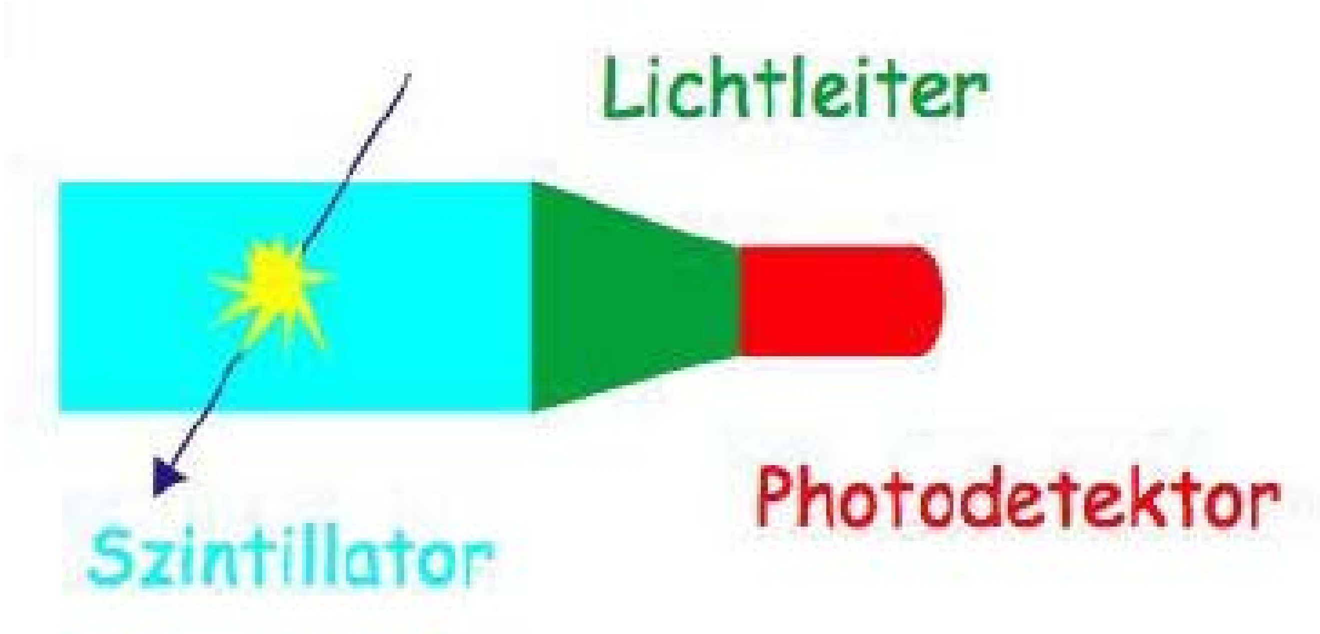
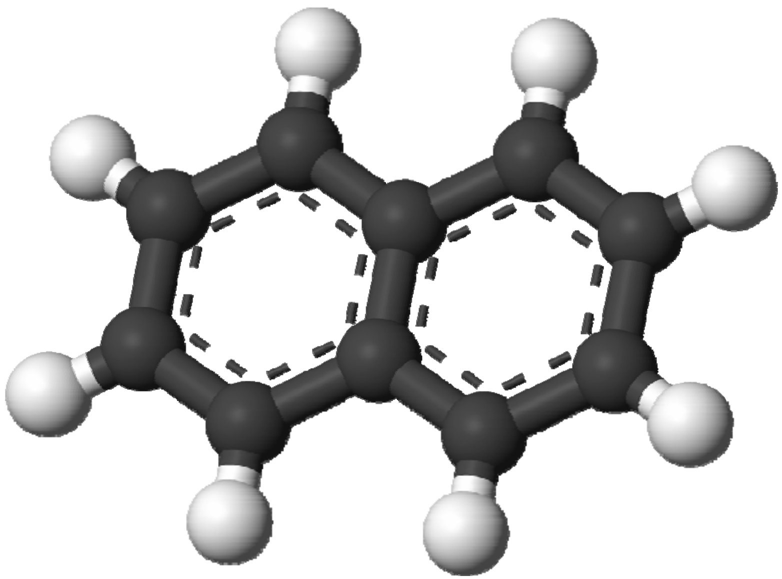
Scintillators and photodetectors

1. Generation of Optical Photons
2. Transport of Optical Photons
3. Detection of Optical Photons



A) Organic (molecular) scintillators



Naphtalene:
π-electron system

Advantages:

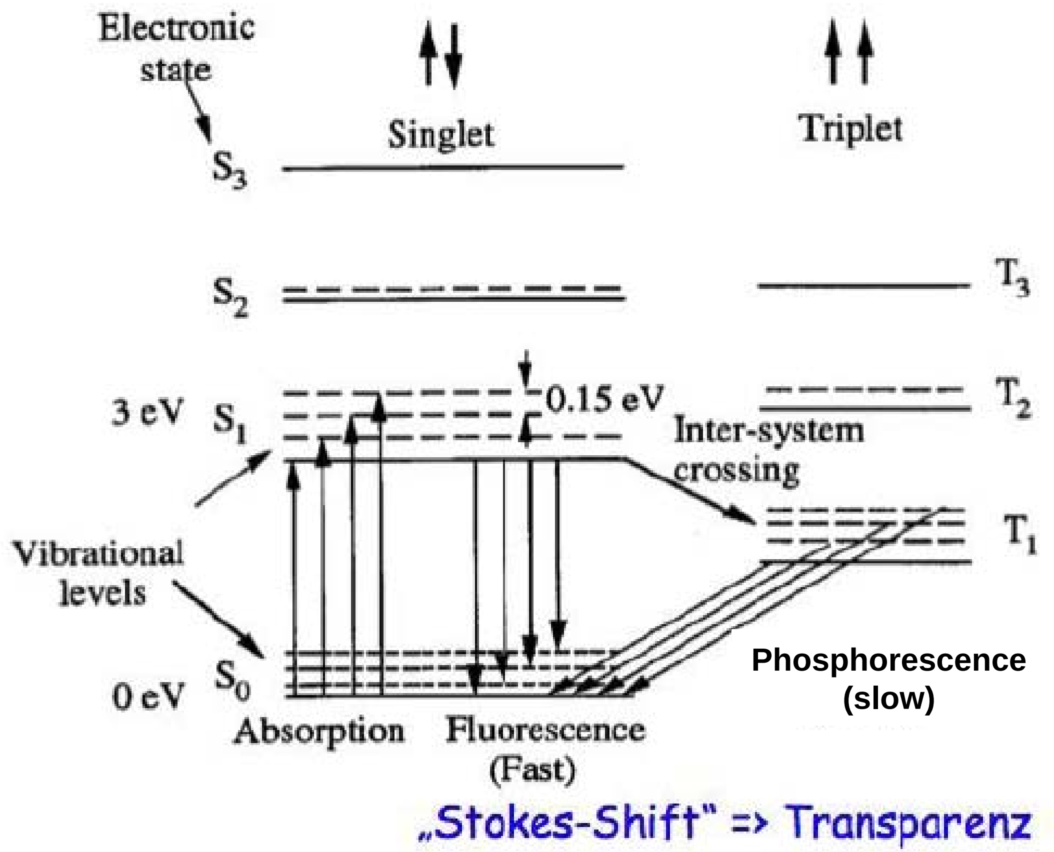
- Fast
- No need for Xtals

➔liquids, glasses, …

Disadvantages:

- inefficient
- Non-linear (quenching)
- not good for γ's

The electronic levels:

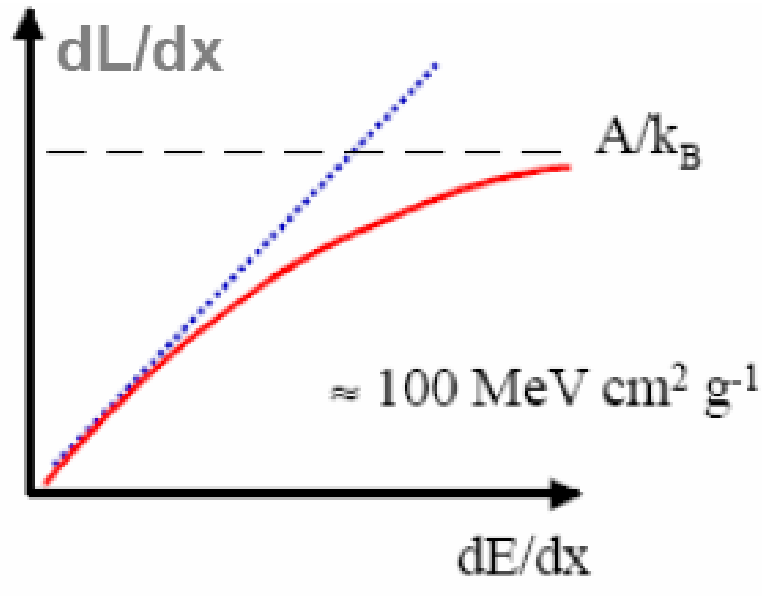


1) Prompt fluorescence
2) Phosphorescence
3) Delayed fluorescence
➔ Complicated time structure

Non-linearity: Birk's law

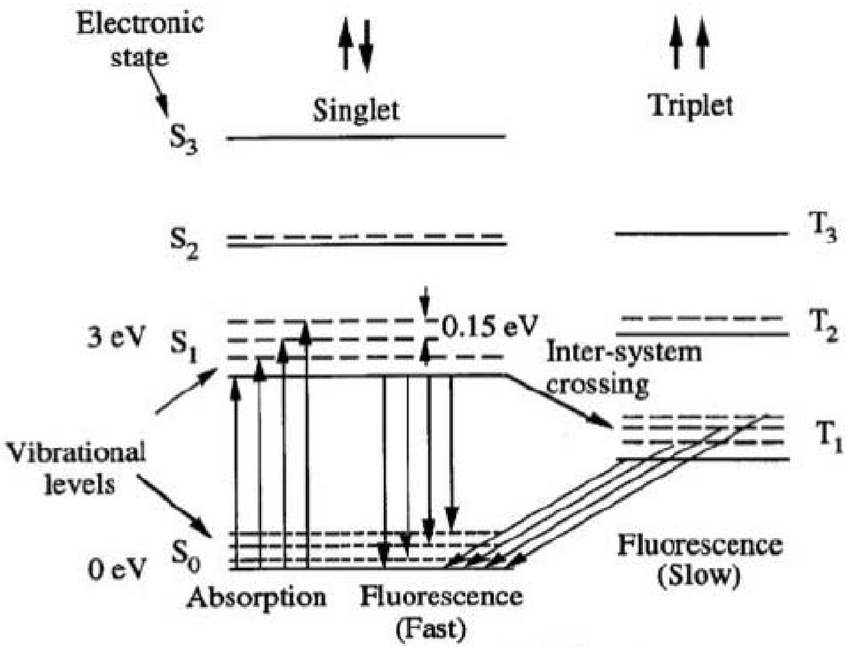
- Interaction between two (or more) excited molecules ➔ Non-radiative decay = **quenching** ➔ Becomes more important with increasing ionization density ➔ non-linearity.

$$\frac{dL}{dx} = \frac{A \cdot dE / dx}{1 + k_B \cdot dE / dx}$$



How to avoid re-absorption?

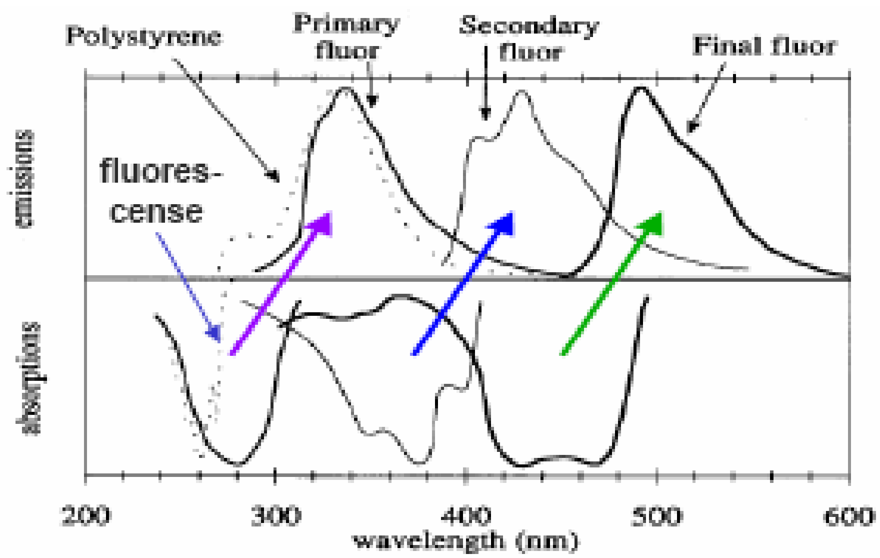
Natural Stokes shift (not enough)



„Stokes-Shift" => Transparenz

Wavelength shifters
via additional scintillators

Principle of WLS:



Eigenschaften organischer Szintillatoren

scintillator	density (g/cm³)	index of refraction	wavelength of maximum emission (nm)	decay time constant (ns)	scintillation pulse height [1]	H/C ratio [2]
Monocrystals						
naphthalene	1.15	1.58	348	11	11	0.800
anthracene	1.25	1.59	448	30-32	100	0.714
trans-stilbene	1.16	1.58	384	3-8	46	0.857
p-terphenyl	1.23		391	6-12	30	0.778
Plastics [3]						
NE 102 A	1.032	1.58	425	2.5	65	1.105
NE 104	1.032	1.58	405	1.8	68	1.100
NE 110	1.032	1.58	437	3.3	60	1.105
NE 111	1.032	1.58	370	1.7	55	1.096
Plastics [4]						
BC-400	1.032	1.581	423	2.4	65	1.103
BC-404	1.032	1.58	408	1.8	68	1.107
BC-408	1.032	1.58	425	2.1	64	1.104
BC-412	1.032	1.58	434	3.3	60	1.104
BC-414	1.032	1.58	392	1.8	68	1.110
BC-416	1.032	1.58	434	4.0	50	1.110
BC-418	1.032	1.58	391	1.4	67	1.100
BC-420	1.032	1.58	391	1.5	64	1.100
BC-422	1.032	1.58	370	1.6	55	1.102
BC-422Q	1.032	1.58	370	0.7	11	1.102
BC-428	1.032	1.58	480	12.5	50	1.103
BC-430	1.032	1.58	580	16.8	45	1.108
BC-434	1.049	1.58	425	2.2	60	0.995

- Organische Szintillatoren haben niedriges Z (hauptsächlich H und C)
- Geringe γ-Nachweiswahrscheinlichkeit (praktisch nur Comptoneffekt)
- Jedoch hohe Neutron Nachweiswahrscheinlichkeit via (n,p) Reaktionen

[1] relative to anthracene
[2] ratio of hydrogen to carbon atoms
[3] Nuclear Enterprises Ltd. Sighthill, Edinburgh, U.K.
[4] Bicron Corporation, Newbury, Ohio, USA

b) Inorganic crystalline scintillators (NaI:Tl)

Origin does not stem from molecular energy levels but from band-structure levels.

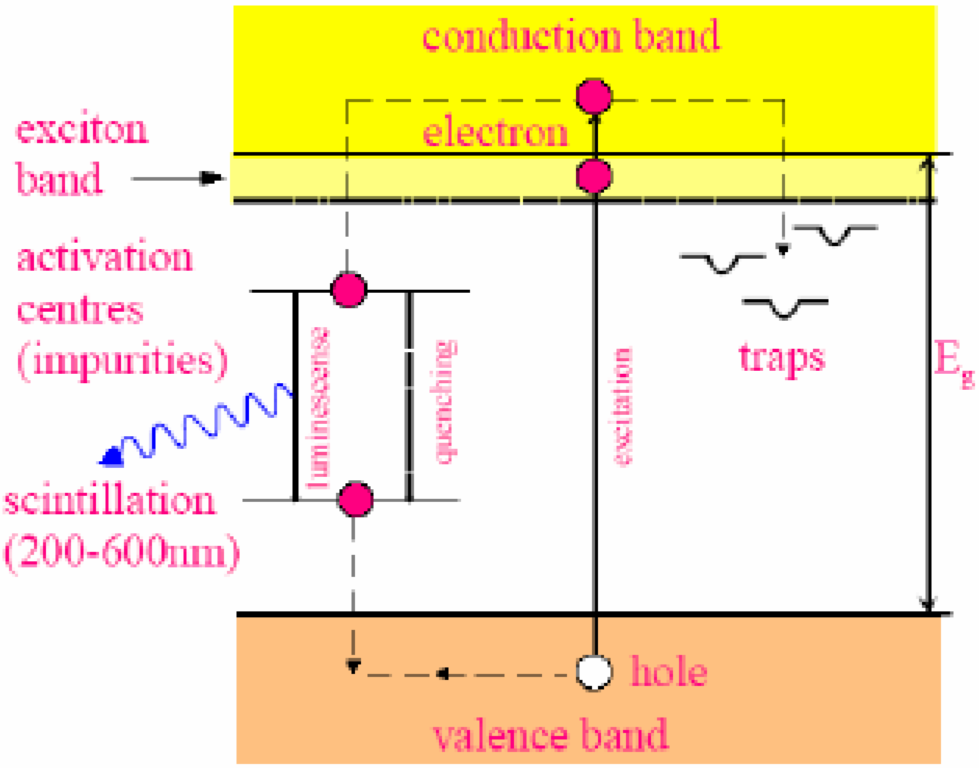
Advantages:

- Good efficiency
- Good linearity
- Radiation tolerance

Disadvantages:

- Relatively slow
- Crystal structure needed (small and expensive)

Three different scintillation mechanisms (crystals like NaI, CsI, BGO, BaF_2, ...)



→ > 1 decay time constants

- fast recombination (ns ... µs) from activation centres
- slow recombination due to trapping (~100ms)

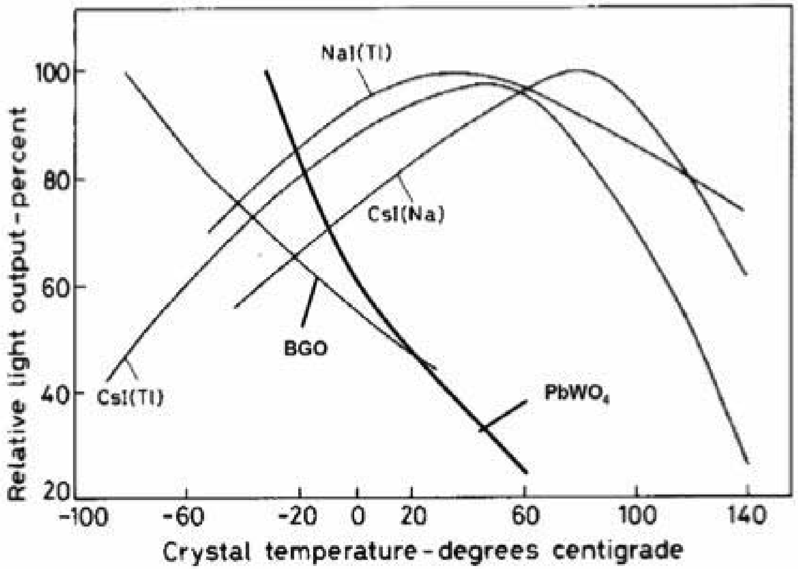
Gebräuchliche anorganische Szintillatoren

Eigenschaften gebräuchlicher Kristalle

Material	λ_{max} (nm)	τ_f (ns)	ρ (g/cm^3)	Photons per MeV
NaI(Tl) (20°C)	415	230	3.67	38,000
pure NaI (-196°C)	303	60	3.67	76,000
$Bi_4Ge_3O_{12}$ (20°C)	480	300	7.13	8,200
$Bi_4Ge_3O_{12}$ (-100°C)	480	2000	7.13	24,000
CsI(Na)	420	630	4.51	39,000
CsI(Tl)	540	800	4.51	60,000
CsI (pure)	315	16	4.51	2,300
CsF	390	2	4.64	2,500
BaF_2 (slow)	310	630	4.9	10,000
BaF_2 (fast)	220	0.8	4.9	1,800
Gd_2SiO_5(Ce)	440	60	6.71	10,000
$CdWO_4$	530	15000	7.9	7,000
$CaWO_4$	430	6000	6.1	6,000
CeF_3	340	27	6.16	4,400
$PbWO_4$	460	2, 10, 38	8.2	500
Lu_2SiO_5(Ce)	420	40	7.4	30,000
$YAlO_3$(Ce)	390	31	5.35	19,700
Y_2SiO_5(Ce)	420	70	2.70	45,000
$LaBr_3$ (Ce)	380	20	5.1	63,000

<- viel versprechende Entwicklung der letzten Jahre

Temperaturabhängigkeit der Lichtausbeute



Konsequenz: Notwendigkeit von

- Kalibration
- Temperaturstabilisierung

Weitere Daten

Scintillator Crystal Data Table

Material	NaI:Tl	CsI:Tl	CaF_2:Eu	BaF_2	BGO	YAG:Ce	YAP:Ce	GSO:Ce	CWO	PWO	NB:WO	ZnSe:Te	LAG:Ce
Physical Properties													
Chemical Formula	NaI:Tl	CsI:Tl	CaF_2:Eu	BaF_2	Bi_4GeO_4	$Y_3Al_5O_{12}$	$YAlO_3$	Gd_2SiO_5	$CdWO_4$	$PbWO_4$	NB$(WO_4)_2$	ZnSe:Te	$Lu_3Al_5O_7$
Density g/cm^3	3.67	4.51	3.18	4.89	7.13	4.57	5.37	6.71	7.9	8.28	7.57	5.42	6.73
Hardness-Moh	2	2	4	3	5	8.5	8.6	5.7	4.0-4.5	3.5-4.0	6		
Hydroscopic	Yes	Slightly	No	No	No	No	No	-	No	No	No		
Crystal Structure	Cubic	Cubic	Cubic	Cubic	Cubic	Cubic	Rhomb.	Mono.	Mono.	Tetra.			Cubic
Therm. Exp. - PPM	47.5	50	19.5	18.4	7.0	8-9	4-11	4-12	10.2	10.0			
Melting Pt – C°	651	621	1360	1280	1050	1970	1875		1325	1125		1779	
Luminescence Properties													
Integrated Light Output (%NaI:Tl)	100	45	50	20/2	15-20	15	40	20-25	35-40	5 (of BGO)			15
Wave Length of Max. Emissions (nm)	415	550	435	325/220	480	550	370	440	490	430/520	540		535
Decay Constant n/s	230	900	940	630/0.6	300	70	25	30-60	5000	2/10/30	20		70
Afterglow (% at 6 ms)	0.5-5	<2	<0.3	-	<0.005	<0.005	<0.005	<0.005	0.1	-		<0.05	
Radiation Length cm	2.9	1.86	3.05	2.03	1.1	3.5	2.7	1.38	1.06	0.85	0.98		
Photon yield @ 300K - 10^3 pH/MeV	38	52	23	10	2-3	8	10	8-10	28	22.6-25.6		8	10

http://www.marketech-scintillators.com/pdfs/ScintillatorsData.pdf

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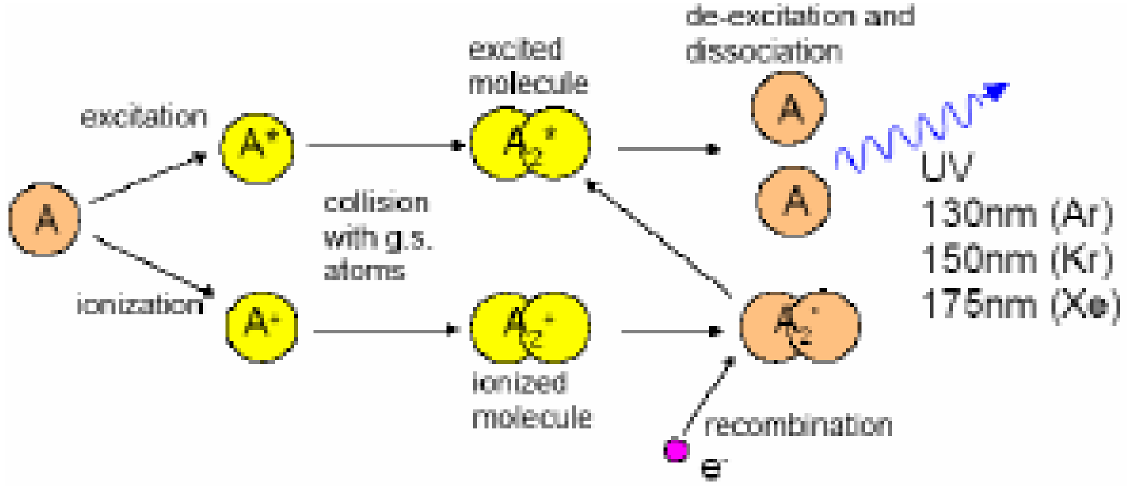
- also noble liquids (Ar, Xe, Kr) scintillate → ionisation + light → precision energy measurement+particle ident.



- time constants: ns and 100…1000 ns

Summary:

- Organics (molecular):
  fast, large, cheap; inefficient, non-linear
- Inorganics (crystalline):
  Efficient, rad-hard; slow, small
- Noble liquids:
  Large, cheap, inefficient

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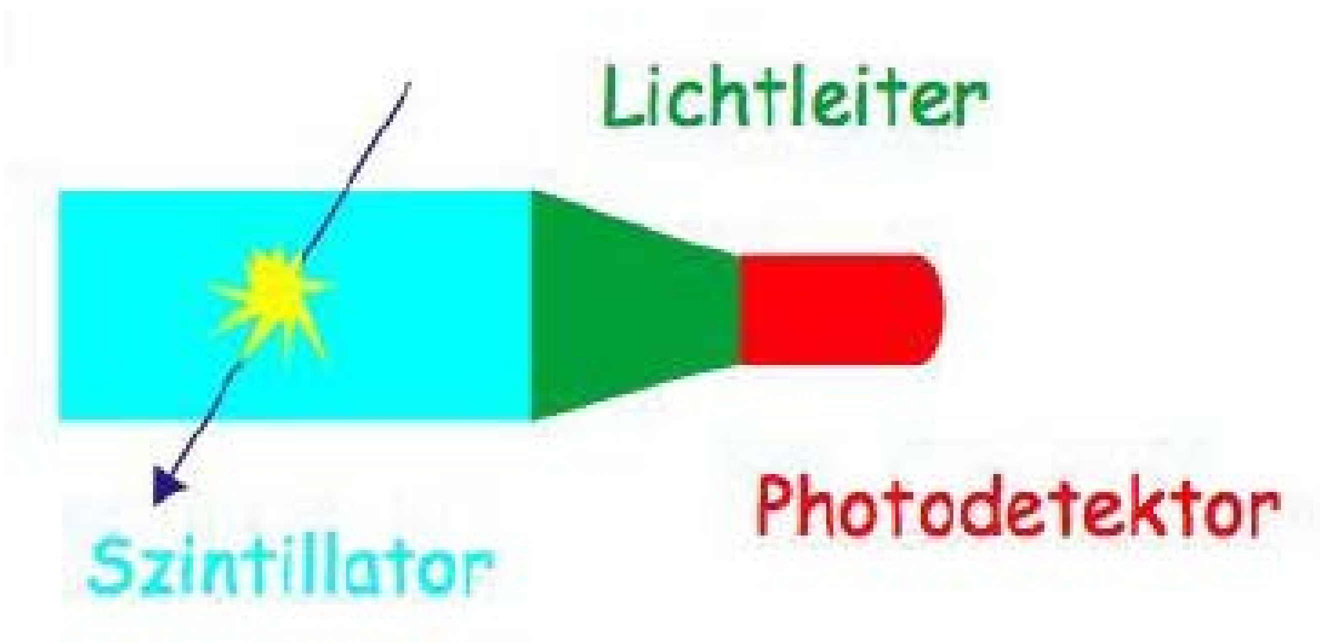


2) Transport of optical photons

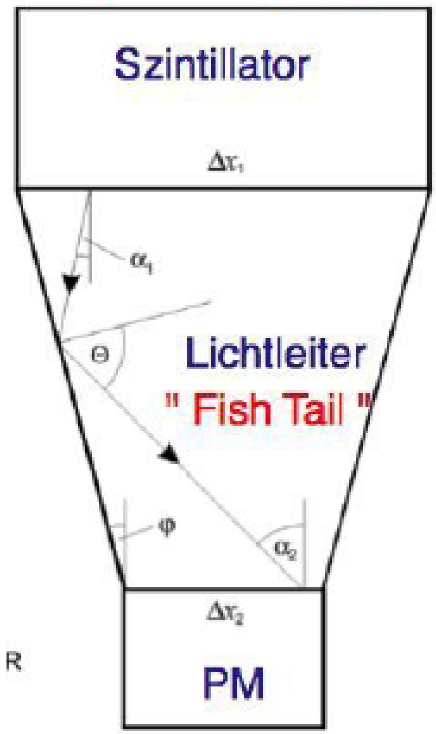
Often it is unavoidable or even desirable to have the photo-detector remote from the scintillator:

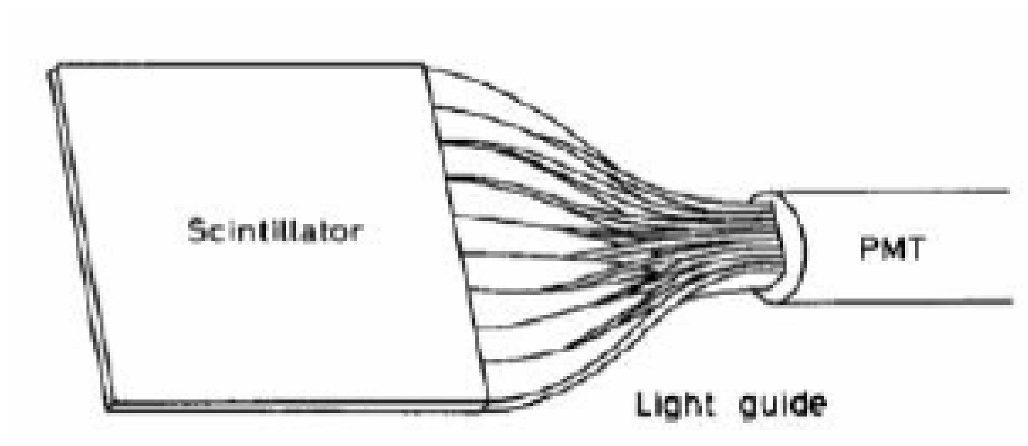
- Space limitations (particle detectors)
- Photodetector out of the magnetic field
- Couple a large scintillator surface (volume) to a single photo-detector
- …

➔ Use optical wave guides: Total internal reflection at interface with material with lower index of reflection.

2) Transport of optical photons

Aufgabe der Lichtleiter ist es das im Szintillator erzeugte Licht möglichst verlustfrei zum Photodetektor zu leiten. In der Regel verwendet man Plexiglas $(C_5O_2H_8)_n$: PMMA (Polymethylmethacrylat)



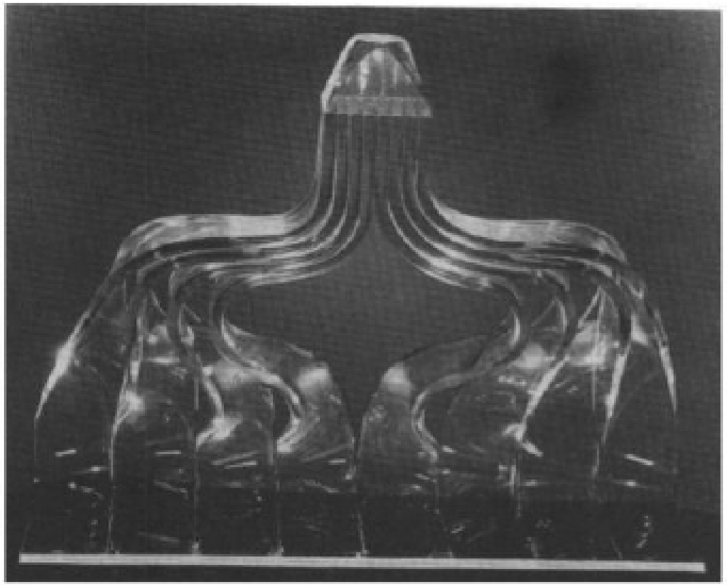


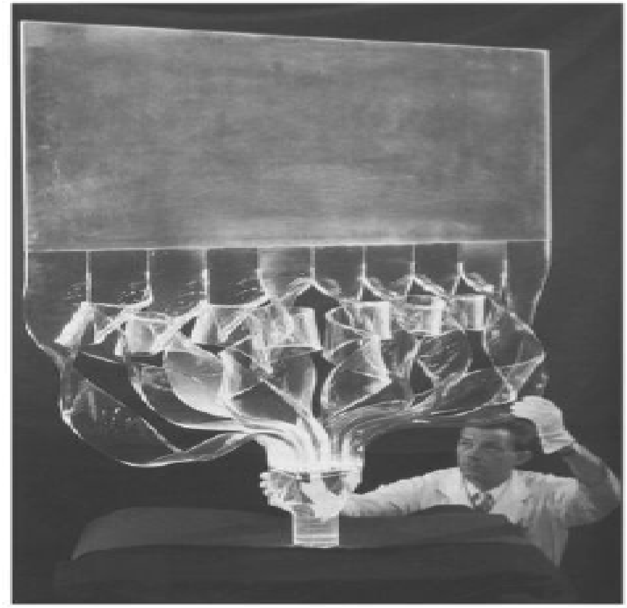
"Adiabatic": for better time resolution (path length is position independent)

Liouville's Theorem:

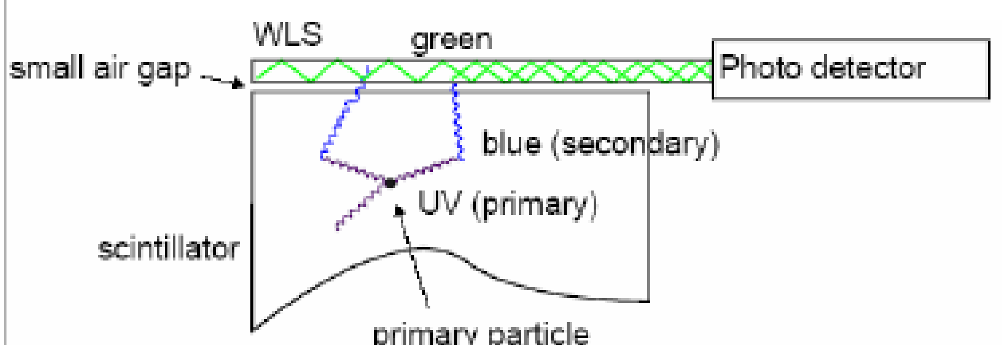
Phase space volume (area x angle) is preserved

2) Transport of optical photons





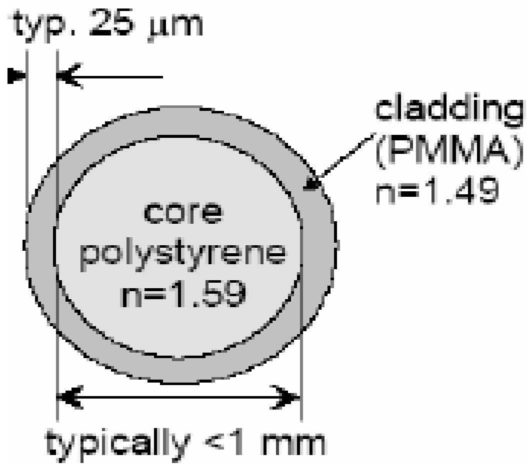
Liouville's theorem can be overcome by wave-length-shifting (WLS)



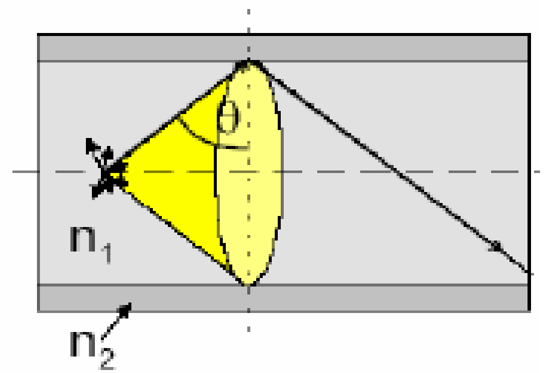
WLS used: BBQ, Y7, K27 embedded in lucite (PMMA), polystyrol, ...

- absorb 300-400 nm emit 500 nm (technique well understood)

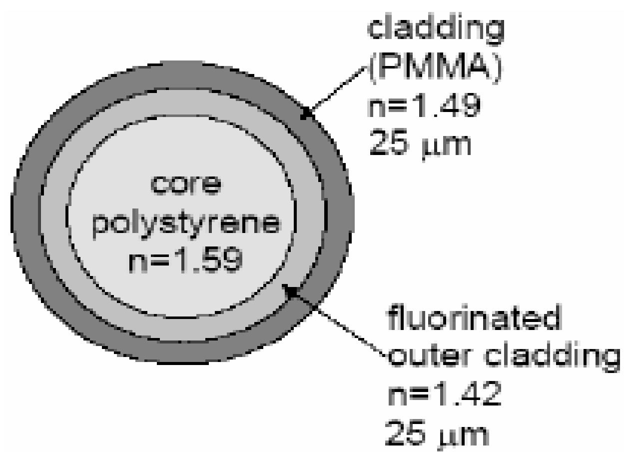
use of "**fiber**" read-out



light transport by total internal reflection



- $\sin\theta > n_2/n_1 \rightarrow \theta > 70^\circ \rightarrow$ accept 3.1%
- improvement acceptance (5.3%) and transmission ($l > 10$m) $\rightarrow$ multi-clad fibers



Scintillators and photodetectors

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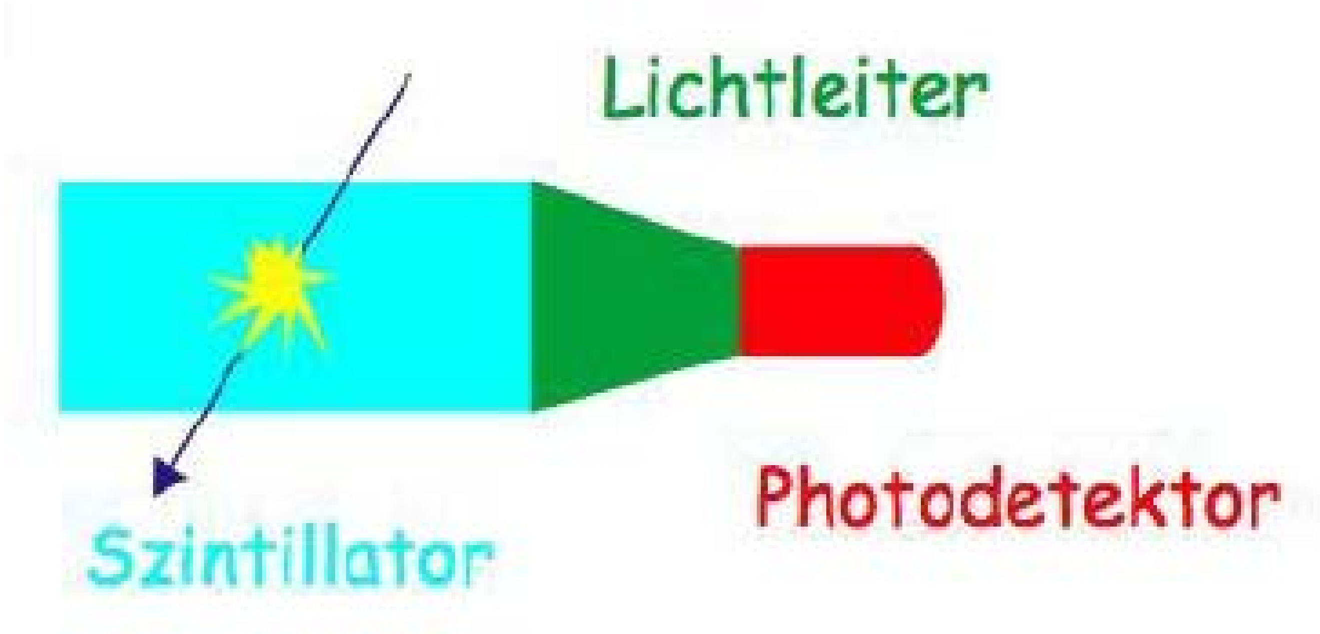
3. **Detection of Optical Photons**



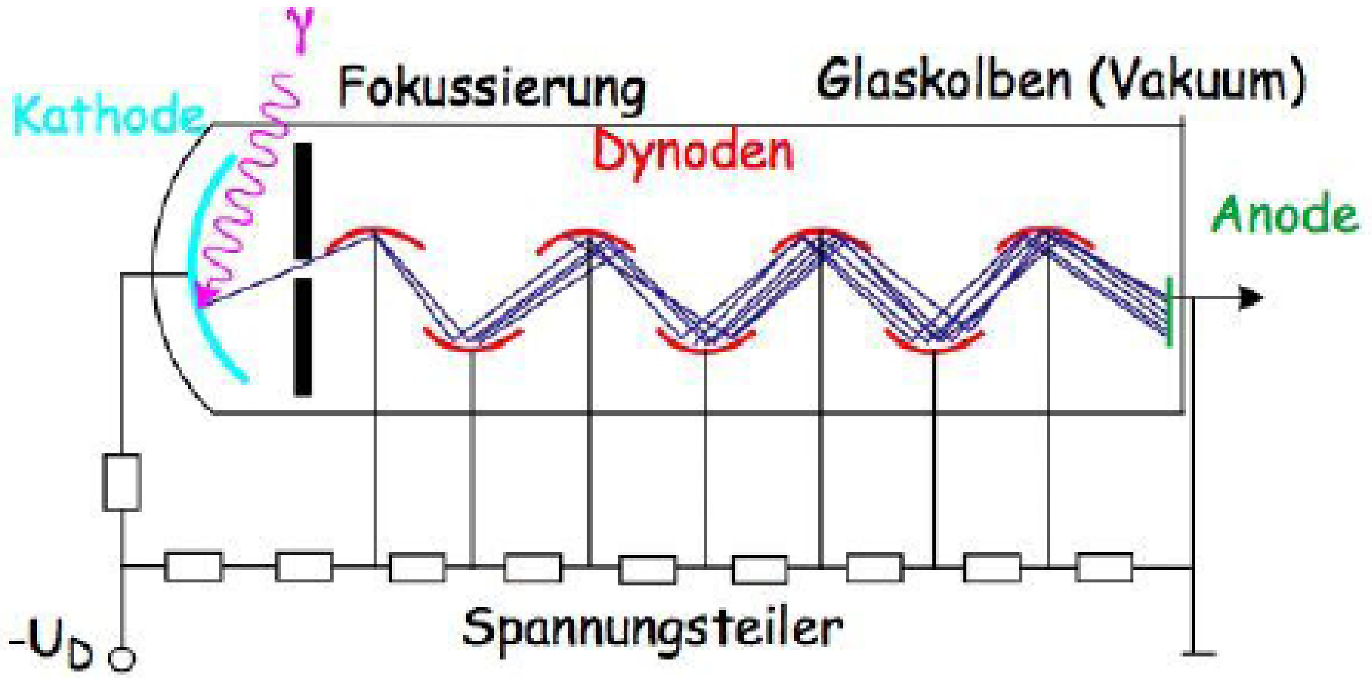
Photodetectors:

Goal: Conversion of the fluorescent light into an electrical signal that can subsequently be digitized.

Requirements:

- High Quantum Efficiency: $QE = N_{photoelectrons}/N_{photons}$
- Minimum time spread (keep time resolution)
- Good lifetime
- Large dynamic range
- …

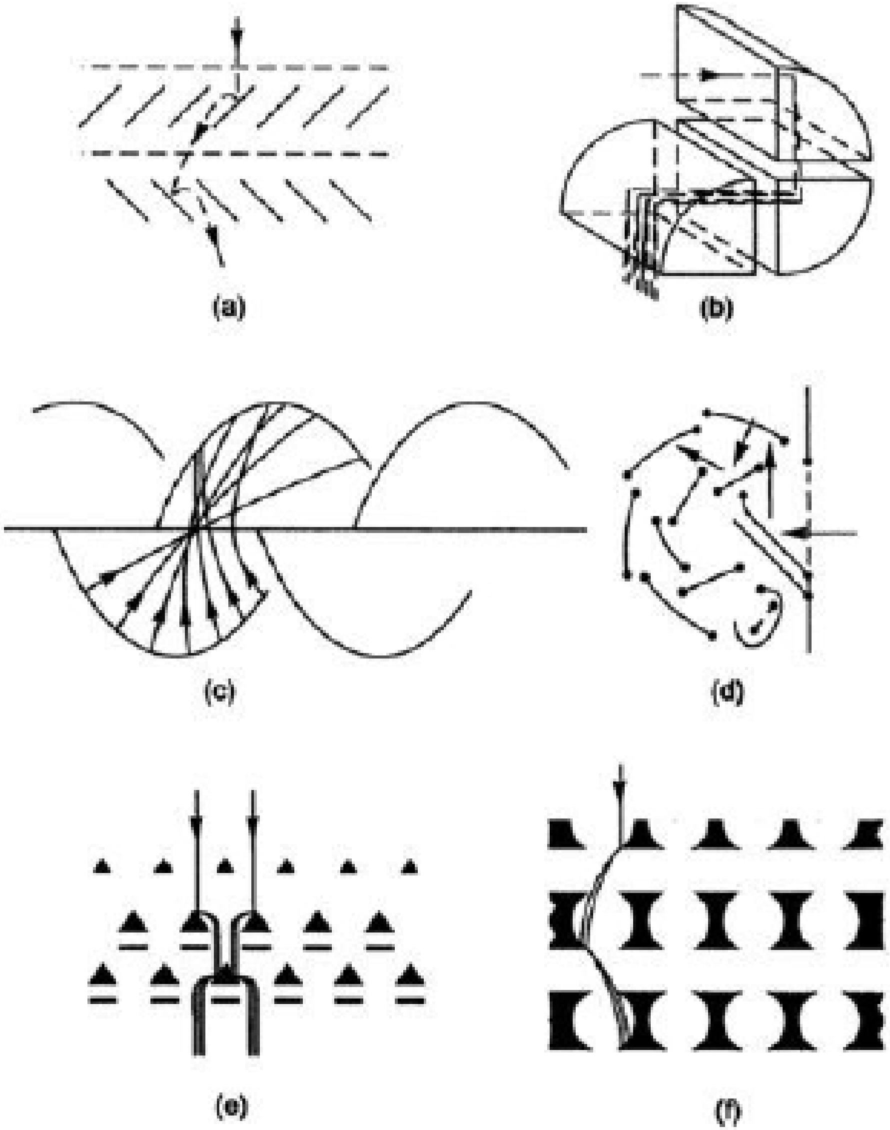
(still) the workhorse: Photo Multiplier Tubes (PMT's)



Beispiel: 10 Dynoden, jeweils Verstärkungfaktor $g = 4$

$\Rightarrow$ Gesamtverstärkung: $M = \prod_{i=1}^{N} g_i = 4^{10} \approx 10^6$

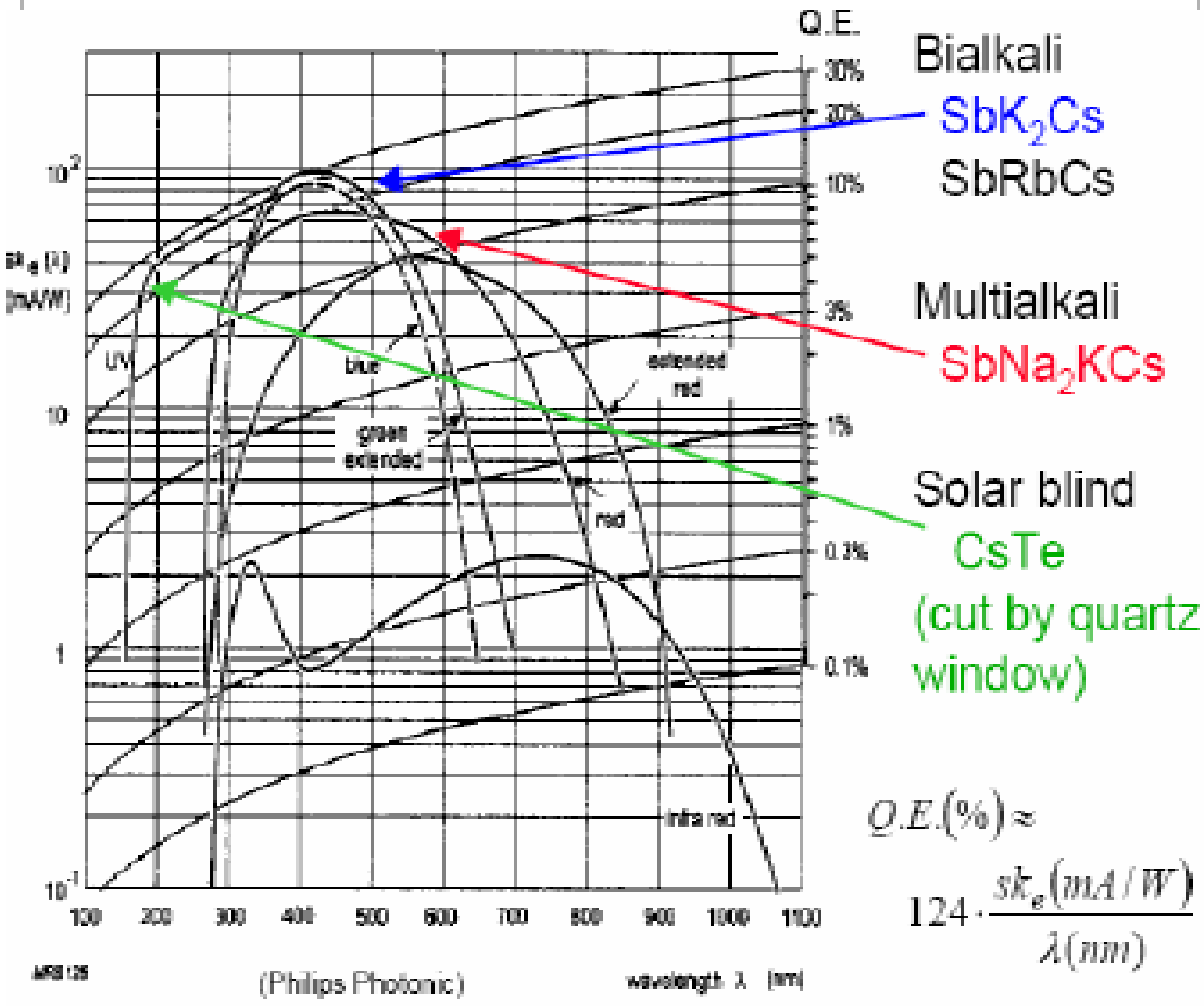
PMT's can have different shapes and size



a) Venetian blind
 (simple, efficient)
b) Box and grid
 (simple, efficient)
c) Linear focusing
 (good time resolution)
d) Circular cage
 (compact)
e) Mesh dynodes
 (good in B fields)
f) Foil dynodes
 (position sensitive)

Photo-cathode and first dynode stage are the critical components.

Quantum efficiencies of photo-cathodes



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

Einfluss auf Energieauflösung

Energieauflösung bestimmt durch die Fluktuation in der Anzahl der Sekundärelektronen:

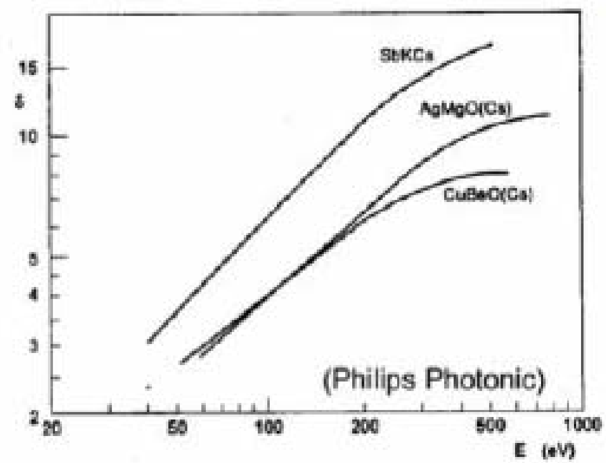
- pro Dynode gibt es einen Verstärkungsfaktor von $\delta(E) = 3\ldots20$
- die Anzahl der emittierten Elektronen folgt einer Poisson-Statistik

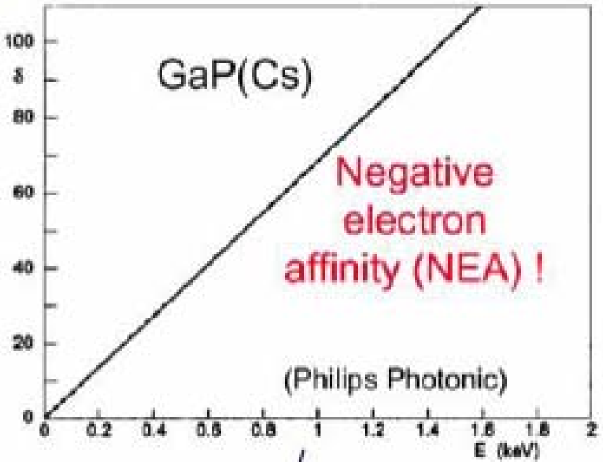
$$P(\bar{n}, m) = \frac{\bar{n}^m e^{-m}}{m!}$$

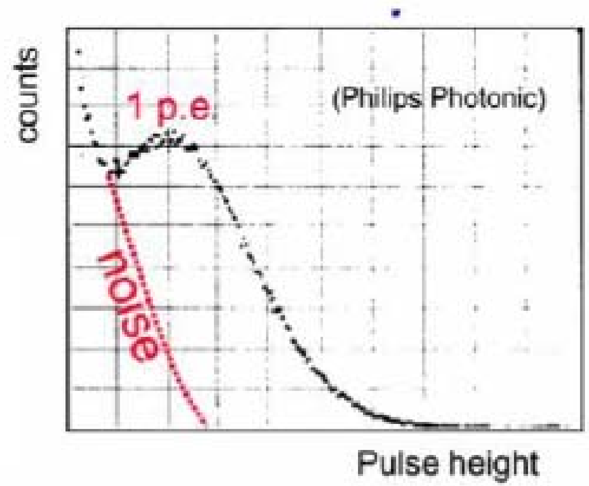
- relative Fluktuation

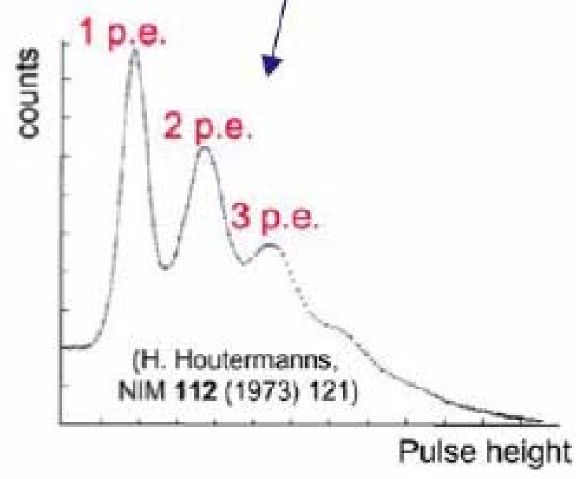
$$\frac{\sigma_{\bar{n}}}{\bar{n}} = \frac{1}{\sqrt{\bar{n}}}$$

Verstärkungsfaktor δ

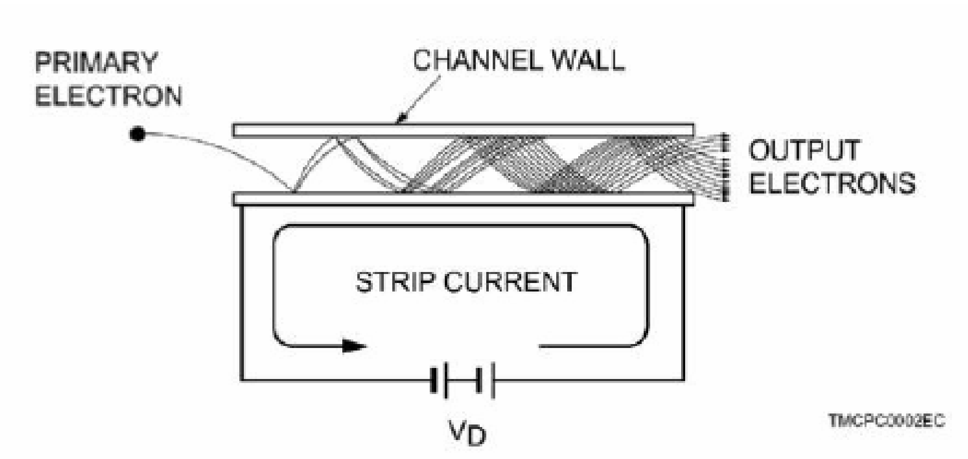


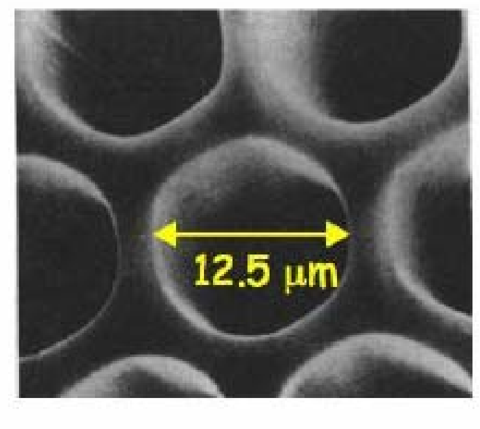






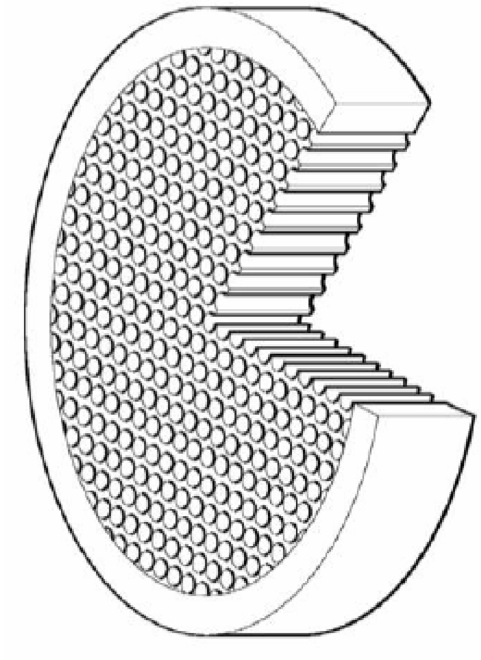
Special structures: Micro-channel plates





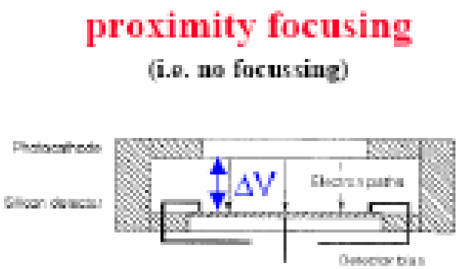
Characteristics:

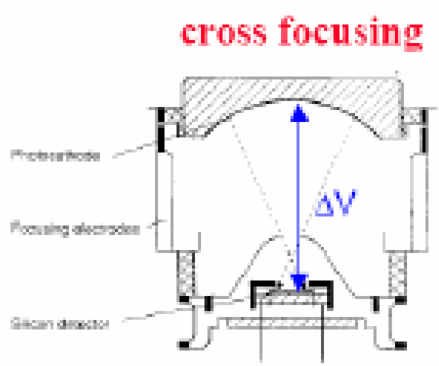
- fast (transit time spread 50 ps)
- works at B-fields of 0.1 Tesla
- limited life-time (0.5 C/cm^2)
- limited rate capability
- used commercially (and research) as image intensifiers

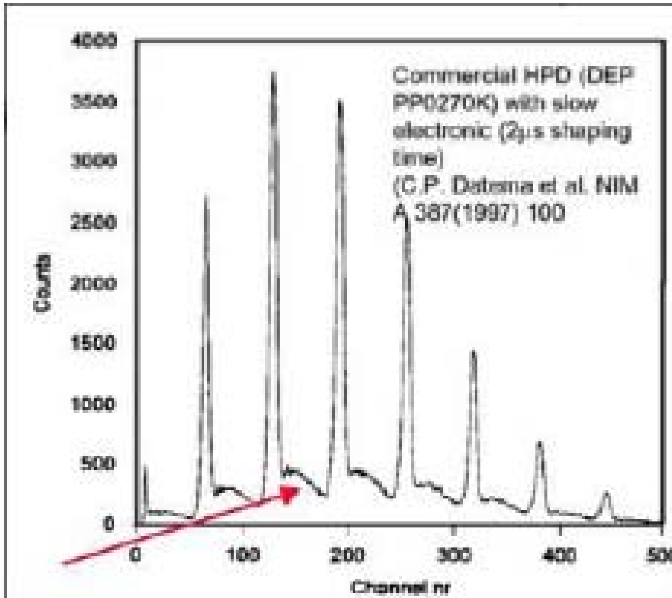


Hybrid Photo diodes (HPD)

Combination of:
- Photocathode (like in a PMT)
- Vacuum electron acceleration structure
- Silicon detectors (direct detection of electrons)







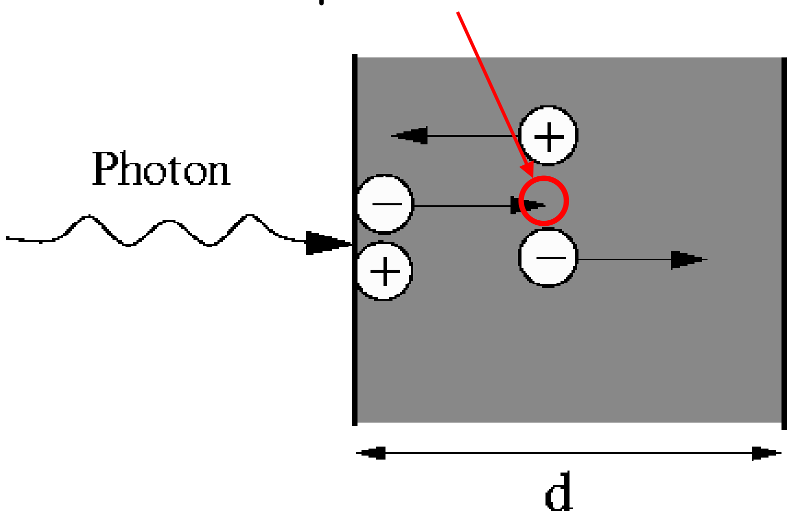
Electron backscattering
of silicon diodes

Avalanche Photodiodes

Solid state detectors with internal amplification (c.f. proportional counter)

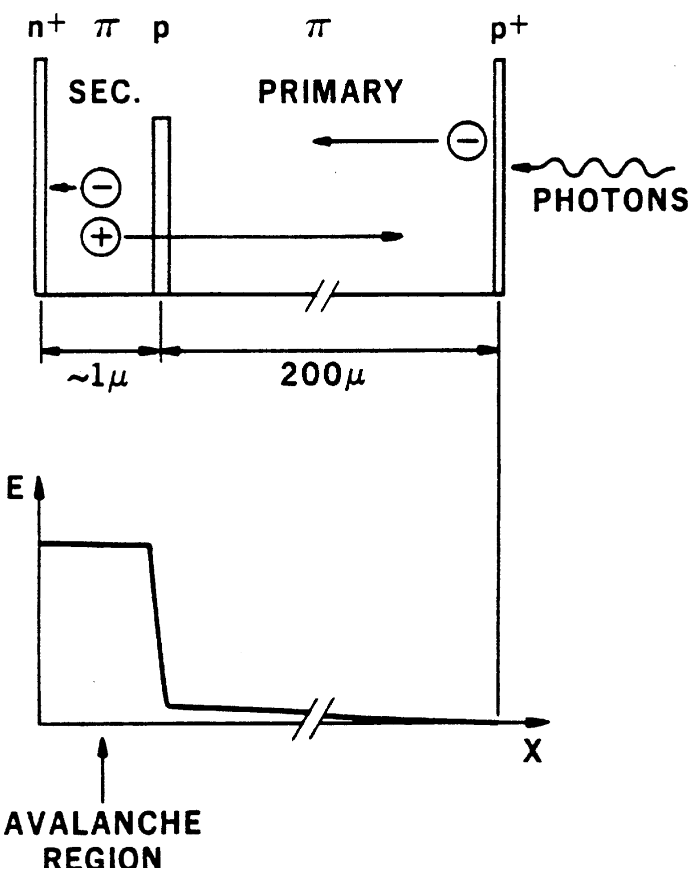
Charge carriers are accelerated sufficiently to form additional electron-hole pairs

impact ionization

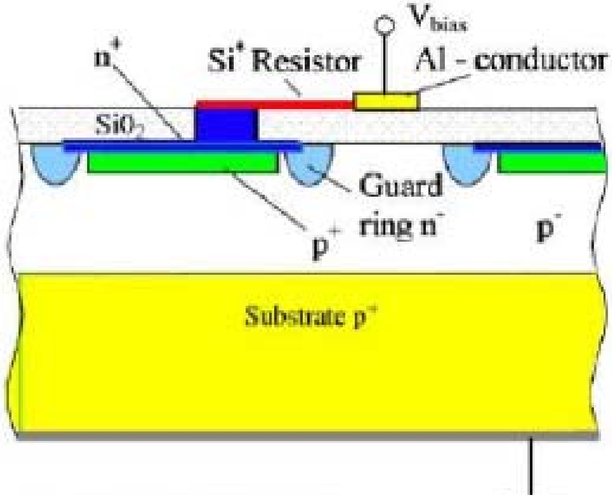


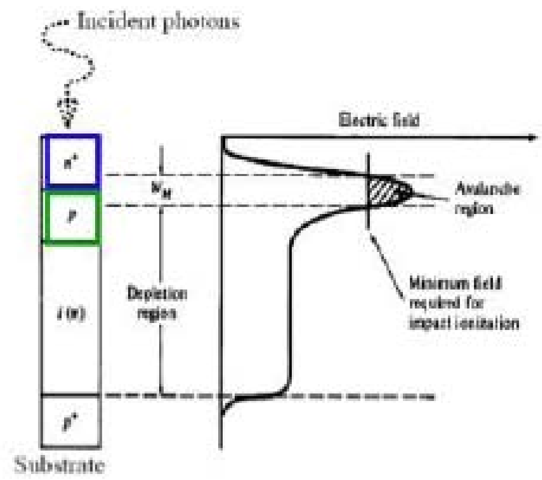
An electron-hole pair is created on the left by incident light

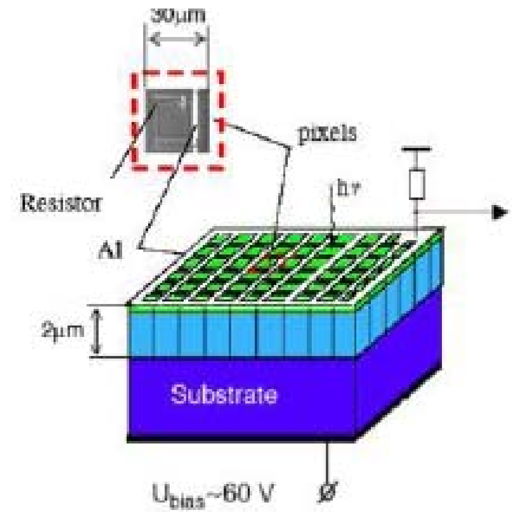
Creation of a particular multiplication zone:



Silicon PM's = Pixellated avalanche diodes; run in Geiger mode (very high gain)



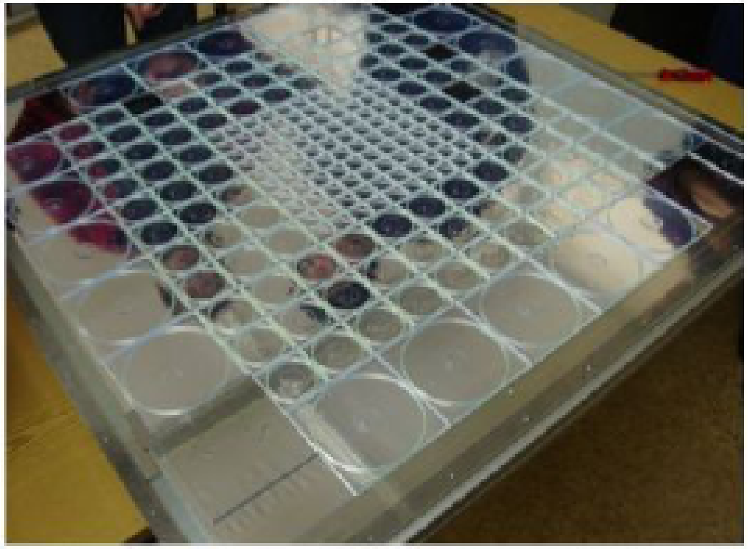


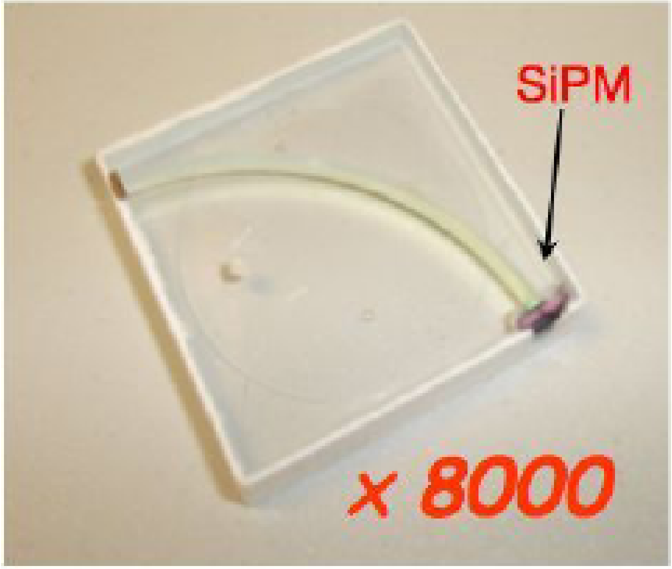


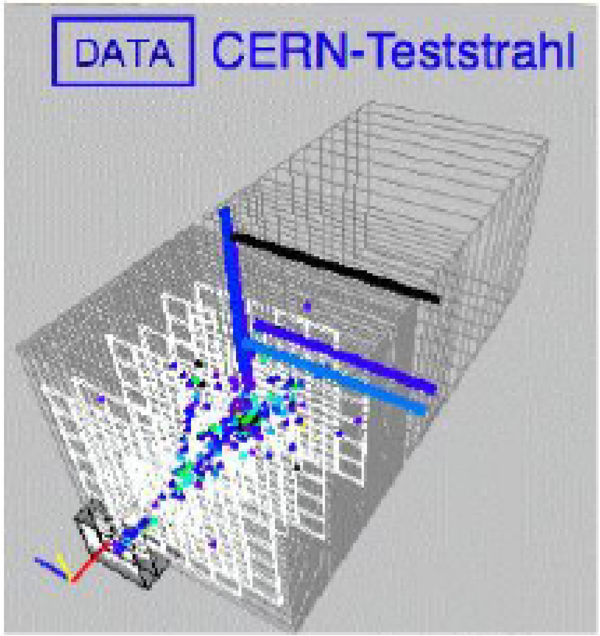
- Small dimensions ~ 300 μm pixel size
- Insensitive to B-fields
- Low voltages
- High gains (strong signals)
- Relatively cheap.

DESY is very active in developing Calorimeters for ILC

Tile HCAL für den ILC
DESY Prototyp





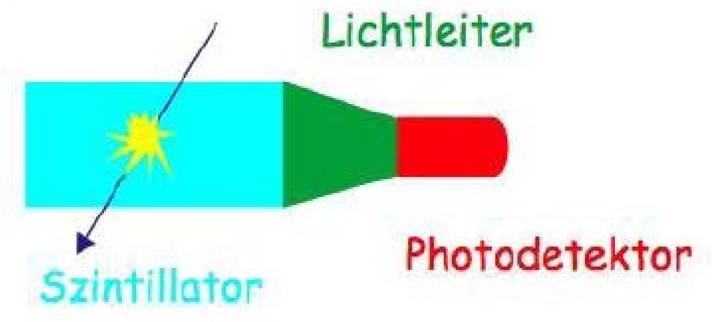


Comparison of various photo-detectors

	PMT	APD	HPD	SiPM
Photon detection efficiency:				
blue	20%	50%	20%	12%
green - yellow	a few %	60-70%	a few %	15%
red	<1%	80%	<1%	15%
Gain	10^6-10^7	100-200	10^3	10^6
High voltage	1-2 kV	100-500 V	20 kV	25 V
Operation in the magnetic field	problematic	OK	OK	OK
Threshold sensitivity S/N≫1	1 ph.e.	~10 ph.e.	1 ph.e.	1 ph.e.
Timing /10 ph.e.	~100 ps	a few ns	~100 ps	30 ps
Dynamic range	$\sim 10^6$	large	large	$\sim 10^3/\text{mm}^2$
Complexity	high (vacuum, HV)	medium (low noise electronics)	very high (hybrid technology, very HV)	relatively low

Summary
Scintillators and photo-detectors

1. Generation of Optical Photons
2. Transport of Optical Photons
3. Detection of Optical Photons



1) Generation: Organic and inorganic scintillators; noble gasses and liquids
2) Transport: waveguides; wavelength shifters; optical fibers.
3) Detection: PMT; HPD; APD or SiPM.

Each component and combination has its own advantage and disadvantage. Application specific (HEP, Photon Science, Medical Imaging, Industrial Imaging