THE CYGNO PROJECT: PERFORMANCE AND STABILITY OF AN OPTICALLY READOUT GEM-TPC

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CYGNO PROJECT

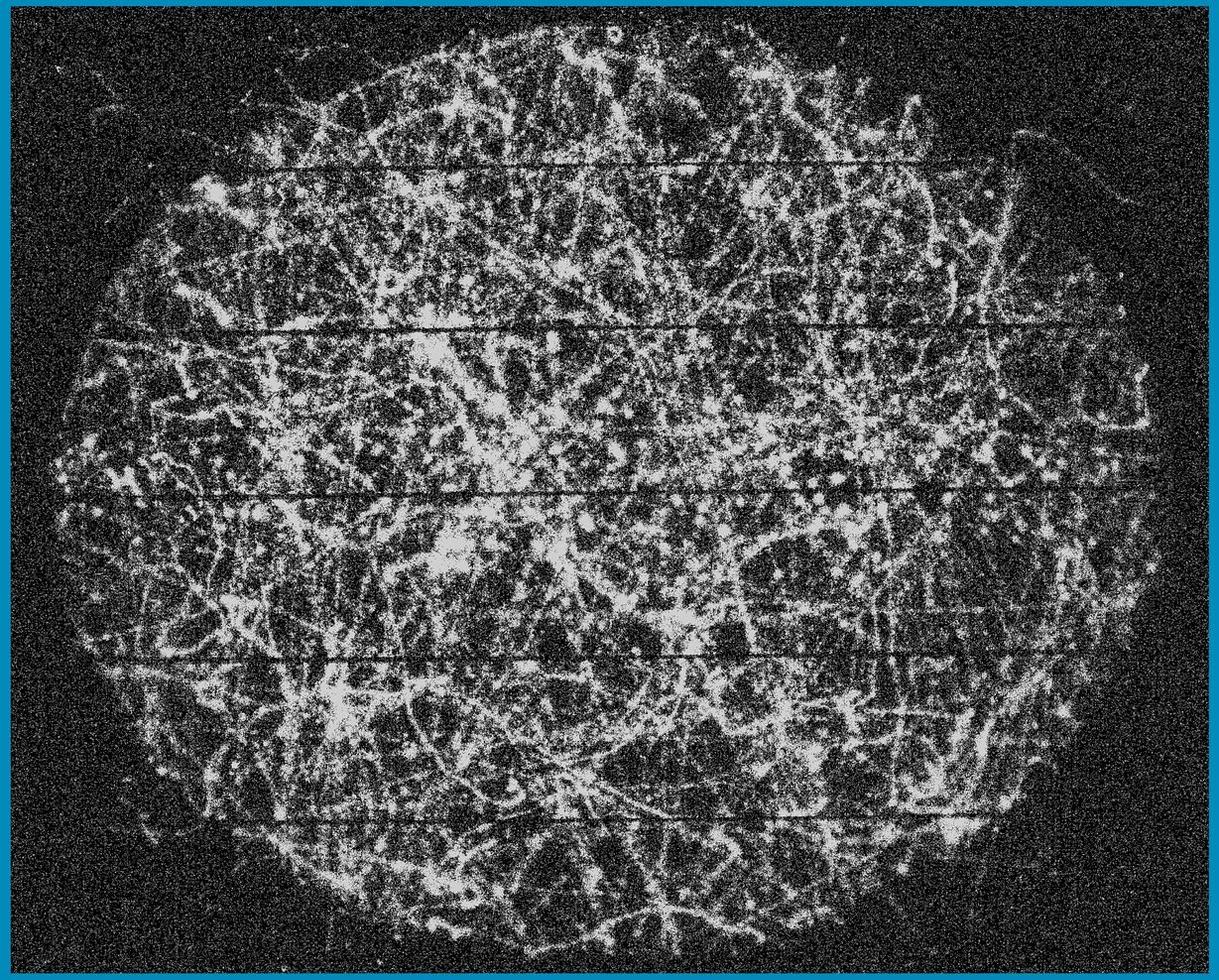
The aim of CYGNO project is the development and realisation of a **GEM-based Optically Readout Time Projection Chamber** for the study of rare events with energy releases in the **range 1-100 keV**.

Expected performance is:

- High **detection efficiency** down to **1 keV**;
- **Directionality** at **10 keV**;
- Background **rejection below 10 keV**;

Main ideas of the technology are:

- **He/CF_4** based gas target (atmospheric pressure);
- **GEM** amplification stage;
- **Combined optical readout** CMOS + PMT;

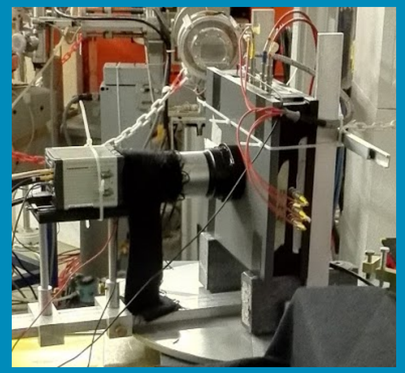


PROJECT PHASES

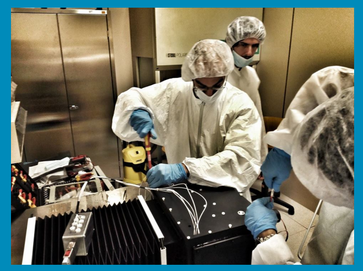
PHASE 0: R&D

PHASE 1: ~1M³ DEMONSTRATOR

2016/17	2018/19	2019/20	2021/22	2023
@ ROMA1/LNF	@ LNF	@ LNF/LNGS	@ LNF/LNGS	@ LNGS
ORANGE	LEMON	LIME	Construction & test	Installation & commissioning

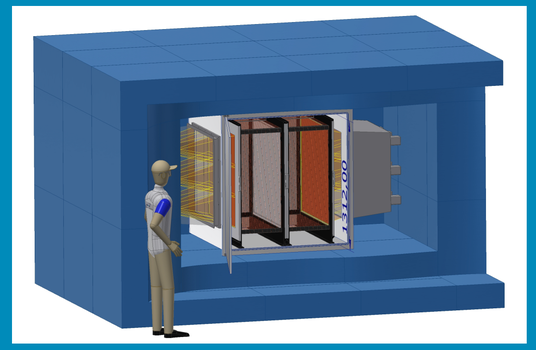


- 1 cm drift



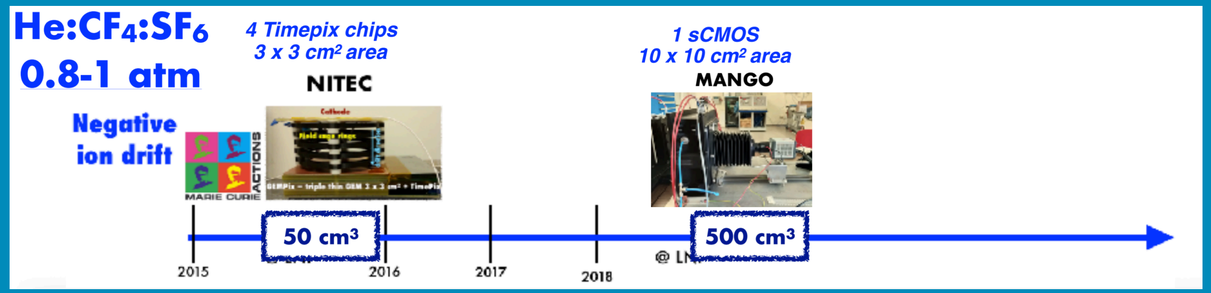
- 3D printing
- 20 cm drift

- 50 cm drift
- underground tests
- shielding



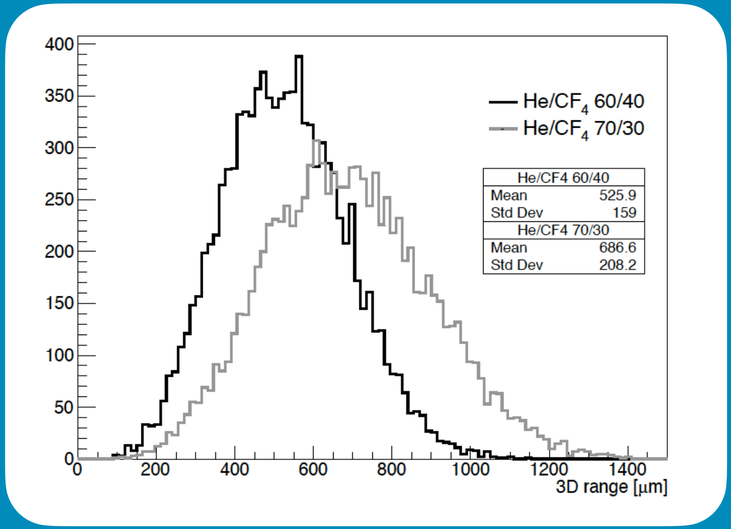
- background
- materials test
- gas purification
- scalability
- reliability

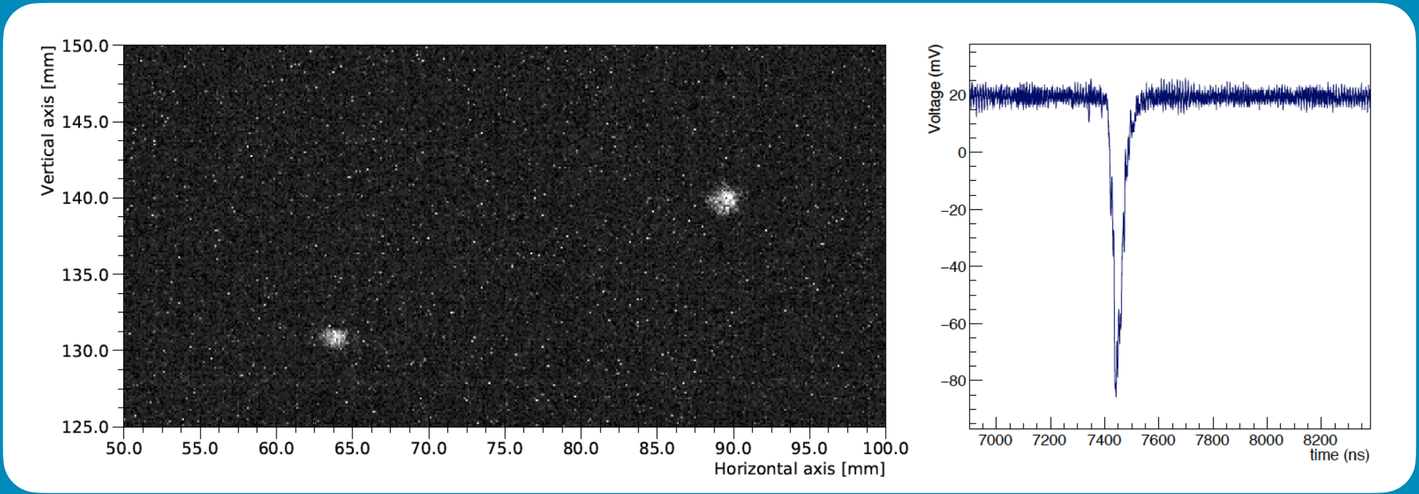
CYGNUS 30-100 m³

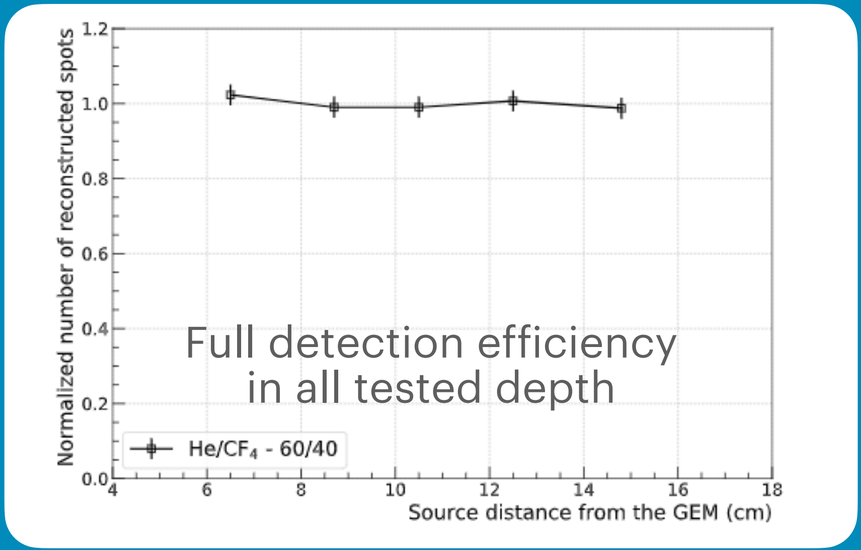


PERFORMANCE WITH ^{55}FE: SPOT SIGNALS

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

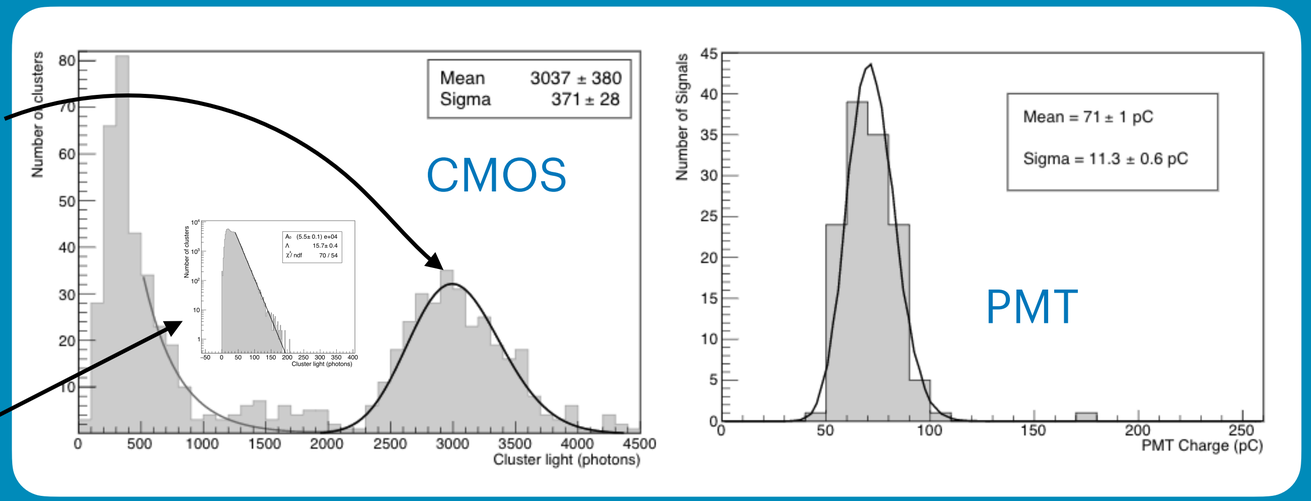






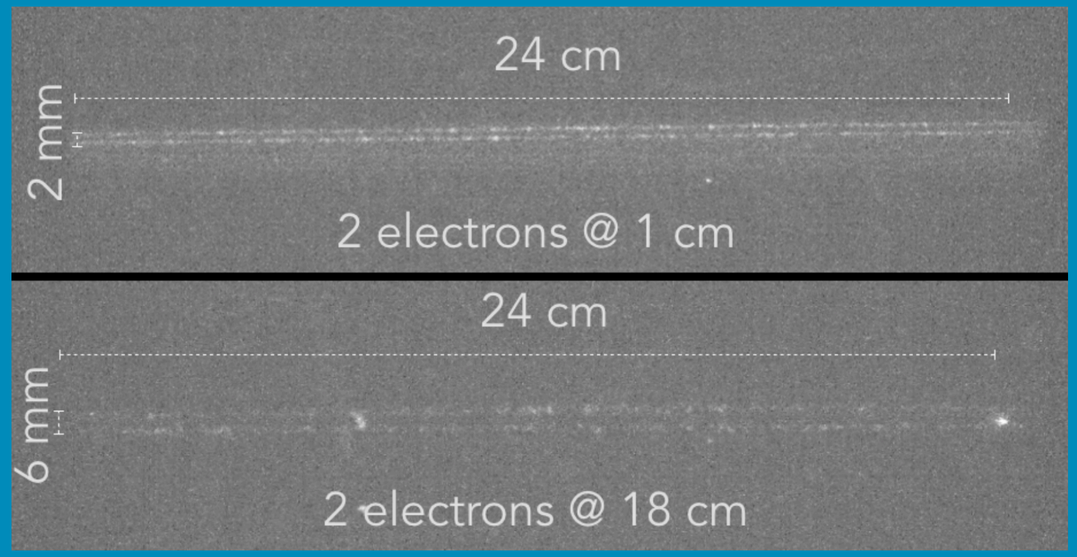
500 photons collected per keV

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

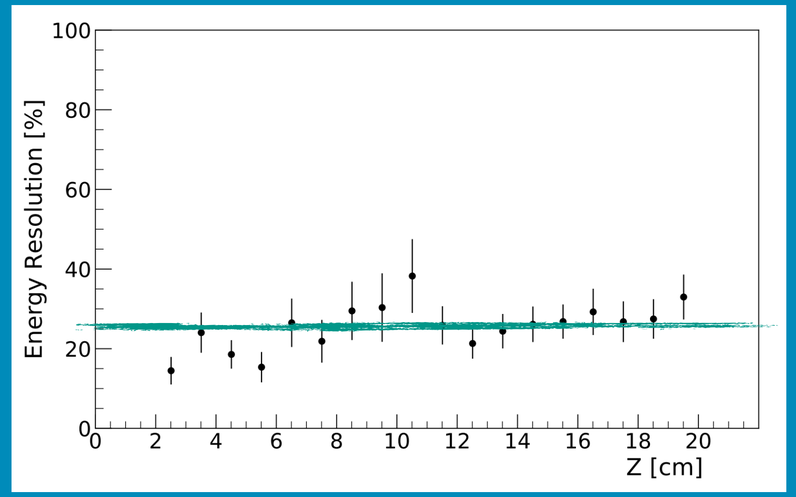


Energy resolution of 15% with CMOS and PMT

PERFORMANCE ON ELECTRON BEAM: LONG TRACKS

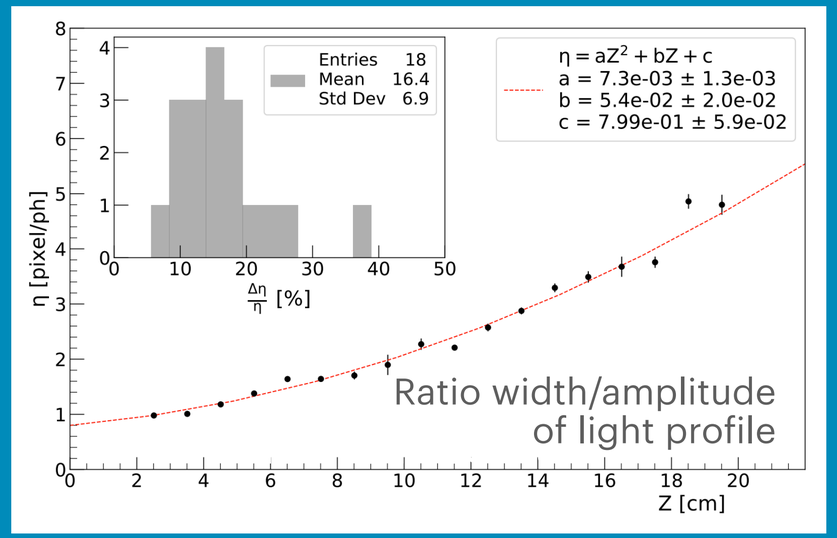


Analysis was performed by splitting tracks in 36 slices **7 mm** long (i.e. **1.6 keV**)

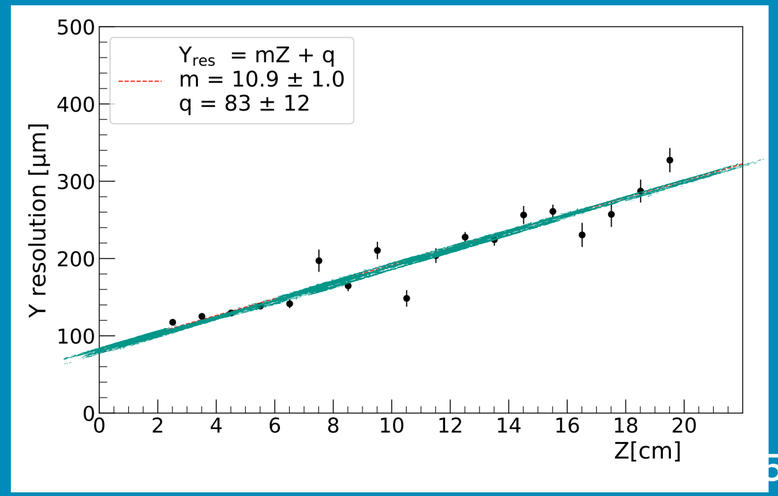


Average Energy resolution of **25%** (i.e. **400 eV**)

Diffusion can be exploited to evaluate **absolute Z position** with an average **resolution of 15%**



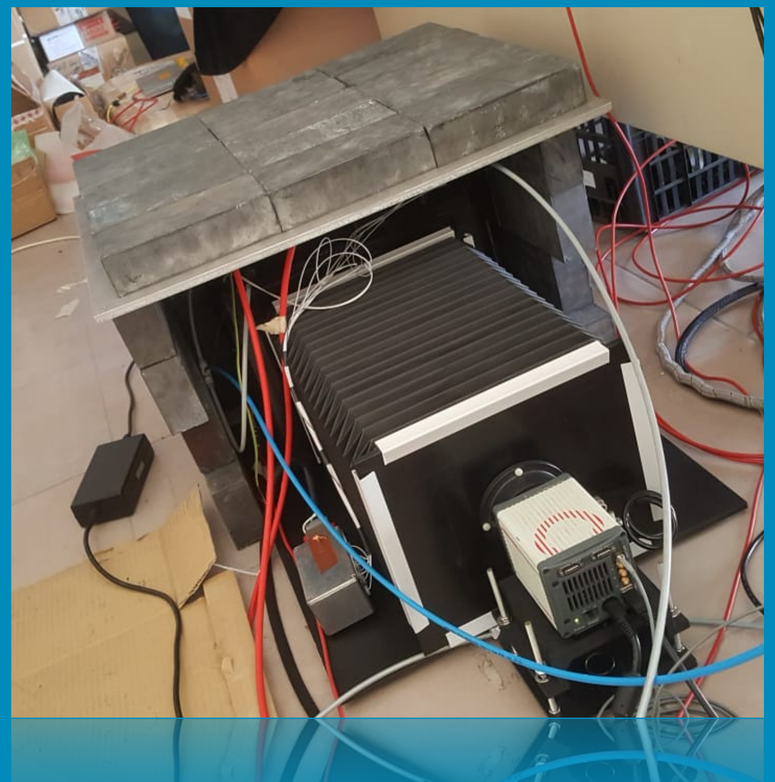
Relative **position** evaluated with a resolution between **100 µm and 300 µm**



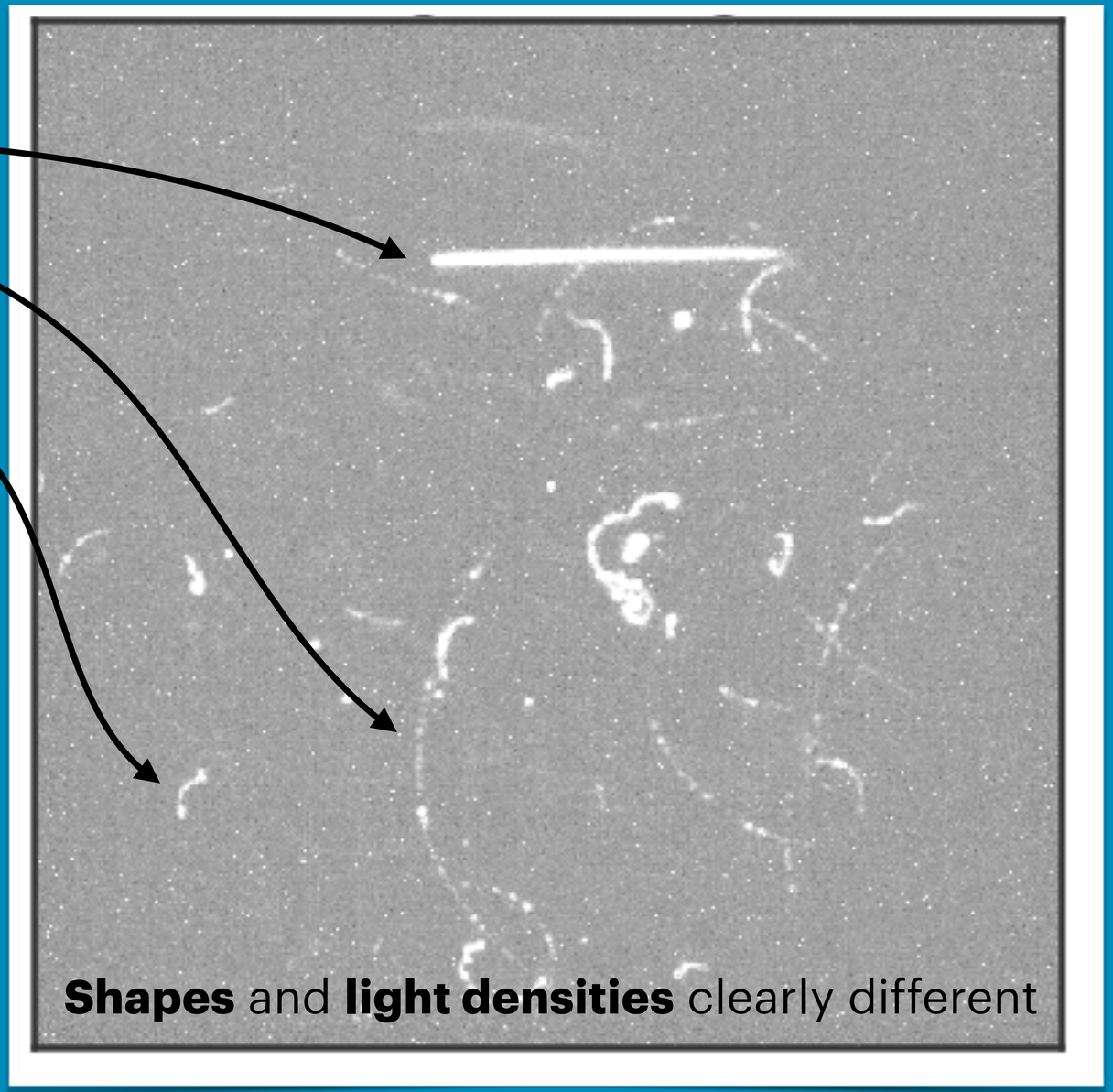
PERFORMANCE WITH NUCLEAR RECOILS

Detector was tested with **AmBe** source:

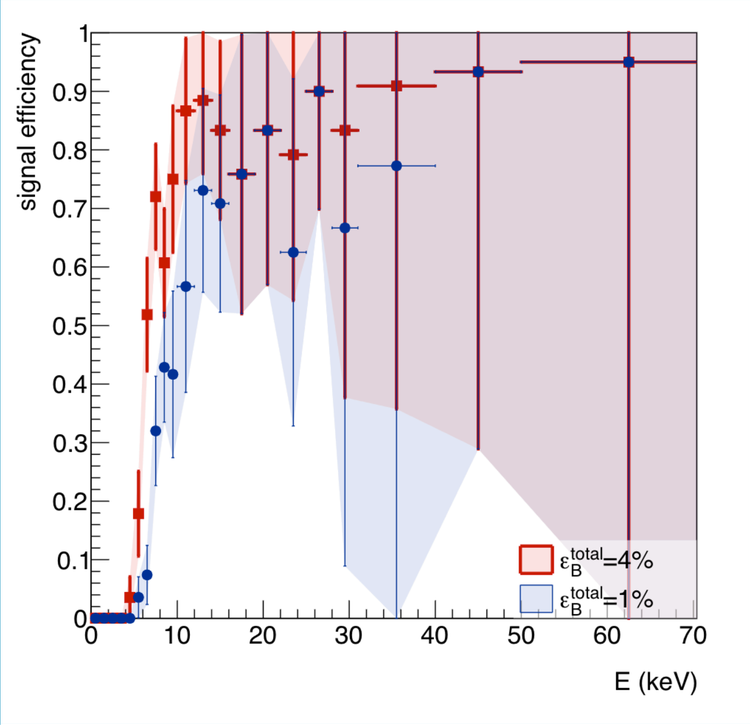
- 1-10 MeV neutrons -> **nuclear** recoils
- 4 MeV photons -> high energy **electrons**
- 59 keV photons -> 59 keV **electrons**

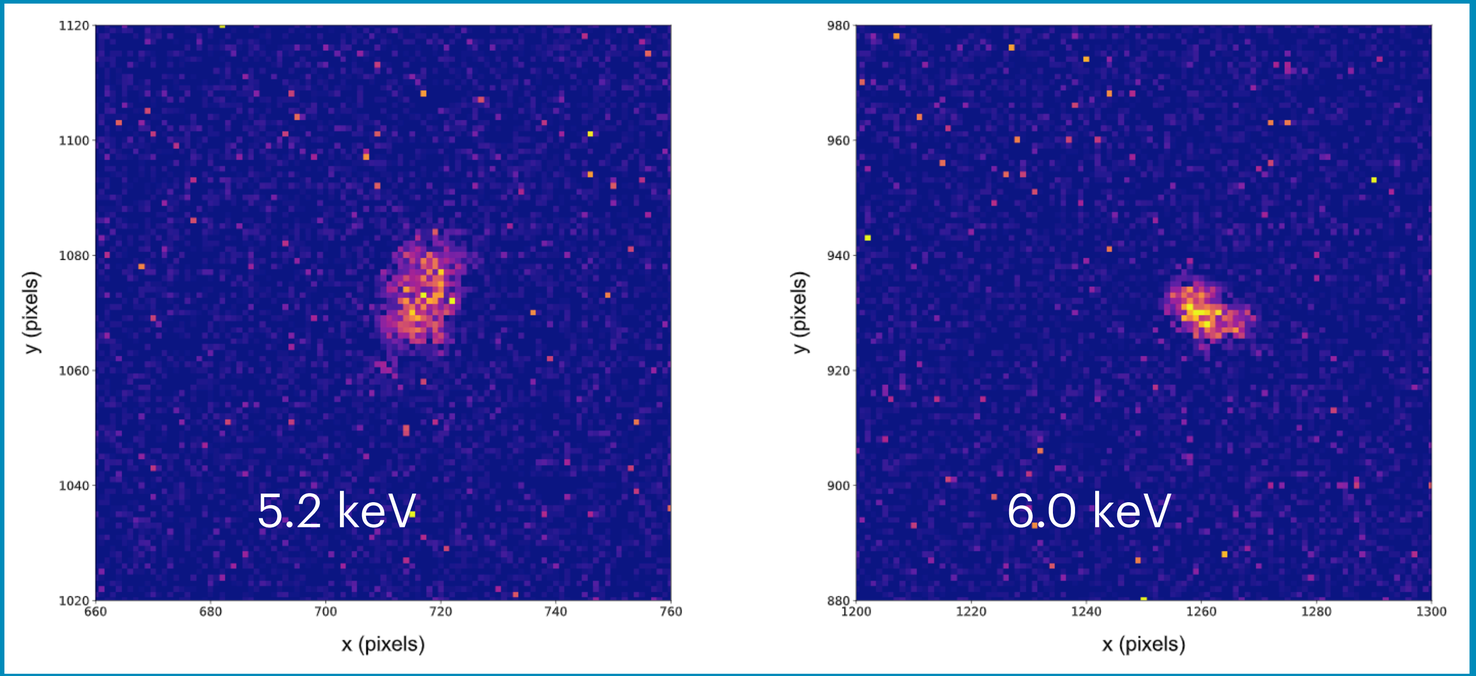


A 5 cm Pb shield was used



PERFORMANCE WITH NUCLEAR RECOILS





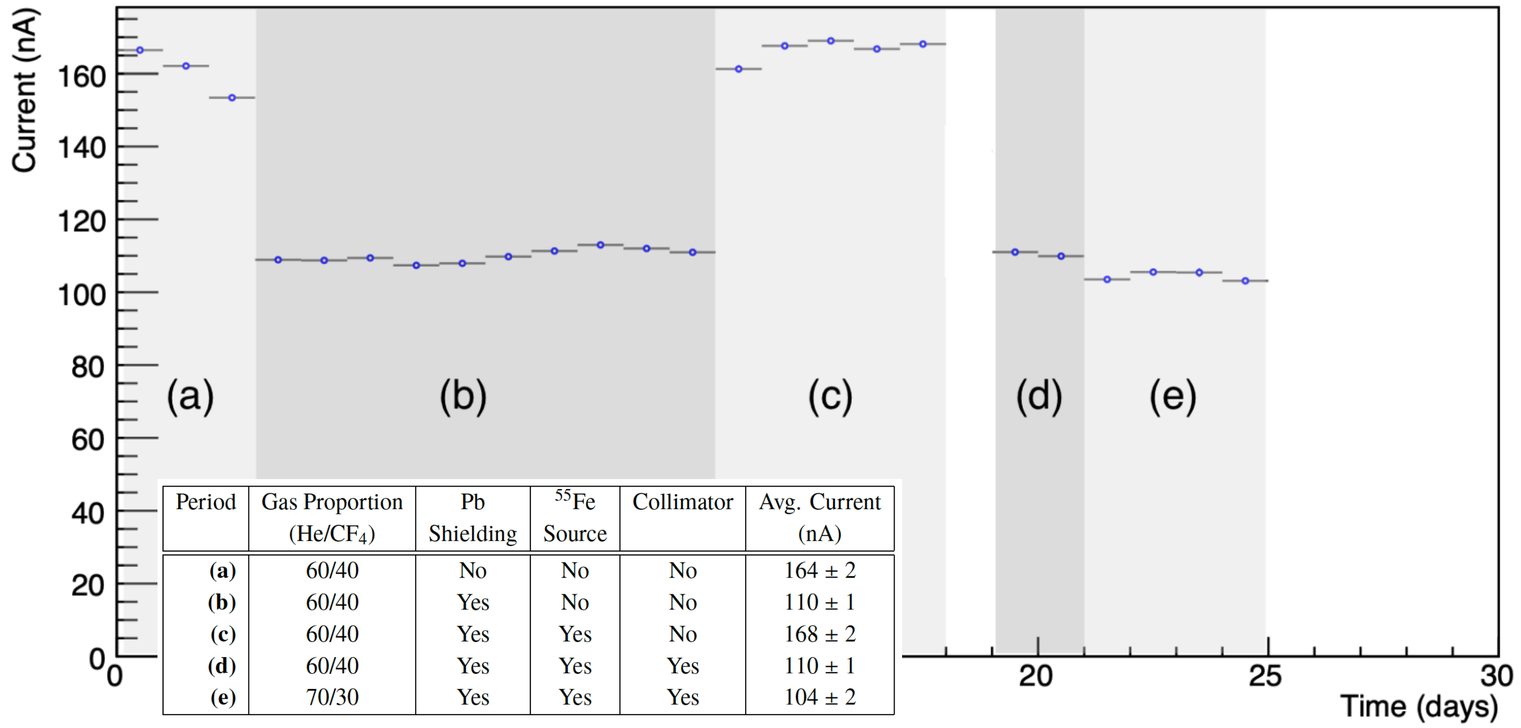
working point	Signal efficiency			Background efficiency		
	ε_S^{presel}	ε_S^{δ}	ε_S^{total}	ε_B^{presel}	ε_B^{δ}	ε_B^{total}
WP_{50}	0.98	0.51	0.50	0.70	0.050	0.035
WP_{40}	0.98	0.41	0.40	0.70	0.012	0.008

Nuclear recoil signals well visible even below **10 keV**

A sizeable efficiency in the range 5-10 keV was measured while more than **95% (99%) ^{55}Fe photons** were **rejected**

DETECTOR STABILITY

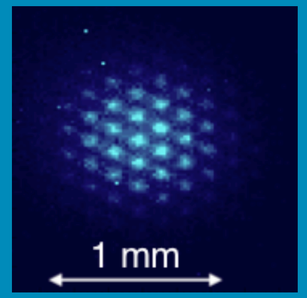
Detector high voltage was kept ON for a **25 day** period, while currents were monitored and logged
Stable and smooth operation without any “human” intervention.



Period	Gas Proportion (He/CF_4)	Pb Shielding	^{55}Fe Source	Collimator	Avg. Current (nA)
(a)	60/40	No	No	No	164 ± 2
(b)	60/40	Yes	No	No	110 ± 1
(c)	60/40	Yes	Yes	No	168 ± 2
(d)	60/40	Yes	Yes	Yes	110 ± 1
(e)	70/30	Yes	Yes	Yes	104 ± 2

Two kinds of instabilities were discovered in current behaviour:

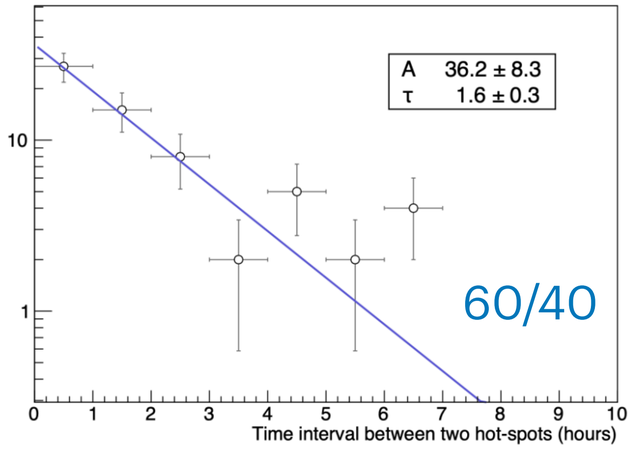
- **Discharges**: rapid and very high increases in current with a complete drop of the GEM voltage;
- **Hot spots**: small and stable increases in current accompanied by the appearing of a luminous spot on the GEM surface (likely due to self-sustaining micro-discharges).

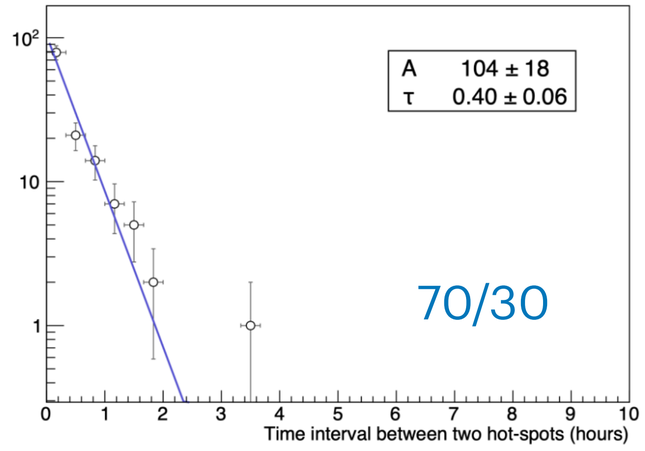


An **automatic** high voltage power cycle was developed to **dump hot-spots** that resulted very effective

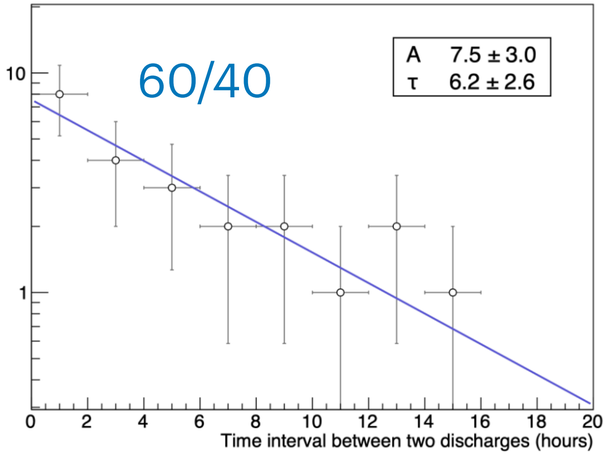
DETECTOR STABILITY

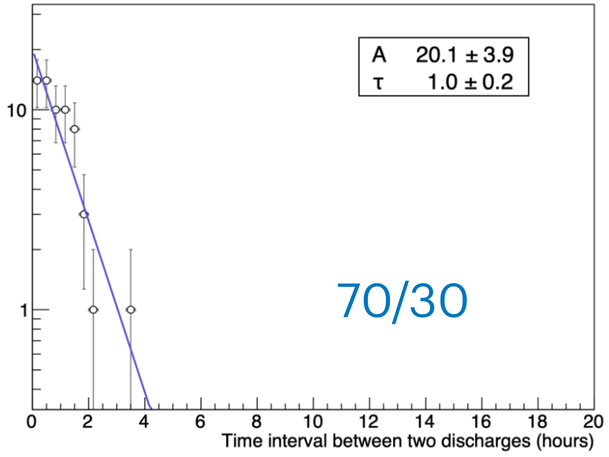
Hot-Spot time distance





Discharge time distance





The **time intervals** between the occurrence of two subsequent events were evaluated for two different He/CF_4 proportions.

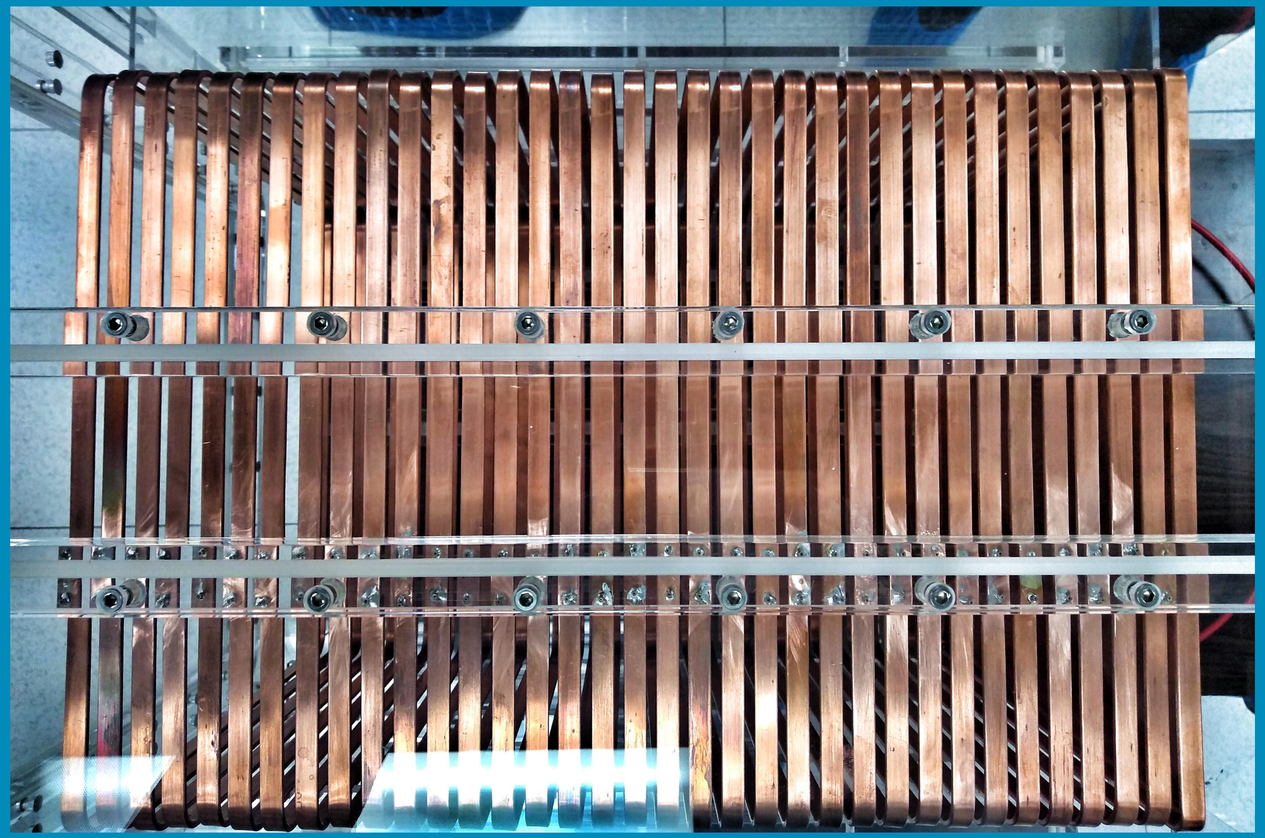
- their distributions showed a negative exponential behaviour typical of **non-correlated events**;
- mixture with less CF_4 resulted less stable with a larger frequency of instability events

He/CF_4	Hot-spot frequency	Discharge frequency
60/40	0.6/hour	2.5/hour
70/30	0.16/hour	1.0/hour

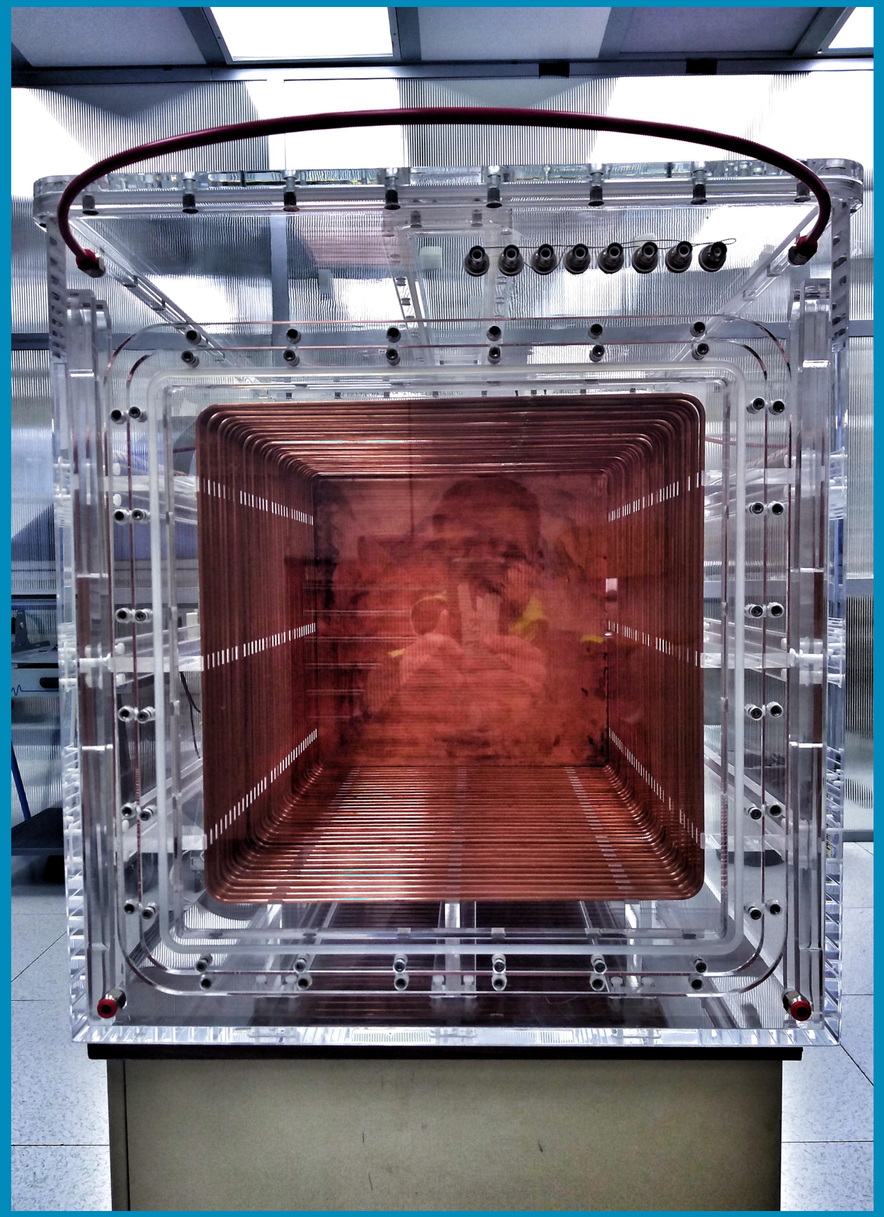
LIME

50 litre sensitive volume:

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

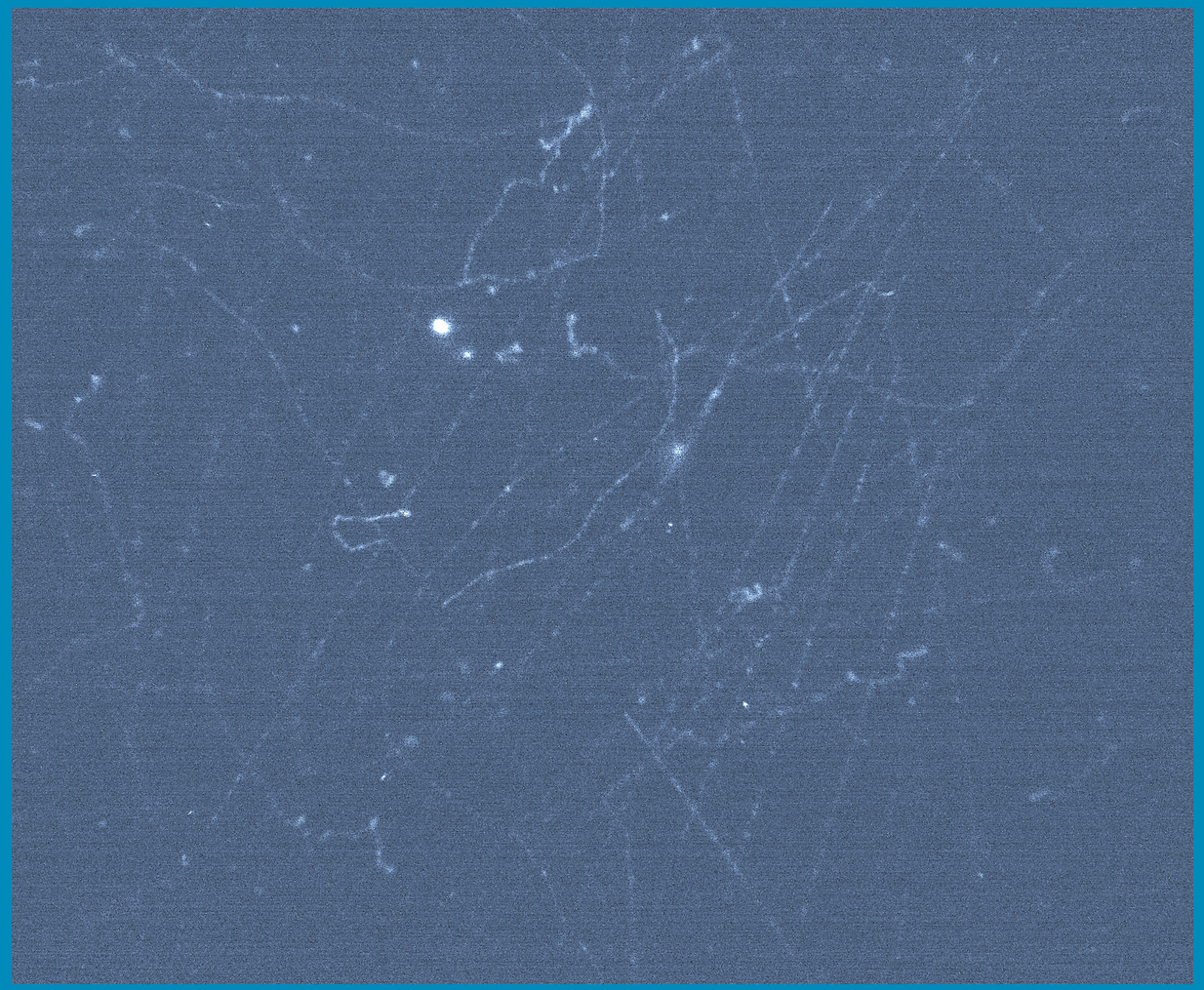


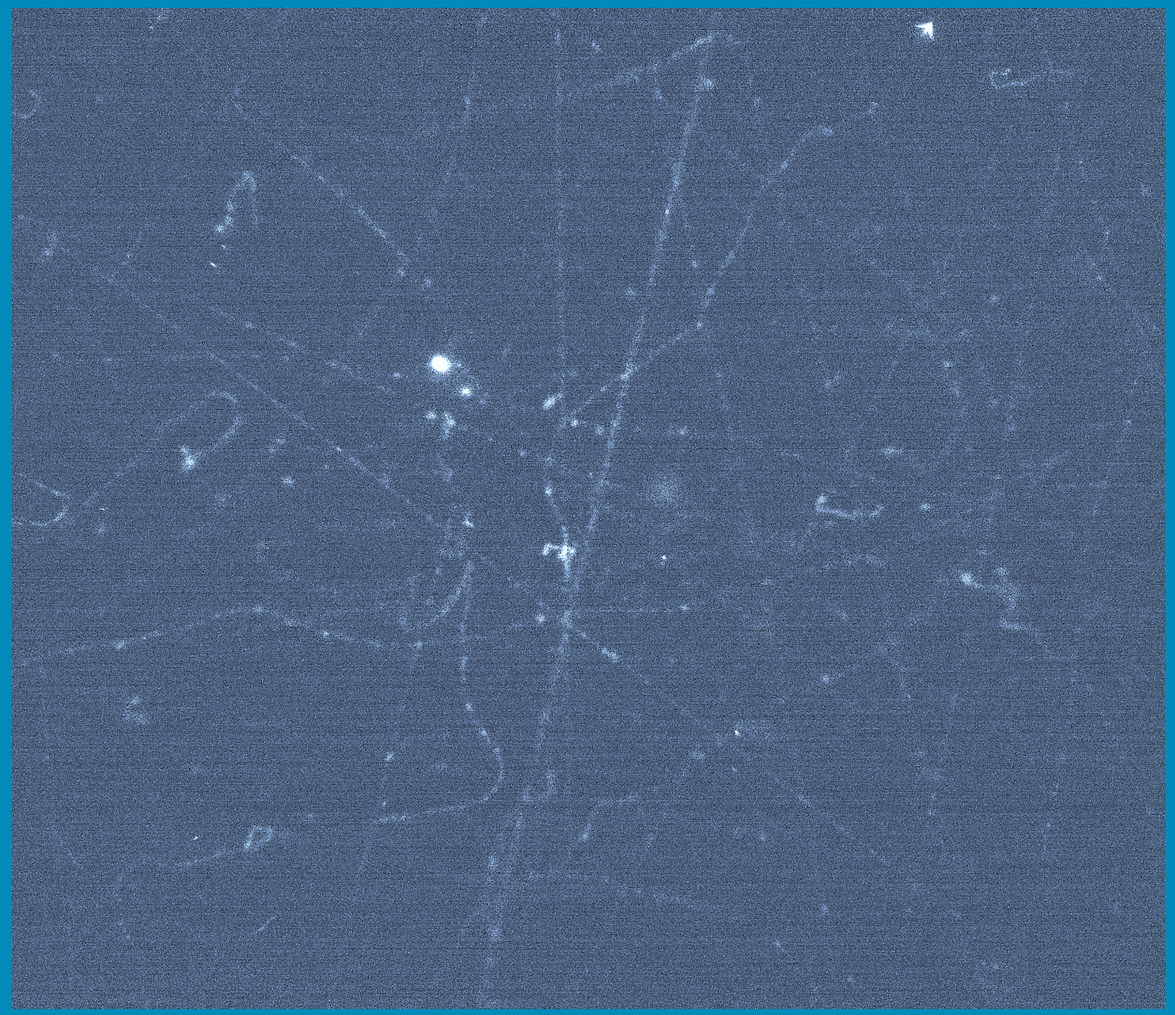
Copper ring field cage



Acrylic gas vessel

LIME: FIRST IMAGES

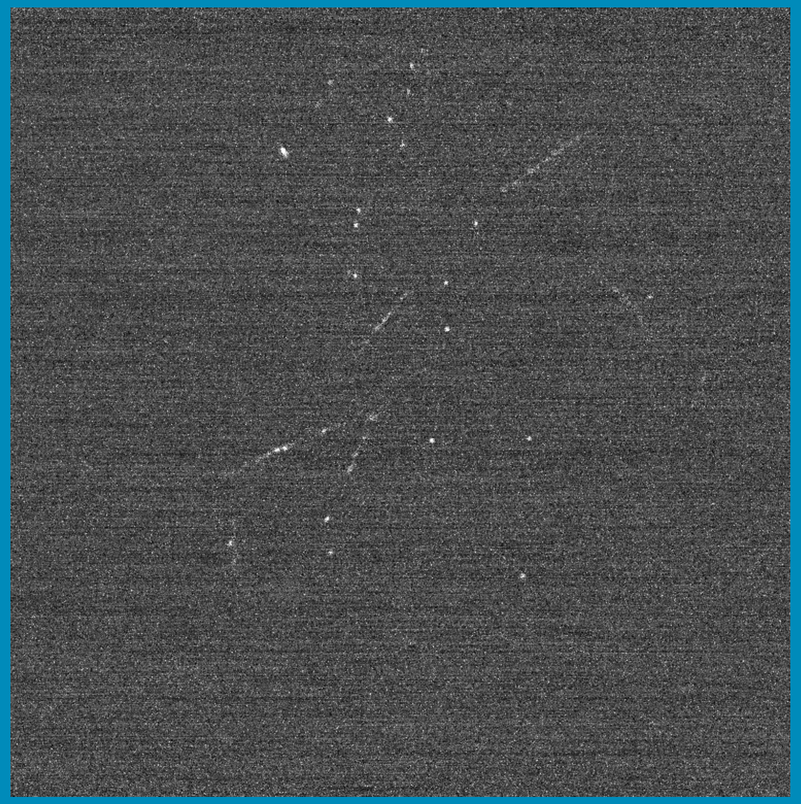




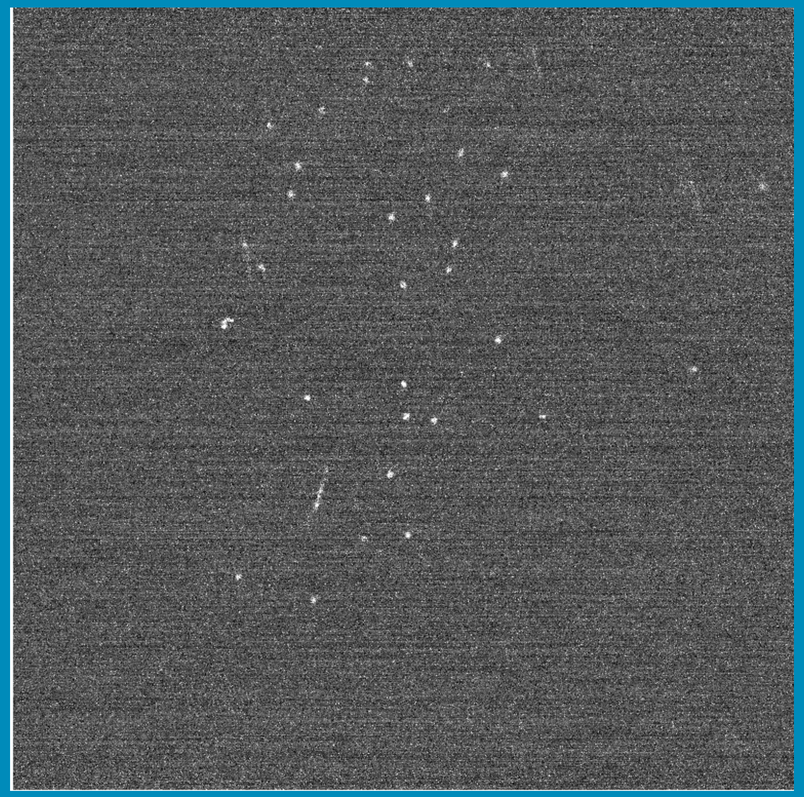
33 cm

LIME - ^{55}FE SPOTS

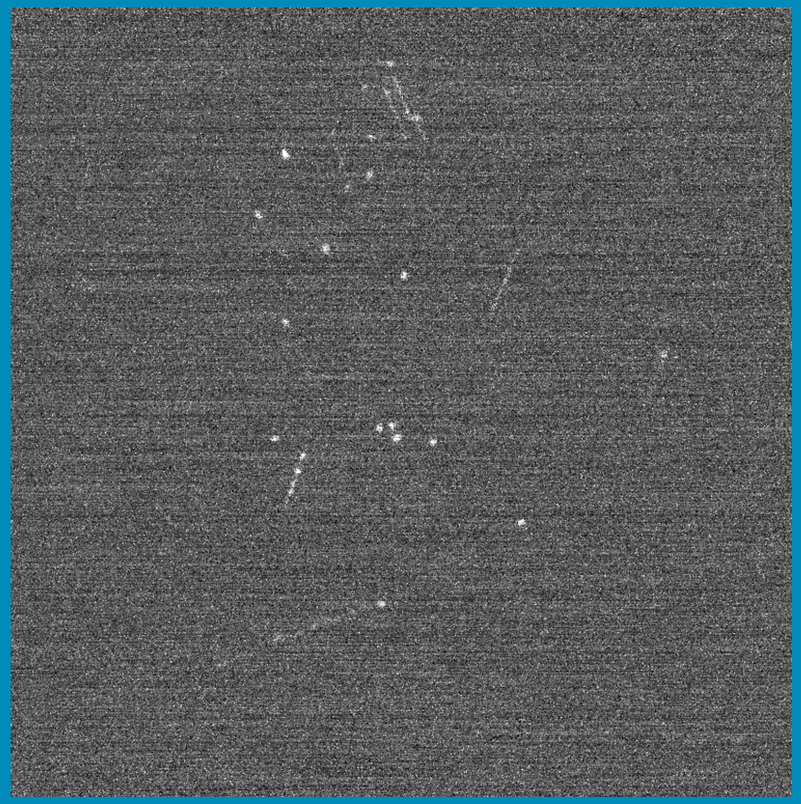
- 5 cm from GEMs



- 20 cm from GEMs



- 45 cm from GEMs

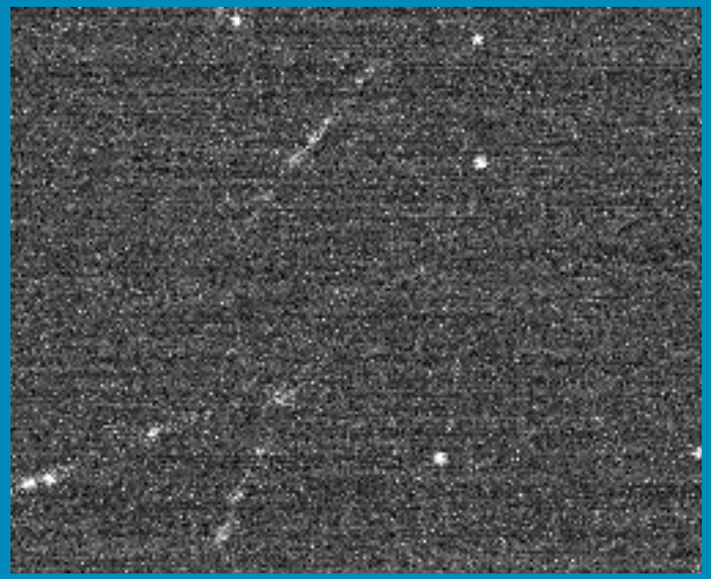


V_{GEM} = 440, E_D = 0.8 kV/cm

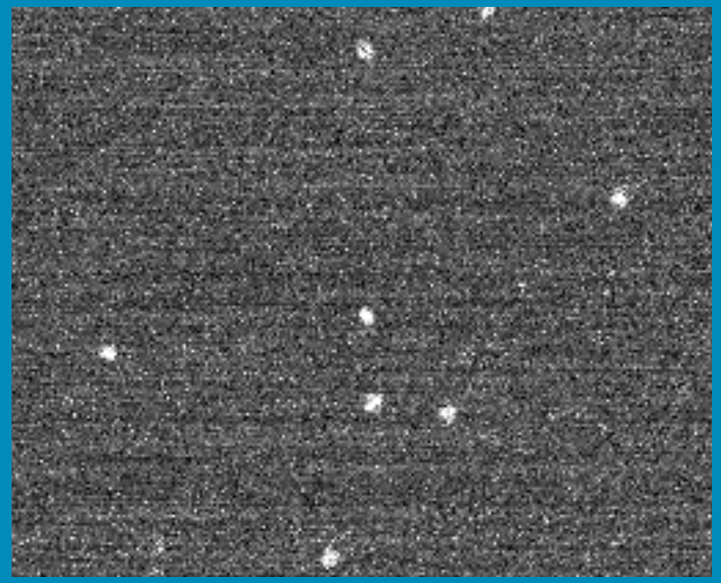
No evidence of large efficiency drop

LIME - ^{55}FE SPOTS (ZOOM)

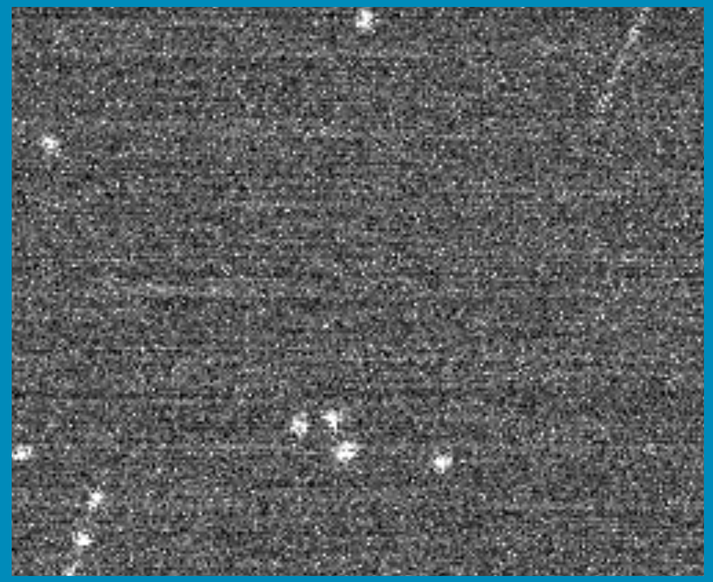
- 5 cm from GEMs



- 20 cm from GEMs

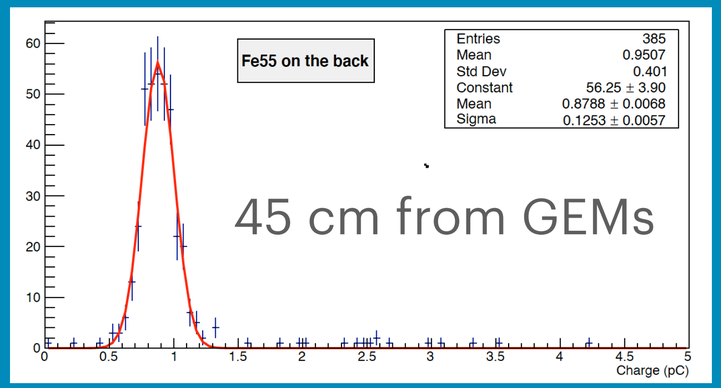


- 45 cm from GEMs



V_{GEM} = 440, E_D = 0.8 kV/cm

Spectra of charge on the last GEM shows an **Energy resolution** of **15%** in the whole volume



Diffusion effect **visible**

BACKGROUND STUDIES: EXTERNAL

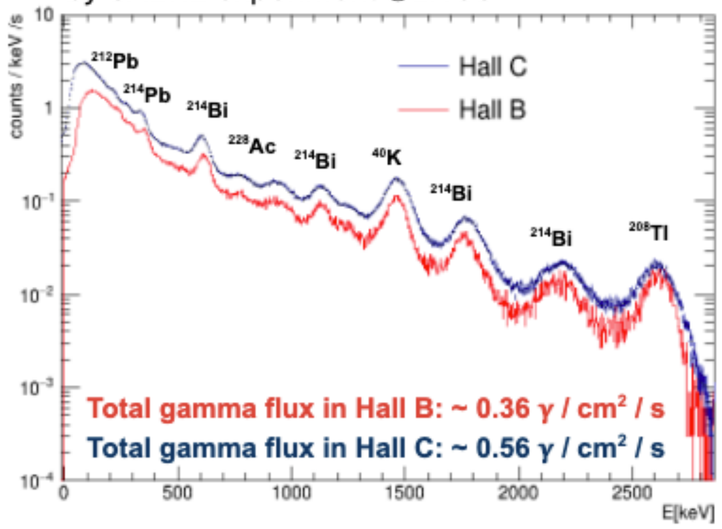
Full Detector simulation in **GEANT4**

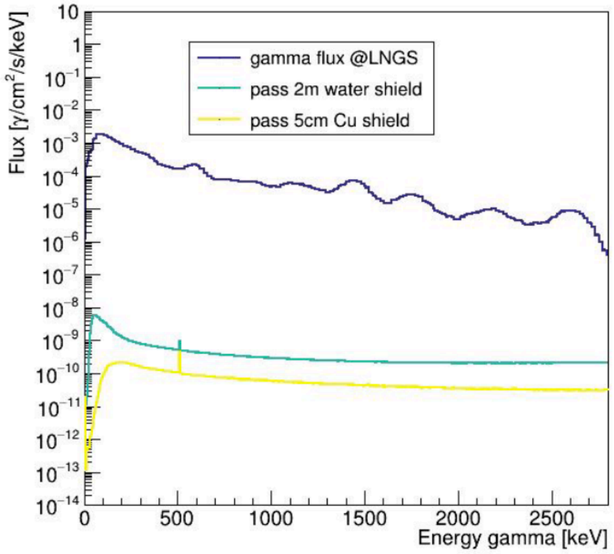
Gamma and **neutron** background due to external radioactivity simulated

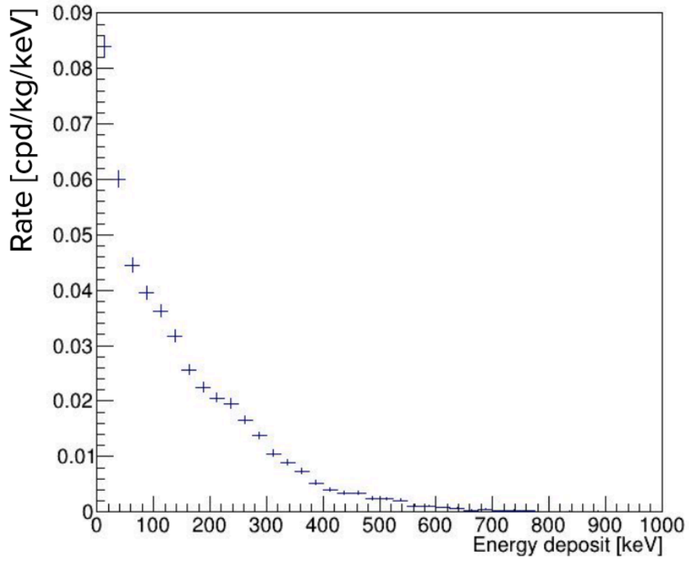
200 cm water + 5 cm Cu

Gamma Flux at LNGS 0.56 cm^{-1} s^{-1}
Gamma Flux after 2 m water shield 1.4 10^{-6} cm^{-1} s^{-1}
Gamma Flux after 5 cm Cu shield 1.8 10^{-7} cm^{-1} s^{-1}

Input → gamma flux measured by SABRE experiment @LNGS





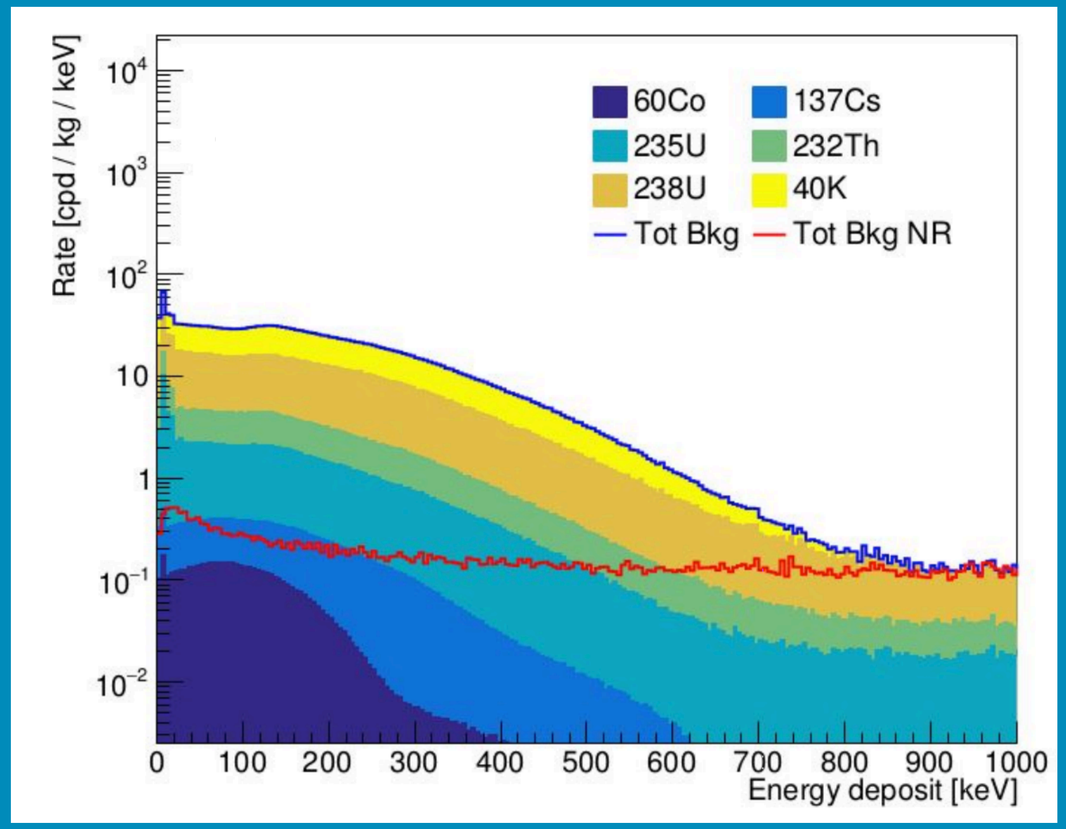


Expected background coming from outside of **5 x 10²** cpy in the [1-20] keV;

BACKGROUND STUDIES: INTERNAL

Measured **radioactivity** of different **Cameras** and **GEMs**

Camera	Sensitivity (eV/count)	Resolution (%)	Noise (eV)	^{228}Ra (Bq)	^{228}Th (Bq)	^{226}Ra (Bq)	^{234}Pa (Bq)	^{40}K (Bq)	Total activity
Hamamatsu ORCA FLASH 4.0	2.96	15.2	4.6	2.1	2.1	1.9	7.0	1.9	15.0
ORCA FLASH sensor	2.6	15.2	8	1.0	1.0	1.1	1.1	4.3	8.5
Photometrics Prime BSI Mode 1	3.3	19.0	9.7	-	-	-	-	-	tbm
Photometrics Prime BSI Mode 2	1.12	16.4	4.5	-	-	-	-	-	tbm
Photometrics BSI Express Mode 2	0.84	13.4	3.0	1.3	1.8	1.0	6.0	3.6	13.7
Hamamatsu Fusion Closer (LEMON)	0.65	17.5	1.58	-	-	-	-	-	tbm
Hamamatsu Fusion Farther (LIME)	0.85	16.4	2.06	-	-	-	-	-	tbm
Thorlab Quantalux	tbm	tbm	tbm	0.3	0.6	0.2	3.0	1.2	5.3



Internal background **5 x 10^5** cpy in 1-20 keV

Cameras and **GEM** are responsible of **main** radioactivity budget within the detector.

With a rejection of **10^2-10^3** an avoidable **internal** bkg of several **hundreds** of events/year expected.

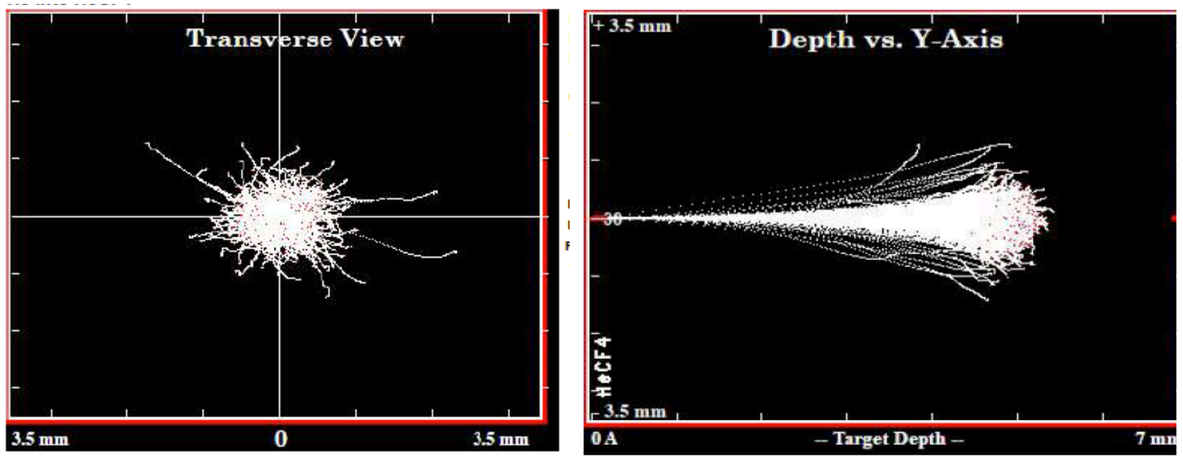
Studies on how to reduce it needed

SIGNAL SIMULATION

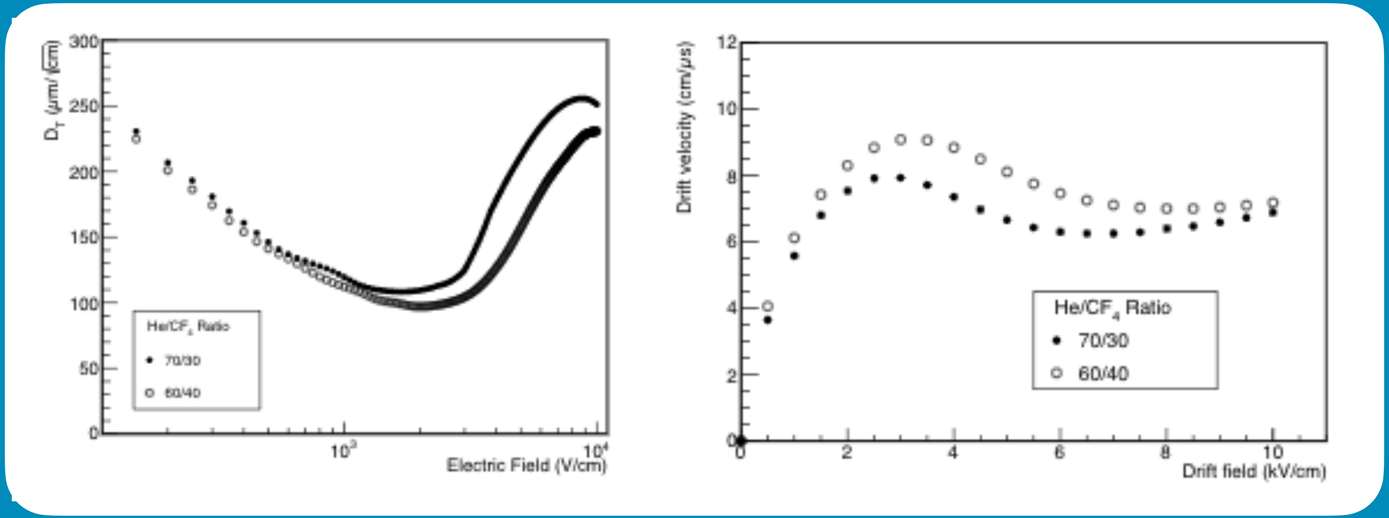
Interactions of recoils in gas simulated:

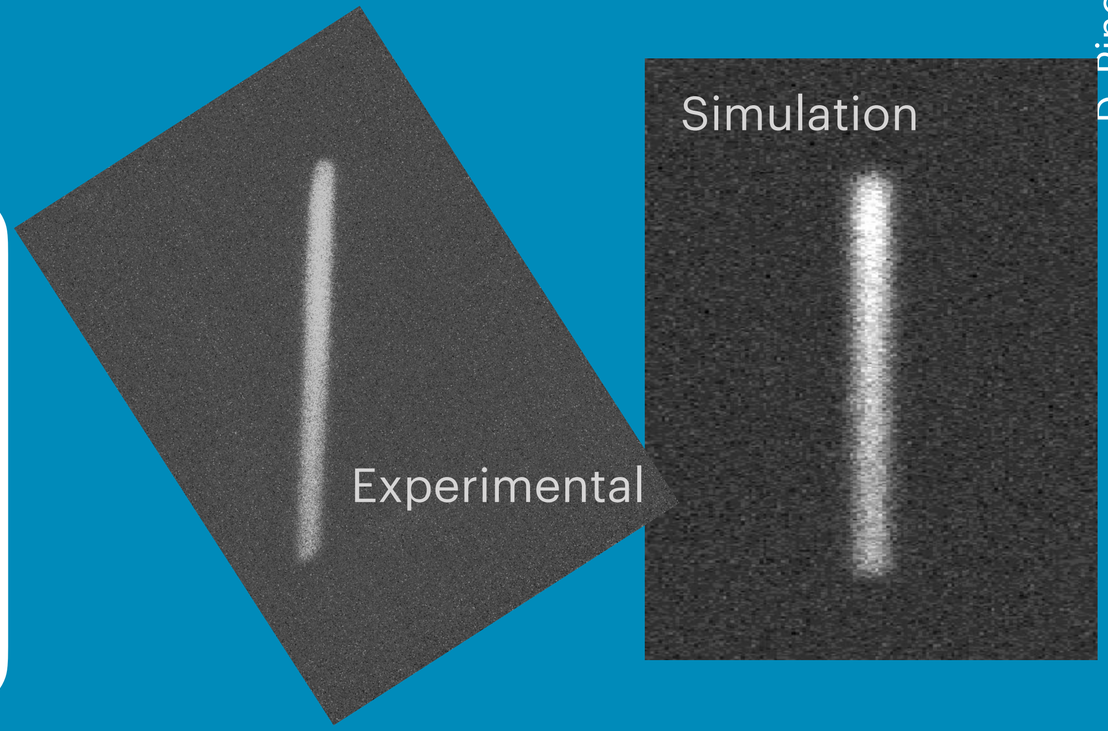
- **GEANT** for electrons;
- **SRIM** for nuclei;

Gas parameters (ionization, diffusion, drift velocity, attachment) simulated with **GARFIELD**;



Sensor noise studied and **simulated** accordingly to data

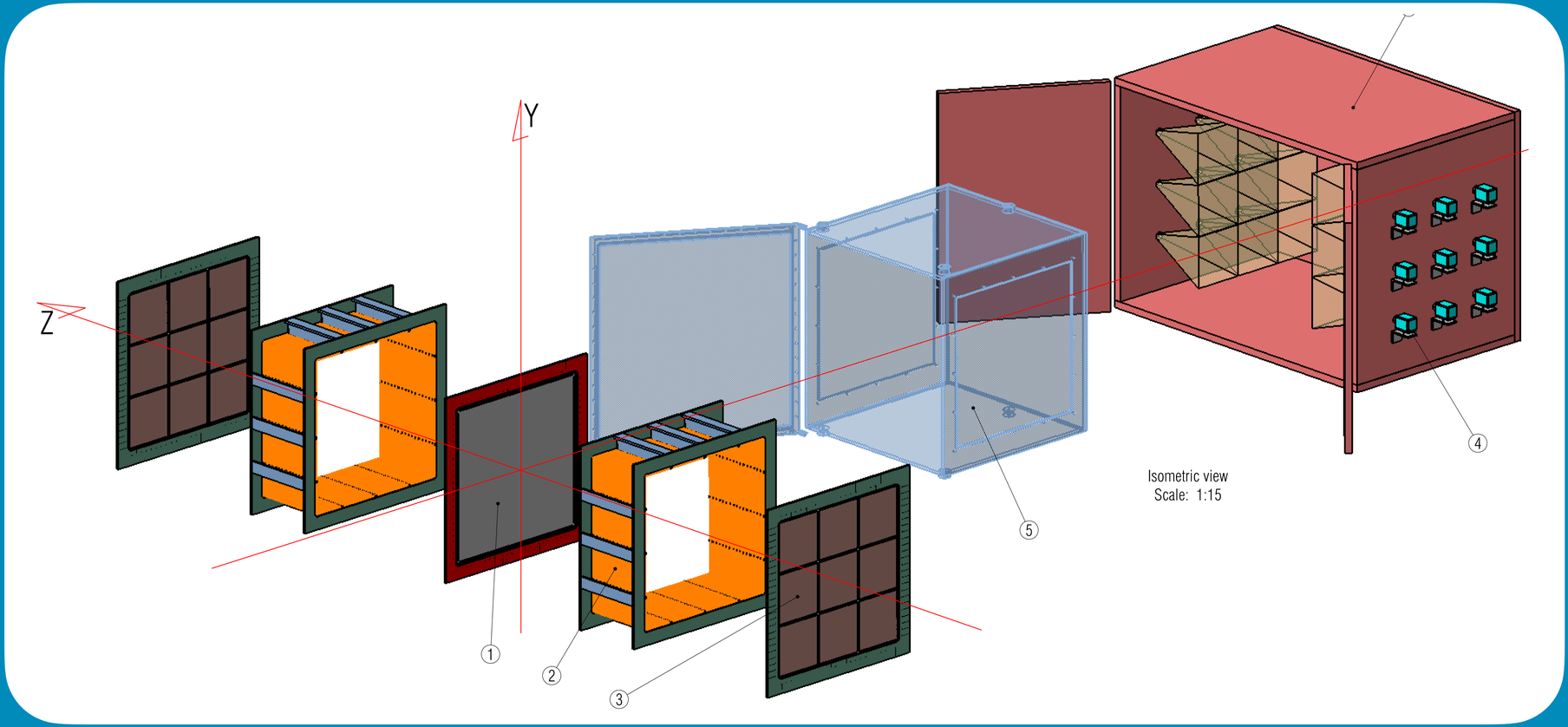




1M³ DEMONSTRATOR: BASELINE LAYOUT

1 m³ of **He/CF_4 60/40** (1.6 kg) at **atmospheric pressure** subdivided in two 50 cm long parts by the cathode with a drift field of about 1 kV/cm;

Acrylic vessel ensuring gas tightness and high voltage insulation;



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

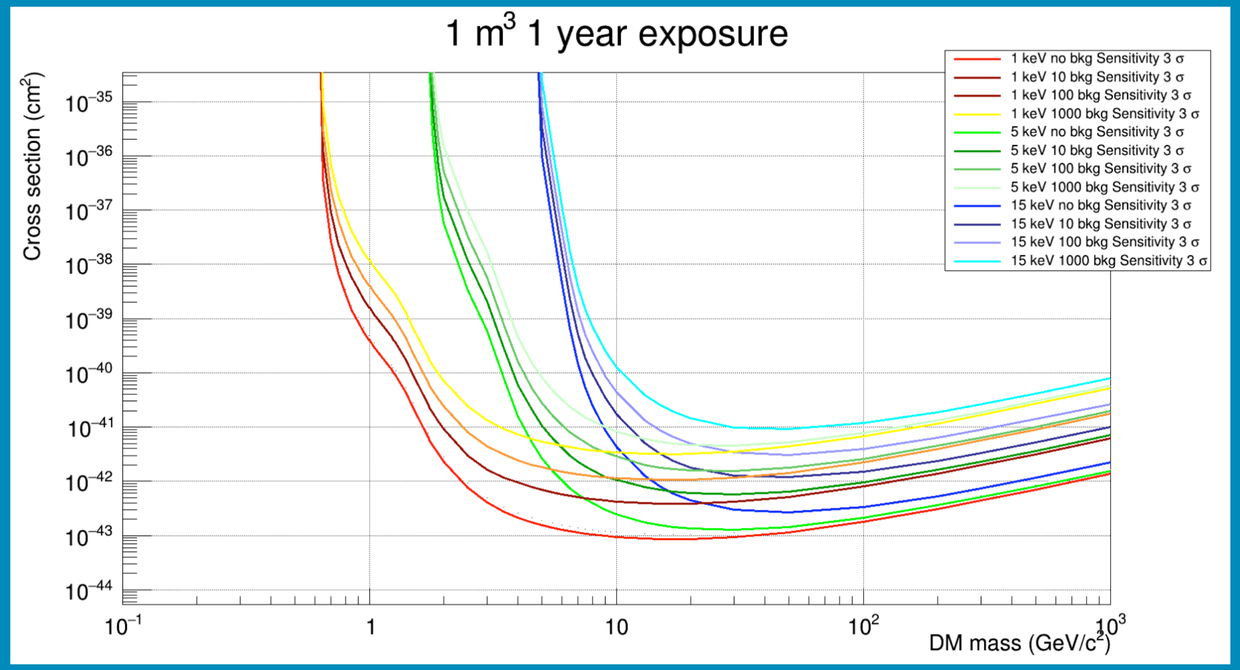
- sCMOS sensor 65 cm away;
- Fast light detector (PMT or SiPM).

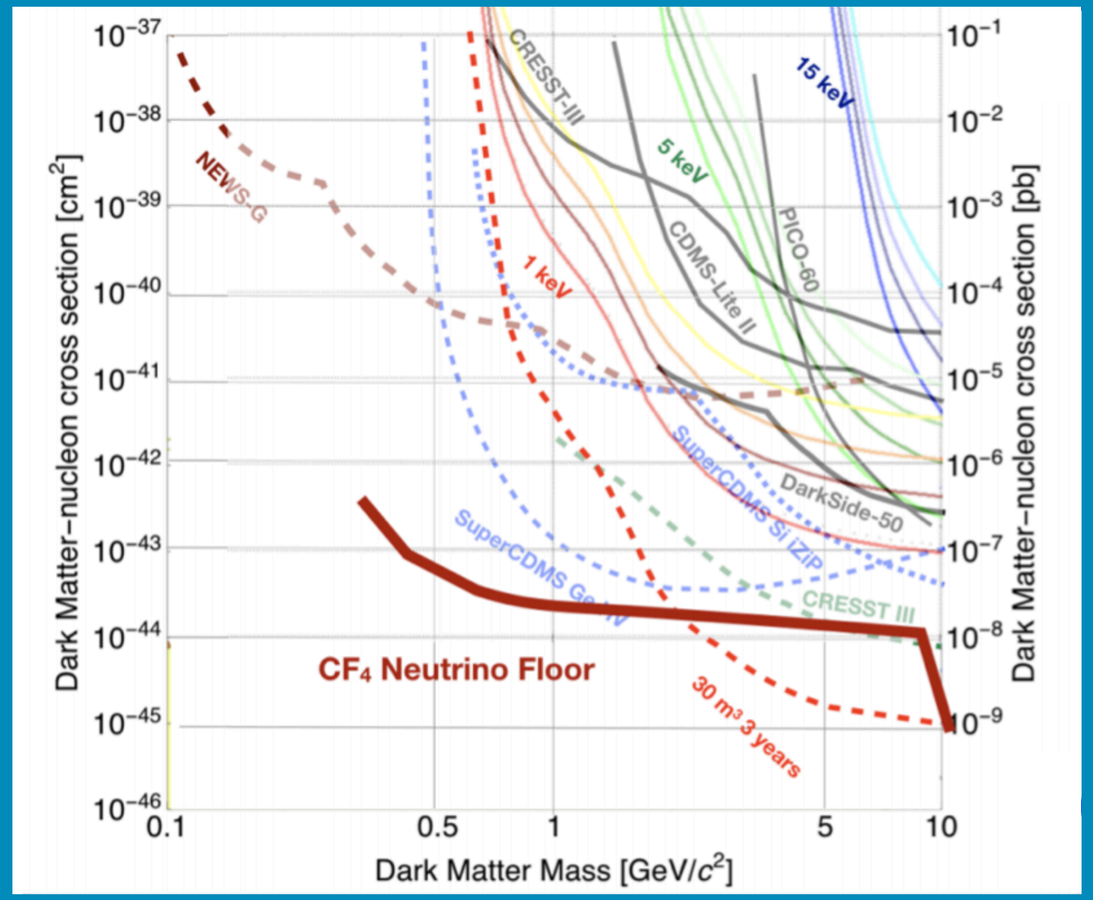
Radioactivity shielding:

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

WHAT CYGNO CAN DO: DM SEARCH AND STUDY

Because of the low mass of Helium nuclei, CYGNO can be very sensitive to **light** DM (~1 keV released per GeV)





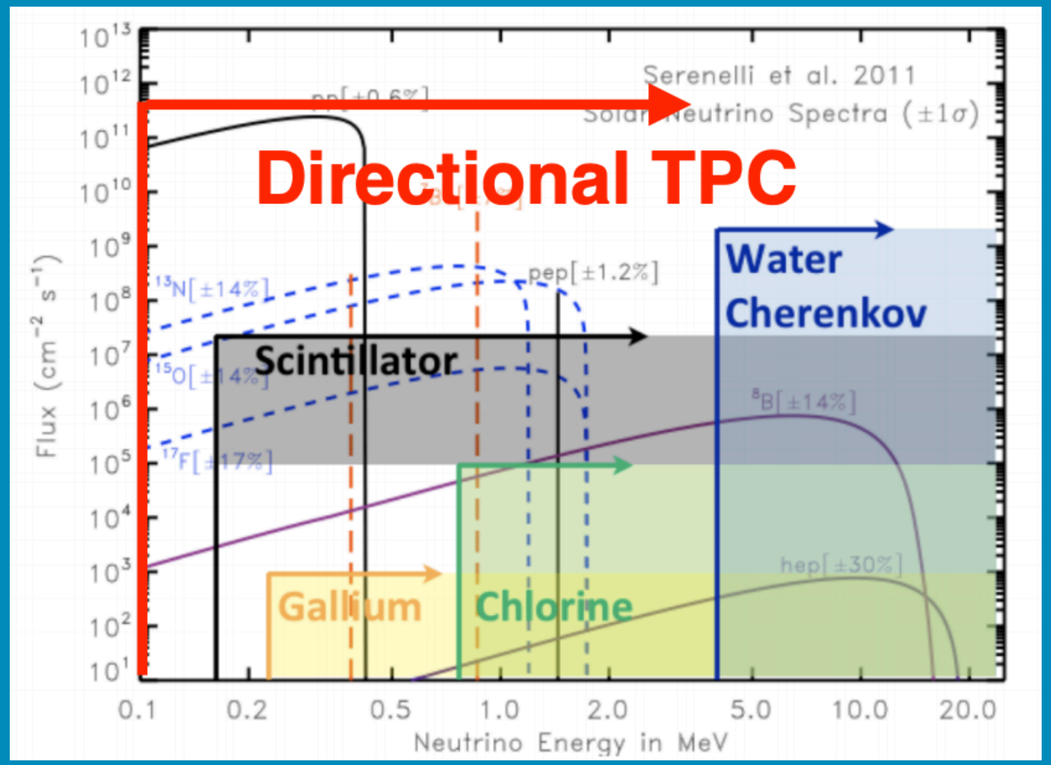
DAMA region covered even with 15 keV and 1000 bkg events

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

With 30 m³, a 100 kg-year exposure can be achieved in 3 years

WHAT CYGNO CAN DO: NEUTRINO SPECTROSCOPY

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

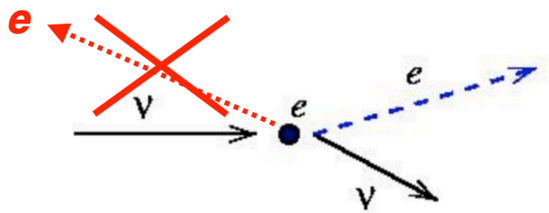


- sub-millimetre tracking capability (Borexino is 12 cm)
- 10 keV directional threshold (Borexino has 160 keV)
- keV energy resolution
- low mass

For 1 m³ of He:CF₄ 60:40 with 20 keV threshold

$$R = N_e \cdot \int_{E_{min}}^{E_{max}} w(E)\varphi_{ppI}(E)\sigma(E)dE \qquad R = 2.9 \cdot 10^{-8}\ \frac{events}{s \cdot m^3} = 0.9\ \frac{events}{y \cdot m^3}$$

Given the Sun position, recoils in opposite direction are kinematically forbidden

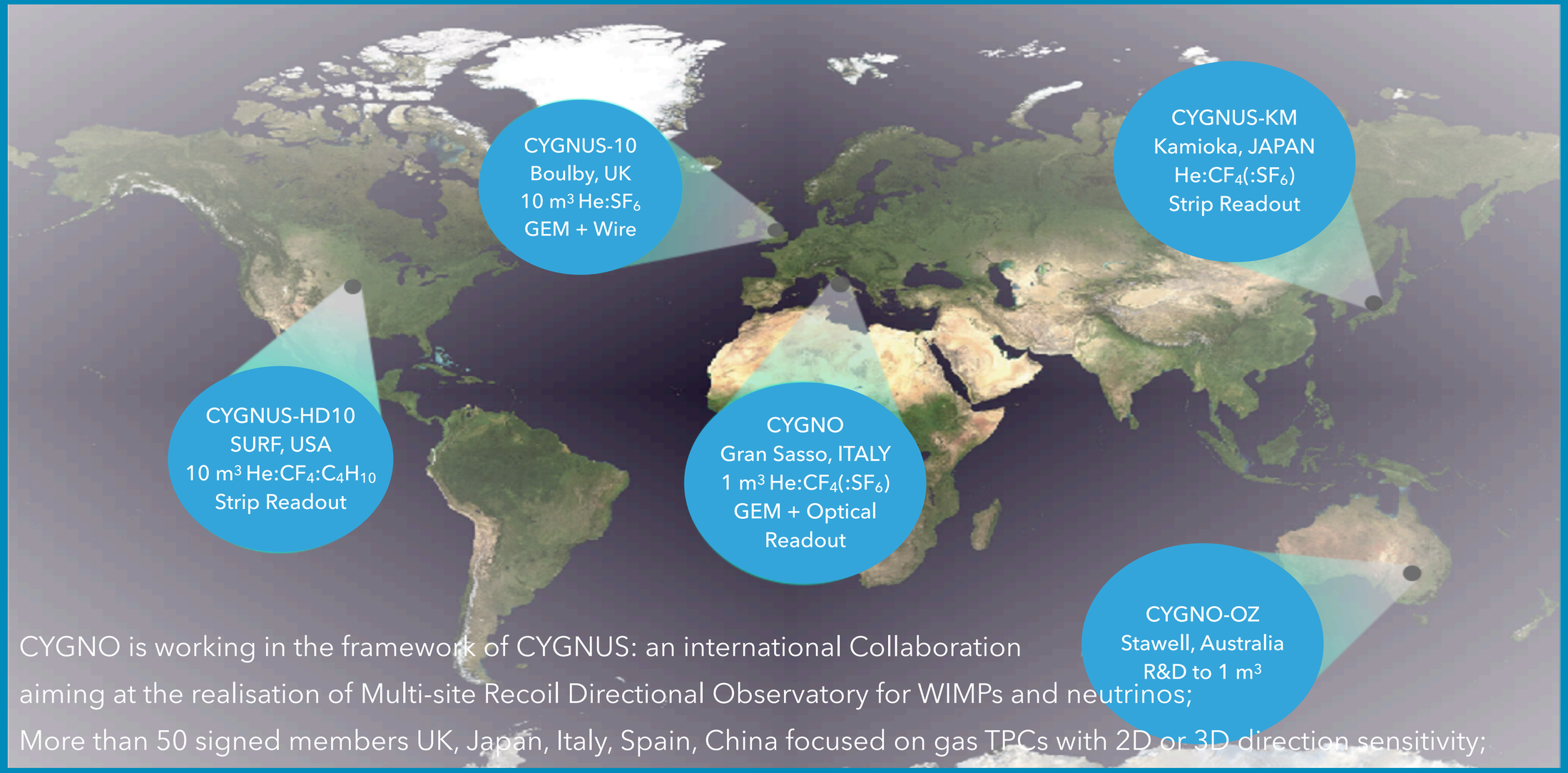


Differently from WIMPs, background can be measured on sidebands data

CONCLUSION

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

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



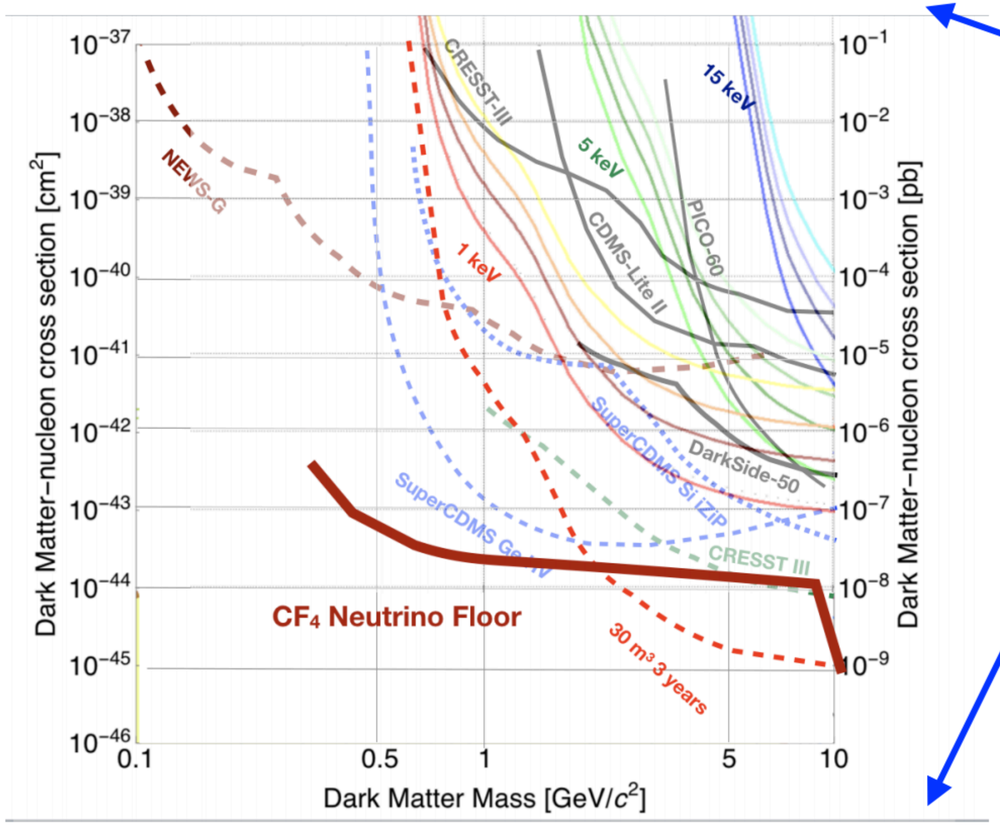
CYGNO is working in the framework of CYGNUS: an international Collaboration aiming at the realisation of Multi-site Recoil Directional Observatory for WIMPs and neutrinos;

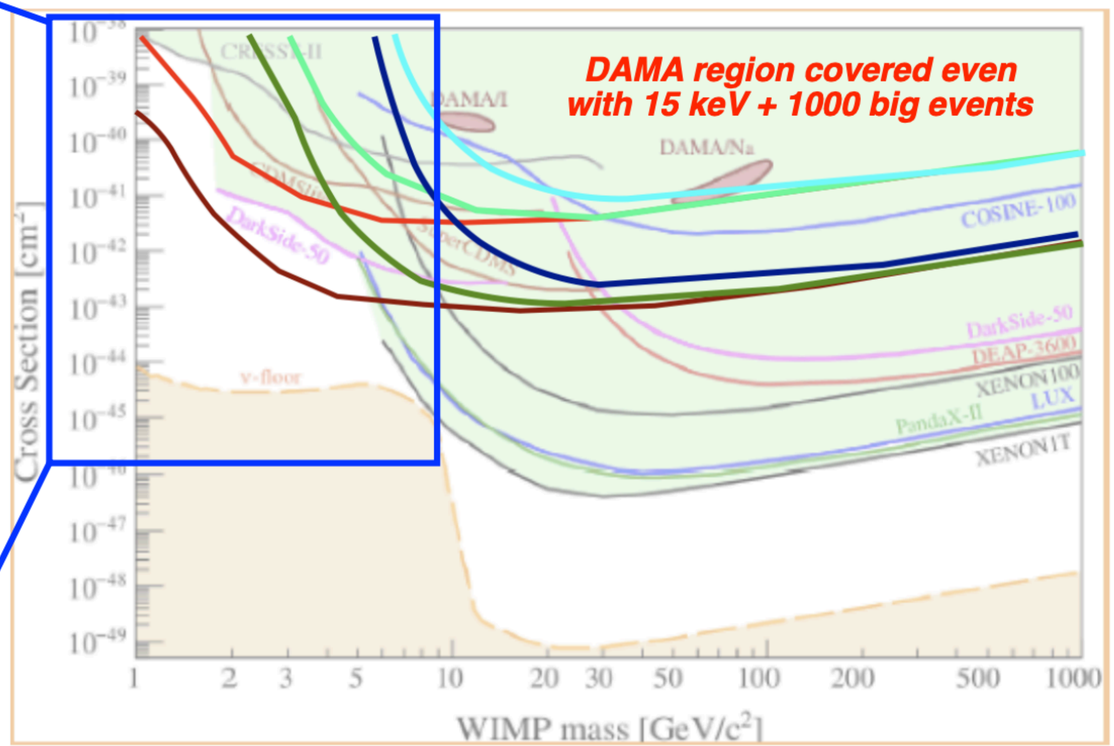
More than 50 signed members UK, Japan, Italy, Spain, China focused on gas TPCs with 2D or 3D direction sensitivity;

THANKS!

SPARES

Please, keep in mind that only 1 m³ year exposure is shown for CYGNO





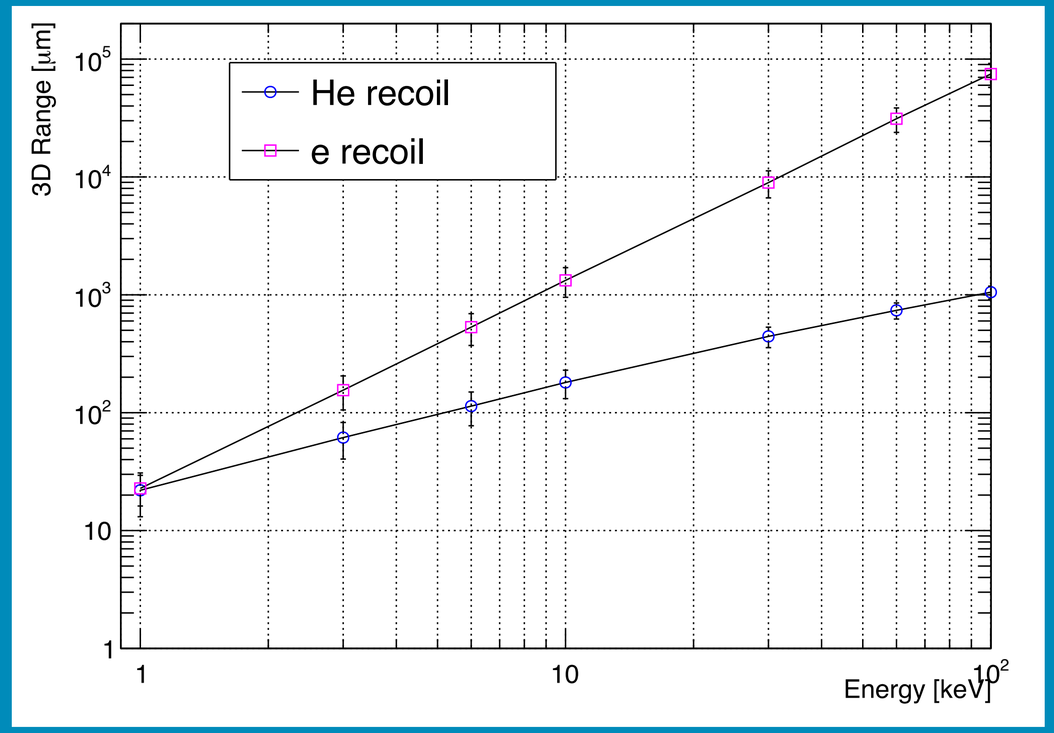
get up to ± 100 kg year exposure with 30 m³ 3 years

0 bkg & 1000 bkg shown for each threshold

IS IT POSSIBLE?

- The maximum energy that can be transferred by a DM particle to a recoil of mass m_N, is given by:

$$\epsilon = \frac{4\rho}{(\rho+1)^2} \quad \text{where} \quad \rho = \frac{m_N}{m_{WIMP}}$$



Element	Max E transferred by a 1GeV DM particle	Min DM particle mass with 1 keV threshold
Ar	0.2 keV	5.25 GeV
He	1.2 keV	0.78 GeV
F	0.4 keV	2.63 GeV
Xe	0.06 keV	16.6 GeV

Sensitivity to direction:

- for nuclear recoils starting from energies larger than 10 keV;
- for electron recoils starting from 2 keV (useful for separation)