The CYGNO project for directional Dark Matter searches

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

*A. Prajapati** on behalf of CYGNO collaboration*

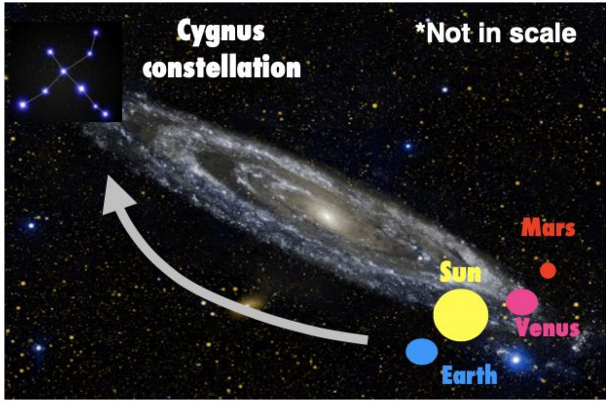
*Gran Sasso Science Institute, L'Aquila, Italy / Ph.D. student / Email: atul.prajapati@gssi.it

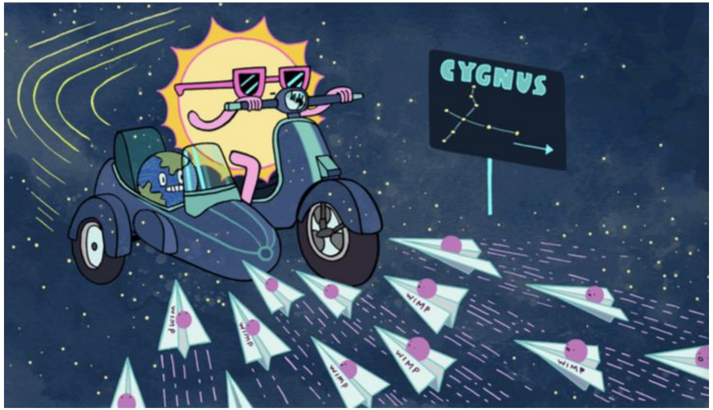
F. Amaro, R. Antonietti, E. Baracchini, L. Benussi, D. S. Cardoso, C. M. B. Monteiro, S. Bianco, C. Capoccia, M. Caponero, G. Cavoto, R. J. C. Roque, I. A. Costa, E. Di Marco, G. D'Imperio, G. Dho, F. Di Giambattista, R. R. M. Gregorio, F. Iacoangeli, H. P. L. Júnior, G. S. P. Lopes, G. Maccarrone, R.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

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

Travelling through Dark Matter

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





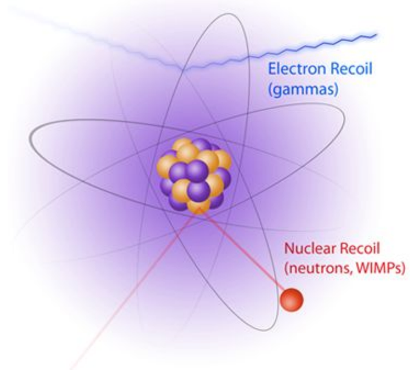
Wind of DM particles

↓

Elastic scattering with ordinary matter

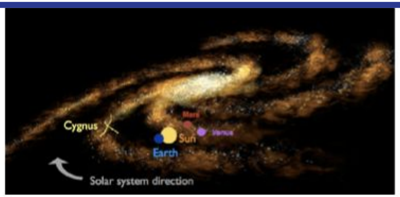
↓

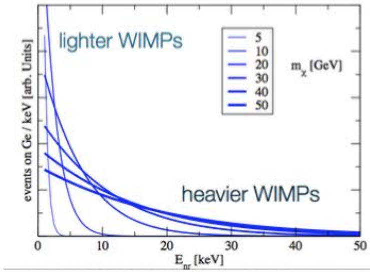
Recoiling Nuclei



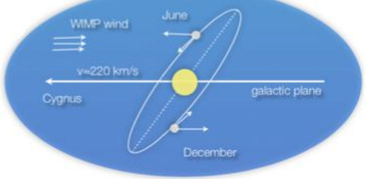
Dependencies to explore

Energy Dependence → **Temporal Dependence** → **Directional Dependence**

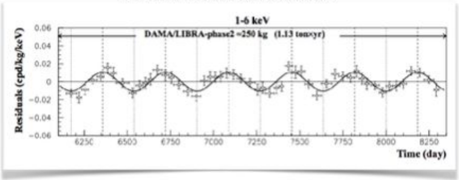




Energy dependence: a falling exponential with no peculiar features

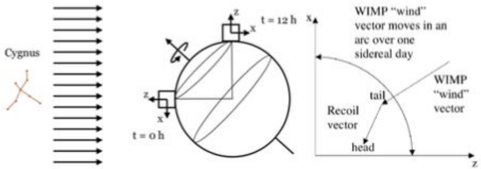


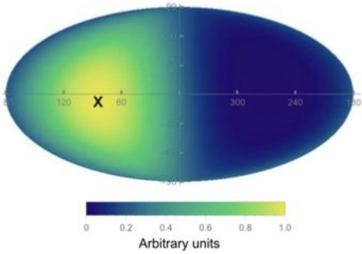
DAMA/LIBRA Collaboration



Universe 4 (2018) no.11, 116

Temporal dependence: a few % annual modulation

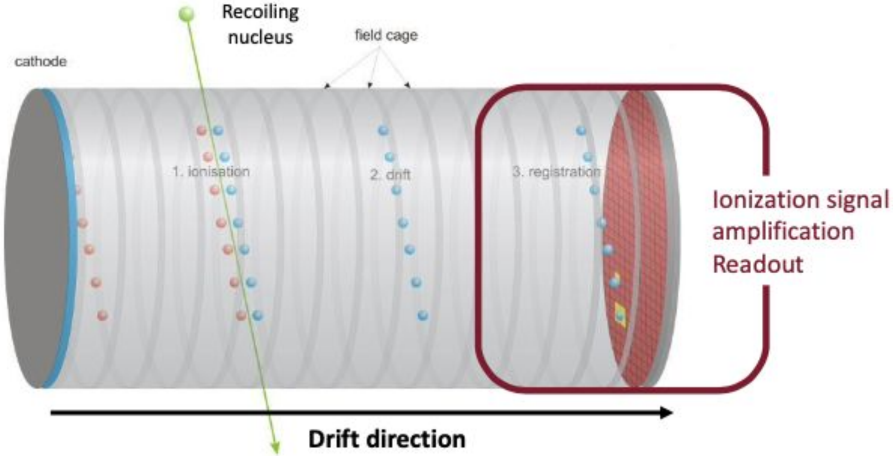


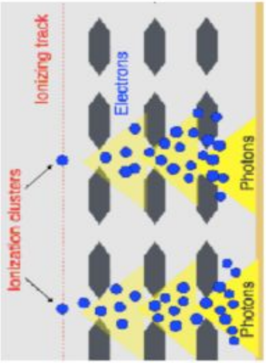


Directional dependence: an O(1) effect that no background whatsoever can mimic

Increasing reliability but increasing difficulty in the experimental technique.

CYGNO Approach





PMT

sCMOS

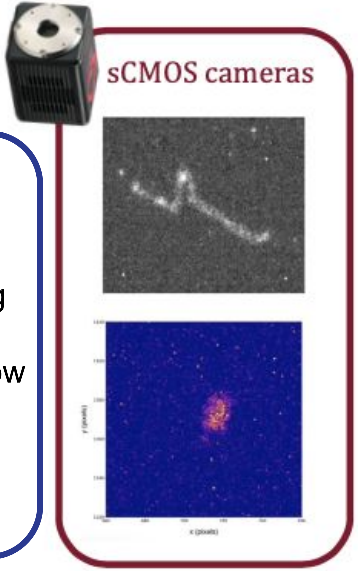
- CYGNO uses **He:CF_4** gas mixture at 1 atm
- **3 GEM** stack is used for charge amplification and light production

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

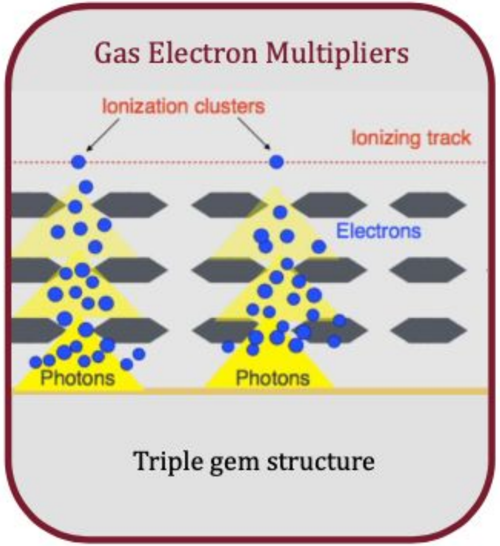
CYGNO Readout

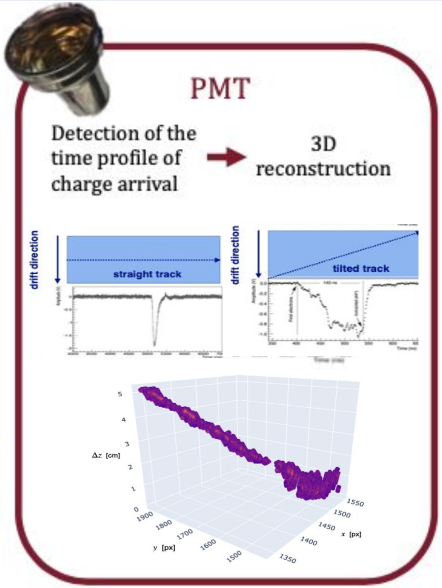
Time Projection Chamber → **Triple GEM** Charge amplification & light production → **Camera & PMT** **Light produced by the de-excitation of the gas molecules** during electron multiplication is optically read by sCMOS and PMT

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



X-Y + Energy

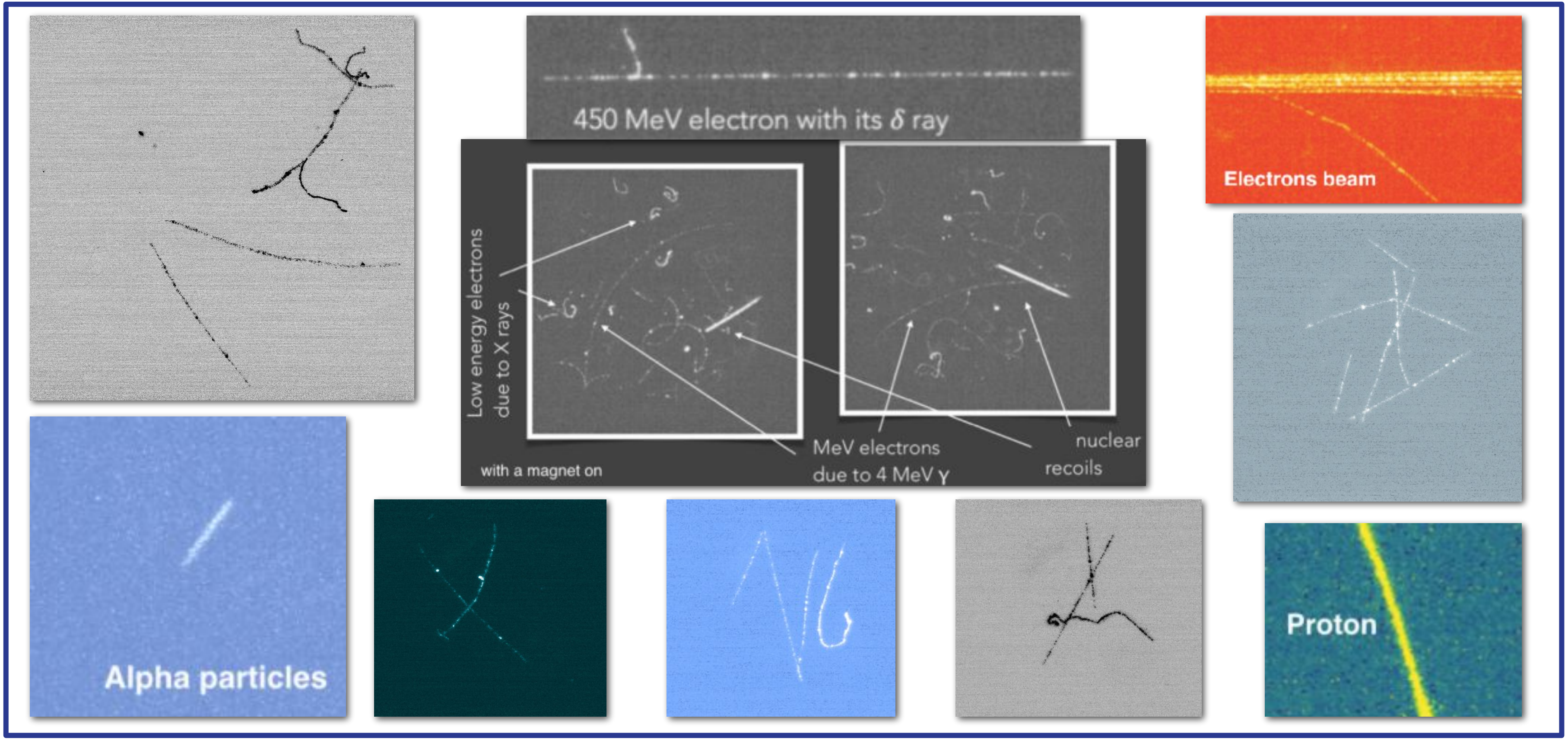




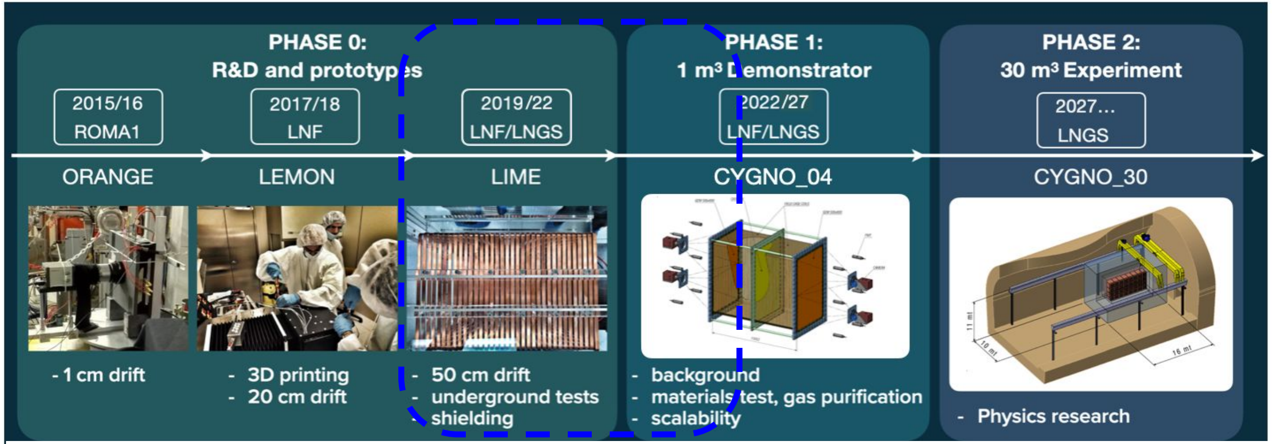
Z + Energy

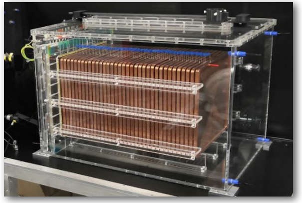
PMT measures the integrated **energy** and **time of arrival (dZ)** of charge carriers with high sampling rates.

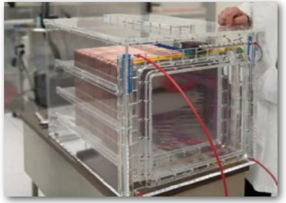
Particle tracks recorded with sCMOS

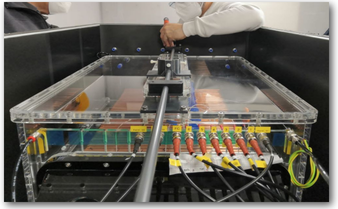


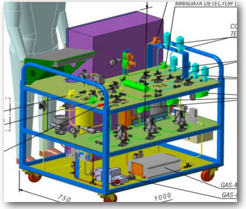
CYGNO Roadmap











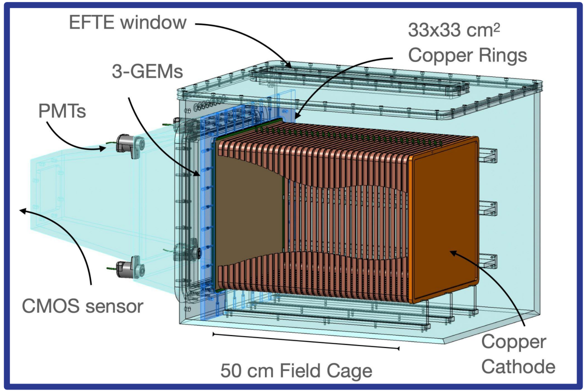
Ongoing studies:

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

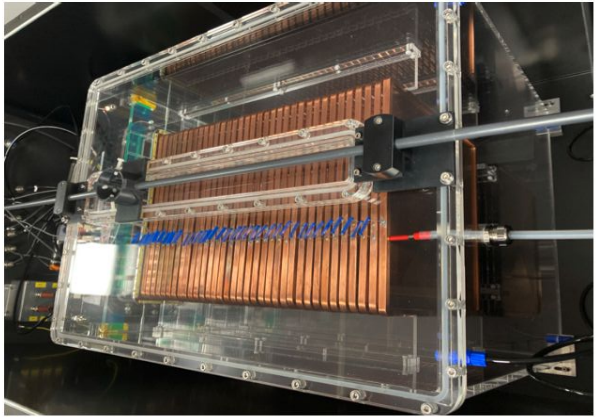
❖ Parallel research with MANGO detector for studying different GEM configuration, gas mixtures and Negative Ion Drift.

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 cm^2 GEM** stack for amplification
- **Optical readout**
  - 4 PMTs
  - 1 sCMOS camera (Orca Fusion)



ORCA-Fusion

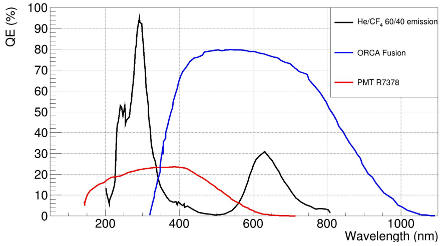
CAMERA SPECS

LOW NOISE AND EXCEPTIONAL READOUT NOISE UNIFORMITY

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

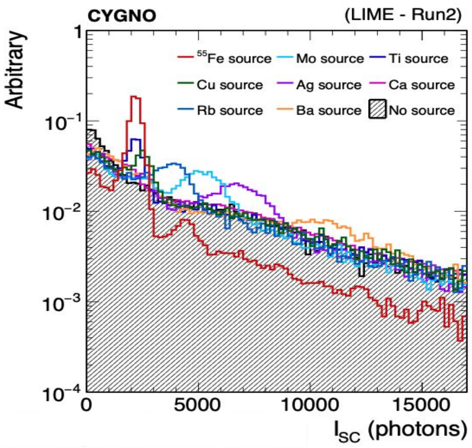
Carbon tetrafluoride (CF4)

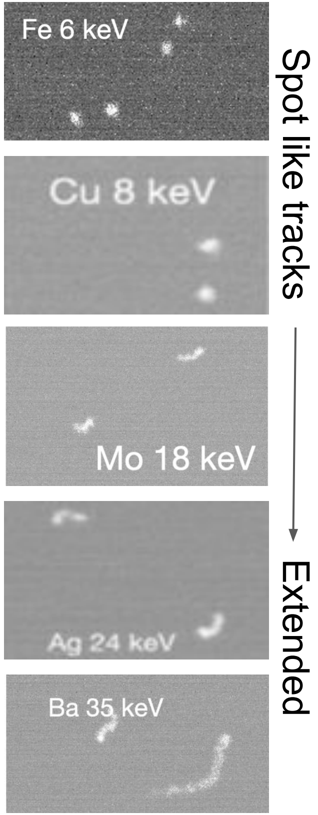
Significant light yield at the camera's QE peak

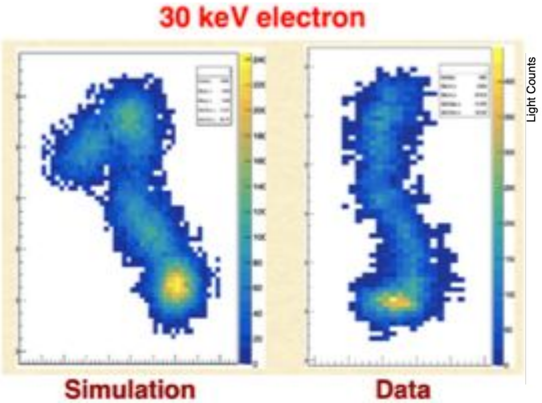


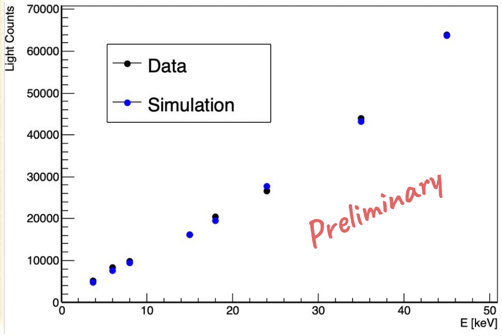
LIME: Overground Operation

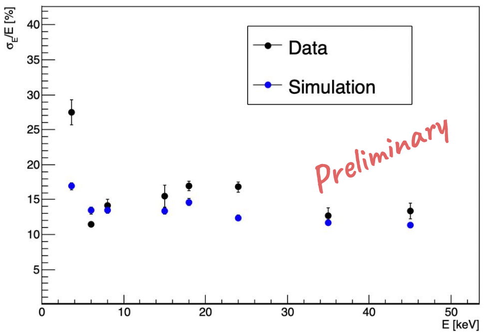
- Multiple X-Rays sources were used to study linearity and energy resolution of the detector
- Data shows good linearity in [4-50] keV
- Energy resolution ~ 14% in [4-50] keV
- Data is in good agreement with simulation
- Simulation developed taking into account the detector effects.





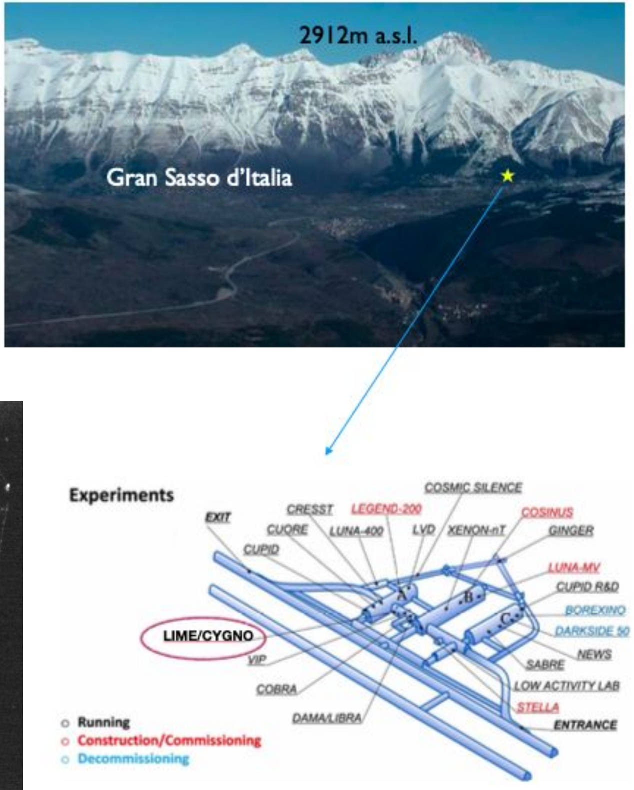


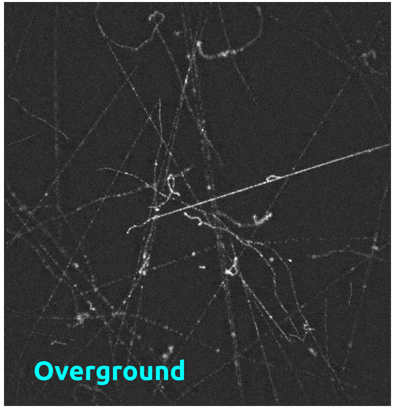


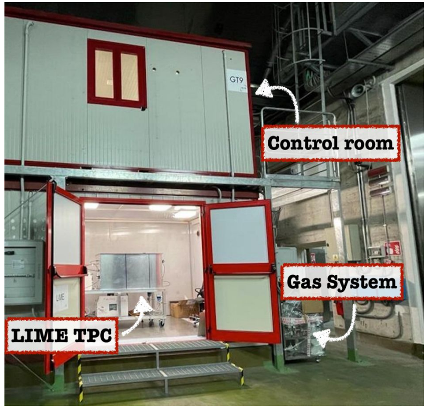


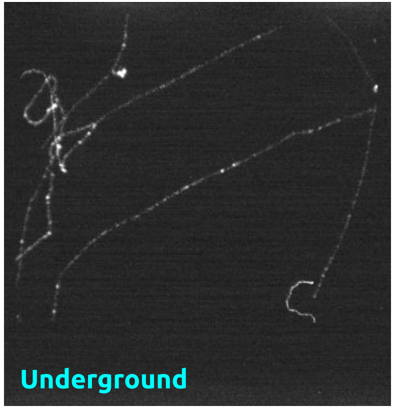
LIME: Underground Operation

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









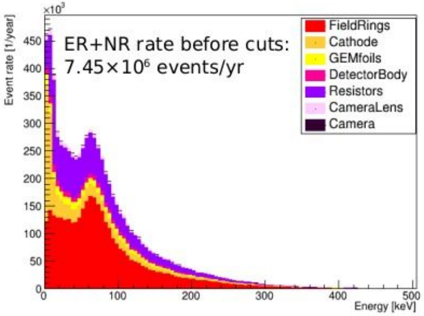
LIME : Underground Program

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

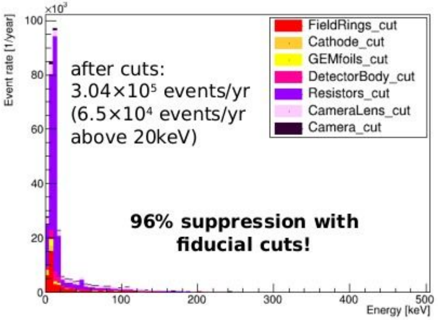
Data taking program:

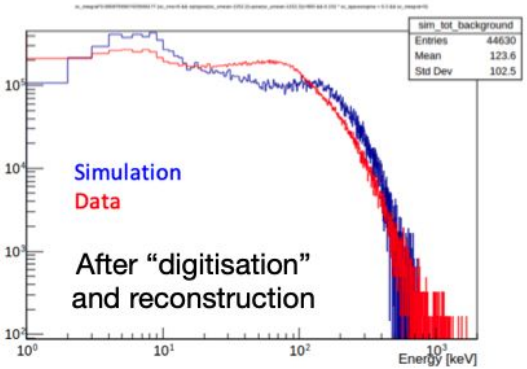
- **No shielding**
  - External bkg study and detector calibration
- **10 cm Cu**
  - Measurement of underground neutron flux
  - AmBe data to model response of neutrons
- **10 cm Cu + 40 cm water**
  - Study of internal bkg and validation with MC (reduction of ext. bkg. at a level less than internal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

ER + NR **before** cuts



ER **after** cuts





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

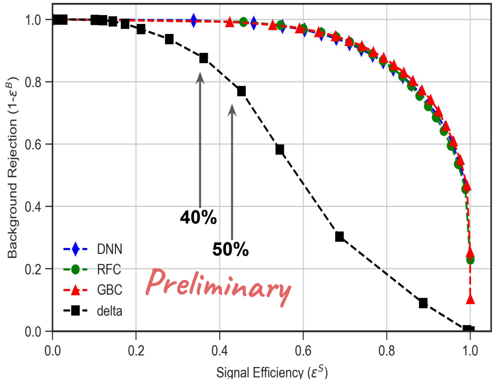
↓

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

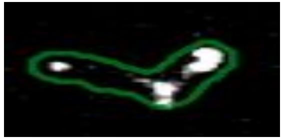


Models	Signal Eff. [ϵ^S]%	Bkg. Rej. [1-ϵ^B]%
RFC	40	99.54
	50	98.78
GBC	40	99.38
	50	98.55
DNN	40	99.43
	50	98.50
Cut-based	40	83.13
	50	67.20

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

Reconstructed tracks

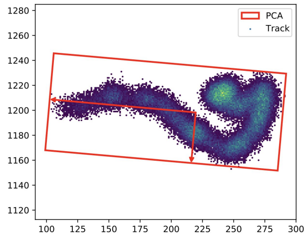
Electron Recoil



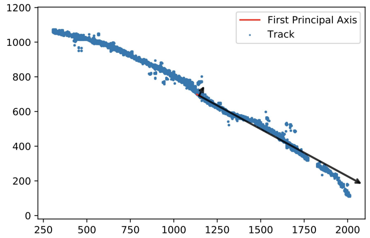
Nuclear Recoil

My PhD thesis

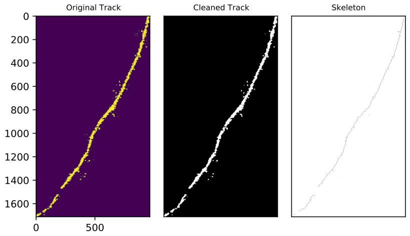
Topological Variables



a) Cylindrical Thickness



b) LAPA

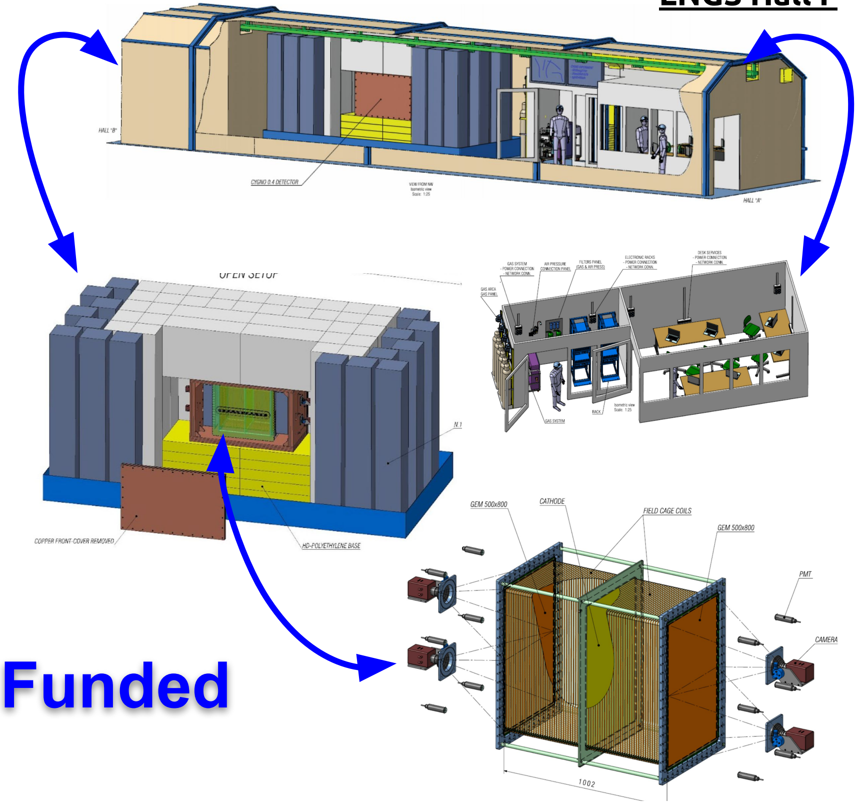


c) Skeleton

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)

LNGS Hall F

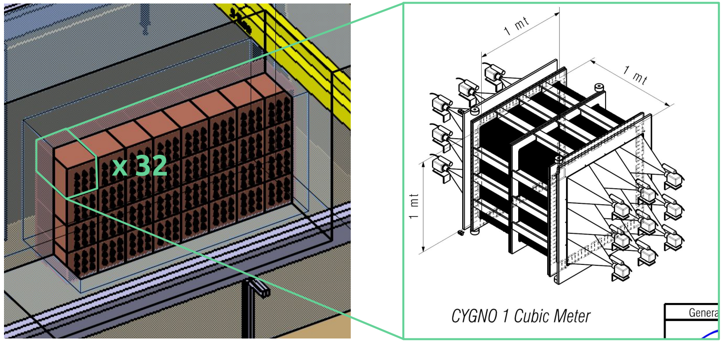


Funded

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

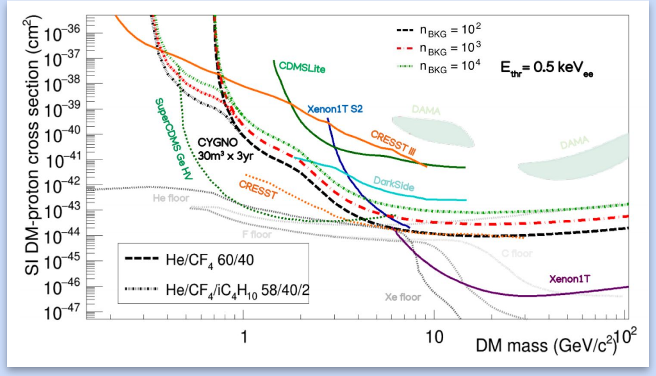
Quenching factor simulated

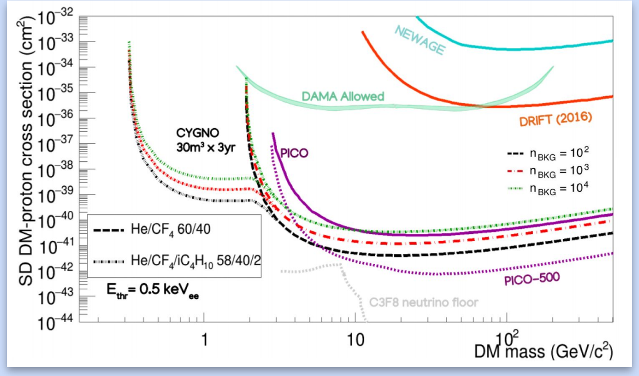
with **SRIM** → Direct

measurement incoming!

He allows us to explore very low DM

masses!





NID : Negative Ion Drift

Advantages

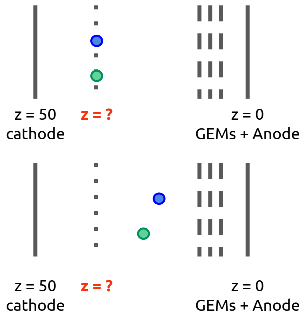
Reduced diffusion

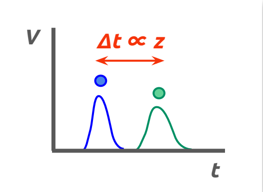
Longitudinal and transverse **diffusion reduced to thermal limit**

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

Better spatial resolution!

Multiple charge carriers

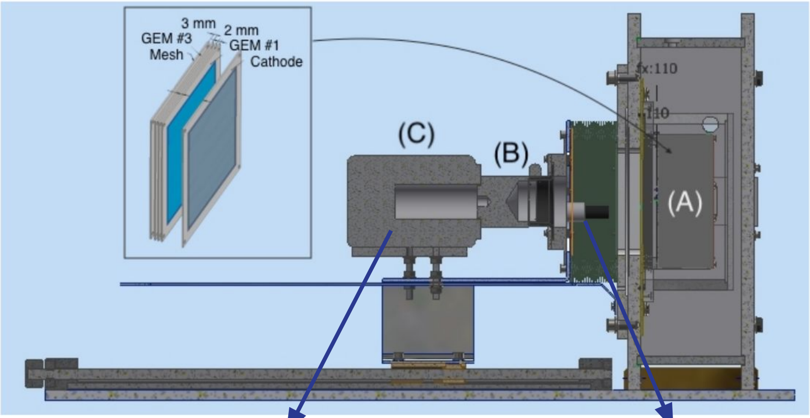




Absolute Z from Δt between minority charge carriers

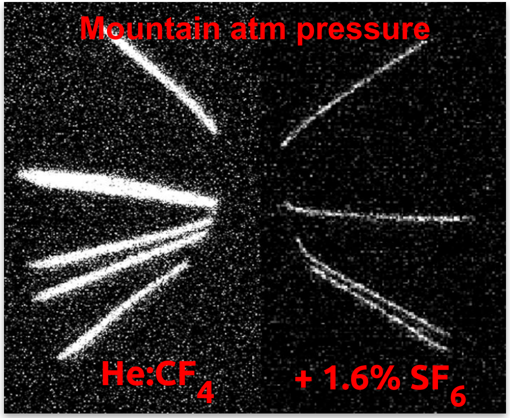
- Highly **electronegative dopant** is added to the gas (CS_2, SF_6,...)
- Primary electrons are captured by the dopant at O(100 um)
- **Anions** are majority charge carriers instead of electrons
- $\boldsymbol{\sigma_T}$ and $\boldsymbol{\sigma_L}$ reduced to **thermal limit**
- **Lower drift** velocity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

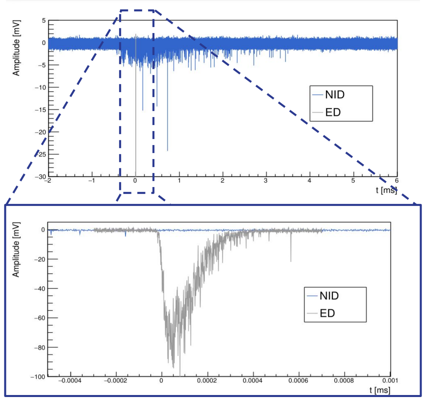
NID with MANGO detector

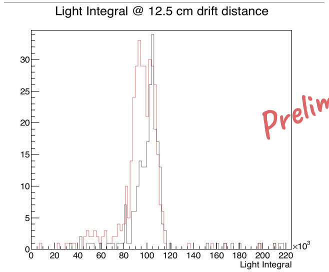


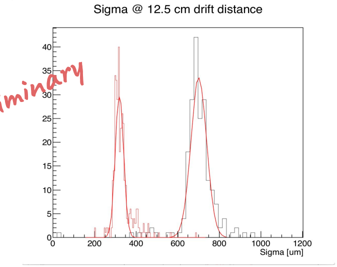
sCMOS camera

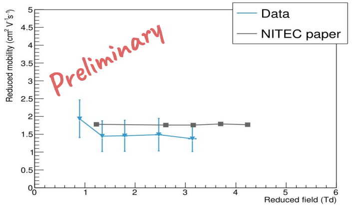
PMT











Same light … smaller sigma

Reduced mobility compatible with SF_6

Conclusions

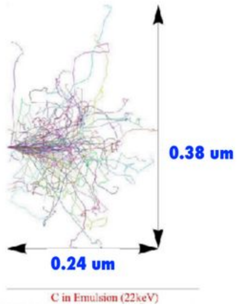
- ❖ The **CYGNO** collaboration is developing a **high-precision gaseous TPC** at atmospheric pressure with **optical readout**.
- ❖ The main focus is the **direct search** of **DM WIMP-like particles** in the **low mass range** (0.5-10 GeV).
- ❖ Through **directionality**, solar neutrinos can be discriminated and **unambiguous confirmation of DM** is possible.
- ❖ The **50L LIME prototype** is currently taking data the **underground LNGS** facilities.
  - ➢ The first **stability tests, background evaluations** and **neutrons 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**:
  - ➢ **Enhancement of light with strong electric field external to GEMs** observed in our conditions and its **potentialities** are under study
  - ➢ **INITIUM: Negative ion drift** observed for the first at atmospheric pressure and with PMTs. (Funded)
  - ➢ **HypeX**: **H**igh **Y**ield **P**olarimetry **E**xperiment in **X**-rays (Funded)
  - ➢ **FINEM**: **F**ull **I**maging of **N**uclear recoils for **E**xperimental **M**igdal measurements (Funded)


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

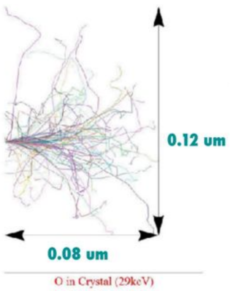
Why TPC?

Directionality preservation

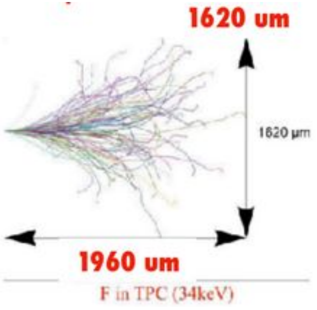
1. Emulsion layers



2. Crystal scintillators



3. Low pressure/ **density** TPCs



Main advantages of gaseous TPCs:

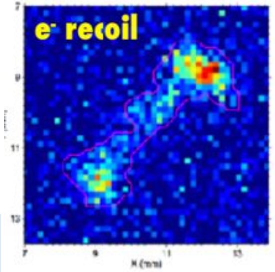
1. Tracking
2. **Directionality**
3. Head tail asymmetry identification
4. **Track topology (dE/dx)**
5. Gas flexibility

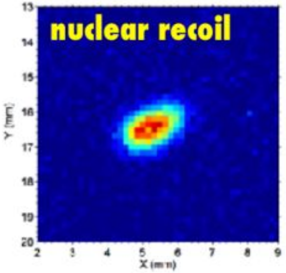
Track's direction is better preserved in TPCs

Knowledge of the track's deposited energy topology (dE/dx)

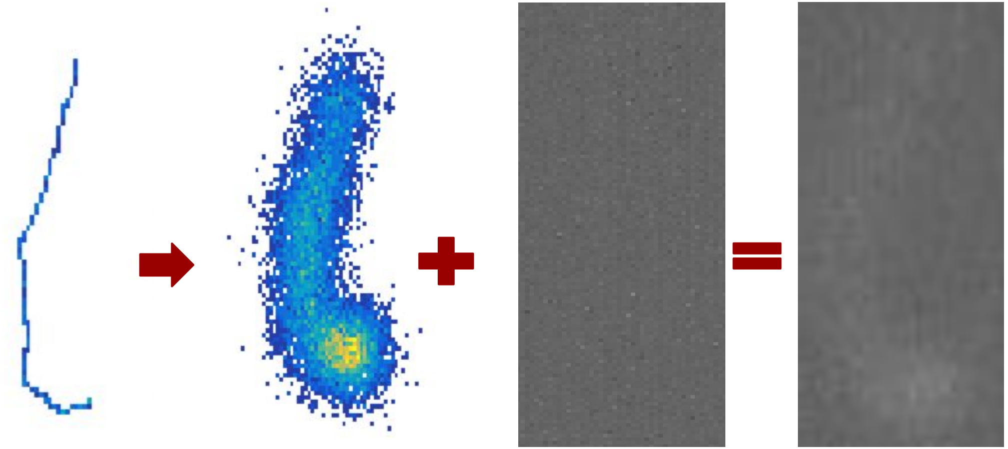
Head-tail asymmetry → Directionality

Particle → Background rejection





Digitization



(a) Track w/o diffusion (b) Track after diffusion (c) CMOS Noise (d) Digitised track

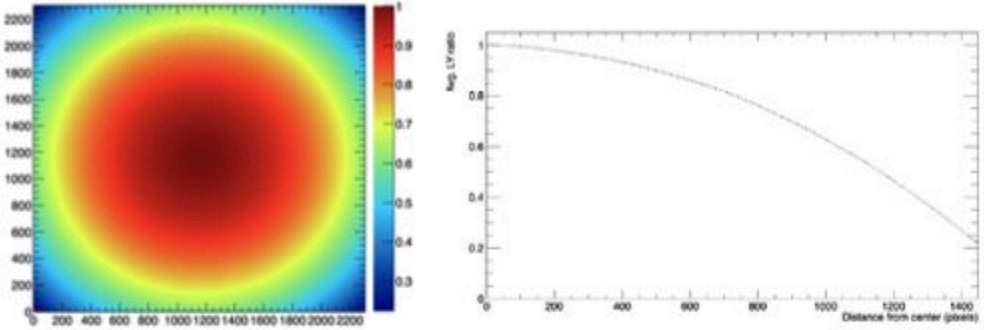
- Interaction of the particles with gas is simulated using either GEANT4 (for ER) or SRIM (for NR)

- These tracks are then projected to a 2D plane and detector effects are added like diffusion, camera noise, effective ionisation, gain fluctuation and geometrical acceptance etc.

Track Reconstruction

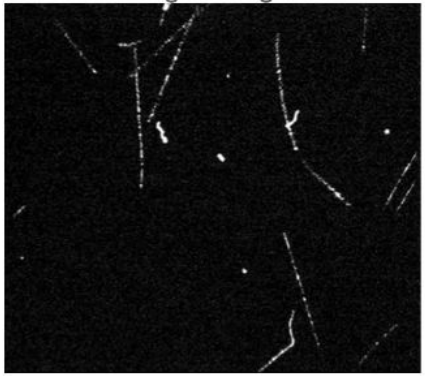
- ❖ Digitised/sCMOS images are reconstructed using an iterative density based scanning algorithm called iDBSCAN to find the tracks.
- ❖ Tracks are also corrected for vignetting effects.

+ Vignetting correction:



E Baracchini et. al., “Identification of low energy nuclear recoils in a gas TPC with optical readout”, arXiv:2007.12508v1

Original image



Tracks reconstructed