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

Towards an optically readout TPC for rare events: the LIME prototype

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on behalf of:

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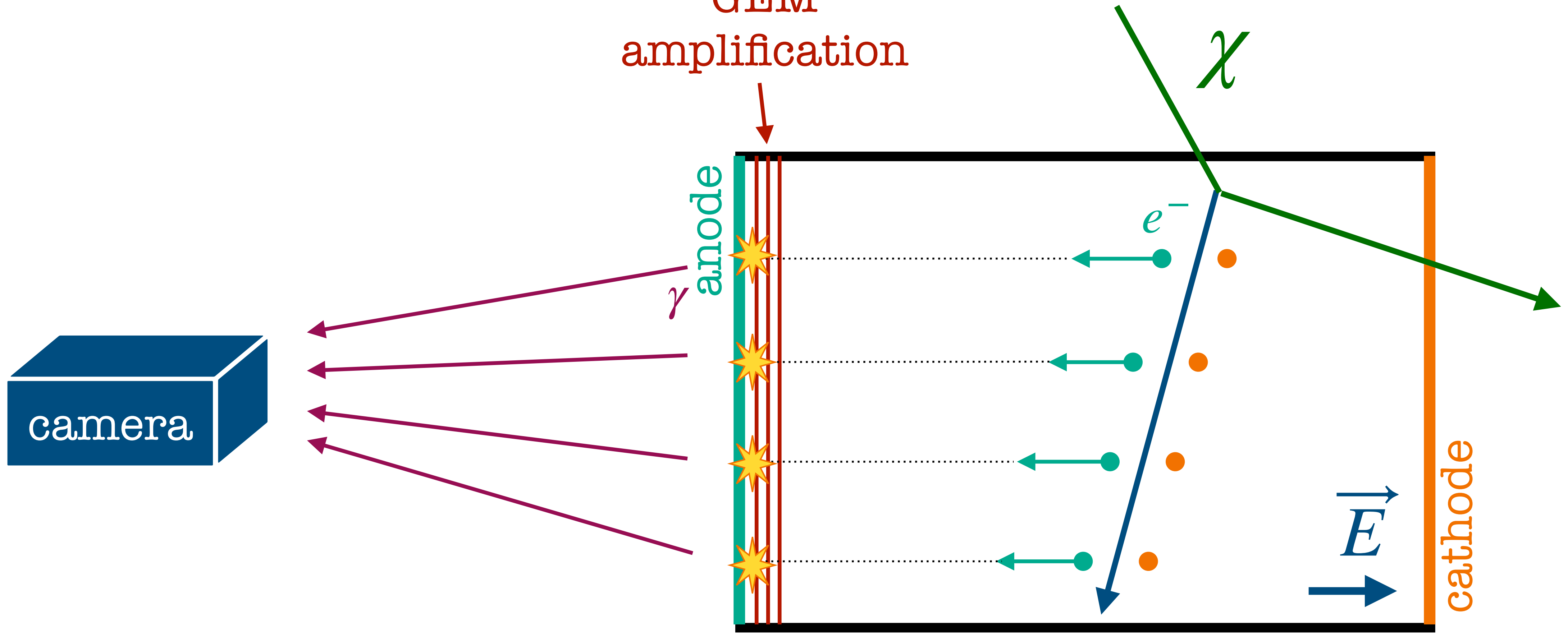
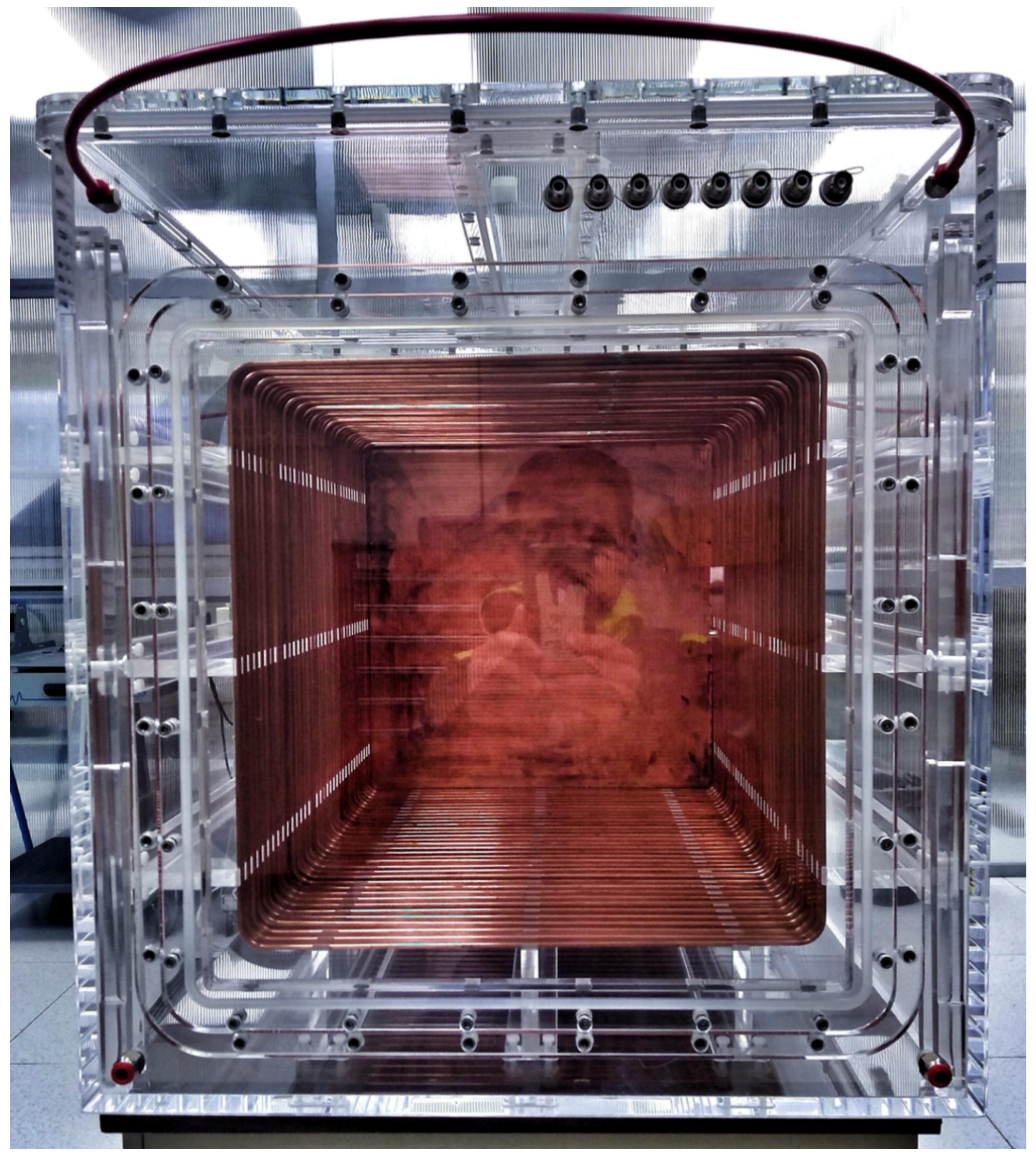
The CYGNO project

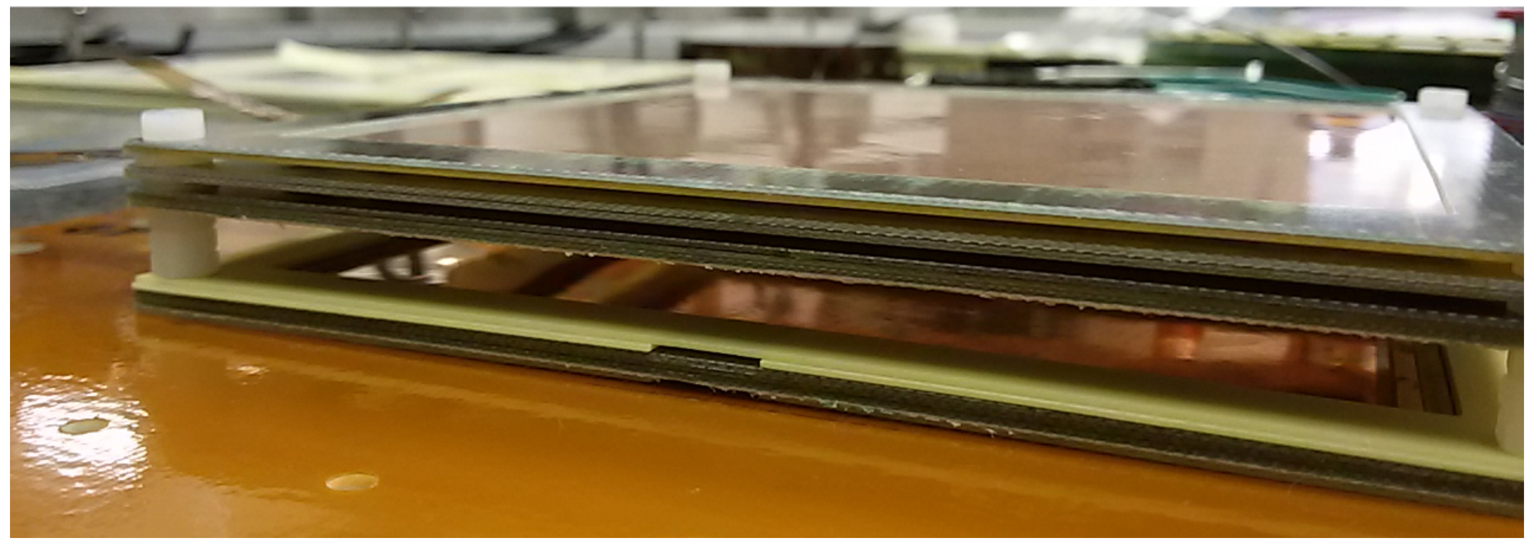
- **Aiming for** a large detector for high precision **3D tracking of rare low energy nuclear recoils** (keV) possibly induced by **dark matter** (DM) particles and solar neutrinos
- **Experimental challenges:** rate O(evt/kg/year), background rejection, and energy threshold (keV)
- **Strategy: photograph nuclear recoils** in a (1 atm) $He:CF_4$ TPC with a GEM amplification stage

➡ low energy events in 1 atm gas ⇒ visible tracks





TPC of the LIME prototype @ LNF



Amplification with GEMS

sCMOS camera [Hamamatsu Orca-Fusion]

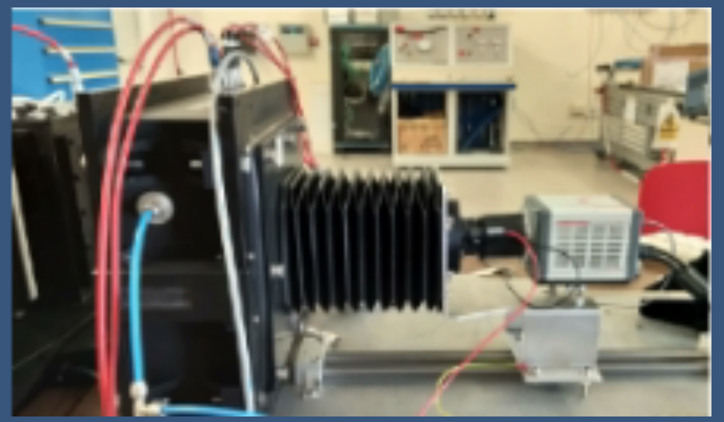
4 PMTs [Hamamatsu R7378]

The CYGNO timeline

INITIUM: NID studies

Currently at LNGS

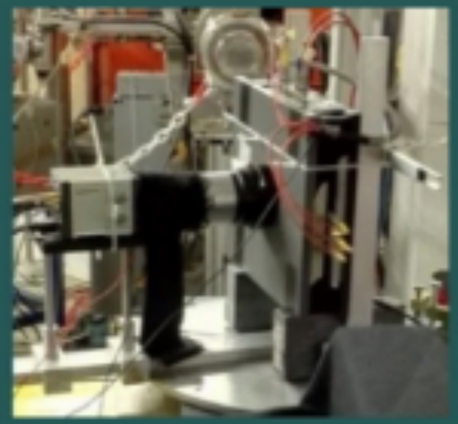
MANGO



- up to 5 cm drift
- for gas studies

PHASE 0: R&D and prototypes

2015/16 ROMA1 — ORANGE



- 1 cm drift

2017/18 LNF — LEMON

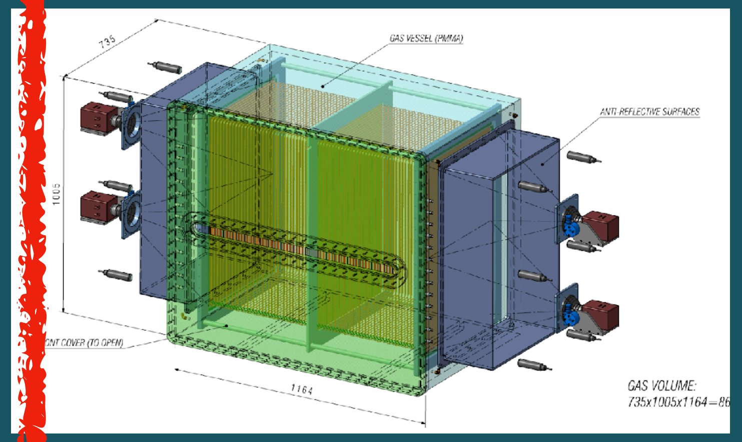
- 3D printing
- 20 cm drift

2019/23 LNF/LNGS — LIME

- 50 cm drift
- underground tests
- MC validation

PHASE 1: O(1) m^3 demonstrator

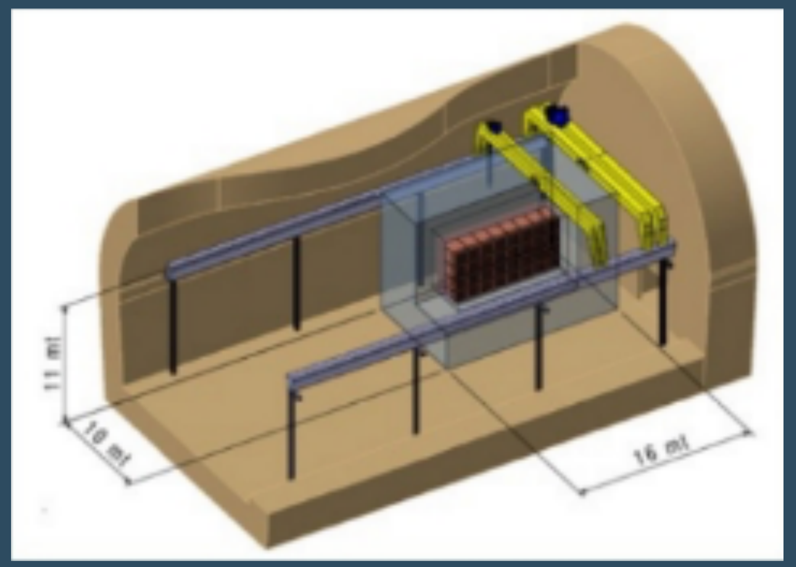
2023/26 LNF/LNGS — CYGNO_04



- background
- material tests, gas purification
- scalability

PHASE 2: 30 m^3 experiment

2026 ... LNGS — CYGNO_30



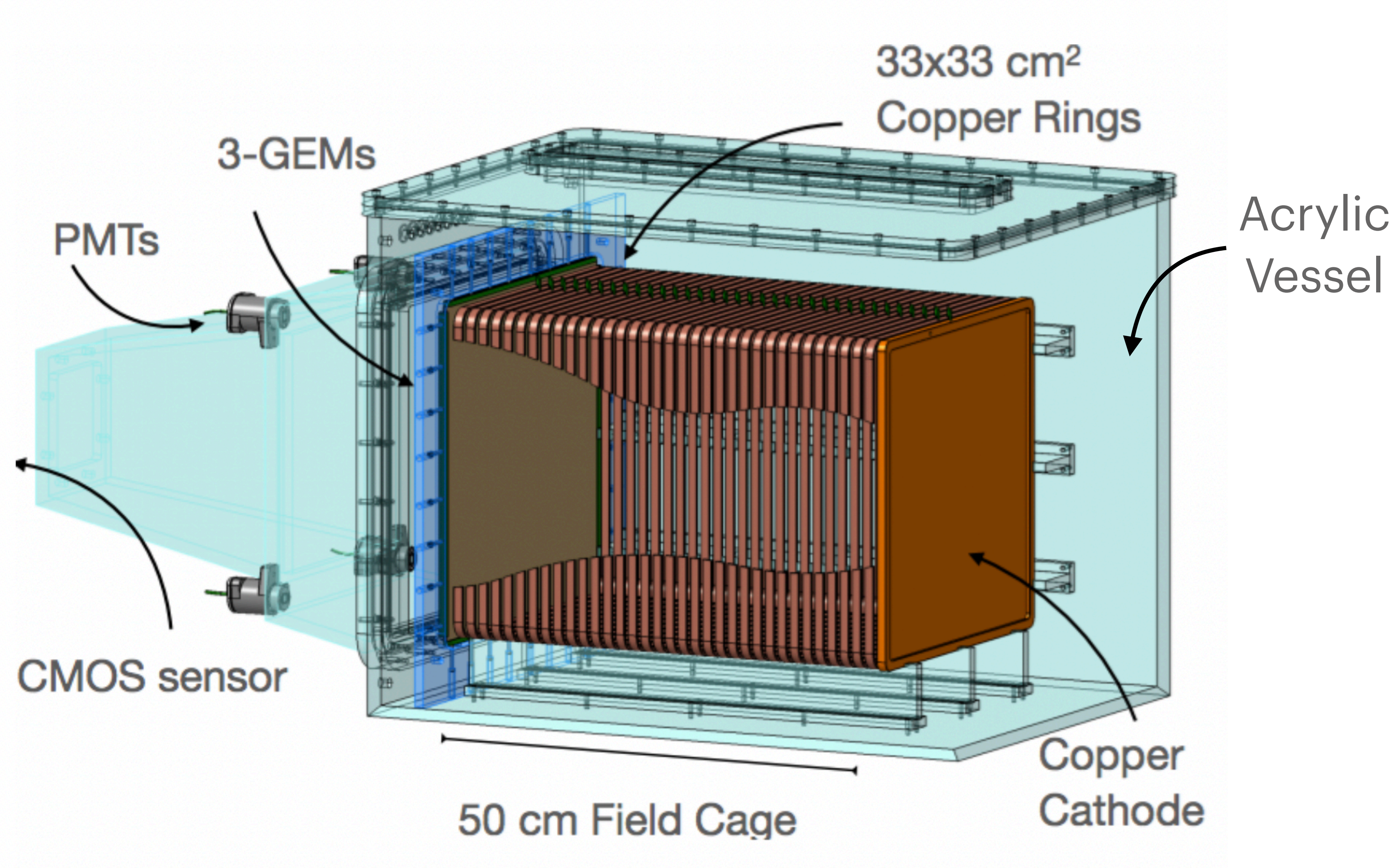
- Physics research

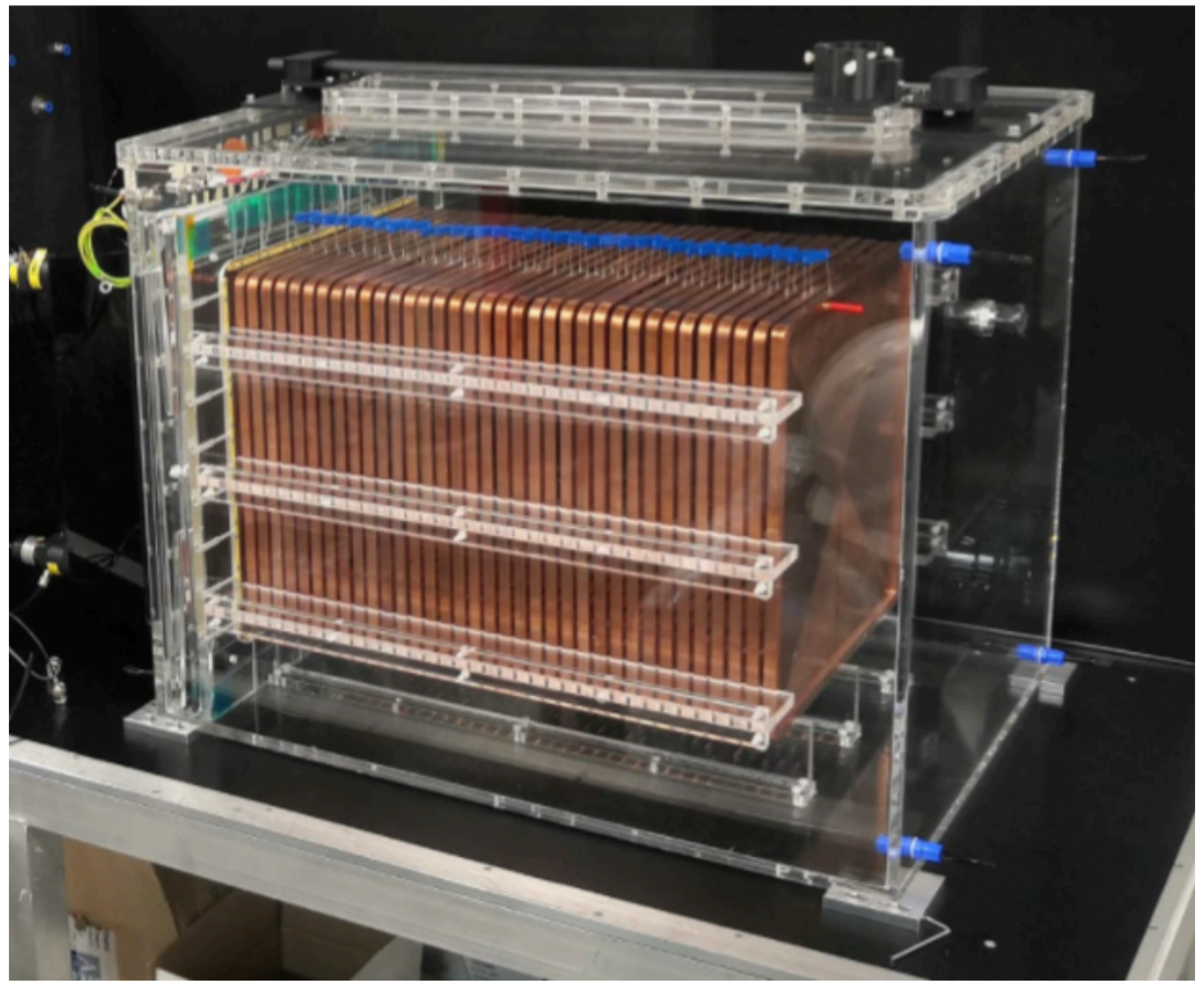
Instruments 6 (2022) 1, 6
JINST 15 (2020) 12, T12003
JINST 15 (2020) P08018
Measur.Sci.Tech. 32 (2021) 2, 025902
JINST 15 (2020) P10001
2019 JINST 14 P07011
NIM A 999 (2021) 165209

LIME: Long Imaging ModulE

4 Hamamatsu R7378 PMTs

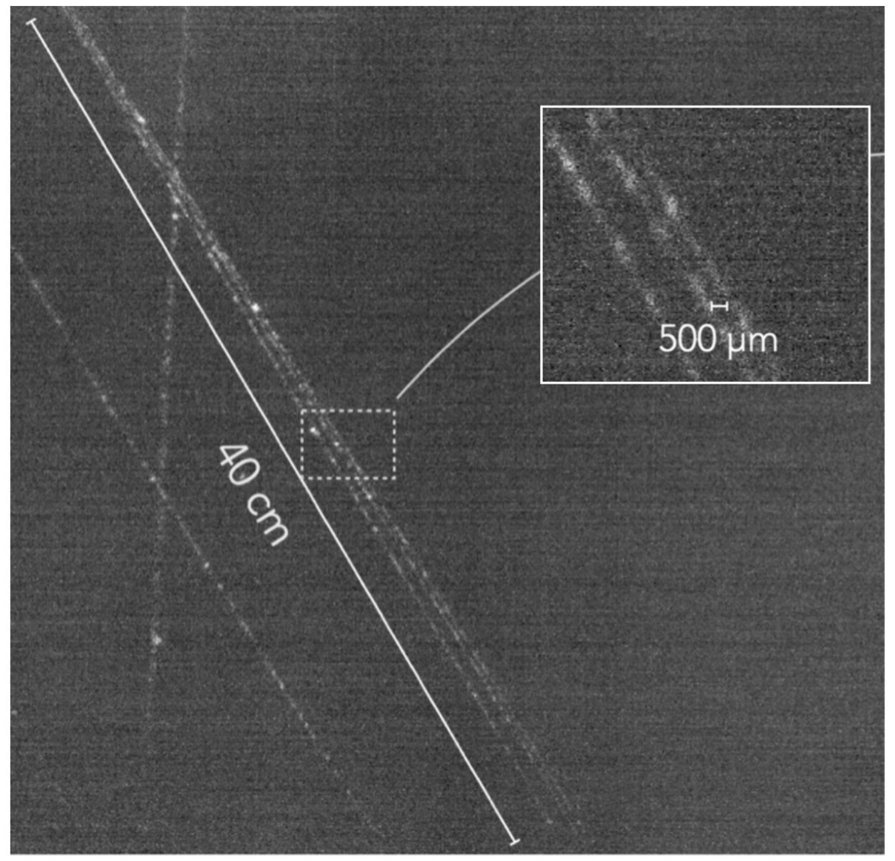
- Designed at **RM1 and LNF** and built at **LNF**



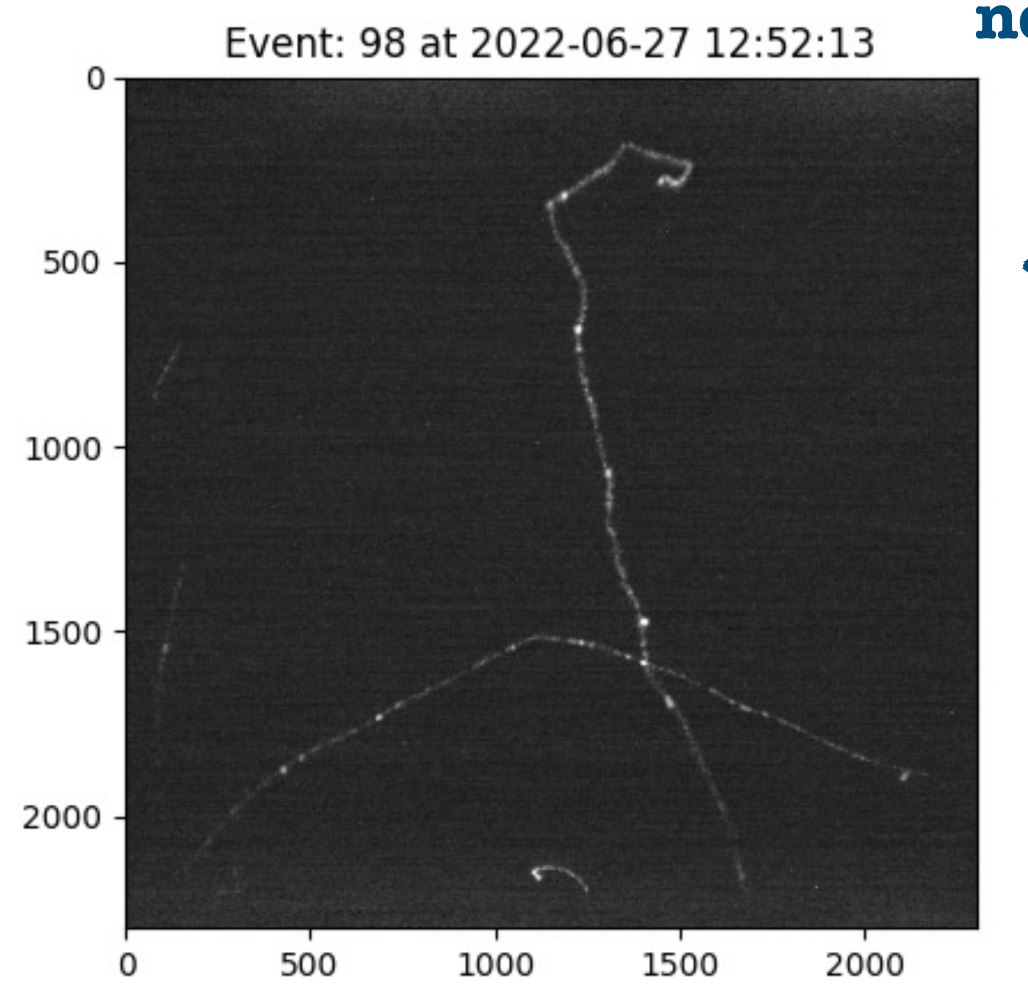


- Copper ring field cage, 50 cm drift
- 1 sCMOS sensor + 4 PMT
- 3 GEMs for a 33 x 33 cm^2 sensitive area
- 50 L sensitive volume

Cosmic rays (overground, no shielding)



Natural radioactivity (underground, no shielding)



The LIME optical readout

sCMOS camera
[Hamamatsu Orca-Fusion]

PMTs
[Hamamatsu R7378]

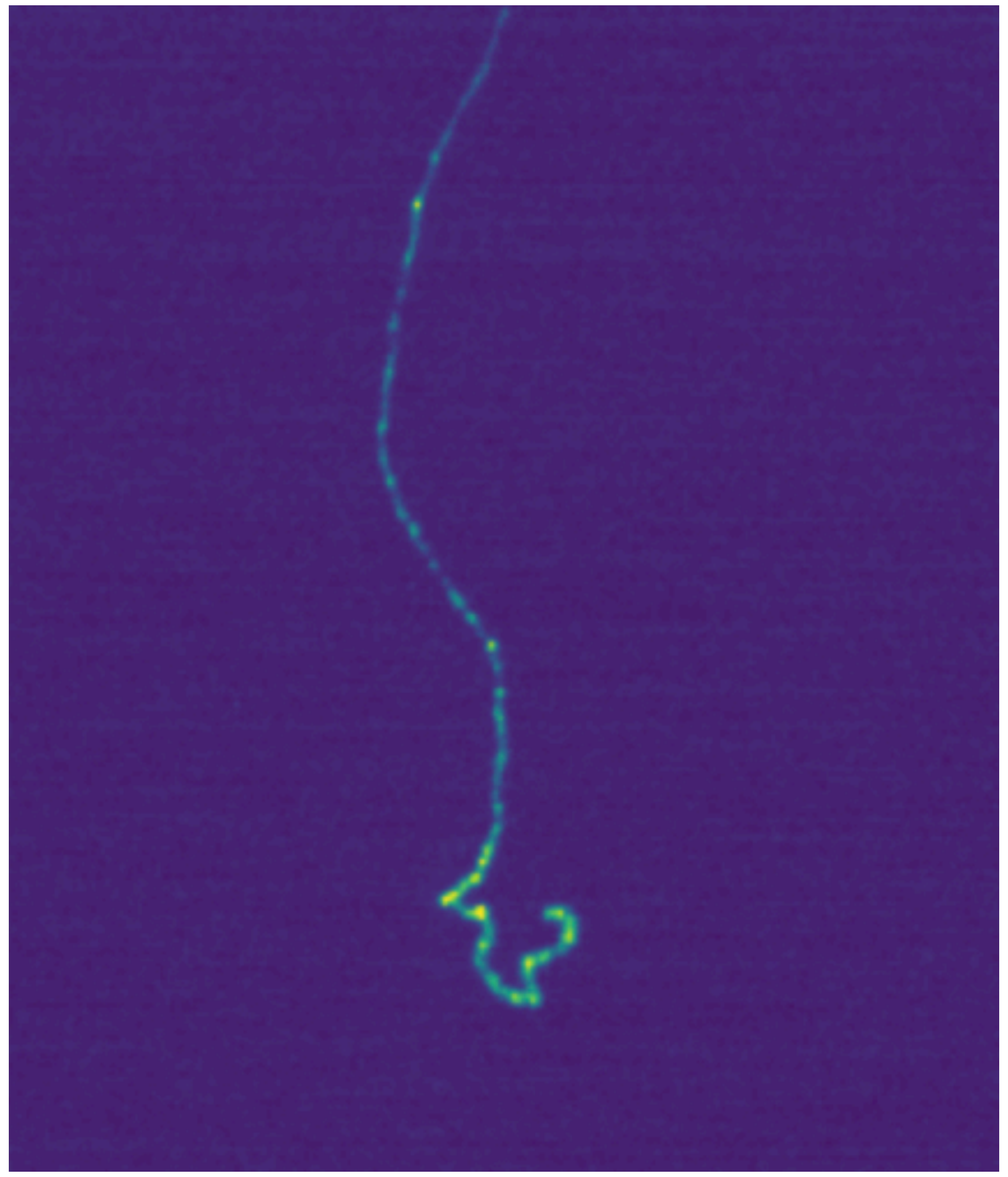
- The **CYGNO** project proposes the **readout** of the **electro-luminescence light** produced during the **GEMs amplification** of the charge:
  - ➡ **CMOS**: high performance **optical sensors**, capable of providing **high granularity**, **high sensitivity**, and very **low noise**
  - ➡ Suitable **lens** to channel the light on these sensors
  - ➡ Fast photosensors (**PMTs**) for temporal information
- **Optical coupling** ⇒ sensor **out of the sensitive volume**
- Camera **geometrical acceptance**:

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

➡ High GEMs' gain

De-magnification: $\delta = \frac{f}{d - f}$ with f = 25.6 mm [focal length], d = 623 mm [distance from GEMs]

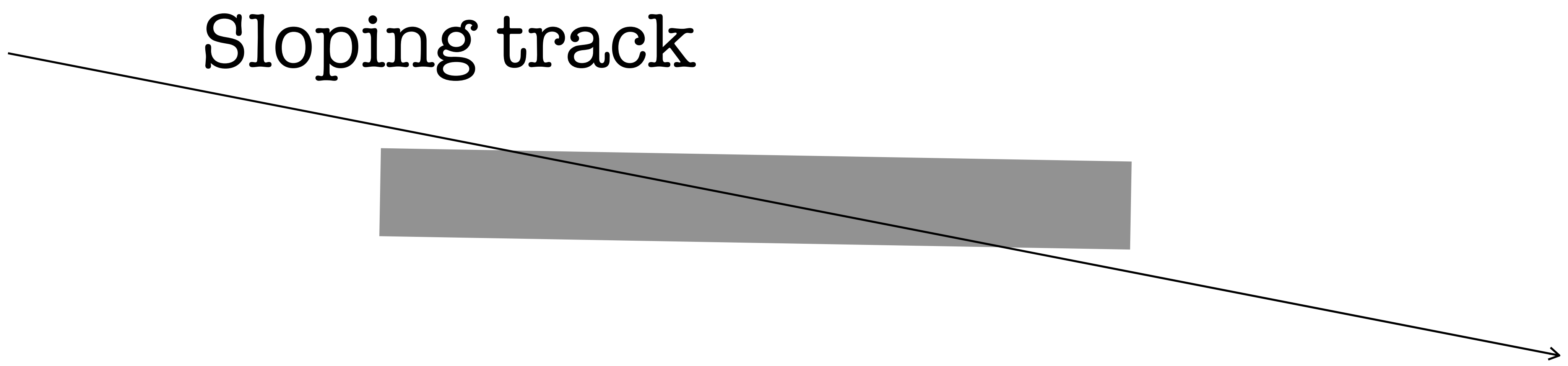
Aperture = 0.95

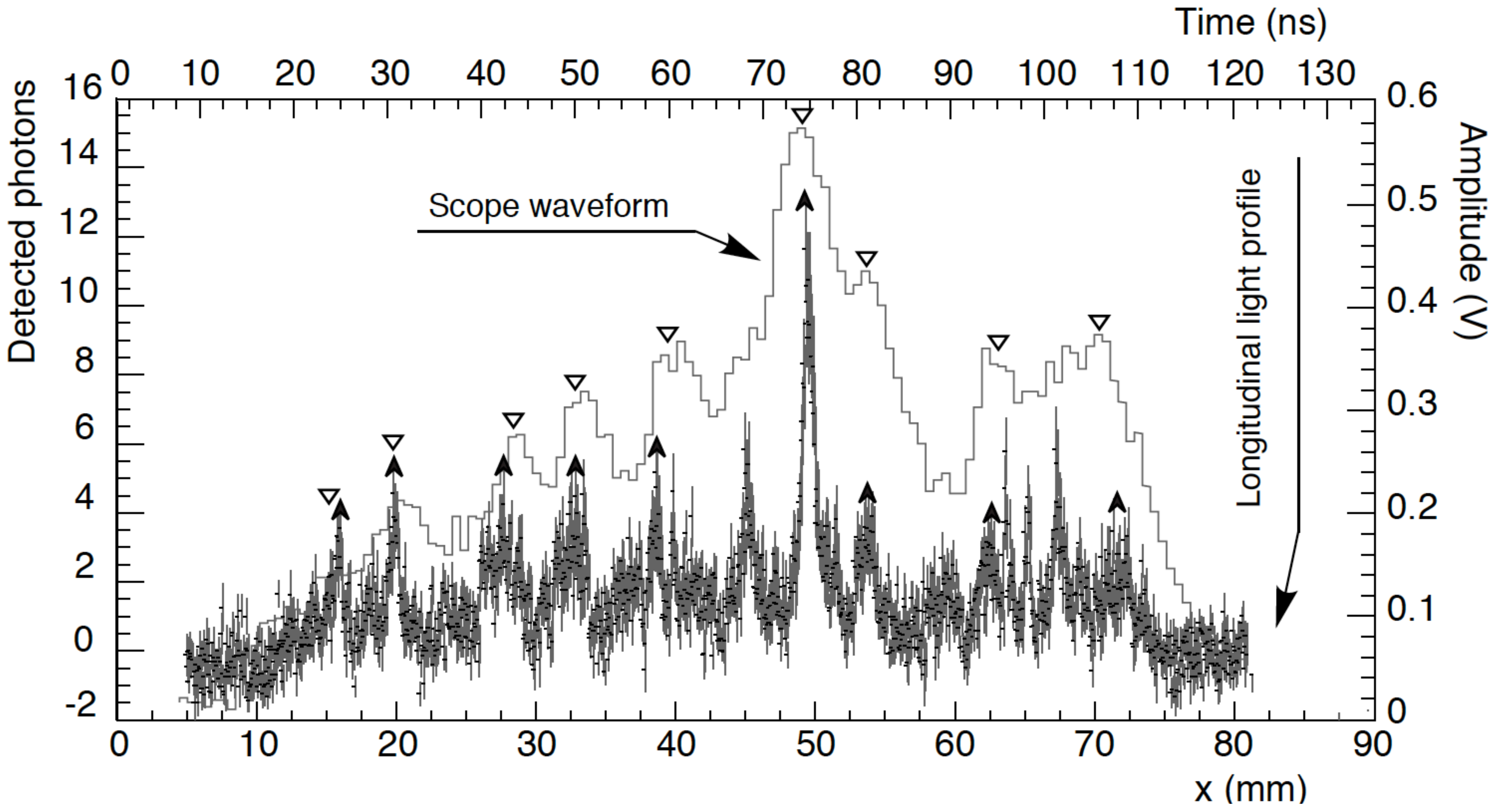


CMOS combined with Photomultipliers

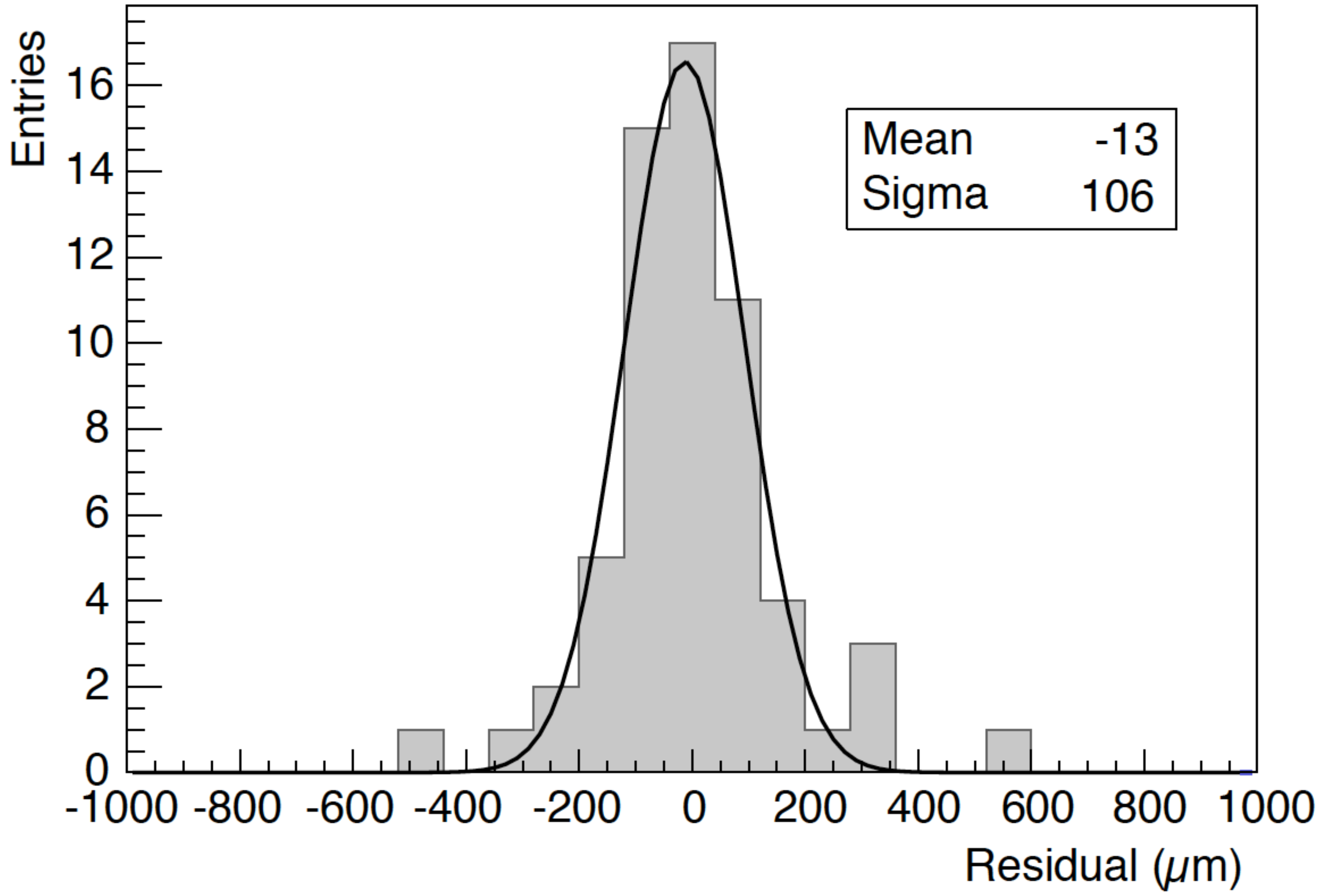
JINST 13 (2018) 05, P05001

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



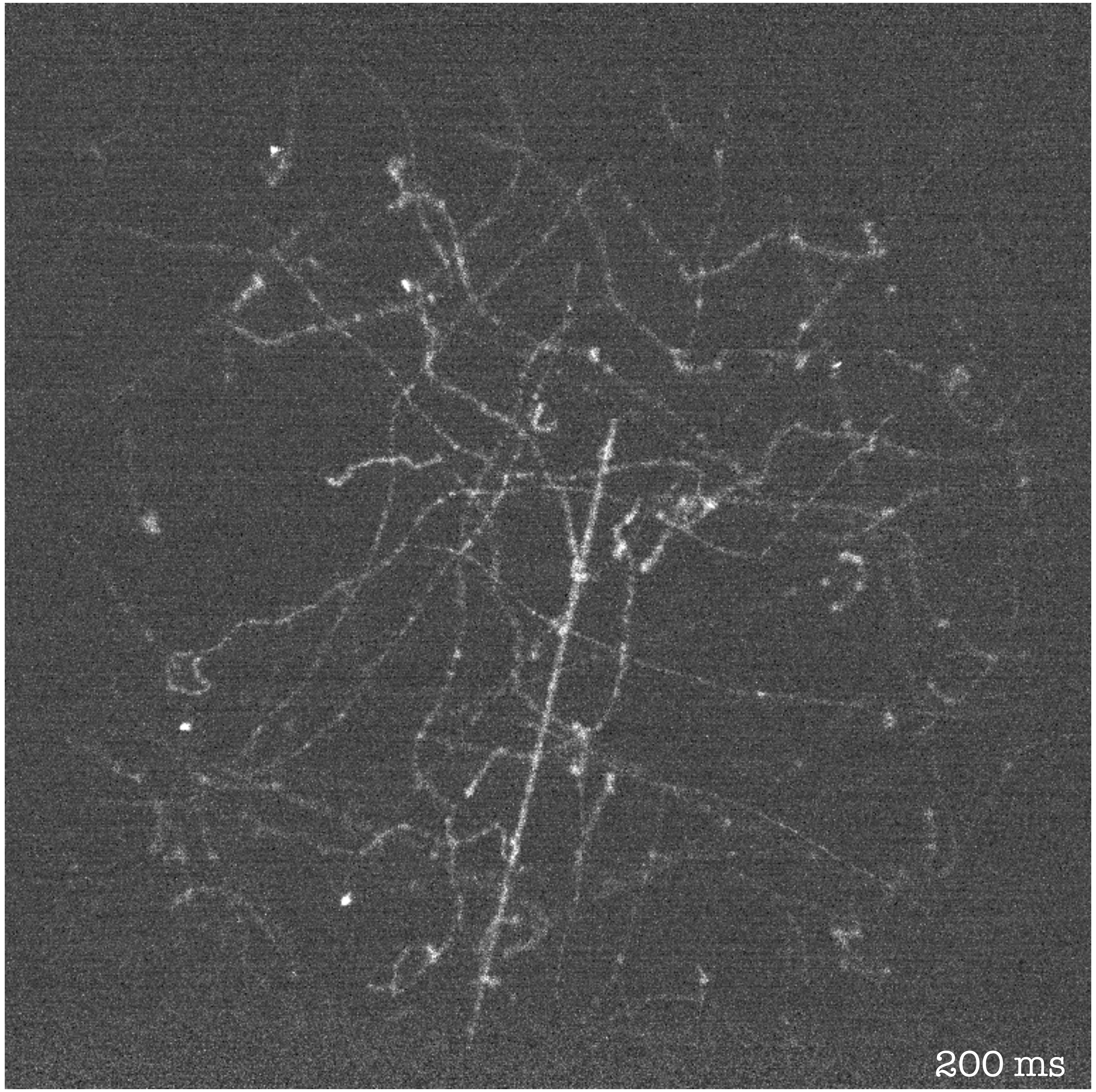


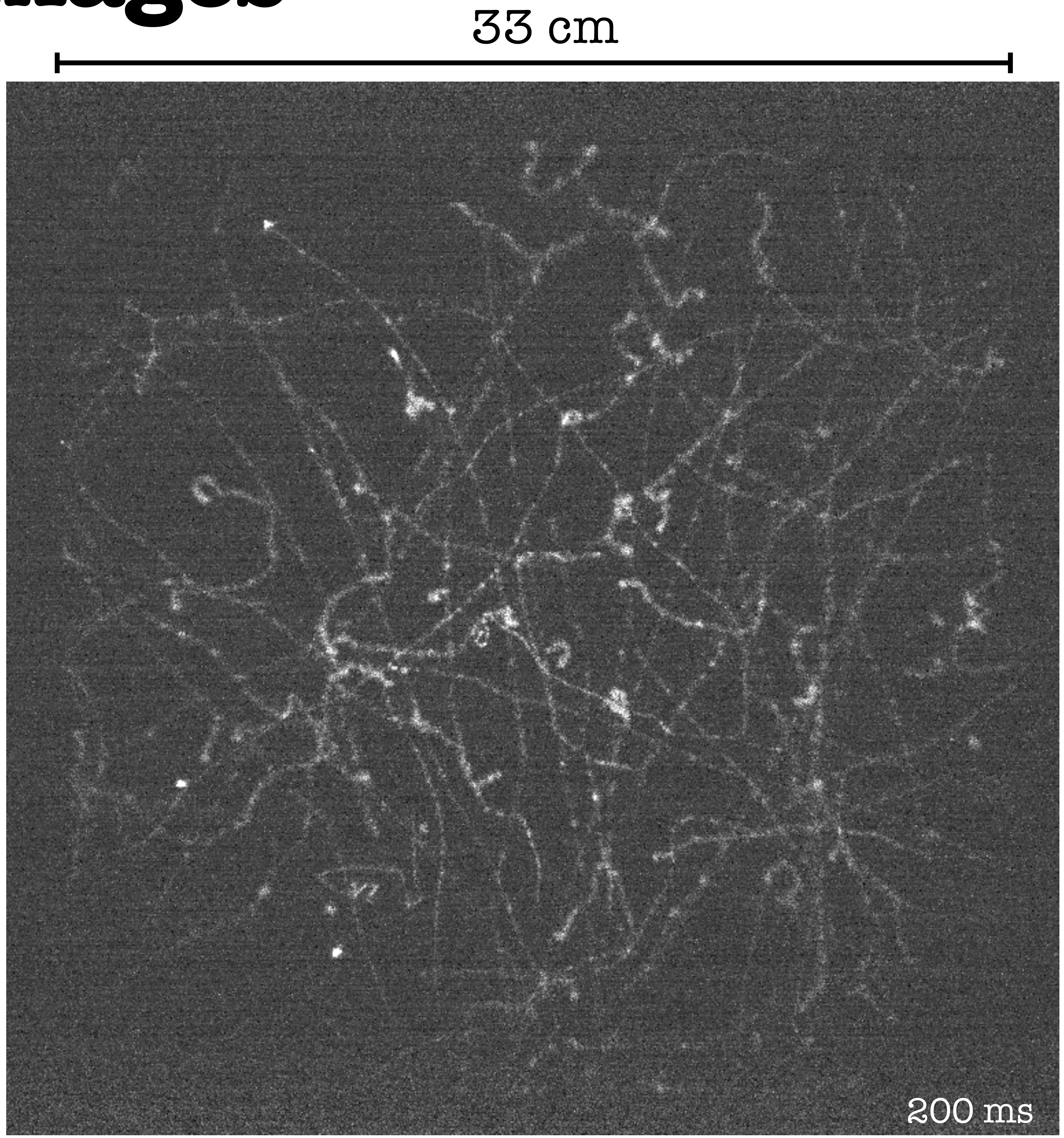
Time + drift velocity ⇒ relative z coordinate



100 μm resolution on relative cluster **z**

LIME: Overground images

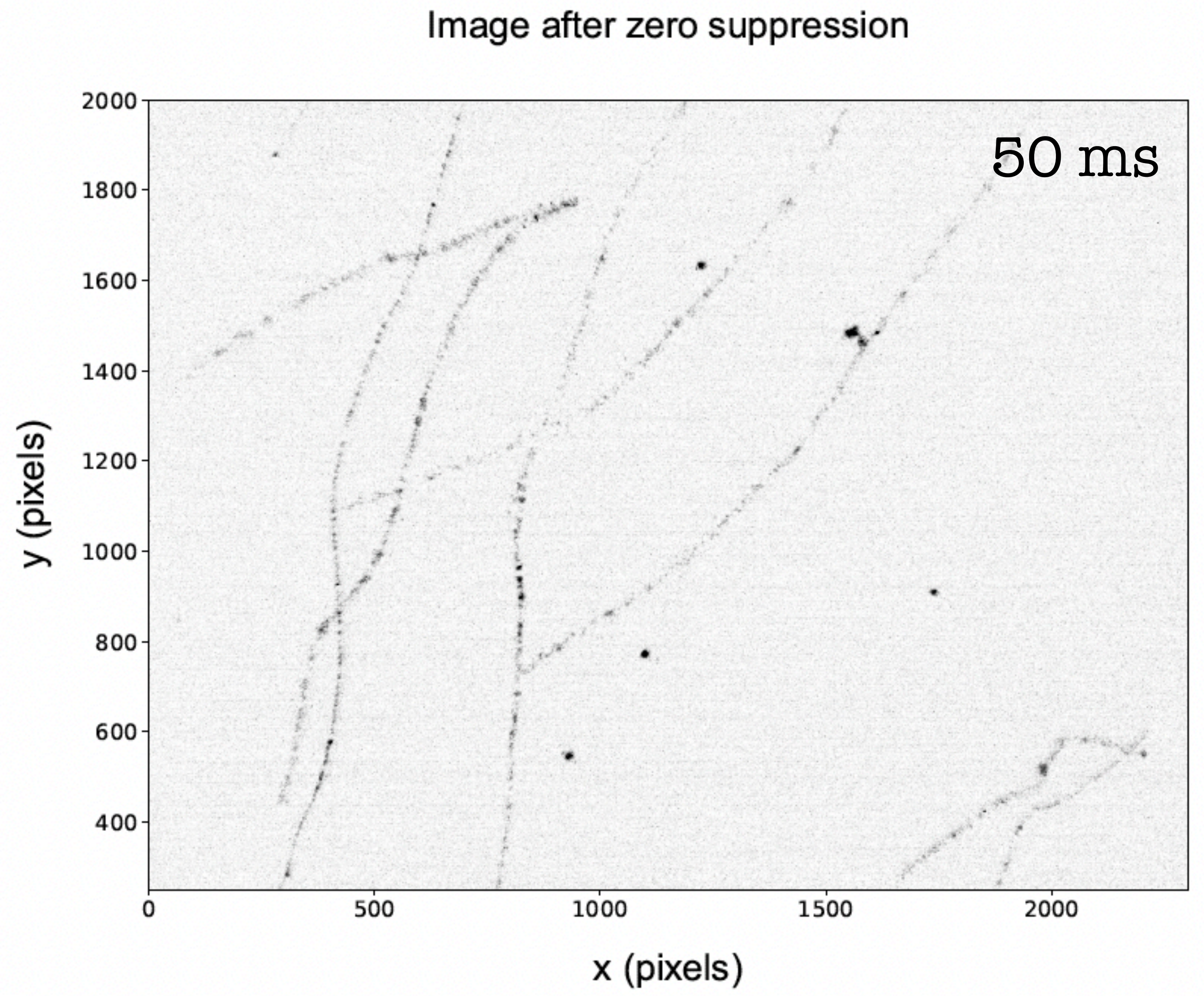


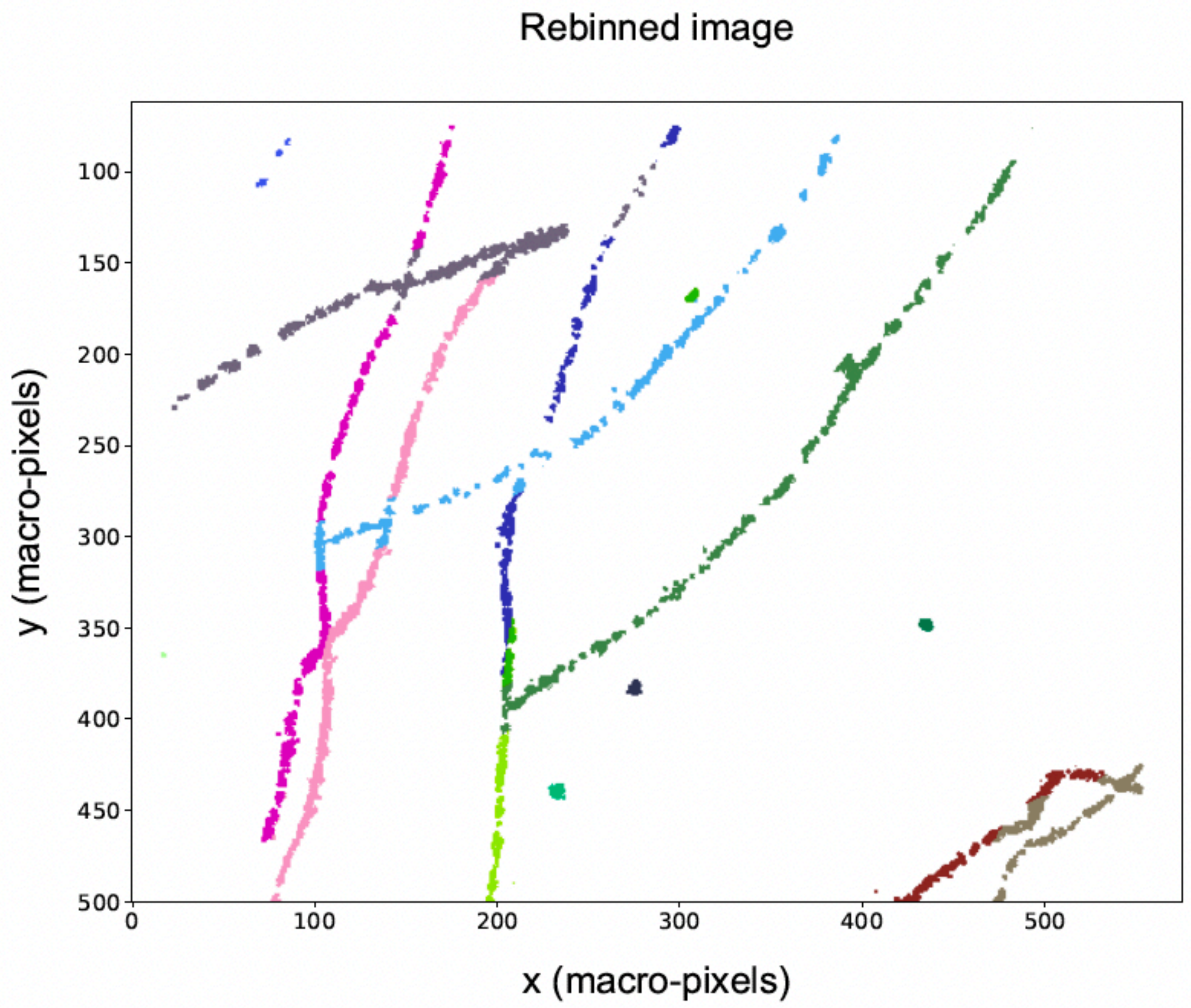


Picture reconstruction

- **Reconstruction** algorithm: **clustering** + **computation of observables** (energy, length, width, etc.)

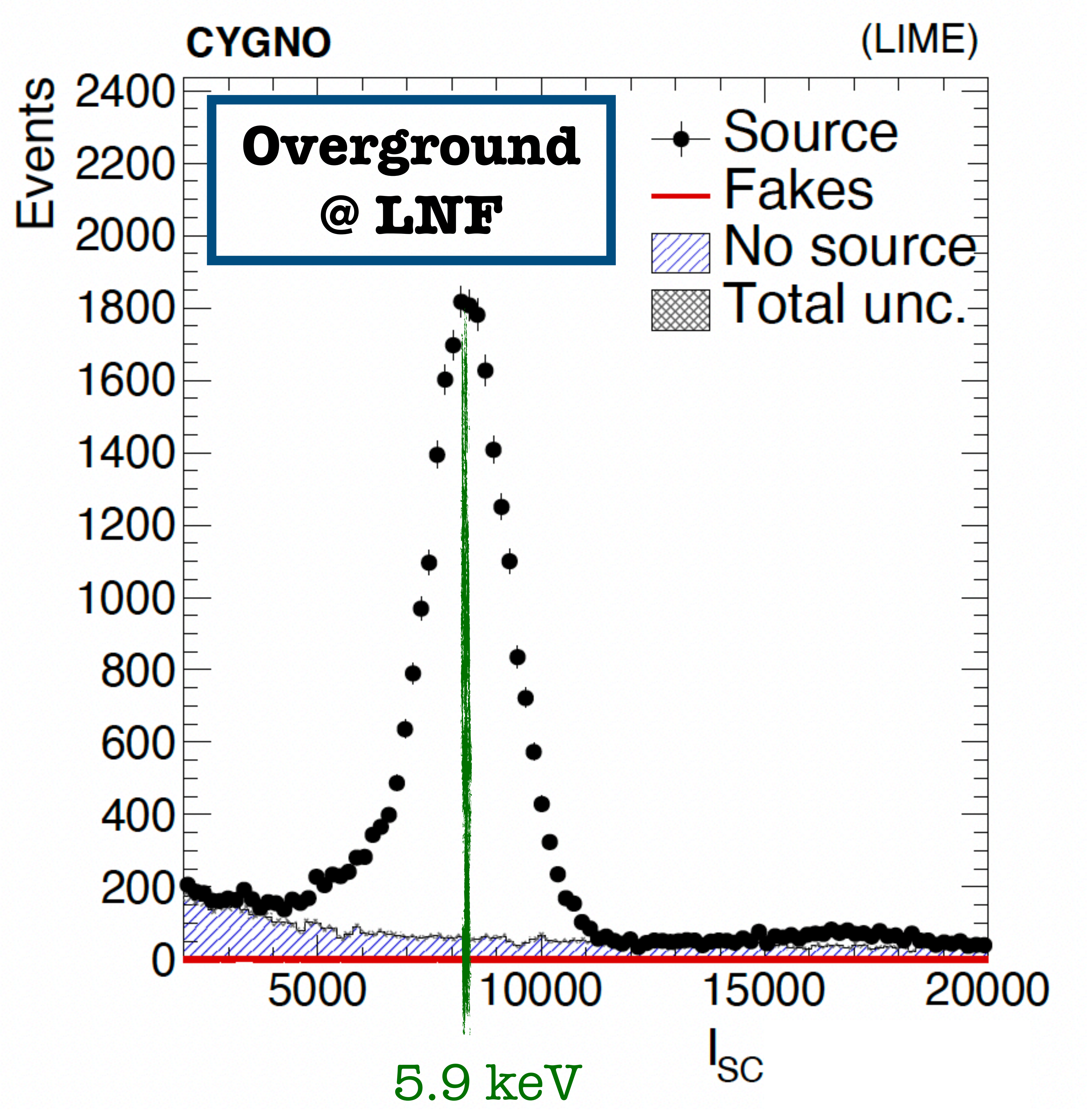
- **4 steps for clustering:**
    1. zero suppression
    2. optical corrections
    3. super-clustering for long tracks
        ➡ generalization of RANSAC algorithm
        ➡ needed to deal with overlapping tracks
    4. additional clustering step for small deposits
        ➡ based on iDBSCAN algorithm [2020 JINST **15** T12003]

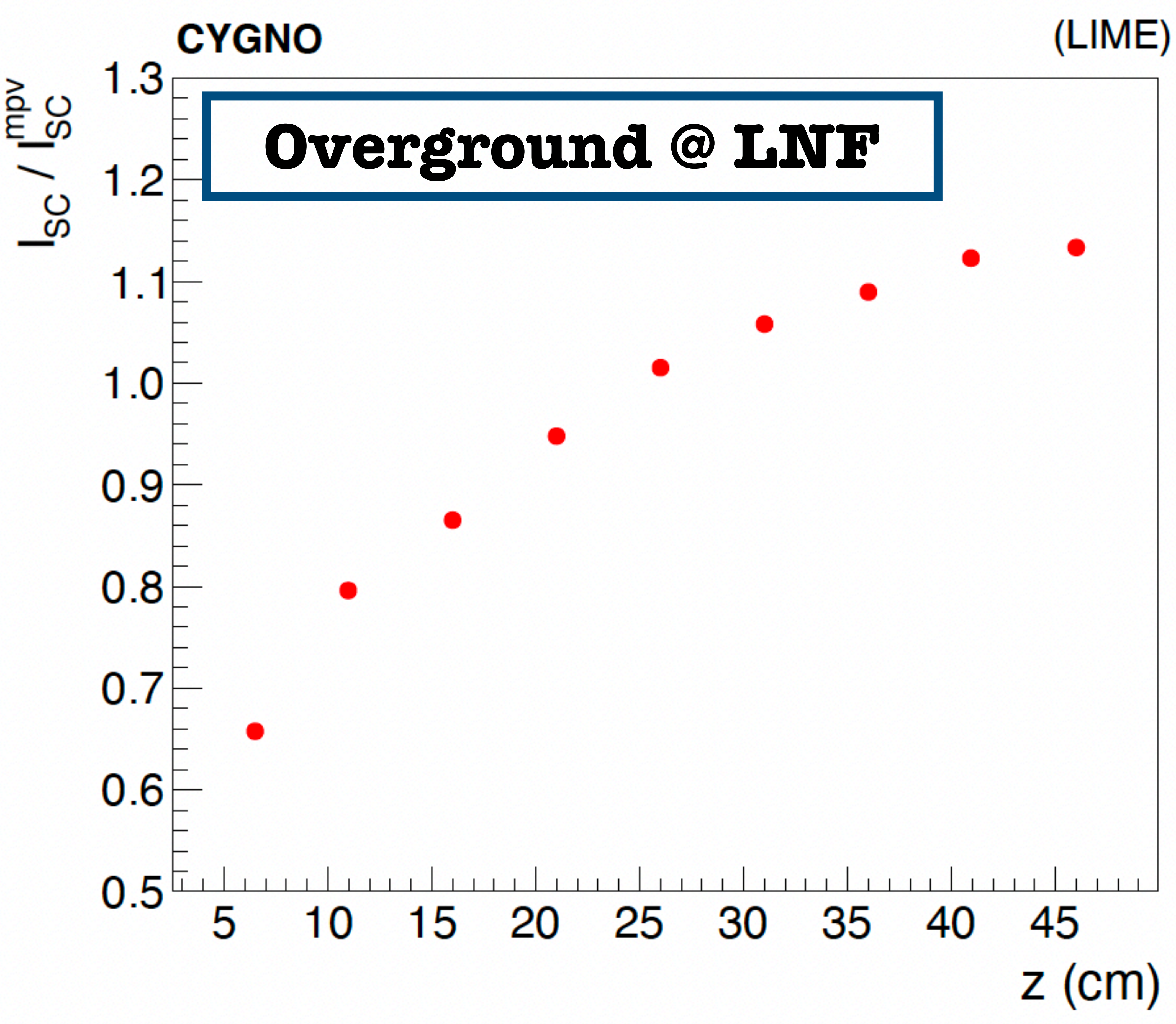




The ^{55}Fe source and energy calibration

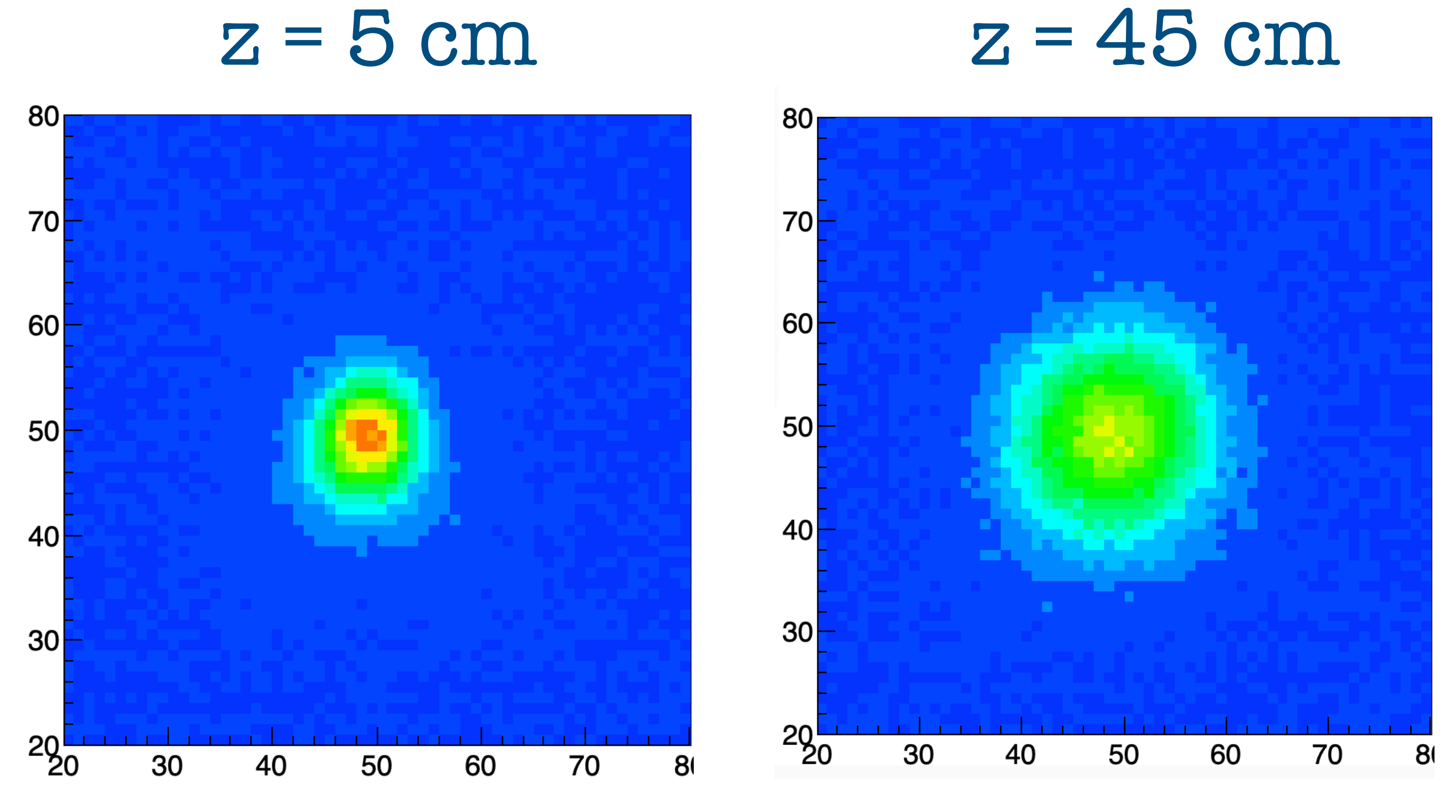
- Total **light integral** proportional to the **energy**, and dependent on **z** due to the saturation of GEM gain



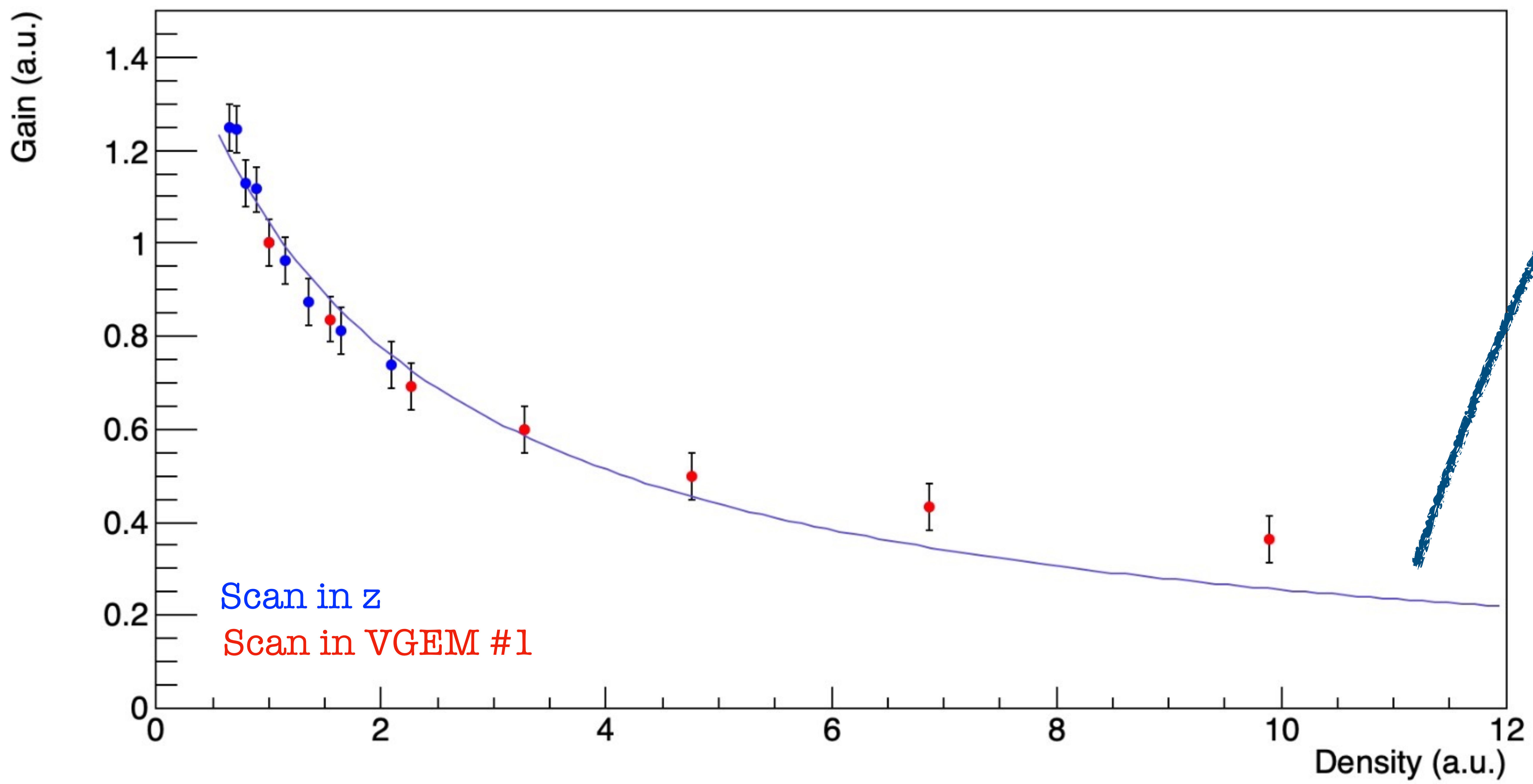


Saturation of the GEM gain

5.9 keV ^{55}Fe spots



- **Saturation** of GEM gain due to positive **ions back-flow** screening the electric field, as already found by our CERN colleagues [arXiv:1512.04968]
- **Denser energy deposits ⇒ more charge in the same holes**



We developed a simple model to simulate it:
[modified Townsend model]

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

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

The z coordinate

EPJC 83 (2023) 10, 946

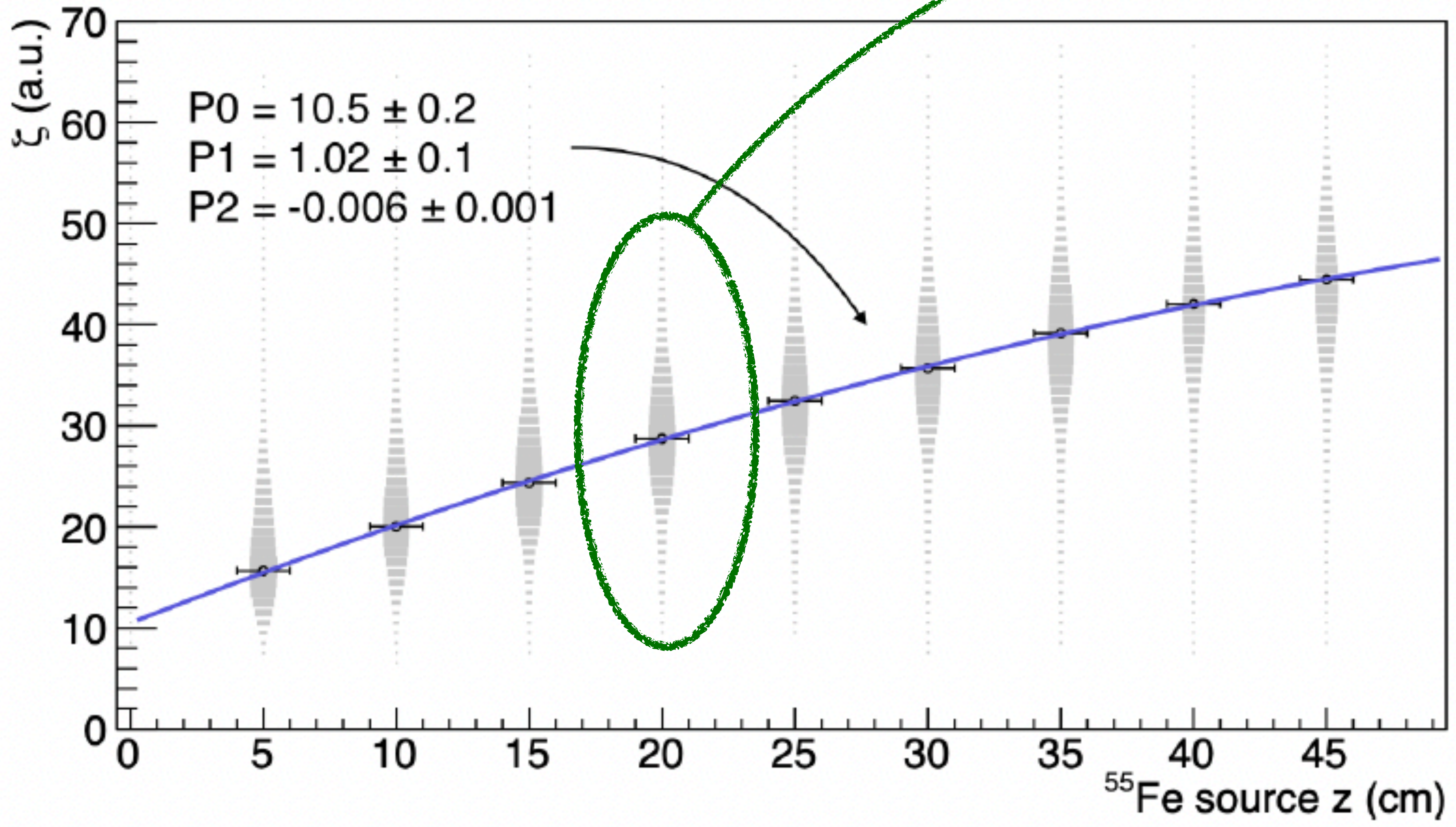
- Variable most sensitive to **z:**

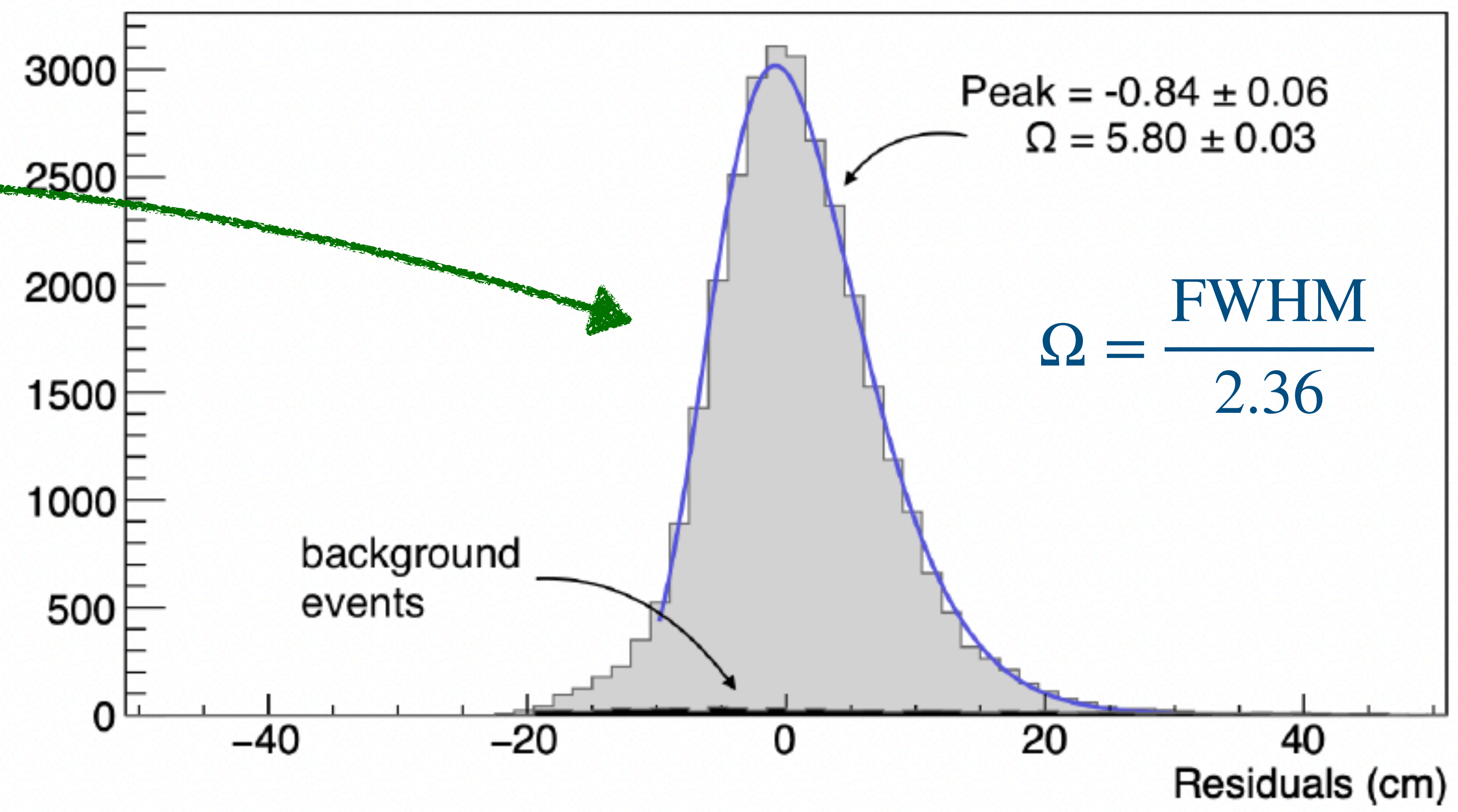
$$\zeta \equiv \sigma_T \, I_{\text{rms}}$$

Transverse size (σ_T)

RMS of the light intensity of the pixels (I_{rms})

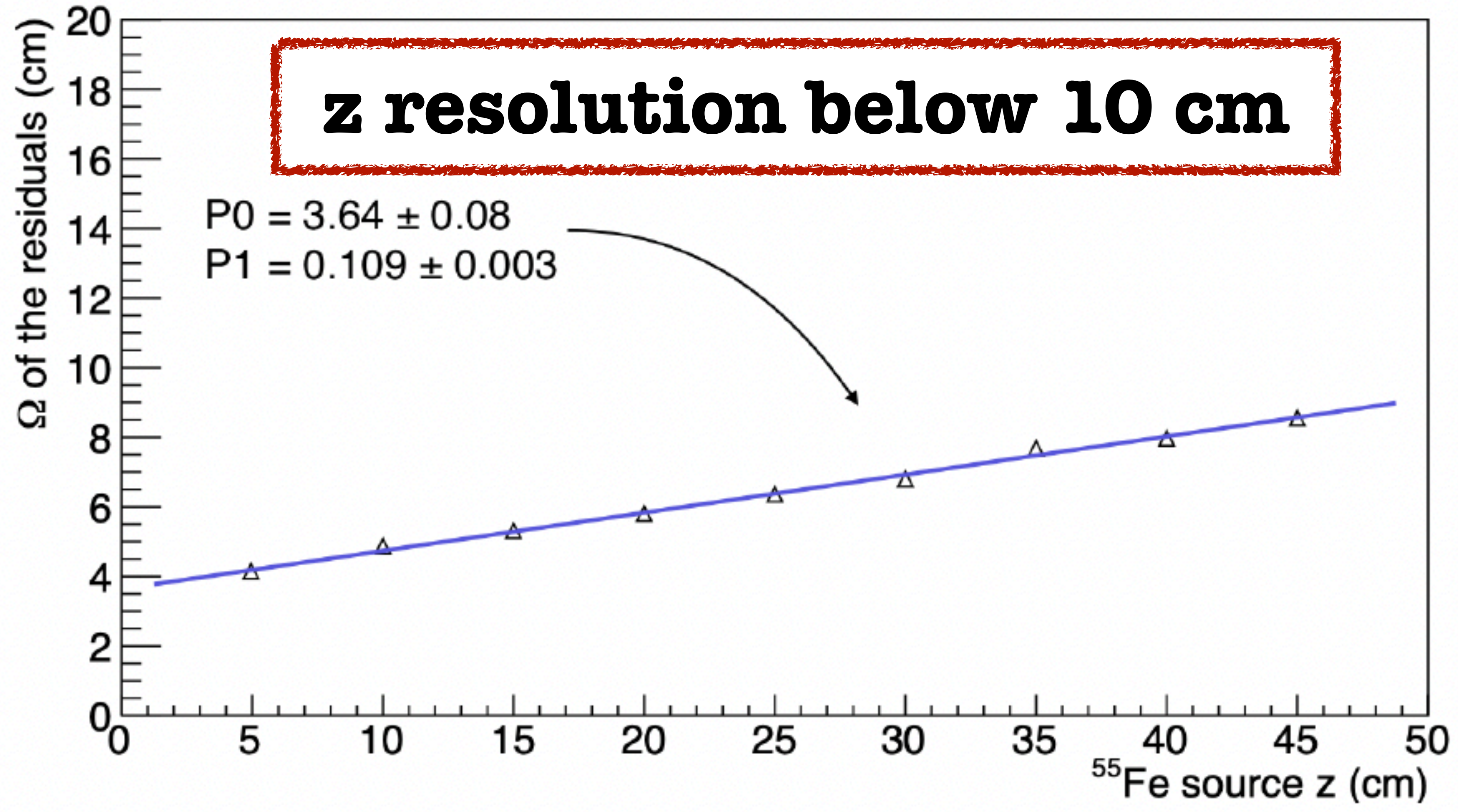
Overground @ LNF





$$\Omega = \frac{\text{FWHM}}{2.36}$$

z resolution below 10 cm



Overground: ER calibration

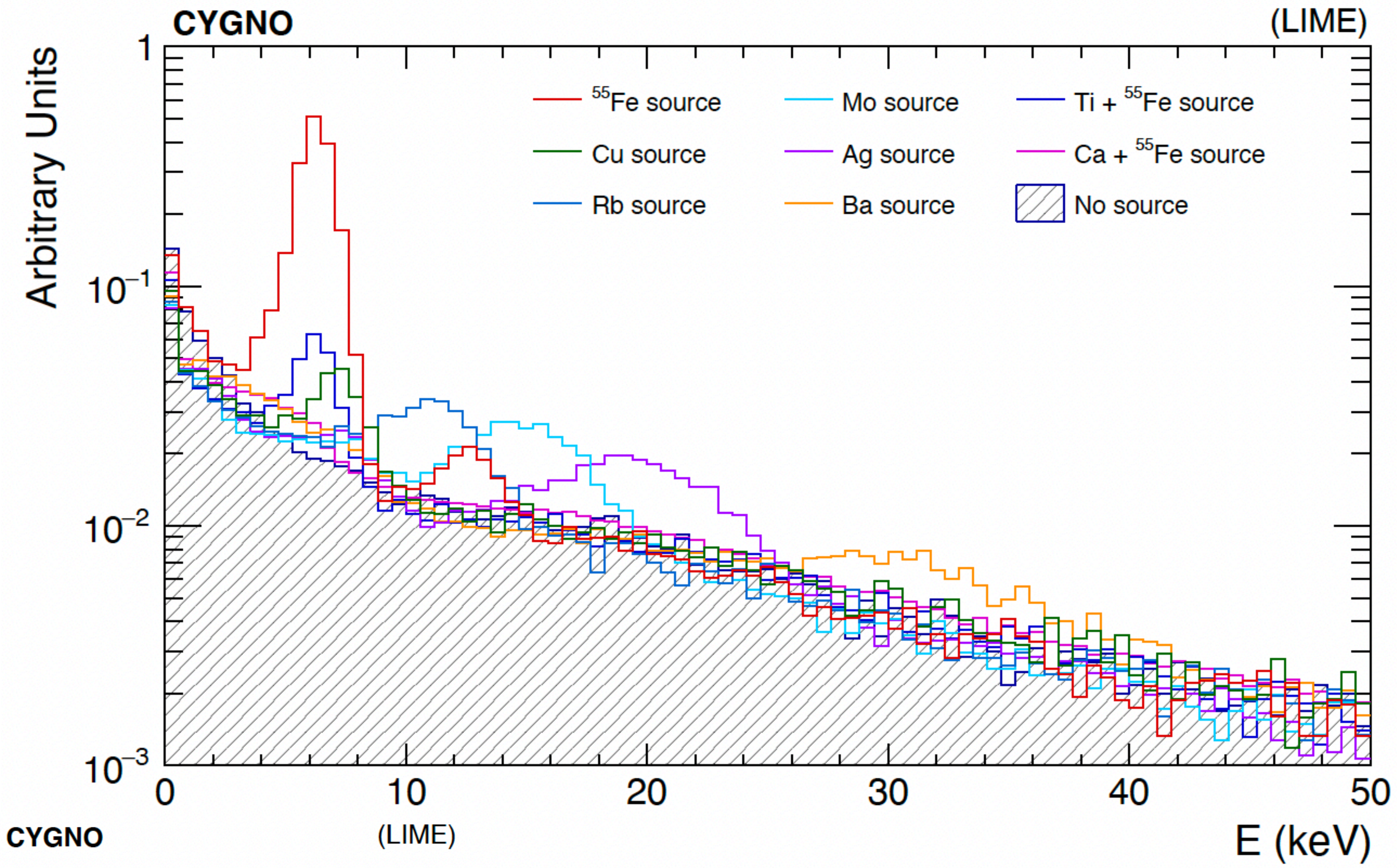
- ^{55}Fe source
  $[K_\alpha \sim 5.9 \text{ keV}, K_\alpha \sim 6.4 \text{ keV}]$

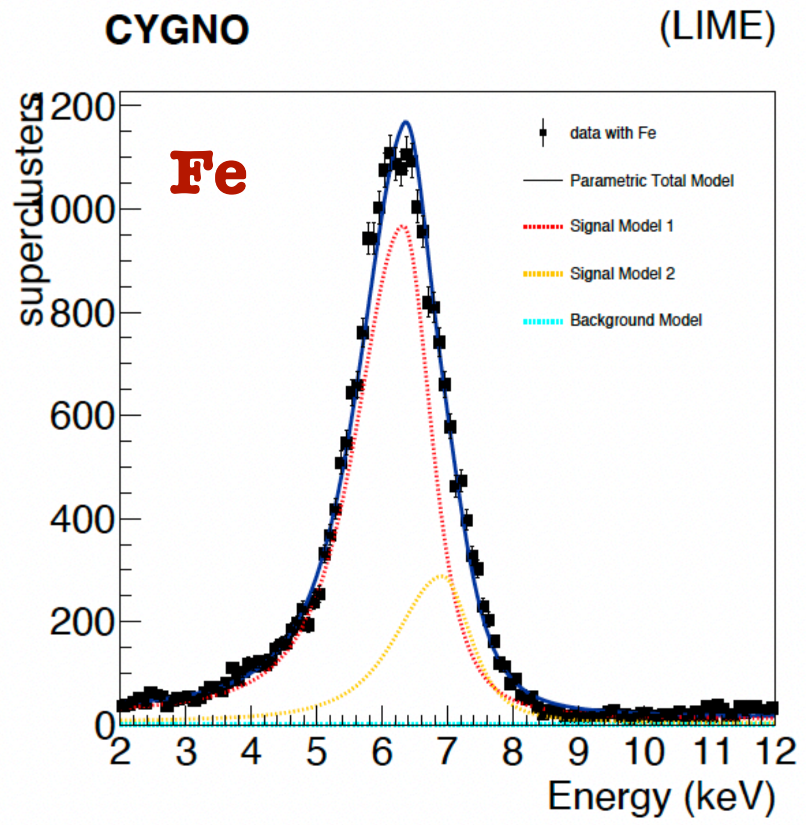
- Multi-target source

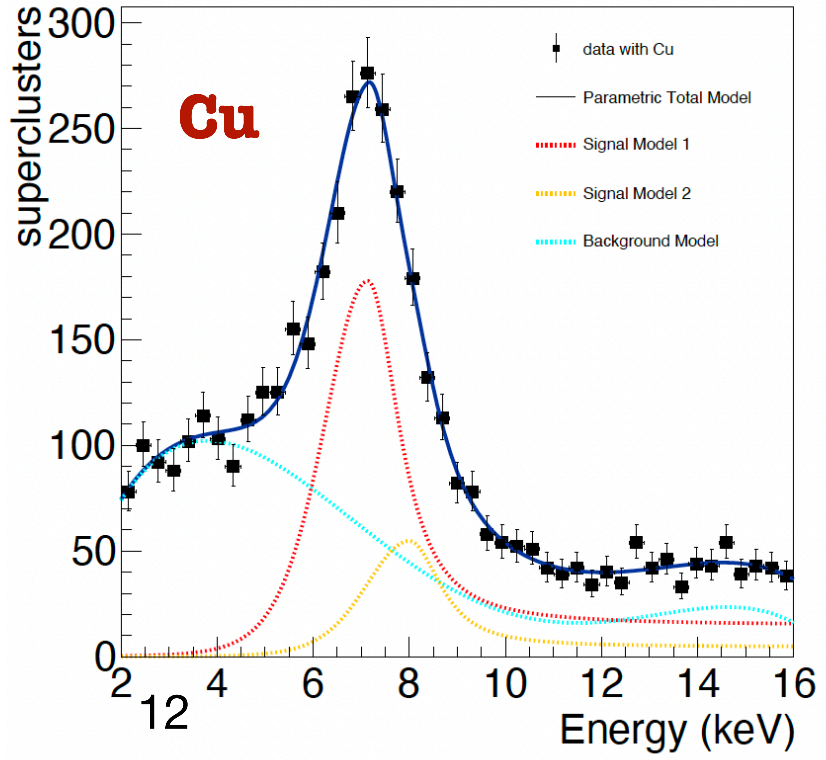
Material	Energy K_α [keV]	Energy K_β [keV]
Cu	8.04	8.91
Rb	13.37	14.97
Mo	17.44	19.63
Ag	22.10	24.99
Ba	32.06	36.55

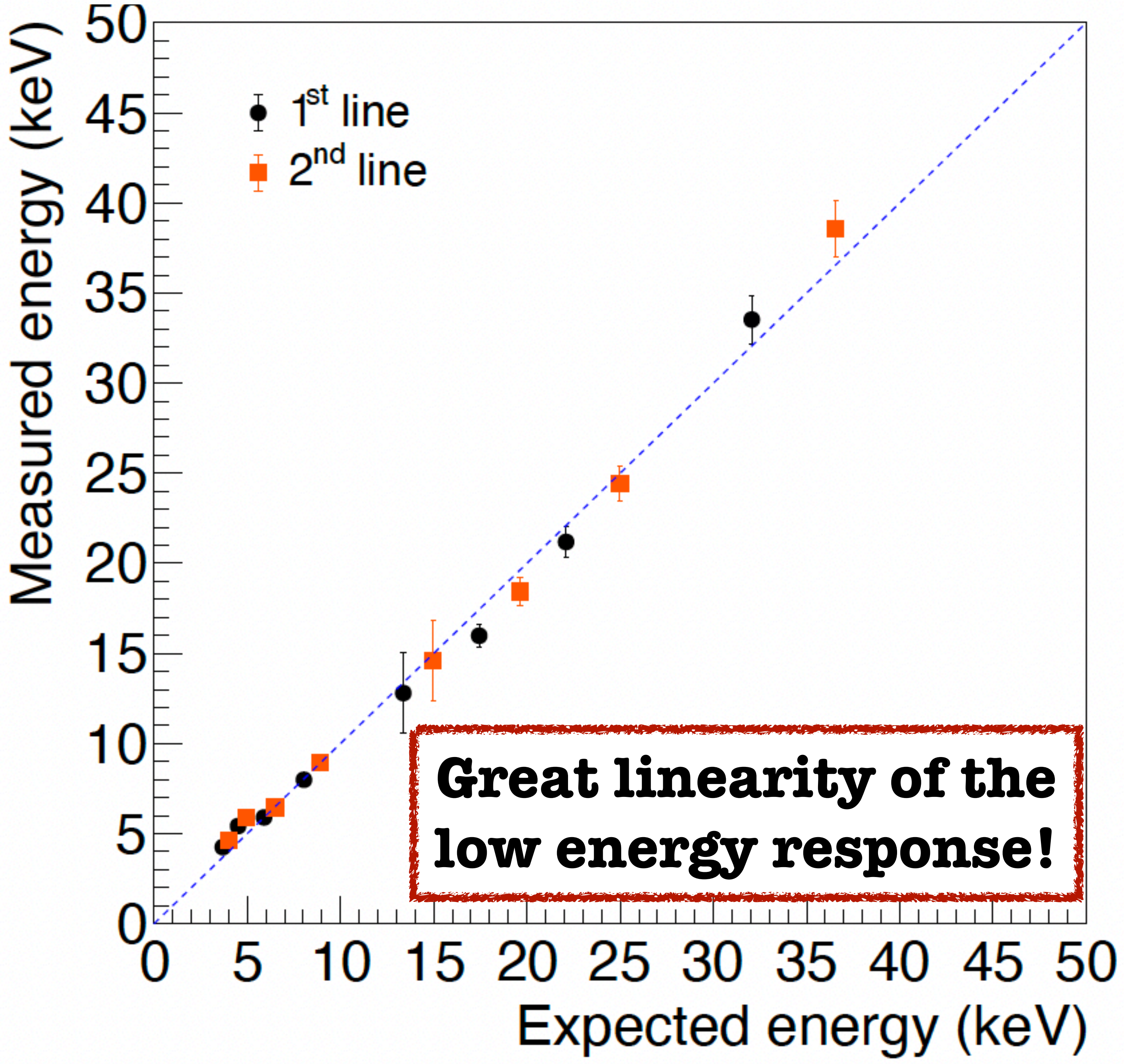
- Ti and Ca X-ray source

Material	Energy K_α [keV]	Energy K_β [keV]
Ti	4.51	4.93
Ca	3.69	4.01



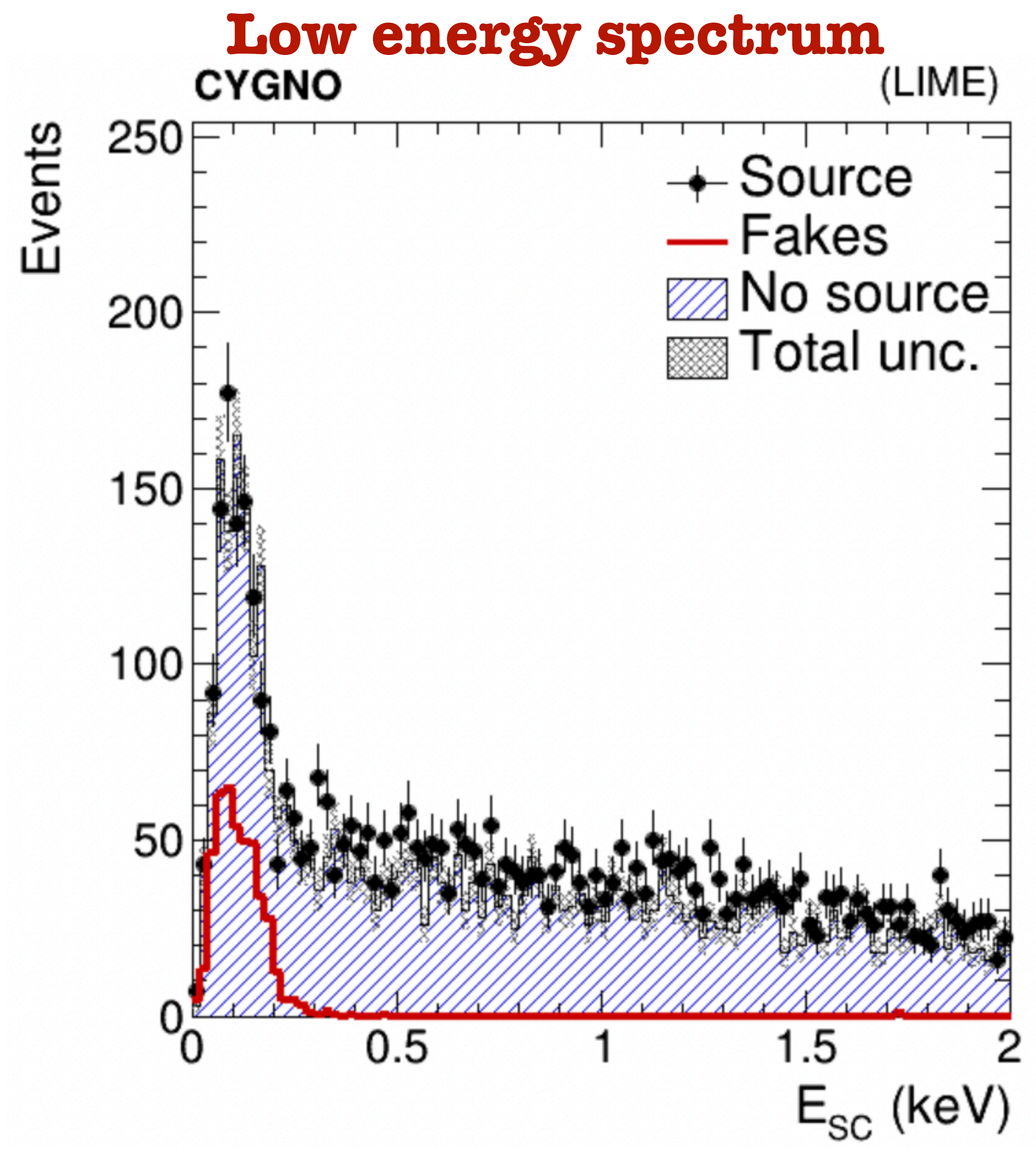


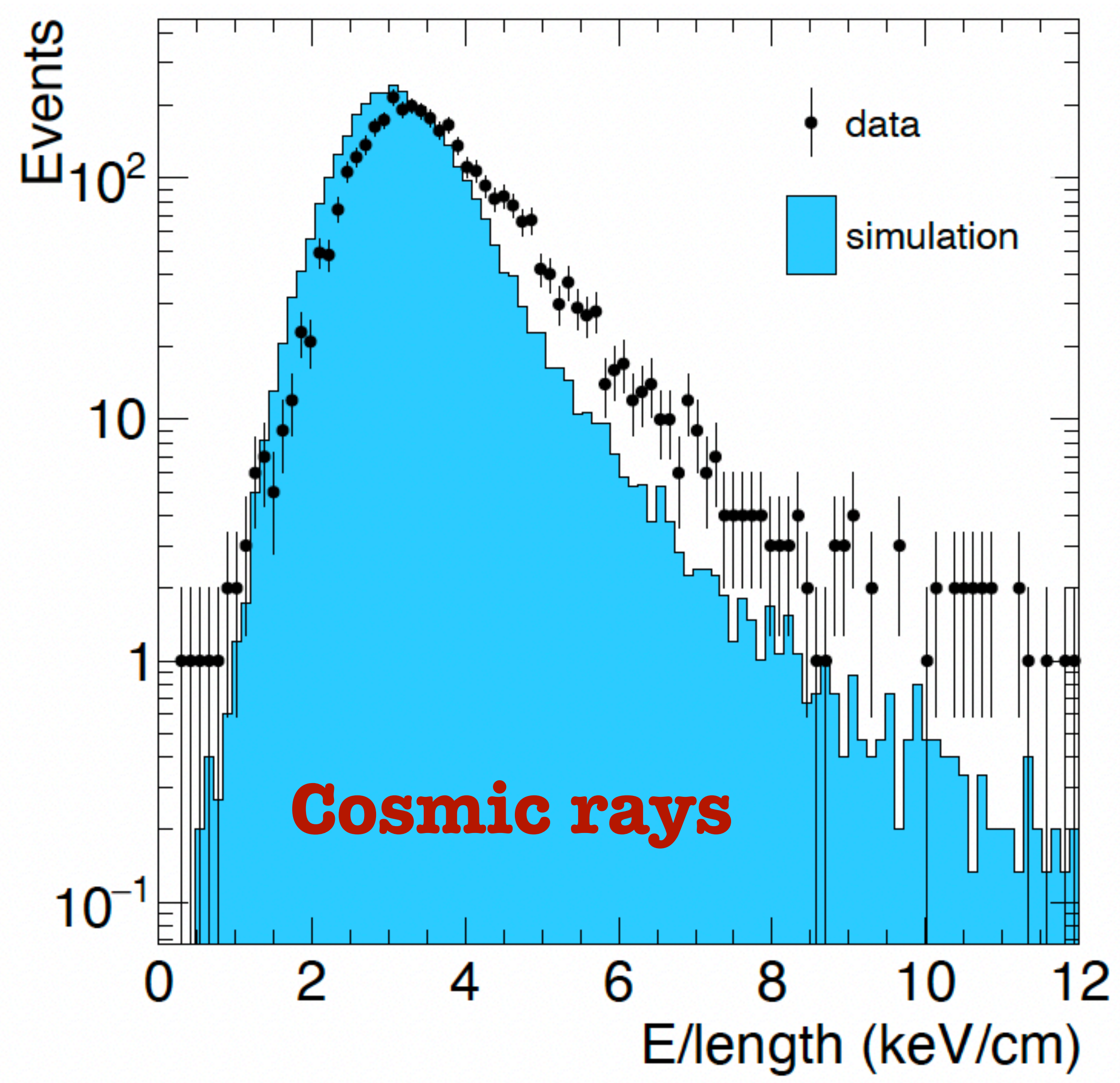




LNF background

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





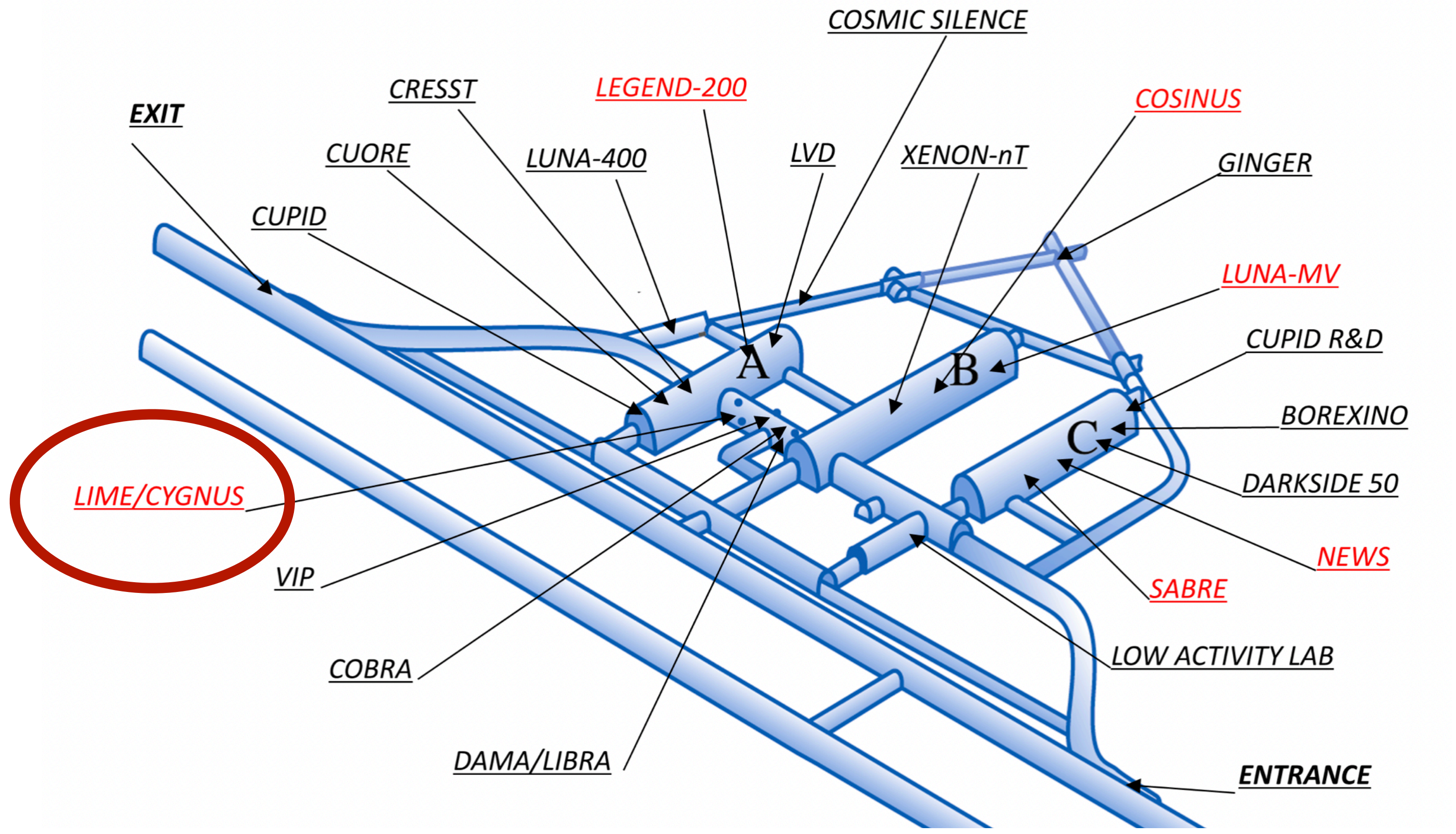
Part of the observed rate can be explained by the ambient radioactivity

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

⇩

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

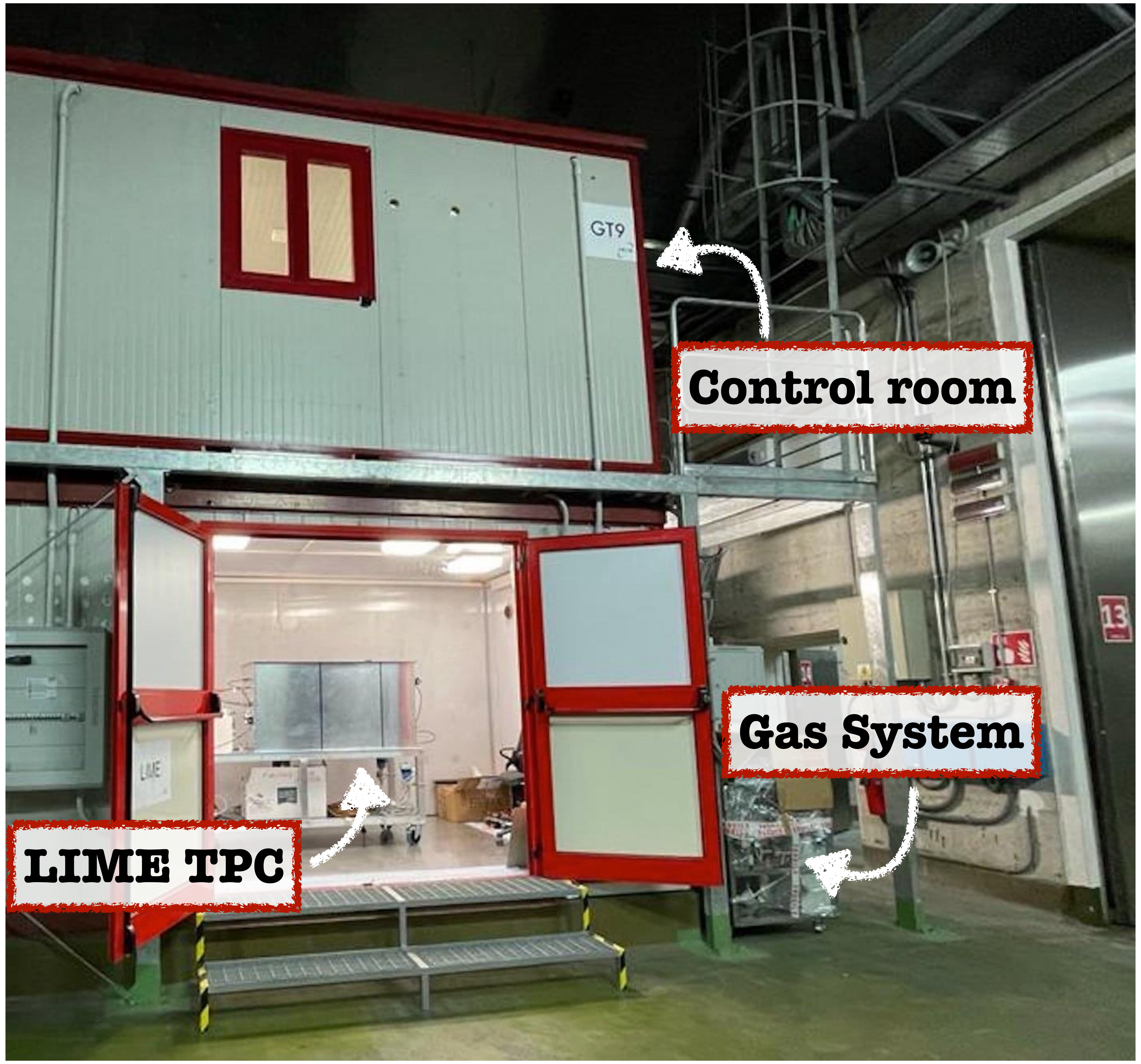
Underground installation



- 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

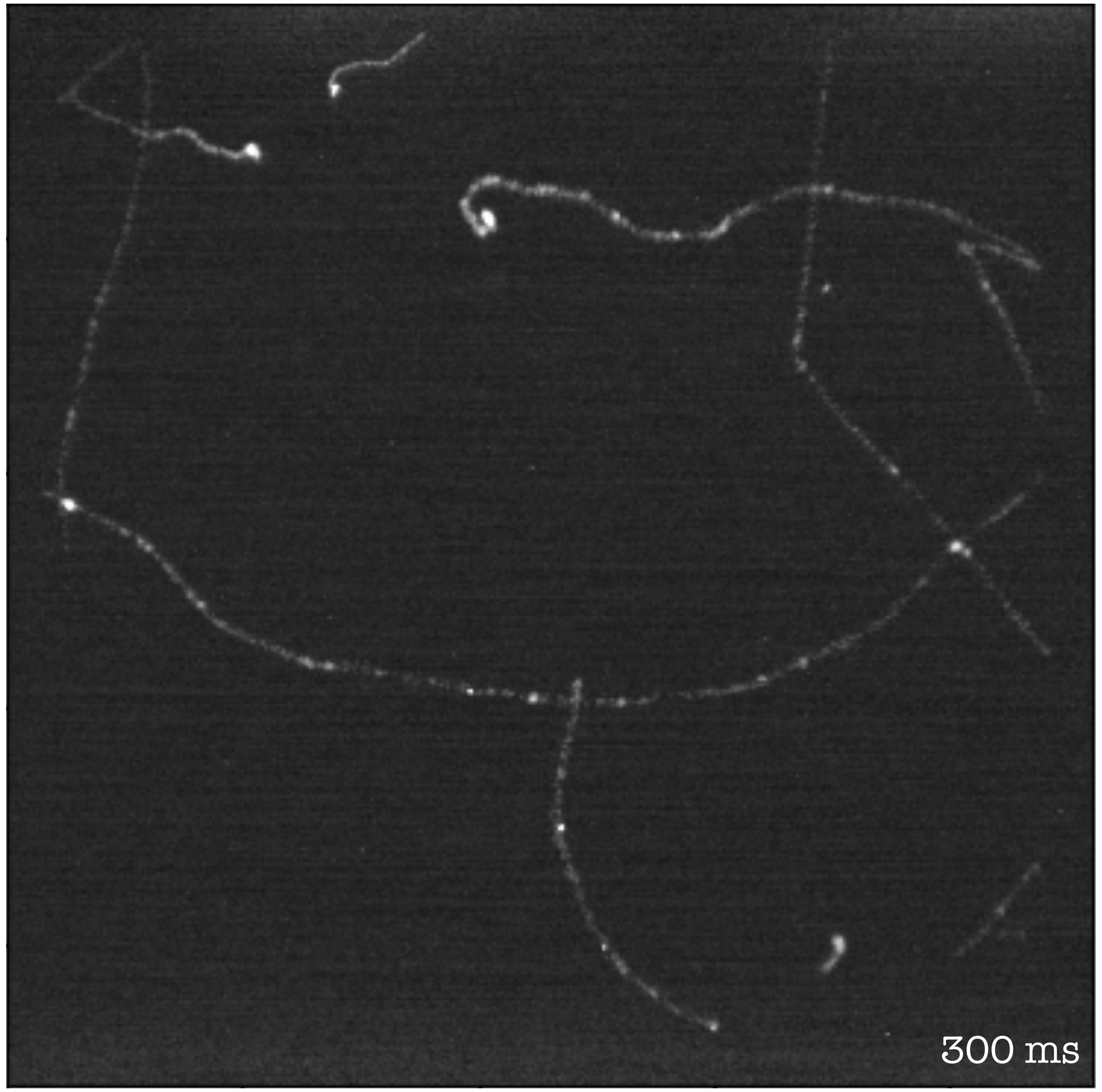


Underground LIME data taking plan

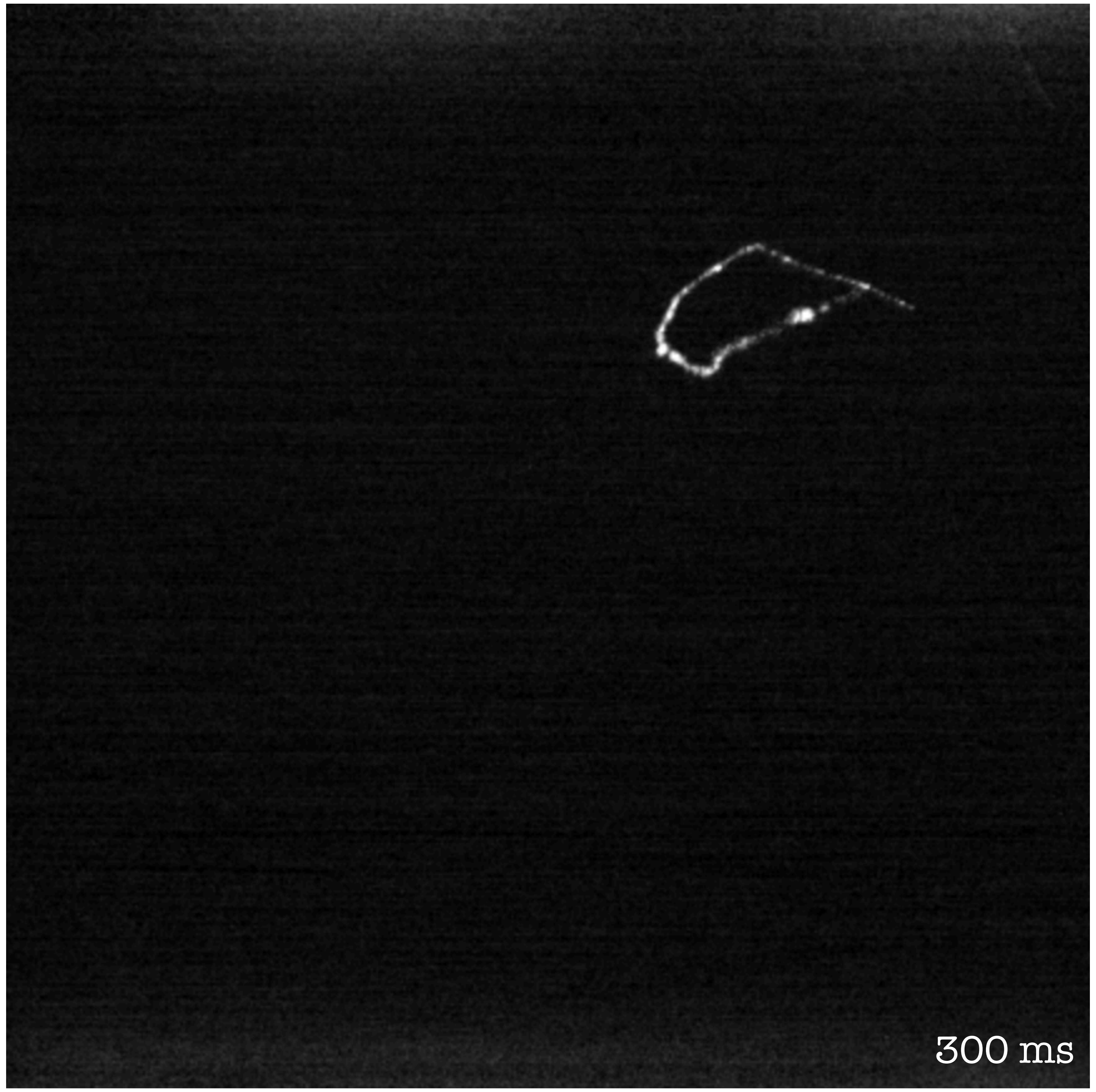
Spring and Summer 2022	• **RUN 0: Commissioning**
Autumn 2022	• **RUN 1: No-shielding**
Winter 2023	• **RUN 2: 4 cm Cu shielding**
Spring and Summer 2023	• **RUN 3: 10 cm Cu shielding** ➡ measurement of NR response with AmBe ➡ High energy X-ray sources
Autumn 2023	• **RUN 4: 10 cm Cu + 40 cm water shielding**

Underground data so far

RUN 1: No-shielding



RUN 2: 4 cm Cu shielding

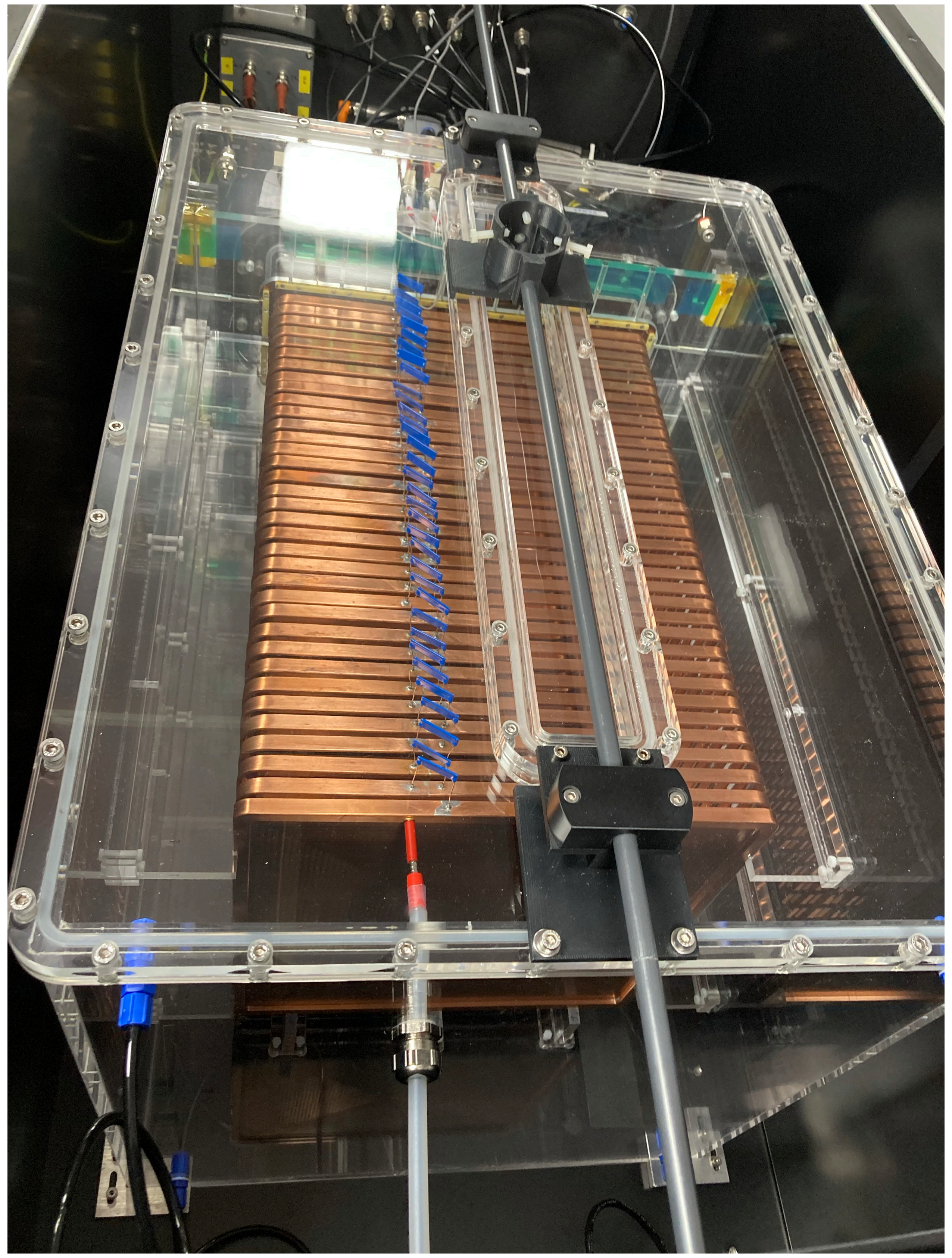


Underground data so far

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 ± 0.58) Hz
  - ➡ Background **expected** event **rate** (from MC): ~37 Hz

~ 4.0 x 10⁶ events in ~ 33 h cam exposure



RUN 2: 4 cm Cu shielding

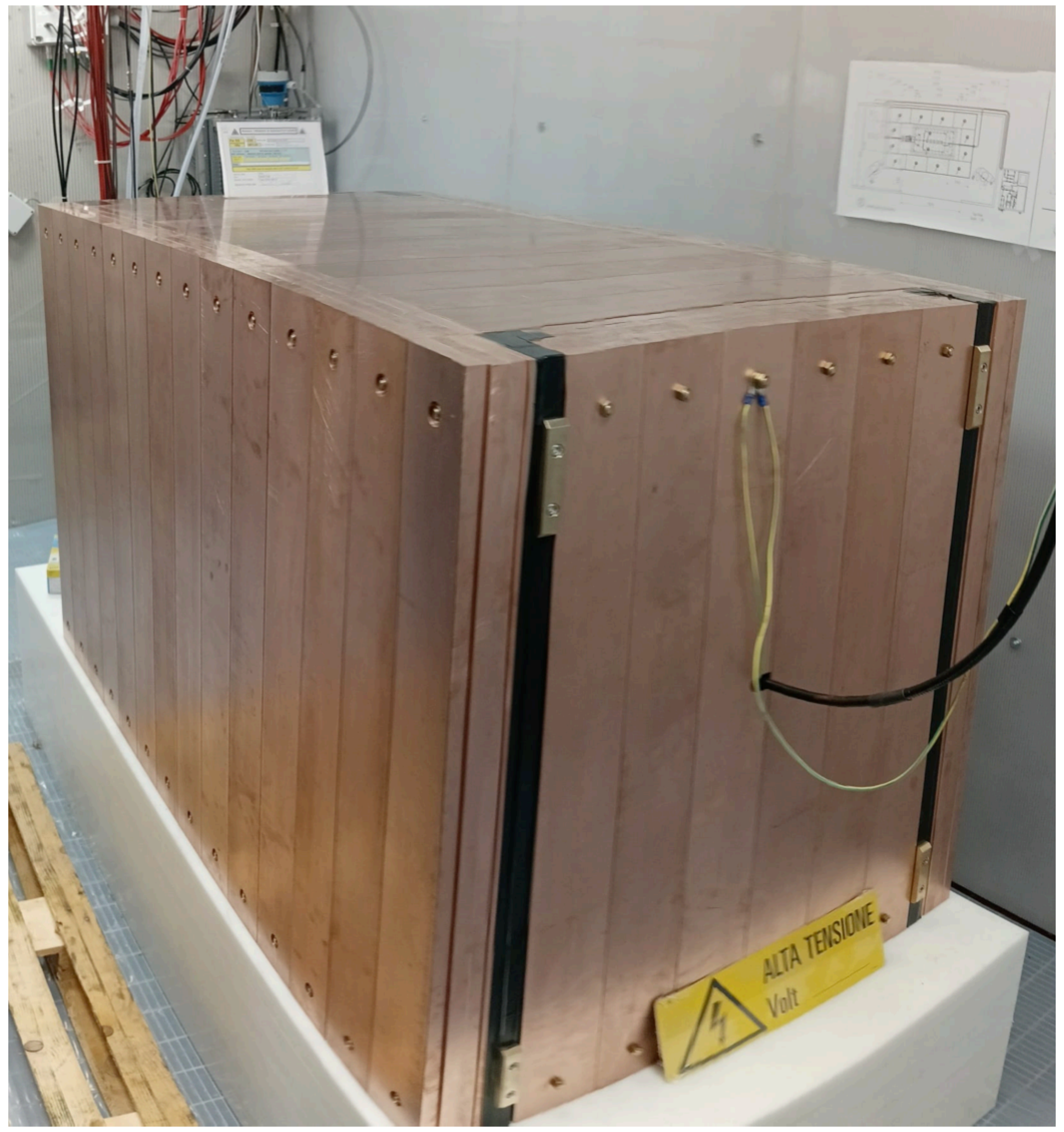
- **From Feb 15, 2023 to Mar 9, 2023**
- Some numbers:
  - ➡ Integral number of **BKG pictures**: $\sim 4.5 \times 10^5$
  - ➡ Background **observed event rate**: ~ 3.5 Hz (data not fully analyzed)
  - ➡ Background **expected** event **rate** (from MC): ~ 1.1 Hz

~ 0.48 x 10⁶ events in ~ 38 h cam exposure

Underground data so far

RUN 3: 10 cm Cu shielding

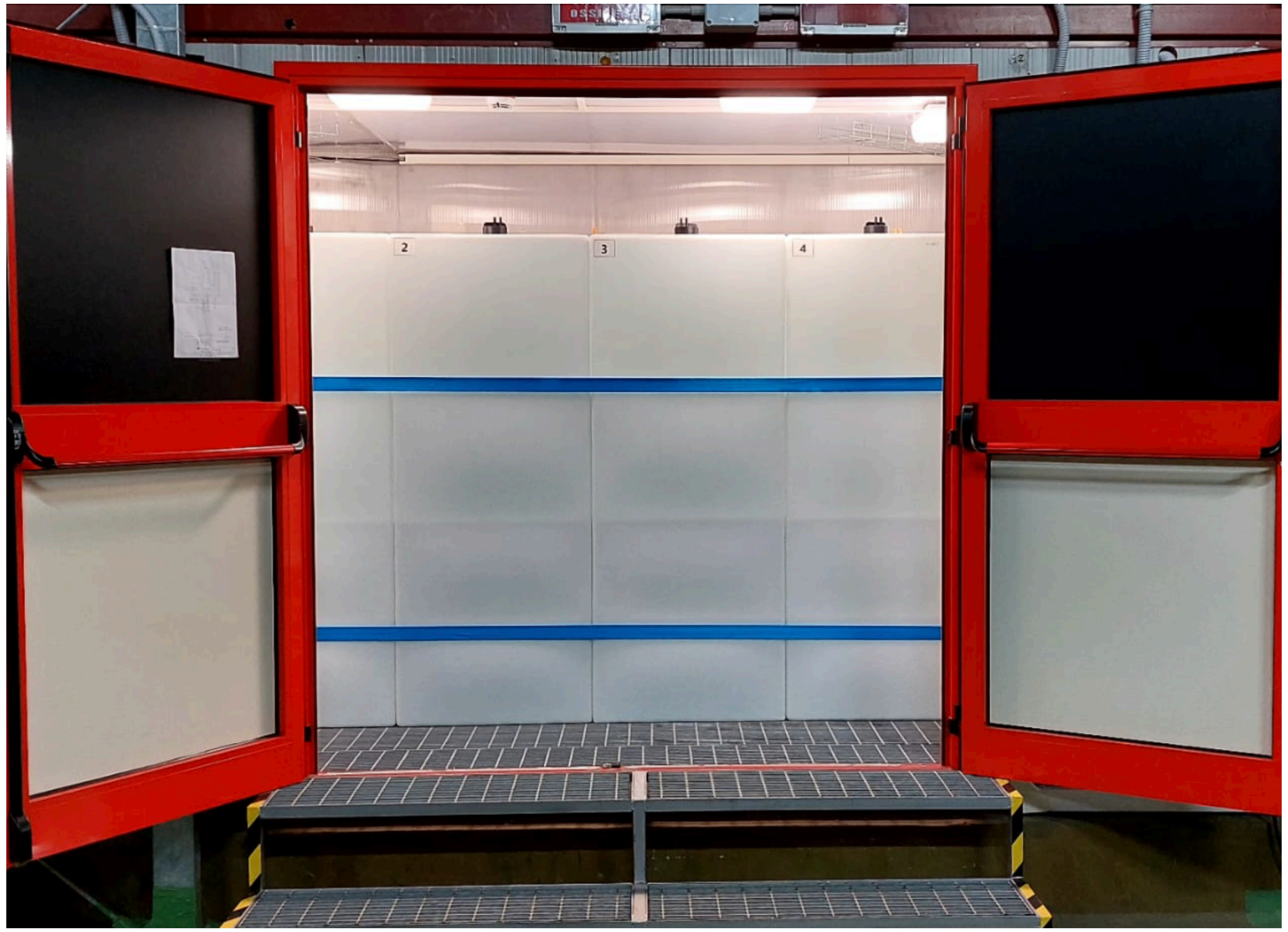
- **From May 5, 2023 to Nov 16, 2023 + 2024**
- Some numbers:
  - ➡ 6 months of operations
  - ➡ Background **observed event rate**: ~ 1.6 Hz
  - ➡ Background **expected** event **rate** (from MC): ~ 0.5 Hz



LIME tested with AmBe neutron source and high energy X-ray sources

RUN 4: 10 cm Cu + 40 cm water

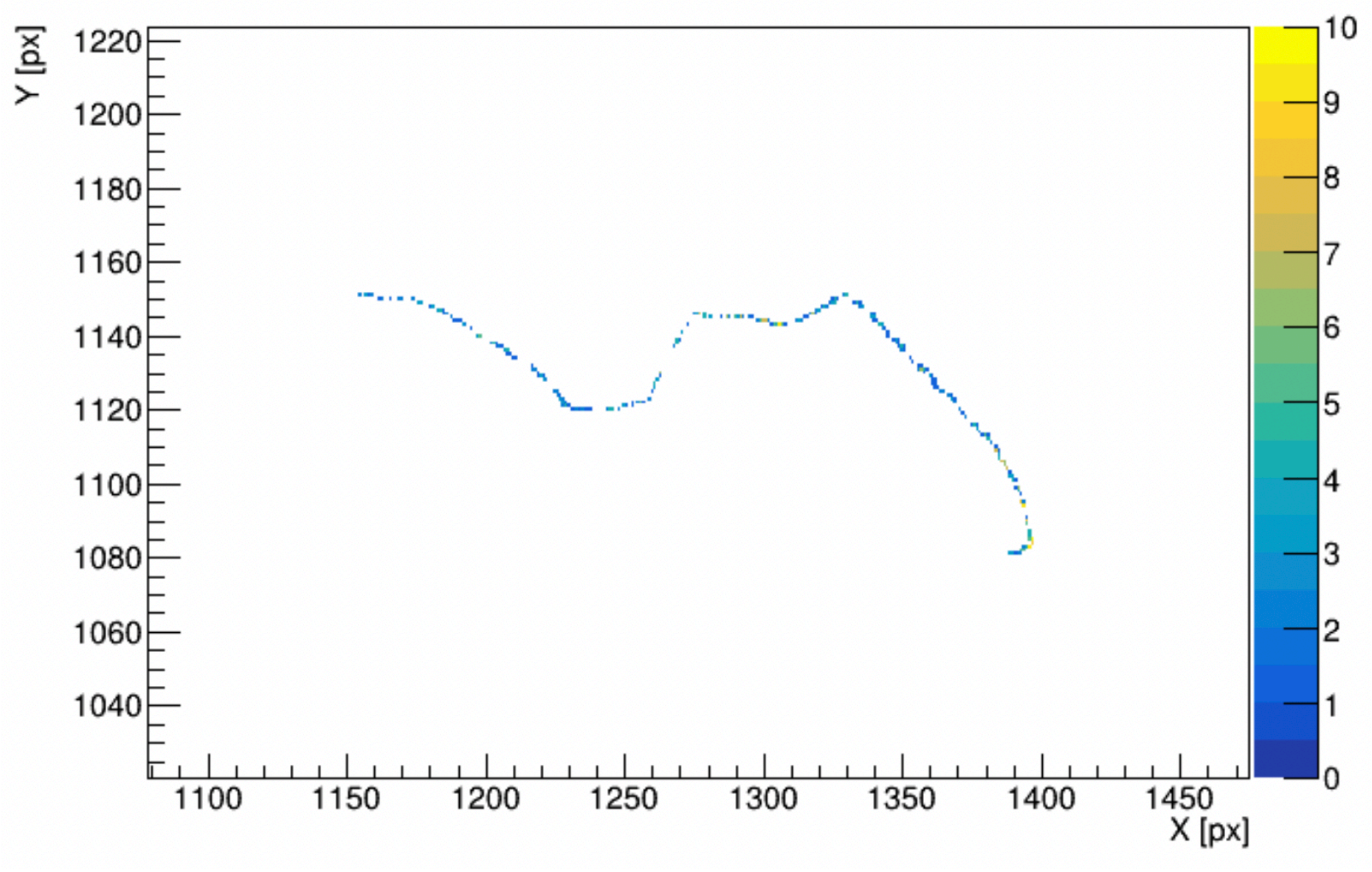
- **From Dec 4, 2023 to Dec 15, 2023 + 2024**



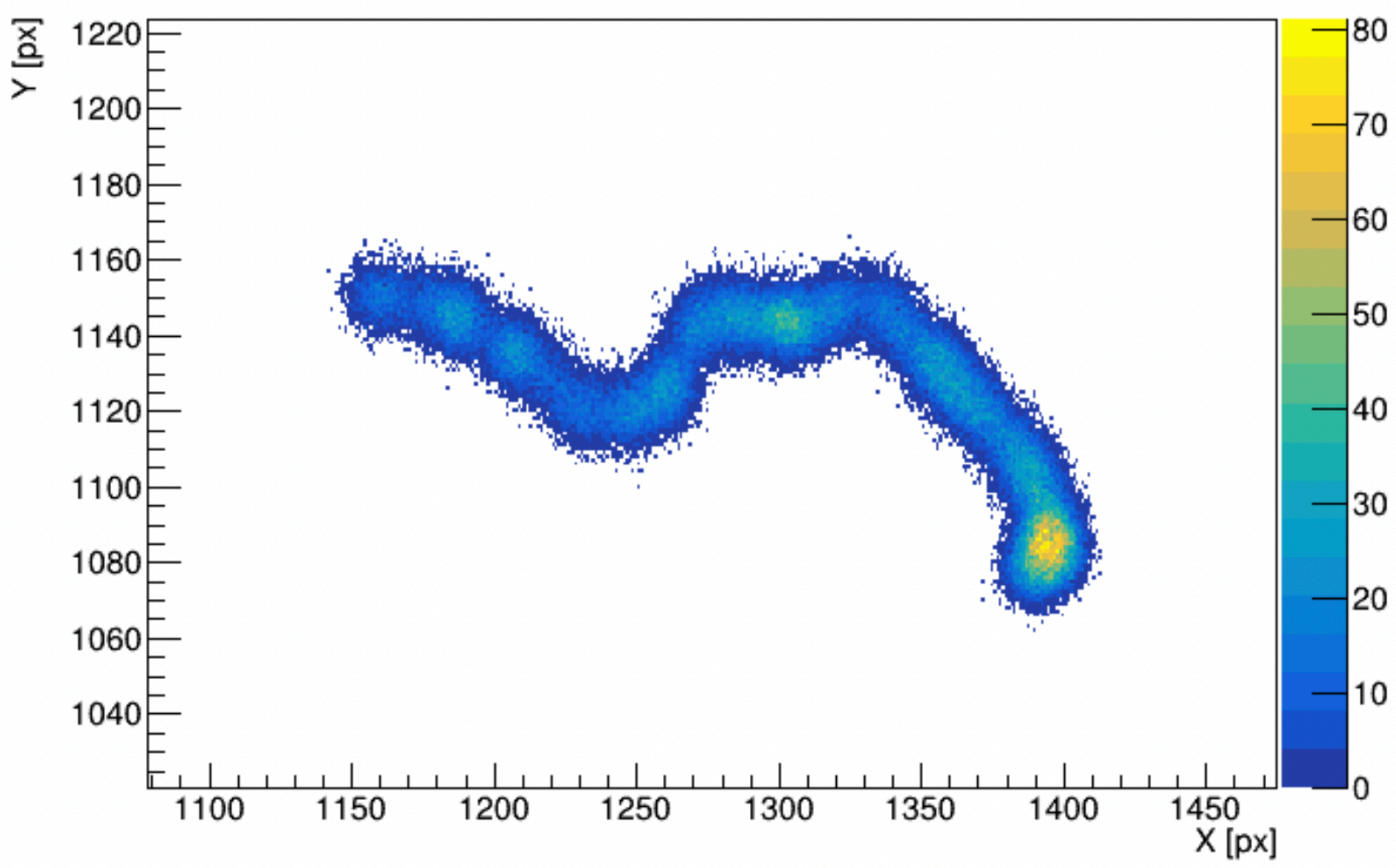
Simulation

- **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

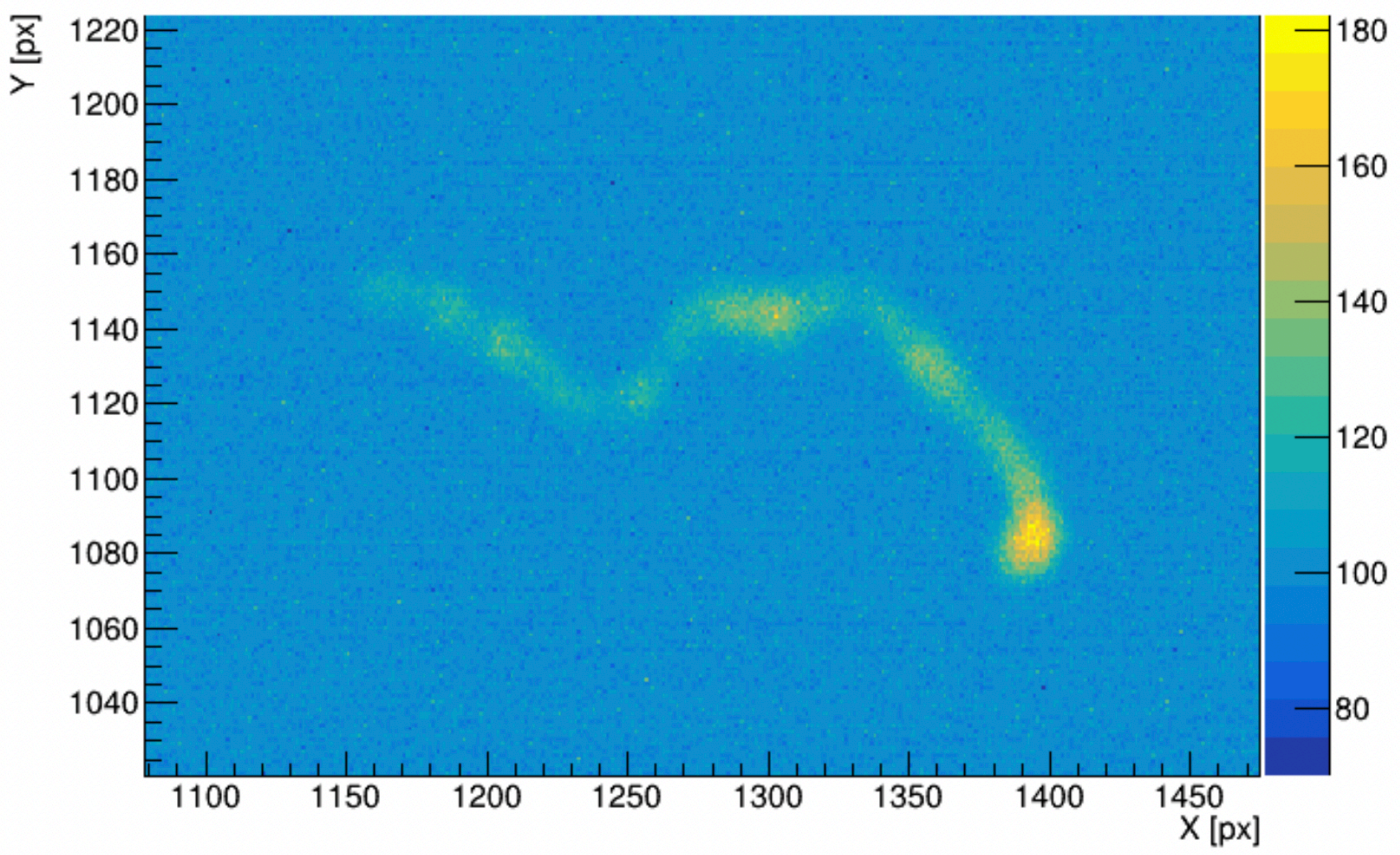
Tracks



Charge transport

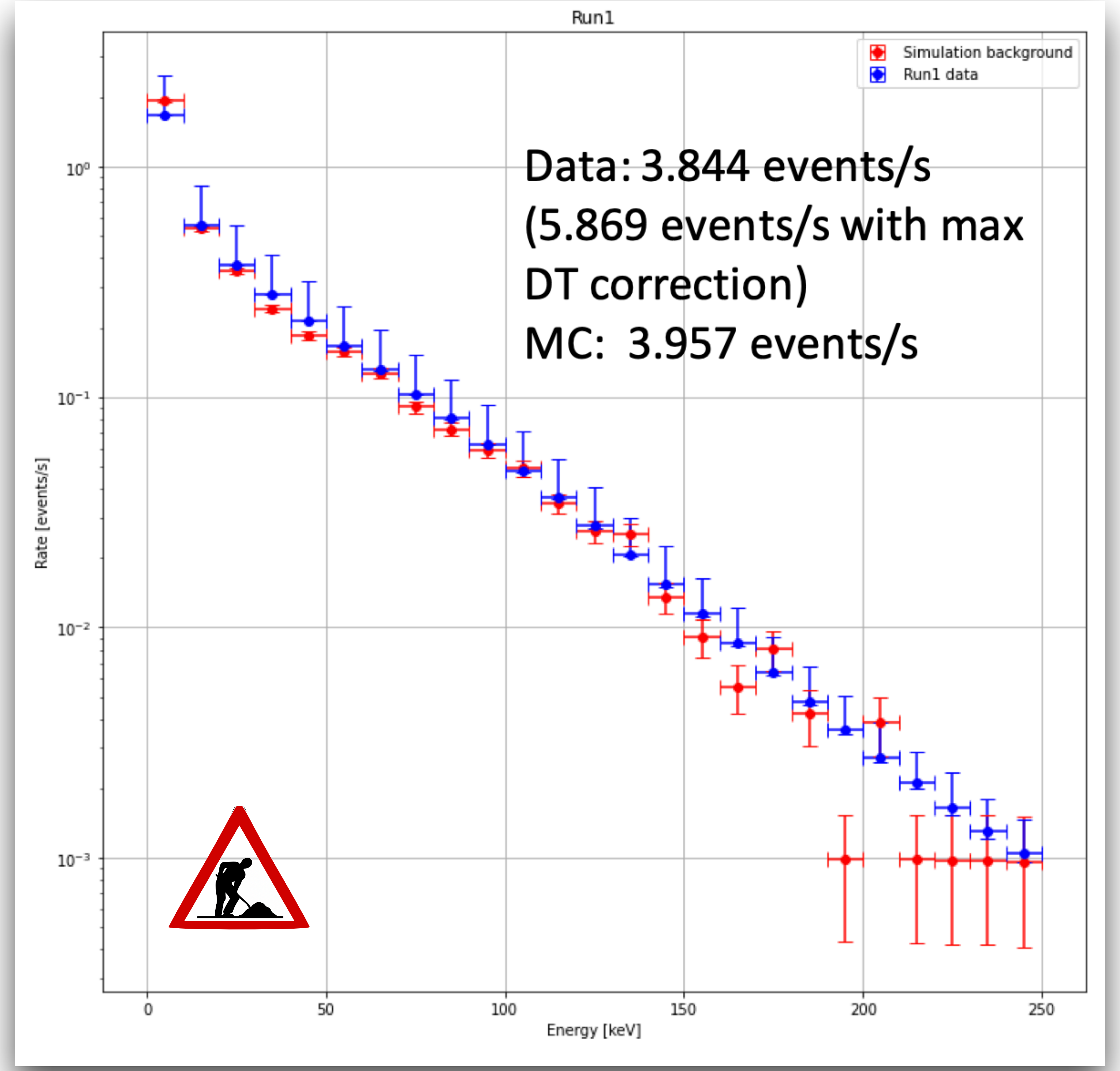


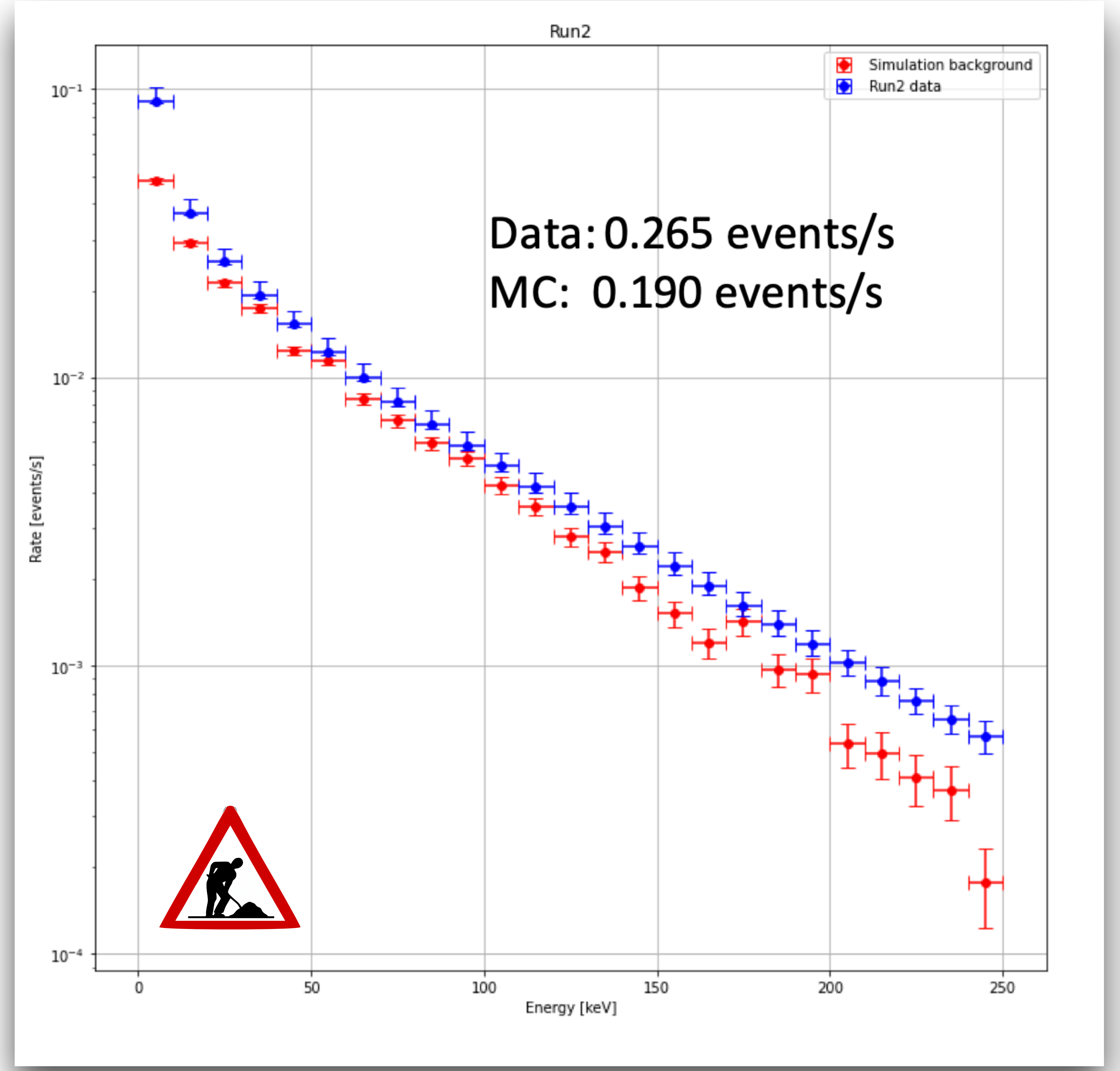
Gain + Digitization

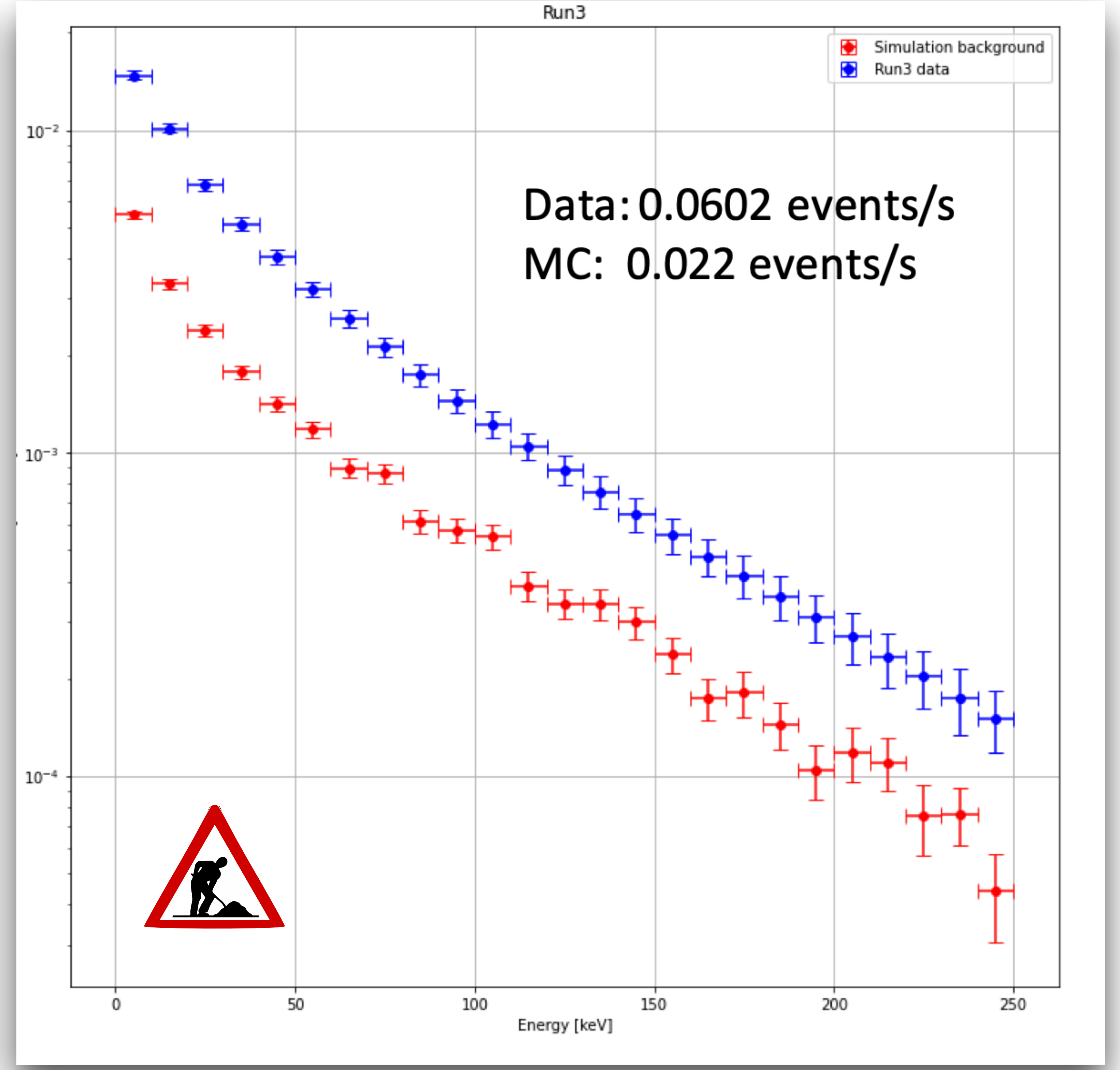


Energy spectrum with low background

- **First encouraging results** from **data - MC comparison**
  - ➡ **RUN1**: ✓
  - ➡ **RUN2 & RUN3**: difference in internal component (probably gas contaminants)

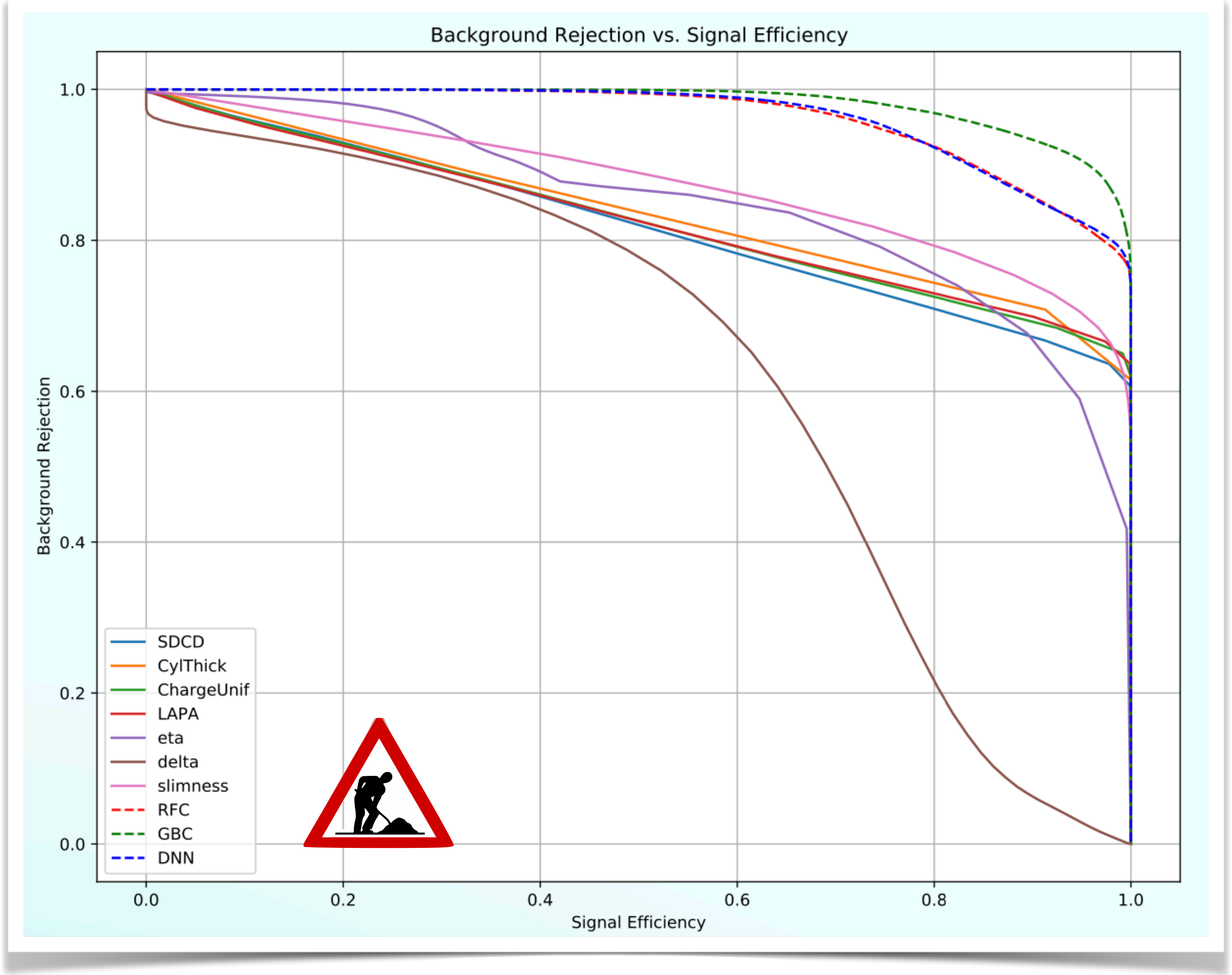


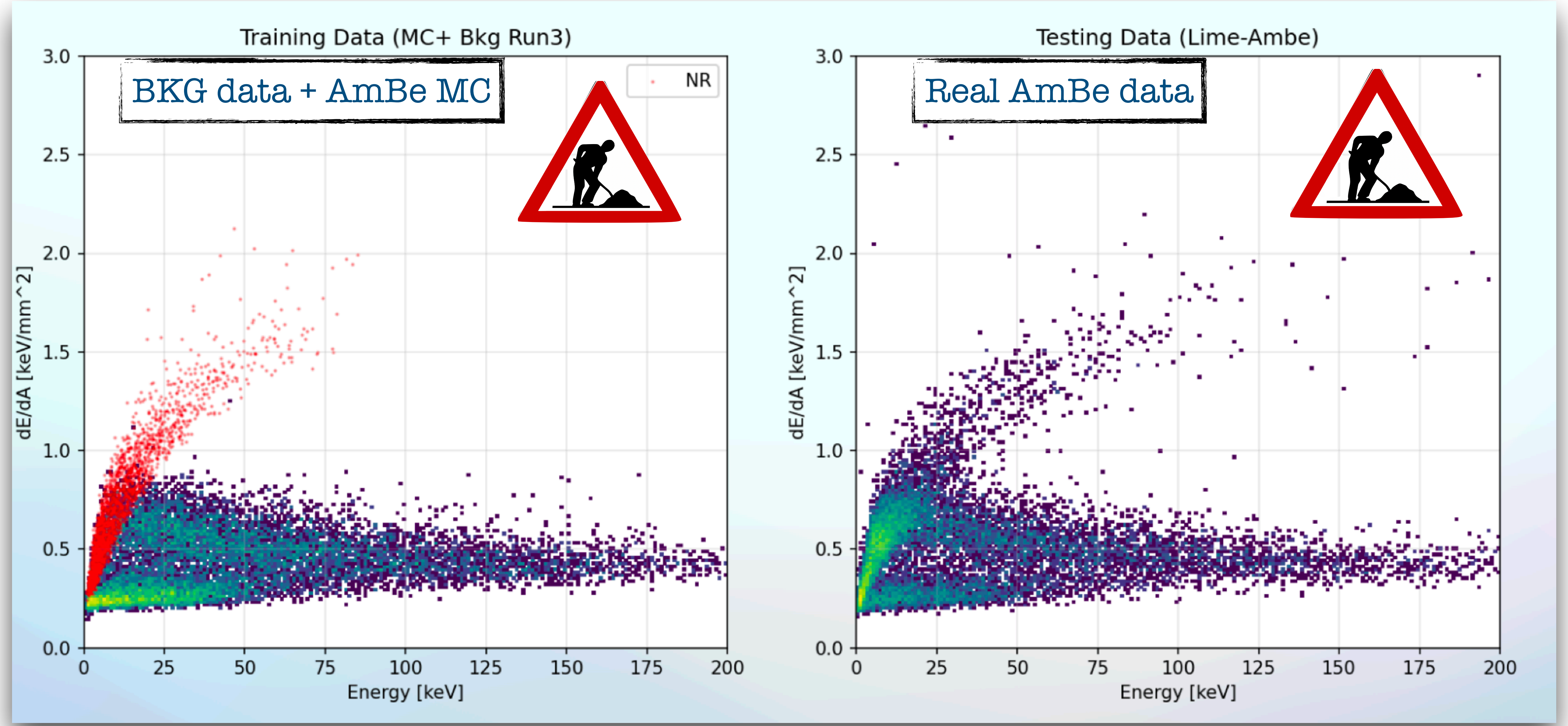


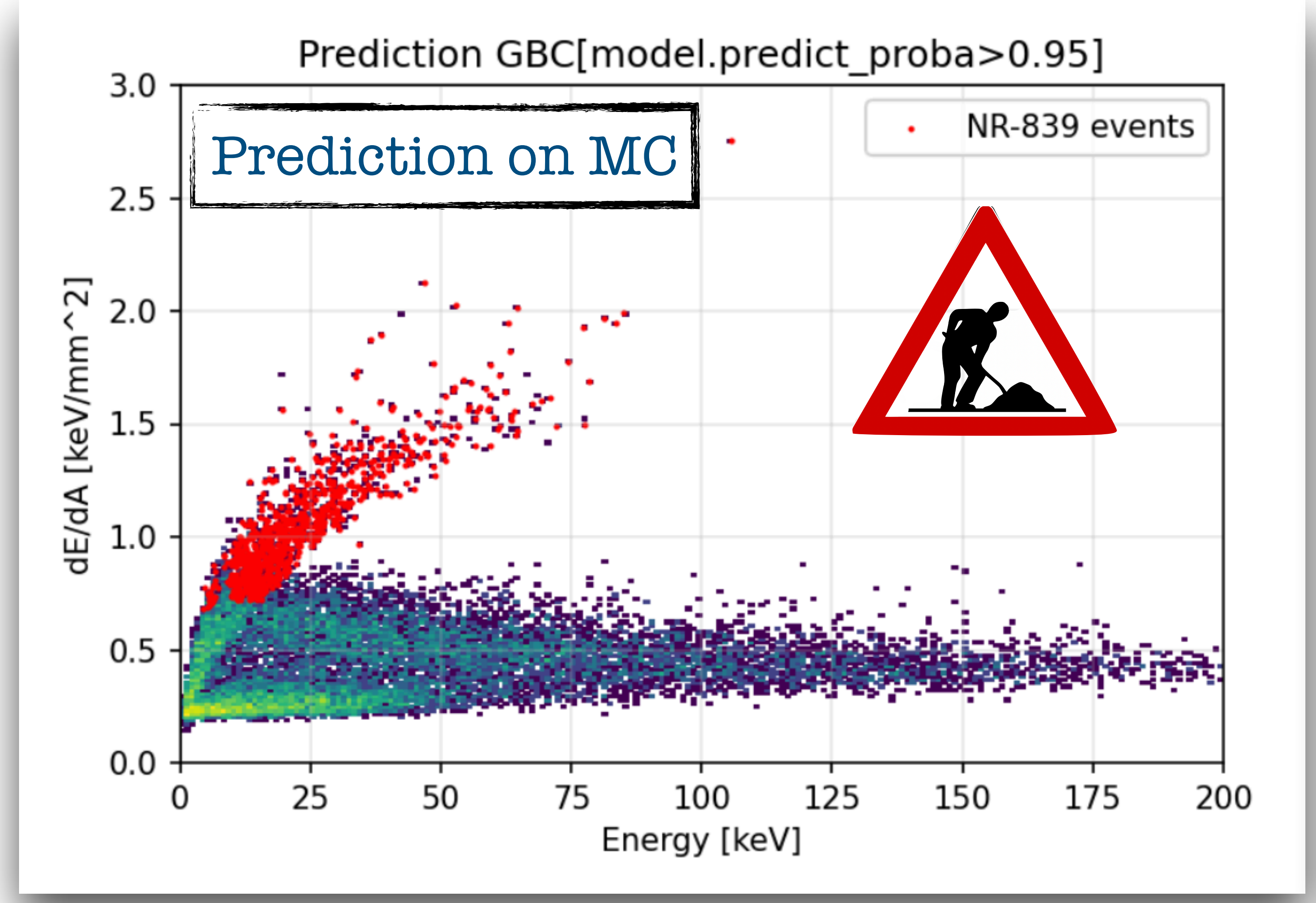


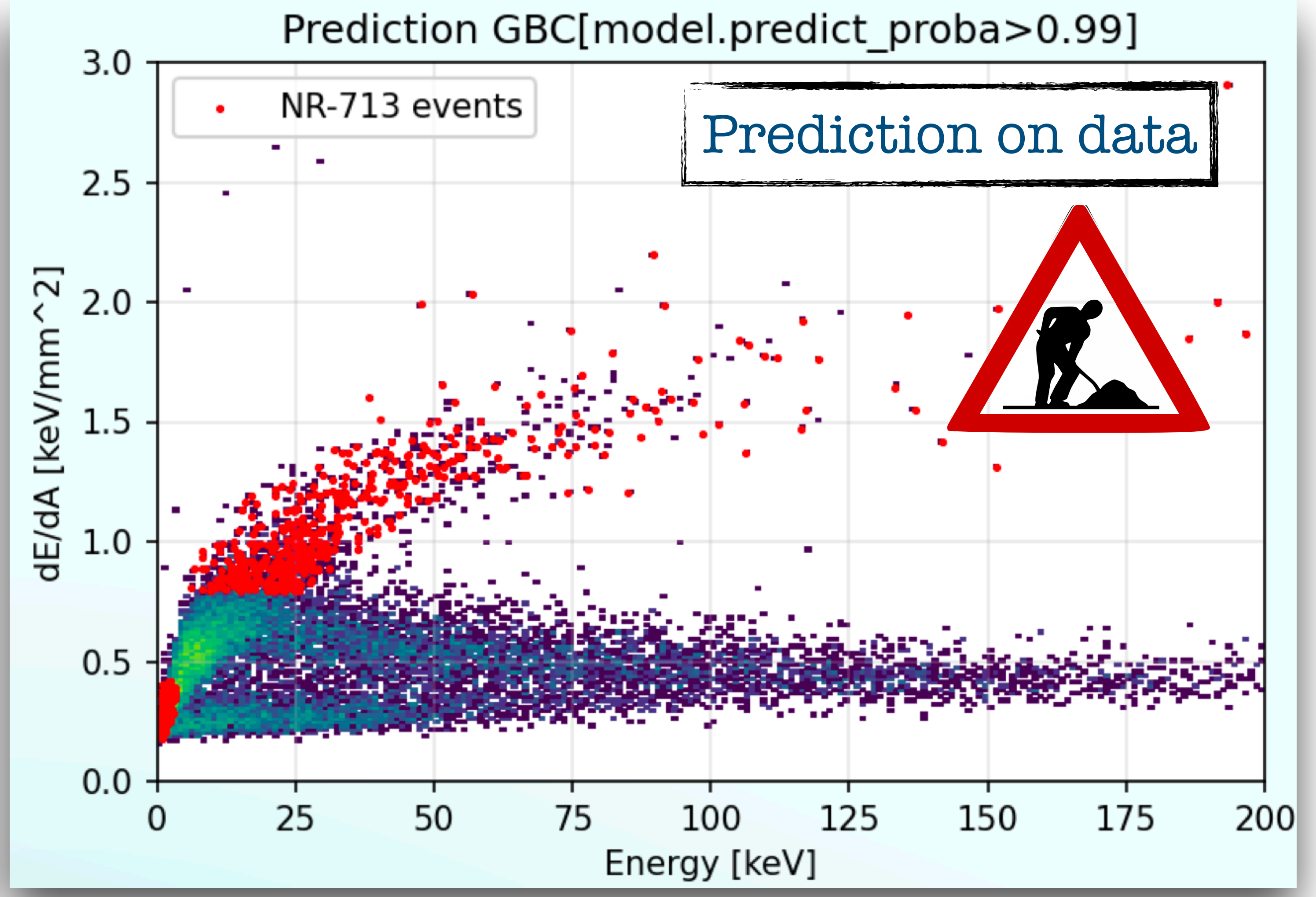
NR vs ER discrimination

- **AmBe neutron source underground!**
- **ML** technique (GBC) to distinguish ERs from NRs



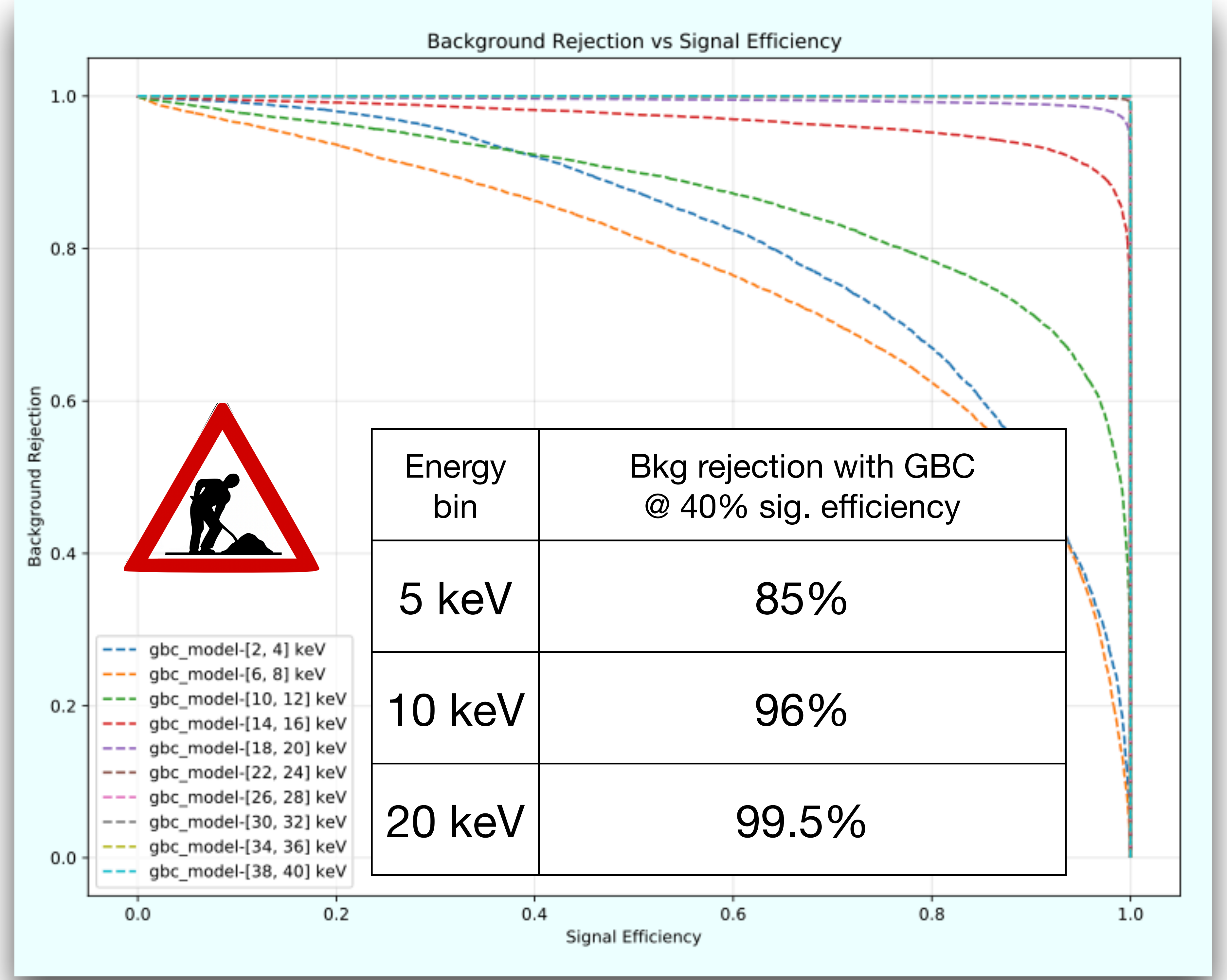




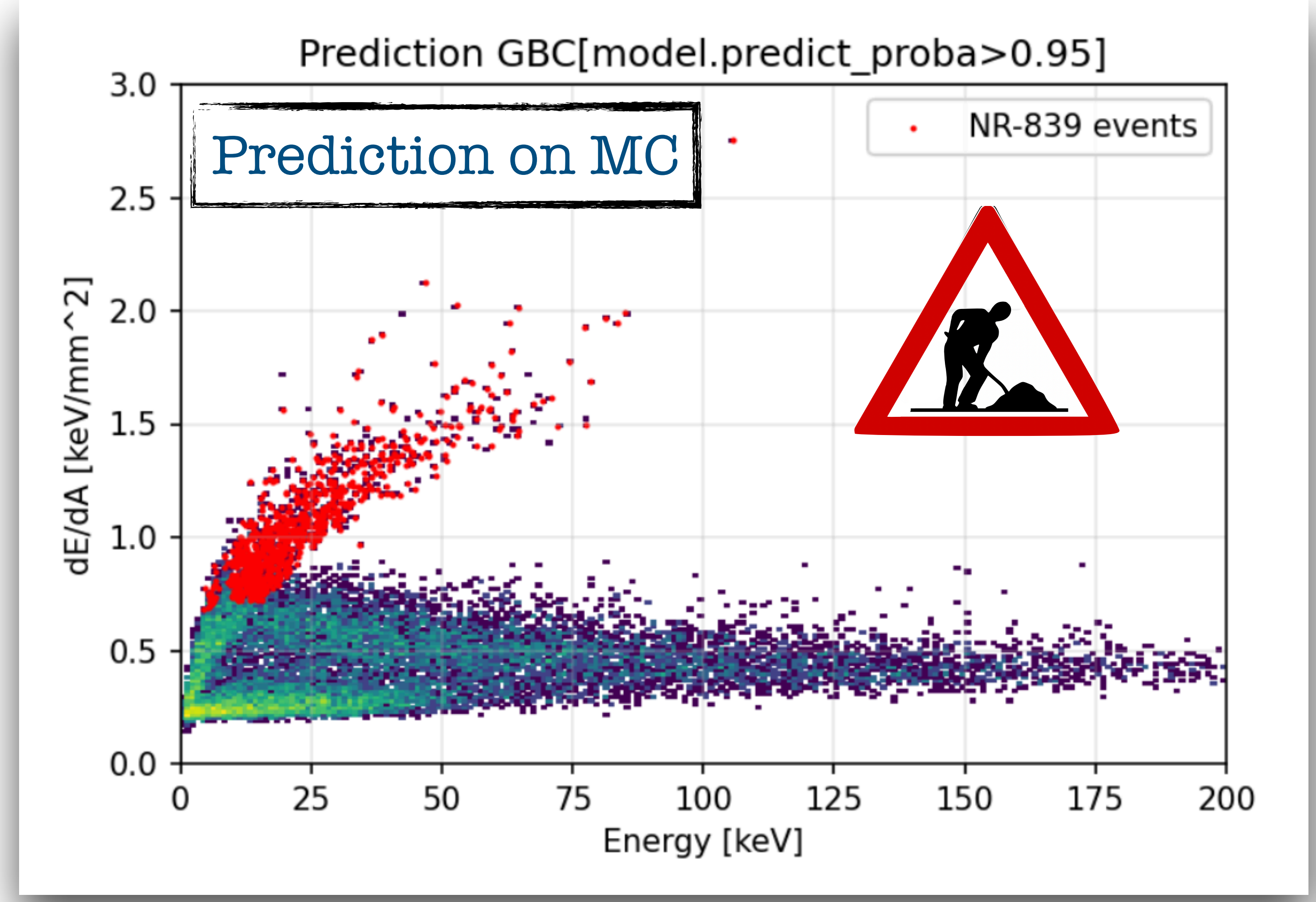


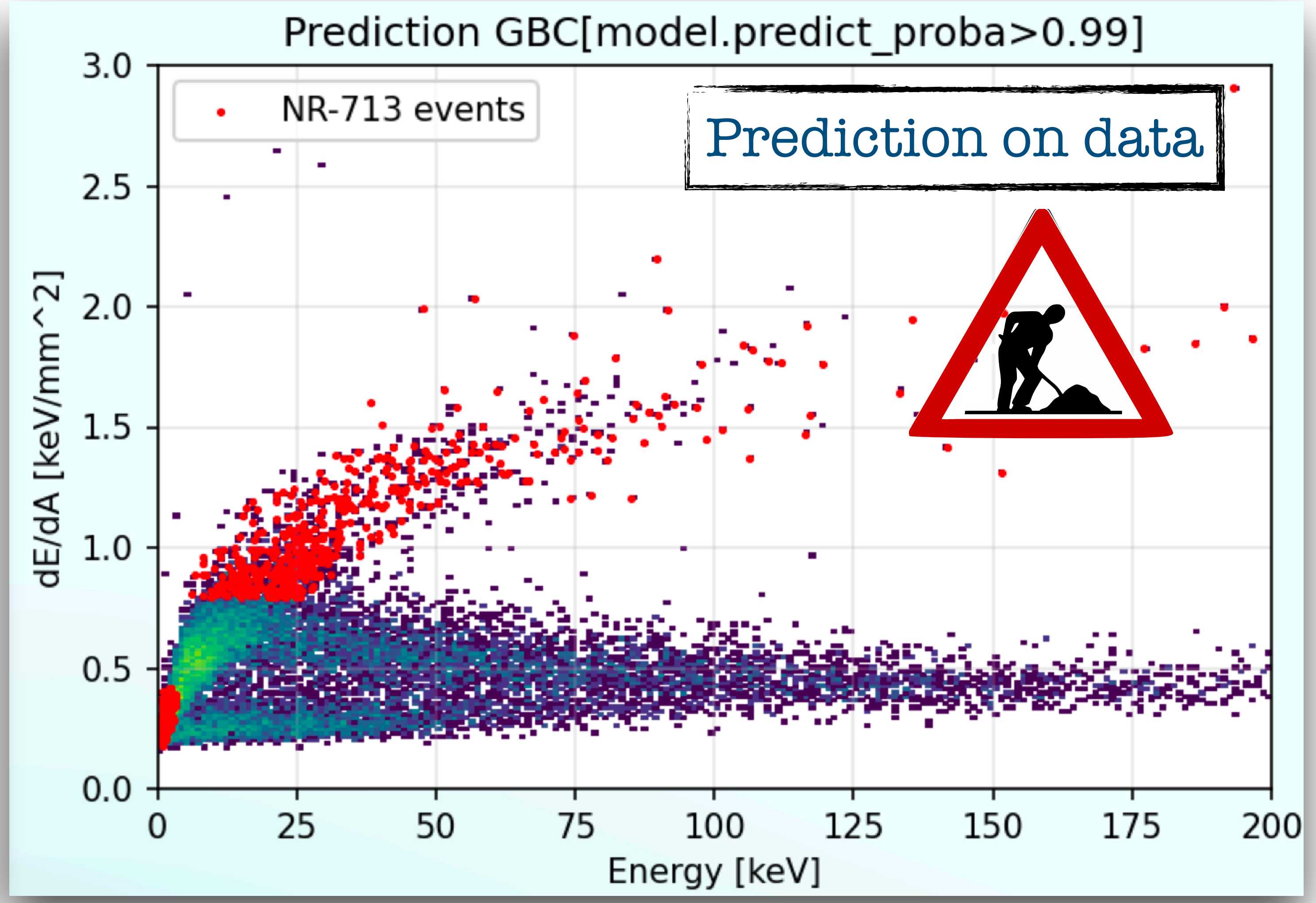
NR vs ER discrimination

- **AmBe neutron source underground!**
- **ML** technique (GBC) to distinguish ERs from NRs
- Due to the saturation effect, ERs and low energy NRs appear similar and we are working to optimize the selection especially on the overlapping region
- Preliminary results show a good selection performance at high energy, and a degradation towards lower energies

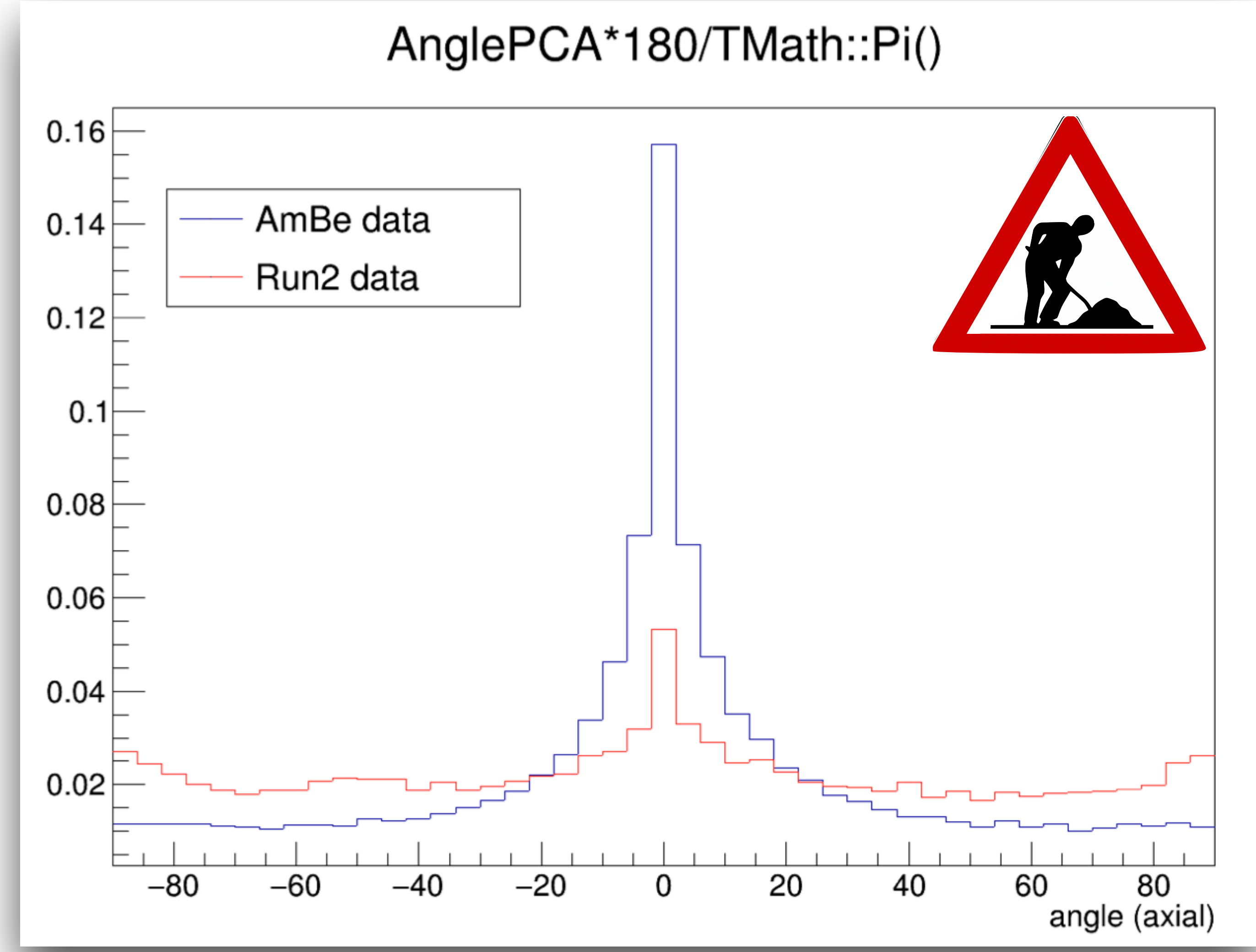


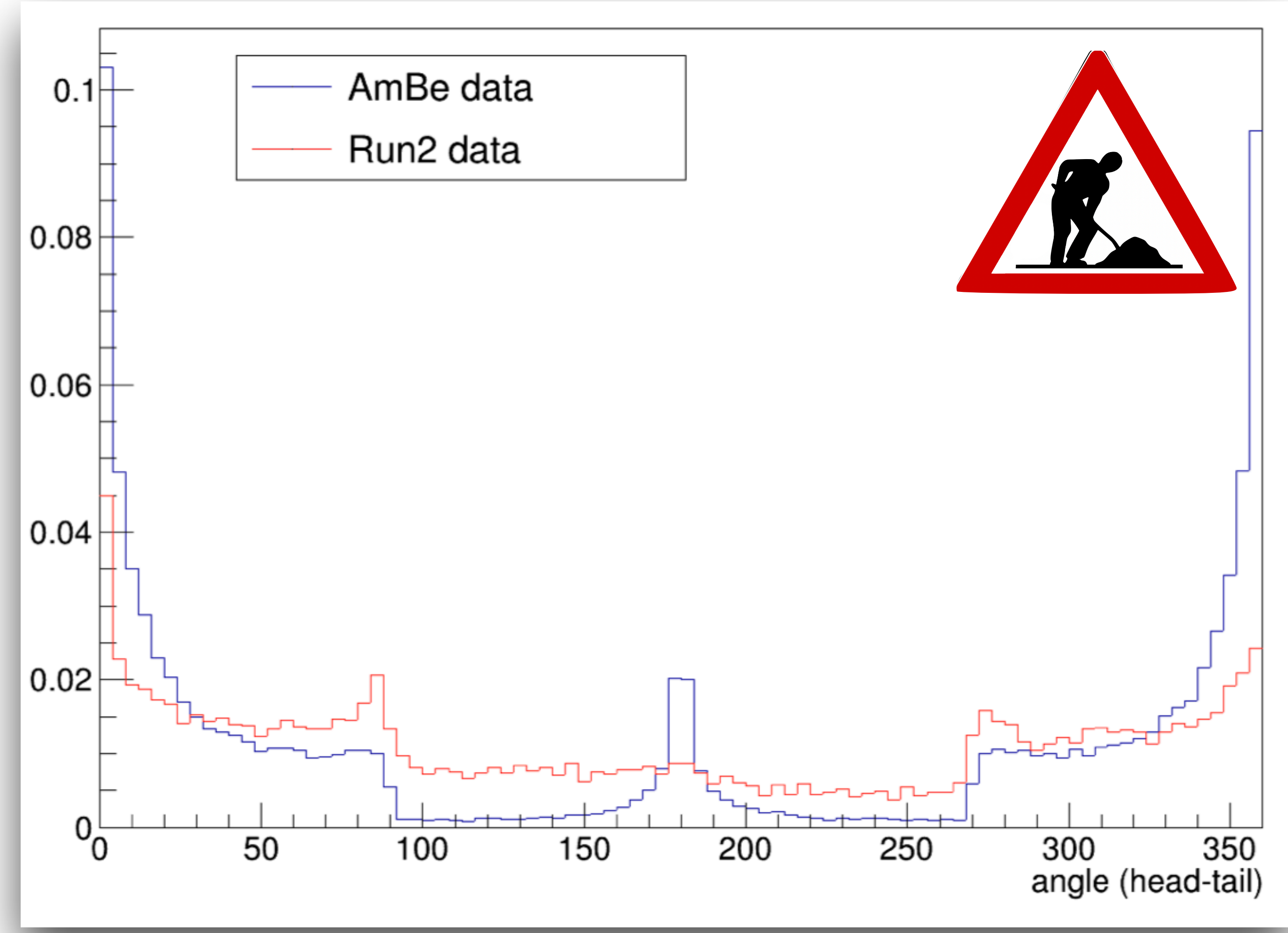
Energy bin	Bkg rejection with GBC @ 40% sig. efficiency
5 keV	85%
10 keV	96%
20 keV	99.5%



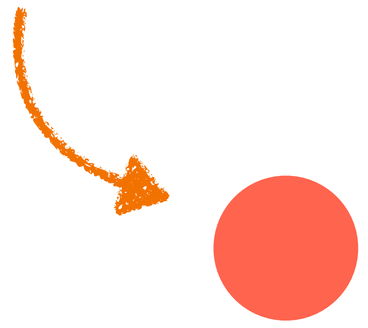


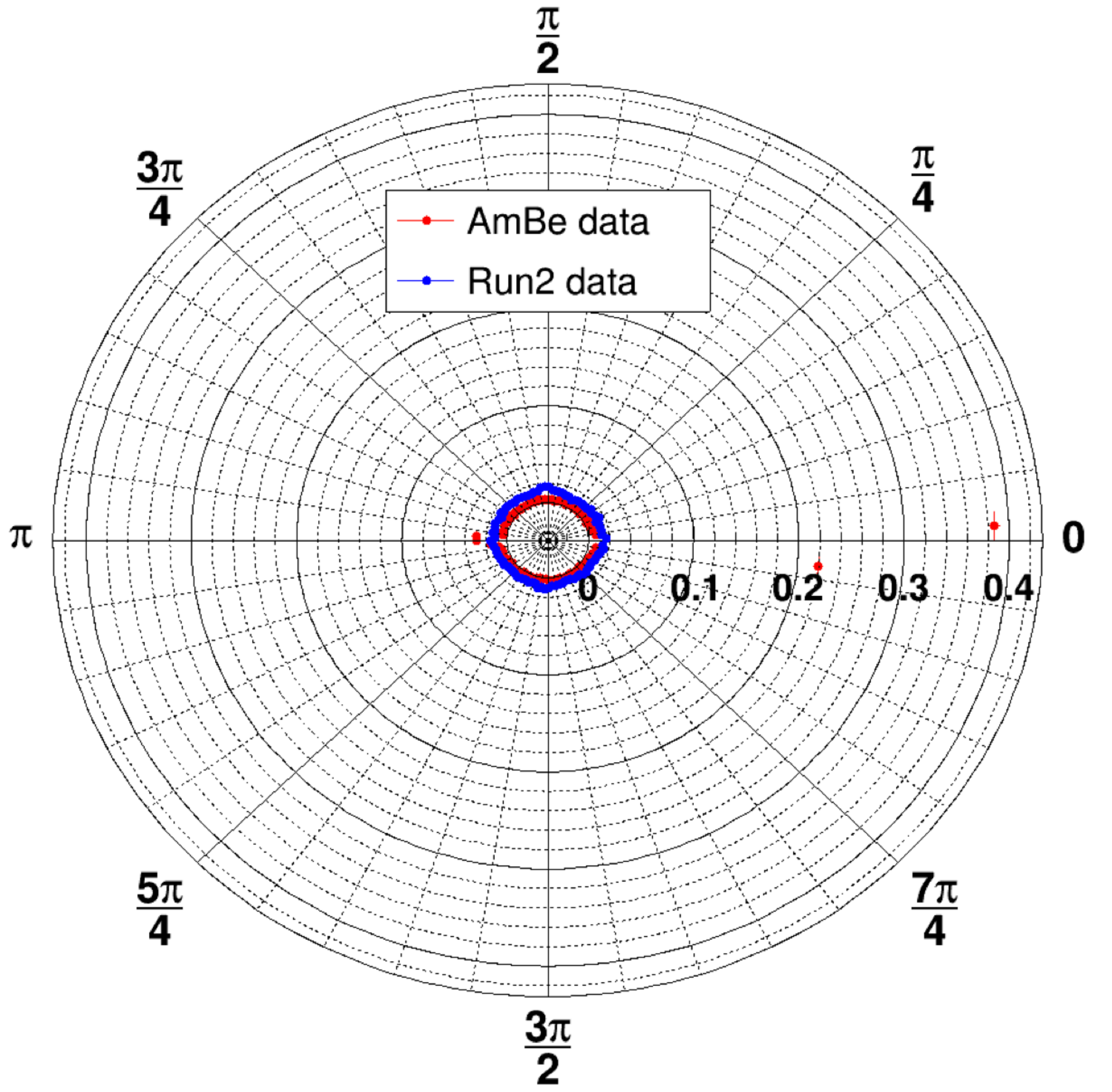
First hints of NR directionality





In this coordinates
the AmBe source
is here!

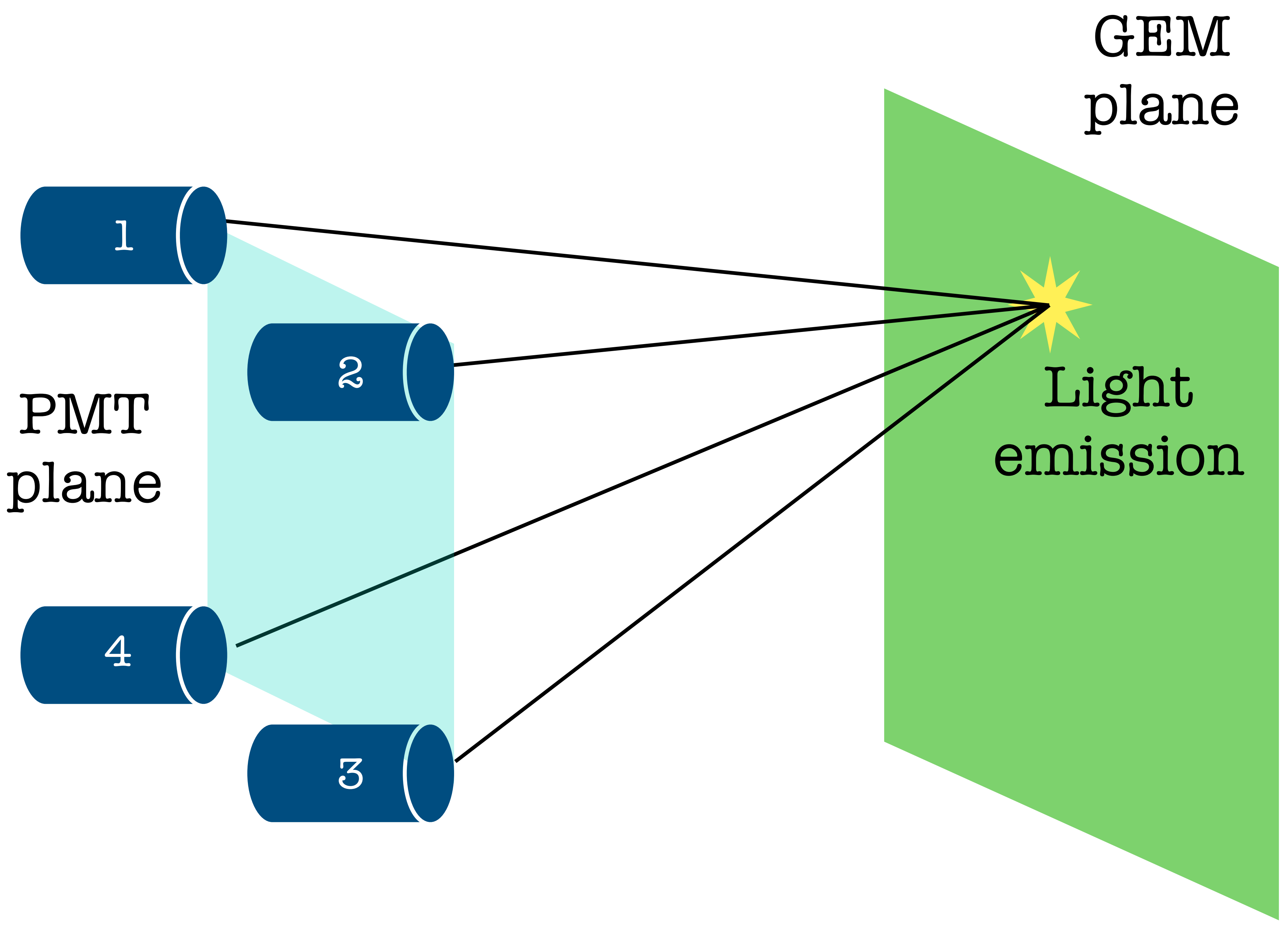




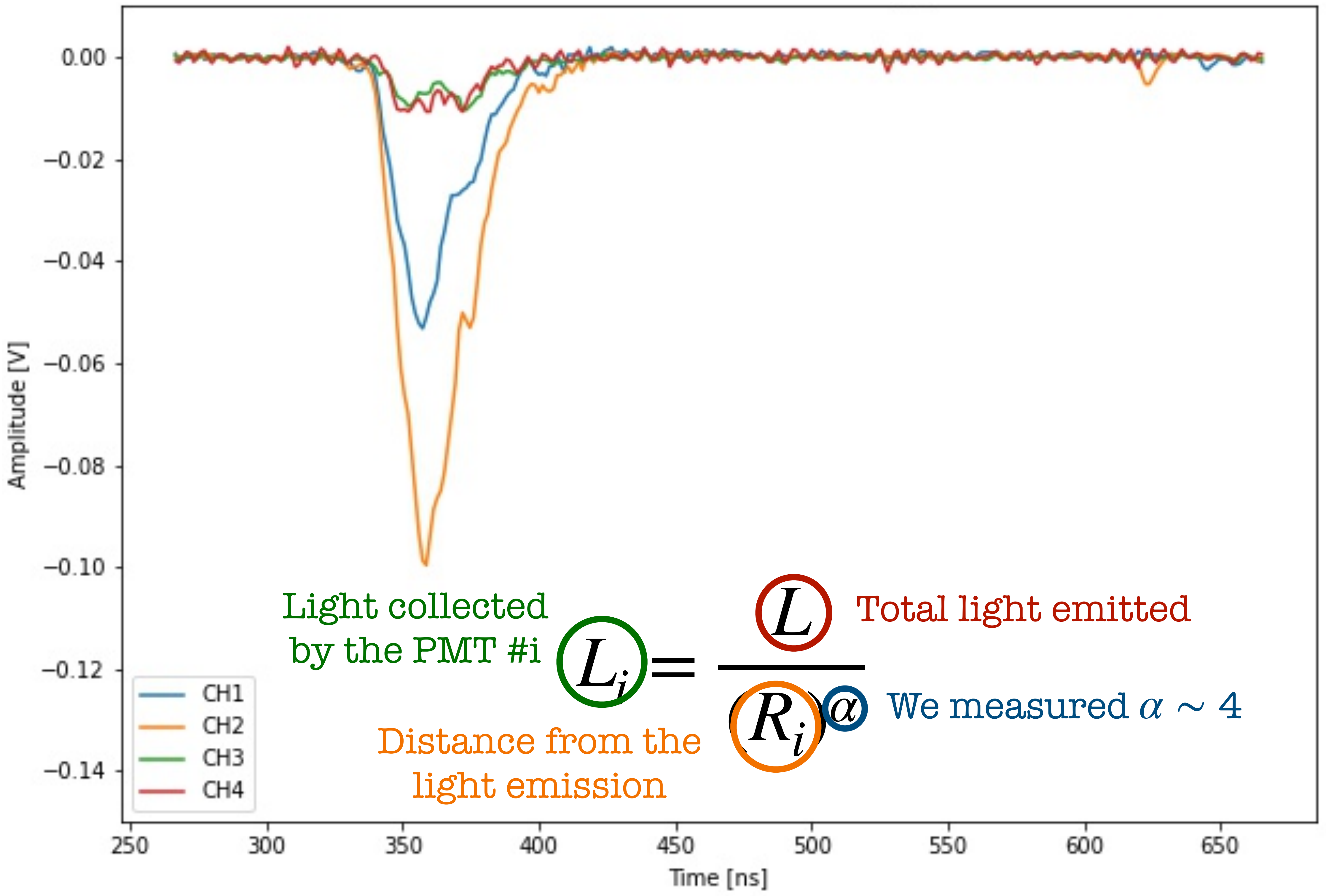
- Focus on the high density tracks ($dE/dA > 0.46$ keV/mm^2)
- **First hint of NR directionality in the AmBe dataset!**

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



Typical ^{55}Fe spot-like interaction

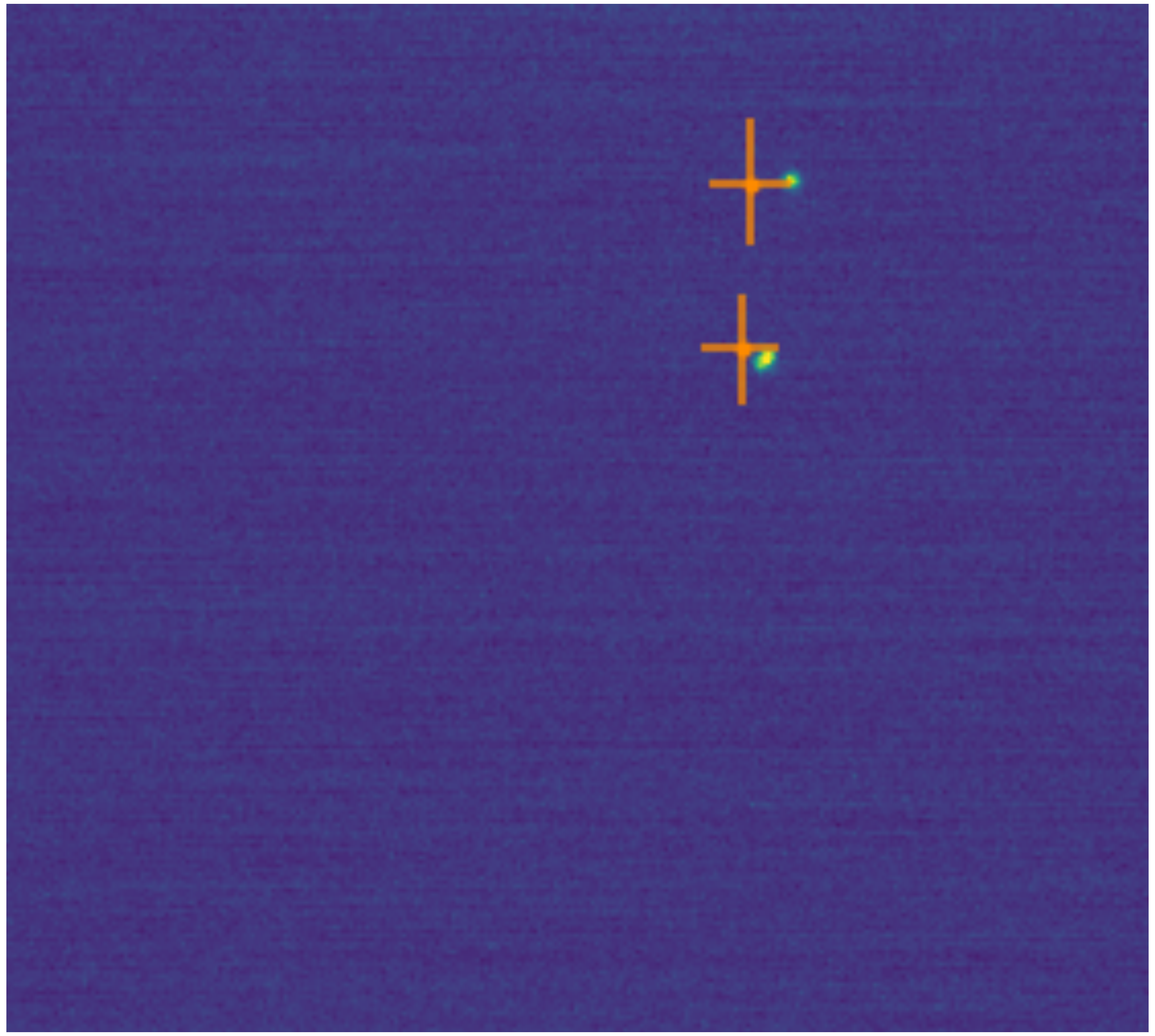


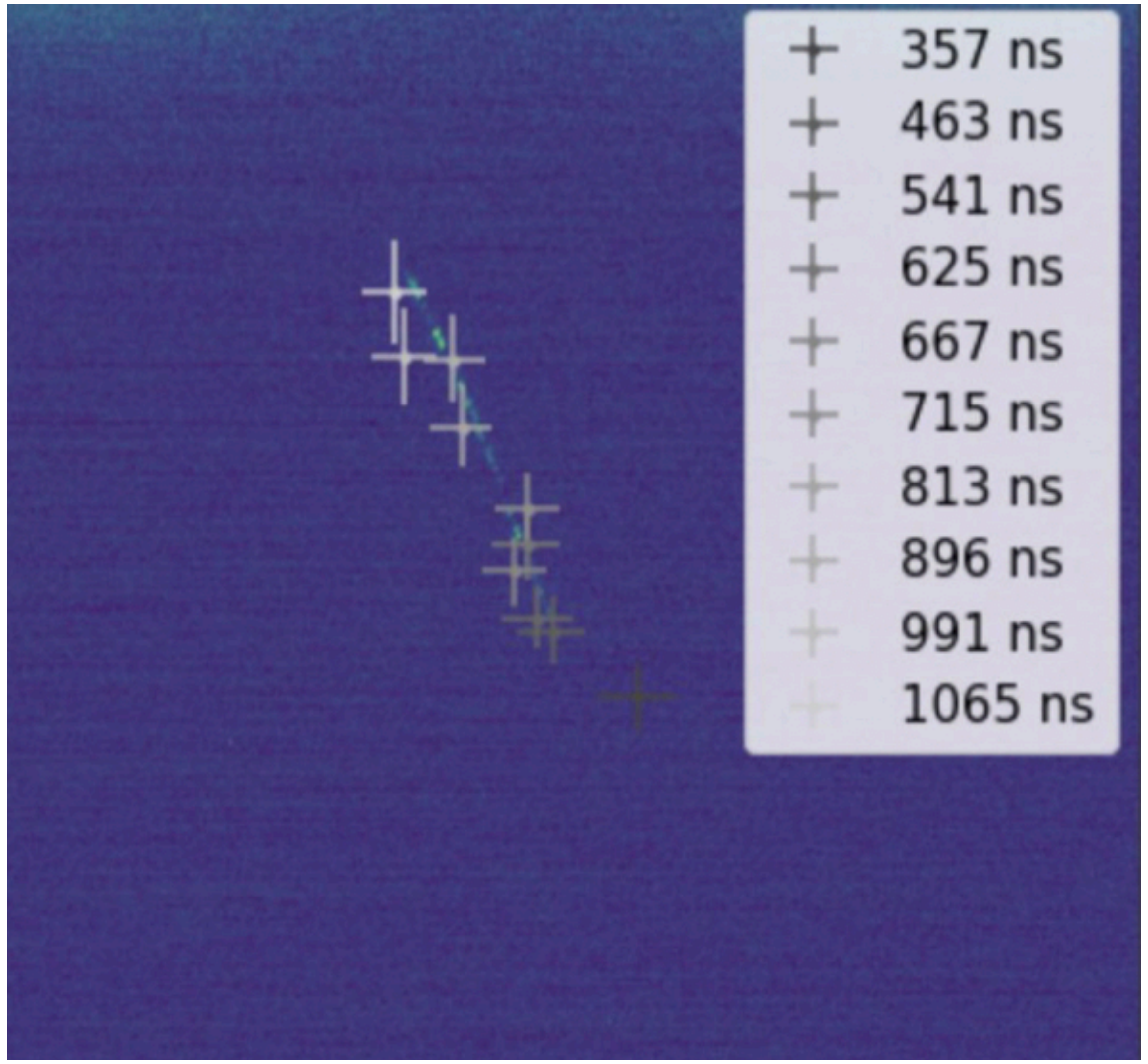
$$L_i = \frac{L}{(R_i)^\alpha}$$

- 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



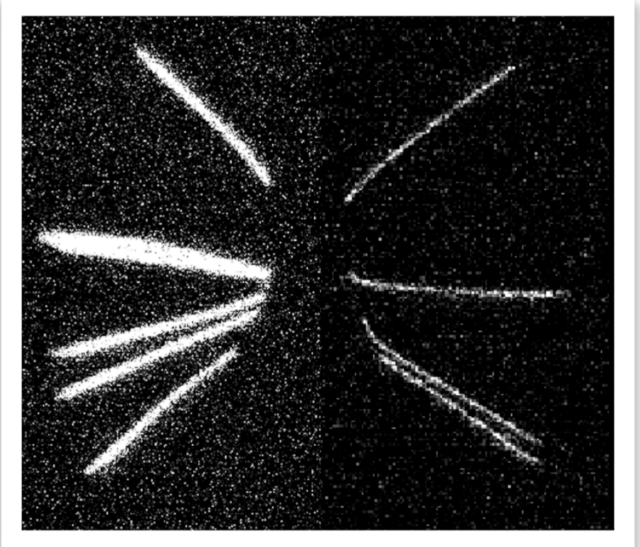


R&D Projects

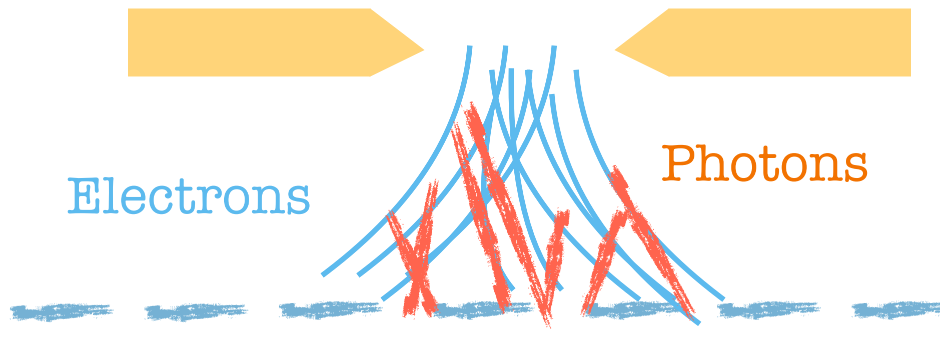
E. Baracchini et al., JINST 15 (2020) 08, P08018

Negative Ion Drift (NID)

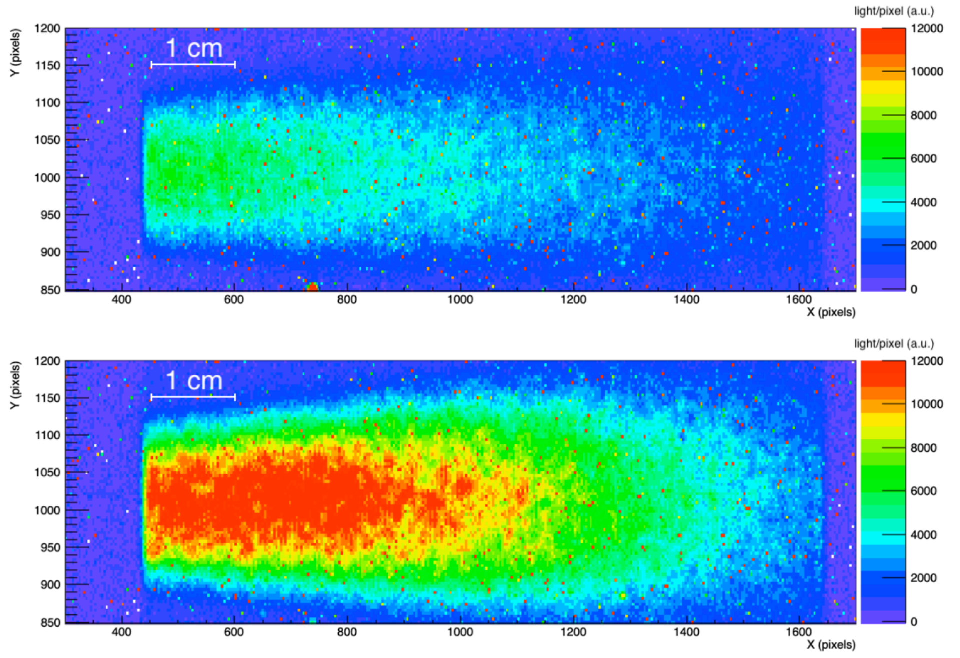
- **INITIUM project:** the first **1 m³ Negative Ion TPC** (NITPC) with **GEMs** amplification [in **He/CF$_4$/SF$_6$** mixture] and **optical readout** with CMOS-based cameras and PMTs.
- See prof. Elisabetta Baracchini's talk



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**



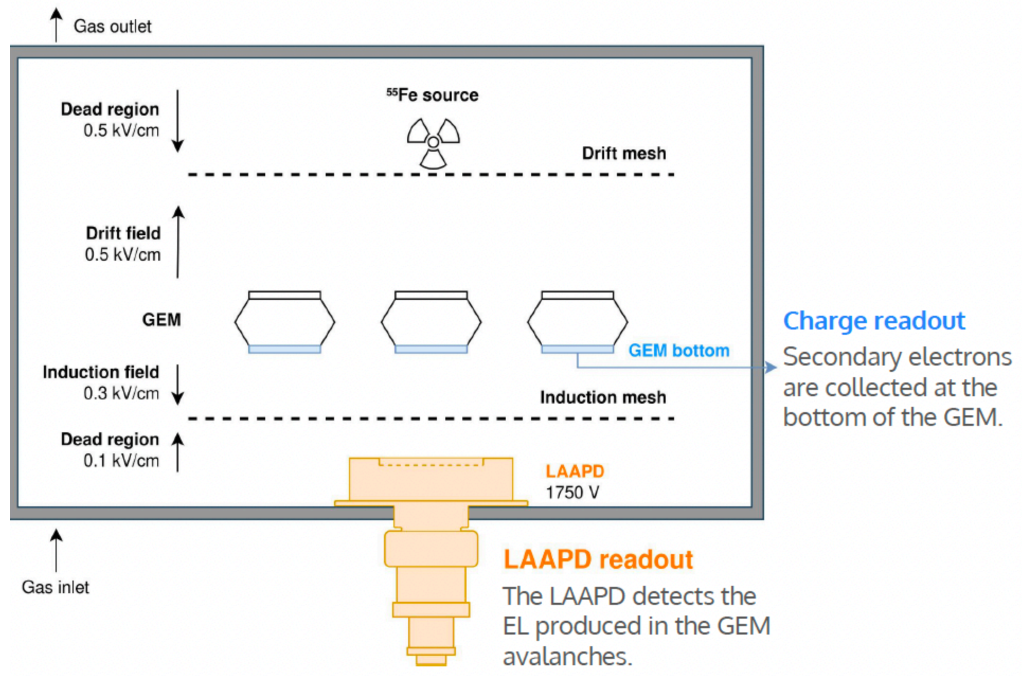
E = 0 kV/cm

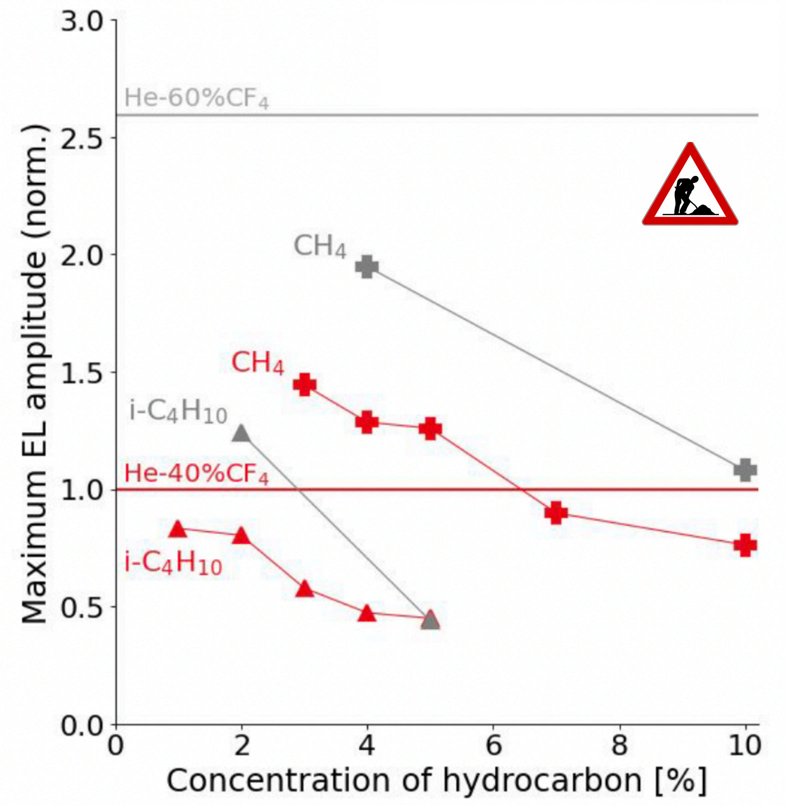
E = 13.5 kV/cm

Hydrocarbons

- Tests to study the possibility of adding hydrogen-rich gas (**C_4H_{10} and CH_4**) to the mixture
- Adding up to 5% CH_4 to He:CF_4 increases the maximum attainable EL yield
- In terms of EL yield, CH_4 seems to be a better alternative than isobutane.

Single GEM dedicated setup

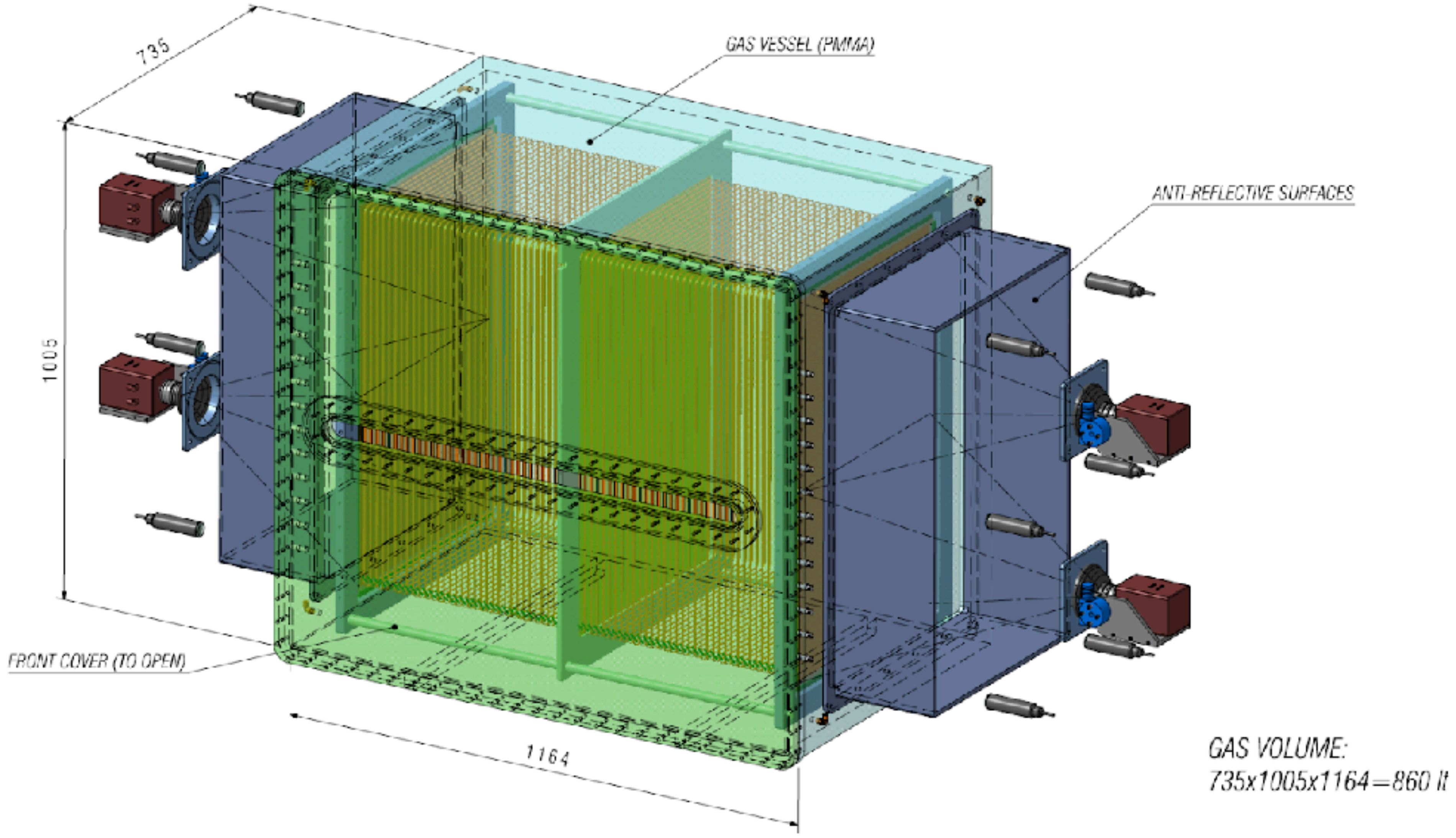


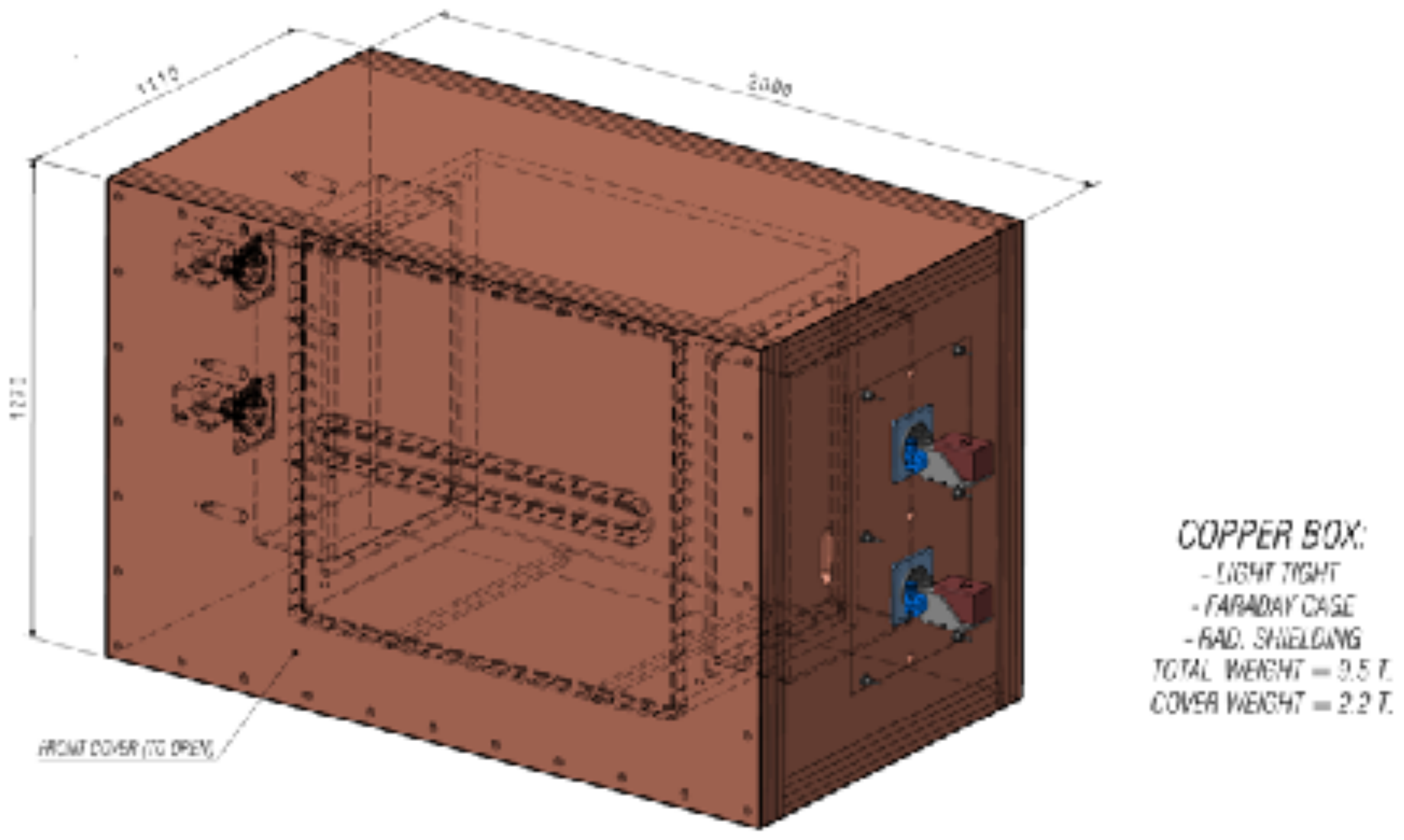


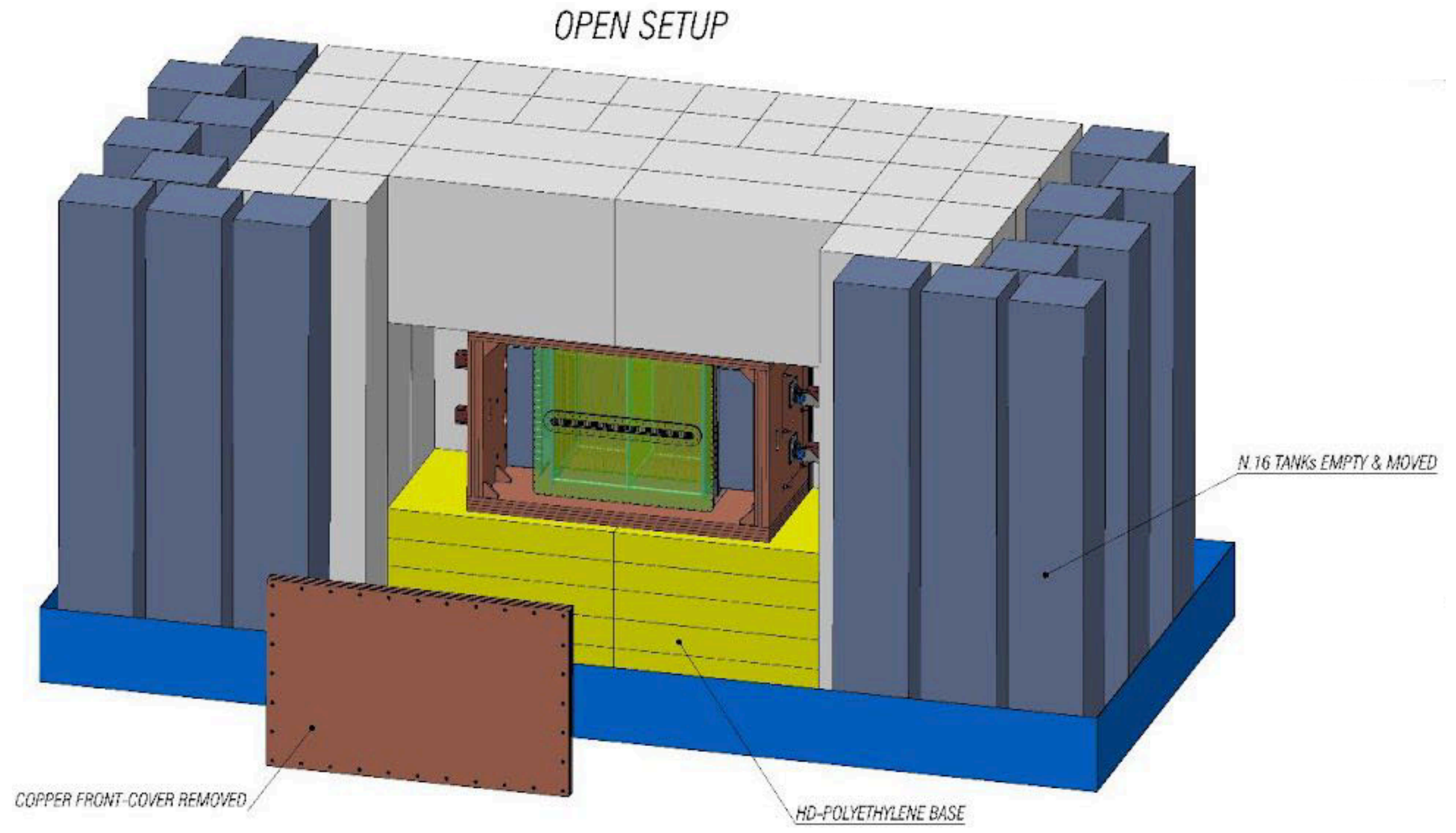
CYGNO PHASE 1: CYGNO_04

- **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) + 8 PMTs

Designed at LNF and to be installed at LNGS







Conclusions

- The CYGNO 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_{ee}) 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!

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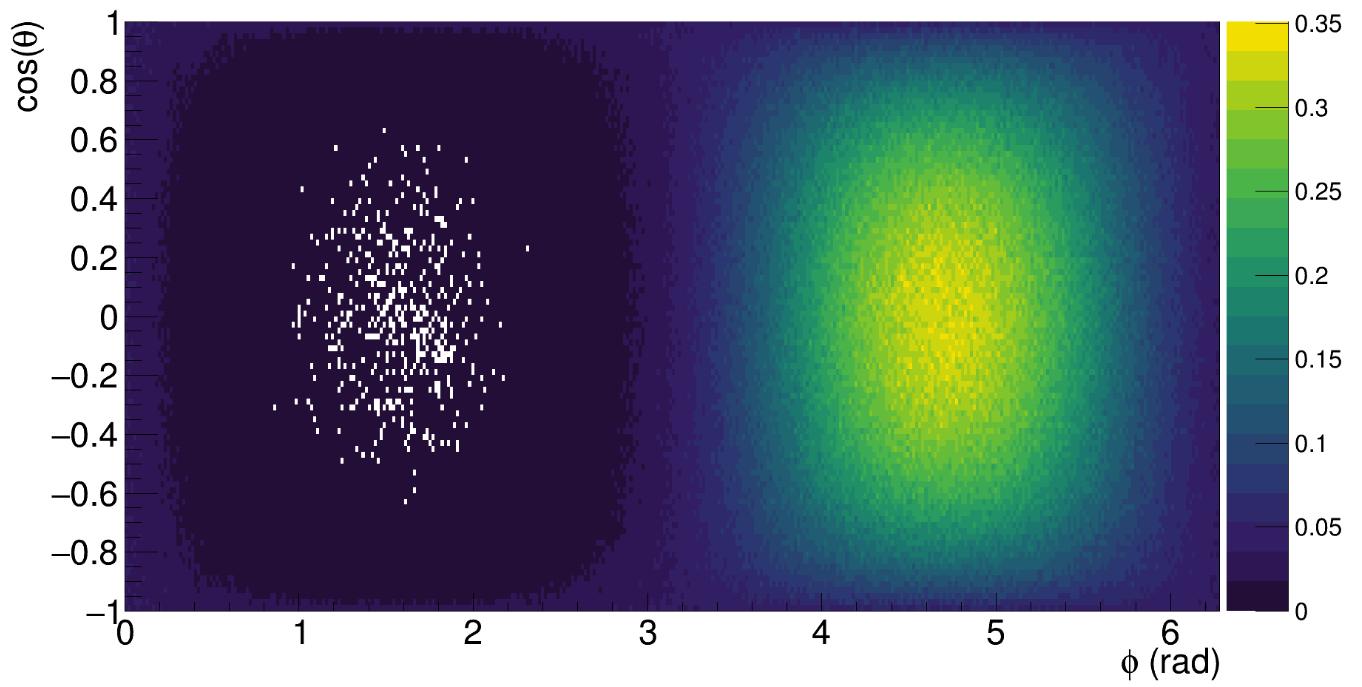
Backup

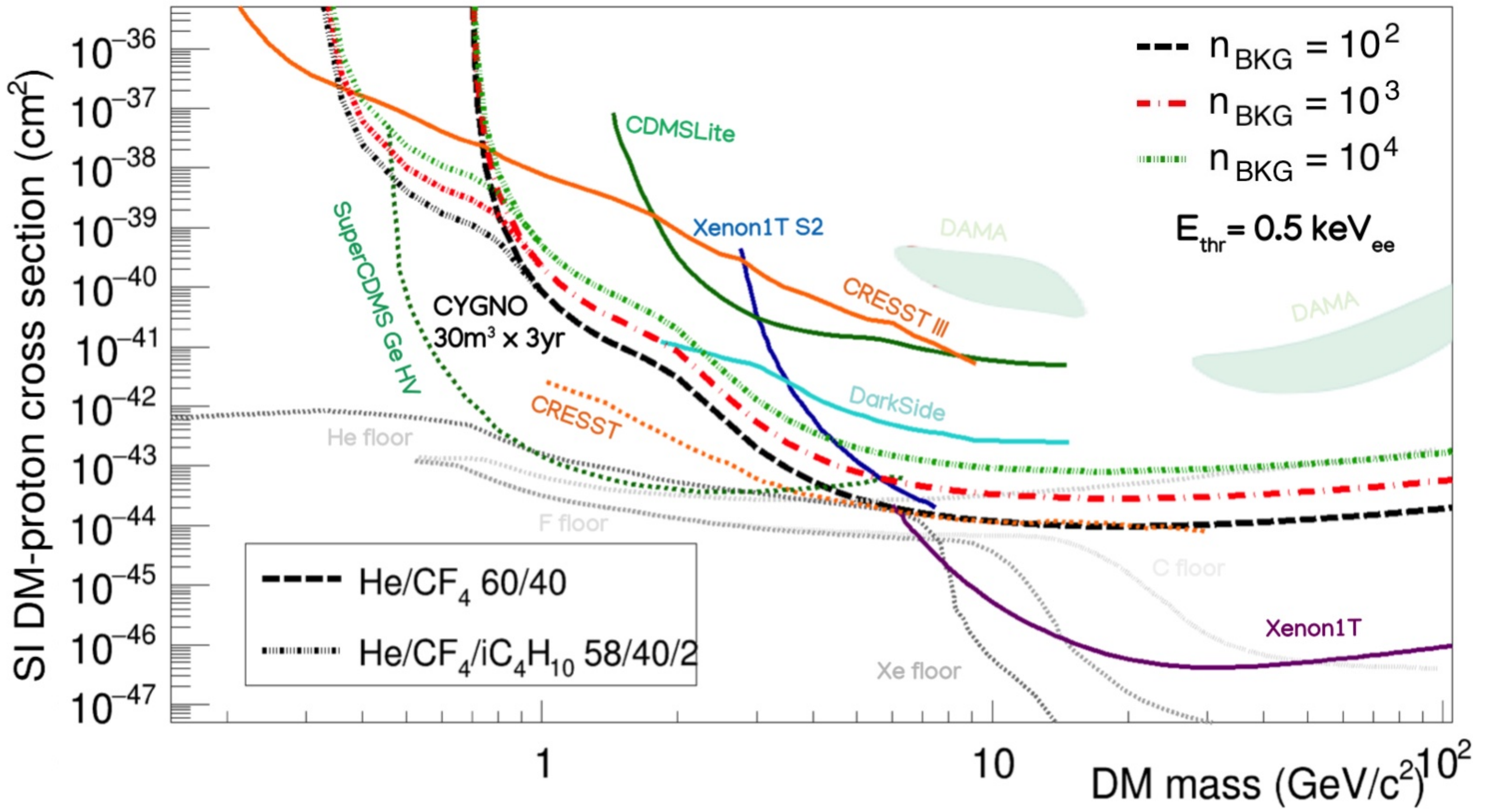
CYGNO PHASE 2: the 30 m^3 experiment for low mass DM searches

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

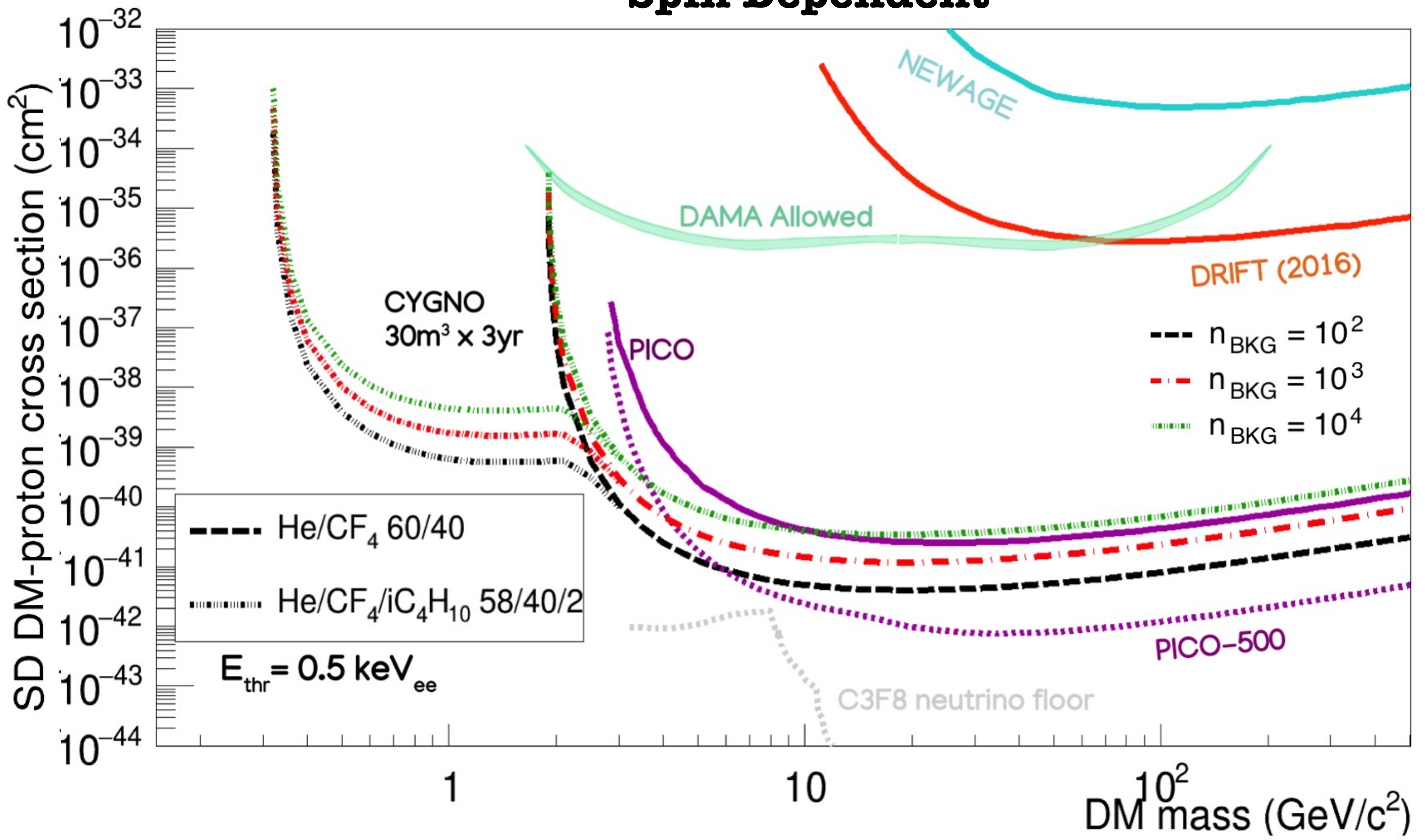
10 GeV/c^2 WIMP-like signal on He



Spin Independent



Spin Dependent



CYGNO PHASE 2: the 30 m^3 experiment for low mass DM searches

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- Preliminary sensitivity projections. **Assumptions**:
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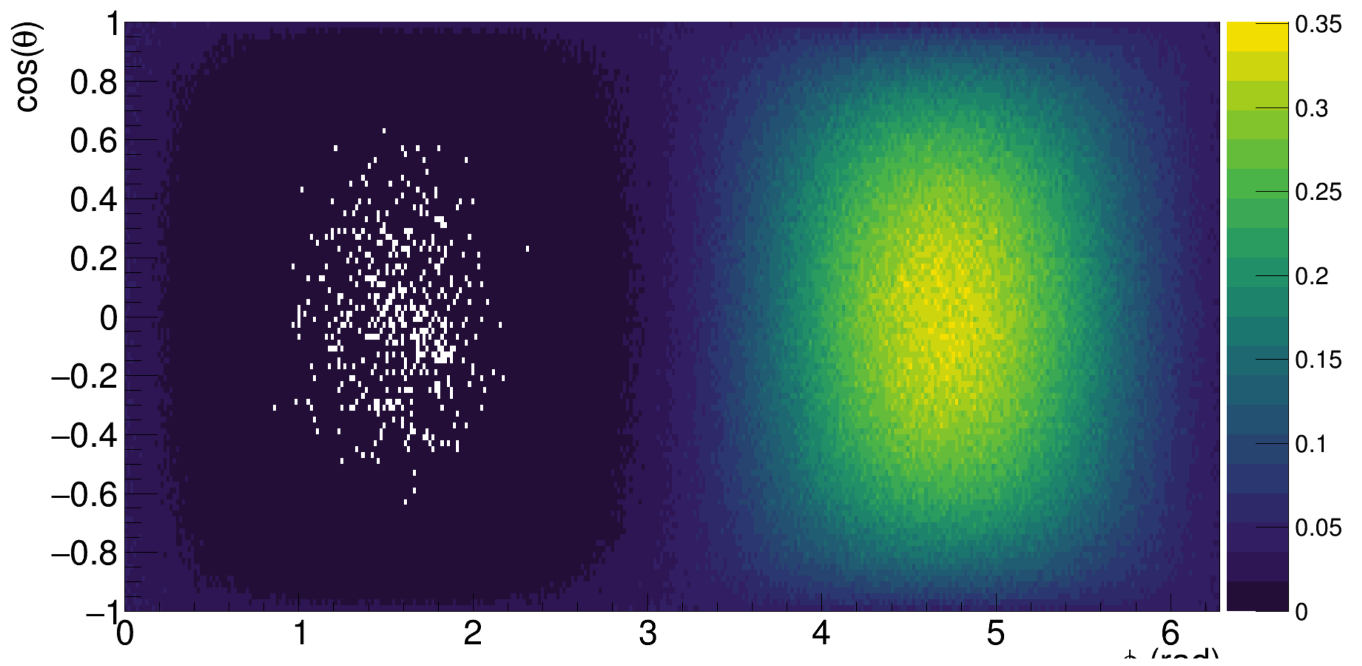
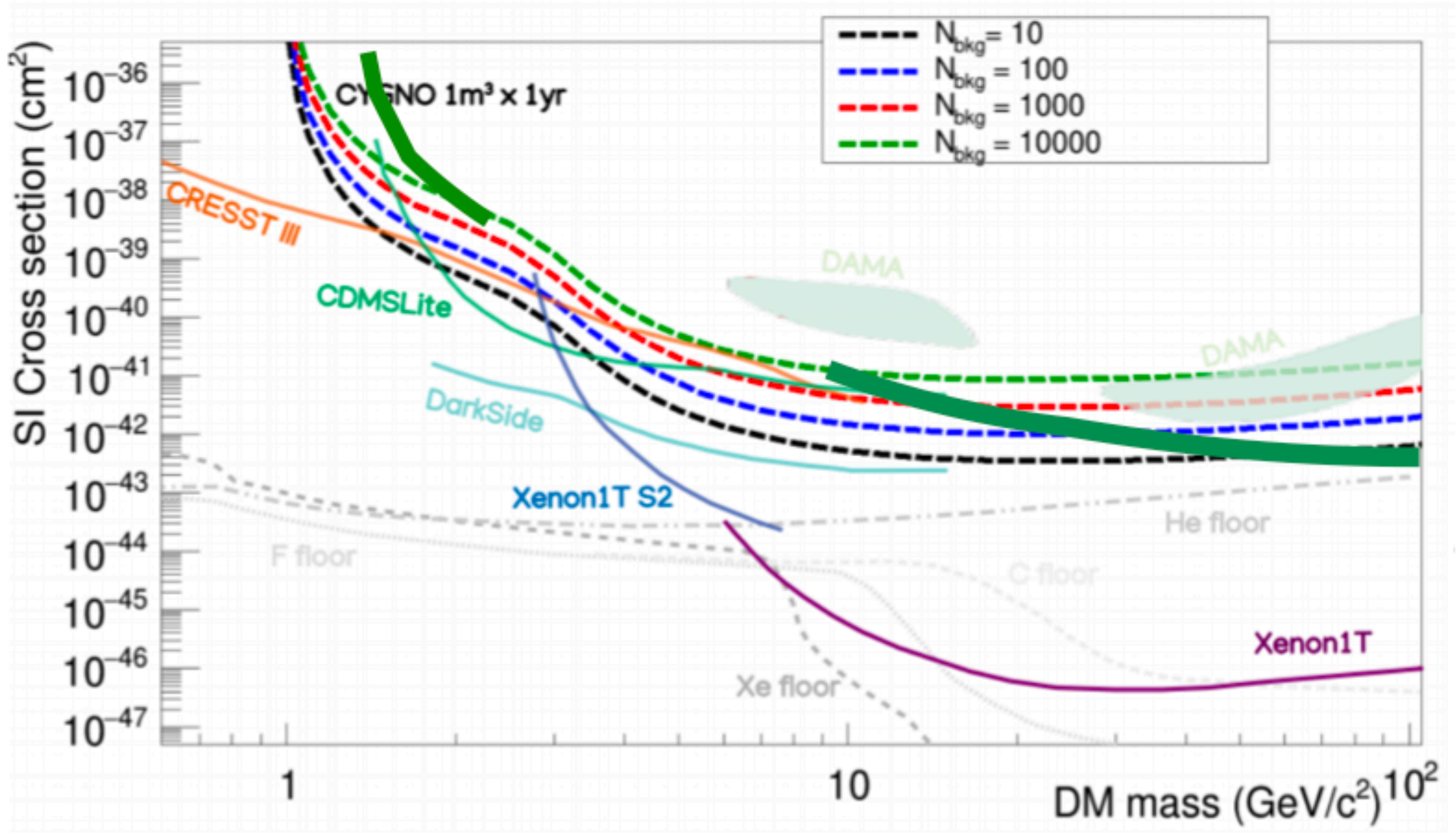
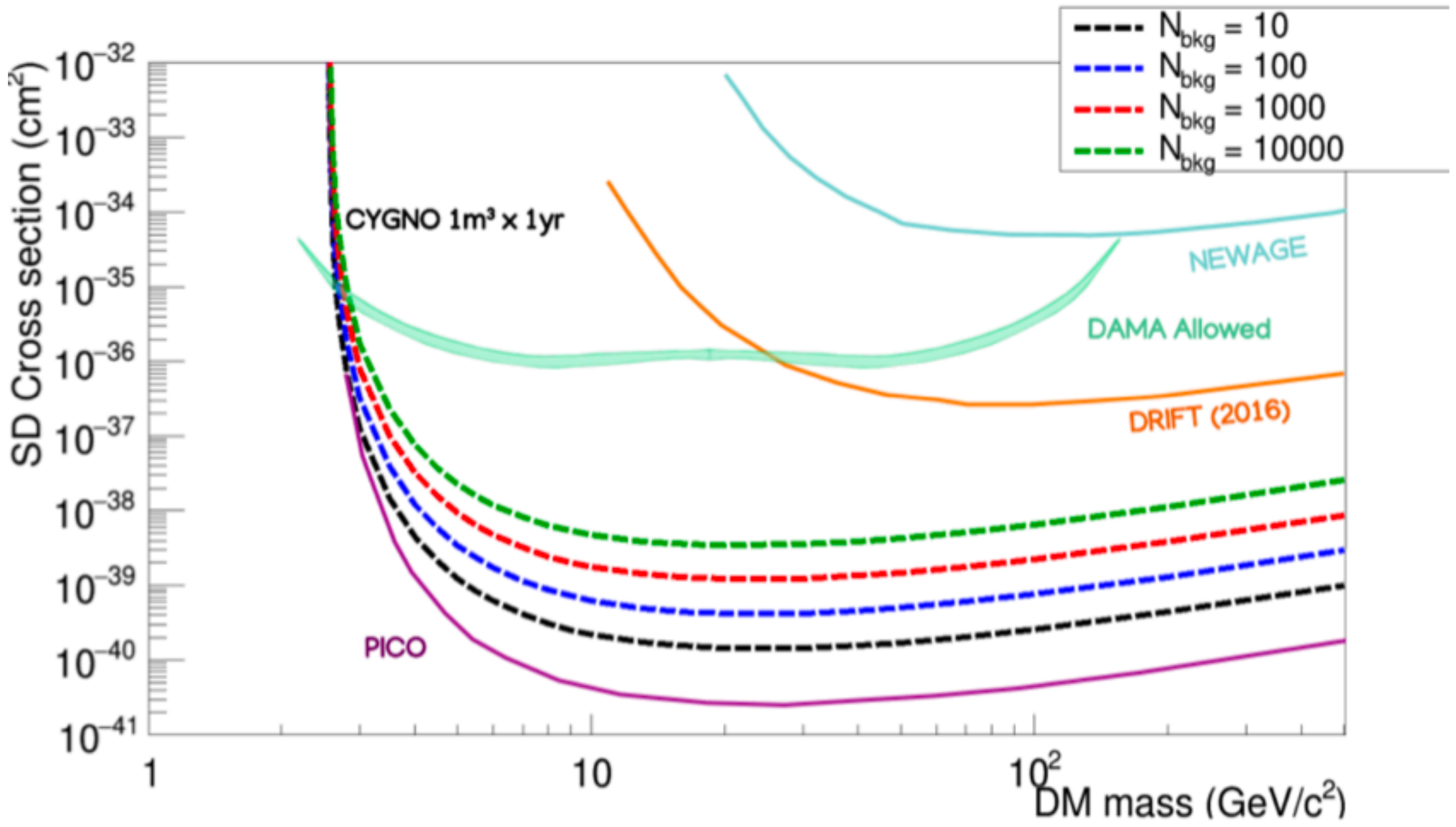






Light emission

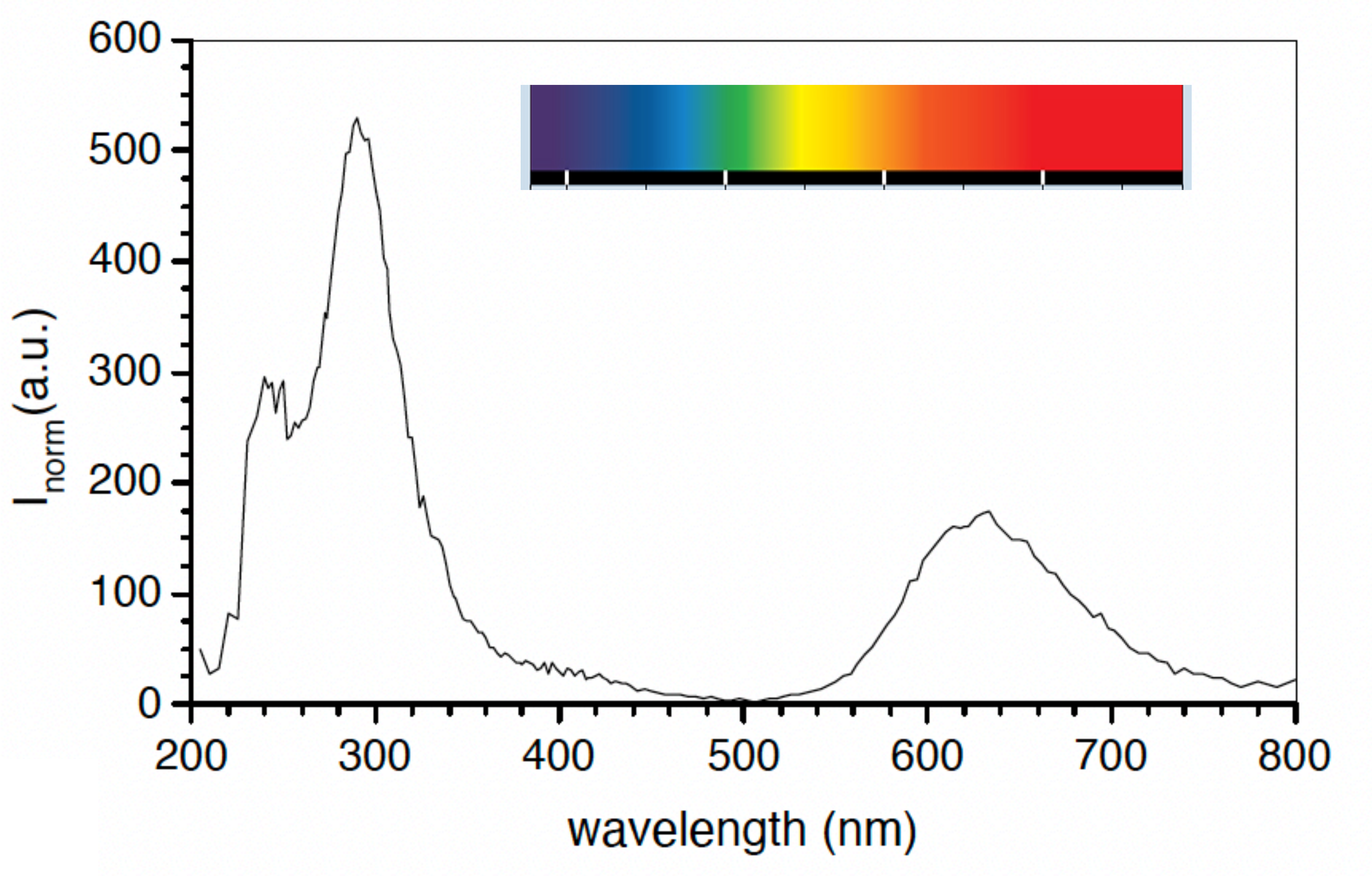
- Emitted as de-excitation of CF_3 **at the last multiplication layer**

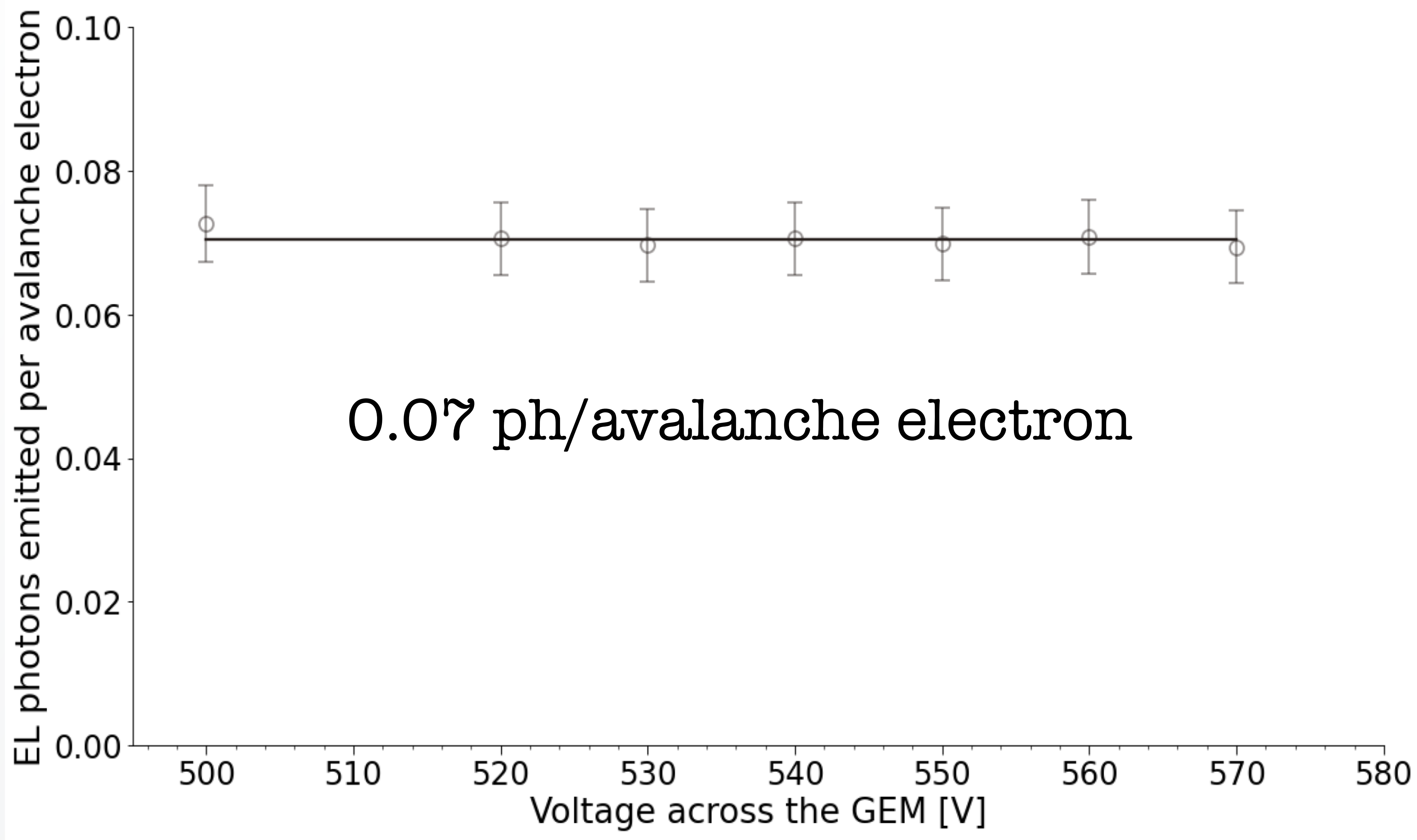
$$e^- + CF_4 \rightarrow CF_3 + F + e^-$$

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

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

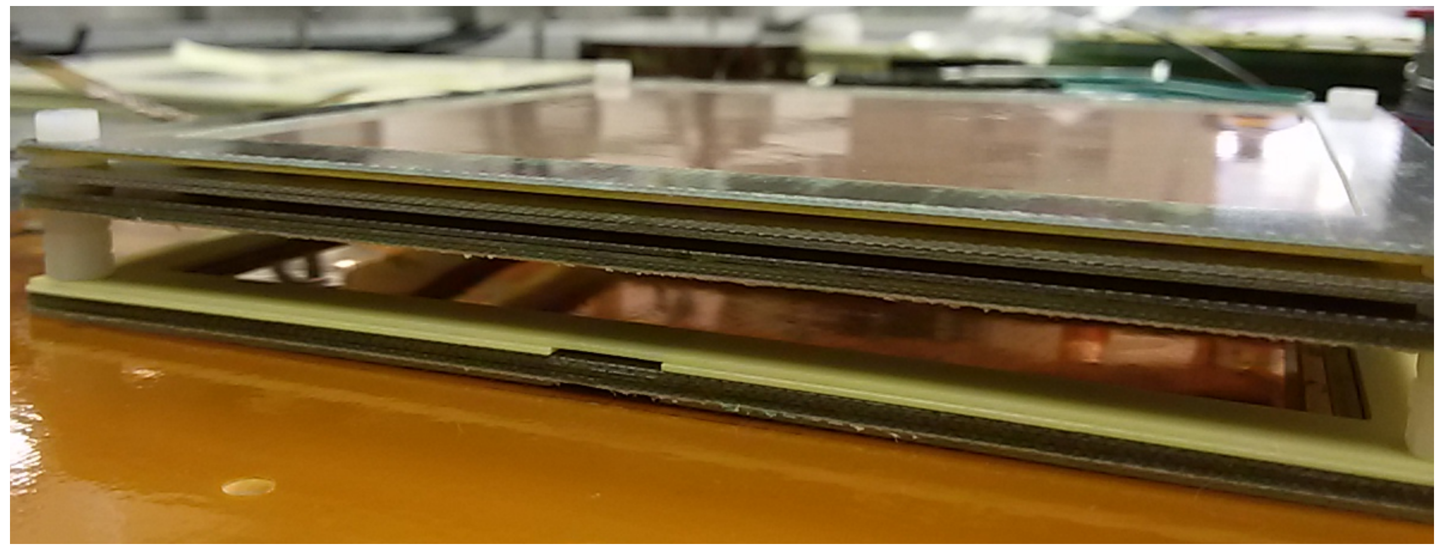
$$\gamma/e^- \text{ ratio} \sim 0.07 \text{ ph/aval. elec.}$$

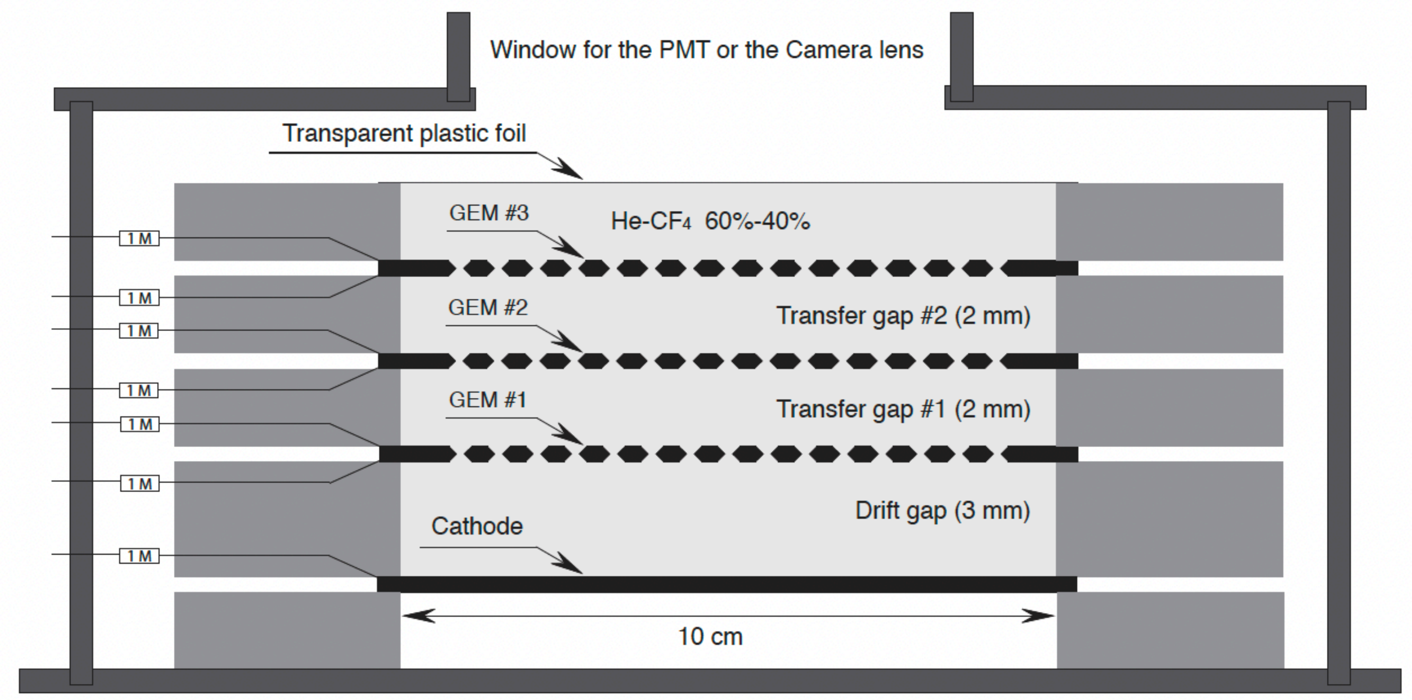


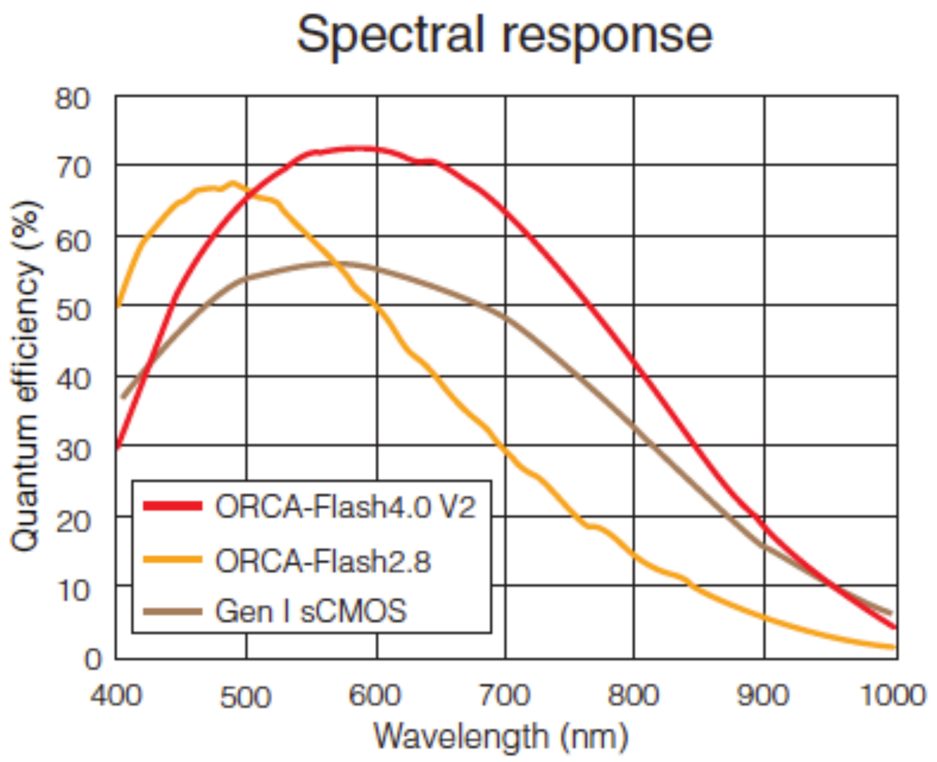


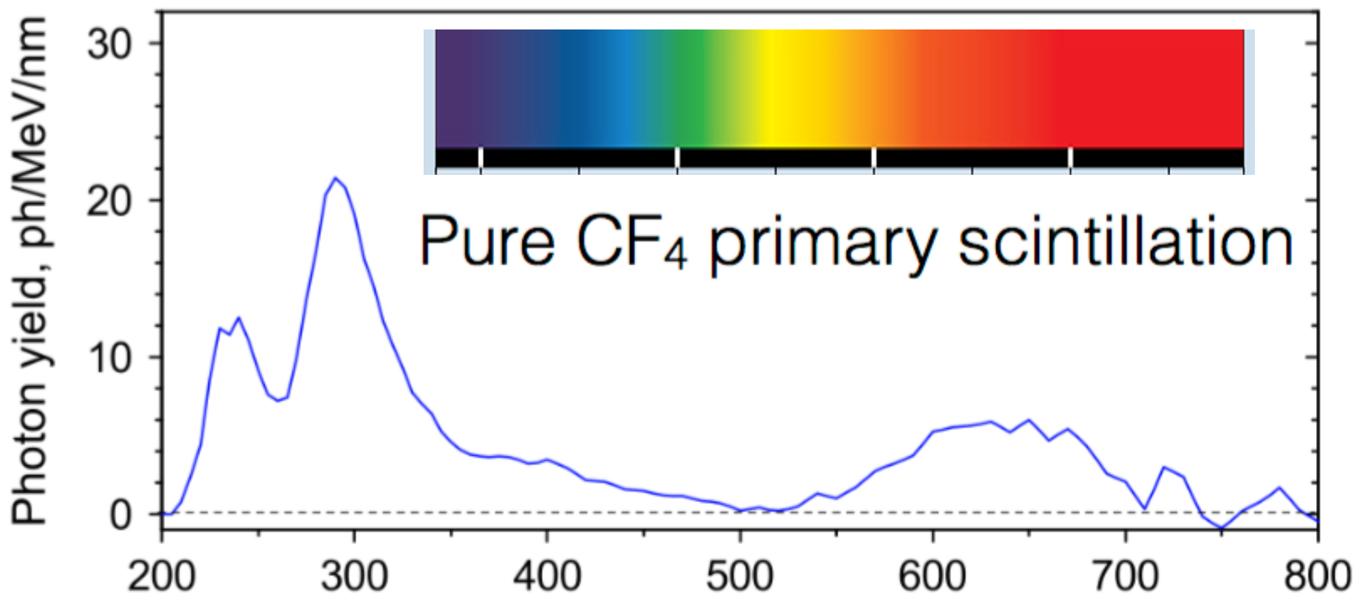
ORANGE: an Optically ReAdout GEm device

- Triple 10 x 10 cm^2 GEM layer
- 1 cm sensitive drift gap
- $He:CF_4$ (60:40) gas mixture at atmospheric pressure
- Hamamatsu Orca-Flash 4.0 camera + 1 PMT

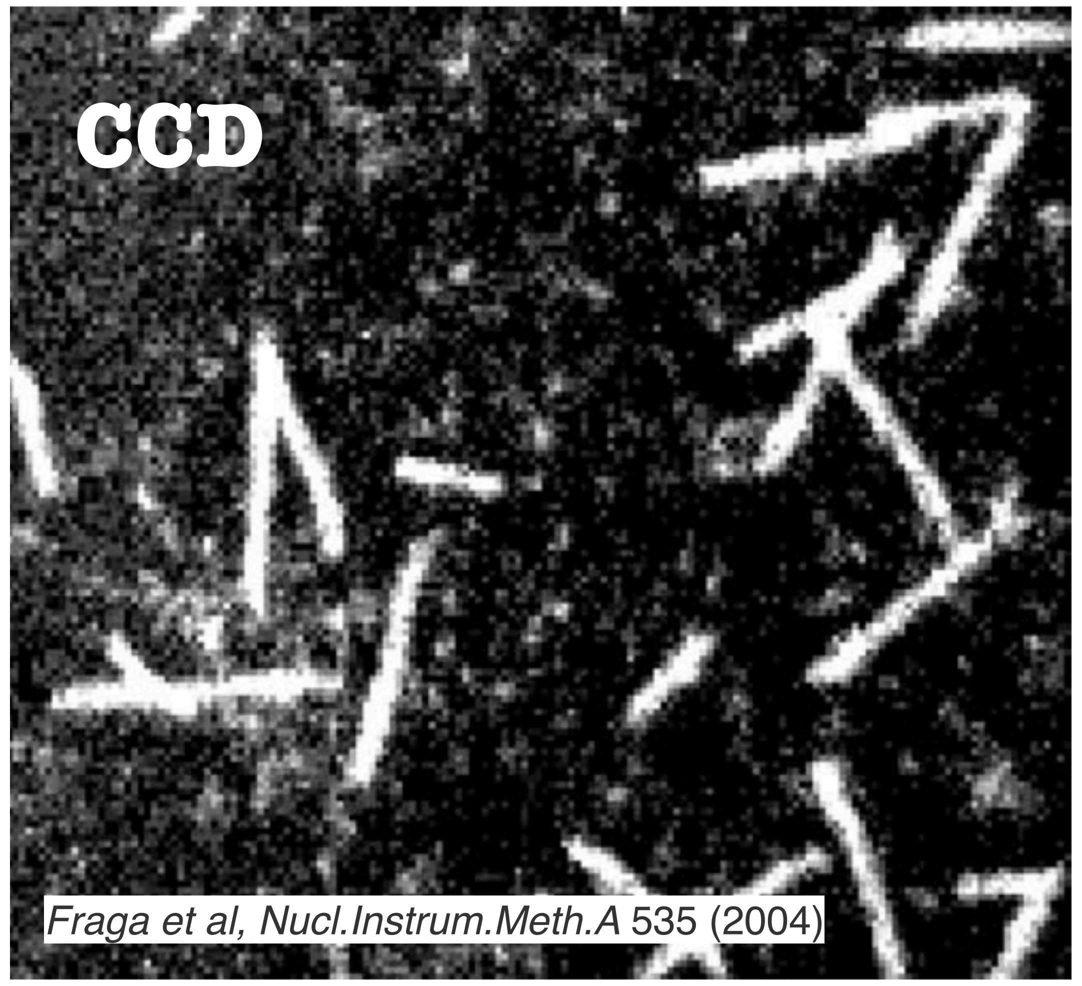


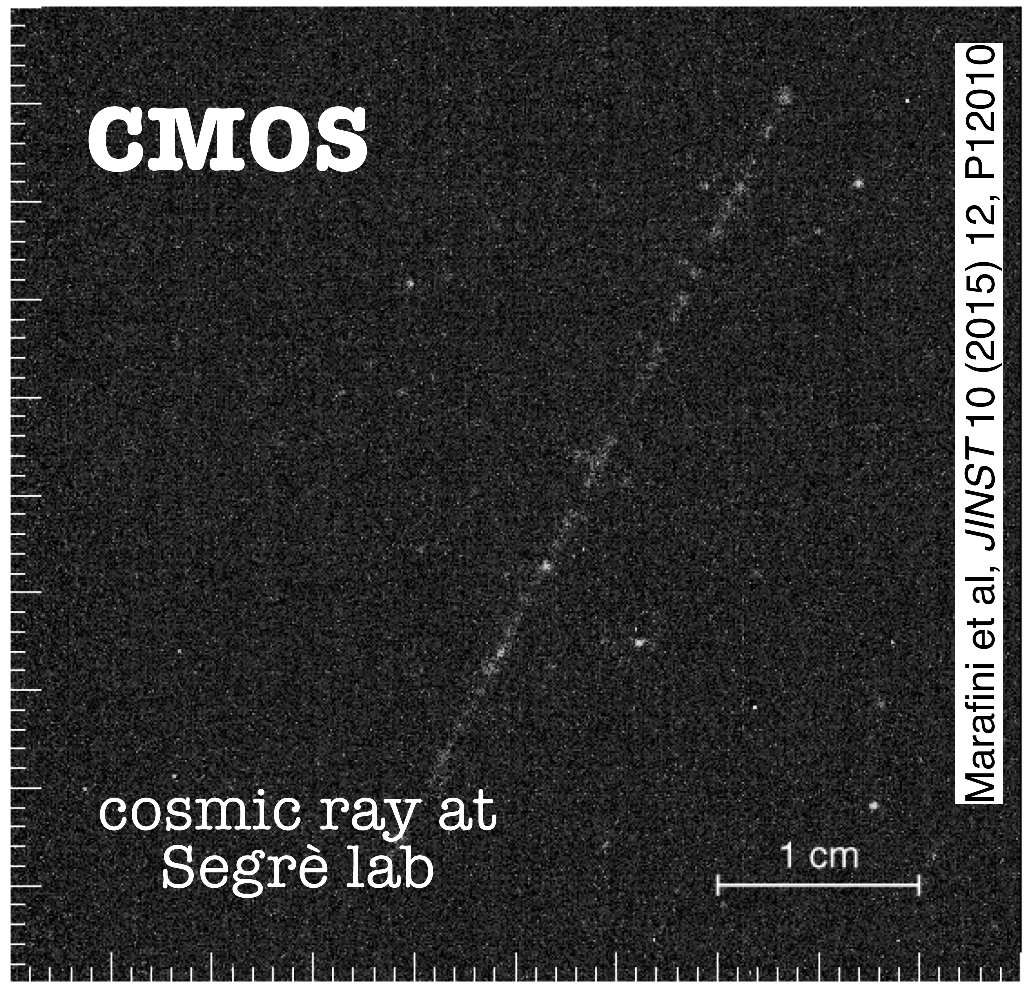






- **sCMOS** sensor showed significant lower noise w.r.t. **CCD** sensors





z resolution from diffusion

z = distance from the GEM plane

S = width of the signal

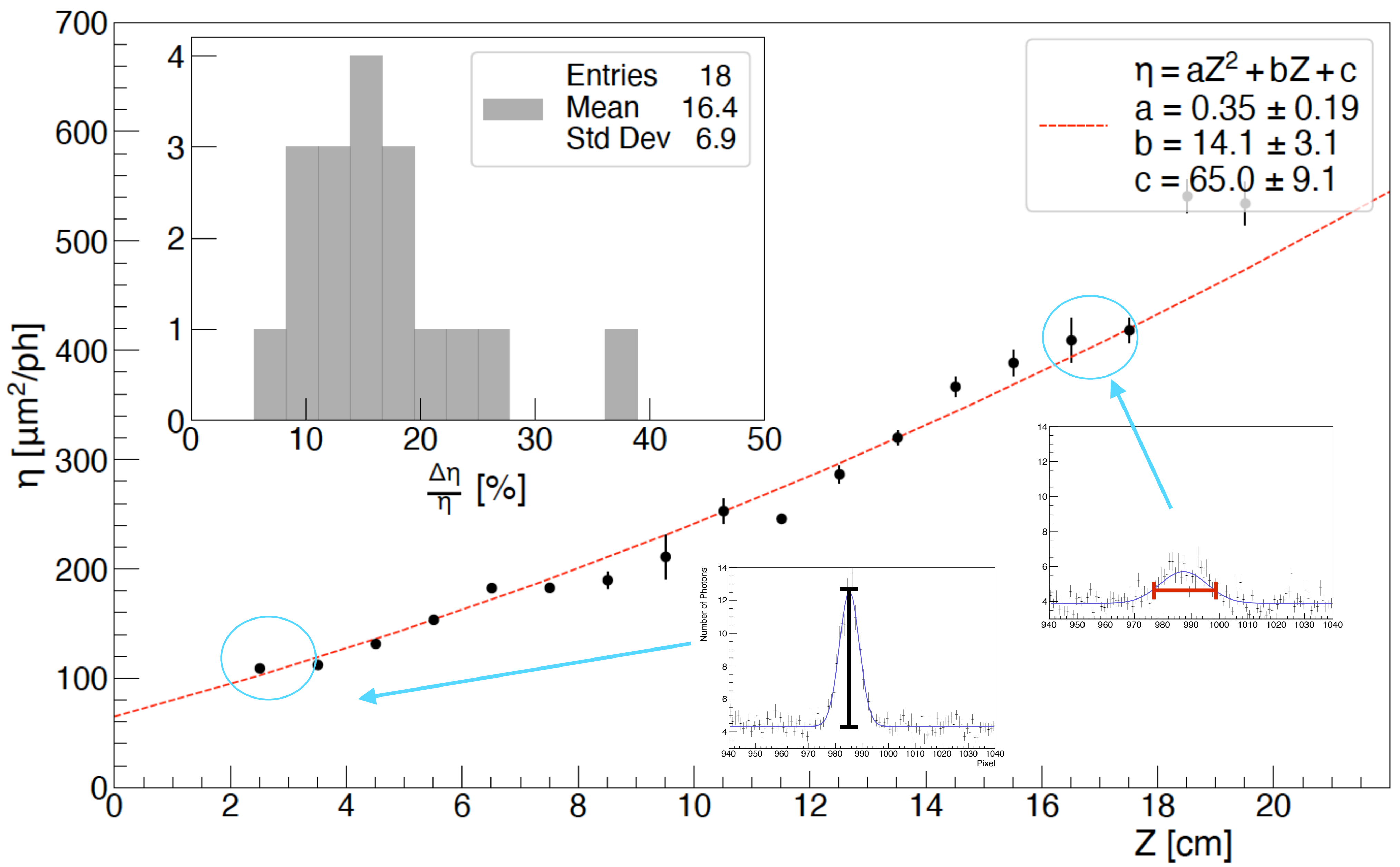
A = amplitude of the signal

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

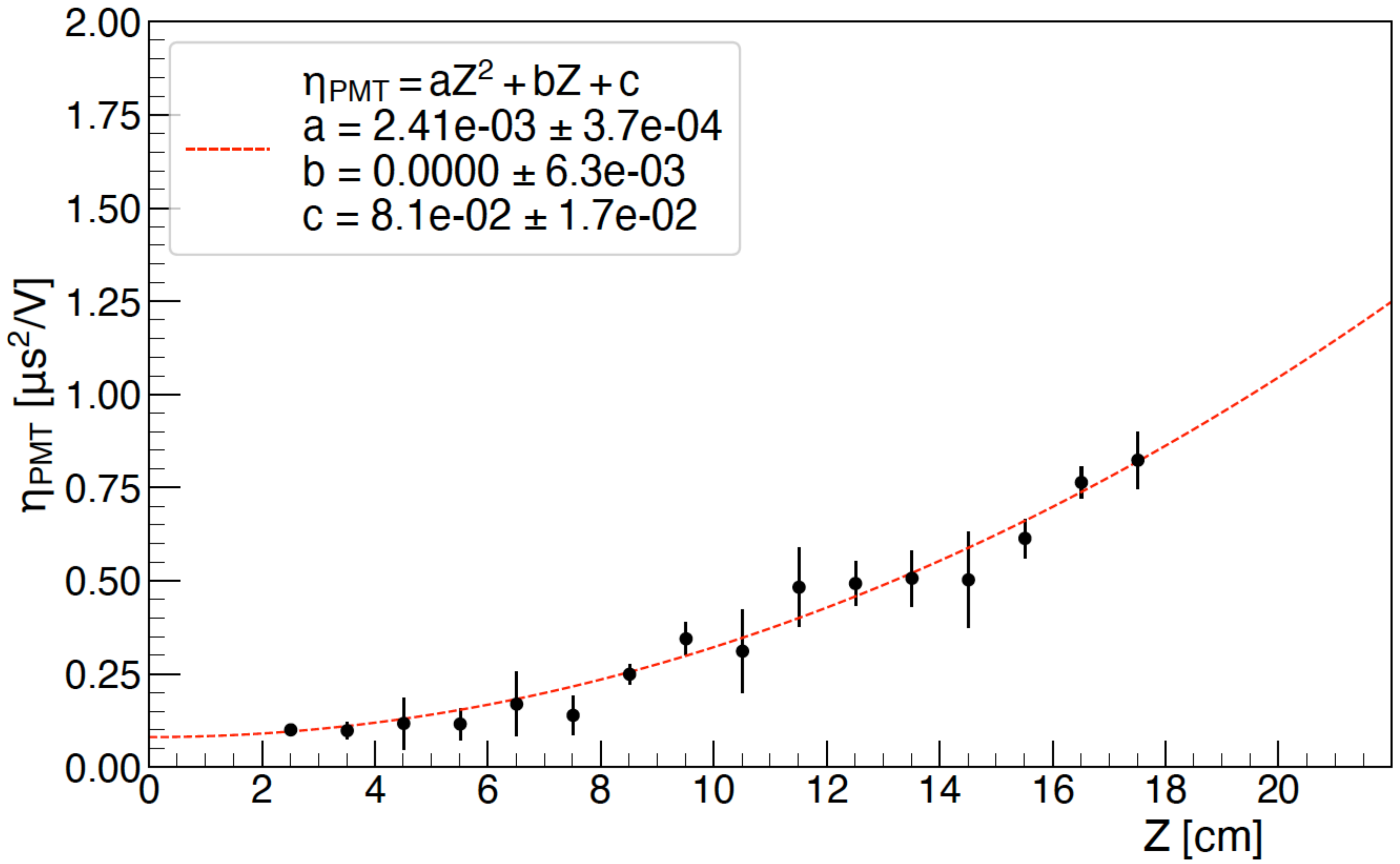
$$\eta \equiv \frac{S}{A} \text{ increases with z}$$

$$\Downarrow$$

We can infer the z position measuring η



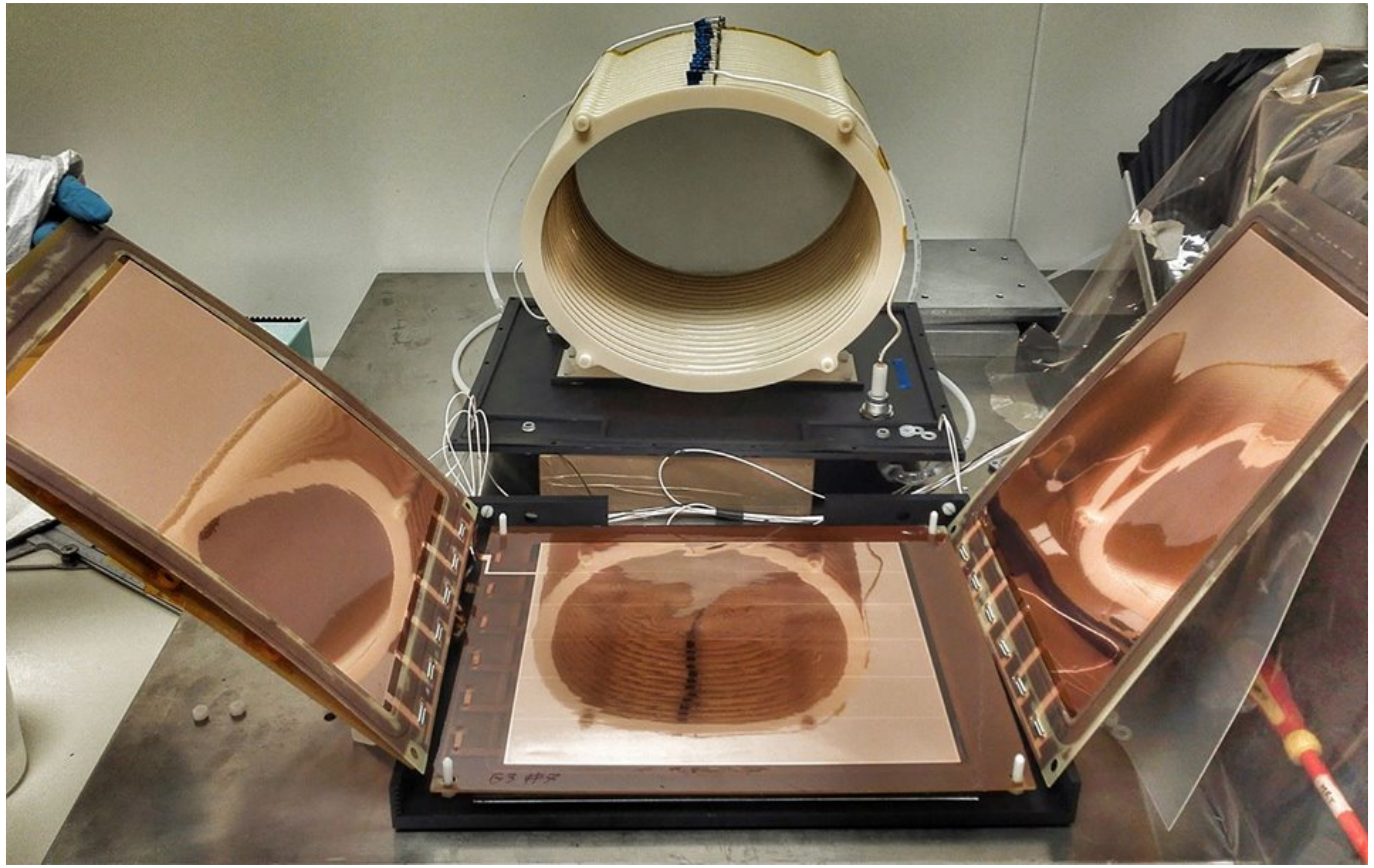
Antochi et al, Nucl.Instrum.Meth.A 999 (2021)



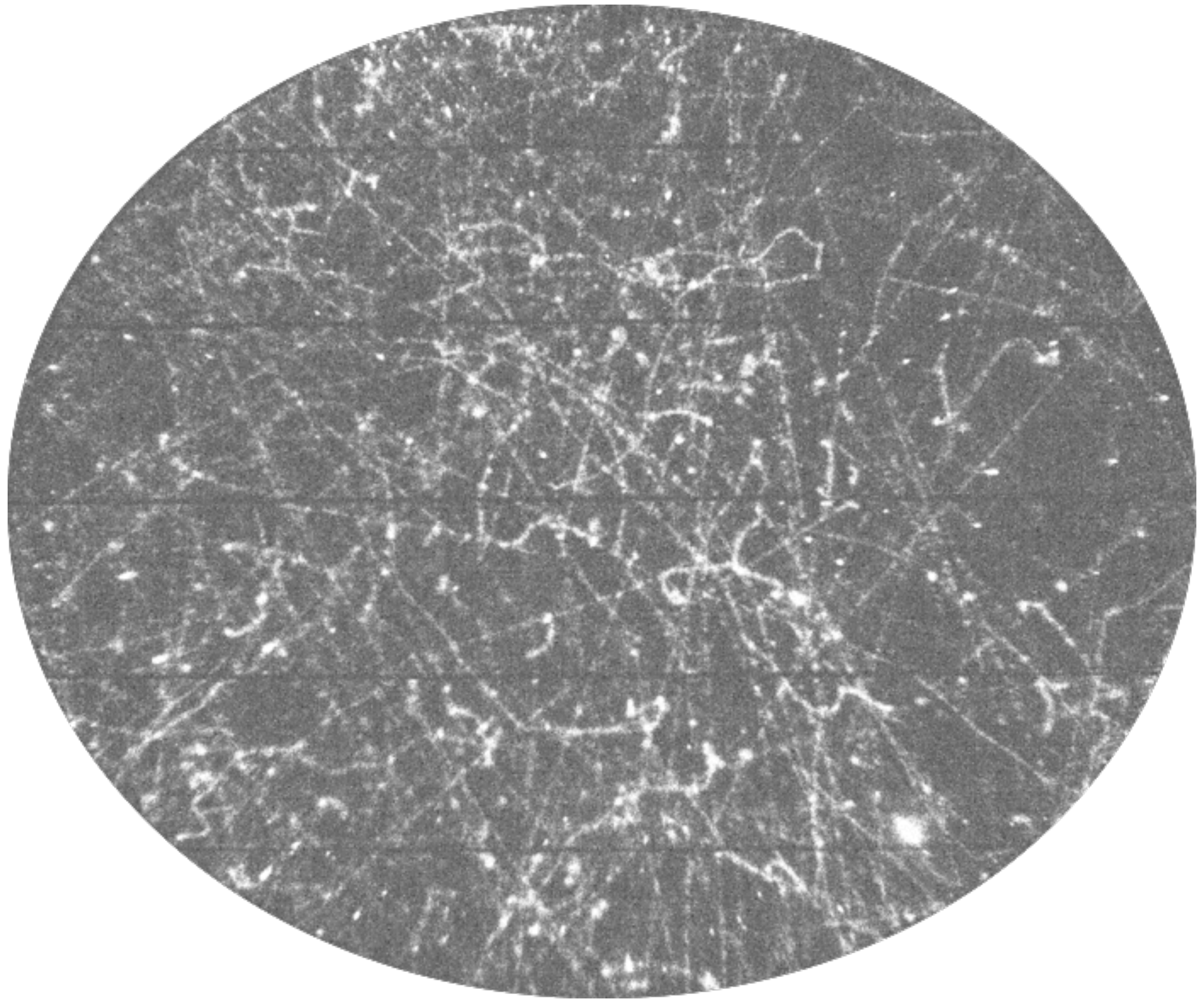
z resolution of 15%

LEMON: Large Elliptical Module Optically Readout

- Designed and built at **LNF**, realized using a **3D printer**



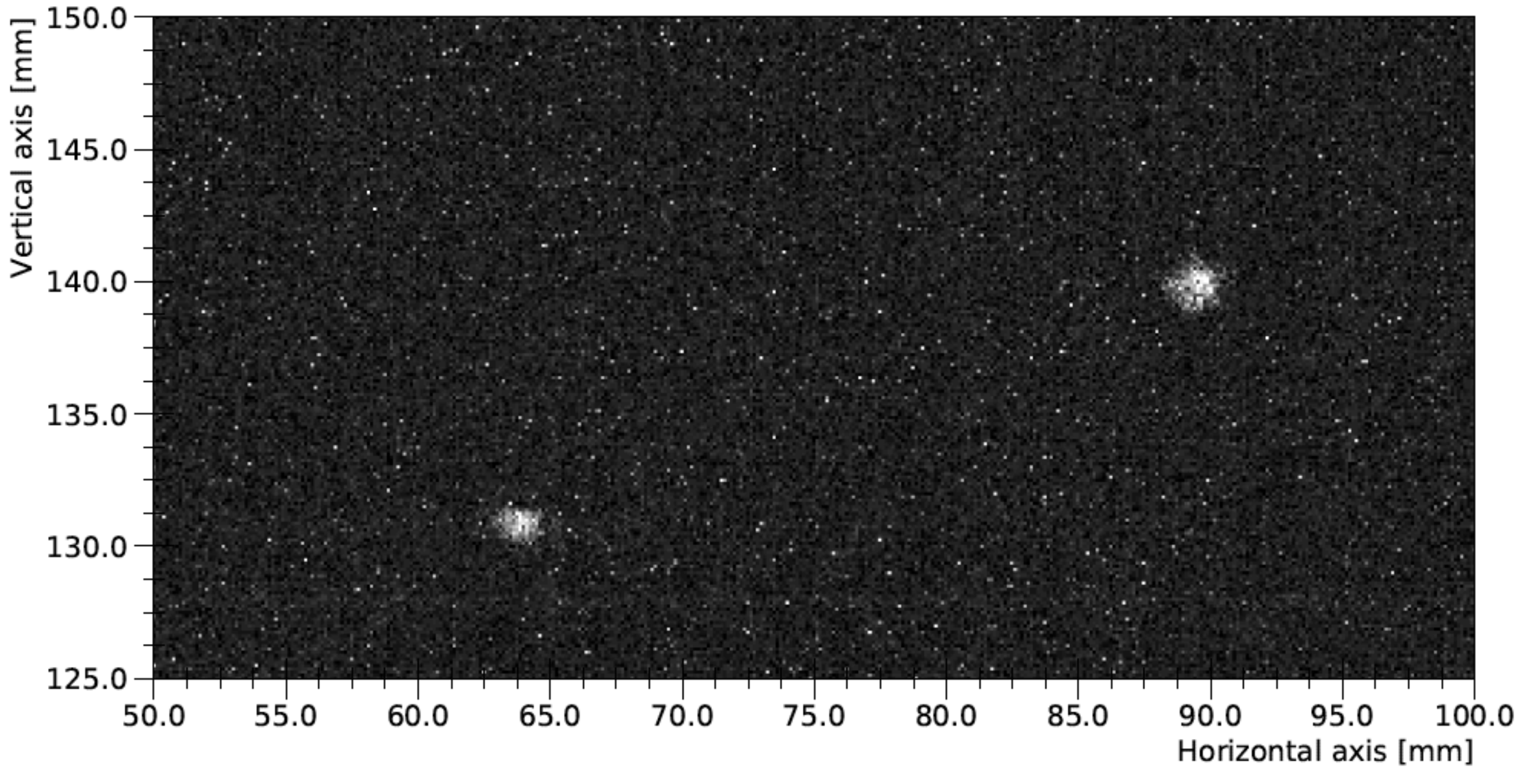
- 7 L of sensitive volume
- 500 cm^2 GEM surface
- 20 cm drift gap

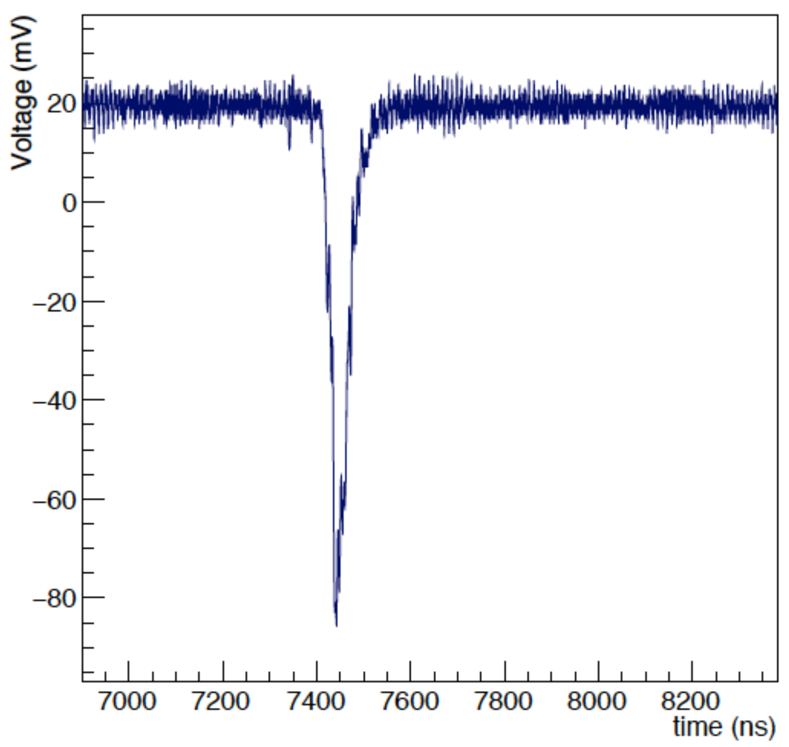


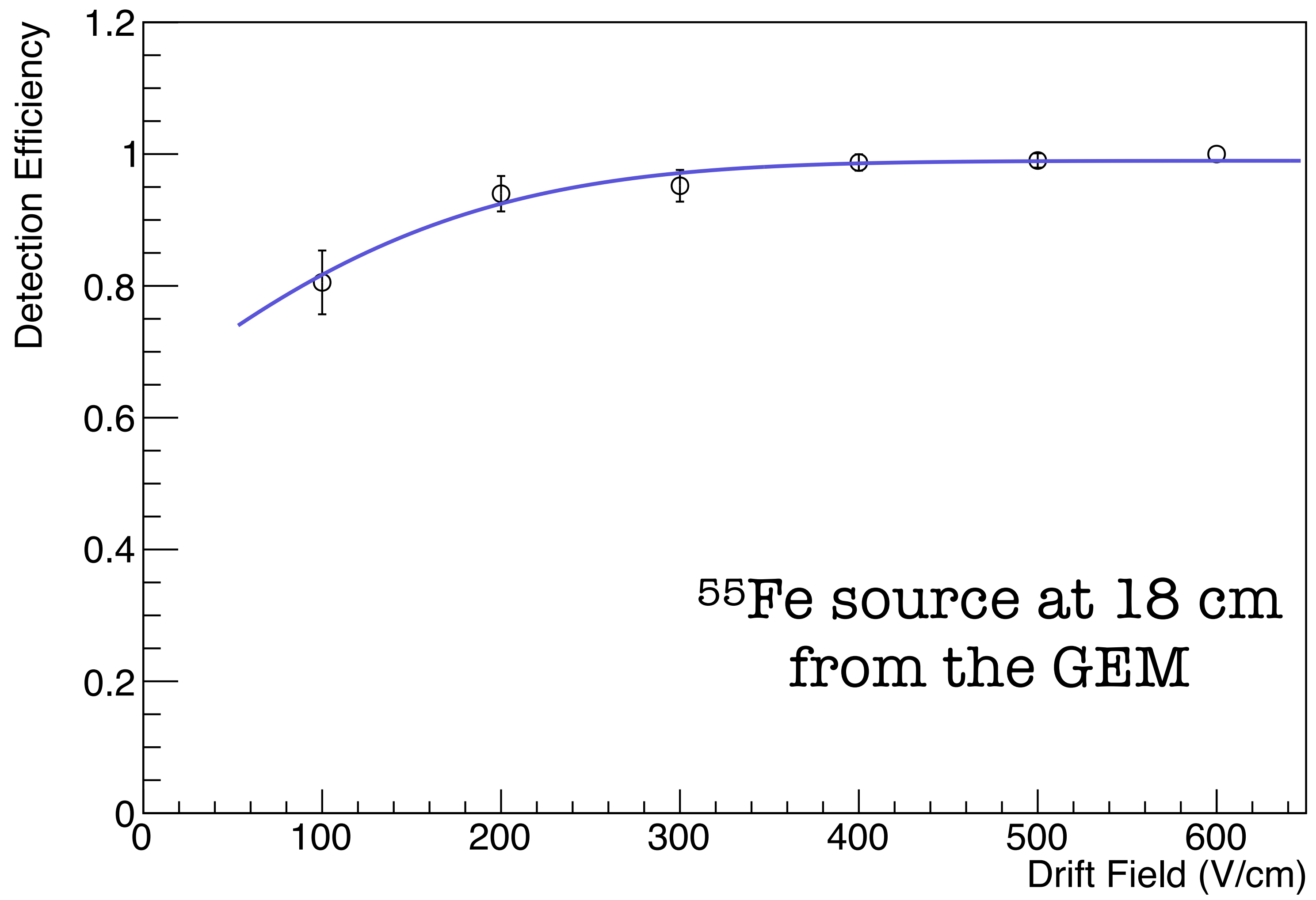
Picture with 5 s exposure

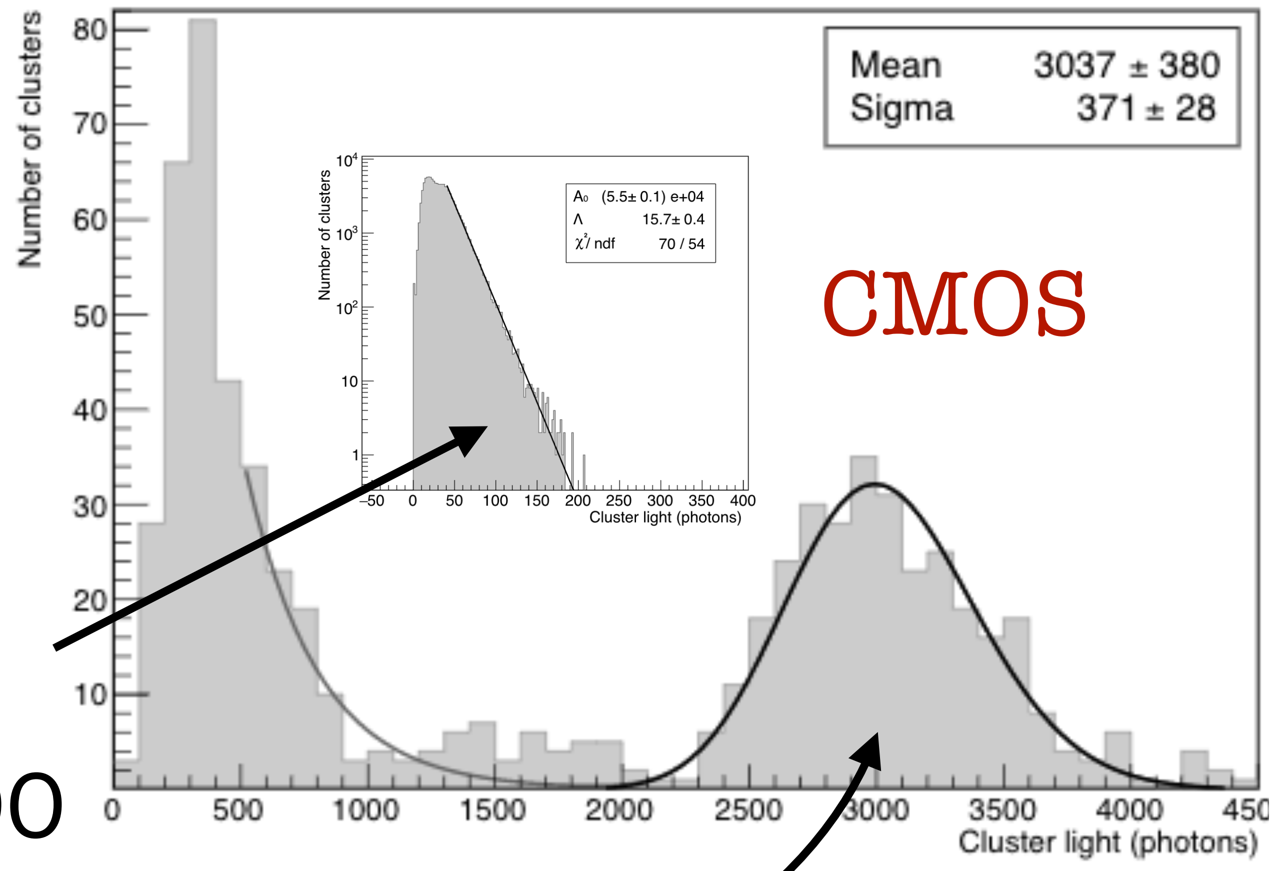
LEMON performance: the ^{55}Fe source

- ^{55}**Fe** source: **5.9 keV photons ⇒ spot-like tracks**





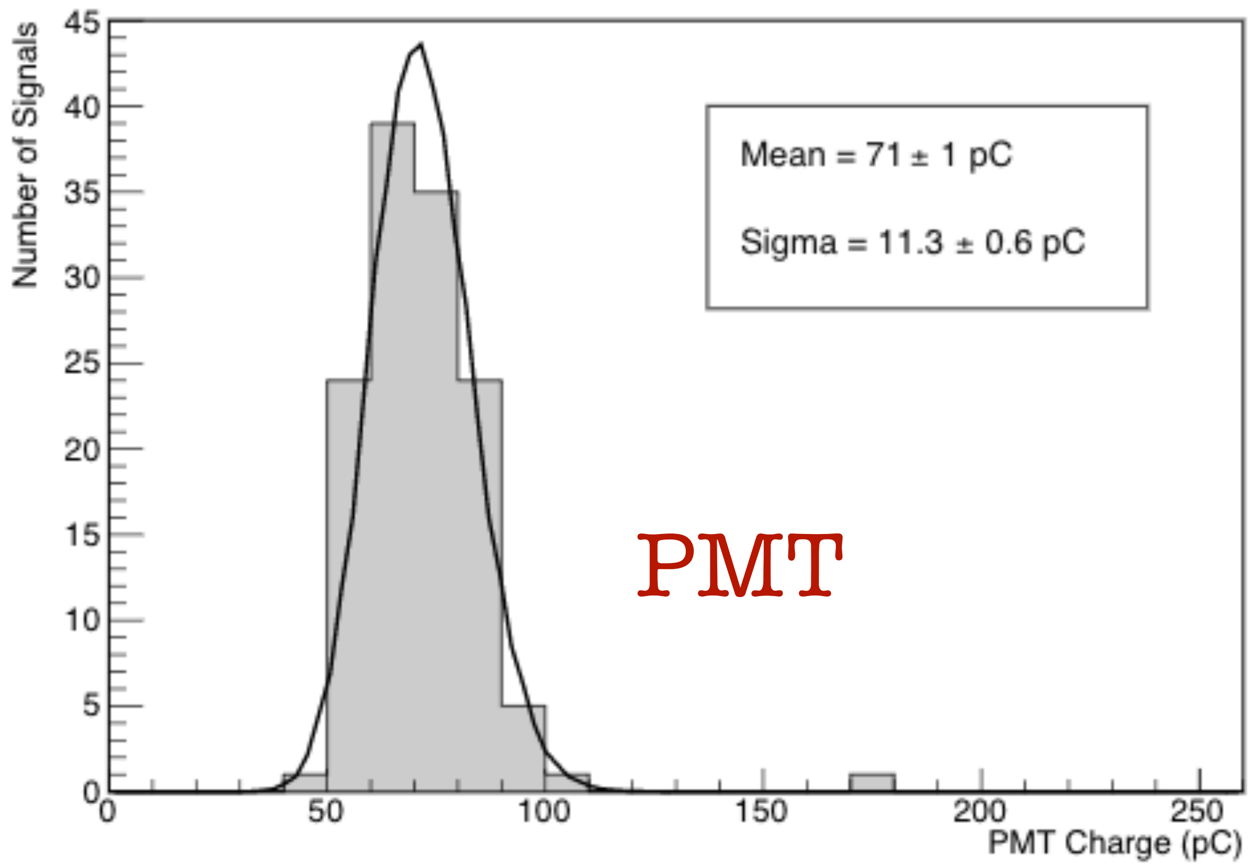


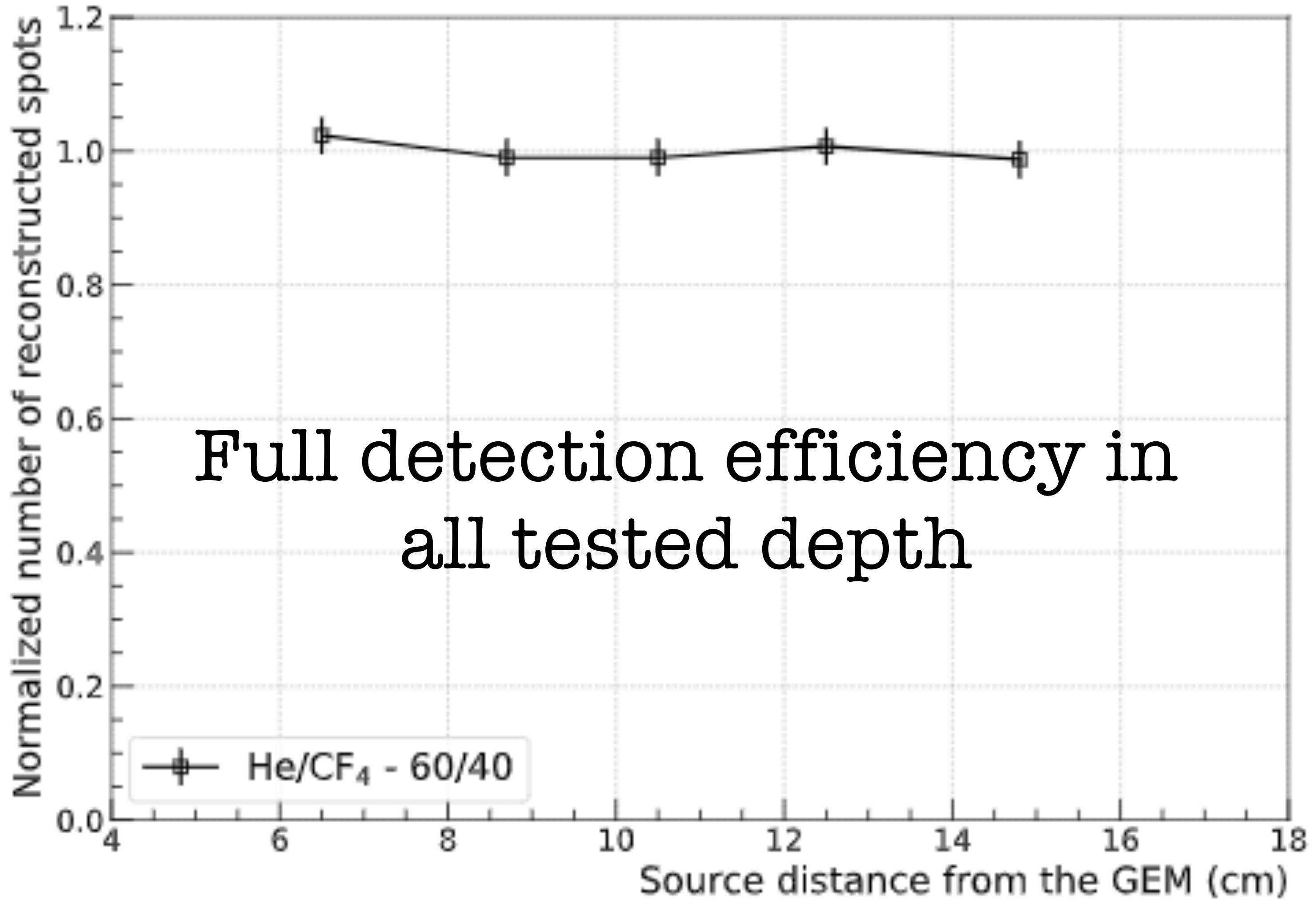


Abritta et al, *J.Phys.Conf.Ser.* 1498 (2020) 012017

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

~ 500 ph / keV





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

Energy resolution of 15% with CMOS and PMT

The LIME optical readout

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

- **CMOS** sensor noise:
  - ➡ Readout noise of 0.7 e^-/px ~ 0.9 γ/px
  - ➡ Dark current of 0.2 e^-/px/s ~ 0.25 γ/px/s
  - ➡ Acquisition time ~ 30-300 ms

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

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

De-magnification:

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

with f = 25.6 mm [focal length]

d = 623 mm [distance from GEMs]

Aperture = 0.95

- 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)

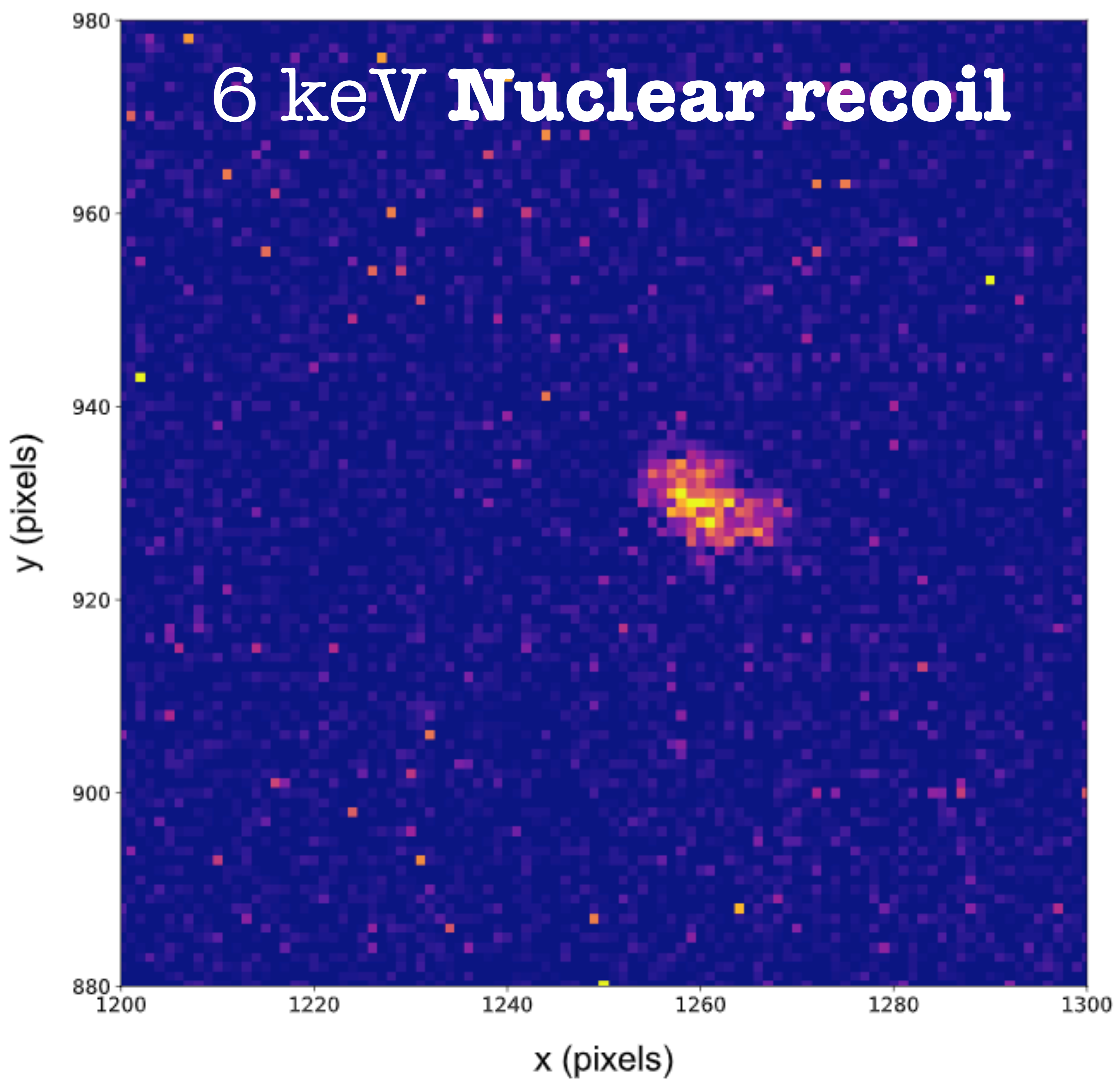
Total light emitted (L)

Distance from the light emission (R_i)

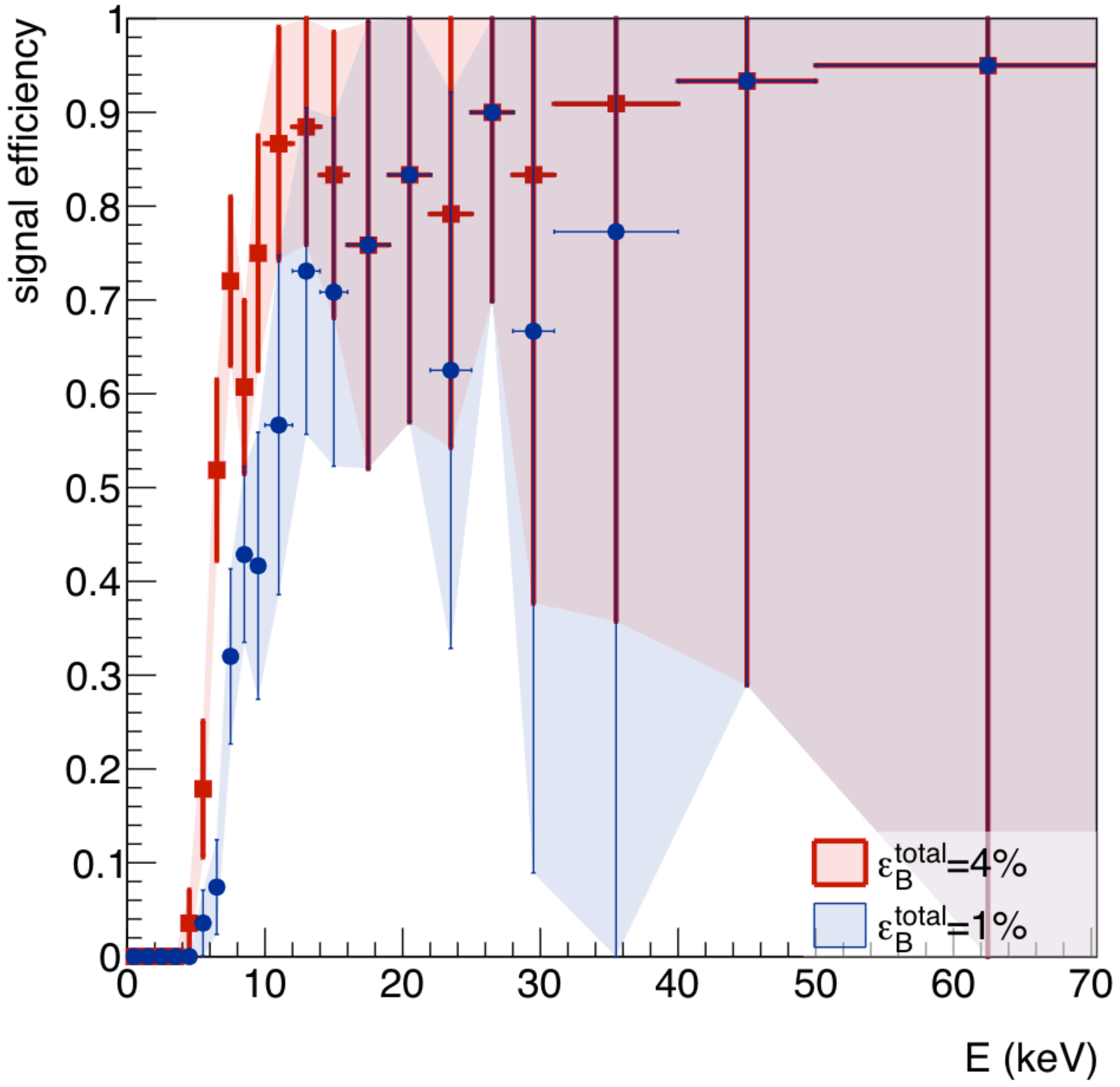
We measured α ~ 4

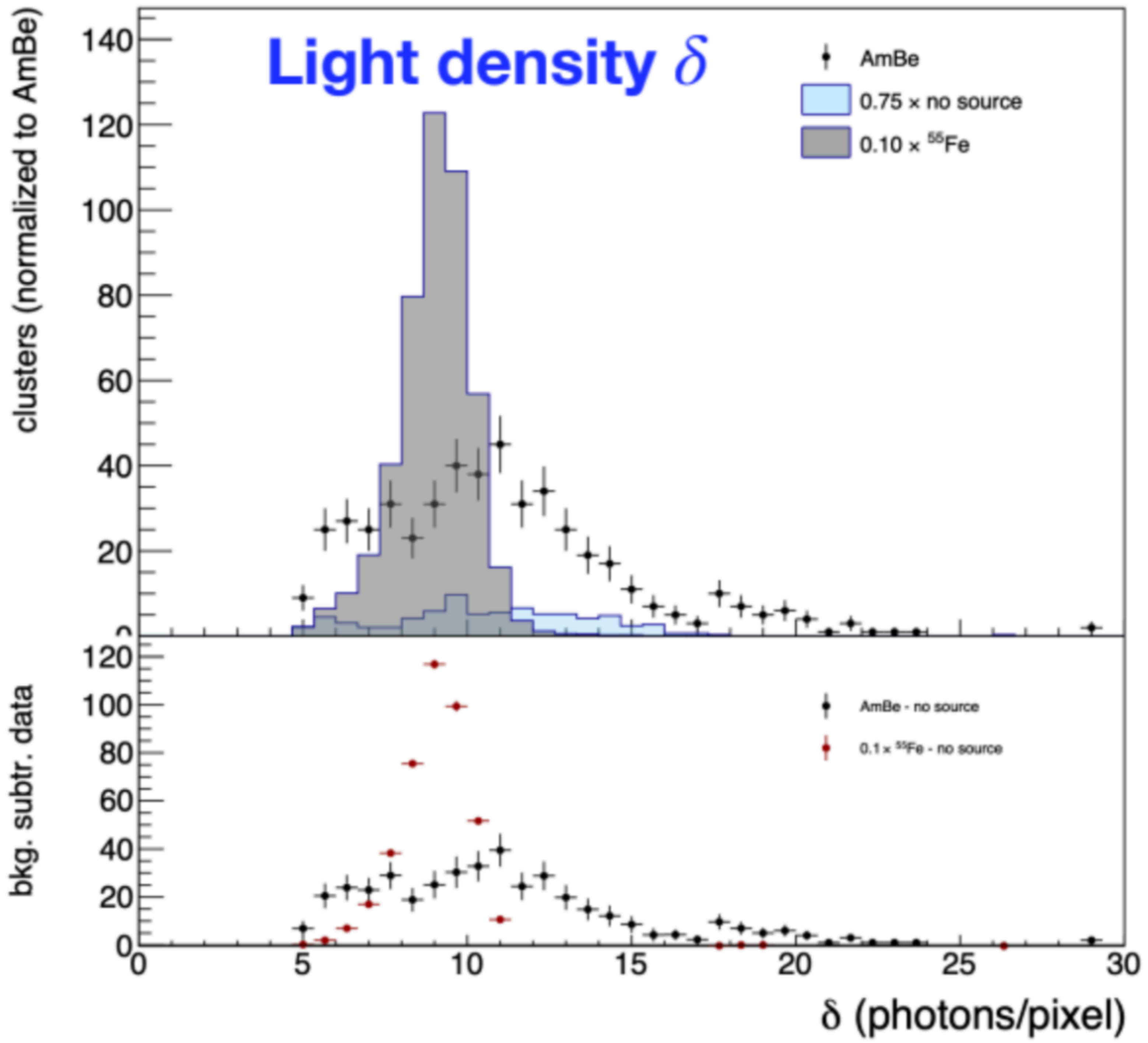
NR vs ER discrimination

- **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**



Baracchini et al, *Measur.Sci.Tech.* 32 (2021) 2, 025902

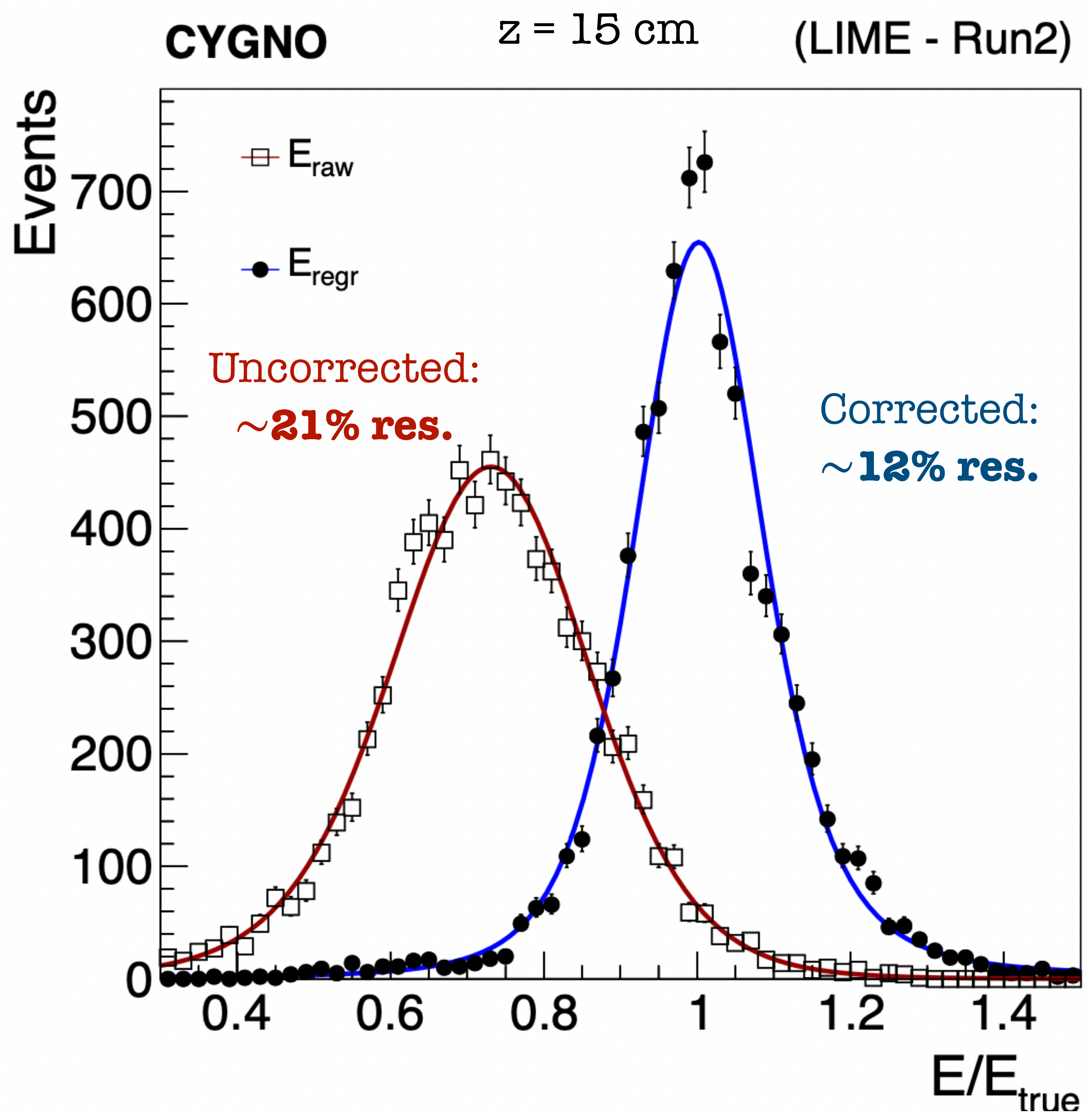


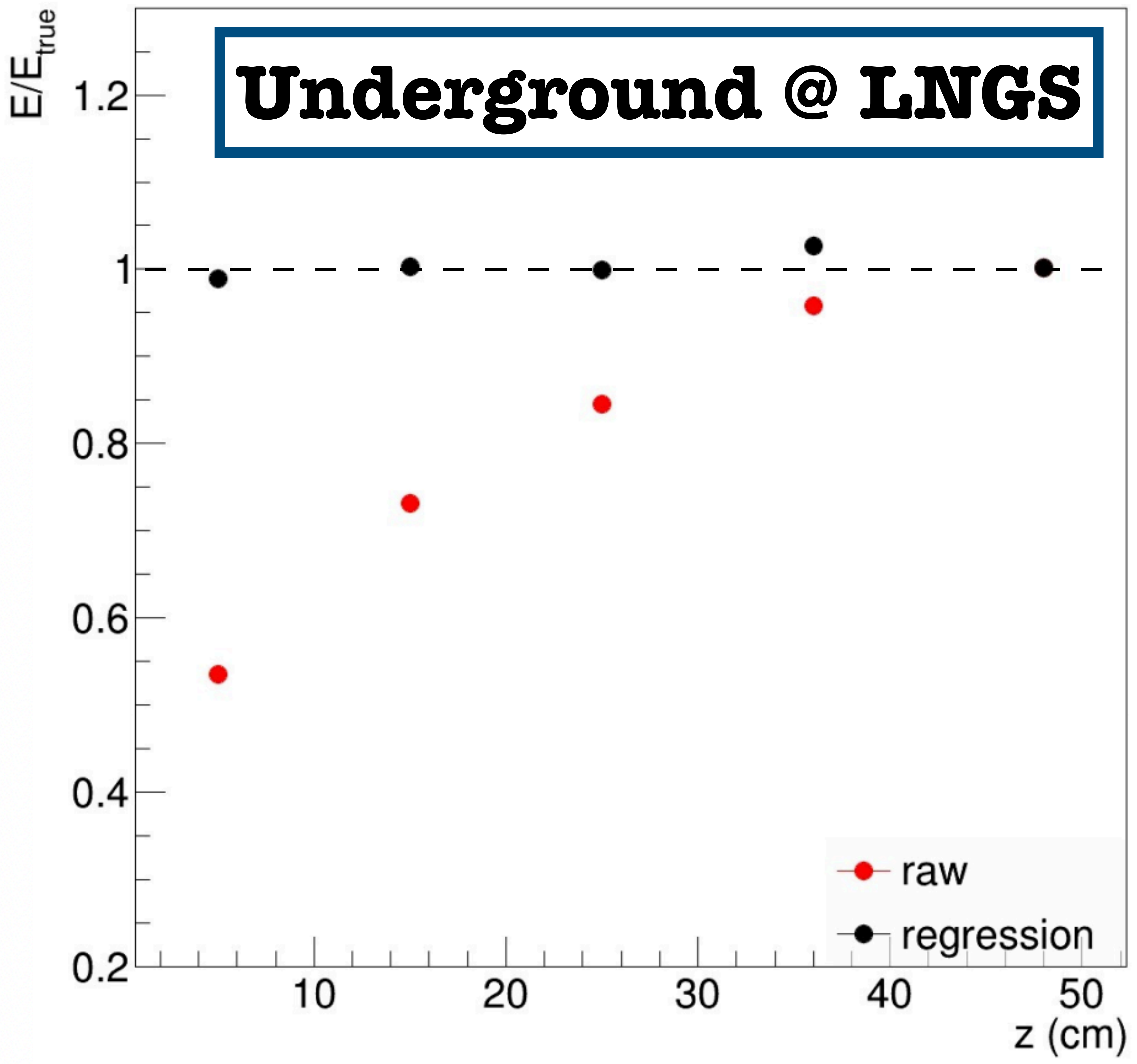


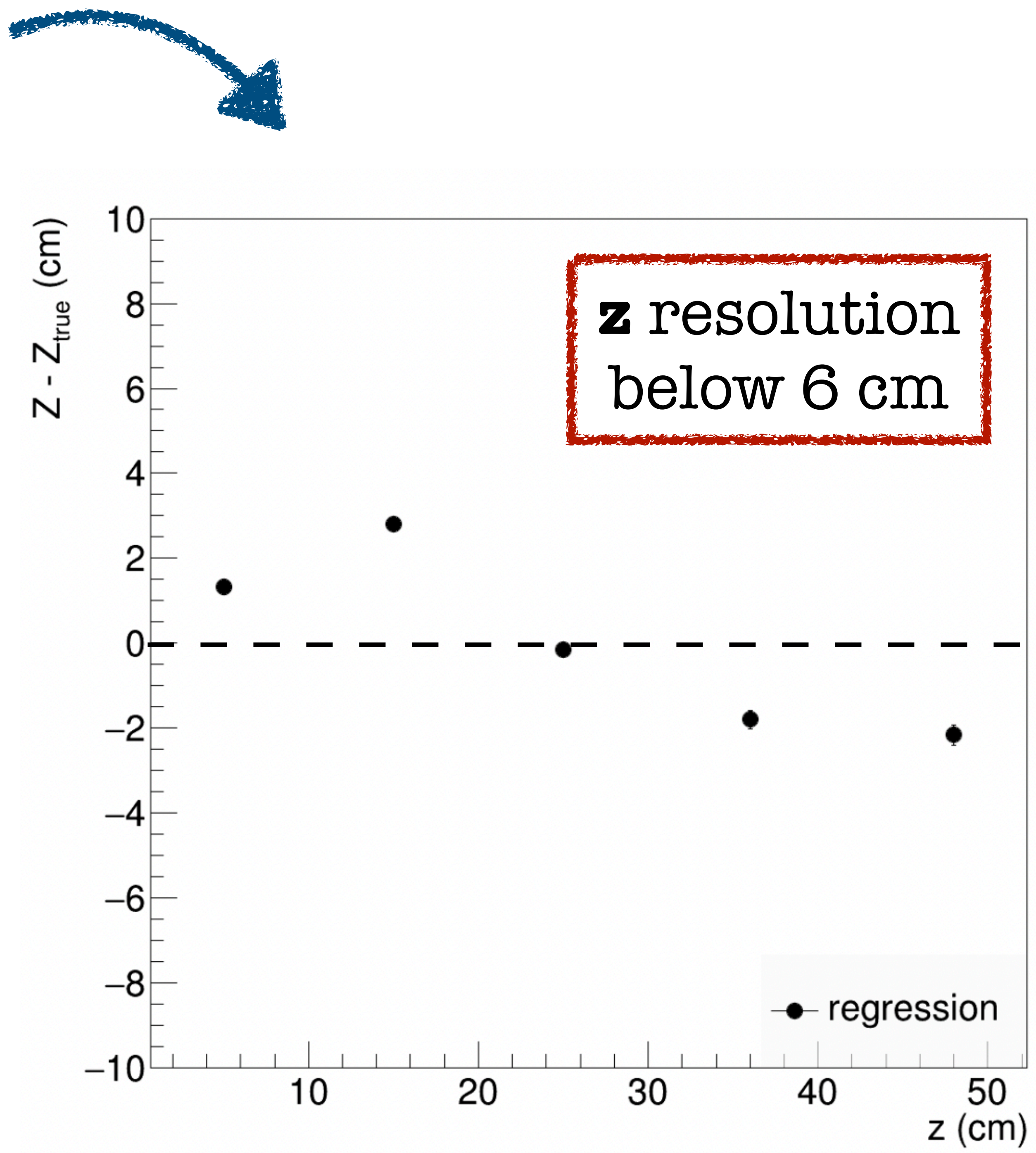
- Performance:
  - ➡ **NR** detection efficiency over **40%** above 6 keV
  - ➡ **96% rejection** power on the 6 keV ^{55}Fe **ERs**

The multivariate regression

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







LIME: ER calibration

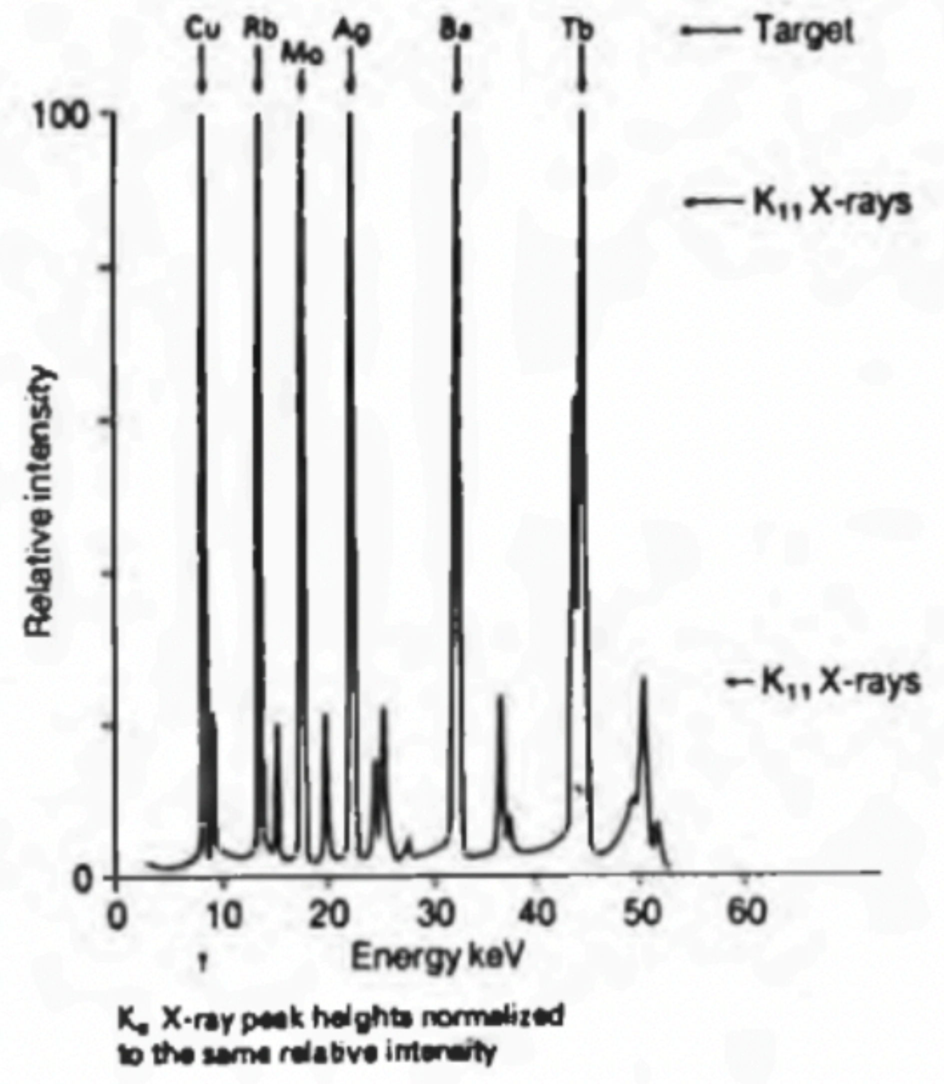
- ^{55}Fe source
  [$K_\alpha \sim 5.9$ keV, $K_\alpha \sim 6.4$ keV]

- Multi-target source

Material	Energy K_α [keV]	Energy K_β [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_α [keV]	Energy K_β [keV]
Ti	4.51	4.93
Ca	3.69	4.01



X-ray emission

target selected	energy (keV)(1) Kα	Kβ	photon yield(2) (photons/sec per steradian)
Cu	8·04	8·91	$2{\cdot}5 \times 10^3$
Rb	13·37	14·97	$8{\cdot}8 \times 10^3$
Mo	17·44	19·63	$2{\cdot}43 \times 10^4$
Ag	22·10	24·99	$3{\cdot}85 \times 10^4$
Ba	32·06	36·55	$4{\cdot}65 \times 10^4$
Tb	44·23	50·65	$7{\cdot}6 \times 10^4$

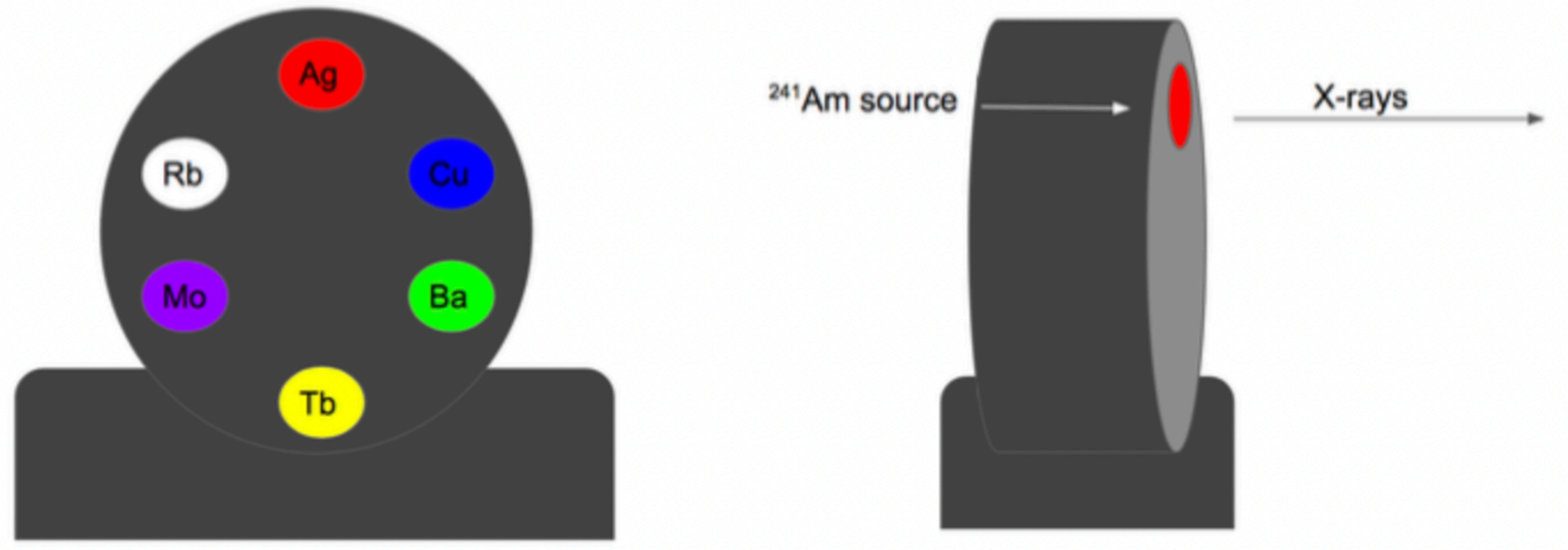
Notes
(1) Weighted mean energies
(2) The photon output is highly collimated limiting emission to ~0·5 steradians.

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%

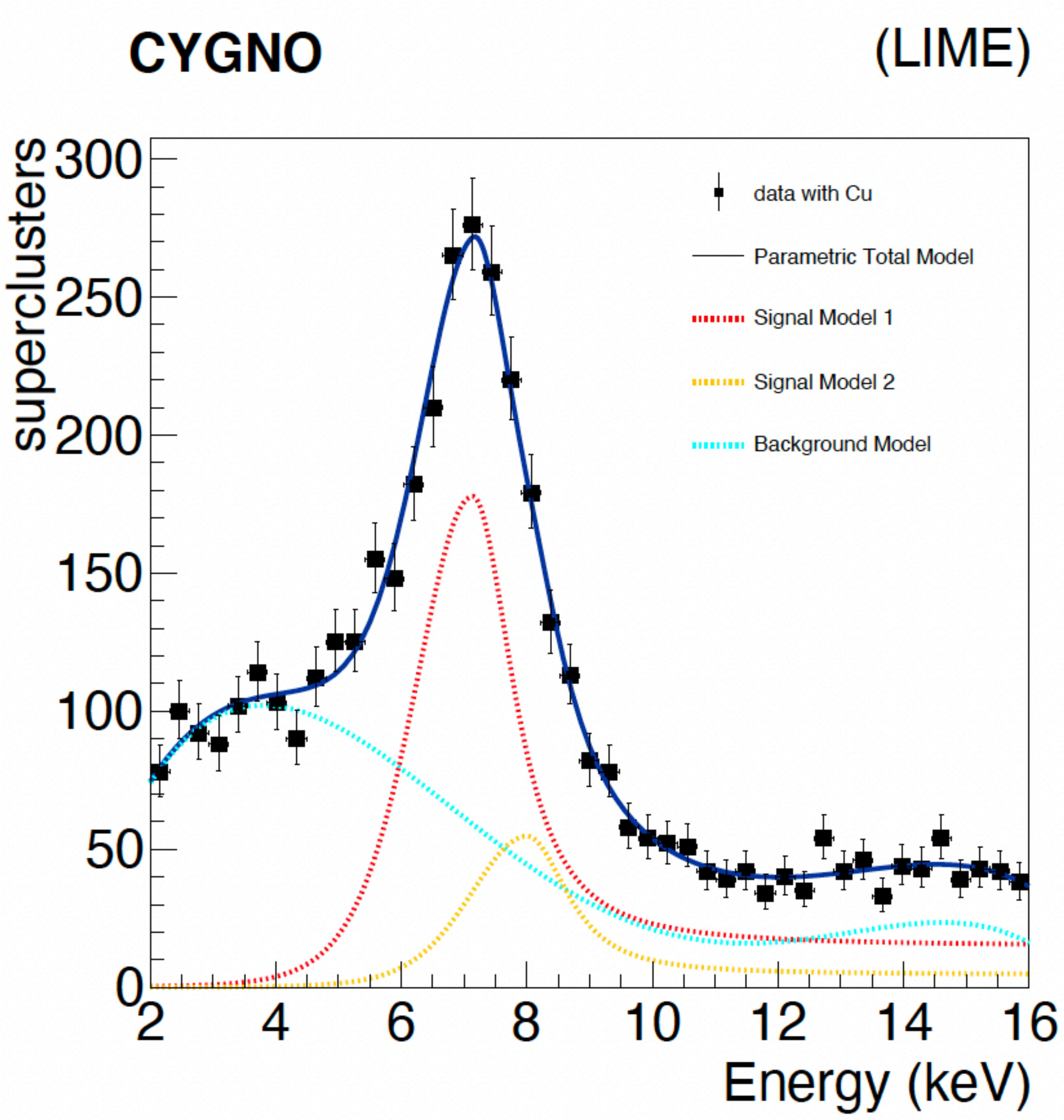
These sources are also available with an iron-55 primary source for lower energy spectrometry.

Recommended working life 15 years



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

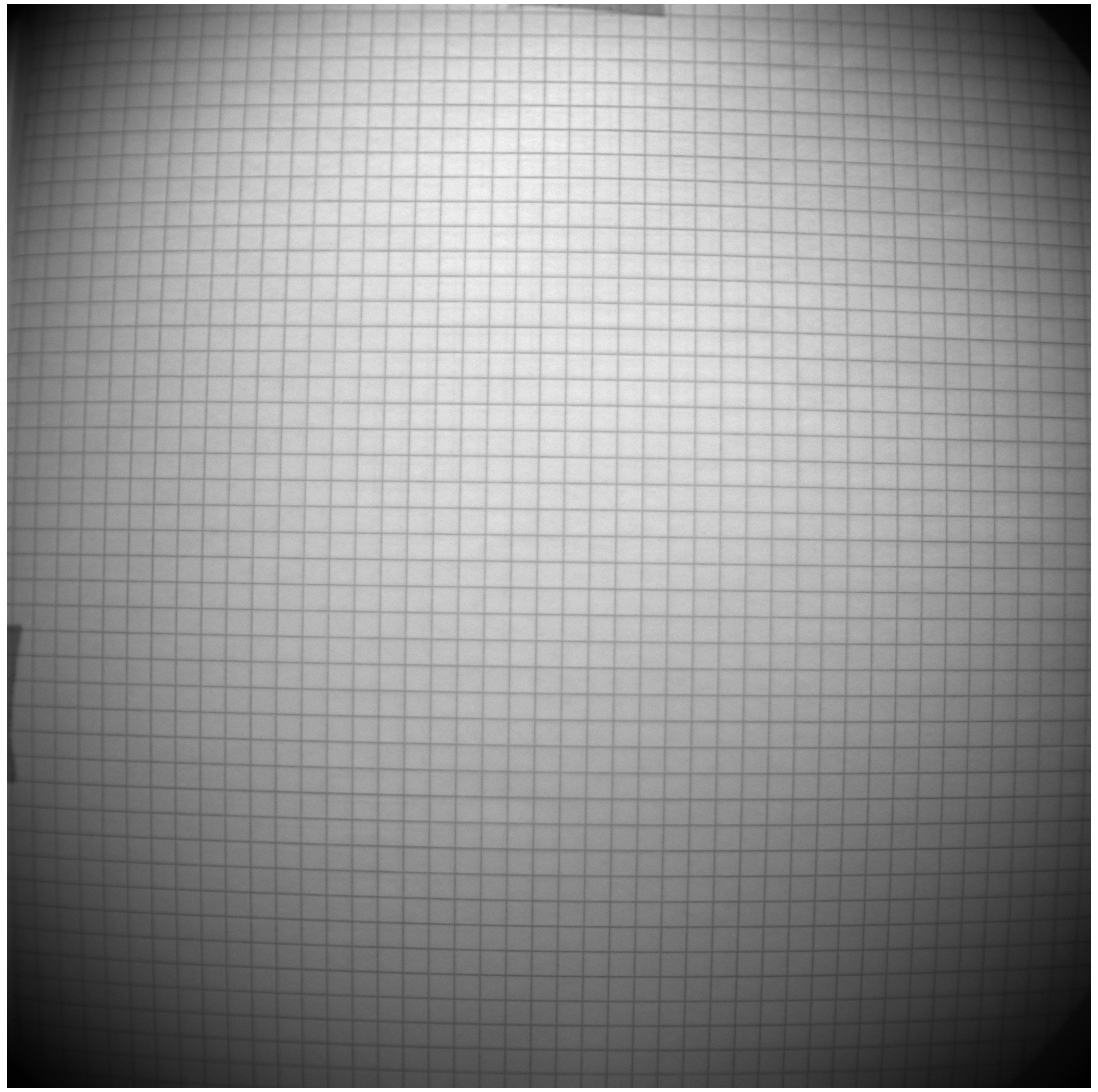
LIME: ER calibration



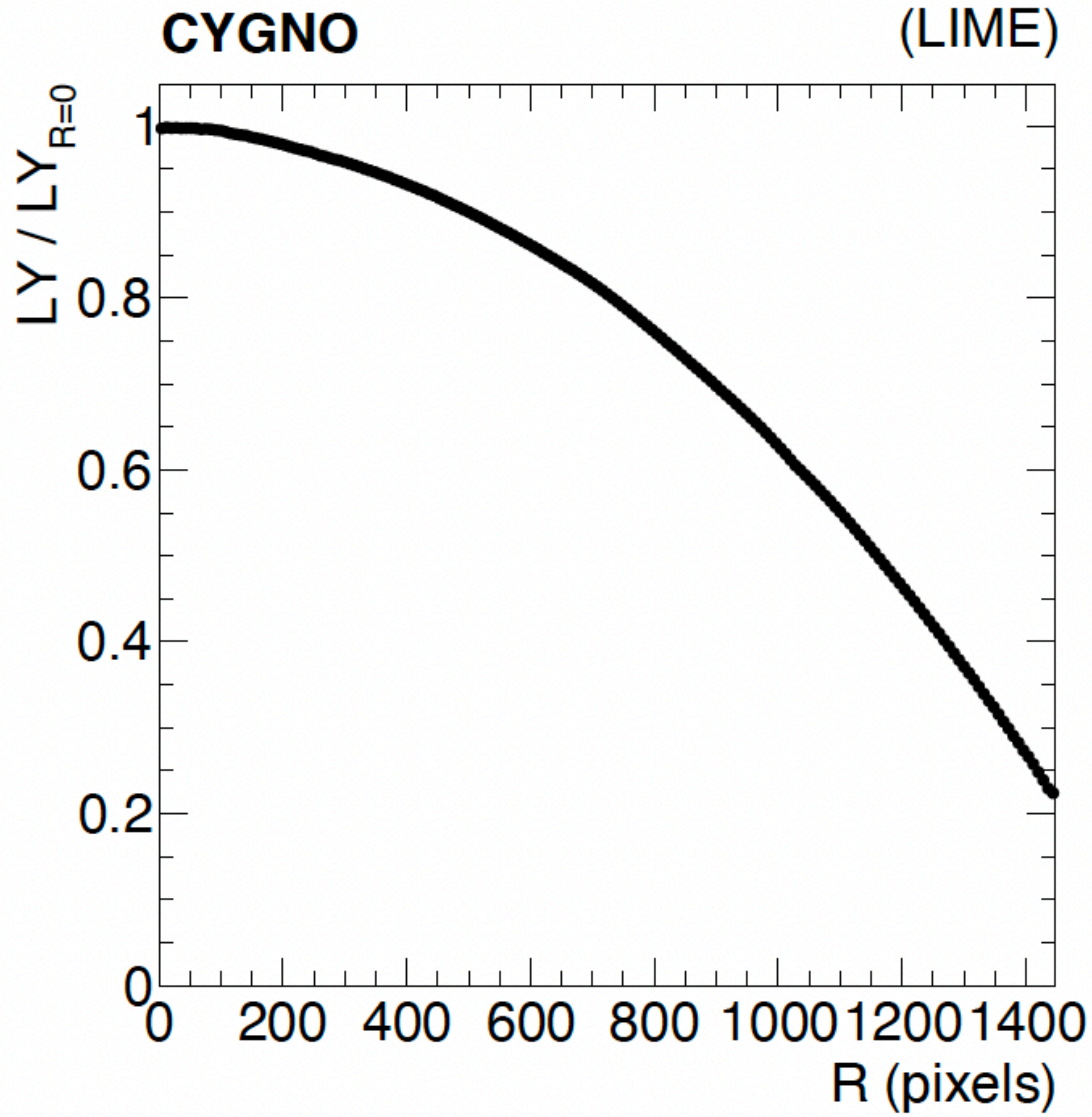
- **Data selection (DS):**
  - ➡ Loose DS to enhance SNR
- **Backgrund Model:**
  - ➡ Bernstein Polynomials fitted on the no-source spectrum
- **Signal Model** for the two lines:
  - ➡ Two Cruijff functions
  - ➡ Constraints:
    - fixed energy difference
    - same shape parameters
    - contribution 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

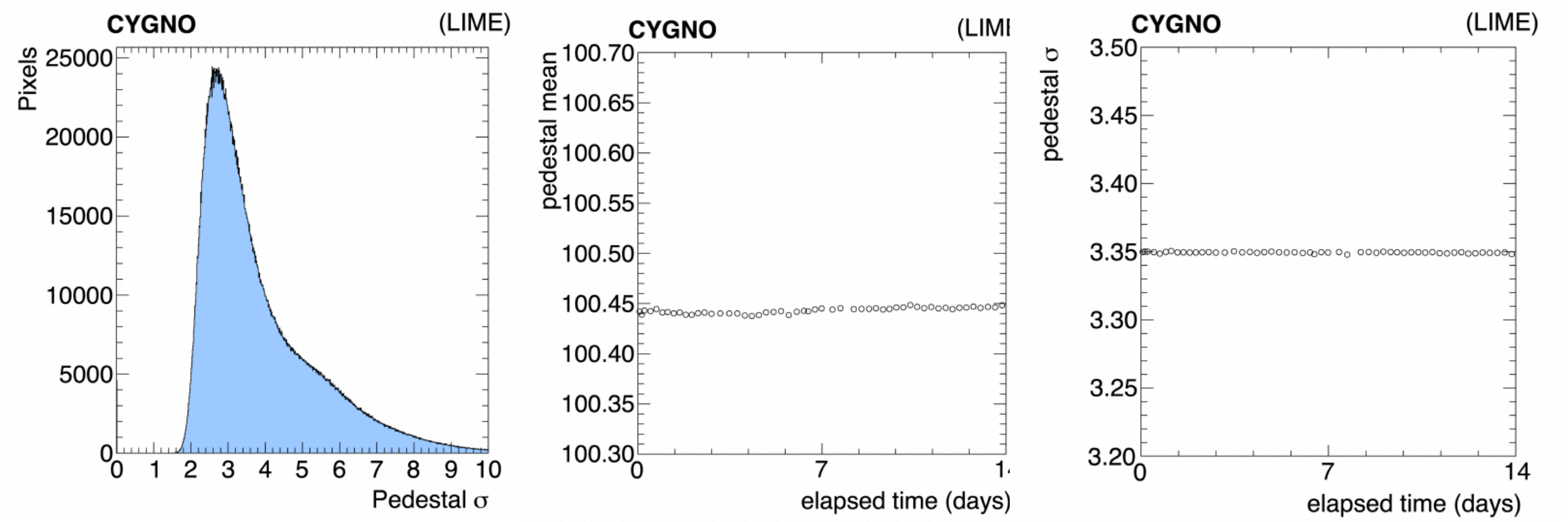


LIME: sensor noise and pedestal subtraction

- 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.

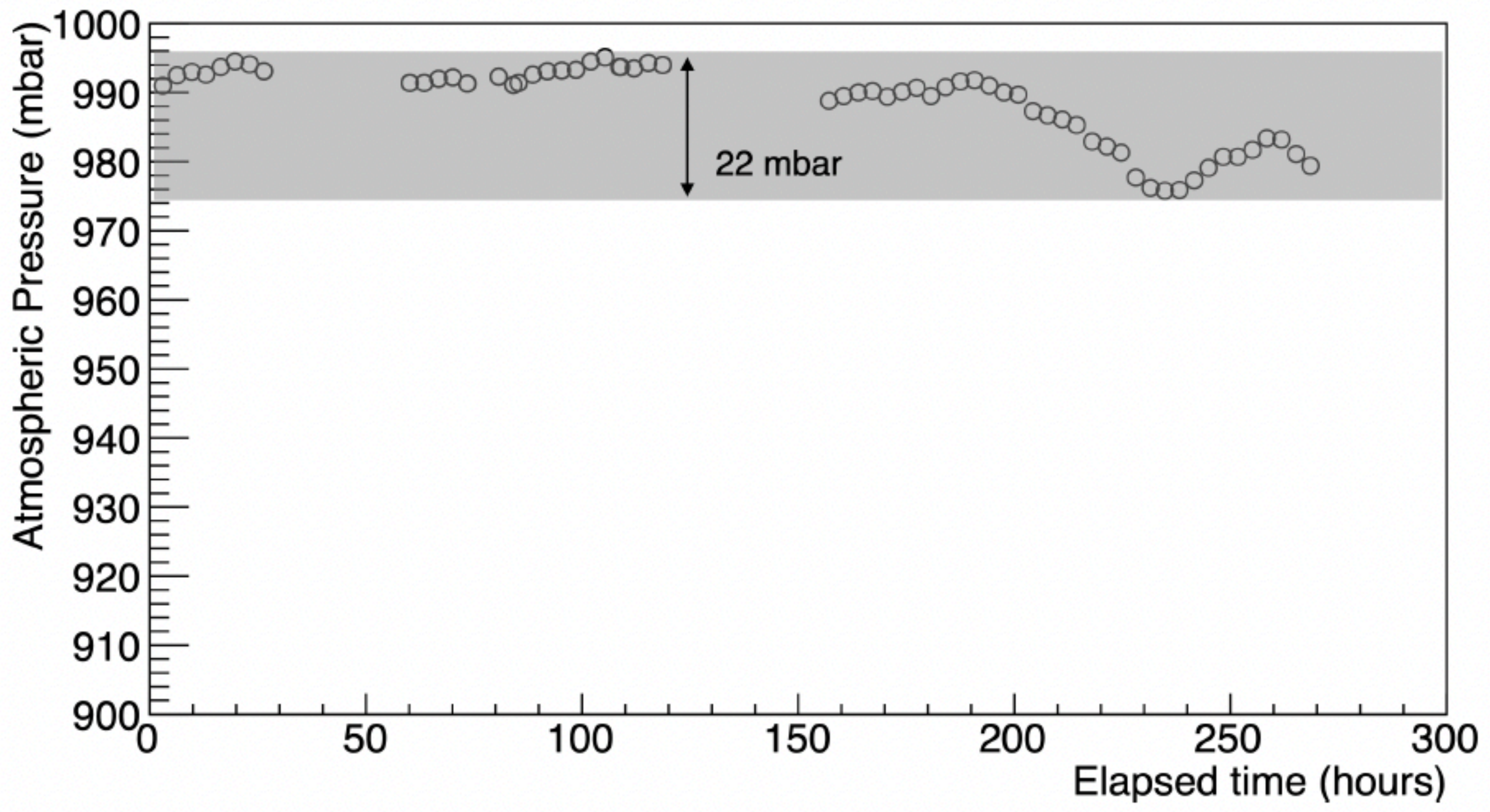
Dark current:
➡ related to the camera photo-diodes
➡ 0.2 electrons / pixel / s

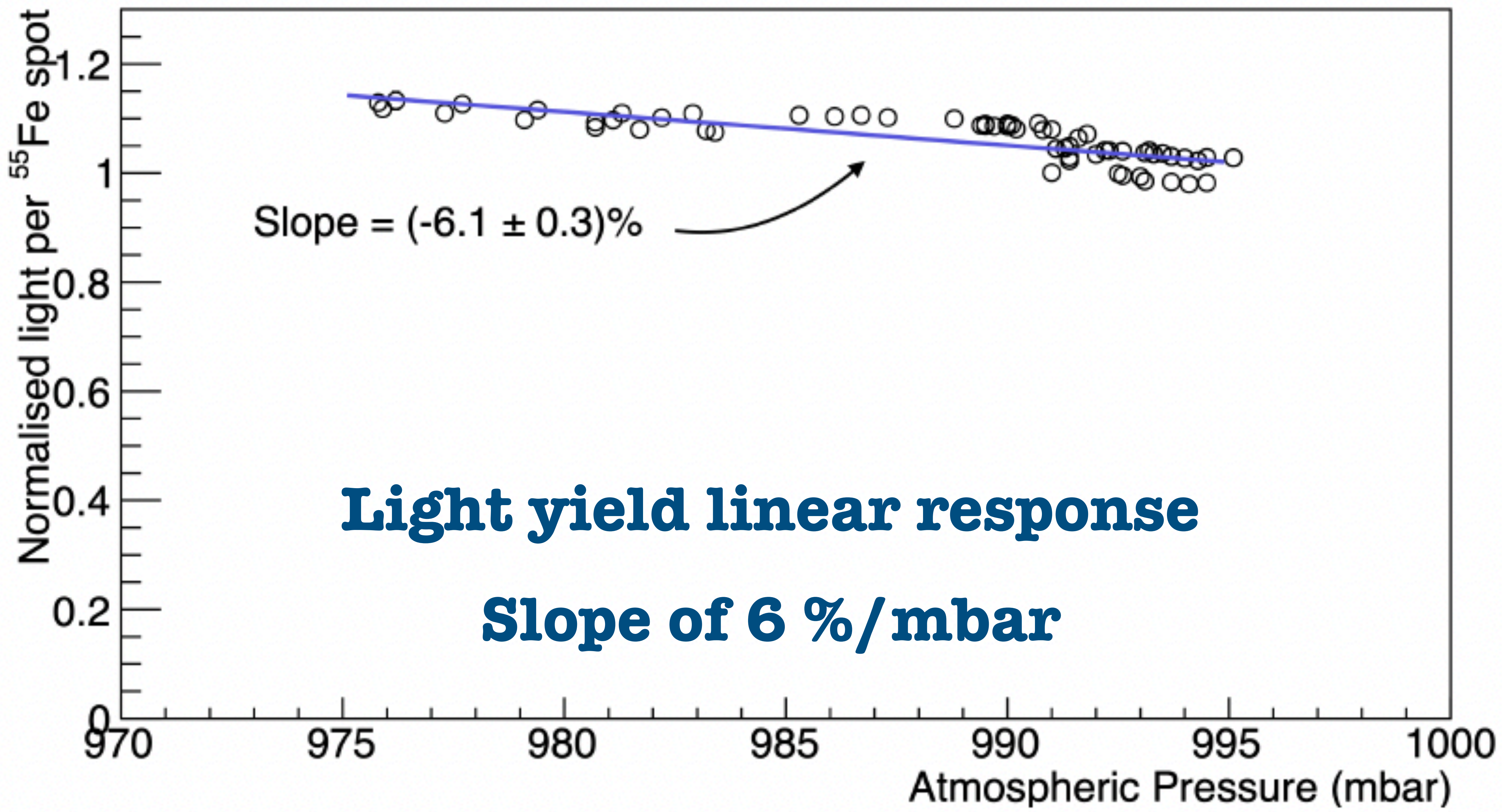


- **Very good stability**
- **Top** and **bottom** part of the sensor are **noisier**
- **Pedestal** pixel-by-pixel **mean**: subtracted to the pictures
- **Pedestal** pixel-by-pixel **std**: used to define a threshold for reconstruction

LIME: long term stability

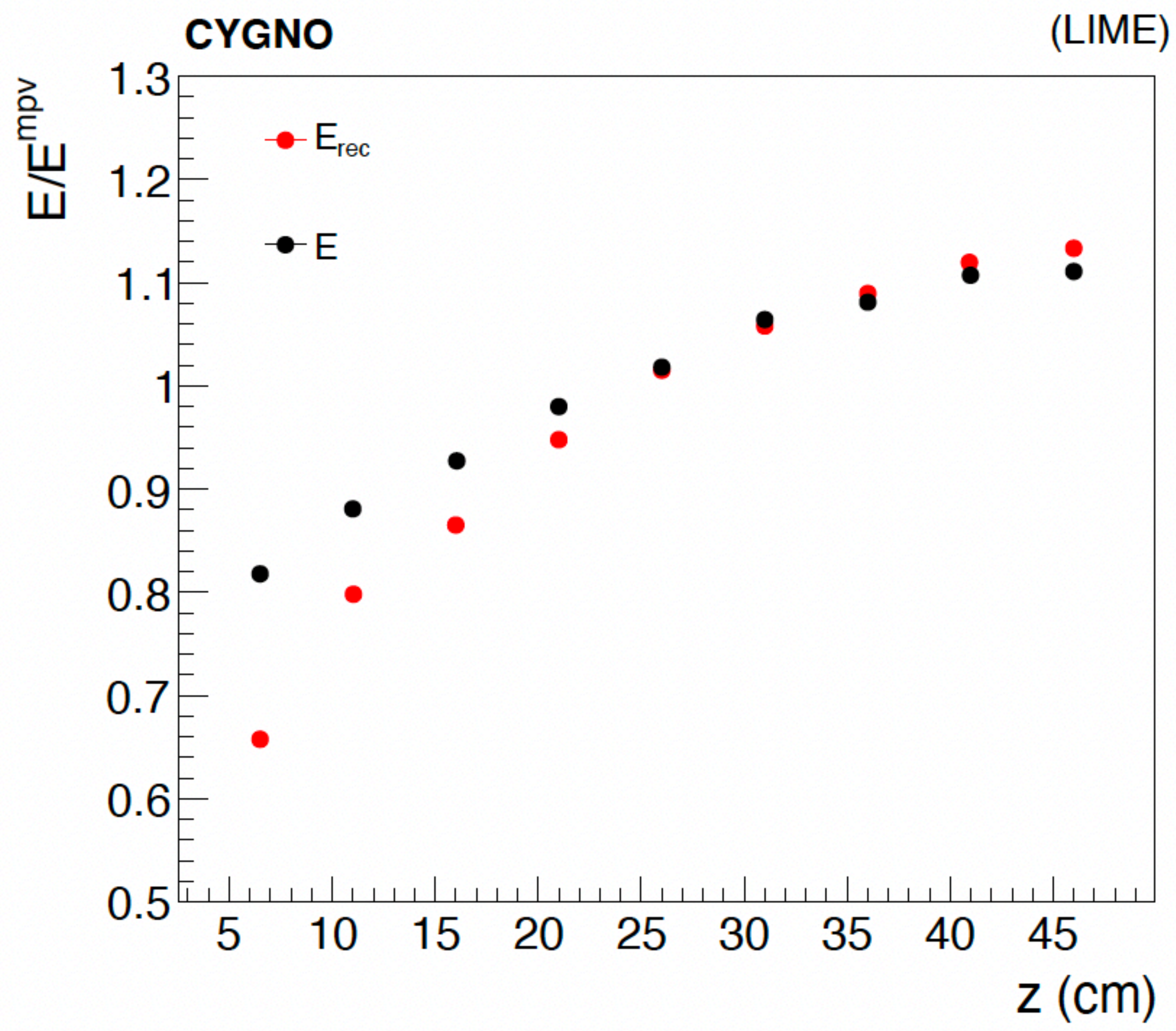
- Two weeks of continuous overground data taking
- Controlled **temperature** of (298.7±0.3) K
- **Pressure** monitoring



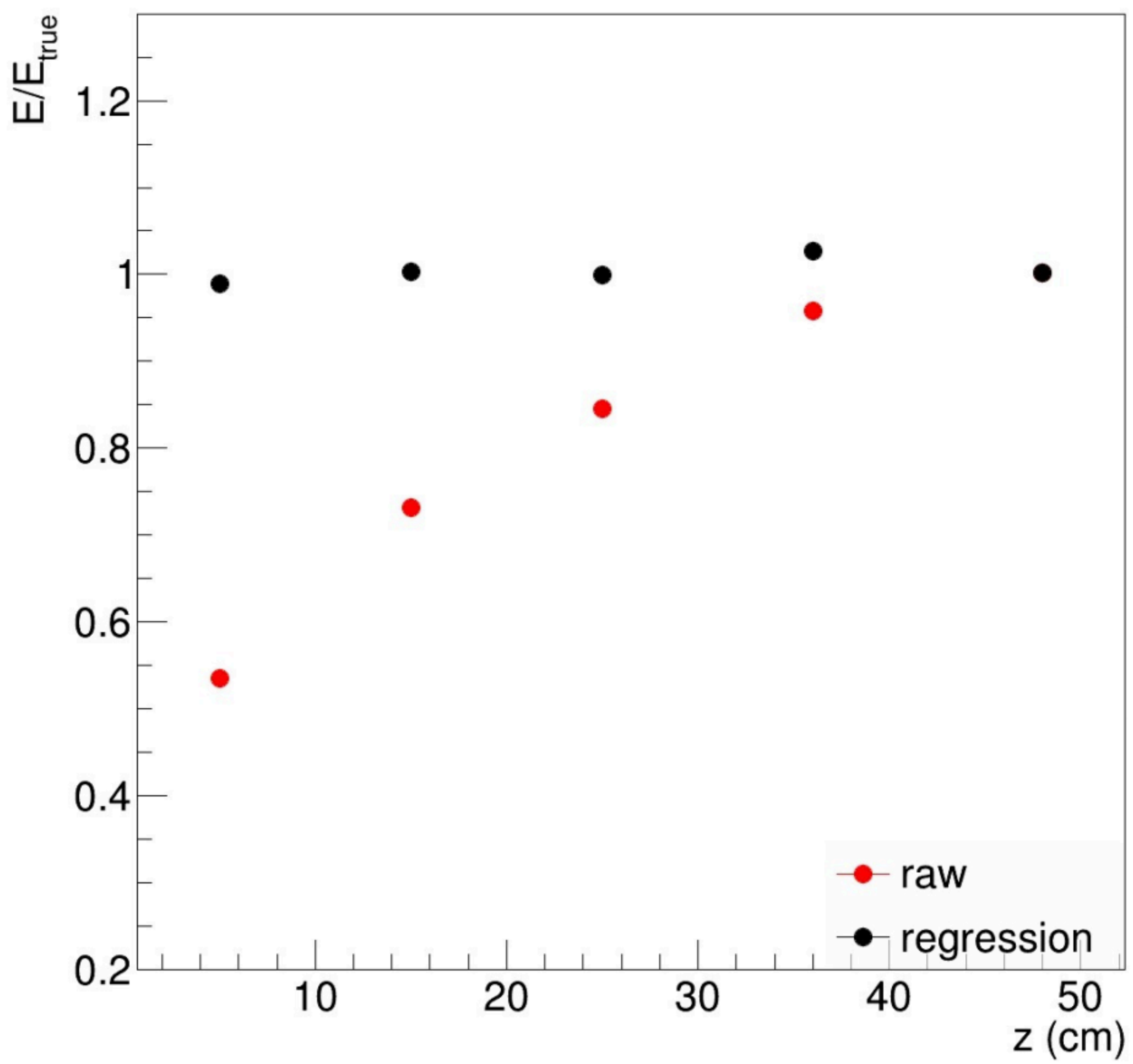


Preliminary: multivariate regression

Overground



RUN 2: 4 cm Cu shielding



Thanks to the very low pile up the algorithm is way more efficient

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**