CYGNO, an optically readout TPC for low energy events study

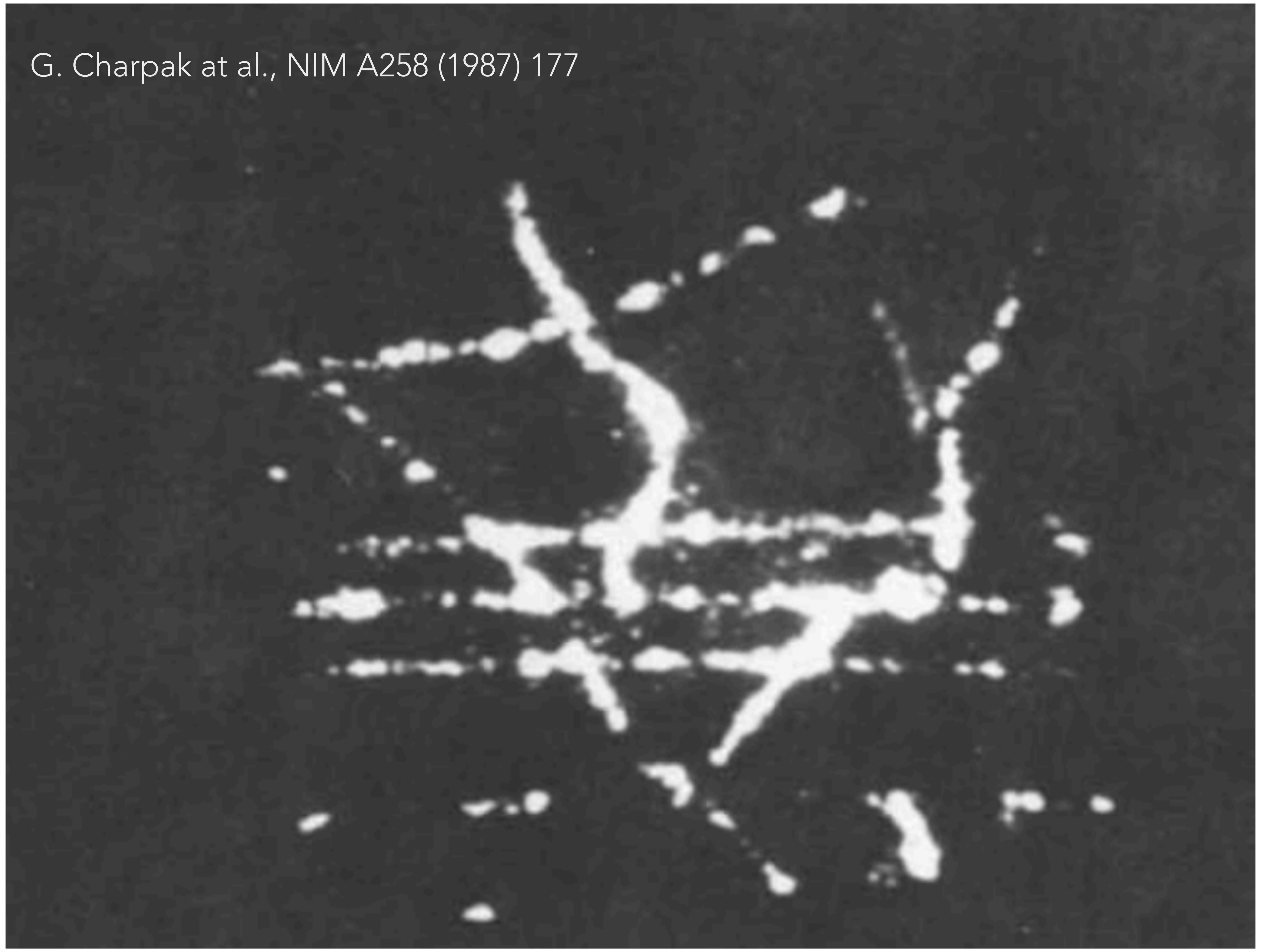
F. Amaro, R. Antonietti, E. Baracchini, L. Benussi, S. Bianco, R. Campagnola, L. G. M. Carvalho, C. Capoccia, M. Caponero, D. S. Cardoso, G. Cavoto, I. A. Costa, A. Croce, M. D'Astolfo, E. Di Marco, G. D'Imperio, E. Dané, G. Dho, D. Fiorina, F. Di Giambattista, F. Iacoangeli, Z. Islam, E. Kemp, H. P. Lima Júnior, G. S. P. Lopes, G. Maccarrone, R. D. P. Mano, R. R. Marcelo Gregorio, D. J. G. Marques, G. Mazzitelli, A.G. McLean, P. Meloni, A. Messina, C. M. B. Monteiro, R. A. Nobrega, I. F. Pains, E. Paoletti, L. Passamonti, S. Pelosi, F. Petrucci, S. Piacentini, D. Piccolo, D. Pierluigi, D. Pinci, A. Prajapati, F. Renga, R. J. C. Roque, F. Rosatelli, A. Russo, J. M. F. dos Santos, G. Saviano, P. A. O. Silva, N. Spooner, R. Tesauro, S. Tomassini, S. Torelli, D. Tozzi

INFN Istituto Nazionale di Fisica Nucleare
ROMA TRE Università degli Studi
1290 Universidade de Coimbra
Sapienza Università di Roma
The University Of Sheffield.
CBPF
UFJF Universidade Federal de Juiz de Fora
GSSI Gran Sasso Science Institute — Center for Advanced Studies INFN
erc European Research Council

LIGHT: A CHANGE OF PARADIGM

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

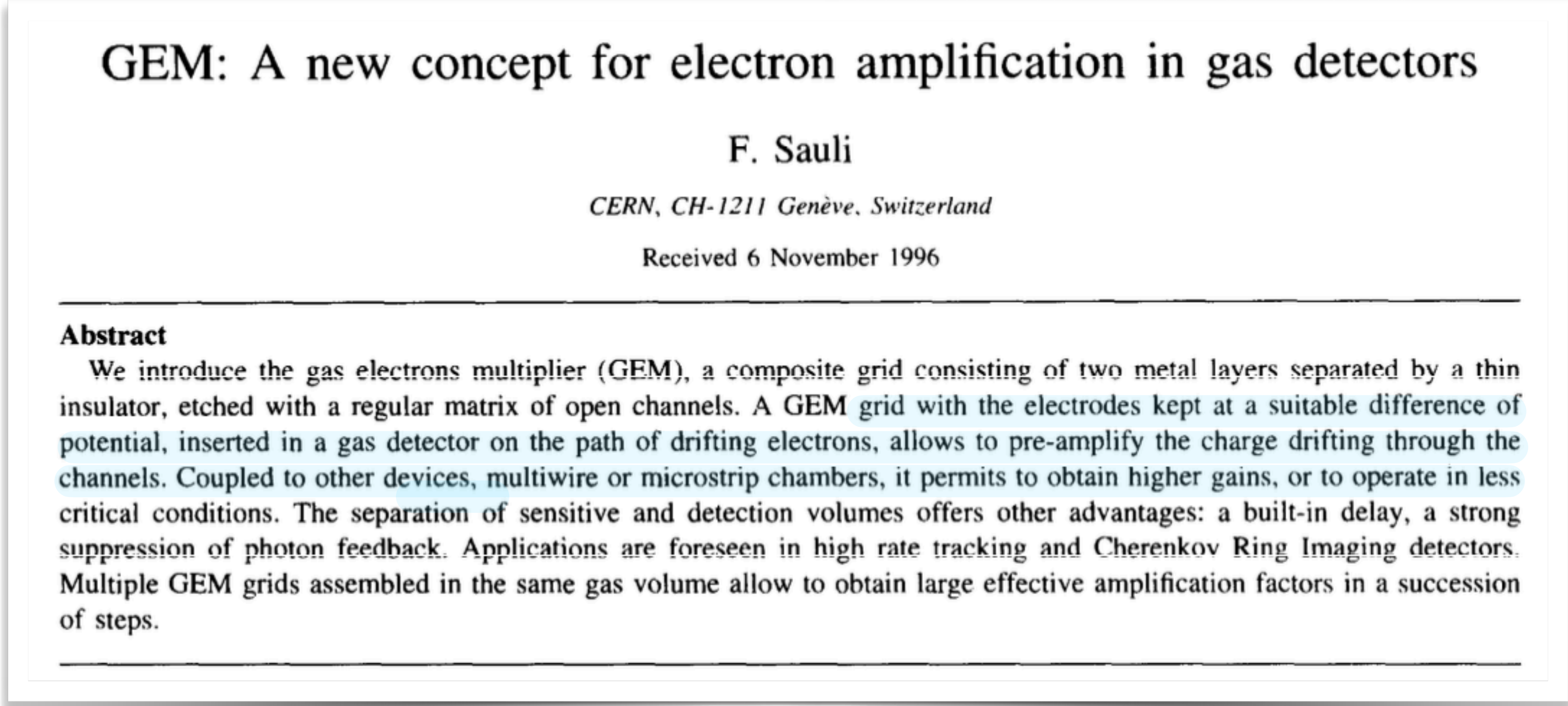
Energy can be transferred to **excite** atoms and molecules to make them **emitting light through atomic and molecular de-excitation;**



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

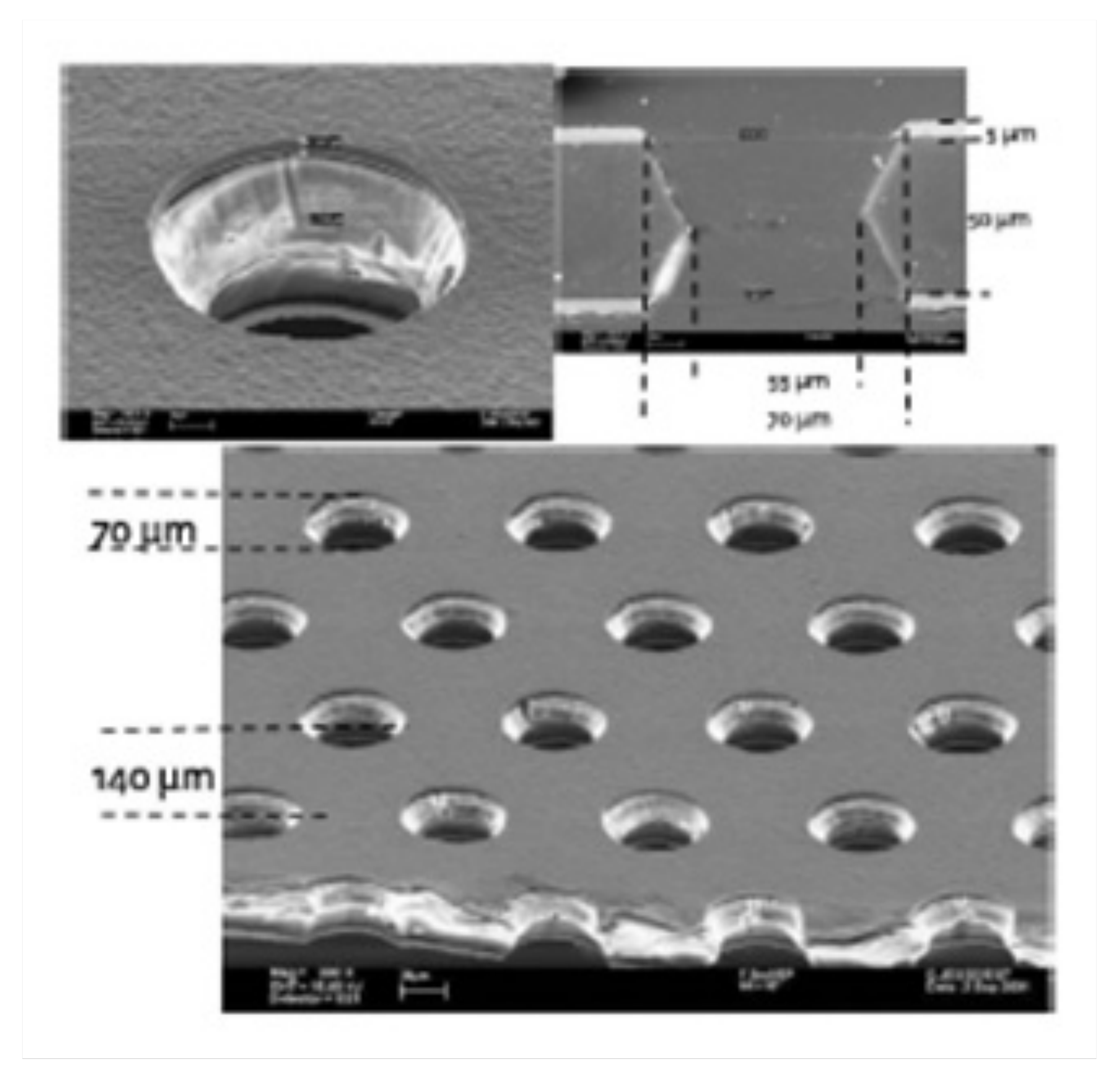
F. Sauli

CERN, CH-1211 Genève, Switzerland

Received 6 November 1996

Abstract

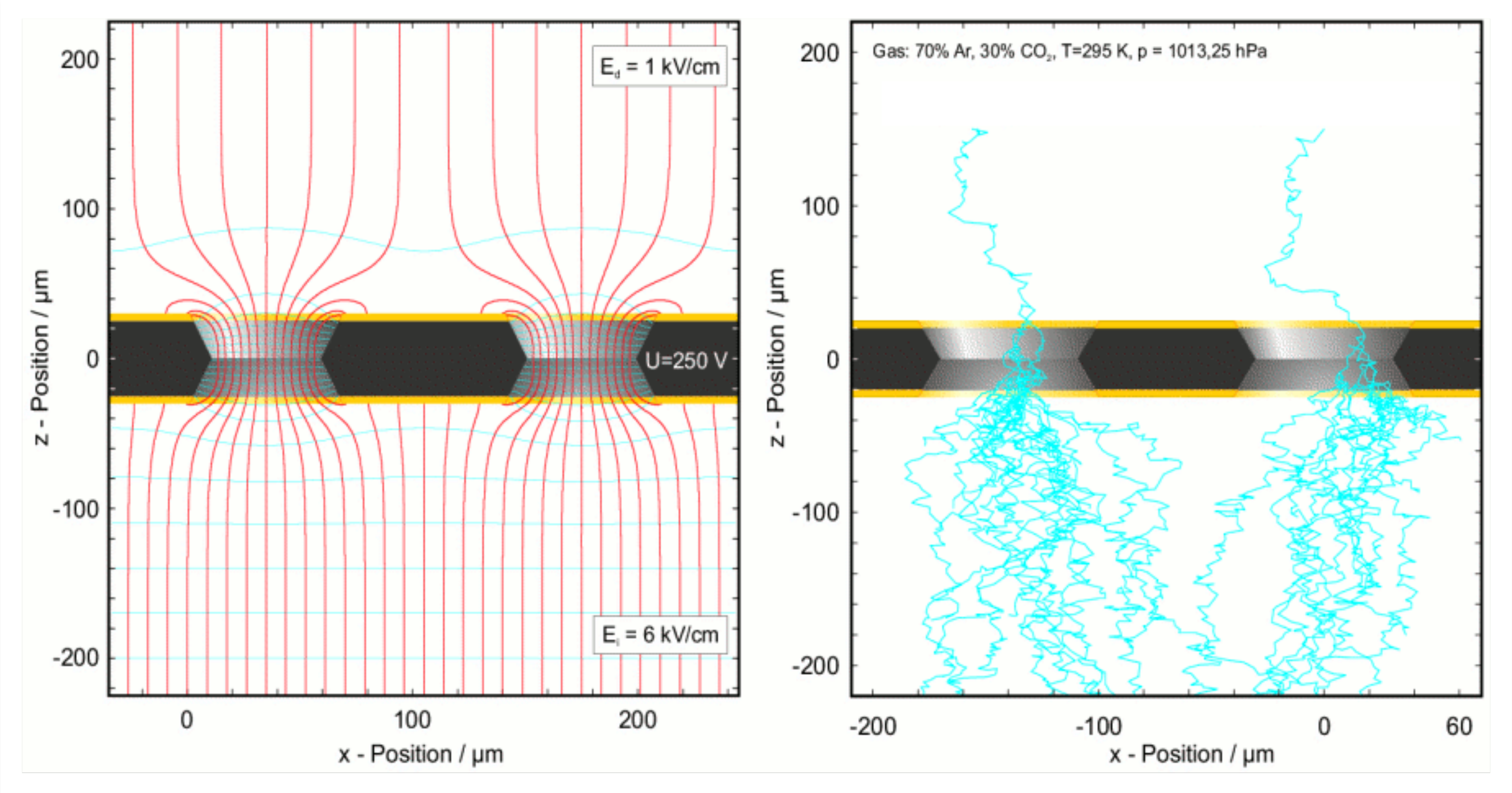
We introduce the gas electrons multiplier (GEM), a composite grid consisting of two metal layers separated by a thin insulator, etched with a regular matrix of open channels. A GEM grid with the electrodes kept at a suitable difference of potential, inserted in a gas detector on the path of drifting 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**

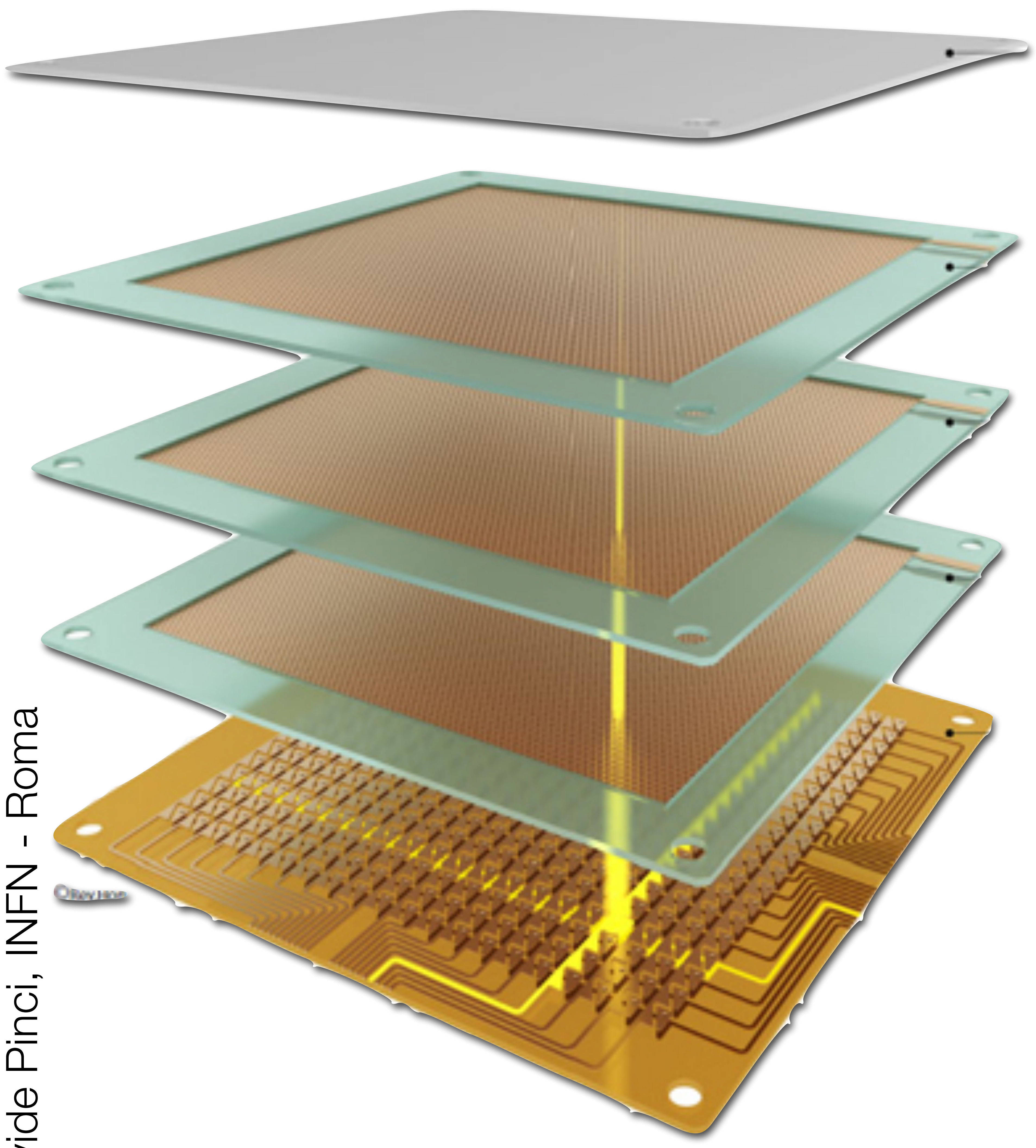
Two **external** electric **fields**:

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



Multiple GEM structures can be used to share the gain and better **stability**

THE TRIPLE GEM DETECTOR



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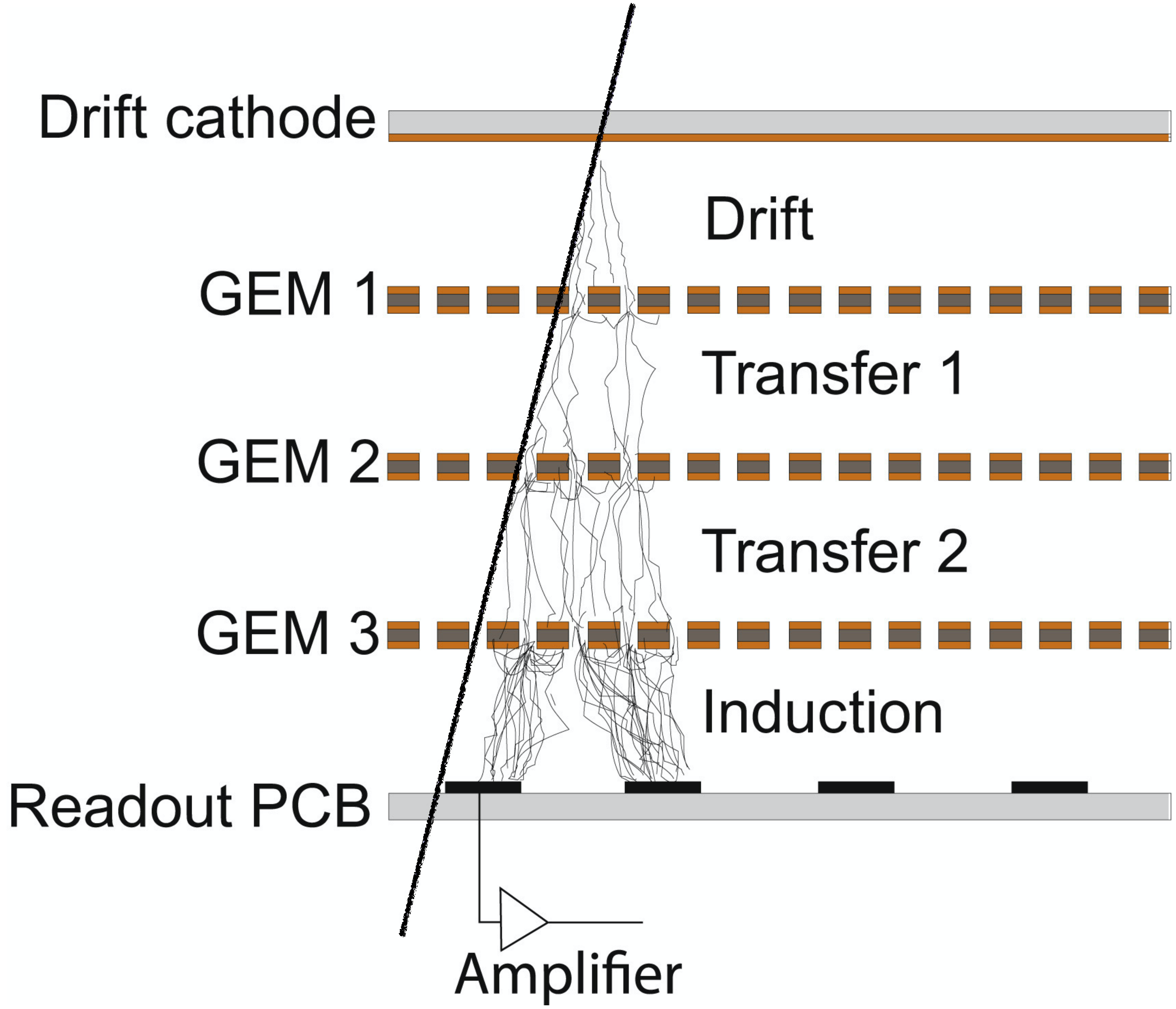
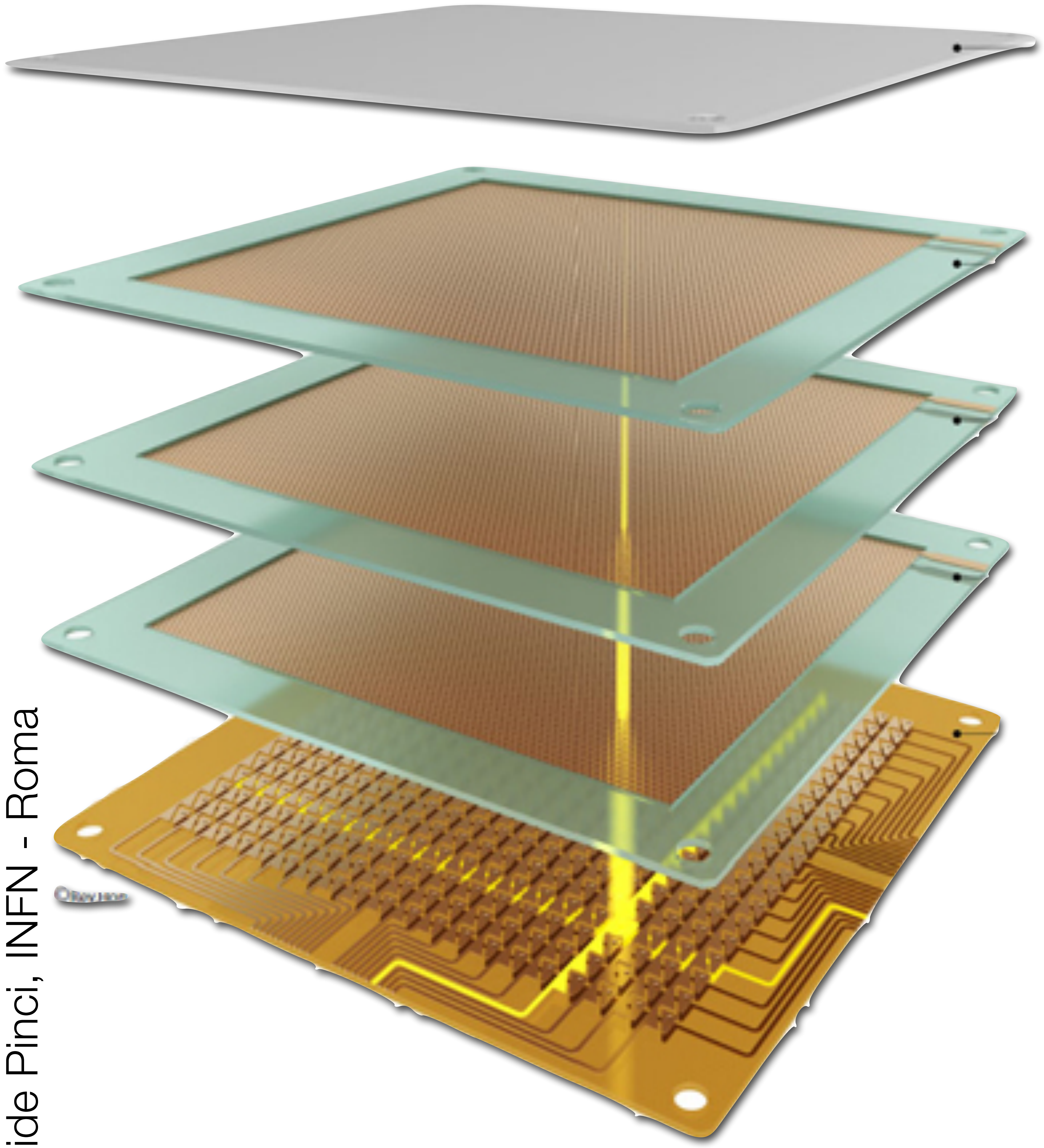
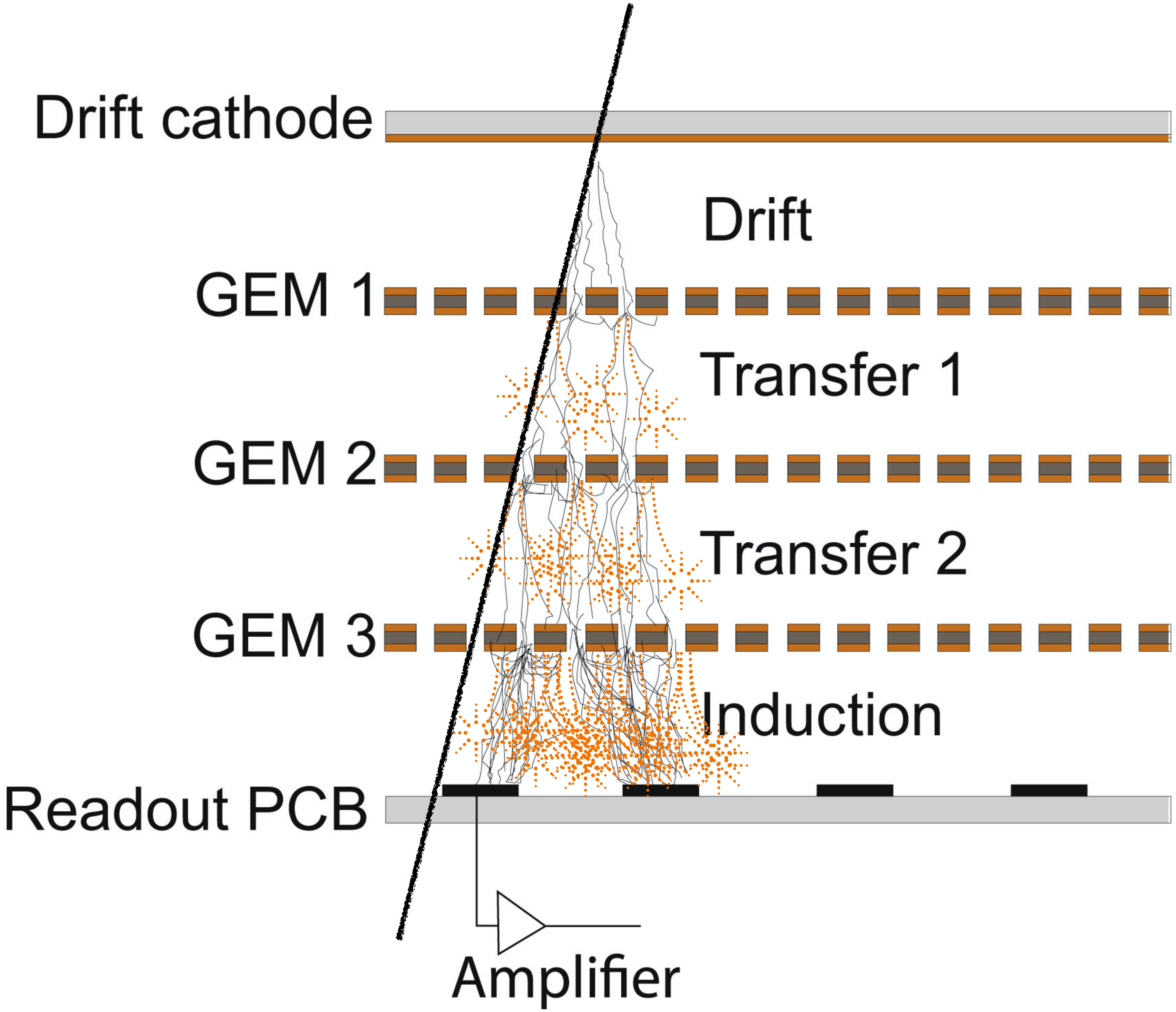


THE TRIPLE GEM DETECTOR





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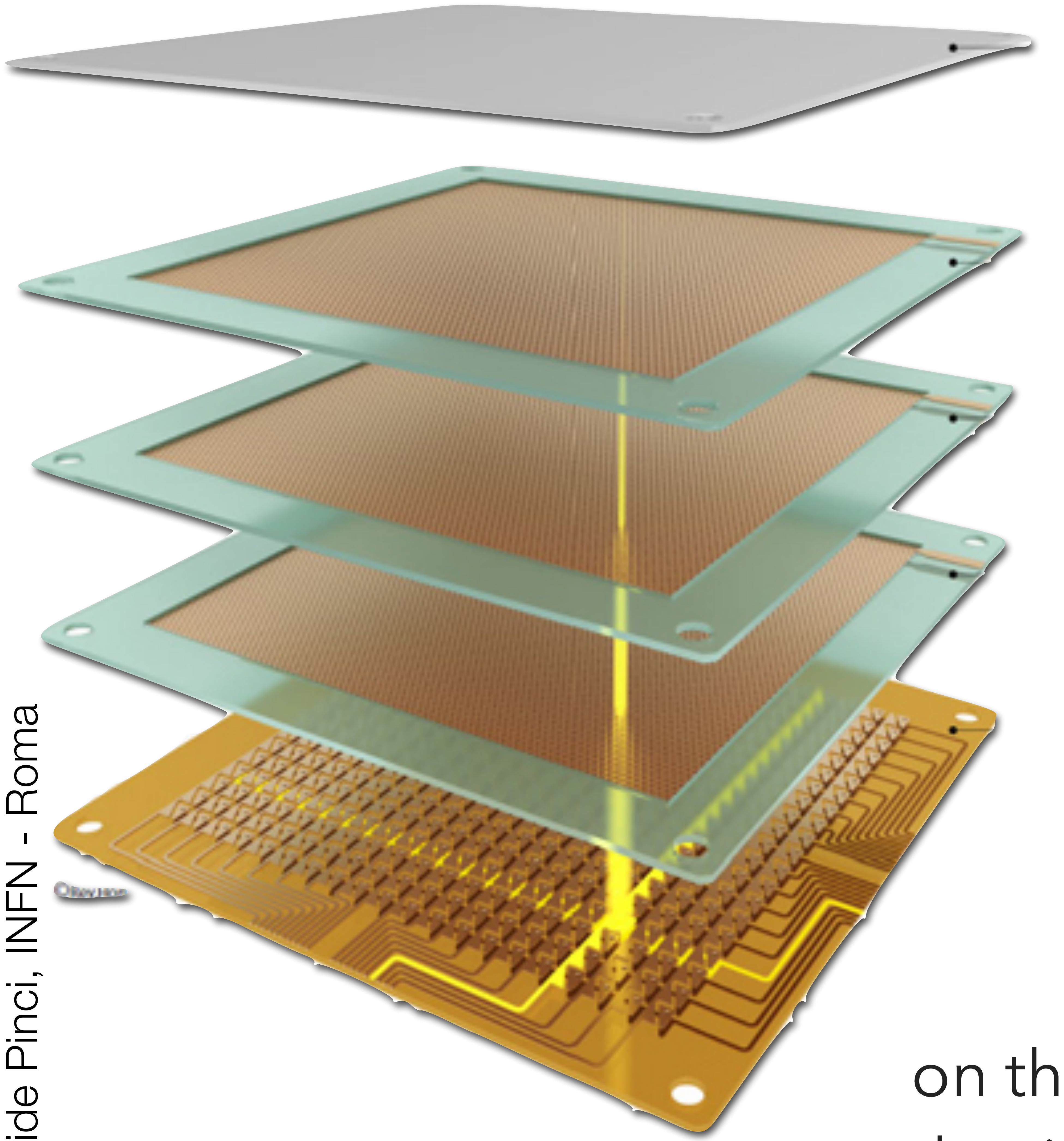
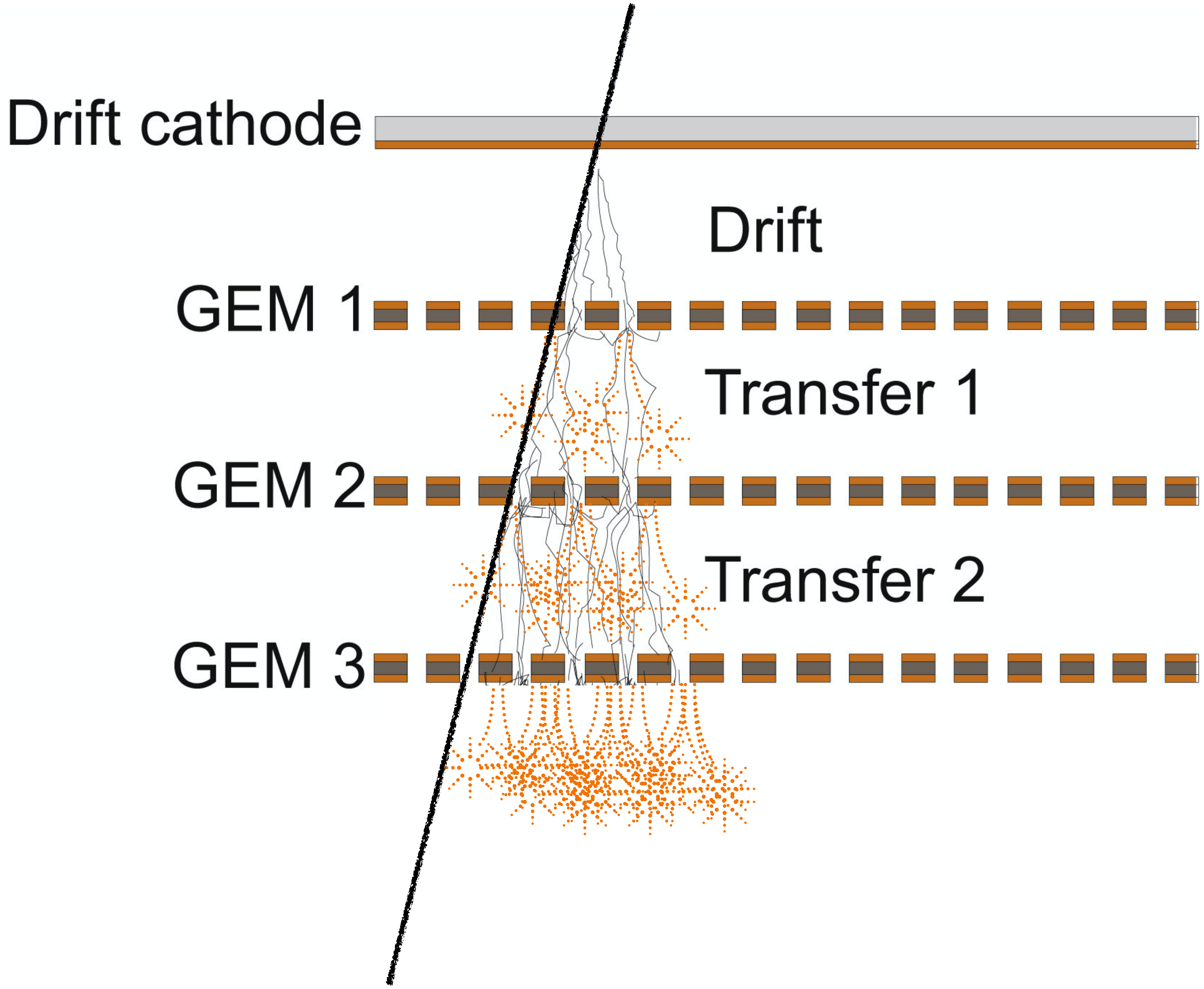
THE TRIPLE GEM DETECTOR





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

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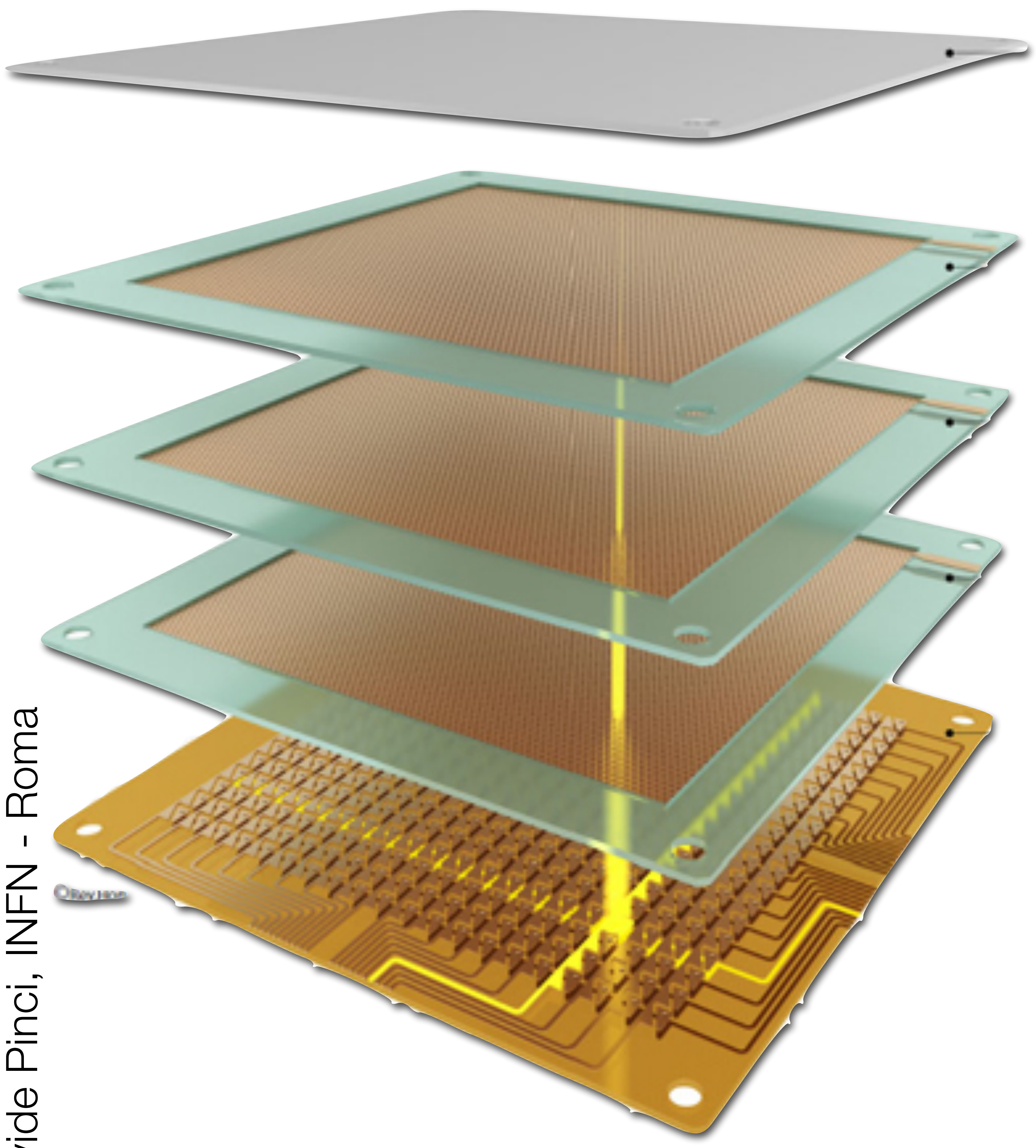
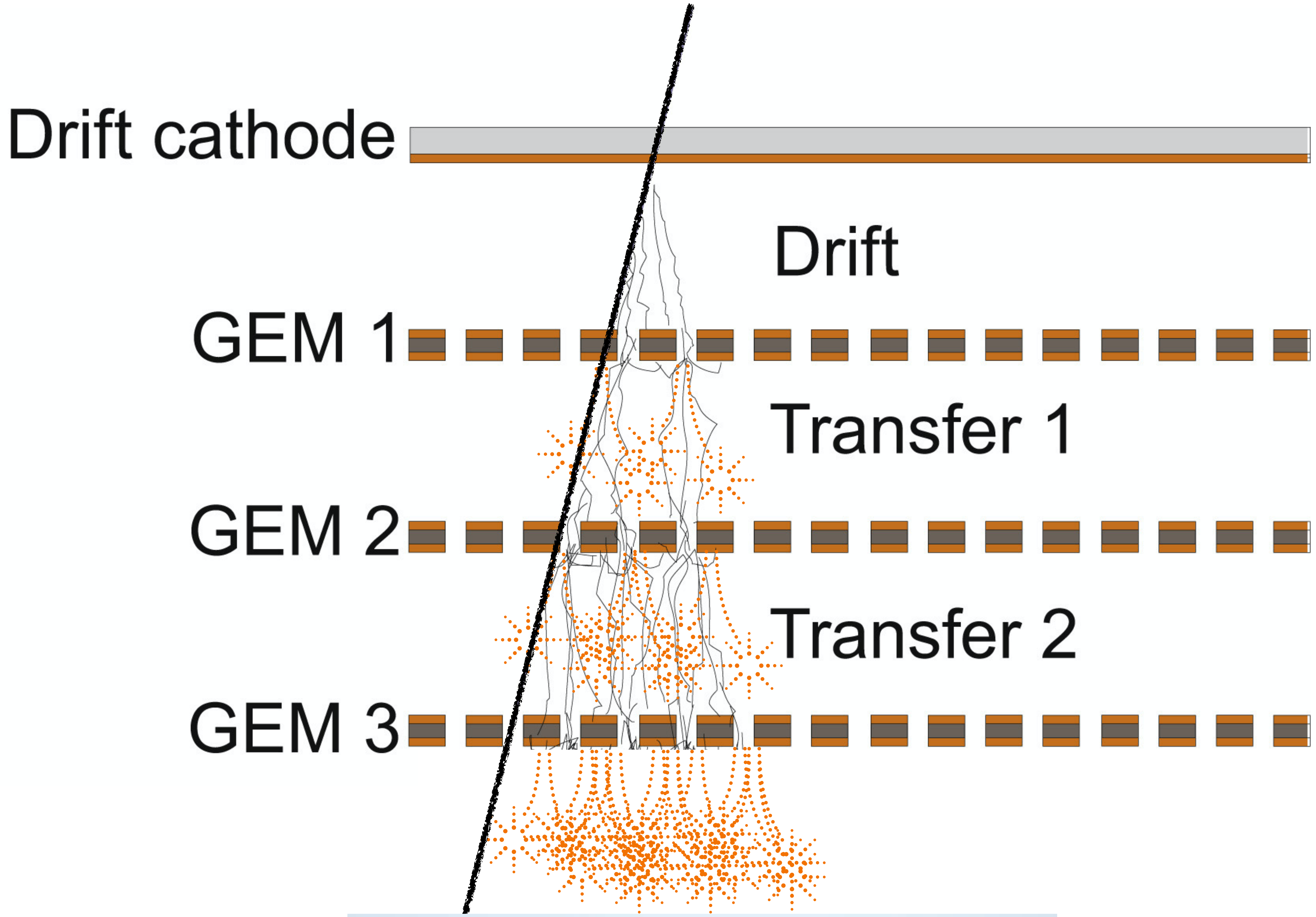
THE TRIPLE GEM DETECTOR





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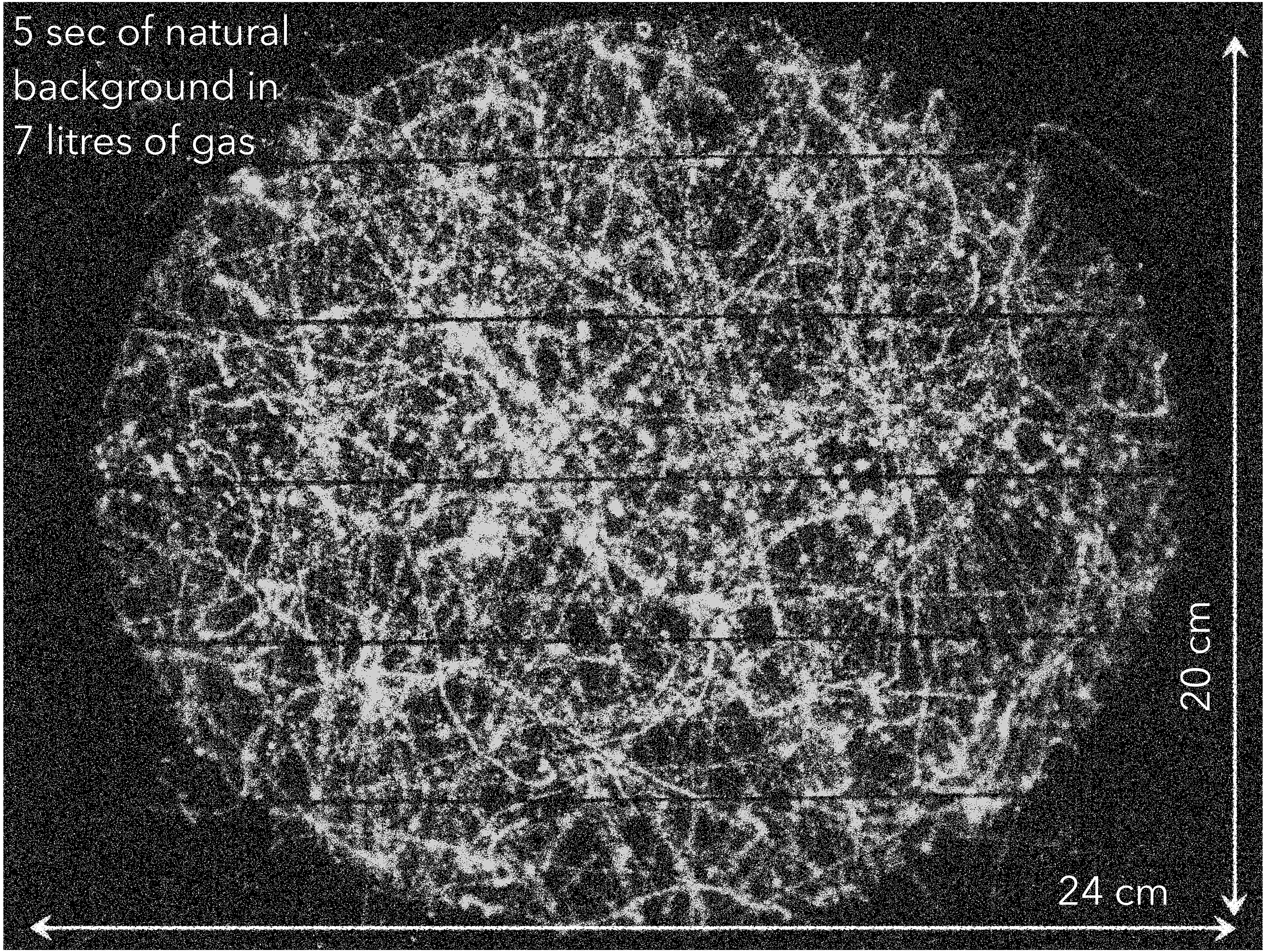
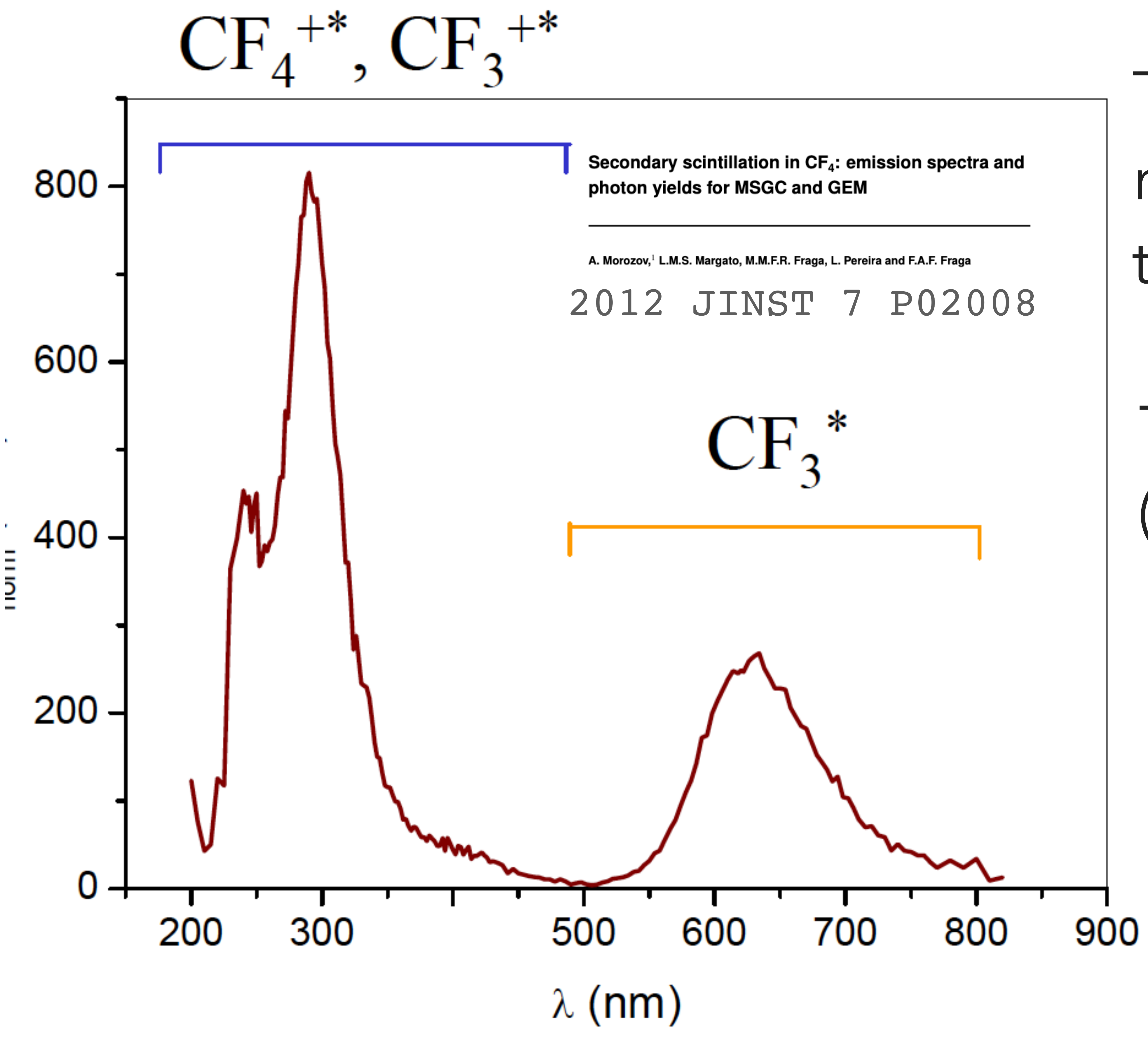

5 sec of natural
background in
7 litres of gas
20 cm
24 cm
CYGNO
Experiment

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.

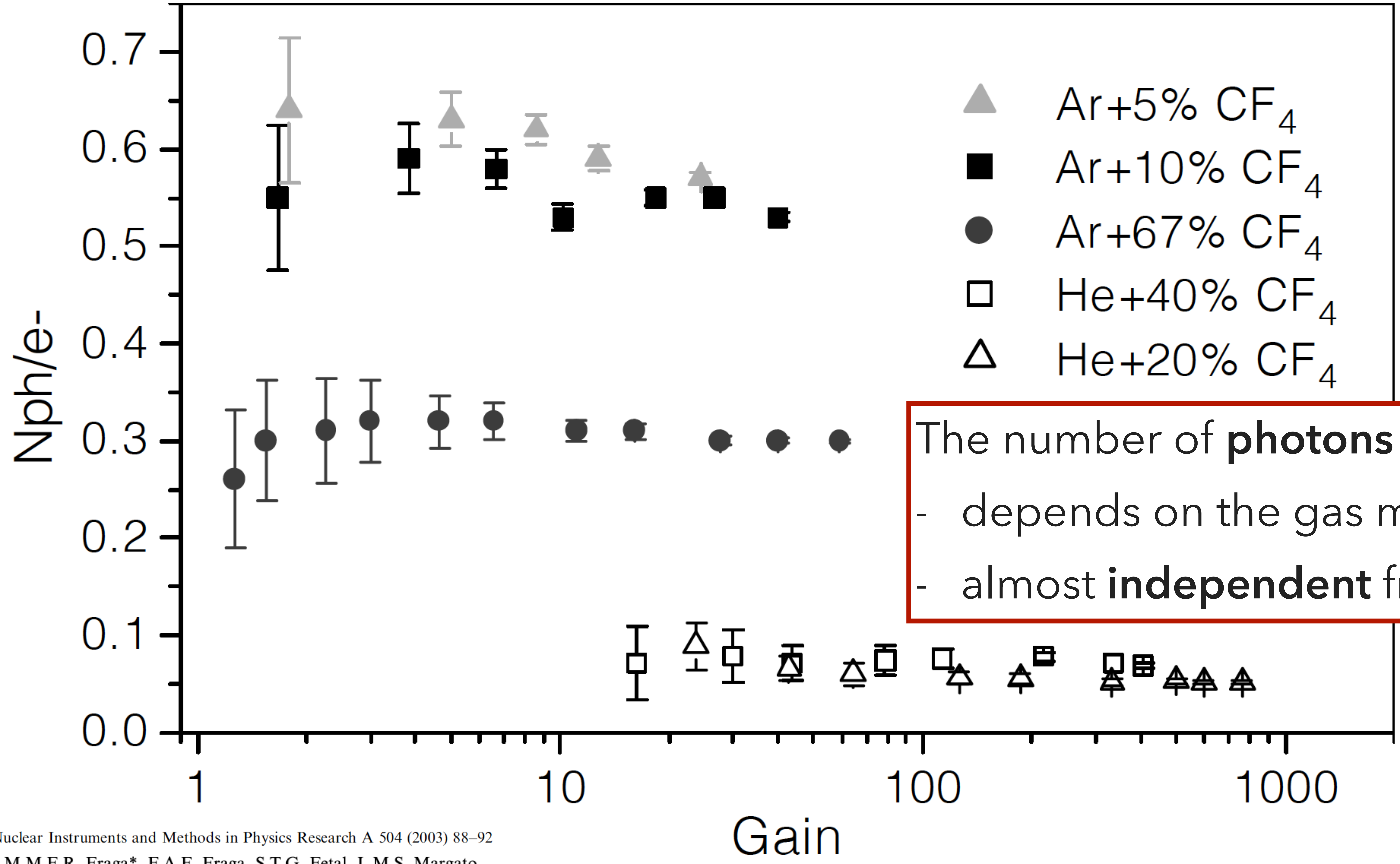


The broad band in the **visible region (620 nm)** results from the excitation of the **CF_4** molecule that **dissociates** into an emitting **CF_3^* fragment**.

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 IN GEM: HOW BRIGHT?



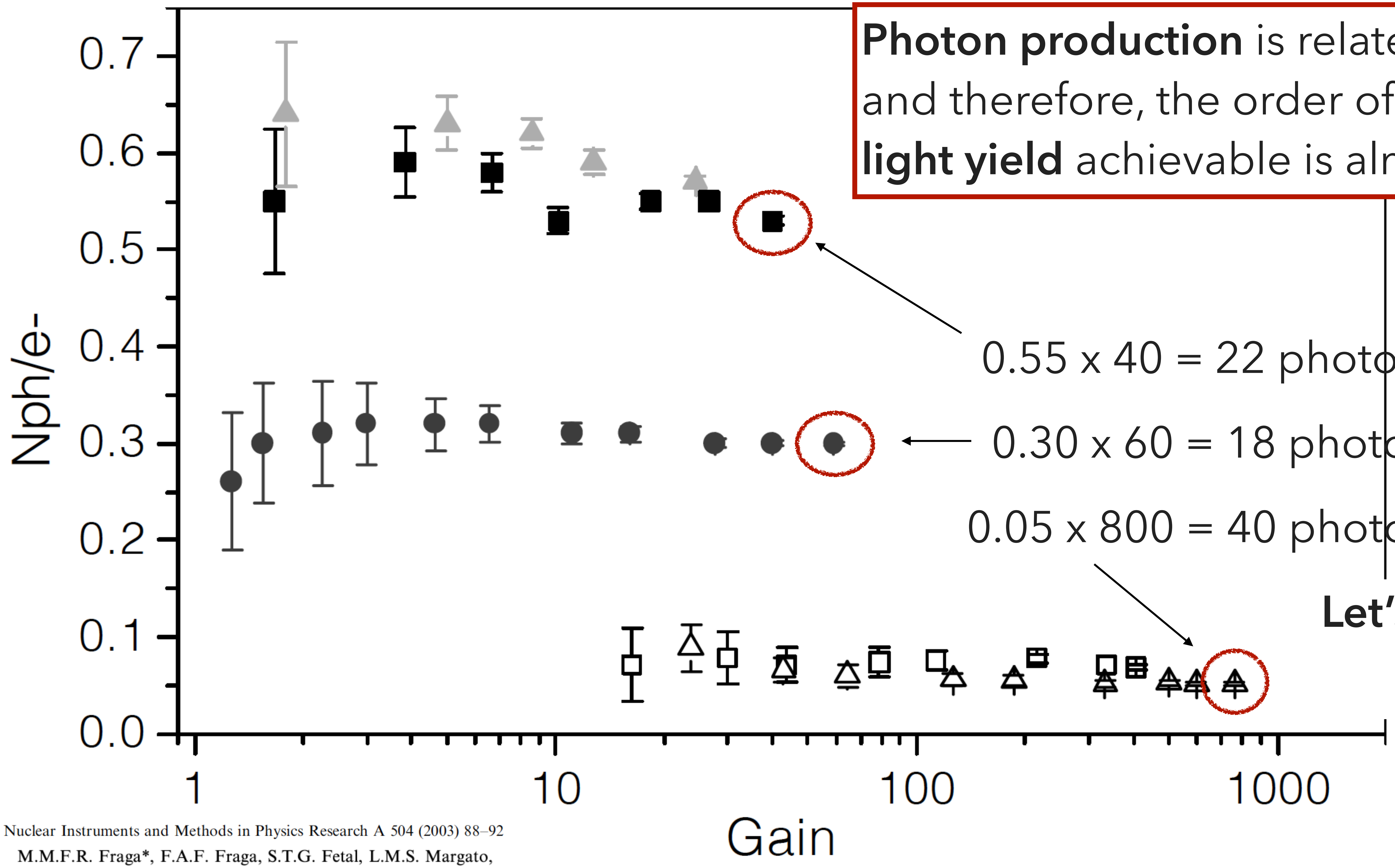
The number of **photons** per **secondary e-**:

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

Nuclear Instruments and Methods in Physics Research A 504 (2003) 88–92
M.M.F.R. Fraga*, F.A.F. Fraga, S.T.G. Fetal, L.M.S. Margato, R. Ferreira Marques, A.J.P.L. Policarpo

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

Let's focus on this one:

He/CF_4 60/40

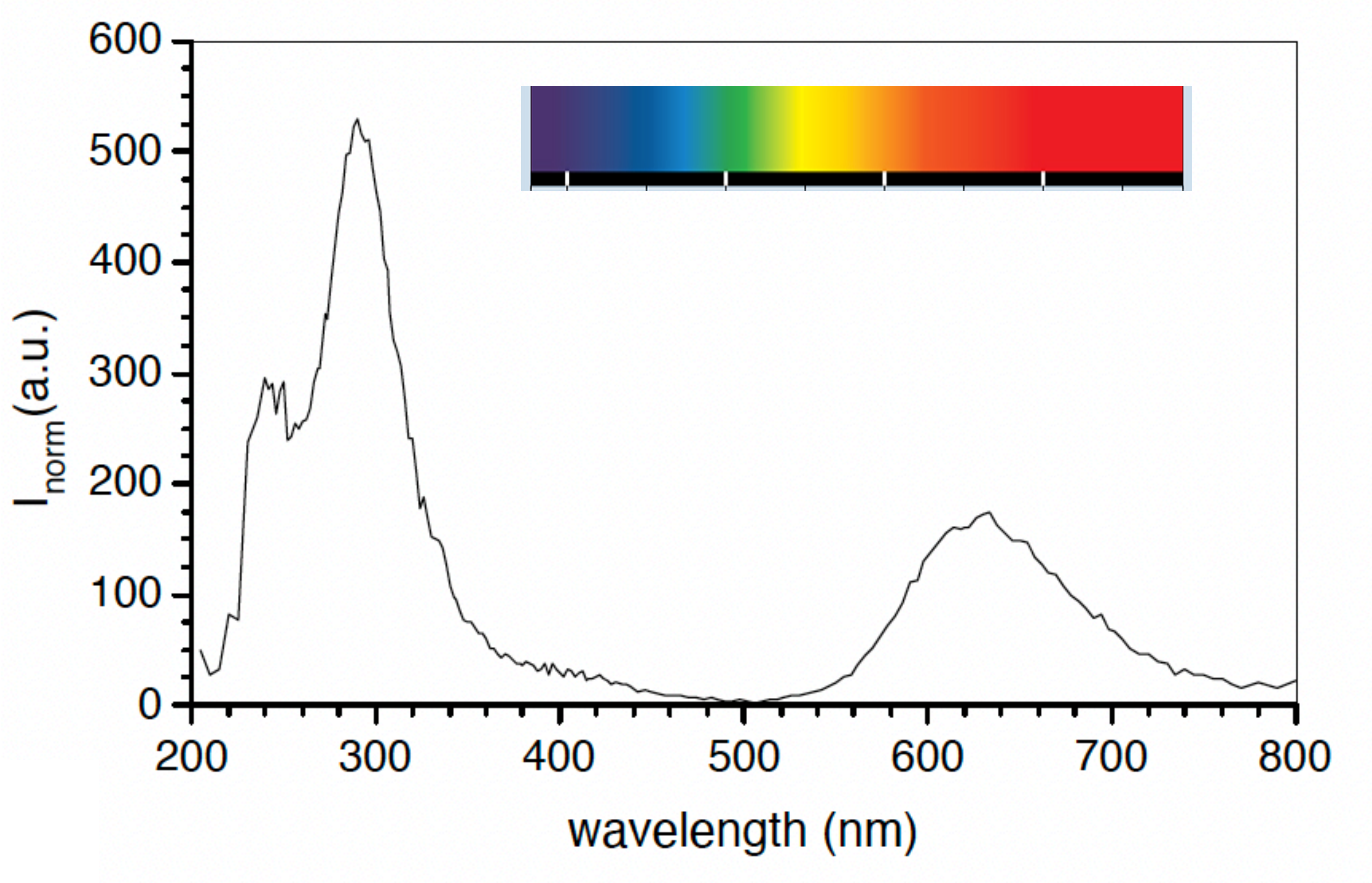
Nuclear Instruments and Methods in Physics Research A 504 (2003) 88–92
M.M.F.R. Fraga*, F.A.F. Fraga, S.T.G. Fetal, L.M.S. Margato, R. Ferreira Marques, A.J.P.L. Policarpo

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

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

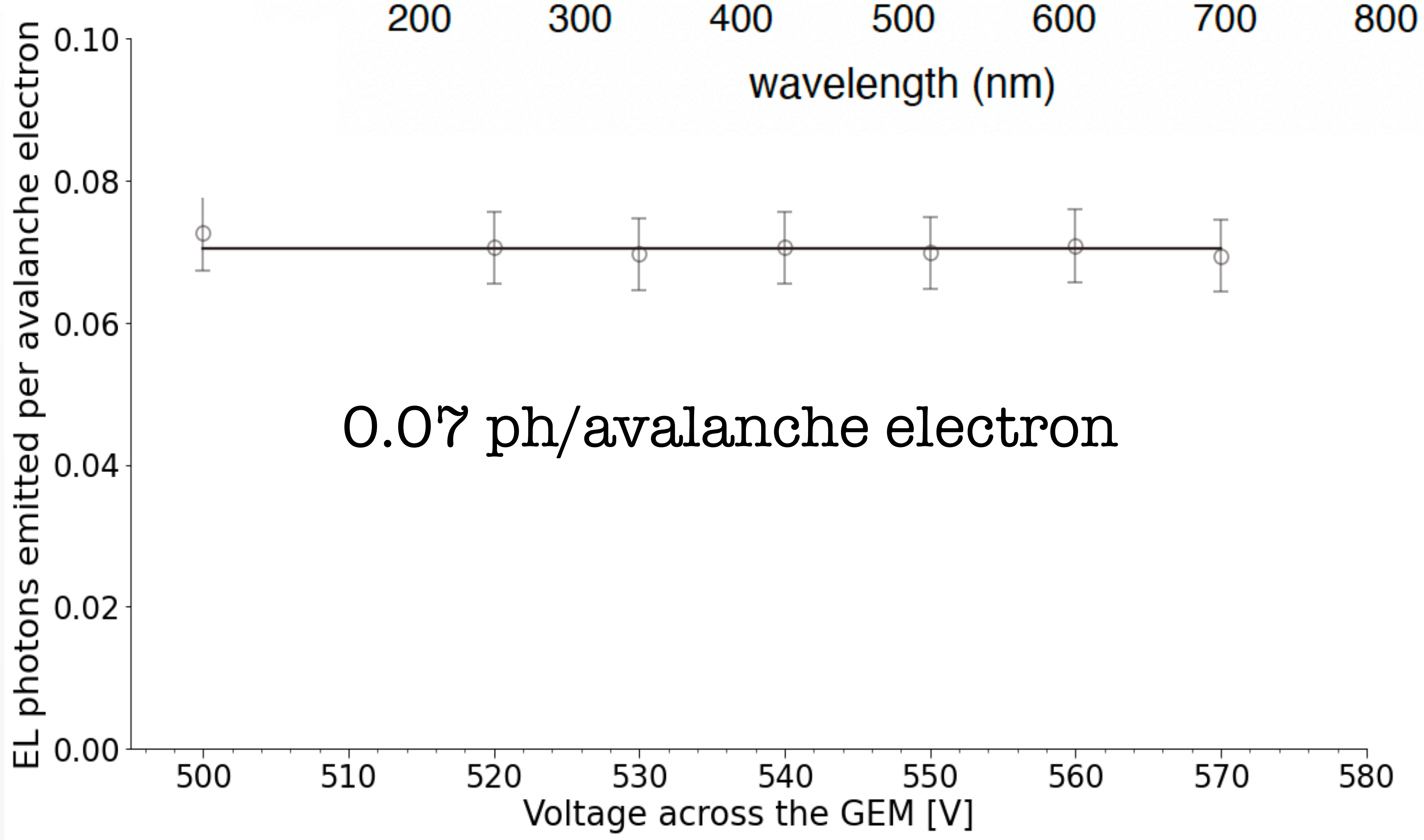
$$e^- + CF_4 \rightarrow CF_3 + F + e^-$$

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

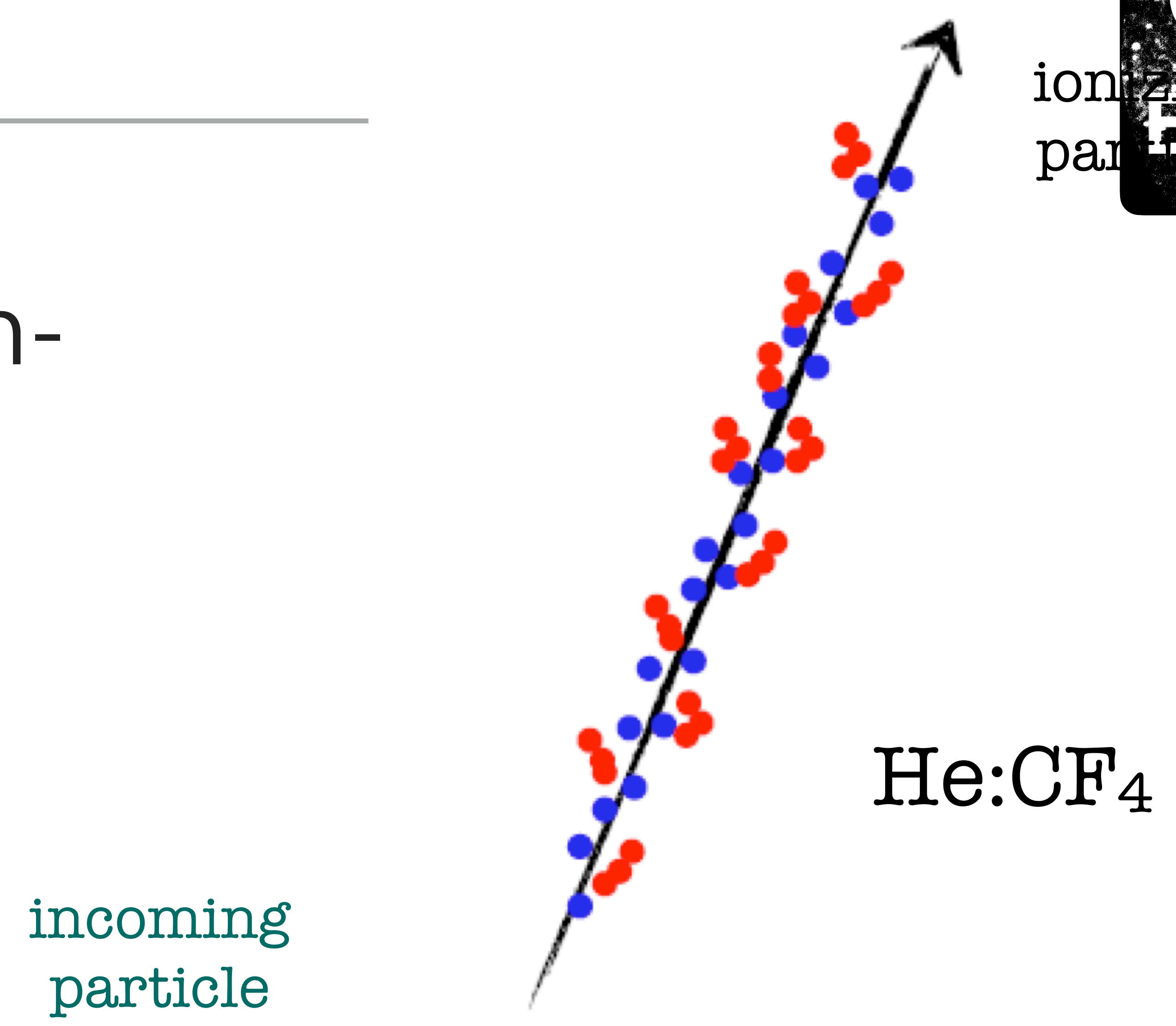


- **Relative light** production **independent** from **voltage**:

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



IONIZATION AND DRIFT PROCESSES



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

$$\mathbf{W \sim 38\ eV} \Rightarrow 1\ \mathrm{keV} \sim 26\ \mathrm{electrons}$$

- Because of the 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 1 mm** with an **area** of about **3 x mm²**
- Suppose to operate **triple GEM** at a HV of **440 V each, a total gain** has been measured to be **2 x 10⁶**
- Therefore, after multiplication we get:

$$@\ 1\ \mathrm{keV_{ee}}$$
$$26\ e^- \rightarrow 5.0 \times 10^7\ e^- \rightarrow 3.5 \times 10^6\ \mathrm{ph}$$

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** and the **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 **δ=10** and Ω is of the order of $\mathbf{10^{-3}}$

only **1 photon over 1000** is collected

@ 1 keV
→ 3500 collected photons

PHOTON DETECTION

CYGNO Experiment

- Therefore we end up with **3500 ph / 3 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:

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

@ 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 order of **few photons/pixel**

PIXELATED LIGHT SENSORS: CCD AND APS-CMOS COMPARISON

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

Active Pixel Sensor (CMOS)

ORCA®-Fusion

CAMERA SPECS

LOW NOISE AND EXCEPTIONAL READOUT NOISE UNIFORMITY

READOUT NOISE 0.7 electrons rms Ultra quiet Scan	DSNU 0.06 electrons	
PRNU 0.06 % At 7500 electrons	HIGH SPEED 100 frames/s At 2304 × 2048 ROI	HIGH RESOLUTION 2304 × 2304 5.3 Megapixels
PIXEL SIZE 6.5 μm × 6.5 μm	DYNAMIC RANGE 21 400:1	PEAK QE 80 %

Charge Couple Device (CCD)

ORCA® II

Digital CCD camera C11090-22B

FEATURES

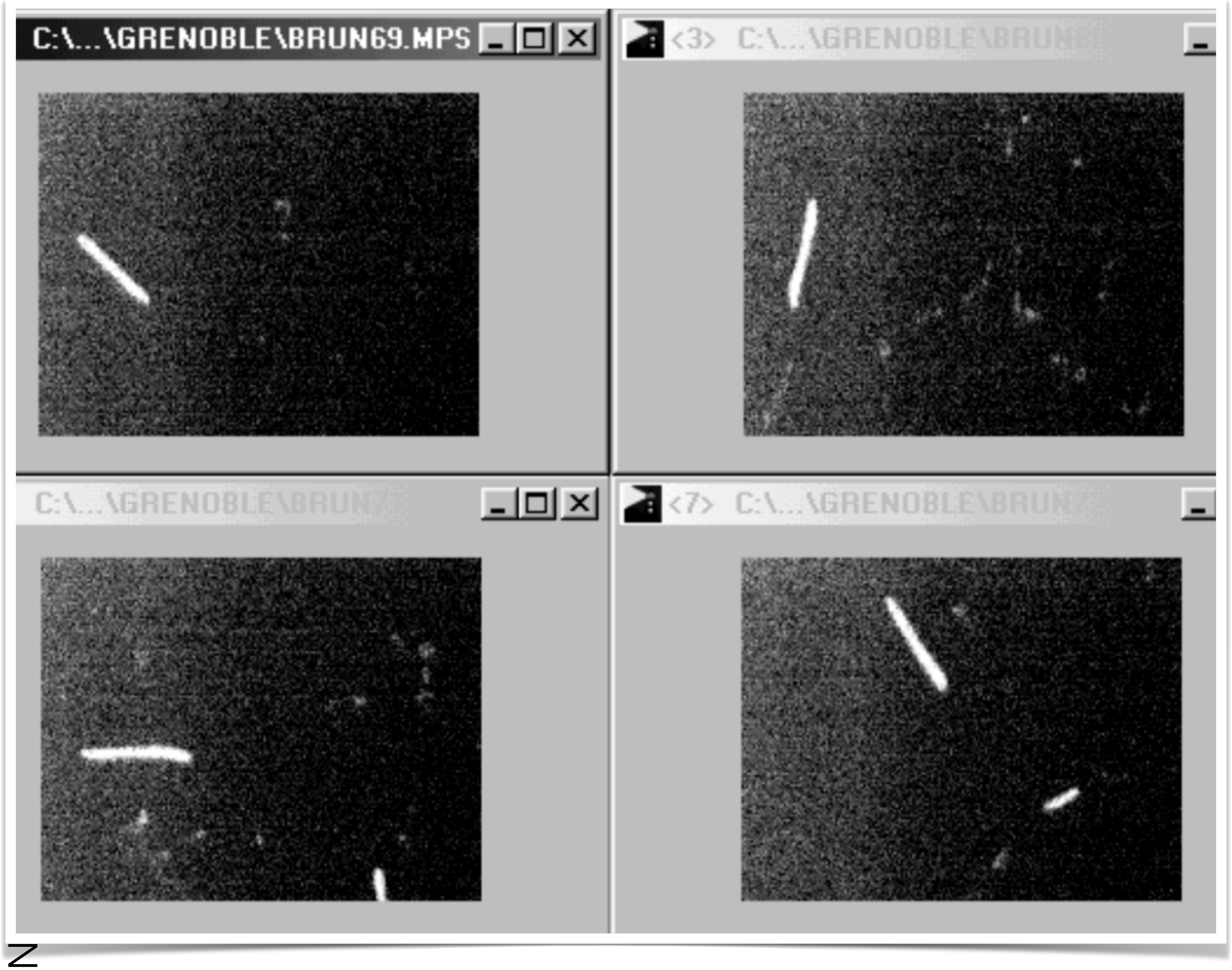
- High resolution format (1024 × 1024 pixels)
- High quantum efficiency from UV to NIR
- Long exposure time (Max. 2 hours)
- Low readout noise (6 electrons rms. typ.)

APPLICATIONS

- Luminescence and fluorescence imaging
- X-ray scintillator readout

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

STARTING POINT



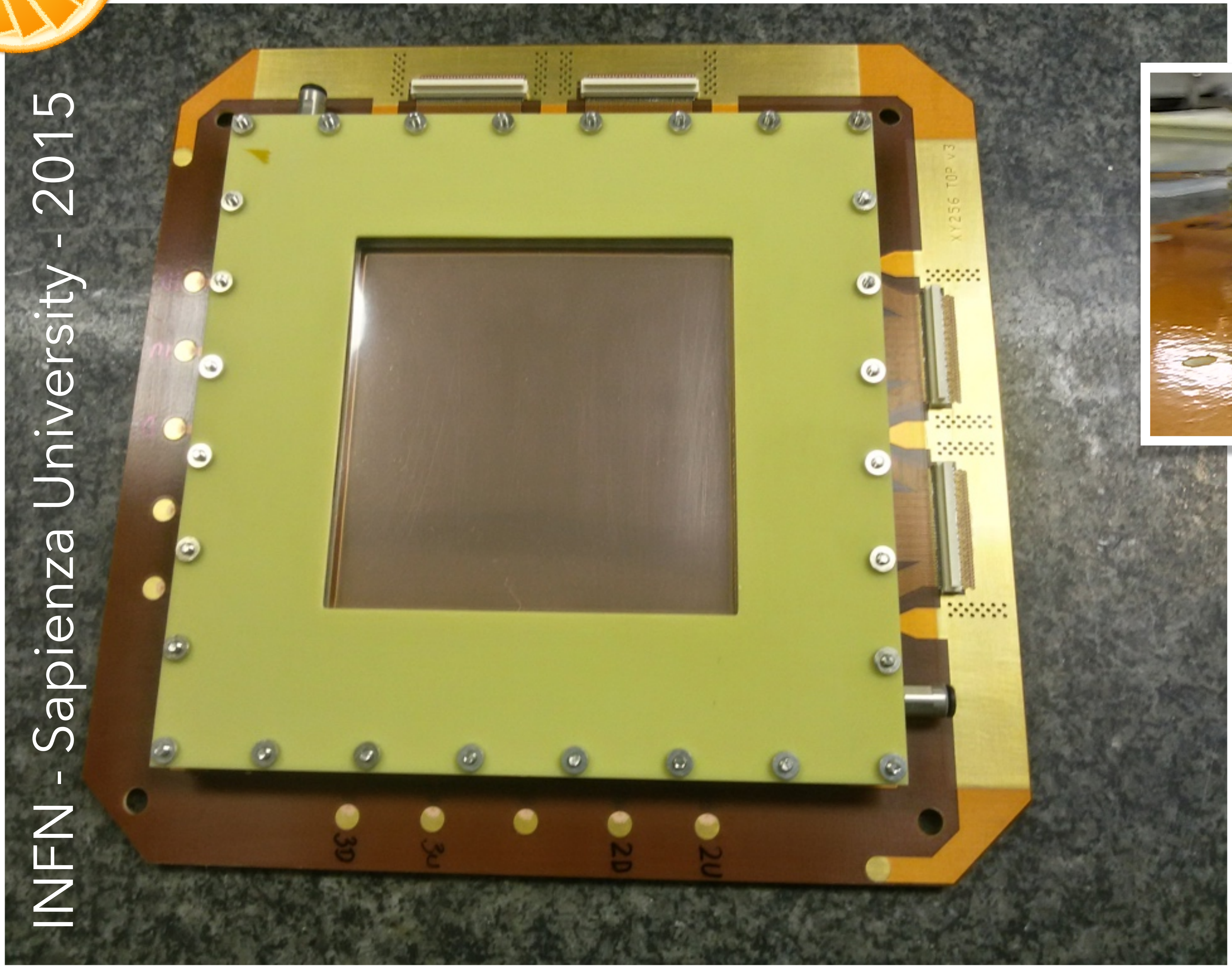
Nuclear Instruments and Methods in Physics Research A 471 (2001) 125–130

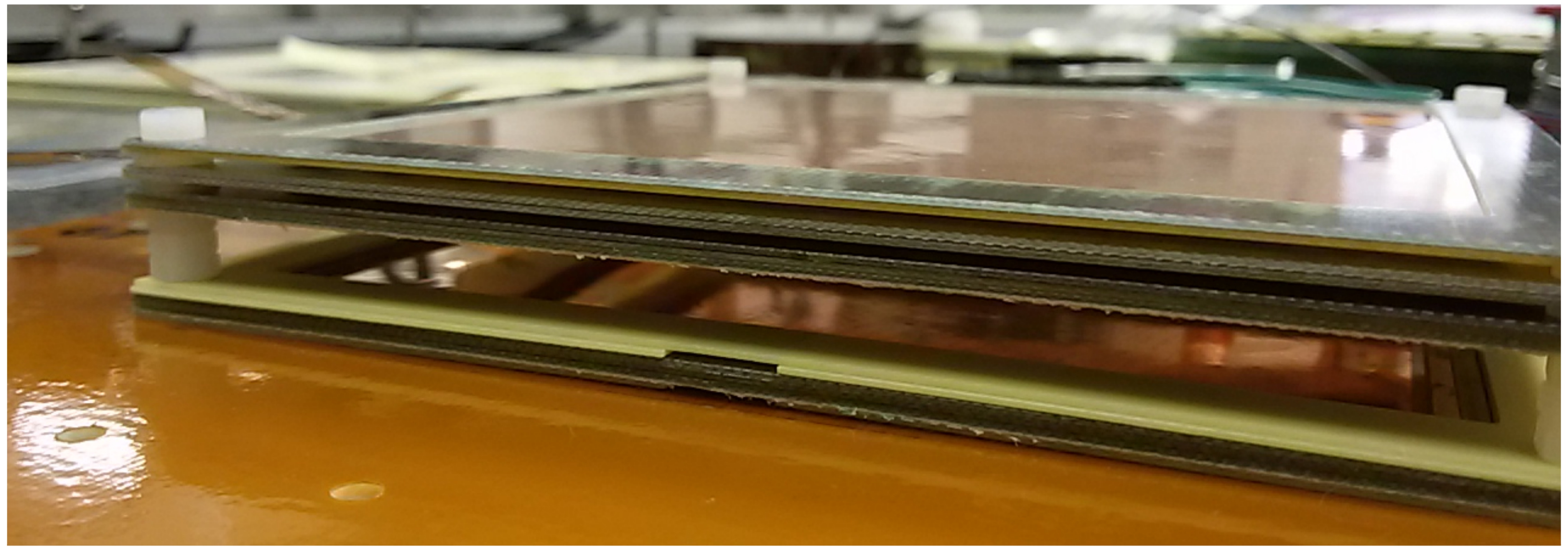
Optical readout of GEMs

F.A.F. Fraga*, L.M.S. Margato, S.T.G. Fetal, M.M.F.R. Fraga, R. Ferreira Marques, A.J.P.L. Policarpo

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

ORANGE: AN OPTICALLY READOUT GEM

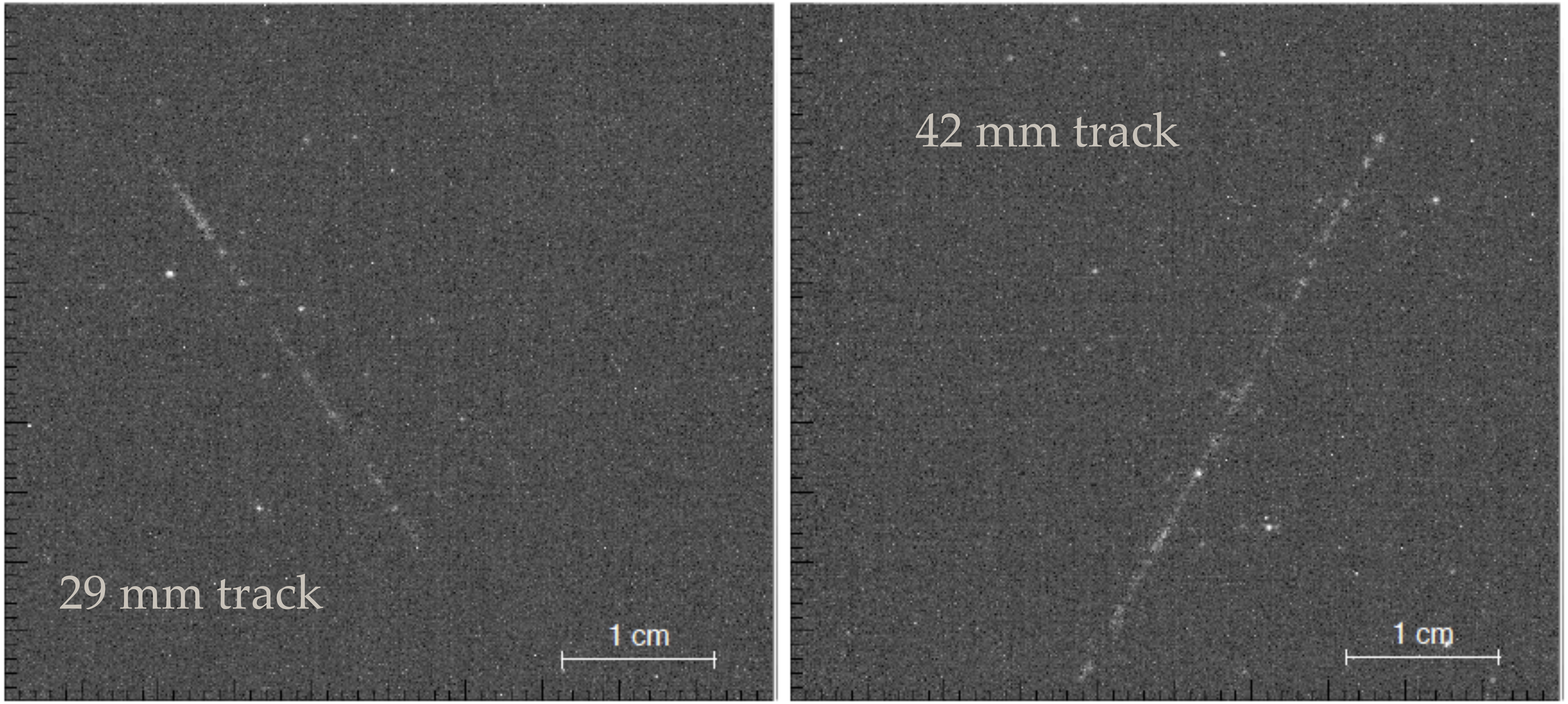




Triple GEM structure (10x10 cm^2) with 1 cm sensitive gap

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**;

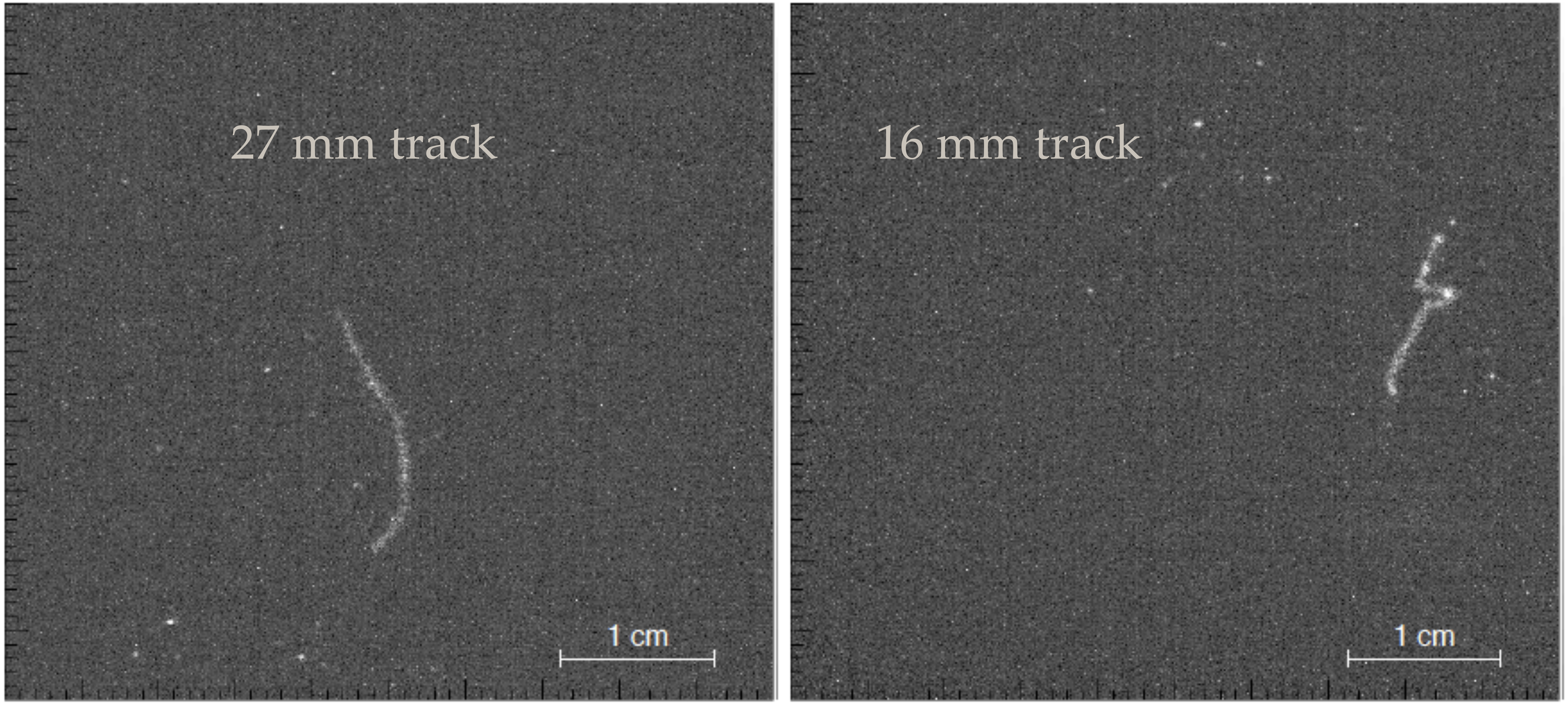
High granularity tracker based on a Triple-GEM optically read by a CMOS-based camera

M. Marafini[a,b], V. Patera[a,b,d], D. Pinci[a*], A. Sarti[b,c,d], A. Sciubba[a,b,d] and E. Spiriti[c]

JINST 10 (2015) 12, P12010

ELECTRONS FROM NATURAL RADIOACTIVITY

CYGNO Experiment



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;

High granularity tracker based on a Triple-GEM optically read by a CMOS-based camera

M. Marafini[a,b], V. Patera[a,b,d], D. Pinci[a*], A. Sarti[b,c,d], A. Sciubba[a,b,d] and E. Spiriti[c]

JINST 10 (2015) 12, P12010

CYGNO

A CYGNus TPC module with Optical readout[1]

The CYGNO Experiment

Volume 6 · Issue 1 | March 2022

[1] Instruments 6 (2022)

THE CYGNO PROJECT AND CYGNUS COLLABORATION

CYGNO Experiment

The **CYGNO** collaboration is **developing** and **optimising** an optically readout Time Projection Chamber for the detailed study of Low Energy Rare Events;

CYGNO is working in the framework of **CYGNUS**: an **international proto-collaboration** aiming at the realisation of **Multi-site Recoil Directional Observatory** for WIMPs and neutrinos;

INFN Istituto Nazionale di Fisica Nucleare

Universidade de Coimbra

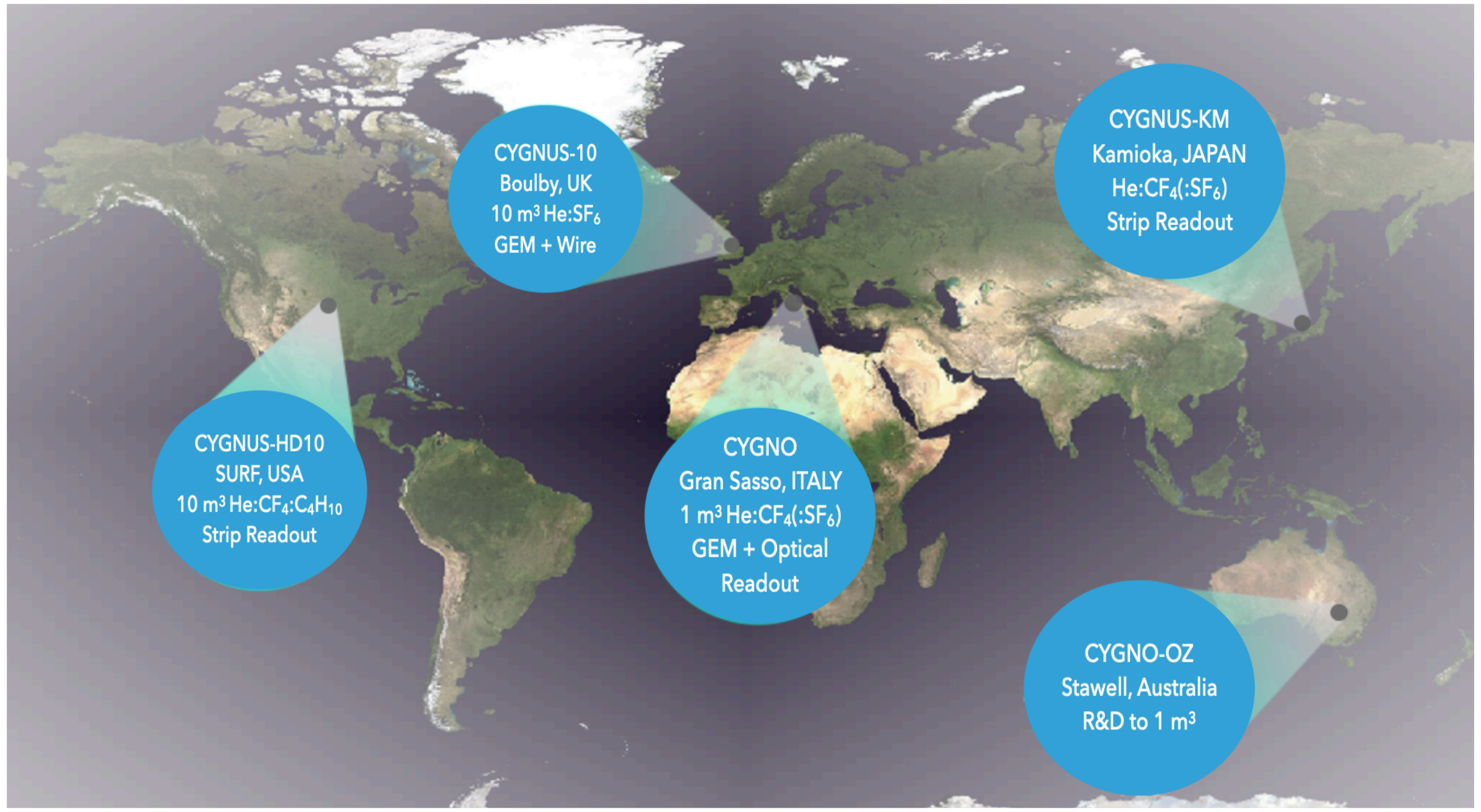
The University Of Sheffield.

Roma Tre Università degli Studi

GSSI

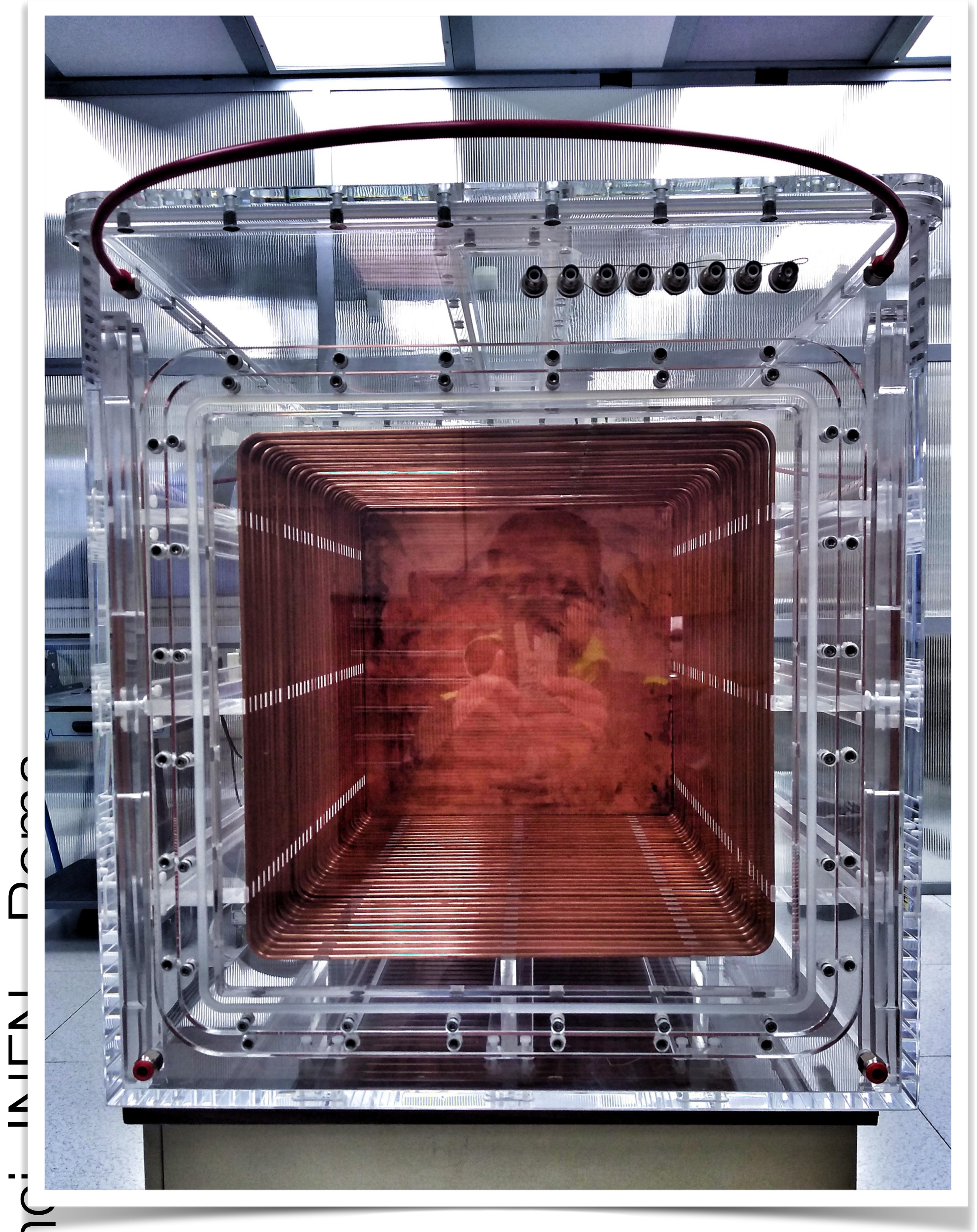
UFJF Universidade Federal de Juiz de Fora

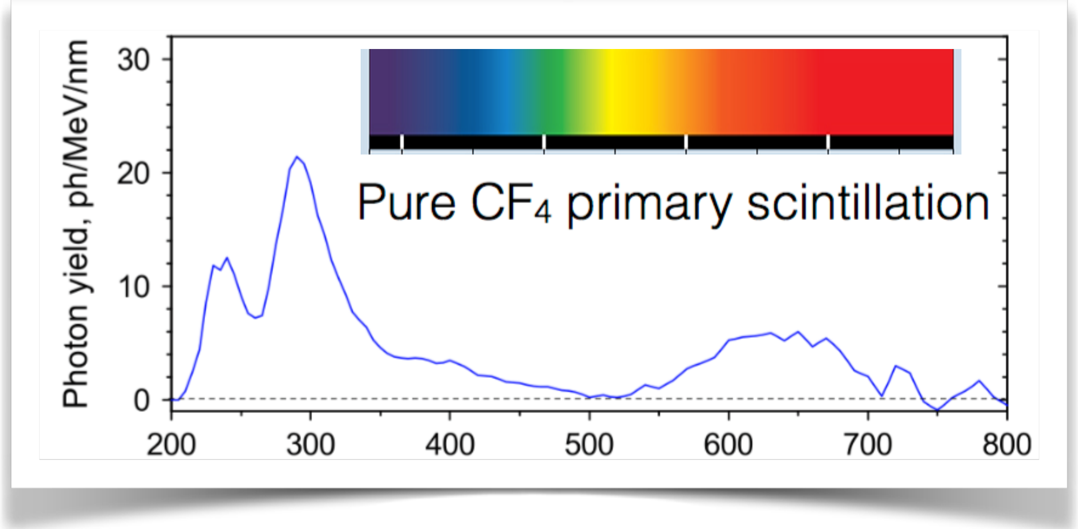
CBPF

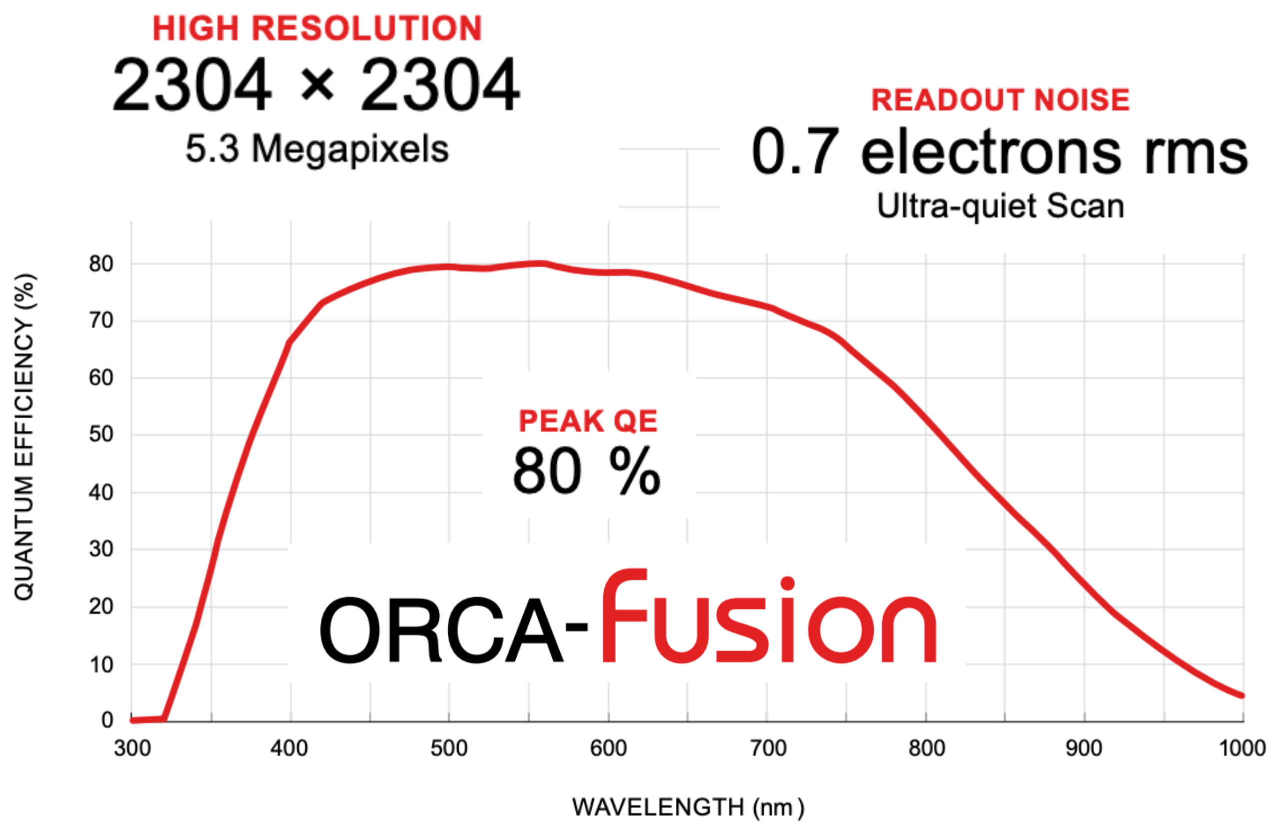


LIME: LARGE IMAGING MODULE

The Largest produced prototype is LIME with 50 litres sensitive volume: 33 x 33 ~ 1000 cm^2 GEM surface and 50 cm drift path with a **He/CF$_4$ (60/40)** based mixture at **atmospheric pressure**;





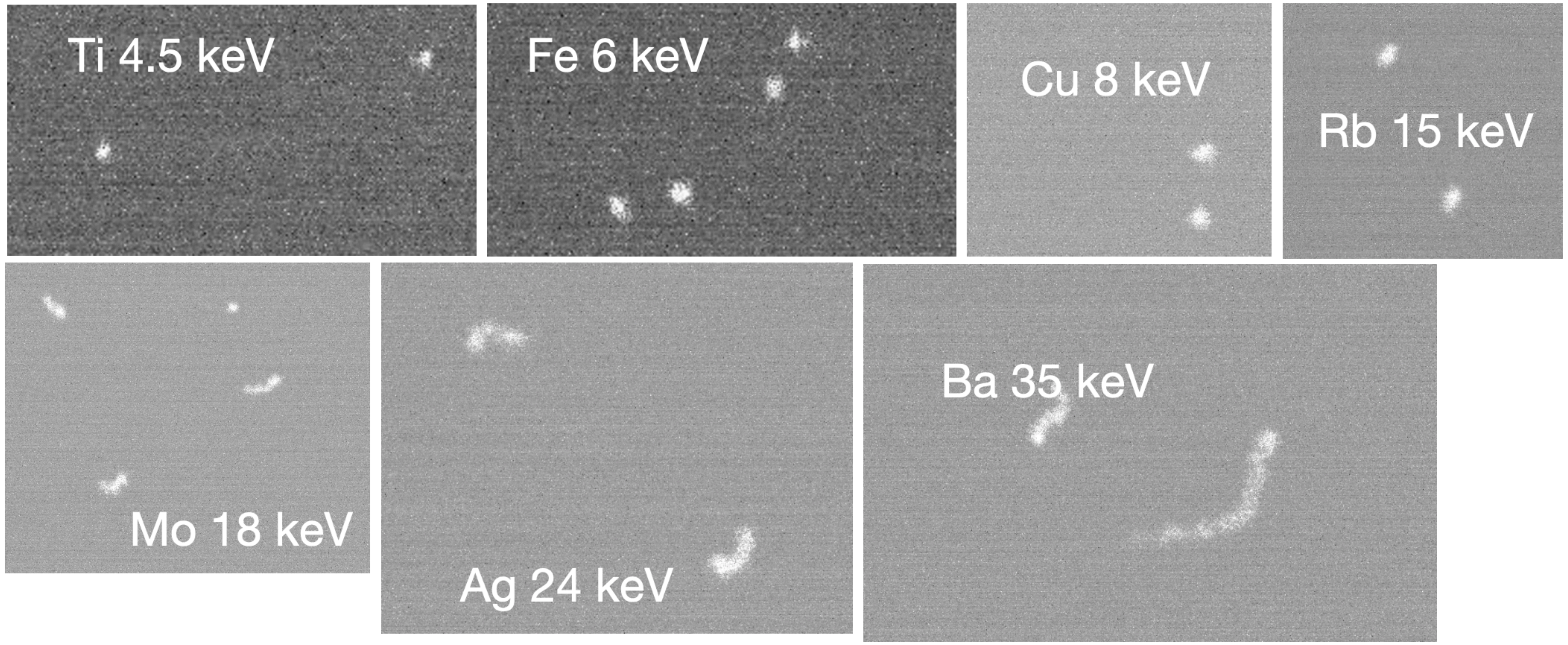


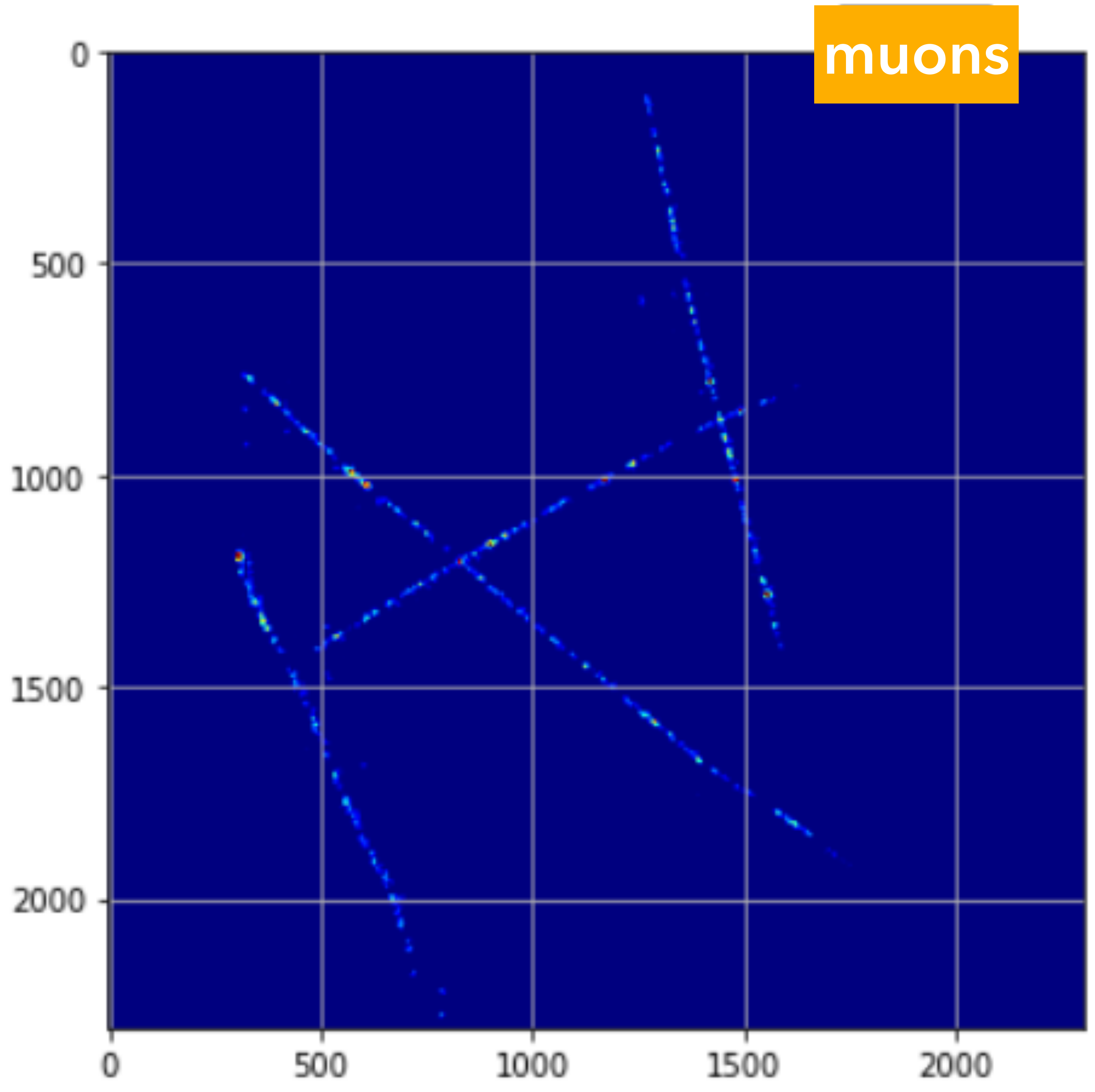
LIME is now in **operation** in the **Gran Sasso Labs Tunnel** to take data in **low radiation conditions**

A 50 l Cygno prototype overground characterization

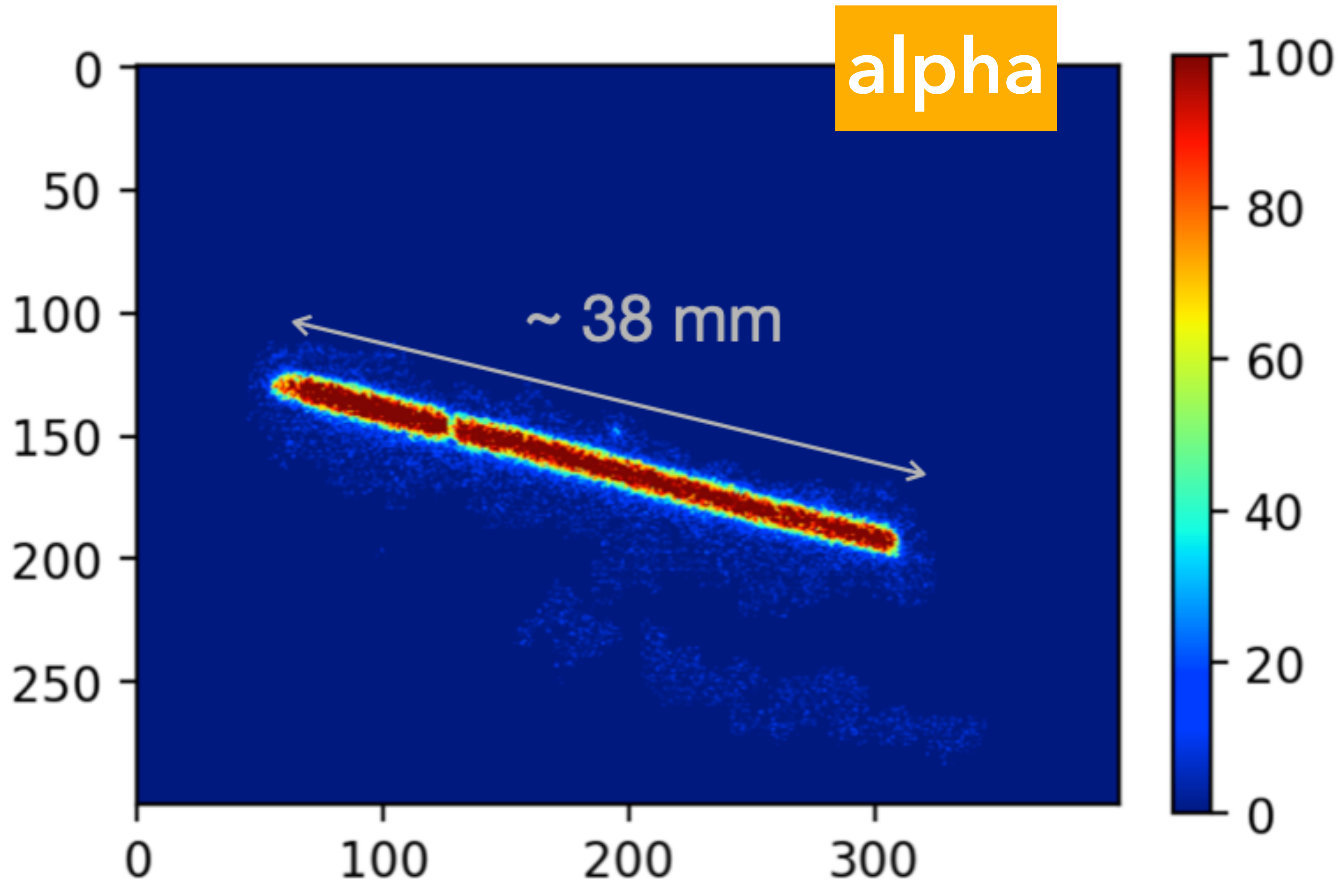
Eur.Phys.J.C 83 (2023) 10, 946

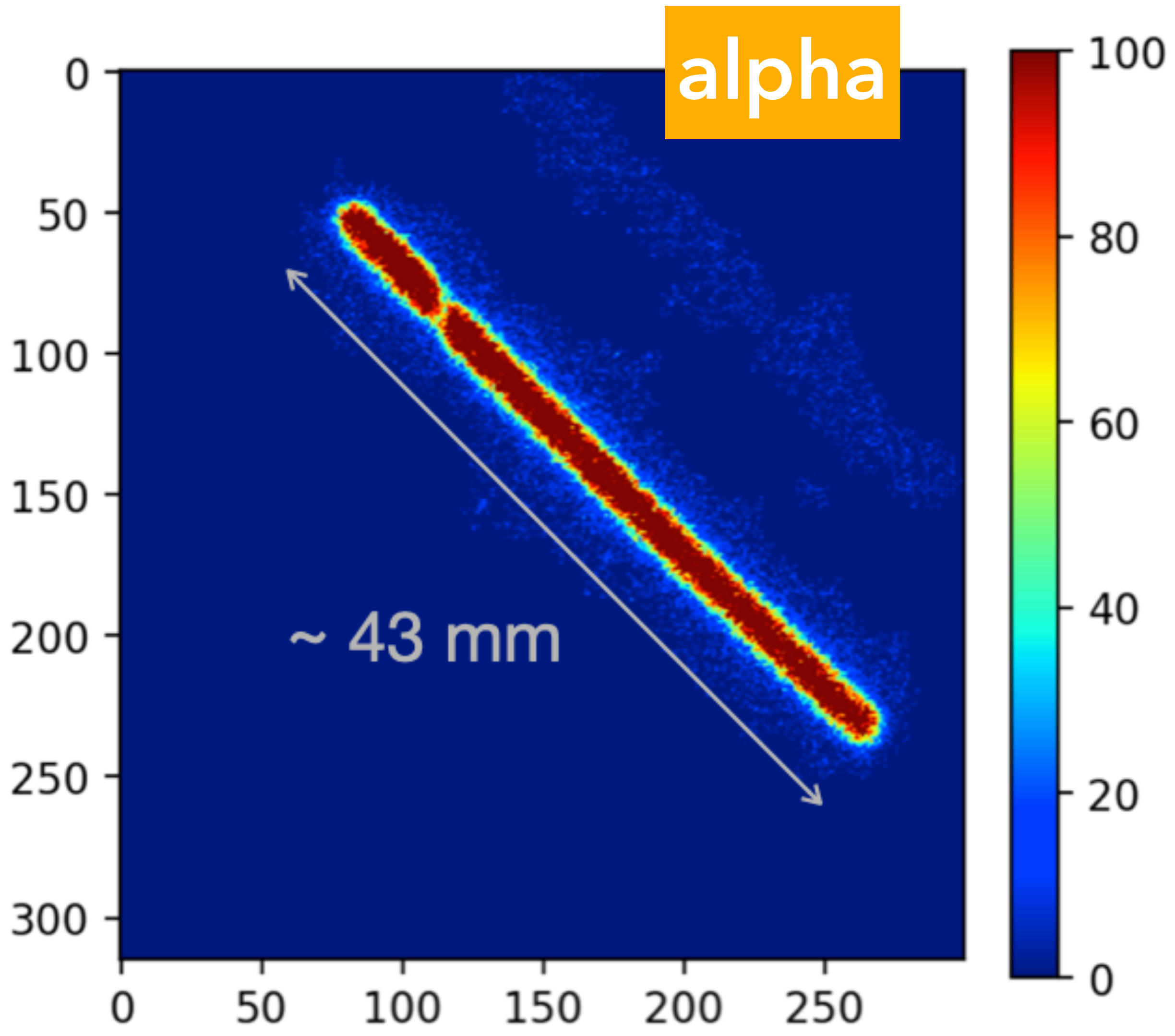
LIME: PARTICLE DETECTION





The **shapes** and **intensity** of the tracks produced by **electronic** and **nuclear recoils** are very **different** and this provides a **good tool for particle identification**





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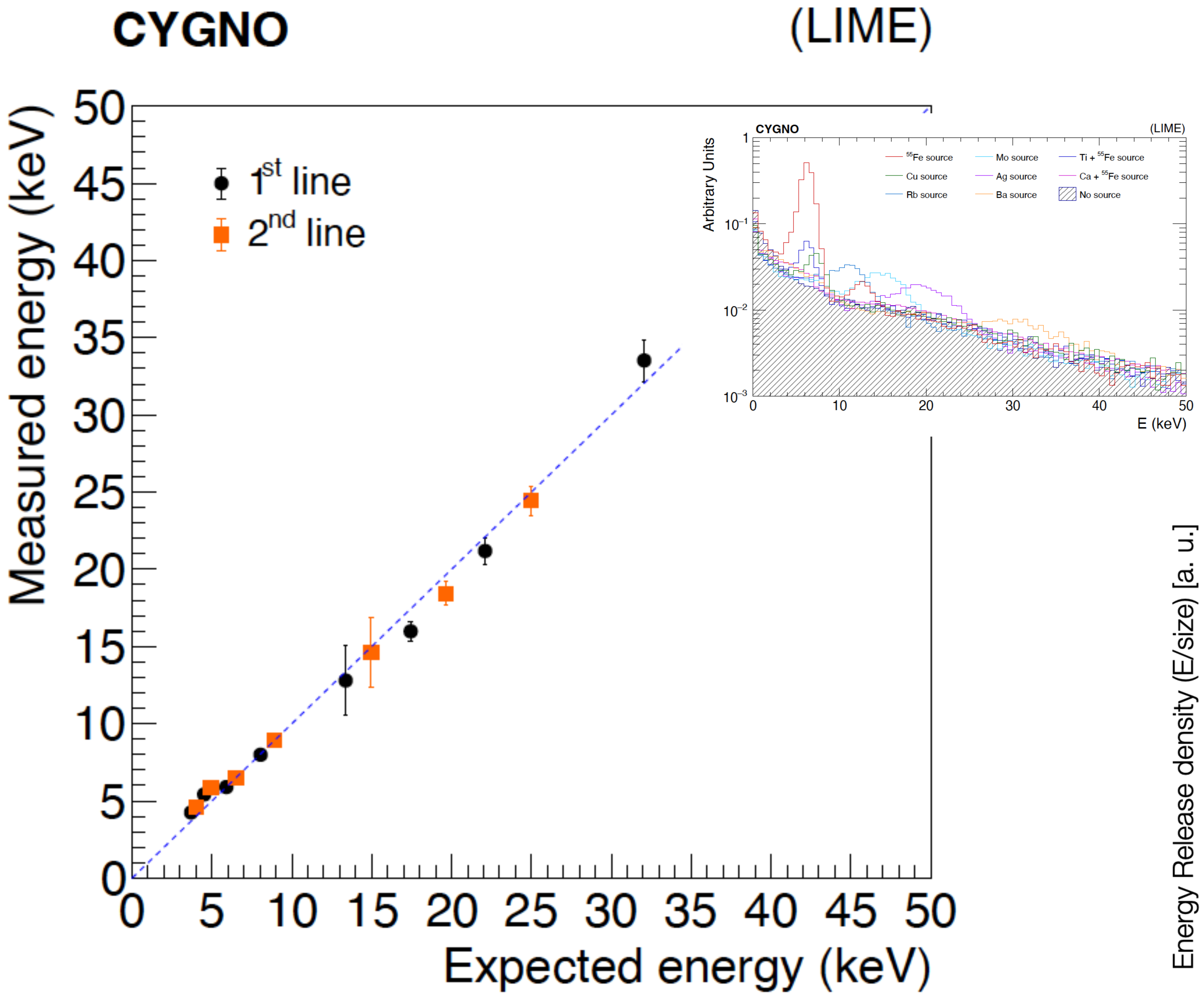
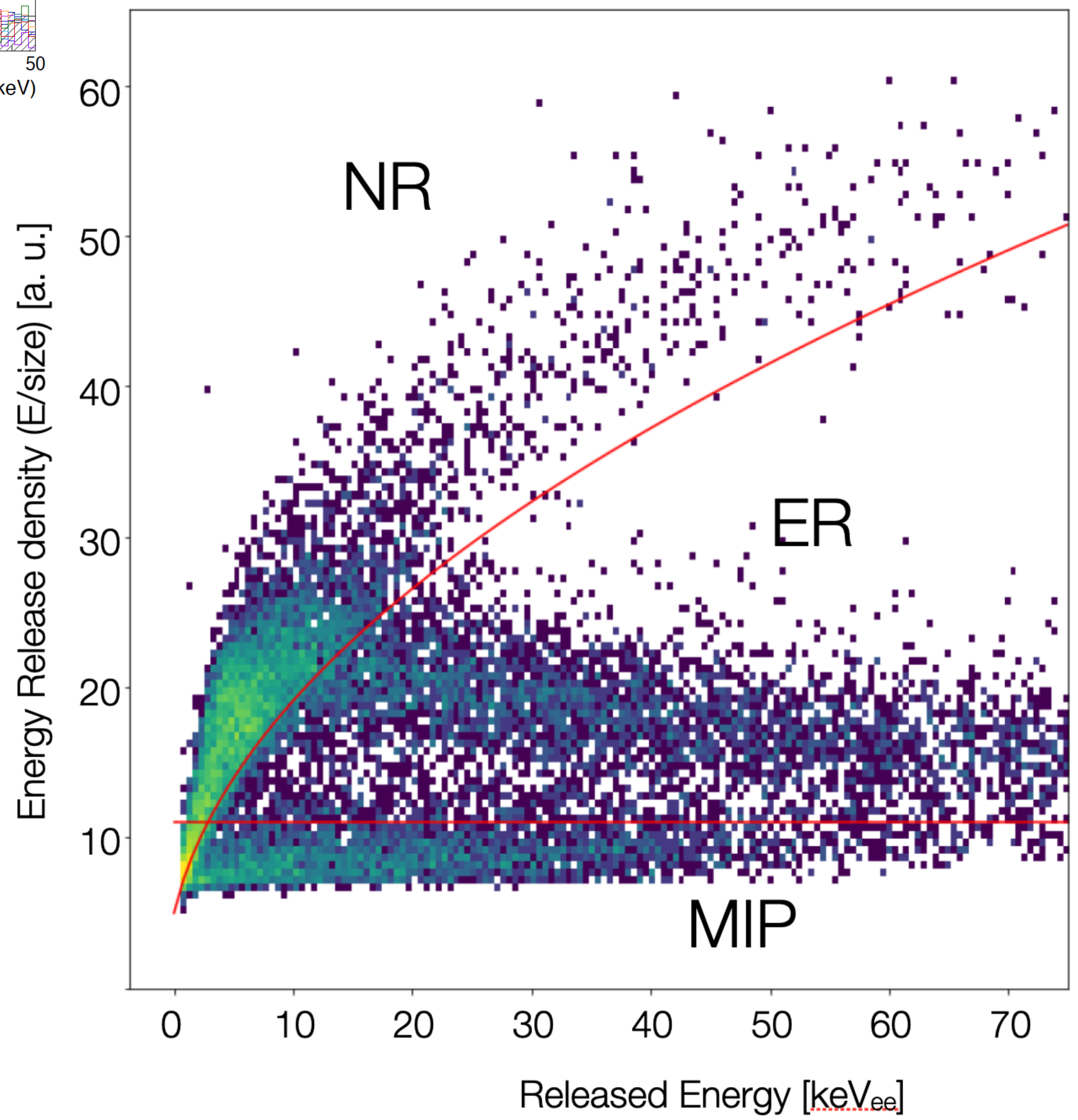
LIME: ENERGY MEASUREMENT AND PARTICLE IDENTIFICATION



Electron Recoils (ER): good response **linearity** found in the 4-40 keV range

Nuclear Recoils: by means of the **energy** release **density** (E/size) it is possible to **separate** the **NR** from the **ER** and **MIP** tracks



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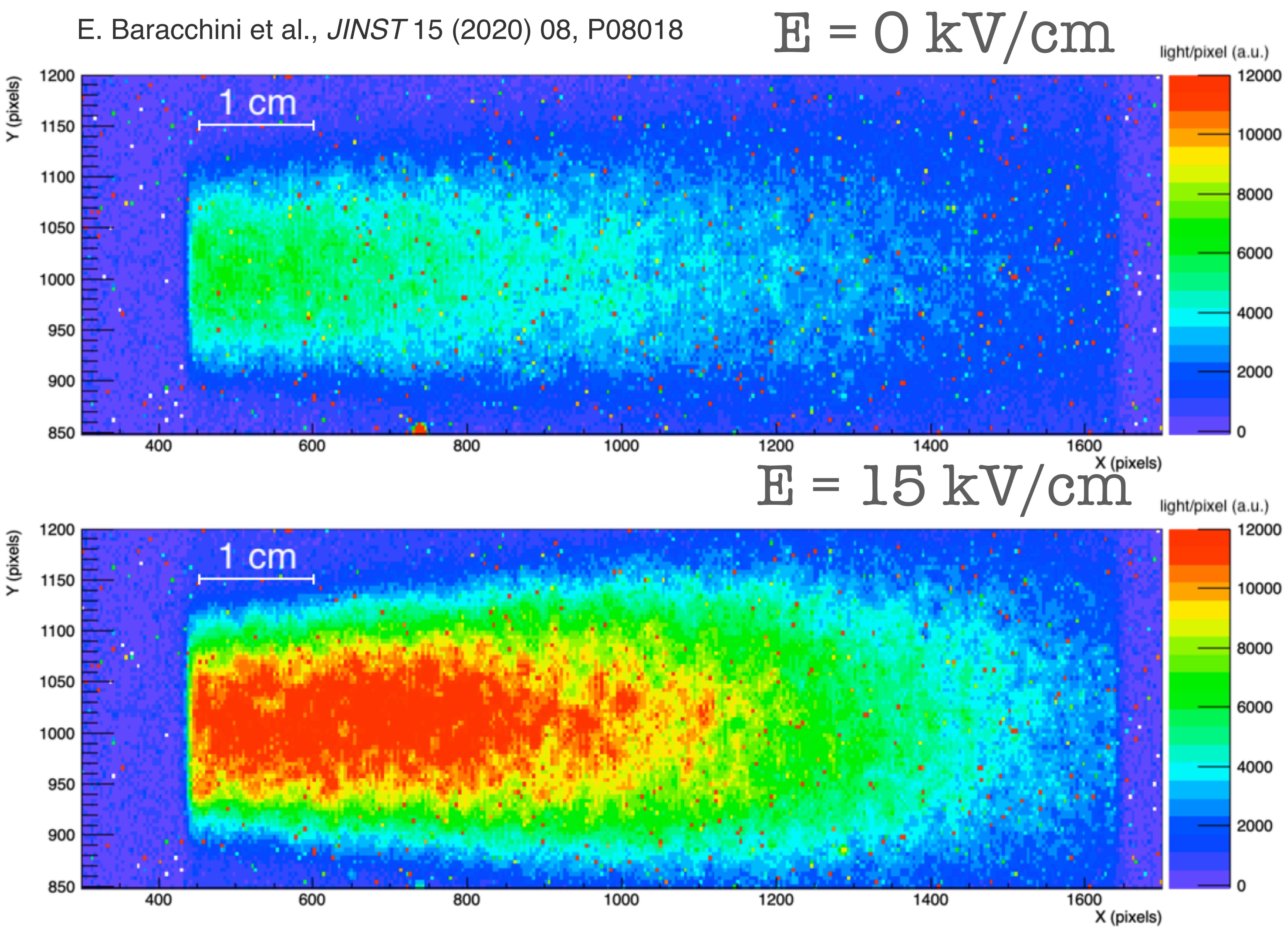
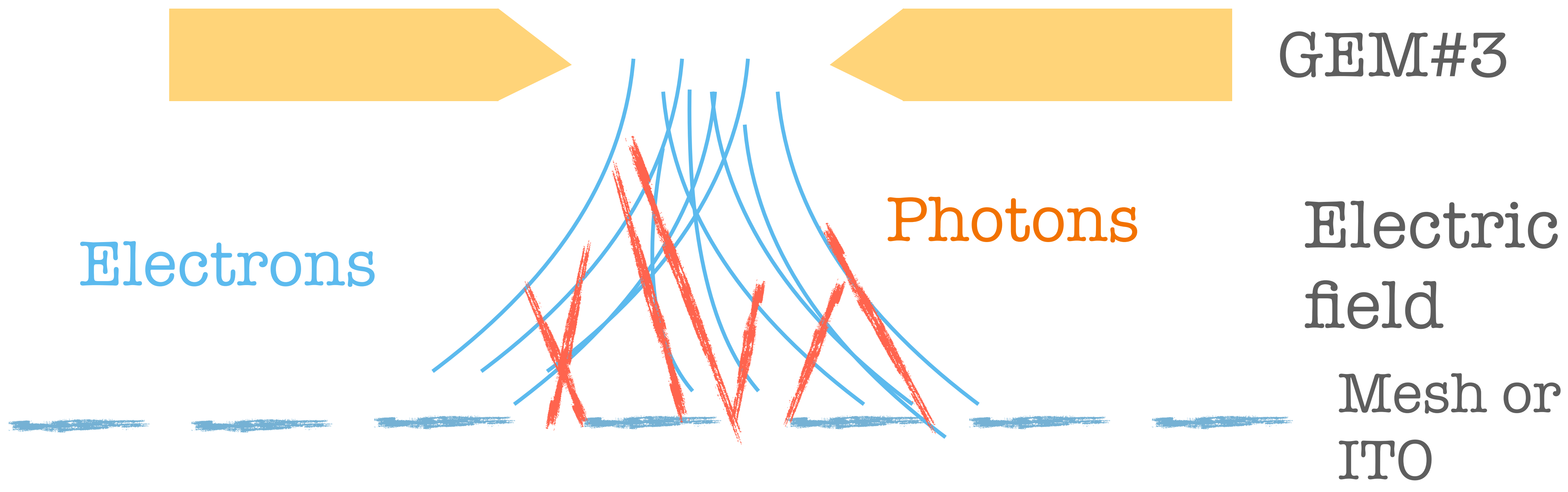
R&D: ELECTRO-LUMINESCENCE

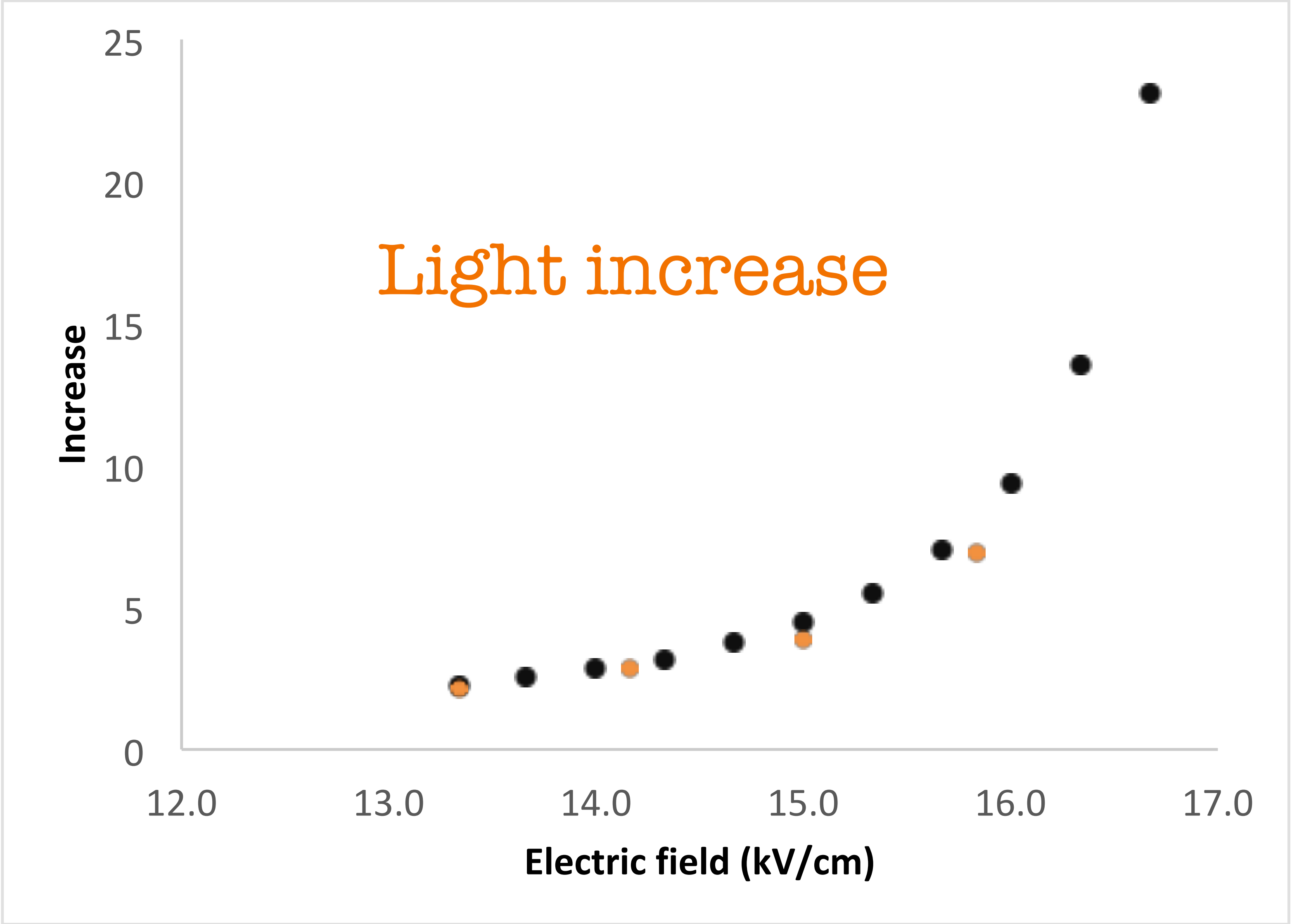
CYGNO Experiment

By **accelerating electrons** below the last GEM it is also possible to induce **luminescence in gas** and **increase** the total light **signal** in the detector;

E. Baracchini et al., *JINST* 15 (2020) 08, P08018







First evidence of an increase of light production **factor about 25** quite larger than total charge increase (factor 3-4)

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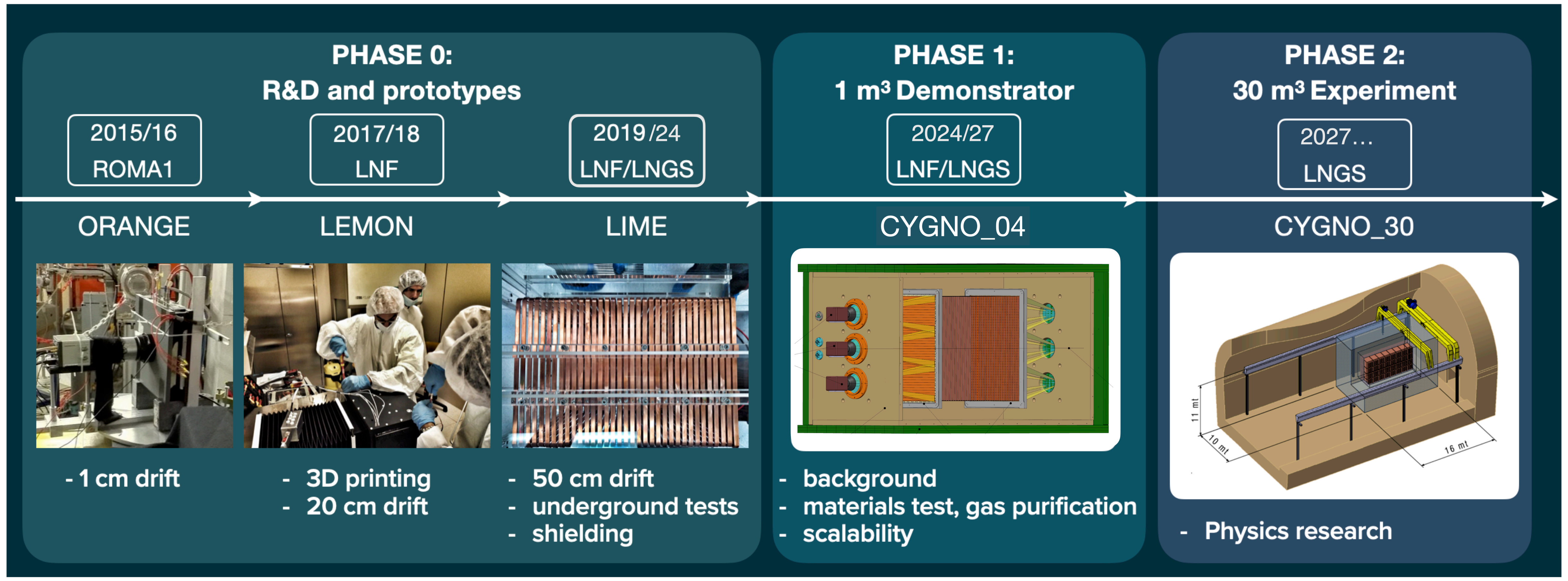
ADVANTAGES OF OPTICAL READOUT AND FUTURE PLANS

- 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:
- 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;



After **10 years of R&D**, a **0.4 m³ demonstrator** is expected to be installed underground in **Gran Sasso Labs in 2025**

According to its results**, a large size experiment** can be **proposed**

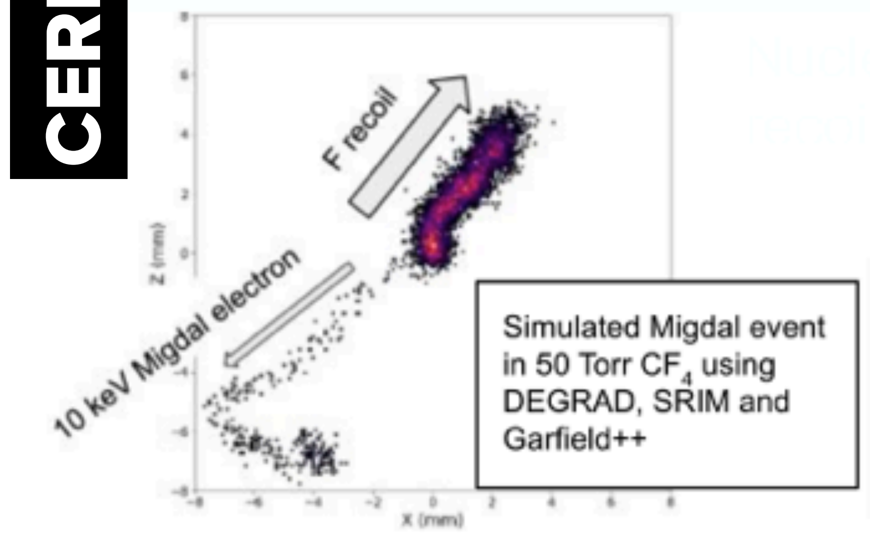
CYGNO PROGENY: OPTICAL READOUT TPC PROJECTS

CYGNO Experiment

CERN 2020

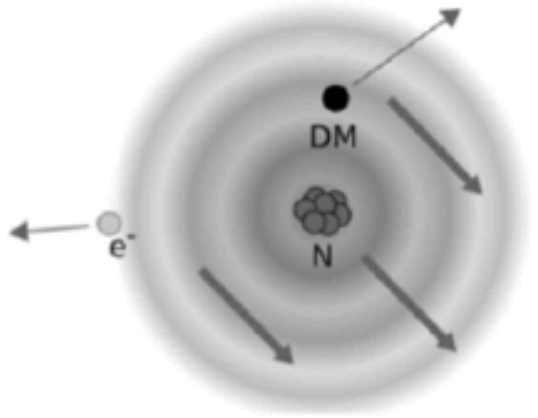
MIGDAL
Migdal In Galactic Dark mAtter expLoration

Low-pressure TPC with optical+electronic readout



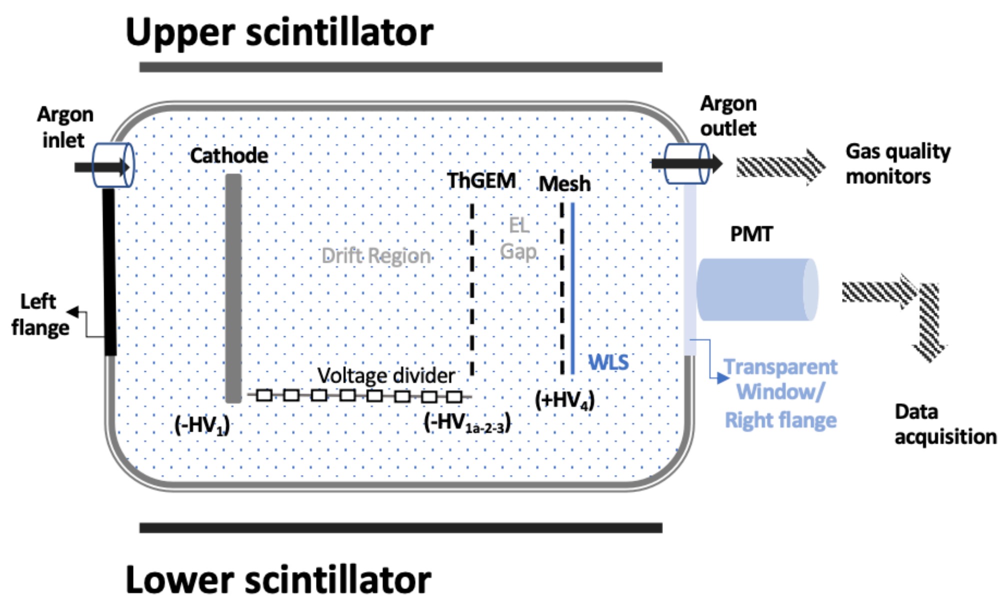
Migdal effect search in low-pressure CF_4 for DM searches in

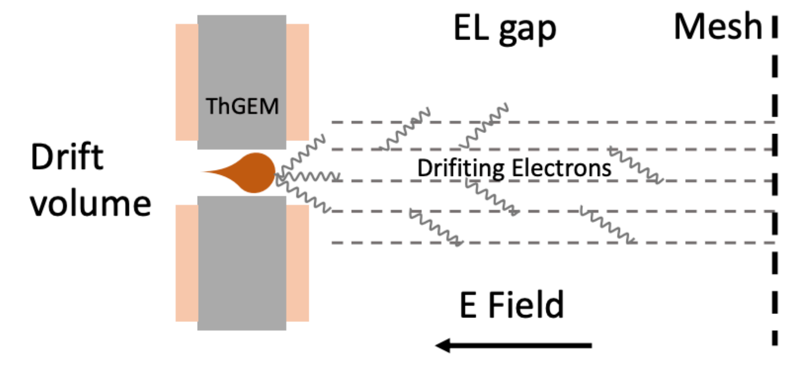
CMOS + electronic readout of **transparent strip anode**



P. Majewski, RD51 Mini-Week 2020, https://indico.cern.ch/event/872501/contributions/3730586/attachments/1985262/3307758/RD51_mini_week_Pawel_Majewski_ver2.pdf

A gaseous argon time projection chamber with electroluminescence enhanced optical readout



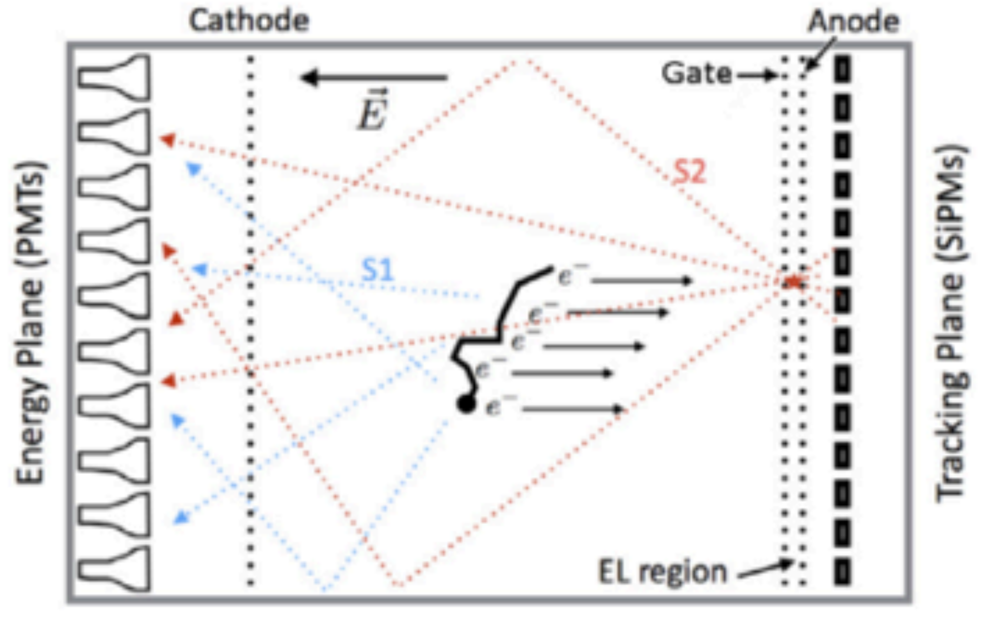


GENEVA UNIVERSITY 2022

arXiv:2212.02385v1 [physics.ins-det] 5 Dec 2022

next

High Pressure Xe gas TPC with electroluminescent amplification



Neutrinoless double beta decay searches in ^{136}Xe

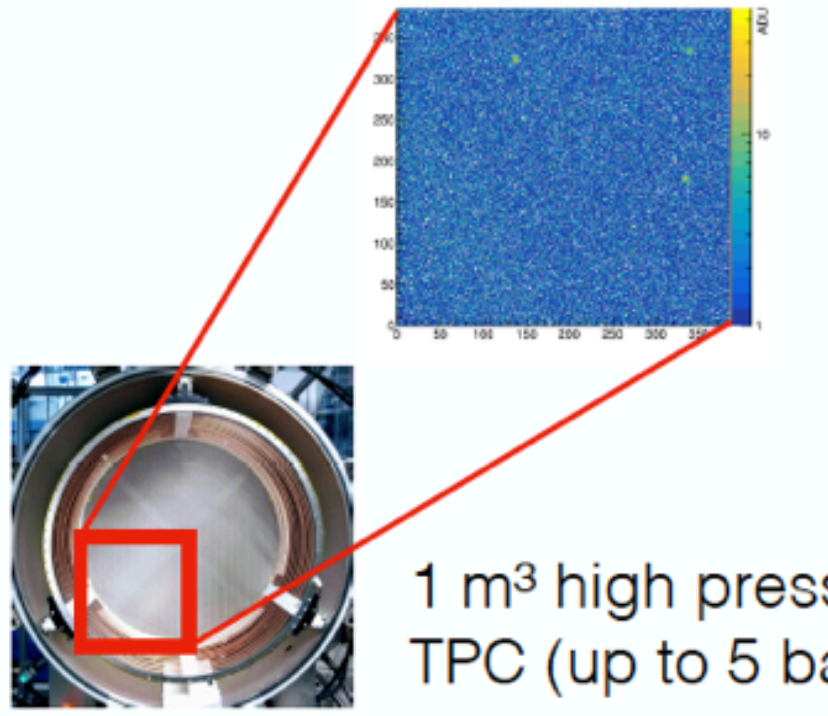
PMTs for energy measurement & t_0 from S1, **SiPM-based tracking** plane recording electroluminescence

https://next.ific.uv.es/next/experiment/detector.html
L. Arazi, Status of the NEXT project, https://doi.org/10.1016/j.nima.2019.04.080

CANFRANC 2019

High Pressure TPC

Towards a neutrino-nucleus cross section experiments



Stitched optical readout (4 CCD cameras) + **electronic signals** from meshes used for amplification

1 m³ high pressure TPC (up to 5 bar)

DUNE COLLABORATION 2021

A. Deisting, HPTPC, https://arxiv.org/pdf/2102.06643.pdf


THANKS!