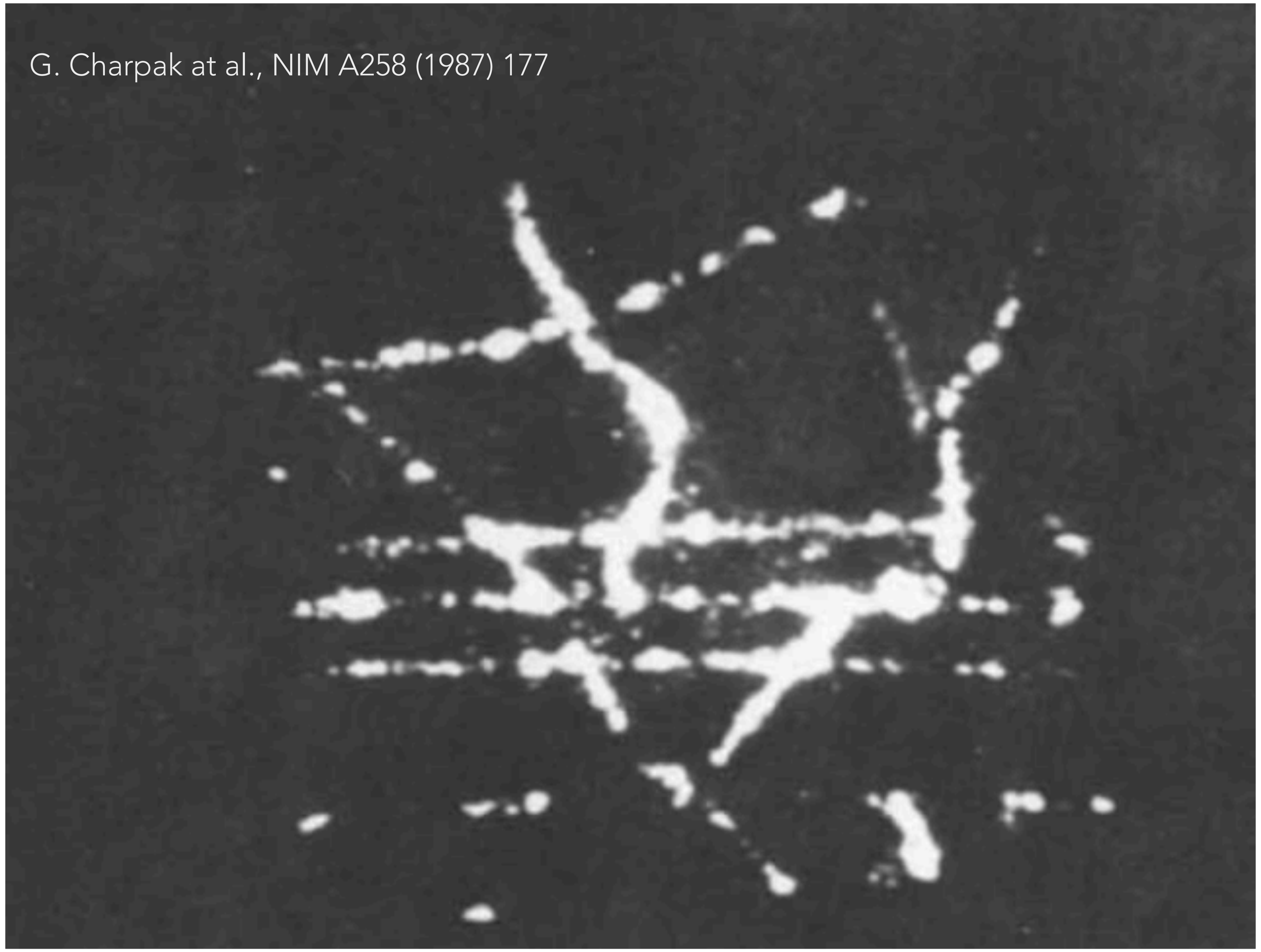
Davide Pinci - INFN Roma

CYGNO: Optical and readout for TPC

LIGHT: A CHANGE OF PARADIGM

In the **interaction** of **charged** particles with gases, **not only ionisation** happens;



Energy can be transferred to **excite** atoms and molecules to make them **emitting light through atomic and molecular de-excitation**;

Light can be produced:

- by the **primary** particle (**primary** scintillation)
- **avalanche electrons** (**secondary** scintillation)

GEM: PRINCIPLE OF OPERATION

GEM: A new concept for electron amplification in gas detectors

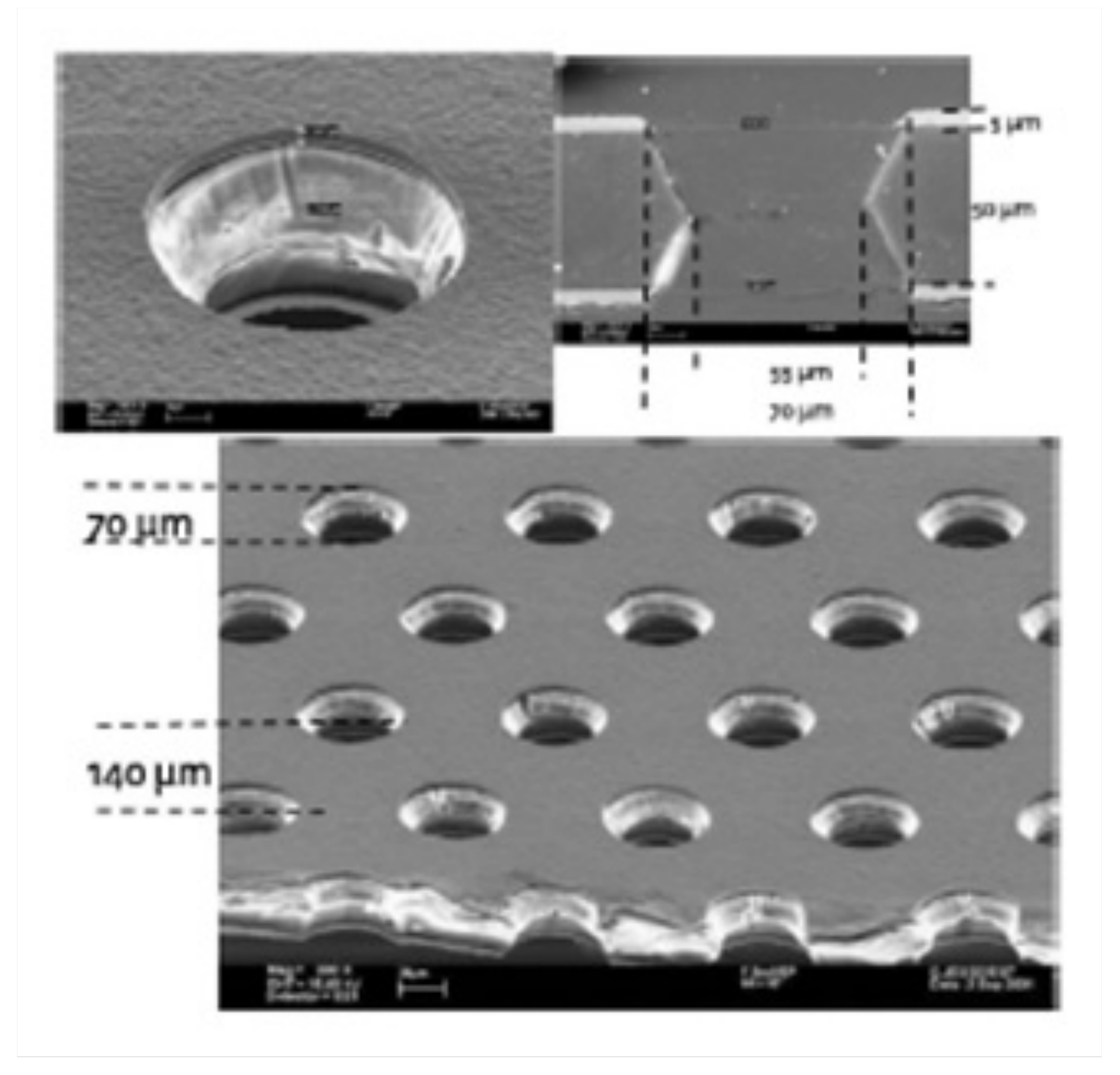
F. Sauli

CERN, CH-1211 Genève, Switzerland

Received 6 November 1996

Abstract

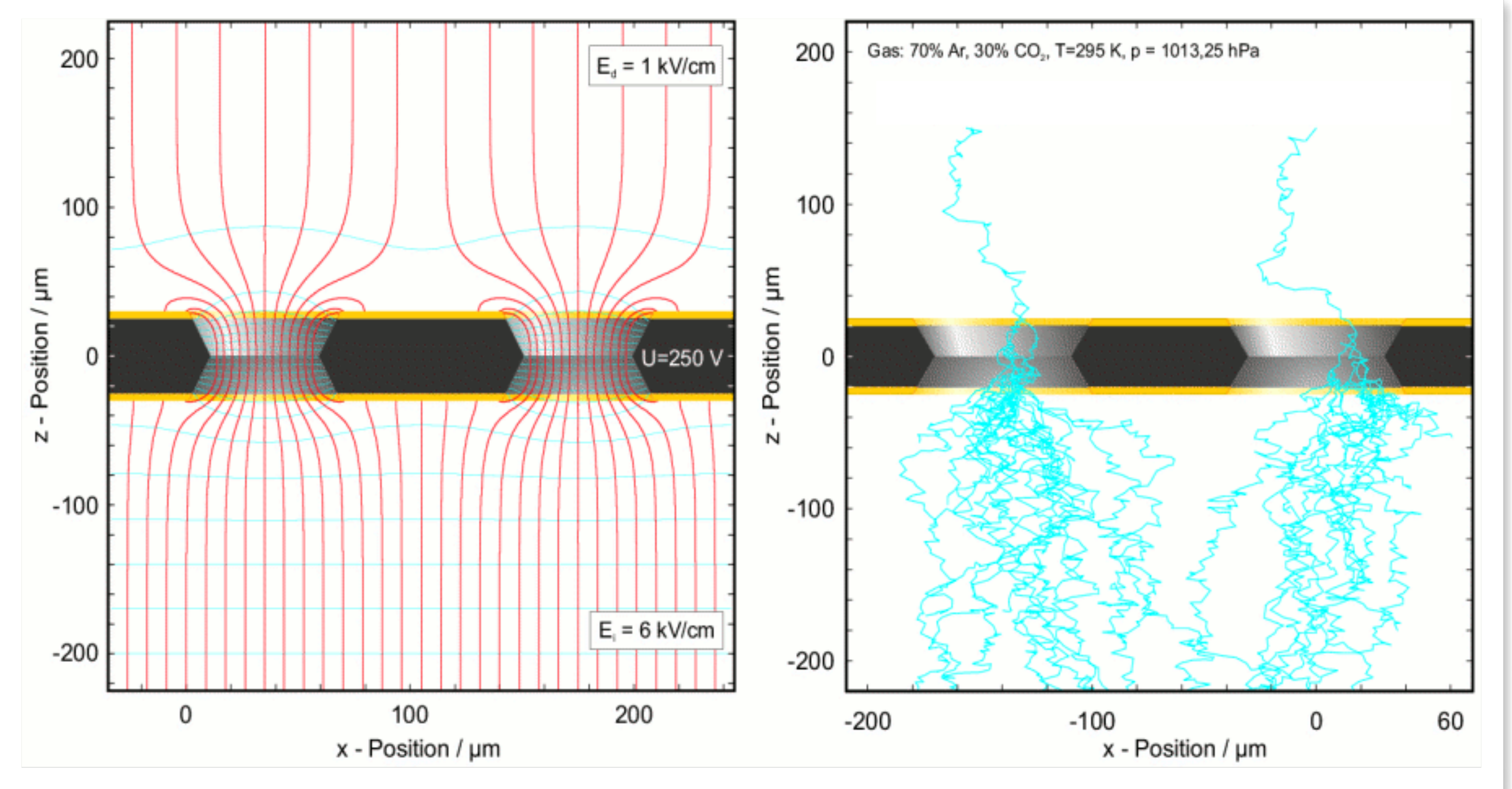
We introduce the gas electrons multiplier (GEM), a composite grid consisting of two metal layers separated by a thin insulator, etched with a regular matrix of open channels. A GEM grid with the electrodes kept at a suitable difference of potential, inserted in a gas detector on the path of drifting electrons, allows to pre-amplify the charge drifting through the channels. Coupled to other devices, multiwire or microstrip chambers, it permits to obtain higher gains, or to operate in less critical conditions. The separation of sensitive and detection volumes offers other advantages: a built-in delay, a strong suppression of photon feedback. Applications are foreseen in high rate tracking and Cherenkov Ring Imaging detectors. Multiple GEM grids assembled in the same gas volume allow to obtain large effective amplification factors in a succession of steps.



Multiplication happens in the high fields present in the **GEM channels**

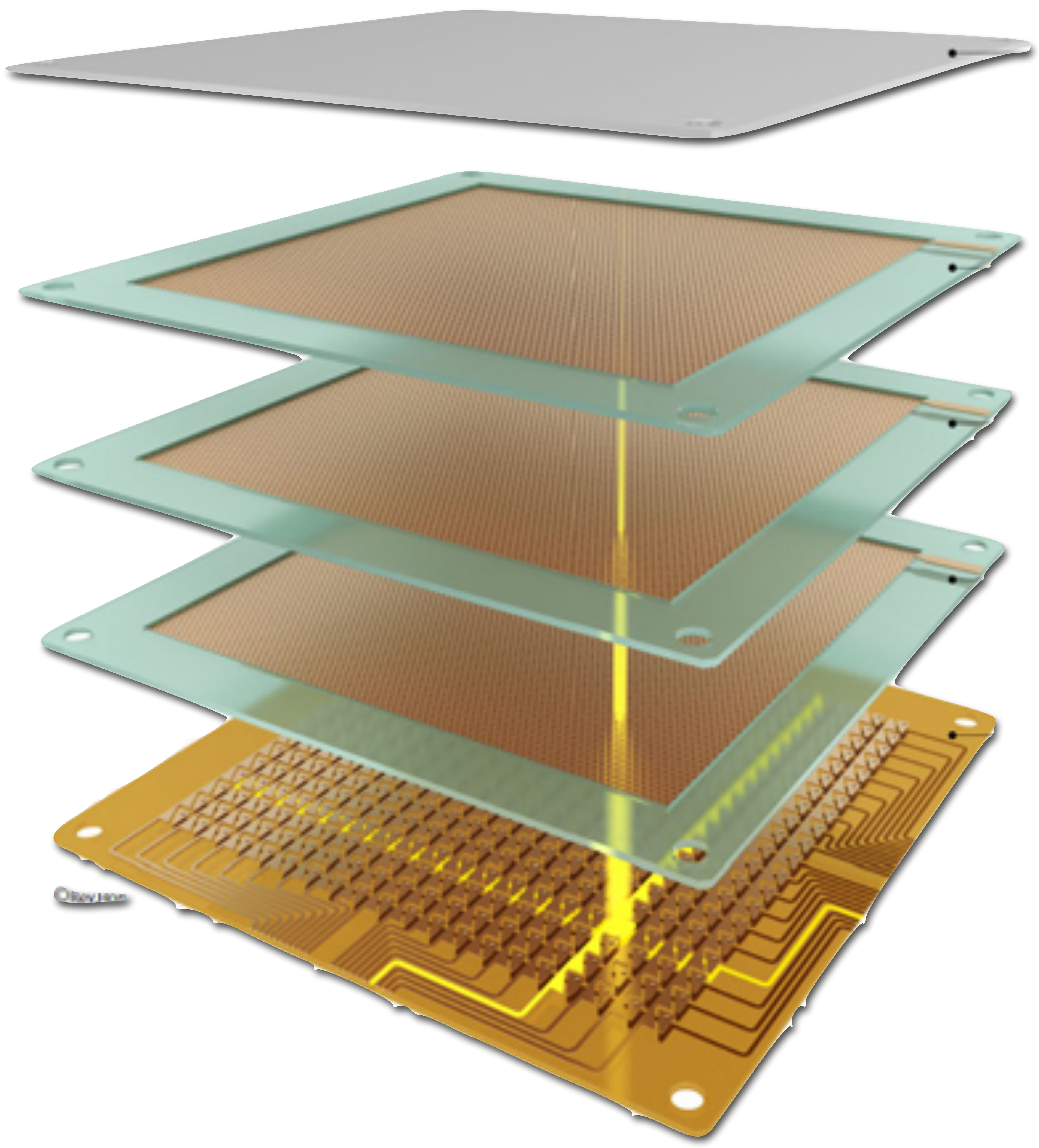
Two **external** electric **fields**:

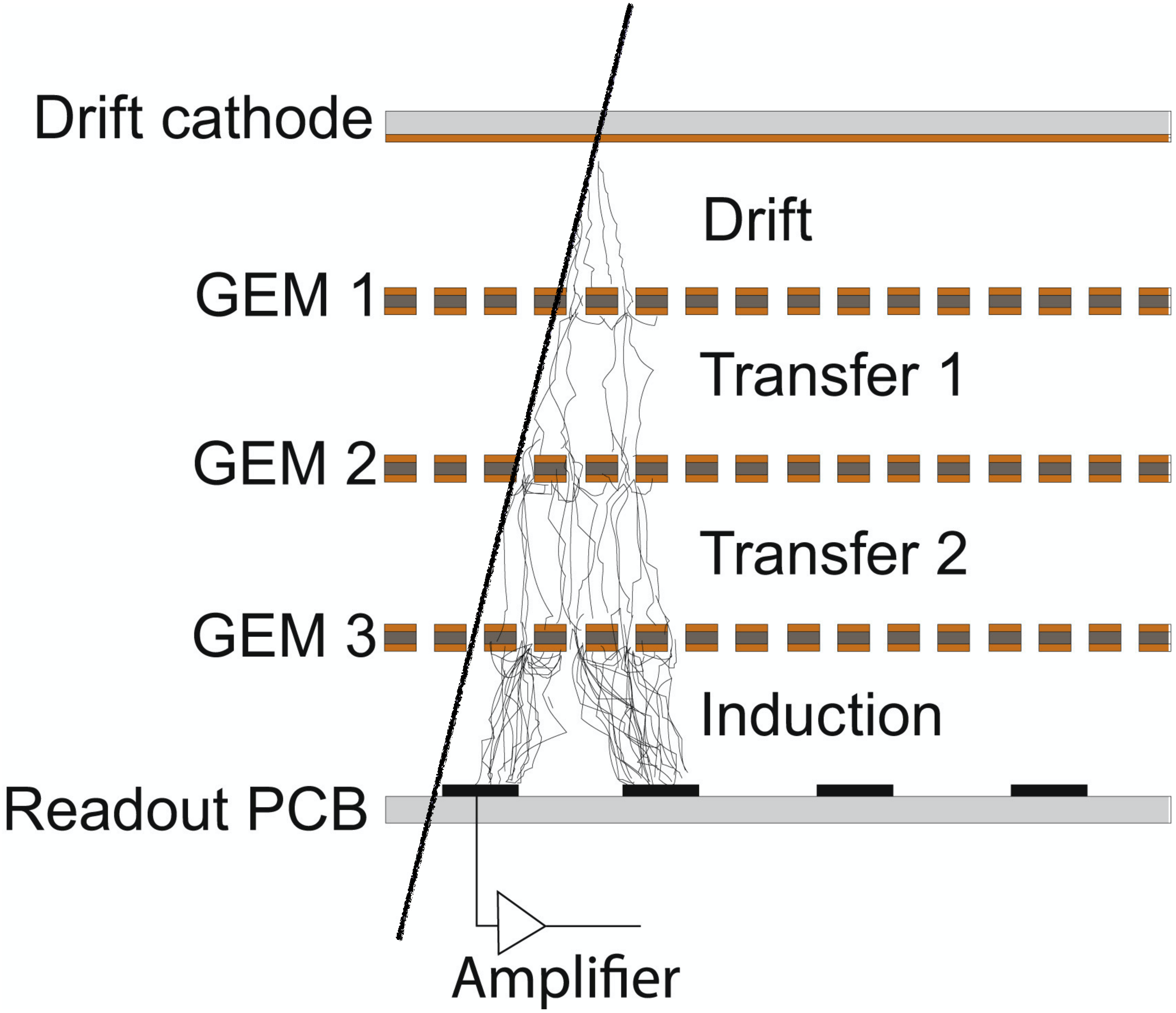
- **collect** electrons in the GEM channels;
- **extract** secondary electrons from the multiplication channels.



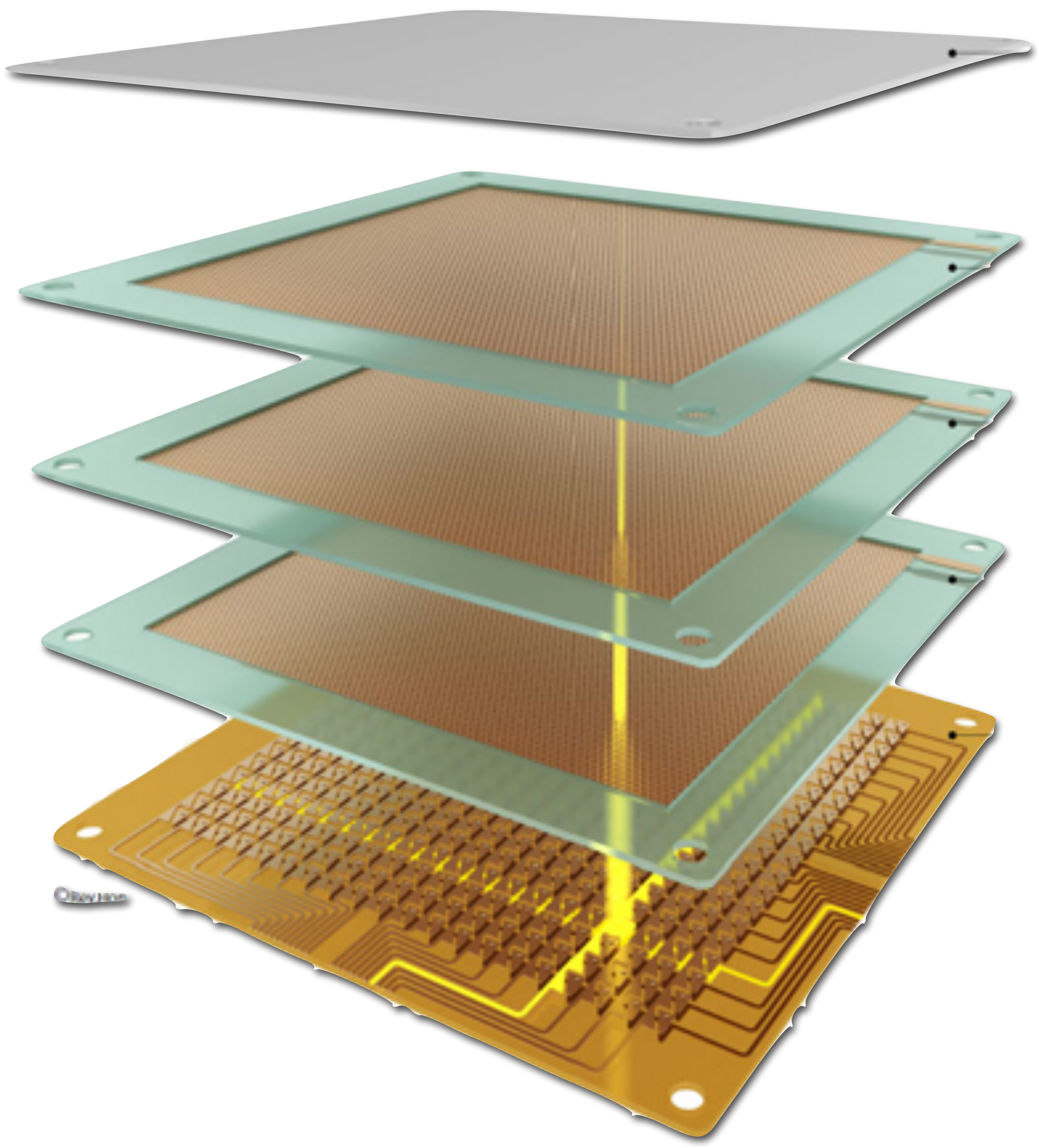
Multiple GEM structures can be used to share the gain and make more stable detectors.

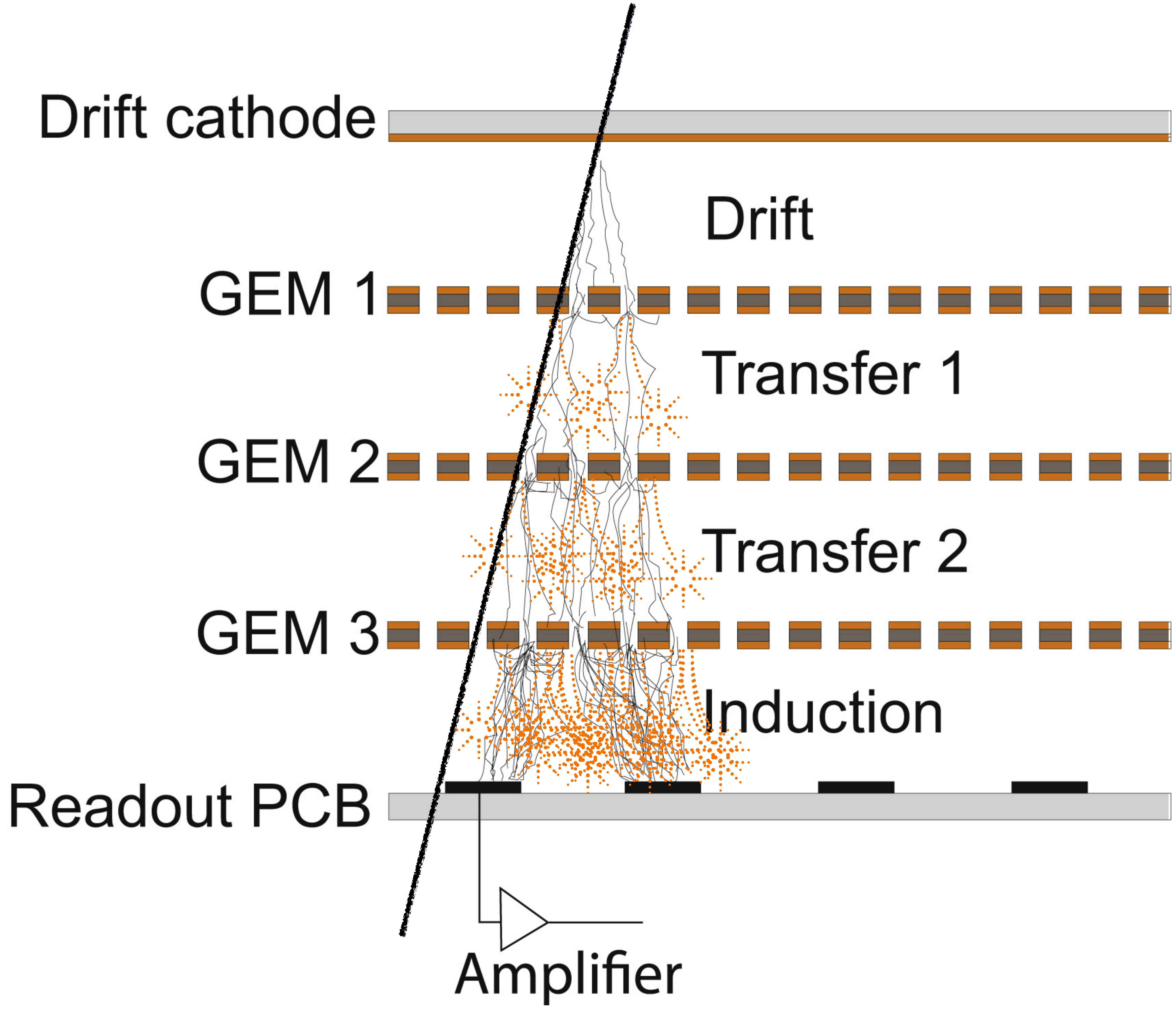
THE TRIPLE GEM DETECTOR



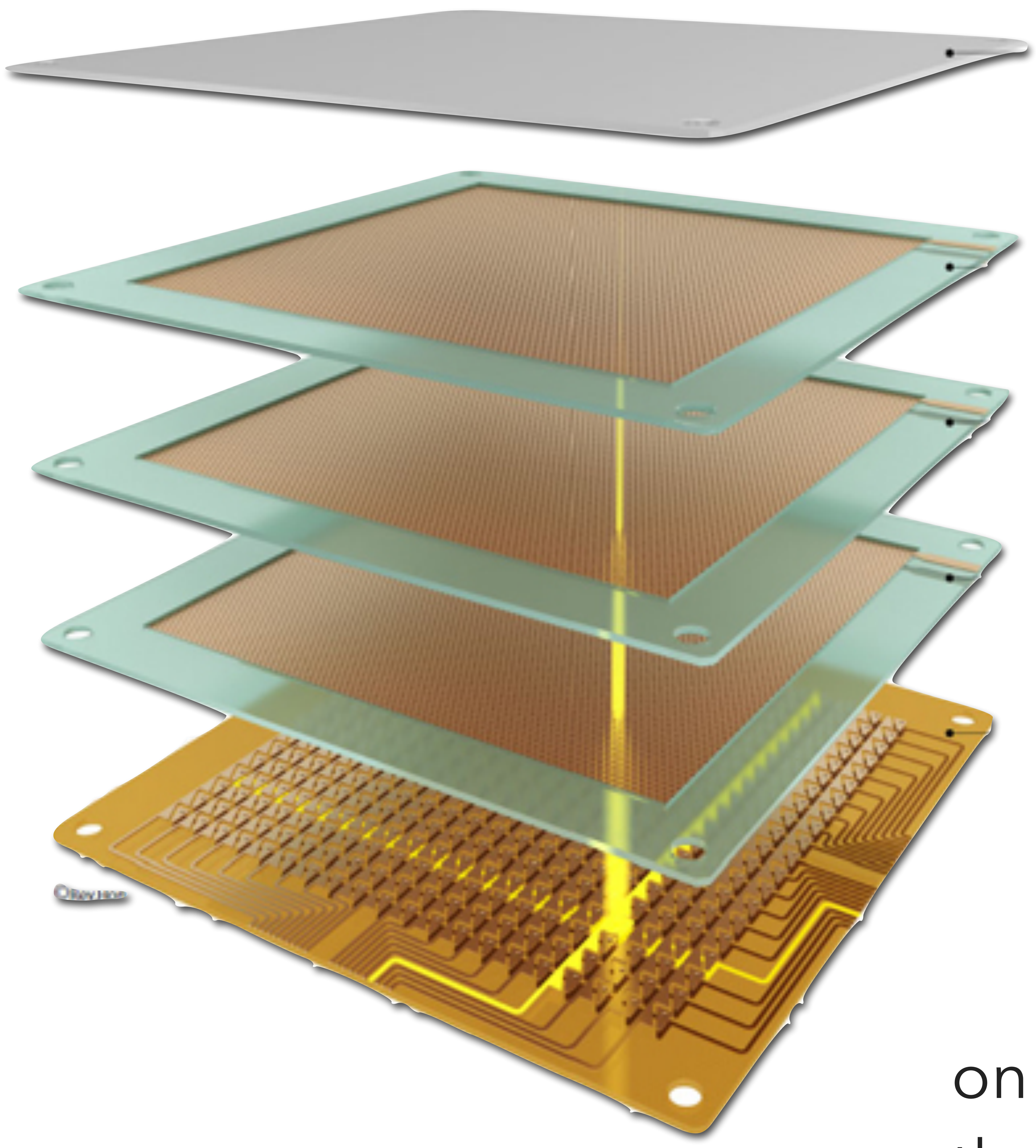


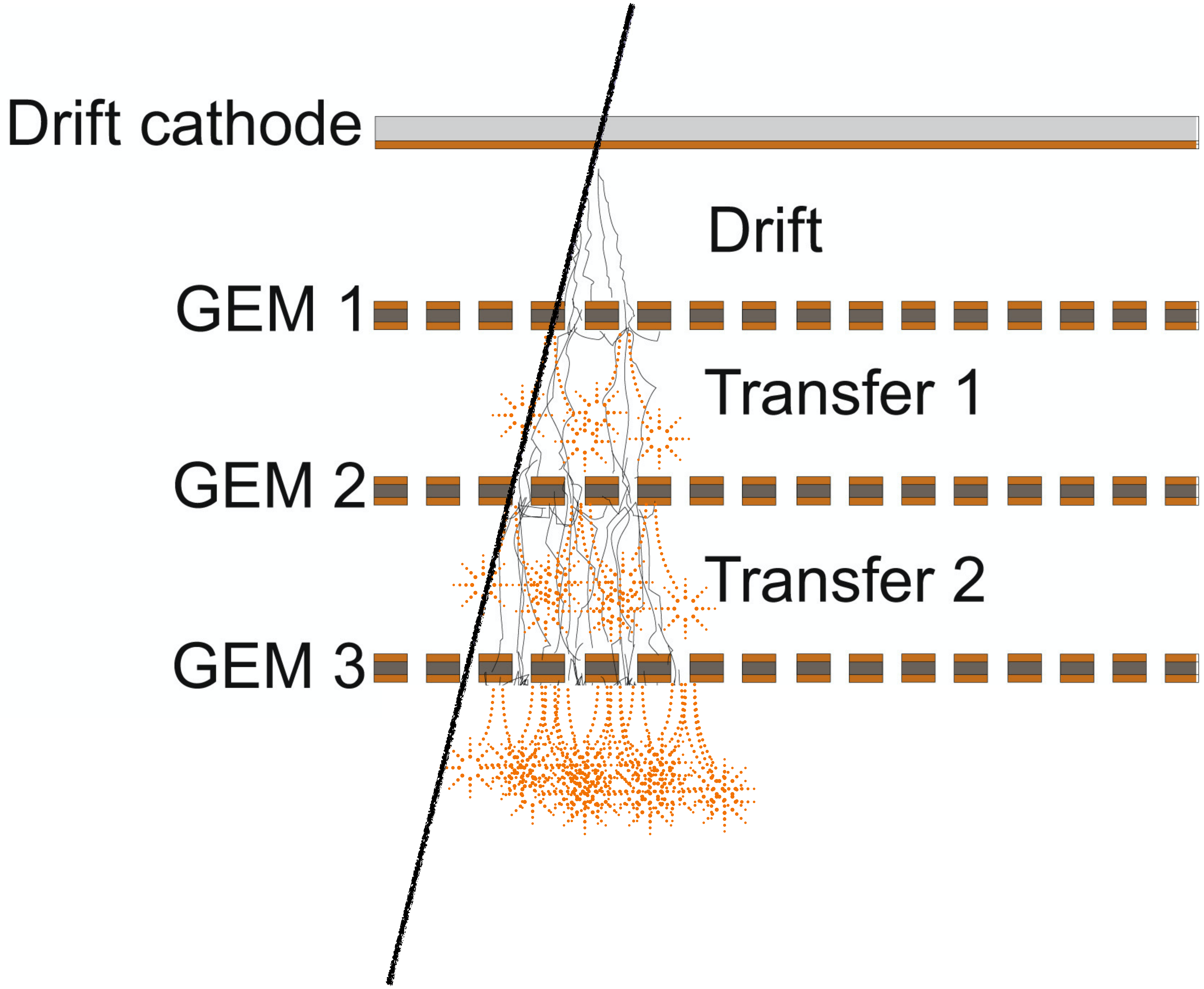
THE TRIPLE GEM DETECTOR





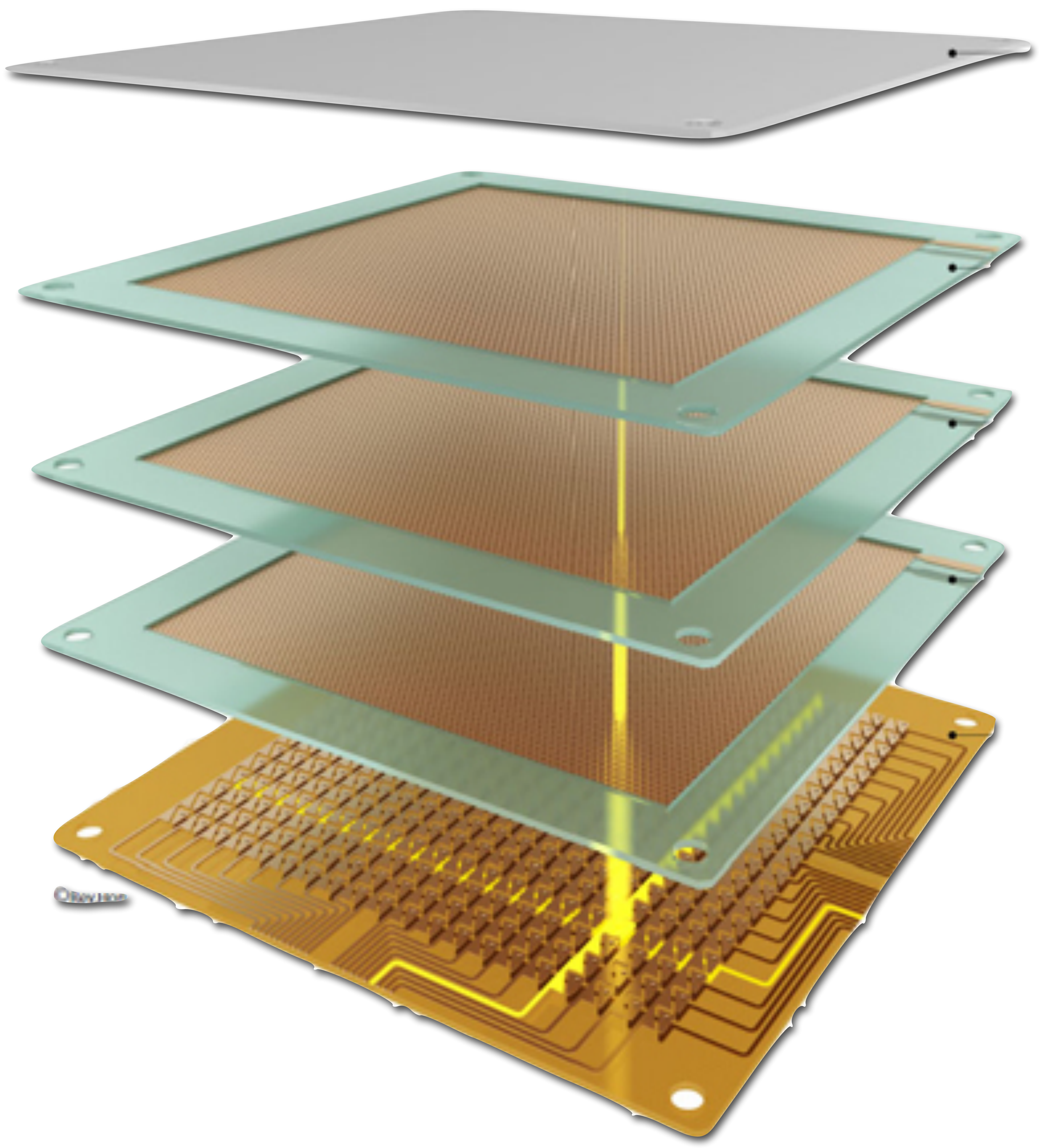
THE TRIPLE GEM DETECTOR

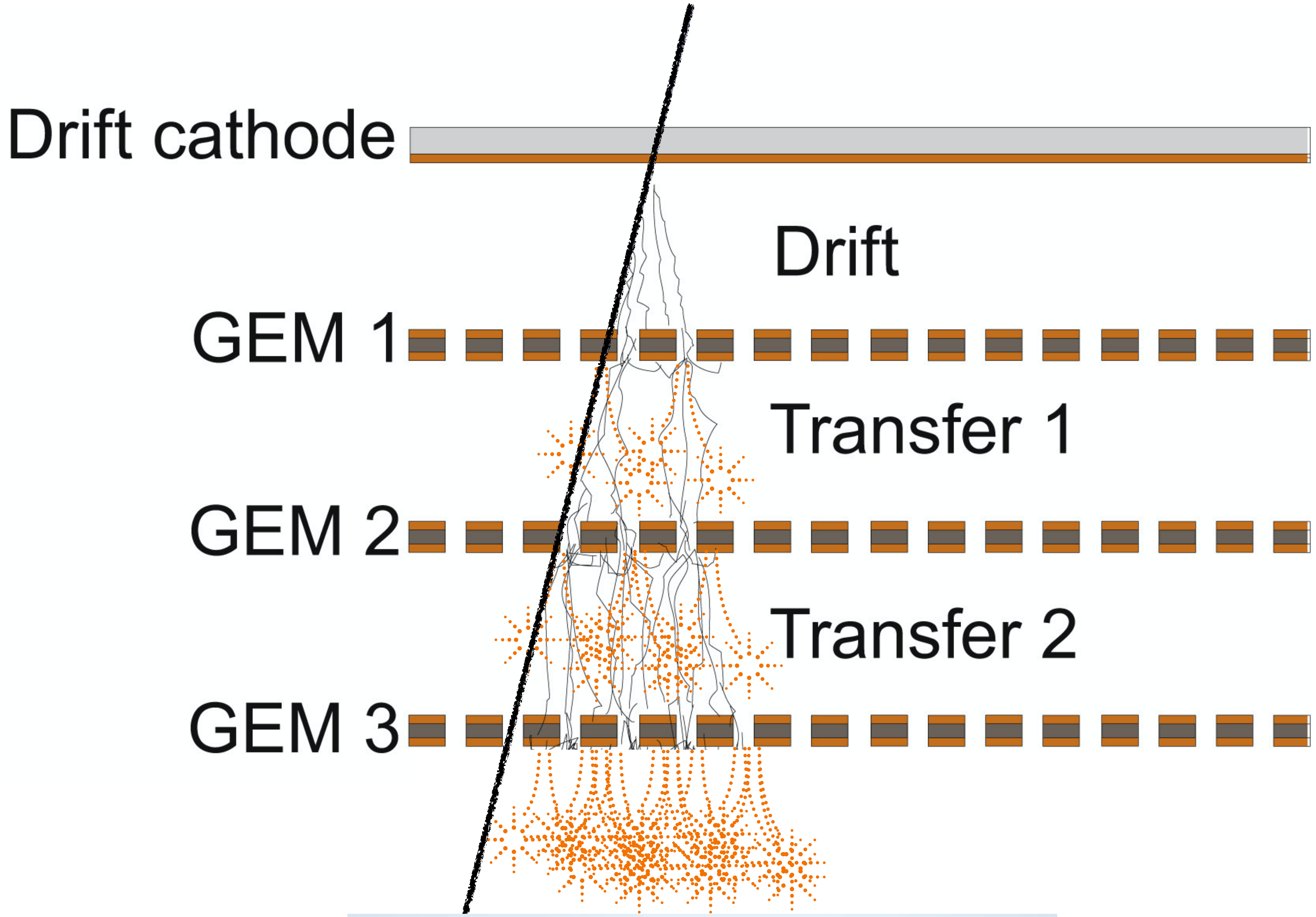




on the **GEM plane** a **2D image** (**projection** of the **event** that ionised the gas in the in the drift region) **is produced**

THE TRIPLE GEM DETECTOR

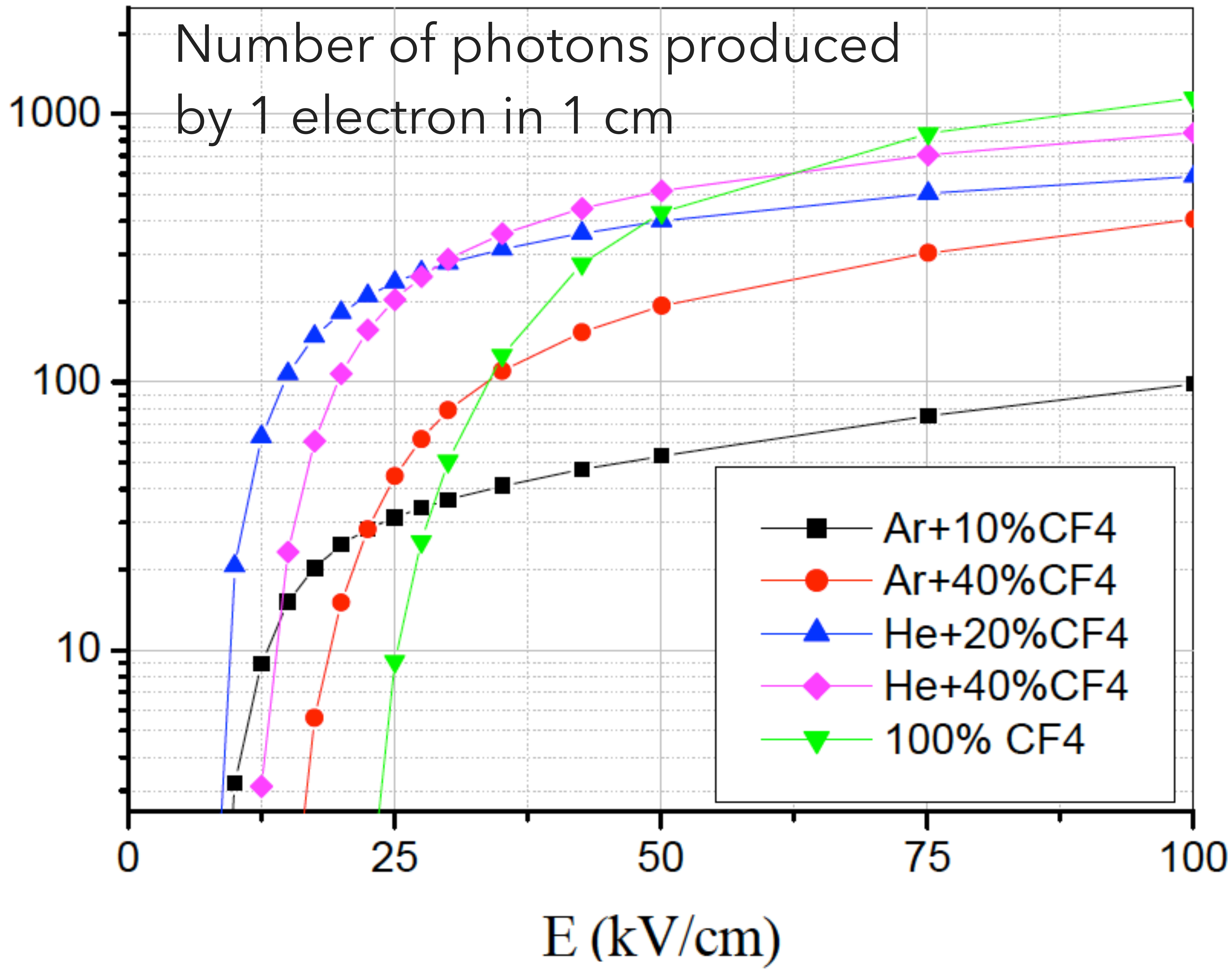





200 ms
1000 ms

HOW MUCH LIGHT AND HOW BRIGHT?

SECONDARY LUMINESCENCE



Nuclear Instruments and Methods in Physics Research A 504 (2003) 88–92

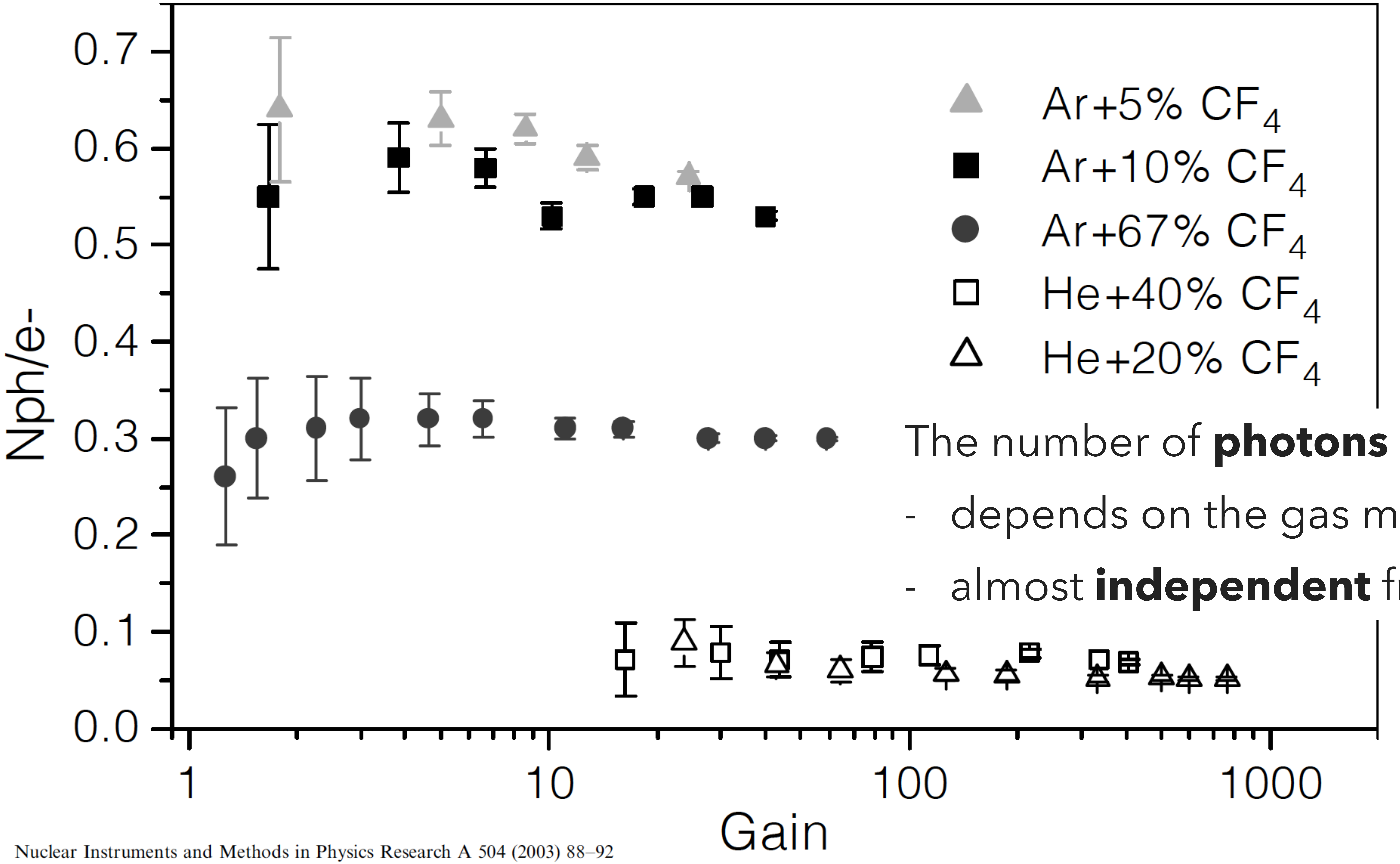
The probability for 1 electron to produce a photon depends on:

- **projectile energy** (i.e. electric field)
- **target cross section** (i.e. gas mixtures)

In general $1 \div 10^3$ photons/cm

The **total light yield** is proportional to the **number of electrons**, the amount of **secondary electroluminescence** produced in the avalanche processes increases (at first order) **exponentially**

LUMINESCENCE IN GEM: HOW BRIGHT?



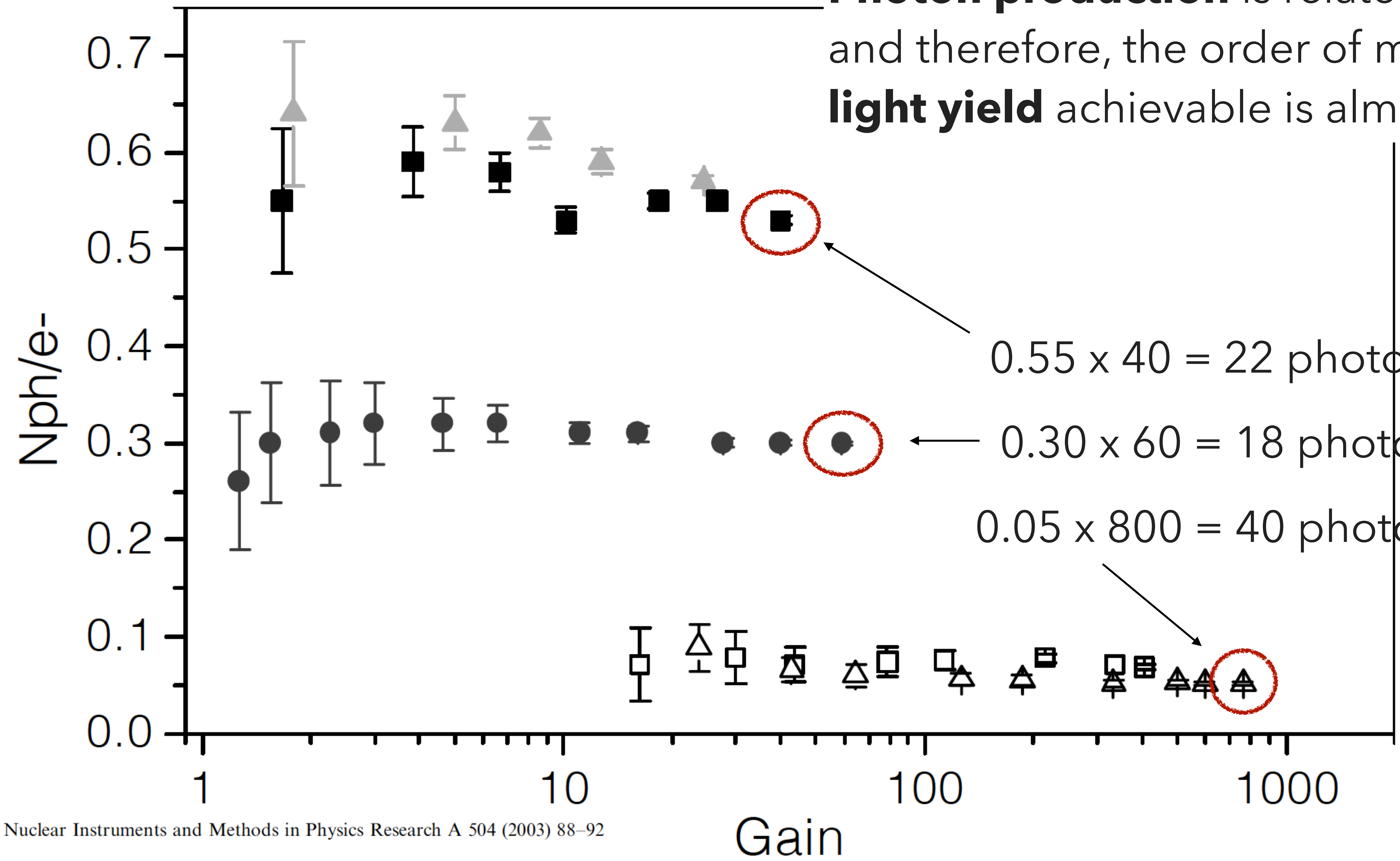
The number of **photons** per **secondary e-**:

- depends on the gas mixture
- almost **independent** from the gain

Nuclear Instruments and Methods in Physics Research A 504 (2003) 88–92

LUMINESCENCE IN GEM: HOW BRIGHT?

Photon production is related to gas **stability** and therefore, the order of magnitude of **total light yield** achievable is almost the same



0.55 x 40 = 22 photons/primary electron

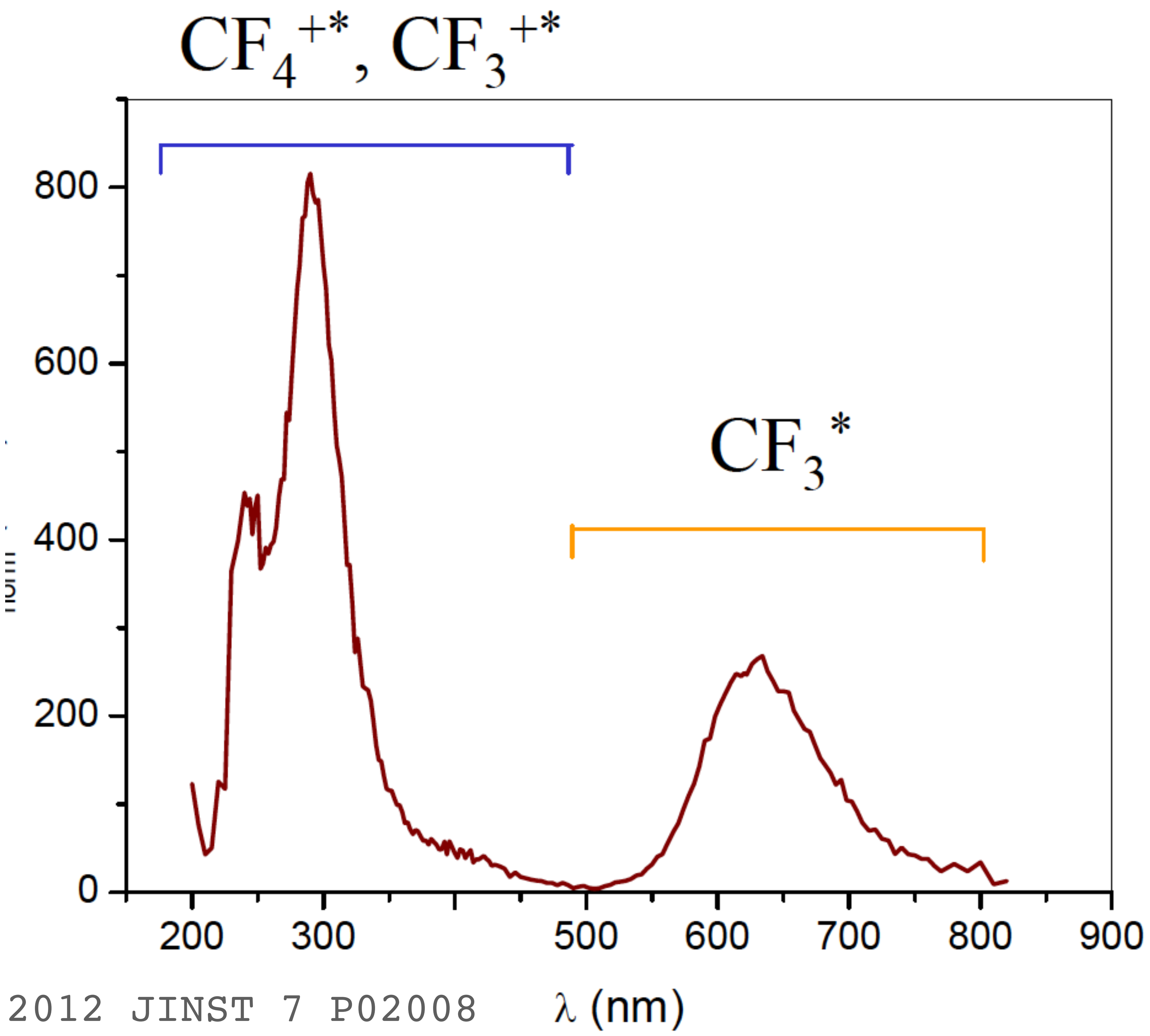
0.30 x 60 = 18 photons/primary electron

0.05 x 800 = 40 photons/primary electron

Nuclear Instruments and Methods in Physics Research A 504 (2003) 88–92

LUMINESCENCE: WHAT COLOR? THE CF_4 EXAMPLE

Studies performed on the electronic and molecular structure of the CF_4 molecule show that all the **electronic excited states** of **CF_4** seem to **dissociate** with high probability.



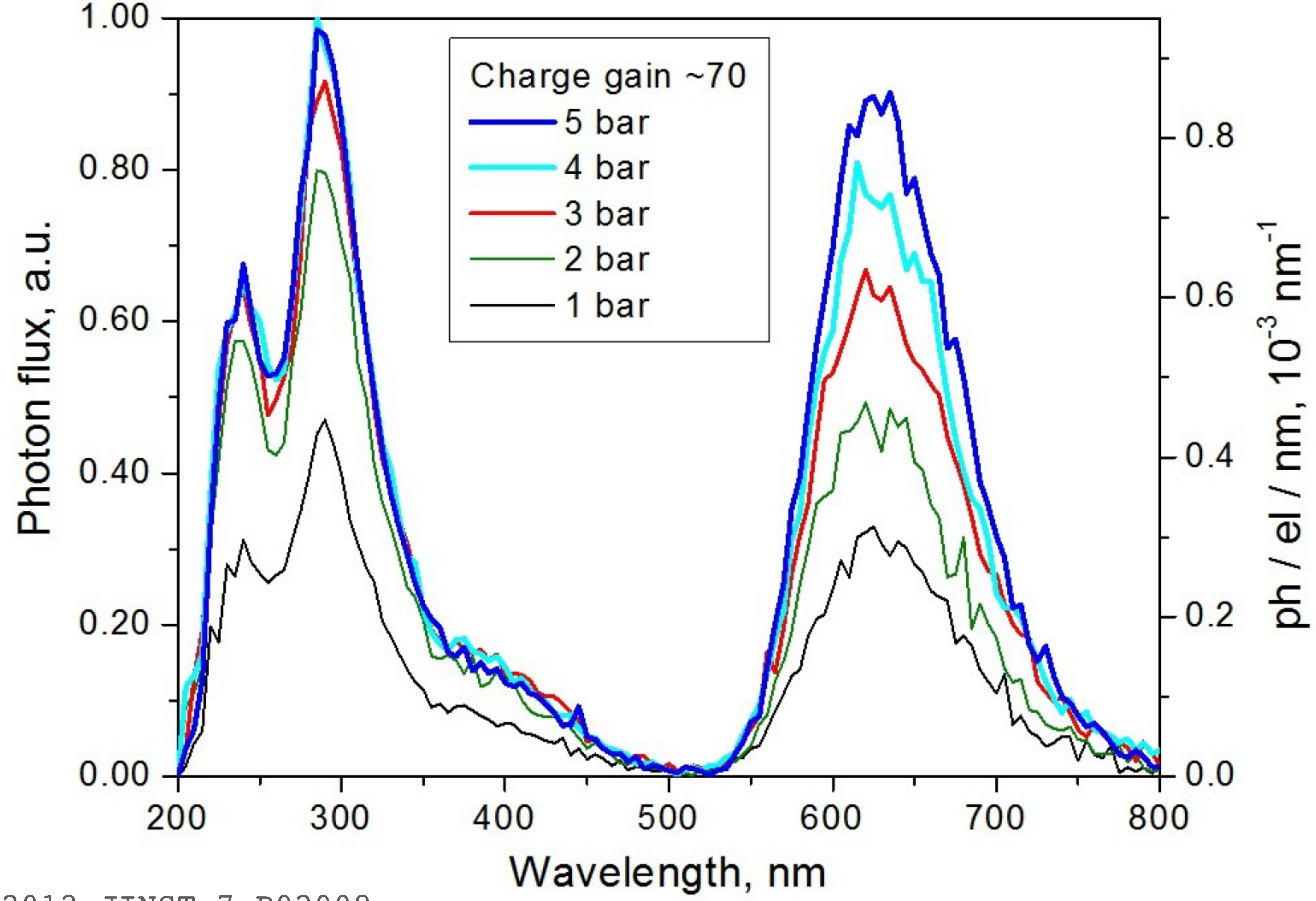
2012 JINST 7 P02008

The broad band in the **visible region (620 nm)** results from the excitation of the **CF_4** molecule that **dissociates** into an emitting **CF_3^* fragment**.

The **energy threshold** for this emission, is **12 eV** (**ionization** threshold is **16 eV**)

The origin of the **UV band**, on the other hand can be due to the **radiative decay** of the **CF_4^{+*}** or **CF_3^{+*} ions**

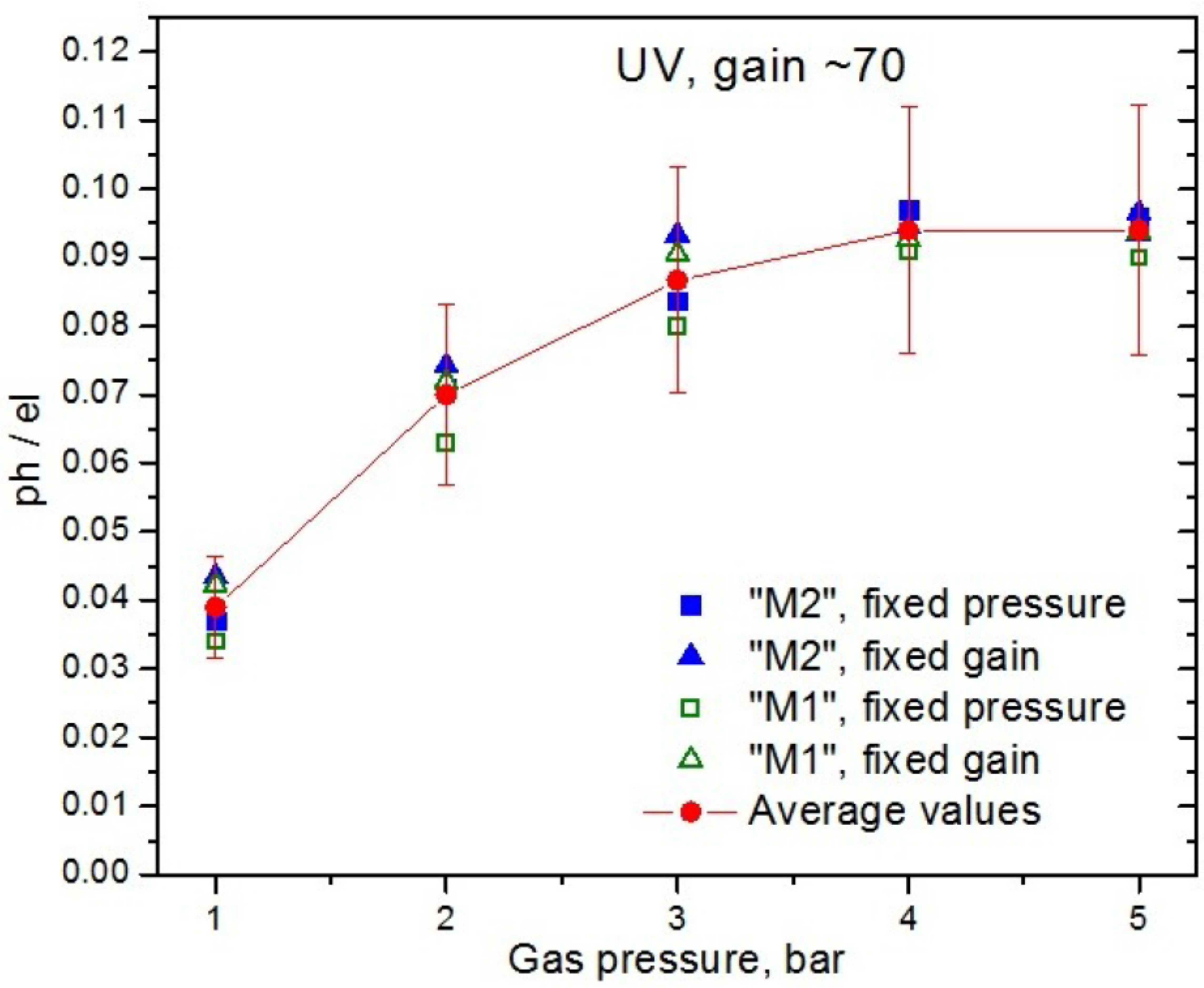
LUMINESCENCE: WHAT COLOR? THE CF_4 EXAMPLE

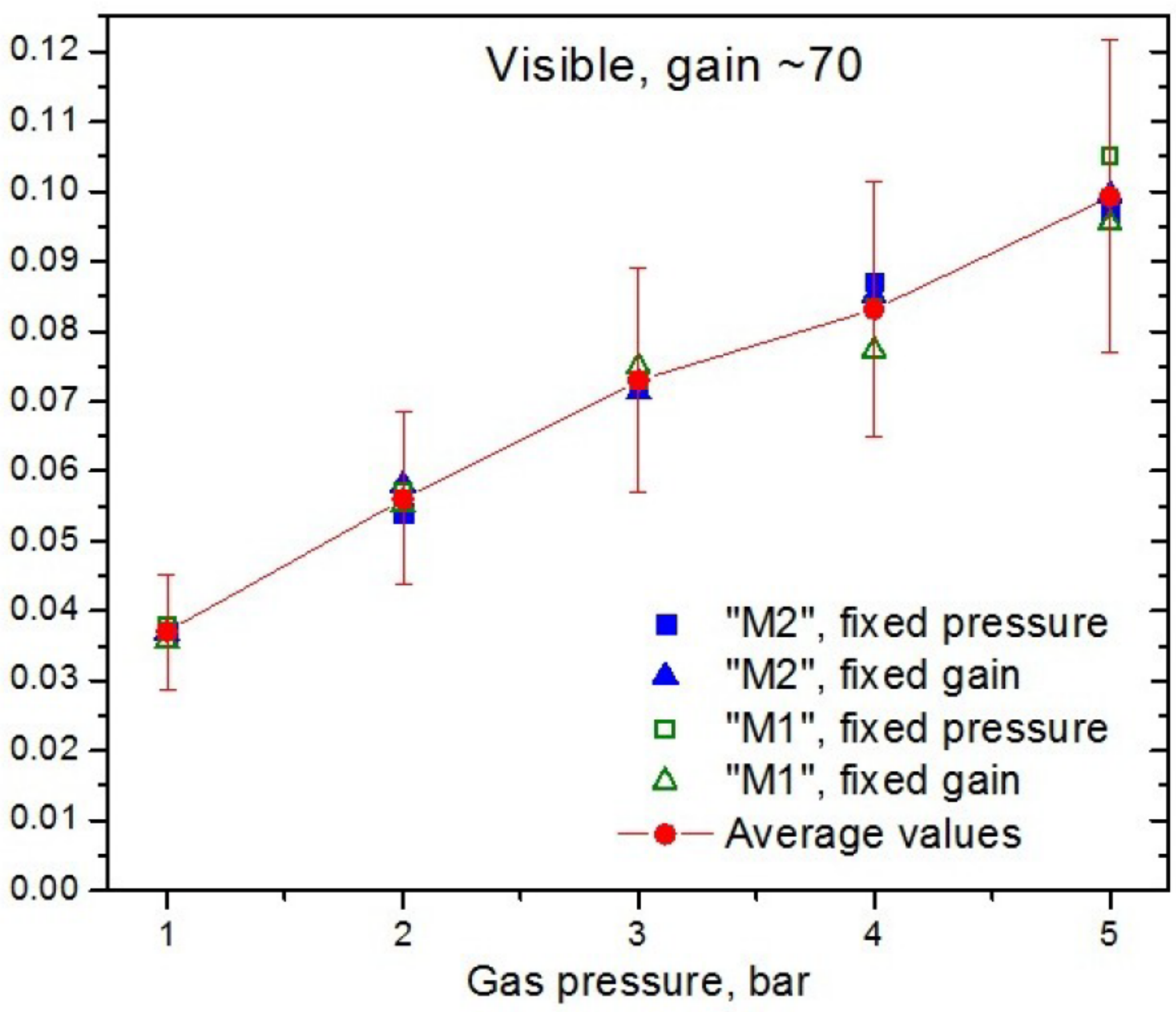


2012 JINST 7 P02008

While in general the number of **secondary electrons (gain) decreases** with the gas **pressure**, the number of **photons** produced per secondary electron was found to **increases** with the gas pressure;

LUMINESCENCE: WHAT COLOR? THE CF_4 EXAMPLE





A **higher pressure reduces** the **average energy** an **electron** can gain before hitting a molecule, **increasing the probability** of **light emission** instead of further ionisations

LIGHT EMISSION IN HE/CF_4 60/40 – A SUMMARY

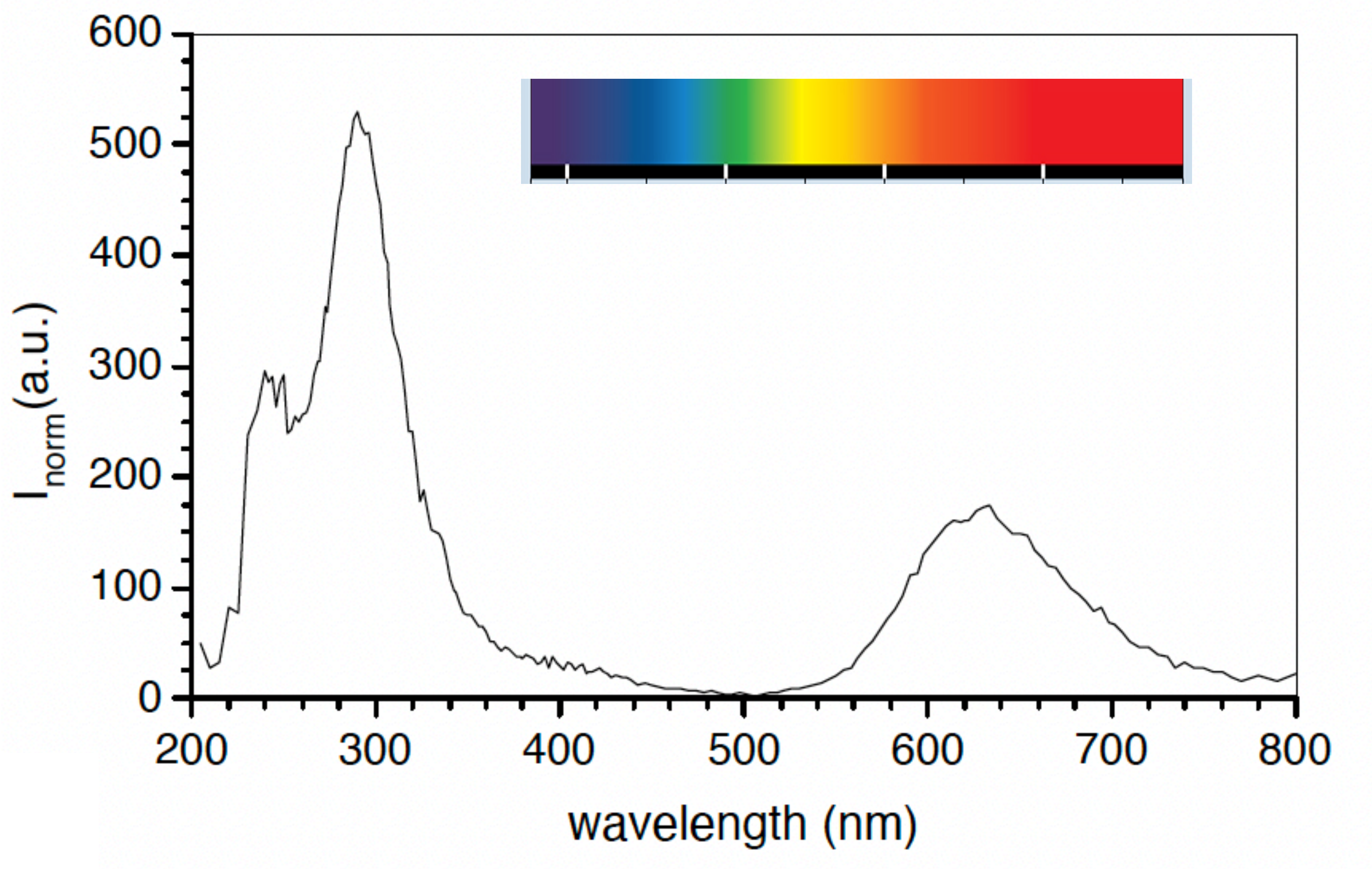
- Emitted as de-excitation of CF_3 **at the last multiplication layer**

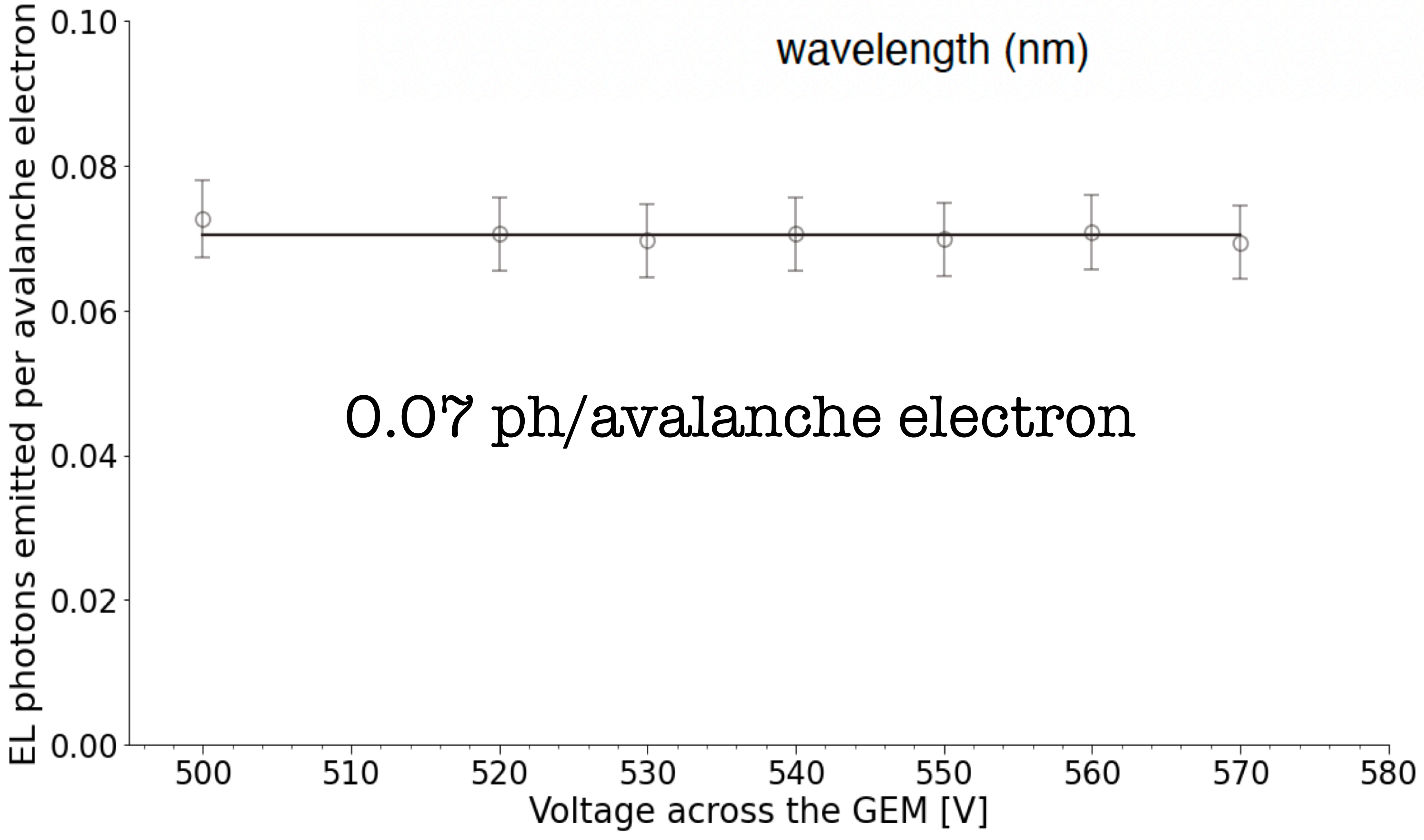
$$e^- + CF_4 \rightarrow CF_3 + F + e^-$$

- Two main lines, excited by accelerated electrons:
  ➡ Visible: **620 nm**
  ➡ UV light: 265 nm

- **Relative light** production **independent** from the **voltage:**

$$\gamma/e^- \text{ ratio} \sim 0.07 \text{ ph/aval. elec.}$$



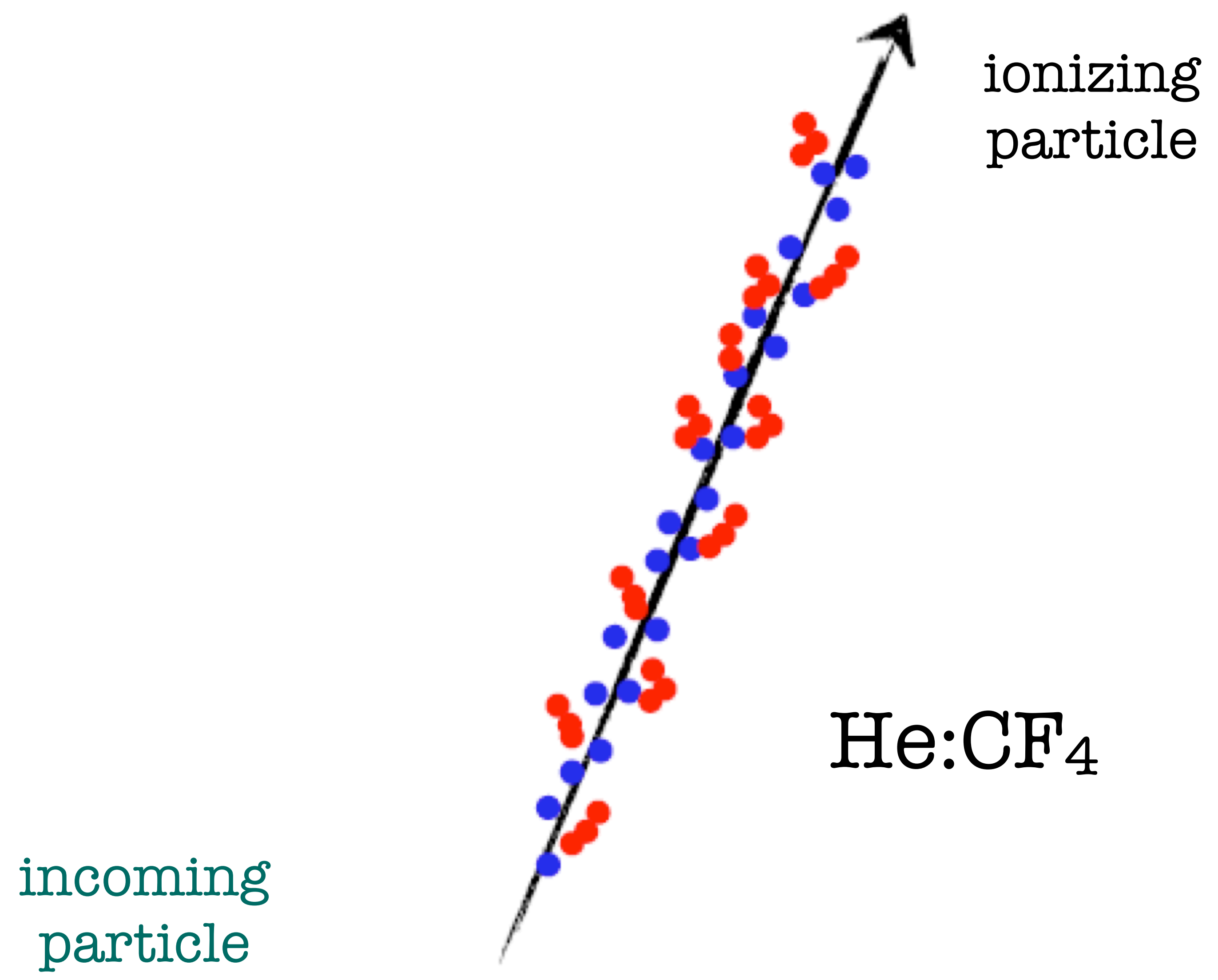


LET'S COUNT PHOTONS (FOR 1 keV RELEASED IN GAS)

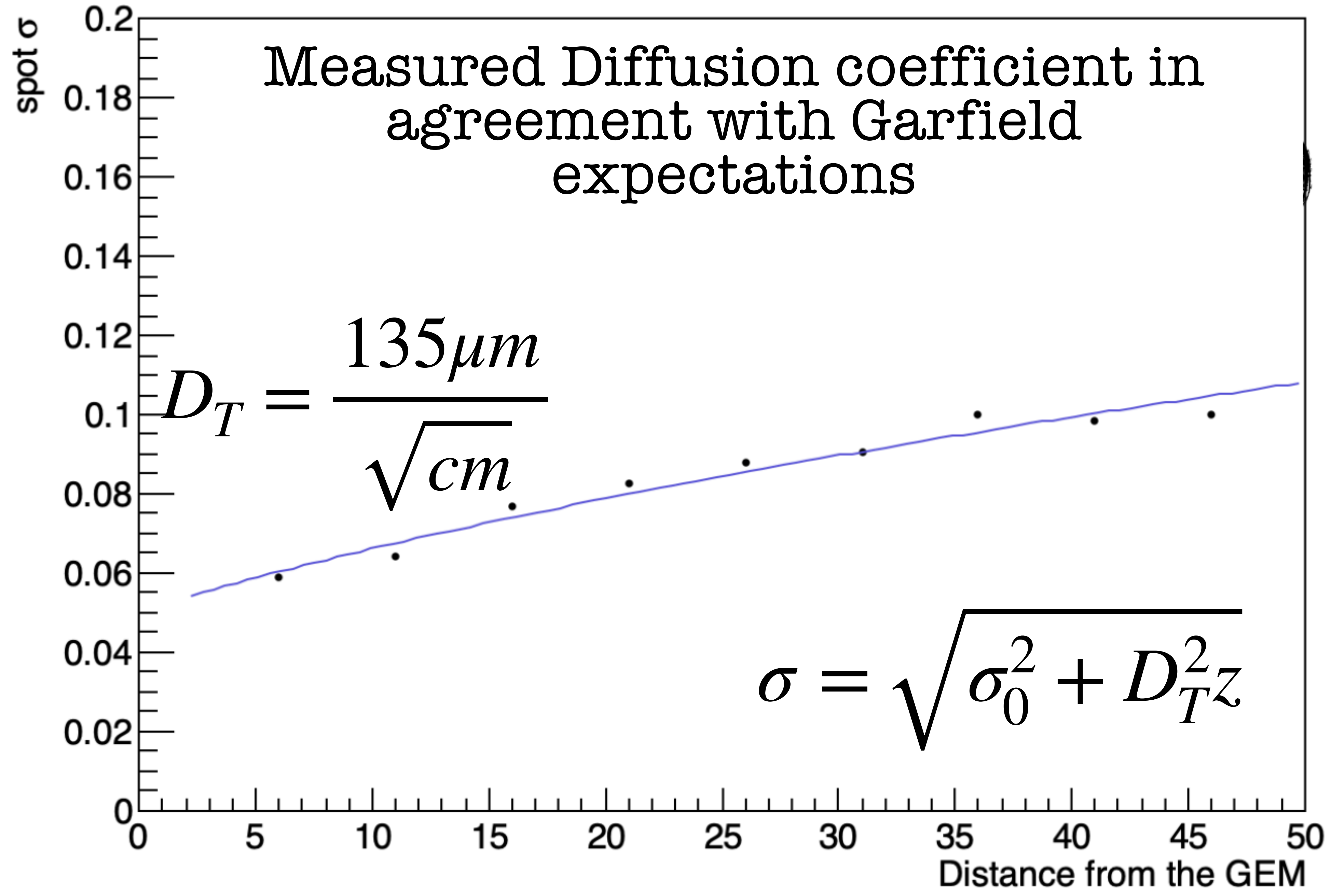
IONIZATION AND DRIFT PROCESSES

- **average energy** lost to produce an ion-electron pair in He:CF_4 (60/40):

$$\mathbf{W} \sim \mathbf{35\ eV} \Rightarrow 1\ \mathrm{keV} \sim 30\ \mathrm{electrons}$$



- Continuous hits during the path ⇒ **diffusion**

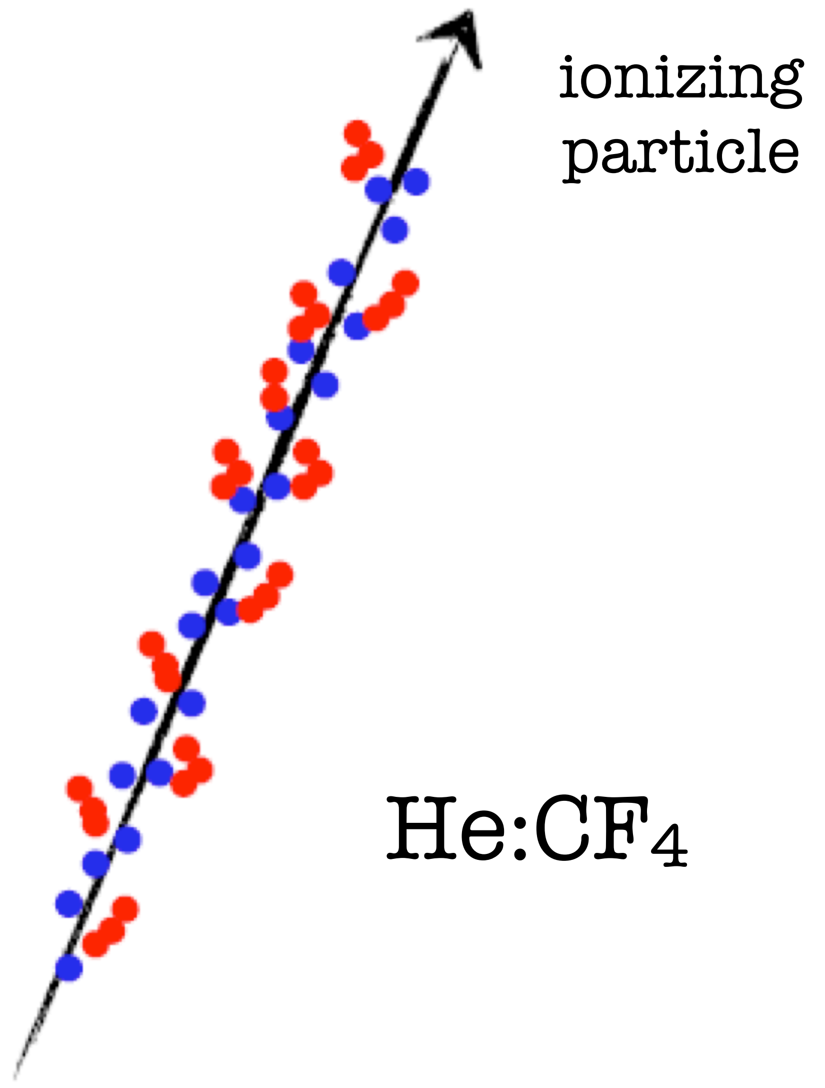


- after **1 cm** of drift, primary electrons will be **spread over an area** that we can approximate in a **circle with a radius of 2σ**
- **Area** = π x (2 x 0.05 cm)^2 = π **x mm^2**

IONIZATION PROCESS

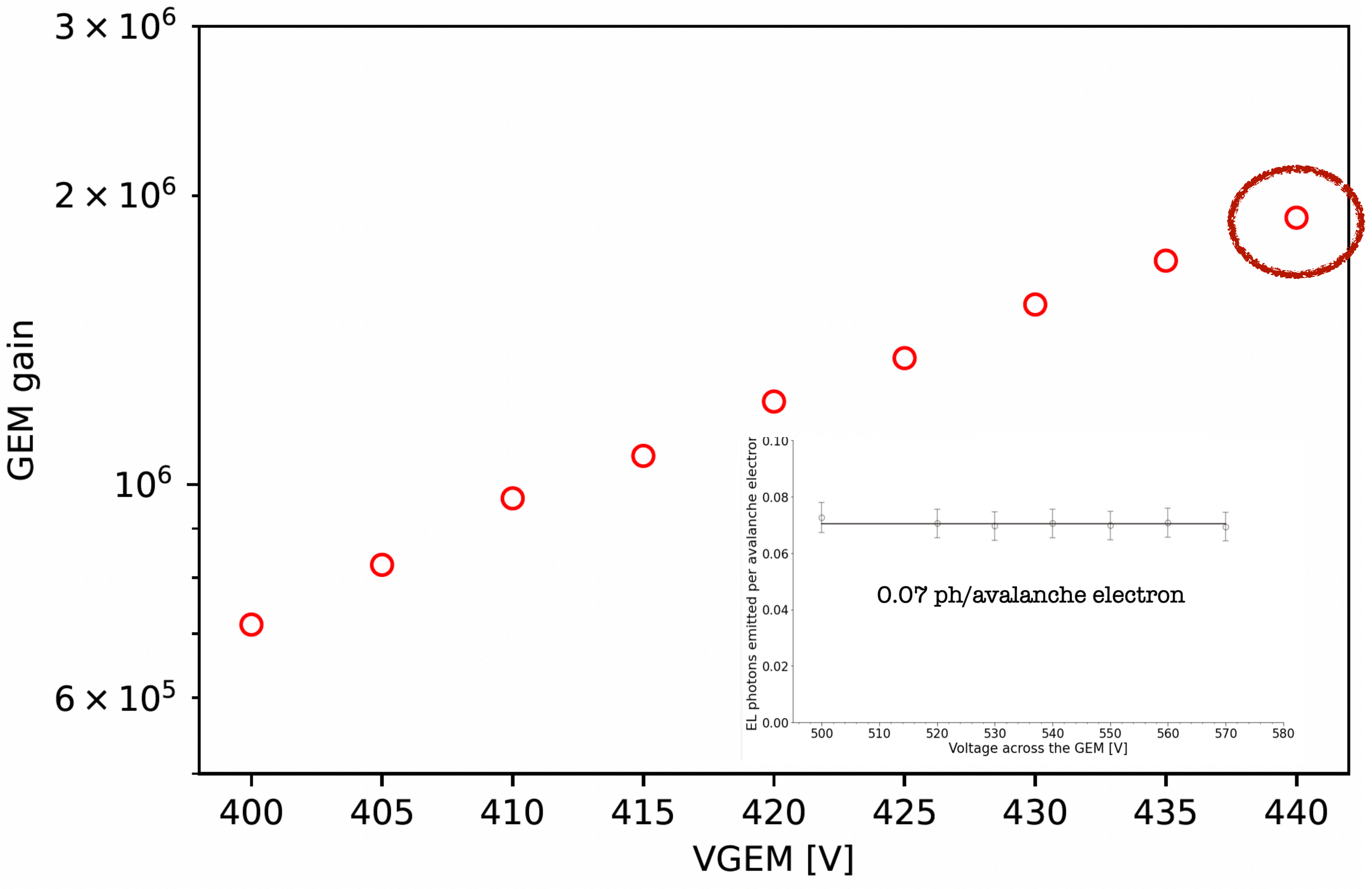
- average energy lost after producing an ion-electron pair in He:CF_4 (60/40):

$$\mathbf{W \sim 35\ eV} \Rightarrow 1\ \mathrm{keV} \sim 30\ \mathrm{electrons}$$



- Suppose to operate **triple GEM** at a HV of **440 V each**
- At this voltage, the **total gain** has been measured to be ab **2 x 10⁶**
- Therefore, after multiplication we get:

$$@\ 1\ \mathrm{keV_{ee}}$$
$$30\ e^- \rightarrow 6.0 \times 10^7\ e^- \rightarrow 4.2 \times 10^6\ \mathrm{ph}$$



THE OPTICAL SYSTEM

To focus the image produced on the GEM, a **lens** is needed

Specifications

Focal Length FL (mm)	25.00
Maximum Camera Sensor Format	1"
Aperture (f/#)	f/0.95 - f/11
Field of View, 1/2" Sensor (°)	20
Distortion (%)	<-3
Field of View @ Min Working Distance (mm)	76.80
Working Distance (mm)	300 - ∞
Filter Thread	M39 x 0.5

Lens **aperture** is the ratio between focal length diameter

$$\# = a = f/D$$

The **geometrical acceptance** is given by

$$\Omega = \frac{1}{(4(\delta + 1) \times a)^2}$$

where **δ** is the **ratio** between captured **area** and the **sensor sides** (suppose 1 cm);

If for example you want to image a **10 x 10 cm² area**, **δ=10** and Ω is of the order of 10^{-3}

only **1 photon over 1000** is collected

@ 1 keV
→ 4200 collected photons

PHOTON DETECTION

- Therefore we end up with **4200 ph / π x mm²** → **1000 ph/mm²**
- Let's suppose we use a **1x1 cm² sensor** with a granularity **2000 x 2000 pixels**, to "observe" a **10x10 cm² GEM**, we can evaluate how many pixels will collect those photons:

$$1\ \text{mm}^2 = \frac{1\ \text{mm}^2}{100 \times 100\ \text{mm}^2} \times 2000 \times 2000\ \text{pixels} = \ 400\ \text{pixels}$$

@ 1 keV_{ee}
→ 2-3 ph/pixel

- Thus to be able to **detect energy releases** of the order of **few keV** (or less) **sensor noise** should be **lower than few photons/pixel**

PIXELATED LIGHT SENSORS

THE PHOTO-DIODE

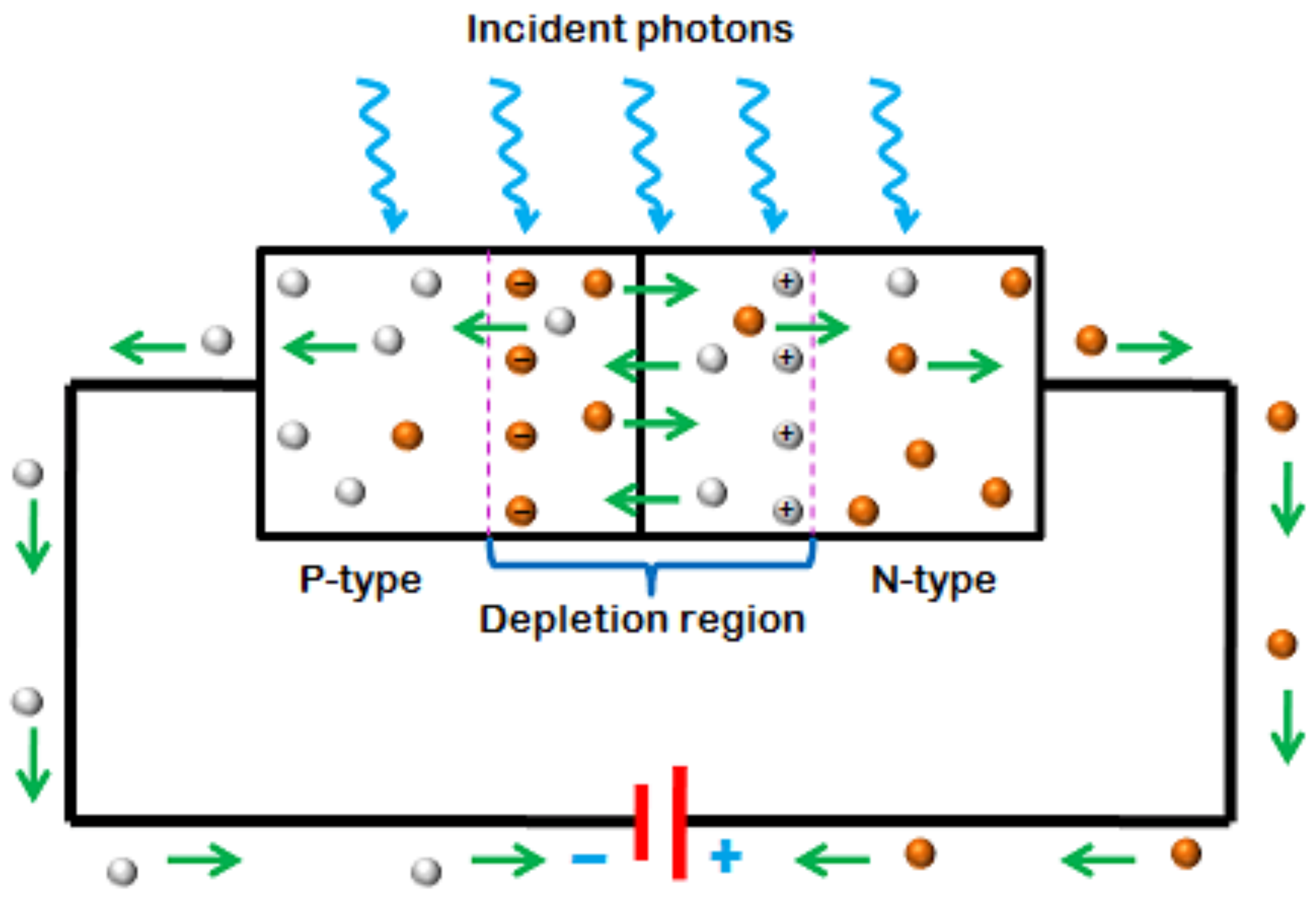
In the Beginning is the **photo-diode**

It works on the principle of the **photoelectric effect** to convert a photon into a **photo-electron**.

The operating principle of the photodiode

- a **PN junction** with reverse bias

- **energy** released by the **photo-electron** within **depleted region** produces several **electron-hole pairs** (i.e. it provides to electrons enough energy to be promoted to **conduction band**, about **3 eV in Si**) ;

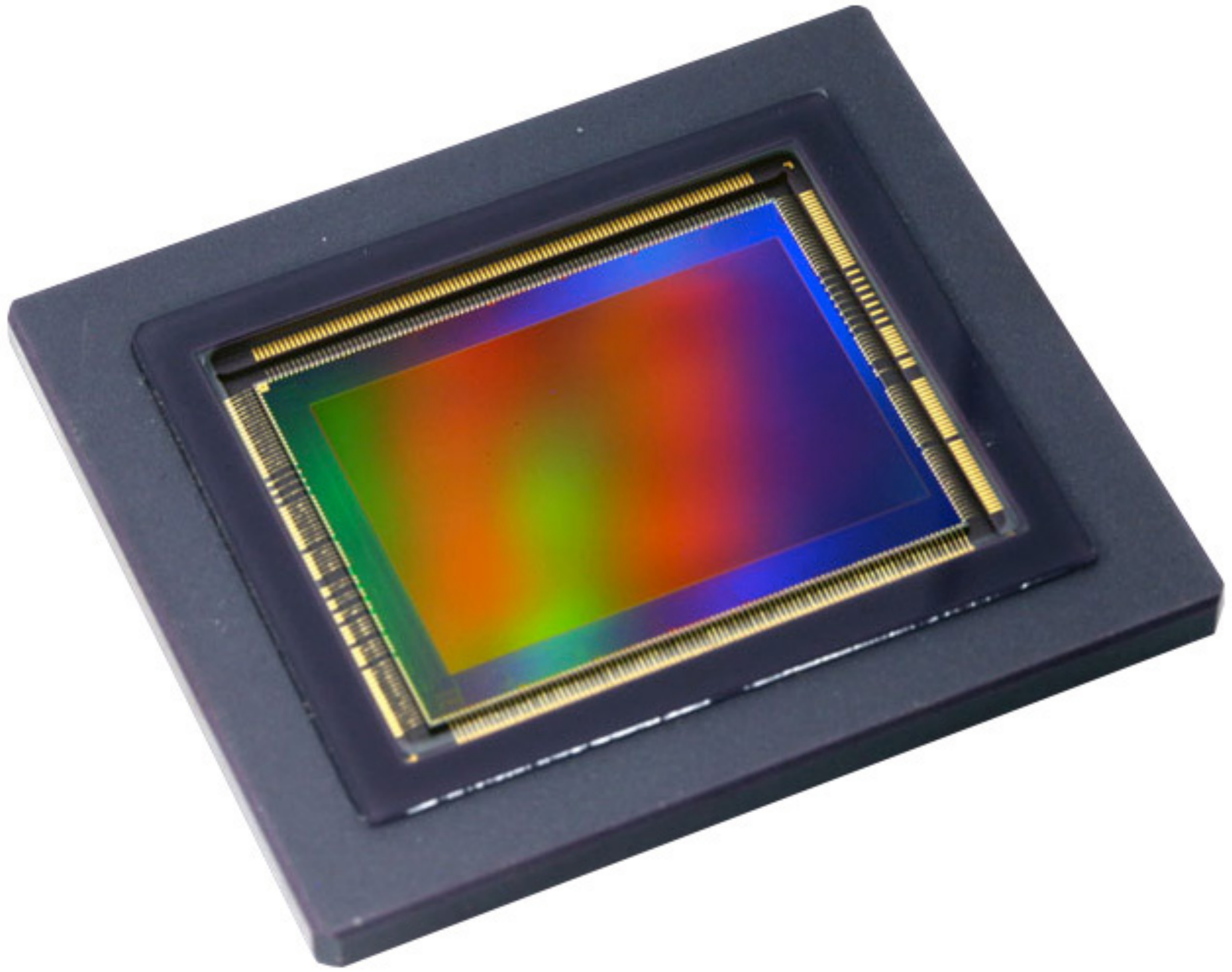


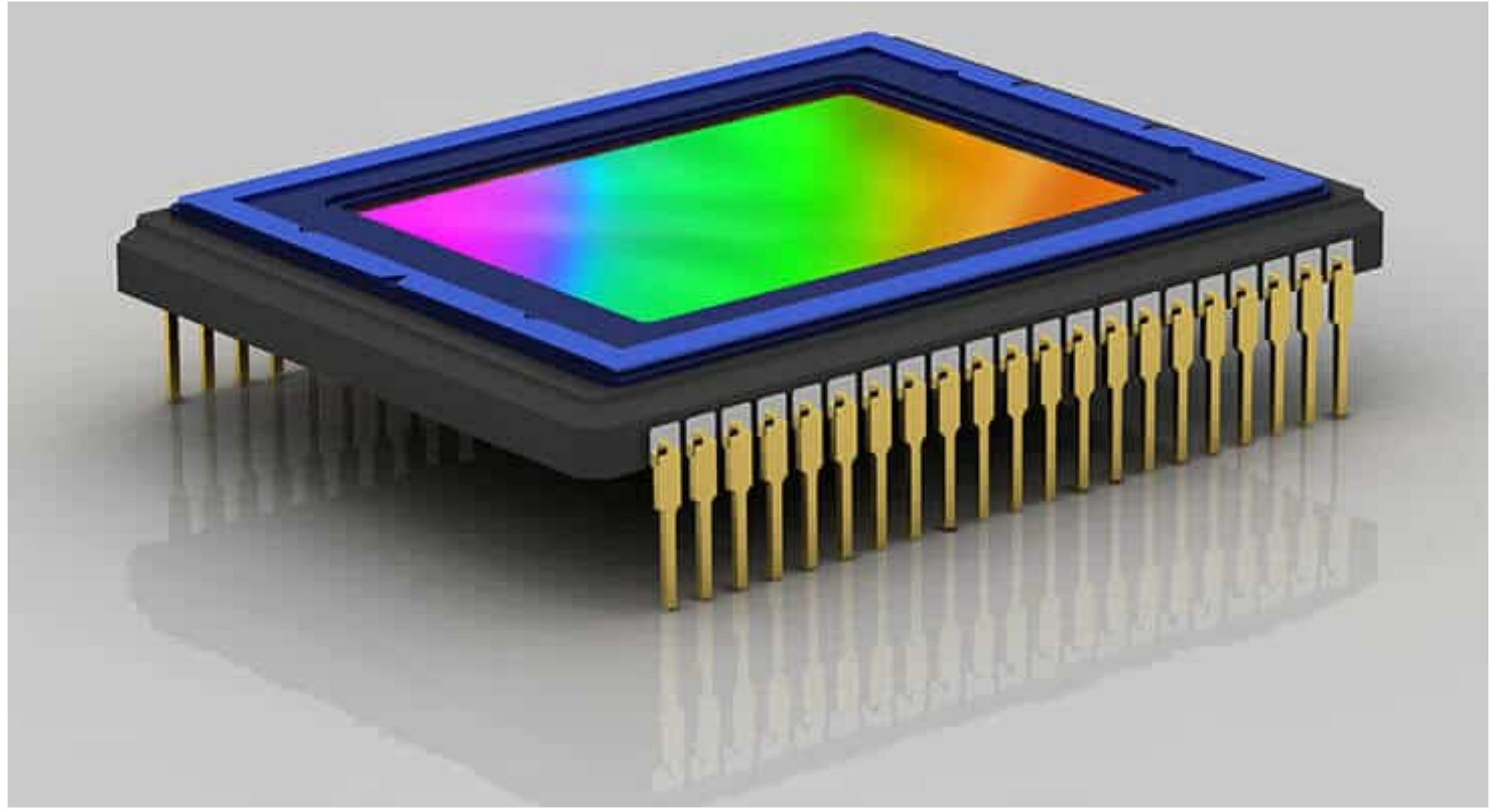
PN Junction photodiode

Because of bias, the **electron** and the **hole** start **drifting inducing** an electrical **signal**

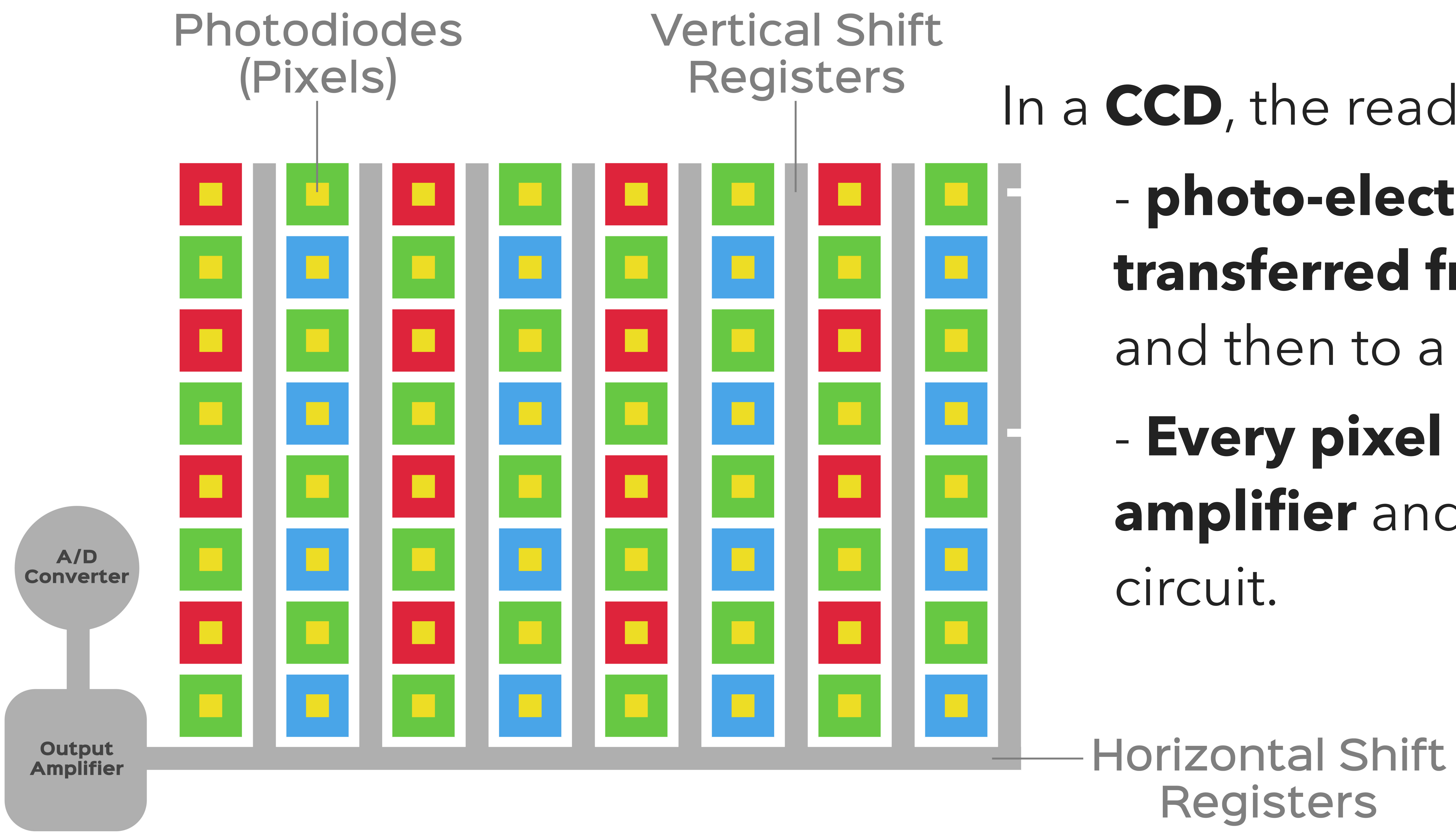
CCD AND CMOS SENSORS

- **CCD** (charge coupled device) and **CMOS** (complementary metal oxide semiconductor) image sensors are **two different technologies** for capturing images digitally;
- each has unique strengths and weaknesses giving advantages in different applications;
- those technologies were **both invented in the late 1960s and 1970s;**





THE CCD



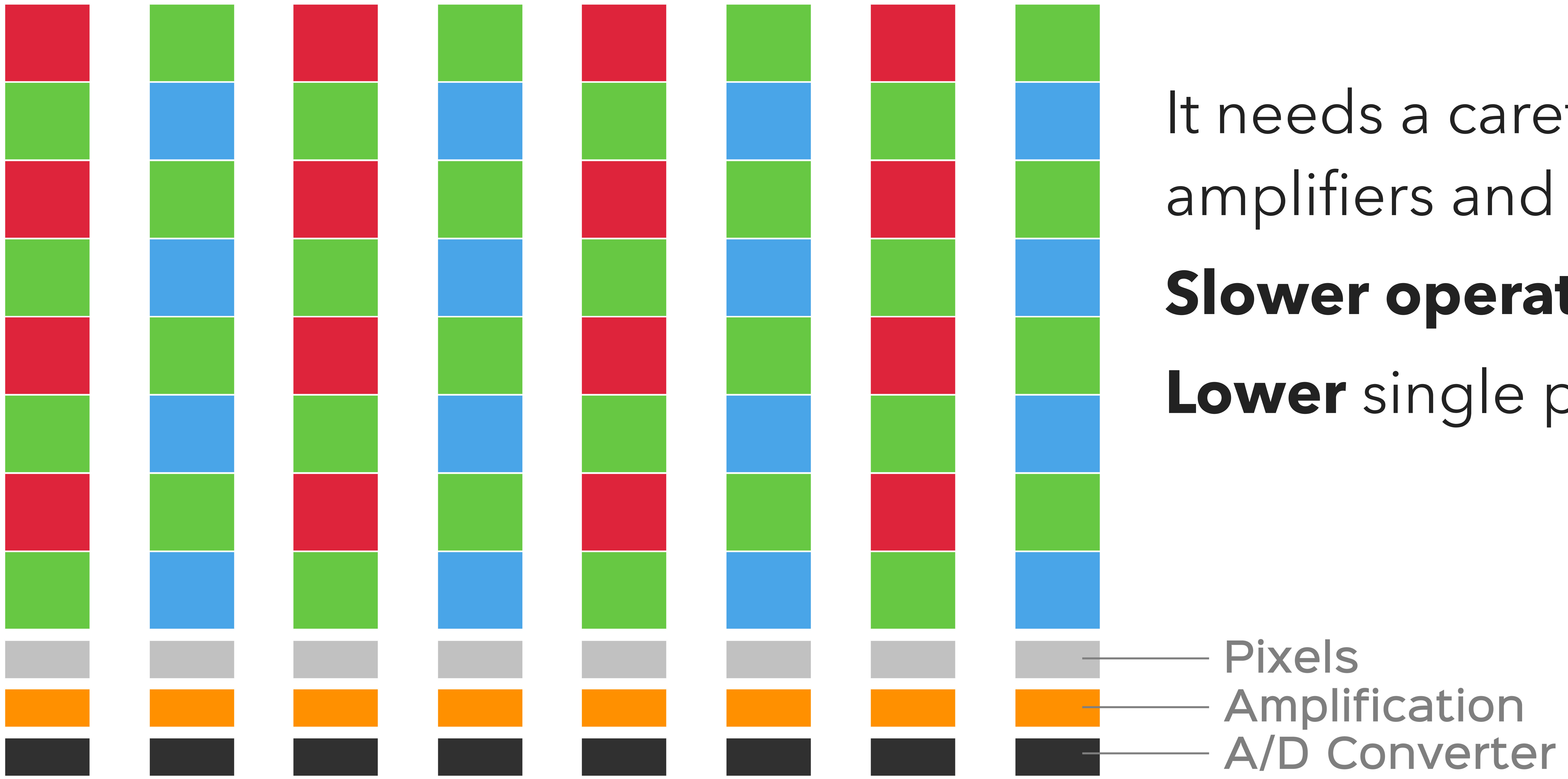
In a **CCD**, the read out happens **serially**:

- **photo-electrons** produced in each **pixel** is **transferred from pixel to pixel** in columns and then to a horizontal **shift register**.
- **Every pixel** is then **read out** through an **amplifier** and **Analog to Digitial** Converter circuit.

Along their path, **increasing noise** can be collected that can be **feed** to the **amplifier**;

THE ACTIVE PIXEL SENSORS CMOS

In **Active Pixel Sensors** CMOS, **each pixel has its own amplifier** (FDA), so the charge is **converted into a voltage and pre-amplified in each pixel** and then analog to digital conversion is achieved in column ADCs.



It needs a careful **equalisation** of the amplifiers and ADC;

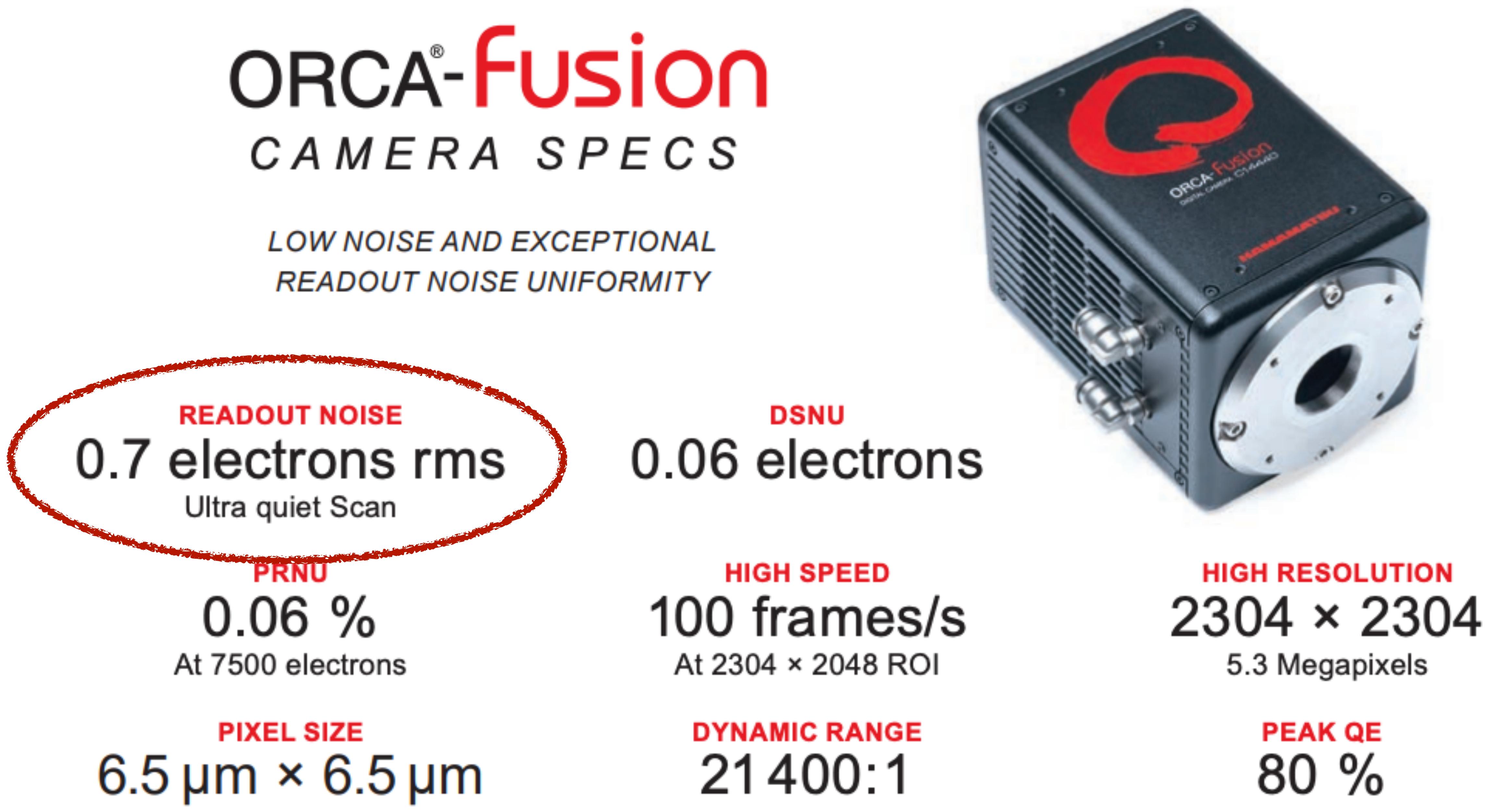
Slower operation w. r. t. the CCD;

Lower single pixel **readout noise** level;

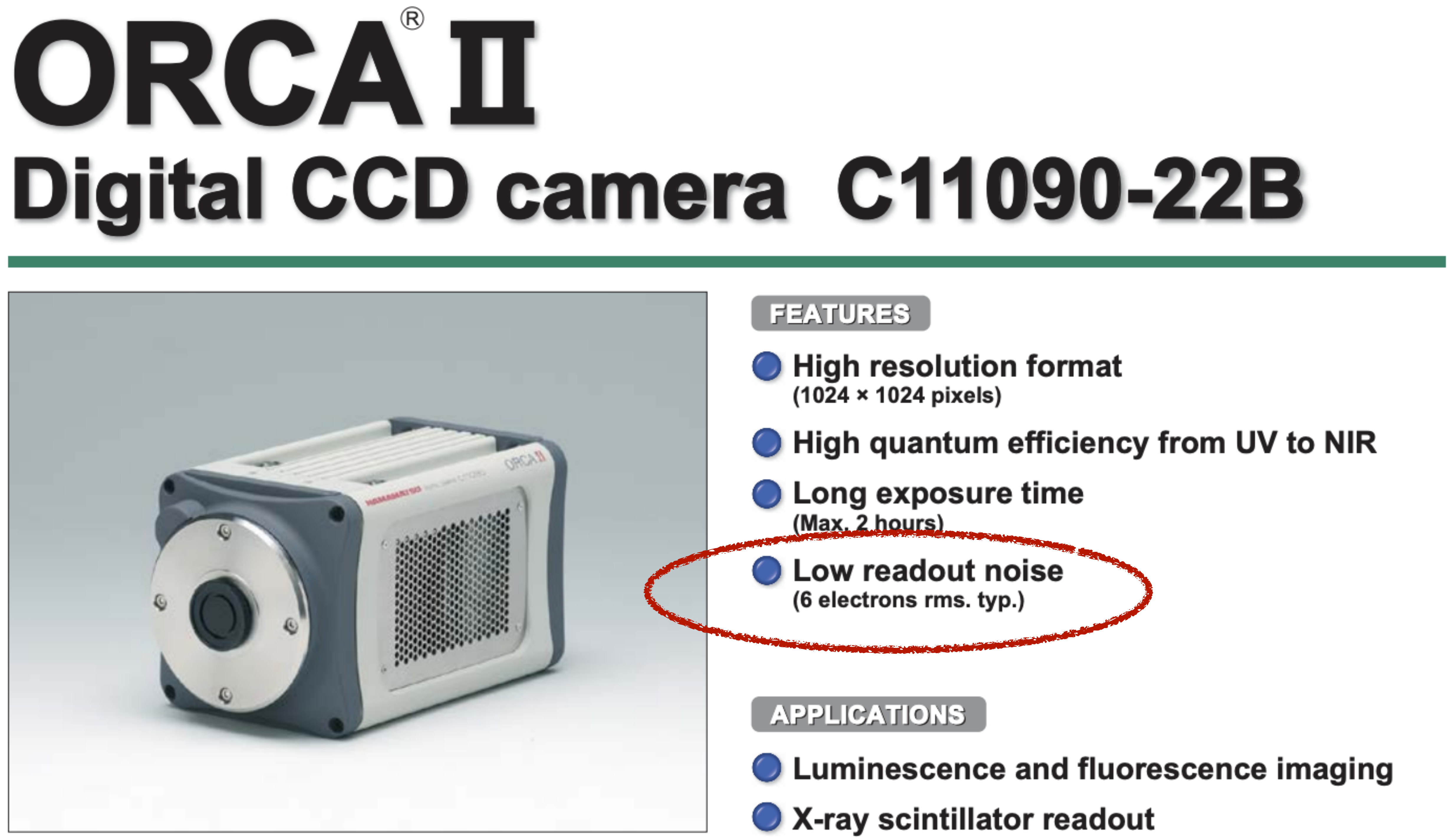
A REAL COMPARISON

Below the performance of **latest cameras** produced by Hamamatsu

Active Pixel Sensor (CMOS)



Charge Couple Device (CCD)



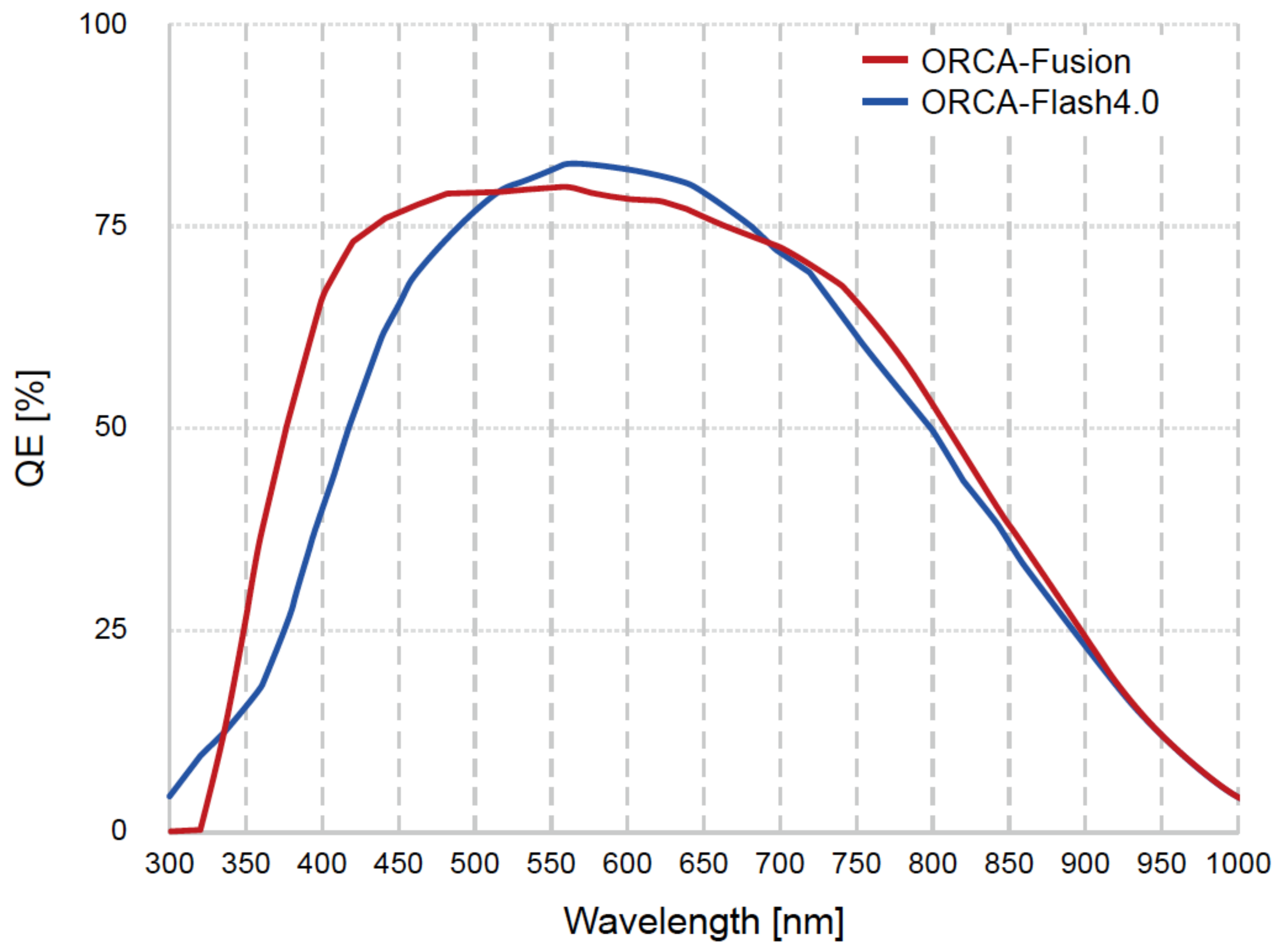
CMOS ensure a noise level **below the electron level**, **CCD** is at the level of **6 electrons**.

To **convert** those numbers in **photons**, we should use **quantum efficiency**

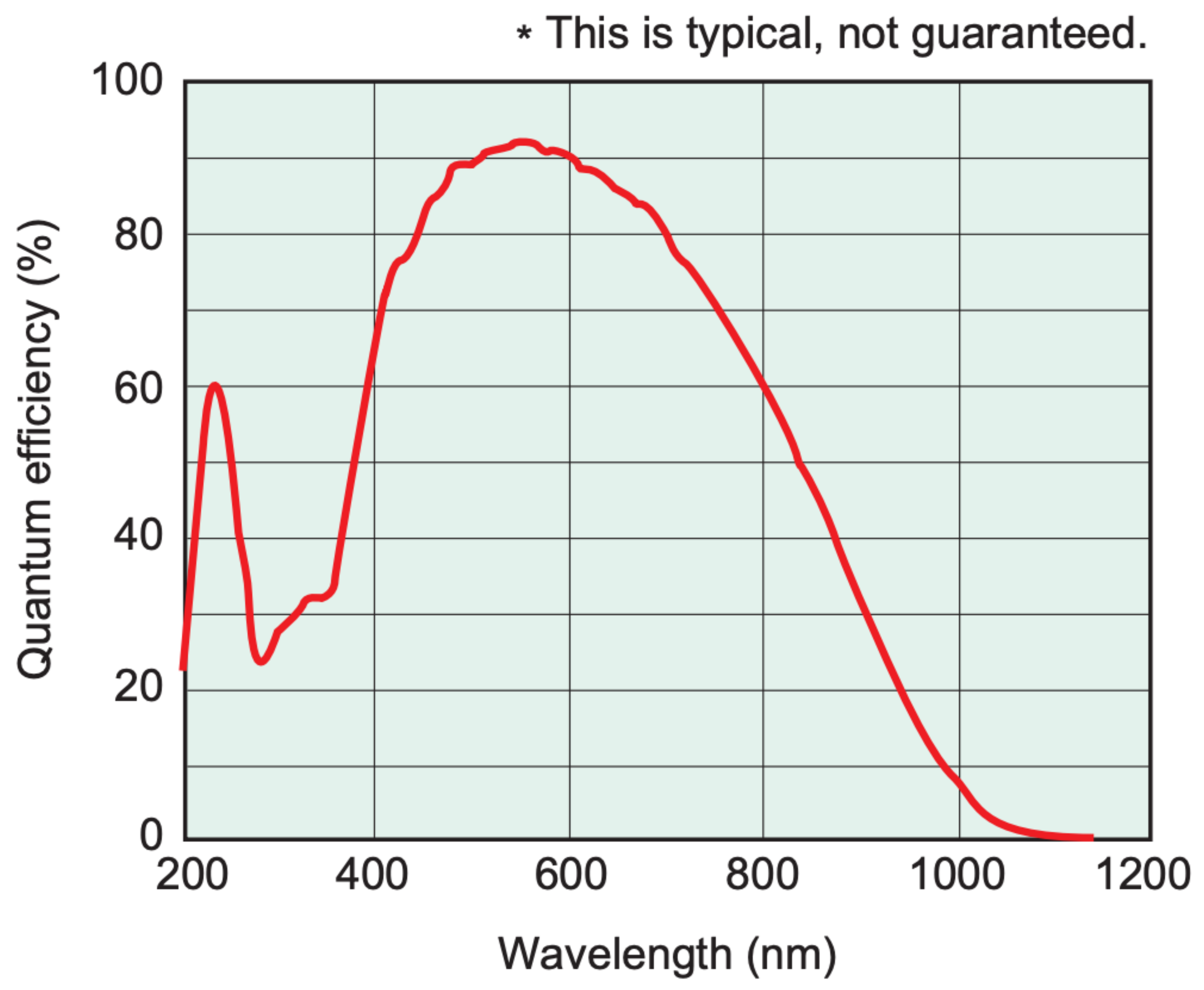
A REAL COMPARISON

Below the performance of **latest cameras** produced by Hamamatsu

Active Pixel Sensor (CMOS)



Charge Couple Device (CCD)



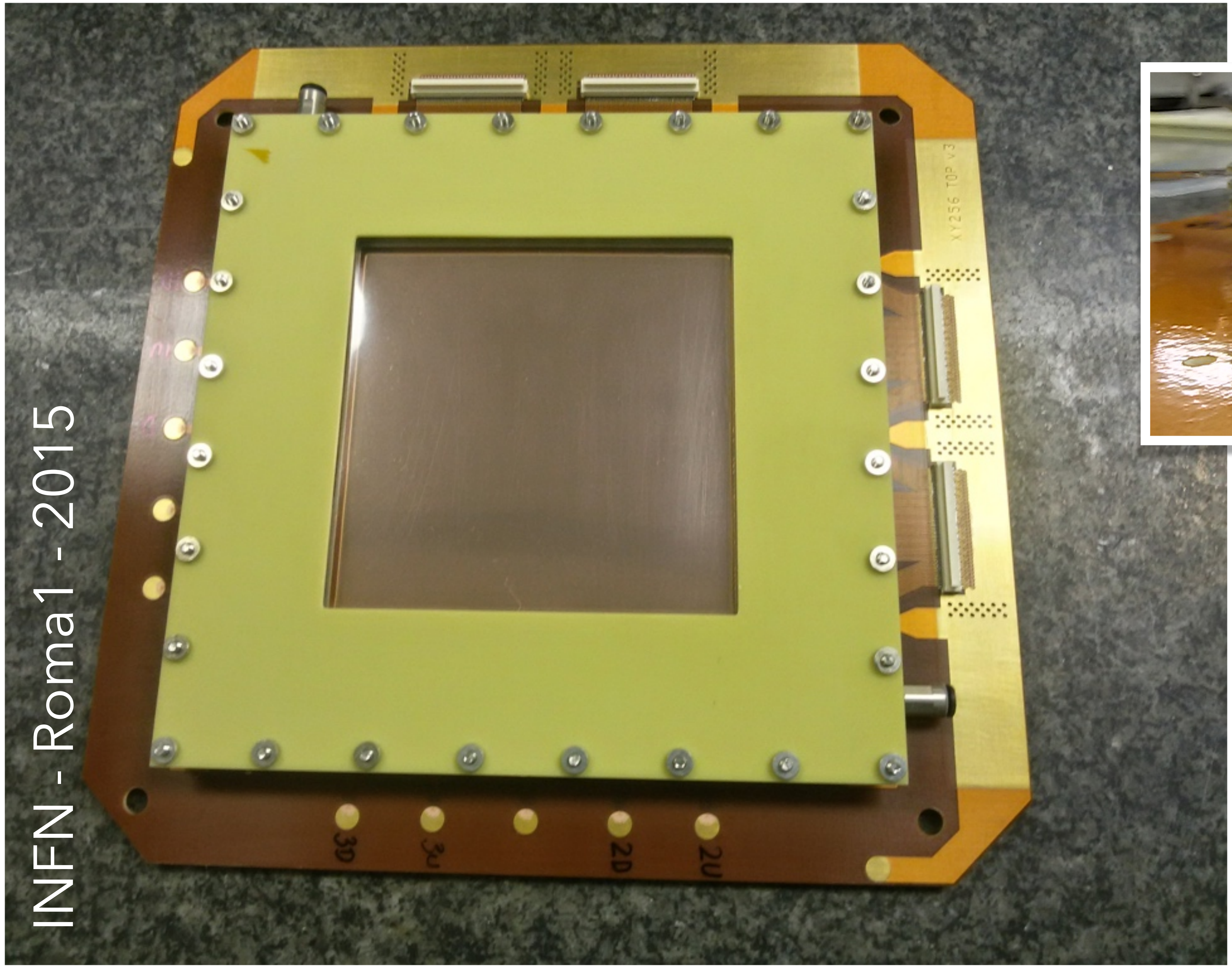
Both of them have a **maximum** (80%-90%) around **600 nm**

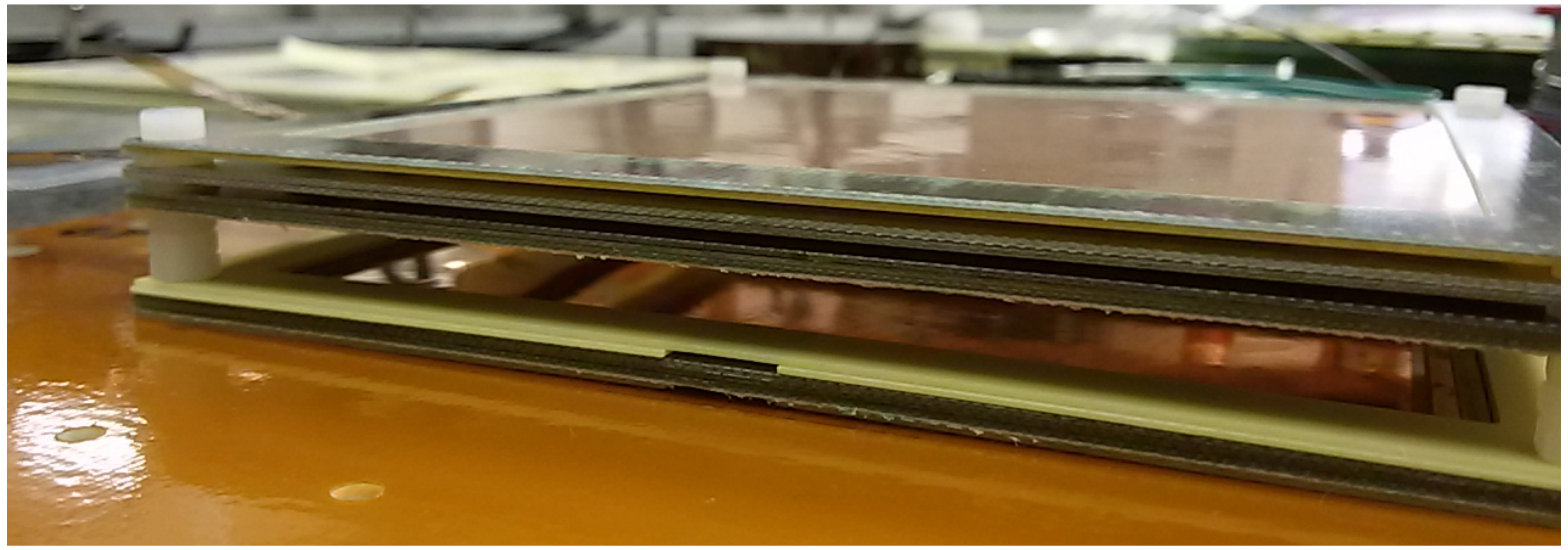
STARTING POINT – BEGINNING OF THE CENTURY

Nuclear Instruments and Methods in Physics Research A 471 (2001) 125–130

Due to the high noise level of CCD sensors used in previous attempts, only results related to **highly ionising particles** (alpha) were found literature only

AN OPTICALLY READOUT GEM (ORANGE) DEVICE – 2015

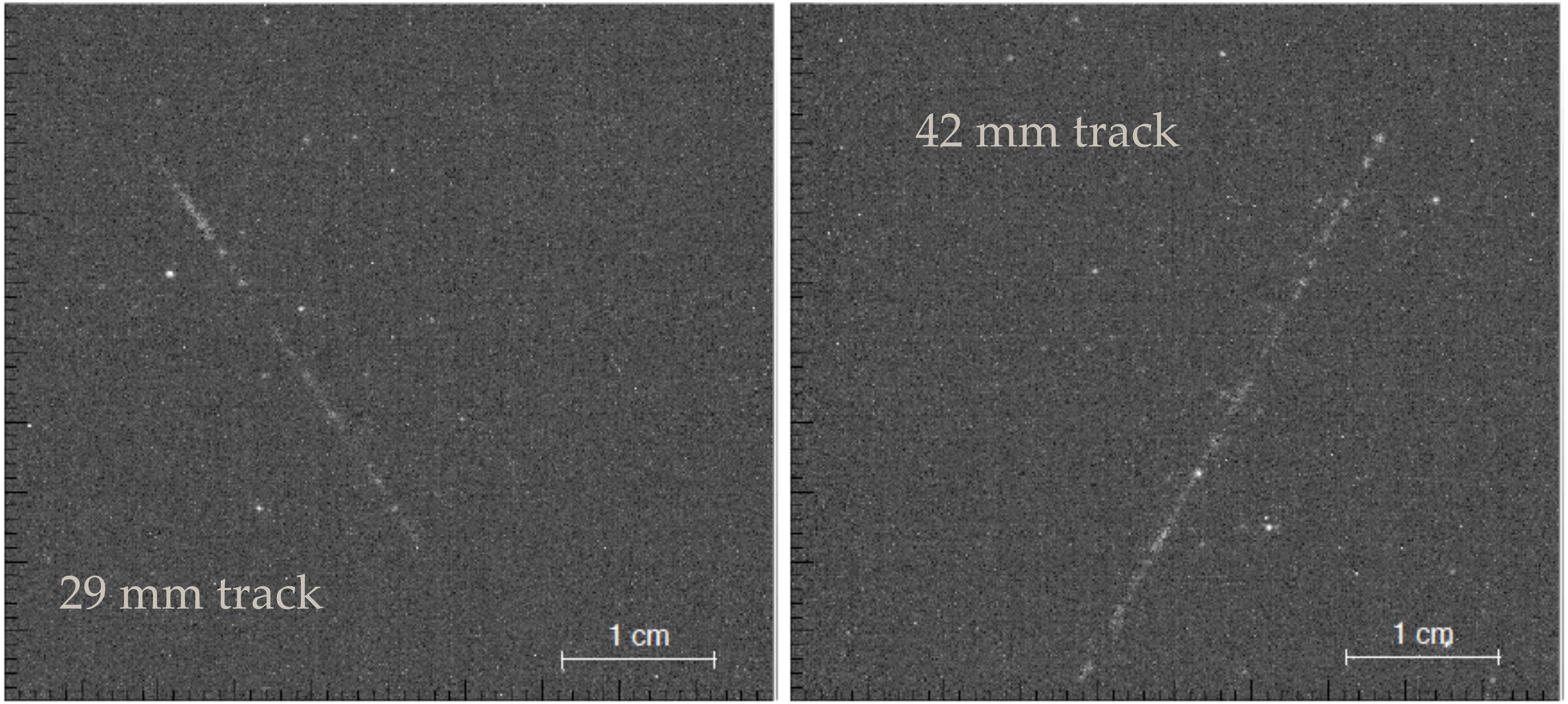




Triple GEM structure (10x10 cm^2) with 1 cm sensitive gap

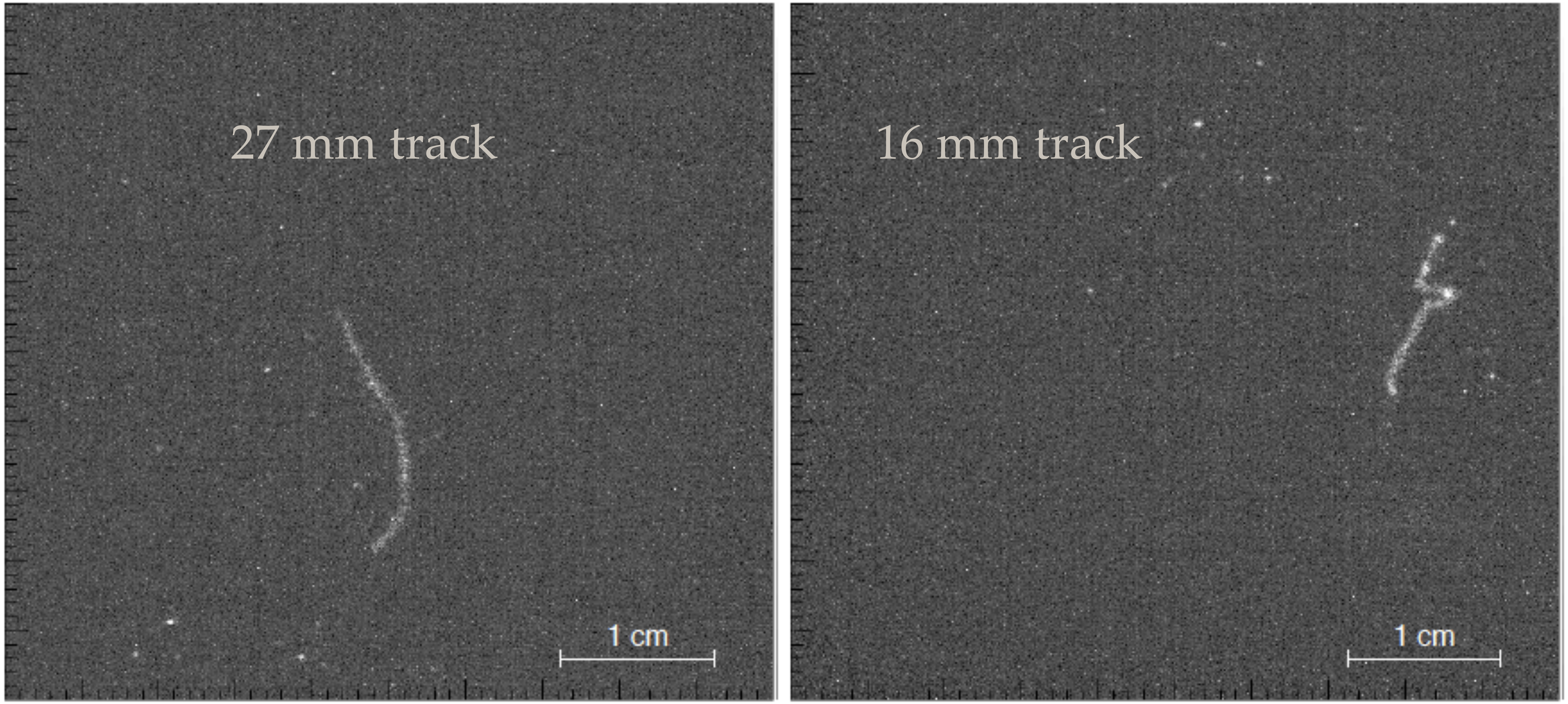
He/CF_4 (60/40) mixture was used

FIRST MUON TRACKS



By means of this setup we were able to acquire several **images** of **long** and **straight tracks** as the above ones. They are **very likely** due to **cosmic rays**;

ELECTRONS FROM NATURAL RADIOACTIVITY

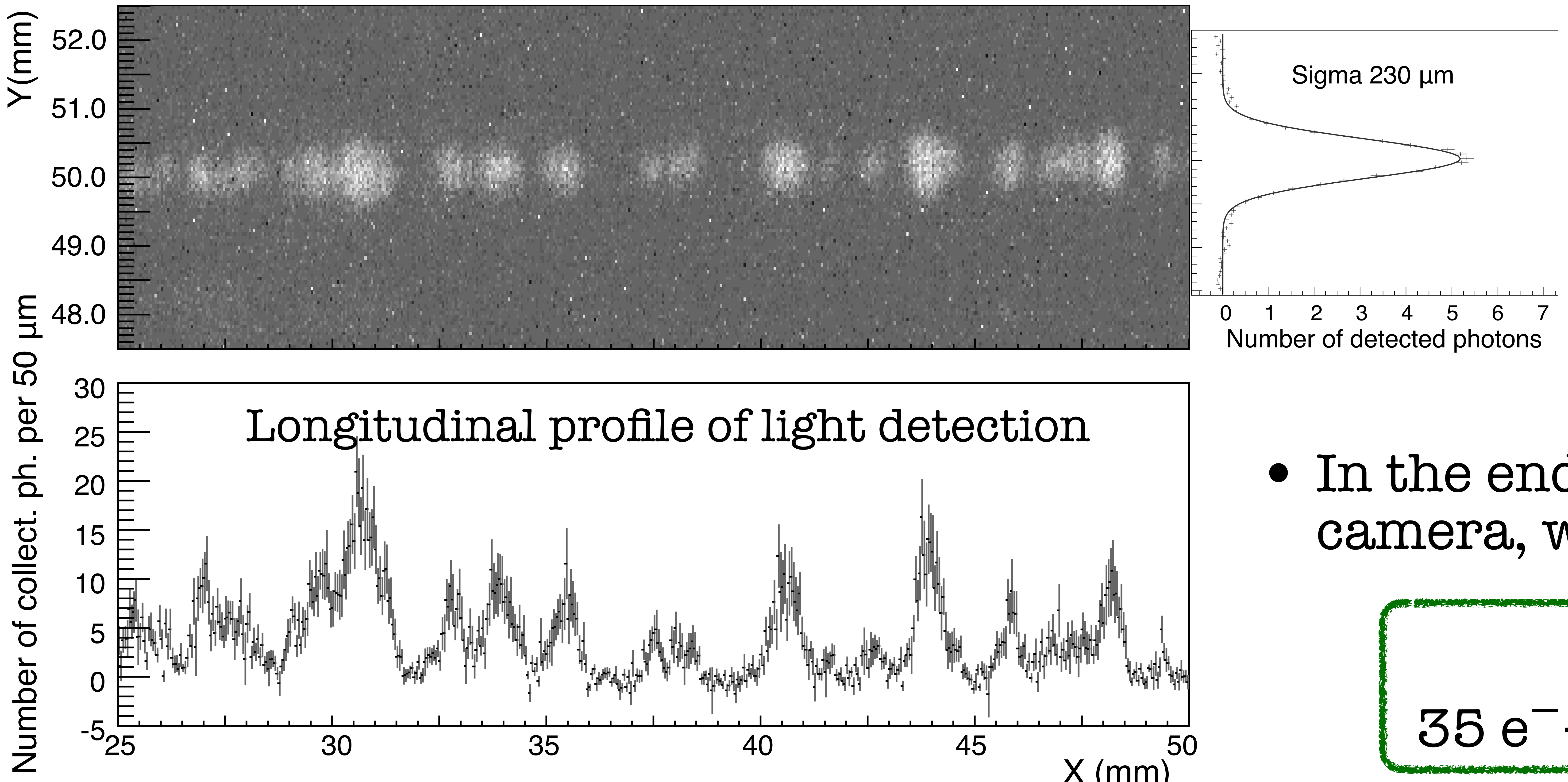


During the data taking, several images of short, intense and **curly tracks** were acquired very likely due to ionizing **electrons** produced by **natural radioactivity** and traveling within the drift gap;

ADVANTAGES OF OPTICAL READOUT GASEOUS DETECTORS

THE OPTICAL READOUT: DETAILS OF CLUSTERISATION

Marafini et al, IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 65, NO. 1, JANUARY 2018



clear cluster structure

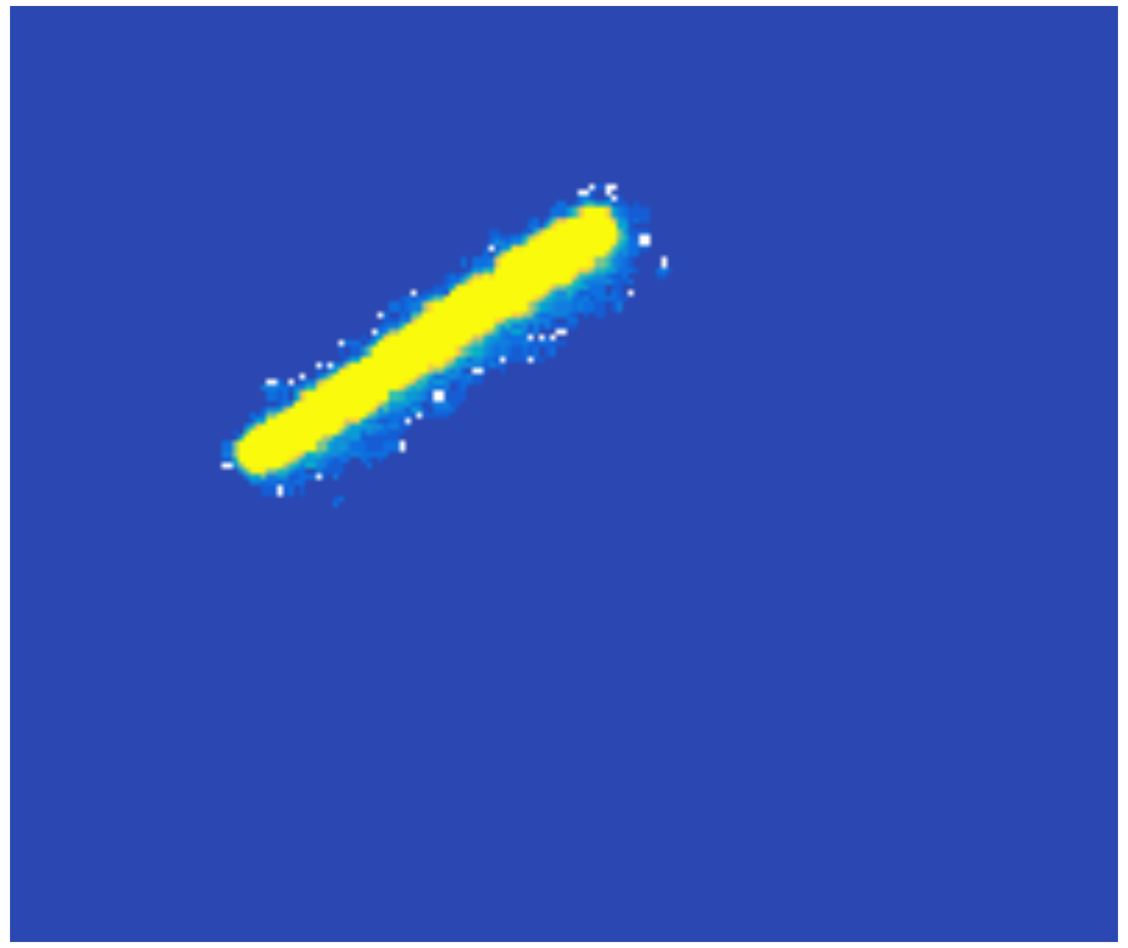
- In the end, if we consider only the camera, we obtain:

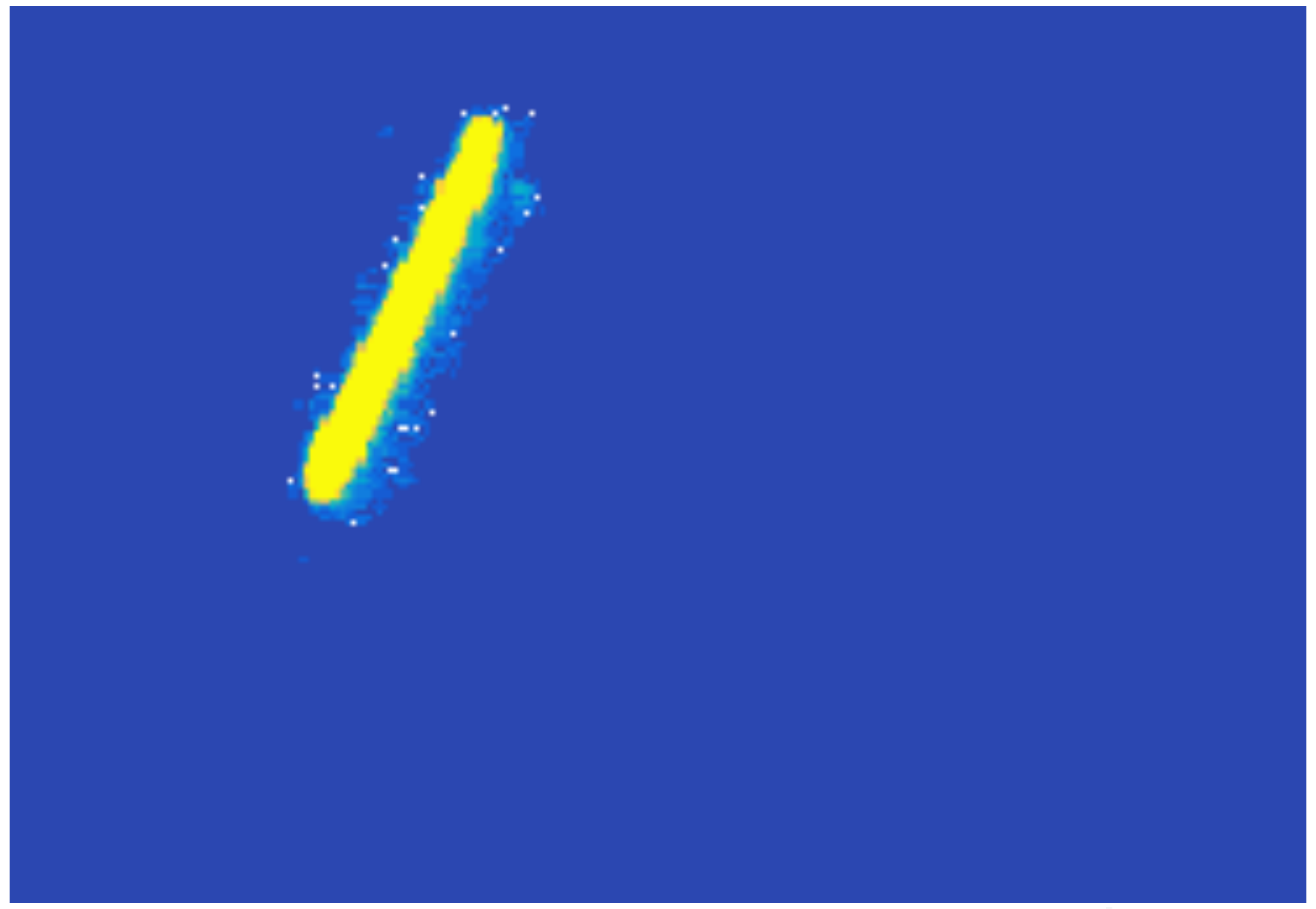
@ 1 keV_{ee}

35 $e^- \rightarrow \sim$ 400 detected ph

This is equivalent to ~ **12 detected photons every primary ionization electron**

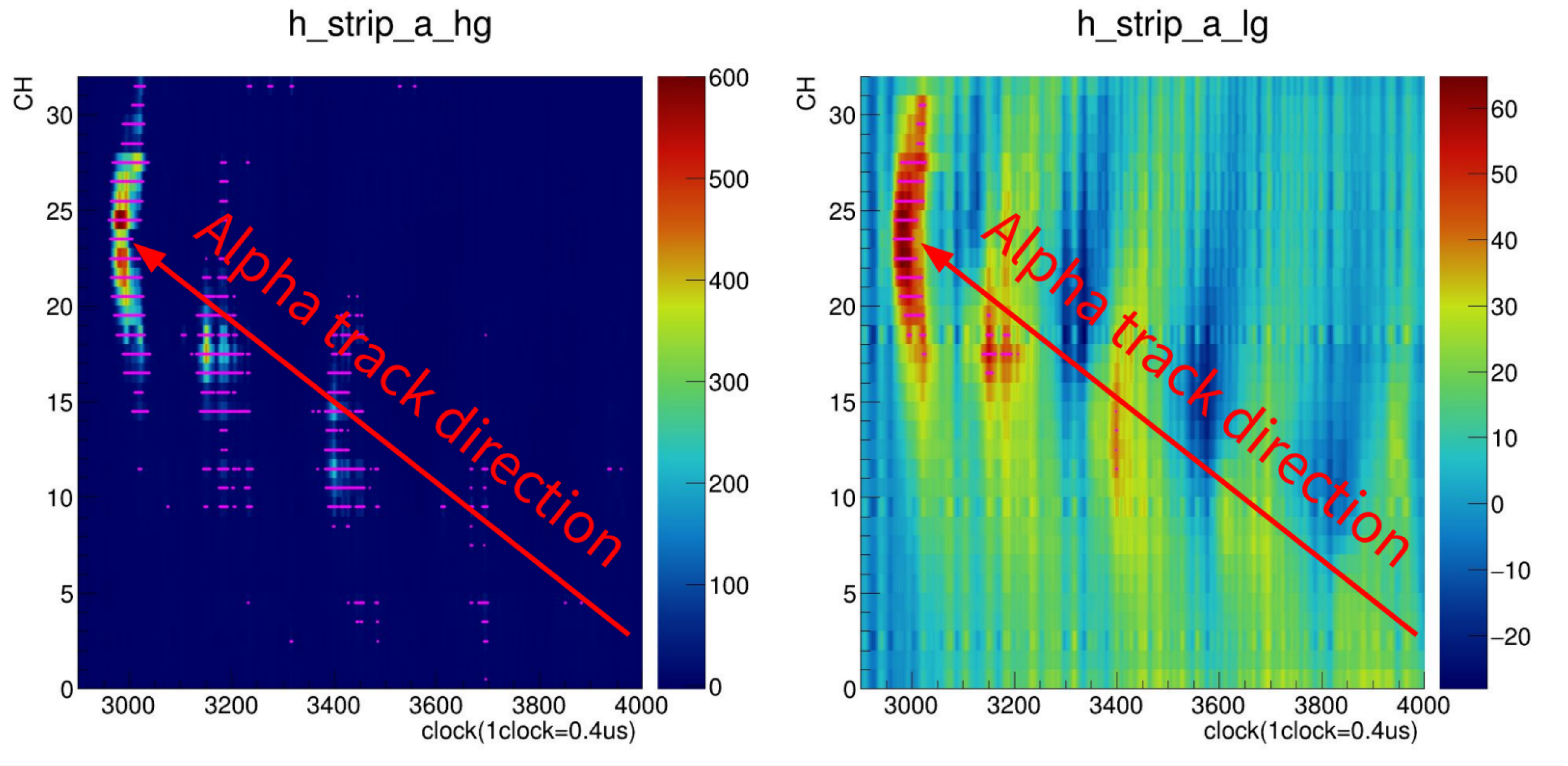
DIRECTION MEASUREMENT





- High energy particles create sizeable tracks in gas with a very clear images and **direction**

Coupled MMThGEM-Micromegas - Kobe Test Vessel



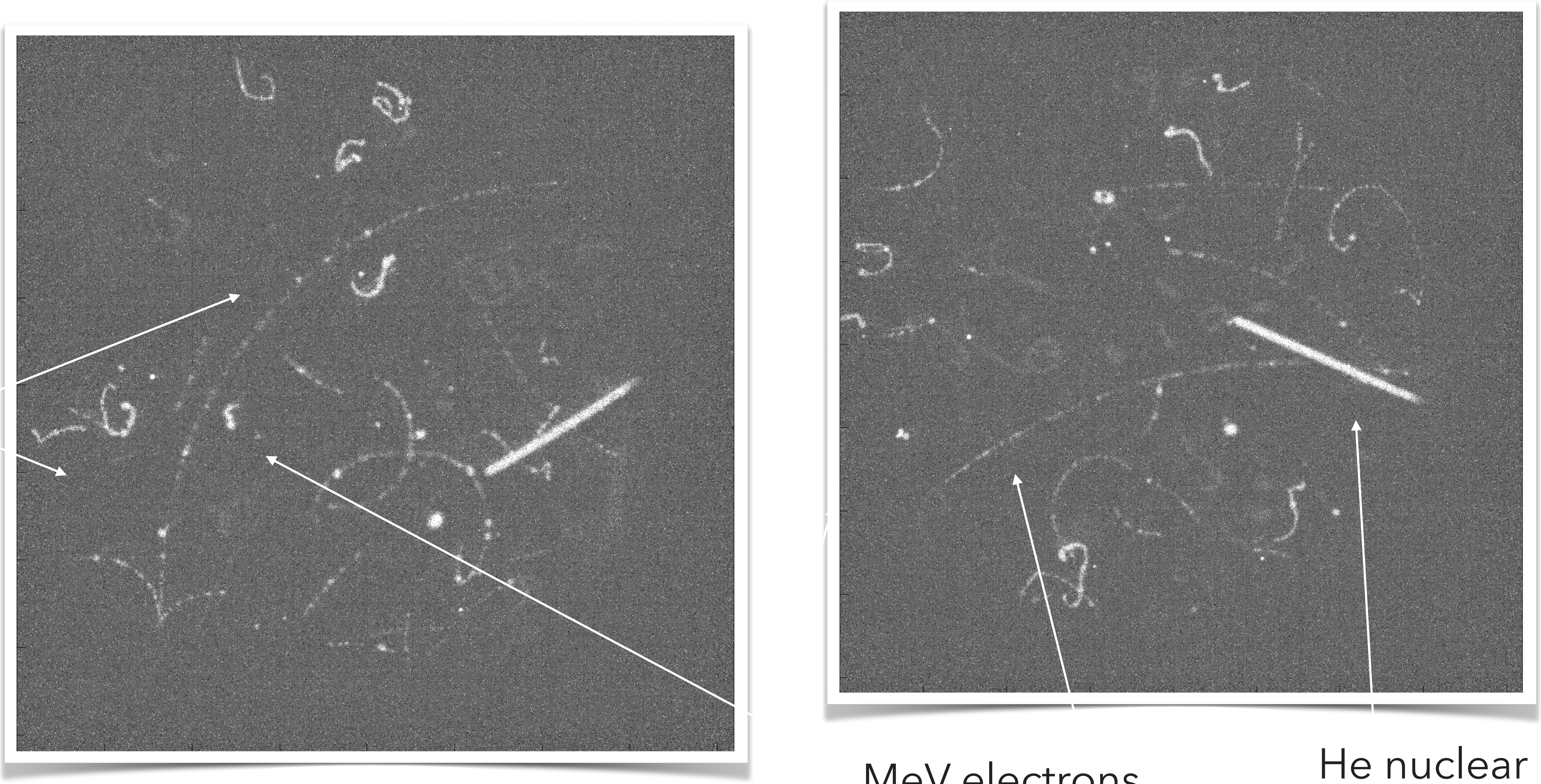
Micromegas Device -
(MMThGEM is used as a gain stage device)

- Perpendicular x-y strip readout plane
- Resolution/strip pitch: 250 µm
- Strip width: 100 µm (y) and 220 µm (x)
- Active area: 10 x 10 cm
- Amplification gap: 256 µm
- Diamond Like Carbon (DLC) layer: 50 MΩ/□

- **Not easy** to obtain so high granular performance **with electrical readout**

PARTICLE IDENTIFICATION WITH dE/dx

Prototype was exposed to an **AmBe** source, providing **1-10 MeV neutrons** along with **4 MeV** and **60 keV photons**. A **0.2 T magnetic field** was present within the drift field



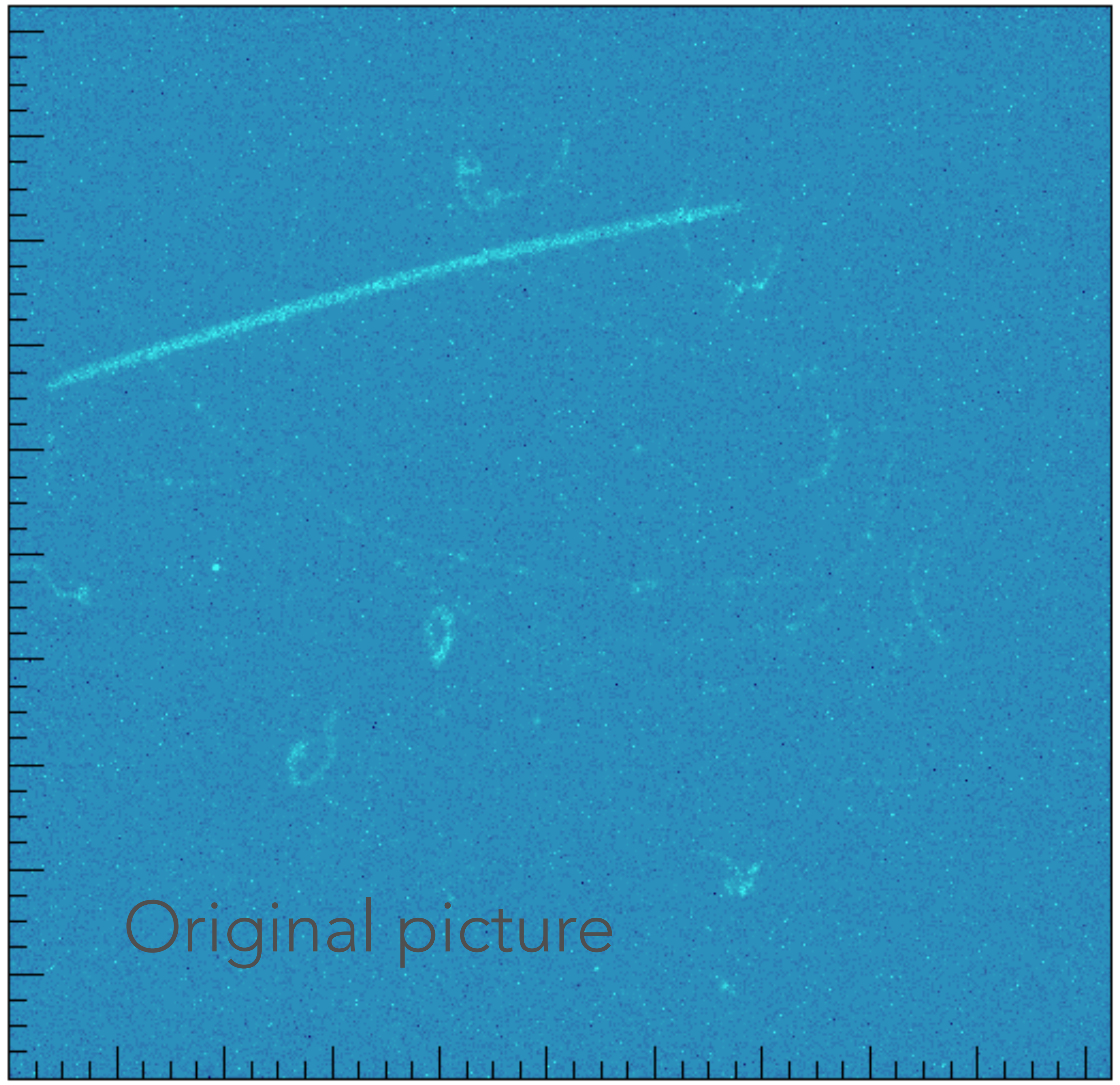
Low energy electrons due to X rays

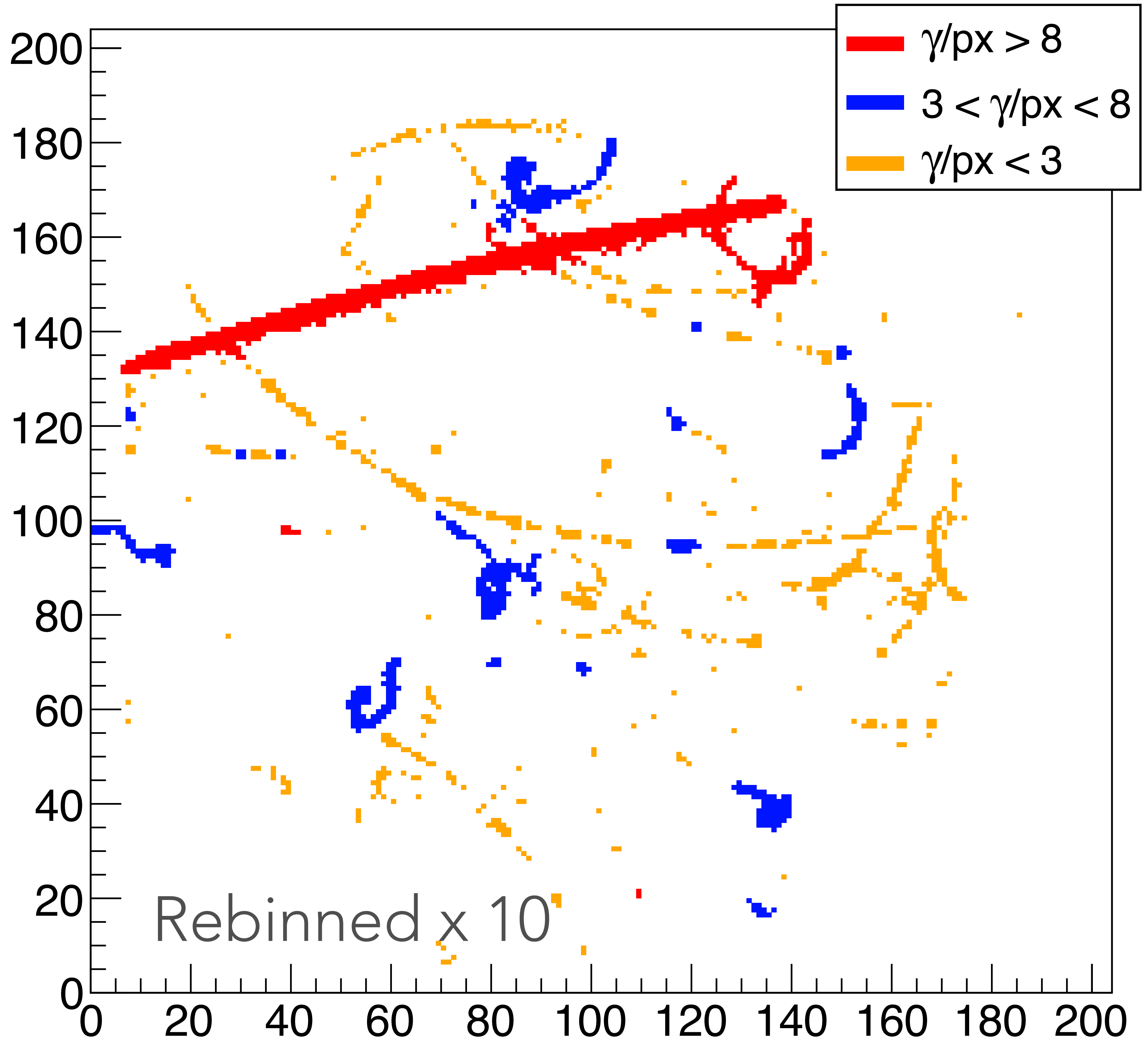
MeV electrons due to 4 MeV γ

He nuclear recoils (alpha)

PARTICLE IDENTIFICATION WITH dE/dx

Specific ionisation allows a fast particle **identification**.





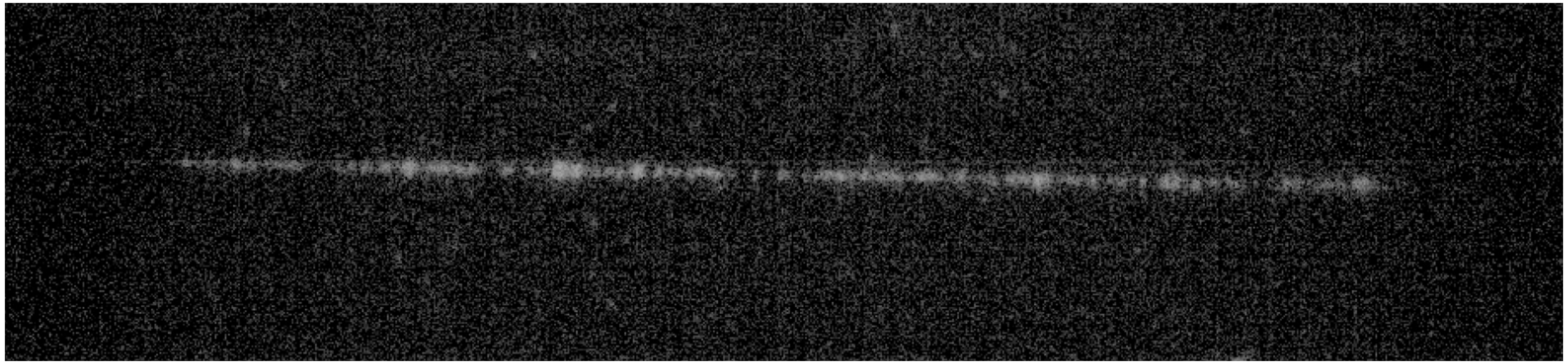
By simply assigning **different colours** to identify clusters as a function of their **average light density**, the three species are almost completely separated.

WHAT ABOUT TIME?

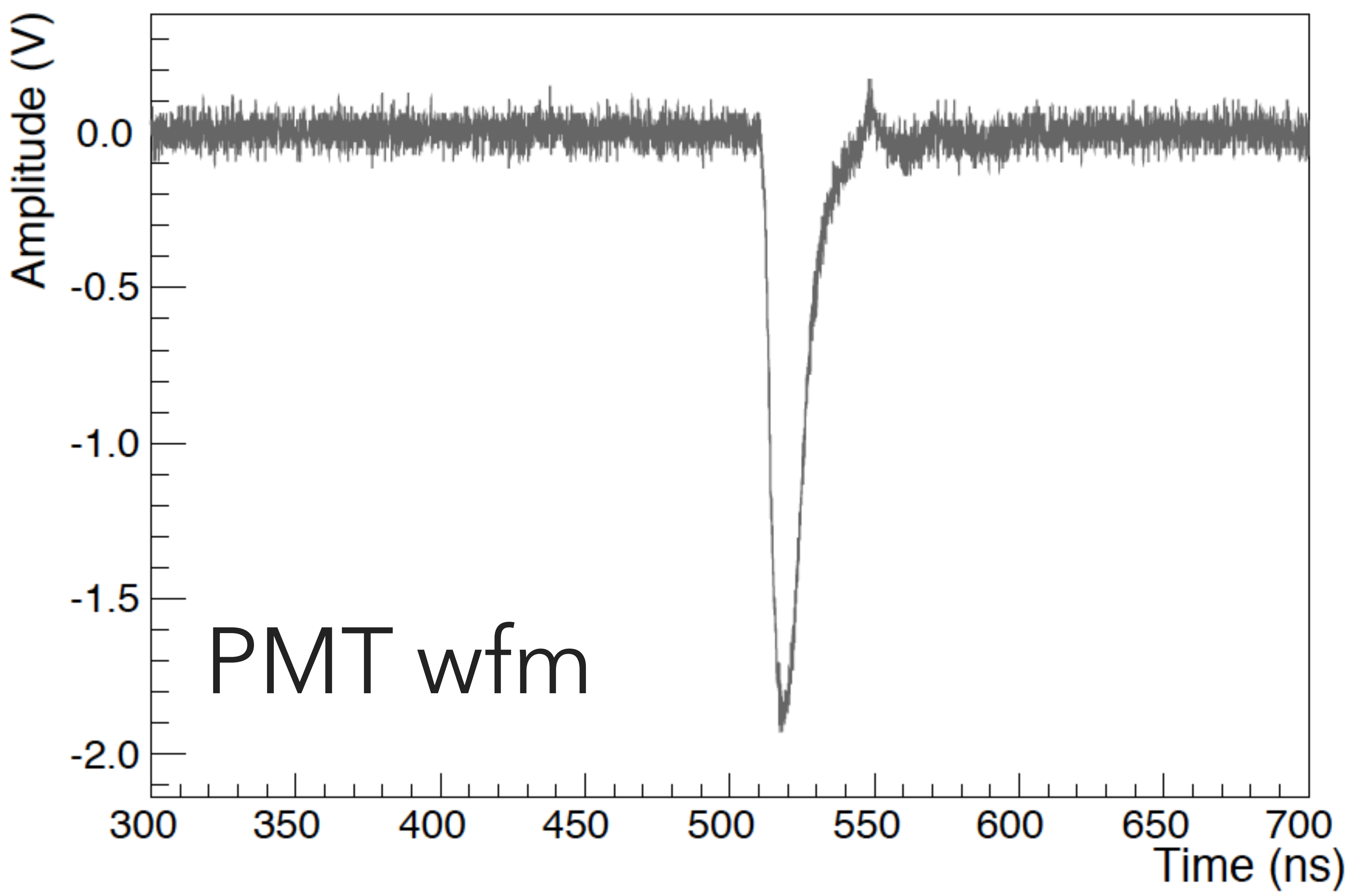
TRIPLE READOUT: CAMERA + PMT + ELECTRIC SIGNAL

CMOS granularity provides useful measurements about **X** and **Y** of the track;

The **Z coordinate** can be extracted from **time measurement** (TPC mode);



https://doi.org/10.1088/1748-0221/13/05/P05001
2018 JINST 13 P05001

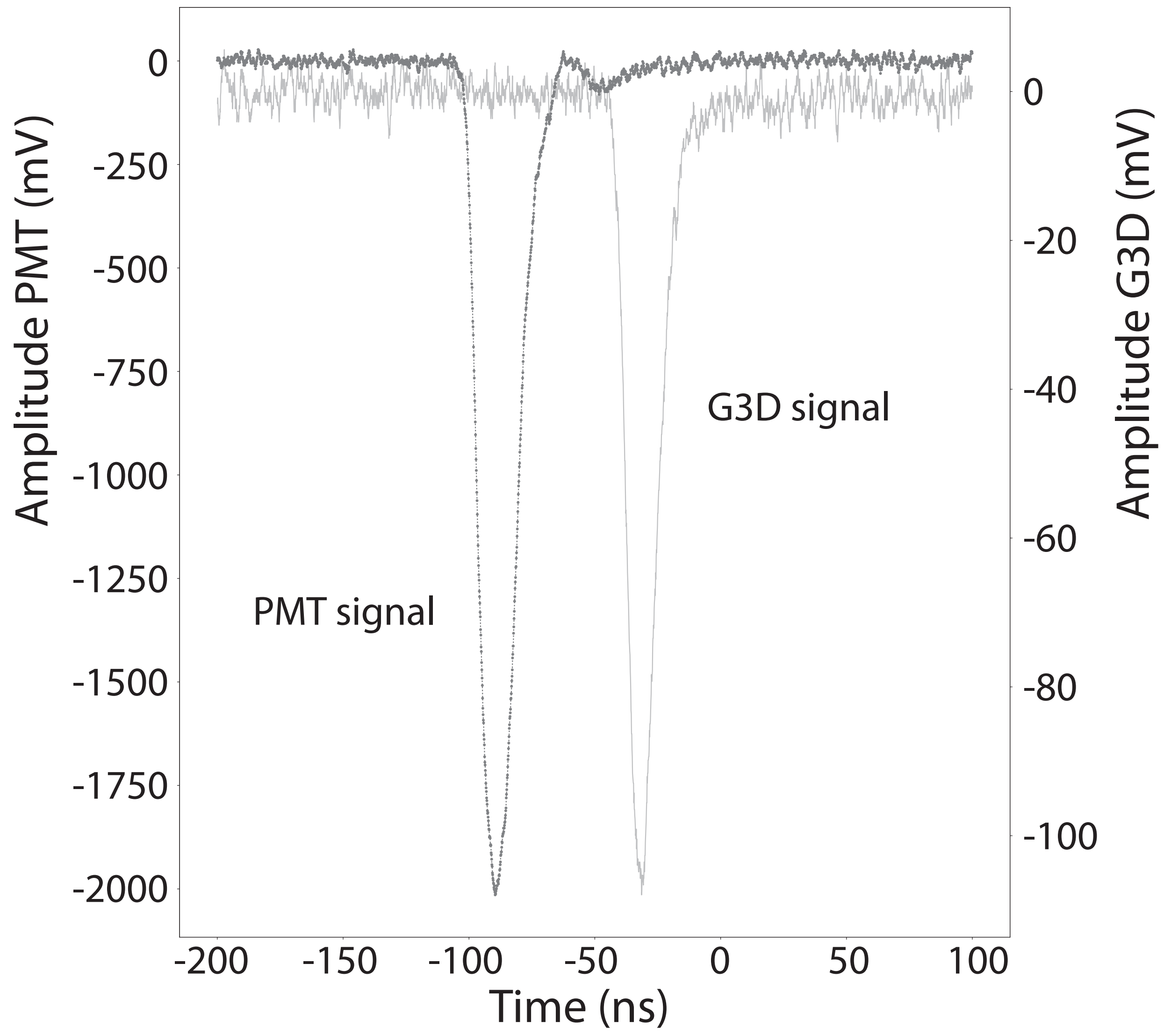


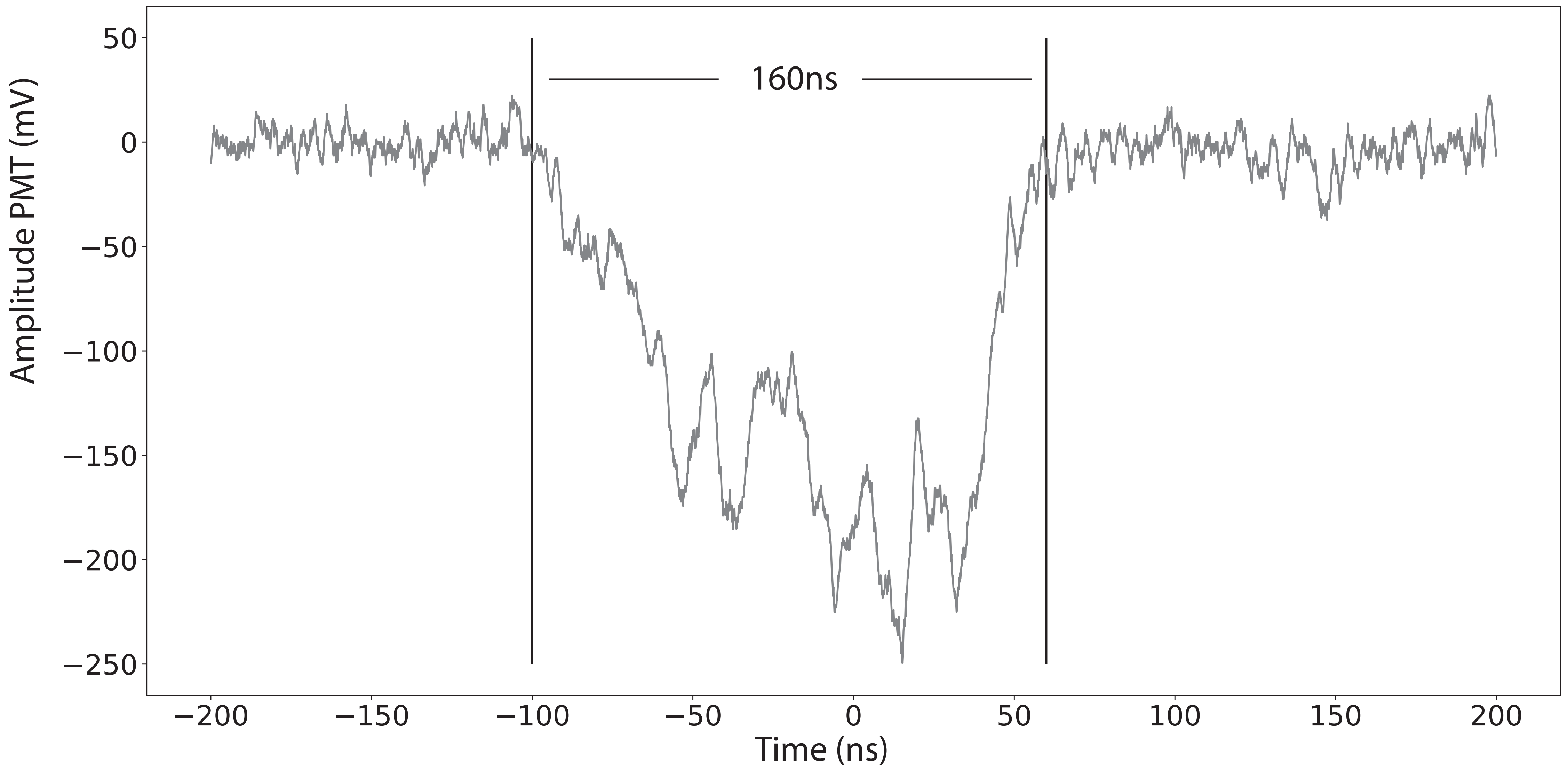
In order to get precise information about the **time structure** of the signal, light can be concurrently readout with a **PMT**;

PMT+GEM COMBINED READOUT

Sensitive gap
parallel to the beam

Sensitive gap **tilted**
w.r.t. the beam

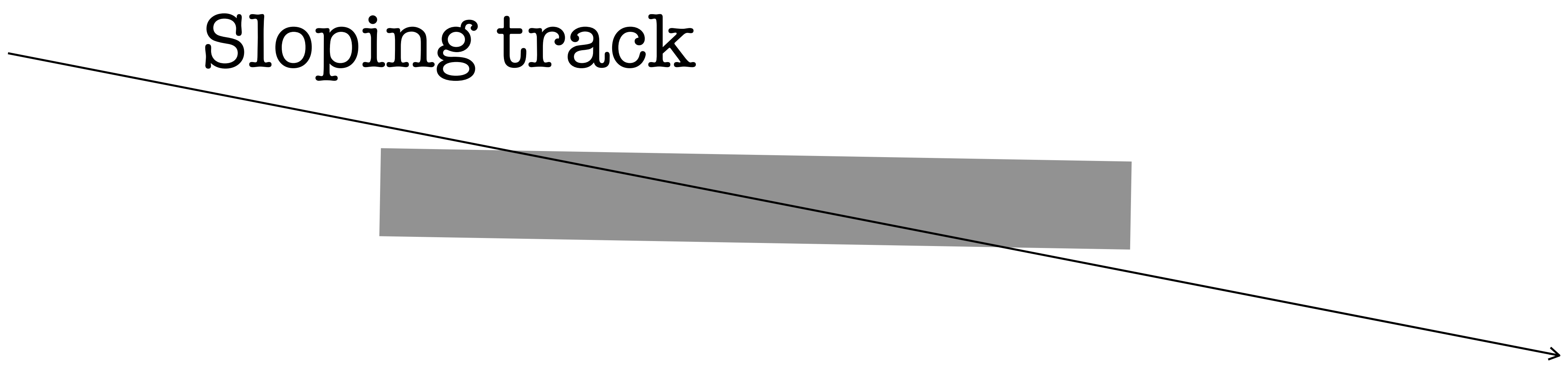




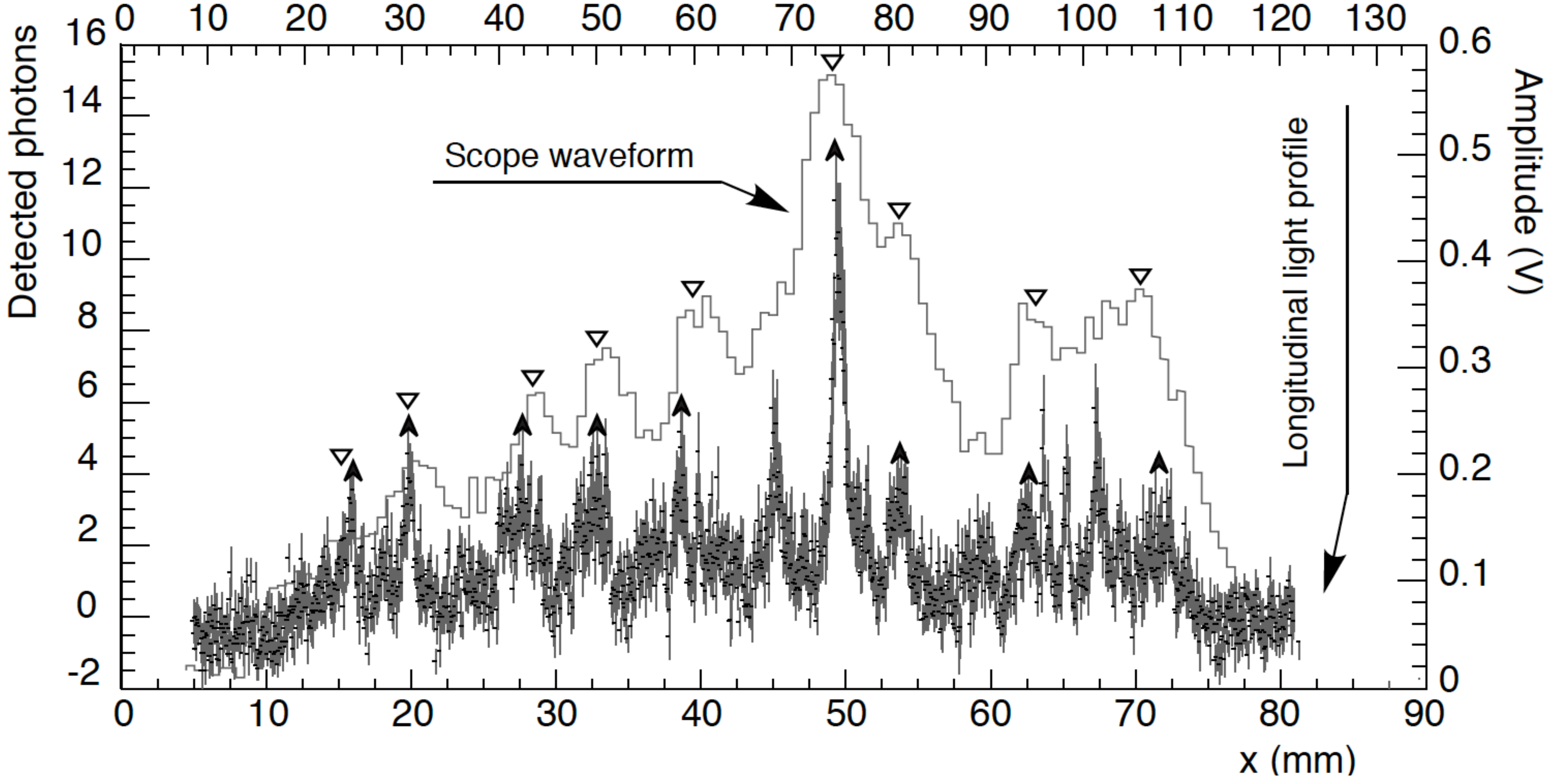
1 cm in 160 ns => drift velocity 6.5 cm/μs in agreement with Garfield expectation of 7.0 cm/μs.

CMOS COMBINED WITH PHOTOMULTIPLIERS

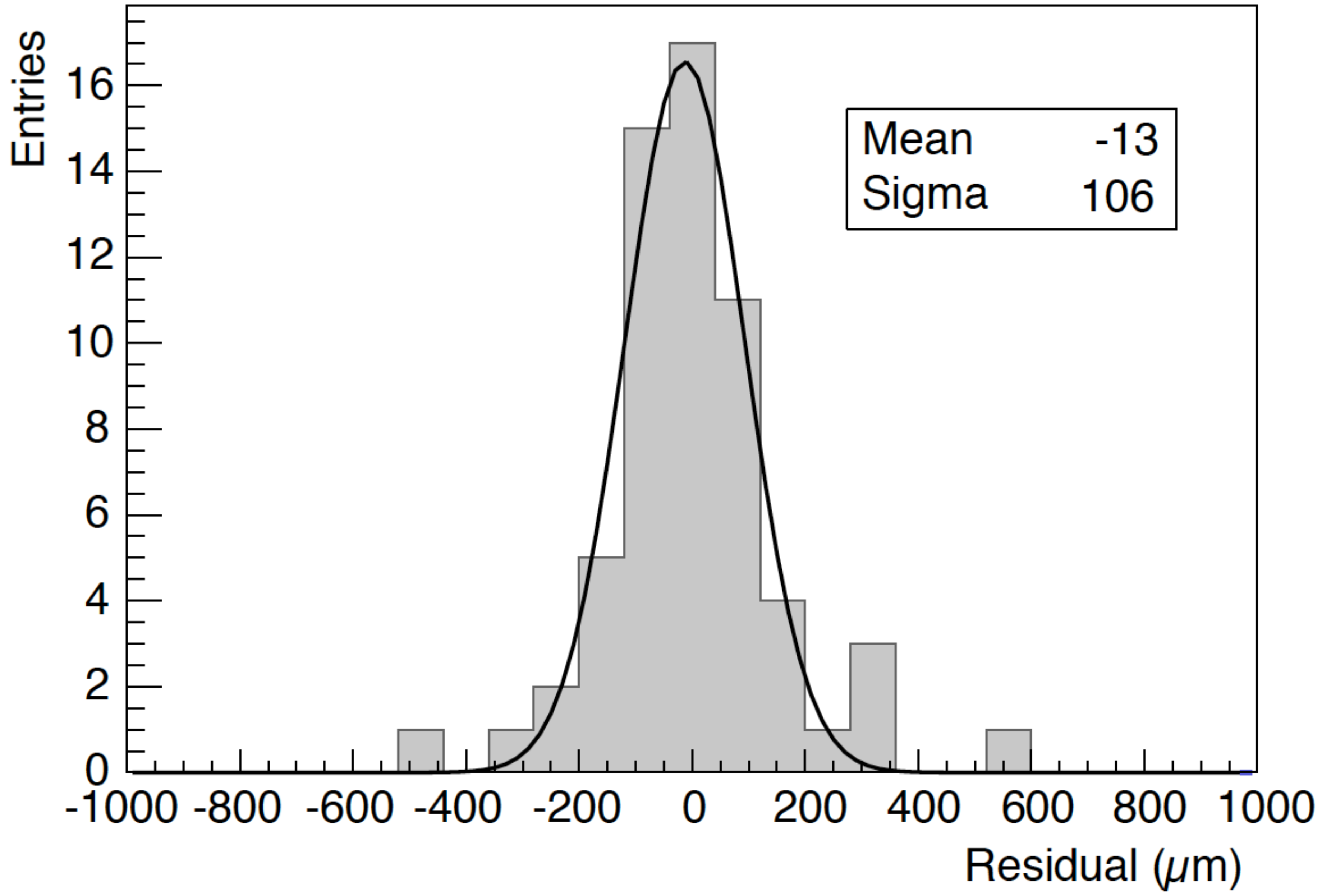
- Fast photosensors (PMTs) to get the time information ⇒ reconstruct z inclination



Antochi et al, 2018 JINST 13 P05001



Time + drift velocity ⇒ relative z coordinate



100 μm resolution on relative cluster **z**

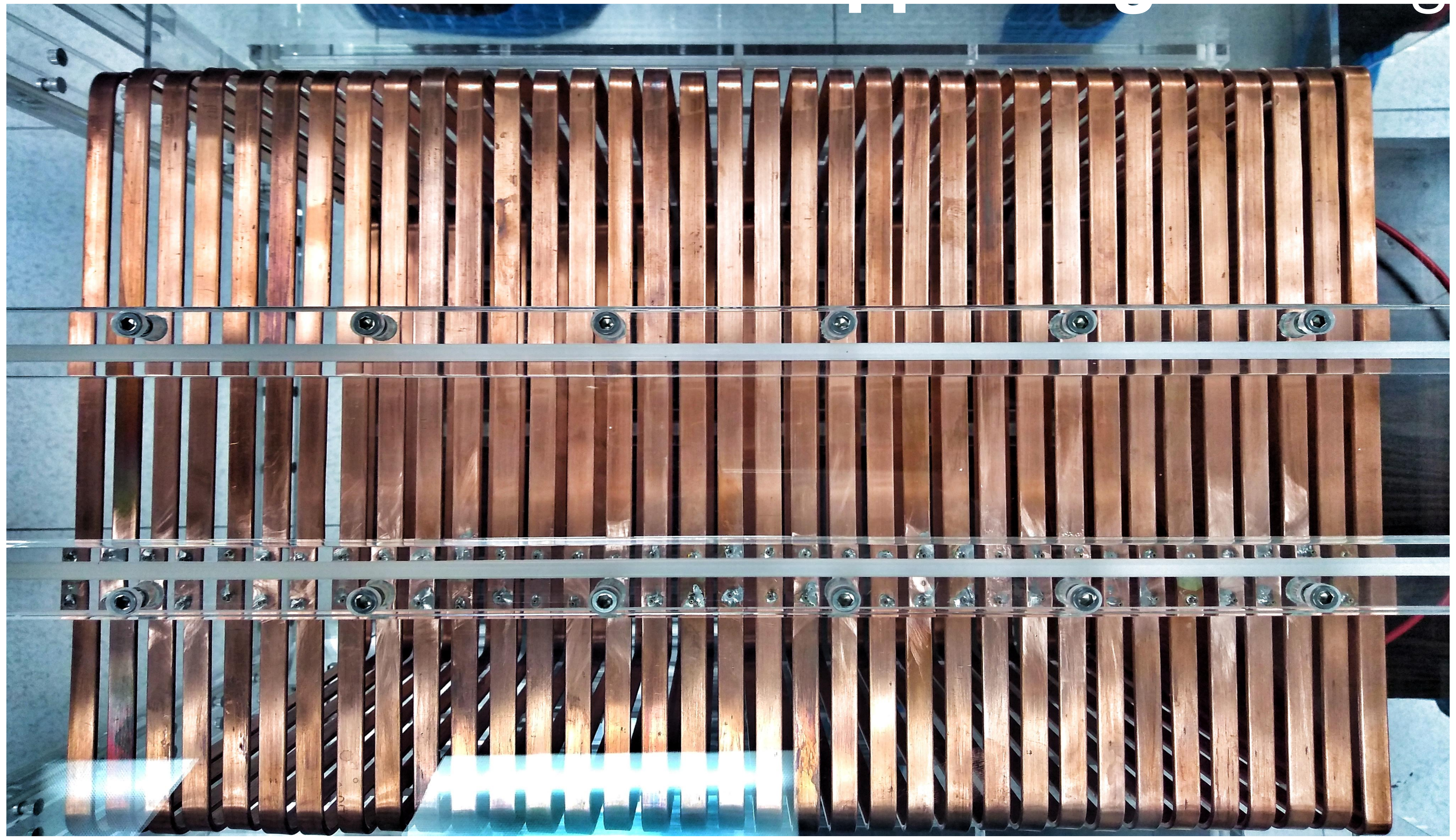
TIME PROJECTION CHAMBERS WITH OPTICAL READOUT (THE EXAMPLE OF THE CYGNO EXPERIMENT[1] PROTOTYPE)

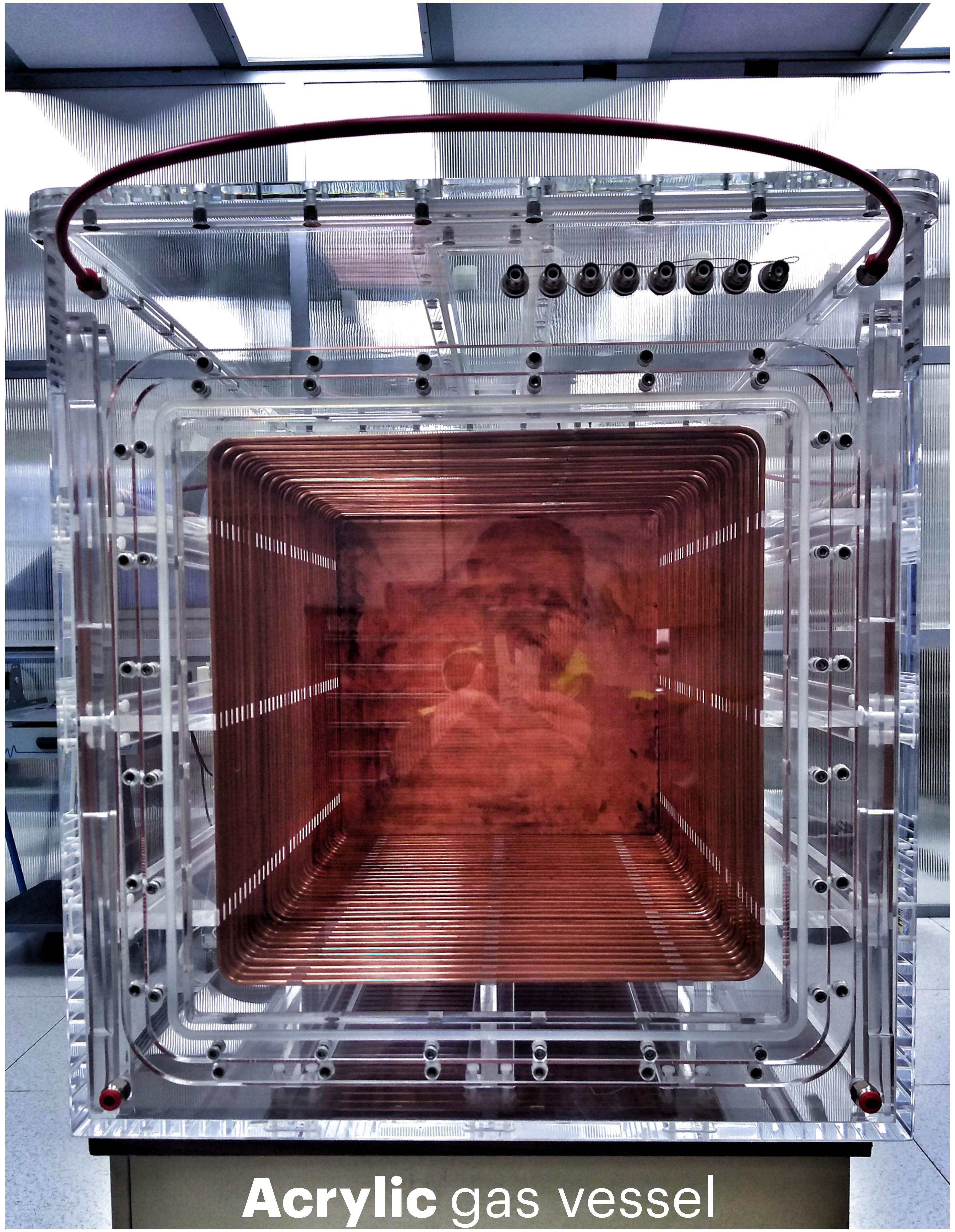
[1] Instruments 6 (2022)

LIME: LARGE IMAGING MODULE

50 litres sensitive volume:

- 33 x 33 ~ 1000 cm^2 GEM surface;
- 50 cm drift path;



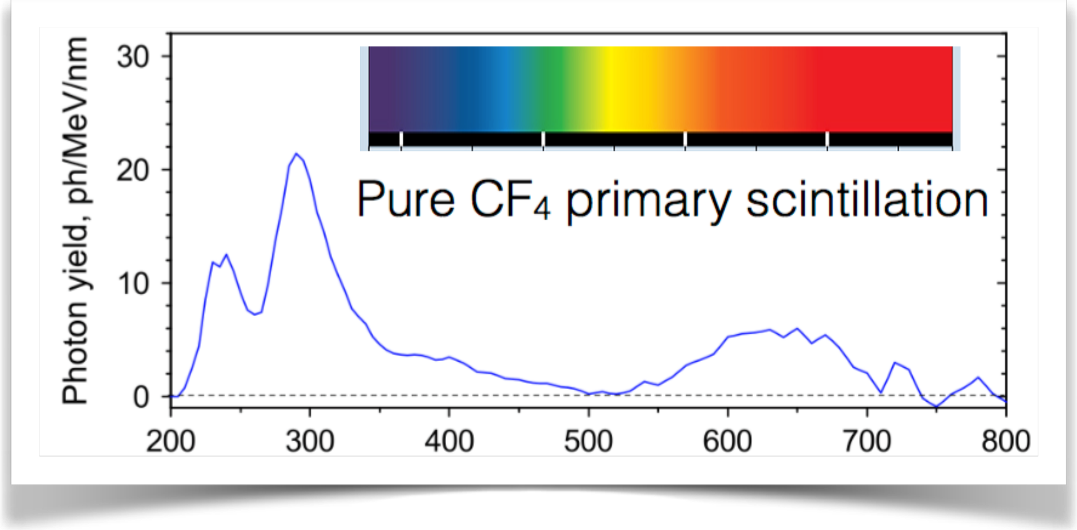


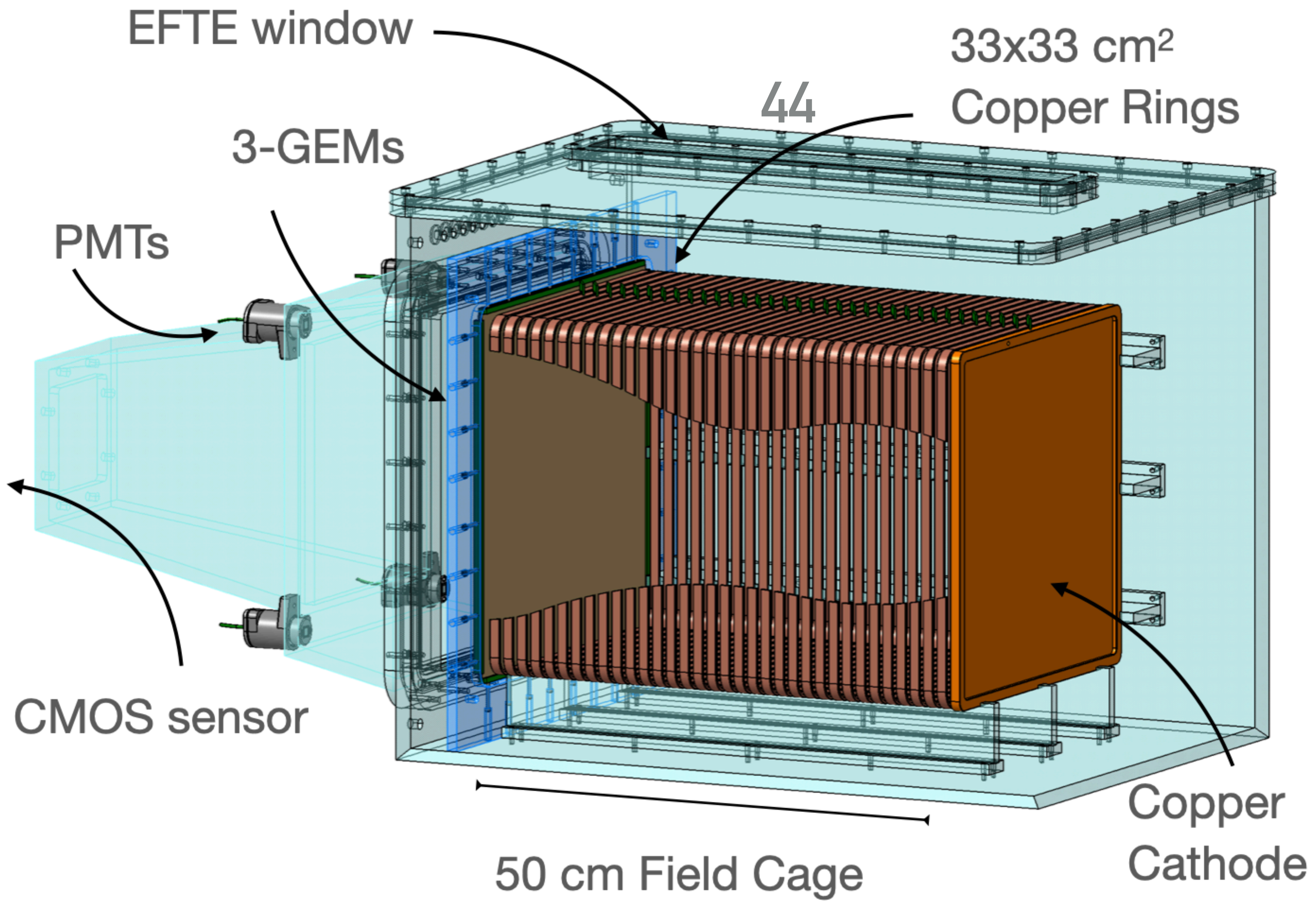
A 50 l Cygno prototype overground characterization

Eur.Phys.J.C 83 (2023) 10, 946

LIME: LARGE IMAGING MODULE

50 litres sensitive volume with an **He/CF_4** based mixture at **atmospheric pressure**

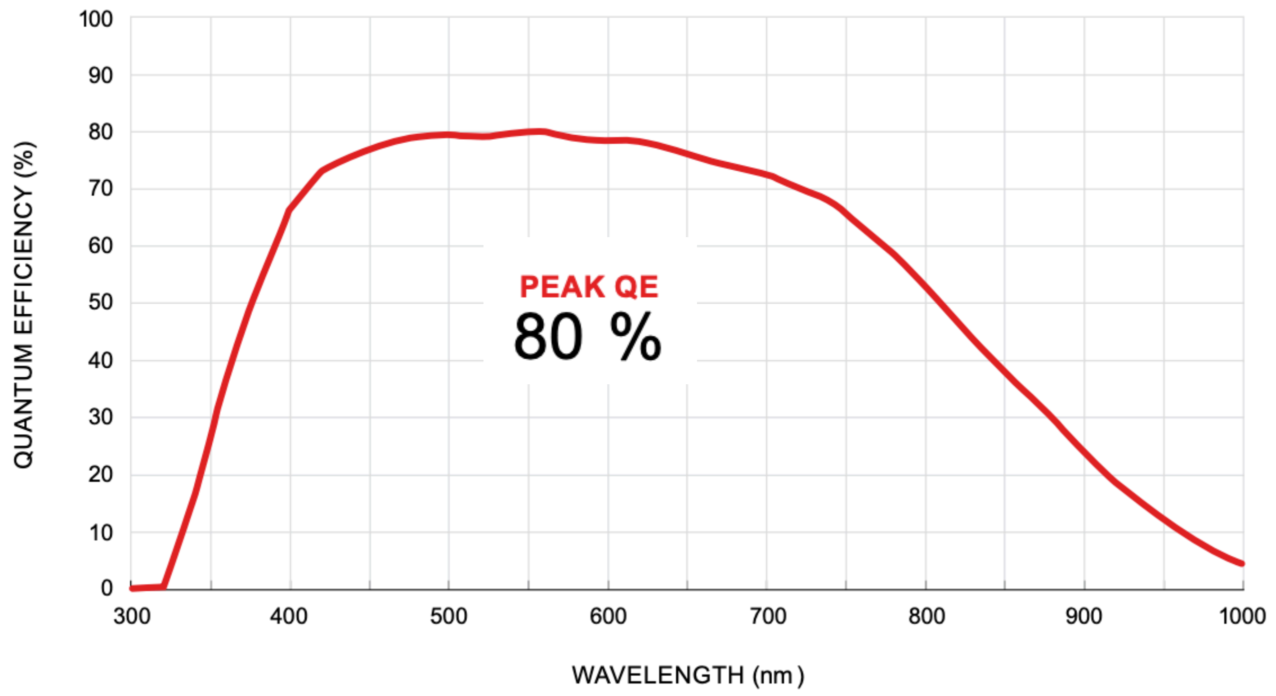




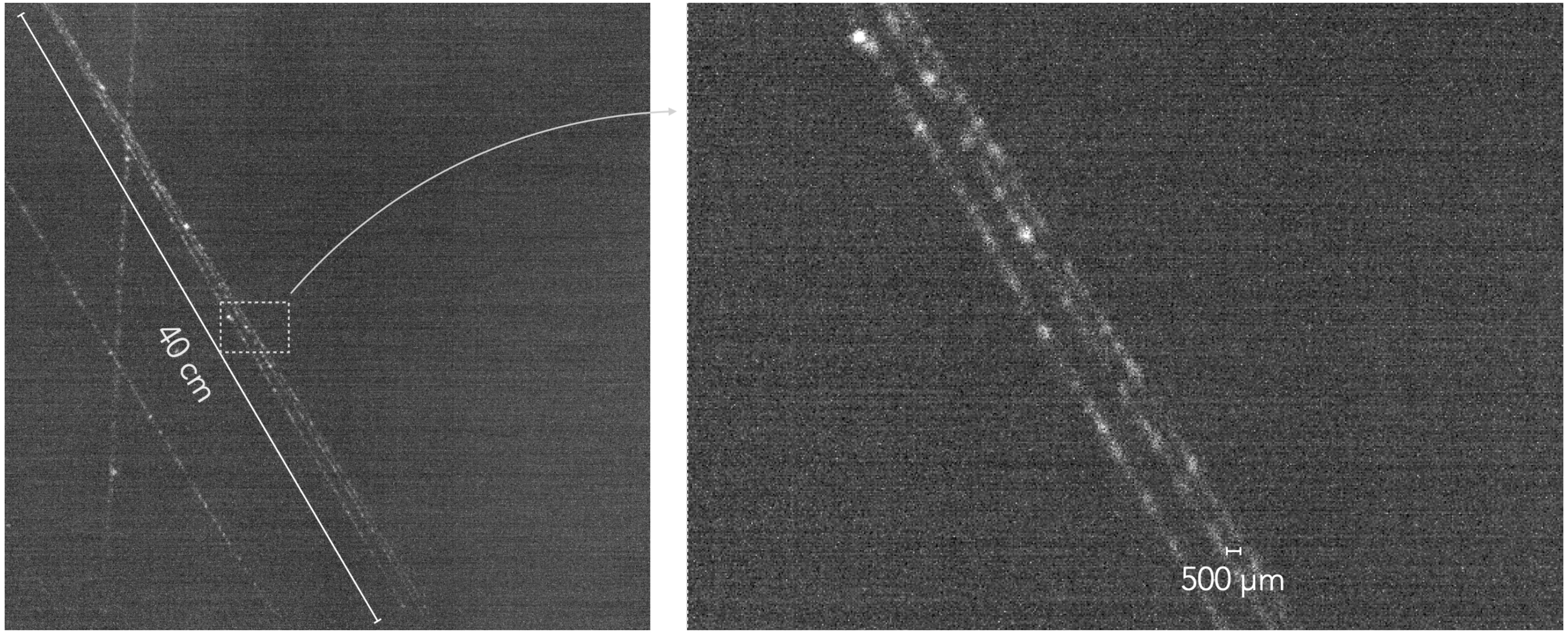
ORCA-Fusion

HIGH RESOLUTION
2304 × 2304
5.3 Megapixels

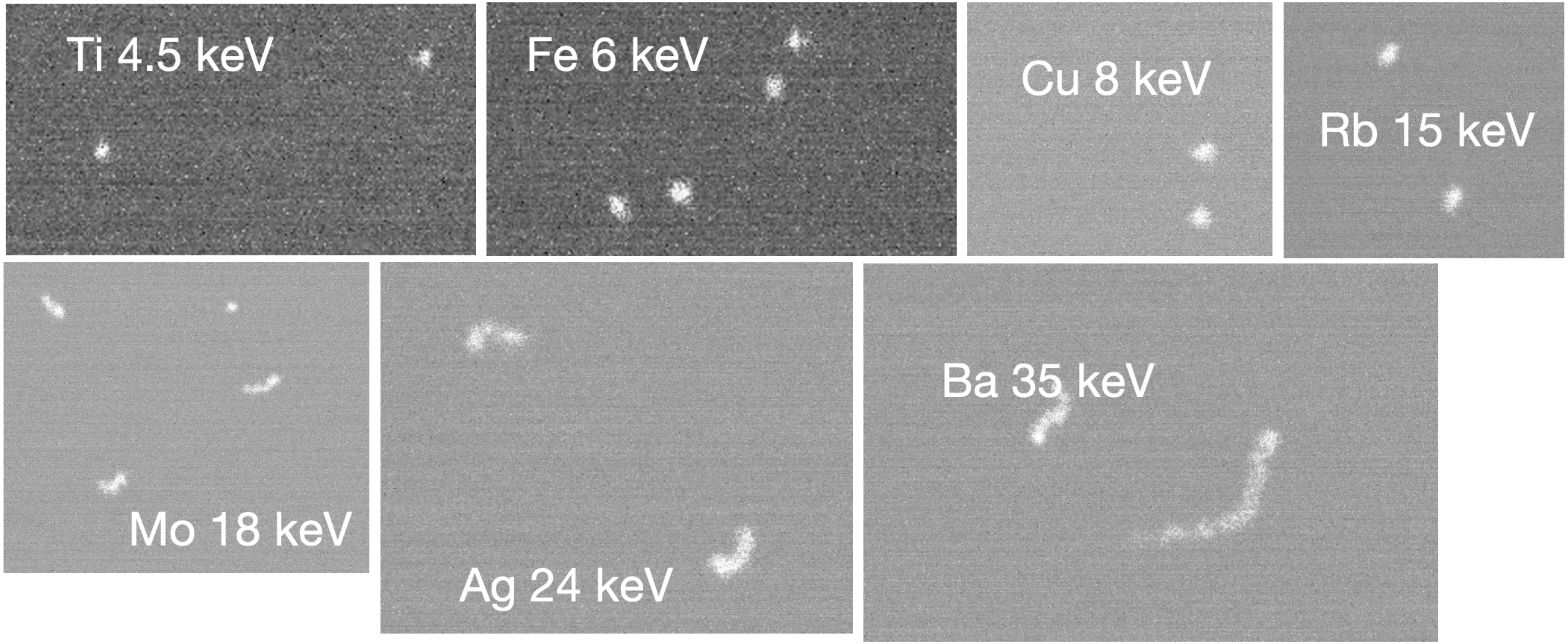
READOUT NOISE
0.7 electrons rms
Ultra-quiet Scan



Example of a few cosmic tracks in LIME (Long Imaging ModulE)



PERFORMANCE WITH LOW ENERGY X RAYS



While below **10 keV signals** are **spot-like**,
electrons with larger energies **travel in gas**.

LIME IN OPERATION IN THE GRAN SASSO TUNNEL

LIME is now in operation in the Gran Sasso Tunnel to take data in low radiation conditions

Run 1 (no shield)

Dominated by external background,
expected background rate ~ 36 ev/s

Run 2 (4 cm Cu)

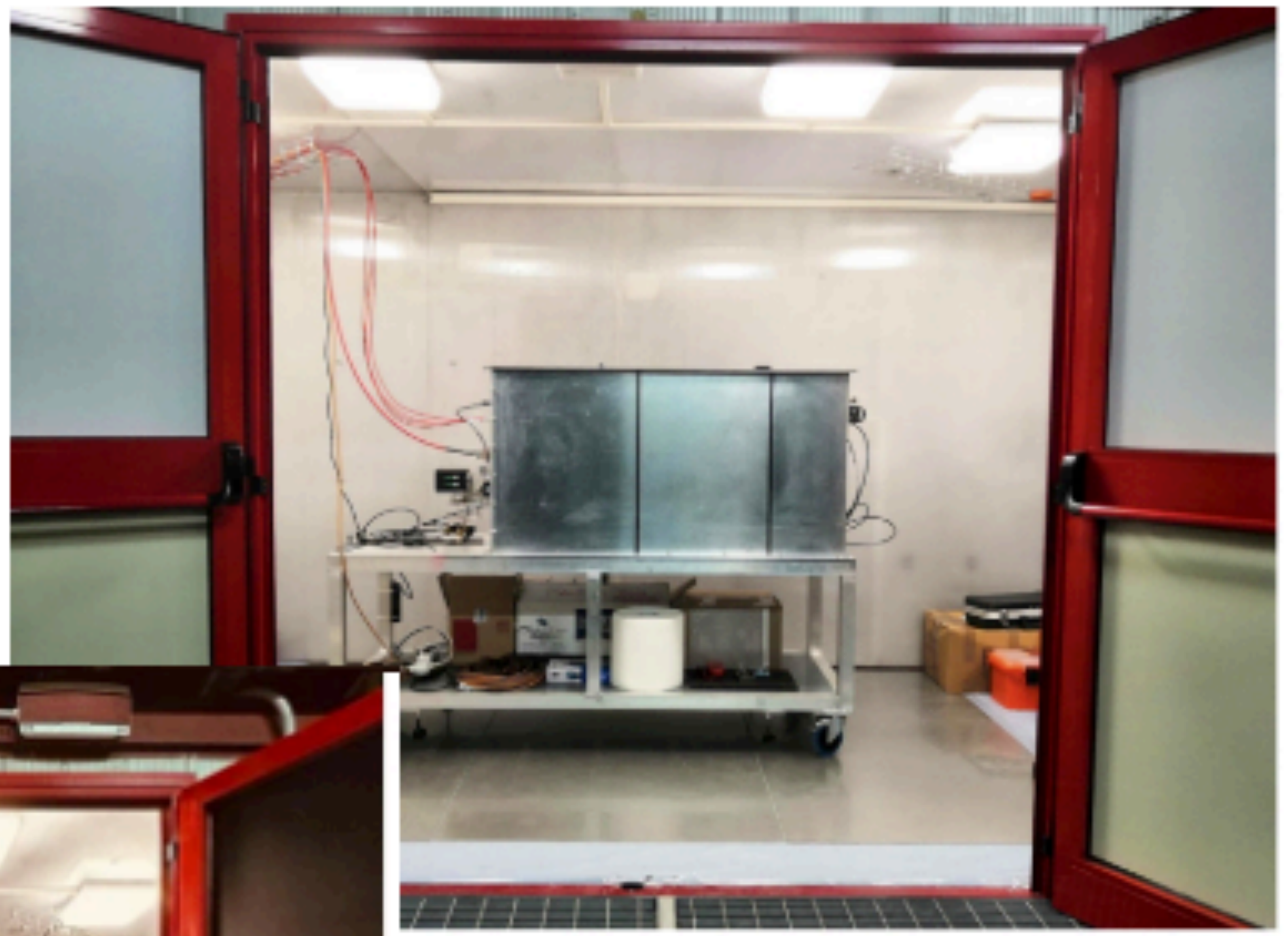
Start to probe internal background,
expected background rate ~ 1.1 ev/s

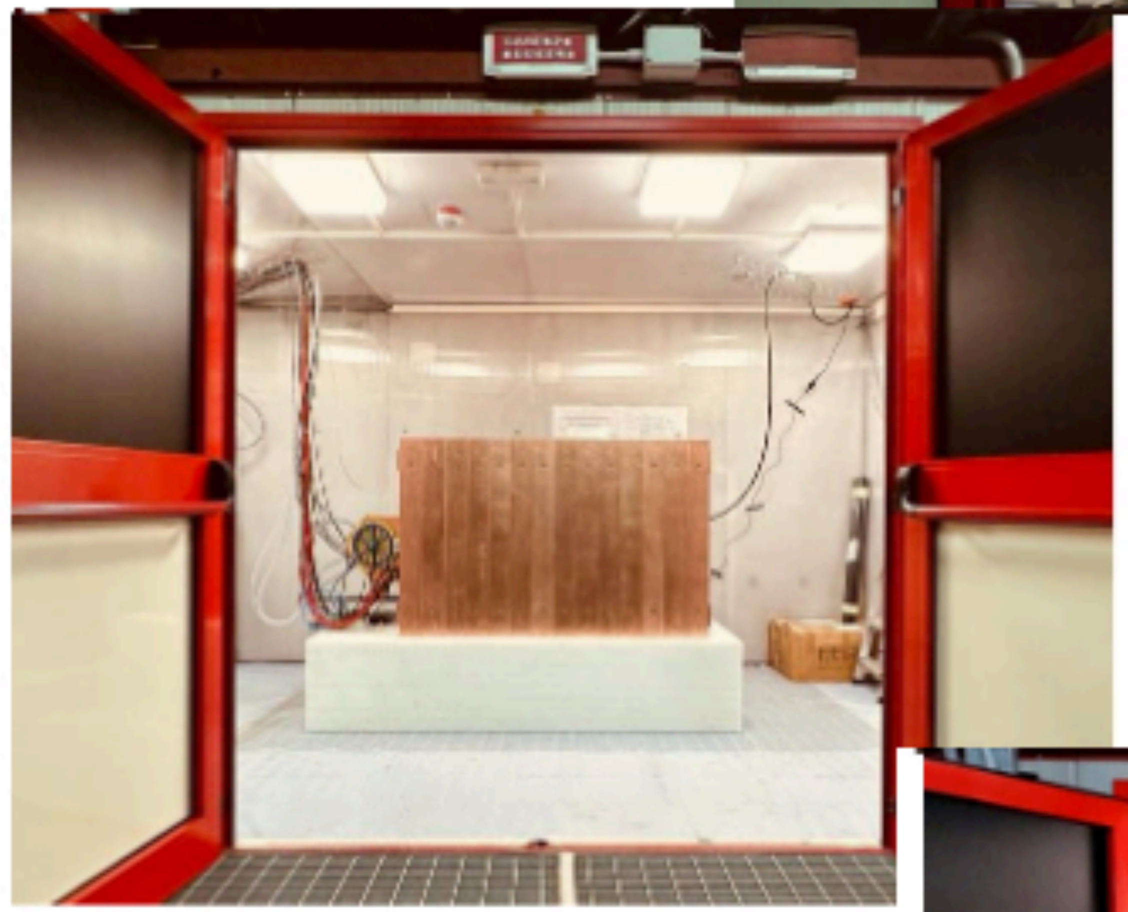
Run 3 (10 cm Cu) + AmBe

Mostly internal background,
expected background rate ~ 0.29 ev/s

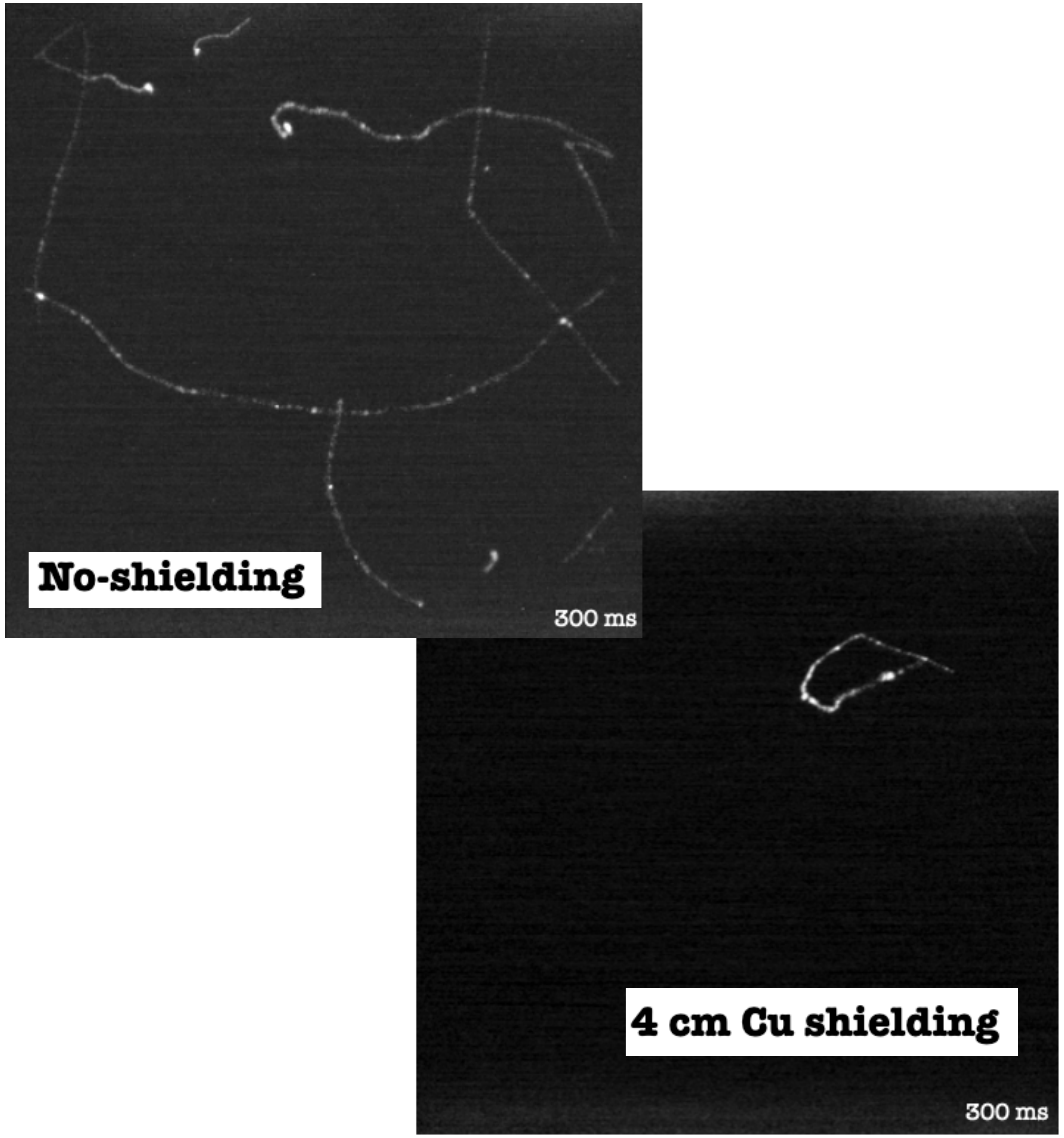
Run 4 (10 cm Cu + 40 cm H_2O)

Dominated by internal background,
expected background rate ~ 0.27 ev/s

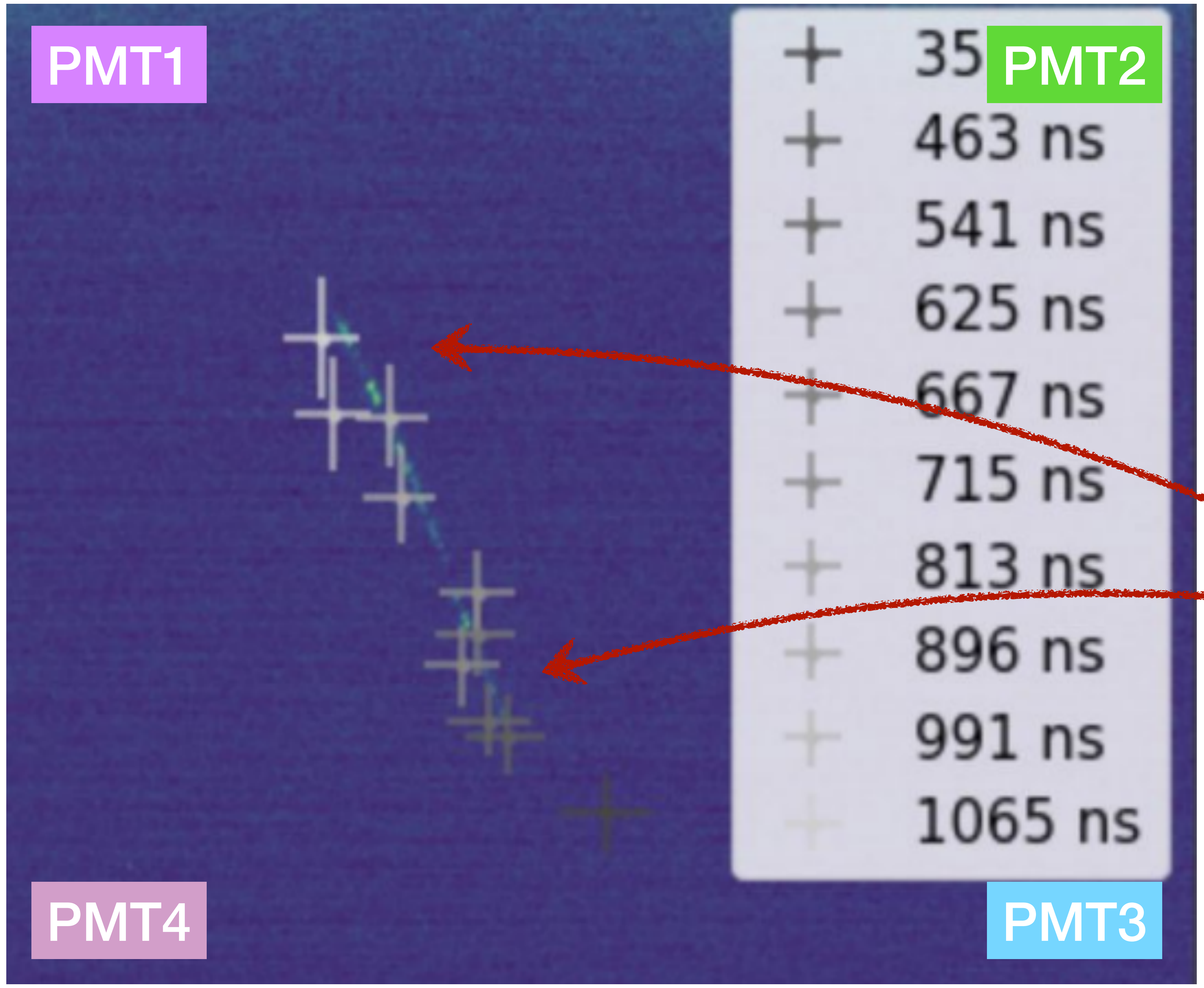




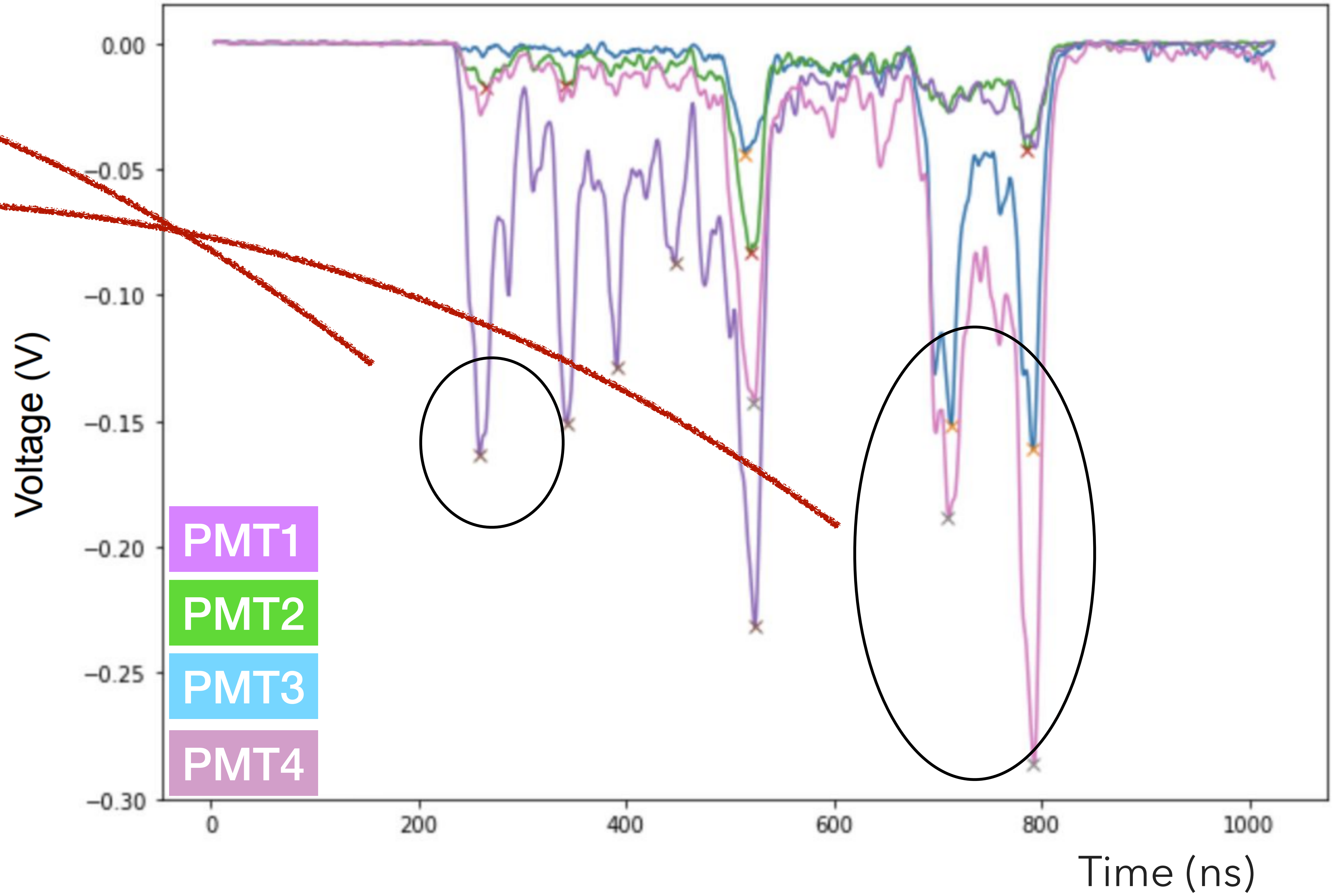
LIME IN OPERATION IN THE GRAN SASSO TUNNEL



DOUBLE READOUT



Since the PMT are placed **close** the **GEM corners**, the **sharing** of the **light** changes among them accordingly to the **track position**



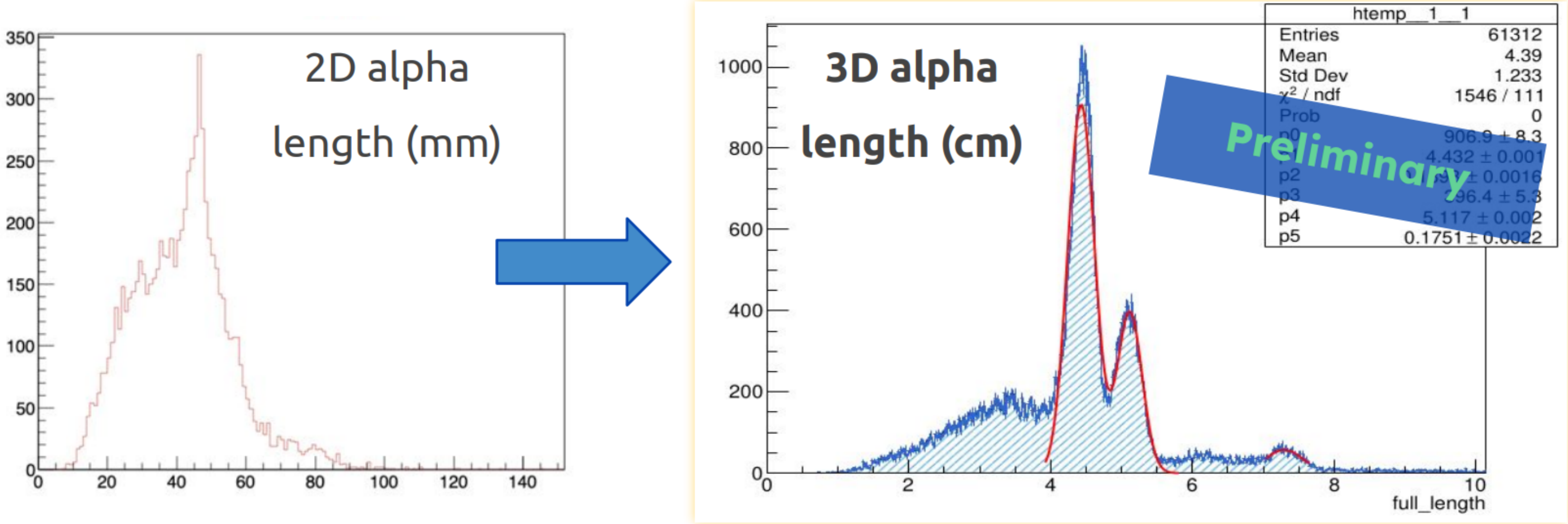
Track starts close to PMT1 ends

ends between PMT3 and PMT4

A relative **z** can be **assigned** to each **subpart** of the **tracks**

DOUBLE READOUT: TEST ON RADON ALPHAS

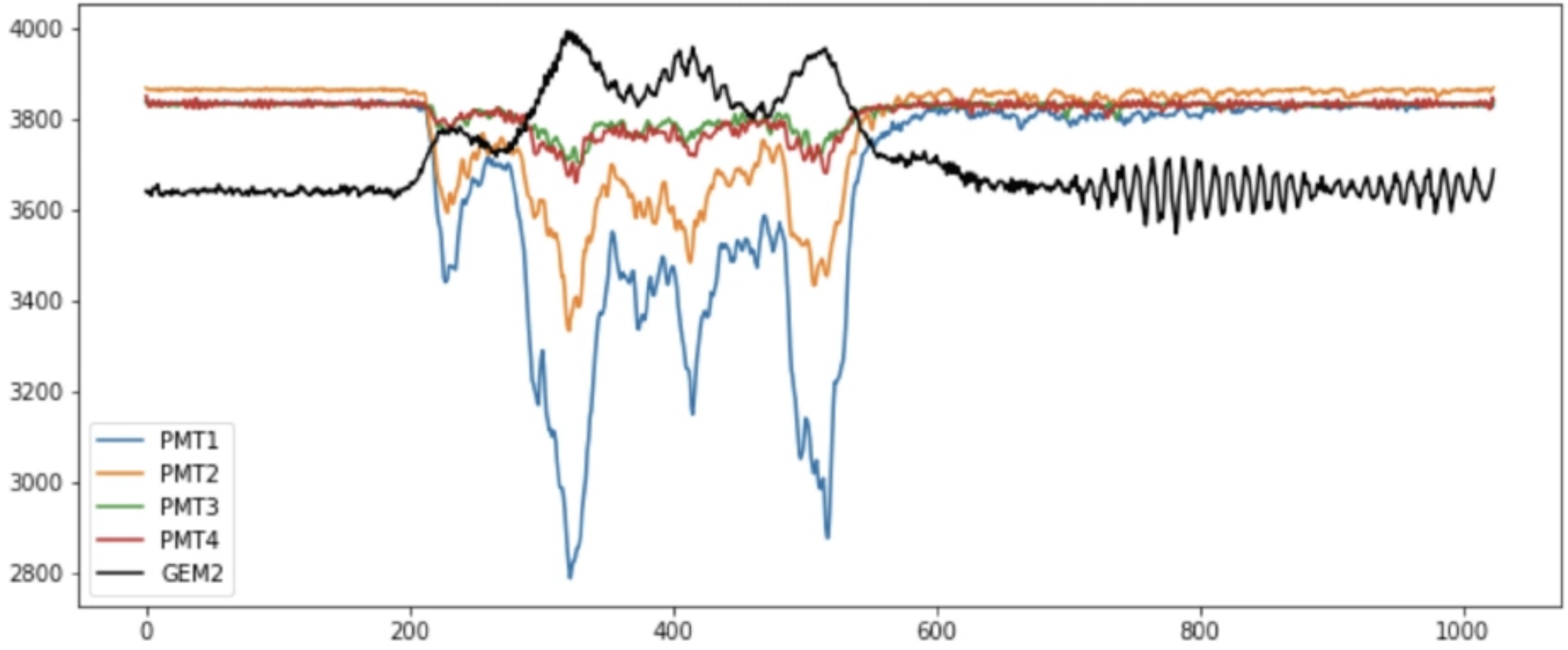
- A **Radon** contamination would produce **3 alphas**: ^{222}Rn (5.590 MeV ~ 43 mm), ^{218}Po (6.115 MeV ~ 50 mm) and ^{214}Po (7.833 MeV ~ 73 mm)



- The combined use of CMOS-sensor and PMT allows to evaluate the 3D length of the tracks and

TRIPLE READOUT

The waveforms of the **electrical signal** is registered for **each GEM**;



PMT waveforms

Electrical signal on GEM

While **PMT waveforms** depend on the position of each track segment, the waveform of the electrical signal is position independent:

- **cross-check** for **total energy**
- **position reconstruction**

CONCLUSION: ADVANTAGES OF OPTICAL READOUT

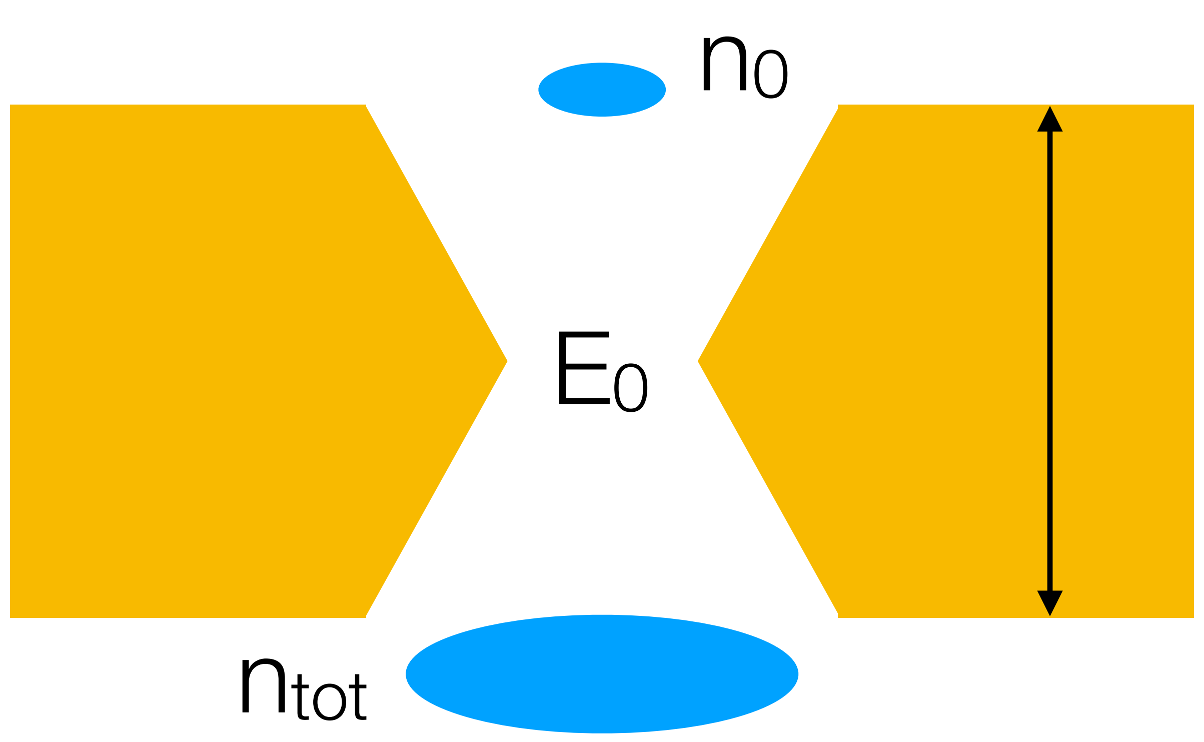
- optical sensors are able to provide **high granularities** along with very **low noise** level and **high sensitivity** allowing to reconstruct very detailed information about the track and its topology:
    - total energy release;
    - length;
    - direction;
    - slimness;
    - energy release distribution (dE/dx);
- combining **with PMTs**, a 3D reconstruction is in principle possible;
- optical coupling allows to **keep sensor out** of the sensitive volume (no interference with HV operation and lower gas contamination);
- suitable lens allow to **acquire large surfaces** with small sensors;

DISADVANTAGES OF OPTICAL READOUT GASEOUS DETECTORS:

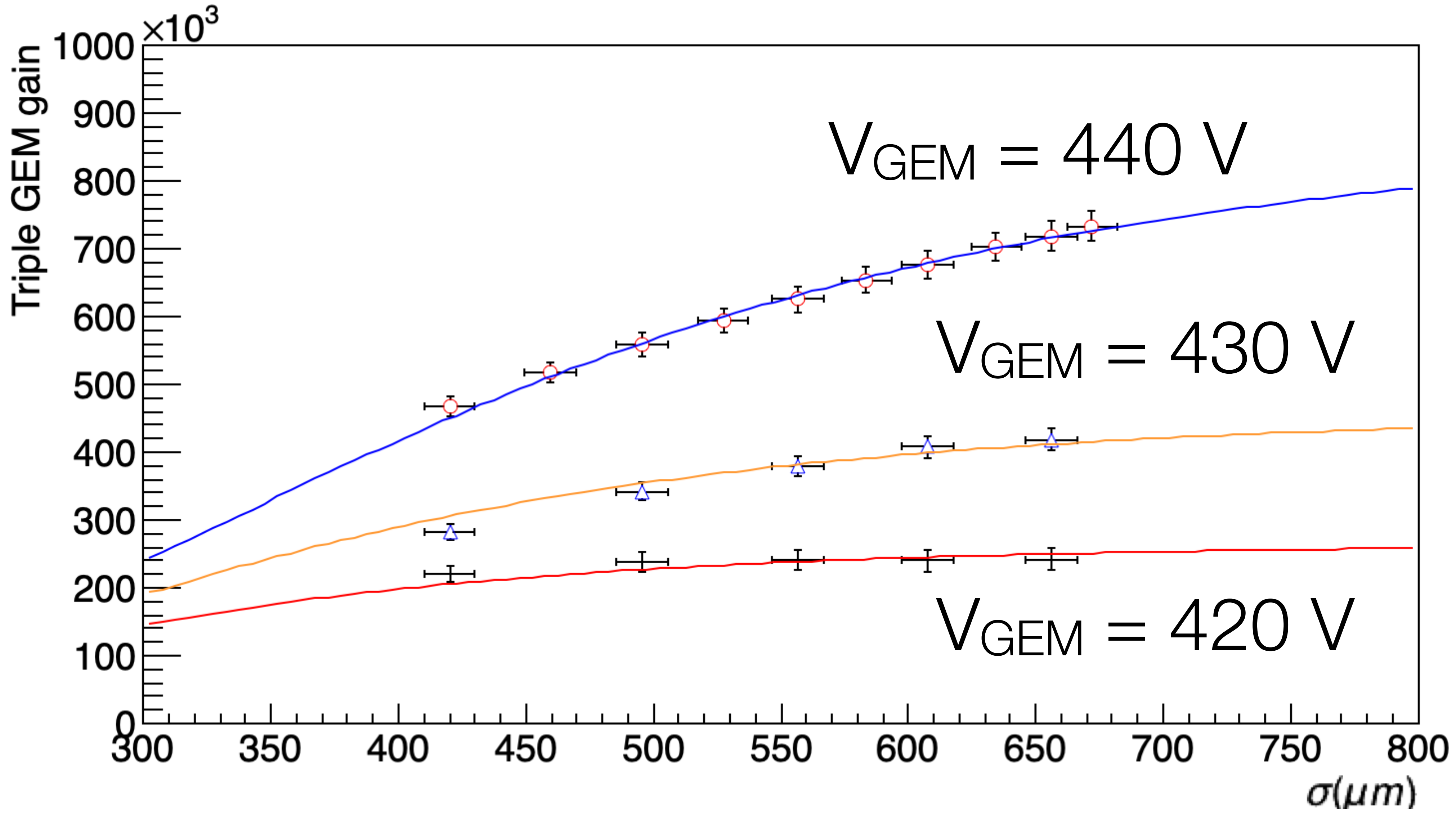
NON-LINEARITY OF THE GEM RESPONSE

NON-LINEARITY OF THE GEM RESPONSE

Because of the large gain needed, during the development of the avalanche within the GEM multiplication channels a significant amount of electrons and positive ions are produced that can partially shield the electric field and “dump” the avalanche



The GEM gain is not constant, but a function of the charge density



Multiplication is described by a modified Townsend equation

$$\frac{dn}{ds} = \alpha E_0(1 - \beta n)n$$

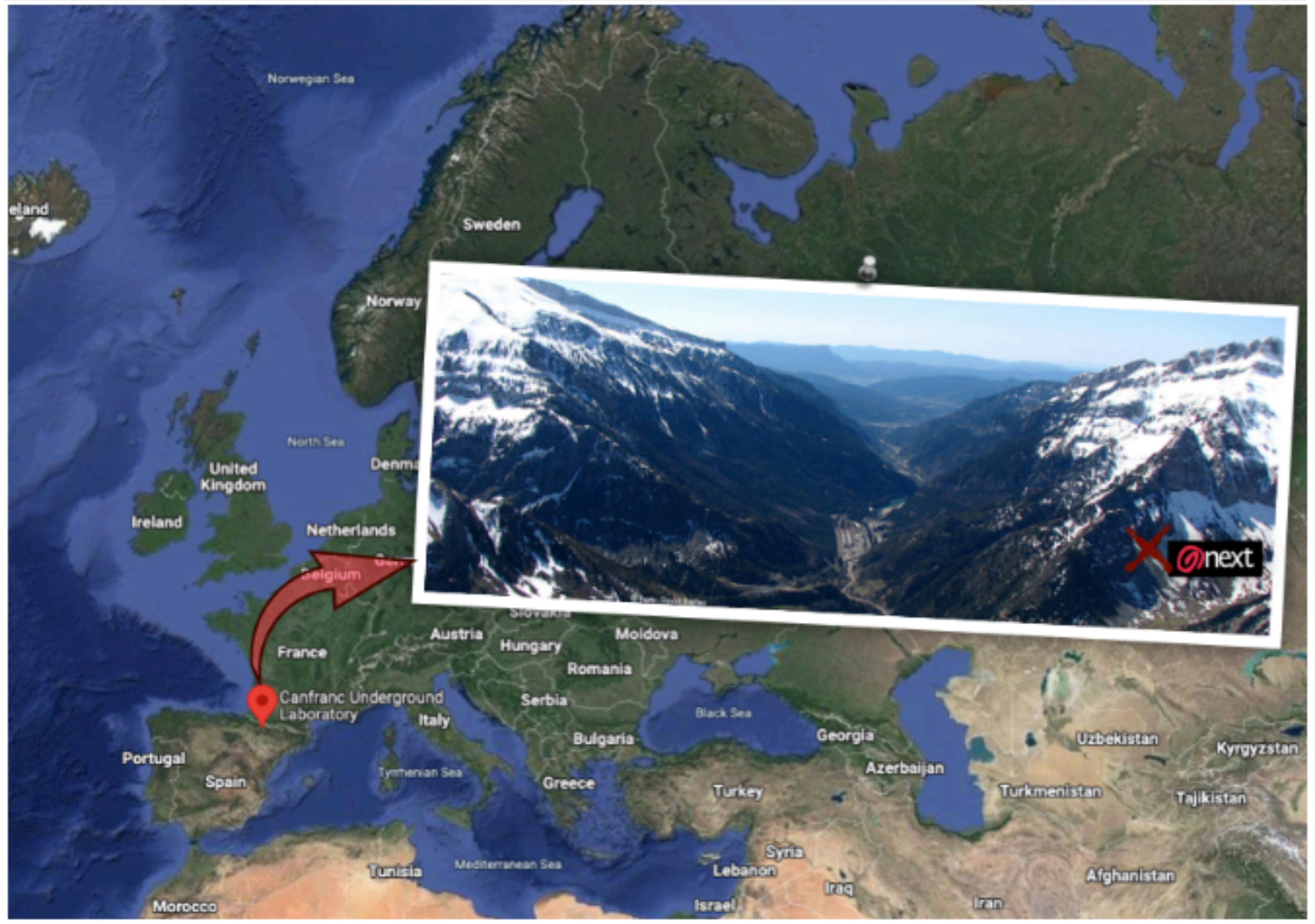
Single-GEM effective gain can be described as

$$G = \frac{ce^{\alpha V_{GEM}}}{1 + \beta n_0(ce^{\alpha V_{GEM}} - 1)}$$

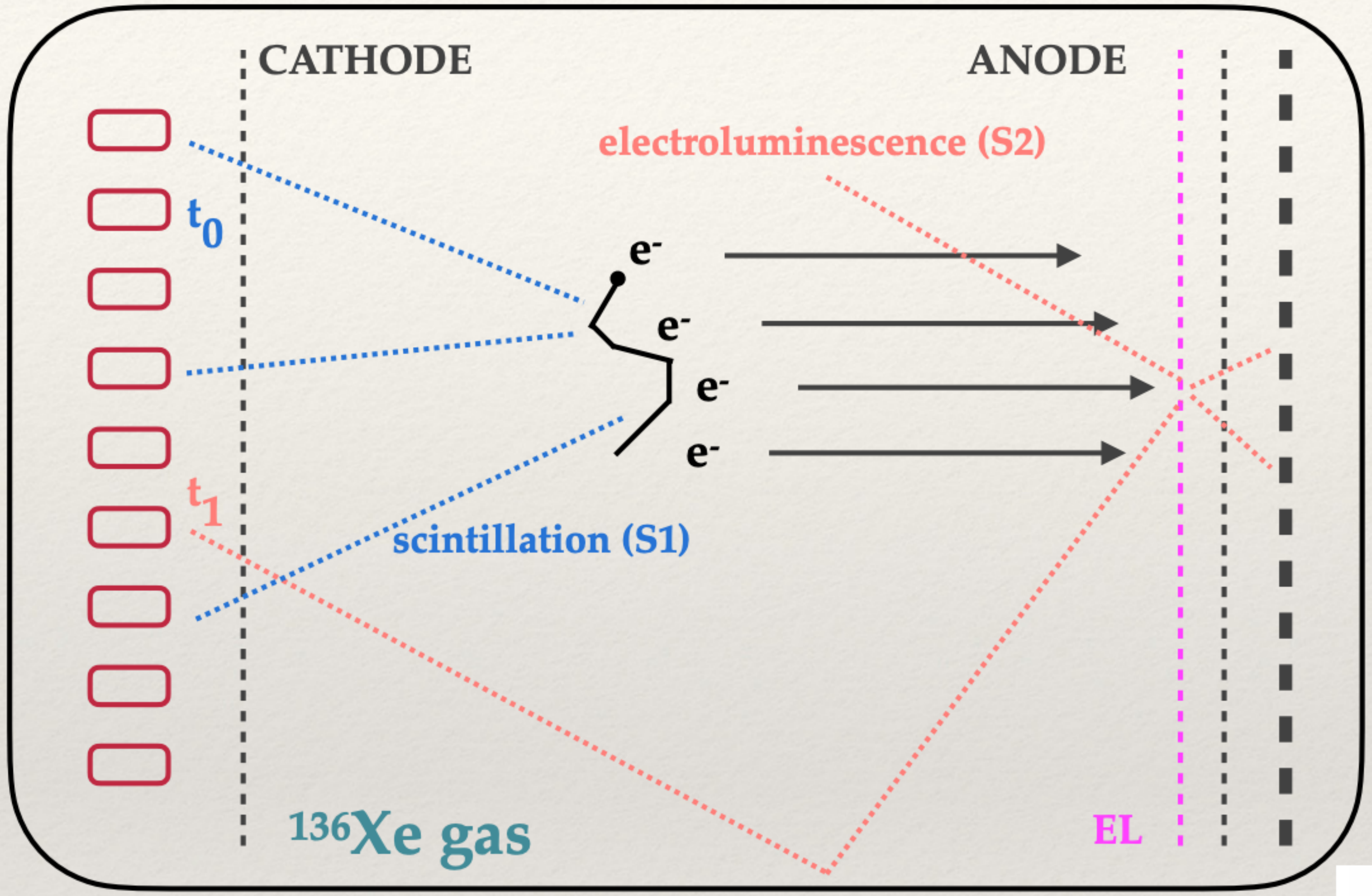
- if $n_0 \ll n_{eq} \rightarrow \beta n_0 \simeq 0$ negligible screen effect;
- if $n_0 \simeq n_{eq} \rightarrow \beta n_0 \simeq 1$ i.e. total screen effect;

OTHER EXAMPLES OF COMBINED – HYBRID READOUT

THE NEXT EXPERIMENT



Energy plane (PMTs)



Tracking plane (SiPMs)

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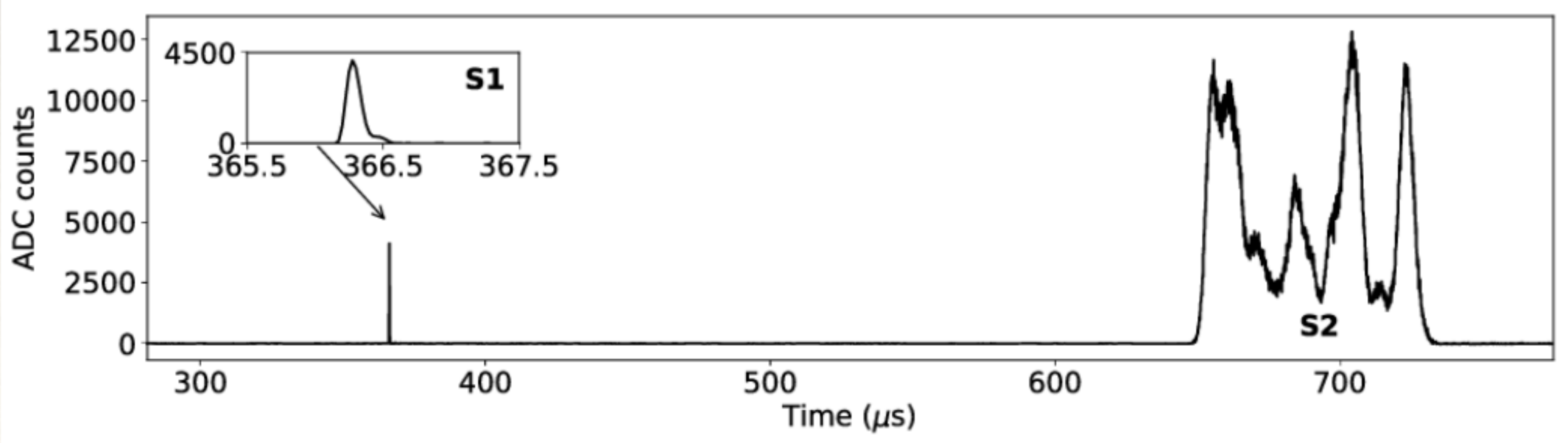
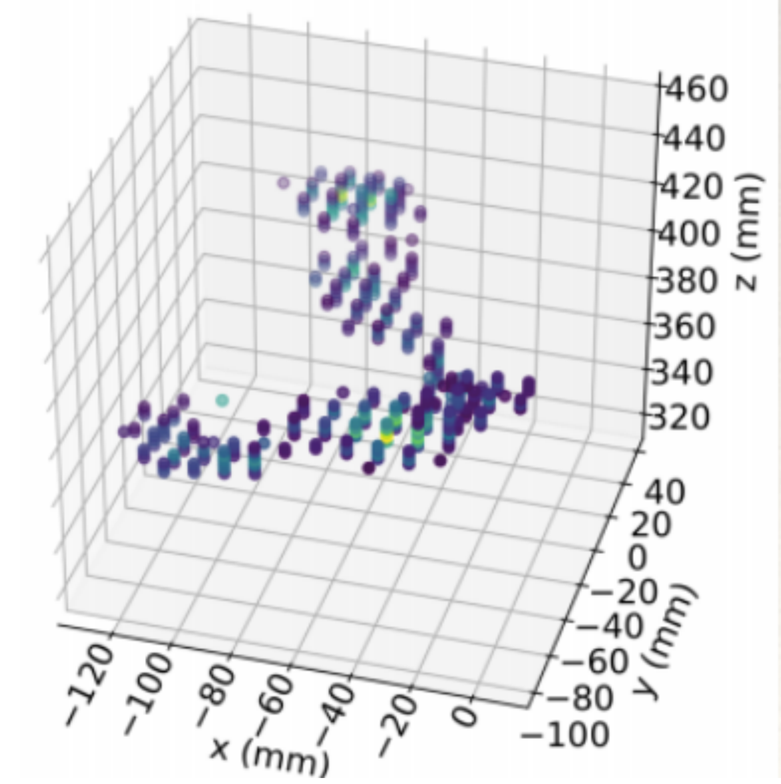
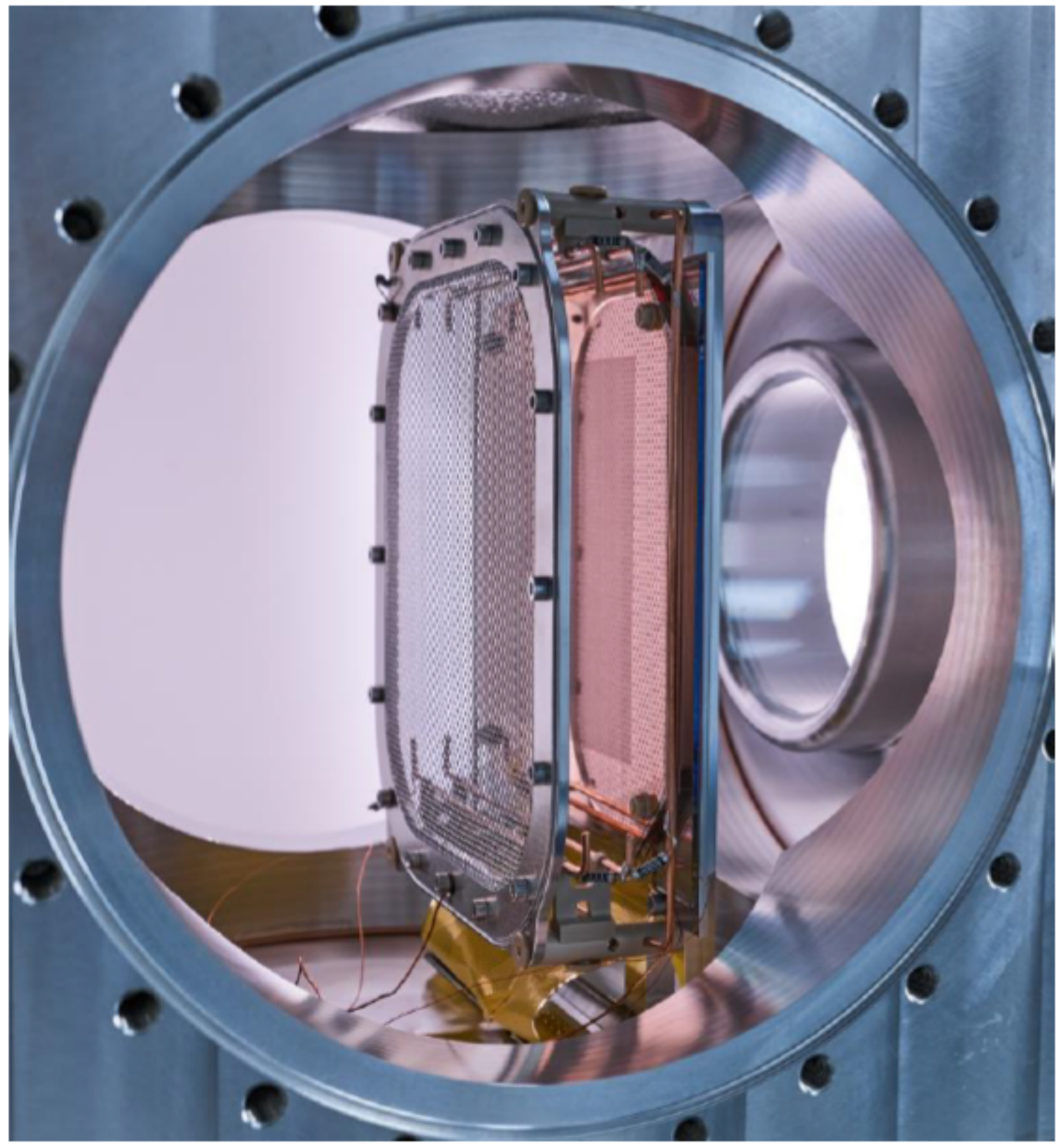
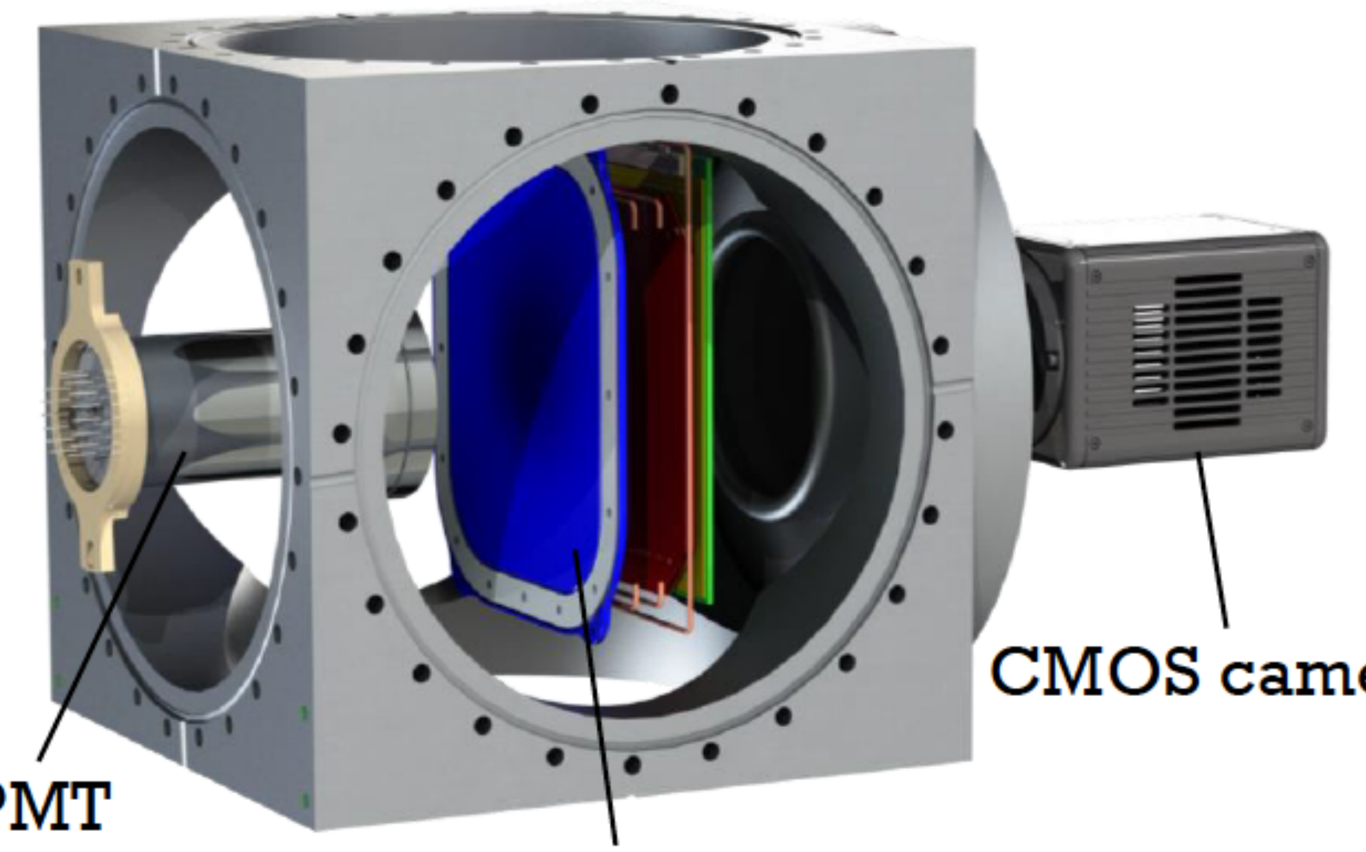




The MIGDAL optical-TPC

MIGDAL
Migdal In Galactic Dark mAtter expLoration

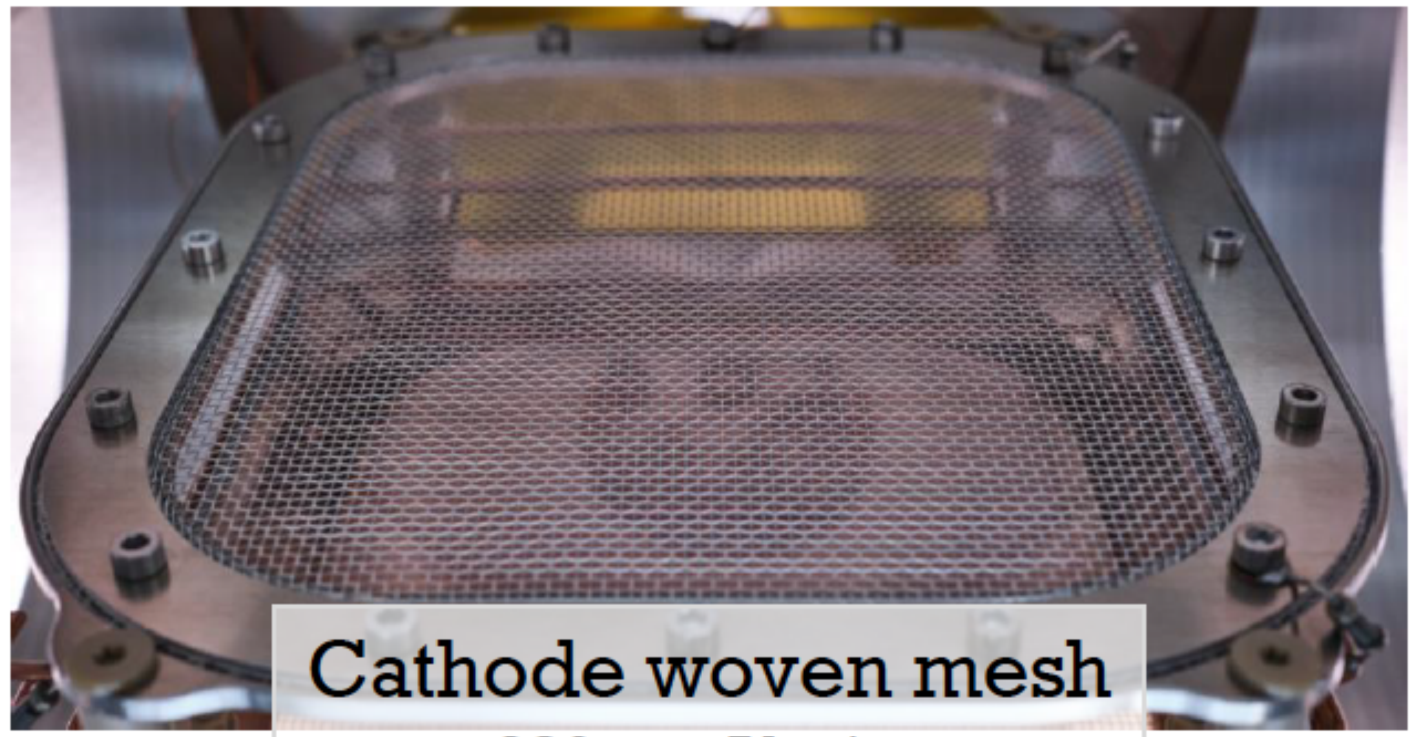




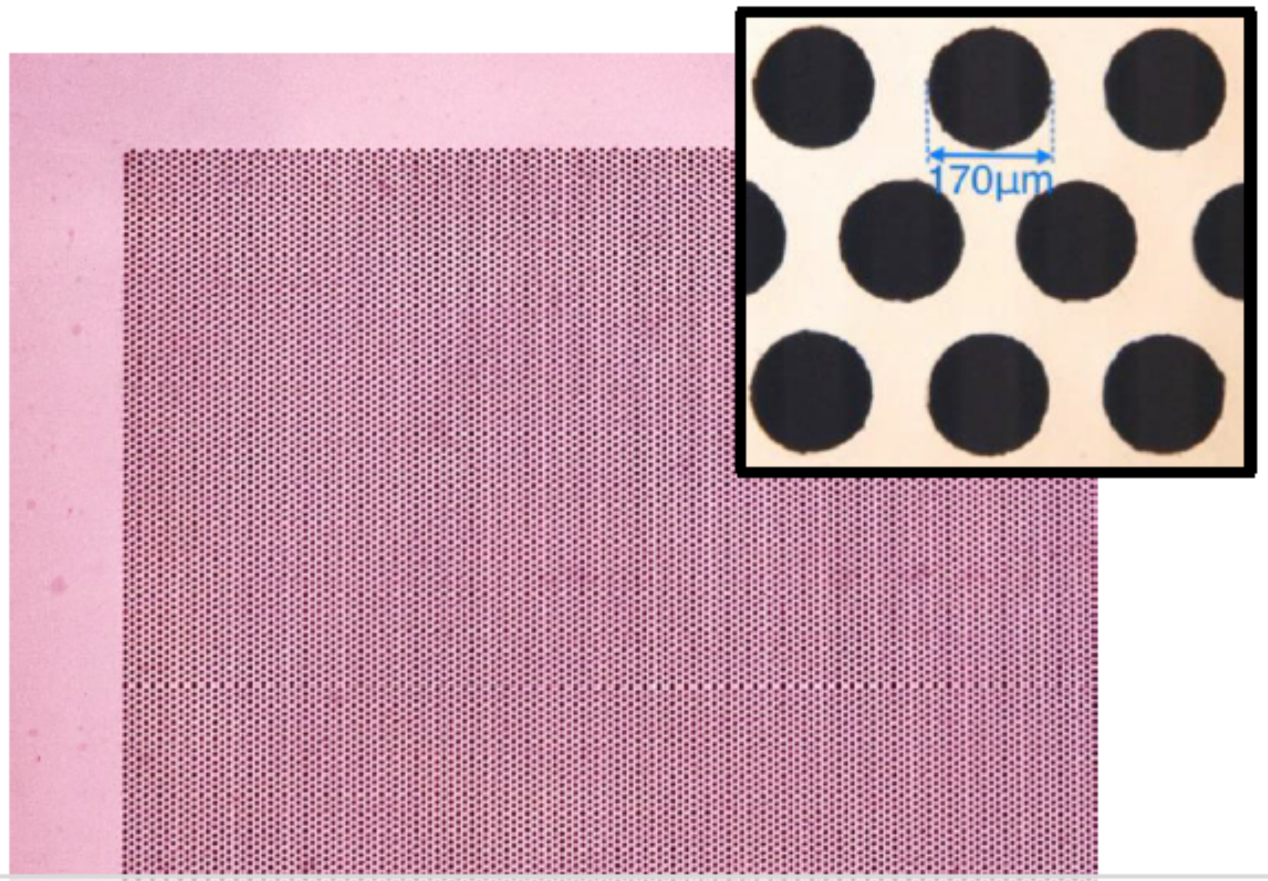
PMT

CMOS camera

Cathode, GEM stack, ITO
10×10×3 cm^3 active region
(compact!)



Cathode woven mesh
280 μm Al wire



Double glass-GEMs
Diameter: 170 μm | pitch: 280 μm | thickness: 570 μm

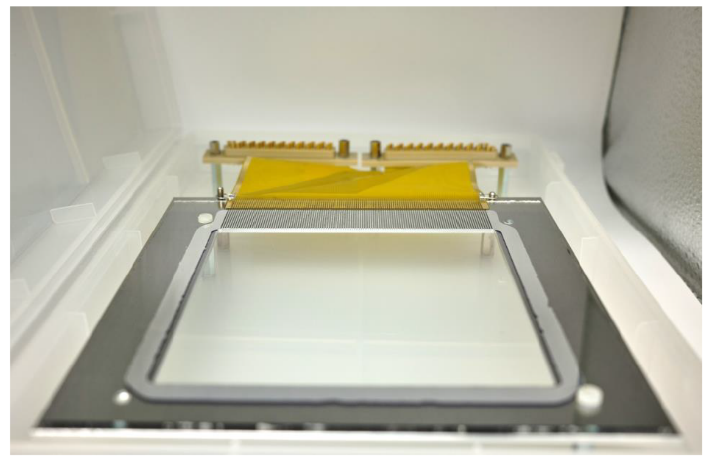
MIGDAL

Migdal In Galactic Dark mAtter expLoration

Triple readout

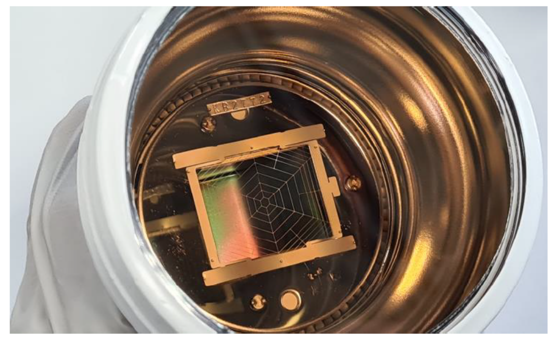
- Amplification: 2x glass-GEMs
- Optical: camera + photomultiplier tube
- Charge: 120 ITO anode strips

Charge readout

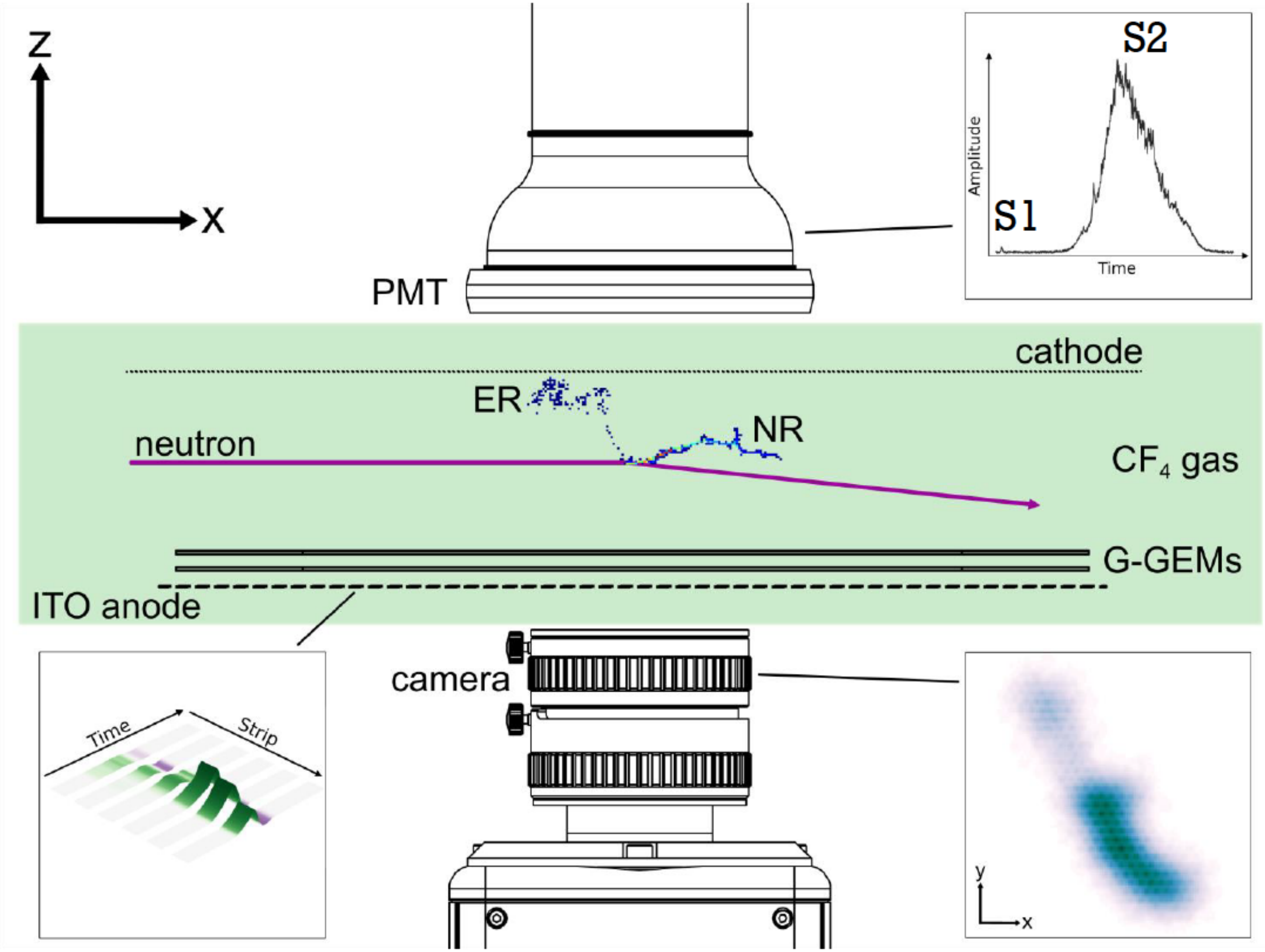


Optical readout

New camera!

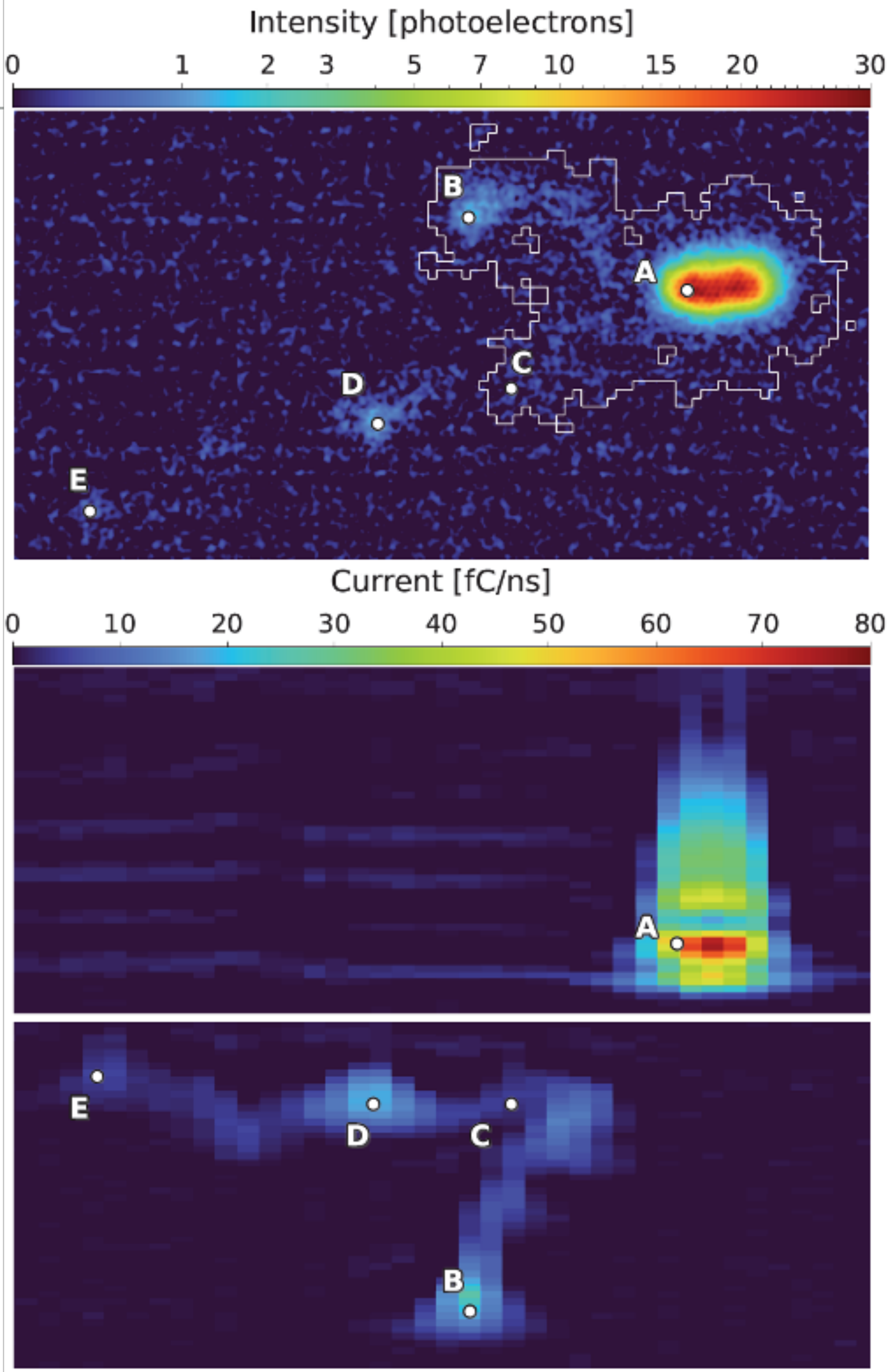


VUV PMT (Hamamatsu R11410)



THE MIGDAL EXPERIMENT AT RAL

- The **ITO's 2ns timing resolution** allows for separation of events that pileup due to the camera's 8.33ms exposure time.
- The example on the right looks Migdal-like in the camera.
- In the ITO we see **these are two separate events** which occurred ~few ms apart.
- If an event does not appear in the ITO, we reject it outright as a coincidence.



Tim Marley
Imperial College London
On behalf of the MIGDAL Collaboration

The 15th International Workshop on the Identification of Dark Matter – 8-12 July 2024 – L'Aquila, Italy


Davide Pinci - INFN Roma
Thank you!