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

**INITIUM: Innovative Negative Ion TIme projection chamber for Underground dark Matter searches**


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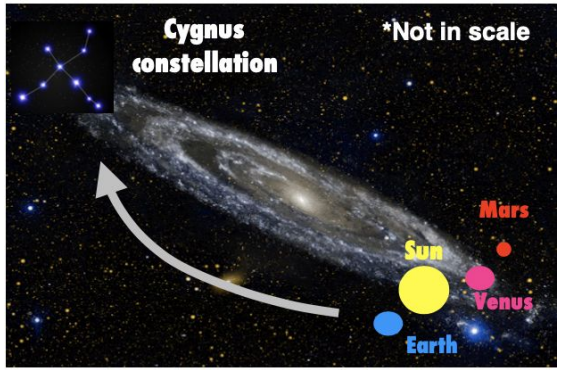
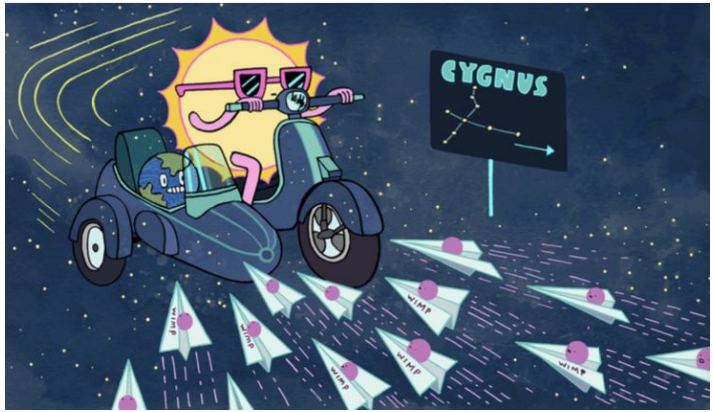
# Travelling through Dark Matter




- Dark Matter forms a halo around our galaxy
- Our solar system rotates around galaxy towards Cygnus constellation
- Motion of our galaxy creates an apparent wind of DM coming from Cygnus constellation towards Earth



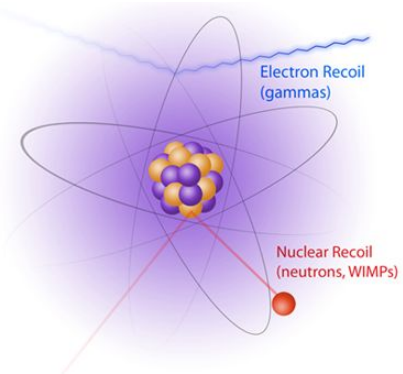

Wind of DM particles

↓

Elastic scattering with ordinary matter

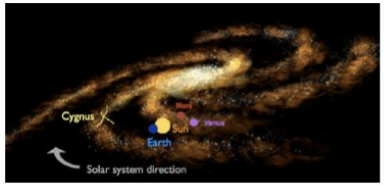
↓

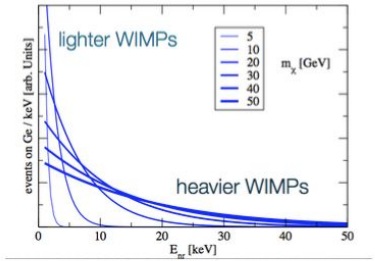
Recoiling Nuclei



# Dependencies to explore

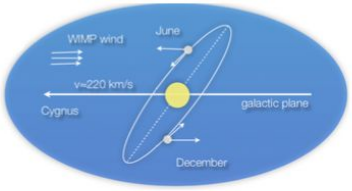
## Energy Dependence

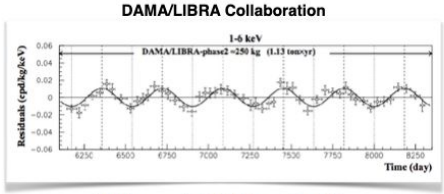



**Energy dependence:**
**a falling exponential with no peculiar features**

## Time Dependence

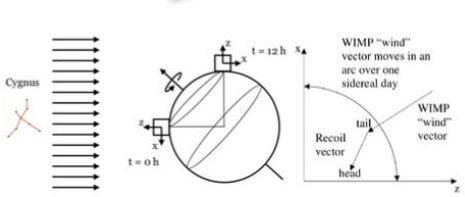


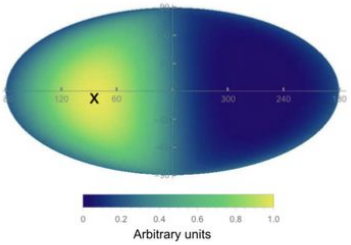




Universe 4 (2018) no.11, 116

**Temporal dependence:**
**a few % annual modulation**

## Directional Dependence

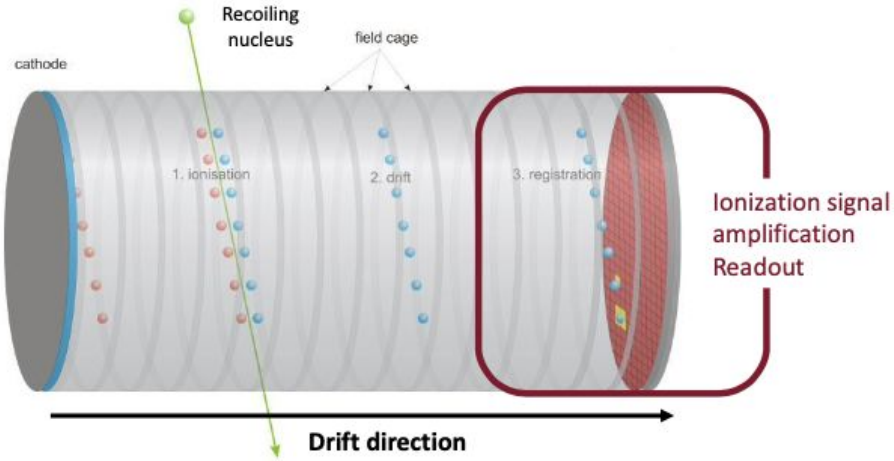


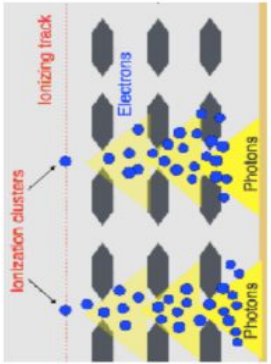




**Directional dependence:**
**an O(1) effect that no background whatsoever can mimic**

**Increasing reliability but increasing difficulty in the experimental technique.**

# CYGNO Approach




PMT

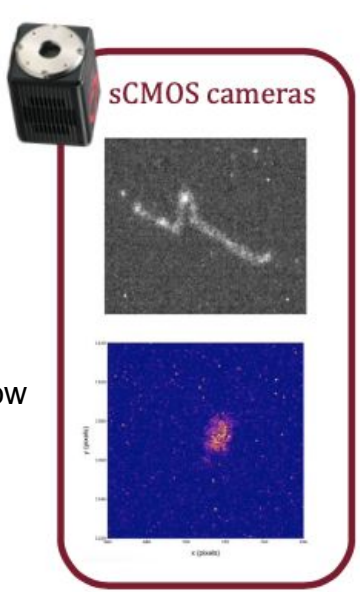
sCMOS

- CYGNO uses **He:$CF_4$** gas mixture at 1 atm
- **3 GEM** stack is used for charge amplification and light production

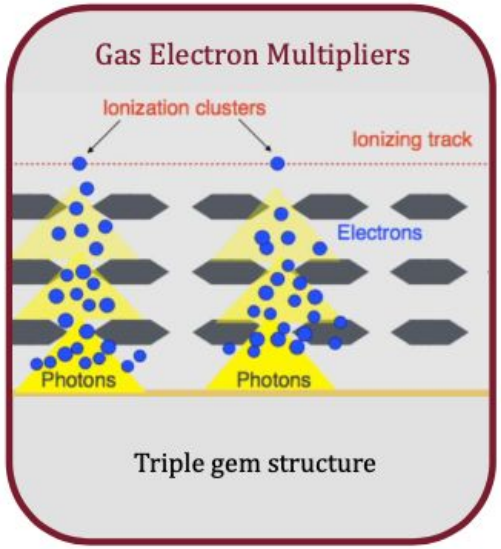
- Inherently a 3D detector
- Head/Tail recognition
- Background Rejection
- Particle Identification
- 3D fiducialization

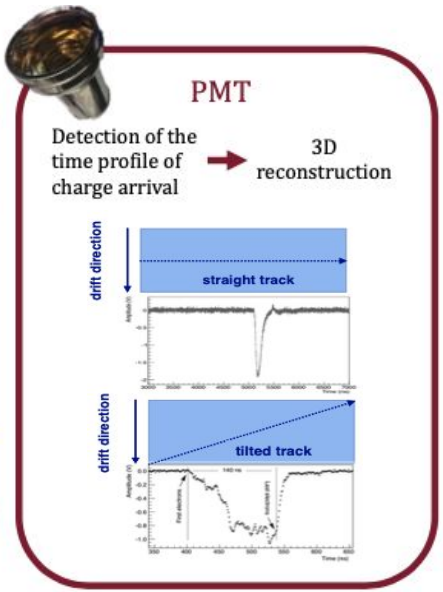
**Time Projection Chamber** → **Triple GEM** Charge amplification & light production → **Camera & PMT** **Light produced by the de-excitation of the gas molecules** during electron multiplication is optically read by sCMOS and PMT

We can measure energy and X-Y coordinate using sCMOS's high granularity and low readout noise.




X-Y + Energy

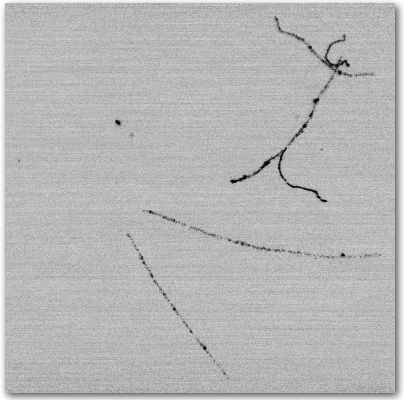


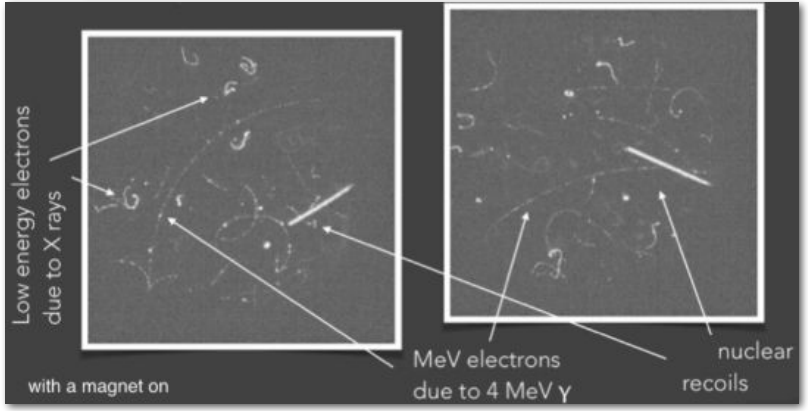



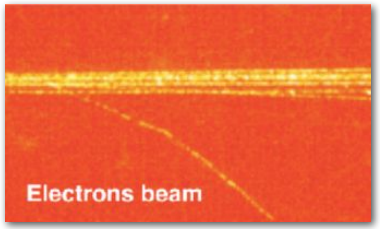

Z + Energy

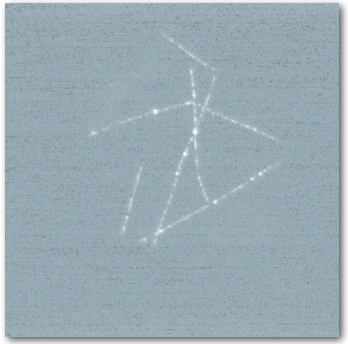
PMT measures the integrated energy and time of arrival (dZ) of charge carriers with high sampling rates.

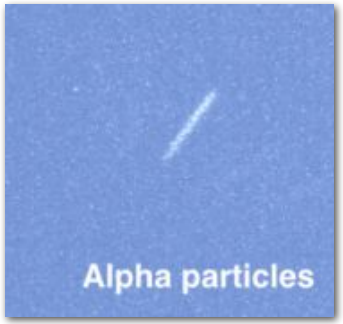
# Some tracks recorded with sCMOS

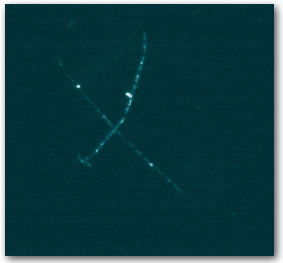


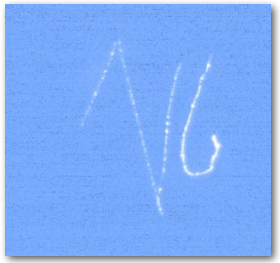



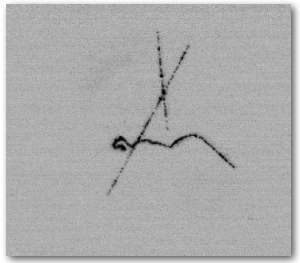



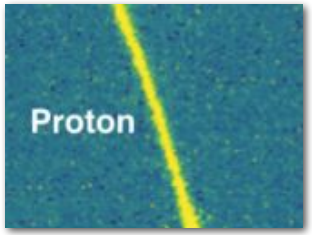





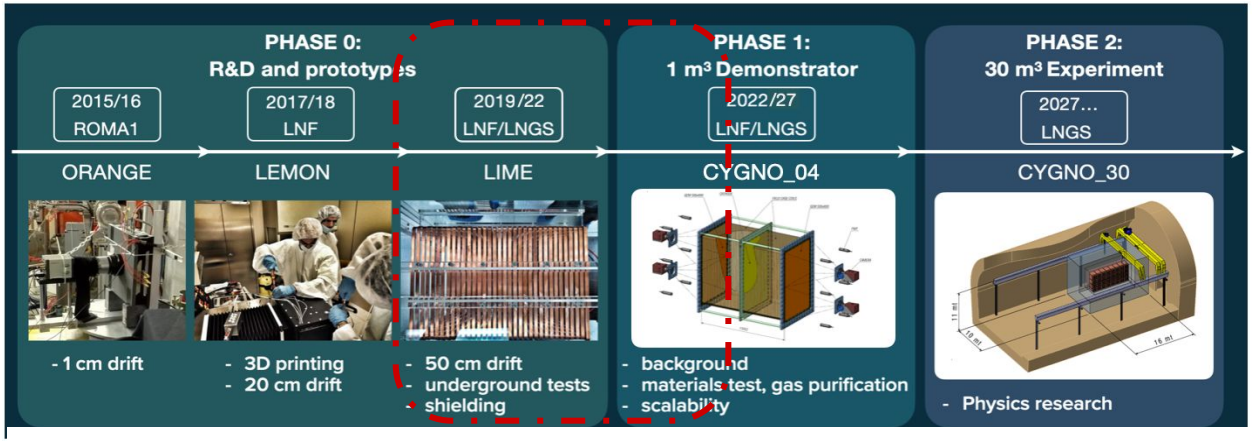



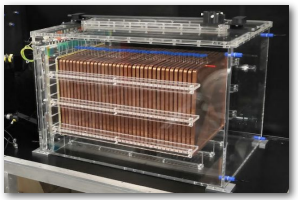


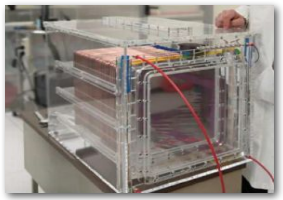


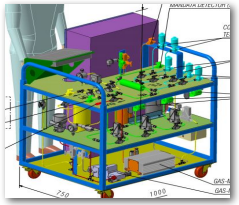


# CYGNO Roadmap







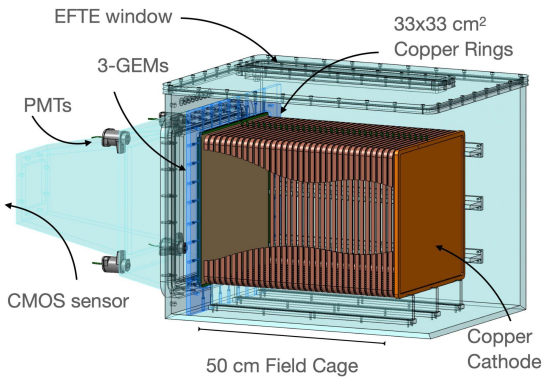
## Ongoing studies:

- Performance and stability test
- 3D reconstruction
- Directionality
- ER vs. NR discrimination
- Shielding materials
- Data/MC comparison

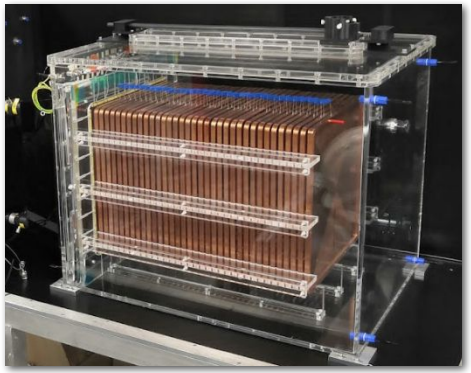
- Parallel research with MANGO detector for studying different GEM configuration, gas mixtures and Negative Ion Drift.

E. Baracchini et. al, JINST 13(2018) no.04, P04022

# LIME: the Long Imaging ModulE




- **50 L** gaseous TPC with **50 cm drift**
- **He:$CF_4$ (60:40)** gas mixture at room temperature and atm pressure
- **Triple 33x33 cm² GEM** stack for amplification
- **Optical readout**
  - 4 PMTs
  - 1 sCMOS camera (Orca Fusion)



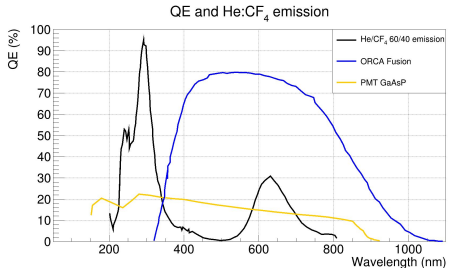
ORCA-Fusion
CAMERA SPECS

*LOW NOISE AND EXCEPTIONAL READOUT NOISE UNIFORMITY*

| | | |
|---|---|---|
| READOUT NOISE<br>0.7 electrons rms<br>Ultra-quiet Scan | DSNU<br>0.3 electrons rms | |
| PRNU<br>0.06 % rms<br>At 7500 electrons | HIGH SPEED<br>100 frames/s<br>At 2304 × 2048 ROI | HIGH RESOLUTION<br>2304 × 2304<br>5.3 Megapixels |
| PIXEL SIZE<br>6.5 µm × 6.5 µm | DYNAMIC RANGE<br>21 400:1 | PEAK QE<br>80 % |

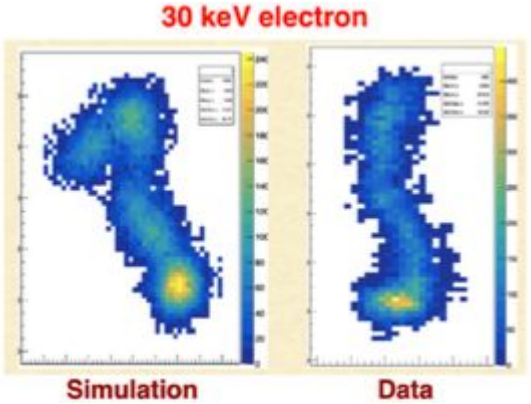
**Carbon tetrafluoride (CF4)**

- Significant light yield at the camera's QE peak

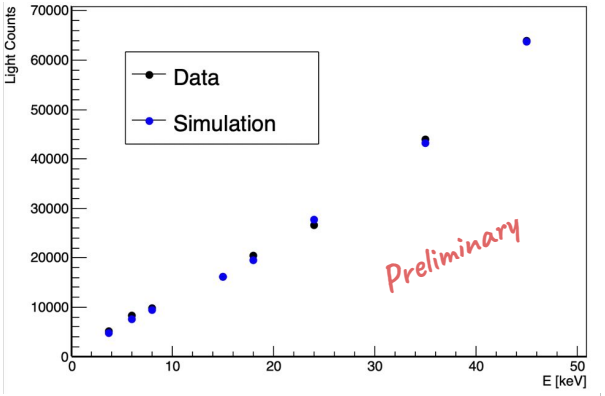


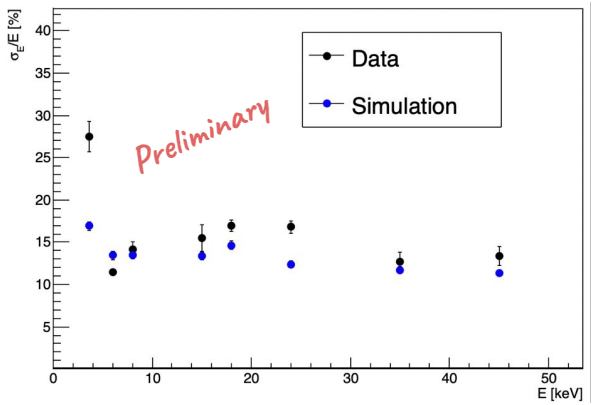
# LIME : Overground performance

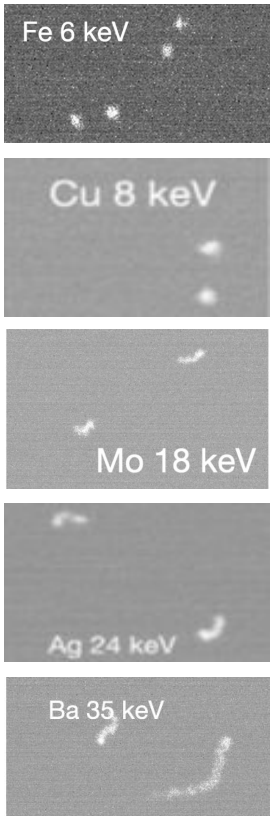
- Multiple X-Rays sources were used to study linearity and energy resolution of the detector
- Data shows good linearity in [4-50] keV
- Energy resolution ~ 13% in [4-50] keV
- Data is in good agreement with simulation




- Simulation developed taking into account the detector effects.

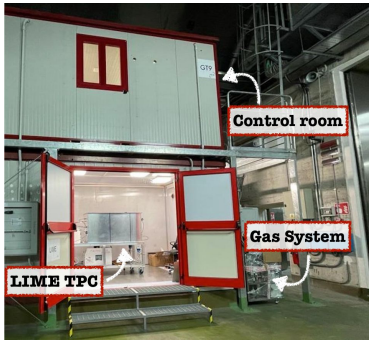


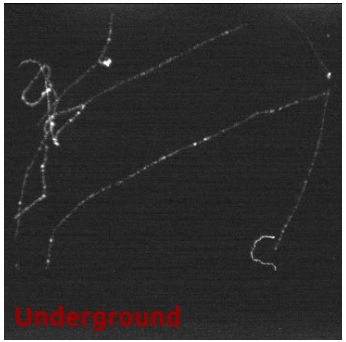



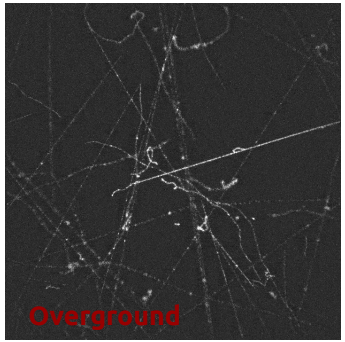



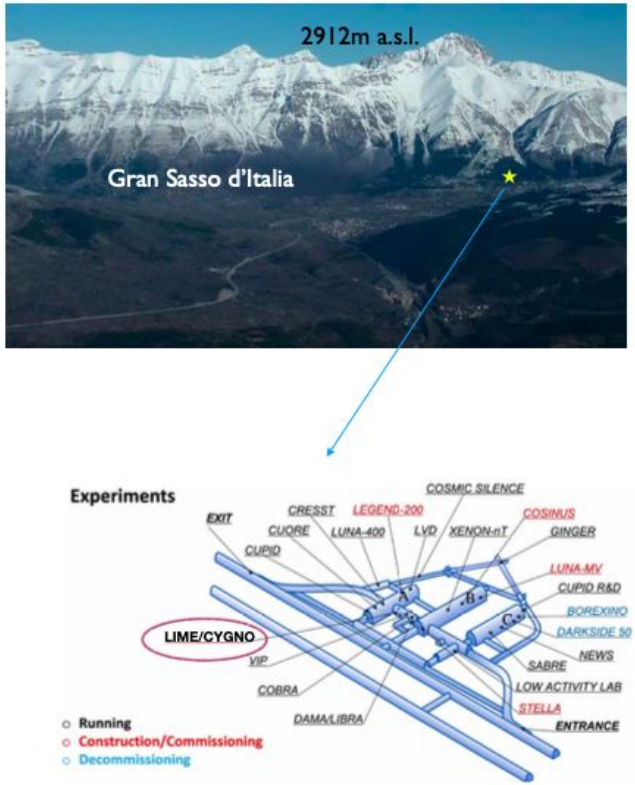
# LIME - Underground operation

- LIME is currently installed at National Laboratory of Gran Sasso (LNGS) - INFN
- Continuously acquiring data for
  - Validation of simulated background model
  - Operating conditions optimization



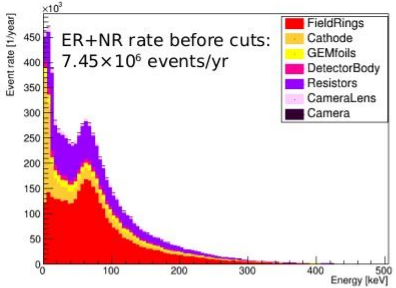
# LIME - Underground program

- Study of expected internal bkg
- Radioactivity measured for all the detector components
- Main contribution is from resistors, GEMs and camera (lens and sensor)

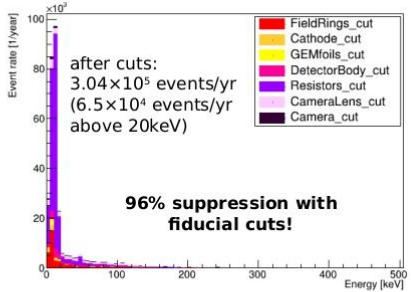
**Data taking program:**

- **No shielding**
  - External bkg study and detector calibration
- **10 cm Cu**
  - Measurement of underground neutron flux
- **10 cm Cu + 40 cm water**
  - Study of internal bkg and validation with MC (reduction of ext. bkg. at a level less than internal bkg.)

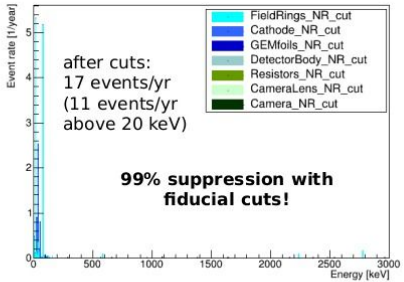
ER + NR **before** cuts




ER **after** cuts




NR **after** cuts




**Fiducial cuts*** bring a **96% suppression** of total number of recoils (ER + NR)

↓

**After cuts** and **above 20 keV**, we arrive at 6.5x10$^4$ ER/yr and **11 NR/yr**

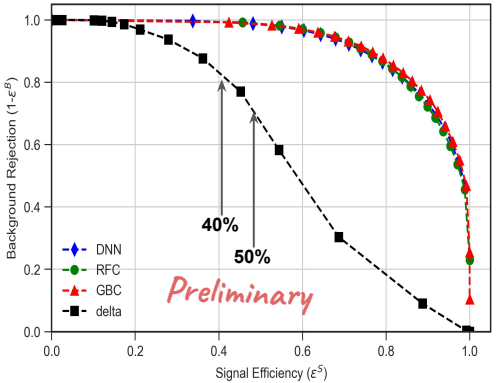
*Cuts: 1 cm of image, 1 cm from GEMs, 4 cm from cathode

# Background rejection on Simulated LIME data

- Simulated ER and NR tracks are reconstructed in [2-36] keV range
- Topological variables are built from the reconstructed tracks
- 3 ML algorithms are trained on topological variables:
  - Random Forest Classifier (RFC)
  - Gradient Boosted Classifier (GBC)
  - Deep Neural Network (DNN)

My PhD thesis

- Development of convolutional neural networks (CNN) based model for track reconstruction and PID is ongoing

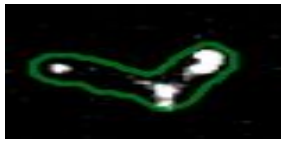



| Models | Signal Eff. [$\epsilon^S$]% | Bkg. Rej. [1-$\epsilon^B$]% |
|---|---|---|
| RFC | 40 | 99.54 |
| | 50 | 98.78 |
| GBC | 40 | 99.38 |
| | 50 | 98.55 |
| DNN | 40 | 99.43 |
| | 50 | 98.50 |
| Cut-based | 40 | 83.13 |
| | 50 | 67.20 |

delta (light density): light integral/ no. of pixels
cut-based* : Applying simple selection on the variable delta

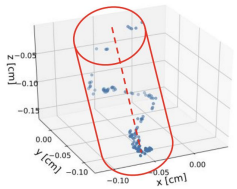
Reconstructed tracks

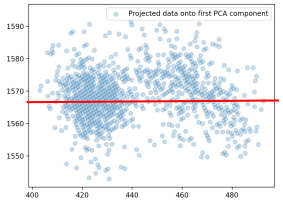
Electron Recoil

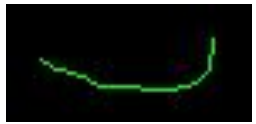


Nuclear Recoil

**Topological Variables**



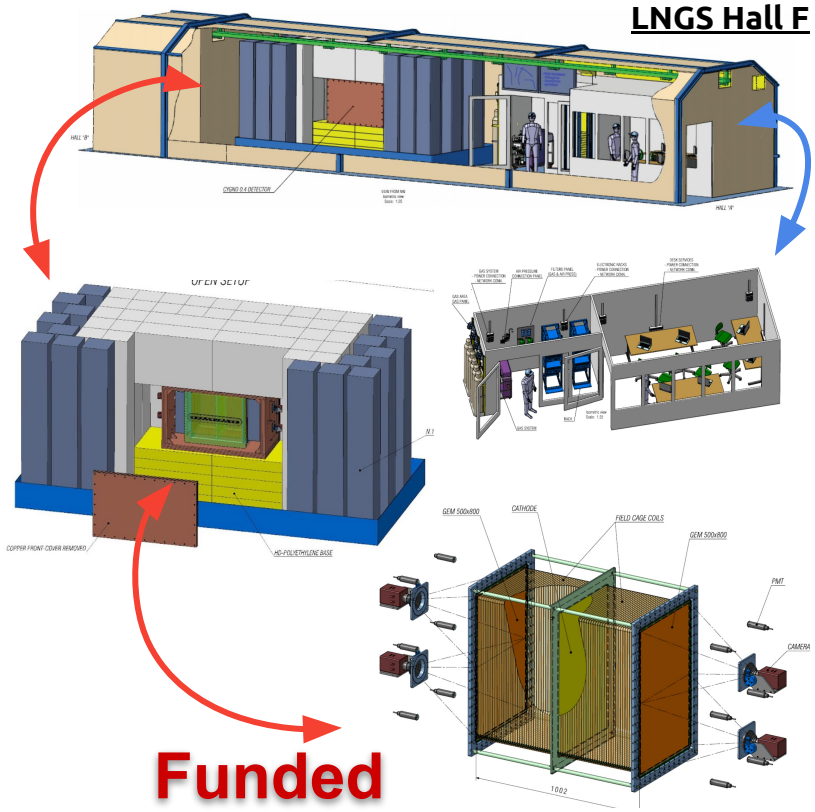


a) Cylindrical Thickness b) LAPA c) Skeleton

# CYGNO_04 - Phase I

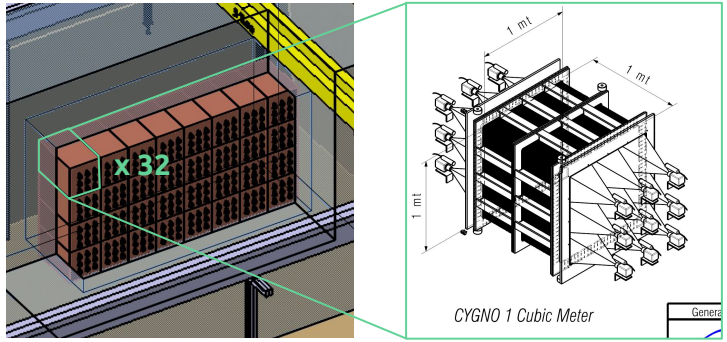
- **0.4 $m^3$** detector
- **Triple 50 x 80 $cm^2$** GEMs
- Common central cathode
- Readout by **4 sCMOS** (ORCA Quest) and **12 PMTs**
- Low radioactivity acrylic glass vessel
- Field cage made by **copper strips on insulator support** (DRIFT like)
- Will be used to demonstrate the scalability/feasibility of detection technique towards **CYGNO_30** with O(30 $m^3$)



# CYGNO_30 - Phase II

- **Low mass (0.5 - 10 GeV) directional DM searches**
- > 2027
- **30 - 100 $m^3$** detector
- **0.5 - 1 $keV_{ee}$** energy threshold
- **30°** angular resolution

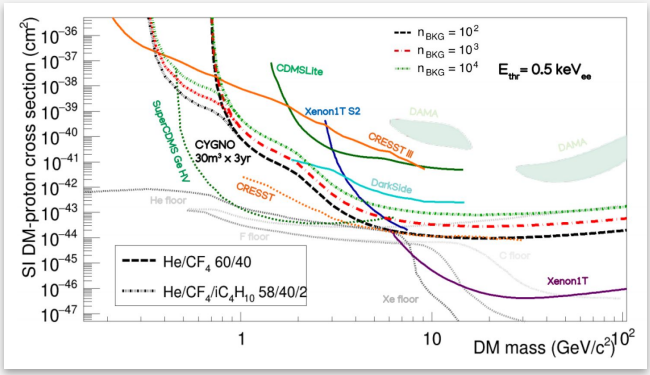
Amaro, F.D. et. al The CYGNO Experiment. Instruments 2022, 6, 6.

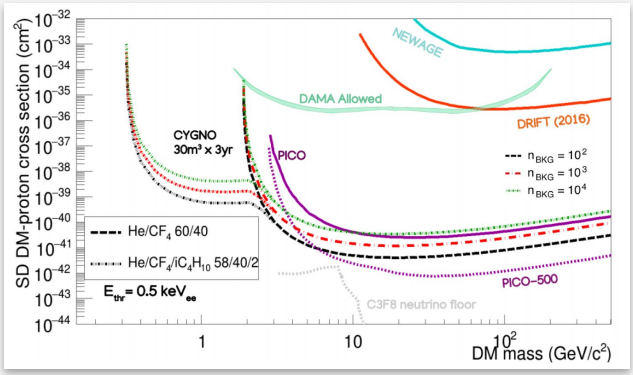



Expected **SI** and **SD** (90% CL) **interaction cross-section exclusion**

**Quenching factor** simulated with **SRIM** → Direct measurement incoming!

**He** allows us to explore very low DM masses!



# Negative Ion Drift (NID)

**Advantages**

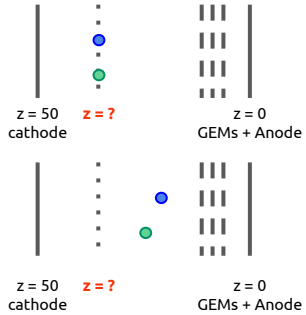
**Reduced diffusion**

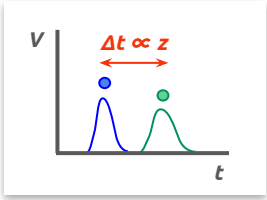
Longitudinal and transverse **diffusion reduced to thermal limit**

$$\sigma_D = \sqrt{\frac{4\varepsilon L}{eE}}$$

**Better spatial resolution!**

**Multiple charge carriers**

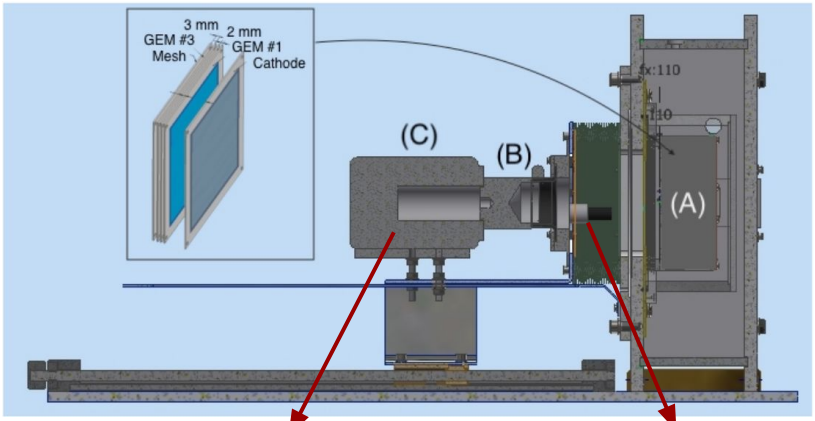


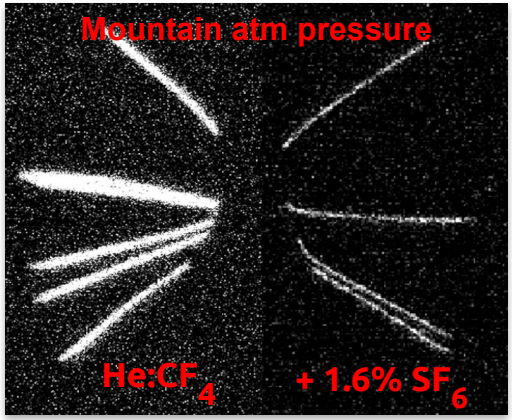



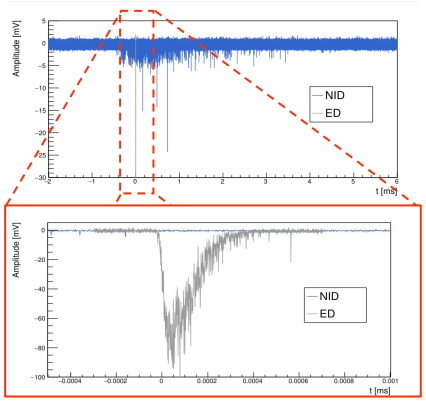

**Absolute Z from Δt between minority charge carriers**

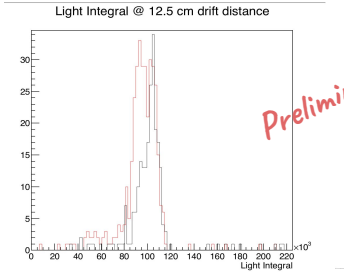
- Highly **electronegative dopant** is added to the gas ($CS_2$, $SF_6$,...)
- Primary electrons are captured by the dopant at O(100 um)
- **Anions** are majority charge carriers instead of electrons
- $\boldsymbol{\sigma_T}$ and $\boldsymbol{\sigma_L}$ reduced to **thermal limit**
- **Lower drift** velocity of Negative ions **O(cm/ms)** significantly improves the resolution along the drift direction

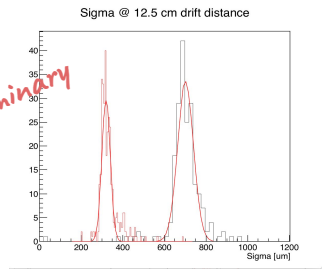
# NID with MANGO detector



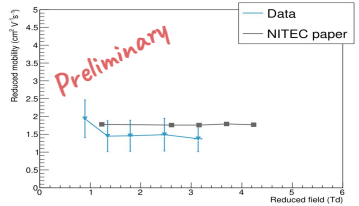




**Same light … smaller sigma**




**Reduced mobility compatible with $SF_6$**

# Conclusions

- The **CYGNO** collaboration is developing a **high-precision gaseous TPC** at atmospheric pressure with **optical readout**.
- The main focus is the **direct search** of **DM WIMP-like particles** in the **low mass range** (0.5-10 GeV).
- Through **directionality**, solar neutrinos can be discriminated and **unambiguous confirmation of DM** is possible.
- The **50L LIME prototype** was recently installed in the **underground LNGS** facilities.
  - The first **stability tests, background evaluations** and **measurements** are being carried out.
- **CYGNO_04**, already funded and with a TDR submitted, will allow us to test the experiment's **scalability**.
- **CYGNO_30** is under study, with it's sensitivities looking promising.
- Several **R&D projects** are ongoing in order to find **optimal means of TPC operation:**
  - **Electroluminescence** observed in our conditions and its **potentialities** are under study
  - **Negative ion drift** observed for the first at atmospheric pressure and with PMTs.


...for more info:
CYGNO – Directional
Dark Matter Search
https://www.facebook.com/
cygno.experiment
THANKS!