



Directional Dark Matter searches with CYGNO



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

F. Amaro, E. Baracchini, L. Benussi, D. S. Cardoso, C. M. B. Monteiro, S. Bianco, C. Capocchia, M. Caponero, G. Cavoto, A. Cortez, G. G. di Cortona, R. J. C. Roque, I. A. Costa, E. Dané, 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, M. Marafini, **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, J. M. F. dos Santos, G. Saviano, A. S. L. Júnior, N. Spooner, R. Tesaro, S. Tomassini, S. Torelli



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The
University
Of
Sheffield.

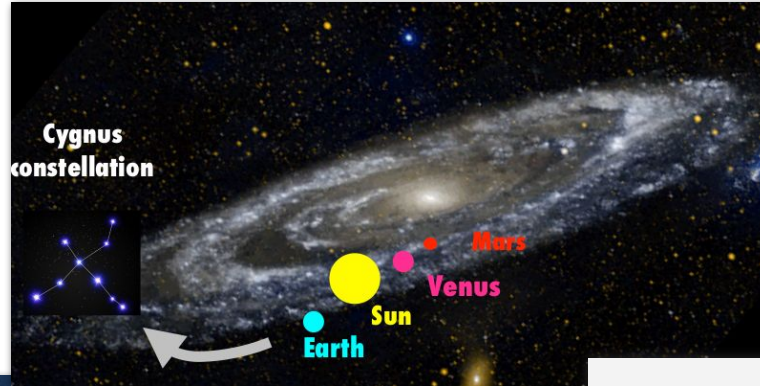
WIMPs - How to see them?

DM forms an halo within our galaxy.

+

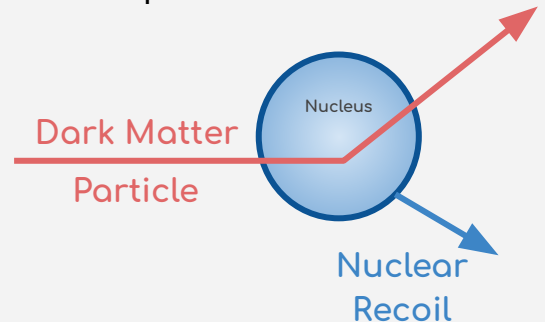
Solar system rotates around galaxy
towards Cygnus constellation

Earth susceptible to an
apparent WIMP wind from
Cygnus direction!



Direct detection

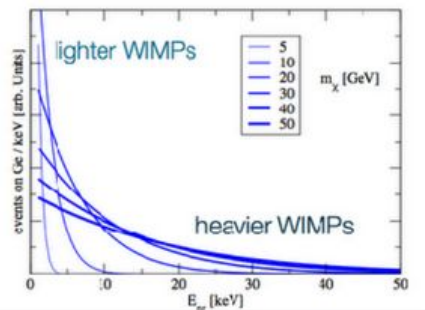
- ❖ $SM + \chi \rightarrow SM + \chi$
- ❖ SM particle's recoil



WIMPs - What dependency to explore?

Increasing reliability but increasing difficulty in the experimental technique.

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



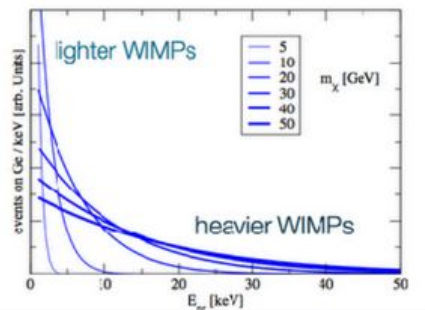
Results in a falling
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peculiar features.

The background has a
similar spectrum.

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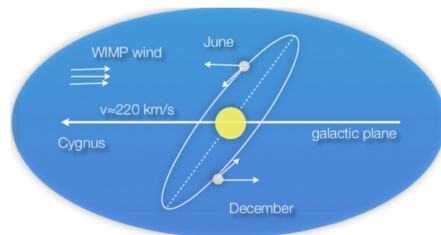
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Results in a falling exponential with no peculiar features.

The background has a similar spectrum.

2. Exploring the **TIME** dependency

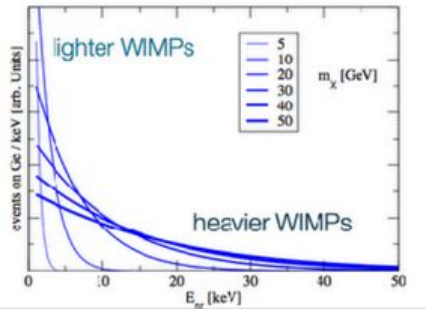


Results in a few % annual modulation.

WIMPs - What dependency to explore?

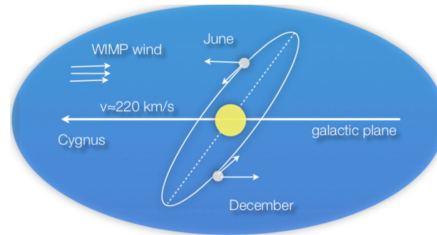
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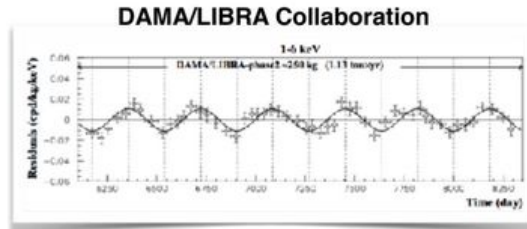


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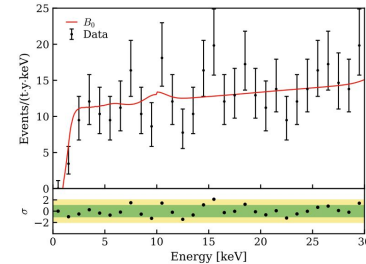
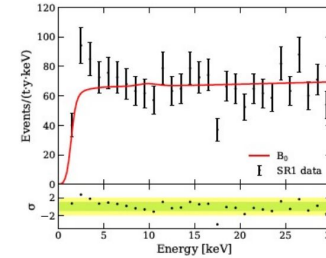
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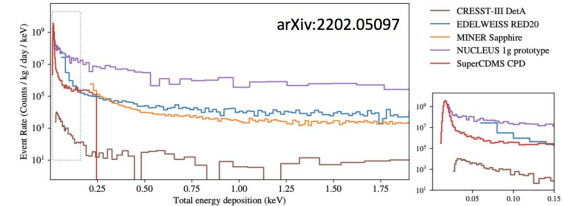
Results in a few % annual modulation.



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



Exponentially rising background towards lower energies

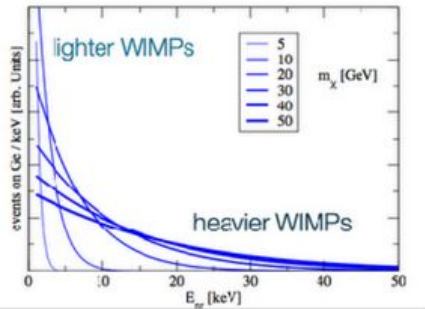


Currently limiting the sensitivity globally!
Origin still unknown, but a lot of R&D is going on ...

WIMPs - What dependency to explore?

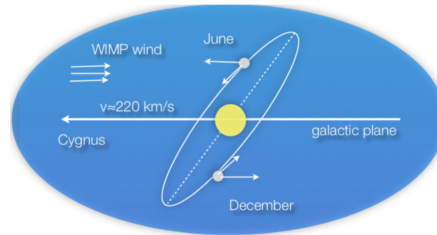
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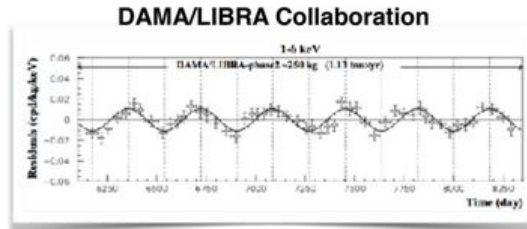


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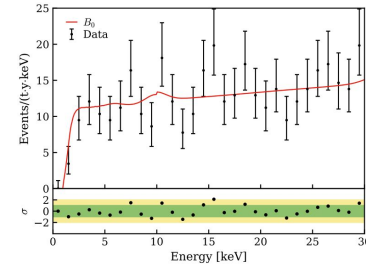
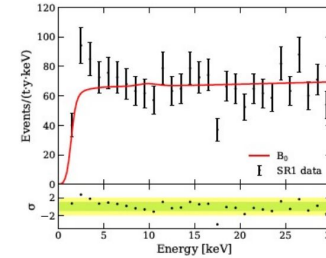
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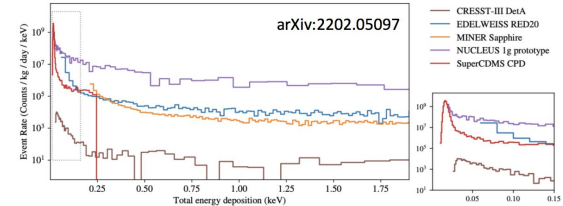
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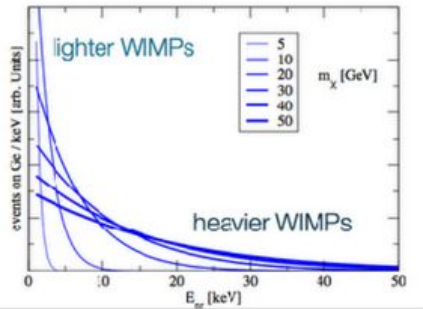
Currently limiting the sensitivity globally!
Origin still unknown, but a lot of R&D is going on ...

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

WIMPs - What dependency to explore?

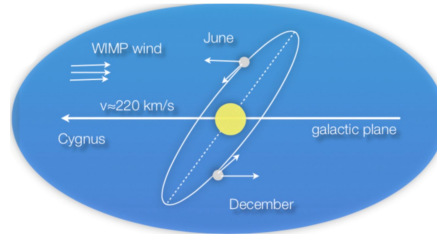
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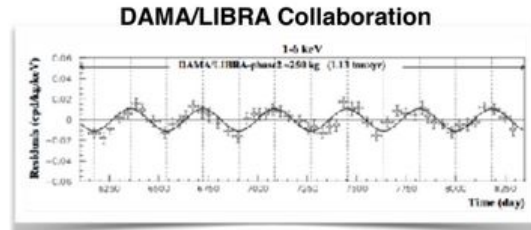


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2. Exploring the **TIME** dependency

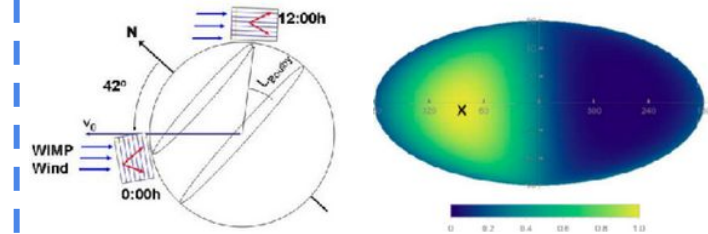


Results in a few % annual modulation.



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

3. Exploring the **DIRECTION** dependency



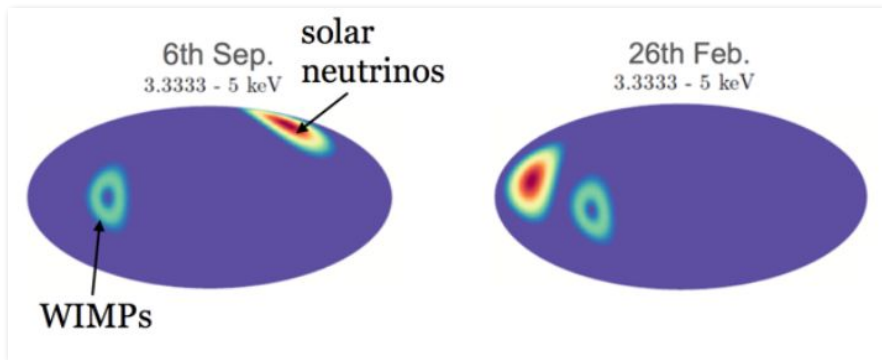
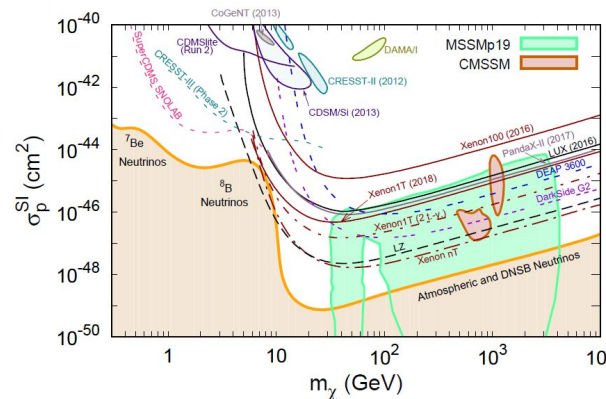
Results in characteristic effect - anisotropy in the angular distribution of **nuclear recoils** → no background can mimic.

...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!**



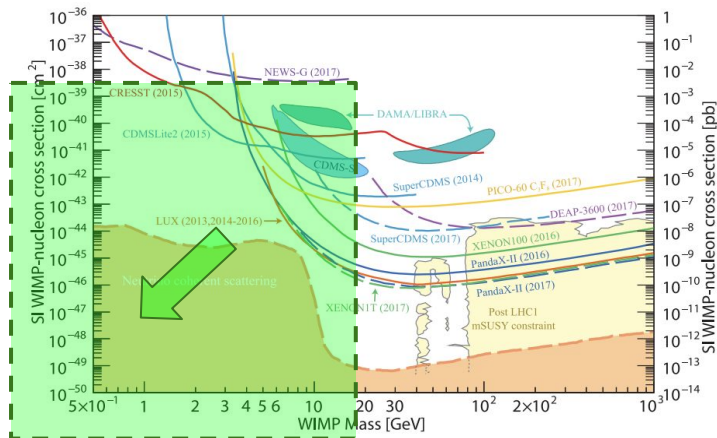
- **Directional** discrimination is the only way to **unambiguously identify a DM** signal!
- Searching **beyond** the neutrino floor
- Properties of the **solar neutrino flux**
- **DM halo properties** (DM astronomy)



The logo for the CYGNO project features the word "CYGNO" in a bold, red, sans-serif font. The letter "Y" is replaced by a black silhouette of a bird in flight, with its wings spread wide.

A CYGNus tpc module
with Optical readout

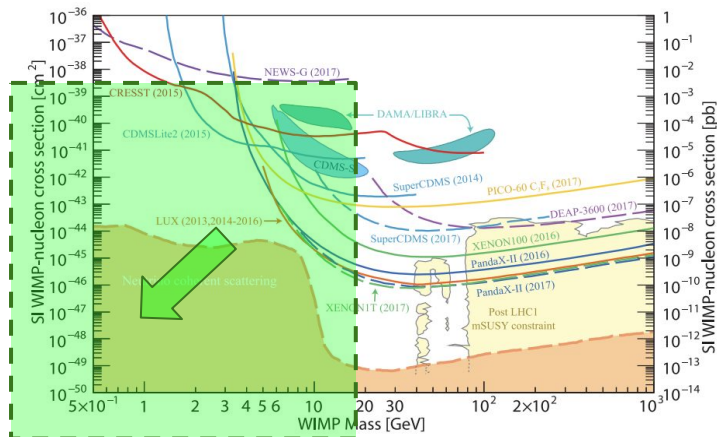
CYGNO Dark Matter exploration region



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

- To observe lower WIMP masses:
- ◆ Lower thresholds are necessary since lower $m\chi$ originate lower energy recoils.
 - ◆ Light nuclei used to maximize energy transfer.

CYGN0 Dark Matter exploration region



Low Density @ atm pressure

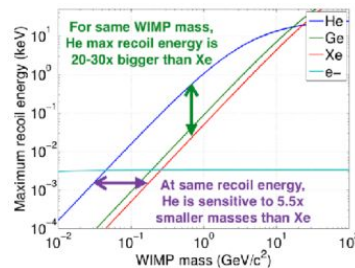
- Allows tracks of several millimeters at few keV without compromising exposure.

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

- To observe lower WIMP masses:
 - ◆ Lower thresholds are necessary since lower m_{χ} originate lower energy recoils.
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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).

CYGNO - What's the setup?

Time
Projection
Chamber



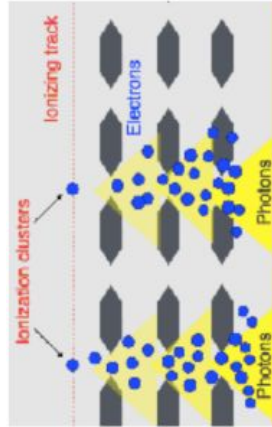
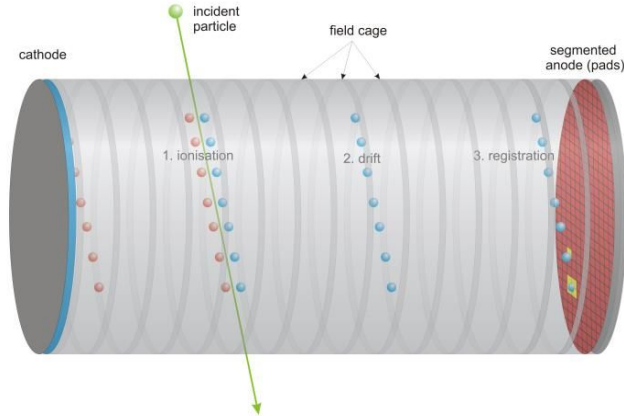
Triple GEM

Charge
amplification
& light production



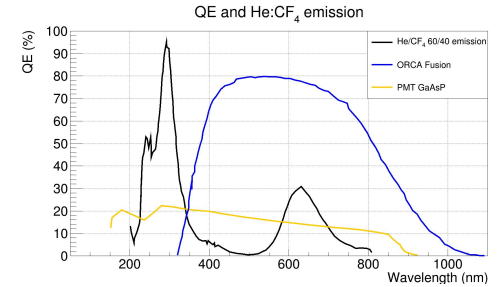
Camera & PMT

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



CYGNO - What's the setup?

Time
Projection
Chamber



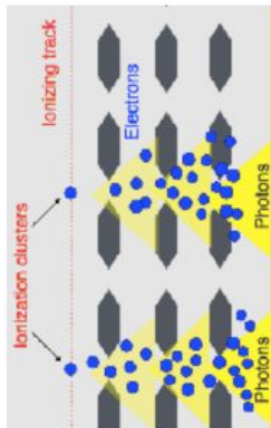
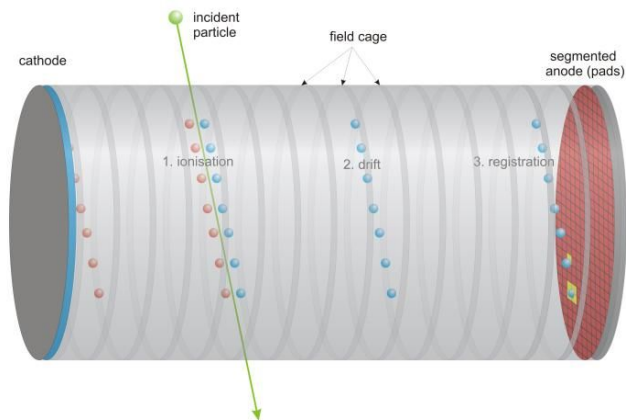
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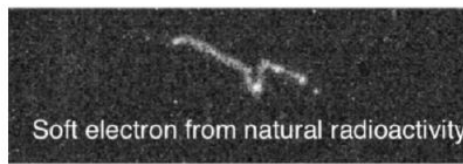
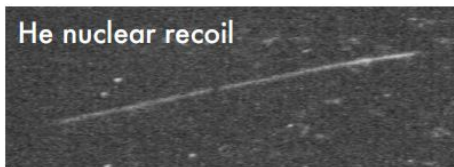


Camera & PMT

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



CYGNO - What's the setup?

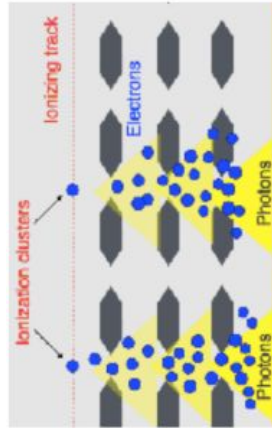
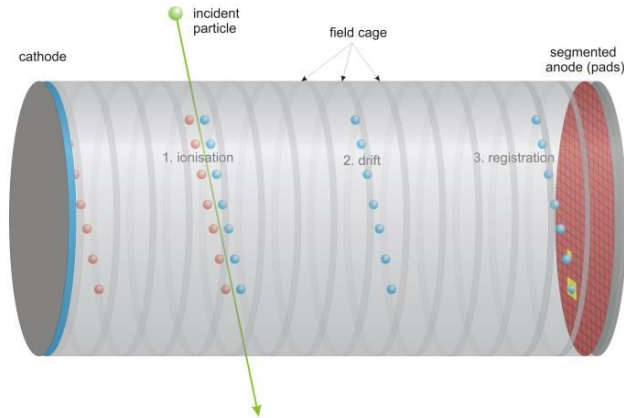
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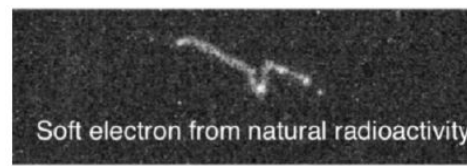
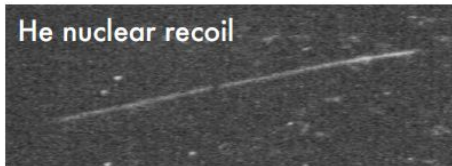
Charge
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Camera & PMT

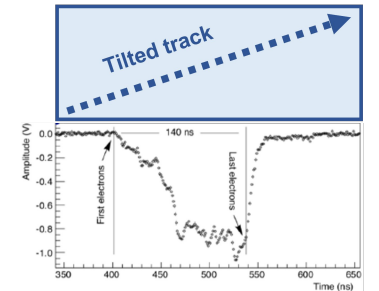
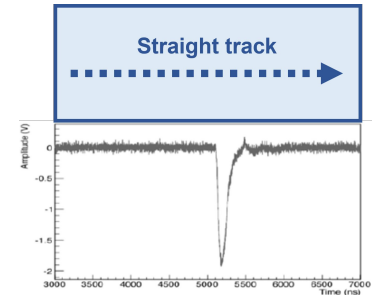
Optically read the **light produced by the de-excitation of the gas molecules** during electron multiplication.



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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

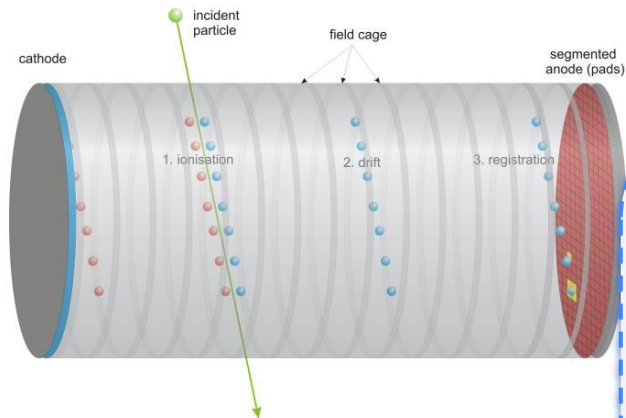
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Straight track

$$X + Y + dZ =$$

3D reconstructed track

Track's deposited energy
topology (dE/dx)

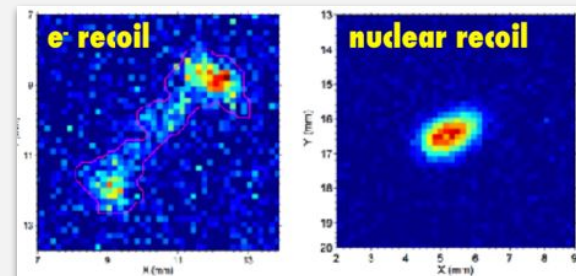
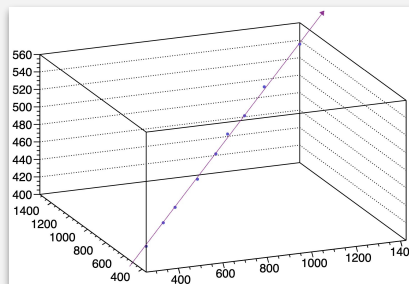
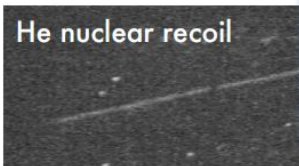
Head-tail asymmetry

Particle

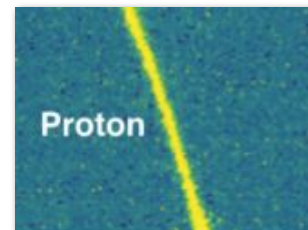
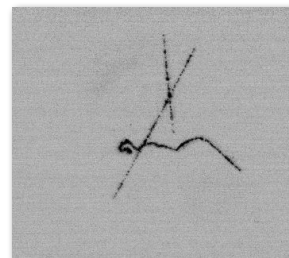
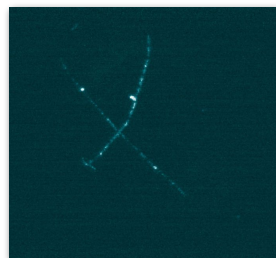
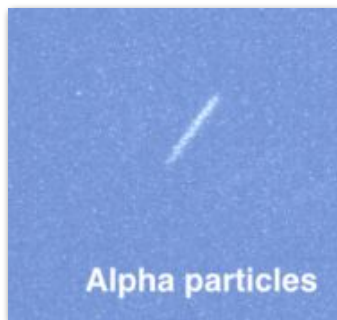
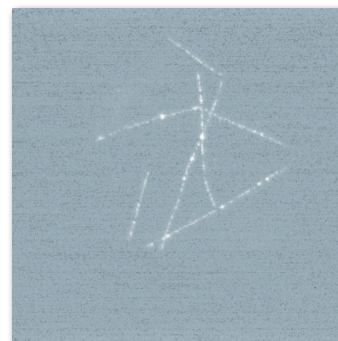
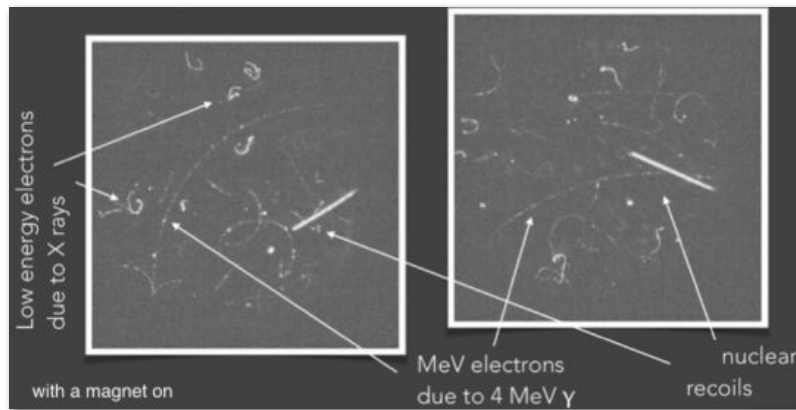
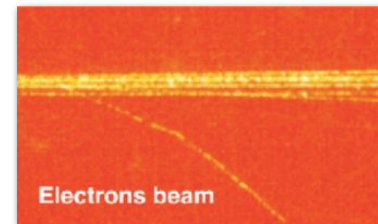
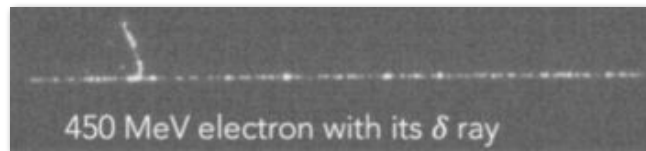
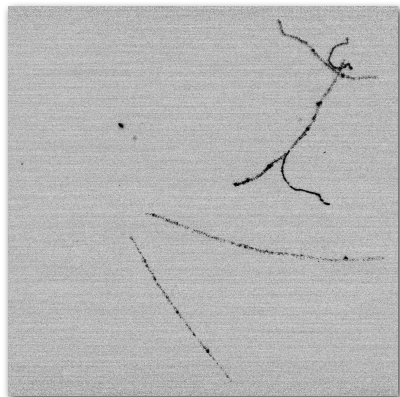
Directionality

BG rejection

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



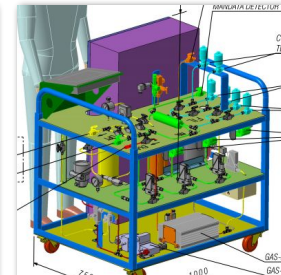
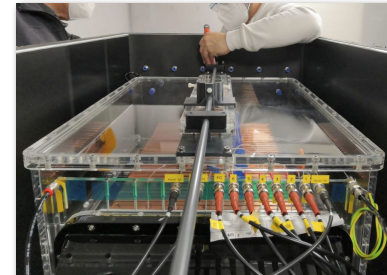
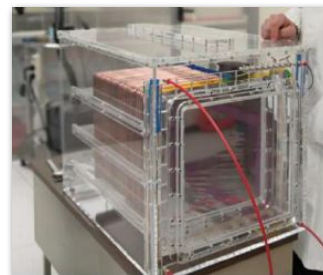
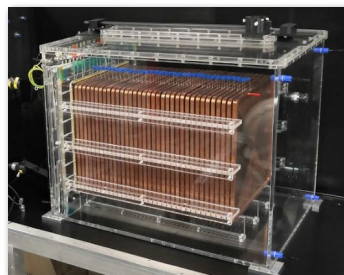
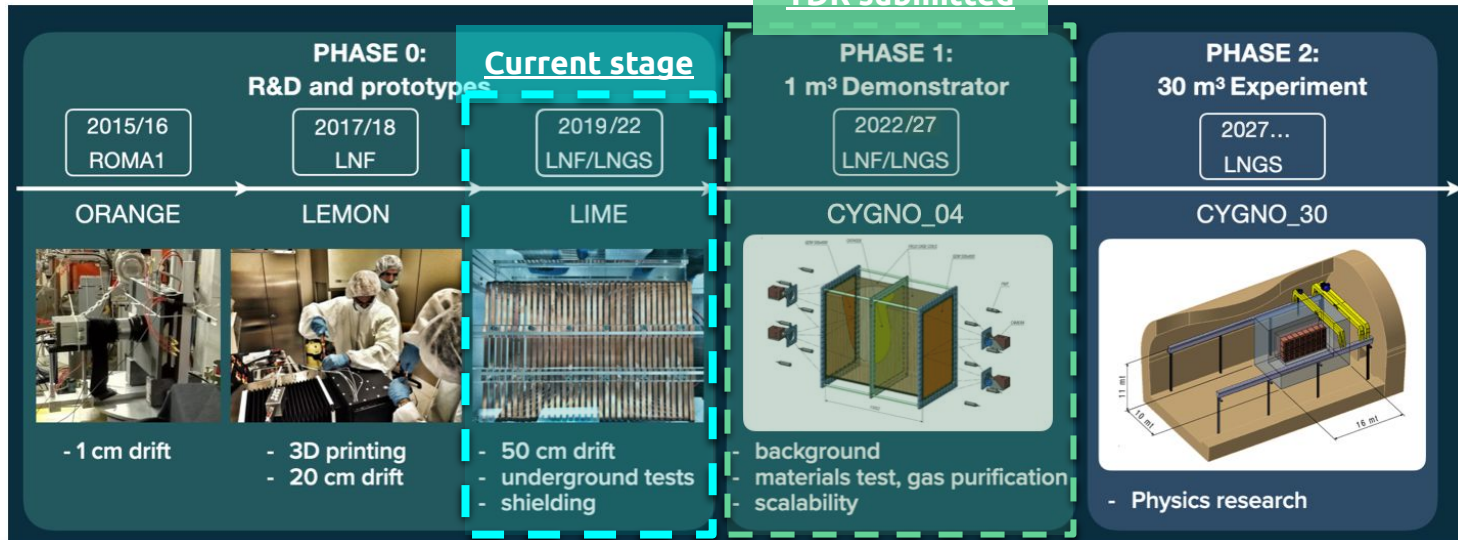
CYGNO - *Some pictures!*



CYGNO - The roadmap

Several ongoing efforts in different fronts:

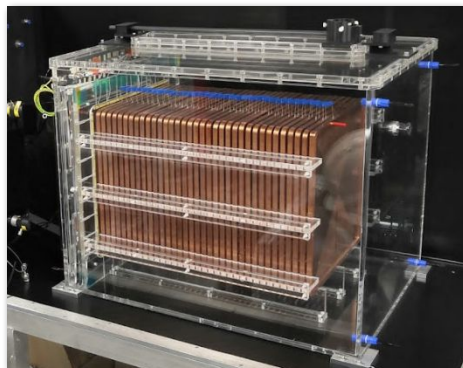
- Sensitivity
- 3D reconstruction
- Directionality
- ER vs. NR discrimination (ML)
- Shielding optimization
- Data vs. MC



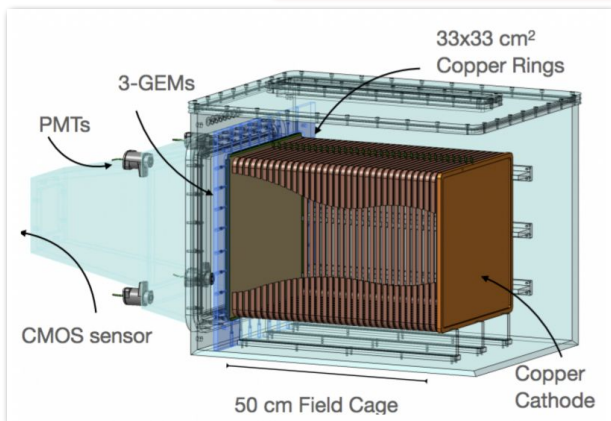
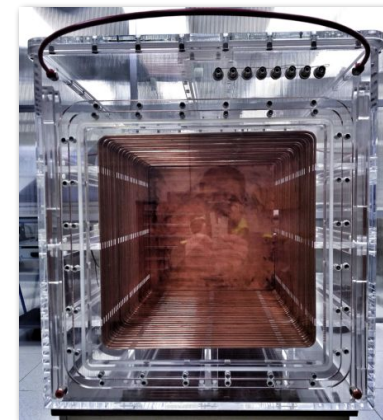
...for more info:

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





- 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

PIXEL SIZE
6.5 μm × 6.5 μm

DYNAMIC RANGE
21 400:1

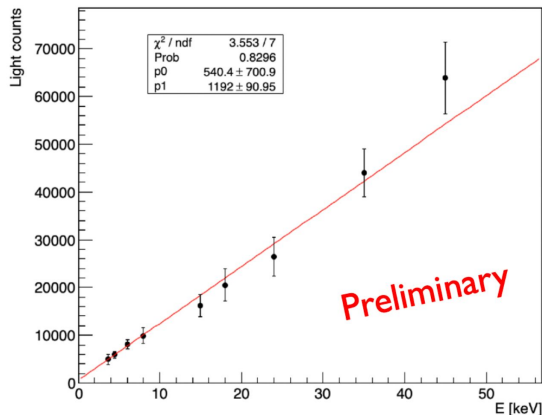
HIGH RESOLUTION
2304 × 2304
5.3 Megapixels

PEAK QE
80 %

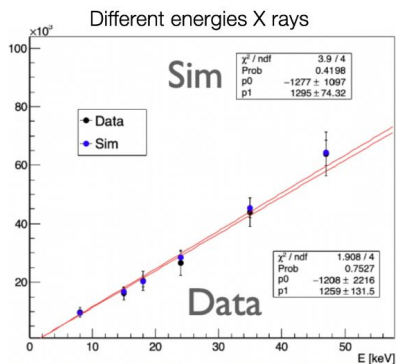


Electron recoil response

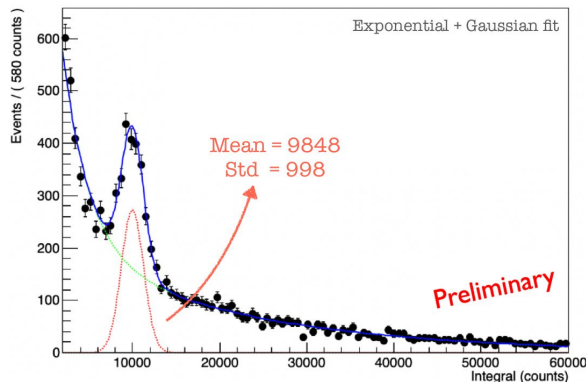
- ◆ Different energy **electron recoils** were generated*
- ◆ Detector **light response** measured



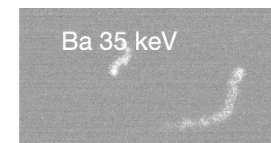
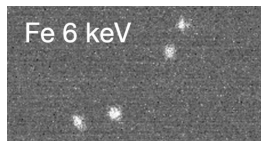
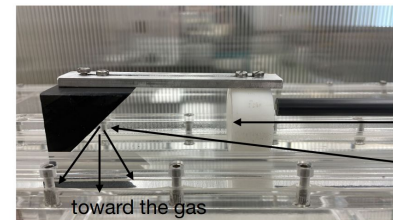
Data vs.
Monte-Carlo



Calibration example with Cu 8 keV X-ray

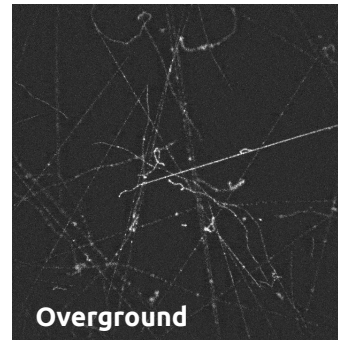
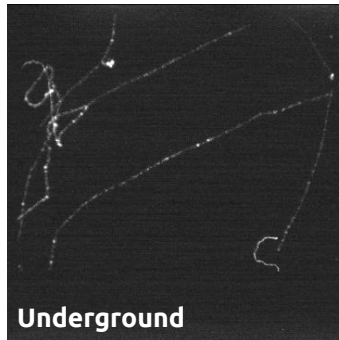
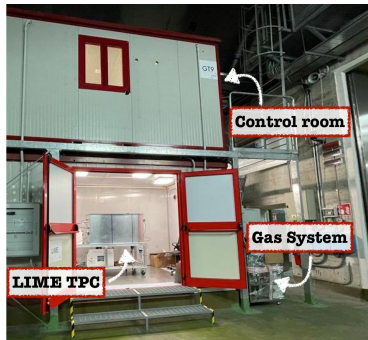


*Different materials irradiated
by a Am-Be source



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

- **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.

Background simulation

→ No shield

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

→ 10 cm Cu

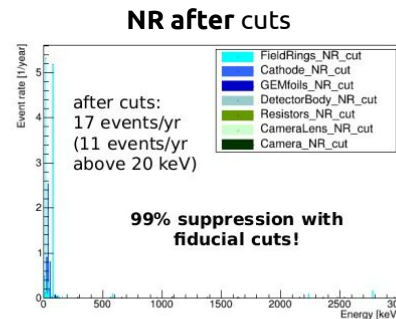
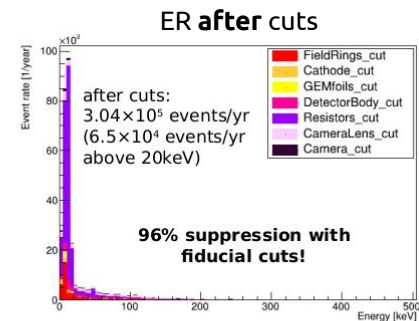
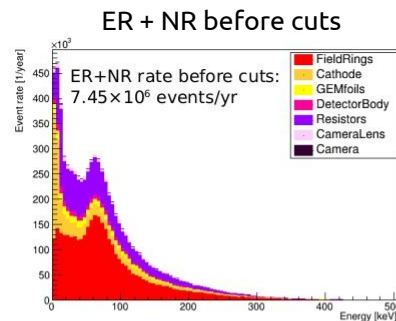
- ◆ Measurement of *underground neutron flux* (~150 events above 20 keV in 4 months).

→ 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 of ionization tracks.
- ◆ Development of *convolutional neural networks* ongoing.



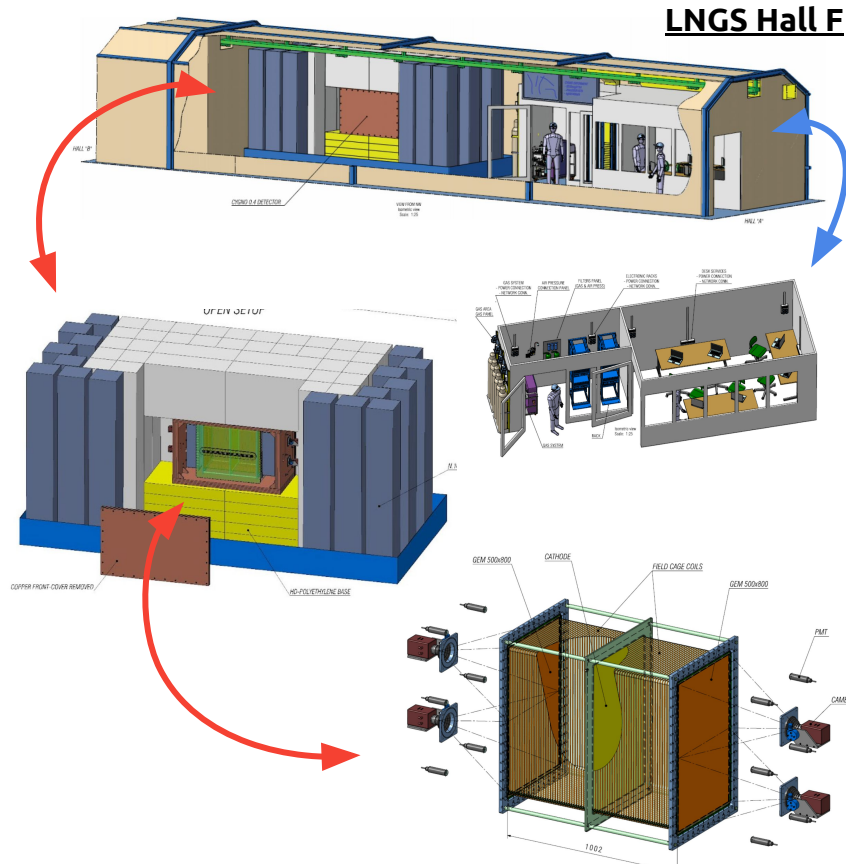
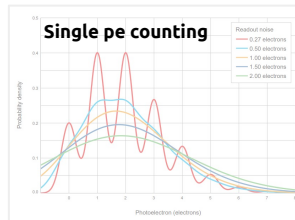
Fiducial cuts* bring a 96% suppression of total number of recoils (ER + NR)

↓

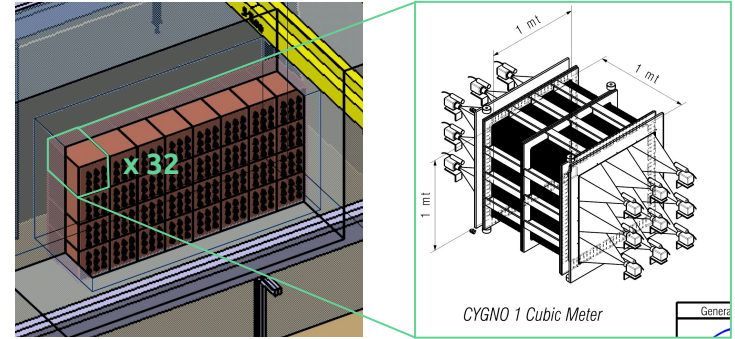
After cuts and above 20 keV, we arrive at 6.5×10^4 ER/yr and 11 NR/yr!**

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

- 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
- **Optical readout**
 - ◆ 12 PMTs
 - ◆ 4 (**vanguard**) ORCA Quest
- Low radioactivity **acrylic glass vessel**
- Field cage made by **copper strips on insulator support** (DRIFT-like)
- Projected shielding composed of **10 cm Copper + 100 cm water**
- Test scalability / feasibility on realistic scale
 - ◆ Evaluate potentialities of **CYGNO 30**
- Test all ancillary systems



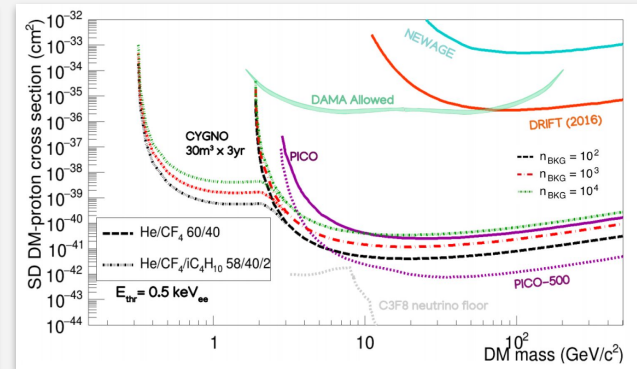
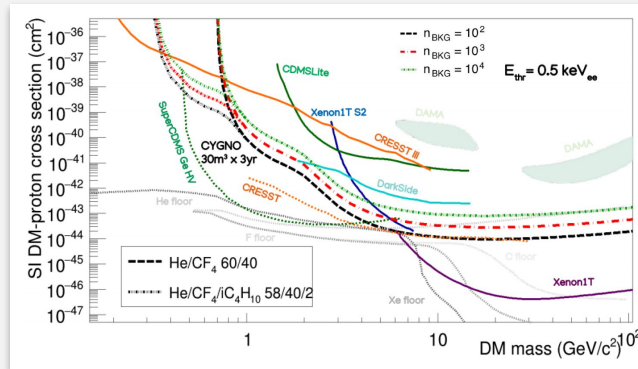
- **Low mass (0.5 - 10 GeV) directional DM searches**
- > 2027
- **30 - 100 m³** detector
- **0.5 - 1 keV_{ee}** energy threshold
- **30°** angular resolution



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!



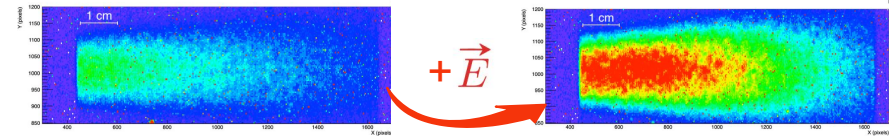
● Internal background reduction

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



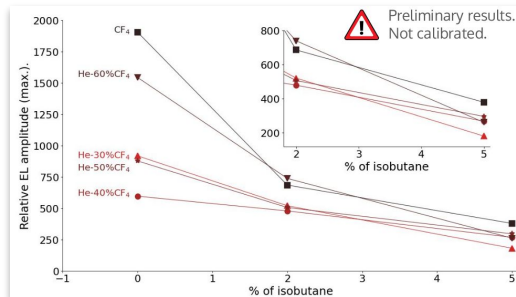
● Electroluminescence for light enhancement

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



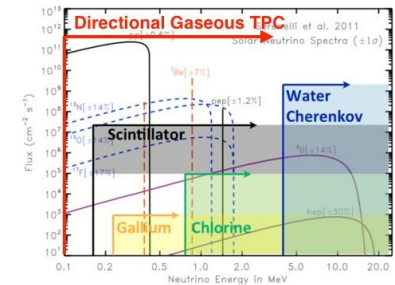
● Addition of H-based gases in the mixture

Improvement
of low Dark Matter
Mass detection
sensitivity



● Neutrino spectroscopy feasibility

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



Advantages:

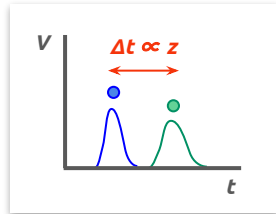
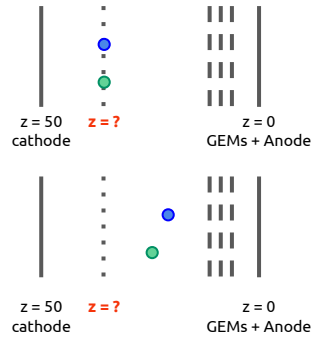
Reduced diffusion

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:

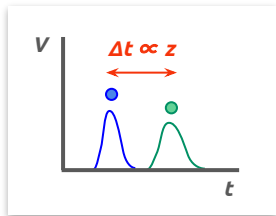
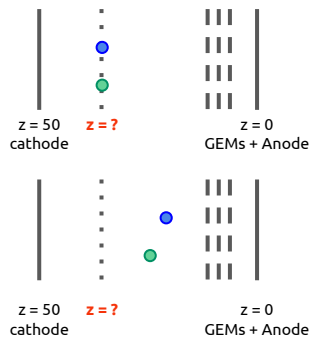
Reduced diffusion

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

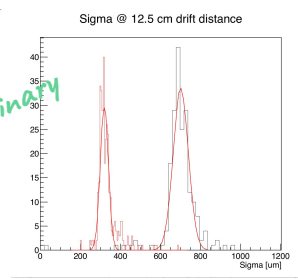
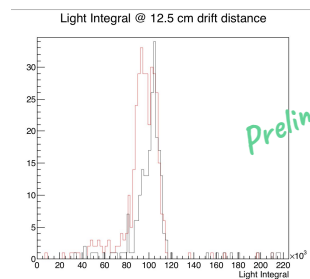
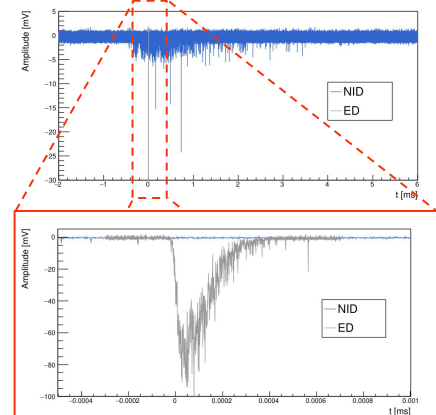
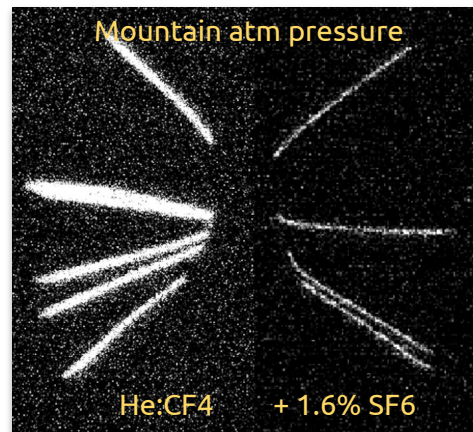
$$\sigma_D = \sqrt{\frac{4\epsilon L}{eE}}$$

Better spatial resolution!

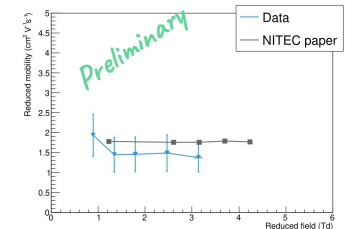
Multiple charge carriers



Absolute Z from Δt between minority charge carriers



Same light ... smaller sigma



Reduced mobility compatible with SF₆

- 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 recent paper :)
[The CYGNO Experiment - Instruments](#)



Thank you for
your attention!

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



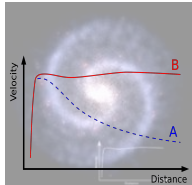
Backup

& more details

Dark Matter - What, why and where?

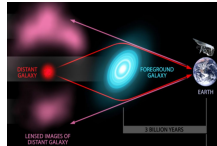
→ In the past few years, several **gravitational** anomalies have been found that **support the existence of a new type of matter.**

1. Galaxy rotation curves



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

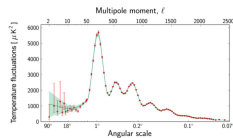
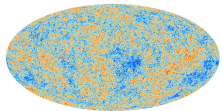
2. Gravitational lensing



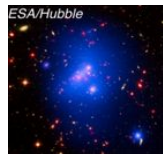
$$\Delta\Phi = \frac{4MG}{bc^2}$$

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!**

...but there are some problems...

Event rate is very low...

Considering:

- $\sigma_{\text{WN}} = 10^{-38} \text{ to } 10^{-45} \text{ cm}^2$
- $\langle v \rangle = 220 \text{ km s}^{-1}$
- $\rho_0 = 0.3 \text{ GeV cm}^{-3}$

R < 1 events / kg / year

There are a lot of backgrounds...

- **Cosmic rays**
- **Natural radioactivity**
(^{238}U , ^{232}Th , ^{222}Rn , ^{40}K)
- **Neutrinos** from the Sun, supernovae and atmosphere

...we can try to minimize these...

Go underground!

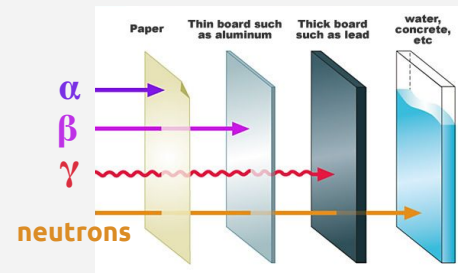
Gran Sasso d'Italia



Use radioactive PURE materials!

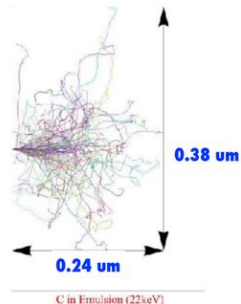


Shield the detector!

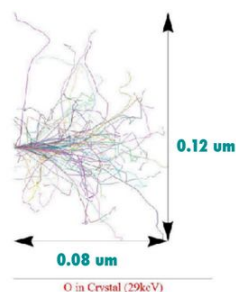


Directionality preservation

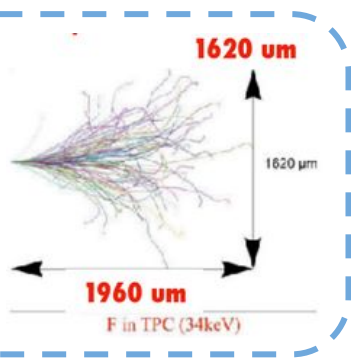
1. Emulsion layers



2. Crystal scintillators



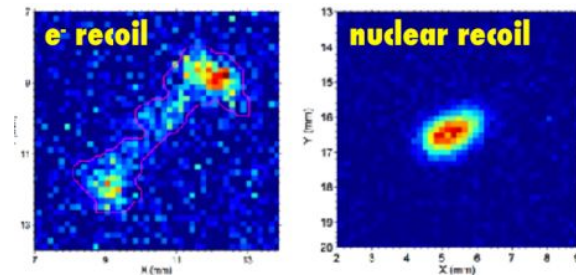
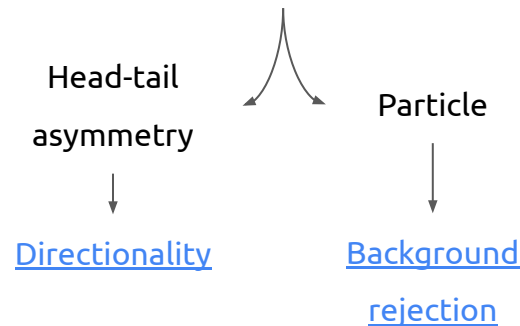
3. Low pressure/
density
TPCs



Main advantages of gaseous TPCs:

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

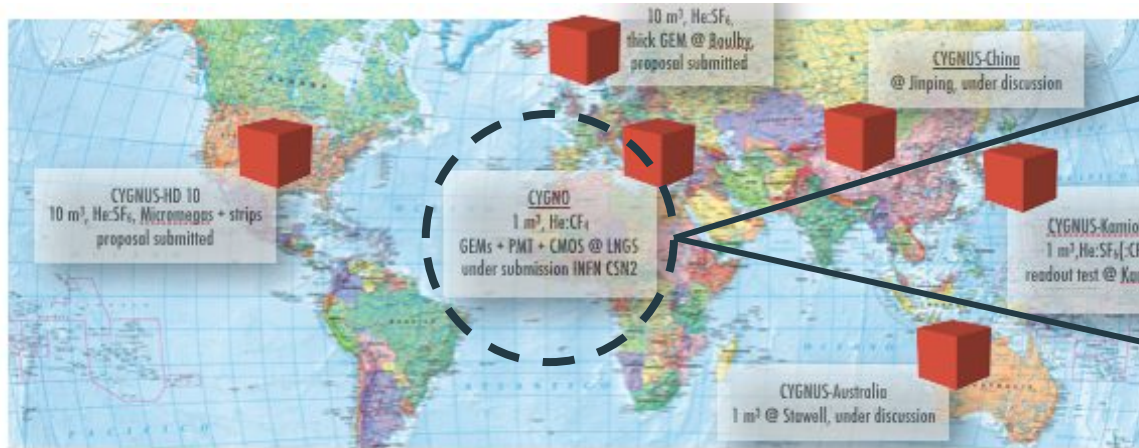
Knowledge of the track's deposited energy topology (dE/dx)



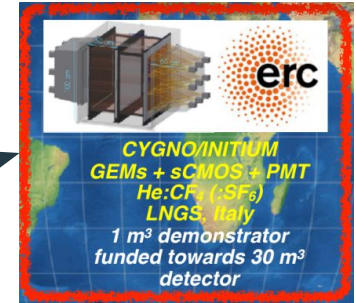
Track's direction is better preserved in TPCs!

The CYGNO project

CYGN 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>

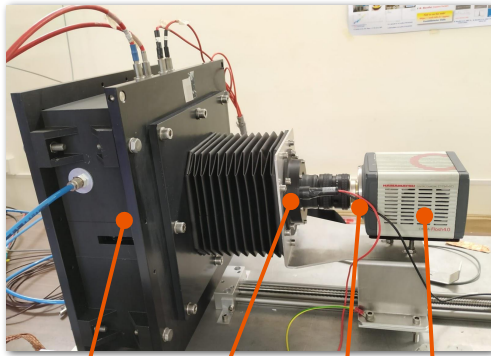


Within the CYGNUS collaboration, several approaches are being studied.
The Italian group, CYGN, is developing a **gaseous TPC** based on the setup:

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

Electroluminescence - A new feature

MANGO



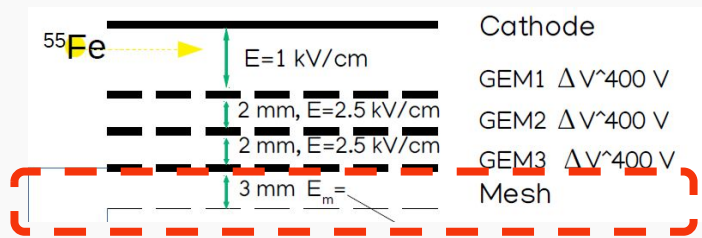
PMT

Lense:
17mm FL

sCMOS Camera
Orca Flash 4.0
Noise < 2ph/pixel

3 GEMS:
50 μm thick
140 μm pitch
70 μm diameter holes

Gas: He:CF4 60/40, 1 atm



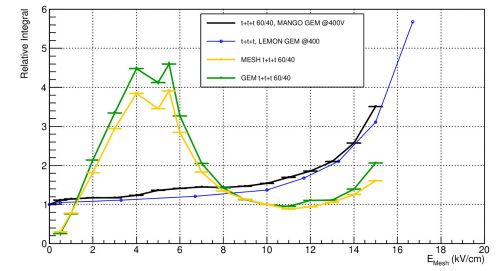
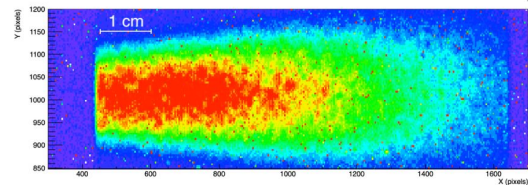
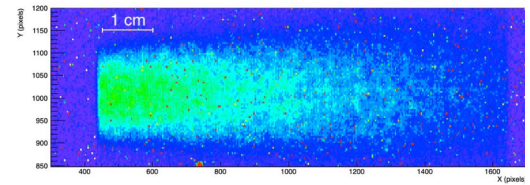
Electroluminescence region

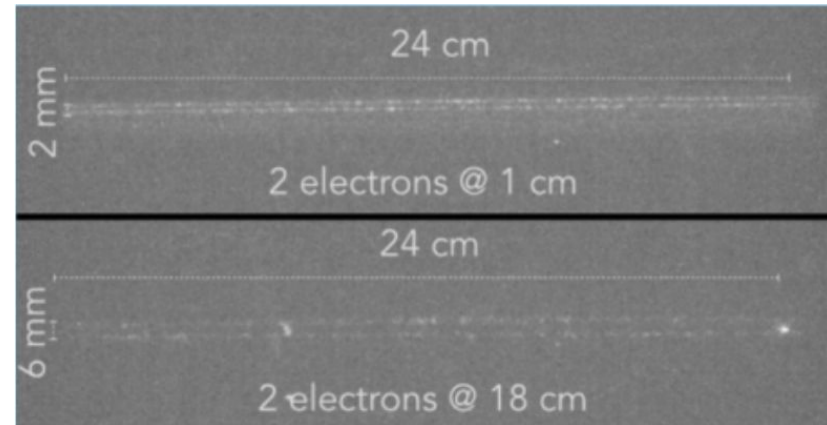
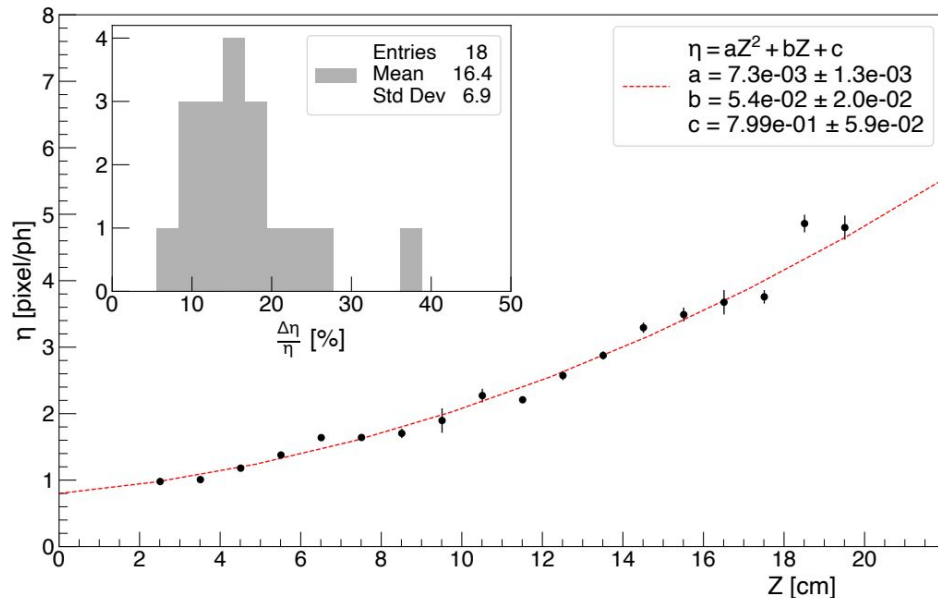
After crossing the last GEM, in the induction gap, electrons are further **accelerated only up** to the gas **excitation threshold**

Electroluminescence

Additional light is produced

Higher SNR without worsening of ΔE .

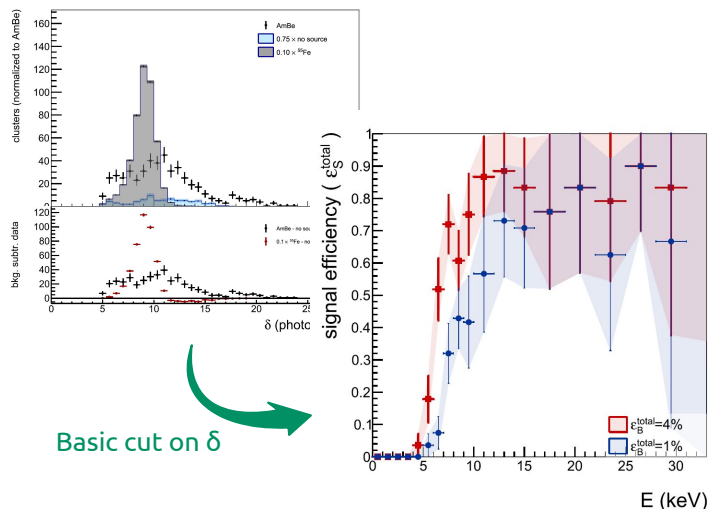




- Electron **transverse diffusion** can be exploited to infer the **track's Z coordinate**.
- **Track transverse light profile** measured to have **gaussian shape** which **enlarges linearly with Z**.
- Under study the method using **PMTs**.

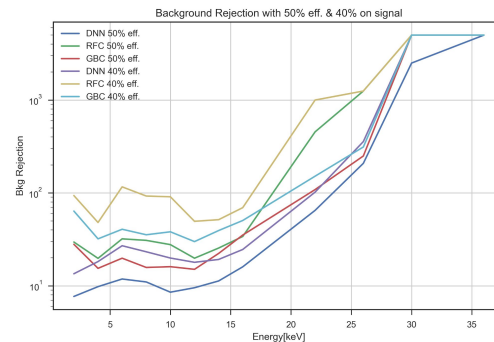
NR vs ER discrimination

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



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

- ➔ Currently testing different **deep learning models** to improve NR vs. ER
- ➔ Development of a **Convolutional Neural Network** ongoing.



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