Scintillation Detectors - Basic Introduction

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IEEE NPSS Rabat EduCom International Summer School, July 1-10, 2024

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- Experimental part:

  Charge-exchange reactions → Measurement of the Gamow-Teller transition strength in different nuclear reactions at RCNP (Osaka University, Japan).

  Beta beams → R&D of target materials for the production of ^{6}He and ^{18}Ne beta beams for the “Beta beam neutrino oscillation facility” at ISOLDE (CERN, Switzerland).

- Theory:

  Calculations→ Relic neutrino capture rates; β and ββ decay at FMPI CU and during research stays at University of Tuebingen / JINR Dubna

- Postdoc position at Institute of Experimental and Applied Physics, Czech Technical University in Prague, Czech Republic
  - Experimental physicist, leading the Neutrino & Underground Laboratory LSM group

- Postdoc position at Institute of Experimental and Applied Physics, Czech Technical University in Prague, Czech Republic
  - Experimental physicist, leading the Neutrino & Underground Laboratory LSM group

- Research fields

  Neutrino physics → Double beta decay experiments; Neutrino oscillations, Reactor antineutrinos.

  Plastic scintillators → R&D and application of plastic scintillators in different experiments.

  Hadronic physics → R&D of Forward Spectator Detector within future CBM (Compressed Baryonic Matter) experiment (FAIR, GSI Darmstadt, Germany).

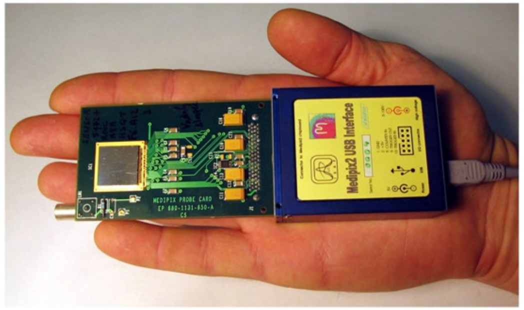
  New technologies for underground experiments at LSM (Modane, France) → Sensitive radon detectors; Radon free ISO5 clean room; Anti-radon facility.

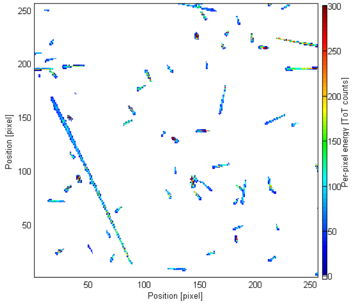
- Collaborations
  - NEMO-3/SuperNEMO (Neutrino Ettore Majorana Observatory) → Searching for neutrinoless ββ (0νββ) decay with ^{82}Se
  - LEGEND (Large Enriched Germanium Experiment for Neutrinoless ββ Decay) → Searching for 0νββ decay with ^{76}Ge
  - COBRA (Cadmium Zinc Telluride 0-Neutrino Double-Beta Research Apparatus) → Searching for 0νββ decay with CdZnTe
  - CERN – Neutrino platform: NP03 project (platform for Developing Neutrino Detectors) → Cosmic Ray Tagger for ICARUS

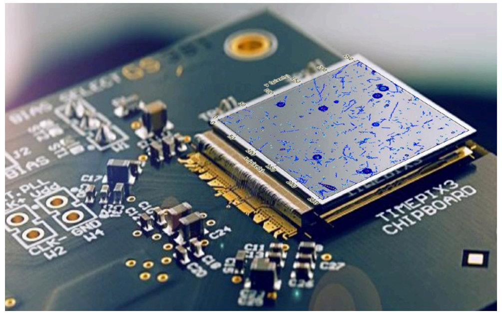
- Conferences
  - ANIMMA (Advancements in Nuclear Instrumentation Measurement Methods and Applications) - deputy general chair
  - MEDEX (Matrix Elements for the Double beta decay EXperiment) - organizing committee chair

Institute of Experimental and Applied Physics, CTU in Prague (www.utef.cvut.cz)

- founded in 2002 as the experimental unit of the CTU for fundamental and applied research

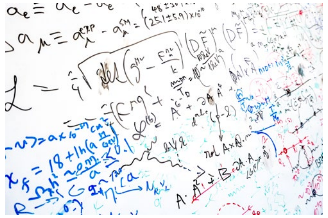


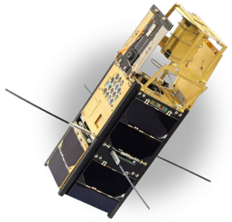


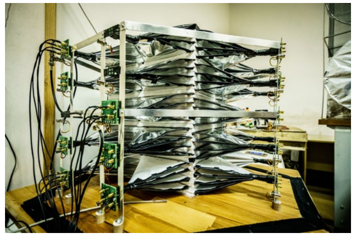


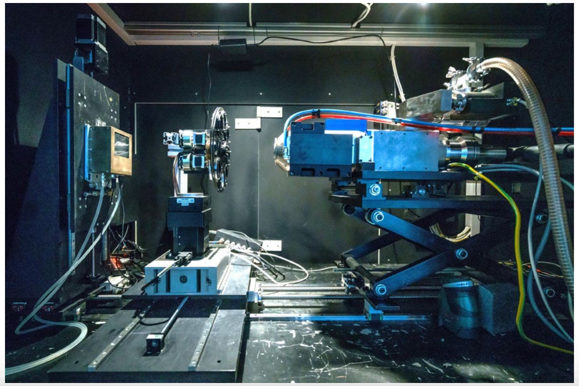
Research fields:

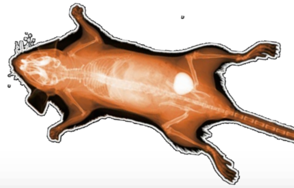
- R&D of semiconductor pixel detectors (Timepix type)
- Accelerator particle physics (Van de Graaff accelerator)
- Neutrino physics – 0νββ, reactor ν, cosmic ν, ν oscillations
- Astroparticle physics – dark matter, cosmic rays
- Applied nuclear spectroscopy
- Applications in biology, medicine, material sciences
- Theory and phenomenology in high energy physics
- Outreach and education → MX-10 particle camera + book of exercises











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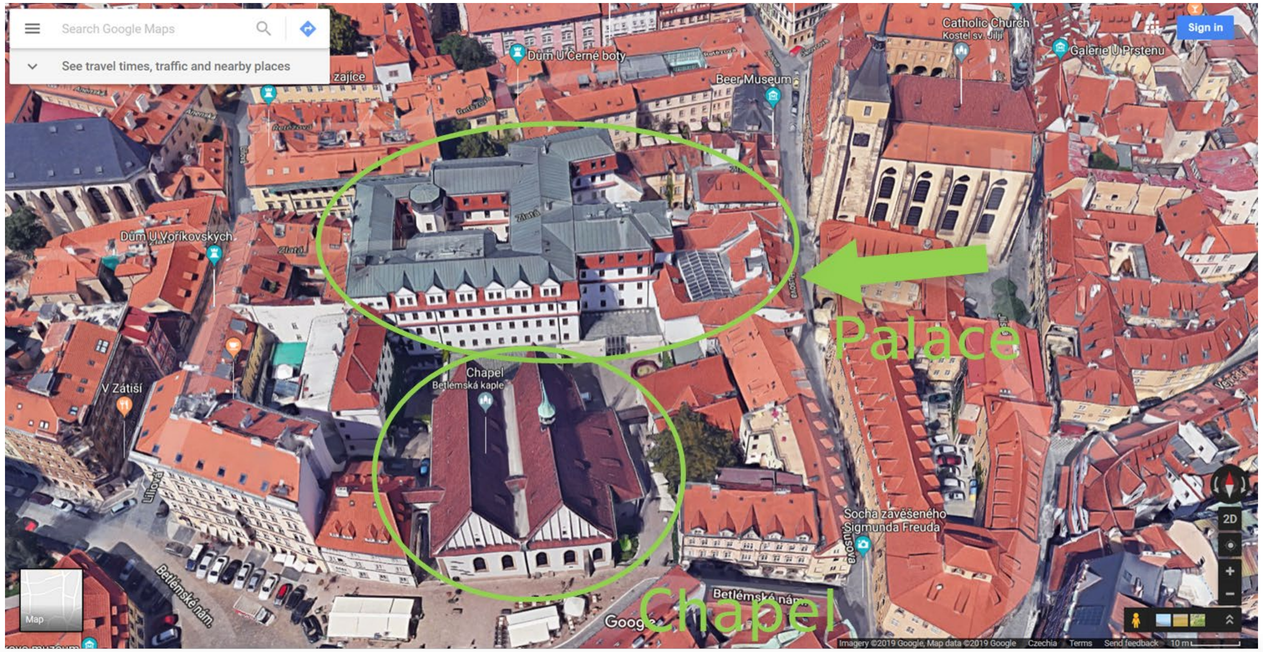
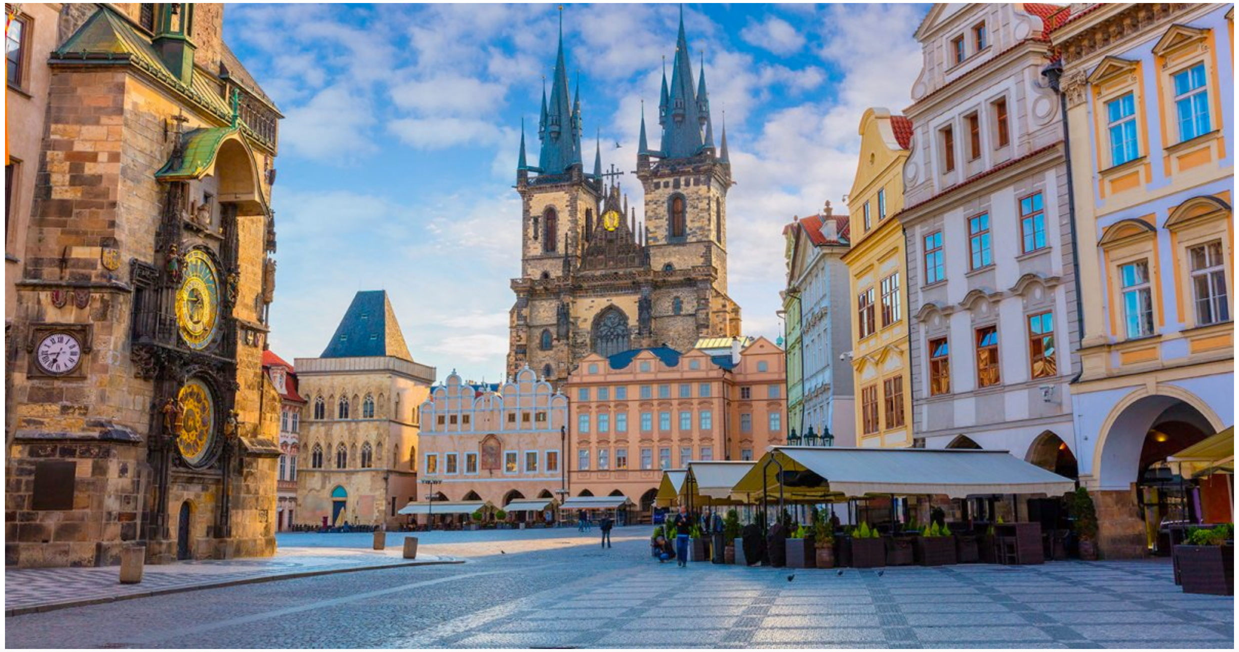




Outline

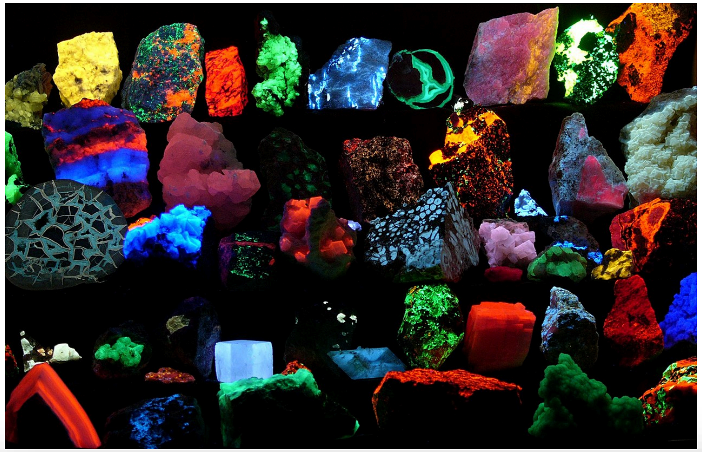
- General introduction
- Inorganic scintillators
- Organic scintillators
- Light collection techniques
- Photodetectors
- Application examples in fundamental research

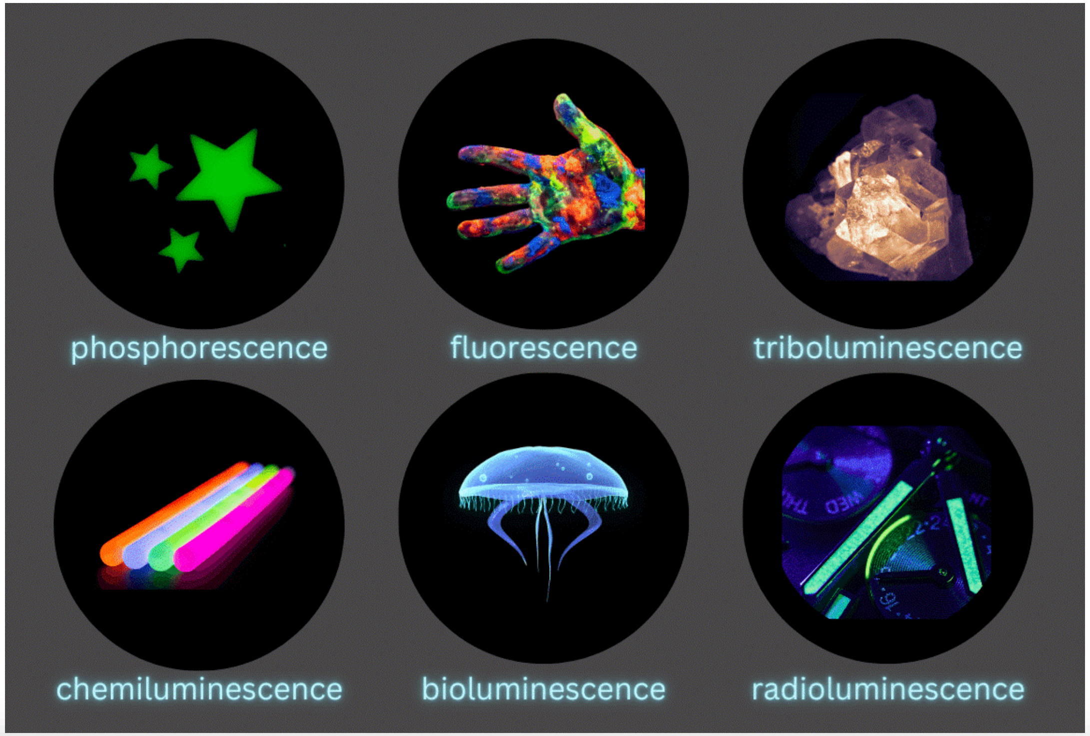
General introduction

Luminescence

→ emission of photons (visible light, UV or X-ray) by a substance following the absorption of energy (at moderate temperature)
→ energy deposition in the material by:

- Light → Photoluminescence (fluorescence and phosphorescence)
- Heat → Thermoluminescence
- Sound → Sonoluminescence
- Electric current/field → Electroluminescence
- Mechanical deformation → Triboluminescence
- Chemical reactions → Chemiluminescence
- Living organisms → Bioluminescence
- Ionizing radiation/particles → Radioluminescence (scintillation)



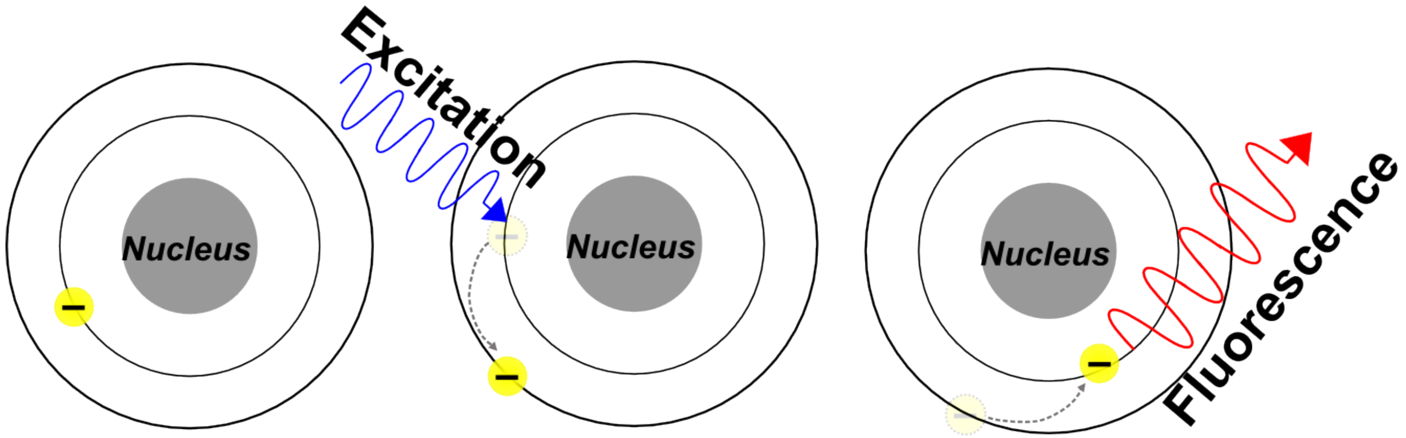


Photoluminescence → light emission caused by the absorption of photons. The absorbed energy excites electrons, which emit lower-energy photons (longer wavelength) when they return to a more stable state.

→ two main types of photoluminescence:

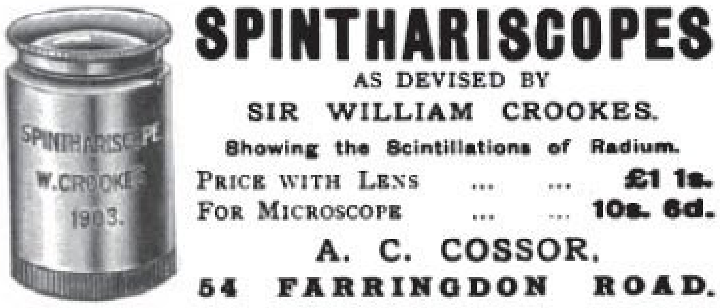
- Fluorescence → occurs when a substance absorbs photons and re-emits them very quickly, within nanoseconds (fluorescent highlighter pen, which glows under UV light).

- Phosphorescence → similar to fluorescence, but the substance re-emits the absorbed photons over a longer period (ms up to hours), resulting in a sustained glow even after the removal of the exciting source (glow-in-the-dark stars).



Brief history

- 1903: Early scintillation experiments by British chemist and physicist, Sir William Crookes, using zinc sulfide (ZnS) and microscope



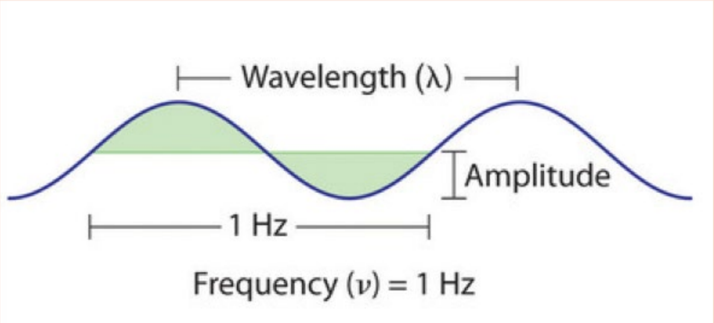
- 1944: Development of the first practical scintillation detector (introduced PMT) by Sir Samuel Curran and W. Baker.
- 1948: Introduction of thallium activated sodium iodide crystals (NaI:Tl) scintillators by Robert Hofstadter.
- 1960s - 1970s: Development of various inorganic scintillators like BGO, LSO.
- 1980s - 1990s: Advances in organic scintillators and plastic scintillators.
- 2000s - Present: Continuous improvements in material science, leading to better efficiency and energy resolution in scintillators.

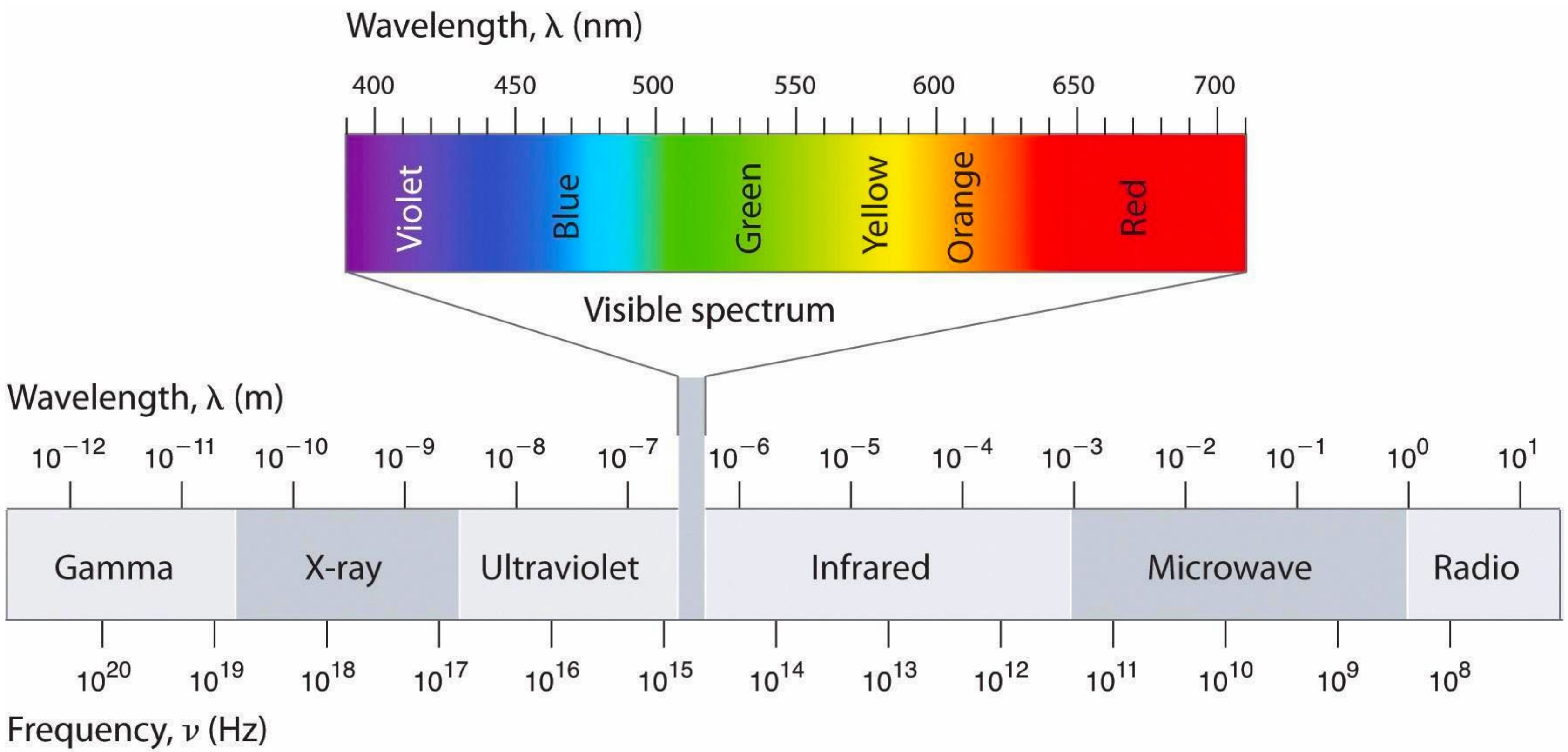
- Current Trends: Research in semiconductor nanocrystal scintillators (quantum dots) and other novel materials.

Planck equation → fundamental equation in quantum mechanics which states, that the energy **E** of a photon is proportional to its frequency **v** & inverse proportional to its wavelength **λ**

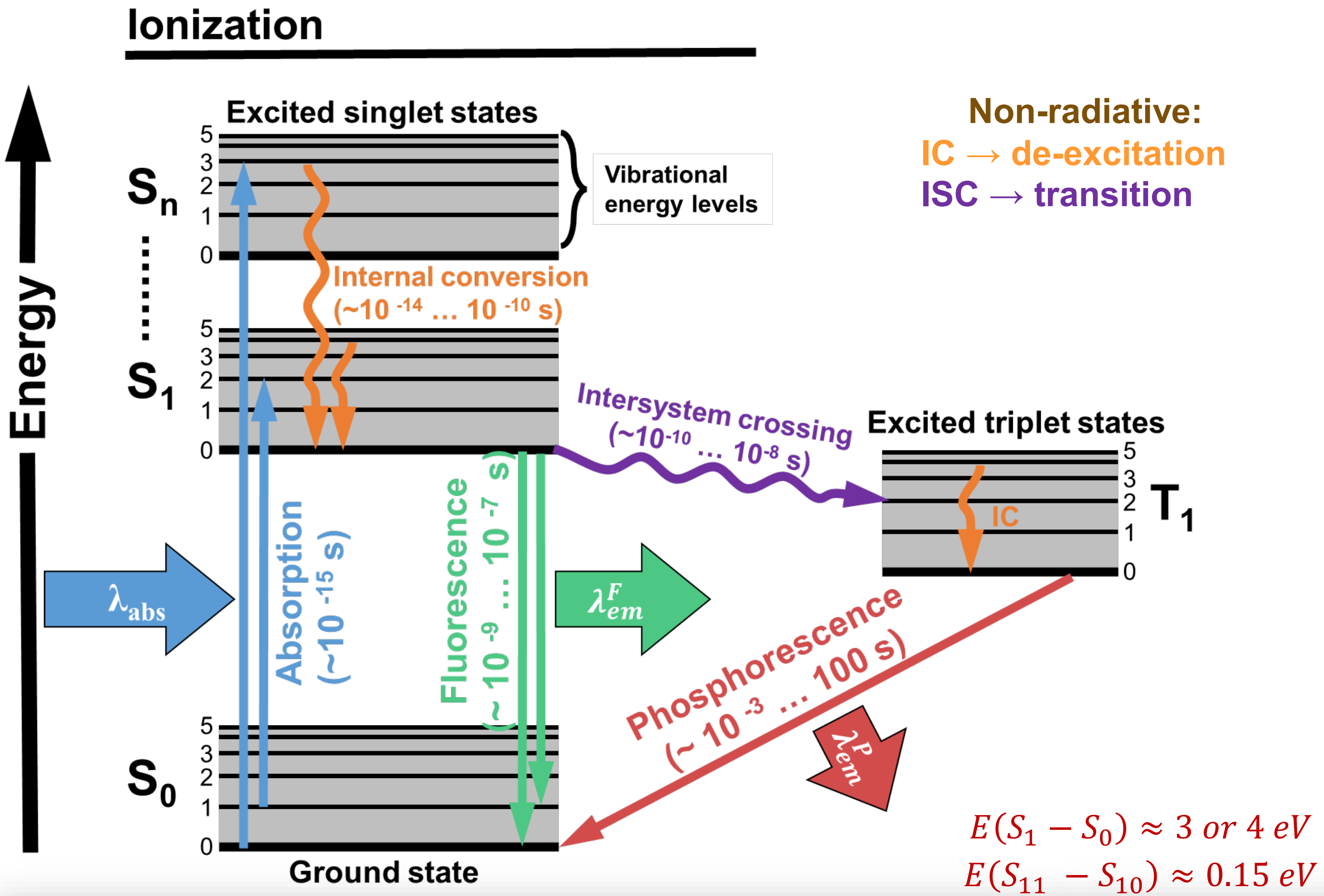
$$E = h\nu = \frac{hc}{\lambda}$$

E = energy
h = Planck const. = 6.626×10^{-34} J·s^{-1}
ν = frequency of photon
c = speed of light = 3×10^{8} m.s^{-1}
λ = wavelength of photon





Photoluminescence mechanism → Jablonski energy diagram illustrating the transitions between electronic states of a molecule for the quantum mechanical processes of fluorescence and phosphorescence.



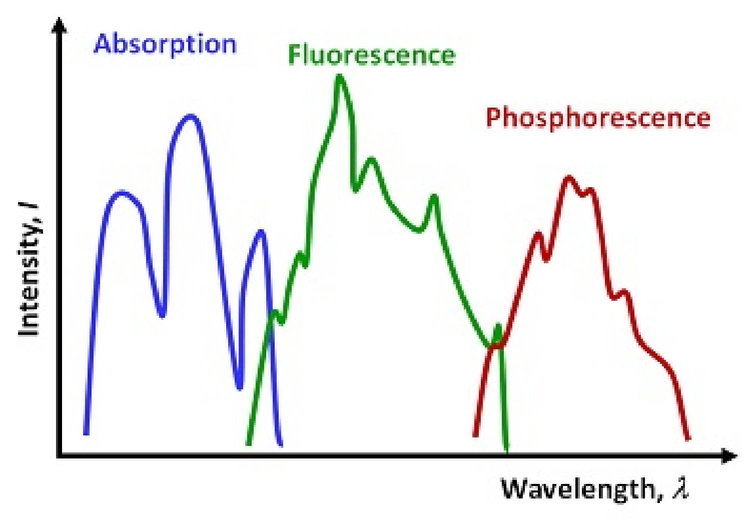
$E(S_1 - S_0) \approx 3 \text{ or } 4\ eV$

$E(S_{11} - S_{10}) \approx 0.15\ eV$

$\lambda_{abs} < \lambda_{em}^{F}$

$\lambda_{abs} \ll \lambda_{em}^{P}$

The Stokes Shift: emission is always of lower energy (higher λ) than absorption due to nuclear relaxation in the excited state.



Radioluminescence (Scintillation)

→ Emission of photons following the excitation of atoms and molecules by ionizing radiation/particles.

→ Detection of ionizing radiation/particles by scintillation light produced in certain materials belongs to one of the oldest techniques.

→ One of the most common detection techniques in nuclear and particle physics.

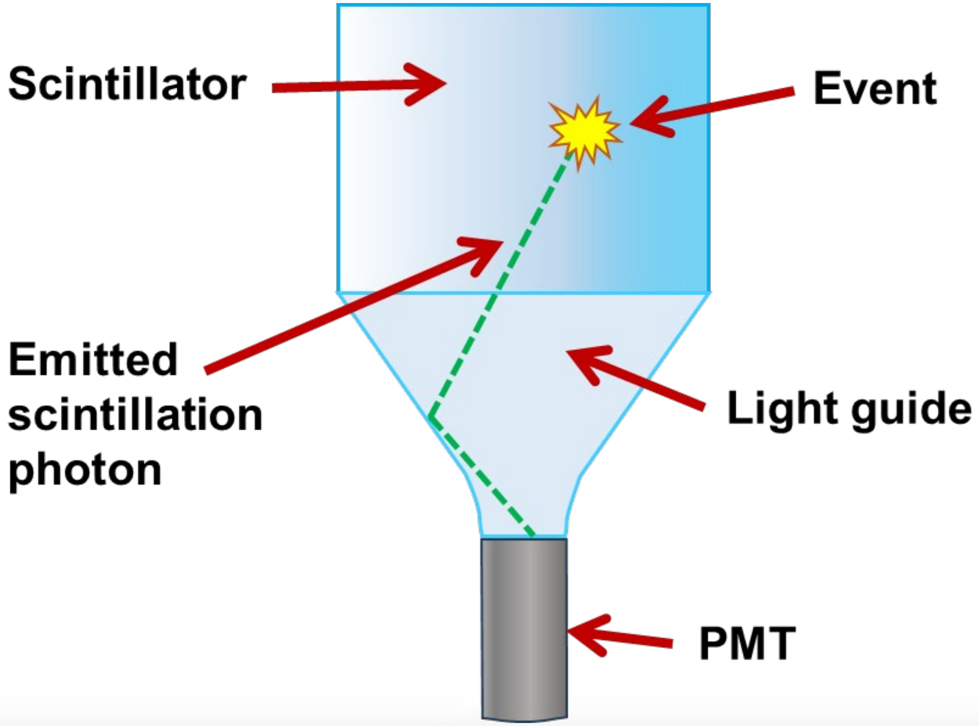
→ Scintillation detectors are used to detect all types of radiation: gammas, electrons/positrons, neutrons, alphas, neutrinos, ions (no universal material is perfect for all types of radiation).

Steps involved in detecting radiation using scintillation:

1. Electromagnetic interaction of radiation with scintillation material
2. Energy transfer to the electronic states of the material (atomic / molecular effect) → excitation and ionization
3. Relaxation of the excited states to the ground state resulting in the emission of photons
4. Collection of photons by photo sensitive device
5. Detection of the signals by associated electronics

Scintillation detector: consists of scintillating material wrapped in a reflective layer, coupled to a light guide, and to a photodetector

- Scintillating material converts gamma and particle radiation into light (visible, UV, sometimes X-rays). Often, a wavelength shifter is mixed into the primary scintillator matrix. Wavelength shifters absorb photons of a certain wavelength and re-emit photons at a longer wavelength to better match the scintillator light to the readout device..
- Light guide (acrylic plastic) conveys scintillation light to the photodetector. Again, a wavelength shifter is often used to match the wavelength to the response characteristics of the photodetector and hence improves the signal.
- Photo detector converts the light into an electric signal. Various photodetectors are used, e.g. PMTs (photomultiplier tubes) or SiPMs.



- Scintillating materials
  - → Inorganic crystals
  - → Scintillating glasses
  - → Nobel gases (gaseous or liquid)
  - → Organic crystals
  - → Organic liquids
  - → Plastic scintillators

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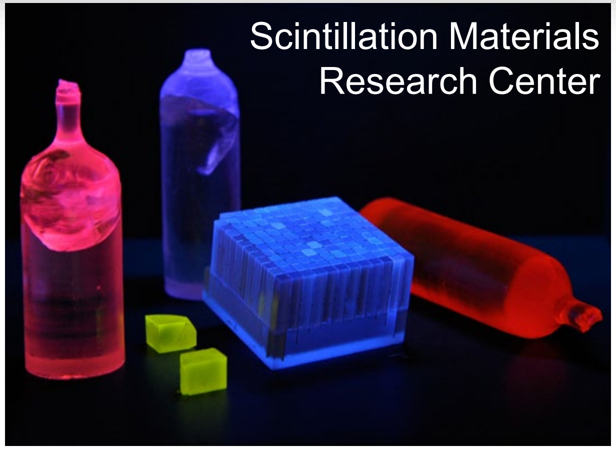
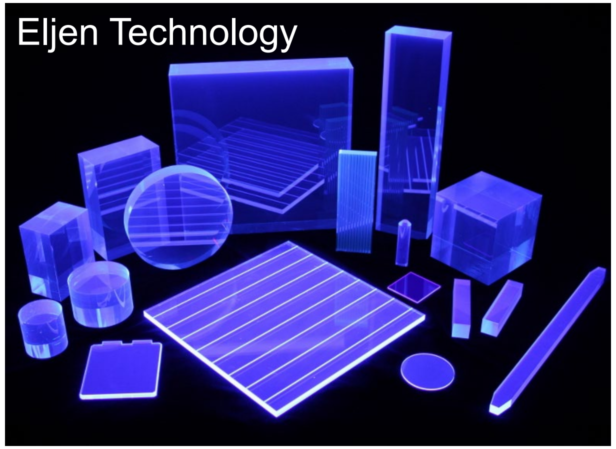
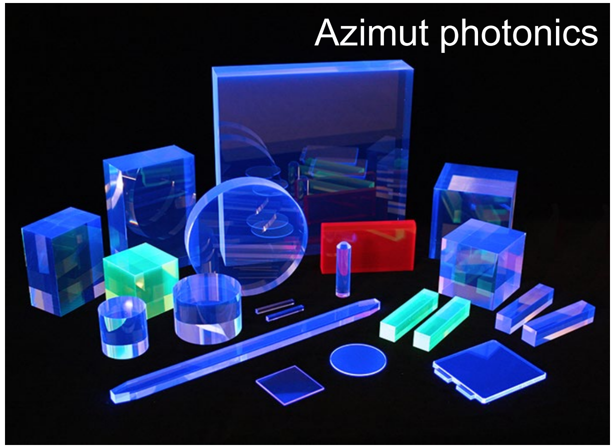






- Applications in nuclear and particle physics
  - → Trigger detectors for slow detectors (e.g., drift chambers)
  - → Time of flight counters (TOF-Counters)
  - → Calorimeters
  - → Position detectors (scintillating fibers)
  - → Detection and spectroscopy of thermal and fast neutrons
  - → Neutrino detectors (liquid scintillators)

Basic properties:

- Advantages
  - → Fast response time (especially organic scintillators, ~ ns)
  - → Sensitive to deposited energy
  - → Construction flexibility (any shape) and simple operation
  - → Cheap and reliable

- Disadvantages
  - → Aging (especially plastic scintillators)
  - → Radiation damage (especially plastic scintillators)
  - → Hygroscopic (especially inorganic crystals)
  - → Low light output (especially gaseous scintillators)
  - → Magnetic field and temperature influences - in combination with the photodetector readout sensitive to magnetic fields (when using PMTs) or to temperature (when using SiPMs)

Requirements → Many materials show luminescence. However, a useful scintillation detector must fulfil the following requirements:

- High light yield, i.e., high efficiency to convert the excitation energy into fluorescence.
- Good energy resolution, i.e., ability to distinguish between different energies of incident radiation.
- Low self-absorption, i.e., transparency with respect to the own fluorescence light. Otherwise, light is absorbed within the material itself.
- Emission wavelength, i.e., emission spectra matched to the spectral sensitivity of the photodetector. Matching can also be achieved by introducing a wavelength shifter.
- Short decay time (ns).

Signal shape → Many scintillators exhibit a single exponential decay in their signal. However, when multiple signal components are present, the resulting decay curve is a composite of overlapping exponential decays, each corresponding to a different scintillation process or material component.

→ Rise time of the signal is usually very fast.

→ Pulse shape discrimination (gammas, neutrons)

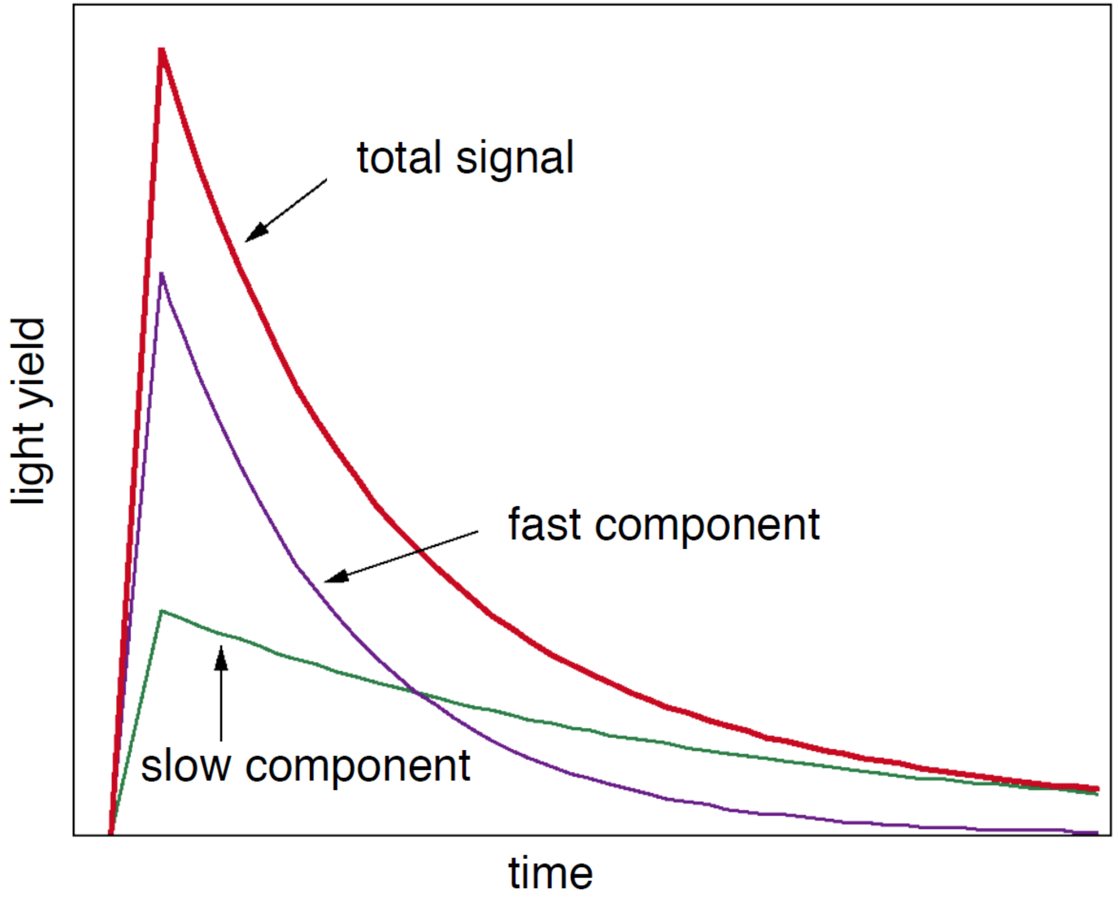
The combined scintillation light output as a function of time can be described by a sum of exponential decay terms corresponding to the fast and slow components. The general form of the signal *N(t)* is:

$$N(t) = A_f\, e^{-\frac{t}{\tau_f}} + A_s\, e^{-\frac{t}{\tau_s}}$$

A_f and A_s are the amplitudes of the fast and slow components.

τ_f and τ_s are the decay time constants of the fast and slow components.

Signal vs. time of a scintillator with fast and slow component



Light output

→ Only a few percent of the deposited energy is transferred into light. The remaining energy is used up by ionization, heat generation, self-absorption, etc.

→ Mean energy required to create a photon:

Anthracene ($C_{14}H_{10}$)	~ 60 eV
NaI:Tl	~ 25 eV
BGO ($Bi_4Ge_3O_{12}$)	~ 300 eV
Plastic	~ 100 eV

→ Anthracene or NaI are often used as reference material, i.e., light yield is given in percentage of the yield of Anthracene or NaI.

→ In addition, photons are lost in the scintillator itself (self-absorption) and also in the light guide.

→ Quantum efficiency (QE) of the photodetectors also only about 30%. QE is a measure of how effectively the photodetector coverts incident radiation into detectable electronic signals.

Material properties of some important scintillators

Material	Type	Density [g/cm³]	Emission peak [nm]	Light output [% Anthracene]	Light yield [photons/MeV]	Decay time [ns]
Anthracene	Organic	1.25	447	100	17000 - 20000	30
trans-Stilbene	Organic	1.16	410	50		4.5
NaI:Tl	Inorganic	3.67	415	230		230
CsI:Tl	Inorganic	4.51	400	300		600
BGO	Inorganic	7.13	480	35 – 45		350
$PbWO_4$	Inorganic	8.28	440 – 500	2.5		5–15
p-Terphenyl	In liquid solution, plastic	1.23	420	58		5
PPO	In liquid solution, plastic	1.09	355	~ 50		1-5
$LaBr_3$:Ce	Inorganic	5.29	380	350		16

https://scintillator.lbl.gov/

Energy resolution → ability to distinguish between different energies of incident radiation. Many physical processes, including photon production in scintillators, result in a Gaussian-shaped energy distribution.

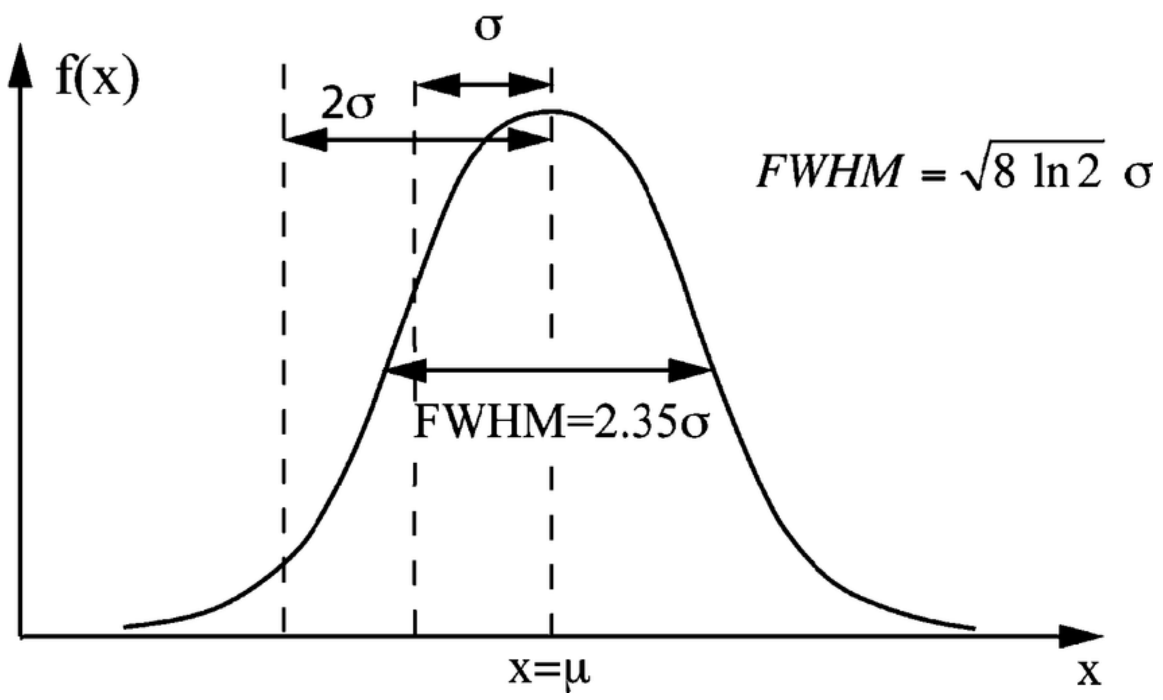
$$f(x) = \frac{1}{\sigma\sqrt{2\pi}}\, e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

μ is mean or centroid ($\rightarrow E_{peak}$)
σ is standard deviation ($\rightarrow FWHM \approx 2.355\ \sigma$)

$$E_{rel} = \frac{FWHM}{E_{peak}} \times 100\ \%$$

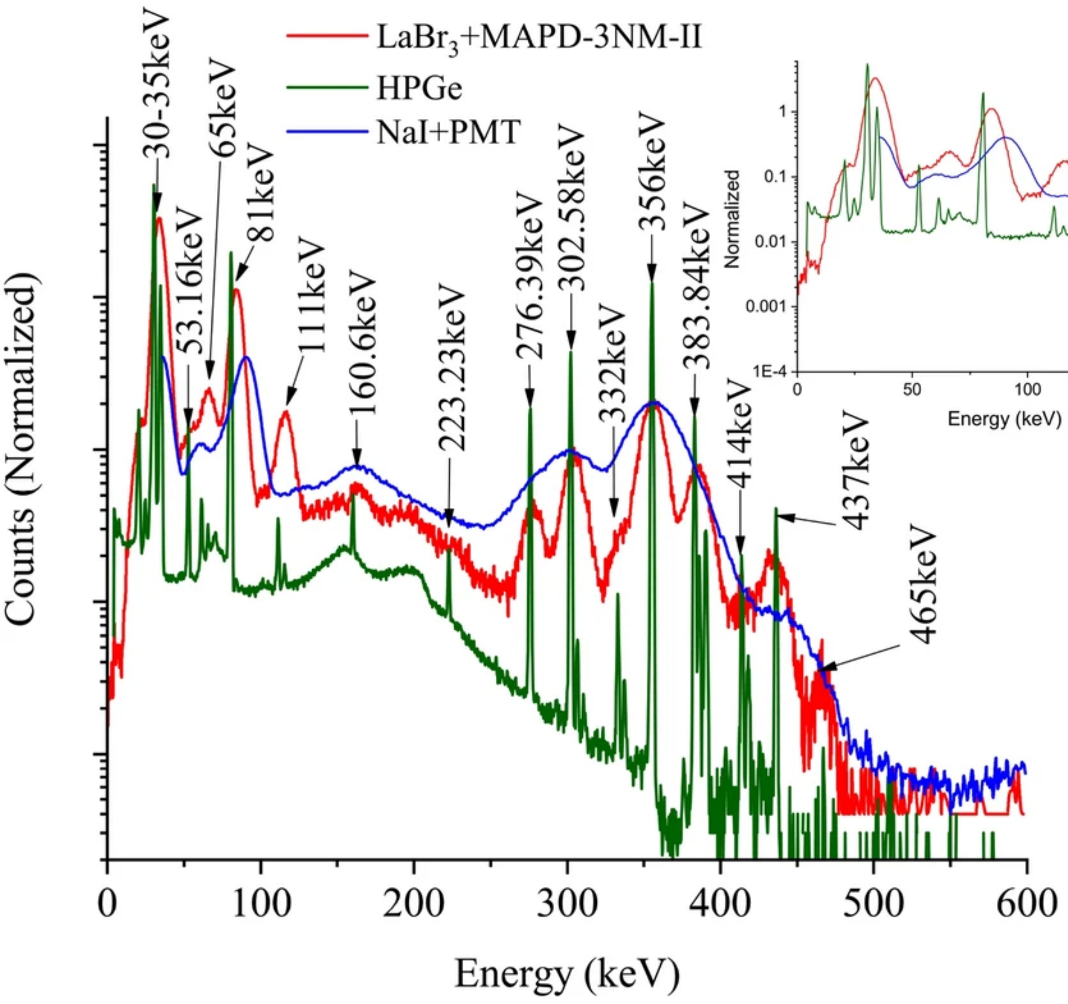
R is relative energy resolution
$FWHM$ is Full Width at Half Maximum of the energy peak
E_{peak} is mean energy (centroid) of the energy peak

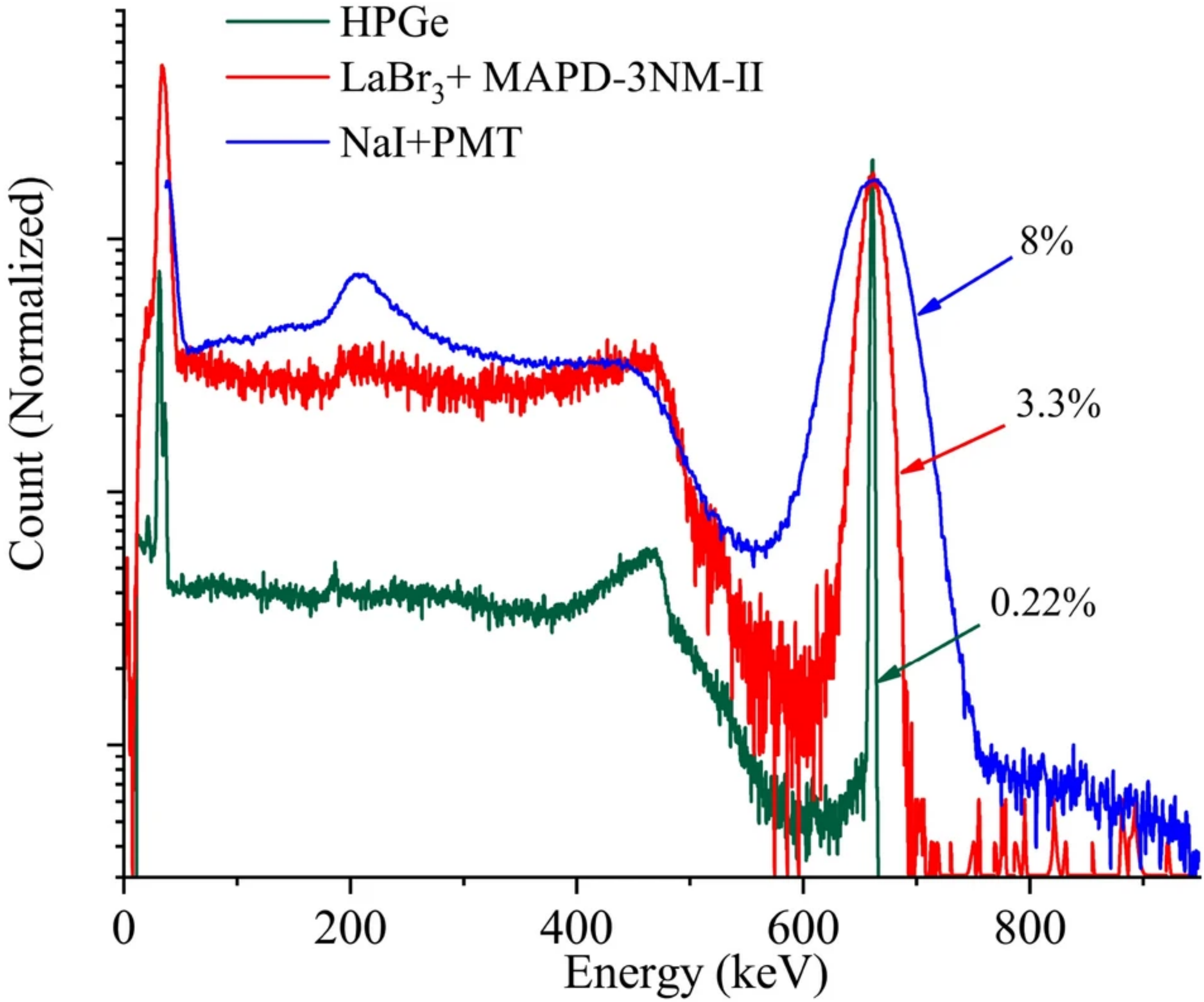
Gaussian distribution



FWHM → width of the peak at half of its maximum height in a distribution. FWHM indicates the spread or uncertainty in measurements.

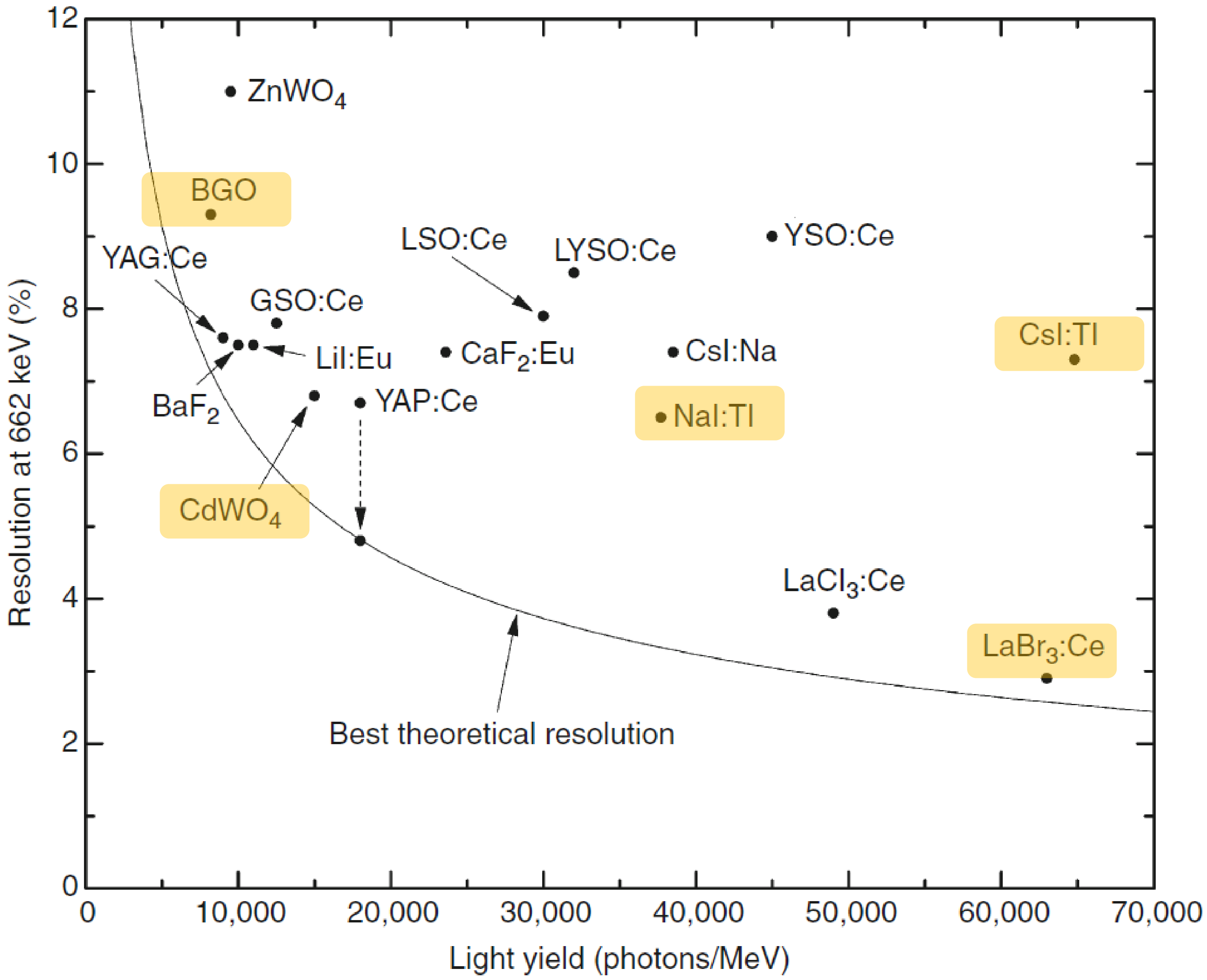
Comparison of normalized pulse height spectrum for ^{133}Ba (left) and ^{137}Cs (right) with HPGe, NaI(Tl) and $LaBr_3(Ce)$ detectors.





Holik, M et al., Scientific Reports 12 (2022) 15855

Best theoretical resolution and observed energy resolution of different scintillators.



Prices of different inorganic scintillators.

Material	$\frac{1}{L}\frac{dL}{dT}$ [a]	Neutron sensitive?	Radiation hardness (Gy)[b]	Radiation length (cm)	Price (US$/cm^3)[c]
NaI:Tl	−0.2	Yes (F)[d]	10	2.6	$6
CsI:Tl	~0 (fast)	Yes (F, S)[e]	10	1.86	$4
CsI:Na	0.39	Yes (F, S)	10	1.86	$4
CaF_2:Eu	−0.33	No		3.50	$20
^{6}LiI:Eu		Yes (F, S)		2.55	~$100
^{6}Li glass		Yes (S)		7.09	~$1, 500
BaF_2	−1.3 (slow)	No	>10^5	2.03	$15
YAP:Ce		No	10^4	2.67	$100
YAG:Ce	−0.27	No		3.5	$90
LSO:Ce		Yes (S)	10^{4-5}	1.14	$60
LYSO:Ce	−0.2	Yes (S)	10^{4-5}	1.15	$70
YSO:Ce		No	10^4	2.75	~$85–100
GSO:Ce	−0.1	Yes (S)	10^6	1.38	
BGO	−0.9	No	100–1,000	1.11	$35
$CdWO_4$	−0.1	Yes (S)	10–1,000	1.06	$60
$PbWO_4$	−2.7	Yes (S)	>10^5	0.89	$5–6[f]
$ZnWO_4$	−1.2	Yes (S)		1.10	$40
$LaBr_3$:Ce	~0	Yes (S)	10^5	1.88	~$500
$LaCl_3$:Ce	0.7	Yes (S)	10^5	3.12	~$500

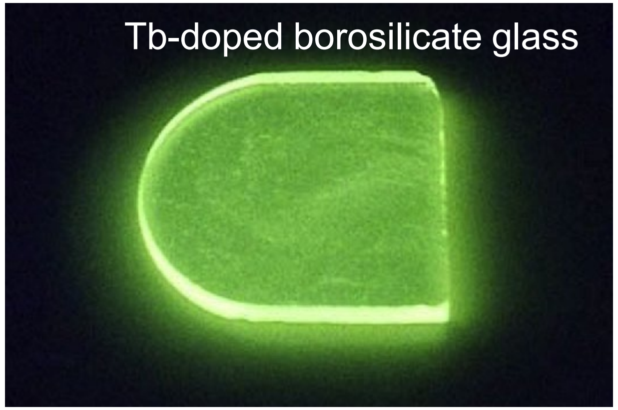
Inorganic Scintillators

Overview

- Different types of inorganic scintillators:
  - Inorganic crystals
  - Glasses
  - Noble gases (gaseous or liquid)

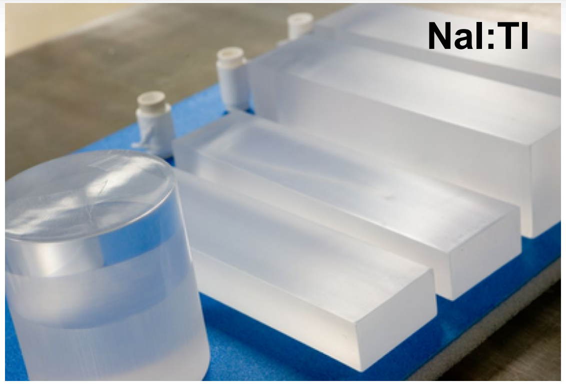
- Scintillation mechanism is different for inorganic crystals, glasses and noble gases.
  - The consequence are very different response times:
    → inorganic crystals and glasses: rather slow (compared to organic crystals)
    → noble gases: fast

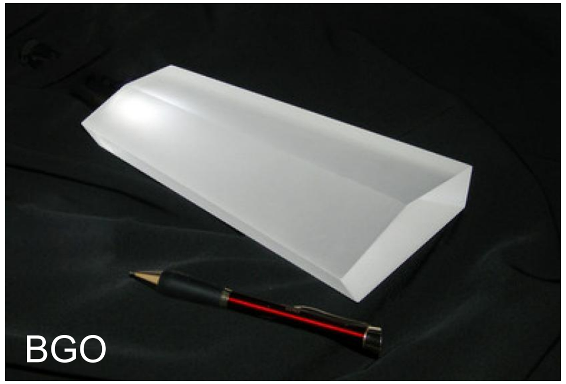
- Inorganic scintillators are relative radiation resistant.

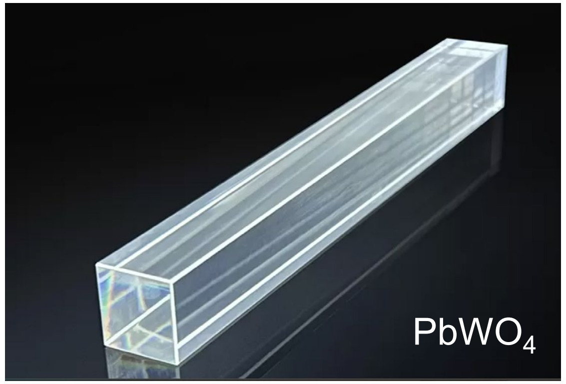


Inorganic crystals - Properties

- Important inorganic crystals:
  - NaI,CsI → as pure crystal or doped with Thallium (NaI:Tl, CsI:Tl)
  - BGO (Bismuth Germanate: $Bi_4Ge_3O_{12}$)
  - GSO (Gadolinium silicate: Gd_2SiO_5), usually doped with Cerium (Ce)
  - BaF_2, CeF_3, $PbWO_4$
- Emitted light usually at 400 - 500 nm
- Advantages:
  - High density
  - High light output: ≈ 100 % - 400% of Anthracene
  - Relative radiation resistant (especially: CeF_3, GSO, $PbWO_4$, but BGO is worst)
- Disadvantages:
  - Slower than organic scintillators: Decay times a few hundred of ns, phosphorescence. Exception: CsF_2 ~ 5 ns and $PbWO_4$ ~ 5 - 15 ns.
  - Some are hygroscopic (moisture-absorbing): especially NaI:Tl, but BGO, $PbWO_4$,CeF_3 are not
  - Complicated crystal growth → expensive
- Applications:
  - The light output of inorganic crystals is in good approximation linear to the energy deposited by high energy particles → perfect devices for homogeneous calorimeters in high energy physics (accelerators)

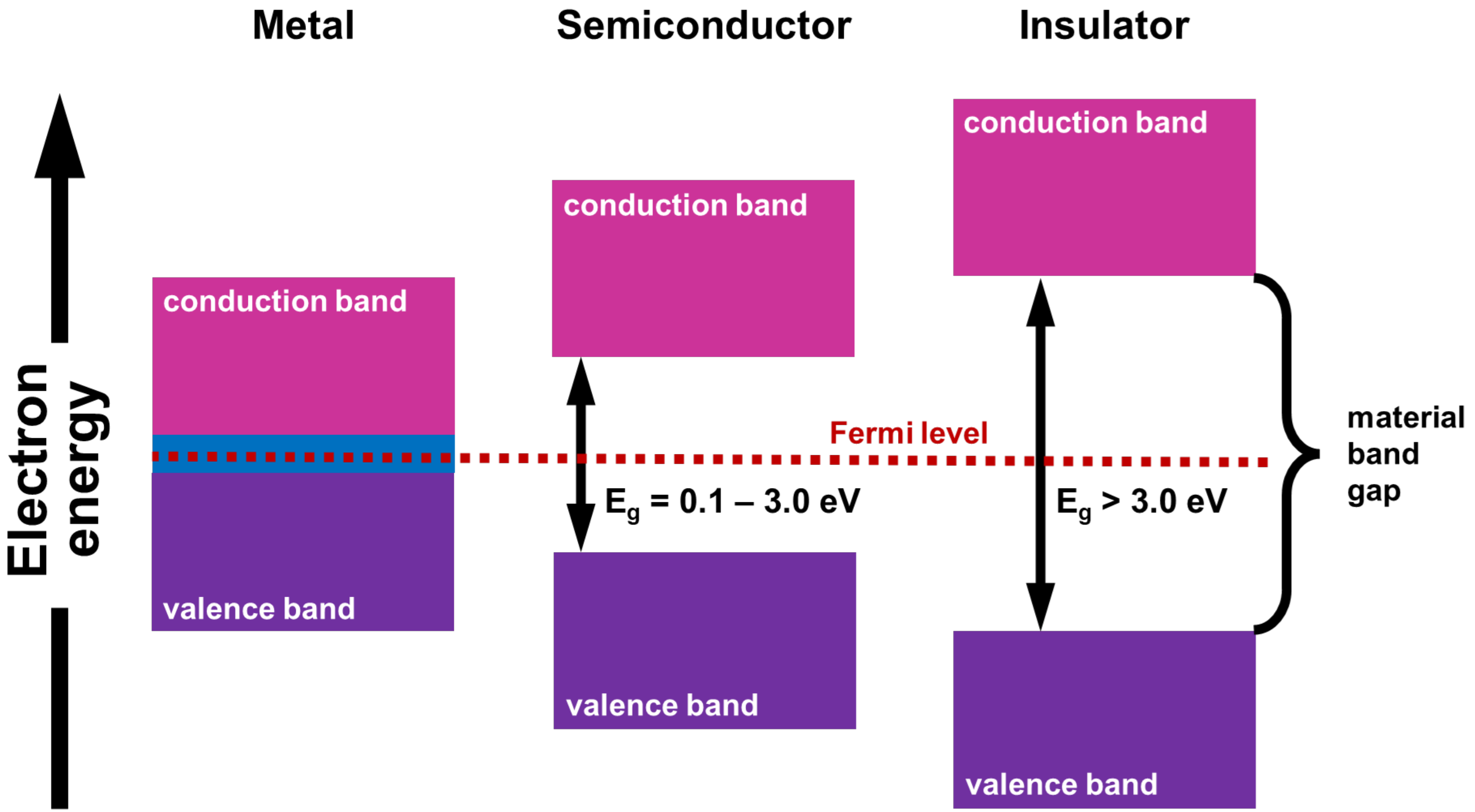






Scintillation mechanism – crystal band structure

Band theory – Energies of electrons are quantized = can possess only allowed energies, can occupy only allowed levels, cannot enter forbidden band gaps.



The Fermi level is a concept in quantum mechanics and solid-state physics that represents the highest energy level occupied by electrons in a material at absolute zero temperature.

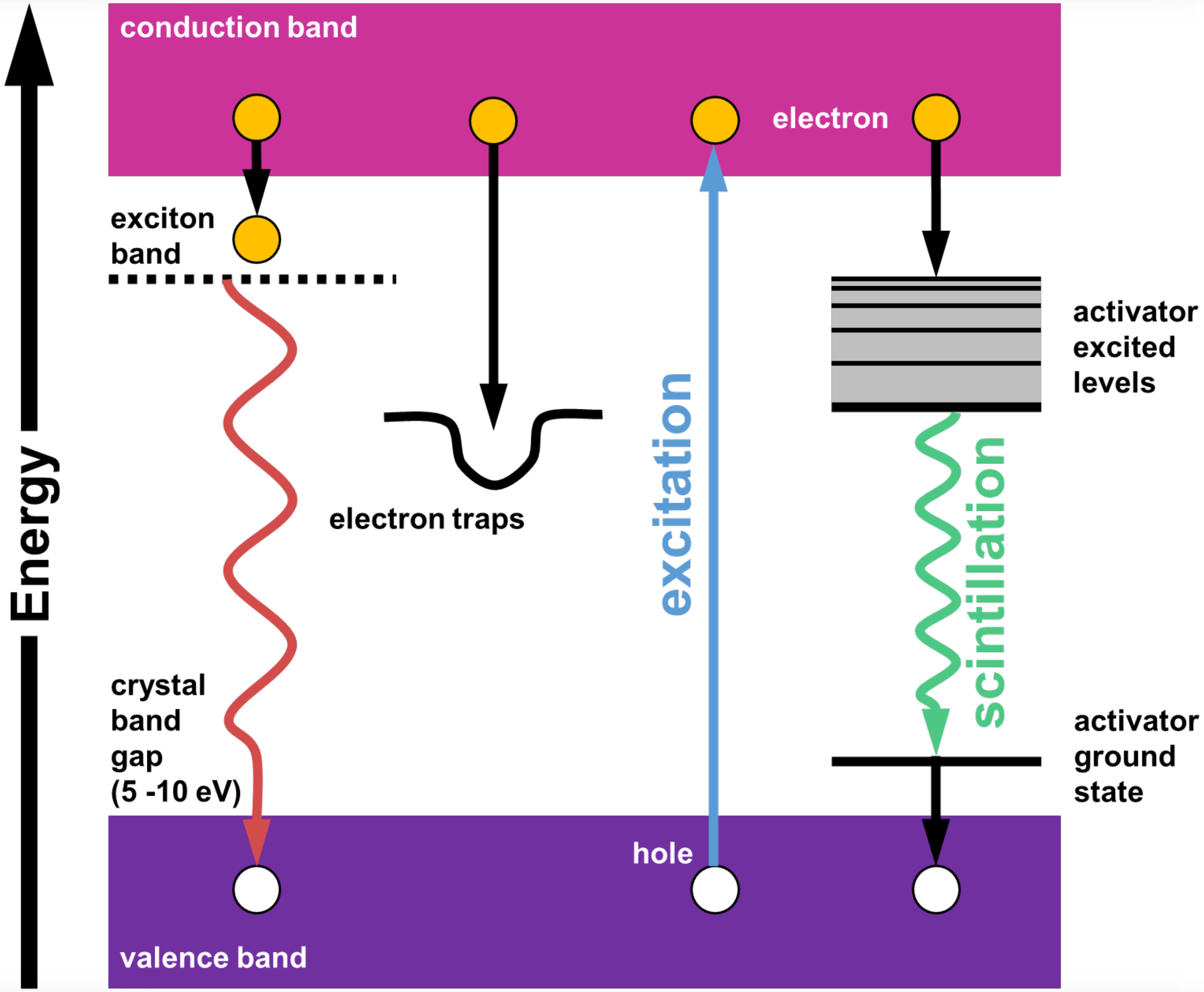
Scintillation mechanism – crystal band structure

→ Excitation: Radiation interacts with the scintillator material, exciting electrons from the valence band to the conduction band.

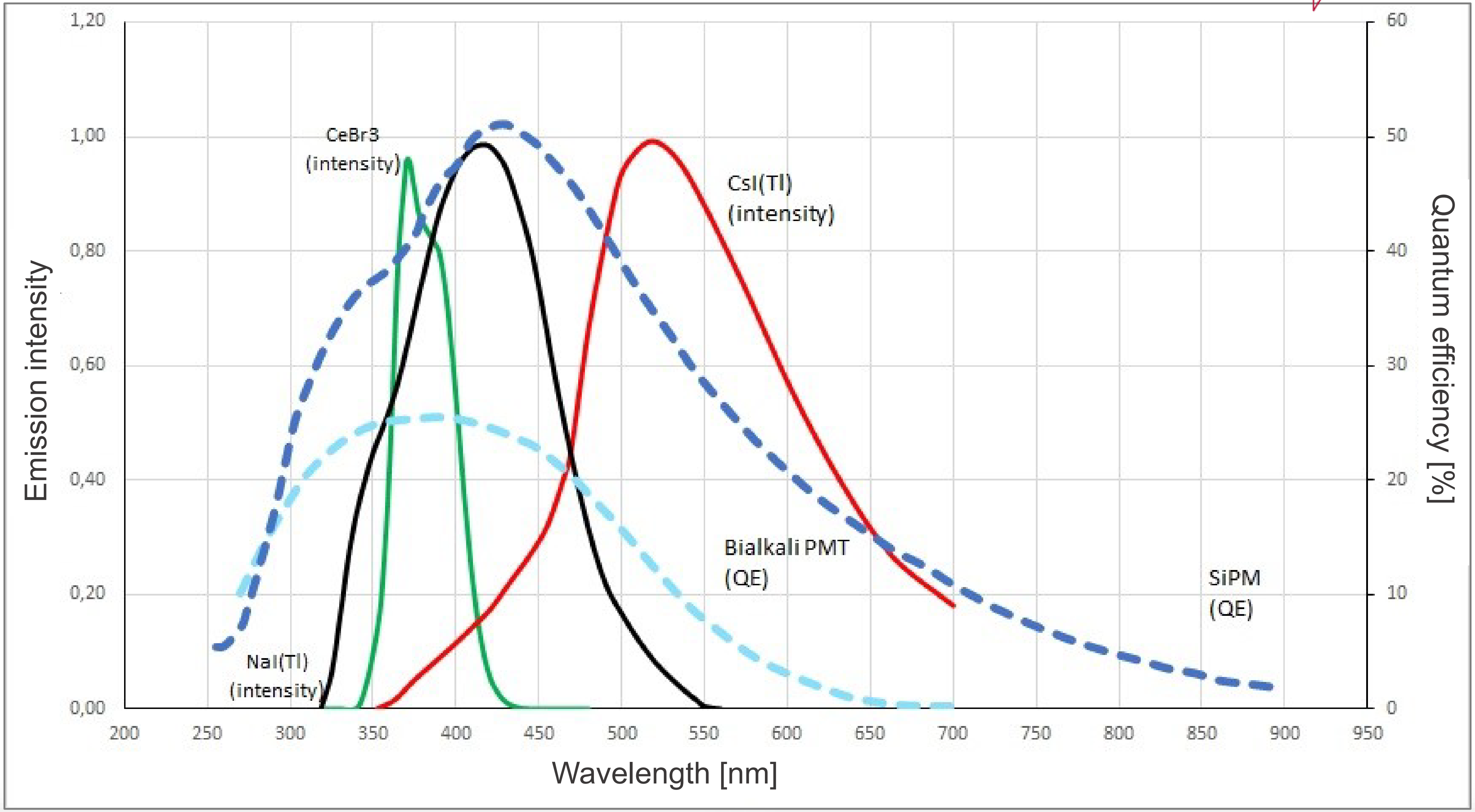
→ Energy Transfer: These excited electrons move through the crystal lattice, transferring energy to luminescent centers (activators) in the scintillator material.

→ Emission: The luminescent centers then de-excite by emitting photons.

- Electrons could also be bound as excitons (coupled electron-hole pairs). De-excitation causes also the emission of photons.
- Electron could be captured by defects or impurities. These sites can hold the electron for some time before recombination with a hole.

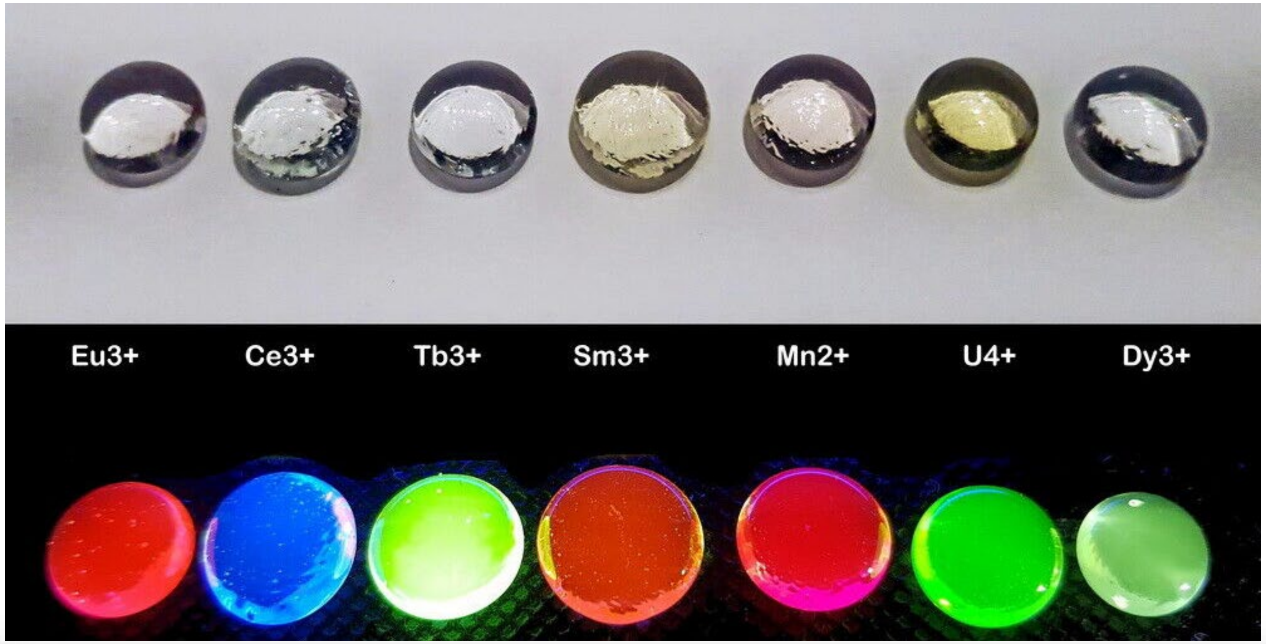


Emission spectra of various scintillators



Scintillating glasses

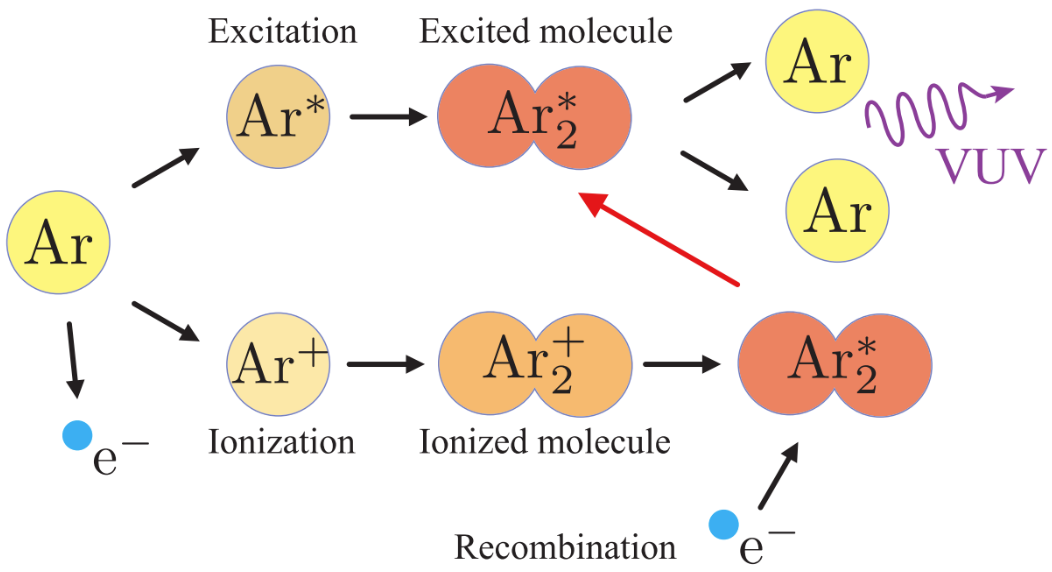
- Common types: cerium (Ce), europium (Eu) and terbium (Tb) doped glasses
- A typical scintillating glass is cerium doped with lithium borosilicate glass.
- High melting point and high resistance against organic and inorganic substances (except hydrofluoric acid) → applications under extreme conditions.
- Light yield is relatively low ~ 20 – 30 % of Anthracene.
- Application of scintillating glasses predominantly as neutron detector (detectors also sensitive to β and γ radiation). Sensitivity to slow neutrons is increased by enrichment of lithium with ^{6}Li.
- Low cost, durable, fast response, non-toxic, chemically stable, non-hygroscopic, capable of being formed in appropriate sizes and shapes



Scintillating noble gases

- Scintillating gases used: Helium, Neon, Argon, Krypton and Xenon
- 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, i.e., response time ≤ 1 ns.
- The emitted light is in the VUV (Vacuum Ultraviolet, for wavelengths 10 - 200 nm) range. In this range classic PMTs are not sensitive. The use of wavelength shifters (e.g., tetraphenyl-butadiene (TPB)) 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.

excimer (excited dimer)



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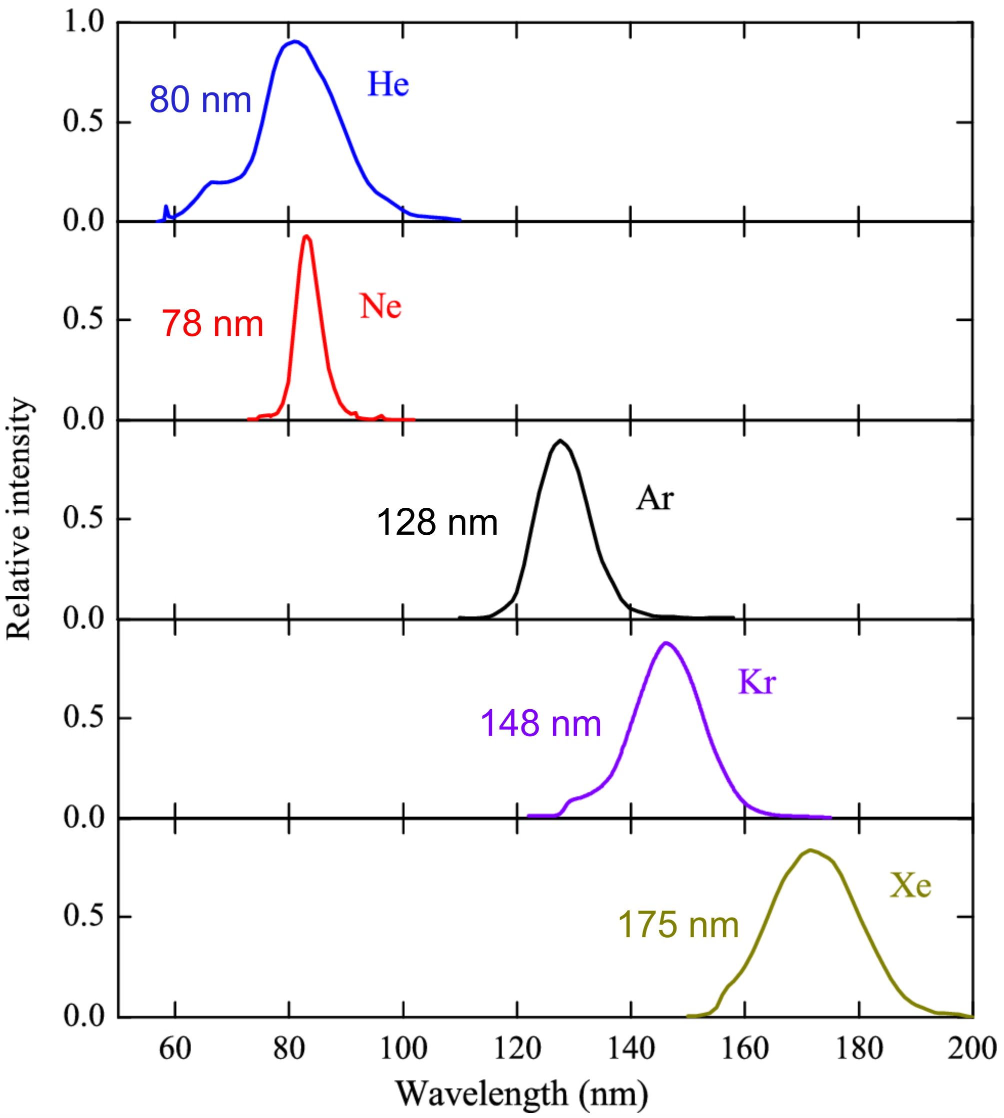
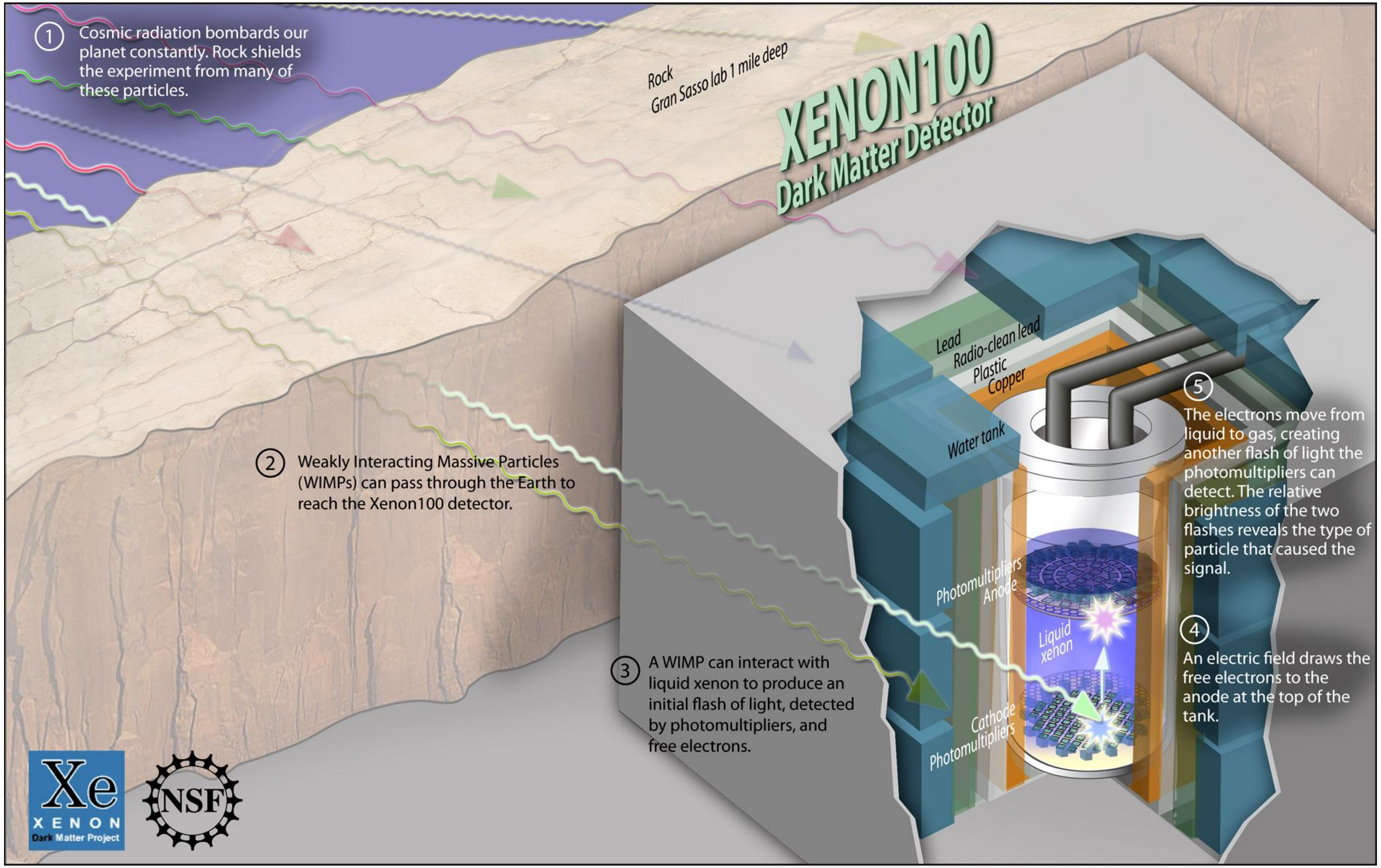
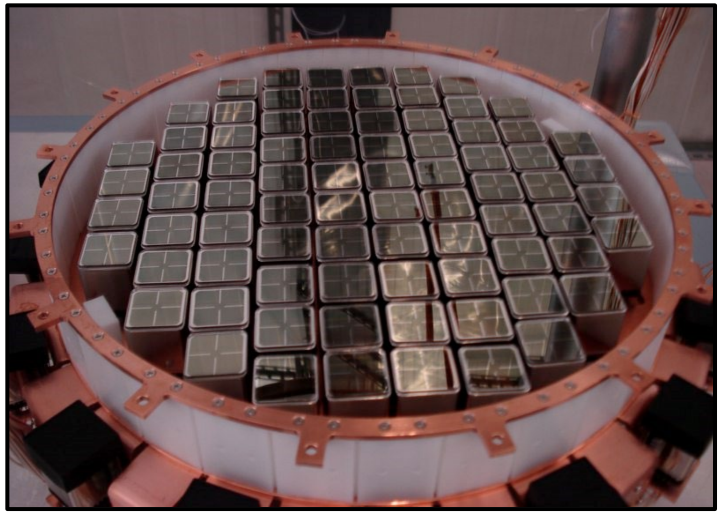
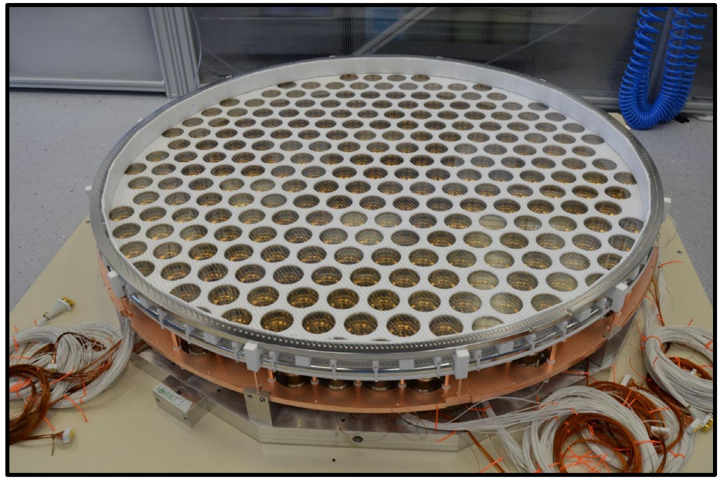


- Applications in fundamental physics: Liquid noble gas scintillators used in experiments searching for dark matter:
  e.g., XENON100 → XENONnT at Underground Laboratory Gran Sasso (LNGS , Italy), 5900 kg (total 8600 kg) LXe TPC, 494 PMTs



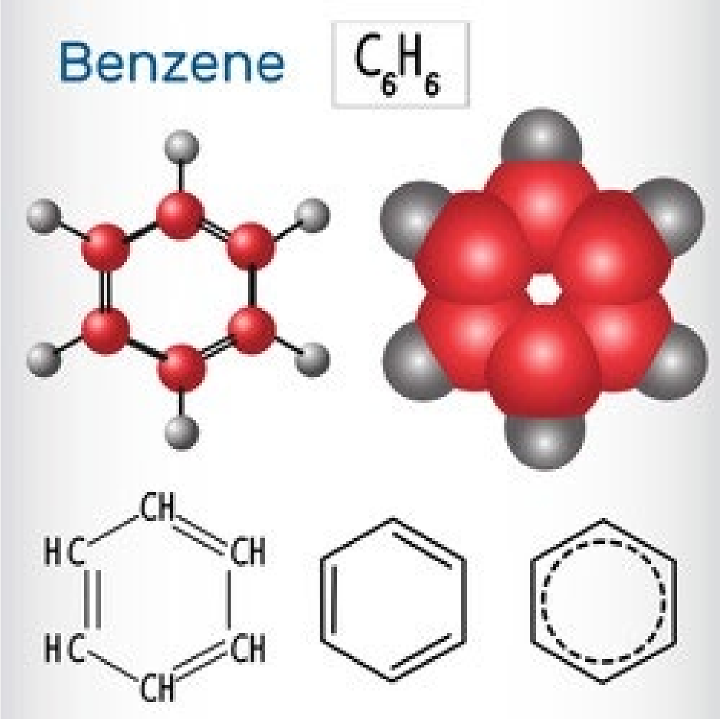




https://xenonexperiment.org/

Organic Scintillators

Overview



- Different types of organic scintillators:
  - Organic crystals
  - Organic liquids
  - Plastic scintillators

- Organic scintillators are aromatic hydrocarbon compounds (containing benzene ring)

- 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 and plastic scintillators are usually composed of 2–3 components:
  - Base matrix - supporting material
  - Primary scintillator
  - Secondary scintillator as wavelength shifting component

Overview

- Dependence of light output on energy deposition by ionizing particles is typically nonlinear in organic scintillators.

- High density of excited molecules along the particle track causes deexcitation without photon emission (quenching effect) and the light output becomes saturated.

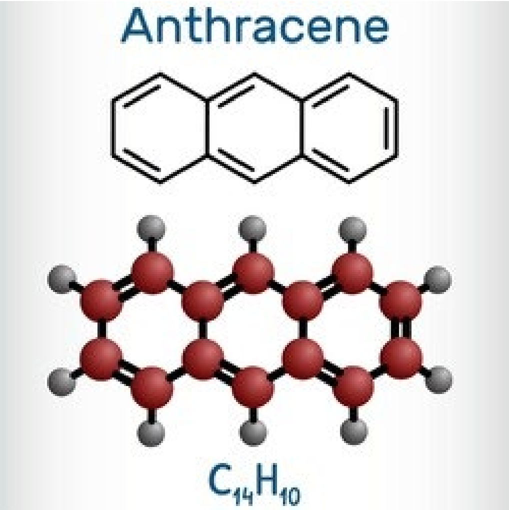
- Light output - described by semiempirical formula → **Birks law**:

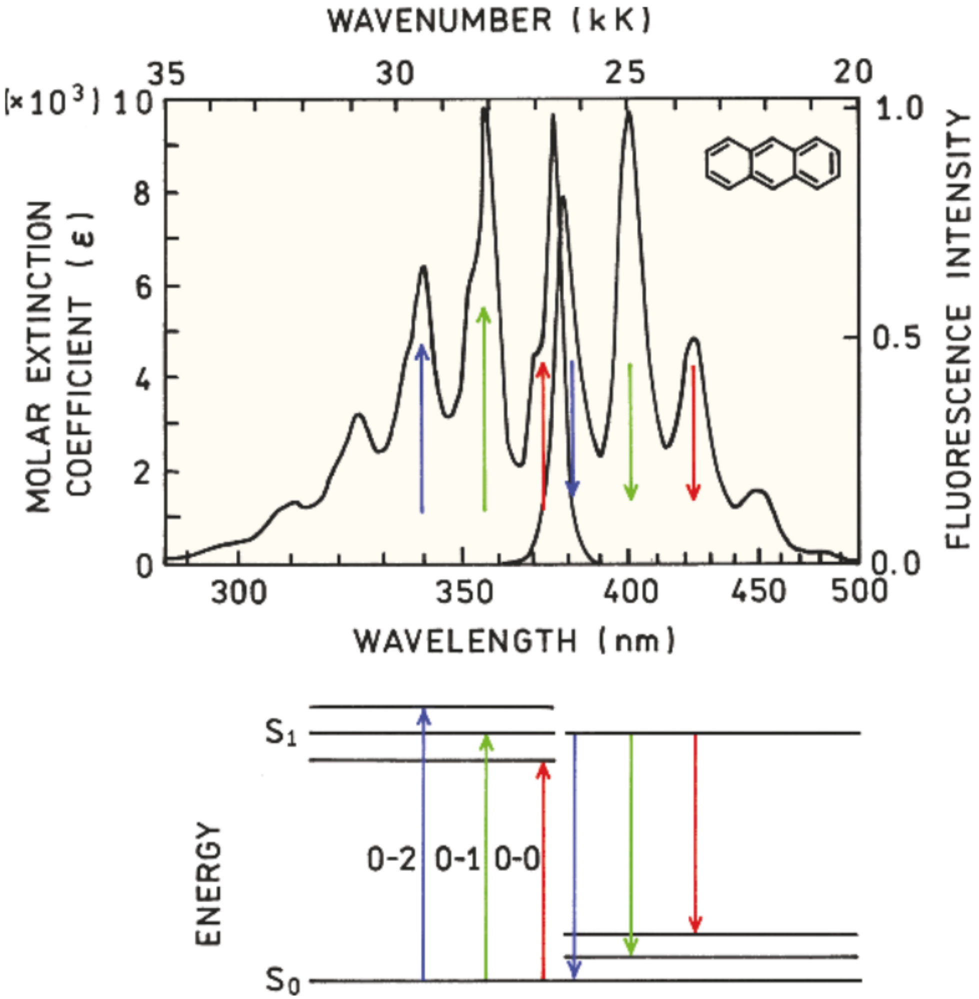
$$\frac{dL}{dx} = L_0 \frac{\frac{dE}{dx}}{1 + k_B \frac{dE}{dx}}$$

dL/dx is light output per path length
dE/dx is energy loss of particle per path length
L_0 is absolute scintillation efficiency
k_B is Birks' constant, determined by measurement

- Typical empirical values determined from experimental data → $k_B \sim 10^{-4} – 10^{-2}$ g/(cm^2 MeV).

- Important Organic crystals:
  - Naphtalen ($C_{10}H_8$)
  - Anthracen ($C_{14}H_{10}$)
  - rans-Stilbene ($C_{14}H_{12}$)
- Advantages:
  - Fast fluorescence: few ns (exception: anthracene ~ 30 ns)
  - Mechanically strong (exception: stilbene is brittle)
- Disadvantages:
  - Anisotropic light output: “channeling” effect in crystals
  - Mechanically difficult to process

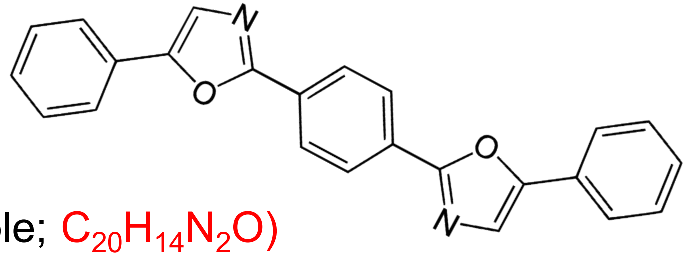




The absorption and emission spectra are for anthracene.
The numbers 0, 1, and 2 refer to vibrational energy levels.

Organic liquids - Properties

- Mixture of one or several organic scintillators in an organic solvent



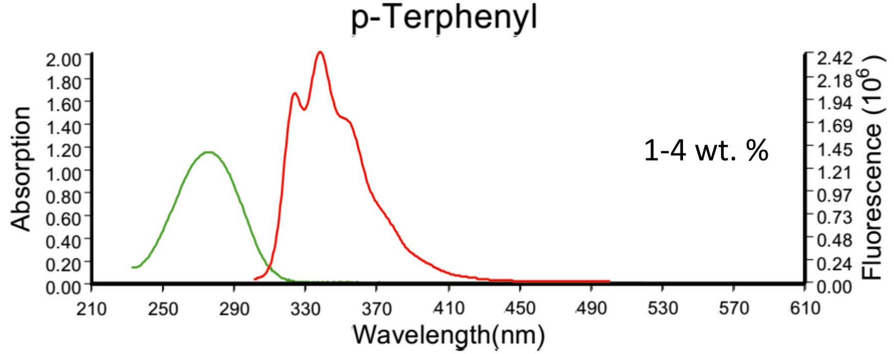
- Important liquid scintillators
  - p-Terphenyl ($C_{18}H_{14}$)
  - PPO (2,5-diphenyloxazole; $C_{15}H_{11}NO$)
  - PBD (2-phenyl,5-(4-biphenylyl)-1,3,4-oxadiazole; $C_{20}H_{14}N_2O$)
  - wavelength shifter such as POPOP ($C_{24}H_{16}N_2O$).

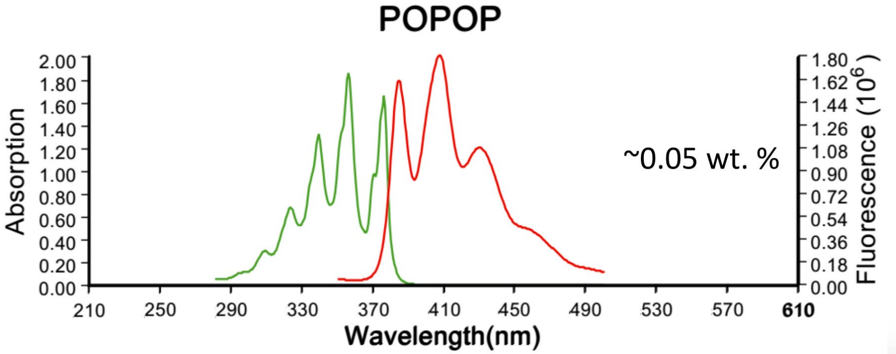
- Important solvents:
  - Benzene (C_6H_6), Toluene (C_7H_8), Xylene (C_8H_{10}), Decalin ($C_{10}H_{18}$), Phenylcyclohexane ($C_{12}H_{16}$),Triethylbenzene ($C_{12}H_{18}$),

- Advantages:
  - Possible any detector shape
  - Fast fluorescence: ~ 3 – 4 ns
  - Easy use of additives (wavelength shifter, additive to increase neutron cross section, etc.)

- Disadvantages:
  - Very sensitive to impurities (especially Oxygen)

Water, water-based LS, and LS excited by UV





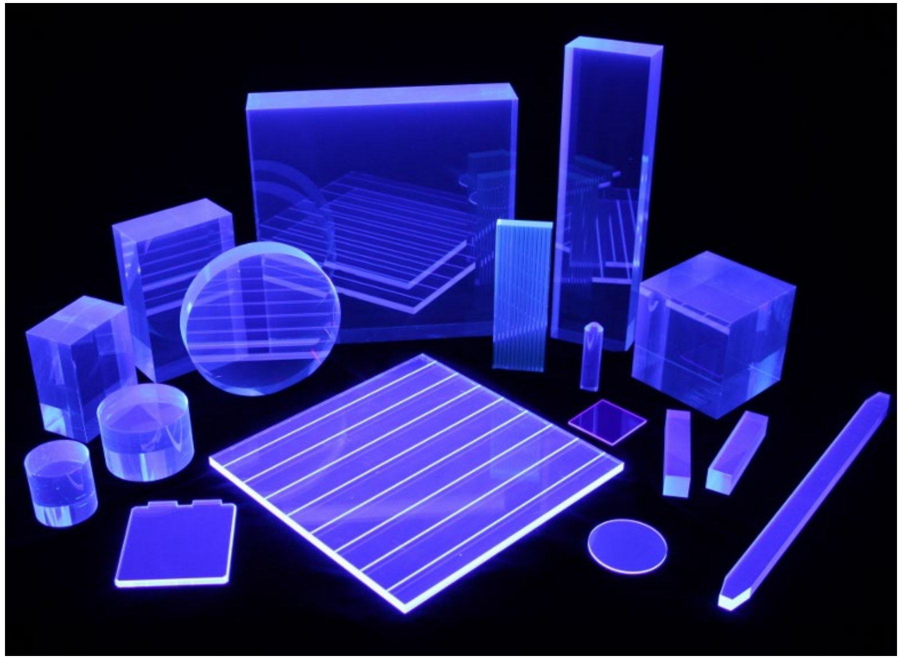
- Commonly used in numerous applications in particle and nuclear physics

- Support structure is a polymer matrix containing primary scintillator (luminophore or fluors) and wavelength shifter
  → Matrix materials: polyvinyltoluene (PVT), polystyrene (PS), Polyphenylbenzol (PPB), polymethylmethacrylate (PMMA)
  → Primary scintillators: p-Terphenyl (pTP), 2,5-diphenyloxazole (PPO), 2-phenyl-5-(4-biphenylyl)-1,3,4-oxadiazole (PBD)
  → Wavelength shifter: 1,4-di-(5-phenyl-2-oxazolyl)-benzene (POPOP), benzimidazo-benzisochinolin-7-on (BBQ)

- Advantages:
  - Cheap
  - Fast fluorescence: ≤ 3 ns
  - Possible any detector shape
  - Easy to machine

- Disadvantages:
  - Lower light yield (< 50 % of anthracene)
  - Low attenuation length (40 − 50 cm)
  - Not very radiation resistant
  - Material ageing

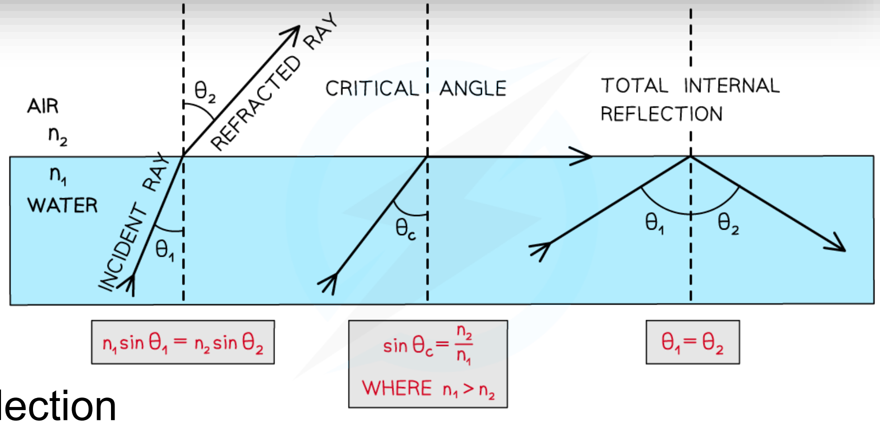

NUVIATech Instruments

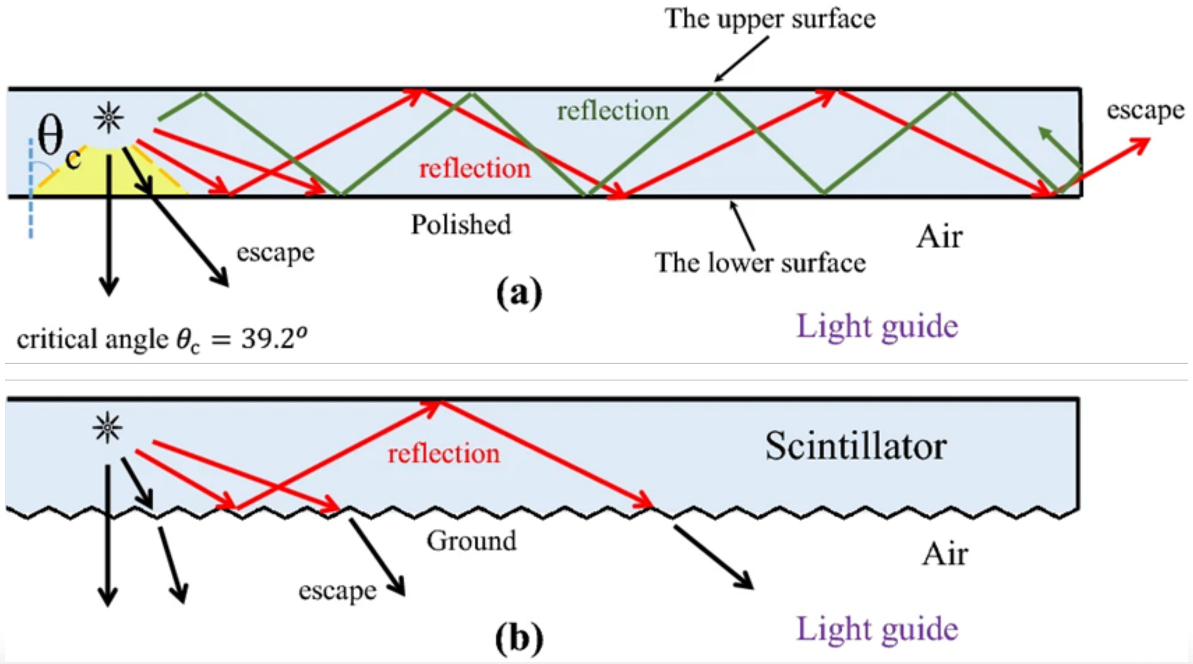

Eljen Technology

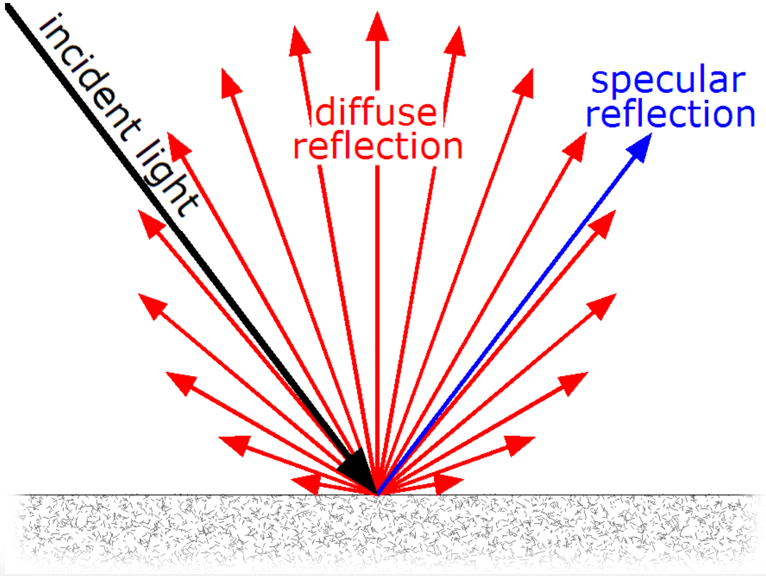
Light collection techniques

Light collection techniques → Direct reflection or use of reflective materials

- Scintillation light is produced isotopically
  - Some light fraction will be trapped in the scintillator by internal reflection
    → requires good polished surface
  - Escaping fraction can be reflected back into scintillator by an external reflector
    → requires air gap between scintillator surface and reflector to preserve internal reflection
    → specular reflector (aluminized Mylar foil) preserves angle
    → diffuse reflector (Teflon tape, Tyvek paper, titanium dioxide TiO_2) can change the angle of exiting rays to improve efficiency







Light collection techniques → Focusing light guides

- Often, scintillators cannot be directly coupled to readout devices due to space constraints or the presence of magnetic fields. Additionally, shapes of scintillators and photodetectors rarely match. To address these issues, light guides are used for coupling.

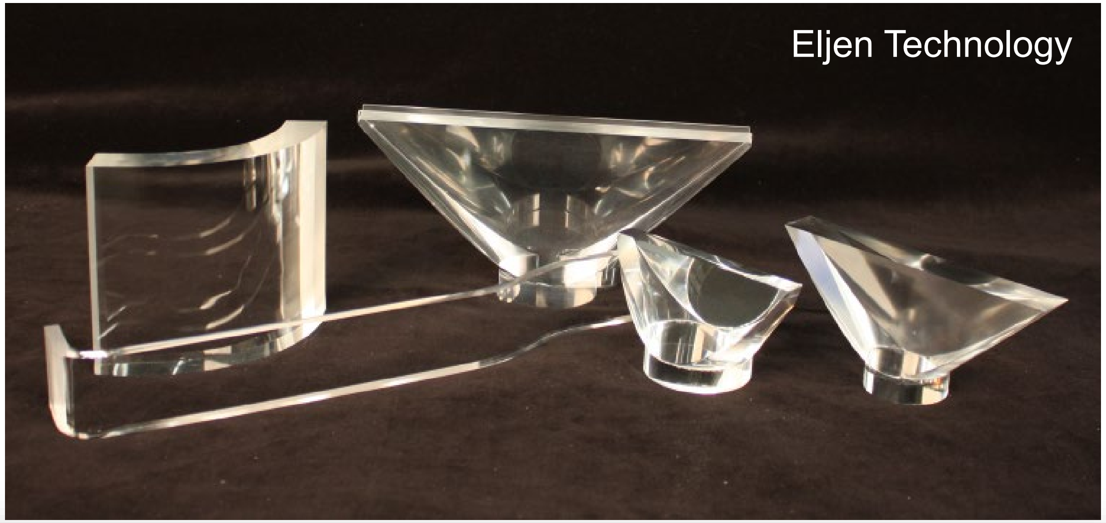
- Light is guided by total reflection (surfaces polished and with reflective coating). However, density of photons cannot be compressed (Liouville Theorem). The maximum light transferred is proportional to the ratio of surface cross sections of light guide output to input:

$$\frac{I_{out}}{I_{in}} \leq \frac{A_{out}}{A_{in}}, \qquad (A_{out} \leq A_{in})$$

A is surface cross section
I_{in} is total light intensity

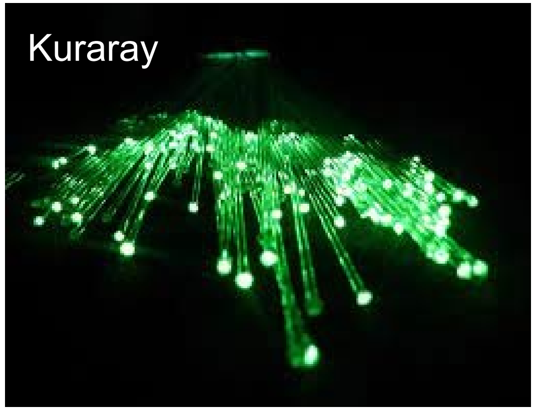
- The shape of the light guide is generally not important, but sharp kinks should be avoided.

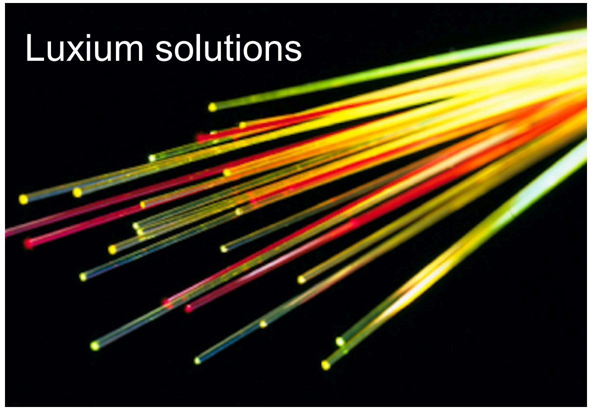
- Commonly used material polymethylmethacrylate (PMMA), often with wavelength shifter material added.

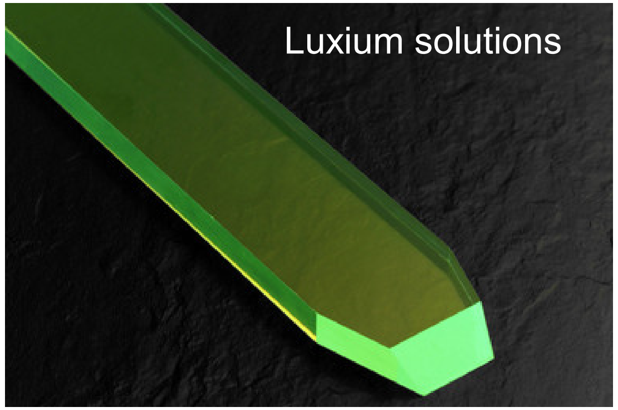


Light collection techniques → Wavelength shifting fibers (or bars)

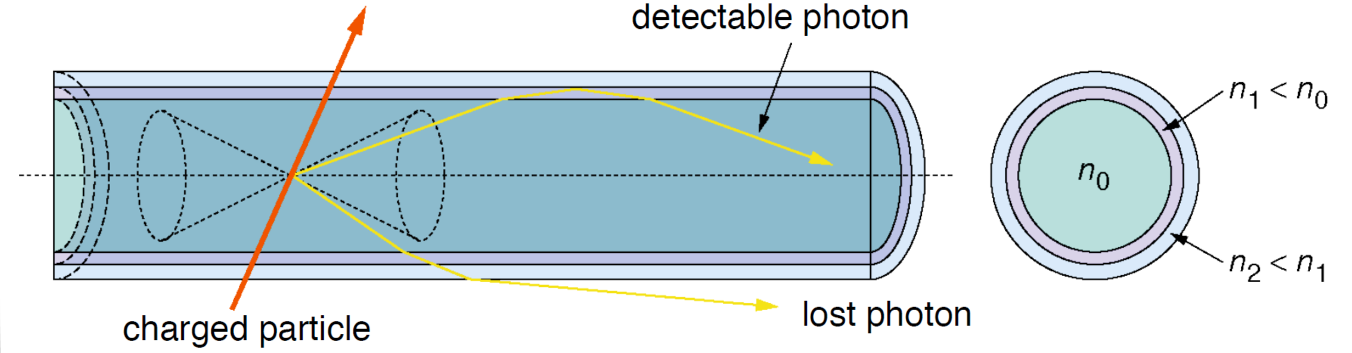
- Different fiber technologies: plastic fibers, glass fibers or capillaries filled with scintillating liquid
- Scintillating fibers are used in calorimeters, position sensitive detectors, etc.







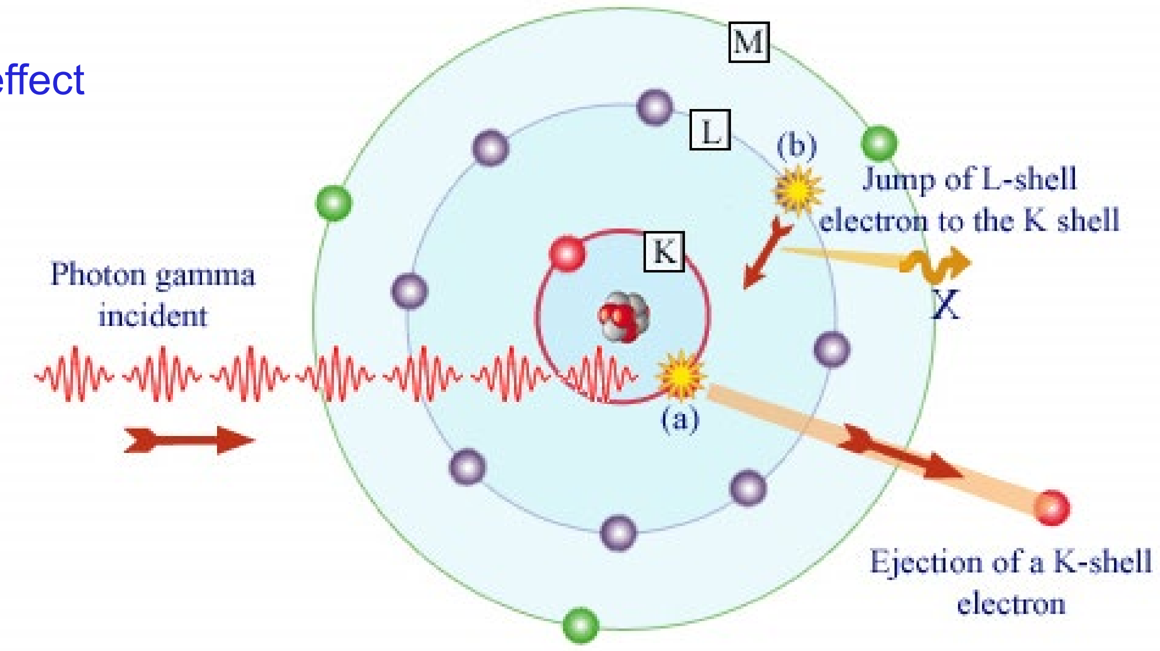
- Core of plastic fibers is made of polystyrene or polyvinyltoluene. It includes a primary scintillator and an additive for WLS.
- The core is surrounded by at least one thin layer (cladding) of a material with refraction index smaller than that of the core, resulting in total internal reflection at the boundary.
- Only a small fraction of the emitted light remains in the fiber and is forwarded through total internal reflection.



Photodetectors

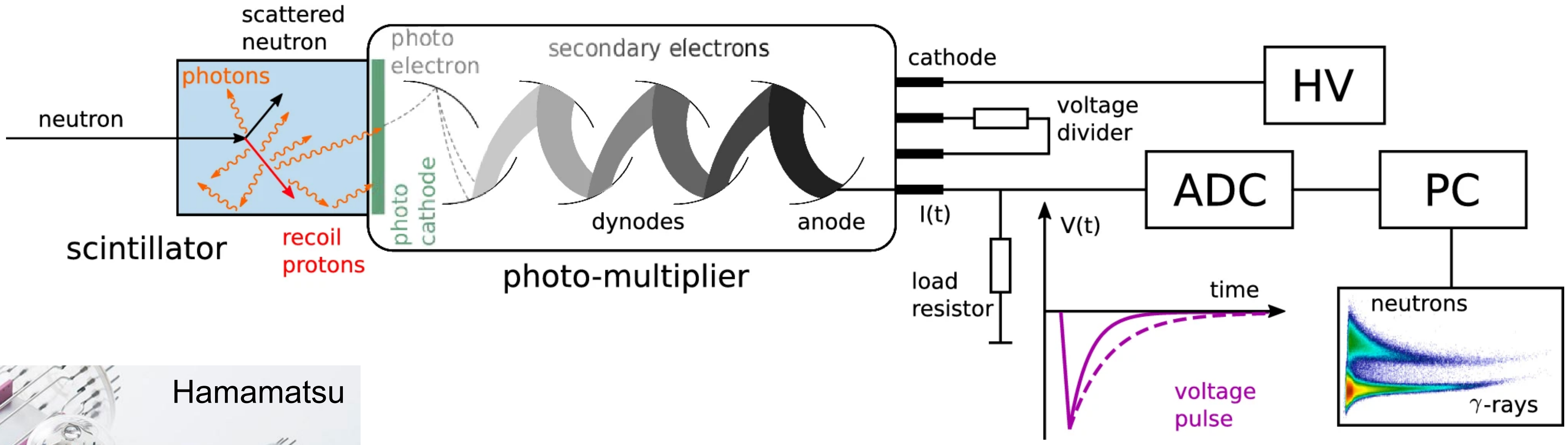
- Different photodetectors are used to collect light from scintillators and transform it into electric signals:
  - Photomultiplier tubes (PMTs) → standard and most common
  - Avalanche Photo Diodes (APDs), Silicon photomultipliers (SiPMs) → pixelated semiconductor photon detectors
  - Hybrid photon detectors (HPD) → vacuum PMT with silicon sensor
  - Gaseous photon detectors (GPD) → solid & gaseous photocathode – can cover large areas

- Photodetectors consist of two basic elements:
  - Photocathode
    - → Converts photons into photoelectrons via the photoelectric effect
    - → Performance determined by the quantum efficiency
  - Charge amplification
    - → Can involve gain or only direct conversion
    - → Performance is determined by signal-to-noise ratio
    - → Requires appropriate readout electronics



Photomultiplier tubes (PMTs)

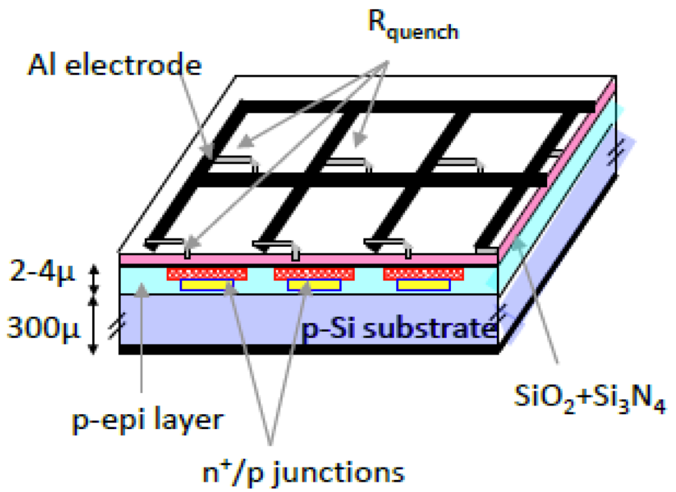
- Photons hitting the photocathode release photoelectrons (photoelectric effect). These electrons are accelerated towards the 1st dynode and produce secondary emission. This process is repeated at each dynode and finally the largely amplified electrons reach the anode.

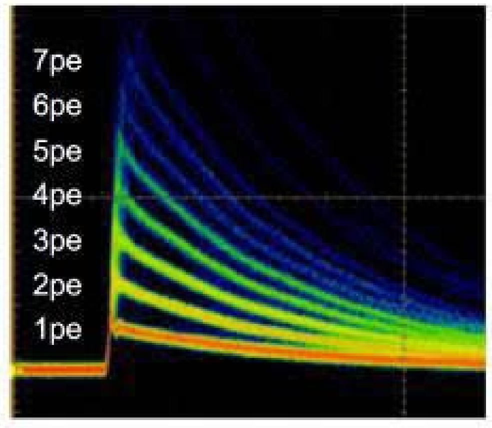


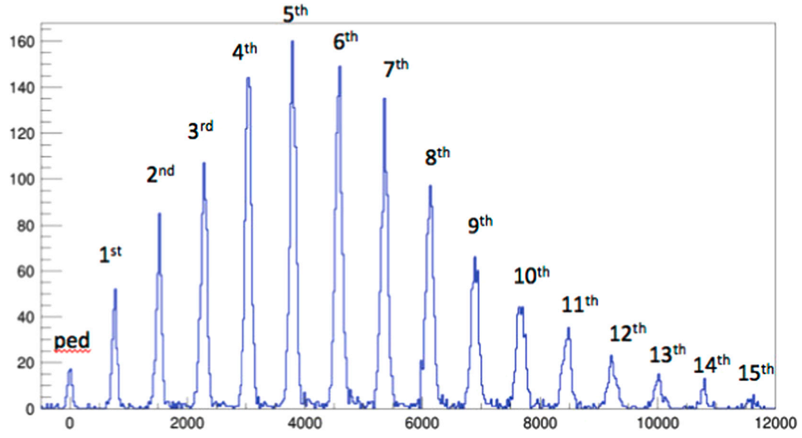
- QE ~ 10 – 30% depending on wavelength, entry window material, photocathode.
- Advantages: High amplification gains 10^4 – 10^7.
- Disadvantages: HV bias ~ up to 2000 V; sensitive to magnetic fields.

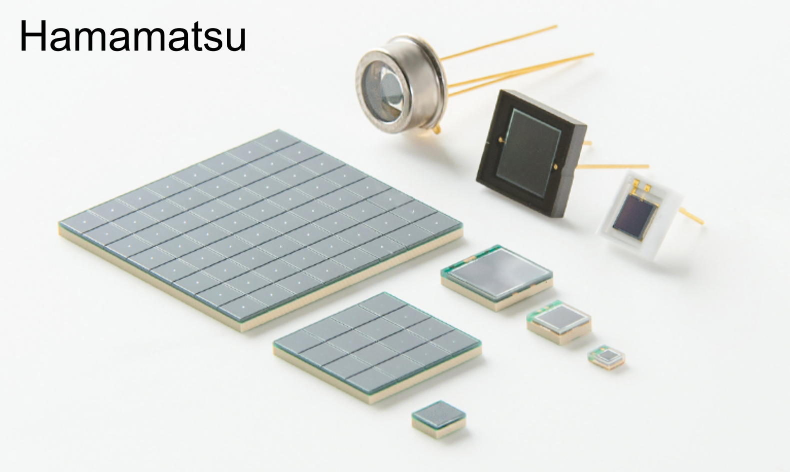
Silicon photomultupliers (SiPMs)

- SiPMs are arrays of single photon avalanche diodes biased slightly above the breakdown voltage (in Geiger mode), allowing even a single photon or particle to trigger an avalanche of electrons.









- SiPMs are increasingly favored as replacements for standard PMTs.
- Advantages:
  - Excellent single photon resolution
  - High QE and fast response < 200 ps
  - High gain in the range of 10^5 to 10^7
  - Operation at low bias voltage < 70 V
  - Insensitive to magnetic fields
  - Radiation hard
  - Small size and lightweight, Cheap

Disadvantages:
- Large dark counts
- Large temperature dependence
- Non-linear output at high incident flux (saturation of pixels)

Application examples in fundamental research

R&D of SuperNEMO calorimeter – based on polystyrene scintillators

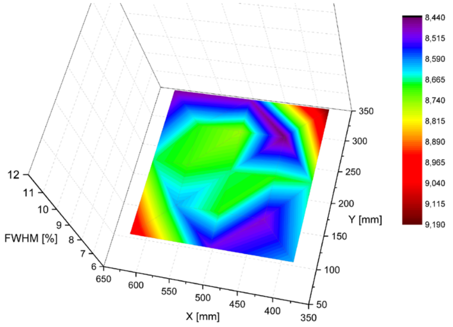
→ Search for 0νββ with 6.11 kg of ^{82}Se using tracker–calorimeter technique @LSM (located in the Fréjus tunnel near Modane, France)

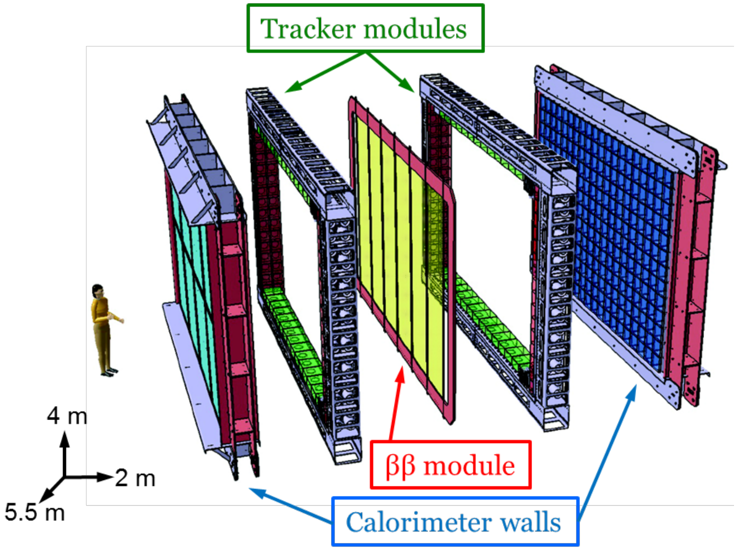
→ Improvement of PS light properties (optimization of concentrations of pTP and POPOP

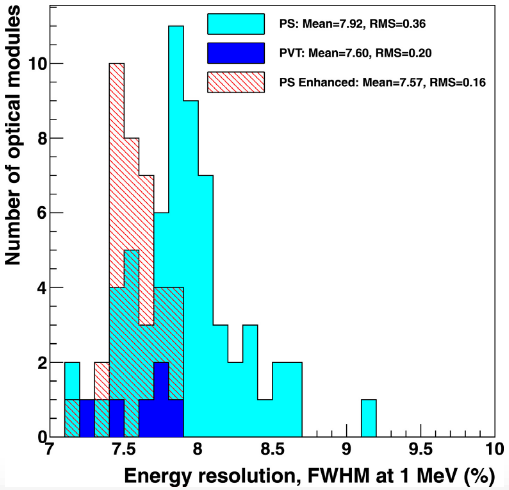
→ Czech patents (305761, 305762)

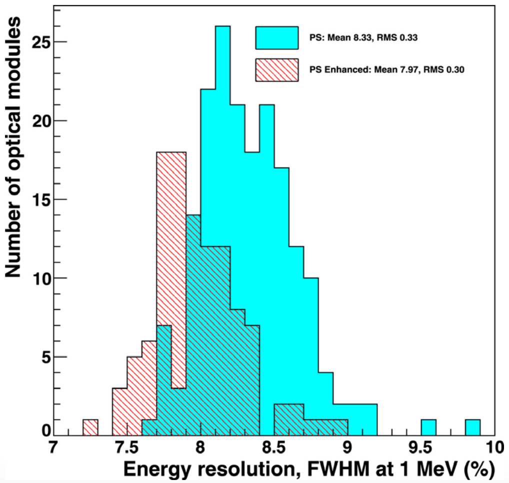
→ Close cooperation with Czech company NUVIA a.s.

→ Common laboratory with tunable electron spectrometer (200 keV – 1.6 MeV) in Kralupy n.V. (Detectors Technology Division)







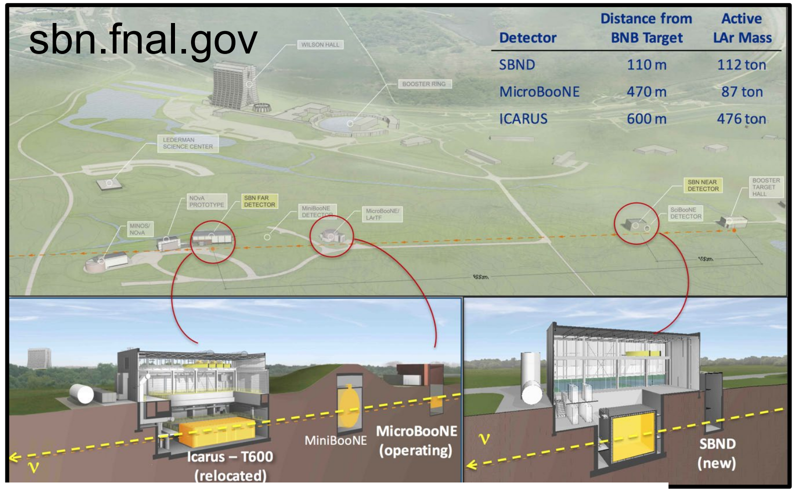


Development of CRT muon veto for ICARUS experiment (Imaging Cosmic And Rare Underground Signals)

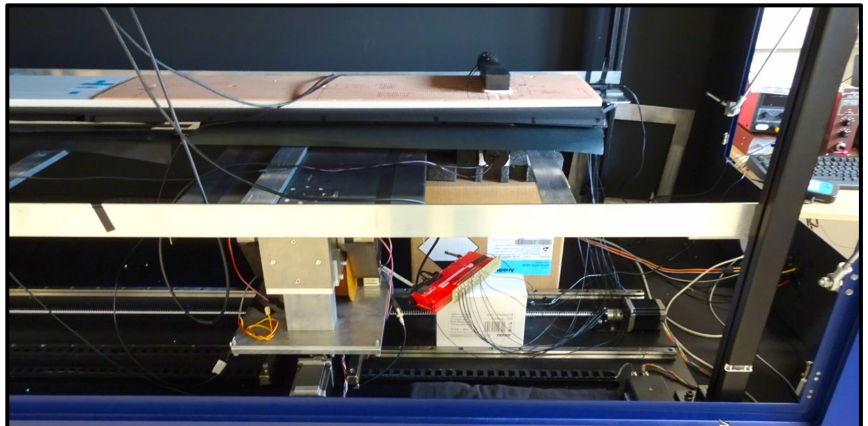
→ study of neutrino properties (oscillations of neutrinos) within Short-Baseline Neutrino Program at Fermilab, USA

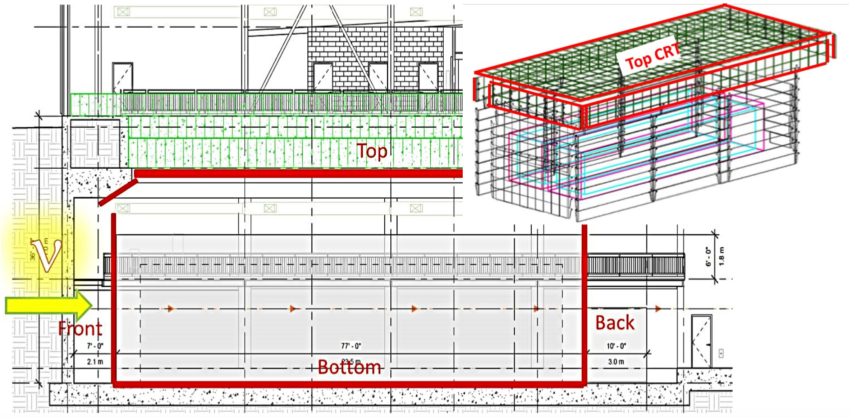
→ R&D of the muon veto (Cosmic Ray Tagger) based on PS scintillators; in cooperation with CERN & NUVIA

→ based on this experience - invitation of IEAP to the CERN Neutrino Platform – NP03 (Platform for Developing Neutrino Detectors)

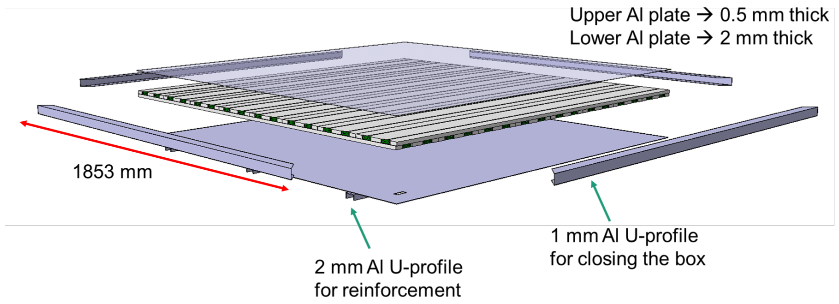



PS: 200x20x1 cm^3


measurements @ Kralupy n.V. (NUVIA a.s.)



99.9% coverage efficiency



→ 8 bars in X and 8 bars in Y directions

→ 125 modules for CRT

→ Totally 2000 bars


CRT installation: Sept.-Dec. 2021

R&D of polyethylene naphthalate (PEN) scintillator for LEGEND experiment

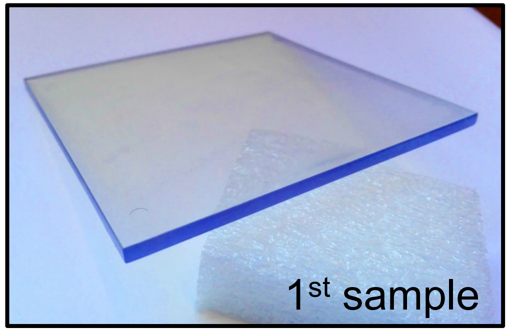
→ "PEN" consortium (Max Planck Institute for Physics Munich, TU Munich, Lancaster Univ., TU Dortmund, Oak Ridge National Laboratory, AstroCeNT Warsaw, Univ. of Tennessee, TU Dresden)

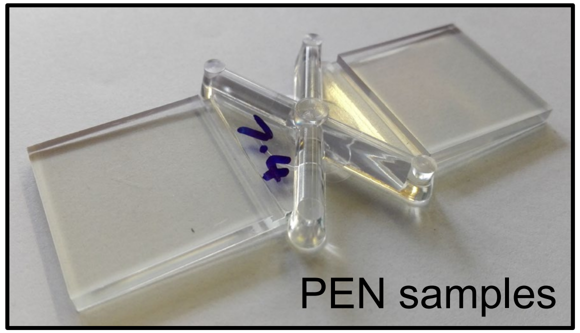
→ R&D of PEN as active self-vetoing structural material for HPGe detectors in LAr - for LEGEND experiment (GERDA + Majorana)

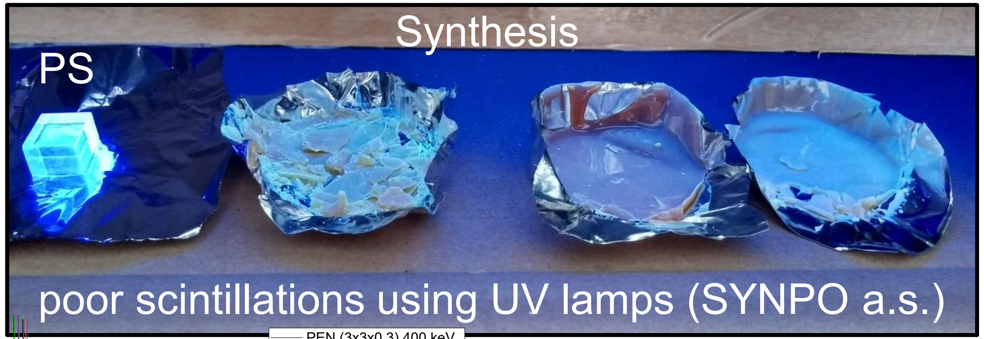
→ advantages: no fluorescent additives, radiopurity (measured on HPGe detector OBELIX @LSM), mechanically resistant, cheap

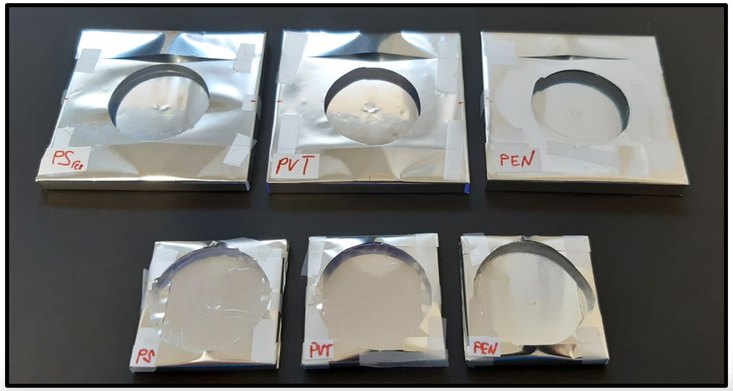
→ investigation of PEN optical properties → light output (tests with muons, ^{90}Sr, tunable electron source @Kralupy n.V.)

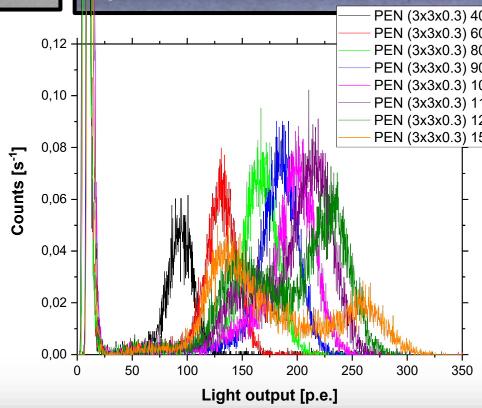
→ PEN samples prepared by injection molding technique from resin

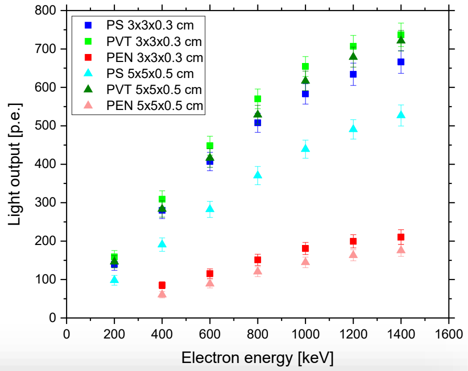












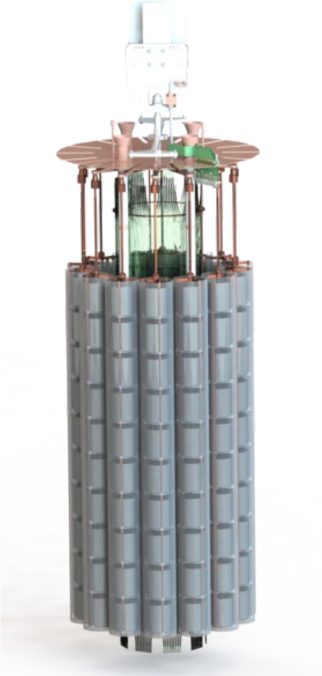
LEGEND-200 (1st stage) & LEGEND-1000 (2nd stage) experiment

→ would probe the $0\nu\beta\beta$ decay of ^{76}Ge with a sensitivity of $\tau_{1/2}^{0\nu}$ **> 10^{27} yr** at 90% (C.L.) corresponding to a range of the effective Majorana neutrino mass of **$m_{\beta\beta}$ < 33 − 71 meV** within about 5 years

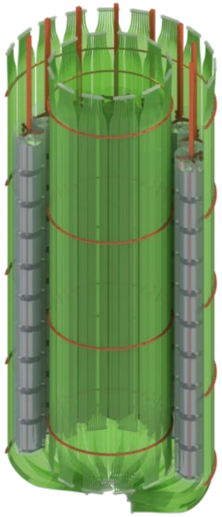
→ **L-200** will use existing GERDA infrastructure at underground laboratory Gran Sasso (LNGS, Italy)

LEGEND
Large Enriched Germanium Experiment for Neutrinoless ββ Decay

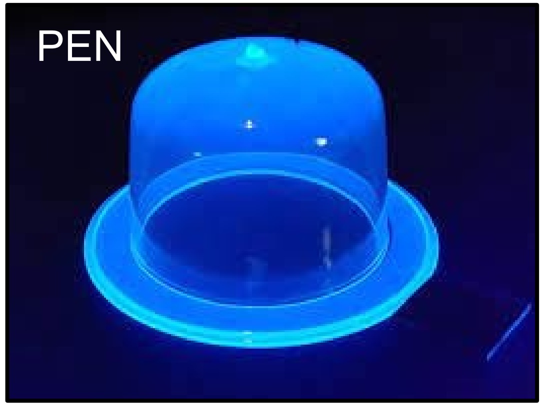
590 m³ instrumented tank filled with ultra-pure water

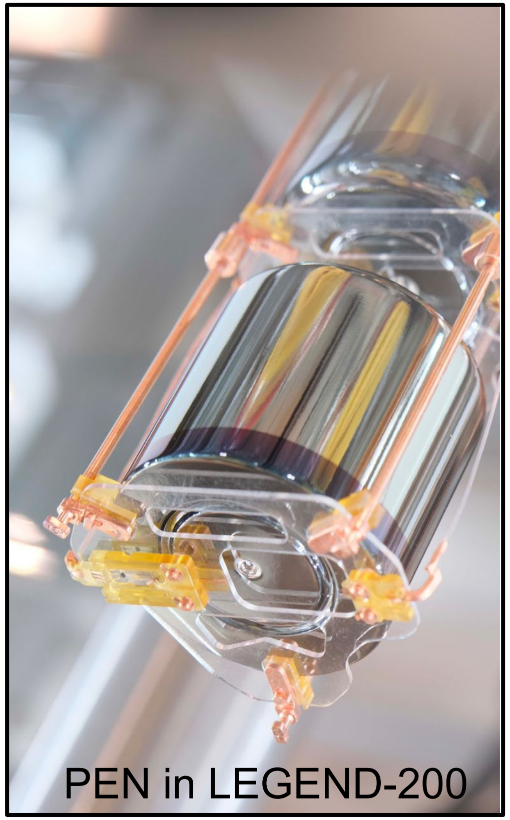


200 kg HPGe detectors



Outer & inner WLS fiber barrel

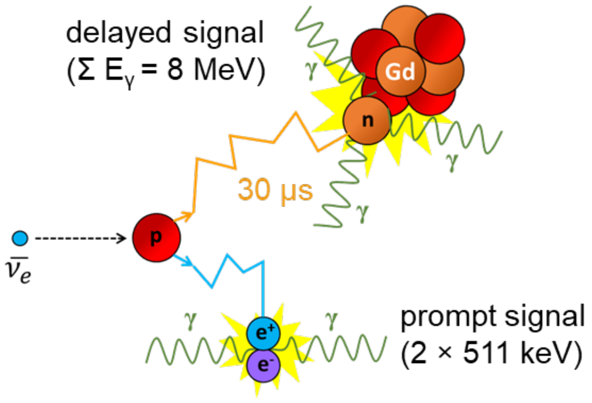


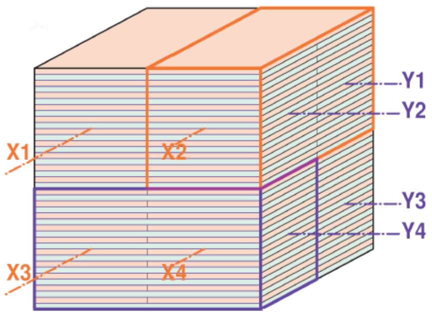


https://youtu.be/tCgWxmT2jpE

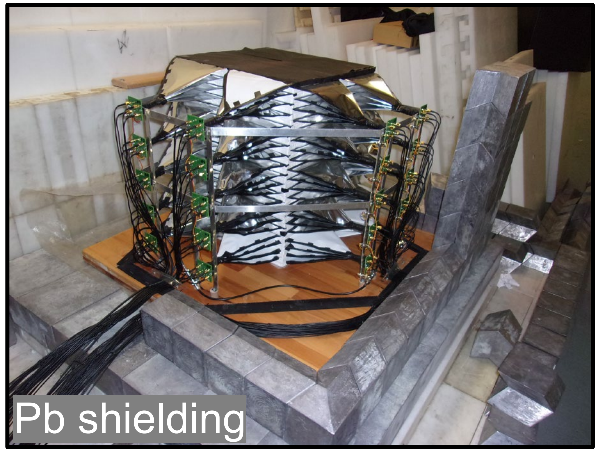
R&D of detector of reactor antineutrinos

→ detection technique → inverse beta decay
→ small prototype: 40 x 40 x 40 cm^3; 80 plastic scintillators; WLS fibers with SiPM; Gd foil (PE + Gd_2O_3); shielding (Pb, BPE, PE); 80 digital channels readout; located in nuclear shelter to suppress cosmic rays
→ new project with Comenius Univ. in Bratislava - bigger detector: more scintillating plates, $Li_6FZnS(Ag)$ instead of Gd foils



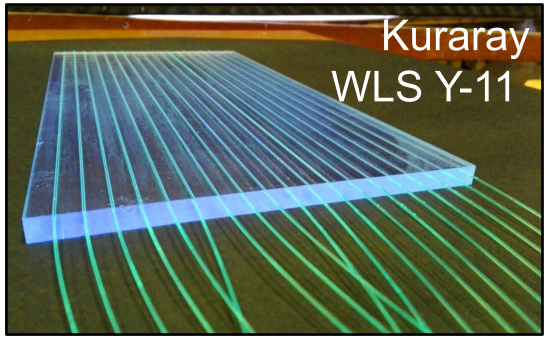


80 plates: 40 x 40 x 40 cm^3



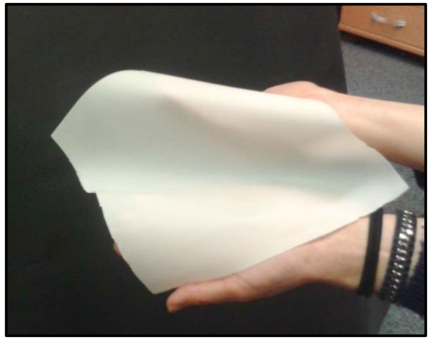
- background in nuclear shelter = 384 events/day.
- simulations: S^3 detector should be able to detect 700 IBD events under the 1 GW reactor; S/B = 1.8

→ PS composition optimization → ΔE/E best for 2% pTP and 0.05% POPOP



40 x 20 x 1 cm^3

tests of 80 plates

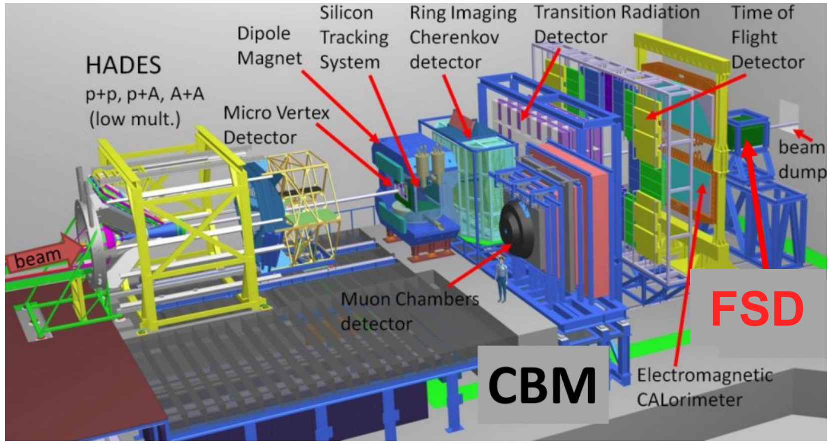


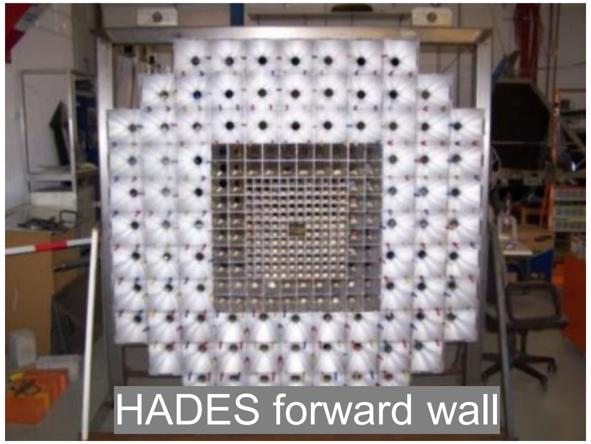
Gd foils (PE + Gd_2O_3)

BPE + PE shielding

R&D and testing of Forward Spectator Detector within future CBM experiment (at FAIR, GSI Darmstadt)

→ CBM (Compressed Baryonic Matter) – will explore the QCD phase diagram in the region of high baryon densities using high-energy nucleus-nucleus collisions



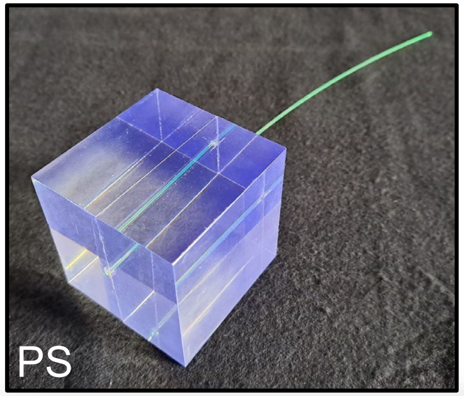


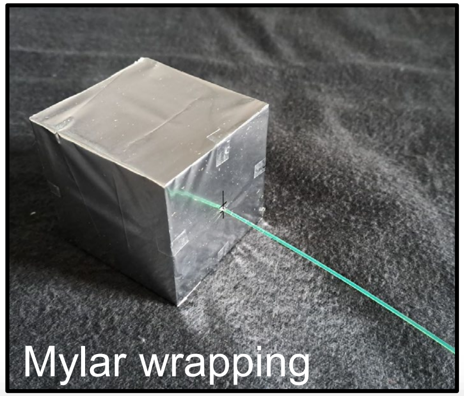
Goals:

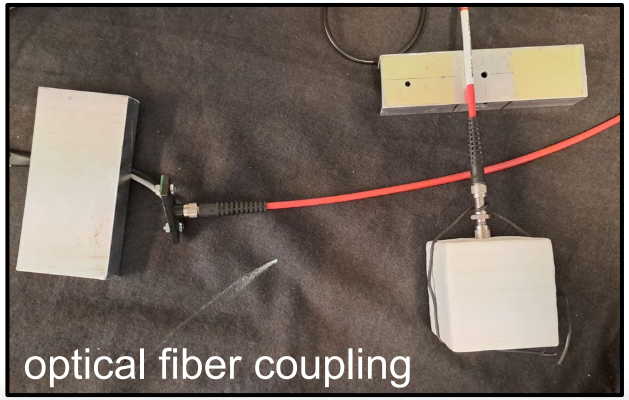
- detect nuclear fragments with E_{kin} = 1.5 to 10 A GeV at 10 MHz rate
- fast & radiation hard detectors
- WLS fibers (Y-11) and SiPM technology

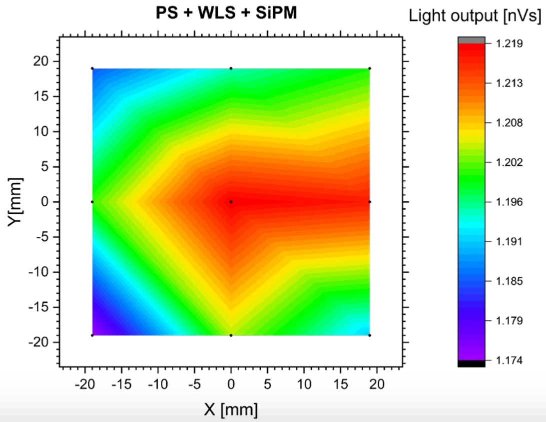
→ Cooperation with Nuclear Physics Institute CAS & Faculty of Nuclear Sciences and Physical Engineering CTU

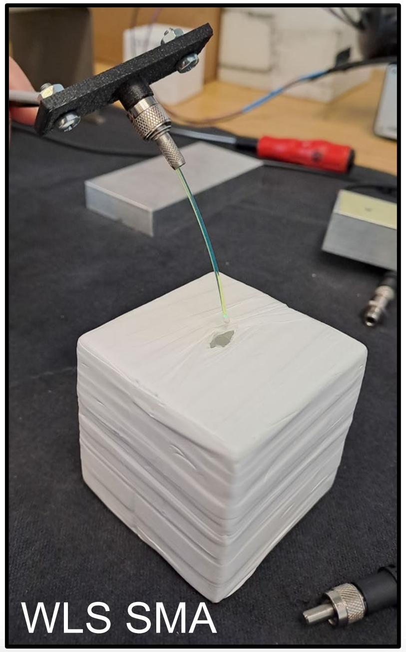
→ PS scintillators produced by NUVIA a.s. – R&D: LO, wrapping, WLS & optical fiber couplings, etc.











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Thank you for attention!

INSTITUTE OF EXPERIMENTAL AND APPLIED PHYSICS CTU IN PRAGUE

Nuclear Physics Institute

CERN

LSM Laboratoire Souterrain de Modane

supernemo collaboration

LEGEND Large Enriched Germanium Experiment for Neutrinoless ββ Decay

Imaging Cosmic And Rare Underground Signals

CBM

Back-up

Property	Plastics	Inorganics
Light yield	Up to 10 000 photons/MeV	Up to 100 000 photons/MeV
Decay time	0.3–280 ns, low afterglow	Down to sub ns
Emission wavelength	580 nm–650 nm	180 nm–IR
Material loading	Multiple elements	Multiple elements
Effective atomic number	Low (mostly H, C and O): 5.7	Can be high (> 60)
Density	1.04–1.56	Up to 9
Radiation hardness	Up to ≈ 30 kGy with γ-rays	Depends on impurities
Temperature dependence	Low below 40 °C	Can depend from low to high temperature
Humidity	Partially fogging with moisture	Some are hygroscopic
Magnetic field influence	Light output increase with magnetic field	No studies