

Status of the CYGNO project

S. Piacentini for the CYGNO collaboration

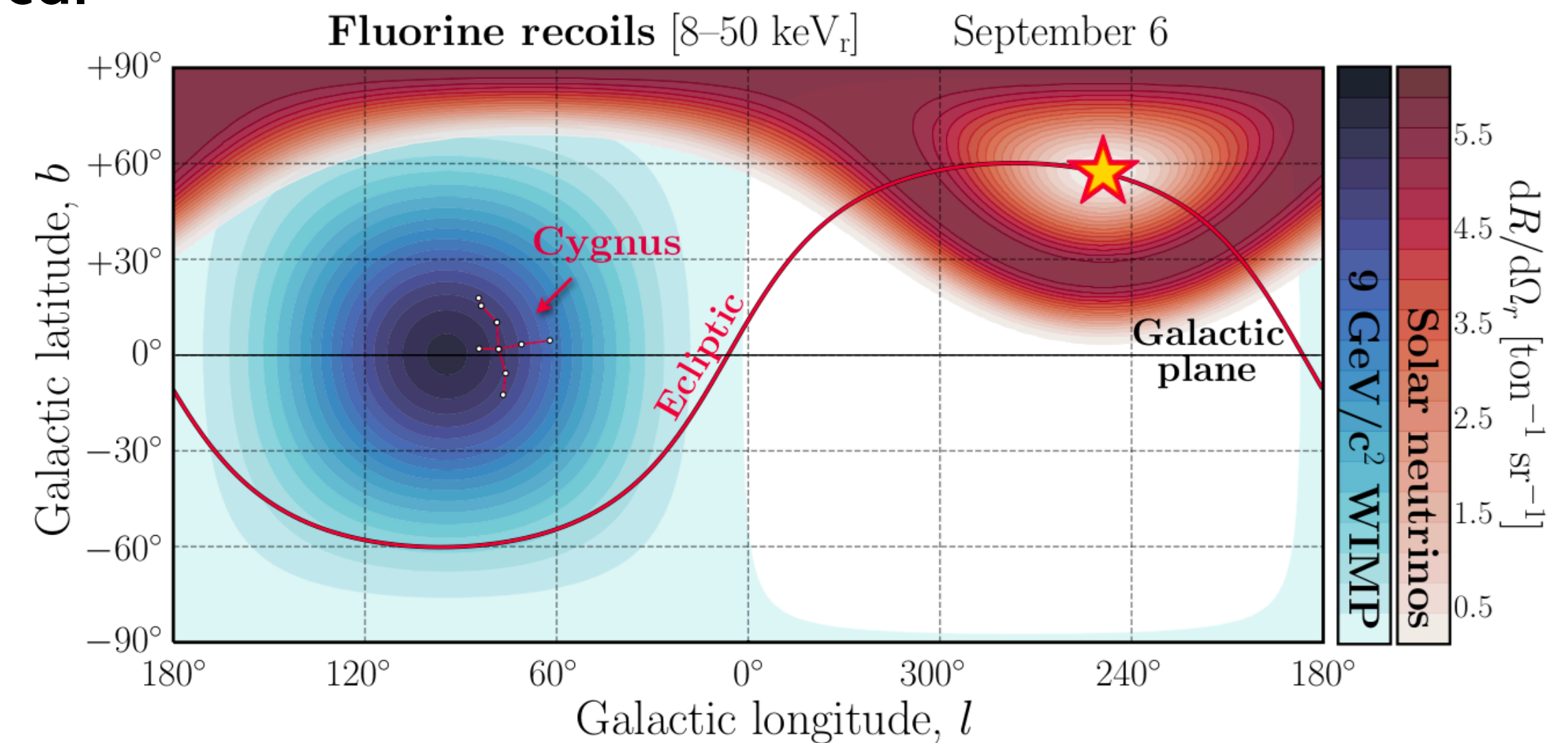
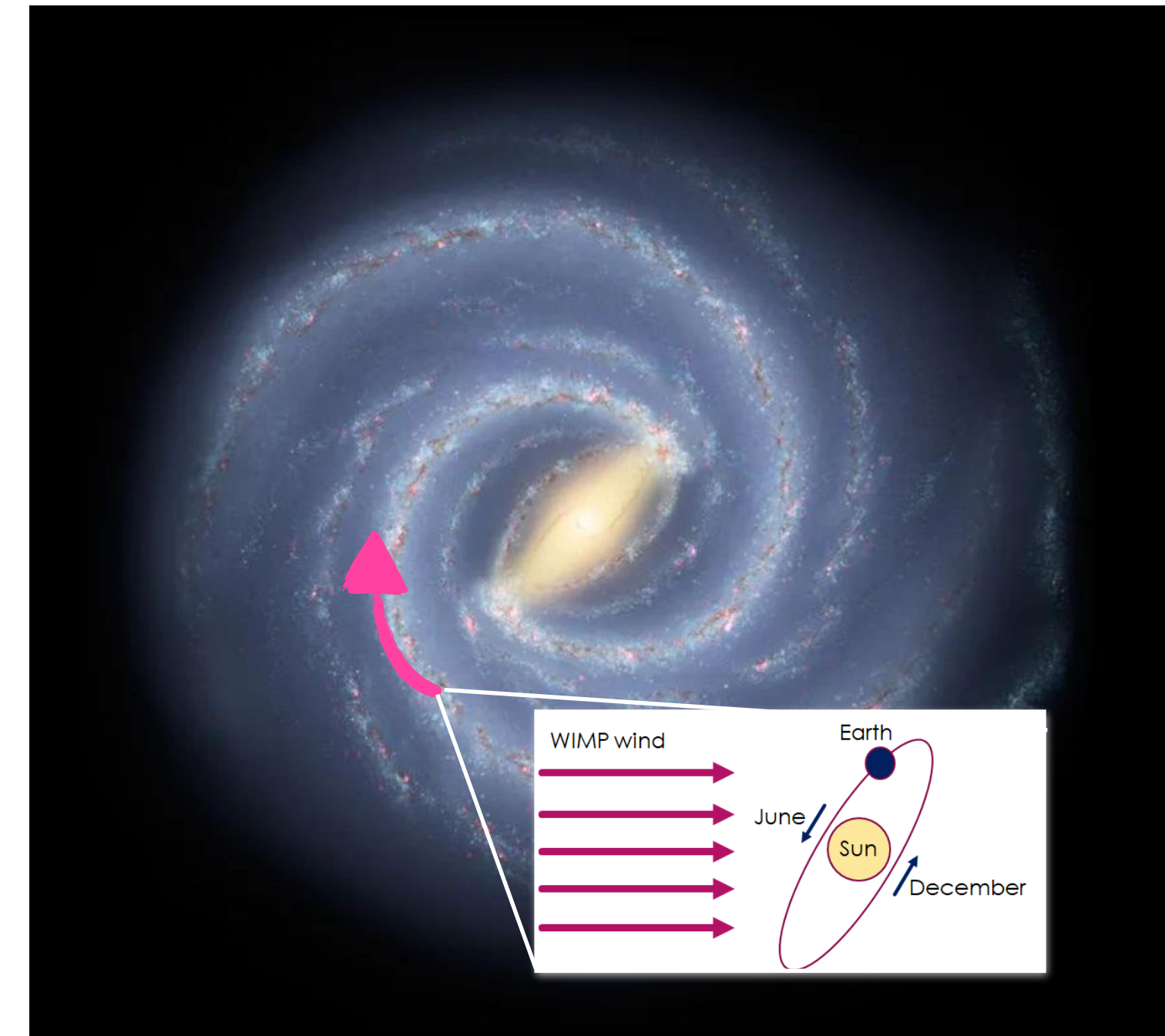
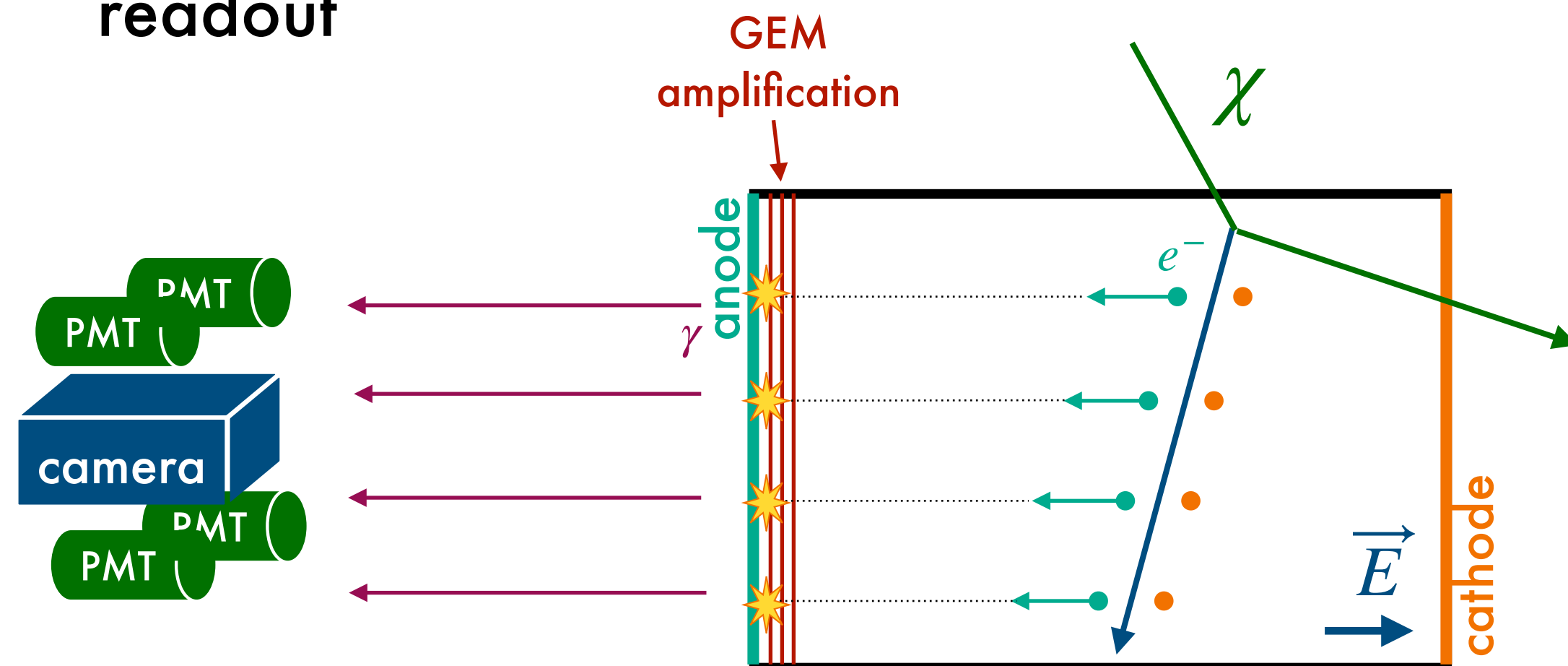


R. Antonietti, E. Baracchini, L. Benussi, S. Bianco, R. Campagnola, C. Capoccia, M. Caponero, L. G. Carvalho, G. Cavoto, I. A. Costa, A. Croce, M. D'Astolfo, G. D'Imperio, E. Danè, G. Dho, F. Di Giambattista, E. Di Marco, J. M. F. dos Santos, D. Fiorina, F. Iacoangeli, Z. u. Islam, E. Kemp, H. P. Lima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

The **CXGNO** project

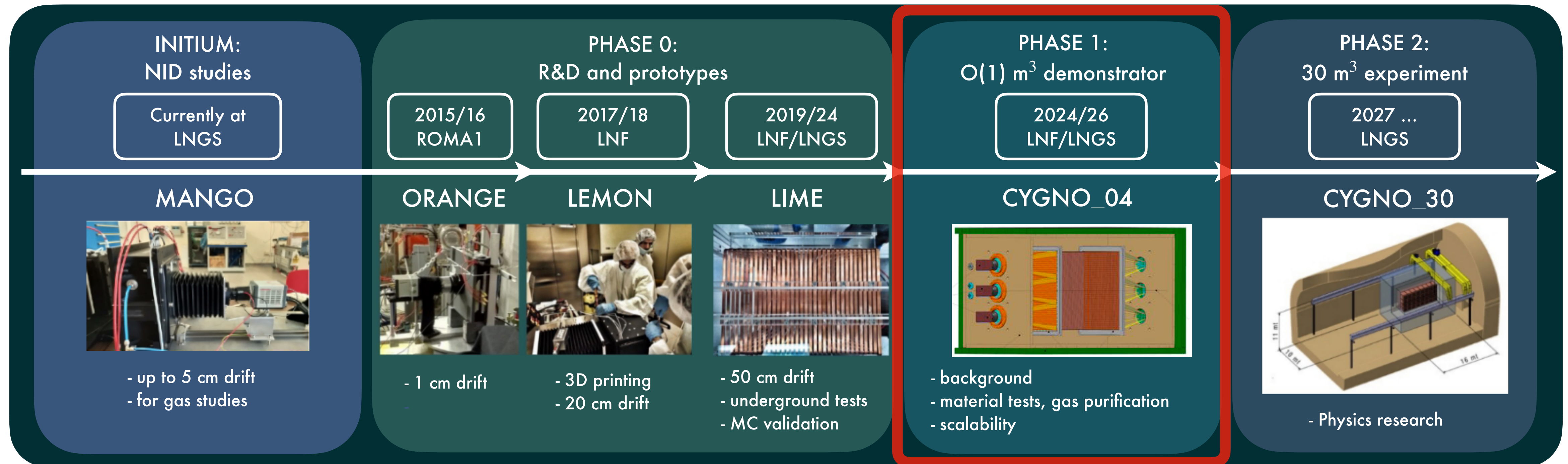
- **Large gaseous detector** for high precision **3D tracking** of rare **O(keV) nuclear recoils (NR)** possibly induced by **dark matter (DM)** particles and solar neutrinos
- **Experimental challenges:** rate $< \mathcal{O}(\text{evt/kg/year})$, background rejection, and energy threshold (keV)
- **Strategy:** photograph nuclear recoils in a (atmospheric pressure) He:CF₄ TPC with a GEM amplification stage

➡ low energy events in the gas $\Rightarrow$ visible tracks $\Rightarrow$ optical readout



The **CXGNO** timeline

CXGNO
Experiment



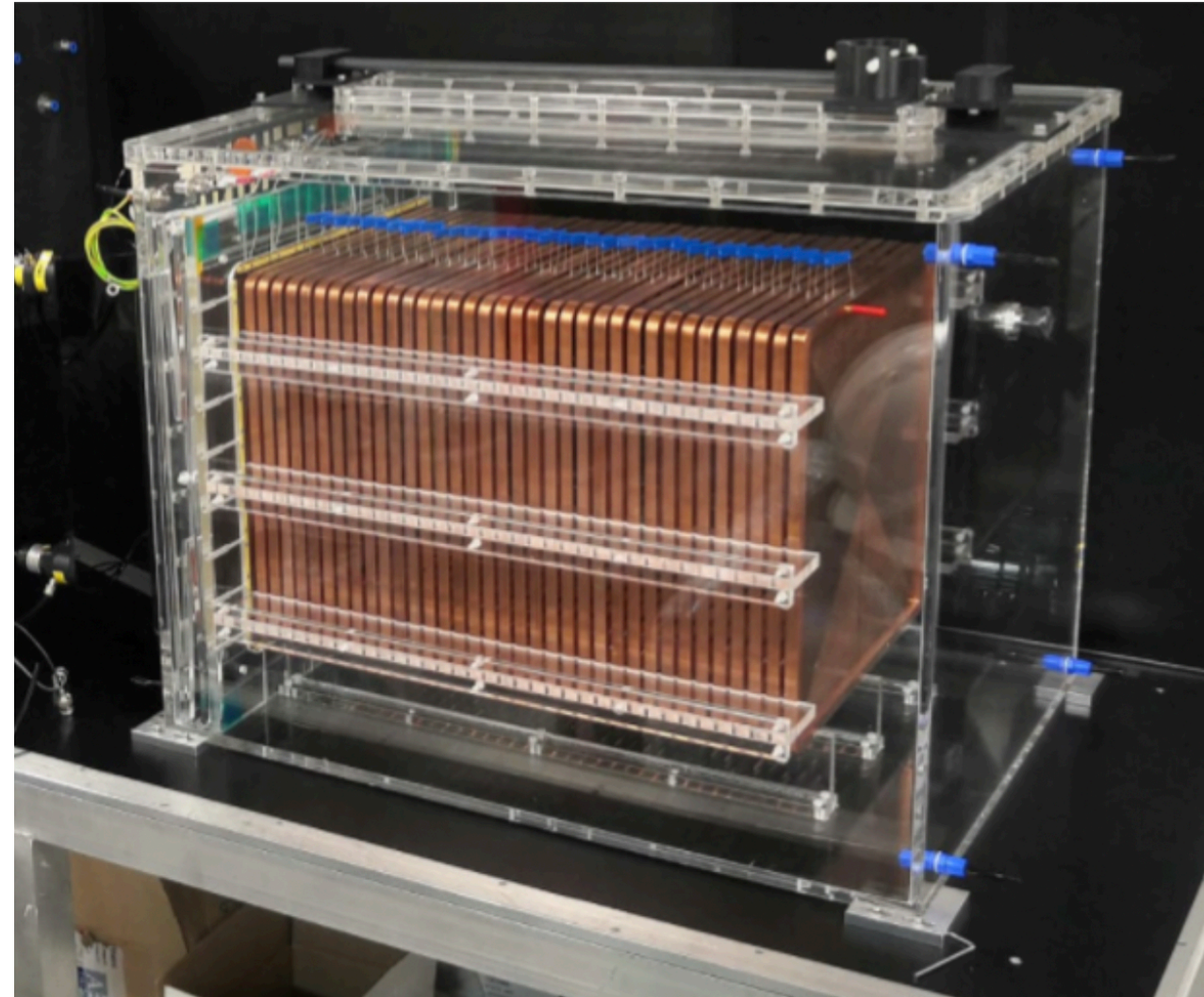
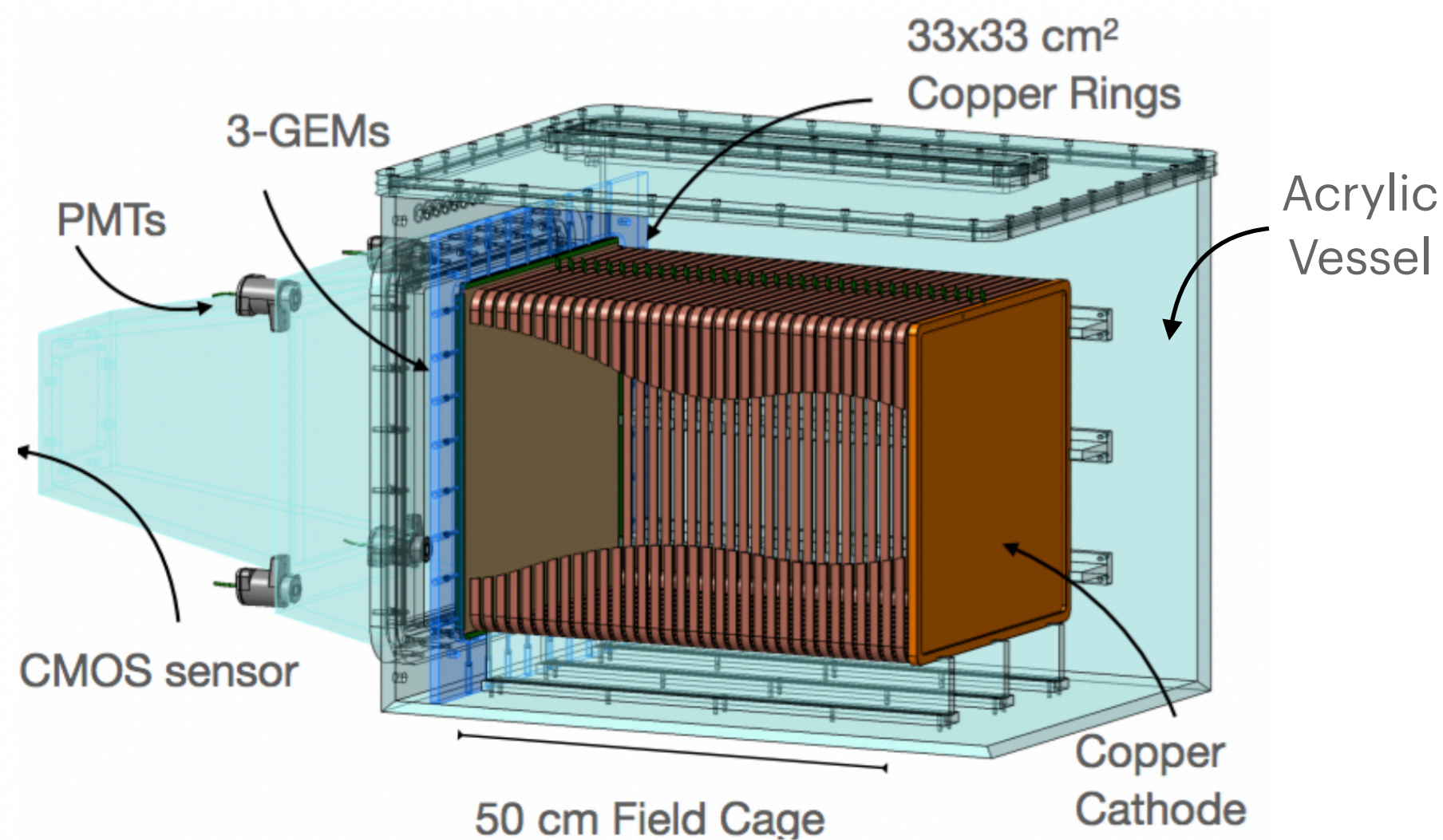
Phys.Lett.B 855 (2024) 138759
Eur.Phys.J.C 83 (2023) 10, 946
Instruments 6 (2022) 1, 6
Measur.Sci.Tech. 32 (2021) 2, 025902
NIM A 999 (2021) 165209

JINST 15 (2020) 12, T12003
JINST 15 (2020) P10001
JINST 15 (2020) P08018
2019 JINST 14 P07011

LIME: Long Imaging Module

CXGNO
Experiment

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



Purpose of LIME:

- Prove we can operate such a detector underground
- Study and improve our Monte Carlo simulation



4 Hamamatsu R7378 PMTs

ORCA-FUSION

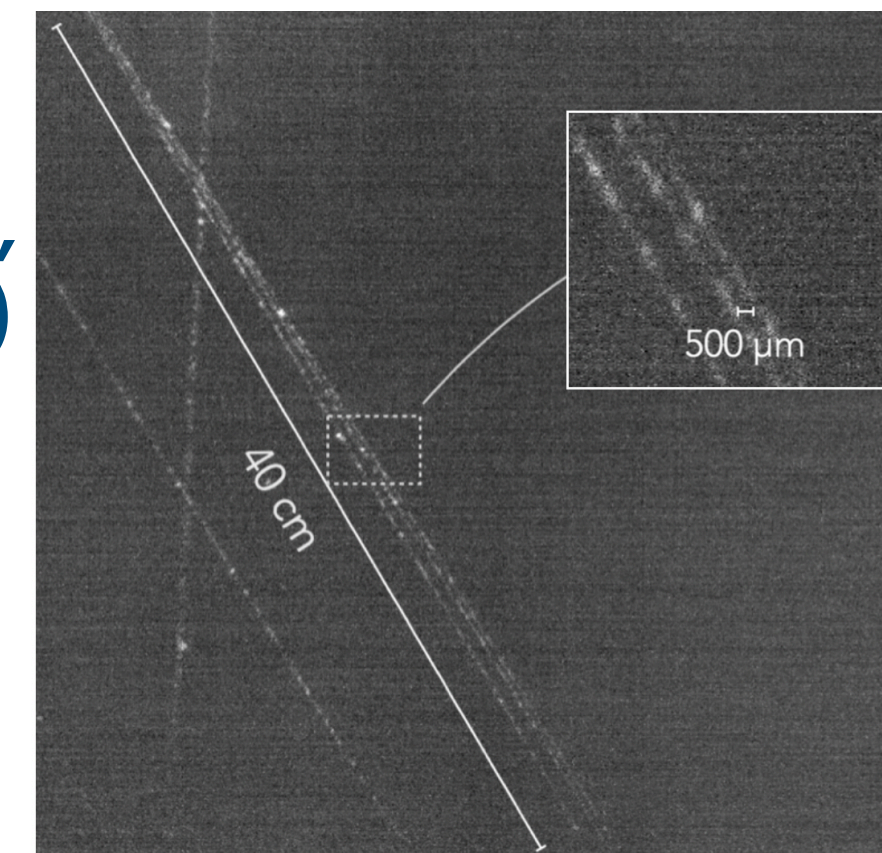
HIGH RESOLUTION
2304 × 2304
5.3 Megapixels

READOUT NOISE
0.7 electrons rms
Ultra-quiet Scan

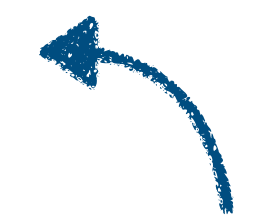
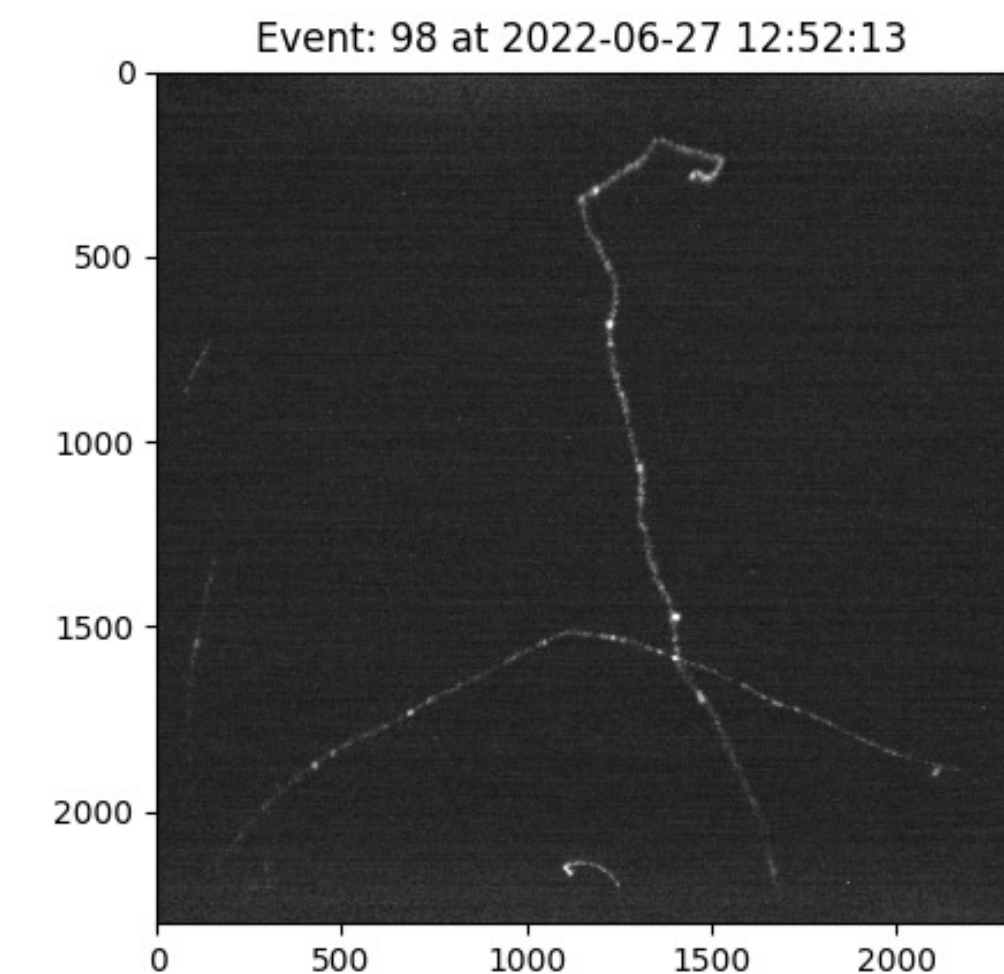


- Copper ring **field cage**, 50 cm **drift**
- 1 **sCMOS** sensor + 4 **PMTs**
- 3 **GEMs** for a 33 x 33 cm² sensitive area
- 50 L** sensitive volume

Cosmic rays
(overground,
no shielding)



4

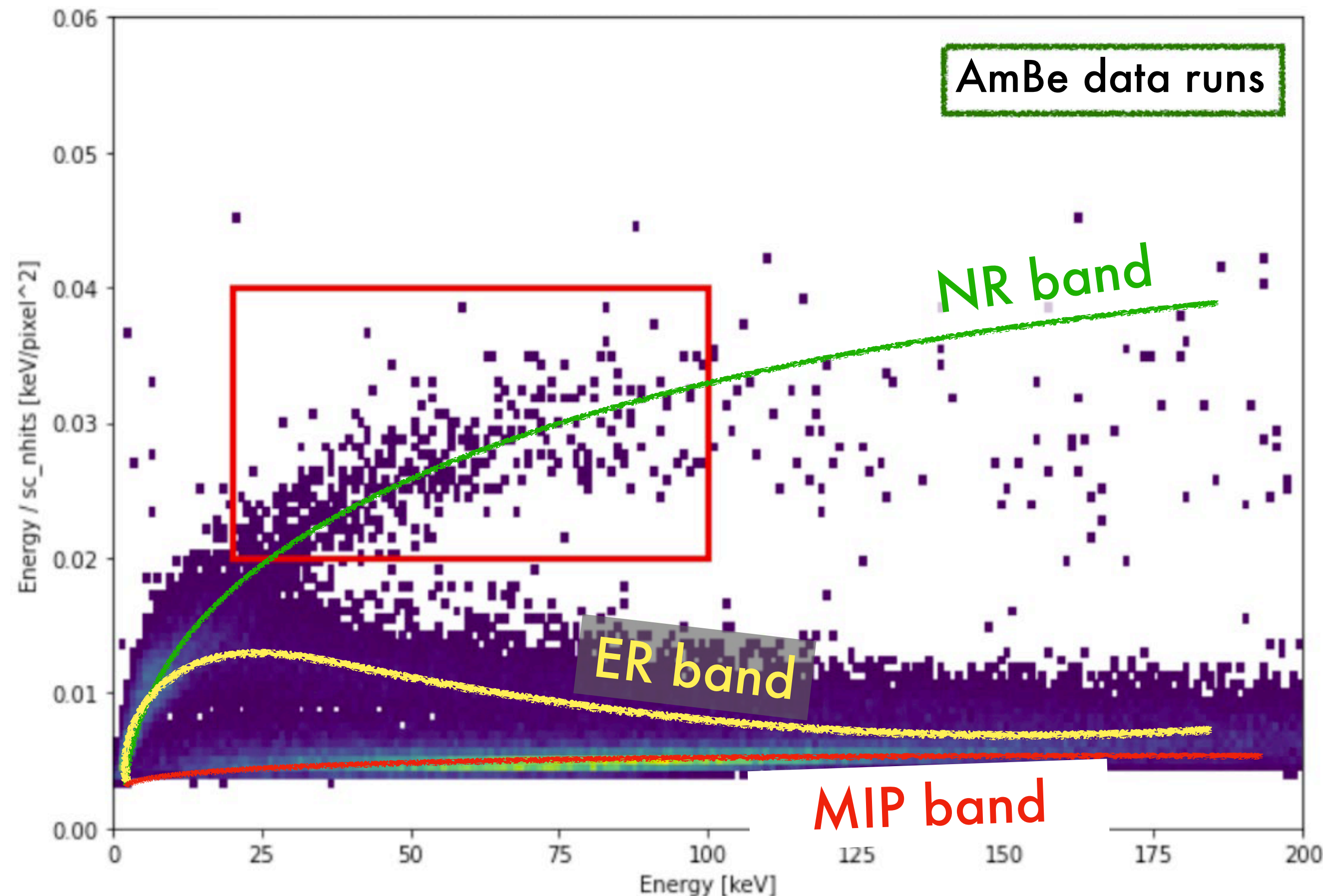


Natural
radioactivity
(underground,
no shielding)

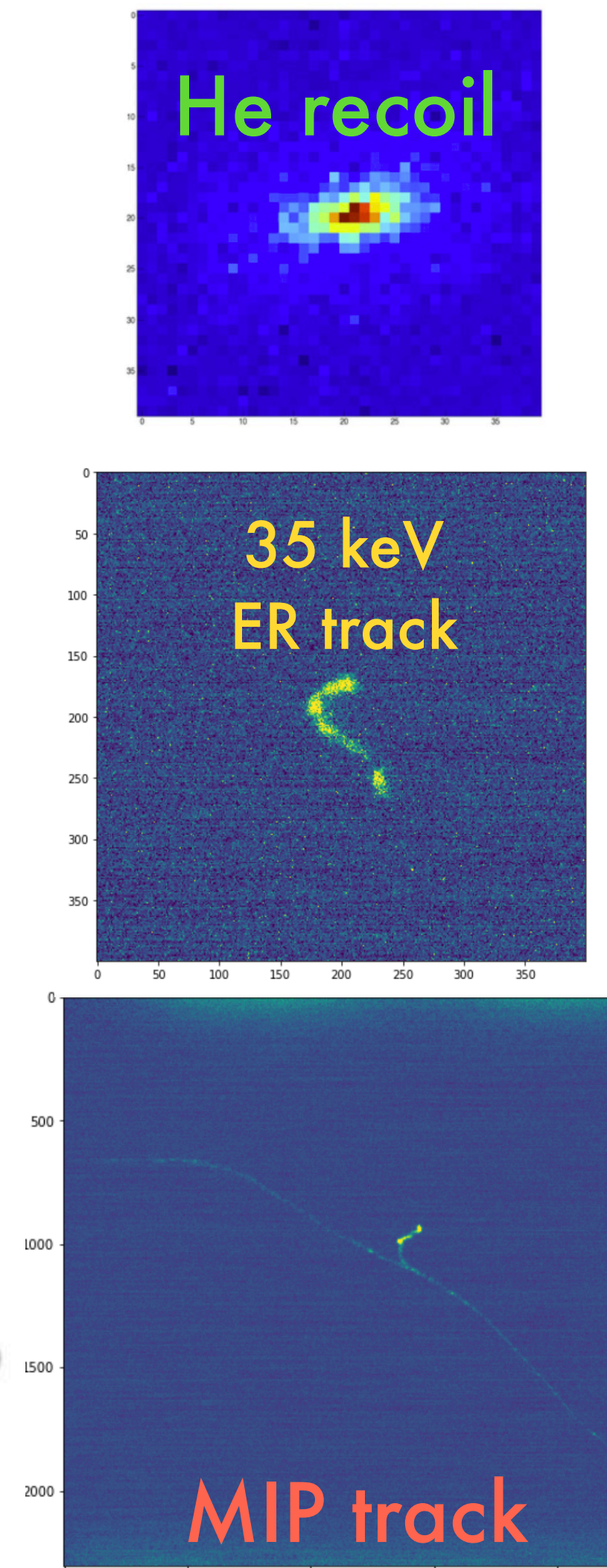
LIME response to different deposits



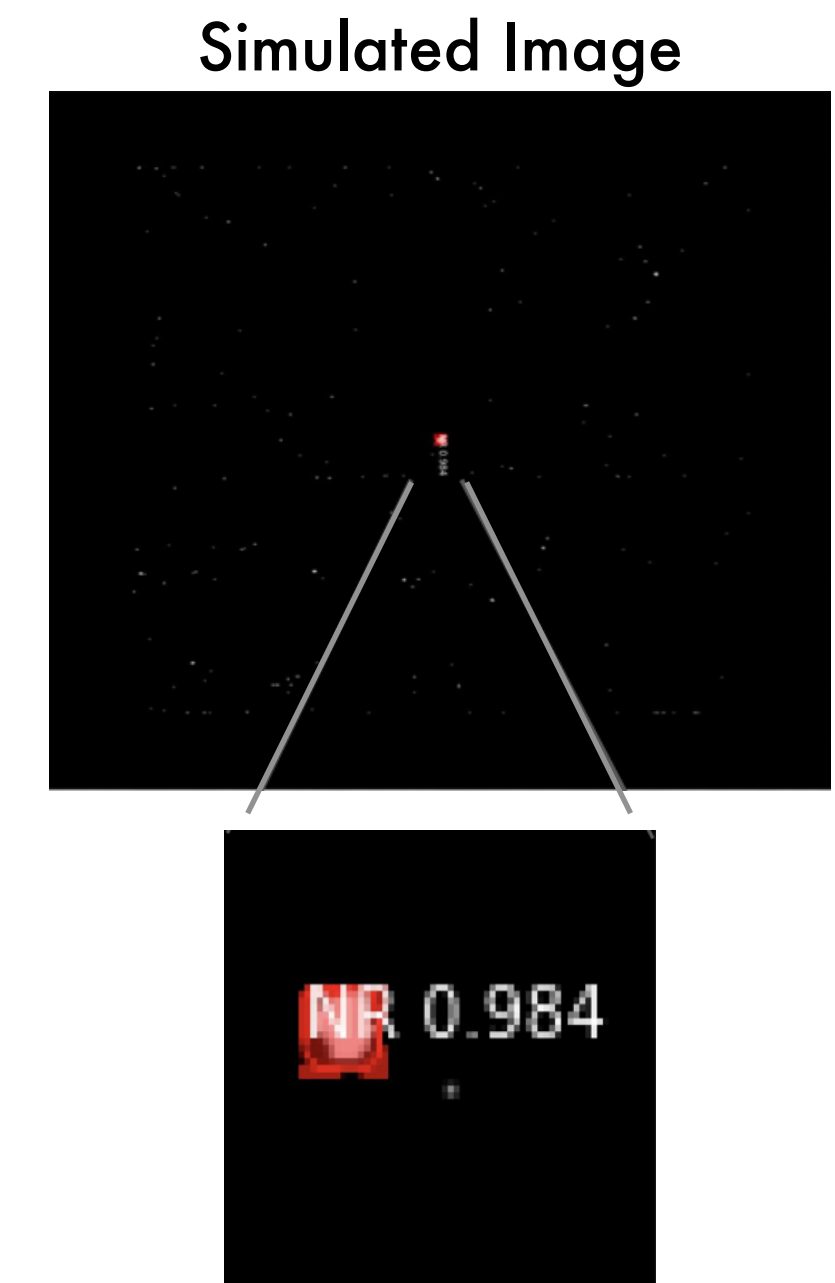
- NR induced by **AmBe neutron source**



- Saturation** of the GEM gain a serious limitation below $\sim 20 \text{ keV}_{ee}$



- Working on a **machine learning application for refined ER vs NR discrimination** $\Rightarrow$ promising results on MC images, to be validated on real data



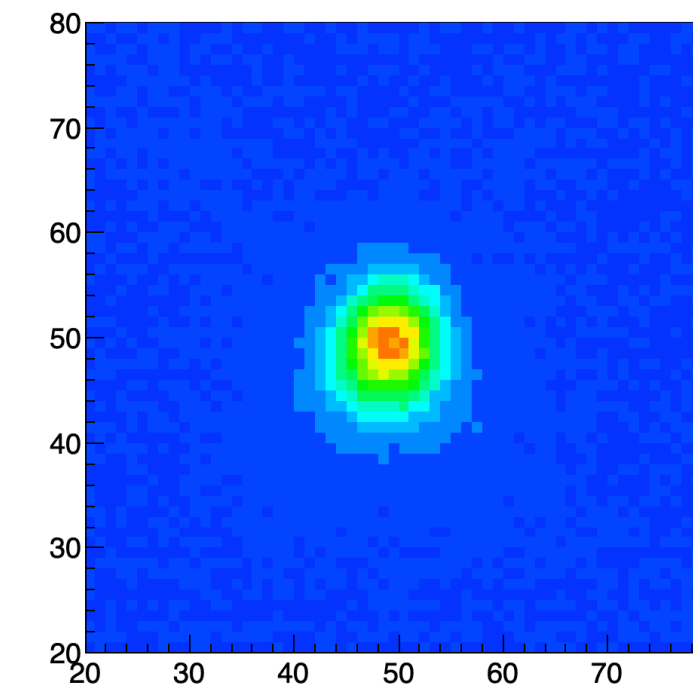
Saturation of the GEM gain



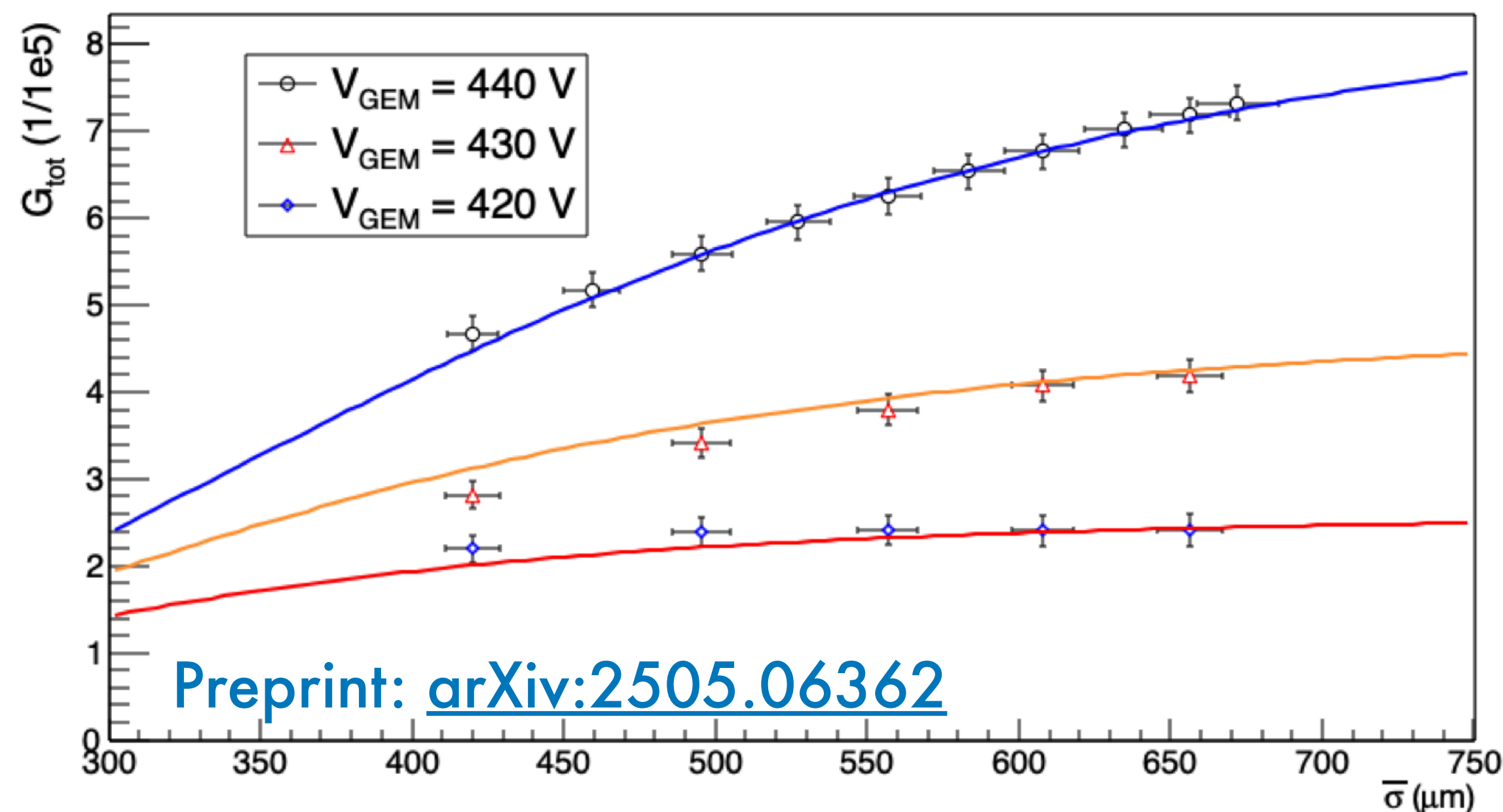
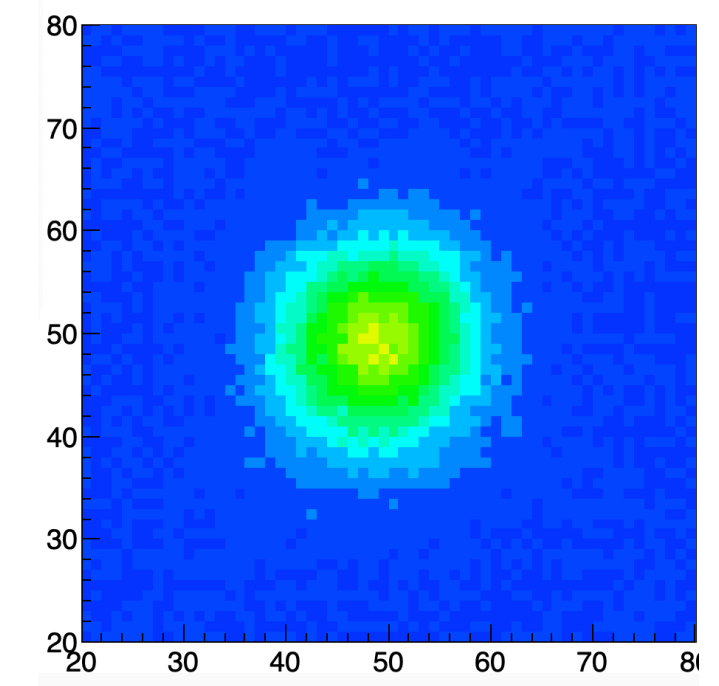
- **Saturation** of GEM gain due to positive **ions back-flow** screening the electric field, as already found by our CERN colleagues [[arXiv:1512.04968](https://arxiv.org/abs/1512.04968)]
- **Denser energy deposits** $\Rightarrow$ **more charge in the same holes**

5.9 keV ^{55}Fe spots

$z = 5 \text{ cm}$



$z = 45 \text{ cm}$



We developed a simple model:
[modified Townsend model]

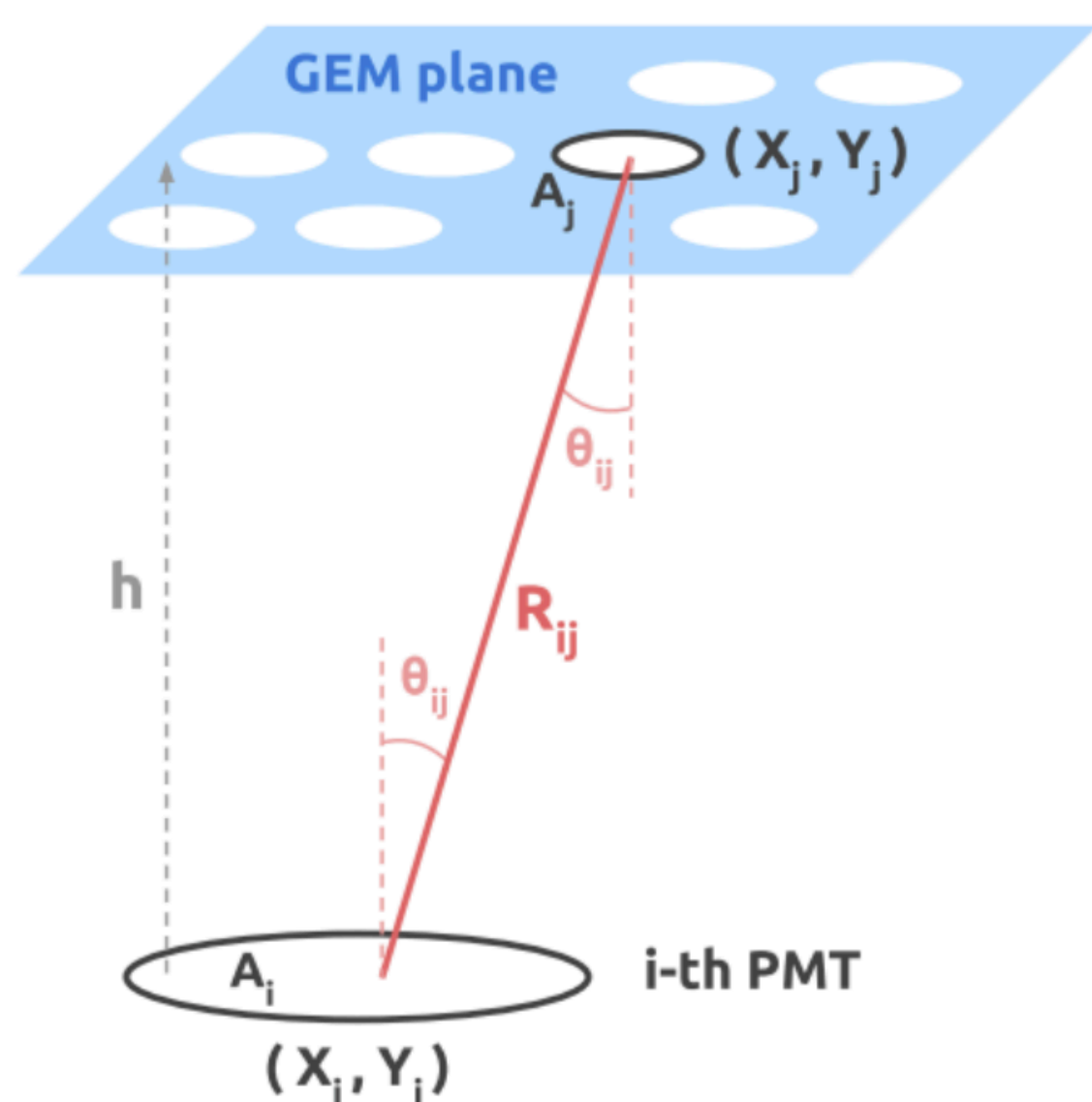
$$\frac{dn}{ds} = \alpha n E (1 - \beta n)$$

$$G_{tot} = \frac{(ce^{\alpha V_{GEM}})^3 \sigma^3}{\sigma^3 + (p/V_{GEM})(ce^{\alpha V_{GEM}})^2 (ce^{\alpha V_{GEM}} - 1)}$$

3D reconstruction: cam-to-PMT association with bayesian inference

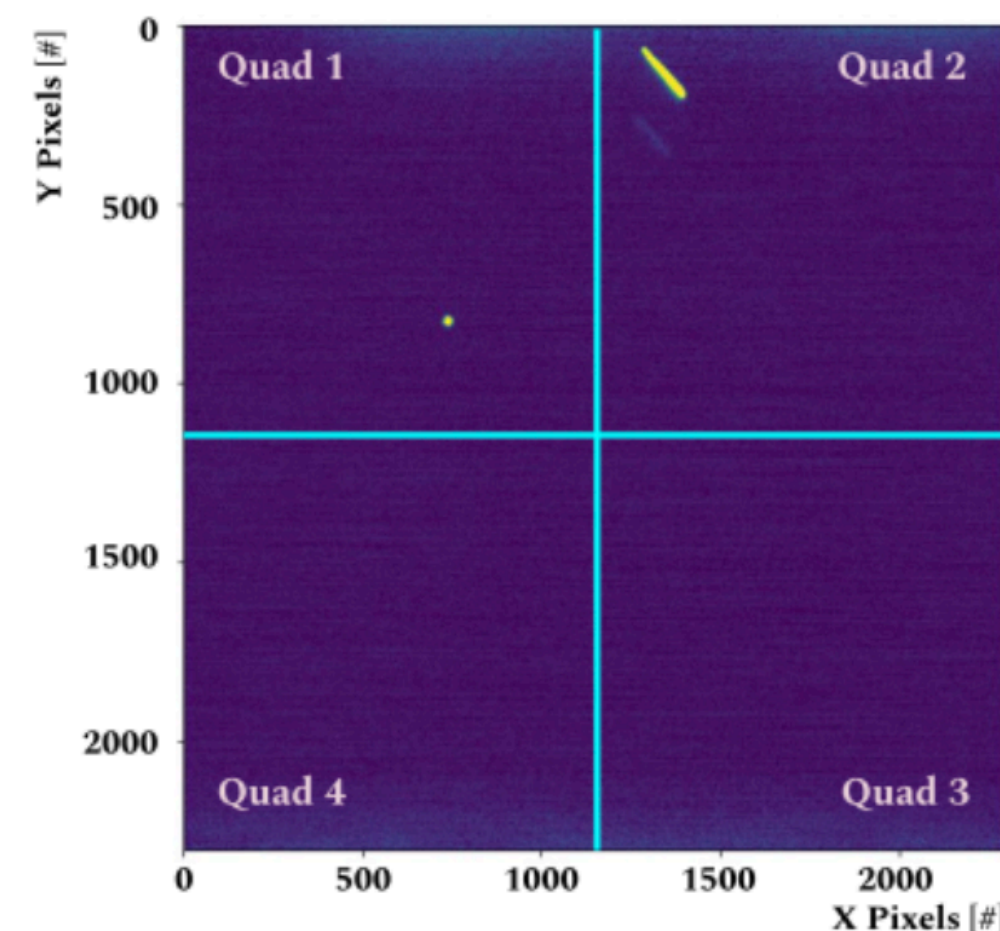
Preprint: [arXiv:2506.04973](https://arxiv.org/abs/2506.04973)

- Combined information from the 4 PMTs → **inference** on the track **position** and light **intensity**

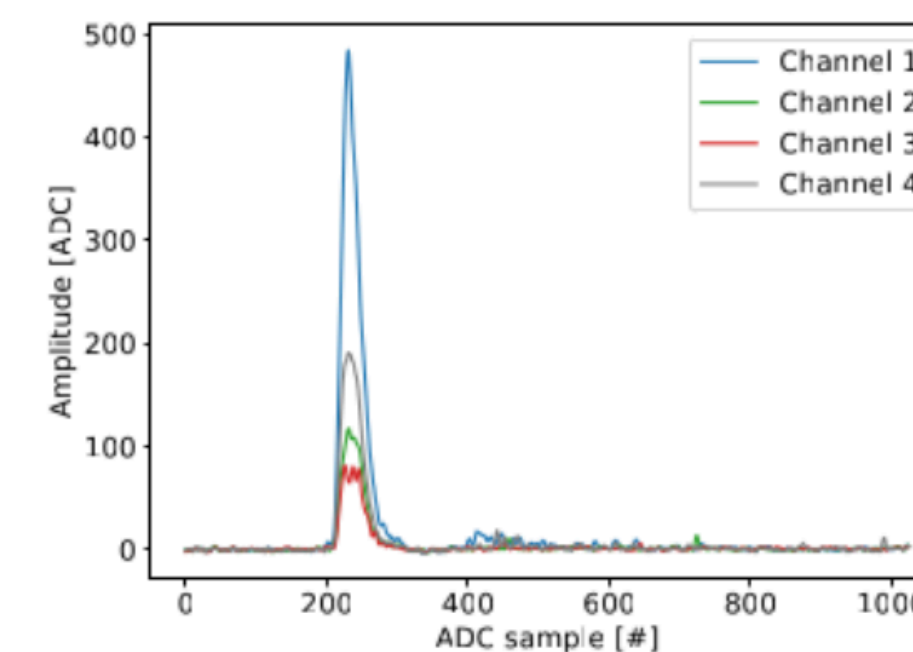


$$\Phi = \frac{L_j A_j A_i \cos^2 \theta_{ij}}{R_{ij}^2}$$

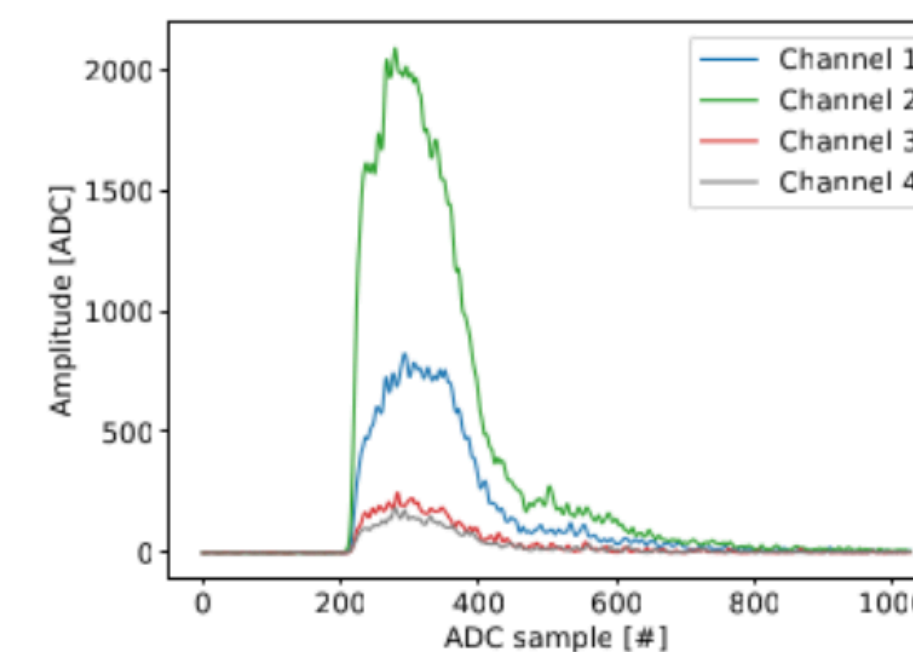
$$L_{ij} \propto \frac{L_j}{R_{ij}^4}$$



(a) CMOS image



(b) Trigger #1



(c) Trigger #2

3D reconstruction: cam-to-PMT association with bayesian inference

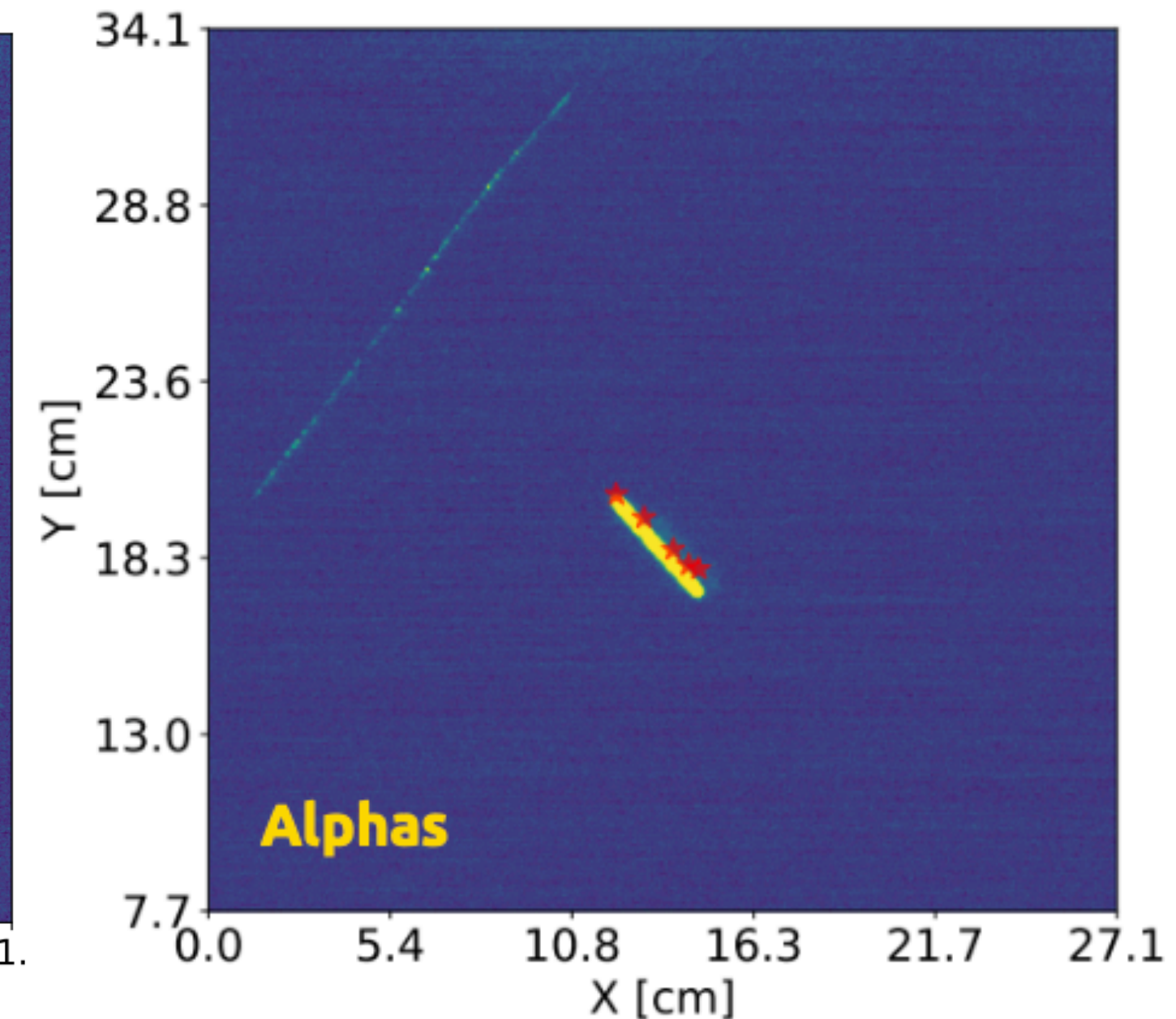
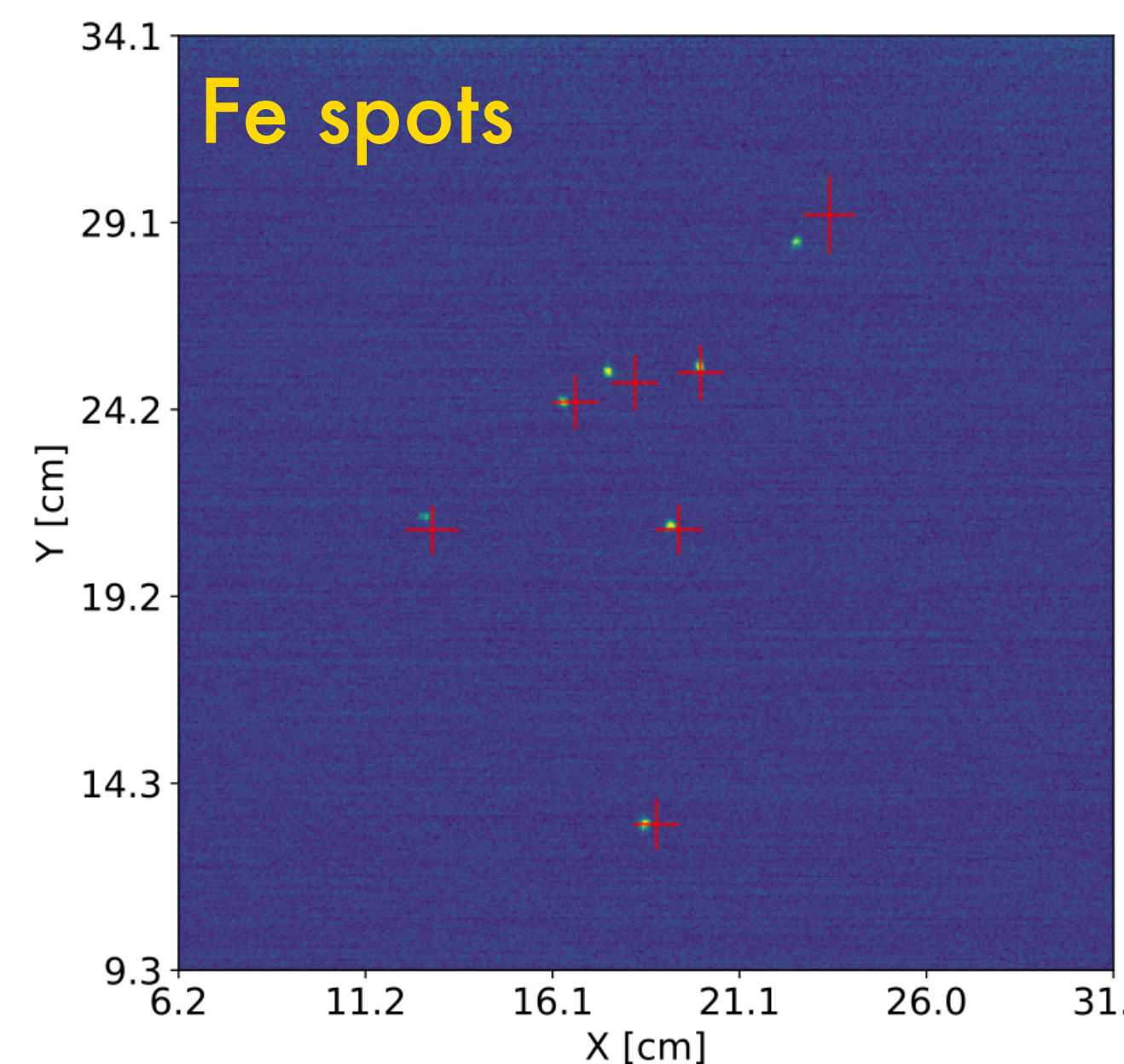
Preprint: [arXiv:2506.04973](https://arxiv.org/abs/2506.04973)

- Combined information from the 4 PMTs → **inference** on the track **position** and light **intensity**

$$p(\{x\}|\theta) = \prod_{j=1}^N \prod_{i=1}^4 \mathcal{N}(Q_{ij} | L'_{ij}(\theta))$$

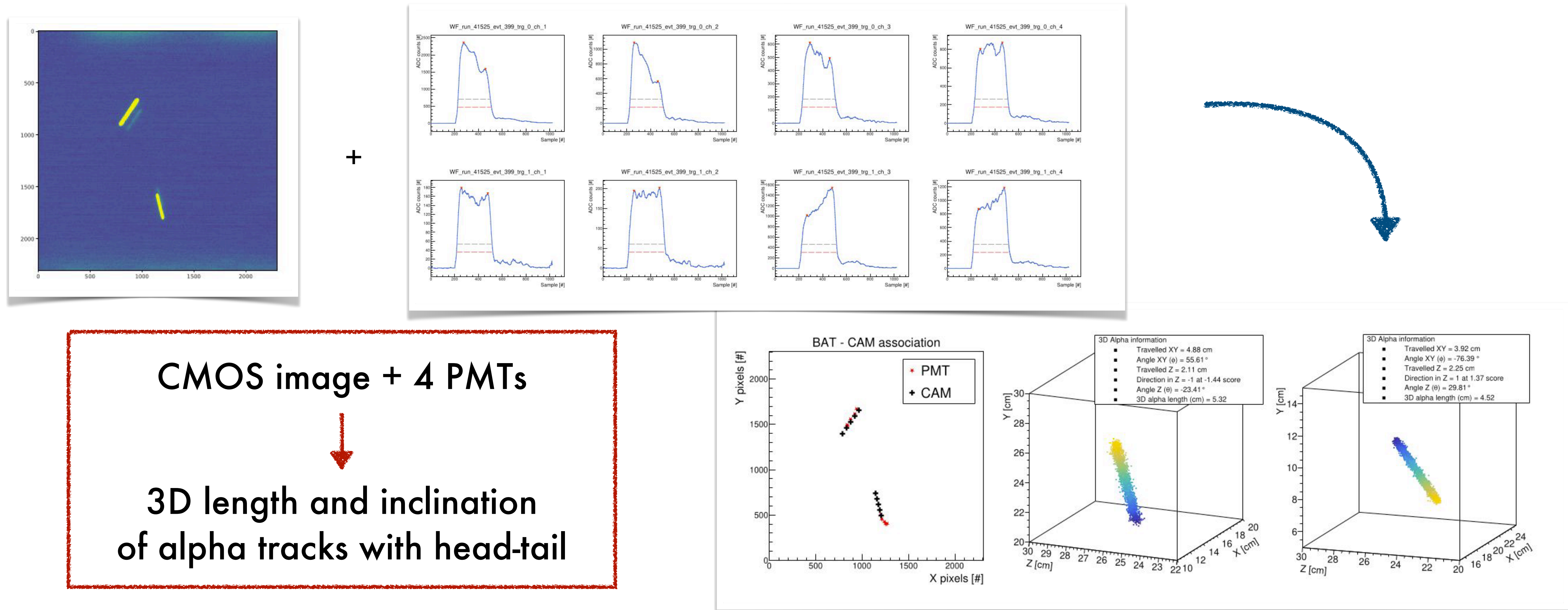
$$= \prod_{j=1}^N \prod_{i=1}^4 \frac{1}{\sqrt{2\pi}\sigma_{ij}} \exp \left[-\frac{(Q_{ij} - L'_{ij}(\theta))^2}{2\sigma_{ij}^2} \right]$$

- Matched information from camera and PMTs → **3D reconstruction of the tracks!**



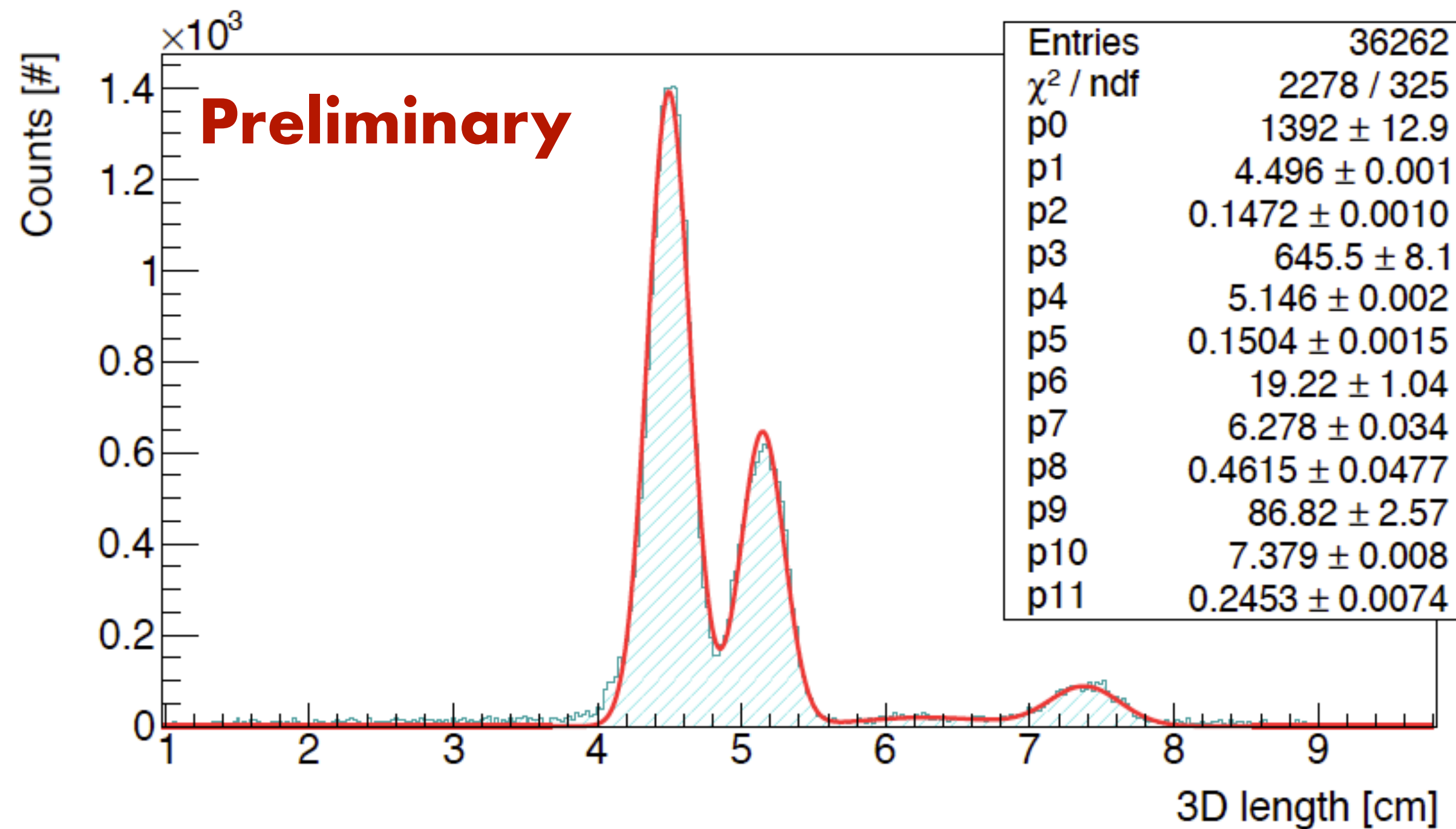
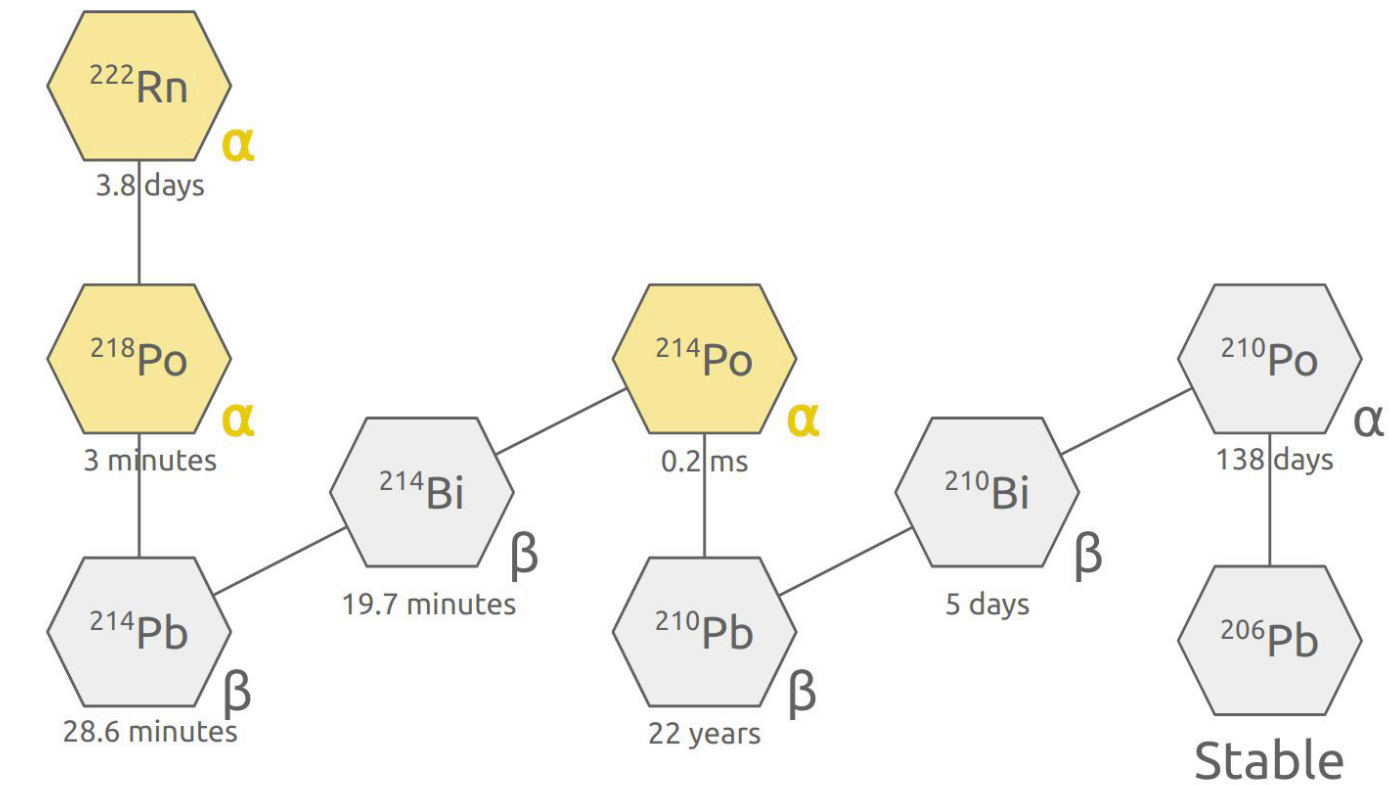
3D reconstruction of alpha tracks

- First application: the **Radon** chain → **alpha tracks**
- For alpha tracks, we are able to do **full 3D reconstruction**, combining PMT and CMOS



3D reconstruction of alpha tracks

- First application: the **Radon** chain → **alpha tracks**
- For alpha tracks, we are able to do **full 3D reconstruction**, combining PMT and CMOS
- **Energy** ↔ **3D range**

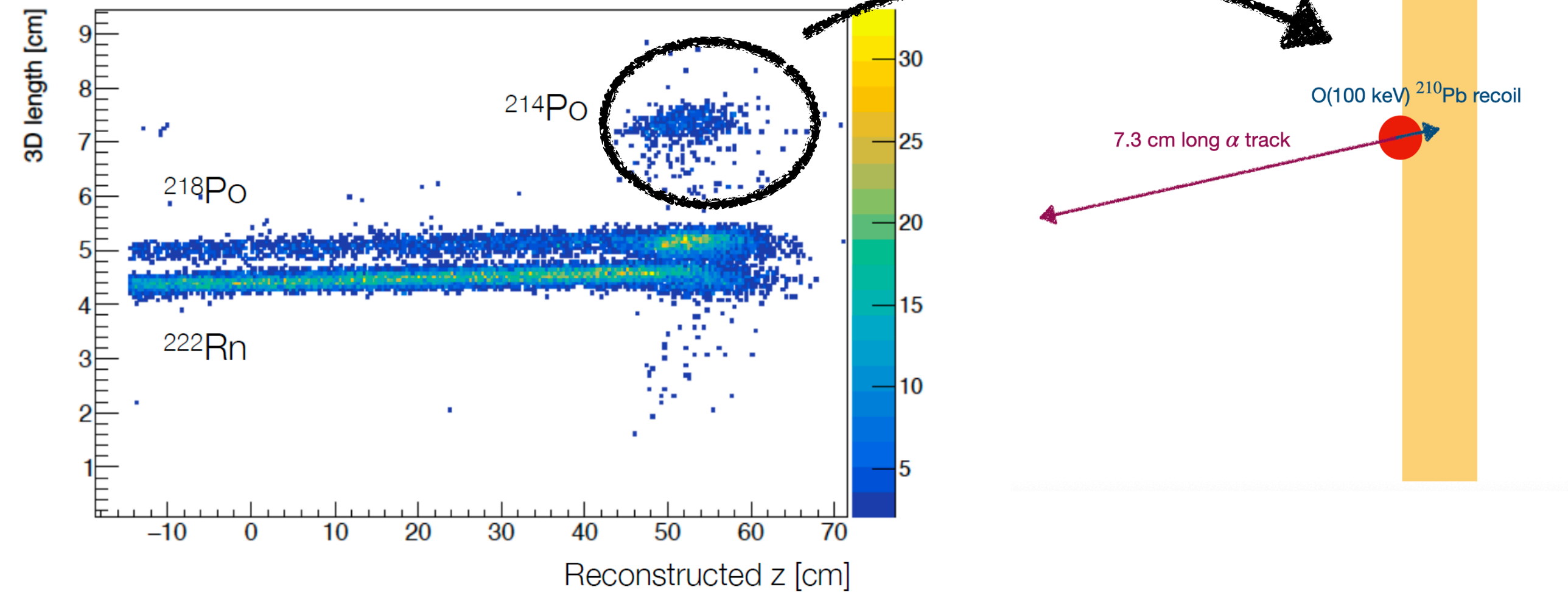
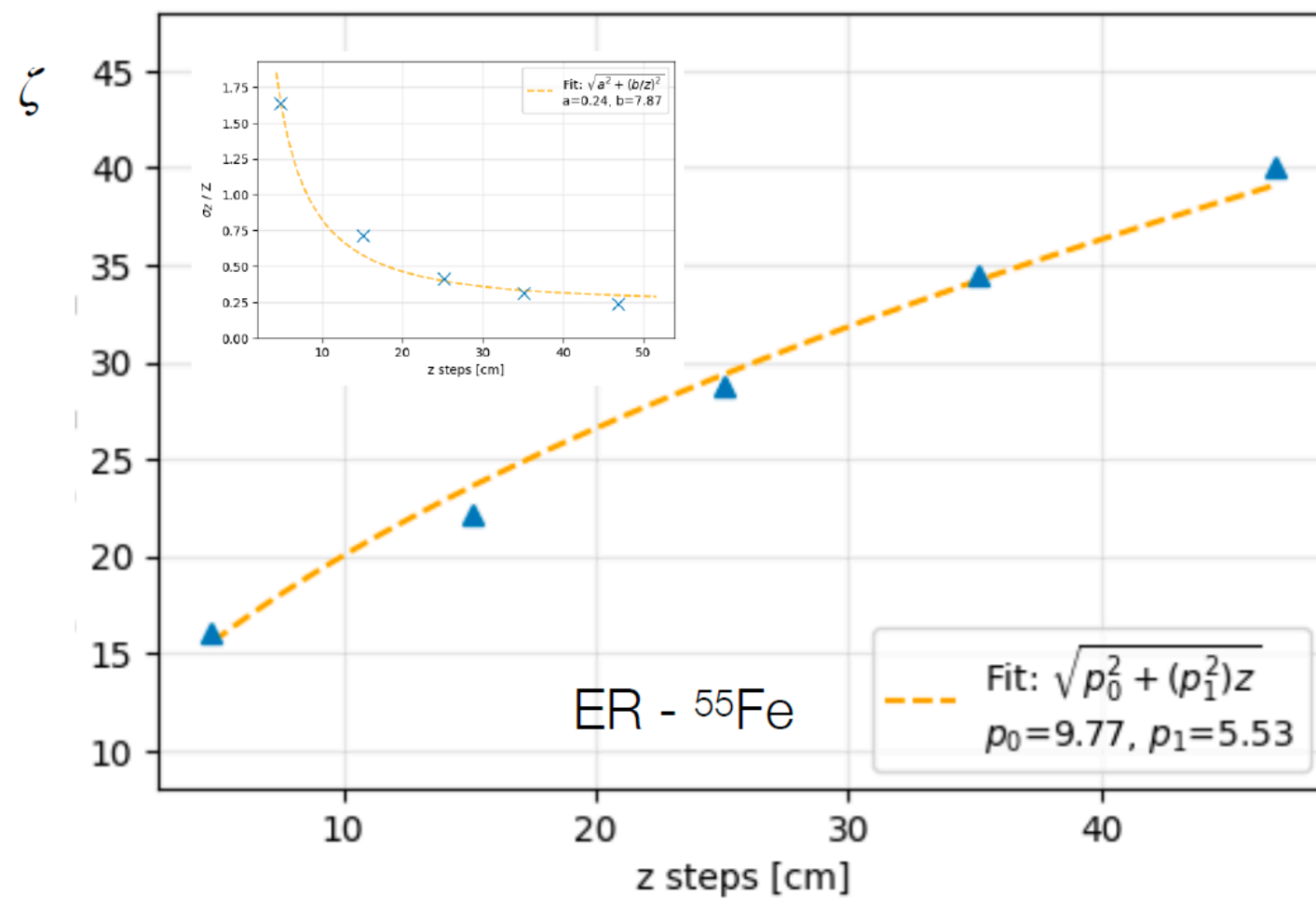


- Selecting alpha tracks at the **center of the detector**
- **Three peaks** that are consistent, within diffusion, with the 3D range in He:CF_4 at 910 mbar of:
 - ^{222}Rn (5.59 MeV)
 - ^{218}Po (6.12 MeV)
 - ^{214}Po (7.83 MeV)

z position of alpha tracks



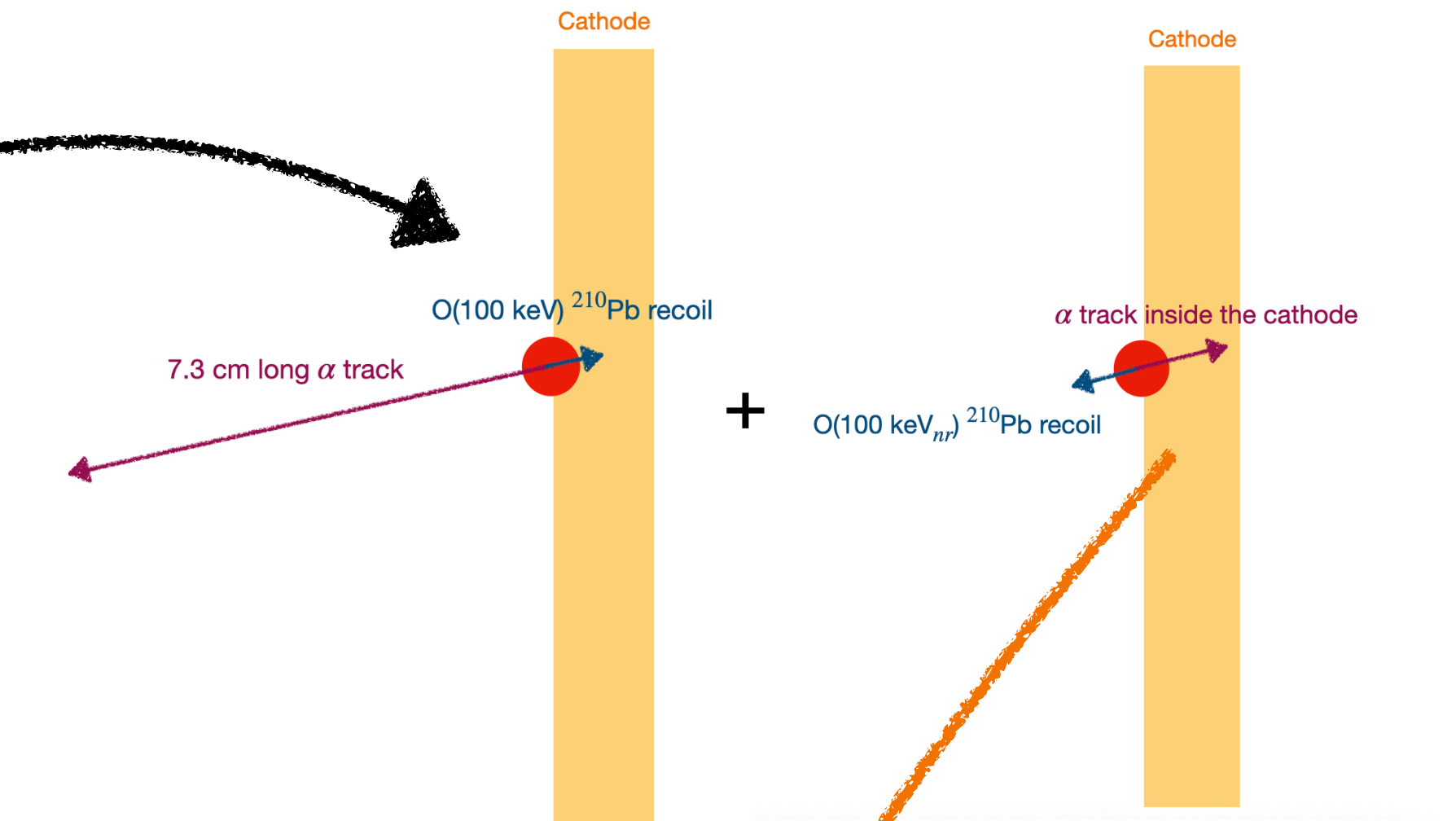
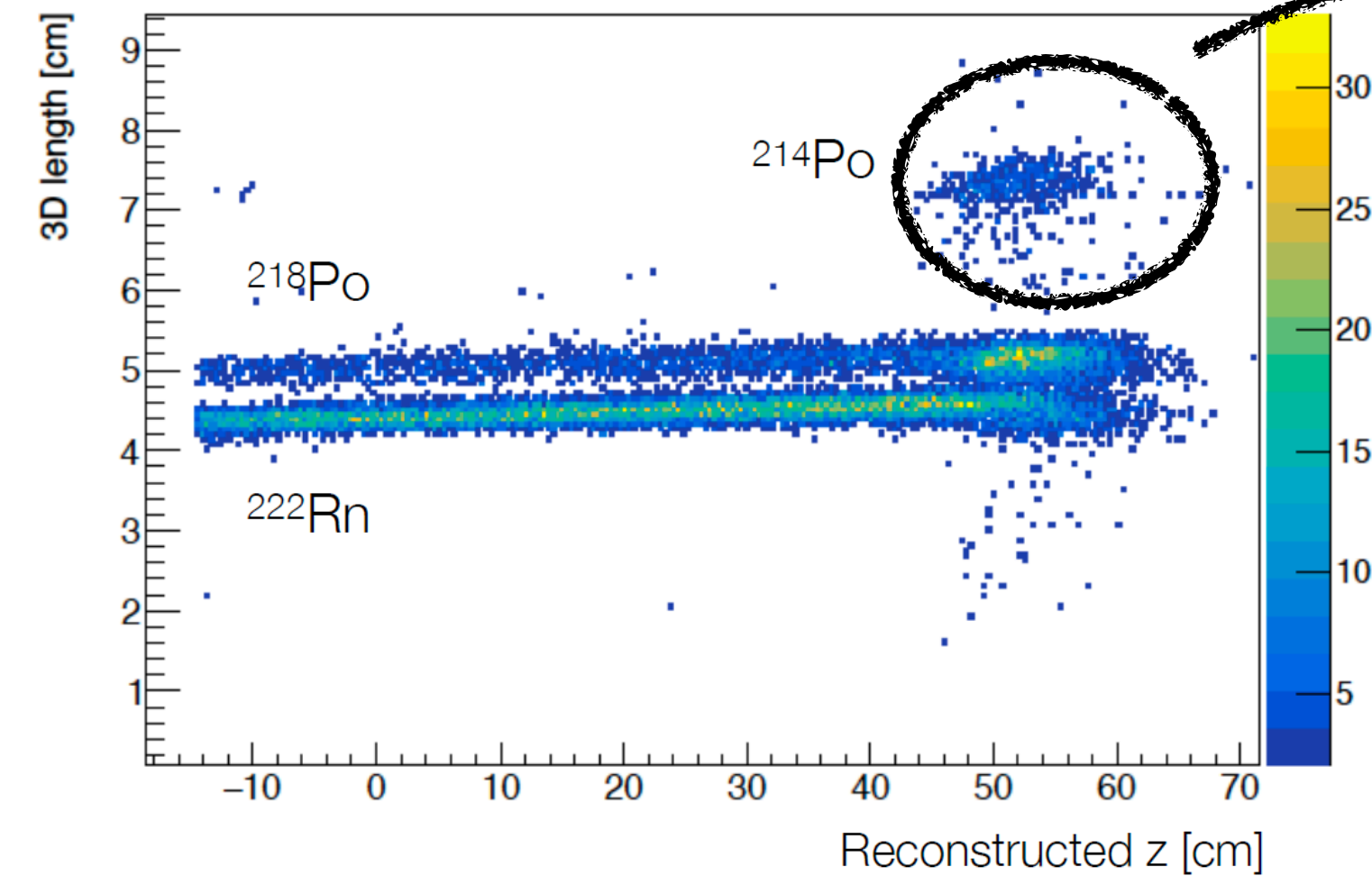
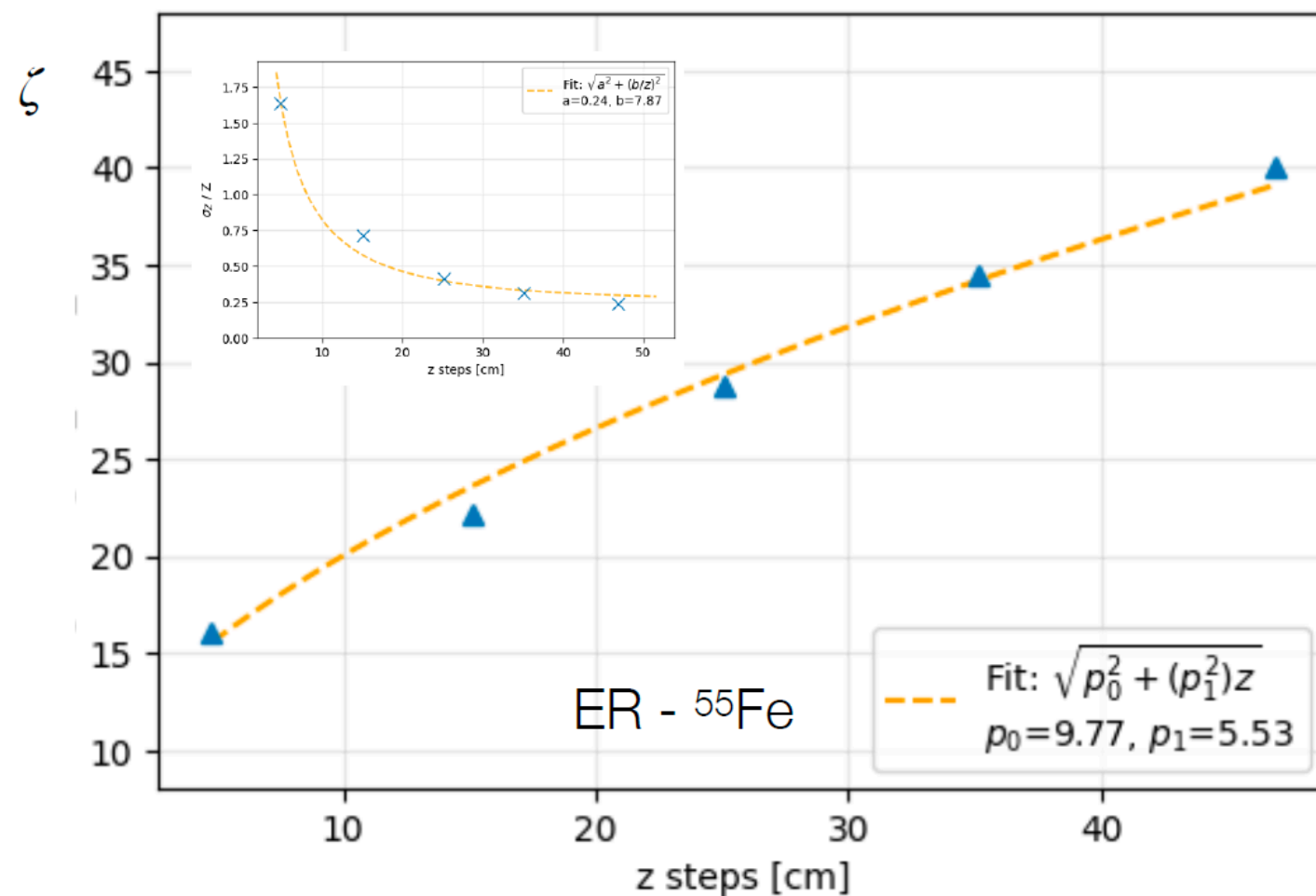
- First application: the **Radon** chain → **alpha tracks**



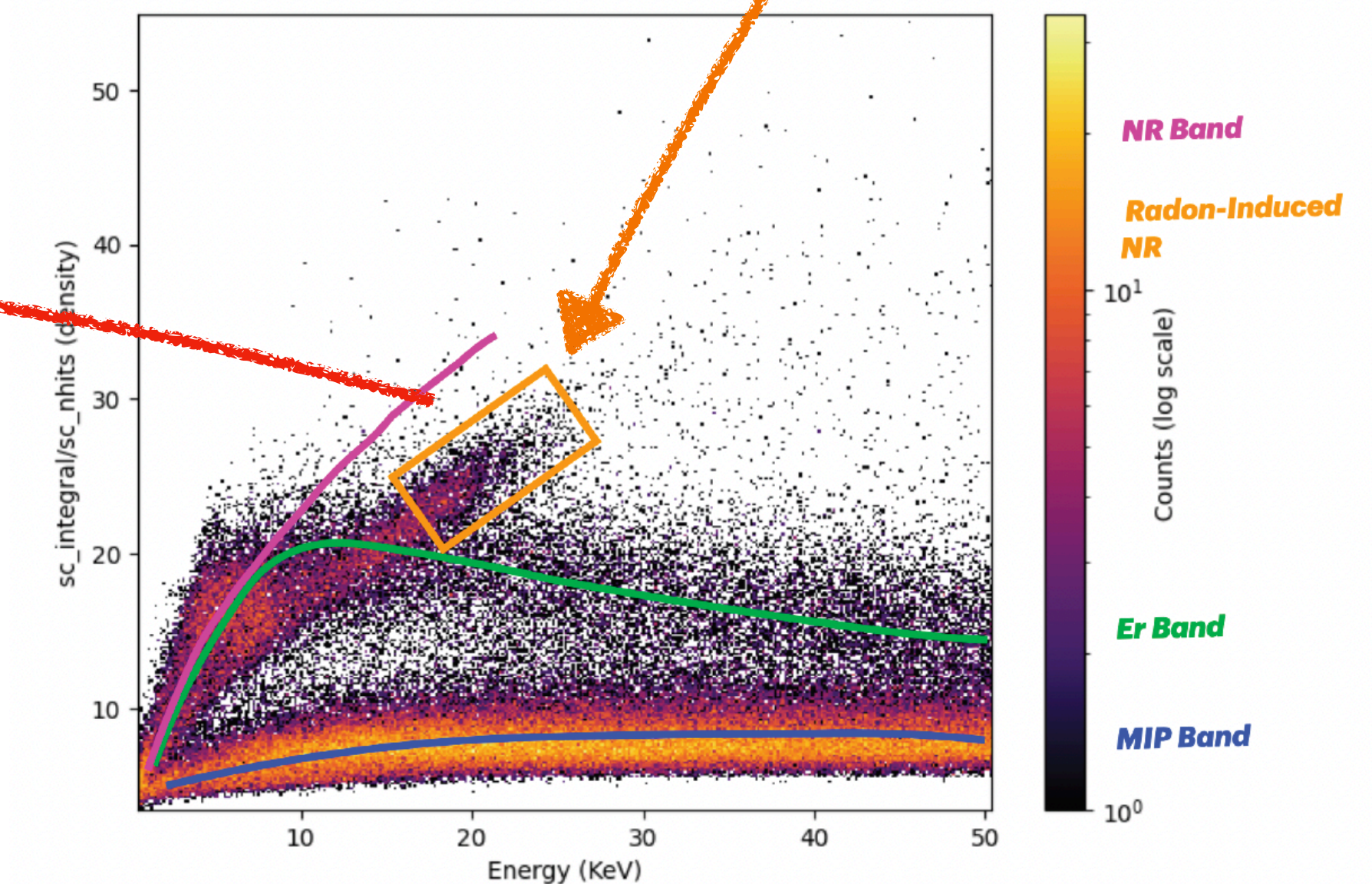
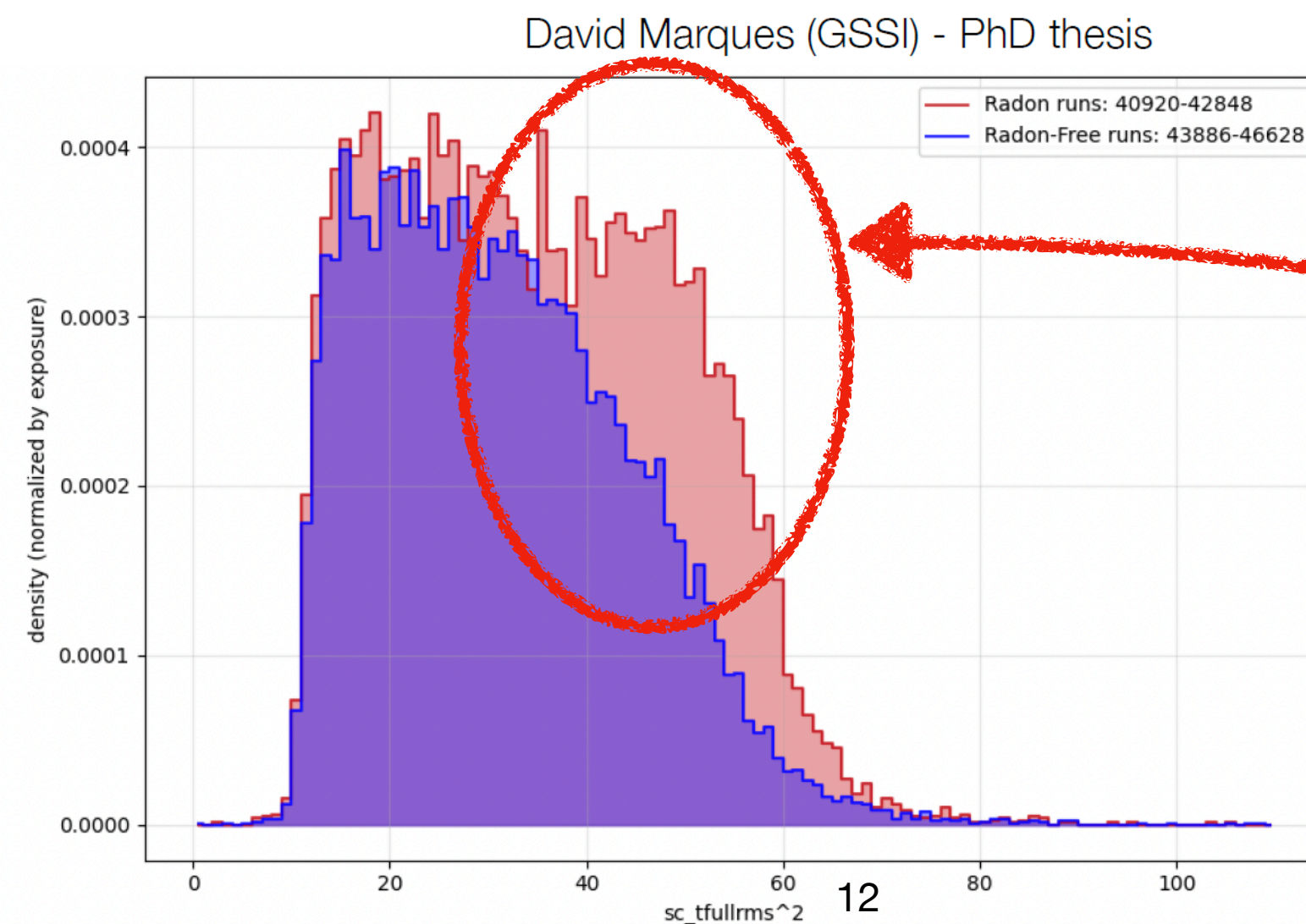
David Marques (GSSI) - PhD thesis

z position of alpha tracks

- First application: the **Radon** chain → **alpha tracks**



Evidence of an **excess of NR-like events** at the cathode correlated to the activity of Radon progeny in LIME detector



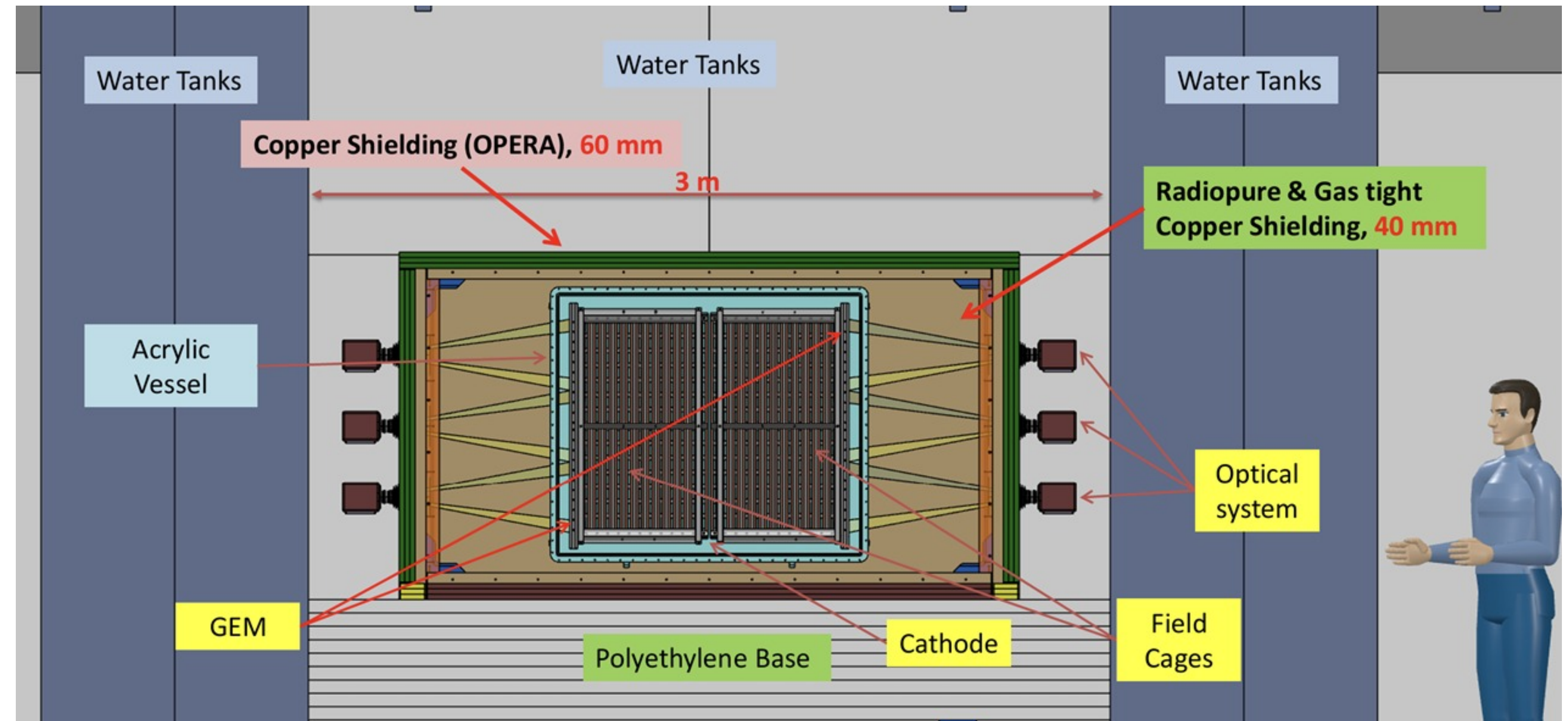
CXGNO PHASE 1: CYGNO_04



Designed at LNF and to be installed at LNGS

- **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: 3 cameras with rectangular sensors (ORCA Quest) + 8 PMTs
- ◎ **Vessel:** low radioactivity PMMA
- ◎ **Shielding:** 10 cm copper + 100 cm water with a polyethylene base



Purpose of CYGNO-04:

- Feasibility large scale detector (radiopure materials, gas purification)
- Demonstrate scalability of the technology

CXGNO PHASE 1: CYGNO_04



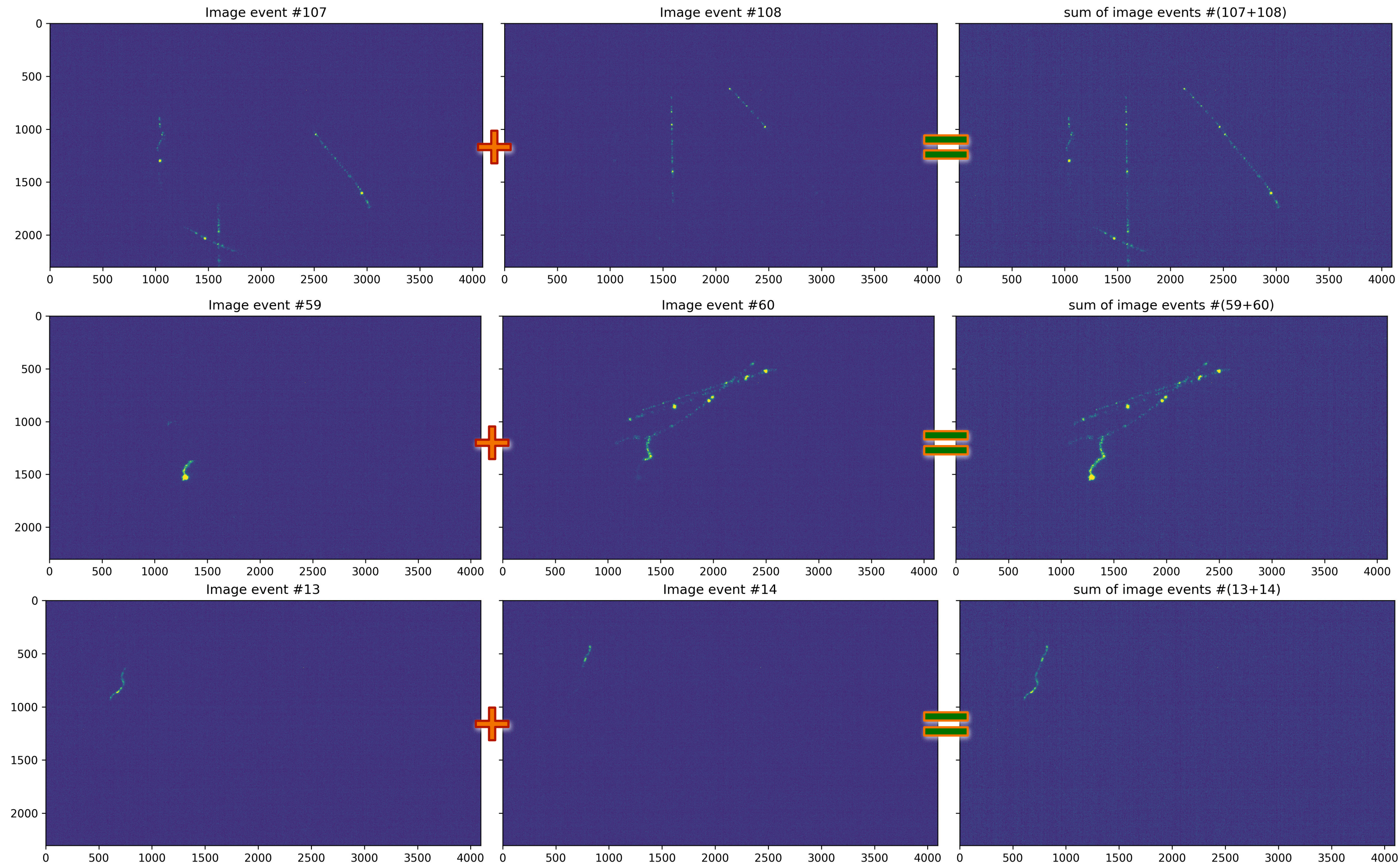
300 ms exposed images of overground radioactivity

- **New requirements for the DAQ:**

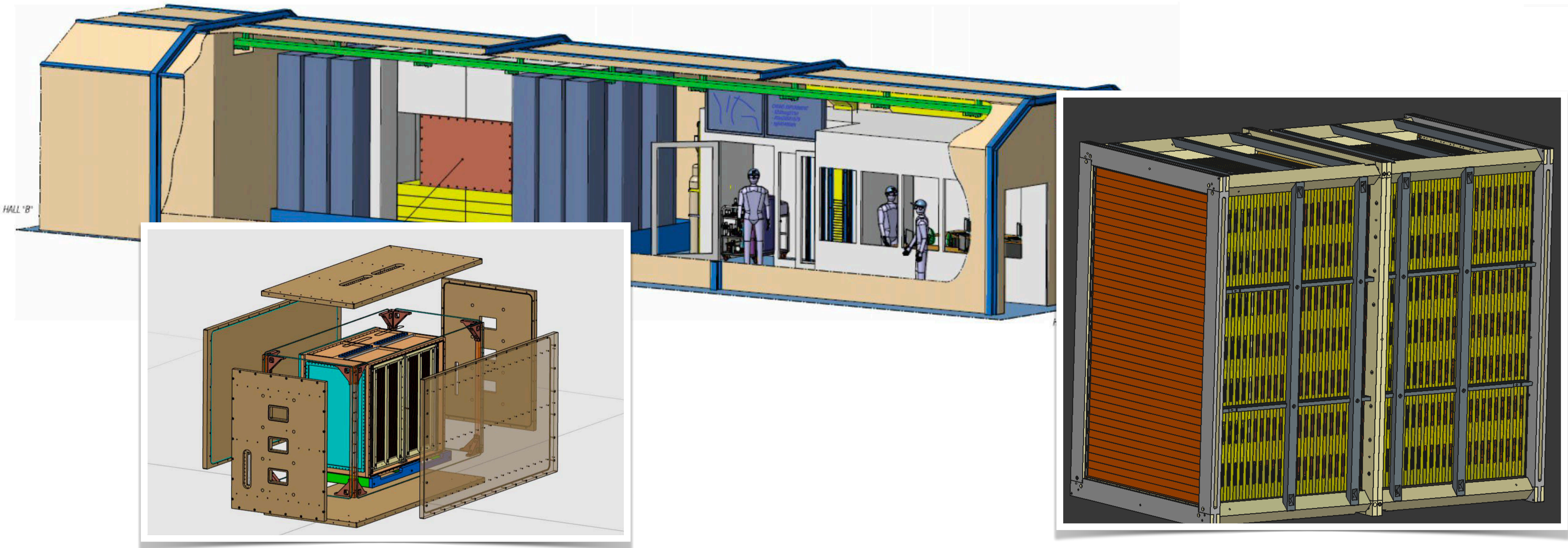
- **Reduce dead time** by operating cameras with continuous readout
→ fraction of dead time reduced from 40% to $<0.3\%$ ✓

- **Synchronization** of multiple camera setup ✓

- Not sustainable **data throughput** of ~ 330 MB /s by simply rescaling LIME DAQ scheme →
new ML algorithms for online data reduction (work in progress 🙅)



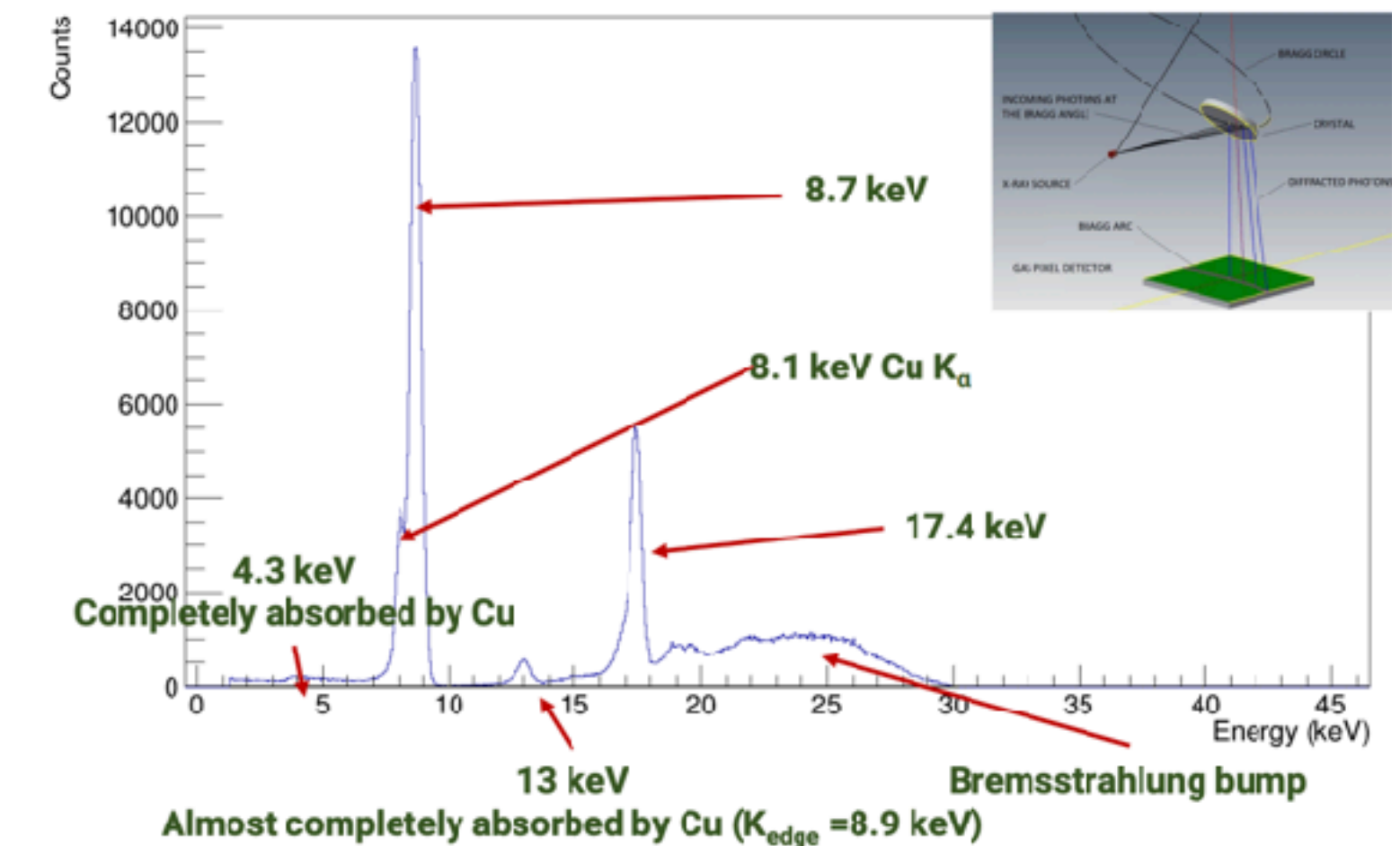
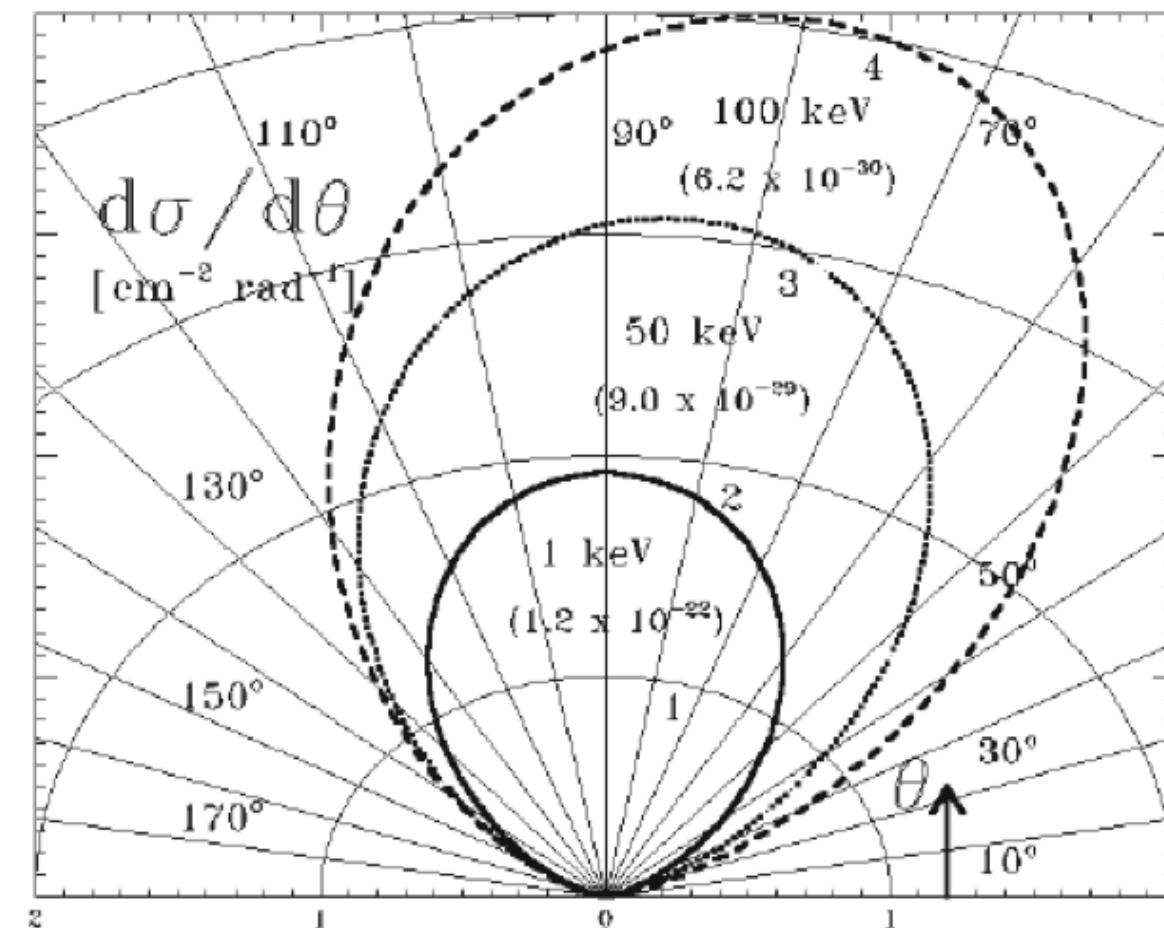
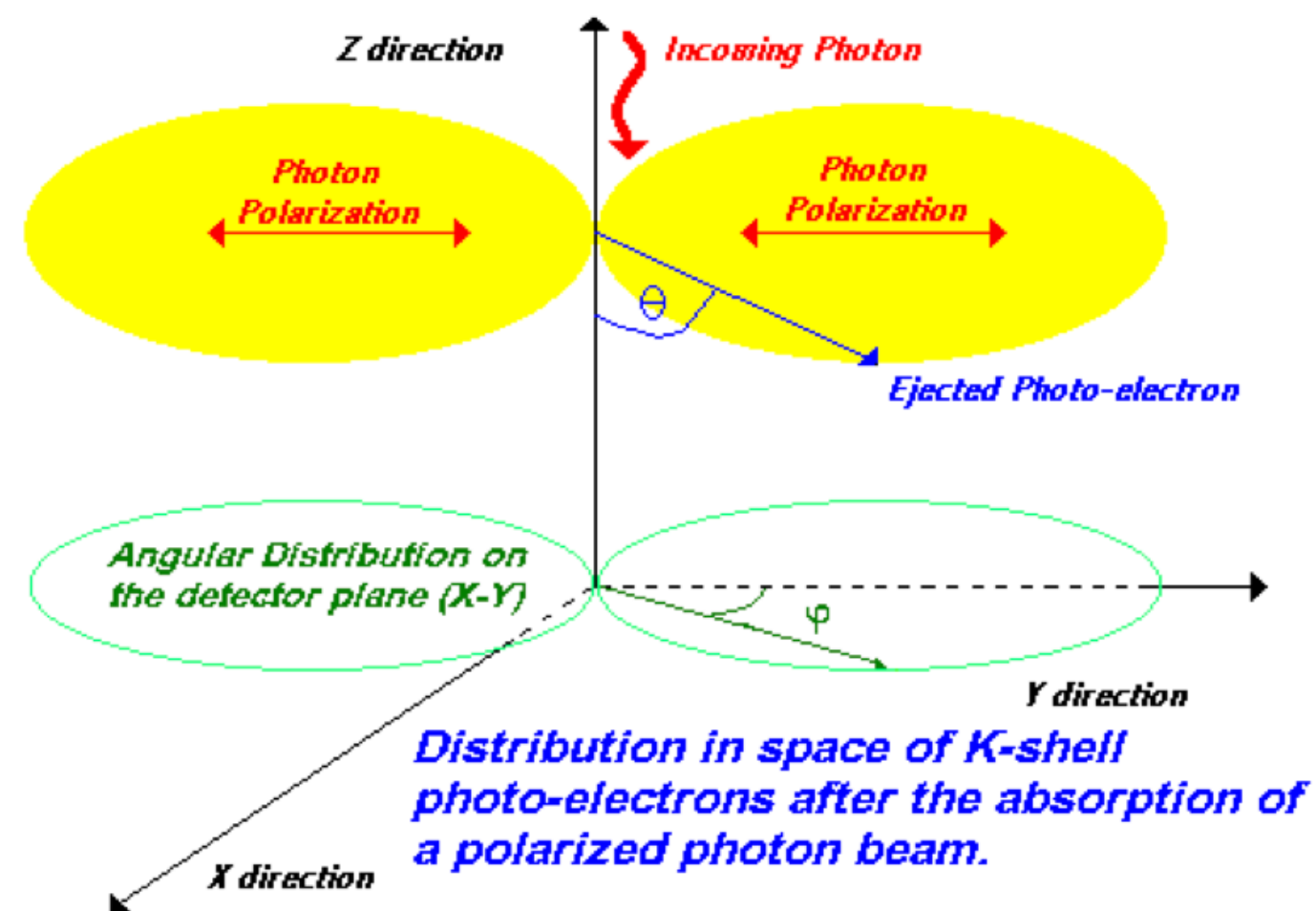
Status of the commissioning



- Civil works in **Hall F** at LNGS finalized to **build the structure** hosting the detector and the control room
- **Executive design** of the inner detector ready for first pre-commissioning at LNF before the end of 2025
- We plan to be able to **assemble the detector** in place by the beginning of 2026

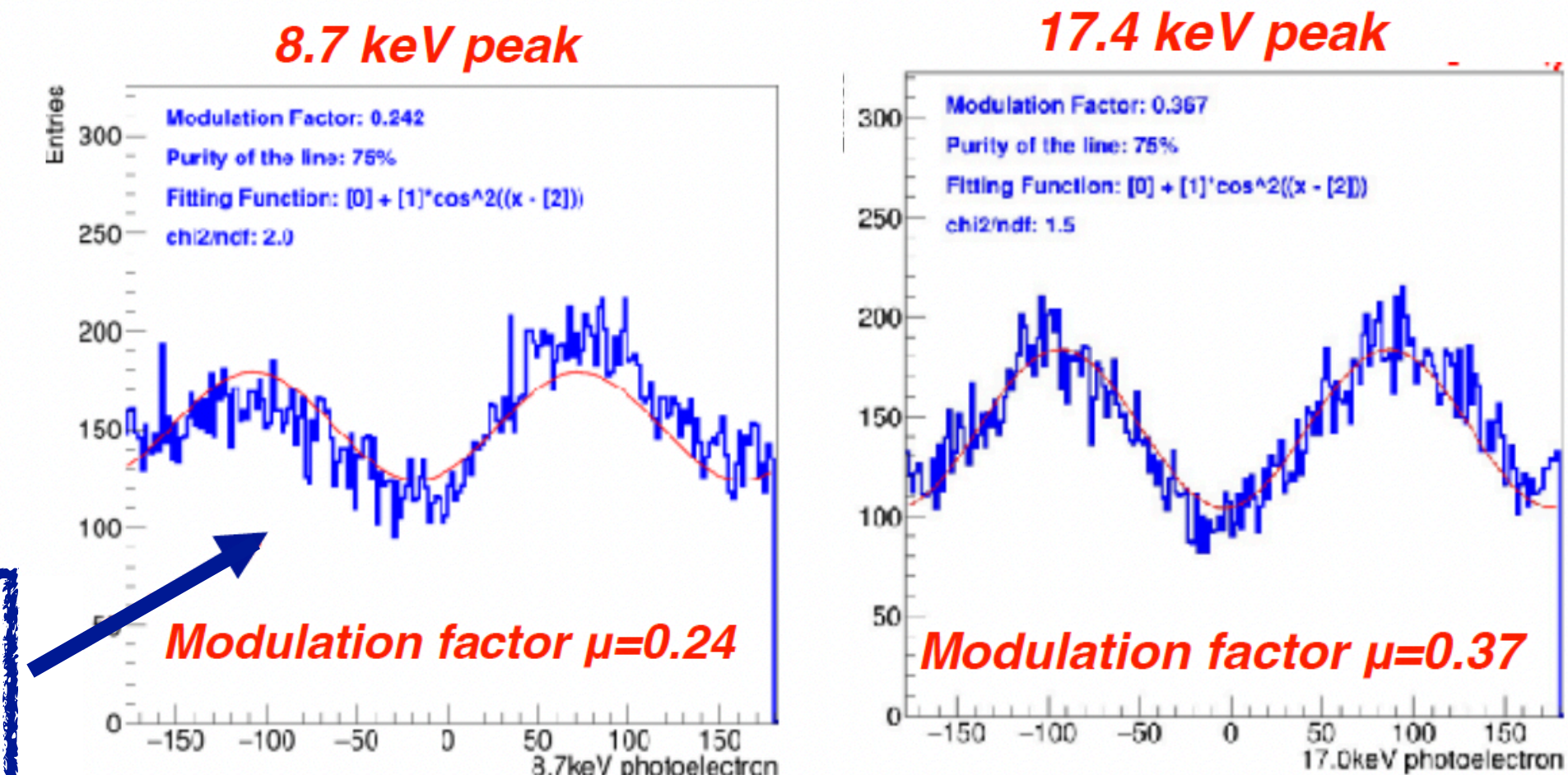
Other applications: X-ray polarimeter

First calibration with polarized source at INAF/IAPS facility



- Direction of low energy photo-electrons → **X-ray polarization**, but very high position resolution is needed
- **Idea**: measure the polarization of X-rays in the range of **10-50 keV** with the **CYGNO** experimental **approach**

First indications of sensitivity to modulation **down to 8.7 keV!**



Conclusions



- The **CYGNO** collaboration is developing a **gaseous TPC with optical readout**
- **LIME**, a 50 L prototype, has been taking data underground @ LNGS from 2022 until December 2024
- **Analysis** collected in the 2-years-long data taking in process. Detector showed **15% energy resolution** at the keV_{ee} energy scale, a satisfactory **stability** on the long run, and the ability to separate ER / NR just with simple cuts above $\sim 20\text{-}25 \text{ keV}_{ee}$.
 - Evidence of **saturation** of the GEM gain $\rightarrow$ characterization of such an effect and determination of the best working point for future data taking campaigns
 - Several steps towards full **3D reconstruction**:
 - Validated camera-to-PMT track association $\rightarrow$ **full 3D head-tail reconstruction** of tracks induced by alpha particles emitted by Radon daughters
- A bigger demonstrator, **CYGNO-04**, is currently being commissioned at LNGS, and will be hosted in Hall F at LNGS
 - Feasibility large scale detector
 - Demonstration of scalability of the technology
- A new application for our technology: **X-ray polarimeter** for X-ray astronomy. Promising results from first measurements in the 10-50 keV range.

Acknowledgements

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CYGNO Project is funded by INFN.



Thanks for the attention!

The **CXGNO** collaboration:

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Istituto Nazionale di Fisica Nucleare

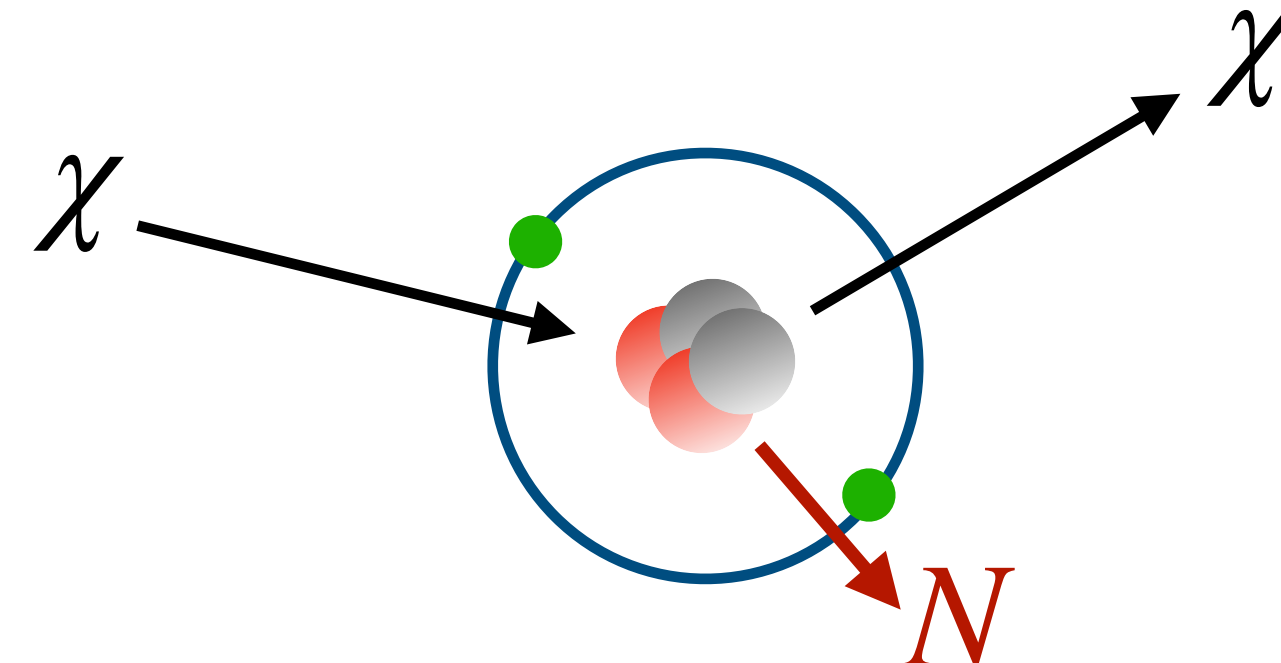
Backup

Background to direct detection

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

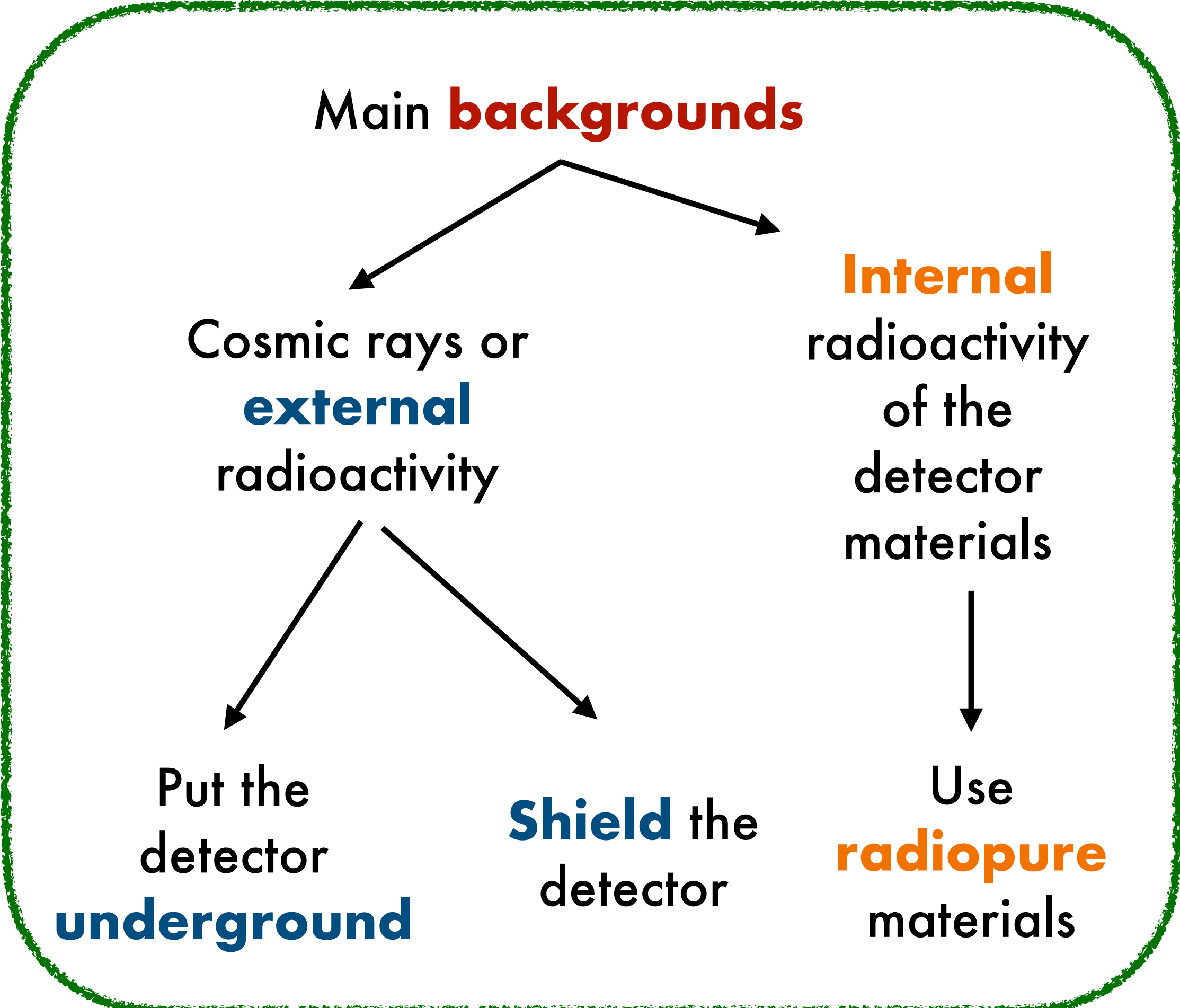
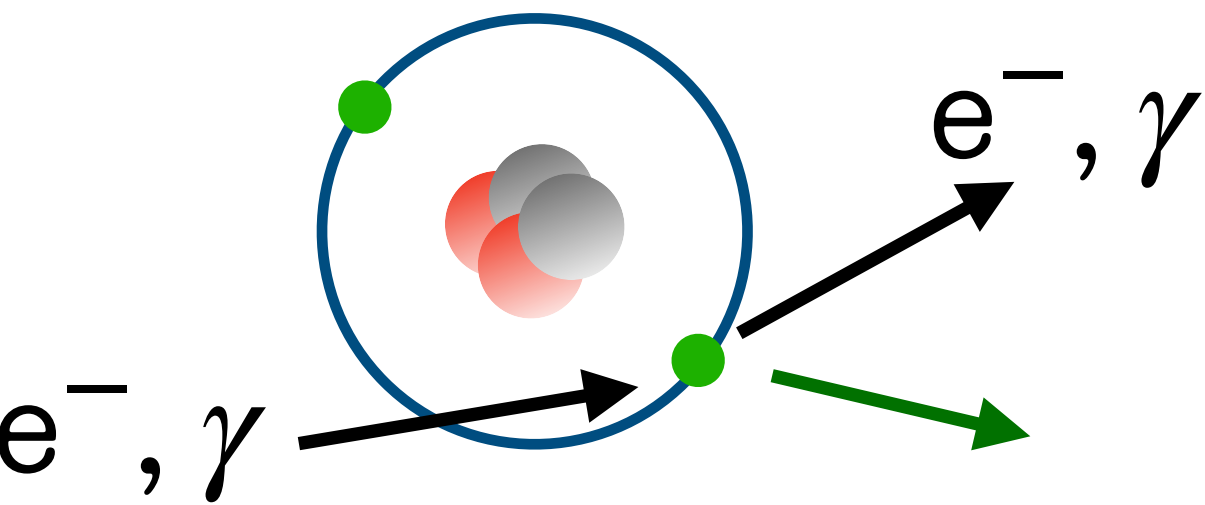
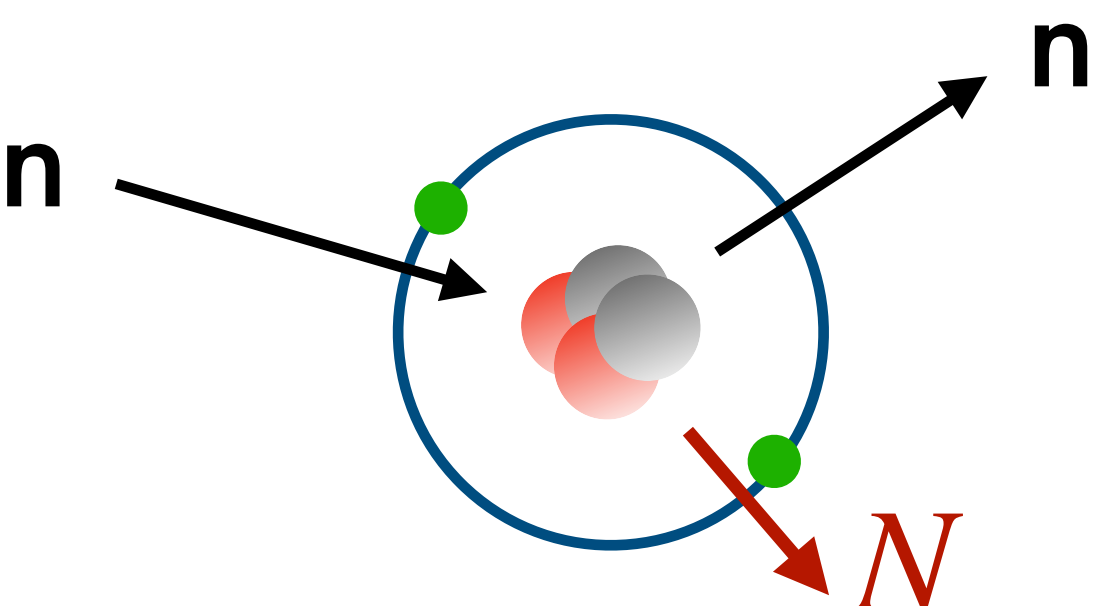
Signal:

NR



Background:

NR and ER



The CYGNO optical readout

- **CMOS** sensor noise:
 - ➔ Readout noise of $0.7 \text{ e}^-/\text{px} \sim 0.9 \gamma/\text{px}$
 - ➔ Dark current of $0.2 \text{ e}^-/\text{px}/\text{s} \sim 0.25 \gamma/\text{px}/\text{s}$
 - ➔ 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: $\delta = \frac{f}{d-f}$
 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

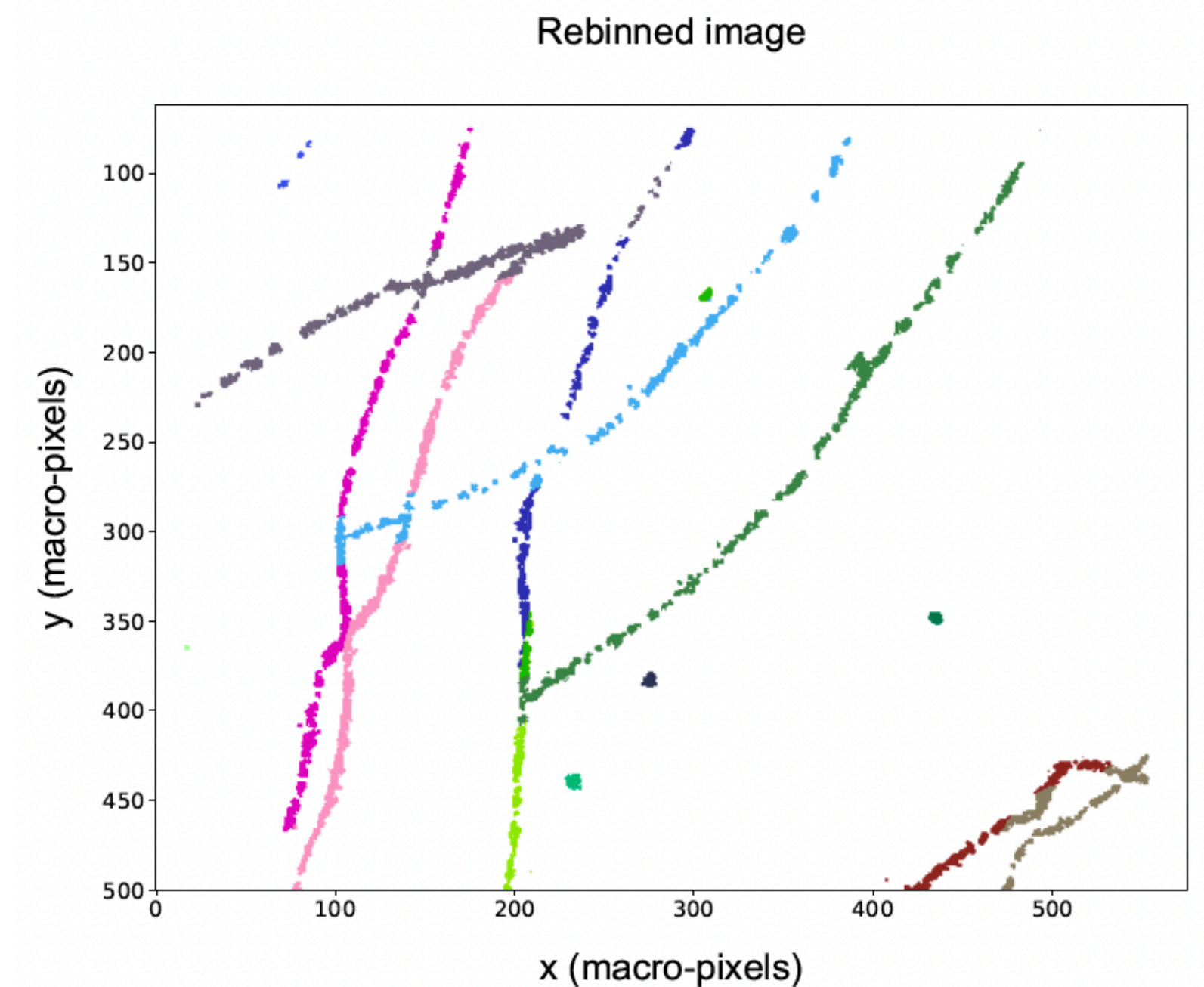
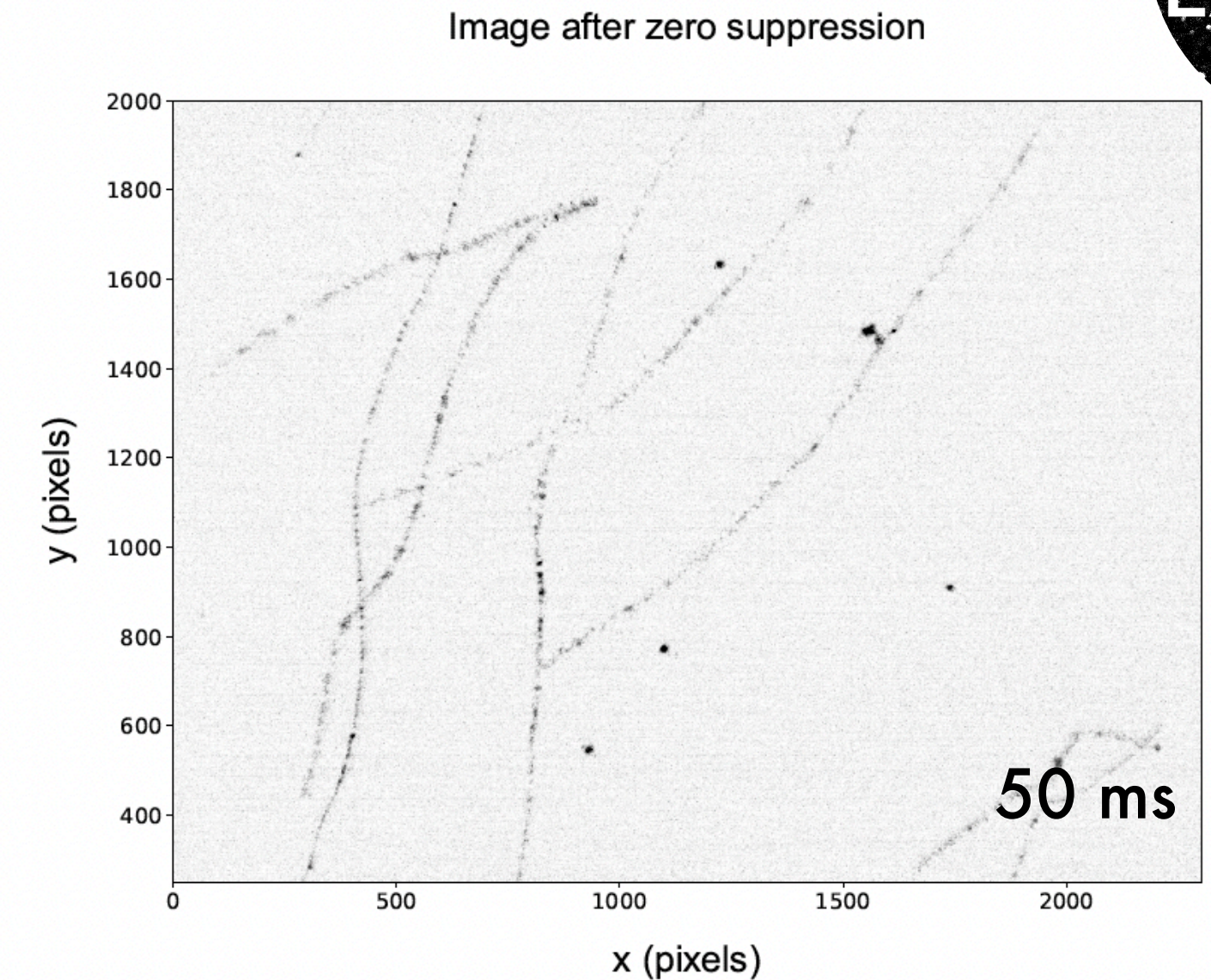
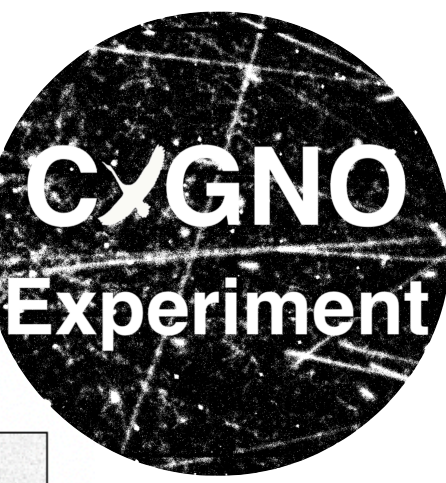
- **PMTs geometrical acceptance**:
 - ➔ critically **depends** on the **position** of the emission on the GEM plane w.r.t. the PMT position
 - ➔ Empirical measured scaling:

Light collected by the PMT #i $L_i = \frac{L}{R_i^\alpha}$ Total light emitted

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

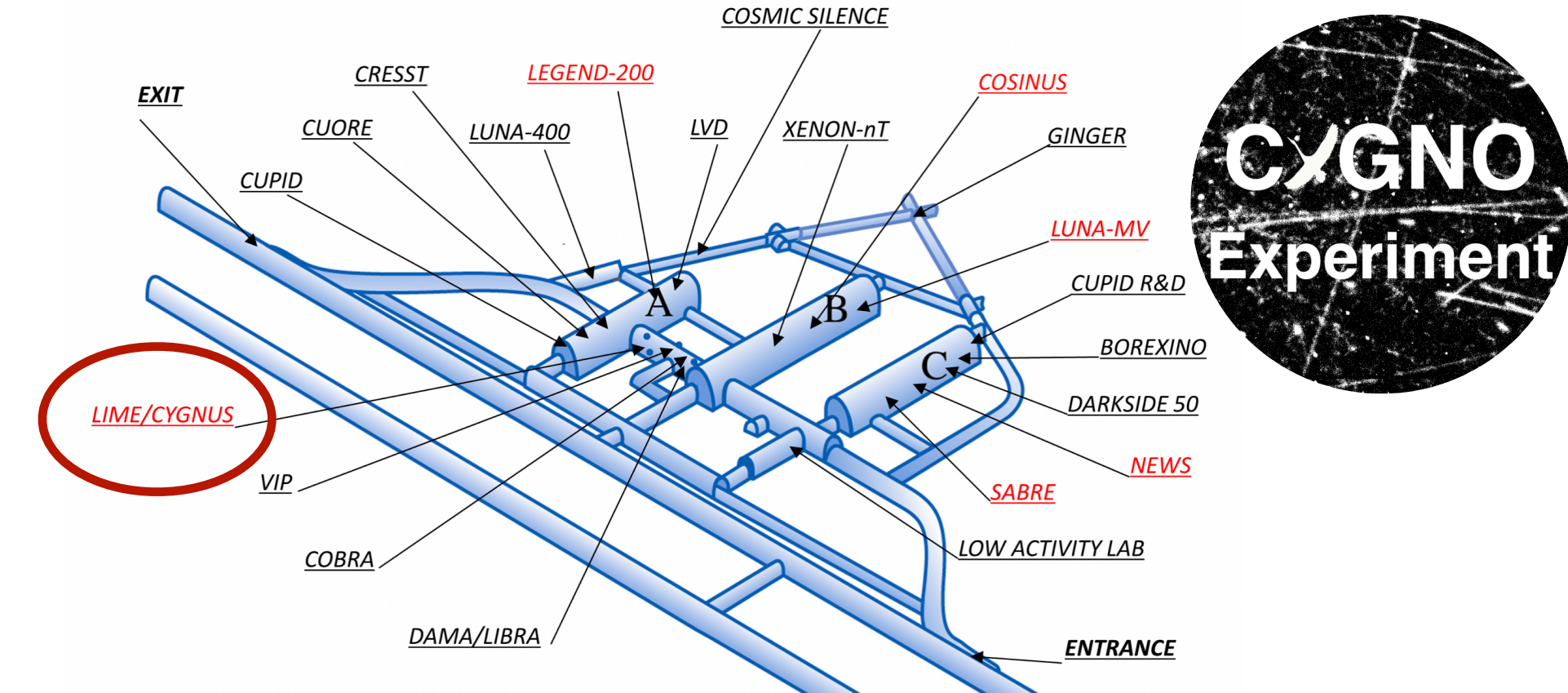
Image reconstruction

- **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 DBSCAN algorithm



Underground installation

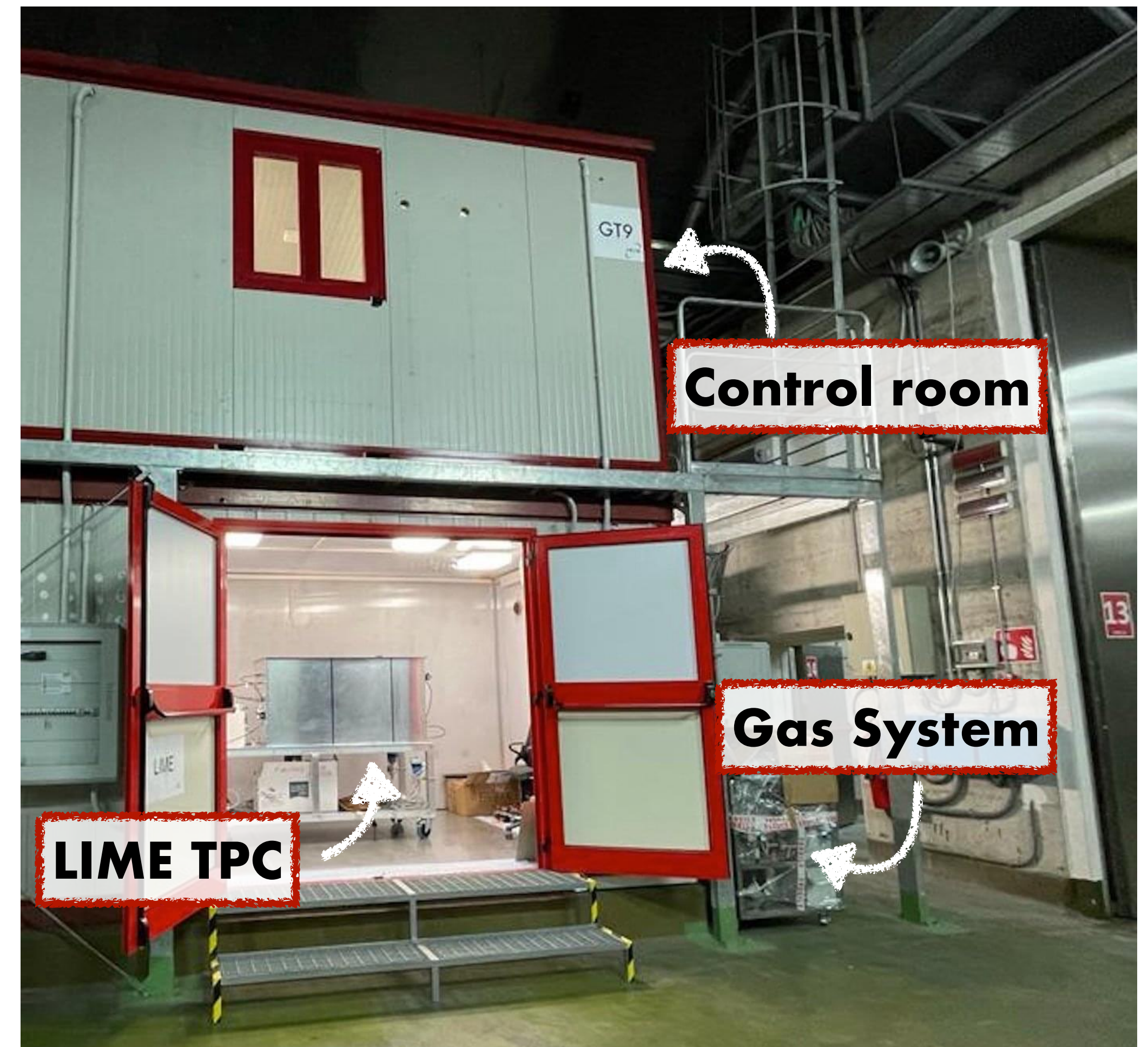
- The **LIME** prototype has been preliminarily **tested overground** at Laboratori Nazionali di Frascati (**LNF**)
- **Moved underground** at Laboratori Nazionali del Gran Sasso (**LNGS**) the beginning of 2022



The TPC inside the Faraday cage



HV and DAQ crate



ER energy response



- First characterization **overground at LNF**

- ⁵⁵Fe source**

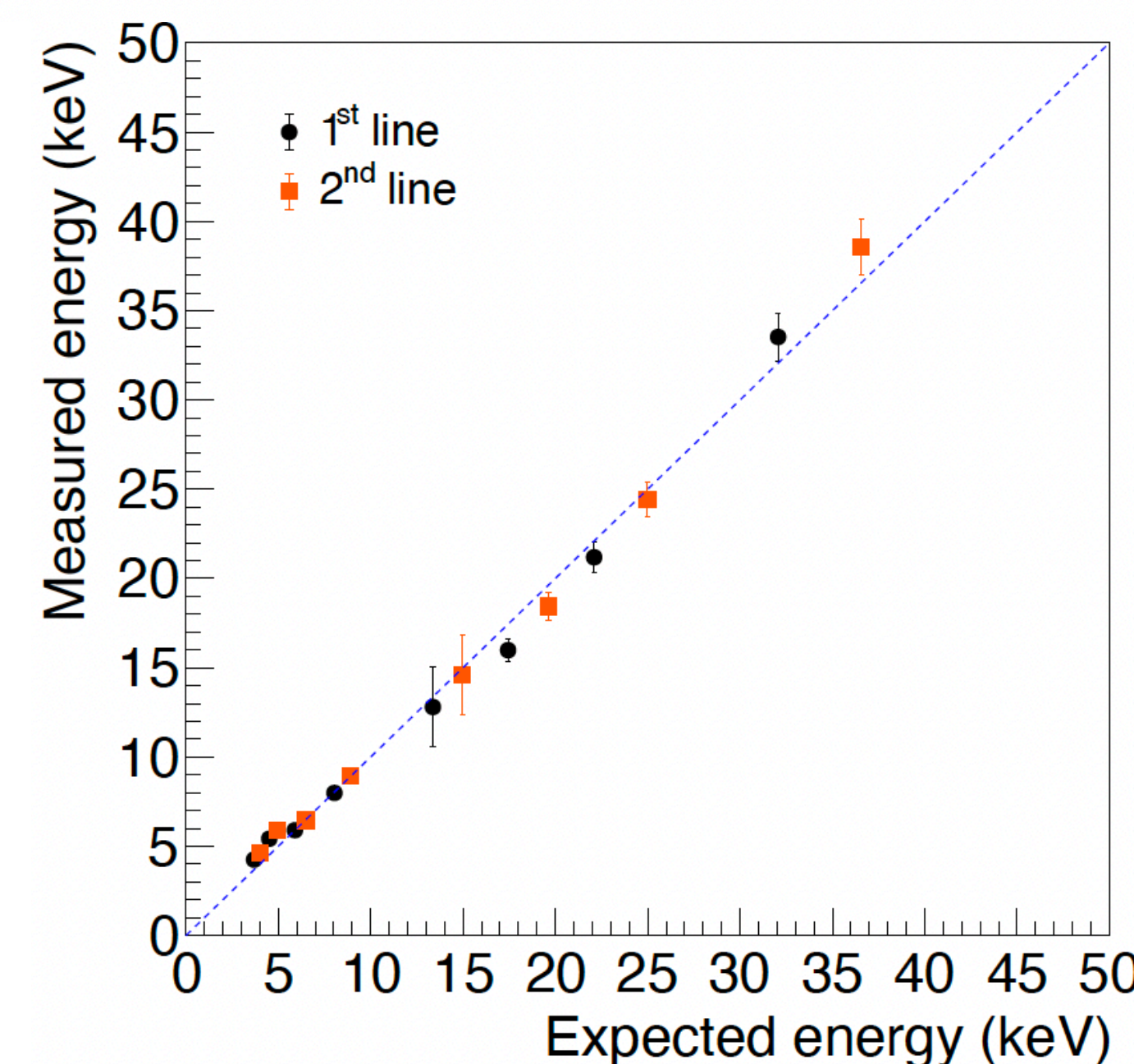
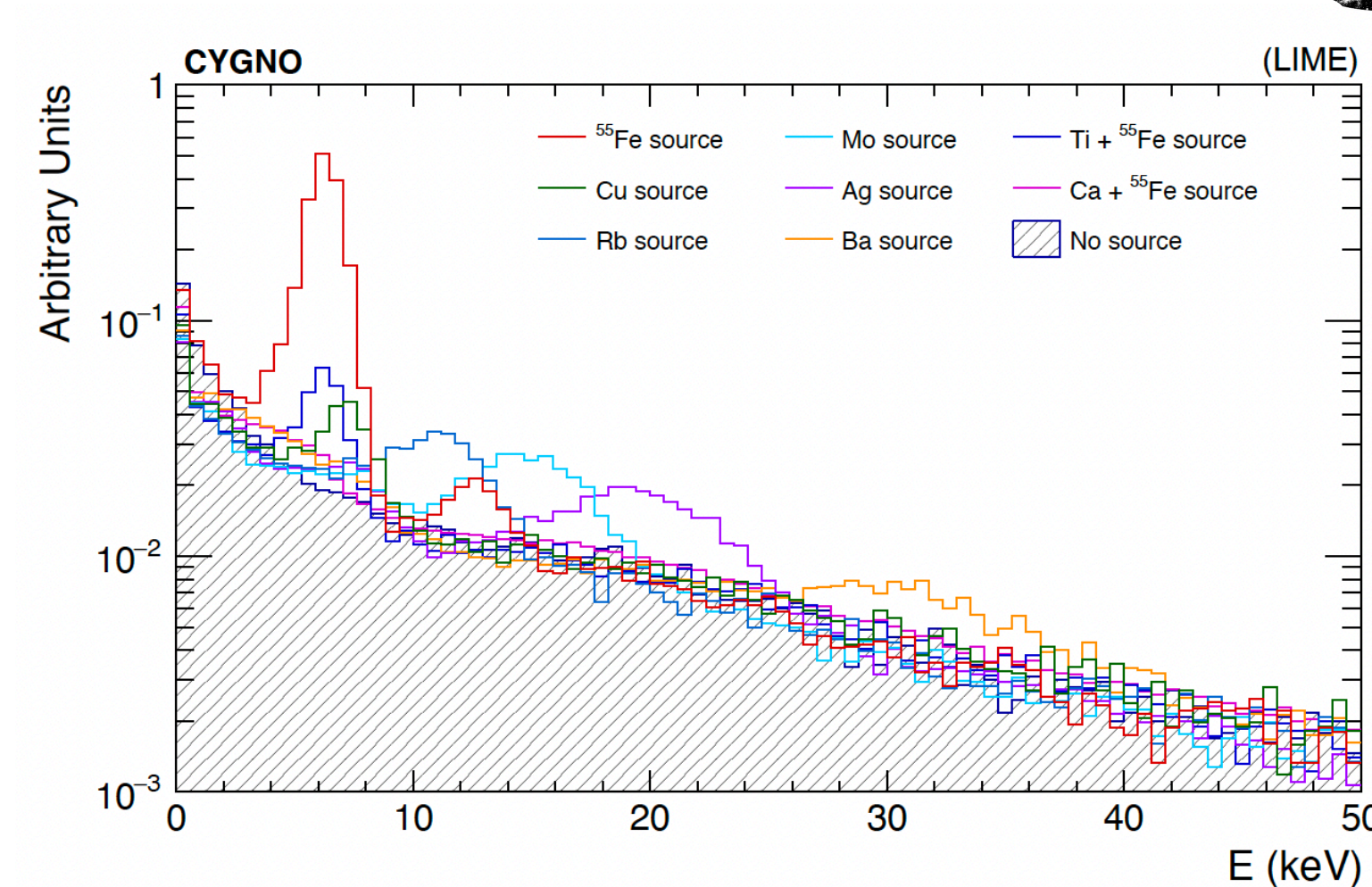
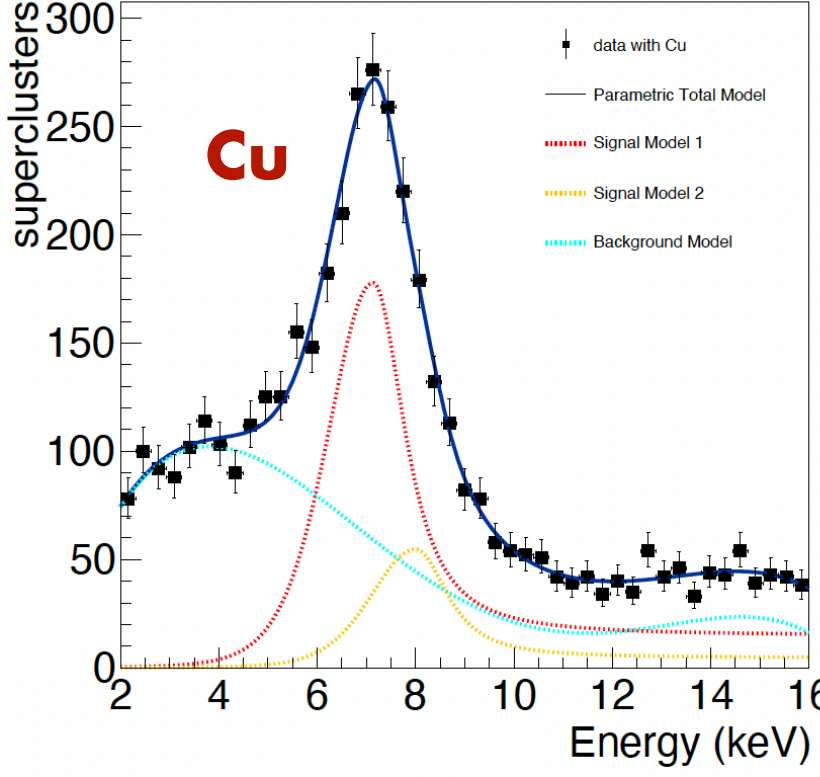
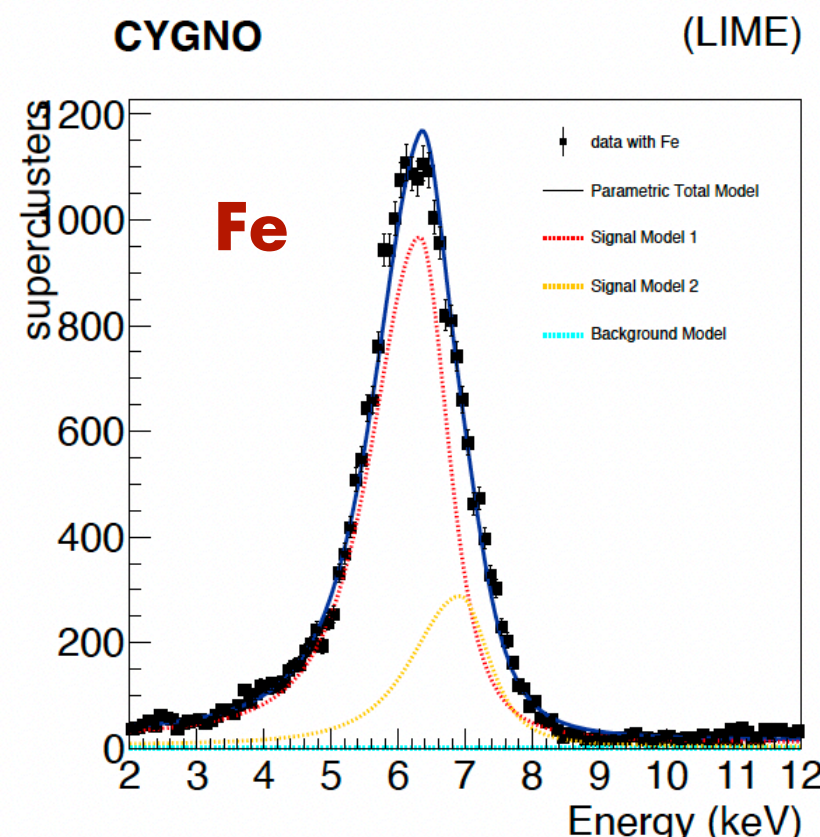
$[K_{\alpha} \sim 5.9 \text{ keV}, K_{\alpha} \sim 6.4 \text{ keV}]$

- 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**

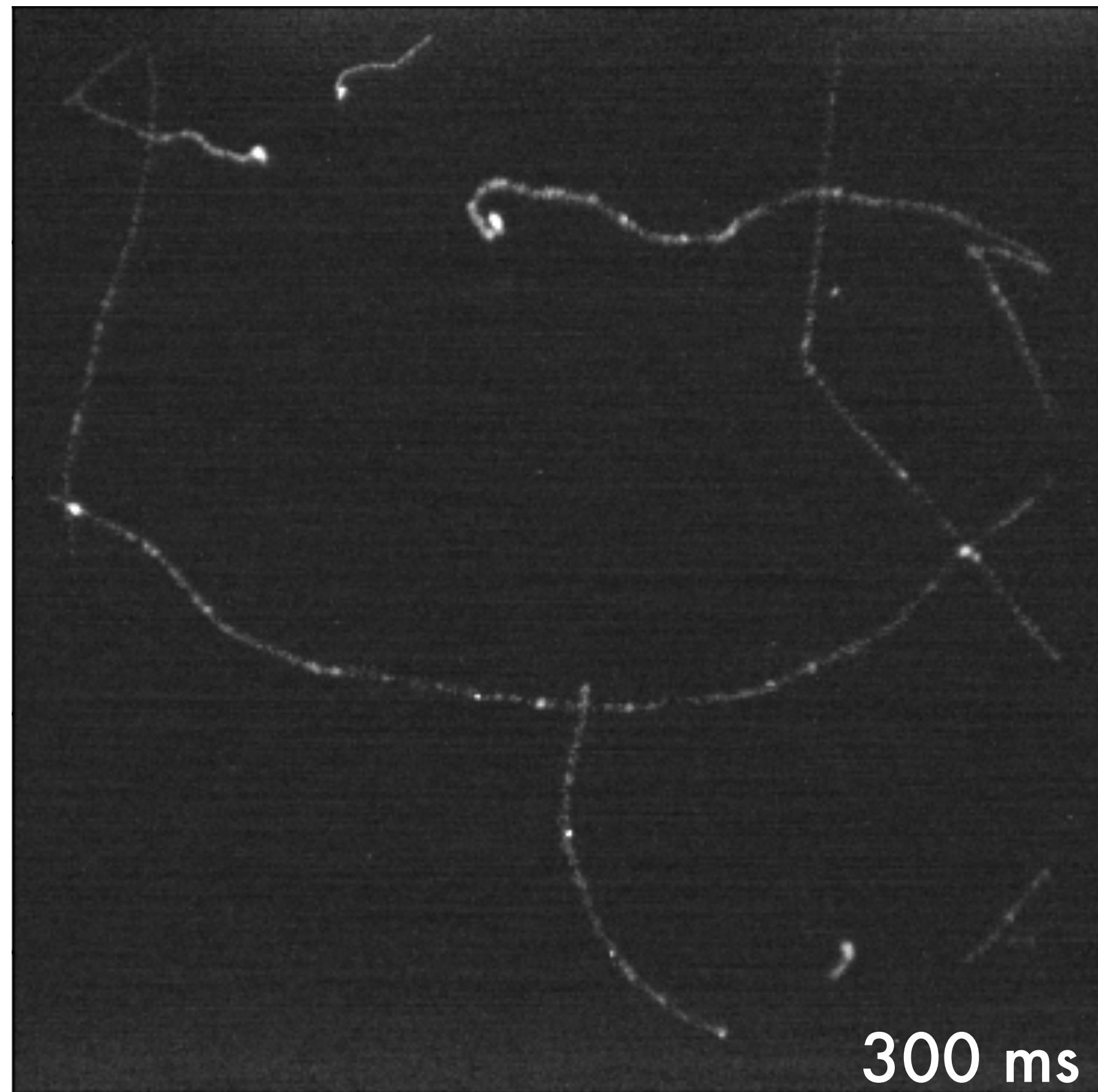
Material	Energy K_{α} [keV]	Energy K_{β} [keV]
Ti	4.51	4.93
Ca	3.69	4.01



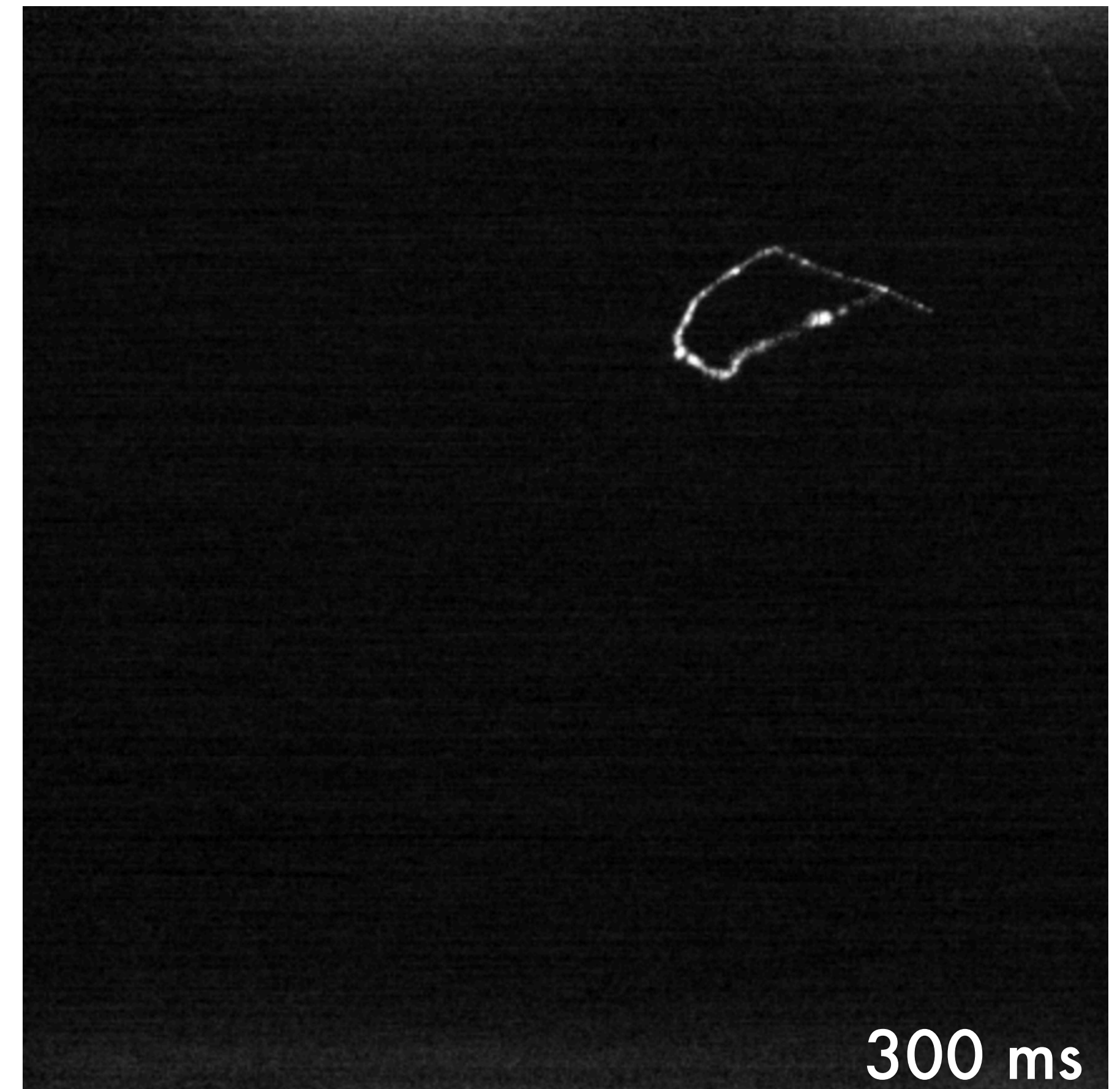
Underground data with different shielding layers



RUN 1: No-shielding



RUN 2: 4 cm Cu shielding



Underground data taking plan



Spring and Summer 2022

Autumn 2022

Winter 2023

Spring to Autumn 2023

Winter 2023 to Spring 2024

Spring 2024 to Winter 2024

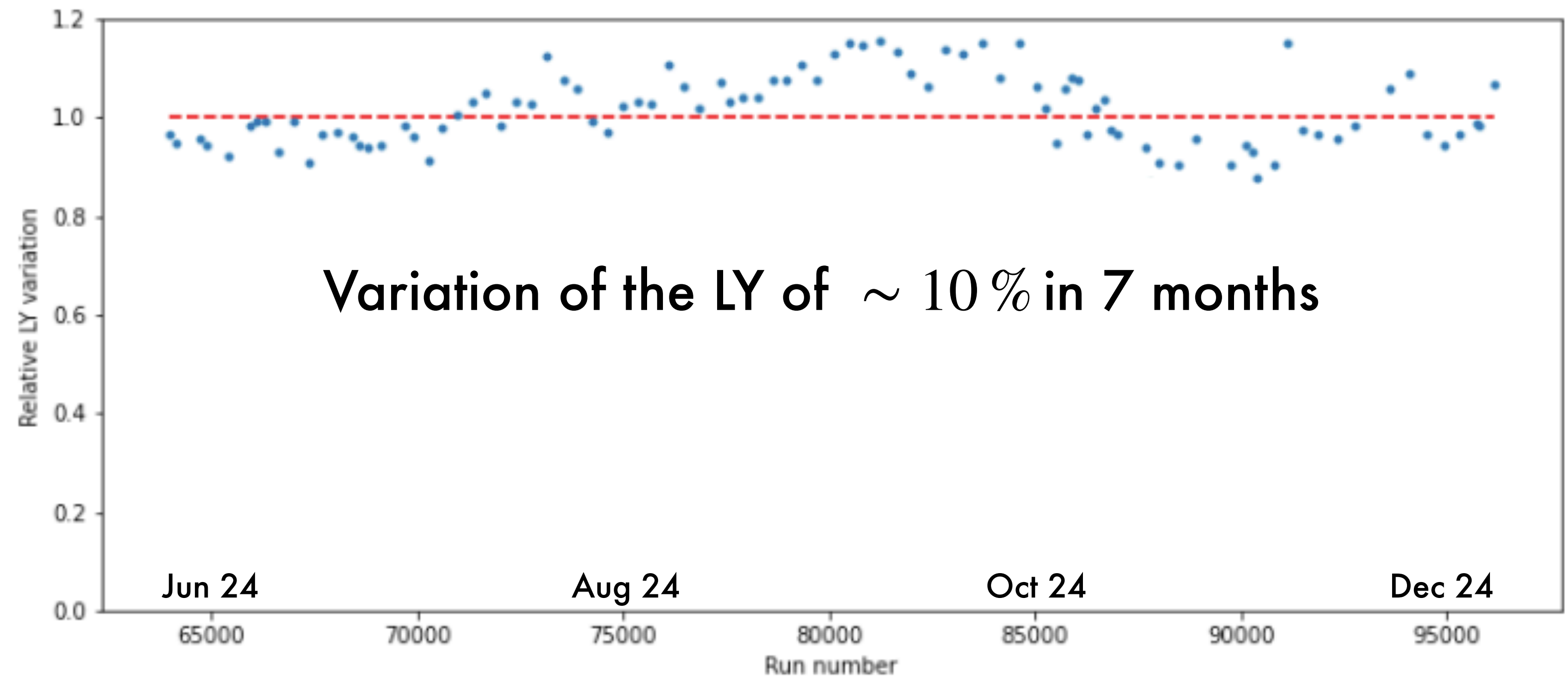
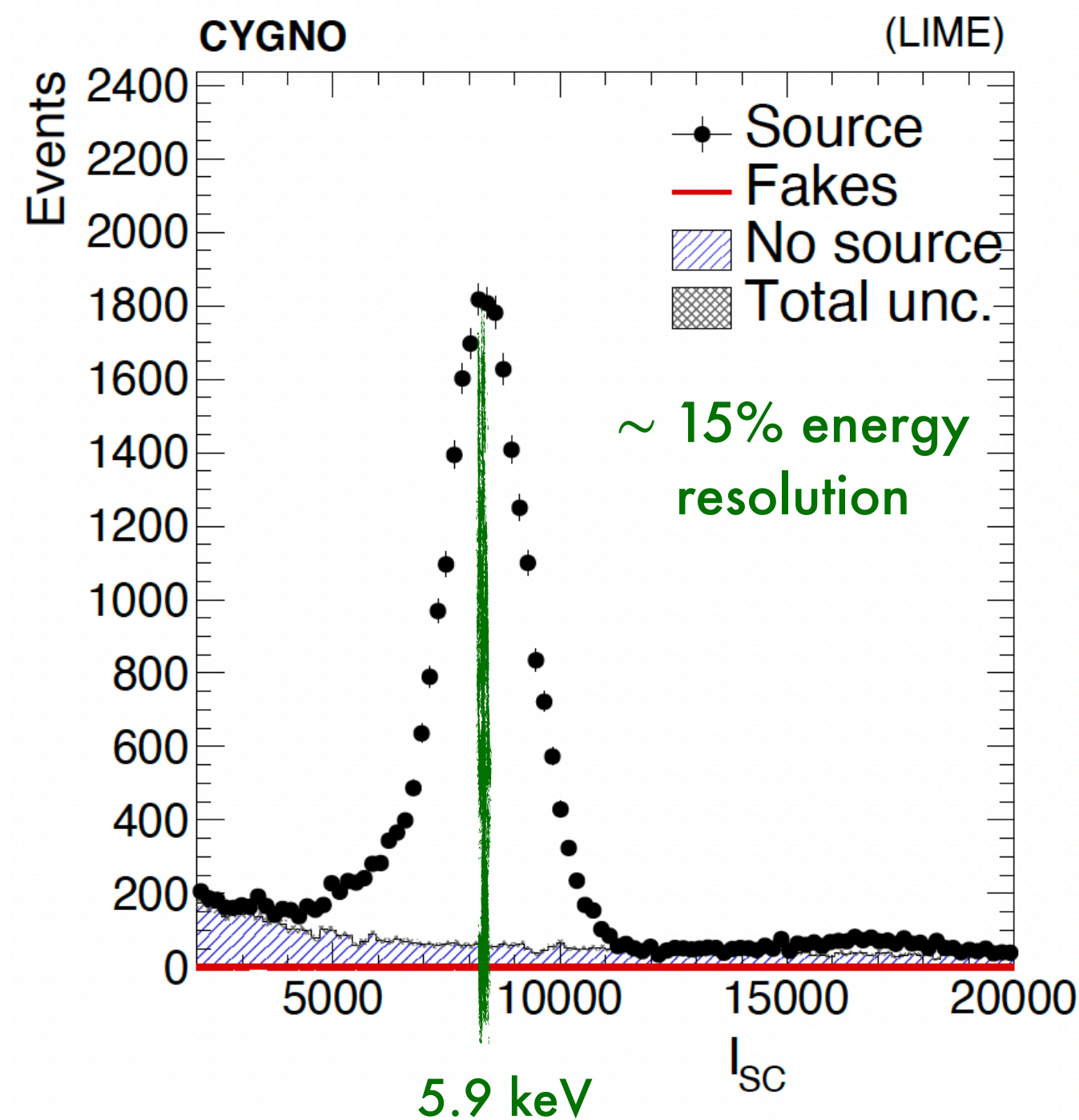
End of 2024/Beginning of 2025

- **RUN 0: Commissioning**
- **RUN 1: No-shielding**
- **RUN 2: 4 cm Cu shielding**
- **RUN 3: 10 cm Cu shielding**
- **RUN 4: 10 cm Cu + 40 cm water shielding**
- **RUN 5: 10 cm Cu shielding (cave neutrons)**
- **Decommissioning**

Stability during the underground operation



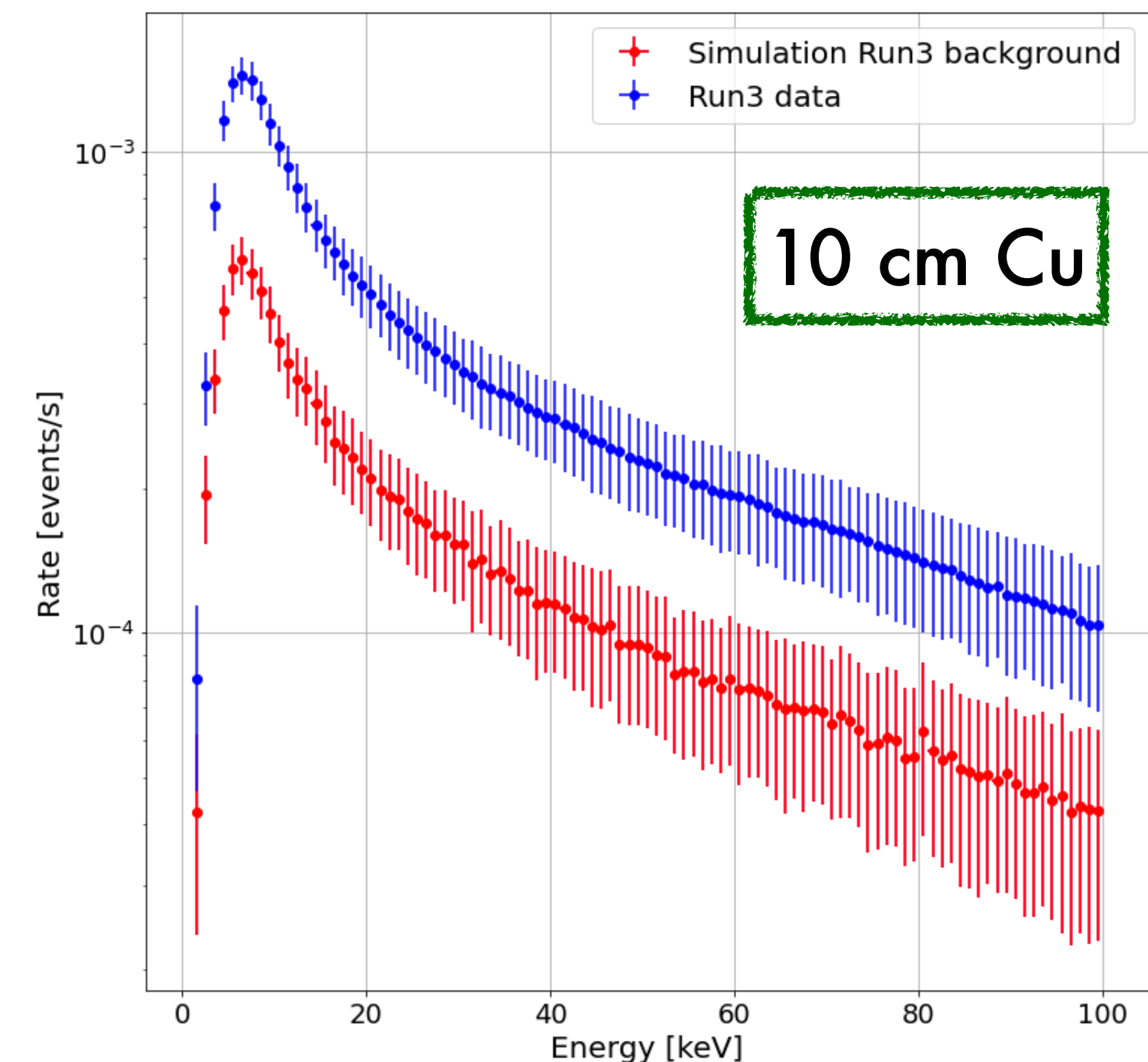
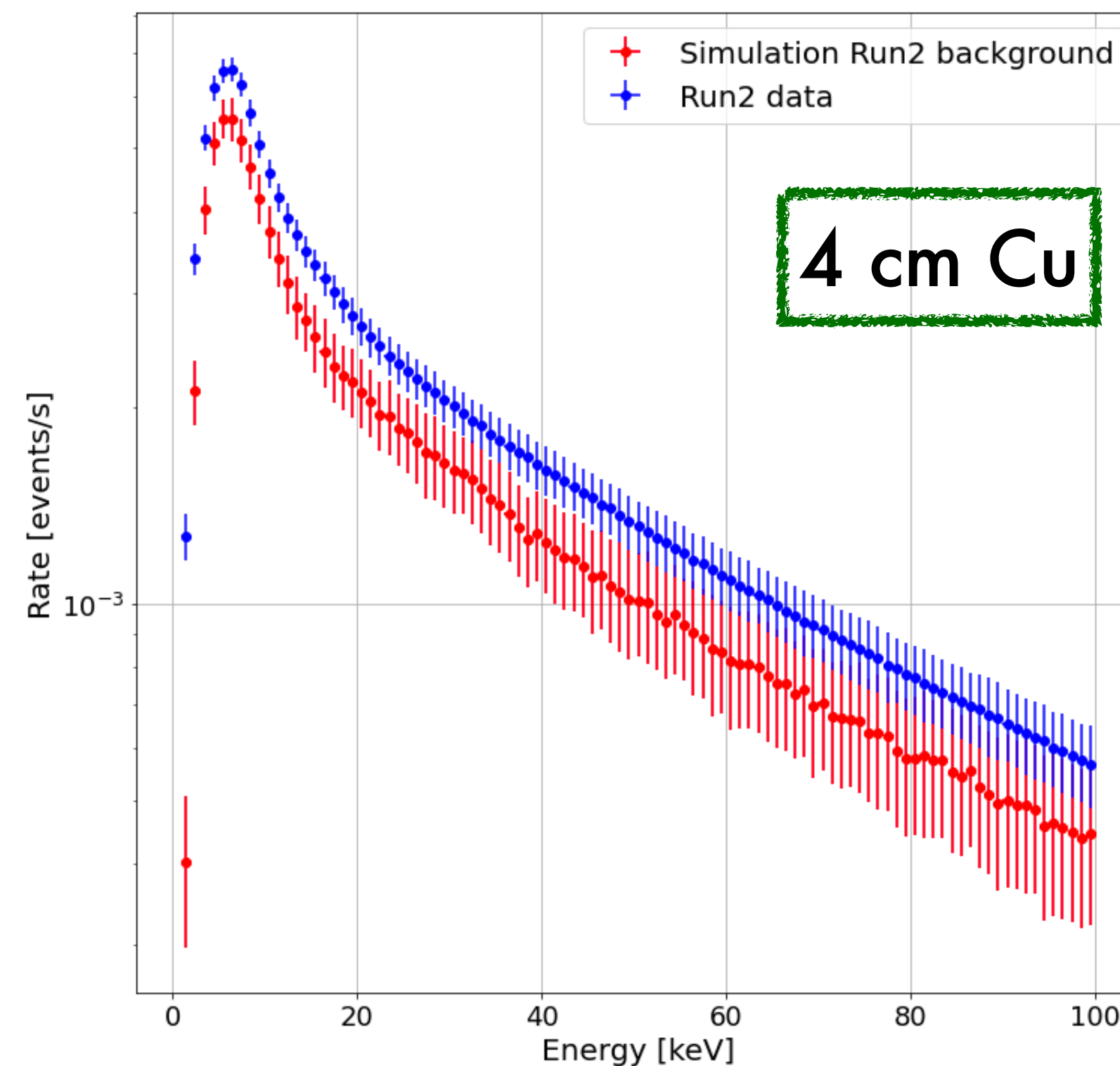
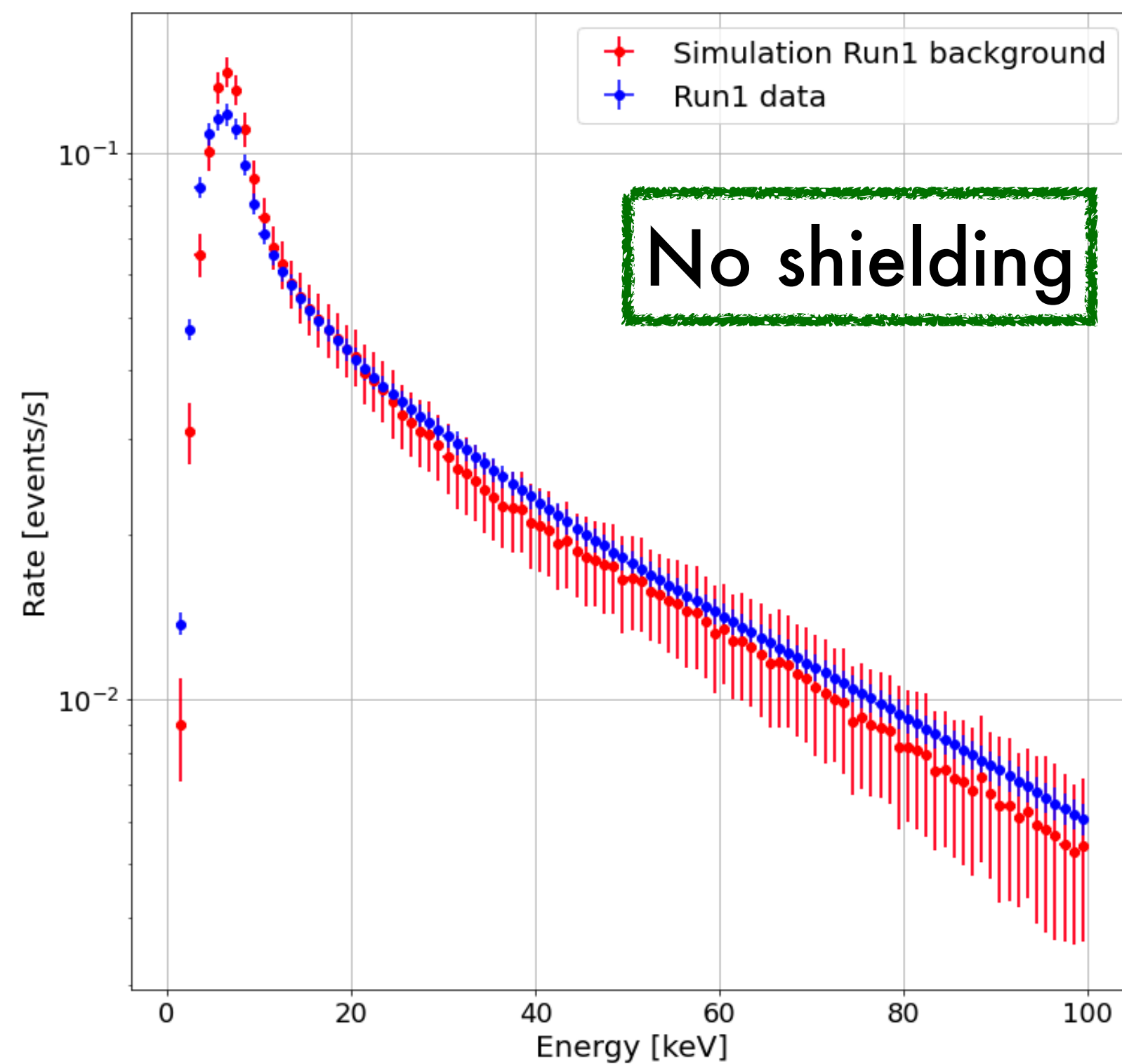
- **RUN 5:** 7 months of continuous data-taking with no major interruptions
- Light yield measured using a **6 keV ^{55}Fe X-ray source** collimated in z



MC and comparison with data



- **MC and data agreement is good in RUN1** (no shielding) but the disagreement increases as the shielding increases.
- **Missing internal component** in the **MC**?



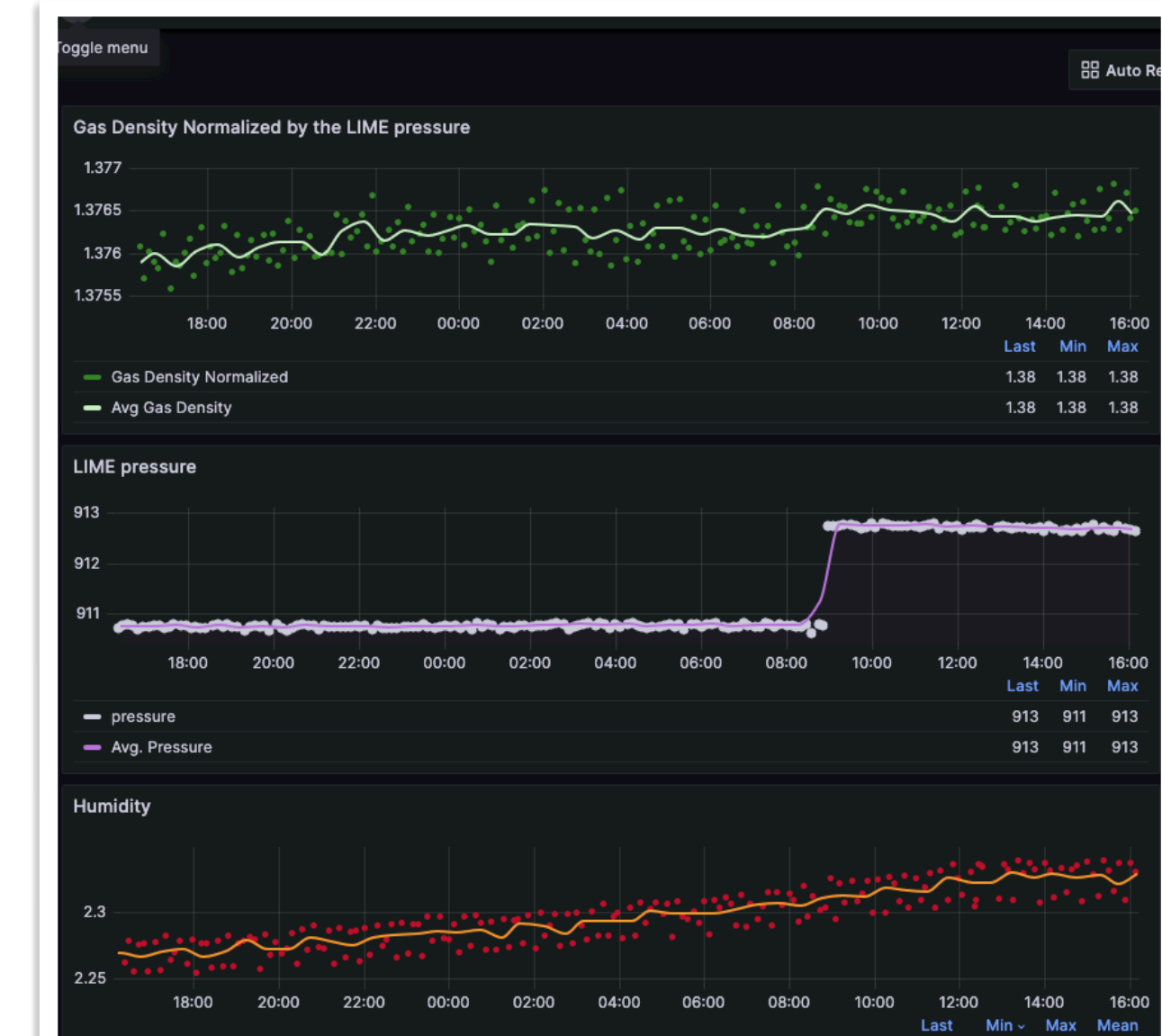
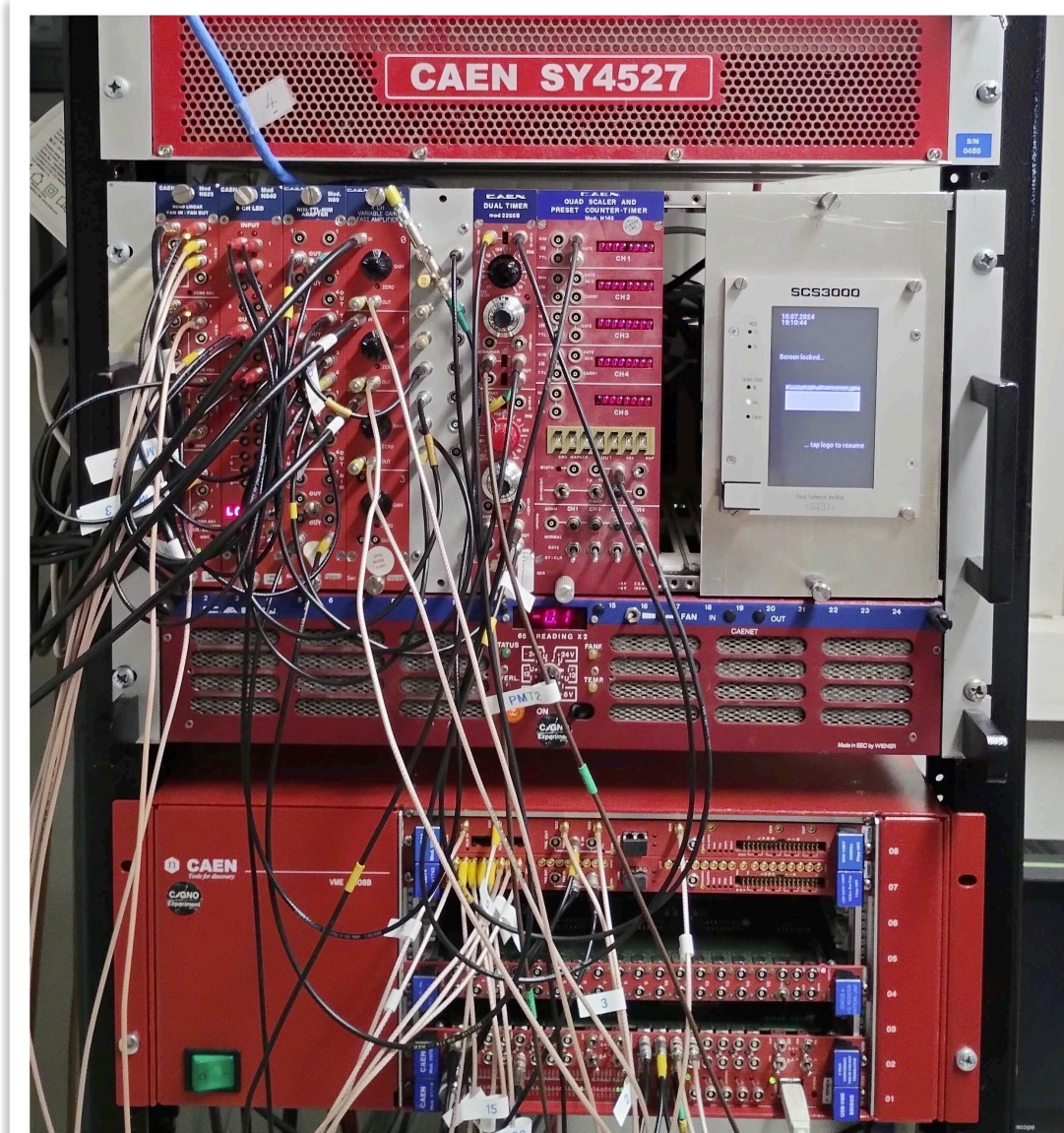
LIME subsystems

DAQ and HV System:

- **NIM:** splitting (N625), discriminating (N840), and logic (custom FPGA-based module)
- **VME:** fast digitization (V1742), slow digitization (V1720), controller (V1718), and logic (V976).
- **HV:** GEM and PMTs (SY 4527), Cathode (ISEG HPn 500 705)
- **Slow Control:** environmental variables (SCS3000 controller)
- **Server:** two Xeon 16 core 4216 + 96 GB RAM+ 2x8 TB HD + NVIDIA RTX5000 24 GB
- **Software:** complete MIDAS integration

Cloud storage and services for remote monitoring:

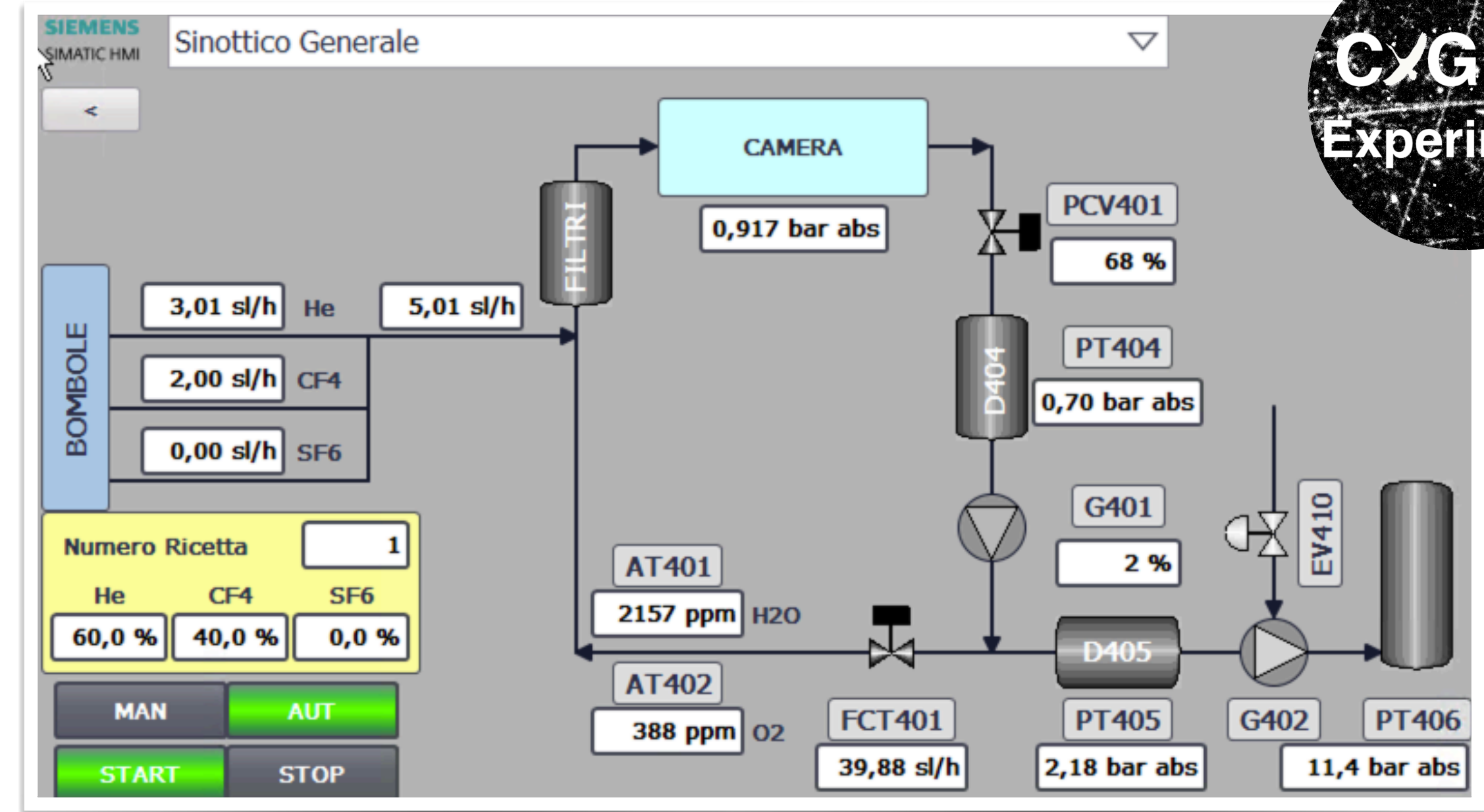
- Beta tester of the **INFN-Cloud** project
- Data streamlined to cloud for **storage** and **reconstruction**
- Reconstruction queue of **~ 40 CPUs**
- Data throughput of **~ 3 MB/s**



LIME subsystems

Gas System

- Regulation of the TPC **internal pressure**
- **Recirculation** circuit
 - Moisture filters
 - Oxygen filters
 - Radon filters
- **Remote control** integrated with MIDAS
- Typical **operation**:
 - 5 L/h of fresh gas flow
 - 20 L/h of recirculated gas



CXGNO
Experiment



CYGNO-04: gas distribution

