Scintillation detectors

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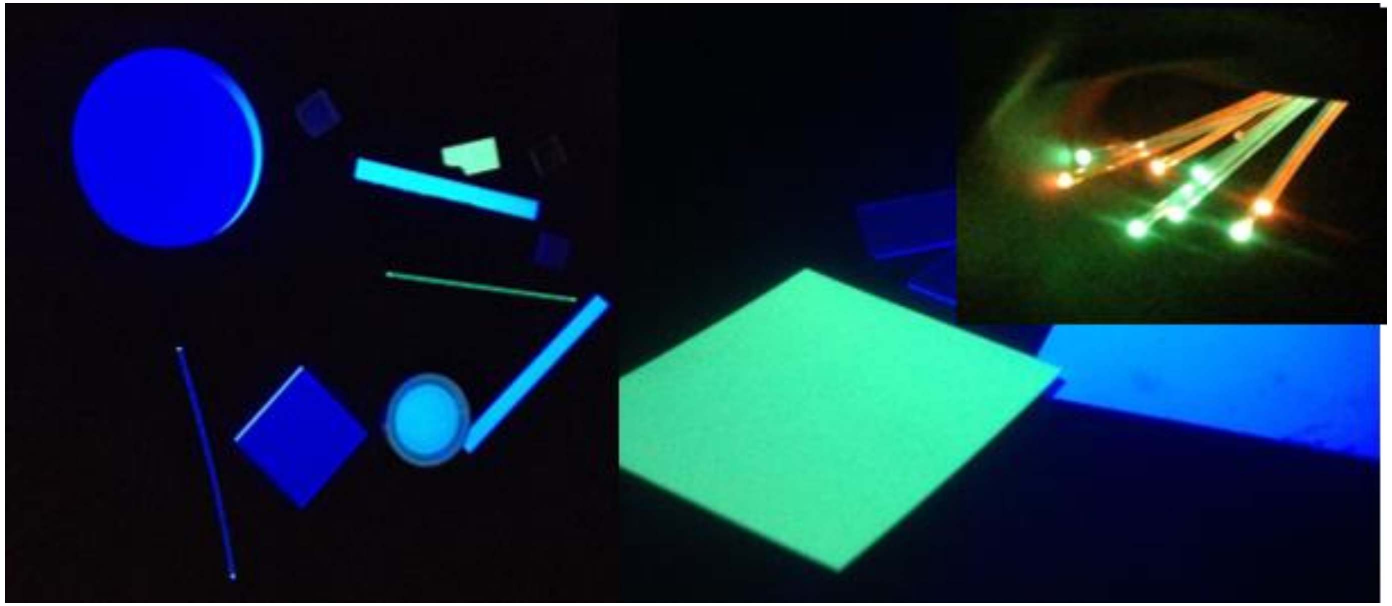
UNIVERSITY OF ALBERTA

Outline

- Introduction
- Pre-requisite: photodetectors
- Organic scintillators
- Inorganic scintillators
- Scintillating fibers
- Summary



Content based on:

Particle Detectors: Fundamentals and Applications by Hermann Kolanoski and Norbert Wermes

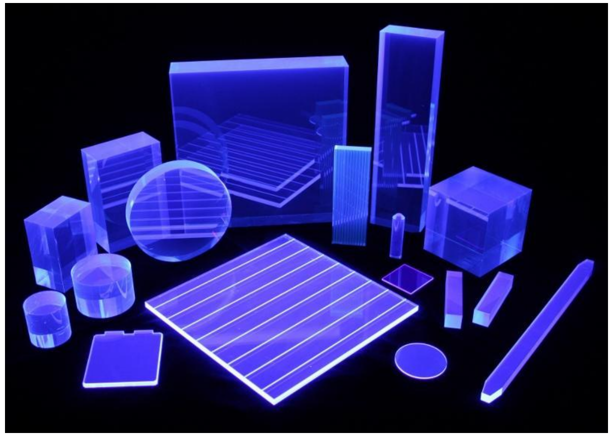
What is **scintillation**?

- Creation of **luminescence** by absorption of **ionizing radiation**

  <u>Luminescence</u>: light emission with characteristic spectrum caused by some inherent molecular or crystalline properties of materials

  <u>Ionizing radiation</u>: subatomic particles or electromagnetic waves with enough energy to ionize atoms or molecules by detaching electrons from them

  The effect somewhat proportional to energy of incident radiation.



- Classification based on chemical composition: organic and inorganic

  The mechanism that produces light differs

- Classification based on time delay of emission process

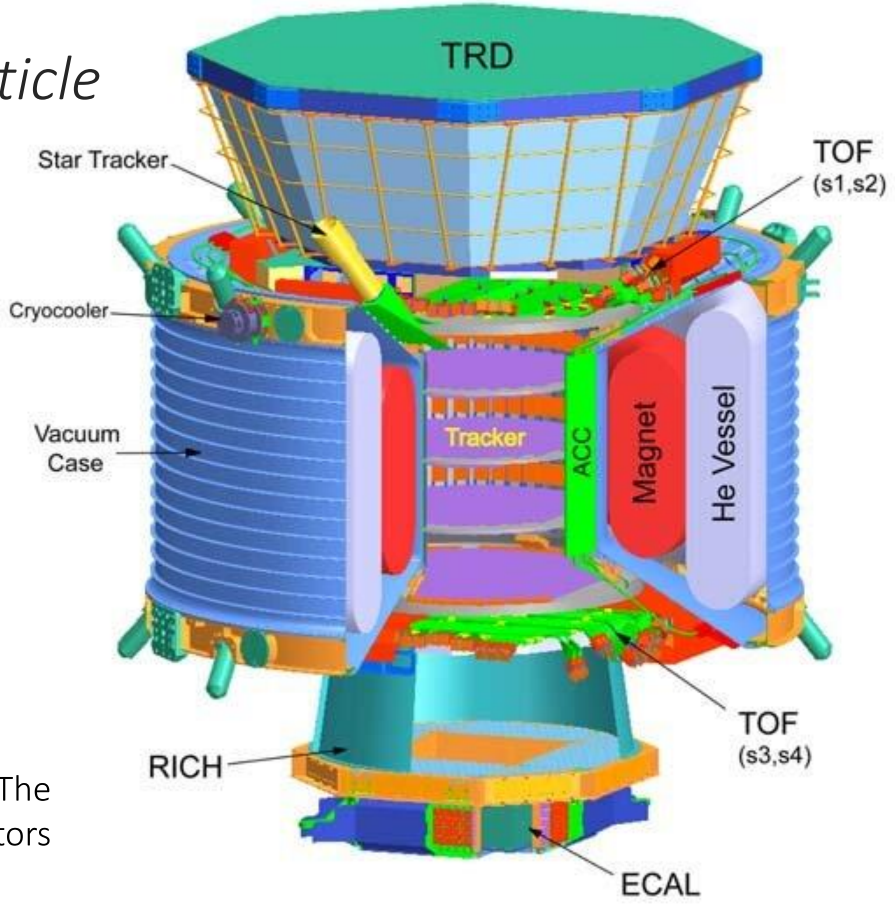
  Fluorescence (prompt), phosphorescence and delayed fluorescence

Uses of scintillators

- Ionizing radiation can be EM waves (photons, X-rays, gamma-rays) or particles (e, p, alphas)

- They can be **used** for
  Calorimetry – measuring the energy deposited by the particle
  Time of flight – establishing speeds
  Tracking detectors – following the trajectory
  Trigger, veto counters – establishing their presence

- Can be **found** in
  Nuclear and particle physics experiments
  Astrophysics detectors
  Medical imaging

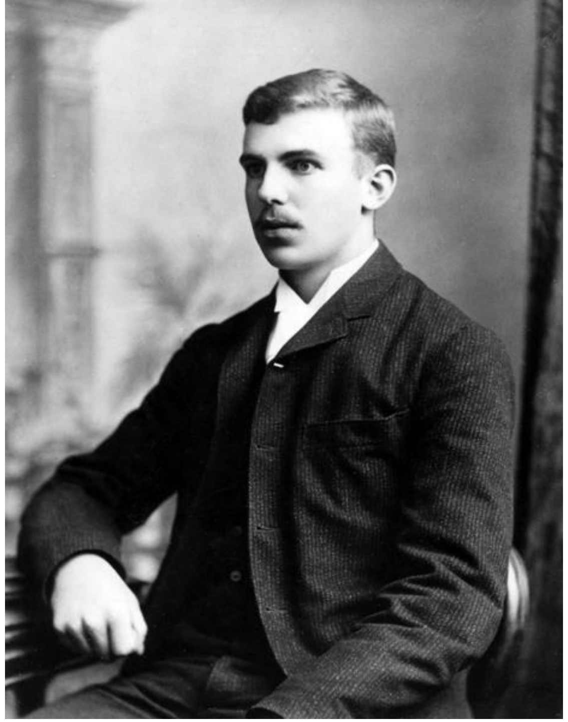


Schematic diagram of the AMS-02 apparatus. The TOF systems are made using plastic scintillators

A little history

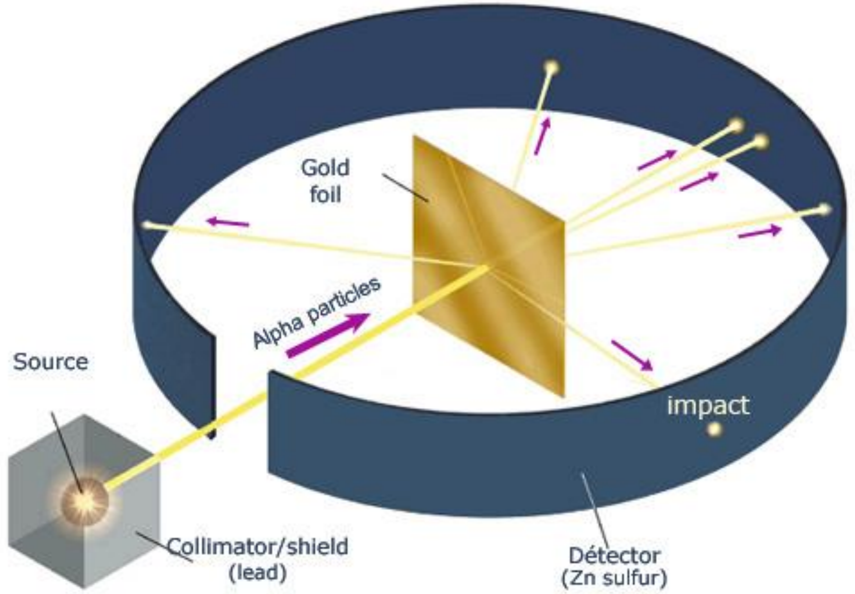
- One of the **oldest** techniques for particle detection

  1910 – Rutherford detected α particles with his eyes when they created scintillation flashes impinging on a zinc sulfide screen



Side note: The human eye can detect flashes of light with as few as 15 photons arriving in $\Delta t = 1$ ms

(Hecht, Shlaer, Pirenne, 1942)



A little history

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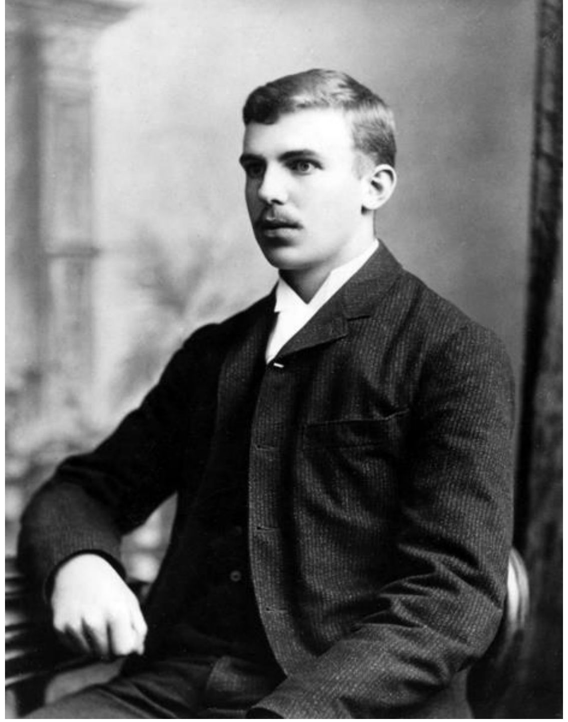
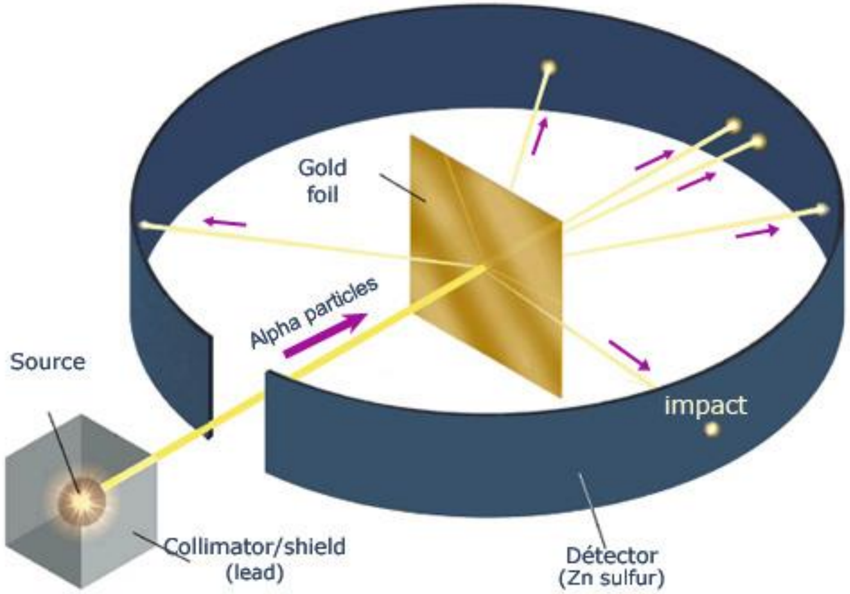
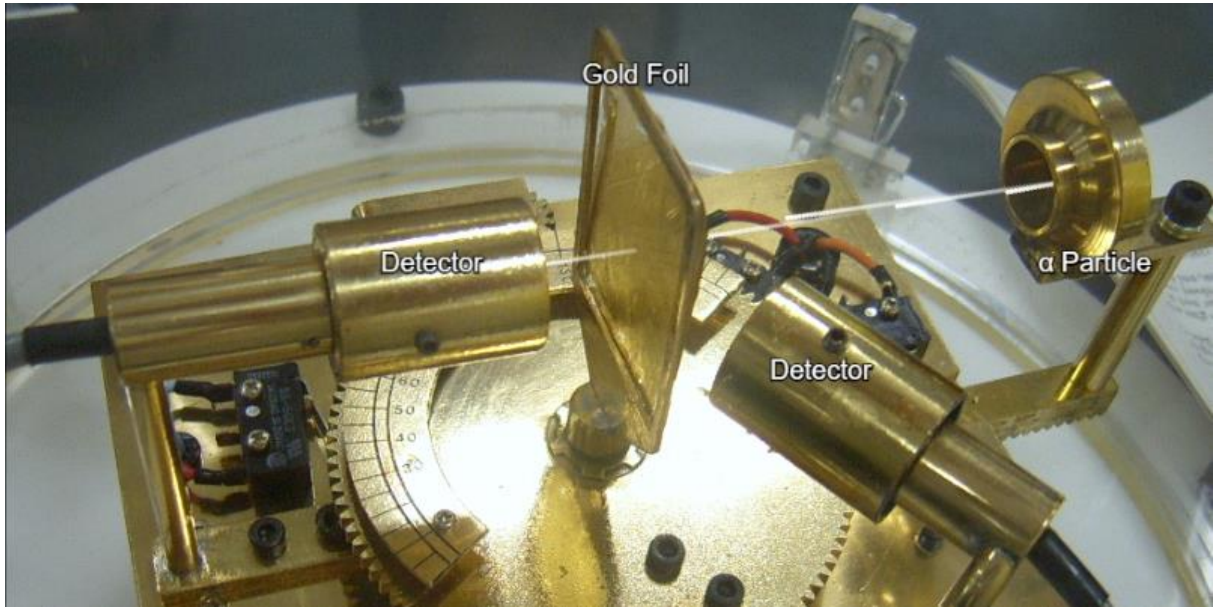
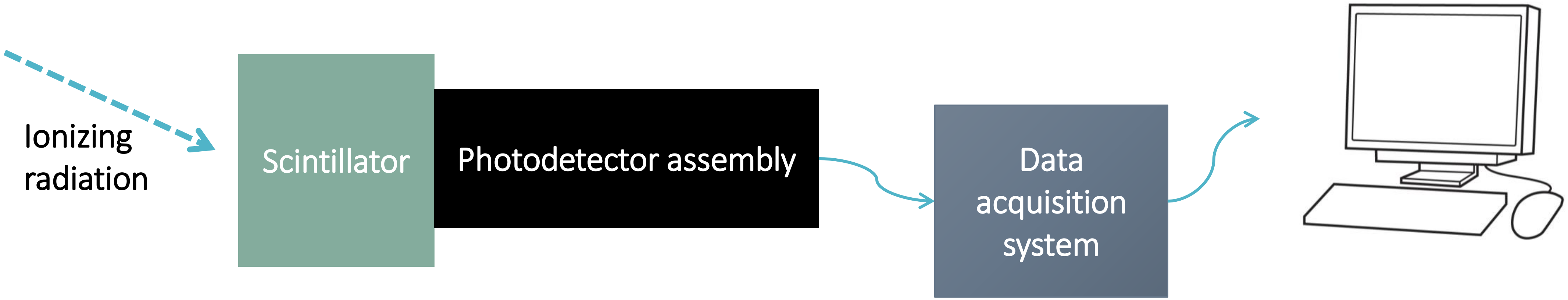
- Today, we detect scintillation photons <u>electronically</u>







Scintillators for **particle detection**



- High efficiency conversion of energy deposit into light
- Light yield L_s should be proportional to the energy released (linearity)
- <u>Scintillation medium should be transparent to the light emitted</u>
- Decay time of luminescence should be as short as possible (fast signal)*
- Refractive index should allow easy coupling to readout device
- Spectrum of scintillator should overlap with the sensitive region of the readout device

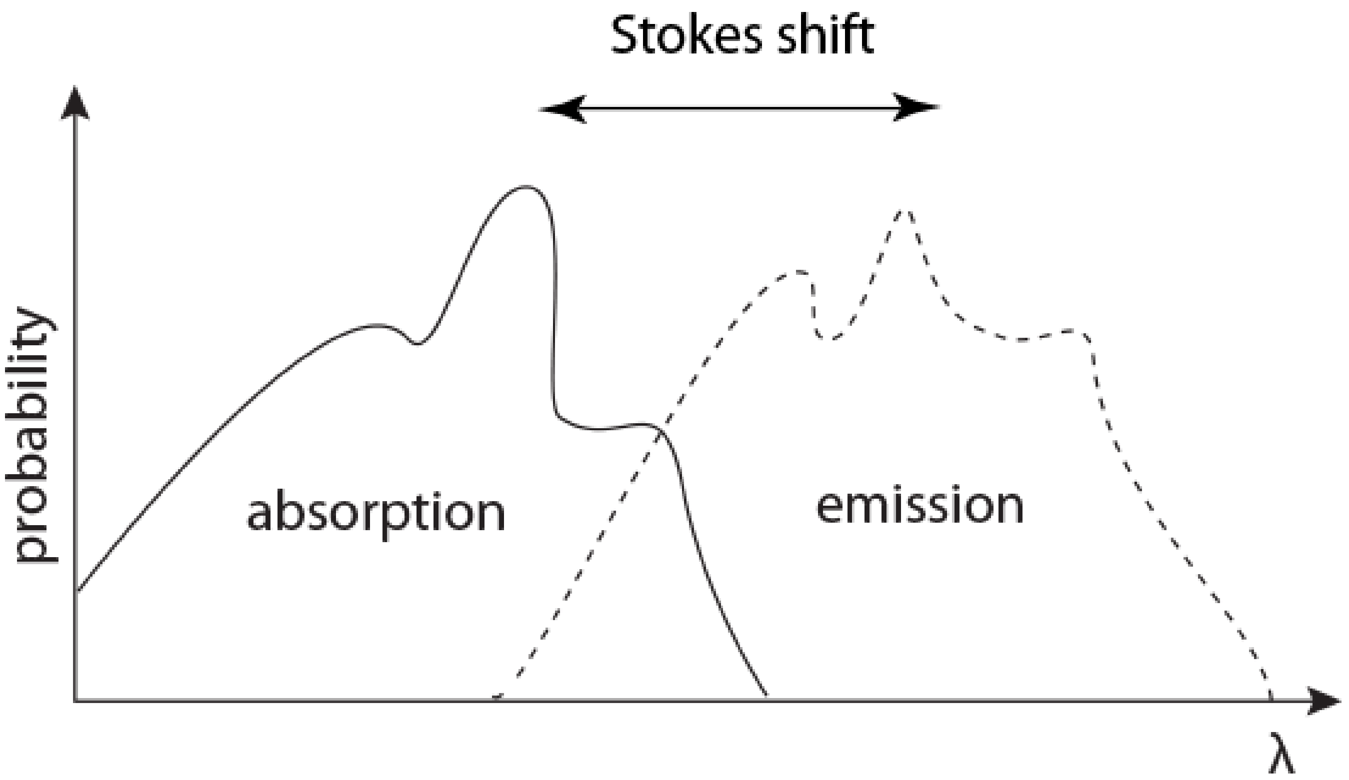
Key process: **Stokes shift**

- Scintillation medium should be transparent to the light emitted

  Light emitted can, in principle, be reabsorbed by the scintillator – we don't want that

  For light to escape, the emission energy has to <u>be lower</u> than the absorption energy

  This phenomenon is known as Stokes shift, and it can be due to different physics processes as we will see

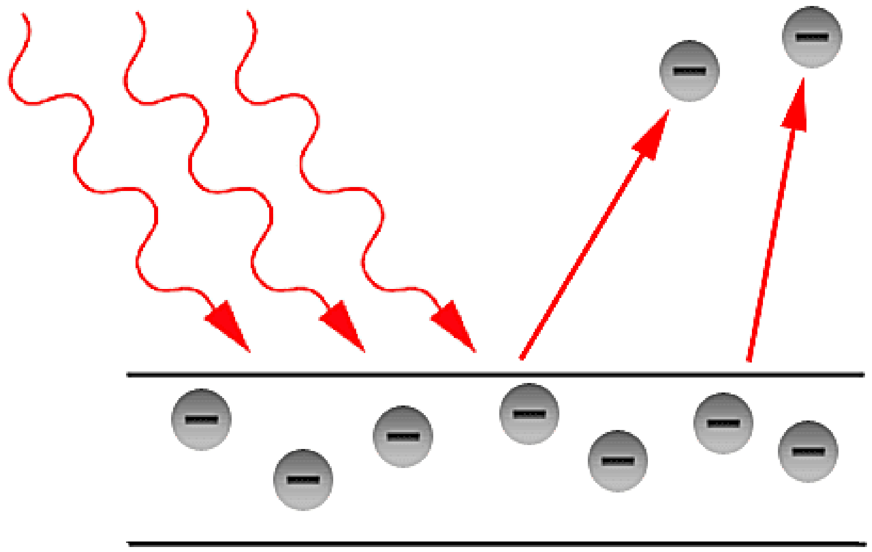


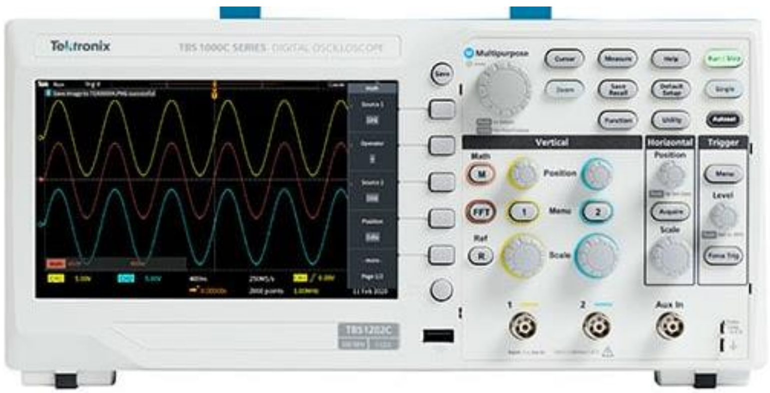
Electronic
Photodetectors

In the UV and optical regime (200 – 700 nm)

Photoconverters

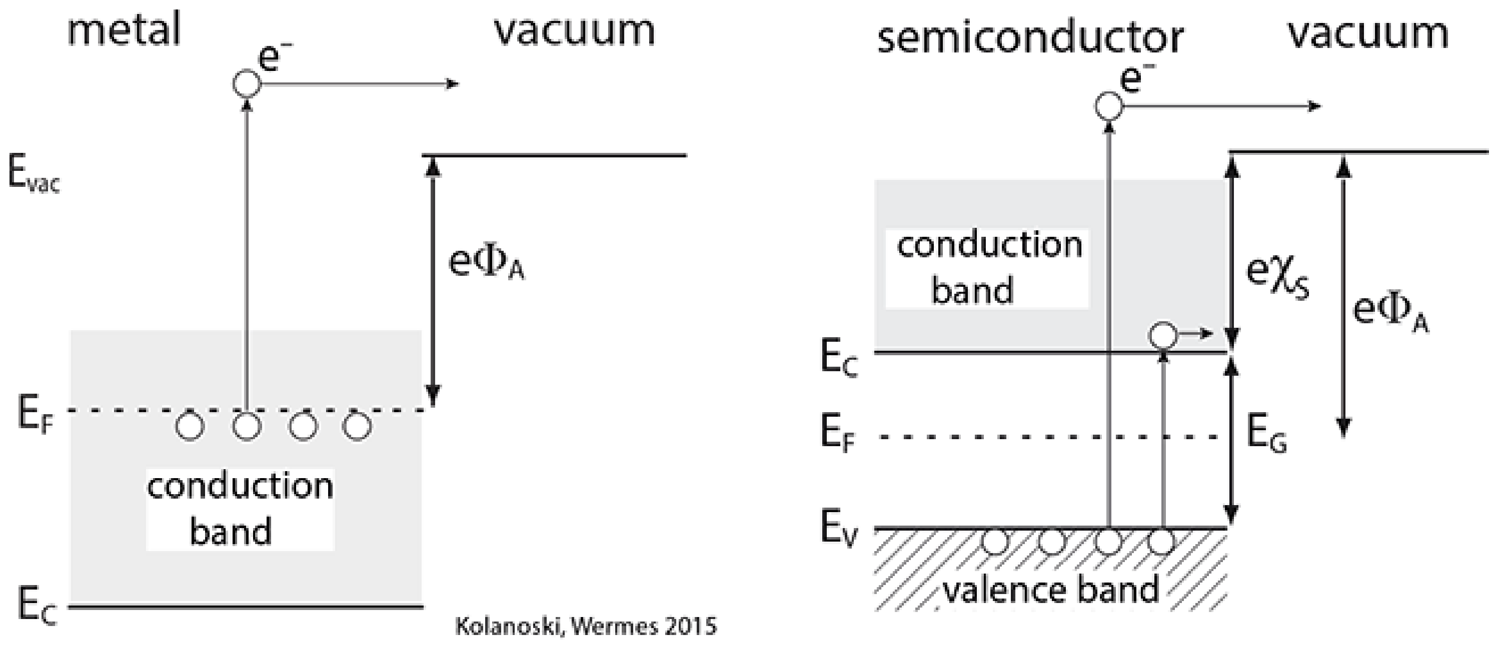
- Goal: Convert photons and generate an electrical signal
- Starting point: photoelectric effect
  - *External photoelectric effect is used in PMTs*
  - *Internal photoelectric effect is used in silicon-based detectors*
- Second step: amplification
  - *Mechanism depends on the device*
- Signals can then be collected by readout electronics





Photomultiplier **tubes**

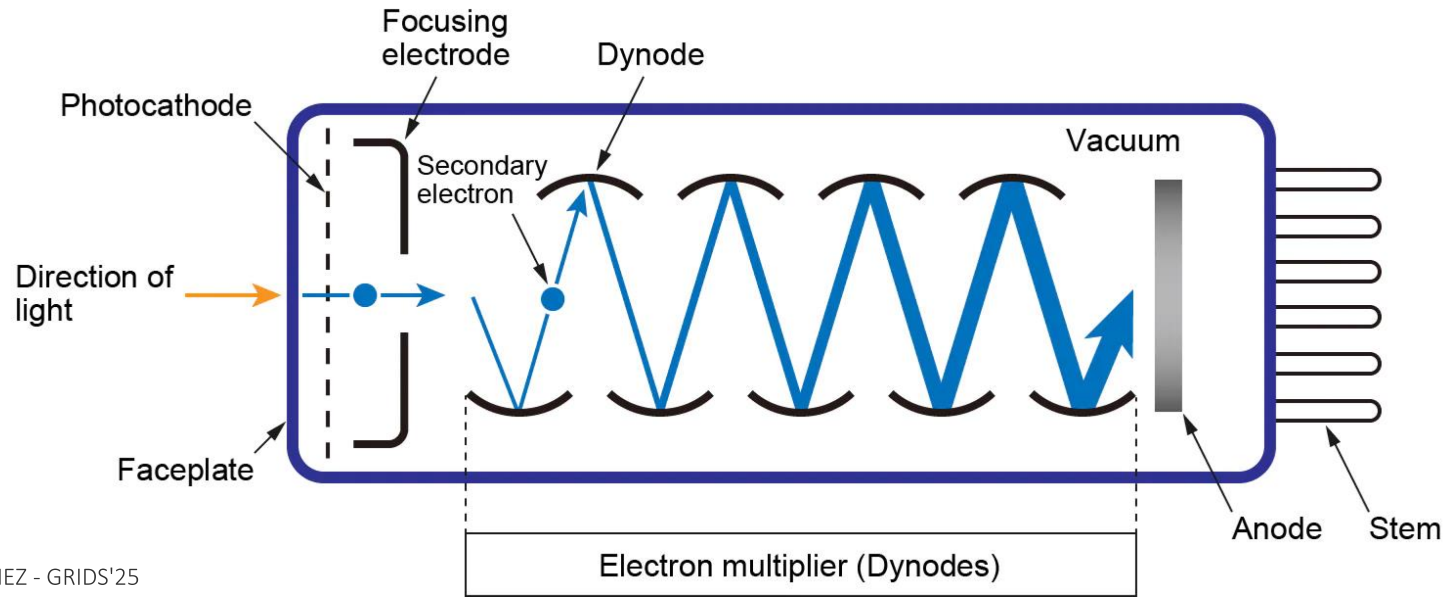
- Photon releases an electron from the photocathode
  1. *Absorb the photon, release an electron*
  2. *Electron moves to the surface*
  3. *Electron escapes to the vacuum*



(a) Electron emission from a metal. (b) Electron emission from a semiconductor.

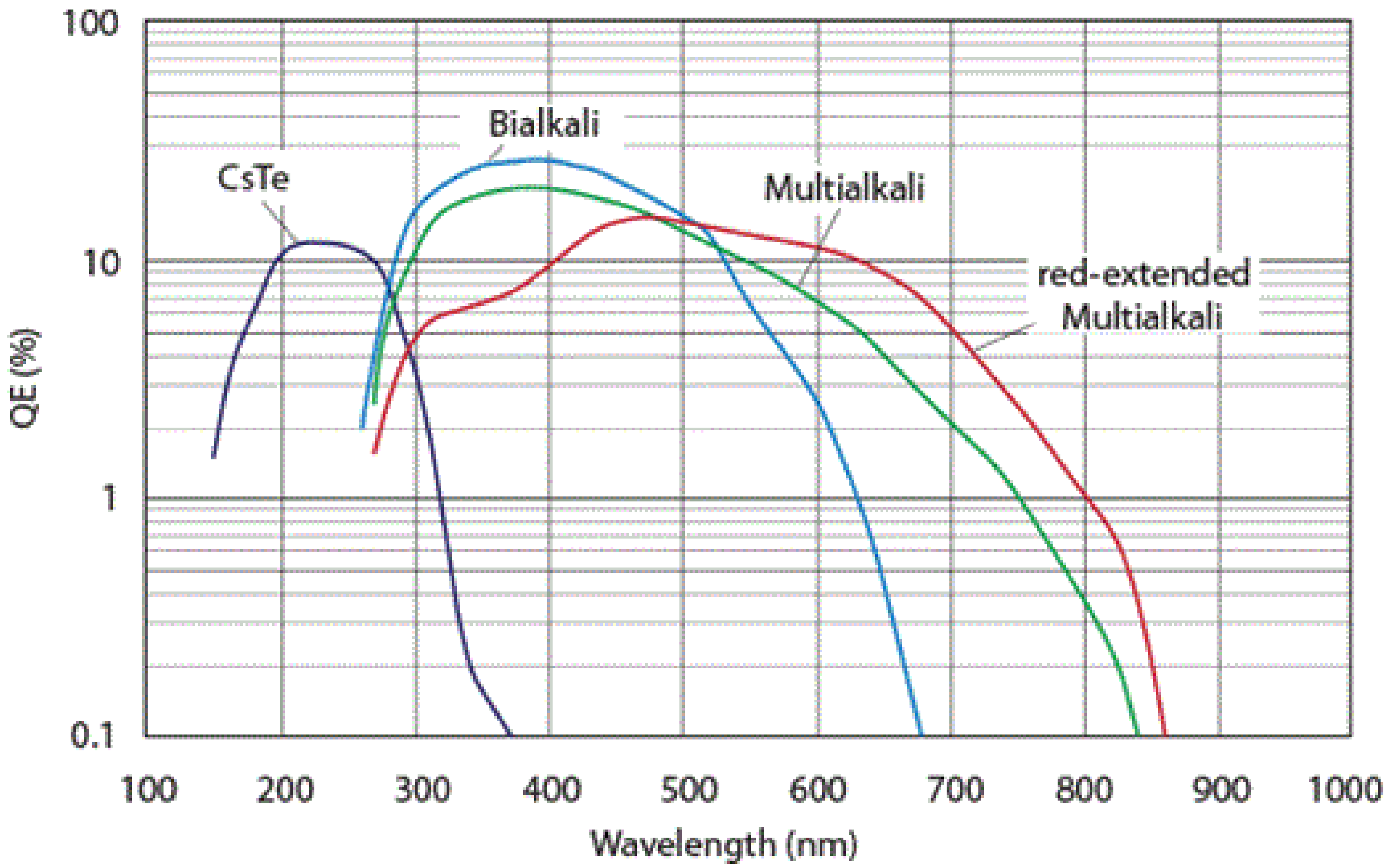
Photomultiplier **tubes**

- Photon releases an electron from the photocathode
- The electron is accelerated by HV between dynodes
- More electrons are produced by secondary emission
- Amplification factors of order 10^6 after multiple steps
- The result is a measurable current



Photomultiplier **tubes**

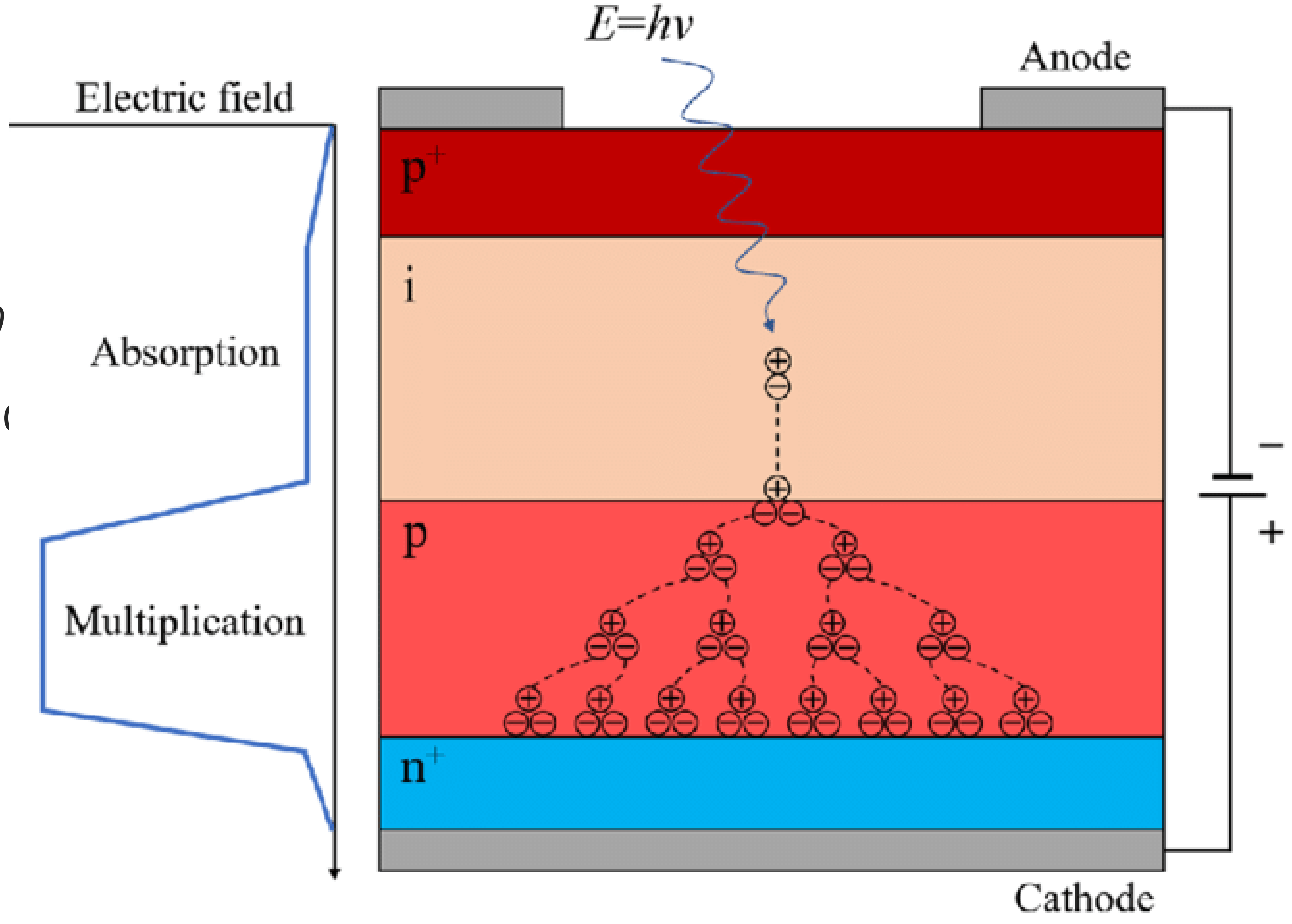
- Photocathode material defines the sensitive wavelengths
  - Monoalkali
    - *e.g. Cs–I, Cs–Te, K–Br*
  - Bialkali
    - *e.g. Sb–Rb–Cs3*
  - Multialkali materials
    - *e.g. Sb–Na–K–Cs3*
  - III–V semiconductors ‘activated’ (doped) with caesium,
    - *GaAs(Cs), GaP(Cs), InGaAs(Cs)*
- Glass needs to be transparent to the desired wavelength



Avalanche **photodiodes** (APDs)

- Formed by multiple p-n junctions
- In reverse bias, the high doping creates strong electric field

  Operating voltages are of the order of 20-100
- Electrons moved to the conduction ban go towards the high field region, where avalanche amplification takes place
- Signal is picked up by an electrode, can be amplified further



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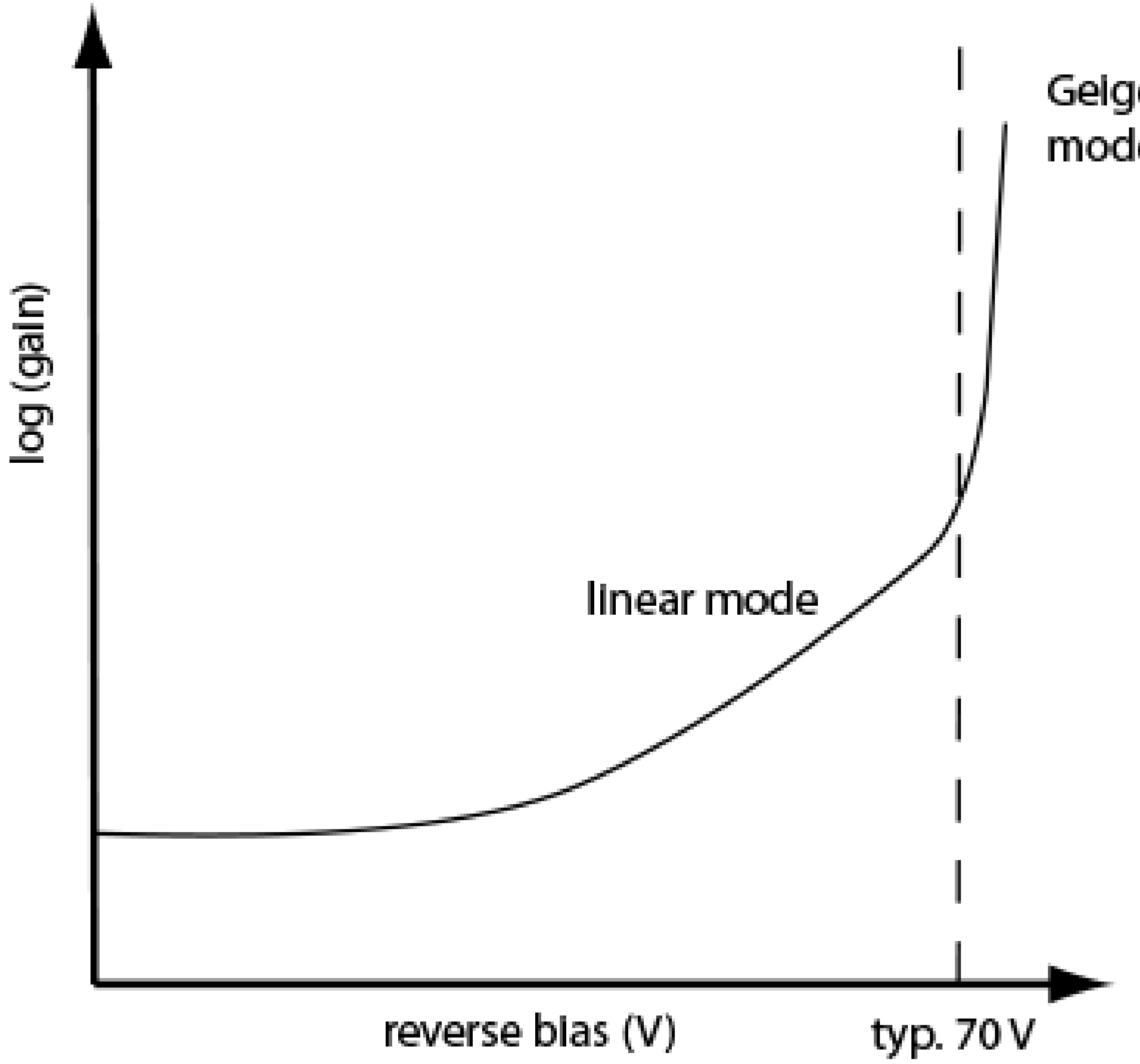
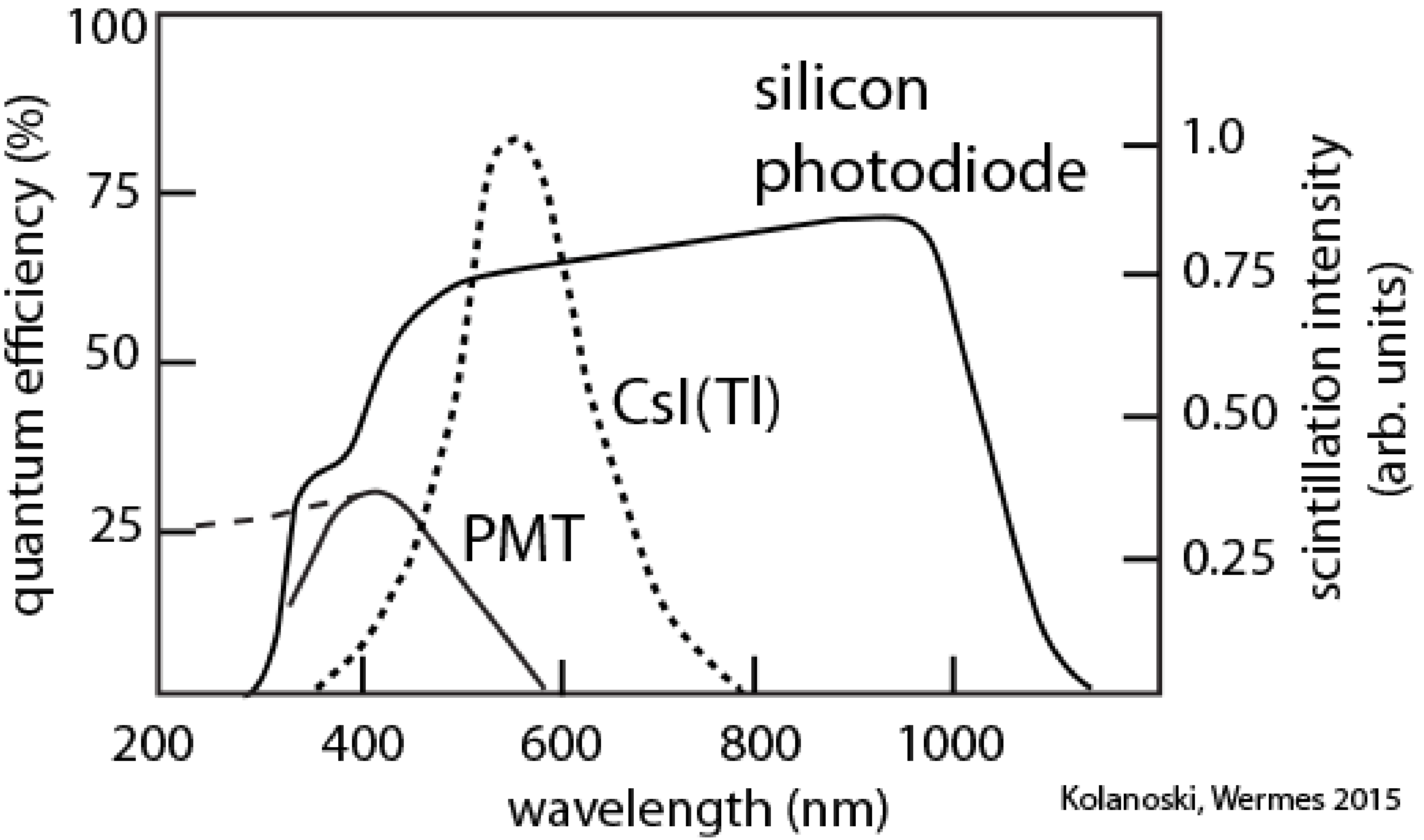


Avalanche **photodiodes** (APDs)

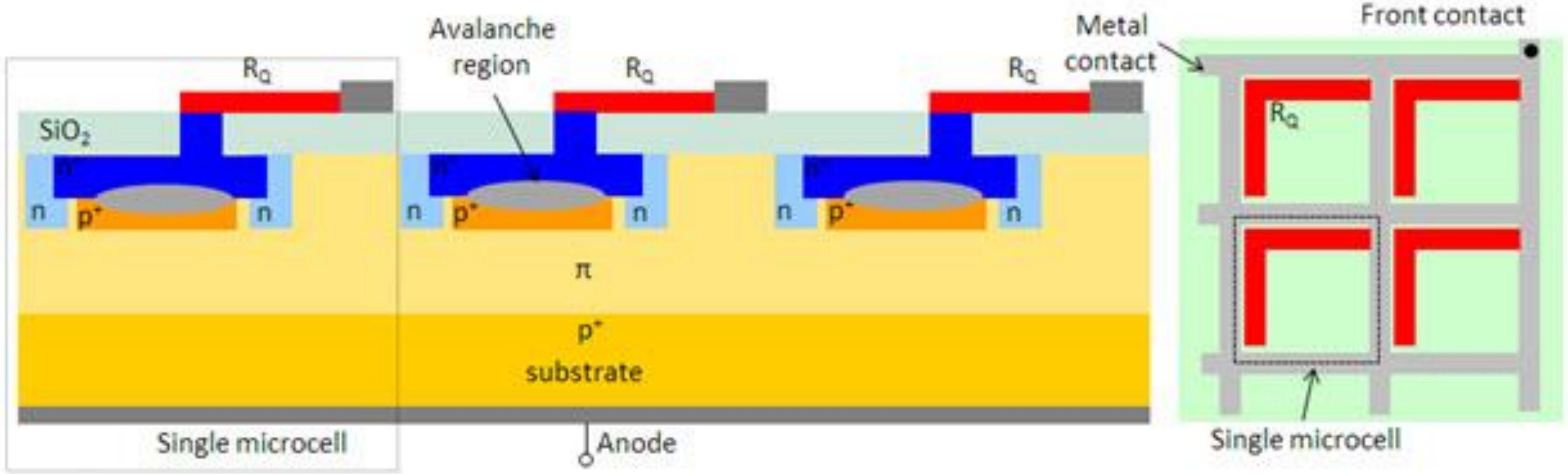
- Sensitive over a larger wavelength range than PMTs



Kolanoski, Wermes 2015

Silicon Photomultipliers (**SiPMs**)

- Also known as Single Photon Avalanche diode (SPAD), Geiger-mode avalanche photodiode (G-APD) or Multi-Pixel Photon Counter (MPPC) arrays
- Matrix (array) of APDs operated in Geiger mode, with gains of 10^6
  - *Cells are binary (yes/no)*
  - *Number of **yes** cells is proportional to light intensity*



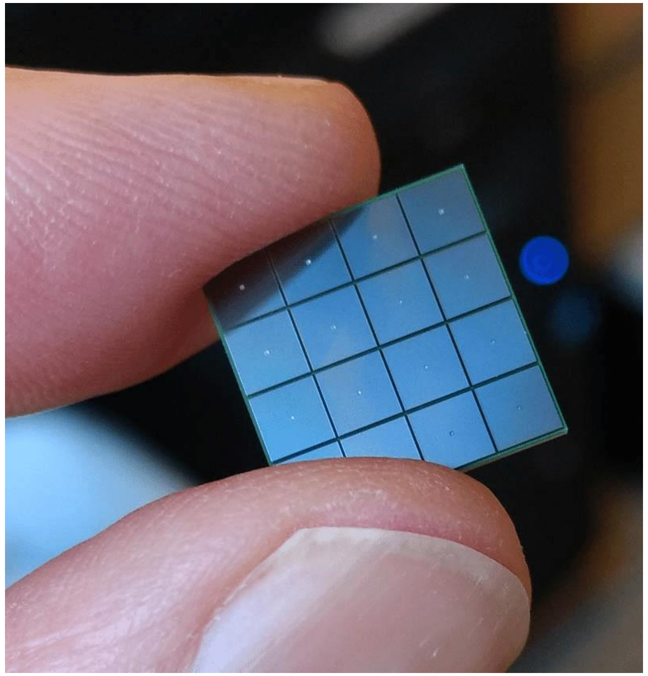


Table 10.2 Characteristics of different photodetectors in comparison. Given are typical values without claim of completeness and accounting for all detector variants.

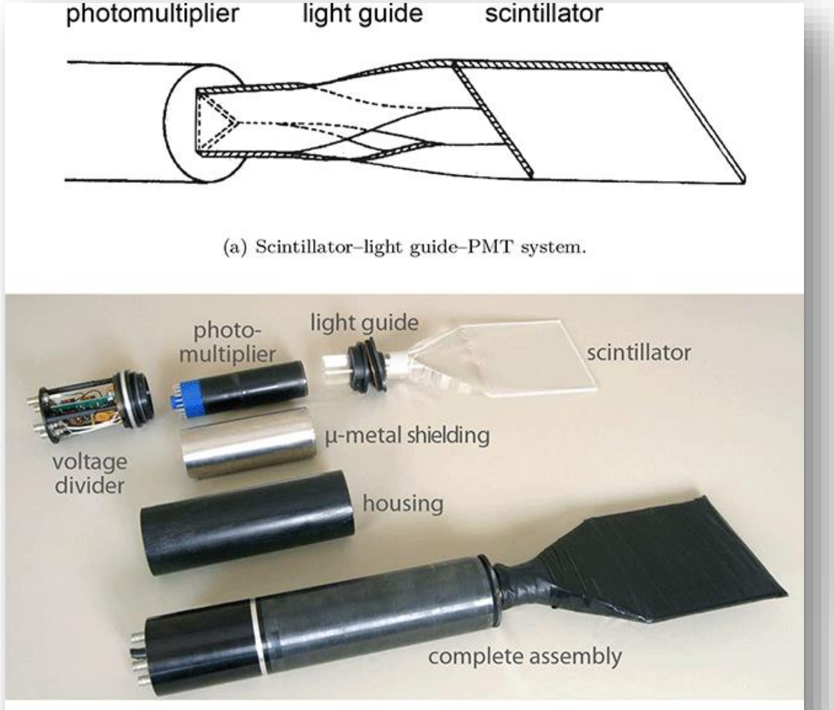
The abbreviations are: PMT = photomultiplier, VPT = vacuum phototriode, MCP = microchannel plate, PD = photodiode, APD = avalanche photodiode operated in linear mode, HAPD = hybrid APD (linear operation mode), HPD = hybrid photodiode, SiPM = silicon photomultiplier (APD arrays operated in Geiger mode).

QE = quantum efficiency at λ_{max}, λ_{max} = approximate wavelength of maximum efficiency, $\Delta\lambda$ = sensitive wavelength region at 50% QE, gain = intrinsic amplification, PDE = typ. photon detection efficiency according to (10.8) at λ_{max}, DR = dark rate at room temperature if the device is sensitive to single photons, SNR (1γ) = signal-to-noise ratio related to a single primary photon (typical, dependent on the bandwidth), σ_t = time resolution, A = typical (maximal) sensitive area, V_{op} = operating voltage, v/c = indicates if a detector is typically rather voluminous or compact/small, sens. 1γ = single photon detection possible (y/n), sens. B = sensitive to magn. fields, sens. T = temperature sensitive gain, price = high/medium/low for small area units.

	PMT	VPT	MCP	PD	APD	HAPD	HPD	SiPM
QE (%)	25 – 40	20 – 22	20 – 25	75	75	25	25	70 – 80
λ_{max} (nm)	400	400	400	750 – 900	750 – 900	400	400	750
$\Delta\lambda$ (nm)	300 – 550	300 – 550	300 – 550	400 – 1000	400 – 1000	300 – 550	300 – 550	400 – 1000
gain	10^{5-9}	10	10^{4-6}	1	50	10^{4-5}	3000	10^{5-6}
PDE (%)	25	20	20	75	60 – 70	20	20	60
DR ($\frac{\text{MHz}}{\text{cm}^2}$)	$< 10^{-3}$		$< 10^{-3}$			$< 10^{-2}$		10 – 20
SNR (1γ)	10^{2-3}	3×10^{-4}	10^{1-2}	5×10^{-4}	3×10^{-4}	≈ 15	≈ 20	>100
σ_t (ps)	200	1000	10	2000	20	200	50	100
A (cm^2)	< 2000	< 50	< 200	< 5	< 1	50	2.5	1
V_{op}	1.0–1.5 kV	1 kV	2.5 kV	5–40 V	100–500 V	> 10 kV	< 20 kV	50 V
vol/comp	v	v	v/c	c	c	v/c	v	c
sens. 1γ	yes	no	yes	no	no	yes	yes	yes
sens. B	high	low	medium	low	low	medium	low	low
sens. T(*)	med/low	medium	high	low	high	high	low	high/med.
price(*)	high	high	high	low	medium	medium	medium	medium

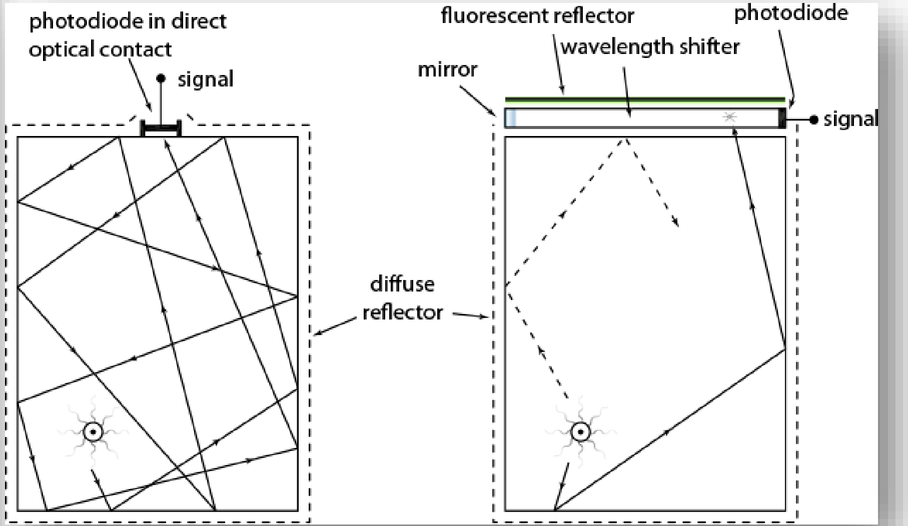
(*) Ratings given are subject to rapid changes, especially for newly developed devices.

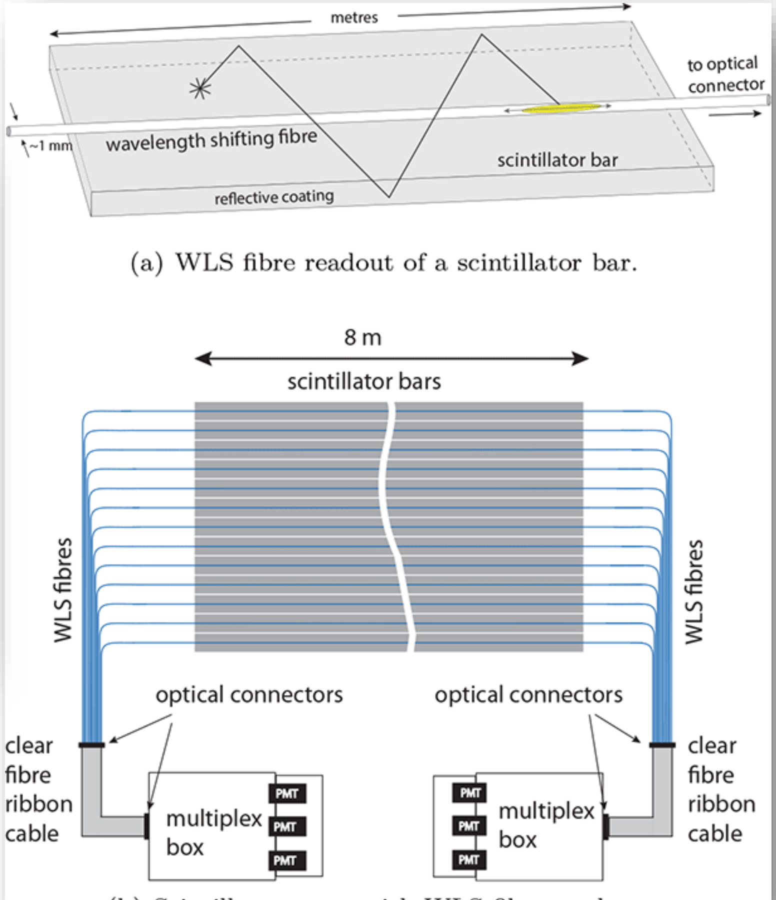
Typical **connection** to scintillators



(a) Scintillator–light guide–PMT system.

(b) Components and complete assembly.





(a) WLS fibre readout of a scintillator bar.

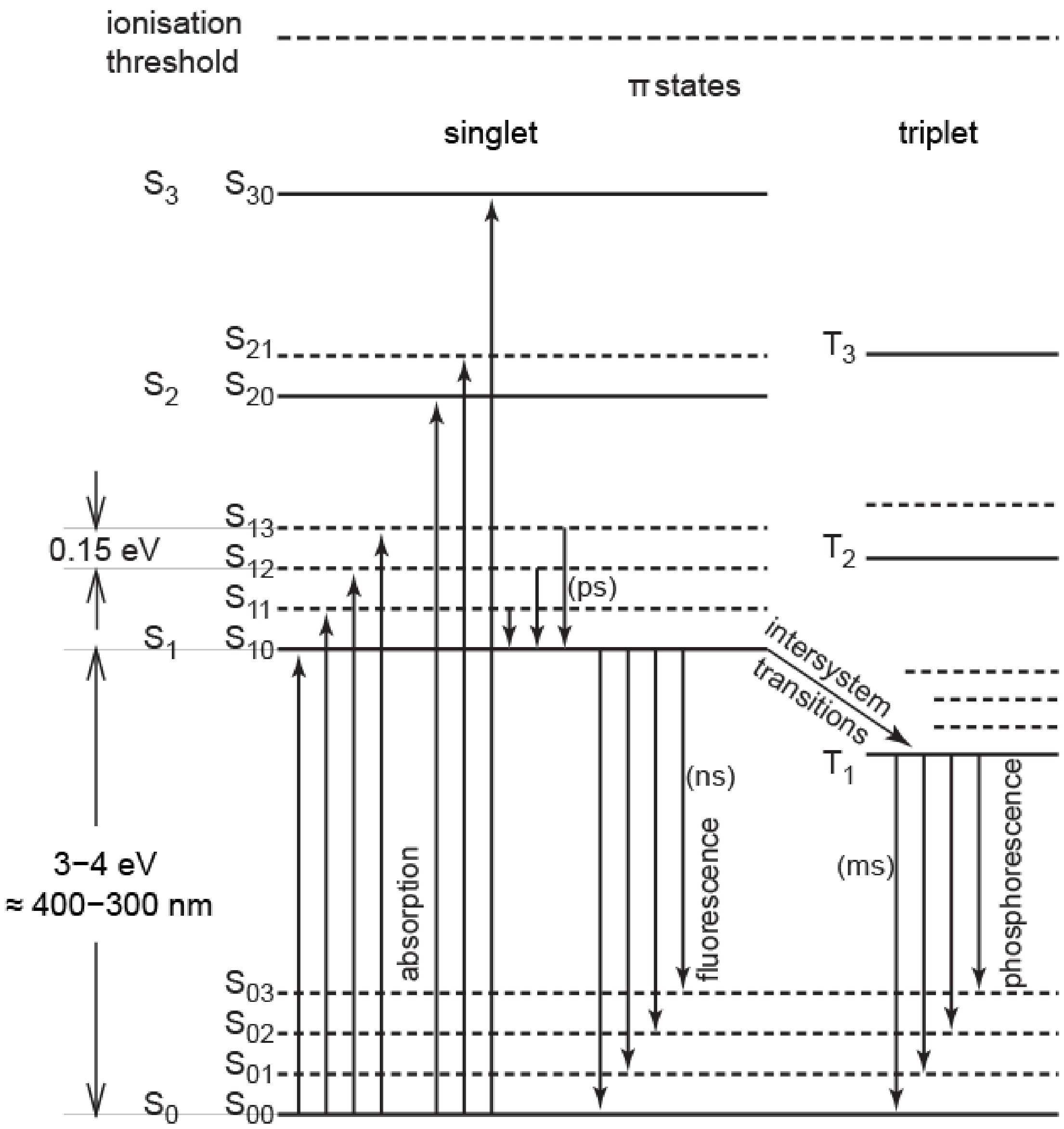
(b) Scintillator array with WLS fibre readout.

Organic scintillators

Aromatic hydrocarbons

Light emission **mechanism**

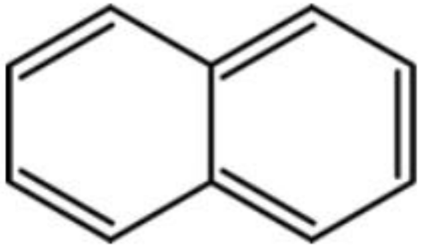
- The process happens at the molecule level
  - *No interactions with neighboring molecules, no need for structure*
  - *Materials can be solid (powder), fluid or gases*
  - *Emission is largely determined by electronic structure of carbon*
- ΔE between levels is 3-4 eV → 400-300nm
  - *Some energy is lost via "radiationless transitions", released via vibrations*
  - *Stokes shift occurs thanks to these losses*
- Transitions typically take place in nanosecond time-scales



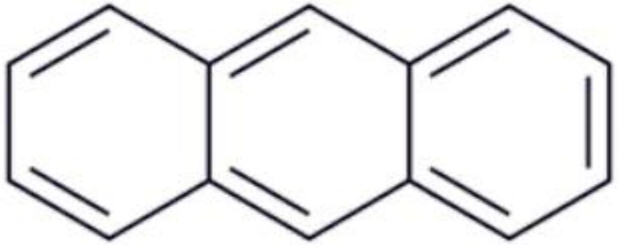
Organic materials - **solids**

- Solid, crystalline form are
  Naphthalene ($C_{10}H_8$)
  Anthracene ($C_{14}H_{10}$)
  Stilbene ($C_{14}H_{12}$)
- Anthracene has the largest yield
  - *Produces 15k photons per MeV*
  - *Sometimes used as the reference for yield*
- They are fragile, limited in size
- Rarely used today

Naphtalene

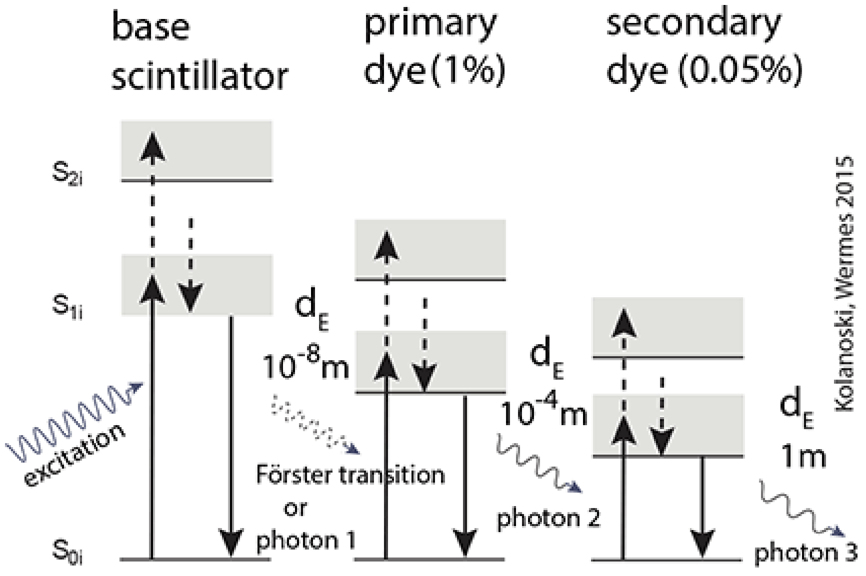


Antracene

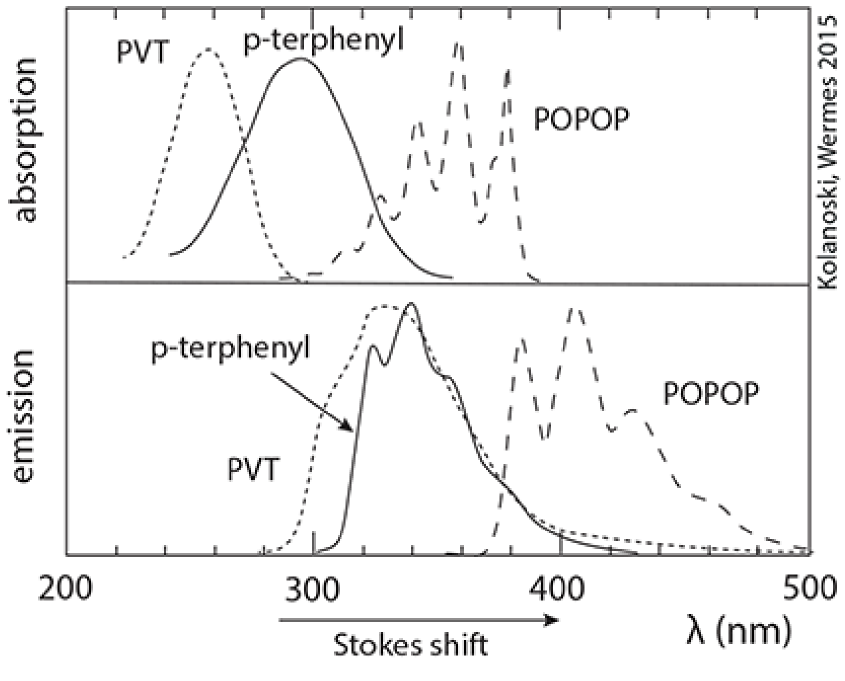


Organic materials - **liquids**

- Dissolved in solvents → liquids or in polymerised form
  - *P-terphenyl* ($C_{18}H_{14}$)*, PBD* ($C_{24}H_{22}N_2O$)*, DPO* ($C_{15}H_{11}NO$)*, POPOP* ($C_{24}H_{16}N_2O_2$)
  - *Solvents usually scintillate by themselves, but with very low yield*
  - *Best is to mix*
- Typical organic scintillator mix
  - *Solvent (aromatic compounds like benzene, xylene)*
  - *High concentration of primary fluor (fluorescence emitter)*
  - *Low concentration of secondary fluor – acts as wavelength shifter*
- High purity standards to avoid unwanted chemicals
  - *Oxygen can quench (reduce) the light output*
  - *Usually operated under dry nitrogen atmosphere*



(a) Wavelength shifting: principle.



(b) Absorption and emission spectra.

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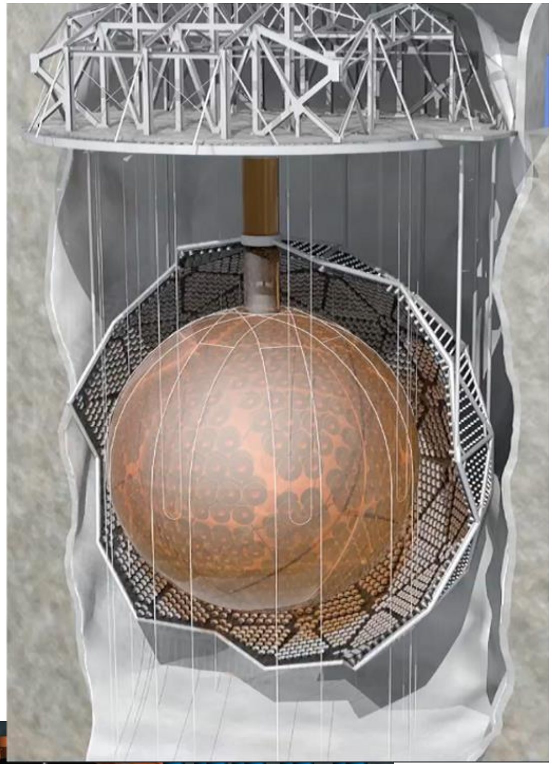
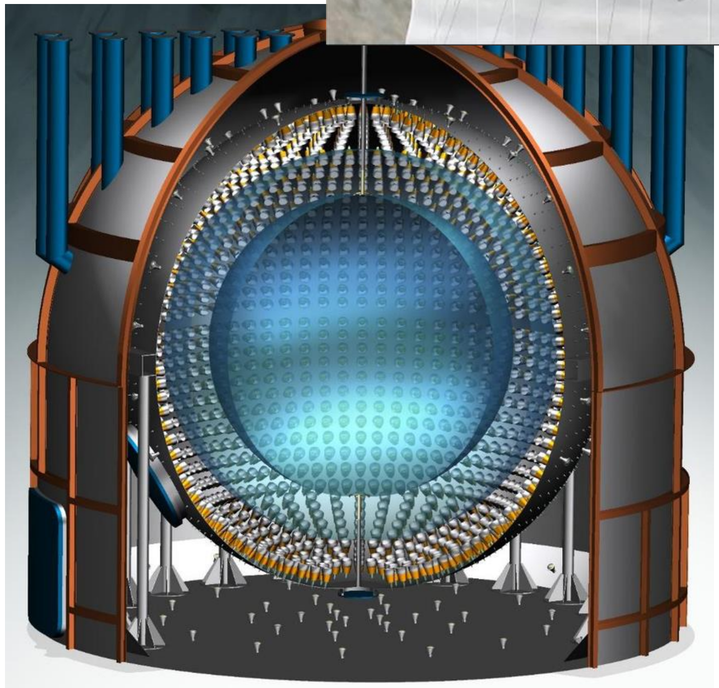
SNO+





Borexino

Plastic scintillators

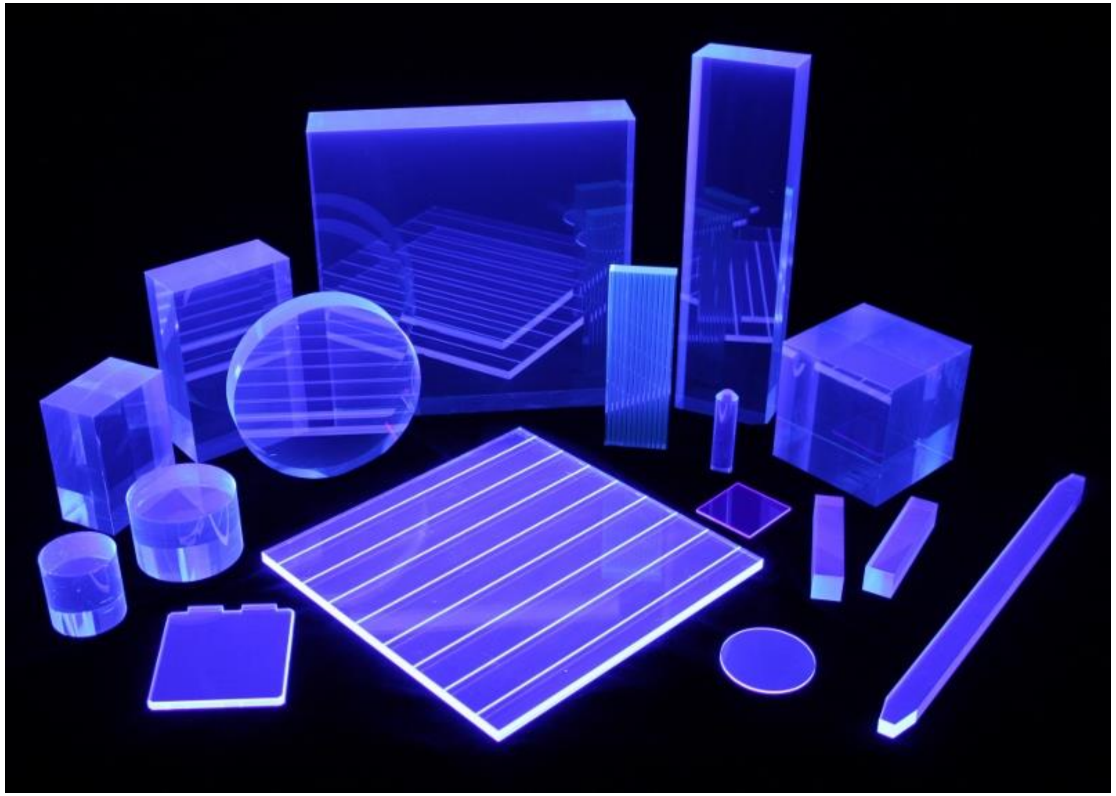
- Polymerized liquid scintillator

  Can be cast into any shape, and they are easy to handle and cheap

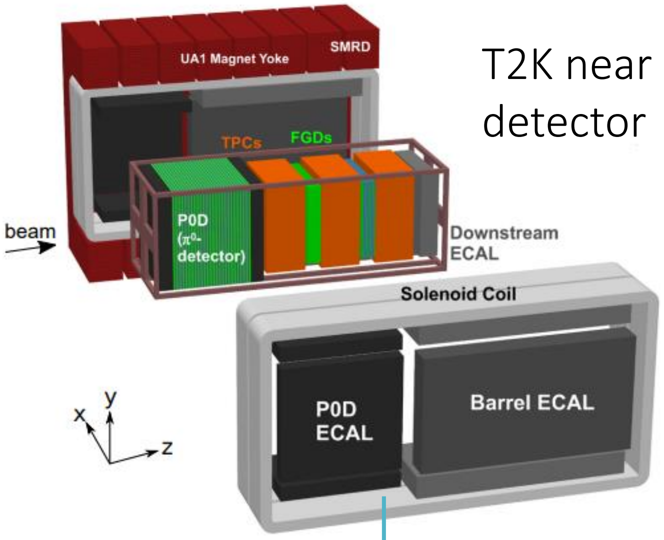
  Well suited for particle and nuclear physics experiments

- Typical solvent/base used are polyvinyl toluene (PVT) or polystyrene (PS)
- Used for charged particles and neutrons
- Disadvantages:

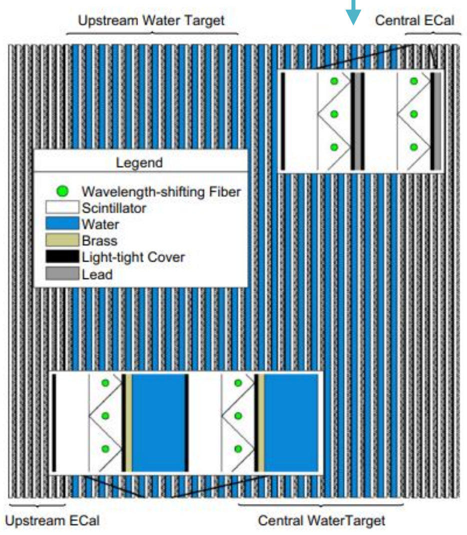
  Light yield can decrease due to ageing, exposure to solvents and greases, high temperatures and ionizing radiation



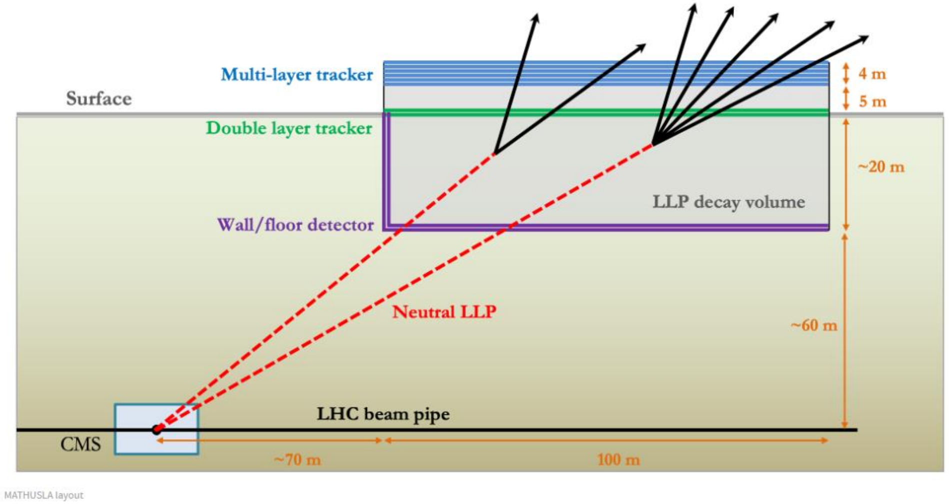
Plastic scintillators



T2K near detector



MATHUSLA proposed layout



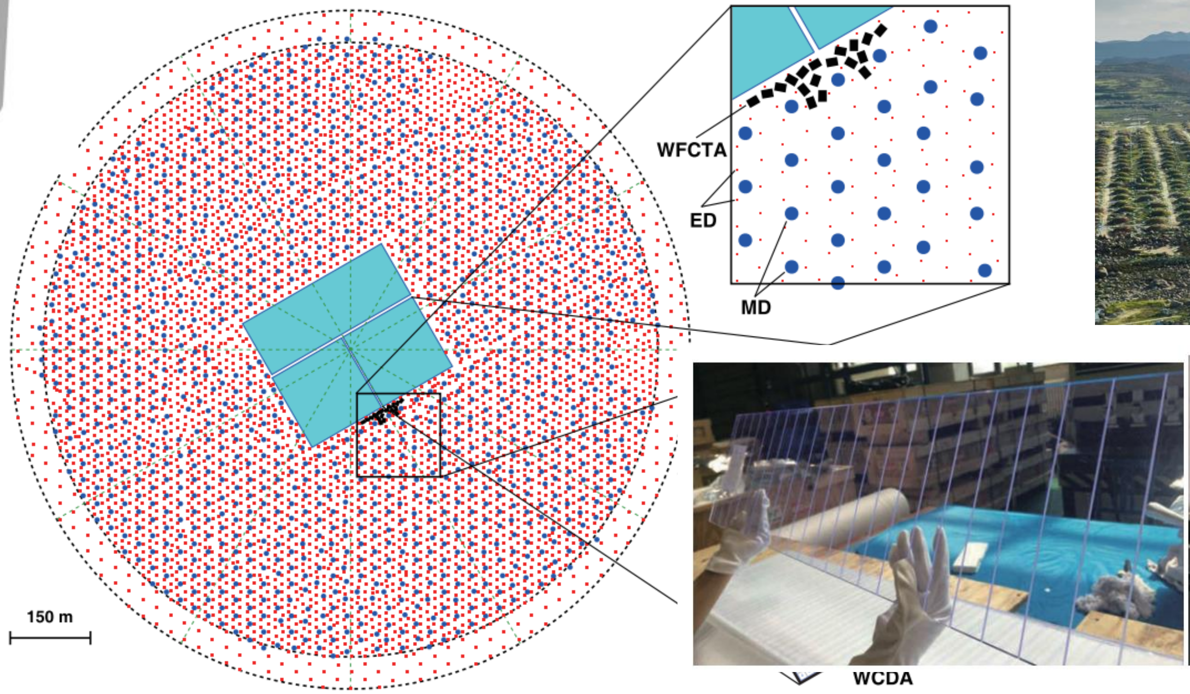
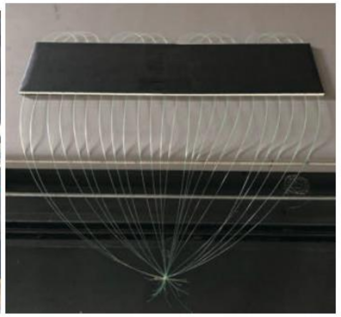


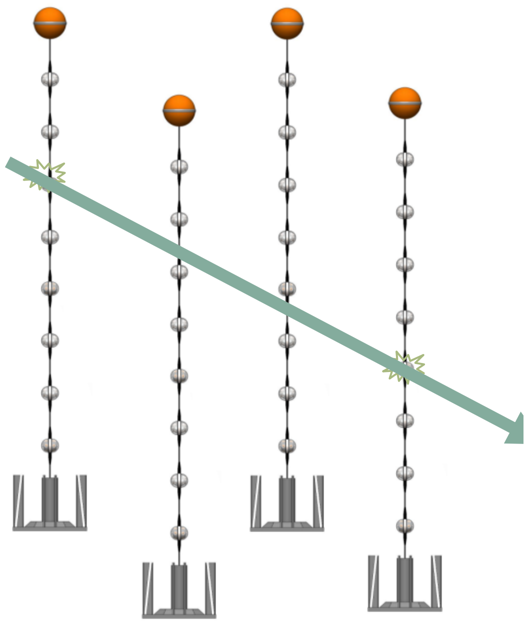
Fig. 1. (color online) Layout of LHAASO.

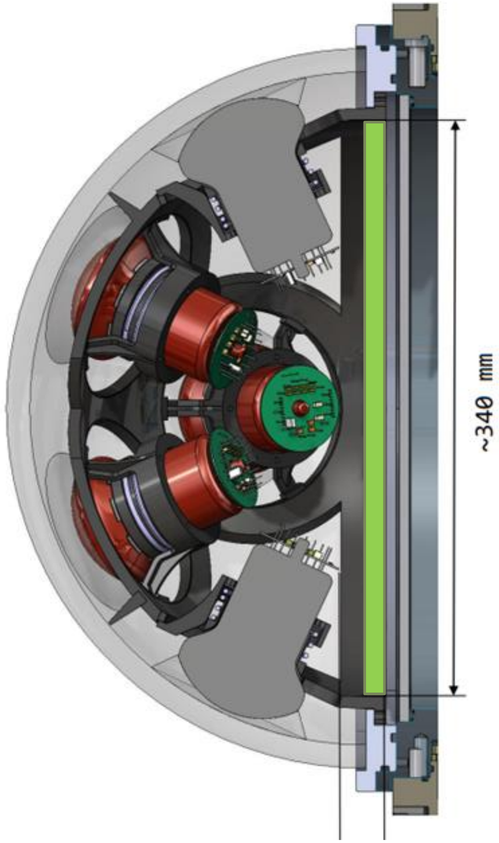


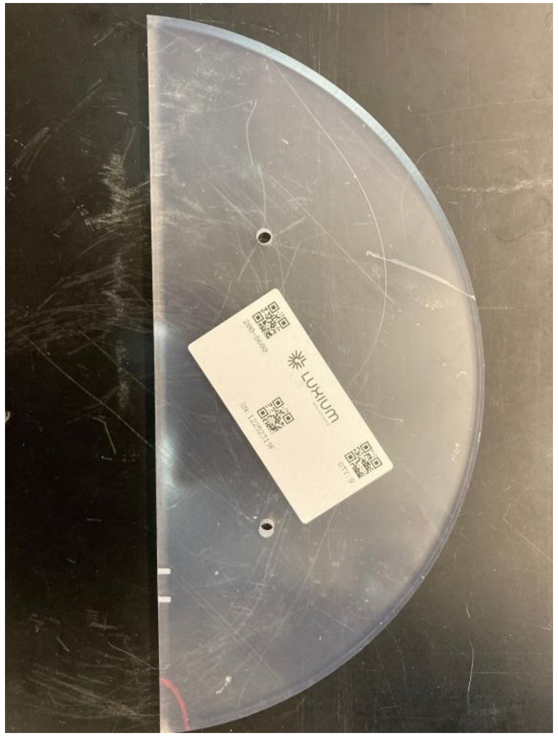
The LHASSO gamma ray detector

Plastic scintillators in P-ONE

- The Pacific Ocean Neutrino Telescope is a project in Canada
- The main photodetection device are PMTs – scintillators as calibration







Light yield

- Determined by Birk's law

$$\frac{dL}{dx} = \frac{S\frac{dE}{dx}}{1 + k_B\frac{dE}{dx}}$$

  S is the scintillation efficiency
  k_B is the quenching strength – ionization saturates

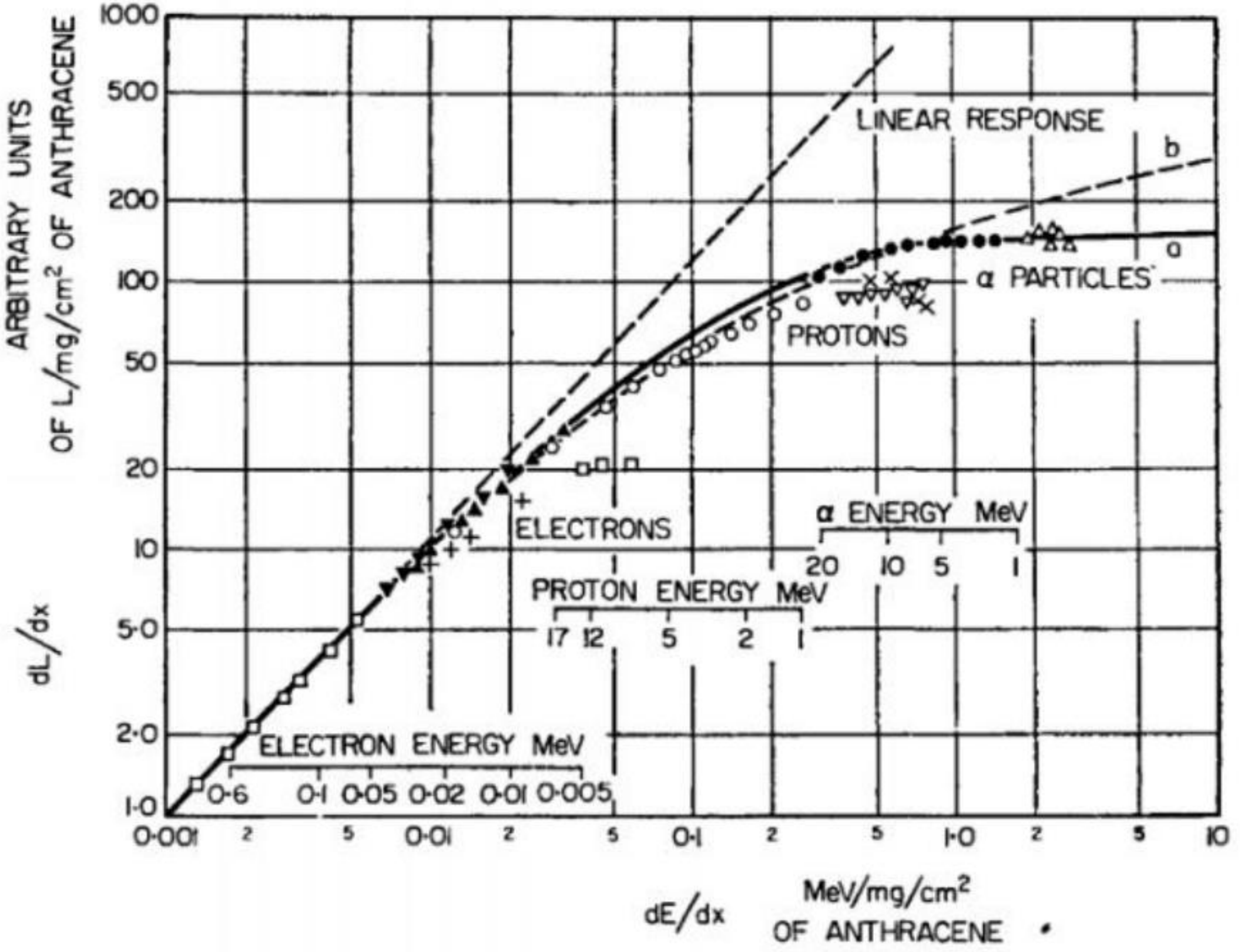
- When energy losses are small with respect to the energy of the particle (e.g. GeV cosmic muon)

$$\frac{dL}{dx} = S\frac{dE}{dx}$$

- For strongly ionizing radiation (e.g. MeV α particle)

$$\frac{dL}{dx} = \frac{S}{k_B}$$

- k_B needs to be determined experimentally



Signal **shape**

- The prompt fluorescence follows an exponential decay. If one wants to describe the rise time, you get

$$I(t) = I_0\, g(t)\, e^{-t/\tau_{dec}}$$

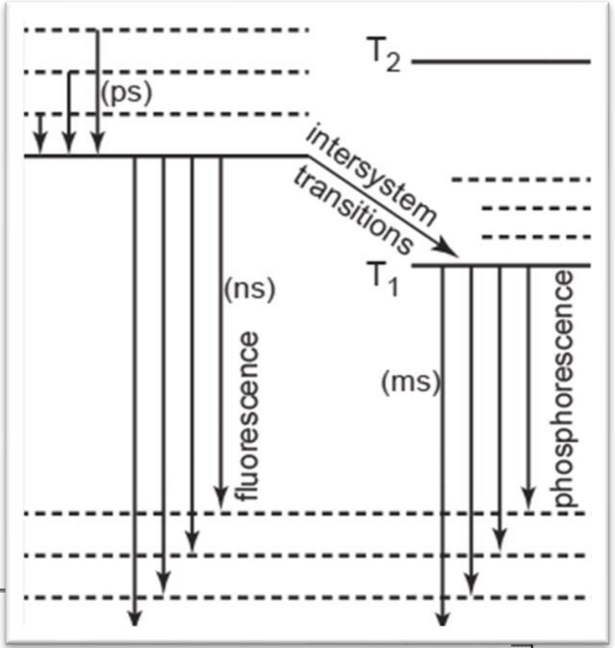
- Many scintillators have a second component with longer decay time

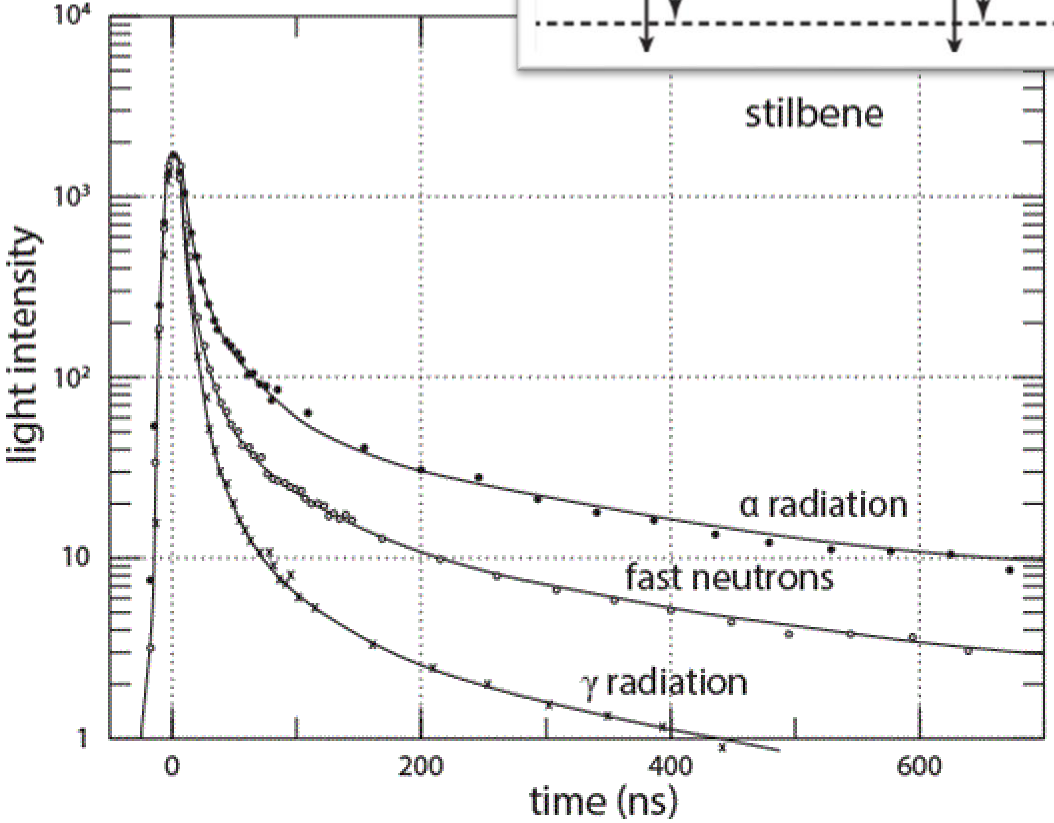
$$I(t) = I_1\, g(t)\, e^{-t/\tau_f} + I_2 e^{-t/\tau_s}$$

- Relative contribution of I_1, I_2 can depend on the ionization density of the incident particles (p, α, n, γ)

    Effect is exploited to distinguish particles

    "Pulse shape discrimination"



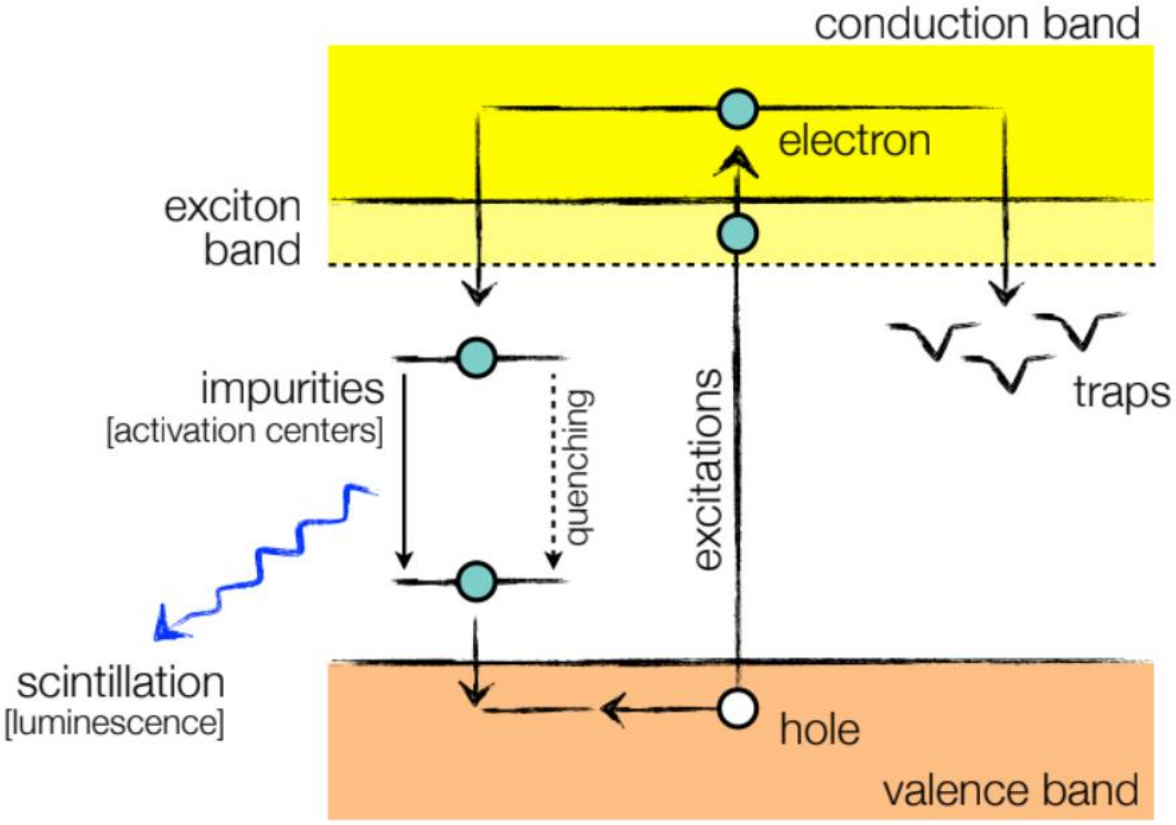


Inorganic scintillators

Inorganic scintillators - **mechanisms**

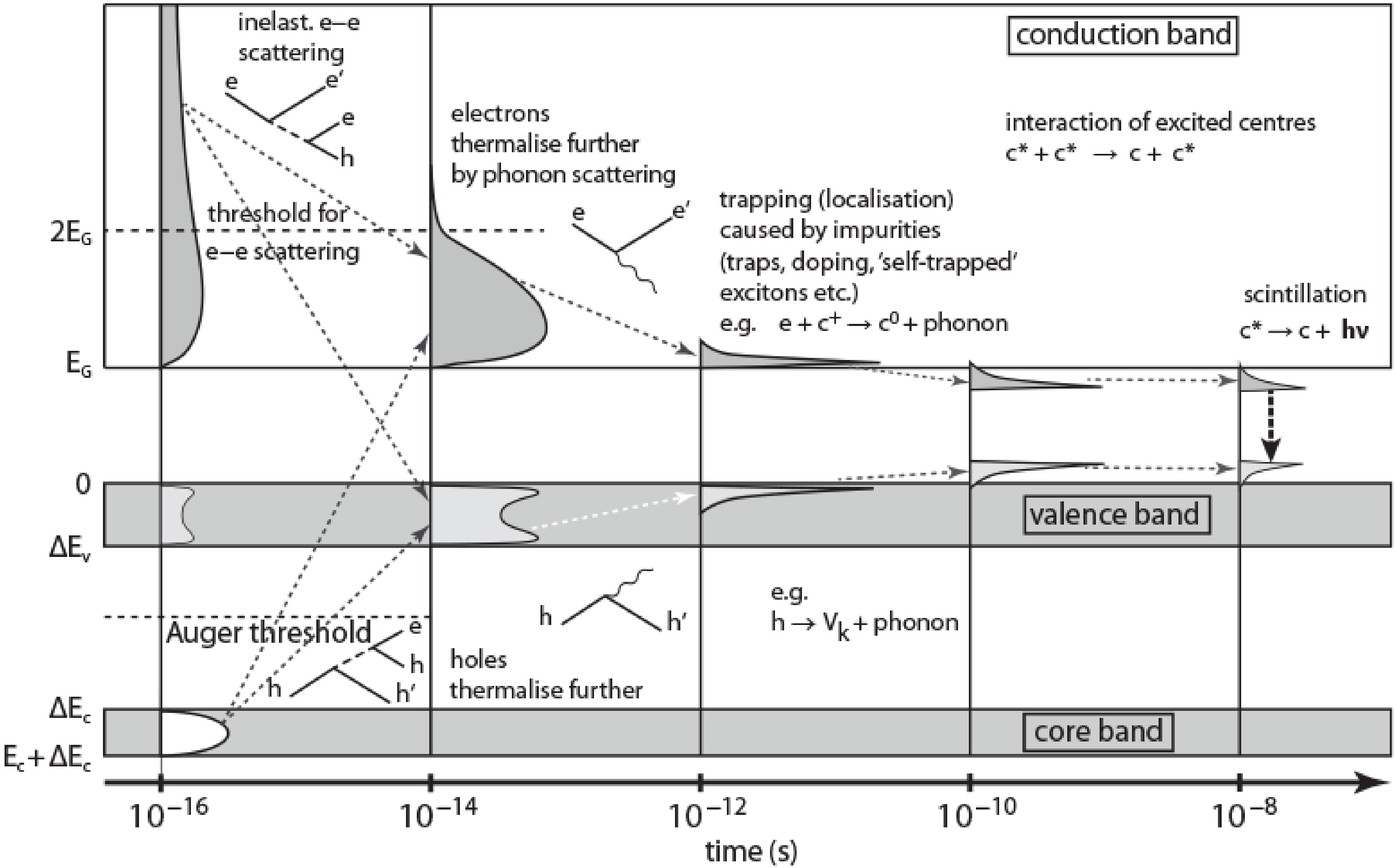
- Scintillation mechanism rests on the lattice structure of crystals
  - *Depends on the band structure created*
  - *Requires energy levels created by impurities in the band gap (aka luminescence centers)*

- General idea
  - *Energy deposition → e's to conduction band*
  - *Electron is free to move*
  - *Captured by luminescence center*
  - *Light emitted by de-excitation*

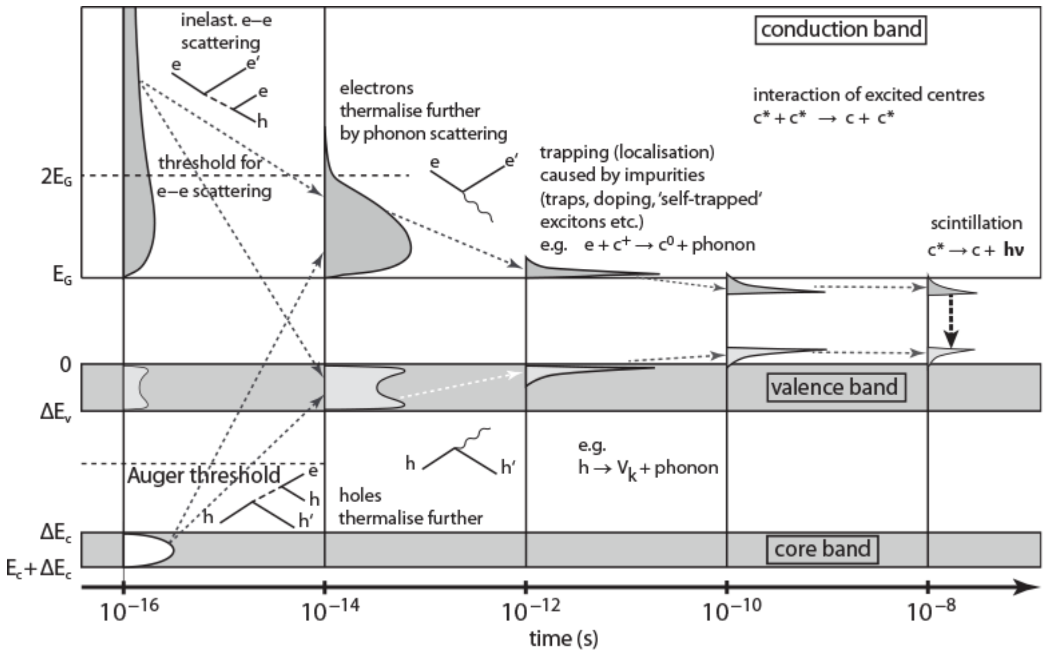


Inorganic scintillators - **mechanisms**

- Evolution



Signal **shape** in crystals



- Multiple processes with different time constants play a role
  - *(i) Time span for generation of electrons and holes* ($\tau_1 = 10^{-18} - 10^{-9}$ s)
  - *(ii) Thermalization/cooling process through lattice interactions* ($\tau_2 = 10^{-16} - 10^{-12}$ s)
  - *(iii) Transfer time for electrons and holes to reach a luminescence center* ($\tau_3 = 10^{-12} - 10^{-8}$ s)
  - *(iv) Decay time of the luminescence center* ($\tau_4 > 10^{-10}$ s)

- Interaction between luminescence centers mean simple exponentials won't do
  - *Approximation of decay time requires sum of multiple exponential functions*
  - *This problem does not exist in organics because there are no particle interactions*

Light yield

- Light yield depends on absorbed energy E_{abs} and average energy required to produce an electron-hole pair $w_{e/h}$

$$L = \frac{E_{abs}}{w_{e/h}} S\, Q$$

S is the energy transfer efficiency from thermalized pairs to luminescence centers

Q is the quantum yield of the luminescence center

- Maximum theoretical yield is estimated to be 140 000 photons / MeV

See Lecoq, P. et al.: Inorganic Scintillators for Detector Systems: Physical Principles and Crystal Engineering. Springer, 2006

Scintillation crystals **comparison**

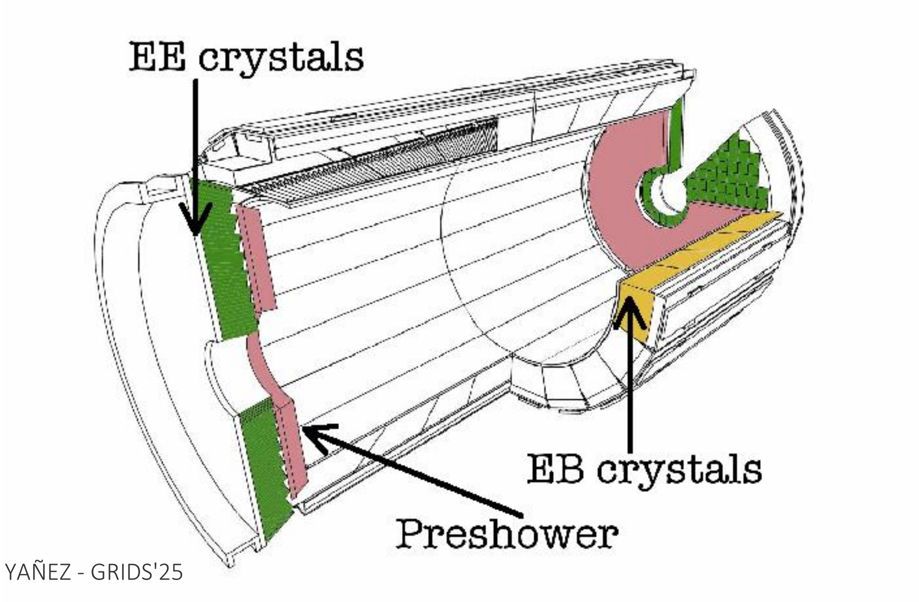
Material	ρ (g/cm^3)	X_0 (cm)	λ_{max} (nm)	Photons per MeV	τ_{dec} (ns)
plast. scint.	1.03	42.5	423	10 000	≈2
NaI(Tl)	3.67	2.59	410	43 000	245
CsI(Tl)	4.51	1.86	550	52 000	1220
BaF_2	4.89	2.03	220	1 430	0.8
			310	9 950	620
$LaBr_3$(Ce)	5.29	1.88	356	61 000	17–35
CeF_3	6.16	1.77	330	4 500	30
GSO	6.71	1.38	430	9 000	56
BGO	7.13	1.12	480	8 200	300
LYSO(Ce)	7.10	1.14	420	33 000	40
LSO(Ce)	7.40	1.14	402	27 000	41
$PbWO_4$	8.30	0.89	425	130	30

- ρ – density
- X_0 – radiation length
- λ_{max} – wavelength at maximum of emission spectrum
- τ_{dec} – decay constant

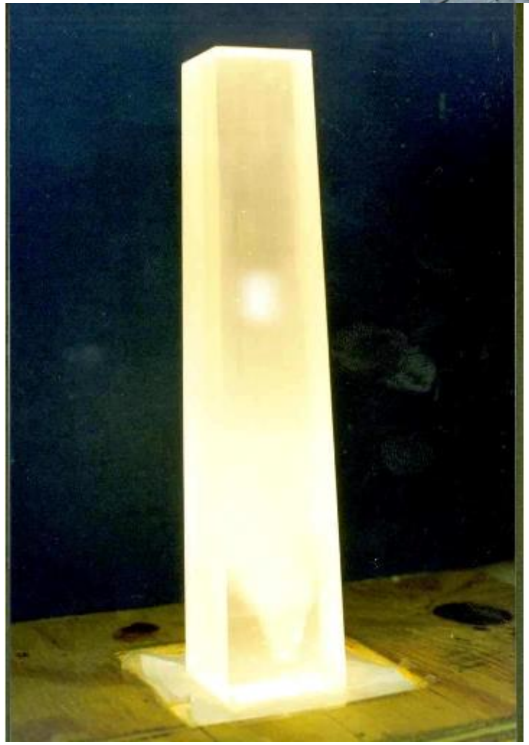
- High density and short radiation lengths make it easy to efficiently absorb the energy of particle showers
- Higher light yield than organics
- Much longer decay time than organic scintillators

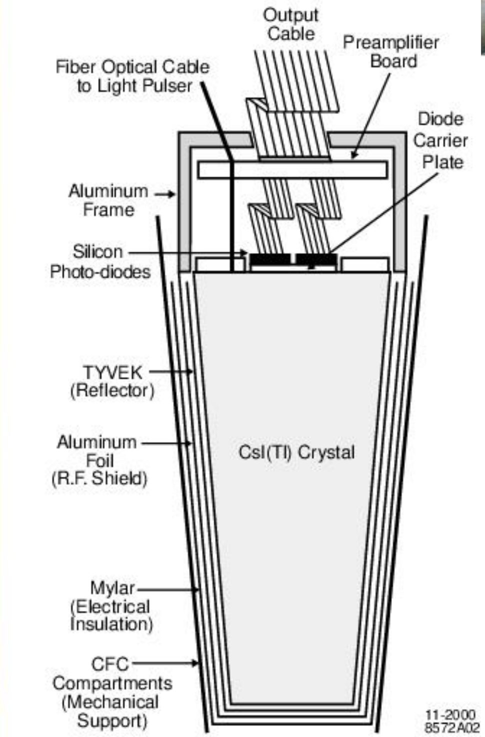
Scintillation crystals in **use**

CMS crystal calorimeter

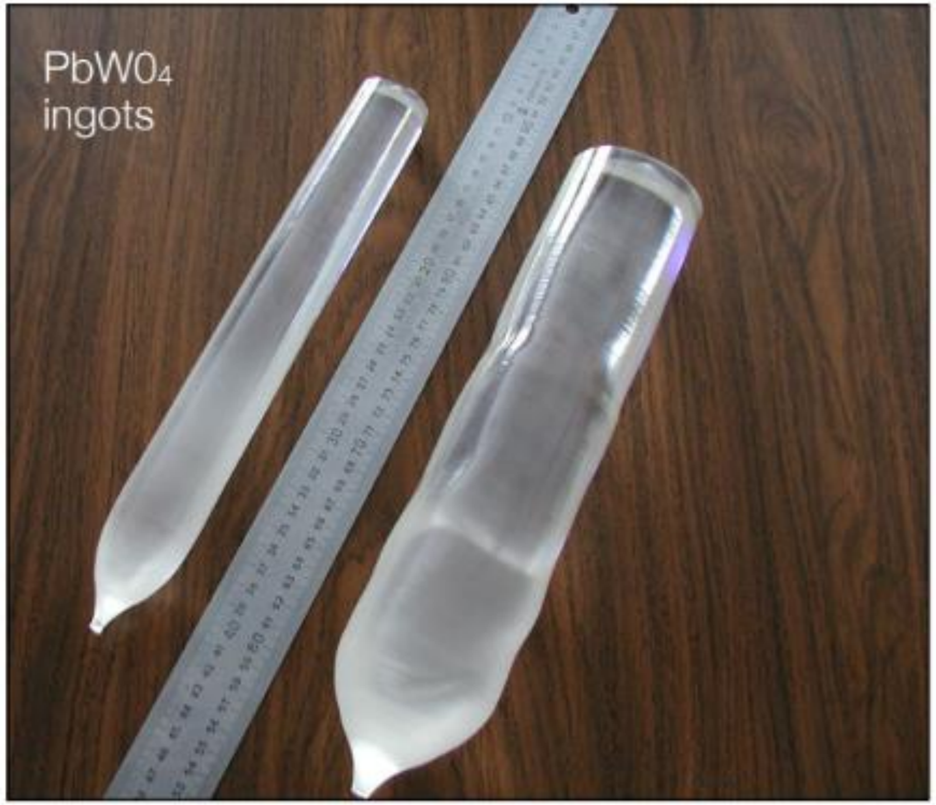


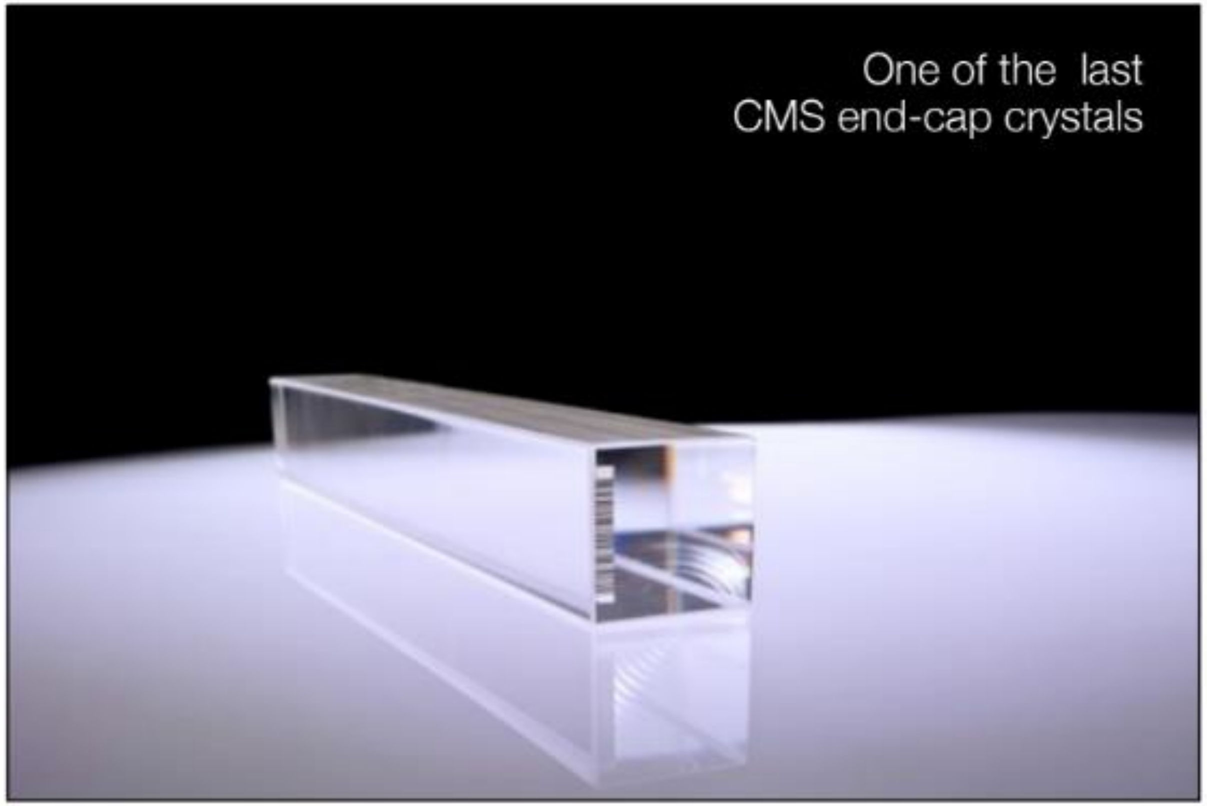
BaBaR calorimeter





Example CMS
Electromagnetic Calorimeter

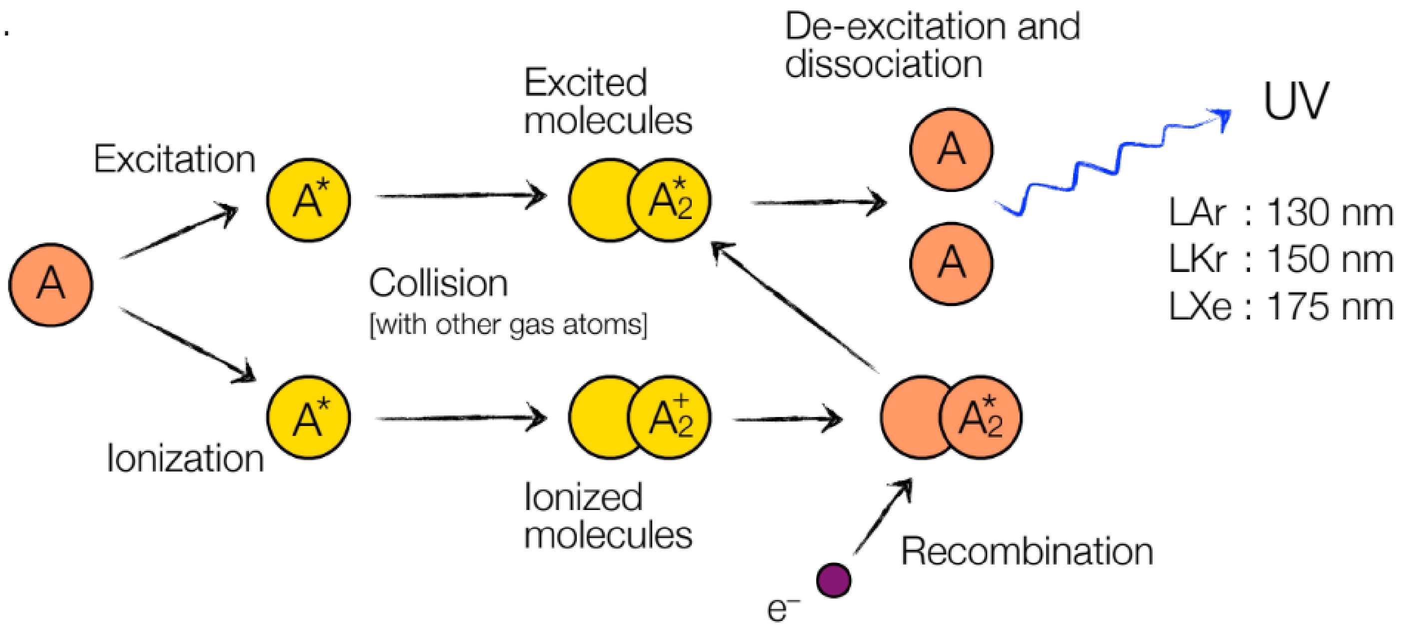


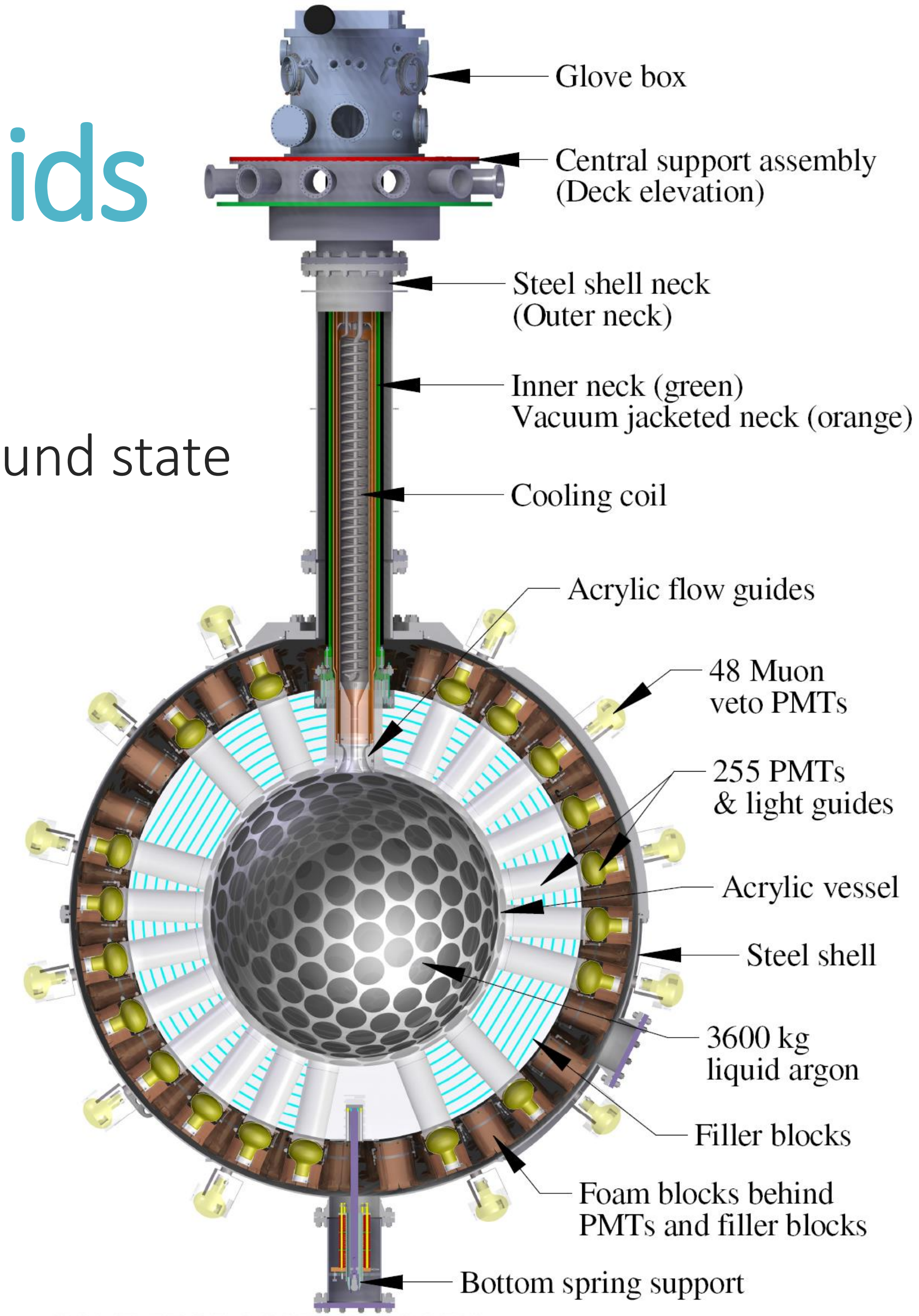


Scintillation in **gases** and **liquids**

- High-purity inert gasses can scintillate
- Light emission comes from decay of excited dimers to ground state
  Direct excitation or electron-ion recombination
- Light is deep in the UV, requires wavelength shifters

…





Schematic of DEAP

Comparison

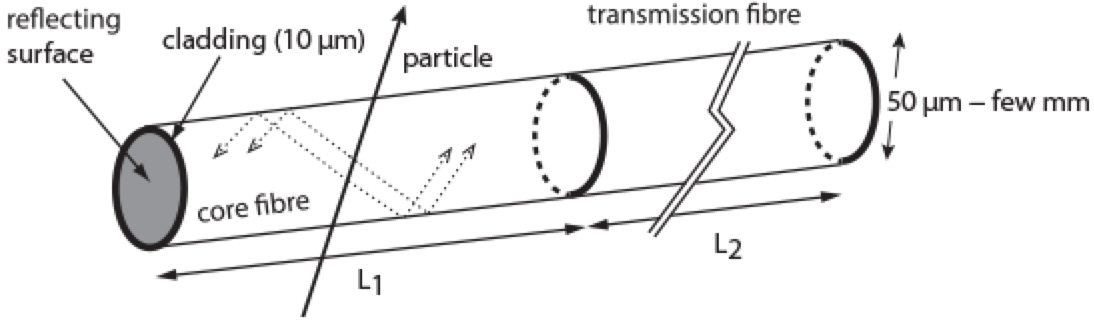
- Very fast (ns)
- Wide range of light yields, can reach that of crystals
- Light in deep UV
- Very low densities

Gas/liquid	Z	Boiling point at 1 bar (K)	ρ (liquid) (g/cm^3)	λ^{em}_{peak} (nm)	Photons per MeV	τ_{dec} (typ.) (ns)
gases (1 atm, 20 °C)						
N_2	7	77	1.17×10^{-3}	390	100	2.5
CF_4	8.6	145.3	3.93×10^{-3}	300/630	1200	6
Helium	2	4.2	1.66×10^{-4}	78	1100	<20
Neon	10	27.1	8.39×10^{-4}	~80		1.2
Argon	18	87.3	1.66×10^{-3}	127	18 200	6
liquids						
Helium	2	4.2	0.13	80	15 000	10
Neon	10	27.1	1.21	78	30 000	15
Argon	18	87.3	1.40	127	40 000	6
Krypton	36	119.8	2.41	147	25 000	3
Xenon	54	165.0	3.06	175	46 000	3
solid (for reference)						
NaI(Tl)	46.5		3.67	410	43 000	245

Scintillating **fibers**

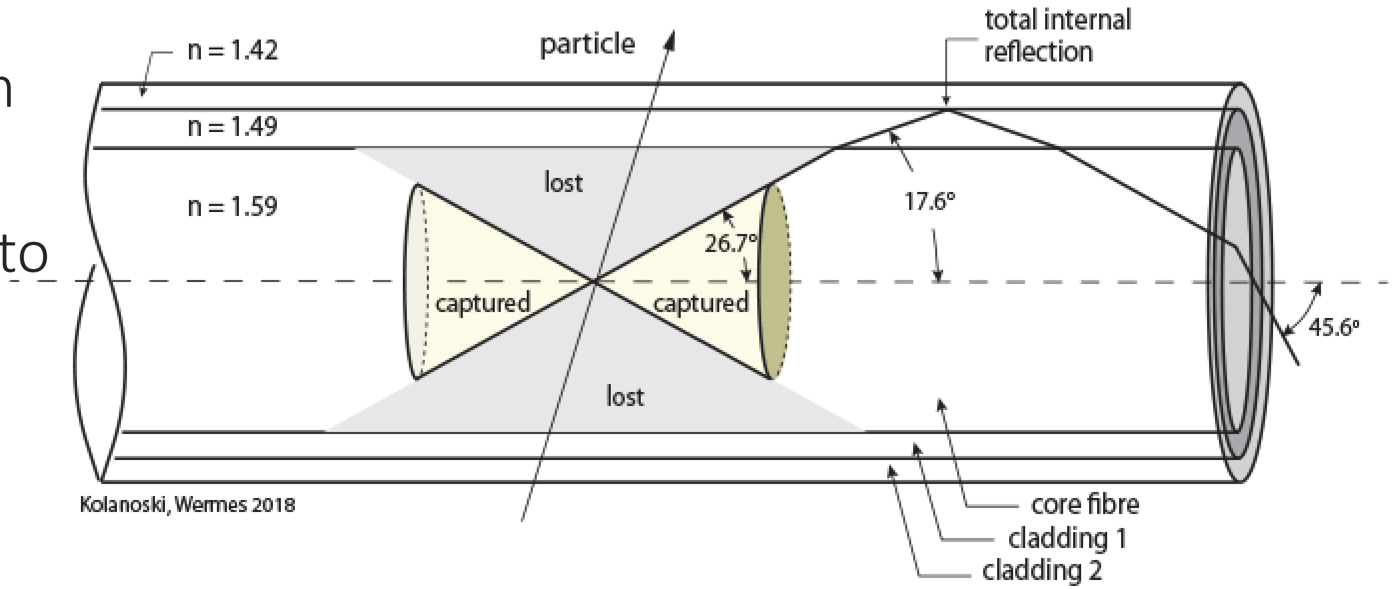
Scintillators as **fibers**

- Fibers can be made of scintillating glasses, plastic scintillators or by filling a capillary with liquid scintillator
- A transmission fiber can be coupled to transport the light produced to a sensor



(a) Fibre geometry.

- Adjacent fibers can have cross-talk from the light produced in the first process
- Organic materials are preferred: easier to produce and robust

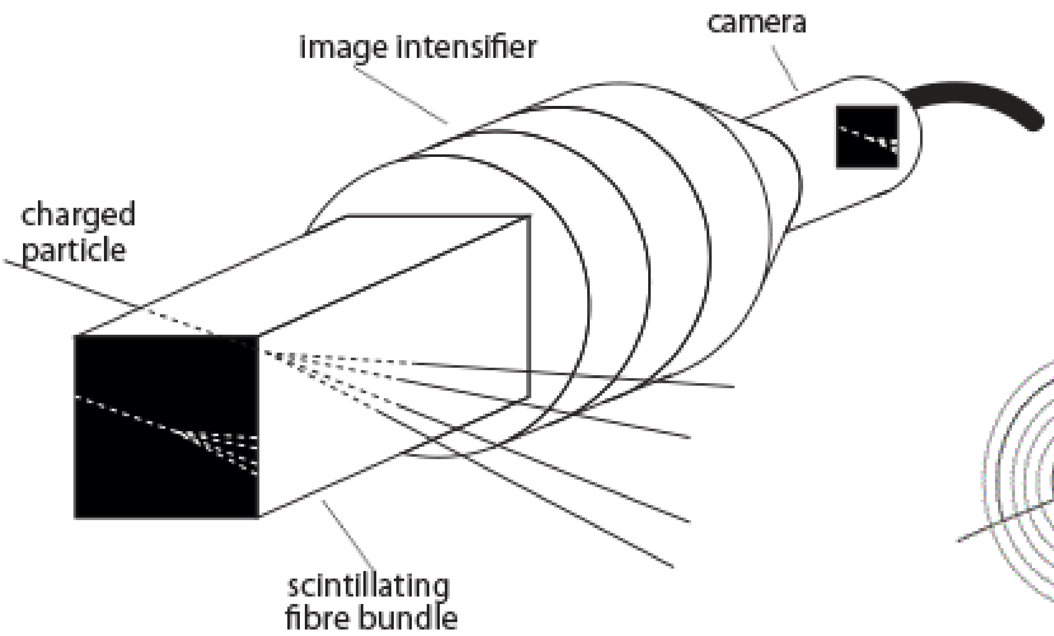


Kolanoski, Wermes 2018

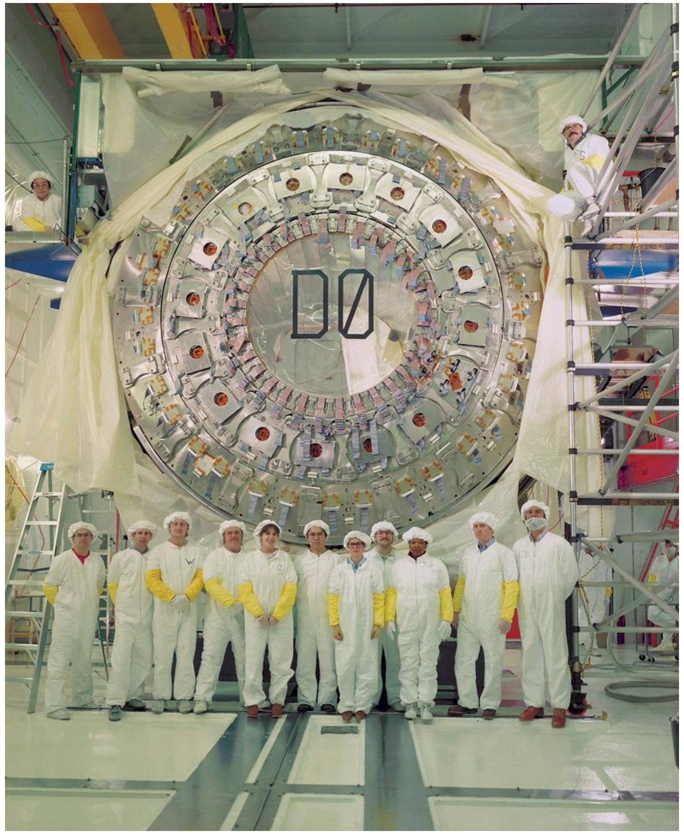
Scintillating fiber **detectors**

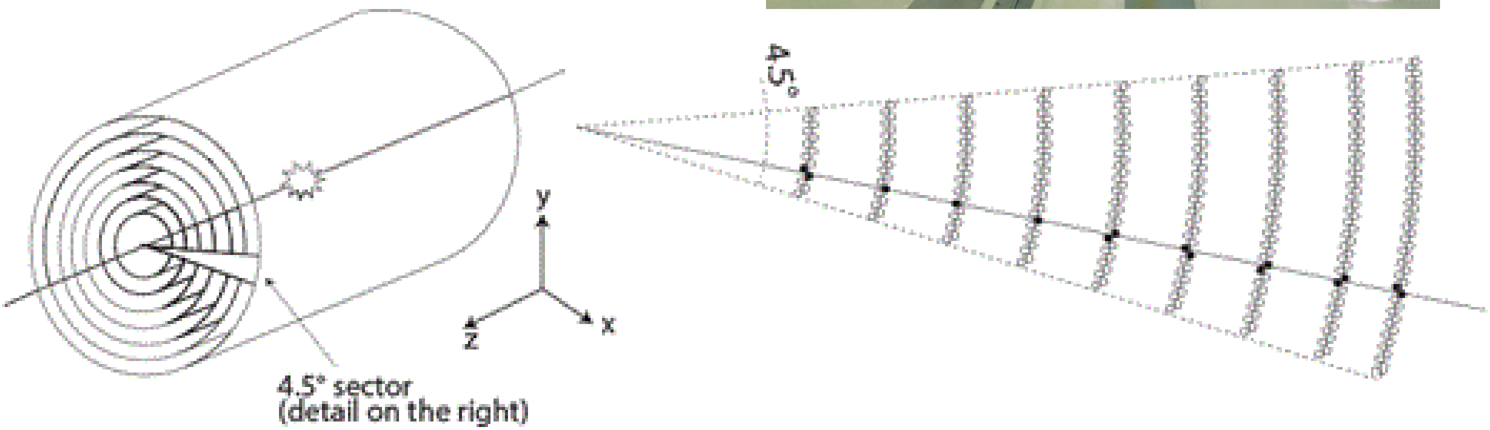
- Typical configuration

Tracking with fiber bundles



Fibers in the D0 detector





Summary

Summary

❖ Nature likes emitting light. Three scintillation mechanisms useful for particle detection.

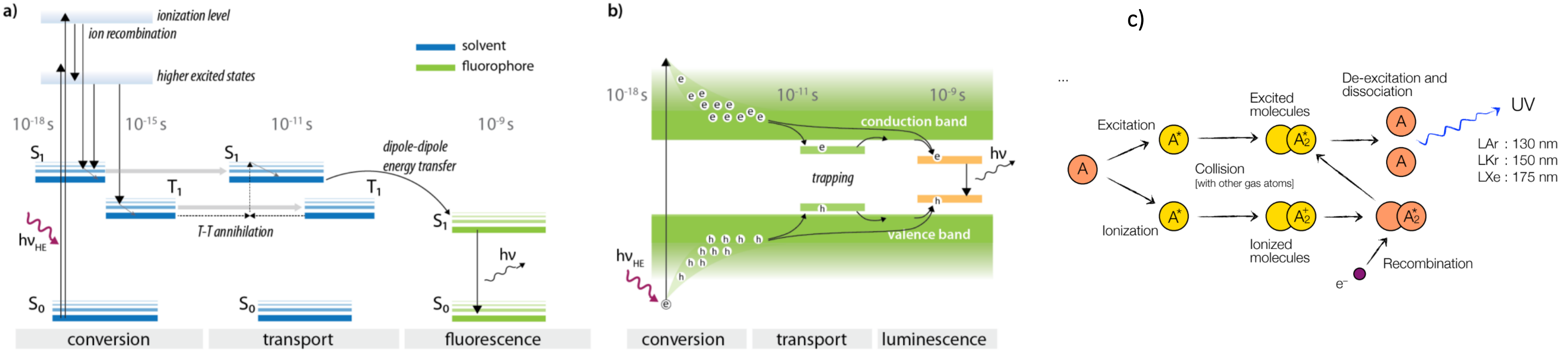


Figure 9. Typical processes of scintillation in **a)** organic and **b)** inorganic scintillators. The time scales over which these processes occur are also shown, indicating excellent temporal resolution. Figure b) was adapted from Nikl et al[82]

Frontiers in Physics, 8, 328, 2020

Summary

❖ Nature likes emitting light.

❖ Organic scintillators are very versatile

Polymerized (plastics) excel in ease of use

Fast response

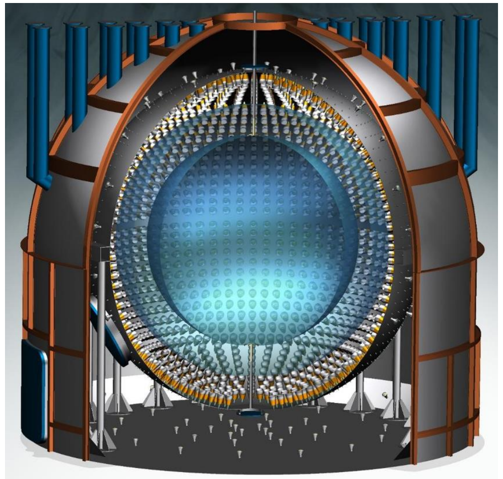
❖ Inorganic crystals are great calorimeters

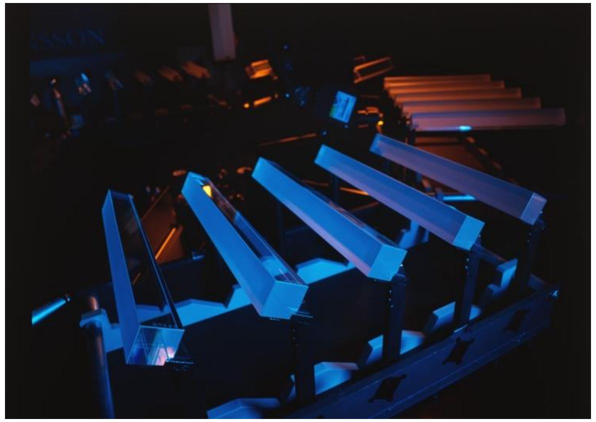
Dense and high light yields

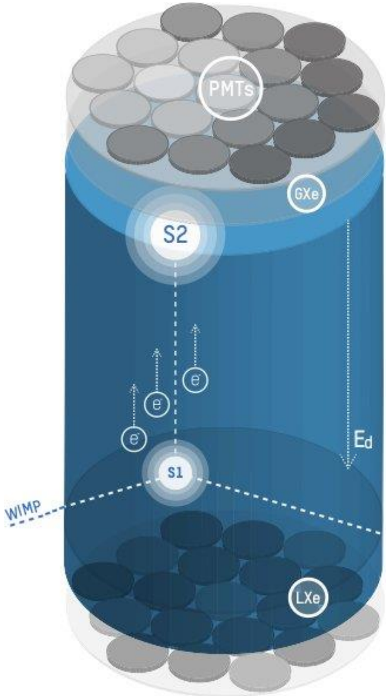
Can withstand some level of radiation

❖ Inert gases can be highly pure

Light is deep UV, but can be shifted for detection







Summary

- Nature likes emitting light.

- Organic scintillators are very versatile
  - *Polymerized (plastics) excel in ease of use*
  - *Fast response*

- Inorganic crystals are great calorimeters
  - *Dense and high light yields*
  - *Can withstand some level of radiation*

- Inert gases can be highly pure
  - *Light is deep UV, but can be shifted for detection*

- Electronic photodetectors used to collect scintillation light

- PMTs, APDs or SiPMs are commonly used

- Need to match the scintillator emission and the environment

- Combination of scintillators+photodetector work as the main detection mechanism or auxiliary systems

Backup

Organic scintillators – Light emission

- From [Chem LibreTexts]

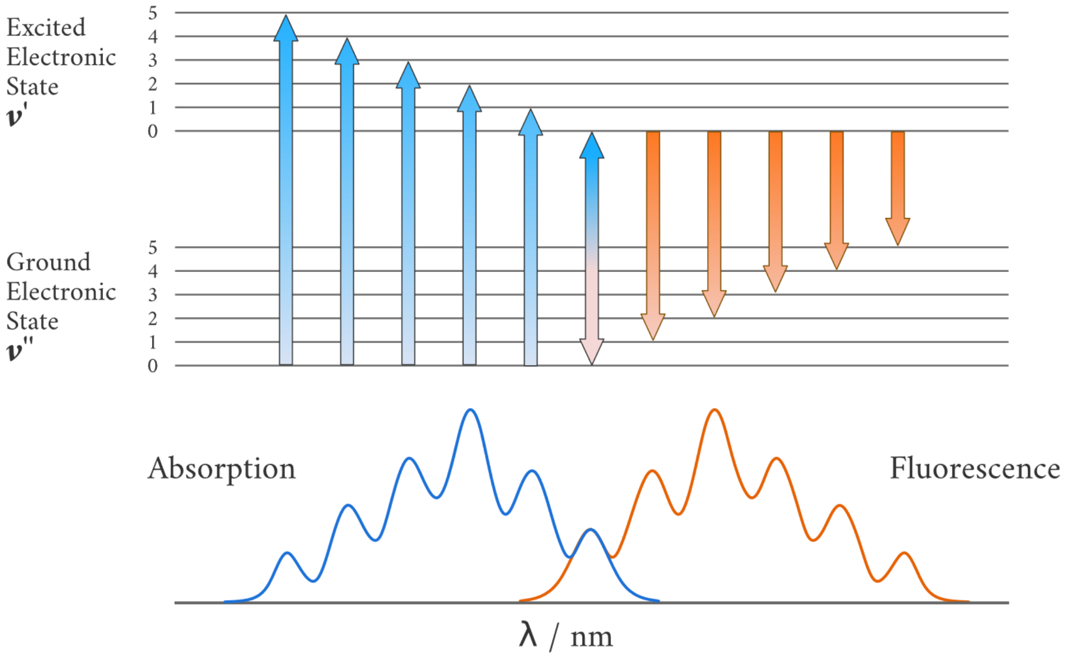


Figure 15.1.615.1.6 shows the fluorescence transitions of a hypothetical diatomic molecule in which the equilibrium bond length of the ground state and the first singlet excited state are identical. In this molecule all absorptions involve transitions from the lowest vibrational level of the electronic ground state (v″=0$v''=0$) to various vibrational levels in the excited electronic state. Because vibrational relaxation occurs more rapidly than fluorescence, the fluorescence spectrum is composed of lines showing transitions from the lowest vibrational level of the excited state (v′=0$v'=0$) to various vibrational levels in the electronic ground state.

Photon energy measurements

- Inorganic crystal scintillators for gammas from 10keV to 100 GeV

  Emission mechanism depends on energy, from photoeffect, Compton scattering and pair production playing a role

- Spectra will depend on the processes that take place

- Totally absorbing detectors have E resolution limited by photon statistics

$$\frac{\sigma_E}{E} \propto \frac{1}{\sqrt{N_\gamma}} \propto \frac{1}{\sqrt{E}}$$

- For BGO, intrinsic resolution (L3 experiment): $\frac{2\%}{\sqrt{E/GeV}}$