WEIZMANN INSTITUTE OF SCIENCE

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The CYGNO Experiment: A Directional Dark Matter Detector with Optical Readout

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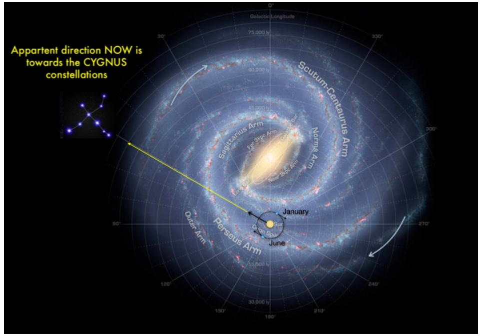
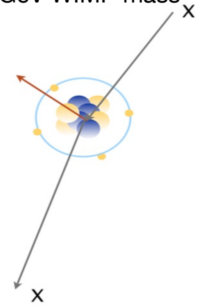
Introduction & talk layout

DM should form an halo around the galaxy → DM "wind" from CYGNUS



- WIMPS are natural DM candidates;
- Direct observation:
  - scattering off target nuclei.

1-100 keV recoil energy for ~1-100 GeV WIMP mass



- Underground, large volume experiments;
- DIRECTIONALITY

Talk layout:

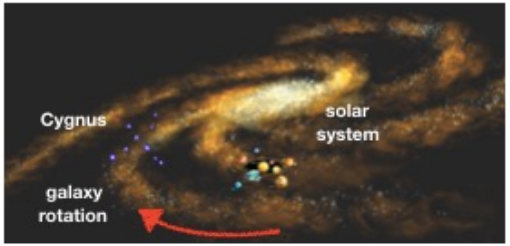
- DM detection and directionality
- The CYGNO technique
- Ongoing work (selected topics):
  - Detector response simulation
  - Performace of the Long Imaging ModulE (LIME)
  - LIME@LNGS
- Outlook: the 0.4 m^3 detector

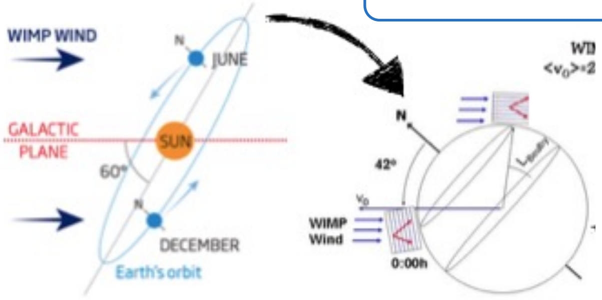
DM detection and directionality

WIMP flux
(<v>~220km/s)

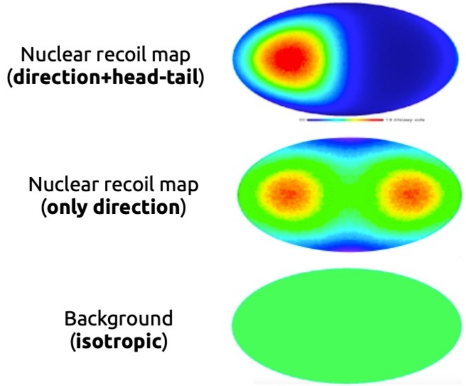
few % DM flux
annual
modulation

- Anisotropy in the angular distribution of nuclear recoils;
- **No background can mimic it.**

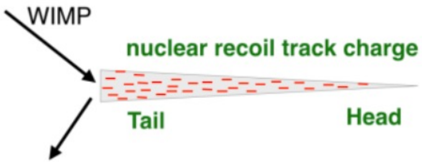




A. M. Green et. al, Astropart. Phys. 27 (2007) 142



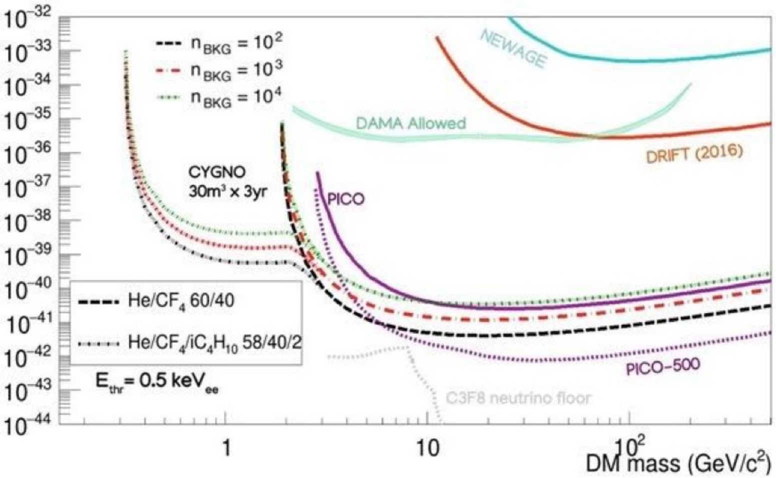
<u>Directional discrimination</u> is the only way to:
- **Unambiguously identify a DM signal**
- Searching beyond the neutrino floor
- Moreover:
  - Properties of the solar neutrino flux;
  - DM halo properties (DM astronomy).



NR (partially) retain the direction

DM searches with CYGNO

Spin Dependent



To observe light (<10 GeV/c²) WIMPs:

- Less energy transferred to the recoiling nucleus
  → lower the detectable signal threshold
- Exploit light target nuclei to maximize energy transfer.

Gas mixture

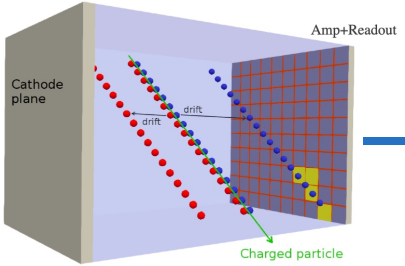
Helium: light target for low mass WIMPs
Fluorine:
- Heavier target for intermediate masses
- Sensitive to SD couplings

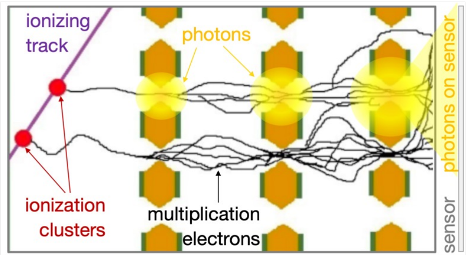
Low density (atmospheric pressure)
- Allows several mm tracks at few keV
- Direction and energy deposit topology

The CYGNO technique *(in 1 slide…)*

A TPC with He/CF_4 at atmospheric pressure:

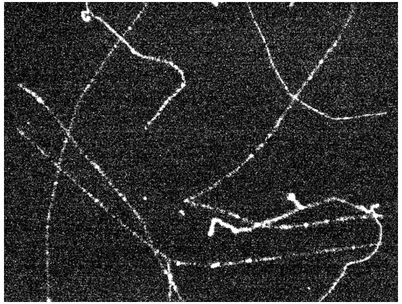
- Primary ionization electrons are transported by the drift field and multiplied by a 3-GEM stack.





- X-Y position in the GEM plane
- Energy deposition topology:
  - Direction;
  - Head-tail asymmetry;
  - Background rejection.

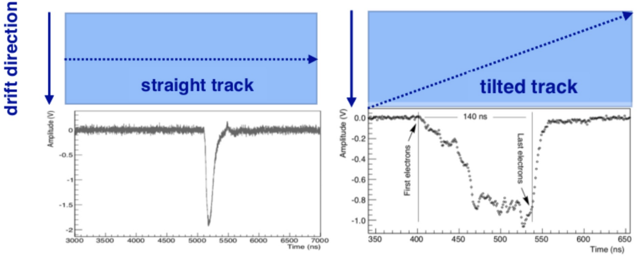
sCMOS



PMT

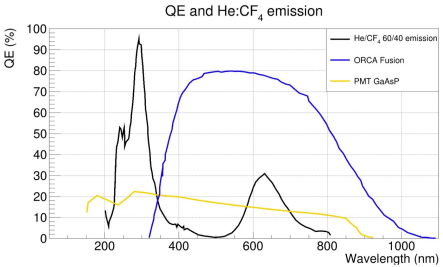
- Integrated energy
- Ionization electron's time of arrival

→ track tilt (dZ)

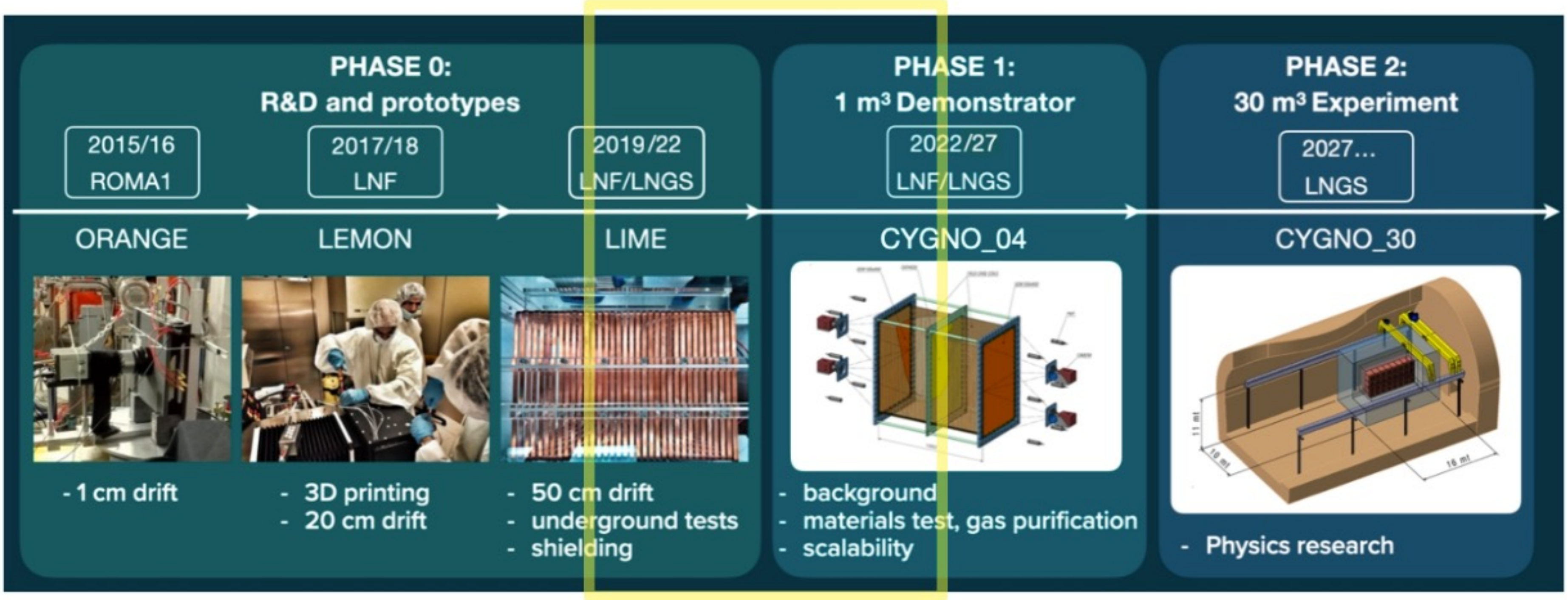


JINST 13 (2018) no.05, P05001

Light produced by the de-excitation of the gas molecules during electron multiplication;
significant yield at the camera's QE peak.

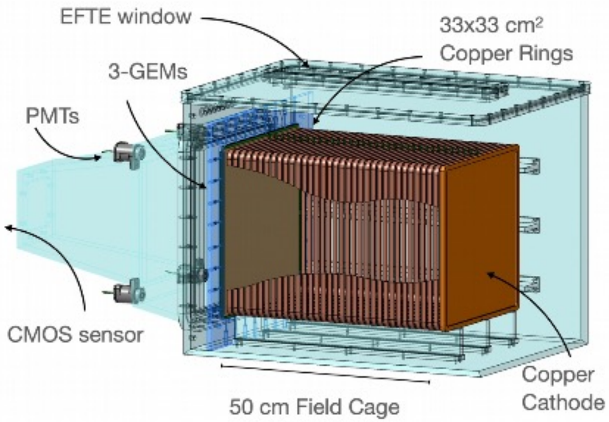


The CYGNO roadmap



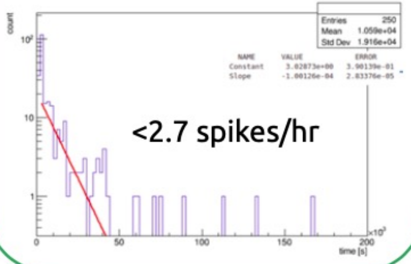
The Long Imaging ModulE - LIME

- Our largest prototype: 50L sensitive volume
  - 33x33 cm^2 thin (50 μm) GEMs, 50 cm drift;
- Optical readout:
  - 4 PMTs at the corners;
  - 1 sCMOS camera (Hamamatsu ORCA Fusion);
  - 2304×2304 pixels, low noise (1 ph/pixel), high granularity 160×160 μm^2, 2 counts/photon;
- Operated for few months @INFN LNF.



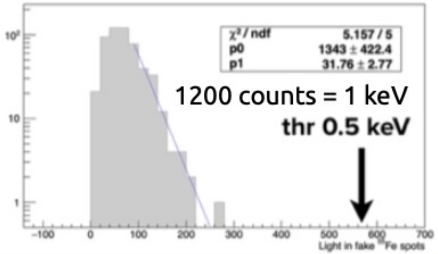
Stability

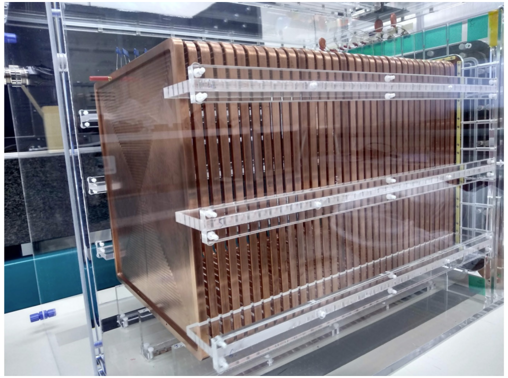
Tested for > 1 month



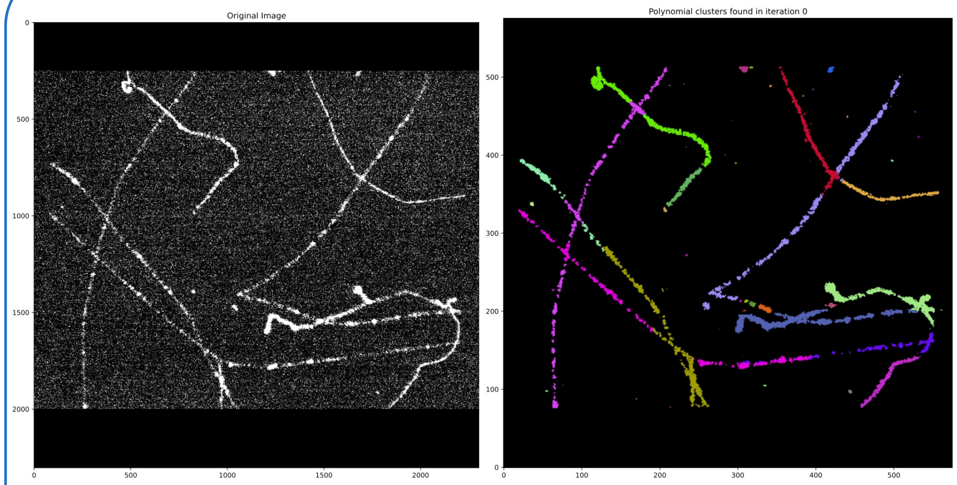
Energy threshold

<10 fake events/year (tested with ^{55}Fe)



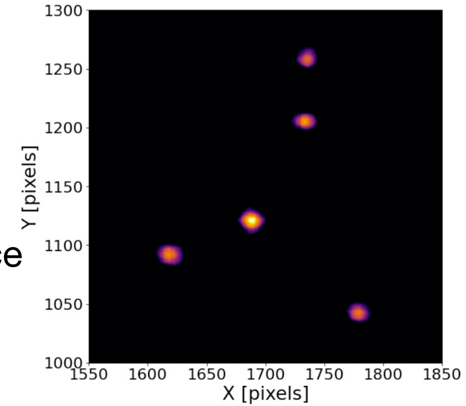


LIME images

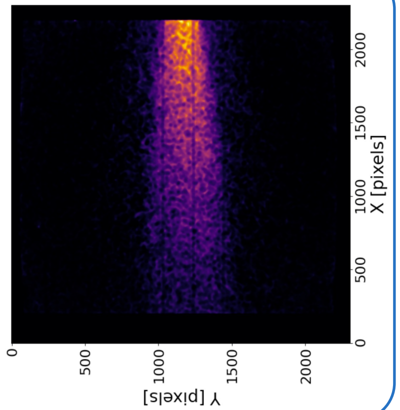


- Background image with 50 ms exposure
- Reconstructed tracks are shown in different colours

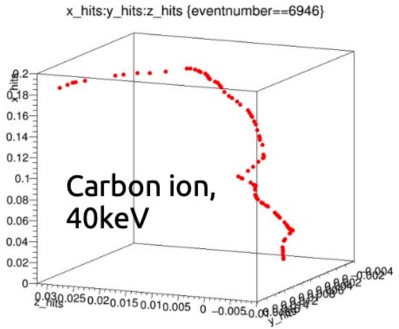
Interaction of 5.9 keV X-rays from a ^{55}Fe source



Positions of the spots illuminating the detector in a run with ^{55}Fe source



Simulation: Modelling the detector response



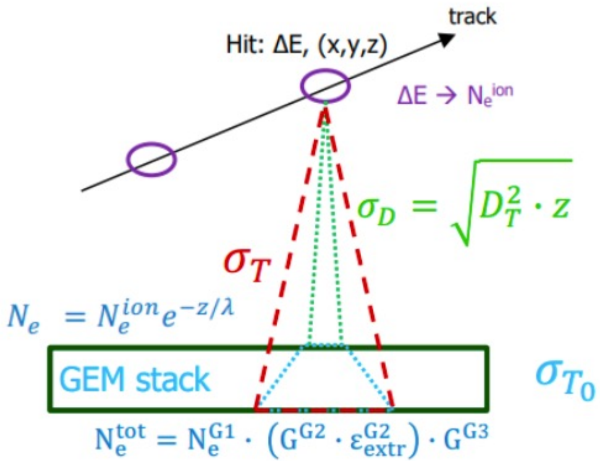
MC simulation of 3D energy deposition:

GEANT4 for ER, SRIM for NR

The following processes are considered (including fluctuations):

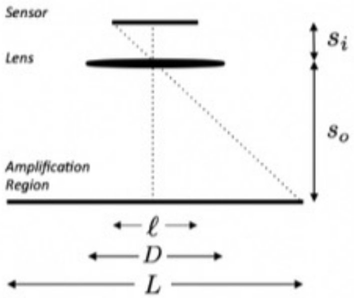
- Ionization;
- Diffusion (in the gas and in the GEMs);
- Absorption;
- Multiplication in the 3-GEM stack;
- Gain Saturation effect (depending on the charge density);

- Production of photons in the multiplication process;
- Photon collection on the sensor;
- Sensor noise.



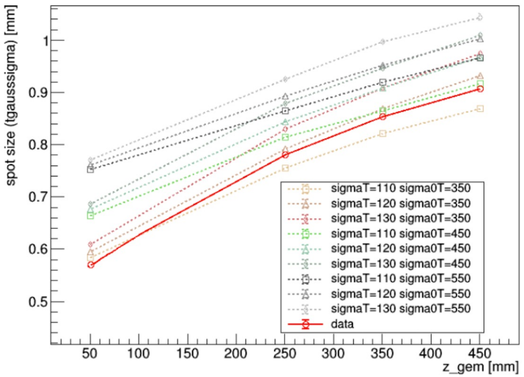
Optical acceptance:

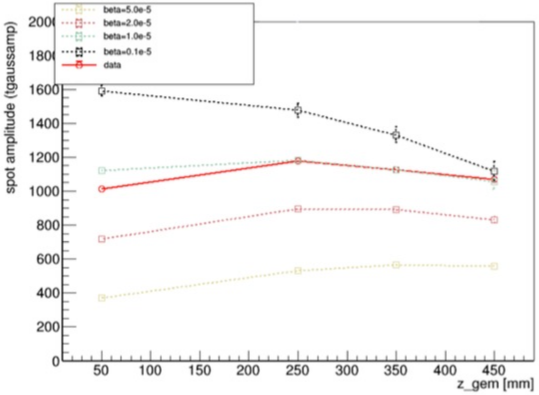
$$\Omega = \frac{1}{(4(L/\ell + 1)a)^2}$$



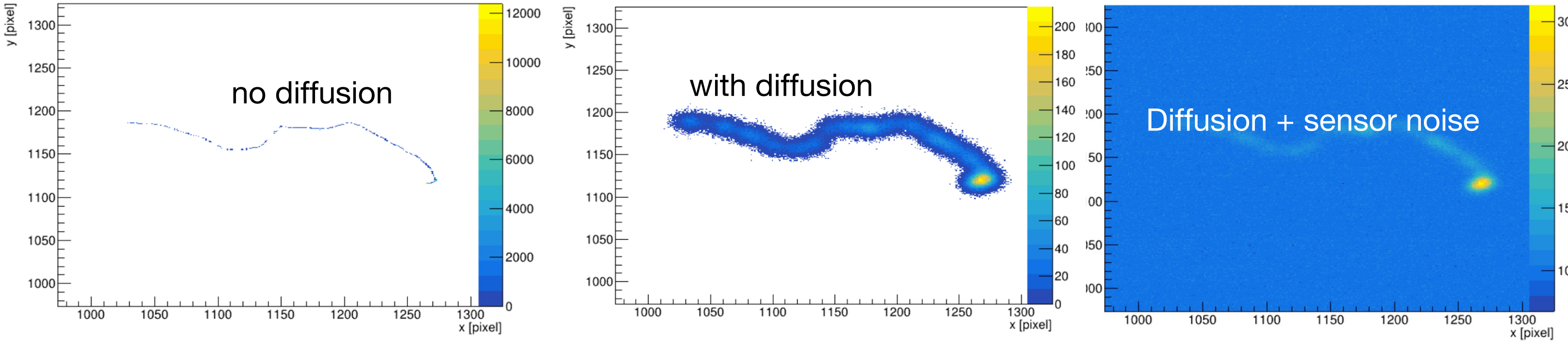
Tuning the simulation

Simulation parameters are **optimized** in comparison with LIME data (^{55}Fe source in different positions for different detector settings)





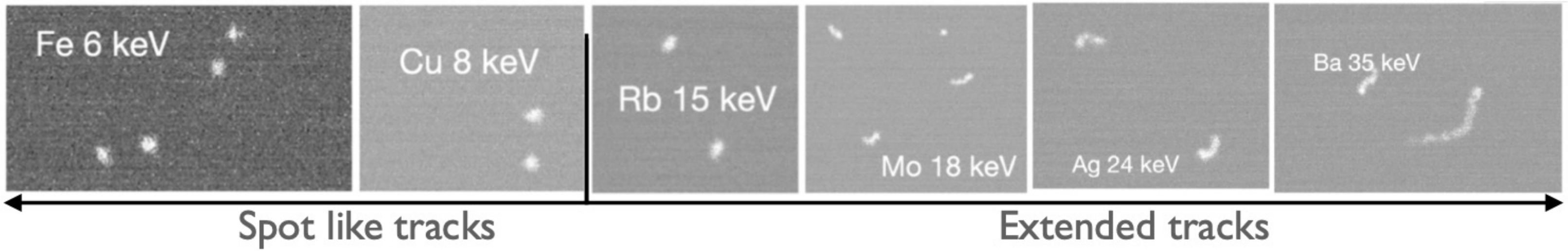
30 keV electron



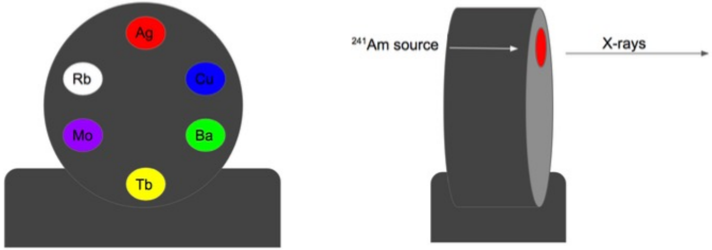
LIME performances

Study of linearity and energy resolution overground performed with different X-Ray source:

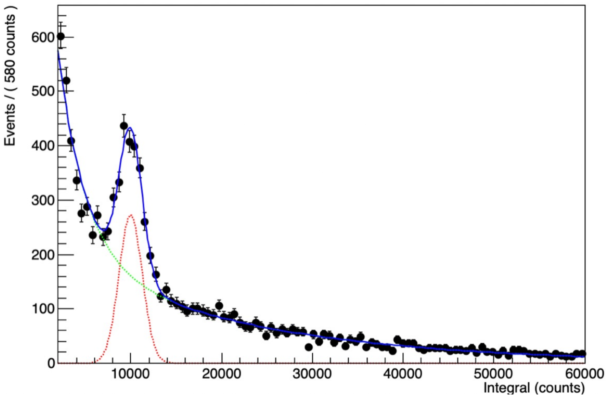
- ^{55}Fe-source for 6 keV;
- Different materials (Cu, Rb, Mo, Ag, Ba, Tb) irradiated by a ^{241}Am-source for higher energies;
- ^{55}Fe on a gypsum (Ca) target for 3.7 keV.



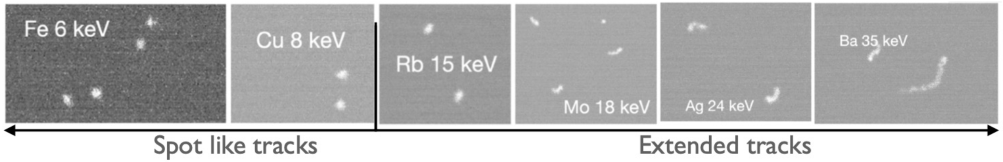
Amersham AMC.2084 X-ray source



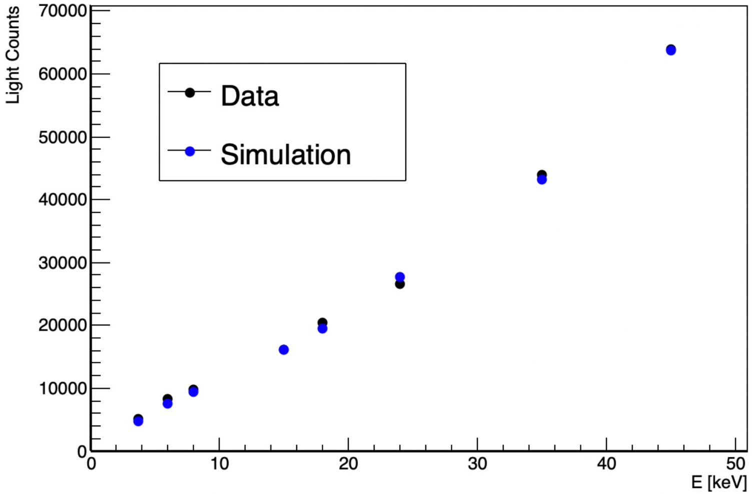
Combined fit of the source signal over the background

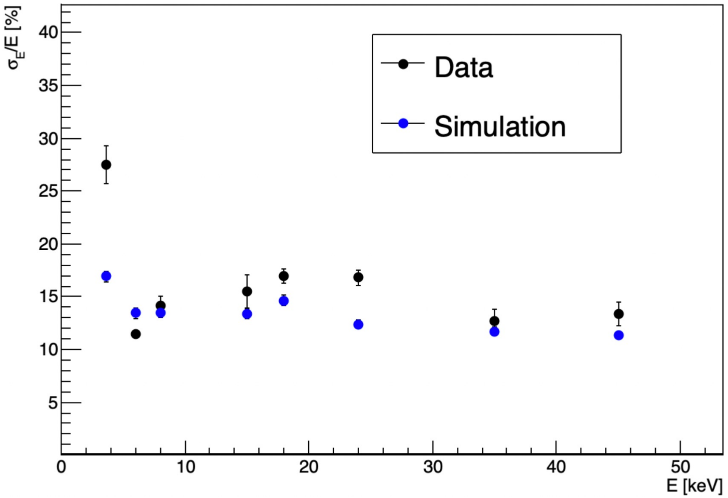


LIME performances



- **Linear energy response** was found between 3.7 keV and 44 keV;
- **Energy resolution ~14%** in the whole volume;
- 100% reconstruction efficiency at 5.9 keV in the whole volume; *[E. Baracchini et al., JINST 15 no.12, T12003 (2020)]*
- **Very good data-MC agreement.**

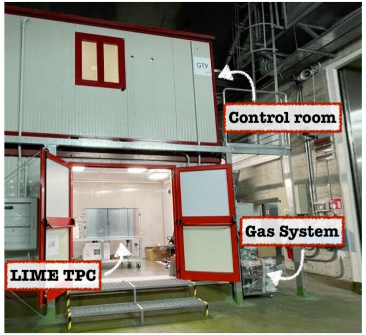


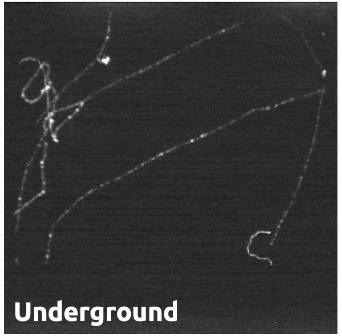


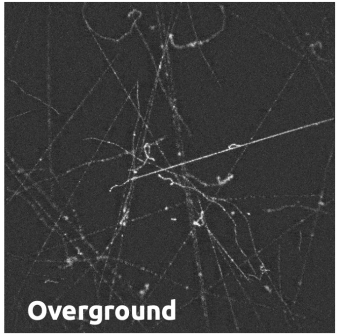
LIME underground@LNGS

LIME installed underground at National Laboratories of Gran Sasso (3600 m.w.e.) early in 2022:

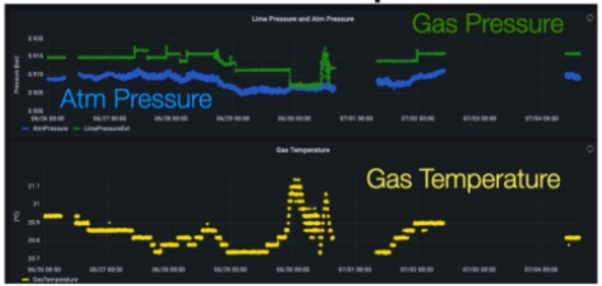
- Automated system allows to control remotely the gas system, environmental sensors, HV, and data acquisition system allowing a continuous data taking → stability tests;
- First data underground (without any shielding) are being analysed to be compared with MC simulations.



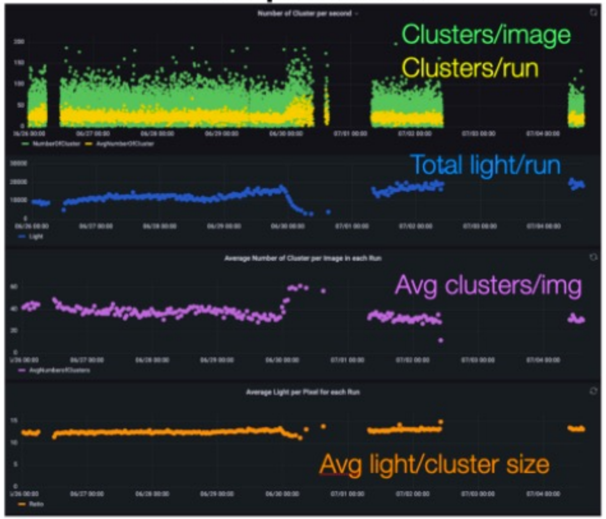




Gas and environmental parameters



Detector performance



Lime background studies

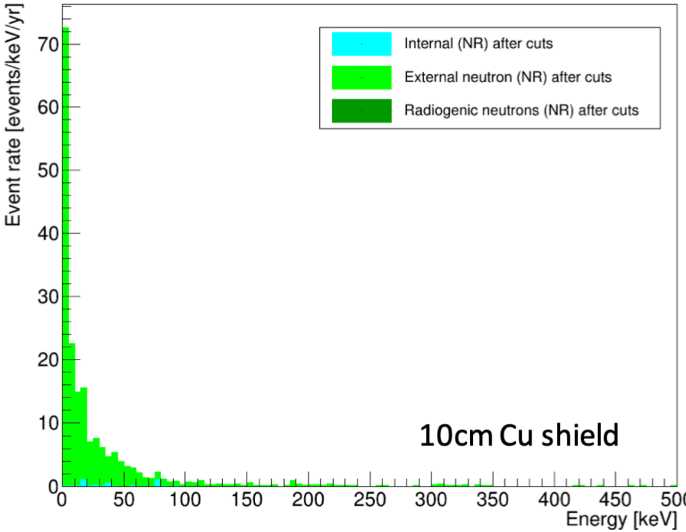
Aiming at the **characterization of the background** in different phases:

- No external shielding: external background measurement
- Copper shielding (10 cm): reduced external gamma background → neutron background measurement
- Water tanks (40 cm) + copper shielding:
  - Internal background measurement
  - Final test in low background and low pile up conditions

Neutron flux measurement.

After fiducial cuts (next slide):

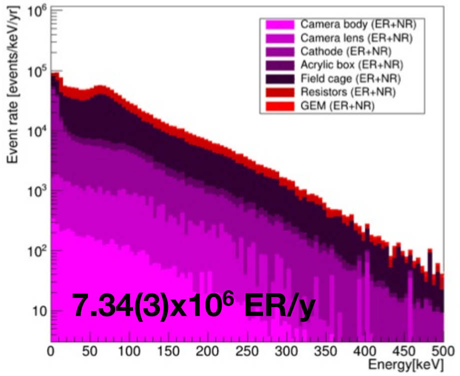
- 772 NR/yr from neutrons (+16 NR/yr from other sources) above 1 keV
- 316 NR/yr from neutrons (+11 NR/yr from other sources) above 20 keV

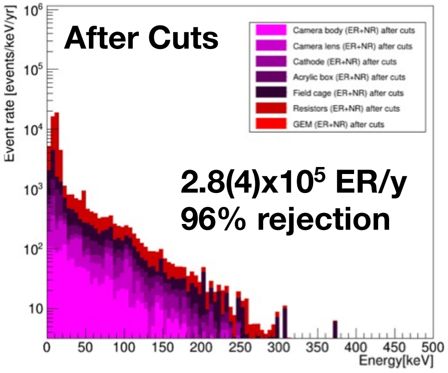


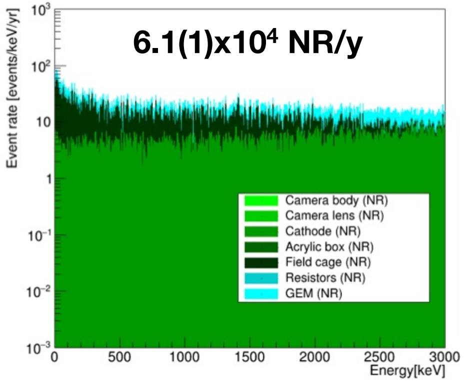
Internal background

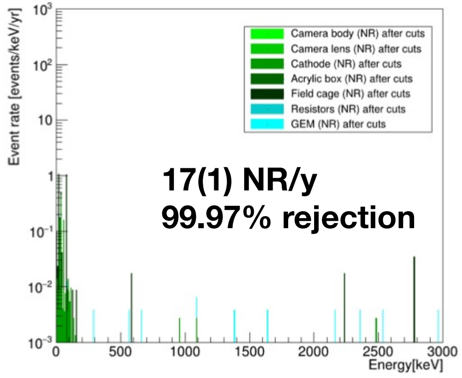
Radioactivity from all main detector components were measured with HPGe detectors

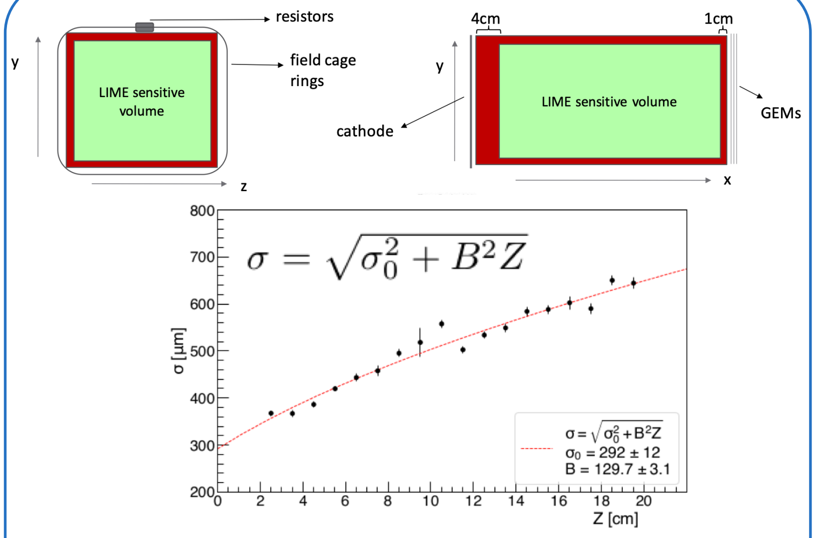
- Camera components measured separately: the **sensor** and the **lens** are the most radioactive





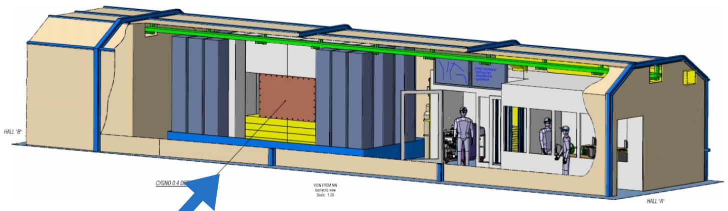


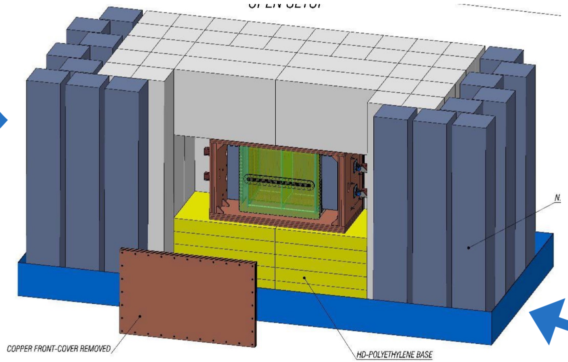




V.C. Antochi et al, NIMA 999 (2021) 165209

The CYGNO_04 demonstrator



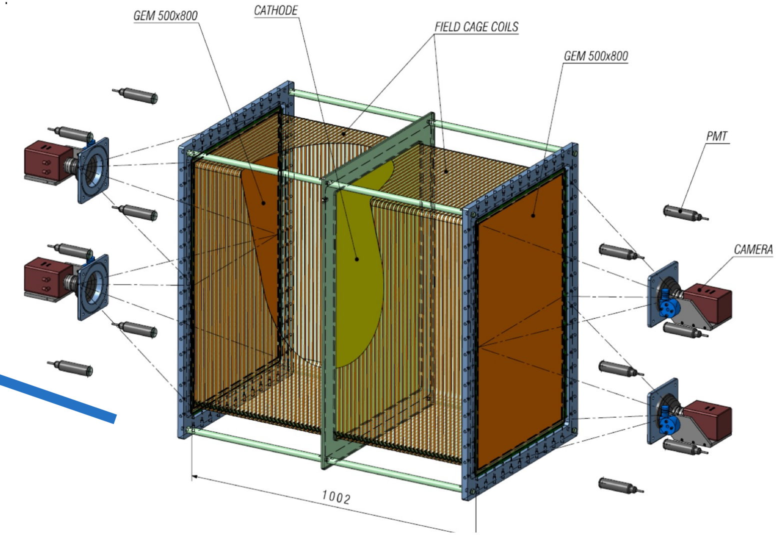


Internal background reduction:

Building low radioactivity camera sensosrs, lens and windows (Suprasil, PMMA, polycarbonate)

Phase 1 - CYGNO_04: Funded and TDR ready!

- 0.4 m^3 detector in LNGS hall F
- 50 x 80 X 100 cm^3 volume
- Common cathode
- Readout by 4 sCMOS and 12 PMTs
- Demonstrate the full scalability of the technique

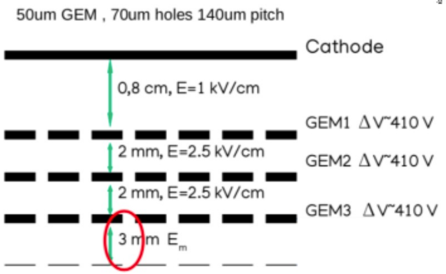


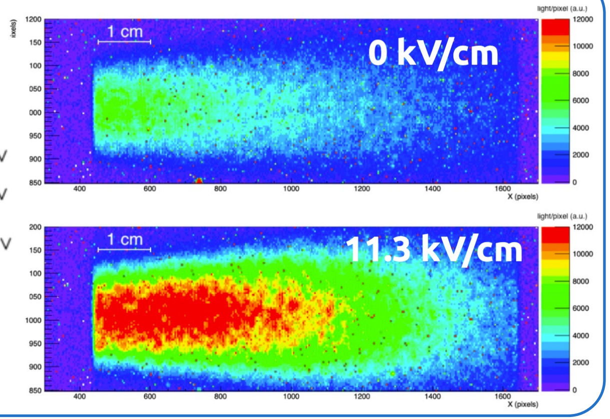
R&D on gas

<u>Electroluminescence</u> (increase light yield, with no further ionization):

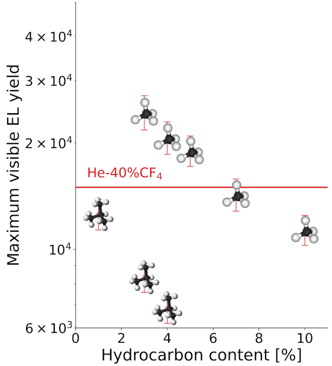
- Add a mesh (or ITO glass) 3 mm after last GEM;
- Apply drift field between GEM and mesh;
- Electrons travelling in the GEM-mesh gap produce additional light

→ decrease threshold.





A new paper is in preparation



Addition of H-based gas:

- Improve sensitivity for low mass WIMP;
- Both isobutane and methane quench some of the the visible and UV photons emitted by He/CF4. For concentrations up to 10%, the absorption is partial and does not compromise the operation of the CYGNO TPC.

Look at the poster *"Electroluminescence in He/CF4 and hydrocarbons gas mixtures for directional dark matter searches with the CYGNO Optical Time Projection Chamber" from* ***F. Amaro*** *presented by E. Baracchini*

Outlook

- Data taking underground with LIME will continue in the coming month:
  - MC validation;
  - Internal background measurement;
  - Neutron flux measurement underground;
  - AmBe neutron source to test directionality with NR data.

- Design under finalization for the next phase CYGNO O(1 m^3) demonstrator to be installed underground at LNGS (funded, TDR submitted).

Thanks for your attention!