

# An optically readout TPC for rare events study: the CYGNO project

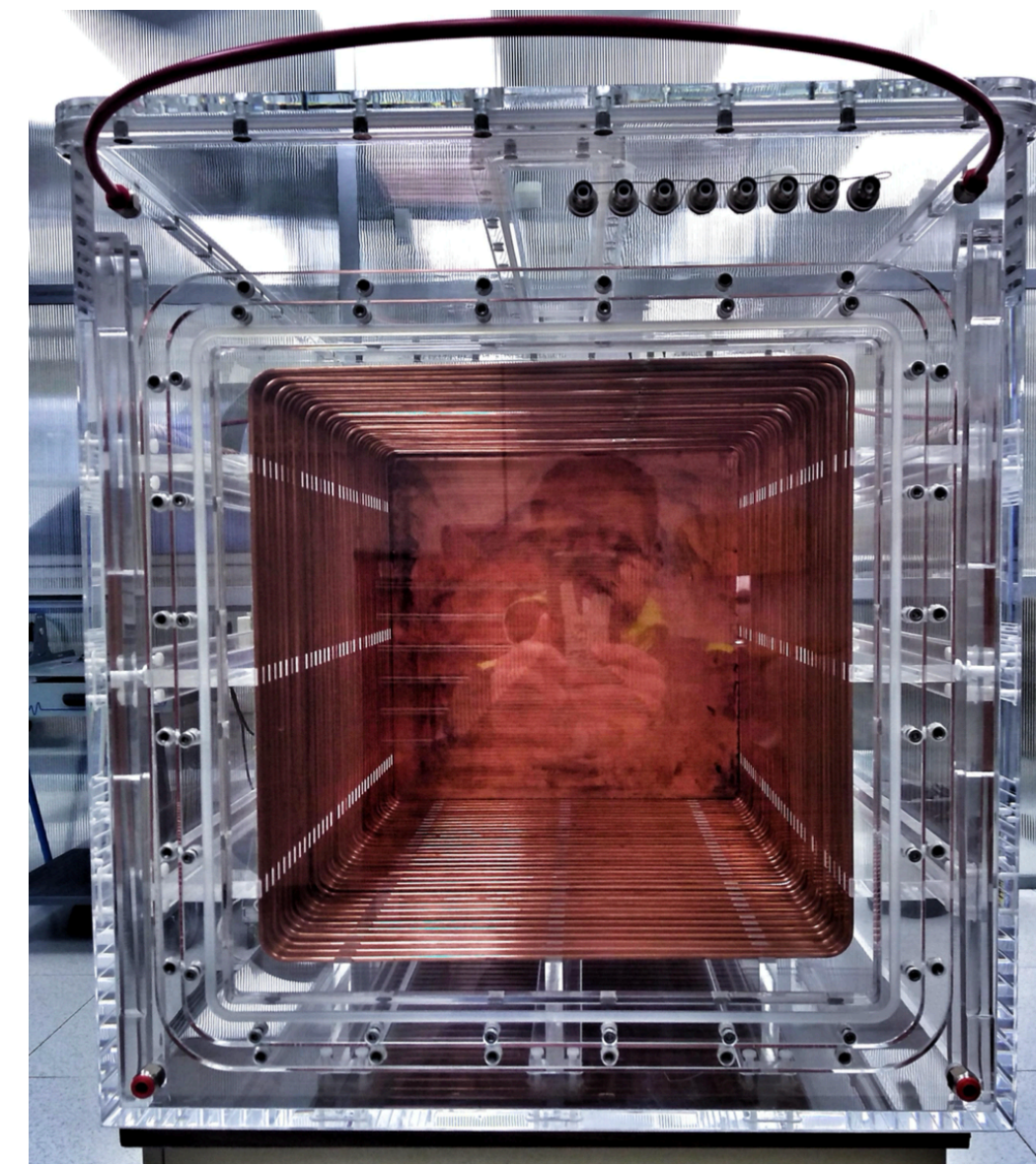


Stefano Piacentini - Sapienza Università di Roma & INFN Roma 1  
on behalf of:

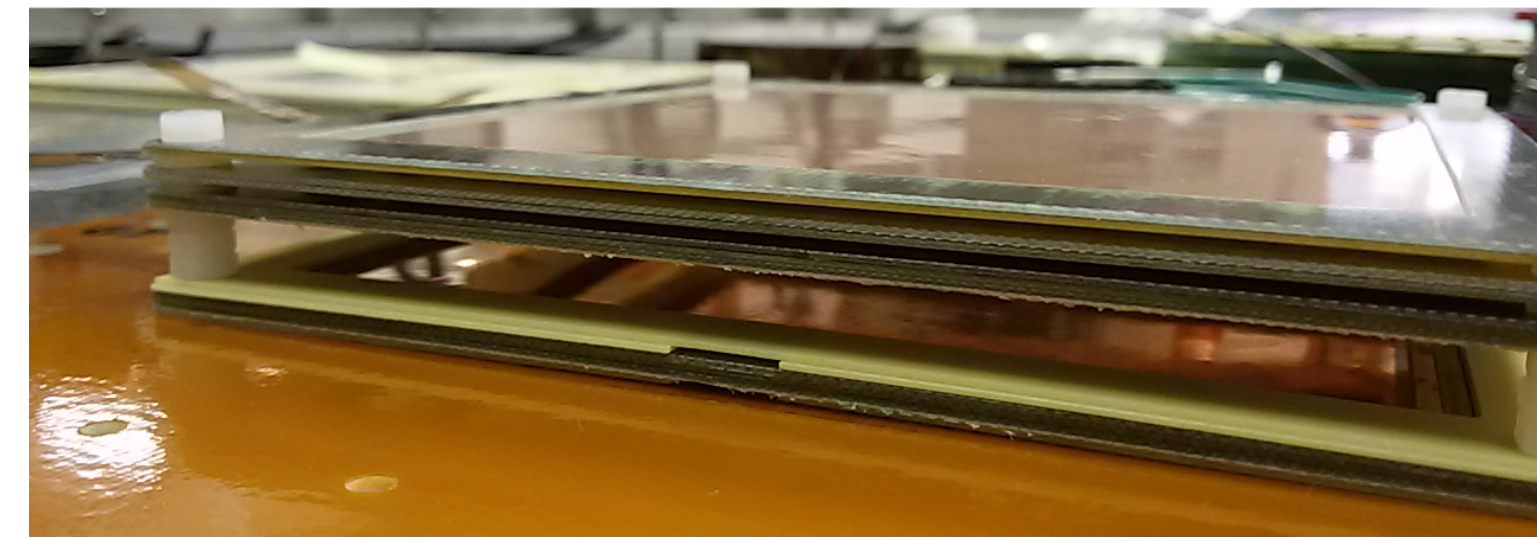
F. D. Amaro, R. Antonietti, E. Baracchini, L. Benussi, S. Bianco, F. Borra, C. Capocchia, M. Caponero, D. S. Cardoso, G. Cavoto, R. J. de Cruz Roque, I. A. Costa, E. Dané, G. Dho, E. Di Marco, G. D'Imperio, F. Di Giambattista, R. R. M. Gregorio, F. Iacoangeli, E. Kemp, H. P. Lima Júnior, G. S. P. Lopes,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

# The CXGNO project

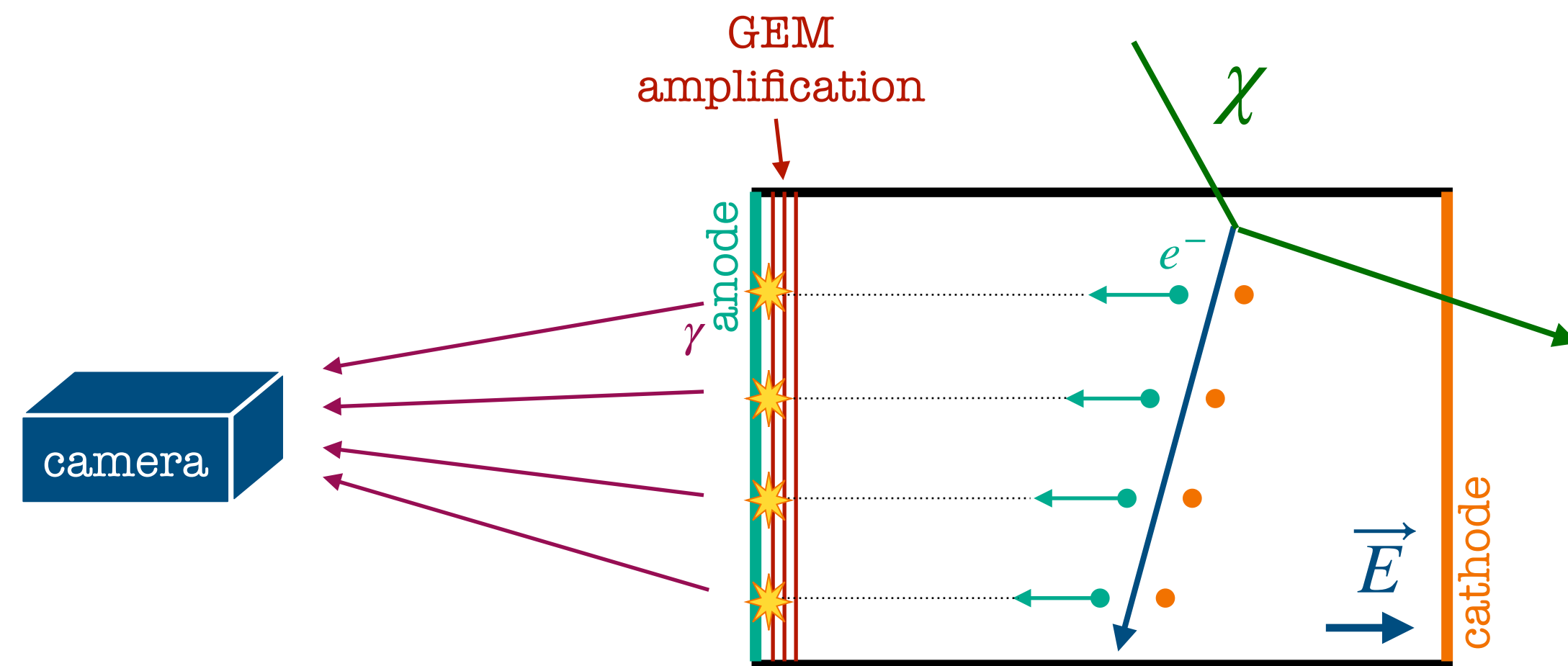
- **Aiming for** a large detector for high precision **3D tracking of rare low energy nuclear recoils** (keV) possibly induced by **dark matter** (DM) particles and solar neutrinos
- **Experimental challenges:** rate  $O(\text{evt/kg/year})$ , background rejection, and energy threshold (keV)
- **Strategy: photograph nuclear recoils** in a (1 atm)  $\text{He:CF}_4$  TPC with a GEM amplification stage  
➡ low energy events in 1 atm gas  $\Rightarrow$  visible tracks



TPC of the LIME prototype @ LNF



Amplification with GEMS



sCMOS camera [Hamamatsu Orca-Fusion]



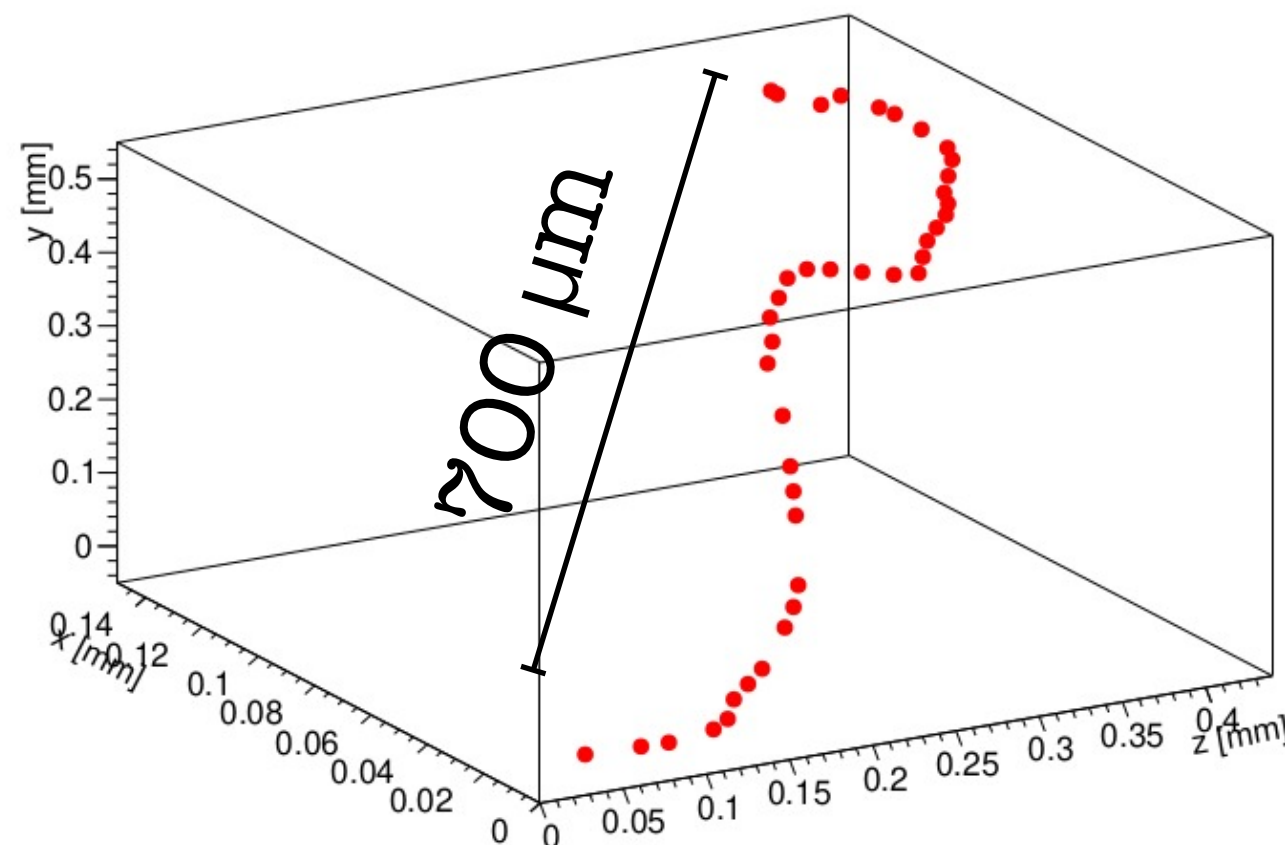
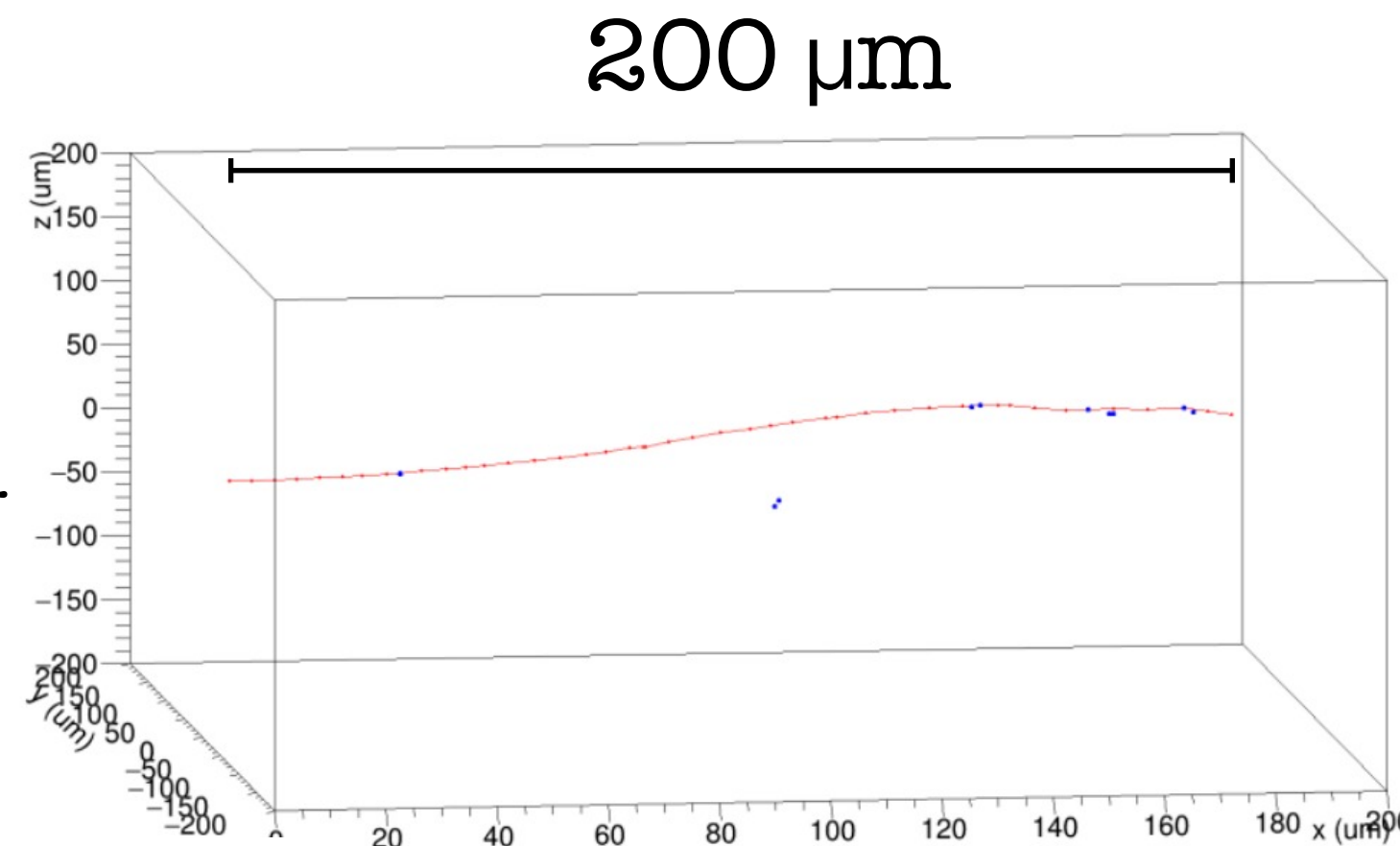
4 PMTs [Hamamatsu R7378]



# Low mass DM searches

- Explore the region below  $10 \text{ GeV}/c^2 \Rightarrow$  low mass nuclei such as H and He
- We started with **helium**, easier to manipulate

6 keV helium



6 keV electron

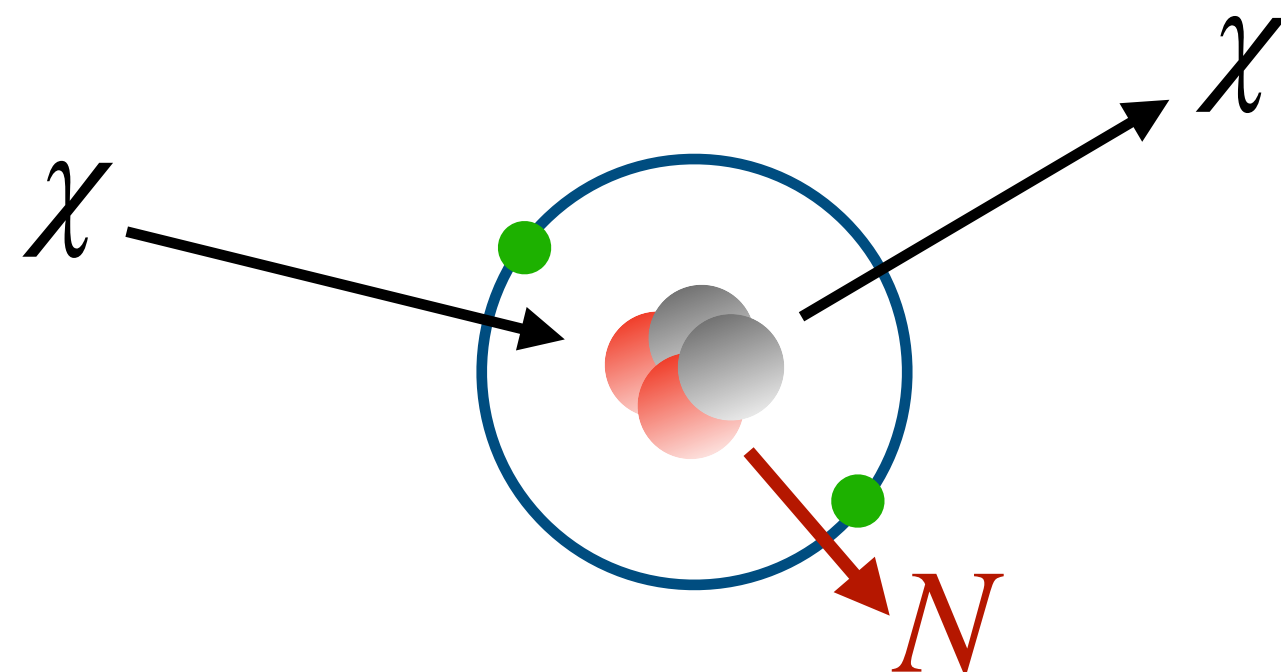
- In a **helium based** gas mixture at **atmospheric pressure**:
  - ➡ nucleus average range of **150 μm**  $\sim 1/4$  than an electron
  - ➡ In principle possible to measure the **direction** of the recoiling nuclei
  - ➡ In principle possible to **discriminate** recoiling nuclei from recoiling electrons

# Background to direct detection

- **Not only DM** can induce nuclear recoils (**NR**) or electronic recoils (**ER**)
- We would expect:

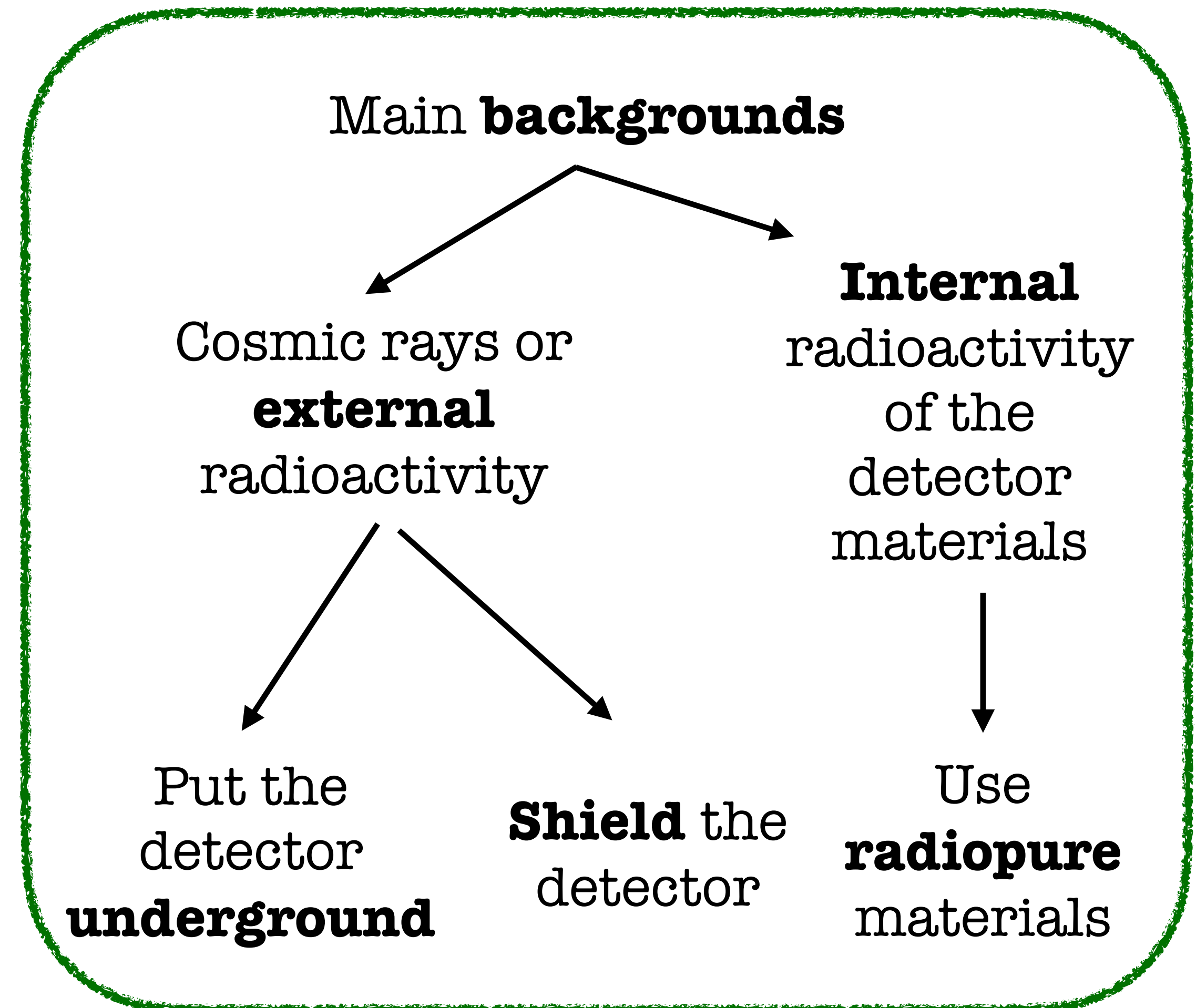
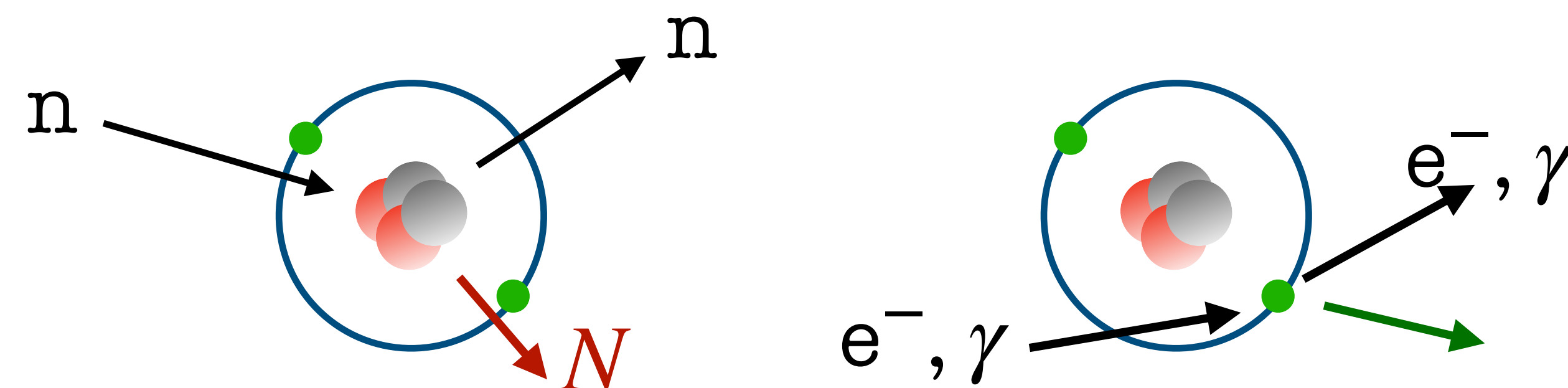
**Signal:**

**NR**

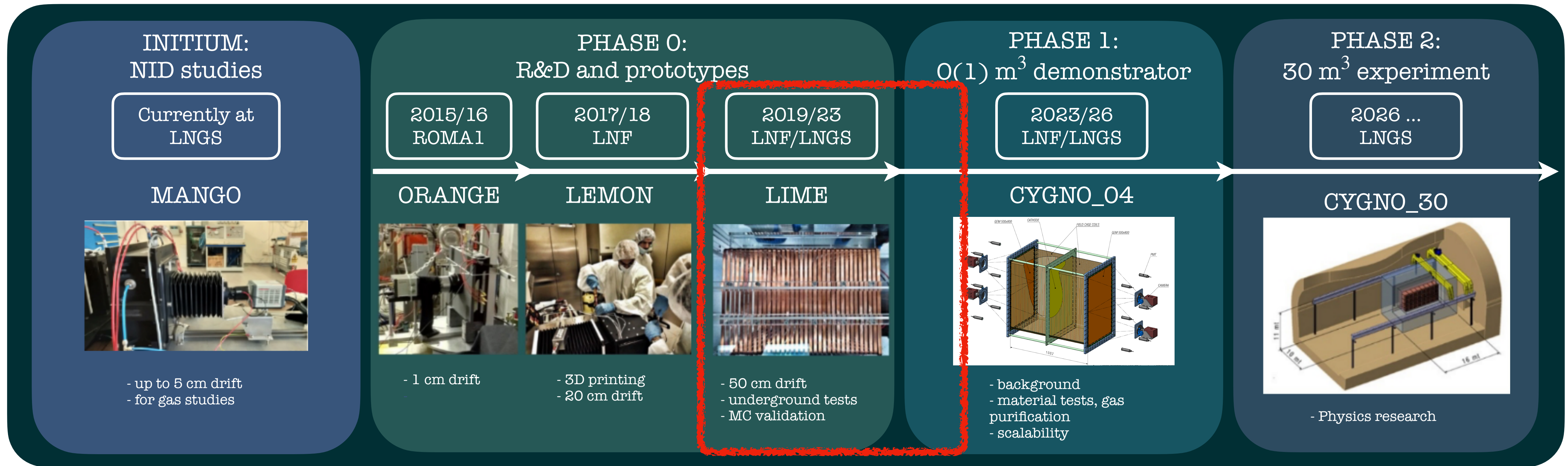


**Background:**

**NR and ER**



# The **CXGNO** timeline



Instruments 6 (2022) 1, 6

JINST 15 (2020) 12, T12003

JINST 15 (2020) P08018

Measur.Sci.Tech. 32 (2021) 2, 025902

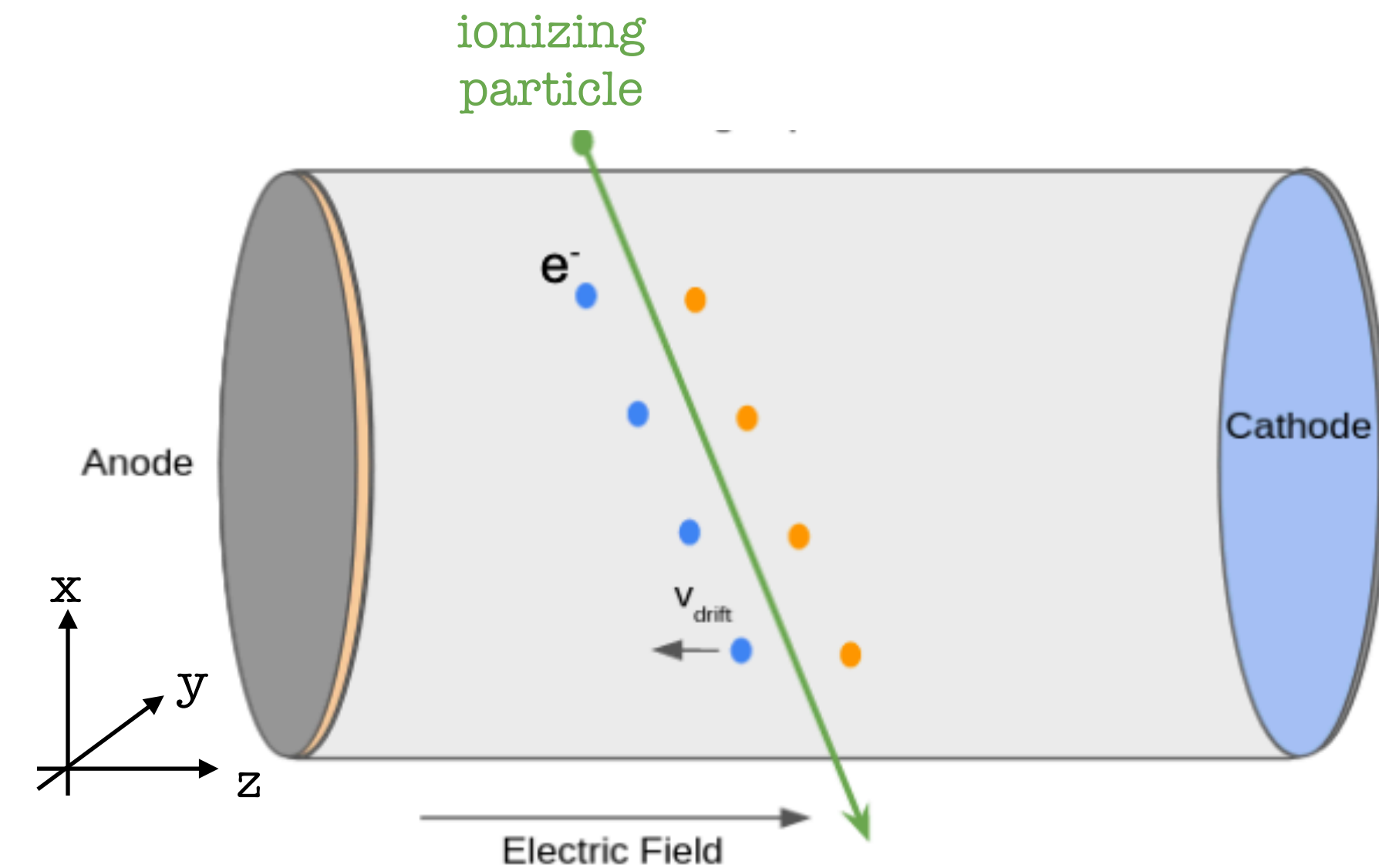
JINST 15 (2020) P10001

2019 JINST 14 P07011

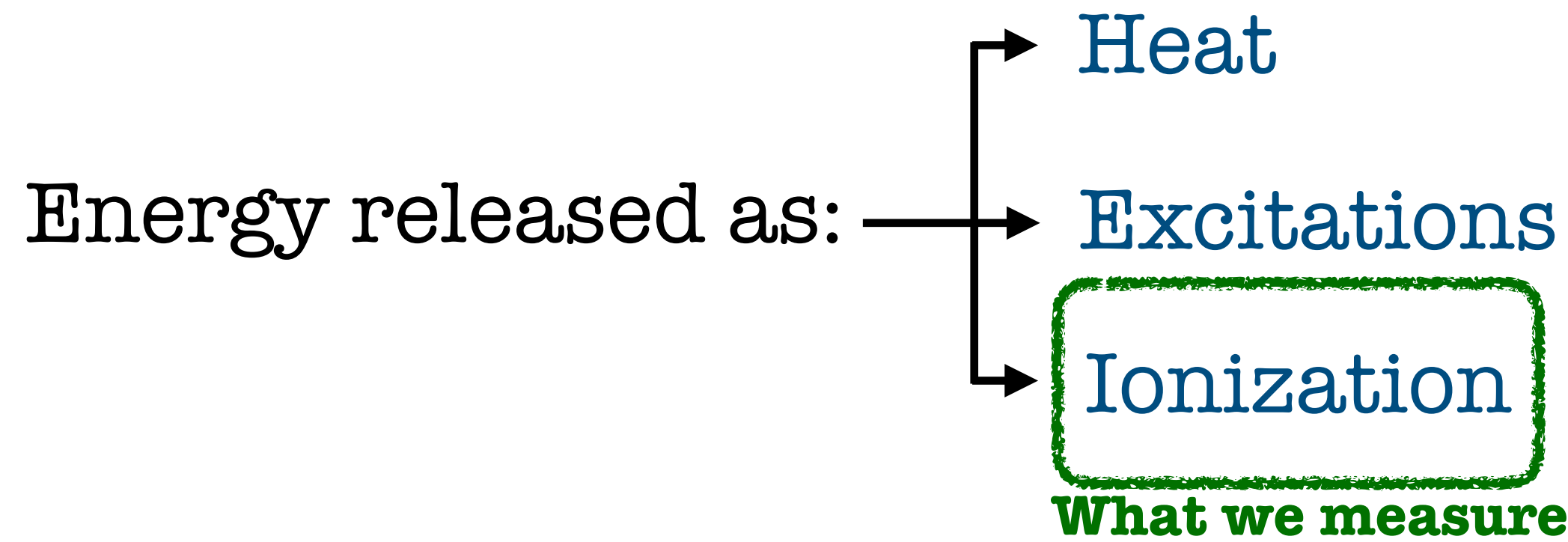
NIM A 999 (2021) 165209

# Gaseous Time Projection Chambers

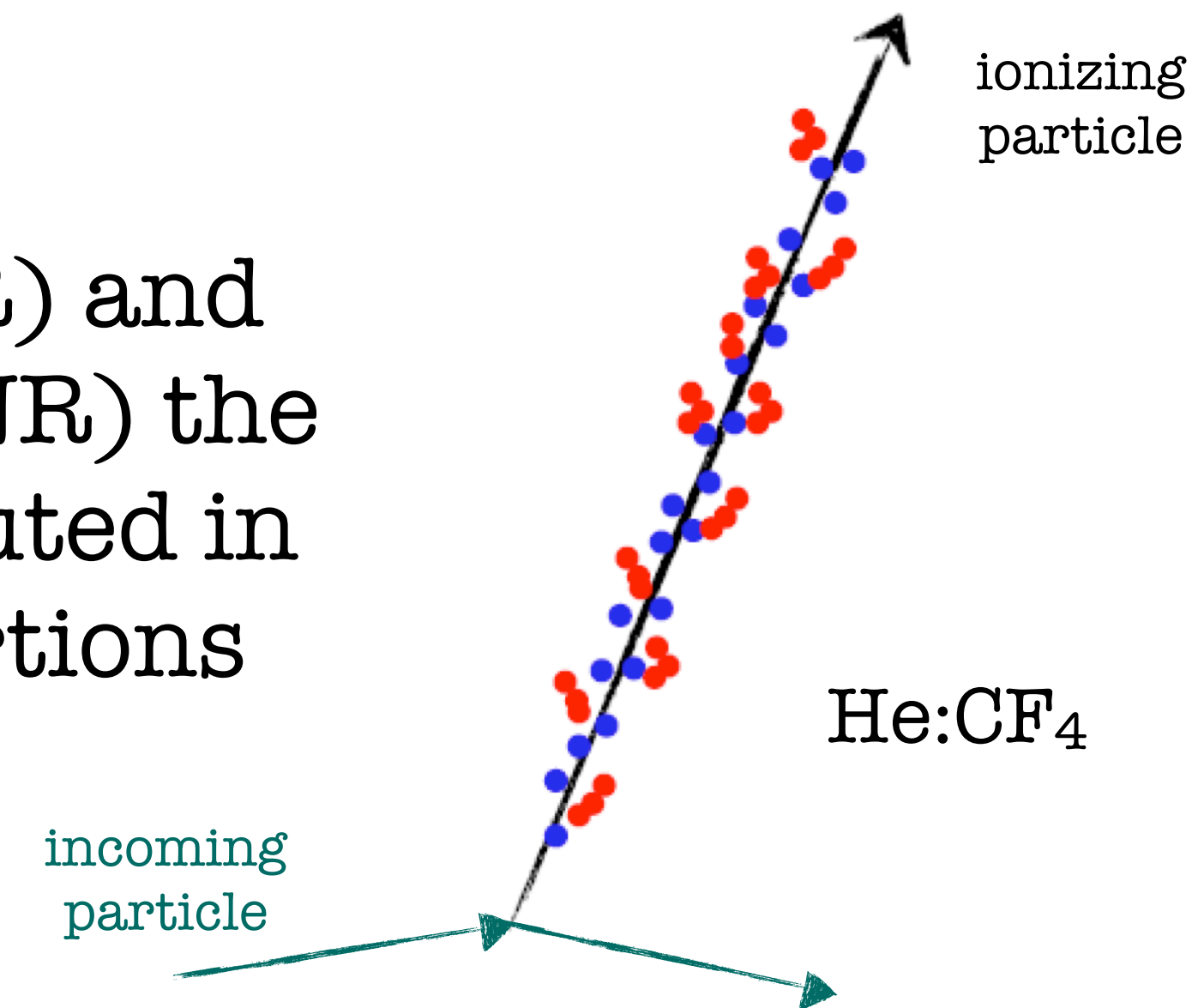
- Measure the **3D position** of the event, and the **direction** of the tracks
- Measure of the **energy released** by the collisions
- Measure of the energy loss ( $dE/dx$ )  $\Rightarrow$  particle identification and head-tail discrimination
- A **small number** of detection **channels** with respect to other experimental techniques
- Possibility of operating at **room temperature** and **atmospheric pressure**  $\Rightarrow$  relatively easy to manage



# Ionization process



For electron (ER) and nuclear recoils (NR) the energy is distributed in different proportions



- **ER** average energy lost after producing an ion-electron pair in He:CF<sub>4</sub> (60/40):

$$W \sim 42 \text{ eV} \Rightarrow 1 \text{ keV}_{\text{ee}} \sim 24 \text{ electrons}$$

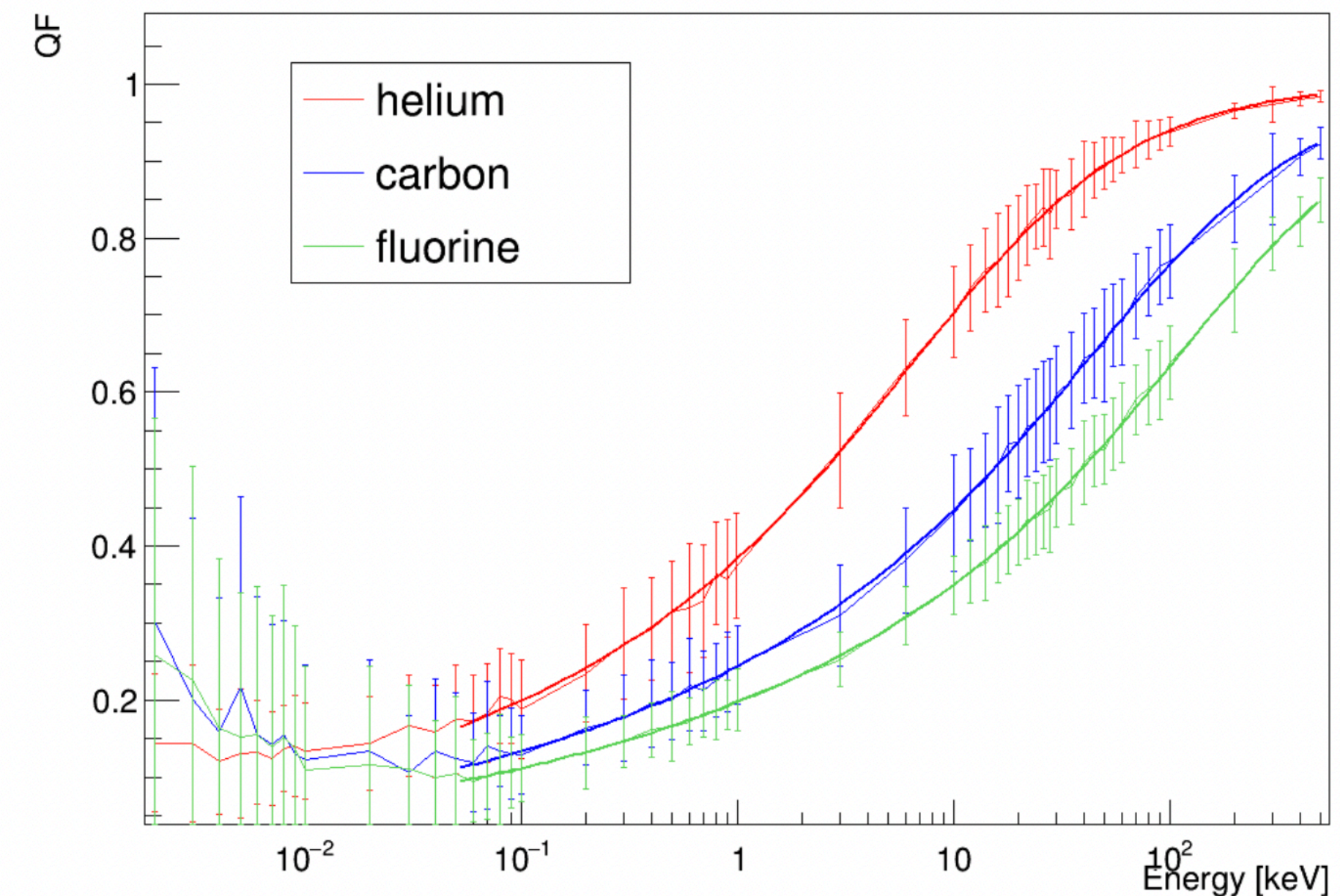
- In **NR** events, a sensitive portion of the energy is **lost** in the **heat channel**  $\Rightarrow$  **quenching factor (QF)**

$$E[\text{keV}_{\text{ee}}] = QF \times E[\text{keV}_{\text{nr}}]$$

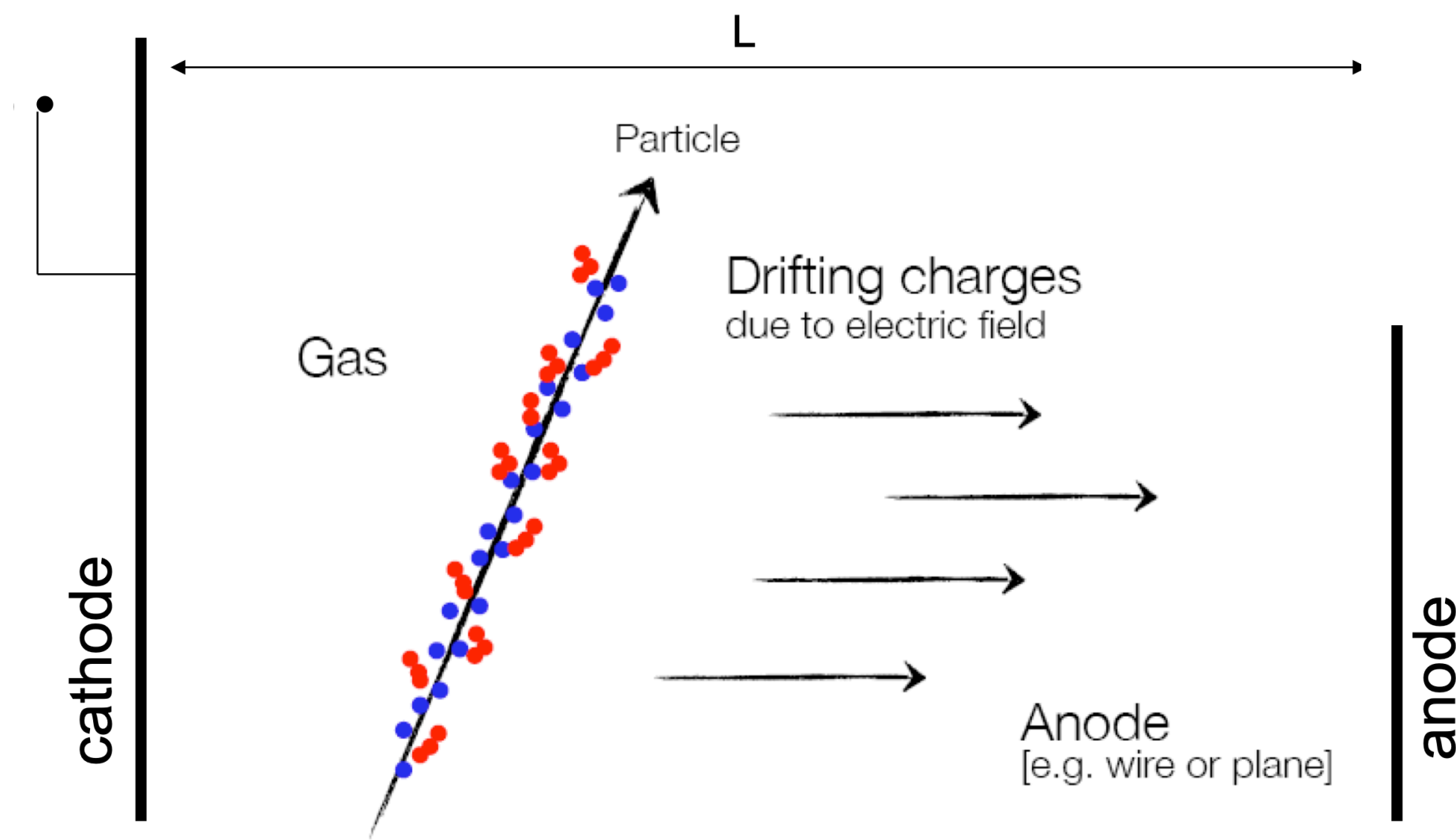
$\Rightarrow$  QF evaluated in **SRIM**. For **He** nuclei in our mixture:

$$QF(E = 100 \text{ eV}_{\text{ee}}) \sim 20 \%$$

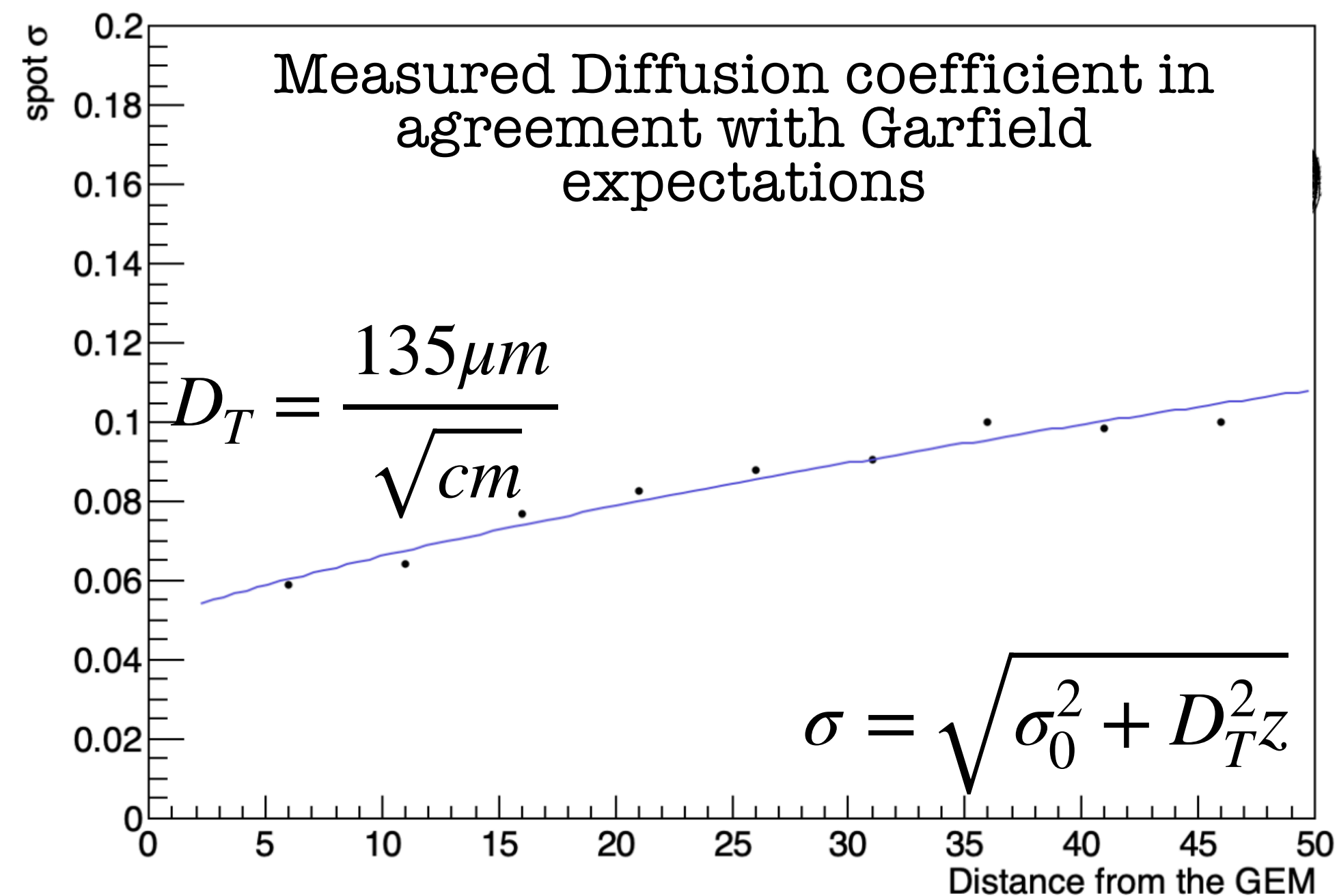
$$QF(E = 10 \text{ keV}_{\text{ee}}) \sim 75 \%$$



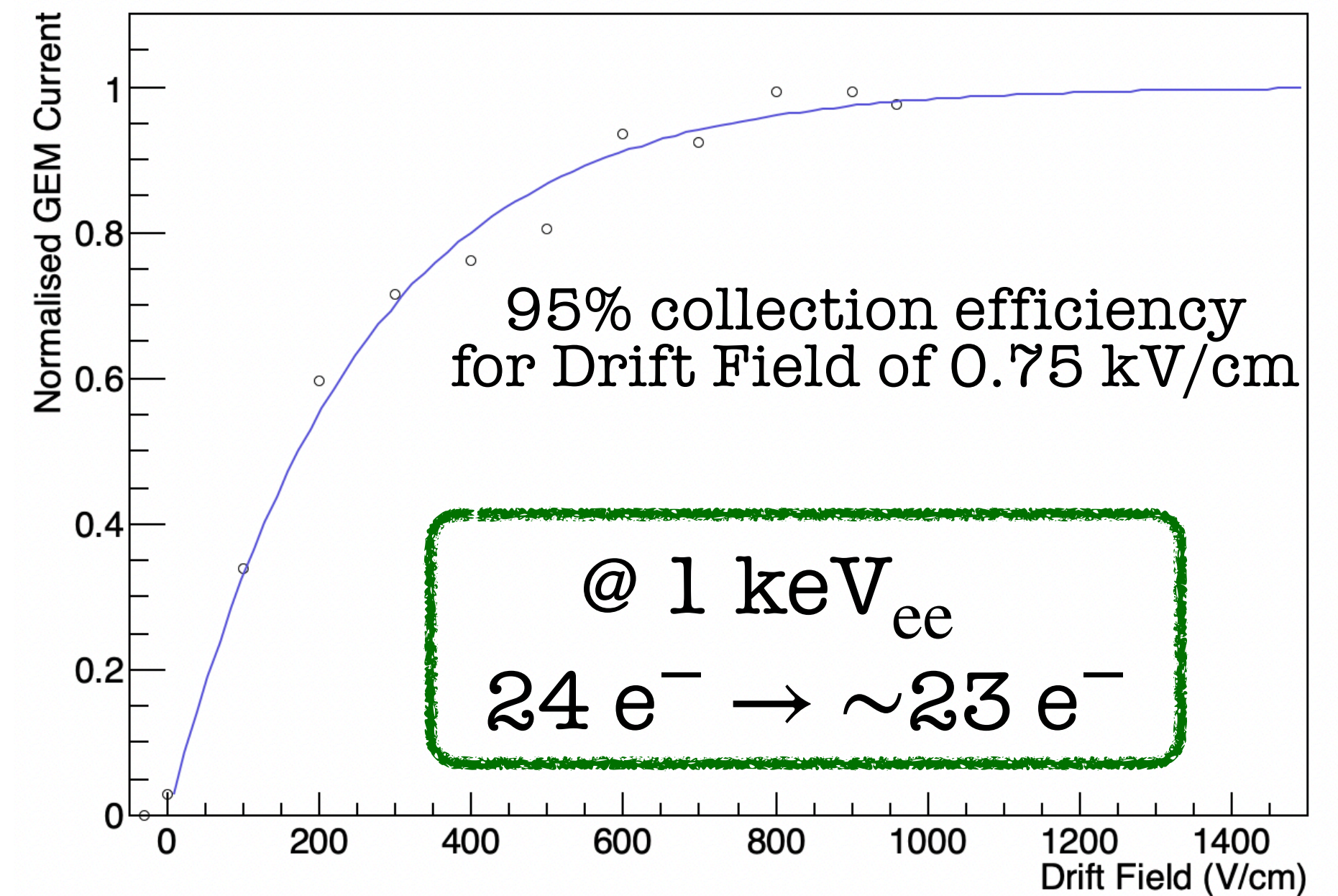
# Drift along the drift gap



- Continuous hits during the path  $\Rightarrow$  diffusion

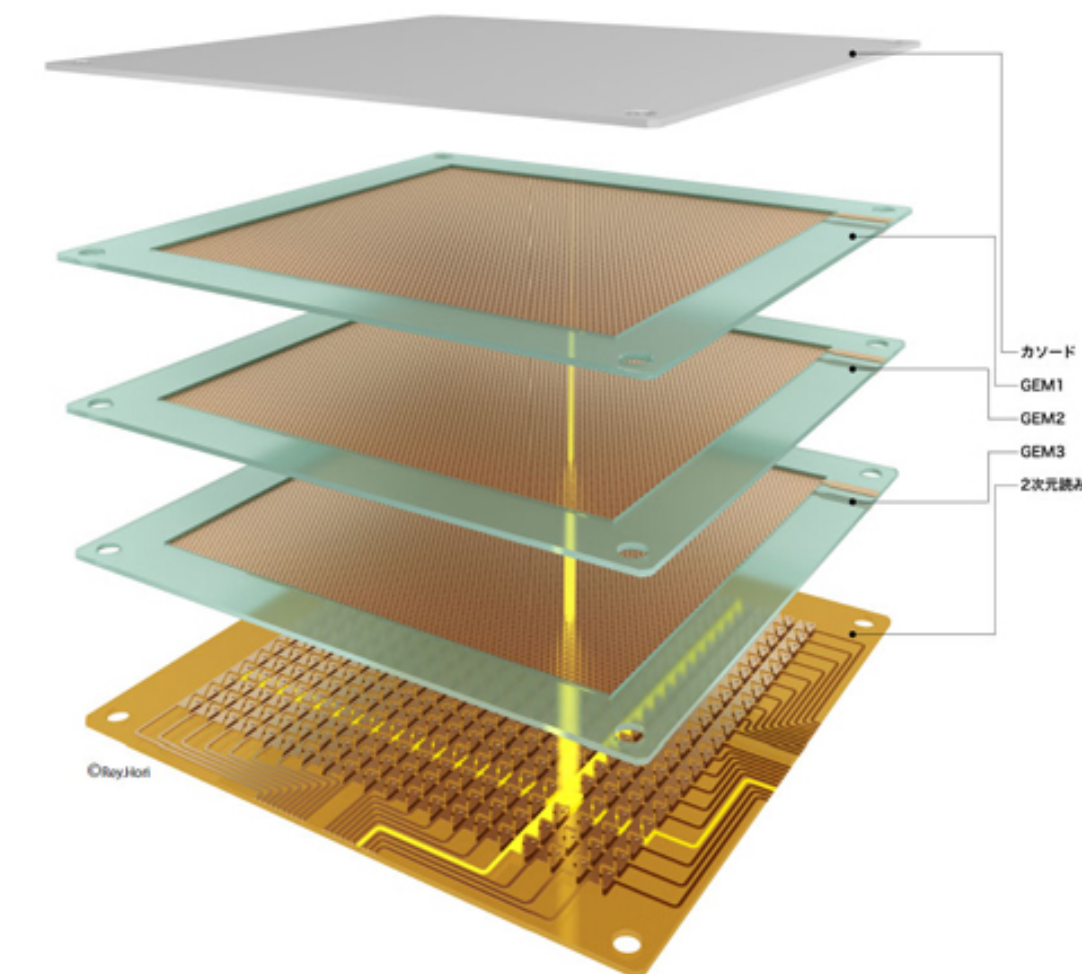
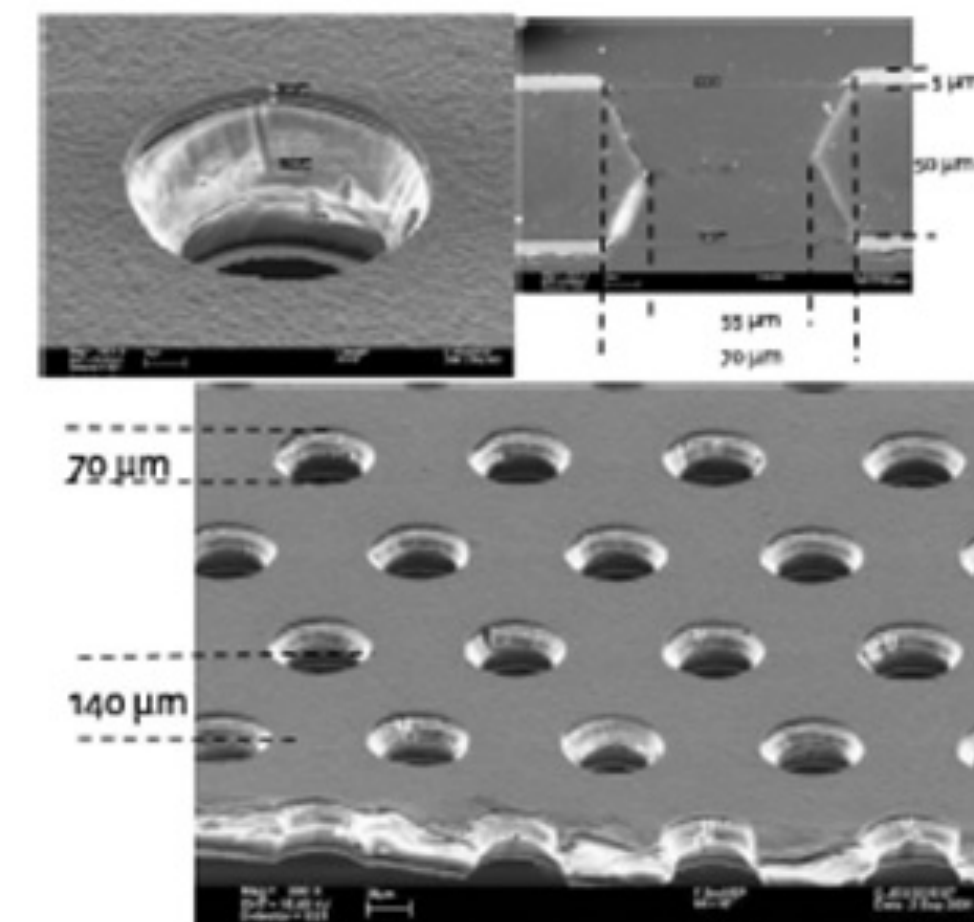
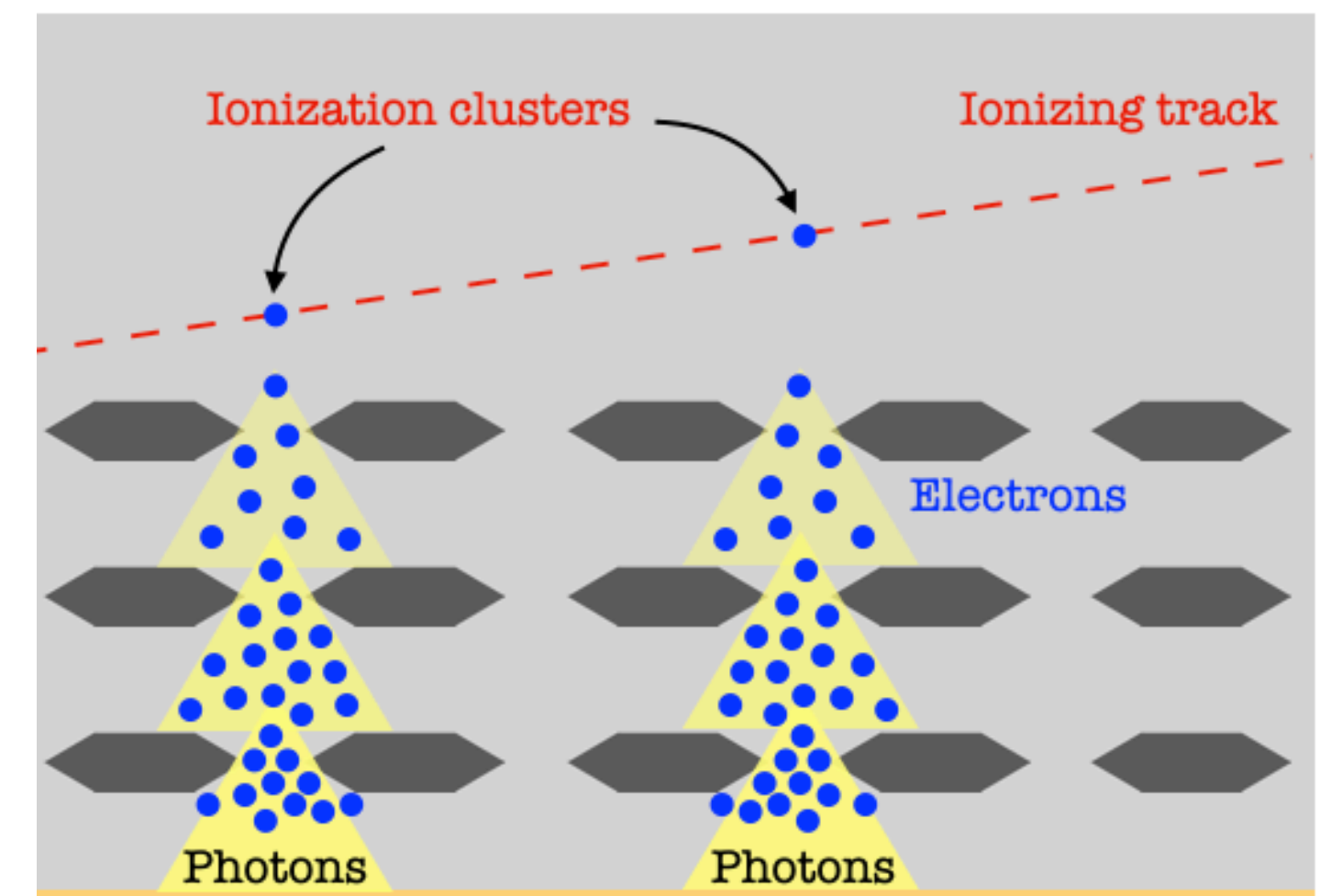


- Electrons captured by electronegative impurities along the drift



# The Gas Electron Multipliers (GEMs)

- Once the energy has been released in the form of **ionization**, the primary electrons are drifted to the **GEMs channels**
- Thanks to the high electric fields, the charges are **multiplied** via an **avalanche process**
- **Secondary electrons** and **photons** produced within the channels
- **Multiple GEMs** to share the **gain**  $\Rightarrow$  **stable detector**



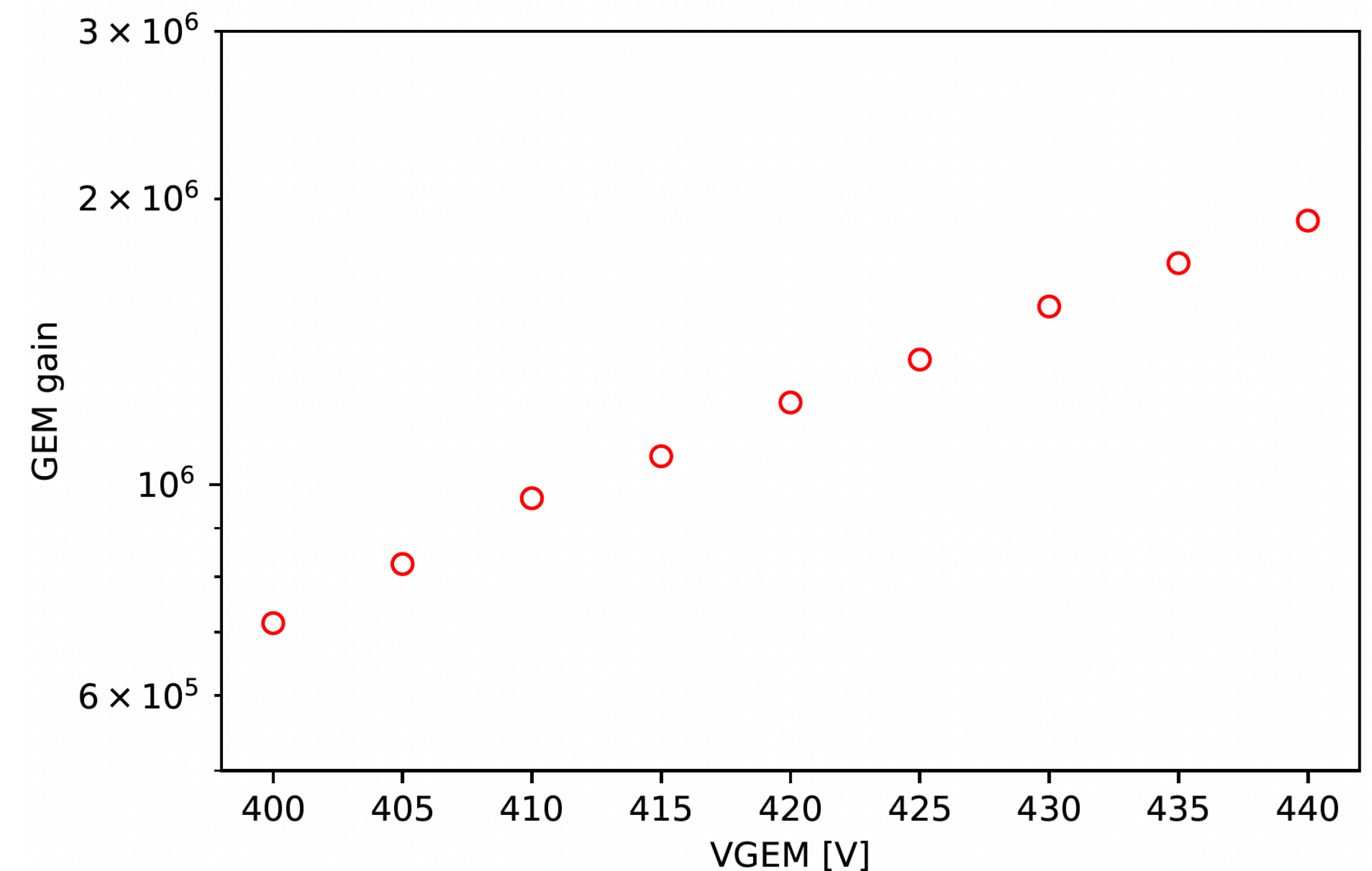
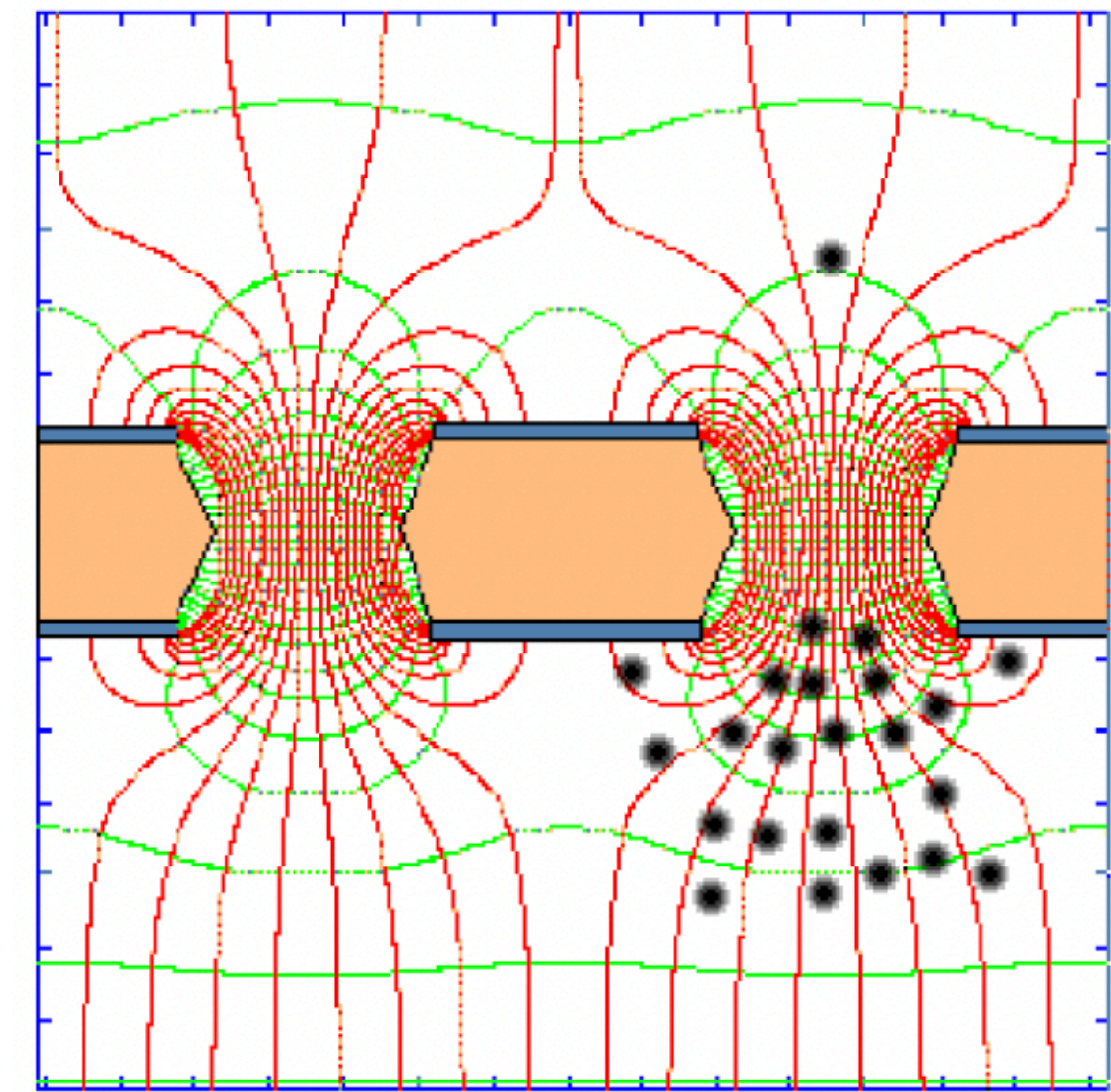
# Multiplication stage

- We operated our detector setting the **GEM HV to 440 V**
- At this voltage, the GEM gain has been measured to be, in He:CF<sub>4</sub> (60/40):

$$G \sim 2 \times 10^6$$

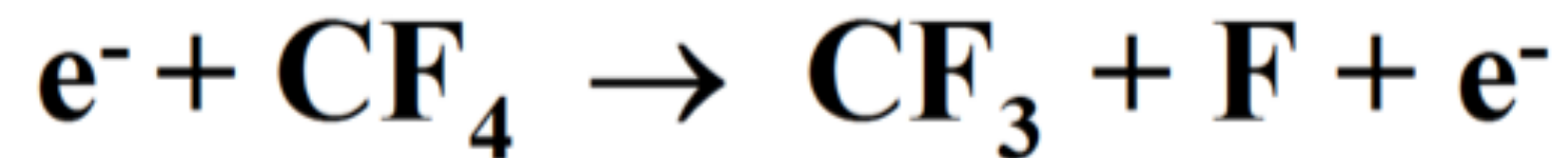
- Therefore, **after multiplication** we get:

$$\begin{array}{c} @ 1 \text{ keV}_{\text{ee}} \\ 24 \text{ e}^- \rightarrow \sim 4.6 \times 10^7 \text{ e}^- \end{array}$$



# Light emission

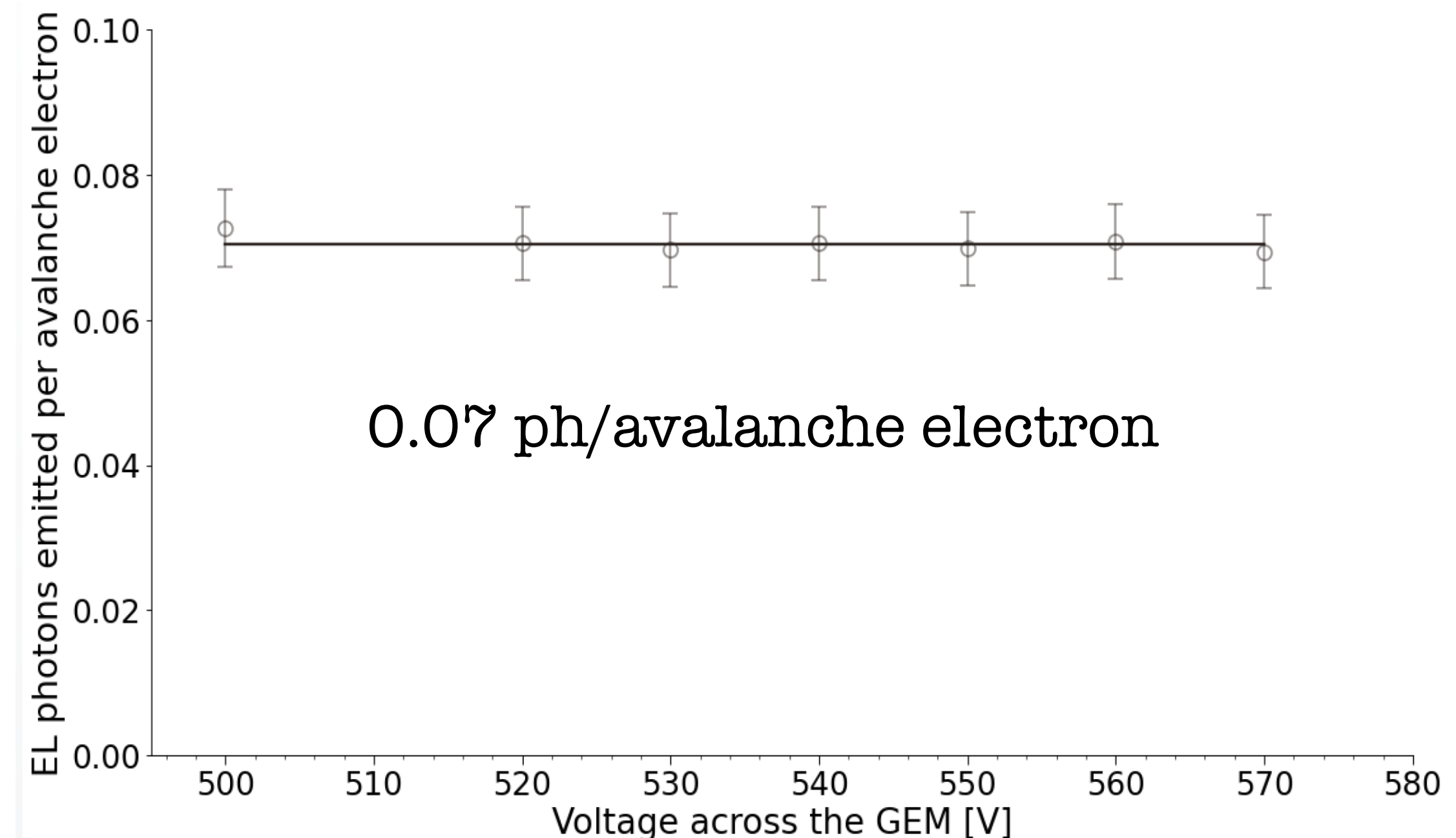
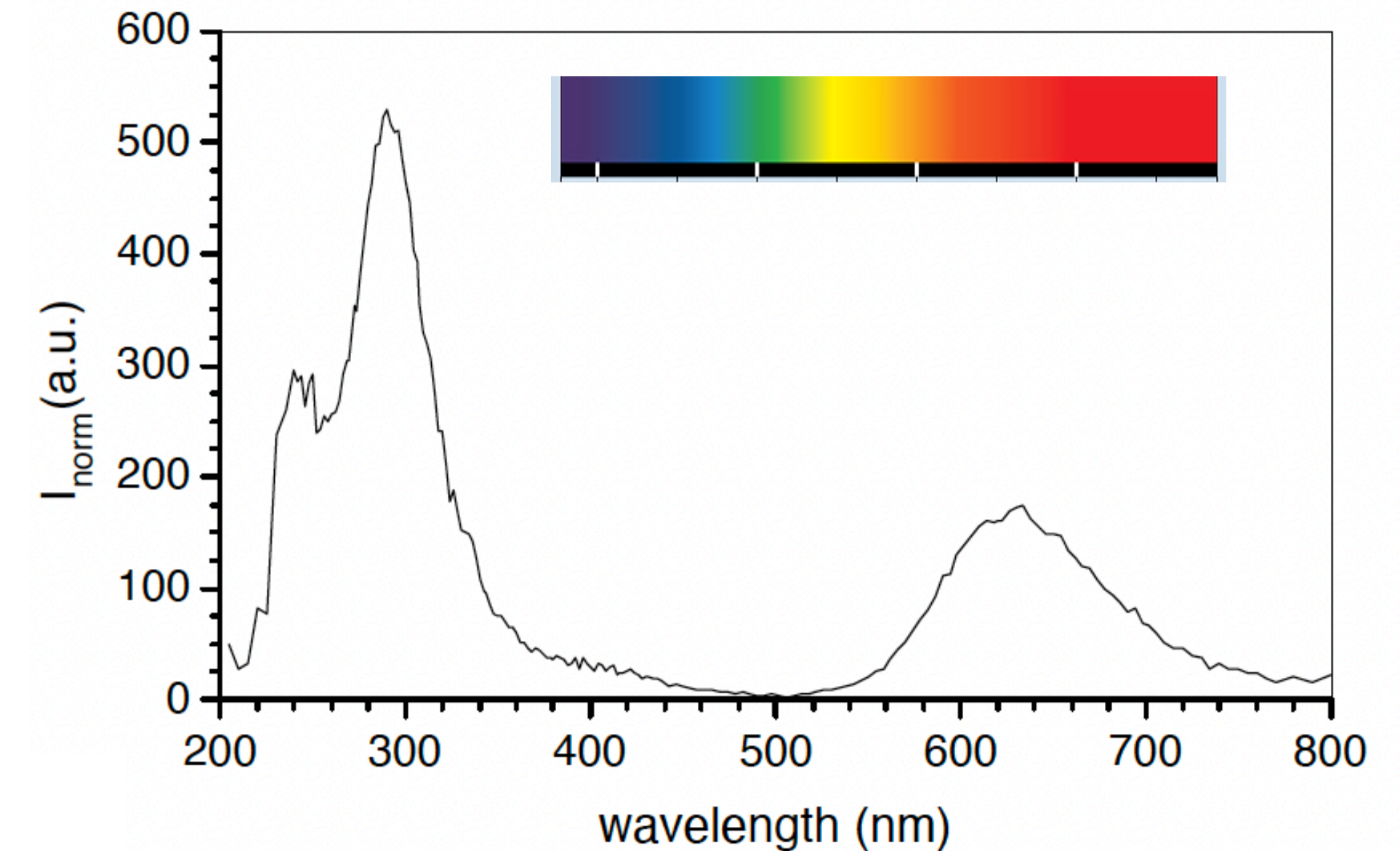
- Emitted as de-excitation of  $\text{CF}_3$  **at the last multiplication layer**



- Two main lines, excited by accelerated electrons:
  - ➡ Visible: **620 nm**
  - ➡ UV light: **265 nm**
- **Relative light** production **independent** from the **voltage**:

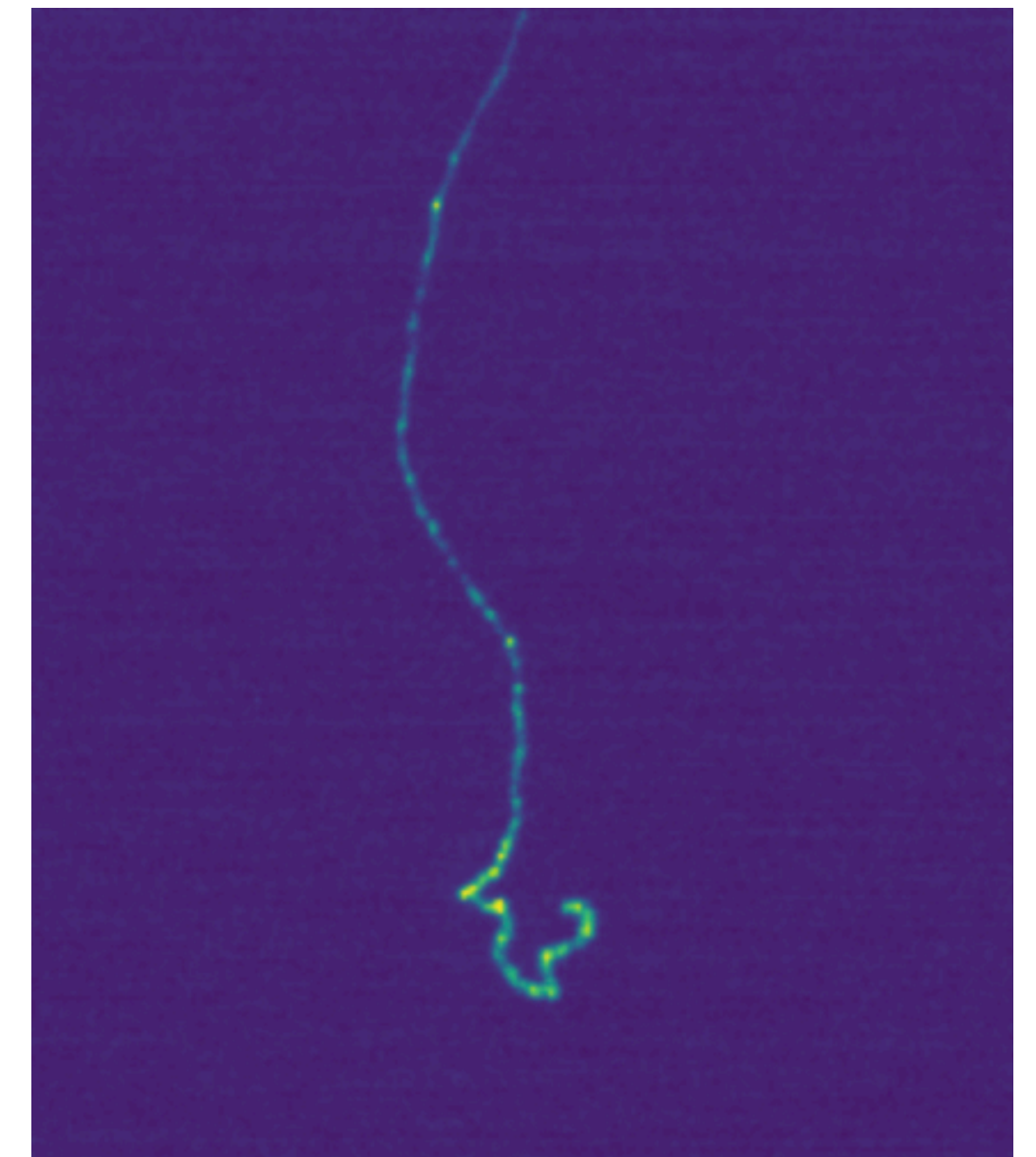
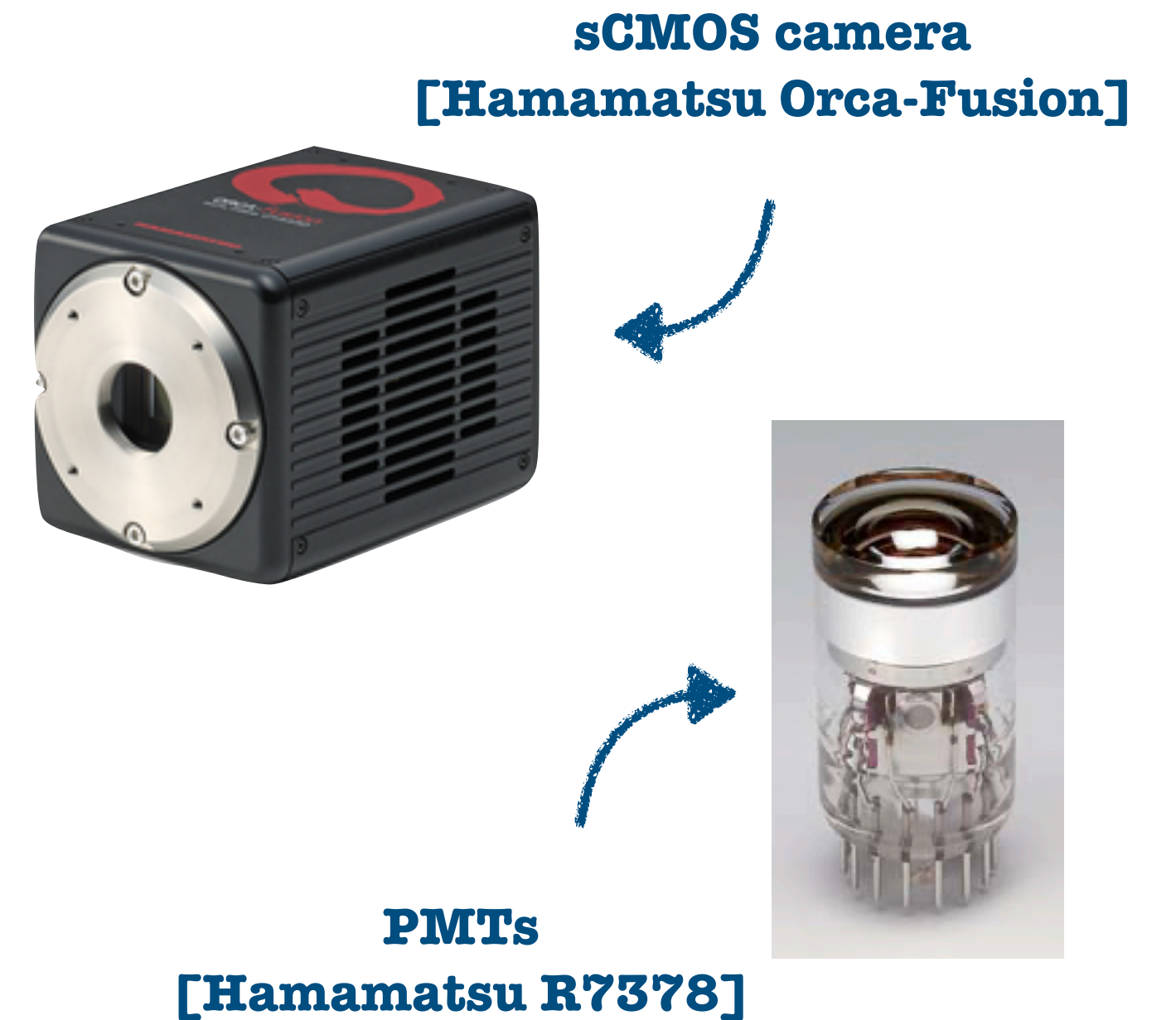
$\gamma/\text{e}^-$  ratio  $\sim 0.07$  ph/aval. elec.

@ 1 keV<sub>ee</sub>  
 $24 \text{ e}^- \rightarrow \sim 3.2 \times 10^6 \text{ ph}$



# The optical readout

- With GEMs:
  - ➡ we amplify **charge**
  - ➡ we produce **light** by the **de-excitation of  $\text{CF}_4$  gas** molecules
- The **CYGNO** project proposes the **readout of this light**
- To attain this goal we need:
  - ➡ High performance **optical sensors**, capable of providing **high granularity**, **high sensitivity**, and very **low noise**
  - ➡ Suitable **lens** to channel the light on these sensors
- **Optical coupling**  $\Rightarrow$  sensor **out of the sensitive volume**



# The CYGNO optical readout

- **CMOS** sensor noise:
  - ➡ Readout noise of  $0.7 \text{ e}^-/\text{px} \sim 0.9 \text{ } \gamma/\text{px}$
  - ➡ Dark current of  $0.2 \text{ e}^-/\text{px/s} \sim 0.25 \text{ } \gamma/\text{px/s}$
  - ➡ Acquisition time  $\sim 30\text{-}300 \text{ ms}$

- Camera **geometrical acceptance** for light emitted on the GEM plane:

$$\epsilon_{\Omega} = \frac{1}{[4(1/\delta + 1) \times a]^2} = 1.2 \times 10^{-4}$$

De-magnification:

Aperture = 0.95

with  $f = 25.6 \text{ mm}$  [focal length]

$d = 623 \text{ mm}$  [distance from GEMs]

$$\delta = \frac{f}{d - f}$$

- **Camera** Hamamatsu Orca-Fusion:
  - ➡ 80 % QE at 600 nm
  - ➡ 2304x2304 pixels
- 4 Hamamatsu R7378 **PMTs**:
  - ➡ 22 mm diameter
  - ➡  $\sim \text{ns}$  time response
- **Lens**: Schneider Xenon with 25.6 mm focal length and 0.95 aperture

- PMTs **geometrical acceptance**:

➡ critically **depends** on the **position** of the emission on the GEM plane w.r.t. the PMT position

➡ Empirical measured scaling:

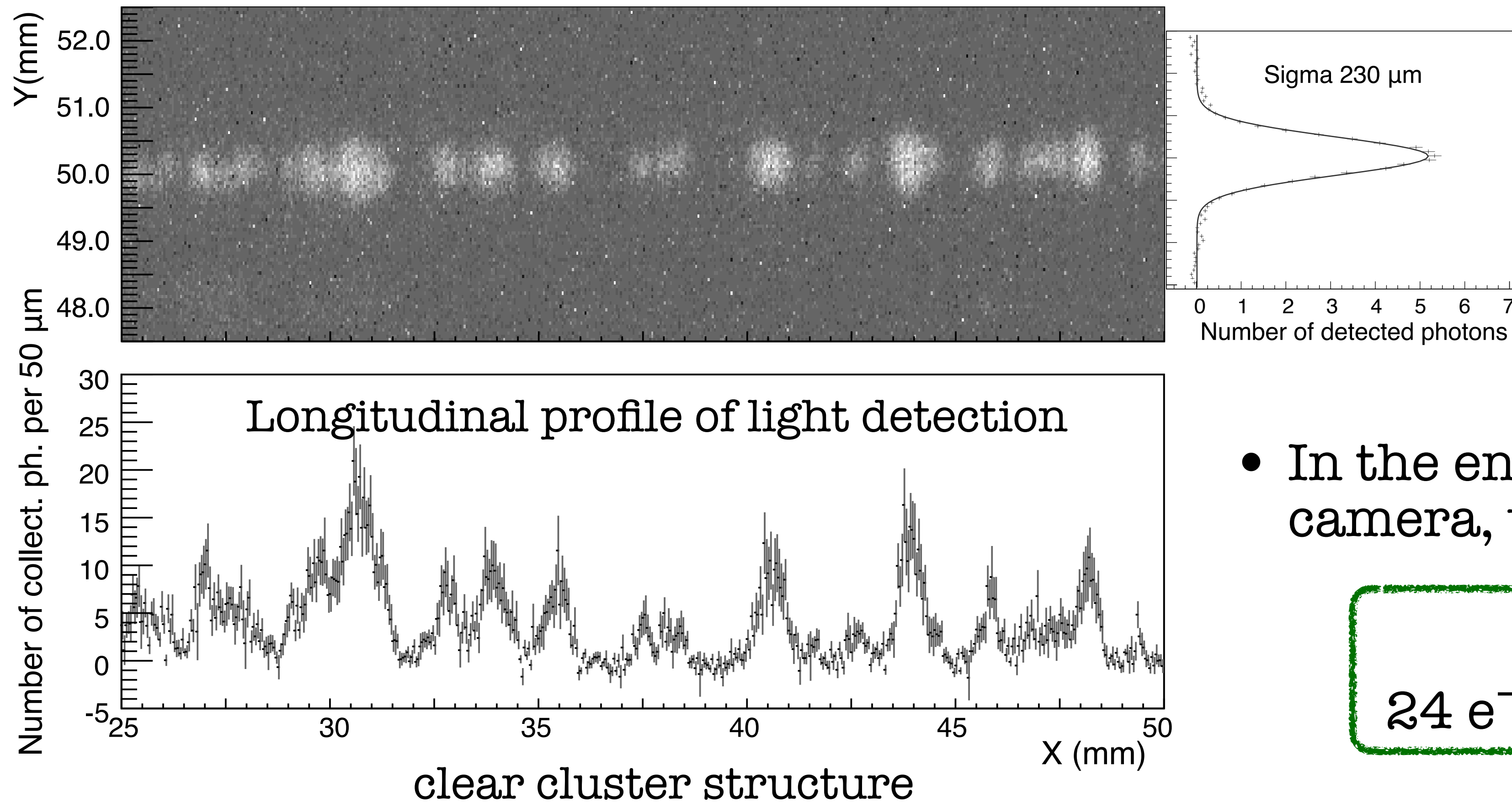
$$L_i = \frac{L}{R_i^\alpha}$$

Light collected by the PMT #i  $L_i$  = Total light emitted  $L$

Distance from the light emission  $R_i$  We measured  $\alpha \sim 4$

# The CYGNO optical readout

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



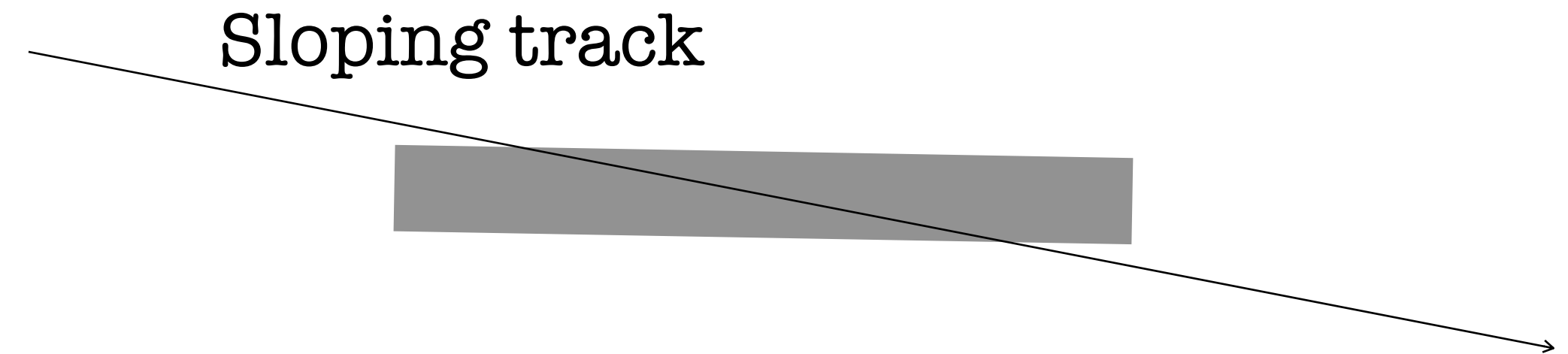
- In the end, if we consider only the camera, we obtain:

$$\begin{aligned} & @ 1 \text{ keV}_{ee} \\ & 24 e^- \rightarrow \sim 400 \text{ detected ph} \end{aligned}$$

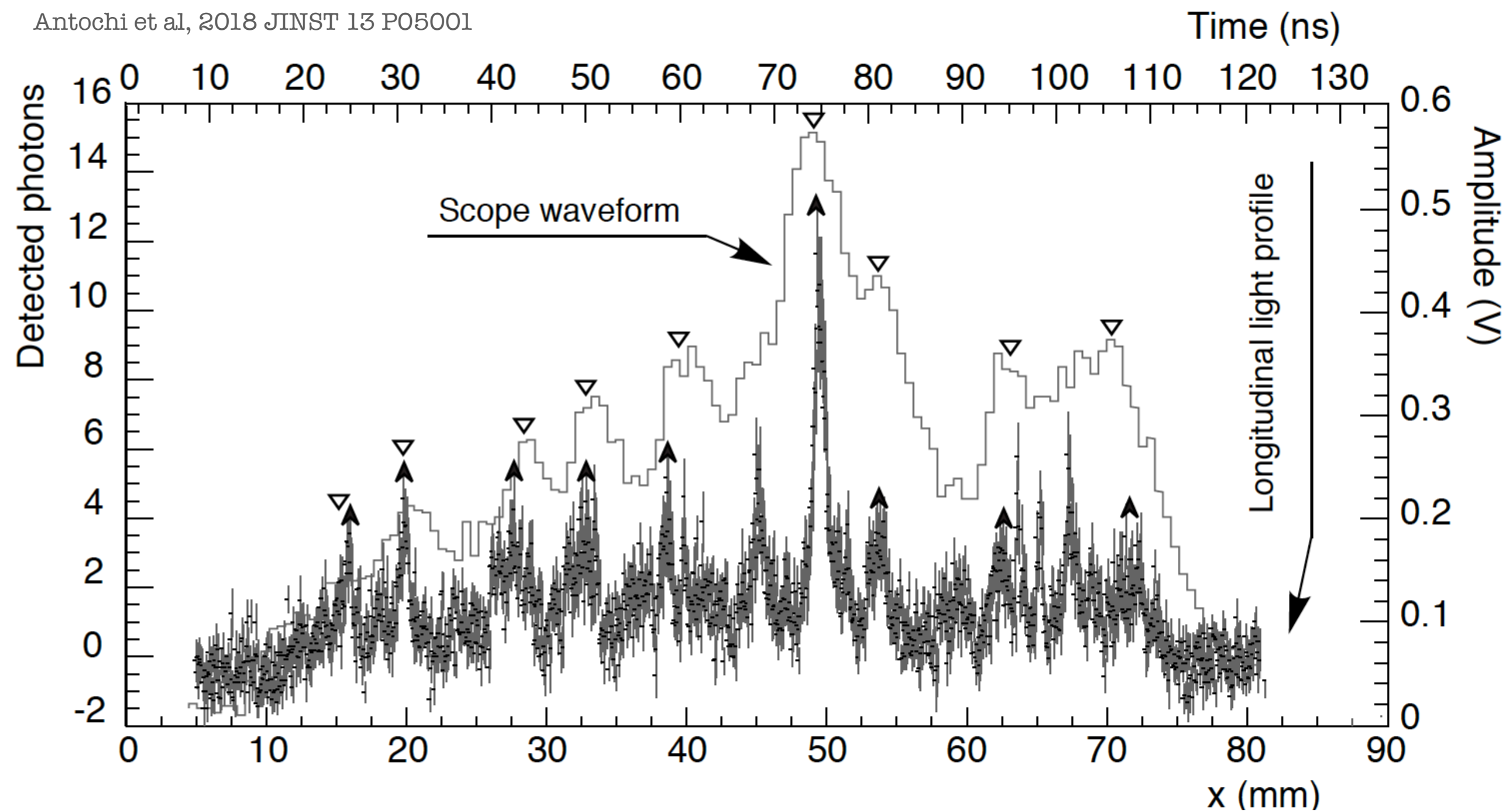
This is equivalent to  $\sim$  **20 detected photons every primary ionization electron**

# CMOS combined with Photomultipliers

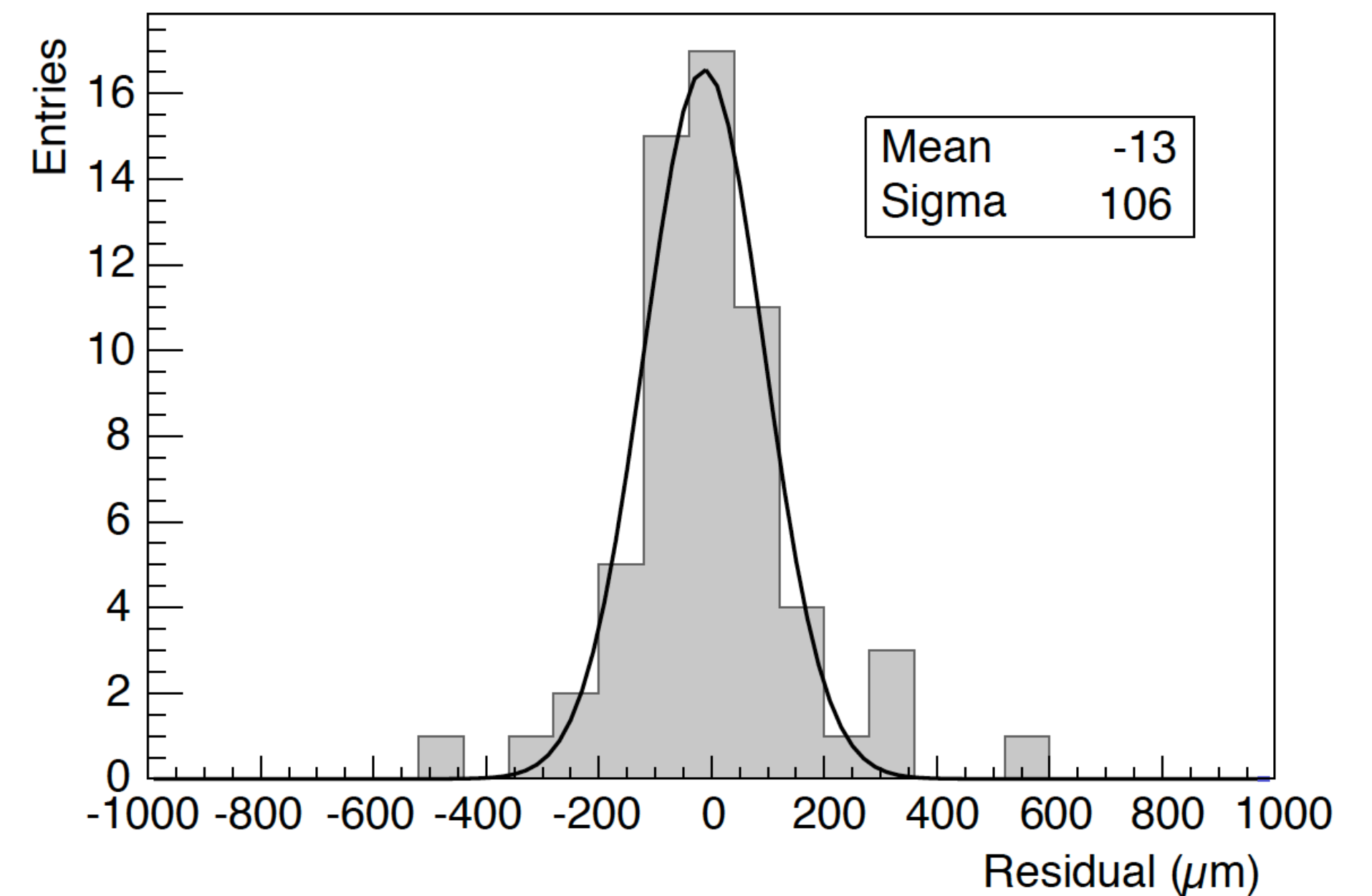
- Fast photosensors (**PMTs**) to get the **time** information  $\Rightarrow$  reconstruct **z inclination**



Antochi et al, 2018 JINST 13 P05001



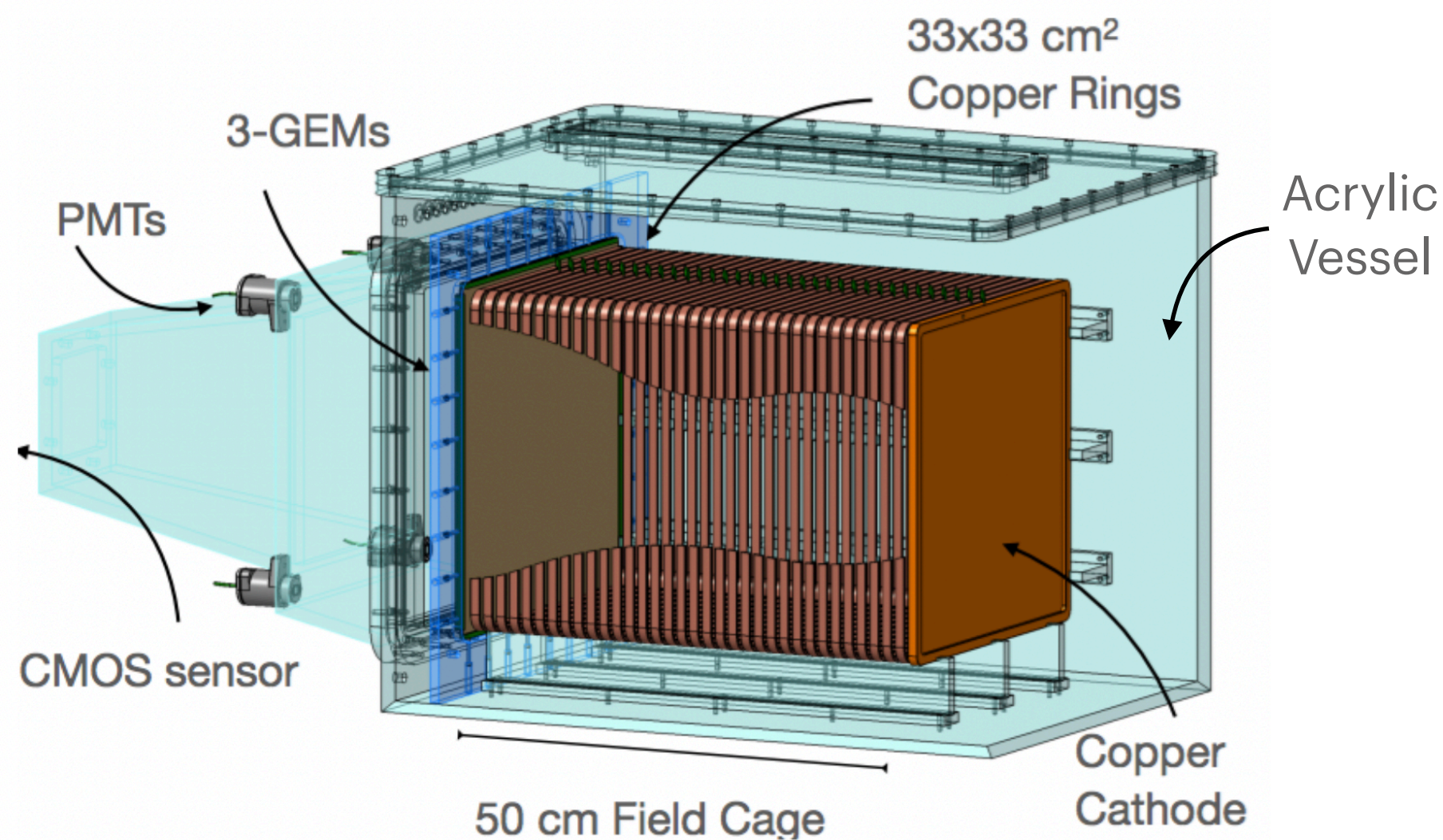
Time + drift velocity  $\Rightarrow$  relative z coordinate



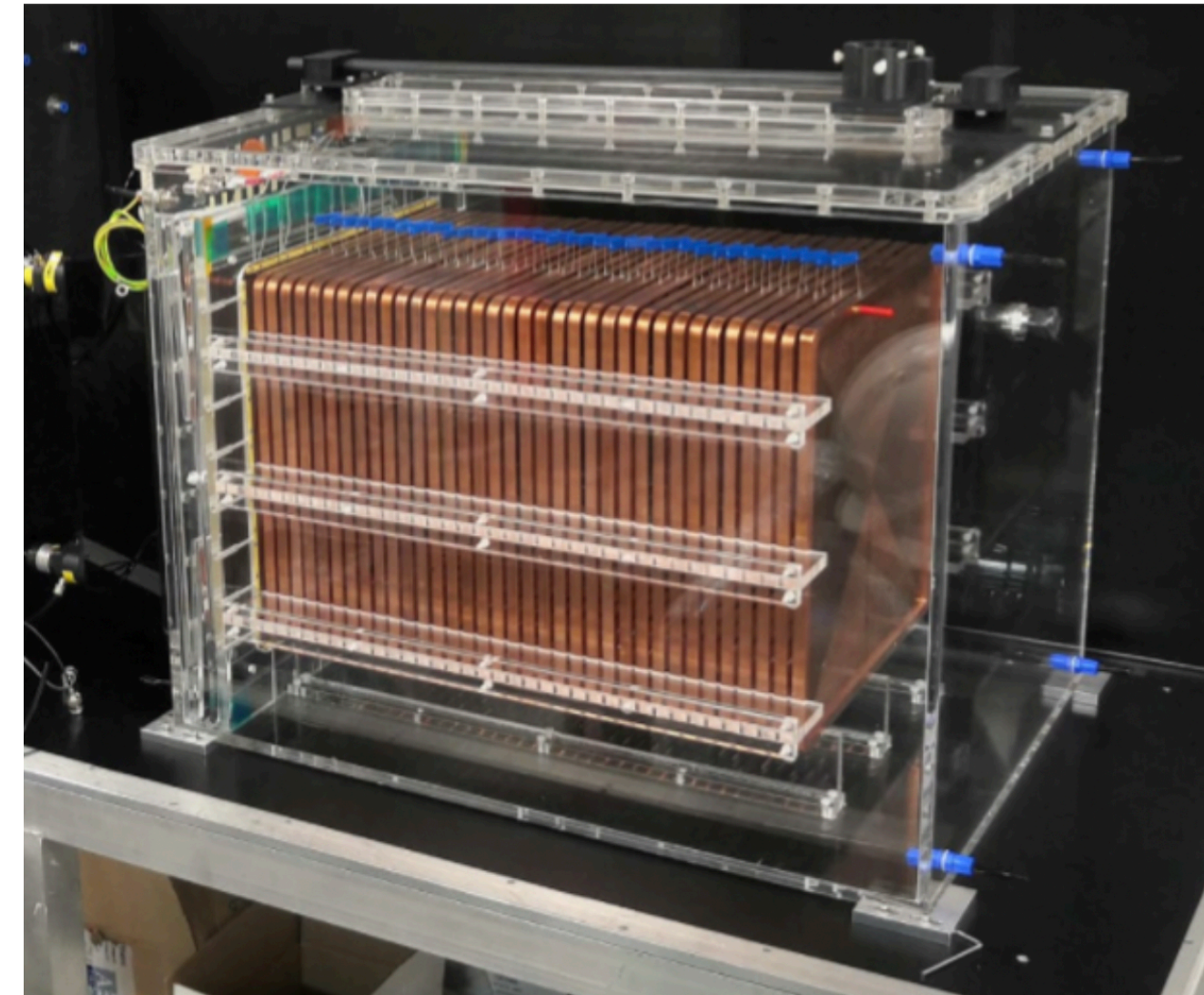
**100  $\mu\text{m}$  resolution** on  
relative cluster **z**

# LIME: Long Imaging Module

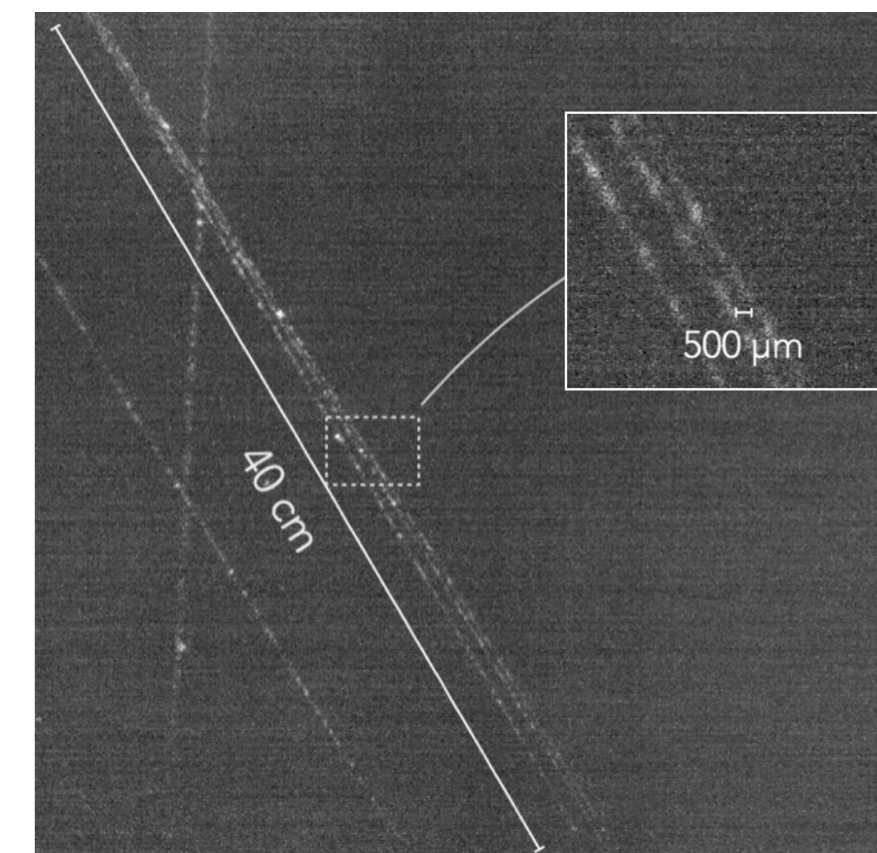
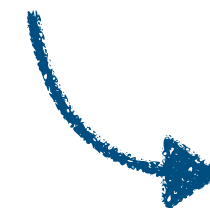
- Designed at **RM1** and **LNF** and built at **LNF**



- Copper ring field cage, 50 cm drift
- 1 sCMOS sensor + 4 PMT
- 3 GEMs for a 33 x 33 cm<sup>2</sup> sensitive area
- 50 L sensitive volume



**Cosmic rays  
(overground,  
no shielding)**



**4 Hamamatsu R7378 PMTs**

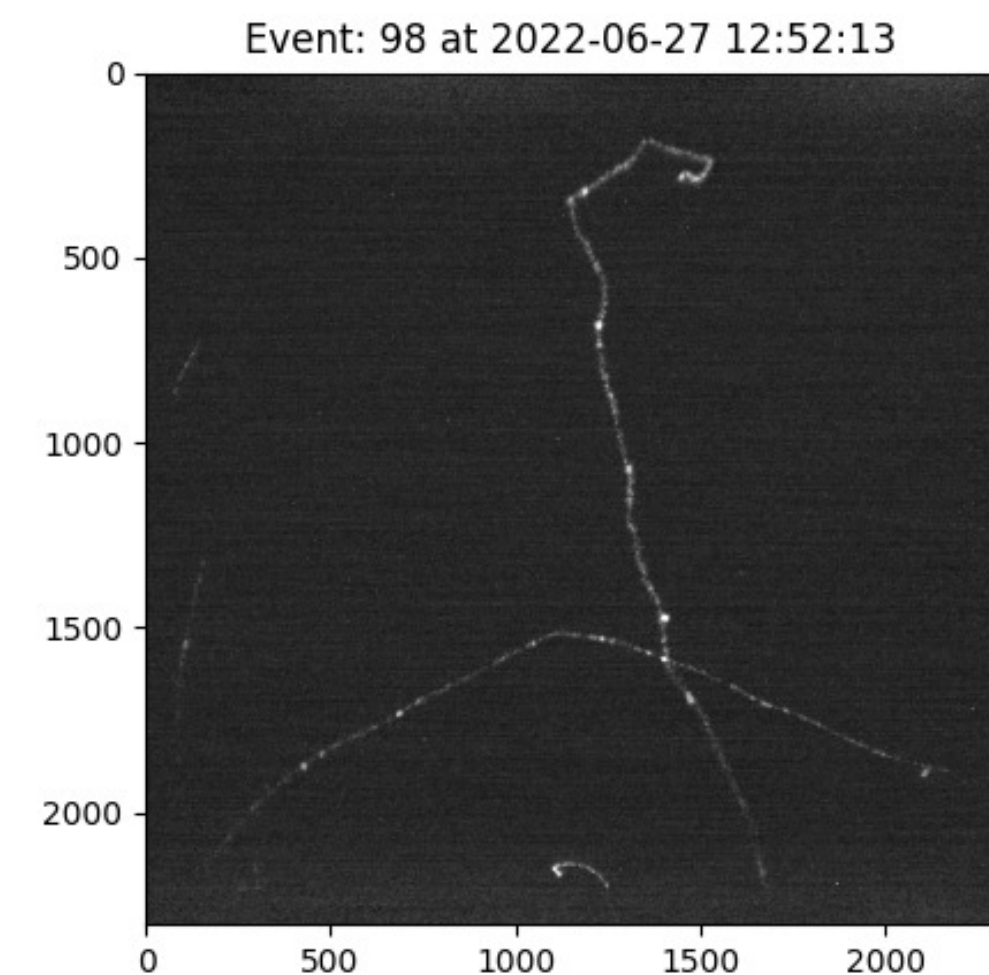
**ORCA-Fusion**

**HIGH RESOLUTION**  
2304 × 2304  
5.3 Megapixels

**READOUT NOISE**  
0.7 electrons rms  
Ultra-quiet Scan

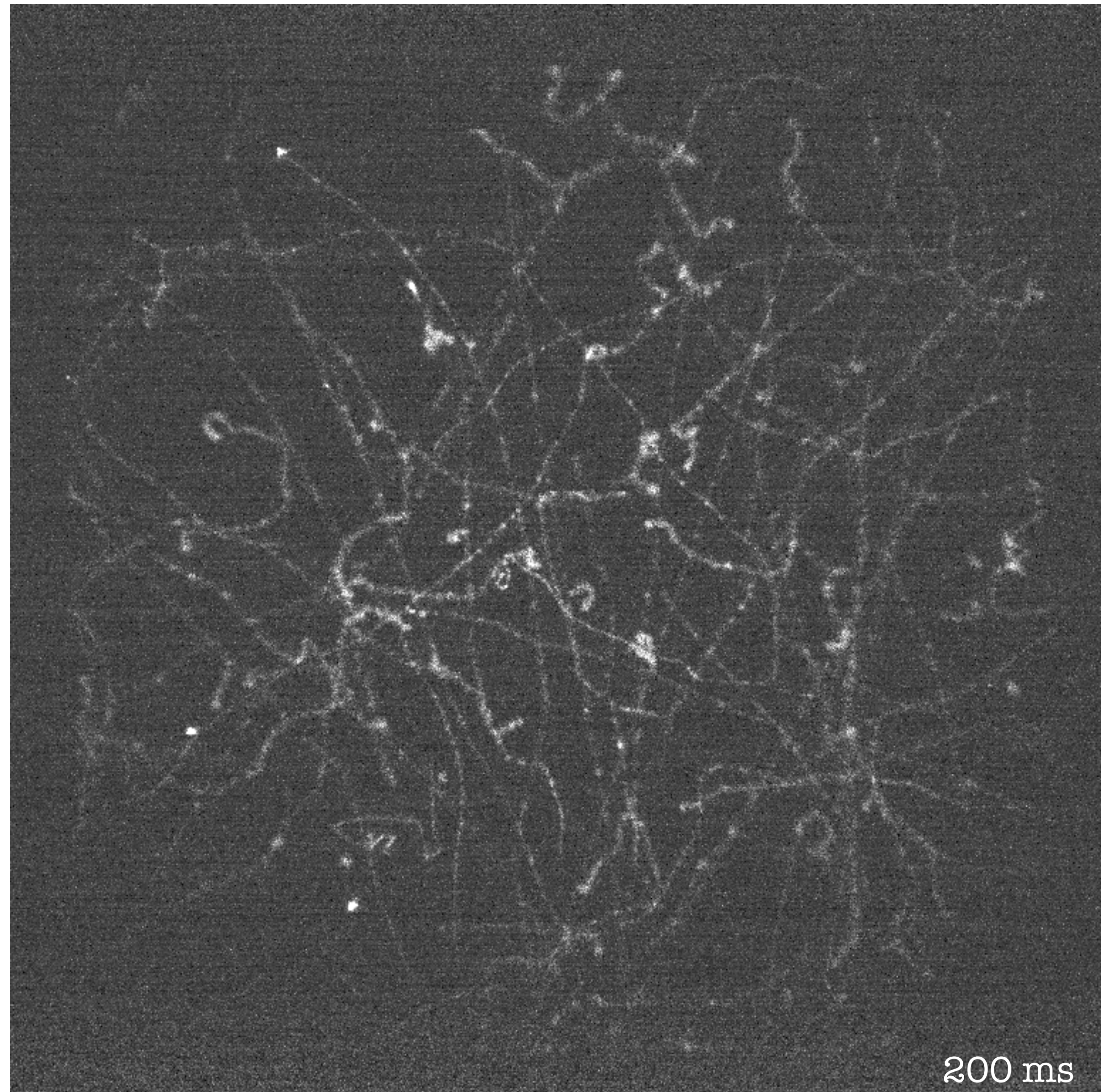
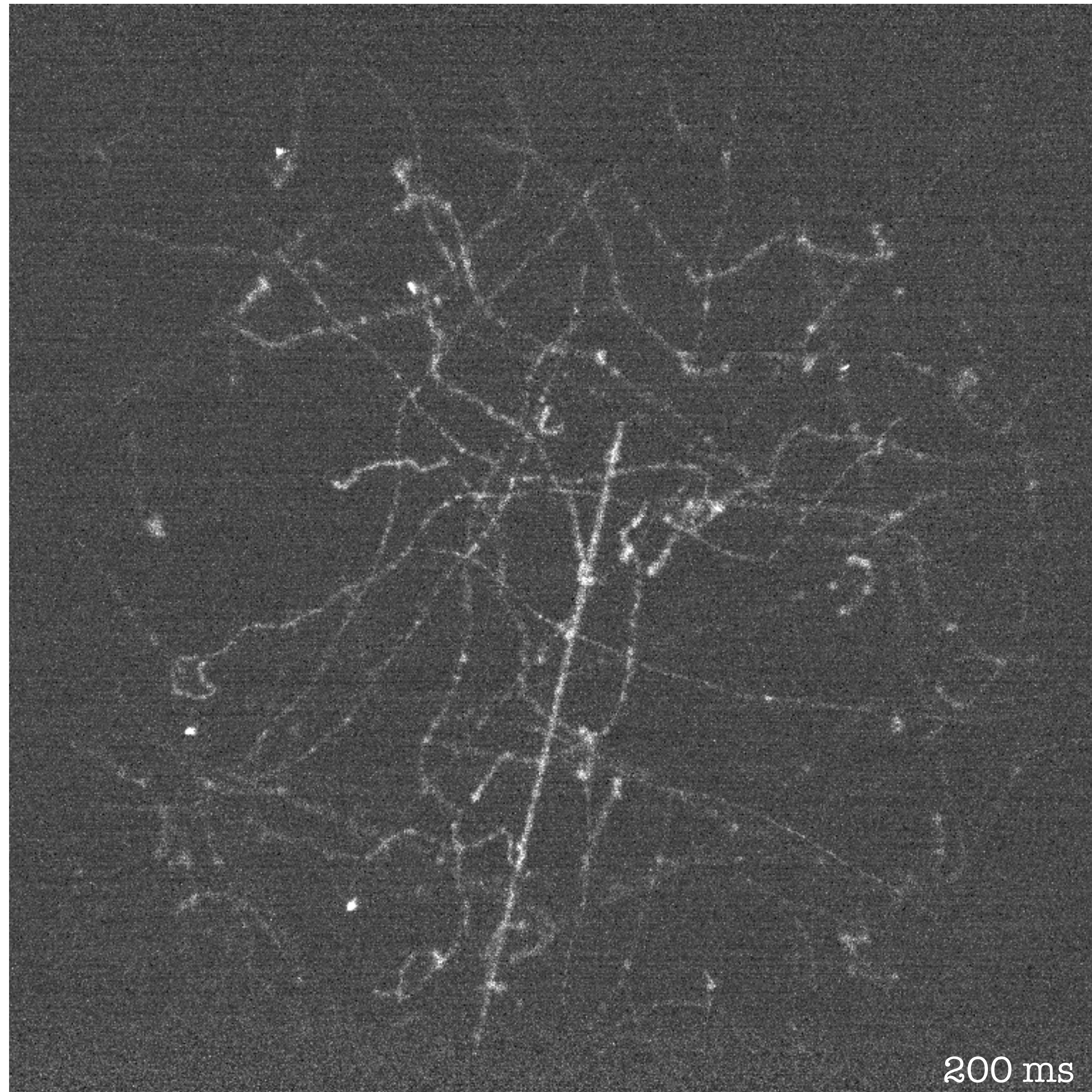


**Natural radioactivity  
(underground,  
no shielding)**



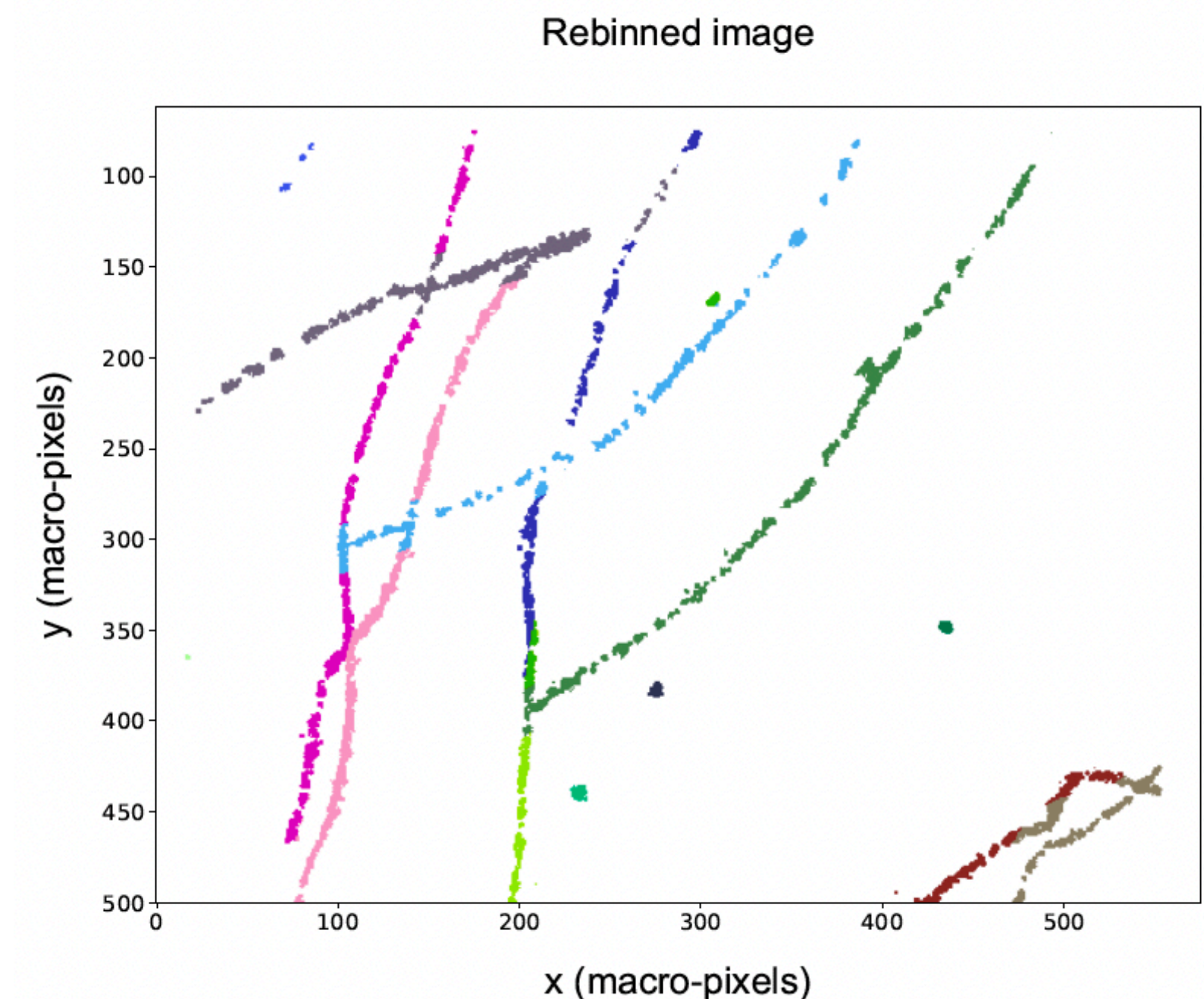
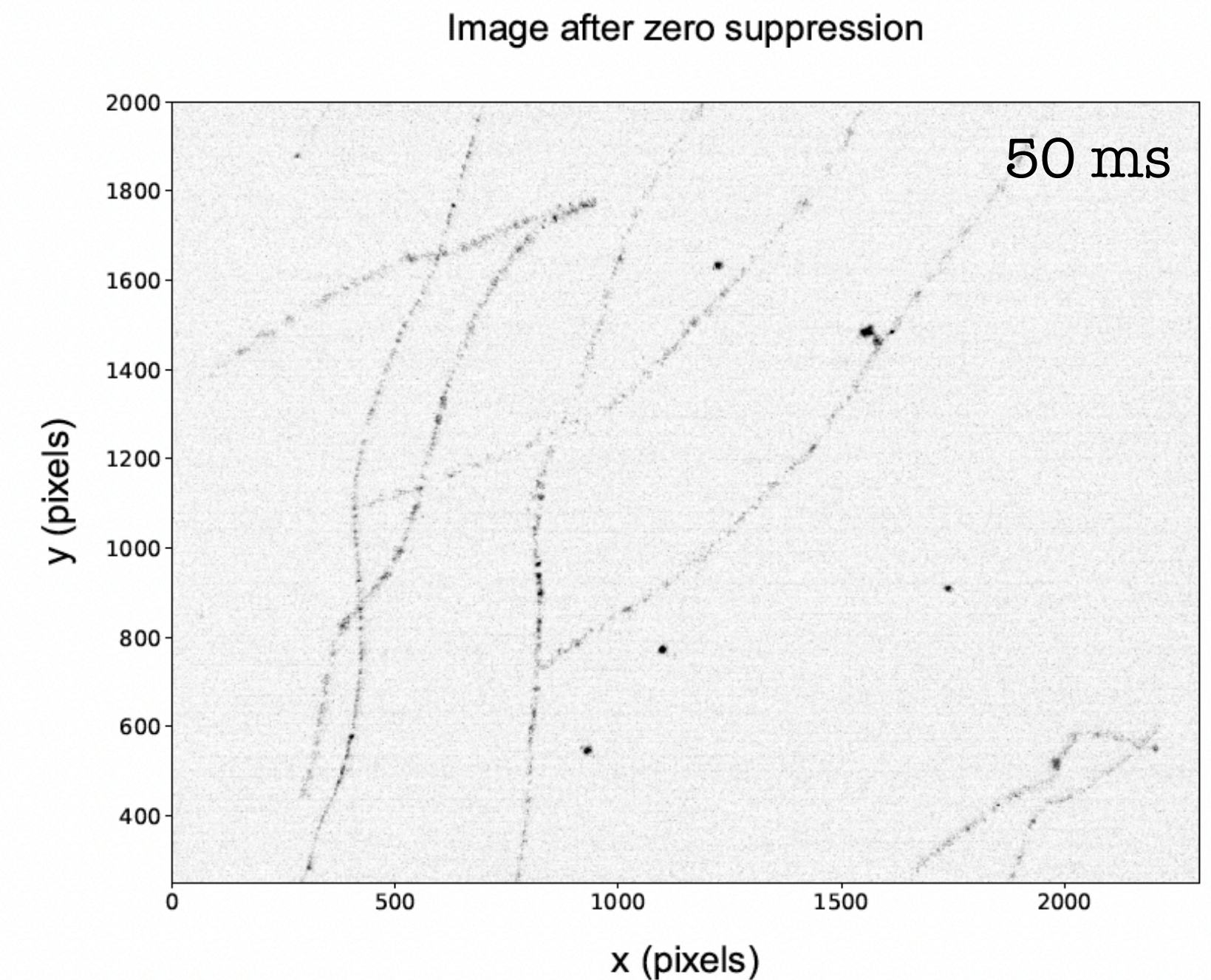
# LIME: Overground images

33 cm



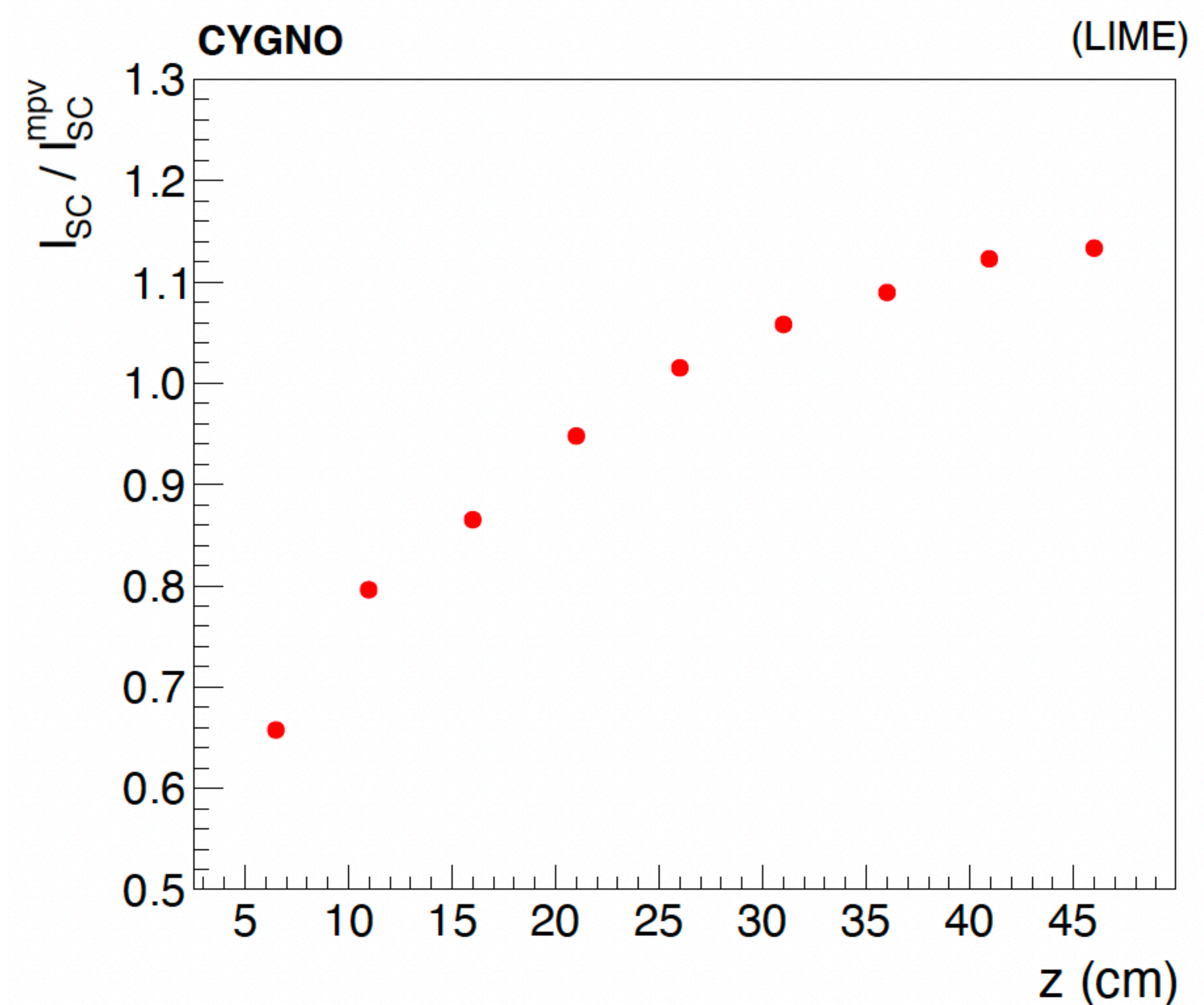
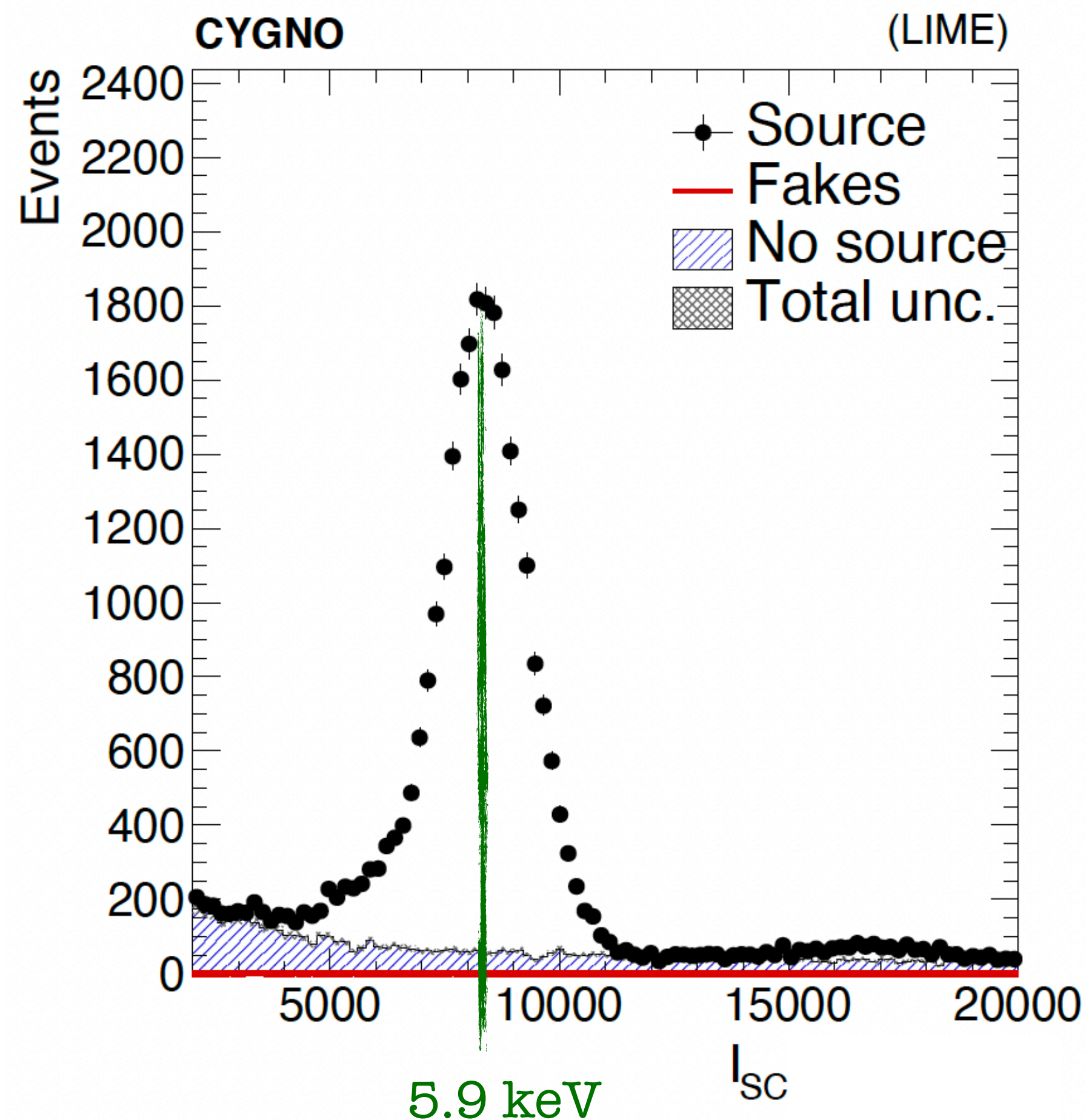
# Picture reconstruction

- **Reconstruction** algorithm: **clustering** + **computation of observables** (energy, length, width, etc.)
- **4 steps for clustering:**
  1. zero suppression
  2. optical corrections
  3. super-clustering for long tracks
    - ➡ generalization of RANSAC algorithm
    - ➡ needed to deal with overlapping tracks
  4. additional clustering step for small deposits
    - ➡ based on iDBSCAN algorithm



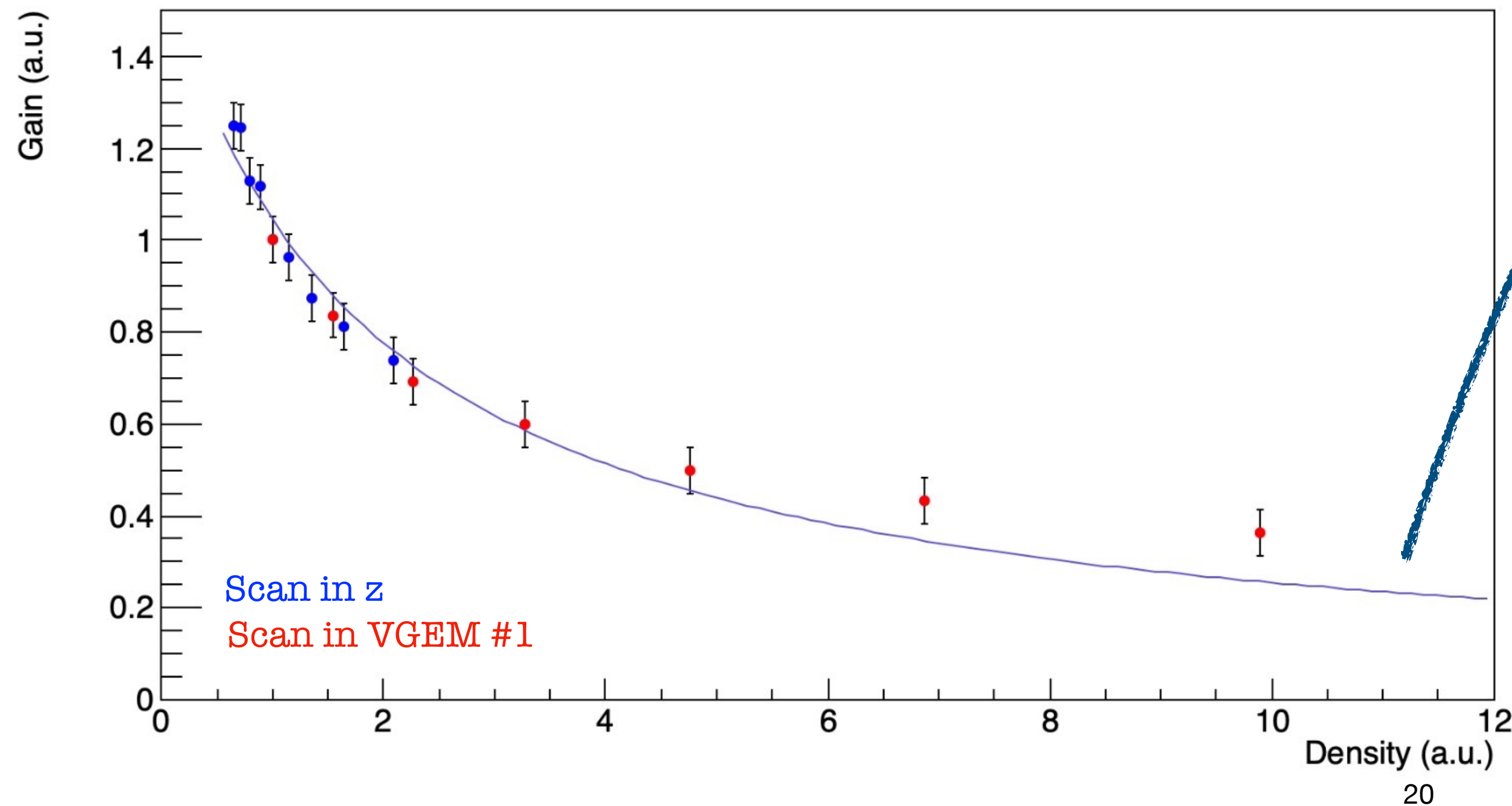
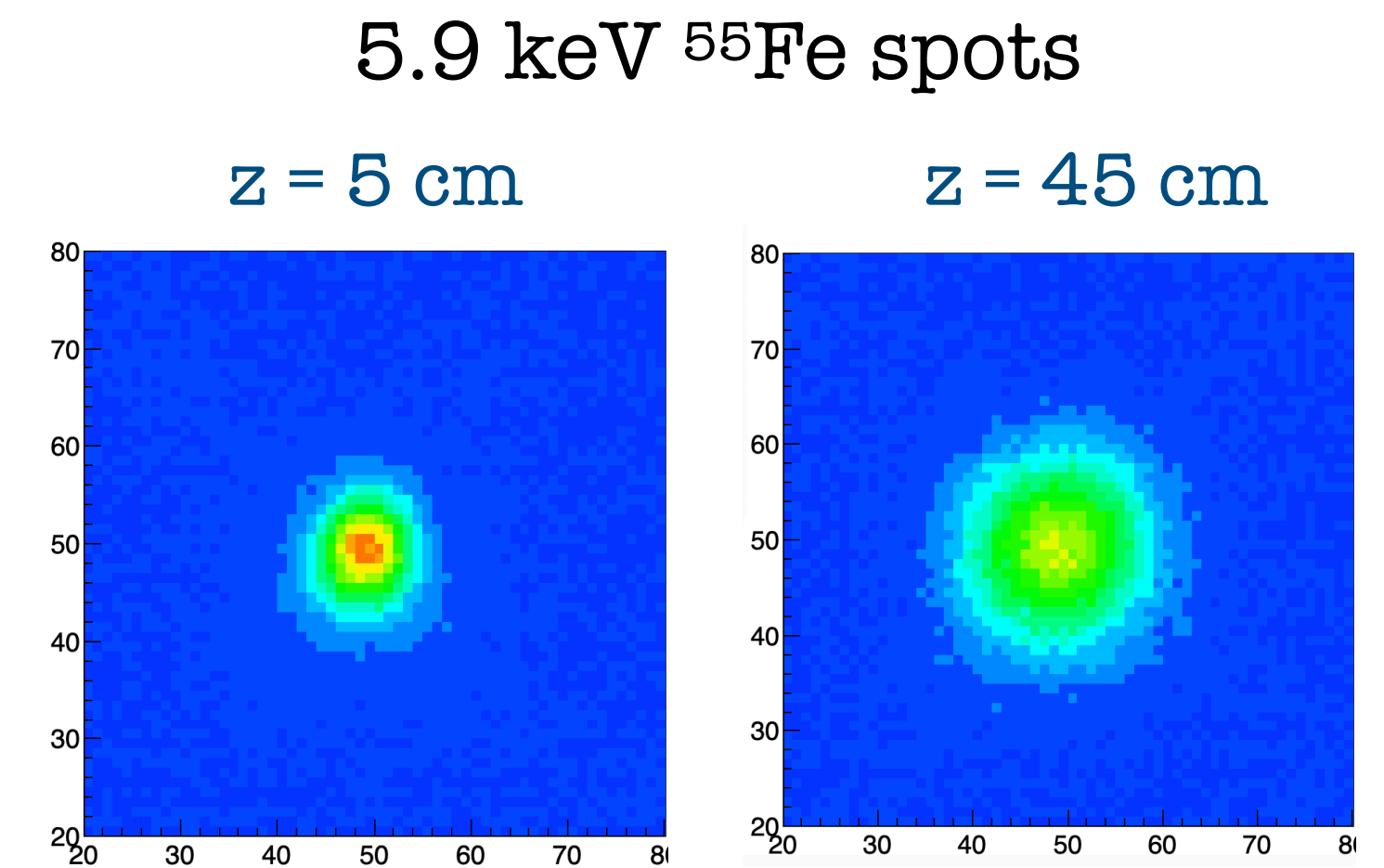
# The $^{55}\text{Fe}$ source and energy calibration

- Total **light integral** proportional to the **energy**, and dependent on **z** due to the saturation of GEM gain



# Saturation of the GEM gain

- **Saturation** of GEM gain due to positive **ions back-flow** screening the electric field, as already found by our CERN colleagues [[arXiv:1512.04968](https://arxiv.org/abs/1512.04968)]
- **Denser energy deposits**  $\Rightarrow$  **more charge in the same holes**



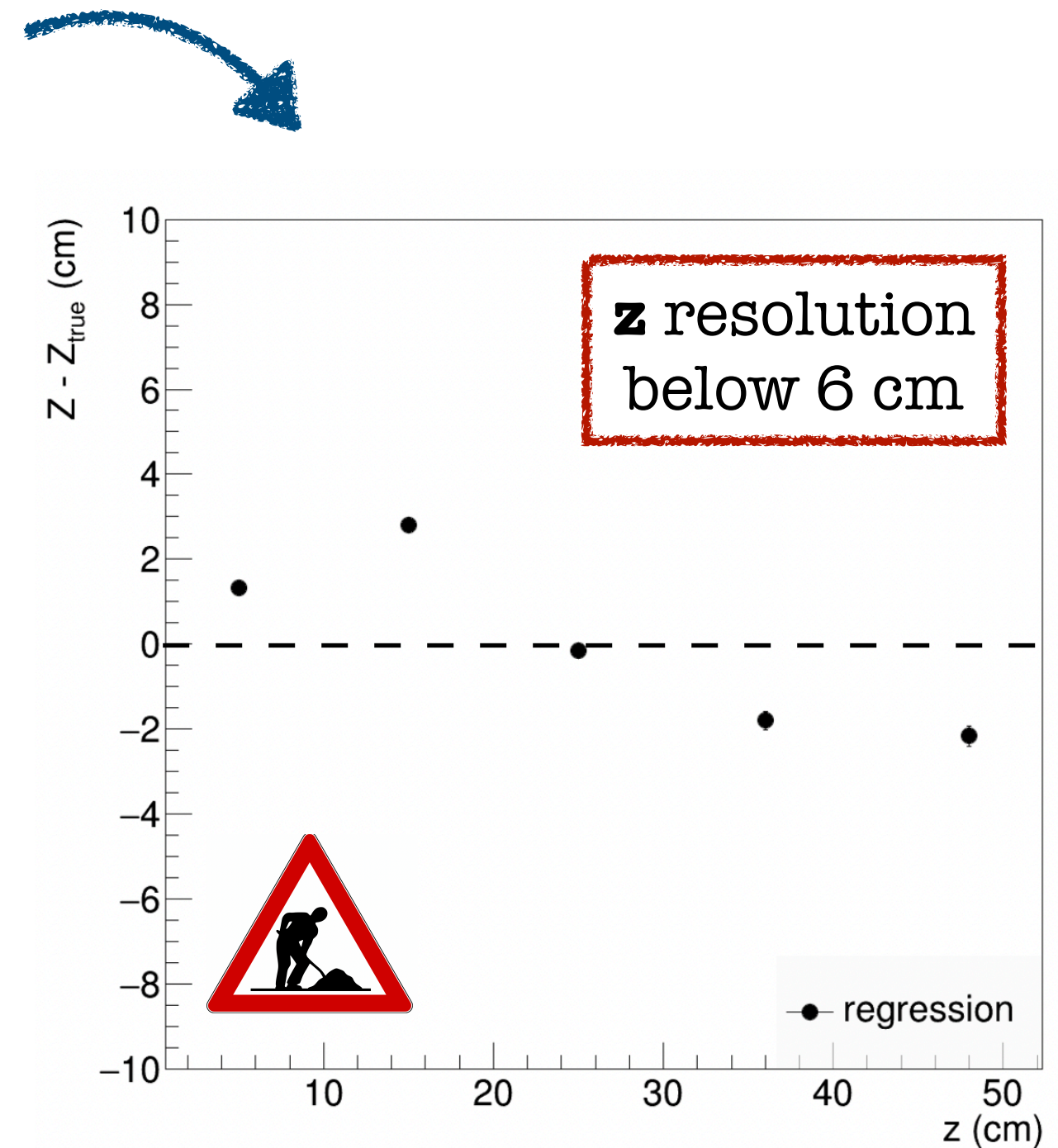
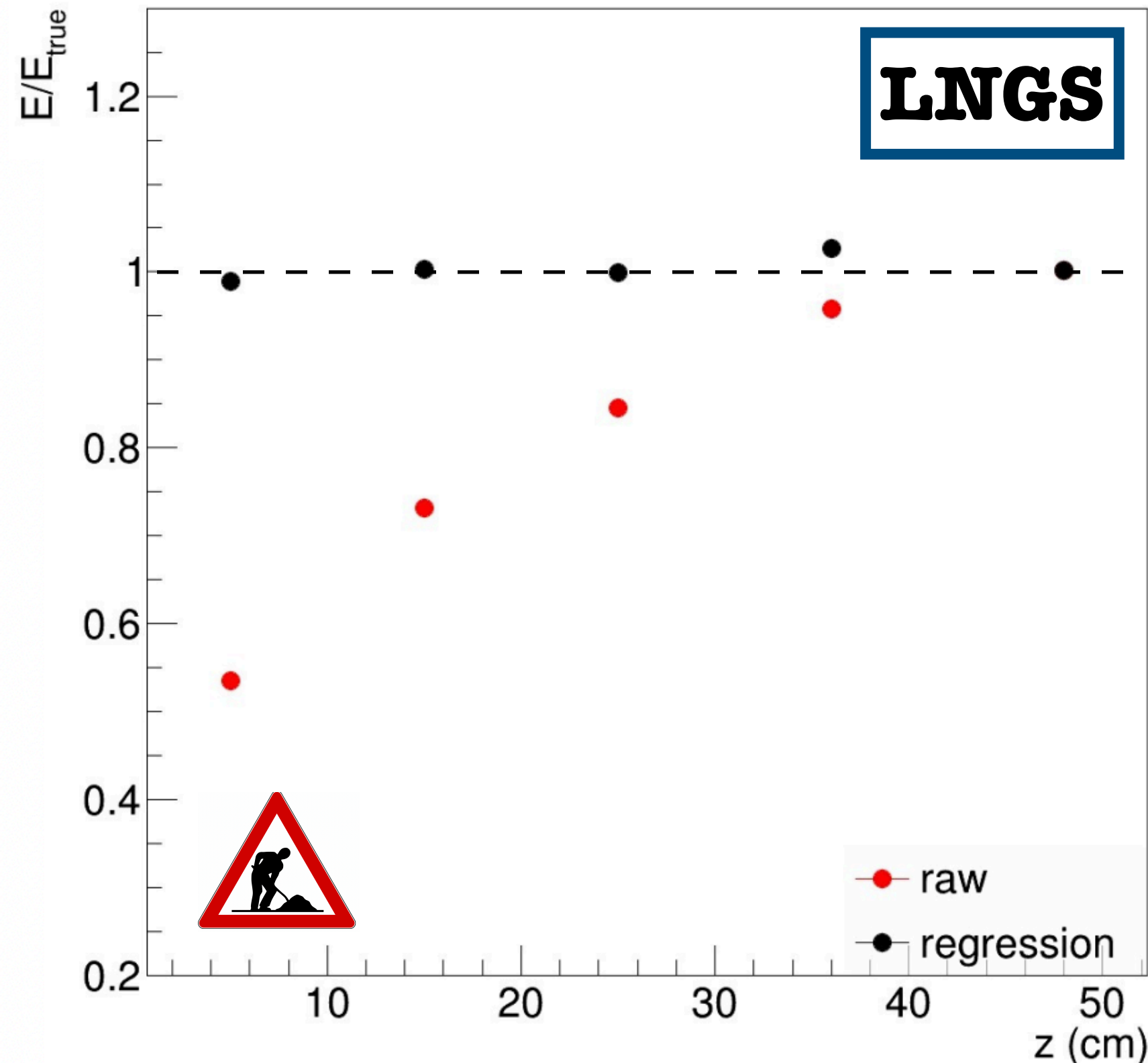
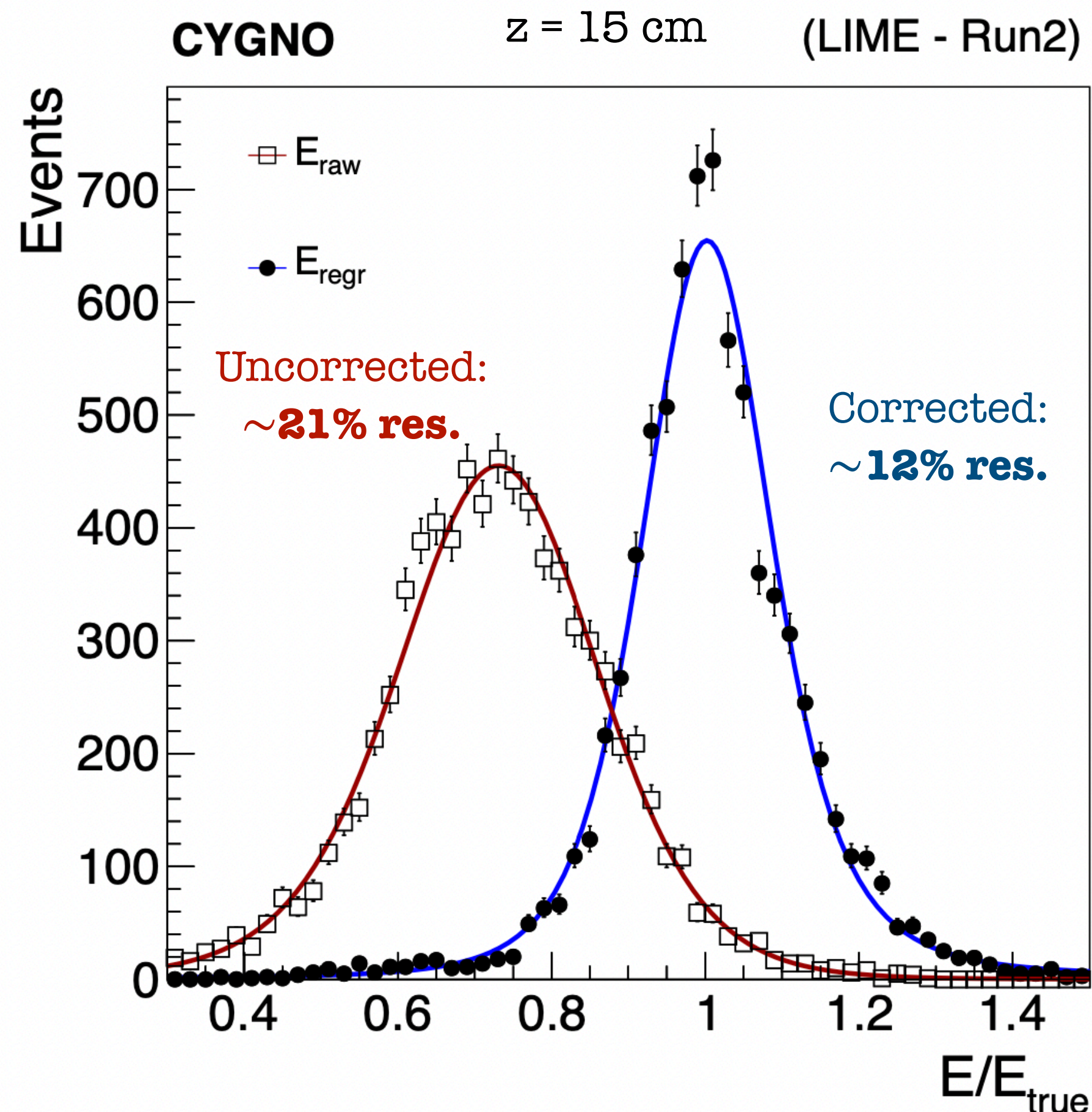
We developed a simple model:  
[[modified Townsend model](#)]

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

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

# The multivariate regression

- **Multivariate regression** algorithm to **correct** for x-y non uniformity of the light yield, and partially the saturation effect  $\Rightarrow$  **big improvement in the energy resolution**



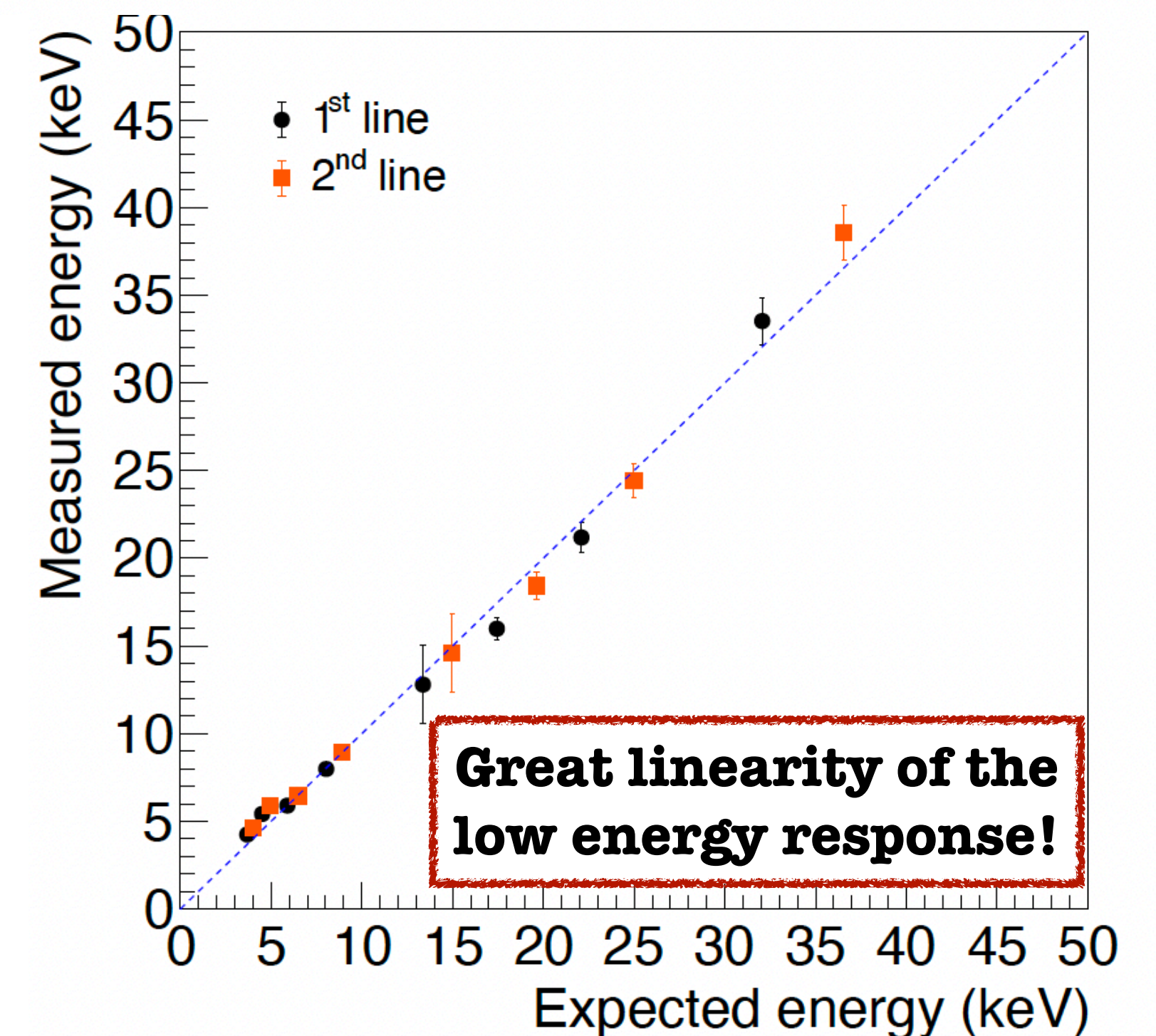
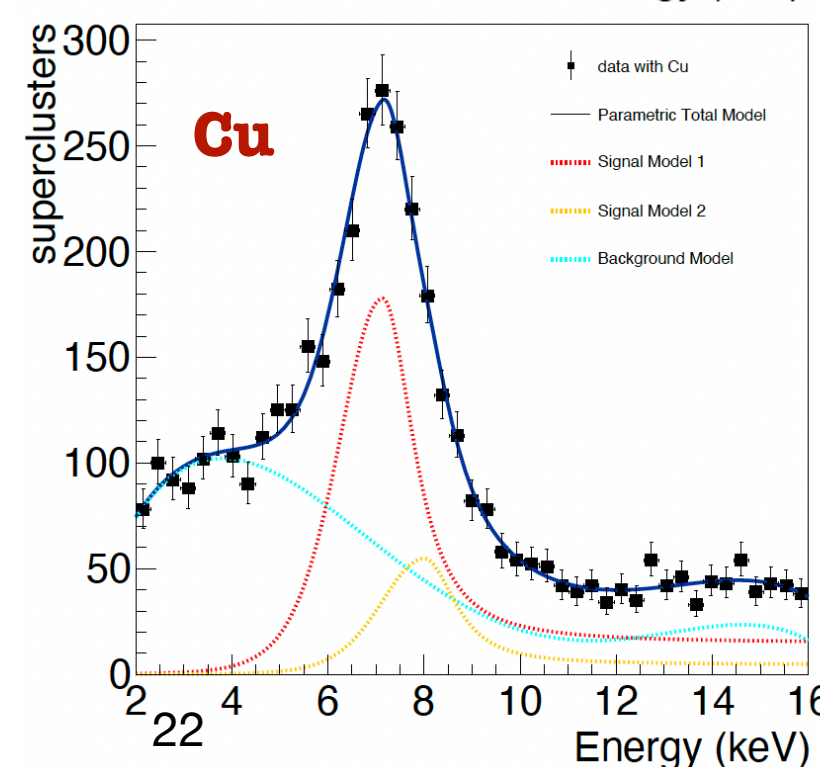
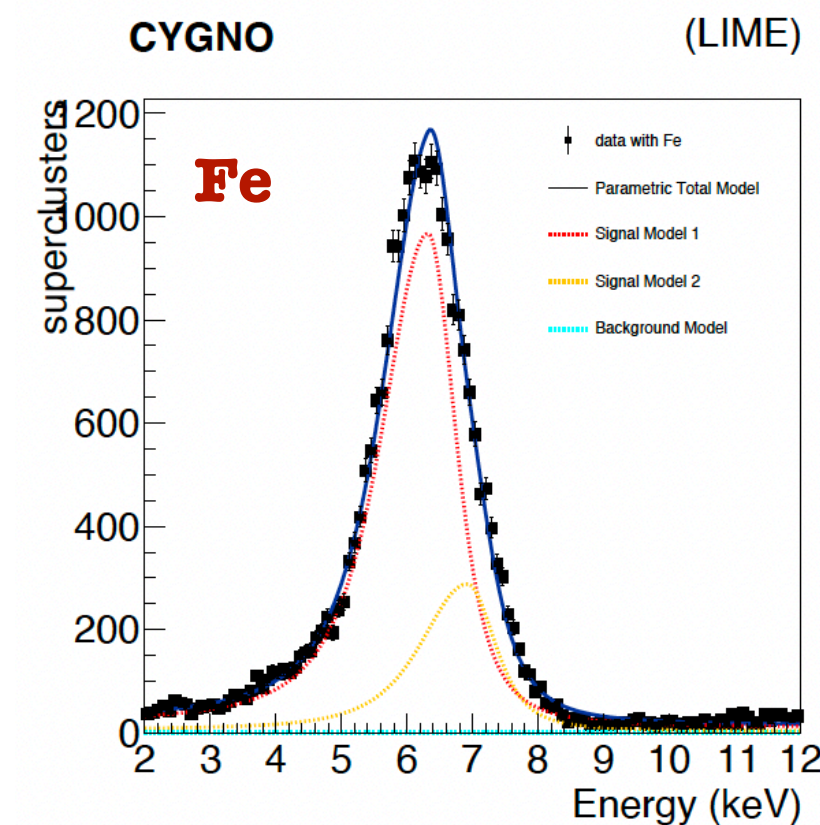
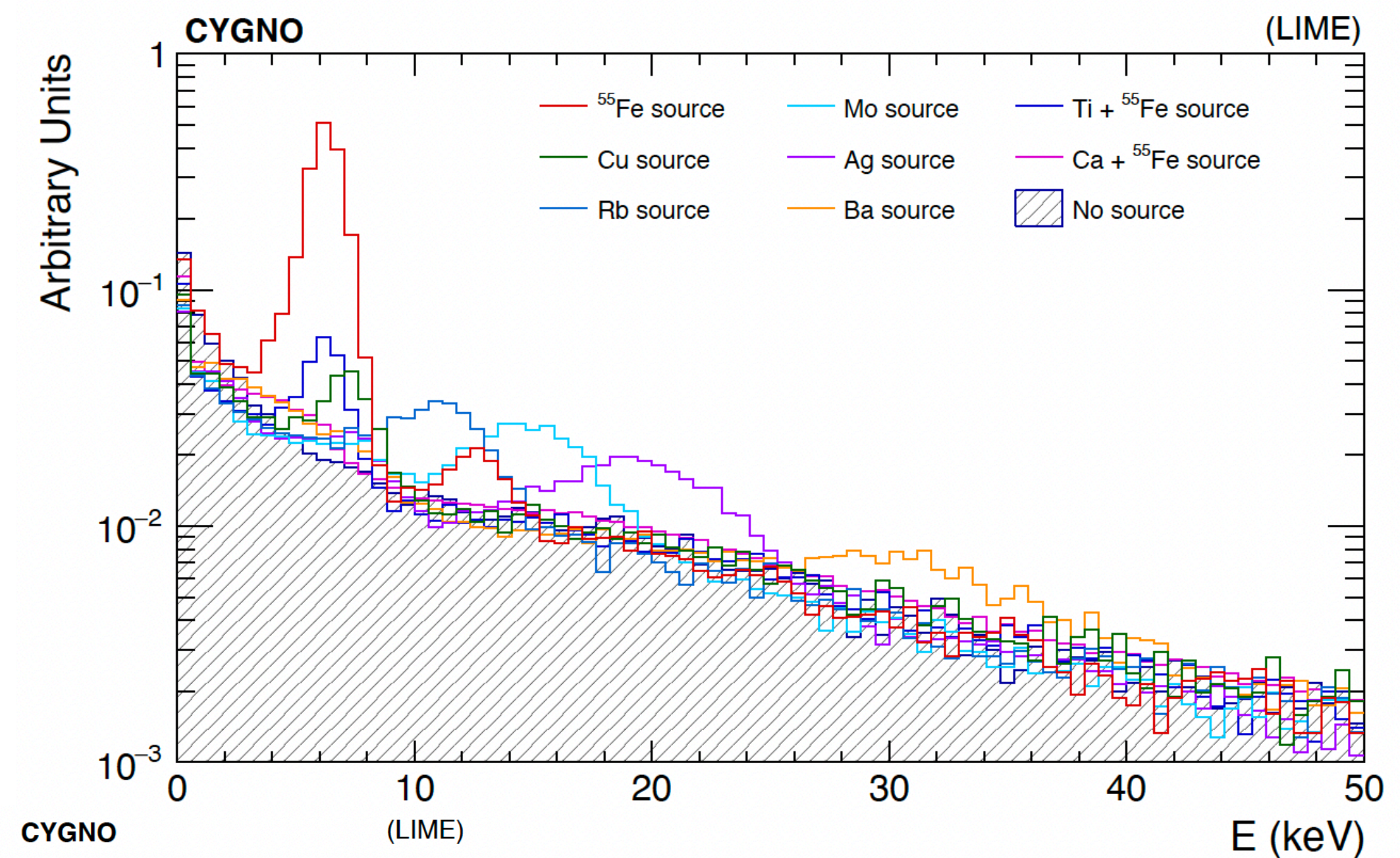
# ER calibration

- $^{55}\text{Fe}$  source  
[ $K_\alpha \sim 5.9 \text{ keV}$ ,  $K_\beta \sim 6.4 \text{ keV}$ ]
- Multi-target source

Material	Energy $K_\alpha$ [keV]	Energy $K_\beta$ [keV]
Cu	8.04	8.91
Rb	13.37	14.97
Mo	17.44	19.63
Ag	22.10	24.99
Ba	32.06	36.55

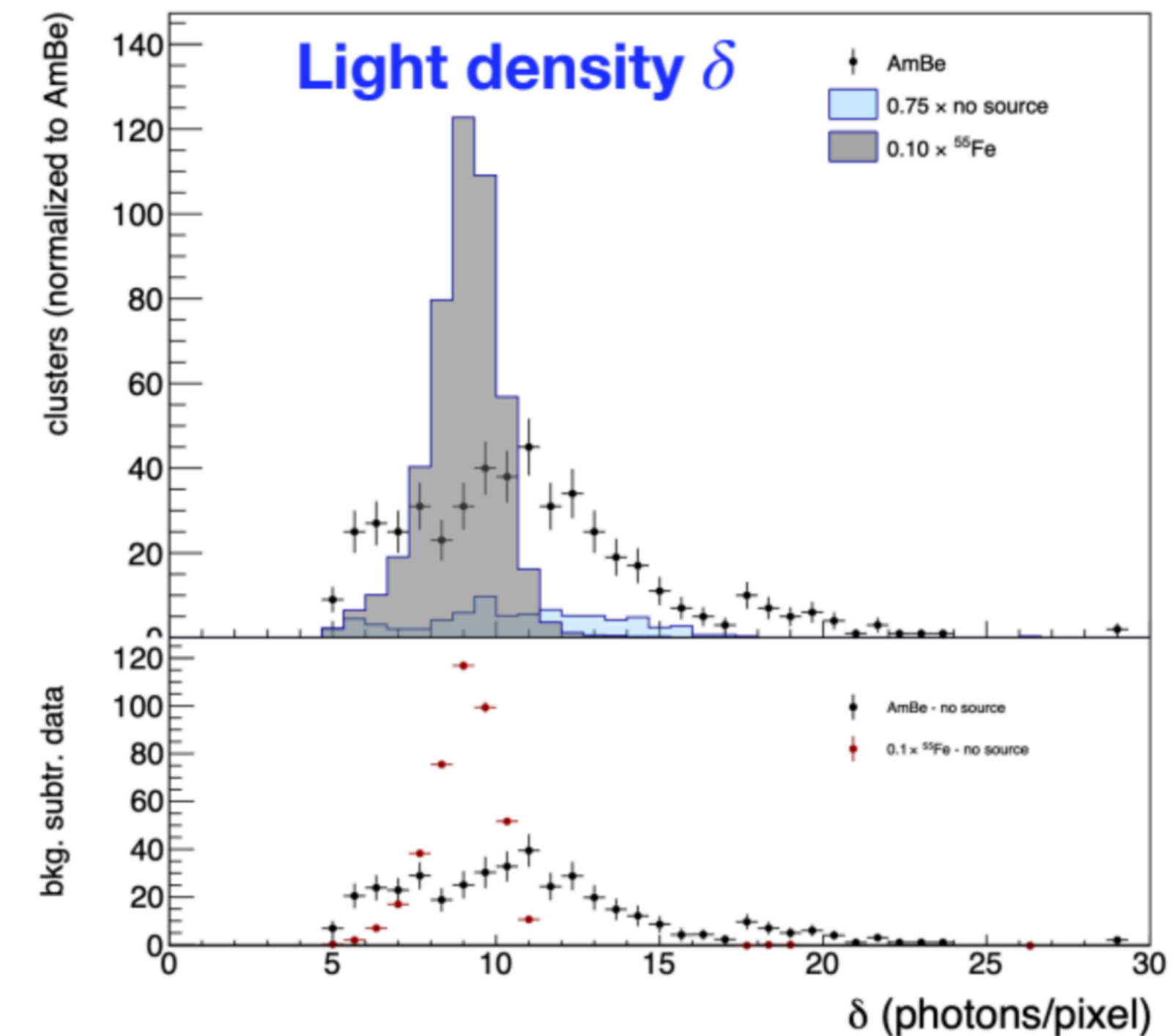
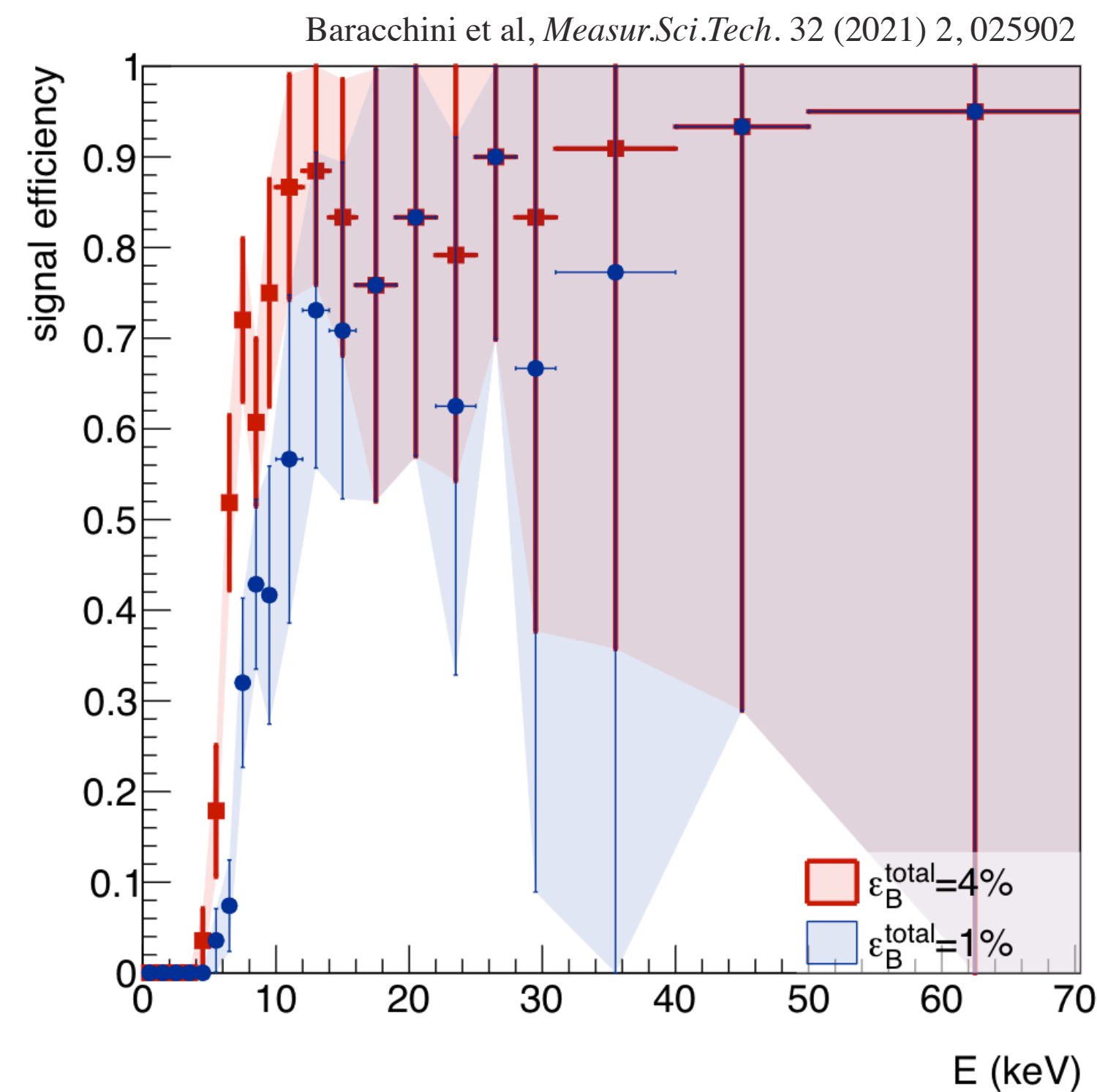
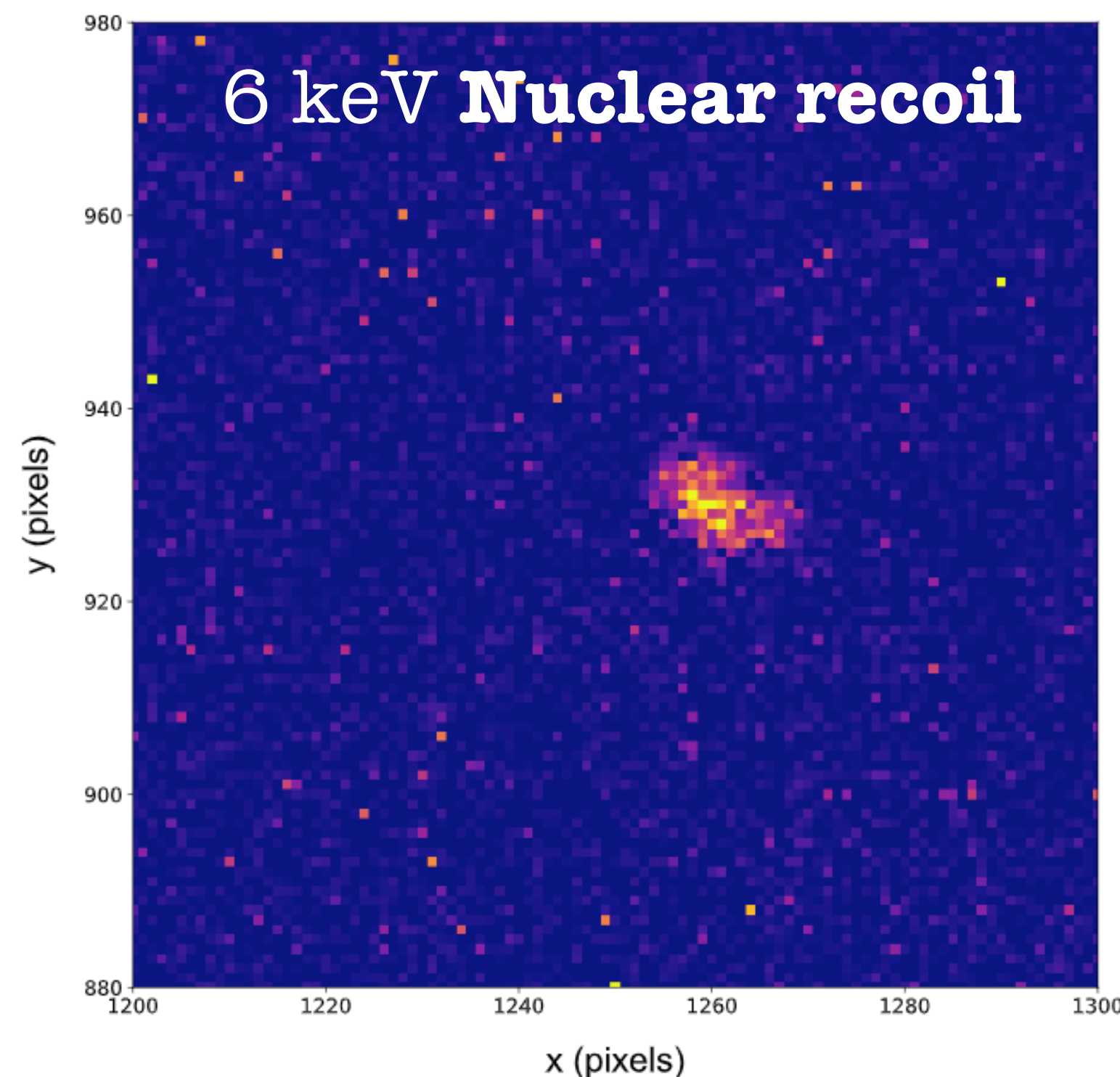
- Ti and Ca X-ray source

Material	Energy $K_\alpha$ [keV]	Energy $K_\beta$ [keV]
Ti	4.51	4.93
Ca	3.69	4.01



# NR vs ER discrimination

- **AmBe neutron** source to induce NRs
- **Selection** based on **topological information** of the tracks (size, shape and light density)
- **Discrimination** based on single variable: **light density**

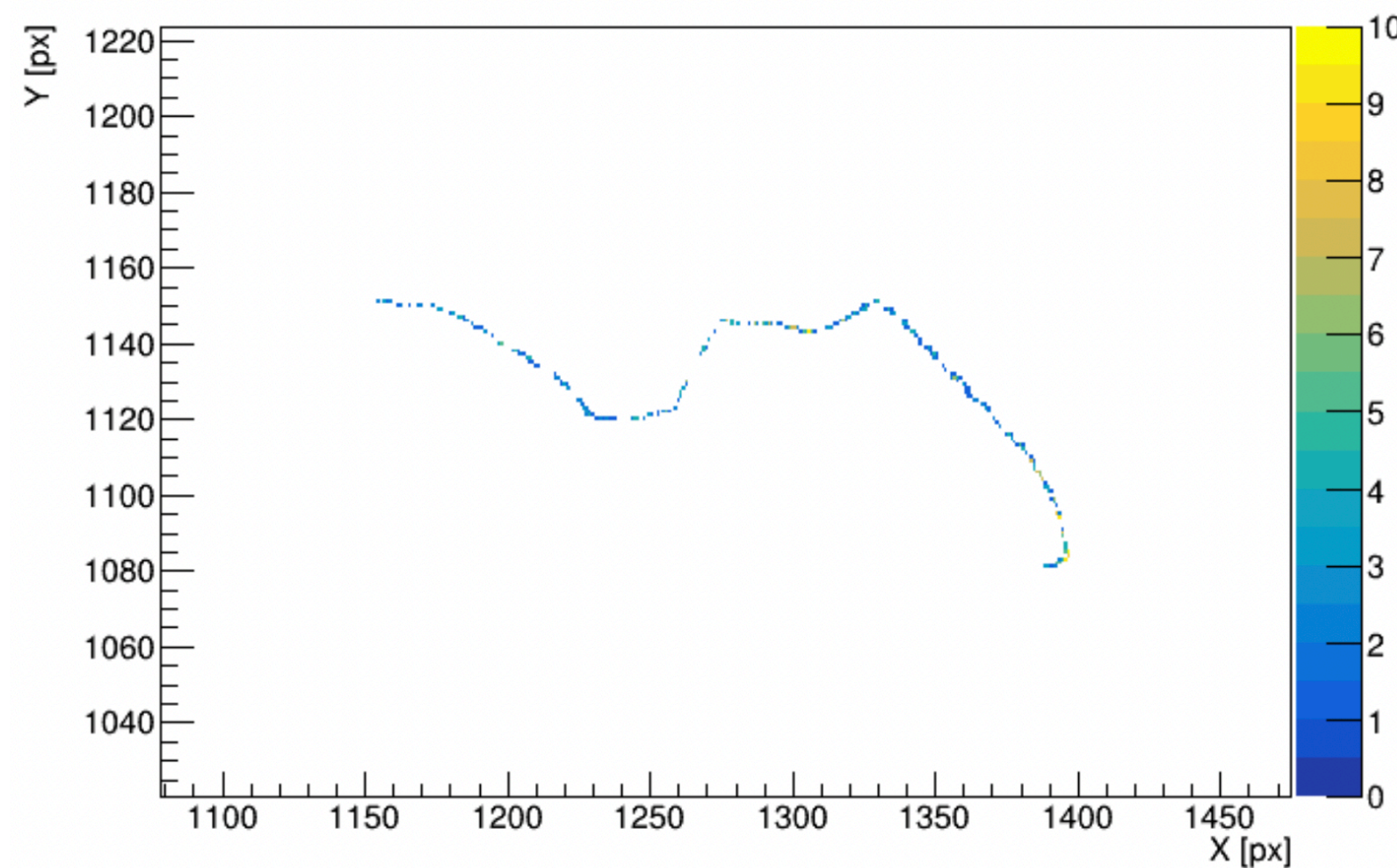


- Performance:
  - ➔ **NR** detection efficiency over **40%** above 6 keV
  - ➔ **96% rejection** power on the 6 keV  $^{55}\text{Fe}$  **ERs**

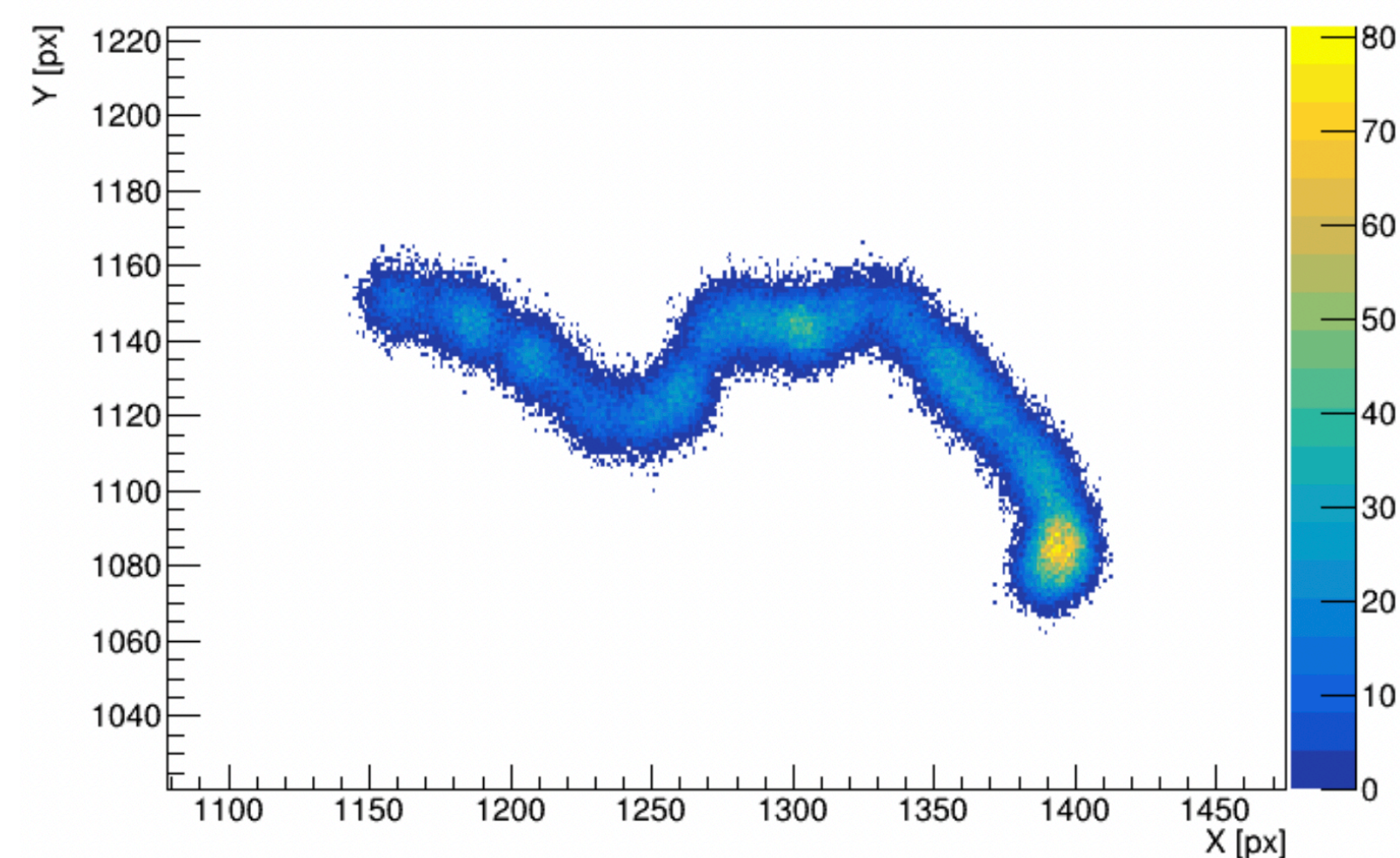
# Simulation

- **Energy deposit** simulation with **GEANT 4** and **SRIM**
- **Charge transport** (diffusion, electron attachment) with **Garfield**
- **Gain** with a **dedicated MC** simulation based on the modified Townsend model
- **Digitization** to reproduce the noise of the camera sensor

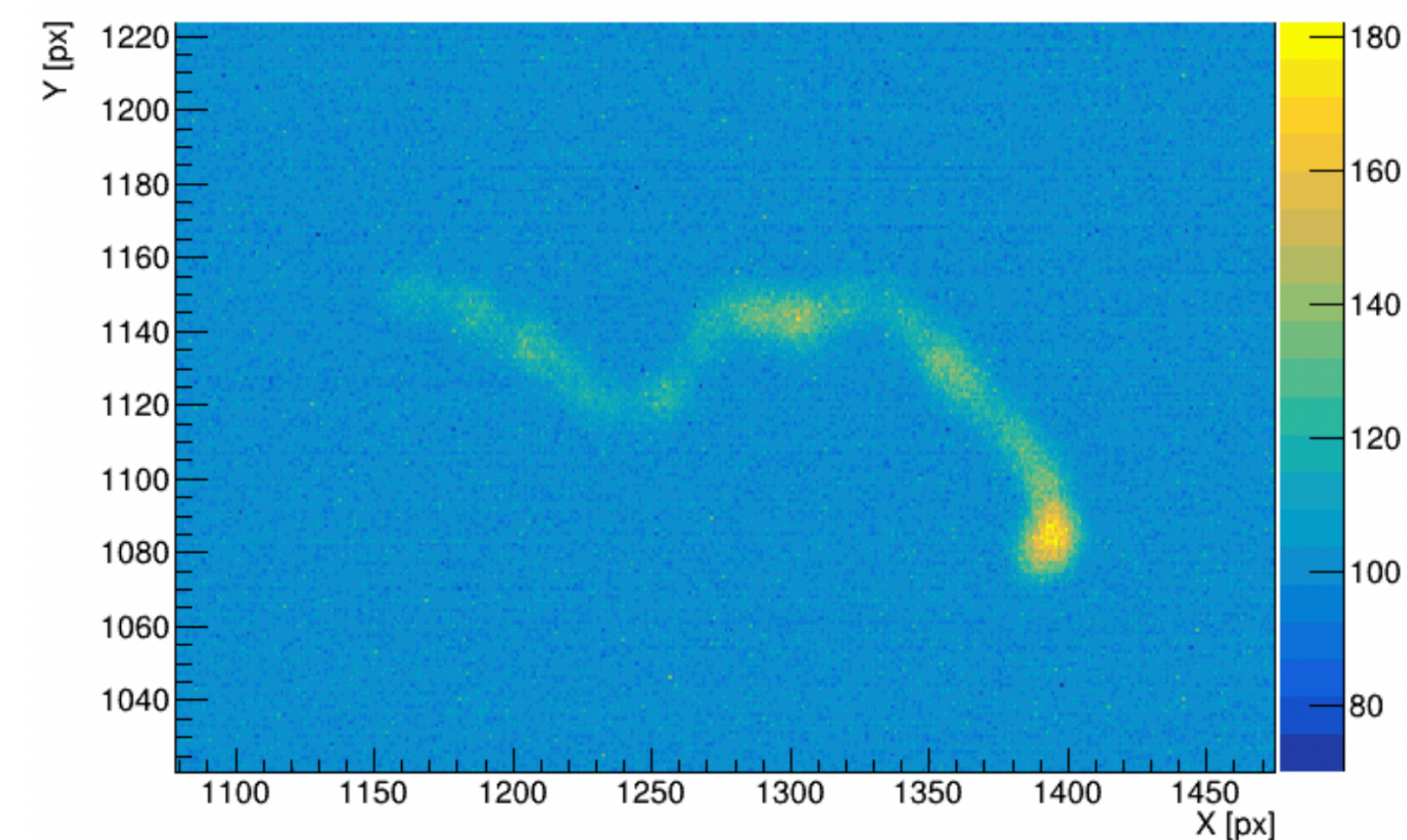
Tracks



Charge transport



Gain + Digitization



# Preliminary: discrimination with Machine Learning

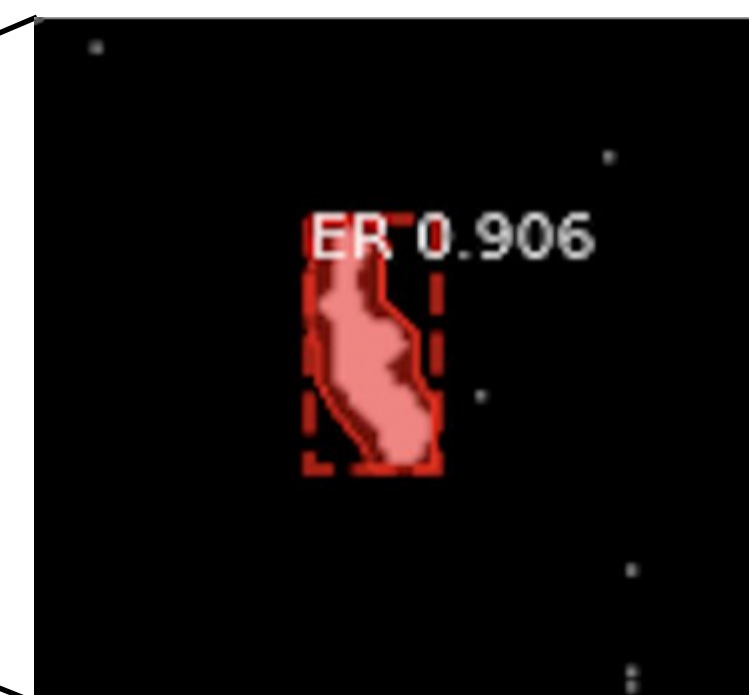
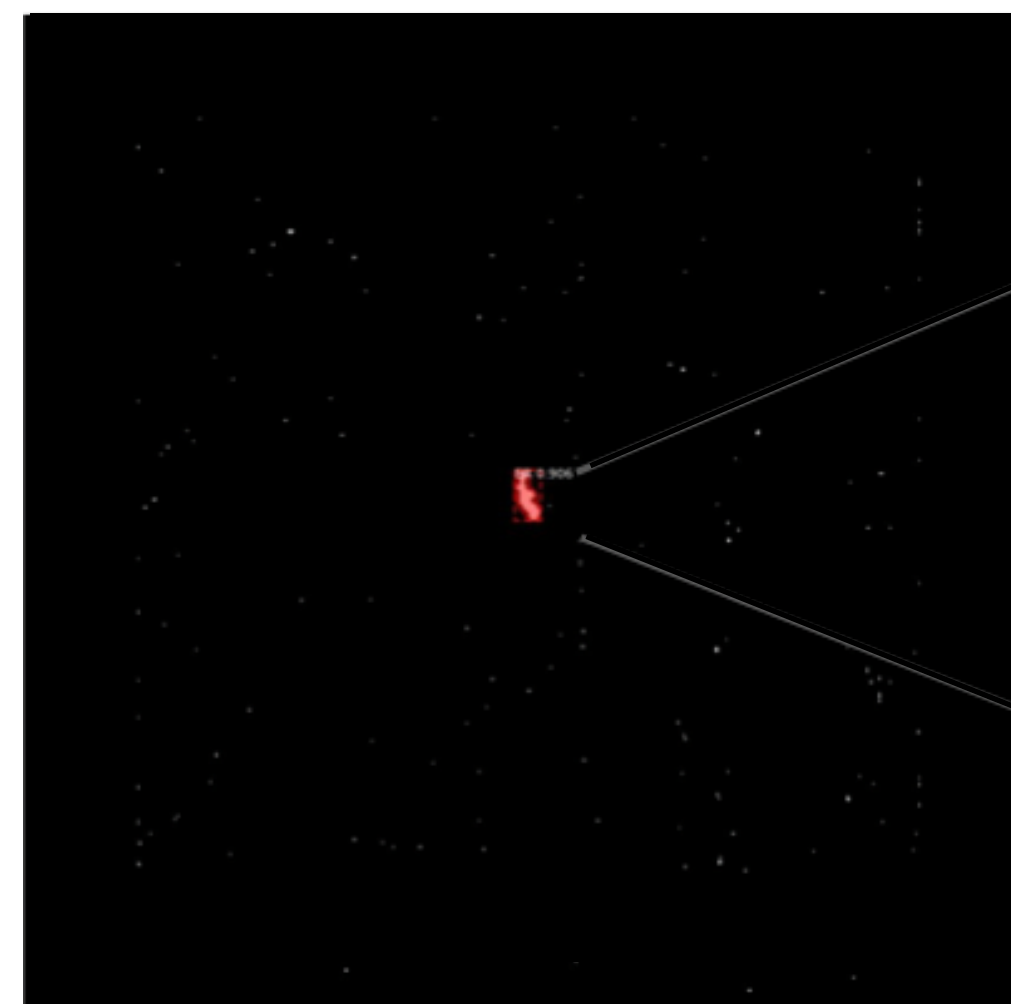


- Working on a **machine learning application**  $\Rightarrow$  promising results on MC images, to be validated on real data

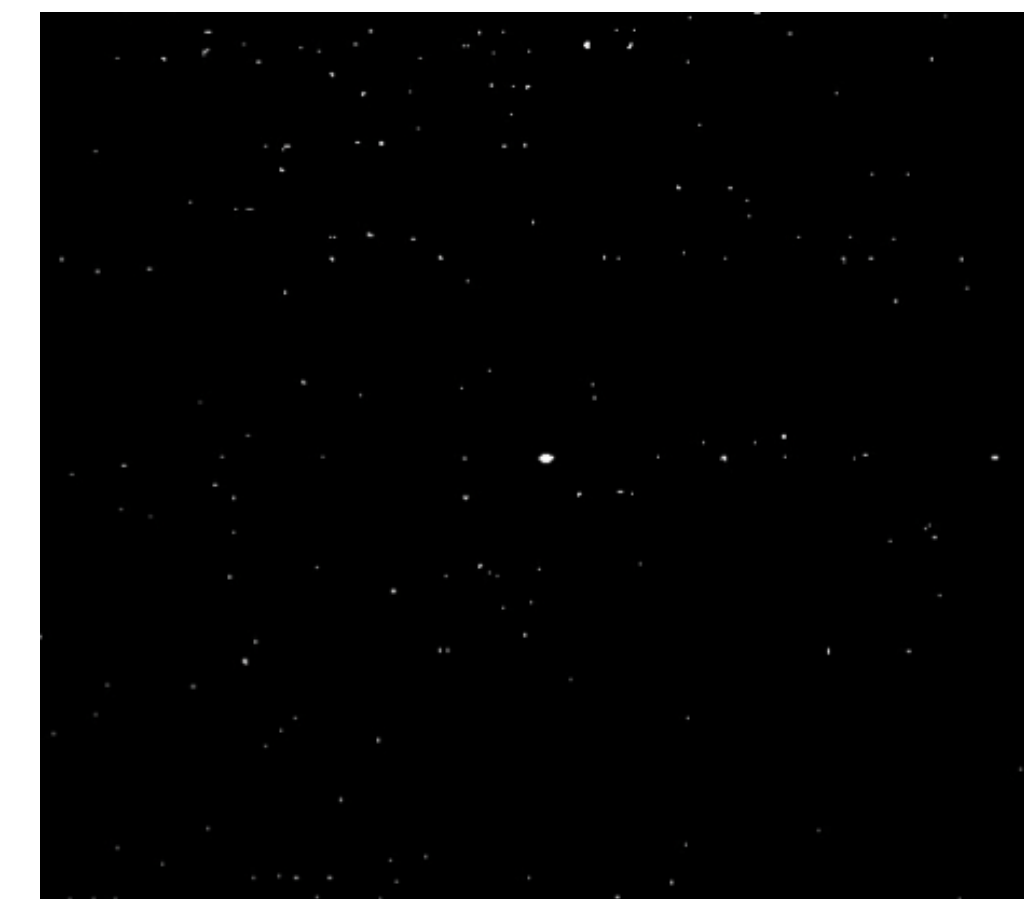
Input [MC]



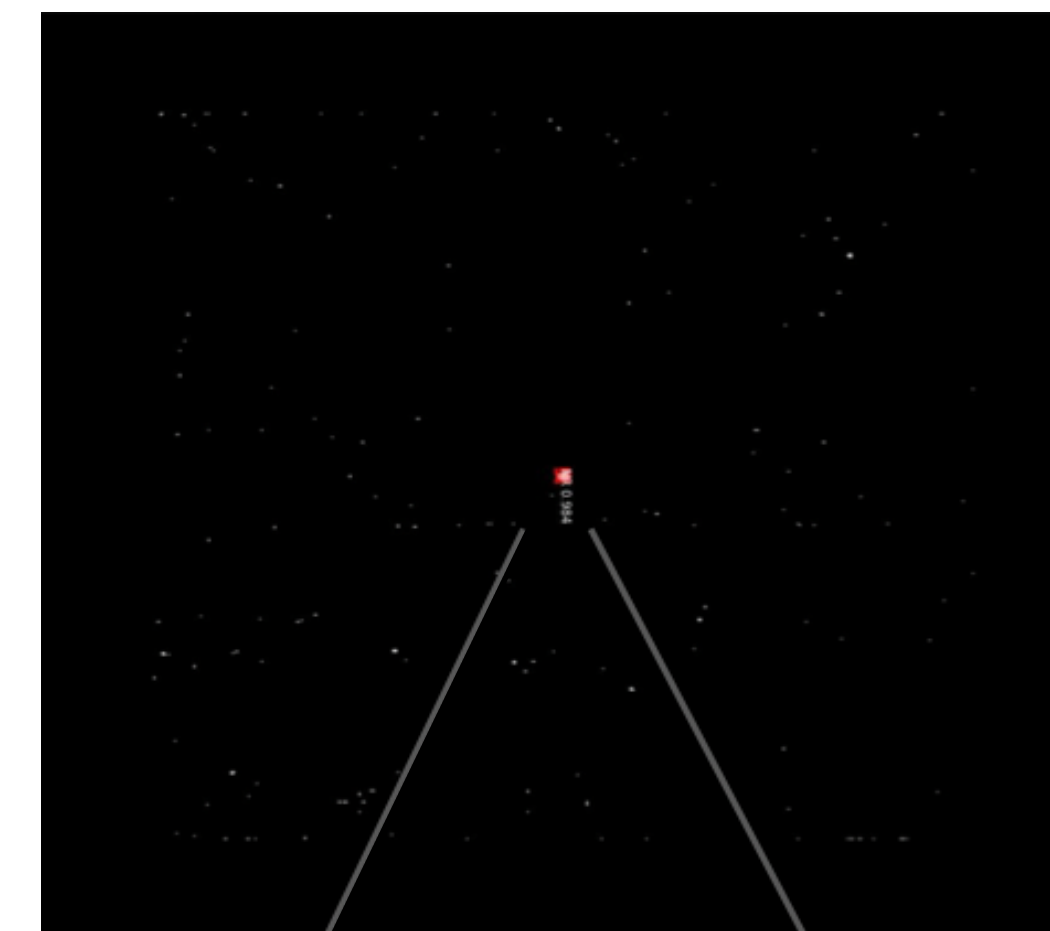
Prediction



Input [MC]



Prediction



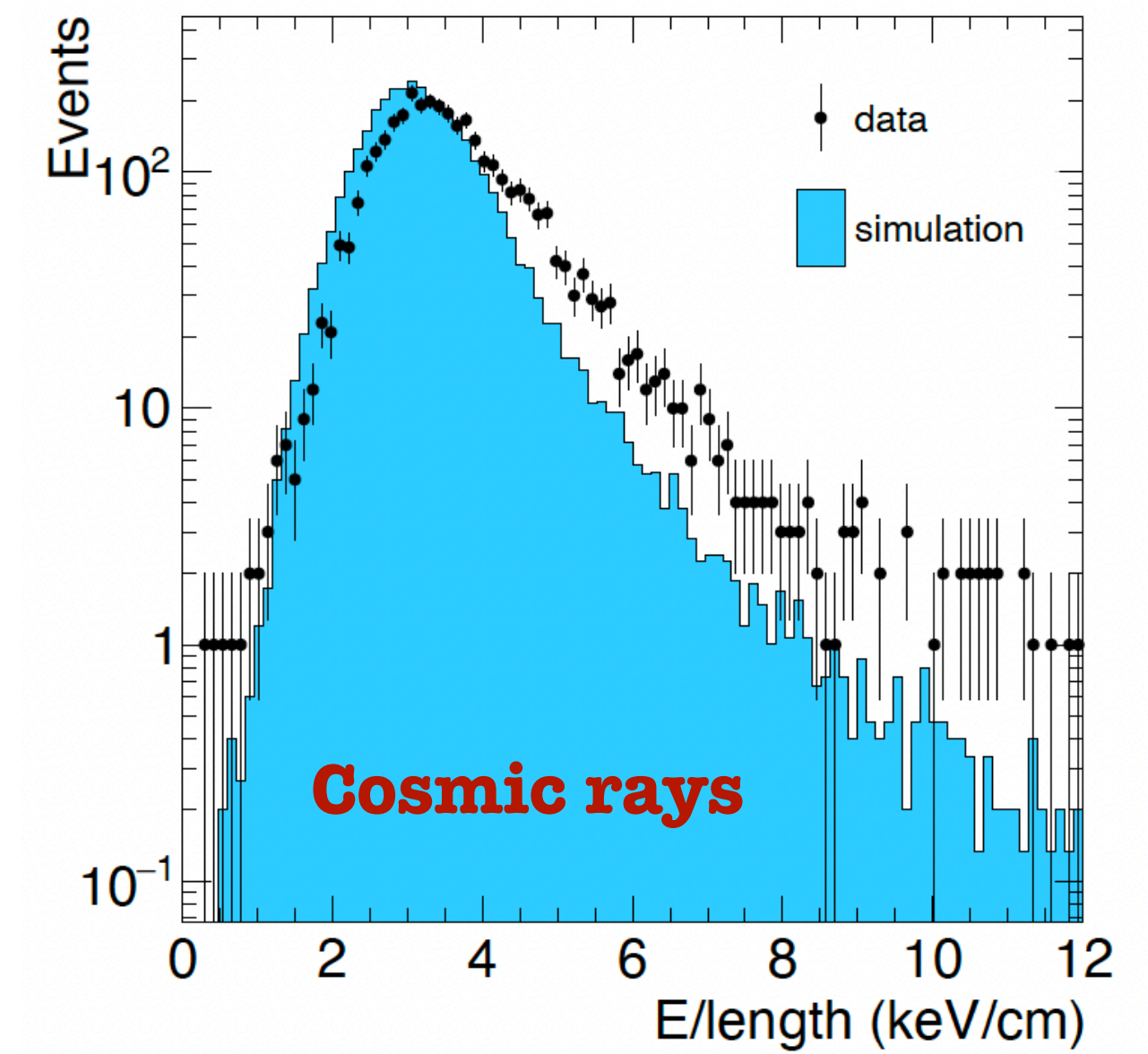
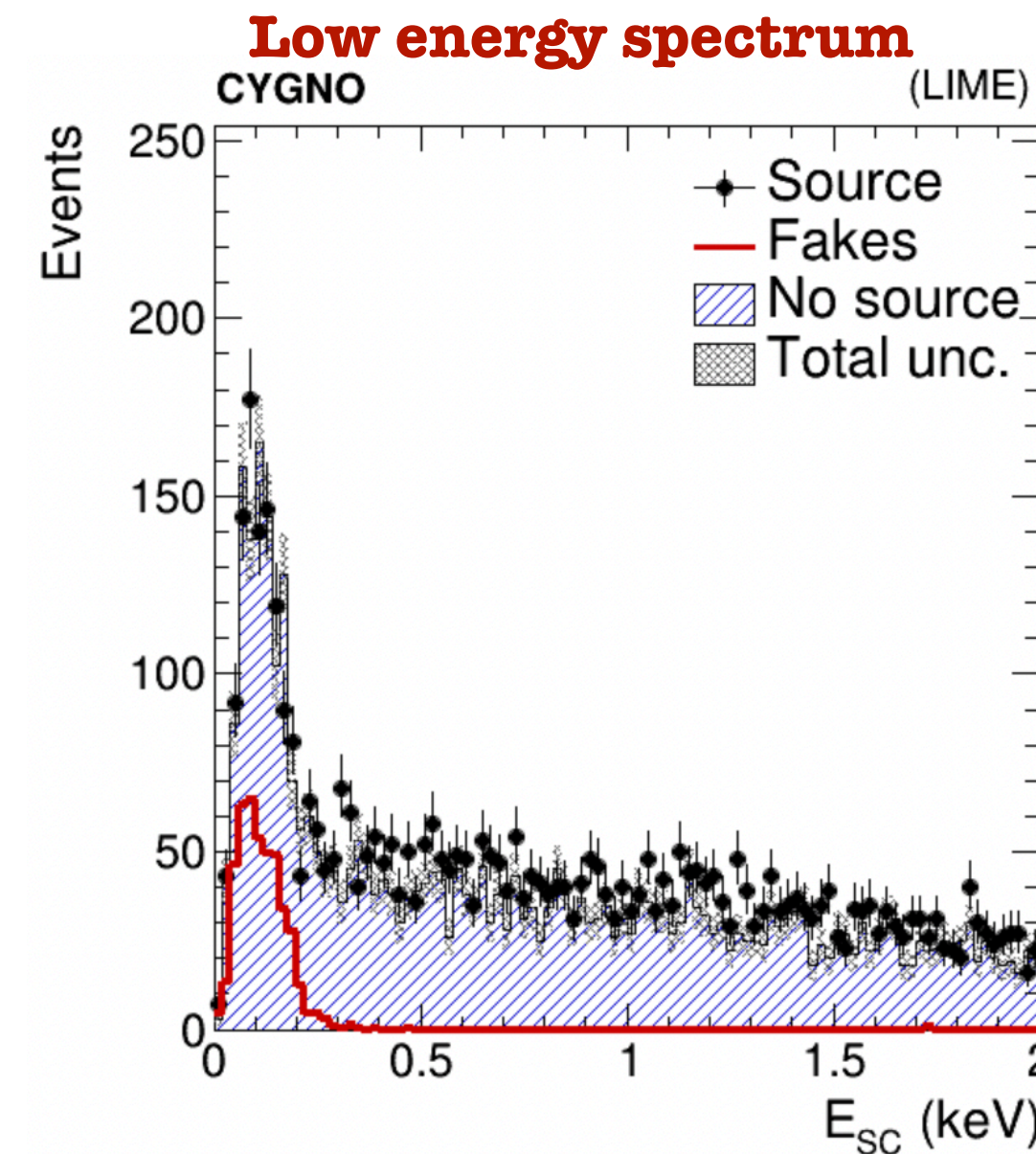
# LNF background

- Camera **exposure**: 50 ms
- Fake cluster cut  $\Rightarrow$  **low energy threshold** of  $E_{\text{thr}} = 300 \text{ eV}$
- Detected **rate of  $\sim 250 \text{ Hz}$**
- **Rate of events with  $E > 85 \text{ keV}$ :**
  - $\Rightarrow$  **LIME**:  $\sim 20 \text{ Hz}$
  - $\Rightarrow$  **Ortec 905-4** [NaI scintillator] :  $\sim 11 \text{ Hz}$

} Part of the observed rate  
can be explained by the ambient  
radioactivity

Due to the **high pile up**, reconstruction may  
systematically **overestimate** the **number of tracks**

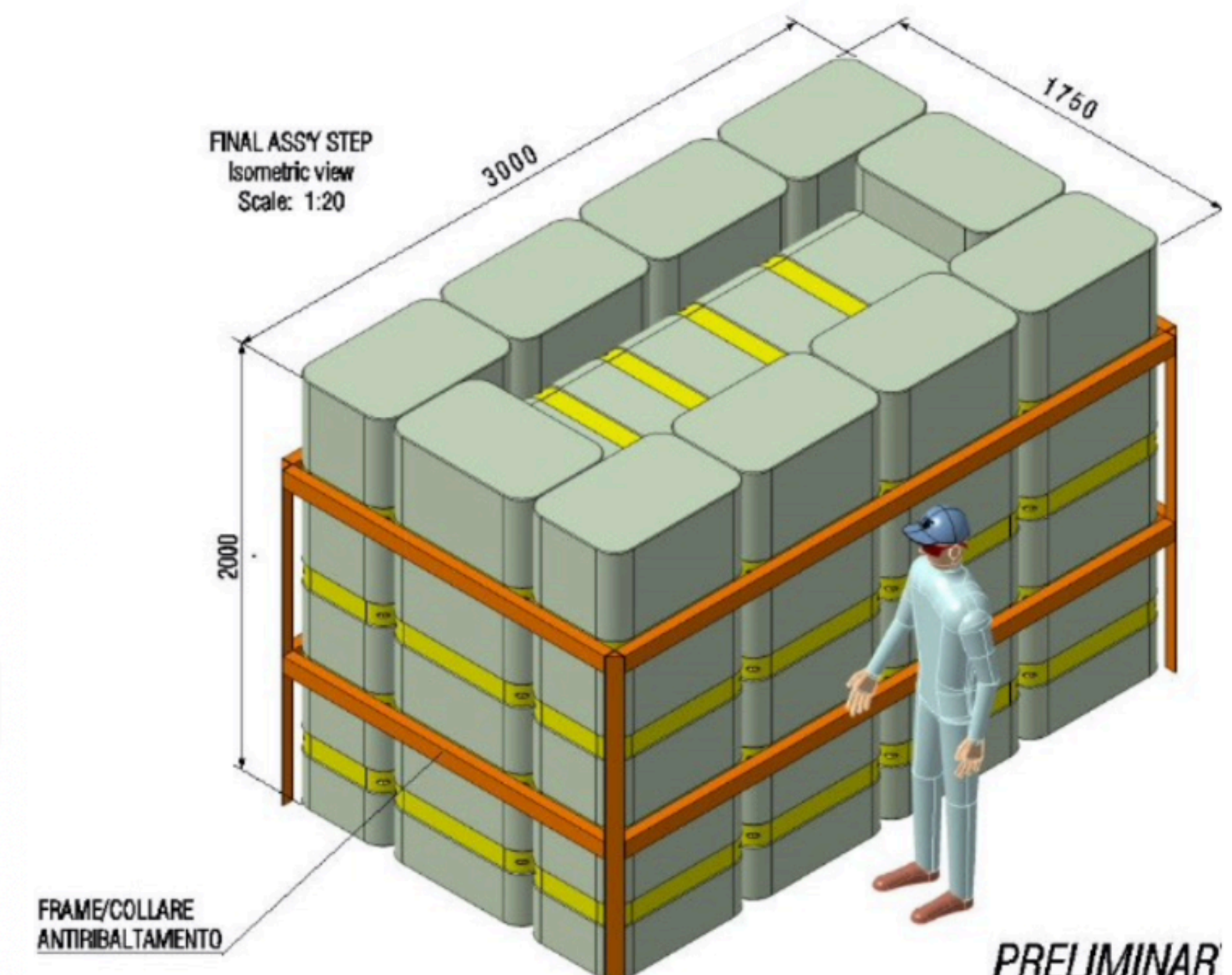
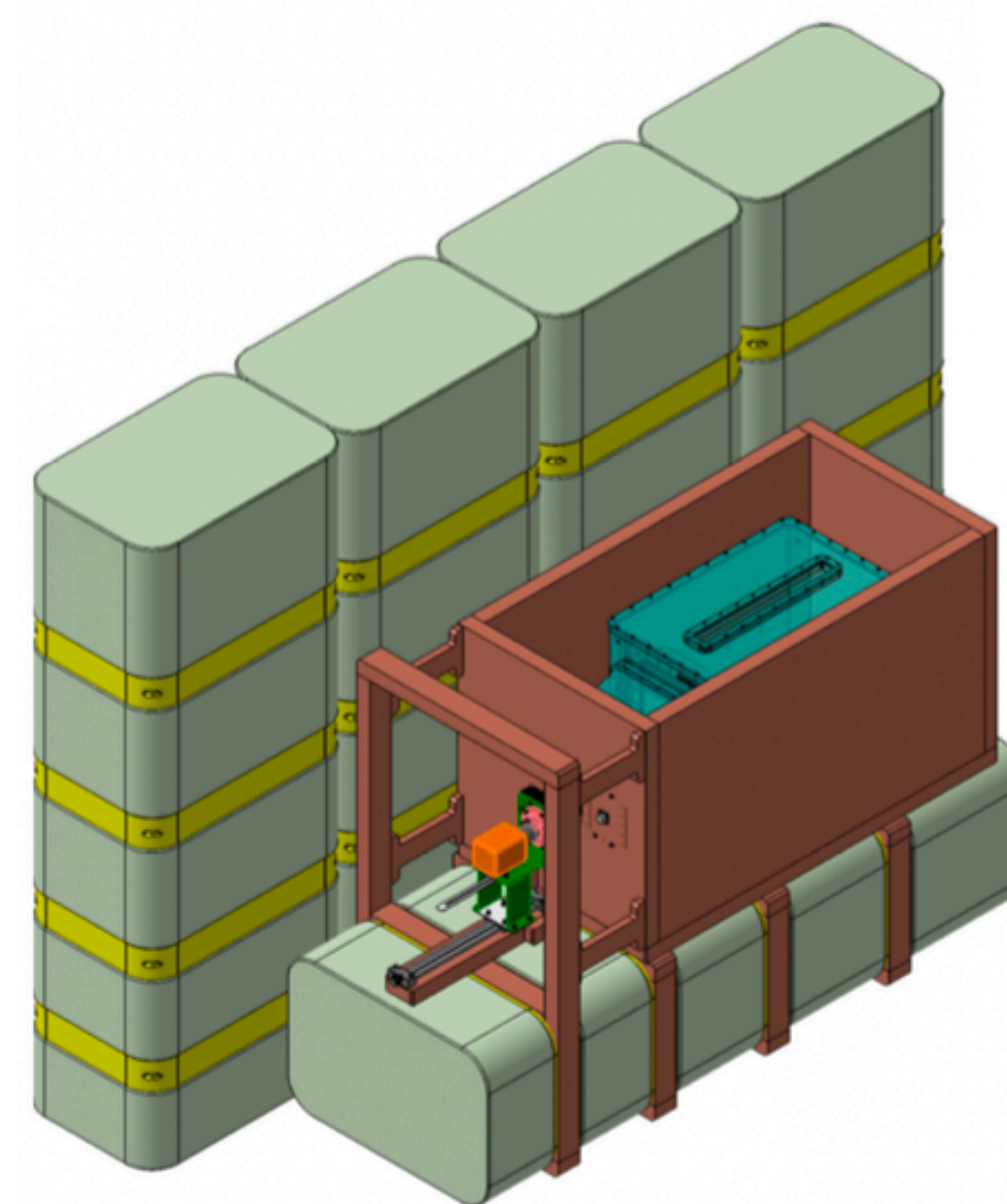
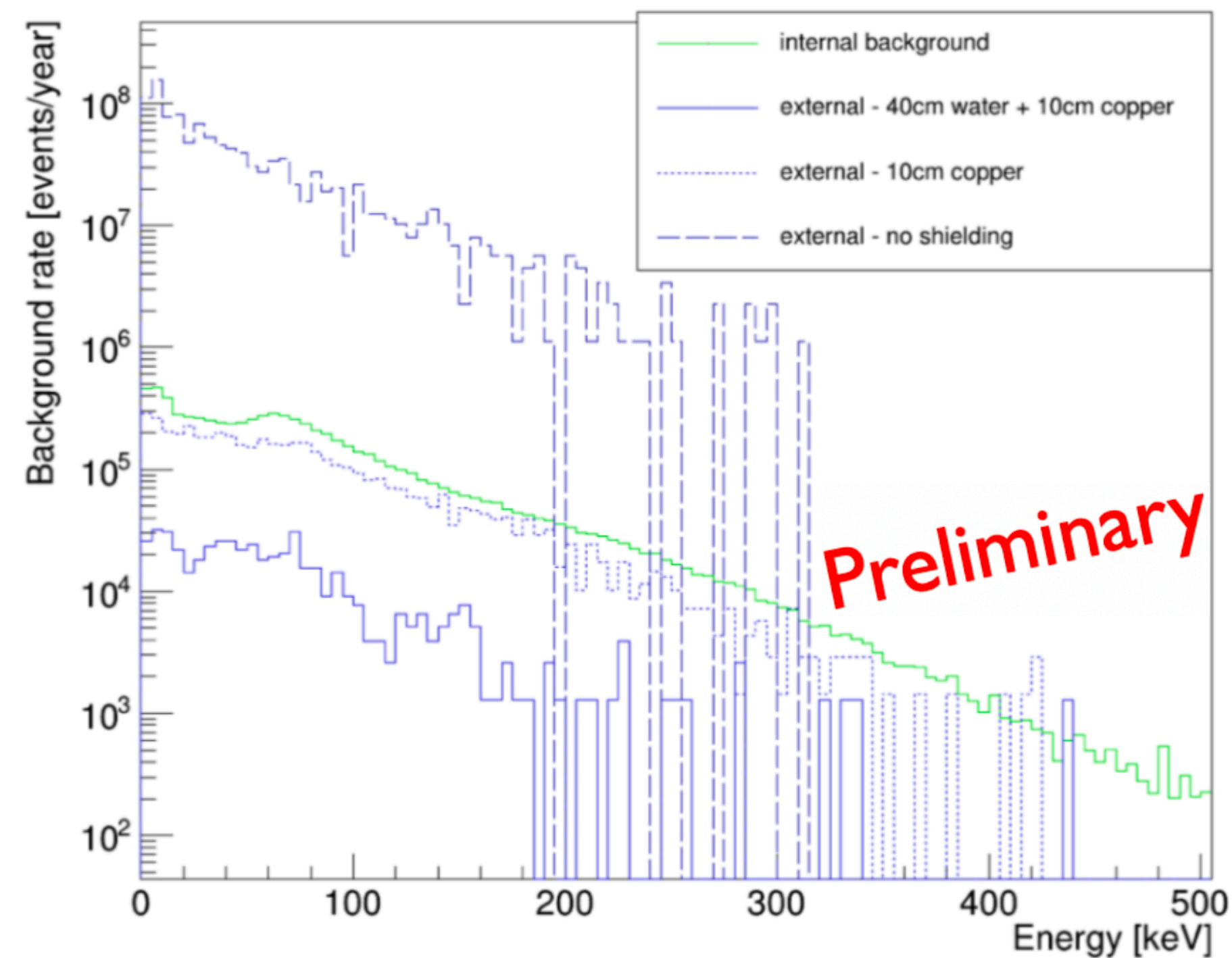
Necessity to test **LIME underground** in a **shielded** condition



# LIME: the underground campaign

Shielding	Internal [ev/yr] (1-20 keV)	External [ev/yr] (1-20 keV)
None	1.52E+06	4.06E+08
4 cm Cu	1.52E+06	6.36E+06
10 cm Cu	1.52E+06	6.42E+05
10 cm Cu + 40 cm water	1.52E+06	2.86E+05

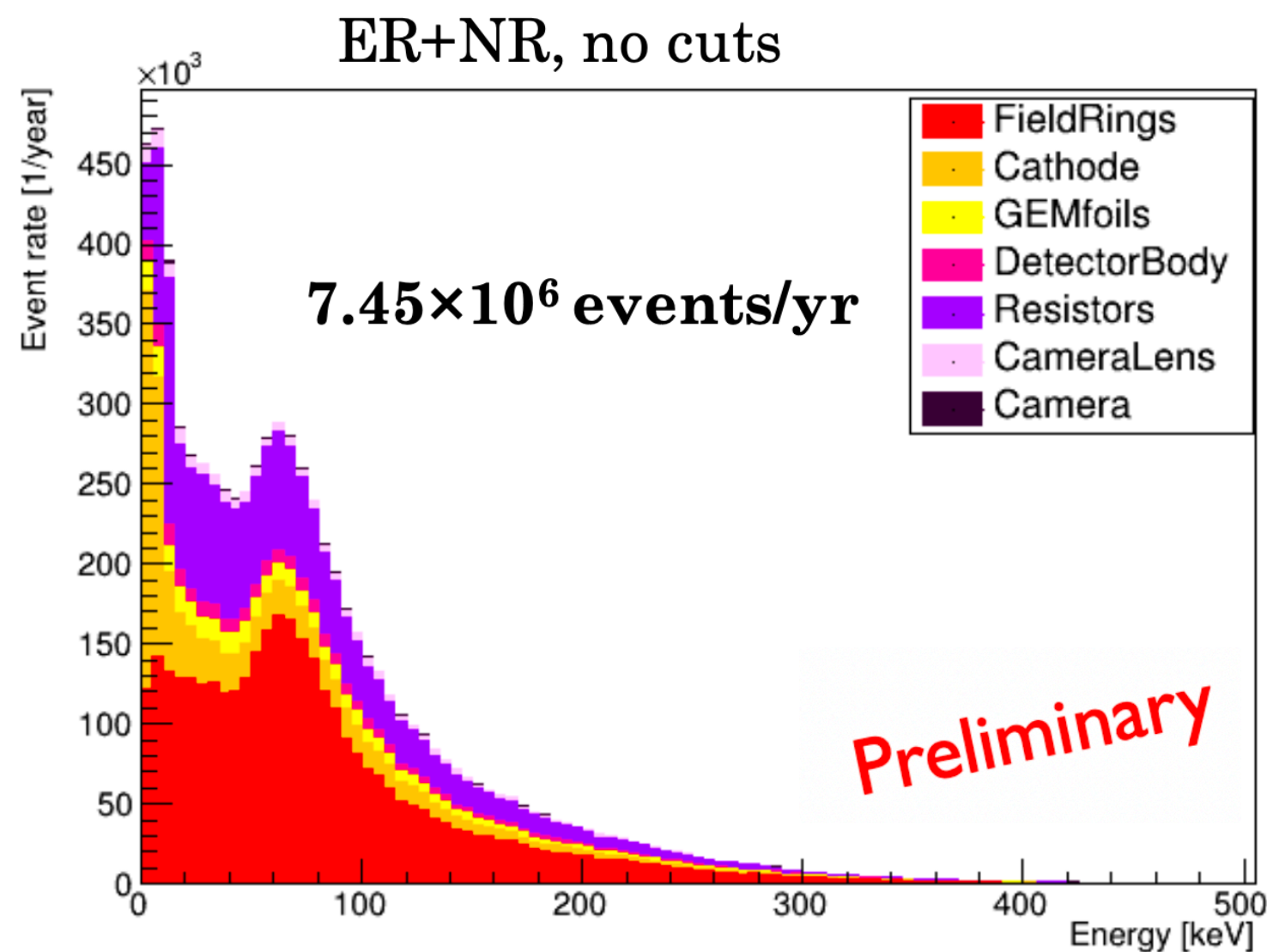
- **Shielding:** 10 cm of copper + 40 cm of water
- **Validate detector MC simulation**
- Measure the **neutron flux** (expected 300 NRs from neutrons in 6 months)



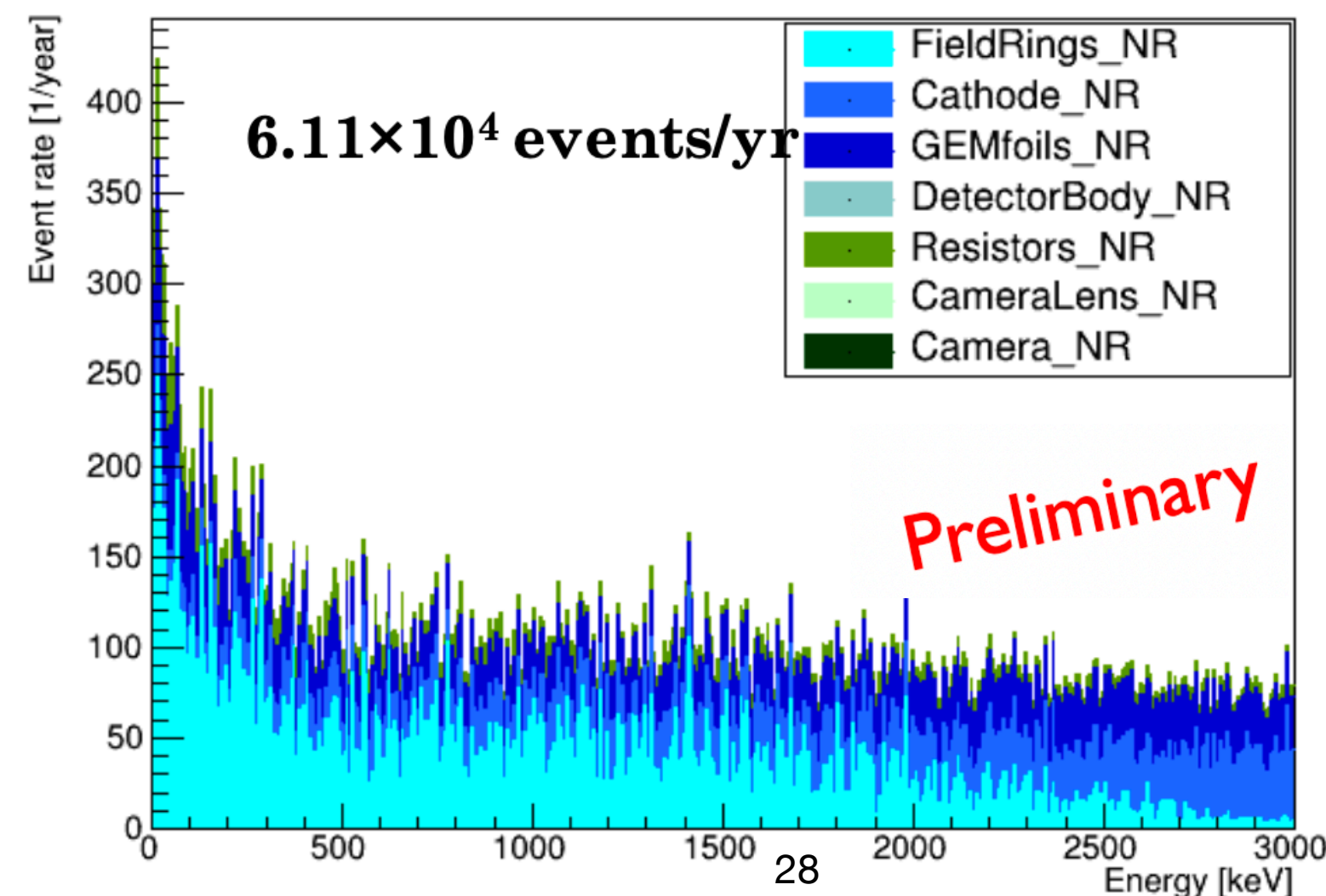
# LIME background simulation

- **Activity** of the **components: measured @ LNGS**
- Main contribution to the **internal backgrounds**: copper rings, resistors, GEM/cathode
- 96% (99.97%) reduction of ER (NR) events with **fiducial cuts**

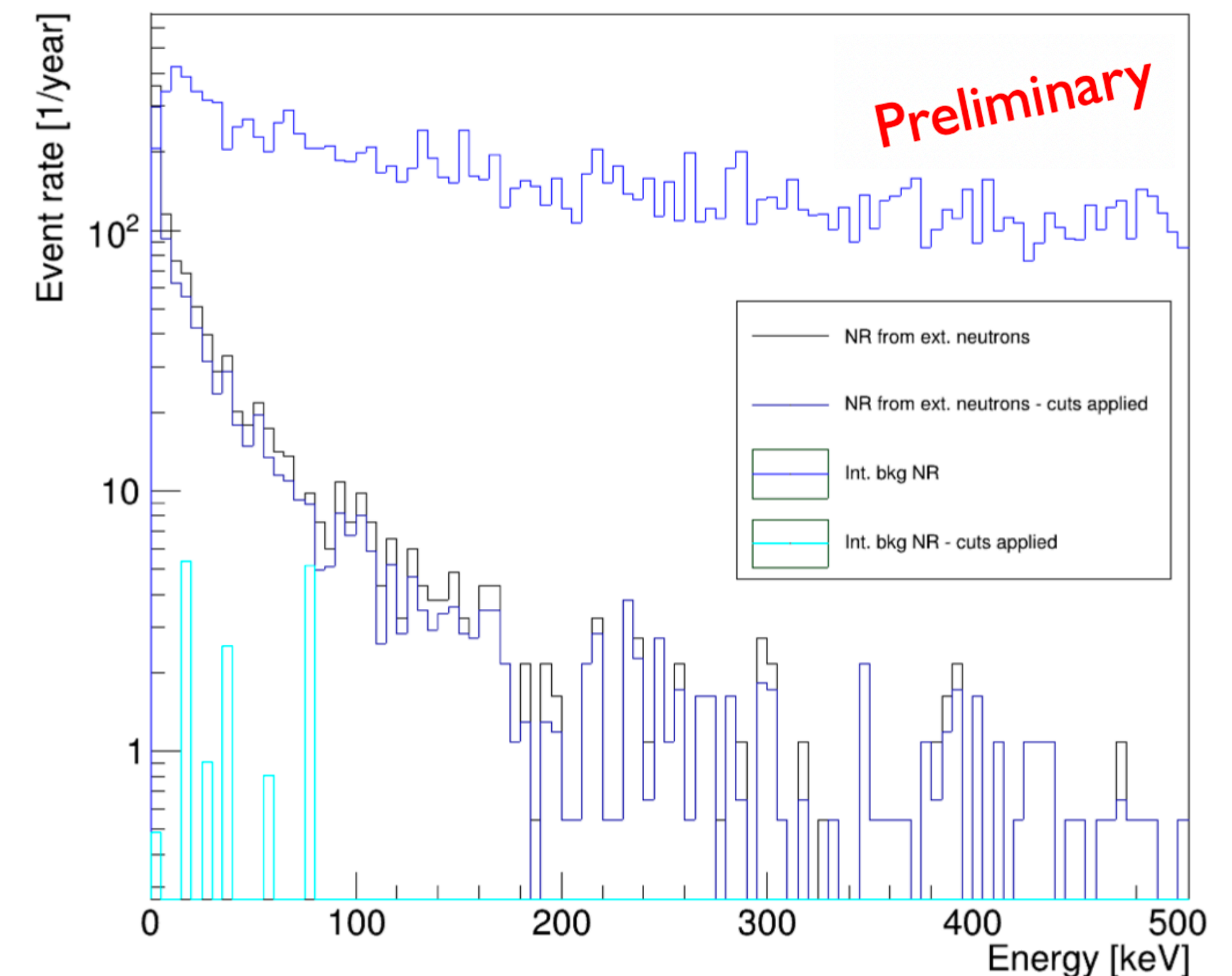
**ER and NR internal background**



Only NR, no cuts

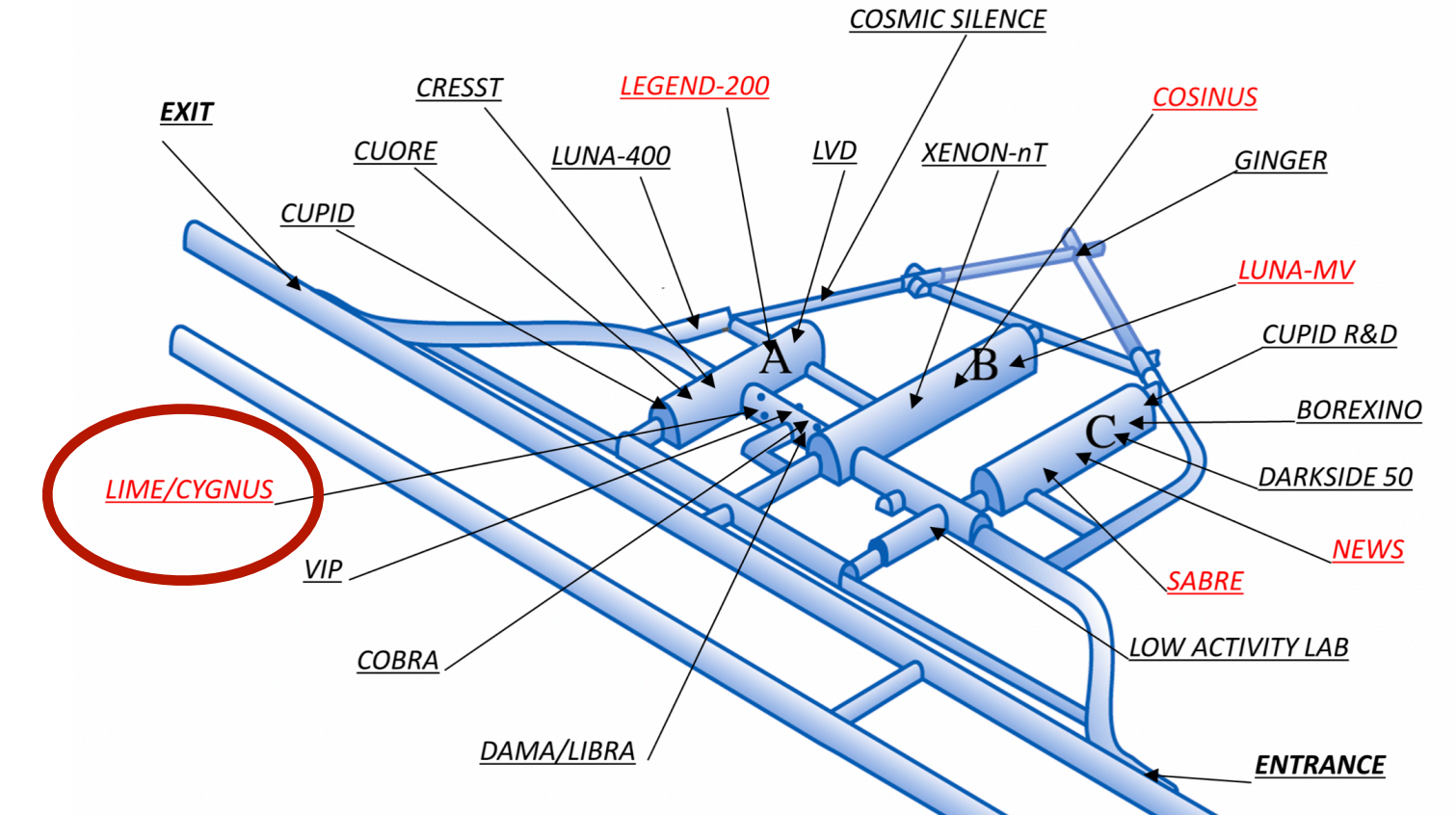


**Neutron external background**



# Underground installation

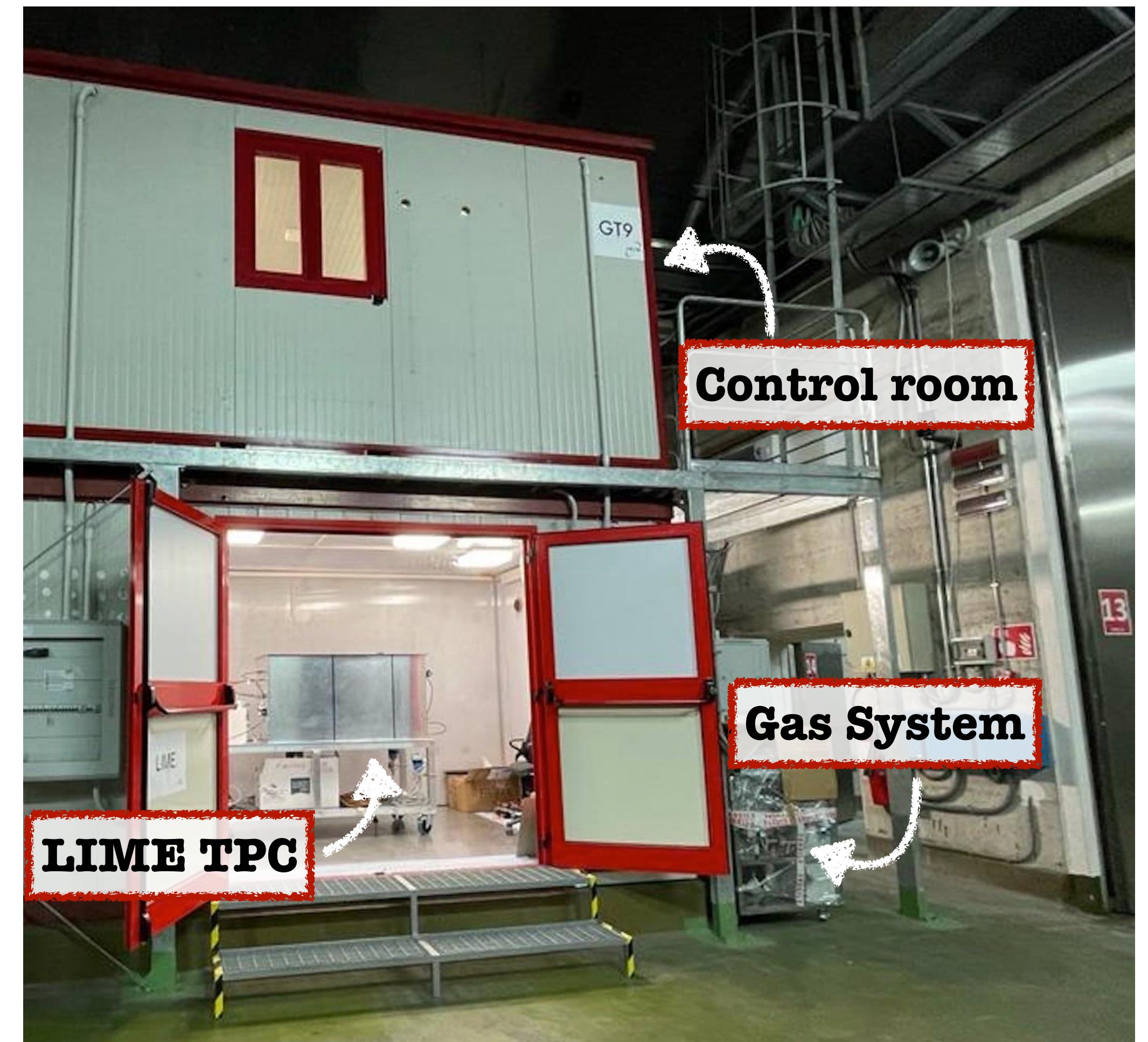
- The LIME prototype has been preliminarily **tested overground** at Laboratori Nazionali di Frascati (**LNF**)
- **Moved underground** at Laboratori Nazionali del Gran Sasso (**LNGS**) the beginning of 2022



The TPC inside the Faraday cage



HV and DAQ crate



# Underground data taking plan

Spring and Summer 2022

Autumn 2022

Winter 2023

**Today**

Spring and Summer 2023

Autumn 2023

- **RUN 0: Commissioning**

- **RUN 1: No-shielding**

- **RUN 2: 4 cm Cu shielding**

----- We are here

- **RUN 3: 10 cm Cu shielding**

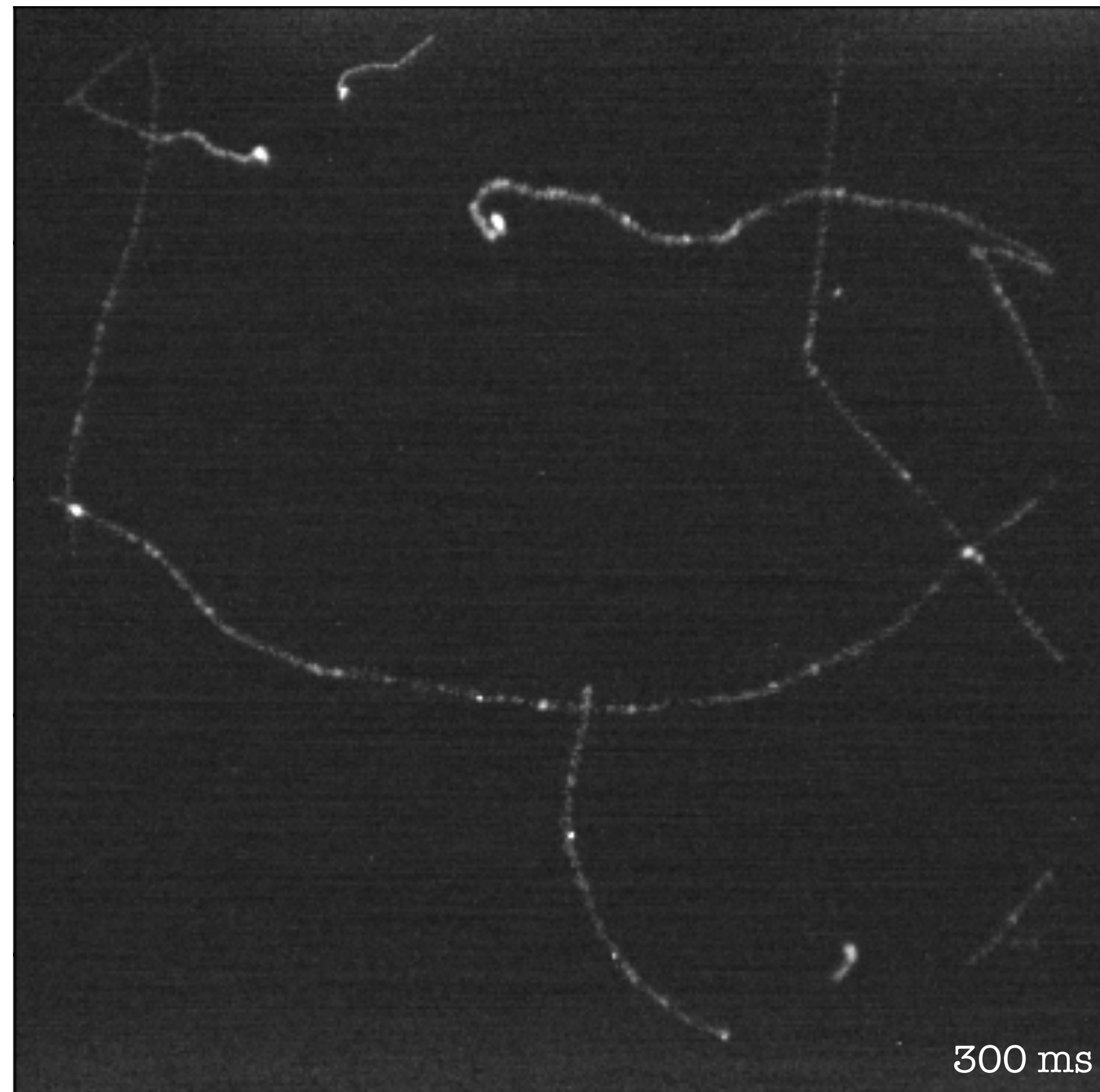
- ➡ measurement of NR response with AmBe

- ➡ Measurement of the underground neutron flux

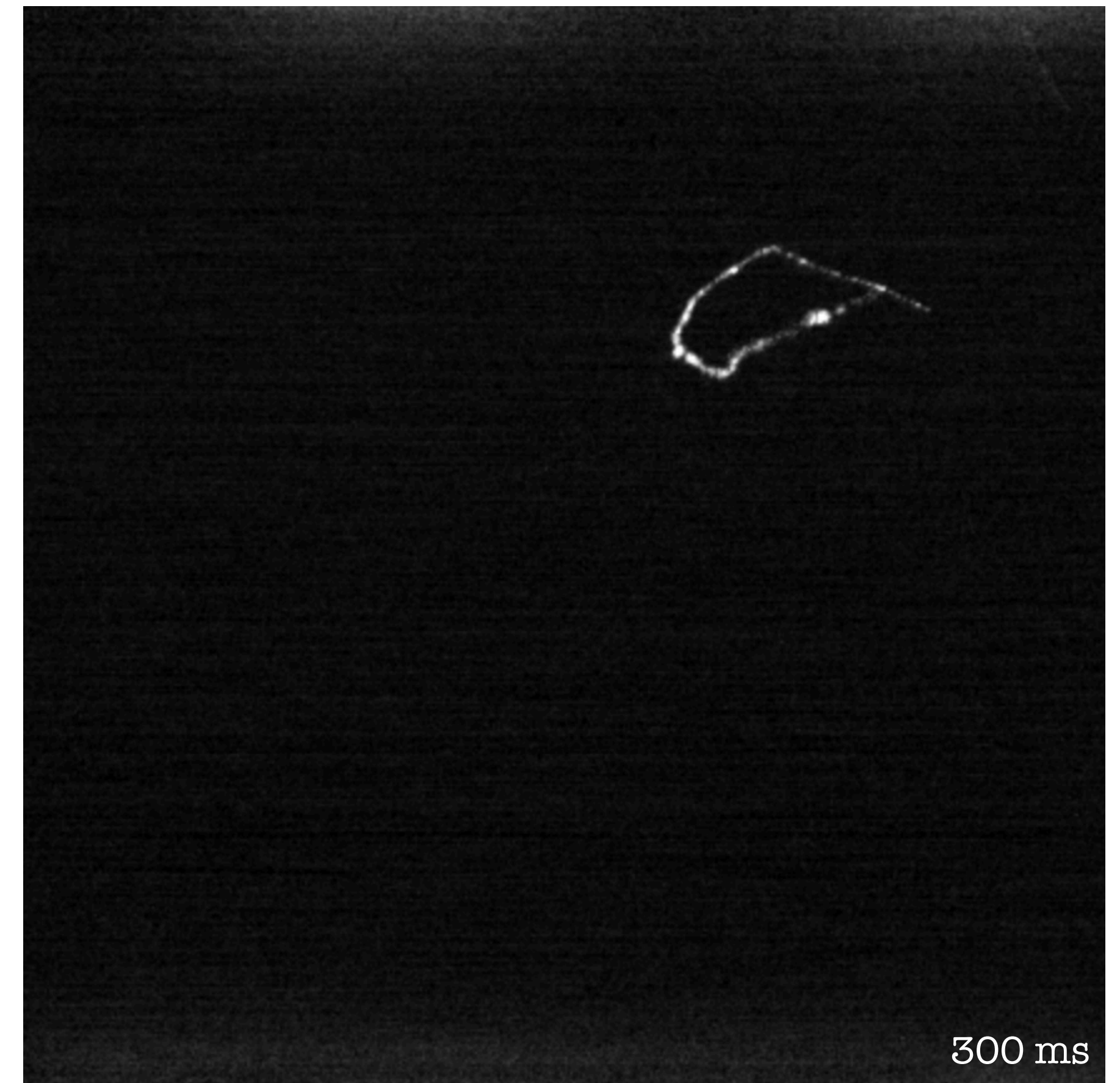
- **RUN 4: 10 cm Cu + 40 cm water shielding**

# Underground data so far

**RUN 1: No-shielding**



**RUN 2: 4 cm Cu shielding**



# Underground data so far

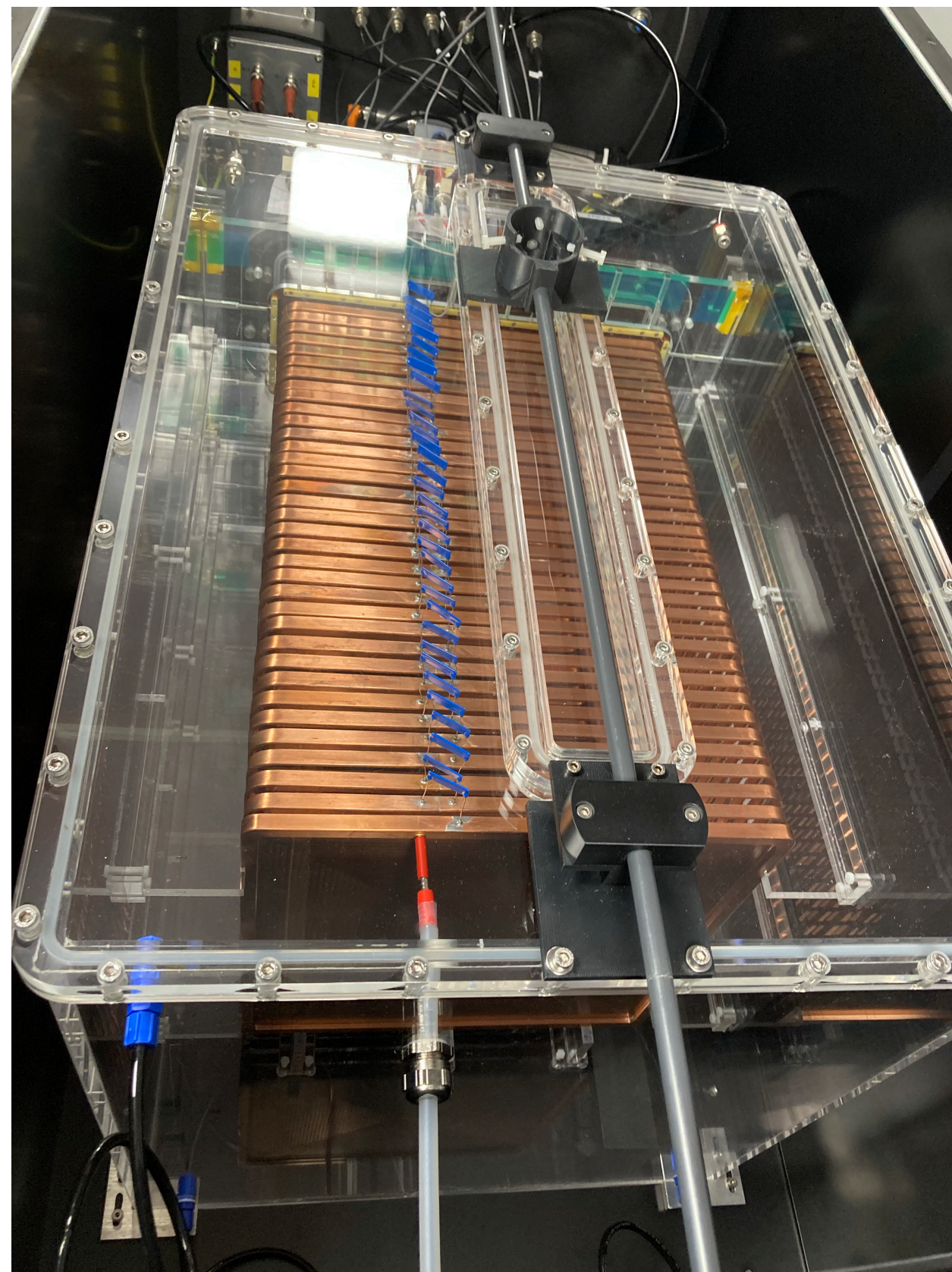
## RUN 1: No-shielding

- From Oct 8, 2022 to Dec 6, 2022

- Some numbers:

- ➡ Integral number of **BKG pictures**:  
 $\sim 4 \times 10^5$
- ➡ Background **observed event rate**:  
 $(33.88 \pm 0.58) \text{ Hz}$
- ➡ Background **expected event rate** (from MC):  
 $\sim 37 \text{ Hz}$

$\sim 4.0 \times 10^6$  events  
in  $\sim 33 \text{ h}$  cam exposure



## RUN 2: 4 cm Cu shielding

- From Feb 15, 2023 to Mar 9, 2023

- Some numbers:

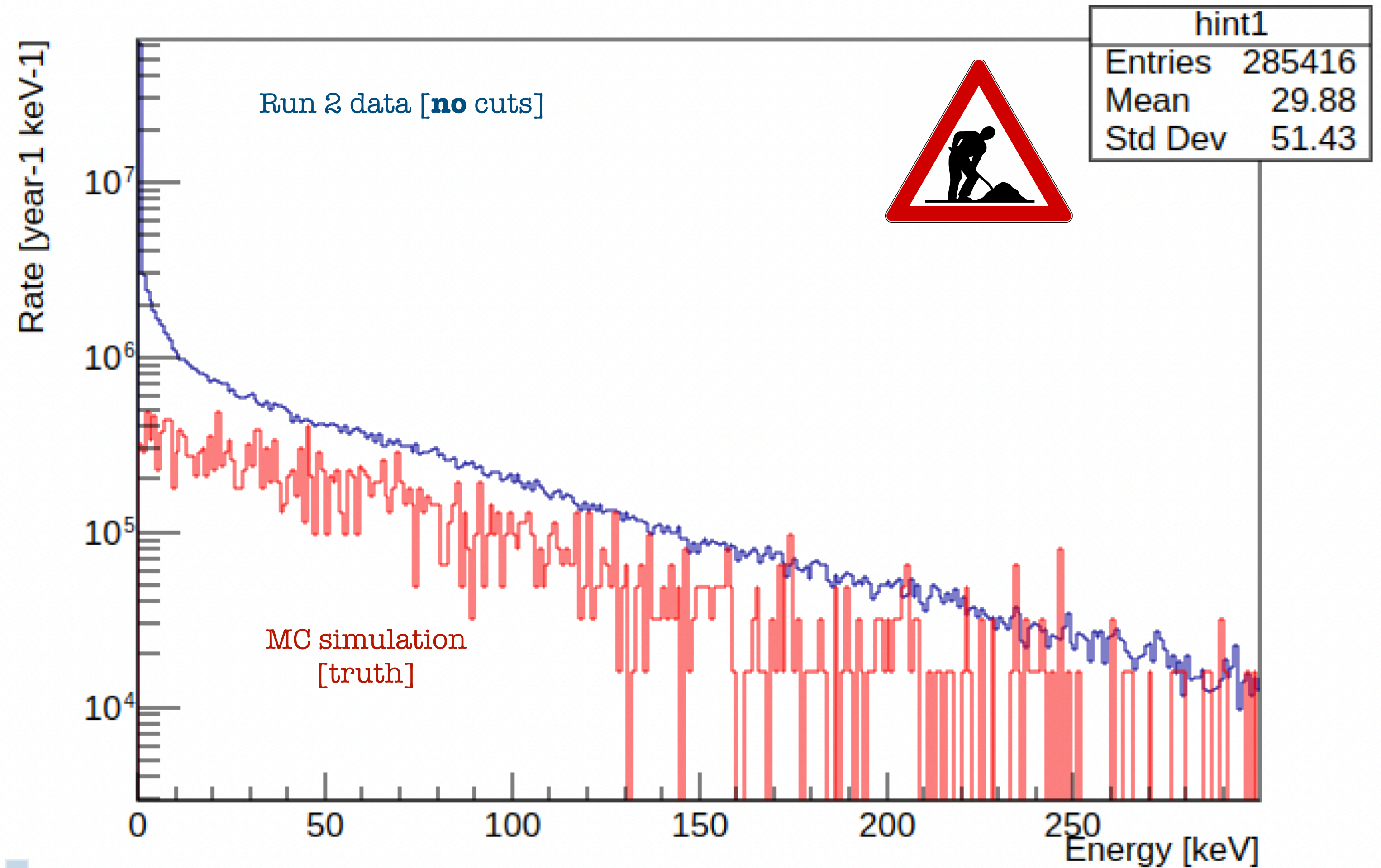
- ➡ Integral number of **BKG pictures**:  
 $\sim 4.5 \times 10^5$
- ➡ Background **observed event rate**:  $\sim 3.5 \text{ Hz}$   
(data not fully analyzed)
- ➡ Background **expected event rate** (from MC):  
 $\sim 1.1 \text{ Hz}$

$\sim 0.48 \times 10^6$  events  
in  $\sim 38 \text{ h}$  cam exposure



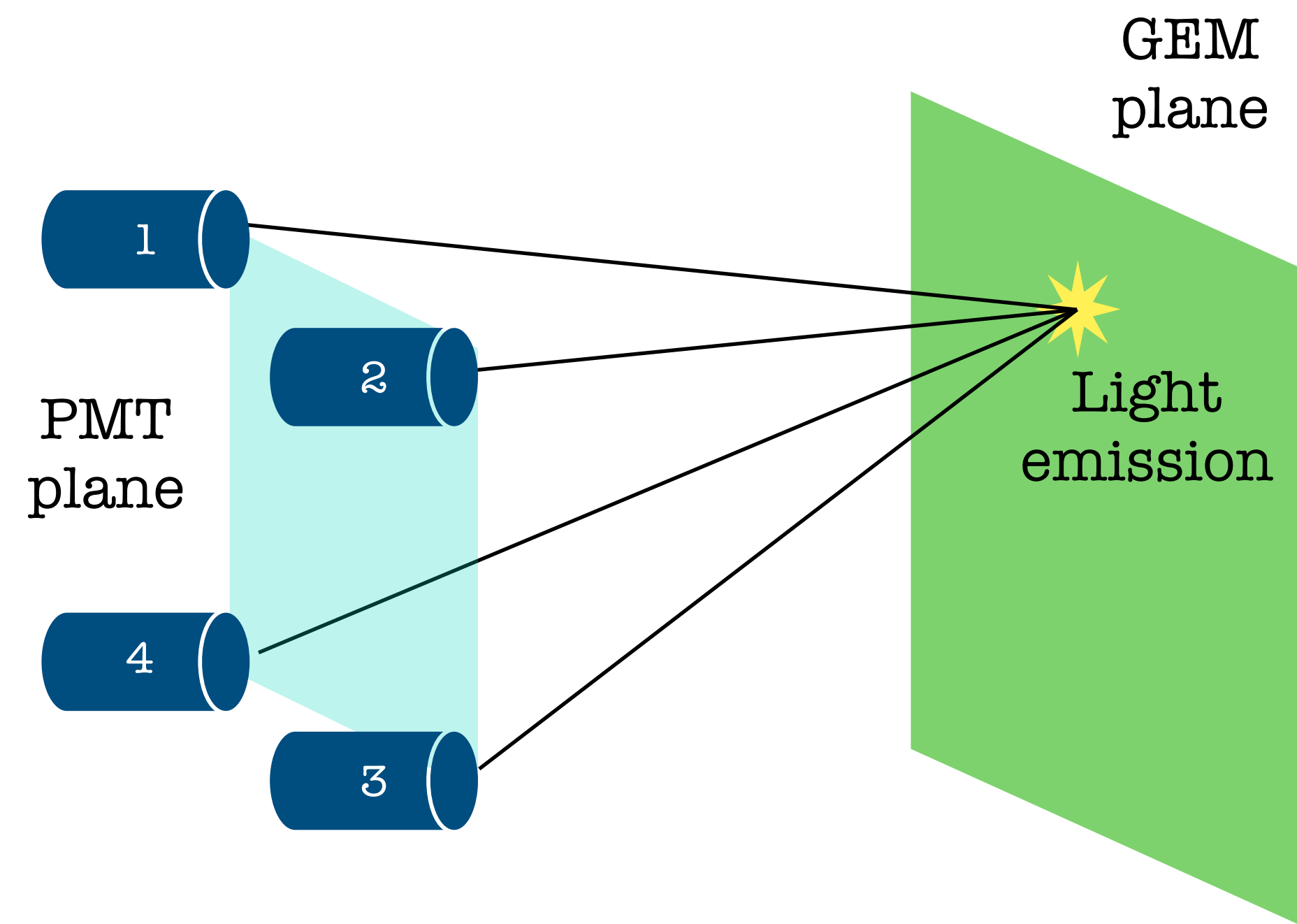
# Energy spectrum with low background

- **Preliminary** results from MC simulation:
  - ➔ low energy bump in data
  - ➔ overall factor of  $\sim 4$  missing in the rate

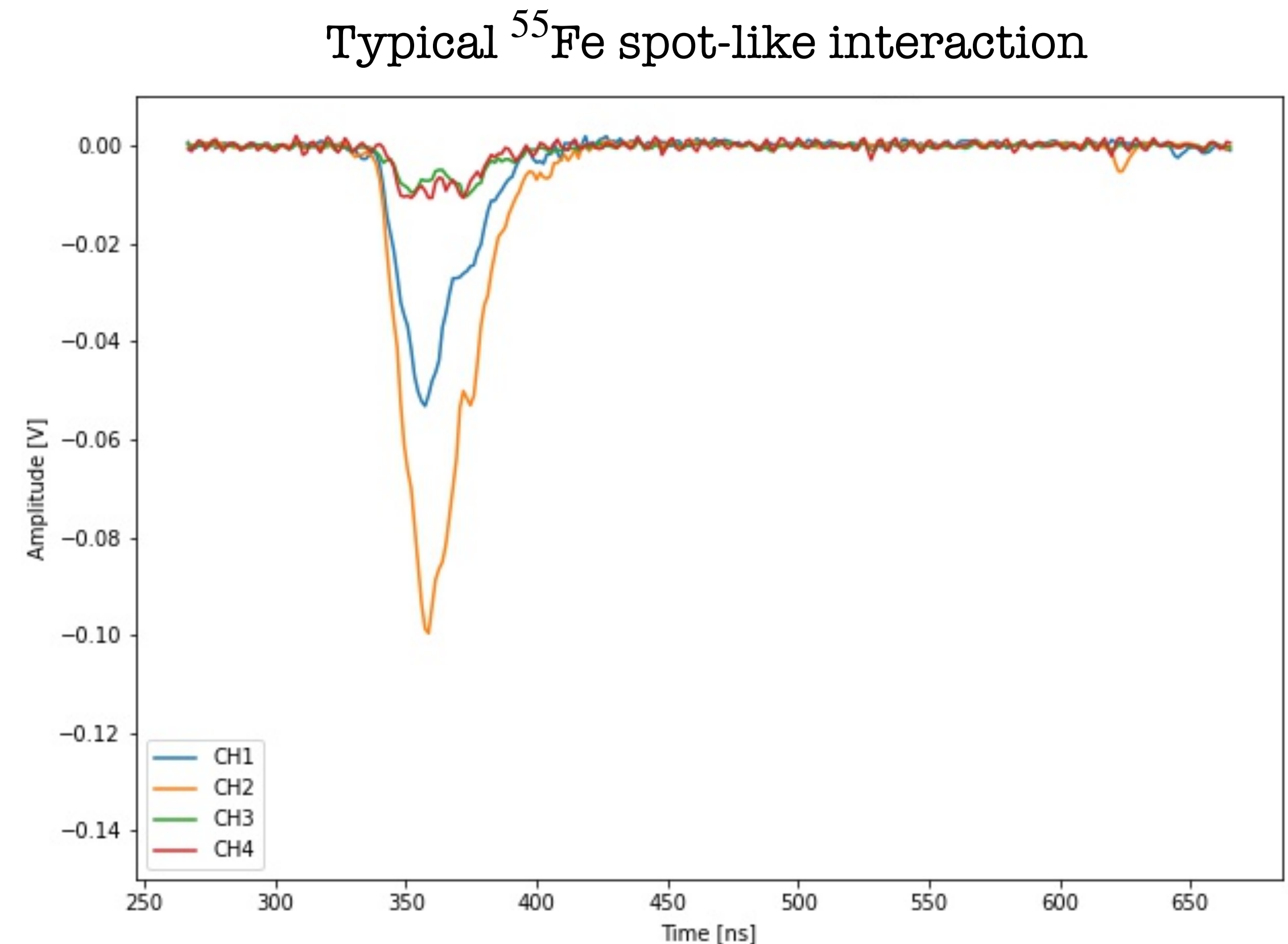


# Preliminary: analysis from PMTs

- Amount of **light collected** by PMTs **scales** with the **distance**
- Join information from **4 PMTs**  $\Rightarrow$  **2D position** and **energy** reconstruction



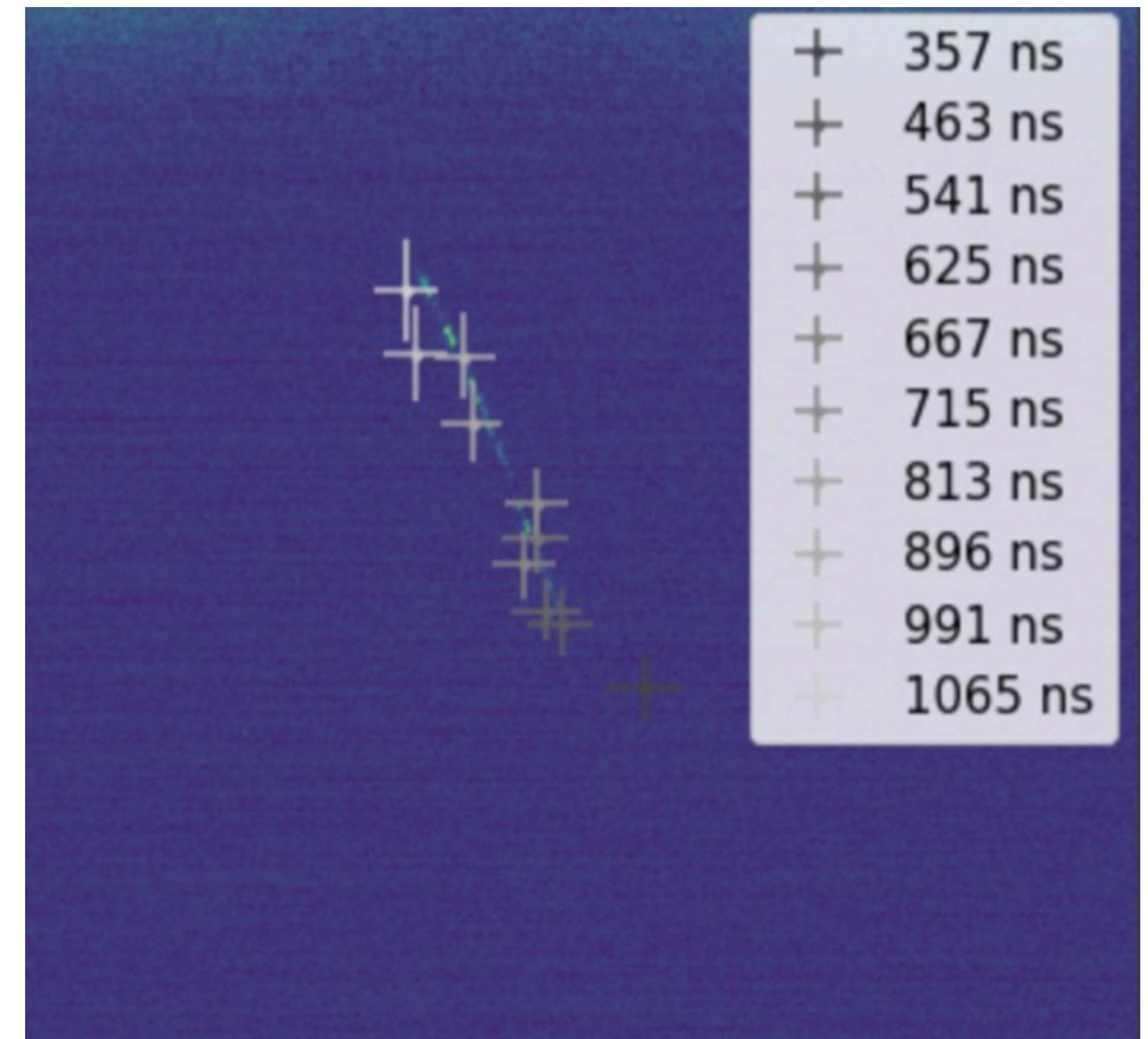
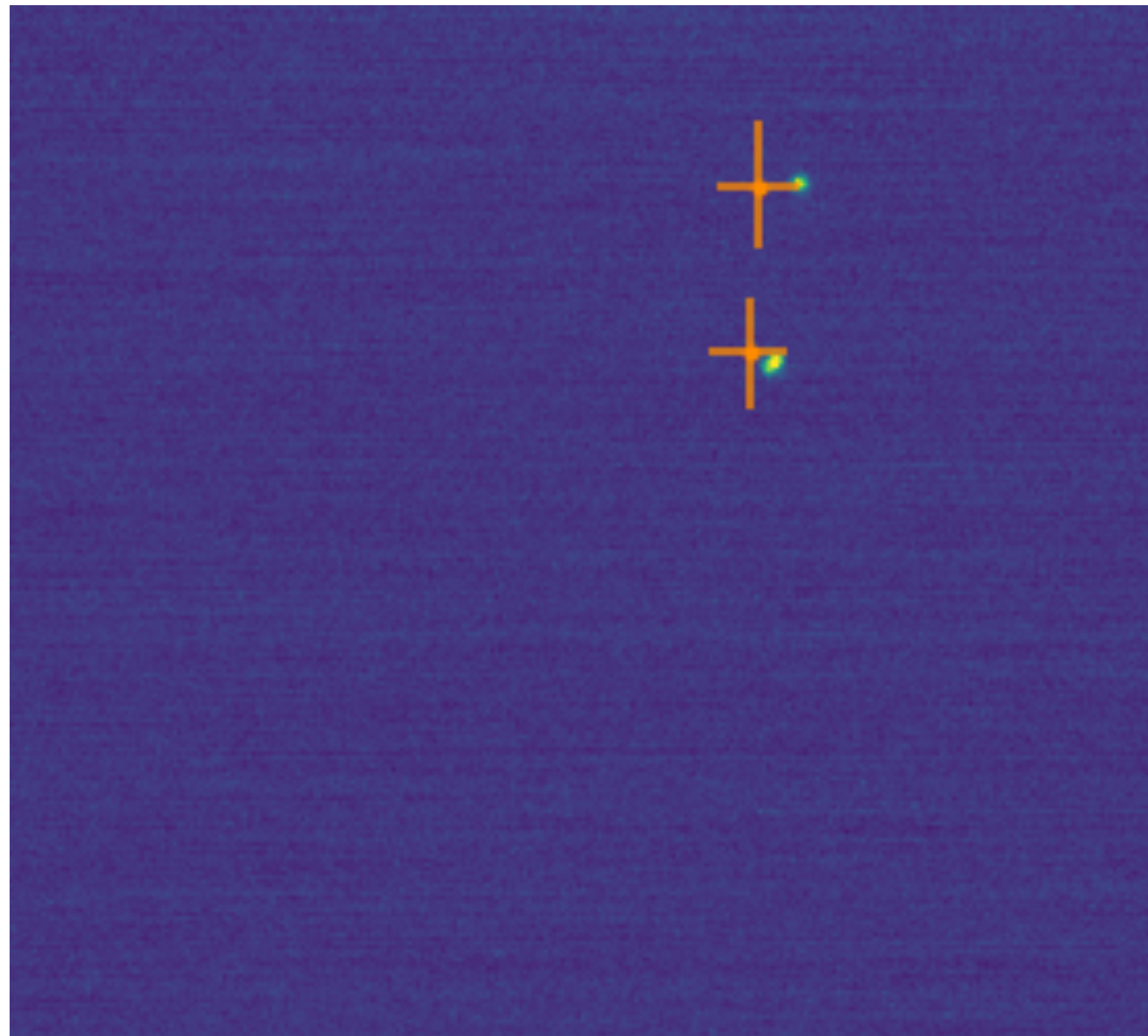
- In principle possible to **associate** single **waveforms** to single **tracks** in the pictures!



# Preliminary: analysis from PMTs



- **First attempts** are encouraging, but still a lot of **work to do**, especially on long tracks

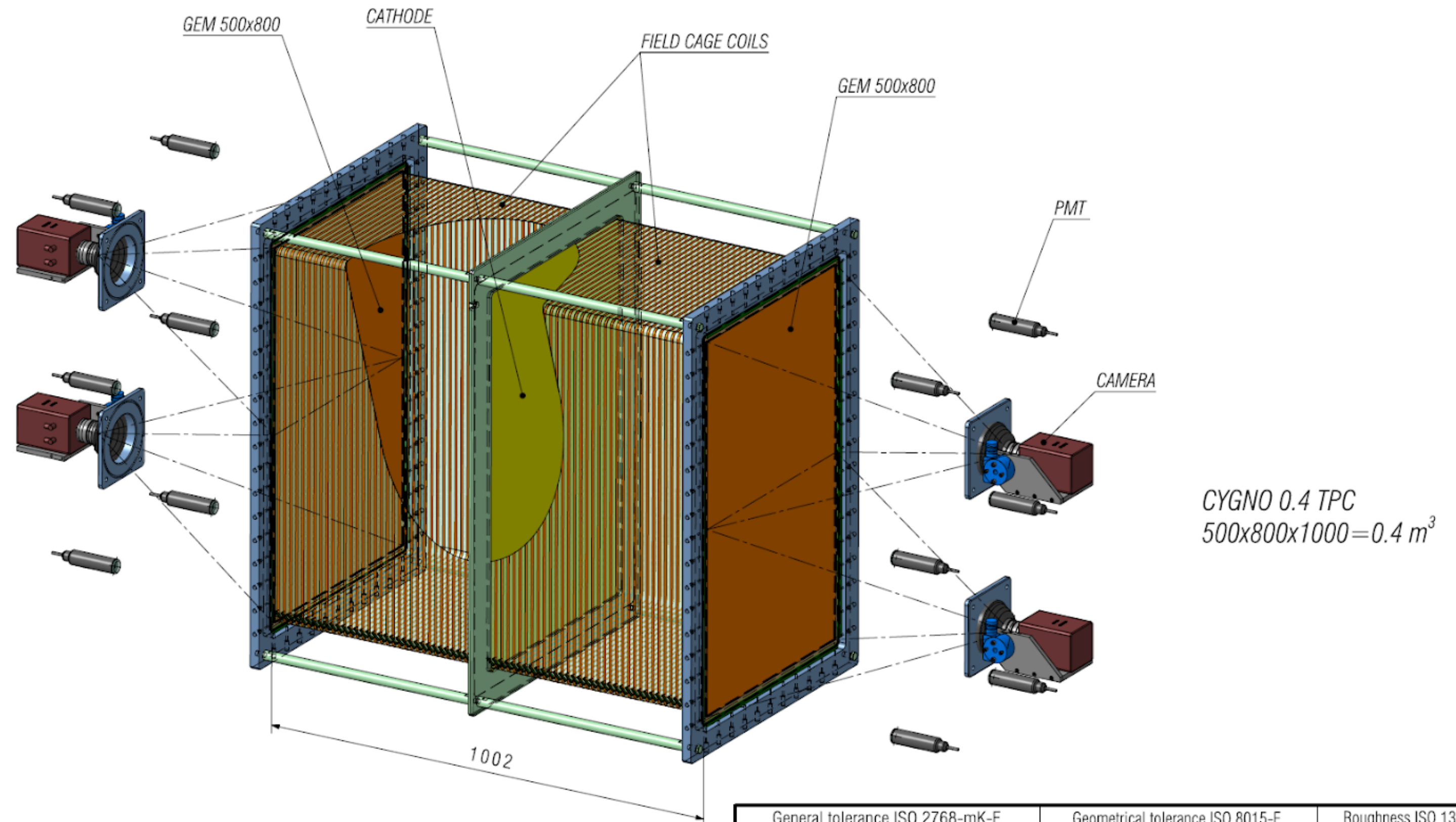




# CYGNO PHASE 1: CYGNO\_04

- **Preliminary design:**

- TPC made of **2 chambers** with a **common cathode**.
- Closed by 2 sets of **50 cm x 80 cm triple GEMs**
- **Readout** of each GEM side: 2 cameras with rectangular sensors (ORCA Quest) + 6 PMTs
- **Vessel:** low radioactivity PMMA
- **Shielding:** 10 cm copper + 100 cm water with a polyethylene base

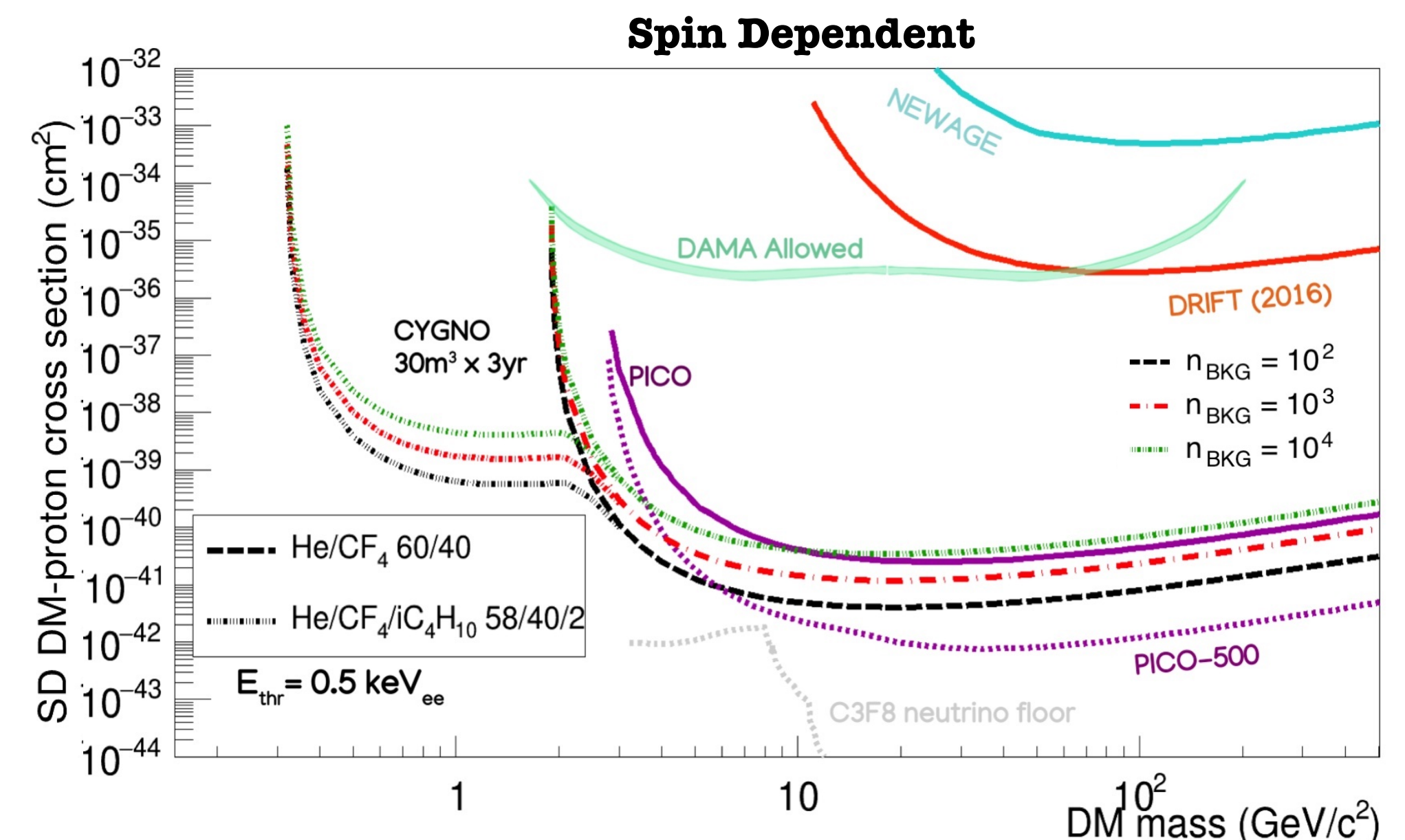
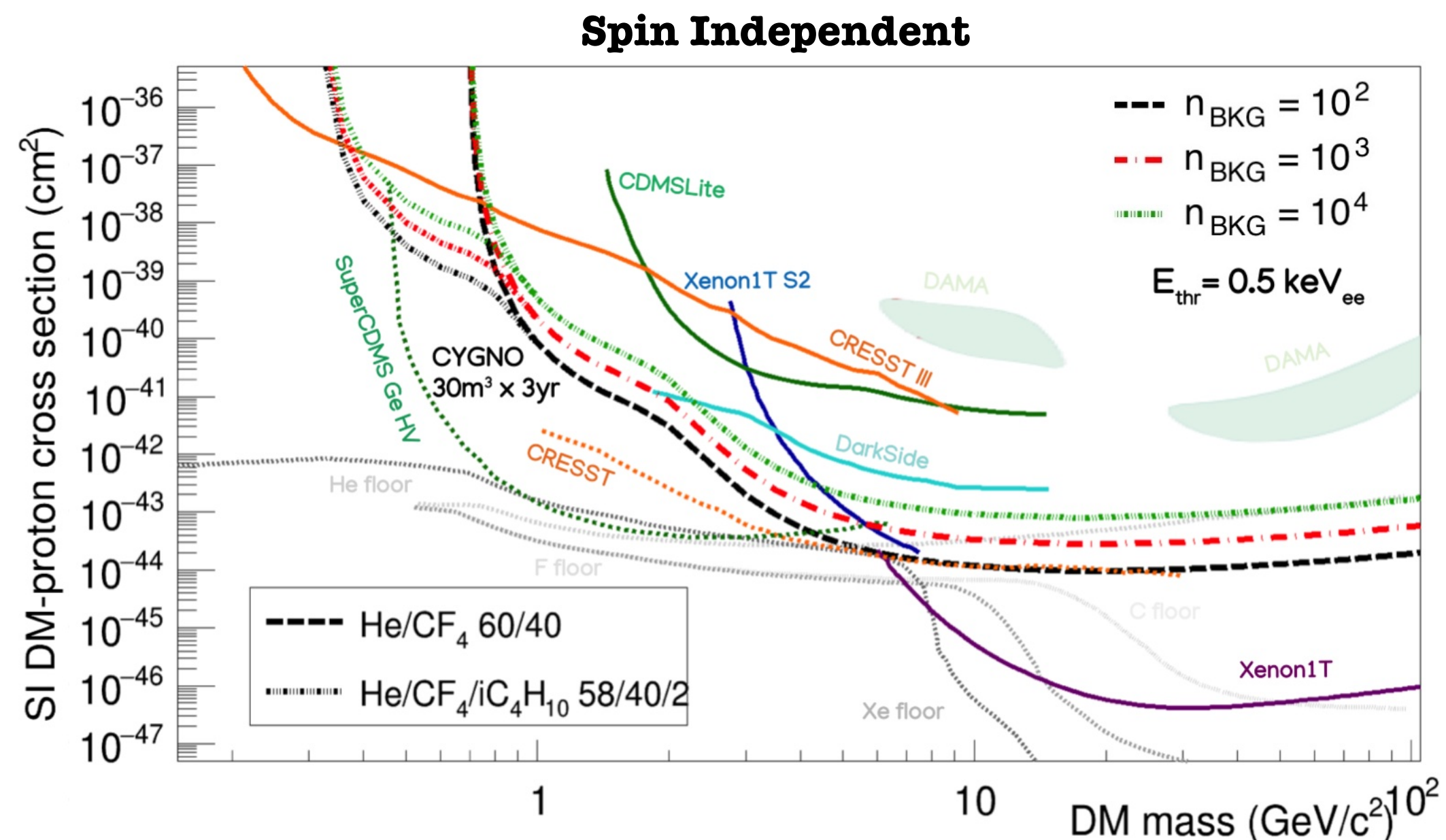
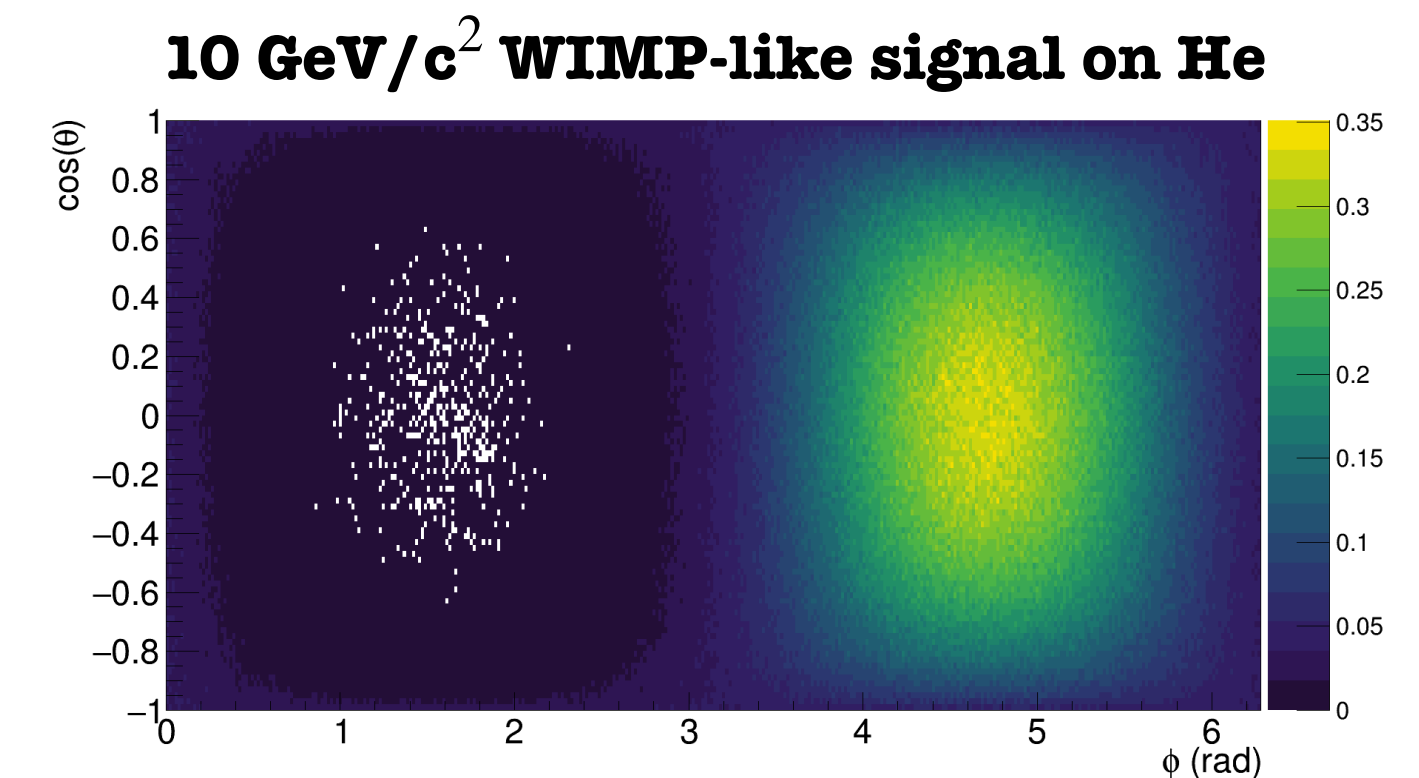
Designed at LNF and to be installed at LNGS



General tolerance ISO 2768-mK-E		Geometrical tolerance ISO 8015-E		Roughness ISO 1302	
 <div>NATIONAL INSTITUTE FOR NUCLEAR PHYSICS FRASCATI NATIONAL LAB RESEARCH DIVISION - SEM</div>	 <div>SIZE A3 PROJECTION</div>	REVISION	DATE	NAME	
			DATE	NAME	
			DATE	NAME	
		TOTAL WEIGHT (kg)	DATE	DRAWN	C.Capoccia
		CYGNO EXPERIMENT CYGNO 0.4 DETECTOR TPC COMPONENTS SCHEME		SCALE	DATE
1:8					
SHEET 1/3	DATE			APPROVED	
CY4-01-P					

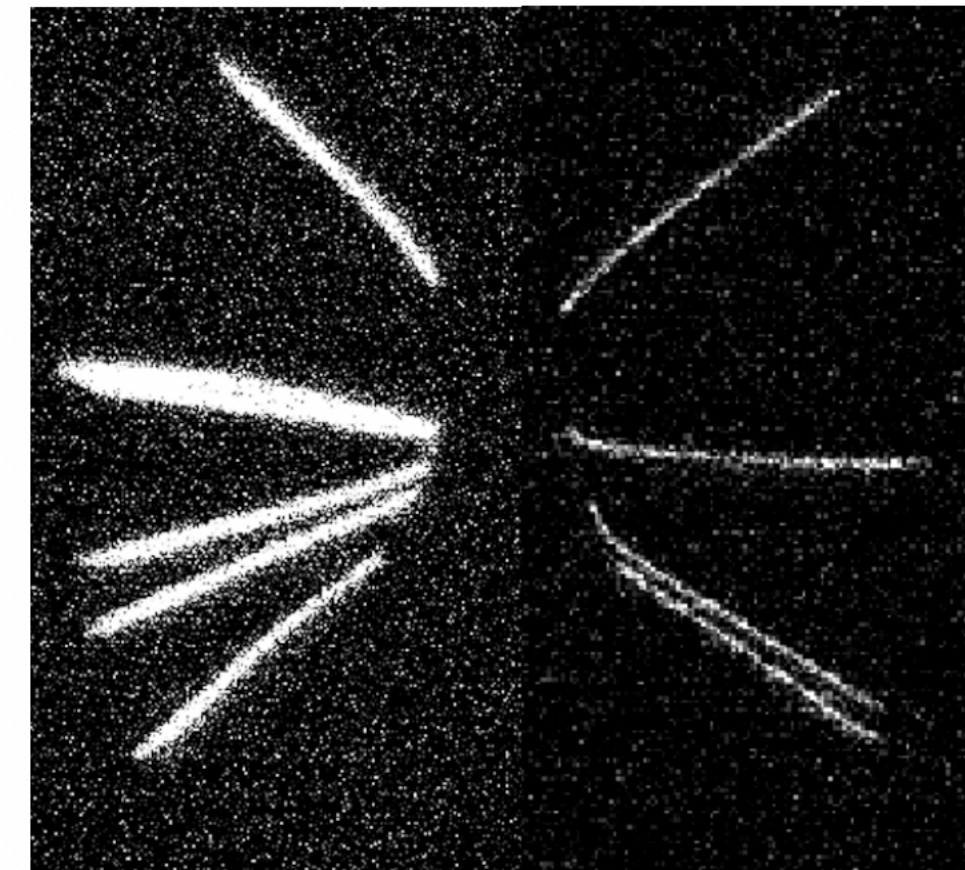
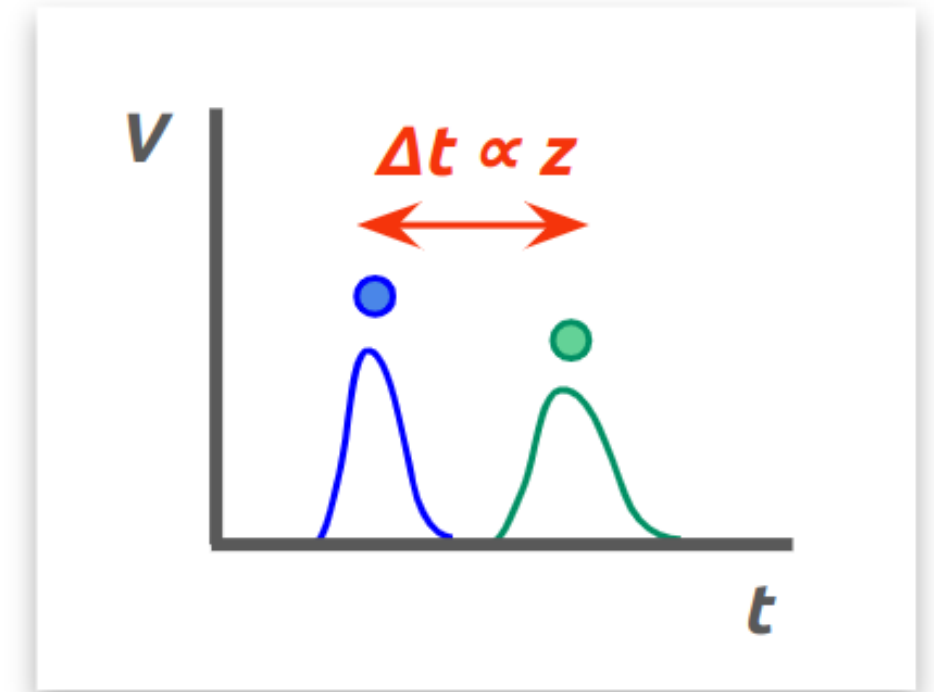
# CXGNO PHASE 2: the 30 m<sup>3</sup> experiment for low mass DM searches

- $\mathcal{O}(30\text{-}100\text{ m}^3)$  detector for directional dark matter (**DM**) search in the  $\sim\text{GeV}/c^2$  mass region.
- Preliminary sensitivity projections. **Assumptions:**
  - Low energy **threshold**:  $1\text{ keV}_{ee}$  ( $0.5\text{ keV}_{ee}$ )
  - **Quenching Factor**: SRIM simulation
  - **Observable**: angular distribution
  - **Angular resolution**:  $30^\circ$
  - **Head-tail discrimination**: 100%
  - **Background**: different scenarios (isotropic background)



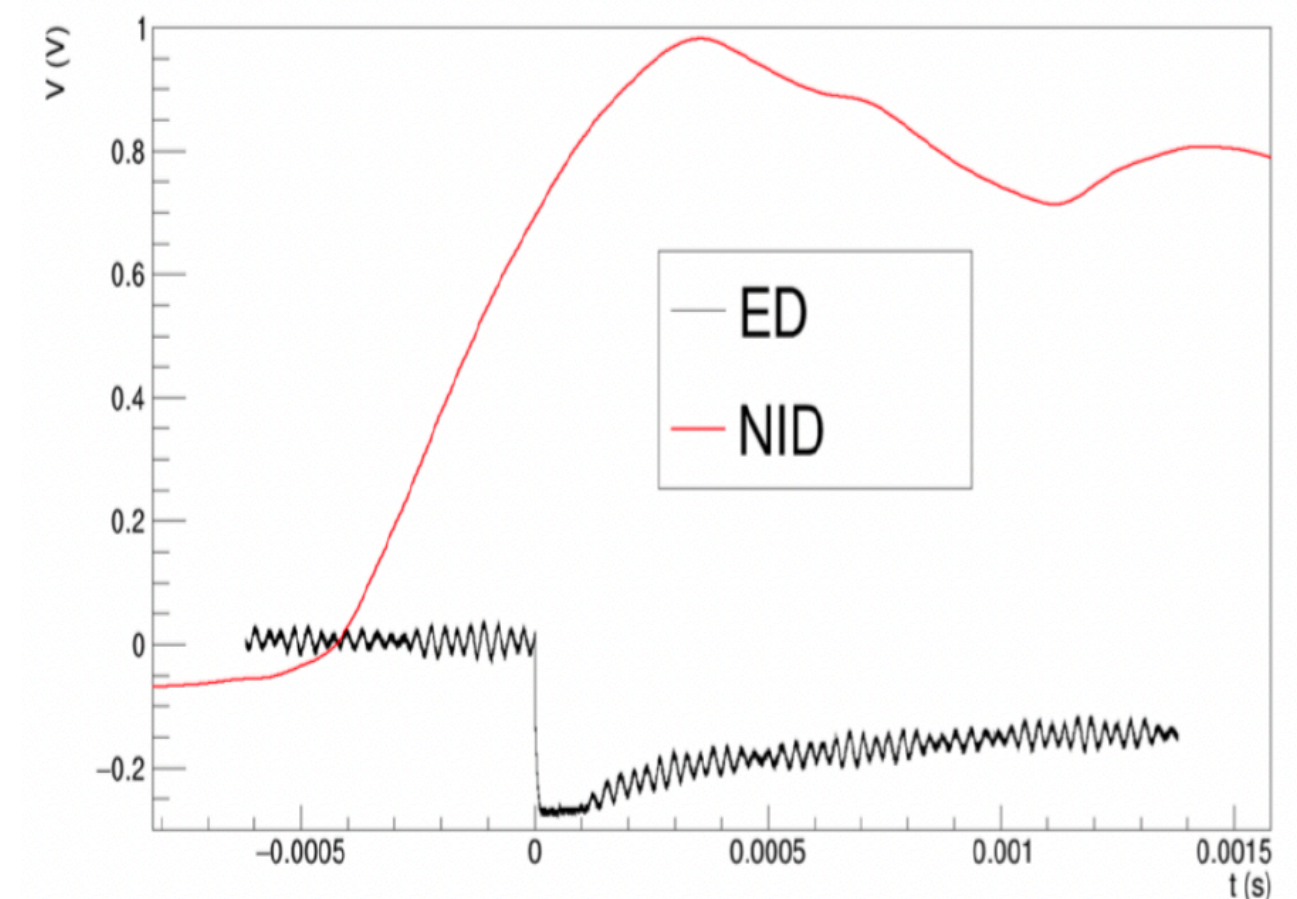
# R&D: Negative Ion Drift (NID)

- Addition of **electronegative** gas ( $\text{SF}_6$ ) to the mixture  $\Rightarrow$  **capture primary electrons** and produce **negative ions**
- **Negative ions:**
  - $\Rightarrow$  **slower drift velocity**
  - $\Rightarrow$  **different species** will have **different velocities**
  - $\Rightarrow$  **very low diffusions**
- **Absolute  $z$**  with **high accuracy** from the  $\Delta t$
- Tested successfully in low pressure gases (<100 mbar), it was **observed** at **nearly atmospheric pressure** (900 mbar) **by CYGNO team with an optical readout.**



He:CF<sub>4</sub>  
60:40  
1 kV/cm  
(ED)

He:CF<sub>4</sub>:SF<sub>6</sub>  
59:39.4:1.6  
0.4 kV/cm  
(NID)

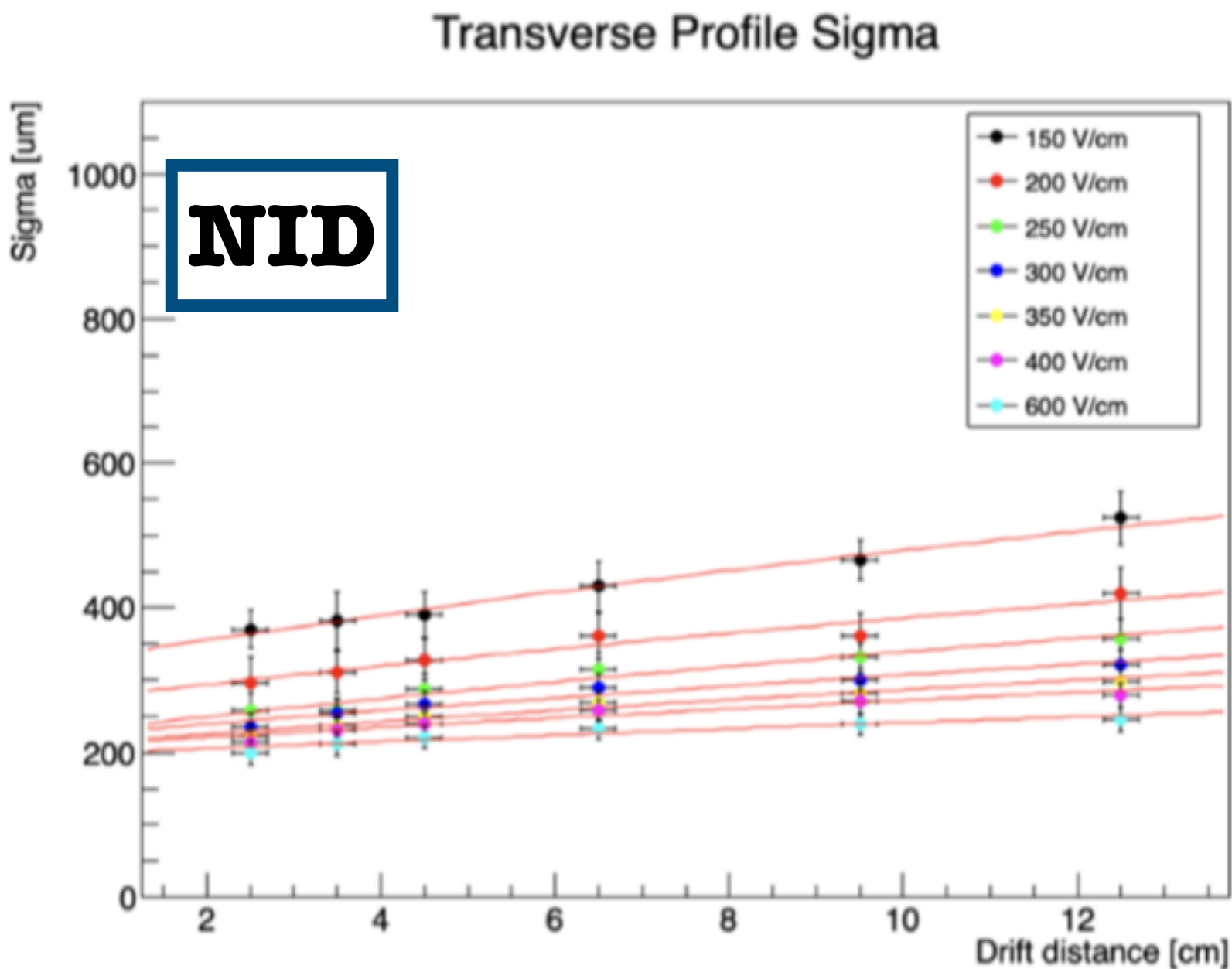
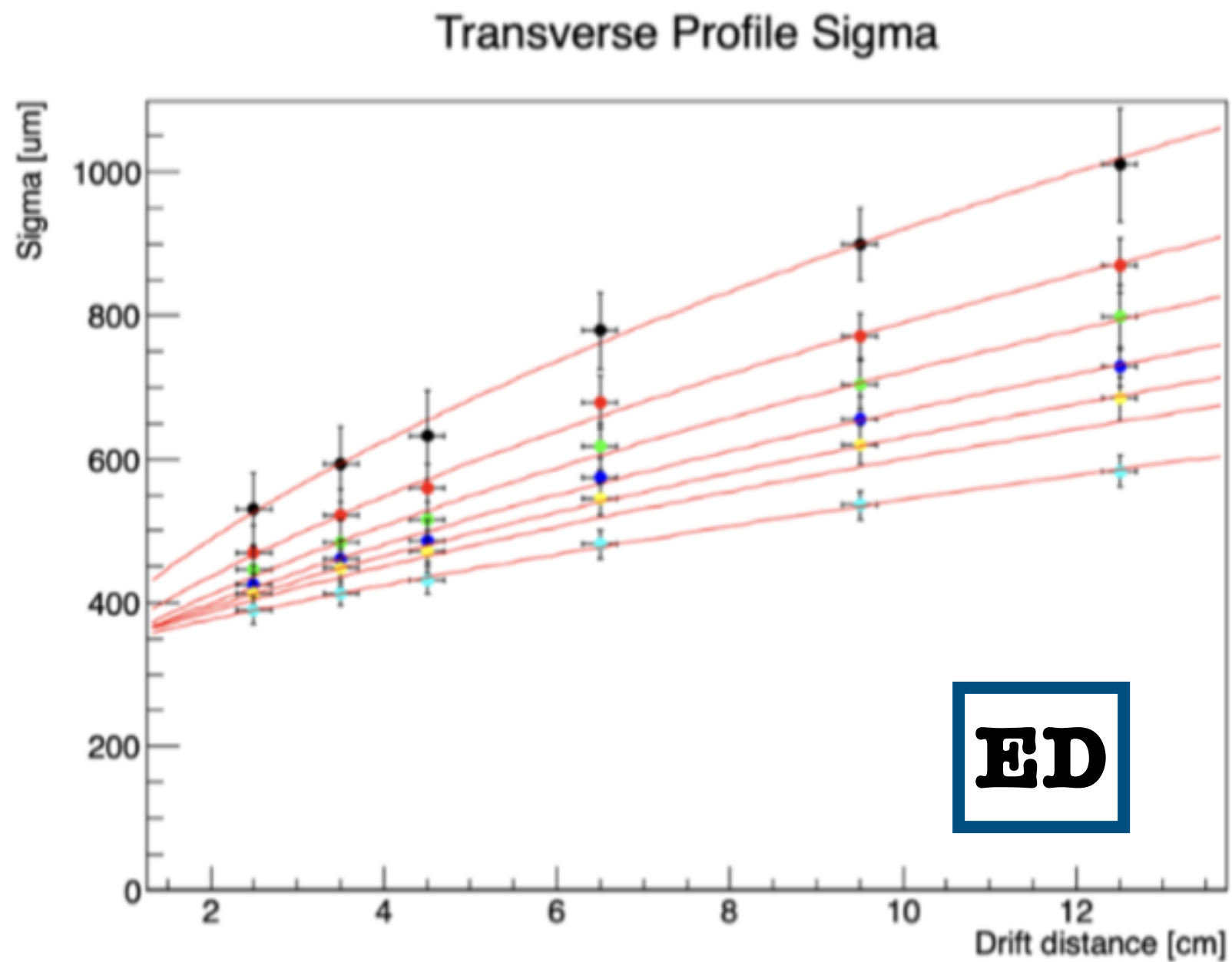


GEM preamp output  
O(μs) rise for ED  
O(ms) rise for NID

# R&D: Negative Ion Drift (NID)



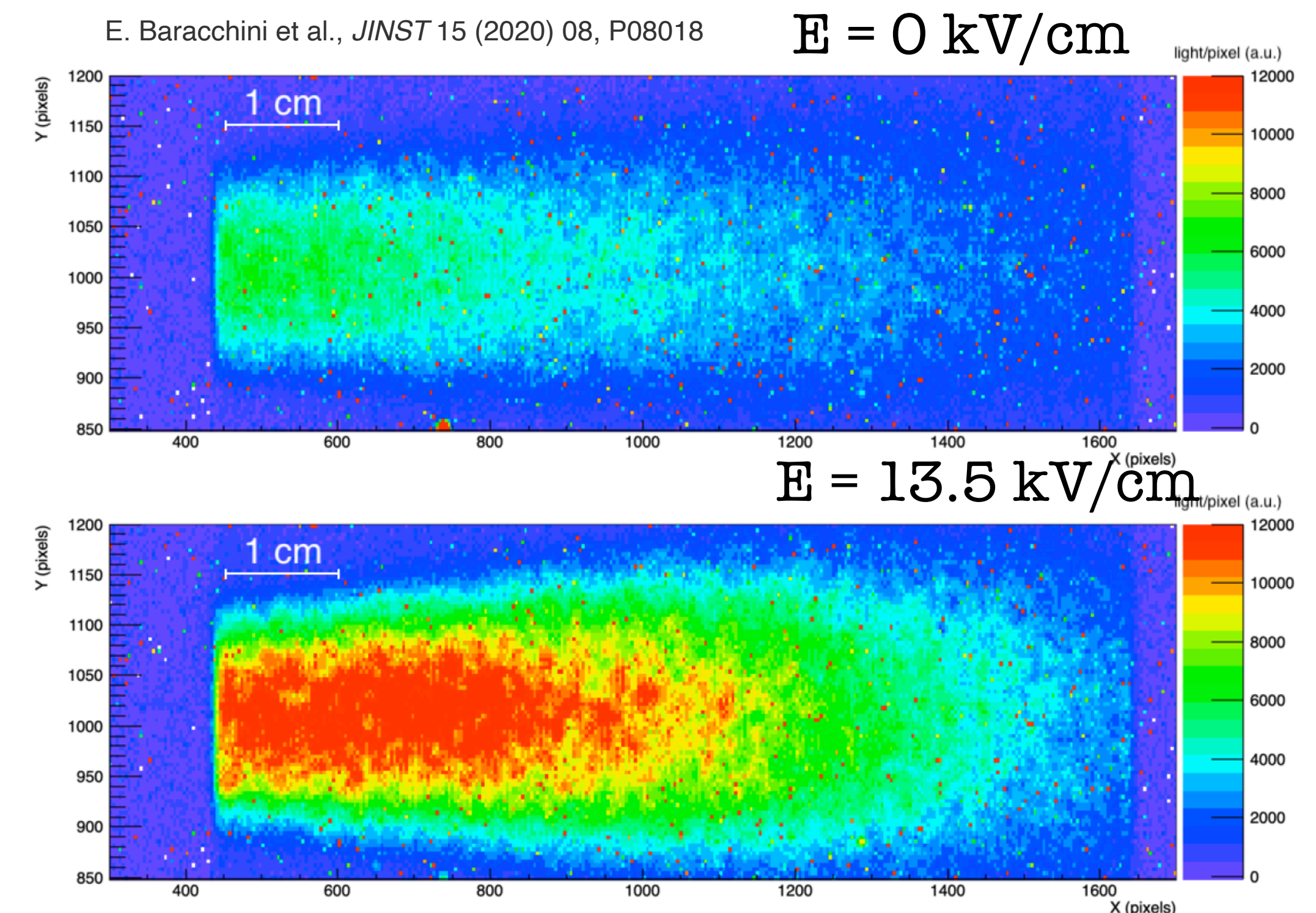
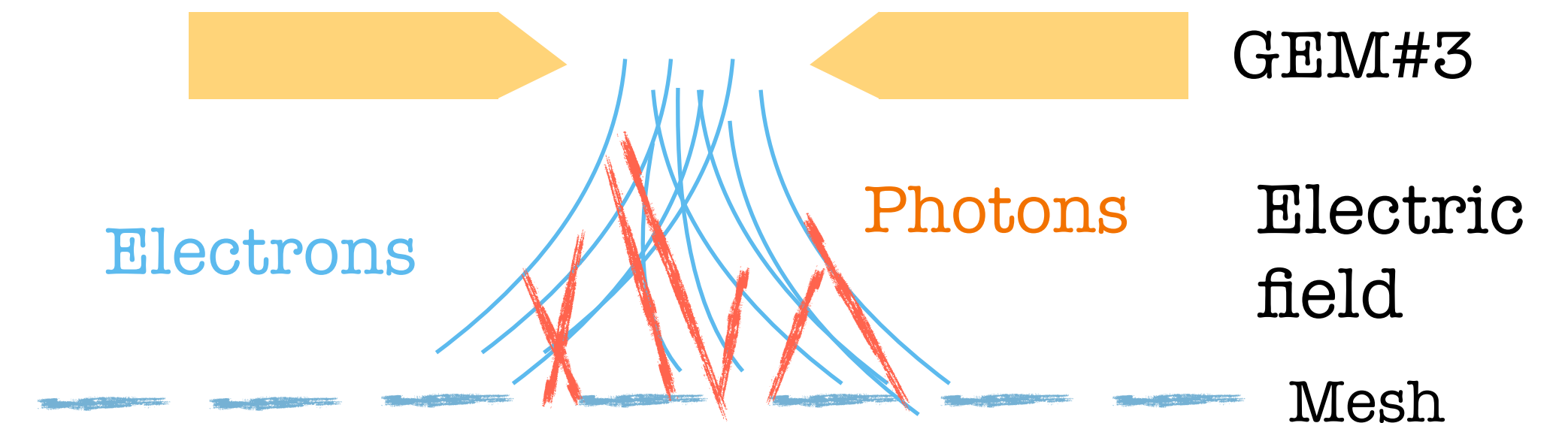
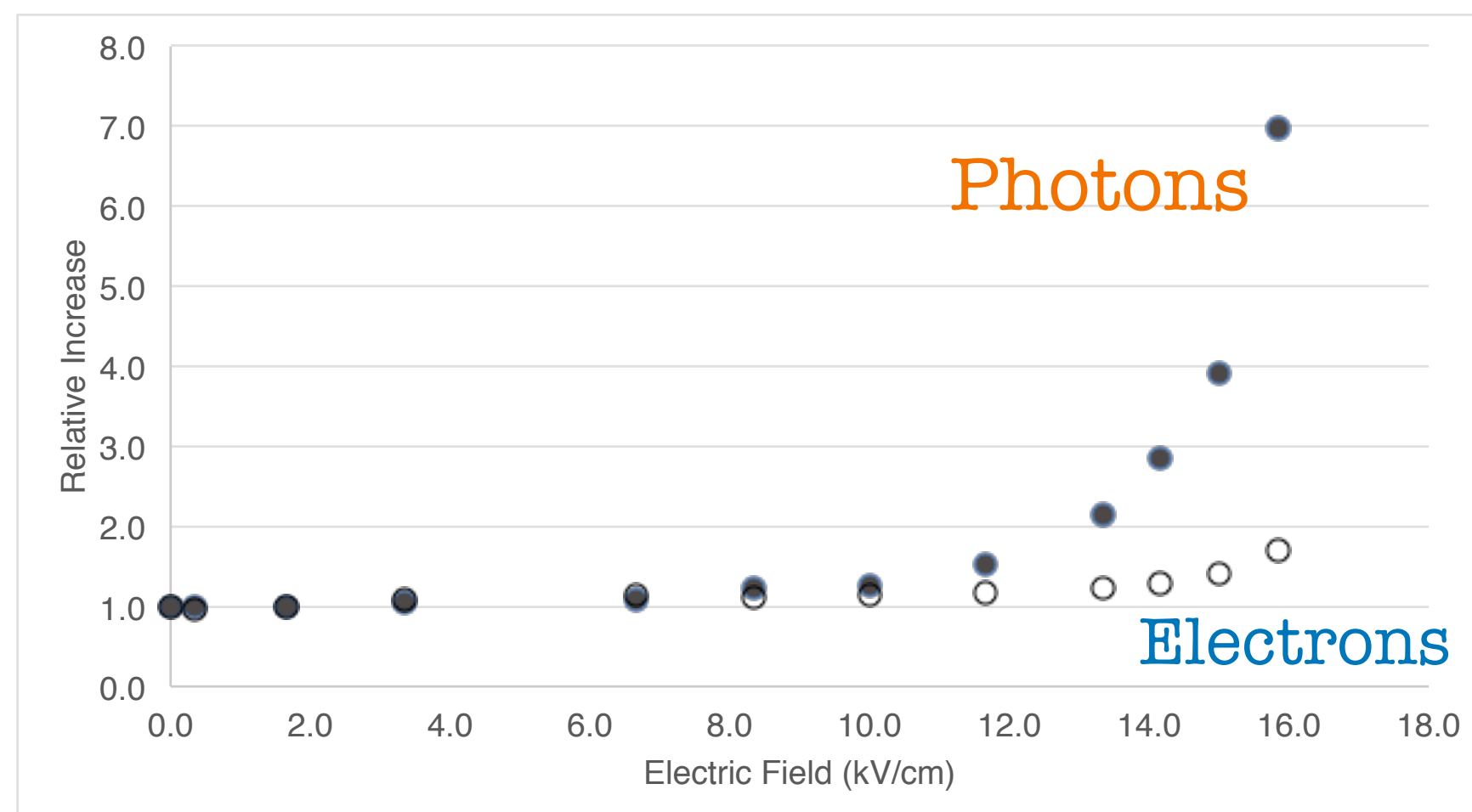
- **INITIUM project:** the development and operation of the first **1 m<sup>3</sup> Negative Ion TPC** (NITPC) with **GEMs** amplification [in **He/CF<sub>4</sub>/SF<sub>6</sub>** mixture] and **optical readout** with CMOS-based cameras and PMTs.



Drift field [V/cm]	$\sigma_0^{ED}$ [um]	$\sigma_T^{ED}$ [um/ $\sqrt{cm}$ ]	$\sigma_0^{NID}$ [um]	$\sigma_T^{NID}$ [um/ $\sqrt{cm}$ ]
150	300 ± 100	280 ± 20	320 ± 30	110 ± 10
200	290 ± 60	230 ± 10	260 ± 30	88 ± 20
250	284 ± 60	210 ± 10	220 ± 20	81 ± 10
300	300 ± 40	190 ± 10	220 ± 20	68 ± 10
350	300 ± 40	170 ± 10	210 ± 20	62 ± 10
400	310 ± 30	160 ± 10	210 ± 20	56 ± 9
600	320 ± 22	140 ± 10	200 ± 20	45 ± 10

# R&D: enhanced light yield

- **Idea:** enhance the light yield in the gas by accelerating electrons below last GEM
- **First evidence:**
  - ➔ **Charge yield** increased by a factor of **x1.7**
  - ➔ **Light yield** increased by a factor of **x7.0**

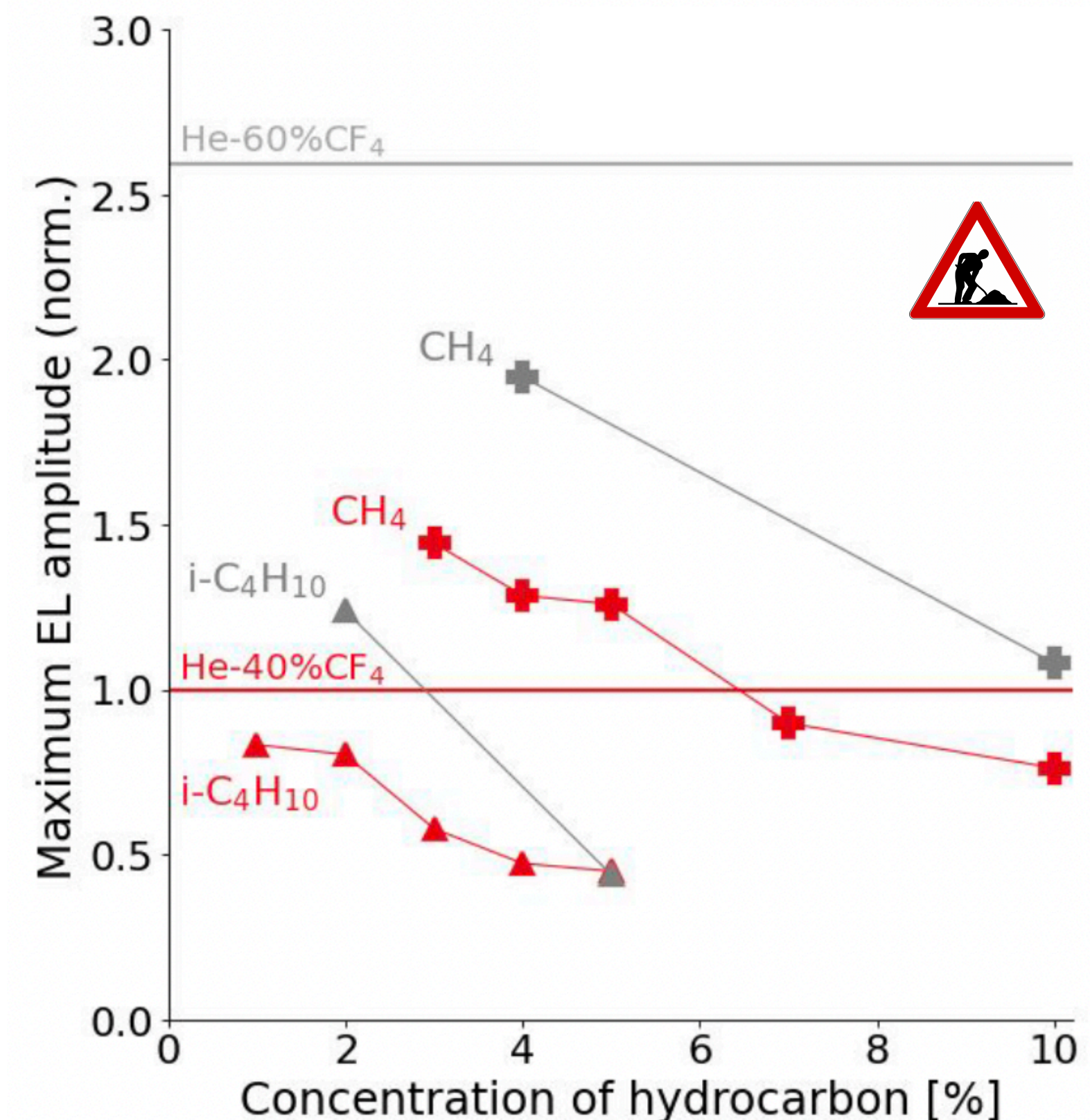
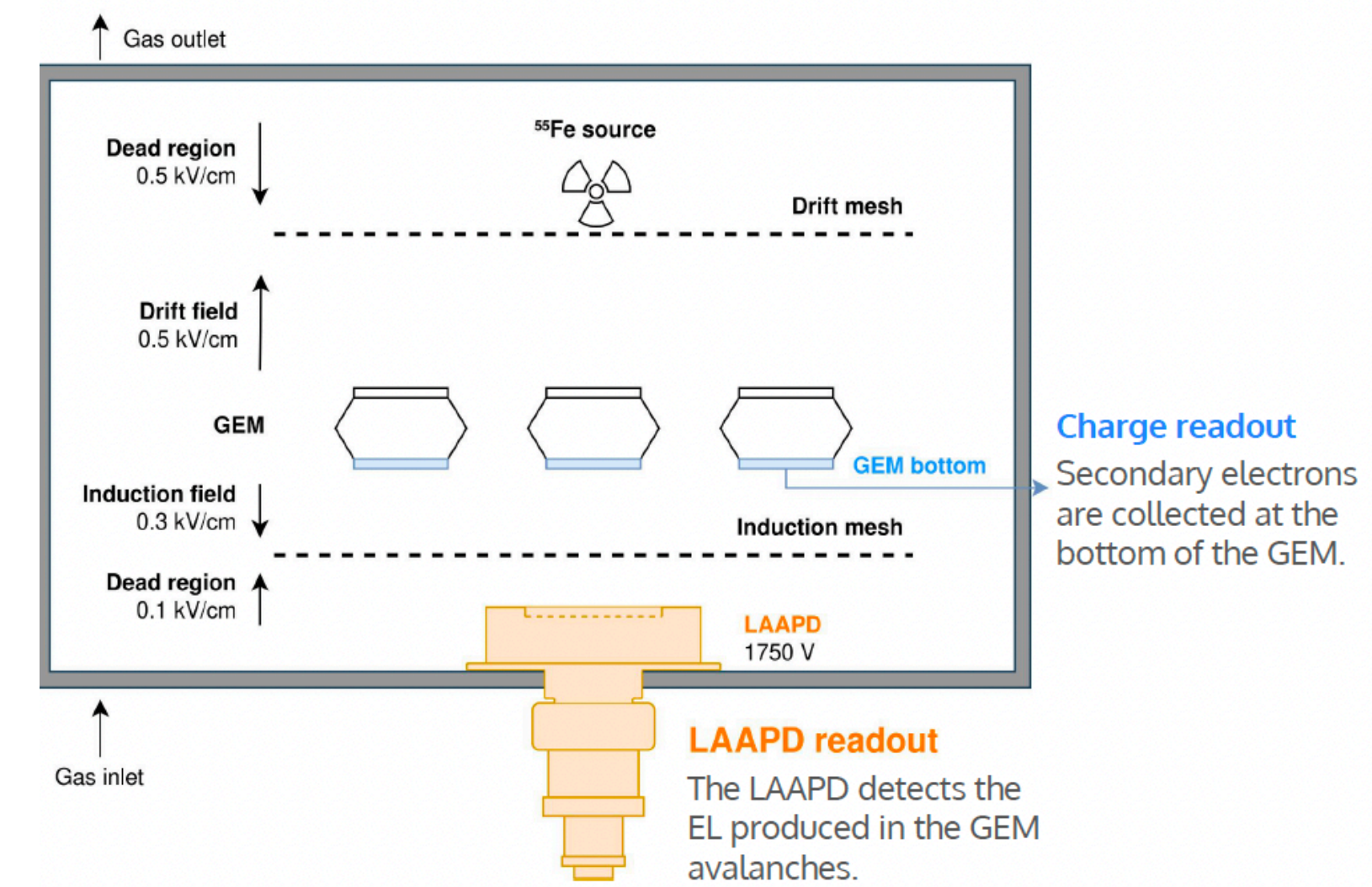


# R&D: Hydrocarbons

- Tests to study the possibility of adding hydrogen-rich gas (**C<sub>4</sub>H<sub>10</sub>** and **CH<sub>4</sub>**) to the mixture
- Adding up to 5% CH<sub>4</sub> to He:CF<sub>4</sub> increases the maximum attainable EL yield
- In terms of EL yield, CH<sub>4</sub> seems to be a better alternative than isobutane.

We demonstrates of a very good light yield from a mixture with hydrocarbons

## Single GEM dedicated setup



# Pros & Cons of this technology

## Pros:

- Good **energy resolution**  $\sim 12\%$
- **Excellent linearity** in the detector **energy response**
- **2D+1D detailed track reconstruction** \*
- Possibility of accessing **topology of the track** (shape, size, ...)  $\Rightarrow$  PID, head-tail, ...\*
- Very **easy operation** at atmospheric pressure and room temperature
- **CMOS** with very low noise  $\Rightarrow$  single electron detection, energy **threshold well below 1 keV**, in principle  $O(100\text{ eV})$
- **CMOS** sensor relatively **cheaper** w.r.t. other readout systems with the same granularity
- Access to **directionality**  $\Rightarrow$  crucial for a positive DM identification\*

## Cons:

- Limited **geometrical acceptance**  $\Rightarrow$  high gain to compensate
- **Saturation** of the GEM gain  $\Rightarrow$  non uniform light yield along the drift direction
- Components (CMOS sensor, GEMs, etc.) with relatively intense **internal radioactivity**  $\Rightarrow$  develop radio-pure components for DM searches
- To search for dark matter, a lot of **sensitive mass** is needed  $\Rightarrow$  with a gas TPC is not trivial to reach big sensitive mass in the available space.

# Conclusions

- The **CXGNO** collaboration is developing a **gaseous TPC with an optical readout** of CMOS sensors and PMTs with a **GEM amplification stage**
- **LIME**, a 50 L prototype, has been moved @ LNGS and collected underground data in its first two data runs.
- The detector shows **good low energy resolution** (12% at 6 keV<sub>ee</sub>) and an **good 3D position resolution at low energy**
- **Promising preliminary results** from the analysis of the **PMT information**
- The **goal** of the LIME prototype is to **study the background** in different shielding configuration and validate the Monte Carlo simulation
- This is just a step towards larger detectors for **directional dark matter search**

# Acknowledgements

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# Thanks for the attention!

The **CYGNO** collaboration:

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



**SAPIENZA**  
UNIVERSITÀ DI ROMA



Istituto Nazionale di Fisica Nucleare

# Backup

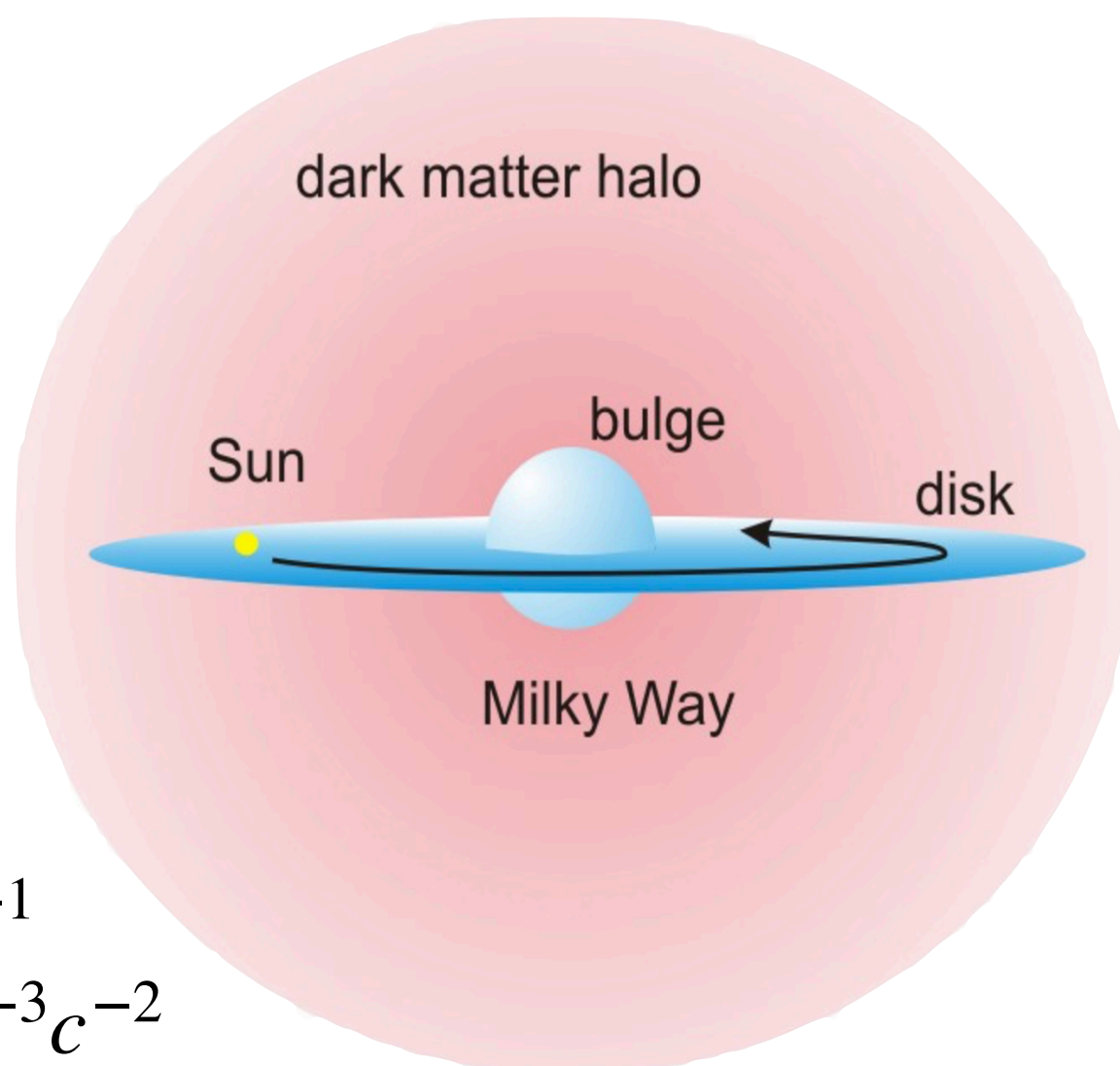
# The dark matter problem

- Cosmological and astronomical observations at very different scales strongly support the existence of dark matter (DM)
- Weakly Interacting Massive Particles (WIMPs): neutral non-relativistic stable particles feebly interacting with the ordinary matter as a possible explanation
- In the Milky Way: modeled as a spherical halo of particles

## Standard Galactic Halo Model (SHM)

Maxwell-Boltzmann distribution, and the parameters are:

- $v_c(R_\odot) = 230 \text{ km s}^{-1}$
- $v_{esc}(R_\odot) = 544 \text{ km s}^{-1}$
- $\rho(R_\odot) = 0.3 \text{ GeV cm}^{-3} c^{-2}$

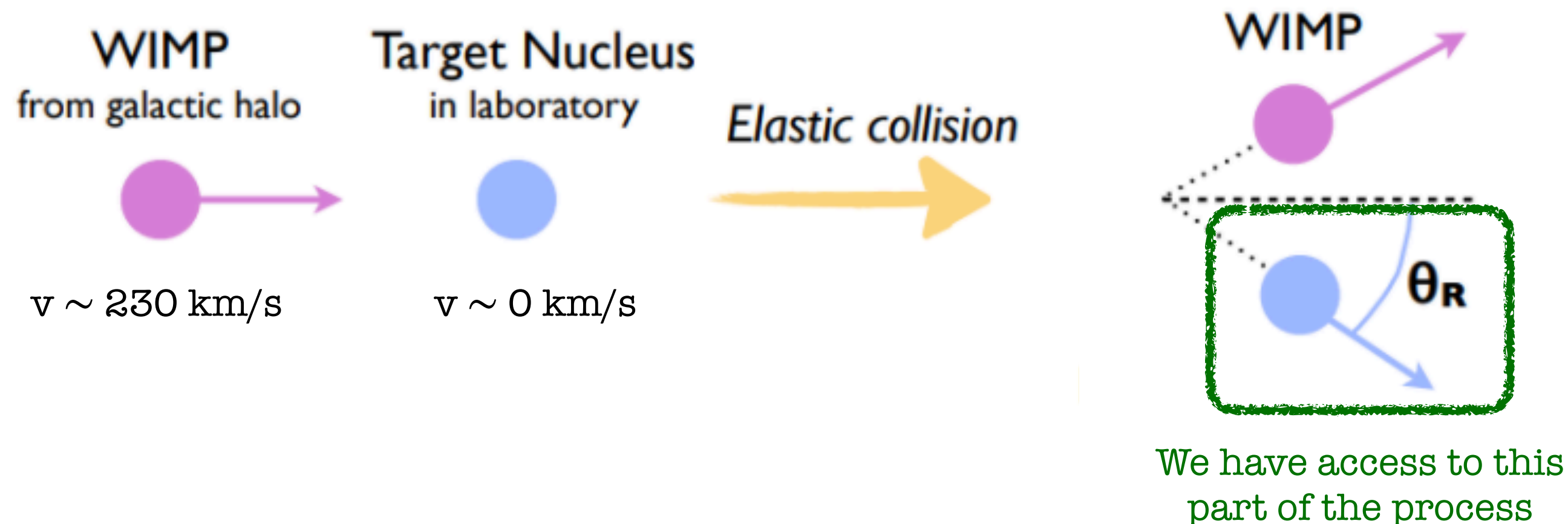


- The solar system is moving through this gas-like halo:
  - ➡ at  $\sim 230 \text{ km/s}$
  - ➡ towards the Cygnus constellation
  - ➡ Non-relativistic wind of WIMPs

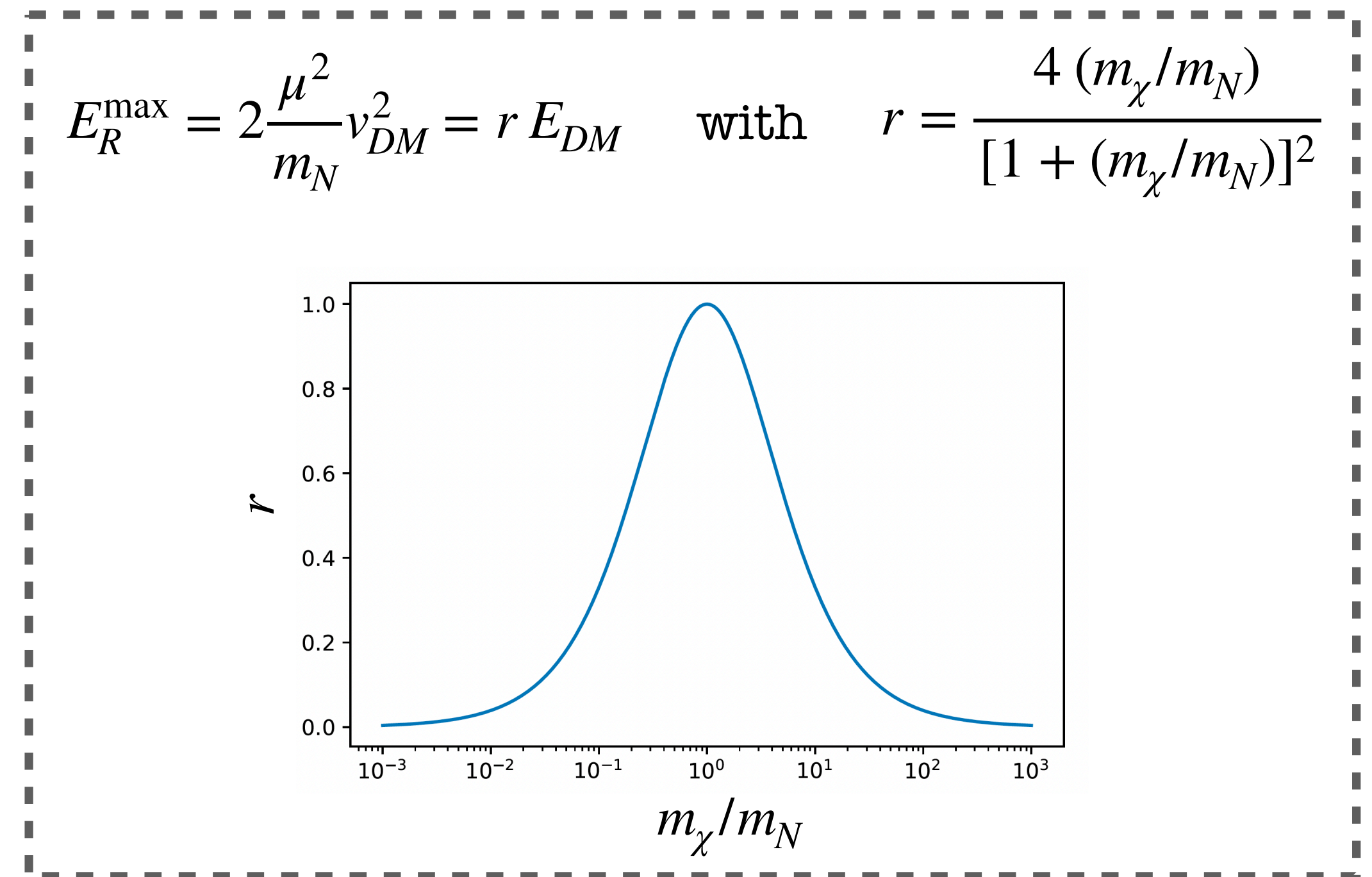


# Direct detection of WIMPs on the Earth

- **Strategy:** detect the recoils induced by the elastic scattering of DM particles off the ordinary matter constituents (mainly nuclei)



Assuming  $m_\chi = 10 \text{ GeV}/c^2$  and  $v_\chi = 2 \times 10^{-3} c \Rightarrow E_R \leq 20 \text{ keV}$



- Main message from **kinematics**: the **mass of the target** should be **close to  $m_\chi$**  to produce more energetic recoils and thus enhance the sensitivity

# DM - nucleus interaction rate

- From kinematics:

$$\text{diff. rate } \left( \frac{dR}{dE_R} \right) \sim \frac{\text{total rate } R_0}{E_0} \exp \left[ - \frac{\text{recoil energy } E_R}{\text{a constant given by the kinematics } E_0} \right]$$

- Time modulation:

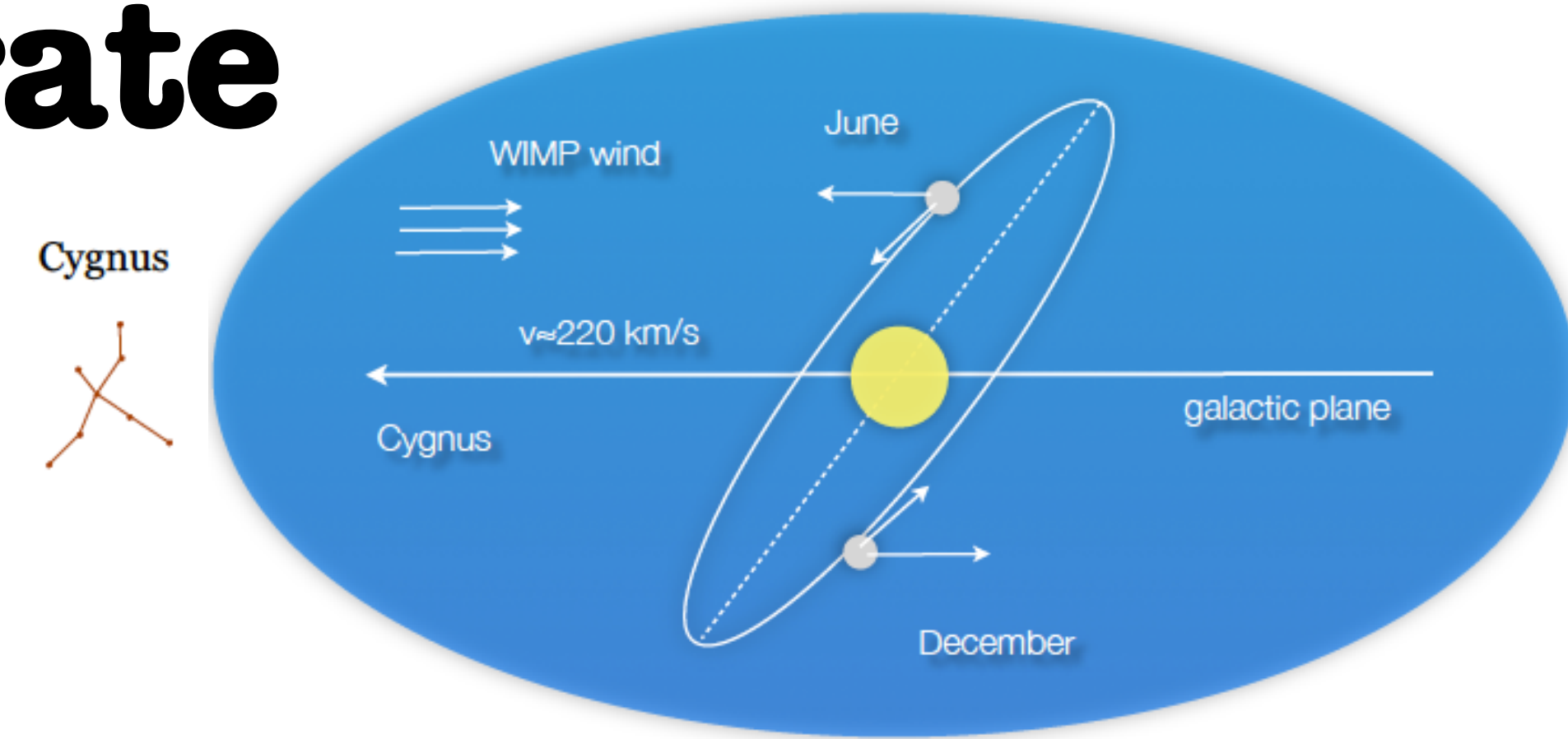
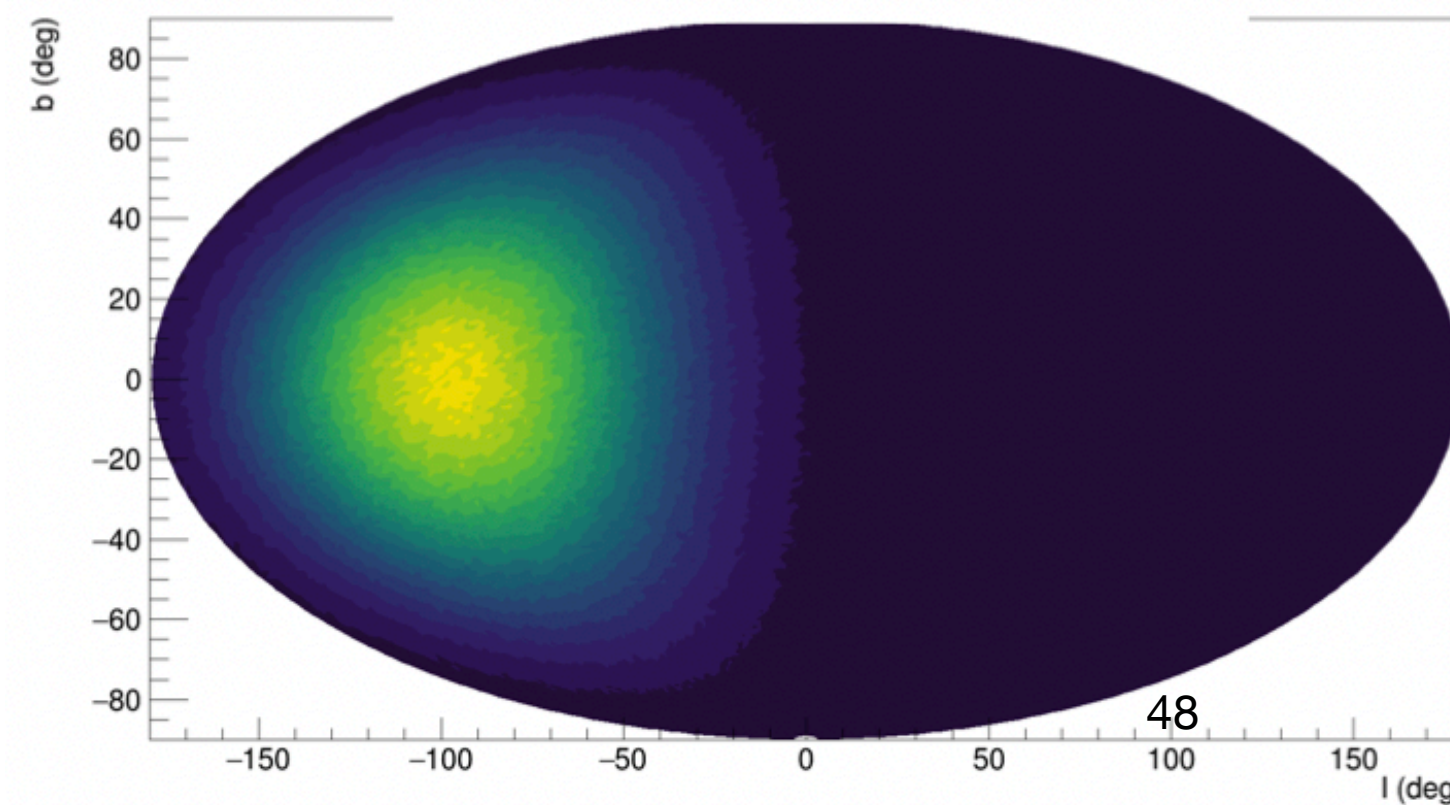
$$v_{\text{DM}}(t) = v_{\text{sun}} + v_{\text{orb}} \cos \gamma \cos [\omega (t - t_0)]$$

$\gamma = 60^\circ$

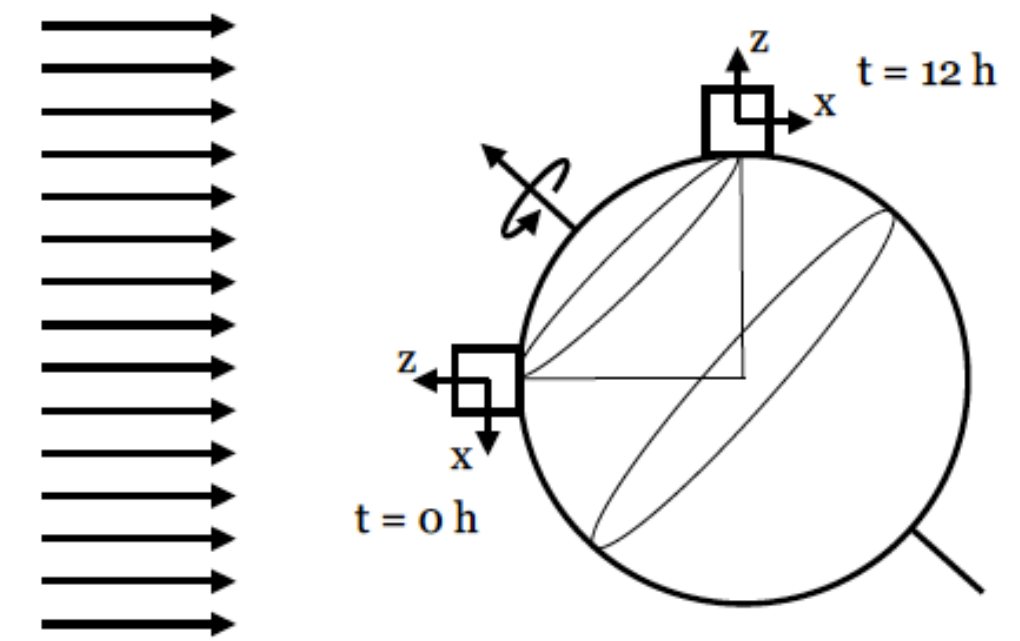
Annual modulation of 2%-10%

- Directionality:

Forward-backward asymmetry



Directionality + Time modulation



Diurnal modulation of the DM direction:

➡ at  $40^\circ$  degree latitude, every 12 h, vertical → horizontal

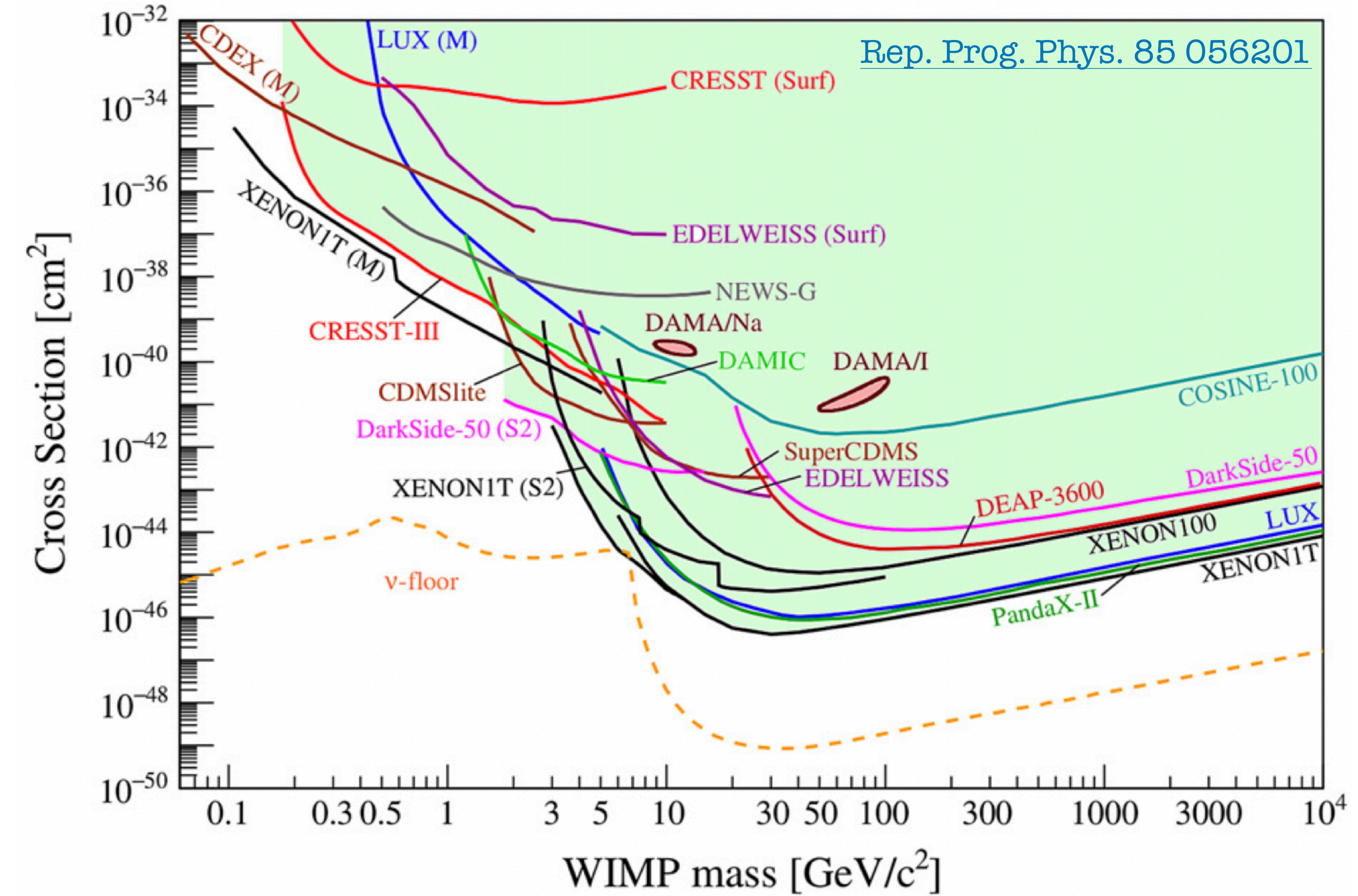
# WIMP mass region

- Other than DAMA, the **null results** of the direct detection experiments translates to tighter and tighter **constraints** in the cross-section vs mass parameter space

Element	Max E transferred by a 1 GeV/c <sup>2</sup> WIMP	Min WIMP mass with 1 keV threshold
H	2.00 keV	0.5 GeV/c <sup>2</sup>
He	1.30 keV	0.9 GeV/c <sup>2</sup>
C	0.57 keV	1.4 GeV/c <sup>2</sup>
F	0.38 keV	1.7 GeV/c <sup>2</sup>
Na	0.32 keV	1.8 GeV/c <sup>2</sup>
Si	0.27 keV	2.0 GeV/c <sup>2</sup>
Ar	0.20 keV	2.4 GeV/c <sup>2</sup>
Xe	0.06 keV	4.2 GeV/c <sup>2</sup>

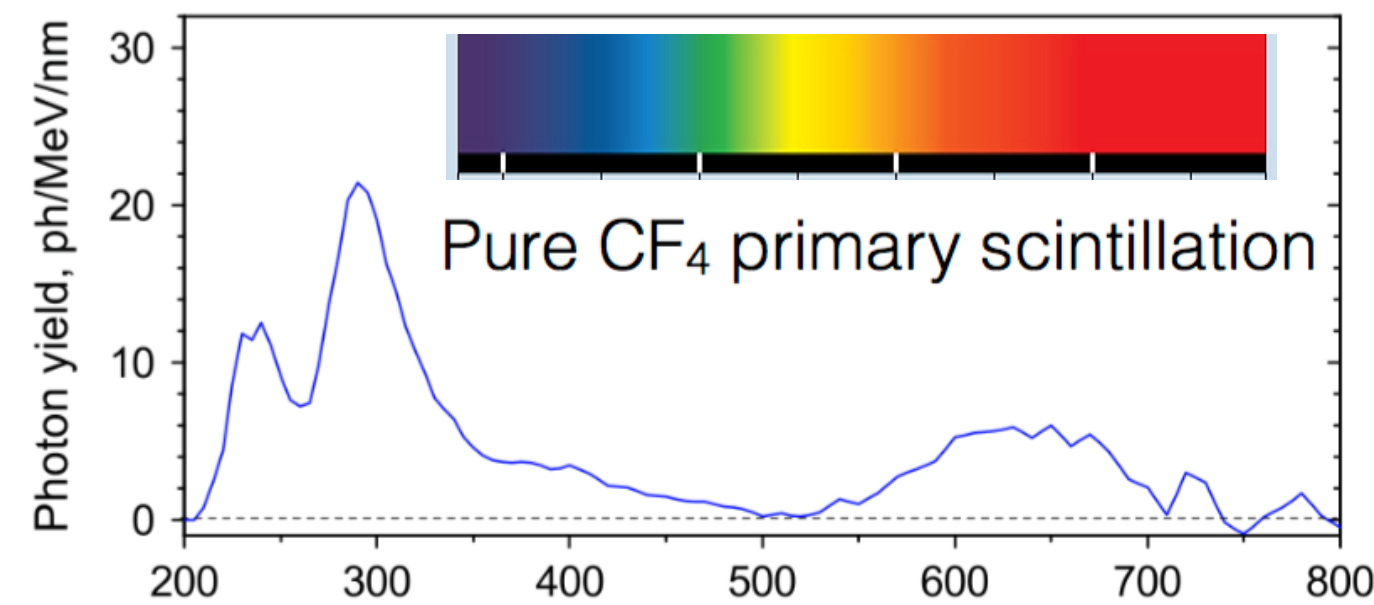
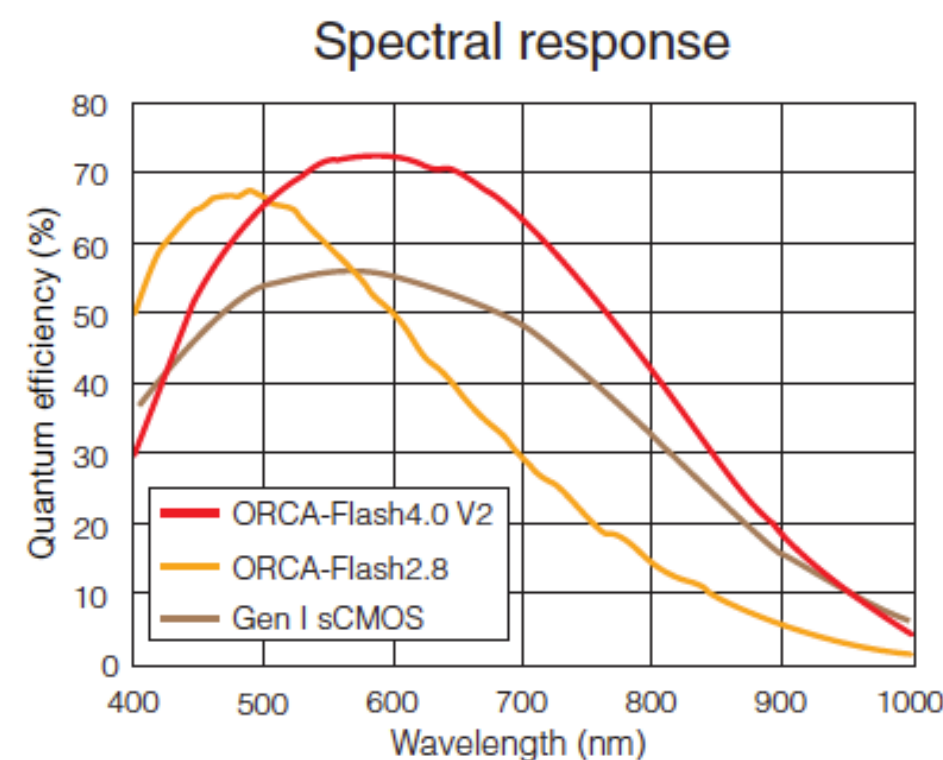
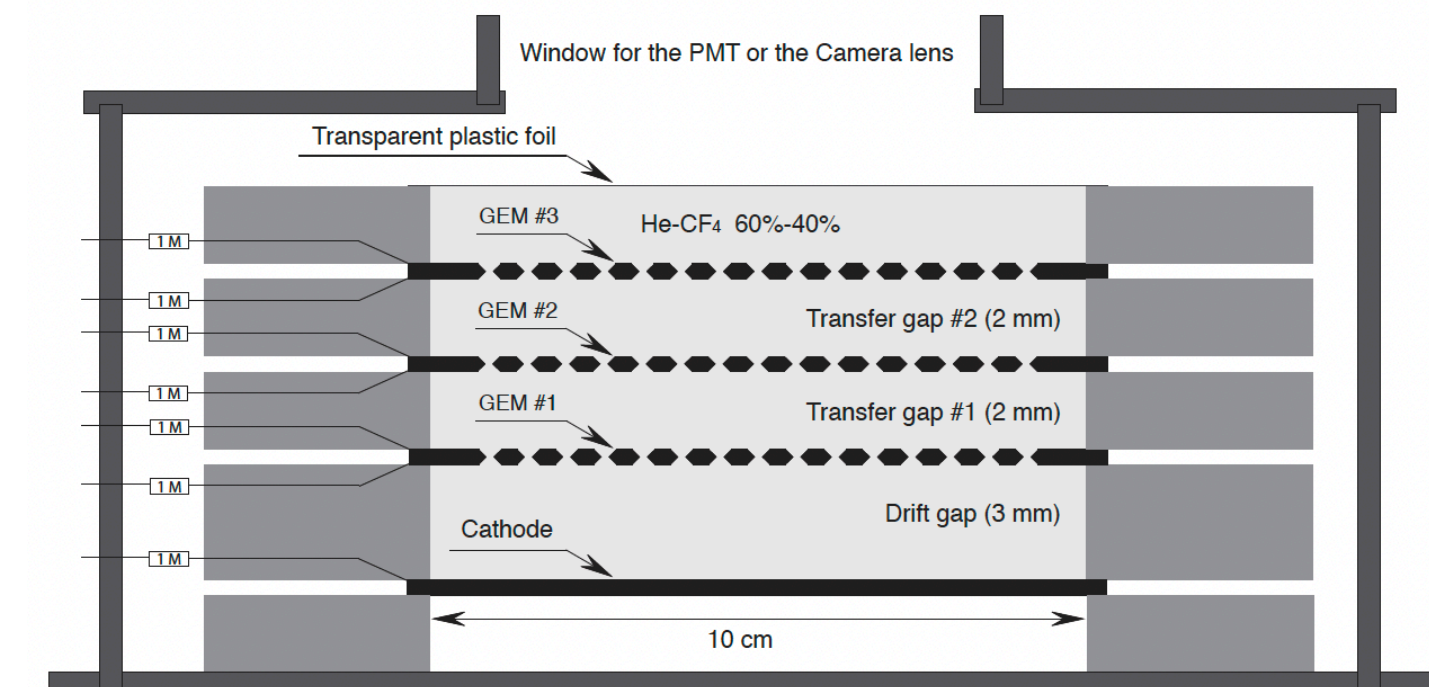
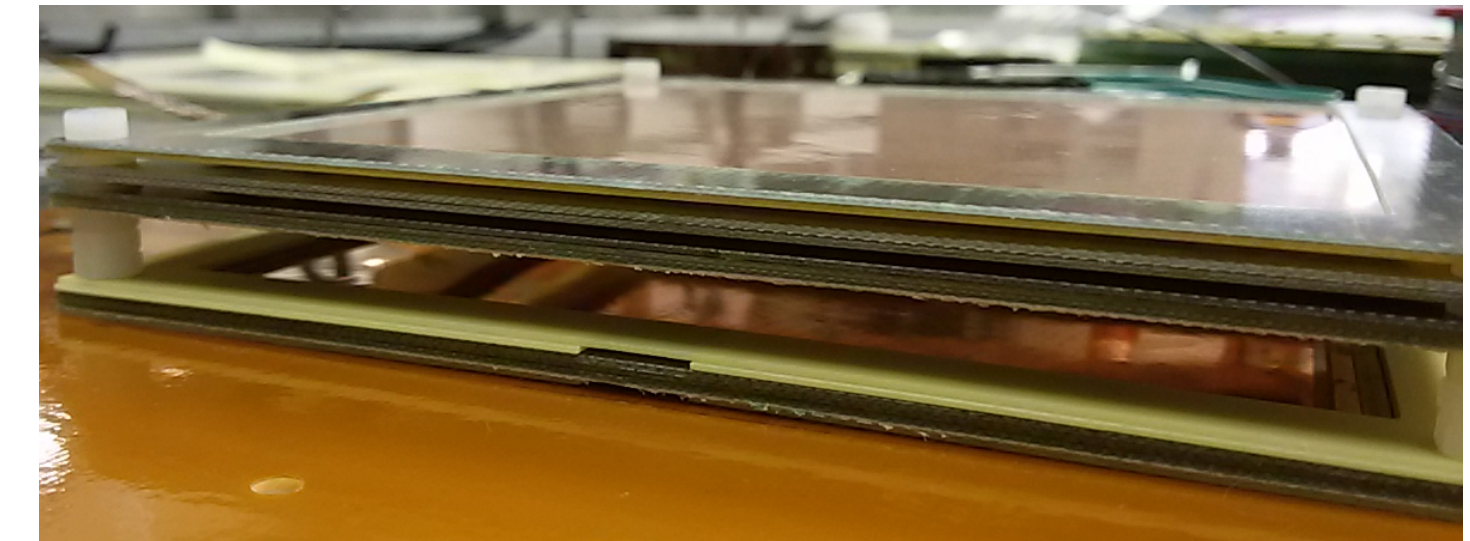
Assuming  $v_\chi = 2 \times 10^{-3} c$  and taking into account the QF

- Explore the region below 10 GeV/c<sup>2</sup>  $\Rightarrow$  low mass nuclei such as H and He

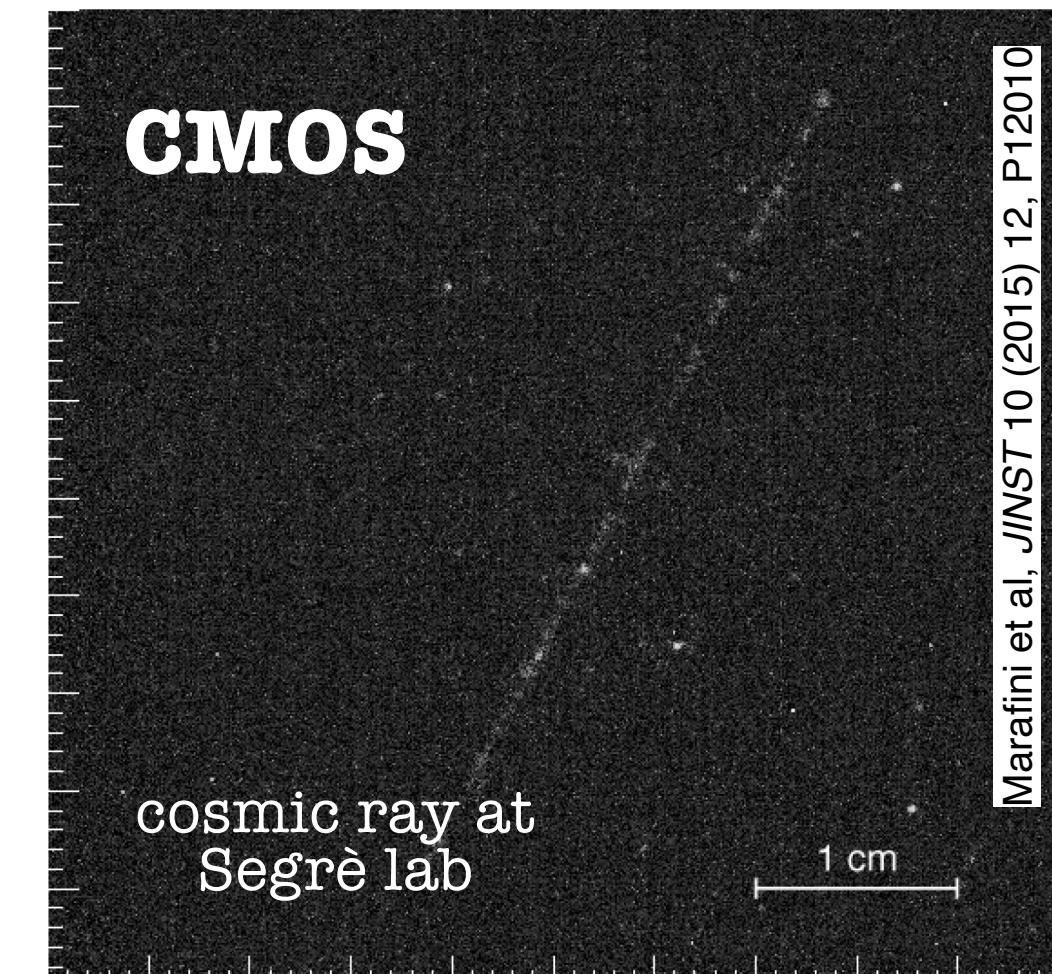
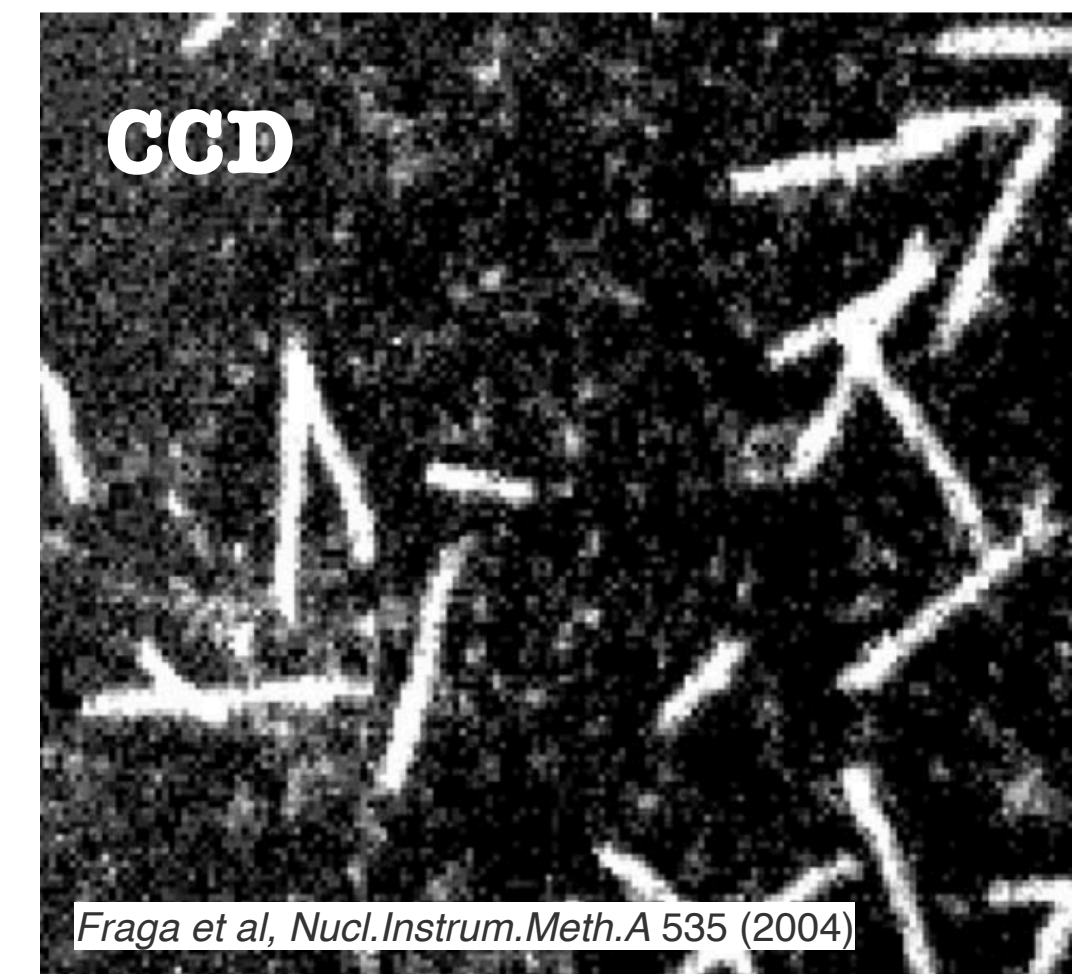


# ORANGE: an Optically ReAdout GEm device

- Triple 10 x 10 cm<sup>2</sup> GEM layer
- 1 cm sensitive drift gap
- He:CF<sub>4</sub> (60:40) gas mixture at atmospheric pressure
- Hamamatsu Orca-Flash 4.0 camera + 1 PMT



- **sCMOS** sensor showed significant lower noise w.r.t. **CCD** sensors



# z resolution from diffusion

$z$  = distance from the GEM plane

$S$  = width of the signal

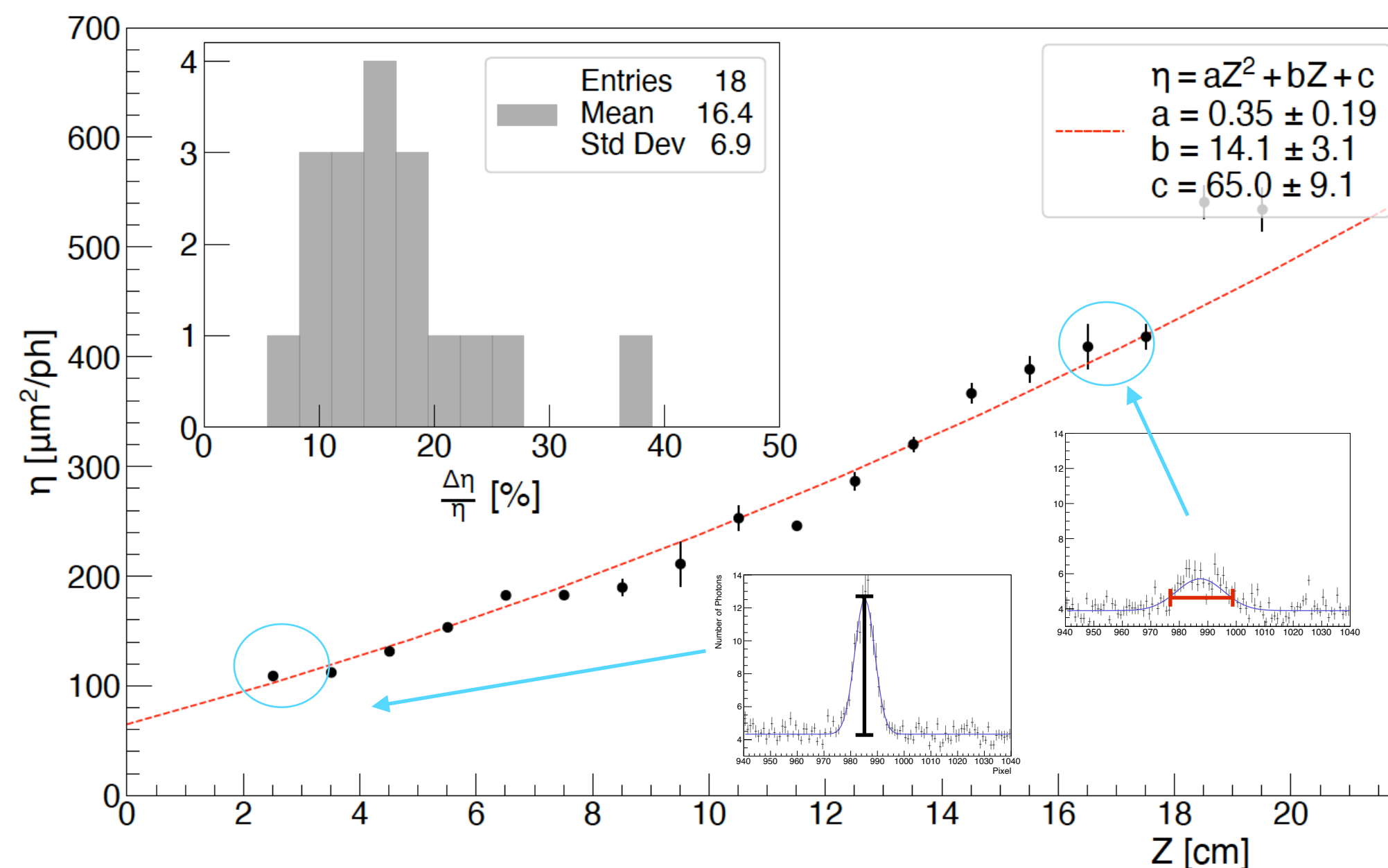
$A$  = amplitude of the signal

- Electron **diffusion** grows with increasing  **$z$**  (drift direction)
- **Light profile** and **PMT signals: lower and wider** with increasing  **$z$**

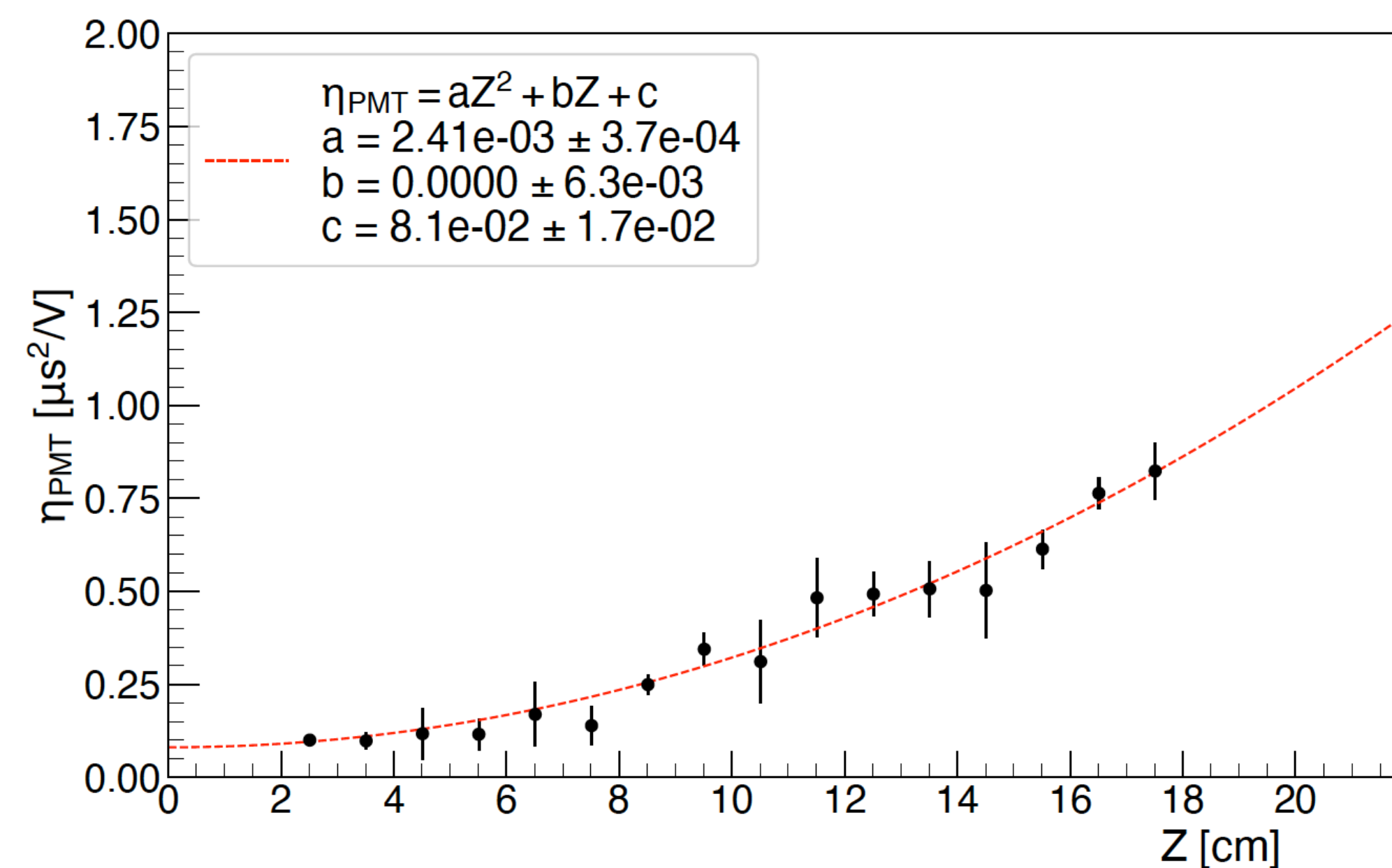
$$\eta \equiv \frac{S}{A} \text{ increases with } z$$

⇓

We can infer the  $z$  position measuring  $\eta$



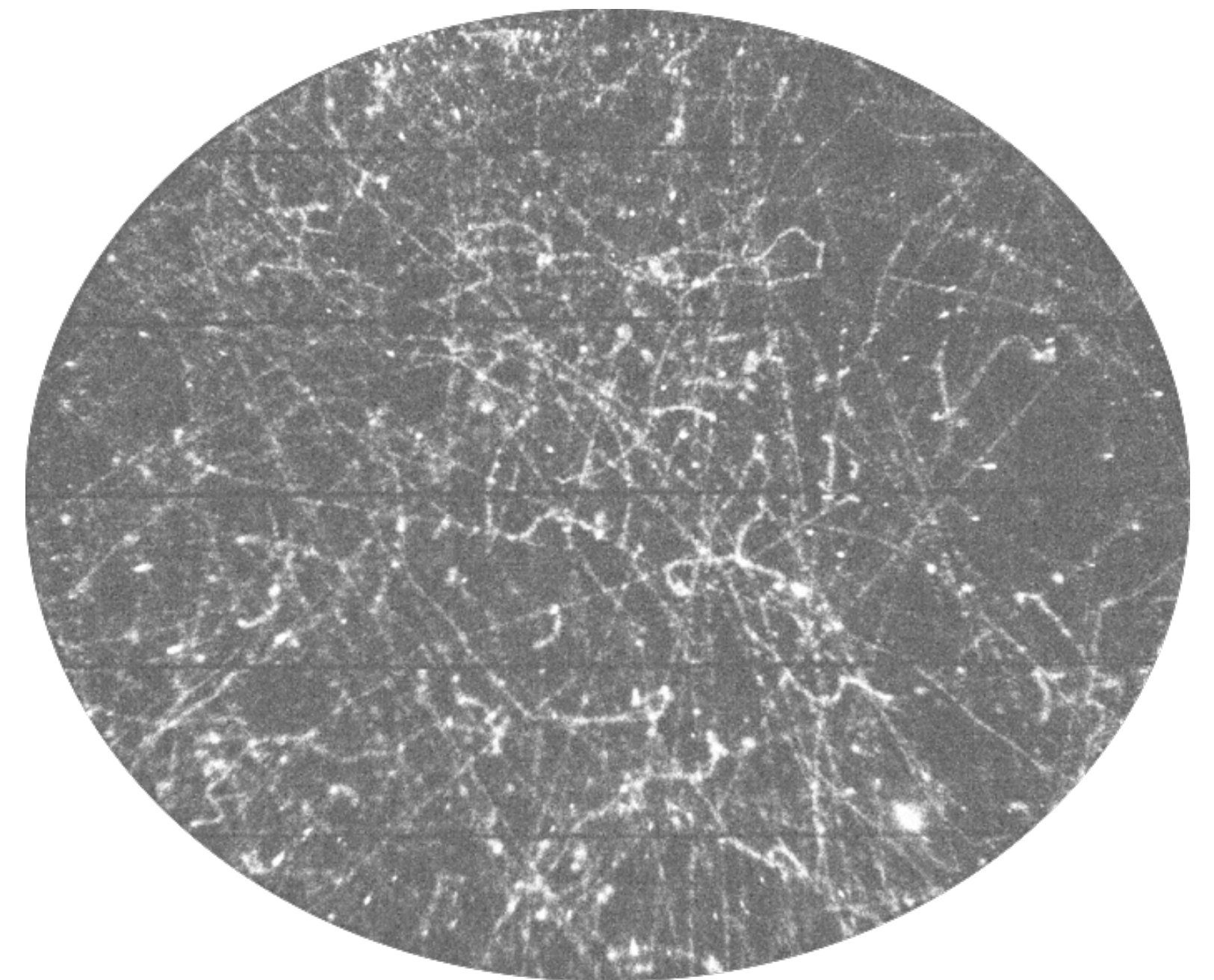
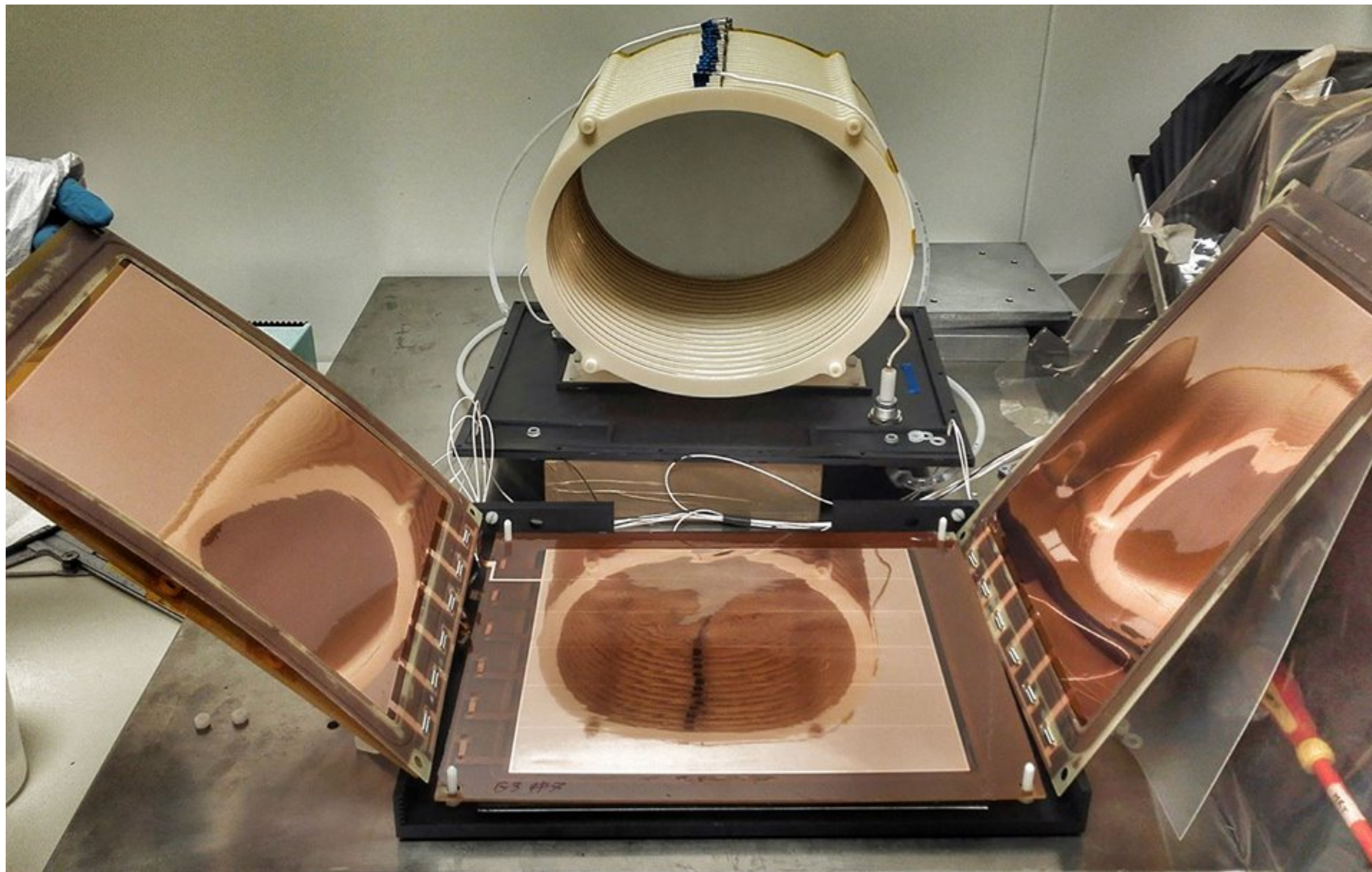
Antochi et al, Nucl.Instrum.Meth.A 999 (2021)



**z resolution of 15%**

# LEMON: Large Elliptical Module Optically Readout

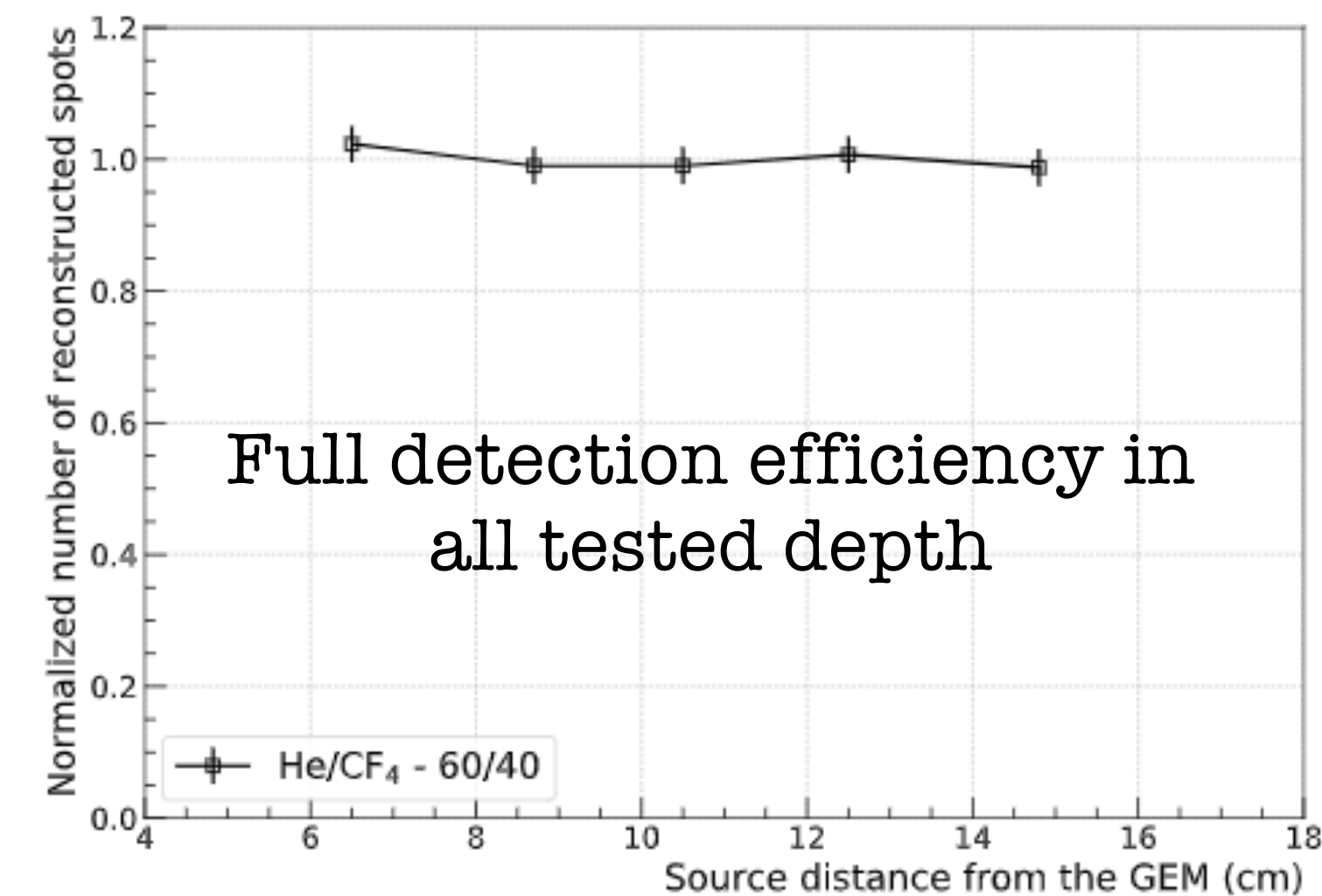
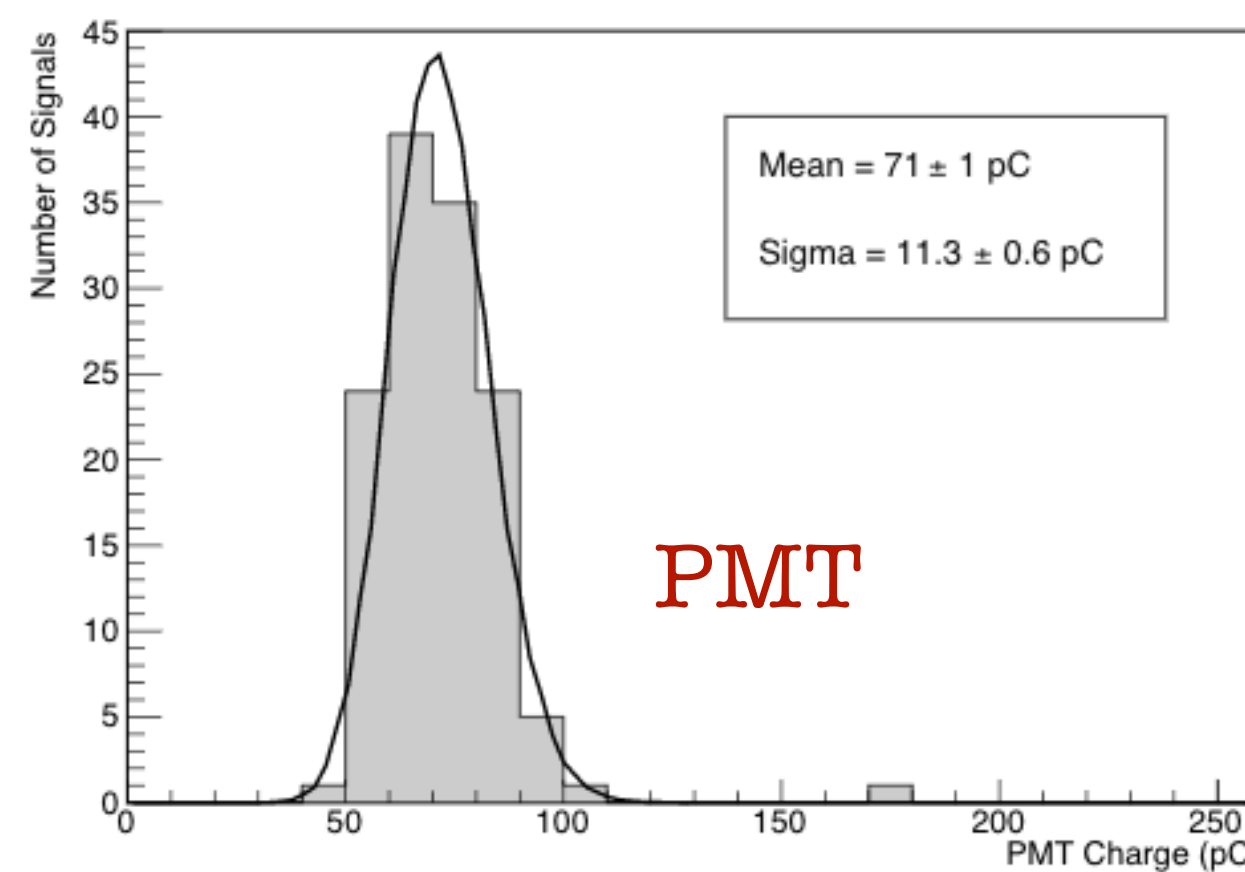
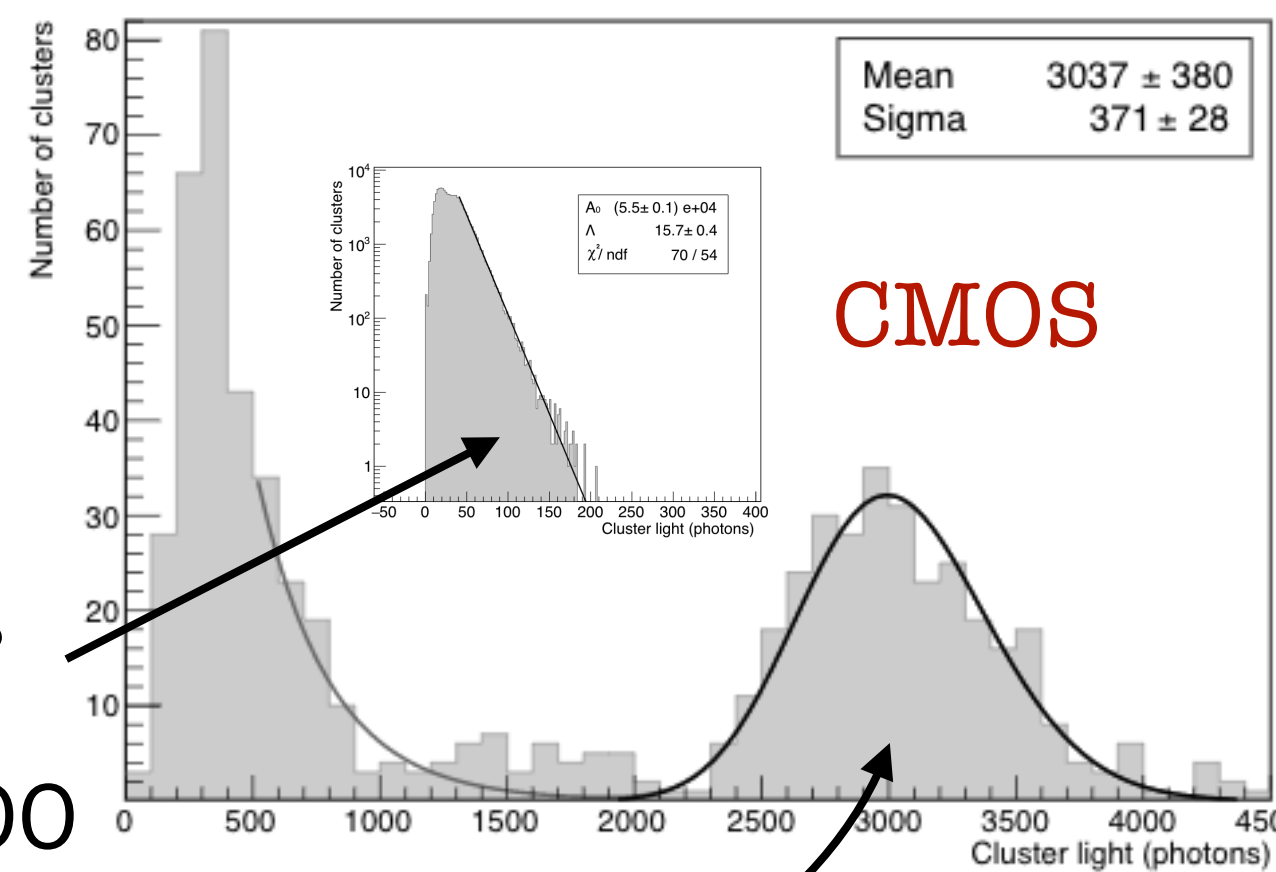
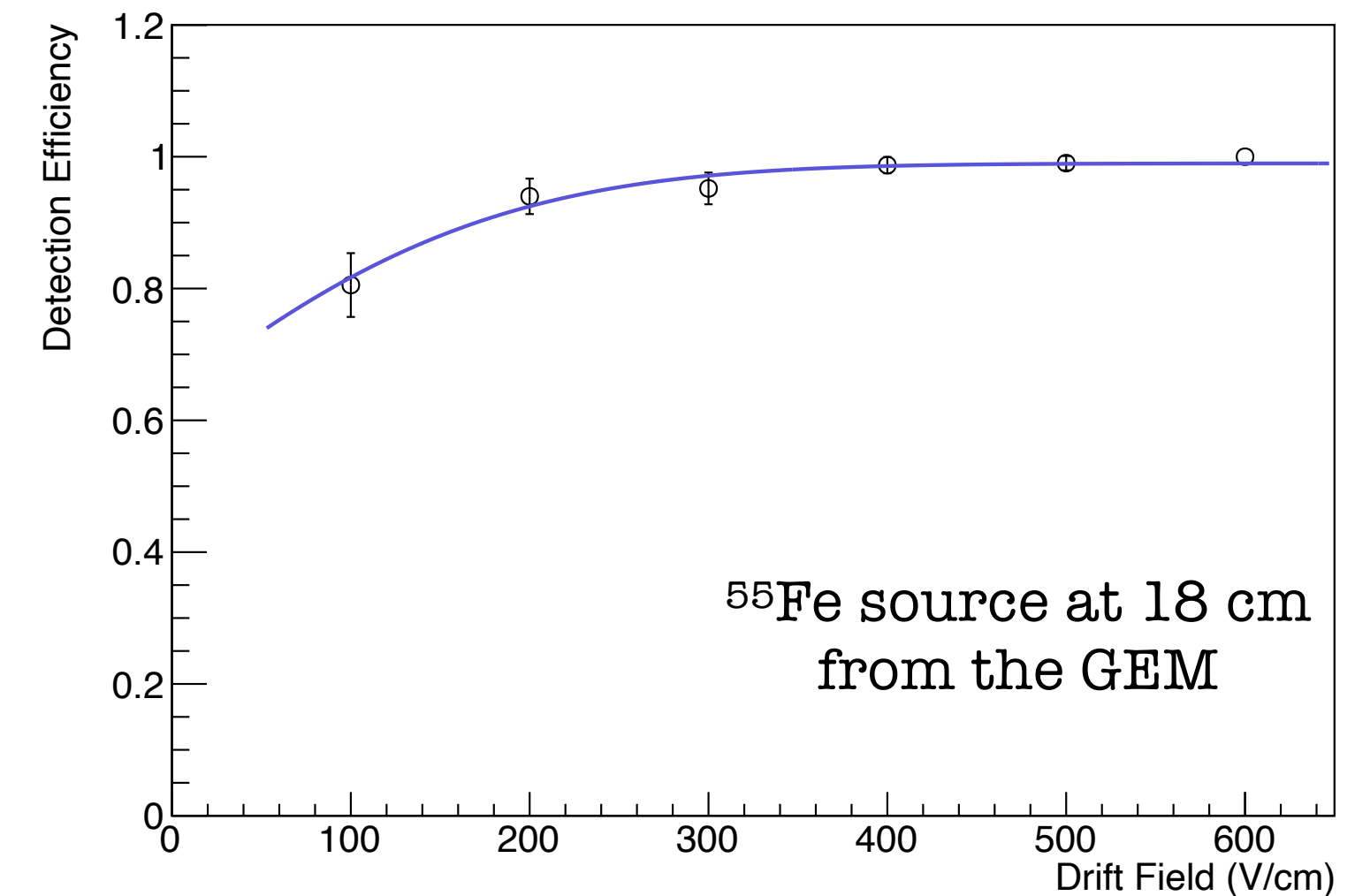
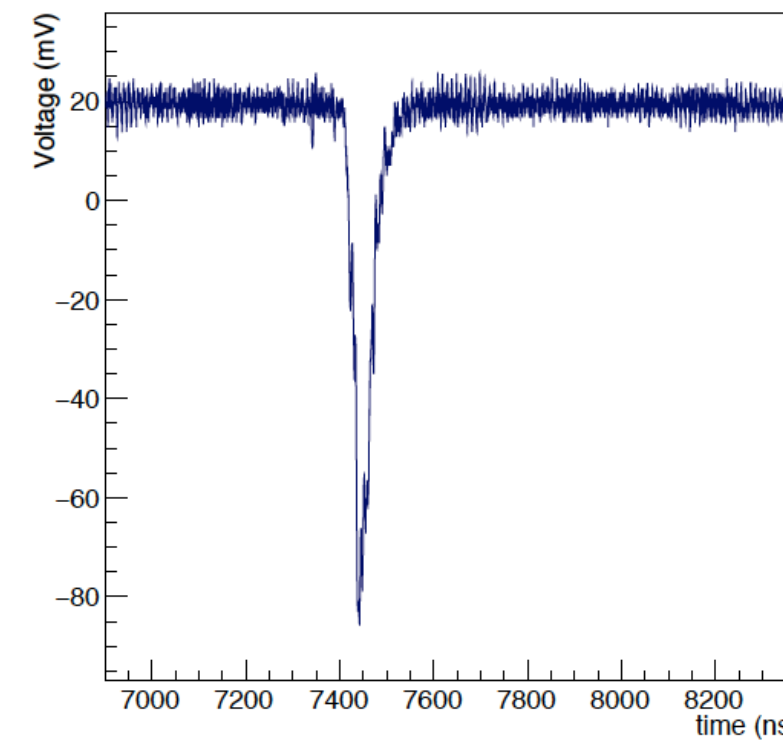
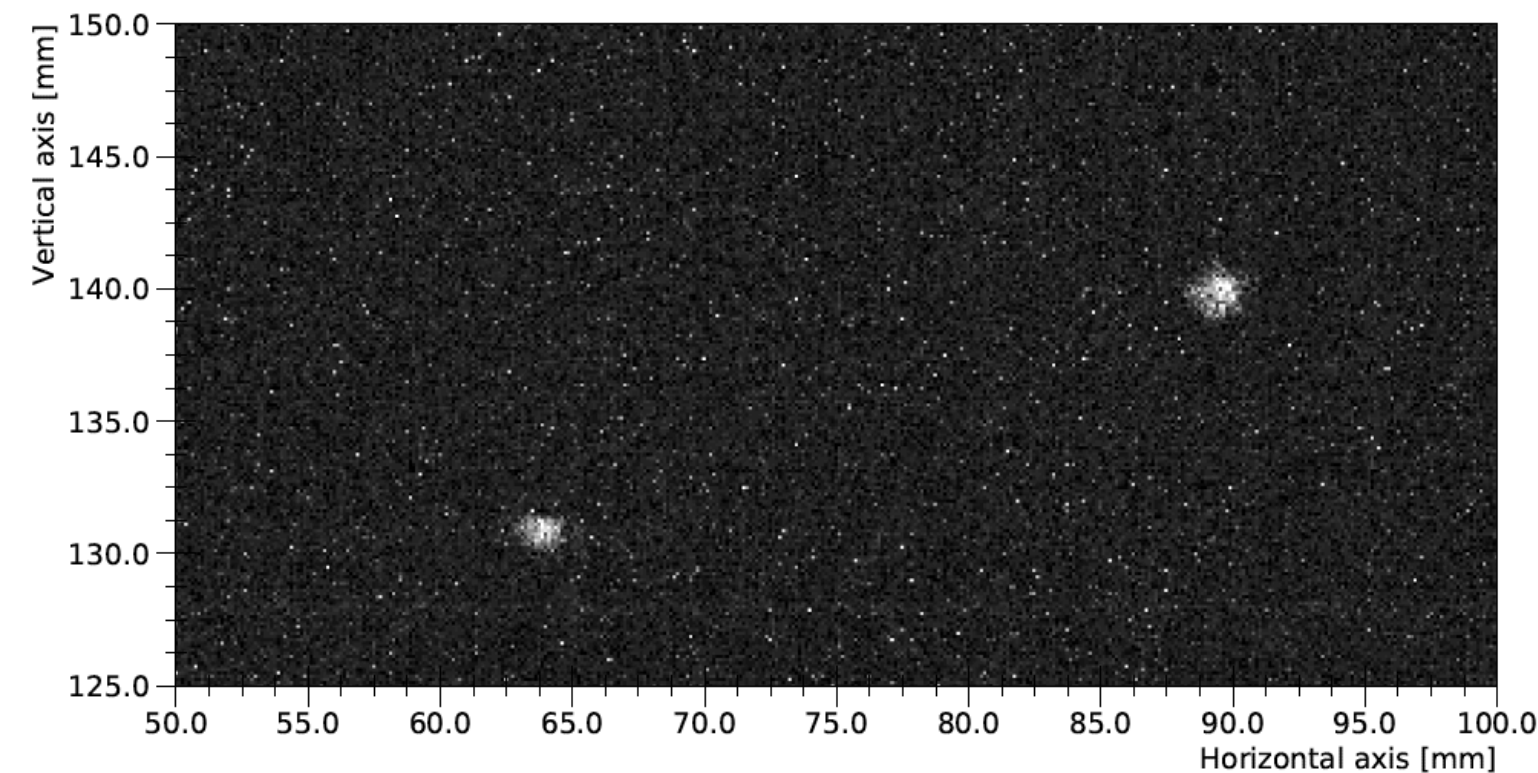
- Designed and built at **LNF**, realized using a **3D printer**
- 7 L of sensitive volume
- 500 cm<sup>2</sup> GEM surface
- 20 cm drift gap



Picture with 5 s exposure

# LEMON performance: the $^{55}\text{Fe}$ source

- $^{55}\text{Fe}$  source: 5.9 keV photons  $\Rightarrow$  spot-like tracks



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

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

$\sim 500$  ph / keV

**Energy resolution of 15% with CMOS and PMT**

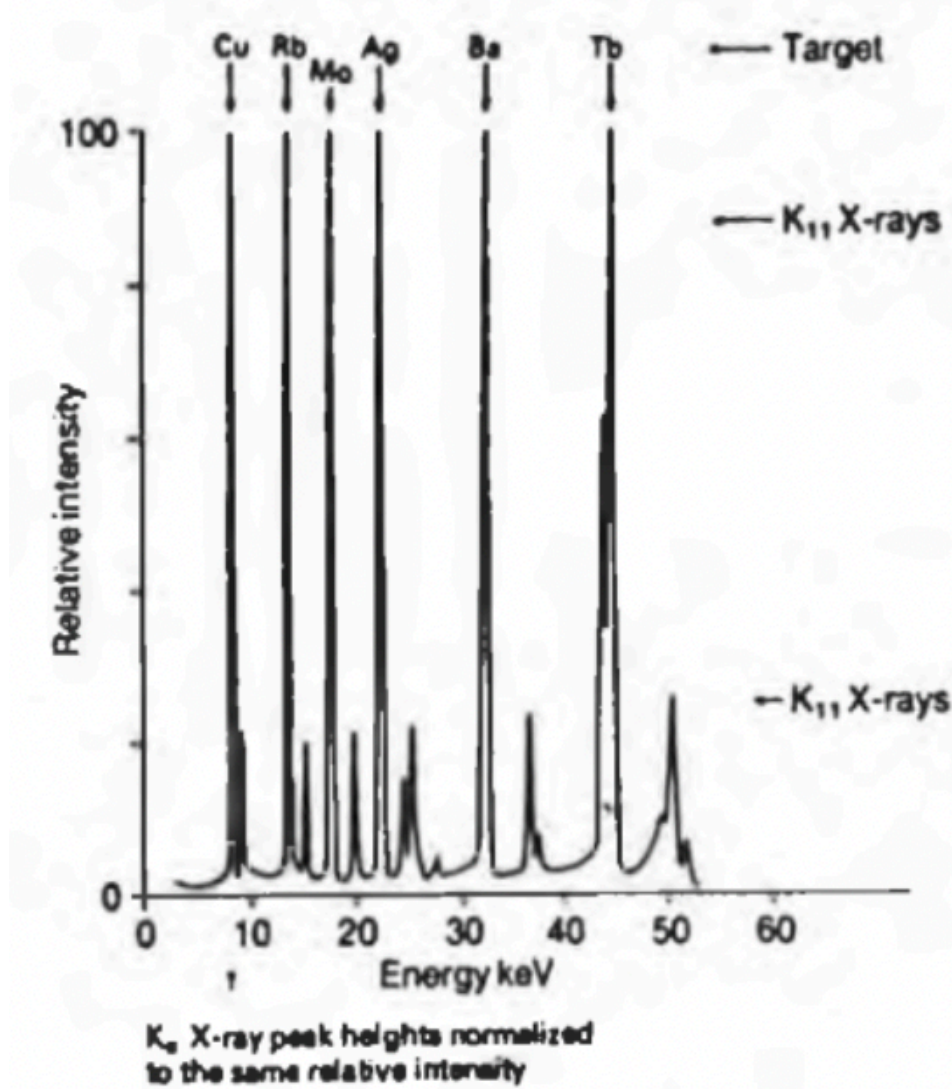
# LIME: ER calibration

- $^{55}\text{Fe}$  source  
[ $K_{\alpha} \sim 5.9 \text{ keV}$ ,  $K_{\beta} \sim 6.4 \text{ keV}$ ]
- Multi-target source

Material	Energy $K_{\alpha}$ [keV]	Energy $K_{\beta}$ [keV]
Cu	8.04	8.91
Rb	13.37	14.97
Mo	17.44	19.63
Ag	22.10	24.99
Ba	32.06	36.55

- Ti and Ca X-ray source

Material	Energy $K_{\alpha}$ [keV]	Energy $K_{\beta}$ [keV]
Ti	4.51	4.93
Ca	3.69	4.01



target selected	energy (keV) <sup>(1)</sup>		photon yield <sup>(2)</sup> (photons/sec per steradian)
	$K_{\alpha}$	$K_{\beta}$	
Cu	8.04	8.91	$2.5 \times 10^3$
Rb	13.37	14.97	$8.8 \times 10^3$
Mo	17.44	19.63	$2.43 \times 10^4$
Ag	22.10	24.99	$3.85 \times 10^4$
Ba	32.06	36.55	$4.65 \times 10^4$
Tb	44.23	50.65	$7.6 \times 10^4$

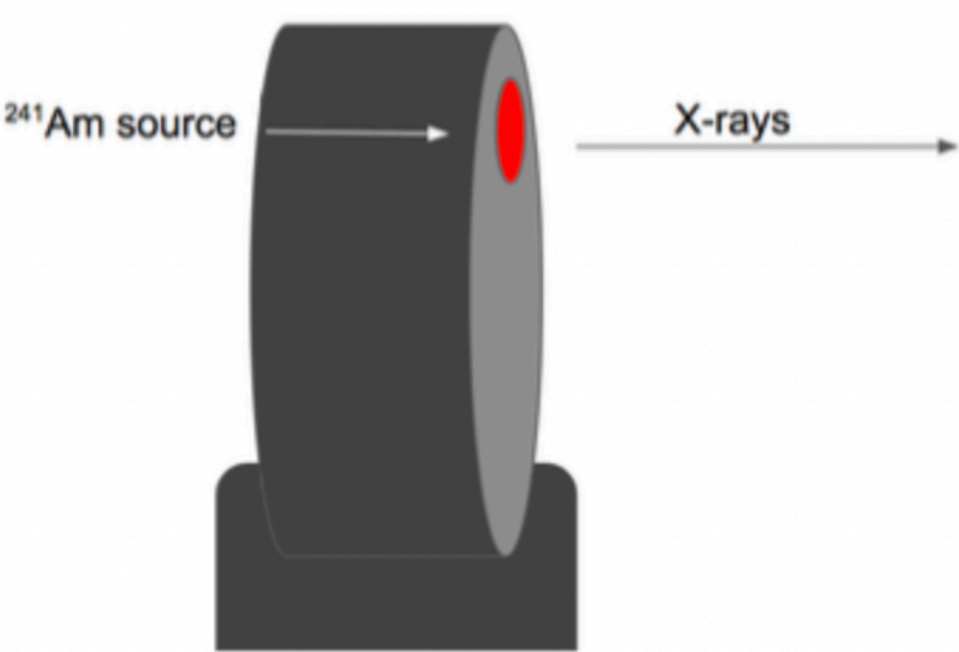
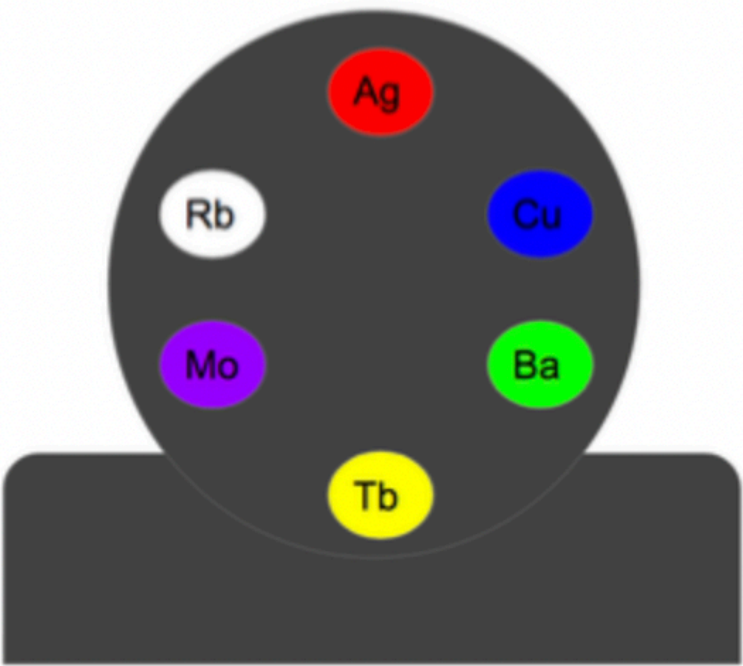
**Notes**  
(1) Weighted mean energies  
(2) The photon output is highly collimated limiting emission to  $\sim 0.5$  steradians.

**Primary source**  
A 10mCi, 370MBq americium-241 source\*, consisting of a ceramic active component in a welded stainless steel capsule, with integral tungsten alloy rear shielding.

\*activity tolerance  $-0, +25\%$

These sources are also available with an iron-55 primary source for lower energy spectrometry.

**Recommended working life 15 years**



(a) Front view of the Amersham AMC.2084 (b) Side view of the Amersham AMC.2084 x-ray

# LIME: ER calibration

- **Data selection (DS):**

➡ Loose DS to enhance SNR

- **Background Model:**

➡ Bernstein Polynomials fitted on the no-source spectrum

- **Signal Model** for the two lines:

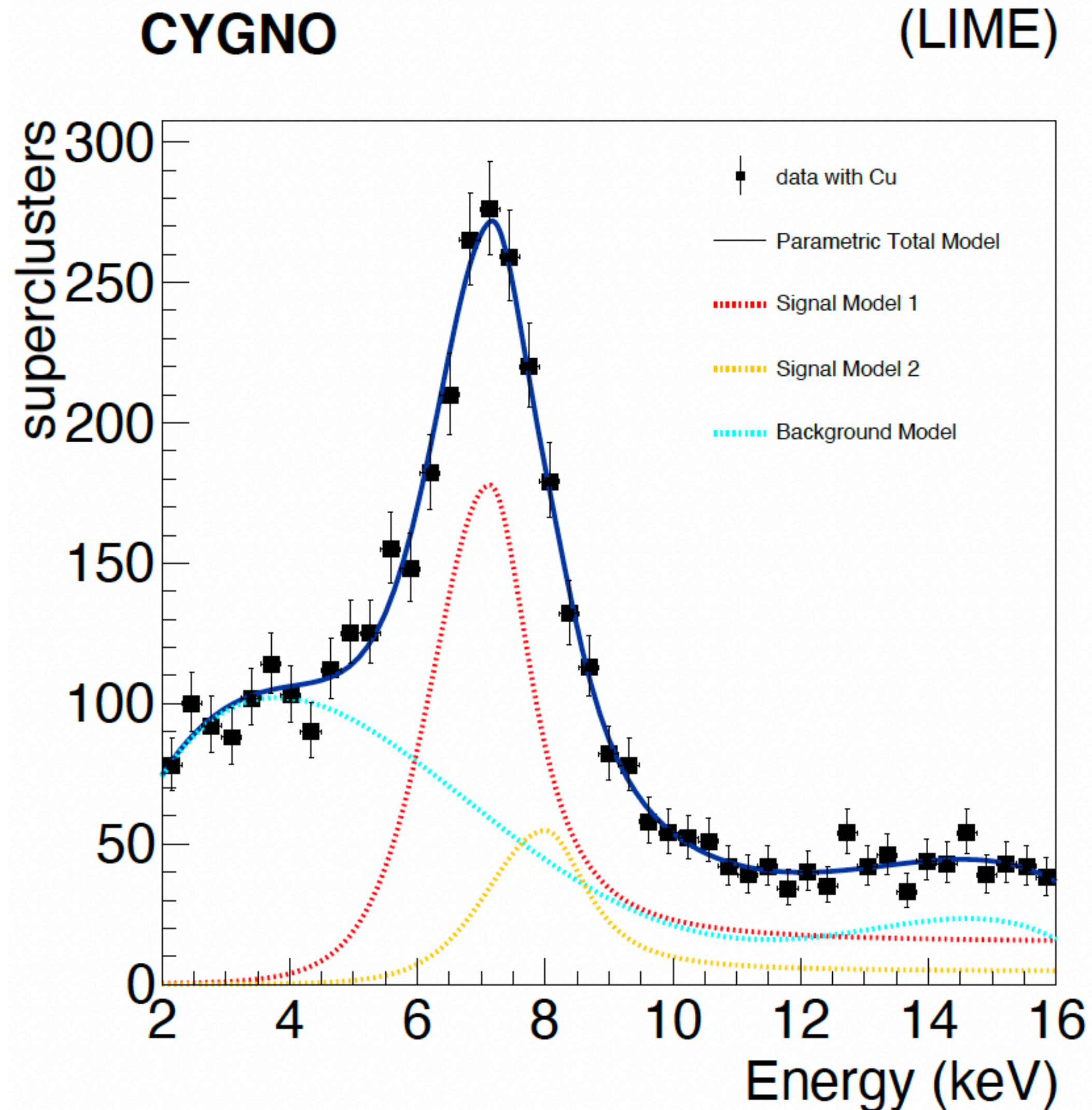
➡ Two Cruiff functions

➡ Constraints:

▶ fixed energy difference

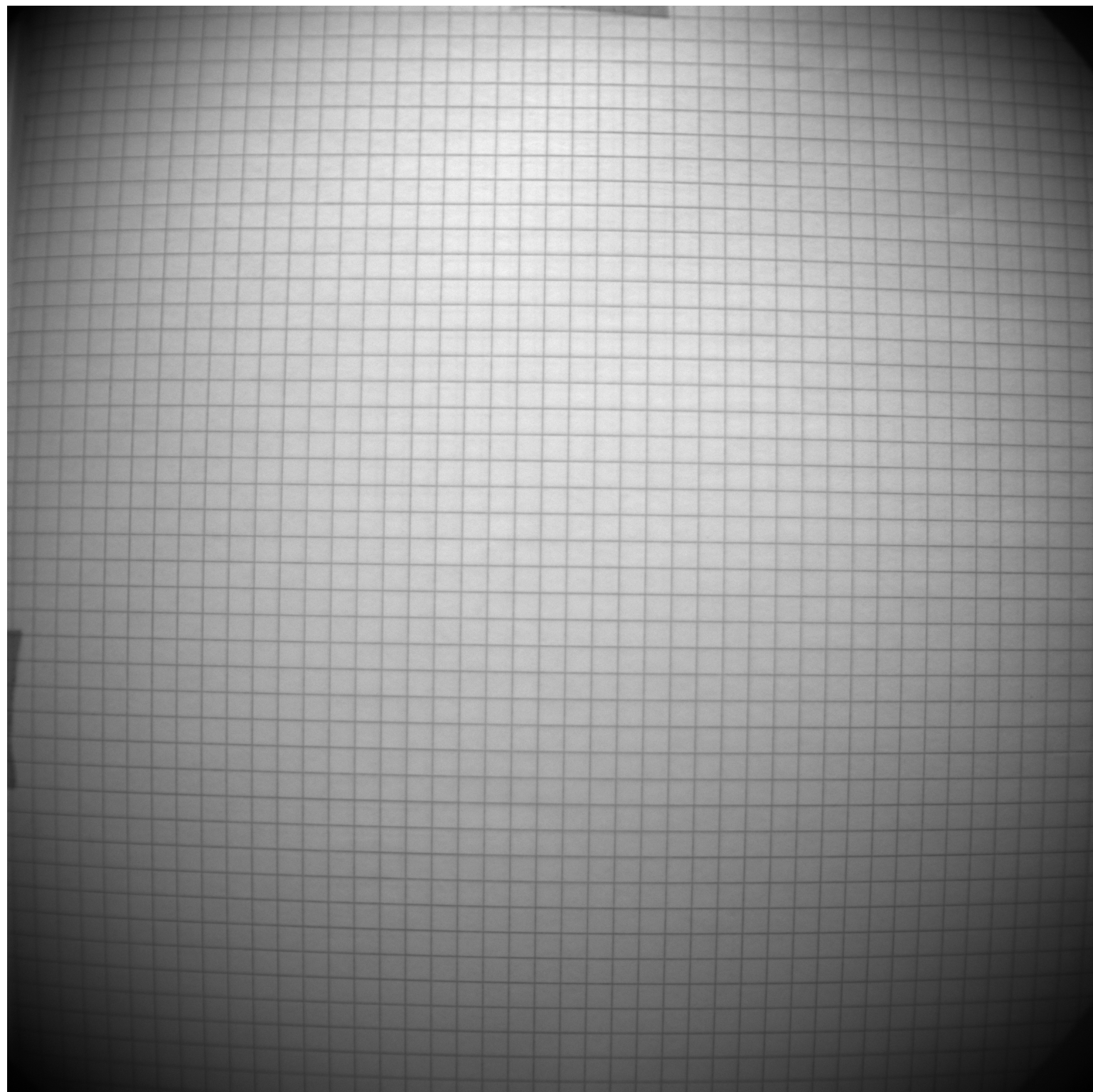
▶ same shape parameters

▶ contribution of the smaller line  $f_2 < 0.3$

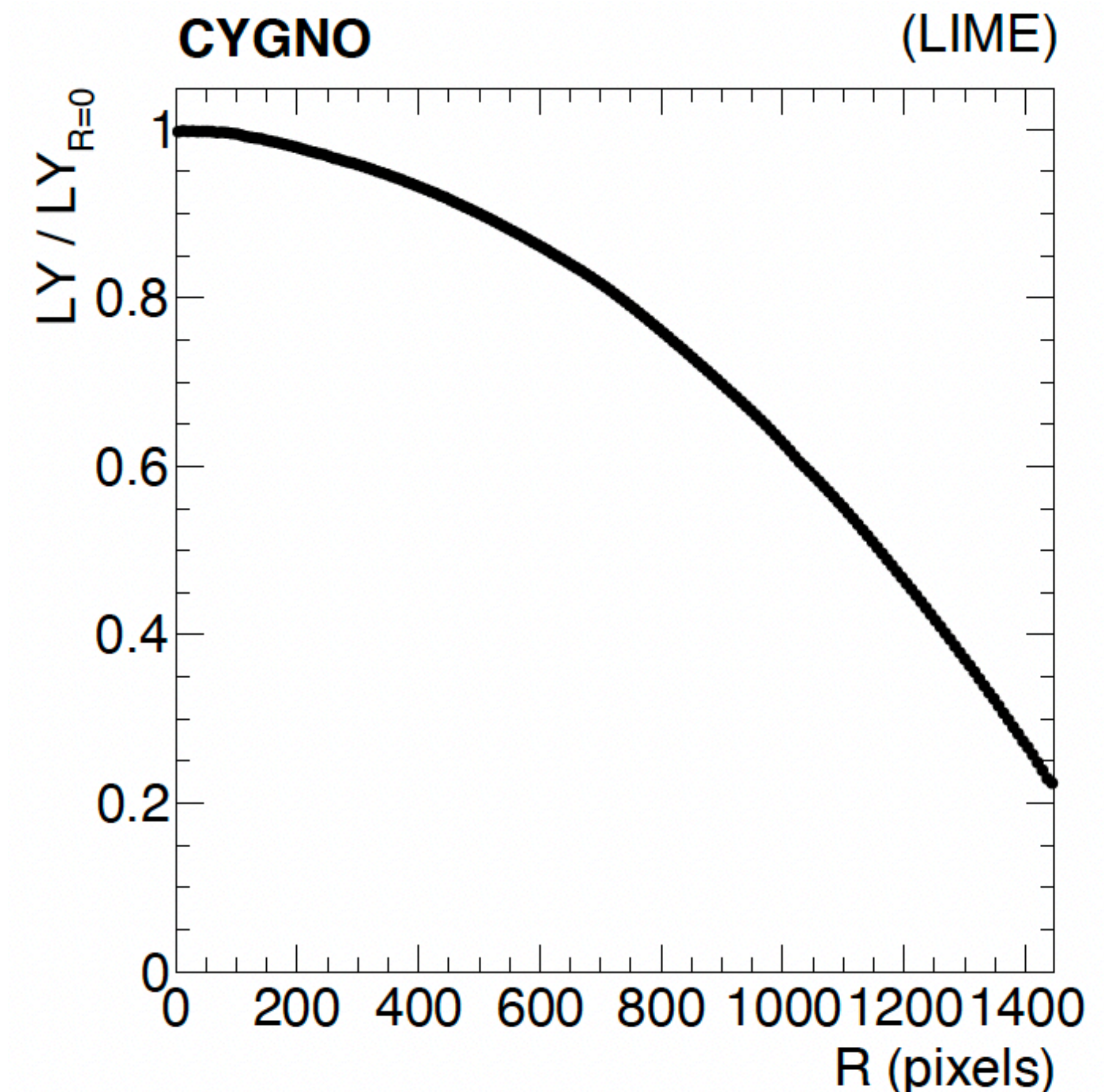


# LIME: optical vignetting

- **Vignetting:** reduction of light in the peripheral region of the sensors **due to the lens**

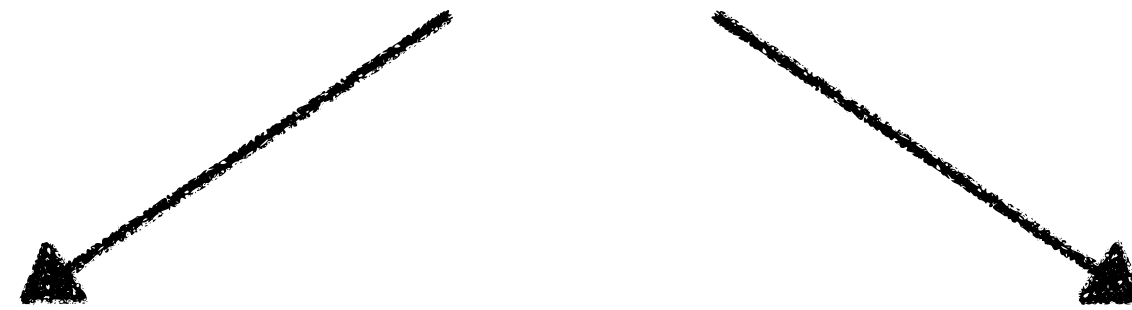


- **Correction map** extracted from pictures to uniformly illuminated white surfaces



# LIME: sensor noise and pedestal subtraction

- Dedicated “**pedestal**” runs with GEMs voltage at 200 V to infer the **sensor noise** in absence of any light

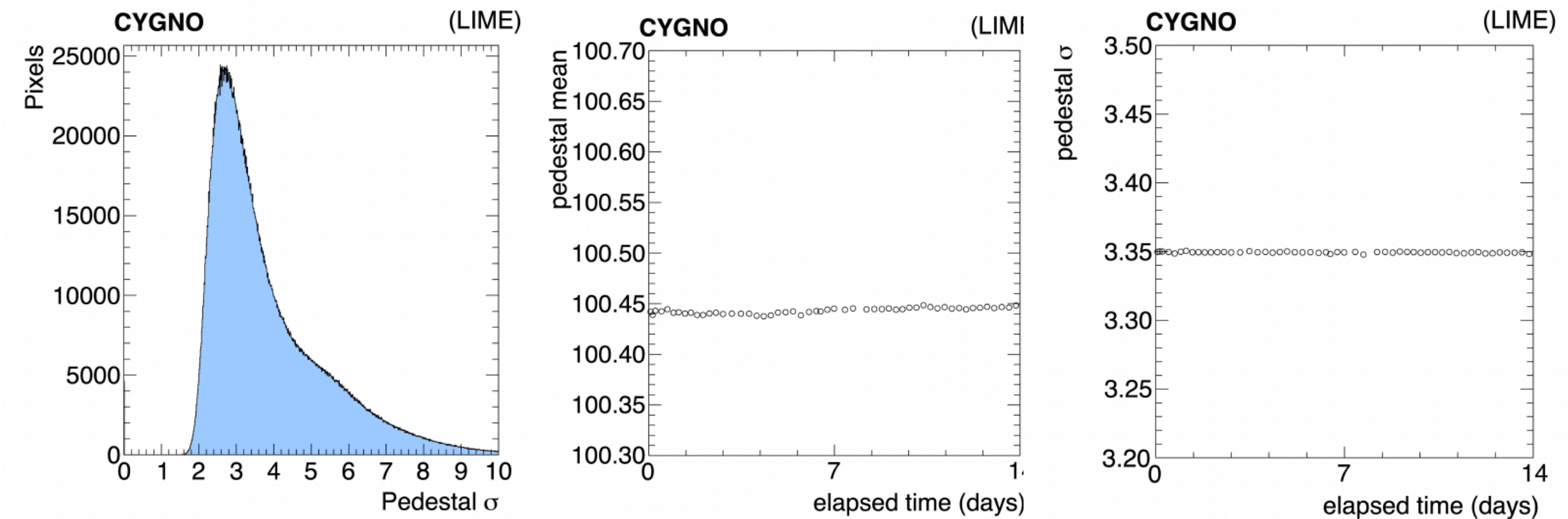


## Readout electronic noise:

- ➔ due to the amplifiers of each pixel
- ➔  $< 0.7$  electrons r.m.s.

## Dark current:

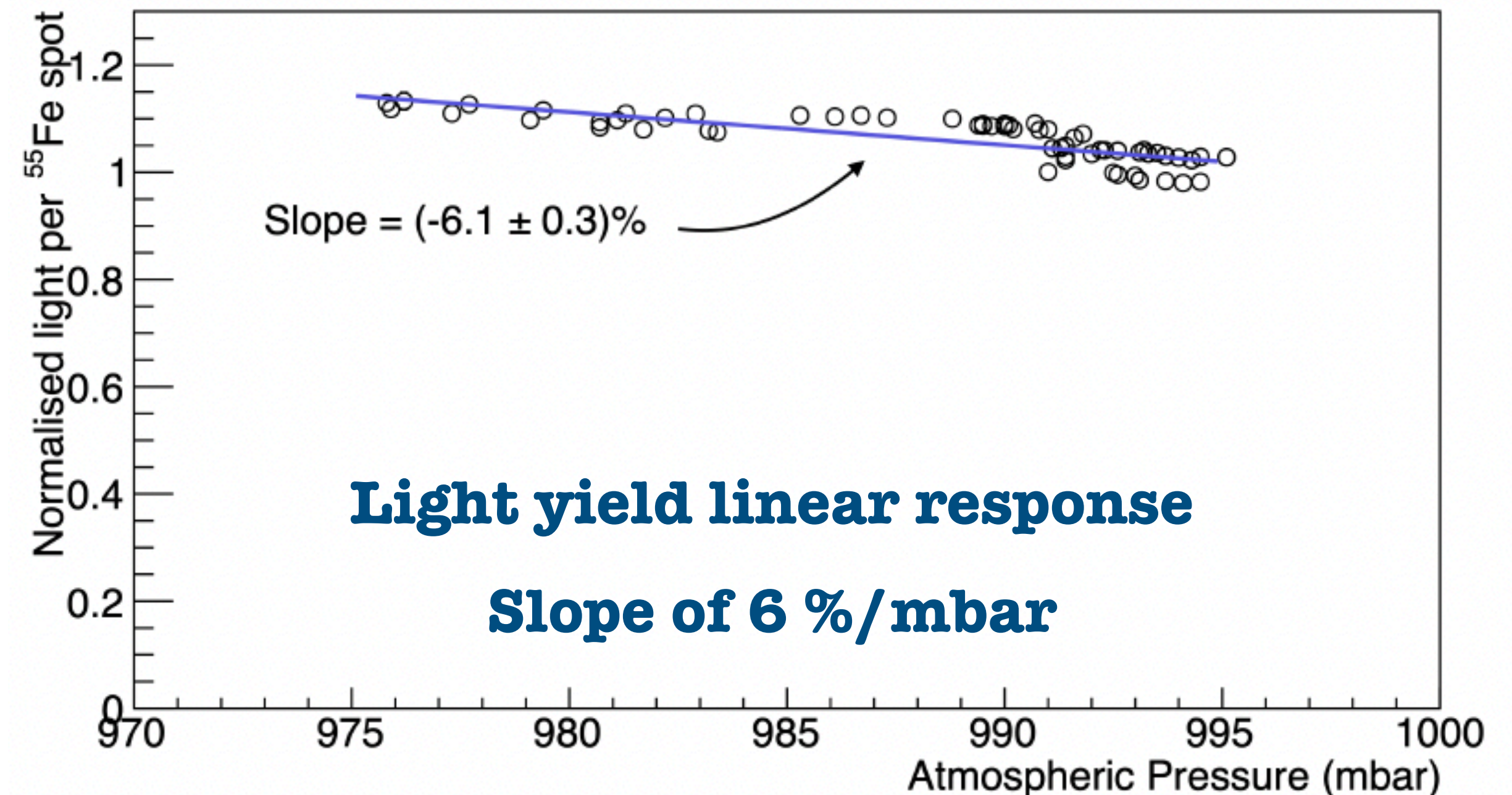
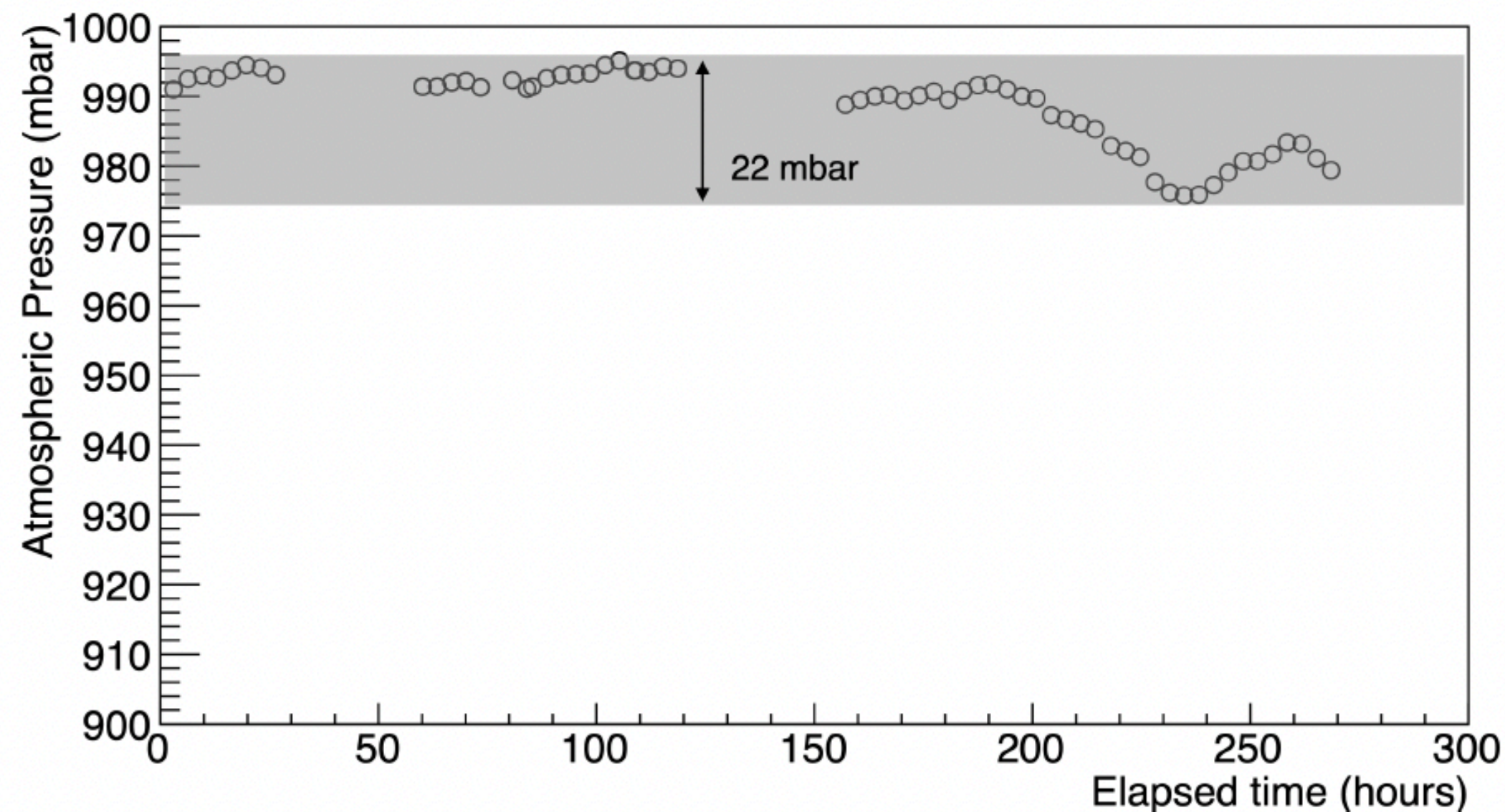
- ➔ related to the camera photo-diodes
- ➔ 0.2 electrons / pixel / s



- **Very good stability**
- **Top** and **bottom** part of the sensor are **noisier**
- **Pedestal** pixel-by-pixel **mean**: subtracted to the pictures
- **Pedestal** pixel-by-pixel **std**: used to define a threshold for reconstruction

# LIME: long term stability

- Two weeks of continuous overground data taking
- Controlled **temperature** of  $(298.7 \pm 0.3)$  K
- **Pressure** monitoring



# R&D: enhanced light yield

- **Idea:** enhance the light yield in the gas by accelerating electrons below last GEM
- **First evidence:**
  - ➔ **Charge yield** increased by a factor of **x1.7**
  - ➔ **Light yield** increased by a factor of **x7.0**

