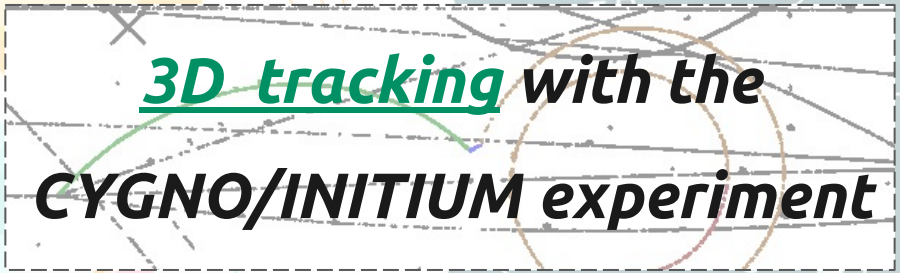
Directional Dark Matter searches with the CYGNO/INITIUM detector



3D tracking with the CYGNO/INITIUM experiment

David J. G. Marques

Ph.D. 3rd year report - Astroparticle Physics

Gran Sasso Science Institute - XXXVI cycle

October, 2023

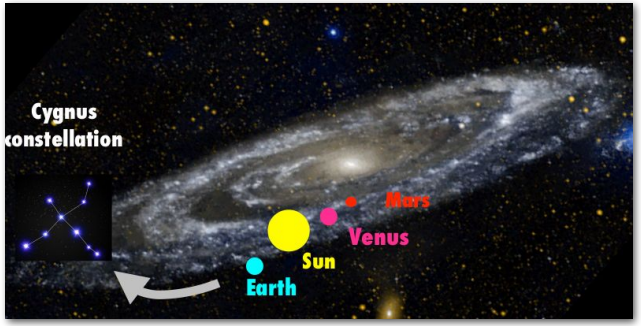
WIMPs - How to see them?

DM forms a halo within our galaxy.

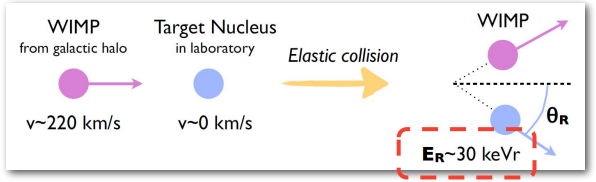
+

Solar system rotates around galaxy towards Cygnus constellation

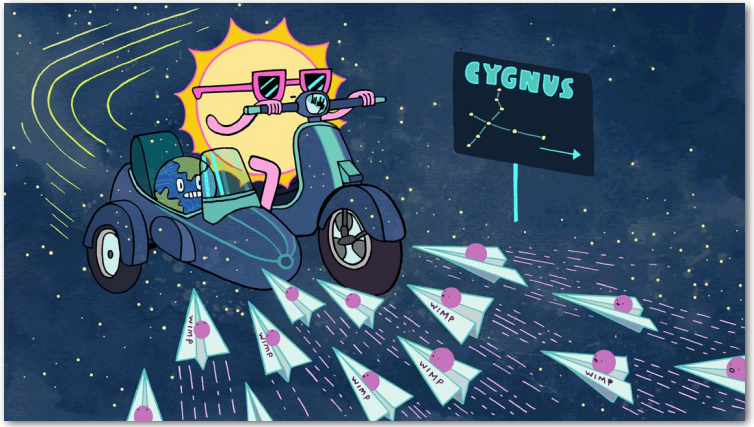
Earth susceptible to an apparent WIMP wind from Cygnus direction!



...from WIMP scattering kinematics...

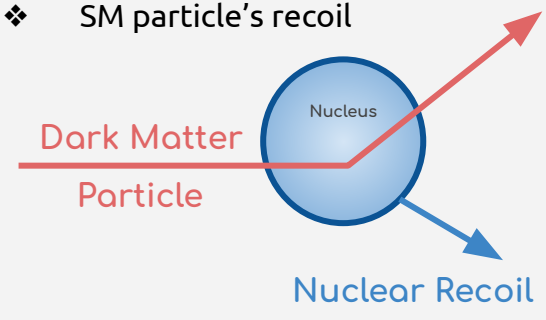


...the nuclear recoil is **non-relativistic**, of energies in the range 1 - 100 keV



Direct detection

- SM + χ → SM + χ
- SM particle's recoil

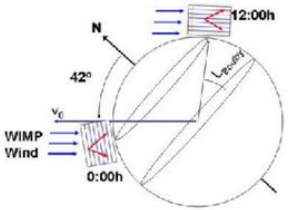


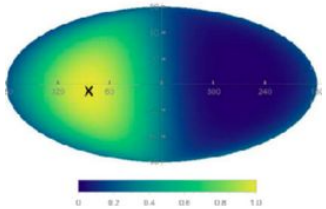
WIMPs - Directionality and beyond the neutrino floor

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

↓

No background can mimic





The **CEνNS** produces NRs identical to the DM-induced ones.

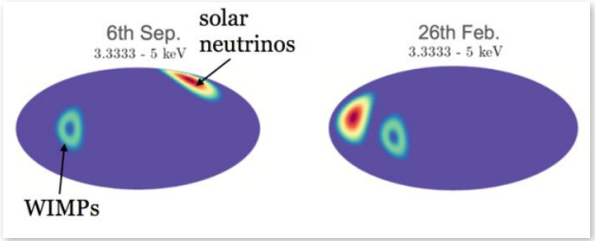
To ***search DM at smaller cross-sections***, experiments need to ***somehow venture into the neutrino fog***

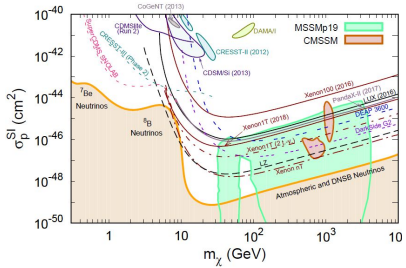
↓

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

↓

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





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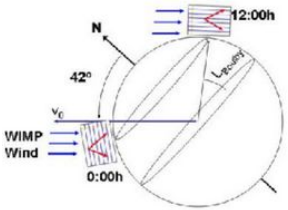

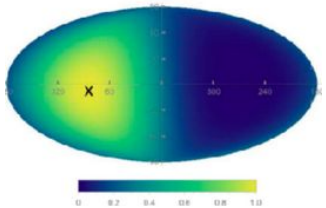

Where other experiments struggle to **prove / disprove DM**, **directional discrimination** strikes as the only way to ***positively prove the existence*** *of* **Dark Matter!**

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

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

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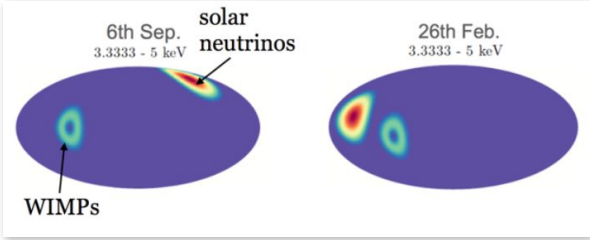
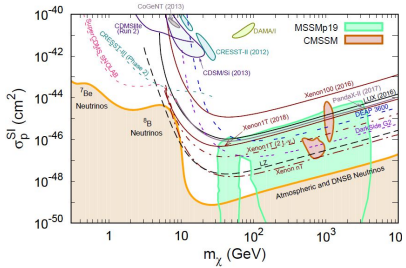




- ➔ Searching **beyond** the ***neutrino floor***
- ➔ Properties of the ***solar neutrino flux and DM halo***

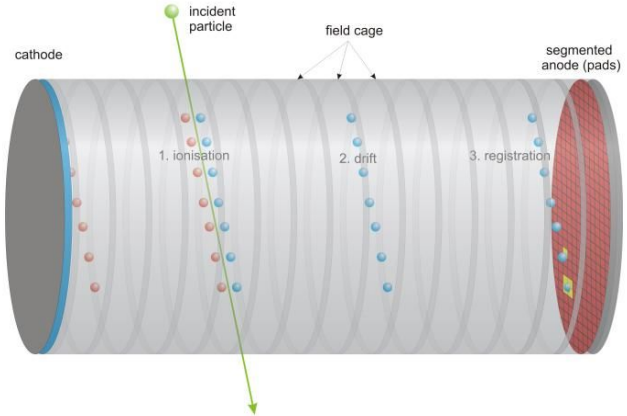
The CYGNO project

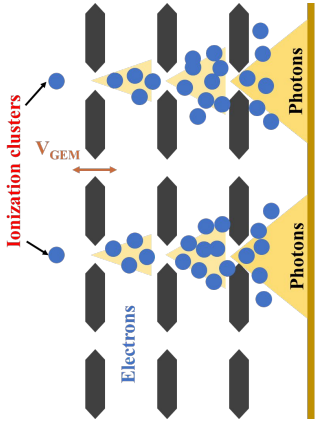
A CYGNus tpc module

with Optical readout

CYGNO - What's the setup?

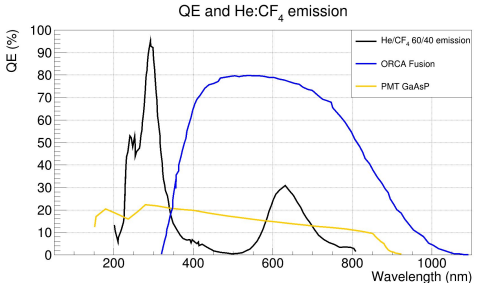
Time Projection Chamber → **Triple GEM**: Charge amplification & light production → **Camera & PMT**: Optically read the **light produced by the de-excitation of the gas molecules** during electron multiplication.





Carbon tetrafluoride (CF4)

➔ Significant light yield at the camera's QE peak



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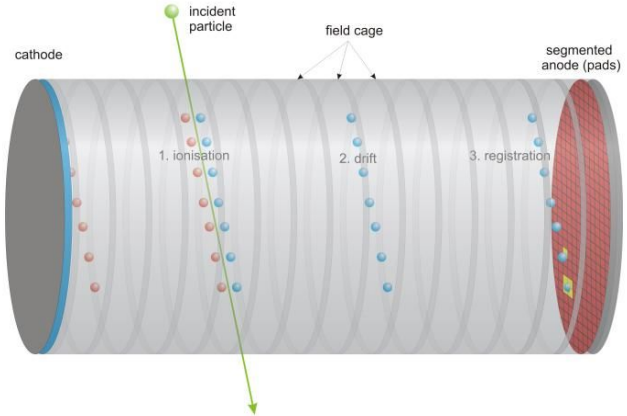
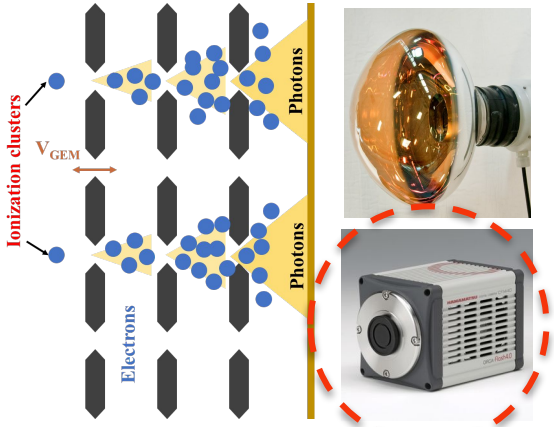
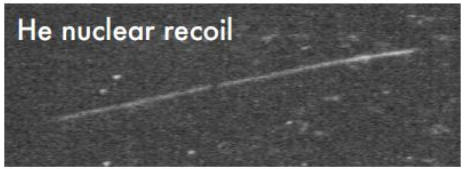
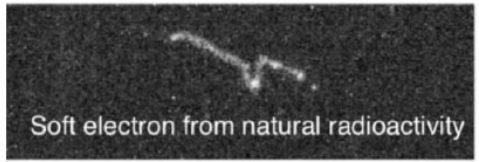




Using the camera's high granularity, we can measure the **energy** & **X & Y coordinates**





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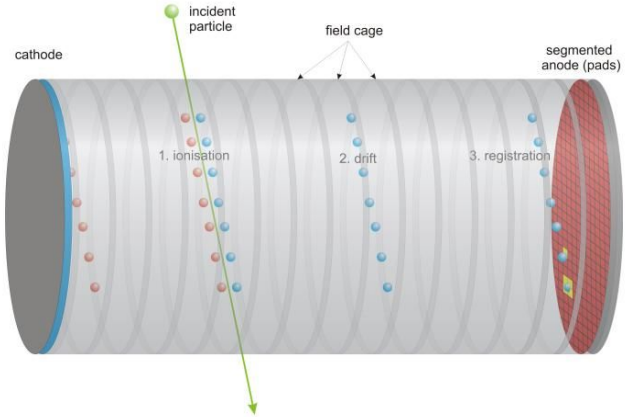

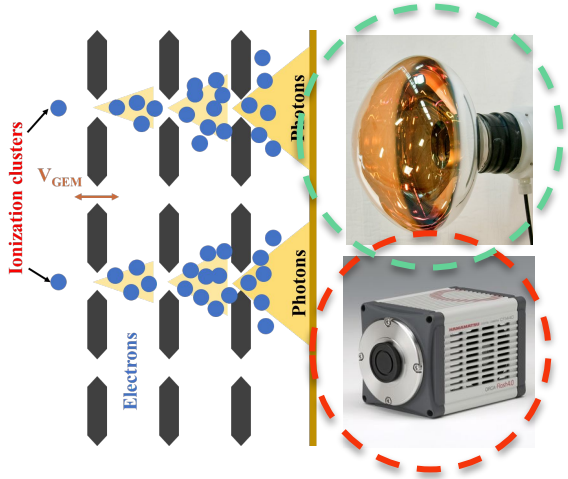

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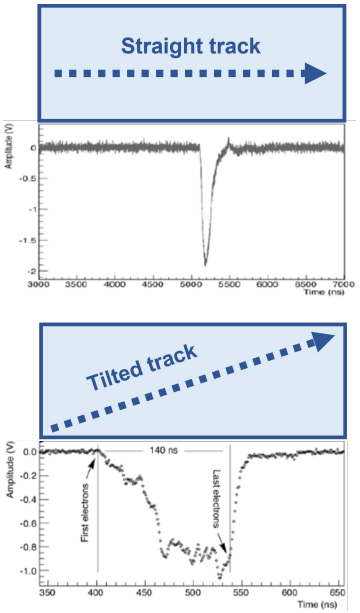
2. Charge carriers' **times of arrival →** **dZ coordinate** (track's tilt)



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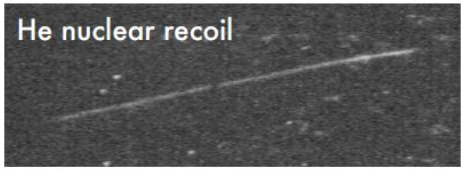

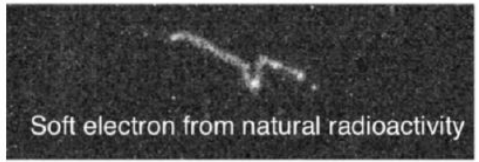

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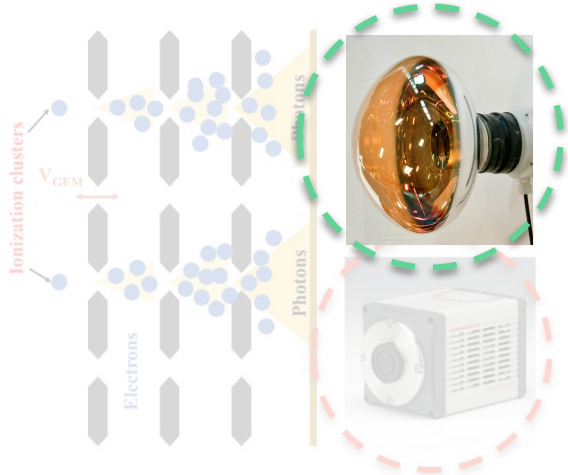

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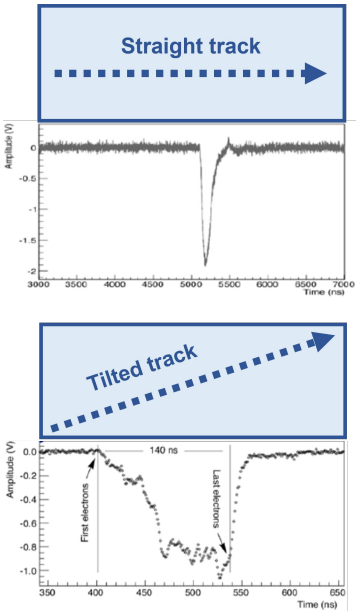

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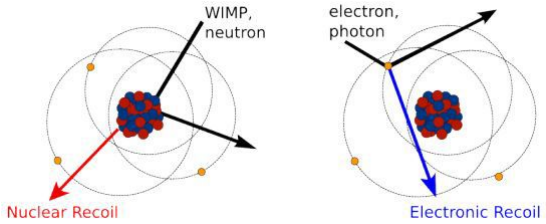

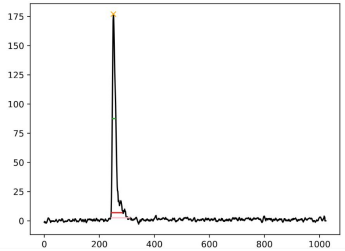

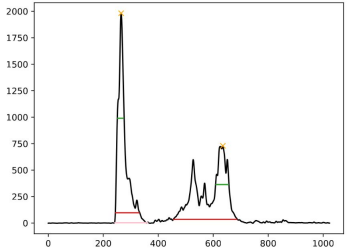

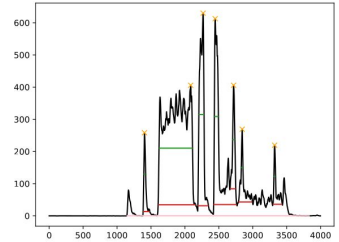

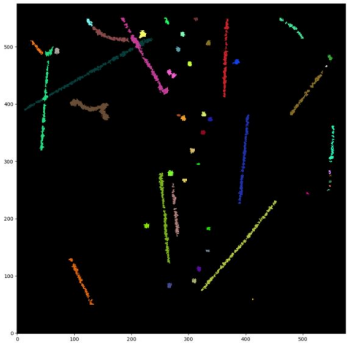

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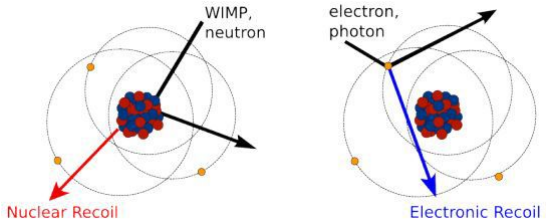

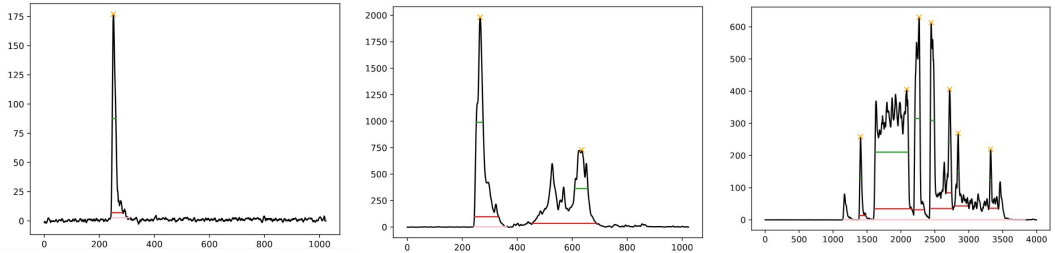

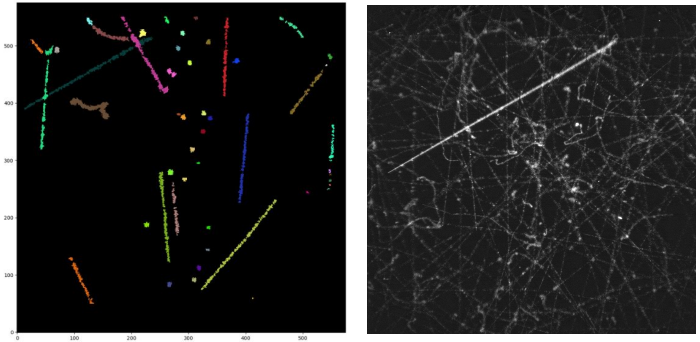

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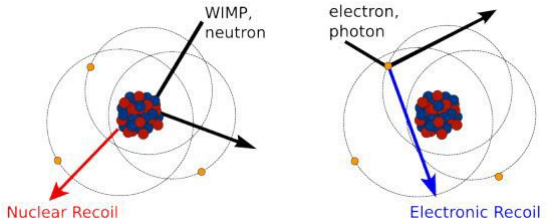

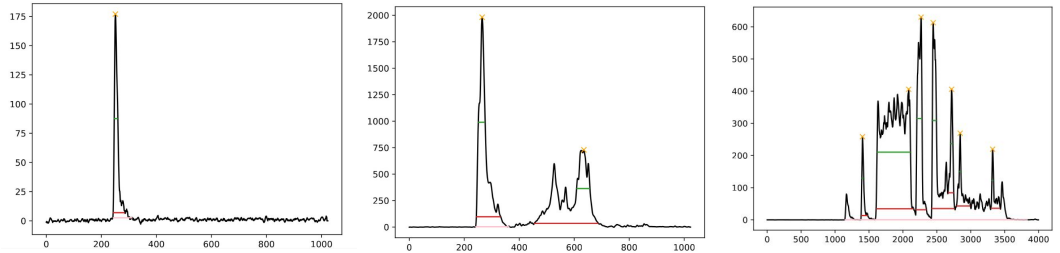

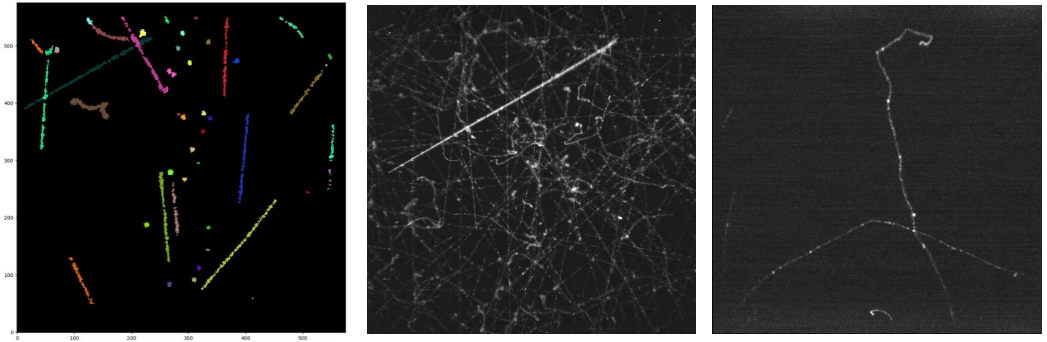

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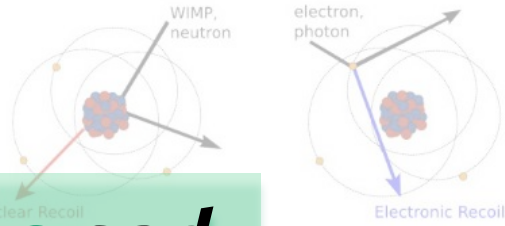

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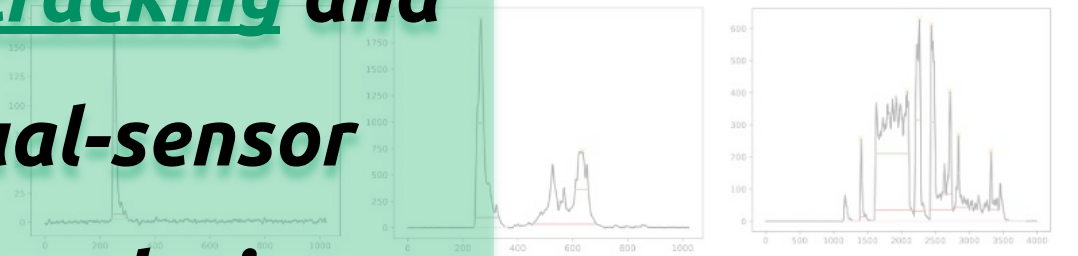

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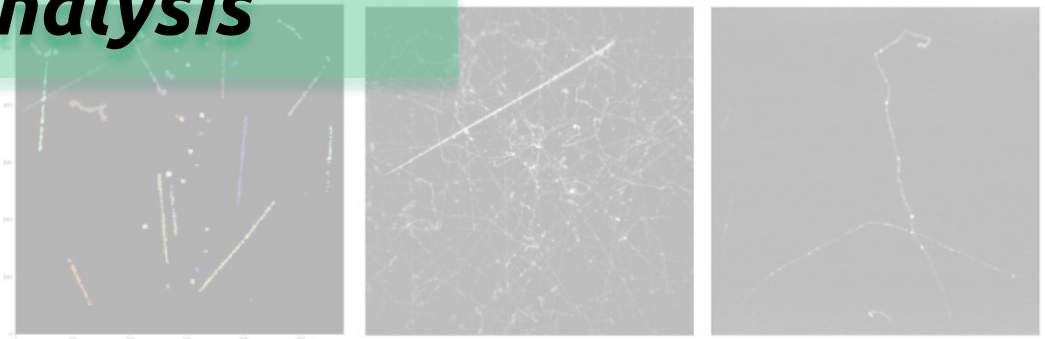
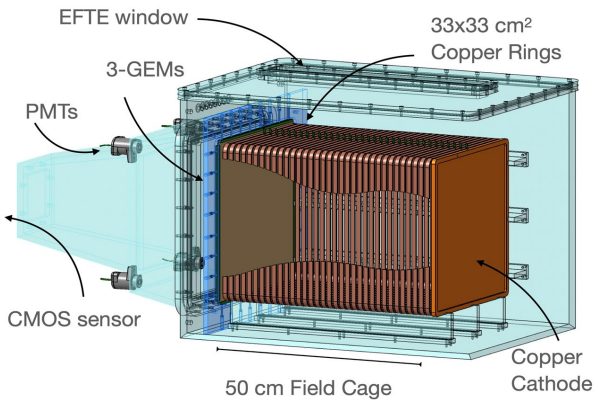
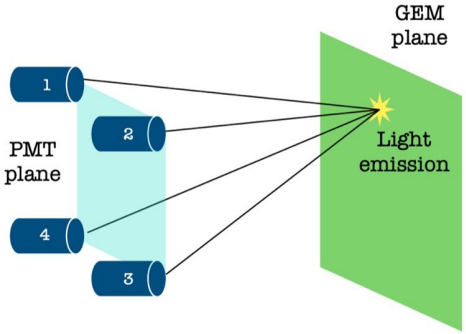
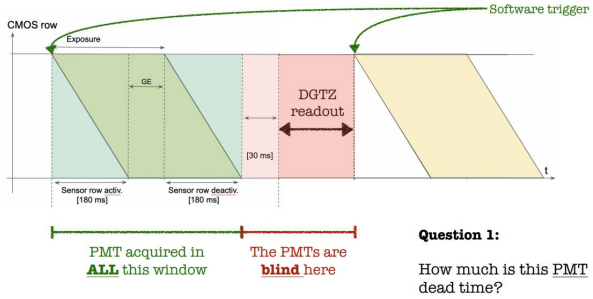


3D tracking and dual-sensor analysis

Ph.D. with CYGNO - How does LIME work?

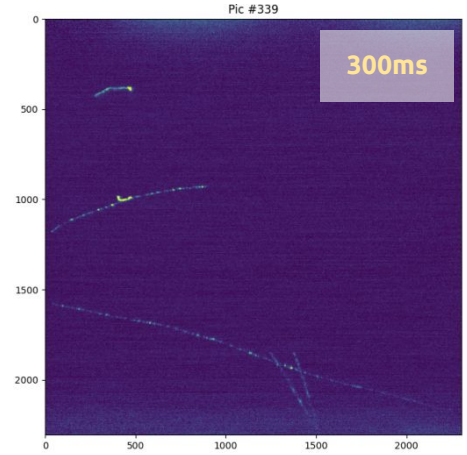






Question 1:

How much is this PMT dead time?



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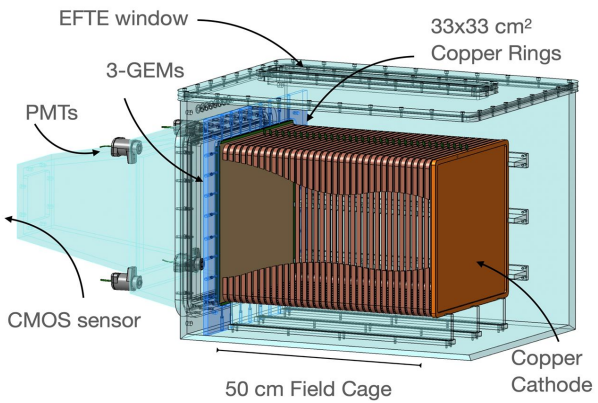

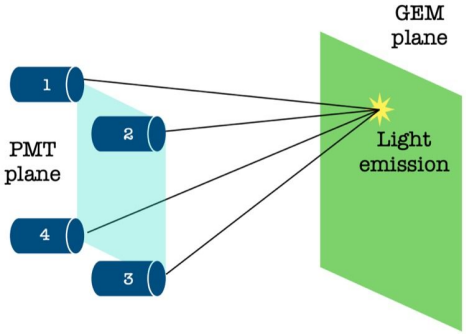

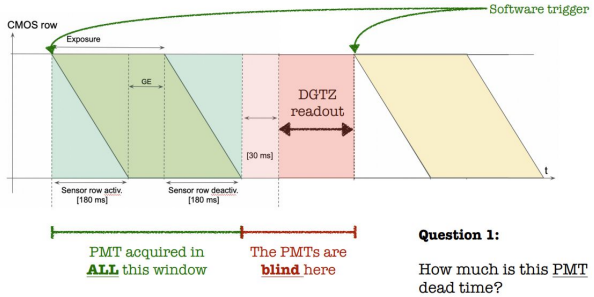

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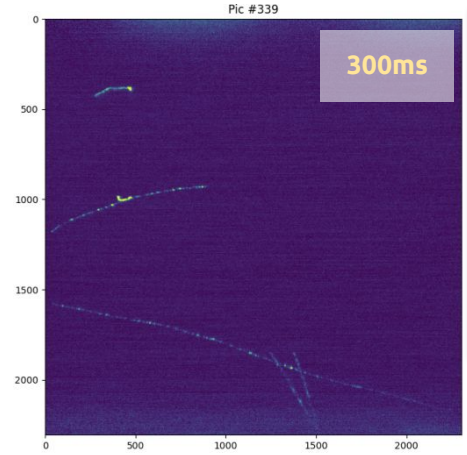
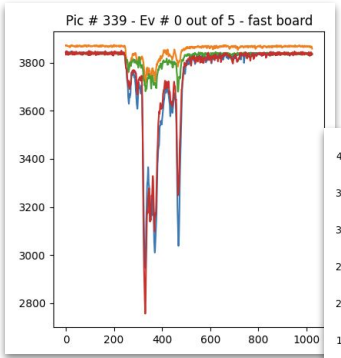
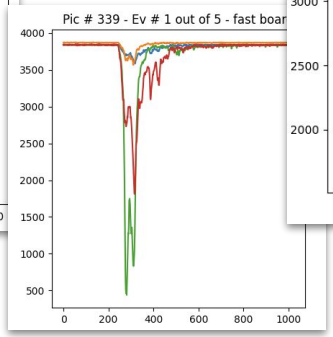
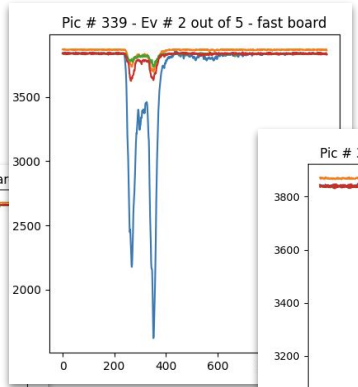


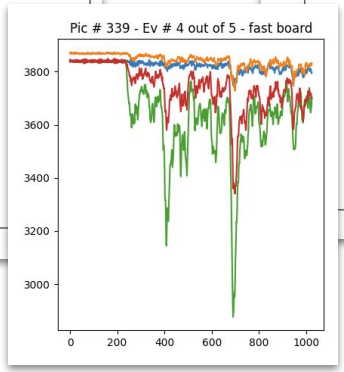


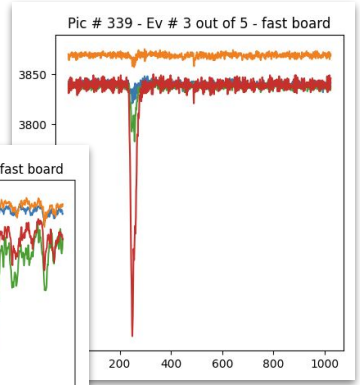
1.5us
16us





1.5us
16us





PMT Working Group - Activities Rundown

1. **PMT reconstruction**
   a. Full integration of **waveforms information** within CYGNO's data framework
2. **(L,x,y) Bayesian fit**
   a. Simultaneously fits **ionization X - Y and Light**
      i. This because the **light** seen by each PMT **changes with distance** ($L \propto 1/R^{\alpha}$)
3. **Association of PMT & camera events**
   a. A picture might contain **many events**. These must be **disentangled** for connection with PMT.
      i. **Closest neighbour approach** under study with comparison with camera variables
4. **3D reconstruction**
   a. Compute track angle / ΔZ
      i. ***Single peaks*** vs. ***Time over Threshold (ToT)***
5. **Cross-analysis with camera's info.**
   - dE/dx
   - NR vs ER
   - PID
6. **Longitudinal diffusion** from ^{55}Fe spots ***(+ NID)***
7. Fully or partial **integration of (x,y,L) fit** in PMT reconstruction.
8. **PMT Simulation**
9. Study of the **α parameter in $L \propto 1/R^{\alpha}$**

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7. Fully or partial **integration of (x,y,L) fit** in PMT reconstruction.

- These are the ***points of interest for my work***
- I have also ***actively participated and chaired PMT meetings*** where these topics are discussed.
- I have also met my co-workers in Rome Sapienza many times and well as ***cross-checked and gave suggestions*** in the results of other students

8. **PMT Simulation**
9. Study of the **α parameter in $L \propto 1/R^{\alpha}$**

PMT Work - PMT Reconstruction

First CYGNO PMT analysis

1. **PMT reconstruction** ➡ Full integration of **waveforms information** within CYGNO's data framework

➔ **Goal:**

- Create a **TTree** with the **PMT reconstructed variables**.
- Run PMT reconstruction together with Camera reconstruction on the cloud.
- Create a **framework** that allows the ***analysis of PMT events stand-alone and together with camera***.
  - (L,x,y), Z coordinate, Z diffusion, 3D reco, NR vs ER, PID, etc.

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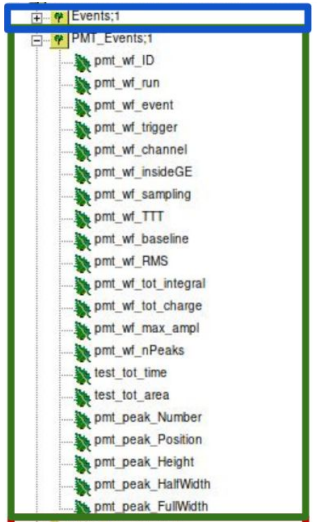
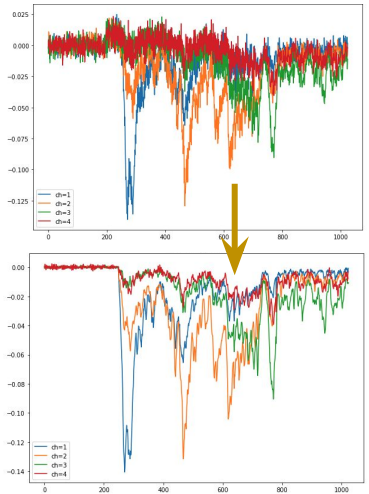




➔ **Steps already taken:**

- **Retrieve data** from DAQ through ***cygno_libs***
  - All four PMTs and all triggers associated with a given picture.
  - Waveforms **automatically corrected**.
- Tree created with basic variables.
  - pmt_wf_[run/event/trigger/channel/sampling]
  - pmt_peak_[Position/Height/HalfWidth/FullWidth]
  - pmt_tot_[integral/charge]
  - pmt_max_ampl
  - pmt_nPeaks
  - pmt_[baseline/RMS]

PMT Work - PMT Reconstruction

2. **(L,x,y) Bayesian fit** ➡ Simultaneously fits **ionization X - Y and Light**
3. **Association of PMT & camera events**
7. Fully or partial **integration of (x,y,L) fit** in PMT reconstruction.

Method (1)

BAT

Measure $L_{1\text{-}4}$
Infer x, y, L

Reconstruction performed with a Bayesian analysis:

Likelihood

$$p(\boldsymbol{\theta}|\{x_i\}) = \frac{p(\{x_i\}|\boldsymbol{\theta}) \cdot \pi(\boldsymbol{\theta})}{p(\{x_i\})}$$

Prior *pdf*

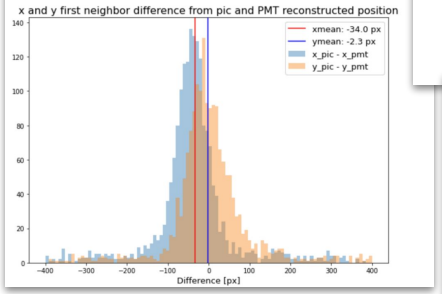
Posterior *pdf*

Normalization factor

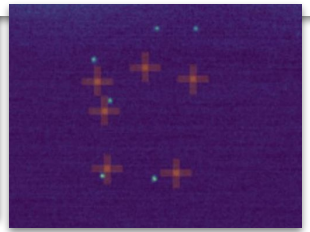
Where: $R_i = \sqrt{x_i^2 + y_i^2 + z_i^2}$

Likelihood: $p(\{x_i\}|\boldsymbol{\theta}) = \prod_i \mathcal{N}(\{x_i\}|\mu_i(\boldsymbol{\theta})) \rightarrow \mu_i = \frac{L}{R_i^4}$

Closest neighbour (PMT waveform assigned to the closest cluster found)



- **Performance:**
  - 37% within 1cm
  - 73% within 2cm



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Infer x, y, L

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Likelihood — Prior pdf — Posterior pdf — Normalization factor

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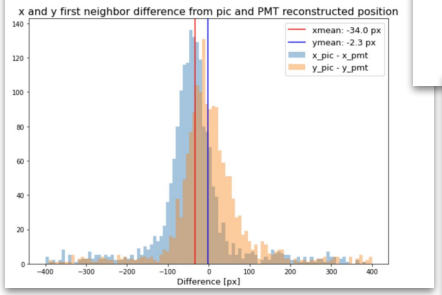

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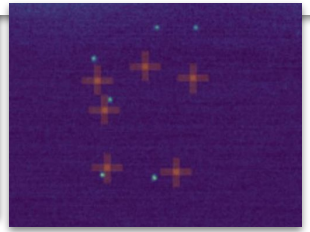
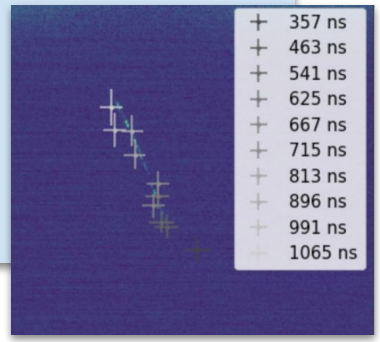


➔ Fit allows to retrieve event's ***energy***
- ◆ **I used it to calculate *dE/dx*** by merging it with it ***Time-over-Threshold***

➔ Fit allows position comparison with camera picture
- ◆ I'm working on a process to do the **1-to-1 coincidence** between ionization cluster and PMT waveform
  - Closest position neighbour
  - Closest energy neighbour

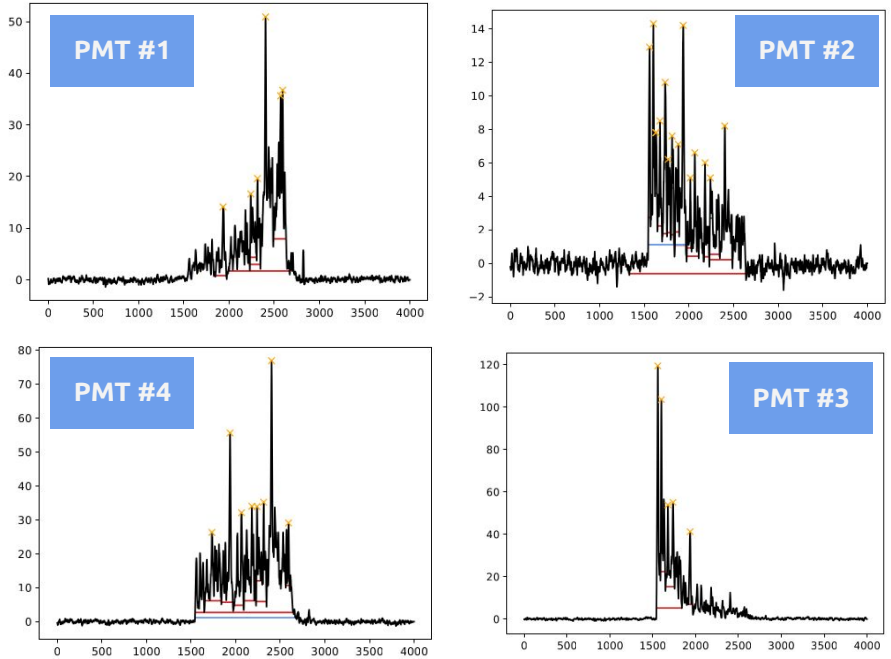
➔ Given it's importance **I'm currently integrating** of the fit in the overall CYGNO analysis framework.



PMT Work - 3D and cross-analysis

4. 3D reconstruction
9. Cross-analysis with camera's info

⇒ Time over threshold (TOT)



➔ Measurement of the **time length** of the signal which is **above a given threshold**.

- Not trivial when each PMT sees a different signal intensity and tracks can have very complicated paths
- I do a ***weighted average based on waveform's SNR*** ⇒ *Only correct for timing purposes*

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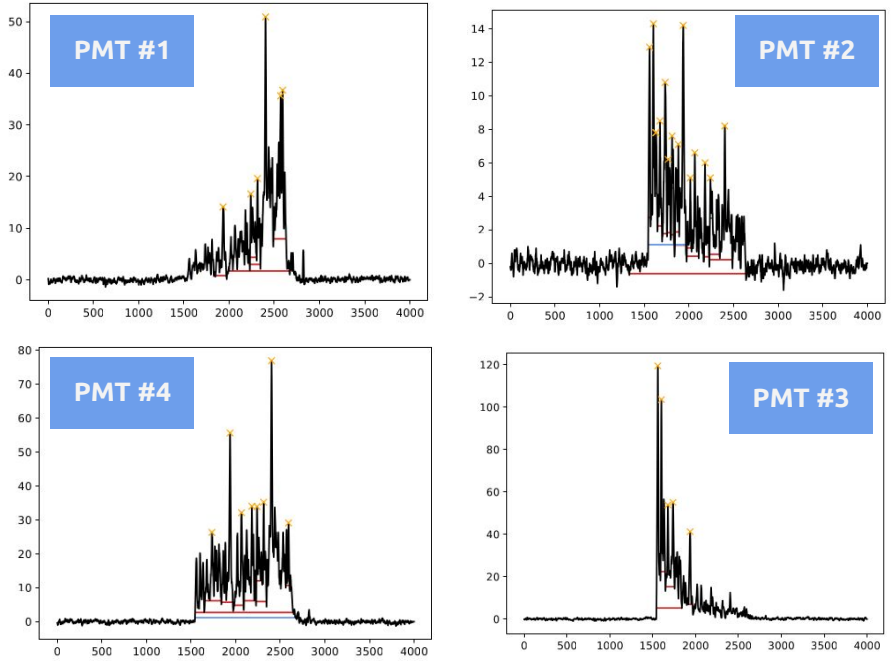

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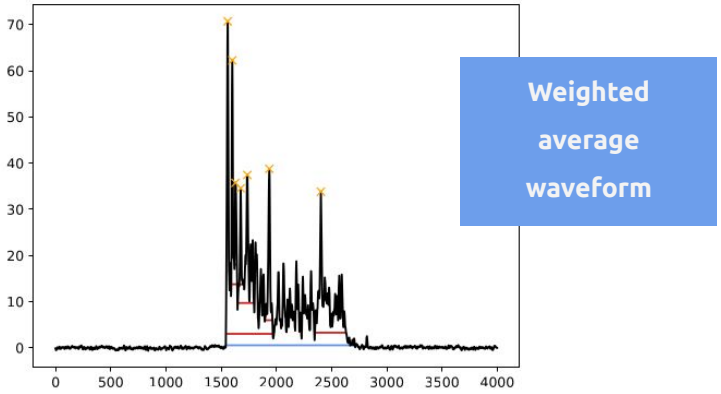

PMT Work - 3D and cross-analysis

4. 3D reconstruction
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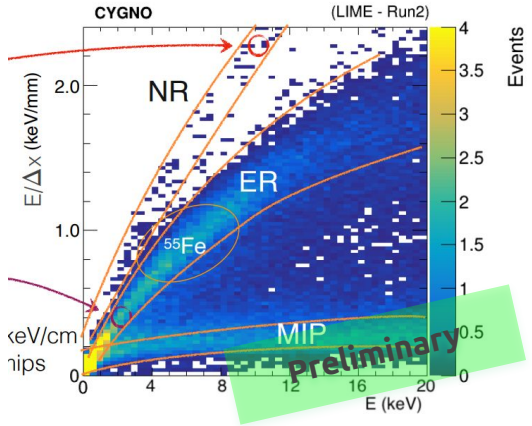
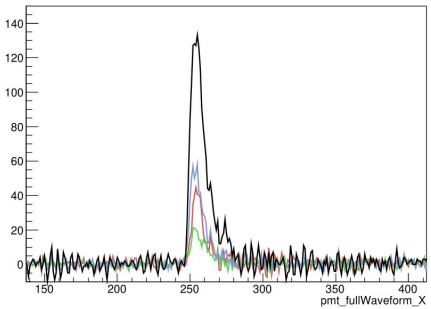
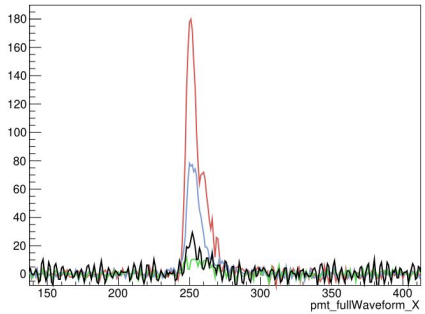
⇒ Time over threshold (TOT)

1. I tried to replicate sCMOS sensor **dE/dx vs. E** plot
   a. Each PMT sees a **different intensity** but approximately the same time extension ⇒ Results in a different dE/dx.
      i. Solved by using Bayesian fit **L (fitted luminosity)** of a given trigger mixing the 4 PMT signals.







For the ***length*** I used the ***Time over Threshold***

↓

Thus, in fact I'm plotting the **dE/dz**

PMT Work - 3D and cross-analysis

4. 3D reconstruction
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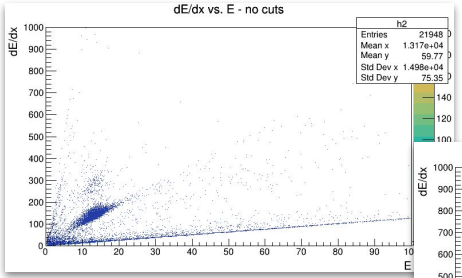
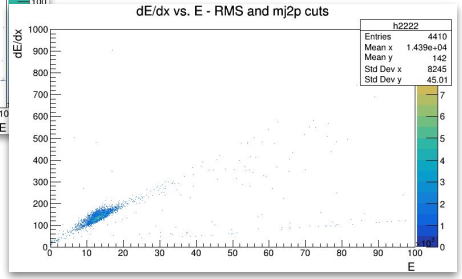
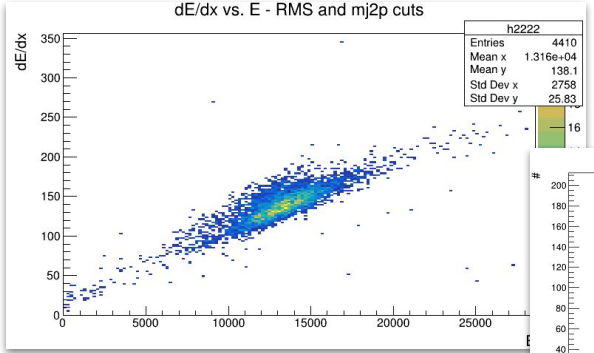
⇒ Time over threshold (TOT)

1. I calculated the dE/dx of calibration runs with ^{55}Fe
2. This is calculated using the the **fitted L** and **time over threshold**
3. Different **cuts** were studies: **RMS** and **mj2p**

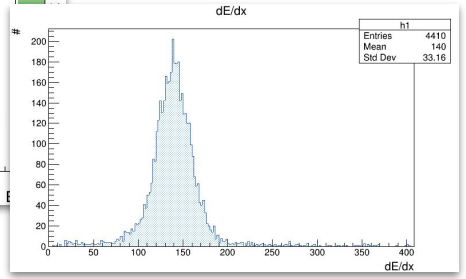


Applying cuts





Zoomed in



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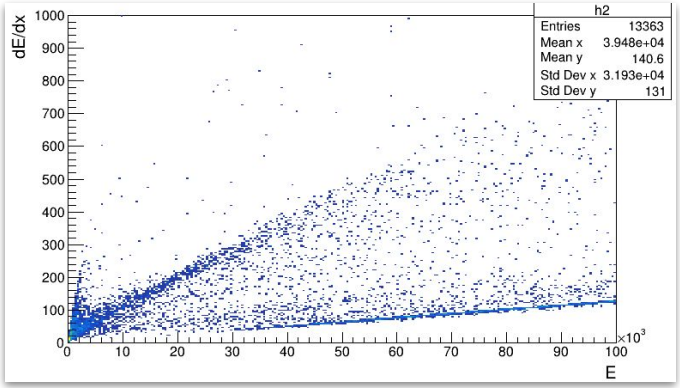
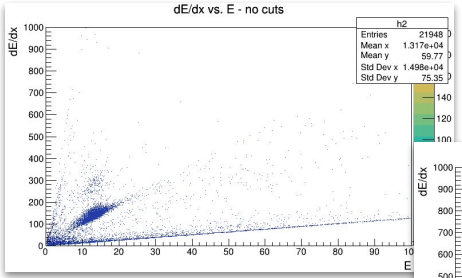
Comparing to BG-only run





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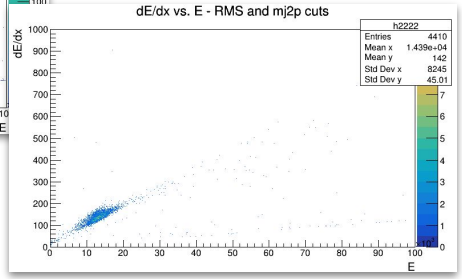

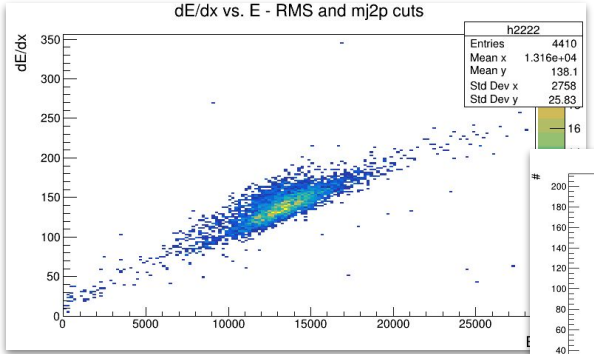

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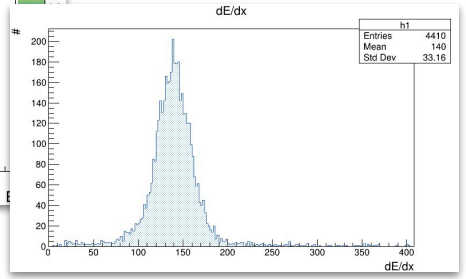

PMT Work - 3D and cross-analysis

4. 3D reconstruction
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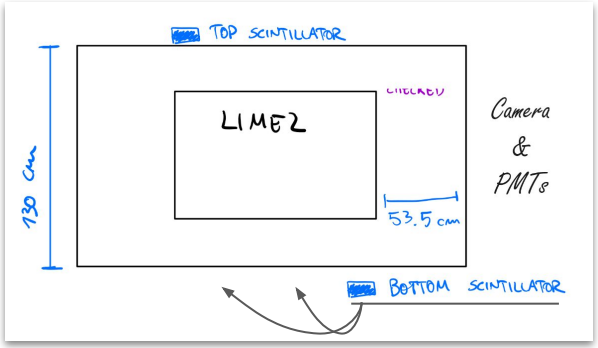
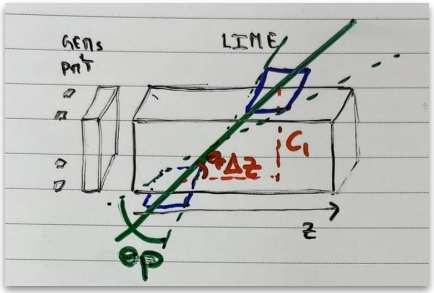
⇒ Next studies ⇒ *Tilted cosmic rays analysis*

Setup:

- ➔ Two scintillator bars are placed on top and bottom of LIME
- ➔ LIME DAQ triggered by coincidence of two scintillators
  - ◆ Only certains angles (by geometry) are possible
  - ◆ 3 different scintillator position were used





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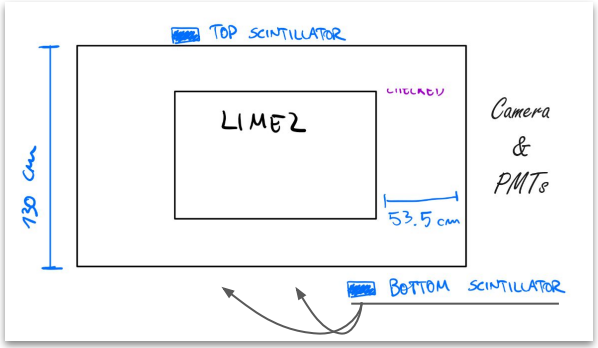
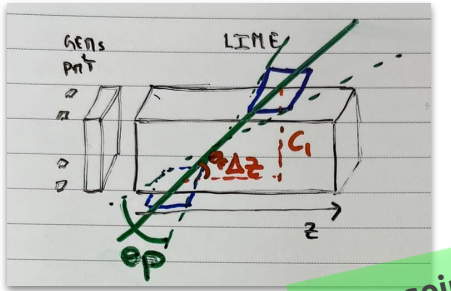




Motivation & Math:

- ***This measurement presents a clear dataset with track with well-defined orientation and energy deposit (MIP)***
  - We have a given **range of possible angles** of entering LIME (given by geometry of LIME + scintillators)
  - We can **superimpose** it with the **cosmic muons angle distribution** at ground ($\propto \cos^2(\Theta)$*) to get the **theoretical angle distribution (Θ_{teo})**.
  - PMT measures the Time over Threshold
    - Multiplied by $v_{drift\ e^-}$ gives the **Δz**
  - Height of LIME (c1) is known (33 cm)
    - The tracks inclination (α) will be **$\tan^{-1}$ (c1/Δz)**
  - We can compare **Θ_{teo}** with **α**.
    - **First CYGNO 3D analysis** (on a distribution)
    - **Gives us a measurement of PMT Reco / ToT efficiency**

Ongoing...

*https://dx.doi.org/10.1088/1475-7516/2023/04/025

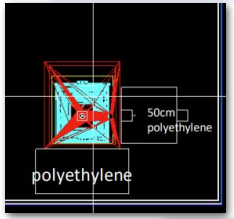
PMT Work - 3D and cross-analysis

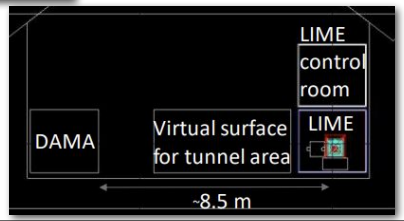
4. 3D reconstruction
9. Cross-analysis with camera's info

⇒ Next studies ⇒ *Nuclear recoil data set*

Setup:

- ➔ ***AmBe*** source placed near LIME
- ➔ ***LIME was shielded*** with Polyethylene, water and copper to block external radiation, thus creating a ***clean dataset***





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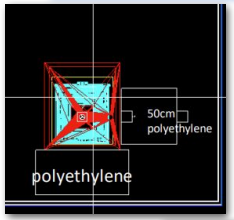
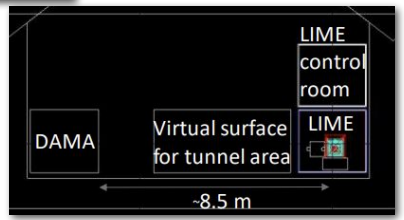
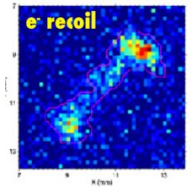
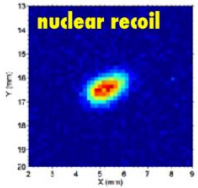


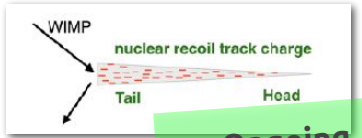


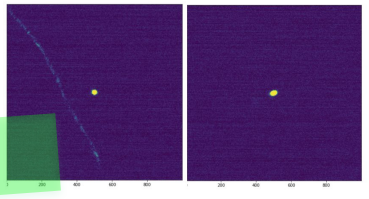
Motivation & Expectations:

- Clean **dataset of NR** obtained with a AmBe source ➡ ***WIMP-like signals***
  - 3D from ToT since they're straight tracks
  - Dual-sensor analysis (sCMOS + PMT)
  - dE/dx analysis ➡ PID for NR vs. ER
  - Track sense/direction from head-tail asymmetry
    - ***Paramount for CYGNO directional searches!***









Ongoing...

Parallel work with MANGO

a **M**ultipurpose **A**pparatus for **N**egative ion studies with **G**EM **O**ptical readout

Parallel work with MANGO

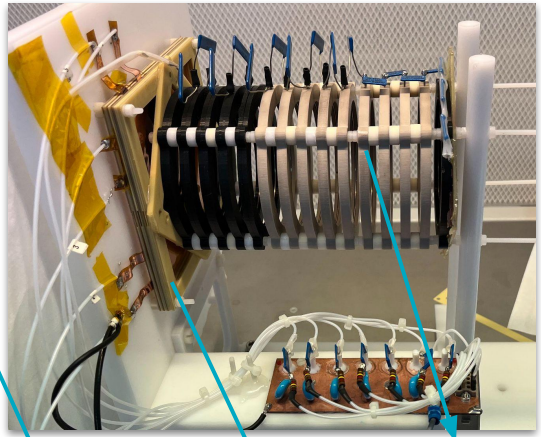
a Multipurpose Apparatus for Negative ion studies with GEM Optical readout

➔ **Enhancement of light yield**

- Different types/configuration of **GEMs**
- ITO vs. Mesh

➔ **Negative Ion Drift**

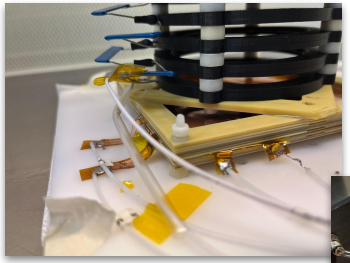
- Optimal **gas pressure**, **composition** & **amplification** config.
- **Transverse & Longitudinal Diffusion**
- **Ion mobility**

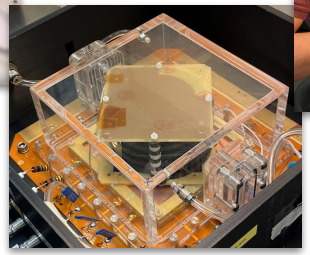


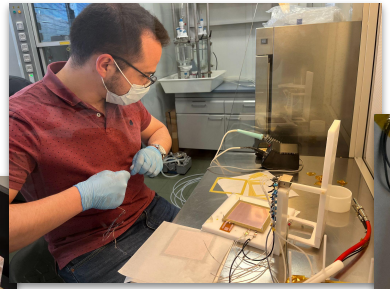
15 cm drift field cage

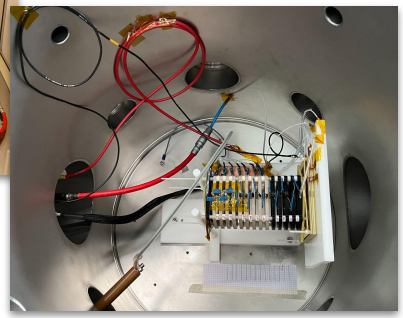
3 GEM stack:
50 μm thick
140 μm pitch
∅70 μm holes

GEMs facing **sCMOS** and **PMT**









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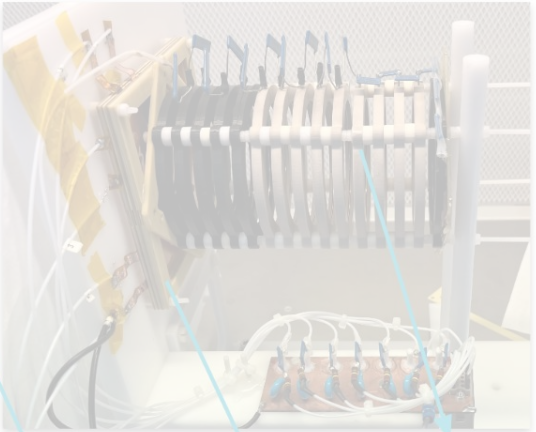

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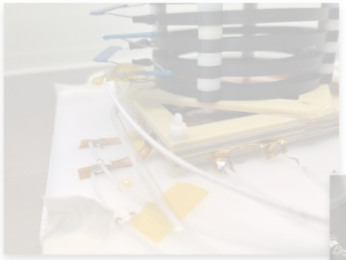
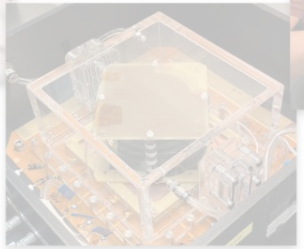
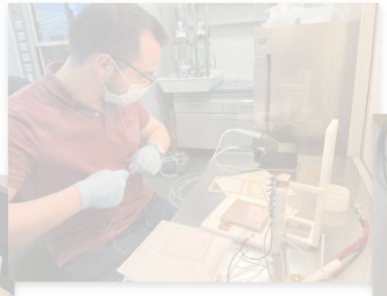
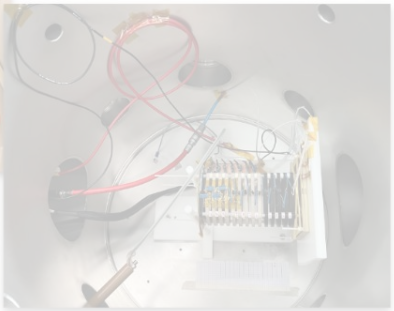




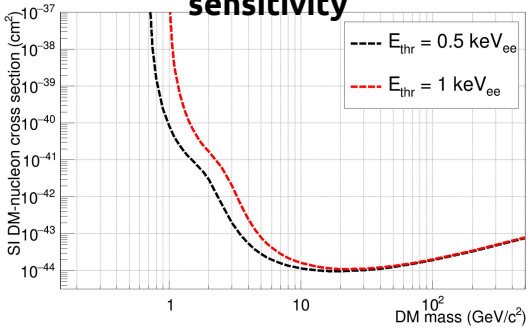




Enhance. of light yield - Motivation & Setup

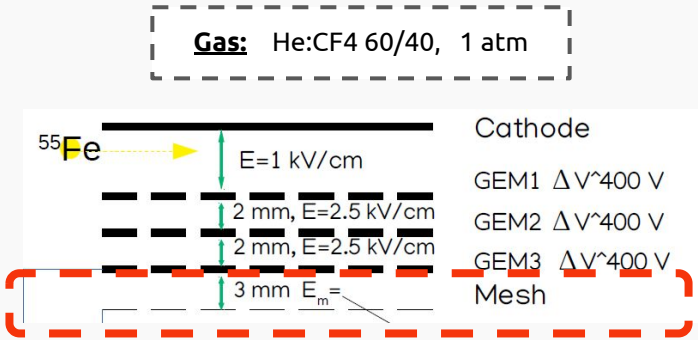
In CYGNO, the energy threshold is proportional to the amount of photons collected.

□ Light ⇒ □ Energy Threshold ⇒ □ DM sensitivity



Options:

- ➔ **Increase V_GEM ⇒ □ Sparks ❌**
- ➔ **Increase #GEMs ⇒ □ Diffusion/saturation ❌**
- ➔ **Applying a stronger electric field after the last GEM ⇒ □ Light + ~ spatial/energy res. ✅**



After crossing the last GEM, in the induction gap, an additional electric field (E_mesh) is applied.

⇓

Electrons are further ***accelerated***

⇓

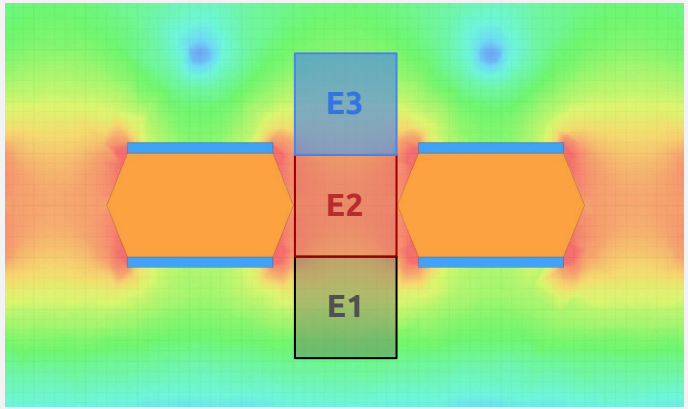
Additional light and charge is produced

⇓

Advantages and limitations were investigated!

Simulation - Model

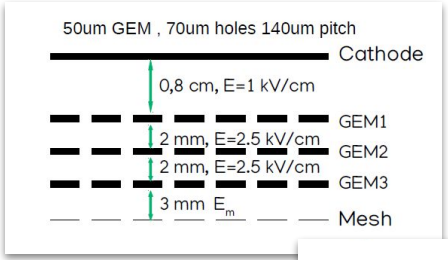
- To better quantify these effects, we used the 3 ***contiguous*** regions were the electric field profile was studied:
  - Below (E1), inside (E2) and above (E3) GEM.
- Box length = length of internal hole diameter, for ***thin*** and ***Thick***.
- Obtain the electric field in matrix in these squares (1 um res).
- Average over all points.
- Average over 10 holes.

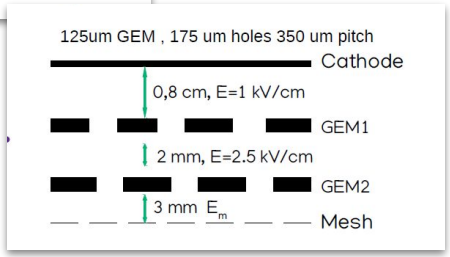


x 10 holes

Tests performed:

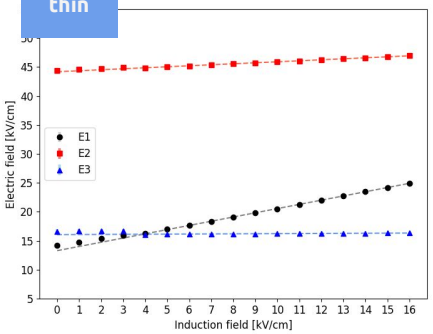
- ***Scan V_mesh***, with fixed V_GEMs
- ***Scan on V_GEMs***, with a fixed V_mesh
- 2 different configurations:
  - **thin** (t - t - t)
  - **Thick** (T - T)



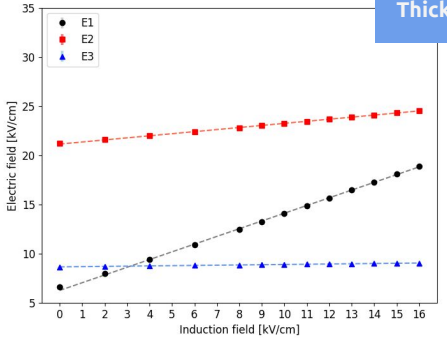


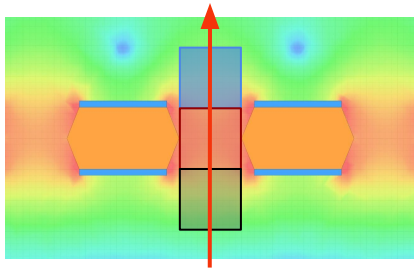
Simulation - Average field - Expectations

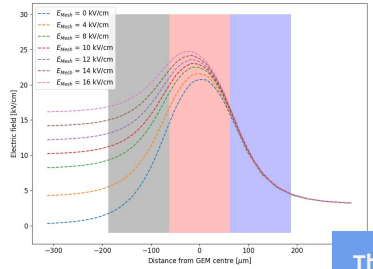
thin



Thick

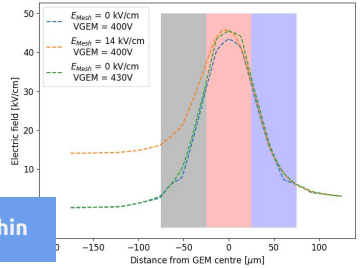


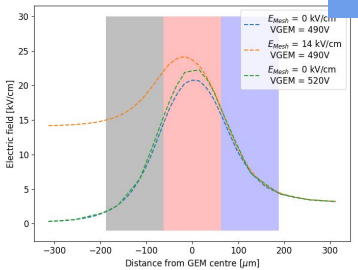




Thick

thin





★ E_mesh **doesn't** change field **above GEM**.

★ E_mesh **increases** field **inside GEM**.

- *Linear increase* of the electric field. ✅

★ E_mesh **greatly** affects field **below GEM**.

- Reaches values enough to produce amplification. ✅
- TT configuration works with lower fields thus we expected the light yield increase to be more notorious with the thick GEMs. ✅

The addition of the **induction field** ***changes the shape*** of the profile:

★ The **field's maximum** ***increases in amplitude and shifts*** towards the **bottom** part of the GEM hole.

★ Generates a ***large region below the GEM where amplification and/or light production can happen.***

★ For Thick GEMs, the influence is ***relatively*** **much larger.** ✅

Enhance. of light yield - Final conclusions

Scenario	GEM conf.	E_mesh [kV/cm]	Light integral	ΔE [%]	Diffusion [μm]
Maximizing induction (E_mesh) field	ttt	15 ± 0.3	33500 ± 140	13.8 ± 0.3	388 ± 5
	TT	14 ± 0.3	58800 ± 300	25.7 ± 0.5	356 ± 5
	Tt	12.8 ± 0.2	11830 ± 50	26.8 ± 0.5	280 ± 4

- When maximizing E_mesh, the **ttt maintains a good ΔE** when compared with the other configurations.
- For the **TT case**, maximizing E_mesh allows for a **very high increase of light yield**, with similar intrinsic diffusion to the ttt (but losing on ΔE).
- Finally, the **Tt configuration excelled in intrinsic diffusion** in all the tests performed (check back-up), but with an overall worse ΔE.

Paper under final collaboration review!

★ In sum, the choice boils down to the experiment's requirements:

- **ttt ⇒ Energy resolution**
- **TT ⇒ Light yield**
- **Tt ⇒ Intrinsic diffusion**

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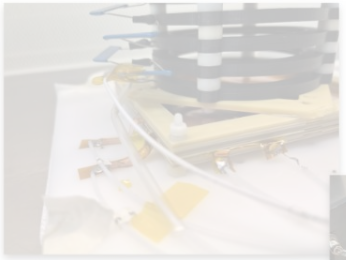

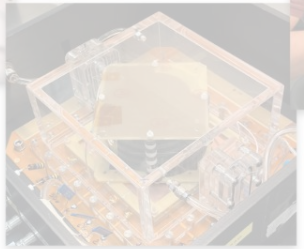

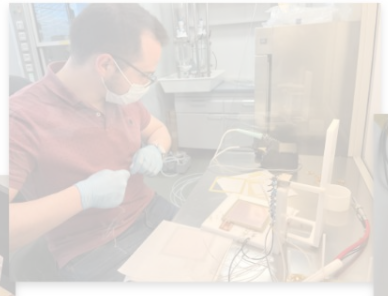

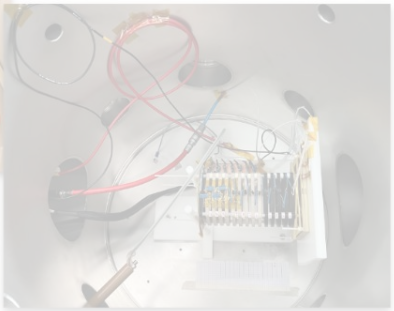

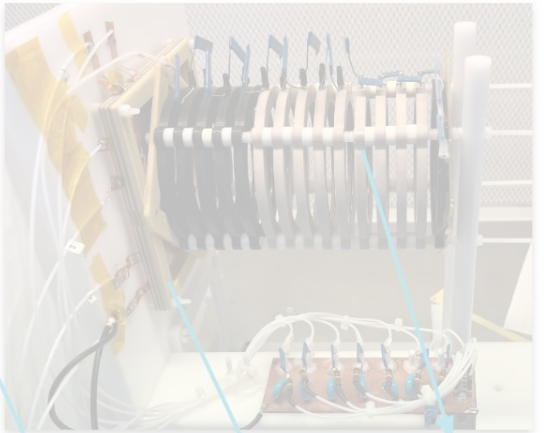

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Negative Ion Drift - INITIUM concept

an Innovative Negative Ion TIme projection chamber for Underground dark Matter searches | INITIUM | Project | Fact sheet | H2020 | CORDIS | European Commission

Advantages:

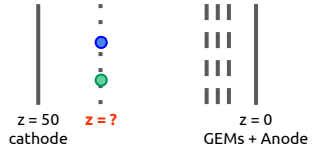
Reduced diffusion

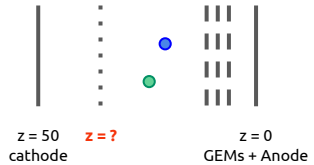
Longitudinal and transverse **diffusion reduced to thermal limit**

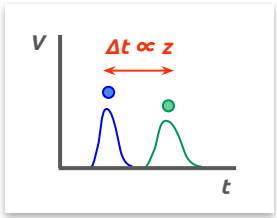
$$\sigma_D = \sqrt{\frac{4\varepsilon L}{eE}}$$

Better spatial resolution!

Multiple charge carriers







Absolute Z from Δt between minority charge carriers

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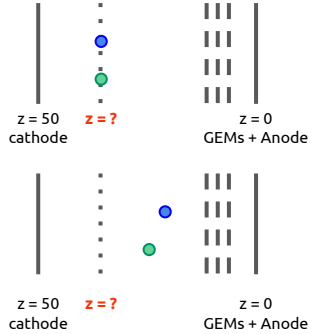

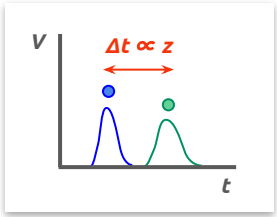

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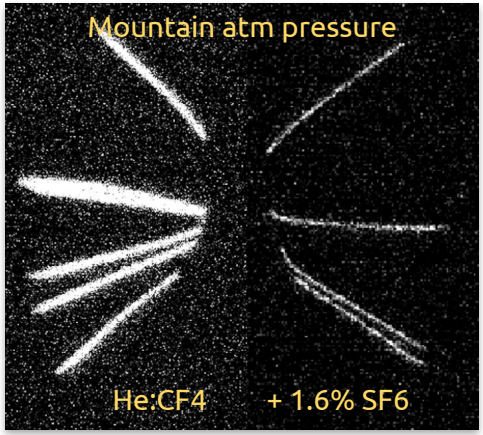
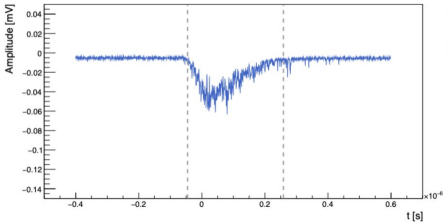




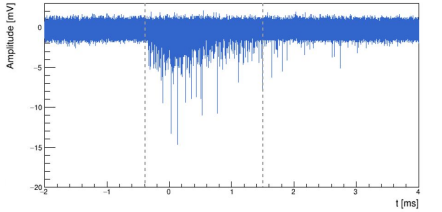
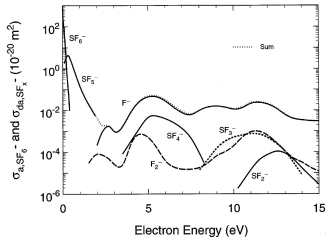


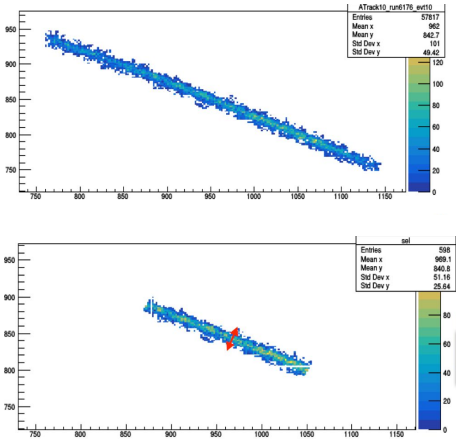
Table 2
Collisional processes that originate the SF_6 ion species of interest for this work. Adapted from Ref. [46].

Reaction	Process	Energy
$e^- + SF_6 \rightarrow SF_6^{-*}$	Electron attachment	<1 meV
$SF_6^{-*} \rightarrow SF_6 + e^-$	Autodetachment	(Metastable: > 1 μs)
$SF_6^{-*} + SF_6 \rightarrow SF_6^- + SF_6$	Collisional stabilization	
$e^- + SF_6 \rightarrow SF_5^- + F$	Dissociative electron attachment	0–2 eV
$e^- + SF_6 \rightarrow SF_4^- + 2F$		3–8 eV
$e^- + SF_6 \rightarrow F^- + SF_5$		1–14 eV
$e^- + SF_6 \rightarrow F_2^- + SF_4$		1–14 eV
$SF_{5/6}^- + SF_6 \rightarrow SF_{5/6} + SF_6 + e^-$	Collisional detachment	>90 eV
$SF_6^- + SF_6 \rightarrow SF_6 + SF_6^-$	Charge transfer	
$SF_6^- + SF_6 \rightarrow SF_5^- + F + SF_6$	Dissociative charge transfer	>1 eV

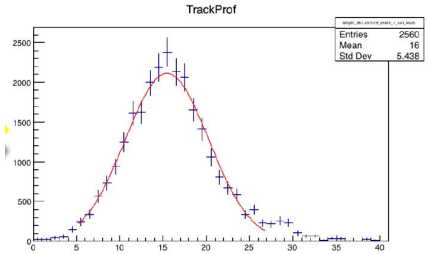


https://doi.org/10.1016/j.nima.2022.1661416

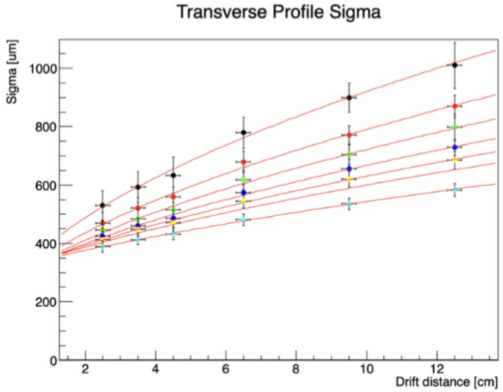
Negative Ion Drift - sCMOS analysis



Transverse profile of track fitted with Gaussian to estimate diffusion



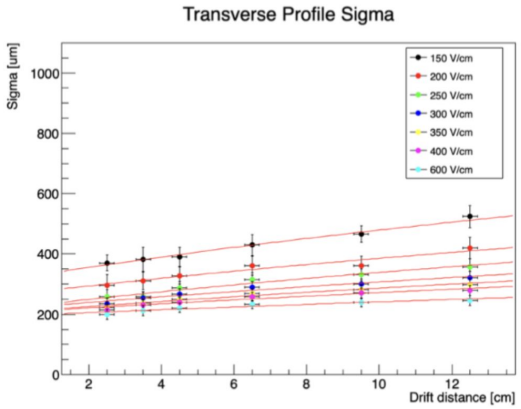
He:CF_4 60:40 (Electron drift)



$$\sigma_{meas} = \sqrt{\sigma_0^2 + \sigma_T^2 L}$$

Drift field [V/cm]	σ_0^{ED}	σ_T^{ED}	σ_0^{NID}	σ_T^{NID}
150	300 ± 100	280 ± 20	320 ± 30	110 ± 10
200	290 ± 60	230 ± 10	260 ± 30	88 ± 20
250	284 ± 60	210 ± 10	220 ± 20	81 ± 10
300	300 ± 40	190 ± 10	220 ± 20	68 ± 10
350	300 ± 40	170 ± 10	210 ± 20	62 ± 10
400	310 ± 30	160 ± 10	210 ± 20	56 ± 9
600	320 ± 22	140 ± 10	200 ± 20	45 ± 10

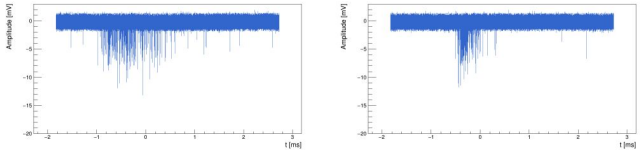
He:CF_4:SF_6 59:39.6:1.6 (Negative ion drift)



- Negative Ion Drift operation!
- ***Transverse diffusion*** reduced by **3 times!**
- ***What about the PMT signals?***

Negative Ion Drift - PMT analysis

➔ I focused on the **PMT analysis**



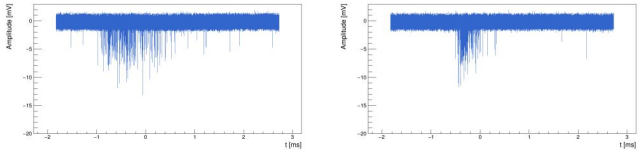
(a) 300 V/cm. (b) 700 V/cm.

Peculiar signal:

- ➔ Thousands of small peaks (~ns width) over large time span (~ few ms) ⇒ ***primary ionization cluster counting?*** ***~> Perfect resolution***
- ➔ Features visible➡ Note the enlargement of signal with lower drift field.
- ➔ ***First optical observation of NID*** ➡ ➡ **Few or none literature** on this

Negative Ion Drift - PMT analysis

➔ I focused on the **PMT analysis**



(a) 300 V/cm. (b) 700 V/cm.

Peculiar signal:

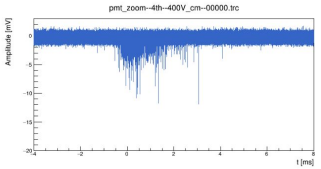
➔ Thousands of small peaks (~ns width) over large time span (~ few ms) ⇒ ***primary ionization cluster counting?*** ***~> Perfect resolution***

➔ Features visible➡ Note the enlargement of signal with lower drift field.

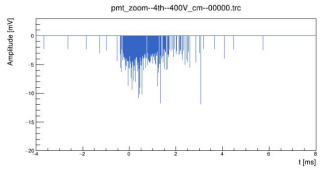
➔ ***First optical observation of NID*** ➡ ➡ **Few or none literature** on this

First ever PMT analysis for optical NID signals

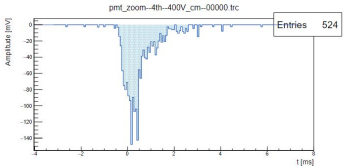
- **Initial approach ⇒ Time rebinning**
  - a. **Threshold** ➡ Only peaks above 6*RMS are taken into account
  - b. **Rebin** ➡ Selected points are put into histogram
  - c. **Delimitation** ➡ Start (end) when 2 bins are above(below) 10 mV
  - d. **Systematics** ➡ Varying #bins & threshold voltage **(reworked analysis)**



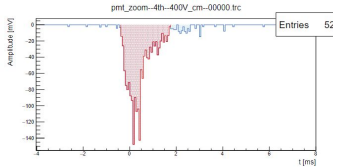
(a) Original signal.



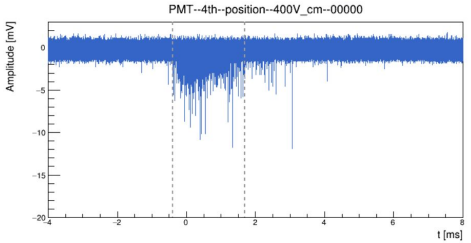
(b) Only peaks over noise threshold (2.5 mV).



(c) Rebinned waveform.



(d) Reconstructed signal in red.

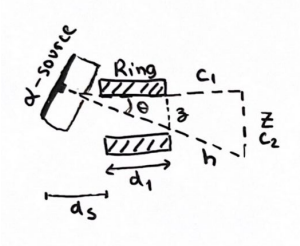


(e) Final boundaries in the original signal.

Negative Ion Drift - PMT analysis

Final measurement: Ion Mobility ➡ *Updated version!*

1. Tilted ED alpha tracks
   a. Distribution ➡ Get mean value (Δt)
   b. Knowing electrons' velocity in gas (v)
      i. **Z travelled by track ➡ 1.5 cm**



2. Tilted NID alpha tracks
   a. Average time window **(Δt)**
      i. **Z / Δt = *v_ion***

Negative Ion Drift - PMT analysis

Final measurement: Ion Mobility ➡ *Updated version!*

1. Tilted ED alpha tracks
   a. Distribution ➡ Get mean value (Δt)
   b. Knowing electrons' velocity in gas (v)
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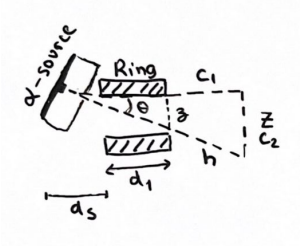
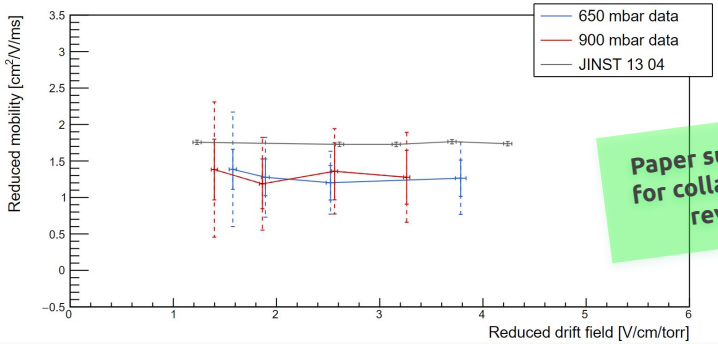


2. Tilted NID alpha tracks
   a. Average time window (Δt)
      i. Z / Δt = *v_ion*

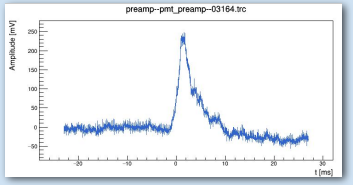


Paper submitted for collaboration review!

- Data ***self-consistent*** with previous year's data (900 mbar)
- Charge carriers' ***mobility*** consistent with ***SF6-*** in literature
- ***PMT signal undoubtedly proved NID with optical readout!***

Future:

➔ New data with pre-amp to be analyzed.



- Could help understanding the signal's structure
- ***Diffusion measurement to complement sCMOS analysis***

Thank you for your attention!

Scientific Communications (November 2022 - October 2023):

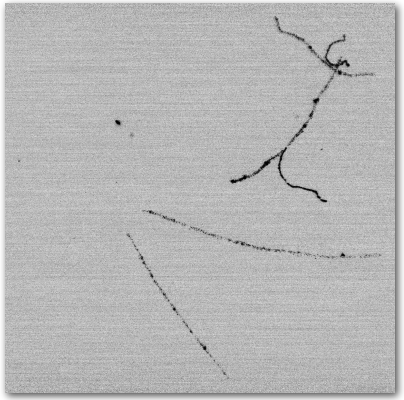
1. **Papers:**
   - 1.1. **LIME — A gas TPC prototype for directional Dark Matter search for the CYGNO experiment**
     Amaro, F. D.; Baracchini, E.; Benussi, L. et al
     NIM A, Mar. 2023
   - 1.2. **50 litres TPC with sCMOS-based optical readout for the CYGNO project**
     Mazzitelli, G.; Amaro, F. D.; Baracchini, E. et al
     NIM A, Jan. 2023
   - 1.3. **Noise assessment of CMOS Active Pixel sensors for the CYGNO Experiment**
     Almeida, B. D.; Amaro, F. D.; Antonietti, R. et al
     Meas. Sci. Technol., Sep. 2023 (accepted)
   - 1.4. **Dual-Polarity Ion Drift Chamber: Experimental results with Xe–SF6 mixtures**
     Marques, A.P.; Marques, D.J.G.; Duarte, N.G.S. et al
     NIM A, Jan. 2023
   - 1.5. **Directional iDBSCAN to detect cosmic-ray tracks for the CYGNO experiment**
     Amaro, F. D.; Antonietti, R.; Baracchini, E. et al
     Meas. Sci. Technol., Sep. 2023
   - 1.6. **A 50 liter CYGNO prototype overground characterization**
     Amaro, F. D.; Baracchini, E.; Benussi, L. et al
     EPJ C (submitted)
   - 1.7. **Secondary scintillation yield from GEM electron avalanches in He-CF4 and He-CF4-isobutane for CYGNO – Directional Dark Matter search with an optical TPC**
     Amaro, F. D.; Baracchini, E.; Benussi, L. et al
     Phys. Letter B (submitted)

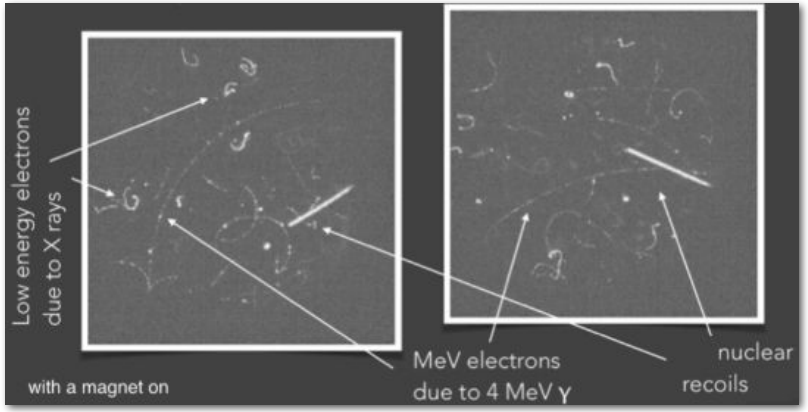
2. **Conference Communications:**
   - 2.1. **The CYGNO experiment, a directional optically readout detector for Dark Matter searches**
     Oral presentation
     CPAD 2022, the Coordinating Panel for Advanced Detectors, 29/11 - 2/12, 2022, Stony Brook, US
   - 2.2. **CYGNO, a directional Dark Matter TPC optically readout**
     Oral presentation
     LIDINE 2023, Light Detection in Noble Elements, 20 - 22 Sep, 2023, Madrid, Spain

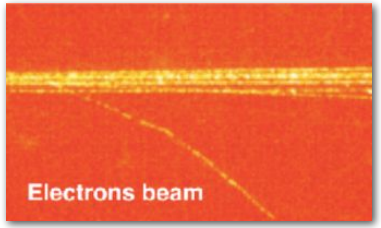
Backup

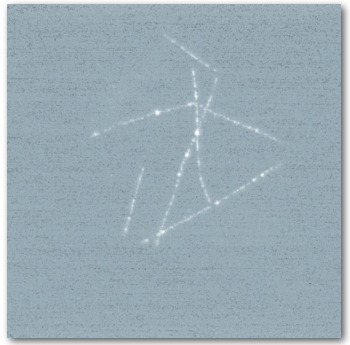
& more details

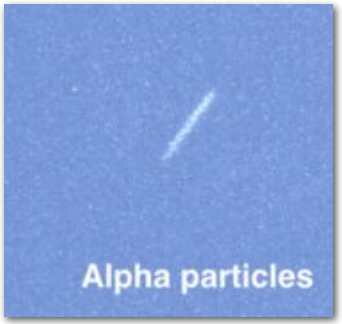
CYGNO - Some pictures!

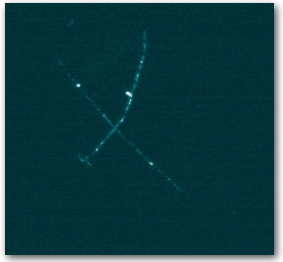


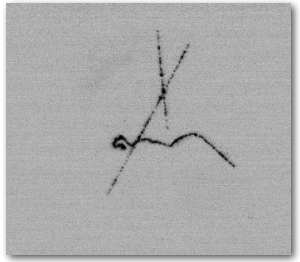


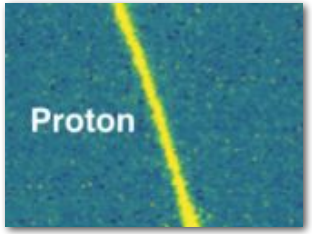












Enhance. of light yield - Simulation with Maxwell

➔ Given a setup with **different materials** and **voltages** applied, Maxwell calculates the **electric field** within a defined region. ***Different GEM configurations were designed and studied***.

Source

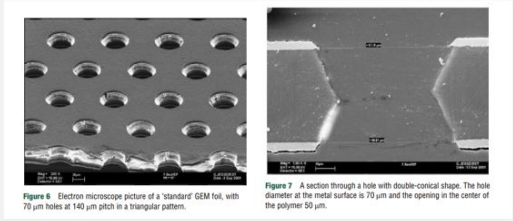
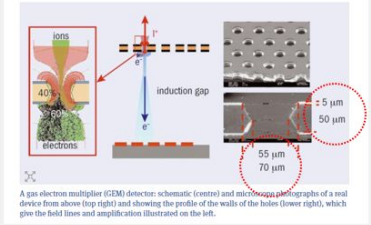


Figure 6 Electron microscope picture of a 'standard' GEM foil, with 70 μm holes at 140 μm pitch in a triangular pattern.

Figure 7 A section through a hole with double-conical shape. The hole diameter at the metal surface is 70 μm and the opening in the center of the polymer 50 μm.

https://doi.org/10.1016/B978-0-444-53632-7.00625-0

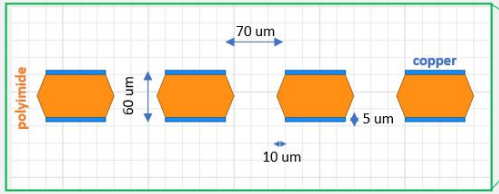


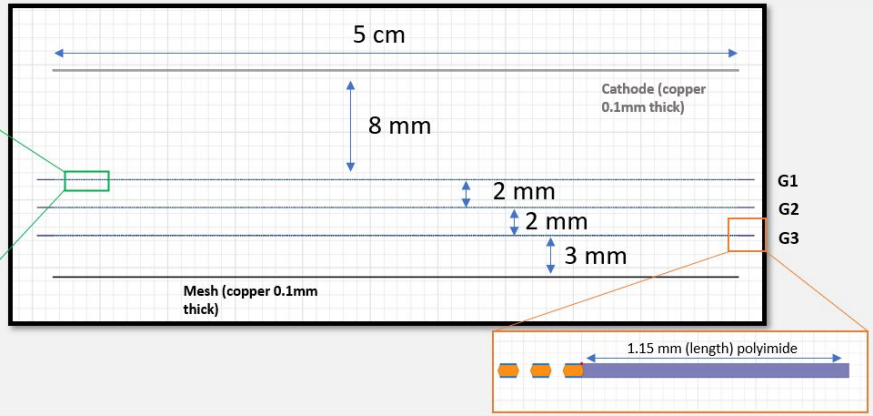
A gas electron multiplier (GEM) detector: schematic (centre) and microscope photographs of a real device from above (top right) and showing the profile of the walls of the holes (lower right), which give the field lines and amplification illustrated on the left.

https://cerncourier.com/a/the-continuing-rise-of-micropattern-detectors/

https://indico.cern.ch/event/346614/contributions/813299/attachments/683646/939073/GEM_at_CERN_seminar.pdf

Outcome





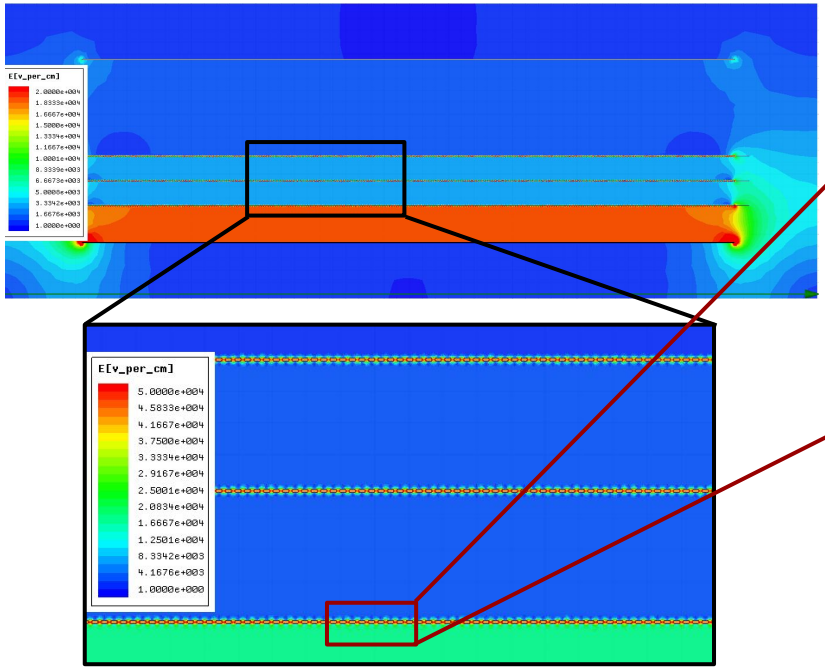
GEMs studied:

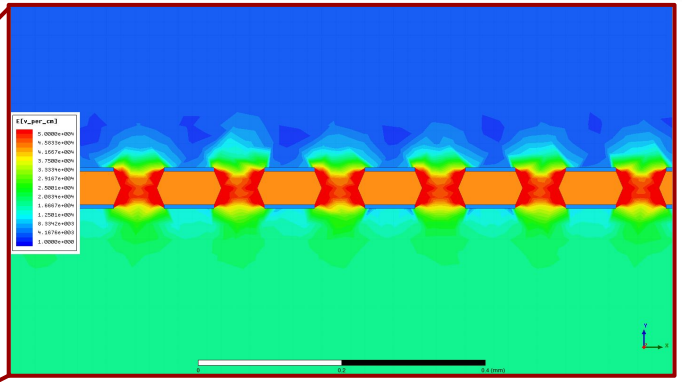
- Thin:
  - 50 um Kapton
  - 70 um holes
  - 140 um pitch
- Thick:
  - 125 um Kapton
  - 175 um holes
  - 350 um pitch

Maxwell - A visual example

❑ **Example of the calculated electric field in the t-t-t configuration.**

- V_GEMs : 400V
- TFs: 2.5 kV/cm, in 2 mm
- DF: 1kV/cm, in 8mm
- **Induction field: 18.3 kV/cm, in 3 mm**



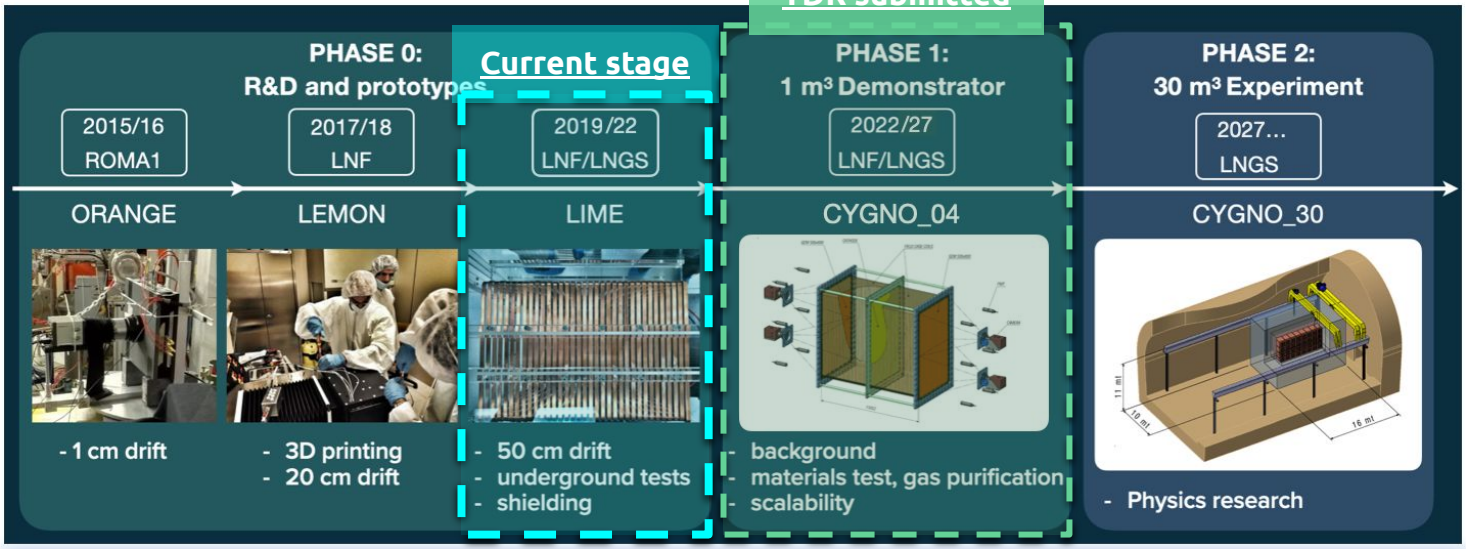


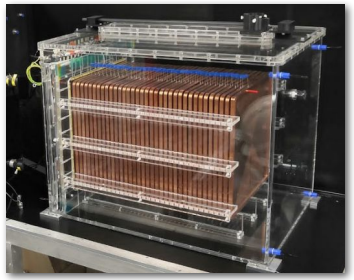
- ➔ We focus on the **middle** to avoid border effects.
- ➔ **Macro fields constant** (parallel plates)
  - ◆ **We focus on the fields close to the GEMs**
- ➔ Induction field innocuous to GEM 1 and GEM 2
  - ◆ **We focus on the effects observed in GEM 3**

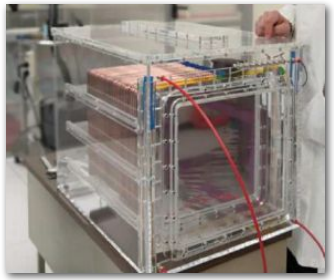
CYGNO - The roadmap

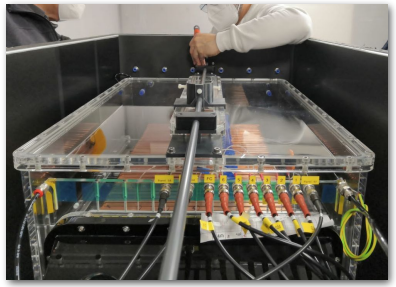
Several ongoing efforts in different fronts:

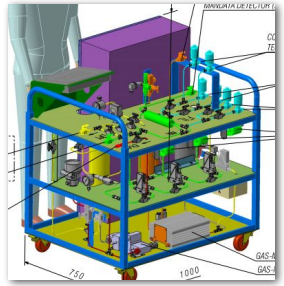
- Sensitivity
- 3D reconstruction
- Directionality
- ER vs. NR discrimination (ML)
- Shielding optimization
- Data vs. MC





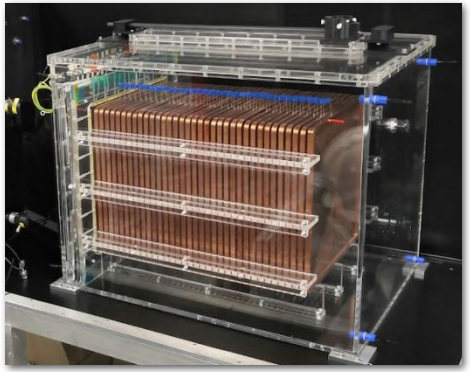




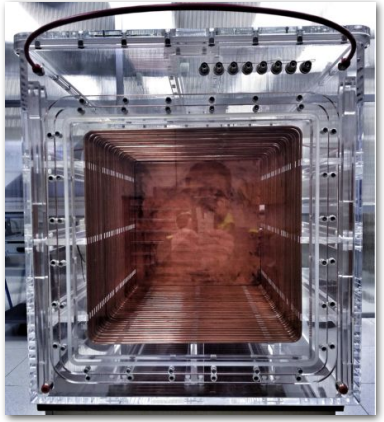


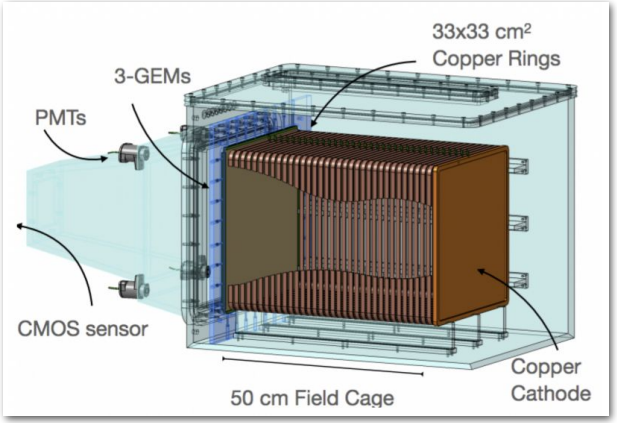
...for more info:
CYGNO – Directional Dark Matter Search
https://www.facebook.com/cygno.experiment

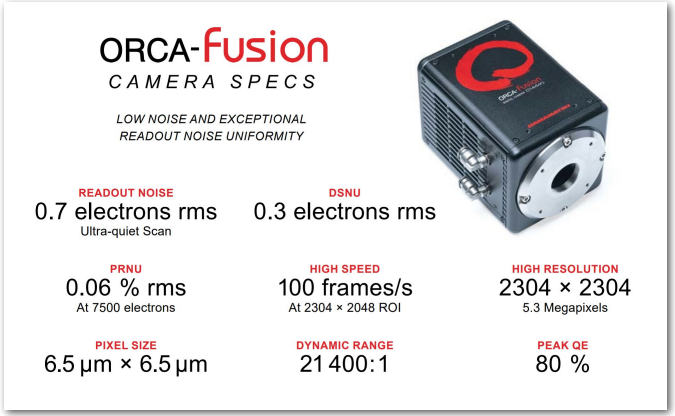
CYGNO - LIME



- Single-sided cathode, **50 L gaseous TPC**
- At **atm pressure**, room temperature and **He:CF4**
- **Triple 33x33 cm^2 GEM** stack for amplification
- **Optical readout**
  - 4 PMTs
  - 1 sCMOS camera (ORCA Fusion)
- Copper ring field cage, **50 cm drift**

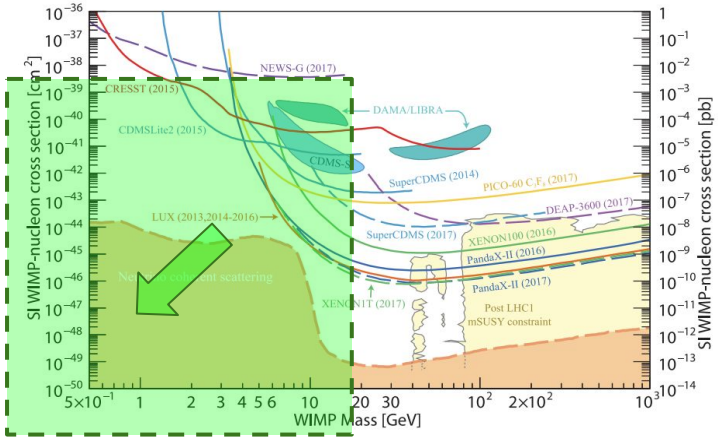






CYGNO - In the Dark Matter paradigm

CYGNO Dark Matter exploration region



Low Density @ atm pressure

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

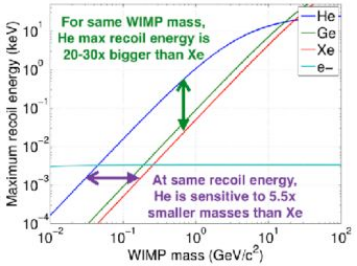
≤ 10 GeV/c^2

➔ To observe lower WIMP masses:

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

Helium (He)

➔ Light target for SI in low mass range.



Fluorine (F)

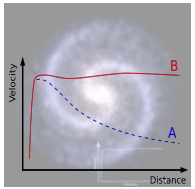
➔ Heavier target to intermediate WIMP masses.

➔ Also Sensitive to SD coupling since A = 19 (odd).

Dark Matter - What, why and where?

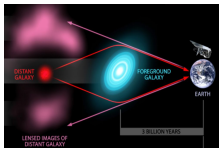
➔ In the past few years, several **gravitational** anomalies have been found that **support the existence of a new type of matter.**

1. Galaxy rotation curves



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

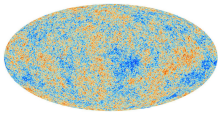
2. Gravitational lensing

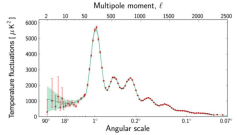


$$\Delta\Phi = \frac{4MG}{bc^2}$$

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

3. Plank'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

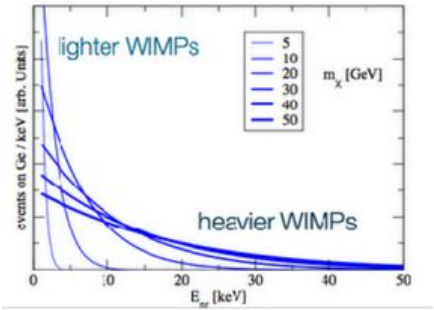
(m_{χ} ~ GeV to TeV)

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

WIMPs - What dependency to explore?

Increasing reliability but increasing difficulty in the experimental technique.

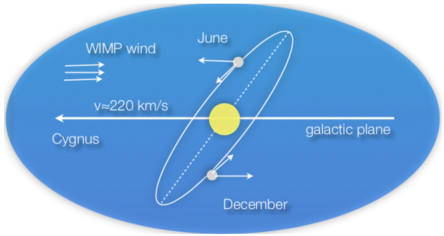
1. Exploring the **ENERGY dependency**



Results in a **falling exponential** with no peculiar features.

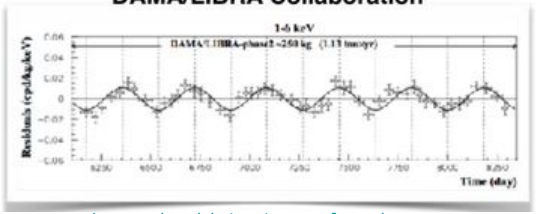
The **background** has a similar spectrum.

2. Exploring the **TIME dependency**

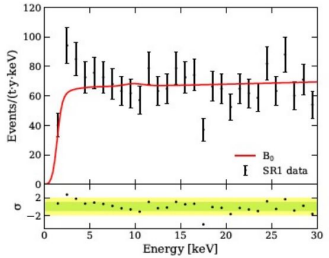


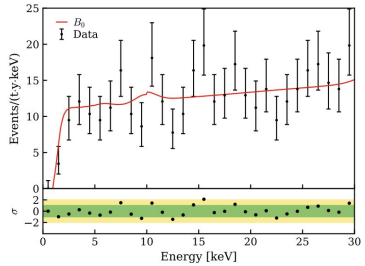
Results in a **few % annual modulation.**

DAMA/LIBRA Collaboration

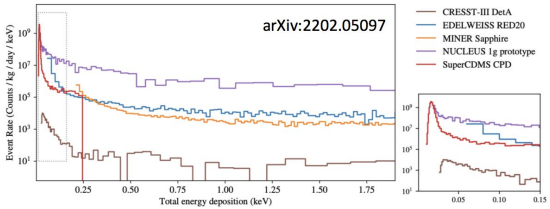


The Annual Modulation Signature for Dark Matter: DAMA/LIBRA-Phase1 Results and Perspectives





Exponentially rising background towards lower energies

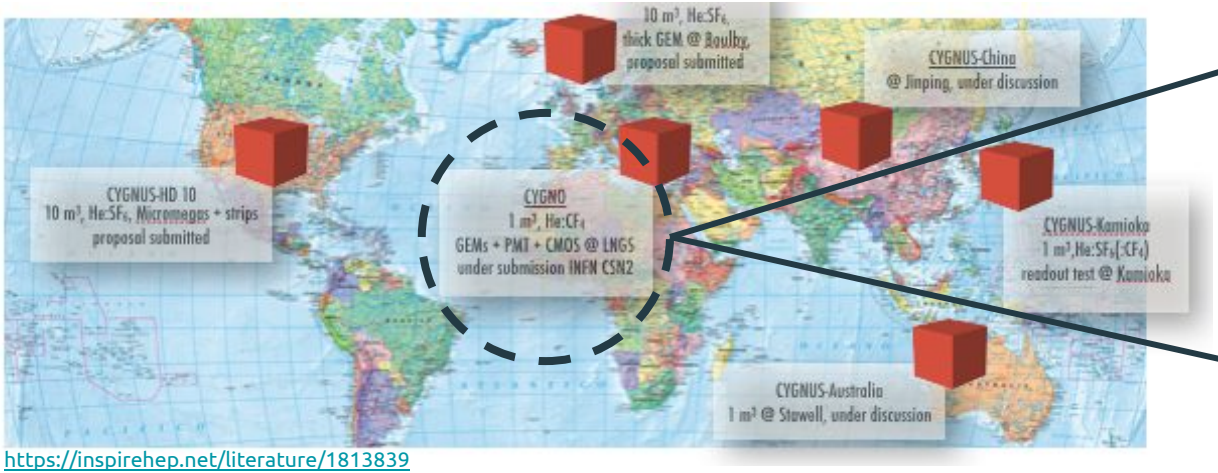


Currently limiting the sensitivity globally !
Origin still unknown, but a lot of R&D is going on ...

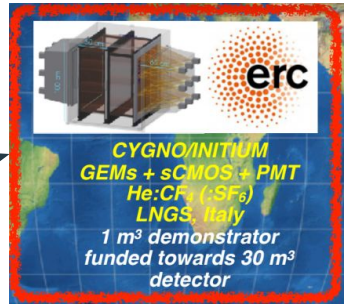
In all of these, it's hard to prove / disprove DM.

The CYGNO 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