in synergy with erc
IN TIUM
funded from ERC in Horizon 2020 program (grant agreement 818744)

Performance of a 3D optical readout TPC for the CYGNO experiment

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

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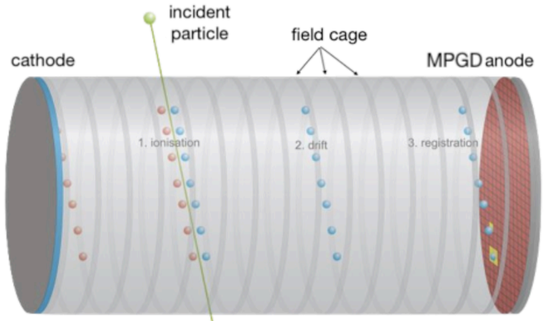
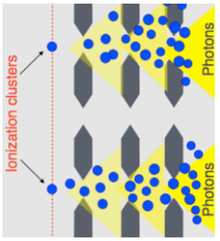
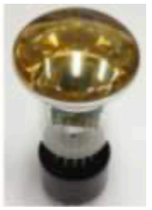
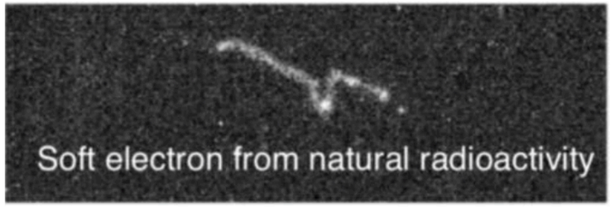
The CYGNO project:

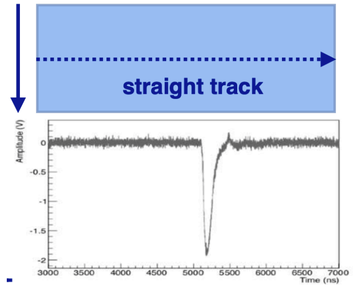
- **Aiming at** a large detector for high precision 3D tracking of rare low energy nuclear recoils (keV) as for example WIMPs
- **Experimental challenges**: rate O(evt/kg/y), background rejection, and energy threshold (keV)
- **Strategy:** photograph nuclear recoil in a He:CF_4 (1 atm) TPC with a GEM amplification stage
  - 3D tracking: position, direction, and fiducialization
  - total released energy, dE/dx (head/tail)
  - **optical sensors**: high granularity, very low noise, and high sensitivity
  - **optical coupling**: sensors outside the sensitive volume, acquire large surfaces with small sensors

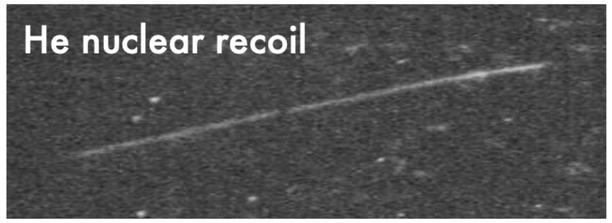


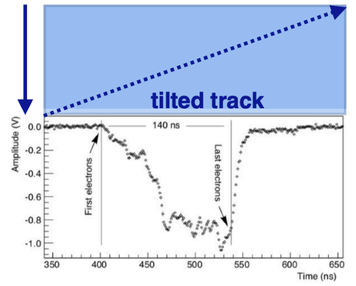












Refer to G. Cavoto's talk in DM section for further details on the physics reach

CYGNO timeline

CYGNO R&D | PHASE 0 | PHASE 1 | PHASE 2

ORANGE @ ROMA1

- 10x10 cm² GEMs
- 1 cm drift
- 100 cm³ volume

LEMOn @ LNF

- 20x24 cm² GEMs
- 20 cm drift
- 0.01 m³ volume
- 3D printing
-

MANGO @ LNF / LNGS

- 10x10 cm² GEMs
- variable drift
- performance studies
- gas mixture tests

LIME @ LNF / LNGS

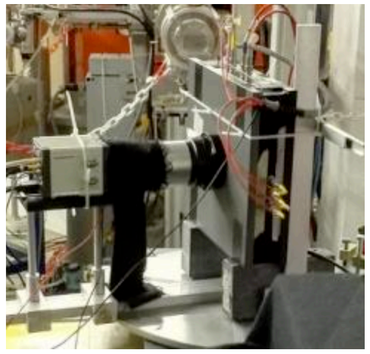
- **30x30 cm² GEMs**
- **50 cm drift**
- **0.05 m³ volume**
- **performance and stability test**
- **underground**
- **shielding**
- **data-taking**

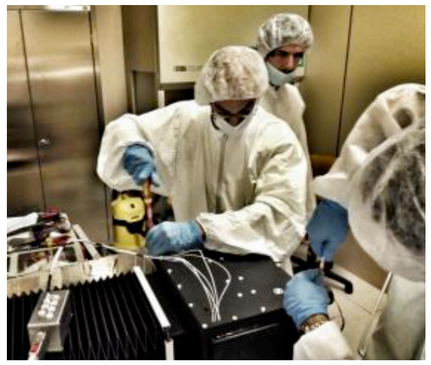
CYGNO demonstrator @ LNF / LNGS

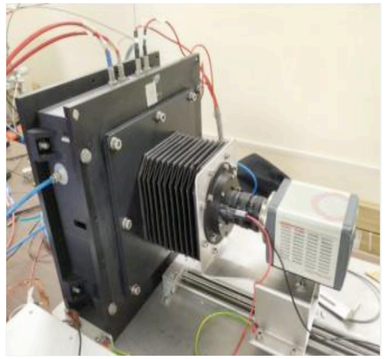
- 9x2 back-to-back LIME modules
- 1 m³ volume
- material tests
- background assessment
- underground installation & commissioning
- gas purification
- scalability

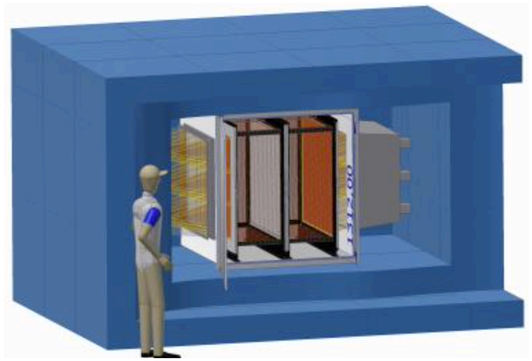
2015-2016 → 2017-2018 → 2019-2021 → 2021 → 2022 → 2023

CYGNO 30-100 m³





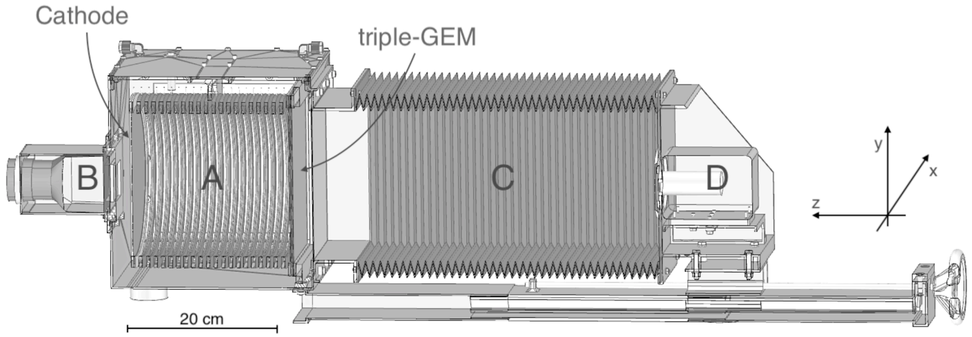


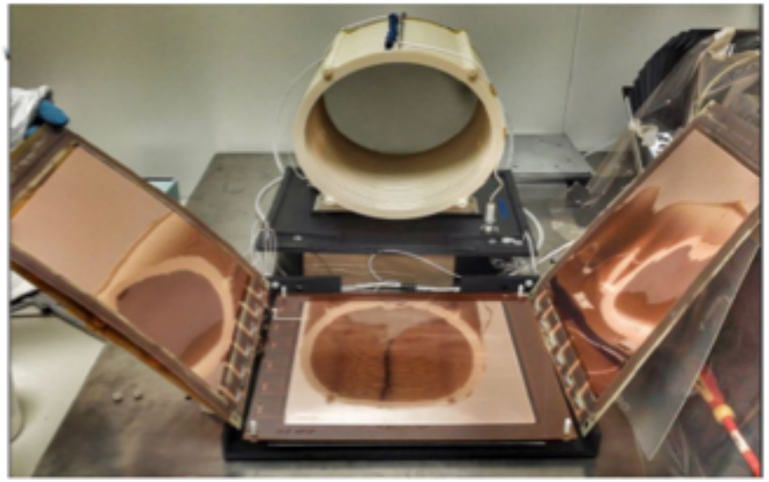


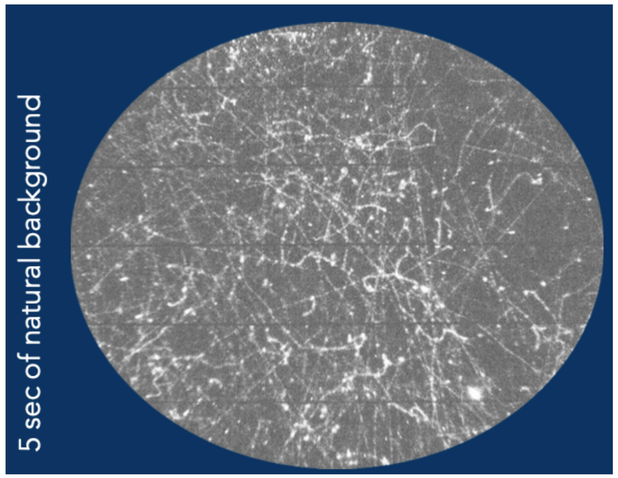
LEMOn prototype

JINST 15 (2020) P10001

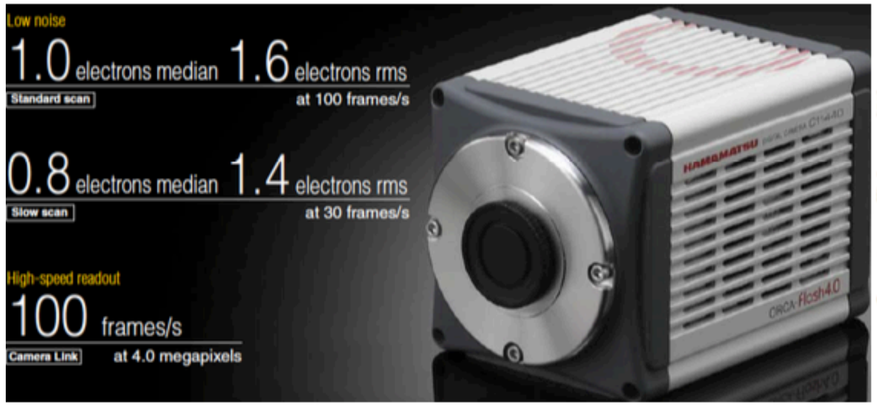
- **24 x 24 cm² readout area**
- **20 cm drift**
- **1 sCMOS + 1 PMT**

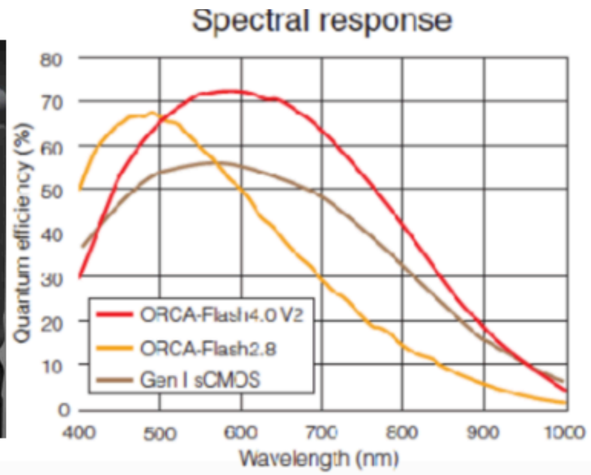




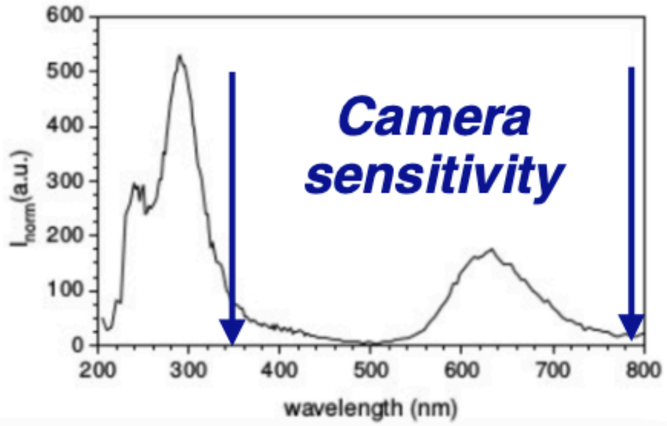


ORCA-Flash4.0



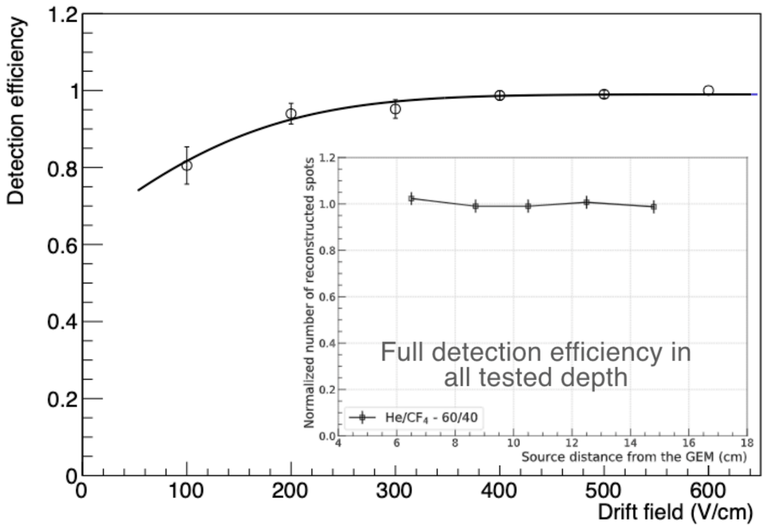


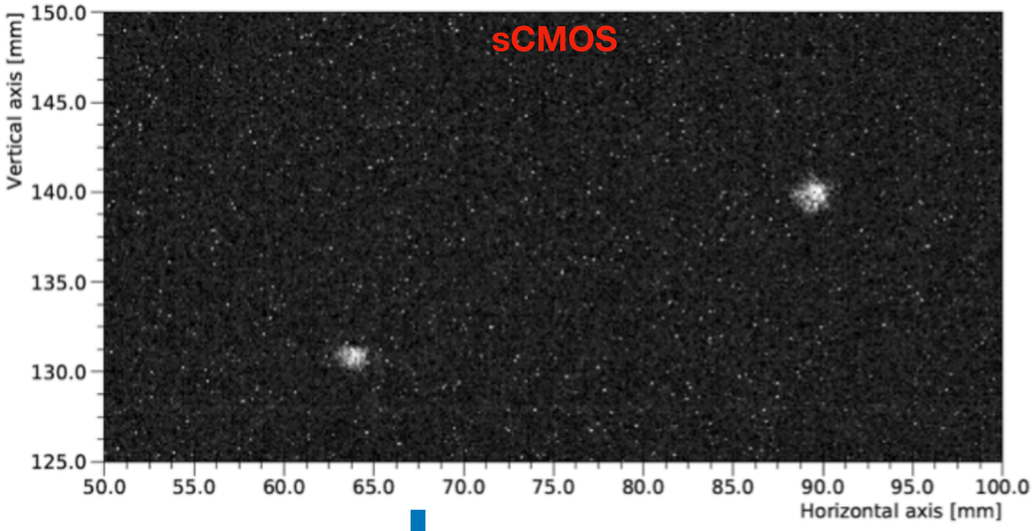
He:CF_4 spectrum

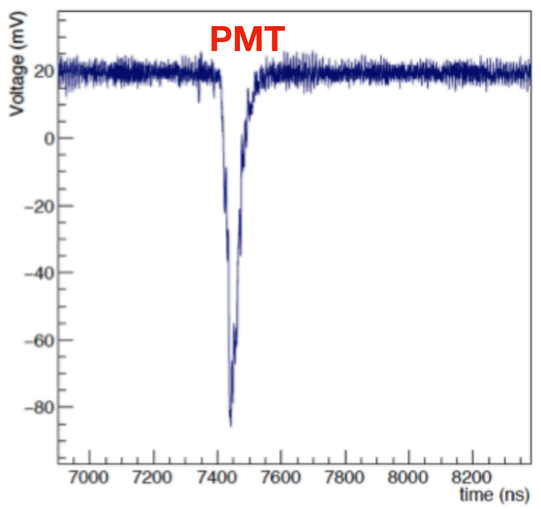


Response to ^{55}Fe X-rays: energy resolution and threshold

JINST 15 (2020) P10001 2019 JINST 14 P07011

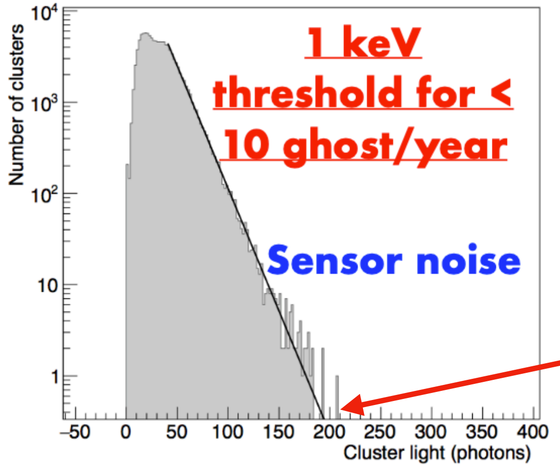






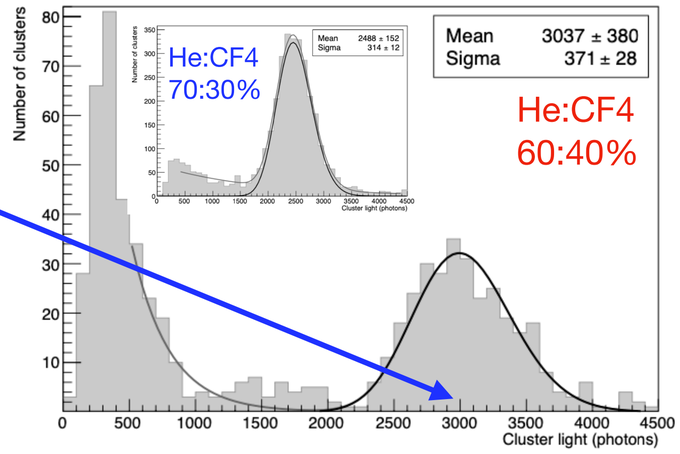
sCMOS

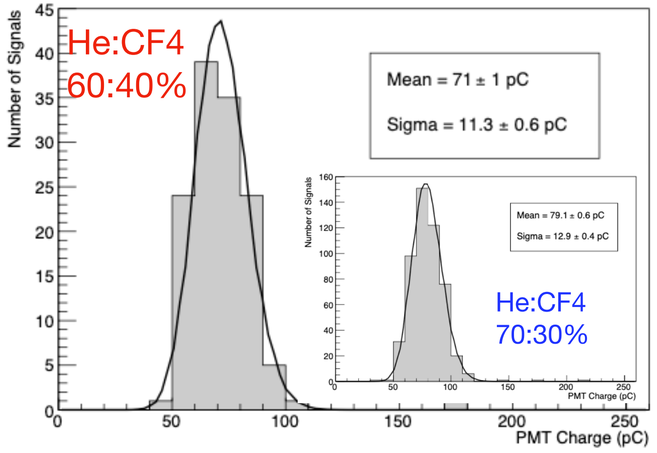
PMT



500 collected photon per keV

sensor noise below 200 ph (400 eV)

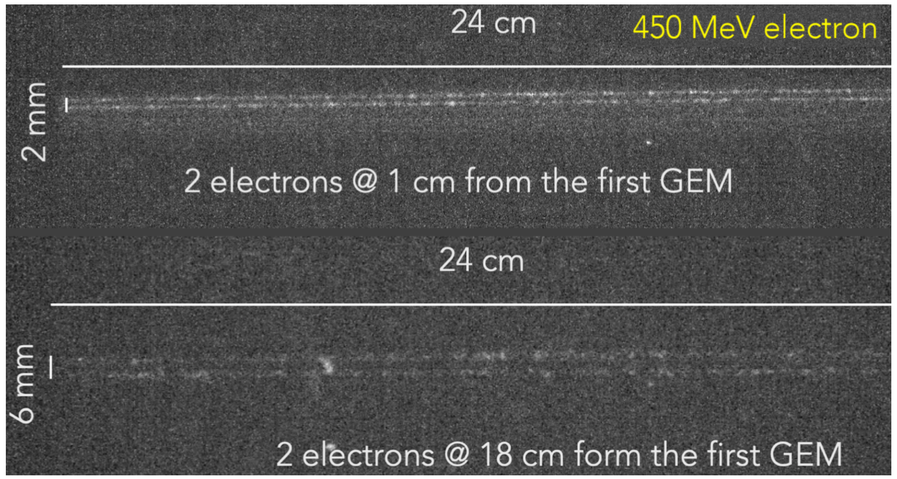




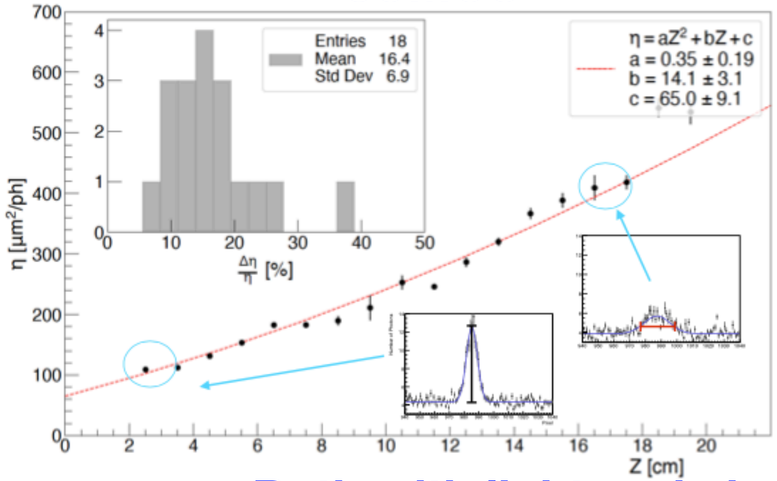
Energy resolution of 15% at 5.9 keV$_{ee}$ with sCMOS and PMT

Response high energy electrons: tracking and fiducalization

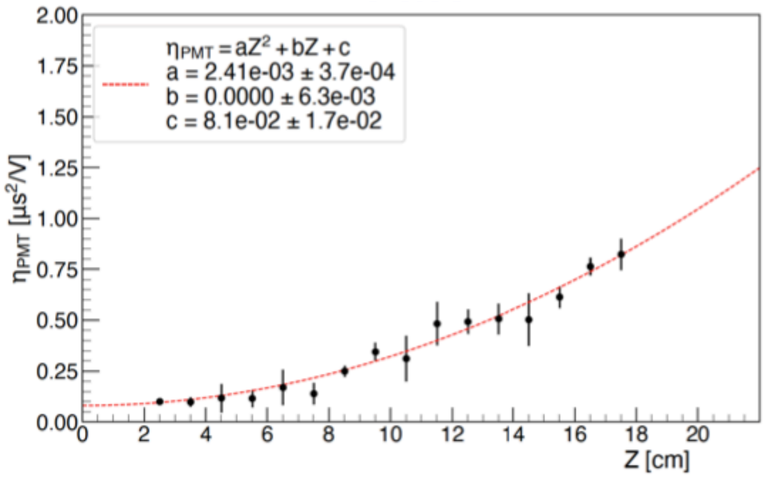
NIM A 999 (2021) 165209



sCMOS



PMT



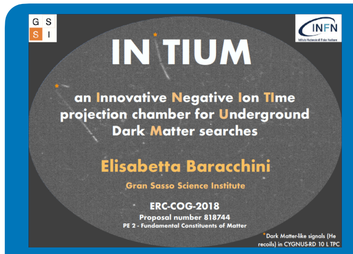
Both with light and charge 15% z position resolution

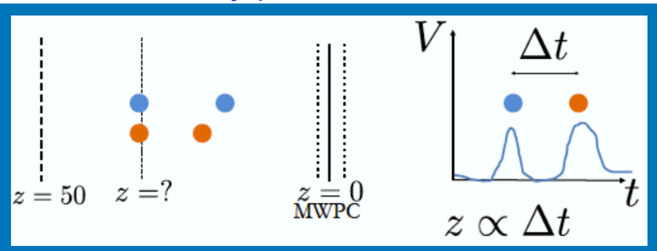
y position evaluated with 100-300 μm resolution

The diffusion can be exploited to estimate the z position of the event.

The width (S) and amplitude (A) of the transverse light profile and PMT waveform become larger and smaller respectively with increasing distance from the GEM (z position).

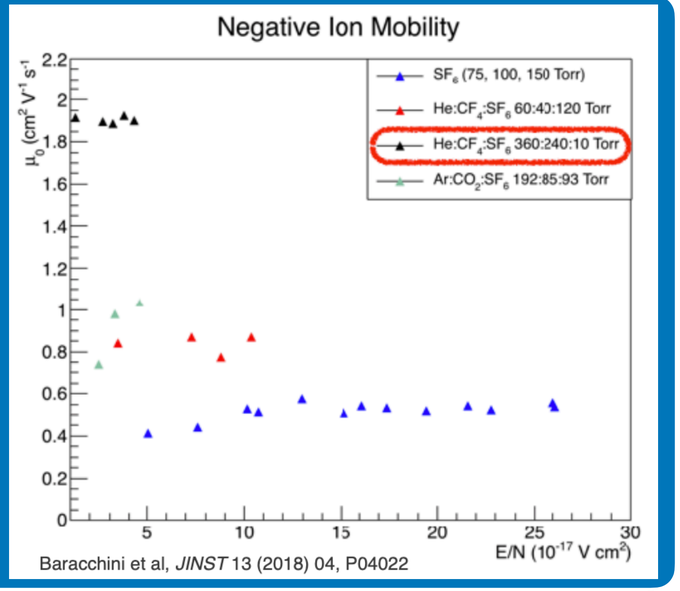
Thus $\eta = \frac{S}{A}$ increases





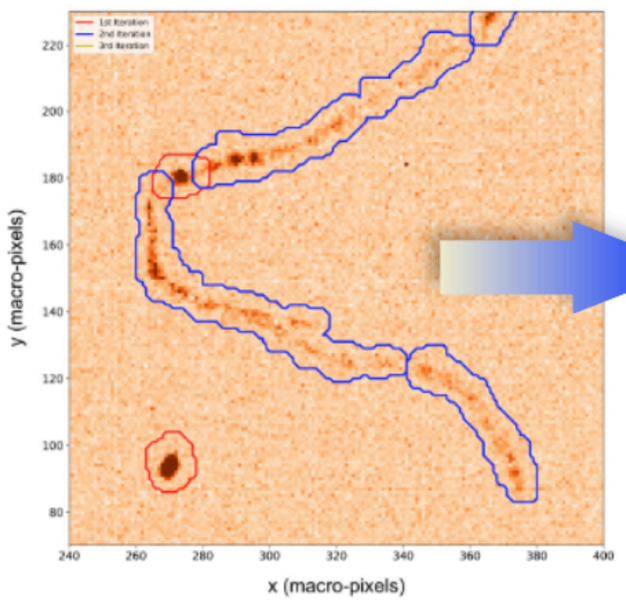
Electronegative gas generates negative ions that drift w/out diffusion with different velocity allowing high accuracy on z from Δt.

JINST 13 (2018) 04, P04022

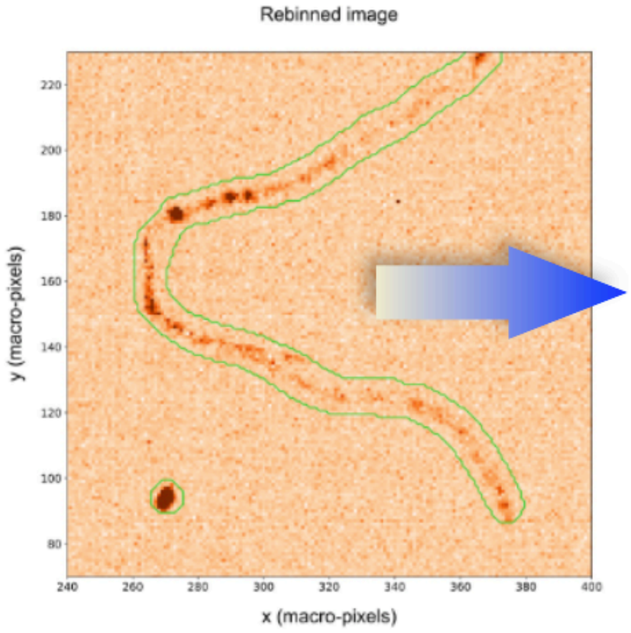


Response to low energy nuclear recoils

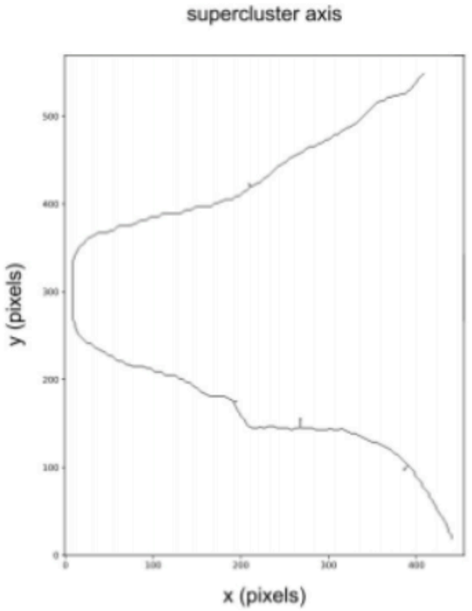
JINST 15 (2020) 12, T12003



Multiple DBSCAN iteration to select different ionisation patters

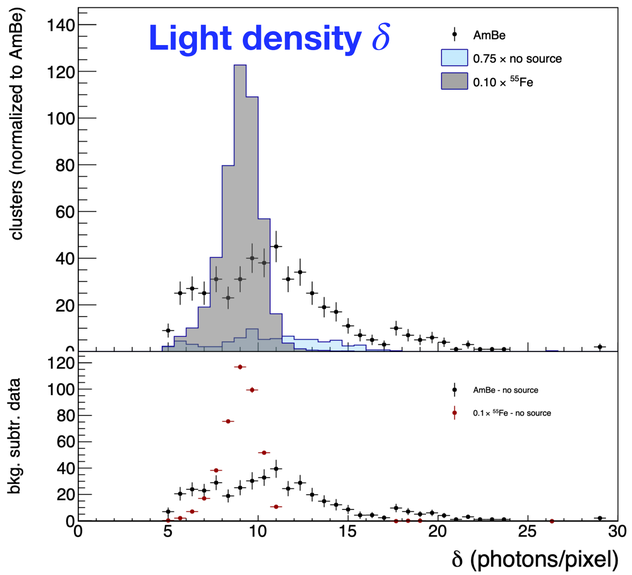


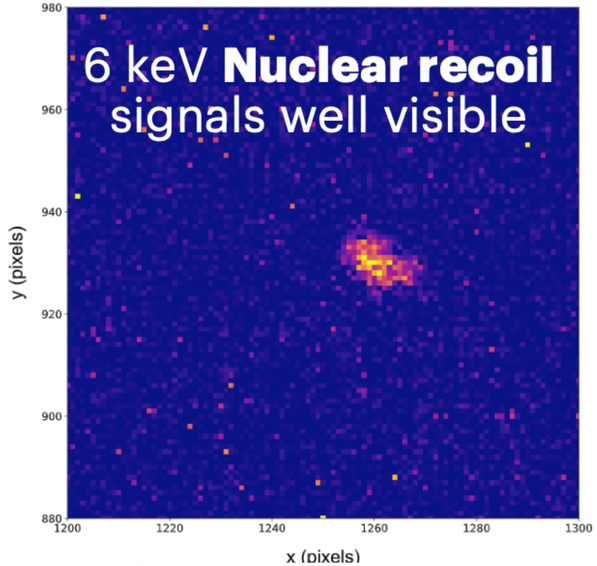
Morphological geodesic active contours (GAC) to connect long tracks

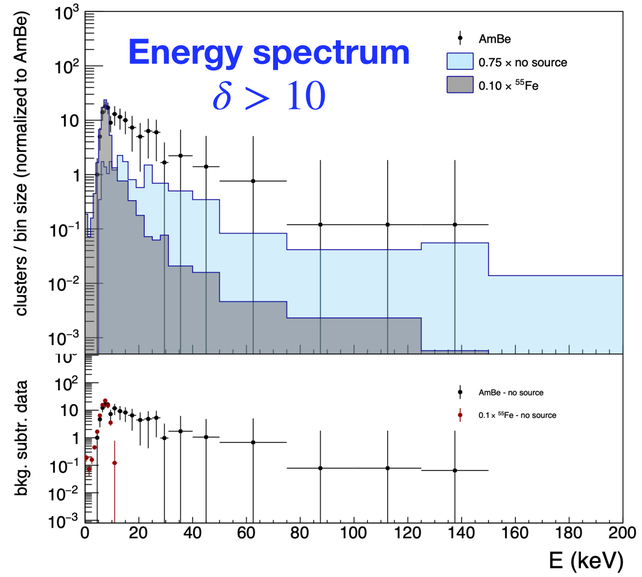


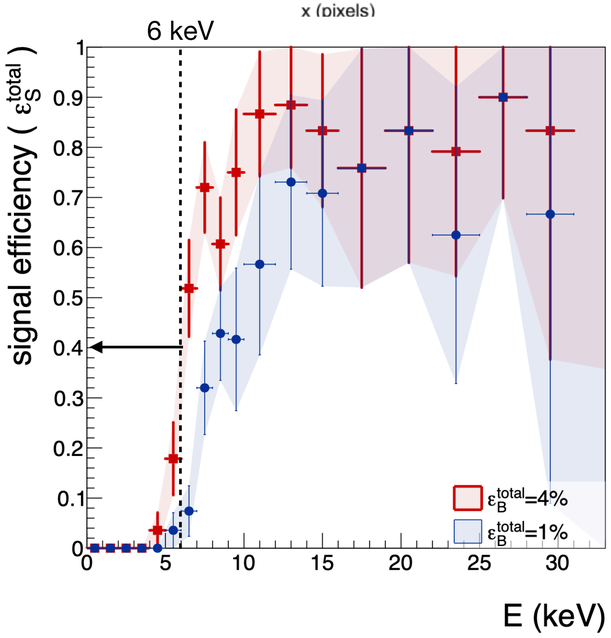
Iterative morphological thinning for actual track length

Response to low energy nuclear recoils









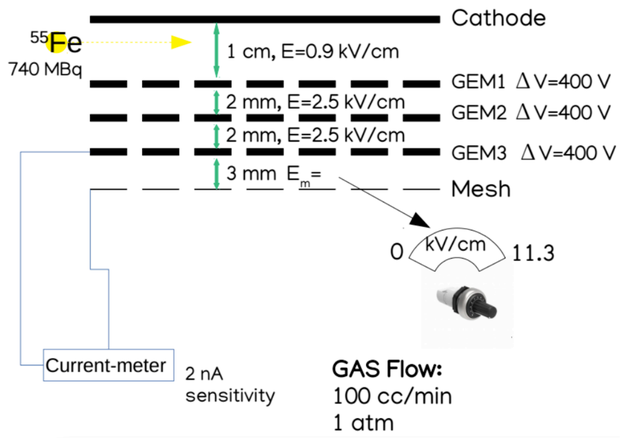
Measur.Sci.Tech. 32 (2021) 2, 025902

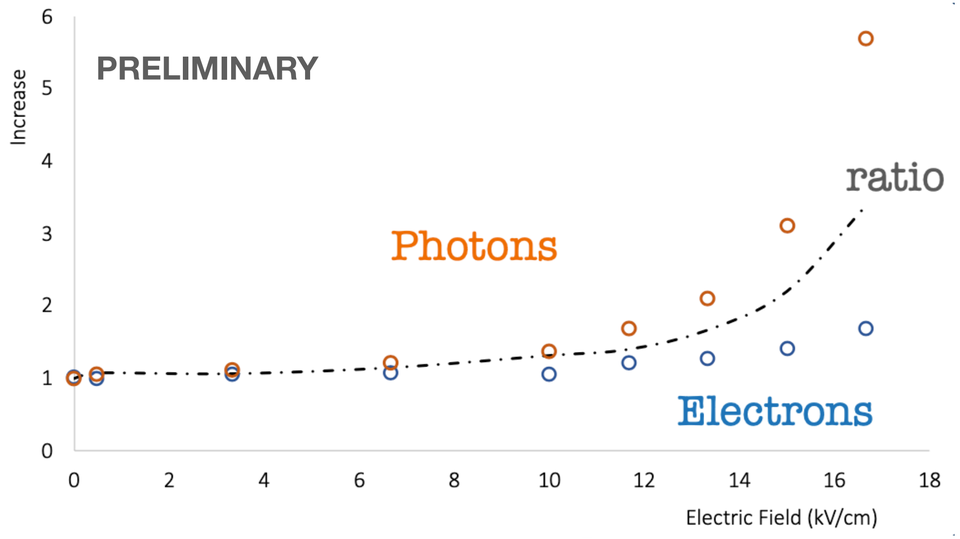
40% nuclear recoil efficiency at 6 keV$_{ee}$ with 96% rejection against ^{55}Fe

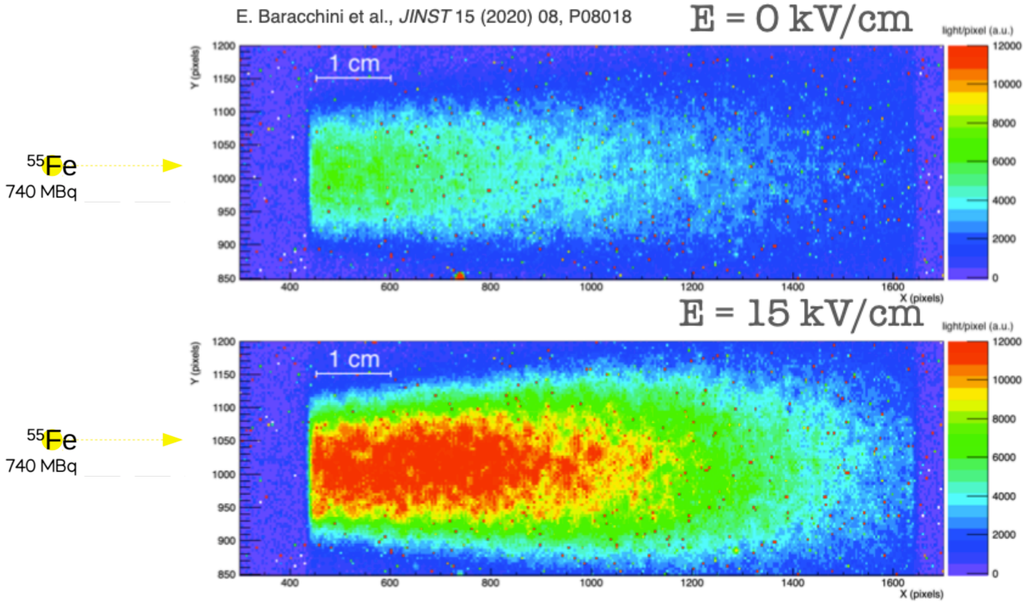
Working on a more refined algorithm to exploit all available information

Electroluminescence studies

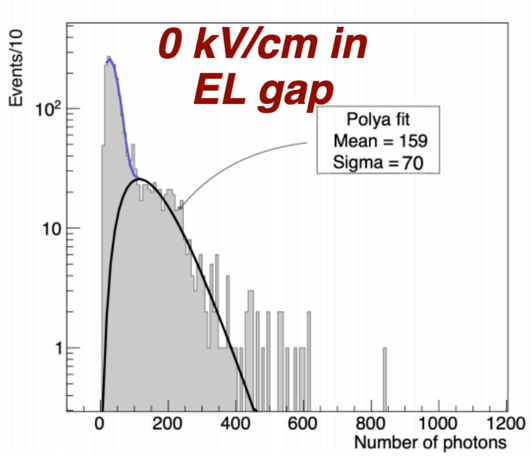
JINST 15 (2020) P08018

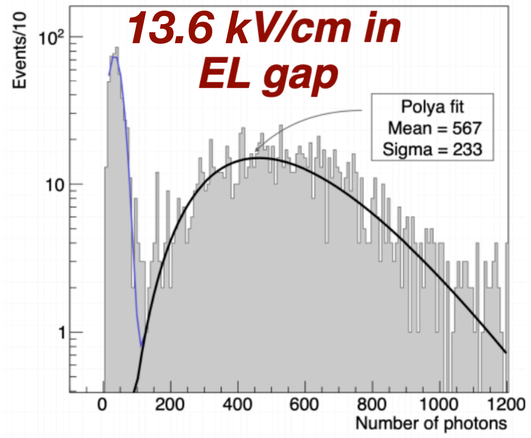






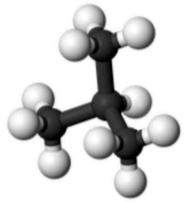
^{55}Fe data





First demonstration of electroluminescence in CF_4

R&D: ternary mixture with hydrocarbons

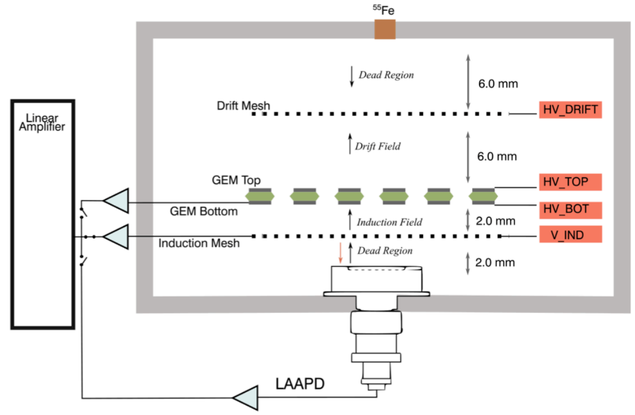


Isobutane (i-C_4H_{10}): ? %

- Improves gas tracking properties;
- Maintains low target mass.

Goal

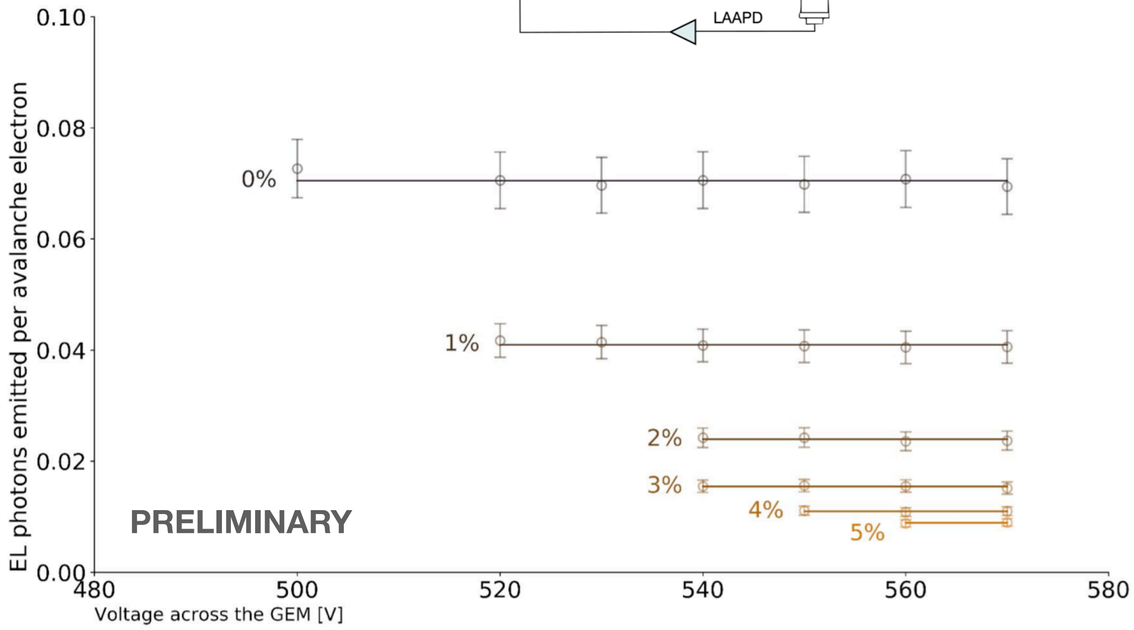
Study how the inclusion of isobutane influences the **Charge** and **EL** signals of the mixture.



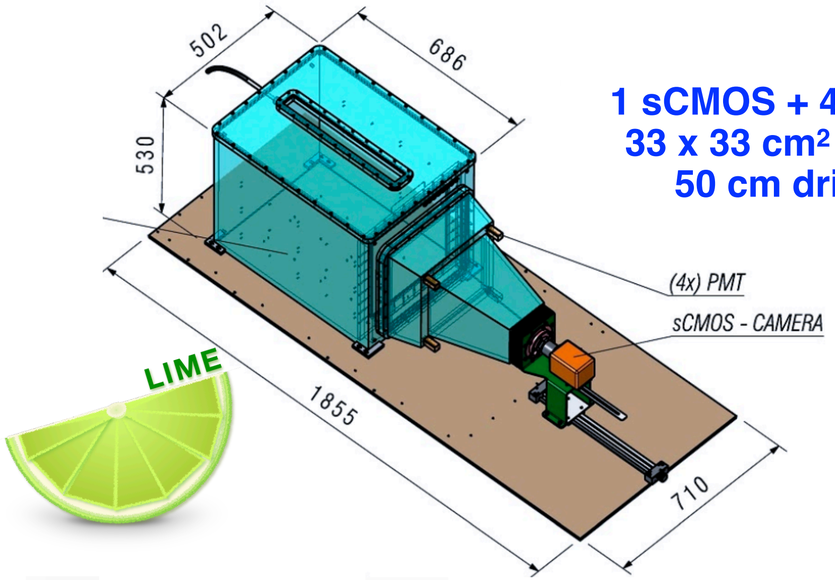
Going from **0 to 5% isobutane** content:

- **7.8 decrees in the EL photon** per avalanche electron
- **2.7 increase** in the maximum number of avalanche **electrons**
- however only **2.8 decrease in the total number of EL photon per absorbed keV**
- energy resolution independent of isobutane content

First demonstration of a very good light yield from a mixture with C_4H_{10}



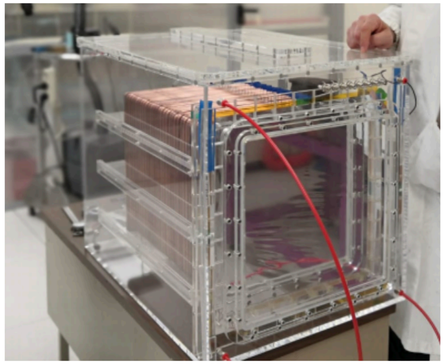
Lime prototype

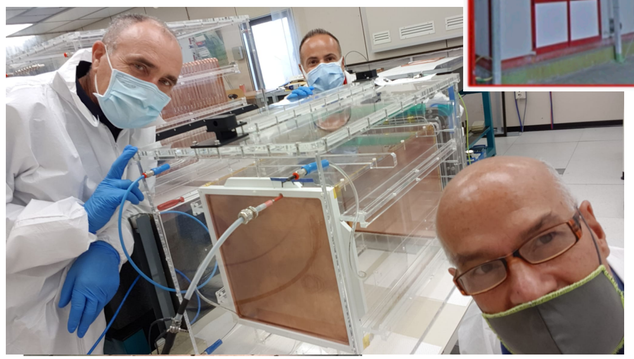


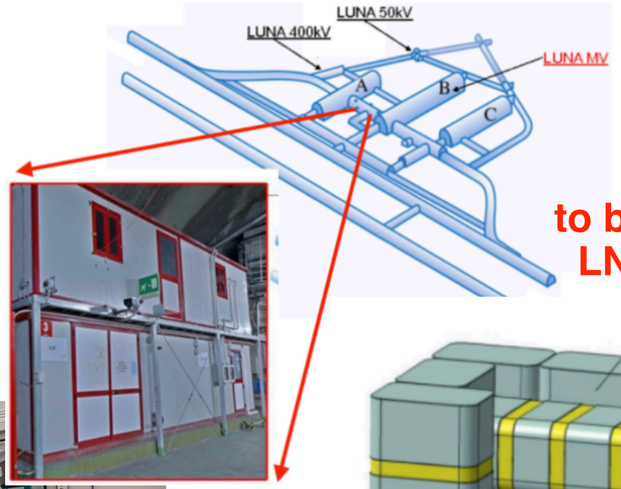
1 sCMOS + 4 PMT
33 x 33 cm² area
50 cm drift

ORCA-Fusion

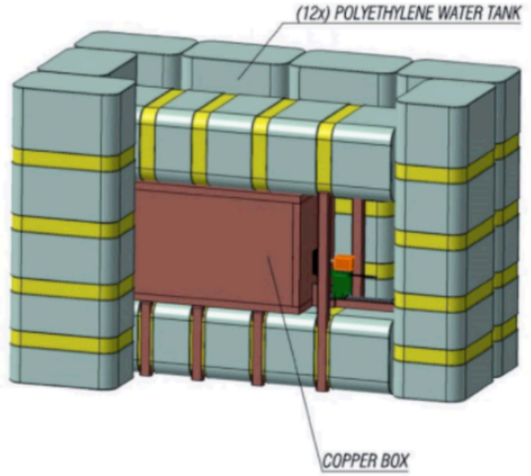
- **reduced noise from 1.4 to 0.7 electrons**
- **more pixels (2304x2304)**
- **larger quantum efficiency 0.8 (0.7)**



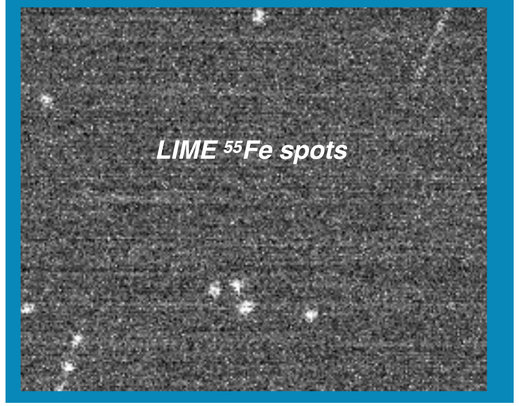


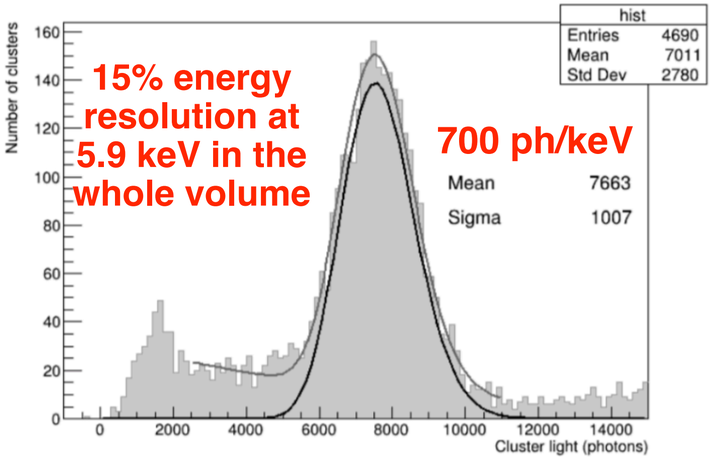


to be installed at LNGS by 2021



- 45 cm from GEMs





Large prototypes stability tests

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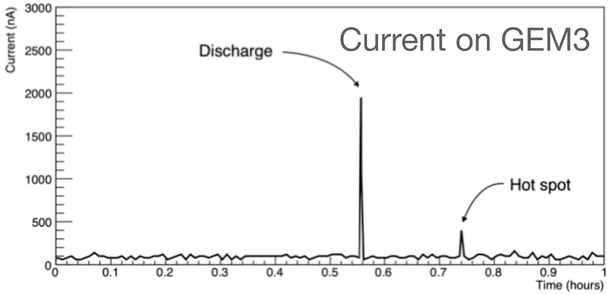
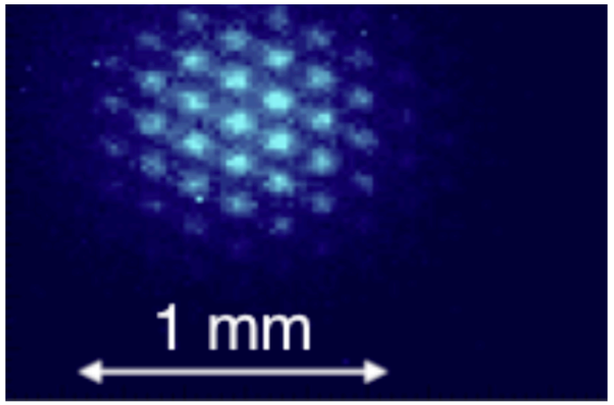


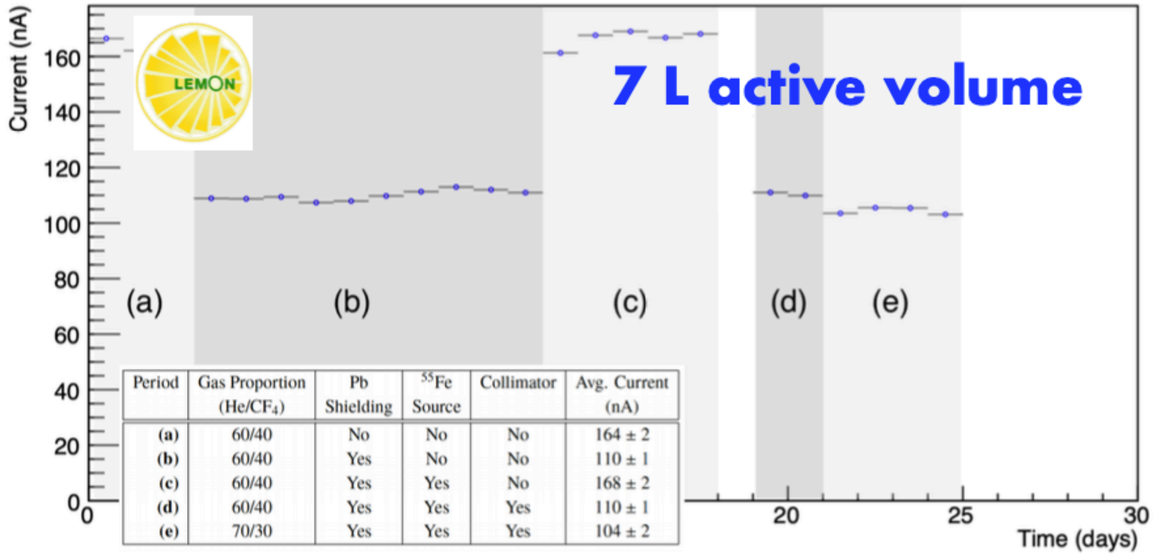


Hot spots and **Discharges:** dumped by lowering GEMs voltage to 100 V and raising it again (3 min deadtime)

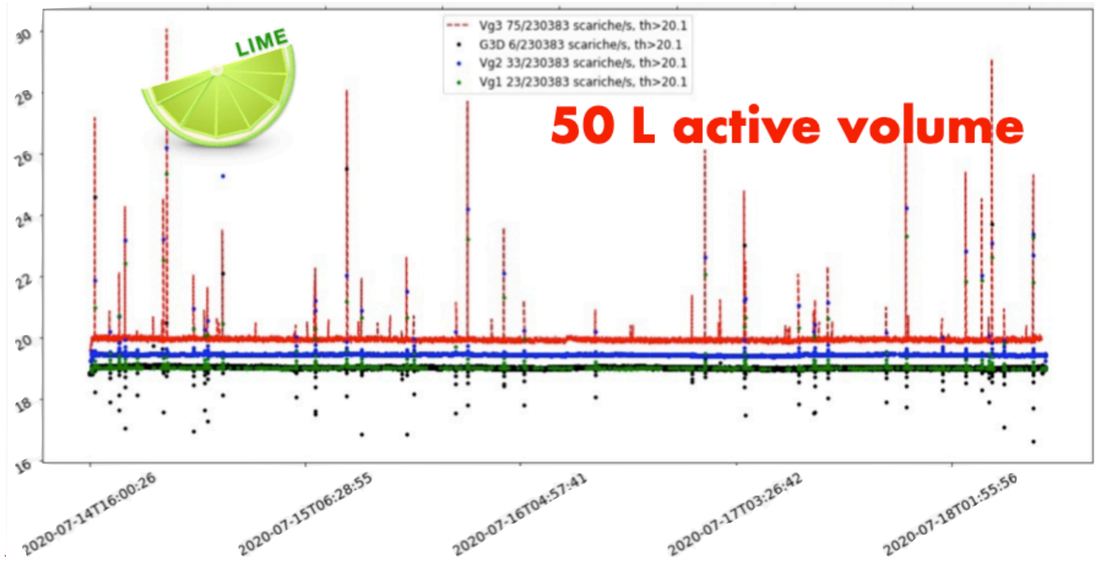
He:CF4 60:40% 1 atm

LEMOn successfully operated for 25 consecutive days with automatic GEM hot spots recovery procedure

Similar stability with LIME: (less than 1 evt/hour) in agreement with a factor of 2 larger GEMs



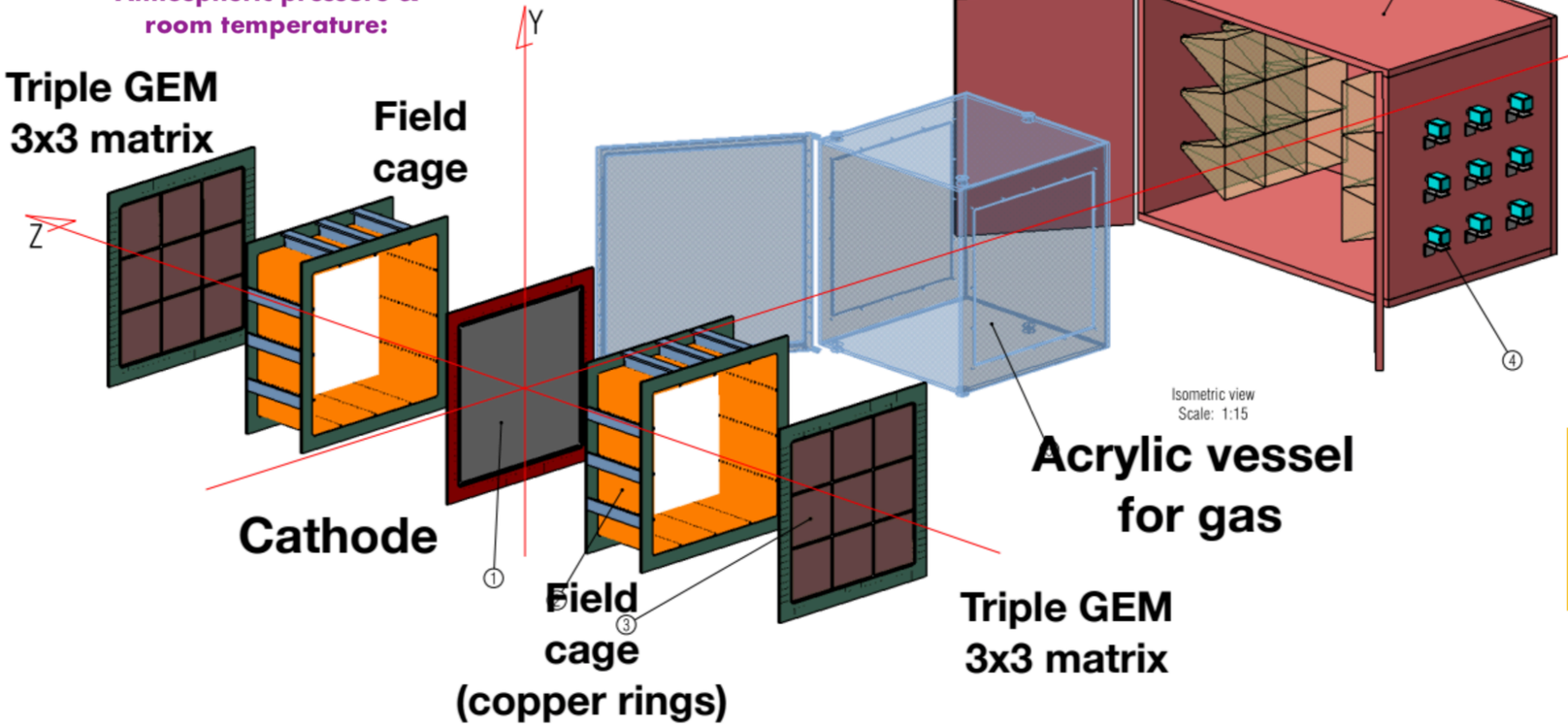
Period	Gas Proportion (He/CF_4)	Pb Shielding	^{55}Fe Source	Collimator	Avg. Current (nA)
(a)	60/40	No	No	No	164 ± 2
(b)	60/40	Yes	No	No	110 ± 1
(c)	60/40	Yes	Yes	No	168 ± 2
(d)	60/40	Yes	Yes	Yes	110 ± 1
(e)	70/30	Yes	Yes	Yes	104 ± 2

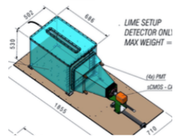


CYGNO 1m³ demonstrator

He/CF4 60:40 (**1.6kg**) in two TPC with a **50 cm** drift and **1 kV/cm** drift field

Atmospheric pressure & room temperature:



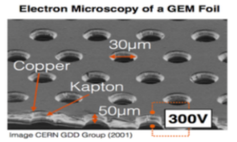


9 LIMEs per 1 m²

Cameras and PMT

100M
165 x 165 μm² pixels

Gas Electron Multipliers (GEMs) amplification



Designed at LNF and to be installed at LNGS

Trigger and DAQ for CYGNO

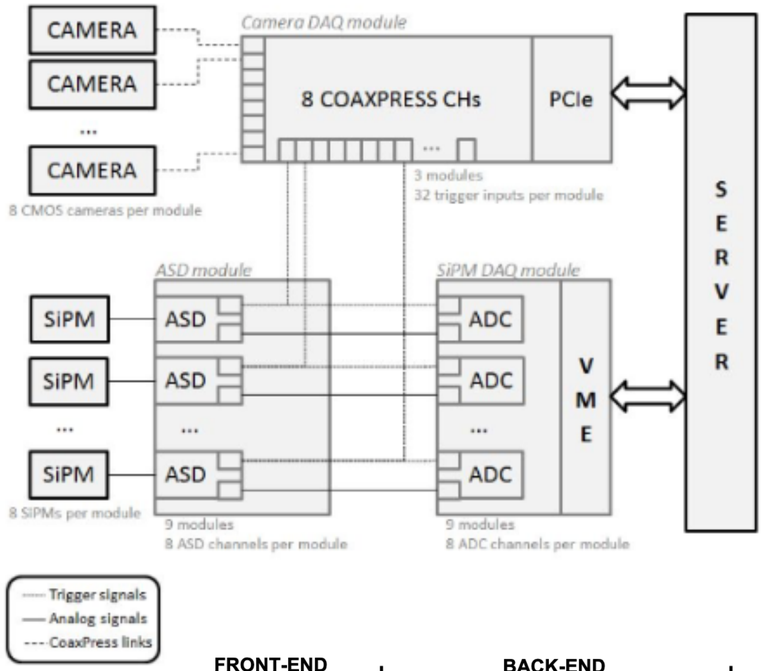
Two readout path:

- **camera (one per module):**
  - exposure 0.2-1 sec. 10MB of data;
  - run in continuum mode, 50 Mb/s
  - CameraLink PCIe frame grabber @ 2.5 GB/s (or USB3)
- **photodetector (up to 8 channels per module):**
  - 12-bit digitisation @ 250 MS/s, $\lesssim 1\mu$s, 1 Mb/s

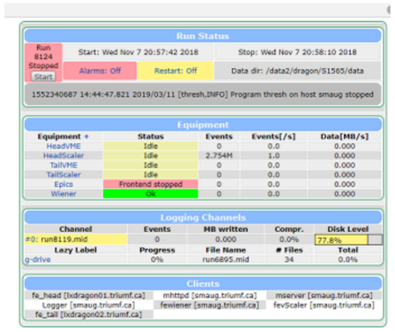
Two possible trigger levels:

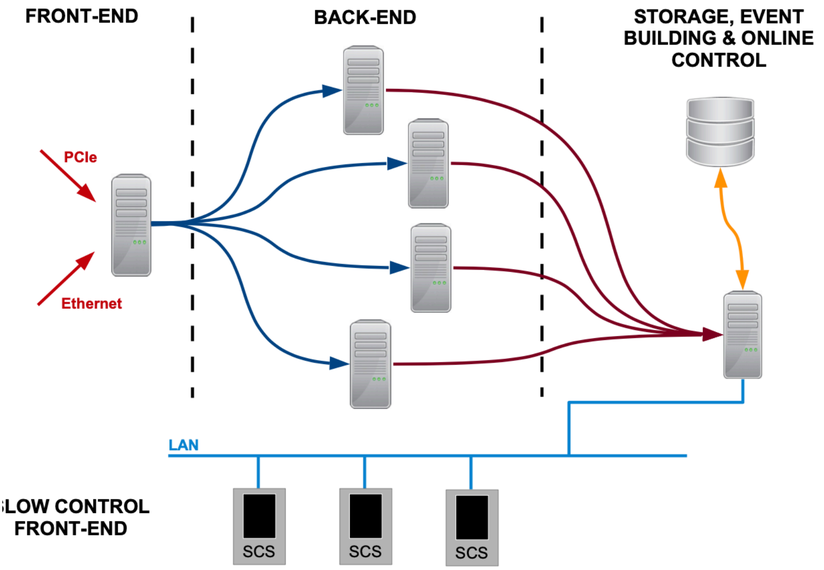
- **HW trigger:** photodetectors with minimal logic (e.g. majority)
- **Software trigger:** reconstruction of images and waveforms on a farm of CPUs/GPUs based and trigger on interesting features (e.g. clusters), typically 1 evt/s

MIDAS used for Readout, Trigger and slow control



MIDAS run control and slow control





Summary

The CYGNO project is developing a **GEM-based TPC with optical readout**

- Very good **energy** and **position resolution**
- High **discrimination power**
- R&D ongoing to optimise the already very good performance
- First **underground campaign** by the end of **2021**

ORANGE @ ROMA1 — 2015-2016

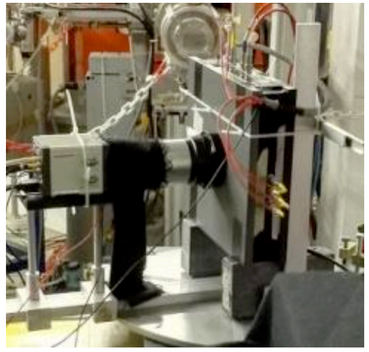
LEMOn @ LNF — 2017-2018

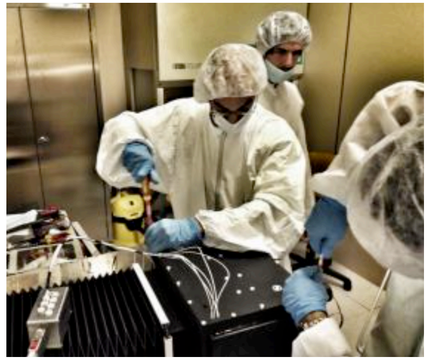
MANGO @ LNF / LNGS — 2019-2021

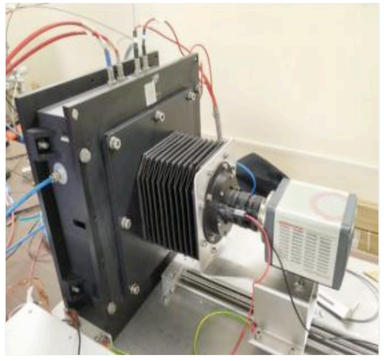
LIME @ LNF / LNGS — 2021

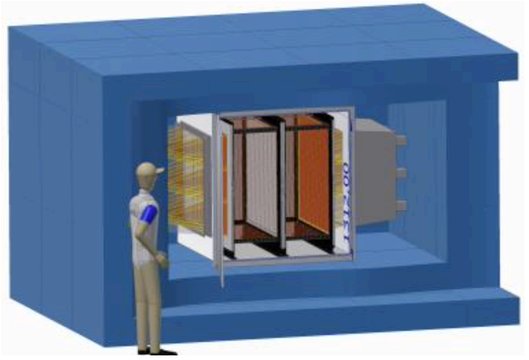
2022

CYGNO demonstrator @ LNF / LNGS — 2023









CYGNO 30-100 m³

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