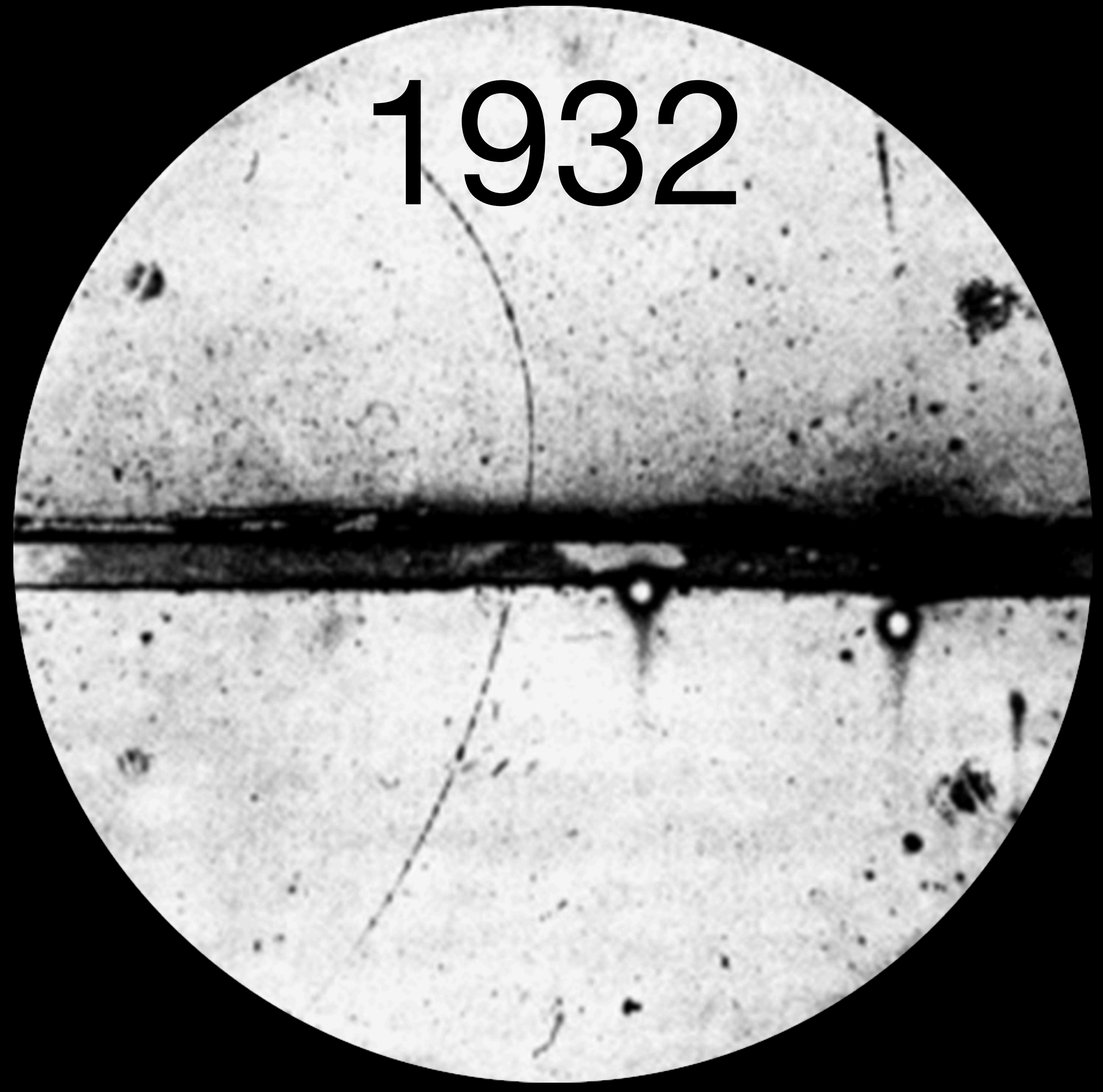
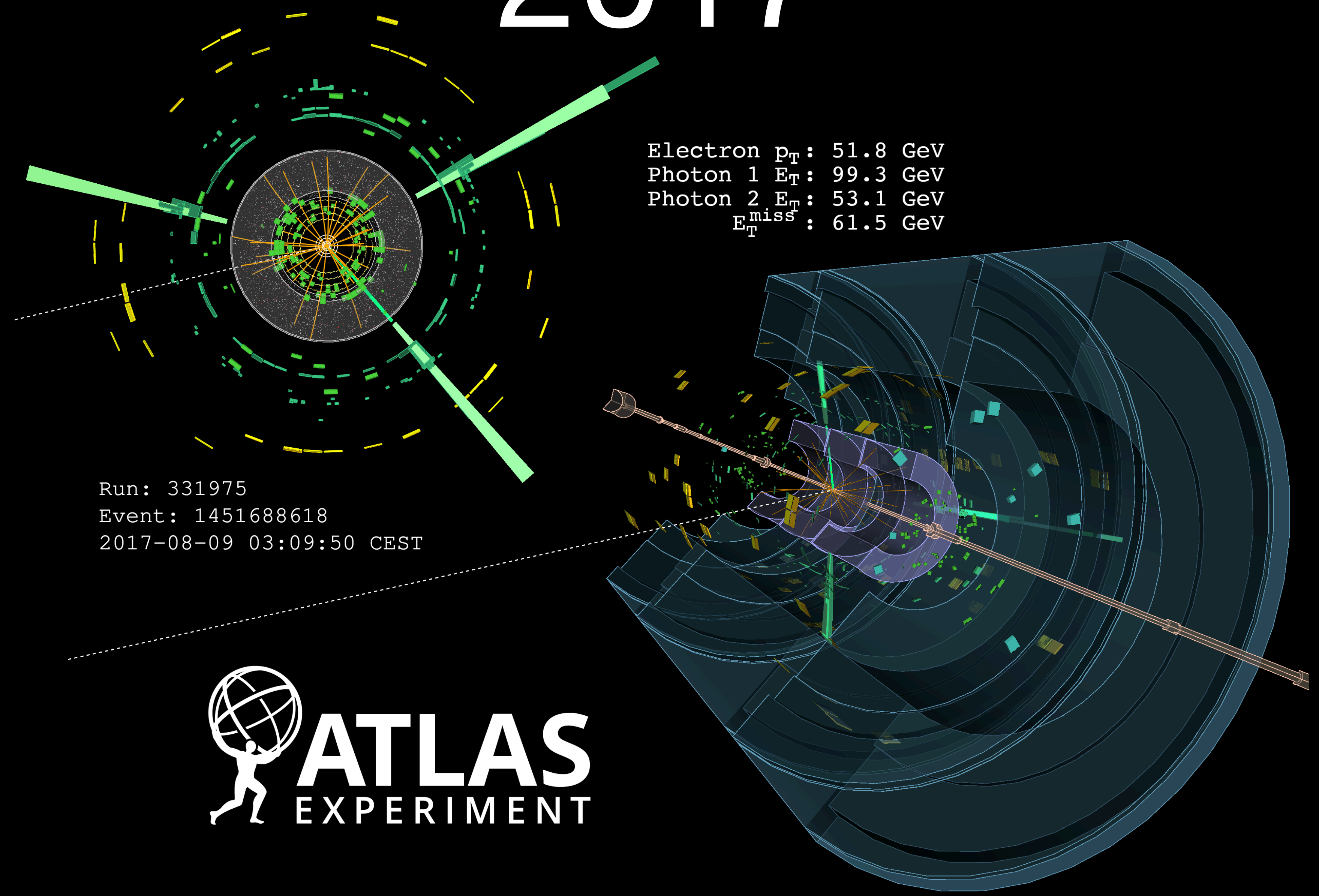
PHYS 7363 - Experimental Particle Detection and Detectors I



Particle detectors are the workhorses of experimental physics. In this course, we'll dive deep into their physics, exploring the incredible evolution of our experimental techniques over the past nine decades. You'll gain a solid understanding of *particle detection* and *identification*, examine the intricate designs of modern detectors, and learn how machine learning is being harnessed to push the boundaries of detector design. If you're intrigued by how we “see” subatomic particles, this course is for you!

2017



Detect Identify Measure

To discuss prerequisites (and any questions on the content of the course), please contact me: saptaparnab@smu.edu

Schedule

Month	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
October	6 ✓ 1.5 hours	7	8 ✓ 1.5 hours	9	10	11	12
	13 ✓ 1.5 hours	14	15 ✓ 1.5 hours	16	17 ✓	18	19
	20	21	22	23 ✓ 1.5 hours	24 ✓ 1.5 hours	25	26
	27: Midterm	28	29 ✓ 1.5 hours	30	31 ✓ 1.5 hours	1	2
November	3 ✓ 1.5 hours	4	5 ✓ 1.5 hours	6	7 ✓ 1.5 hours	8	9
	10	11	12	13	14	15	16
	17	18	19	20	21	22	23
	24	25	26	27	28	29	30
December	1	2	3	4	5	6	7
	8	9	10	11	12	13	14

Scintillators

- Detecting ionizing radiation by observing scintillation light: one of the oldest techniques for radiation detection
- Scintillation: creation of luminescence by absorption of ionizing radiation
- Scintillators for particle detection:
  - Energy deposited in the scintillator should be converted into light with high efficiency
  - Light yield $L_S = \left\langle N_{ph} \right\rangle / E,$ defined as the number of photons of a certain wavelength per deposited energy E should be proportional to energy released (linear response)
  - The scintillation medium should be transparent for the wavelength of the scintillation light
  - The light emission processes should be as fast as possible in order to obtain a fast signal pulse
  - The refractive index of the scintillating material should be close to that of the attached readout unit in order to ensure efficient light transmission
  - Light collection efficiency should be as large as possible
  - Scintillating material should have high Z or low Z and low atomic mass

Scintillators

- Scintillation signals allow measurements of:
  - Energy: linear response of the scintillator → light output is proportional to energy depositio
  - Timing: short pulses and fast recovery times
- Physics:
  - Material absorbs energy and re-emits energy as visible light
    - Fluorescence: immediate re-emission of ligh ($\tau < 10^{-8}$ s)
    - Phosphorescence: delayed emission of meta-stable states
- Time evolution:

$$N(t) = N_f \exp(-t/\tau_f) + N_s \exp(-t/\tau_s)$$

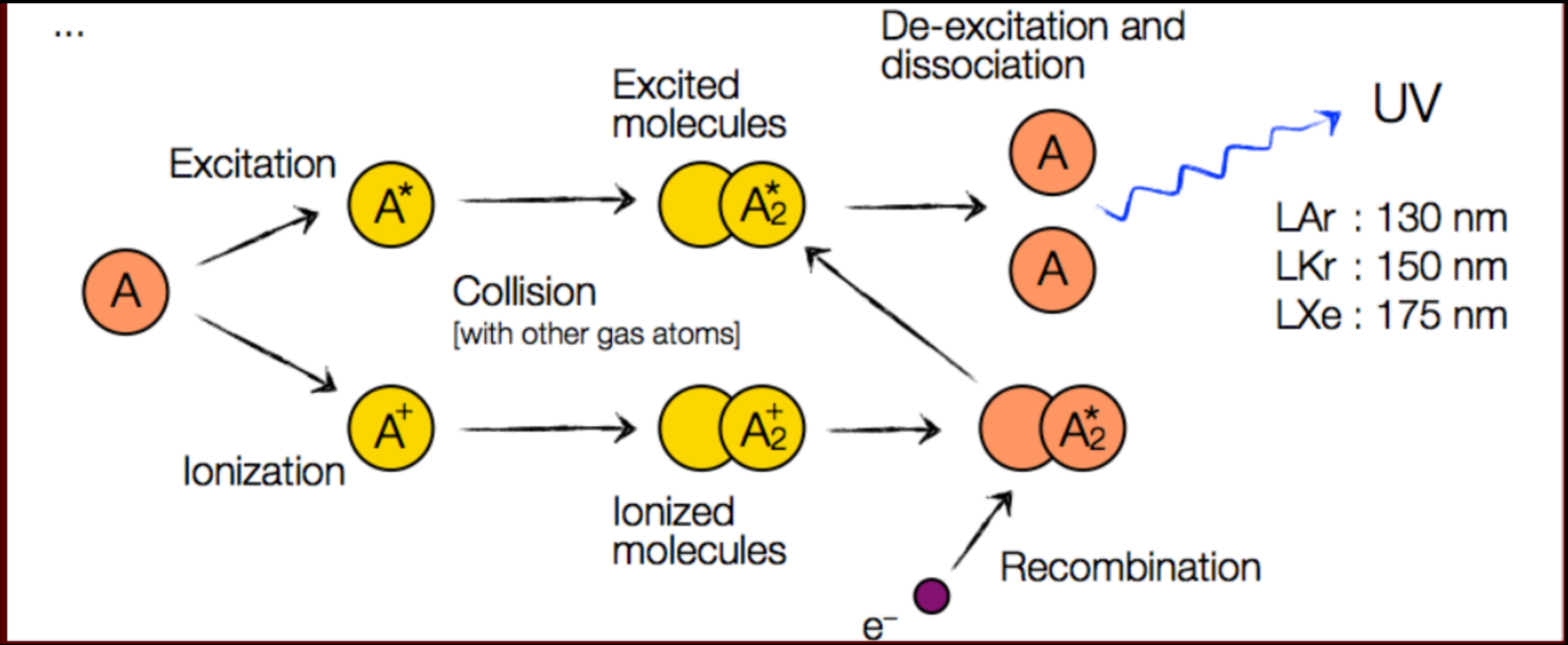
Based on Roger Russack's lecture at Fermilab

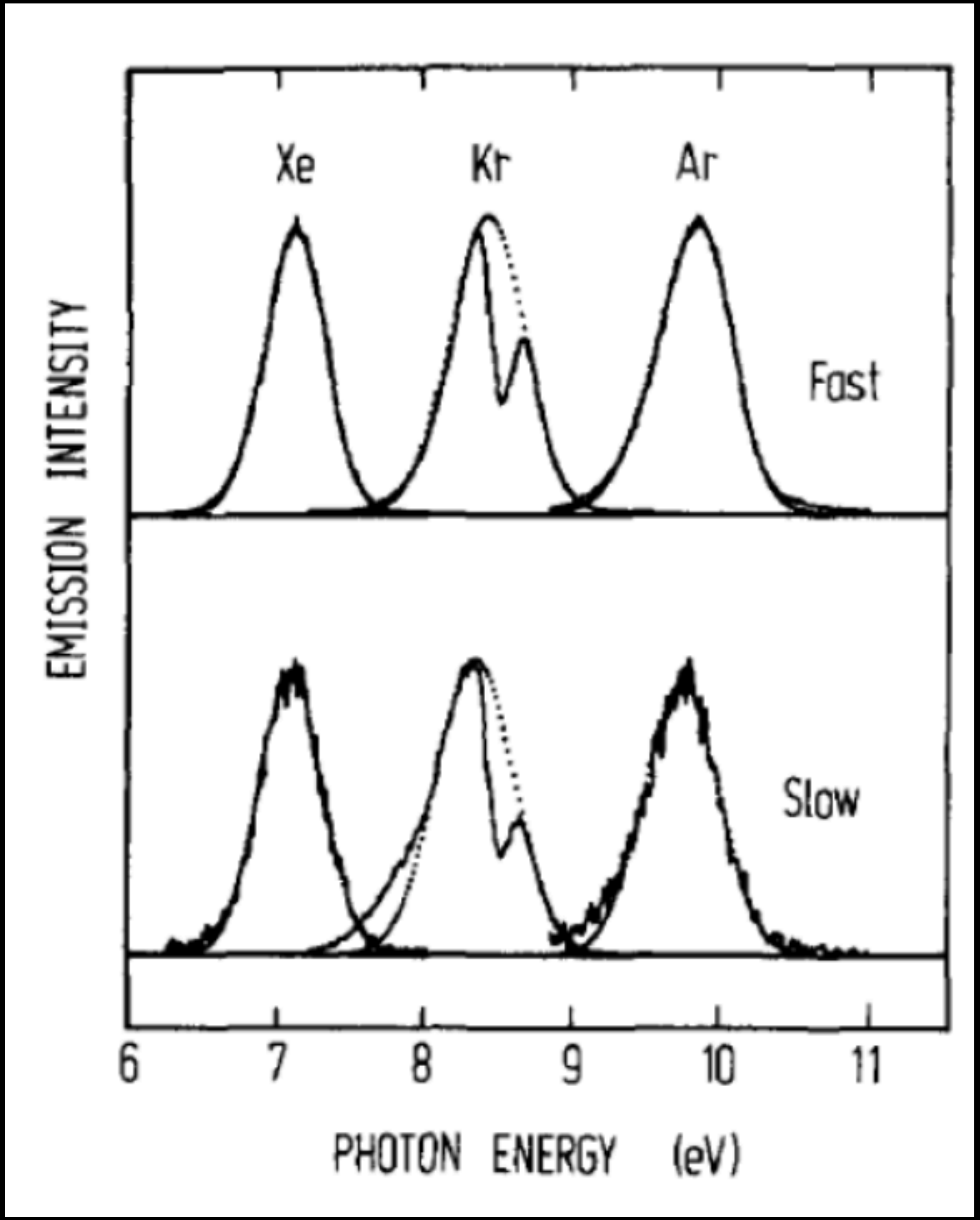
Scintillators in ATLAS

- These slides are rather good: https://cds.cern.ch/record/2835898/files/ATL-TILECAL-SLIDE-2022-532.pdf

Scintillators

- Argon, Xenon and Krypton emit scintillation light in the far UV
- The physics process is the formation of excimers (Ar$^+$Ar) that de-exite emitting a photon with a time constant of ~6 ns
- For liquid argon, the peak wavelength is 128 nm
  - A wavelength shifter is required to shift to the optical region





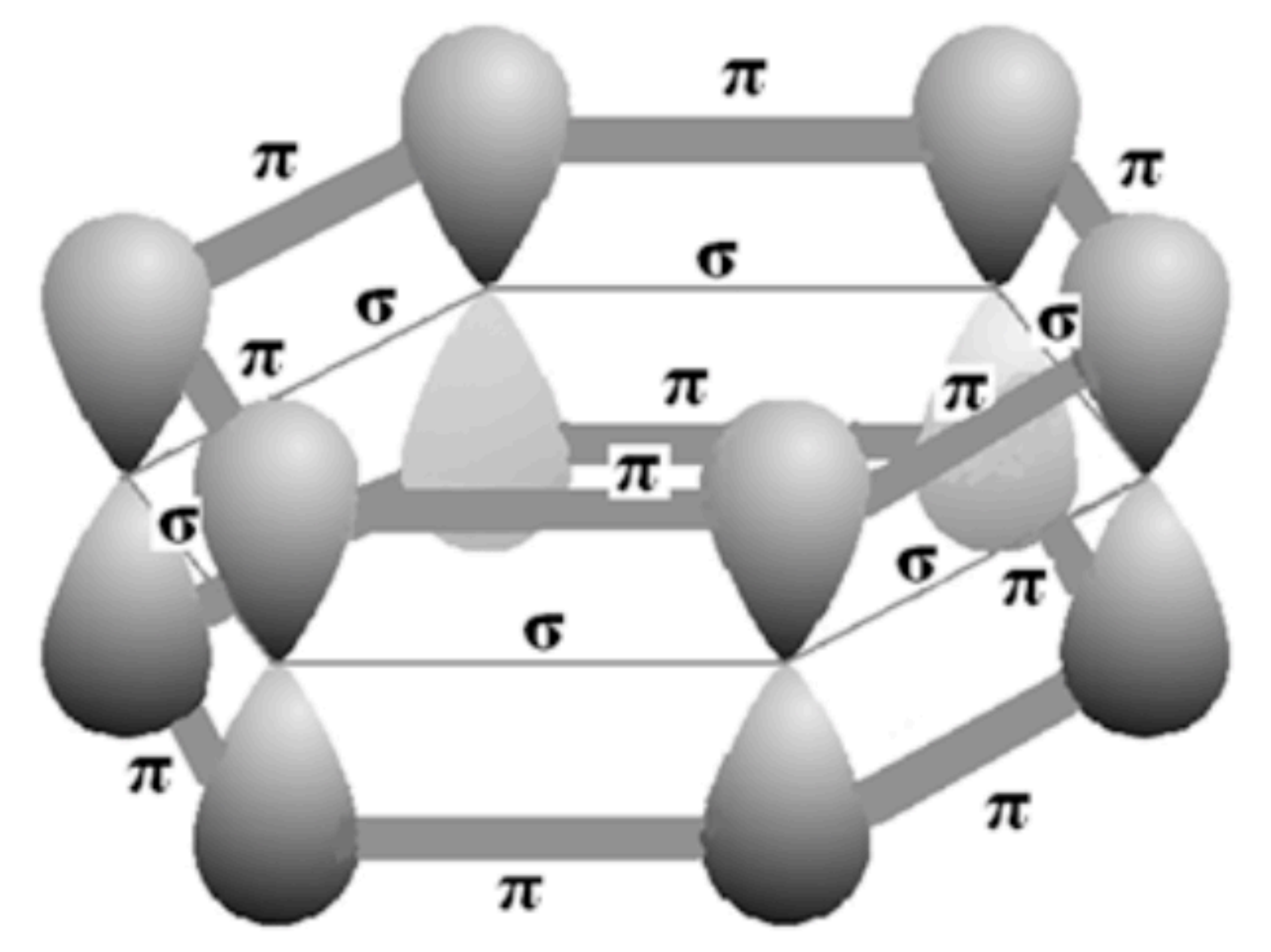
Based on Roger Russack’s lecture at Fermilab

Scintillation Mechanism

- The mechanism generating scintillation light depends on the type of the scintillator material and is very different for organic and inorganic scintillators
- Absorbed energy leads to excitations of atomic/molecular states or crystal excitations
- Organic scintillators: scintillation mechanism largely determined by the electronic structure of the carbon atom
  - Typically solid in crystalline form like naphthalene $C_{10}H_8$
  - In polymerized form, they are plastic scintillators

Organic scintillators

- Light emission at the molecular level
- Plastic scintillators are made with a build material that contains a benzene ring
  - Polystyrene, Acrylic, polyvinyl toluene
- Liquid scintillators have as the build
  - Mineral oil, toluene
- Interaction energy is transferred to fluors bringing emitted radiation to the optical region where it can be detected



What experiments use liquid scintillators

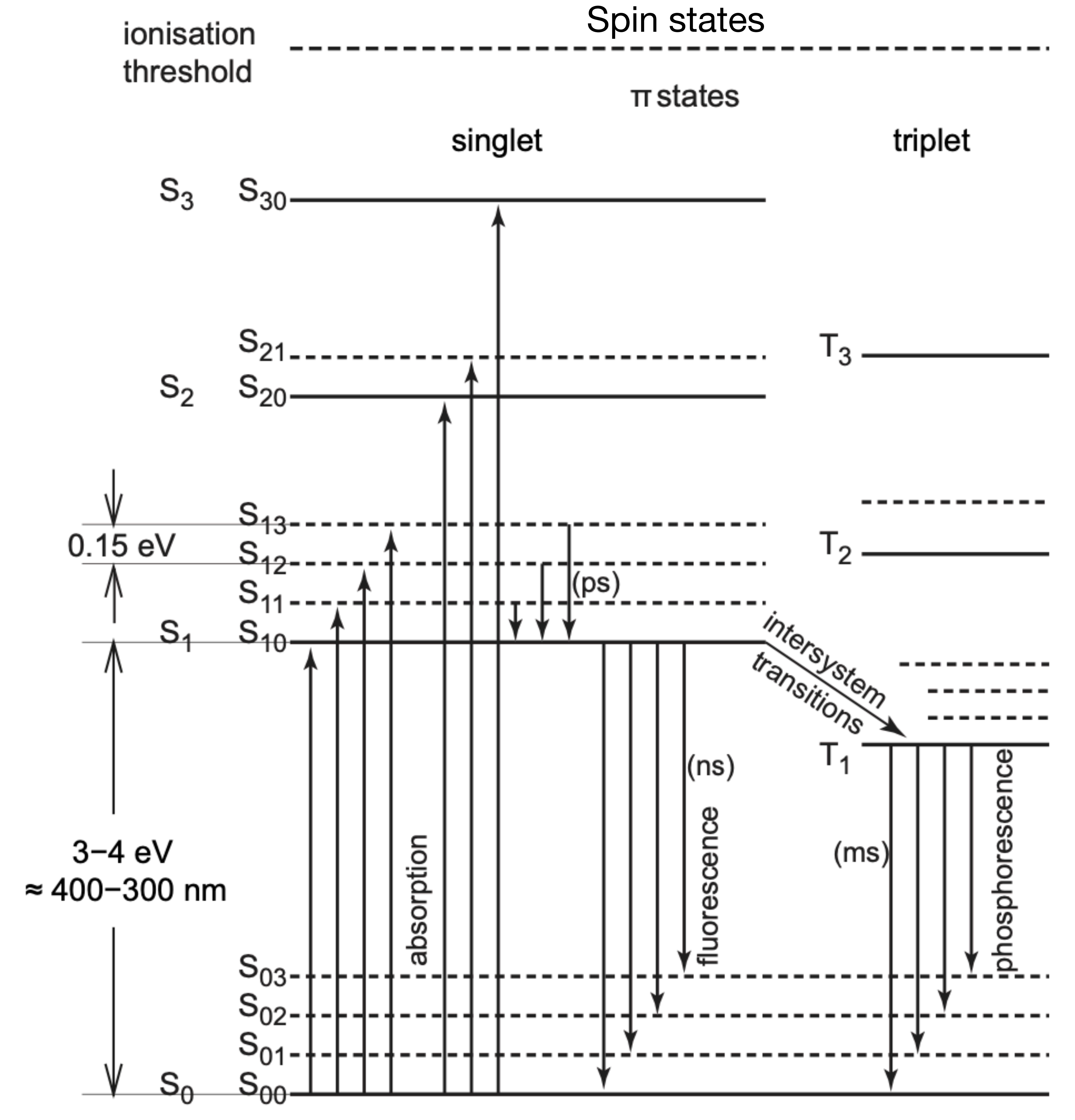
- Spend some time to look it up
  - A primary agent is dissolved in an aromatic solvent to increase the quantum efficiency. The requirements on purity standards are high in order to avoid unwanted effects like the decrease of transparency or, most importantly, a degradation in light output.
- Hint: NOvA detector: https://arxiv.org/pdf/2012.08262

What experiments use liquid scintillators

- Properties (based on classroom responses)

Scintillation Mechanism

- Ionization: absorption into electron and vibrational level (S_{ij})
- Internal degradation to S_{10} (Franck-Condon principle: nuclear configuration of the molecule experiences no significant change during electronic transitions)
- Fluorescence transition
- Non-radiative energy transfer $(S_{10} \rightarrow T_1)$
- Phosphorescence transition



Plastic Scintillators

- Usage: Plastic scintillators are mostly used to detect charged particles and neutrons
  - Simple handling, cheap fabrication to almost any desirable shape, and by their robustness and reliability
  - Which parts of ATLAS or CMS detectors use plastic scintillators?
  - Interesting presentation: https://cds.cern.ch/record/2835898/files/ATL-TILECAL-SLIDE-2022-532.pdf
  - Discussion of scintillators for muon chambers: https://indico.cern.ch/event/1539488/contributions/6478464/attachments/3059924/5410649/3_UTF-8muon-FCCee-v4.pdf

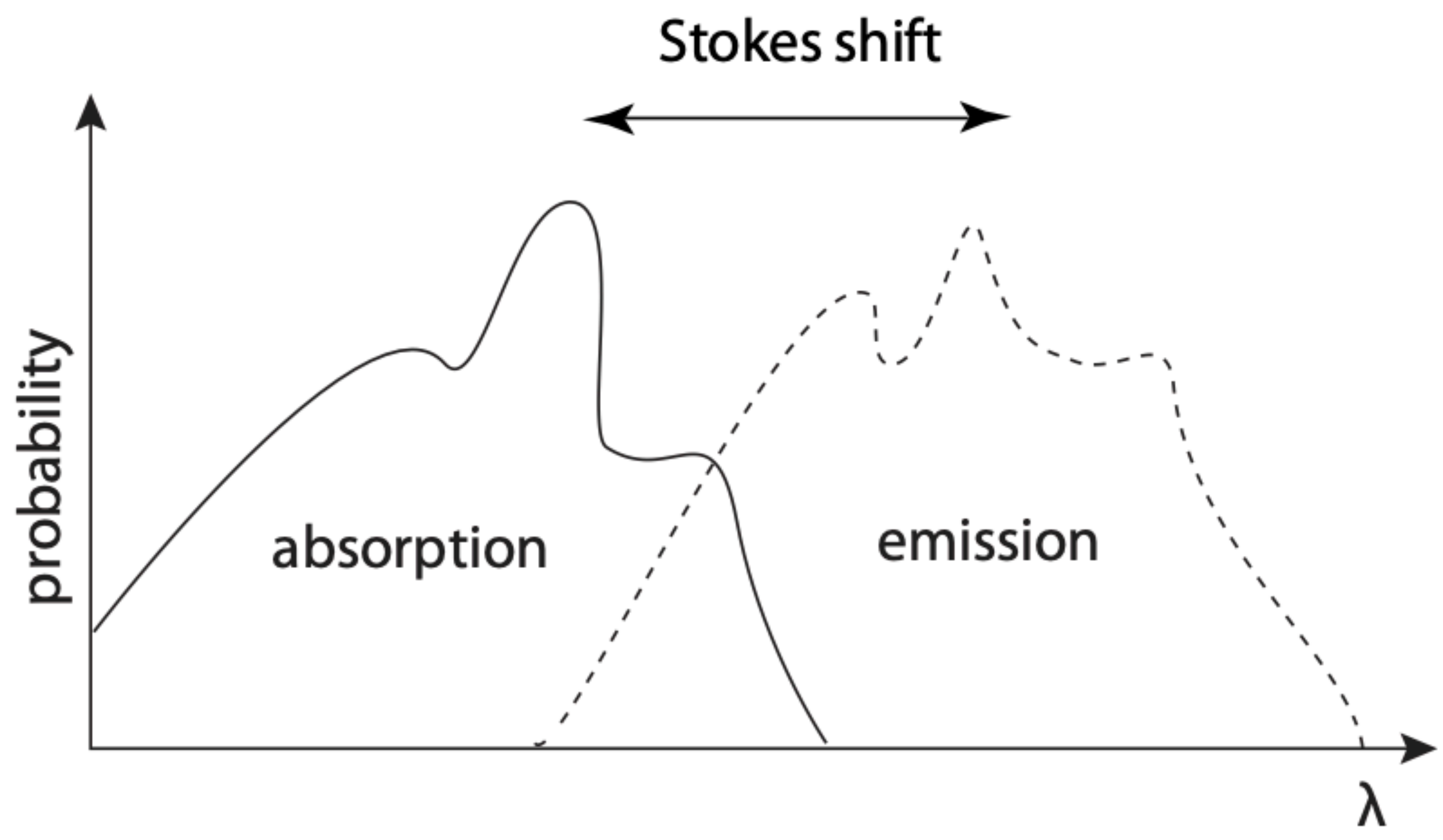
Scintillators — typical setup

- Part 1
  - *Scintillator:* converts ionizing radiation into light. In order to prevent light from escaping the scintillator medium or entering from outside, the scintillator is made light-tight by a foil which is reflecting on the inside, for example an aluminum foil or diffusely backscattering white paper
- Part 2
  - *Light guide:* The part (i.e. the areal cross section) of the scintillator through which the light must pass towards the photomultiplier. A light guide is most often made of plexiglass

Scintillators — typical setup

- Part 3
  - *Photomultiplier:* The photomultiplier tube (PMT) converts scintillation photons into electrons in its photocathode and provides low-noise amplification
- Part 4:
  - *Amplifier:* The output pulse of the photomultiplier can in most cases be processed without further electronic amplification. Only needed in some cases

Stokes Shift

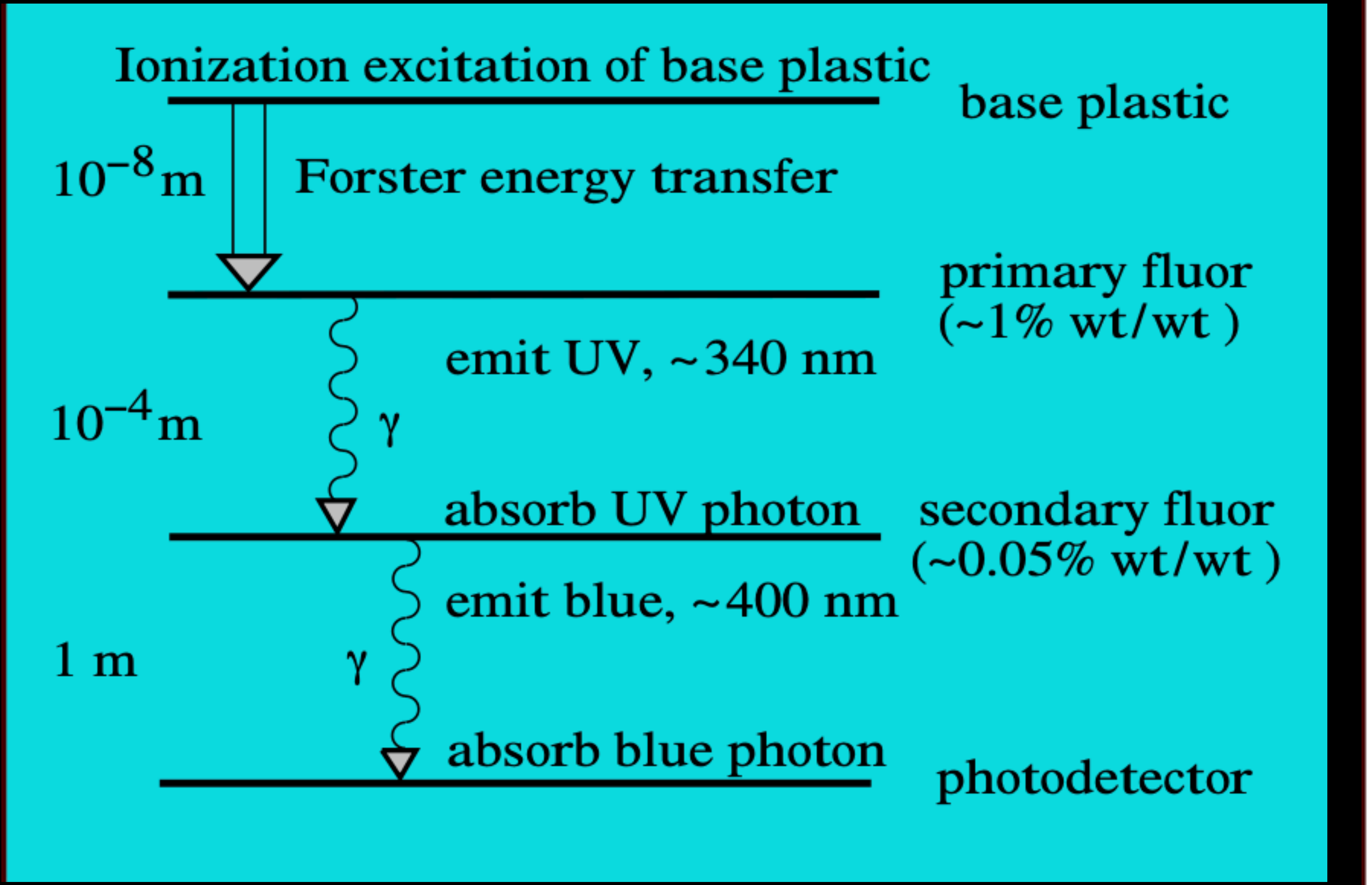


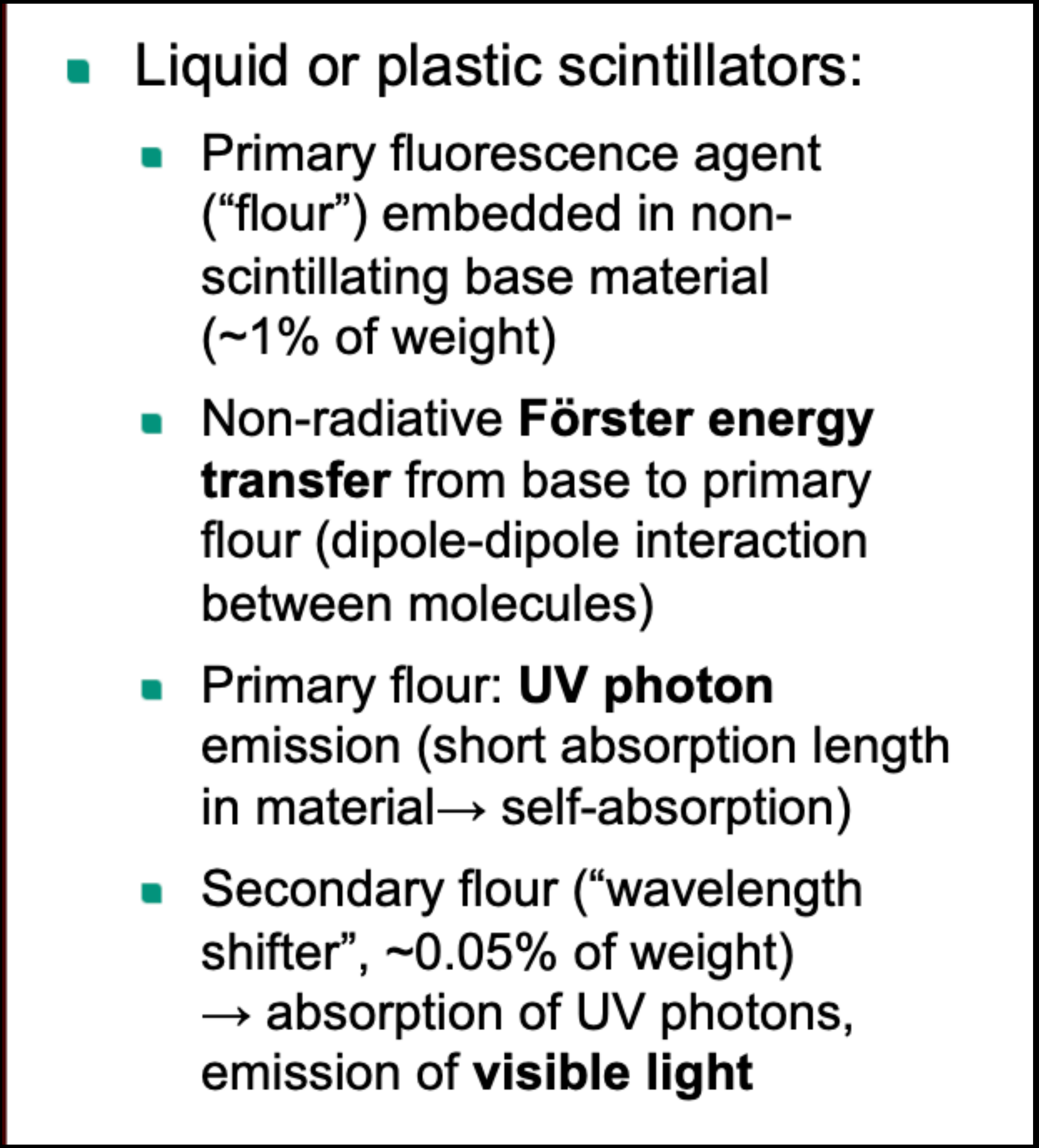
For detectors one aims for a high light yield with little self-absorption. The wavelength ranges for absorption and emission should hence overlap as little as possible

Fig. 13.2 Absorption and emission spectrum of scintillators (schematic).

Wavelength shifters

- Excitation energy of the liquid or the plastic is transformed to visible light through a sequence of energy transfer





- Liquid or plastic scintillators:
  - Primary fluorescence agent (“flour”) embedded in non-scintillating base material (~1% of weight)
  - Non-radiative **Förster energy transfer** from base to primary flour (dipole-dipole interaction between molecules)
  - Primary flour: **UV photon** emission (short absorption length in material→ self-absorption)
  - Secondary flour (“wavelength shifter”, ~0.05% of weight) → absorption of UV photons, emission of **visible light**

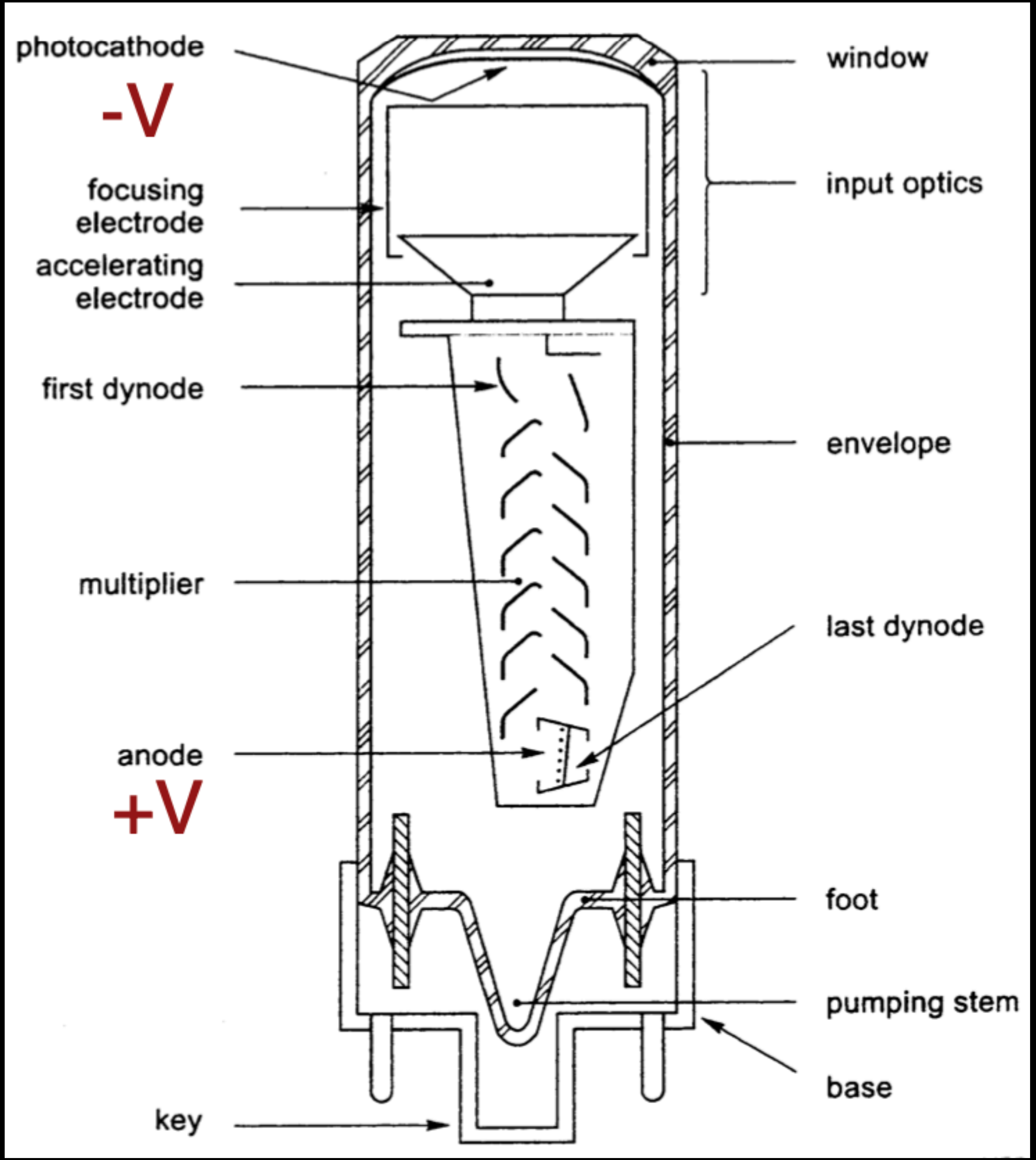
Förster resonance energy transfer (FRET) is a **non-radiative energy transfer process from an excited molecule (the donor) to another nearby molecule (the acceptor), via a long-range dipole-dipole coupling mechanism**

Light detection

- Goal is to convert optical signal to an electronic signal
- Principle:
    - By photoelectric effect covert photon to photo-electron current
    - Amplify the current so that it can be detected
- Different applications - different requirements
    - Single photon counting
    - Multi-photon detection
- Available technologies
    - Photomultiplier tube (PMT)
    - Photodiode or hybrid photodiode
    - Avalanche photodiode (APD) and the Silicon Photomultiplier (SiPM)

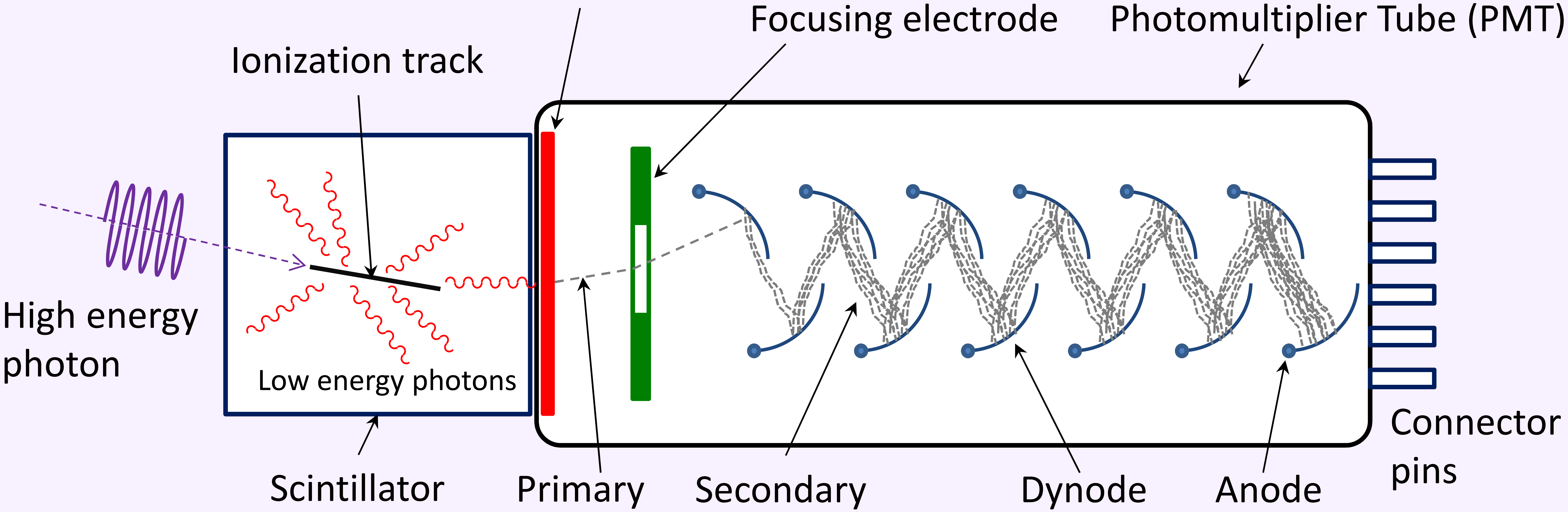
Photomultiplier tubes

- Type of photodetector that has been used for many years in HEP experiment
  - Photocathode on entrance window, treated with high emissivity material, absorbs incoming light and releases a photoelectron
  - Focussing element to steer the photoelectrons onto the first dynode
  - Dynode chain with electron amplification at each step (dynode: an electrode in a vacuum tube that produces secondary electron emission)
  - Anode to collect charge at end of dynode chain
- Good vacuum inside structure to minimize positive ions going to the photocathode



Photomultiplier tubes

Schematic showing incident high energy photon hitting a scintillating crystal, triggering the release of low-energy photons which are then converted into photoelectrons and multiplied in the photomultiplier



Photocathode Converts light (photons) into electrons through the photoelectric effect

Focusing electrode

Photomultiplier Tube (PMT)

Ionization track

High energy photon

Low energy photons

Scintillator

Primary electron

Secondary electrons

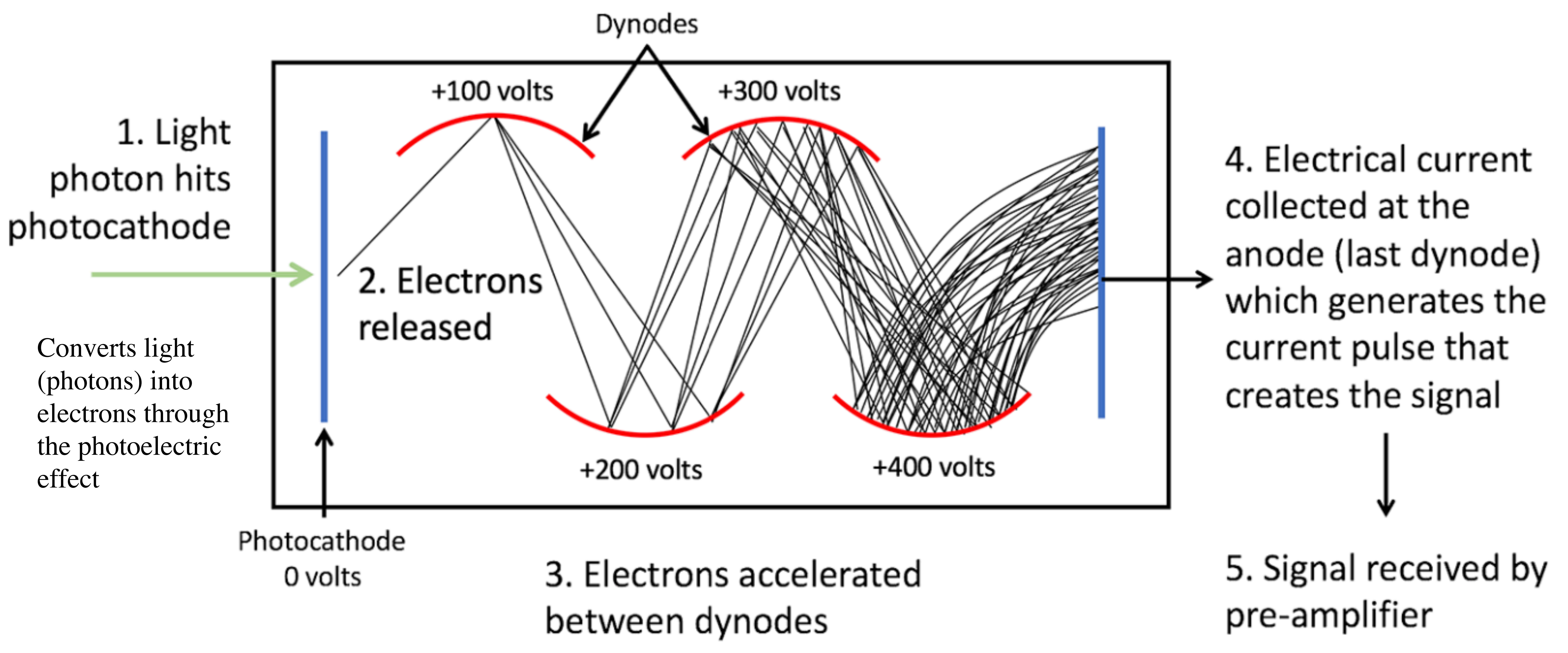
Dynode

Anode

Connector pins

Dynode: release of electrons from the bombarded surface

Photomultiplier tubes



1. Light photon hits photocathode

Converts light (photons) into electrons through the photoelectric effect

2. Electrons released

3. Electrons accelerated between dynodes

4. Electrical current collected at the anode (last dynode) which generates the current pulse that creates the signal

5. Signal received by pre-amplifier

Photomultiplier tubes

- Vendor specific: https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/etd/PMT_handbook_v4E.pdf

Signal shape

- Fluorescence (fast): $N_1(t) = N_f \exp(-t/\tau_f)$
  - ~nanosecond (ns)
- Delayed phosphorescence (slow) $N_2(t) = N_f \exp(-t/\tau_s)$
  - ~100 ns to 1 μs
- Measured pulse shape depends on time constants arising from the readout
  - Assuming a general decay scheme with decay constant τ, current goes as (similar to RC time of an oscilloscope):
    - $i(t) = \dfrac{v(t)}{R} + C\dfrac{dv}{dt}$

Key parameters of a PhotoMultiplier Tube

- Quantum efficiency (QE)
- Photon detection efficiency (PDE)
- Multiplication gain (M) and excess noise factor (ENF)
- Linearity
- Transit time and transit time spread (TTS)
- Dark count rate (DCR) (spurious detector events registered when no signal is present)
- Size and segmentation
- High rate capability/aging
- Immunity to magnetic field
- Radiation tolerance
- Total through current

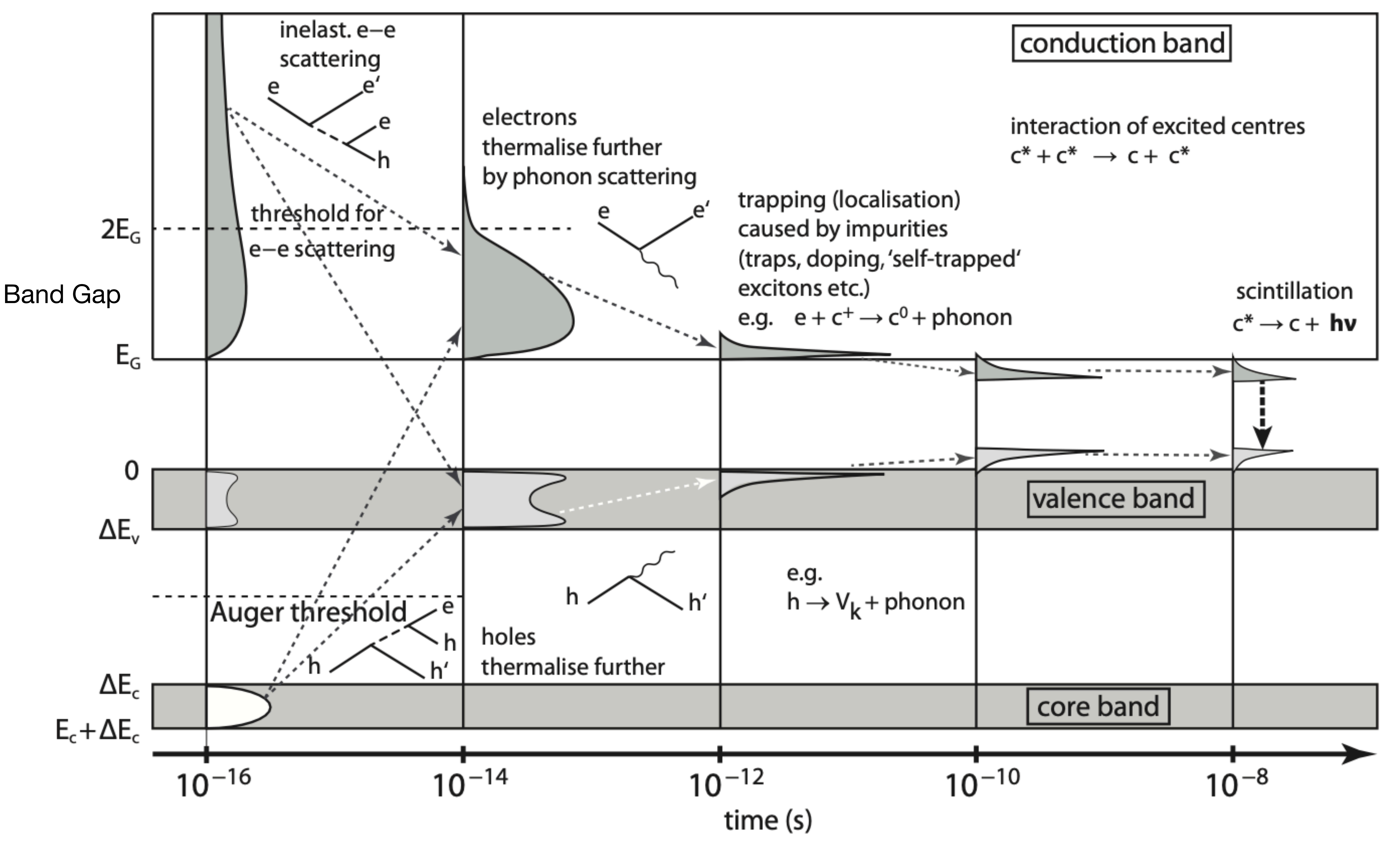
Scintillating fibres

- Scintillators, finely drawn in fibers and then bundled and arranged in layers, find applications in experiments as tracking detectors and for calorimeter readout
- Typical diameters for tracking applications are between 250 µm and 1 mm
  - Trade-off between spatial separation and light yield
- Fiber materials and properties:
  - Fibers can be made of scintillating glasses or plastic scintillators
  - For normal incidence of a particle into a fiber a sufficient amount of light must be generated that stays in the fiber by total reflection and can be detected at the fibre end
  - Self-absorption in the fibre should be low
  - Optical cross talk between neighboring fibers should be vanishingly small

Scintillators

- Where do we use scintillators at the LHC experiments
- Beyond LHC?
    - Look at some of the older experiments

Inorganic scintillators (look at the book)



SiPM on tile (HGCAL)

- Refer to: https://cds.cern.ch/record/2876560/files/CR2023_193.pdf