



# The **CYGNO** project for directional dark matter searches

## XVIII TAUP2023, Vienna 28.08 - 01.09.2023

Andrea Messina - Sapienza Università di Roma & INFN Roma1  
on behalf of:

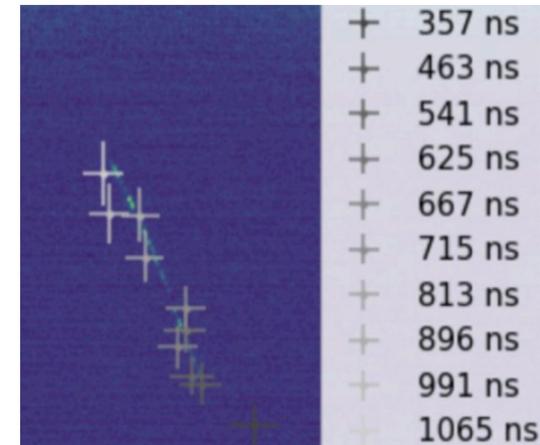
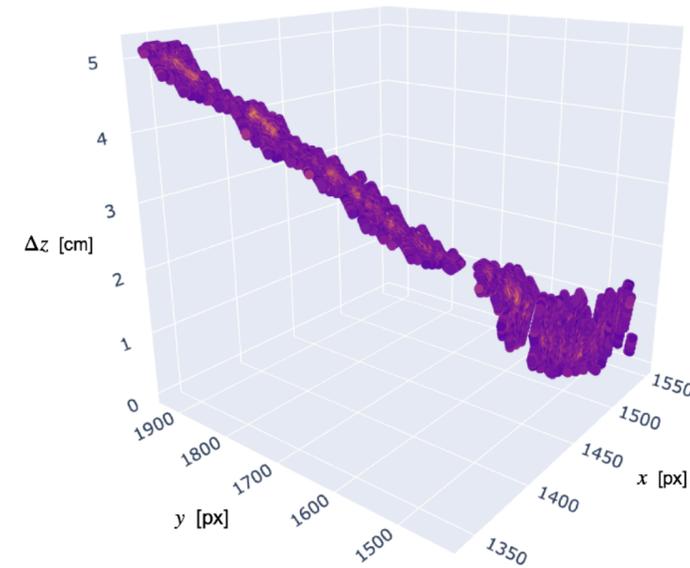
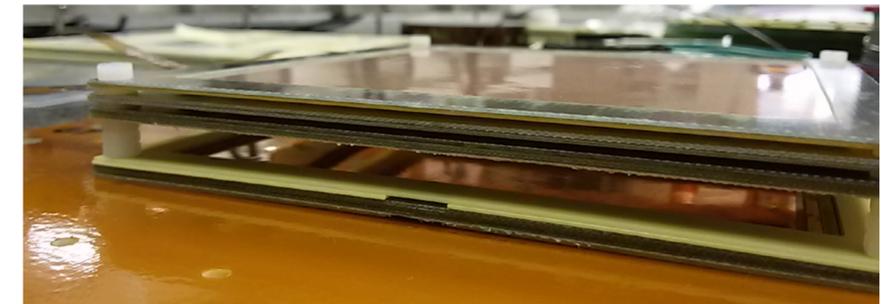
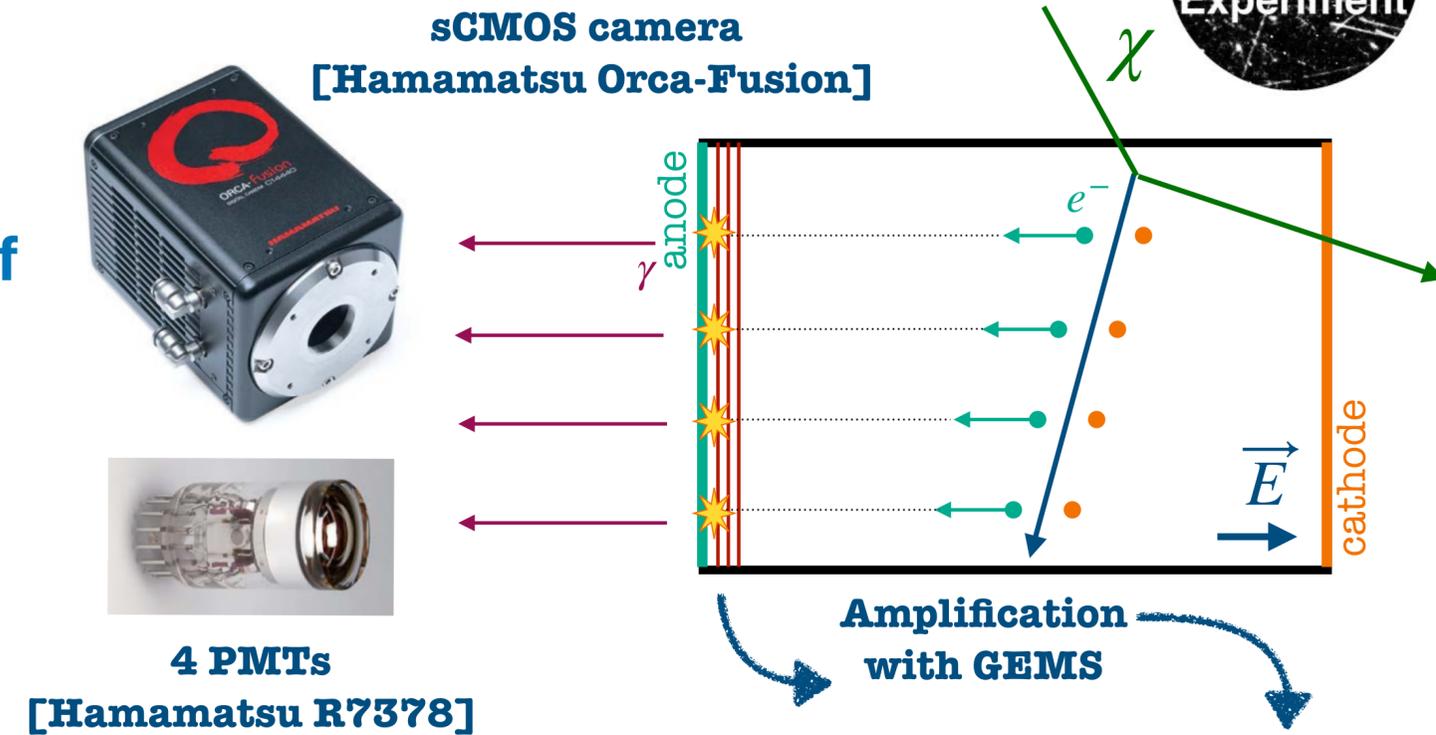
F. D. Amaro, R. Antonietti, E. Baracchini, L. Benussi, S. Bianco, F. Borra, C. Capoccia, M. Caponero, D. S. Cardoso, G. Cavoto, R. J. de Cruz Roque, I. A. Costa, E. Dané, G. Dho, E. Di Marco, G. D'Imperio, F. Di Giambattista, R. R. M. Gregorio, F. Iacoangeli, E. Kemp, H. P. Lima Júnior, G. S. P. Lopes, 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. Tesauero, S. Tomassini, S. Torelli, D. Tozzi



# The **CXGNO** project:



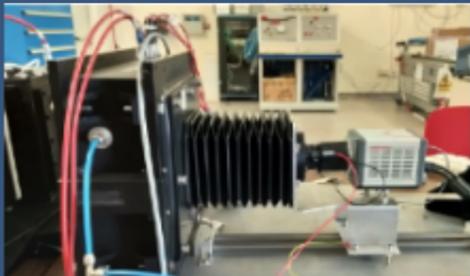
- **Aiming for** a large detector for high precision **3D tracking of rare low energy nuclear recoils (keV)**
- **Experimental challenges:** rate  $O(\text{evt}/\text{kg}/\text{y})$ , background rejection, and energy threshold (keV)
- **Strategy:** **photograph nuclear recoil** in a  $\text{He}:\text{CF}_4$  (1 atm) TPC with a GEM amplification stage
  - **Low density material:** “visible” track for low energy ER/NR
  - **Optical sensors:** high granularity, very low noise, and high sensitivity
  - **Optical coupling:** sensors outside the sensitive volume, acquire large surfaces with small sensors
  - **3D tracking:** position, direction, head/tail, and fiducialization, total released energy,  $dE/dx$ , particle identification



## INITIUM: NID studies

Currently at  
LNGS

MANGO

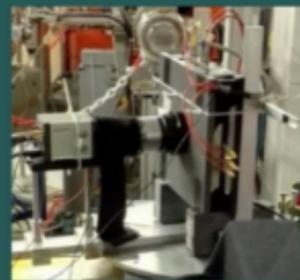


- up to 5 cm drift
- for gas studies

## 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

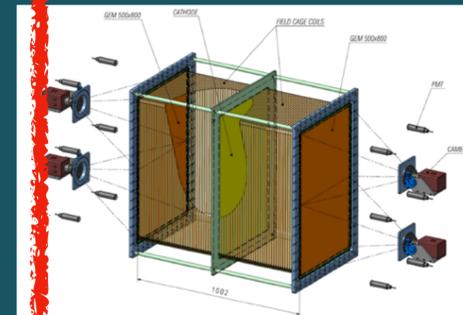


- 50 cm drift
- underground tests
- MC validation

## PHASE 1: 0(1) m<sup>3</sup> demonstrator

2023/26  
LNF/LNGS

CYGNO\_04

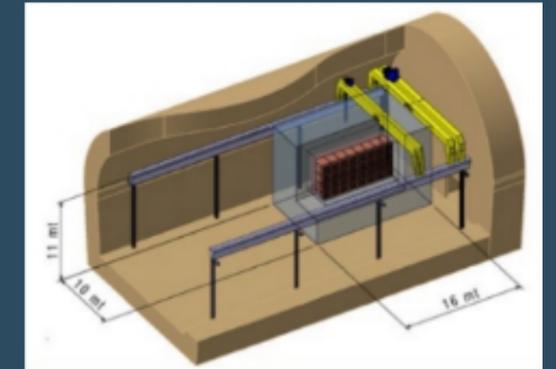


- background
- material tests, gas purification
- scalability

## PHASE 2: 30 m<sup>3</sup> experiment

2026 ...  
LNGS

CYGNO\_30



- Physics research

[Instruments 6 \(2022\) 1, 6](#)

[JINST 15 \(2020\) 12, T12003](#)

[JINST 15 \(2020\) P10001](#)

[JINST 15 \(2020\) P08018](#)

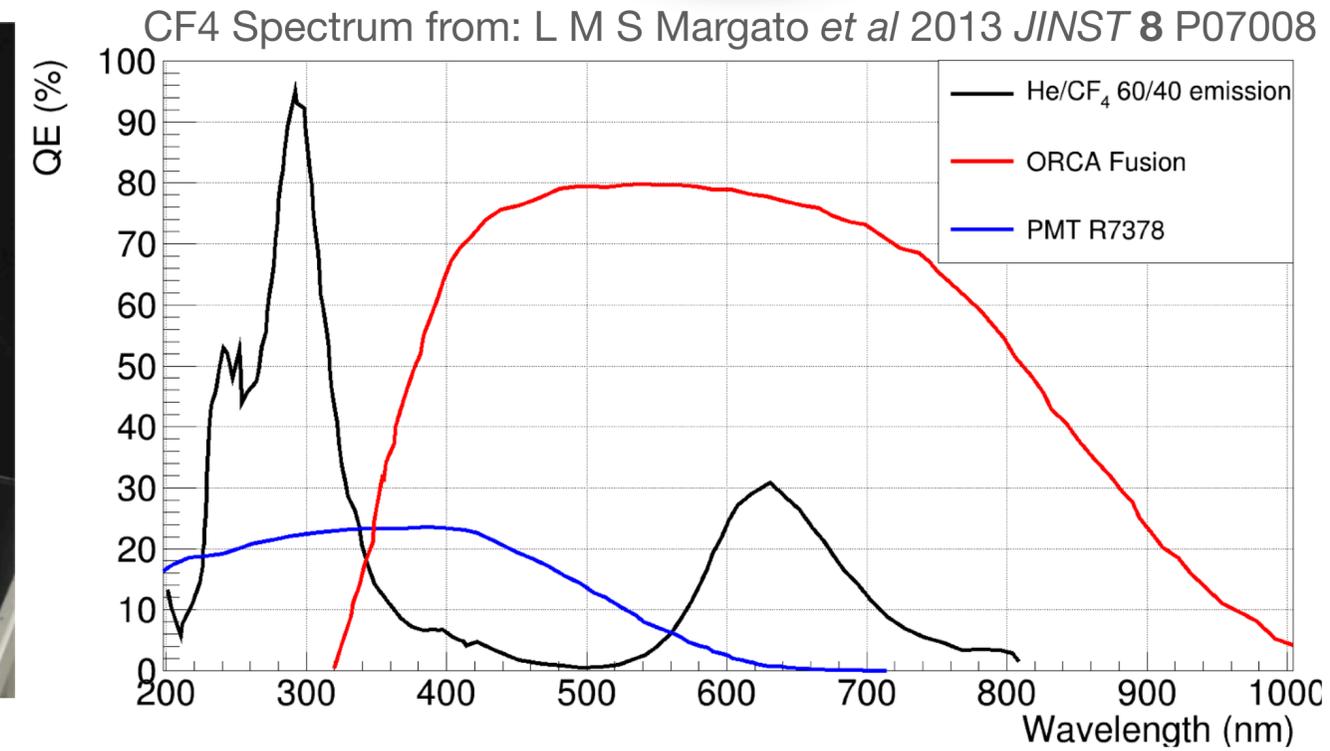
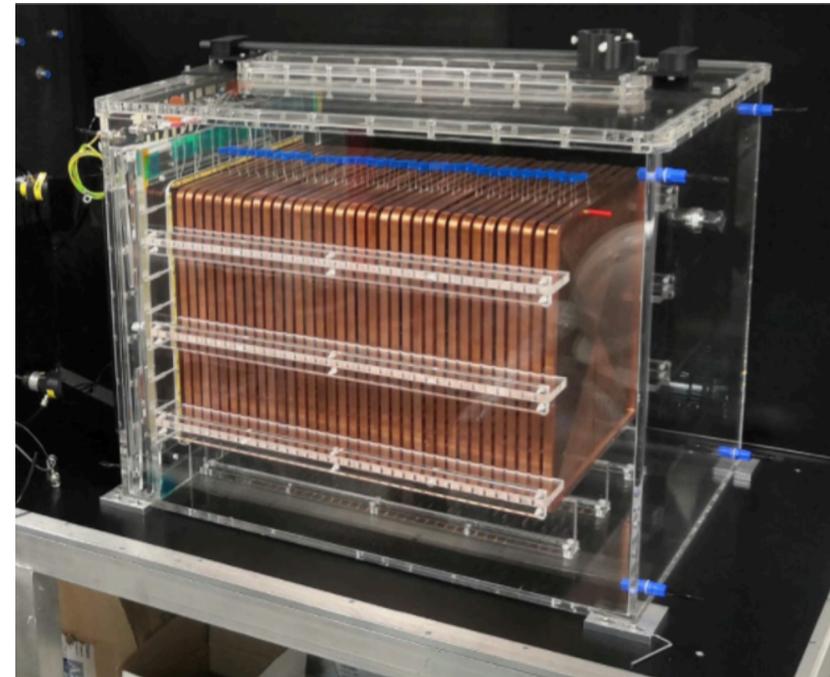
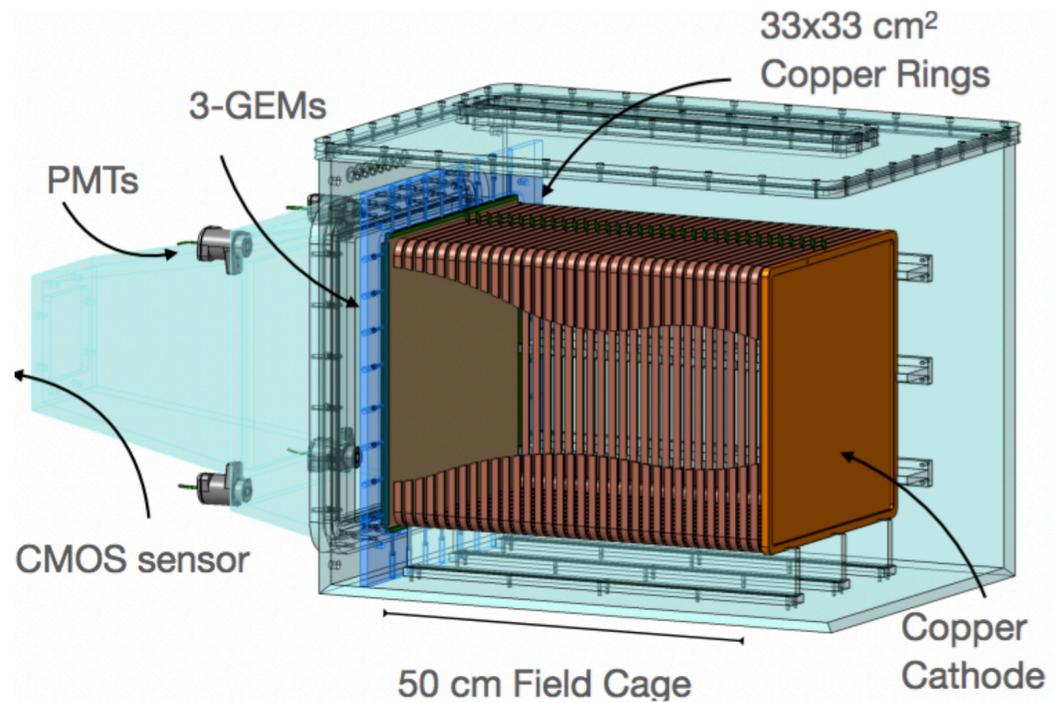
[2019 JINST 14 P07011](#)

[Measur.Sci.Tech. 32 \(2021\) 2, 025902](#)

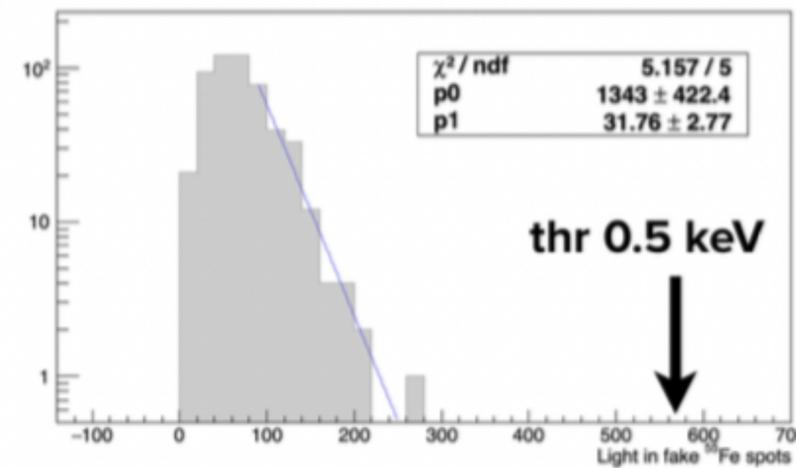
[NIM A 999 \(2021\) 165209](#)

[arXiv:2305.06168 \[hep-ex\]](#)

# CYGNO PHASE 0: Lime prototype



- He:CF<sub>4</sub> 60/40 (1 atm)
- copper ring field cage, 50 cm drift
- 3 GEMs for a 33 x 33 cm<sup>2</sup> sensitive area
- 1 sCMOS sensor + 4 PMT
- acrylic vessel, aluminium faraday cage



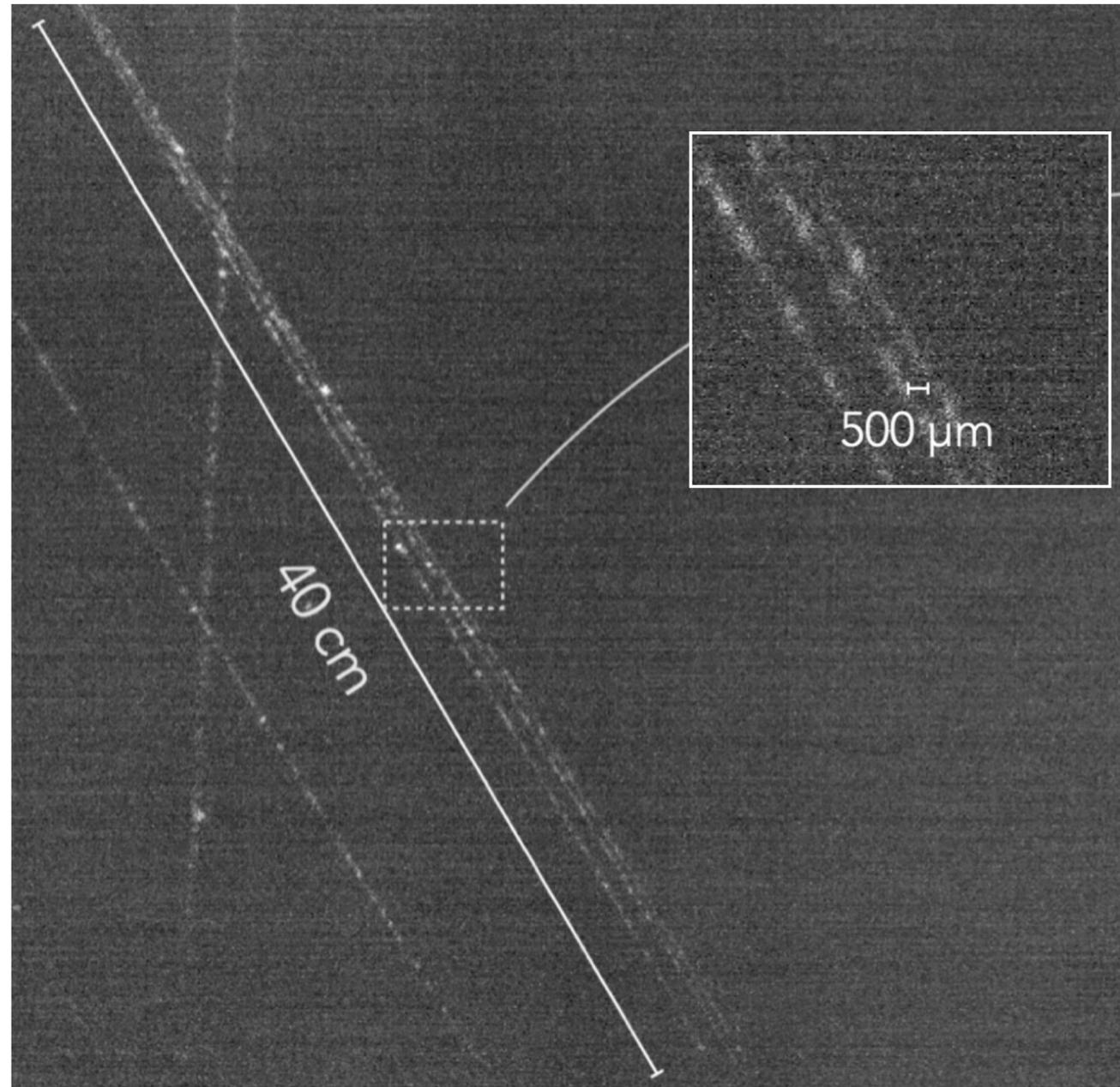
ORCA-FUSION

**HIGH RESOLUTION**  
2304 × 2304  
5.3 Megapixels

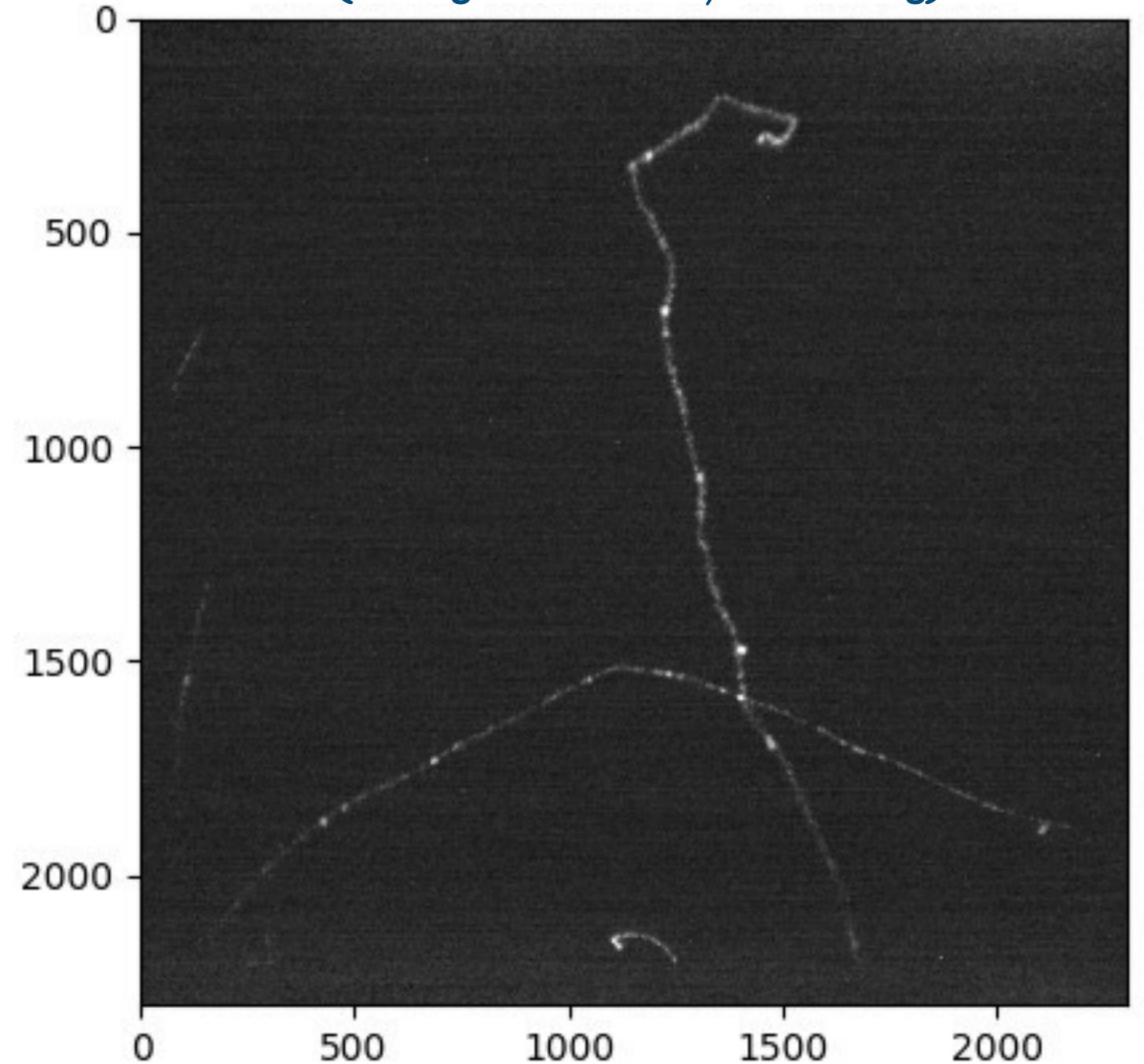
**READOUT NOISE**  
0.7 electrons rms  
Ultra-quiet Scan



# Lime images



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

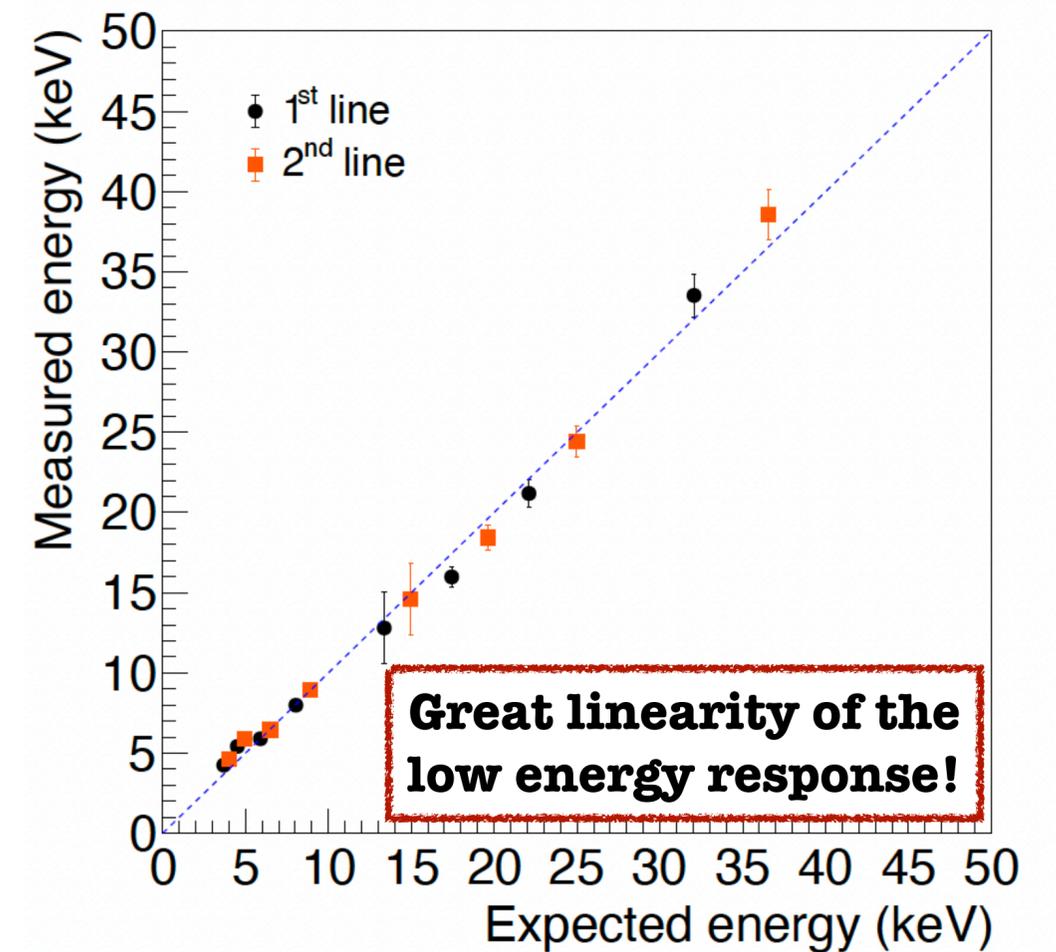
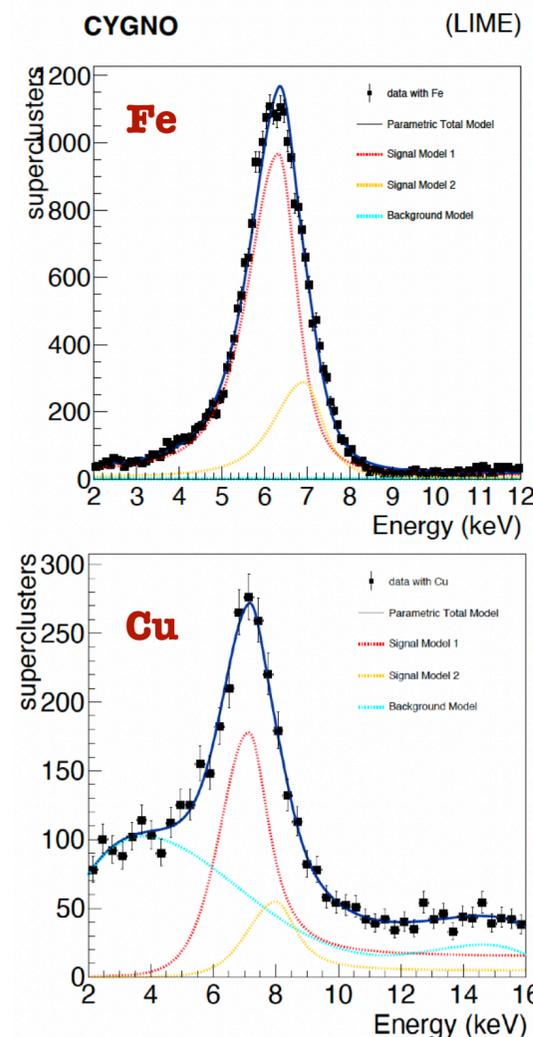
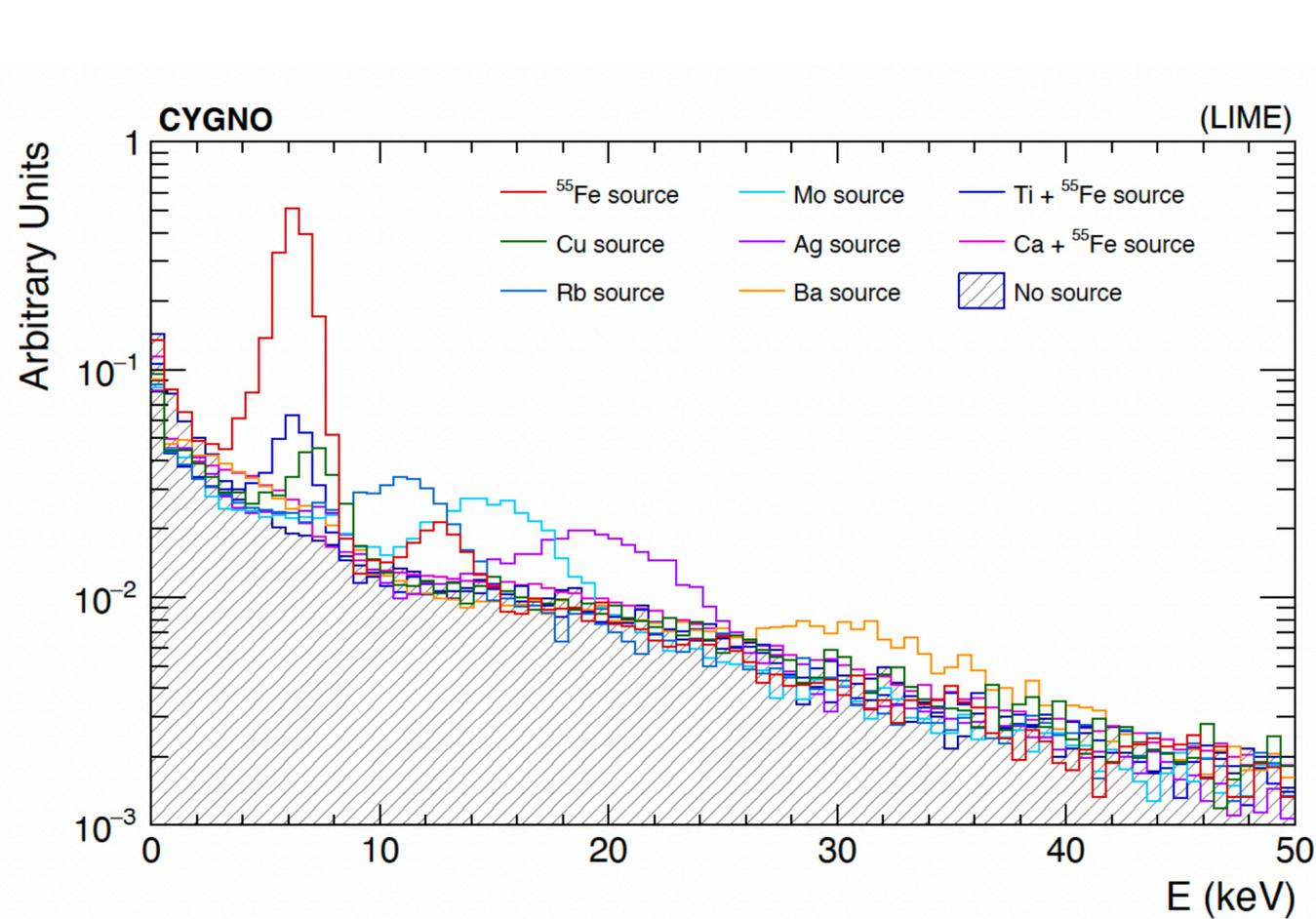
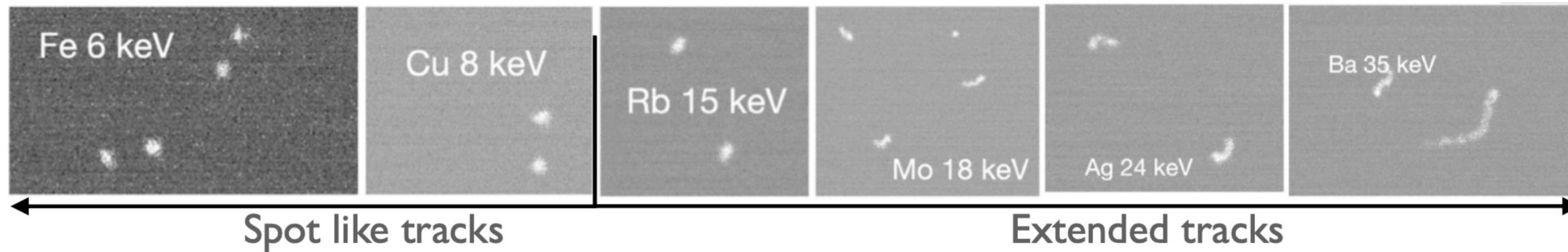


# Energy response

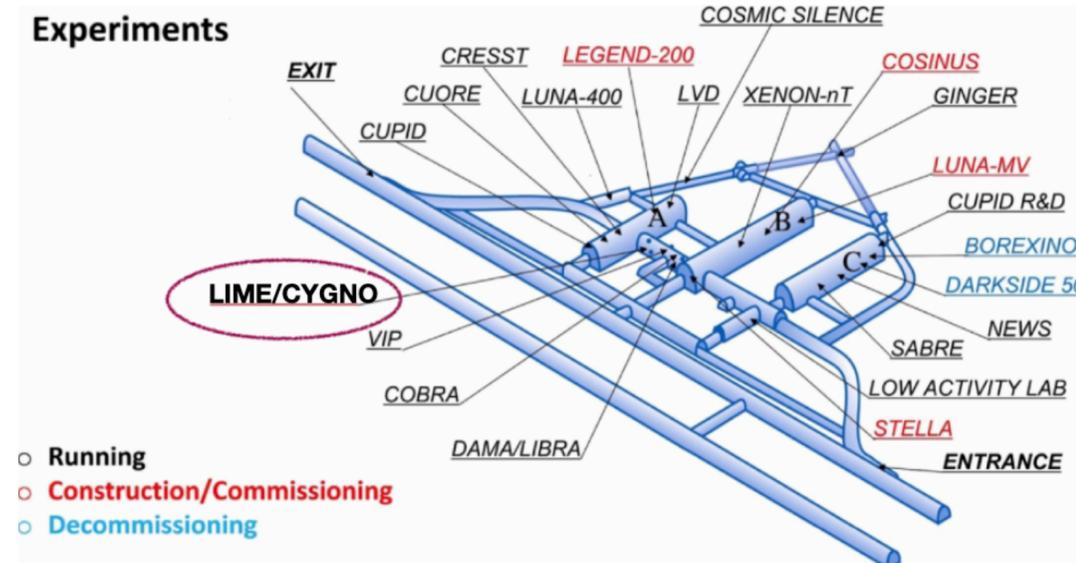
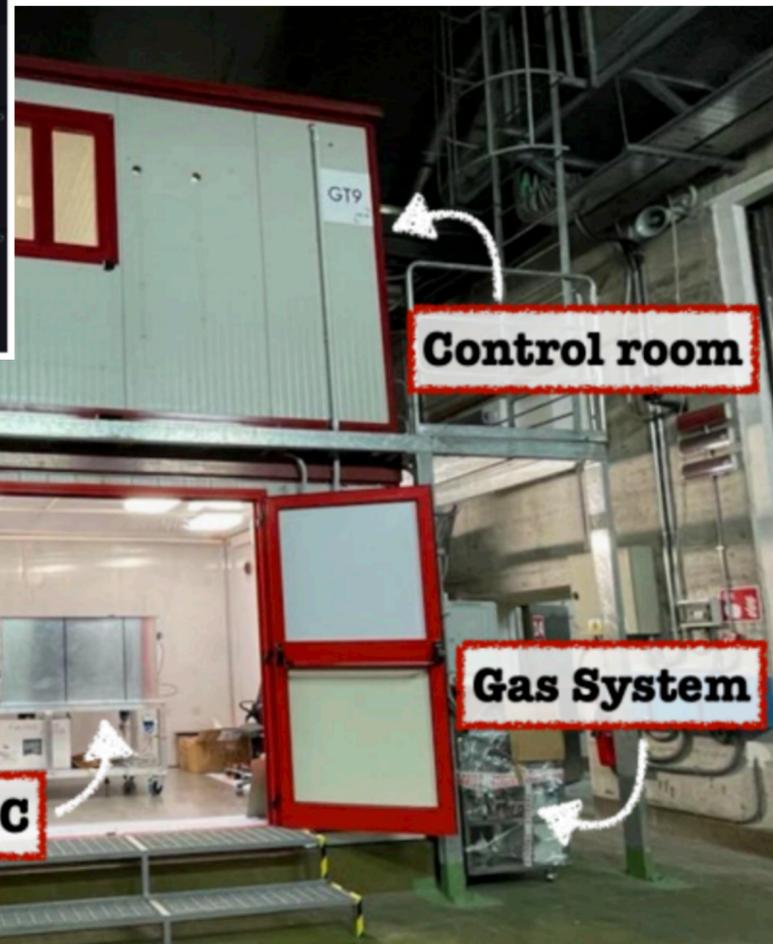
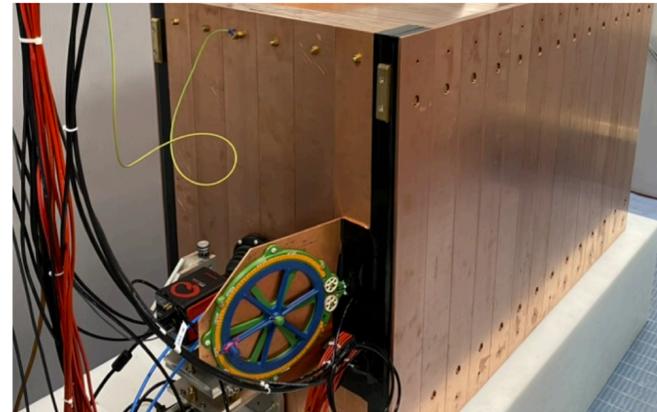
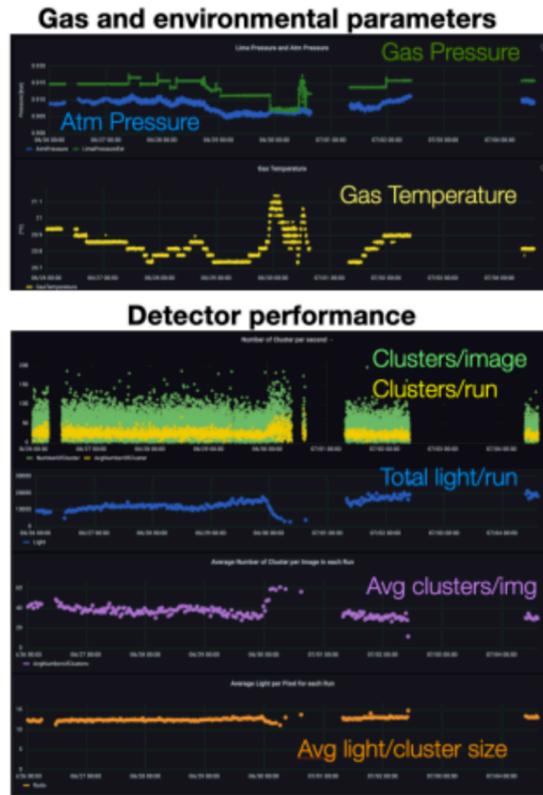


Study of linearity and energy resolution (15-20%) performed with different X-ray sources

arXiv:2305.06168 [hep-ex]



# CYGNO PHASE 0: LIME underground installation



Spring and Summer 2022

Autumn 2022

Winter 2023

Spring and Summer 2023

**Today**

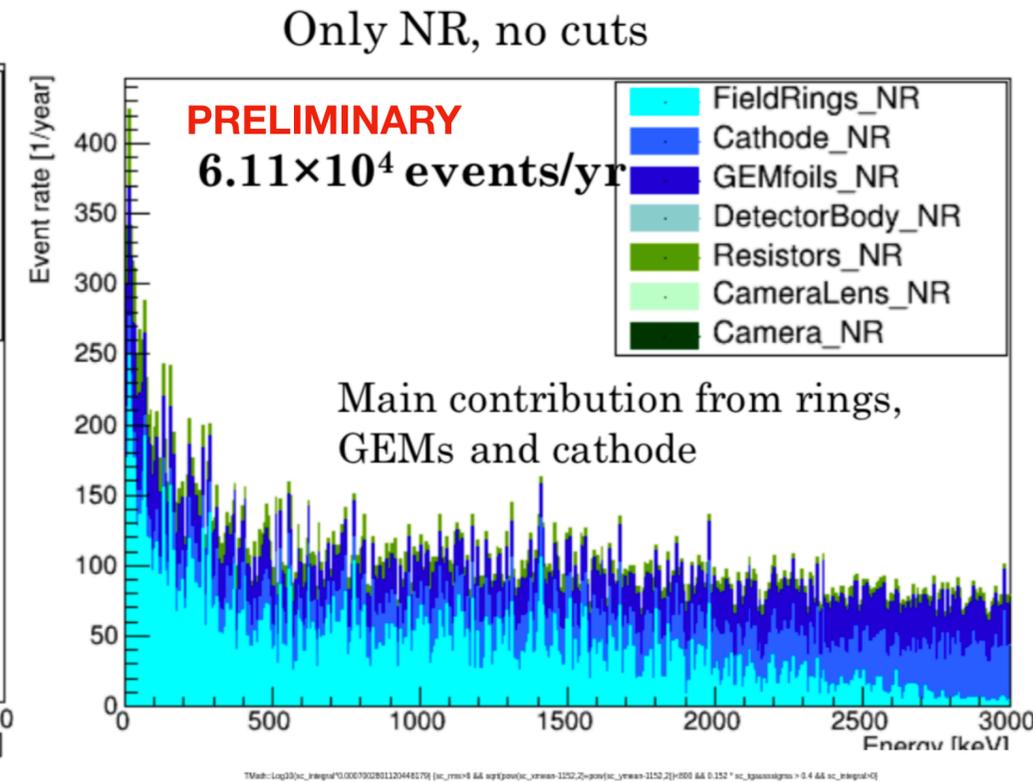
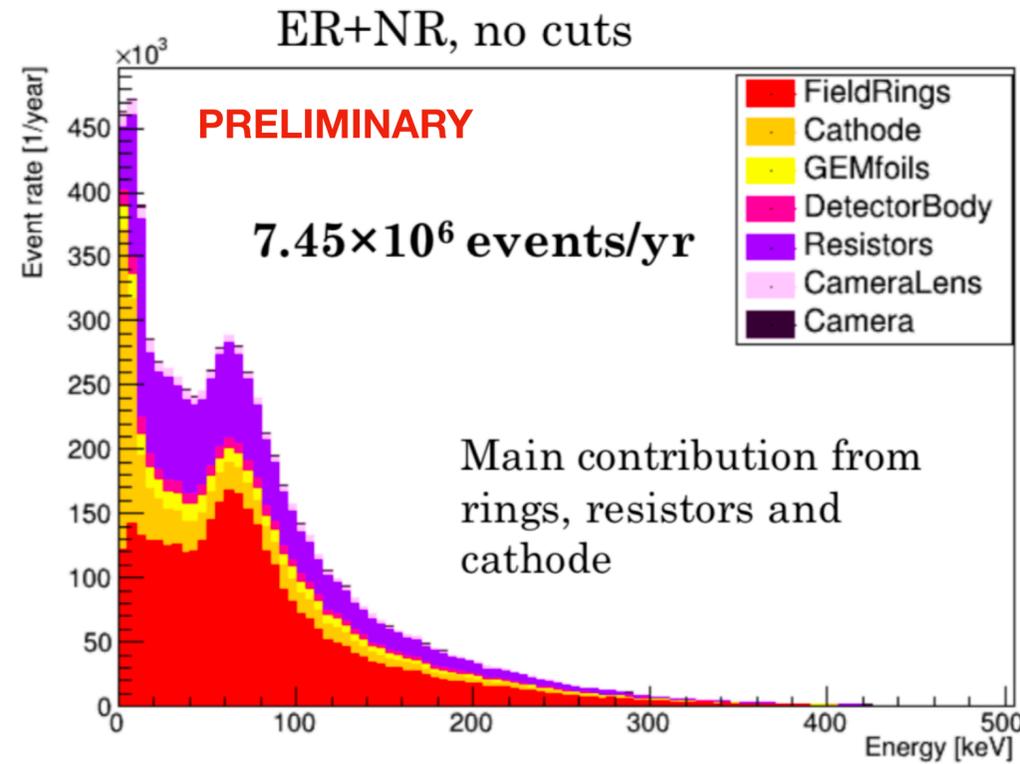
Autumn 2023

- **RUN 0: Commissioning**
- **RUN 1: No-shielding**
- **RUN 2: 4 cm Cu shielding**
- **RUN 3: 10 cm Cu shielding**
  - ➔ measurement of NR response with AmBe
  - ➔ Measurement of the underground neutron flux *We are here*
- **RUN 4: 10 cm Cu + 40 cm water shielding**

# Background and detector simulation

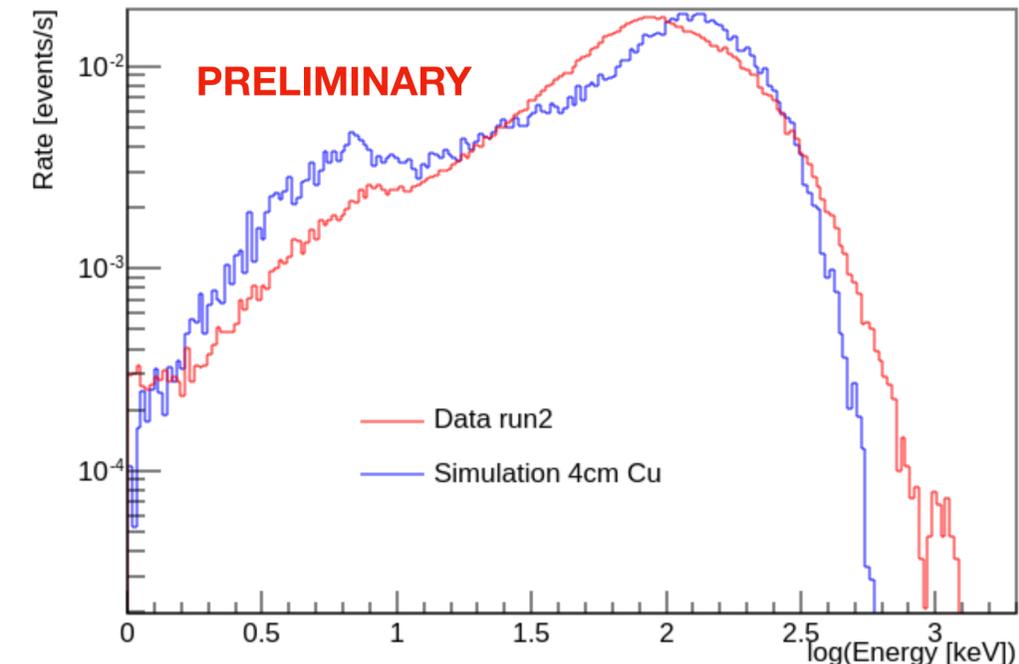
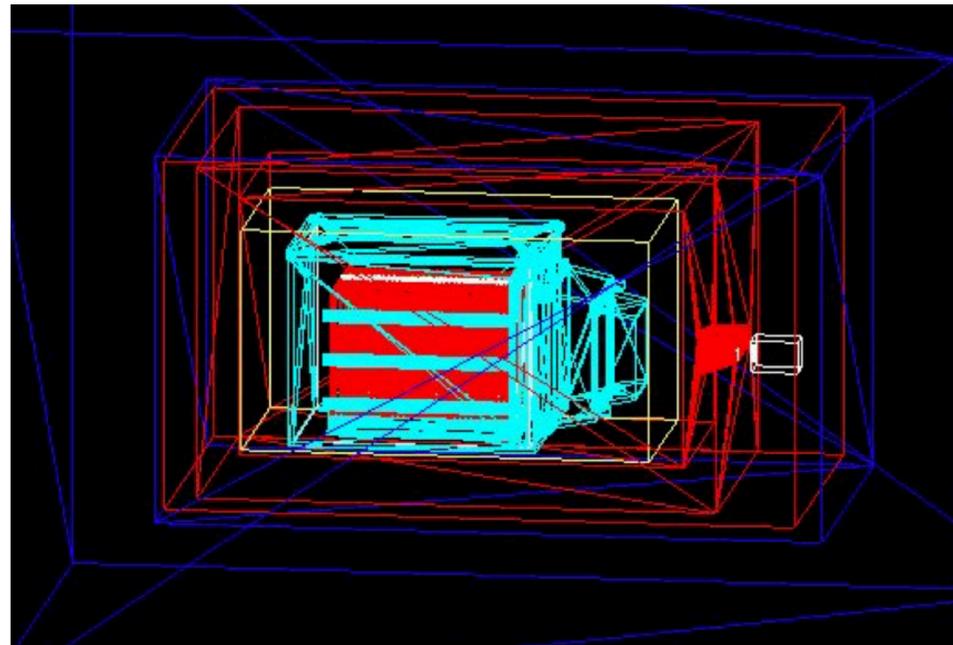


- **Activity** of LIME components **measured underground @ LNGS**
- Natural radioactivity from **decay chains of  $^{232}\text{Th}$ ,  $^{238}\text{U}$ ,  $^{235}\text{U}$ ,  $^{40}\text{K}$**  (rings, resistors, GEM/cathode)
- Internal bkg **reduced** by 96% (99.97%) for ER (NR) with **fiducial cuts**
- External bkg measured with NaI



## Simulation

- **GEANT4**: geometry, material radioactivity, energy deposits
- **GARFIELD**: electron diffusion
- **Detector simulation and digitisation**: primary electrons, light production, CAMERA and PMT



# Underground data so far



## RUN 1: No-shielding

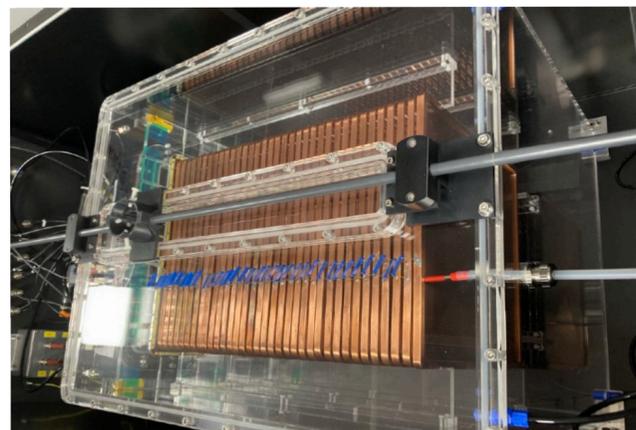
- From Oct 8 - Dec 6, 2022

- Some numbers:

- ➔ Integral number of **BKG pictures**:  $\sim 4 \times 10^5$ , 33 h cam exposure

- ➔ Background **observed event rate**:  $(33.88 \pm 0.58)$  Hz

- ➔ Background **expected event rate**:  $\sim 37$  Hz



## RUN 2: 4 cm Cu shielding

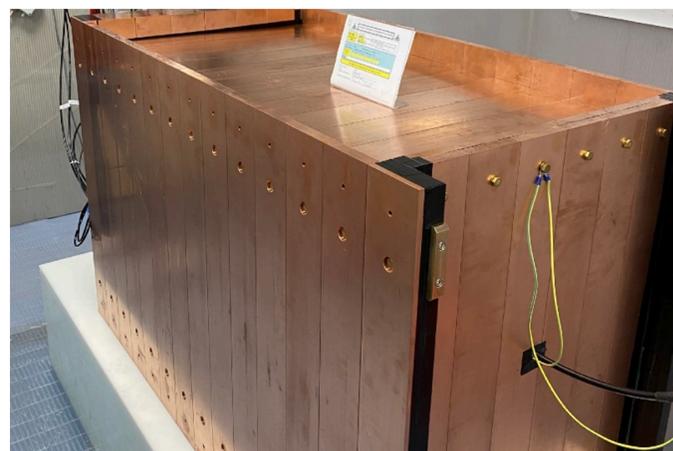
- From Feb 15 - Mar 9, 2023

- Some numbers:

- ➔ Integral number of **BKG pictures**:  $\sim 4.5 \times 10^5$ , 38 h cam exposure

- ➔ Background **observed event rate**:  $\sim 3.5$  Hz

- ➔ Background **expected event rate**:  $\sim 1.1$  Hz



## RUN 3: 10 cm Cu shielding

- From May 13 - ongoing, 2023

- Some numbers:

- ➔ Integral number of **BKG pictures**:  $\sim 6 \times 10^5$ , 17 h cam exposure

- ➔ Background **observed event rate**:  $\sim 1.53$  Hz

- ➔ Background **expected event rate**:  $\sim 0.31$  Hz

- ➔ **AmBe**:  $\sim 2 \times 10^5$  events; 0.04 Hz observed rate;



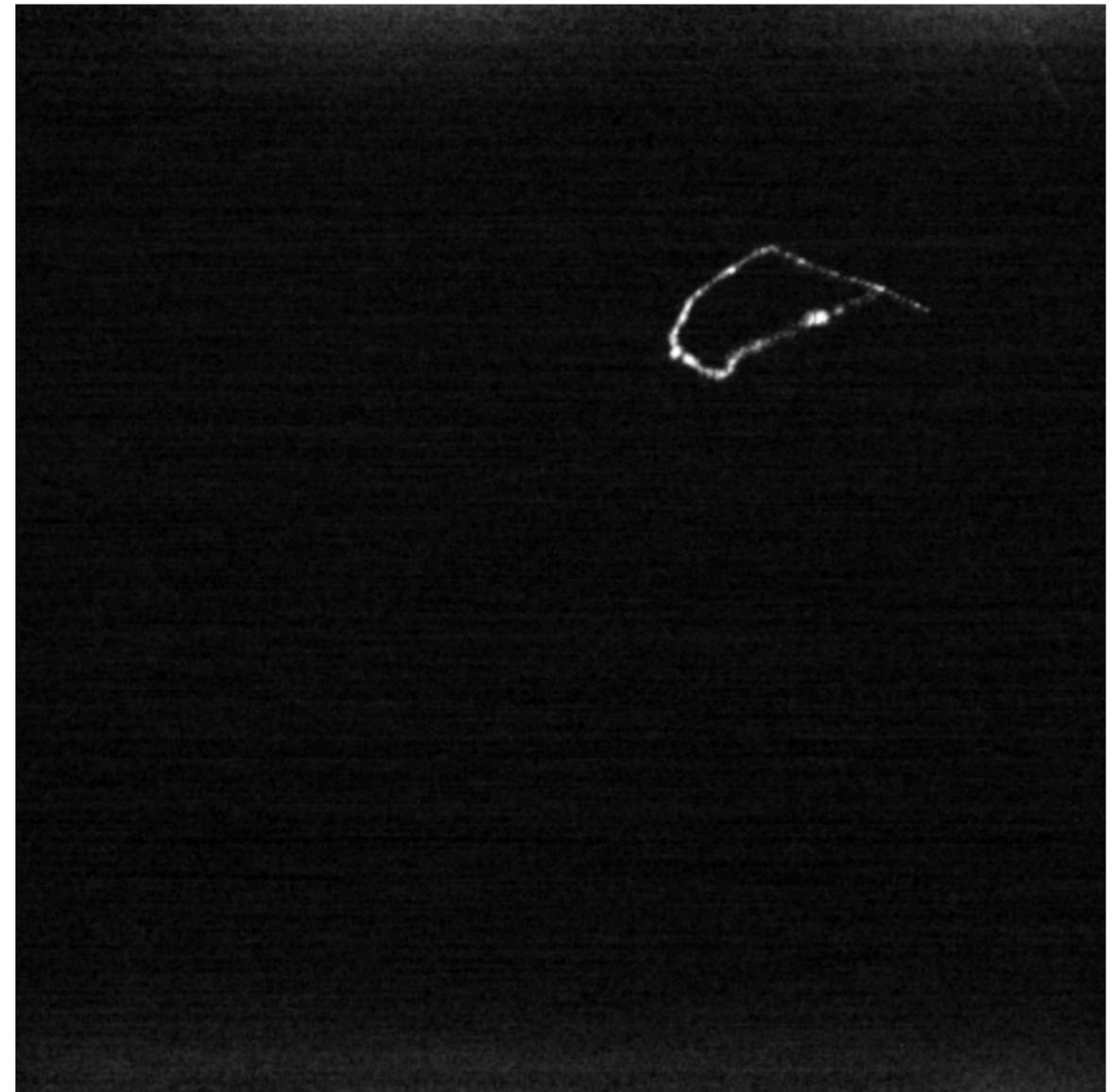
# Underground data so far



**RUN 1: No-shielding**



**RUN 2: 4 cm Cu shielding**



# Response to different type of interactions: LIME Run3 - AmBe



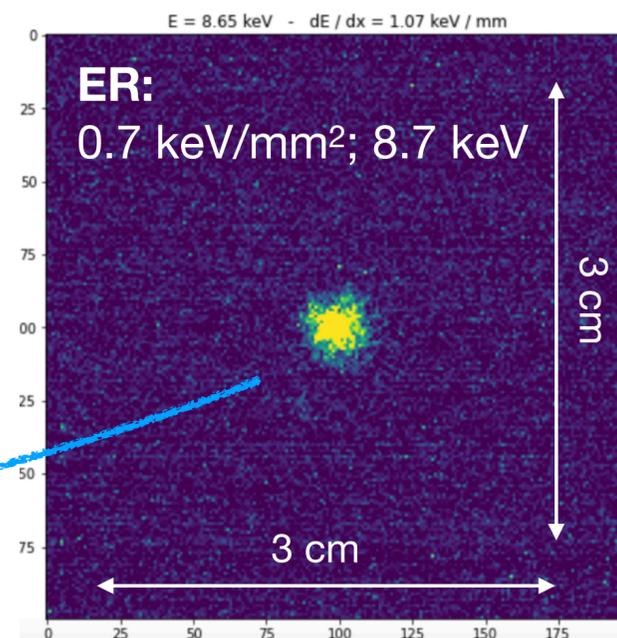
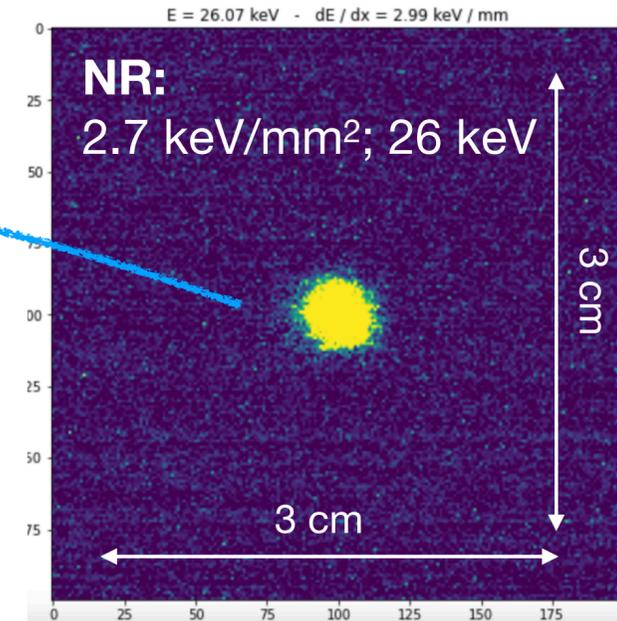
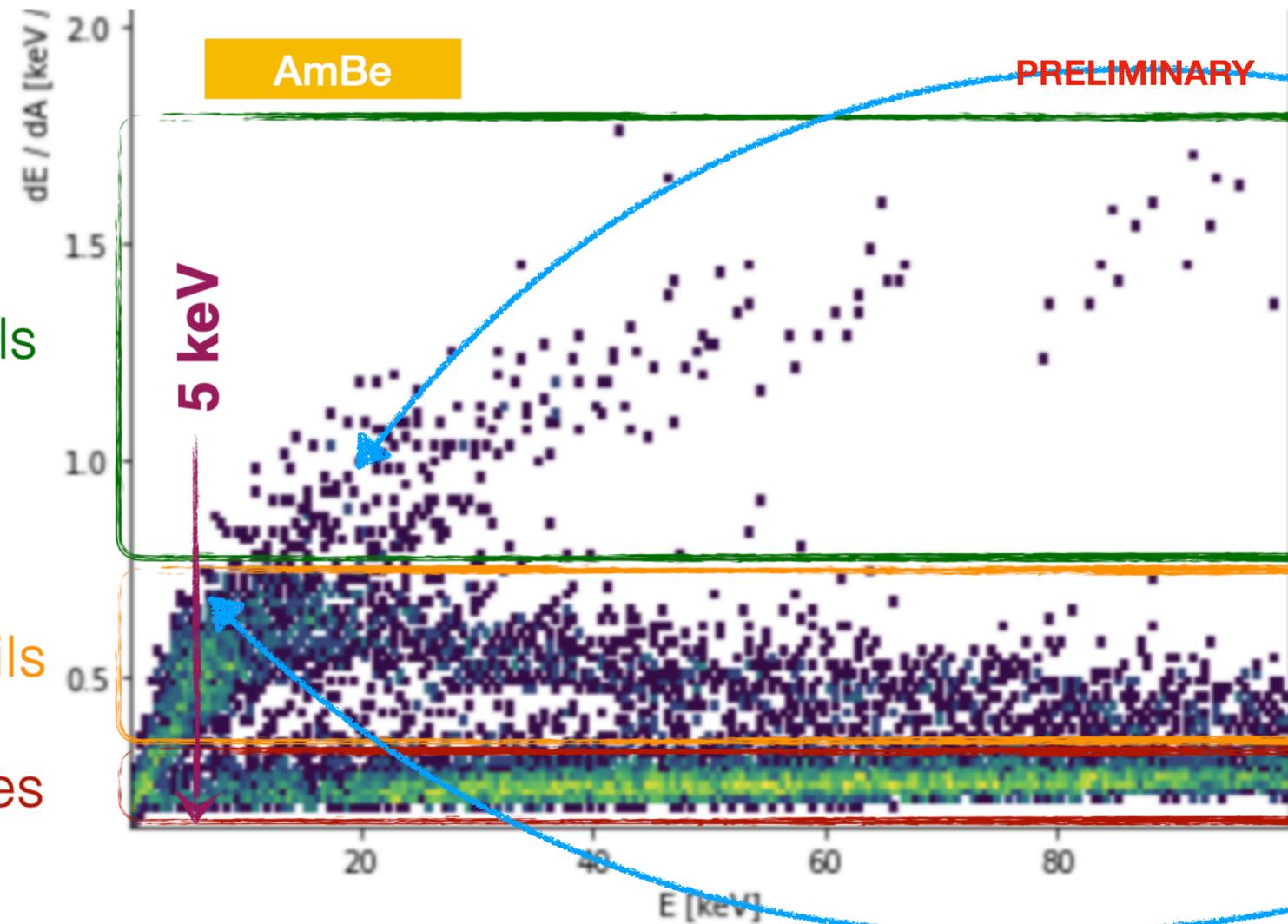
The energy density,  $\Delta E / \Delta A$  or photon/pixel, is a powerful variable to separate NR, ER and MIP

Online analysis on 40% of events

Nuclear Recoils

Electron Recoils

0.2 keV/mm - mip particles

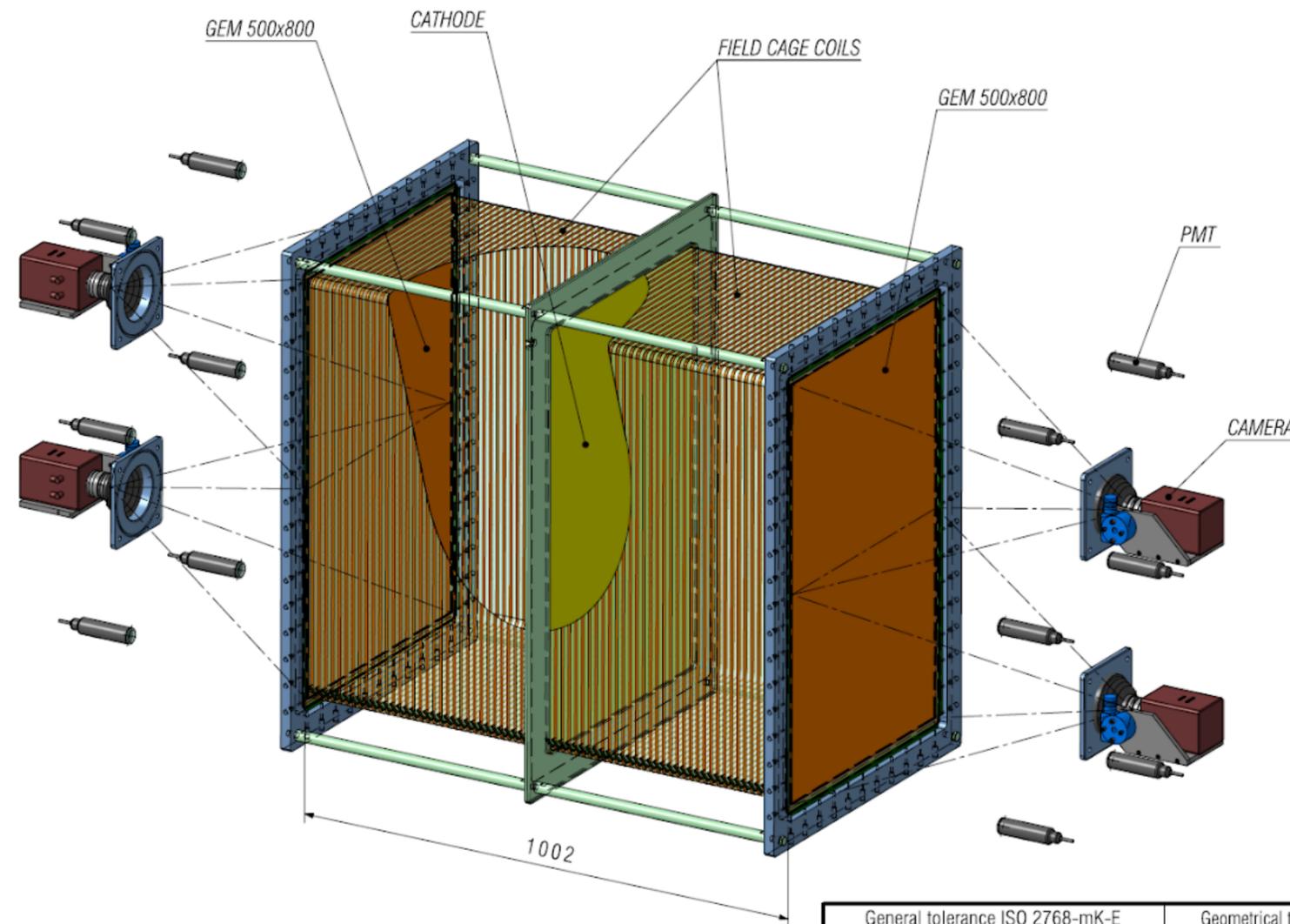


# PHASE 1 CYGNO\_04:

## construct and operate a CYGNO demonstrator to pave the road for a larger apparatus

- **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



CYGNO 0.4 TPC  
 $500 \times 800 \times 1000 = 0.4 \text{ m}^3$

General tolerance ISO 2768-mK-E		Geometrical tolerance ISO 8015-E		Roughness ISO 1302	
 NATIONAL INSTITUTE FOR NUCLEAR PHYSICS FRASCATI NATIONAL LAB RESEARCH DIVISION - SEM	 SEM SUPERCONDUCTING ELECTRON MICROSCOPY	SIZE	A3	REVISION	
		PROJECTION		DATE	
		DATE		NAME	
CYGNO EXPERIMENT		SCALE	1:8	DATE	11/06/2022
CYGNO 0.4 DETECTOR		SHEET	1/3	DATE	
TPC COMPONENTS SCHEME				NAME	C.Capoccia
				CHECKED	
				APPROVED	
				CY4-01-P	

# PHASE 2: The **CYGN**O experiment 30 m<sup>3</sup> Searching for low mass DM

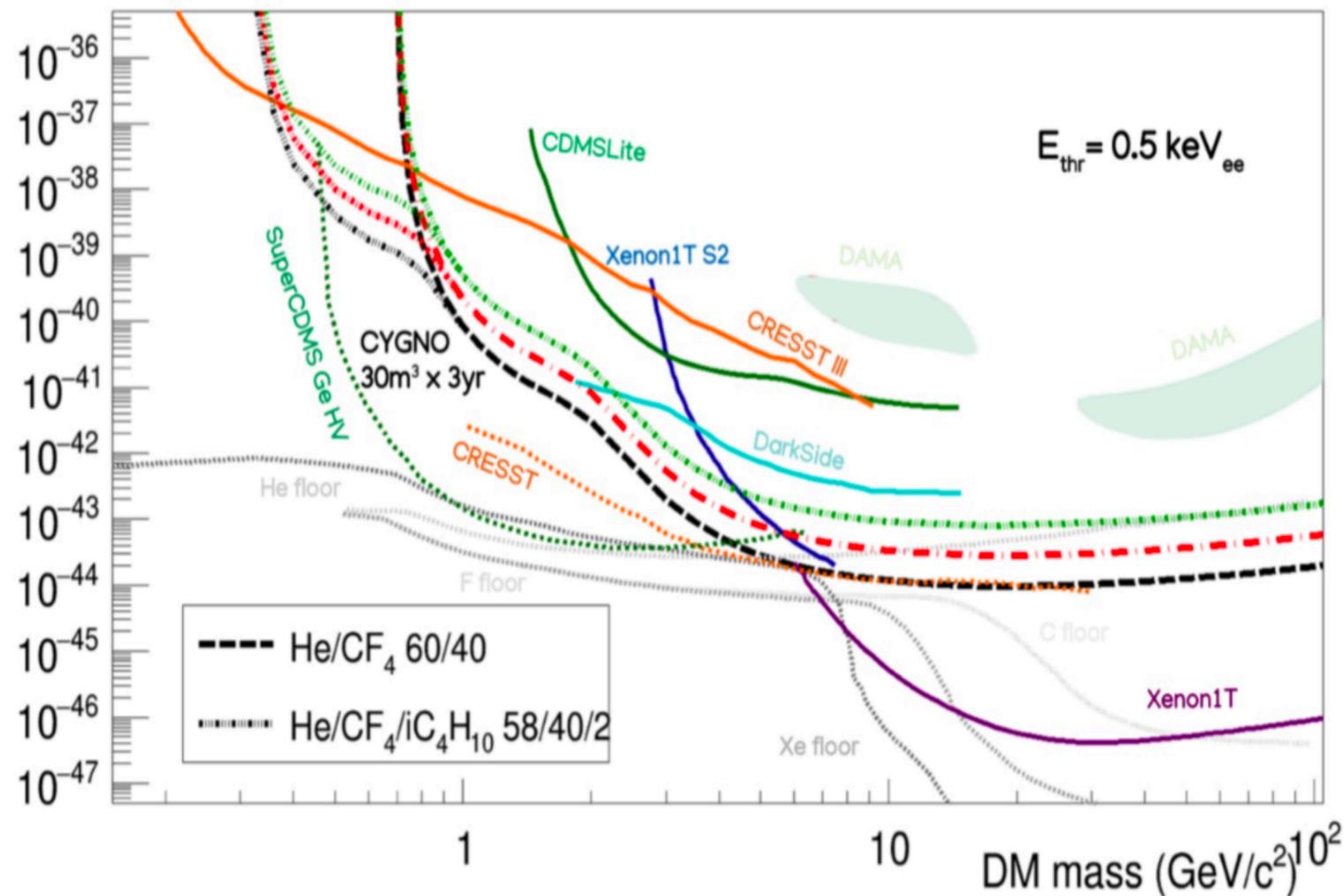


- Use 1(0.5) keV<sub>ee</sub> threshold
- QF evaluated with SRIM
- Angular distribution as discriminating information

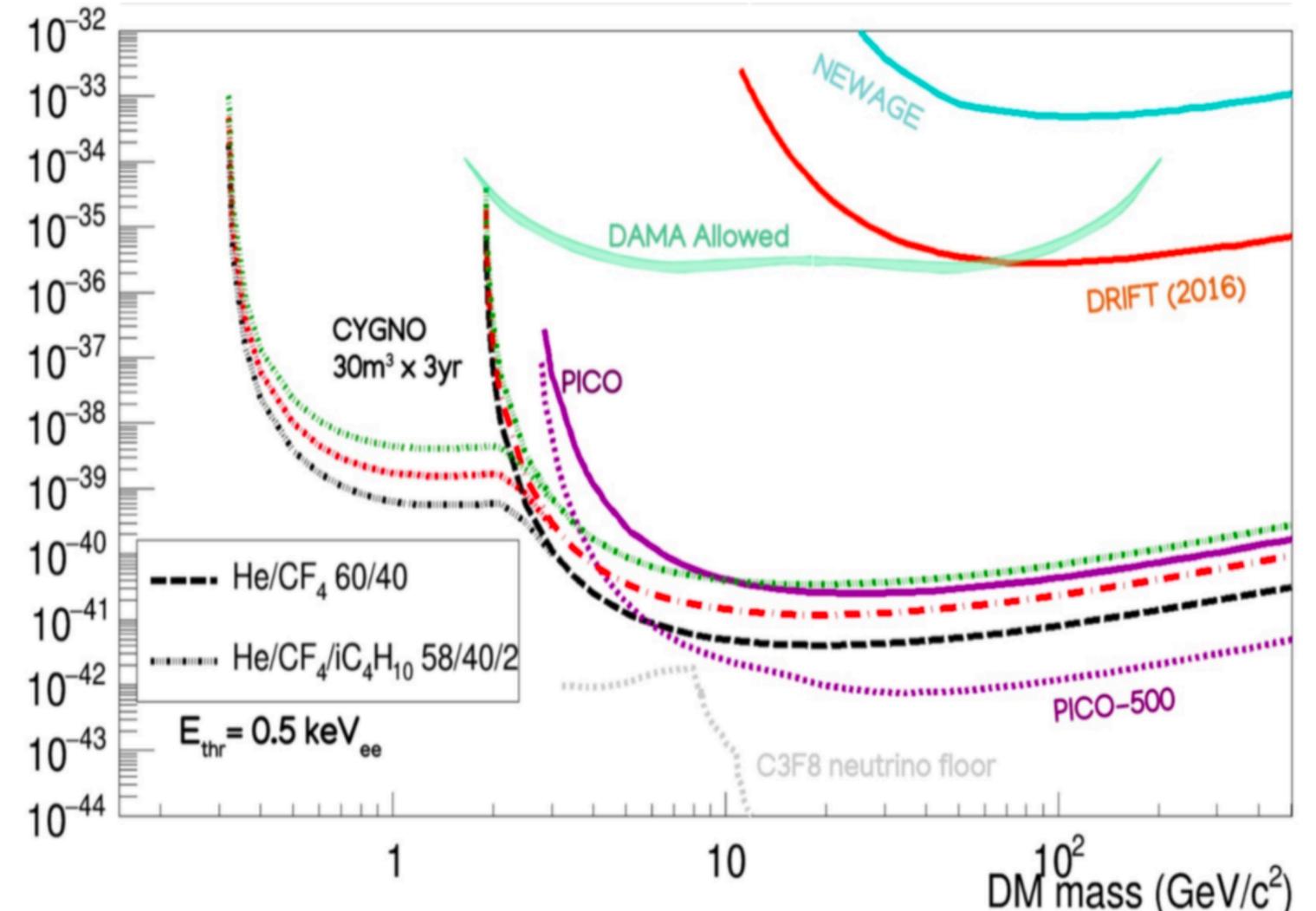
assumed bkg / y

- $n_{\text{BKG}} = 10^2$
- - -  $n_{\text{BKG}} = 10^3$
- ⋯⋯  $n_{\text{BKG}} = 10^4$

## Spin Independent



## Spin Dependent

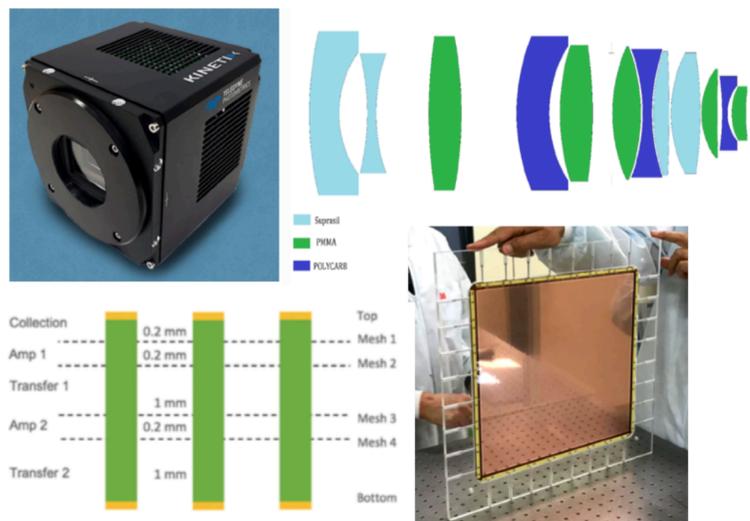


# R&D activities



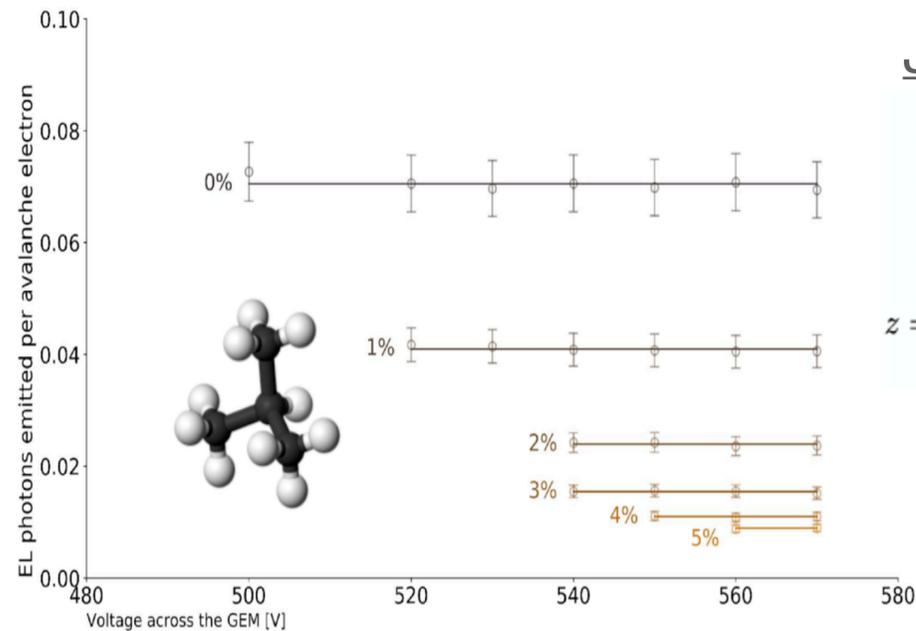
## Minimise internal radioactivity

- Develop **custom sCMOS** sensor
- Realisation of **custom lens** with large aperture & low radioactivity
- Optimise field-cage materials



## Gas studies

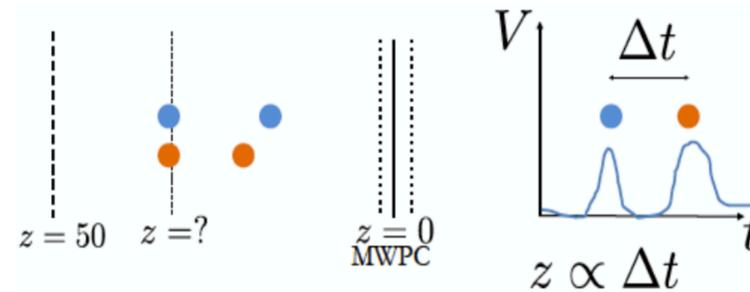
- Adding **hydrogenated gas**
- **Very good light yield** from with hydrocarbons
- Eco-friendly gas studies



## Negative ion drift (ERC INITIUM GA 818744)

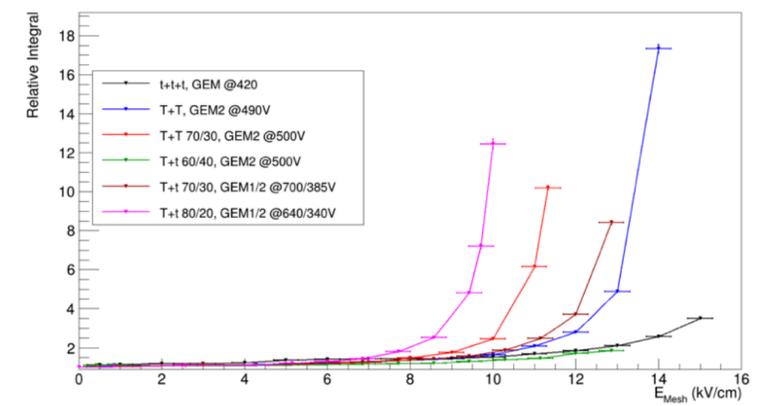
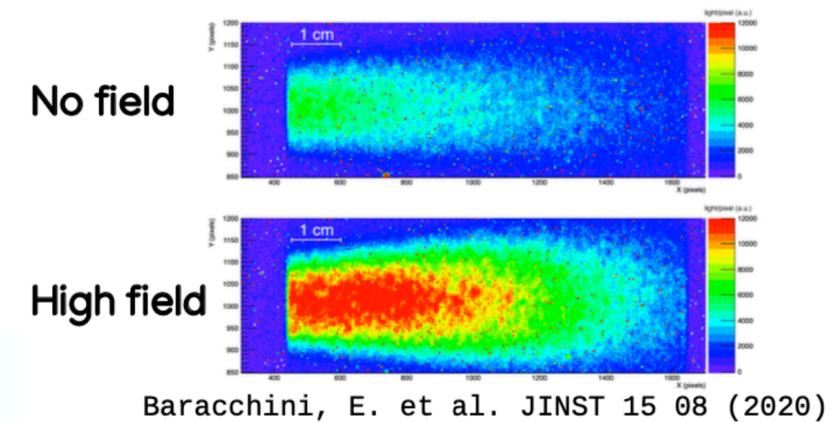
- **Negative ions** SF<sub>6</sub> to improve spatial resolution
- Encouraging results at nearly **atmospheric pressure**

JINST 13 (2018) 04, P04022



## Enhance light with strong electric fields

- Apply strong **electric field after the GEMs** to accelerate electrons and produce more light



# Summary



- The CYGNO collaboration is developing a **He:CF<sub>4</sub> TPC with optical readout**
- **CYGNO PHASE 0 commissioned overground**: very good detector stability, energy and position resolution;
- **CYGNO PHASE 0 underground at LNGS currently ongoing**: validate the background model, shielding configuration, measure neutron flux;
- **CYGNO PHASE 1**: construct and operate a **CYGNO demonstrator** to pave the road for a larger apparatus for Dark Matter search.
- A 30-100 m<sup>3</sup> CYGNO detector might connect to a multi-site **CYGNUS observatory** for rare events

# Acknowledgements

This project has received fundings under the European Union's Horizon 2020 research and innovation programme from the Marie Skłodowska-Curie grant agreement No 657751 and from the European Research Council (ERC) grant agreement No 818744

CYGNO Project is funded by INFN.



# Thank you!

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The University Of Sheffield.



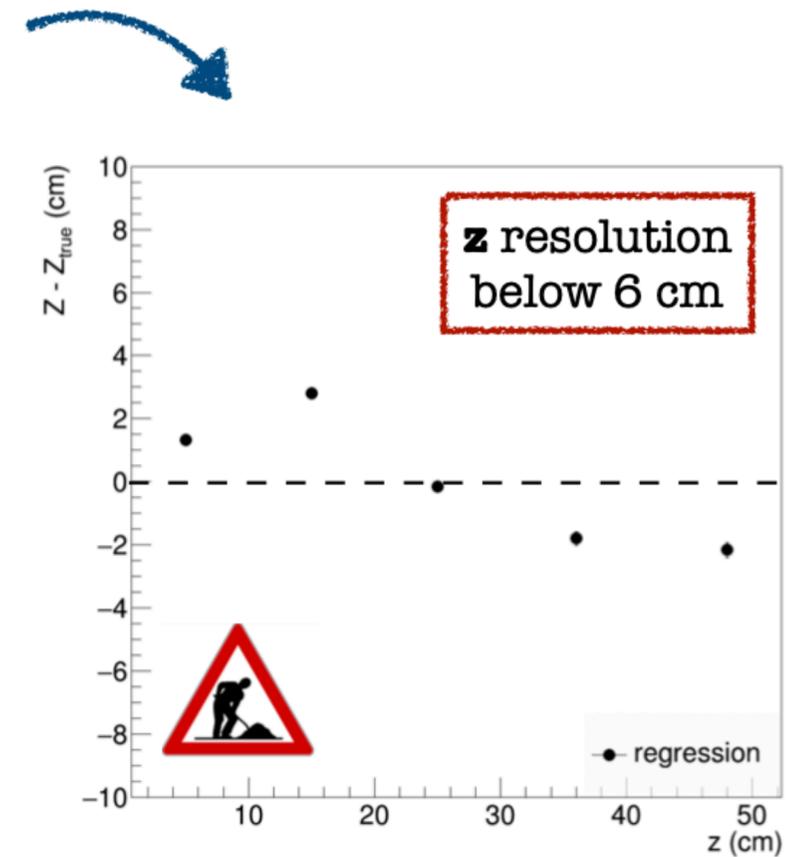
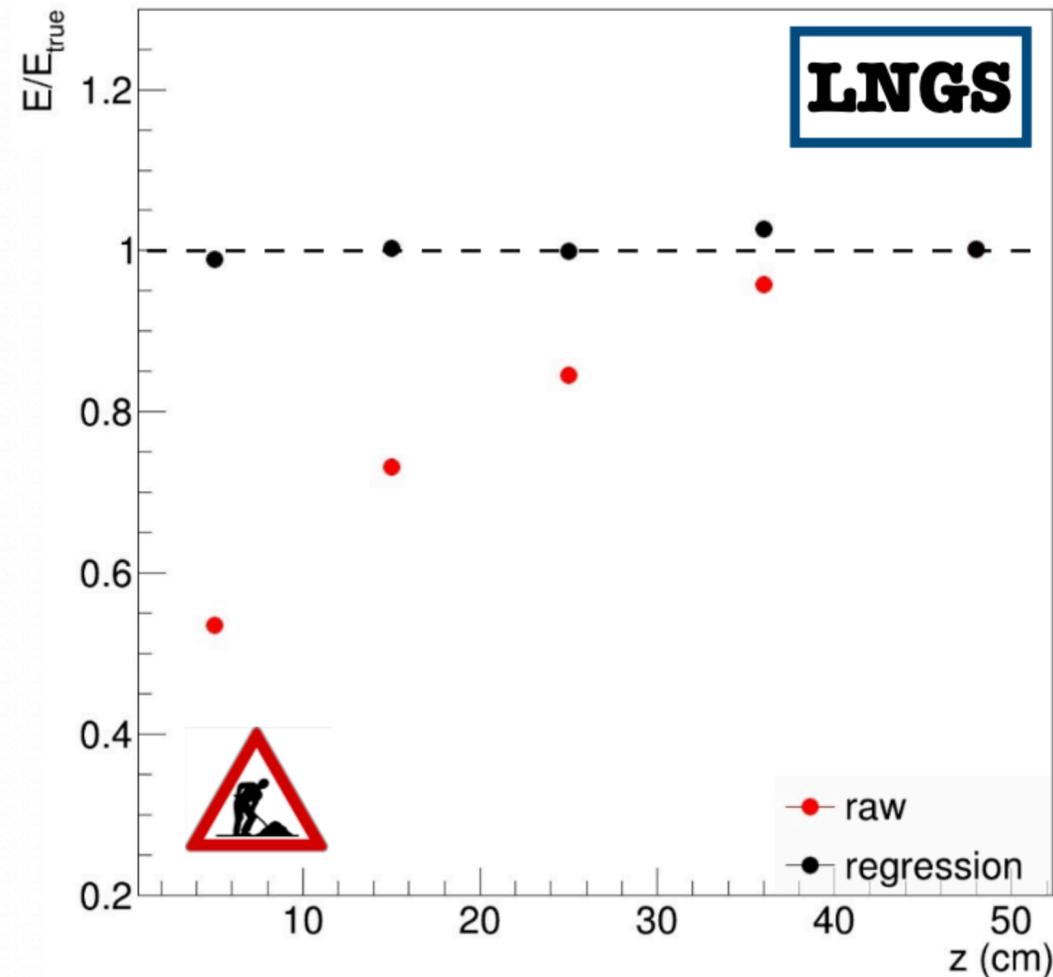
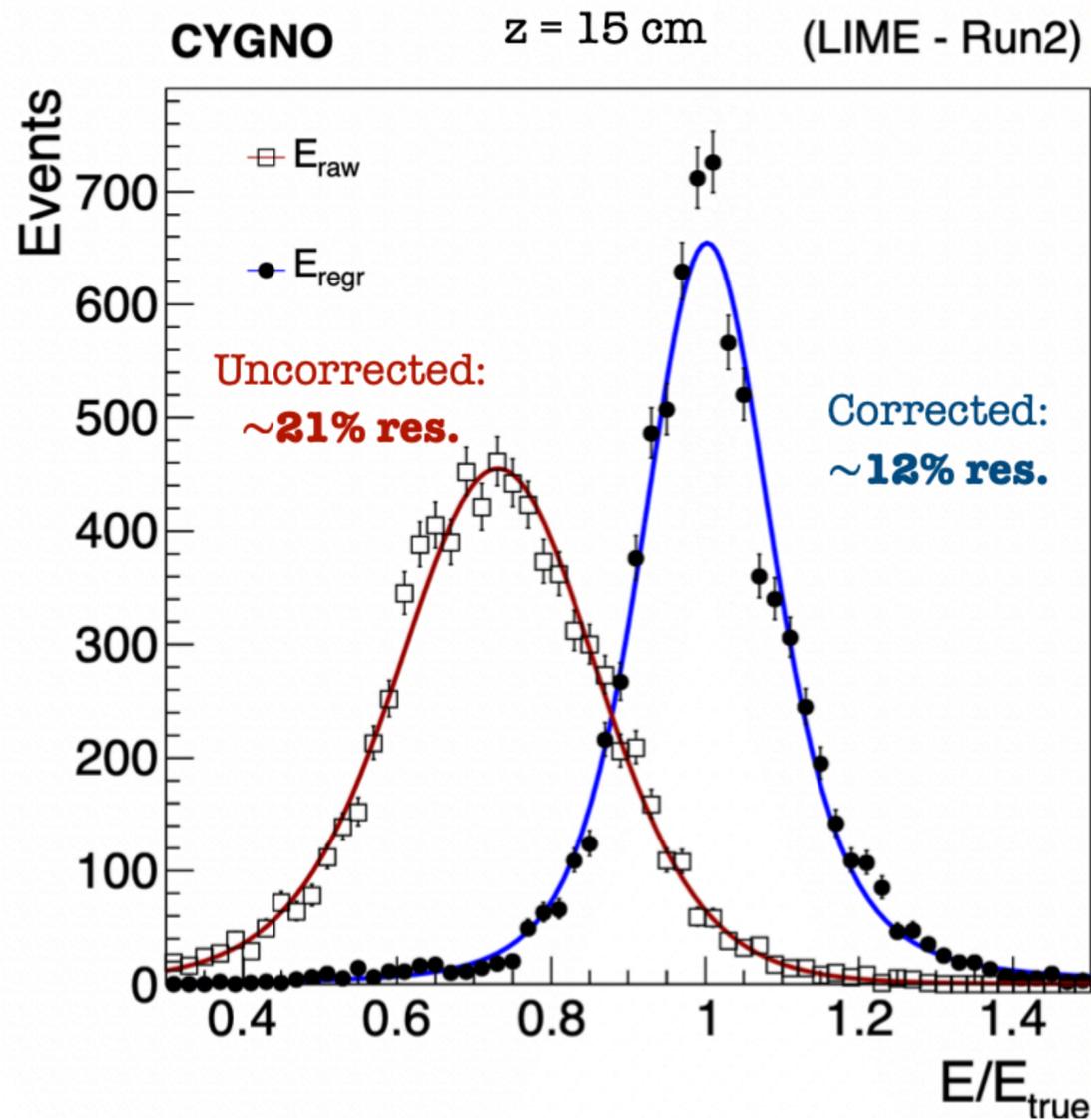
SAPIENZA UNIVERSITÀ DI ROMA

1290 UNIVERSIDADE D COIMBRA

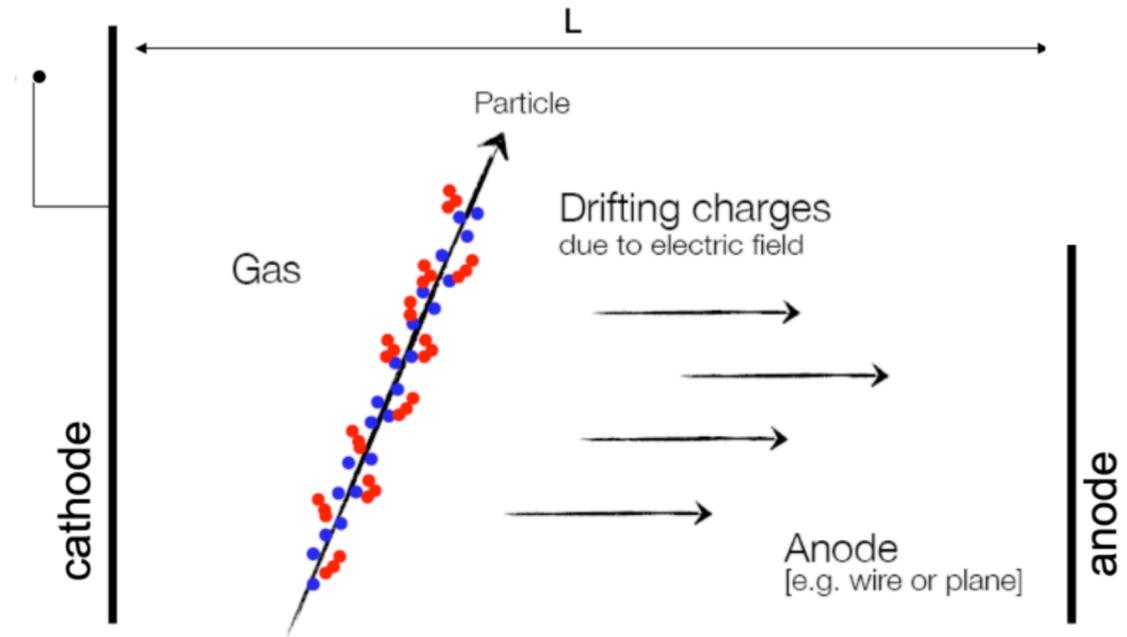


# The multivariate regression

- **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**

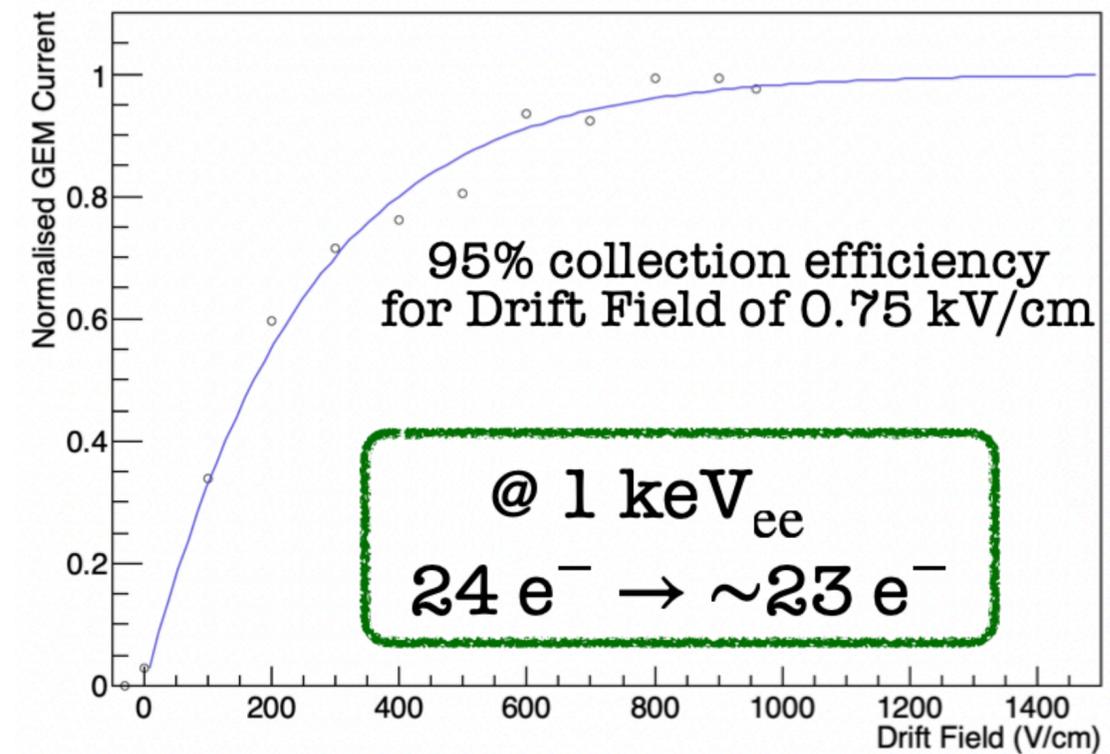
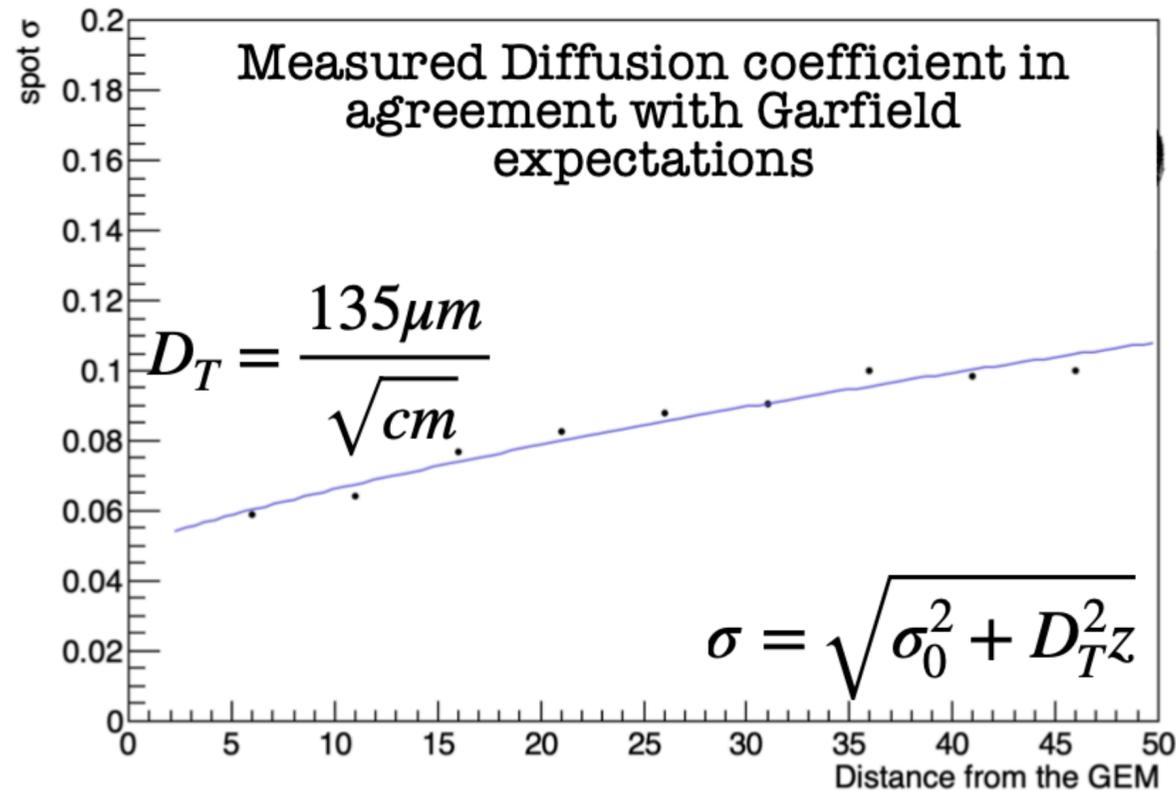


# Drift along the drift gap

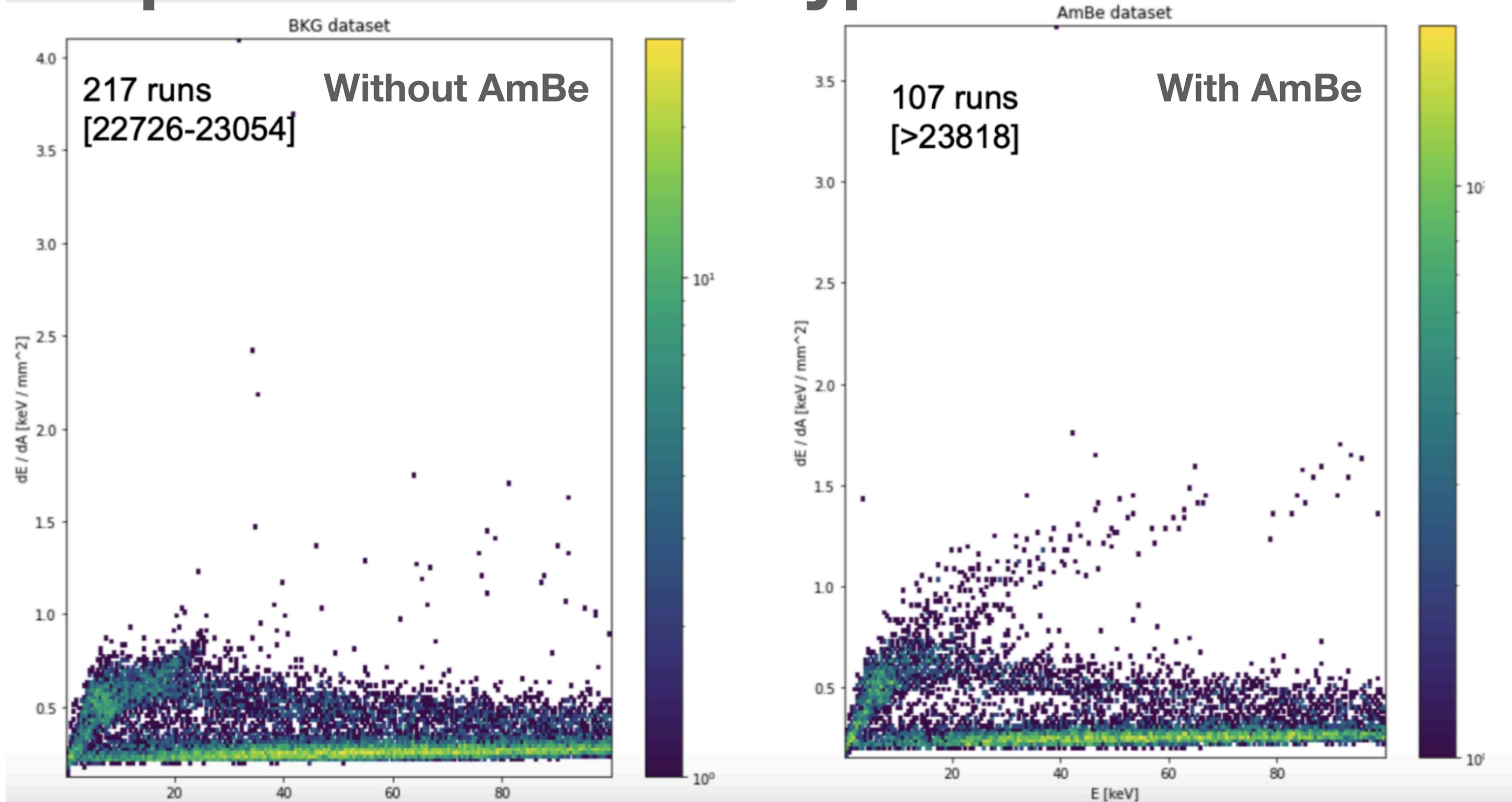


- Continuous hits during the path  $\Rightarrow$  diffusion

- Electrons captured by electronegative impurities along the drift



# Response to different type of interactions:



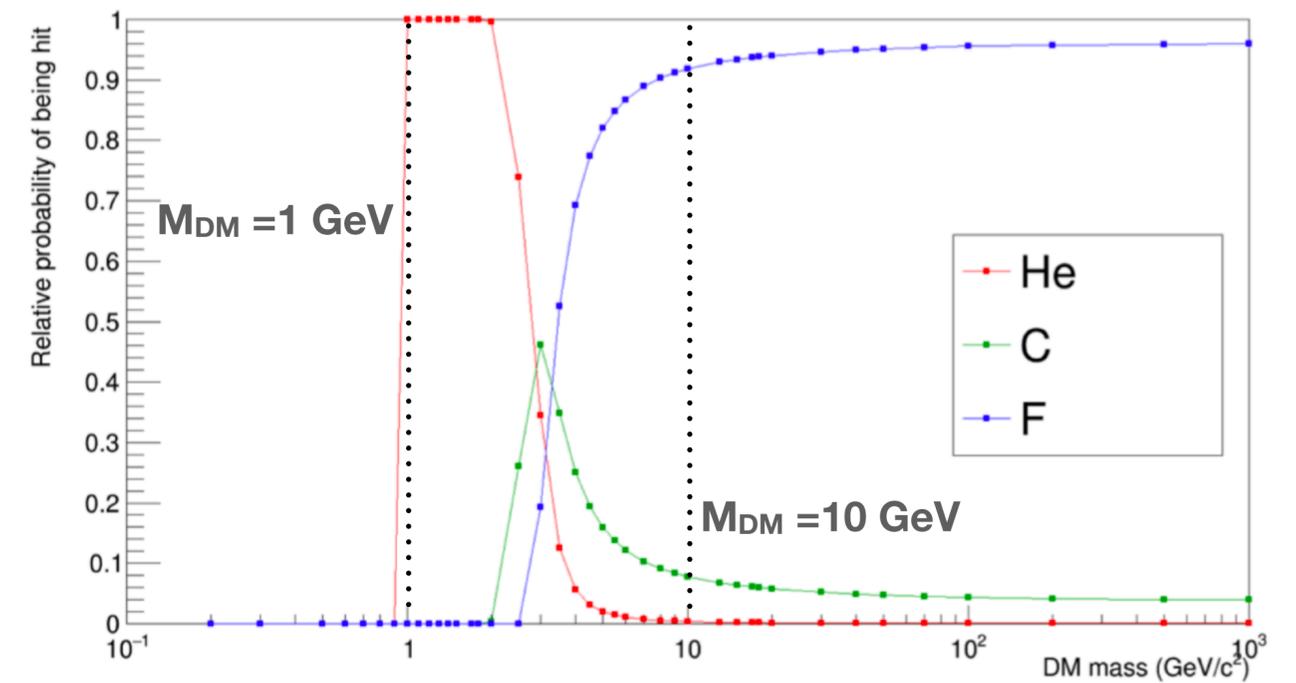
# PHASE 2: The **CXGNO** experiment 30 m<sup>3</sup>

## Searching for low mass DM

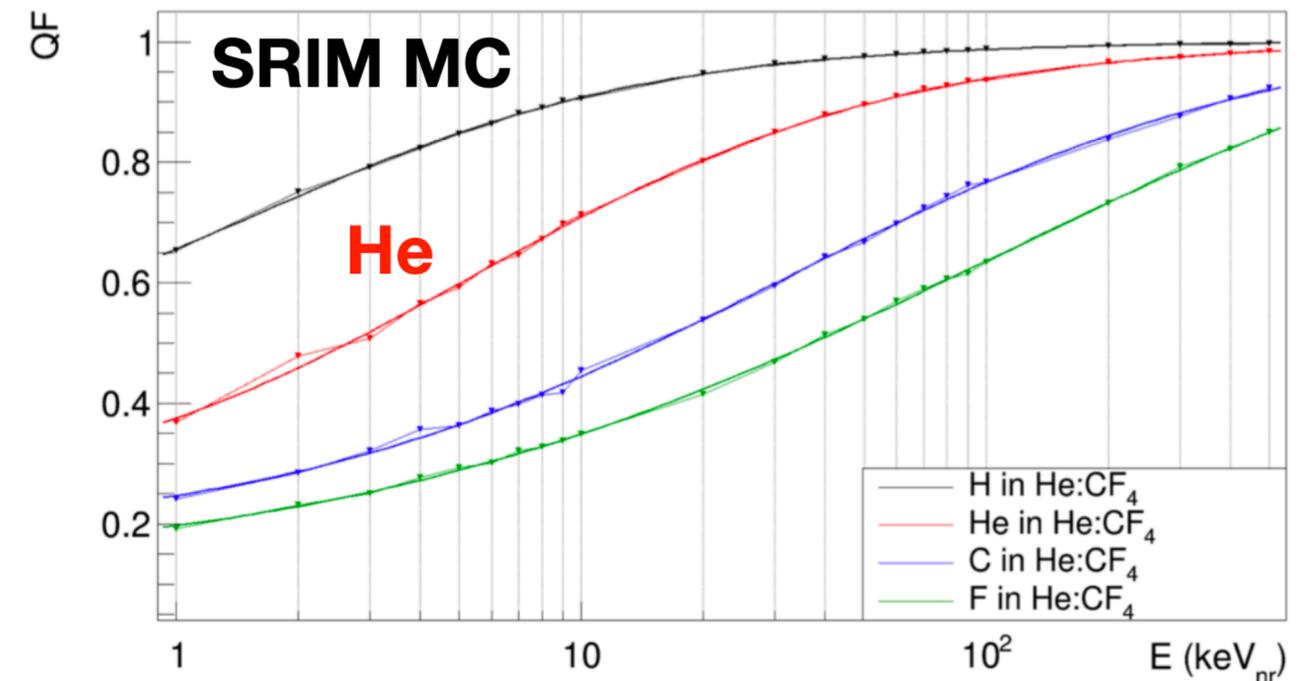
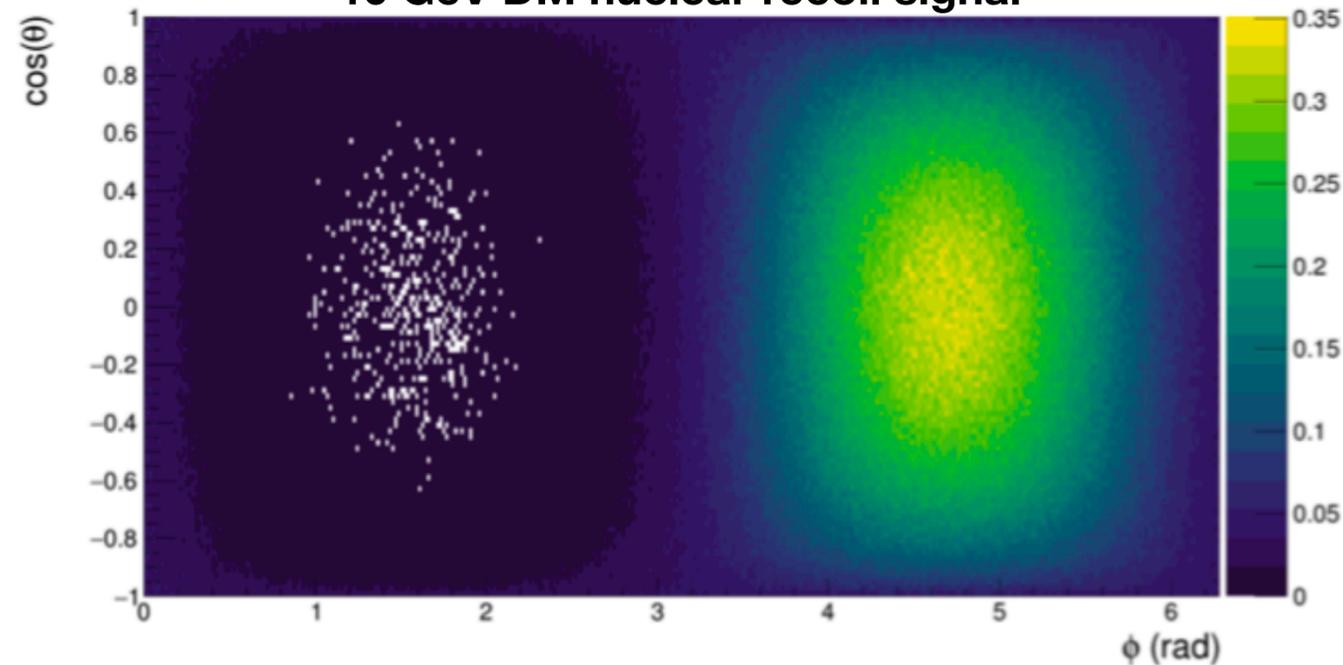


- Use 1(0.5) keVee threshold
- QF evaluated with SRIM
- Angular distribution as discriminating information
  - full head/tail recognition
  - 30 deg. resolution
- Various scenarios with different background levels
  - isotropic distribution

relative probability to detect a NR at 1 keV th.



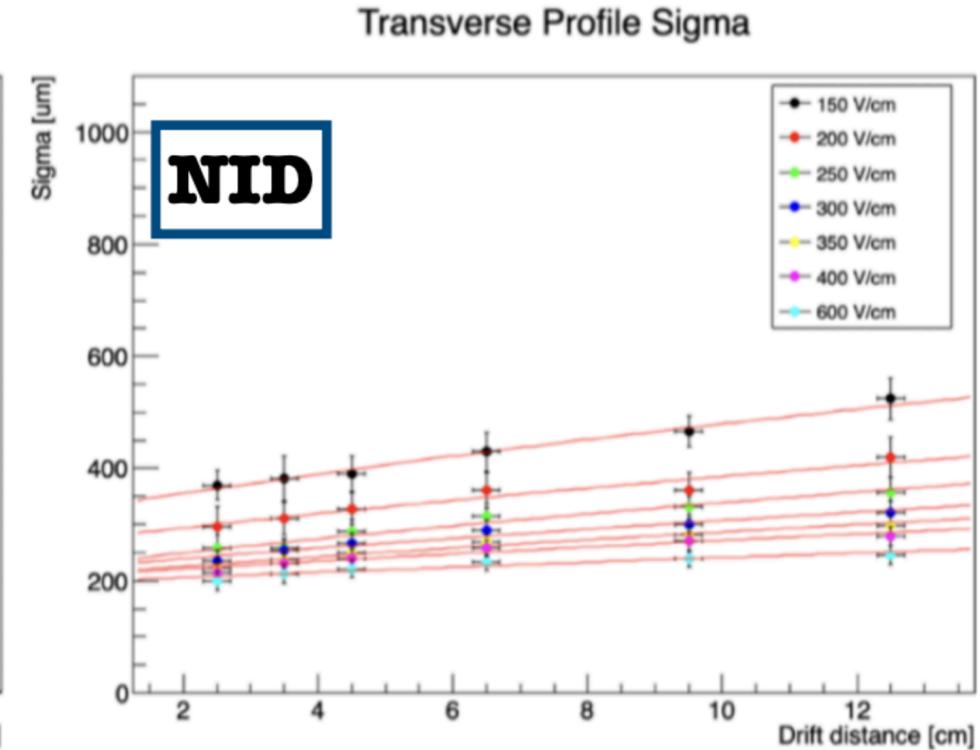
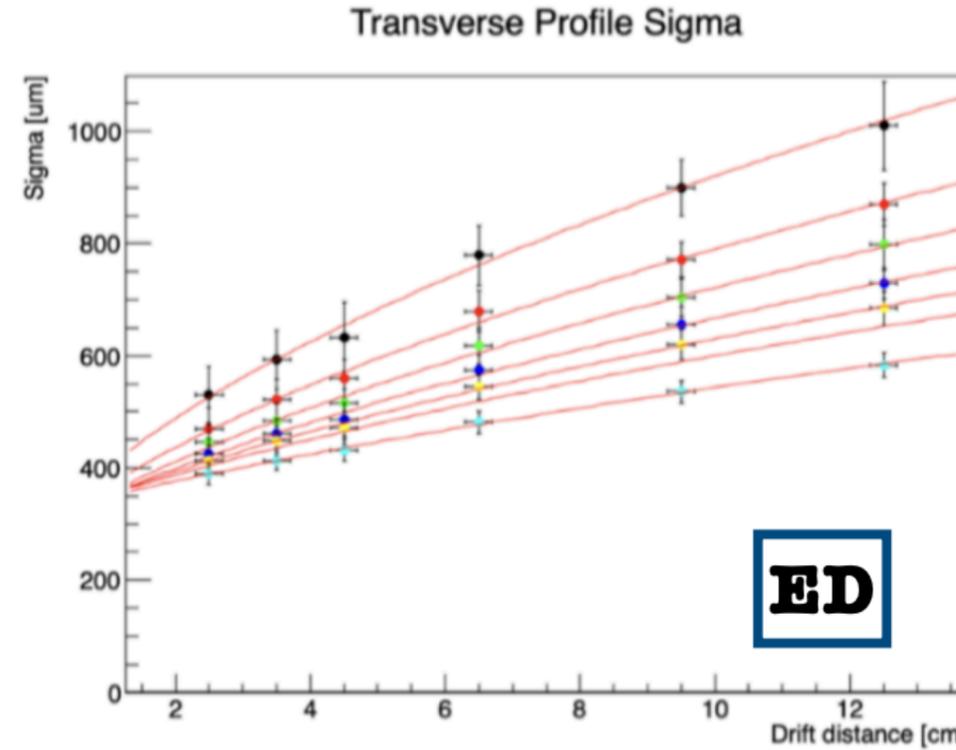
10 GeV DM nuclear recoil signal



# R&D: Negative Ion Drift (NID)



European  
Research  
Council



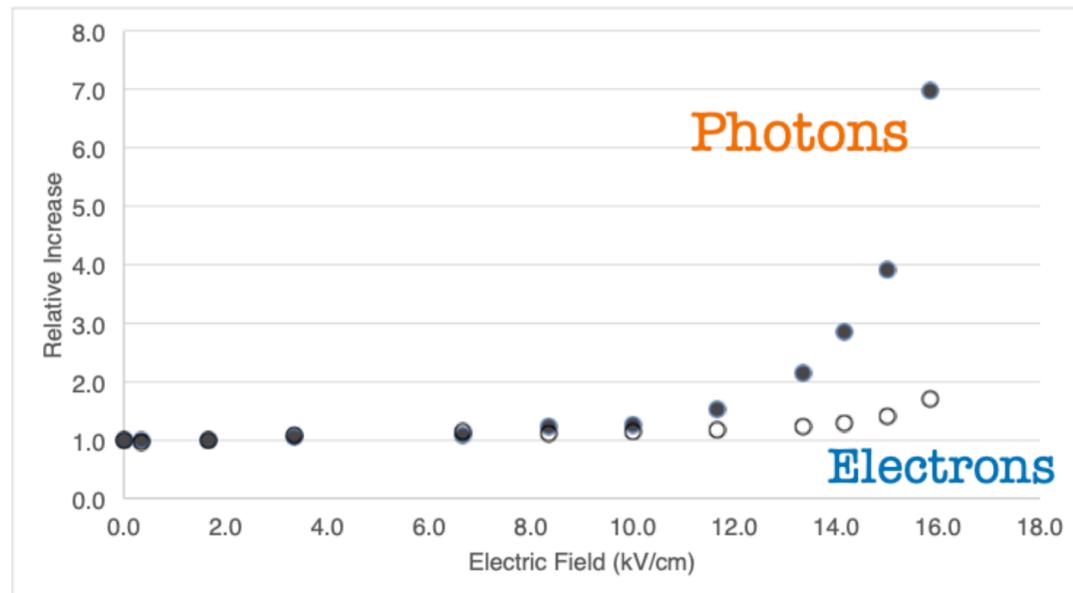
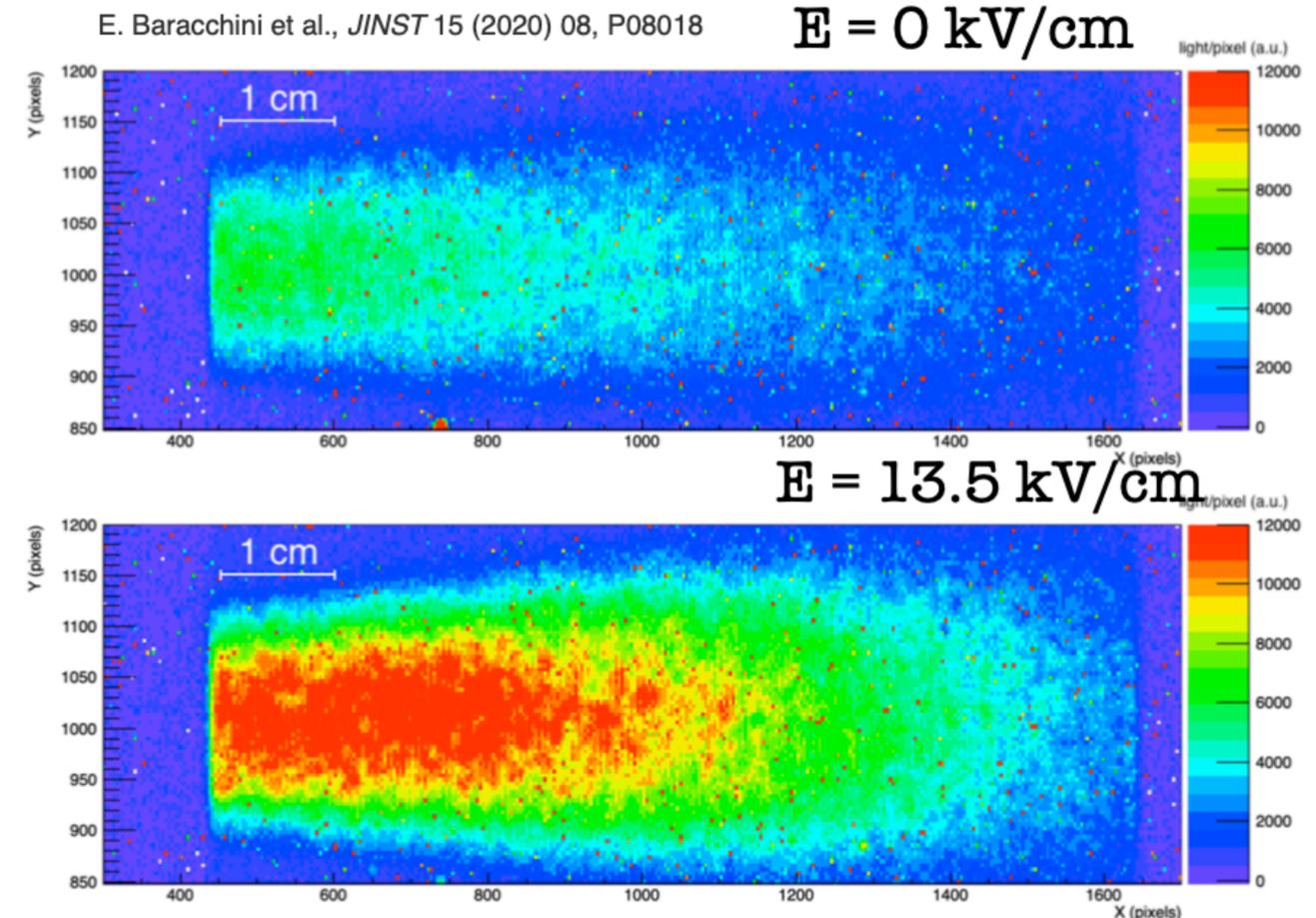
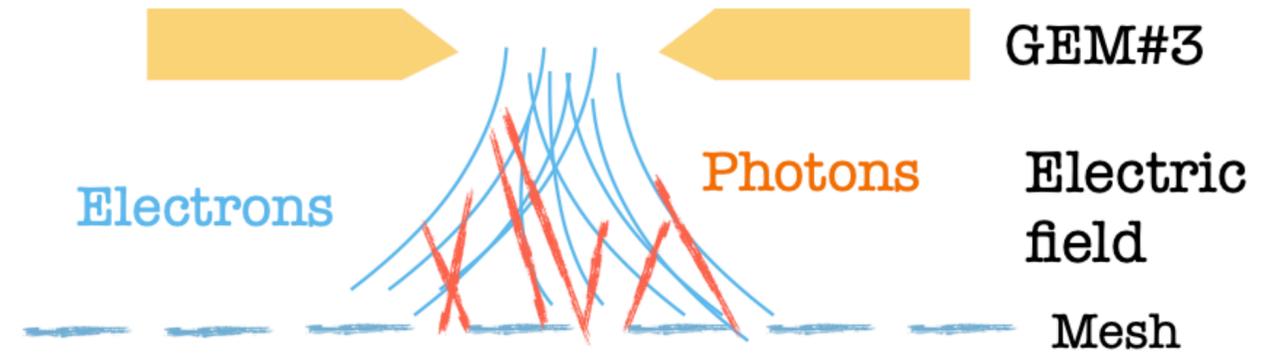
- **INITIUM project:** the development and operation of the first **1 m<sup>3</sup> Negative Ion TPC (NITPC)** with **GEMs** amplification [in **He/CF<sub>4</sub>/SF<sub>6</sub>** mixture] and **optical readout** with CMOS-based cameras and PMTs.

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

