THE CYGNO/INITIUM EXPERIMENT

G. Dho* for CYGNO coll:

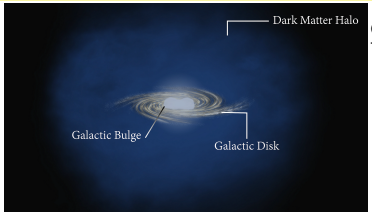
F. D. Amaro, E. Baracchini, L. Benussi, S. Bianco, C. Capoccia, M. Caponero, D. S. Cardoso, G. Cavoto, I. A. Costa, E. Dané, G. Dho, E. Di Marco, G. D'Imperio, F. Di Giambattista, F. Iacoangeli, H. P. L. Jùnior, G. S. P. Lopes, G. Maccarrone, R. D. P. Mano, R. R. M. Gregorio, D. J. G. Marques, G. Mazzitelli, A.G. McLean, A. Messina, C. M. B. Monteiro, R. A. Nobrega, I. Pains, E. Paoletti, L. Passamonti, S. Pelosi, F. Petrucci, S. Piacentini, D. Piccolo, D. Pierluigi, D. Pinci, A. Prajapati, F. Renga, R. J. C. Roque, F. Rosatelli, A. Russo, J. M. F. dos Santos, G. Saviano, N. Spooner, R. Tesauro, S. Tomassini, S. Torelli

*Gran Sasso Science Institute, L'Aquila, Italy

Part of this project has been funded by the European Union's Horizon 2020 research and innovation programme under the ERC Consolidator Grant Agreement No 818744

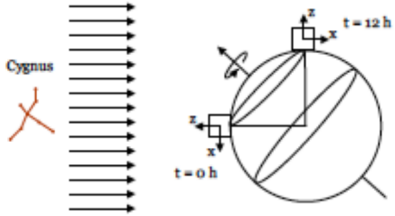
Direct Directional Dark Matter Search

- Dark Matter (DM) is considered a well established paradigm of our universe and our Galaxy is believed to reside in a halo of Dark Matter (DM), possibly WIMP–like particles.

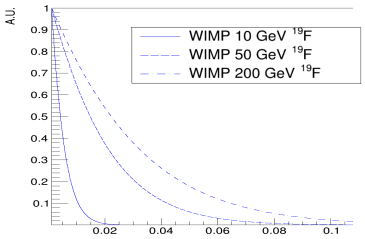


Credit: L. Jaramillo and O. Macias Virginia Tech

- The motion of the Earth together with the Sun produces an apparent wind of DM particles.

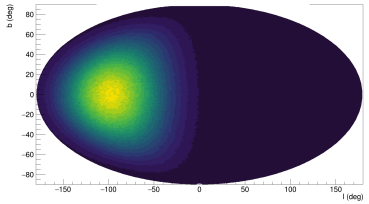


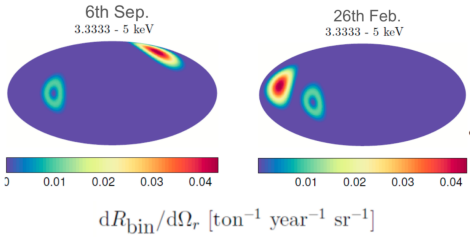
- DM of about 1–10 GeV/c^2 can induce nuclear recoils of light elements of few keV.

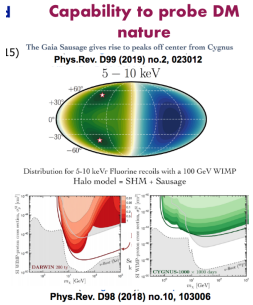


- The angular distribution of the recoils will have a very peculiar structure that no background can mimic and can be used as a powerful tool for **positive discovery, rejection of neutrino floor** and **DM astronomy**

F recoil due to WIMP





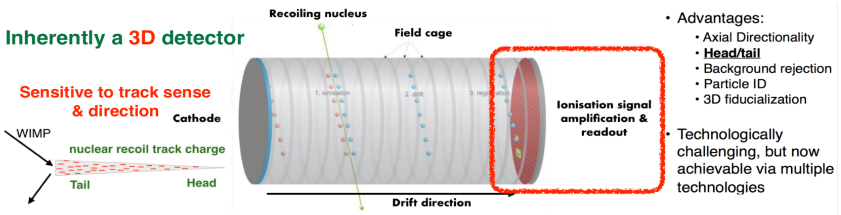


The CYGNO project aims at building a large scale directional detector whose main goal will be the direct detection of DM

Detector Working Principle

- CYGNO features:

Time Projection Chamber (TPC)

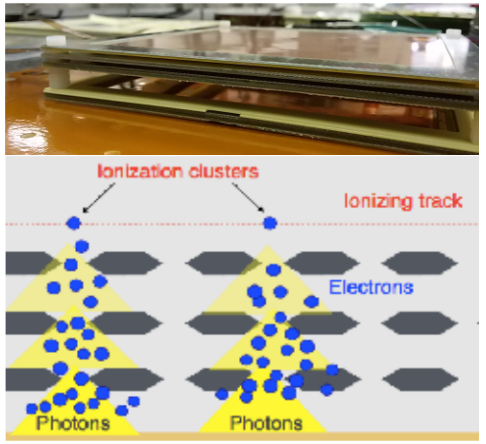


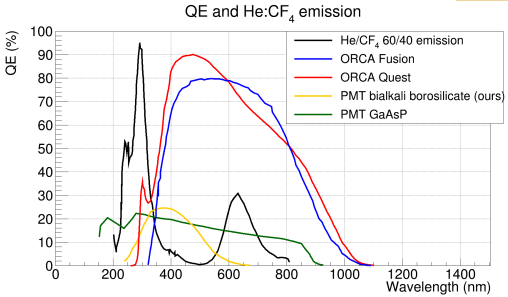
- Intrinsic 3D capable detector
- Operated at room temperature and atmospheric pressure
- He:CF_4 60/40 gas mixture for Spin-dependent and independent sensitivity at low WIMP masses
- 3D fiducialization in drift direction through diffusion fit
- O(keV) energy threshold and background rejection

with GEM amplification optically readout

sCMOS camera

- Single photon sensitivity
- High granularity (2304x2304 pixels)
- Nice match with CF_4 emission

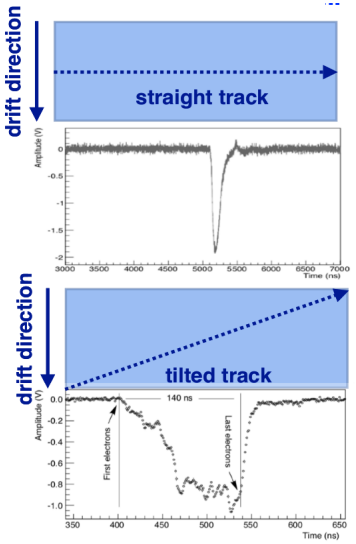




Energy x-y coordinate

Full 3D reconstruction

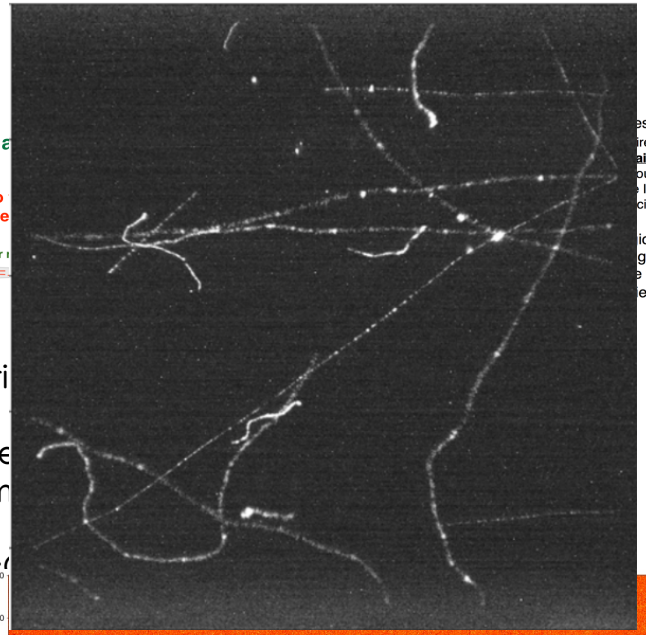
PMT

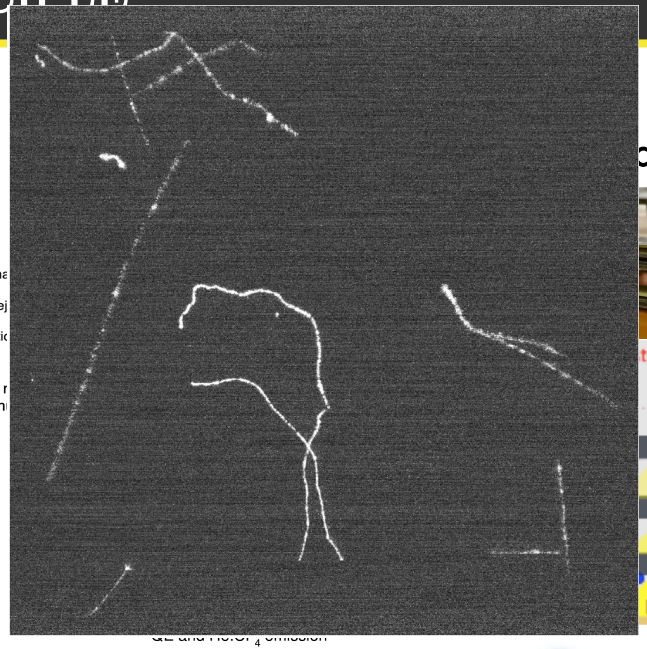


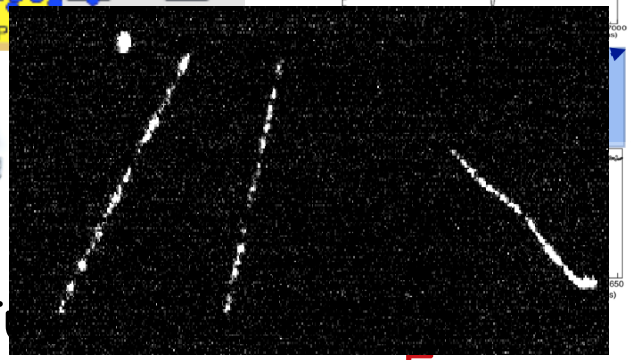
Energy z coordinate

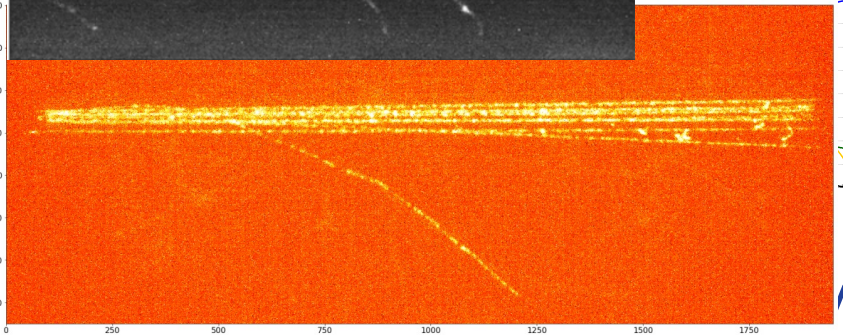
Detector Working Principle

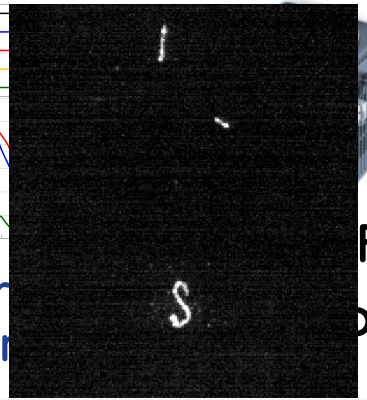
- CYGNO features:

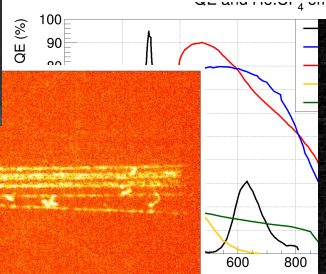












Energy
z coordinate

CYGNO Timeline

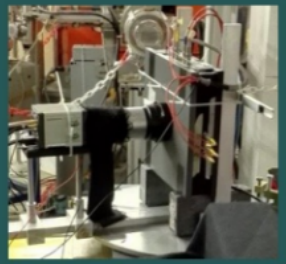
NOW

NEAR FUTURE

FUTURE

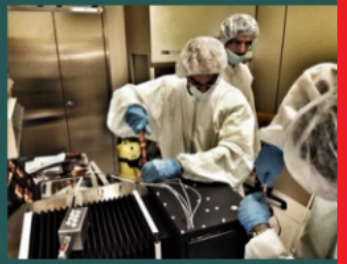
PHASE 0: R&D and prototypes

2015/16 ROMA1 → ORANGE



- 1 cm drift

2017/18 LNF → LEMON



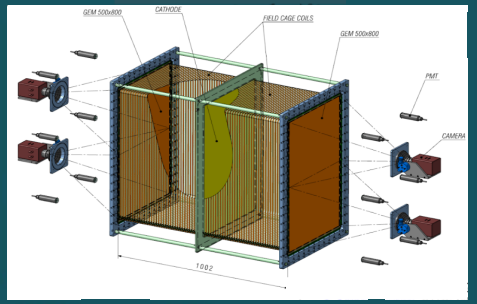
- 3D printing
- 20 cm drift

2019/22 LNF/LNGS → LIME

- 50 cm drift
- underground tests
- MC validation

PHASE 1: O(1) m³ Demonstrator

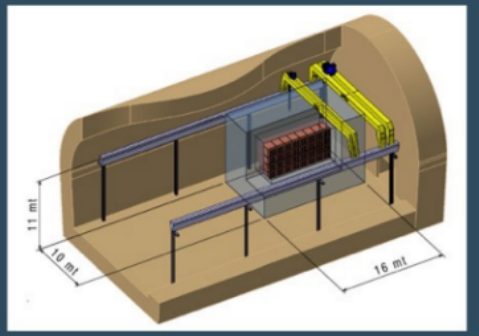
2023/26 LNF/LNGS → CYGNO_04



- background
- materials test, gas purification
- scalability

PHASE 2: 30 m³ Experiment

2026.. LNGS → CYGNO_30



- Physics research

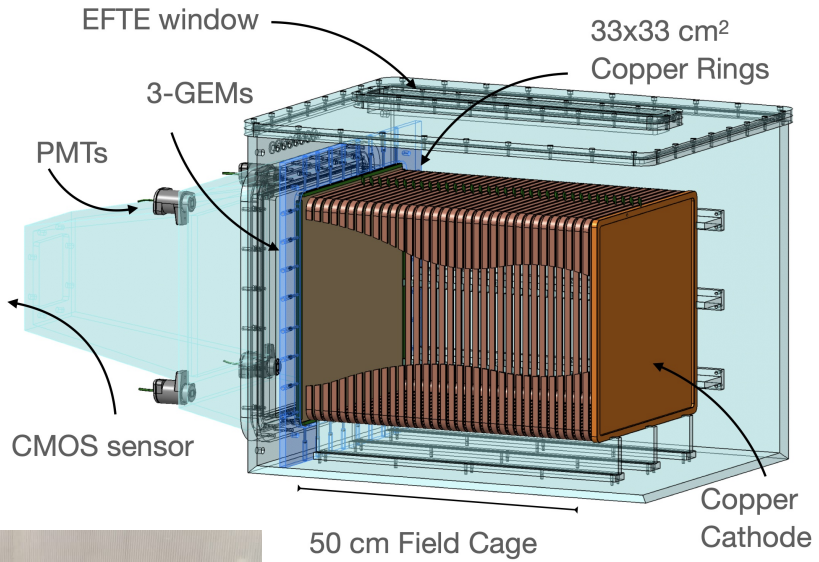
Instruments 6 (2022) 1, 6
JINST 15 (2020) P08018
JINST 15 (2020) P10001
NIM A 999 (2021) 165209

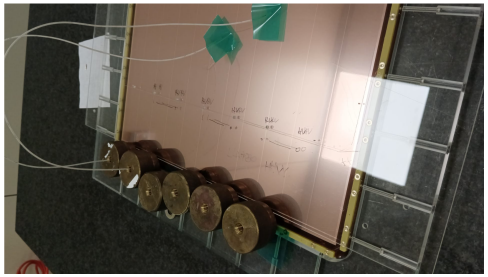
JINST 15 (2020) 12, T12003
Measur.Sci.Tech. 32 (2021) 2, 025902
2019 JINST 14 P07011

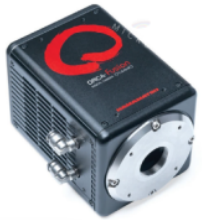
FUNDED

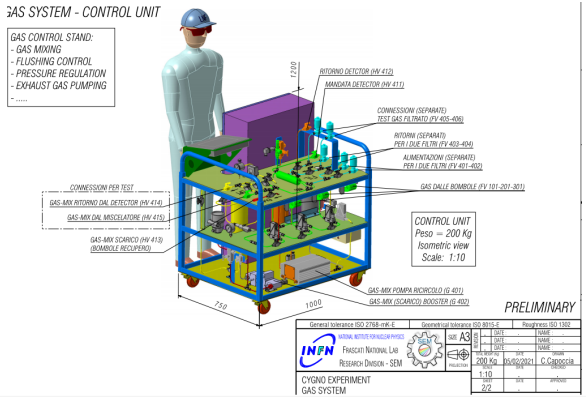
Phase-0: LIME

- 50 l detector with 50 cm drift (copper ring field cage)
- 1 sCMOS and 4 PMTs (Hamamatsu R7378)
- 3 GEMs 50 um thick of 33x33 cm^2 readout area
- He:CF_4 at atmospheric pressure (900 mbar once at LNGS)
- Complex gas system furnished with recirculation system



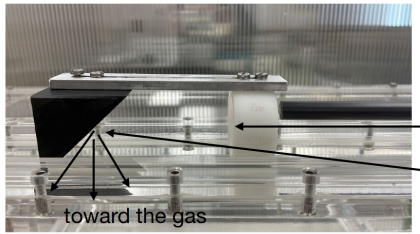




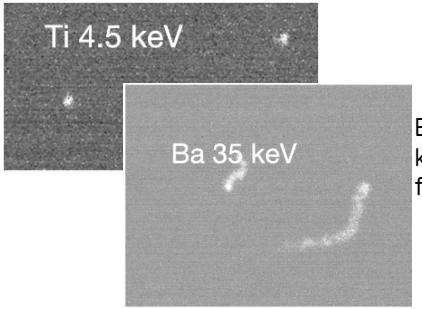


Phase-0: LIME Performances

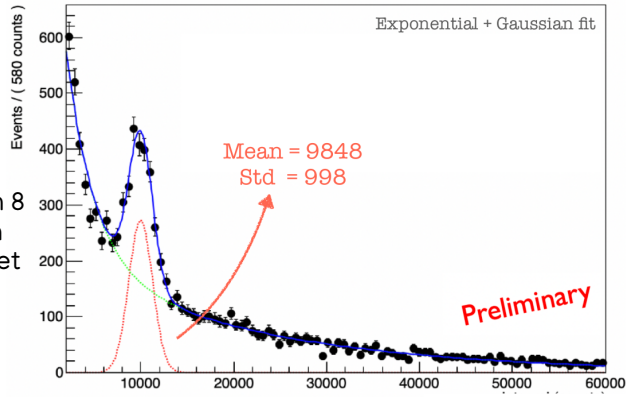
- Tests were performed overground to test the energy response on ER



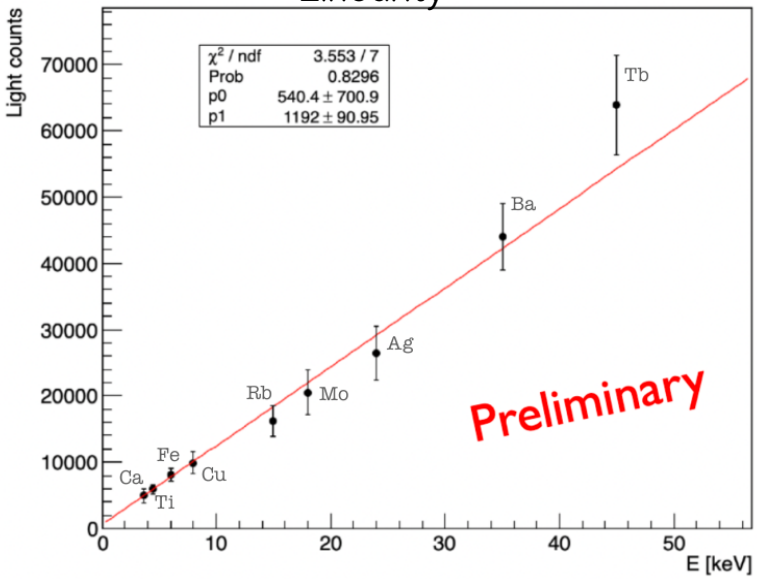
Target of different materials to be irradiated by ^{55}Fe or Am source



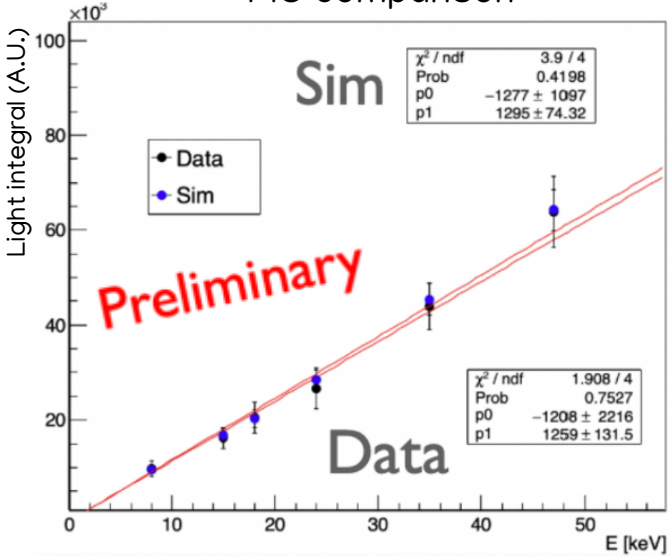
Example with 8 keV emission from Cu target



Linearity



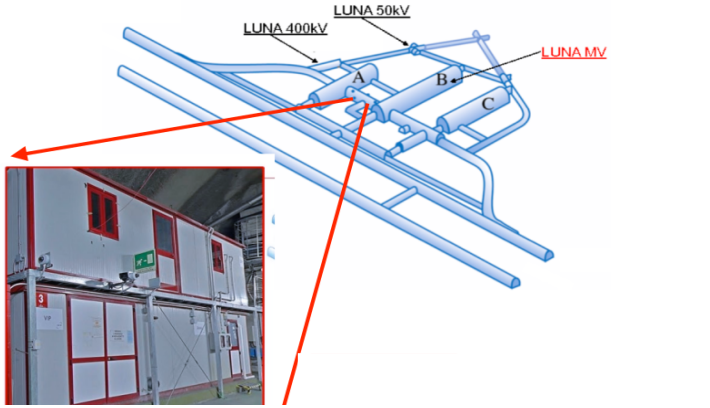
MC comparison

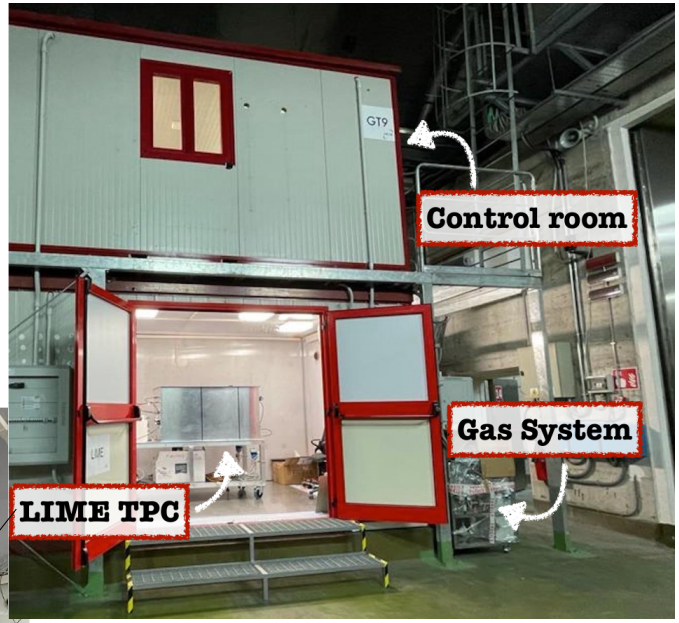


- Good linearity and track reconstruction from few up to 45 keV
- Good energy resolution around 14% in this energy range
- Good matching with simulation

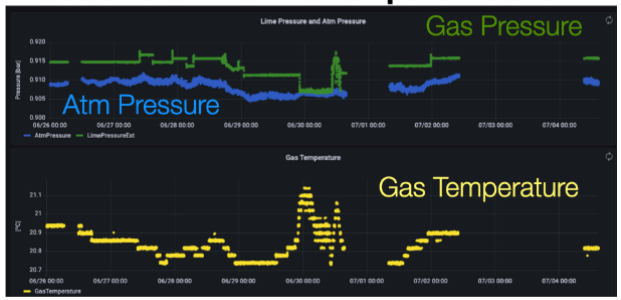
PHASE-0: LIME @ LNGS

- LIME is working underground with continuous data taking with an automatic system to remotely control it

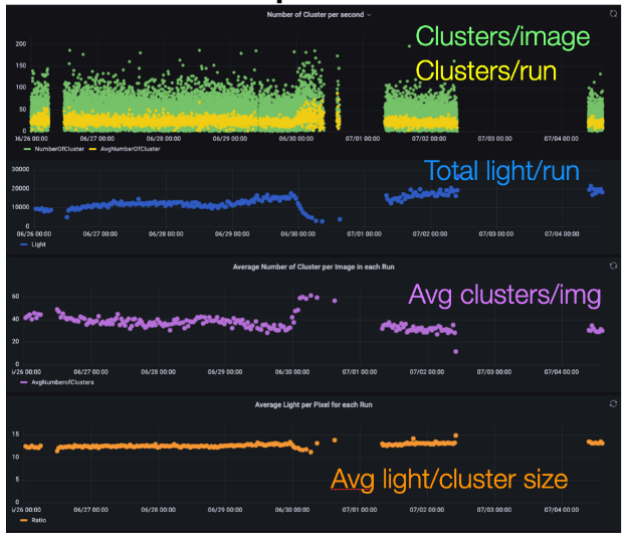




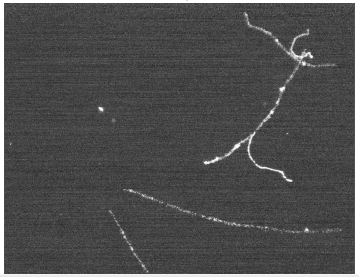
Gas and environmental parameters



Detector performance

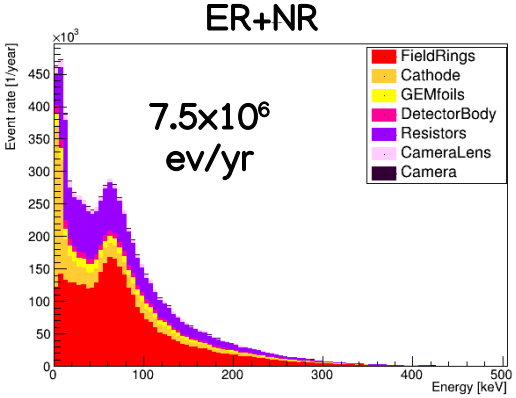


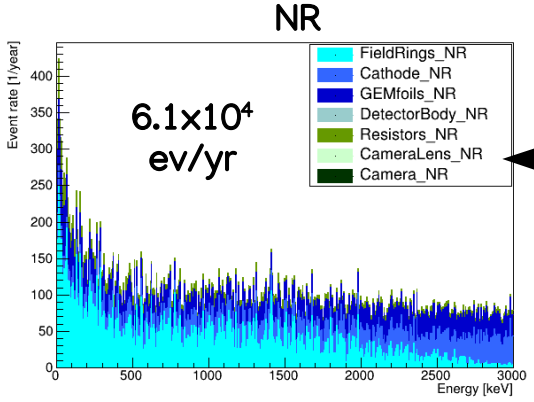
Actual picture



Phase-0: LIME Background

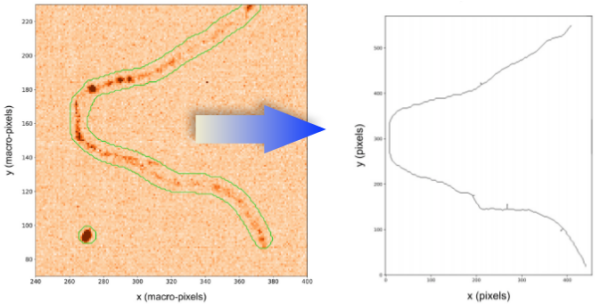
- LIME **background simulation** performed with GEANT4 after measuring @ LNGS the radioactivity of the materials



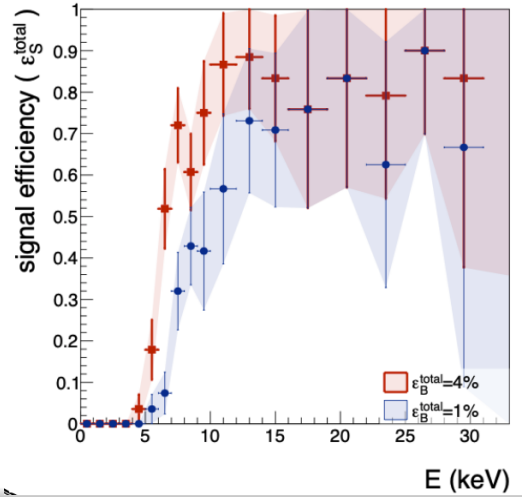


- Shielding configuration under optimization (10 cm Cu + 40 cm water, returns 2x10^5 ev/yr)
- Internal background dominates after shielding
- Geometrical cuts can suppress 96% of total recoils (99,9% of NR)
- Expected 2.4x10^5 ev/yr after cuts below 20 keV (6 ev/yr NR)

- **Background rejection** capabilities were tested with LEMOn prototype



- Algorithm based on DBSCAN recognizes the tracks and allows topogical studies
- A simple cut on the photon density per pixel of the sCMOS pictures allows to reject 96% of background at 6 keV keeping about 40% signal efficiency
- Machine learning techniques exploiting more topological information are under development



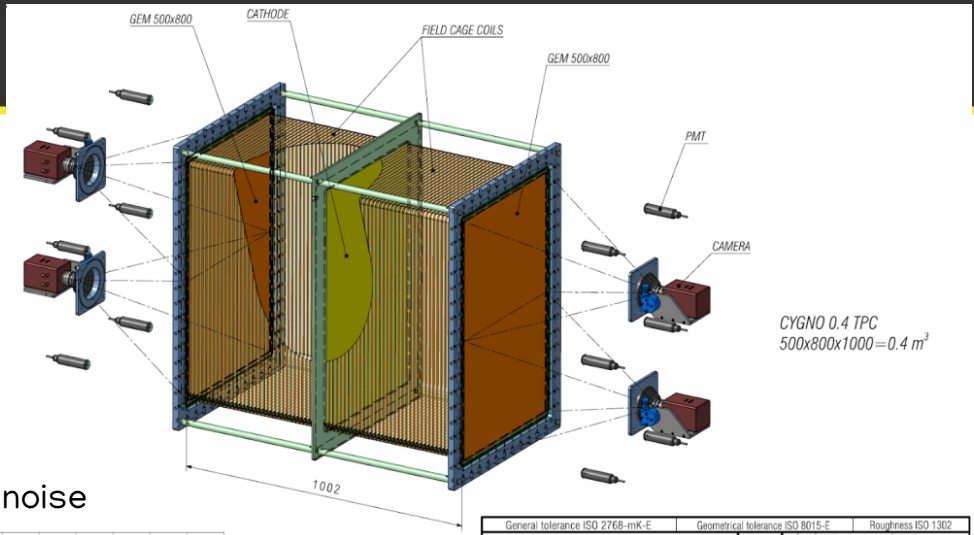
Phase-0: LIME Measurements

- Foreseen measurements with LIME @ LNGS

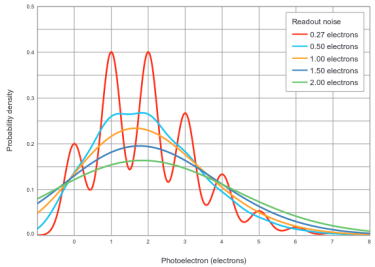
No shield configuration	✗ Characterization of the detector with ^{55}Fe and ^{241}AmBe sources ✗ **External background studies**, to cross-check simulation	2 months
6 cm copper	✗ **External background studies**, to cross-check simulations ✗ ^{55}Fe calibration	1 month
10 cm copper	✗ **External background studies**,to cross-check simulations ✗ **Measurement of underground neutron flux.** Expected **200** events above **20 keV** in 4 months	4 months
10 cm copper and 40 water	✗ **Internal background studies** for final MC validation, when internal and external background are expected to have the same intensity	10 months

PHASE-1: CYGNO_04

- **Structure:** TPC in back–to–back configuration, 50 cm drift per side and 0,4 m^3 total volume
- **Amplification:** Triple thin GEM stack of 50x 80 cm^2 per side
- **Readout:** Optical with 2 sCMOS (Hamamatsu ORCA Quest) and 6 PMTs per side
- **Vessel:** Very low radioactive PMMA
- **Shielding:** 10 cm Cu +100 cm water with polyethylene base
- **Purpose:**
  - Prove the scalability of the technology to large volumes using **two cameras per side** (better than LIME)
  - Test the purification gas system

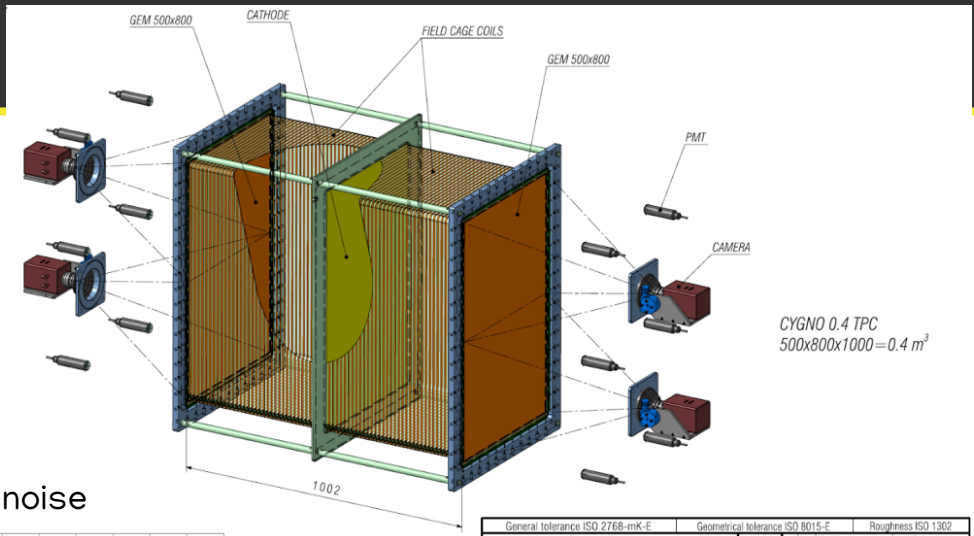


Extremely low noise

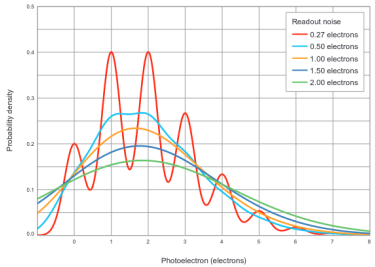


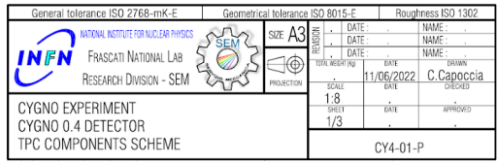
PHASE-1: CYGNO_04

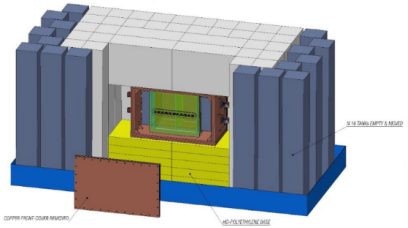
- **Structure:** TPC in back–to–back configuration, 50 cm drift per side and 0,4 m^3 total volume
- **Amplification:** Triple thin GEM stack of 50x 80 cm^2 per side
- **Readout:** Optical with 2 sCMOS (Hamamatsu ORCA Quest) and 6 PMTs per side
- **Vessel:** Very low radioactive PMMA
- **Shielding:** 10 cm Cu +100 cm water with polyethylene base
- **Purpose:**
  - Prove the scalability of the technology to large volumes using **two cameras per side** (better than LIME)
  - Test the purification gas system



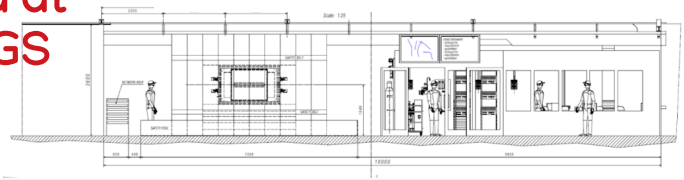
Extremely low noise



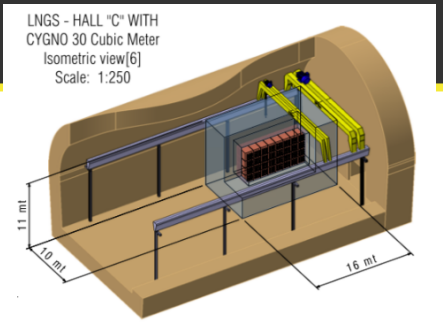




TDR submitted to be hosted at Hall F @ LNGS



PHASE-2: CYGNO_30



- O(30) m^3 detector for the DM physics case

- Expected SI and SD 90% CL are obtained by simulation and statistical analysis based on Bayesian technique

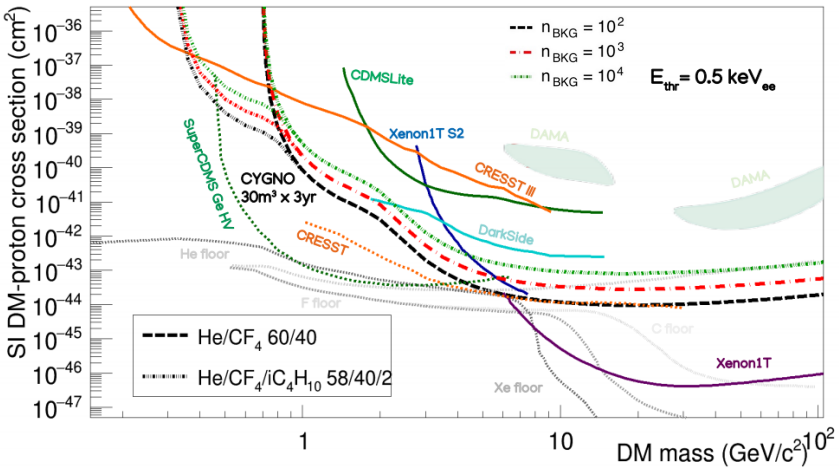
Energy threshold 0.5 keV

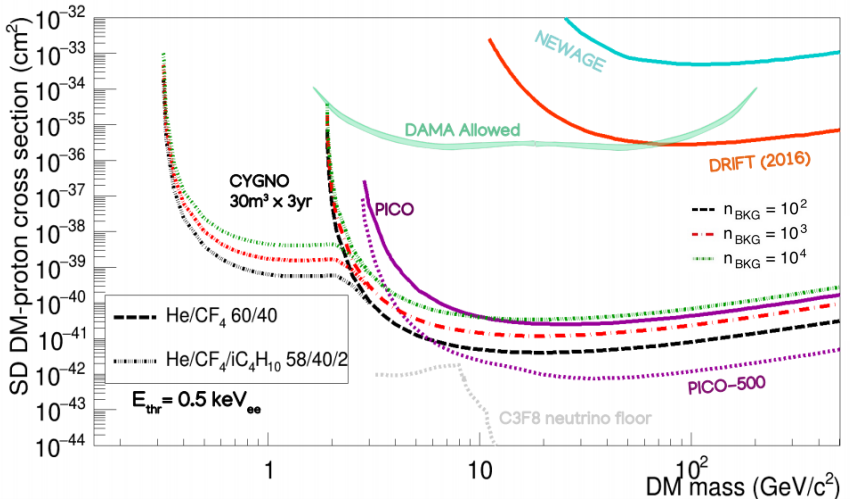
Quenching factor obtained by SRIM simulation

Observable 3D full directional angular distribution

Angular resoution 30x30 degree^2 flat

Background model different number of events in a flat isotropic distribution





Ongoing R&D

- Some R&D are still ongoing to improve the future performances

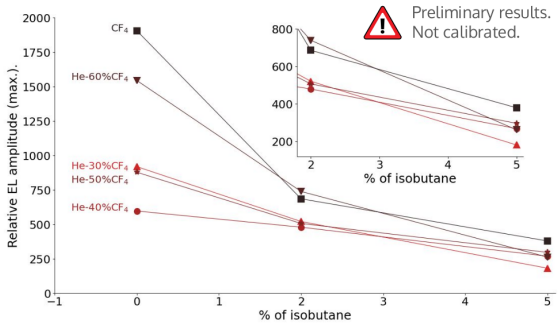
- **Internal background reduction**
  - Building low radioactivity camera sensor
  - Optimize field cage materials
  - Lenses made of fused silica

Feasibility study for low radioactivity lens

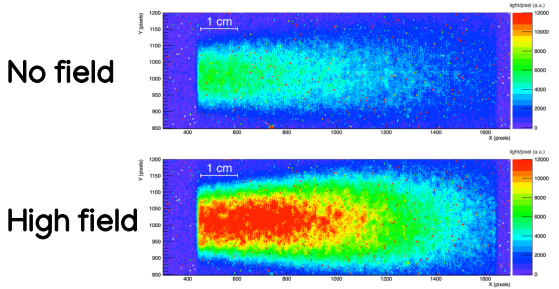
Ready to be produced

- **Hydrogen addition in gas mixture**
  - Introducing hydrogen rich gas to improve the sensitivity at low mass without losing light yield

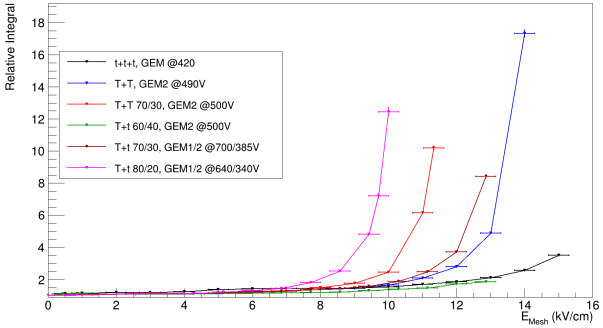
	Minimum detectable DM mass for 0.5 keV_{ee} energy threshold	Minimum detectable DM mass for 1 keV_{ee} energy threshold
H	300 MeV/c²	500 MeV/c²
He	700 MeV/c²	1 GeV/c²
C	1.4 GeV/c²	1.9 GeV/c²
F	1.9 GeV/c²	2.5 GeV/c²



- **Electroluminescence to enhance light**
  - Apply strong electric fields below the GEM to produce light without additional charge

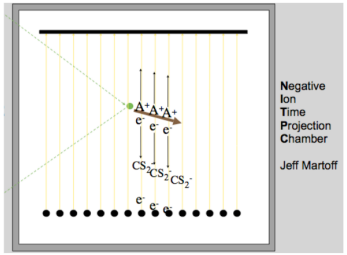


Baracchini, E. et al. JINST 15 08 (2020)



Ongoing R&D: NID Operation

- In sinergy with CYGNO, the INITIUM project aims at utilizing negative ion opearation to improve track performances



– J. Martoff et al., NIM A 440 355

– Adding SF_6 as high electronegative gas, electrons get attached to the dopant close to the ionization position o(100) um

– Anions drift acting as the image carrier but with a longitudinal and transverse diffusion reduced to the thermal limit

+ SF_6 for negative ion drift

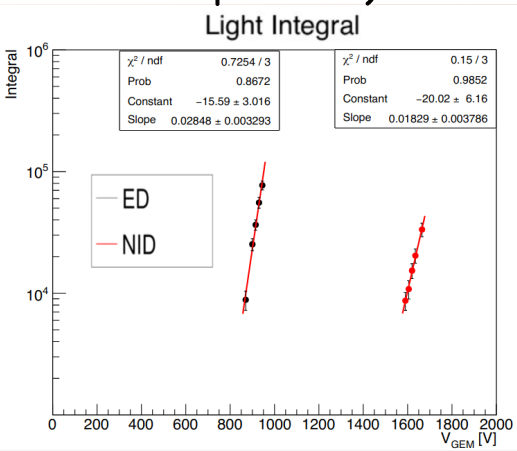
Part of this project has been funded by the European Union's Horizon 2020 research and innovation programme under the ERC Consolidator Grant Agreement No 818744

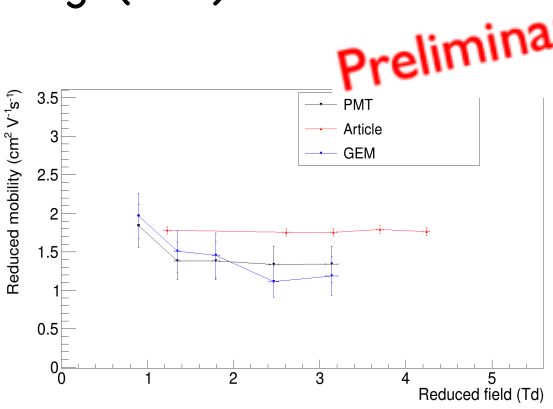
- Using a small prototype it was possible to measure **negative ion drift at nearly atmospheric pressure with optical readout** using an ^{241}Am alpha source

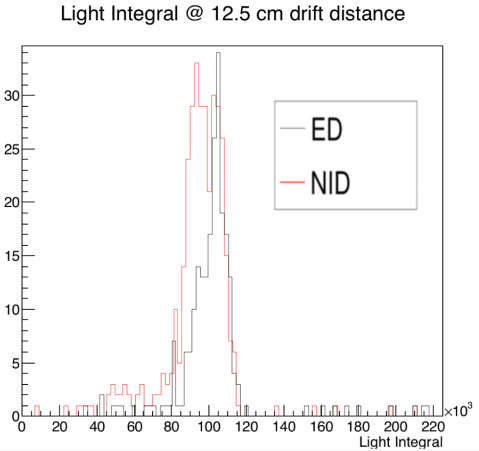
880 mbar (mountain atm pressure) short field cage (5 cm)

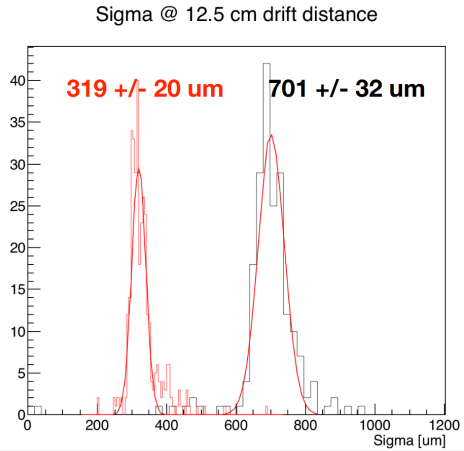
He:CF_4:SF_6 59:39.4:1.6

650 mbar long field cage (15 cm)

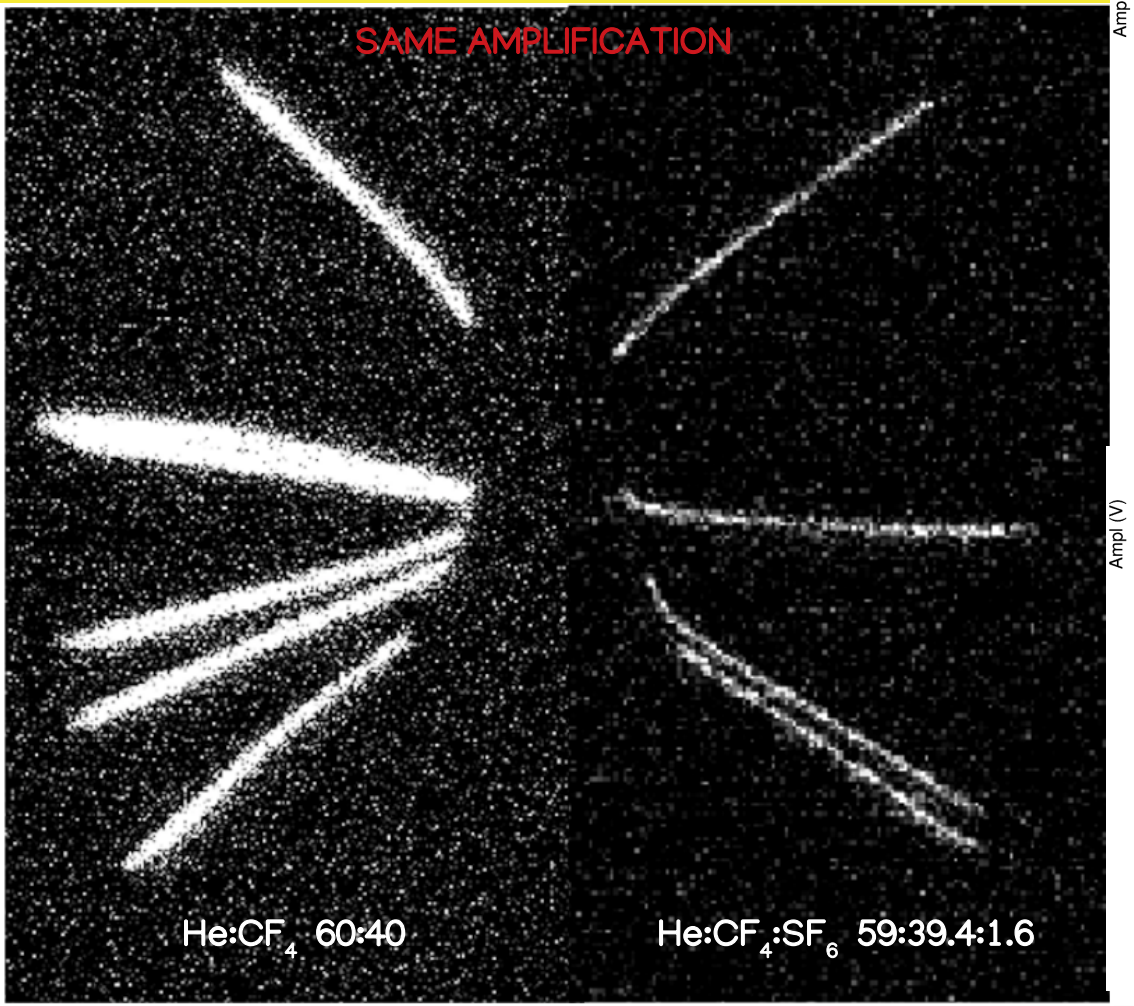


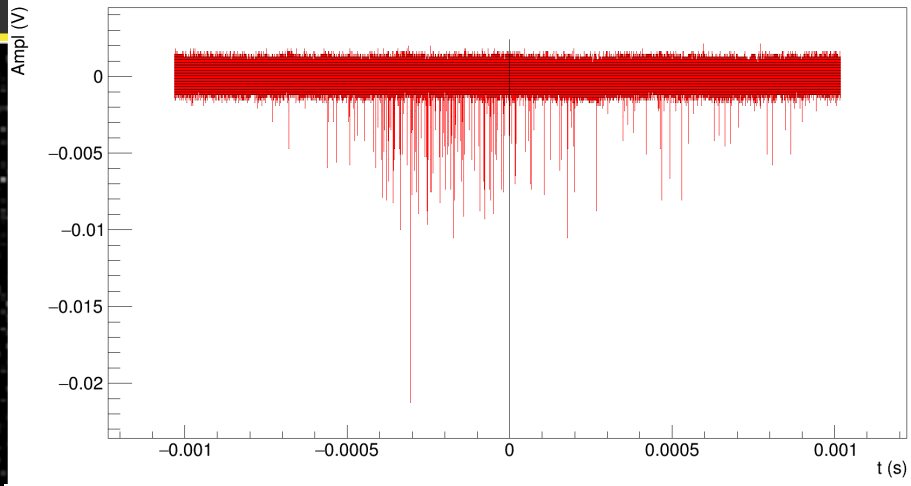


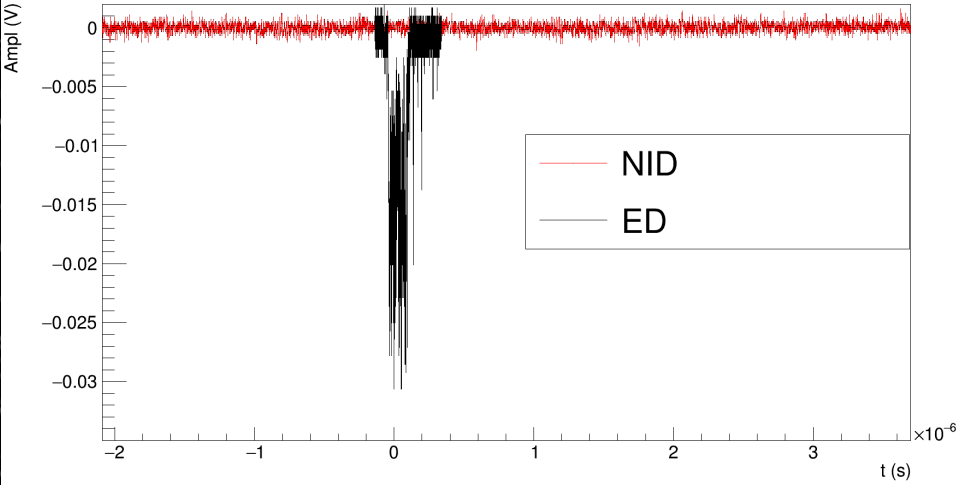




Ongoing R&D: NID Operation







Conclusions

- The CYGNO collaboration is moving toward the realization of large scale Dark Matter detector for O(GeV) WIMP–like particle based on a gaseous Time Projection Chamber.

- The R&D efforts that showed the O(keV) energy threshold and background rejection, the fiducialization, all lead to the realization of LIME, the largest prototype built with 50 l volume. Now it is taking data in the underground laboratories at LNGS to show the performances in a realistic environment towards the construction of phase 1.

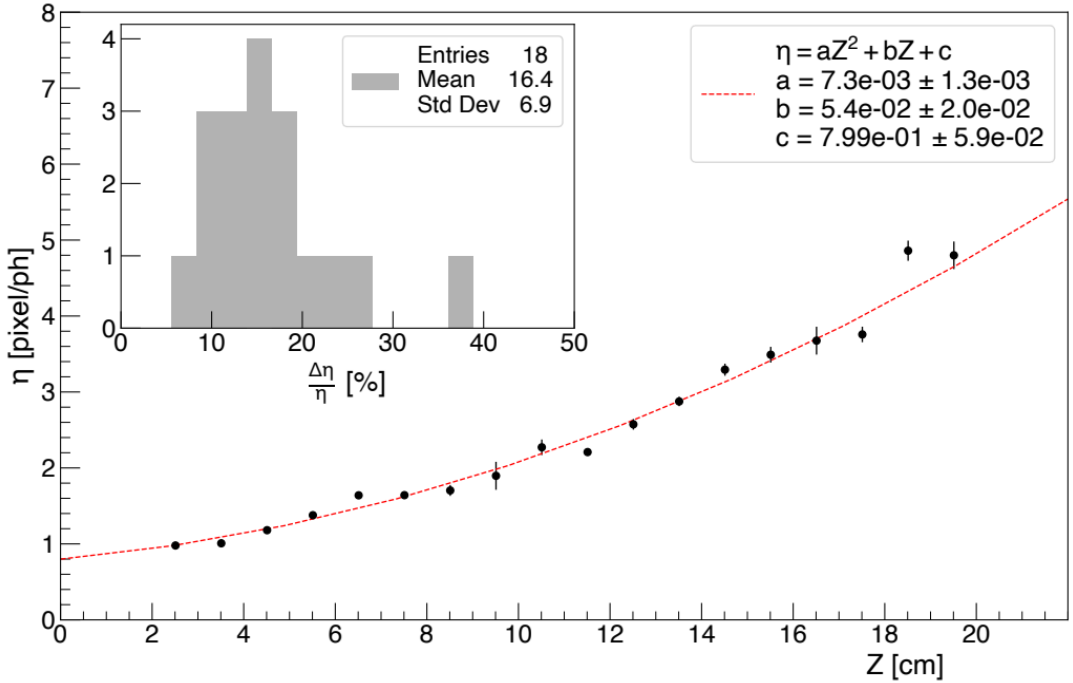
- The future steps toward the construction of the large scale detector are defined with two separate phases. Phase 1 is under development to prove scalability, it is already funded and the TDR has been submitted for it to be hosted at LNGS. Phase 2 is under development and the sensitivity studies show interesting prospects.

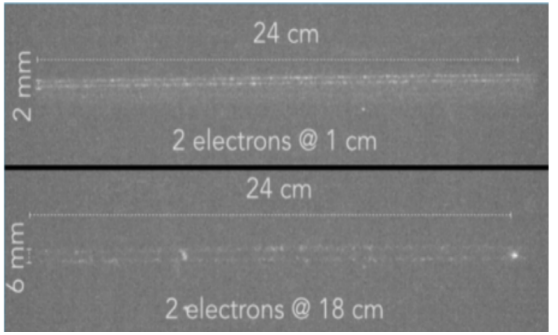
- R&D is being carried out to improve the performances of the detector from the radioactivity of the materials to the gas mixture optimization

- The study on negative ion doped gas mixtures is showing relevant and promising results

BACKUP

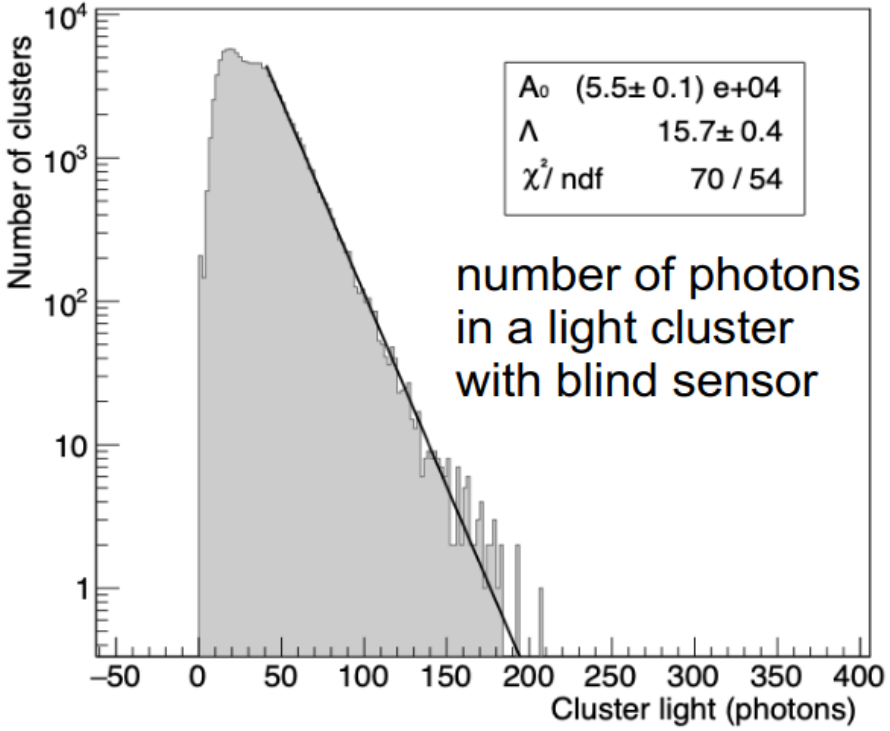
Z (drift direction) Fiducialization





- Electron transverse diffusion can be exploited to infer the track Z coord.
- Track transverse light profile measured to have gaussian shape which enlarges linearly with Z
- Under study the method using a PMT

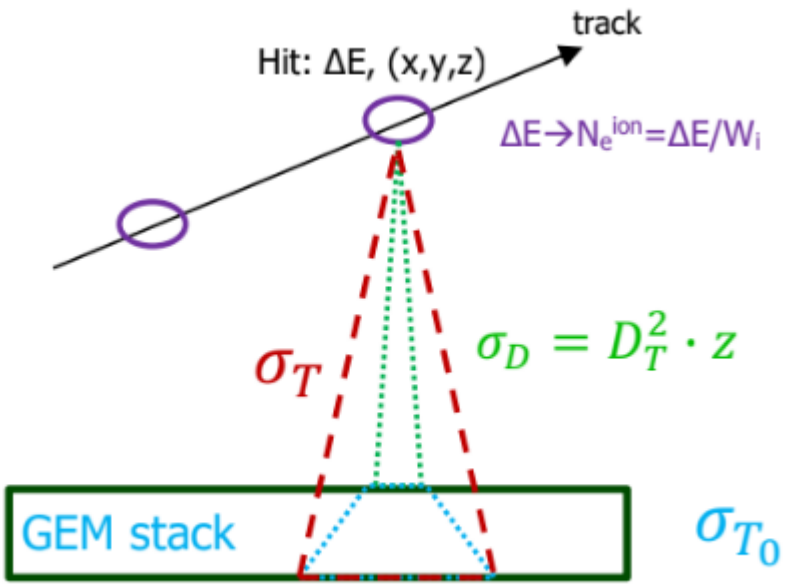
Energy Threshold



Clusters found due to electonic noise:

- Clusters containing >400 photons are less than 10 per year
- LIME setup allows to see about 650 photons per keV
- Energy threshold assumed 1 keV_{ee}
- Positive that 0.5 keV threshold could be achieved with better algorithms

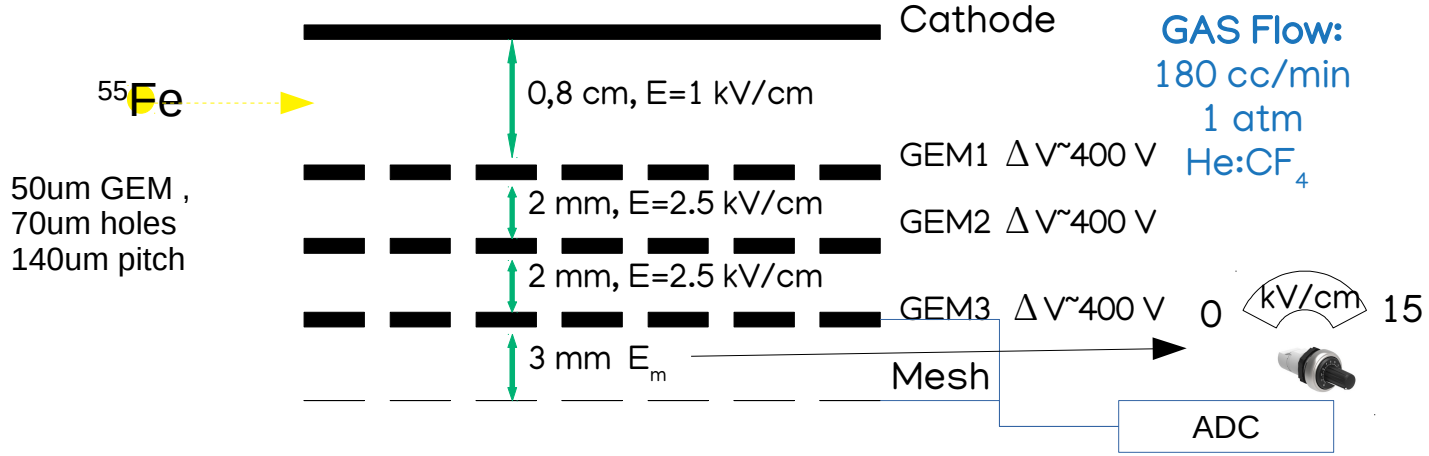
Simulation

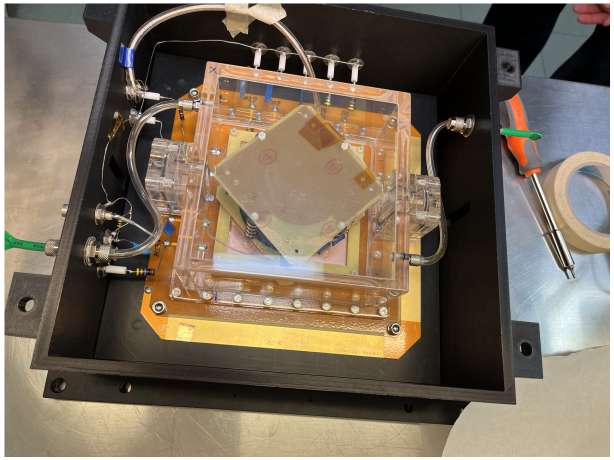


The simulation produces pictures equivalent to the format of the data. It includes:

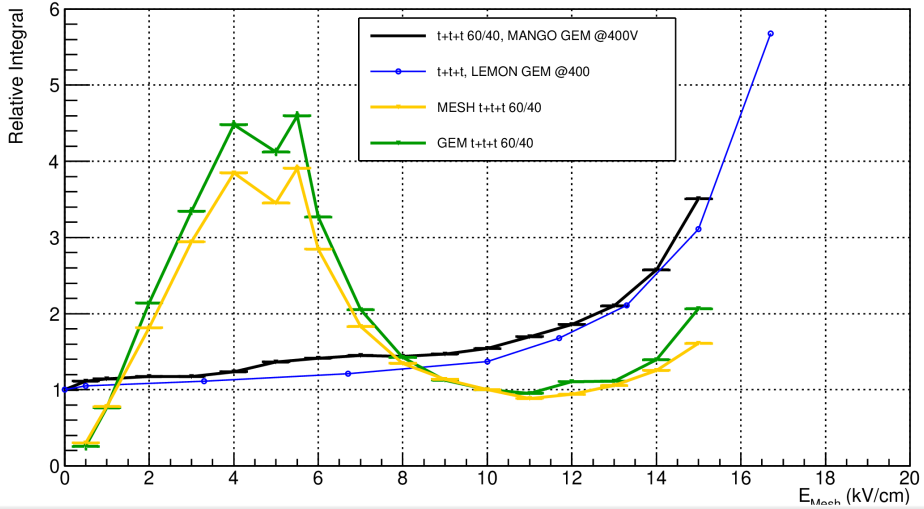
- GEANT4 or SRIM to represent energy deposit on gas
- Primary charge production
- Parametrized diffusion in the gas and through the GEMs
- Parametrized GEM amplification process and saturation effect on third GEM
- Photon production and collection efficiency of the detector
- Electronic noise of the sensor

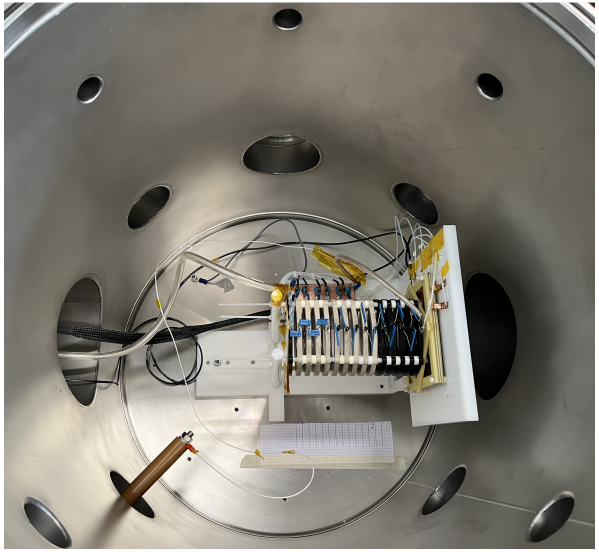
ELECTROLUMINESCENCE

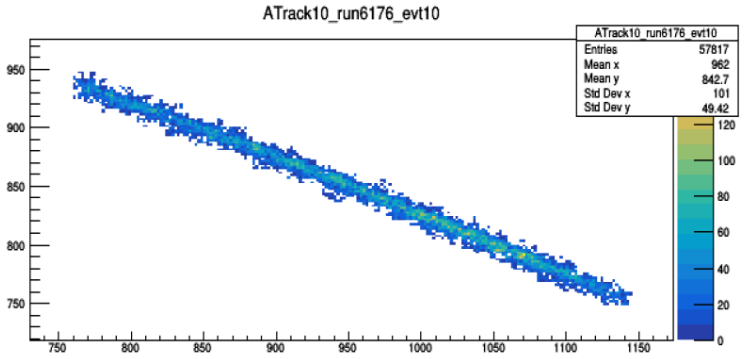


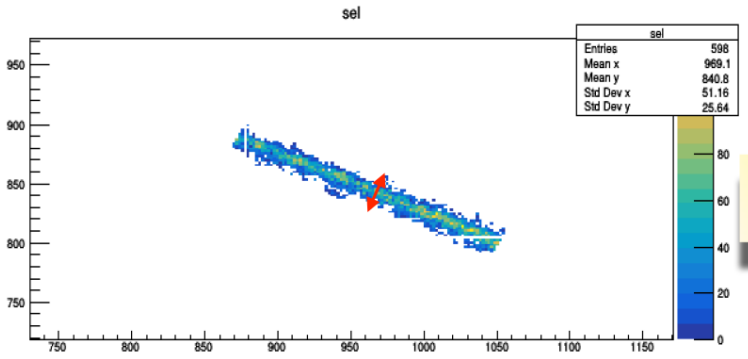


Process	Threshold (eV)	Energy loss (eV)
Direct vibrational excitation ν_4	0.078	0.078
ν_3	0.159	0.159
Indirect vibrational excitation	4.0	0.4
Electron attachment	4.3	4.3
Electronic excitation (dissociation into neutral fragments)†	12.5 (10)	12.5 (10)
Dissociative ionization†	15.9	15.9









- Tracks selection:
  - track length > 8 mm
  - track slimness < 0.3
  - # of peaks in the transverse profile == 1 (select single tracks)
  - Chi2/nDOF of transverse fit profile < 5 (remove additional multiple tracks)