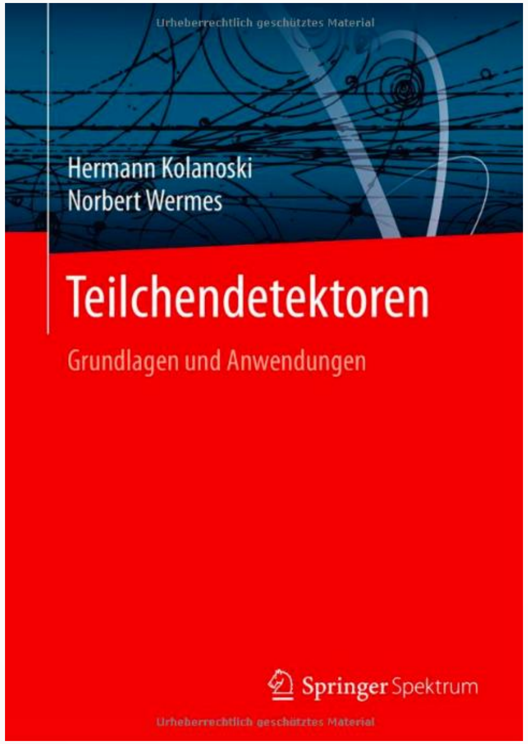
# SCINTILLATORS

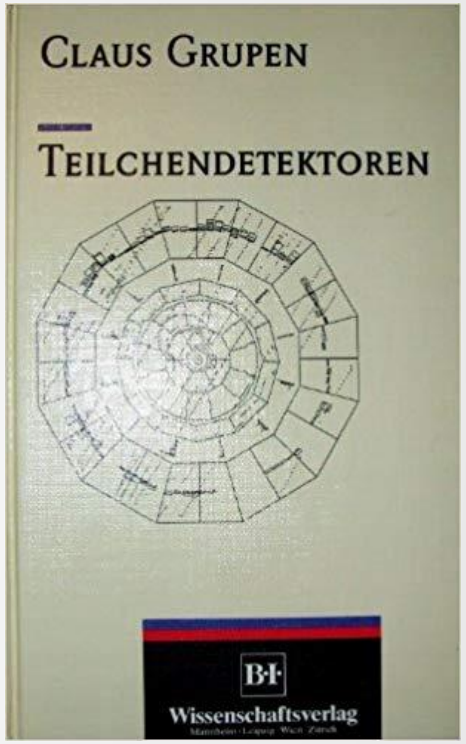
LECTURE 4 PART 3

# REFERENCES

- Vorlesung M. Krammer
  "Teilchendetektoren"
  TU Wien, SS 2015
- "The Physics of Particle Detectors"
  Erika Garutti (DESY)
- Kolanoski, Wermes
  "Teilchendetektoren", 2015
- K. Kleinknecht,
  "Detektoren für Teilchenstrahlung"
- C. Grupen,
  "Teilchendetektoren", 1993







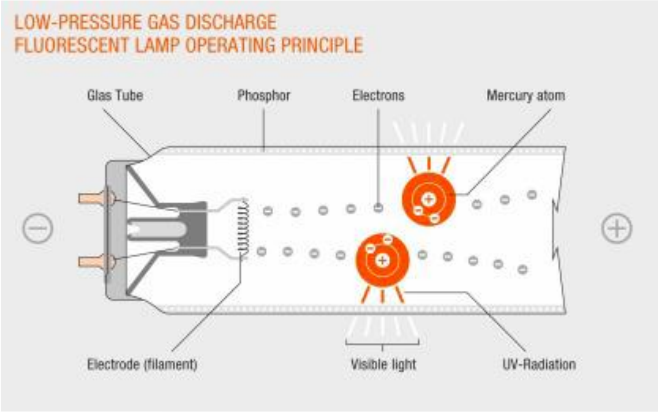
# CONTENT

# 1. INTRODUCTION

# 1.1 DEFINITIONS

- Luminescence:
  Emission of photons (visible light, UV, X ray) after absorption of energy.
- Energy deposition in the material by
  - Light ⟶ Photoluminescence
  - Heat ⟶ Thermoluminescence
  - Sound ⟶ Sonoluminescence
  - Electric energy ⟶ Elektrolumineszence
  - Mechanical deformation ⟶ Triboluminescence
  - Chemical reactions ⟶ Chemoluminescence
  - Living organism ⟶ Bioluminescence
  - Ionizing radiation ⟶ Scintillation
- Scintillation: Emission of photons following the excitation of atoms and molecules by radiation.

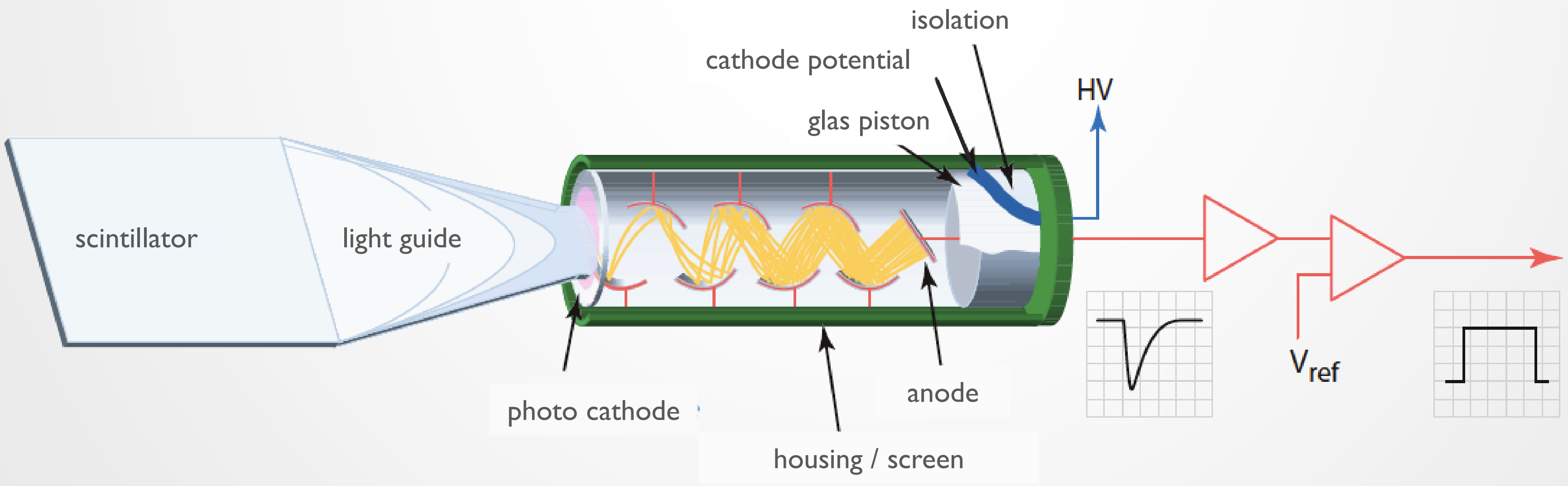
- Fluorescence: emission of light by a substance that has absorbed light or another electromagnetic radiation of a different wave length. In most cases the emitted light has a longer wavelength. The emission follows shortly after (10 ns).




- Phosphorescence: Similar to Fluorescence, however the re-emission is not immediate. The transition between energy levels and the photon emission is delayed (ms up to hours).

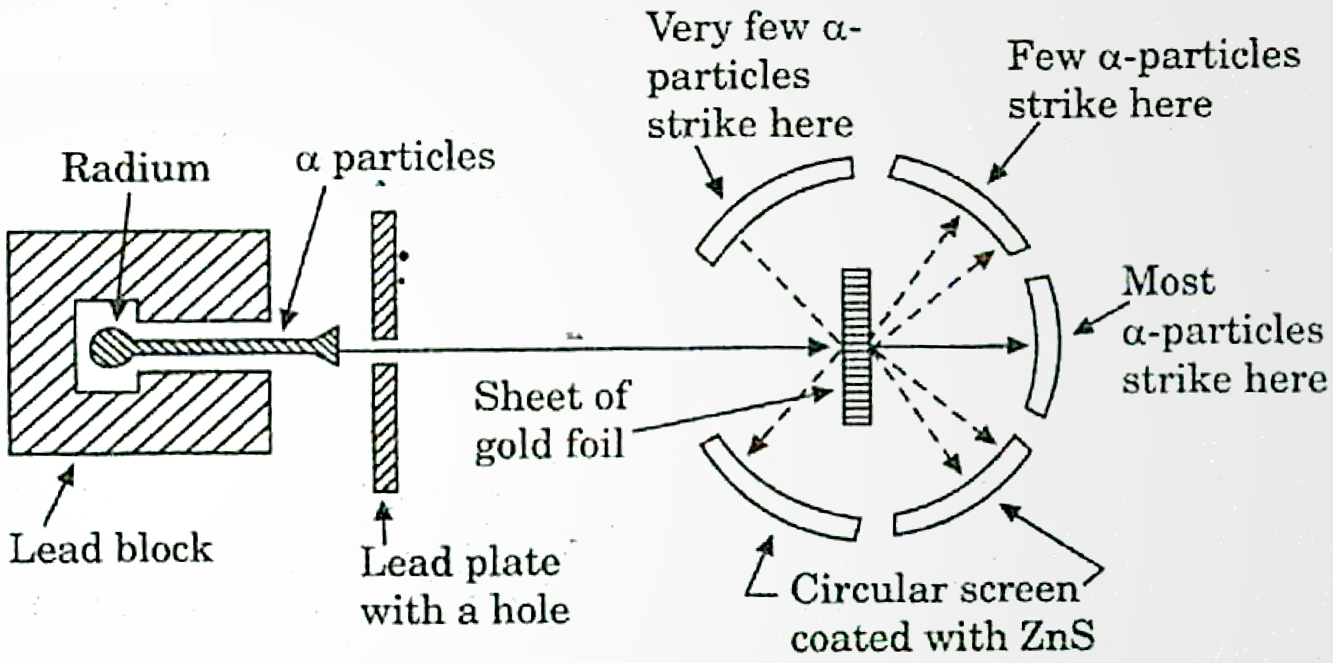
# 1.2 SCINTILLATION DETECTOR

- A scintillation detector consists of a scintillating material, coupled to a light guide, and a photo detector.
- The scintillating material converts γ- and particle-radiation into light (visible, UV, sometimes X-rays). Often a wavelength shifter is mixed to the primary scintillator.
- The light guide leads the light to the photo detector. Again, a wavelength shifter is often used to match the wave length to the response characteristics of the photo cathode and hence improves the signal.
- The photo detector converts the light into an electric signal. Various photo detectors are applied, e.g. photo multipliers, SiPMs, gaseous detectors.



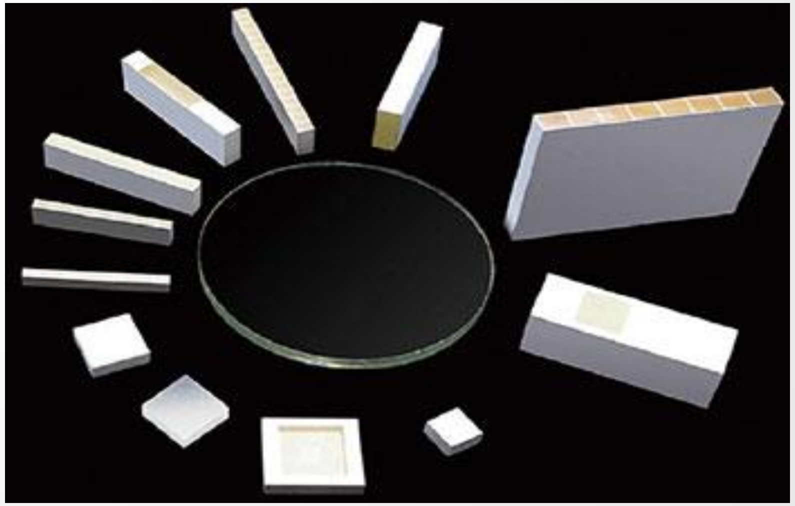
# 1.3 EXAMPLE: RUTHERFORDS EXPERIMENT

- Rutherford's scattering experiment:
  - Discovery of atomic nucleus with positive charge which holds most of its mass (1908-1913)
- Experiment:
  - Scattering of α particles on thin metal (gold) foils
  - Using microscope to count light flashes on ZnS scintillating screen
  - high efficiency (20%) but low transparency to its own light




# 1.4 SCINTILLATING MATERIALS AND APPLICATIONS

- Scintillating materials:
  - Inorganic crystals
  - Organic crystals
  - Organic liquids
  - Plastic scintillators
  - Nobel gases (gaseous and liquid)
  - Scintillating glasses (not discussed)
- Applications in nuclear- and particle physics:
  - Trigger detectors for slow detectors (e.g. drift chambers)
  - Time of flight counters (TOF-Counter)
  - Calorimeters – energy measurement
  - Position detectors (scintillating fibres)
  - Detection and spectroscopy of thermal and fast neutrons
  - Neutrino detectors (liquid scintillators)



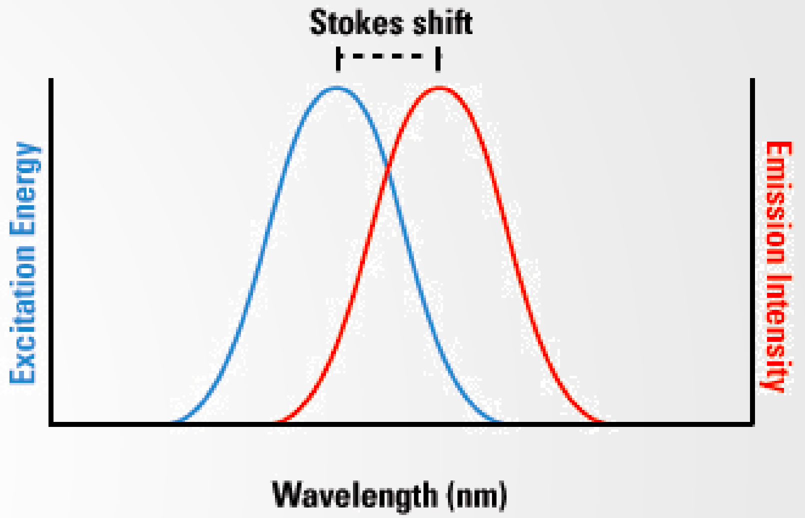
# 1.5 BASIC PROPERTIES AND REQUIREMENTS

- Advantages:
  - Short rise time (esp. organic scintillators, ~ ns)
  - Sensitive to deposited energy
  - Construction and operation simple
    ⟶ cheap and reliable
- Disadvantages:
  - Aging (especially plastic scintillators)
  - Radiation damage (especially plastic scintillators)
  - Hygroscopic – attracts water (especially inorganic crystals, e.g. NaI)
  - Low light output (especially gaseous scintillators)
  - In combination with the optical readout sensitive to magnetic fields (e.g. when using photo multipliers)

- Many materials show luminescence.
  To be useful, the following requirements are important
  - High light yield $Y_L$, i.e. high efficiency to convert the excitation energy into fluorescence: $Y_L = \langle N_\gamma \rangle / E$
  - Transparency with respect to the own fluorescence light. Otherwise the light is absorbed within the material itself.
  - emission spectrum matched to the spectral sensitivity of the photo detector.
    - wave length shifter can help
  - Refractive index of scintillator close to readout
    - e.g. glass in case of PMT
  - Short decay constant.

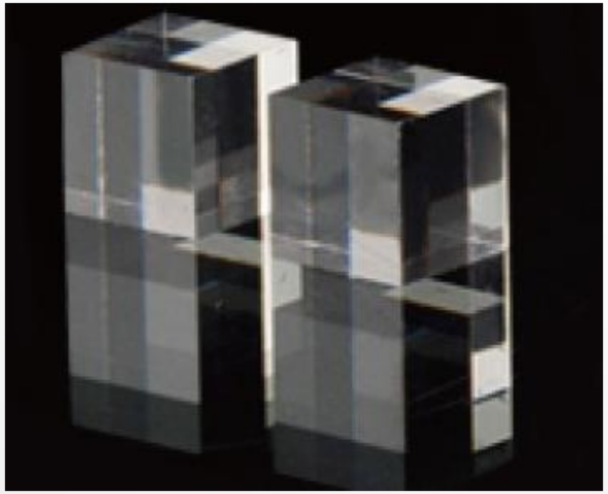
# 1.6 LIGHT OUTPUT

- Only a few per cent of the deposited energy is transferred into light. The remaining energy is used up by ionisation, etc.
  - Emitted light usually of lower energy than deposited energy. Light shifted to longer wavelengths (Stokes shift)
  - In addition photons are lost in the scintillator itself (re-absorption) and in the light guide.



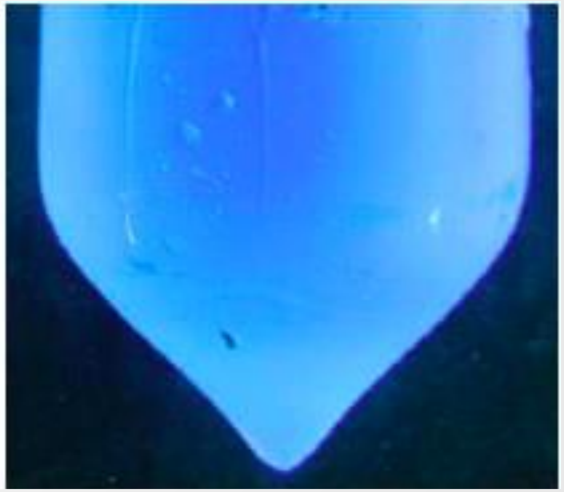

- Mean energies required to create a photon:
  - Anthracen ($C_{14}H_{10}$) ~ 60 eV
  - NaI:Tl ~ 25 eV
  - Anthracen or NaI are often used as reference material.
  - BGO ($Bi_4Ge_3O_{12}$): ~ 300 eV
    - high Z
    - efficient γ ray absorber

BGO inorganic scintillator



Anthracen organic scintillator

NaI:Tl (Sodium Iodide doted with Thallium) ingot under UV light



# 1.7 MATERIAL PROPERTIES

| Material | Typ | Density [g/cm³]] | max. emission λ [nm] | Light output [% Anthracen] | Decay time* [ns] |
|---|---|---|---|---|---|
| NaI:Tl | Inorgan. Cristal | 3.67 | 413 | 230 | 230 |
| CsI | Inorgan. Cristal | 4.51 | 400‡ | 500‡ | 600‡ |
| BGO (= $Bi_4Ge_3O_{12}$) | Inorgan. Cristal | 7.13 | 480 | 35–45 | 350 |
| $PbWO_4$ | Inorgan. Cristal | 8.28 | 440–500 | ≈2.5 | 5–15 |
| Anthracen | Organ. Cristal | 1.25 | 440 | 100 | 30 |
| trans-Stilben | Organ. Cristal | 1.16 | 410 | 50 | 4.5 |
| p-Terphenyl | In liquid solution, plastic | – | 440 | ≈58 | 5 |
| t-PBD | In liquid solution, plastic | – | 360 | – | 1.2 |
| PPO | In liquid solution, plastic | – | 355 | – | ? |

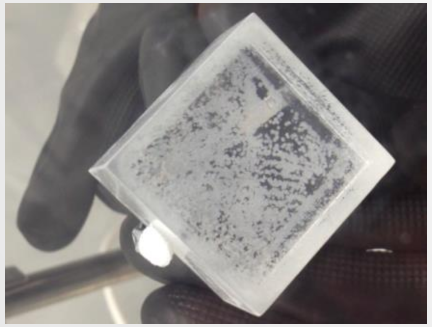
*main component

‡ at $T = 77$ K

# 2. INORGANIC SCINTILLATORS

# 2.1 OVERVIEW

- Different types of inorganic scintillators:
  - Inorganic crystals
  - Glasses
  - Noble gases (gaseous or liquid)
- Scintillation mechanism is different for inorganic crystals, glasses and noble gases.
  - hence, very different response times.
  - inorganic crystals, glasses are rather slow (compared to organic crystals)
  - noble gases: fast
- Inorganic scintillators are relatively radiation hard.

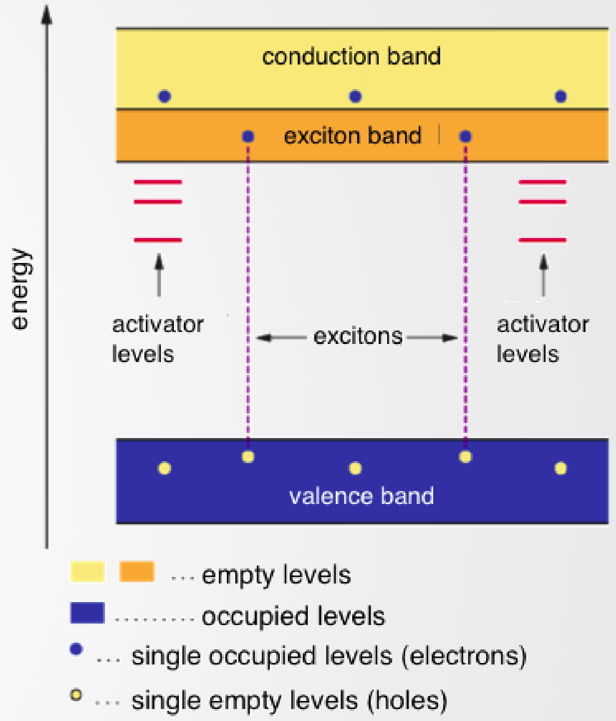


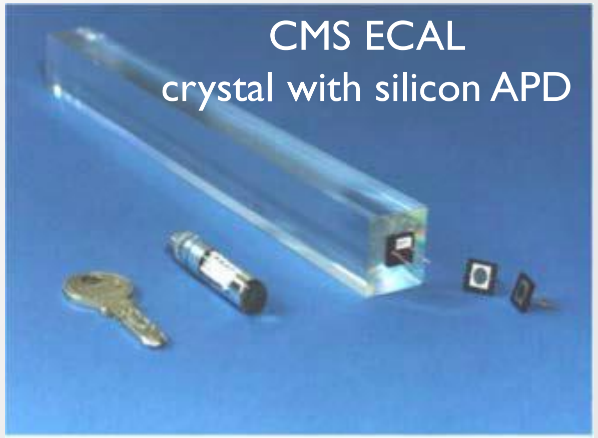
NaI crystal after exposure to water vapor.

- Important inorganic crystals are:
  - NaI, CsI: as pure crystal or doped with Thallium ((NaI:Tl),(CsI:Tl))
  - BGO: $Bi_4Ge_3O_{12}$
  - GSO: Gadolinium silicate ($Gd_2SiO_5$), usually doped with Cer
  - $BaF_2$, $CeF_3$, $PbWO_4$
- Emitted light usuall at 400–500 nm. (NaI: 303 nm, CsI:Tl : 580 nm)
- Advantages:
  - High density, short radiation length $X_0$
  - High light output : ≈100%–400% of Anthracen
  - relative radiation resistant: especially: $CeF_3$, GSO, $PbWO_4$, (bad: BGO)
- Disadvantages:
  - Usually slower than organic scintillators: Decay times a few hundred ns, Phosporescence. Exception: $CsF_2$ ~ 5 ns and $PbWO_4$ ~ 5–15 ns.
  - Some are hygroscopic: especially: NaI. BGO, $PbWO_4$, $CeF_3$ are not hygroscopic.

# 2.2 SCINTILLATION MECHANISM (INORGANIC CRYSTALS)

- Inorganic crystals feature a band structure:
  - The band gap between valance and conduction band is about 5-10 eV (Isolator).
- Absorbed energy excites electrons to the conduction band.
  - Recombination causes the emission of a photon.
  - Increase the transition probability by discrete activator levels with doping
- e/h pairs can form excitons (coupled e/h pairs) that recombine and emit photons
- The light output of inorganic crystals is in good approximation linear to the energy deposited by high energy particles.
- Inorganic crystals are perfect devices for homogeneous calorimeters.




<u>Electromagnetic calorimeter of L3 (LEP):</u>
BGO crystals, short radiation length (1.11 cm), very sensitive to temperate (-1,5% / °C)

<u>Electromagnetic calorimeter of CMS:</u>
$PbWO_4$ crystals, also short radiation length, fast and radiation hard.

# 2.2 SCINTILLATION MECHANISM (INORGANIC CRYSTALS)

W.R. Leo, *Techniques for Nuclear and Particle Physics Experiments*, Springer, 1987

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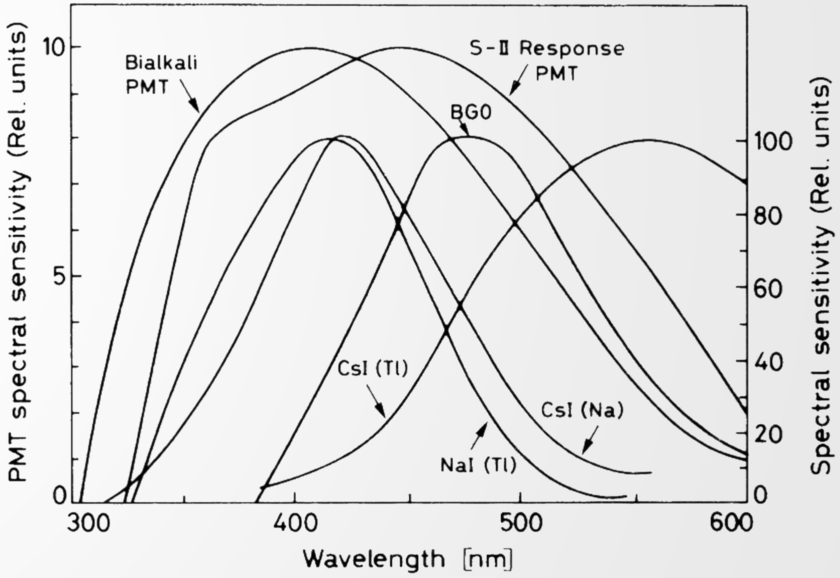
- Inorganic crystals are perfect devices for homogeneous calorimeters.

Emission spectra of various inorganic crystals (right axis) and spectral sensitivity of two typical photo multipliers (left axis)

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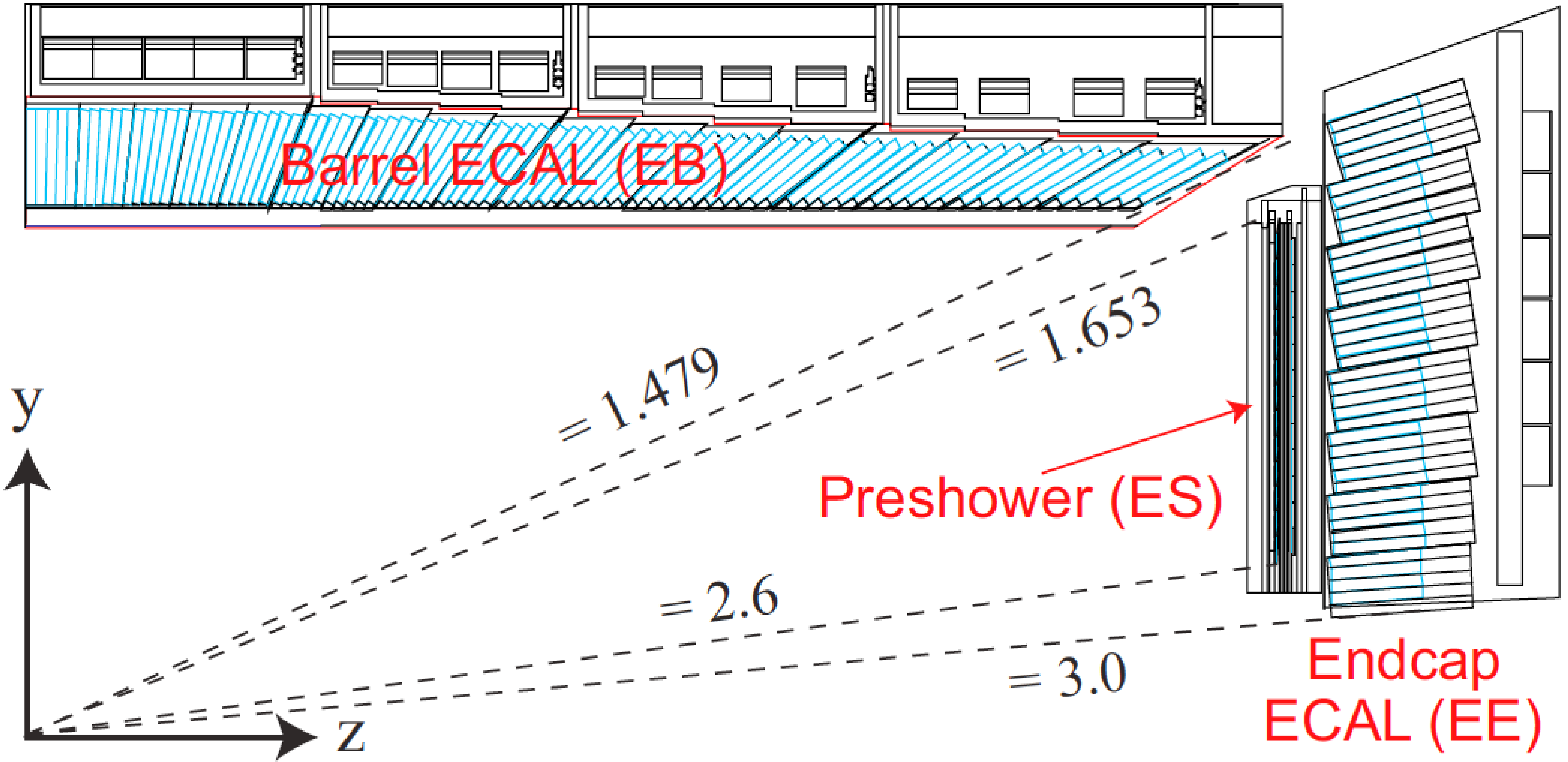
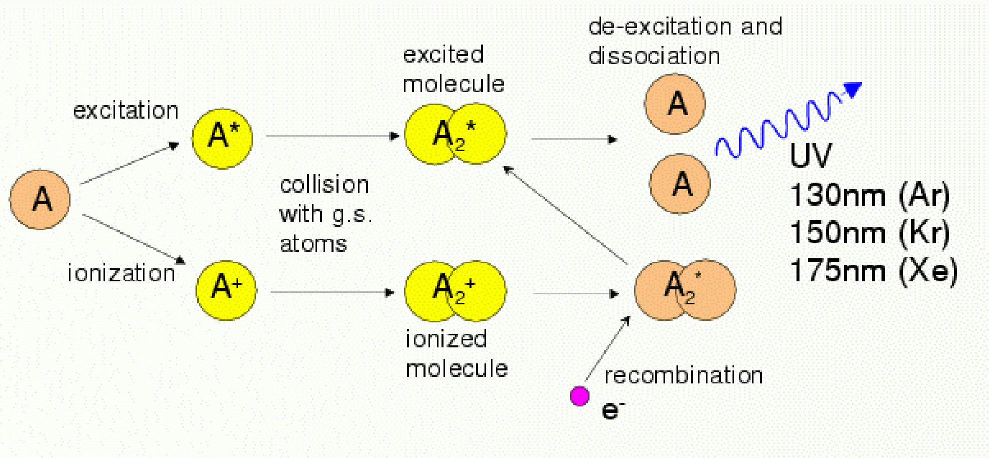
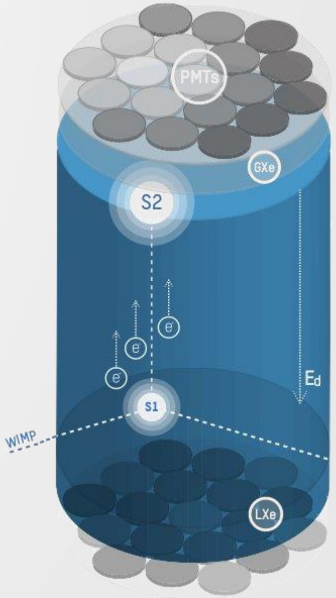

Barrel ECAL (EB)
= 1.479
= 1.653
Preshower (ES)
= 2.6
= 3.0
Endcap
ECAL (EE)
y
z

# 2.3 SCINTILLATING NOBLE GASES

- Scintillating gases used: Helium, Xenon, Krypton and Argon
  - Argon: cheap, simple to purify on industrial scale
  - Krypton: expensive, shorter radiation length.
  - Xenon: very expensive (depending on purity fluctuates up to 1kEUR/kg)
- The fluorescence mechanism in noble gases is a purely atomic process and the life time of the excited states is therefore short.
- Scintillating noble gas detectors are very fast, response time ≤ 1 ns.
- The emitted light is in the UV range. In this range classic photomultipliers are not sensitive. The use of wave length shifters is mandatory (e.g. as coatings on the walls)
- Due to the relative low density the light yield of gaseous scintillators is low. Can be compensated by high pressure operation (up to 200 atm).
- Liquid noble gas scintillators used in direct detection DM experiments: e.g. XENON100 at LNGS, Italy, 161 kg LXe, 242 PMTs (picture) or Xenon1t (3500kg LXe)
  - detect direct scintillation (S1) and ionization signal that causes delayed signal (S2)



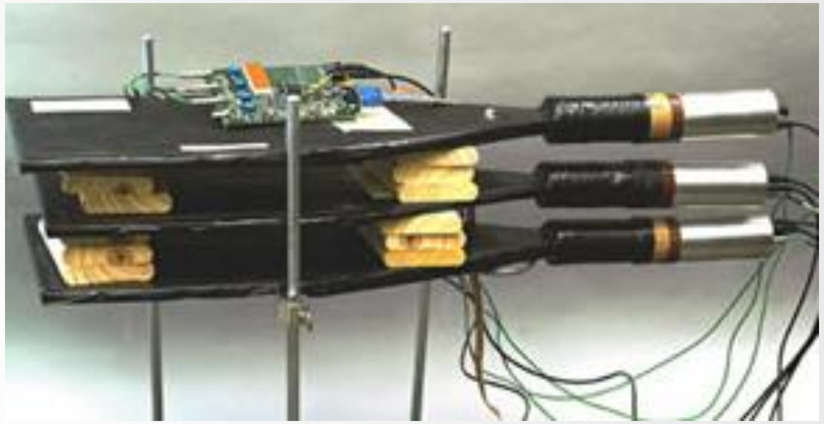



# 3. ORGANIC SCINTILLATORS

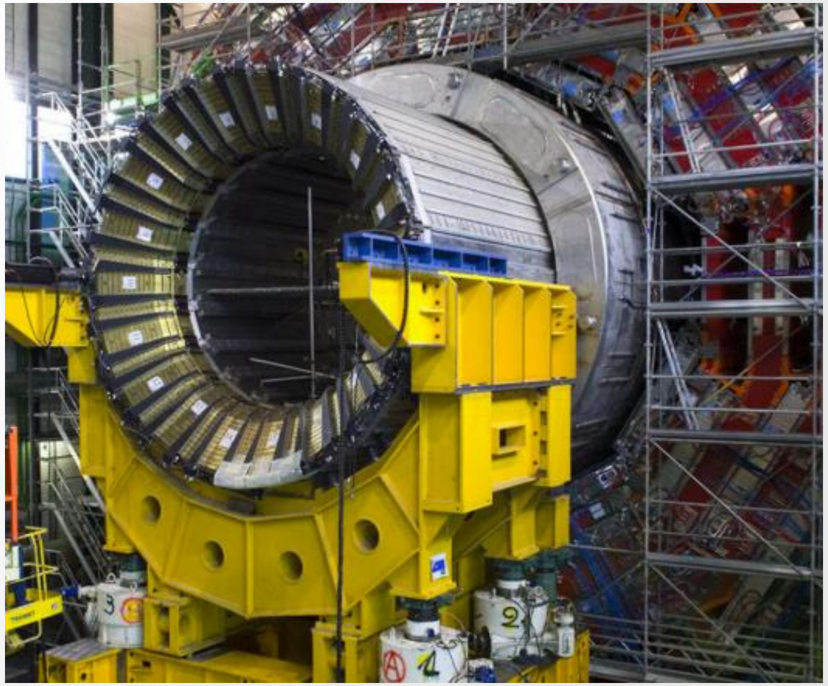
# 3.1 OVERVIEW

- three important types of organic scintillators:
  - Organic crystals
  - Organic liquids
  - Plastic scintillators
- Organic scintillators are aromatic hydrocarbon compounds (containing benzene ring compounds)
- The scintillation mechanism is due to the transition of electrons between molecular orbitals → organic scintillators are fast ~ few ns.
- Organic crystals consist of only one component
- Liquid- und Plastic scintillators are usually composed of 2–3 components:
  - Primary scintillator
  - Secondary scintillator as wave length shifting component (optional)
  - Supporting material

coincidence detector using scintillation light from cosmic muons

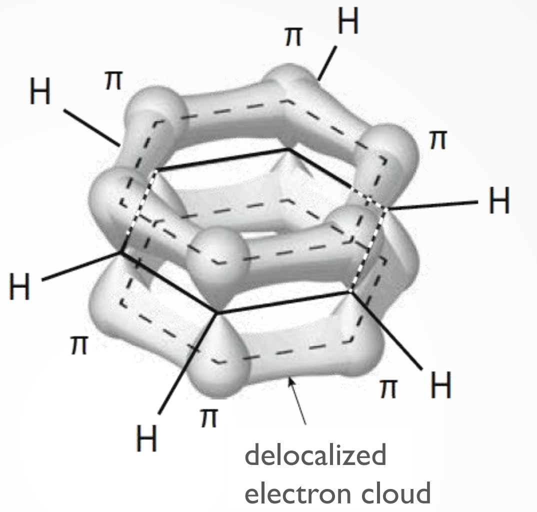


CMS hadron calorimeter (SCSN-81 plastic scintillator, 440nm peak emission)

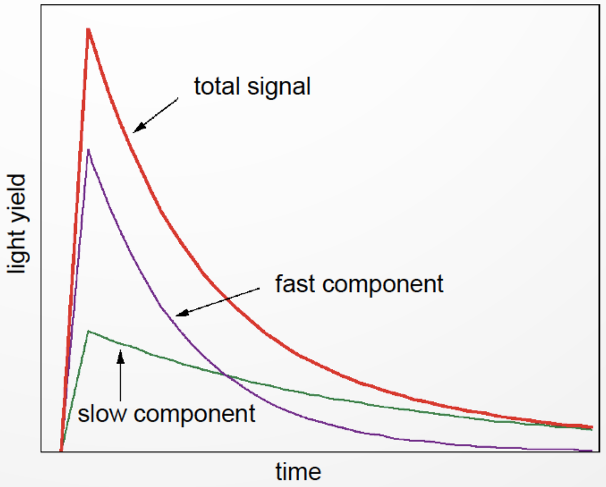


# 3.2 SCINTILLATION IN ORGANIC MATERIALS

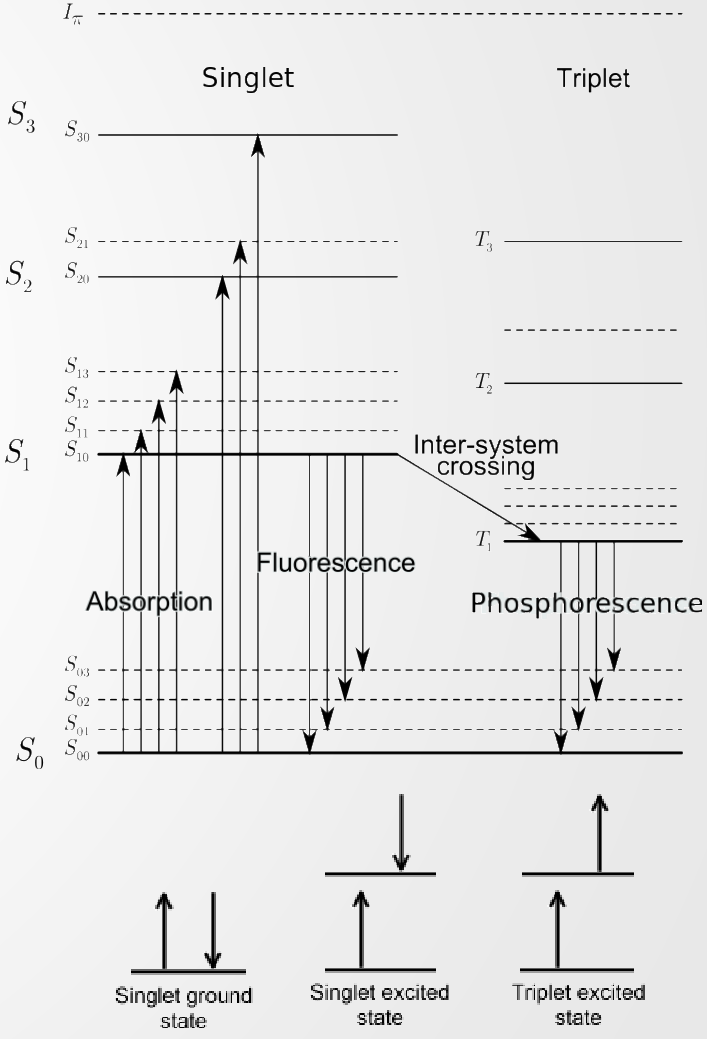
- defined by electron configuration of large carbon molecules: $\sigma$ and $\pi$ orbitals
  - Organic = carbon atoms
- Benzene* ($C_6H_6$):
  - p-orbital contains weakly bound π-electrons
  - fine structure from molecular vibrational and rotational modes
- Scintillation principle:
  - Excitation to $S_{1,i}$ $S_{2,i}$ $S_{3,i}$ levels
  - radiation-less drop to $S_1$(~ps)
  - desired O(ns) fluorescence from $S_1 \longrightarrow S_0$ ~ 3-4 eV, 400-300 nm)
  - a fraction of molecules can transit transition-less to meta-stable triplet states and cause undesired O(ms) phosphorescence.




typical scintillator signal shape




$\pi$ electron states of benzene

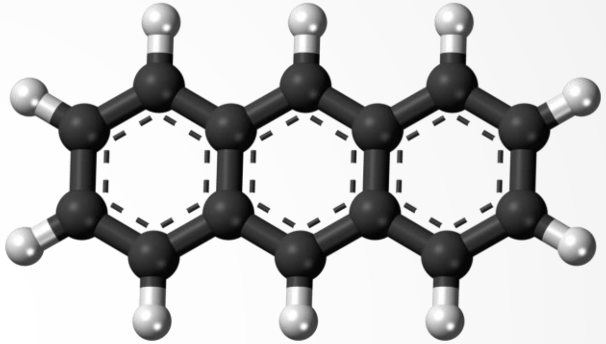



* German: Benzol

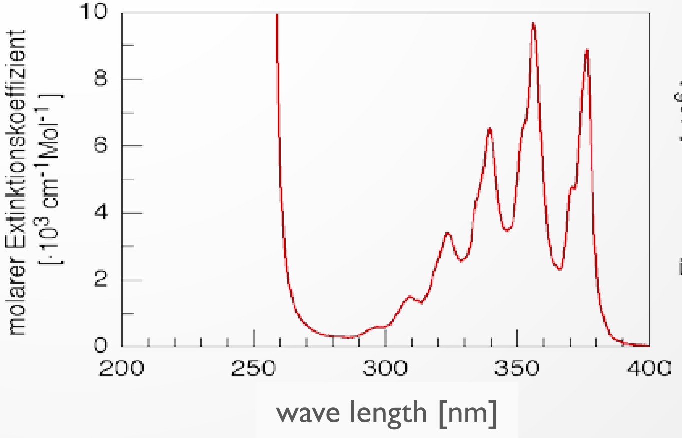
# 3.3 ORGANIC CRYSTALS

- Important organic scintillating crystals:
  - Naphtalen ($C_{10}H_8$)
  - Anthracen ($C_{14}H_{10}$)
  - Stilben ($C_{14}H_{12}$)
- Advantages: Fast fluorescence: ~ 3 ns (exception: Anthracen ~ 30 ns)
- Mechanically strong (exception: Stilben is brittle)
- Disadvantages: Anisotropic light output depending on the orientation of the crystal wrt to the incident radiation: "channeling"
- Mechanically difficult to process (fragile)

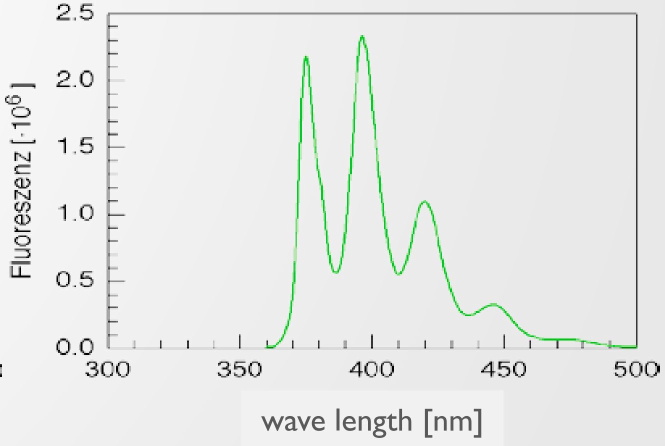
Anthracen molecule




Absorption profile




Emission profile

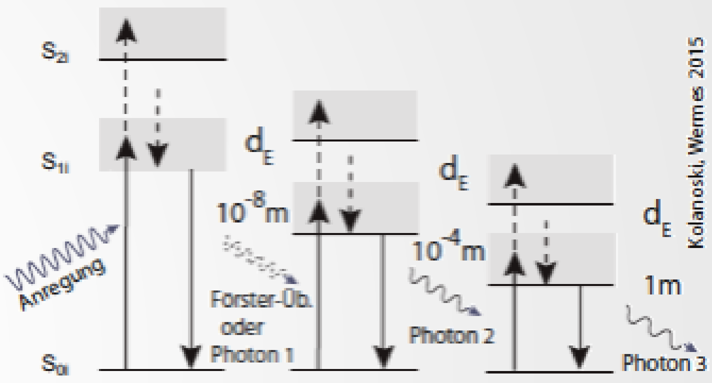


# 3.4 ORGANIC LIQUID AND PLASTIC SCINTILLATORS

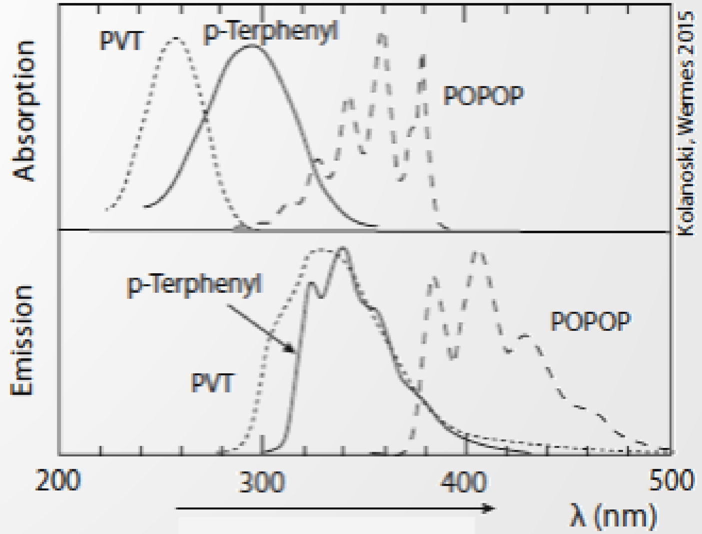
- Important liquid scintillators:
  - p-Terphenyl ($C_{18}H_{14}$), POPOP ($C_{24}H_{16}N_2O_2$), PBD ($C_{24}H_{22}N_2O$), DPO($C_{15}H_{11}NO$)
  - Mixture of one or several organic scintillators in an organic solvent (typically 3g/l solvent).
  - Average distance to molecule of a different solvent should be below the emission wavelength
- Solvents for liquid scintillators:
  - Benzol ($C_6H_6$), Toluol ($C_7H_8$), Xylol ($C_8H_{10}$), Phenylcyclohexan ($C_{12}H_{16}$), Triethylbenzol, Decalin ($C_{10}H_{18}$)
- Can polymerize (low efficiency scinillators Polystrol, Polyvenyltoluol, Polymethylacrylat)
- properties of these 'plastic scintillators'
  - Fast fluorescence: ca. 3–4 ns,
  - any possible detector shape
  - not very radiation resistant
- Easy use of additives
  - wave length shifter
  - increase neutron cross section
- wide range of detector applications

frequently used combinations

| | | | |
|---|---|---|---|
| liquid | Benzol | p-Terphenyl | POPOP |
| | Toluol | DPO | BBO |
| | Xylol | PBD | BPO |
| plastic | Polyvinylbenzol (PVB) | p-Terphenyl | POPOP |
| | Polyvinyltoluol (PVT) | DPO | TBP |
| | Polystyrol (PS) | PBD | BBO/DPS |




principle of wave length shift




Stokes shift

# 4. DETECTOR ASSEMBLIES AND PHOTO DETECTORS

# 4.1 LIGHT GUIDES

Light guide: flat top couples to scintillator, round bottom to photo detect

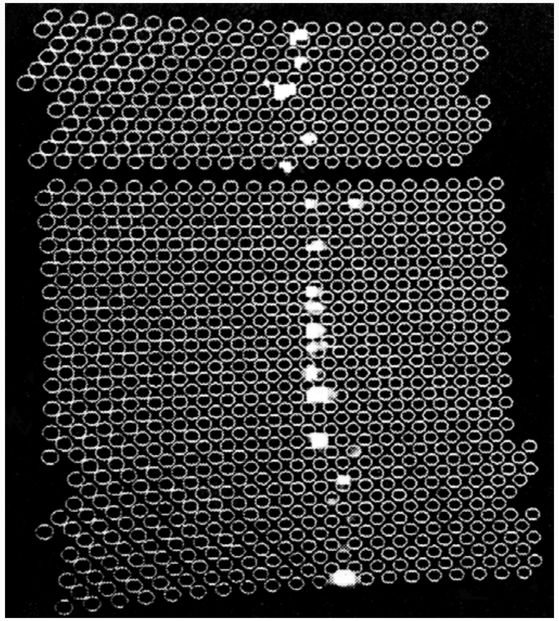
Full system consisting of: scintillator (light-tight packed), light guide, photomultiplier

CERN Microcosm Ausstellung
Photo: M. Krammer

# 4.2 SCINTILLATING FIBRES

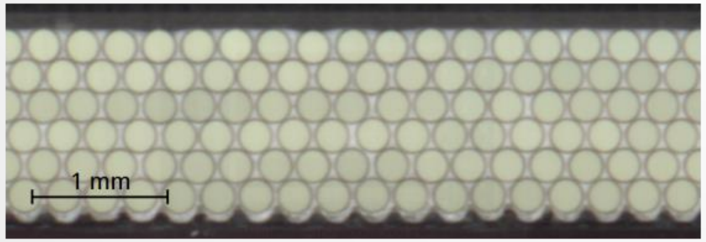
arXiv:1710.08325

- Different fiber technologies:
  - Plastic fibers
  - Glass fibers
  - Capillaries, filled with scintillating liquid
- Scintillating fibers are used in:
  - Calorimeters
  - Pre-shower detectors
  - Position sensitive detectors

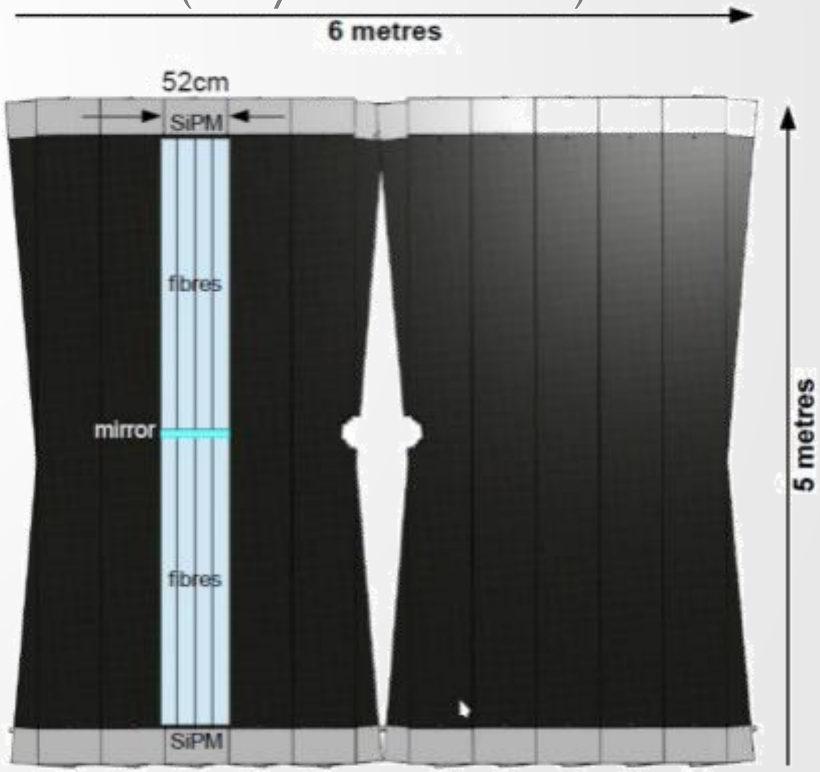


Particle track in a stack of scintillating fibers.
Fiber diameter 1 mm.

Cross section of scintillating fibre mat with 6 fibre layers

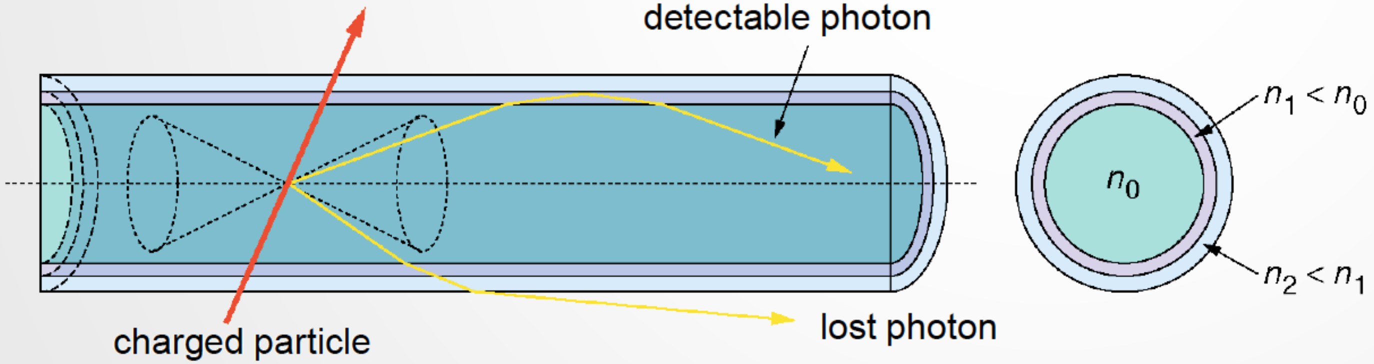



LHCb SciFi tracker upgrade to be installed during LS2 (12 layers of fibre mats)



# 4.3 PLASTIC FIBRES

- Core made of Polystyrol or Polyvinyltoluol (refraction index $n_0$). Inserted is a primary scintillator and often a wave length shifter additive.
- The core is surrounded by at least one thin sheet of a material with refraction index $n_1 < n_0 \longrightarrow$ total reflection at the boundary.
- Only a small fraction of the emitted light remains in the fiber and is forwarded by total reflection.




Longitudinal and cross section of a scintillating fiber with two sheets. Shown is a traversing charged particle with 2 emitted photons and the allowed opening angle for total reflection.

Scintillating fibers for the electromagnetic calorimeter of the CHORUS experiment (SPS, CERN)

Scintillating fibers for the MINOS detector (Fermilab), fiber diameter 1 mm

# 4.4 PHOTO DETECTORS (OVERVIEW)

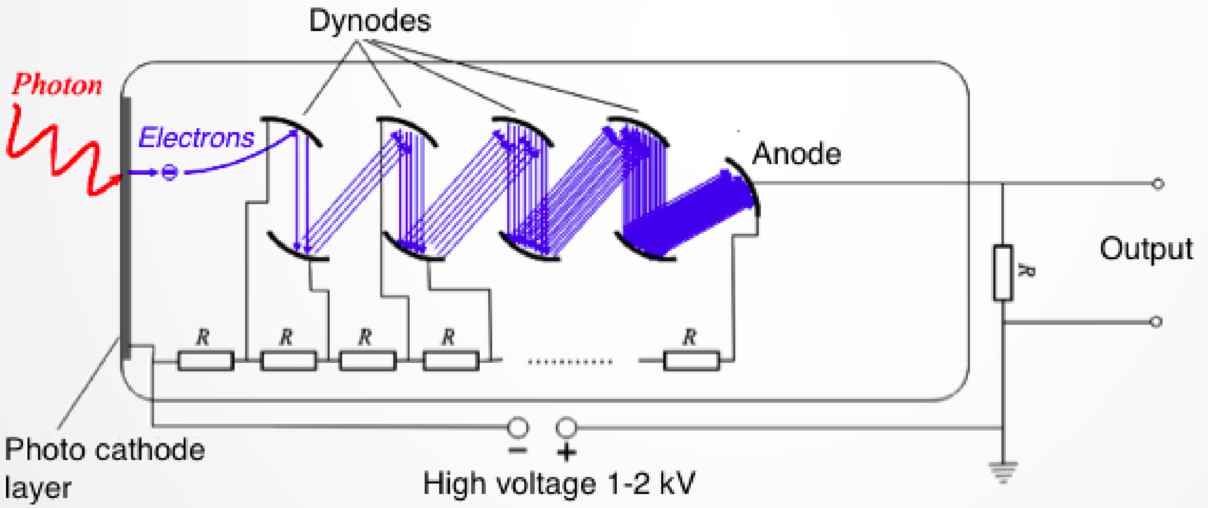
Image: Hamamatsu

- Different photo detectors used to read light from scintillators and transform it into electric signals:
  - "Classical" Photomultipliers
  - "New" silicon devices: APD, SiPM
  - Hybrid Photon Detectors HPD
  - Gaseous Detectors

- can give only few examples!

# 4.5 PHOTOMULTIPLIERS

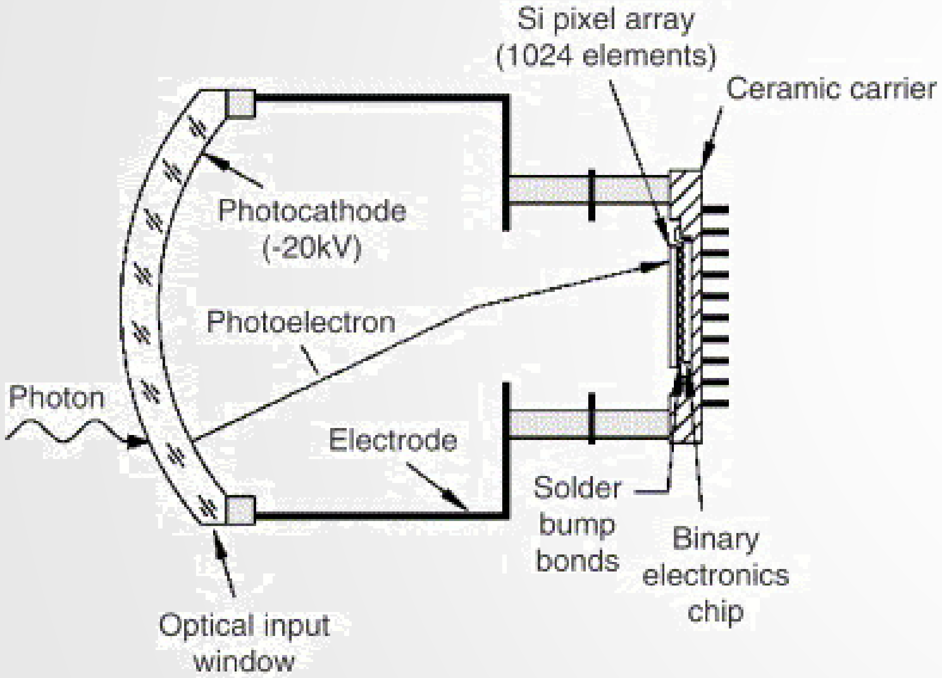
- Photons hitting the photo cathode release electrons (photoelectric effect).
  - The electrons are accelerated towards the 1st dynode and produce secondary emission.
  - This process is repeated at each dynode and finally the largely amplified electrons reach the anode.
- Quantum efficiency 10 – 30% (probability that a photon leads to e- emission), depending on wave length, entry window material, photo cathode.

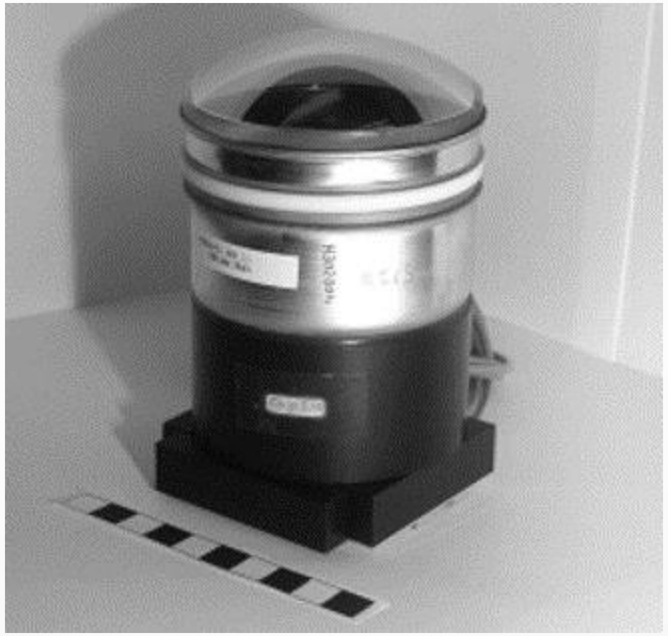



- Advantages: high amplification gains $10^4 – 10^7$
- Disadvantage: sensitive to magnetic fields

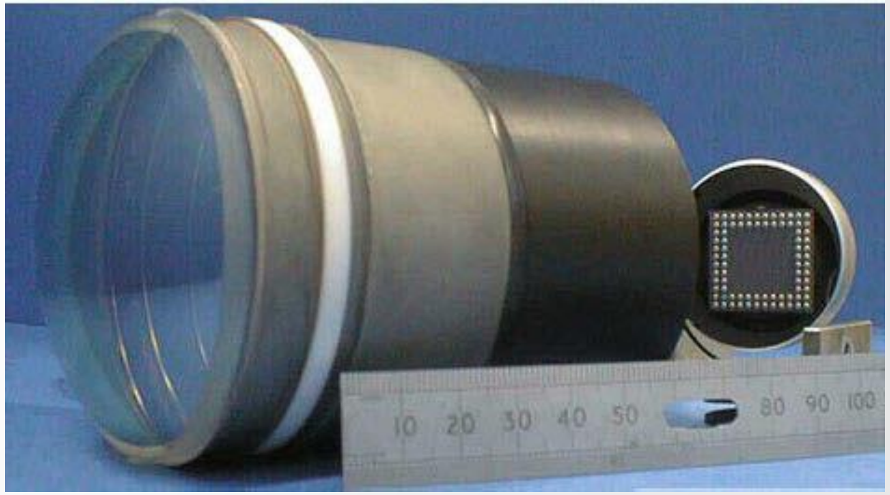
# 4.6 HYBRID PHOTO DIODES

- Photoelectrons are accelerated in vacuum (20 kV) and detected with a silicon hybrid pixel detector.



HPD from LHCb RICH

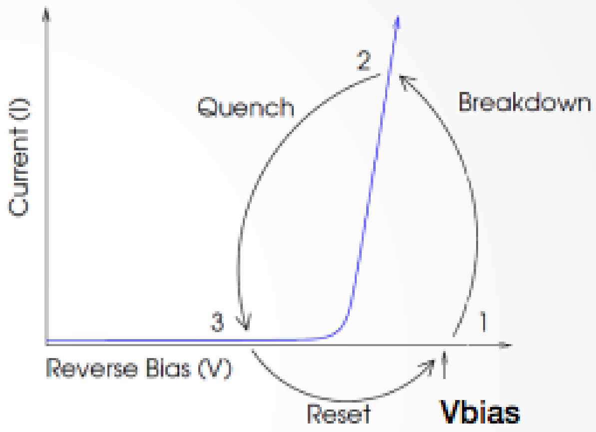


# 4.7 APD/SIPM

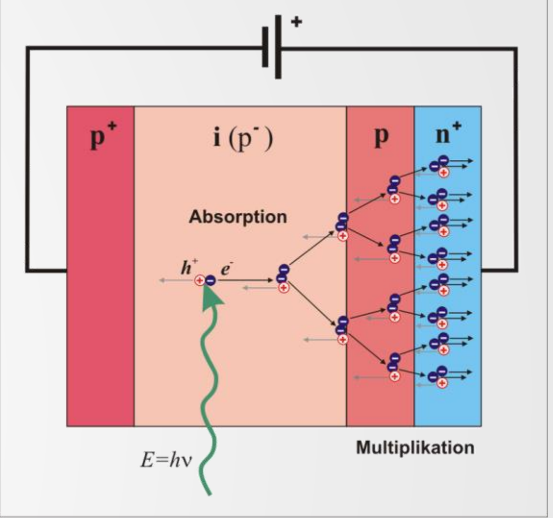
P. Buzhan et al., Nucl. Instr. Methods A 504 (2003) 48

- Avalanche Photo Diodes (APDs) are silicon devices operated in reverse bias mode in the breakdown regime.
- Geiger mode APDs (G-APD) operate in full breakdown (caused by secondary ionization). The current limited by quenching resistor.
  - G-APDs can detect single photons!
  - assembled in matrix (SiPM)
- general properties
  - high gain in the range of $10^5$ to $10^7$
  - Work at low bias voltage ~50 V
  - Low power consumption
  - Insensitive to magnetic fields
  - Radiation hard
  - Tolerant against accidental illumination
  - cheap
  - but high dark counts

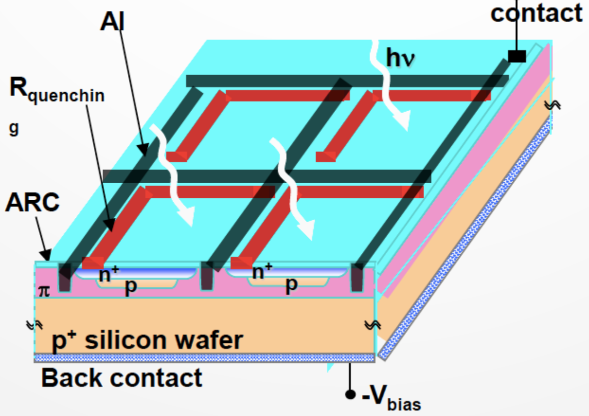
APD operating principle



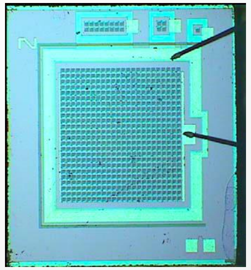

APD schematic



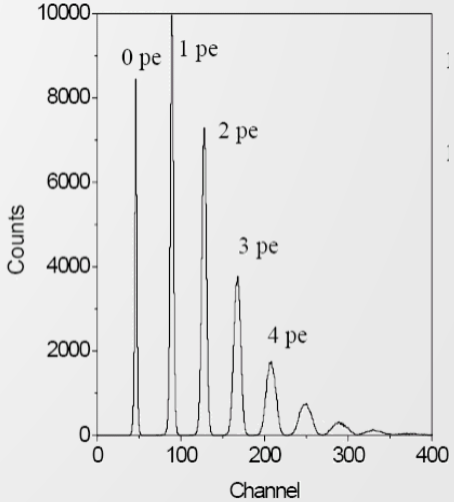

SiPM (G-APD matrix)




SiPM (1mm)



SiPM dark count rate



# THE END!