



Directional Dark Matter searches with CYGNO



David J. G. Marques* on behalf of the CYGNO collaboration:

F. Amaro, R. Antonietti, E. Baracchini, L. Benussi, S. Bianco, C. Capoccia, M. Caponero, D. S. Cardoso, G. Cavoto, I. A. Costa, G. D'Imperio, E. Dané, G. Dho, F. Di Giambattista, E. Di Marco, F. Iacoangeli, E. Kemp, H. P. Lima Júnior, G. S. P. Lopes, G. Maccarrone, R. D. P. Mano, R. R. Marcelo 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, G. Saviano, N. Spooner, R. Tesaro, S. Tomassini, S. Torelli, J. M. F. dos Santos

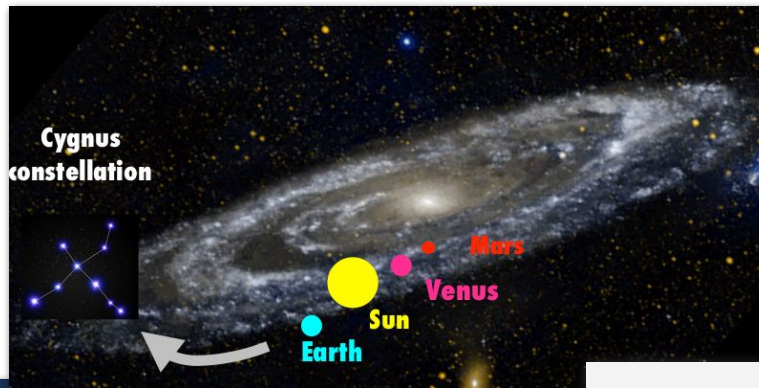
WIMPs - How to see them?

DM forms an halo within our galaxy.

+

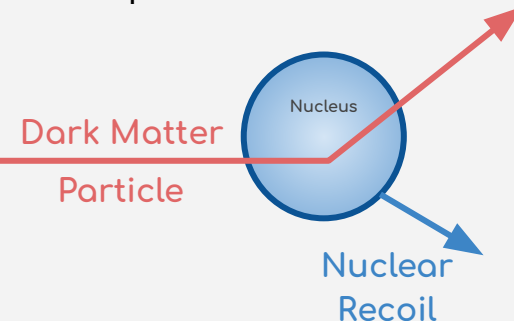
Solar system rotates around galaxy
towards Cygnus constellation

Earth susceptible to an
apparent WIMP wind from
Cygnus direction!



Direct detection

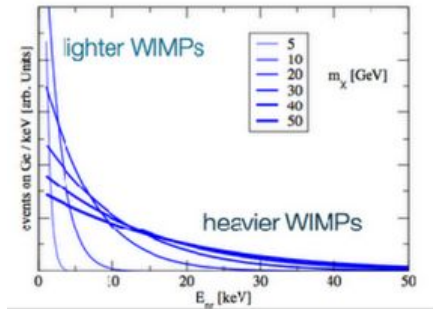
- ❖ $SM + \chi \rightarrow SM + \chi$
- ❖ SM particle's recoil



WIMPs - What dependency to explore?

Increasing reliability but increasing difficulty in the experimental technique.

1. Exploring the **ENERGY** **dependency**



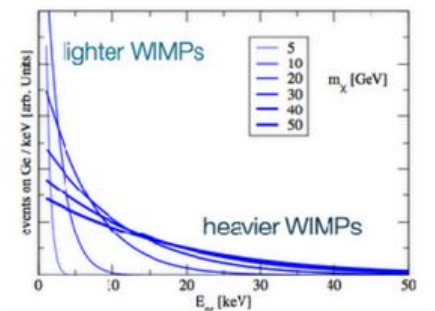
Results in a falling
exponential with no
peculiar features.

The background has a
similar spectrum.

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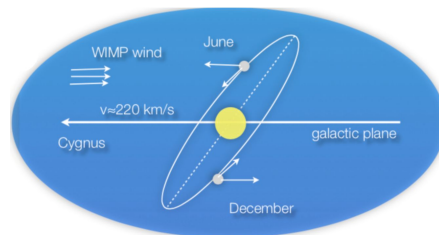
1. Exploring the **ENERGY** dependency



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The background has a similar spectrum.

2. Exploring the **TIME** dependency

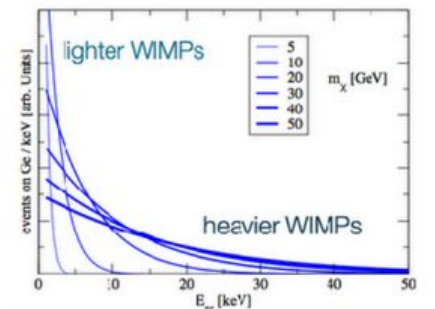


Results in a few % annual modulation.

WIMPs - What dependency to explore?

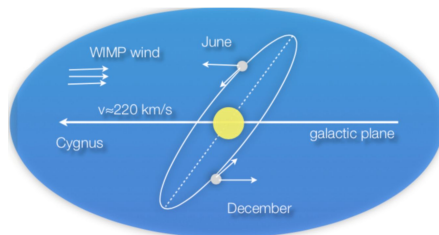
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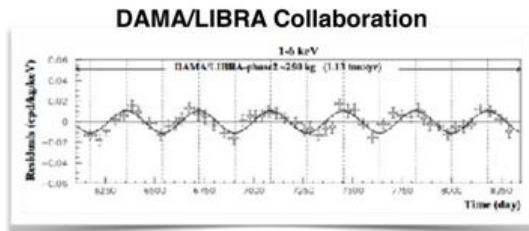


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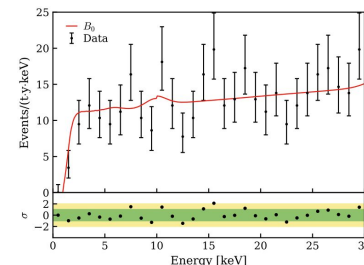
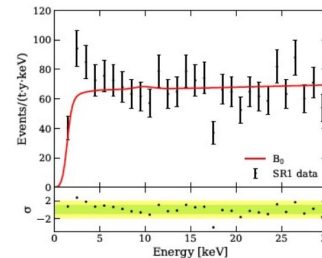
2. Exploring the **TIME** dependency



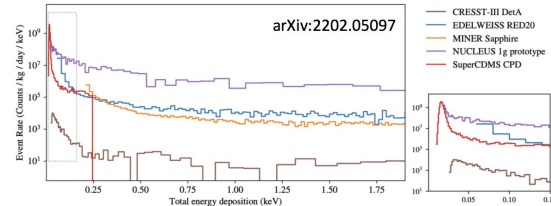
Results in a few % annual modulation.



[The Annual Modulation Signature for Dark Matter: DAMA/LIBRA-Phase1 Results and Perspectives](#)



Exponentially rising background towards lower energies

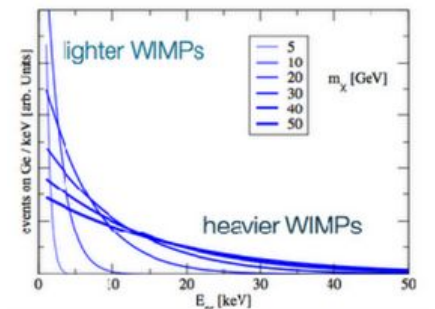


Currently limiting the sensitivity globally!
Origin still unknown, but a lot of R&D is going on ...

WIMPs - What dependency to explore?

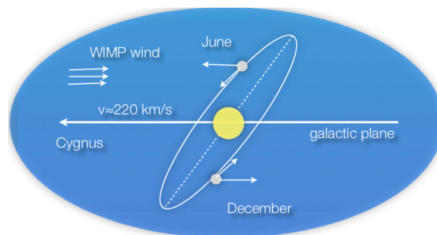
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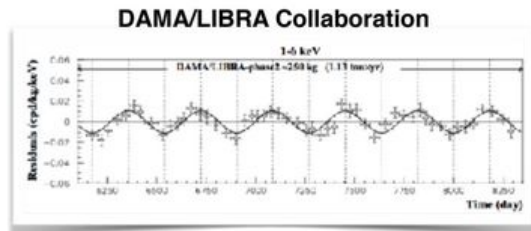


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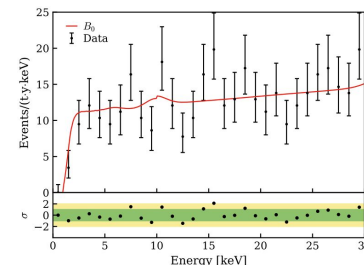
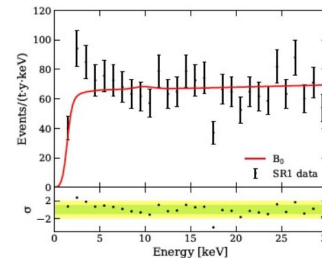
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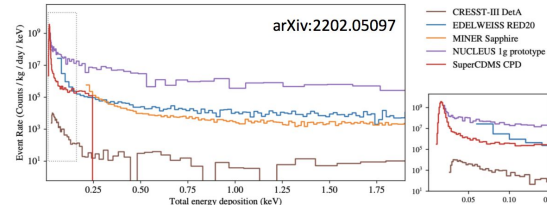
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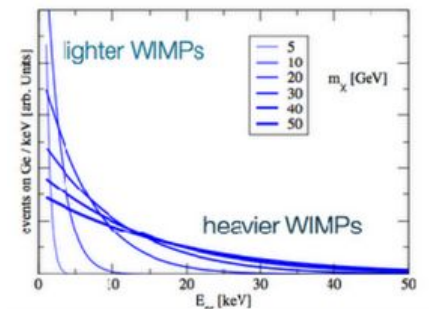
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Origin still unknown, but a lot of R&D is going on ...

In all of these, it's hard to prove / disprove DM.

WIMPs - What dependency to explore?

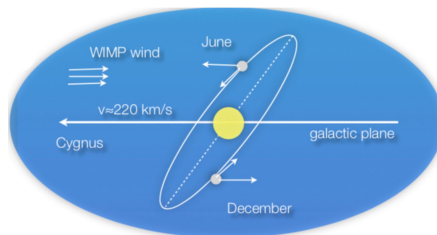
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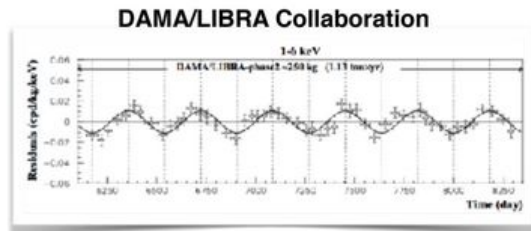


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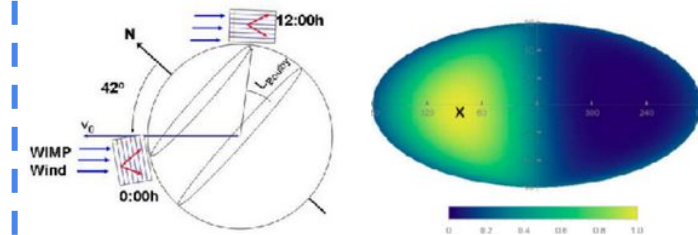


Results in a few % annual modulation.



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3. Exploring the **DIRECTION** dependency



Results in characteristic effect - anisotropy in the angular distribution of **nuclear recoils** → no background can mimic.

...moreover, Beyond neutrino floor

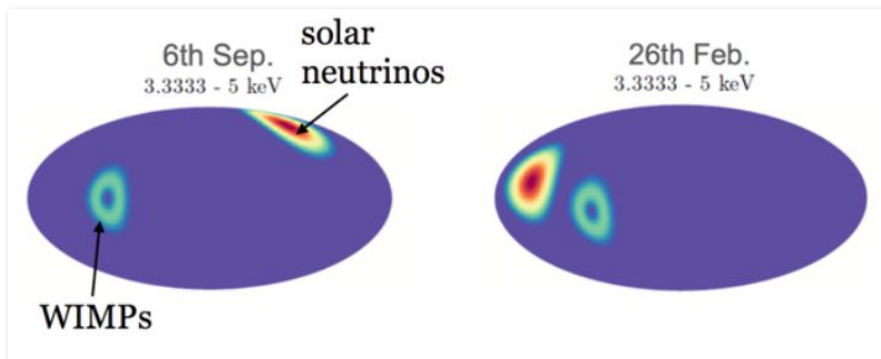
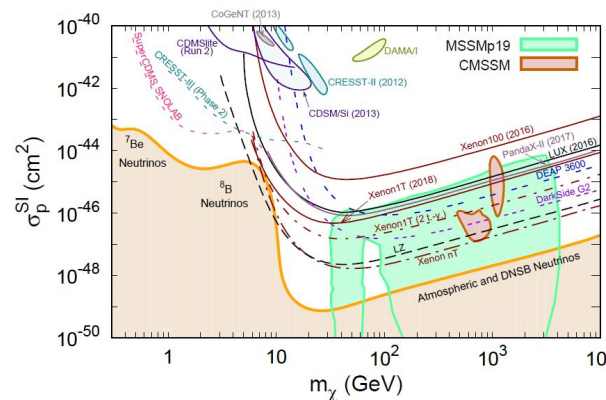
In DM searches, the Coherent Elastic Neutrino-Nucleus Scattering is behind the neutrino floor. This will **always** be **present**!



Below $10 \text{ GeV}/c^2 \rightarrow$ Mostly **solar neutrinos**



In galactic coordinates, the Sun and Cygnus are never superimposed!

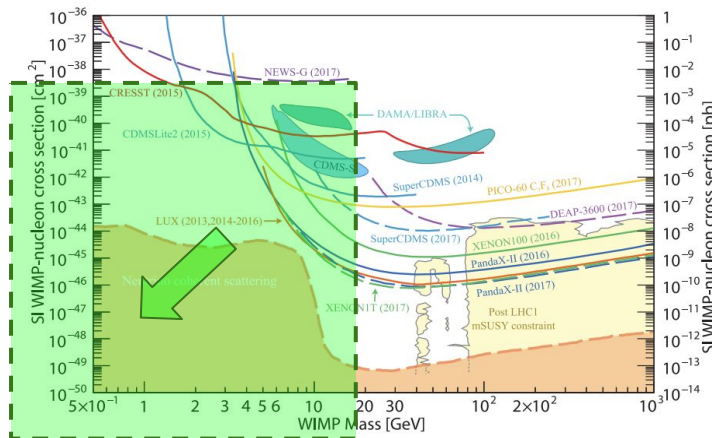


- **Directional** discrimination is the only way to unambiguously identify a DM signal!
- Searching **beyond** the neutrino floor
- Properties of the **solar neutrino flux**
- DM halo properties (DM astronomy)



A CYGNus tpc module
with Optical readout

CYGNO Dark Matter exploration region



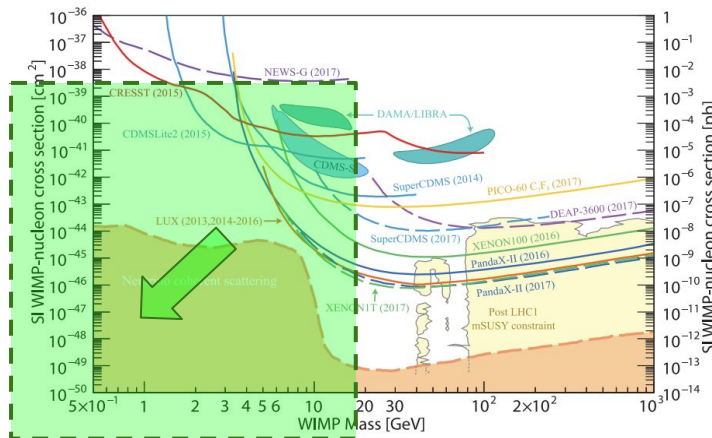
$\leq 10 \text{ GeV}/c^2$



To observe lower WIMP masses:

- ◆ Lower thresholds are necessary since lower m_χ originate lower energy recoils.
- ◆ Light nuclei used to maximize energy transfer.

CYGN0 Dark Matter exploration region



Low Density @ atm pressure

- Allows tracks of several millimeters at few keV without compromising exposure.

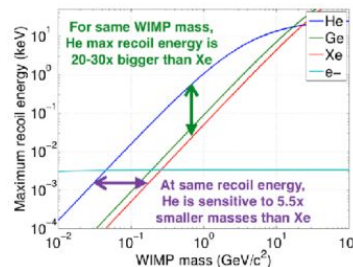
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→ To observe lower WIMP masses:

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Helium (He)

→ Light target for SI in low mass range.



Fluorine (F)

- Heavier target to intermediate WIMP masses.
- Sensitive to SD coupling since $A = 19$ (odd).

CYGN0 - What's the setup?

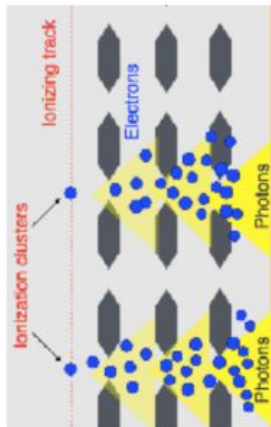
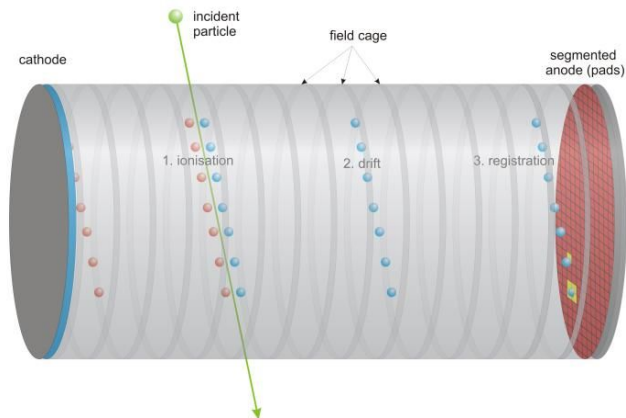
Time
Projection
Chamber

Triple GEM

Charge
amplification
& light production

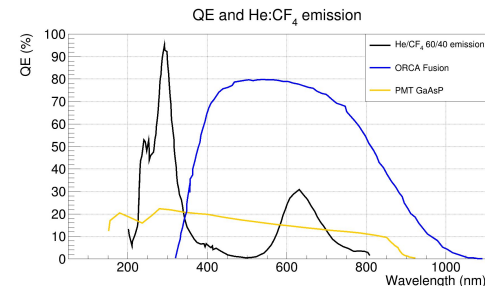
Camera & PMT

Optically read the **light produced by the de-excitation of the gas molecules** during electron multiplication.



Carbon tetrafluoride (CF₄)

→ Significant light yield at the camera's QE peak



CYGN0 - What's the setup?

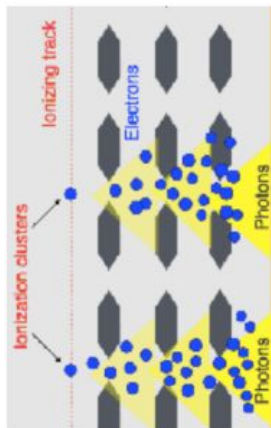
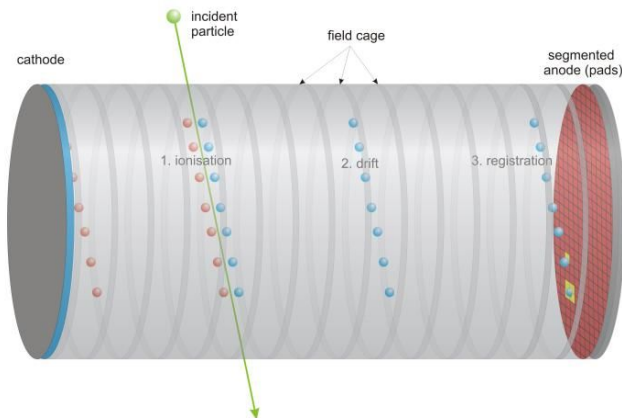
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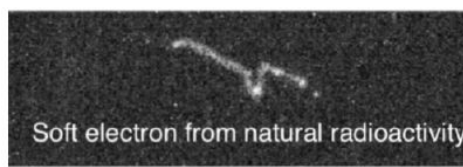
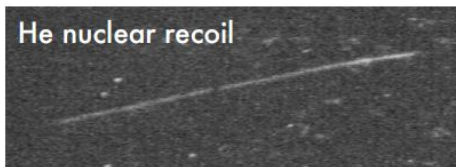
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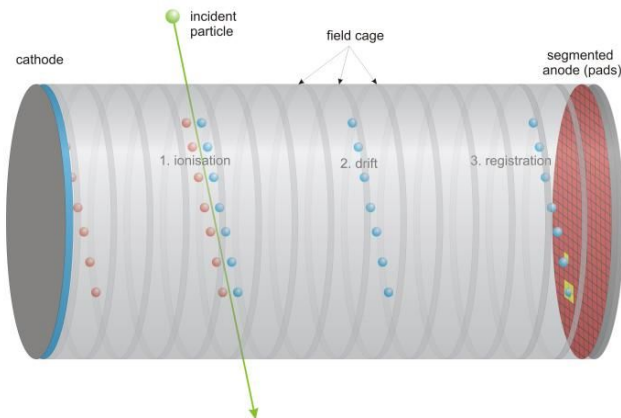


Using the camera's high granularity, we can measure the **energy** & **X & Y coordinates**



CYGN0 - What's the setup?

Time Projection Chamber

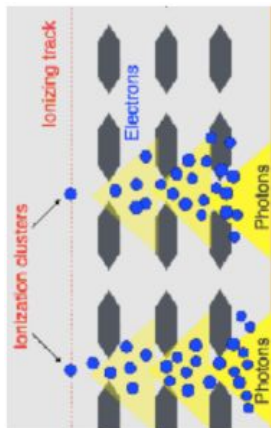


Triple GEM

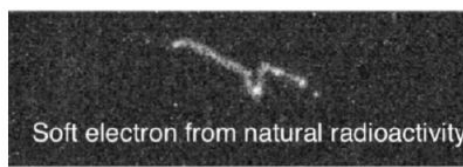
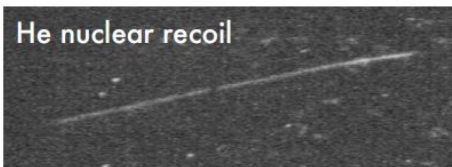
Charge amplification & light production

Camera & PMT

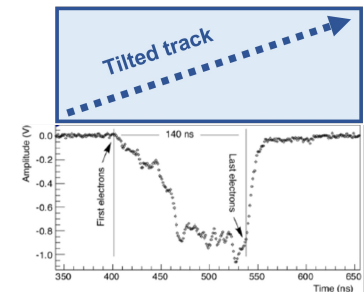
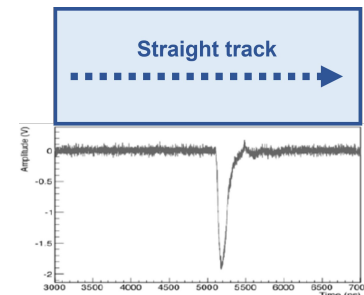
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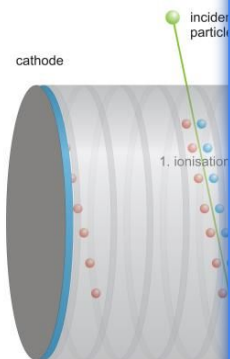


1. Measure integrated energy.
2. Charge carriers' times of arrival → **dZ coordinate** (track's tilt)



CYGNO - What's the setup?

Time
Projection
Chamber



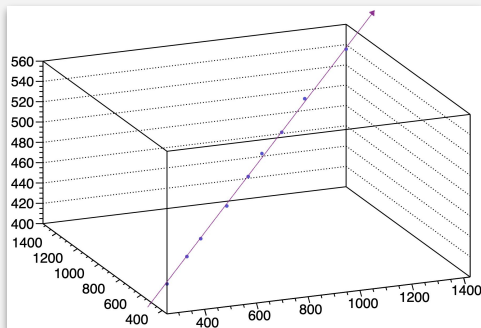
Triple GEM

Charge

Camera & PMT

Optically read the **light produced by the**

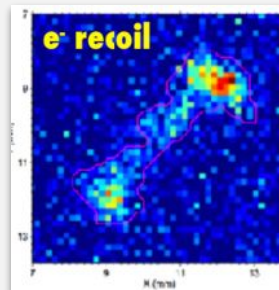
$X + Y + dZ =$
3D reconstructed track



Track's deposited energy
topology (dE/dx)

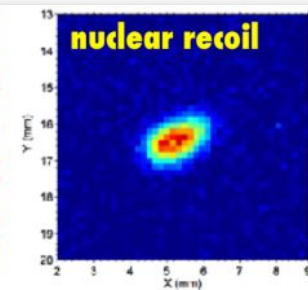
Head-tail asymmetry

Directionality



Particle

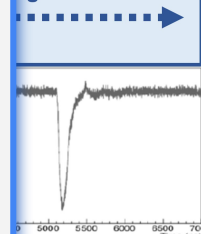
BG rejection



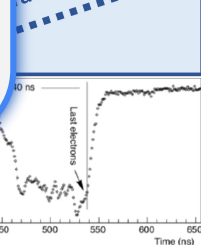
1. Measure integrated energy.

Charge carriers' arrival →
Rate (track's tilt)

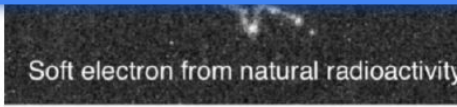
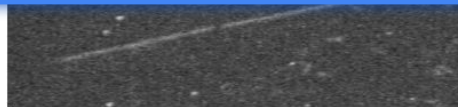
Right track



Track

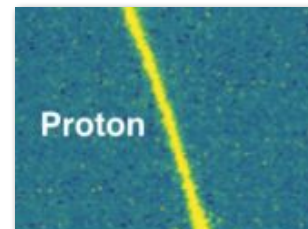
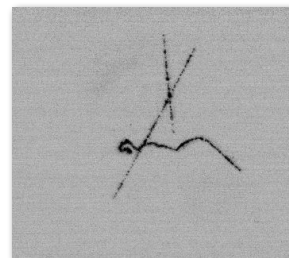
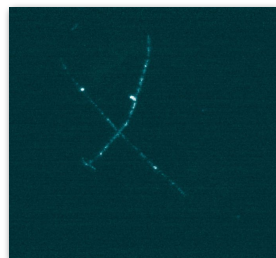
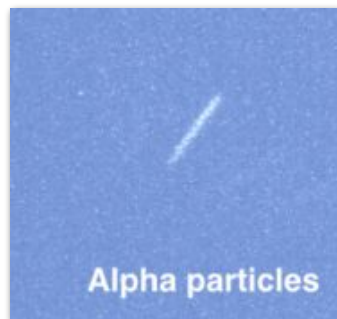
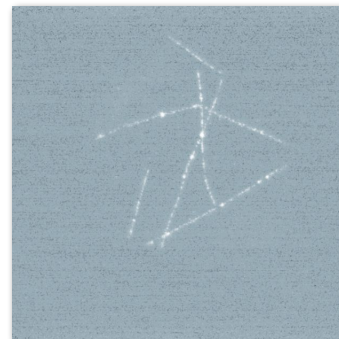
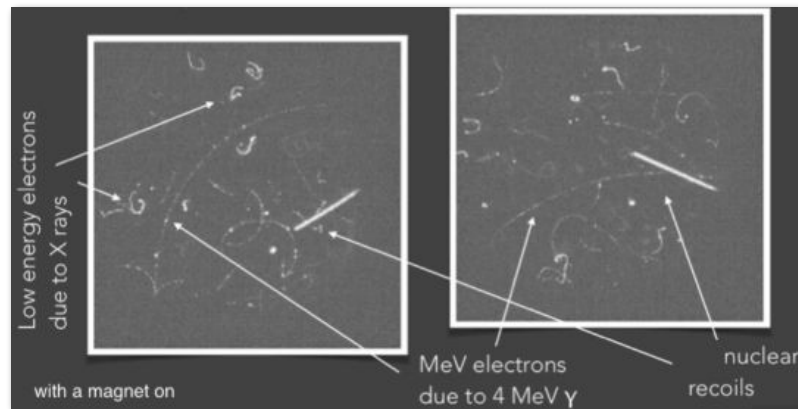
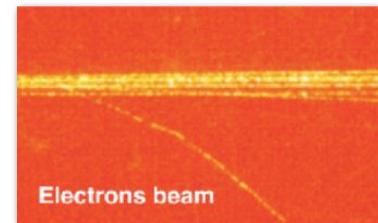
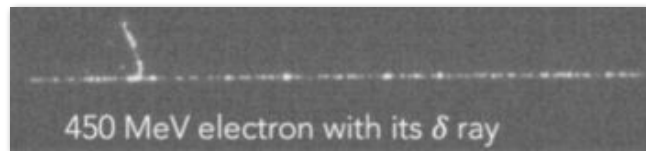
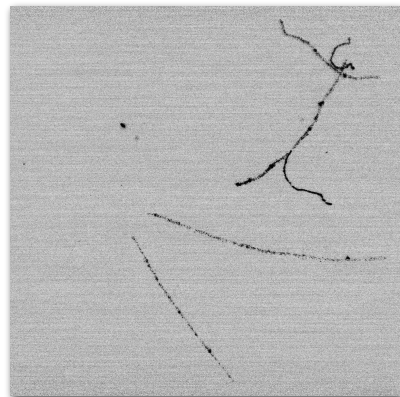


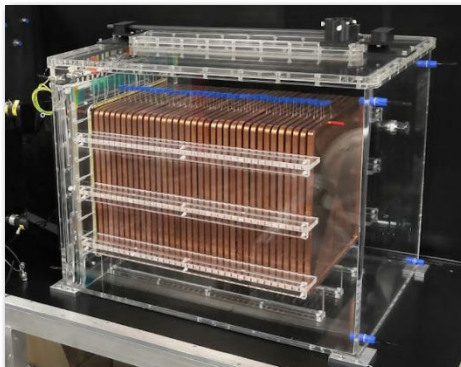
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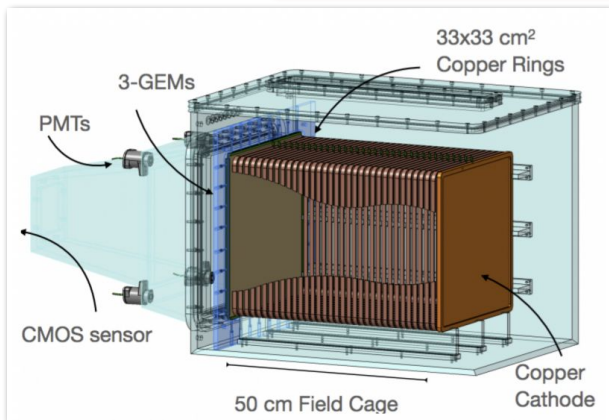
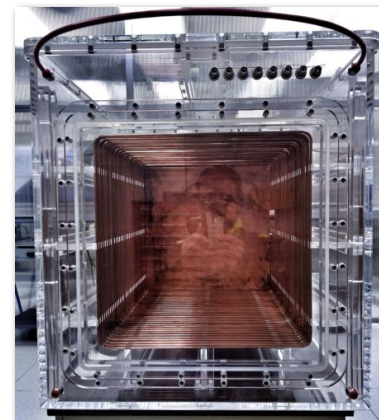
Soft electron from natural radioactivity

CYGN0 - *Some pictures!*





- Single-sided cathode, **50 L gaseous TPC**
- At **atm pressure**, room temperature and **He:CF₄**
- **Triple 33x33 cm² GEM stack** for amplification
- **Optical readout**
 - ◆ 4 PMTs
 - ◆ 1 sCMOS camera (ORCA Fusion)
- Copper ring field cage, **50 cm drift**



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

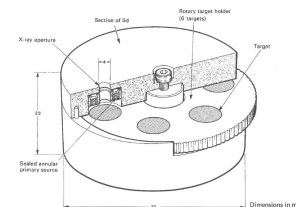
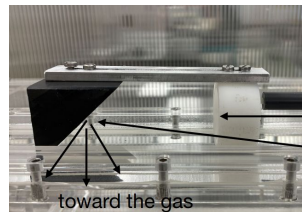
PEAK QE
80 %



Electron recoil response

- ◆ Different energy **electron recoils** were generated*

*Different materials irradiated by a ^{55}Fe -source (Ca, Cl, Ti) or ^{241}Am -source (Cu, Rb, Mo, Ba, ...)

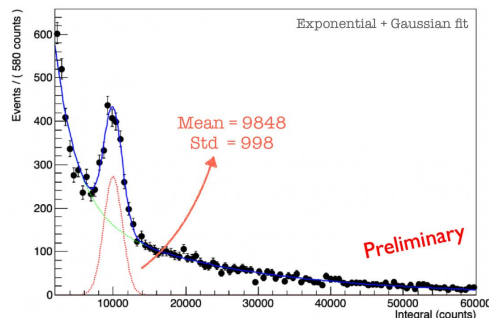


X-ray emission:

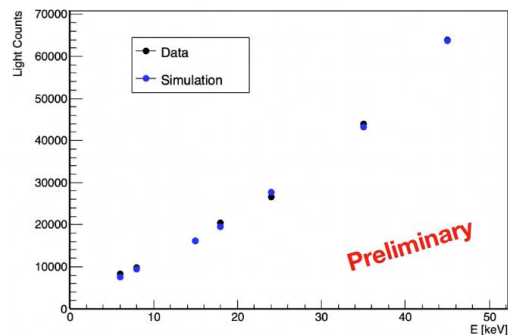
Target selected	Energy (keV) (1)	
	K_{α}	K_{β}
Cu	8.04	8.91
Rb	13.37	14.97
Mo	17.44	19.63
Ag	22.10	24.99
Ba	32.06	36.55
Tb	44.23	50.65

Electron recoil response

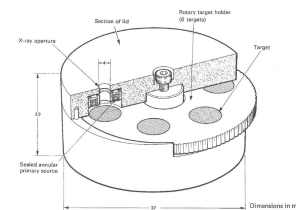
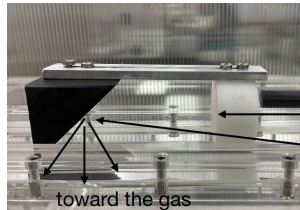
- ❖ Different energy **electron recoils** were generated*
- ❖ Detector **light response** measured
 - Later compared with **simulation**



Calibration example with Cu 8 keV X-ray



*Different materials irradiated by a ^{55}Fe -source (Ca, Cl, Ti) or ^{241}Am -source (Cu, Rb, Mo, Ba, ...)

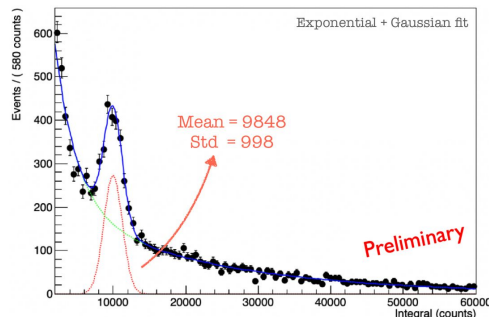


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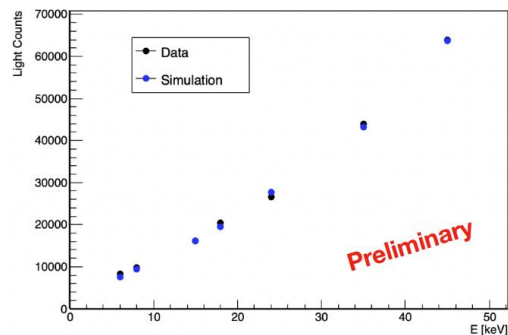
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Electron recoil response

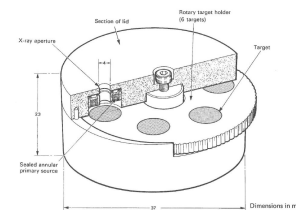
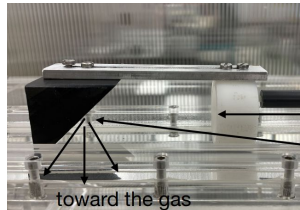
- ❖ Different energy **electron recoils** were generated*
- ❖ Detector **light response** measured
 - Later compared with **simulation**



Calibration example with Cu 8 keV X-ray



*Different materials irradiated by a ^{55}Fe -source (Ca, Cl, Ti) or ^{241}Am -source (Cu, Rb, Mo, Ba, ...)

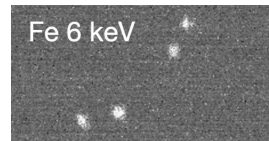


X-ray emission:

Target selected	Energy (keV) (1)	
	K_{α}	K_{β}
Cu	8.04	8.91
Rb	13.37	14.97
Mo	17.44	19.63
Ag	22.10	24.99
Ba	32.06	36.55
Tb	44.23	50.65

- ➔ Good **linearity**
- ➔ **Energy resolution of 14 %** in this energy range, and across the 50 cm drift
- ➔ Good **data-MC** matching

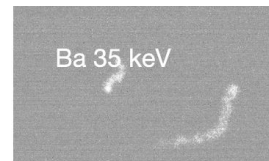
Fe 6 keV



Mo 18 keV

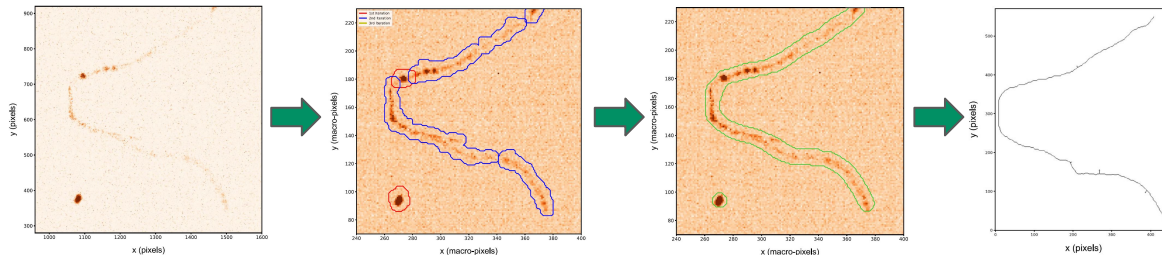


Ba 35 keV



NR vs ER discrimination

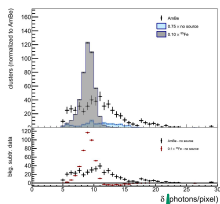
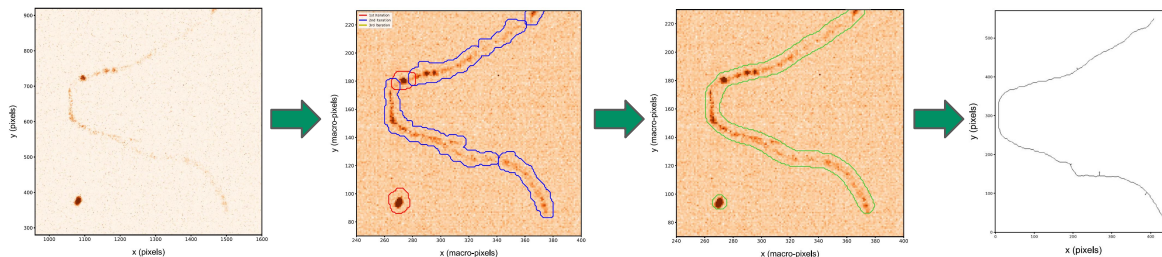
- ❖ **DBSCAN algorithm** reconstructs tracks and their essential parameters (dE/dx , light integral, slimness, photon density (δ), etc.)
- Allows **topological** studies → Particle discrimination



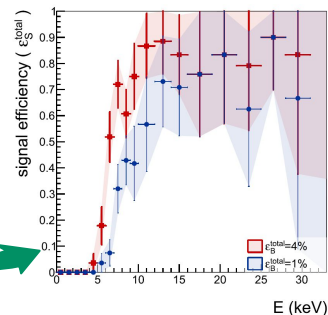
NR vs ER discrimination

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Basic cut on δ

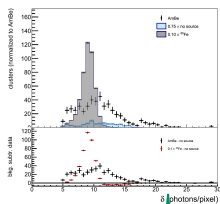
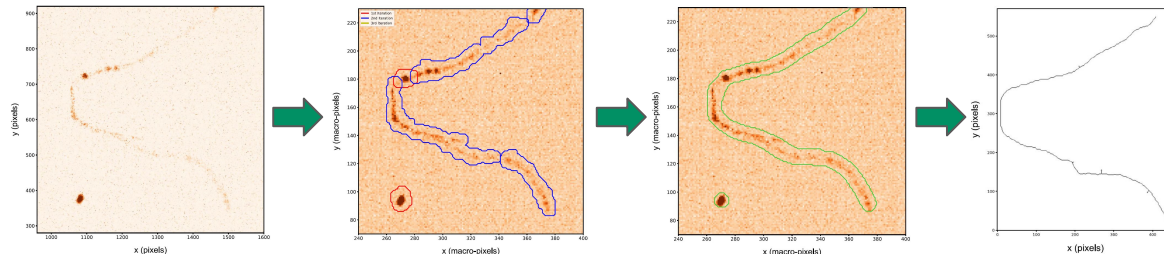


- ➔ With a signal (AmBe-induced-n.r.) efficiency of 40%, we achieve a BG-rejection of 96% at 6 keV.
- ➔ Room for improvement by exploiting **multivariate analysis**.

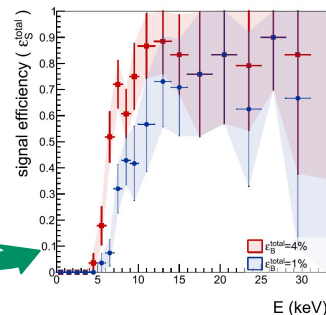
NR vs ER discrimination

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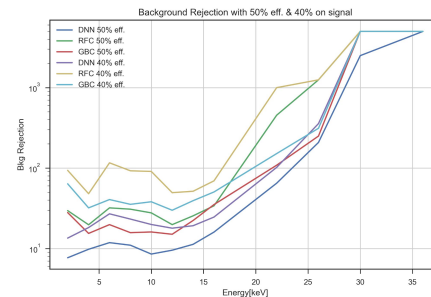
Basic cut on δ



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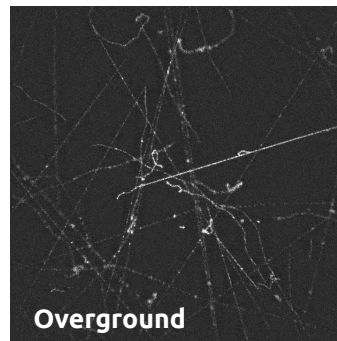
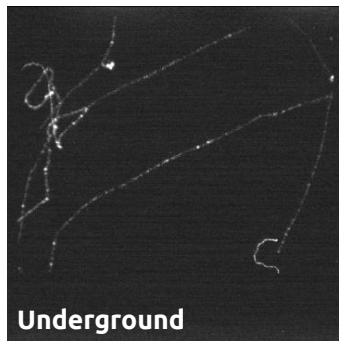
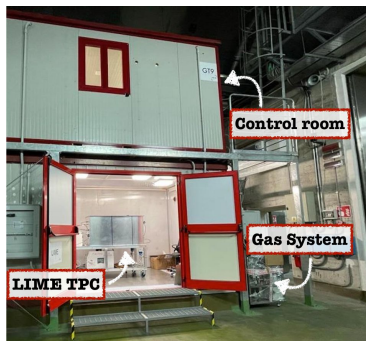
➔ Room for improvement by exploiting **multivariate analysis**.

Currently testing different **deep learning/ neural network models** to exploit other topological information and improve **NR vs. ER discrimination**

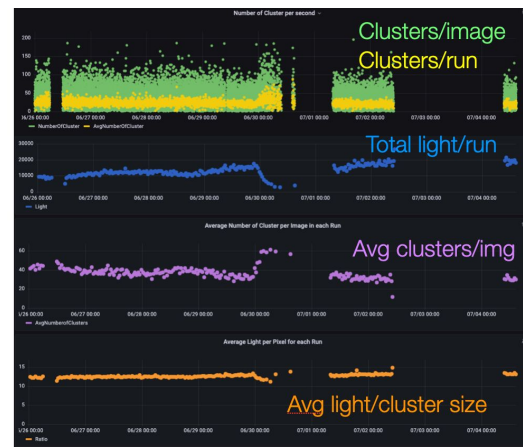


...for more info:
<https://indico.ict.inaf.it/event/1692/contributions/11272/>

- LIME has recently (beginning of 2022) been placed underground at the LNGS.
- Several stability tests are being carried through a semi-automatic and **remote** system responsible for controlling the **detector**, **DAQ** and **ancillary equipment** (HV, gas, sensors).
- Continuously taking data for over a month.
 - ◆ Validation of simulated BG model.
 - ◆ Operating conditions optimization.



Live monitoring of detector performance & data quality



Background simulation

→ No shield

- ◆ Characterization of *external background*
 - Cross-check with simulation.

→ 10 cm Cu

- ◆ Measurement of *underground neutron flux*
(~150 events above 20 keV in 4 months).

→ 10 cm Cu + 40 cm water

- ◆ *Optimized* so that internal background dominates.
- ◆ Internal background study.

→ ER vs. NR techniques** are under study

- ◆ **Multivariate analysis** of reconstructed variables.
- ◆ **Convolutional neural networks.**

Background simulation

→ No shield

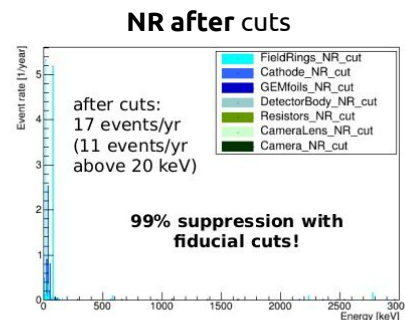
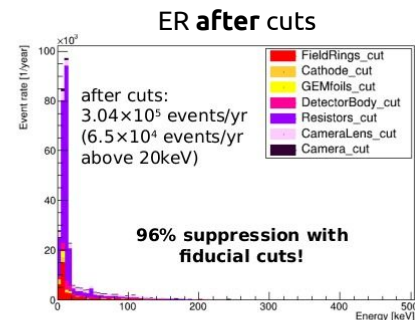
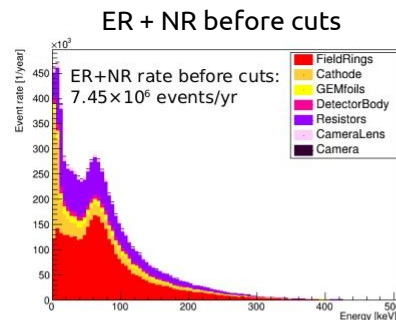
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- ER vs. NR techniques** are under study
 - ◆ **Multivariate analysis** of reconstructed variables.
 - ◆ **Convolutional neural networks**.



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

↓

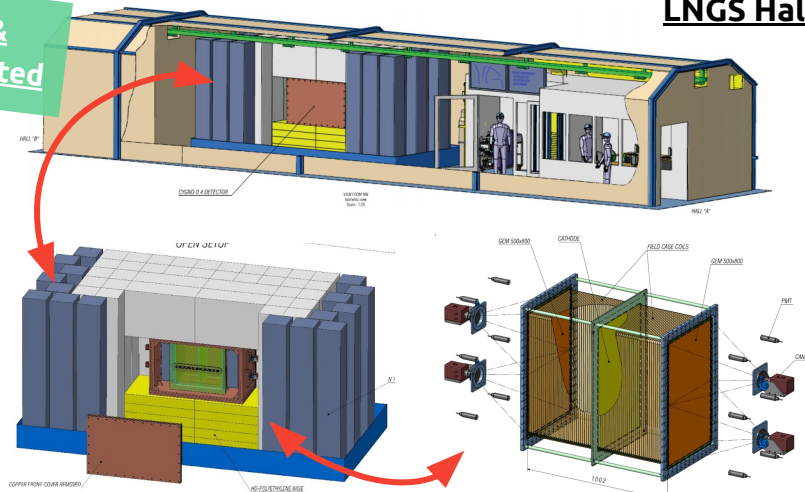
After cuts and above 20 keV, we arrive at 6.5×10^4 ER/yr and 11 NR/yr!**

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

- Test scalability / feasibility on realistic scale
- Test all ancillary systems
- Back-to-back **0.4 m³ gaseous TPC**, with central cathode.
- At **atm pressure**, room temperature and **He:CF₄**
- **Triple 50x 80 cm² GEM stack** for amplification
- Low radioactivity **acrylic glass vessel**
- Field cage made by **copper strips on insulator support** (DRIFT-like)
- Projected shielding composed of **10 cm Cu + 100 cm H₂O**

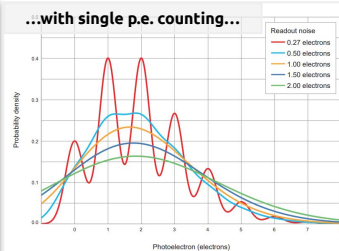
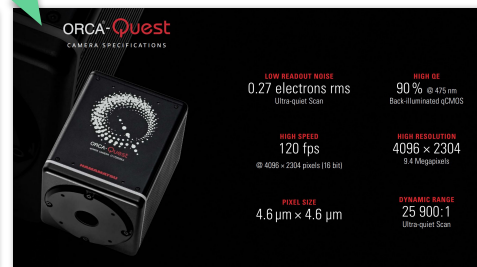
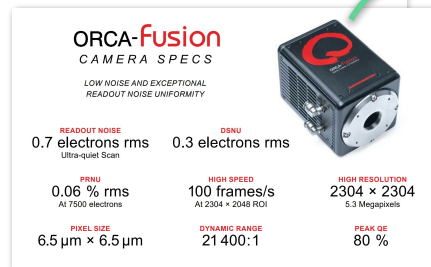
*Funded &
TDR submitted*

LNGS Hall F



Optical readout improvement:

- 12 PMTs
- 4 (**vanguard**) ORCA Quest



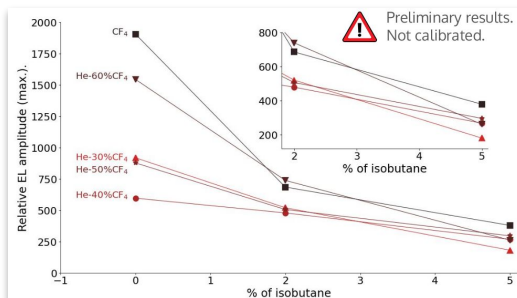
Internal background reduction

- Building low radioactivity camera sensor and lens together with Hamamatsu/BMI experts



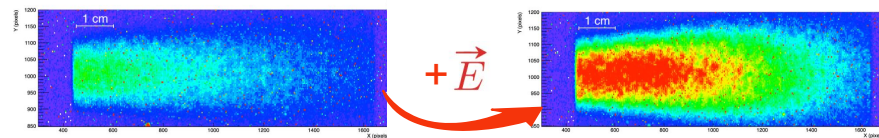
Addition of H-based gases in the mixture

Improvement
of low Dark Matter
Mass detection
sensitivity



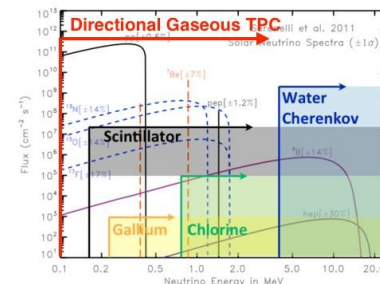
Electroluminescence for light enhancement

- Through strong electric fields, light is increased without charge amplification (energy resolution enhanced)



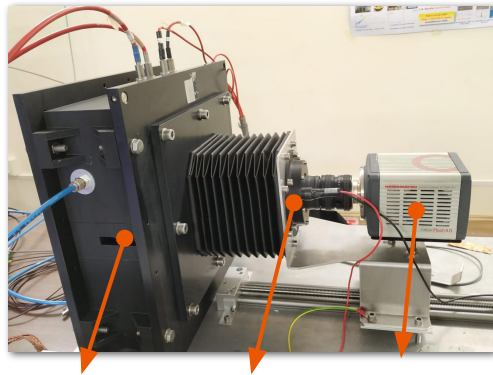
Neutrino spectroscopy feasibility

Closed kinematics
Reconstruction of
ER direction and energy
+ neutrino direction (sun)
↓
[solar] neutrino energy



Electroluminescence - A new feature

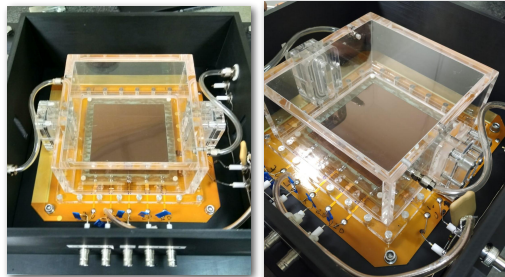
MANGO



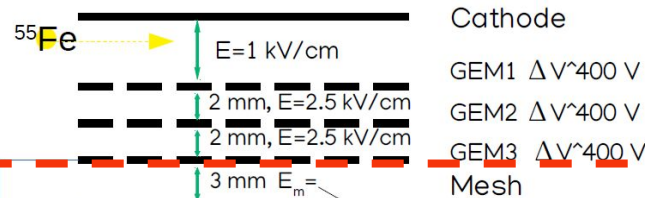
3 GEMS
50 μm thick

PMT

sCMOS
Camera
Orca Flash 4.0



Gas: He:CF₄ 60/40, 1 atm



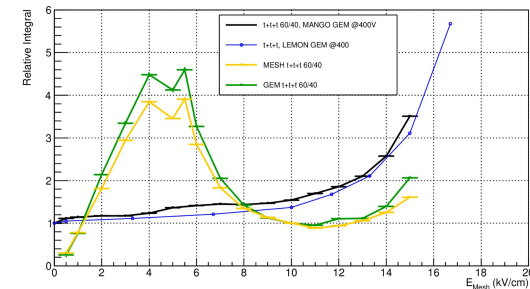
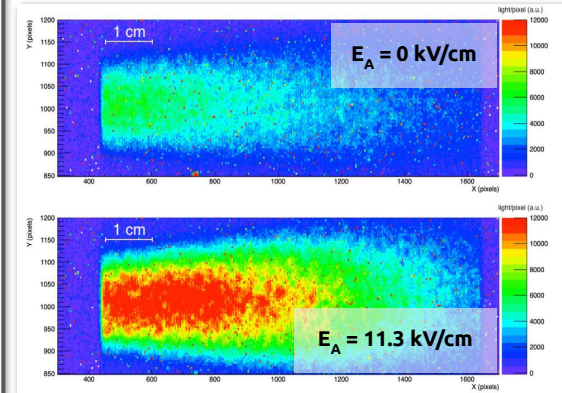
Electroluminescence region

After crossing the last GEM, in the induction gap, electrons are further **accelerated only up** to the gas **excitation threshold**

Electroluminescence

Additional light is produced

Higher SNR without worsening of ΔE .



...paper incoming soon...

Advantages:

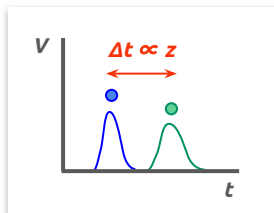
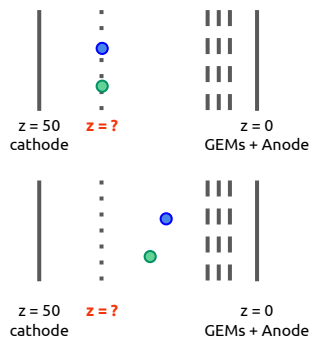
Reduced diffusion

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

Advantages:

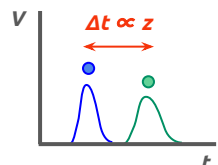
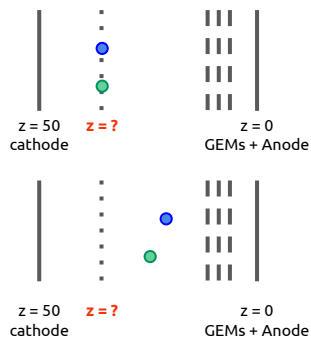
Reduced diffusion

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

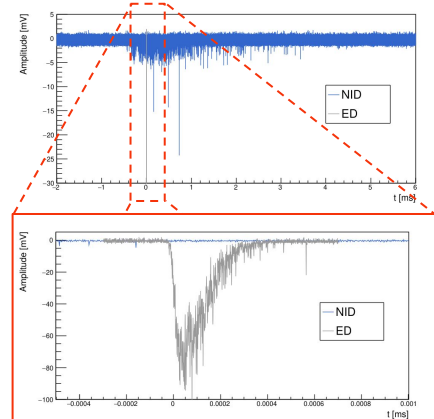
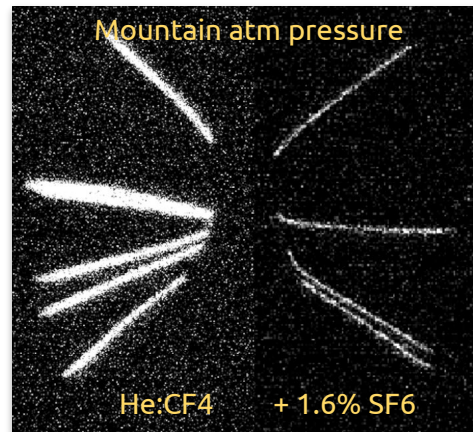
$$\sigma_D = \sqrt{\frac{4\epsilon L}{eE}}$$

Better spatial resolution!

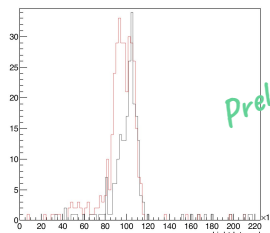
Multiple charge carriers



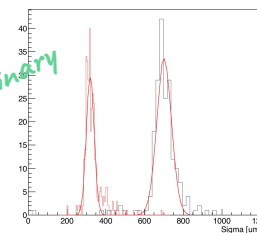
Absolute Z from Δt between minority charge carriers



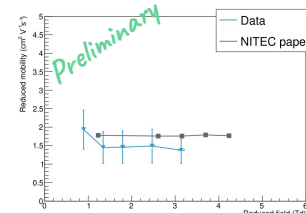
Light Integral @ 12.5 cm drift distance



Sigma @ 12.5 cm drift distance



Same light ... smaller sigma



Reduced mobility compatible with SF6-

Check out full discussion at MPGD 2022 in a few days @ <https://indi.to/VLGWx>

- 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 **nuclear recoil direction**, 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 its 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 – **stay tuned!**



..check out our white paper :)
[The CYGNO Experiment - Instruments](#)



*Thank you for
your attention!*

The CYGNO Project counts
with the collaboration of
several international
researchers coming from:



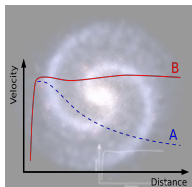
Backup

& more details

Dark Matter - What, why and where?

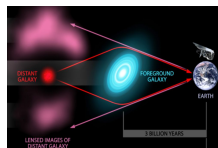
→ In the past few years, several **gravitational** anomalies have been found that **support the existence of a new type of matter.**

1. Galaxy rotation curves



$$v = \sqrt{\frac{GM}{r}}$$

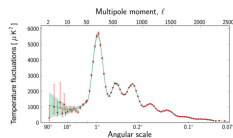
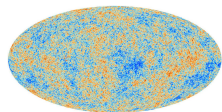
2. Gravitational lensing



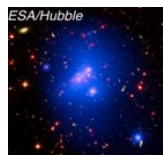
$$\Delta\Phi = \frac{4MG}{bc^2}$$

Universe's weight seems
inconsistent with observations....

3. Planck's CMB measurement



4. Motion of galaxies inside clusters



$$\langle v^2 \rangle \approx \frac{GM}{\langle r \rangle}$$

This “matter” dominates the universe and
only interacts **gravitationally...**



Commonly called **Dark Matter**

Best explanation (?)

WIMPs

($m\chi \sim \text{GeV to TeV}$)

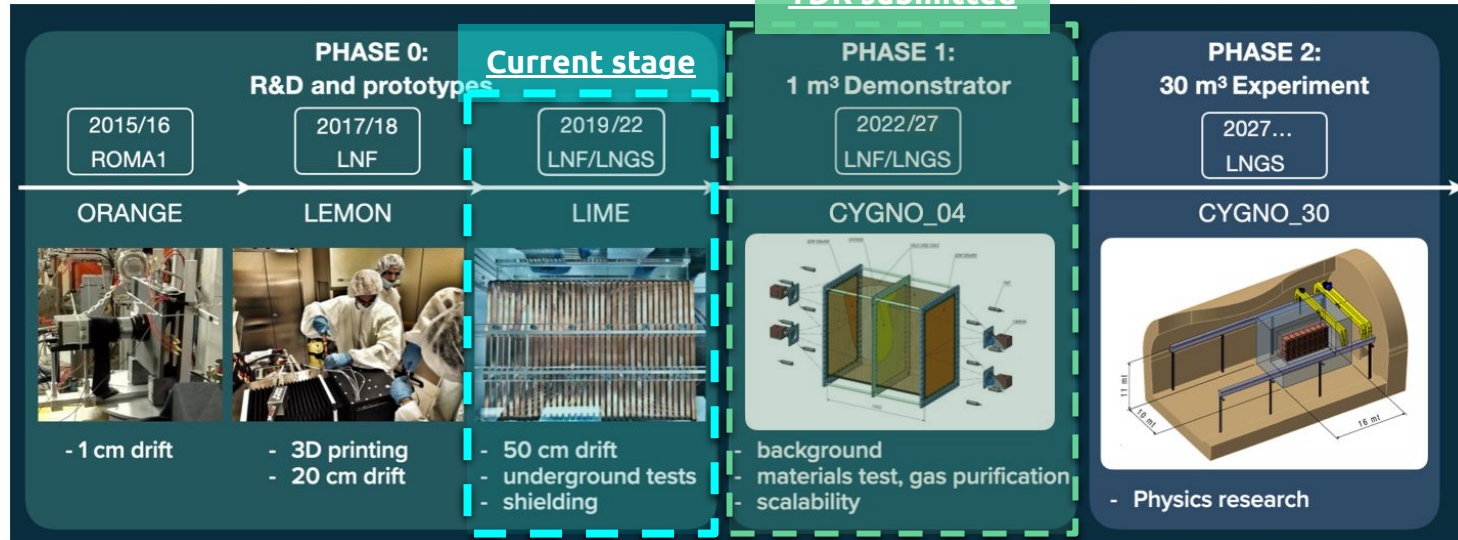
Highly justified theory independently
predicted by **extensions** of the
Standard Model at the weak-scale and
Cosmology!

CYGNO - The roadmap

Several ongoing efforts in different fronts:

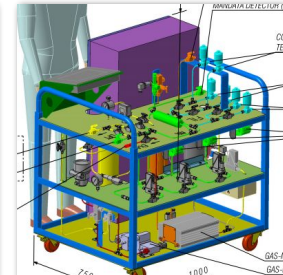
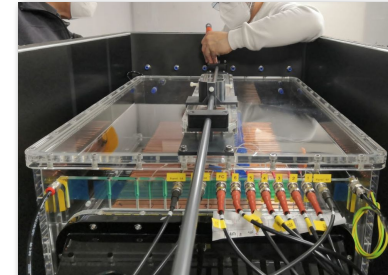
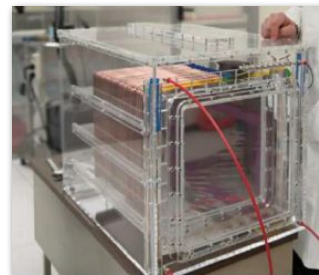
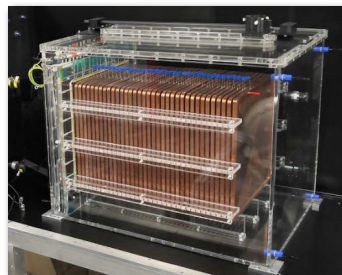
- Sensitivity
- 3D reconstruction
- Directionality
- ER vs. NR discrimination (ML)
- Shielding optimization
- Data vs. MC

Funded & TDR submitted

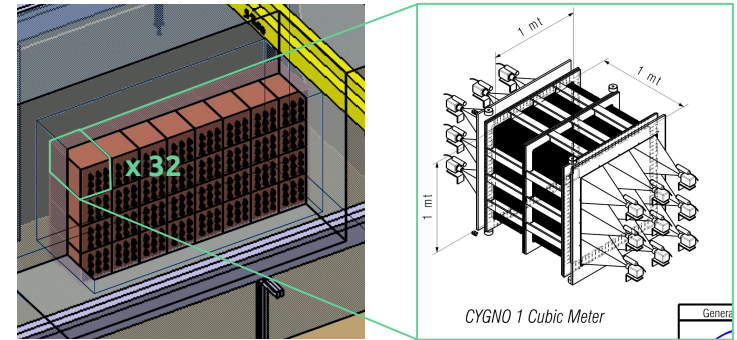


...for more info:

[CYGNO – Directional Dark Matter Search](#)
<https://www.facebook.com/cygno.experiment>



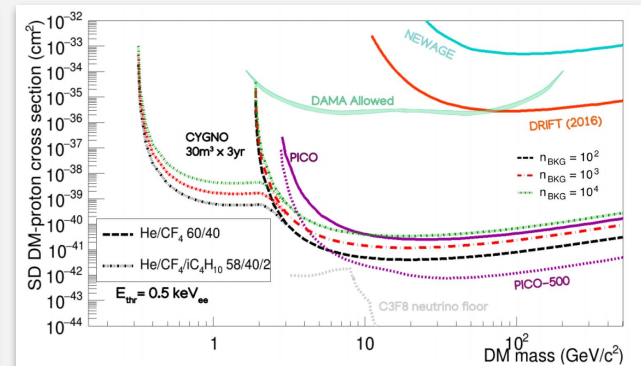
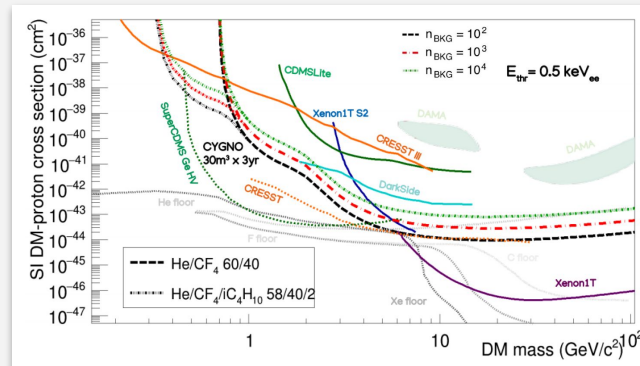
- Low mass (0.5 - 10 GeV) directional DM searches
- > 2027
- **30 - 100 m³** detector
- **0.5 - 1 keV_{ee}** energy threshold
- **30°** angular resolution



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

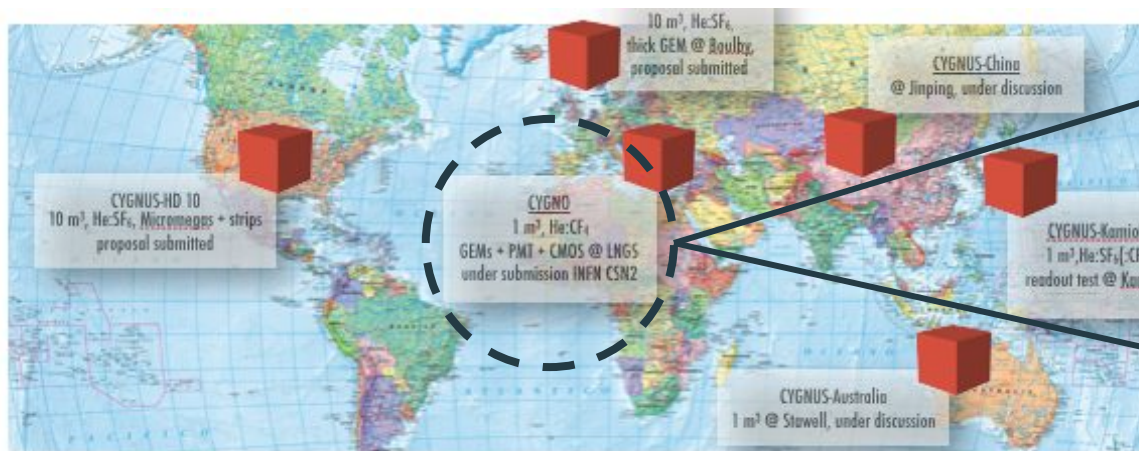
Quenching factor simulated
with **SRIM** → Direct
measurement incoming!

He / (eventually H) allows us to
explore very low DM masses!

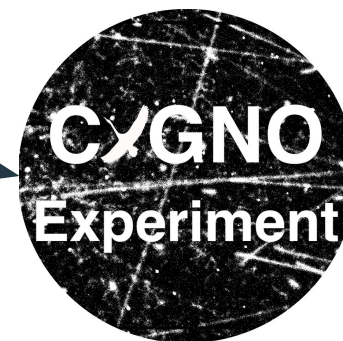
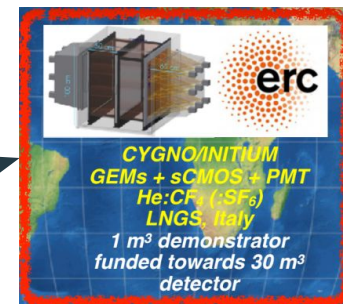


The CYGNO project

CYGNUS is part of a proto-collaboration, CYGNUS, focused on establishing a **Galactic Directional Recoil Observatory** that could test and study DM hypothesis beyond the neutrino floor.



<https://inspirehep.net/literature/1813839>



Within the CYGNUS collaboration, several approaches are being studied.
The Italian group, CYGNUS, is developing a **gaseous TPC** based on the setup:

GEMs + sCMOS + PMT to test **Optical Readout**