









## PhD Thesis Defense Astroparticle Physics, XXXVI (36) cycle

## 3D tracking with the CYGNO/INITIUM experiment

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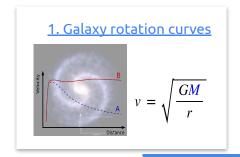
#### Discussion outline

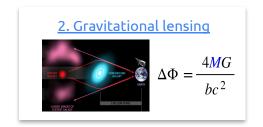
- DM paradigm
  - The CYGNO/INITIUM experiment
- PhD thesis workpoints
  - PMT waveform analysis
  - Tilted cosmics studies
  - Alpha particles 3D tracking
  - Alpha spectroscopy
  - Negative Ion Drift operation

## Dark Matter - Where?

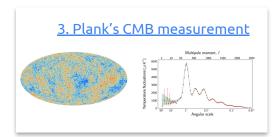


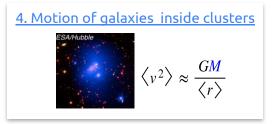
→ In the past few years, several <u>gravitational</u> anomalies have been found that <u>support the existence of a new type of matter.</u>





Universe's <u>weight</u> seems <u>inconsistent</u> with observations....

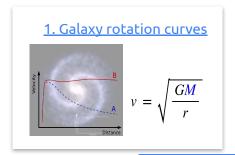


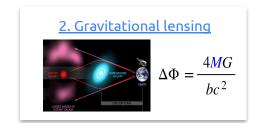


## Dark Matter - Where?

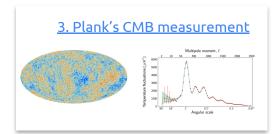


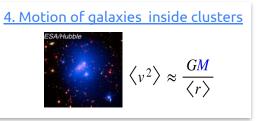
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Universe's <u>weight</u> seems <u>inconsistent</u> with observations....





This "matter" <u>dominates the universe</u> and only interacts <u>gravitationally...</u>

1

Commonly called **Dark Matter** 

#### Best explanation (?)

#### **WIMPs**

(mx ~ GeV to TeV)

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

## WIMPs - Challenges



#### ...but there are some problems...



#### Event rate is very low...

#### Considering:

- $\sigma_{WN} = 10^{-38 \text{ to } -45} \text{ cm}^2$
- $< v > = 220 \text{ km s}^{-1}$
- $\varrho_0 = 0.3 \text{ GeV cm}^{-3}$

R << 1 events / kg / year

#### There are a lot of backgrounds...

- Cosmic rays
- Natural radioactivity (<sup>238</sup>U, <sup>232</sup>Th, <sup>222</sup>Rn, <sup>40</sup>K)
- Neutrinos from the Sun, supernovae and atmosphere

# Go underground! Use radioactive PURE materials! Shield the detector! Paper Thin board such side lead to each order of as aluminum such as lead of the side of t

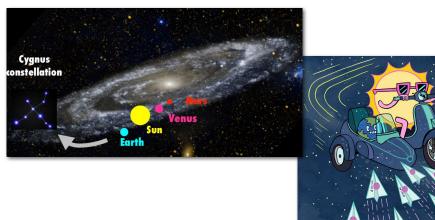


In the WIMP model, DM forms a halo within our galaxy

+

Solar system rotates around galaxy towards Cygnus constellation

Earth susceptible to an apparent WIMP wind from Cygnus direction! CYGNO wants to observe it through direct detection of nuclear recoils





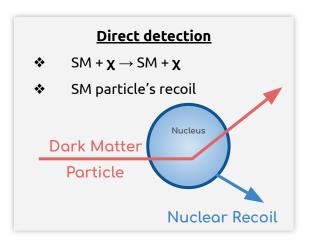
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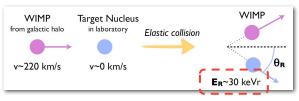
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...from WIMP scattering kinematics...



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



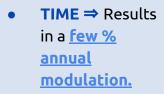
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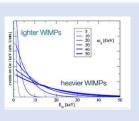
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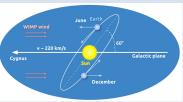
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 ENERGY ⇒ Excess would result in <u>falling</u> <u>exponentials</u>.









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

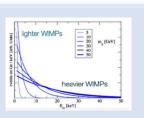
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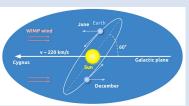
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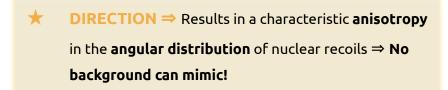
Earth susceptible to an apparent WIMP wind from Cygnus direction! CYGNO wants to observe it through direct detection of nuclear recoils

- ENERGY ⇒ Excess would result in <u>falling</u>
   exponentials.
- TIME ⇒ Results
  in a <u>few %</u>

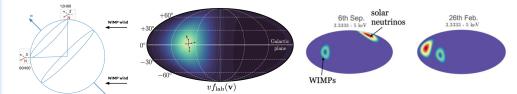
   annual
   modulation.







<u>Directional discrimination is a striking feature to</u>
<u>positively identify Dark Matter!</u>



CEvNS produces NRs identical to the DM-induced ones, but,
below 10 GeV/c², we have mostly Solar neutrinos ⇒ with
directionality\*, these don't superimpose with Cygnus, allowing us
to venture into the neutrino fog.

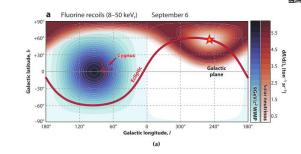
## WIMPs - Head-tail

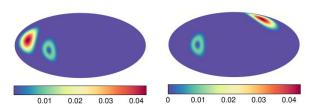
On top of the directionality, the correct identification of the **head-tail asymmetry of NRs** impact the experiment's ability to explore the DM discovery parameter space.

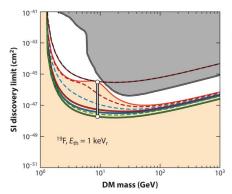
Indeed, directional detectors can only successfully venture the neutrino floor/fog – mitigate the background generated by solar neutrinos – if the HT recognition is above 75%

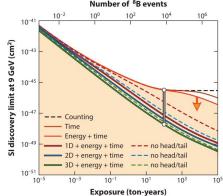
The more "axis" are reconstructed, better are the regions that can be explored and the DM halo parameters that can be constrained, with the less amount of data points needed.

For **3D**, **directional**, and **head-tail** reconstruction, **gas TPCs** are one of the most promising techniques









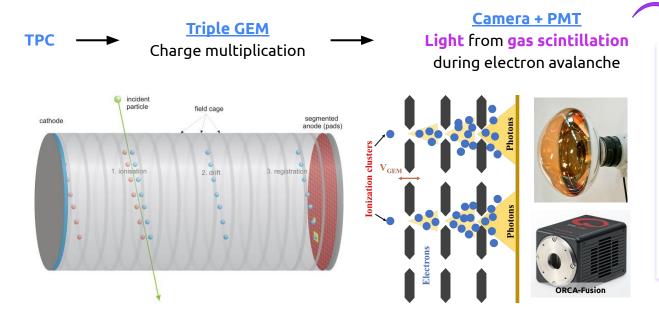




## A <u>CYGN</u>us TPC module with <u>Optical readout</u>

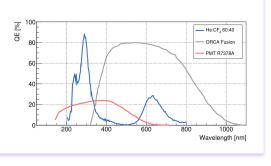
## CYGNO - What's the setup?





#### Carbon tetrafluoride (CF4)

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



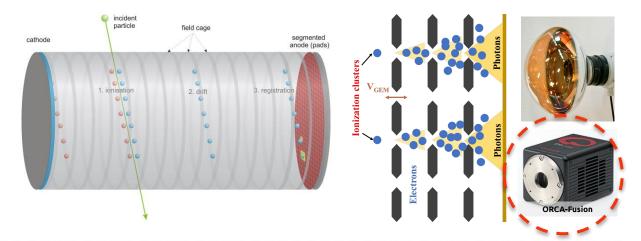
## CYGNO - What's the setup?





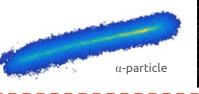
<u>Camera + PMT</u>

Light from gas scintillation
during electron avalanche



With the high granularity of the camera, we measure

energy + X & Y coordinates

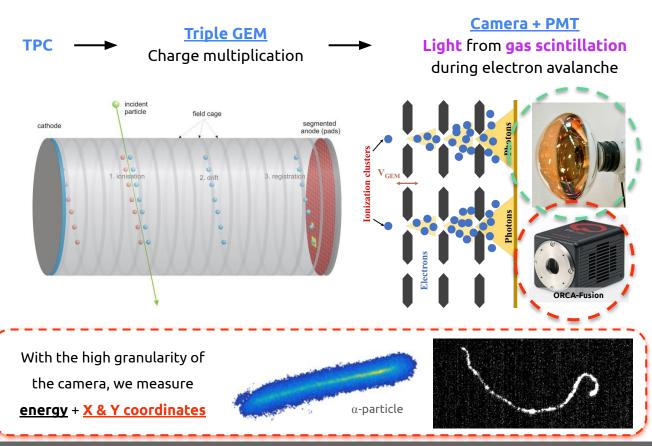




#### https://inspirehep.net/literature/1663137 https://www.mdpi.com/2410-390X/6/1/6



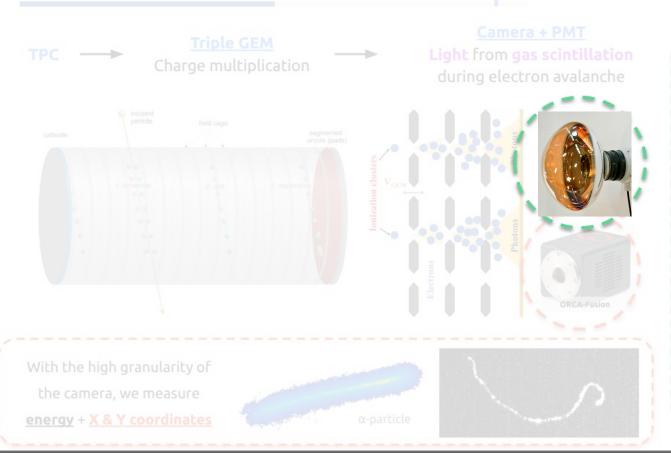




1. Independent energy measurement. 2. Electrons times of arrival ⇒ **dZ coordinate** (track's tilt) Straight track Tilted track

## CYGNO - What's the setup?

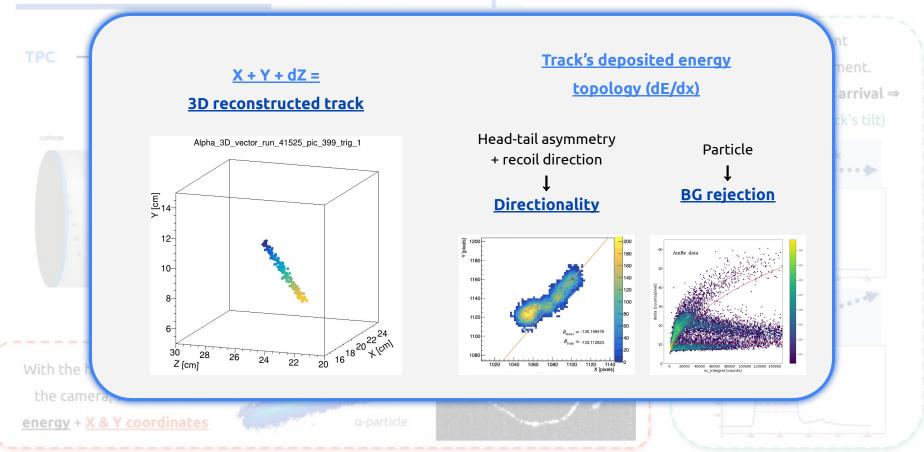




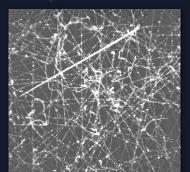
1. Independent **energy** measurement. 2. Electrons times of arrival ⇒ dZ coordinate (track's tilt) Straight track

## CYGNO - What's the setup?

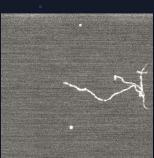


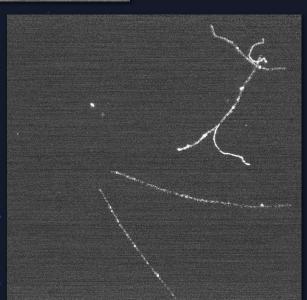


## Some cool pictures

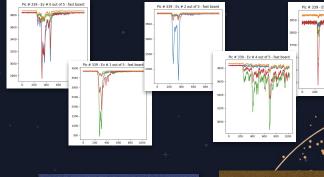














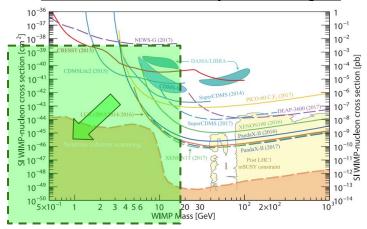




## CYGNO - Dark Matter paradigm



#### **CYGNO Dark Matter exploration region**



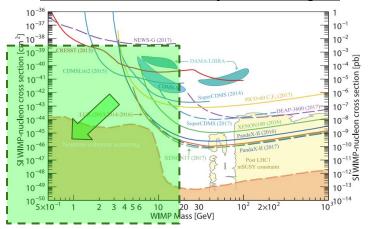
#### < 10 GeV/c<sup>2</sup>

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

## CYGNO - Dark Matter paradigm



#### **CYGNO Dark Matter exploration region**



#### Low Density @ atm pressure

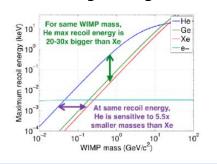
→ Allows tracks of up to millimetres at few keV without compromising exposure.

#### < 10 GeV/c<sup>2</sup>

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

#### Helium (He)

Light target for SI in low mass range + longer recoils



#### Fluorine (F)

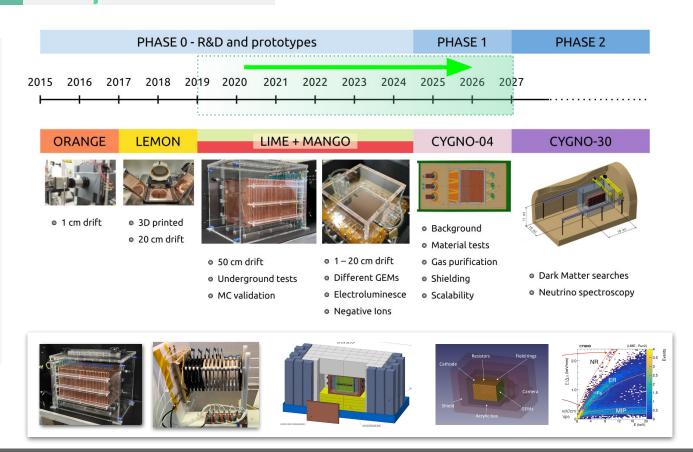
- Heavier target to intermediate WIMP masses.
- → One of the highest sensitivity to SD coupling.

## CYGNO - Roadmap



## Several ongoing efforts in different fronts:

- 3D reconstruction
- Directionality
- ER vs. NR (+ML)
- Shielding optimization
- Background data vs. MC
- DM Sensitivity
- Design and Commissioning of CYGNO\_04
- Enhancement of the light yield
- Negative Ion drift

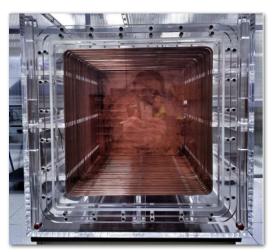




### Where we are at...

## **LIME**

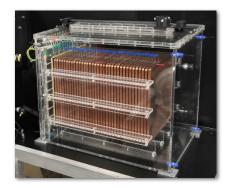






## LIME - The concept





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

LIME is the base module for CYGNO-04

## LIME - The concept







- → <u>50 L</u> & <u>50 cm drift</u> gaseous TPC with **Copper ring** field cage.
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LIME is the base module for CYGNO-04

- ★ LIME was placed <u>underground</u> at LNGS in the beginning of 2022.
- ★ <u>Commissioning</u>: tests on DAQ, remote control, slow control, gas quality,etc.
- ★ Technology test in a <u>realistic</u> underground environment for <u>rare event searches</u>
- ★ <u>Staged shielding</u> approach to <u>validate</u> CYGNO <u>MC</u> and test shielding effectivity
- ★ Multiple radioactive source runs: <sup>55</sup>Fe, <sup>137</sup>Ba, <sup>152</sup>Eu, <sup>241</sup>Am + AmBe



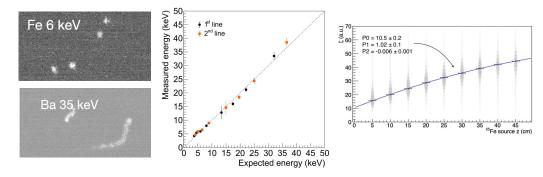
Live monitoring of detector performance & data quality

## LIME - Overground commissioning



#### **CMOS + PMT tests**

- Detector energy linearity measured with different energy ERs
- First studies to determine absolute Zthrough diffusion



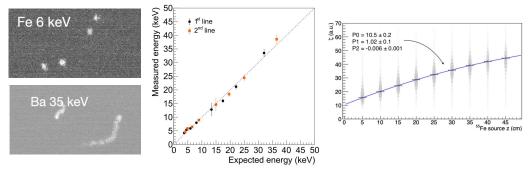
https://link.springer.com/article/10.1140/epic/s10052-023-11988-9

## LIME - Overground commissioning

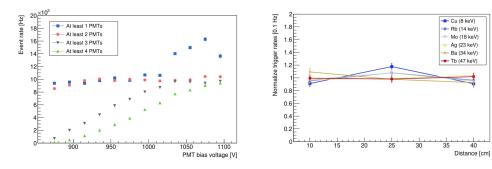


#### **CMOS + PMT tests**

- Detector energy linearity measured with different energy ERs
- First studies to determine absolute Zthrough diffusion
- Find optimal PMT trigger coincidence configuration
  - Testing trigger rate as function of bias voltage, time, and event energy.
- ★ Data taking of <u>cosmic muons</u> to later test the PMT-reconstruction developed for this thesis



https://link.springer.com/article/10.1140/epic/s10052-023-11988-9

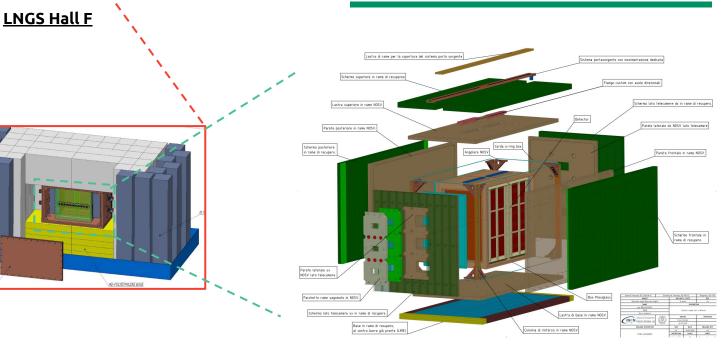


https://ieeexplore.ieee.org/document/9875803



## next step...

## CYGNO-04



OPPER FRONT-COVER REMOVED /

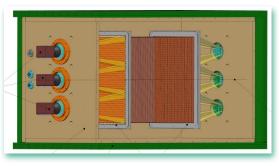




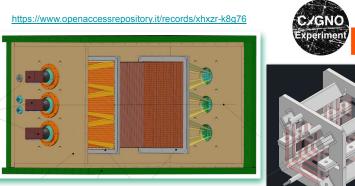


## CYGNO-04 - Phase I

- Test <u>scalability</u> on realistic scale + all <u>ancillary</u> systems
- Test <u>feasibility of physics reach</u> for <u>directional DM</u>  $\rightarrow$ searches with a radiopure large detector

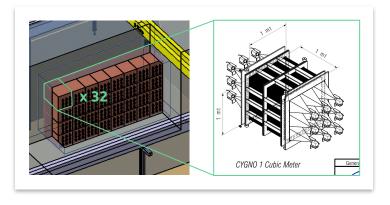


- CIGITO-UT-FINGSET
- → Test <u>scalability</u> on realistic scale + all <u>ancillary</u> systems
- → Test <u>feasibility of physics reach</u> for <u>directional DM</u>
  <u>searches</u> with a <u>radiopure</u> large detector
- → Back-to-back <u>0.4 m3 TPC</u>, with central cathode.
- → Projected <u>shielding</u> composed of 10 cm Cu + 100 cm H2O
- → <u>Low radioactivity materials</u> selected and measured
  - ◆ Improve MC vs. data ⇒ Determine sensitivities
- → Currently validating all the components:
  - **Camera:** Orca Quest ⇒ 3 \* 2
  - ◆ PMT: <u>8 \* 2</u>, with position optimized for coverage
  - Field cage: copper strips on insulator support
  - **♦ GEMs:** 50x80 cm<sup>2</sup>
- → <u>Timeline:</u> Commissioning from Fall 2025



## CYGNO-30 - Prospects

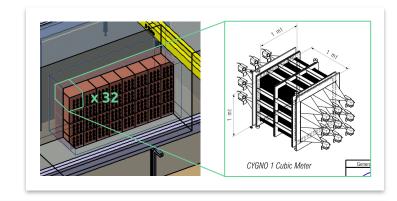




## CYGNO-30 - Prospects

CXGNO C

- Composed by multiple CYGNO-04-like modules
- → 30 100 m3 detector
- → Low mass (0.5 10 GeV) reach for directional DM searches
- **→** > 2027



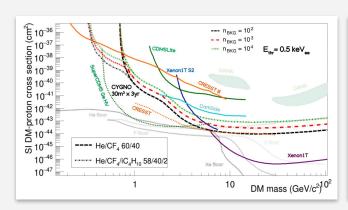
Expected SI and SD (90% CL)

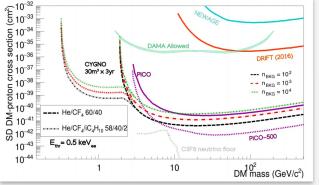
interaction cross-section exclusion

**QF** simulated with **SRIM** 

0.5 - 1 keV<sub>ee</sub> energy threshold &30° angular resolution assumed

H-doped mixtures <u>tested</u> ⇒ allows to explore very low DM masses!







## PhD within the CYGNO experiment

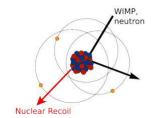
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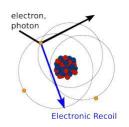
## PhD in CYGNO - Framework



A particle interacts inside our gas, He:CF4 ⇒

We look for the *ionization signal* → *Camera*pictures and *PMT waveforms* are recorded.



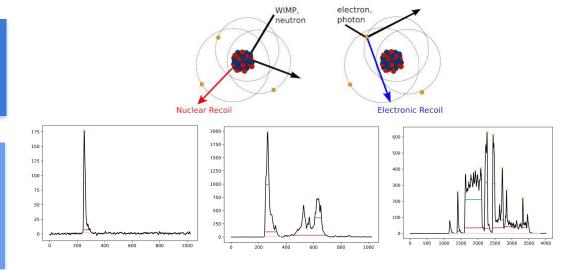


## PhD in CYGNO - Framework



A particle interacts inside our gas, He:CF4 →
We look for the *ionization signal* → *Camera*pictures and PMT waveforms are recorded.

Development of an algorithm for the reconstruction of the longitudinal track pattern and absolute track drift coordinate of ionisation tracks with PMT waveforms



## PhD in CYGNO - Framework

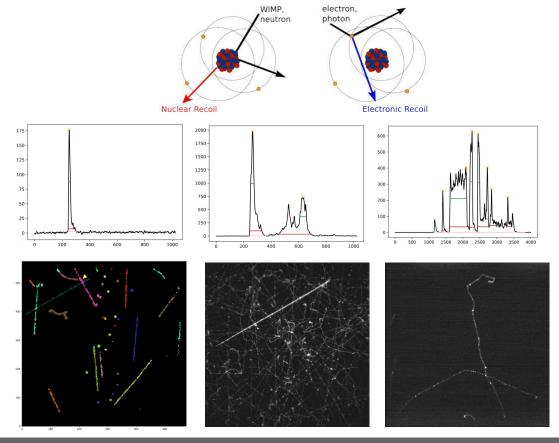


A particle interacts inside our gas, He:CF4 →
We look for the *ionization signal* → *Camera*pictures and PMT waveforms are recorded.

Development of an algorithm for the reconstruction of the longitudinal track pattern and absolute track drift coordinate of ionisation tracks with PMT waveforms

Merge with the sCMOS X-Y projection and variables

Obtain full 3D tracking



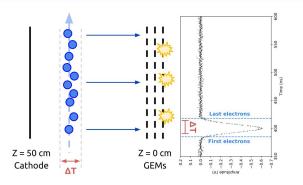
## PhD in CYGNO - PMT importance

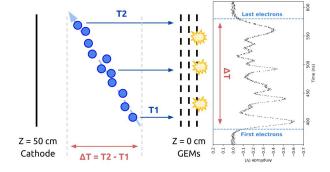


Development of an algorithm for the reconstruction of the longitudinal track pattern and absolute track drift coordinate of ionisation tracks with PMT waveforms

#### Third coordinate (dZ)

Use the charge carriers' times of arrival to calculate the dZ (track's tilt)





## PhD in CYGNO - PMT importance



Last electrons

Development of an algorithm for the reconstruction of the longitudinal track pattern and absolute track drift coordinate of ionisation tracks with PMT waveforms

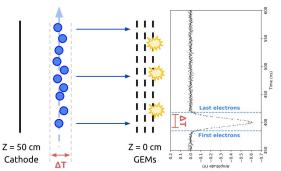
#### Third coordinate (dZ)

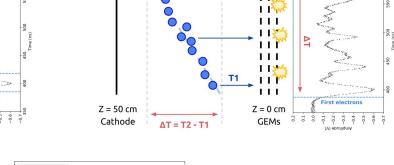
Use the charge carriers' times of arrival to calculate the dZ (track's tilt)

## Particles deposit energy in different ways

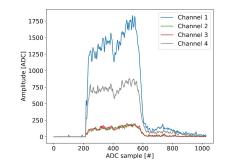
Imprinted in PMT waveform amplitudes in time domain

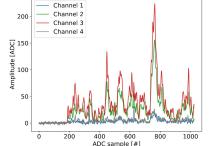
PID and Head-tail

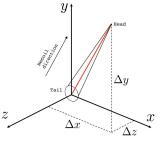




T2

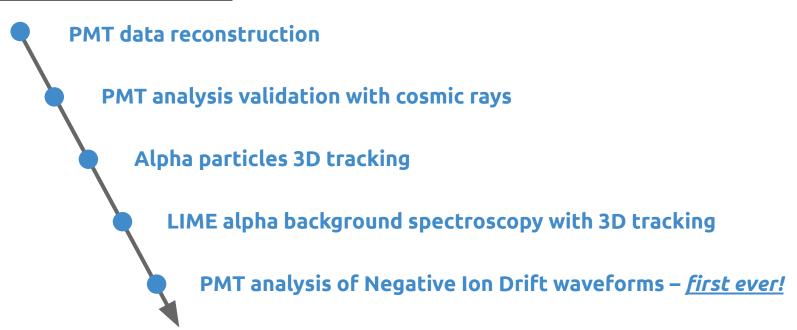






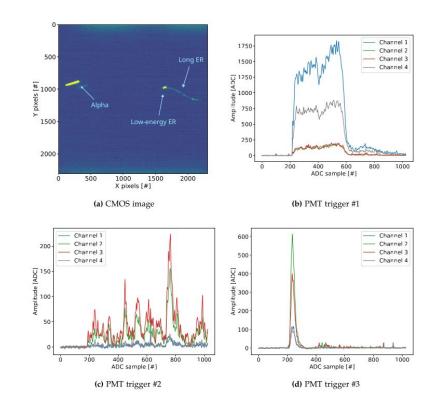
## 3D tracking with the CYGNO/INITIUM experiment

### Thesis work outline



# PMT data reconstruction

Basic data handling waveform analysis



# PhD Reco - Waveform analysis



First CYGNO official PMT analysis

<u>PMT reconstruction</u> → Full integration of waveforms information

within CYGNO's data framework.

# PhD Reco - Waveform analysis



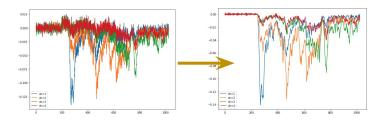


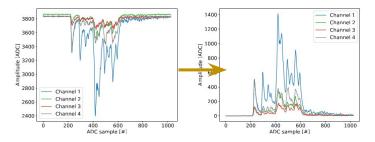
#### First CYGNO official PMT analysis

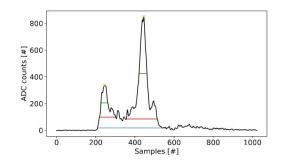
PMT reconstruction → Full integration of waveforms information within CYGNO's data framework.

#### Steps:

- **PMTs** readout by **digitizers** ⇒ **Retrieve data** from DAQ
- Update the waveforms with digitizer corrections
- Apply **basic filters** for HF noise and amplitude correction.
- Employ **peak finder** with simple parameters with possibility of tuning, and other variables
- Create a TTree with the PMT reconstructed variables and integration in the cygno analysis framework
- Create a **framework** that allows for **analysis of PMT** events stand-alone and together with camera.







# PhD Reco - Full integration



#### **Rundown of the variables:**

- pmt\_wf\_[run/event/trigger/channel/sampling]
- pmt\_[baseline/RMS]
- pmt\_tot\_[integral/charge]
- pmt\_max\_ampl
- pmt\_nPeaks
- pmt\_peak\_[Position/Height/HalfWidth/FullWidth]

- ⇒ *Basic* info of each waveform
- ⇒ Baseline and RMS. Useful to check *quality of data*
- $\Rightarrow$  Sum and conversion of **all samples** of a waveform
- ⇒ Waveform's max amplitude. Useful for **PID** (alpha's high signal)
- ⇒ Waveform's number of peaks. Useful for **PID** (55 Fe's single peak)
- $\Rightarrow$  Basic implementation.

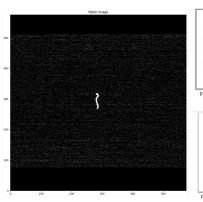
# PhD Reco - Full integration

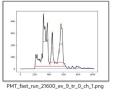


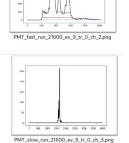
#### **Rundown of the variables:**

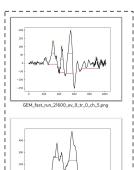
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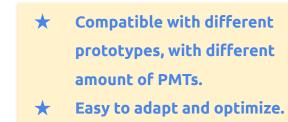








GEM\_fast\_run\_21600\_ev\_9\_tr\_0\_ch\_7.png

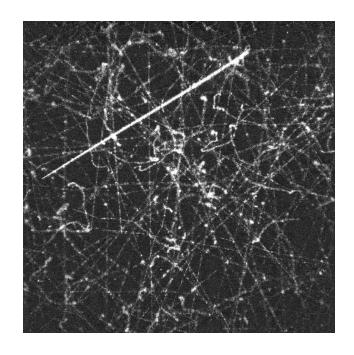




recording for LIME R&D

# PMT data reconstruction Tilted cosmics study

Making use of the PMT-reconstruction developed and time-over-threshold variable to calculate the zenith incident angle of cosmic muons in LIME



## PMT Reco - Tilted cosmics



#### **Motivation:**

• Test the data acquisition system of the PMT signals and validate the PMT-reco waveform reconstruction techniques & capabilities.

#### **Method:**

• <u>Using scintillator bars on top and bottom of LIME, record muon</u> tracks with *well-defined orientation, given by the coincidence of the bars* 

#### Outcome:

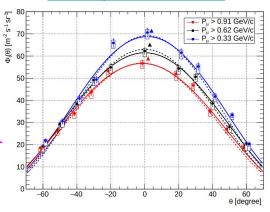
Evaluate cosmic ray flux at ground and its directional dependence w.r.t.
 the zenith angle ⇒ proportional to cos²(Θ)\*

#### **Analysis & Math:**

- 1. Calculate the zenith angle ψ
- 2. Calculate the **event rate N/\Delta t**
- 3. Calculate the **geometric acceptance**  $\Delta\Omega$
- 4. Efficiency ( $\epsilon$ ) and area (S) are known

#### Expected results...

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



$$\Phi_{\rm I}(P_{\mu}^{\rm m}, \psi) \, = \, \frac{N_{\mu}}{\varepsilon \, \, S \, \Delta \Omega \, \, \Delta t}$$

$$\Phi_{\rm I}(\psi) = \Phi_{\rm I}(0^{\circ}) \cdot \cos^{\rm n}(\psi)$$

# Tilted Cosmics - Experimental setup

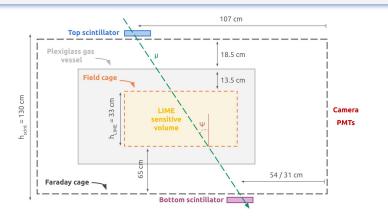


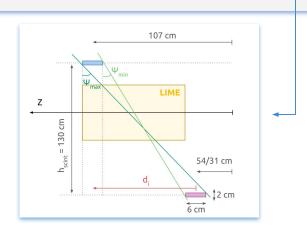
#### **Setup:**

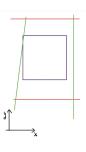
- → Two scintillator bars placed on **top** and **bottom** of LIME. LIME DAQ **triggered by coincidence** of two scintillators.
  - lack 3 different scintillator positions  $\Rightarrow$  By geometry, only certains angles are possible

#### Ассигасу:

- This configuration actually allows for cosmics to enter and trigger from the side of LIME clipped muons.
- Random coincidences from radioactivity or secondary particles are also possible.
- Amount of data points limited by system geometry (large Faraday cage). ⇒ Each point takes ~1 week.







# Tilted Cosmics - Analysis

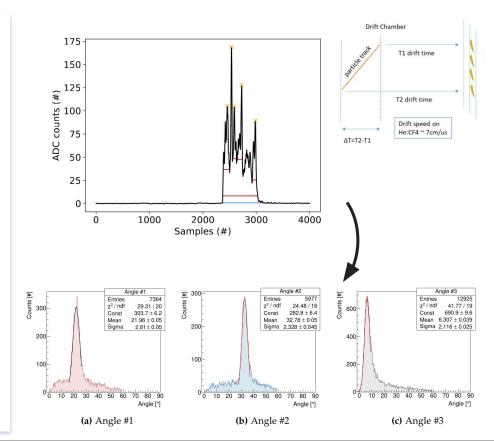


#### **Analysis method:**

- 1. Calculate the **zenith angle** from the PMT
  - Get the *Time over threshold* of the weighted average waveform (see bckp)
  - Multiply with e- drift velocity in He:CF<sub>4</sub> 60:40
     (~5.5 cm/µs) to get travelled Z
  - Use LIME's height to calculate the final incidence angle

$$\psi = \tan^{-1} \left( \frac{\Delta Z}{h_{LIME}} \right)$$

★ Compare obtained angle with geometrically accepted and simulated ones

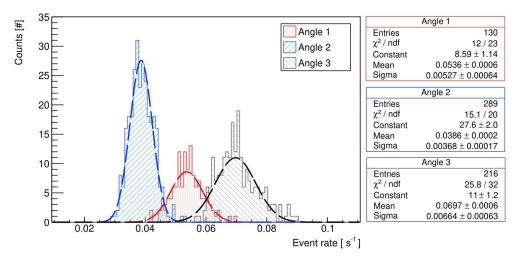


# Tilted Cosmics - Analysis



#### **Analysis method:**

- 2. Calculate the event rate for each of the 3 angle configurations
  - Retrieved from the DAQ timestamps of each run, predefined to have 100 events.
  - With event rate below 0.1 Hz, inefficiencies due to dead-time or overlap are negligible.



⇒ The differences in event rate of each dataset highlights the variations in flux and geometrical acceptance between them

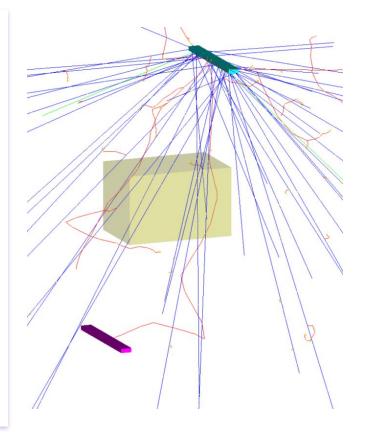
# Tilted Cosmics - Analysis



#### **Analysis method:**

- 3. Simulation of the geometrical acceptance
  - A GEANT4 simulation was designed with a simple 3-body schematic representing the two scintillator bars and the LIME sensitive gas volume.
  - For each geometry, muons with an energy of 4 GeV were shot randomly from top scintillator creating a isotropic flux of muons in 3D.
  - The *geometrical acceptance* is calculated from ratio between the scintillators coincidence and total shot particles.

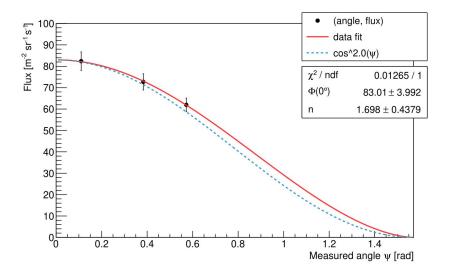
$$GA = \left(\frac{N_{hit}}{N_{total}}\right) * \pi * S$$



## Tilted Cosmics - Results



$$\Phi_{\rm I}(P_{\mu}^{\rm m},\psi) \,=\, \frac{N_{\mu}}{\epsilon \,\, S \,\, \Delta\Omega \,\, \Delta t} \qquad \Phi_{\rm I}(\psi) \,=\, \Phi_{\rm I}(0^{\circ}) \,\, \cdot \, \cos^{n}(\psi)$$

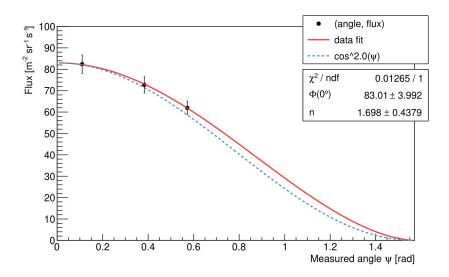


$$\Phi_{\rm I}(0^{\circ}) \ = \ 83.01 \ \pm \ 3.99 \ m^{-2} sr^{-1} s^{-1} \qquad \qquad n \ = \ 1.698 \ \pm \ 0.438$$

## Tilted Cosmics - Results



$$\Phi_{\rm I}(P_{\mu}^{\rm m},\psi) \,=\, \frac{N_{\mu}}{\epsilon \,\, S \,\, \Delta\Omega \,\, \Delta t} \qquad \Phi_{\rm I}(\psi) \,=\, \Phi_{\rm I}(0^{\circ}) \,\, \cdot \, \cos^{n}(\psi)$$



$$\Phi_{\rm I}(0^{\circ}) \ = \ 83.01 \ \pm \ 3.99 \ {\rm m}^{-2} {\rm sr}^{-1} {\rm s}^{-1} \qquad \qquad {\rm n} \ = \ 1.698 \ \pm \ 0.438$$

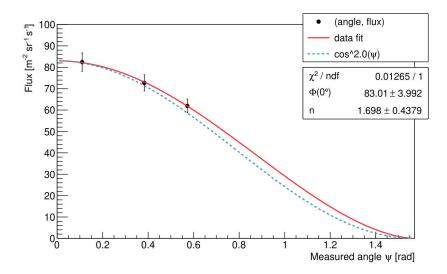
Authors	$P_c$ $(GV)$	Alt. (m)	$P_{\mu}$ $(GeV/c)$	n value	$\Phi_I(0^\circ)$ $(m^2 \ sr \ s)^{-1}$
Pethuraj et al. [34]	17.6	160	≥0.11	$2.00\pm0.16$	70.07±5.26
Sogarwal et al. [35]	16.38	SL	≥0.25	$2.10 \pm 0.25$	66.70±1.54
S. Pal et al. [36]	16	SL	≥0.28	$2.15{\pm}0.01$	$62.17\pm0.05$
Bhattacharyya [37]	14	24	≥0.4	$1.91\pm0.1$	_
			≥1.	$1.85{\pm}0.11$	_
Arneodo et al. [38]	14	SL	≥0.04	$1.91 \pm 0.18$	75.4±1.4
Present data	9.6	38	≥0.33	$1.82 \pm 0.11$	68.77±1.94
			≥0.62	$1.72 \pm 0.10$	61.49±1.44
			≥0.91	$1.72 \pm 0.10$	56.66±1.60
CRY [25]	9.6	SL	≥0.33	2.02	69.26
			≥0.62	1.95	63.02
			≥0.91	1.87	56.80
Riggi et al. [33]	8	3100	≥0.2	$1.83 \pm 0.13$	83.±8
Judge and Nash [39]	2.5	SL	≥0.7	$1.96\pm0.22$	

⇒ Results consistent within published data

## Tilted Cosmics - Conclusions



$$\Phi_{\rm I}(P_\mu^m,\psi) \; = \; \frac{N_\mu}{\varepsilon \; S \; \Delta\Omega \; \Delta t} \qquad \Phi_{\rm I}(\psi) \; = \; \Phi_{\rm I}(0^\circ) \; \cdot \; cos^n(\psi) \label{eq:phi_I}$$



$$\Phi_{\rm I}(0^{\circ}) \; = \; 83.01 \; \pm \; 3.99 \; {\rm m}^{-2} {\rm sr}^{-1} {\rm s}^{-1} \qquad \quad {\rm n} \; = \; 1.698 \; \pm \; 0.438$$

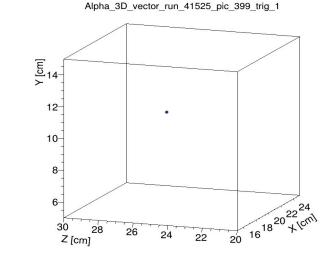
#### **Conclusions:**

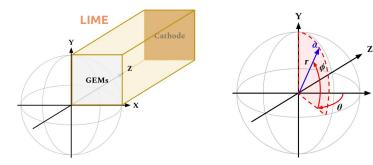
- CYGNO PMT-DAQ working properly
- PMT waveform reconstruction validated
- **ToT is a reliable variable** to assess the track's  $\Delta Z$
- Study could be improve with more angles and more precision in the dimensions measurements
- Similar studies are being carried out to study the transverse and longitudinal diffusions of MIP-like particles selecting vertical-only muons

⇒ Assessment of efficiency of PMT Reco developed and implemented

⇒ First CYGNO full PMT analysis

PMT and sCMOS analysis integration into a complete CYGNO analysis framework for <u>3D</u> <u>directional</u> event reconstruction (including head-tail) of alpha particles in LIME





#### 1. CMOS analysis

- 1.1. Track's XY absolute position and pixel intensity
- 1.2. Directionality algorithm applied to retrieve the  $\phi$  angle
- 1.3. Track transverse profile to retrieve absolute Z

#### 2. PMT analysis

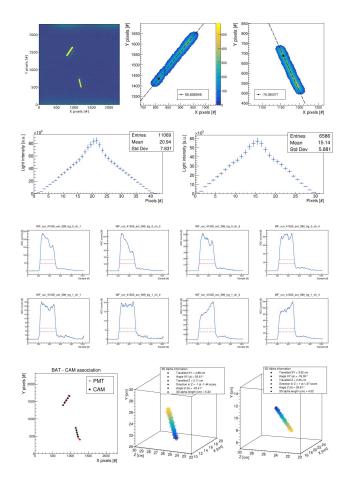
- 2.1. Waveform time-over-threshold to determine track's  $\Delta Z$
- 2.2. Bragg peak analysis to determine the **sign of \theta angle**

#### 3. <u>Combined analysis</u>

- 3.1. Matching alpha track in the CMOS and PMT using the BAT-fit
- 3.2. Merging all the information to retrieve value of  $\theta$  angle

#### → Alpha 3D vector in space achieved

• Results: Alpha spectroscopy in LIME using obtained 3D length



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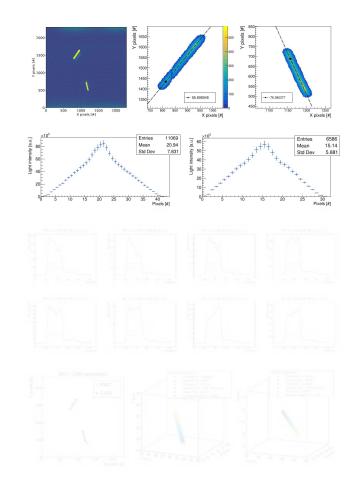
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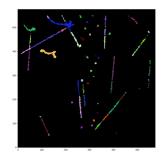
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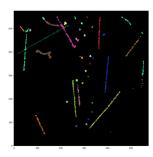


# CMOS analysis - XY position



- The analysis of the CMOS images starts with a <u>directional iDBSCAN algorithm</u> which clusters groups of pixels belonging to the same ionization event.
  - For <u>PID</u>, each <u>cluster</u> can be selected through its: *light integral*, *length*, slimness, photon density, dE/dx, etc.



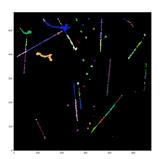


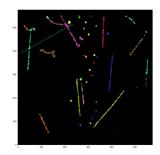
<u>Directional iDBSCAN to detect cosmic-ray tracks for the CYGNO experiment - IOPscience</u>

# CMOS analysis - XY position



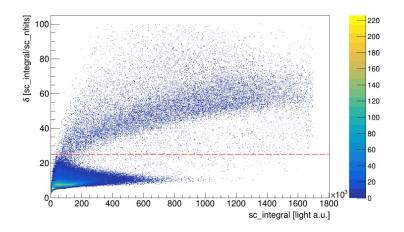
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Directional iDBSCAN to detect cosmic-ray tracks for the CYGNO experiment - IOPscience

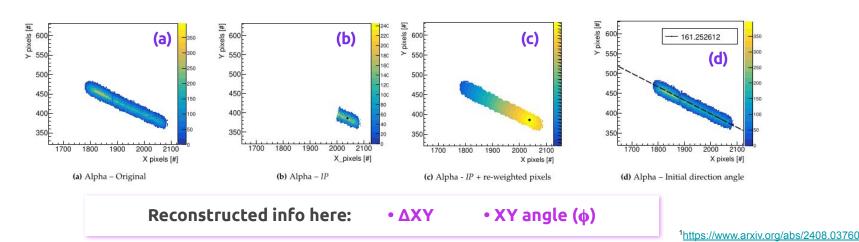
- Alpha tracks are here initially selected ⇒ similar to
   NRs but longer and easier to "3D Track"
- **Fake sensor noise clusters** were analysed in terms of length and width in pedestal runs and the removed.
- Then I select events with **high dE/dx** ( $\delta$  > 25), easily separable from ERs/MIPs.



# CMOS analysis - $\phi$ angle



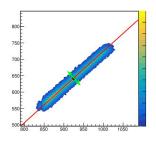
- The *directionality* algorithm initially optimized by S. Torelli<sup>1</sup> for ERs was further tuned for alpha particles.
- The algorithm starts by identifying the track's major axis (a), then estimates the interaction point (IP) (b); then it refines the track direction by reweighting pixel intensities relative to the IP (c); and determines the final orientation of the track (d).
- The XY (2D) length automatically comes out as the distance between the edgemost pixels.
- For alpha particles, two free parameters were adjusted to account for their broader electron cloud and straighter tracks, simplifying the direction and sense reconstruction, without the need for intensive optimization.



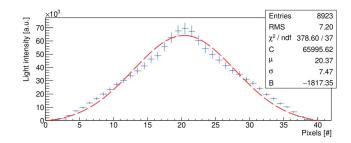
## CMOS analysis - Absolute Z



- In experiments like CYGNO, there is **no information** about the **start position** of the event (t0 or trigger).
- The absolute Z position is determined by through the diffusion of the electron cloud ⇒ fitting the transverse distribution of light of the alpha track's major axis ⇒ Transverse profile
- A gaussian fit does not present well this distribution. The **RMS** results in a better description of the distro.



$$Z = \frac{\sigma^2 - \sigma_0^2}{\sigma_T^2}$$

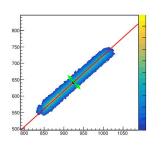


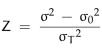
$$\sigma_{T} = 129.7 \pm 3.1 \,\mu\text{m/cm}^{1/2}$$
  
 $\sigma_{0} = 780 \pm 30 \,\mu\text{m/cm}^{1/2}$ 

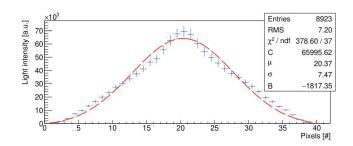
## CMOS analysis - Absolute Z



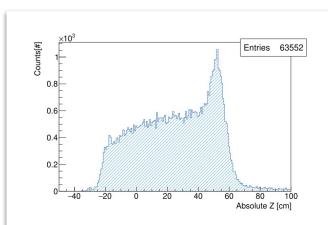
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$$\sigma_{T} = 129.7 \pm 3.1 \,\mu\text{m/cm}^{1/2}$$
  
 $\sigma_{0} = 780 \pm 30 \,\mu\text{m/cm}^{1/2}$ 



- → Peaks at 50 cm, the length of LIME.
- → Offset below 0 cm due to limitations of the formula and parameters measurement
- → Usable to hint absolute Z position
- → First indication of higher amount of events at cathode level

#### 1. CMOS analysis

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- Track transverse profile to retrieve absolute Z

#### 2. PMT analysis

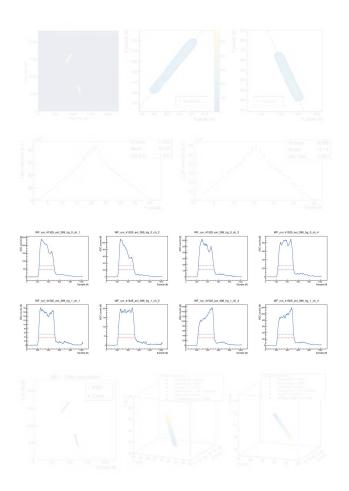
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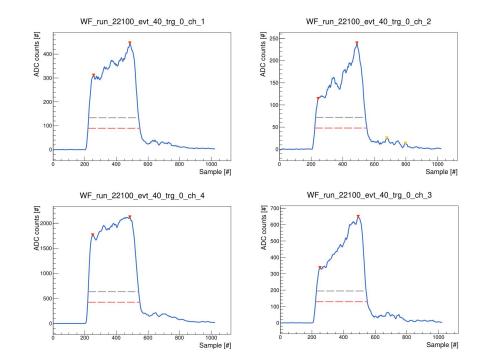
#### → Alpha 3D vector in space achieved

Results: Alpha spectroscopy in LIME using obtained 3D length



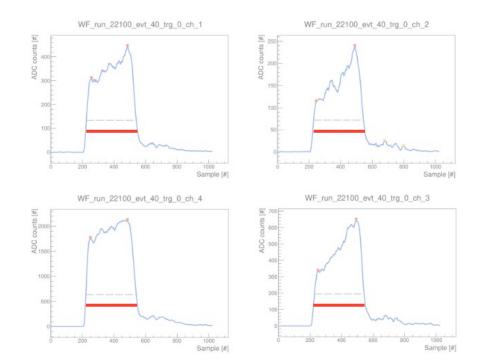


→ The <u>PMTs</u> gives us information regarding the <u>longitudinal coordinate Z</u>, and allows us to close the <u>3D geometry</u>



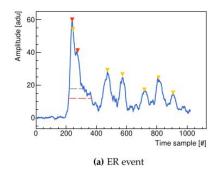


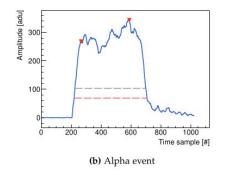
- → The <u>PMTs</u> gives us information regarding the <u>longitudinal coordinate Z</u>, and allows us to close the <u>3D geometry</u>
- Time-over-Threshold ⇒ Traveled Z

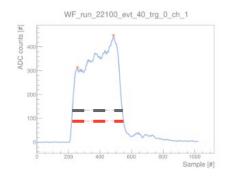


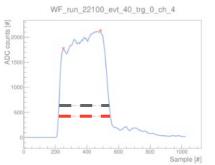


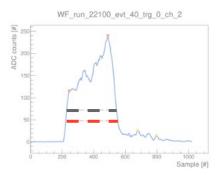
- → The <u>PMTs</u> gives us information regarding the <u>longitudinal coordinate Z</u>, and allows us to close the <u>3D geometry</u>
- Time-over-Threshold ⇒ Traveled Z
- Ratio between TOT20 and TOT30 + number of peaks used to identify alpha waveforms ⇒ PID

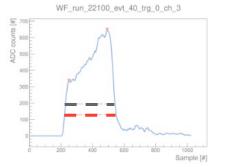








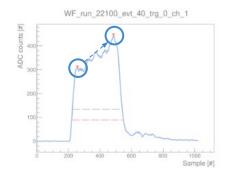


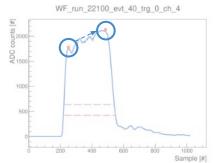


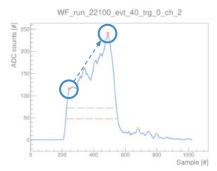


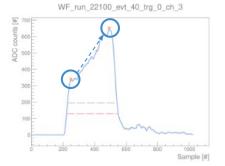
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- Time-over-Threshold ⇒ Traveled Z
- Ratio between TOT20 and TOT30 + number of peaks used to identify alpha waveforms ⇒ PID
- Bragg peak position ⇒ Moving towards GEMs or cathode

\*The position of the Bragg peak in the waveform is convoluted with the geometrical dependence (L∝R<sup>-4</sup>), resulting in an ambiguous direction in ~25% of cases









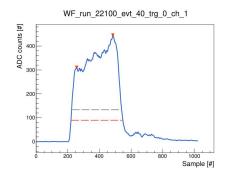


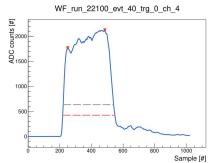
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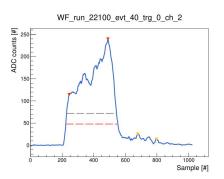
#### Reconstructed info here:

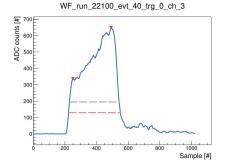
ΔZ

• Z angle (θ) sign









#### 1. CMOS analysis

- 1.1. Track's XY absolute position and pixel intensity
- 1.2. Directionality algorithm applied to retrieve the  $\phi$  angle
- 1.3. Track transverse profile to retrieve absolute Z

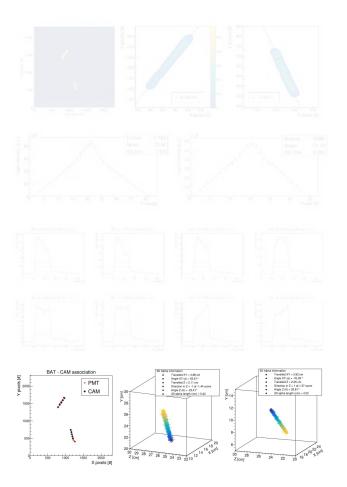
#### 2. PMT analysis

- 2.1. Waveform time-over-threshold to determine track's AZ
- 2.2. Bragg peak analysis to determine the sign of  $\theta$  angle

#### 3. Combined analysis

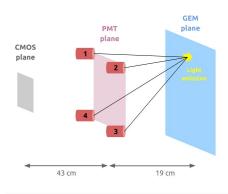
- 3.1. Matching alpha track in the CMOS and PMT using the BAT-fit
- 3.2. Merging all the information to retrieve value of  $\theta$  angle

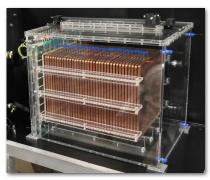
- → Alpha 3D vector in space achieved
  - Results: Alpha spectroscopy in LIME using obtained 3D length



## LIME - Event definition



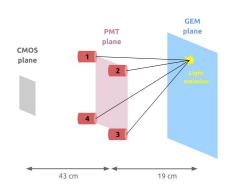


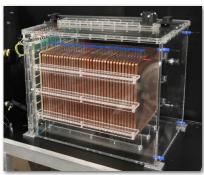


- → 50 L & 50 cm drift gaseous TPC
- → **He:CF4**, 60:40, **1 Atm** (910 mbar), 293 K
- → 4 PMTs + 1 sCMOS camera

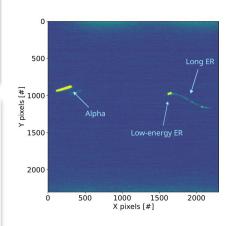
## LIME - Event definition

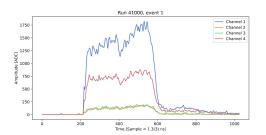


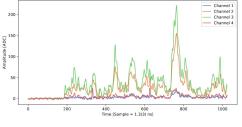




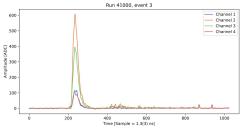
- → 50 L & 50 cm drift gaseous TPC
- → **He:CF4**, 60:40, **1 Atm** (910 mbar), 293 K
- → 4 PMTs + 1 sCMOS camera
- One event =
  - 1 CMOS pic:  $R_{\Delta t} = 500 \text{ ms}$
  - ◆ X PMT WFs = N<sub>triggers</sub> \* N<sub>PMTs</sub> \* N<sub>digitiz</sub>
    - R<sub>AF</sub> = **1.3 ns & 4 ns**





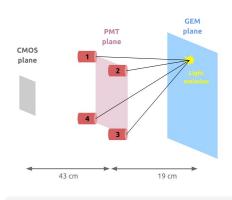


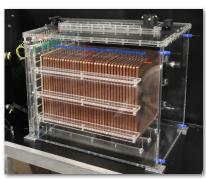
Run 41000, event 2



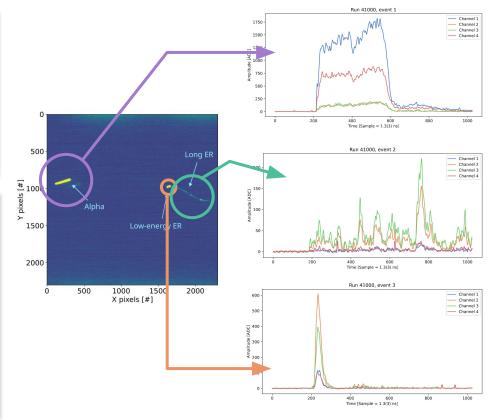
## LIME - Event definition







- → 50 L & 50 cm drift gaseous TPC
- → **He:CF4**, 60:40, **1 Atm** (910 mbar), 293 K
- → 4 PMTs + 1 sCMOS camera
- → One event =
  - 1 CMOS pic:  $R_{\Delta t} = 500 \text{ ms}$
  - lack X PMT WFs =  $N_{triggers} * N_{PMTs} * N_{digitiz}$ 
    - R<sub>AF</sub> = **1.3** ns & **4** ns
- → The information needs to be matched!



## 3D Events - One-to-One association

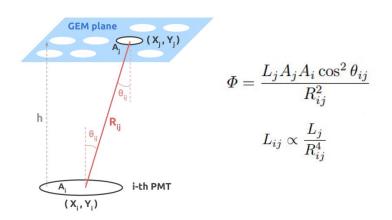


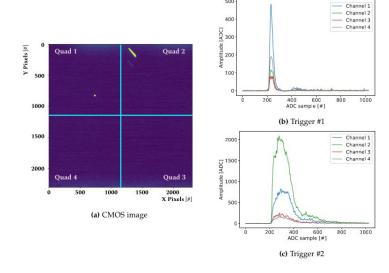
To **fully** reconstruct the information of one event, we developed a <u>1-to-1 association</u> to merge the **CMOS** clusters to **PMT triggers**, using the event's **light barycenter**.

## 3D Events - One-to-One association



- To **fully** reconstruct the information of one event, we developed a <u>1-to-1 association</u> to merge the CMOS clusters to PMT triggers, using the event's light barycenter.
- **Light (L**<sub>ii</sub>) seen by each PMT depends on their relative positions wrt light emission (R;;)





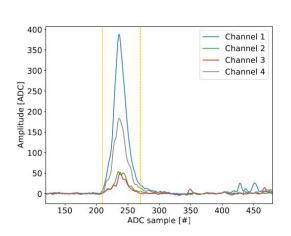
...through the relative amplitudes of each PMT it is possible to determine the overall position of the event in the CMOS FoV...

https://arxiv.org/pdf/2506.04973 (as corresponding author)

## 3D Events - One-to-One association



- → To **fully** reconstruct the information of one event, we developed a <u>1-to-1 association</u> to merge the **CMOS** clusters to **PMT triggers**, using the event's **light barycenter**.
- 2. We integrate the waveform charge in a given time window, and then apply a multi-variable Bayesian fit to retrieve the (x, y, L) information of the track as seen by the PMTs.
  - a. Initially performed for <sup>55</sup>Fe ERs given their spot-like shape



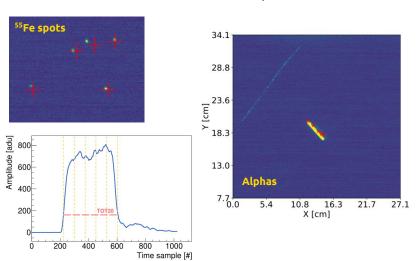
$$\begin{split} p(\theta|\{x\}) \; &= \; \frac{p(\{x\}|\theta) \; \cdot \; \pi(\theta)}{p(\{x\})} \\ p(\{x\}|\theta) \; &= \; \prod_{j=1}^N \prod_{i=1}^4 \frac{1}{\sqrt{2\pi}\sigma_{ij}} \; \cdot \; exp \; \bigg( \; - \; \frac{(Q_{ij} \; - \; L_{ij}'(\theta))^2}{2\sigma_{ij}^2} \bigg) \\ \\ L_{ij}'(\theta) \; &\propto \; L_j/R_{ij}^\alpha \\ \\ R_{ij} \; &= \; \sqrt{(x_j \; - \; x_i)^2 \; + \; (y_j \; - \; y_i)^2 \; + \; h^2}. \end{split}$$

https://arxiv.org/pdf/2506.04973 (as corresponding author)

#### 3D Events - One-to-One association



- → To **fully** reconstruct the information of one event, we developed a <u>1-to-1 association</u> to merge the CMOS clusters to PMT triggers, using the event's light barycenter.
- 3. With (x, y, L) from the PMTs, we compare it with the CMOS clusters and assign them through the closest neighbor.
  - **a.** I extended this work for **alphas** through the 'slice-and-fit' method of the ToT variable.
    - i. ToT is cut in spot-like slices which are individually fitted, create a trail of of XY points ("track")

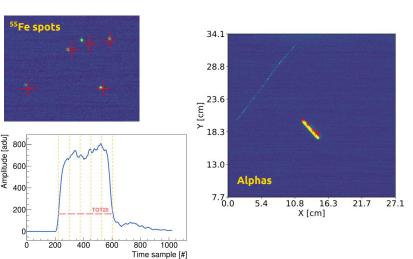


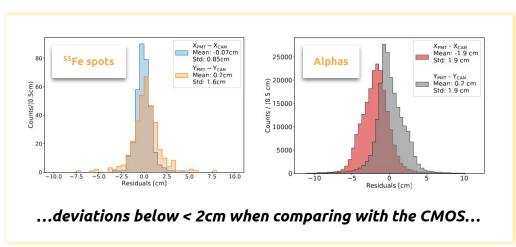
https://arxiv.org/pdf/2506.04973 (as corresponding author)

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#### 3D Events - CMOS-PMT 3D reco



ullet Once the two sensors are matched, the final component (0) can be calculated:  $0=\arctan\left(rac{\Delta Z}{\Delta XY}
ight)$ 

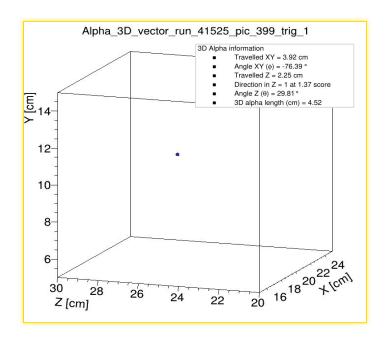
#### 3D Events - CMOS-PMT 3D reco



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ight)$ 

#### Reconstructed info at this stage:

- CMOS: ΔXY + Phi (φ) + Abs Z
- PMT: ΔZ + Sign of Theta (θ)
- Mixed: Value of Theta (θ)
  - o 3D length
  - 3D direction + Head-tail



#### 3D Events - CMOS-PMT 3D reco

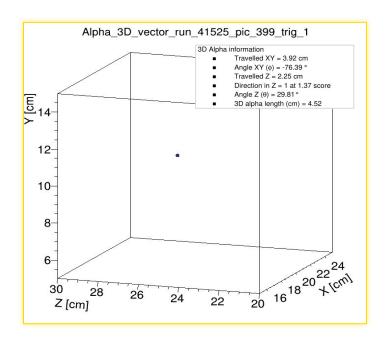


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  - o 3D length
  - 3D direction + Head-tail

⇒ 3D reconstruction is a landmark for CYGNO within the scope of directional DM searches and overall TPC tracking capabilities



#### Alpha particles 3D tracking

#### 1. CMOS analysis

- 1.1. Track's XY absolute position and pixel intensity
- 1.2. Directionality algorithm applied to retrieve the  $\phi$  angle
- 1.3. Track transverse profile to retrieve absolute Z

#### 2. PMT analysis

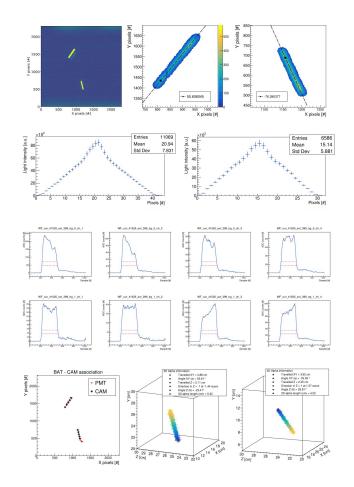
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#### Combined analysis

- 3.1. Matching alpha track in the CMOS and PMT using the BAT-fit
- 3.2. Merging all the information to retrieve value of  $\theta$  angle

#### → Alpha 3D vector in space achieved

• Results: Alpha spectroscopy in LIME using obtained 3D length





# Dual sensor 3D analysis

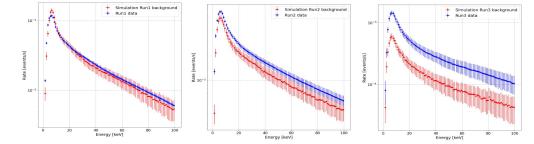
# Alpha spectroscopy

#### Objectives:

- Similarity to NRs at first order, providing good analysis template.
- Complement the previous LIME background studies, shining light to some inconsistencies.
- Different detector materials were studied, highlighting different isotope contributions to the overall background.
- The presence of Rn was studied in more detail, leading to design updates for upcoming detectors.

# 3D Analysis - BG studies conclusions

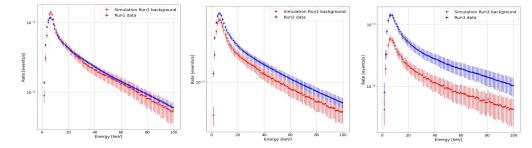
Phase	Shielding	GEM V [V]	# pictures	Live time [s]	Rate PMTs [Hz]		
Run 1	None	420	285665	175627	30		
Run 2	4 cm Cu	440	297992	191382	3.5		
Run 3	10 cm Cu	440	171579	191471	1.6		
Run 4	+40 cm H2O	Great external neutron suppression ⇒ <i>Under analysis</i>					



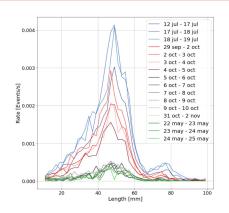
- Shielding strongly suppressed external background
- Difference in Runs 2 & 3 attributed to internal background excess (contaminations of the detector – materials, gas, etc.)
  - LIME was not meant to be radiopure

## 3D Analysis - BG studies conclusions

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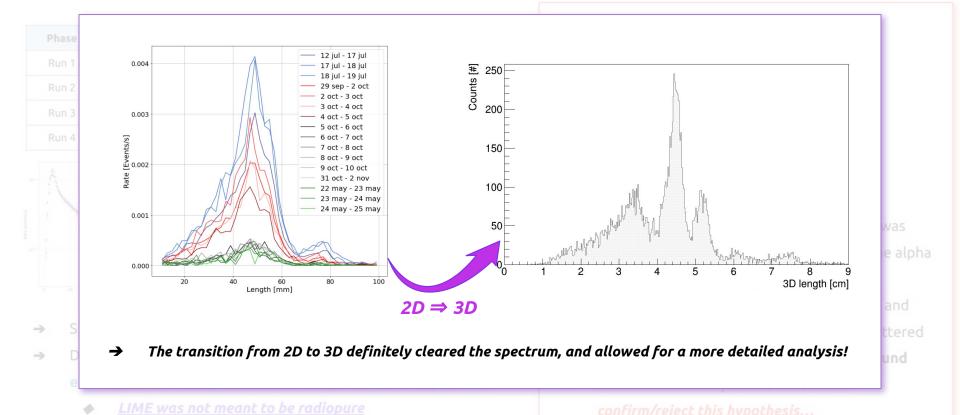


- Shielding strongly suppressed external background
- Difference in Runs 2 & 3 attributed to internal background excess (contaminations of the detector – materials, gas, etc.)
  - LIME was not meant to be radiopure



- When studying the 2D length of alphas<sup>1</sup>, it was found (with low certainty) what could be the alpha peaks of the <sup>222</sup>Rn chain
- This chain has additional beta decays at 1.2 and 3.3 MeV, leading to betas and Compton scattered ERs, which contribute to a diffuse background
- The introduction of the 3D reco could confirm/reject this hypothesis...

# 3D Analysis - BG studies conclusions



# 3D Events - True track 3D length

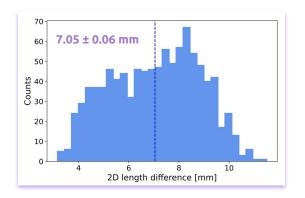


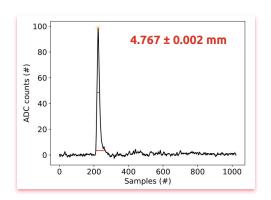
→ The measured 3D length typically results greater than the actual range due to the smearing of the primary ionization cloud which is degraded by diffusion during drift and amplification + by the detector response ⇒ <u>minimum XYZ signal</u>

# 3D Events - True track 3D length



- → The measured 3D length typically results greater than the actual range due to the smearing of the primary ionization cloud which is degraded by diffusion during drift and amplification + by the detector response ⇒ <u>minimum XYZ signal</u>
  - ♦ For the CMOS, images of alpha tracks were generated starting from GEANT4 simulations which are then smearing simulating the CYGNO detector effects. The difference between before and after smearing give an estimate of the detector effect for alphas.
  - $\bullet$  <u>For the PMT</u>, the signals from a <sup>55</sup>Fe source (spot-like) were analysed and assumed as the "minimal visible signal".



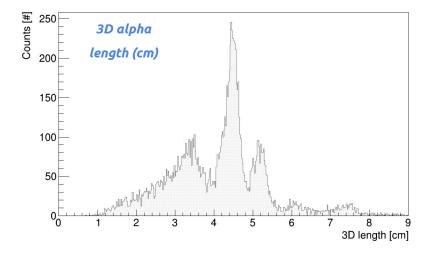


- → Preliminary approach!
- → Other methods under study in the collaboration

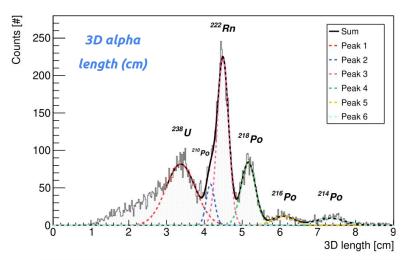
• Final result: 3D length correction factor =  $8.51 \pm 0.06$  (stat.)  $\pm 0.85$  (syst.) mm

# Alphas - 3D length





## Alphas - 3D length



Measured values				Candidate decay		
Peak	3D length	Corrected	Estimated	Isotope	α energy	SRIM
#	$(\pm 1\sigma)$ [mm]	3D length [mm]	energy [MeV]	Isotope	[MeV]	range [mm]
1	$33.73 \pm 3.93$	$25.22 \pm 4.02$	$4.160^{+0.470}_{-0.480}$	<sup>238</sup> U	4.198	25.34
2	$41.60\pm1.11$	$33.09 \pm 1.40$	$5.055^{+0.110}_{-0.120}$	<sup>210</sup> Po	5.304	35.45
3	$44.90\pm1.49$	$36.39 \pm 1.72$	$5.400^{+0.175}_{-0.180}$	<sup>222</sup> Rn	5.489	37.26
4	$51.60\pm1.91$	$43.09 \pm 2.09$	$6.055^{+0.195}_{-0.205}$	<sup>218</sup> Po	6.002	42.52
5	$60.80\pm2.90$	$52.29 \pm 3.02$	$6.880^{+0.255}_{-0.265}$	<sup>216</sup> Po	6.778	51.10
6	$73.24\pm3.84$	$64.73 \pm 3.93$	$7.890^{+0.300}_{-0.305}$	<sup>214</sup> Po	7.687	62.10

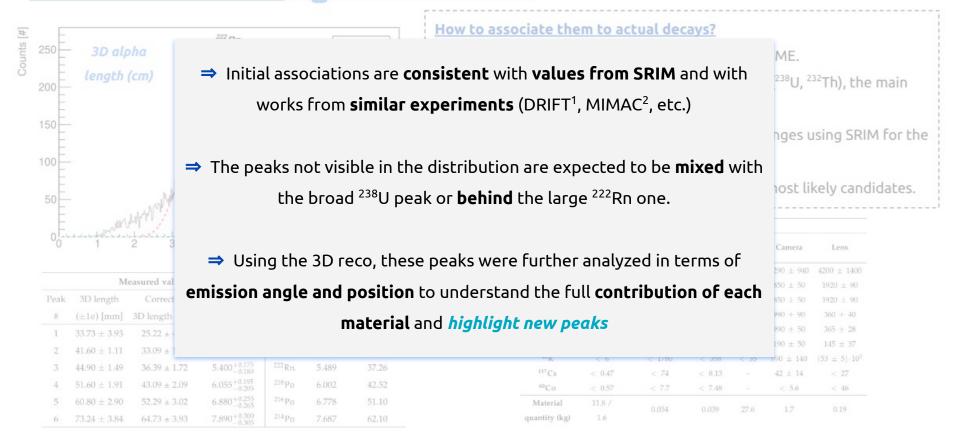
#### How to associate them to actual decays?

- Look at the most common backgrounds in LIME.
- For the most abundant primordial isotopes (238U, 232Th), the main alpha decays are cross-checked.
- The alpha energies are converted into 3D ranges using SRIM for the 3. CYGNO mixture.
- The closest range pairs are considered the most likely candidates.

	Material Activity (mBq/kg)						
Isotope	Fields rings / Cathode	Resistors	GEMs	PMMA	Camera	Lens	
$^{238}U(^{234}Th)$	< 210	$(20 \pm 2) \cdot 10^3$	$163 \pm 65$	< 3.5	3290 ± 940	4200 ± 1400	
$^{238}U(^{226}R\alpha)$	< 1.3	$2160\pm160$	$32\pm16$	< 3.5	$850\pm50$	$1920\pm90$	
<sup>210</sup> Pb	< 13	$(592 \ \pm \ 70) \cdot 10^3$	$32\pm16$	< 3.5	$850\pm50$	$1920\pm90$	
$^{232}Th(^{228}R\alpha)$	< 1.1	$3500\pm320$	< 30.9	< 5	$990\pm90$	$360\pm40$	
$^{232}Th(^{228}Th)$	< 1.3	$3360\pm320$	< 15.6	< 4.5	$990\pm50$	$365\pm28$	
<sup>235</sup> U	< 1.6	$330~\pm~60$	< 15.8	-	$190\pm50$	$145\pm37$	
<sup>40</sup> K	< 6	< 1780	< 358	< 35	$890\pm140$	$(53 \pm 5) \cdot 10$	
<sup>137</sup> Cs	< 0.47	< 74	< 8.13	-	$42\pm14$	< 27	
<sup>60</sup> Co	< 0.57	< 7.7	< 7.48	-	< 5.6	< 46	
Material	11.8 /	0.054	0.039	27.6	1.7	0.19	
quantity (kg)	1.6	0.034	0.039	27.0	1.7	0.19	

# Alphas - 3D length

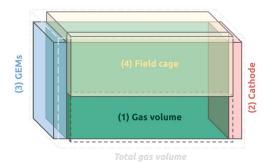




## Alphas - Alpha localization



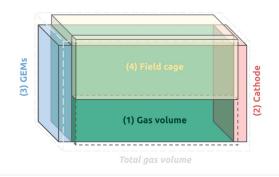
→ Using the variables from the 3D reconstruction, several cuts in X, Y and Z were used to divide the detector in different zones:

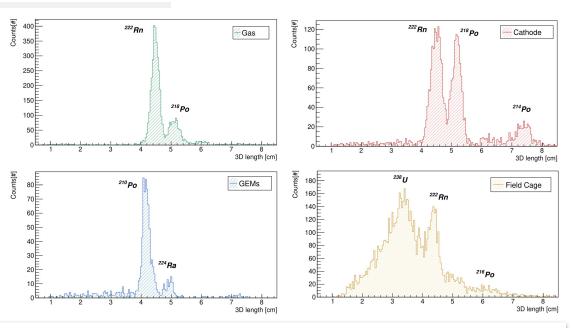


#### Alphas - Alpha localization



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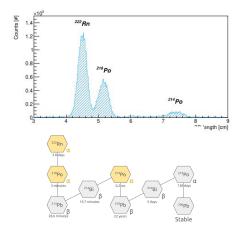




- $\rightarrow$  Gas  $\Rightarrow$  Mostly <sup>222</sup>Rn decay alphas, excluding <sup>214</sup>Po, expected to drift towards the cathode.
- $\rightarrow$  Cathode  $\Rightarrow$  The <sup>214</sup>Po peak appears, confirming the charged nature of the <sup>222</sup>Rn decay daughters; intensity of <sup>218</sup>Po increases.
- $\rightarrow$  GEMs  $\Rightarrow$  A new peak appears, expected from <sup>210</sup>Po, and further motivated by the presence of <sup>210</sup>Pb in the GEMs.
- $\rightarrow$  FC  $\Rightarrow$  Large contribution from <sup>238</sup>U peak due to its measured large presence in the FC. Consistent emission angle and position.

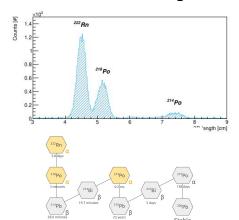
#### Alphas - A closer look at the

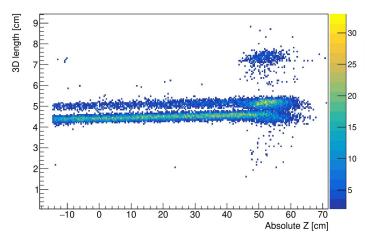
# contamination Gas + cathode regions

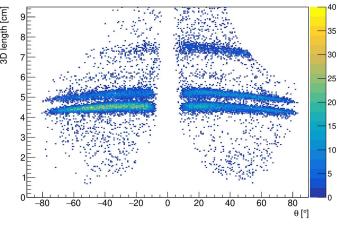


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# contamination Gas + cathode regions

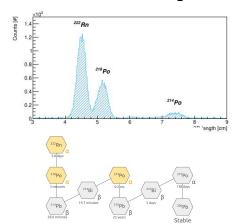


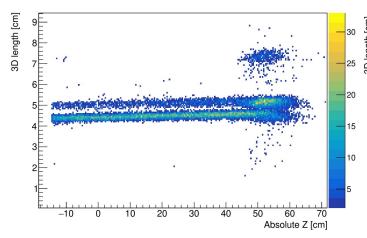


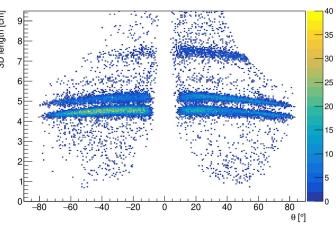


#### Alphas - A closer look at the

# contamination Gas + cathode regions



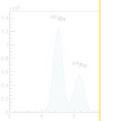




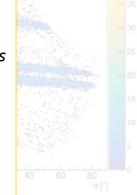
- Three Rn chain bands visible. Daughters decays increase for increased Z, showcasing effect of polarization of daughters:
  - <sup>222</sup>Rn well distributed in Z, showing the neutral nature of the parent.
  - Alphas at  $\sim$ 5 cm length ( $^{218}$ Po) emitted preferentially at higher Z, but not all, since it can decay before arriving to the cathode, or not being polarized (10-20% chance).
  - Alphas at  $\sim$ 7 cm length ( $^{214}$ Po) preferentially towards GEM and at high Z, again showing the polarization effect.

#### Alphas - A closer look at the 222Rn contamination





- $\star$  3D analysis validated through **3D length**, **emission angle** and **position**.
  - Can also be used to characterize <u>alphas energy</u> through cuts.
- ★ **Presence of Rn confirmed**, potentially explaining discrepancies in initial BG studies
  - Additional simulations and studies undergoing
- **★ Polarization** of Rn daughters and consequent drift observed.
- ★ Design optimizations for upcoming larger CYGNO detectors CYGNO-04 from these studies and others involving gas filters.
  - \* Alpha spectroscopy through 3D reconstruction allows for background characterization!



- ◆ Alphas at ~5 cm length (<sup>218</sup>Po) emitted preferentially at higher Z, but not all, since it can decay before arriving to the cathode, or not being polarized (10-20% chance).
- $\bullet$  Alphas at ~7 cm length ( $^{214}$ Po) preferentially towards GEM and at high Z, again showing the polarization effect.

C/GNO G Experiment S

a Multipurpose Apparatus for Negative ion studies with GEM Optical readout

#### R&D work with MANGO





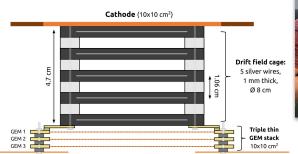


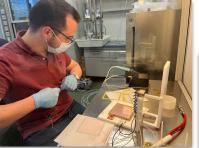


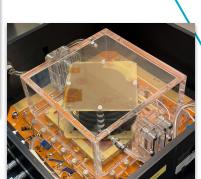
a Multipurpose Apparatus for Negative ion studies with GEM Optical readout

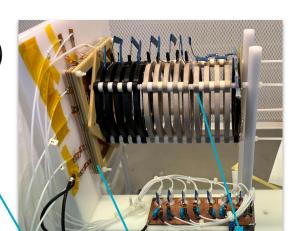
- **Enhancement of light yield** 
  - Different types/configuration of **GEMs**
- ITO vs. Mesh

- **Negative Ion Drift** 
  - Optimal gas pressure, composition & amplification
  - Transverse & Longitudinal Diffusion
- Ion mobility









15 cm drift field cage

#### 3 GEM stack:

50 µm thick 140 µm pitch  $\emptyset$ 70  $\mu$ m holes

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

#### R&D work with MANGO









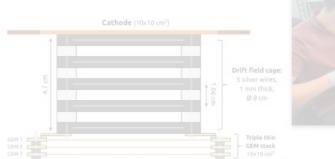
a Multipurpose Apparatus for Negative ion studies with GEM Optical readout

- ITO vs. Mesh

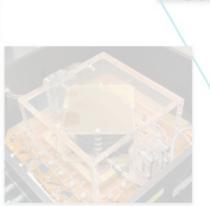
**Negative Ion Drift** 

David Marques

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







15 cm drift field cage

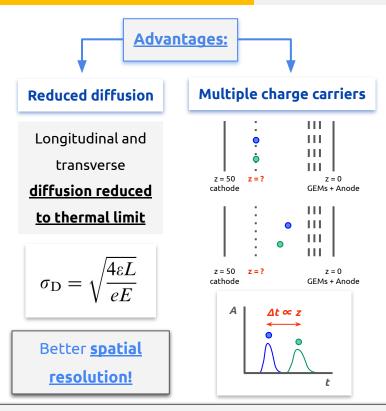
3 GEM stack: 50 µm thick 140 µm pitch

GEMs facing sCMOS and **PMT** 



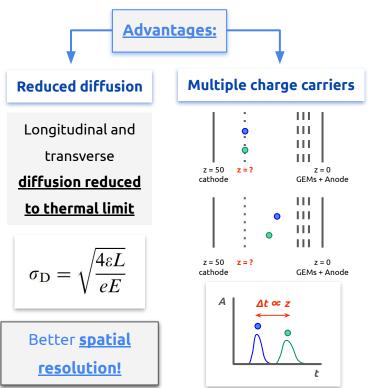


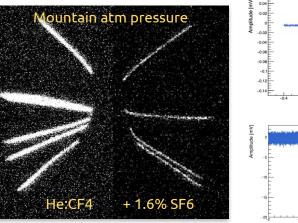
#### Negative Ions - Concept

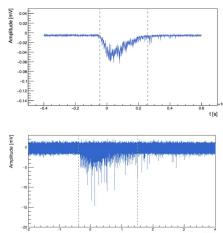


**Absolute Z** from  $\Delta t$  between minority charge carriers

#### Negative Ions - Concept







 $\Rightarrow$  Peculiar waveforms at O(ms) scale!

⇒ First ever Negative Ion Drift operation at atmospheric pressure with optical readout.

⇒ First ever observation of NID through a PMT!

**Absolute Z** from  $\Delta t$  between minority charge carriers

ED: He:CF<sub>4</sub> 60:40

NID: He:CF<sub>4</sub>:SF<sub>6</sub> 59:39.6:1.6



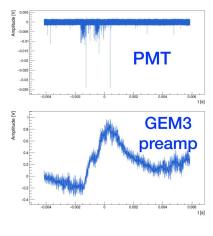


Due to PMT signals shape, a new trigger system

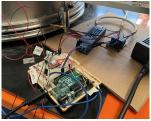
was developed  $\Rightarrow$  <u>GEM3 bottom signal</u>

Alpha source **mover** added + Arduino **remote** 

**control** for repeated measurements







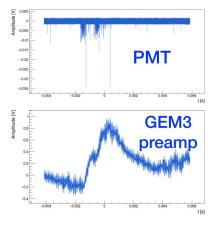
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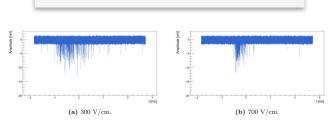
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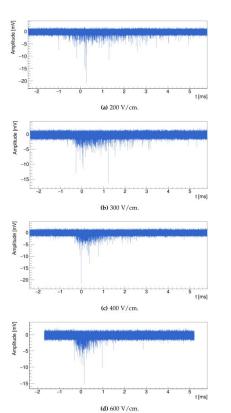




# < PMT > Focus of my work...



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

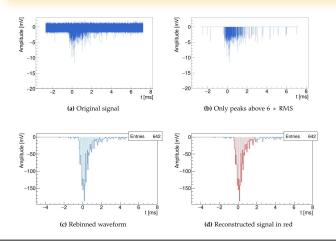


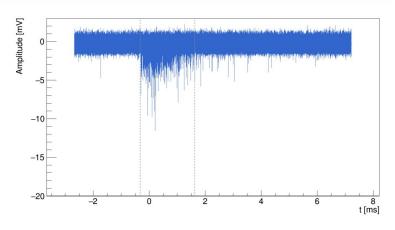




#### \*\* First ever PMT analysis for optical NID signals \*\*

- 0. **Problem**  $\Rightarrow$  How/where to define the beginning and end of the waveform?
- Threshold → Only individual peaks above 6\*RMS
- 2. Rebin → Selected peaks put into histogram
- 3. **Delimitation** → Start (end) when 2 bins are above (below) 10 mV
- 4. Systematics ⇒ Varying #bins & threshold voltage

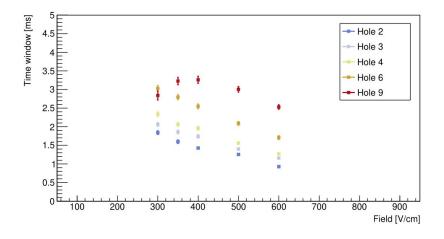




#### Negative Ions - Results



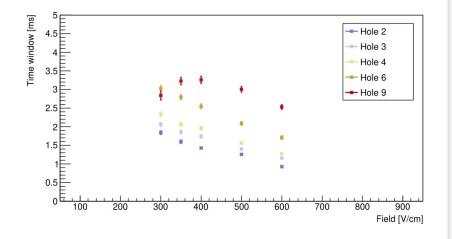
...With the analysis developed, the waveform time window was analyzed for different drift field and drift distances...



#### Negative Ions - Results



...With the analysis developed, the waveform time window was analyzed for different drift field and drift distances...



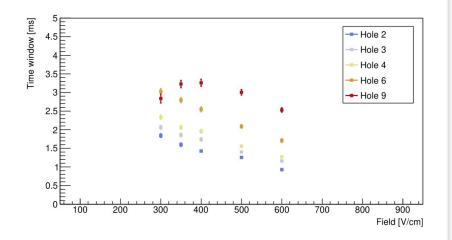
#### → The plot shows the expected trends:

- Reducing Δt for higher fields and smaller distances
- ◆ PMT signals time scale compatible with ions drift (cm/ms) ⇒ Fundamental to prove NID operation
- → Within the data, a convolution of effects diffusion, track length, different anions, etc. play a role, making it hard to retrieve physical meaning from these results (at this point...)
- → Given the limited literature, further analysis of the systematics associated with the data taking and analysis are hard to assess.
- → Future studies involve measuring quantities such as <u>ion mobility</u>
  - The possible use of the signal's primary scintillation could provide the necessary "t0".

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- → Future studies involve measuring quantities such as <u>ion mobility</u>
  - The possible use of the signal's primary scintillation could provide the necessary "t0".
- → Overall, the <u>First optical observation of NID</u> was proved both with CMOS and PMTs, and further work is being done to better characterize the signals, and <u>possibly apply the 3D reco</u> developed to these signals.

Paper in preparation

#### **Conclusions**



- → The <u>CYGNO</u> collaboration is developing a high-precision <u>gaseous TPC</u> at atmospheric pressure with <u>optical readout</u>.
- → The main focus is the <u>directional direct search</u> of <u>DM WIMP-like particles</u> in the <u>low mass range</u> (0.5-10 GeV).
- → I developed a <u>PMT-reconstruction method</u> to retrieve the basic properties of the <u>waveforms</u>.
  - lack Initial tests with <u>cosmic muons</u> showed accurate measurement of the <u>track's  $\Delta Z$ </u> and overall PMT-DAQ interplay.
- → The merging of CMOS (X-Y) with PMT (Z) information for the 3D reconstruction of the alpha particles paths was the main focus of my thesis. This reconstruction of events in 3 dimensions greatly improves spatial resolution and PID capabilities.
  - This analysis uses <u>directionality</u> techniques in the CMOS and analysis of the <u>Bragg peak</u> in the PMT waveforms.
  - The final <u>matching</u> between events in the two sensors is carried out through a <u>Bayesian fit</u>.
  - ◆ Properties such as <u>3D length</u> and emission <u>localization/angle</u> are used to identify <u>different alpha peaks</u> in the LIME background spectra. → The <u>presence of Rn</u> is confirmed!
- → The addition of SF6 at 1 ATM in the CYGNO gas mixture puts the detector in the Negative Ion Drift (NID) regime
  - Stable NID operation was demonstrated and proved through the PMT signals. Preliminary analysis of the complex ion-arrival structures in the waveforms form the basis for <u>future high-resolution</u>, <u>long-drift detectors</u>.

<u>Dual-sensor 3D track reconstruction is a milestone for CYGNO, and is crucial for future directional WIMP</u>

<u>searches through the determination of the nuclear recoils direction!</u>











#### Thank you for your attention!

#### **Main Scientific Communications:**

#### Papers:

- 1.1. Bayesian network 3D event reconstruction in the Cygno optical TPC for dark matter direct detection CYGNO collaboration, arXiv-June 2025
- 1.2. Modeling the light response of an optically readout GEM based TPC for the CYGNO experiment CYGNO collaboration, arXiv May 2025
- 1.3. Charge amplification in low pressure CF4:SF6:He mixtures with a multi-mesh ThGEM for directional dark matter searches CYGNO Collaboration, JINST June 2024
- 1.4. Enhancing the light yield of He:CF4 based gaseous detector CYGNO Collaboration, EPJC October 2024
- 1.5. HypeX: High Yield Polarimetry Experiment in X-rays Fiorina, D. and Baracchini, E. and Dho, G. and Marques, D.J.G. et al., SPIE Aug 2024
- 1.6. Secondary scintillation yield from GEM electron avalanches in He-CF4 and He-CF4-isobutane for CYGNO Directional Dark Matter search with an optical TPC CYGNO Collaboration, Physics Letters B August 2024
- 1.7. Noise assessment of CMOS active pixel sensors for the CYGNO Experiment CYGNO Collaboration, Meas. Sci. Technol. Sept 2023
- 1.8. A 50 L CYGNO prototype overground characterization CYGNO Collaboration, EPCJ Oct 2023
- 1.9. Directional iDBSCAN to detect cosmic-ray tracks for the CYGNO experiment CYGNO collaboration, Meas. Sci. Technol. Sep. 2023
- 1.10. 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
- 1.11. 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., NIMA April 2022
- 1.12. Recoil imaging for dark matter, neutrinos, and physics beyond the Standard Model O'Hare, C. A. J.; Loomba, D.; Altenmüller, K.; Álvarez-Pol, H. et al., arXiV Mar 2022
- 1.13. The CYGNO Experiment CYGNO Collaboration, Instruments Jan 2022
- 1.14. Experimental ion mobility measurements in Ne-CF4 Marques, D.J.G., Cortez, A.F.V., Escada, J., Veenhof, R., Neves, P.N.B., et al., JINST April 2019

#### . Conference Communications:

- 2.1. MPGD 2024 PMT analysis for Negative Ion Drift and 3D reconstruction Hefei, China
- 2.2. IDM 2024 Directional Dark Matter searches with CYGNO L'Aquila, Italy
- 2.3. Lidine 2023 Light yield enhancement in CYGNO Madrid, Spain
- 2.4. CPAD Workshop 2022 The CYGNO experiment, a directional optically readout detector for Dark Matter searches Stony Brook, USA
- 2.5. TeVPA 2022 The CYGNO experiment, a directional detector for direct Dark Matter searches Kingston, Ontario
- 2.6. DCE2021 Electroluminescence studies with a CYGNO/INITIUM prototype Best Oral Communication Porto, Portugal
- 2.7. RD51 Mini-Week June 2020 Measurements with the Dual-Polarity Ion Drift Chamber
- 2.8. DCE2019 Development of a Dual-Polarity Ion Drift Chamber Porto, Portugal
- 2.9. RD51 Mini-Week December 2018 Ion Mobility in Ne-CF4 mixtures



## Backup

& more details

## The CYGNUS project



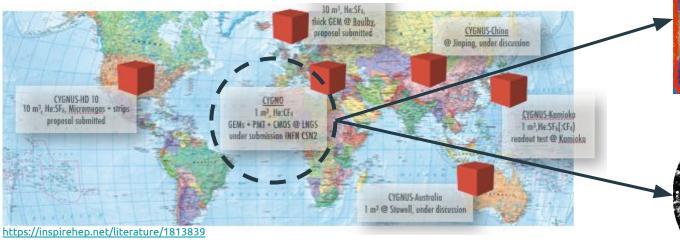
erc

1 m<sup>3</sup> demonstrator funded towards 30 m<sup>3</sup> detector

rperimen

<u>CYGNO</u> is part of a proto-collaboration, <u>CYGNUS</u>, focused on establishing a **Galactic** 

**Directional Recoil Observatory** that could test and study DM hypothesis beyond the neutrino floor.



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

#### DM directional modulations



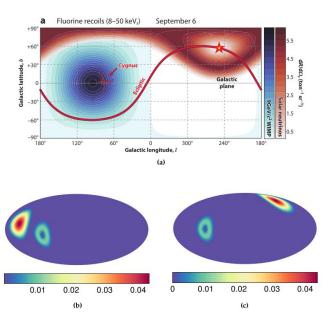
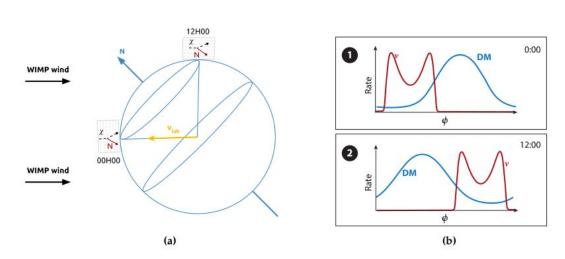
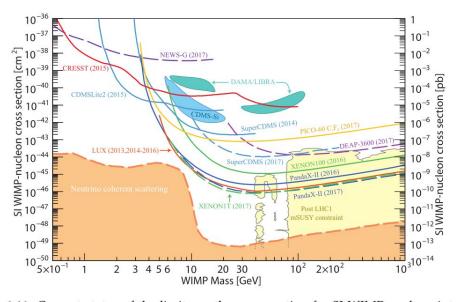


Figure 1.14: (a) Event rates from a 9 GeV WIMP (blue) and solar neutrinos (red) displayed in galactic coordinates on September 6<sup>th</sup>, with the plane of the galaxy running horizontally and the Sun following the Ecliptic line. The star marks the current position of the Sun for this time of the year. The panels below show similar information, highlighting the difference between the expected positions of the angular distributions of recoils induced by WIMPs and solar v at different times of the year: (b) February 26<sup>th</sup> and (c) September 6<sup>th</sup>, the dates corresponding to the highest and lowest differences between the two recoil sources. Further details on these two original works can be found in [67] and [106], respectively.

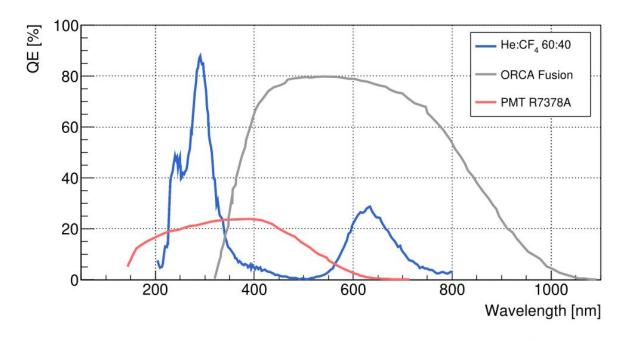


**Figure 1.9:** Illustration of the daily oscillation signature generated by Earth's rotation on its axis, showing (a) a schematic of Earth under the influence of the WIMP wind at different hours of the day and (b) the resulting diphase in the nuclear recoil rate originating from the WIMP wind and solar neutrinos. Retrieved from [67].



**Figure 1.11:** Current status of the limits on the cross-section for SI WIMP-nucleon interactions, as a function of the WIMP mass, based on the SHM model. Each line represents the most stringent lower limit set by each experiment in different subsequent years. The orange region at the lower part indicates the irreducible background from CEvNS interactions, which can mimic WIMP signals (see text for more details). This plot was selected and retrieved from [80] due to its detailed illustration of the various limits. A more up-to-date (but less detailed) version can be found in [81].

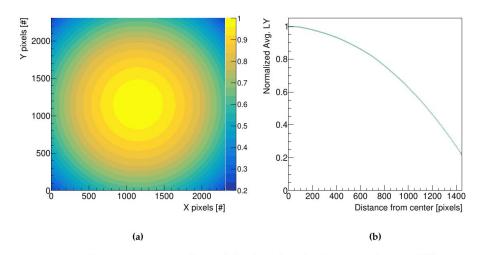
#### CYGNO's gas emission spectra



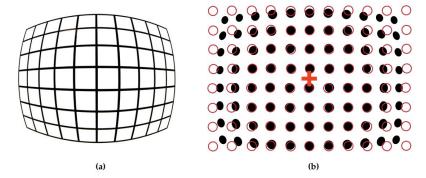
**Figure 2.9:** Normalized emission spectrum of He:CF<sub>4</sub> 60:40 (adapted from [136]) and the quantum efficiencies of the optical sensors used in CYGNO/INITIUM detectors: the ORCA-Fusion CMOS and R7378 PMTs, both from Hamamatsu.







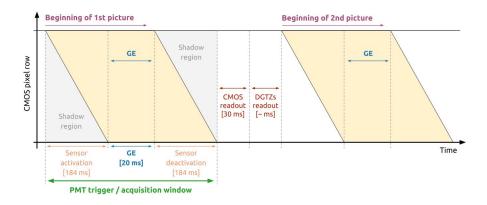
**Figure 2.11:** (a) Vignetting map obtained for the Schneider Onyx Fast lens, and (b) respective values used to correct the pixel light intensity in each picture.



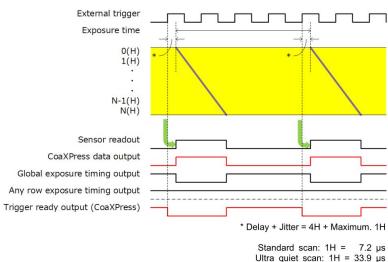
**Figure 2.12:** Example of the barreling effect showing (a) the outward bowing of straight lines in an image, and (b) the inward shift of the perceived position of points. In the latter, the red circles represent the original equally distributed points, while the black circles represent the perceived positions of these points under the influence of the barreling effect. Retrieved from [174].

### ☐ CYGNO's camera recording scheme - old and new





**Figure 2.19:** Schematic of the LIME trigger system. The exposure of the CMOS pixel rows occurs sequentially from top to bottom. While each part of the sensor is exposed, the PMTs can trigger the acquisition of images and waveforms if the light signal produced exceeds the -5 mV threshold on at least two PMTs. The "GE" region corresponds to the *Global Exposure*, where all the pixels of the sensor are exposed and activated. The *shadow region* represents the pixel/time region where the PMTs can trigger (thus saving the image), but no visible event is present in the image. The *CMOS/DGTZs readout* is the time required for the DAQ to save the information of the camera and the digitizers (PMTs).



Ultra quiet scan: 1H = 33.9 μs

2.27: CMOS sensor readout schematic in continuous acquisition mode. Retrieved from

expectations

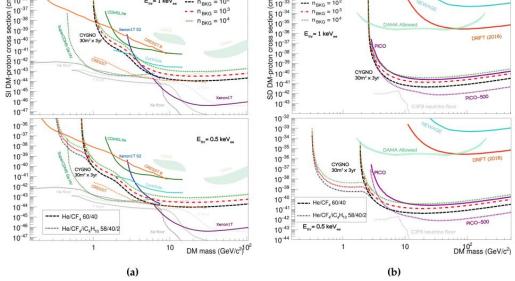
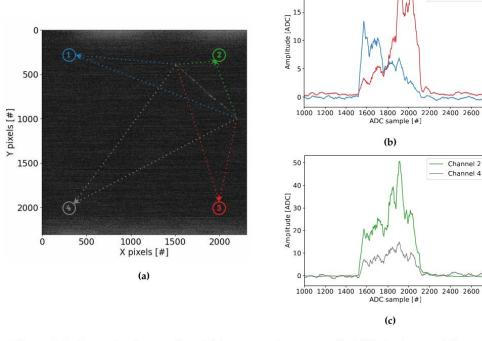


Figure 2.29: Spin-independent (a) and spin-dependent (b) 90% credible interval exclusion limits for CYGNO-30, assuming 3 years of exposure under different background scenarios and operational thresholds of 1 ke $V_{ee}$  (top plots) and 0.5 ke $V_{ee}$  (bottom plots). Dashed curves correspond to a He:CF<sub>4</sub> (60:40) gas mixture with 100 (black), 1000 (red), and 10.000 (dark green) background events. Dotted curves represent the sensitivity for a He:CF4:isobutane (58:40:2) mixture. The remaining solid lines represent the currently published bounds from other experiments, while the dotted lines indicate the projected future limits. Figure adapted from [131] and references therein.

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# Meaning of the PMT signal



20

**Figure 3.13:** Example of a cosmic or high-energy electron recoil visible in the top right corner of the CMOS image, in (a). The position of the four PMTs of LIME is also shown in the CMOS image, with numbers and colors representing the respective channels and waveforms associated with each in (b) and (c). The shape of the PMT signals reflect the path traveled by the track in XY, as it gets closer or father way from each PMT.

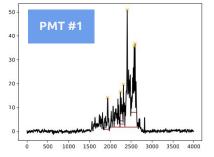


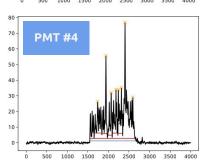
Channel 1Channel 3

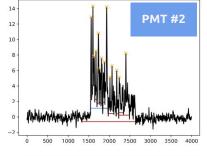
## Tilted Cosmics - Weighted avg.

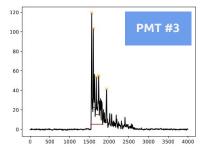


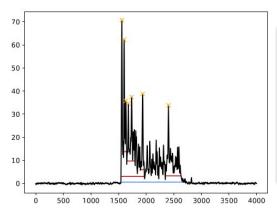
- Measurement of the <u>time length</u> of the signal which is <u>above a given threshold</u>.
  - Not trivial for long tracks where the signal intensity in each PMT changes within the particle track.
  - A weighted average based on waveform's SNR is performed and the ToT is calculated.











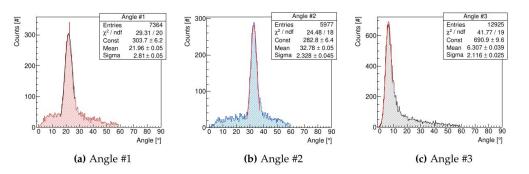
Weighted average waveform

This approach
resolves better the
width of the signals
for *long tracks* with
tortuous paths

(back to presentation)

#### Tilted cosmics – angles cross-check

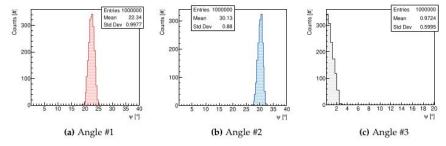




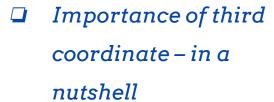
**Figure 4.8:** Distributions of zenith angles obtained from the ToT variables, using Equations 4.3 and 3.4, for the three setups shown in Table 4.1. The distributions were fitted with a Gaussian curve, and the fitted results are overlaid on the data.

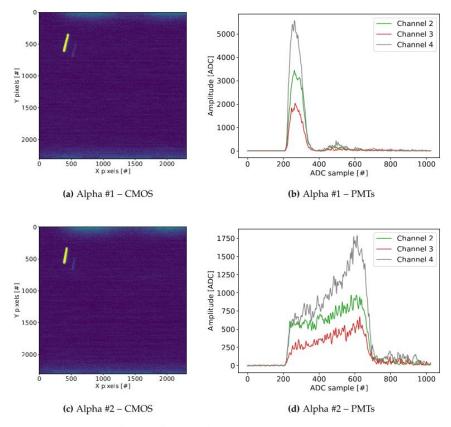
**Table 4.2:** Summary of the geometrically allowed range of angles for the three setups used in this measurement (Table 4.1). The absolute minimum and maximum incidence angles were calculated using the expressions in Equation 4.6.

Setup angle [#]	d <sub>i</sub> [cm]	[ψ <sub>min</sub> , ψ <sub>max</sub> ] [°]
1	$53 \pm \sqrt{2}$	$ [19.88, 24.41]^{+0.55}_{-0.58} $ $ [28.30, 32.24]^{+0.50}_{-0.53} $ $ [0.00, 2.64]^{+0.64}_{-0.00} $
2	$76 \pm \sqrt{2}$	$[28.30, 32.24]_{-0.53}^{+0.50}$
3	$0\;\pm\!\sqrt{2}$	$[0.00, 2.64]^{+0.64}_{-0.00}$



**Figure 4.12:** Distributions of angles for the simulated muons obtained through the GEANT4 simulation for the calculation of the geometrical acceptance of each detector setup.



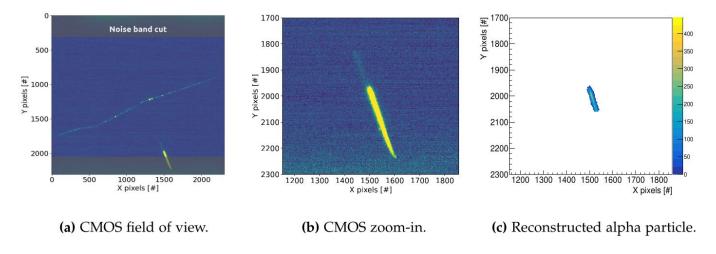


**Figure 3.15:** Example of two different alpha events that appear similar in the CMOS images (a and c) but show significant differences in the corresponding PMT signals (b and d). The signal from PMT #1 has been omitted for clarity.



#### Noise band cuts

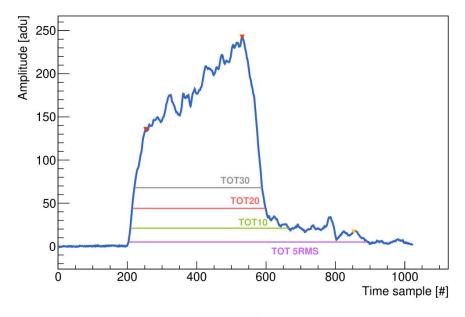




**Figure 5.4:** Example of an alpha particle emitted near the border of the detector and falling within the *noise-band-cut* region. (a) shows the full CMOS field of view, including the *noise-band-cut* indicated by the grey band. (b) provides a zoomed-in view of the alpha event, and (c) shows the same event after the CYGNO-reconstruction algorithm.

#### TOT 20 and other TOTs

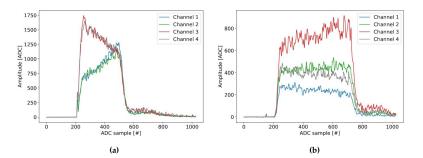




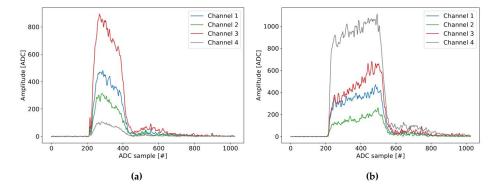
**Figure 5.10:** Example of an alpha particle waveform signal, illustrating the different definitions of the variables TOT 5RMS, TOT10, TOT20 and TOT30. These thresholds are marked in the waveform with, respectively, purple, green, red and grey full lines.







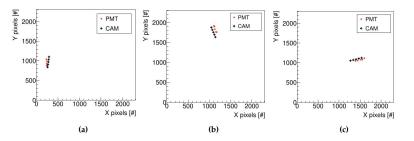
**Figure 5.15:** Two examples of events where the determination of the alpha direction using the skewness of the waveform crown is more complex. In (a), the Bragg peak skewness score was -0.52, indicating low confidence in the alpha's direction, although it still suggests it was moving toward the cathode. In (b), the score was +0.15, meaning no definitive conclusion about the direction of the track in the longitudinal plane can be drawn and, therefore, a random direction is assigned.



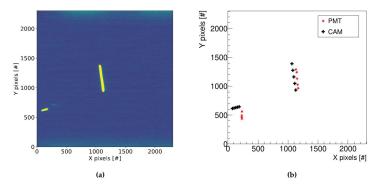
**Figure 5.13:** Example of two PMT signals from alpha events in LIME. In (a), an alpha particle is moving towards the GEMs, while in (b), the alpha is moving towards the cathode. This difference is reflected in the position of the Bragg peak within the waveforms.

### Alpha's slice-and-fit

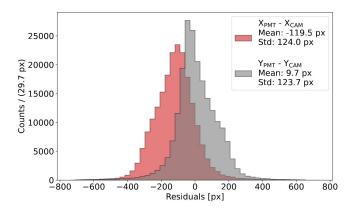




**Figure 5.17:** Three examples of the PMT-CAM matching using the BAT-fit, demonstrating the effectiveness of this approach across different track positions and orientations. The track position as seen by the PMTs through the BAT-fit is shown in red stars, while the position as seen by the CMOS is shown in black crosses. The axis represent the CMOS image.



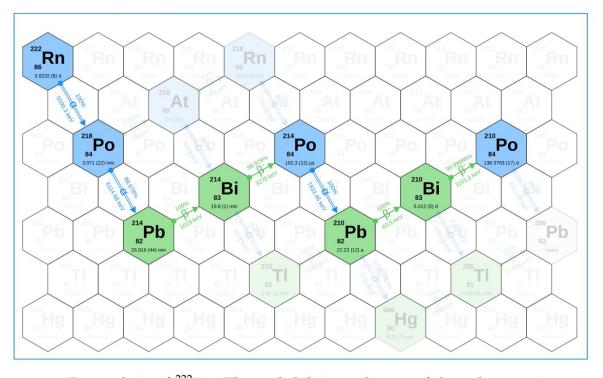
**Figure 5.18:** Example of an event with two alpha particles as seen (a) in the original CMOS picture. In (b), the positions of the identified alphas are shown, as reconstructed with the BAT-fit (red stars) and seen by the CMOS sensor (black crosses), in the CMOS XY plane.



**Figure 5.19:** Distribution of the residuals  $\Delta x$  and  $\Delta y$  between the PMT-based and camera-based track reconstruction methods for extended events. The tracks in the camera images are resampled to match the number of points in the corresponding PMT waveform, and a point-by-point distance is computed. Found also in [221].

#### Rn-222 decay chain





**Figure 6.27:** Decay chain of <sup>222</sup>Rn. The probabilities and types of decay between isotopes are shown (blue for alpha and green for beta decays). The half-life of each element is also indicated. The energies correspond to the Q-values of the decays. Figure taken from [277].

#### U-238 decay chain

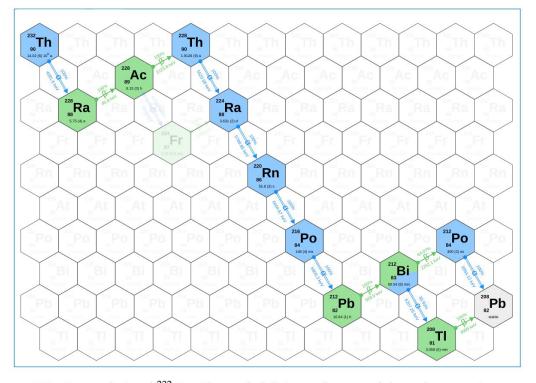




**Figure 6.28:** Decay chain of <sup>238</sup>U. The probabilities and types of decay between isotopes are shown (blue for alpha and green for beta decays). The half-life of each element is also indicated. The energies correspond to the Q-values of the decays. Figure taken from [277]

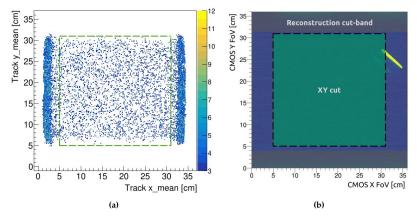
#### ☐ Th-232 decay chain



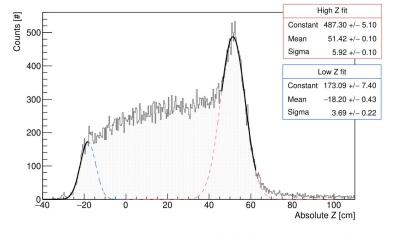


**Figure 6.29:** Decay chain of <sup>232</sup>Th. The probabilities and types of decay between isotopes are shown (blue for alpha and green for beta decays). The half-life of each element is also indicated. The energies correspond to the Q-values of the decays. Figure taken from [277]

#### Alpha's localization cuts

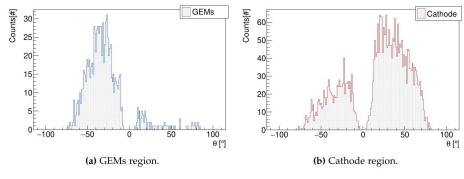


**Figure 6.9:** Geometrical cuts in XY illustrated in (a) as a green dashed line box overlaid on the distribution of the average XY positions of alpha particles in the LIME, and (b) as seen in the CMOS images, used to separate the alphas associated to the field cage from the remaining ones.

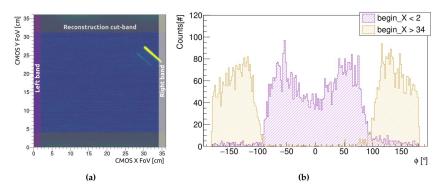


**Figure 6.10:** Geometrical cuts in applied in Z. Specifically, from the distribution of absolute Zs found for the alphas analyzed, two regions corresponding to a low and high Z are defined to isolate the alphas emitted by the GEMs and cathode, respectively.

#### More on alpha's localization



**Figure 6.15:** Distributions of the  $\theta$  angle for the alpha selected through the geometrical defined defined for the (a) GEMs, and (b) cathode regions. A negative  $\theta$  represents an alpha moving or emitted towards the cathode, and vice-versa.



**Figure 6.17:** (a) CMOS field-of-view with the *Left* and *Right bands* used to select the lateral alphas, and (b) showing the distributions of  $\phi$  angles retrieved in each of these bands, within the field cage geometrical cuts.

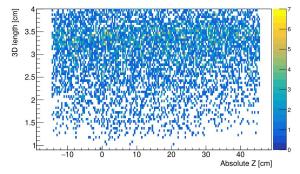
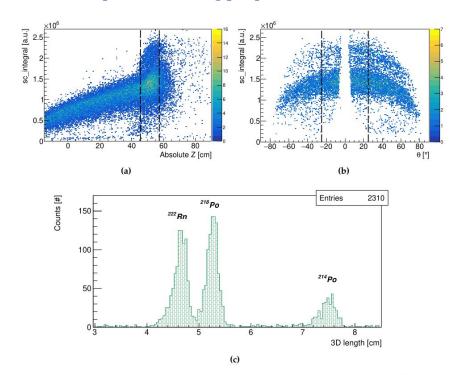


Figure 6.18: Relation between measured 3D lengths and absolute Z of the low energy alpha particles identified within the field cage geometrical cuts.

### Alpha's energy spectrum (with 3D cuts)



**Figure 6.23:** Relations between CMOS measured sc\_integral and (a) absolute Z, and (b)  $\theta$  angle, with the cuts applied in each relation overlaid as black lines. (c) Obtained distribution of alpha 3D lengths using the cuts showed in (a) and (b). The isotopes associated with each peak represent the candidate decays discussed in Section 6.3.2.

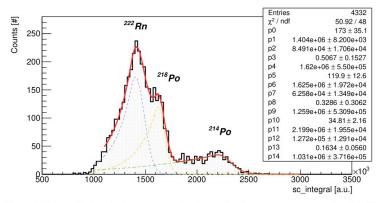


Figure 6.24: Distribution of CMOS measured sc\_integral using the data cuts mentioned in Figure 6.23. The data was fitted with 3 Crystalball functions. Each of these fits is also showed in colored dashed lines, and the fitted parameters are reported in the legend, where the order is from lower to high energy. The isotopes associated with each peak represent the candidate decays discussed in this section and Section 6.3.2.

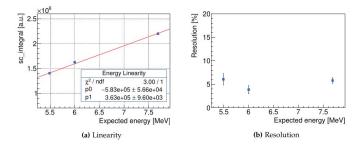


Figure 6.26: Energy (a) linearity and (b) resolution obtained for the <sup>222</sup>Rn decay chain alphas, using the fit parameters showed in Figure 6.24.