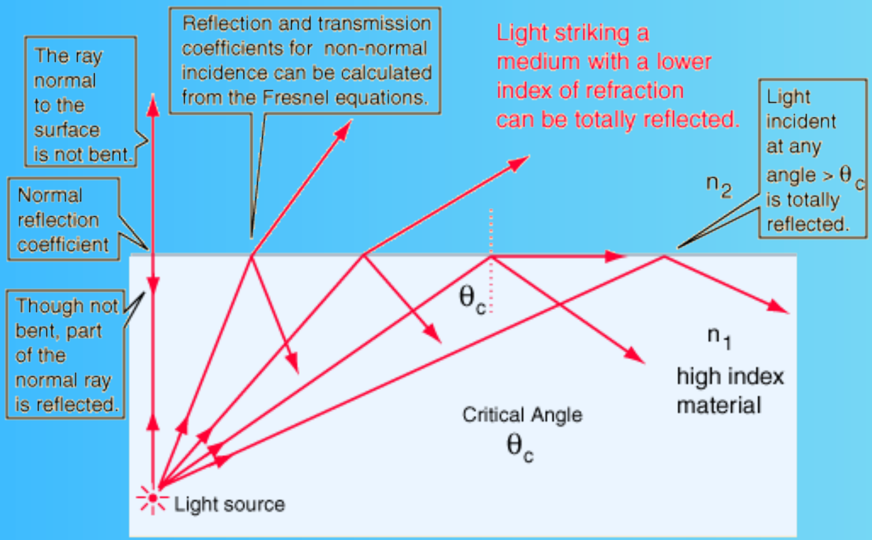

| Scintillator | Light Output % Anthracene[1] | Wavelength of Maximum Emission, nm | Decay Constant, Main Component, ns | Bulk Light Attenuation Length, cm | Refractive Index | H/C Ratio | Loading Element % by weight | Density | Softening Point °C |
|---|---|---|---|---|---|---|---|---|---|
| BC-400 | 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 |

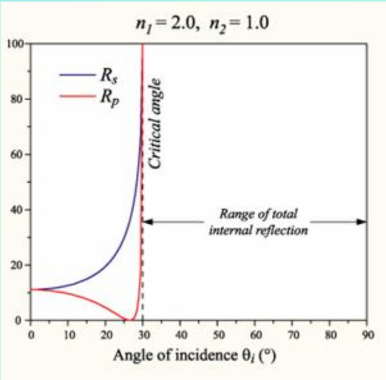
[1] Anthracene light output = 40-50% of NaI(Tl)

* 0.1 to 5 weight % also available

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

# Light collection and transmission



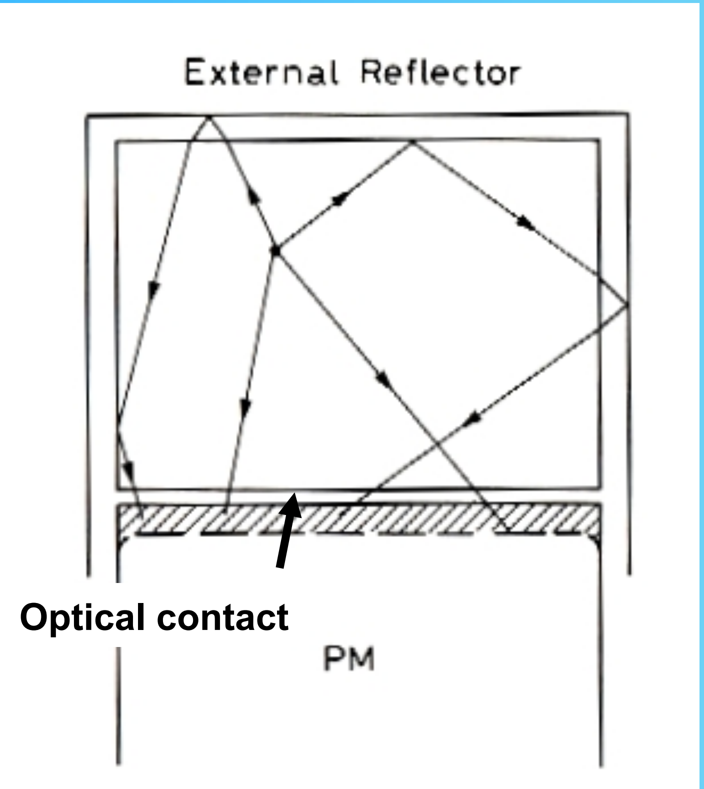




Snell law:

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

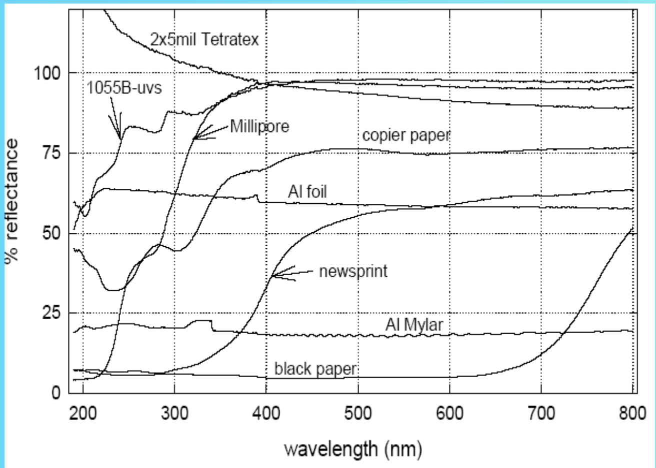
Fresnel formulae:

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



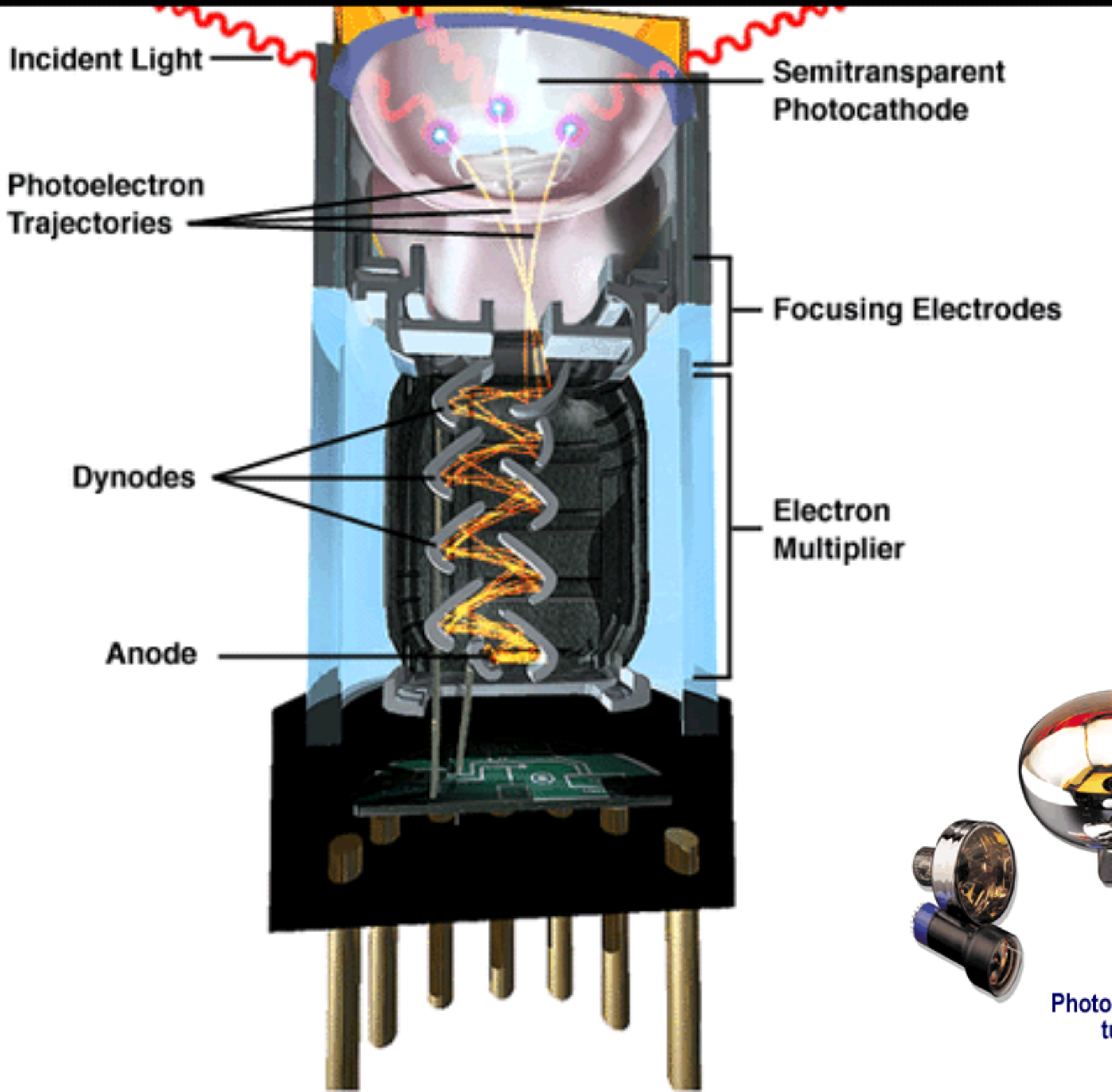

**Reflector:**

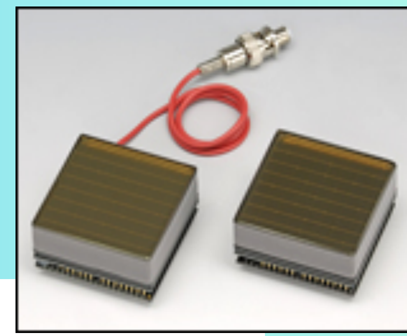
- mirror-like: $\theta_r = \theta_i$
- diffuse: $\theta_r$ random




**Light-guide**

# The Photomultiplier Tube

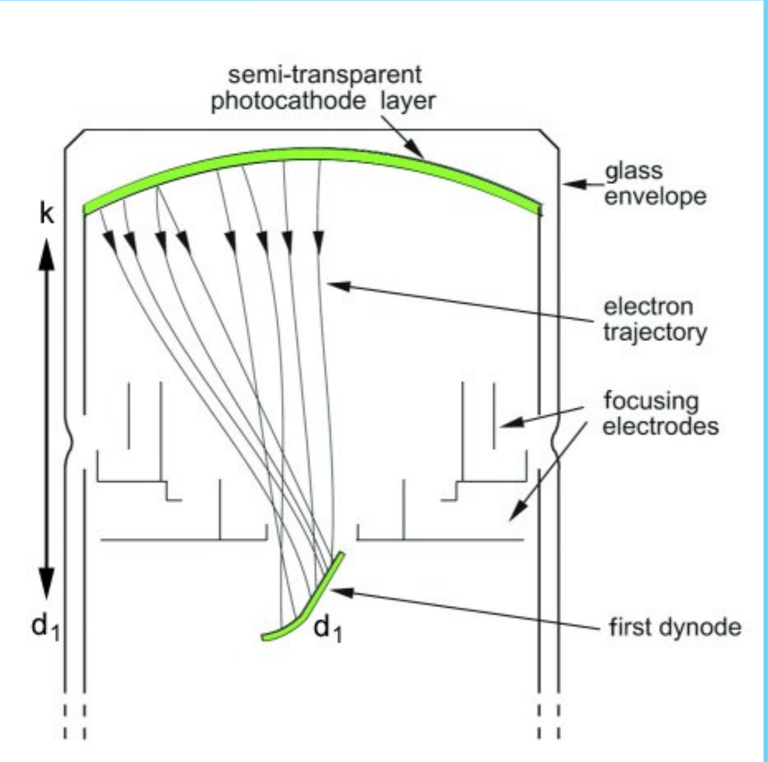


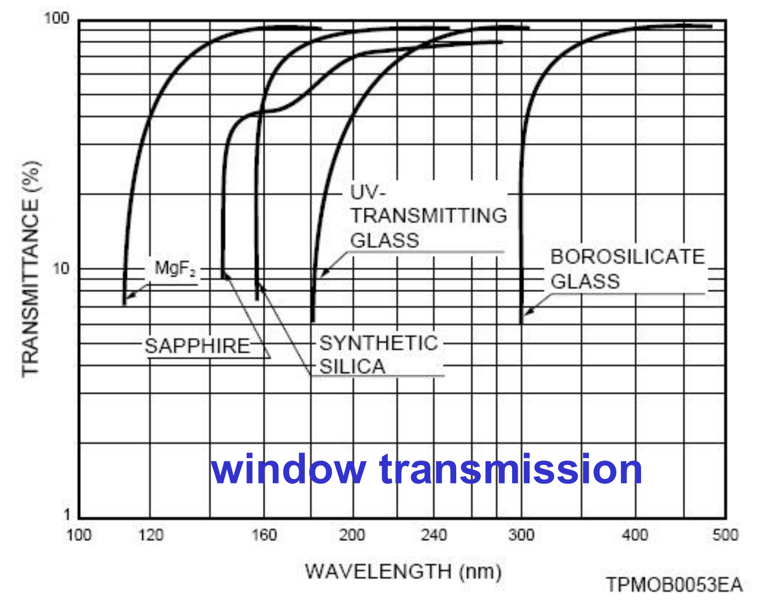
Photomultiplier tubes

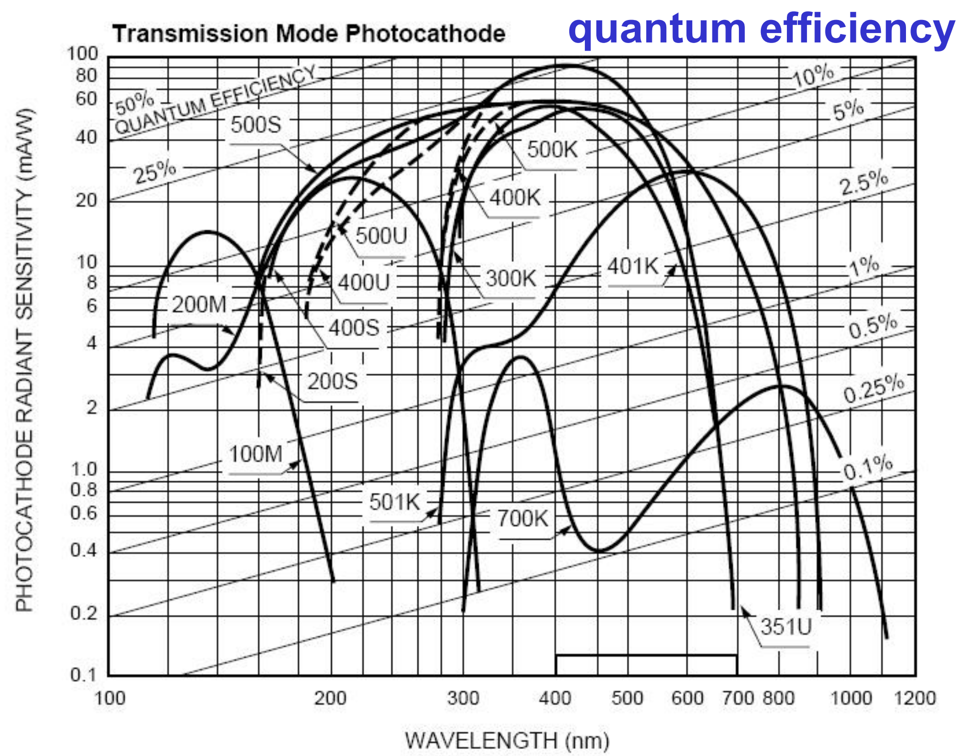
**PMT window, photo-cathode and focusing electrodes:**

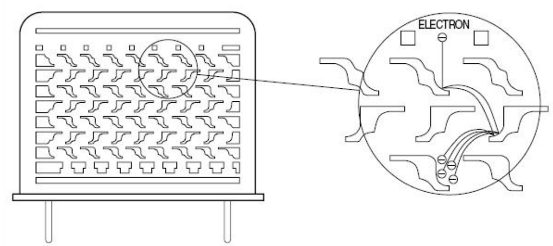
✦ spectral sensitivity, gain, energy resolution and time resolution




Photoelectron trajectories between photocathode and first dynode.





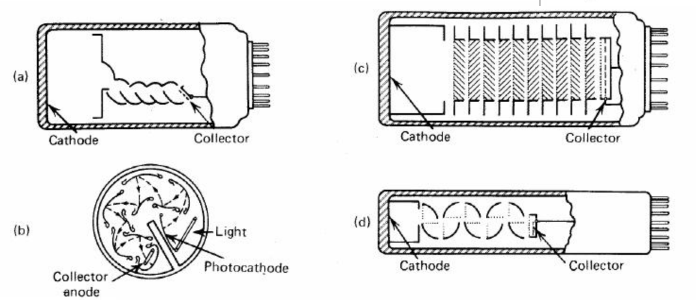
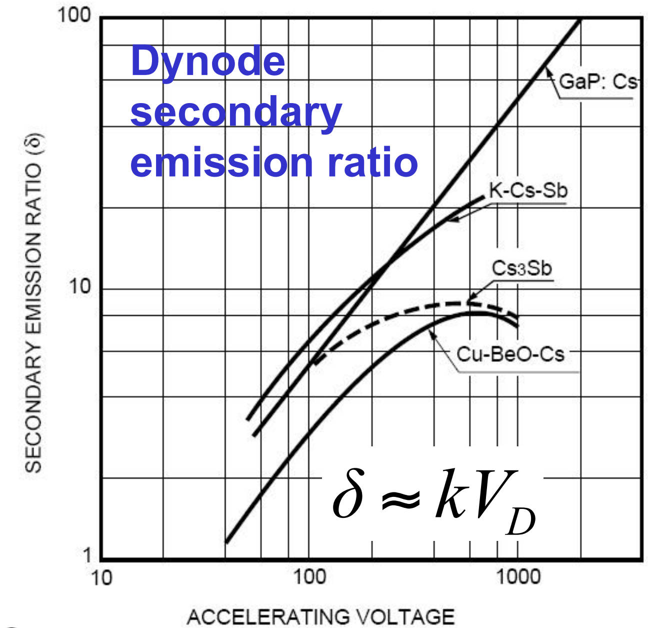




Fig. 4-8. Configurations of some common types of PM tubes. (a) Focused linear structure. (b) Circular grid. (c) Venetian blind. (d) Box-and-grid. (Courtesy of EMI GENCOM Inc., Plainview, NY.)

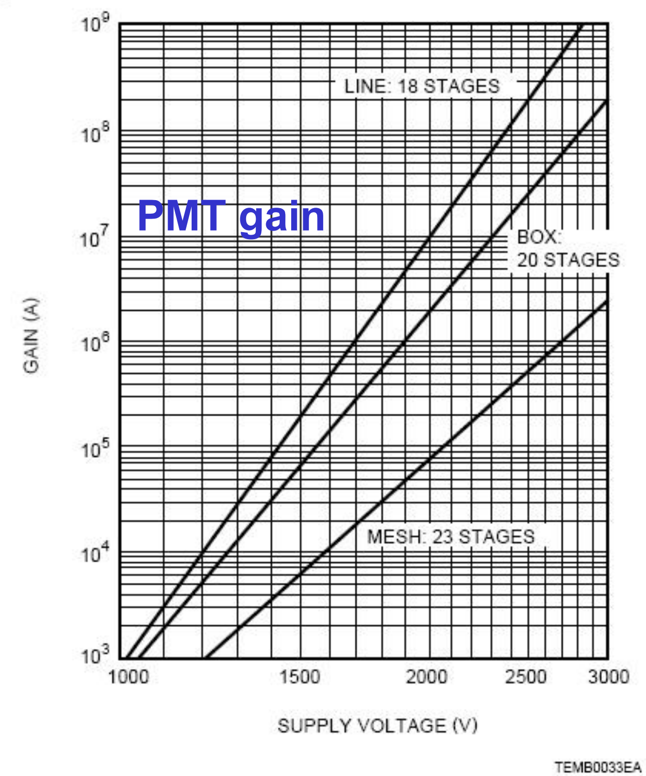



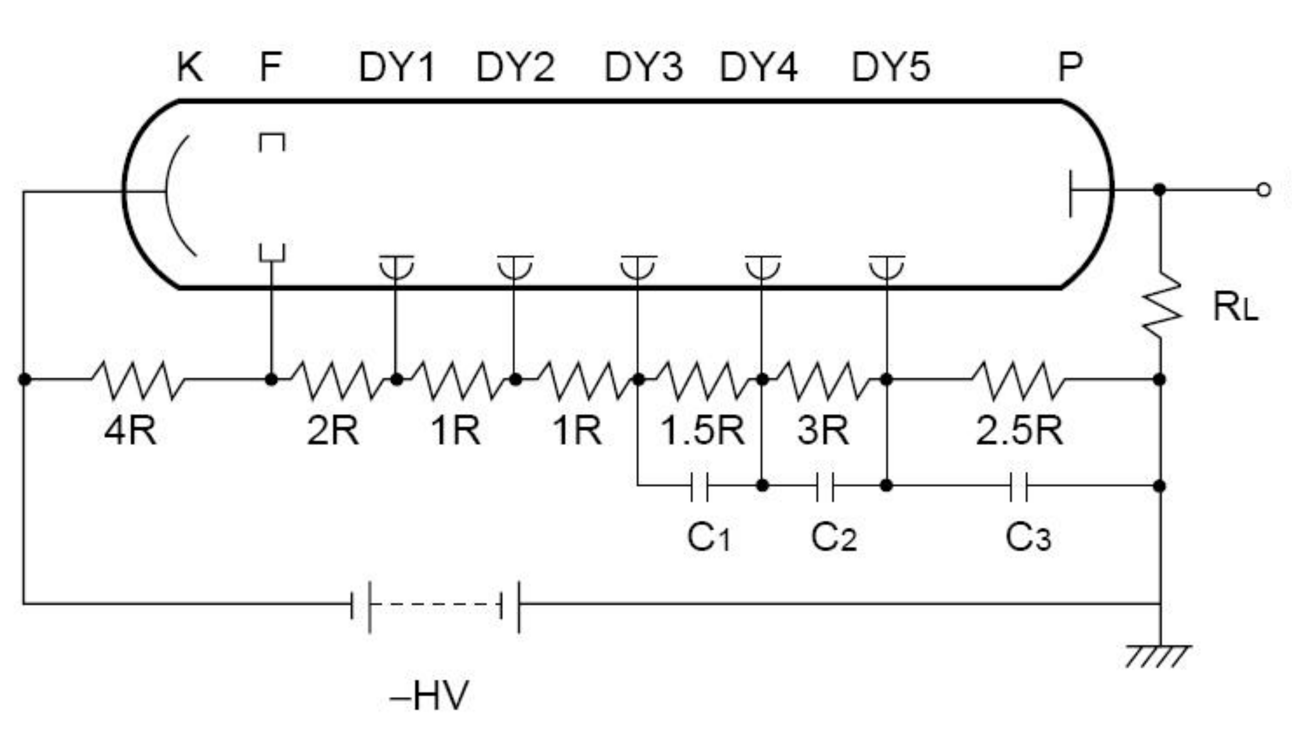

**PMT dynode structure:**

✦ gain & time resolution

$$G \approx \delta^n$$

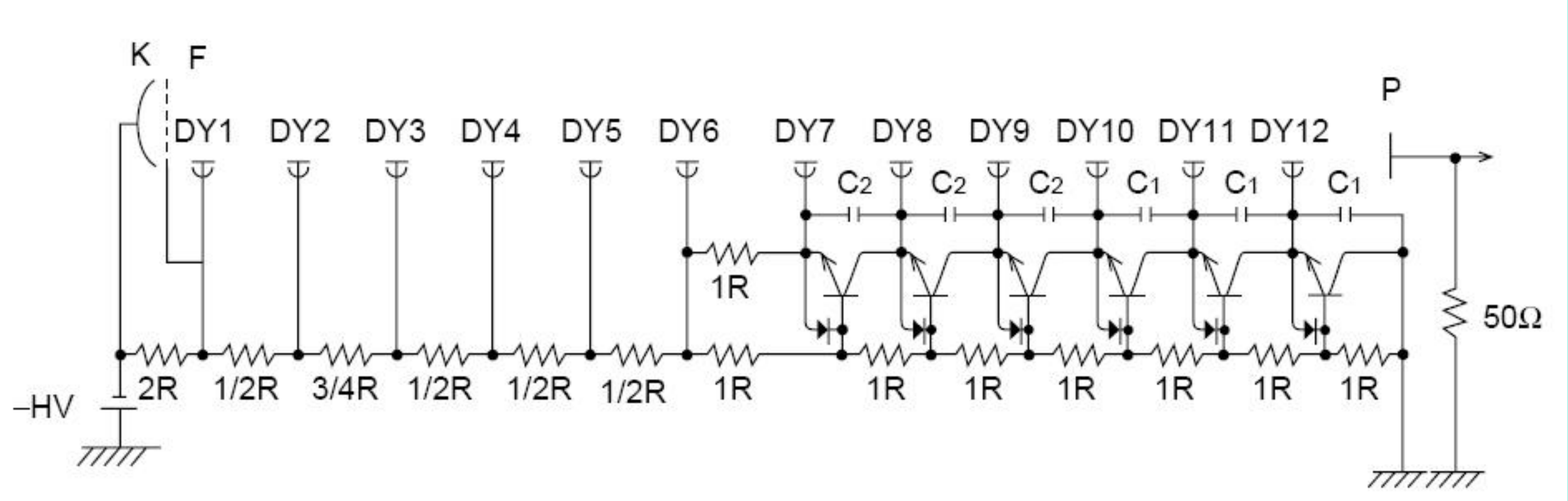
$$\frac{\Delta G}{G} \approx n \frac{\Delta V_D}{V_D}$$



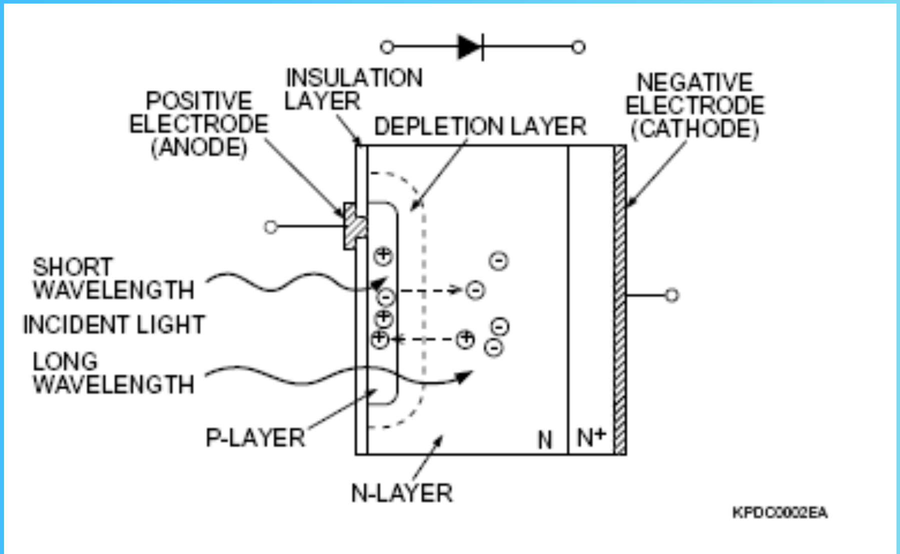


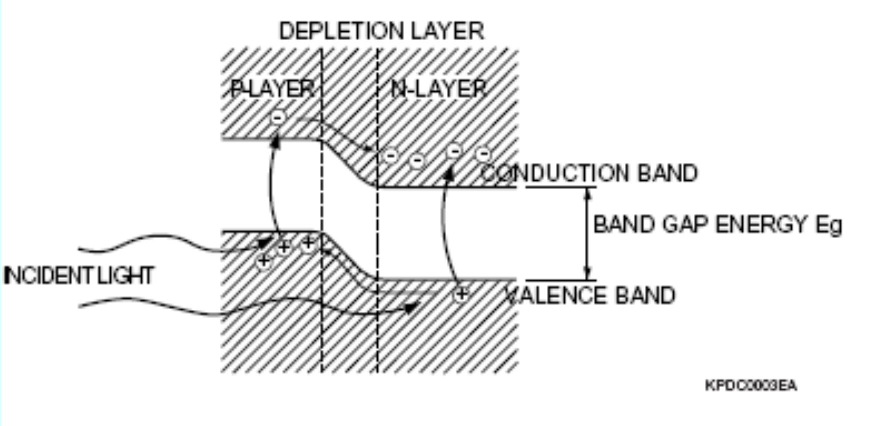

**PMT base - voltage divider:**

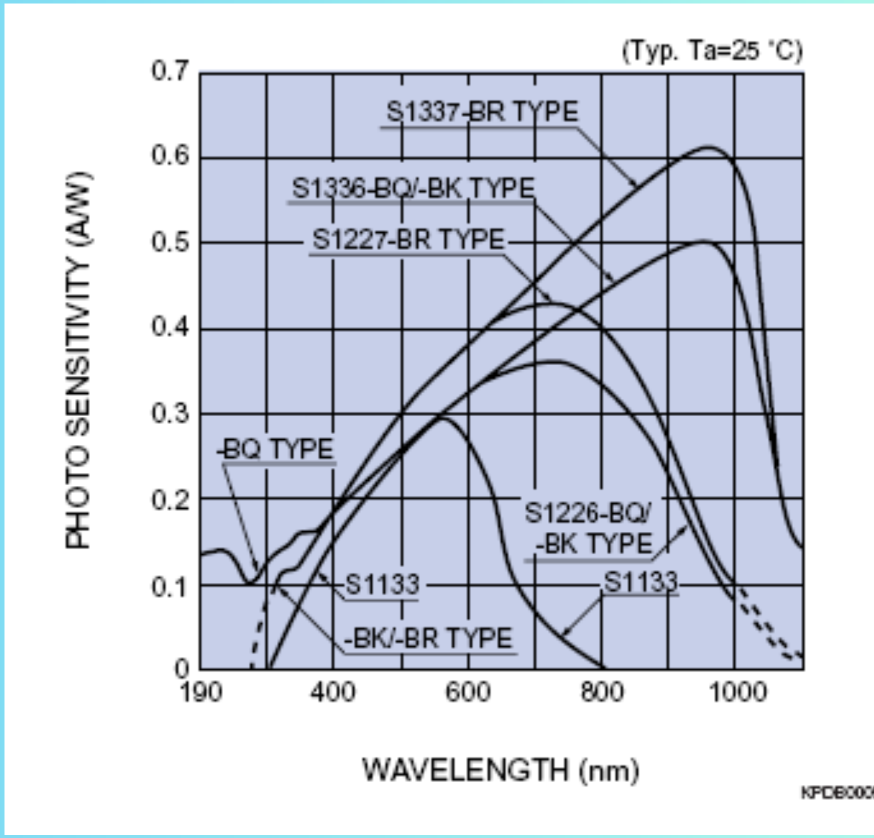
✦ linearity

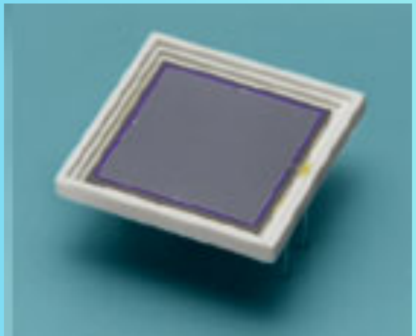


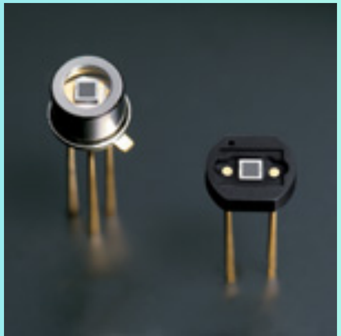
# Semiconductor photon sensors



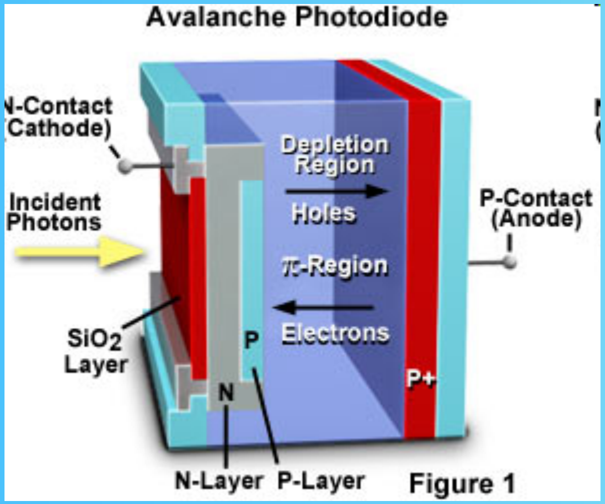



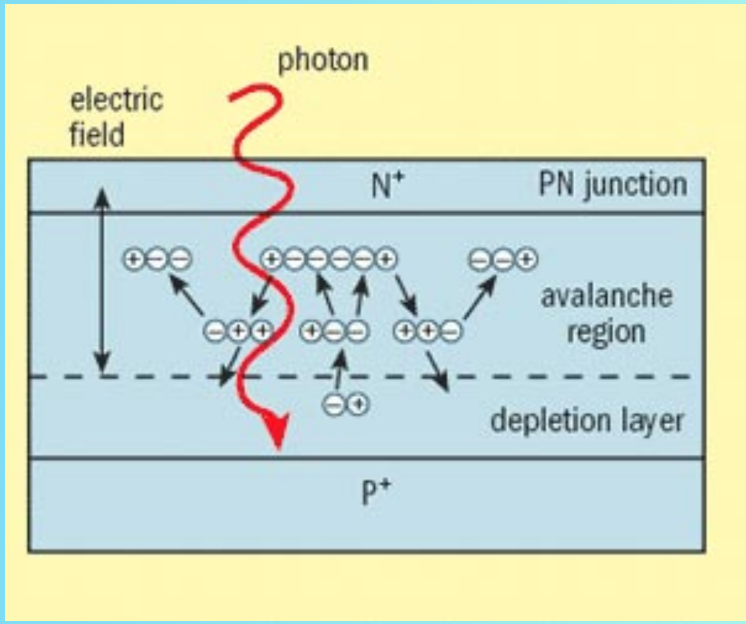



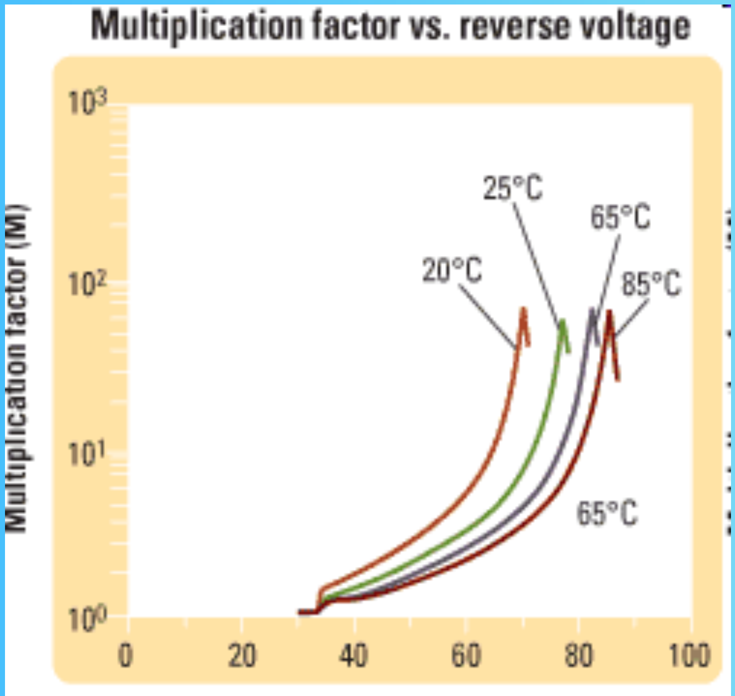


## Si Photo-Diodes (PD)

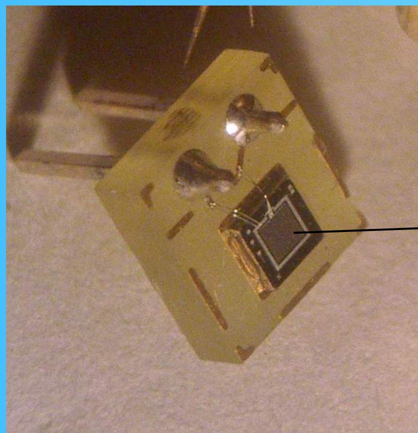
# Avalanche Photo-Diodes (APD)



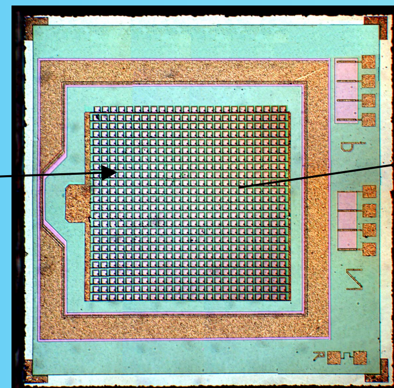



# Silicon Photomultipliers (Si-PMT, SPM, MPPC, DAPD, SPM, …)

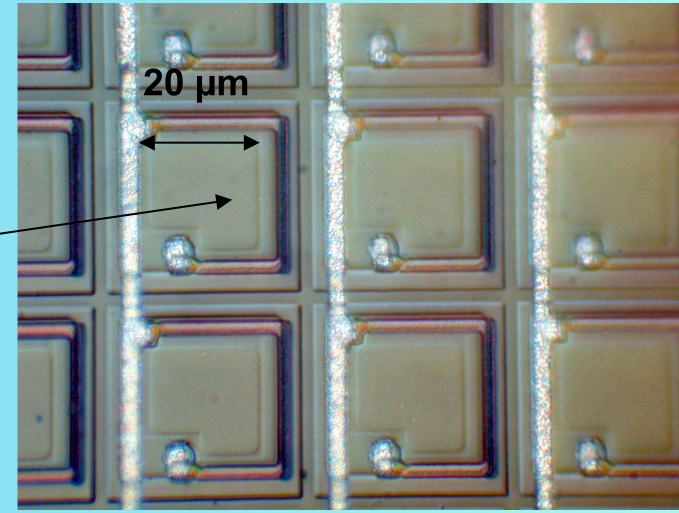


1 mm

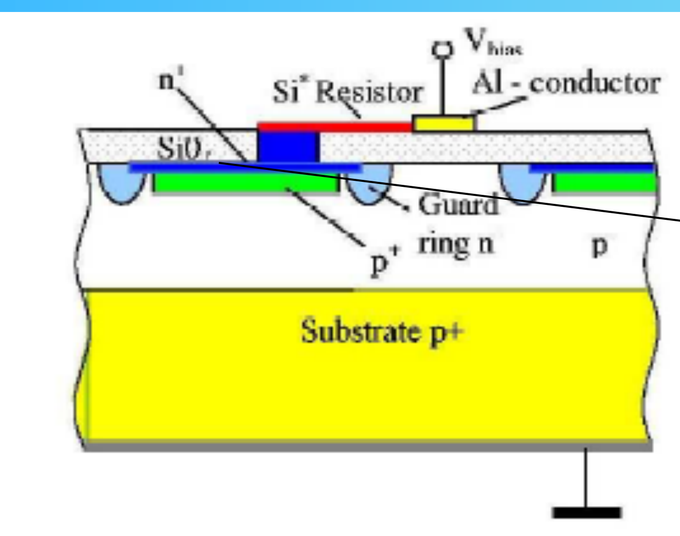


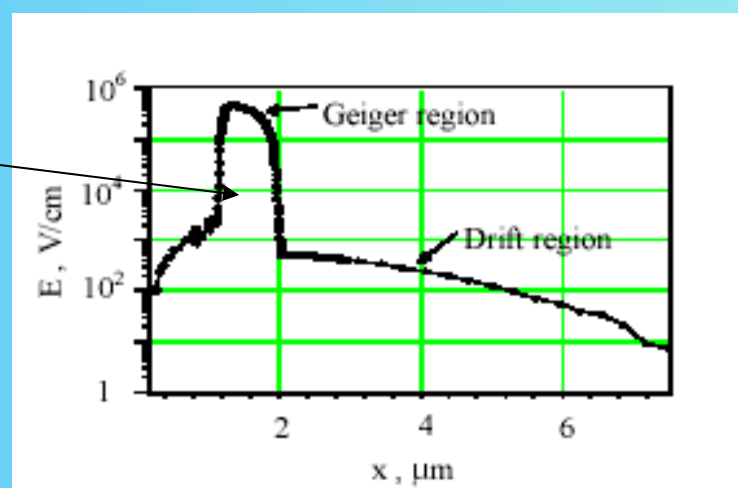
24*24=576 pixels

42 µm




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



**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 (intrinsic: one-photon response), non-uniformity of photo cathode
4. Electron multiplication and collection variations
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