Directional Dark Matter searches with the CYGNO/INITIUM detector

3D tracking with the CYGNO experiment

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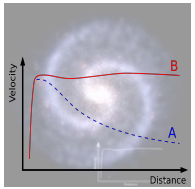
Ph.D. 2nd year report - Astroparticle Physics
Gran Sasso Science Institute - XXXVI cycle
October, 2022

Dark Matter - What, why and where?

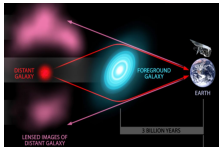
➔ In the past few years, several **gravitational** anomalies have been found that **support the existence of a new type of matter.**

1. Galaxy rotation curves



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

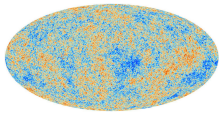
2. Gravitational lensing

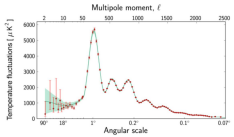


$$\Delta\Phi = \frac{4MG}{bc^2}$$

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!**

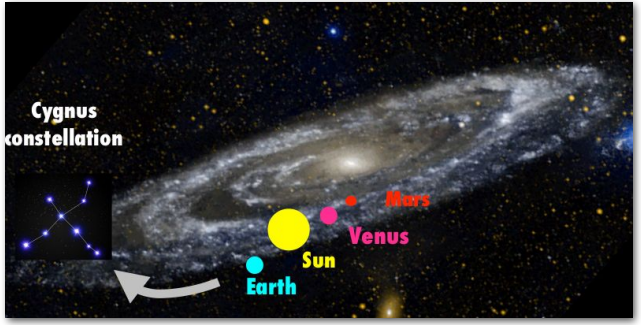
WIMPs - How to see them?

DM forms an halo within our galaxy.

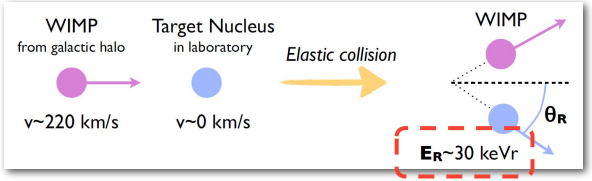
+

Solar system rotates around galaxy towards Cygnus constellation

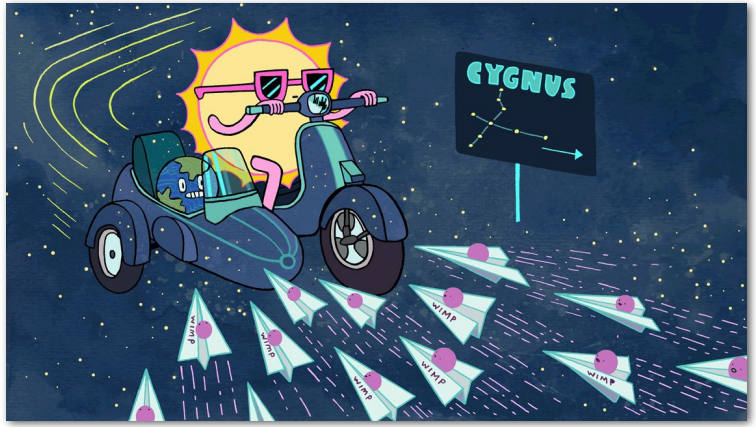
Earth susceptible to an apparent WIMP wind from Cygnus direction!



...from WIMP scattering kinematics...

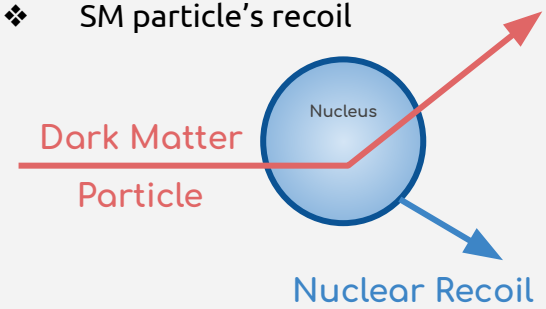


...the nuclear recoil is **non-relativistic**, of energies in the range 1 - 100 keV



Direct detection

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

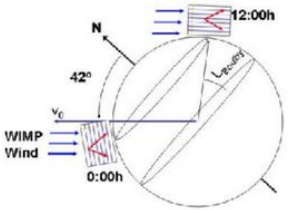


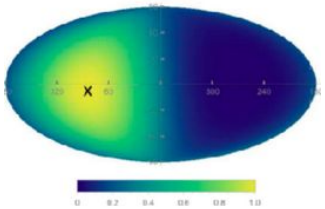
WIMPs - Directionality and beyond the neutrino floor

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

↓

No background can mimic





In DM searches, the **CEνNS** is behind the ***neutrino floor***.

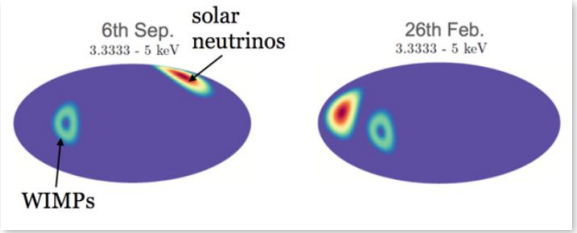
This will ***always be present!***

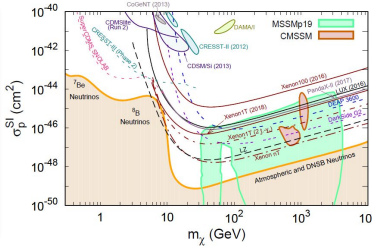
↓

Below 10 GeV/c2 → Mostly ***solar neutrinos***

↓

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





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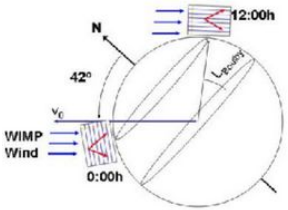

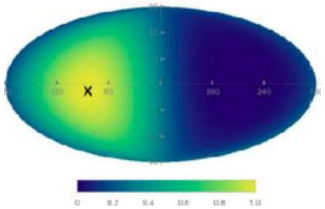

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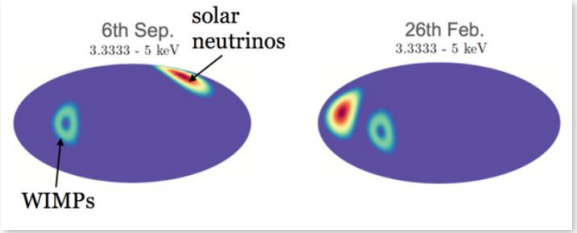
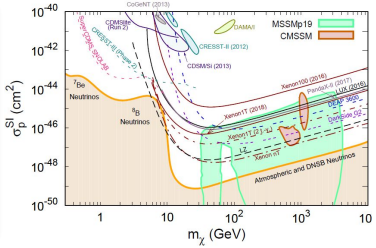




Where other experiments struggle to **prove / disprove DM**, **directional discrimination** strikes as the only way to ***unambiguously identify*** a **DM signal!**

- ➔ Searching **beyond** the ***neutrino floor***
- ➔ Properties of the ***solar neutrino flux***
- ➔ **DM halo properties** (DM astronomy)

The CYGNO project

A CYGNus tpc module

with Optical readout

CYGNO - What's the setup?

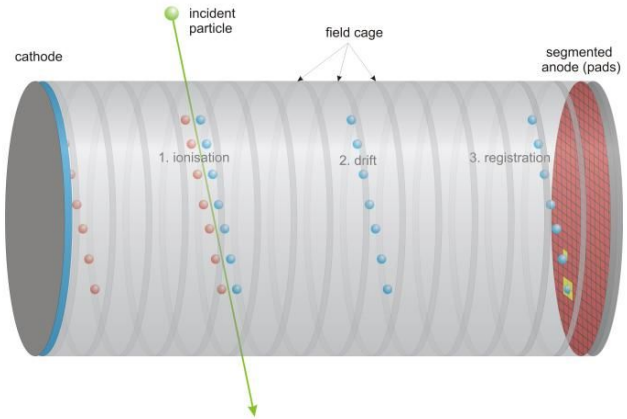
Time Projection Chamber → **Triple GEM** → **Camera & PMT**

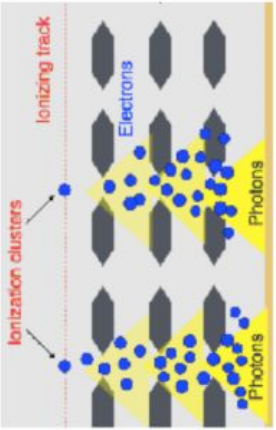
Triple GEM

Charge amplification & light production

Camera & PMT

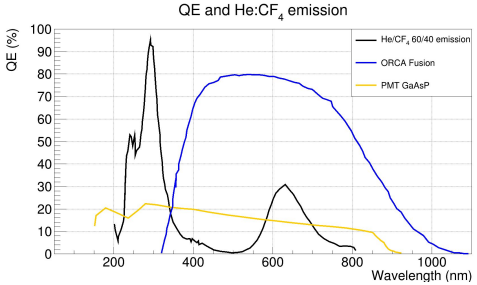
Optically read the **light produced by the de-excitation of the gas molecules** during electron multiplication.





Carbon tetrafluoride (CF4)

➔ Significant light yield at the camera's QE peak



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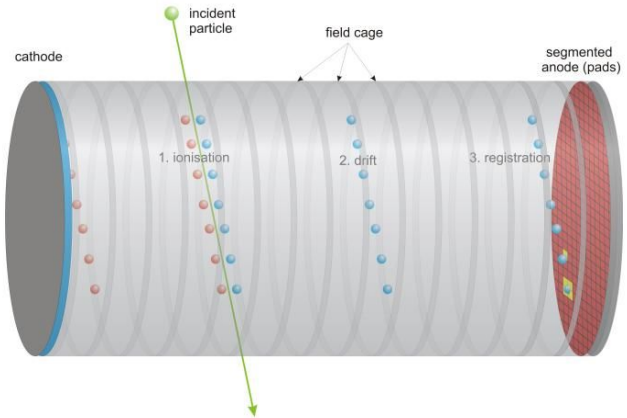
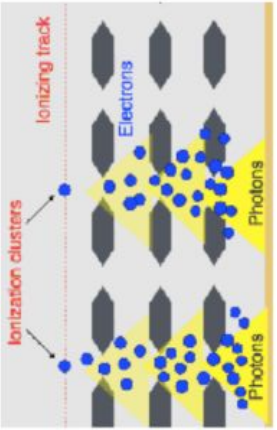
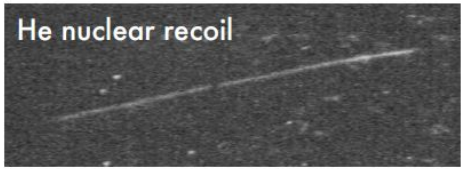
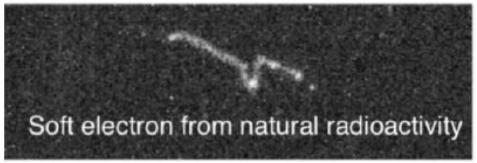




Using the camera's high granularity, we can measure the **energy** & **X & Y coordinates**





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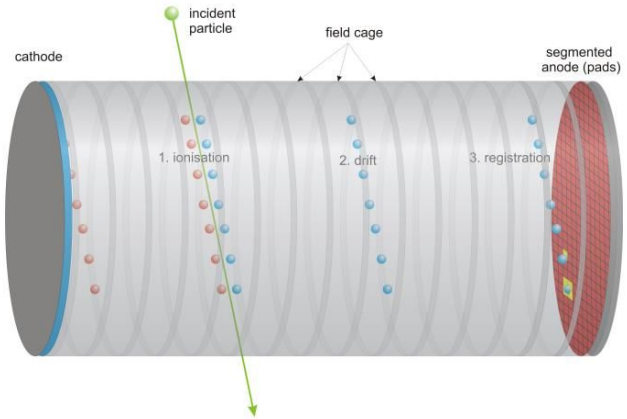
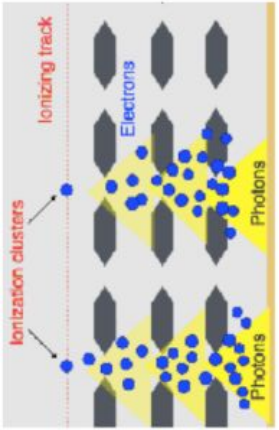
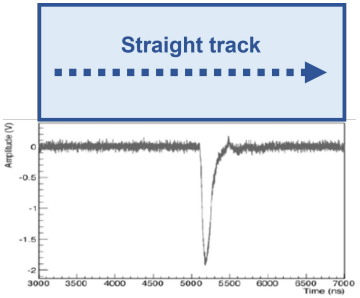
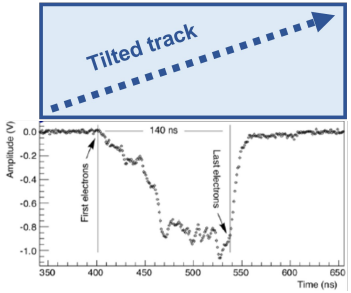




1. Measure integrated energy.
2. Charge carriers' **times of arrival →** **dZ coordinate** (track's tilt)





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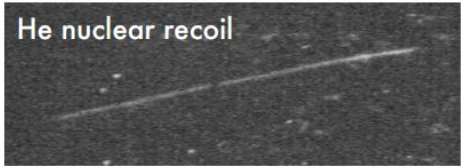

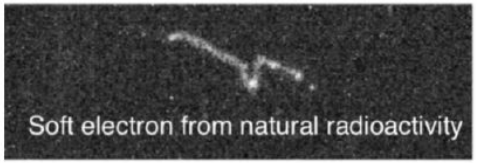

Ph.D. with CYGNO

Development of an algorithm for the reconstruction of the longitudinal coordinate (dZ and Z) of ionisation tracks with PMT waveforms.

Merge with the sCMOS X-Y projection

Reconstruction of ionization tracks in 3D

3D tracking with the CYGNO experiment

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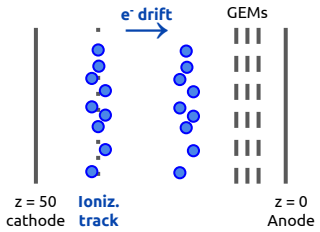
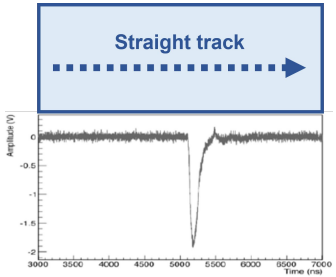
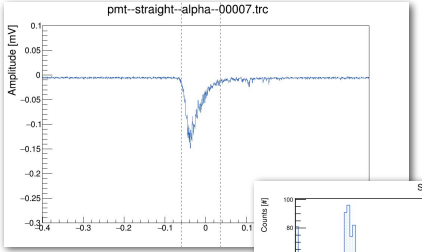
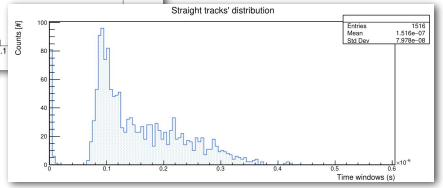
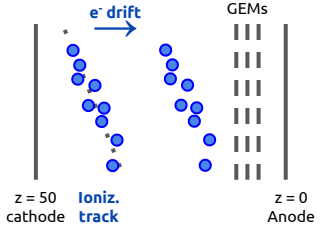
3D reconstruction

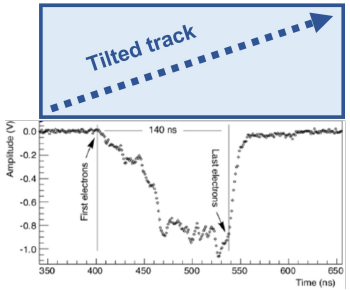


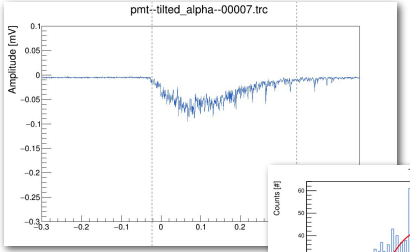


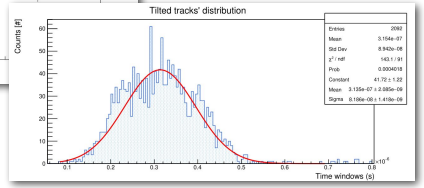












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X - Y from sCMOS

↓↓

3D reconstruction

2. Head-tail asymmetry & dE/dx

Particles deposit energy in different ways

↓

Imprinted in PMT waveform amplitudes in time domain

↓

Particle identification

Nuclear recoils originate more ionization at the beginning

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Head-tail asymmetry

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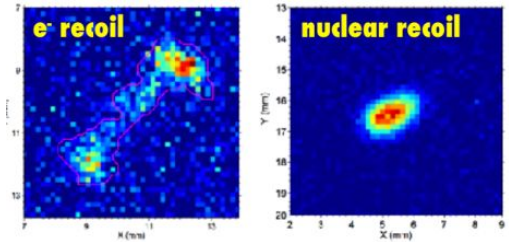
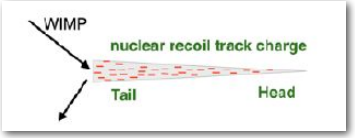
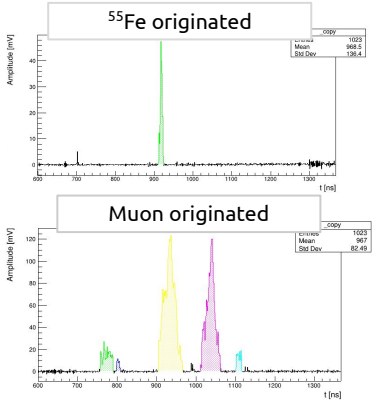
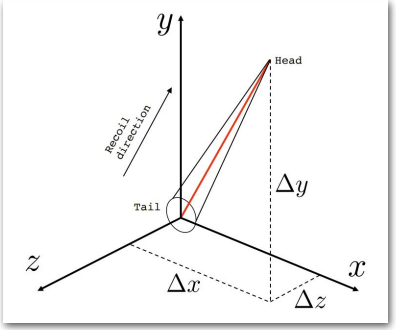
Incoming direction









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3. Absolute third coordinate (Z)

From fit to diffusion

Track transverse & longitudinal width grows with Z due to **diffusion**.

↓

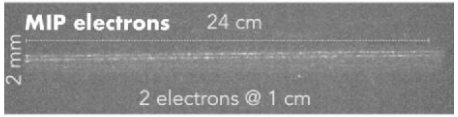
Evaluation of Z

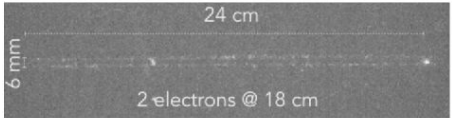
↓

Fiducial region

↓

Reduce surface BGs





Data being taken

The use of negative ions would eventually facilitate this whole process (to see later...)

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4. Total energy released

Independent energy estimation w.r.t. sCMOS camera from PMT waveform integral

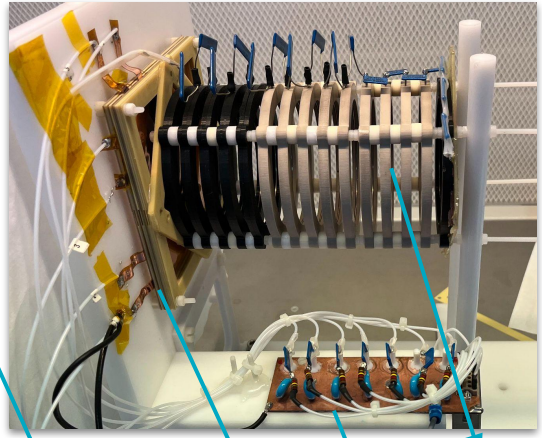
Improved energy resolution

MANGO - The detector

MANGO:

a Multipurpose Apparatus for Negative ion studies with GEM Optical readout

- ➔ Innovative **gas mixtures**
- ➔ Optimization of **amplification stages** (different types/configuration of **GEMs**)
- ➔ **Test Negative Ion Drift**
  - ◆ Find optimal **gas pressure**, **gas composition** and **amplification** configuration

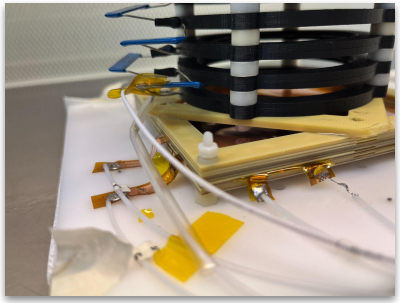


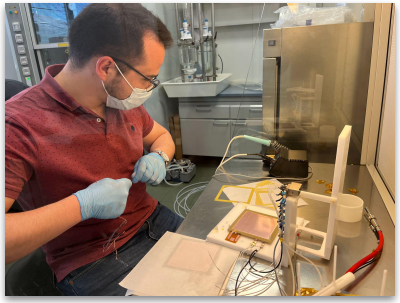
3 GEM stack:
50 μm thick
140 μm pitch
∅70 μm holes

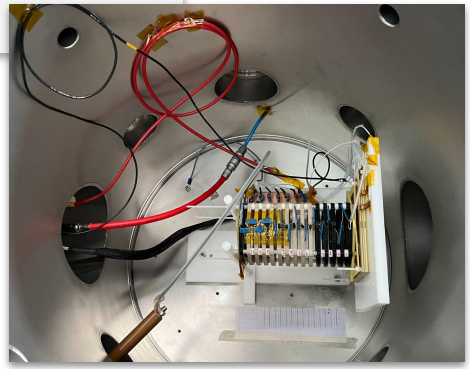
15 cm drift field cage

Voltage divider

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

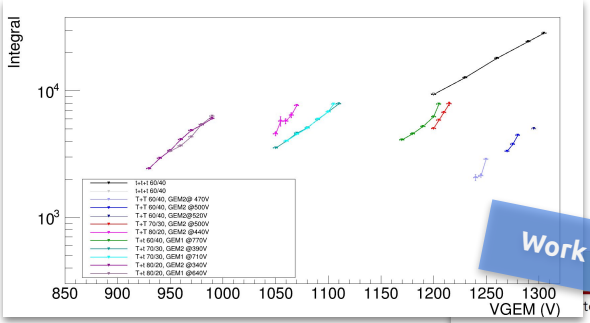




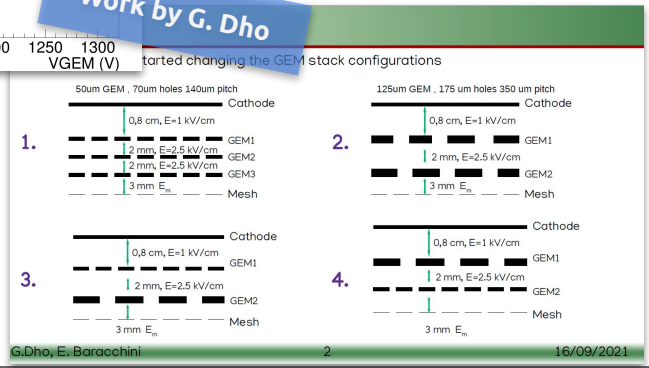


Maxwell - Schematics to simulate

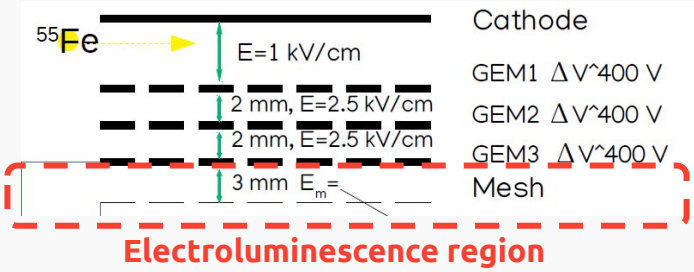
- ➔ **Electroluminescence** studies started by G. Dho.
- ➔ Several GEM thicknesses and configurations were tried.
  - ◆ **Thin (50 um)** and **thick (125 um)** GEMS.
- ➔ Interest in observing the **electric fields inside/around GEMs.**



Work by G. Dho



Gas: He:CF4 60/40, 1 atm



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

↓

Electroluminescence

↓

Additional light is produced

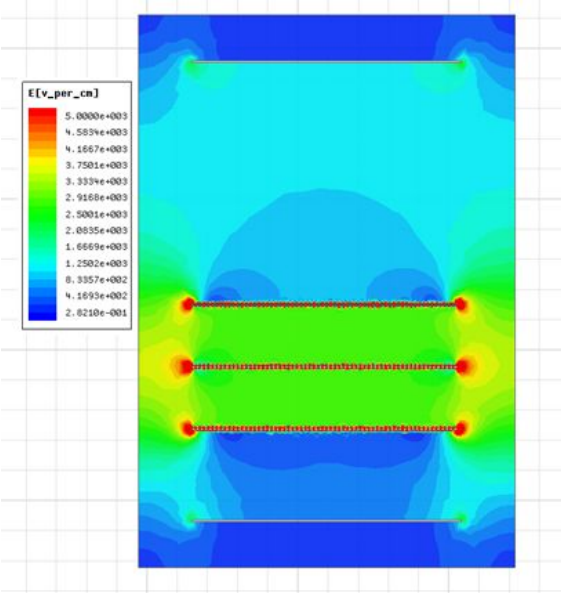
↓

Higher SNR without worsening of ΔE.

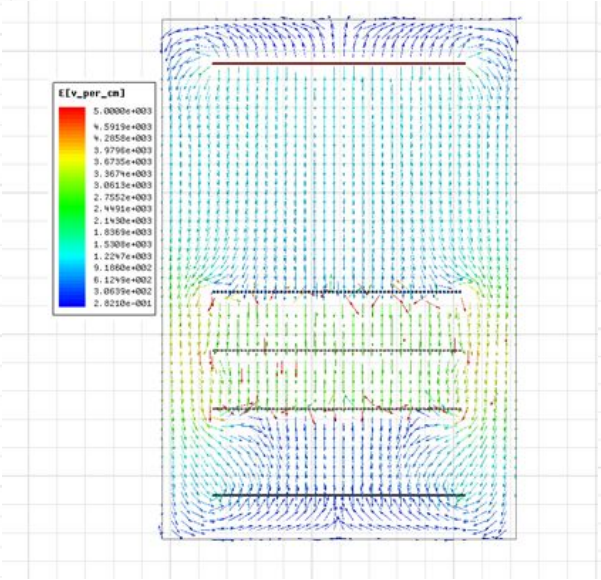
Maxwell - Working principle

➔ Given a setup with **different materials** and **voltages** applied, Maxwell calculates the **electric field** within a defined region. The outputs can be:

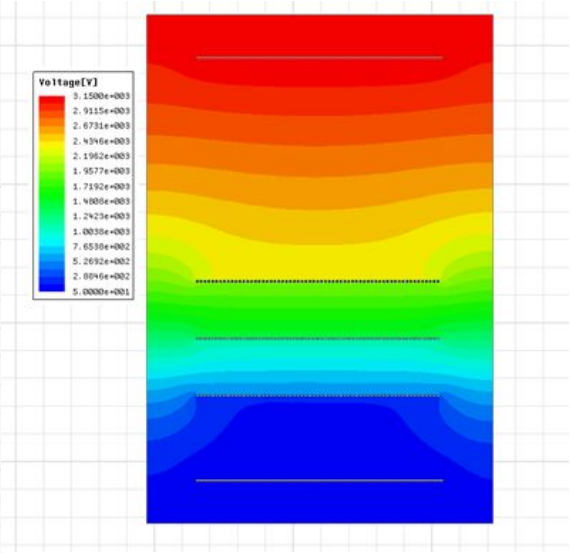
1. Electric **field** (V/cm)



2. Electric field **vector** (V/cm)



3. **Absolute** voltage (V)



Maxwell - Designing a thin GEM

Source

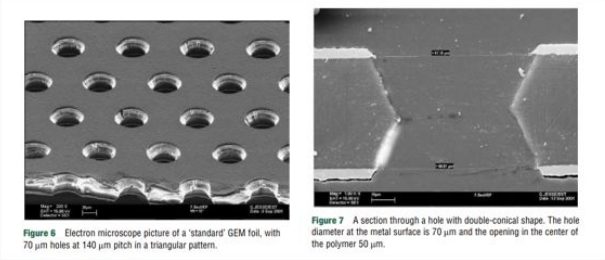
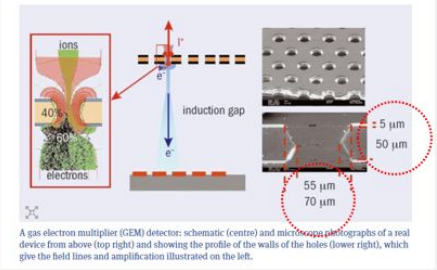


Figure 6 Electron microscope picture of a 'standard' GEM foil, with 70 μm holes at 140 μm pitch in a triangular pattern.

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

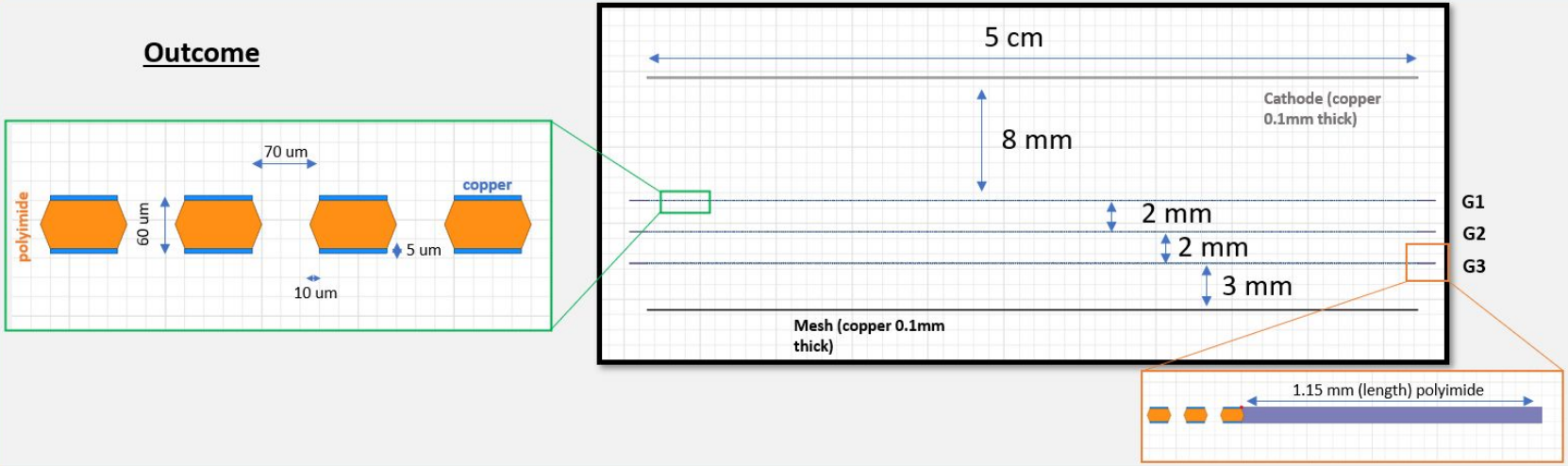


A gas electron multiplier (GEM) detector: schematic (centre) and microscopic photographs of a real device from above (top right) and showing the profile of the walls of the holes (lower right), which give the field lines and amplification illustrated on the left.

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

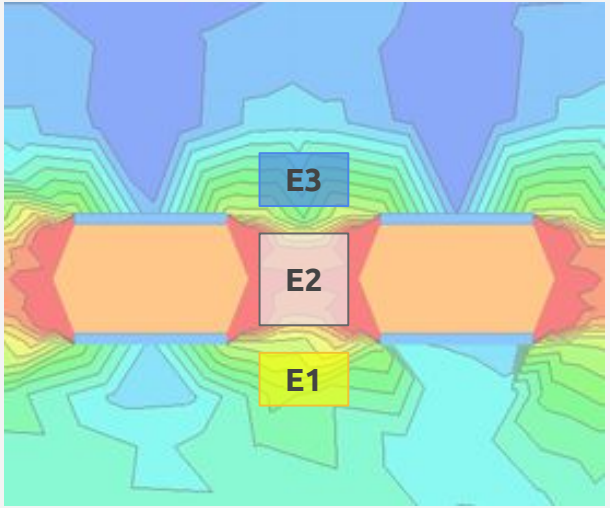
https://indico.cern.ch/event/346614/contributions/813299/attachments/683646/939073/GEM_at_CERN_seminar.pdf

Outcome



Maxwell simulation - Model/Methodology

- Define **three regions**: below (E1), inside (E2) and above (E3) GEM.
- **Map** electric field value in several points (1 um resolution)
- Average over all points
- Average over 10 holes



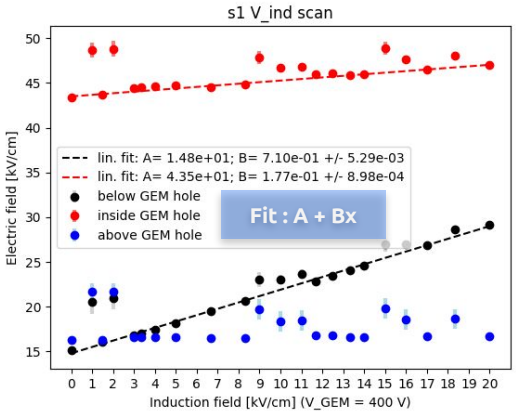
x 10 holes

Tests performed:

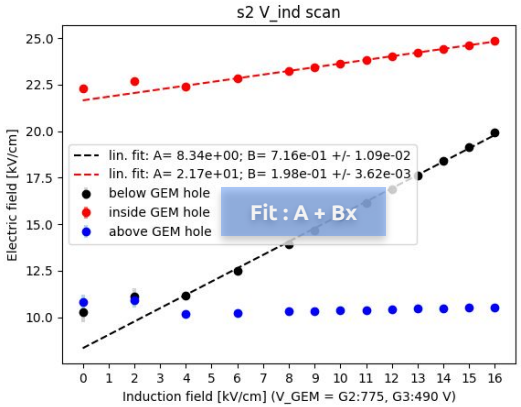
- ➔ Scan induction (luminescence) field, with fixed V_GEMs
- ➔ Scan V_GEMs, with a fixed V_ind
- ➔ 3 different configurations:
  - **t - t - t**
  - **T - T**
  - **T - t**

Maxwell simulation - Results

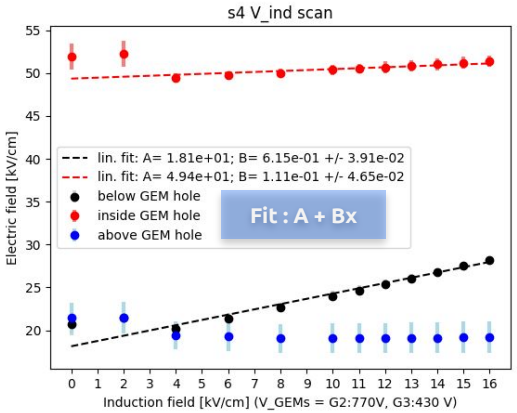
Conf. 1 (t-t-t)



Conf. 2 (T-T)



Conf. 4 (T-t)



- ★ **Increase of induction field (E_ind)** slightly changes the field **inside the GEM [red]**
- ★ Grow below GEM **[black]** is ~**4-5x greater** than inside GEM **[red]**
- ★ **Electroluminescence** is created by E_ind at **fields > 10 kV/cm** while amplification inside GEMs remains mostly unaltered.

Negative Ion Drift - Concept

Advantages:

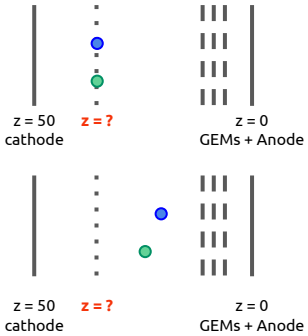
Reduced diffusion

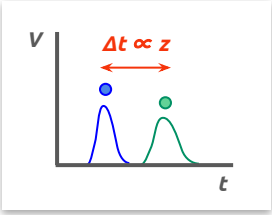
Longitudinal and transverse **diffusion reduced to thermal limit**

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

Better spatial resolution!

Multiple charge carriers





Absolute Z from Δt between minority charge carriers

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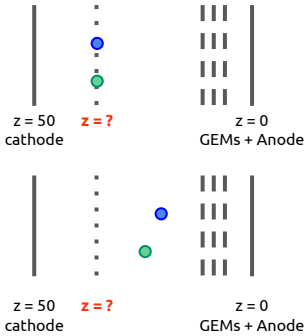
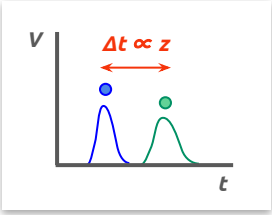
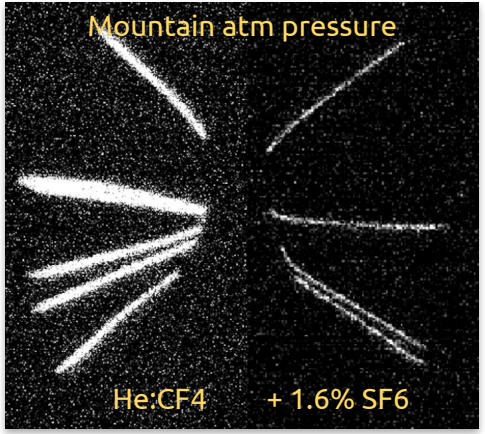
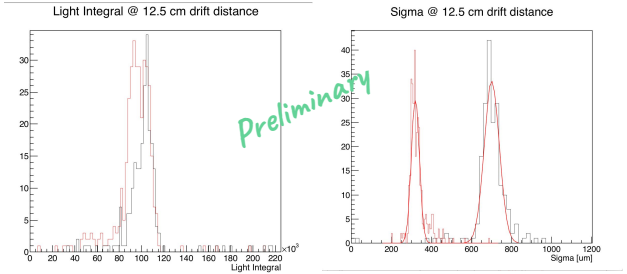




Absolute Z from Δt between minority charge carriers

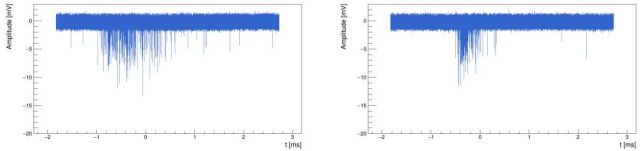




Same light … smaller sigma

Negative Ion Drift - PMT analysis

➔ I focused on the **PMT analysis**



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

Peculiar signal:

➔ Many small peaks (~3 photons) over large time span (~ few ms).

➔ Some features are observed.

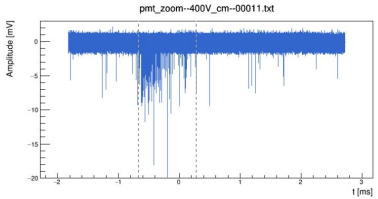
◆ Note the enlargement of signal with lower drift field.

➔ **Few or none literature** on this.

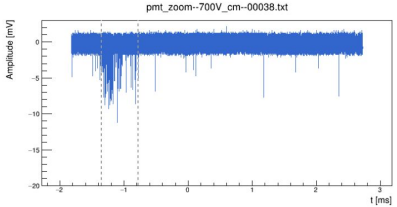
Started two types of analysis:

★ **Peak frequency**

○ Defines **start** and **end** of signal based on **peak frequency**



(b) 400 V/cm.



(d) 700 V/cm.

Negative Ion Drift - PMT analysis

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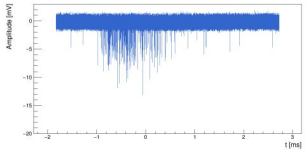

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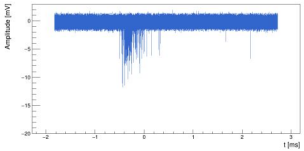

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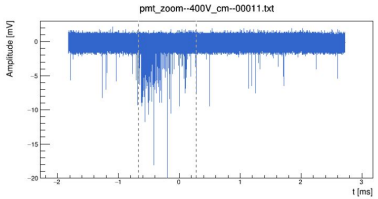

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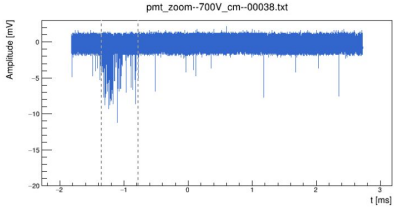
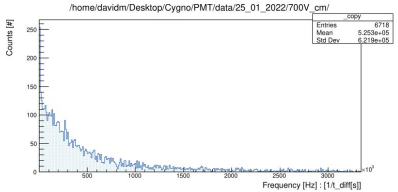


(d) 700 V/cm.

- ❑ Analysis of peak frequency shows **no peculiar feature**
- ❑ Analysis more prone to **failures** and "optimization" **bias**



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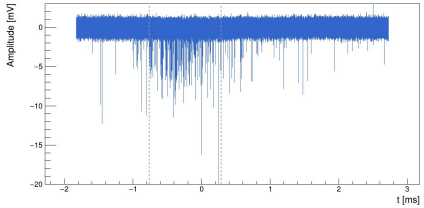
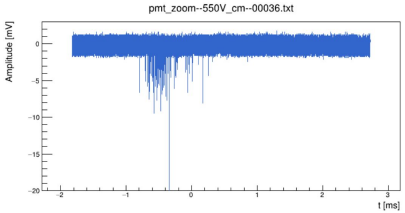


Negative Ion Drift - PMT analysis

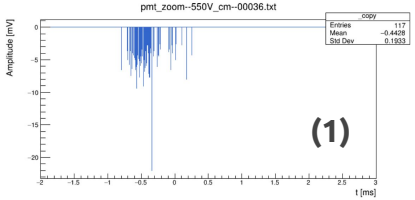
Started two type of analysis:

★ **Time rebinning**

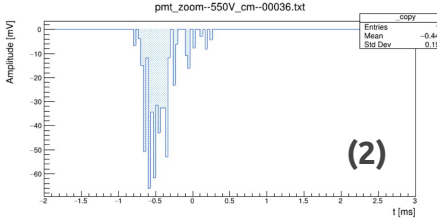
- Threshold(1) → Rebin(2) → Delimitation(3)
- More **consistent** & **accurate**



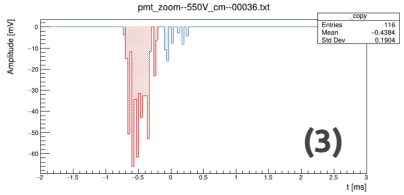
(a) Original signal.



(b) Rebinned – Only over threshold peaks – 1e7 bins.



(c) Rebinned – Only over threshold peaks – 150 bins.



(d) Rebinned – Only over threshold peaks – 150 bins – Signal window in red.

Negative Ion Drift - PMT analysis

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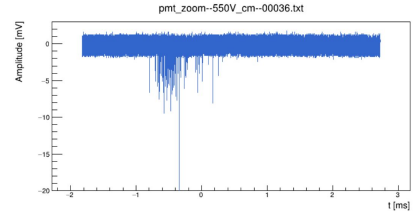

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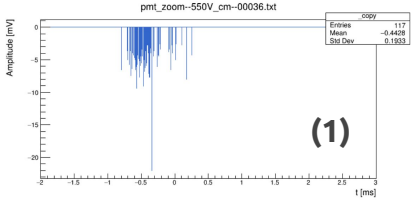

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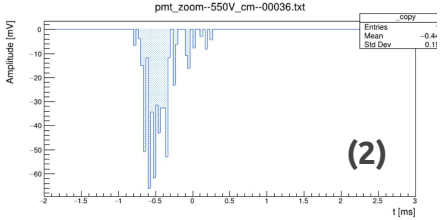

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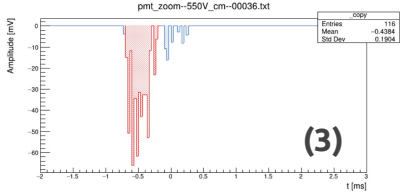
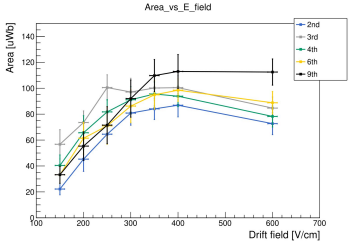
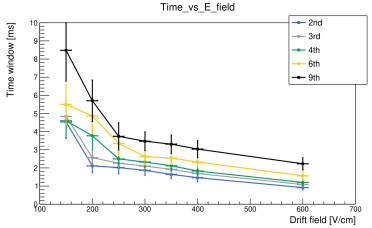


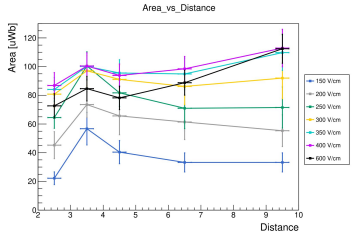
(d) Rebinned – Only over threshold peaks – 150 bins – Signal window in red.

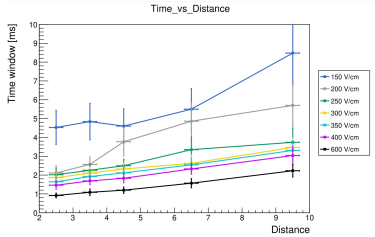
Several dependencies studied:

➔ Area / time window VS. Drift field / Distance







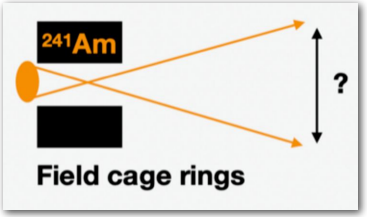


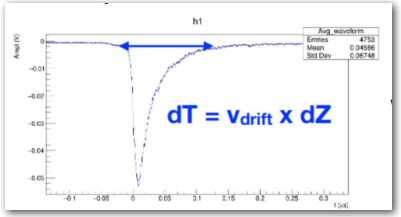
- Conclusions under study
- Paper incoming

Negative Ion Drift - PMT analysis

➔ **Final measurement: Ion Mobility**

1. Tilted ED alpha tracks
   a. Average time window
   b. Knowing electrons' velocity in gas
      i. **Z travelled by track ⇒ *7 mm***





2. Tilted NID alpha tracks
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      i. **Z / Δt = *v_ion***

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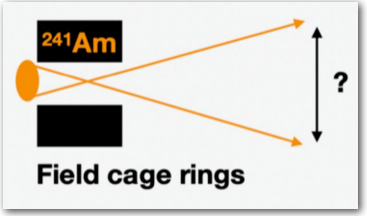

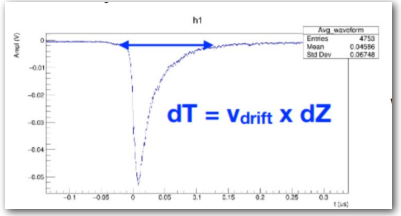

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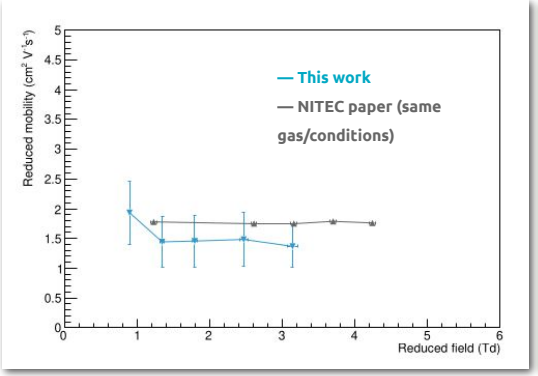

- Charge carriers' **mobility consistent** with **SF6-** in a similar experiment
- **Proved negative ion drift at *~1 ATM* with *optical readout!***

Negative Ion Drift - PMT analysis

➔ **Final measurement: Ion Mobility**

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   b. Knowing electrons' velocity in gas
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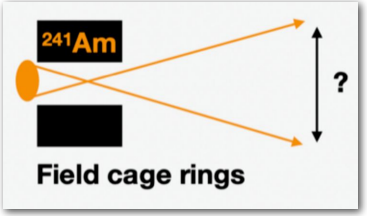

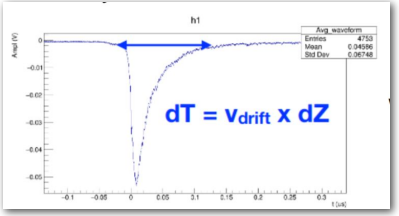

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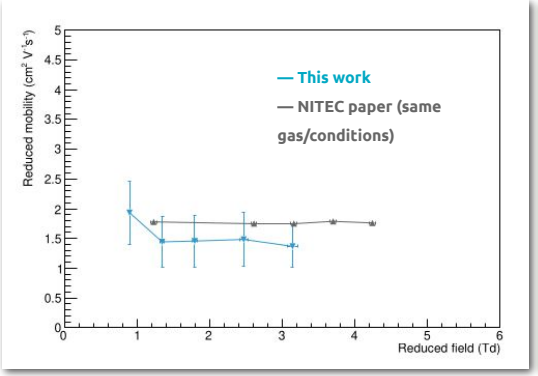

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- **Proved negative ion drift at *~1 ATM* with *optical readout!***

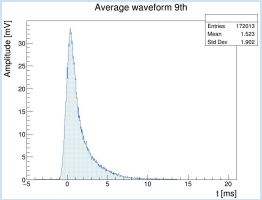
Future:

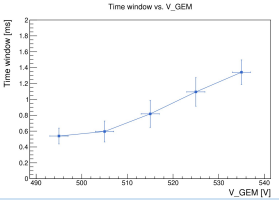
➔ Signals' structure still to be understand.

➔ Data being taken

➔ R&D needed

➔ **State-of-the-art analysis**





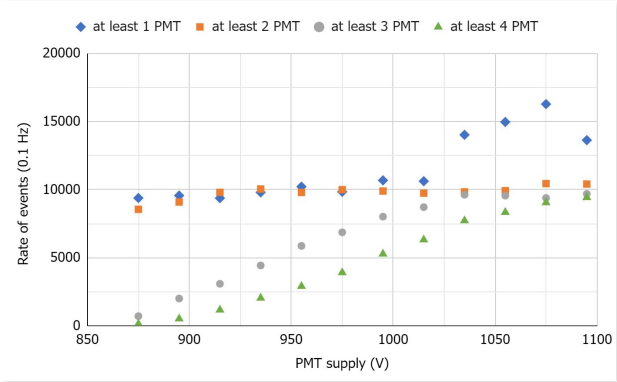
Why these ***tails***? Why ***width increase*** with V_GEM?

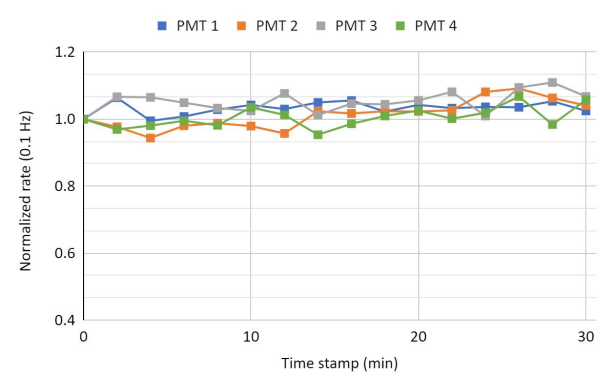
- Property of NID?
- Property of the alpha?
- Property of PMT (afterpulse)?

PMT hardware - PMT calibration at LNF

PMT calibration at Laboratori Nazionali di Frascati:

- ➔ Individual **PMT calibration**
- ➔ **Stability** test
- ➔ **Trigger** configuration
  - ◆ Find optimal coincidence scheme



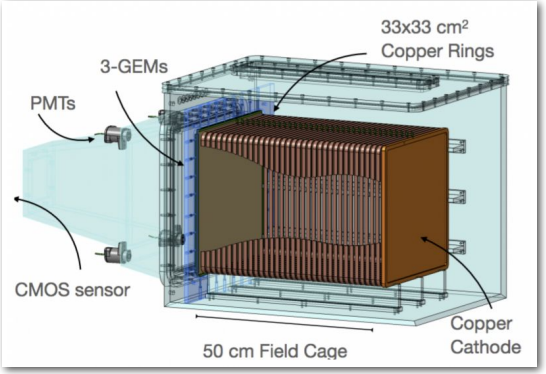


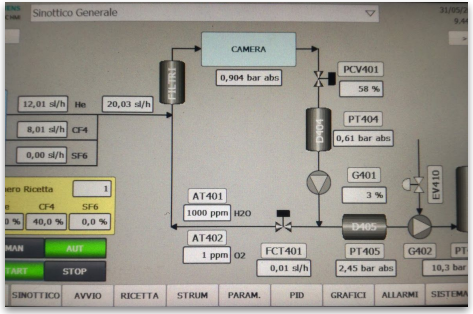
LIME commissioning - Gas system & DAQ

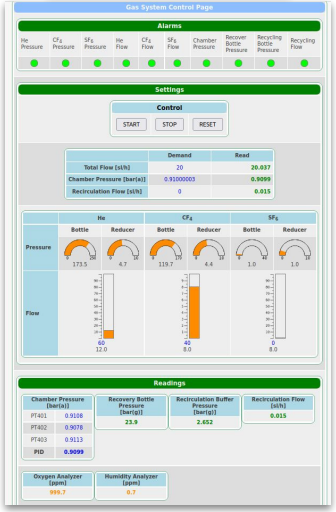
- ➔ **LIME** has recently (beginning of 2022) been **placed underground** at the LNGS.
- ➔ I participated in **stability tests** focusing the **DAQ** and ancillary equipment (HV, **gas**, sensors).

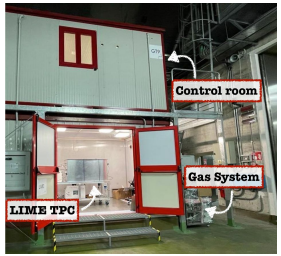
Works:

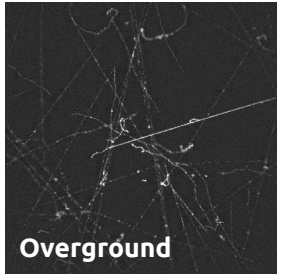
- ➔ Consolidate remote connection **Gas System <-> PC.**
- ➔ **Integration** of gas system into **slow-control.**
- ➔ Test in- and out-fluxes & alarms check.
- ➔ Improvement of **DAQ library** used to recover **ADC's** sporadic calibration failure.

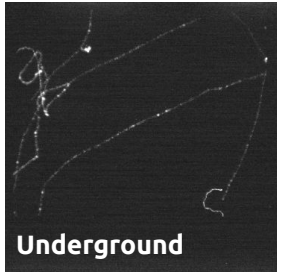






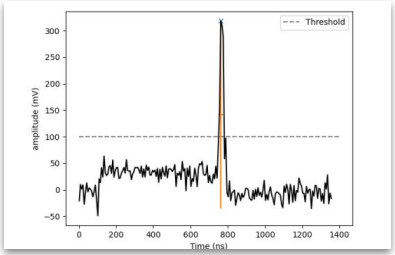


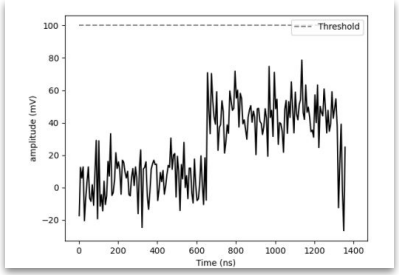




3D reconstruction - Data correction

First data set showed **high noise levels** and strange **baseline jump/step**.



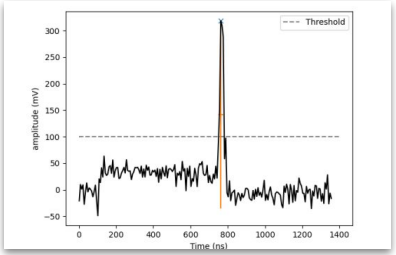


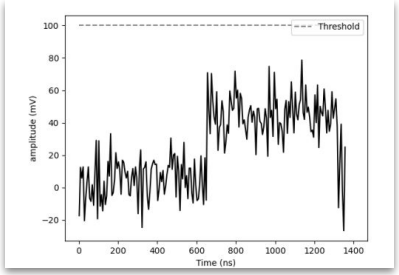
3D reconstruction - Data correction

First data set showed **high noise levels** and strange **baseline jump/step**.

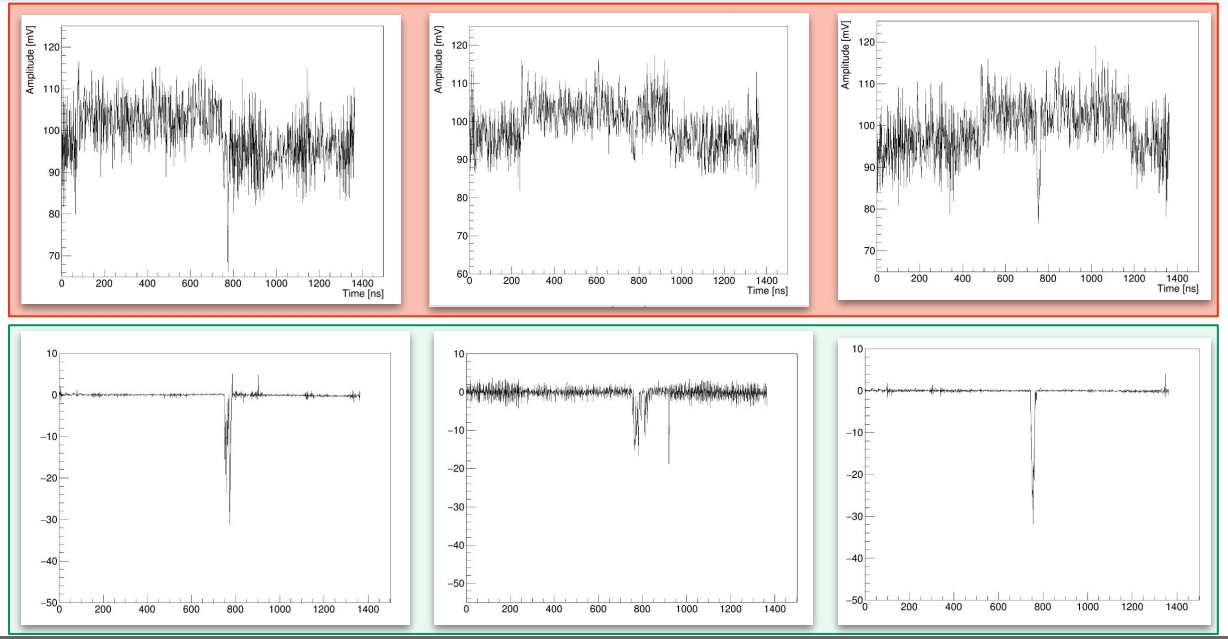
Works:

- ➔ Discussion with **CAEN** to understand problem.
- ➔ Normal solution could only be applied before/at data-taking.
- ➔ **I reverse-engineered the solution** and wrote a **data_correction_script**.





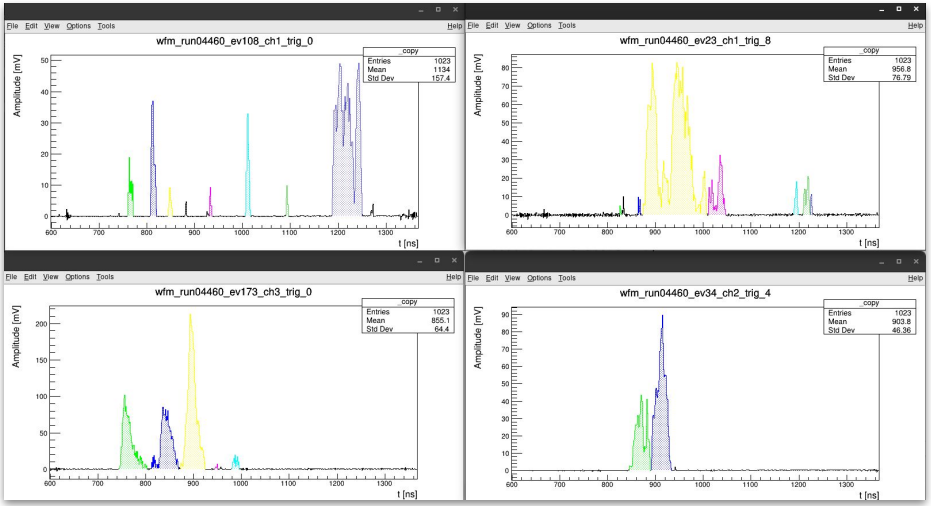
...correction



3D reconstruction - Framework and Analysis

Results:

- ➔ With this done, I started the **analysis**.
- ➔ Data still had some issues.
  - ◆ Good enough to **build the analysis framework**.



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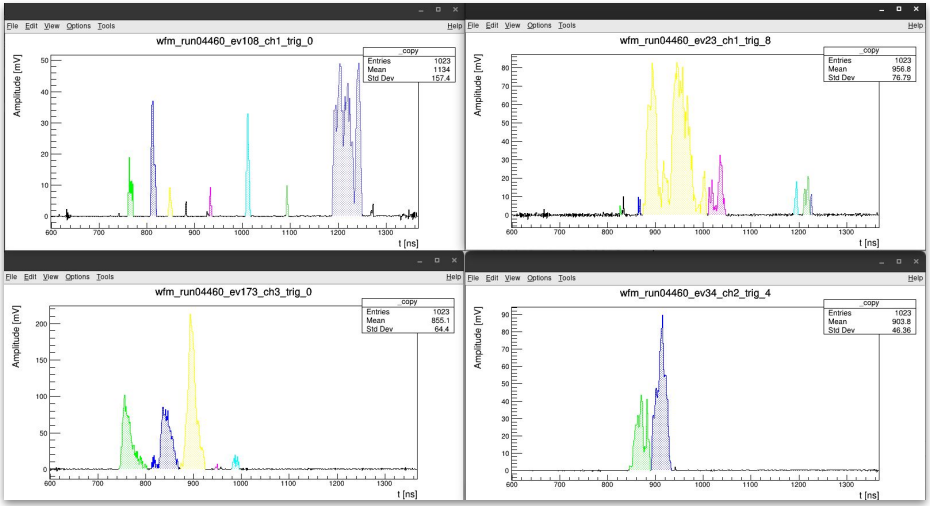

Framework:

- ➔ Peaks counting
- ➔ Peak identification and reconstruction
  - ◆ Time width
  - ◆ Maximum amplitude (height)
  - ◆ Position
- ➔ PMT coincidence logic
- ➔ Total waveform charge

3D reconstruction - Framework and Analysis

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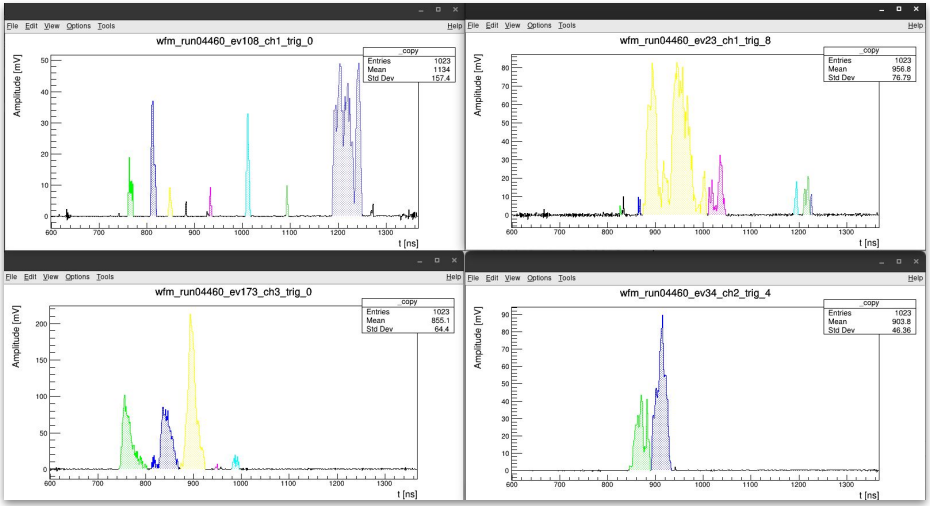

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- ➔ Peak identification and reconstruction
  - ◆ Time width
  - ◆ Maximum amplitude (height)
  - ◆ Position
- ➔ PMT coincidence logic
- ➔ Total waveform charge

Future:

- ➔ Better data:
  - ◆ Underground ^{55}**Fe data**.
  - ◆ Overground **straight alpha** tracks.
- ➔ Integration with sCMOS **X-Y pictures**.
- ➔ First attempts to **3D reconstruct ionization tracks!**

Thank you for your attention!

Scientific Communications:

1. **Papers:**
   - 1.1. **The CYGNO experiment**
     Amaro, F. D.; Baracchini, E.; Benussi, L.; Bianco, S. et al
     MDPI - Instruments, January 2022
   - 1.2. **Dual-Polarity Ion Drift Chamber: A new system to measure the mobility of positive and negative ions**
     Marques, D. J. G.; Cortez, A. F. V.; Santos, M. A. G.; Santos, F. P. et al
     NIM A, April 2022
   - 1.3. **Recoil imaging for dark matter, neutrinos, and physics beyond the Standard Model**
     O'Hare, C.A.J.; Lomba, D.; Altenmuller, K.; Alvarez-Pol, H et al
     Contribution to: 2022 Snowmass Summer Study, March 2022
   - 1.4. **The Cygno experiment for Dark Matter direct detection**
     Amaro, F. D.; Baracchini, E.; Benussi, L.; Bianco, S. et al
     Proceedings of Science - PANIC2021, January 2022
   - 1.5. **Performances of a 3D optical readout TPC for the CYGNO experiment**
     Amaro, F. D.; Baracchini, E.; Benussi, L.; Bianco, S. et al
     Proceedings of Science - EPS-HEP2021, March 2022
   - 1.6. **The Cygno Experiment**
     Amaro, F. D.; Baracchini, E.; Benussi, L.; Bianco, S. et al
     Proceedings of Science - EPS-HEP2021, 2022

2. **Conference Communications:**
   - 2.1. **Electroluminescence studies with a CYGNO/INITIUM prototype**
     Oral presentation (online)
     DCE2021, 4rd Doctoral Congress in Engineering, 28-29 June, 2021, Porto, Portugal
     → ***Awarded with best presentation*** ←
   - 2.2. **The CYGNO experiment, a directional detector for direct Dark Matter searches**
     Oral presentation
     TeVPA2022, TeV Particle Astrophysics, 8-12 August, 2022, Kingston, Canada

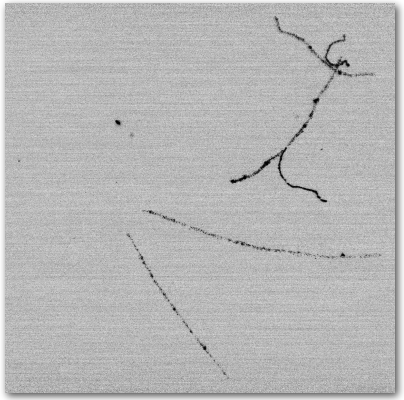
Scientific schools:

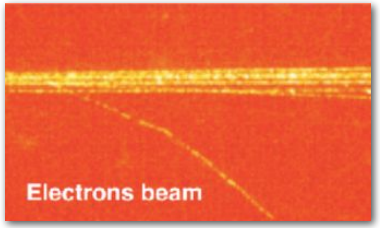
1. **ISAPP 2021 School - Dark Matter: from theory to detection**
   Vienna, Austria, 7-16 July 2021 (online)
2. **INFN School of Statistics 2022**
   Paestum, Italy, 15-20 May 2022

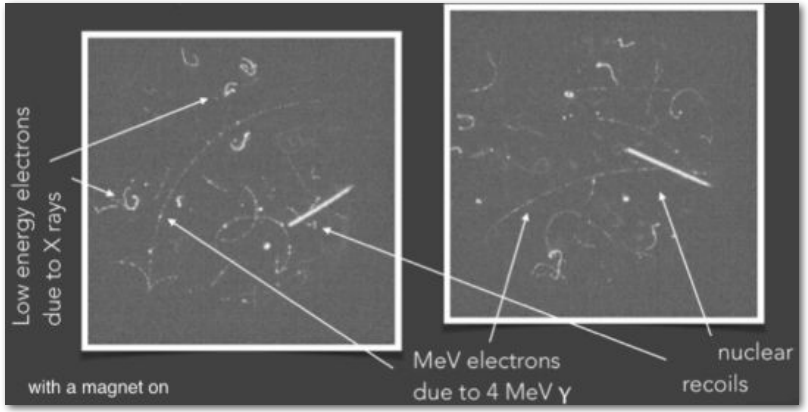
Backup

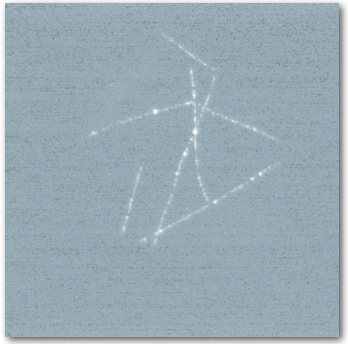
& more details

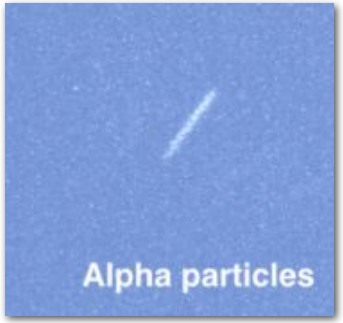
CYGNO - Some pictures!

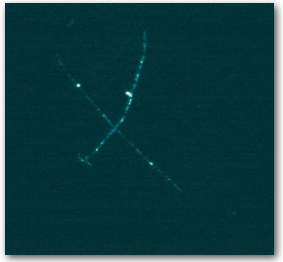


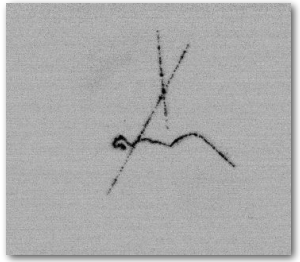


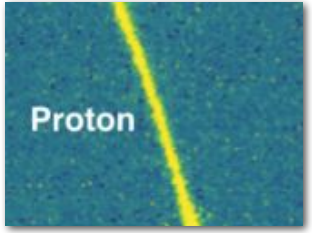








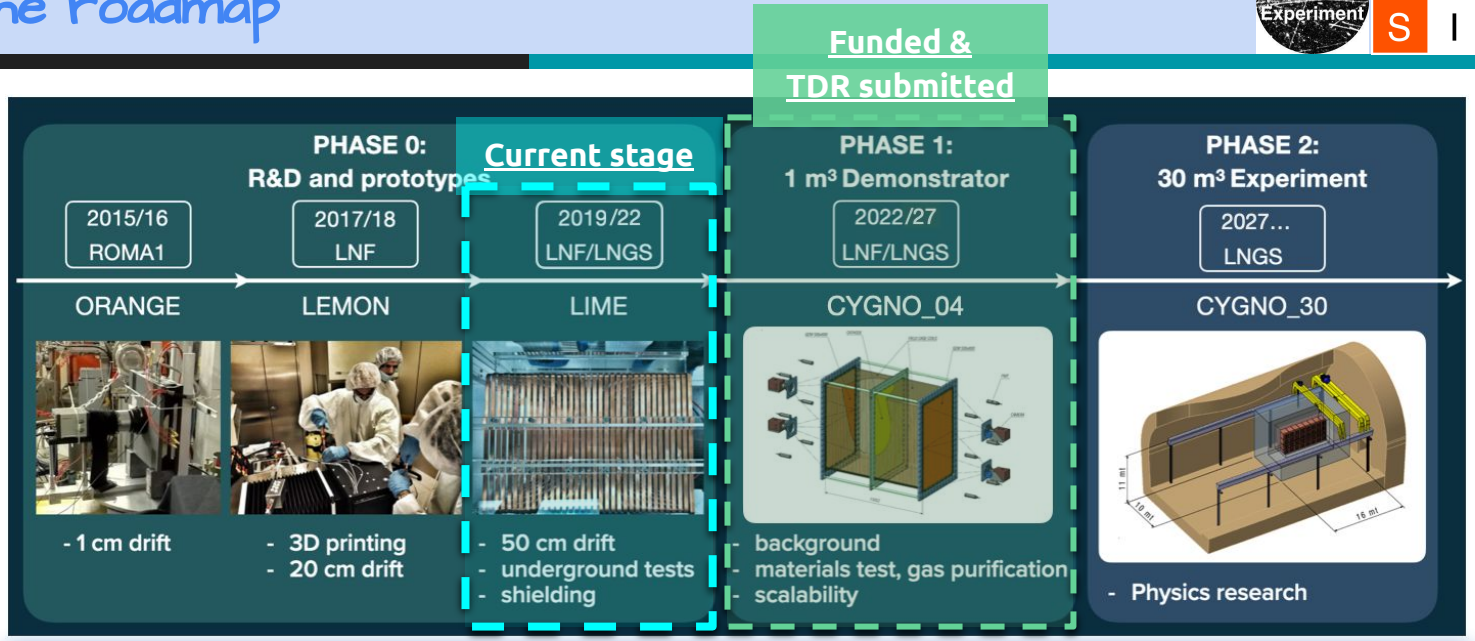


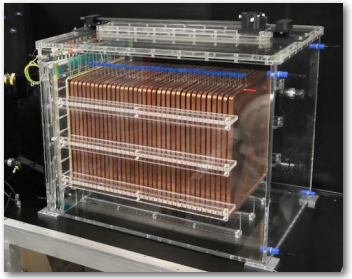


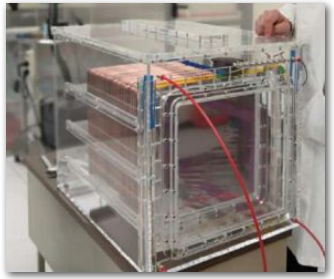
CYGNO - The roadmap

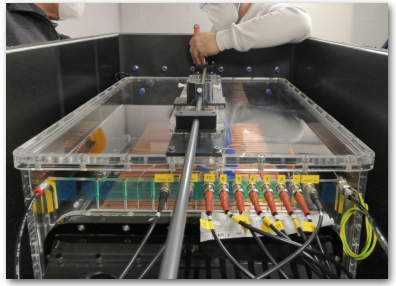
Several ongoing efforts in different fronts:

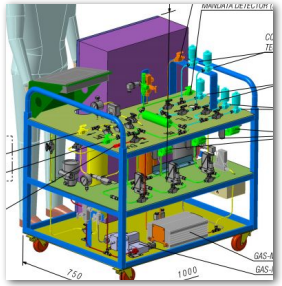
- Sensitivity
- 3D reconstruction
- Directionality
- ER vs. NR discrimination (ML)
- Shielding optimization
- Data vs. MC





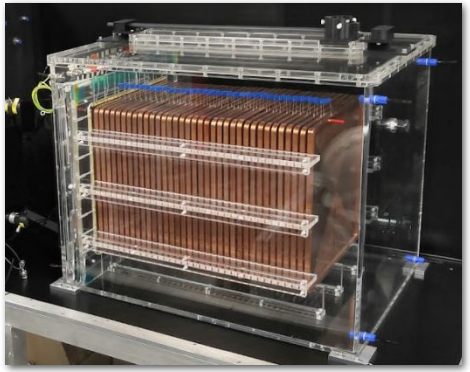




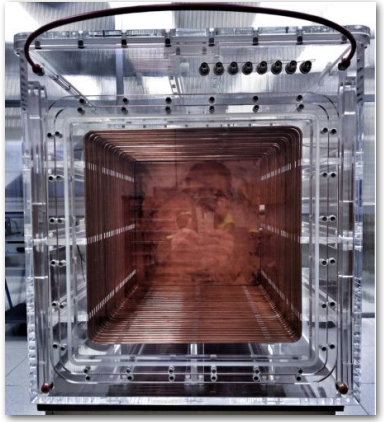


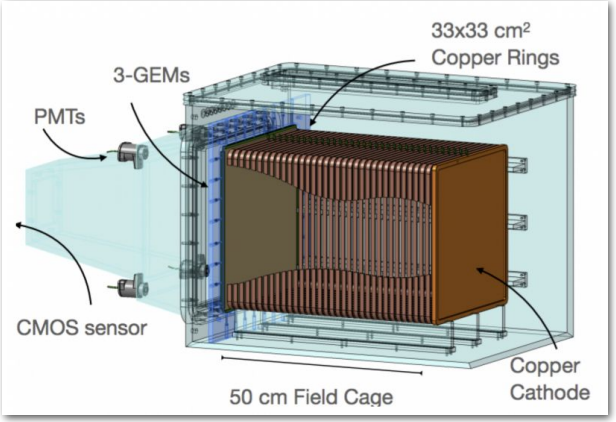
...for more info:
CYGNO – Directional Dark Matter Search
https://www.facebook.com/cygno.experiment

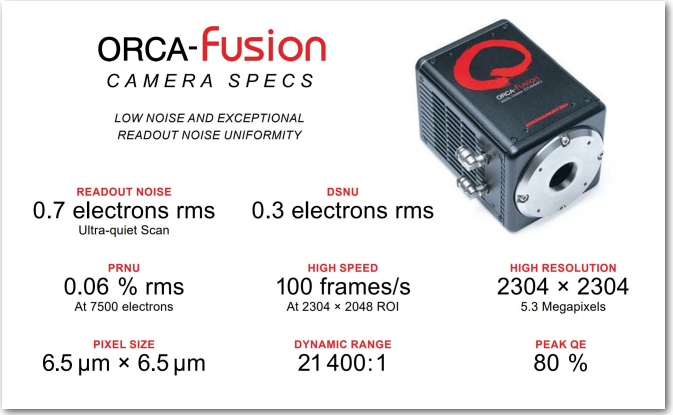
CYGNO - LIME



- 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**

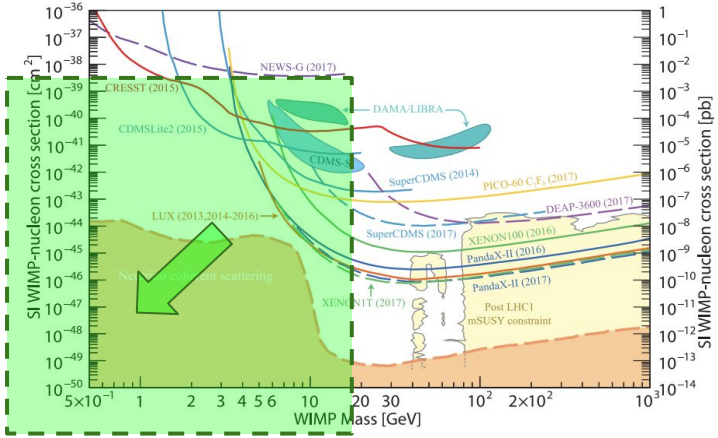






CYGNO - In the Dark Matter paradigm

CYGNO Dark Matter exploration region



Low Density @ atm pressure

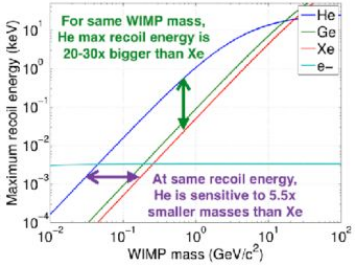
- Allows tracks of several millimeters at few keV without compromising exposure.

≤ 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.



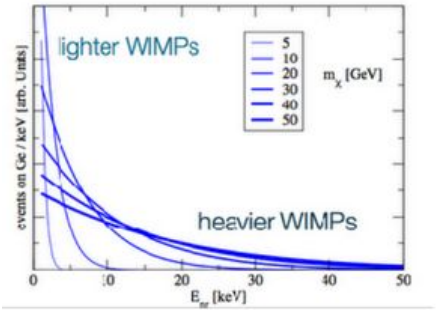
Fluorine (F)

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

WIMPs - What dependency to explore?

Increasing reliability but increasing difficulty in the experimental technique.

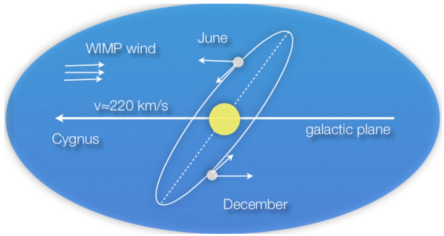
1. Exploring the **ENERGY dependency**



Results in a falling exponential with no peculiar features.

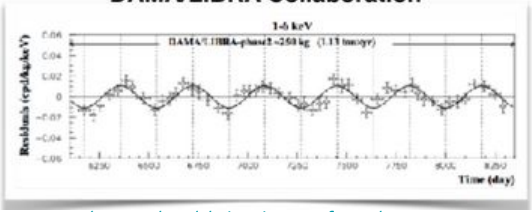
The **background** has a similar spectrum.

2. Exploring the **TIME dependency**

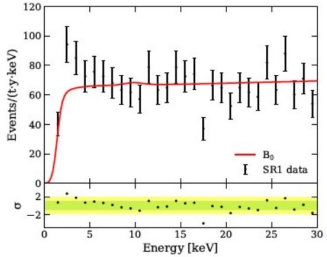


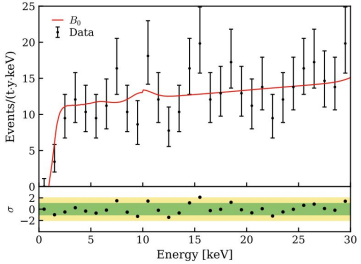
Results in a few % annual modulation.

DAMA/LIBRA Collaboration

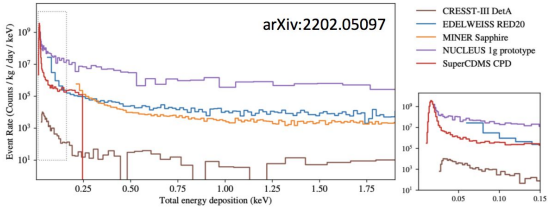


The Annual Modulation Signature for Dark Matter: DAMA/LIBRA-Phase1 Results and Perspectives





Exponentially rising background towards lower energies

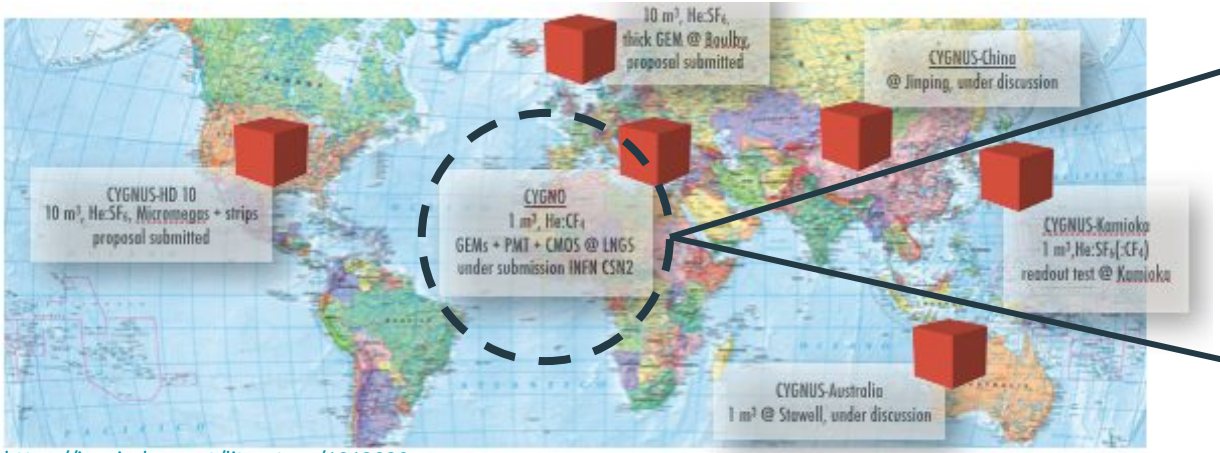


Currently limiting the sensitivity globally !
Origin still unknown, but a lot of R&D is going on ...

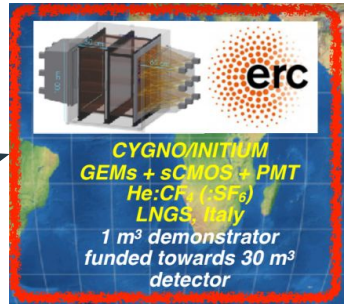
In all of these, it's hard to prove / disprove DM.

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**