



Directional Dark Matter searches with CYGNO



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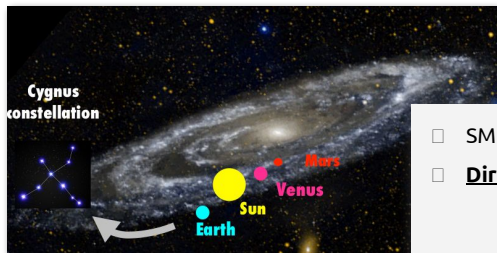
WIMPs - How to see them?

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

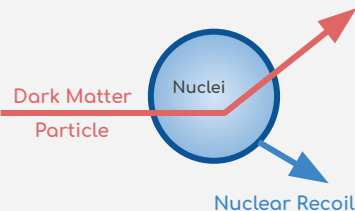
+

Solar system rotates around galaxy towards Cygnus constellation

Earth susceptible to an apparent WIMP wind from Cygnus direction!



- ☐ $SM + \chi \rightarrow SM + \chi$
- ☐ **Direct detection** of nuclear recoil



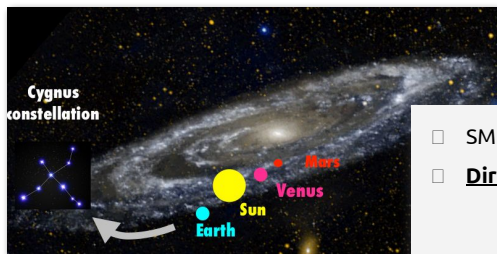
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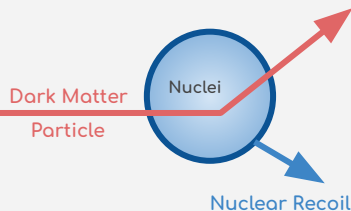
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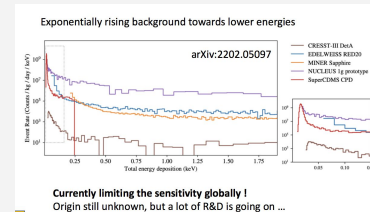
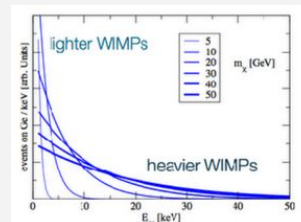


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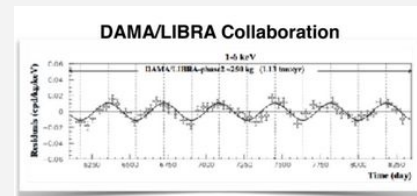
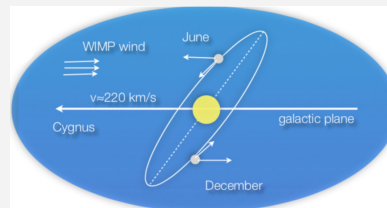


DM interacting in our detectors would create different effects:

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



- **TIME** \Rightarrow Results in a few % annual modulation.



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

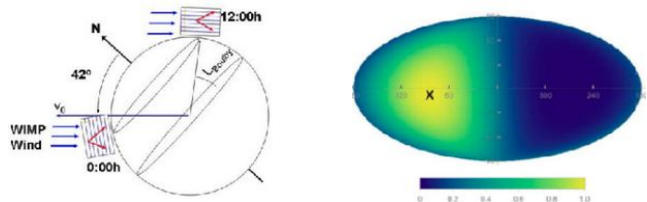
Directionality *and beyond the neutrino fog*

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

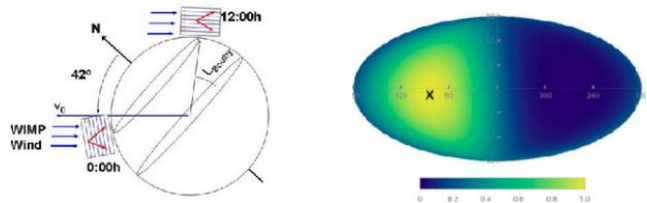


Where other experiments struggle to **find striking**
features to prove the existence of DM, **directional**
discrimination emerges as a unique and efficient
strategy to **positively identify** **Dark Matter!**

Directionality and beyond the neutrino fog

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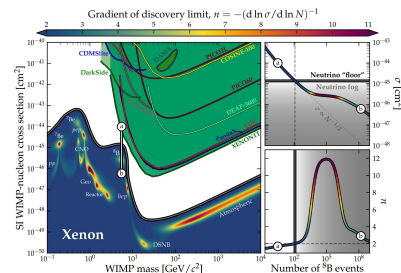
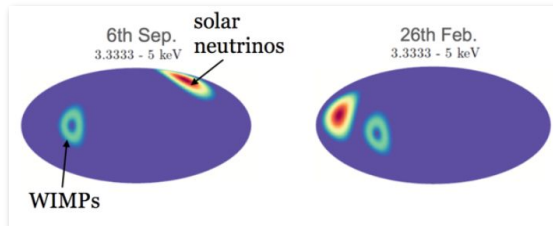


Where other experiments struggle to **find striking features to prove the existence of DM, directional discrimination** emerges as a unique and efficient strategy to **positively identify Dark Matter!**

The **CEvNS** 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/c² → Mostly **Solar neutrinos**

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



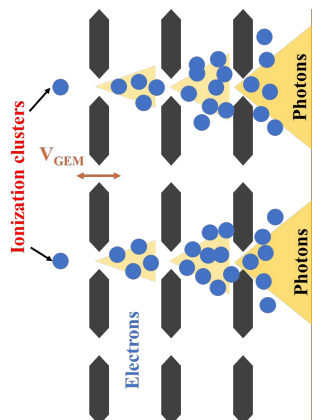
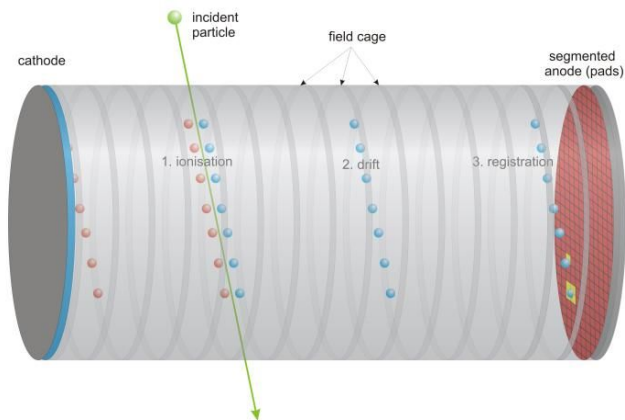
- Searching **beyond** the **neutrino fog**
- Properties of the **solar neutrino flux and DM halo**



A CYGNus TPC module
with Optical readout

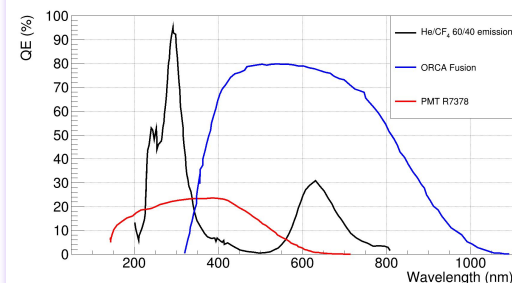
CYGNO - What's the setup?

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



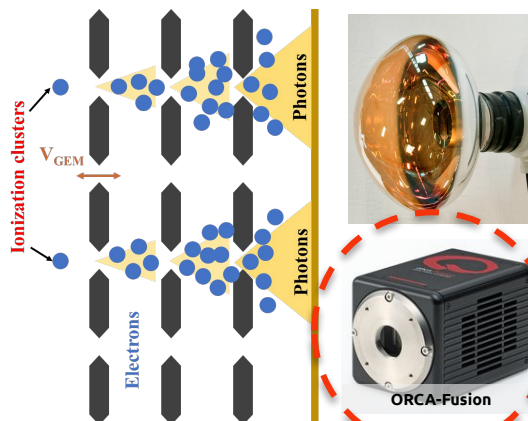
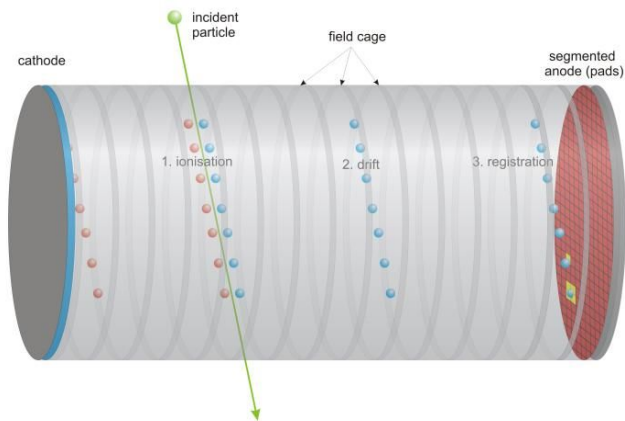
Carbon tetrafluoride (CF₄)

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

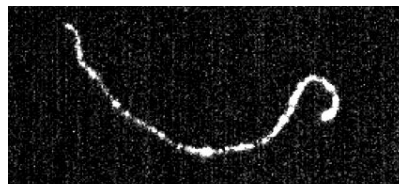
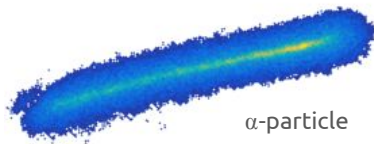


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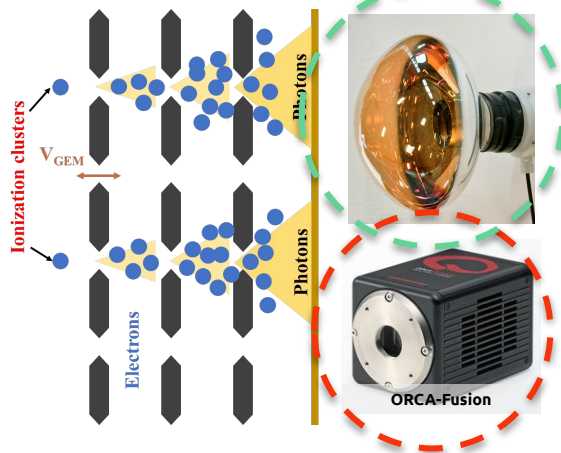
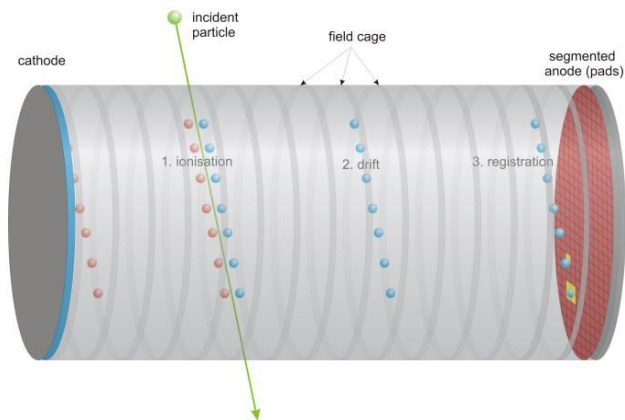


With the high granularity of the camera, we measure **energy + X & Y coordinates**

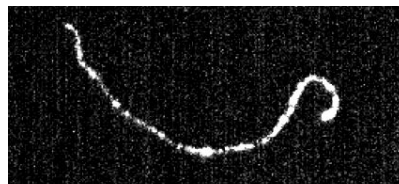
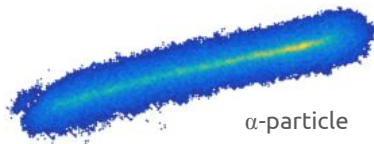


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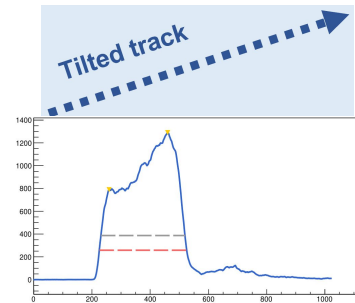
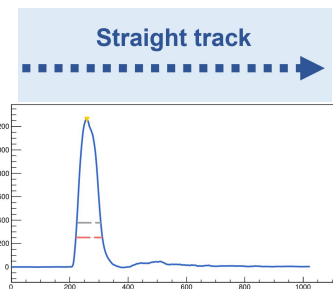
TPC → Triple GEM Charge multiplication → Camera + PMT
Light from gas scintillation during electron avalanche



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



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



Cygn0 - What's the setup?

TPC

$$X + Y + dZ =$$

3D reconstructed track

Track's deposited energy
topology (dE/dx)

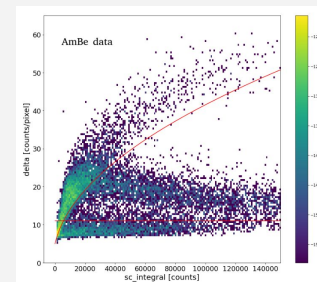
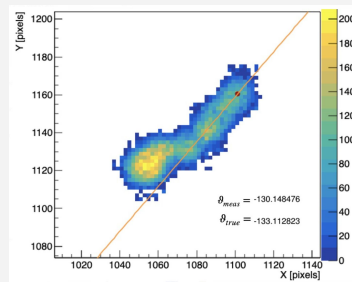
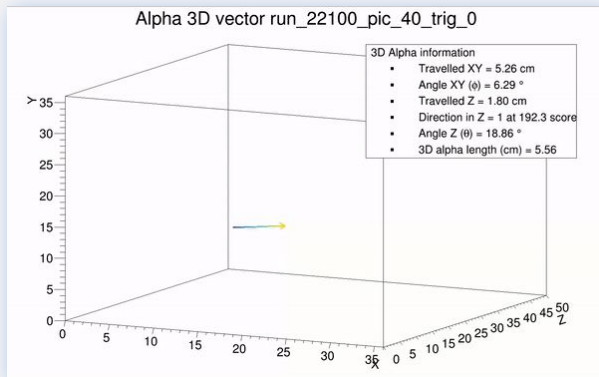
Head-tail asymmetry
+ recoil direction

Directionality

Particle

BG rejection

cathode



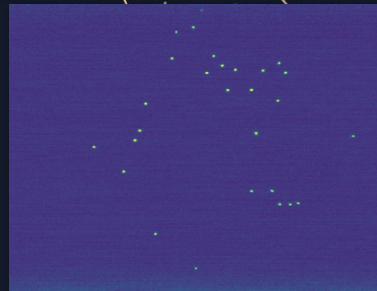
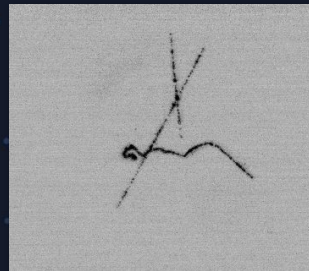
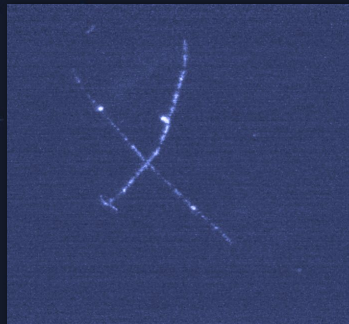
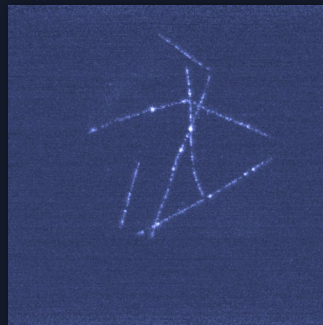
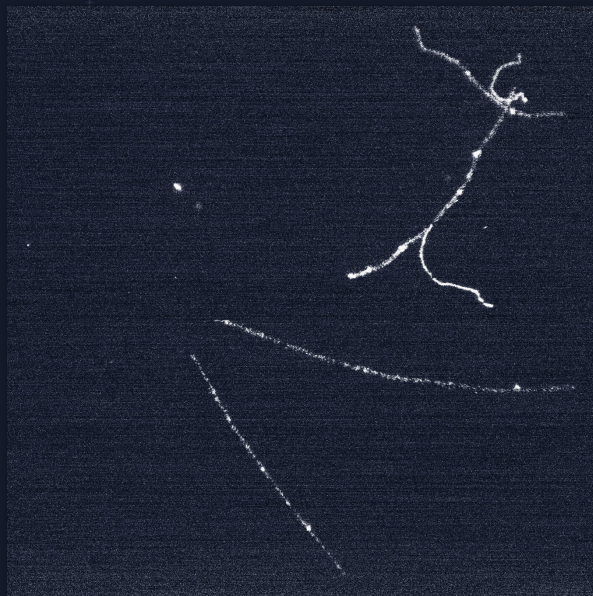
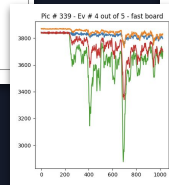
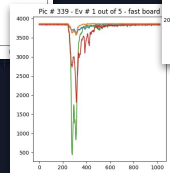
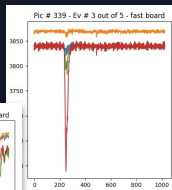
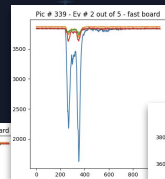
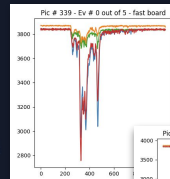
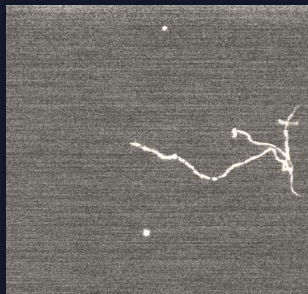
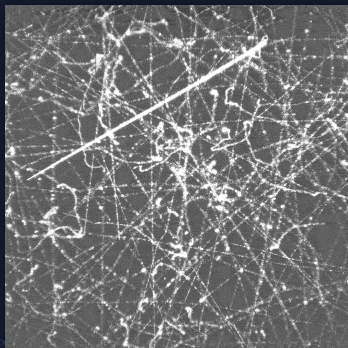
With the

the camera,

energy + X & Y coordinates

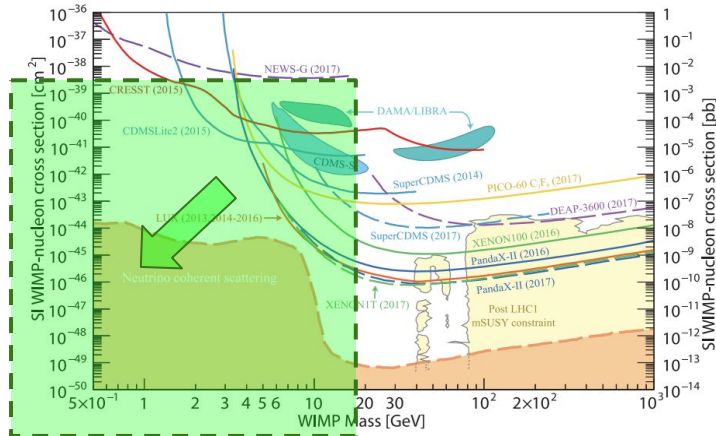
α -particle

Some cool pictures



CYGN0 - Dark Matter paradigm

CYGN0 Dark Matter exploration region

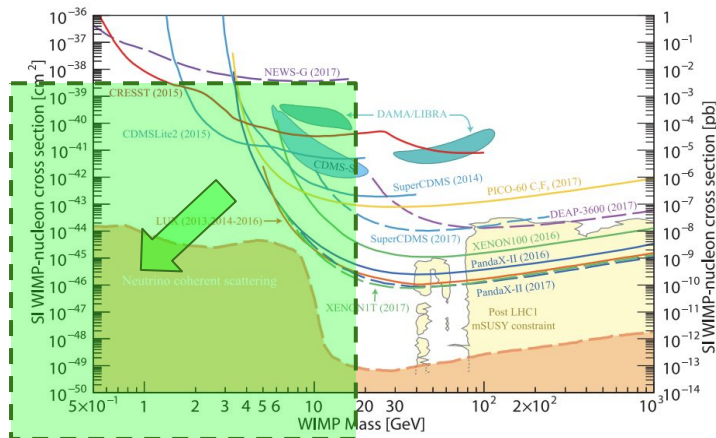


$\leq 10 \text{ GeV}/c^2$

- To observe lower WIMP masses:
- ◆ **Low thresholds** are necessary, since lower m_χ originate lower energy recoils.
 - ◆ **Light nuclei** used to maximize energy transfer.

CYGNO - Dark Matter paradigm

CYGNO Dark Matter exploration region



Low Density @ atm pressure

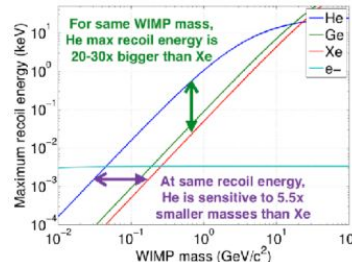
- Allows tracks of up to **millimetres** at **few keV** without compromising exposure.

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- To observe lower WIMP masses:
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Helium (He)

- Light target for SI in low mass range.



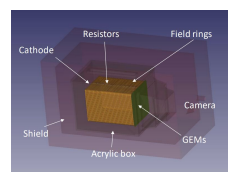
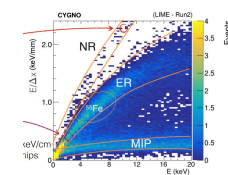
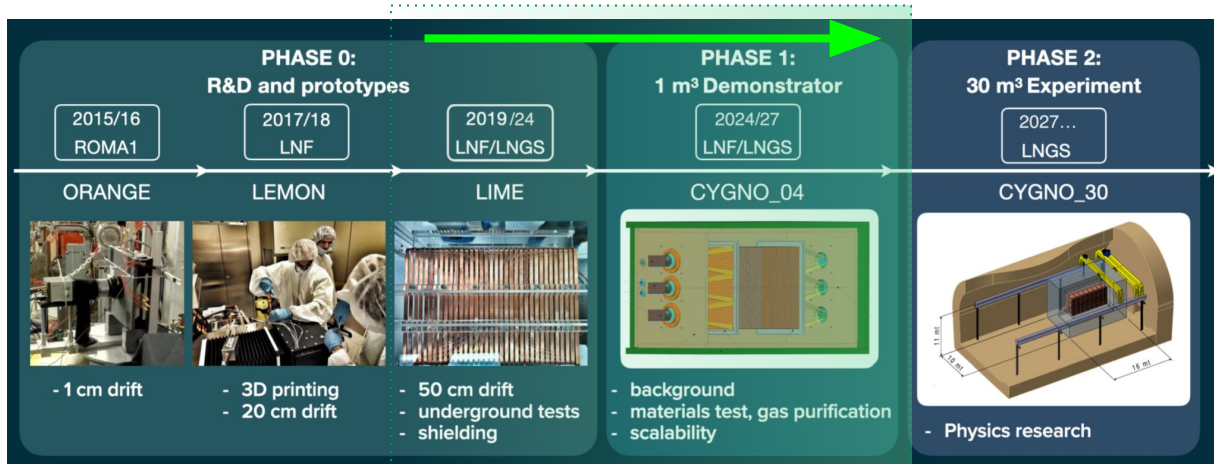
Fluorine (F)

- Heavier target to intermediate WIMP masses.
- One of the highest sensitivity to SD coupling.

- 3D reconstruction
- Directionality
- ER vs. NR (+ML)
- Shielding optimization
- Background data vs. MC
- DM Sensitivity
- Design and Commissioning of

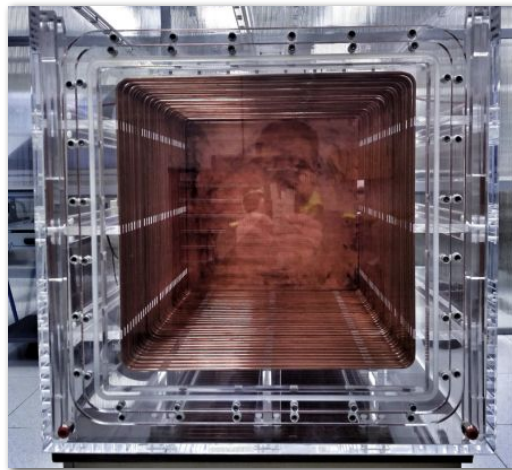
- Enhancement of the light yield
- Negative Ion drift

Check Giorgio Dho's poster!

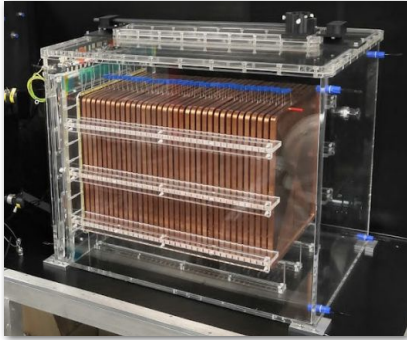


Where we are at...

LIME

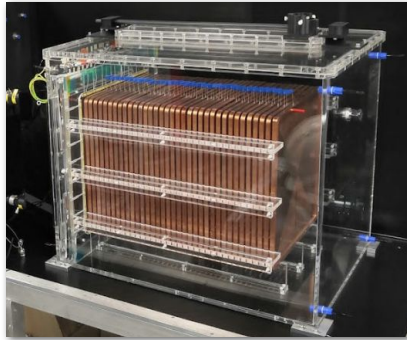


LIME - *The concept*



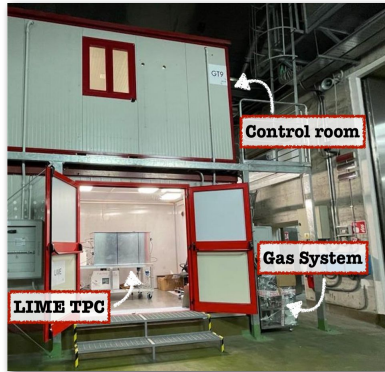
- [50 L](#) & [50 cm drift](#) gaseous TPC with **Copper ring** field cage.
- [Atm](#) pressure (910 mbar), room temperature and [He:CF₄, 60:40](#)
- [Triple](#) 33x33 cm² [GEM](#) stack for amplification
- Optical readout ⇒ [4 PMTs + 1 sCMOS camera](#) (ORCA Fusion)

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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 : ⁵⁵Fe, ¹³⁷Ba, ¹⁵²Eu, ²⁴¹Am + ²⁴¹Am⁹Be



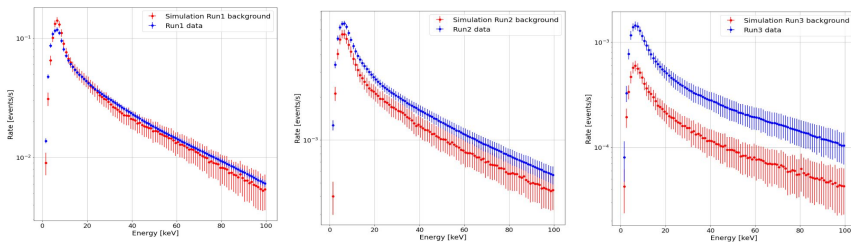
Live monitoring of detector performance & data quality

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 H ₂ O	Great external neutron suppression \Rightarrow <i>Under analysis...</i>			

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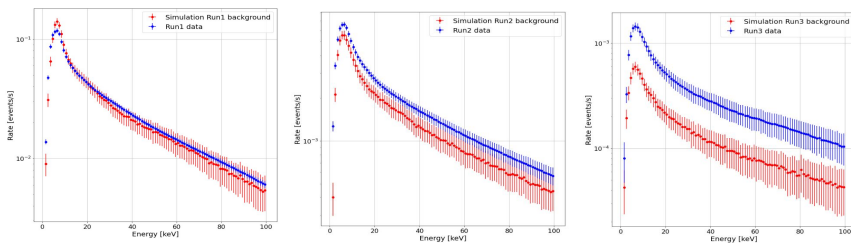
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- Shielding strongly **suppressed external background**
- Difference in Runs 2 & 3 attributed to **internal background excess (contaminations of the detector – materials, gas, etc.)**
- **LIME was not meant to be radiopure**
 - ◆ Not all the components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

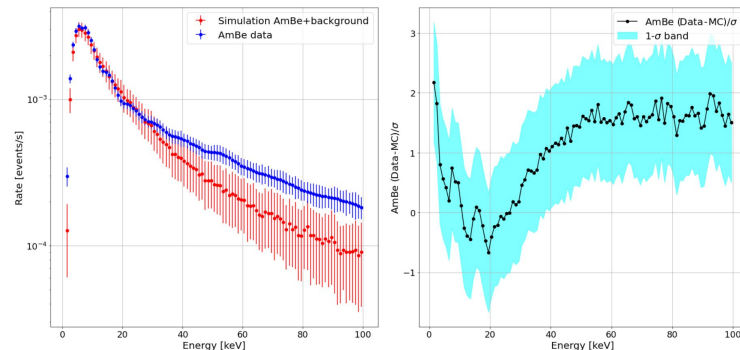
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AmBe run



→ AmBe + background simulation matches data @ $E < 40$ keV

- ◆ External background ✓
- ◆ Source simulation ✓
- ◆ Internal background - Shape ✓
- ◆ Internal background - Absolute 🧑🔧

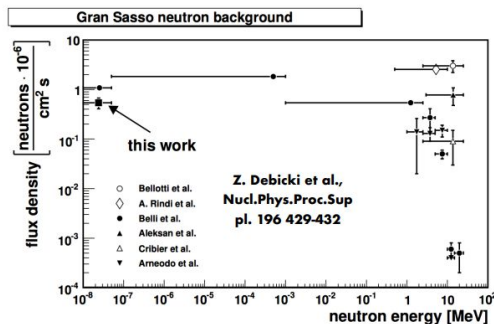
LIME - Run 5 objectives

- 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 ($< 1\text{MeV}$)
 - **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 $>20\text{ keV}$**

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

LIME - 3D reconstruction

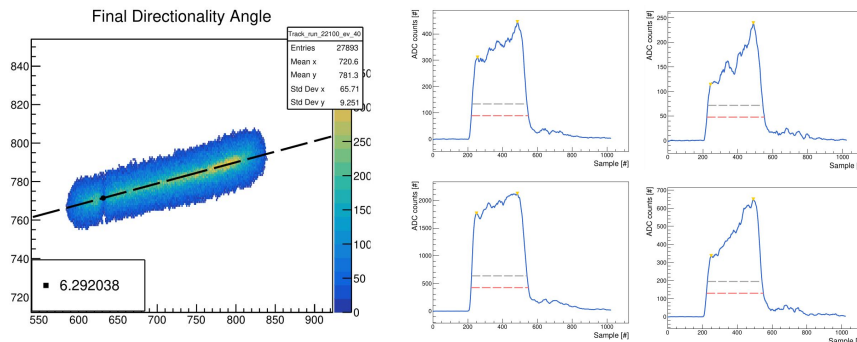
- Merging **camera** with **PMTs** information allows us to get a **full description** of the ionization event.
 - ◆ With this, we will be able to improve our particle ID, reject backgrounds from known sources, and fully characterize the 3D direction of the incoming particles: □□ Directionality □□

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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** \Rightarrow Together with camera X-Y angle \Rightarrow **Z-angle**
- 3. The **position of the Bragg** in PMT waveforms gives **Z-angle signal** = **head-tail** = Towards cathode or GEMs



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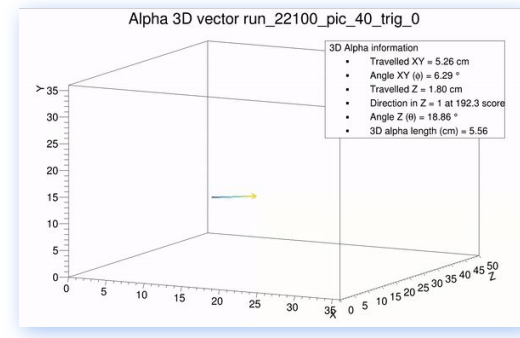
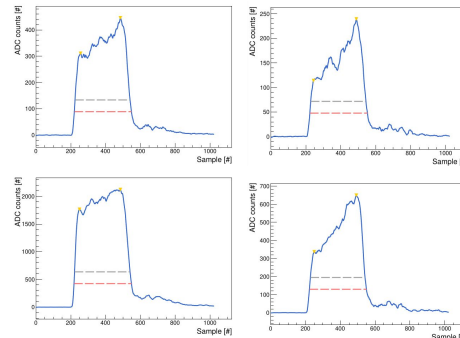
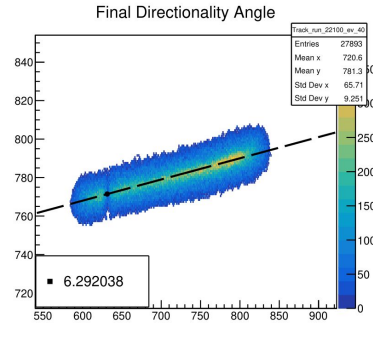
Reconstructed info:

- **$\Delta Z + \Delta XY$**
- **Phi + Theta angles**
- **Signal of theta**

+ phi == Head-tail

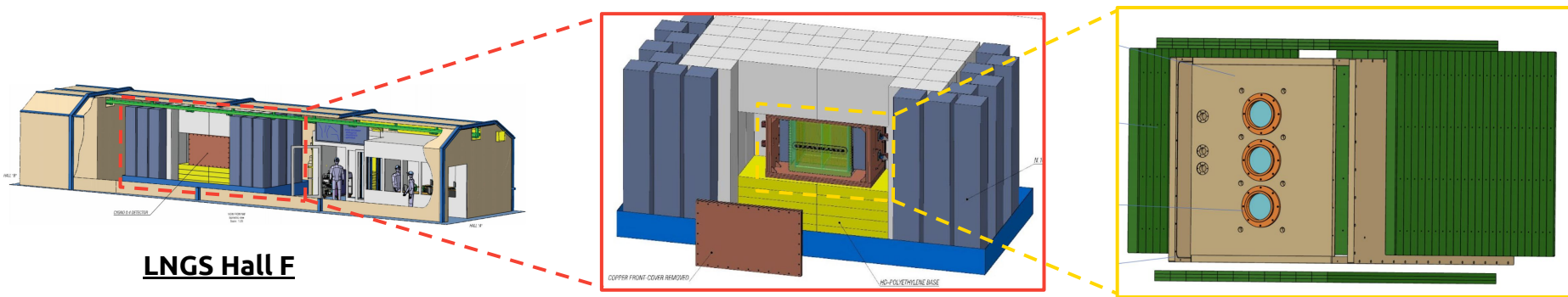


3D reconstruction



next step...

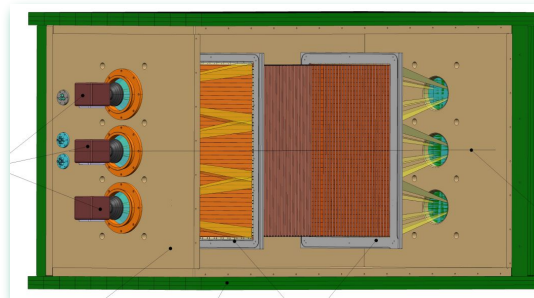
CYGNO-04



LNGS Hall F

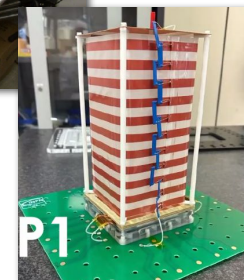
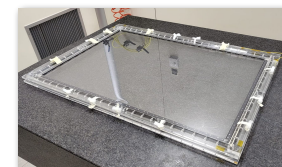
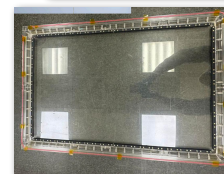
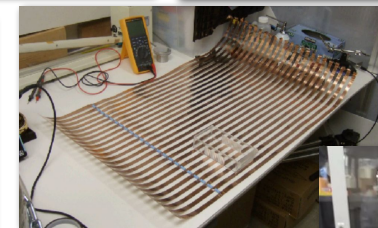
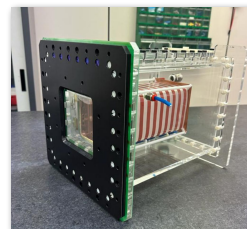
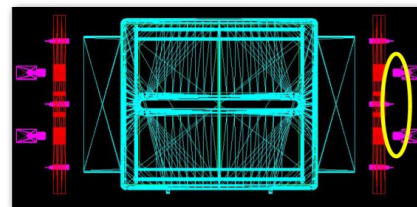
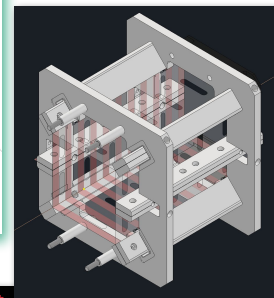
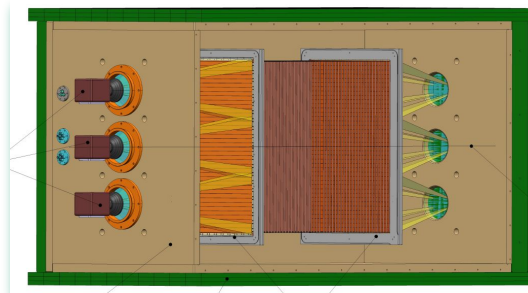
CYGNO-04 - Phase I

- 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 I

- 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 cm²
- Timeline: Commiss. 01/2025 ⇒ Data 08/2025 - 12/2026

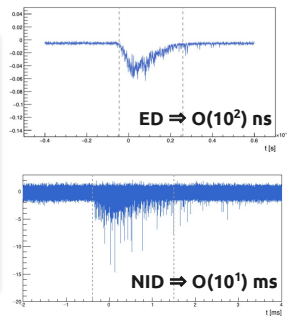
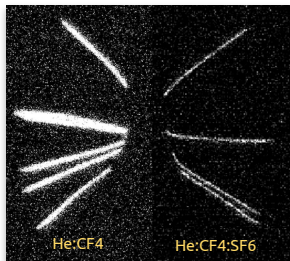


R&D - Ongoing projects

- Negative ions

Reduce diffusion

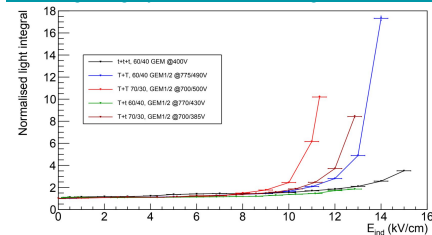
during drift by
adding SF₆ (thus
negative ions) to
the gas mixture



- 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

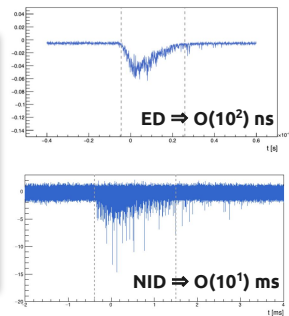
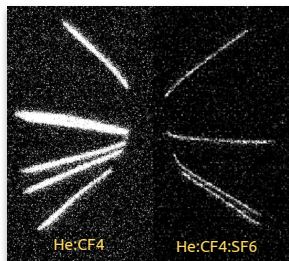


R&D - Ongoing projects

- Negative ions

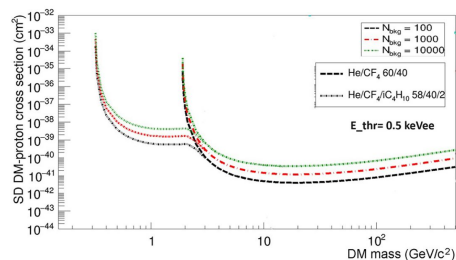
Reduce diffusion

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



- Addition of H-based gases in the mixture

Improvement of low Dark Matter Mass detection sensitivity

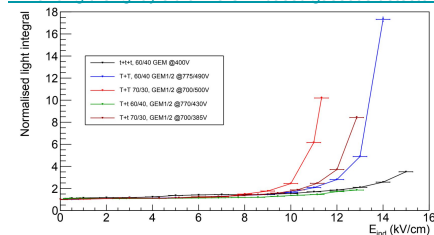


Secondary scintillation yield from GEM electron avalanches in He-CF4 and He-CF4-isobutane for CyGNO — Directional Dark Matter search with an optical TPC

- 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



- Internal background reduction

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

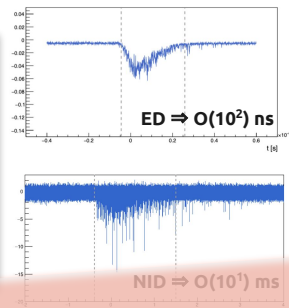
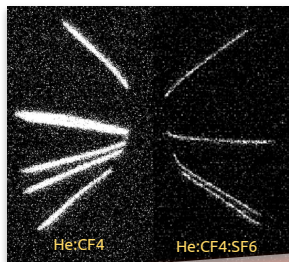


R&D - Ongoing projects

- Negative ions

Reduce diffusion

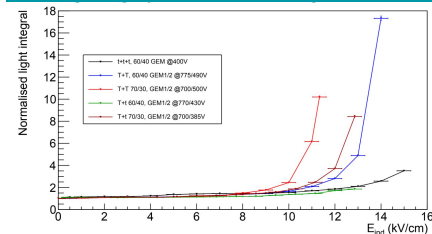
during drift by adding SF₆ (thus negative ions) to the gas mixture



- Light enhancement with strong electric fields

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

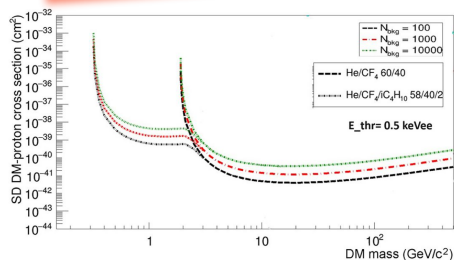
Enhancing the light yield of He:CF₄ based gaseous detector



Check Giorgio Dho's poster!

- 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



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!*



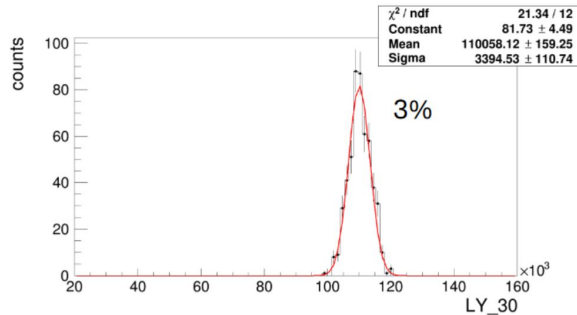
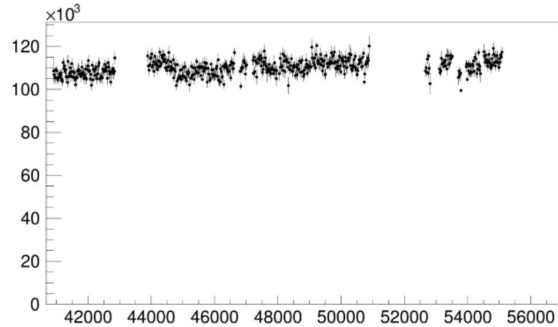
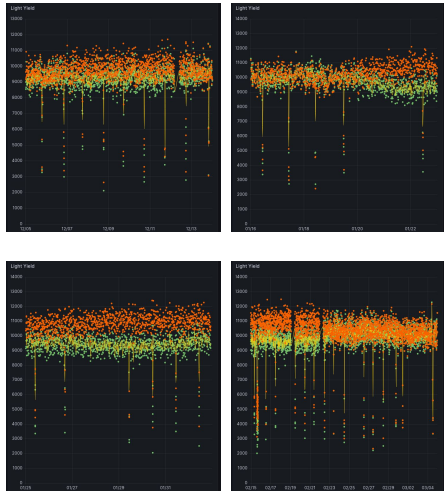
...check out our white paper!
[The CYGNO Experiment - Instruments](#)

Backup

& more

details

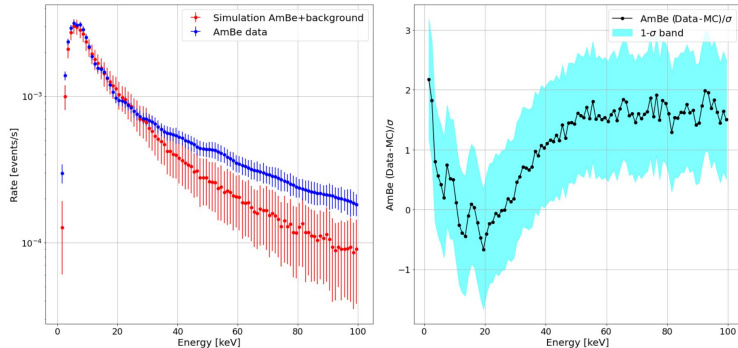
LIME - Light yield stability



- 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



→ AmBe + background simulation matches data @ $E < 40$ keV

- ◆ External background ✓
- ◆ Source simulation ✓
- ◆ Internal background - Shape ✓
- ◆ Internal background - Absolute 🧑🔧

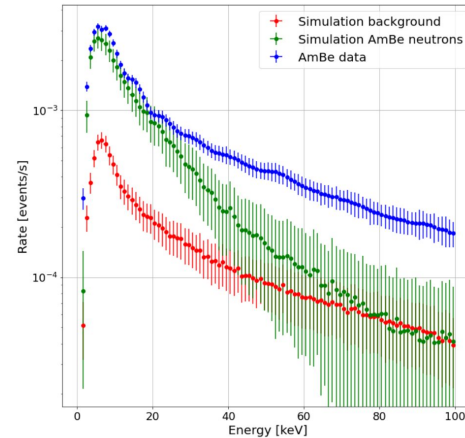
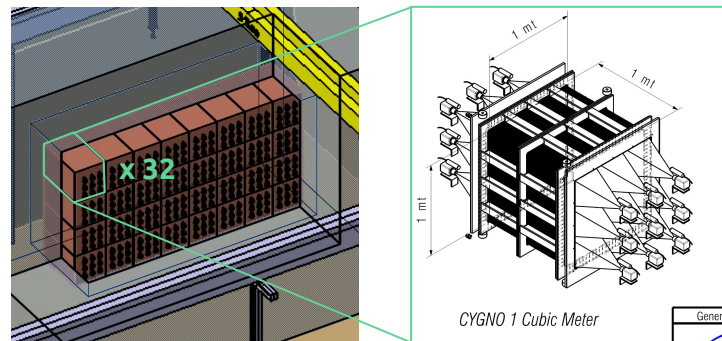


Figure 6.27: Comparison between the data acquired with the AmBe source during Run 3 (blue) and the simulated background (red) and AmBe-induced events (green), below 100 keV. The AmBe-induced events dominate the spectrum below ~ 50 keV.

CYGNO-30 - Prospects

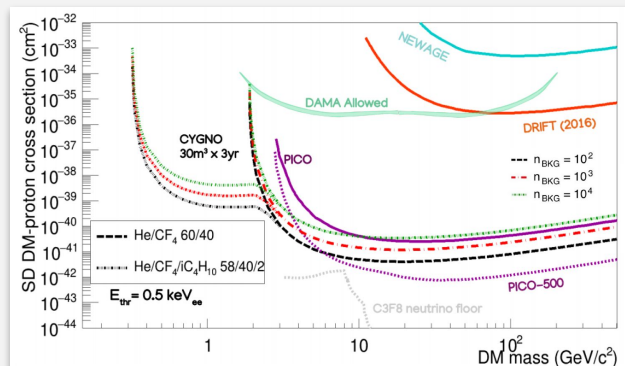
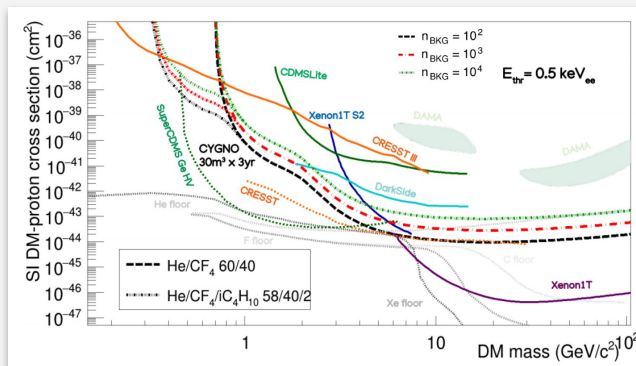
- Low mass (0.5 - 10 GeV) directional DM searches
- > 2027
- **30 - 100 m³** detector
- **0.5 - 1 keV_{ee}** energy threshold
- **30°** angular resolution



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

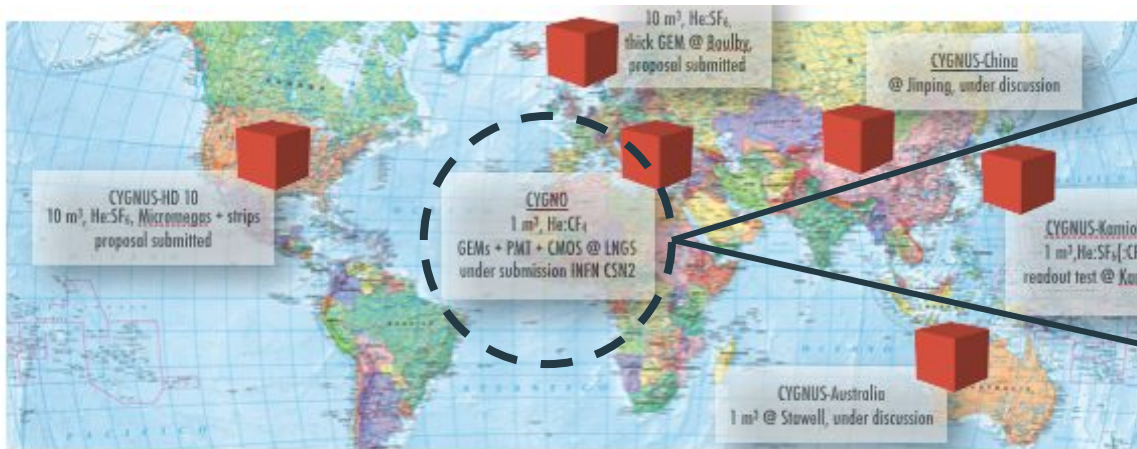
Quenching factor simulated
with **SRIM** → Direct
measurement incoming!

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

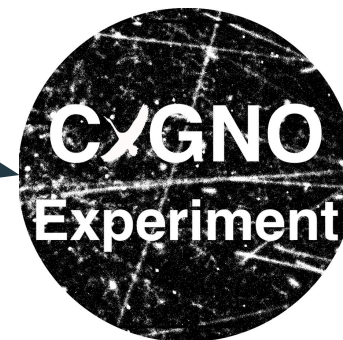
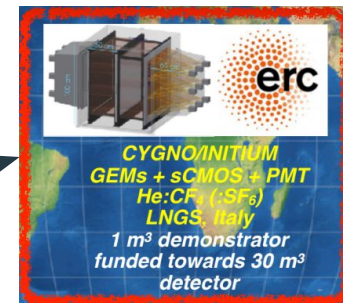


The CYGNUS project

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**