Directional Dark Matter searches with CYGNO

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

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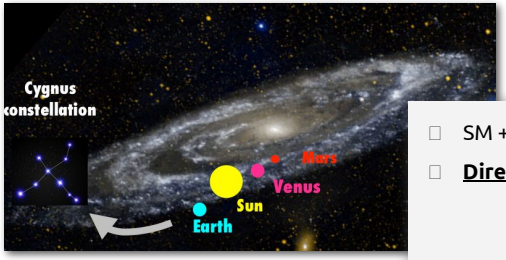
WIMPs - How to see them?

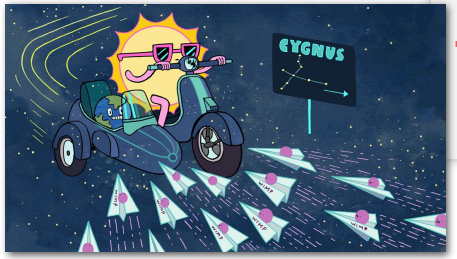
In the WIMP model, DM forms a halo within our galaxy

+

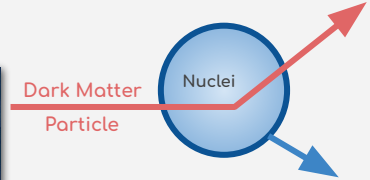
Solar system rotates around galaxy towards Cygnus constellation

Earth susceptible to an apparent WIMP wind from Cygnus direction!





- SM + **χ** → SM + **χ**
- **Direct detection** of nuclear recoil



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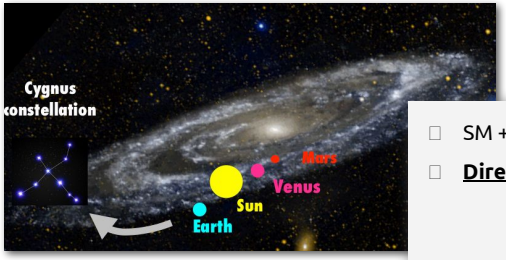

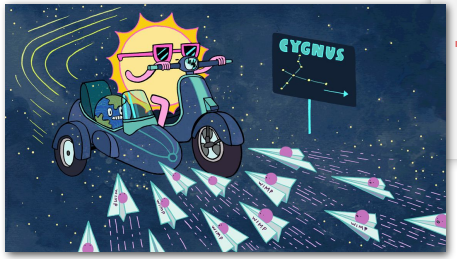

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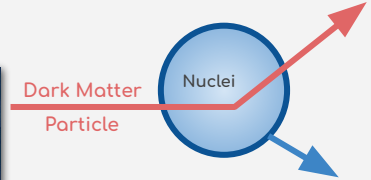
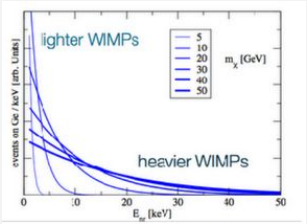
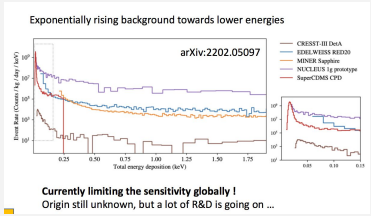


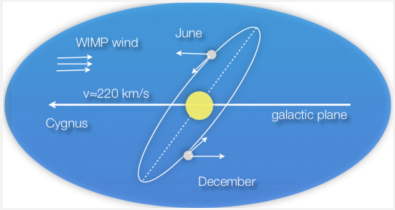
DM interacting in our detectors would create different effects:

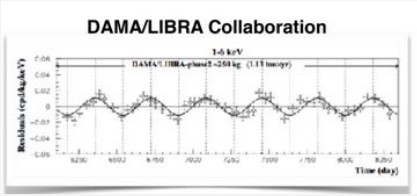
- **ENERGY ⇒** Excess would result in falling exponentials.
  - The **background** has a similar spectrum, as we've seen recently in many experiments…





- **TIME ⇒** Results in a few % annual modulation.





https://doi.org/10.1155/2014/605659

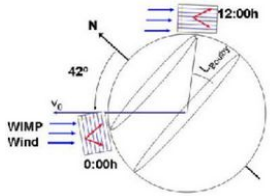
Directionality and beyond the neutrino fog

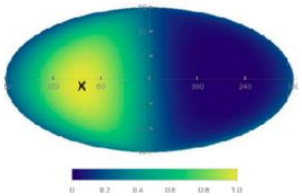
Directionality and beyond the neutrino fog

Exploring the **DIRECTION dependency** results in a characteristic effect - ***anisotropy in the angular distribution of nuclear recoils***

↓

No background can mimic





Where other experiments struggle to **find striking features to prove the existence of DM**, **directional discrimination** emerges as a unique and efficient strategy to ***positively identify*** **Dark Matter!**

Directionality and beyond the neutrino fog

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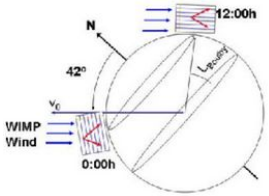

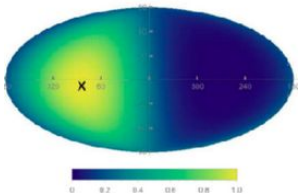

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The **CE*v*NS** produces NRs identical to the DM-induced ones.

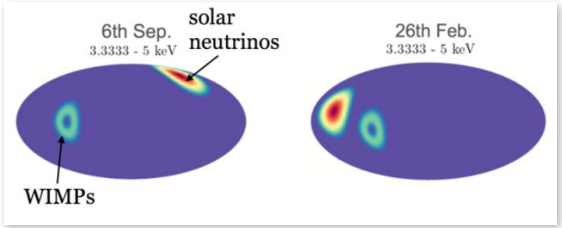
To ***search DM at smaller cross-sections***, experiments need to ***venture into the neutrino fog***

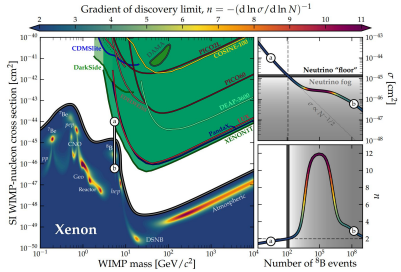
↓

Below 10 GeV/c^2 → Mostly **Solar neutrinos**

↓

In galactic coords., the *Sun and Cygnus are never superimposed!**



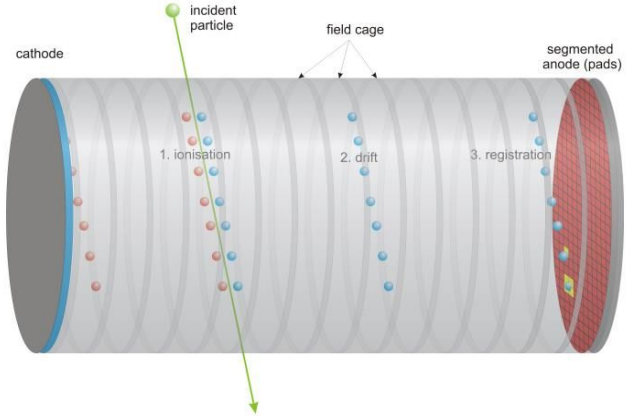


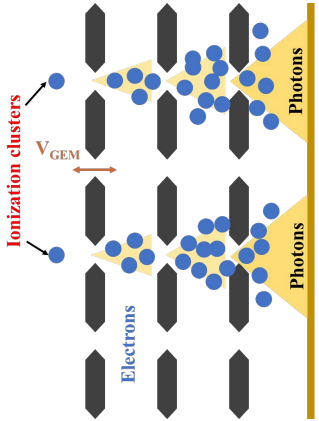
- ➔ Searching **beyond** the ***neutrino fog***
- ➔ Properties of the ***solar neutrino flux and DM halo***

A CYGNus TPC module with Optical readout

CYGNO - What's the setup?

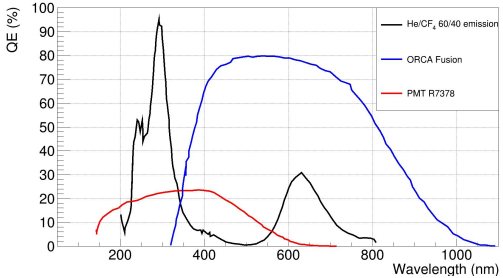
TPC → **Triple GEM**
Charge multiplication →
Camera + PMT
Light from **gas scintillation**
during electron avalanche





Carbon tetrafluoride (CF4)

➔ Significant light yield at the camera's QE peak (~600 nm)



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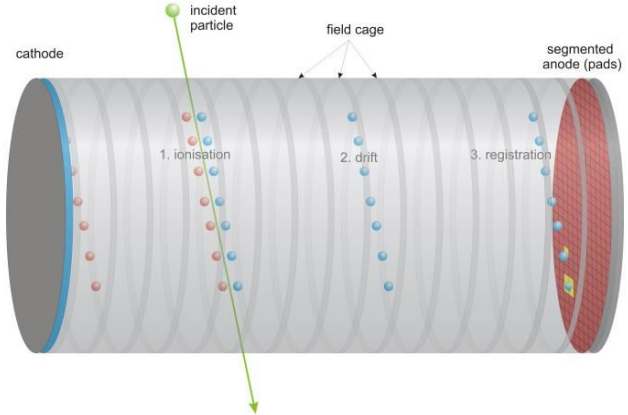
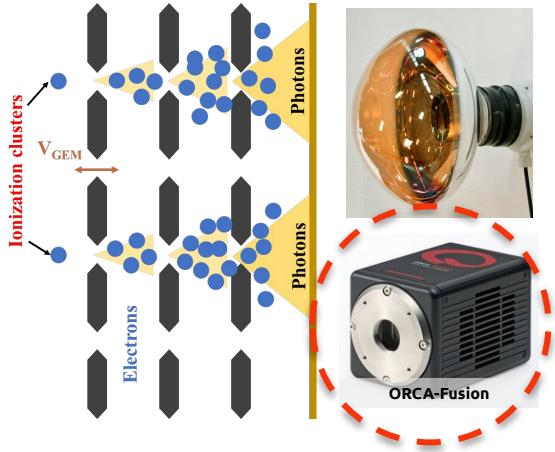
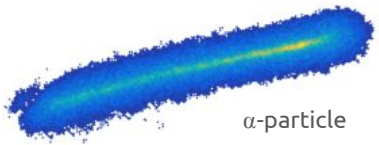




With the high granularity of the camera, we measure **energy** + **X & Y coordinates**



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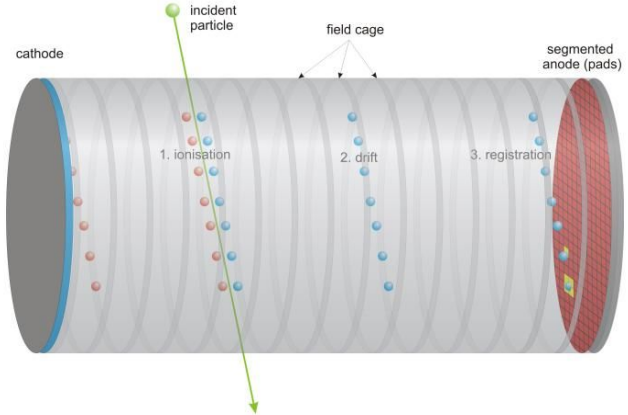
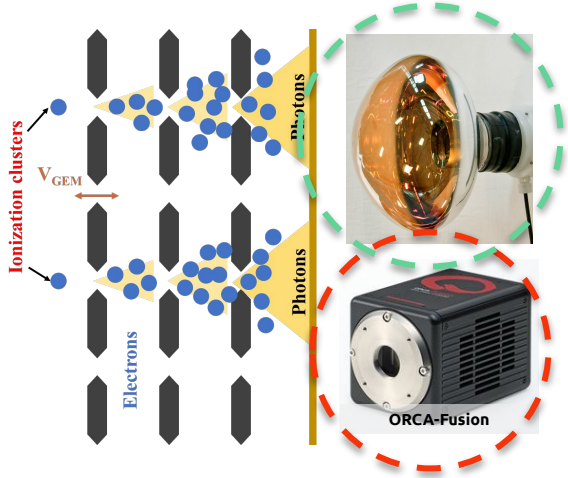
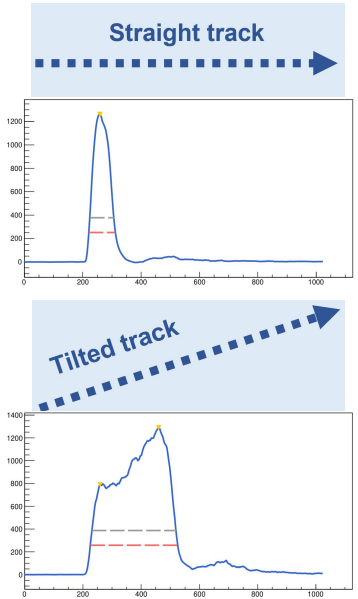




1. Independent **energy** measurement.
2. Electrons **times of arrival** ⇒ **dZ coordinate** (track's tilt)



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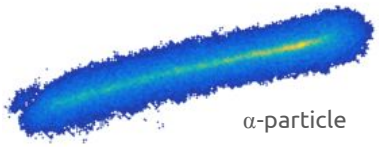
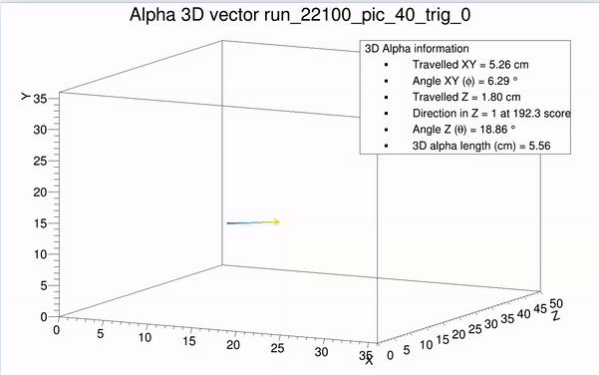


Cygno - What's the setup?

X + Y + dZ =

3D reconstructed track



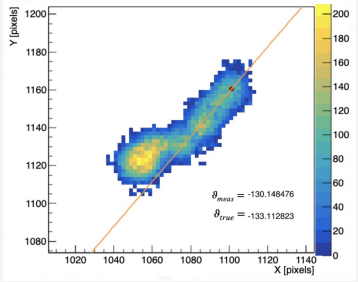
Track's deposited energy

topology (dE/dx)

Head-tail asymmetry
+ recoil direction

↓

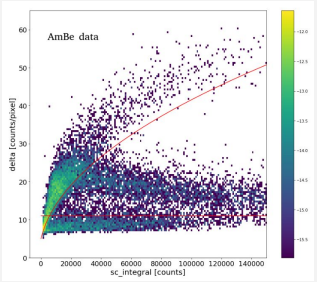
Directionality



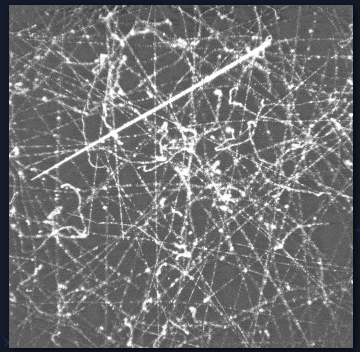
Particle

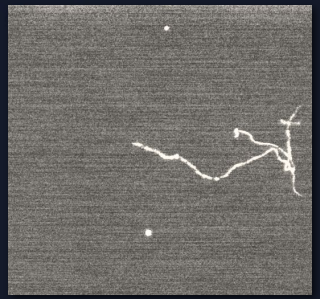
↓

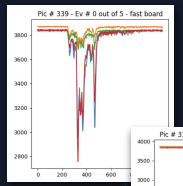
BG rejection

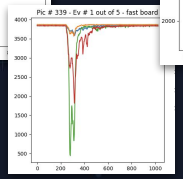


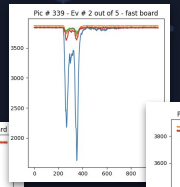
Some cool pictures

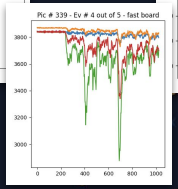


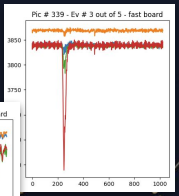


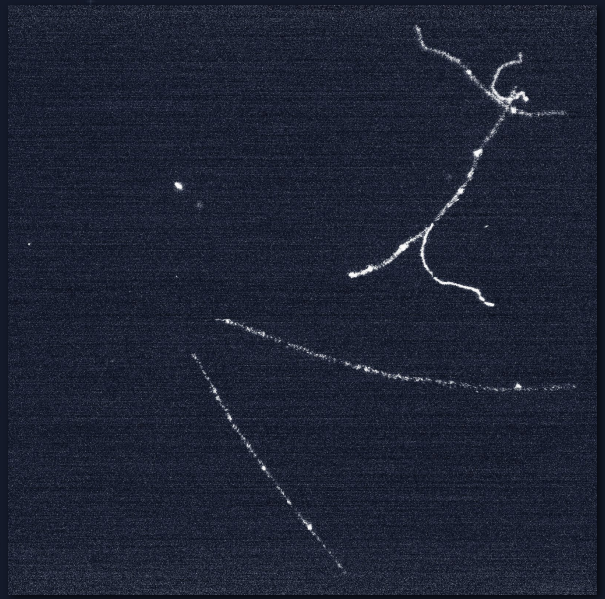


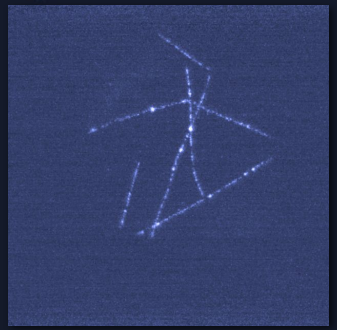


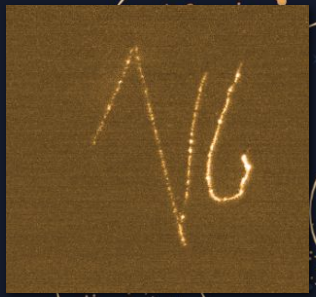


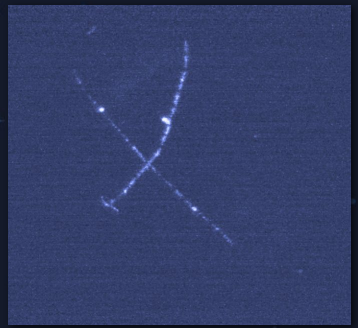


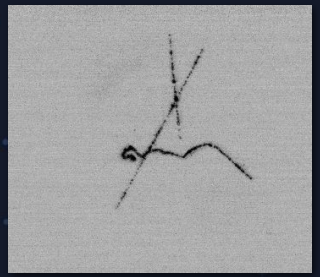


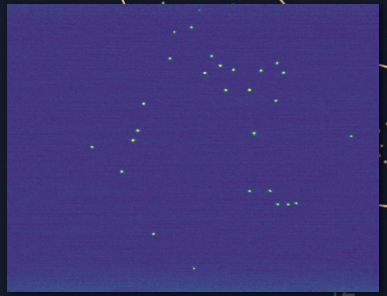






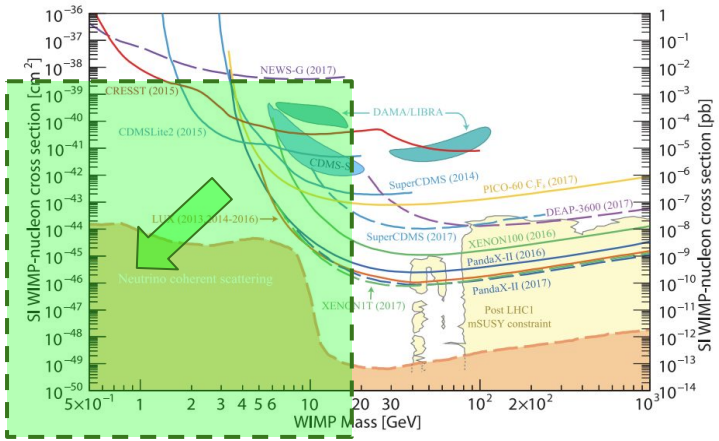






CYGNO - Dark Matter paradigm

CYGNO Dark Matter exploration region



≤ 10 GeV/c^2

➔ To observe lower WIMP masses:

- **Low thresholds** are necessary, since lower m**χ** originate lower energy recoils.
- **Light nuclei** used to maximize energy transfer.

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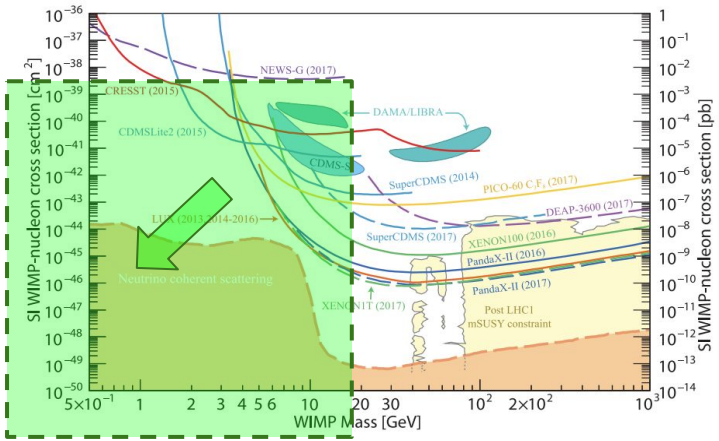

Low Density @ atm pressure

➔ Allows tracks of up to **millimetres** at **few keV** without compromising exposure.

≤ 10 GeV/c^2

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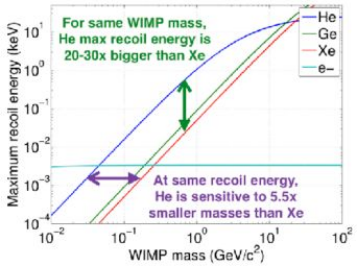
Helium (He)

➔ Light target for SI in low mass range.



Fluorine (F)

➔ Heavier target to intermediate WIMP masses.

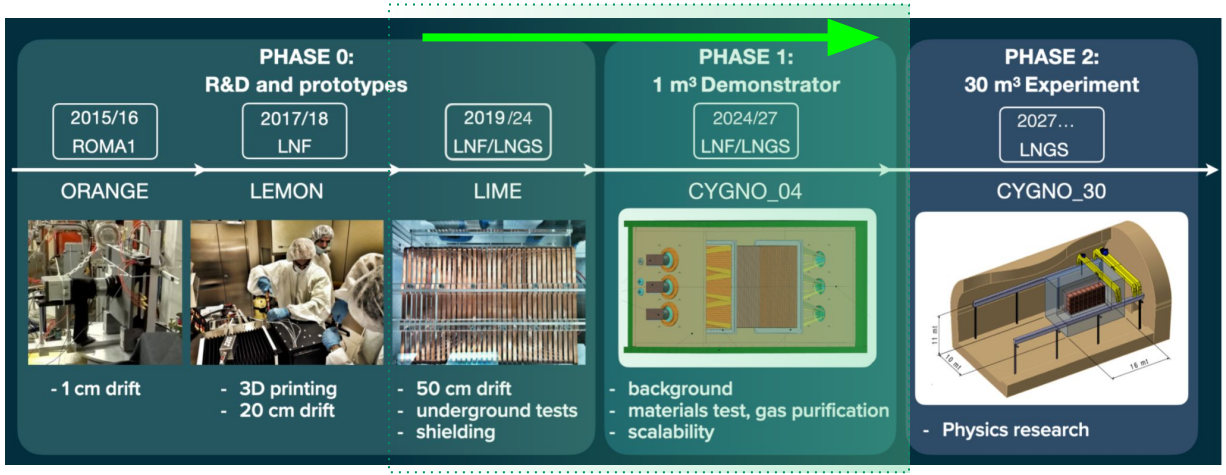
➔ One of the highest sensitivity to SD coupling.

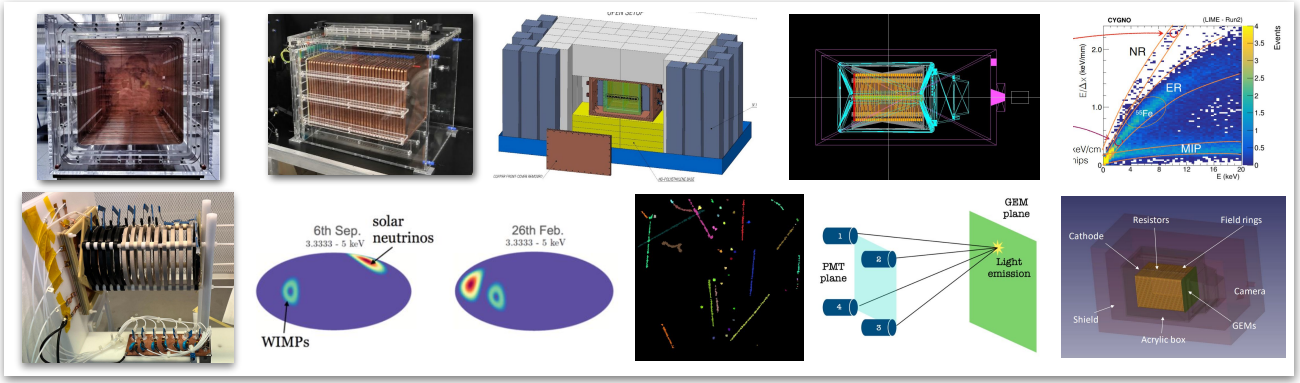
CYGNO - Roadmap

Several ongoing efforts in different fronts:

- 3D reconstruction
- Directionality
- ER vs. NR (+ML)
- Shielding optimization
- Background data vs. MC
- DM Sensitivity
- Design and Commissioning of CYGNO_04
- **Enhancement of the light yield**
- **Negative Ion drift**

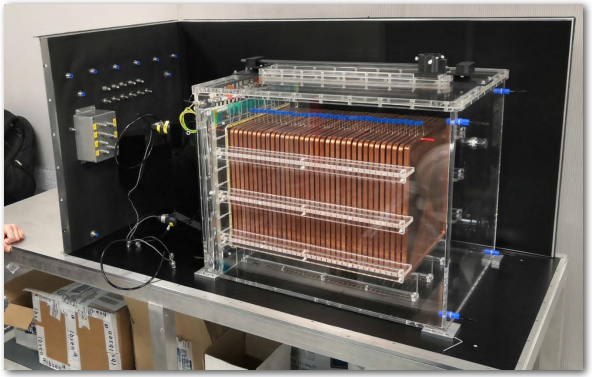
Check Giorgio Dho's poster!

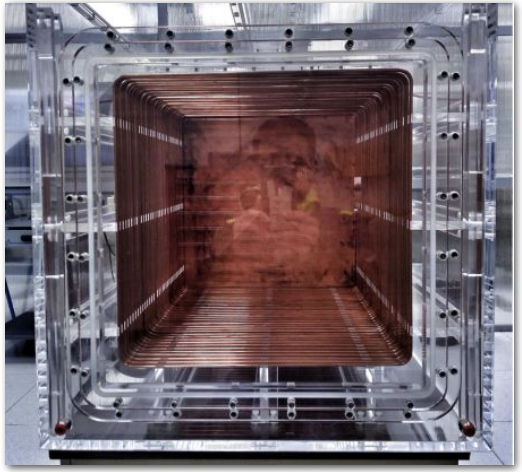




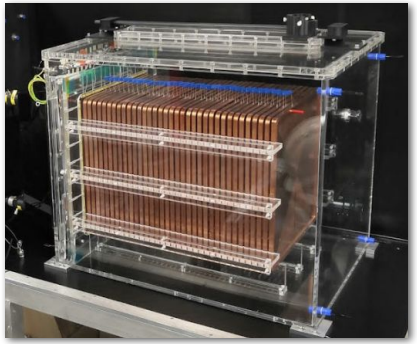
Where we are at...

LIME





LIME - The concept



- ➔ 50 L & 50 cm drift gaseous TPC with **Copper ring** field cage.
- ➔ Atm pressure (910 mbar), room temperature and He:CF4, 60:40
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- ➔ Optical readout ⇒ 4 PMTs + 1 sCMOS camera (ORCA Fusion)

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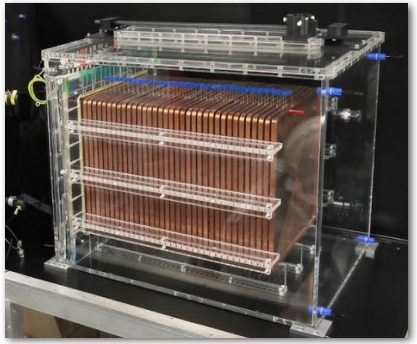

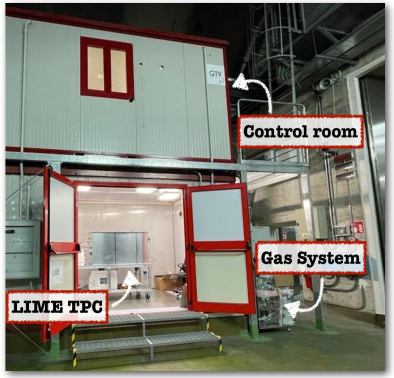

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- ★ LIME was placed underground at LNGS in the beginning of 2022.
- ★ Commissioning: tests on DAQ, remote control, slow control, gas quality,etc.
- ★ Technology test in a realistic underground environment for rare event searches
- ★ Study of shielding for validation of the CYGNO Monte Carlo
- ★ Multiple radioactive source runs : ^{55}Fe, ^{137}Ba, ^{152}Eu, ^{241}Am + $^{241}Am^{9}Be$

Live monitoring of detector performance & data quality

LIME - Data vs. MC

Phase	Shielding	GEM V [V]	# pictures	Live time [s]	Rate PMTs [Hz]
Run 1	None	420	285665	175627	30
Run 2	4 cm Cu	440	297992	191382	3.5
Run 3	10 cm Cu	440	171579	191471	1.6
Run 4	+40 cm H2O	Great external neutron suppression ⇒ *Under analysis…*			

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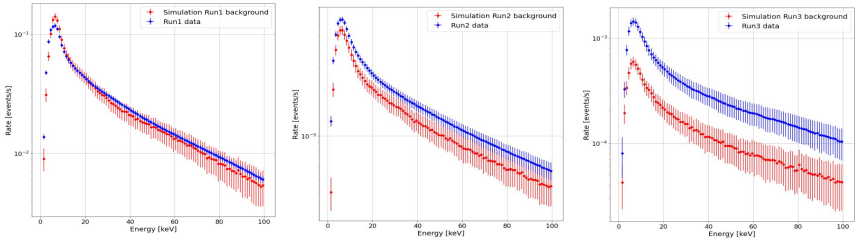

- ➔ Shielding strongly **suppressed external background**
- ➔ Difference in Runs 2 & 3 attributed to **internal background excess (contaminations of the detector – materials, gas, etc.)**
- ➔ **LIME was not meant to be radiopure**
  - ◆ Not all the components were measured
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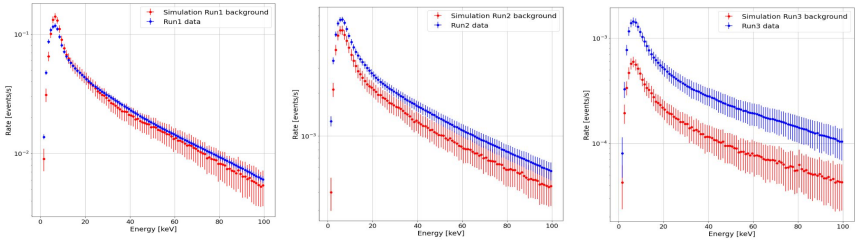

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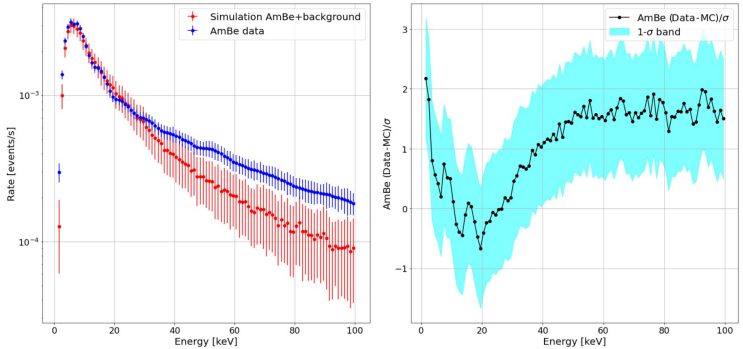
AmBe run



➔ AmBe + background simulation matches data @ E < 40 keV

- External background ✅
- Source simulation ✅
- Internal background - Shape ✅
- Internal background - Absolute 👷⚒️

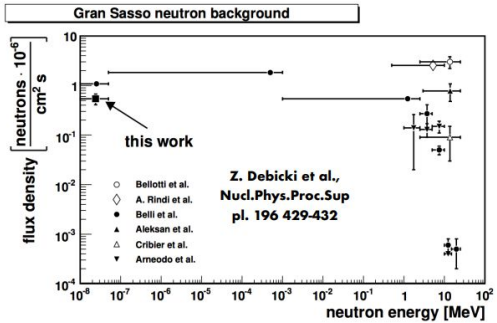
LIME - Run 5 objectives

- In run 5 we want to:
  - Take data in a less saturated configuration

LIME - Run 5 objectives

➔ In run 5 we want to:

- Take data in a less saturated configuration
- **Longer data taking ~ Perform underground LNGS neutron flux measurement**.
  - ~ 250 neutrons in 6 months.
  - Improve current knowledge, especially at low energy (< 1MeV)
  - **Allow us to study in depth:** 3D, directionality, energy resolution on NRs and study our ability to select NR signals.



Current knowledge of underground LNGS neutron flux

10^4 rejection @ 20 keV

Close to 10^5 rejection @ 25 keV (from simulated data)

From BG considerations, **BG-free dataset seems achievable at >20 keV**

⇒ Constitutes a landmark for CYGNO for the study of WIMP-like events

LIME - 3D reconstruction

➔ Merging **camera** with **PMTs** information allows us to get a **full description** of the ionization event.

- With this, we will be able to improve our particle ID, reject backgrounds from known sources, and fully characterize the 3D direction of the incoming particles: □□ *Directionality* □□

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★ **Alpha selection:** cluster density, waveform skewness, etc. + **ER rejection** + **association** between trigger and cluster

1. **Camera analyser class** retrieves **X-Y Angle** and the **ΔXY**
2. **Time over threshold** determines **ΔZ** ⇒ Together with camera X-Y angle ⇒ **Z-angle**
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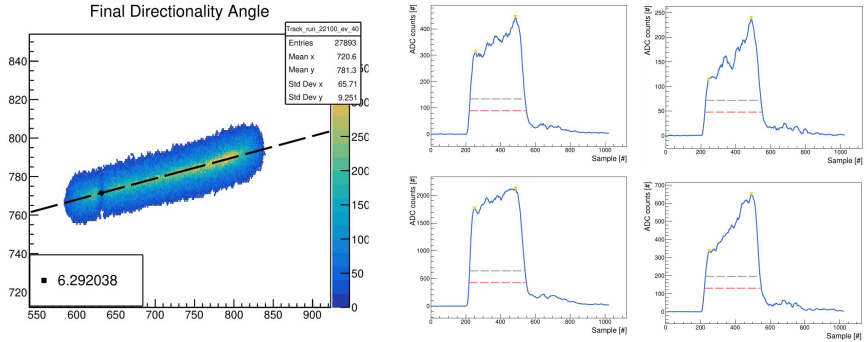

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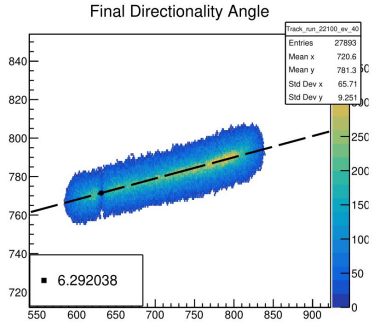
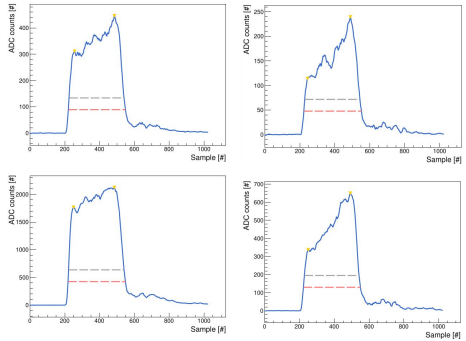
Reconstructed info:

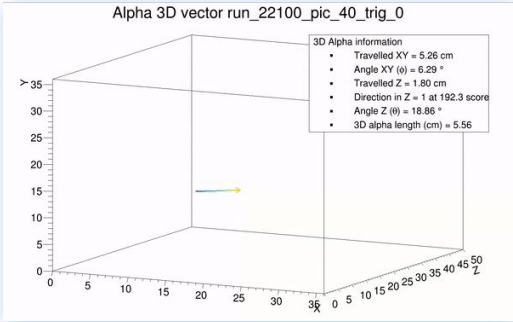
- **ΔZ + ΔXY**
- **Phi + Theta angles**
- **Signal of theta + phi == Head-tail**

⇩

3D reconstruction

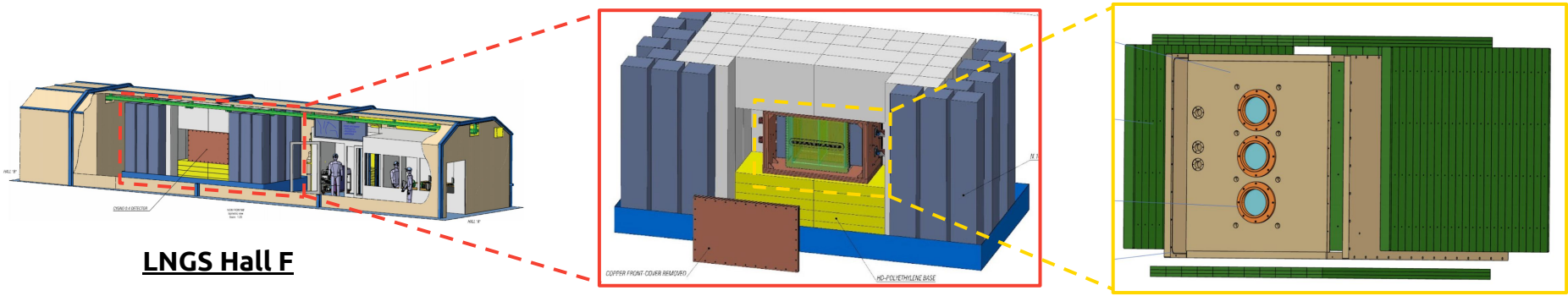






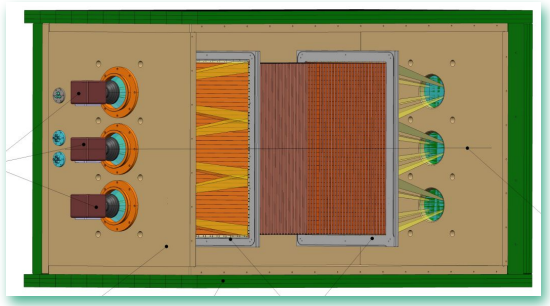
next step...

CYGNO-04



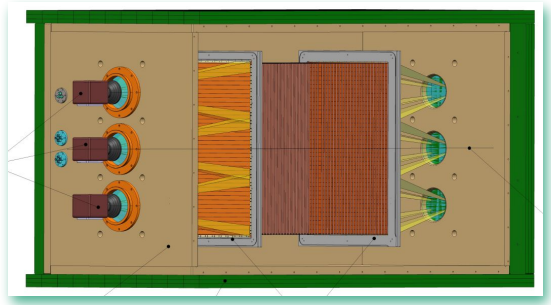
LNGS Hall F

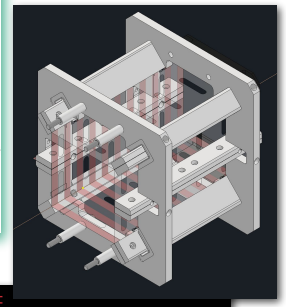
CYGNO-04 - Phase 1



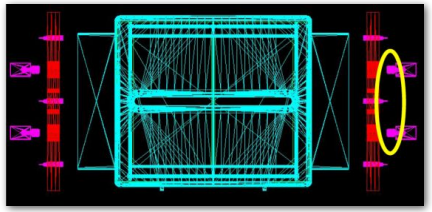
- ➔ Test scalability on realistic scale + all ancillary systems
- ➔ Test feasibility of physics reach for directional DM searches with a radiopure large detector

CYGNO-04 - Phase 1

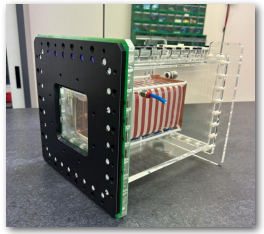


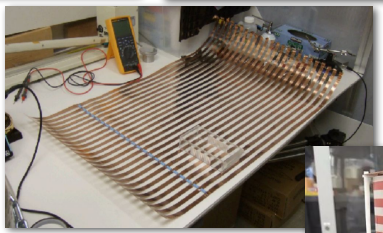


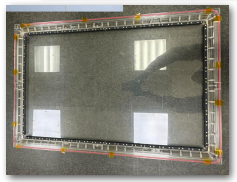
- ➔ **Test scalability on realistic scale + all ancillary systems**
- ➔ **Test feasibility of physics reach for directional DM searches with a radiopure large detector**

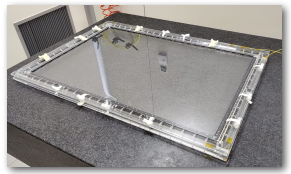


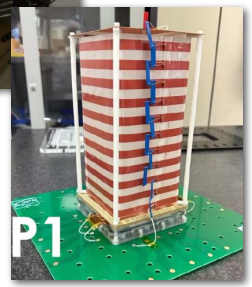
- ➔ Back-to-back **0.4 m3 TPC**, with **central** cathode.
- ➔ Projected **shielding** composed of **10 cm Cu + 100 cm H2O**
- ➔ **Radioactivity** of all materials will be measured
  - ◆ Improve **MC vs. data** ⇒ Determine **sensitivities**
- ➔ Currently **validating** all the components:
  - ◆ **Camera:** Fusion ⇒ **Quest * 6**
  - ◆ **PMT:** Position under study ⇒ **8**
  - ◆ **Field cage: copper strips** on insulator support
  - ◆ **GEMs: 50x80 cm^2**
- ➔ **Timeline: Commiss. 01/2025 ⇒ Data 08/2025 - 12/2026**







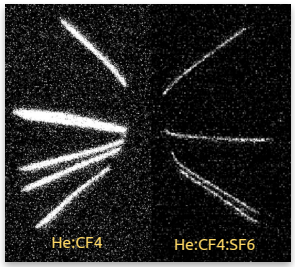


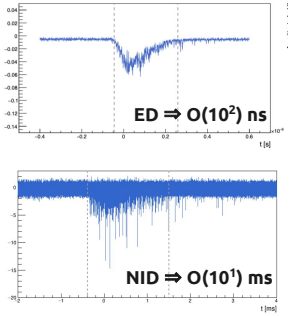


R&D - Ongoing projects

- **Negative ions**

Reduce diffusion during drift by adding SF6 (thus negative ions) to the gas mixture

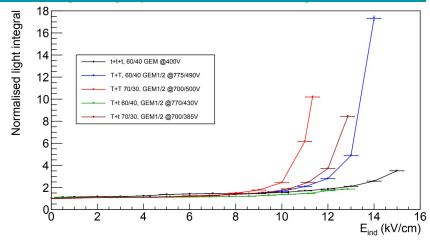




- **Light enhancement with strong electric fields**

Through strong electric fields, light is increased with constant charge and energy resolution

Enhancing the light yield of He:CF4 based gaseous detector



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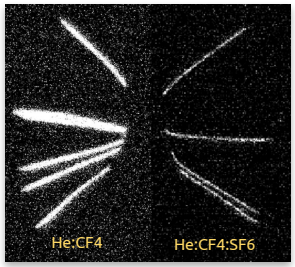

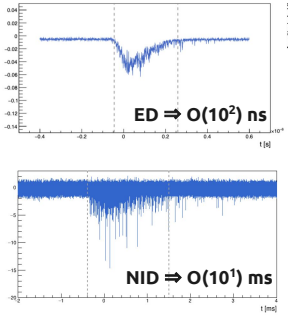

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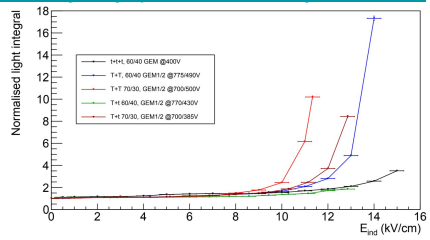
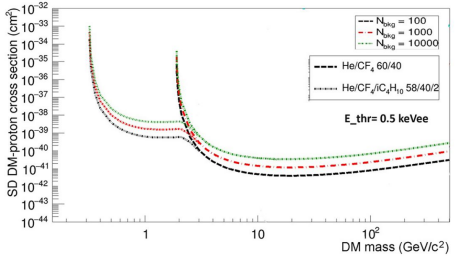


- **Addition of H-based gases in the mixture**

Improvement of low Dark Matter Mass detection sensitivity



Secondary scintillation yield from GEM electron avalanches in He-CF4 and He-CF4-isobutane for CYGNO — Directional Dark Matter search with an optical TPC

- **Internal background reduction**
  - Building low radioactivity camera sensor and lens together with Hamamatsu/BMI experts

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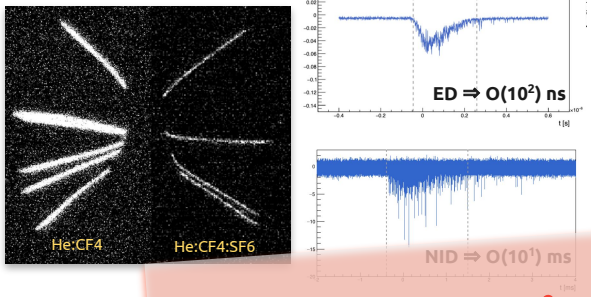

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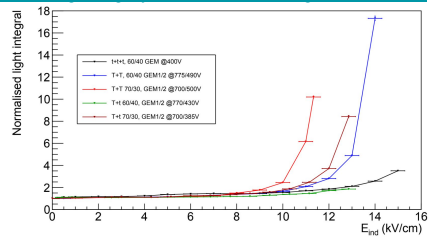

Check Giorgio Dho's poster!

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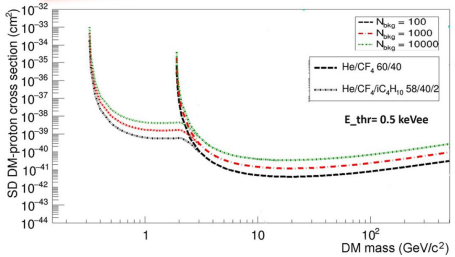

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Conclusions

- The CYGNO collaboration is developing a high-precision gaseous TPC at atmospheric pressure with optical readout.
- The main focus is the directional 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 installed in the underground LNGS facilities.
  - Commissioning tests, background vs. MC evaluations and measurements with sources are being carried out.
- CYGNO-04, will allow us to test the experiment's scalability and physics reach.
- 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:
  - Light enhancement observed, and its potentialities are under study!
  - Negative ion drift observed for the first at atmospheric pressure and with PMTs – ***stay tuned!***

CYGNO

…check out our white paper!
The CYGNO Experiment - Instruments

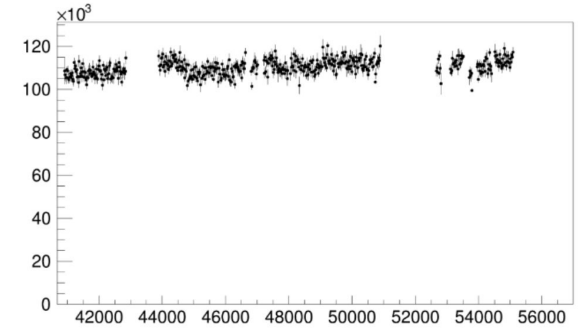

Thank you for your attention!
The CYGNO Project counts with the collaboration of several international researchers, coming from:

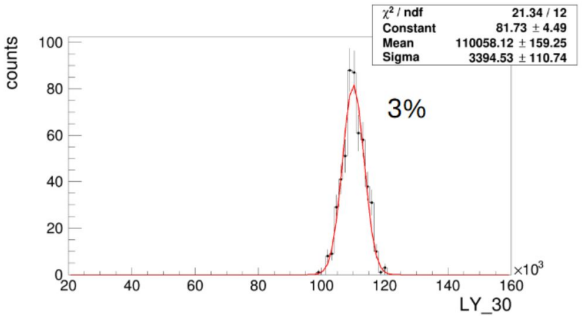
Backup

& more

details

LIME - Light yield stability

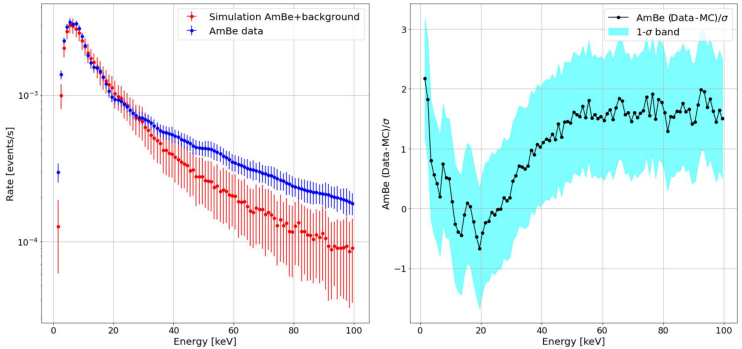




- This corresponds to about **50 days** of "total" data taking.
- The **light yield stability** is evaluated through the mean value of LY for high energy tracks.
- Several efforts have been made throughout the initial runs to **stabilize** the light yield inside LIME, and, in run 4 (latest), we can see a **constant light yield at 3% sigma.**

LIME - AmBe run details

AmBe run



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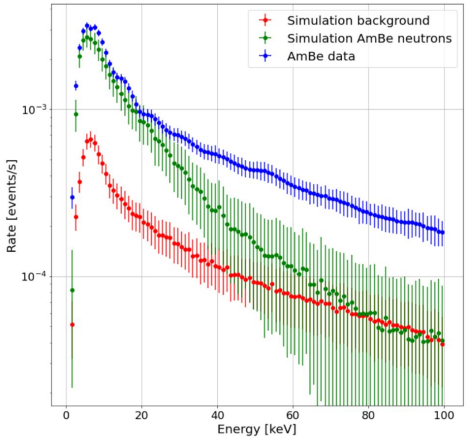
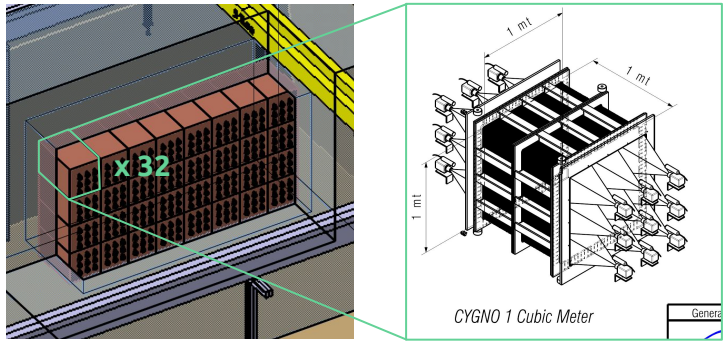


Figure 6.27: Comparison between the data acquired with the AmBe source during Run 3 (blue) and the simulated background (red) and AmBe-induced events (green), below 100 keV. The AmBe-induced events dominate the spectrum below ∼50 keV.

CYGNO-30 - Prospects

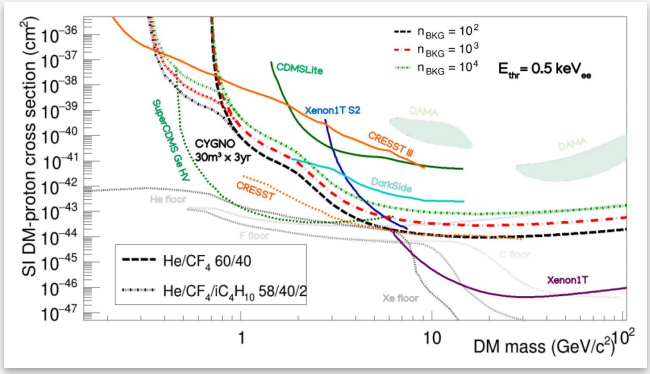
- **Low mass (0.5 - 10 GeV) directional DM searches**
- > 2027
- **30 - 100 m3** detector
- **0.5 - 1 keV$_{ee}$** energy threshold
- **30°** angular resolution

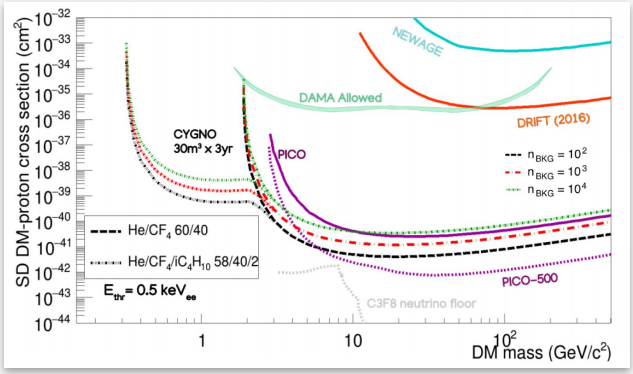


Expected **SI** and **SD** (90% CL)
interaction cross-section exclusion

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

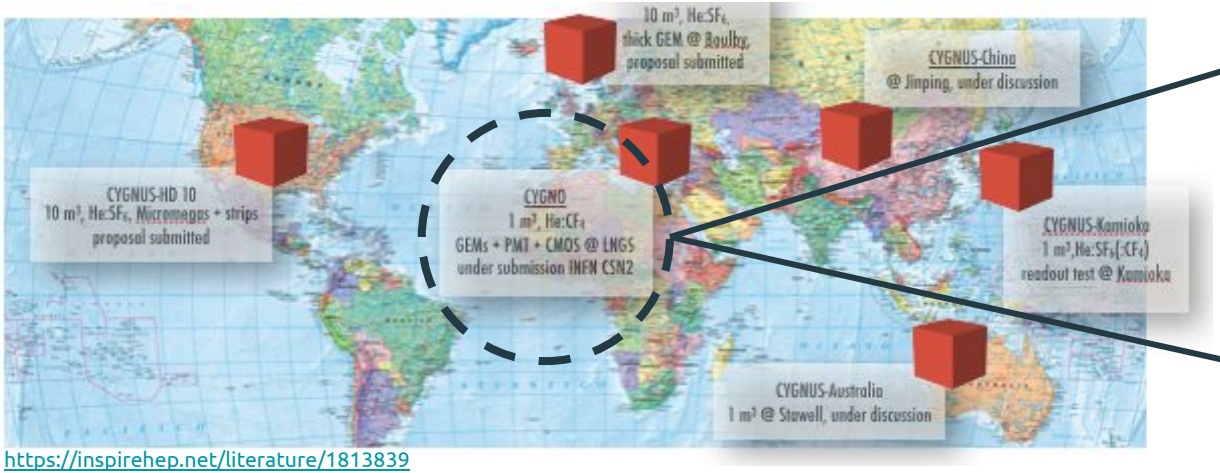
He / (eventually H) allows us to explore very low DM masses!



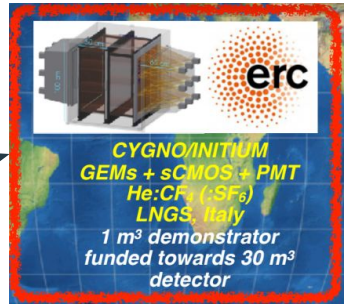


The CYGNUS project

CYGNO 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, CYGNO, is developing a **gaseous TPC** based on the setup:

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