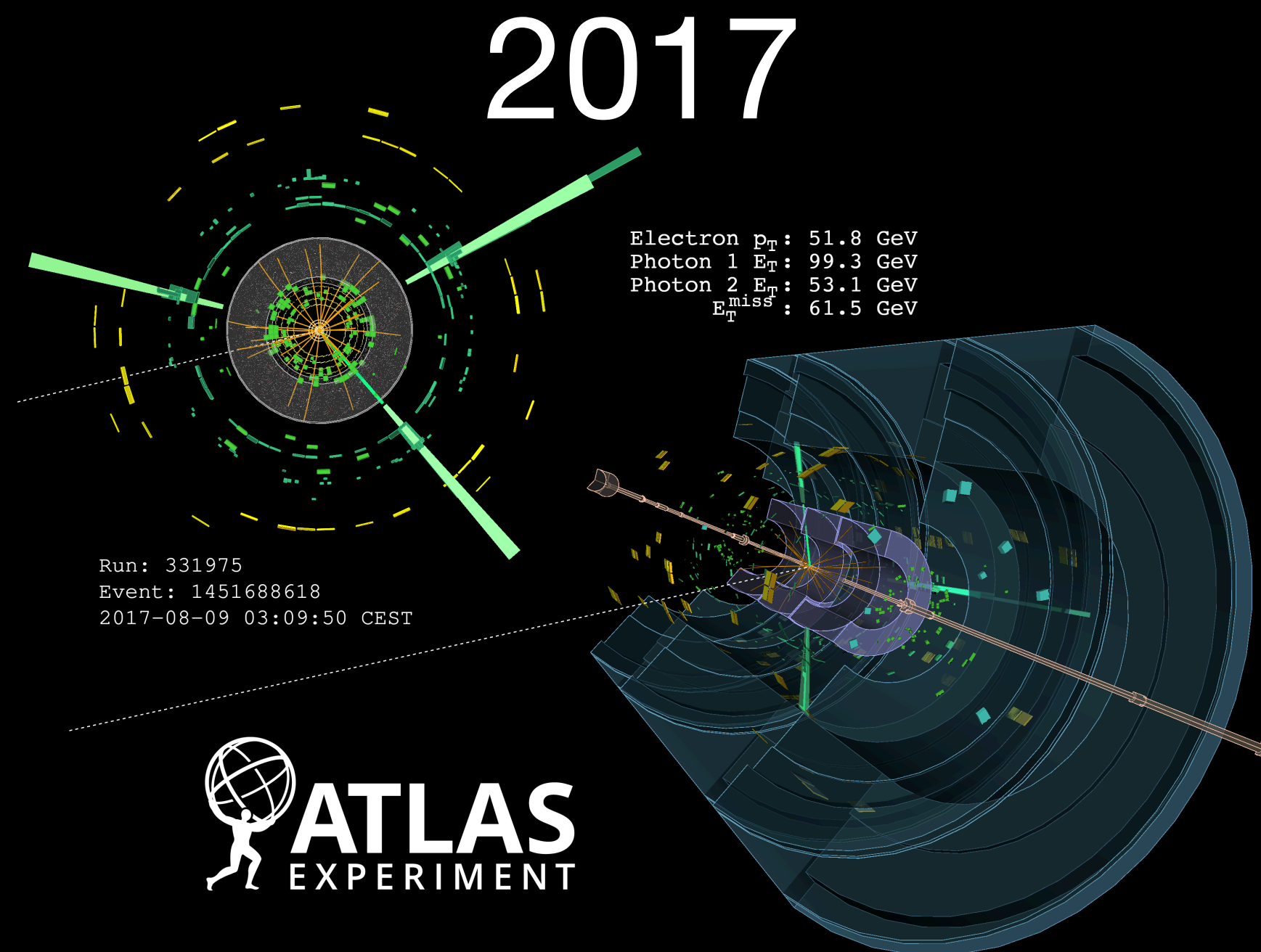


# PHYS 7363 - Experimental Particle Detection and Detectors I



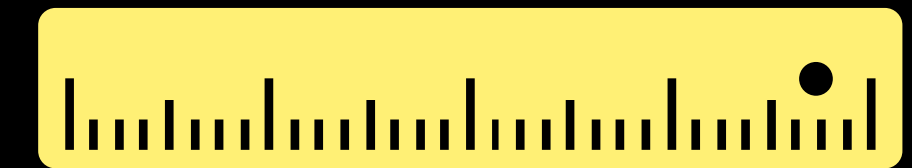
Particle detectors are the workhorses of experimental physics. In this course, we'll dive deep into their physics, exploring the incredible evolution of our experimental techniques over the past nine decades. You'll gain a solid understanding of *particle detection and identification*, examine the intricate 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!



Detect



Identify



Measure

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



# Schedule

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

# Going back to GEANT (for a moment)

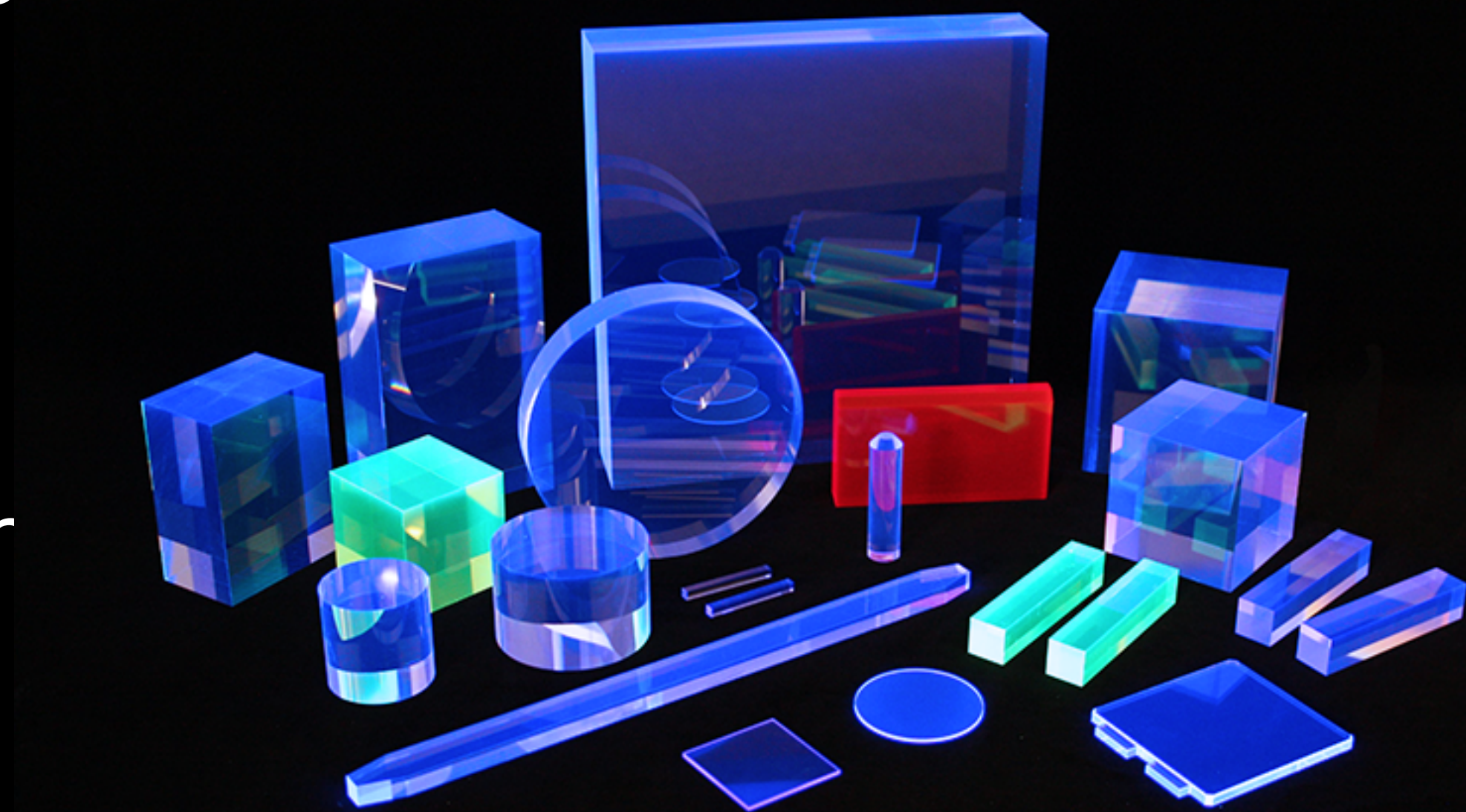
- <https://github.com/jainshilpi/G4Simulation/blob/master/README.md>

# 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  $L_S = \langle N_{ph} \rangle / E$ , 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 deposited
  - Timing: short pulses and fast recovery times
- Physics:
  - Material absorbs energy and re-emits energy as visible light
    - Fluorescence: immediate re-emission of light ( $\tau < 10^{-8}$  s)
    - Phosphorescence: delayed emission of meta-stable states
- Time evolution:
$$N(t) = N_f \exp(-t/\tau_f) + N_s \exp(-t/\tau_s)$$

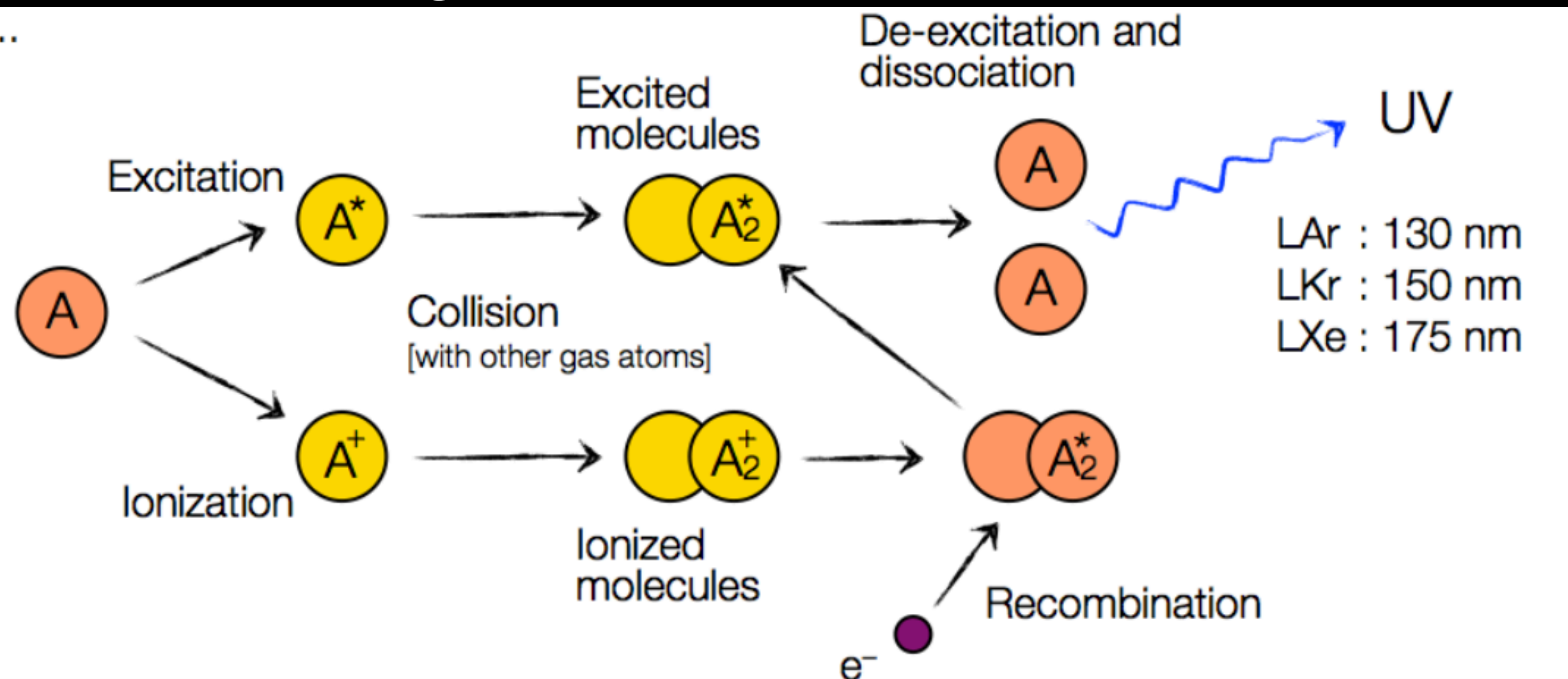
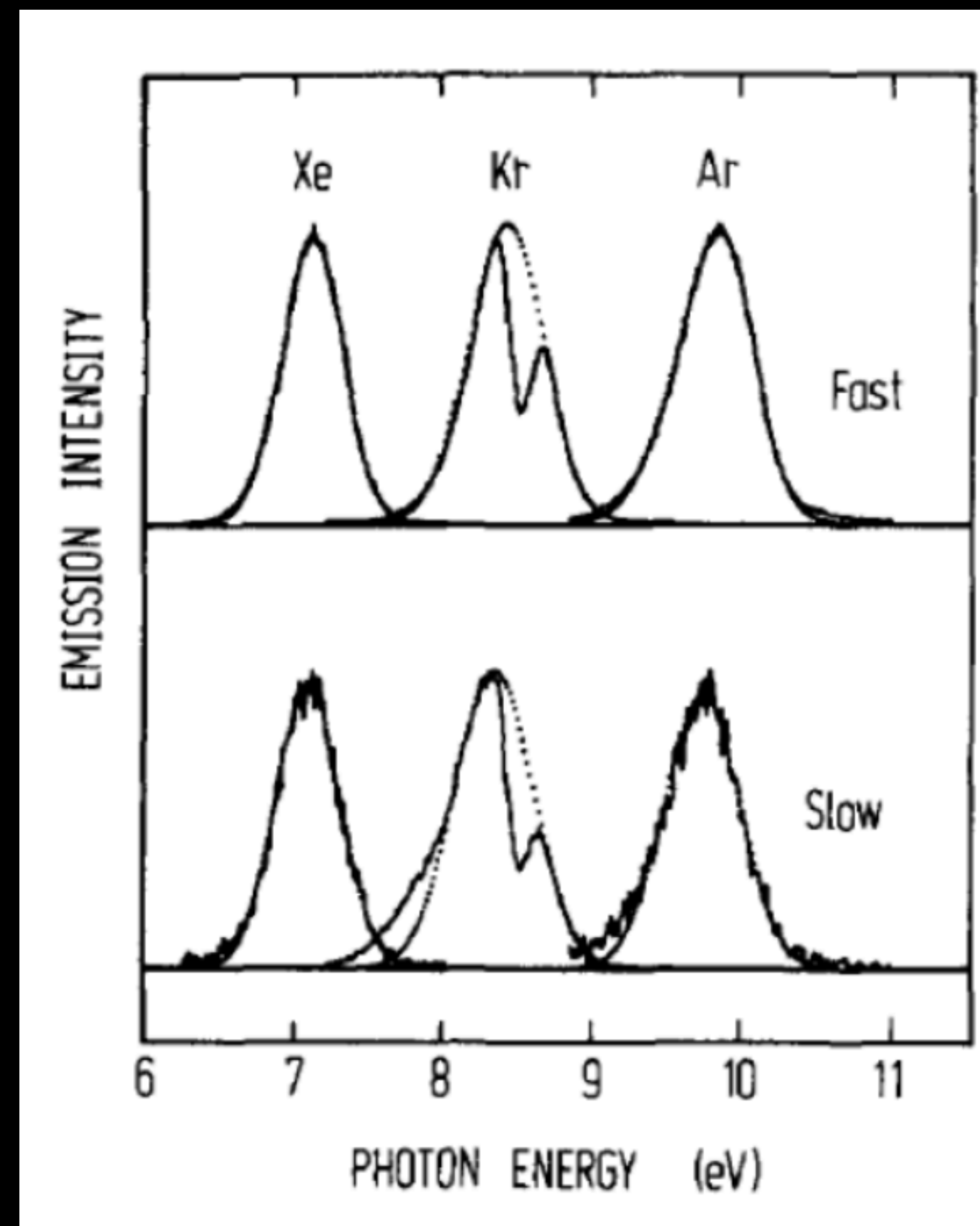


# Scintillators in ATLAS

- 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 ( $\text{Ar}^+\text{Ar}$ ) that de-excite emitting a photon with a time constant of  $\sim 6$  ns
- For liquid argon, the peak wavelength is 128 nm
  - A wavelength shifter is required to shift to the optical region

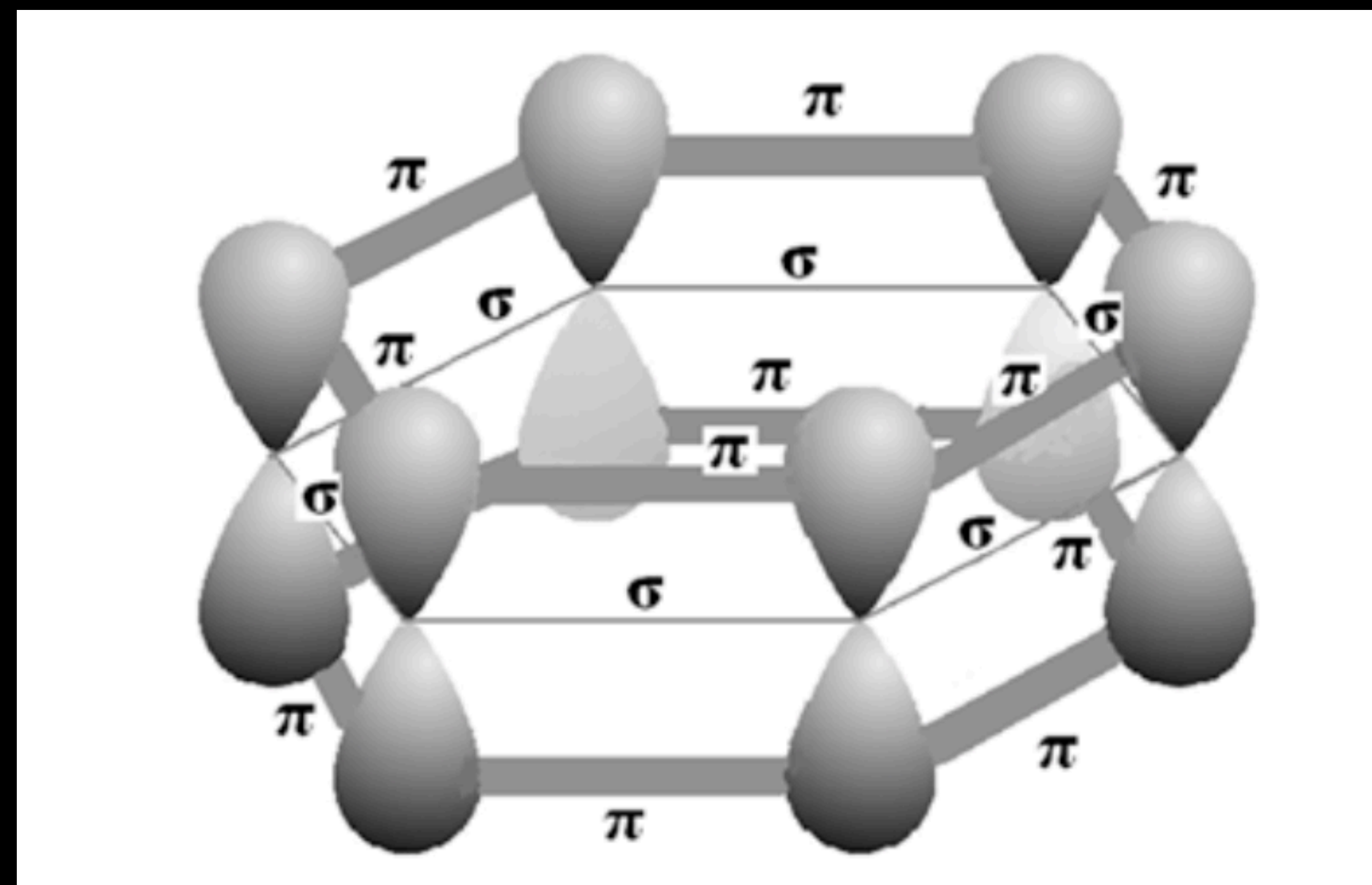


# Scintillation Mechanism

- 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

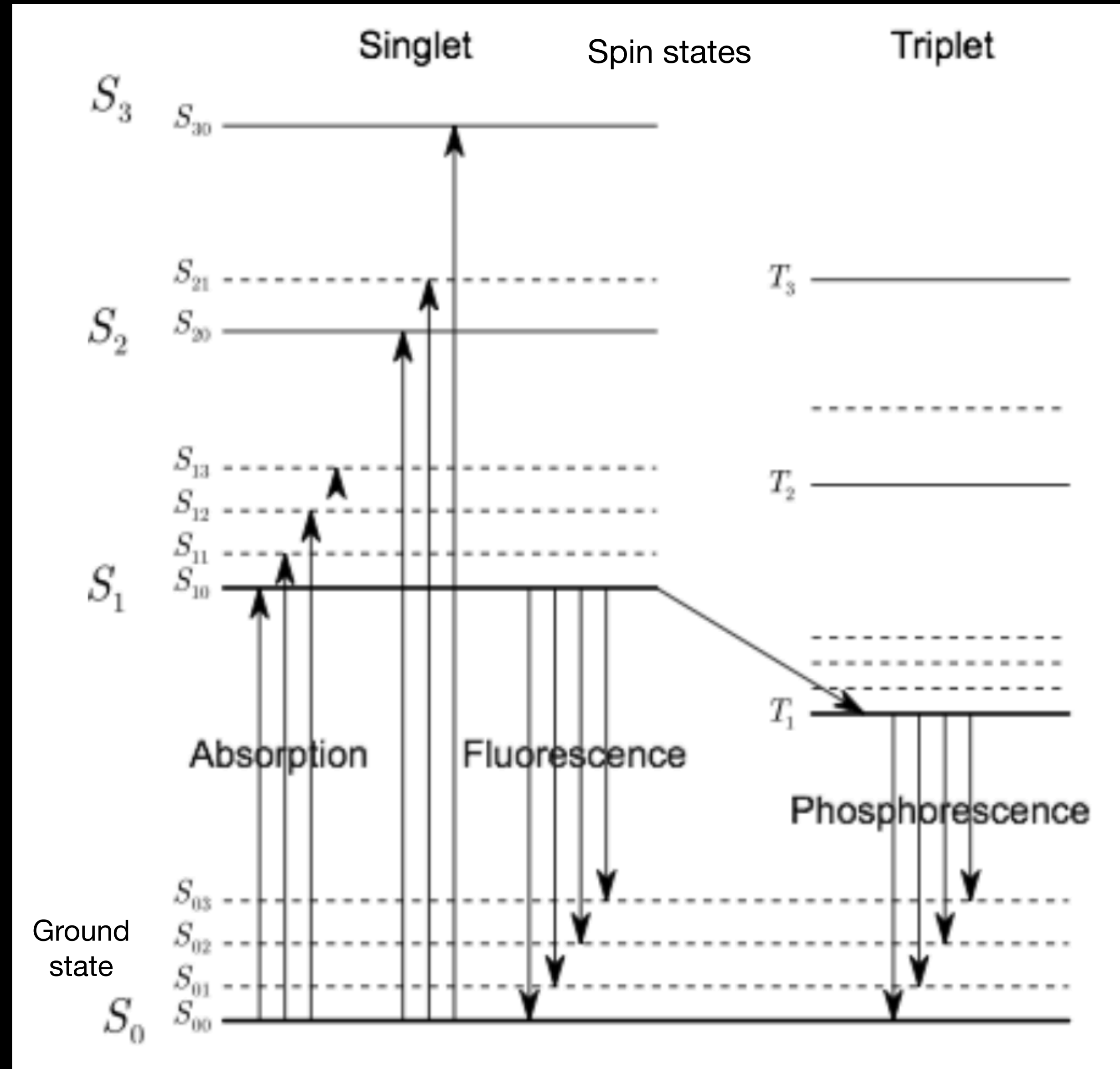
- Spend some time to look it up
- Hint: NOvA detector: <https://arxiv.org/pdf/2012.08262>

# 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>

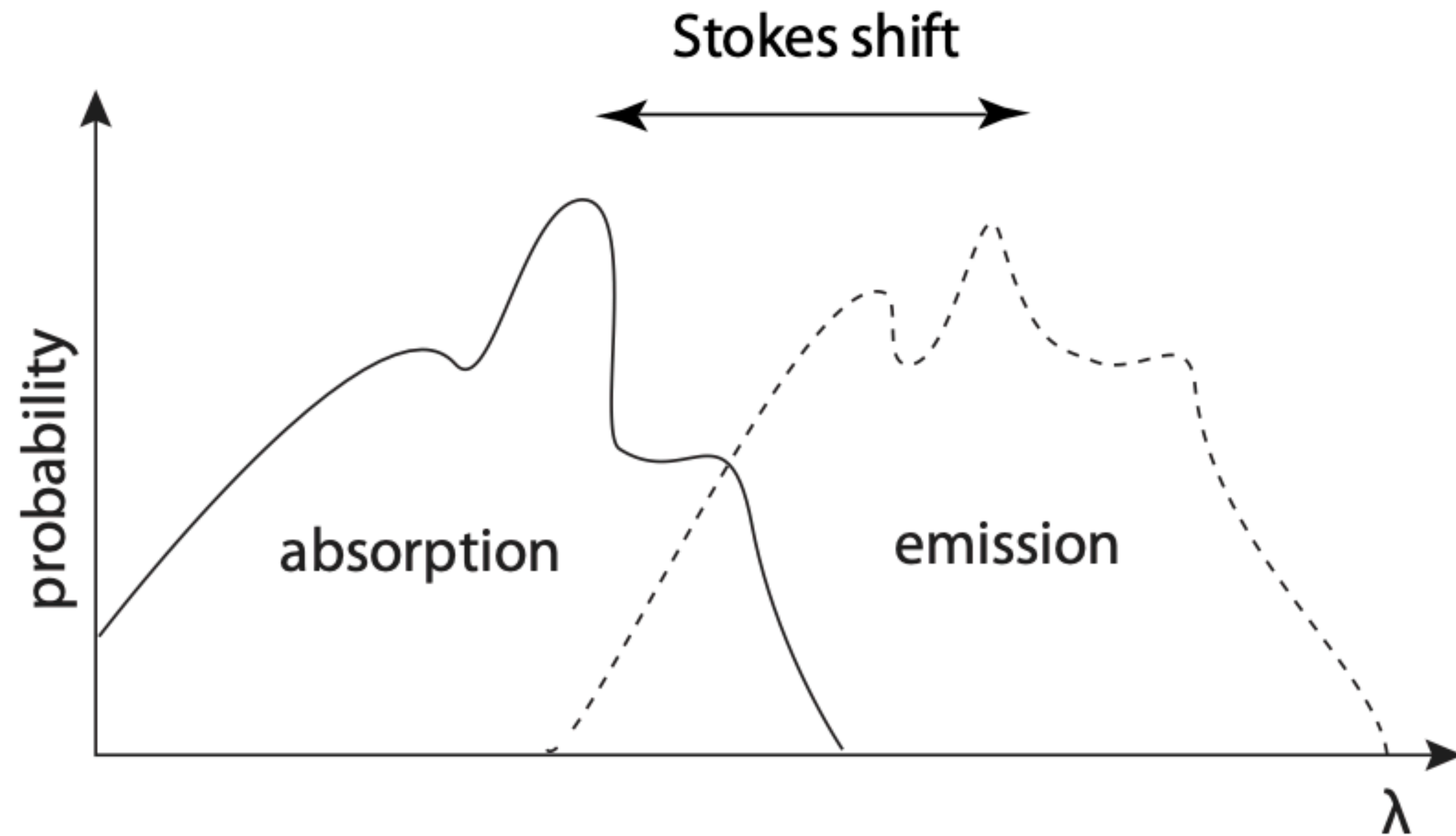
# Scintillators — typical setup

- 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

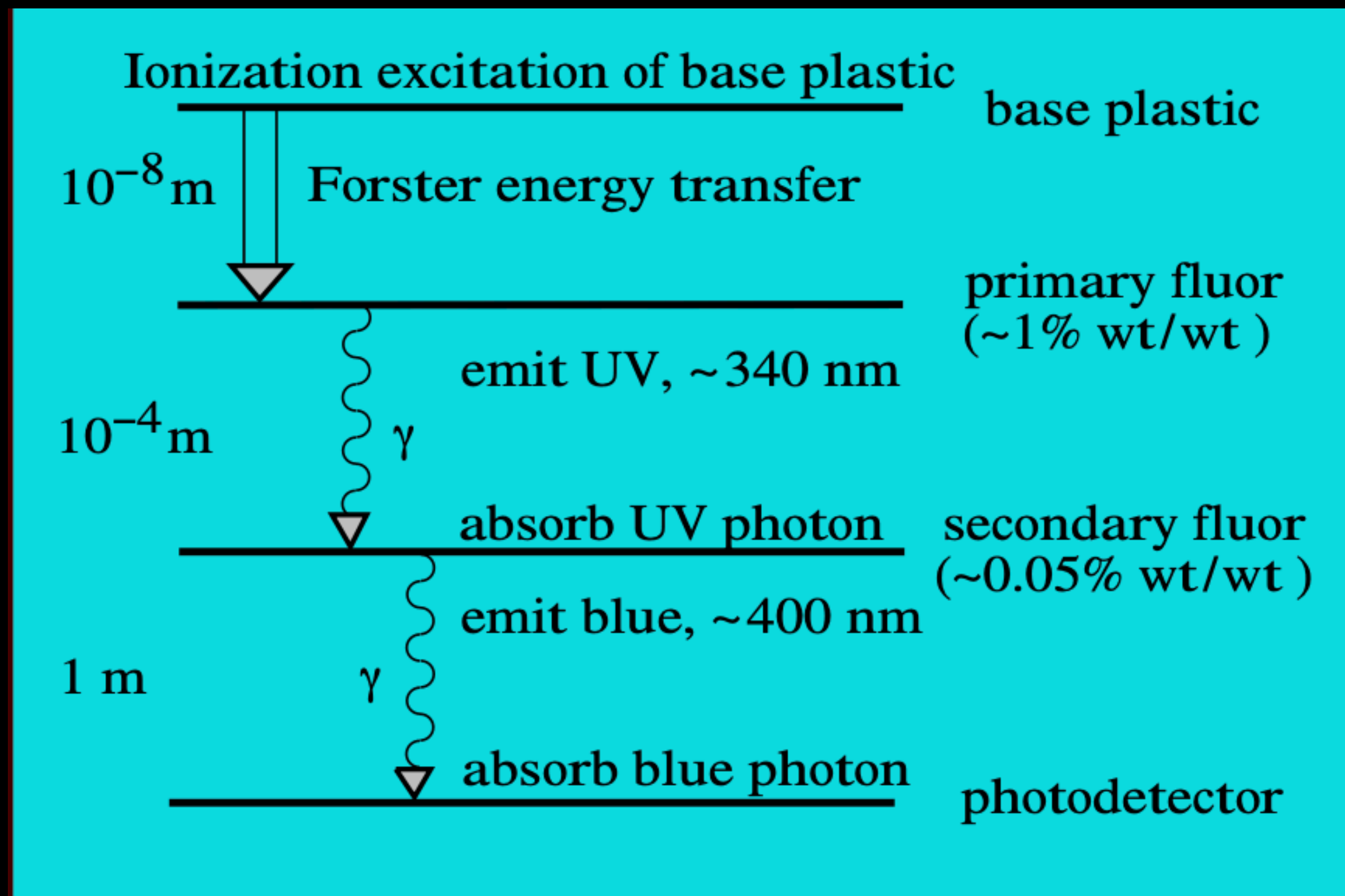
# Stokes Shift



**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 ("fluor") embedded in non-scintillating base material ( $\sim 1\%$  of weight)
  - Non-radiative **Förster energy transfer** from base to primary fluor (dipole-dipole interaction between molecules)
  - Primary fluor: **UV photon** emission (short absorption length in material  $\rightarrow$  self-absorption)
  - Secondary fluor ("wavelength shifter",  $\sim 0.05\%$  of weight)  $\rightarrow$  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 convert 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)

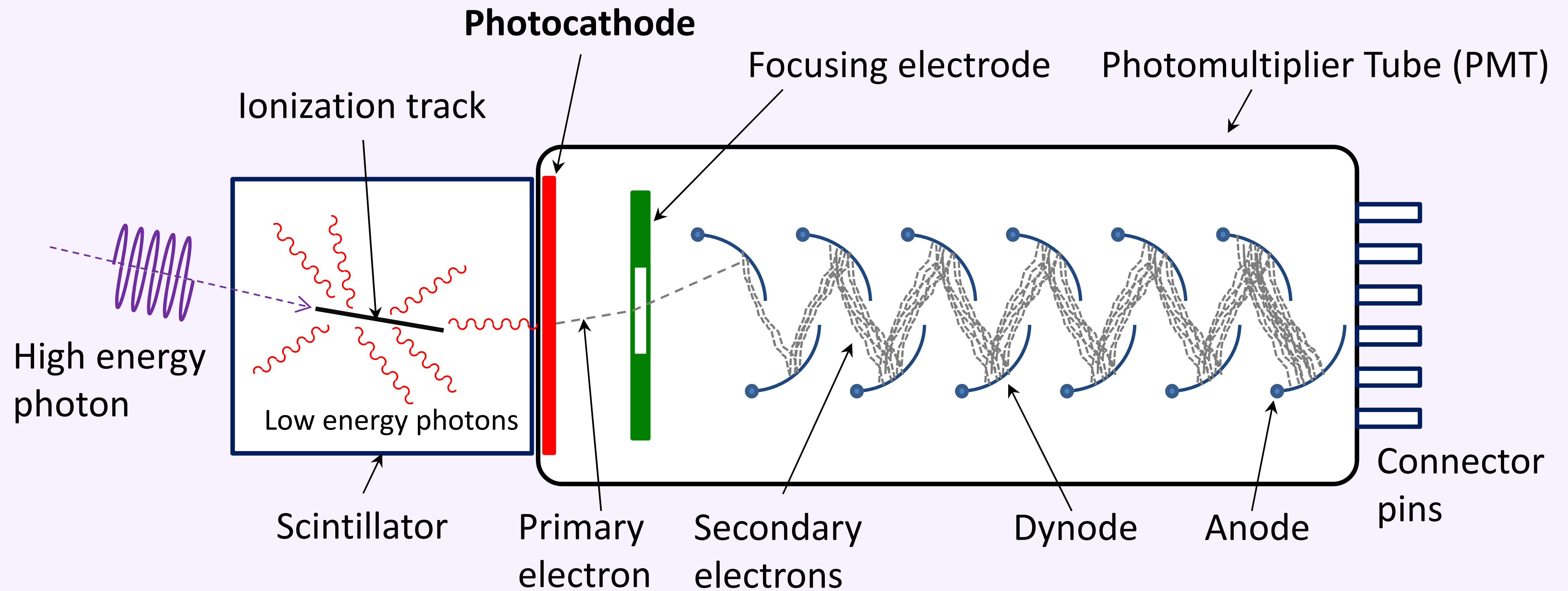
# Photomultiplier tubes

- 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



# 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