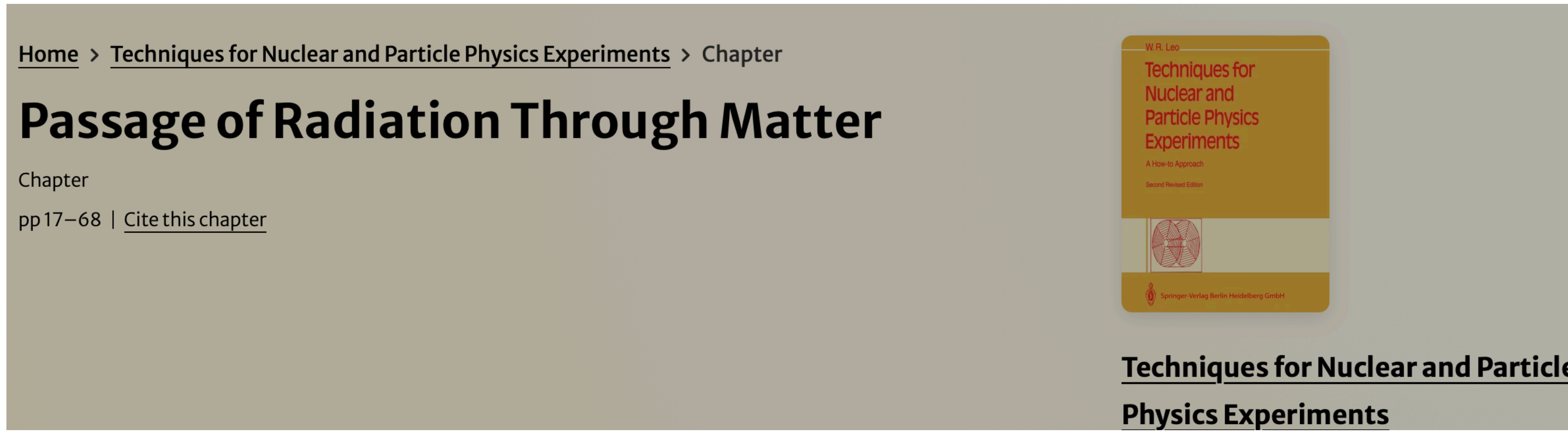
November 13, 2024

Photon Detectors

Flavio Cavanna - FERMILAB & Yale U

Particle Detectors: exploit Mechanisms of Particle Interaction to ***"see"*** (detect) the ***Passage of Radiation through Matter*** -



"Radiation": **Initial State** Incident Projectile **Particles**

"Matter": **Initial State** (Stationary) Target **Particles**

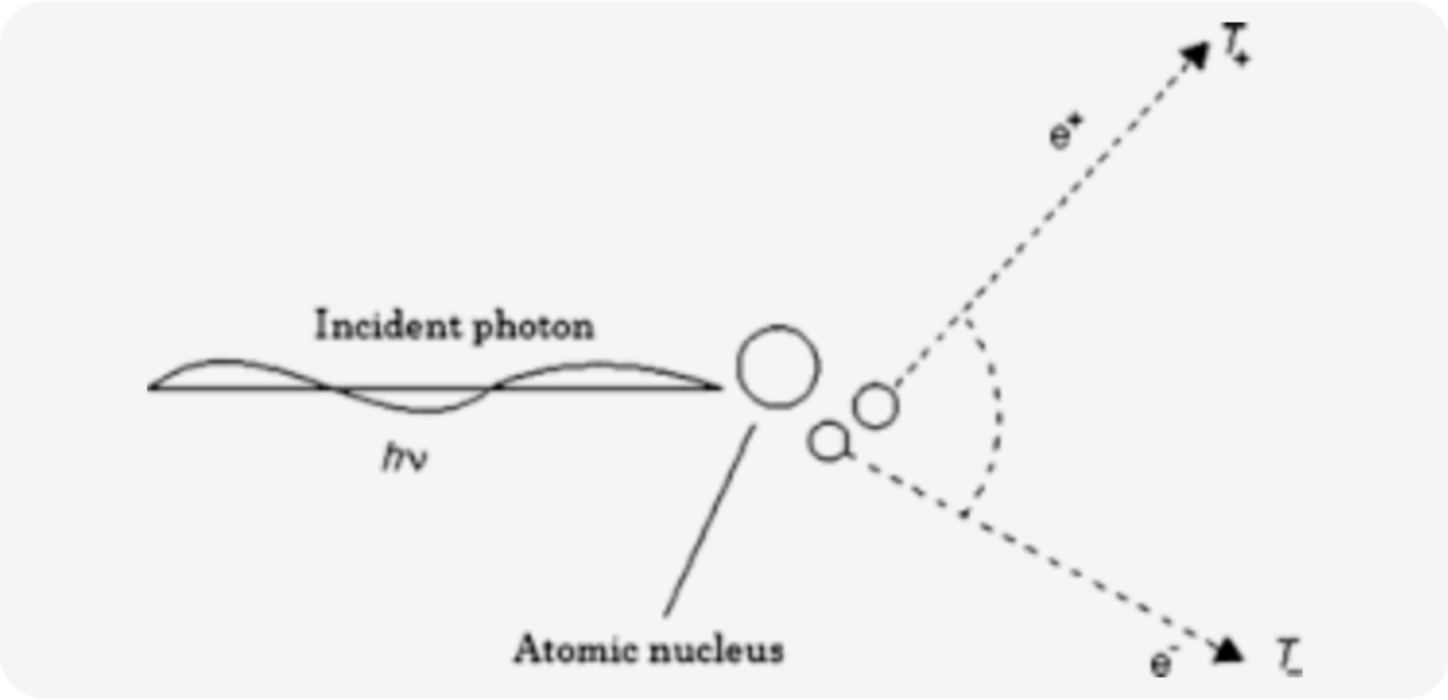
"Passage through": **Force Particles** mediate an interaction creating detectable **Final State Particles**

Particles can be :

Elementary $(e,\ \mu,\ \nu, \ldots)$ or Composite $(\pi, K, \ldots)$

Charged $(p, \alpha, \ldots)$ or Neutral $(n,\ DM-$ *yet to be seen*)

Massive $({}^{Z}_{A}X,\ Y^{+}, Z^{++})$ or Massless (γ)



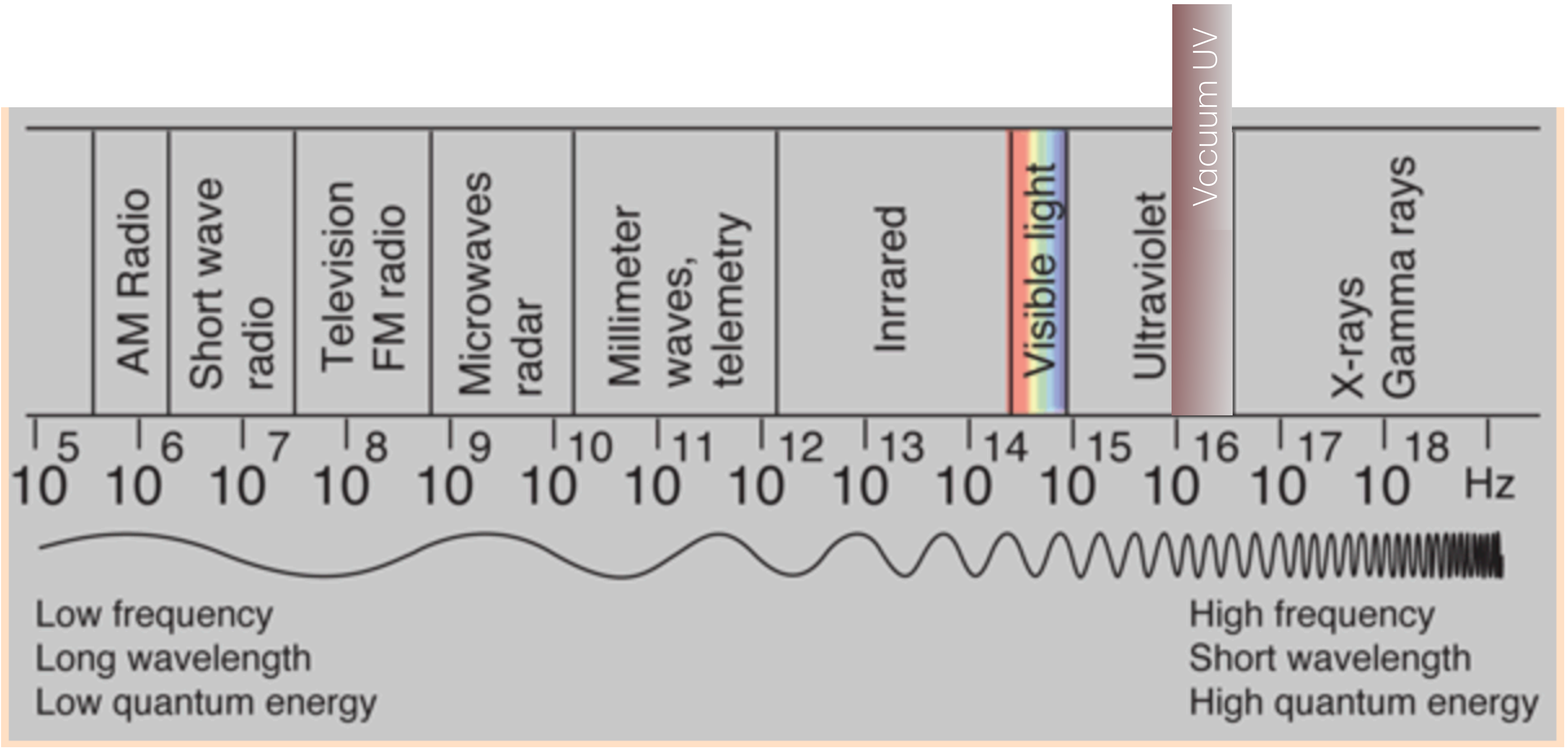
SpringerLink
Passage of Radiation Through Matter ...

Particles can be :

Elementary ($e^{\pm}, \mu^{\pm}, \nu, \bar{\nu} \ldots$) or Composite ($\pi, K, \ldots$)

Charged ($p, \alpha, \ldots$) or Neutral ($n, \ldots,$ $DM-$ *yet to be seen*)

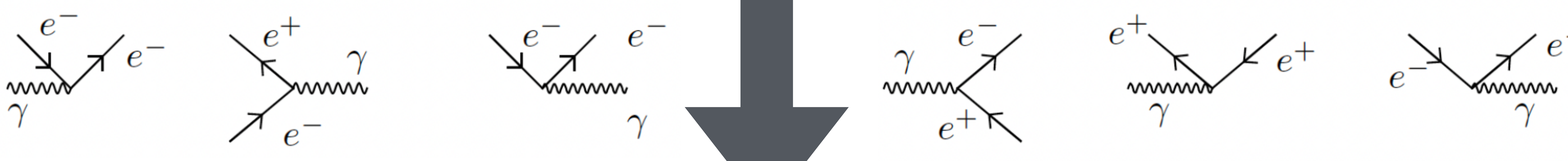
Massive ($^{Z}_{A}X,\ I^{+}, I^{++}$) or **Massless (*Photon* - γ)**



the photon has the dual properties of a particle and a wave

Photons (γ,) are very special: can be either the Projectile (*Initial state Radiation*), or the *Final State Particle* product of interaction in the Target .. or even the *Mediator of the Force (El.M)* that can make incident particles visible-detectable

Lot of Physics involved - from Classical Electrodynamics and optics(applied electrodynamics) to Quantum Electrodynamics (QED) *[and perturbative QCD]*



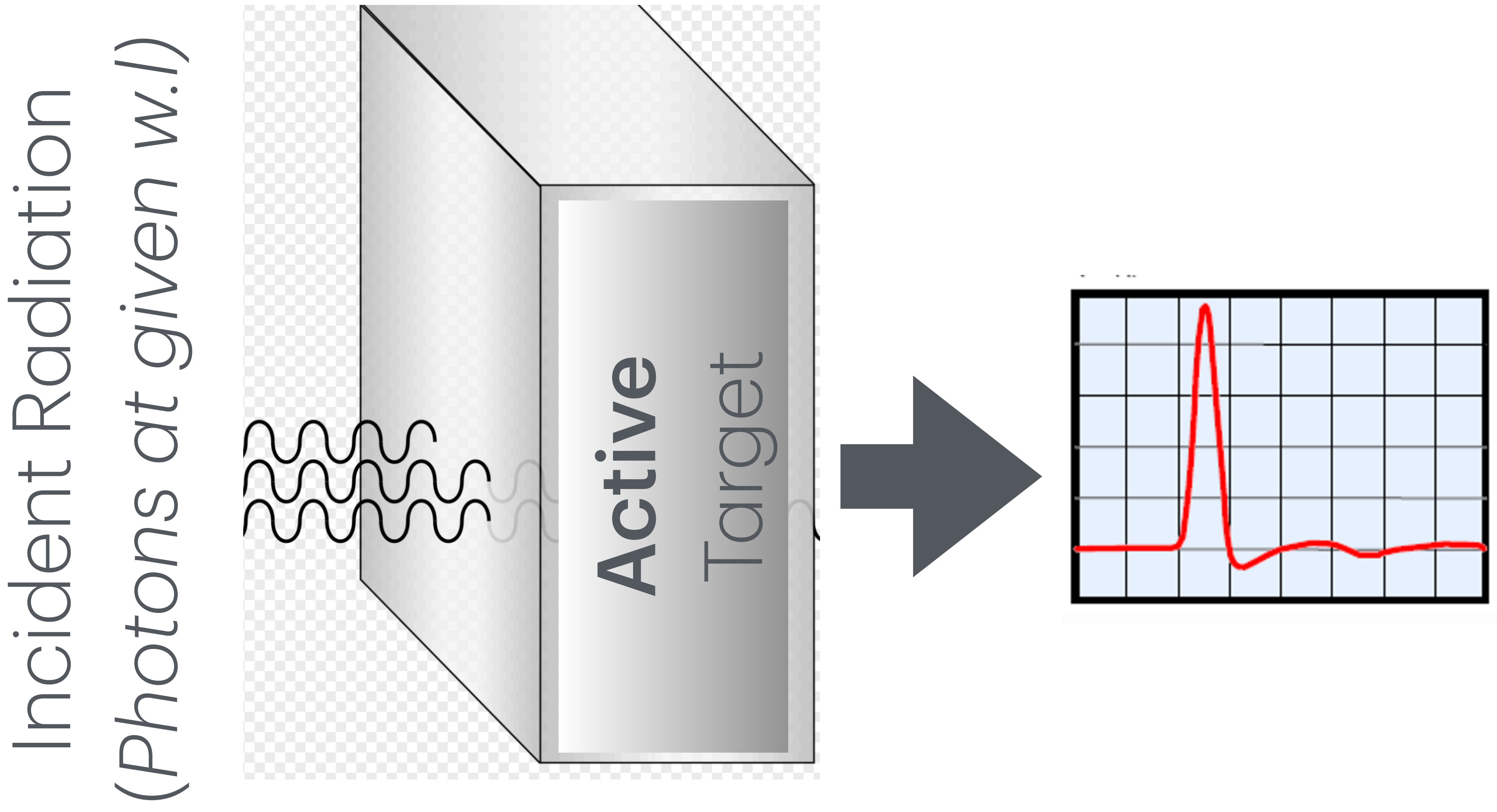
Photon Detectors (PD) are very special too !!

Most common in Physics Research (HEP, NP, Atomic Phys,..), but also find applications in many other fields (Optics, Astronomy, Astrophysics, Space missions) and ...very important in Medical Diagnostic and also ... in every day life

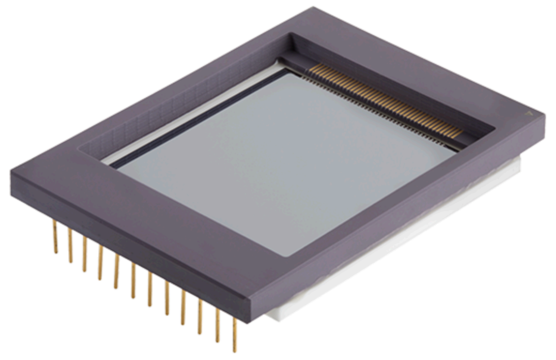
today PD Technology development mainly from Solid State Physics

Photon Detectors

PhotoSensors

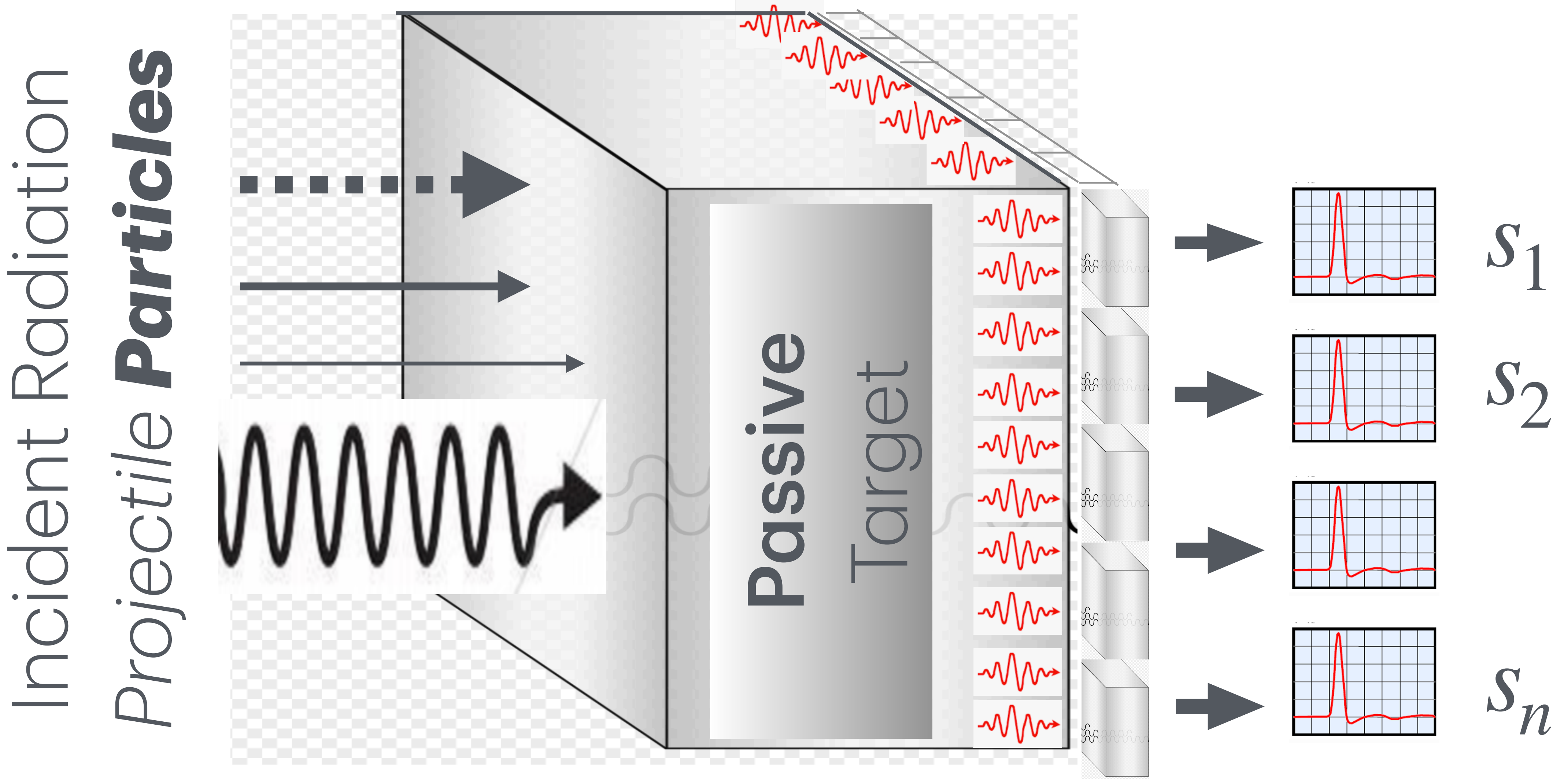


Typically, solid state electrical device capable of converting light input into electronic signal



Photon-Detector Systems

Passive Target + PhotoSensors

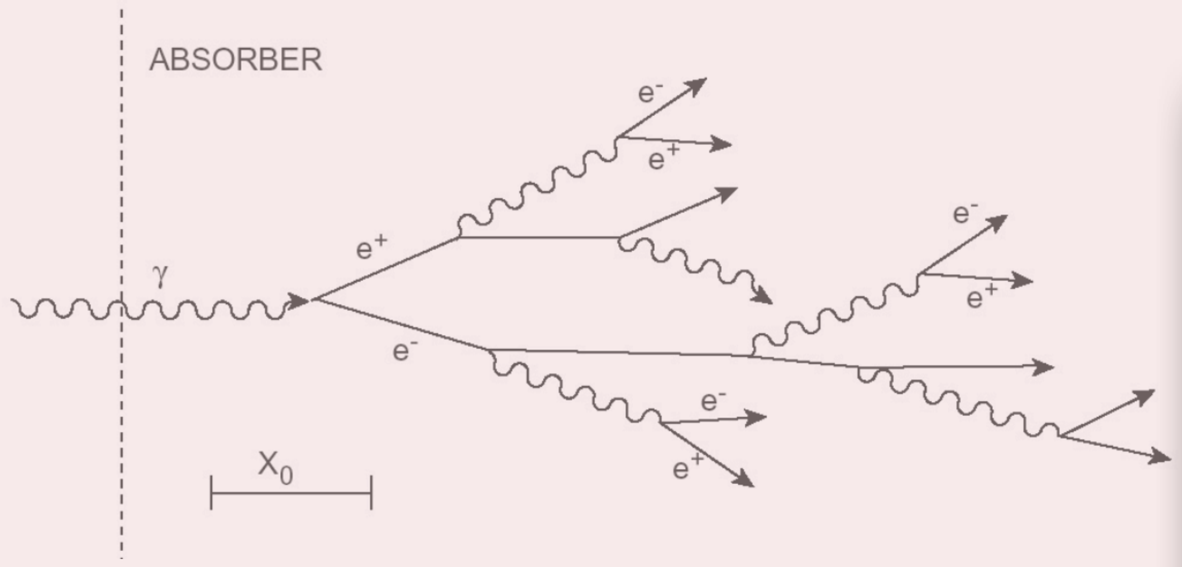


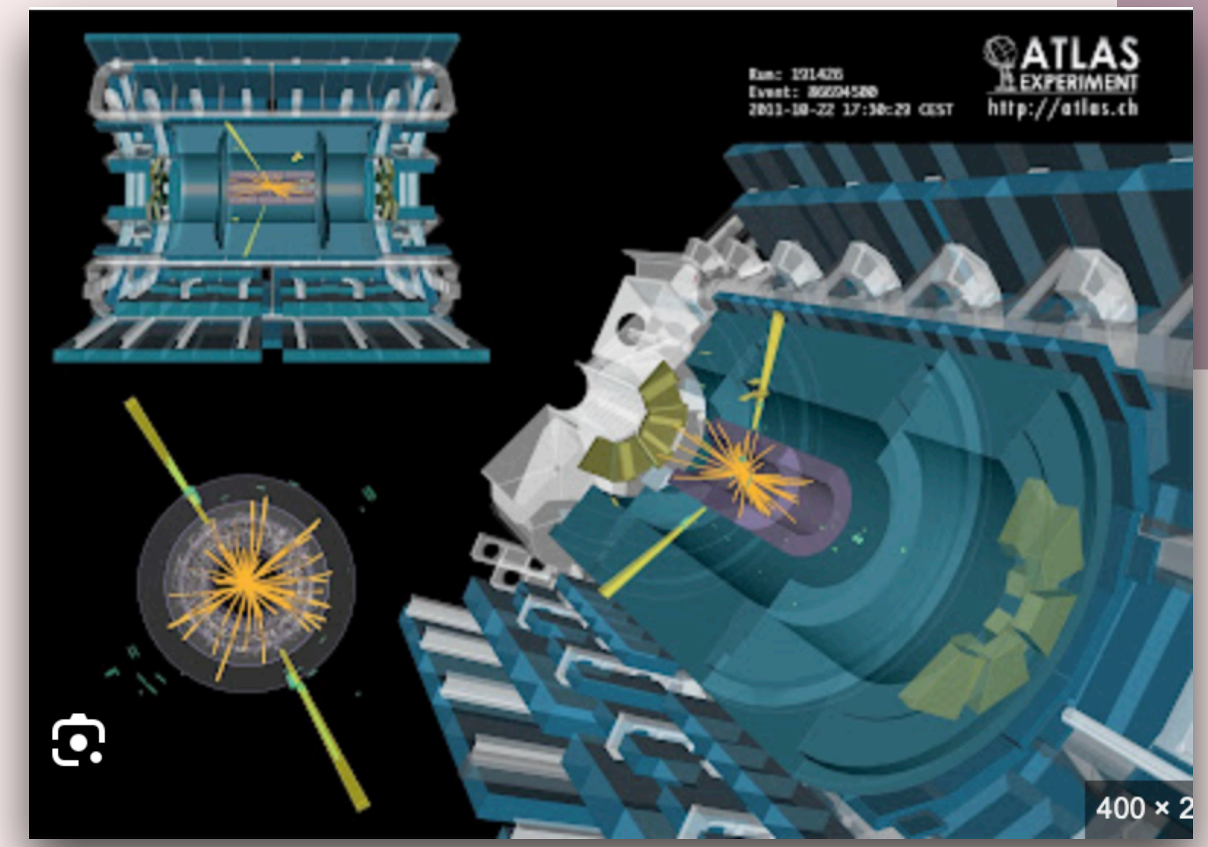
LowEn Photons

Final State Particle product of interaction

Note: Energy of incident particle is converted by interactions in the target into LowEn Photons
Counting the number of detected by the photo-sensors ⇒ Energy of Incident particle $E = \Sigma\ s_i$

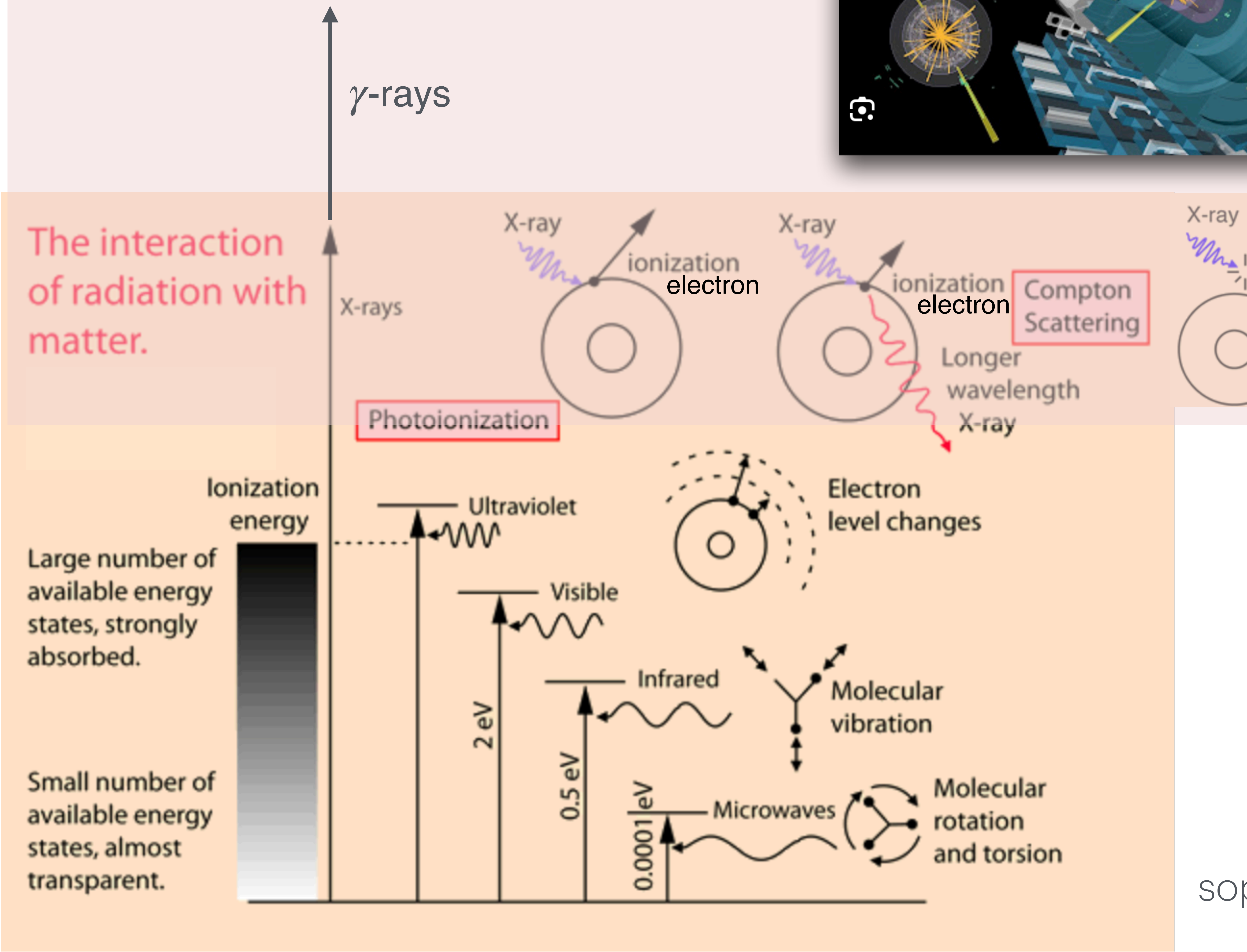
Photon Detectors





Photon Detector Systems

for Incident γ-particles [highest energy photons (e.g. $H \rightarrow \gamma\gamma$ at LHC)]



http://hyperphysics.phy-astr.gsu.edu/hbase/mod3.html#c1

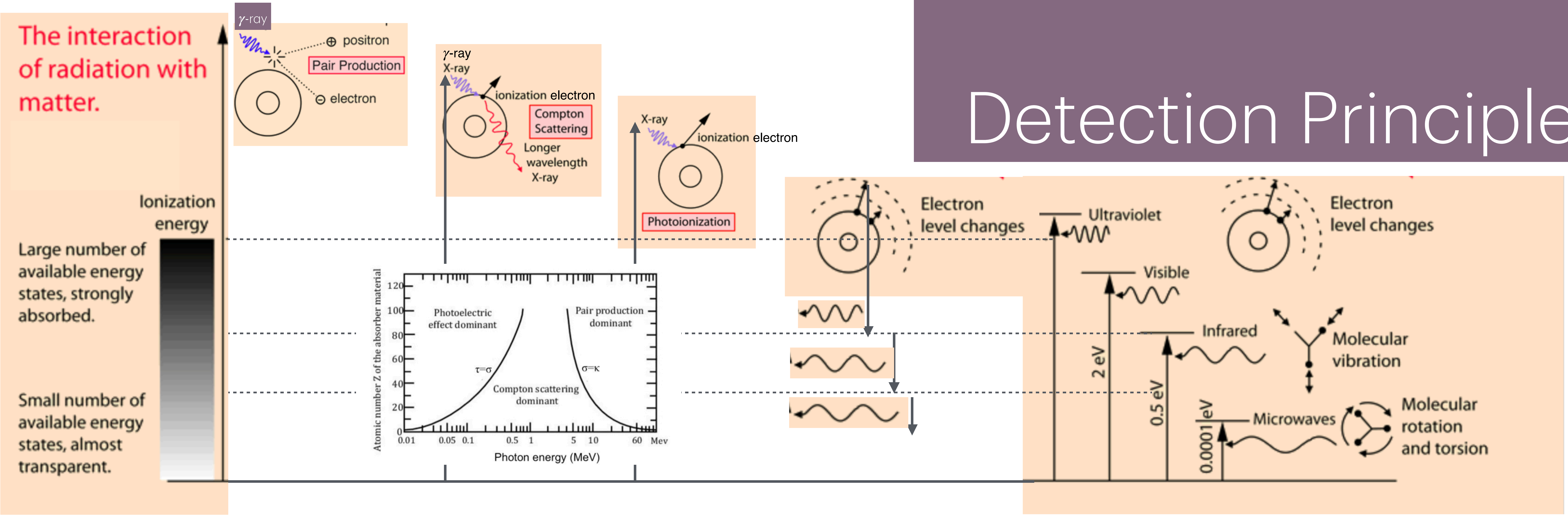
PhotoSensors for Incident Radiation [el.m. waves from Microwaves (e.g. CMB) to X-rays (e.g. AGN)]

(Human) Eye: most sophisticated detector for Visible w.l.

(Electronic) "Eyes": different detectors for different w.l. ranges

Typically, solid state electrical device capable of converting light input into electronic signal

Detection Principles



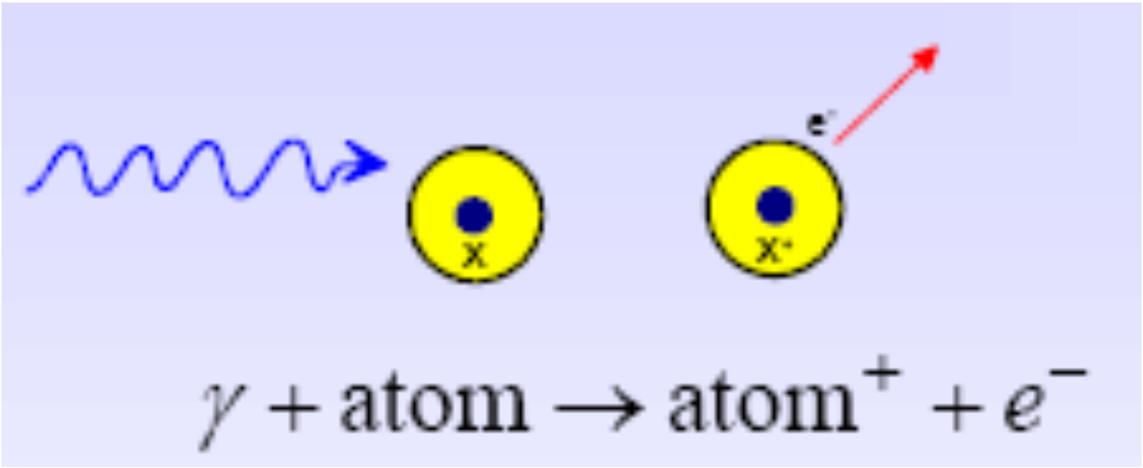
BASIC DETECTION PRINCIPLES

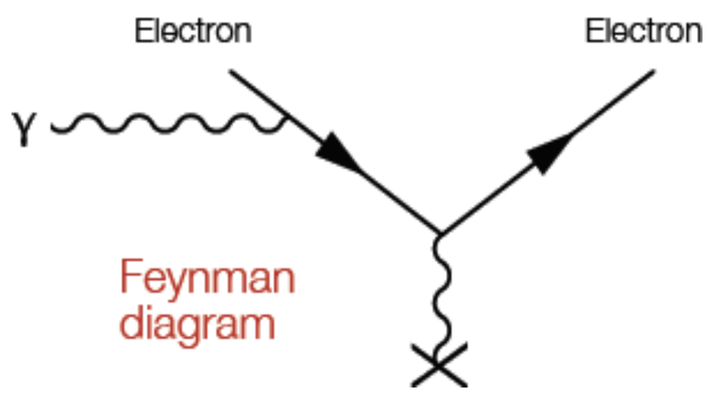
- **Heat:** molecular vibrations by electromagnetic/mechanical interactions generating ***phonons***
- **Scintillation:** atomic or molecular excitations by electromagnetic interactions of charged particle mediated by photons leading to ***photon*** emission by de-excitation
- **Ionization:** unbounded ***electrons*** from their atoms of the target by electromagnetic interactions of charged particle mediated by photons (PhEl - Compton - Pair prod)

- Other Detection Principles:
- **Cherenkov radiation:** light emitted by charged particle exceeding the speed of light

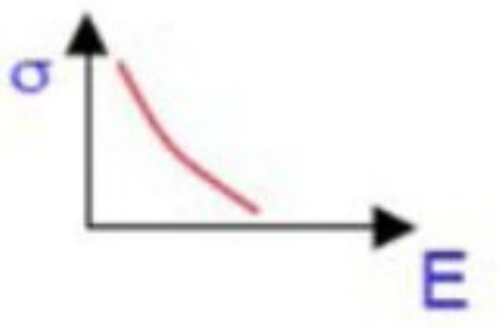
EL.M. Interactions

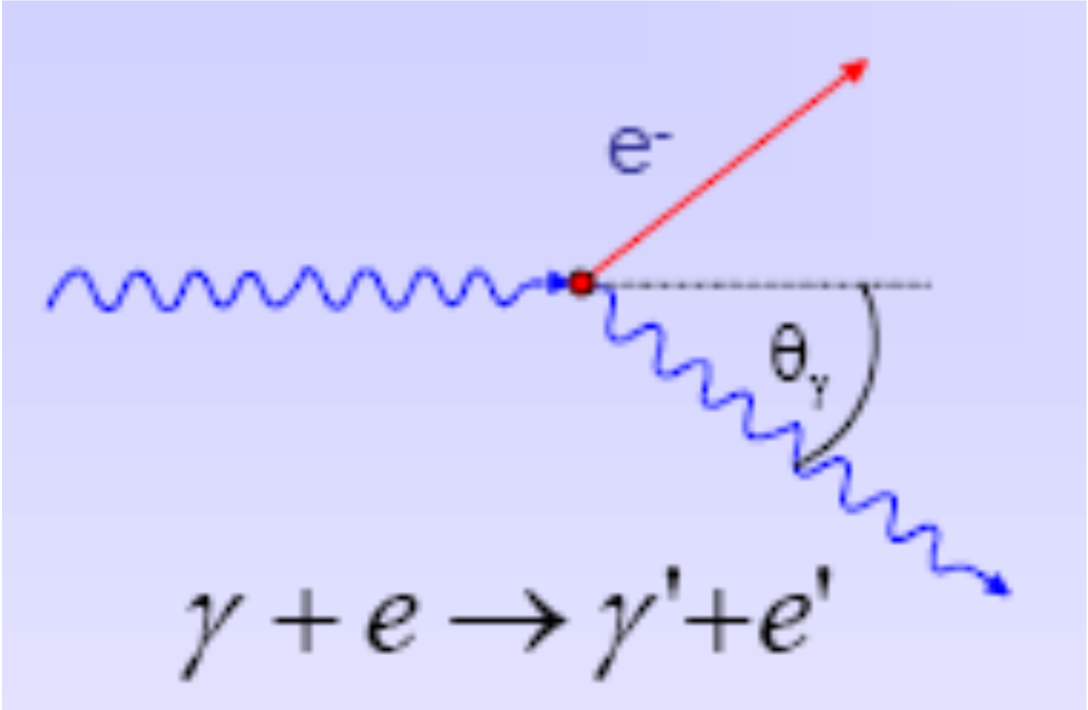
Photons

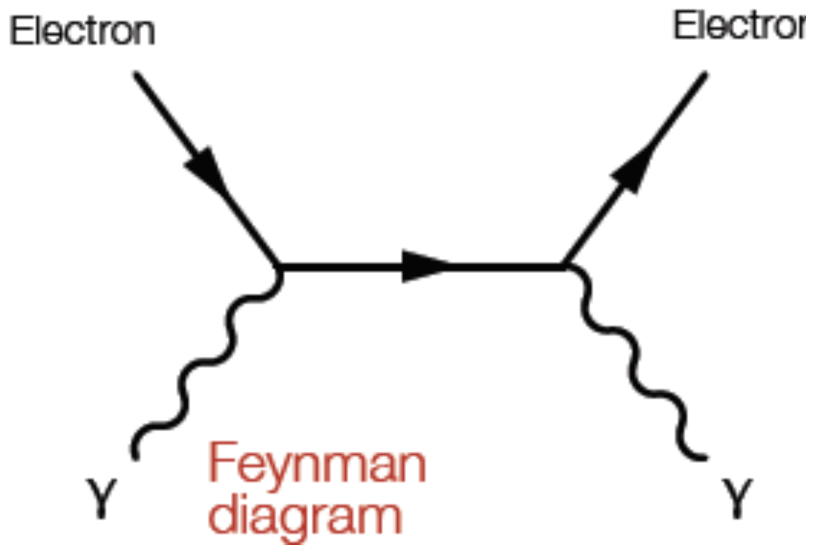




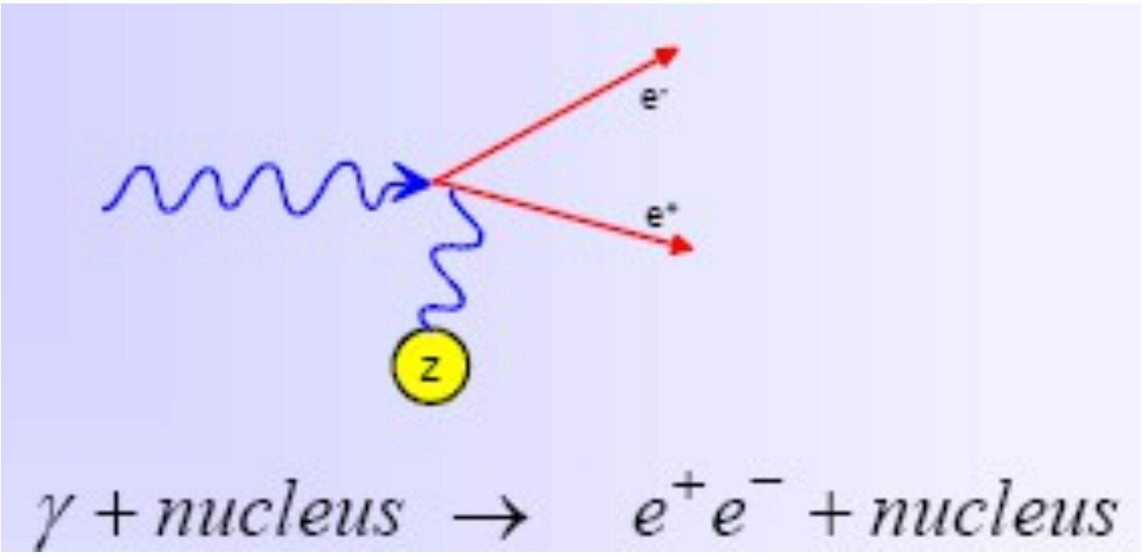
- Photoelectric effect

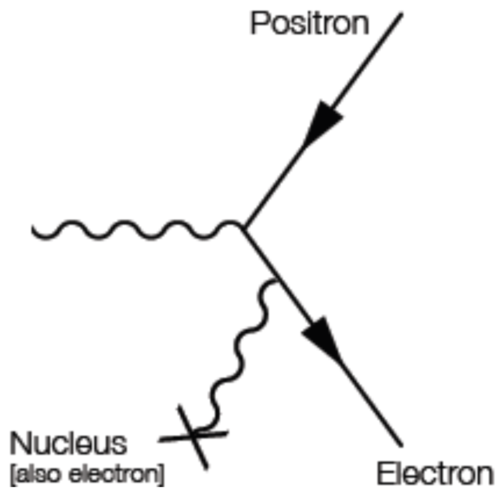




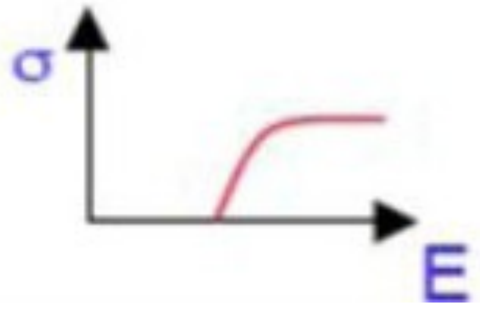


- Compton effect



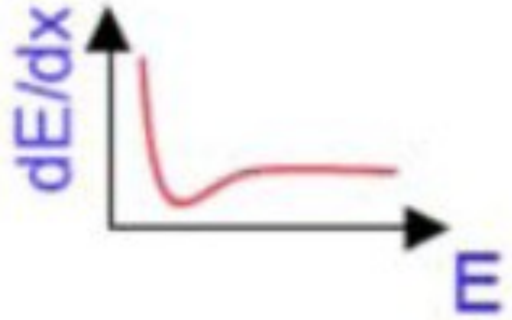


- Pair production

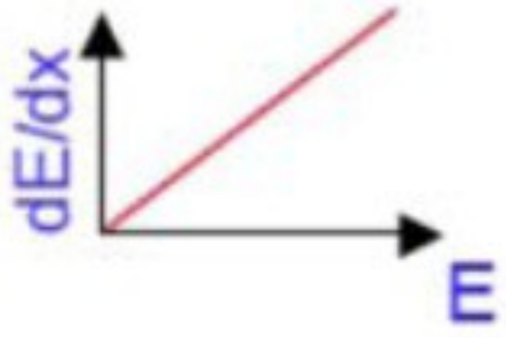


Electrons

- Ionisation

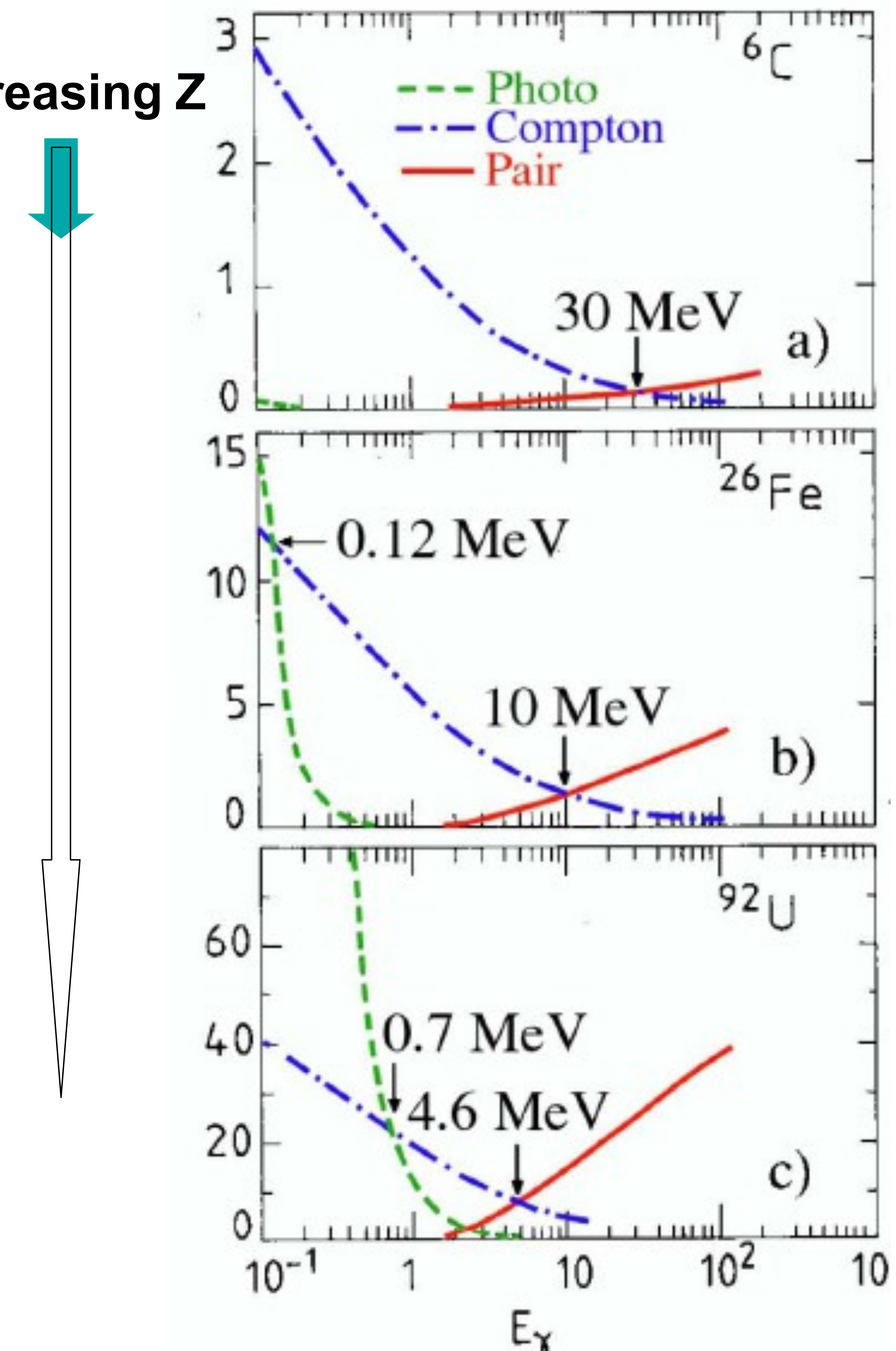


- Bremsstrahlung



EL.M. Interactions

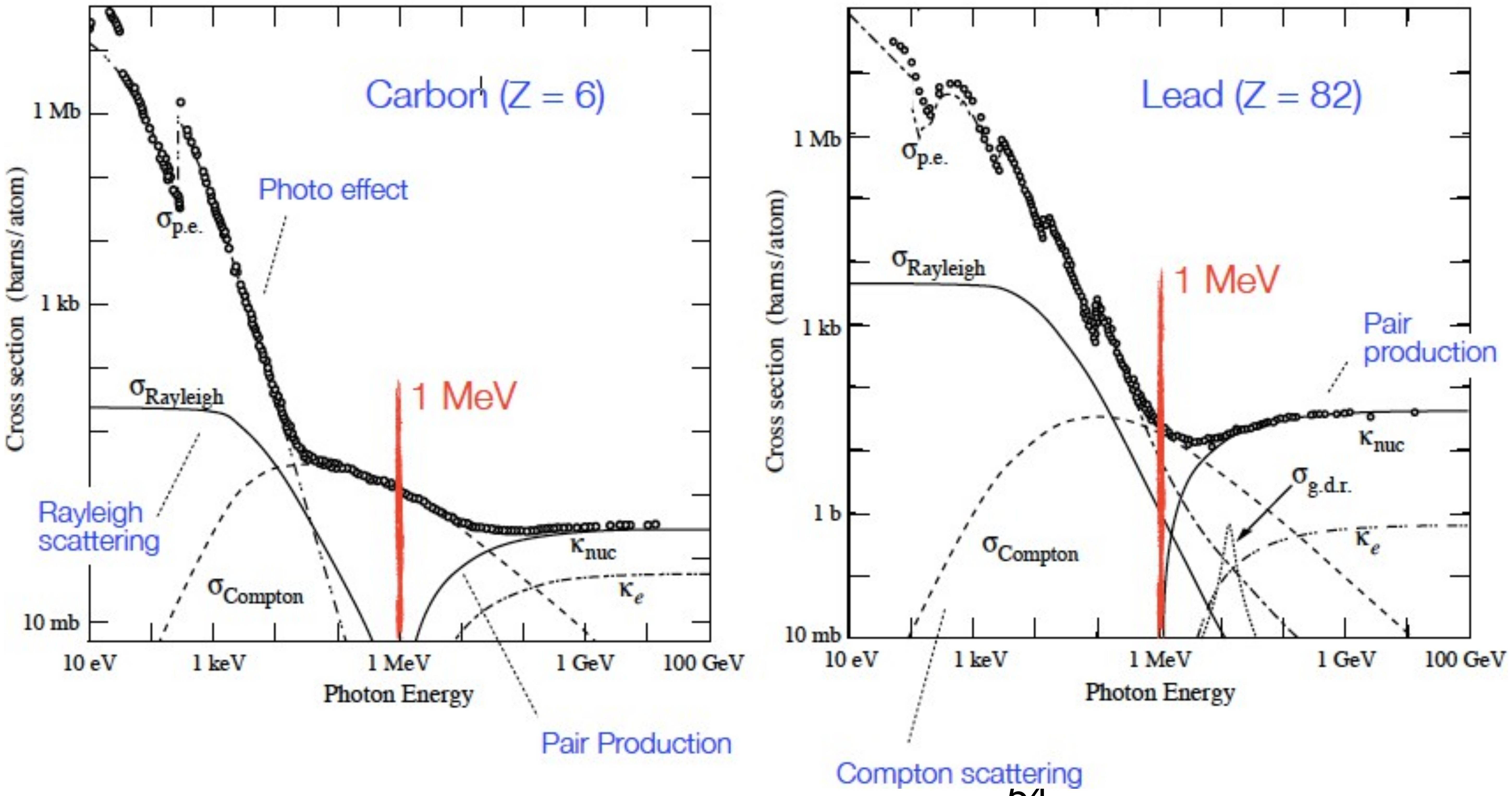
Increasing Z



- *Photons* interact by:

1) *Photoelectric* effect $\sigma \propto Z^5,\ E^{-3}$
2) *Compton* scattering $\sigma \propto Z,\ E^{-1}$
3) *Conversion* into e^+e^- σ increases with E, Z, asymptotic at ~ 1 GeV

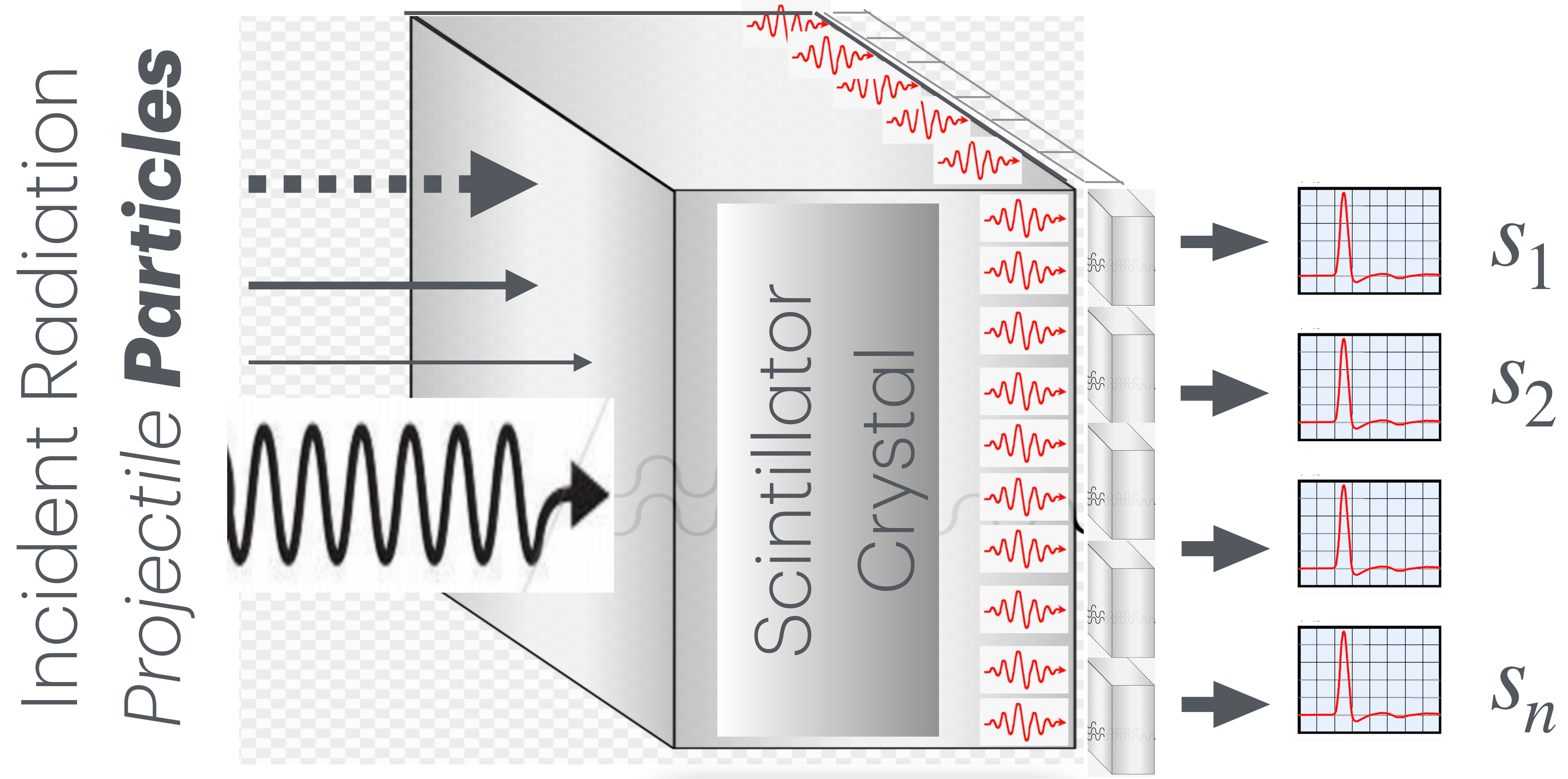
Photon Total Cross Sections

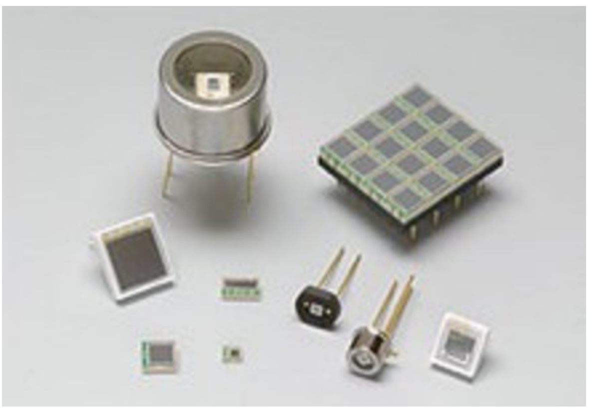


Photon-Detector Systems

Scintillation Counters

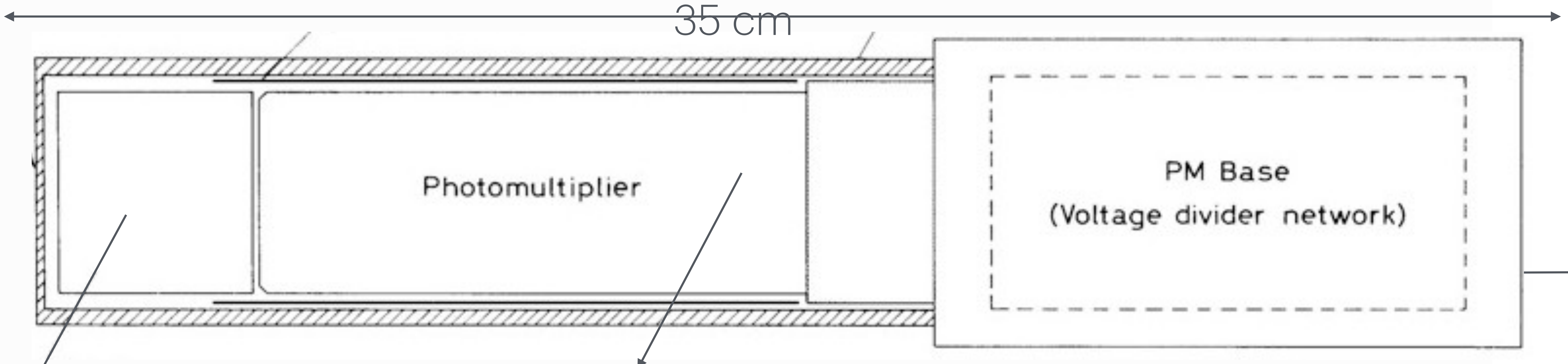
Scintillating Target optically coupled to PhotoSensor





- Energy deposit dE/dx converted into Scintillation Photons (fluorescence light emission when hit by ionising radiation)
- Scintillating materials transparent to their own scintillation light (allow propagation to photo-sensor)
- Fast processes [typical of el.m. interactions - sub picosecond/ns time constant]
  —> fast time response: time-of-flight, triggering, high rate
- Scintillators emits light linearly proportional to deposed energy
  —> photon counting: calorimetry, spectroscopy
- Response of some scintillators depends on the particle (mip vs hip)
  —> photon counting: particle identification

Scintillator Counter – Basic Setup



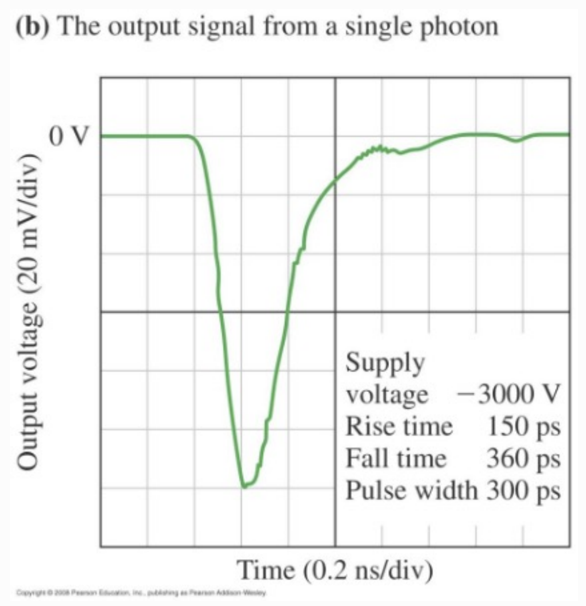
Scintillator Target (passive)

- Organic Scintillators: aromatic hydrocarbon compounds (*benzene ring-structures*)
  - *Solution of organic scintillator(s) in organic solvent*
    - *Liquid*: e.g. pTP in Toluene (En. Transfer from Solvant to Solute scintillator)
    - *Solid: e.g. pTP+POPOP in Polystyrene (plastic)*
- Inorganic Crystals (NaI, CsI, $PbWO_4$)
- *Liquified Noble Gases (LAr, LXe)*

Photosensor (active)

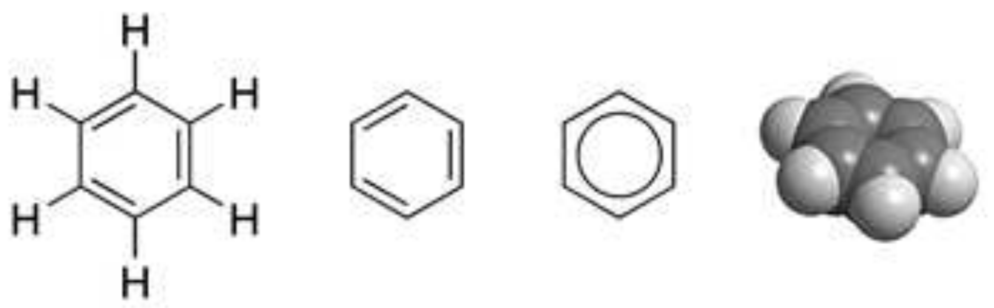
- Photomultiplier Tube (PMT)
- Micro-Channel Plates (MCP)
- Hybrid Photo Diodes (HPD)
- *Silicon PhotoMultiplier (SiPM)*

Electronic Signal Output

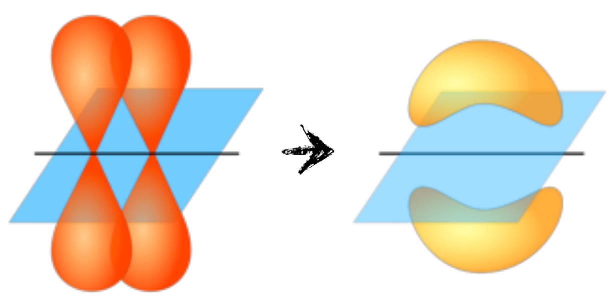


Organic scintillators: mechanism

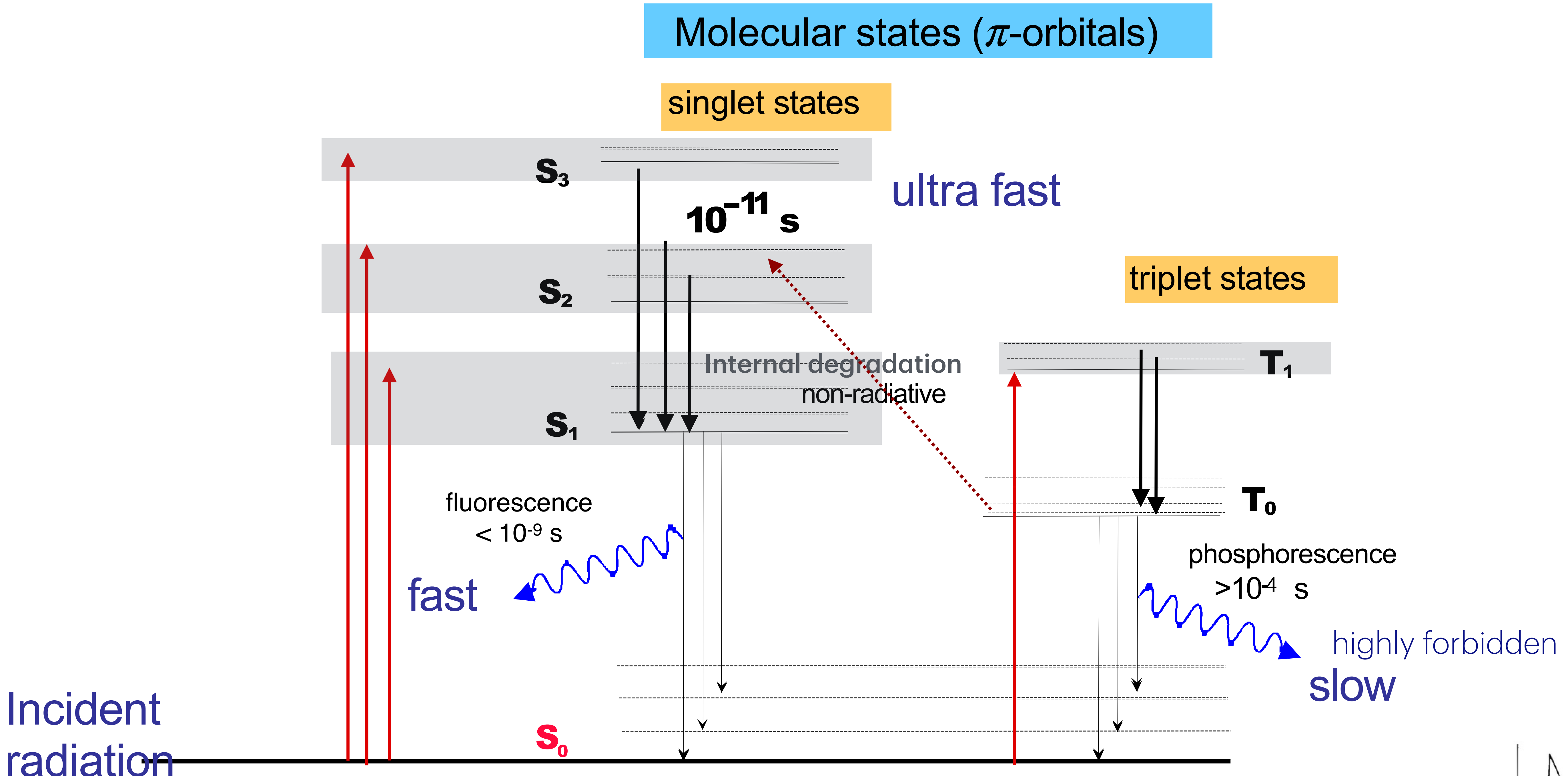
- **aromatic hydrocarbon compounds** (benzene ring) - excitation (Absorption) in 3-5 eV range
- scintillation light is due to de-excitation of delocalised molecular electrons in π-orbitals to ground state - emission in 2-3 eV range
- the two components are related two different de-excitation mechanisms



Scintillation is based on electrons of the C=C bond ...



Two p_z orbitals

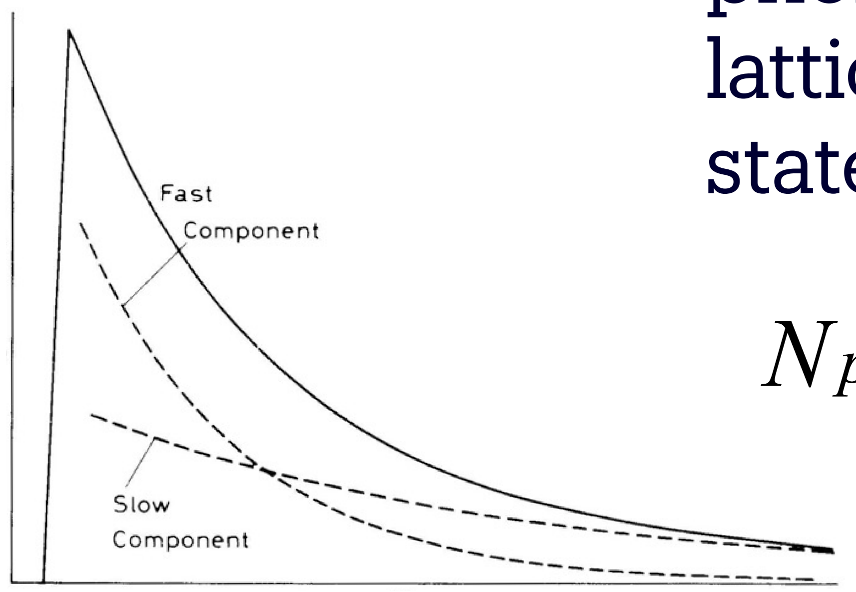


Emission: Visible/UV range

[~ 350 nm - ~500 nm] - Peak in the Blue (400 nm)

Scintillation Yield: 2-4 x 10^4 ph/MeV

- fast: ground S_0 to (high) excited states non-radiative decaying to an intermediate molecular state S_1 (~ps) and subsequent radiative decay back to ground S_0 (~ns) (fluorescence emission)
- slow: non-radiative de-excitation levels to T_0 intermediate level (>100ns) and subsequent (forbidden) decay to ground S_0 (ns) w/ phosphorescence emission or by lattice interactions to singlet excited states



$$N_{ph}(t) = Ae^{-t/\tau_f} + Be^{-t/\tau_s}$$

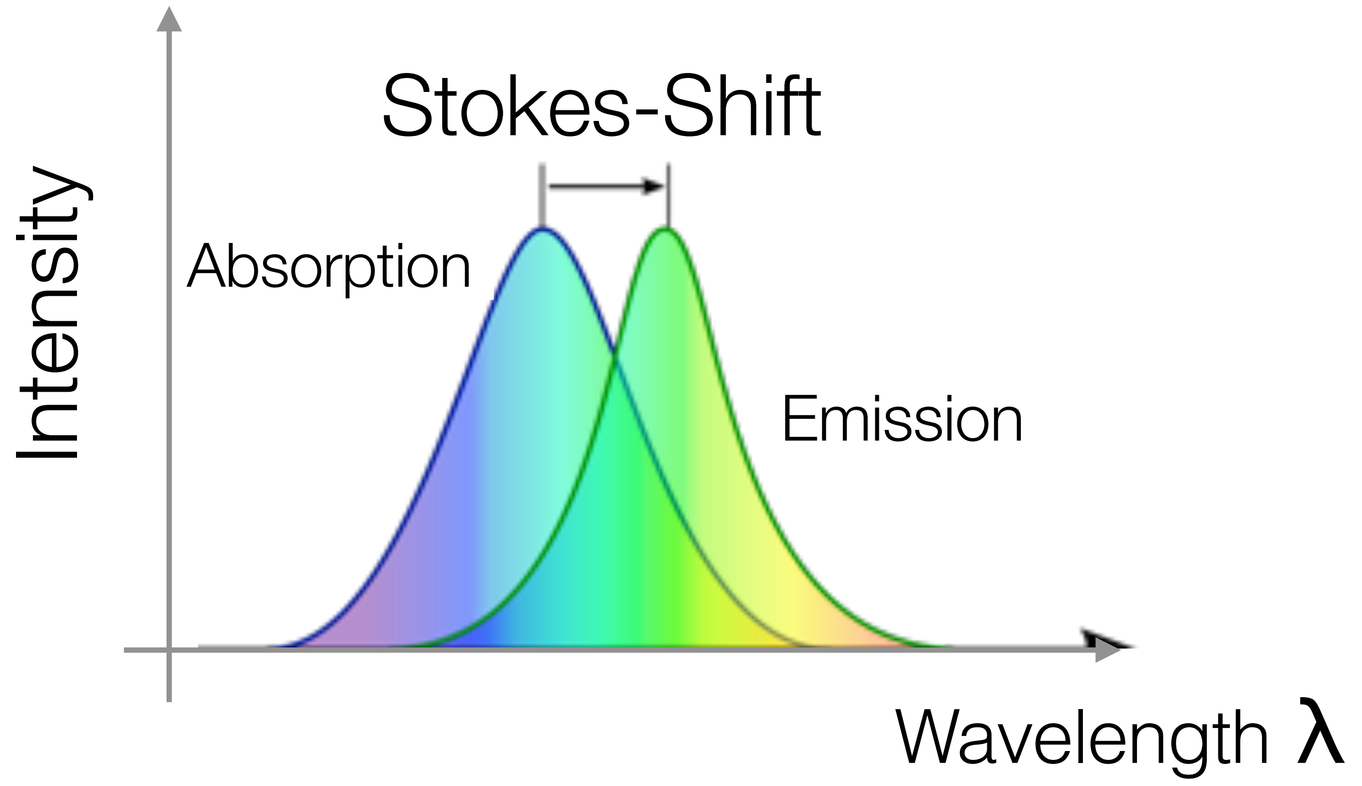
τ_f : decay constant of fast component

τ_s : decay constant of slow component

Organic scintillators: *wavelength shifting* mechanism

The intermediate (long-lived or metastable) states are fundamental to make the material transparent to the its own de-excitation light:

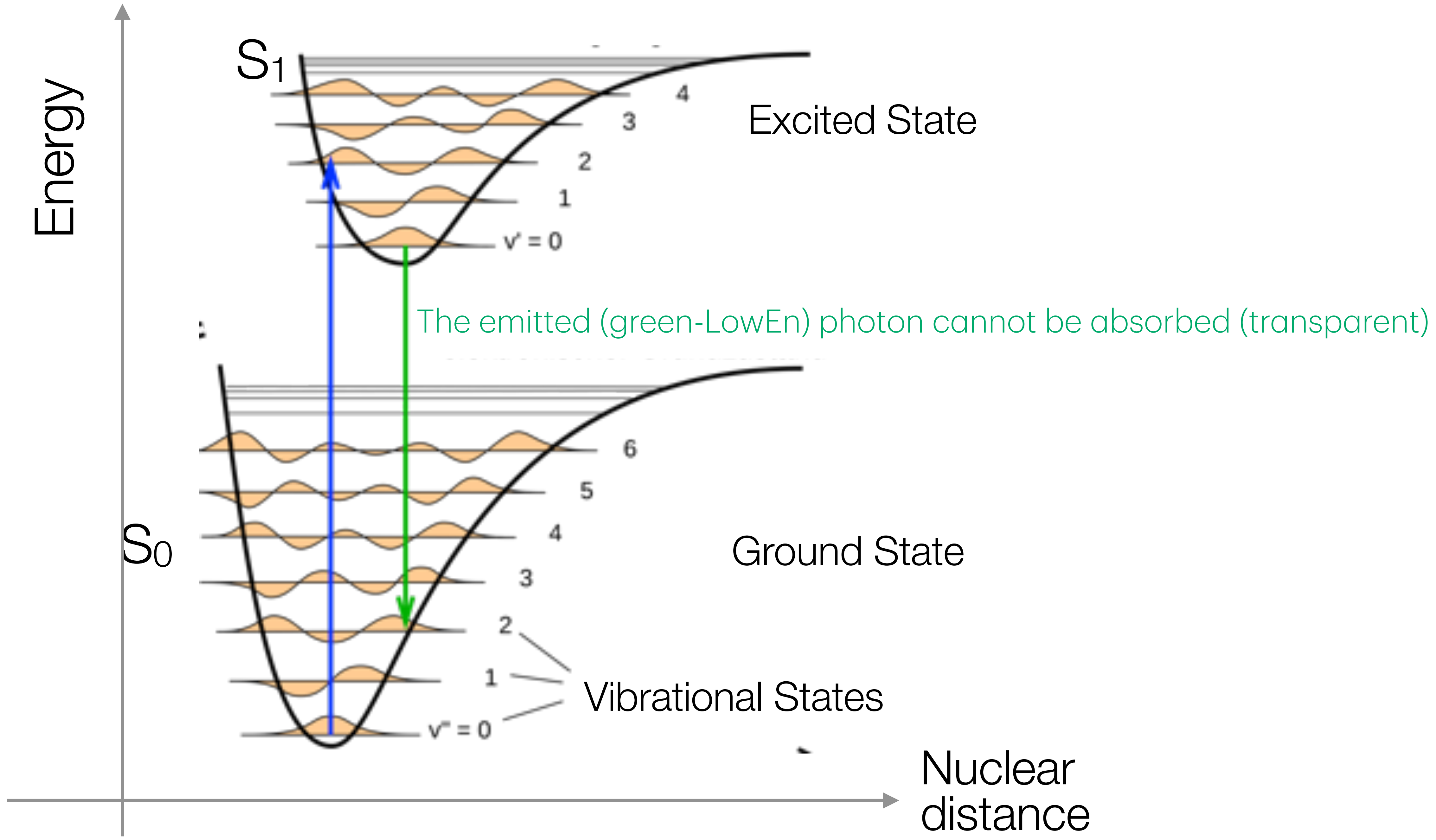
Shift of absorption spectra to emission spectra



Shift due to

Franck-Condon Principle

Excitation into higher vibrational excited states
De-excitation from lowest vibrational state



Excitation time scale : 10^{-14} s
Vibrational time scale : 10^{-12} s
S_1 lifetime : 10^{-8} s

Organic scintillators

Photon Yield Y_{ph}

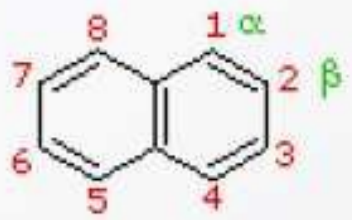
Organic Scintillators – Properties

Scintillator material	Density [g/cm³]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [ns]	Photons/MeV
Naphtalene	1.15	1.58	348	11	$4\cdot10^3$
Antracene	1.25	1.59	448	30	$4\cdot10^4$
p-Terphenyl	1.23	1.65	391	6-12	$1.2\cdot10^4$
NE102*	1.03	1.58	425	2.5	$2.5\cdot10^4$
NE104*	1.03	1.58	405	1.8	$2.4\cdot10^4$
NE110*	1.03	1.58	437	3.3	$2.4\cdot10^4$
NE111*	1.03	1.58	370	1.7	$2.3\cdot10^4$
BC400**	1.03	1.58	423	2.4	$2.5\cdot10^2$
BC428**	1.03	1.58	480	12.5	$2.2\cdot10^4$
BC443**	1.05	1.58	425	2.2	$2.4\cdot10^4$

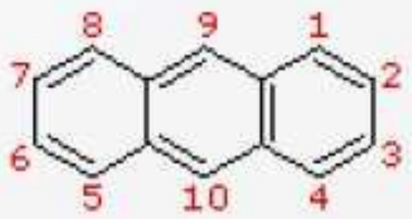
* Nuclear Enterprises, U.K.
** Bicron Corporation, USA

Organic scintillators exist as

crystals (very rarely used in HEP)



naphthalene
$C_{10}H_8$
m.p. 81° C

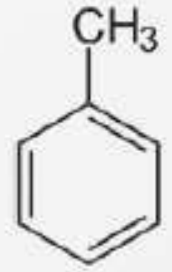


anthracene
$C_{14}H_{10}$
m.p. 217° C

liquids (solutions) (rarely used in HEP)

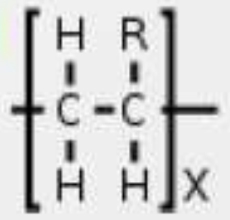
plastics (polymerized solutions) (much used in HEP)

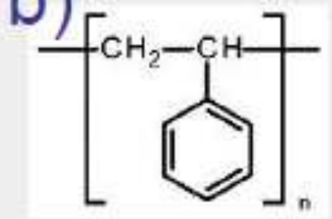
solvent + activator



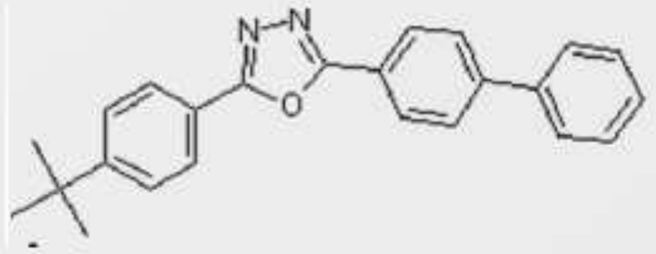
e.g. toluene

e.g. p-terphenyl

a) 

b) 

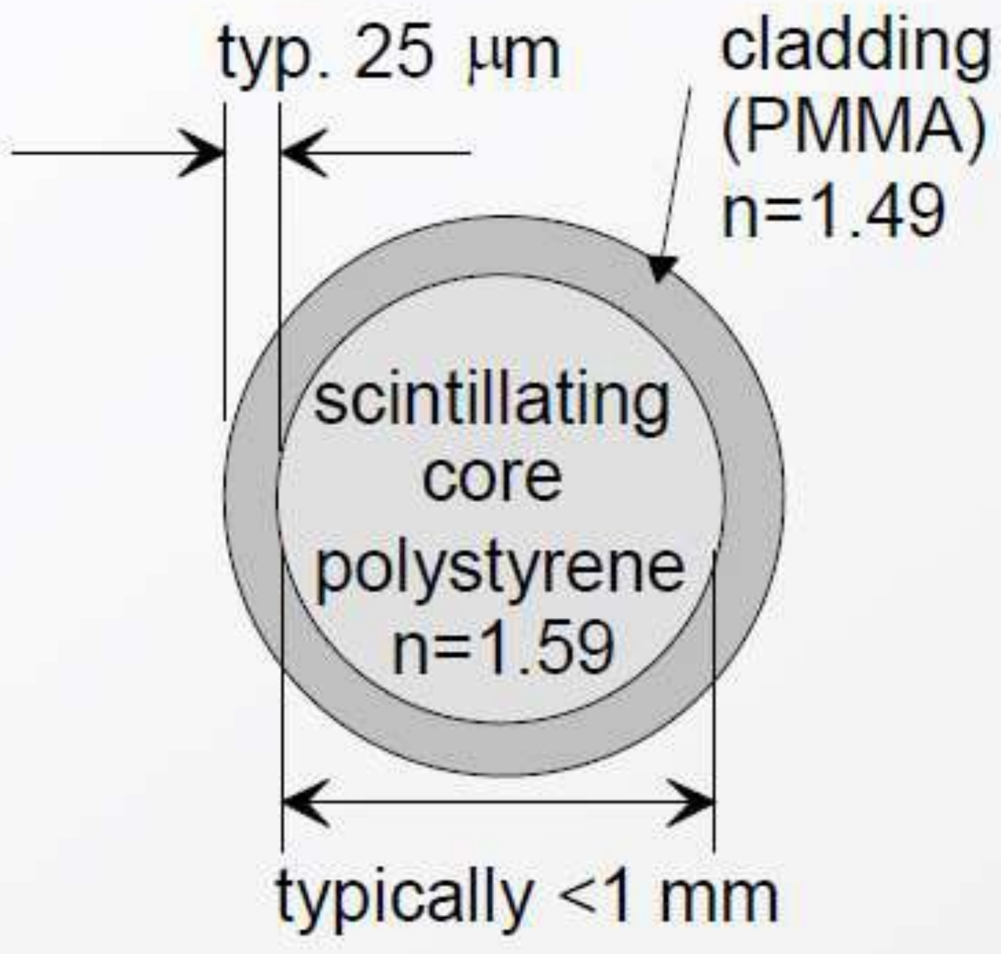
e.g. polyvinlyltoluene (a) or polystyrene (b)



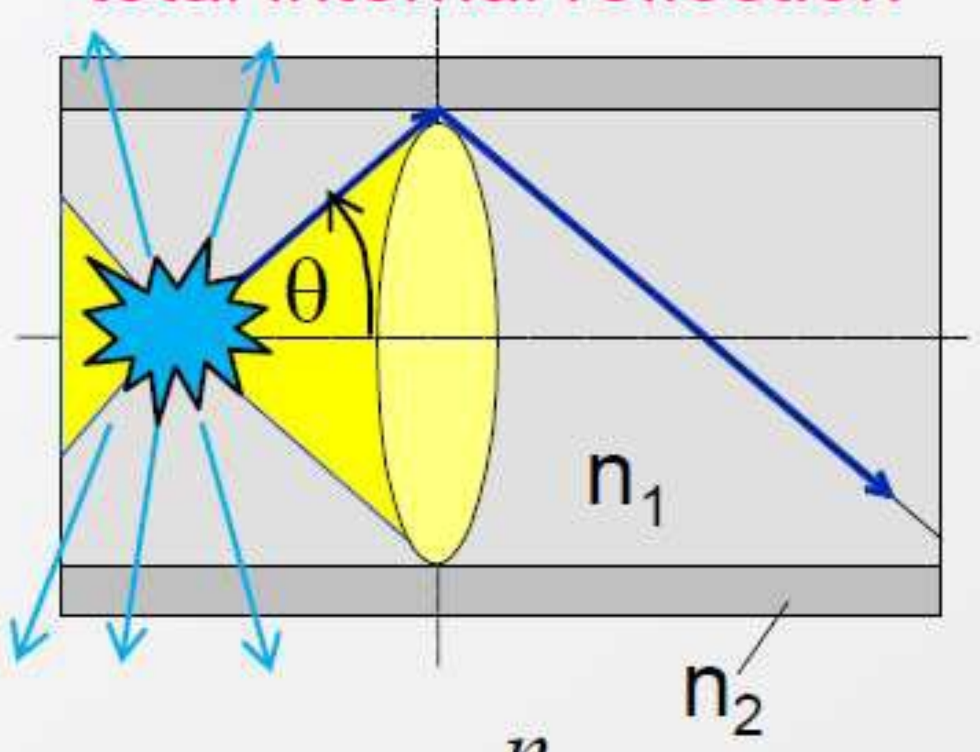
e.g. Butyl-PBD

Scintillating fibres

Working principle of scintillating plastic fibres :



light transport by
total internal reflection



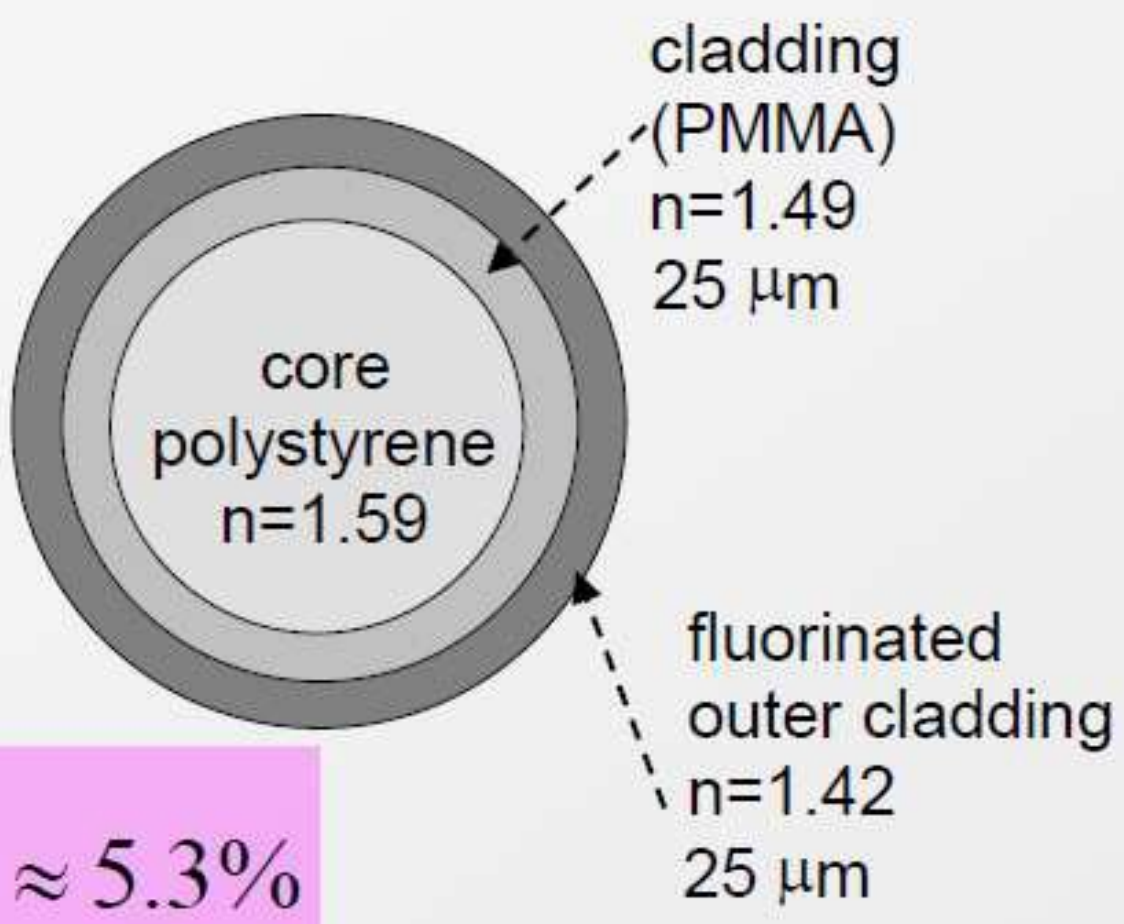
$$\theta \leq \arccos \frac{n_2}{n_1} \approx 20.4^\circ$$

Trapping fraction

$$\frac{d\Omega}{4\pi} = 0.5\,(1-\cos\theta) \approx 3\%$$

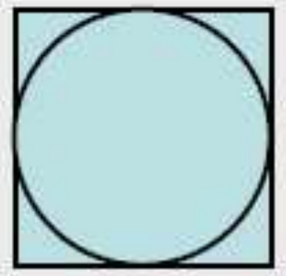
(per side)

Double cladding system
(developed by CERN RD7)



$$\frac{d\Omega}{4\pi} = 0.5\,(1-\cos\theta) \approx 5.3\%$$

There are also square fibres. Their trapping fraction is slightly higher (additional angular phase space), but corners are problematic for light transport.

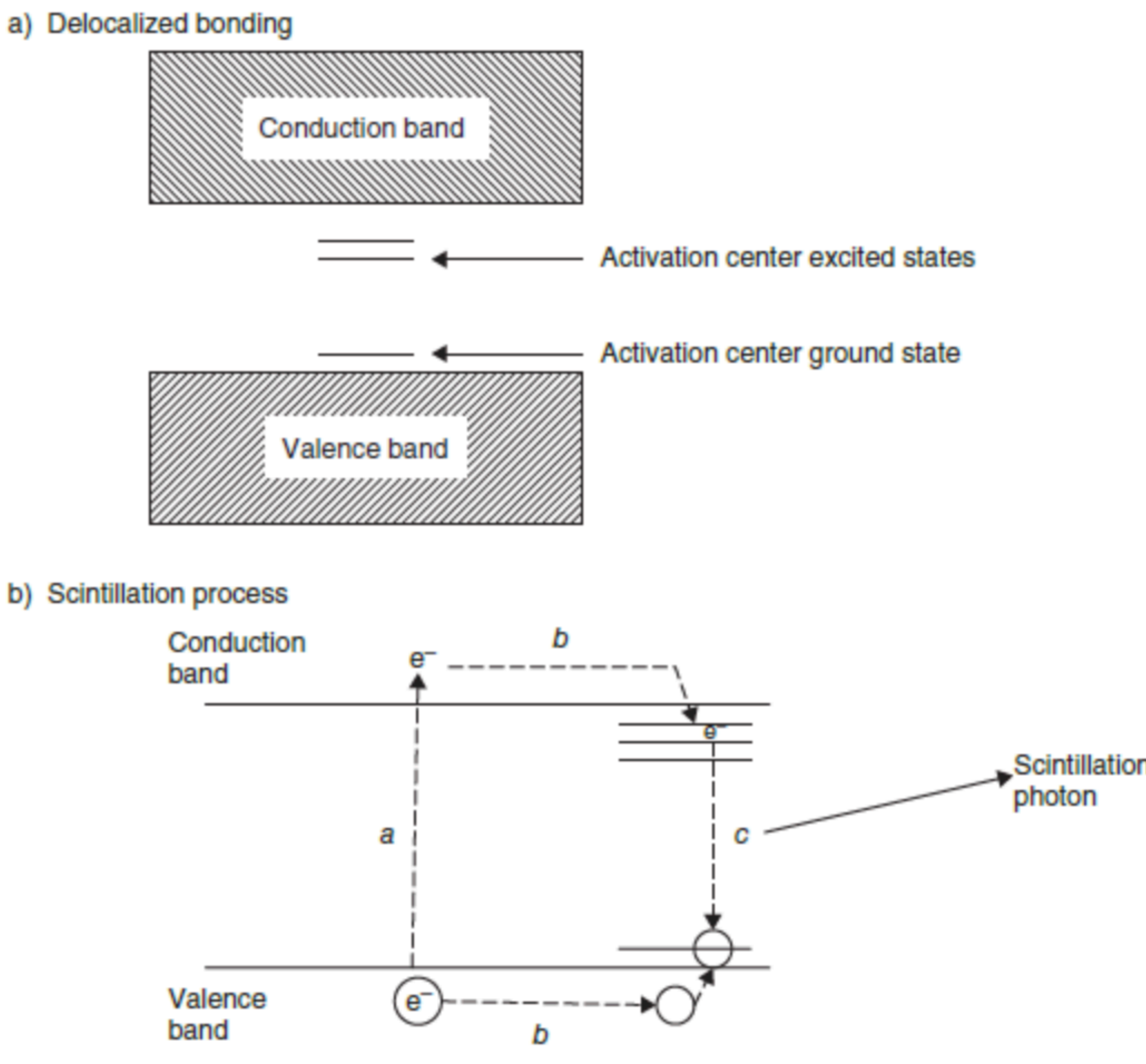


Inorganic Crystal scintillators: mechanism

- **Gamma ray** entering crystal produces one or more secondary electrons with high kinetic energy.
- Electrons cause ionizations and excitations as they move, creating many low-energy electrons.
- Most of these low-energy electrons lose their energy as heat, but some have the right amount of energy to jump up to the conduction band. A hole is left in the valence band for each electron excited to the conduction band.
- The electrons that get into the conduction band are free to move around, but are not allowed to drop directly back into the valence band ("forbidden" by quantum mechanics) but still seek the lowest energy levels available to them, which are the excited state levels of the activation centres.
- Likewise, the holes will allow electrons in the valence band to move, and eventually they will be filled by electrons from activation centres, leaving vacancies in the activation centre ground-state orbitals.
- Quantum mechanics does allow the transition of an electron from the excited state to the ground state in an activation centre. The electron drops down and fills the hole, with the release of the excess energy in the form of a scintillation photon of energy 3eV which is the band gap.

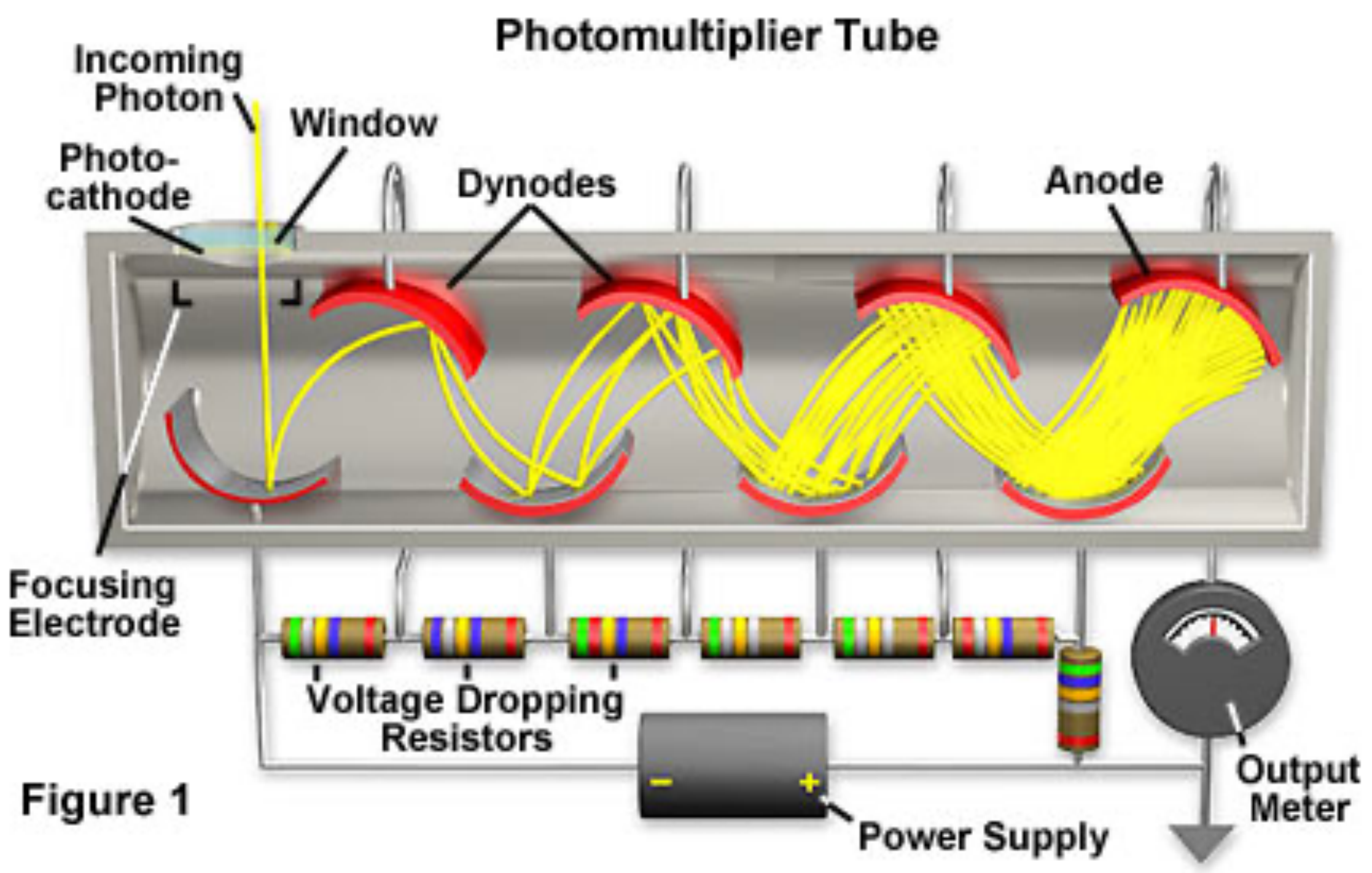
scintillation mechanism related to the crystal lattice bands:

- band gap between ground and excited states - excitations with decay to ground state, emitting photons



PhotoSensors

From scintillation light to detectable electric signal



Classic Solution: PhotoMultiplier Tube PMT

- *Photo-cathode: metal layer/first electrode coated w/ sensitive (biAlkali)* to convert photon to electron by PhotoElectric effect)
- *Dynode chain: series of HV electrodes* to accelerate electron and make secondary electrons emission -
  - Use HV again and again to multiply electrons (gain 10^6-10^7) to generate a current
- *Anode:* last electrode to collect the generated (electron) current

Photon-Detector Systems (Classic Scintillation Counter)

- Optically couple Scintillator (passive target) to PMT Active photoSensor
- Collected Charge proportional to Number of Scintillation Photons in the target
- Reconstruct deposited Energy of incident Radiation in Scintillator target

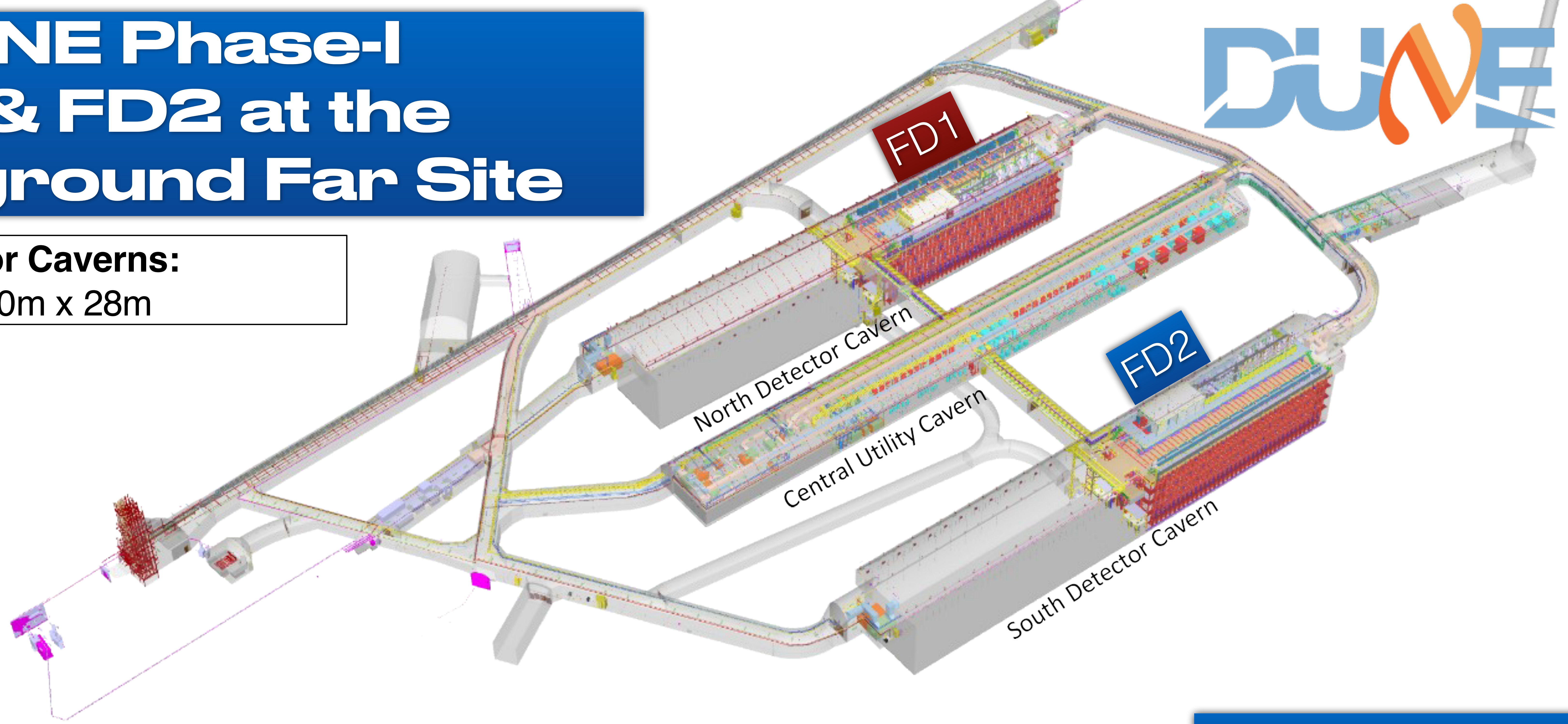
Amplify, Digitize/Record the signal
Analysis

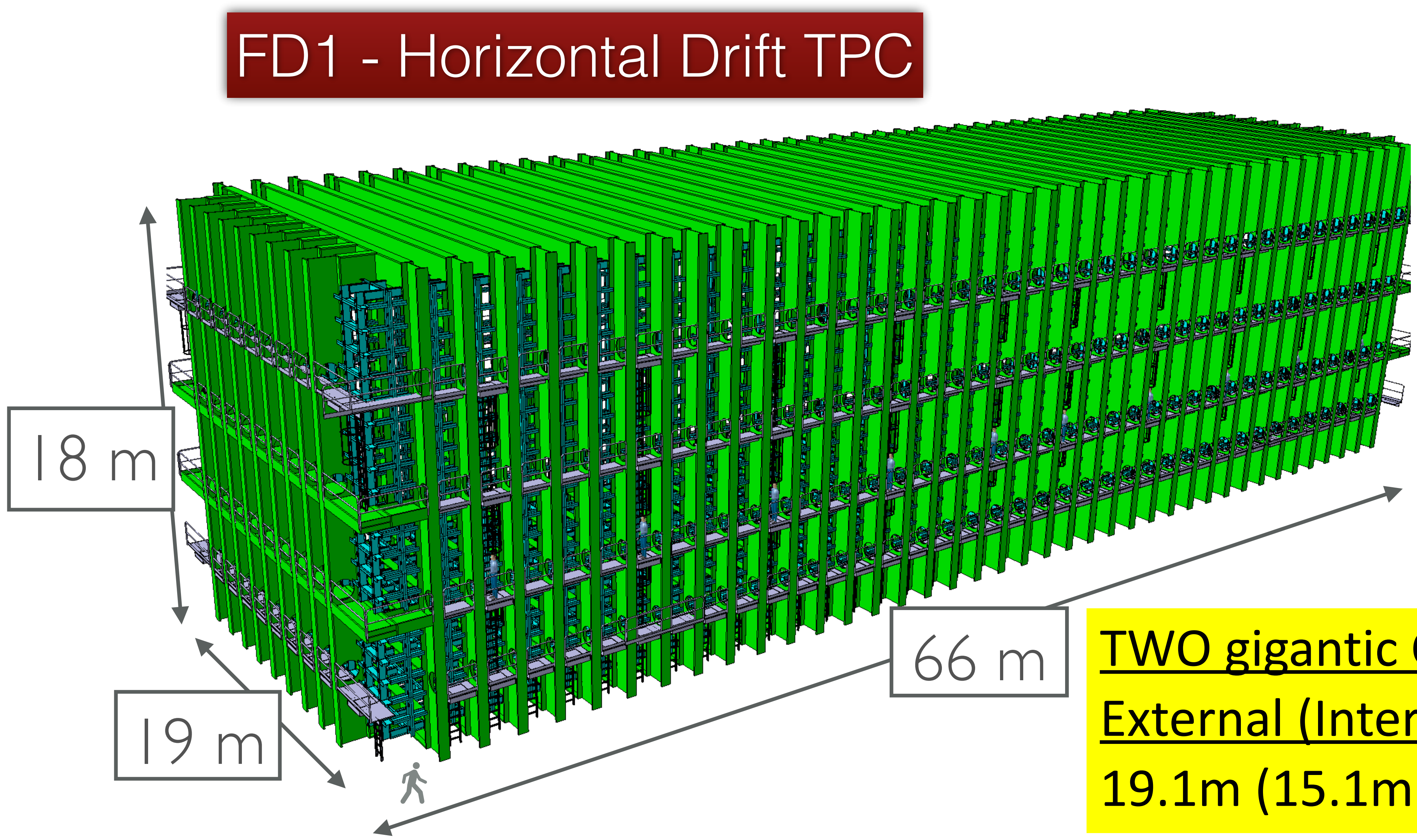
LArTPC and LArPDS

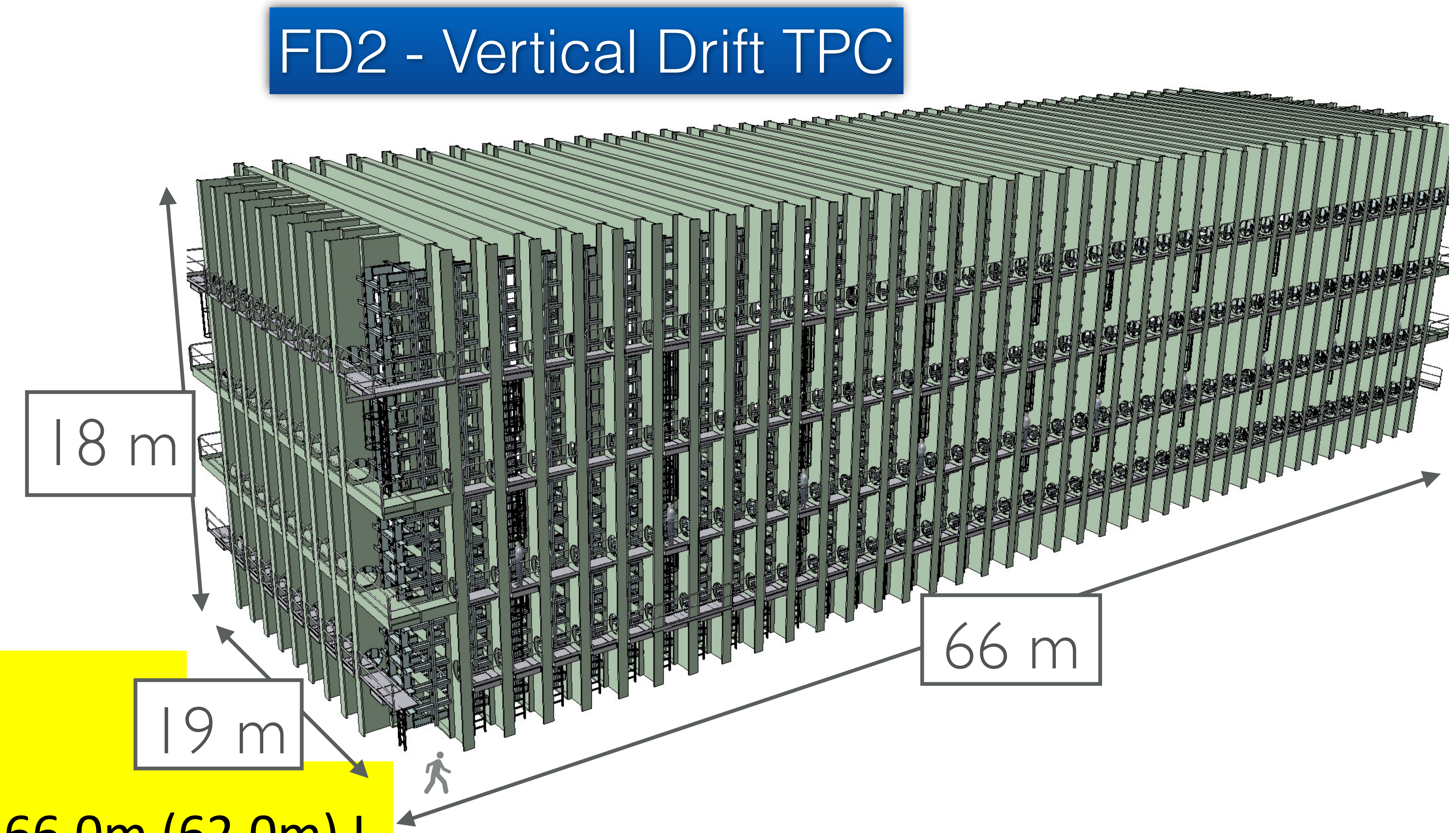
New technologies for new discoveries

DUNE Phase-I FD1 & FD2 at the Underground Far Site

2 x Detector Caverns:
145m L x 20m x 28m







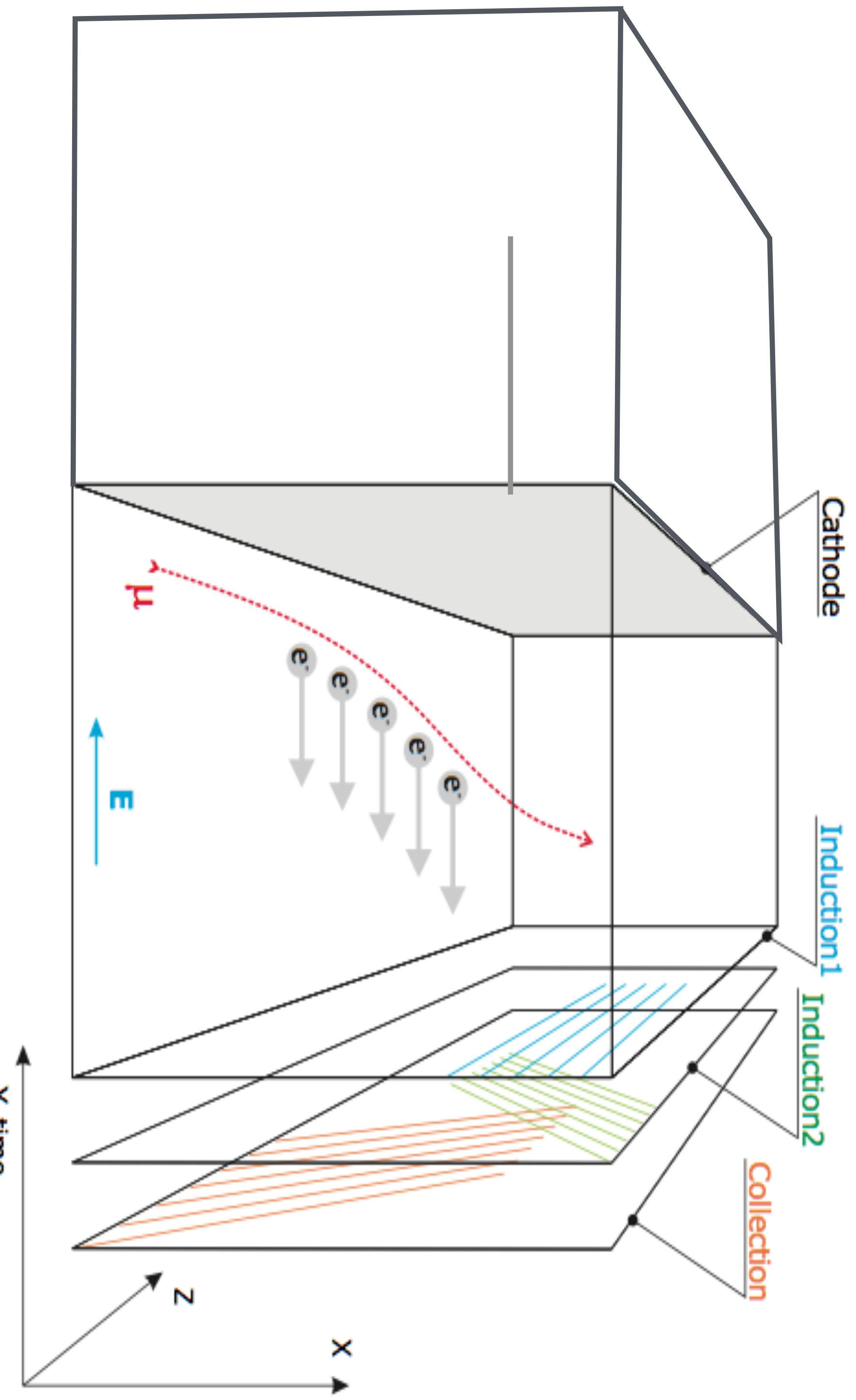
TWO gigantic Cryostats for LAr
External (Internal) Dimensions
19.1m (15.1m) W x 18.0m (14.0m) H x 66.0m (62.0m) L

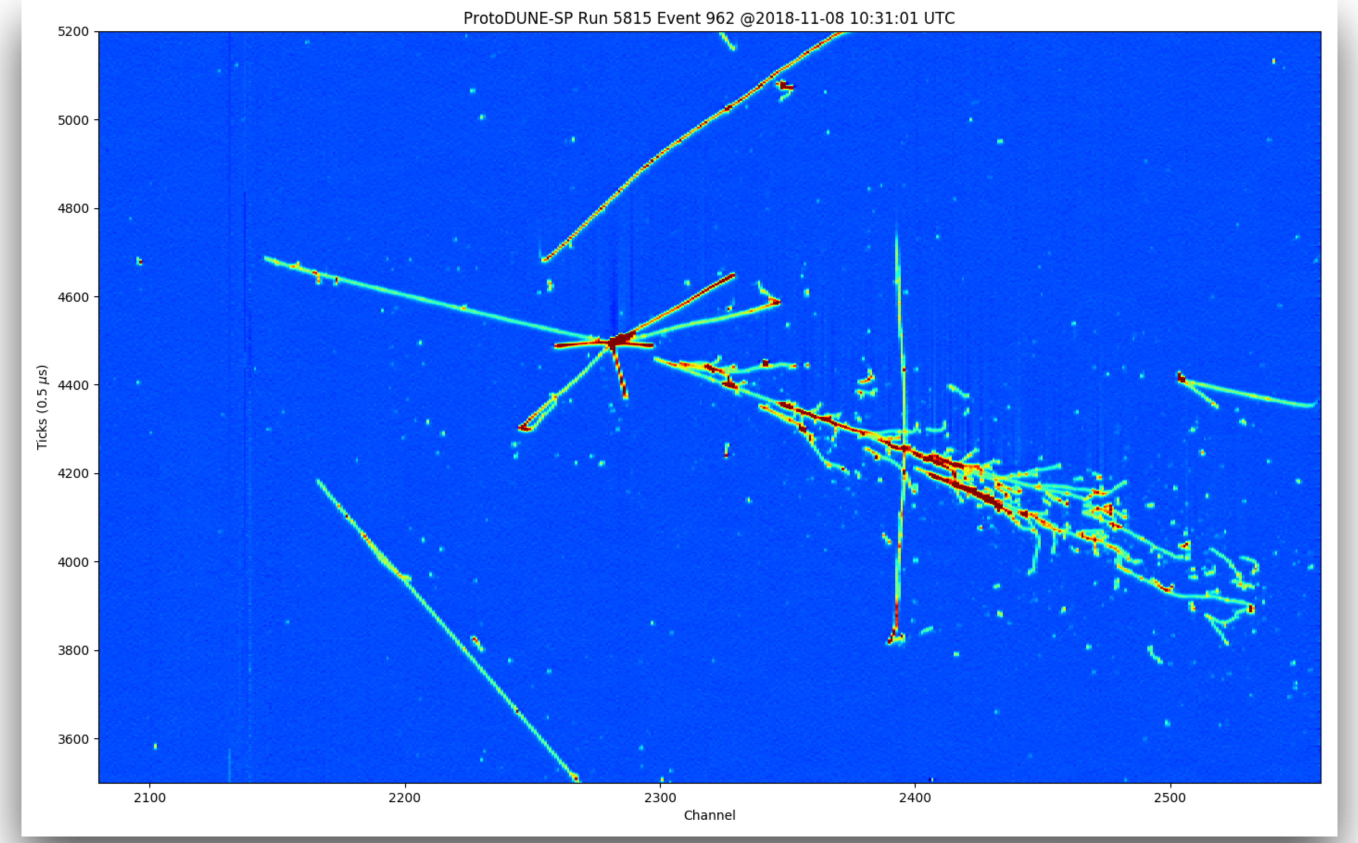
The DUNE Detector Systems

Liquid Argon Time Projection Chamber (LArTPC)

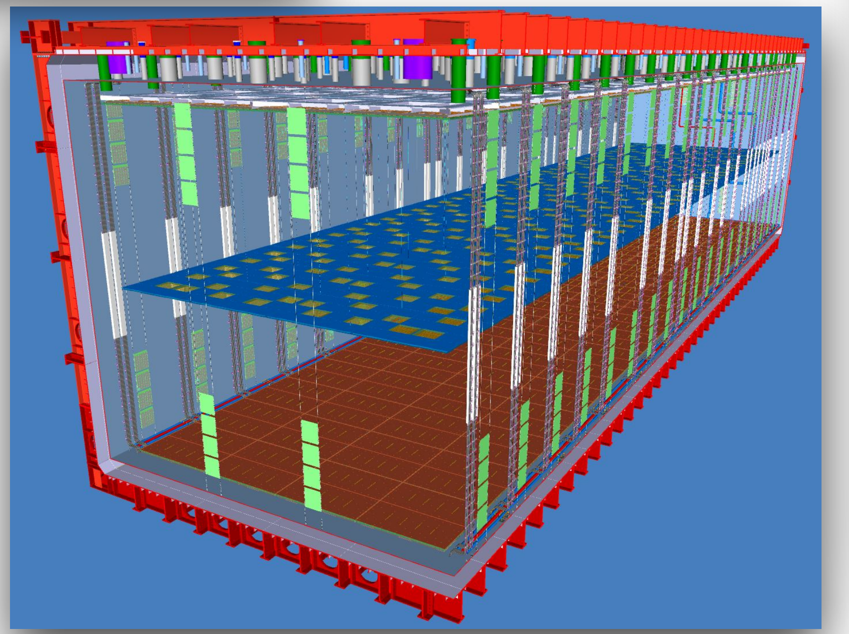
Modern Ionization Chamber

- Sophisticated Ionization Charge Sensing Electronic System with Imaging and Calorimetric Energy reconstruction capability for charged particles produced by Neutrino Interactions in LAr extra-large Volume immersed in uniform Electric Field





Final design (2023)
Now under construction



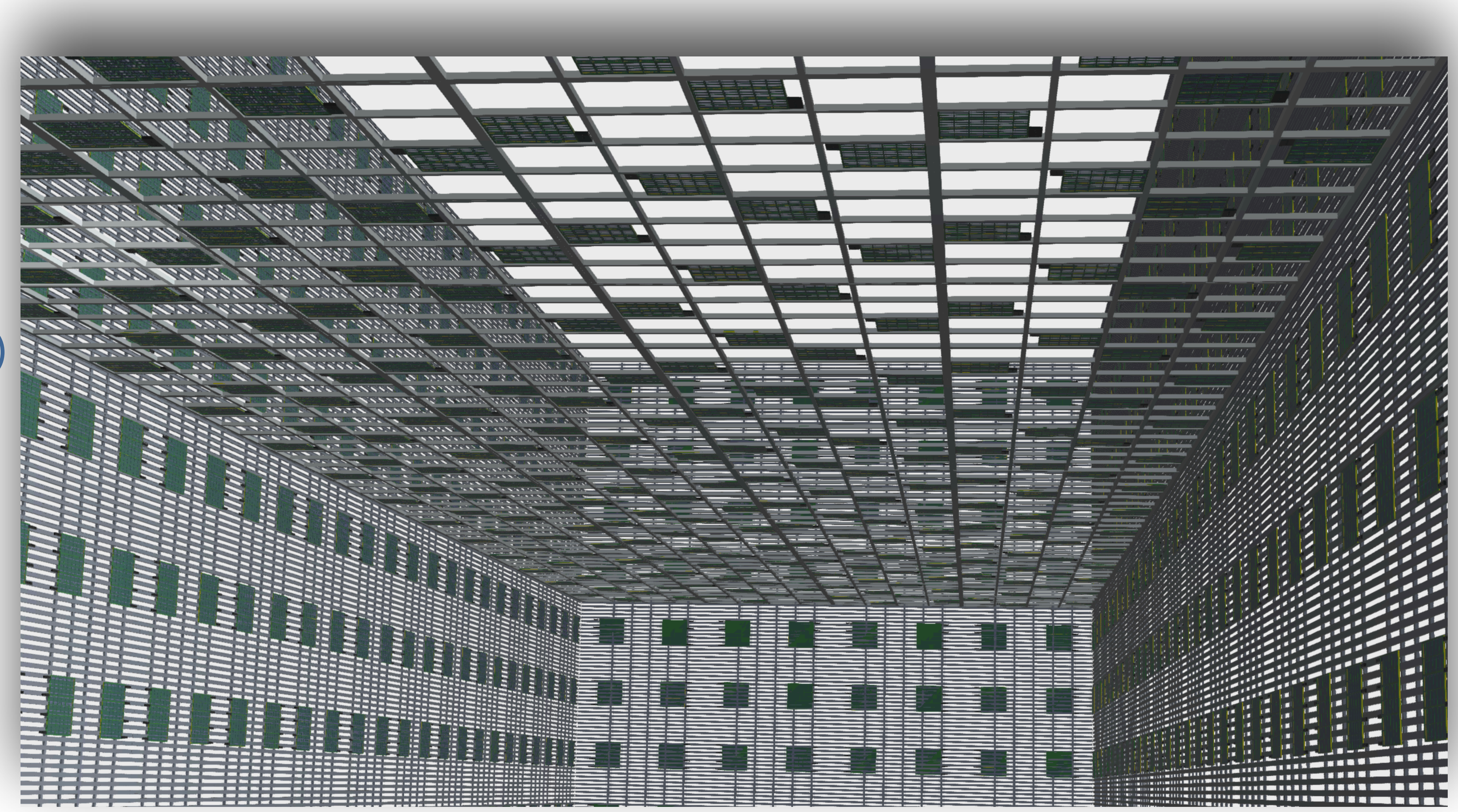
Liquid Argon Photon Detection system (LArPDS)

Modern Scintillation Counter

- LAr Scintillator (extra-large Volume - passive target)
- Optically coupled to Array of XARAPUCA PhotoCollector Modules equipped with
- SiPM Active photoSensor

- Collected Scintillation Photons emitted in the LAr target
- Reconstruct timing of neutrino Events and deposited Energy of charged particles produced by Neutrino Interactions)

$\sim 4\pi$ LArPDS design for the DUNE FD2 (proposal 2021)



Initial Microscopic Fast Processes

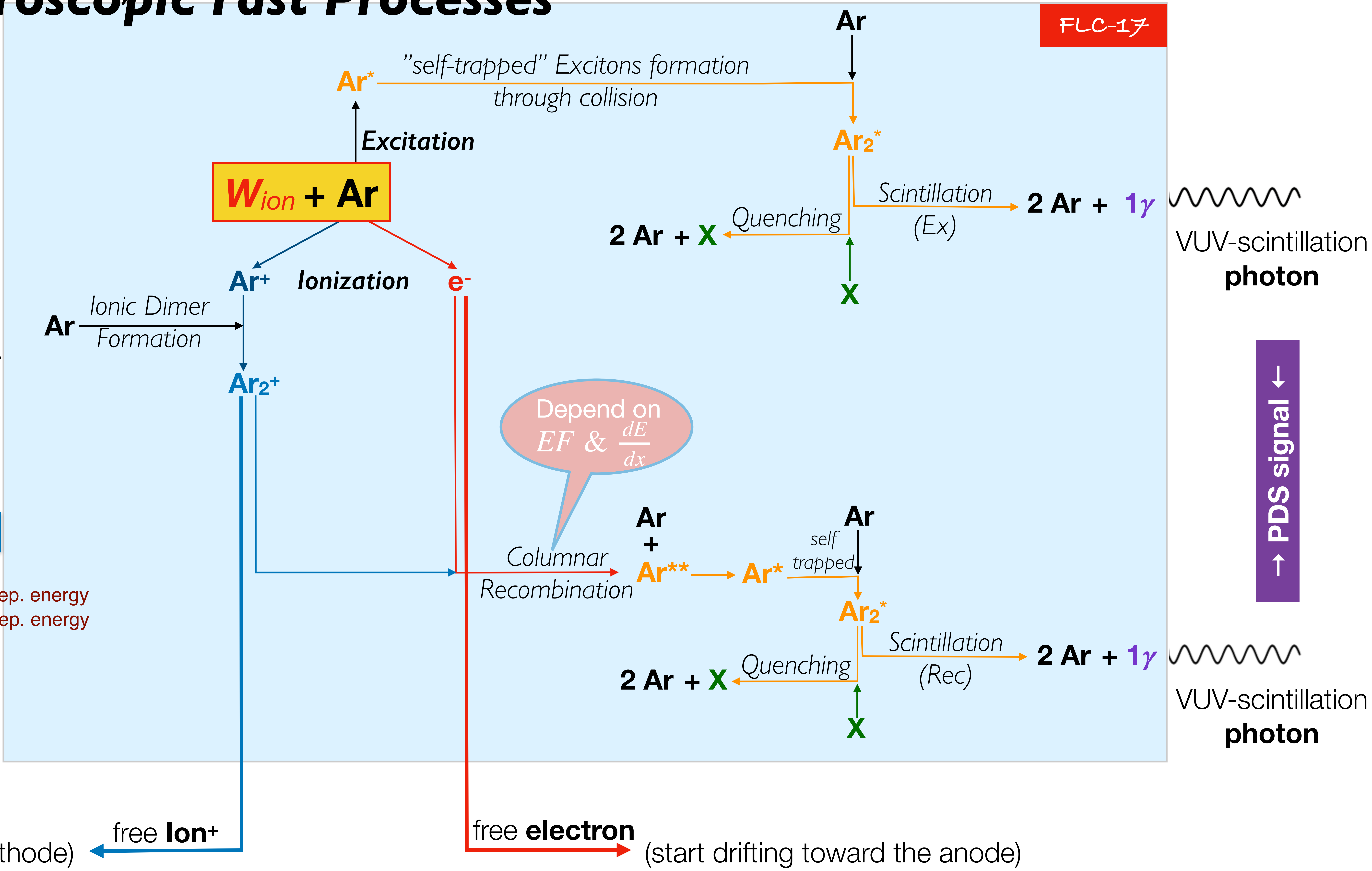
(ps-μs)

induced by Energy release from charged particles in LAr

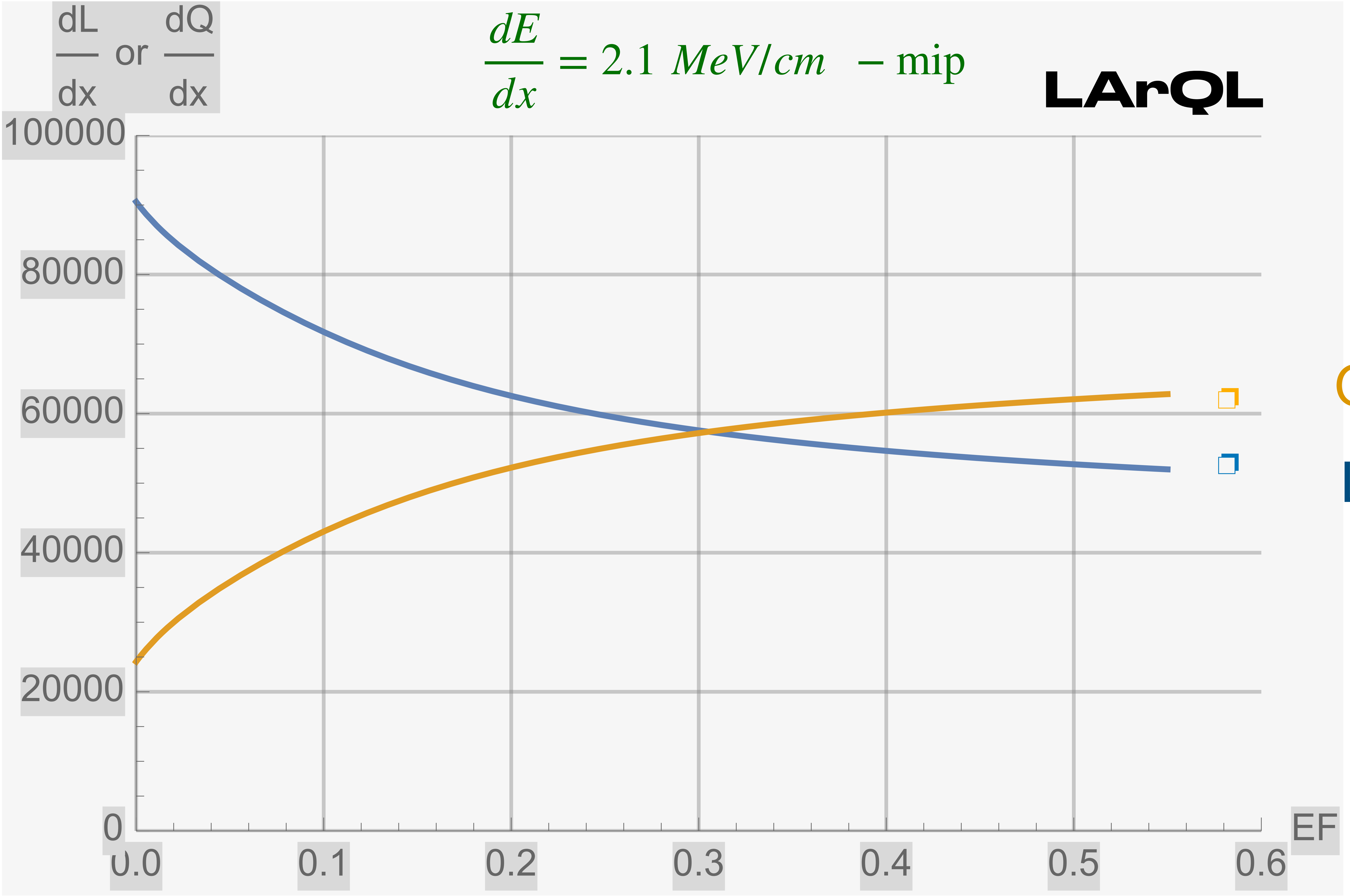
$$W_{ion} = E_i + \epsilon_{kin} + \frac{N_{ex}}{N_i} E_{ex}$$

N_i n. of Ionizations per unit of dep. energy

N_{ex} n. of Excitations per unit of dep. energy



Liquid Argon target medium



Q+L = const

$$= \frac{1}{W_{ion}}\left(1+\frac{N_{ex}}{N_i}\right)\cdot\frac{dE}{dx}$$

At $EF = 0.5\ \frac{kV}{cm}, \frac{dE}{dx} = 2.1\ \frac{MeV}{cm}$

$L = 52700\ \frac{ph}{cm},\ Q = 62000\frac{e}{cm}$

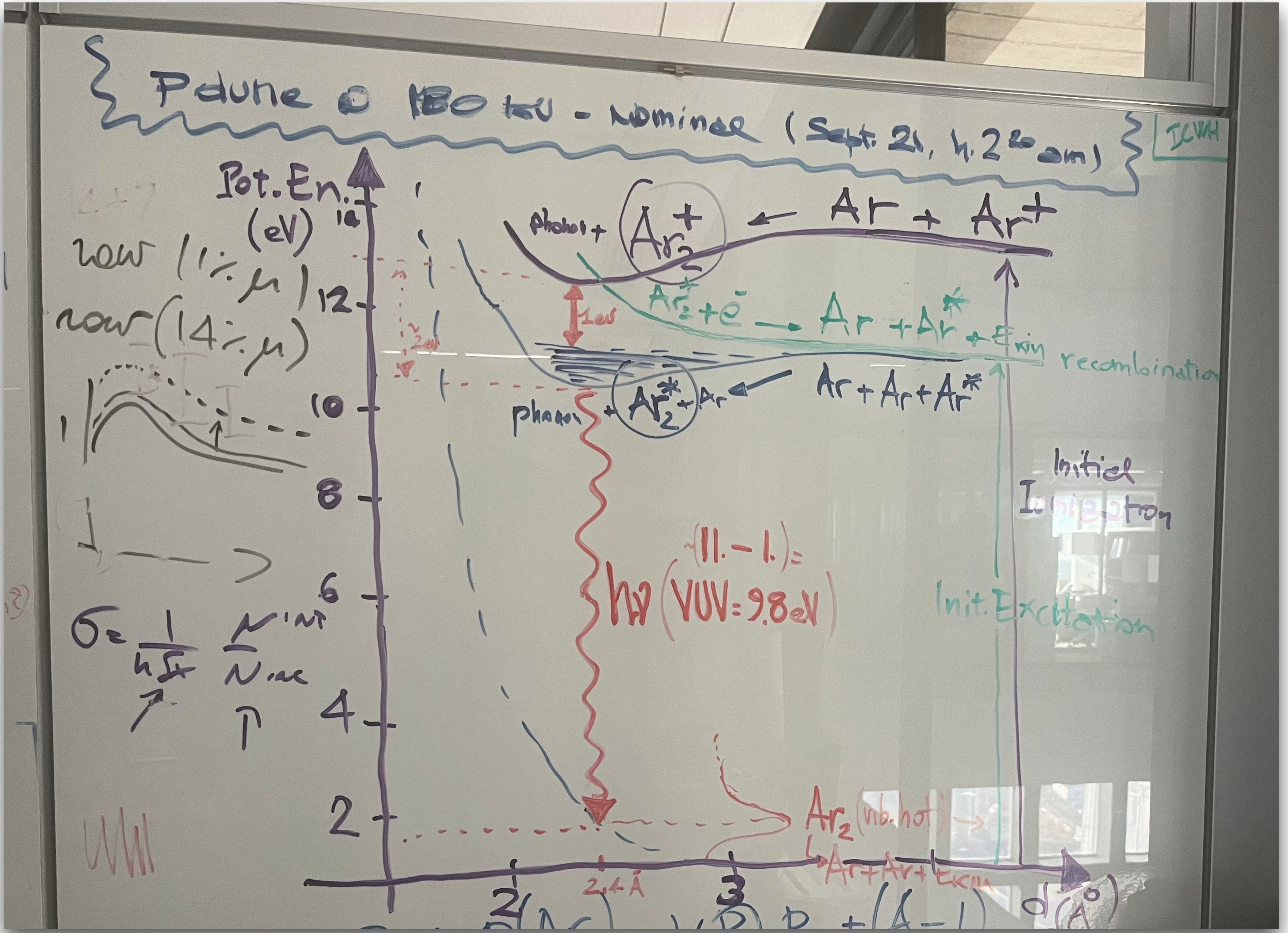
In LArTPC-LArPDS

$L^{mip} = 25{,}000\ \mathrm{ph/MeV}$

$Q^{mip} = 29{,}000\ e/\mathrm{MeV}$

Slide from talk at NuFact'11 - CERN

Liquid Argon Scintillator



The LAr Scintillation VUV photons (9.8 eV) come from Ar_2* excited dimer de-excitation.

The first excited state of Ar (14.4 eV) is higher than 9.8 eV, so no absorption of the VUV photons (and this is why people normally say LAr is transparent to its own scintillation light). However, this statement is not true (or at least largely not true). In fact, a large fraction of Ar atoms are paired by Van Der Walls forces into Ar_2 dimers (up to 88%) in LAr. VUV photons from Ar_2* can thus be re-absorbed with high probability by the many Ar_2 around (absorption length was calculated to be ~ 10 μm !!).

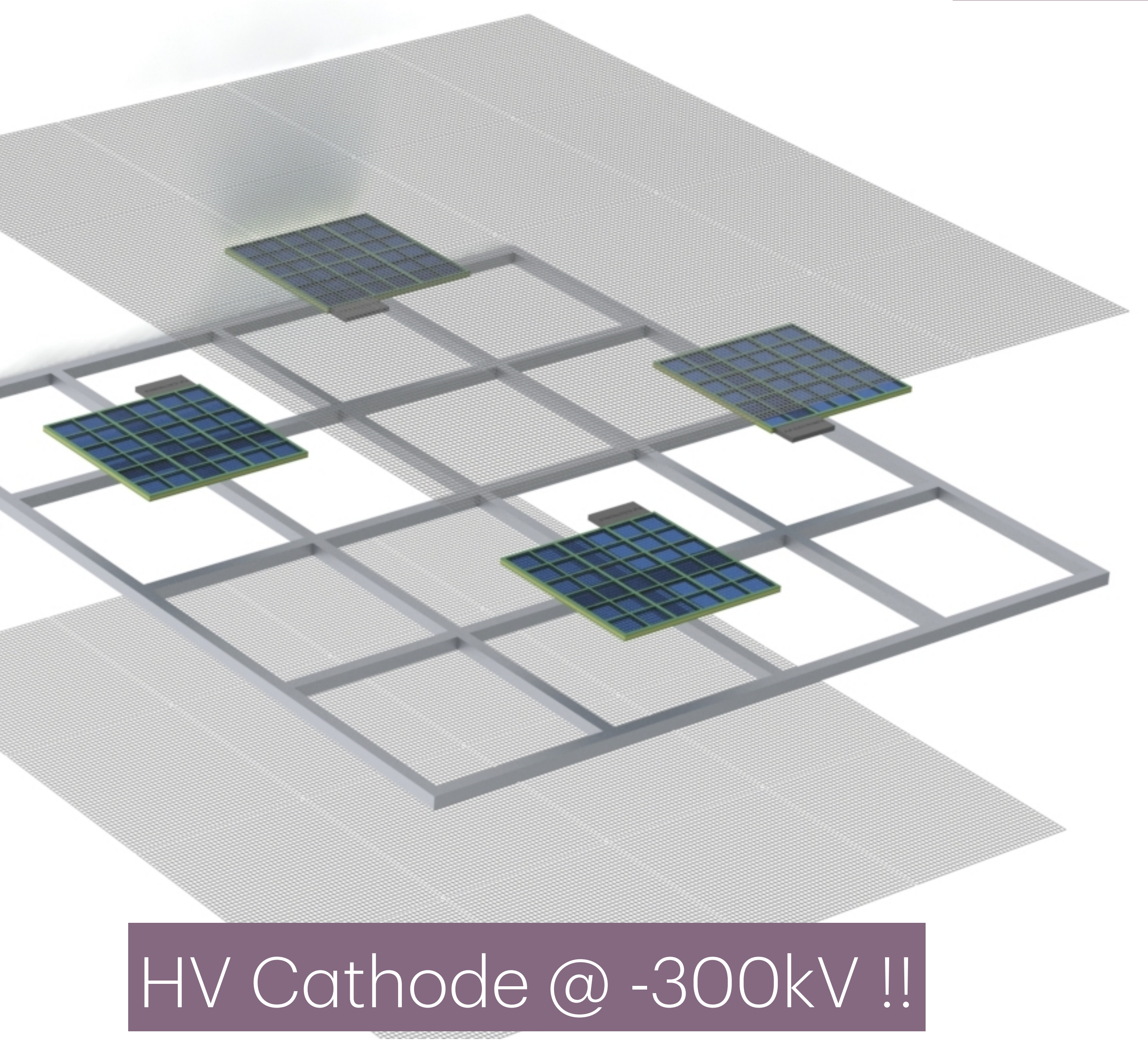
Then, why is Ar (manifestly) transparent to its own VUV light ?

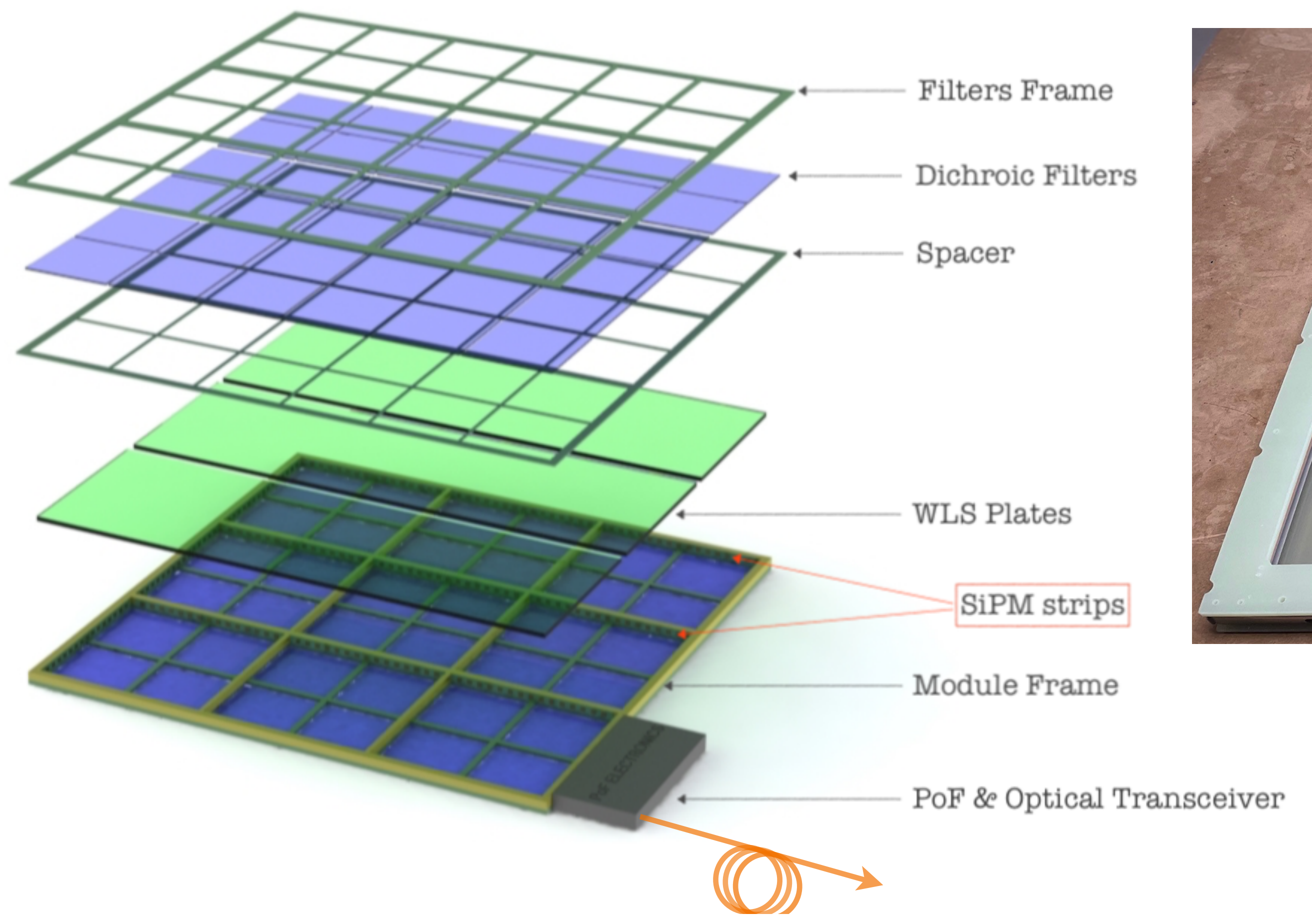
Because the decay from Ar_2* does NOT go into the ground dissociative state ($Ar_2^* \rightarrow \gamma_{VUV} + Ar + Ar$), rather it goes into a vibrational state of Ar_2, ~ 1 eV above ground dissociative state. Therefore the VUV photon has not enough energy to be absorbed by Ar_2 (it would need in fact ~11 eV).

The graph on the white board (FLC Office) shows this.

Photons are emitted with wavelength in the VUV range (around 128 nm) and exponentially distributed in time with two (main) different time constants ($\tau_S \simeq 5$ns for the fast component and $\tau_T' \simeq 1.3$ μs for the slow component), corresponding to the decay of the Ar_2 excimers in Singlet and Triplet states respectively*

PhotoCollector X-ARAPUCA





The X-ARAPUCA: An improvement of the ARAPUCA device

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[b] Instituto de Física Gleb Wataghin, Universidade Estadual de Campinas - Unicamp,, Rua Sergio Buarque de Holanda, No 777, CEP 13083-859 Campinas, SP, Brazil
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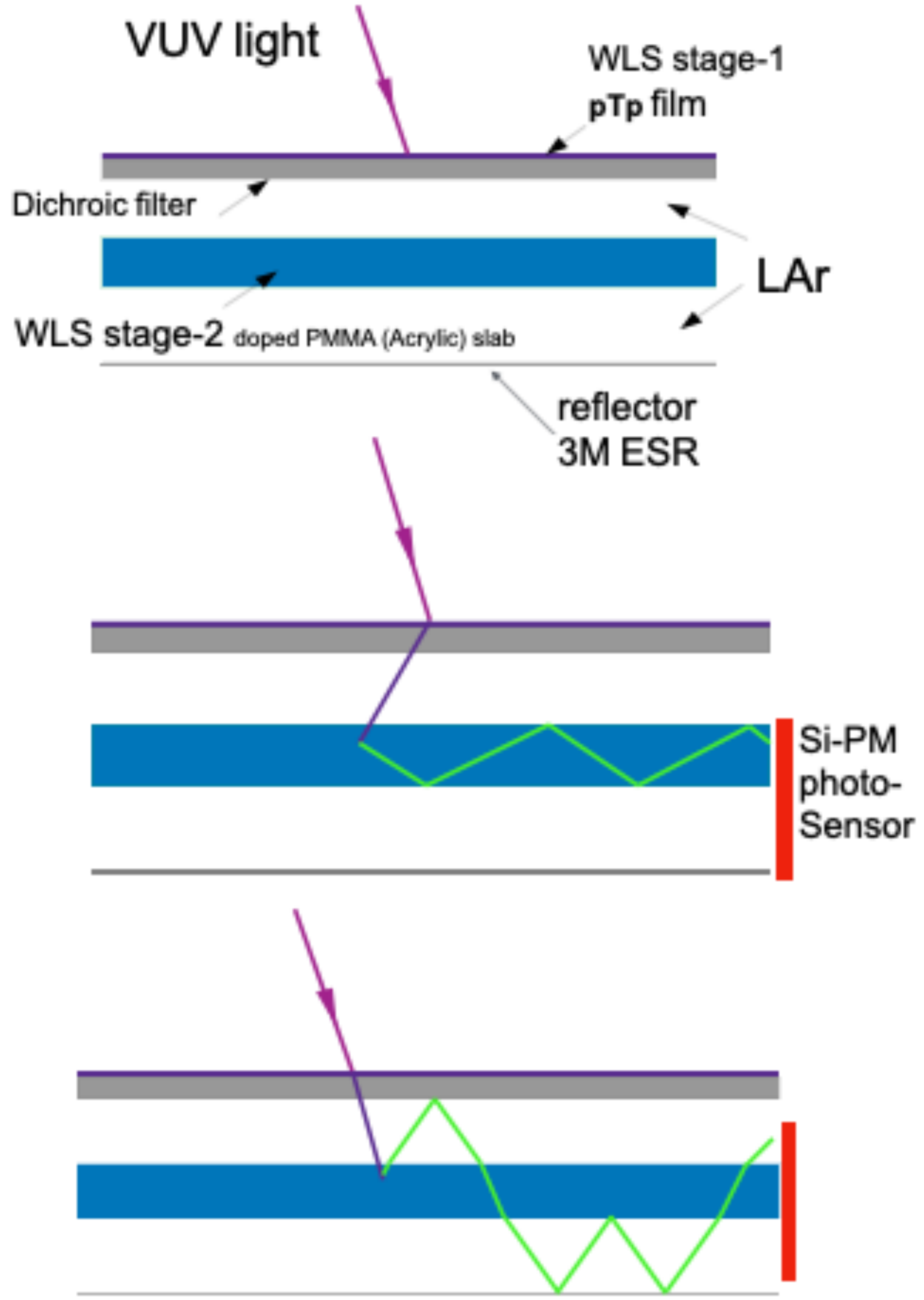
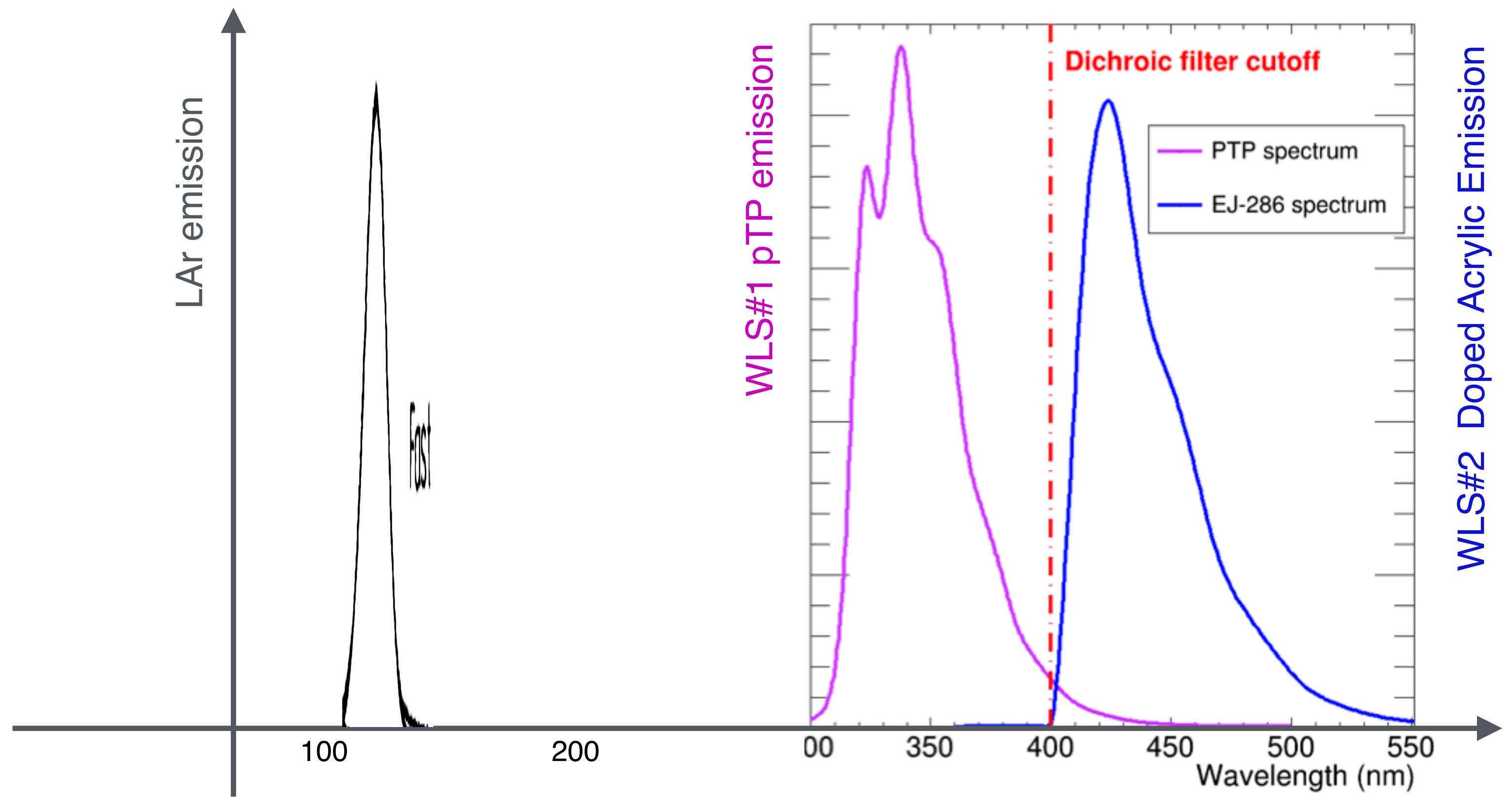
April 5, 2018

Abstract

The ARAPUCA is a novel technology for the detection of liquid argon scintillation light, which has been proposed for the far detector of the Deep Underground Neutrino Experiment. The X-ARAPUCA is an improvement to the original ARAPUCA design, retaining the original ARAPUCA concept of photon trapping inside a highly reflective box while using a wavelength shifting slab inside the box to increase the probability of collecting trapped photons onto a silicon photomultiplier array. The X-ARAPUCA concept is presented and its performances are compared to those of a standard ARAPUCA by means of analytical calculations and Monte Carlo simulations.

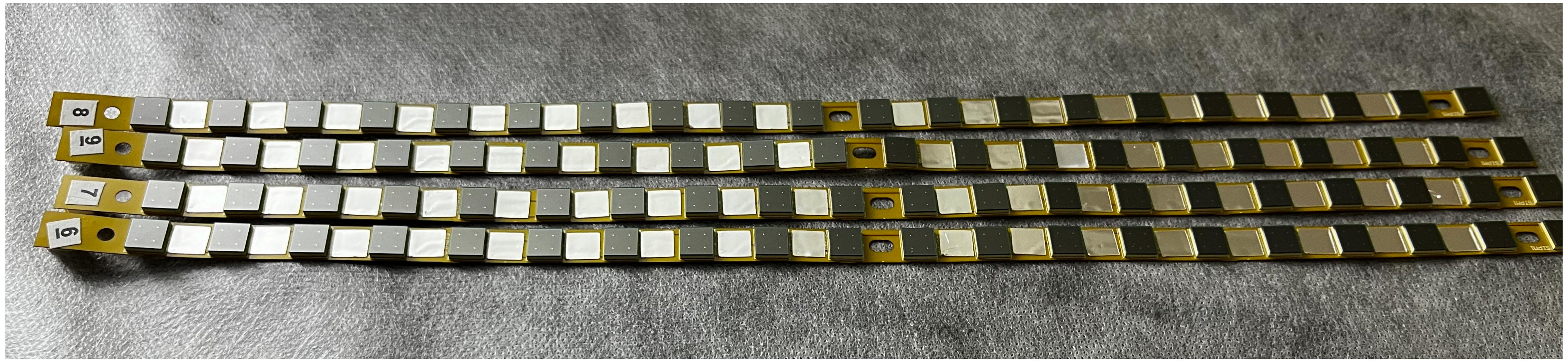


- a novel Photon Collection technology [Machado, Segreto] acting as a “Light Trap”, a clever system made of a dichroic filter and TWO WLS-stages, coupled with an array of SiPM as active photo-sensors.



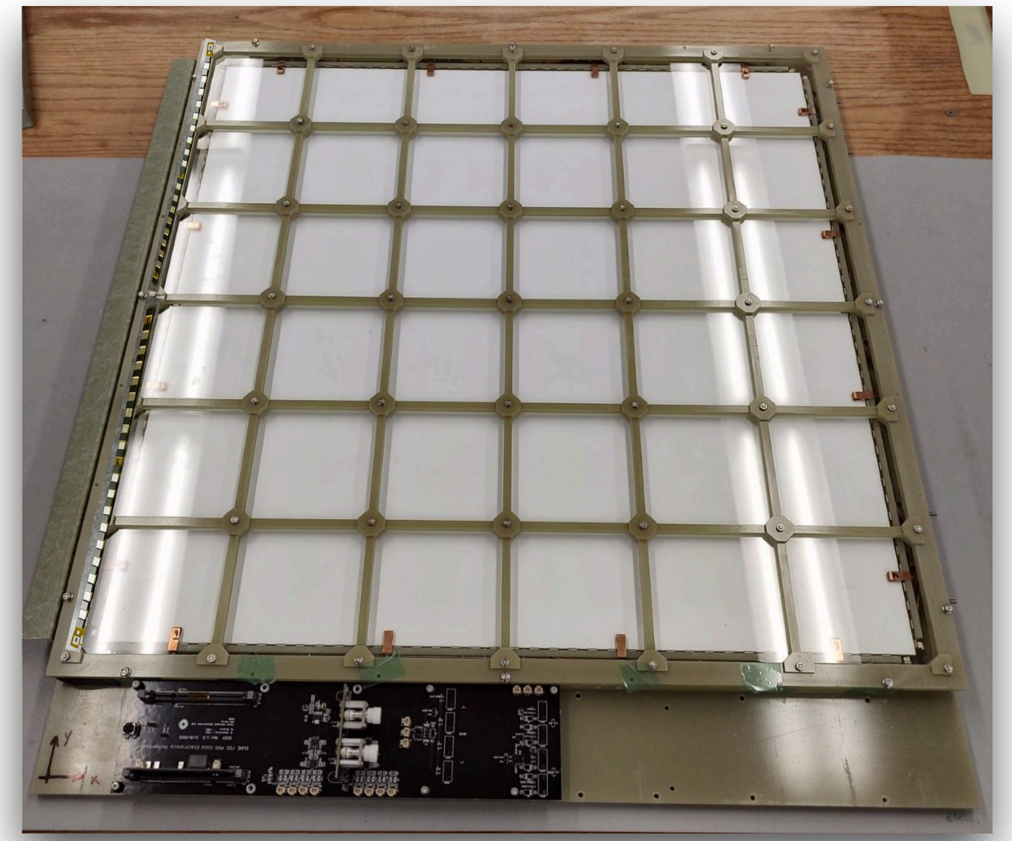
Dichroic filter:
optical device fully transparent to w.l. photons below cutoff,
fully reflective for w.le photons above the cutoff

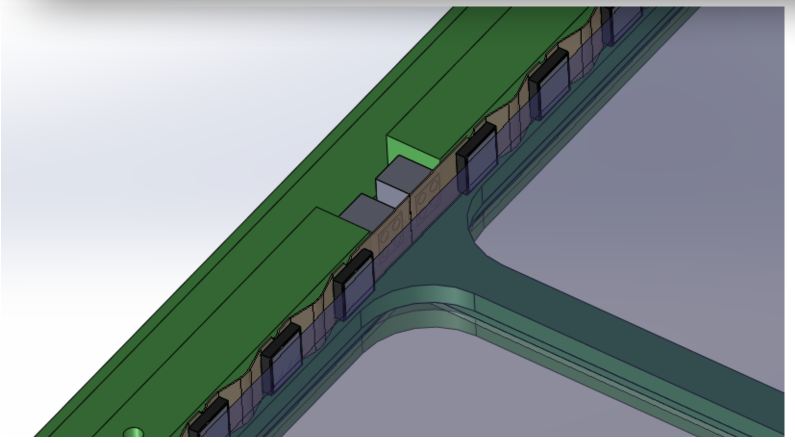
PhotoSensors: SiPM



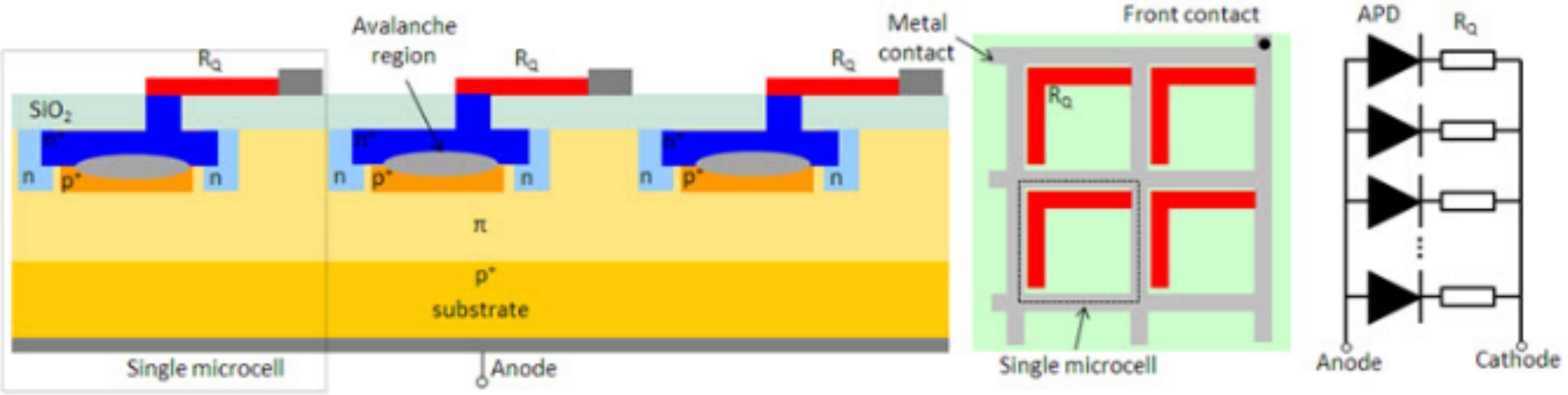
Silicon photomultiplier (SiPM) is a solid-state photodetector

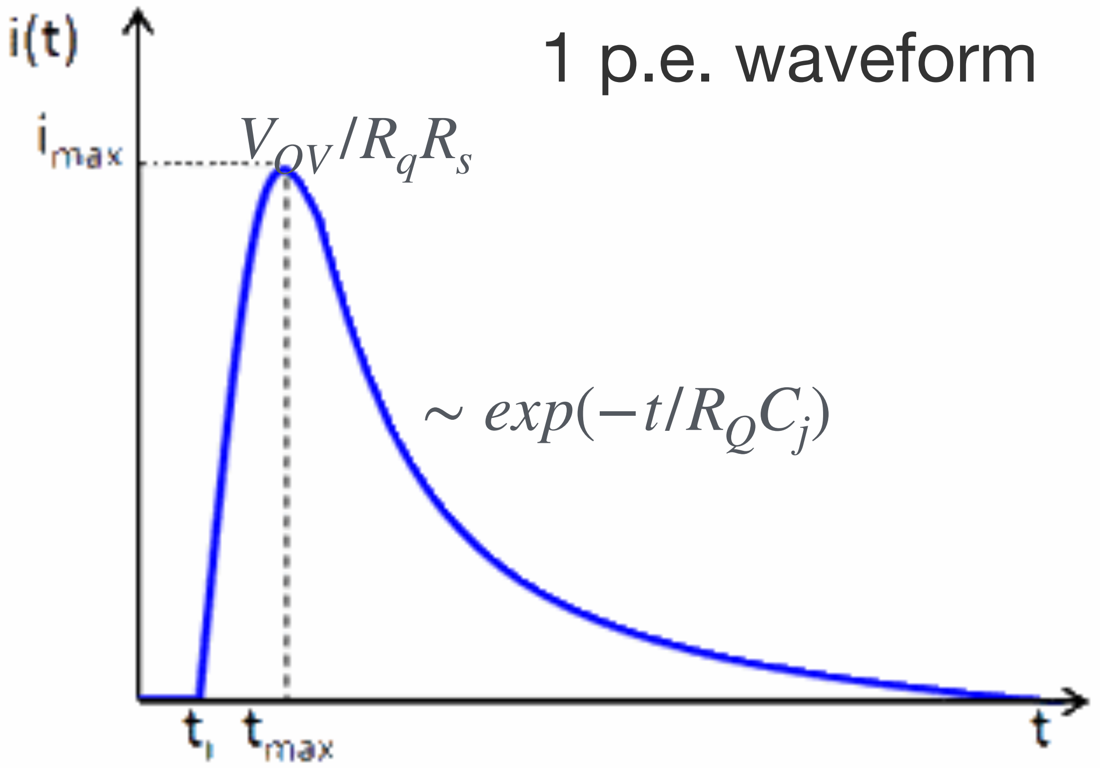
In response to absorption of a photon can produce a current pulse (tens nanoseconds long) containing 10^5 to 10^6 electrons (SiPM gain - comparable to PMT gain).



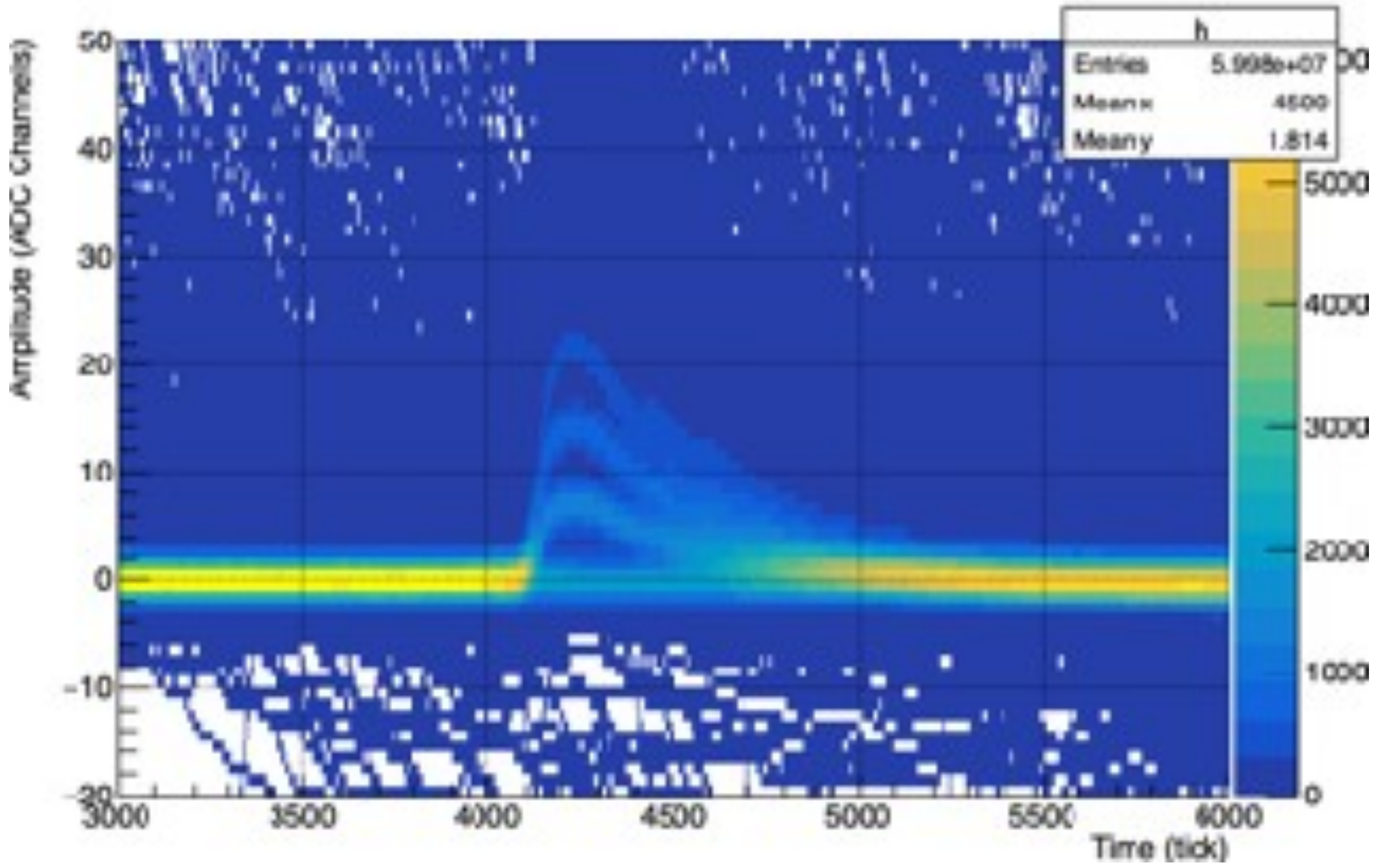


A SiPM is a pixelated device where each pixel, or a microcell, is a series of an avalanche photodiode (APD) and a quenching resistor (RQ). All of the microcells are connected in parallel; thus, a SiPM has two prongs: an anode and a cathode



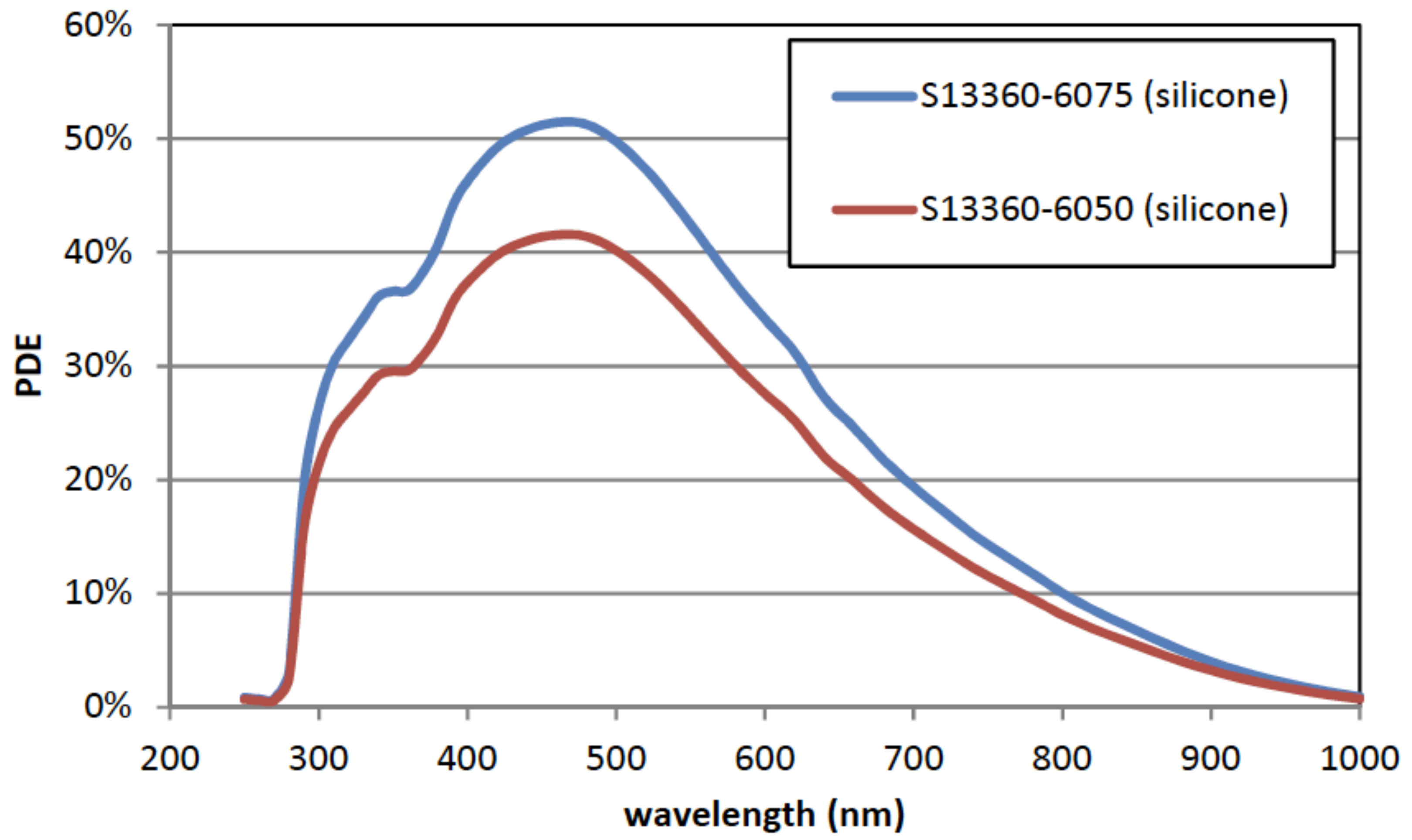


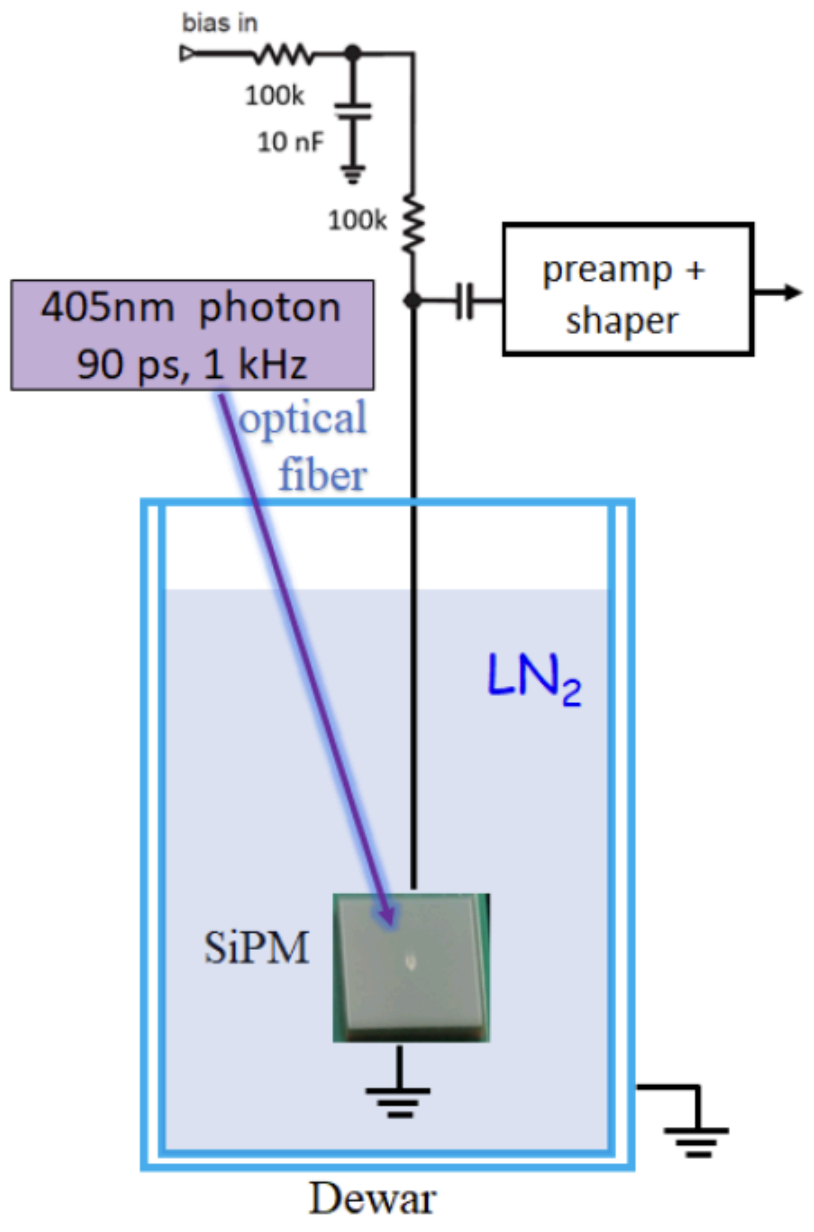
- SiPM is externally biased so that the voltage on each APD is above its breakdown voltage, operates in Geiger mode.
- V over-voltage (Vov = Vbias-Vbd) — main adjustable parameter controlling operation/gain of the device.
- If a SiPM absorbs a photon, the resulting charge carrier (an electron or hole depending on the structure) can trigger an avalanche in the gain region within the p+ - n+ structure.
- Once triggered, the avalanche process is self-sustaining a steady current flows in the device.
- With R_Q, the voltage on the APD drops to approximately V_{BR}, which is not enough to sustain the discharge. the avalanche process is quenched.

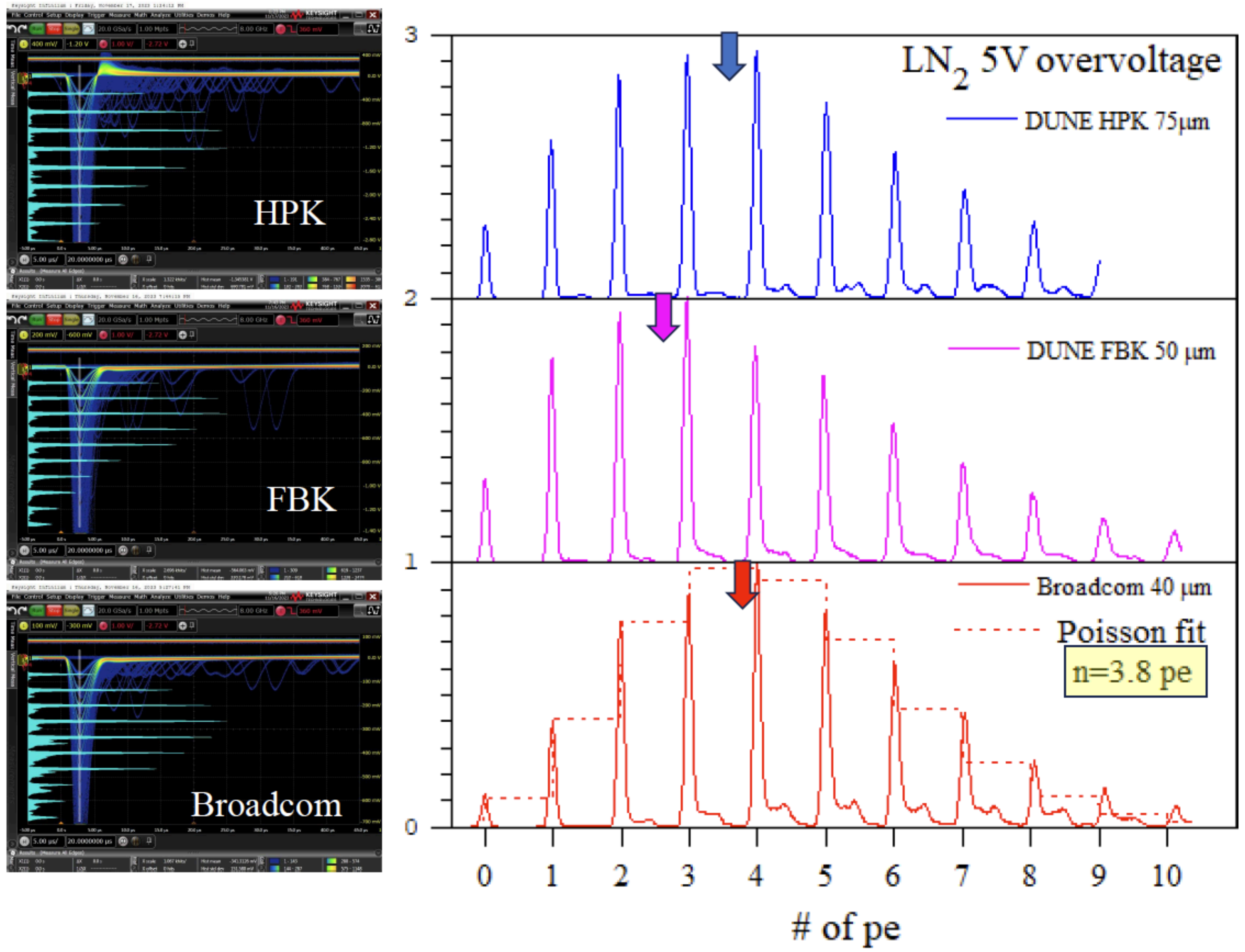


relative PDE in LN_2 (Broadcom, DUNE FBK, DUNE HPK)

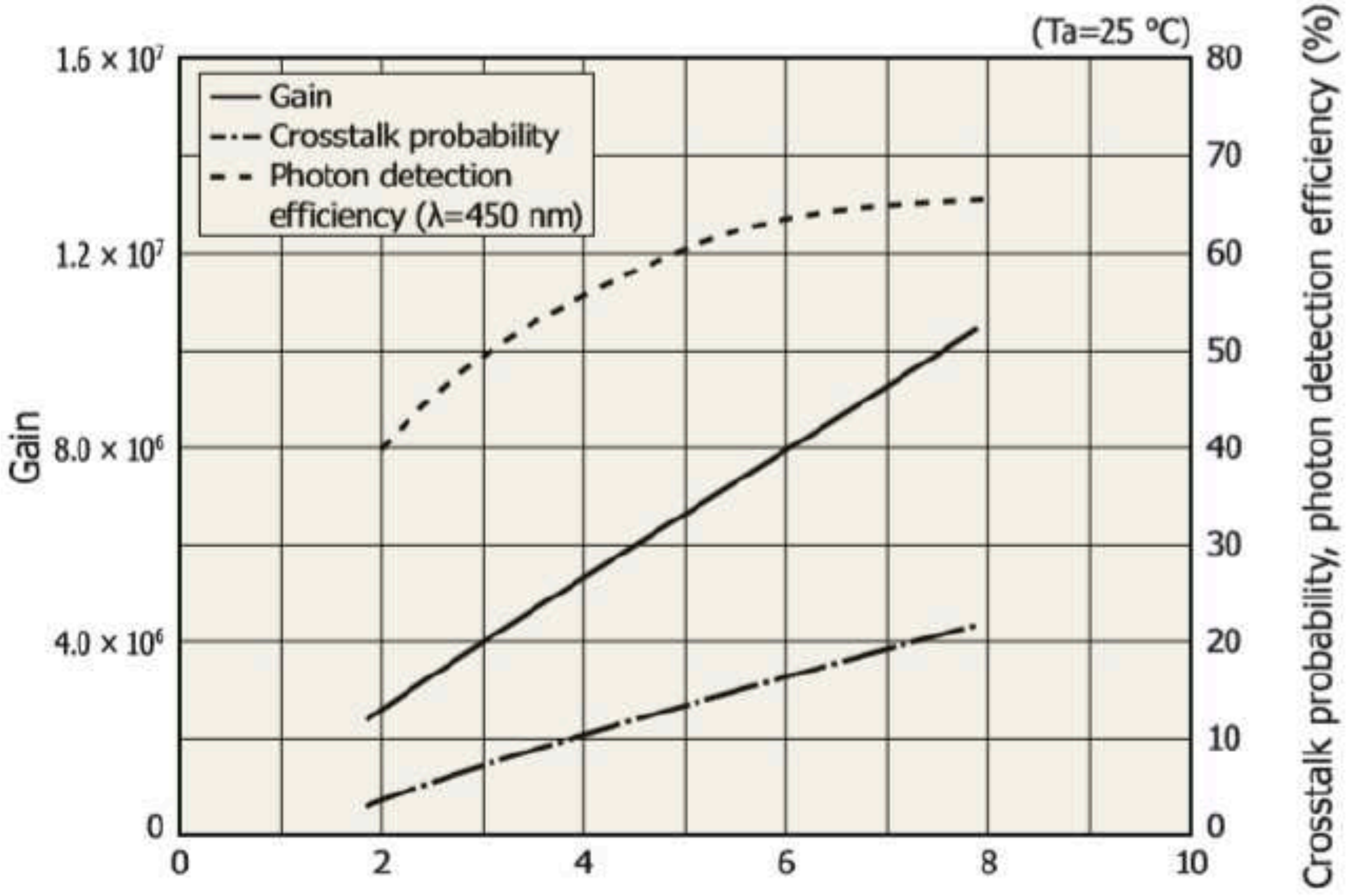
■ Photon detection efficiency v.s. Wavelength (Vr = Vop = Vbr + 3.0V, measurement example)







[S13360-6075HS-LRQ, -HRQ]



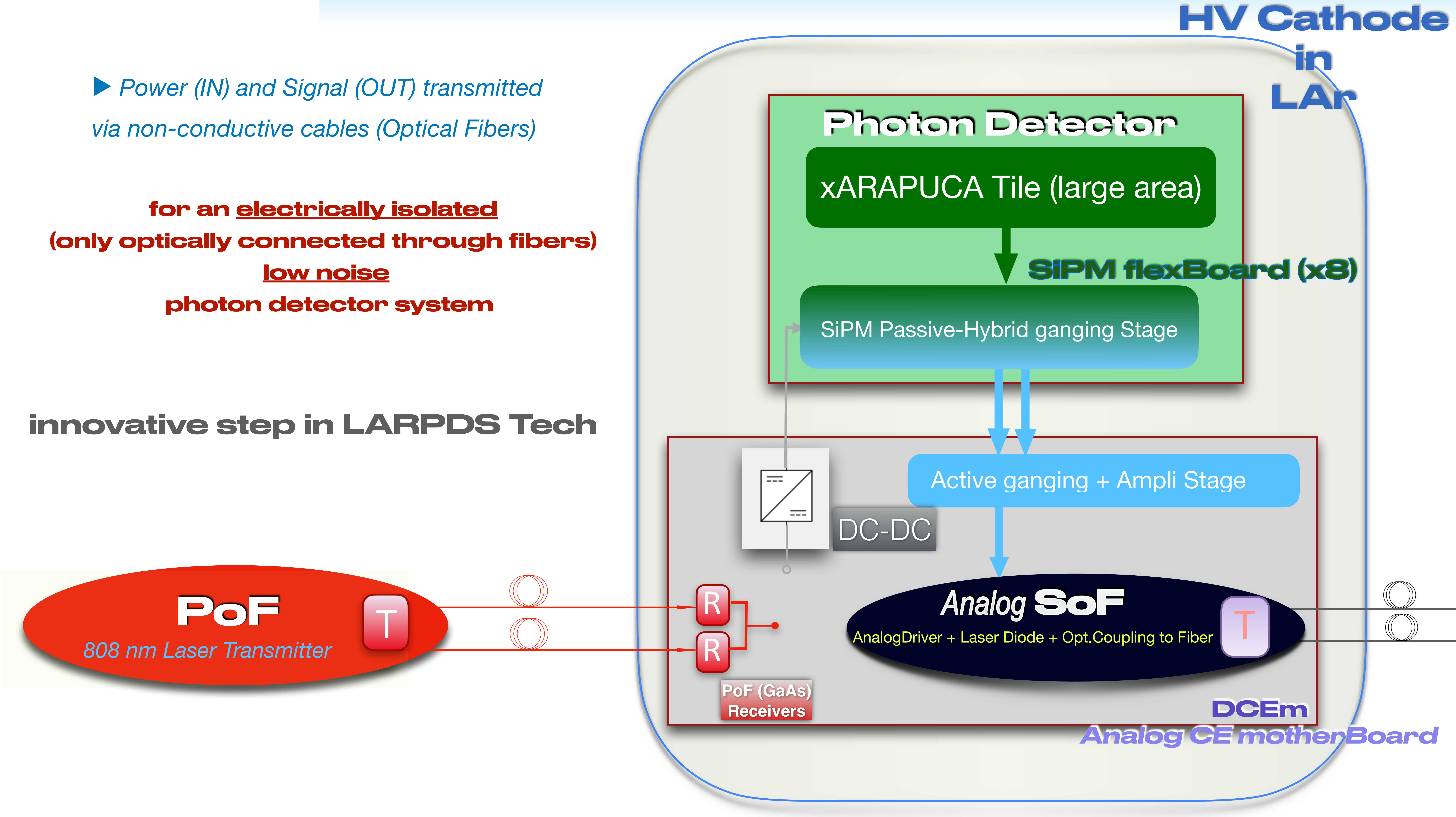
SNR=μ_1/σ_0 index of Single PhElectron sensitivity

From FD1-xARAPUCA to **Power-over-Fiber & Signal-over-Fiber (FD2) x-ARAPUCA**

- *Power (IN) and Signal (OUT) transmitted via non-conductive cables (Optical Fibers)*

for an <u>electrically isolated</u>
(only optically connected through fibers)
<u>low noise</u>
photon detector system

innovative step in LARPDS Tech

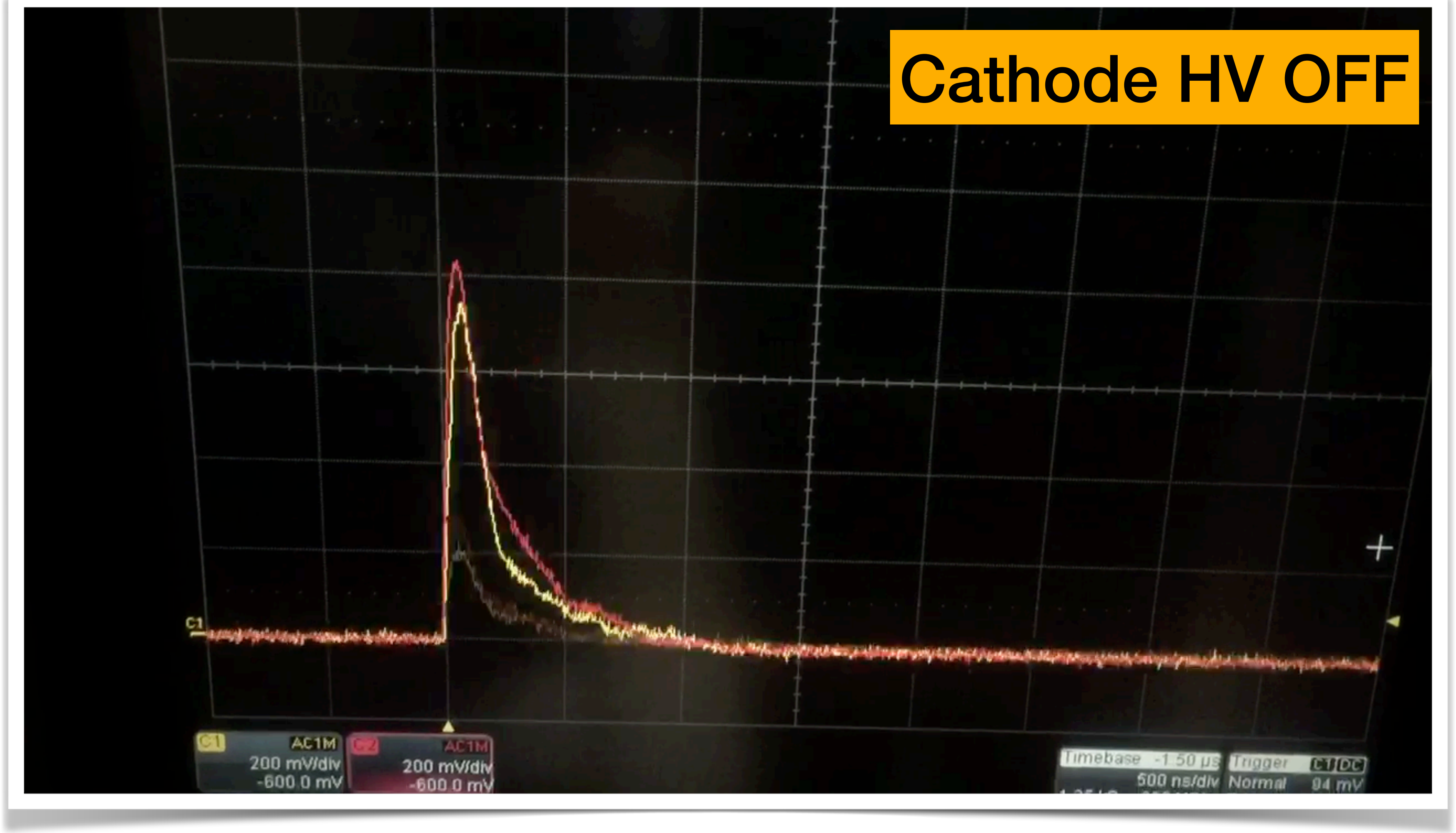


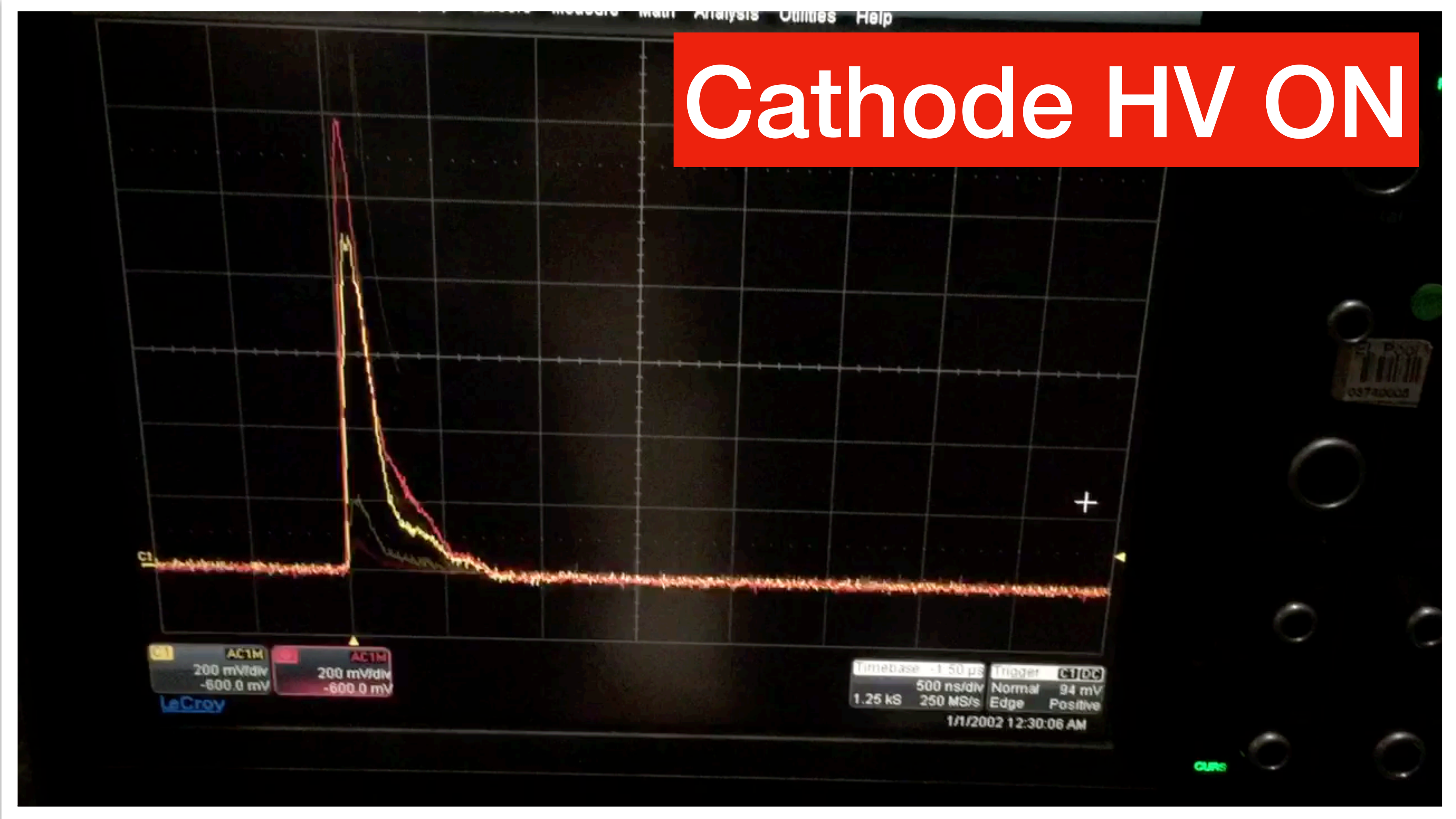
•PDS Demonstration

Cold Box tests at CERN 2021-2022

☑ PoF & SoF validation

Cosmics Run



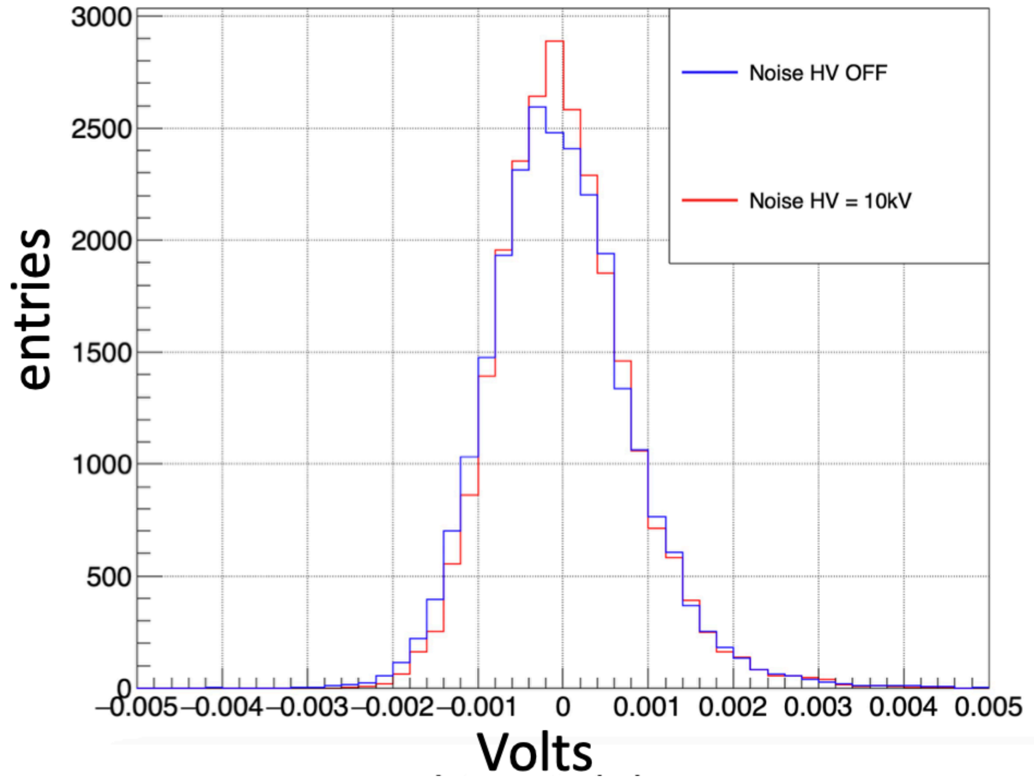


PoF is turned ON on Dec. 15, 2021 at CERN - ColdBox Experiment.

Clean signals immediately seen on the scope

VD PDS signals with Cathode HV ON in LAr

PDS High Level Goal: No noise increase or signal distortion when HV ON



HV OFF:
Mean = -0.05 mV
Sigma =0.77 mV

HV = 10 kV
Mean =-0.02 mV
Sigma=0.71 mV

A new original solution based on Power-over-Fiber and Signal-over-Fiber technology has been evolved for the voltage isolation of the detector with transmission of power and signal via non conductive optical fibers.

The optical transmission and conversion of power and signals, rather than electrical transmission via conductive cables, may find a wide range of applications in detector technology for HEP beyond this first one illustrated here.