Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI
Divisione Ricerca

LNF general seminar

Istituto Nazionale di Fisica Nucleare

Sezione di Roma

Seminari

INFN-Fisica sperimentale delle particelle elementari

CYGNO Experiment

in synergy with erc

INITIUM

funded from ERC in Horizon 2020 program (grant agreement 818744)

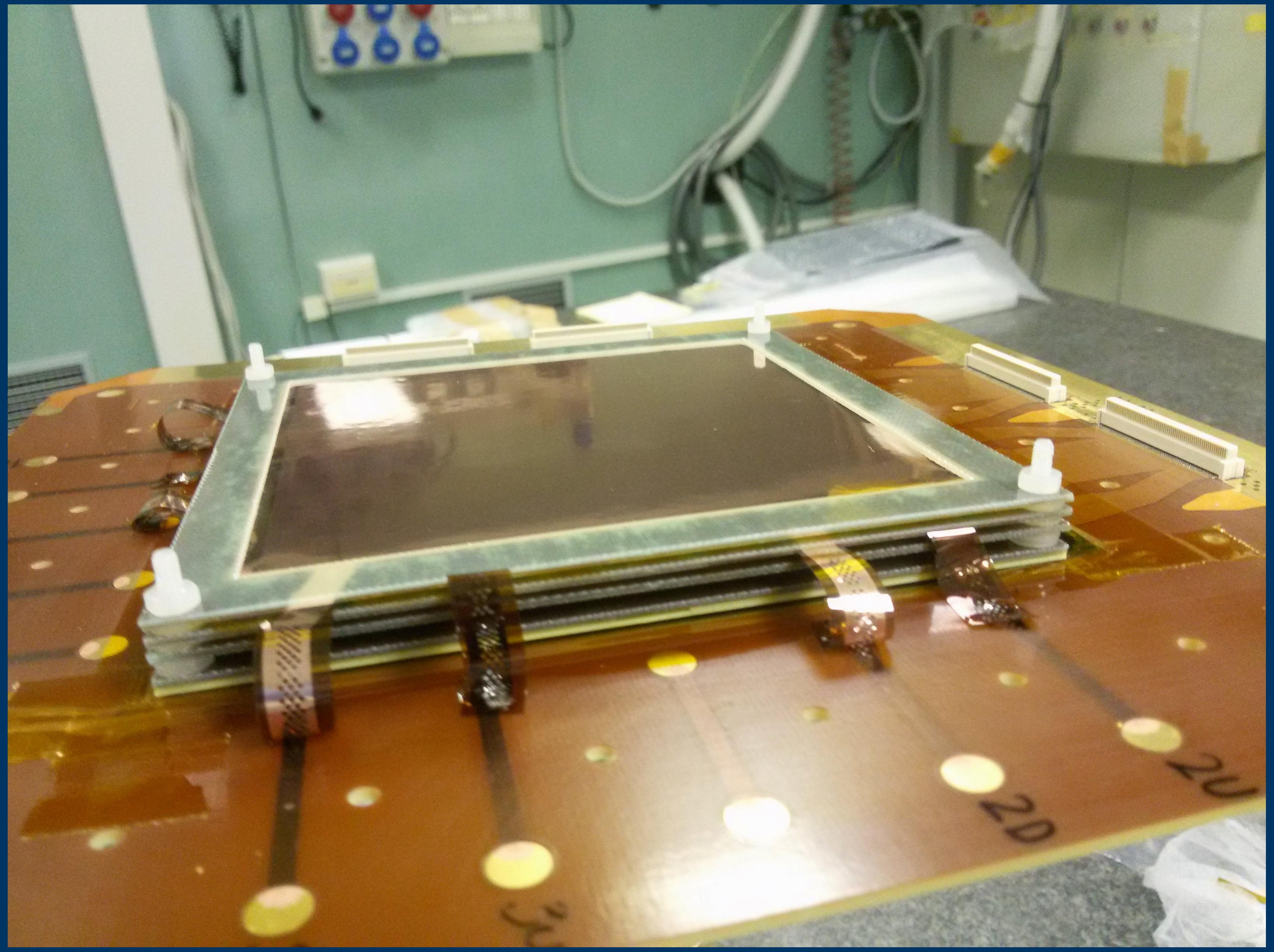
CYGNO: an Optical TPC for the search of rare events

F. D. Amaro, E. Baracchini, L. Benussi, S. Bianco, C. Capoccia, M. Caponero, G. Cavoto, A. Cortez, R. J. de Cruz Roque, I. A. Costa, E. Dané, E. Di Marco, G. D'Imperio, G. Dho, F. Di Giambattista, R. R. M. Gregorio, F. Iacoangeli, H. P. Lima Júnior, G. Maccarrone, R. D. P. Mano, M. Marafini, G. Mazzitelli, A. G. Mc Lean, A. Messina, M. L. Migliorini, C.M.B. Monteiro, R. A. Nóbrega, A. Orlandi, I. F. Pains, E. Paoletti, L. Passamonti, F. Petrucci, S. Pelosi, S. Piacentini, D. Piccolo, D. Pierluigi, D. Pinci, A. Prajapati, F. Renga, F. Rosatelli, A. Russo, J.M.F. dos Santos, G. Saviano, A. da Silva Lopes Júnior, N. Spooner, R. Tesauro, S. Tomassini, S. Torelli

CYGNO Experiment

The **CYGNO** collaboration is **developing** and optimising a new **technique** for the detailed study of Low Energy Rare Events;

This project, started by few people in Rome in 2015, with a small prototype assembled in the Clean Room in Officina Meccanica has now almost **50 collaborators**, from **8 Institutions** in **4 Countries**



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UNIVERSIDADE D COIMBRA

The University Of Sheffield.

ROMA TRE UNIVERSITÀ DEGLI STUDI

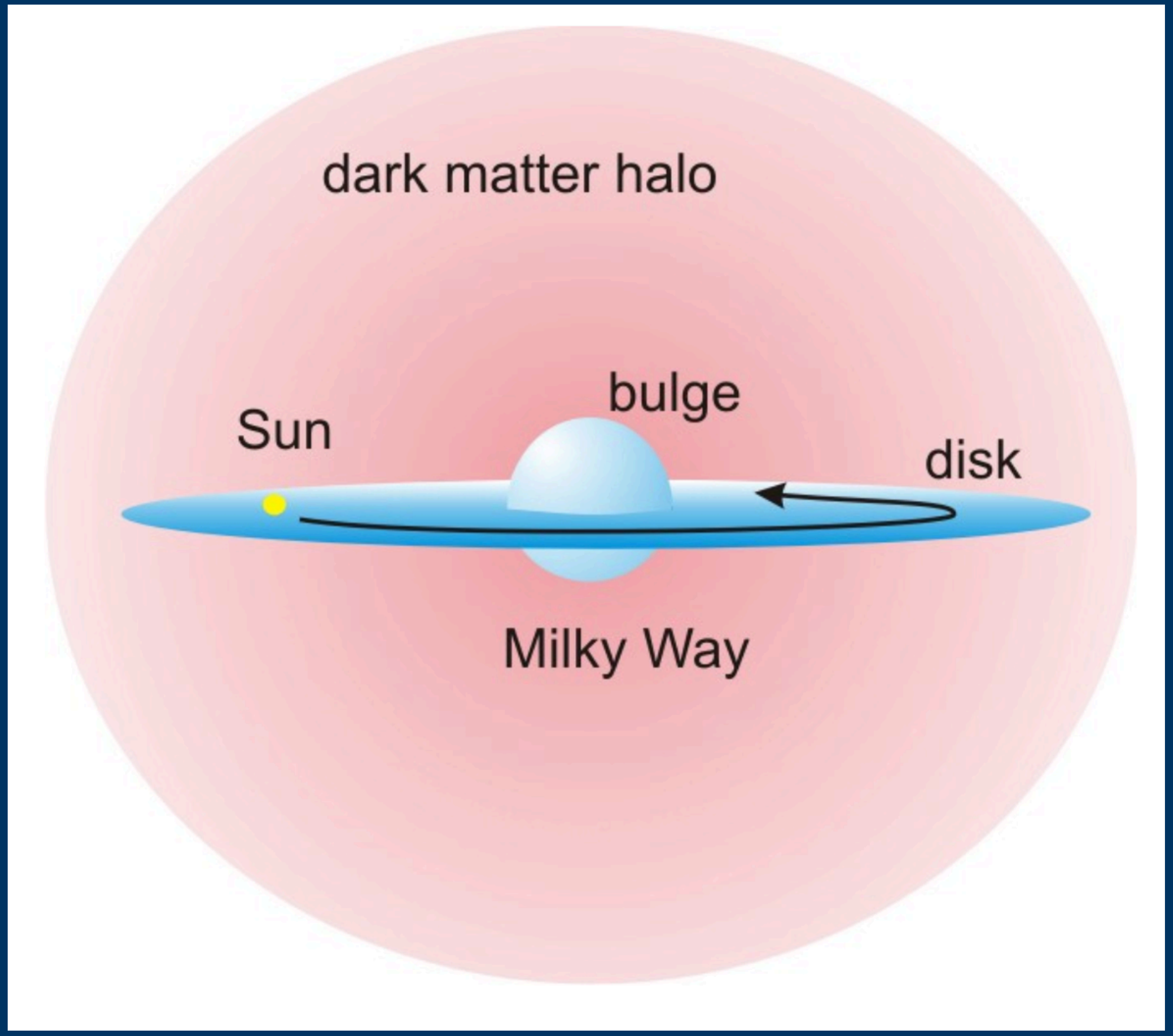
GSSI

ufjf UNIVERSIDADE FEDERAL DE JUIZ DE FORA

CBPF

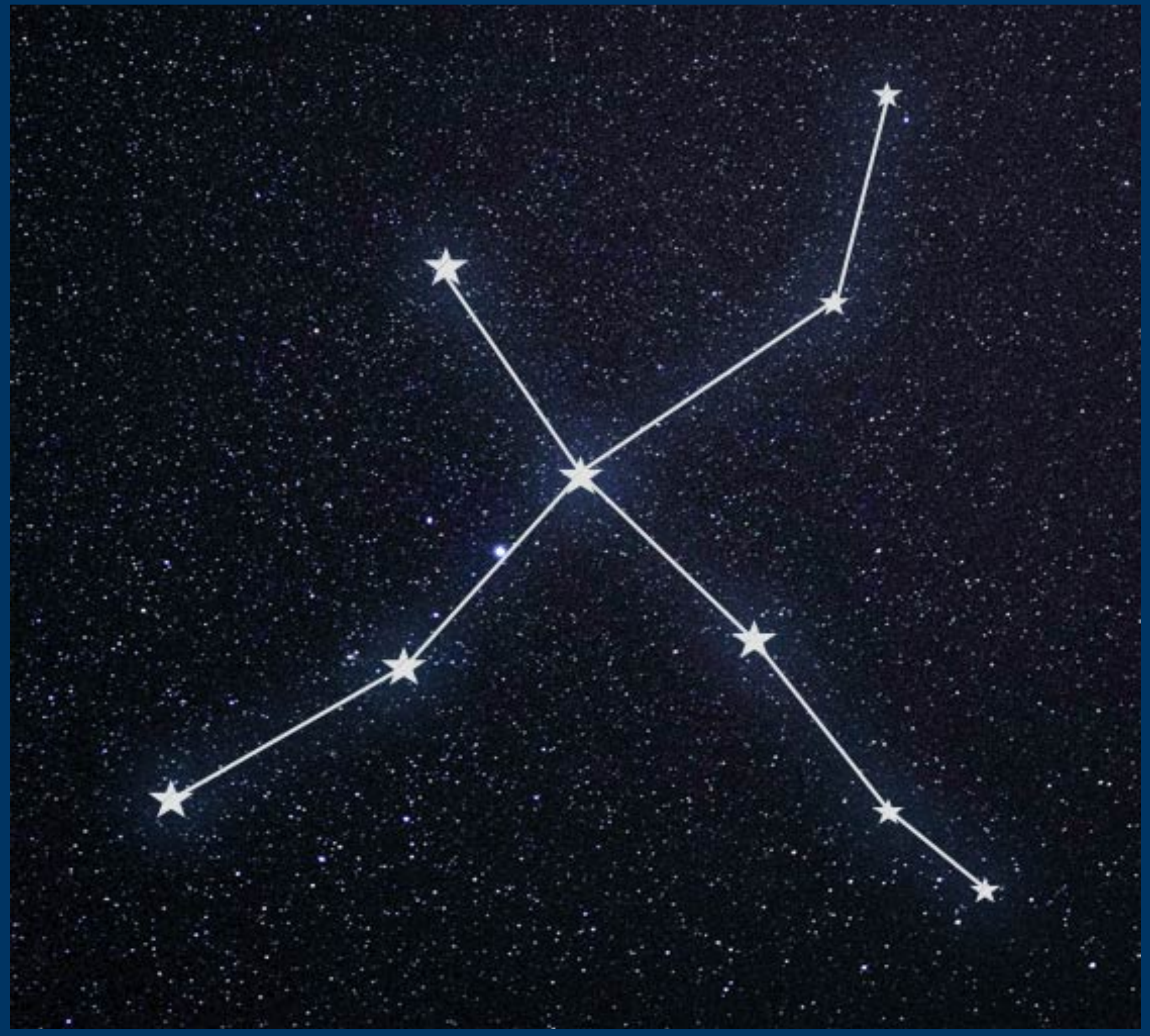
DARK MATTER AND WIMPS

One of possible constituents of **Dark Matter** are the **Weakly Interacting Massive Particles**: neutral particles with a very low interaction probability with ordinary matter;



Our **Milky Way**, is surrounded by an approximately spherical **not luminous halo** of **WIMPs**.

The Sun and the planets move through this halo at **220 km/s** preceded by the **CYGNUS**



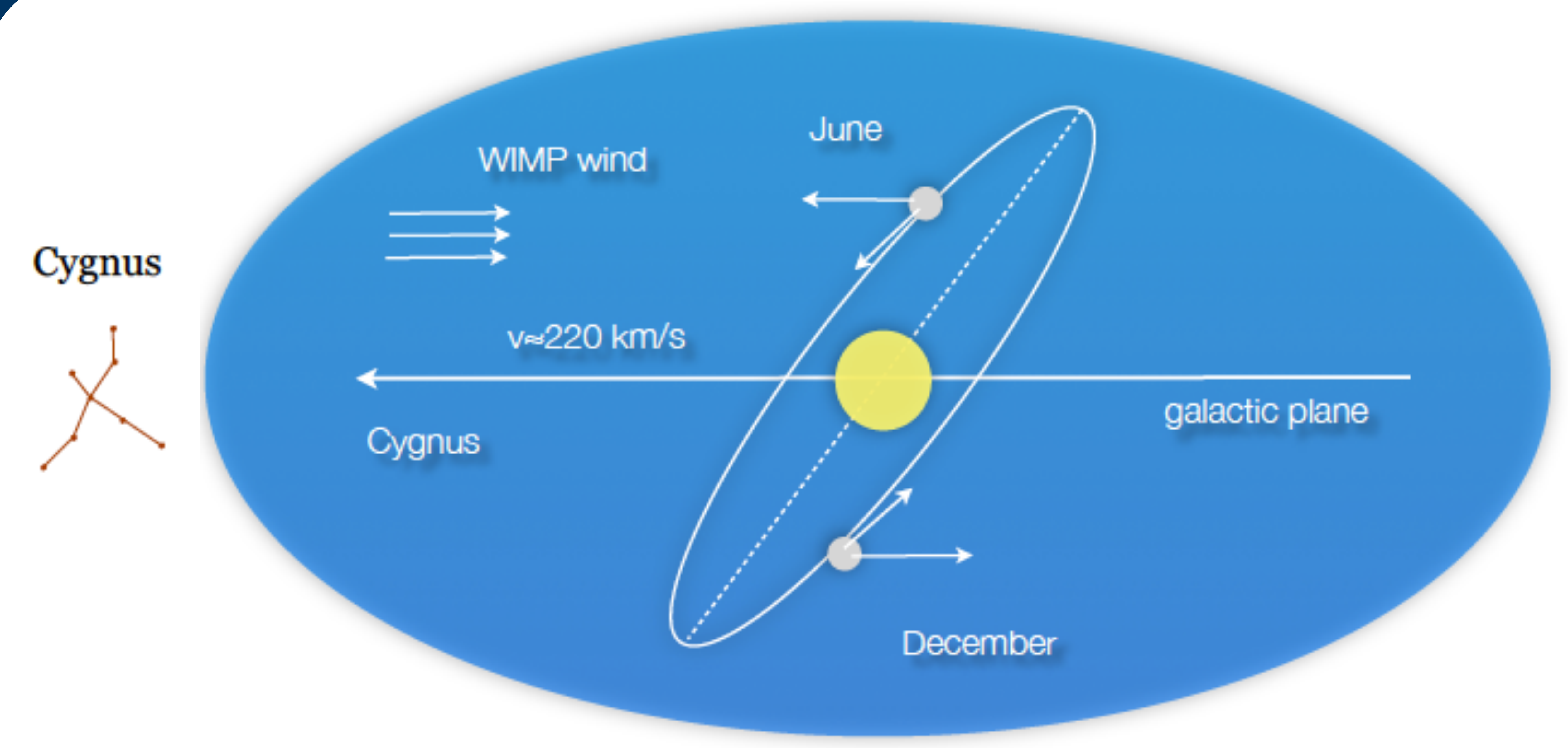
WIMPs have a **Maxwell-Boltzmann-like** velocity distribution with **tail up to 600 km/s** $\beta = 2 \ 10^{-3}$

TIME MODULATION

v_{sun} = 230 km/s

v_{orb} = 30 km/s

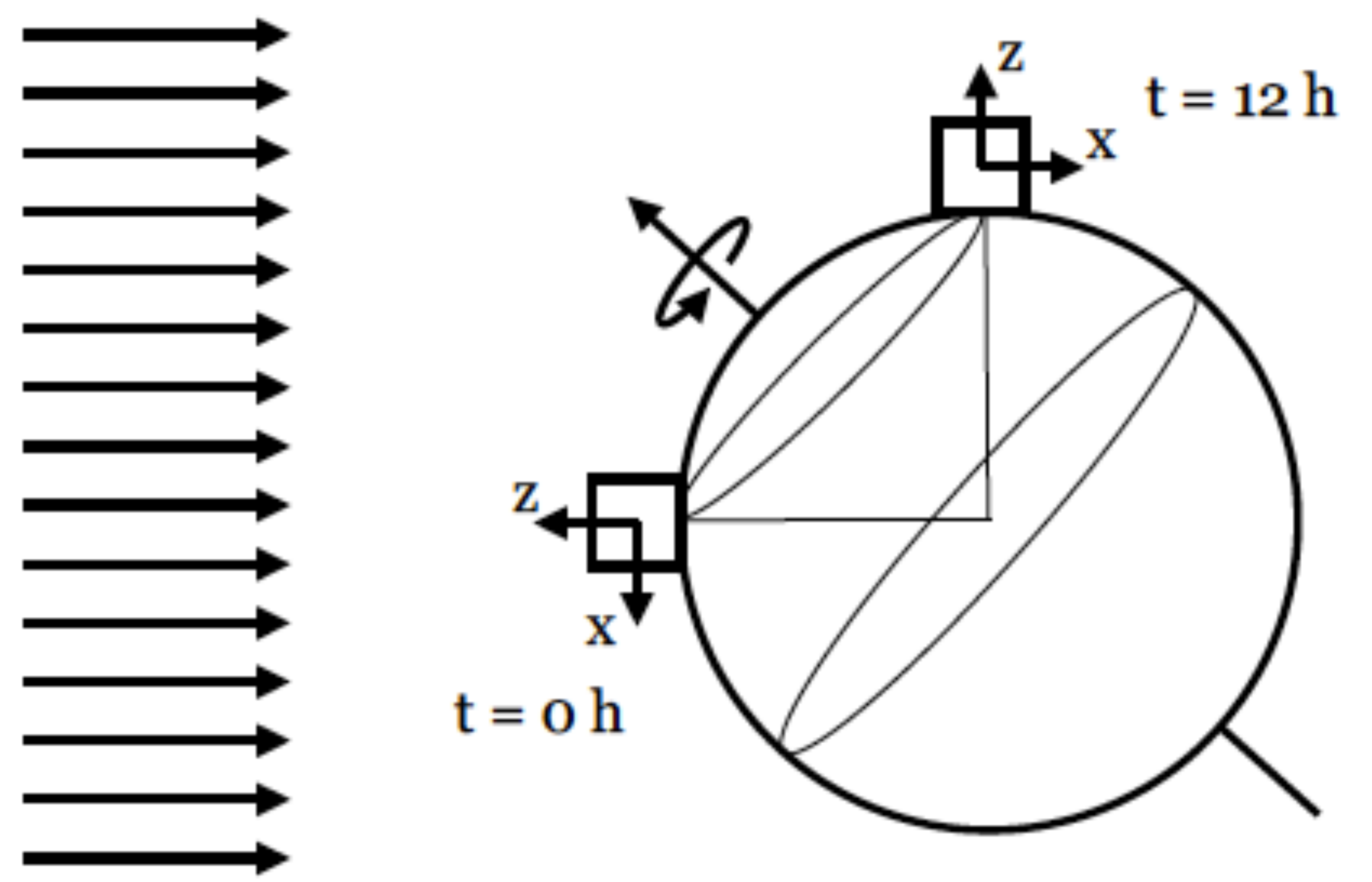
γ = 60°



$$v(t)_{DM} = v_{sun} + v_{orb}\ cos\gamma\ cos(\omega(t - t_0))$$

Asymmetry "forward-backward": 20%-100%

Annual rate **modulation**: 2%-10%



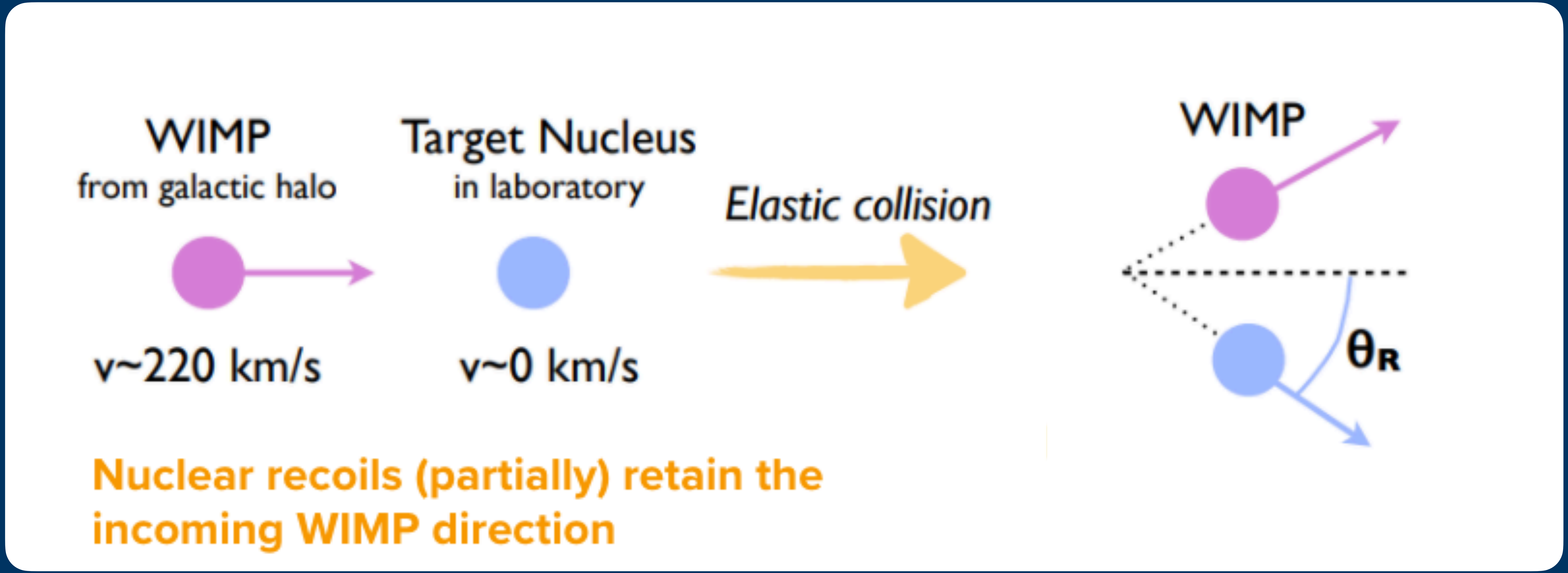
Daily based **modulation** of incoming particle direction

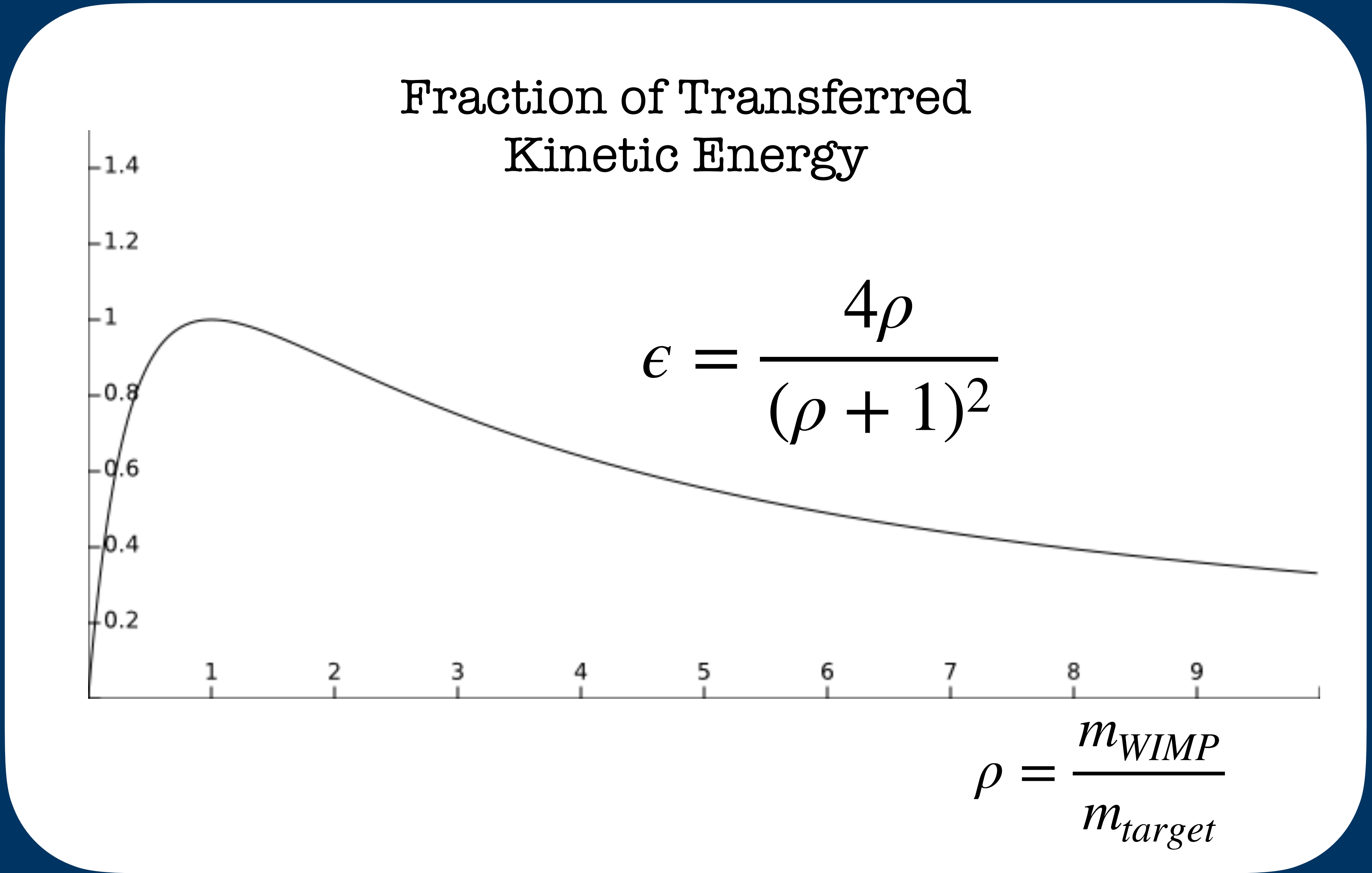
At a 40° latitude, direction is expected to oscillate between **vertical** and **horizontal** with a 12 h period

Strong and unique signature

WIMPS AND HOW TO DETECT THEM

- One possibility is trying to detect the products of its **interactions with ordinary matter**, in particular with **charged particles** that we know how to detect;

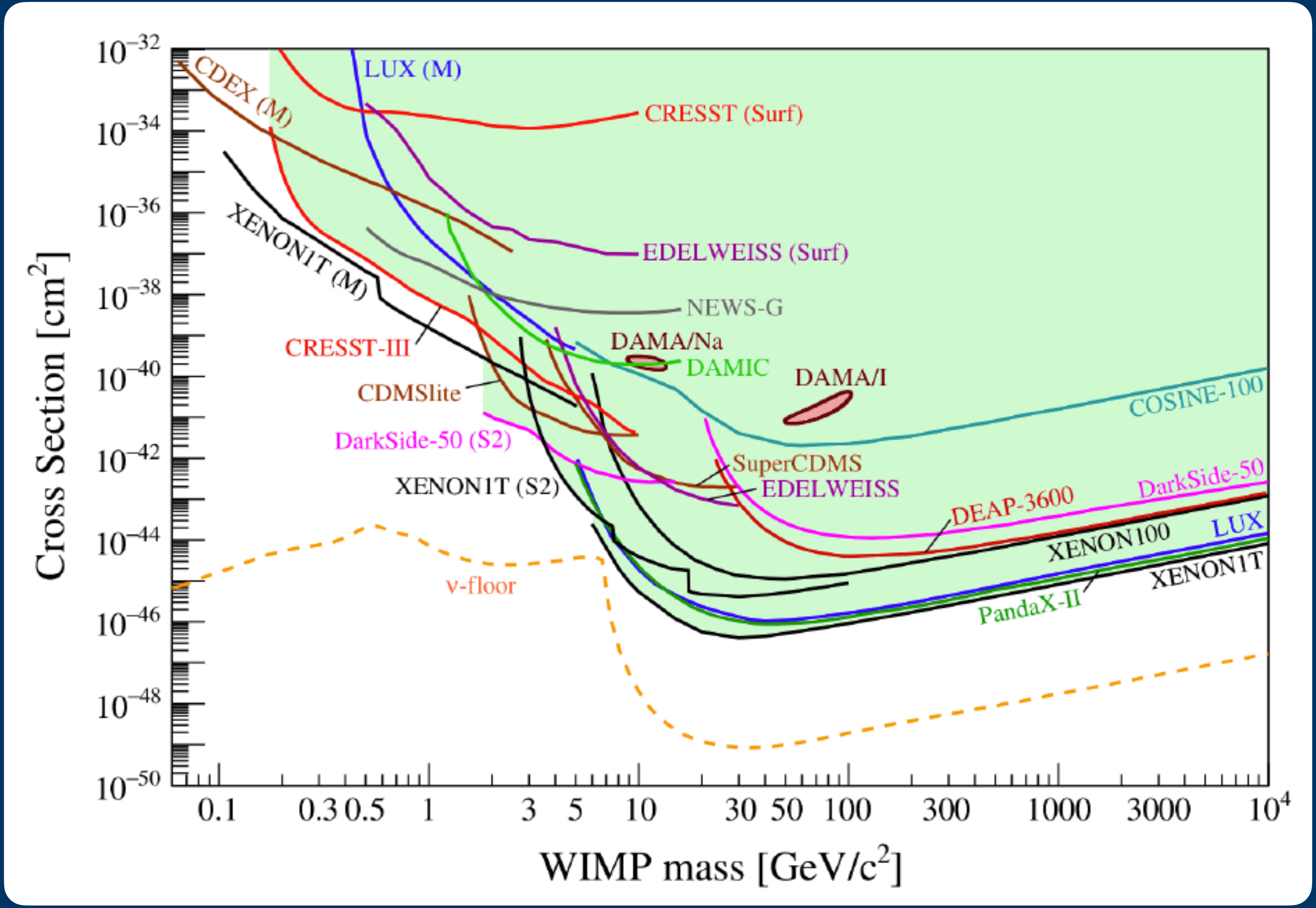




- How to choose a good target?
- In order to **maximise** the fraction of **transferred energy** it is then crucial to have target of almost **same mass**

WIMP MASSES

- Large regions of **high masses** spectrum already explored **without** any confirmed **evidence of WIMP**;



- Future focus on **masses below 10 GeV**;

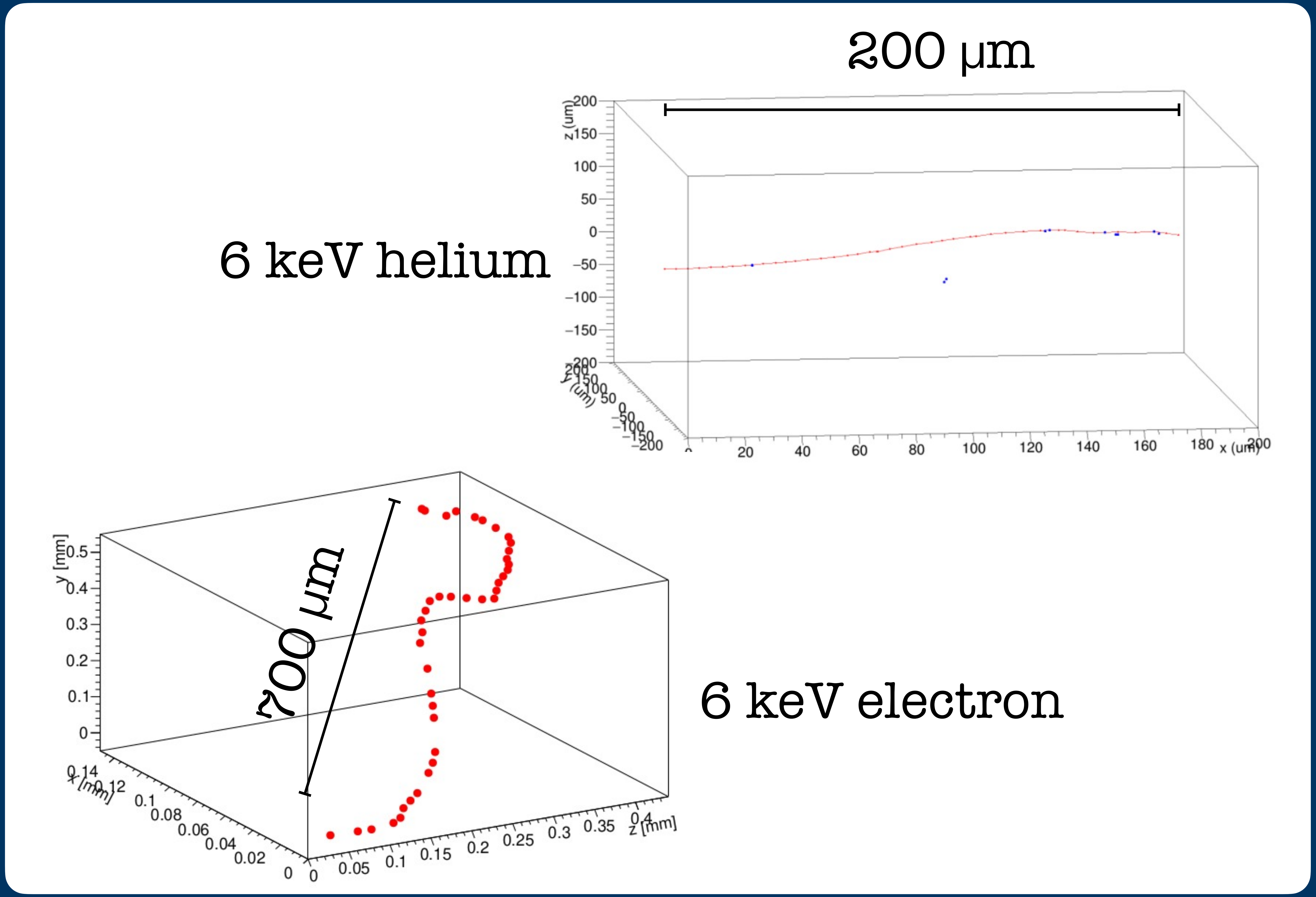
Element	Max E transferred by a 1 GeV WIMP	Min WIMP mass with 1 keV threshold
H	2.00 keV	0.5 GeV
He	1.30 keV	0.9 GeV
C	0.57 keV	1.4 GeV
F	0.38 keV	1.7 GeV
Na	0.32 keV	1.8 GeV
Si	0.27 keV	2.0 GeV
Ar	0.20 keV	2.4 GeV
Xe	0.06 keV	4.2 GeV

(assuming $\beta = 2 \times 10^{-3}$)

- To explore the GeV mass range, **best candidates** are **He** and **H**

WIMP SEARCH

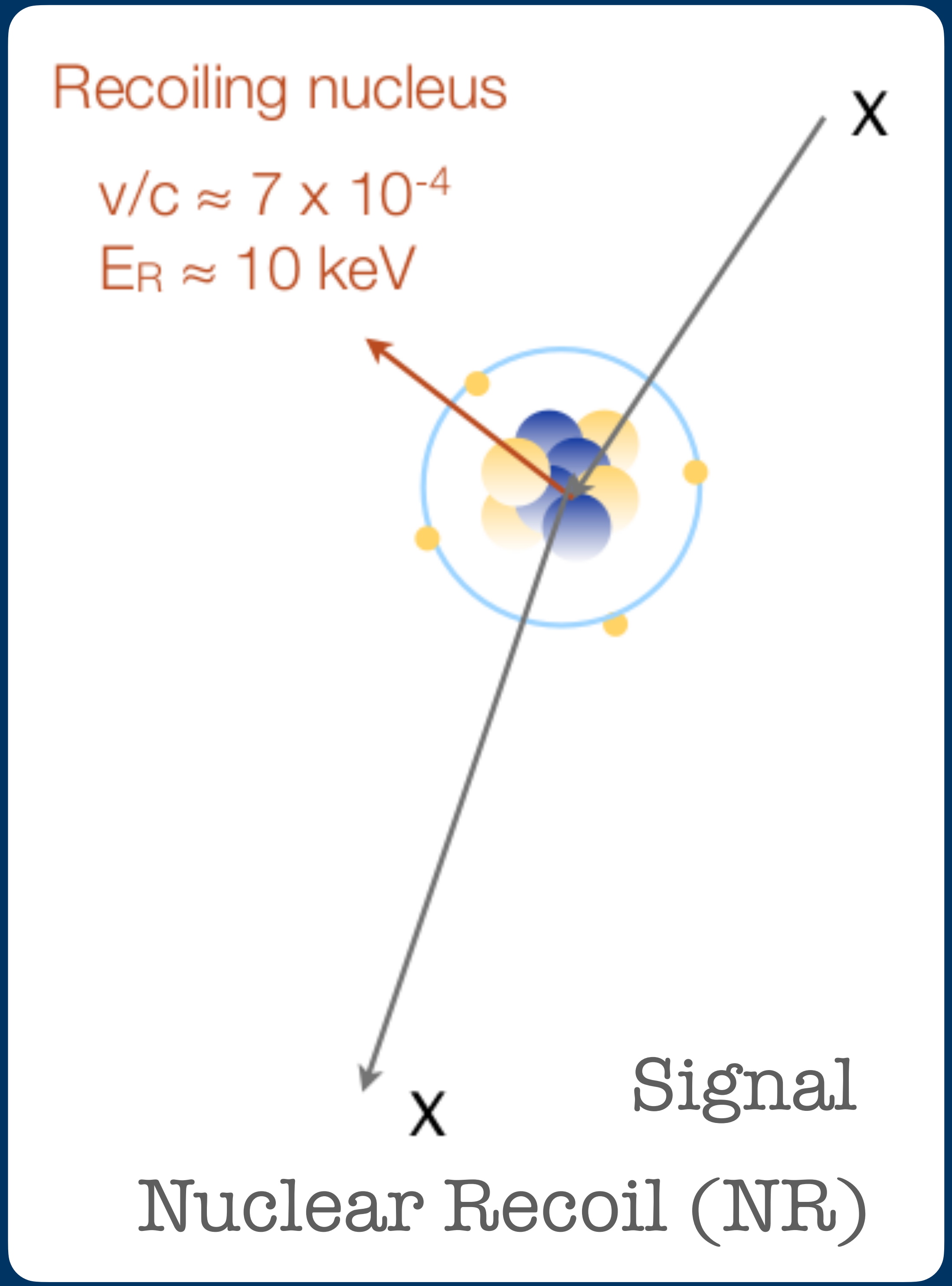
- **Hydrogen** is a **complicated** gas to manipulate (but we have some idea);

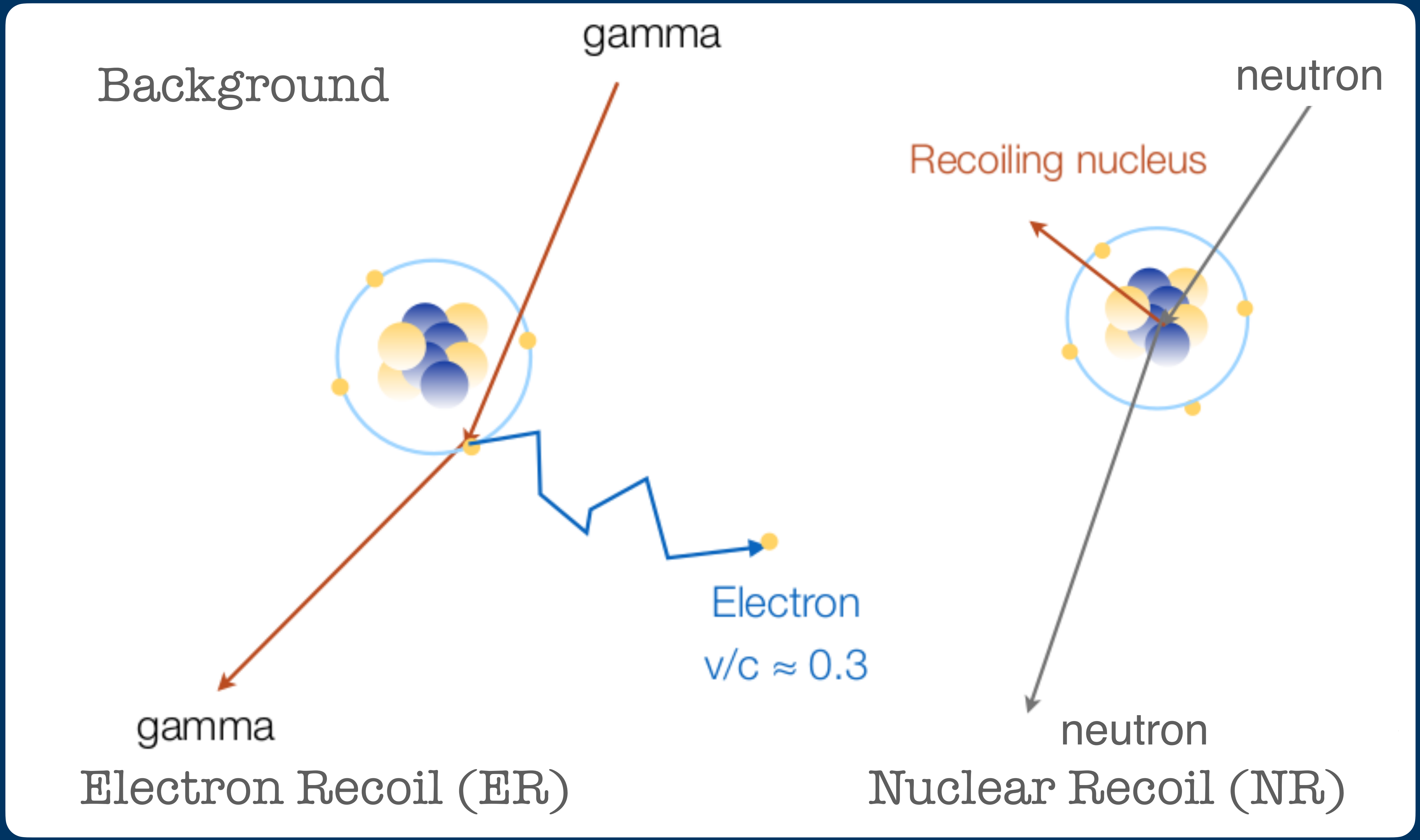


- We started with **Helium**;
- In a Helium (based) **gas** mixture a **6 keV He** at **atmospheric pressure** nucleus has an average **range of 150 µm**, 4 time lesser than an electron;
- 10% of them have almost the double.
- If it would be possible to **"observe"** these events, not only it would be possible to **distinguish them**, but also to measure their **direction** (from CYGNUS?)

NATURAL BACKGROUND

- Ambient or material radioactivity or cosmic rays can produce large background;
- In particular, neutral particles (gamma or neutrons) can mimic DM interactions.





- **Underground lab**;
- **Shield** from external radioactivity;
- **Reduce** internal **contamination;**

- **Identify particles** to distinguish and **reject** background.

TIME PROJECTION CHAMBERS

- **3D tracking**: position and direction;
- total released **energy measurement**;
- **dE/dx** profile (pid, head-tail);
- **reduced readout** channel number with respect to other detectors;
- **Atmospheric pressure** largely more easy to manage

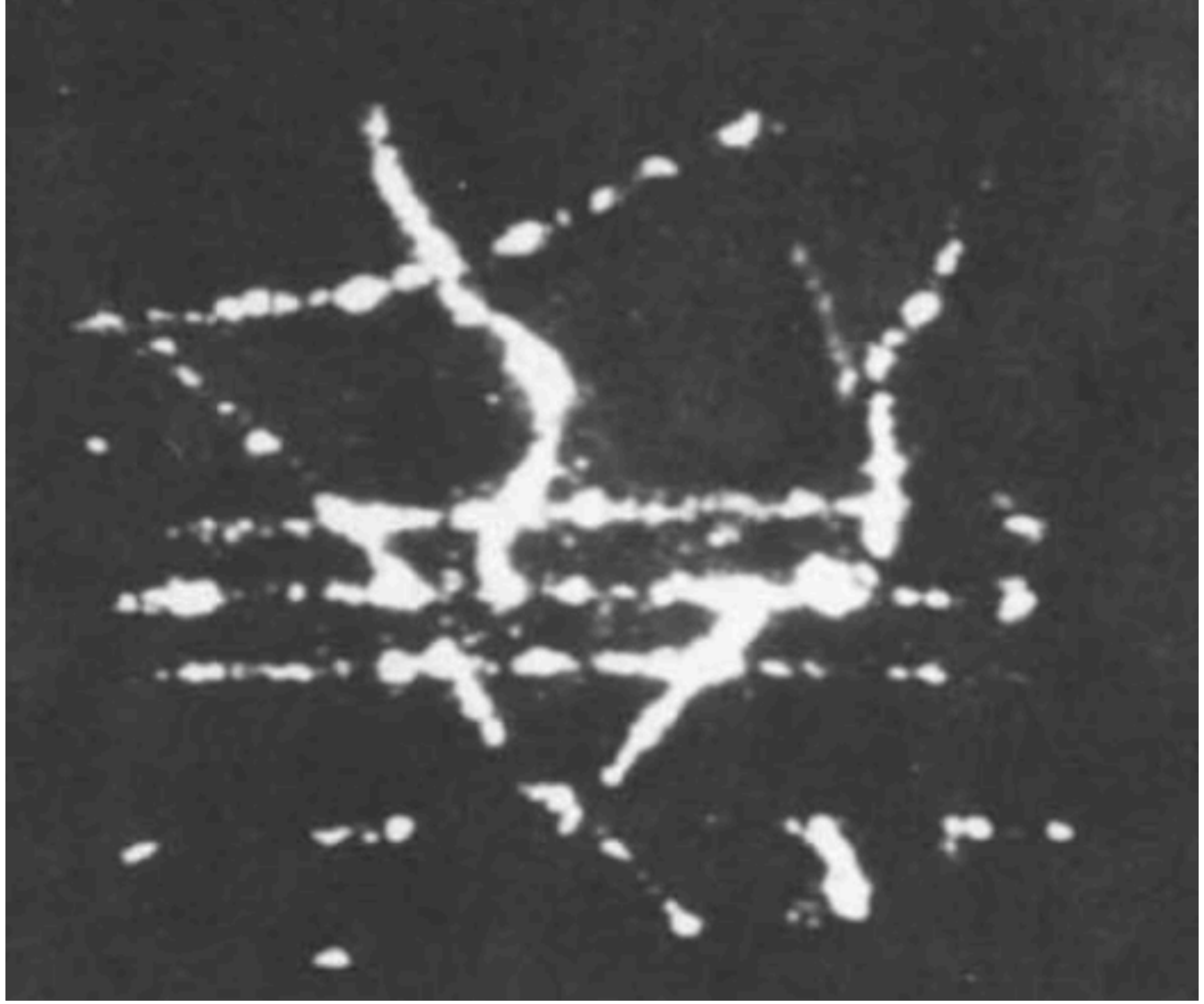
OPTICAL READOUT

During the multiplication processes, **photons** are produced by the **de-excitation of gas** molecules

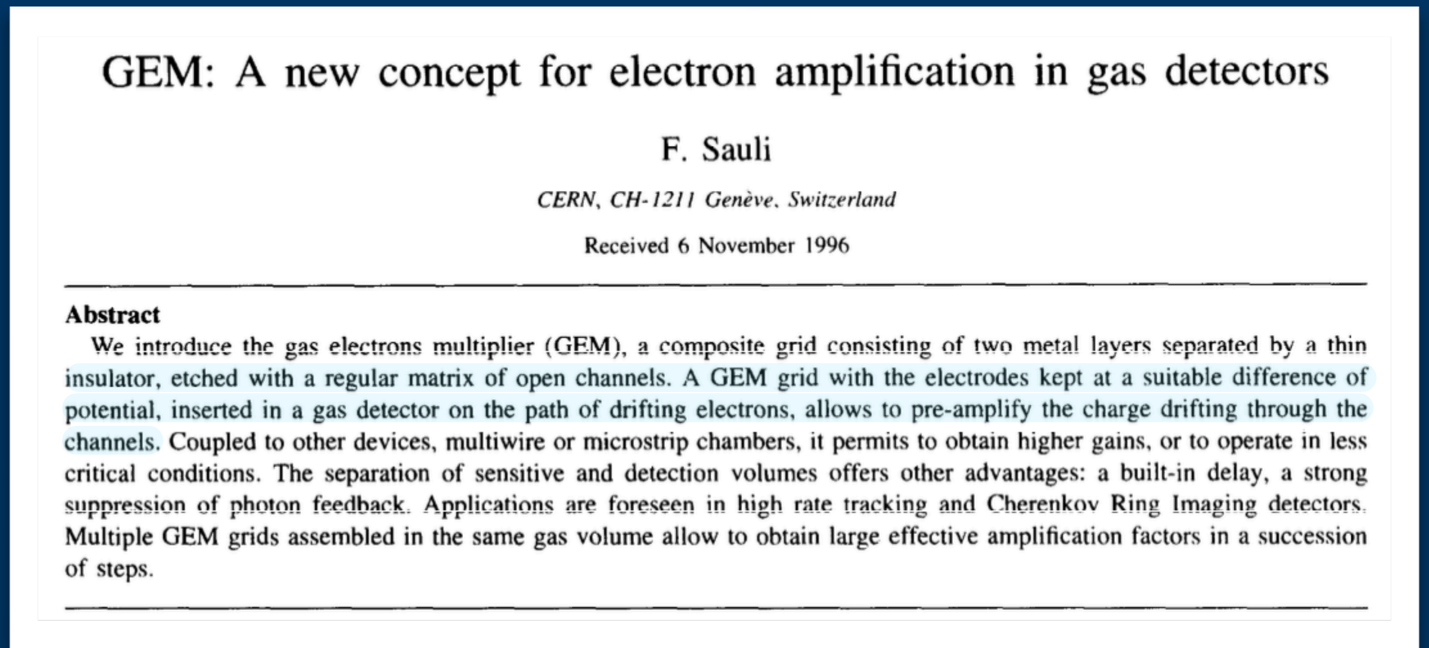
We propose to readout the light produced during the multiplication process:

- optical sensors provide **high granularities** along with very **low noise** and **high sensitivity**;
- optical **coupling** allows to keep **sensor out of the sensitive volume**;
- suitable **lens** allow to acquire **large surfaces** with **small sensors**;

G. Charpak at al., NIM A258 (1987) 177



GAS ELECTRON MULTIPLIERS (GEM)


GEM: A new concept for electron amplification in gas detectors

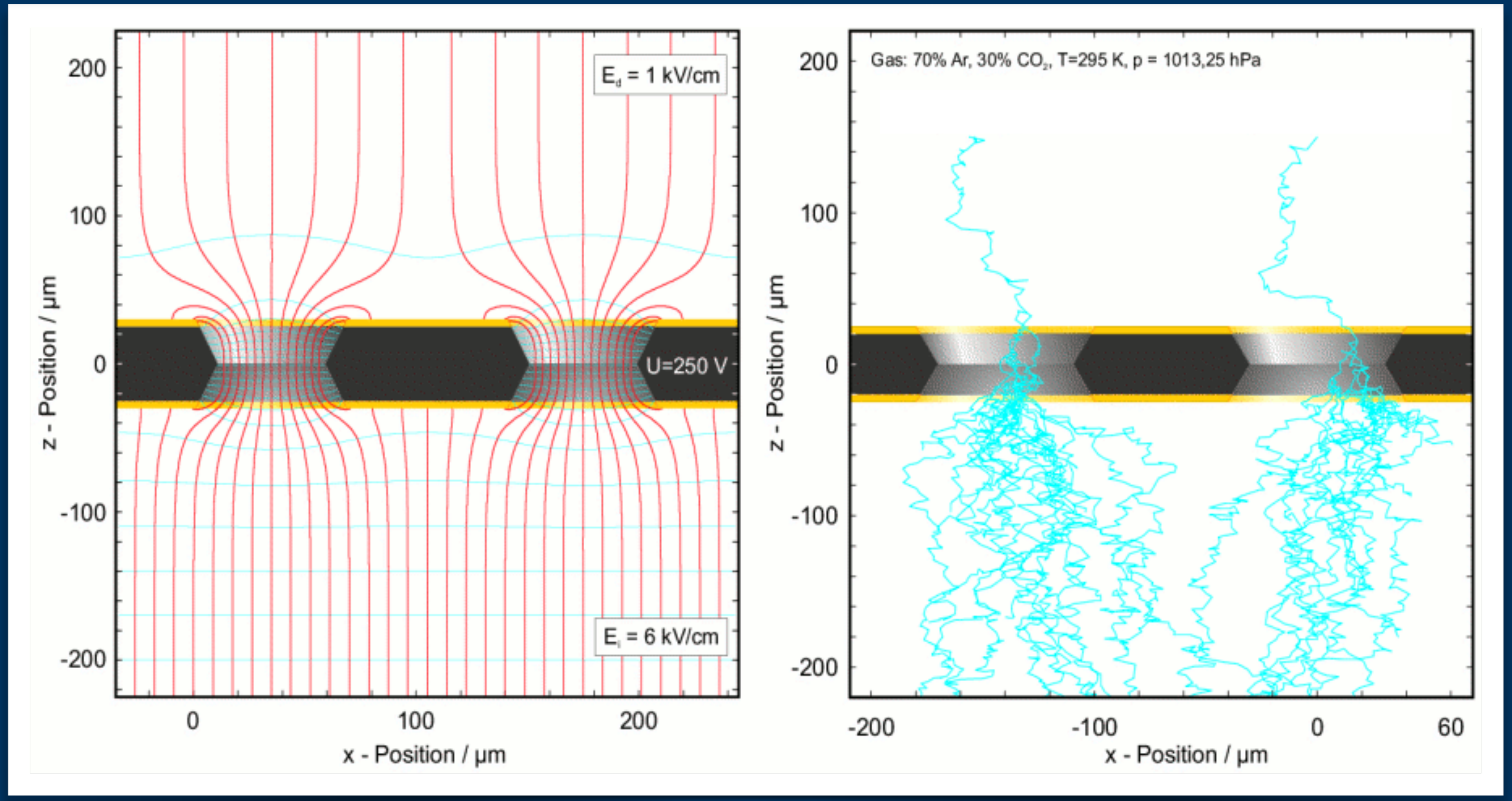
F. Sauli

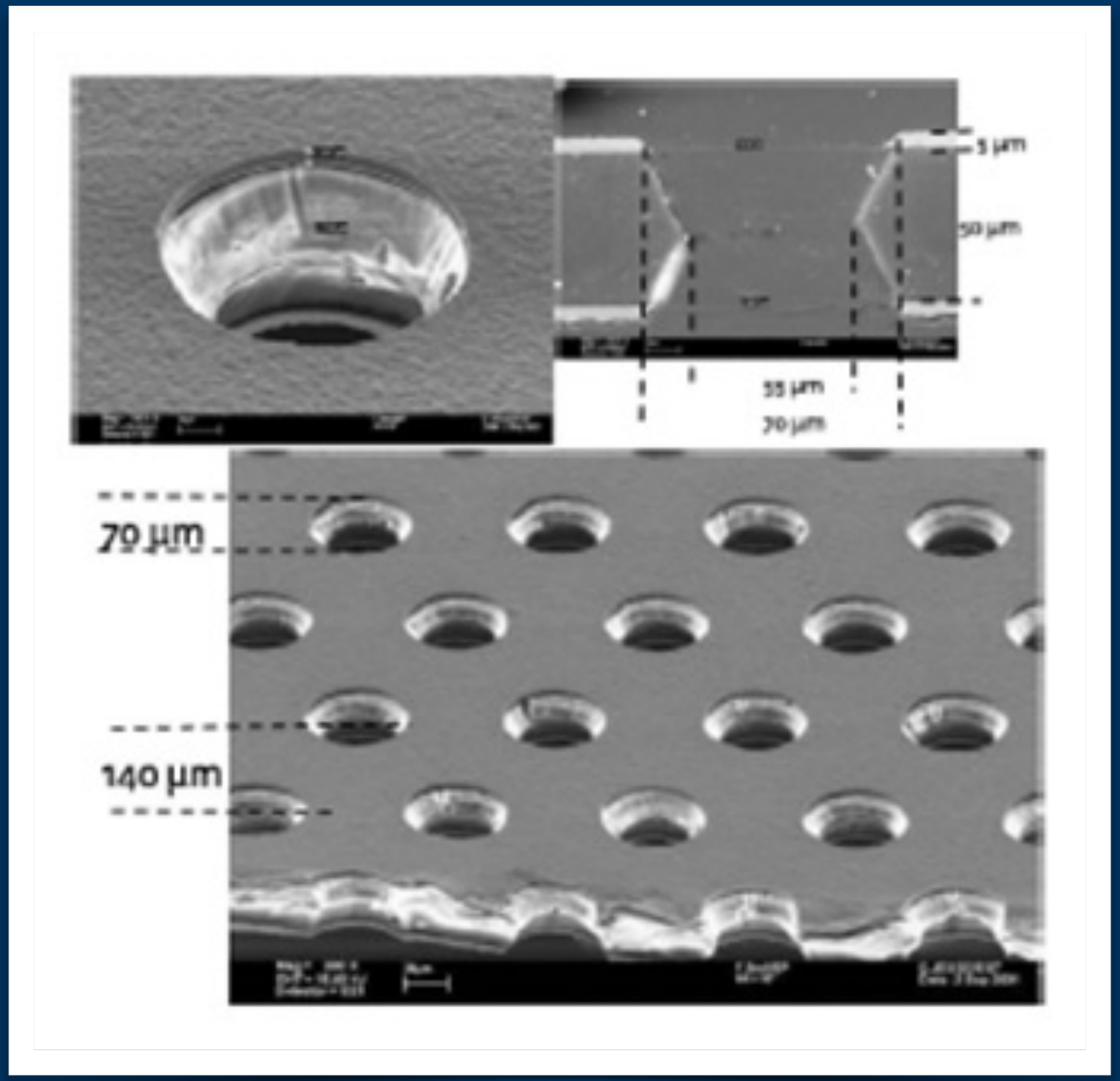
CERN, CH-1211 Genève, Switzerland

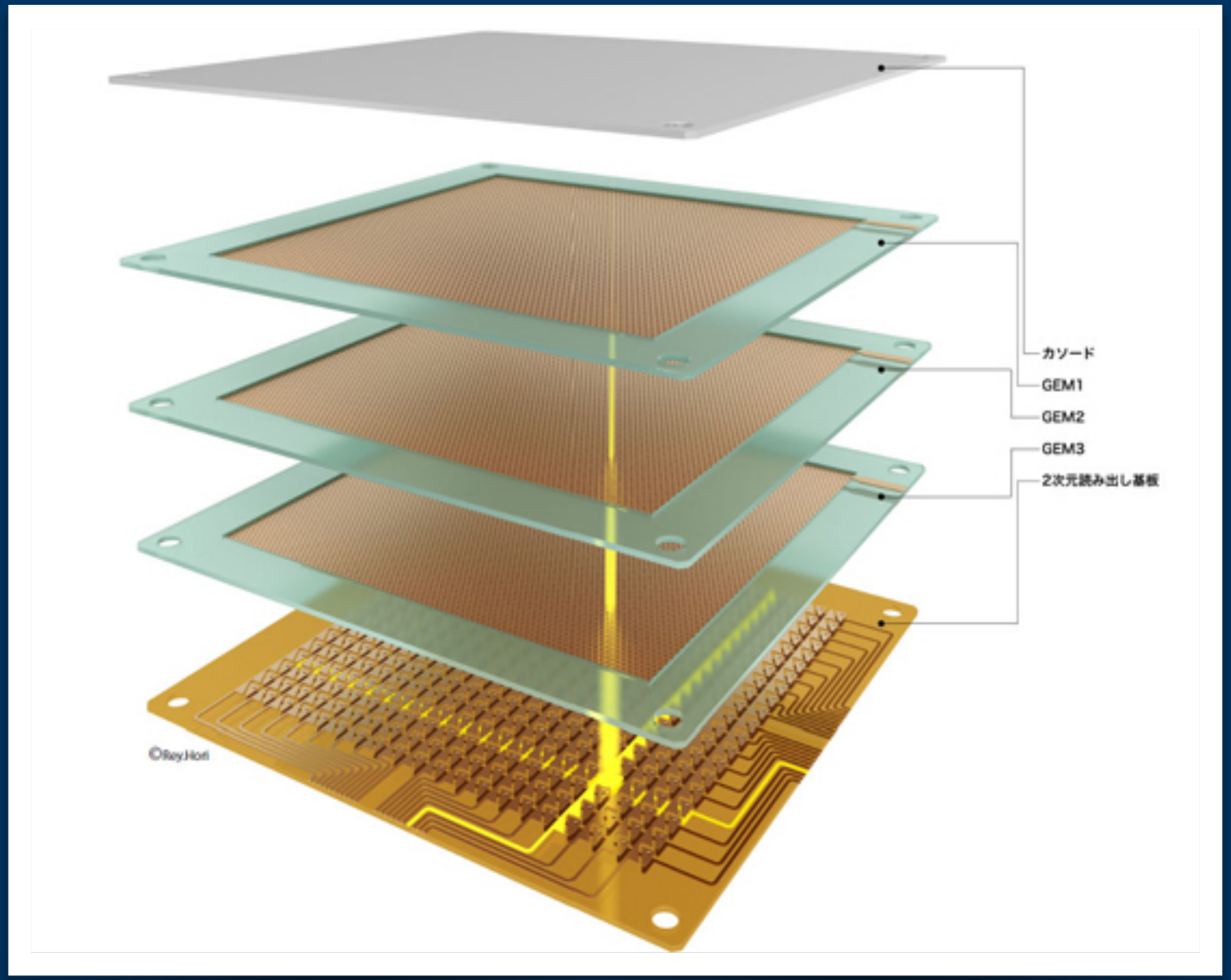
Received 6 November 1996

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.







Primary electrons drift toward the **GEM channels** where a high electric field **trigger avalanche** processes;

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

Photons are produced together with secondary electrons **within the channels**

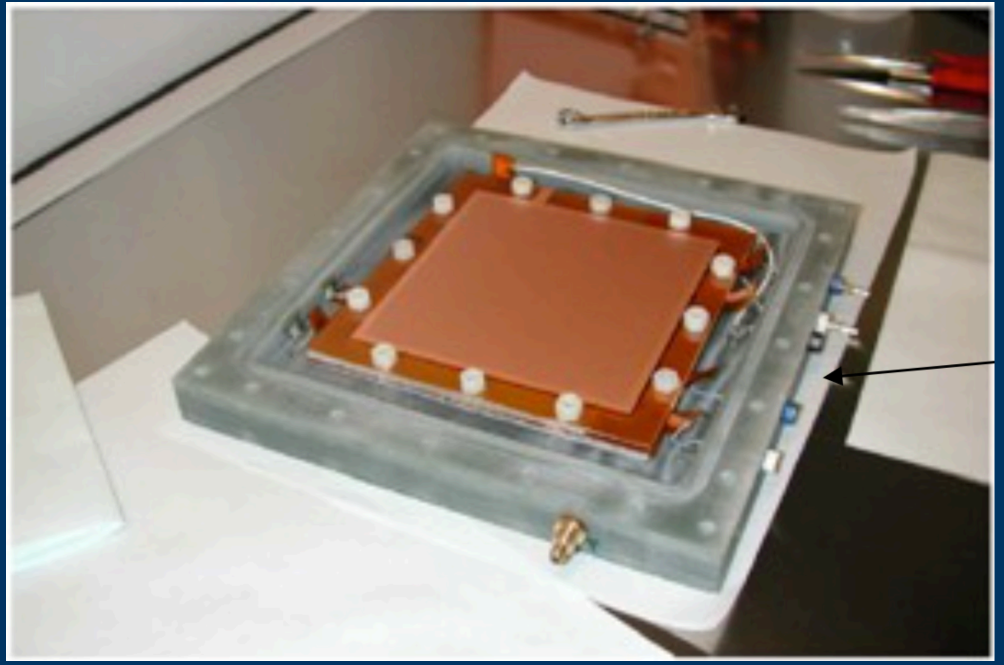
TRIPLE GEM DETECTOR AT LNF

Triple-GEM detectors were developed at LNF!

An R&D was carried out between 2000-2003 and a detector was developed for **LHCb Muon System**.

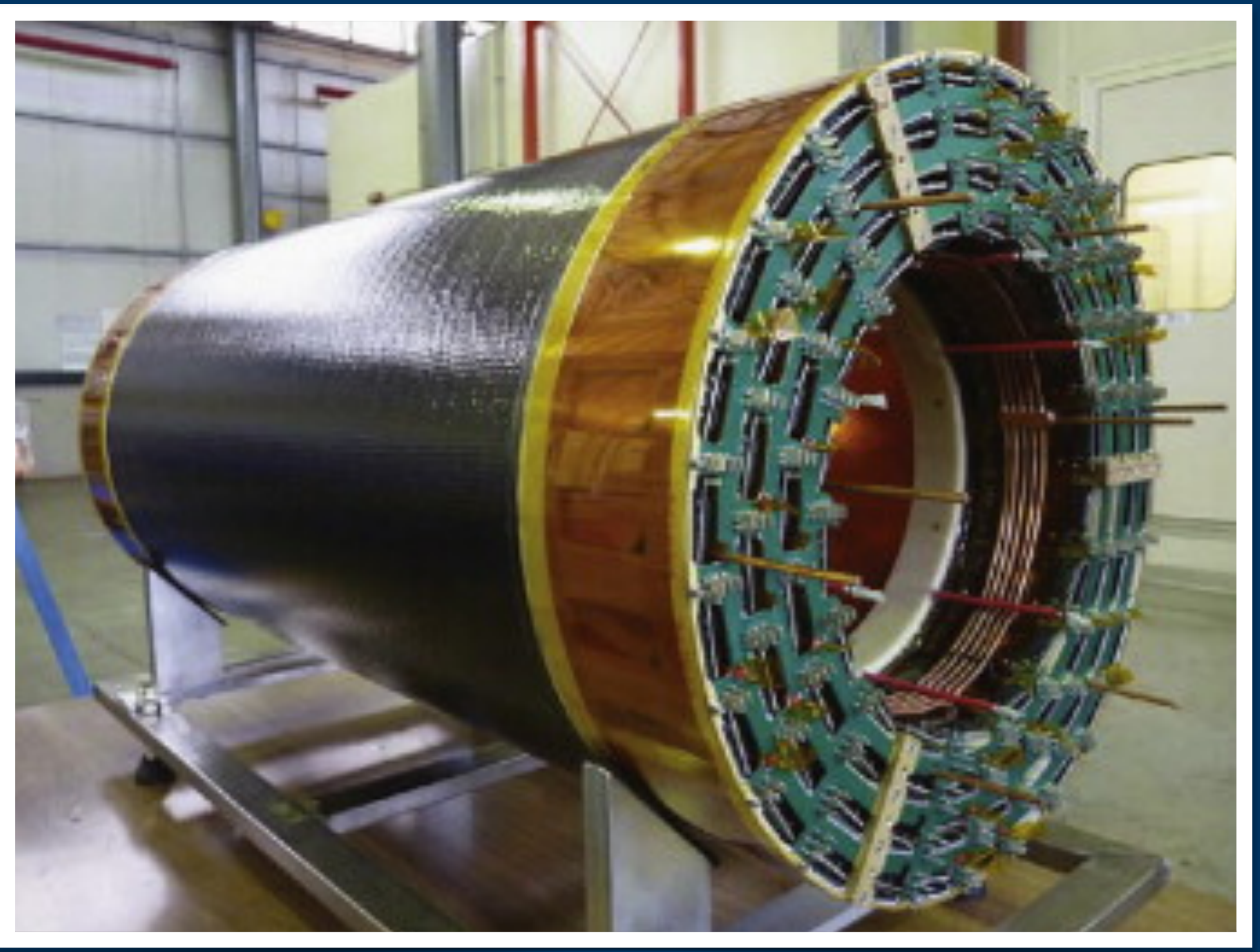
A triple-GEM detector with pad readout for the inner region of the first LHCb muon station

G. Bencivenni, G. Felici, F. Murtas, P. Valente
Laboratori Nazionali di Frascati - INFN, Frascati, Italy
W. Bonivento[1], A. Cardini, A. Lai, D. Pinci[2], B. Saitta[1,2]
Sezione INFN di Cagliari, Cagliari, Italy
[1]Now at European Laboratory for Particle Physics (CERN), CH1211 Genève 23, Switzerland
[2]and Università degli Studi di Cagliari, Cagliari, Italy



Since then, a lot of different R&D on triple-GEM have been completed at LNF.

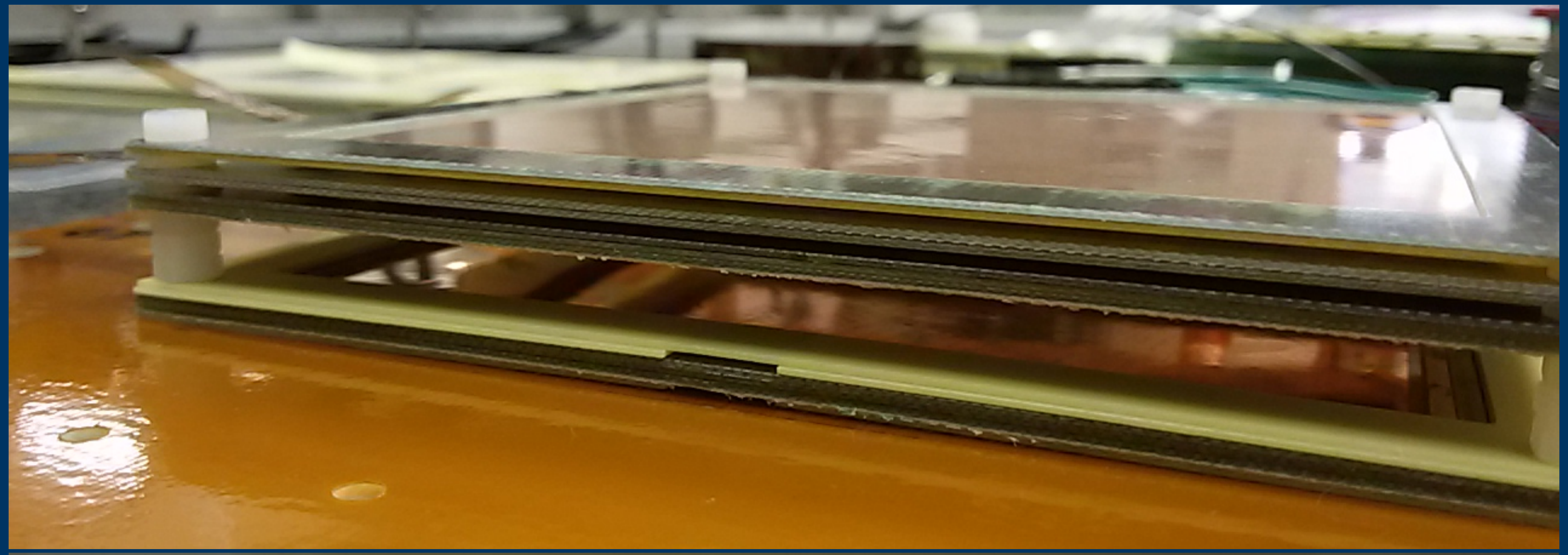
Triple-GEM Test Beam in 2001 (photograph G. Bencivenni).



Now **GEM** are **reliable** and widely used device

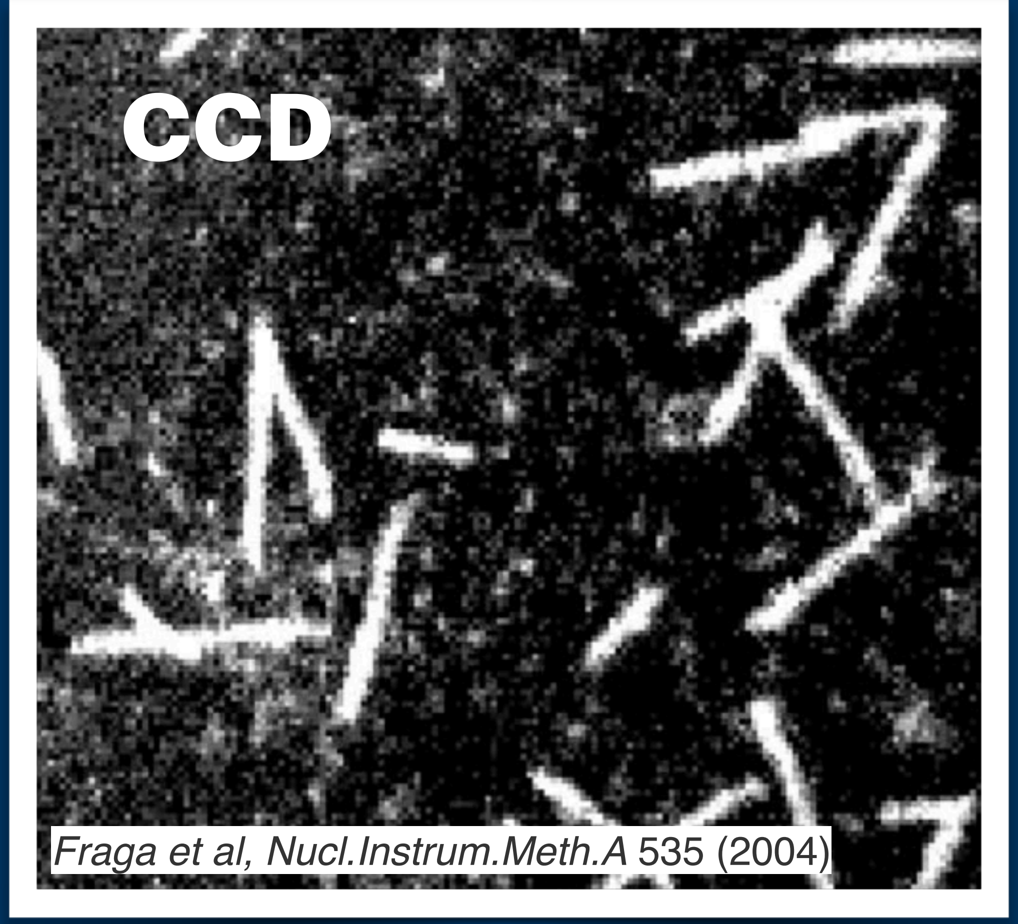
ORANGE: AN OPTICALLY READOUT GEM

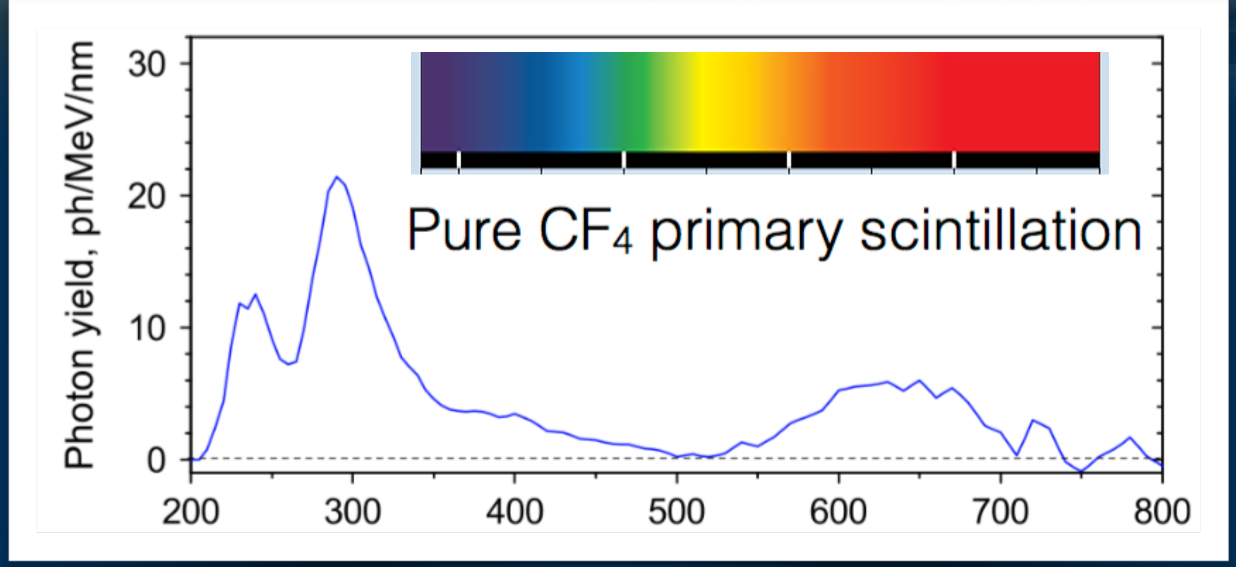
Triple GEM structure (10x10 cm²) with 1 cm sensitive gap.



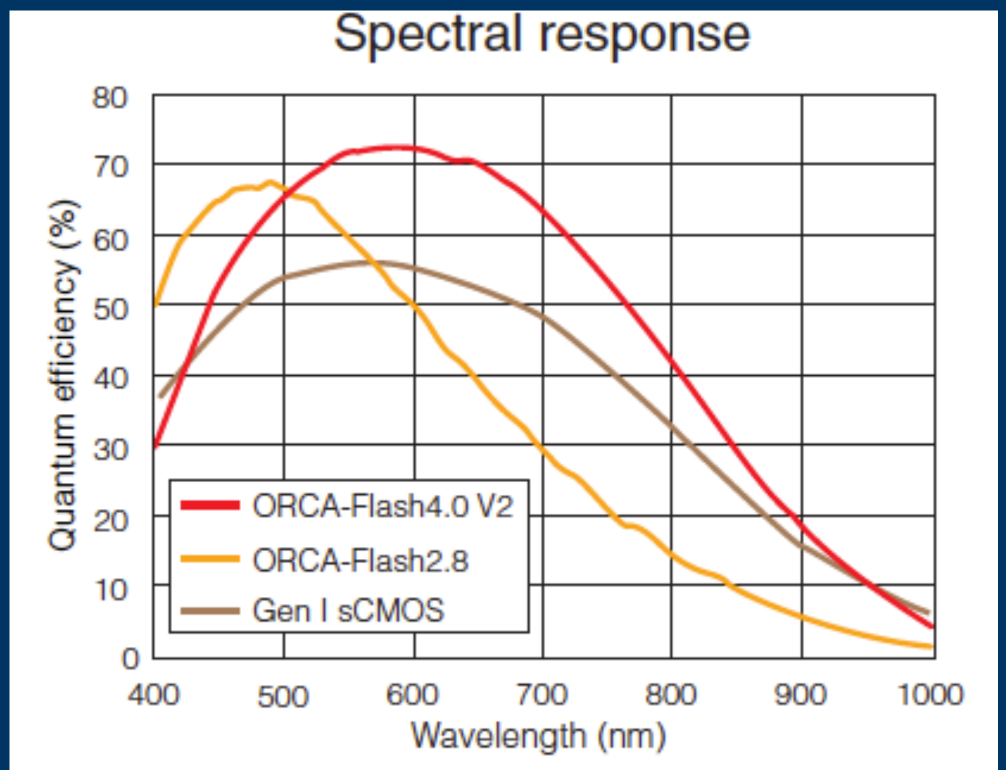
An He/CF_4 (60/40) mixture was used at atmospheric pressure

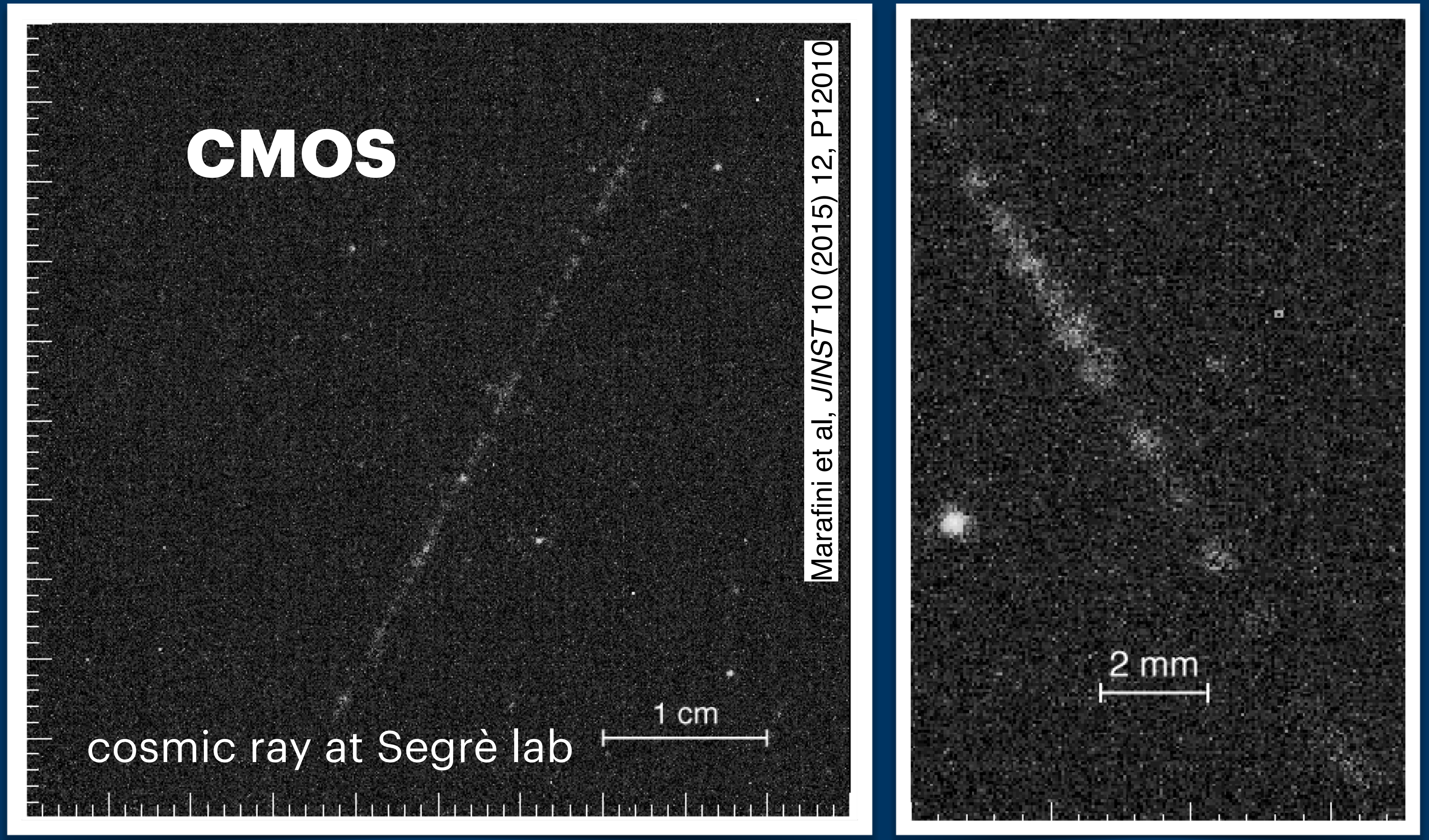
highly ionising tracks





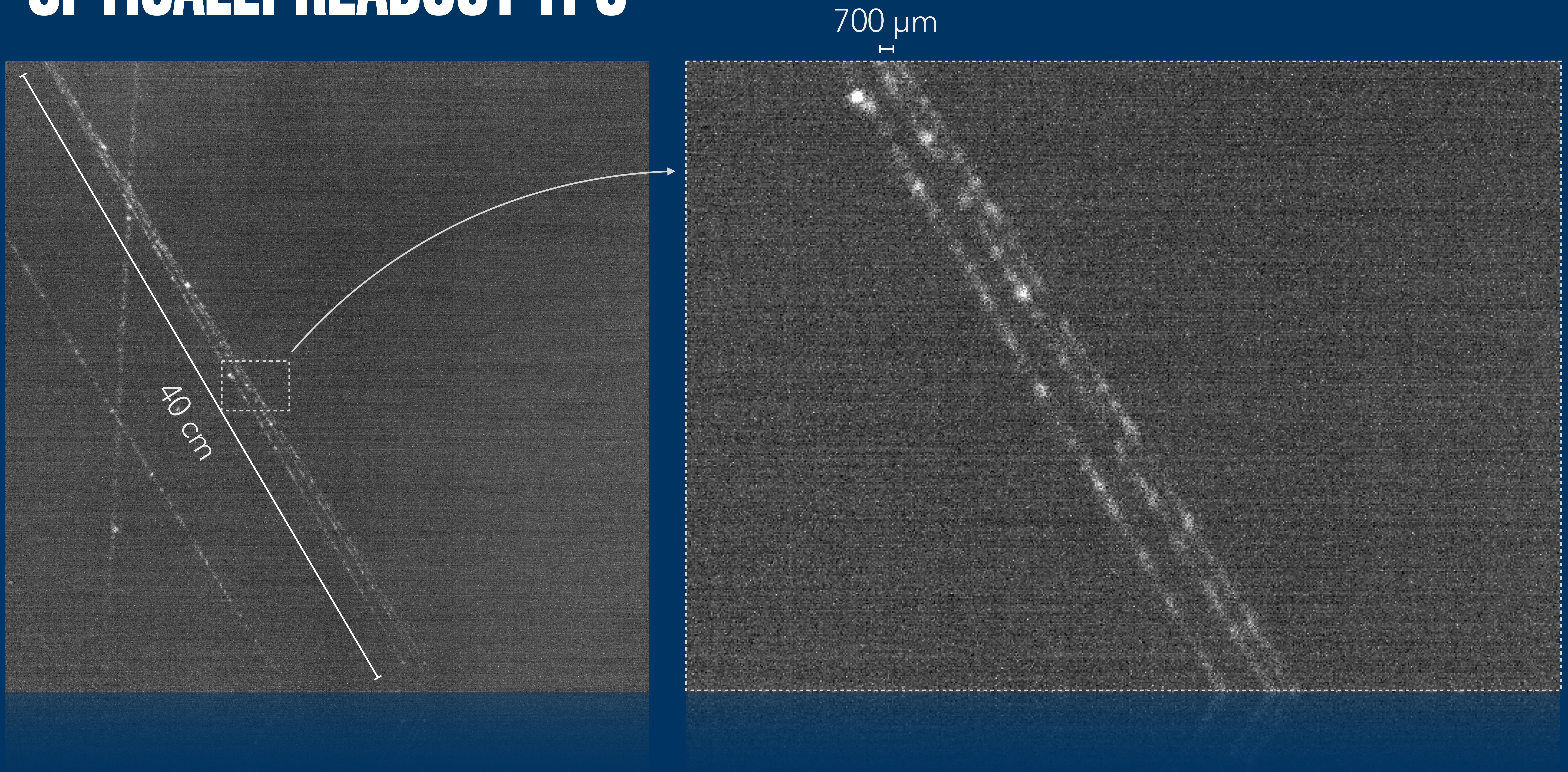
Significantly **lower noise** level of **CMOS** w.r.t **CCD** sensors resulted in a higher sensitivity





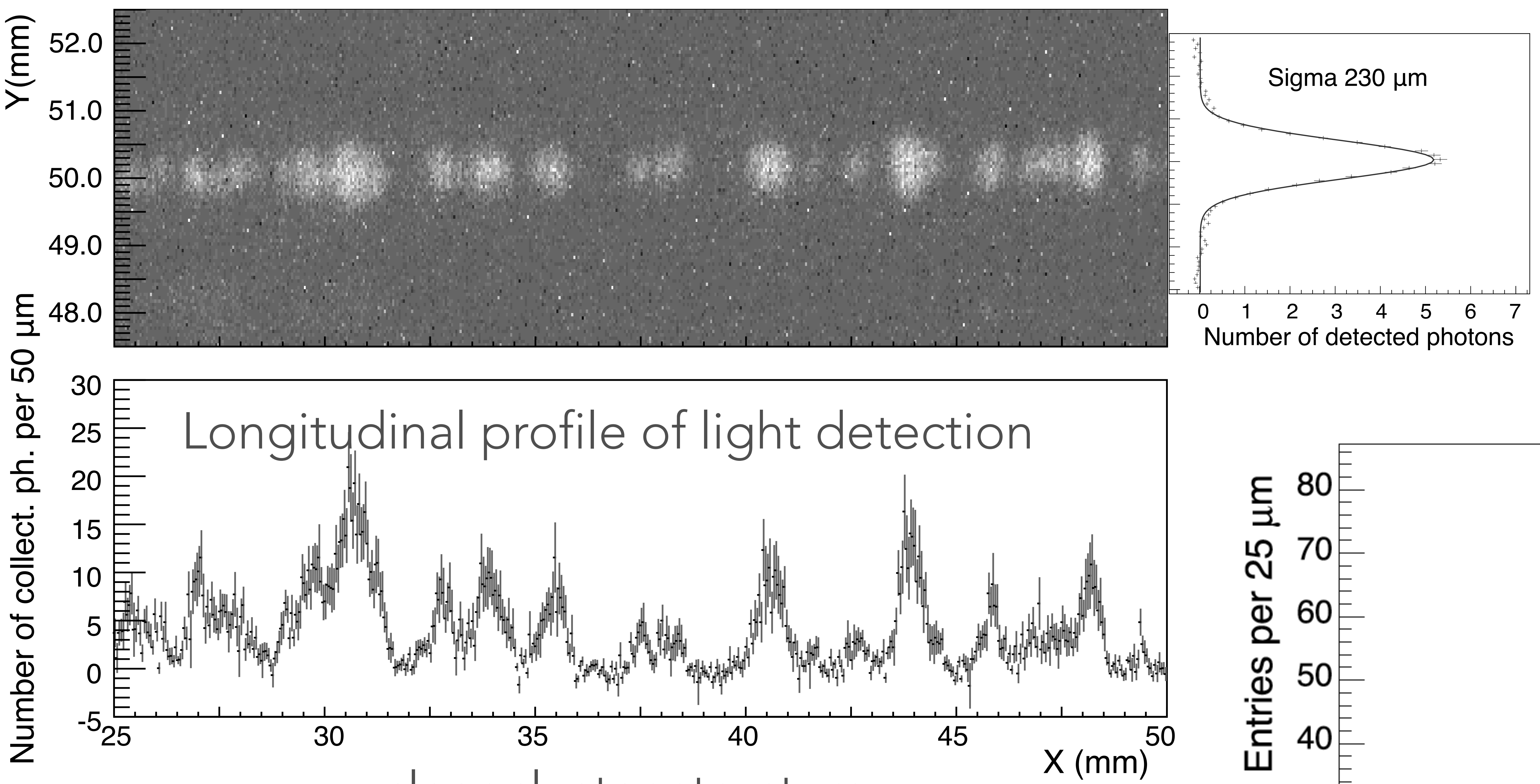
sCMOS sensors provide very low noise and 4MPx granularity and sensitivity

OPTICALLY READOUT TPC

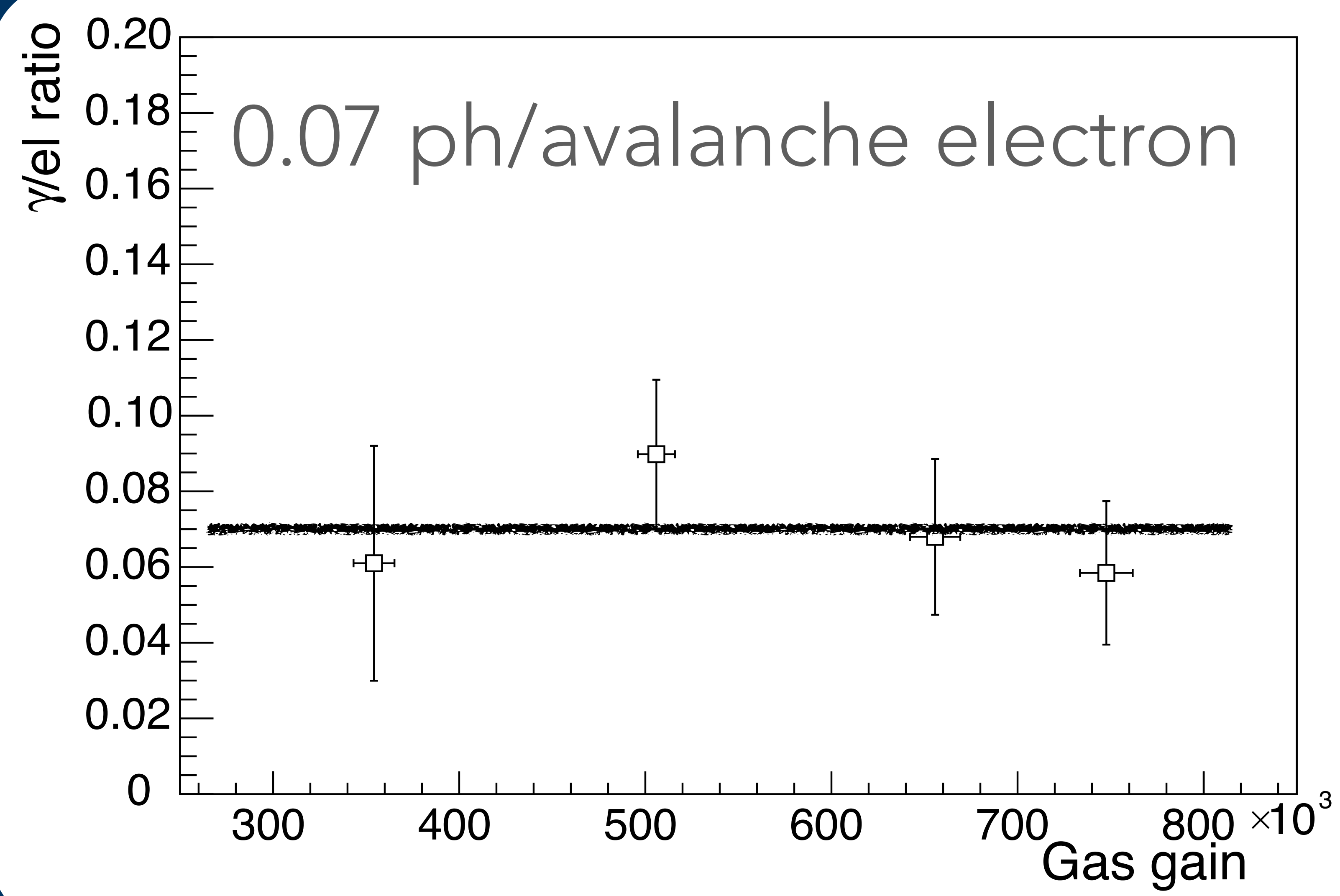


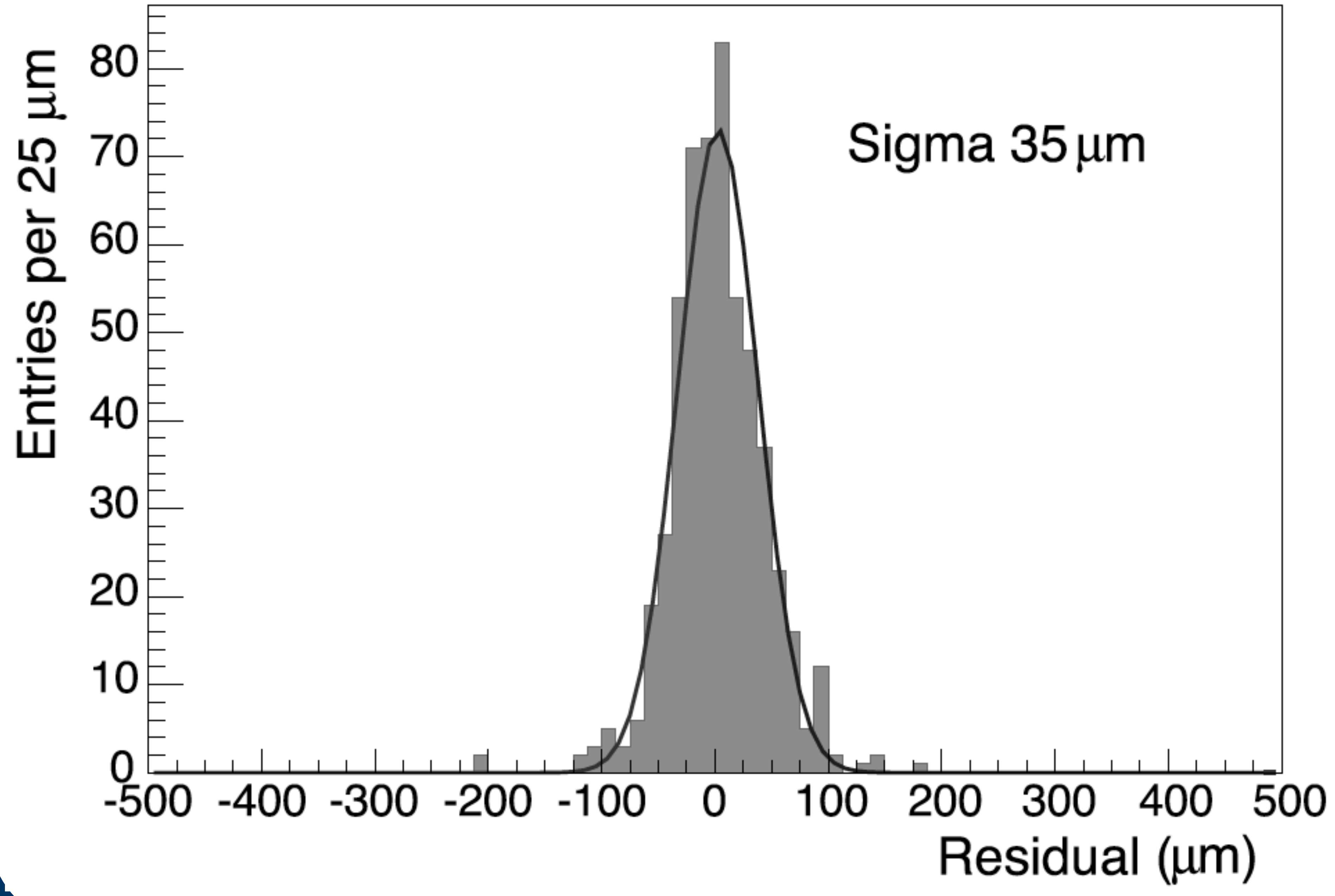
CLUSTER DETAILS

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



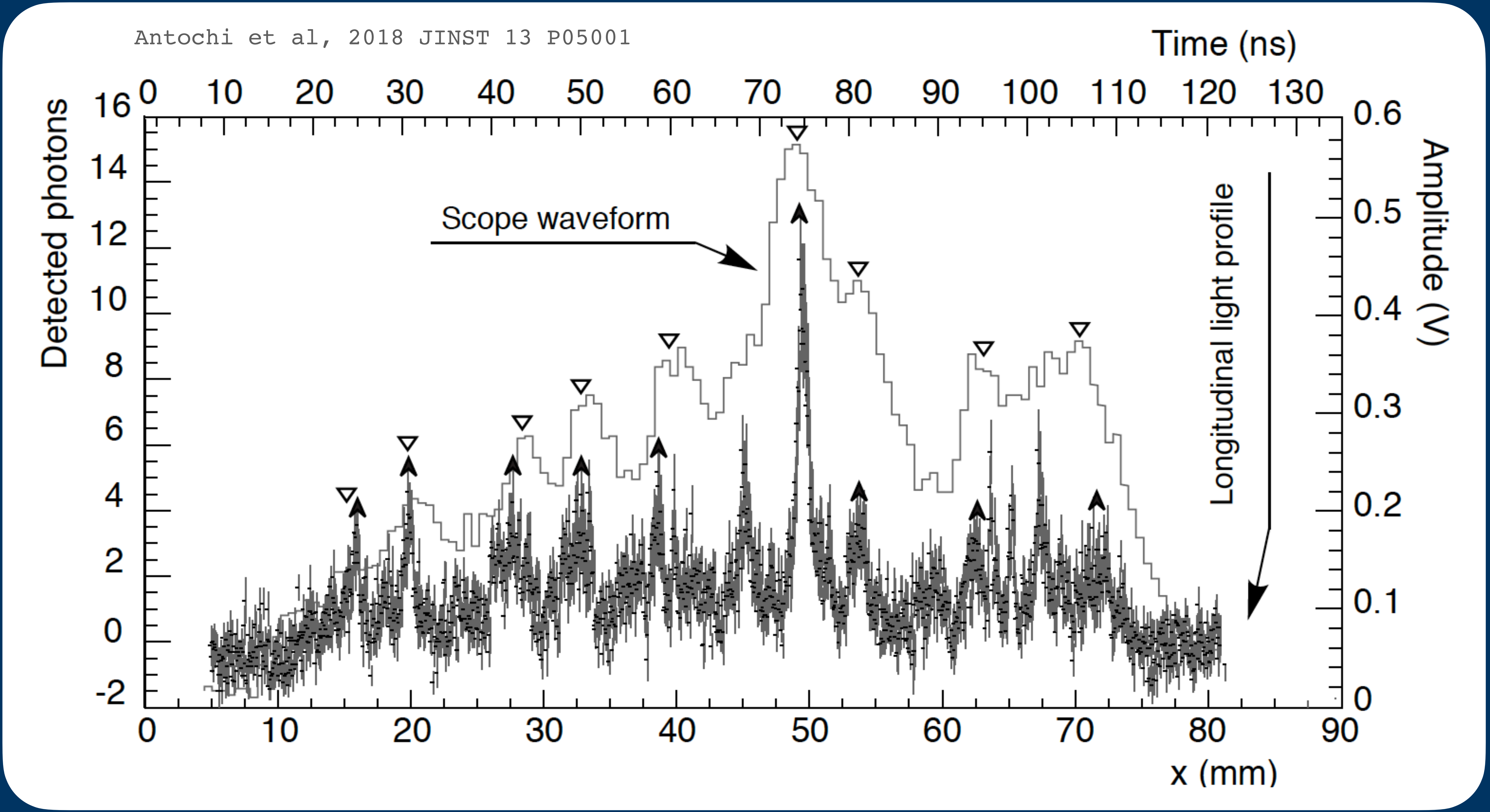
clear cluster structure

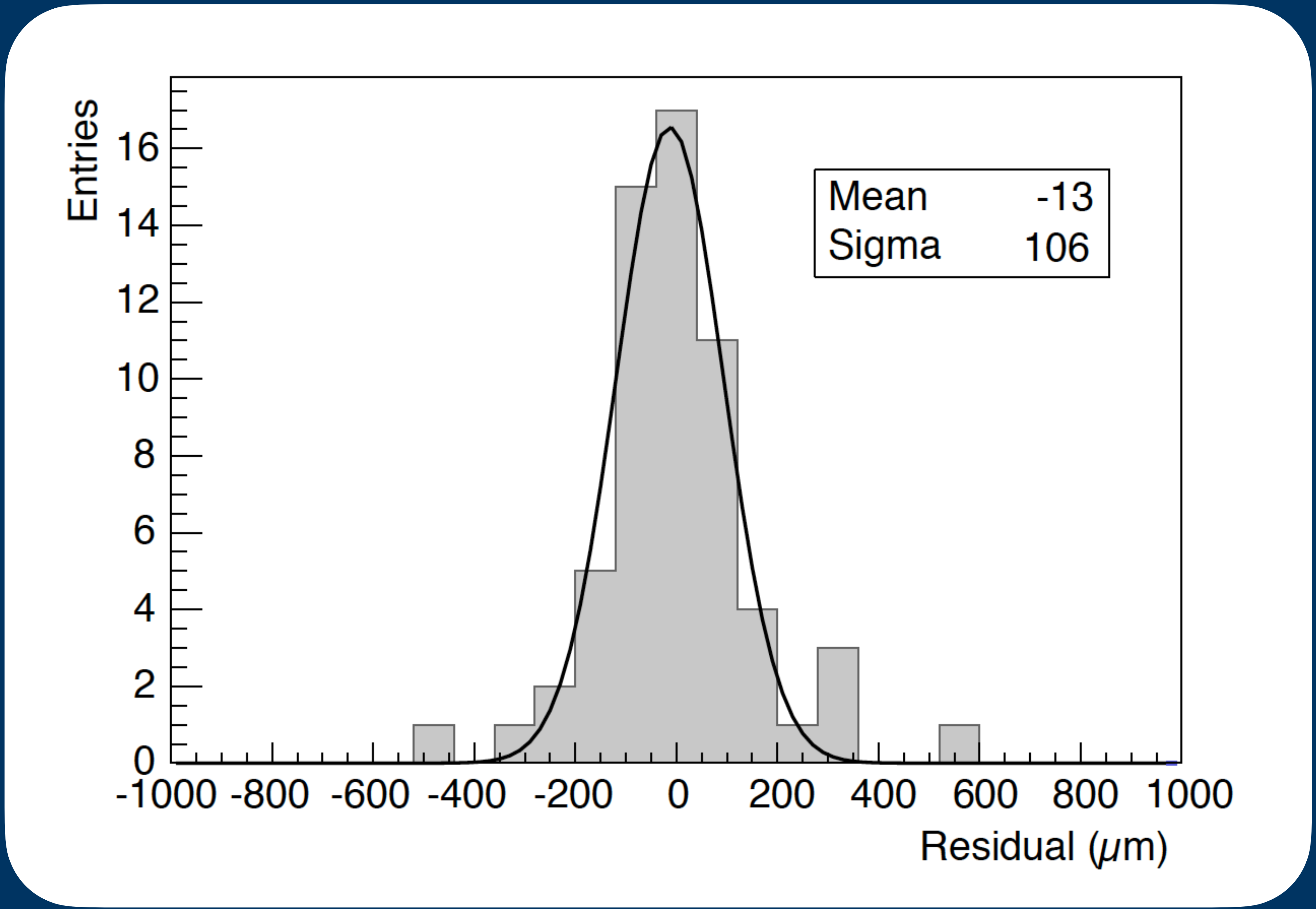




The average **energy** per **cluster** (i.e. 2 primary electrons) is around **90 eV**

COMBINED READOUT WITH PHOTOMULTIPLIER



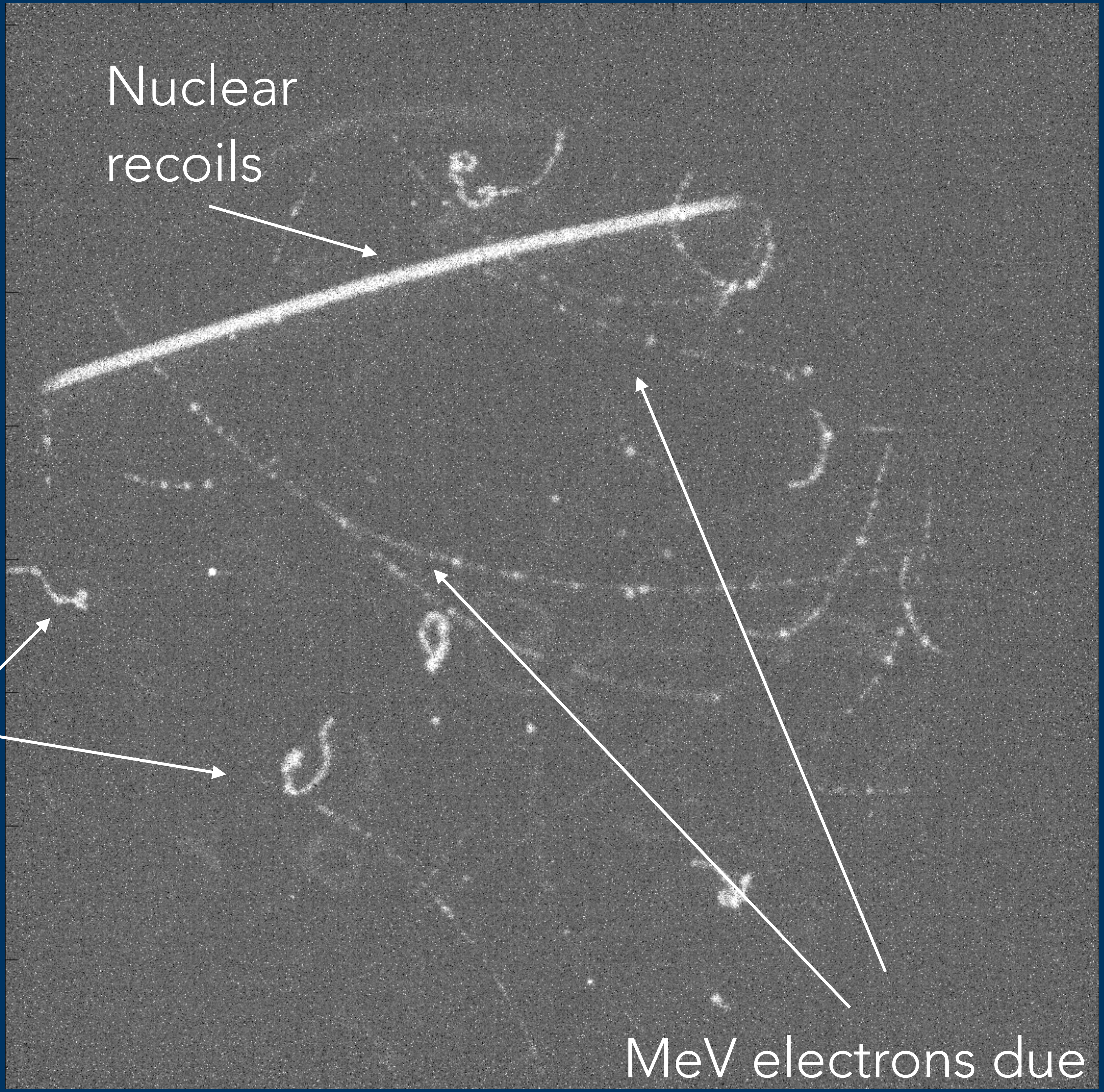


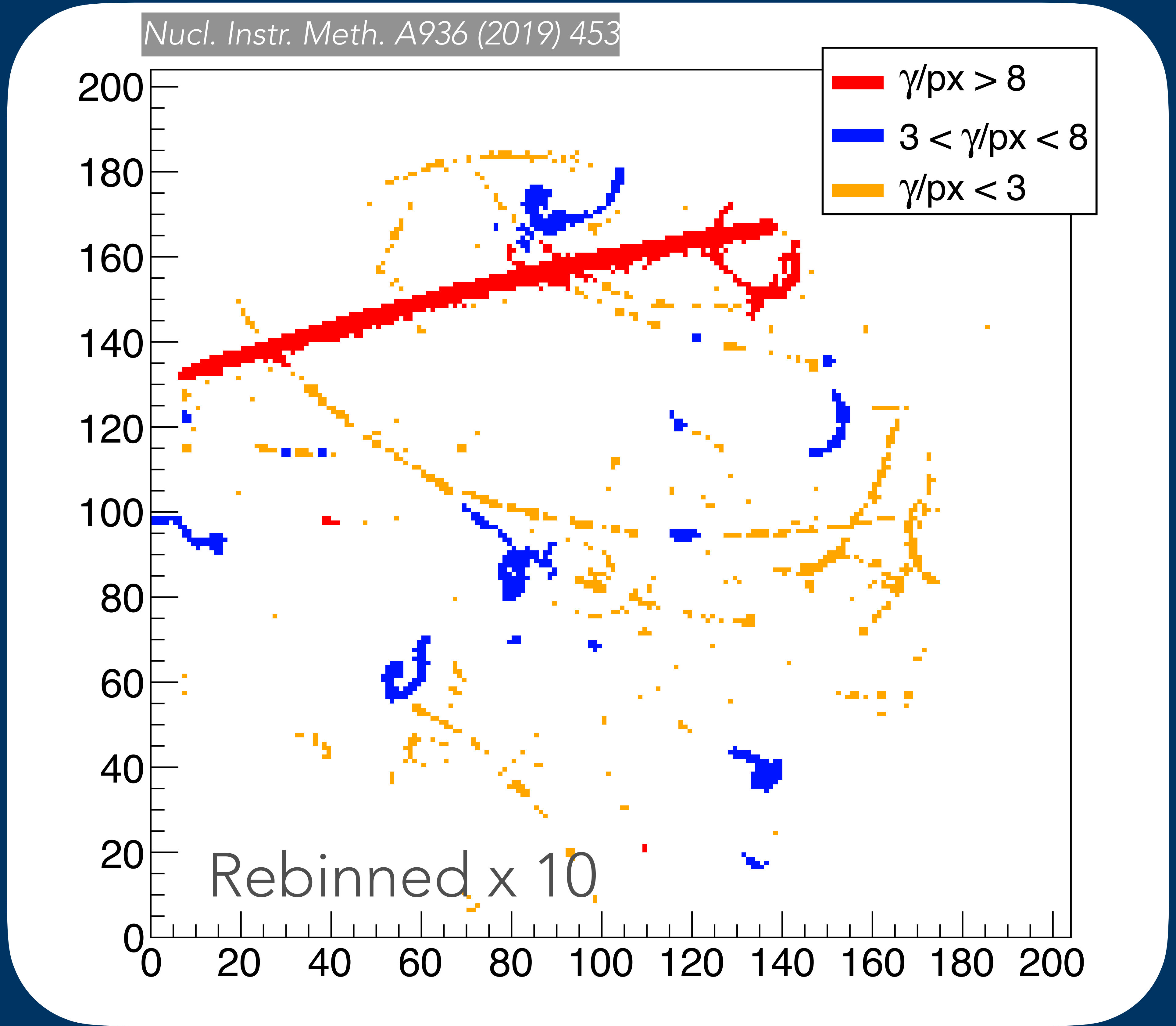
From the **comparison** of CMOS information about distribution of **clusters** along the track and PMT waveform, ***z*** **position** of each cluster can be easily evaluated.

100 μm resolution on relative cluster *z*

PARTICLE IDENTIFICATION

Detector was exposed to an **AmBe** source, providing **1-10 MeV neutrons** along with **4 MeV and 59 keV photons**. A **0.2 T magnetic** field by a permanent magnet

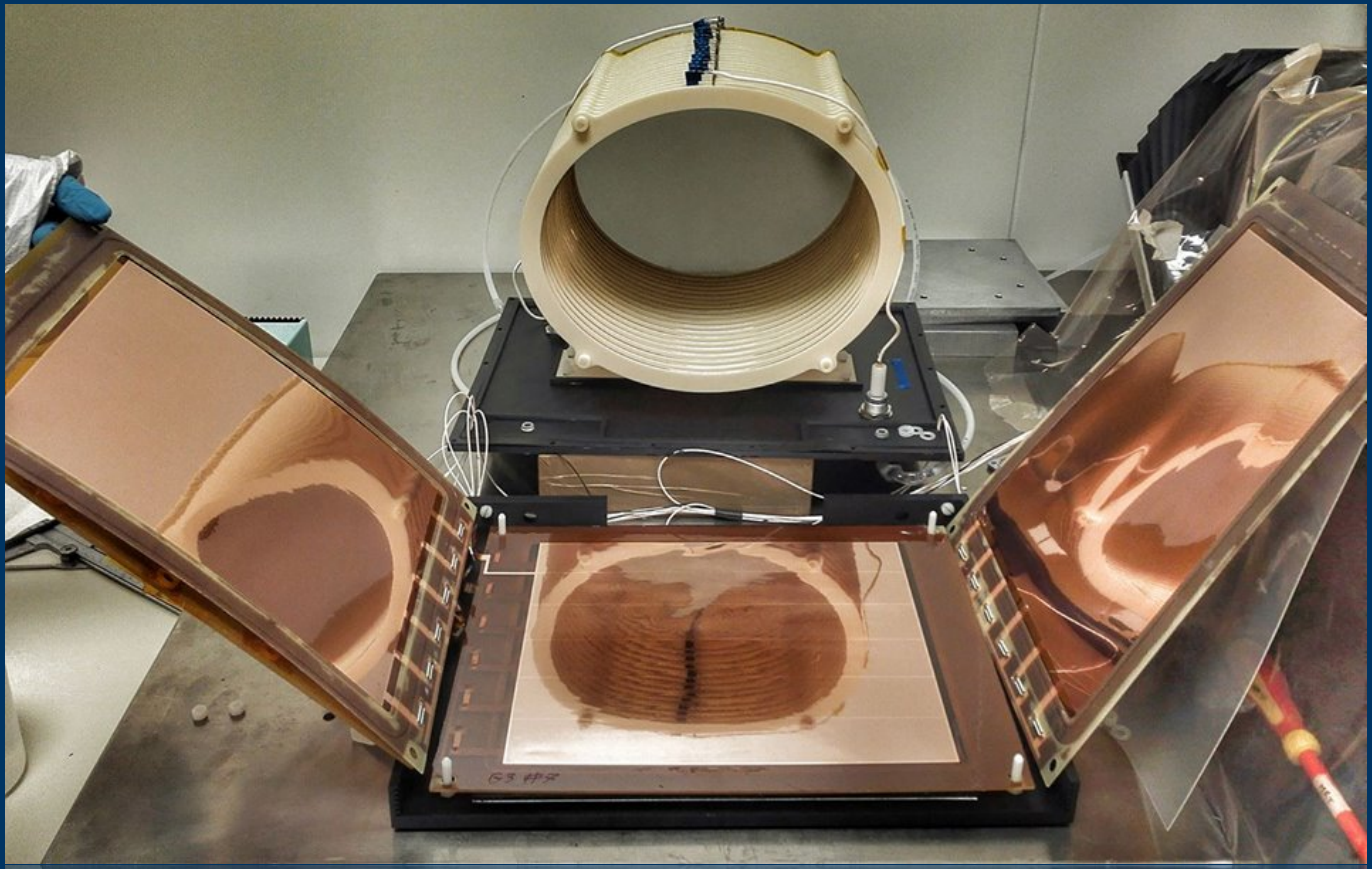




By simply assigning different **colours** to clusters as a function of their **average light density**, the three species are **almost completely separated.**

LEMON: LARGE ELLIPTICAL MODULE OPTICALLY READOUT

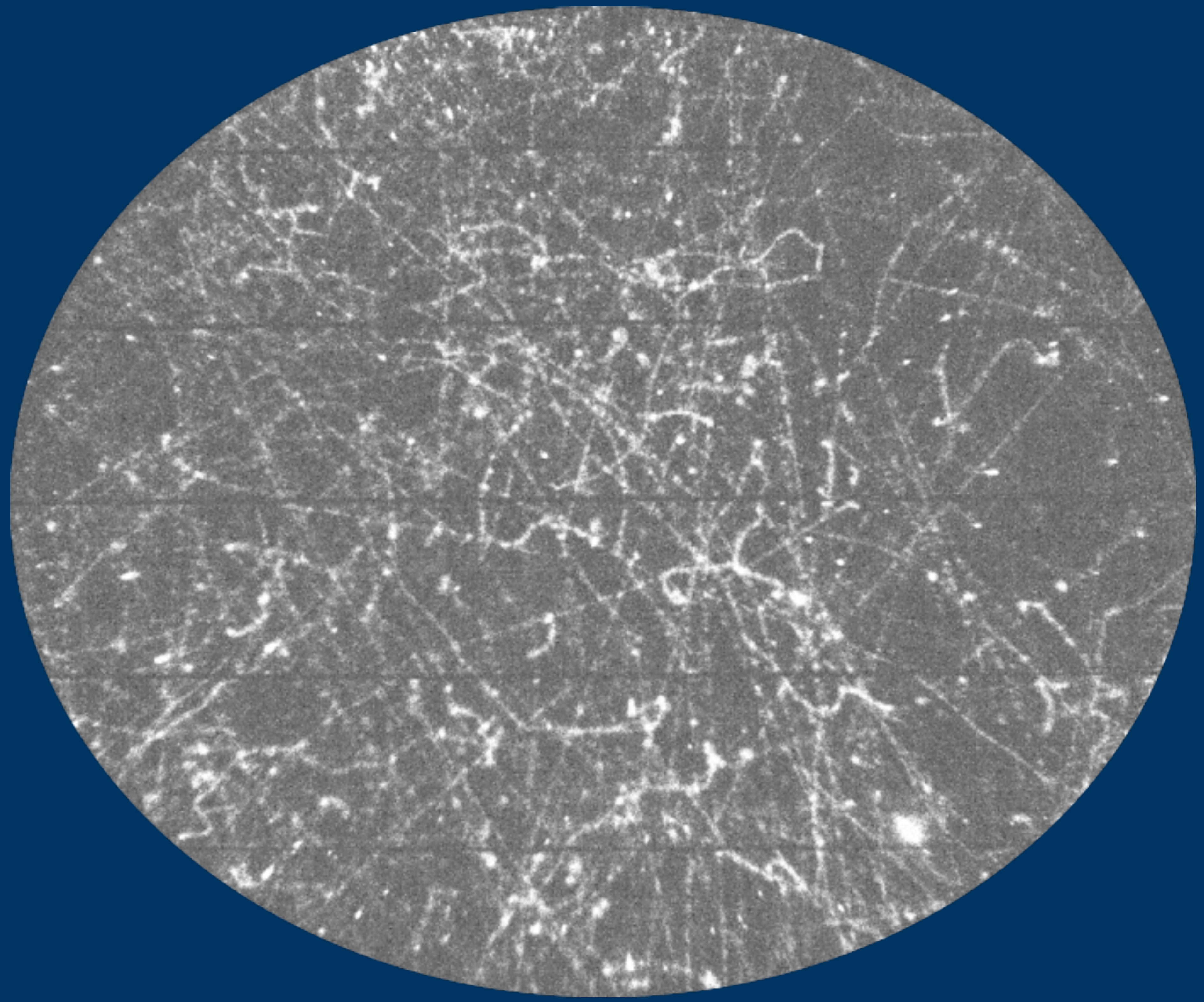
Construction and R&D funded by INFN - CSN5



- designed and assembled at LNF
- 3D printer realisation

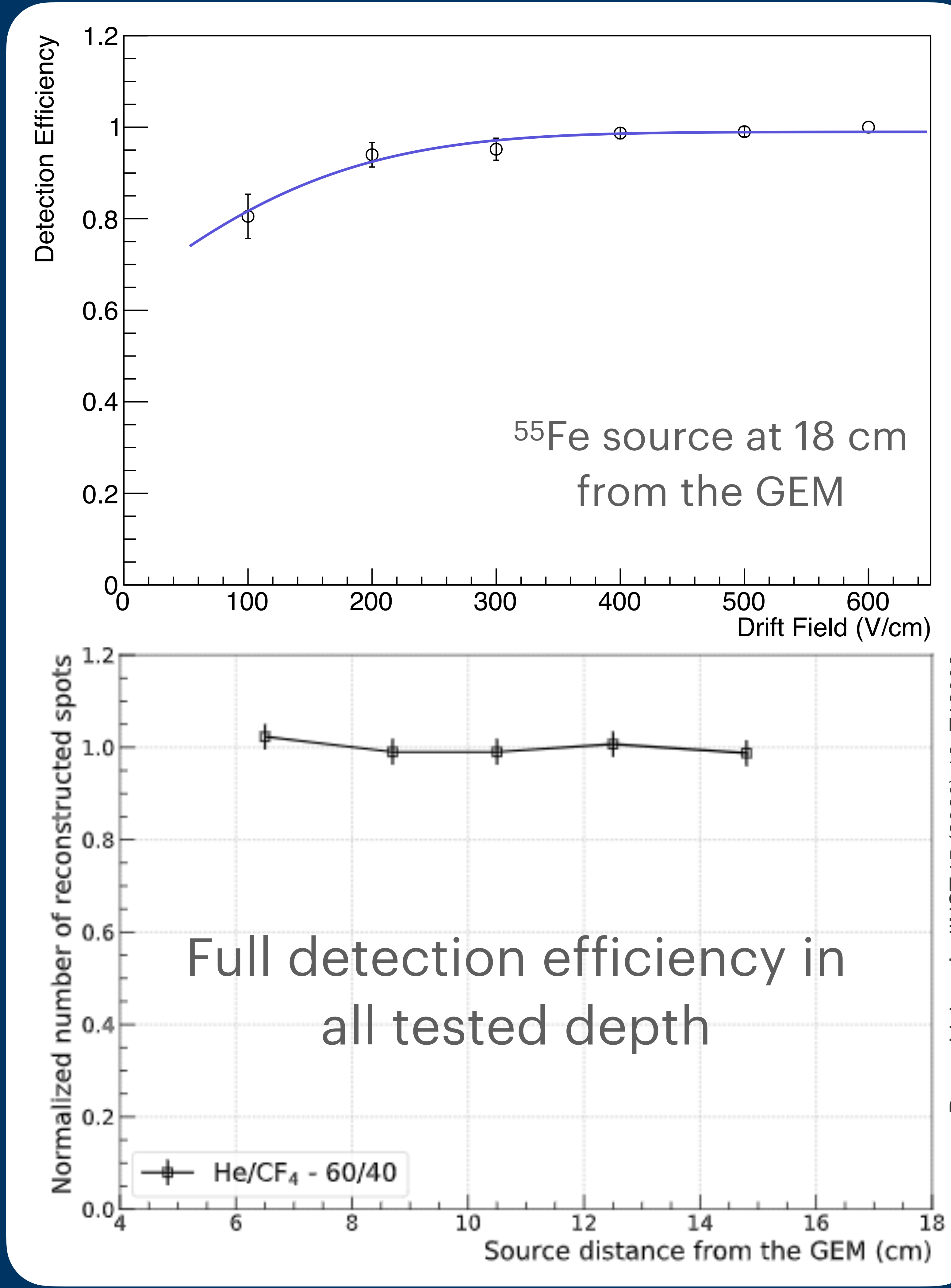
- 7 litre sensitive volume;
- 500 cm^2 GEM surface
- 20 cm drift gap

5 sec of natural background

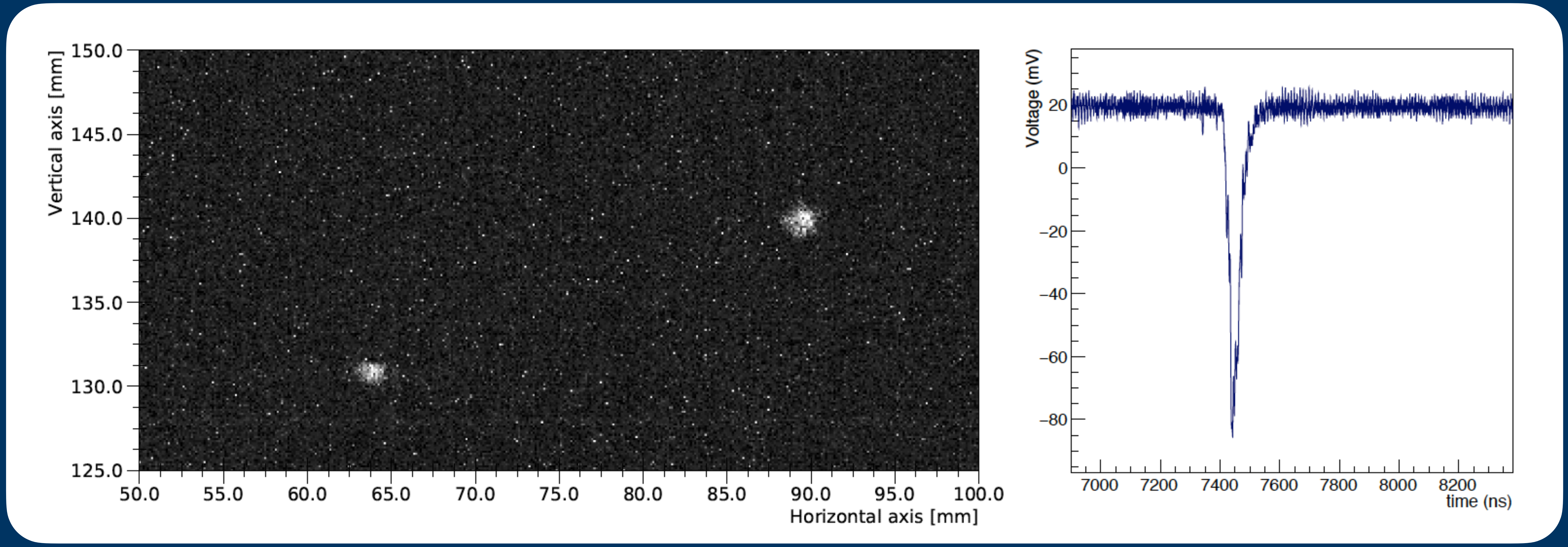


PERFORMANCE WITH ^{55}FE: SPOT SIGNALS

5.9 keV photons from ^{55}Fe source were used to test detection efficiency and light yield.

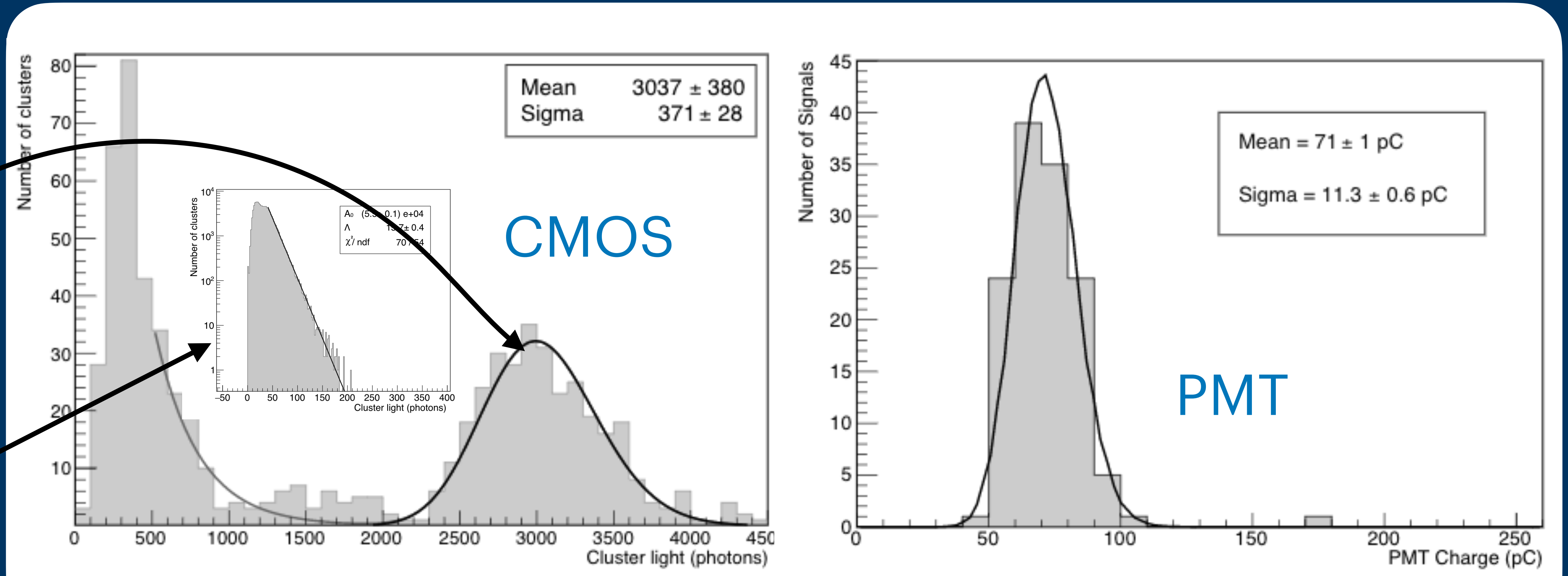


Baracchini et al, *JINST* 15 (2020) 12, T12003



500 photons per keV

Sensor noise below 200 photons (i.e. 400 eV)



Abritta et al, *J.Phys.Conf.Ser.* 1498 (2020) 012017

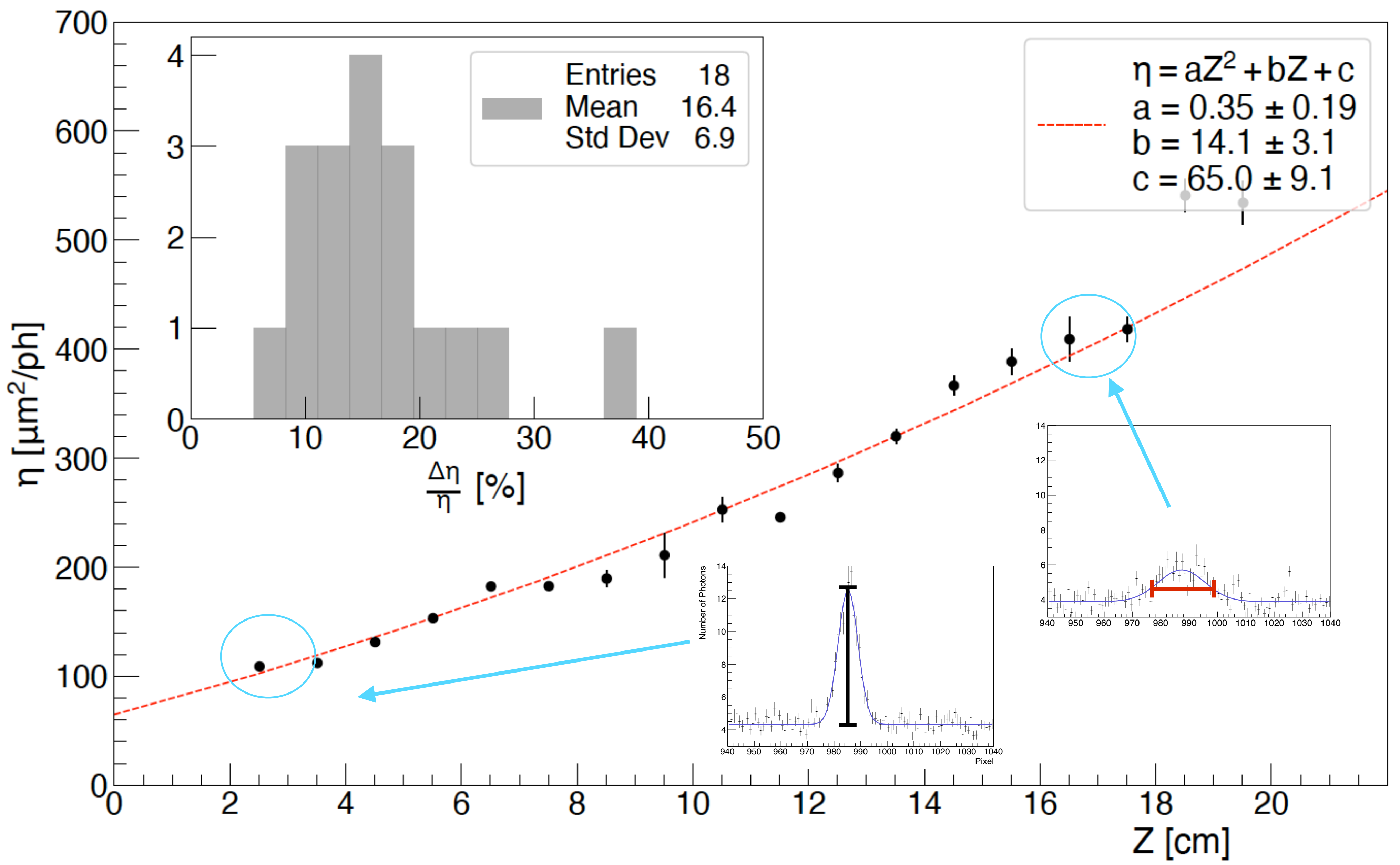
Energy resolution of 15% with CMOS and PMT

Z RESOLUTION

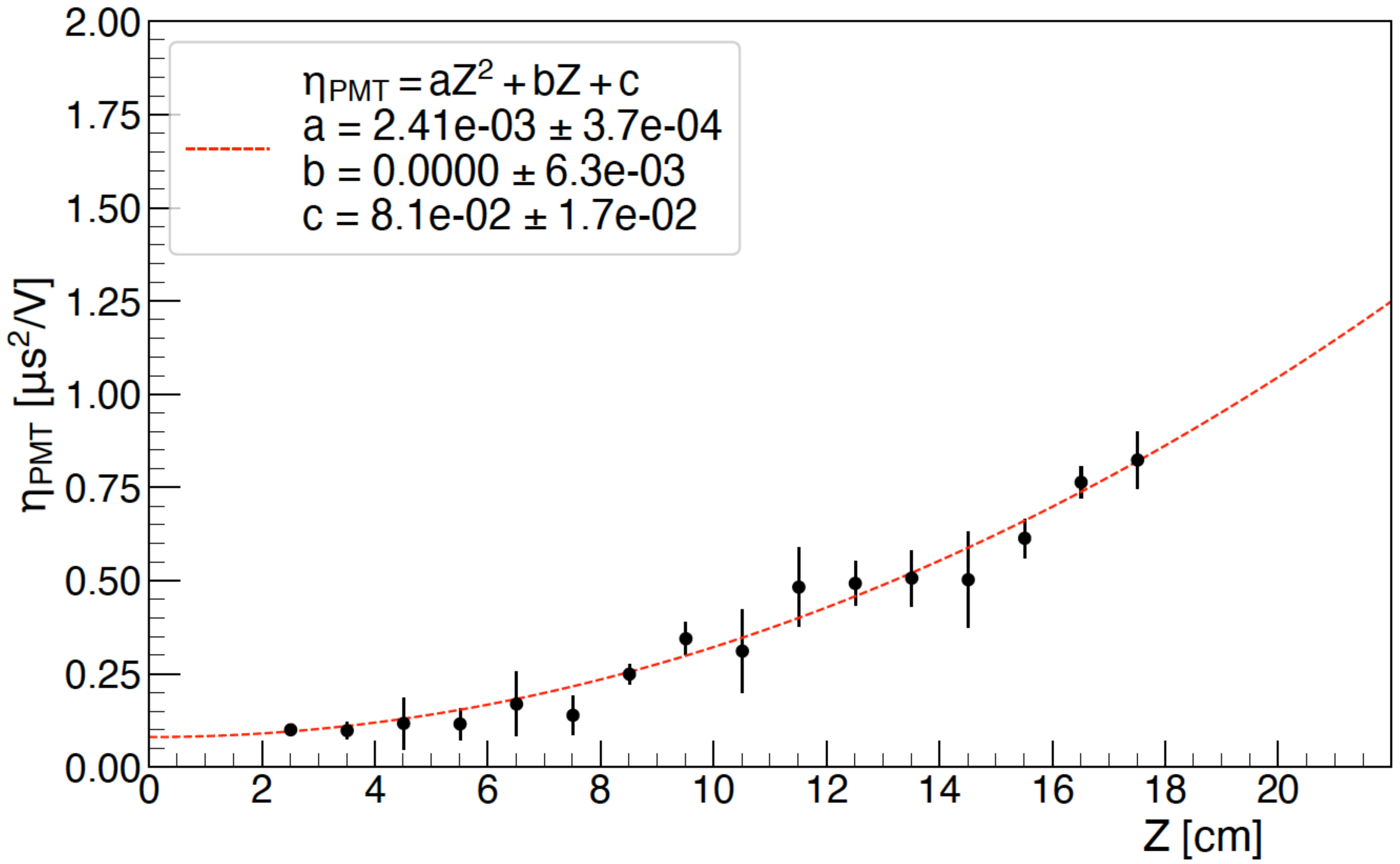
Electron diffusion in the drift gap can be exploited to evaluate the ***z* of the event**.

The **transverse light profile** and the **PMT signal waveform** are expected to become **lower** and **larger** as long as the event is **farther** from the GEM;

Since the width (S) increases and the amplitude (A) decreases with *z*, their ratio η = S/A increases



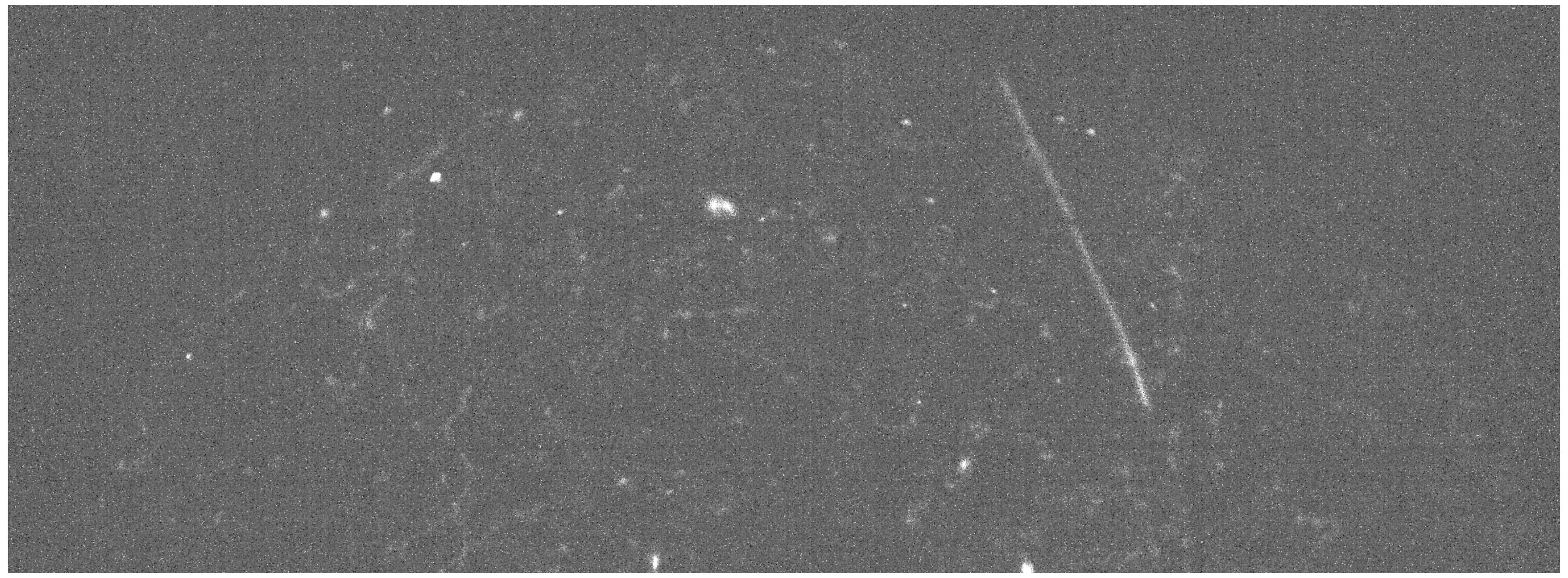
Antochi et al, Nucl.Instrum.Meth.A 999 (2021)

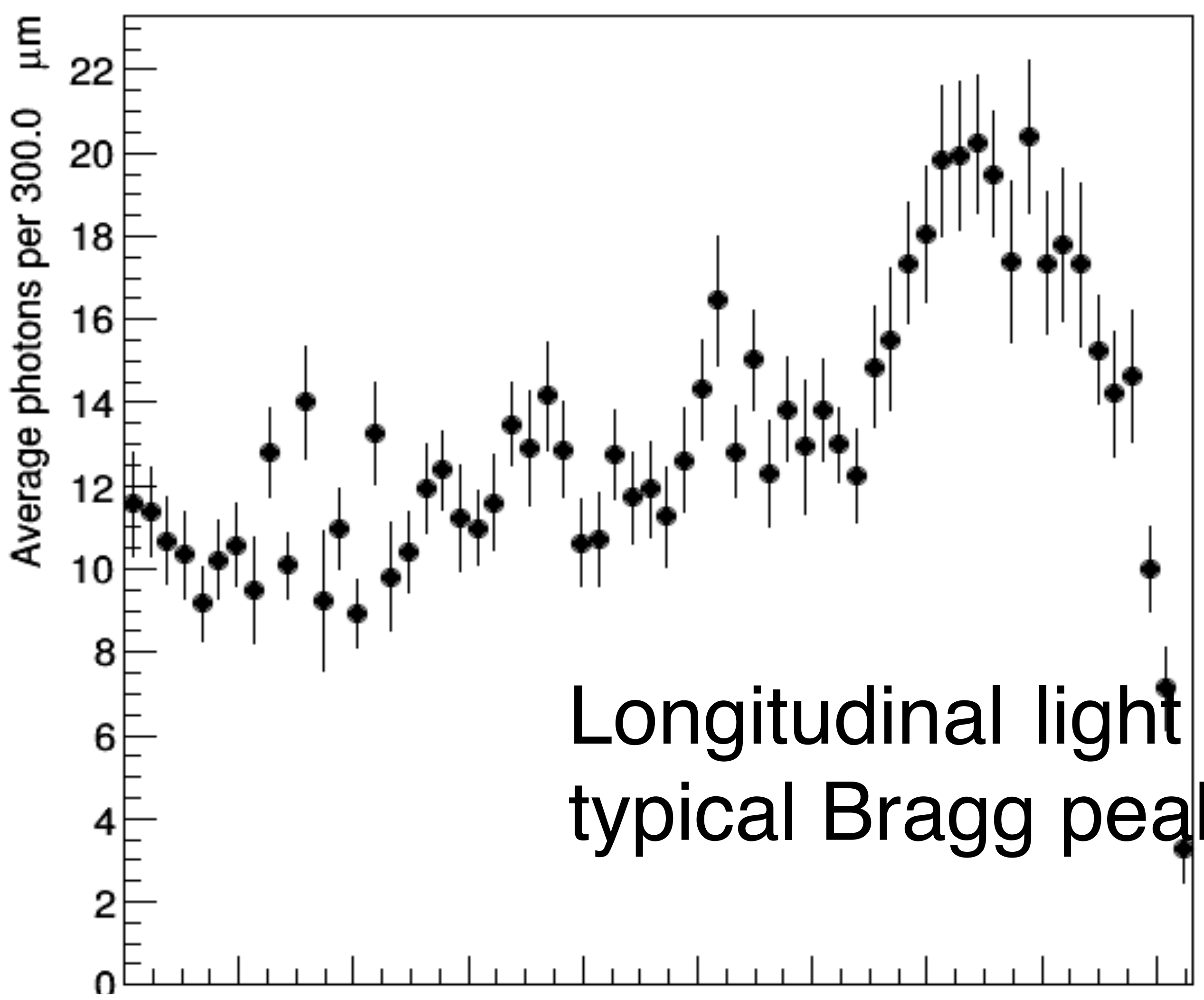


Both methods gives **15%** precision: σ_z ~ 7 cm @ 50 cm

NUCLEAR RECOILS IN LEMON

0.1s exposure @ 2.45 MeV neutrons
Frascati Neutron Generator - ENEA





Longitudinal light profile shows a typical Bragg peak shape

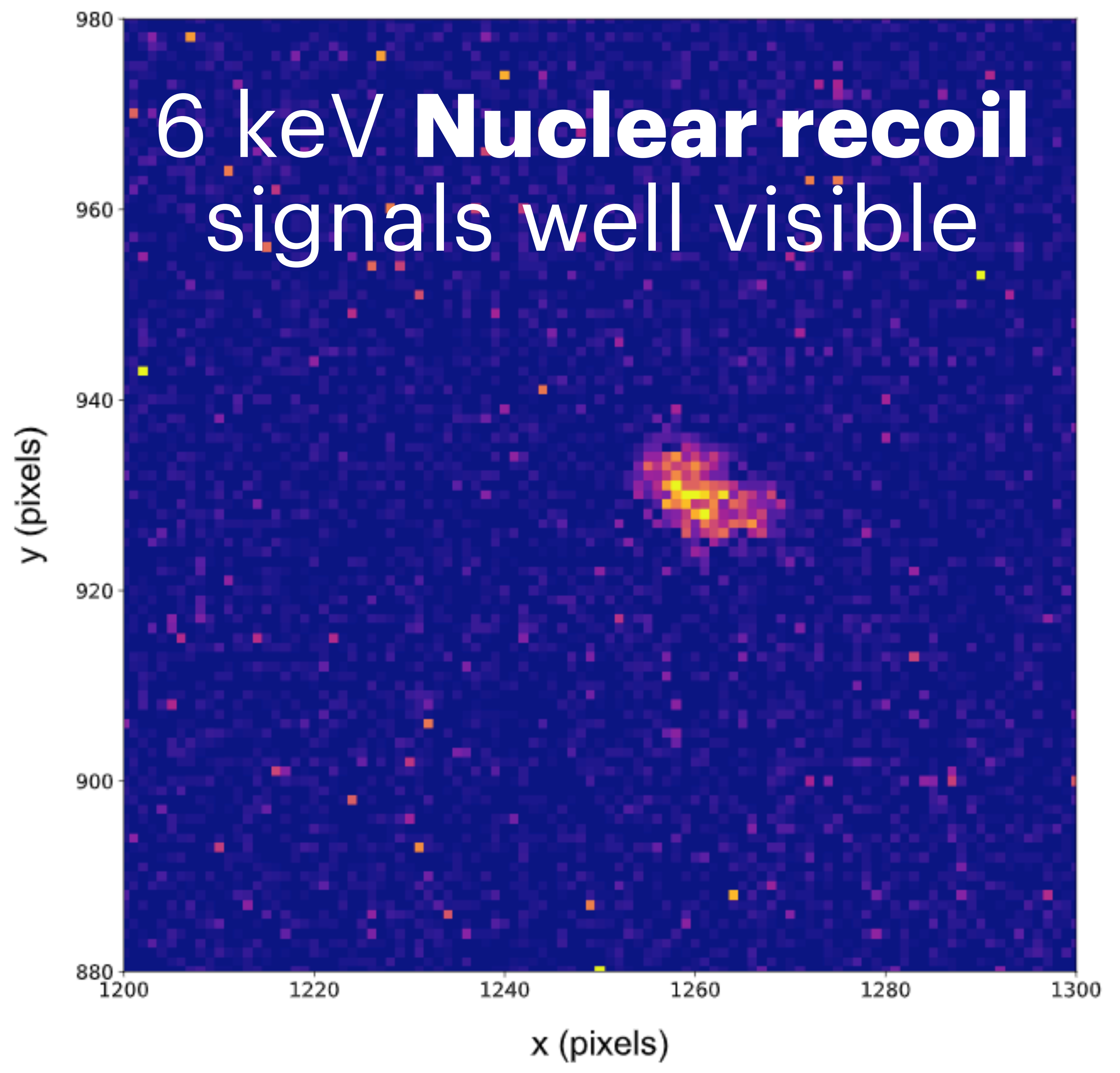
LEMON was exposed to **neutrons** at Frascati Neutron Generator (**FNG-ENEA**) and to **AmBe** neutron source at **LNF**;

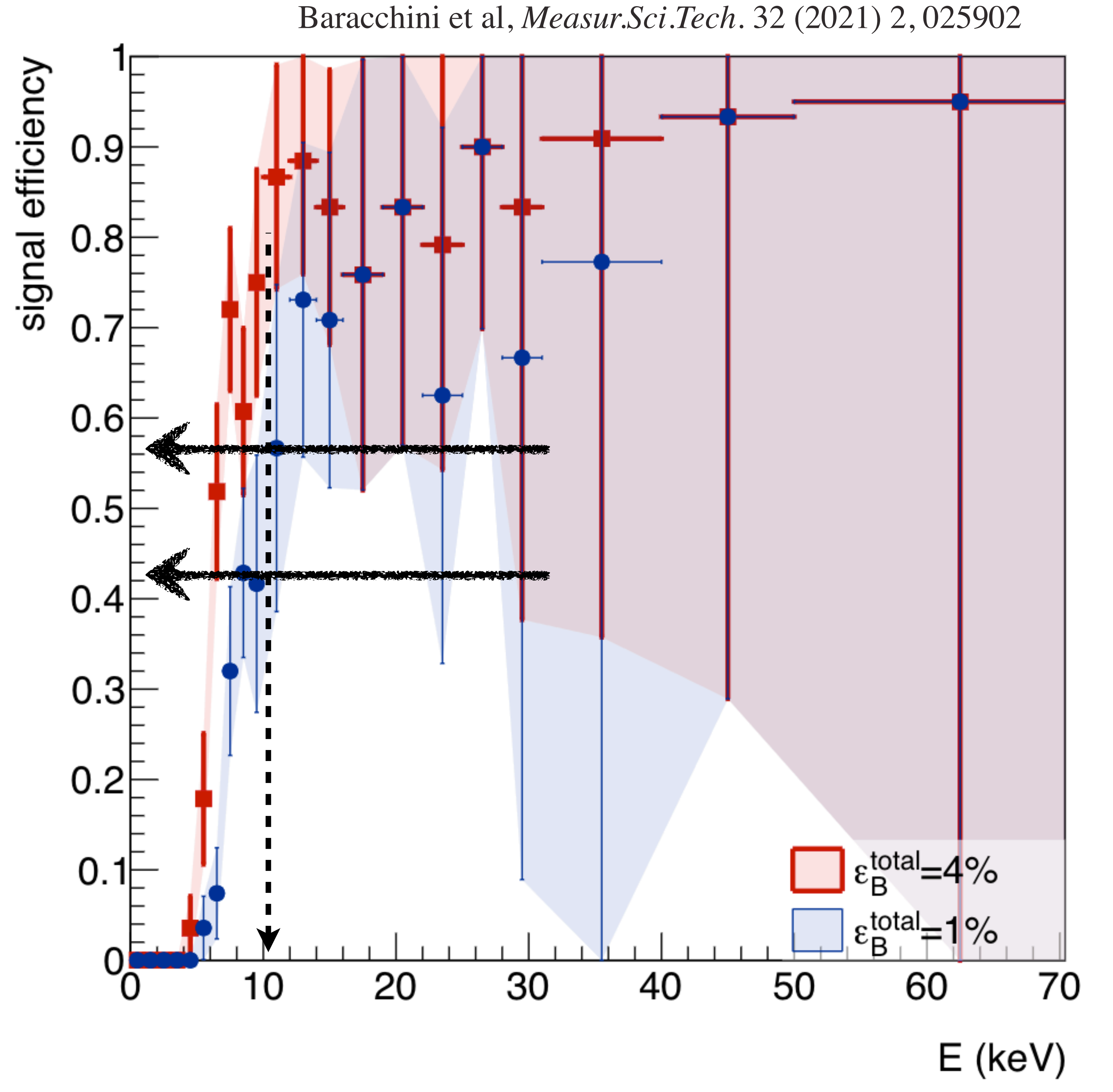
An **algorithm** was developed to **identify** the identity of **recoils** (either an electron or a nucleus) by exploiting the **topological informations** as shape, size and light density.

IDAO
INTERNATIONAL
DATA ANALYSIS OLYMPIAD

Collaboration with IDAO to exploit **ML-based** code to identify signals in the images

PERFORMANCE WITH NUCLEAR RECOILS





A sizeable NR detection efficiency was measured:

- **40%** at 6 keV;

- **55%** at 10 keV;

In the same conditions more than **99% (95%)** **^{55}Fe photons** were **rejected**

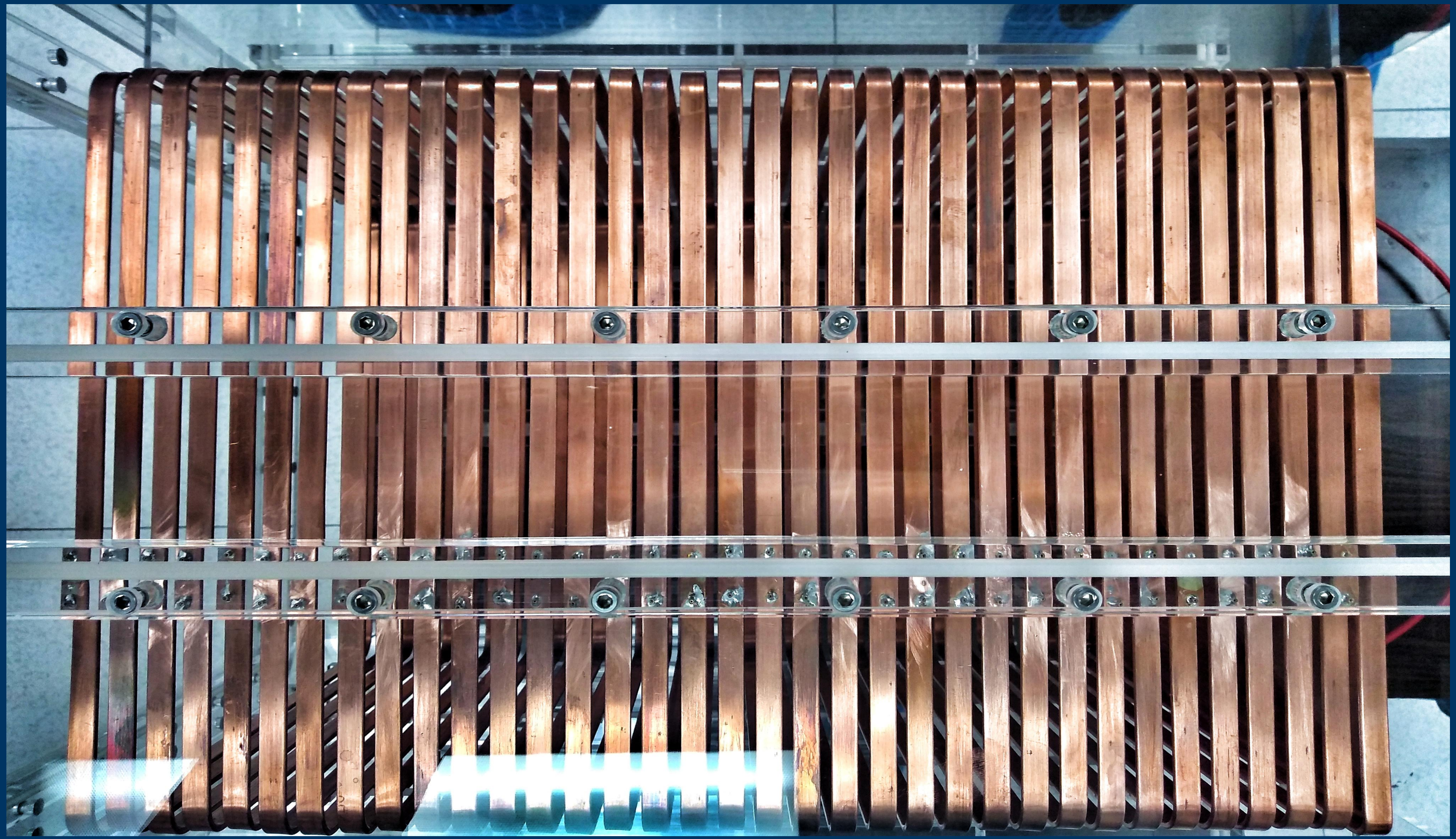
First attempt to prove experimentally **rejection** capability **below 10 keV**

LIME: LARGE IMAGING MODULE

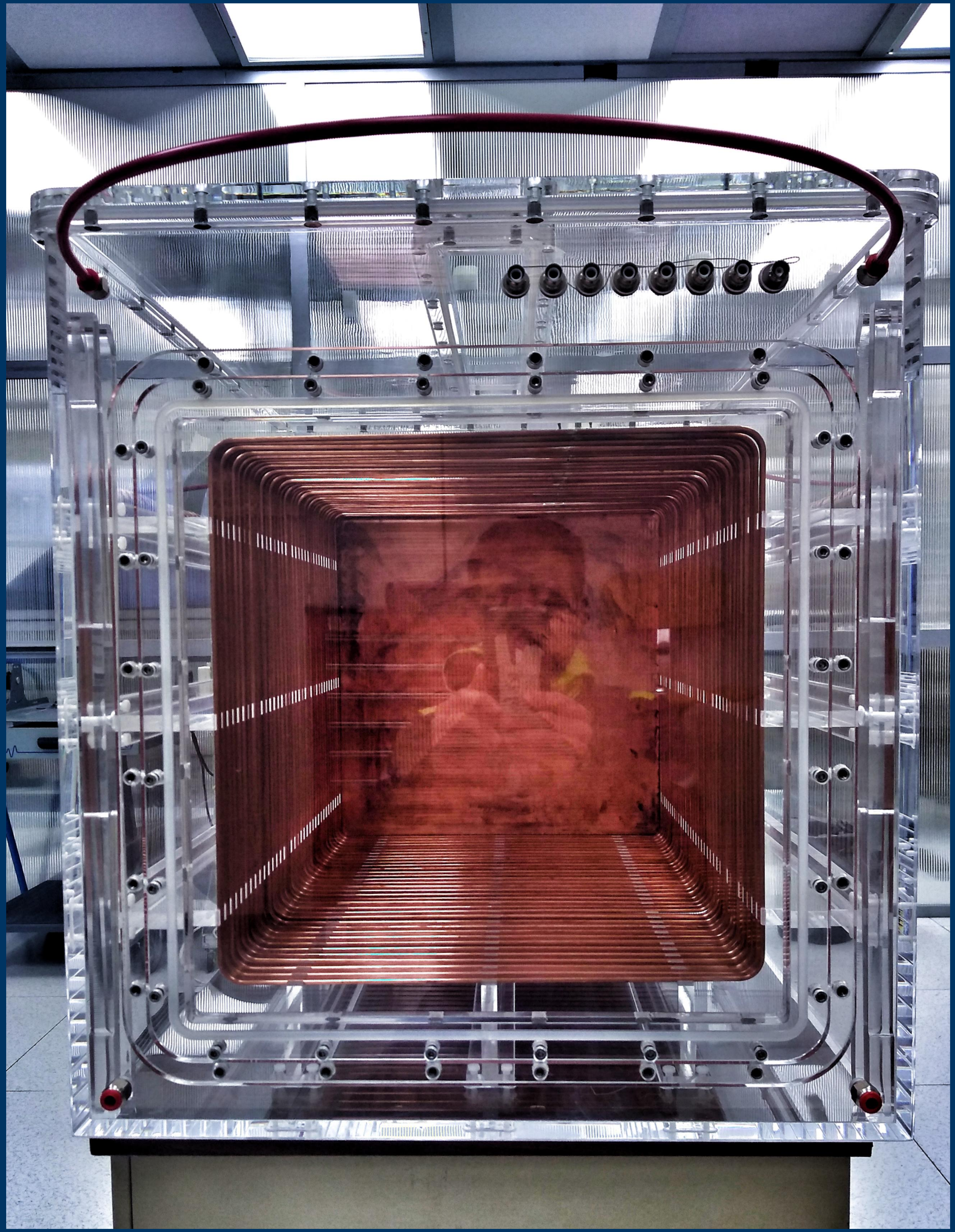
50 litres sensitive volume:

- **33 x 33 ~ 1000 cm²** GEM surface;
- **50 cm** drift path;

Copper ring field cage

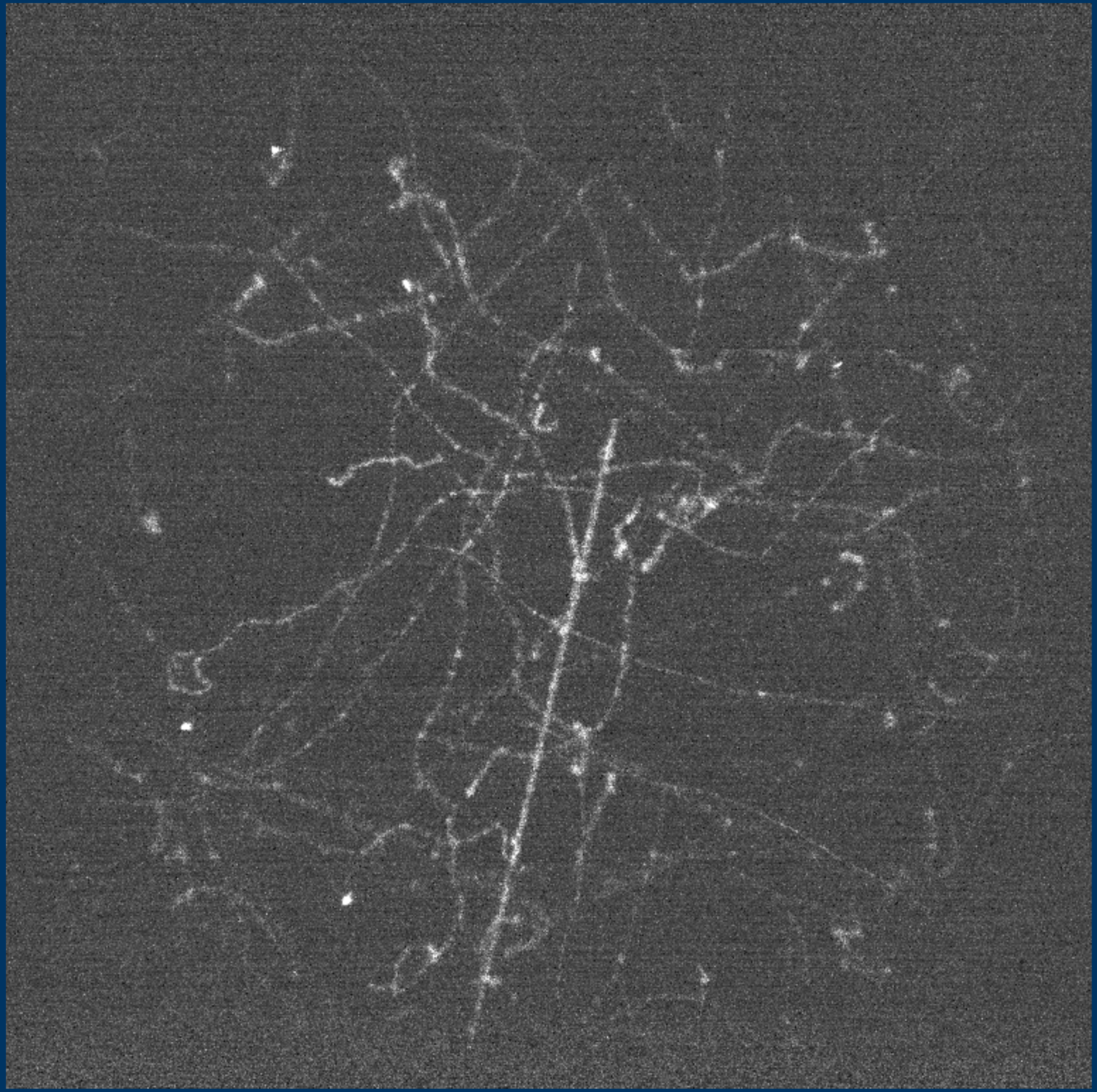


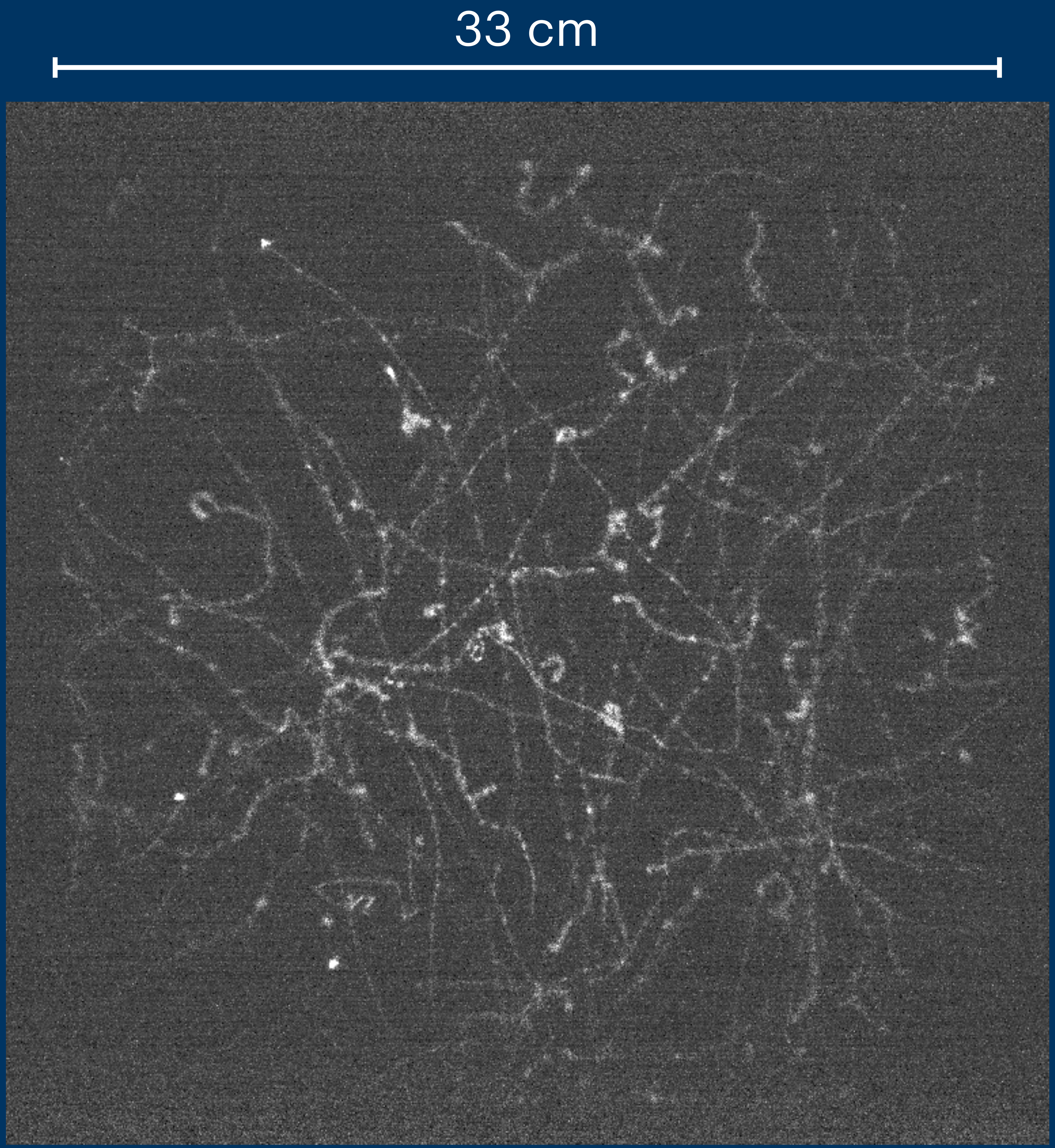
- designed RM1-LNF and assembled at LNF



Acrylic gas vessel

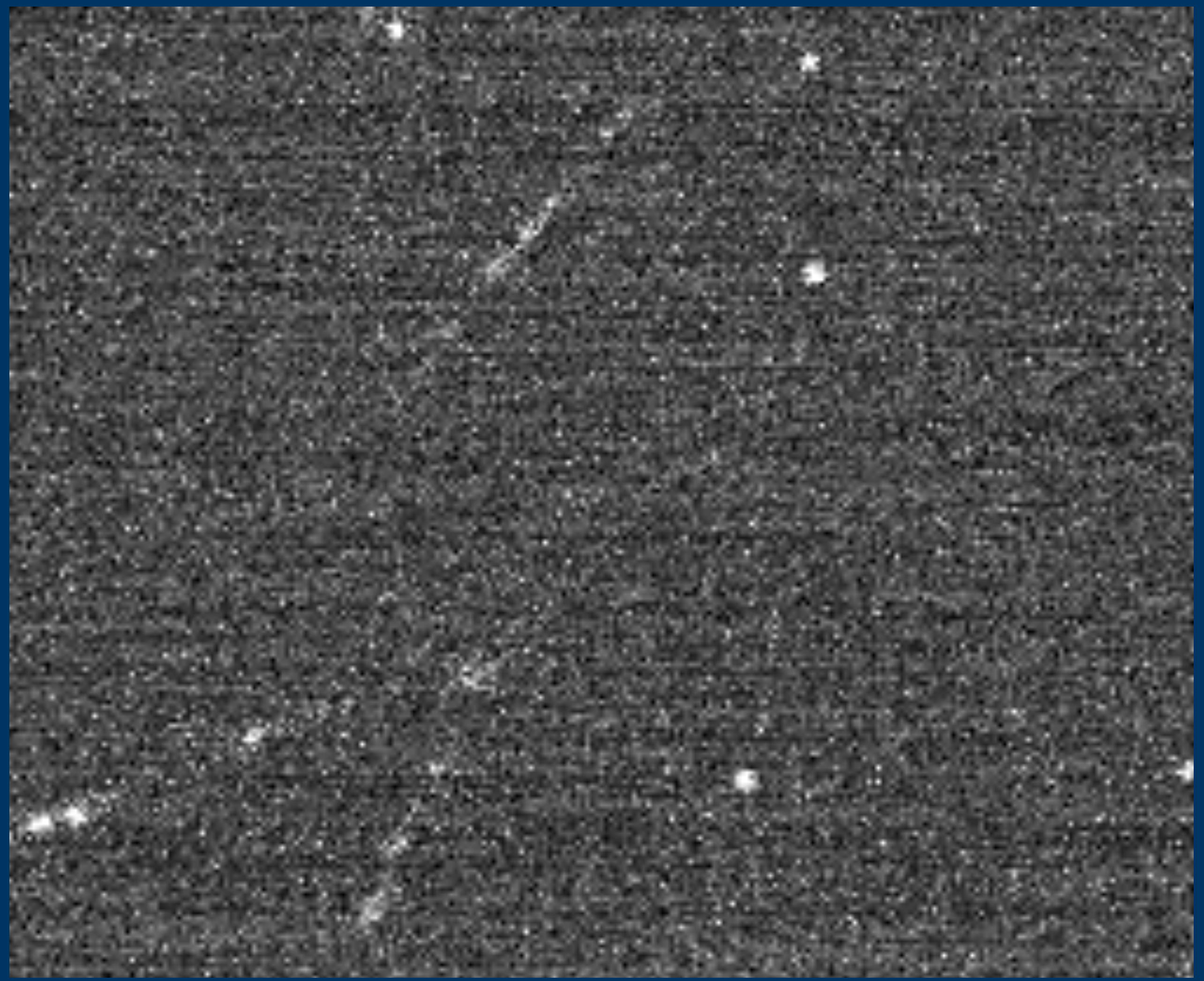
LIME: IMAGES



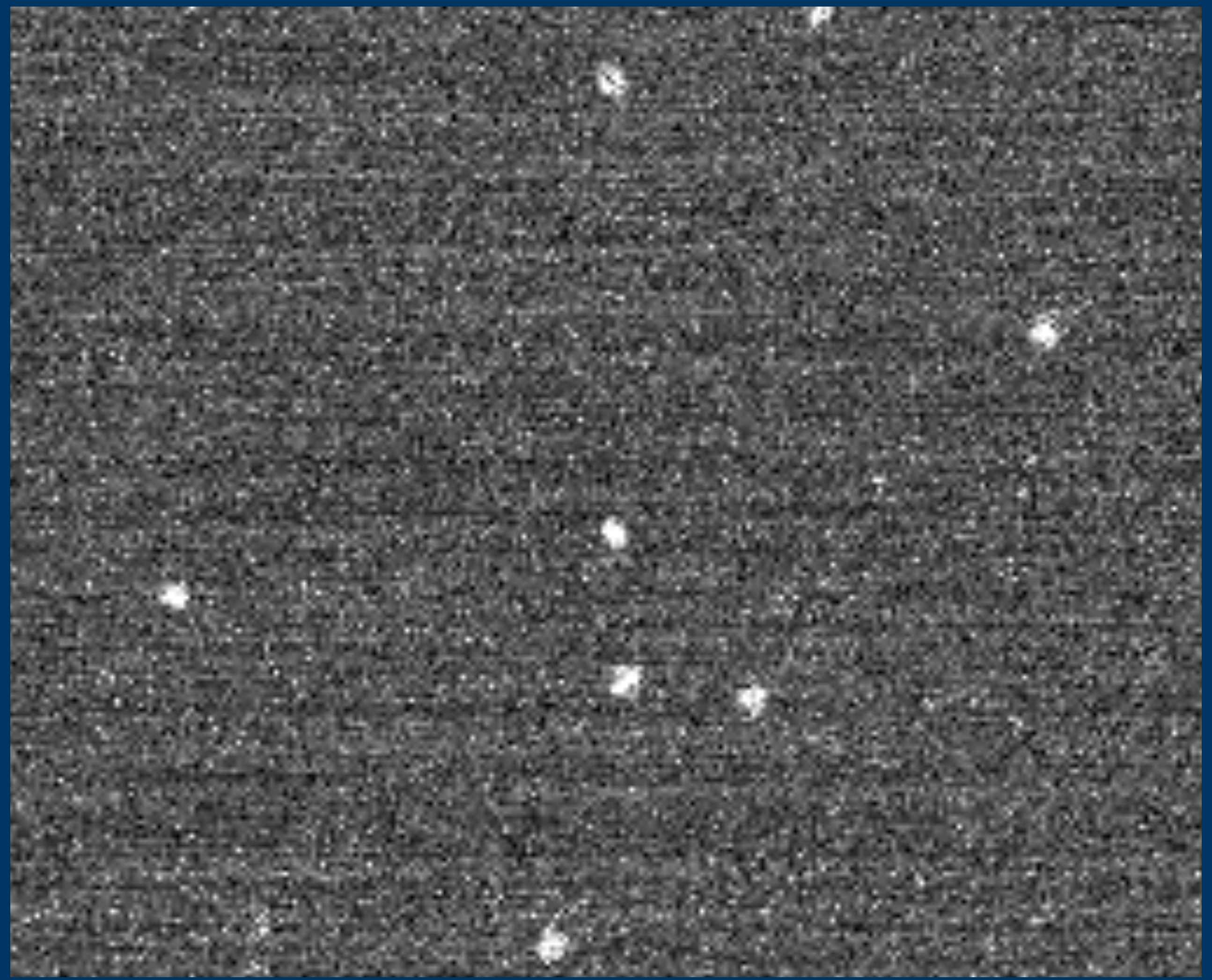


PERFORMANCE WITH ^{55}FE: SPOT SIGNALS

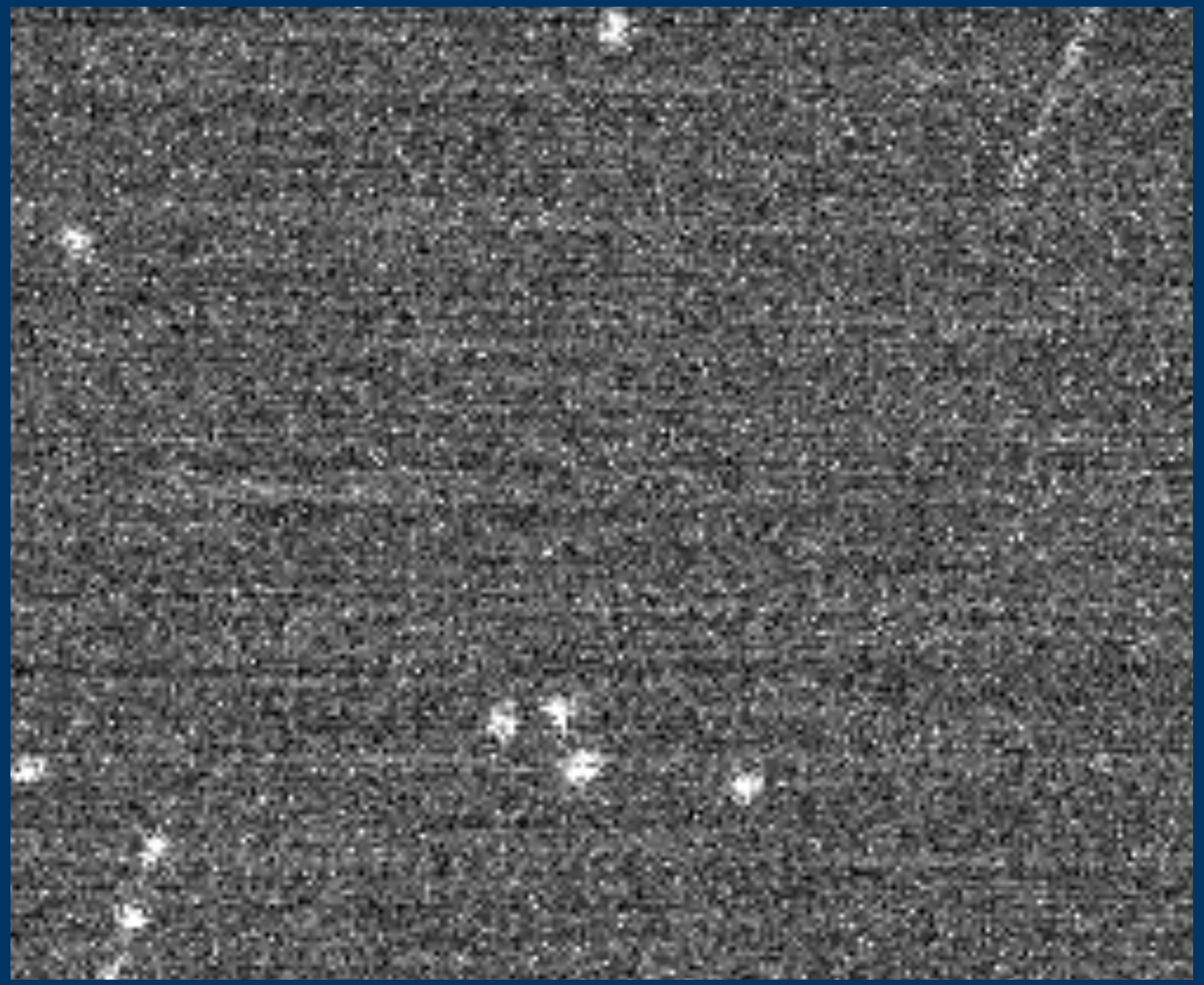
- 5 cm from GEMs



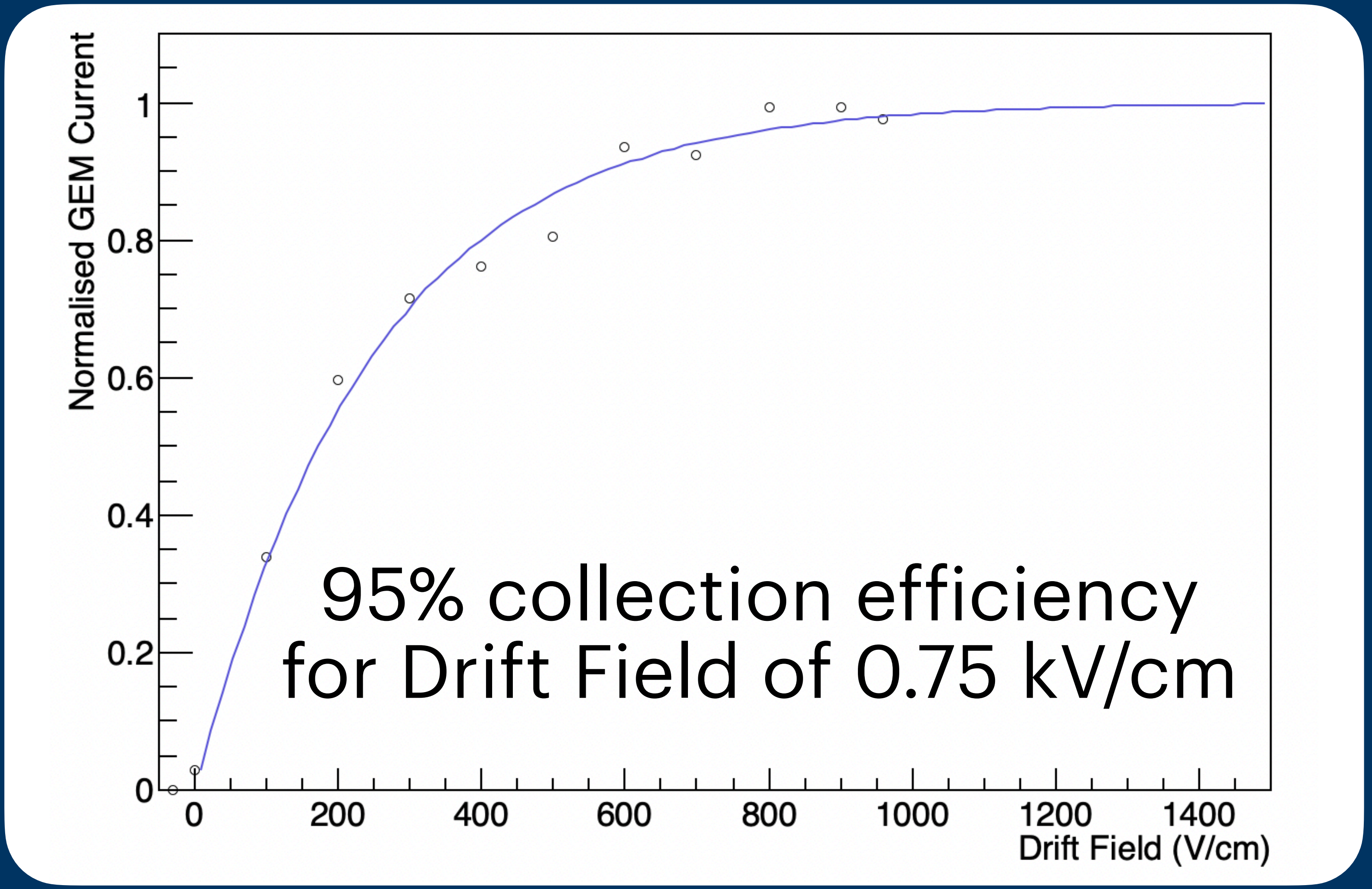
- 20 cm from GEMs

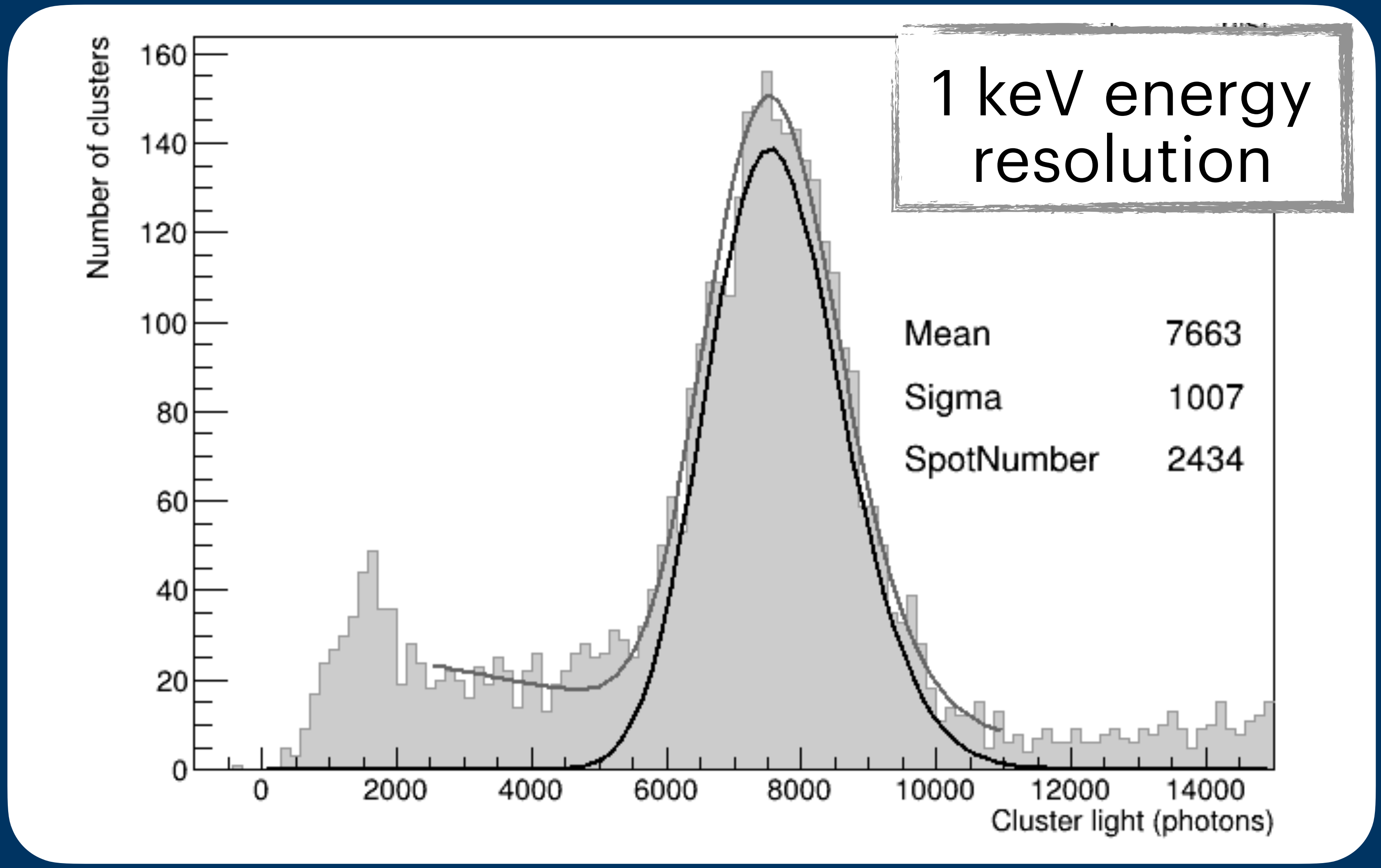


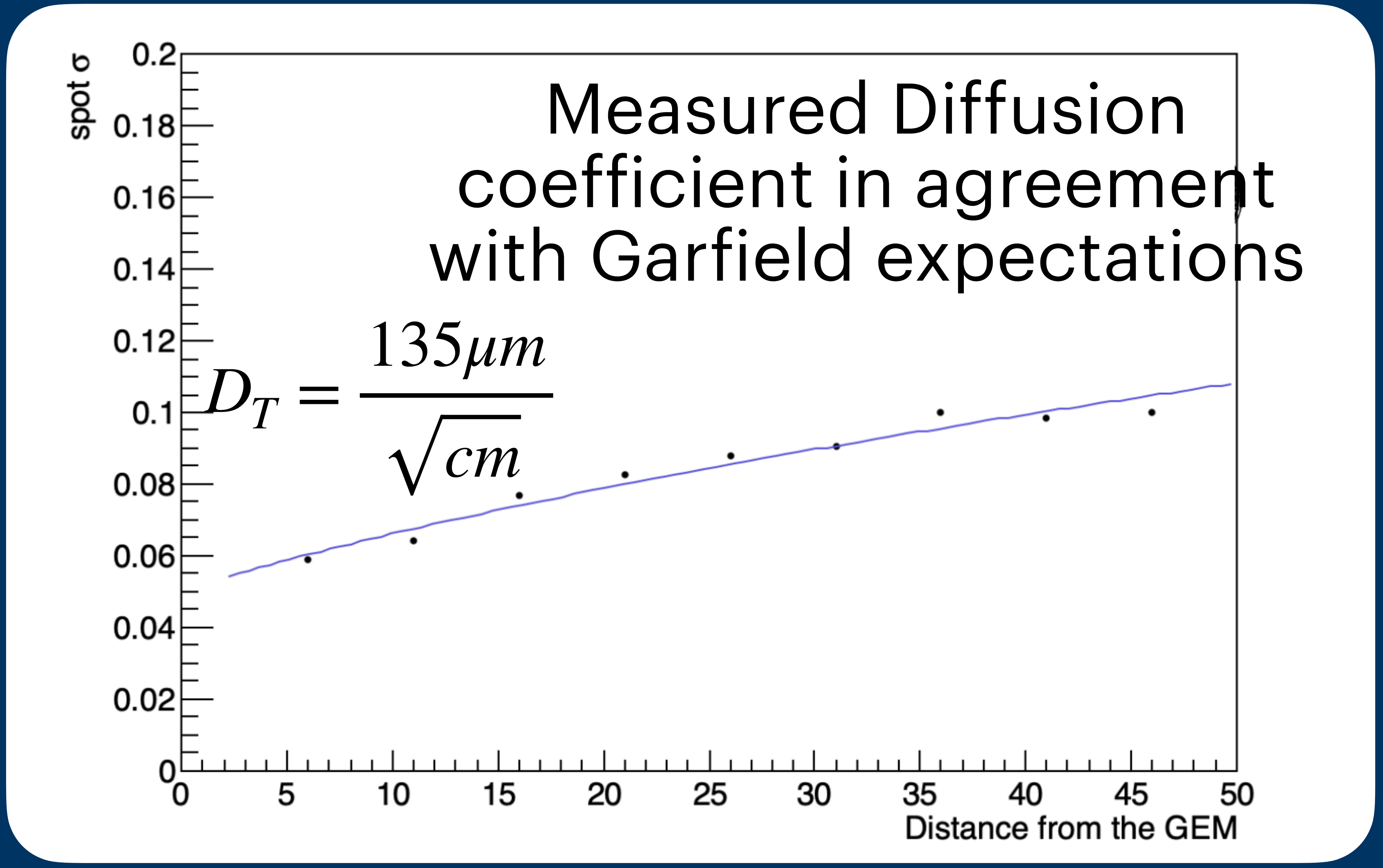
- 45 cm from GEMs



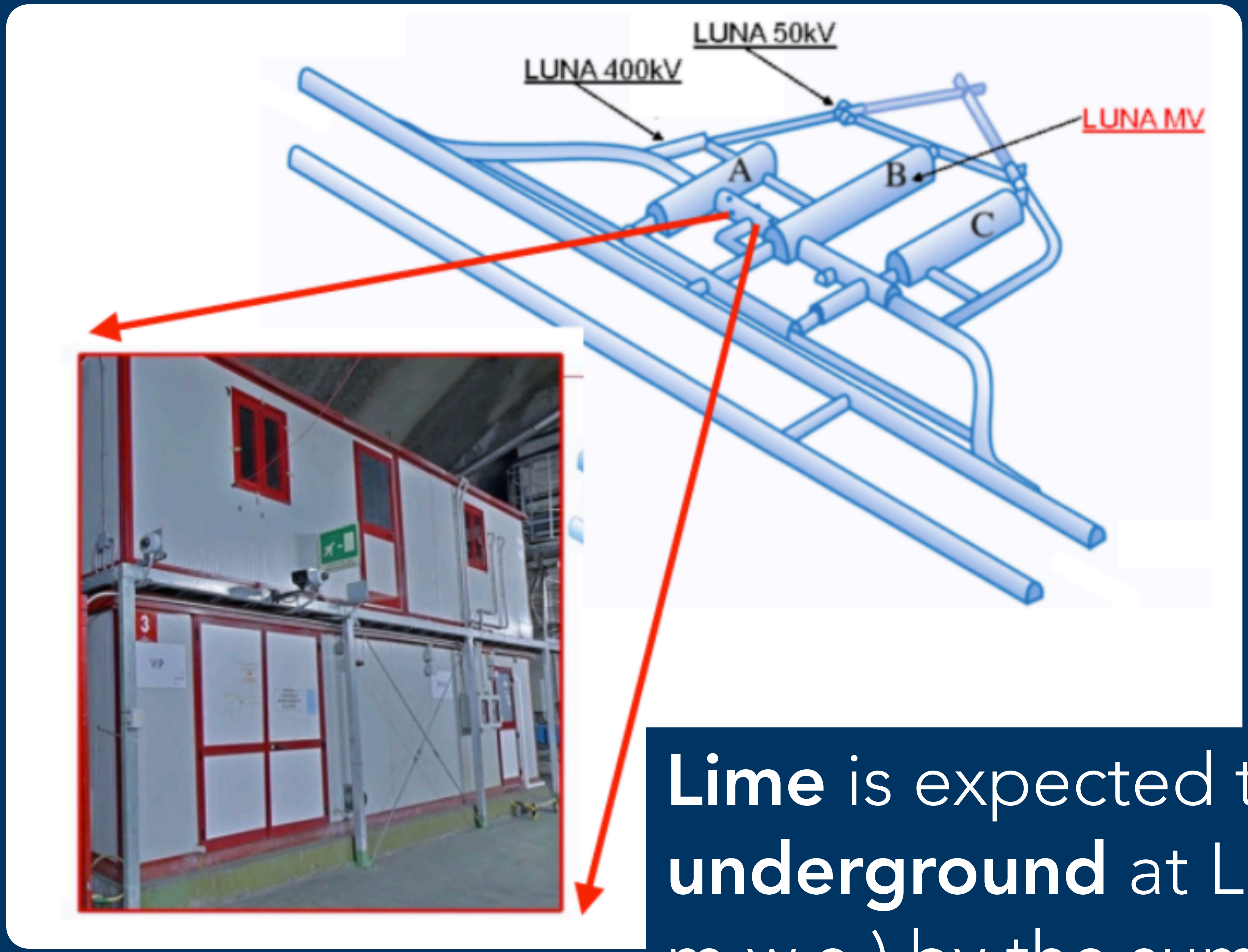
Diffusion effect **visible**

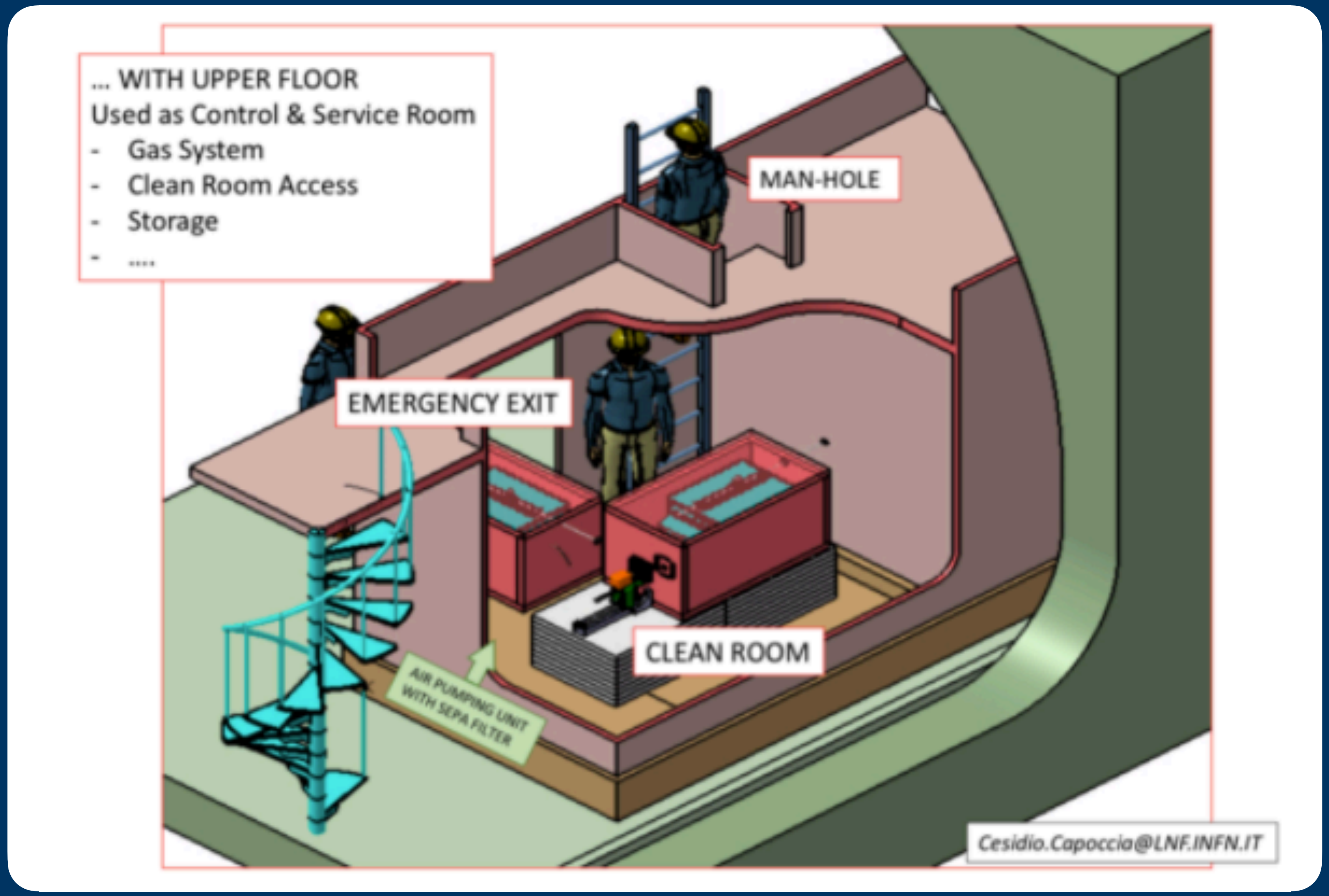






LIME UNDERGROUND

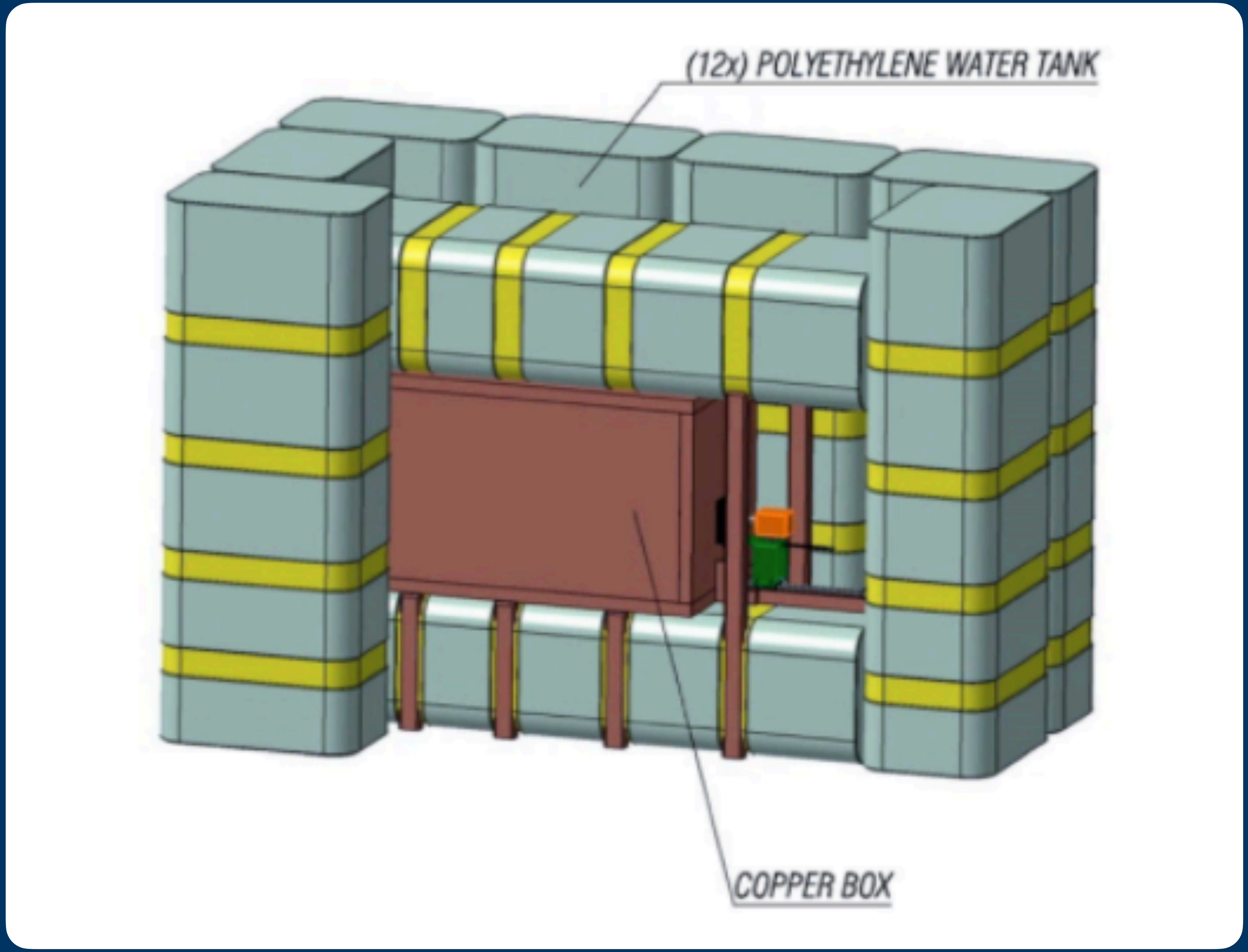




Neutron and other background flux will be studied (activity funded by PRIN project Zero Radioactivity in Future Experiments)

Lime is expected to be installed **underground** at LNGS (3600 m.w.e.) by the summer;

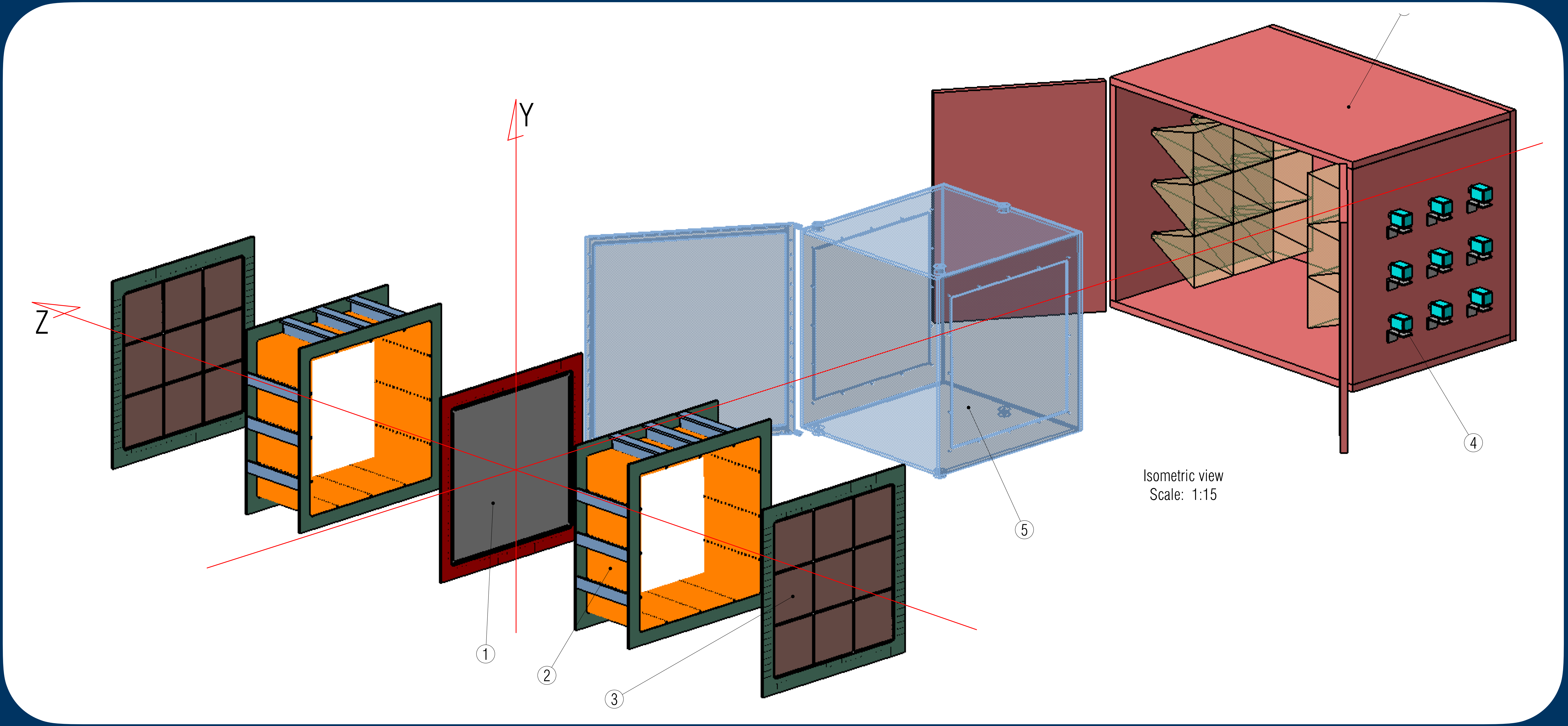
Then, **gamma** and **neutron shields** will be put in place to take date in shielded mode



1M³ DEMONSTRATOR: BASELINE LAYOUT

1 m³ of **He/CF_4 60/40** (1.6 kg) at **atmospheric pressure** with a composed by two 50 cm long TPC with a central cathode and a drift field of about 1 kV/cm;

Acrylic vessel ensuring gas tightness and high voltage insulation;



Each side equipped by a 3x3 matrix of LIME-like:

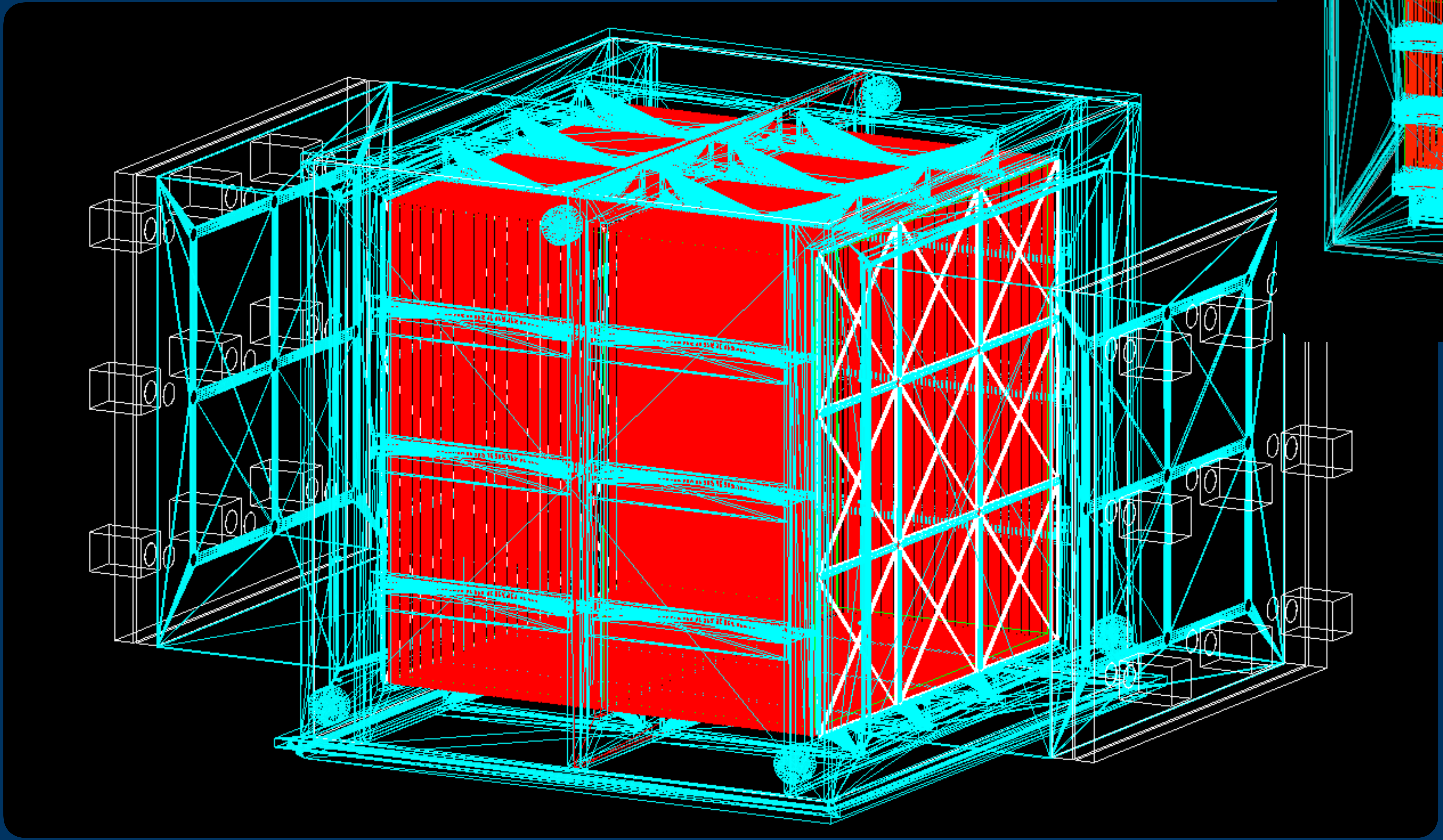
- sCMOS sensor 65 cm away;
- Almost 10^8 readout pixels 165 x 165 μm^2
- Fast light detector (PMT or SiPM).

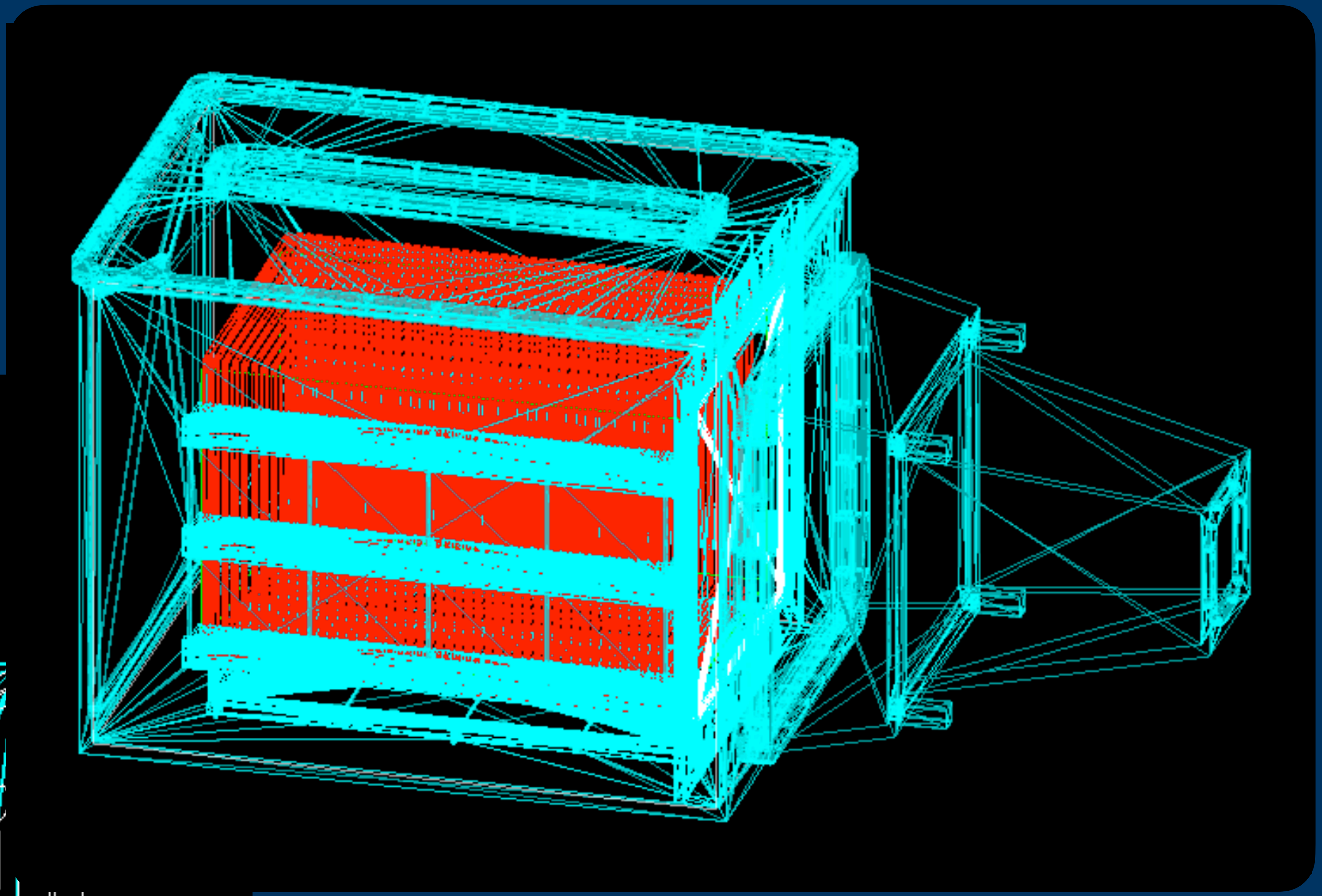
Radioactivity shielding:

- **5 cm** thick **copper** box (Faraday cage too);
- **200 cm** of water.

BACKGROUND STUDIES

Full Detector simulation in **GEANT4**



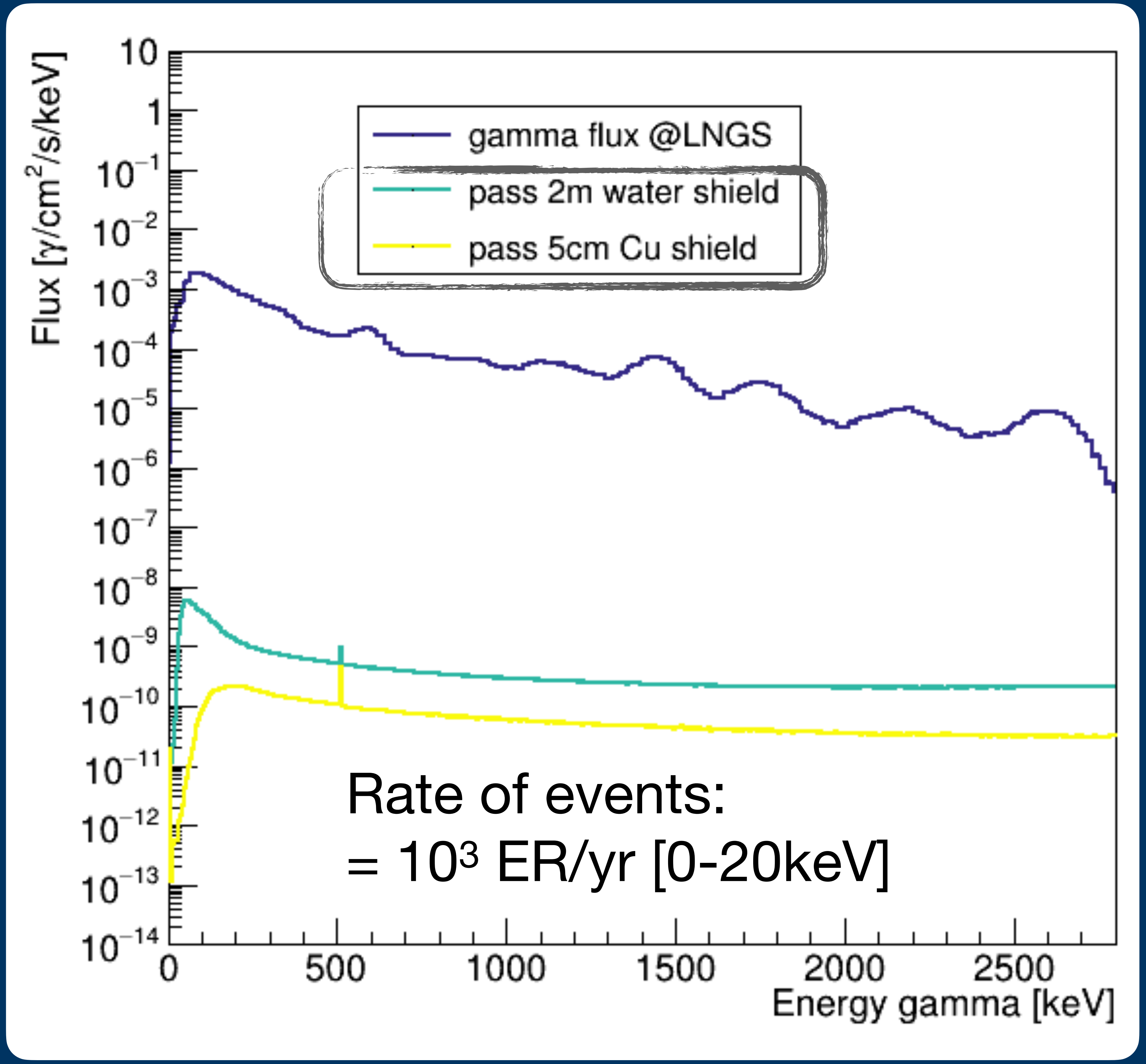


Gamma and **neutron** background due to **external** and **internal** radioactivity simulated.

BACKGROUND STUDIES: EXTERNAL

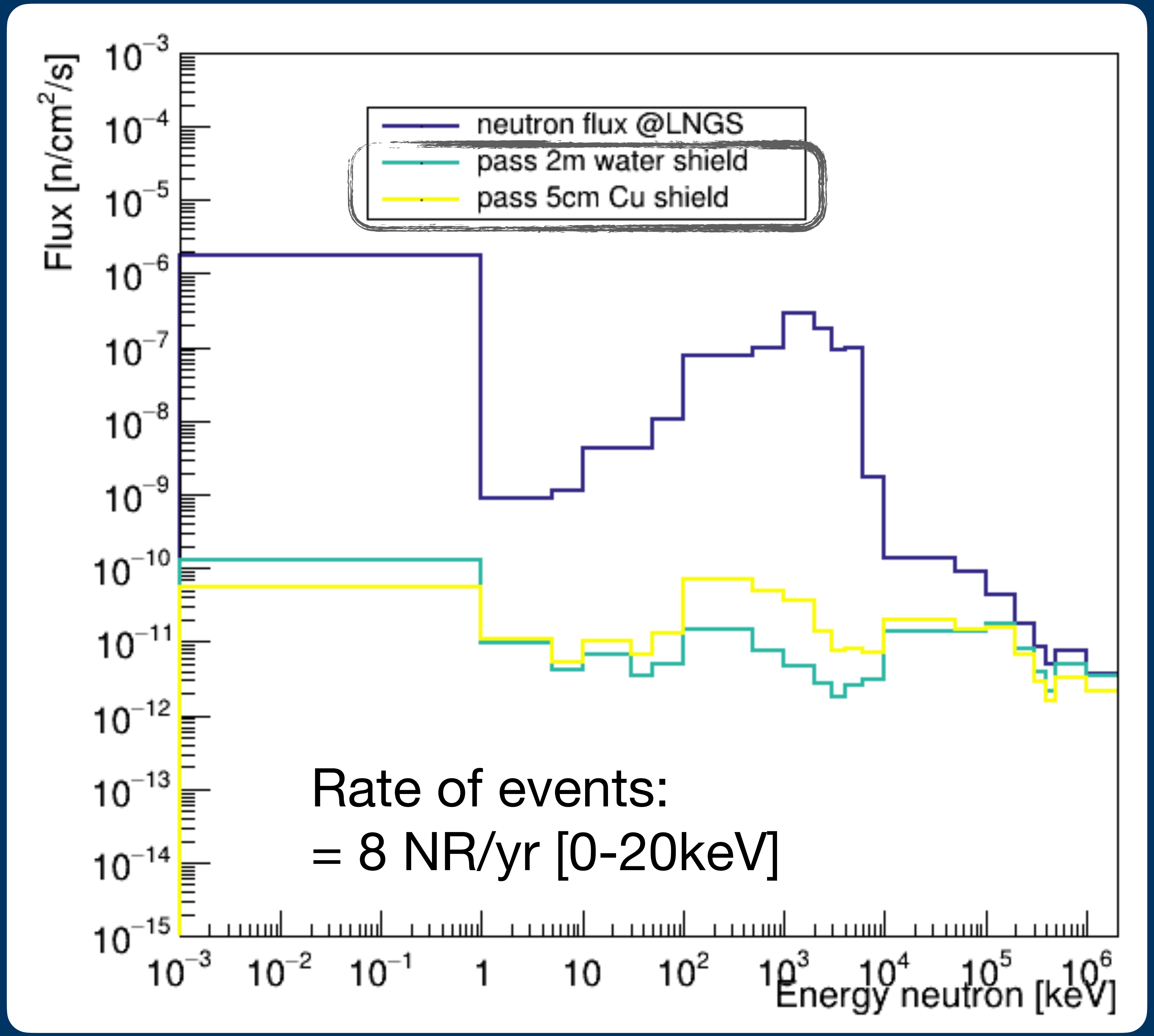
Gamma flux @LNGS (Hall C) -

measured by SABRE : 0.56 Hz/cm^2

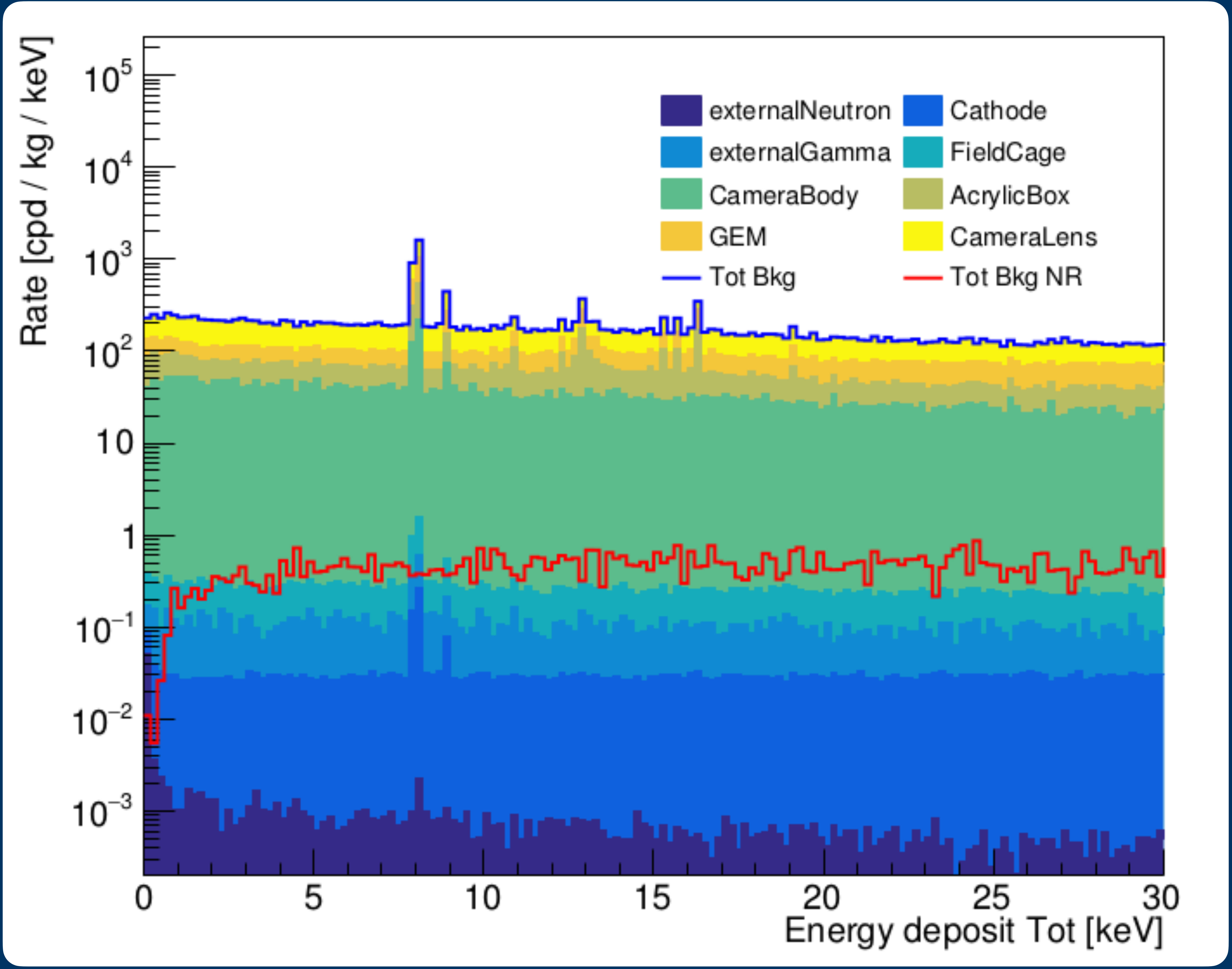


Neutron flux @LNGS (Hall C) -

measured by CUORE : 2.7x10^{-6} Hz/cm^2



BACKGROUND STUDIES: INTERNAL



To quantify **internal** background **radioactivity** of all detector **components was** measured at LNGS

Thanks to M.Laubenstein

Camera Body Orca Flash	Limit/Meas	Activity (Bq/kg)
U238 (Th234)	M	3.16E+00

Camera Lens Orca Flash	Limit/Meas	Activity (Bq/kg)
U238 (Th234)	M	4.22E+00
K40	M	5.15E+01

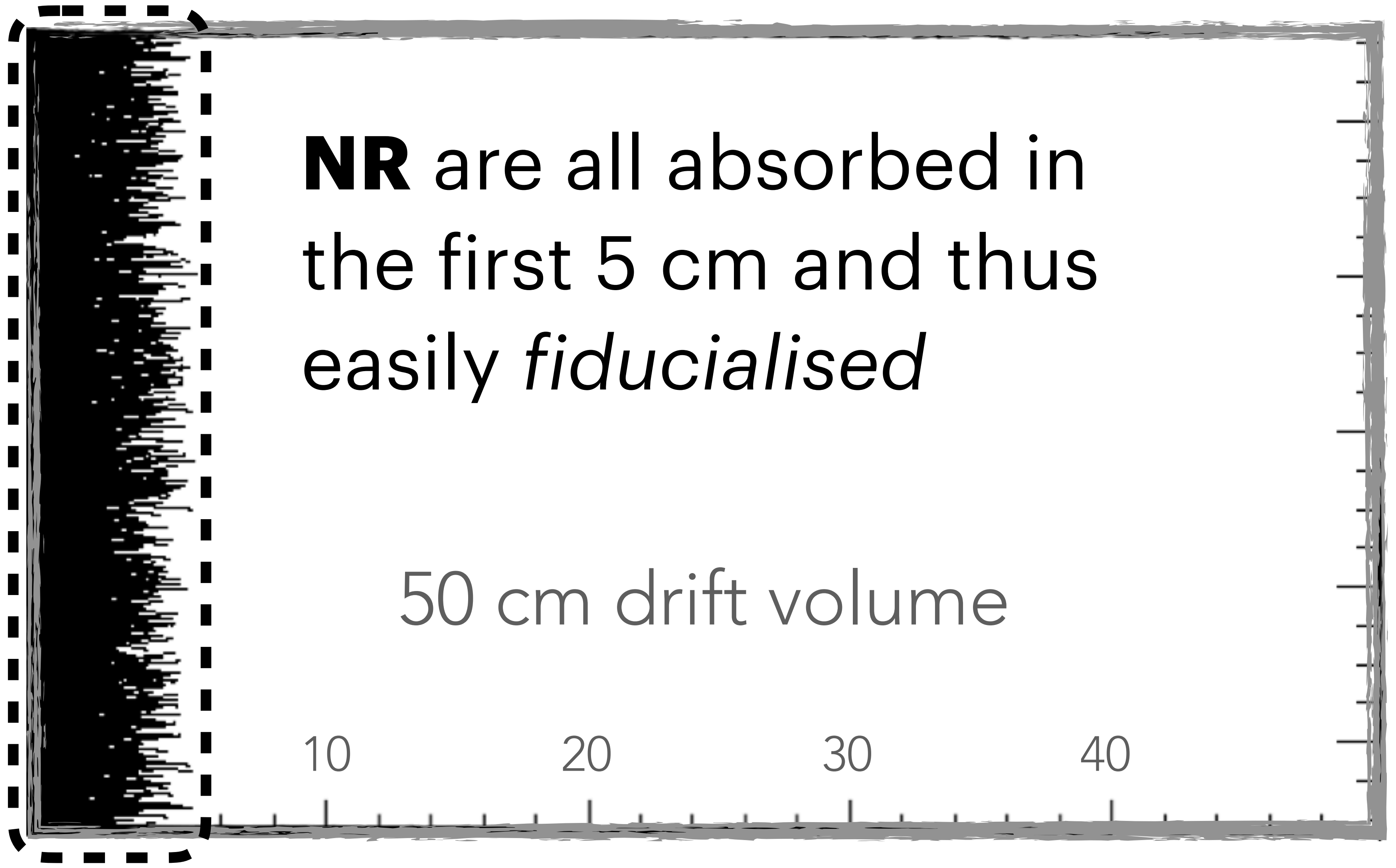
GEM	Limit/Meas	Activity (Bq/kg)
U238 (Th234)	M	1.63E-01
K40	L	3.58E-01

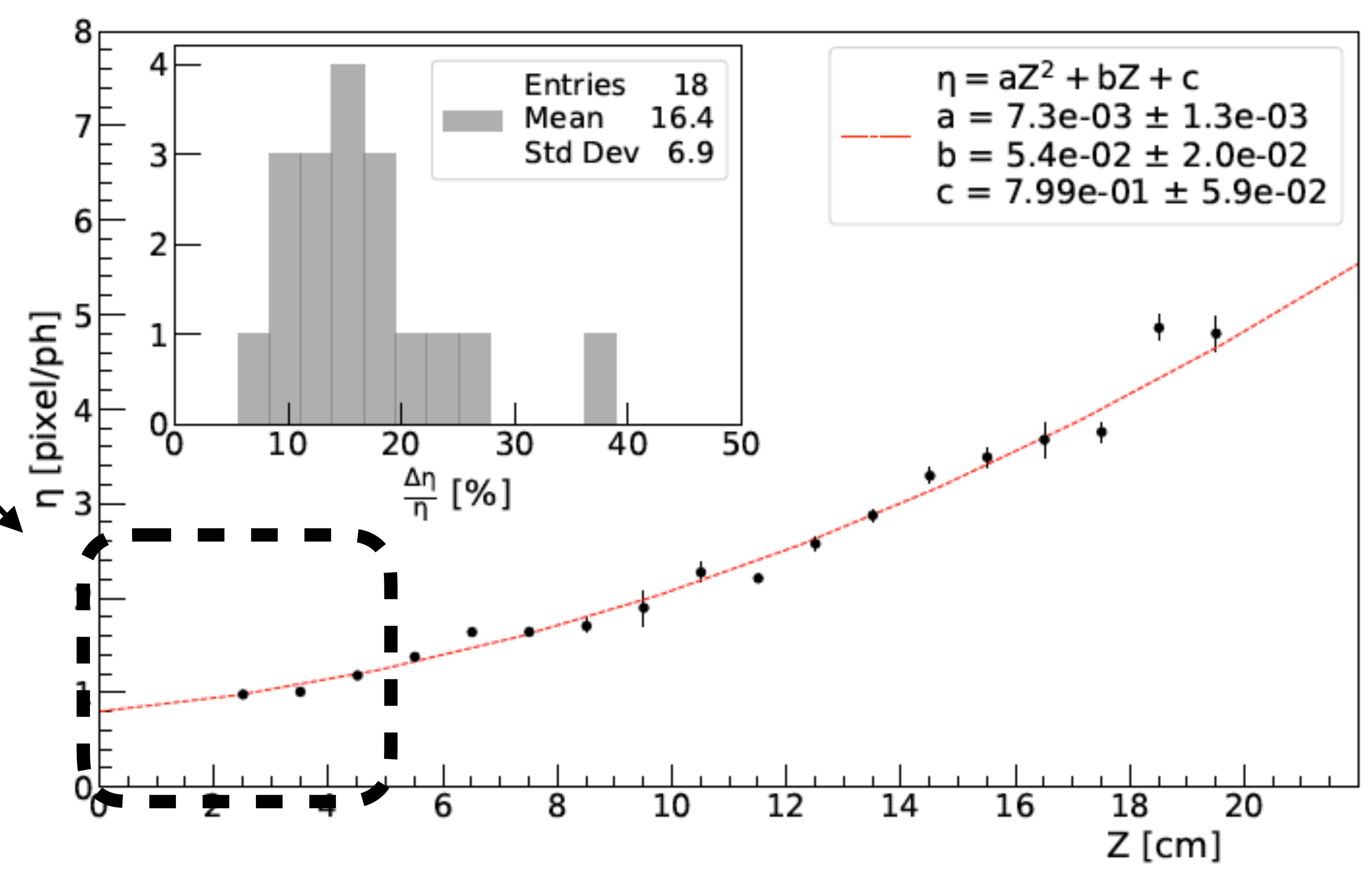
Acrylic Box	Limit/Meas	Activity (Bq/kg)
K40	L	3.50E-02

Largest contributions come from: **Camera**, **Lens**, **GEM** and **Acrylic**.

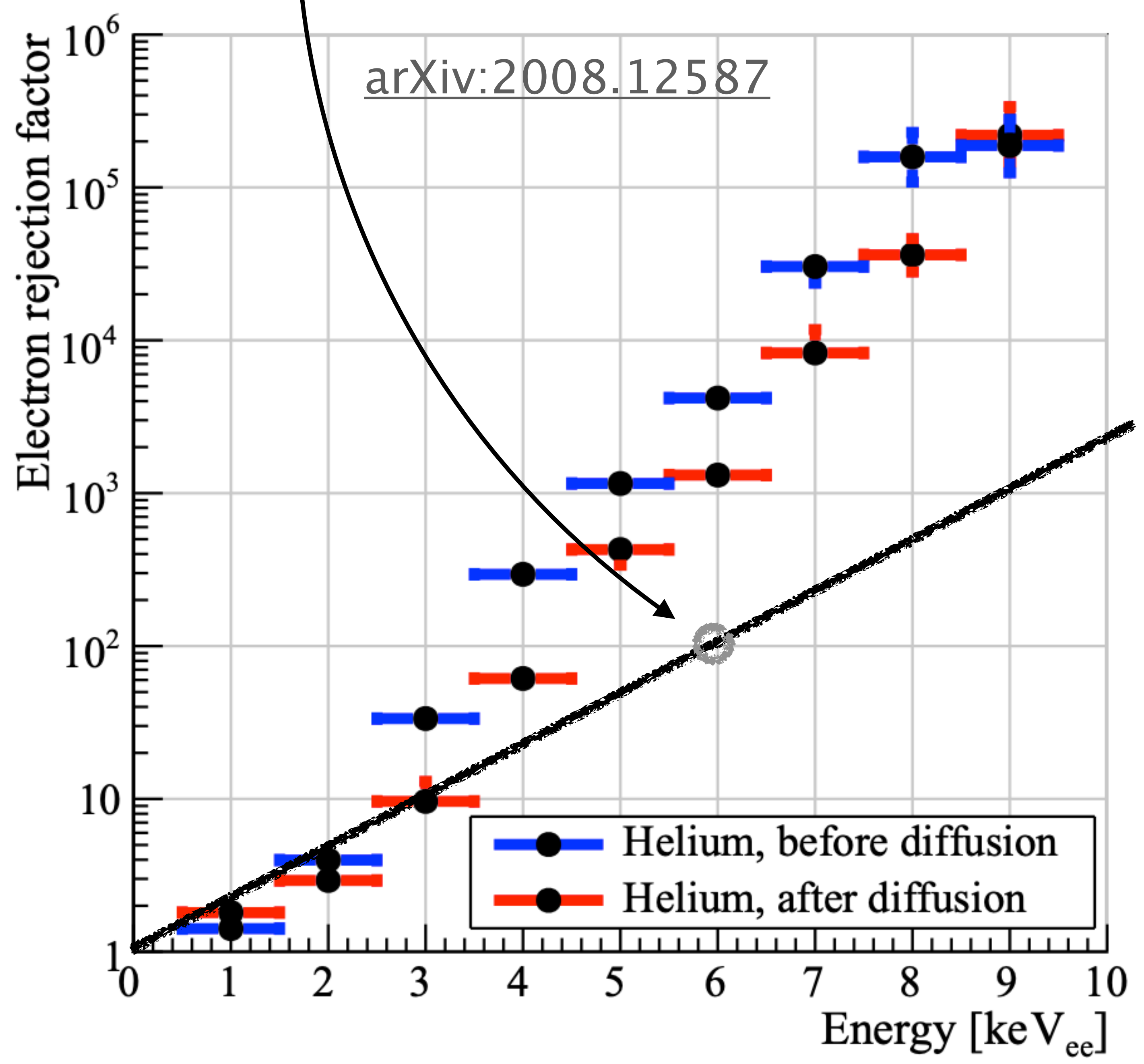
REJECTION CAPABILITY

We expect: **10^3 NR/yr** and **2×10^6 ER/yr** in 1 m^3 [0-20 keV]. 10 times less in LIME.





For **ER** we already demonstrated a rejection of factor (**RF**) **99% at 6 keV** with 2D information



TPC **simulation** with 3D readout foresees a fast increasing RF

Assuming a slower increasing, an **average value of 10^4** can be obtained in the **0-20 keV range**

Rate of **bkg events** = **10^2 - 10^3 ER/yr [0-20keV]**

INTERNAL BACKGROUND REDUCTION

Photometrics – Prime BSI Express stand alone components: stand alone sensor + engineering unit for radioactivity tests

Different **cameras** were **measured** (Thanks to M. Laubenstein)

Each **internal component** of the camera **is being measured**

Radiopurity of Micromegas readout planes

S. Cebrián[a], T. Dafni[a], E. Ferrer-Ribas[b], J. Galán[a], I. Giomataris[b], H. Gómez[a,*], F.J. Iguaz[a,1], I.G. Irastorza[a], G. Luzón[a], R. de Oliveira[c], A. Rodríguez[a], L. Seguí[a], A. Tomás[a], J.A. Villar[a]

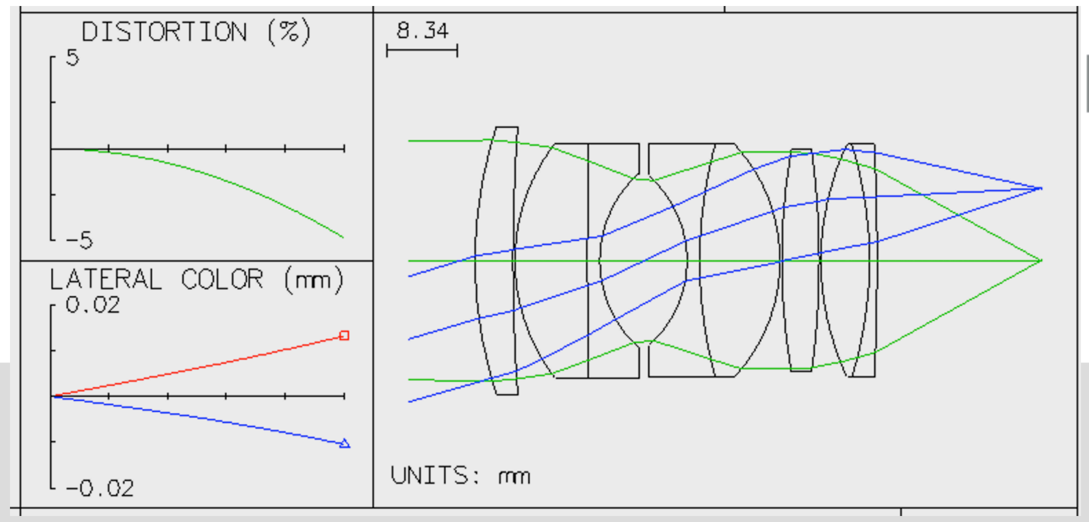
[a]Laboratorio de Física Nuclear y Astropartículas, Universidad de Zaragoza, 50009 Zaragoza, Spain
[b]CEA, IRFU, Centre d'etudes de Saclay, 91191 Gif-sur-Yvette, France
[c]European Organization for Nuclear Research (CERN), CH-1211 Genève, Switzerland

Background assessment for the TREX dark matter experiment

J. Castel[1,2], S. Cebrián[1,2,a], I. Coarasa[1,2], T. Dafni[1,2], J. Galán[1,2,3], F. J. Iguaz[1,2,4], I. G. Irastorza[1,2], G. Luzón[1,2], H. Mirallas[1,2], A. Ortiz de Solórzano[1,2], E. Ruiz-Chóliz[1,2]

[1] Laboratorio de Física Nuclear y Astropartículas, Universidad de Zaragoza, Calle Pedro Cerbuna 12, 50009 Zaragoza, Spain
[2] Laboratorio Subterráneo de Canfranc, Paseo de los Ayerbe s/n, 22880 Canfranc Estación, Huesca, Spain
[3] *Present Address:* Shanghai Laboratory for Particle Physics and Cosmology, INPAC and Department of Physics and Astronomy, Shanghai Jiao Tong University, 200240 Shanghai, China
[4] *Present Address:* Synchrotron Soleil, BP 48, Saint-Aubin, 91192 Gif-sur-Yvette, France

We are studying low radioactive **fused silica** to produce fixed focus **lenses** (thanks to loan)

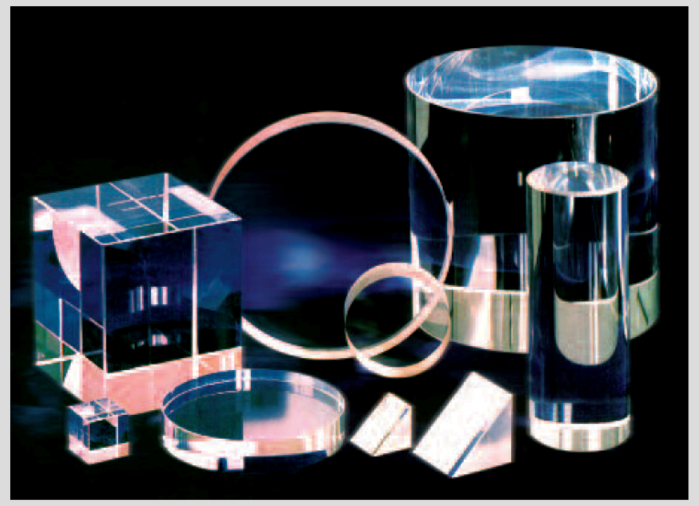


Heraeus

Spectrosil® synthetic fused silica is manufactured using a patented, environmentally friendly process resulting in a glass of exceptional purity and excellent visual quality. It is a very homogeneous synthetic fused silica glass for deep UV optical applications.

Spectrosil® is chlorine-free resulting in outstanding laser damage resistance due to the reduced tendency to form E' centres.

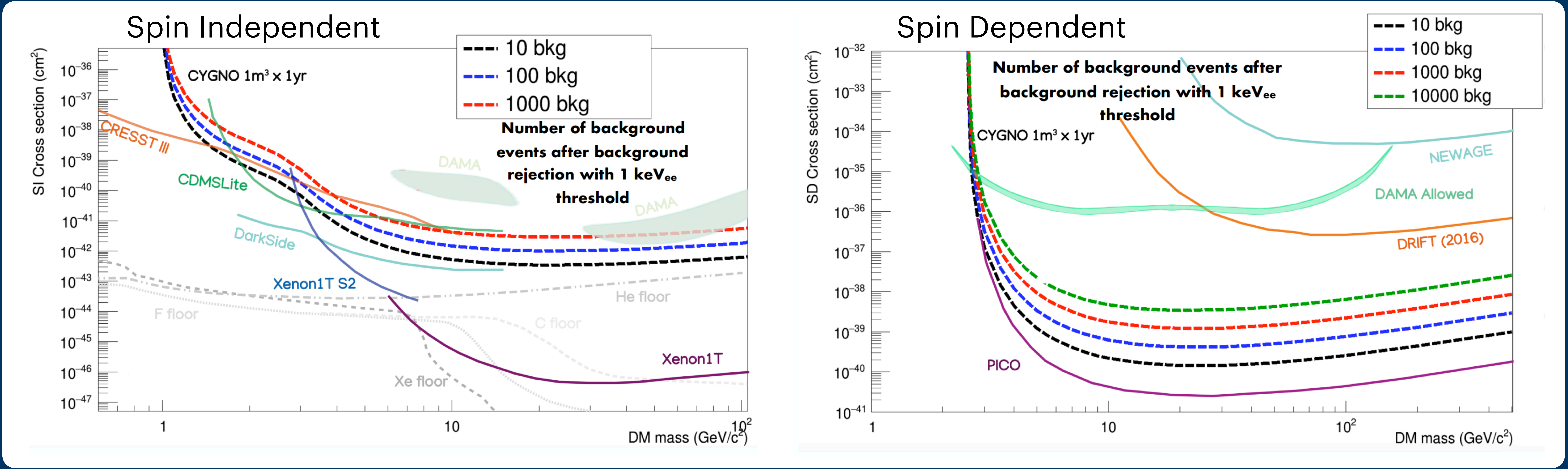
Spectrosil® 2000 is free of bubbles and inclusions and due to its ultra-high purity, has exceptional optical transmission in the deep ultraviolet and visible, with a useful range from below 180 nm through to 2000 nm.



We are in contact with CERN **GEM producer** and T-REX people that developed low-radioactivity MPGD to follow **development of low radioactive GEM**

WHAT CYGNO CAN DO: DM SEARCH AND STUDY

1 cubic meter, 1 year exposure

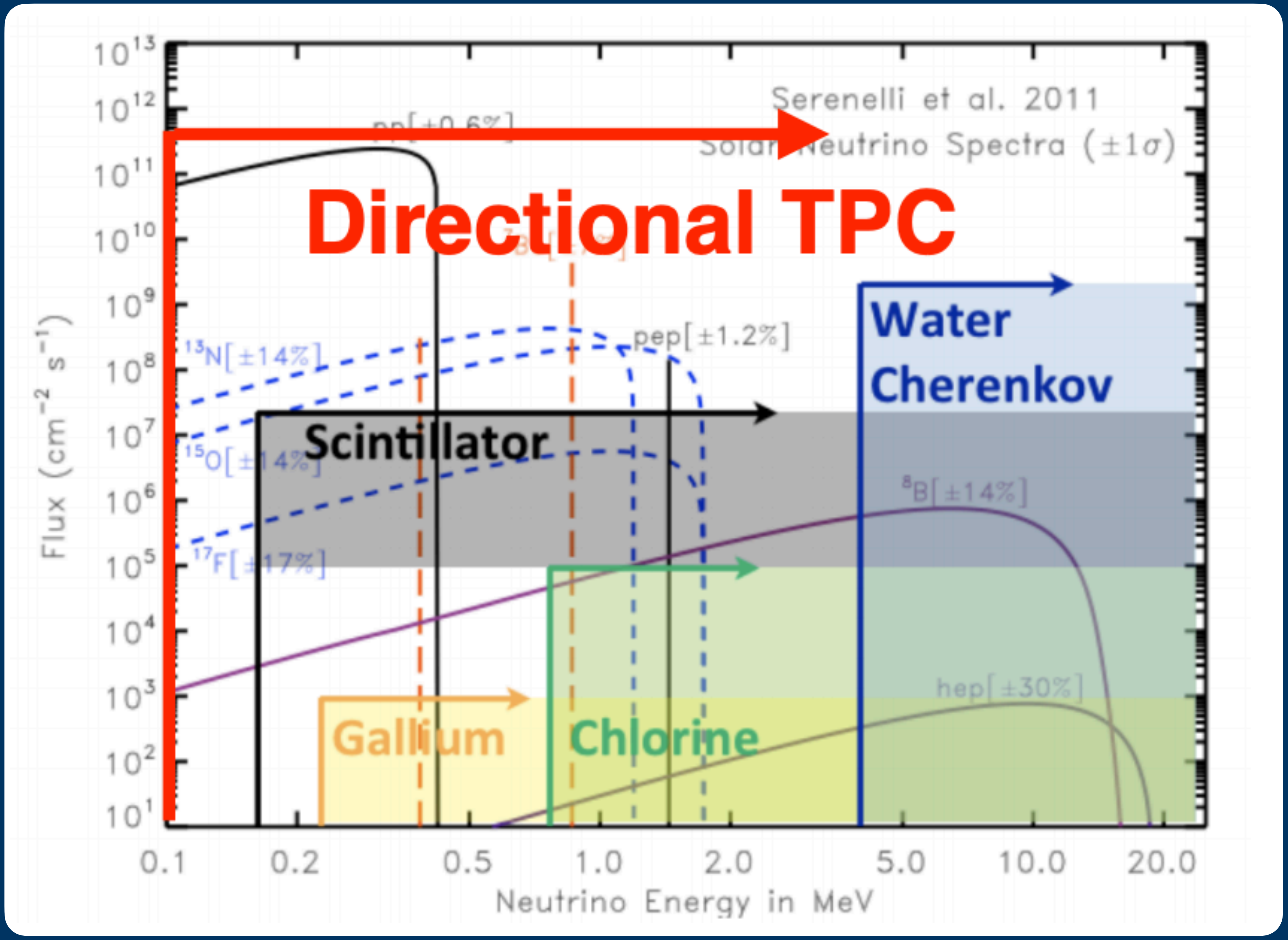


DAMA region covered even with 1000 bkg events

If DM is found, directionality will be crucial to confirm discovery and individuate its source

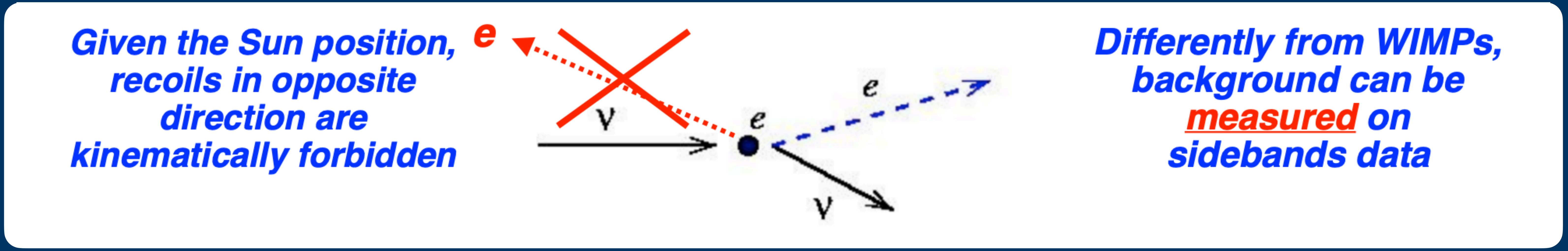
30 cubic meters, 3 year = 150 kgyr exposure

WHAT CYGNO CAN DO: NEUTRINO SPECTROSCOPY



Elastic neutrino - electron scattering with gaseous TPC: revitalising old ideas

- **sub-millimetre** tracking capability
- 10 keV **directional** threshold on electrons
- **keV** energy resolution
- Order of **1 event/(m^3 yr)** would be observed in the pp-Be energy range

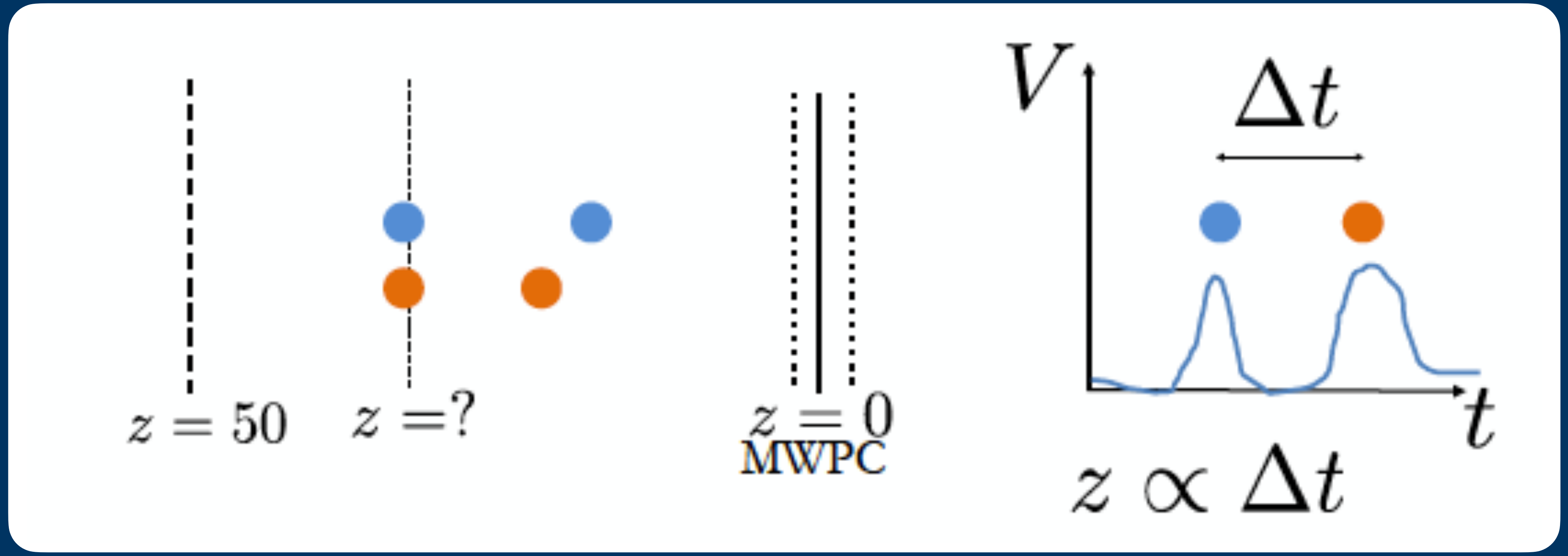


- Directionality will be crucial

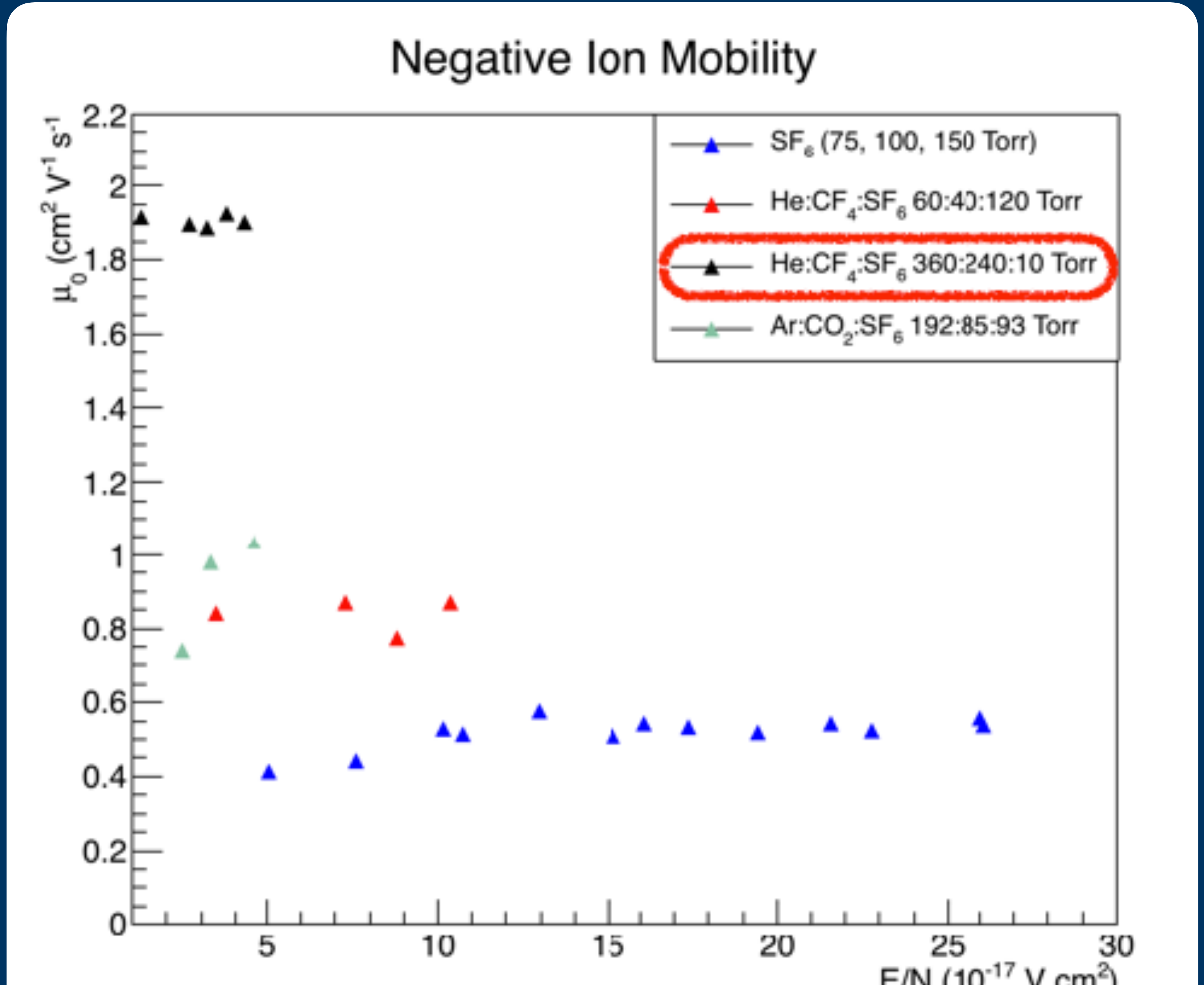
NEGATIVE ION DRIFT

Adding a **highly electronegative** component to gas mixture (e.g. SF_6) would allow to **trap primary electrons** and produce Negative Ions;

They will drift **without diffusion** and different fragments will have **different velocities**.



Tested **successfully** in low pressure gases (<100 **mbar**), it was observed at nearly atmospheric pressure (**800 mbar**) by CYGNO team.



Baracchini et al, *JINST* 13 (2018) 04, P04022

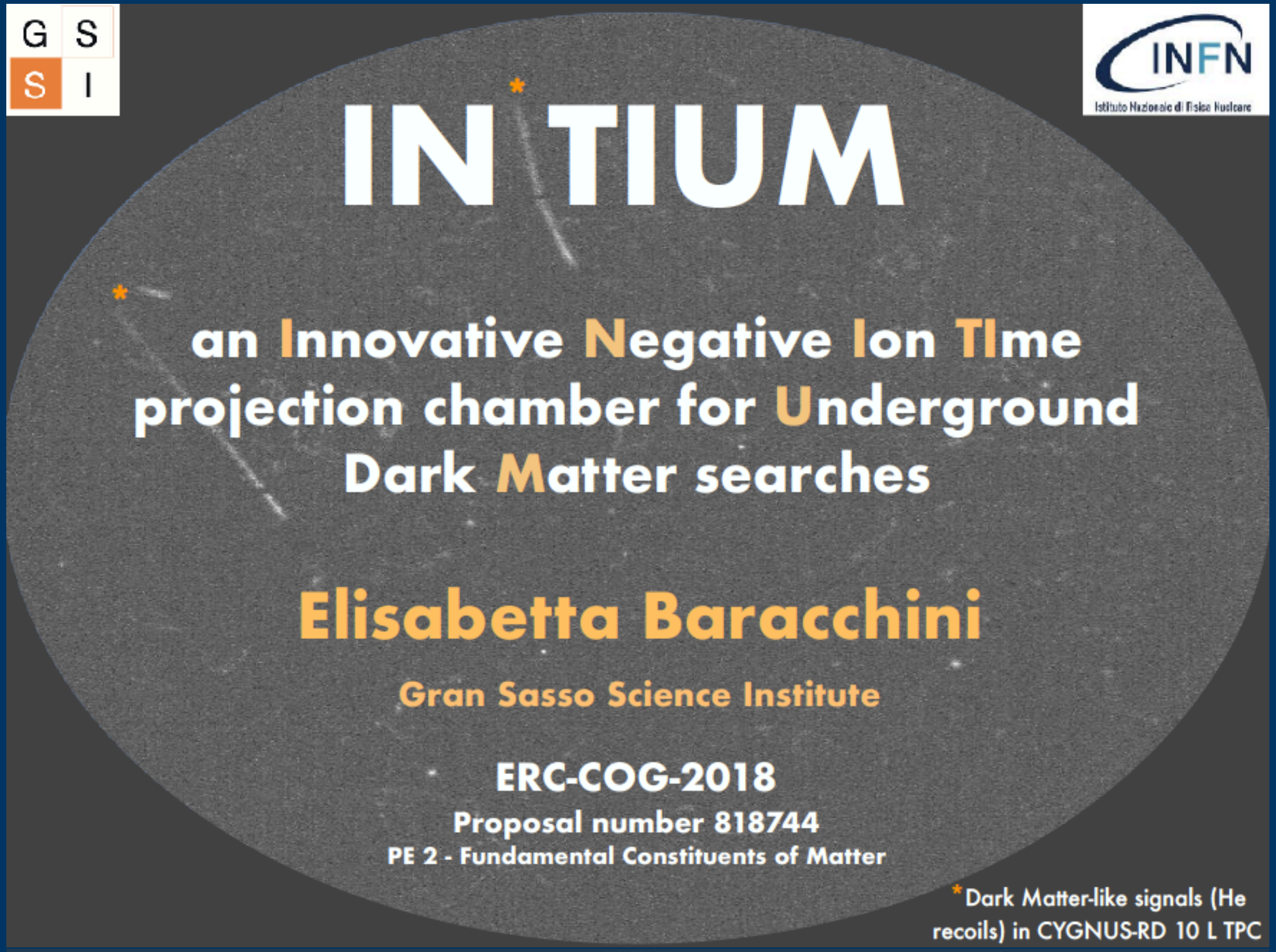
Absolute z can be evaluated with high accuracy from the Δt

THE INITIUM PROJECT

European Research Council

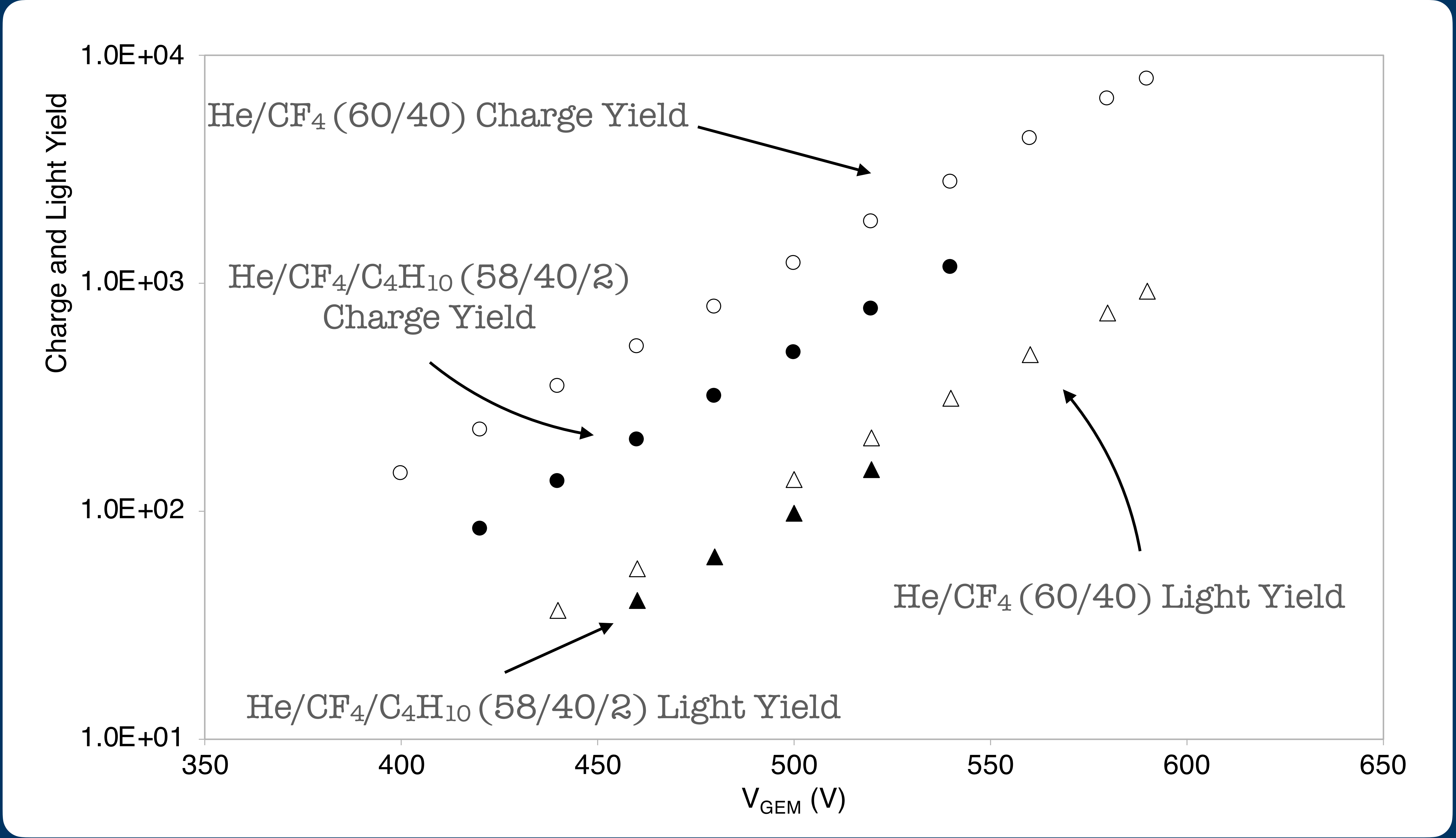
Elisabetta Baracchini (GSSI) won an **ERC Consolidator Grant** with **INITIUM**

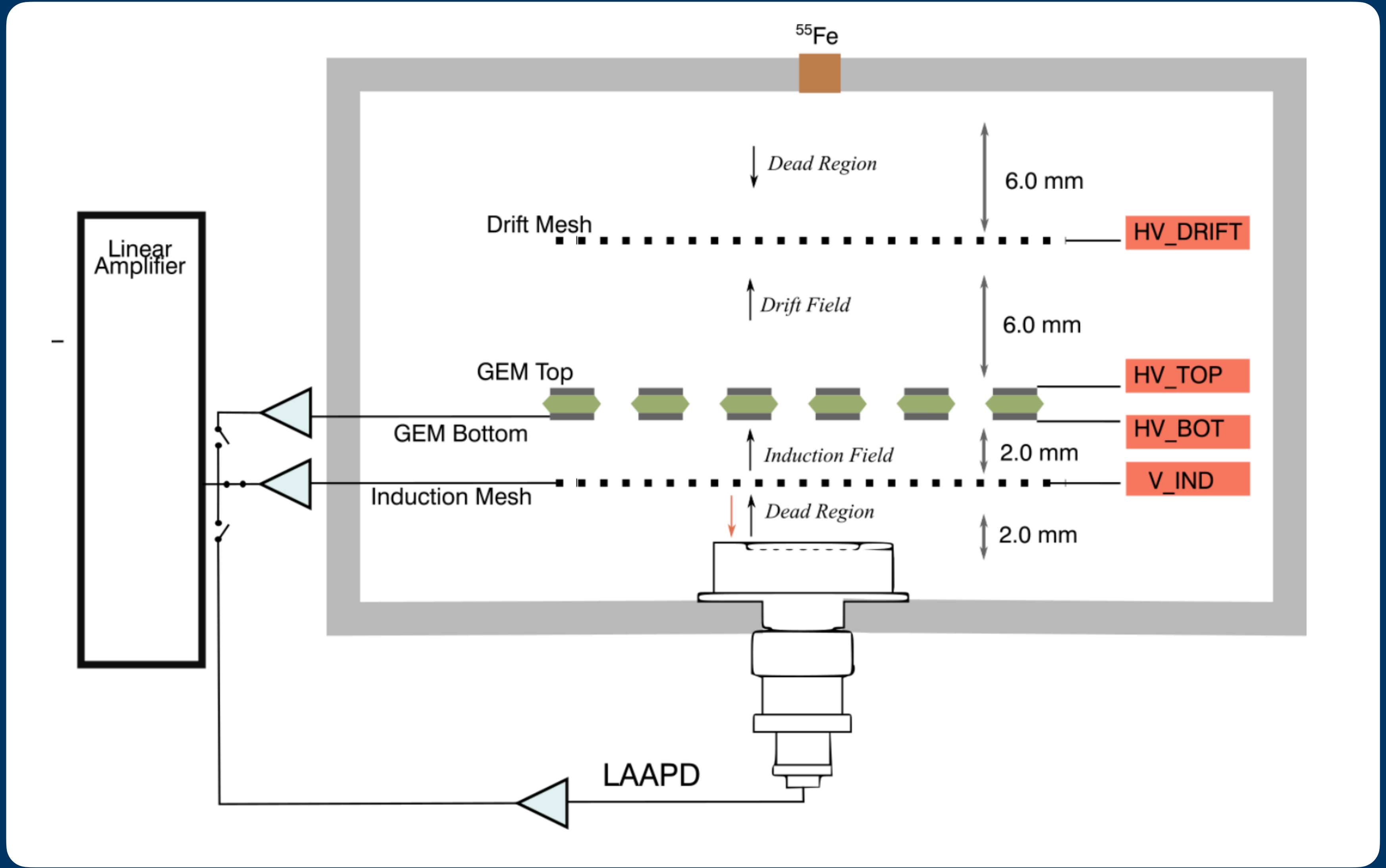
The proposal, presented at the beginning of 2018, is based on the experience gained in NITEC and CYGNUS_RD and aims at "the development and operation of the first **1 m^3 Negative Ion TPC** (NITPC) with Gas Electron Multipliers (**GEMs**) amplification [in **$He/CF_4/SF_6$** mixture] and **optical readout** with CMOS-based cameras and PMTs"



R&D: HYDROCARBONS

In a first test performed with a single-GEM setup, a ternary gas mixture ($He/CF_4/C_4H_{10}$ - 58/40/2) was tested;



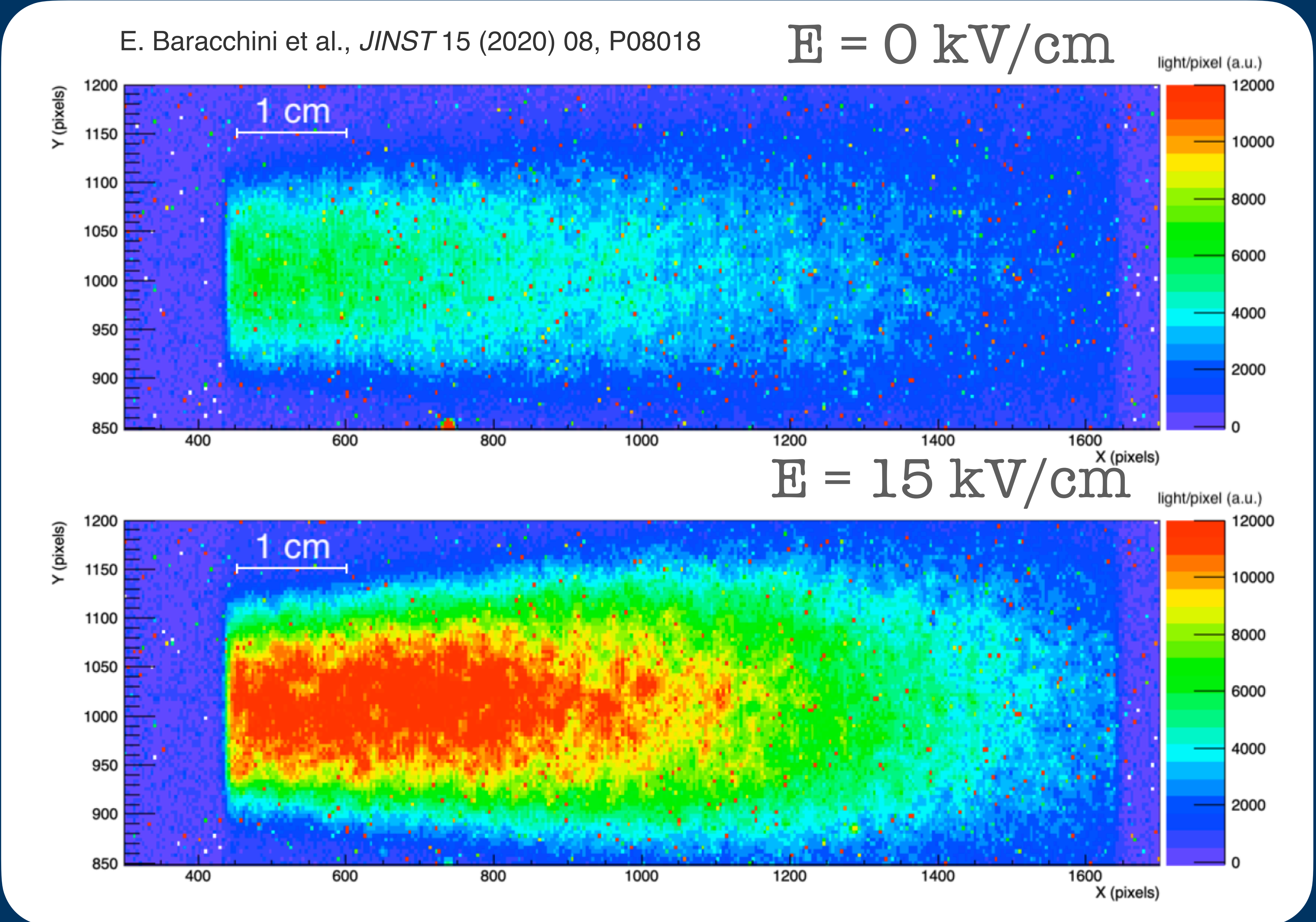


The addition of a 2% Isobutane component reduces:

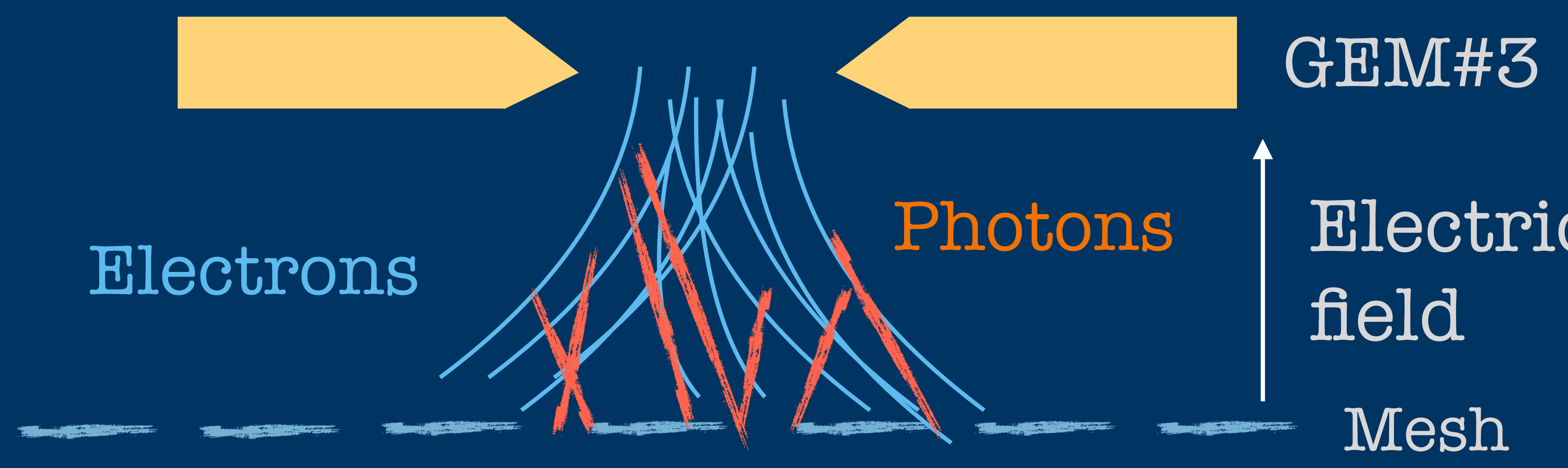
- by a factor 2.5 the Charge Yield;
- only 30% the Light Yield.

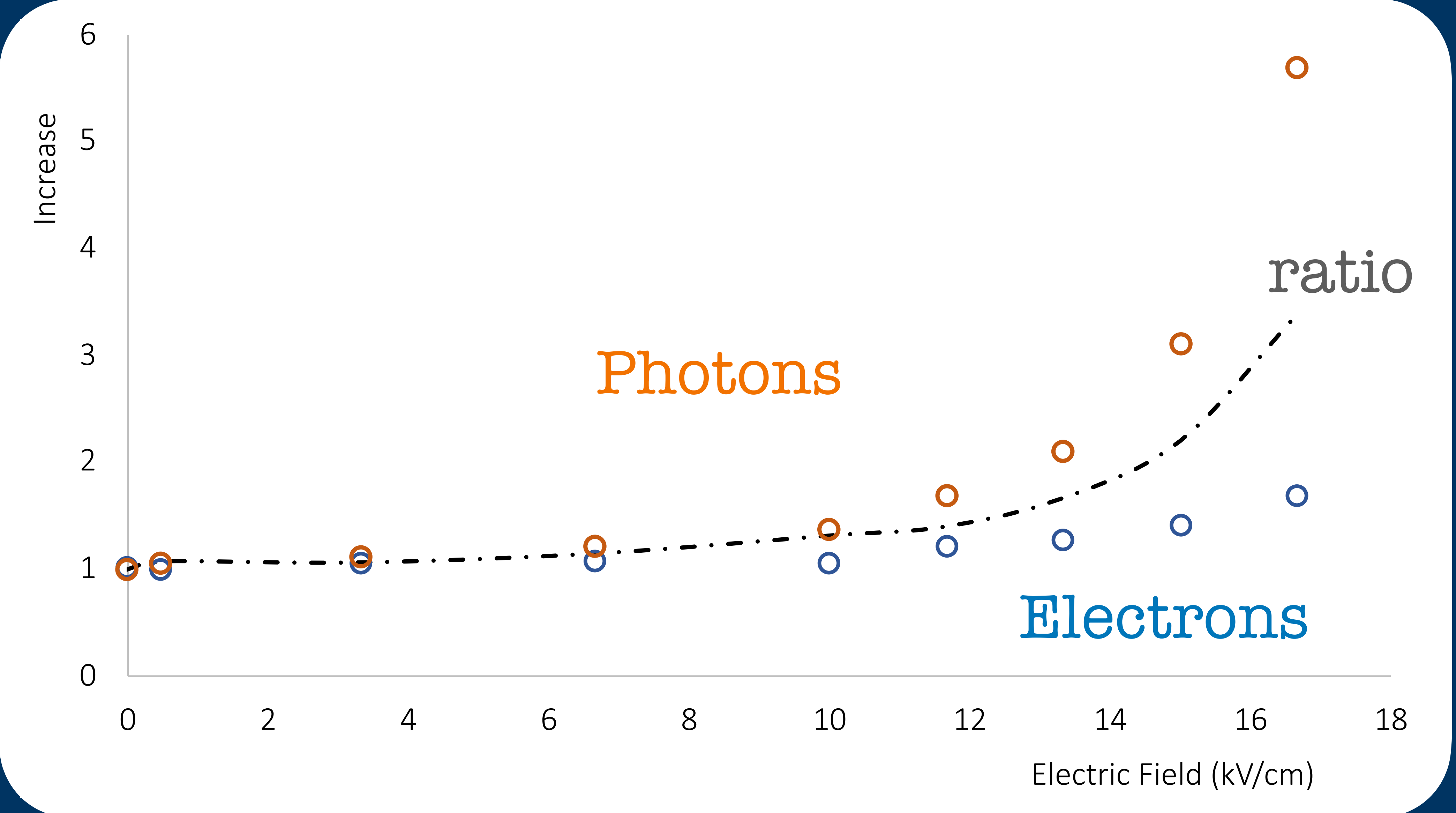
First demonstration of a very good light yield from a mixture with C_4H_{10}

R&D: ELECTRO-LUMINESCENCE



Is it possible to induce luminescence in gas by accelerating electrons below last GEM?





First evidence of an increase of light production (factor 5.7) quite **larger** than total charge increase (factor 1.7).

Study partially funded as Common Project with RD51

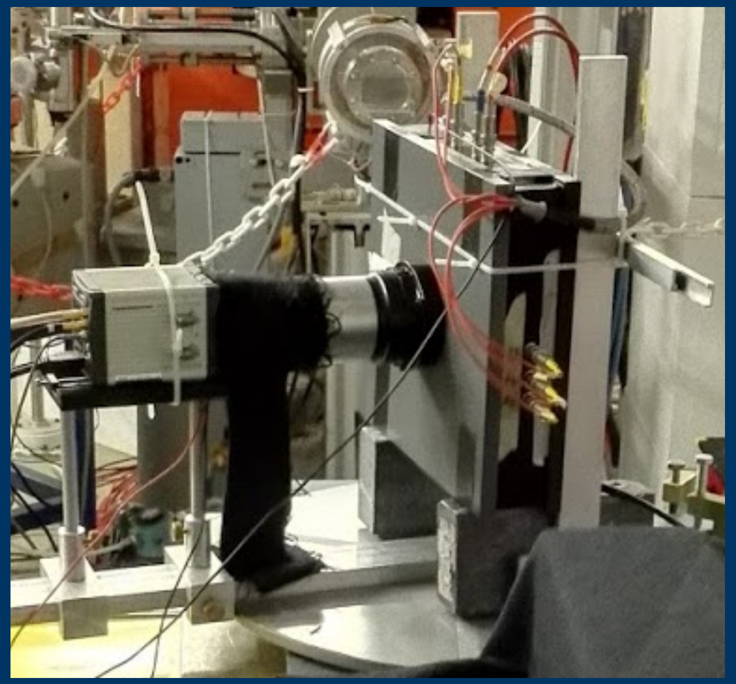
CYGNO: PROJECT PHASES

PHASE 0: R&D

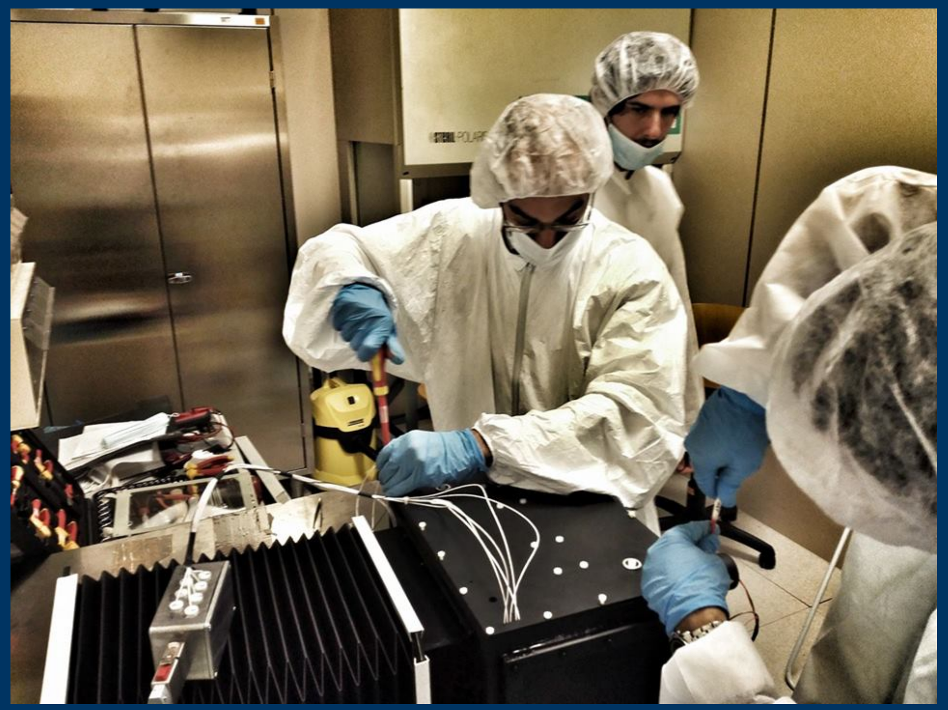
PHASE 1: ~1 m³ Demonstrator

PHASE 2: Experiment

2015/16	2017/18	2019/20	2021/22	2023
@ ROMA1	@ LNF	@ LNF/LNGS	@ LNF/LNGS	@ LNGS
ORANGE	LEMON	LIME	Construction & test	Installation & commissioning

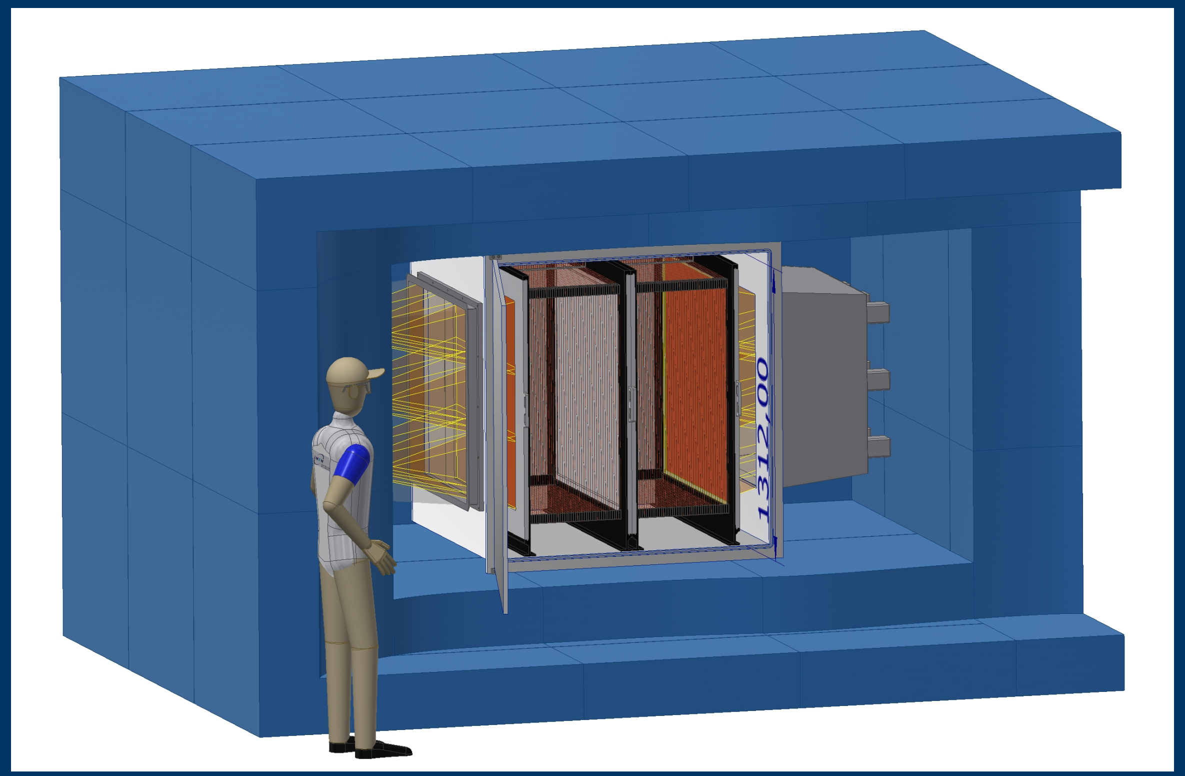


- 1 cm drift



- 3D printing
- 20 cm drift

- 50 cm drift
- underground tests
- shielding



- background
- materials test
- gas purification
- scalability

CYGNUS 30-100 m³

CYGNUS_RD - CSN5

CYGNO - CSN2

NITEC

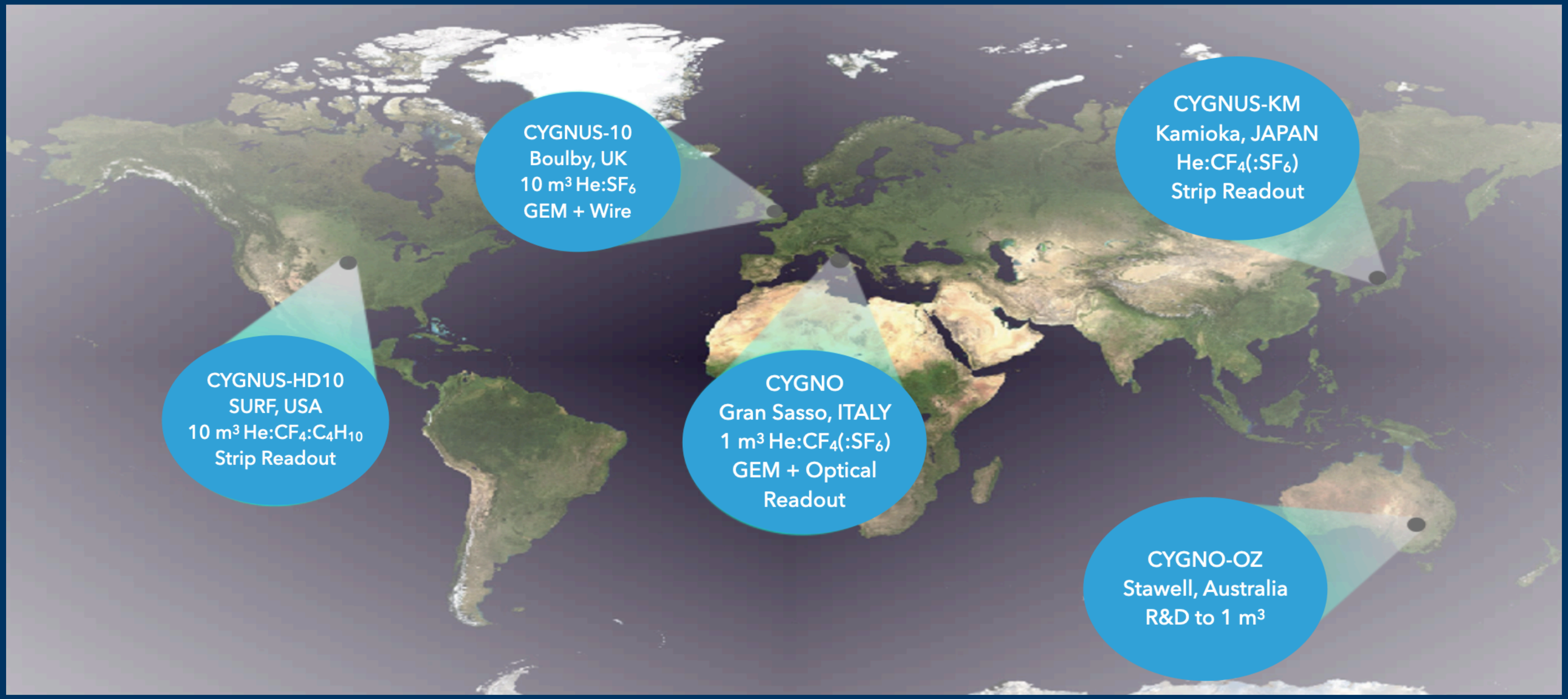
INITIUM

CONCLUSION

CYGNO project is developing a **GEM-based TPC optically readout** for rare event studies

Very promising performance was found in the (few) keV region:

- **high detection** capability;
- very good **energy** and **position resolution**;
- high **discrimination power** provided by the detailed acquisition of readout approach;
- R&D to improve these performance are going on.



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

Signed members from UK, Japan, Italy, Spain, China focused on **gas TPCs with 2D or 3D direction sensitivity;**

Join us!


PULP FICTION
Rita Roque
Cristina Bernardes Monteiro
THANKS!