THE CYGNO EXPERIMENT

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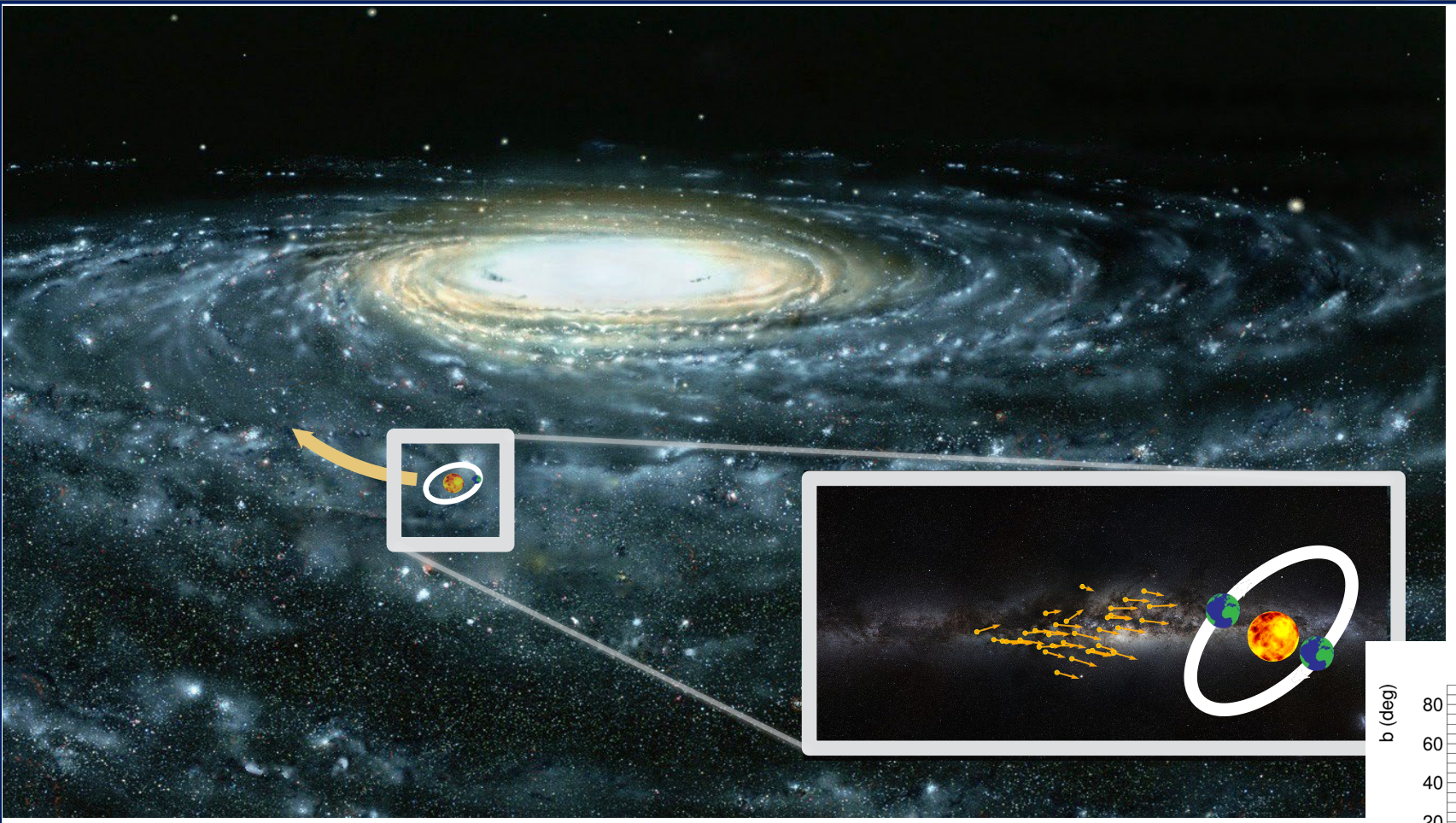
Gran Sasso Science Institute & INFN LNGS

On behalf of the CYGNO collaboration

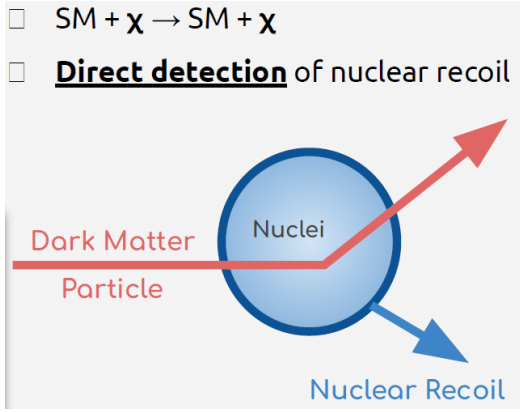
It's a Dark Universe

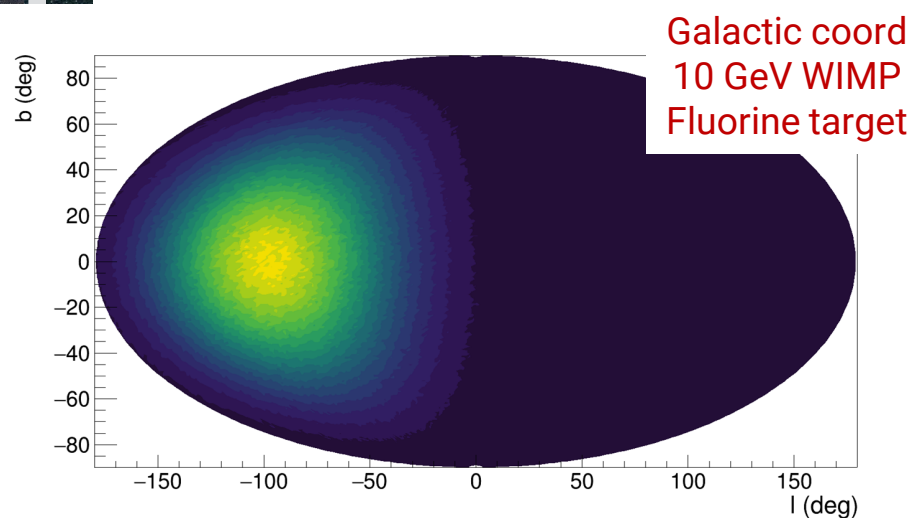


Assumption

→ Dark Matter is made of
Weakly **I**nteracting **M**assive **P**articles.

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





ENERGY → Excess would result in **falling exponentials**.

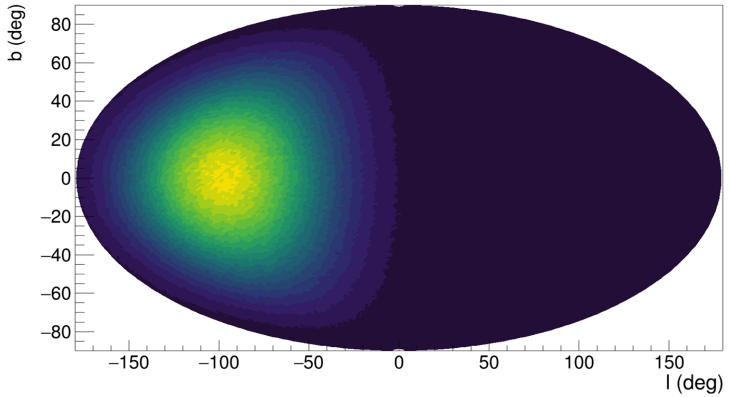
TIME → Results in a **few % annual modulation.**

Directionality of the DM flux

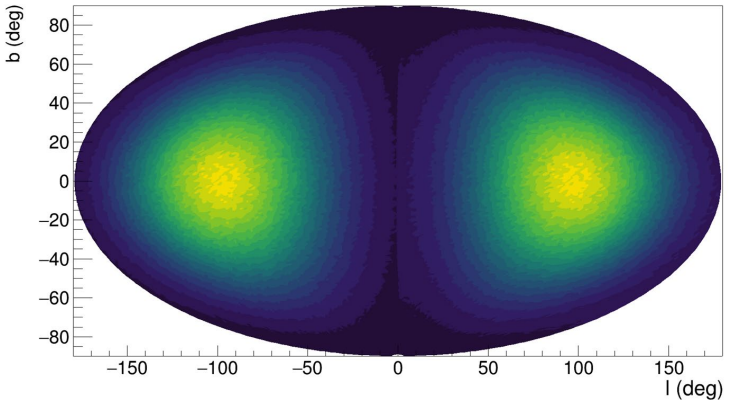
This is the only generic and unambiguous terrestrial signature of DM that results solely from the assumption that we live inside a DM halo.

[The future of directional searches, Ciaran O'Hare]

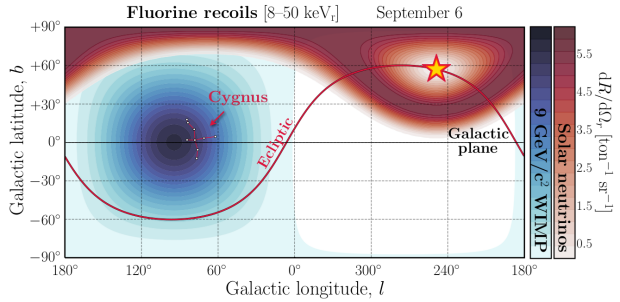
- **Only signature of DM halo presence**
- **Rejection of background isotropy**
- **Identification of solar neutrinos**
- **Only way to do DM astronomy**

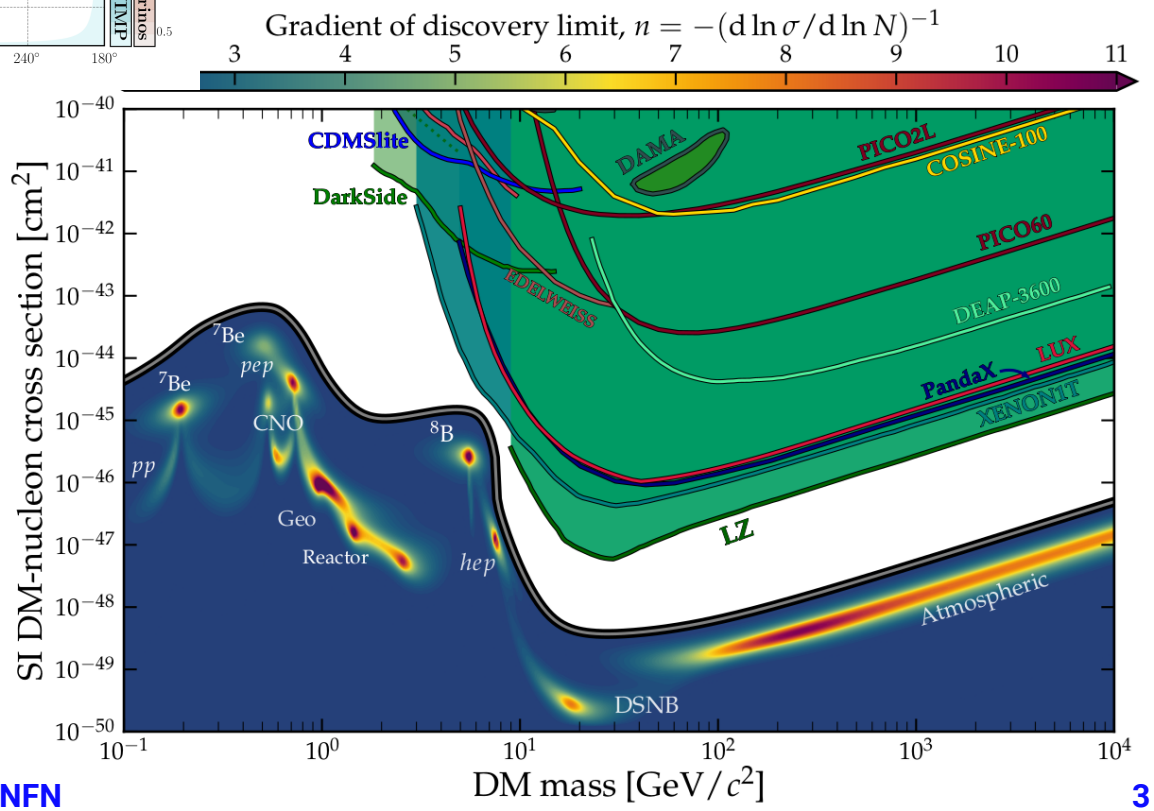


Full Head-Tail



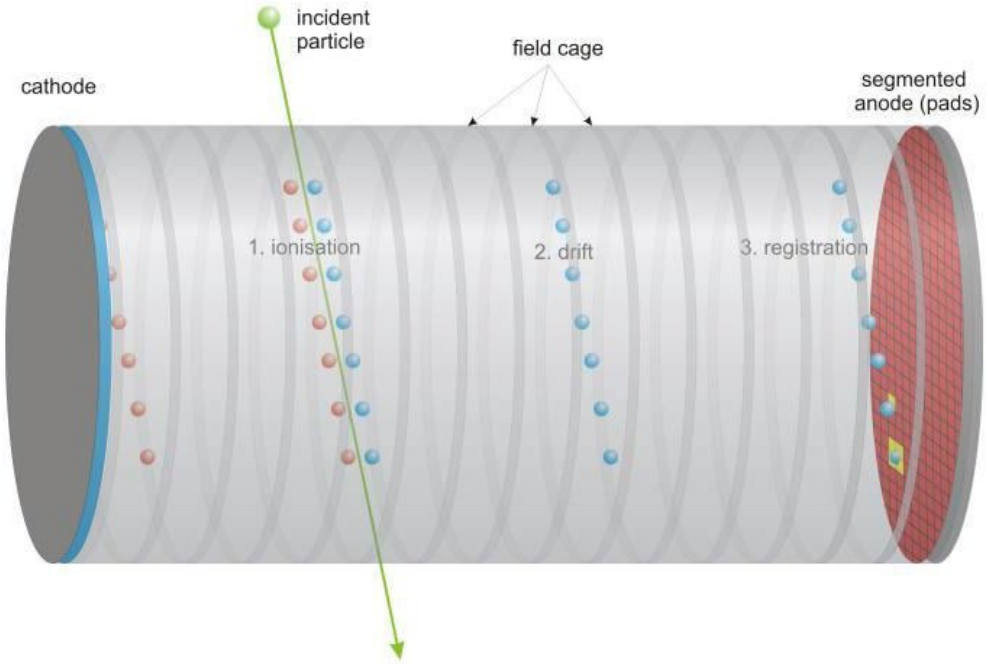
No Head-Tail

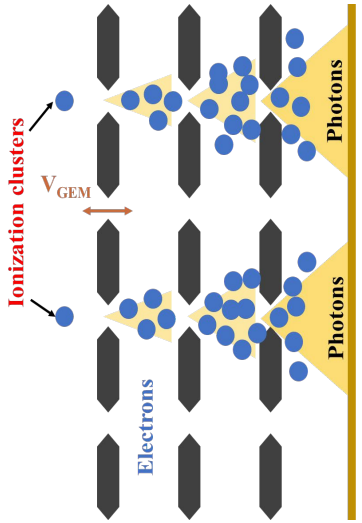




CYGNO paradigm

Gas at 293K and 900mbar (ambient at LNGS) He/CF_4 60/40





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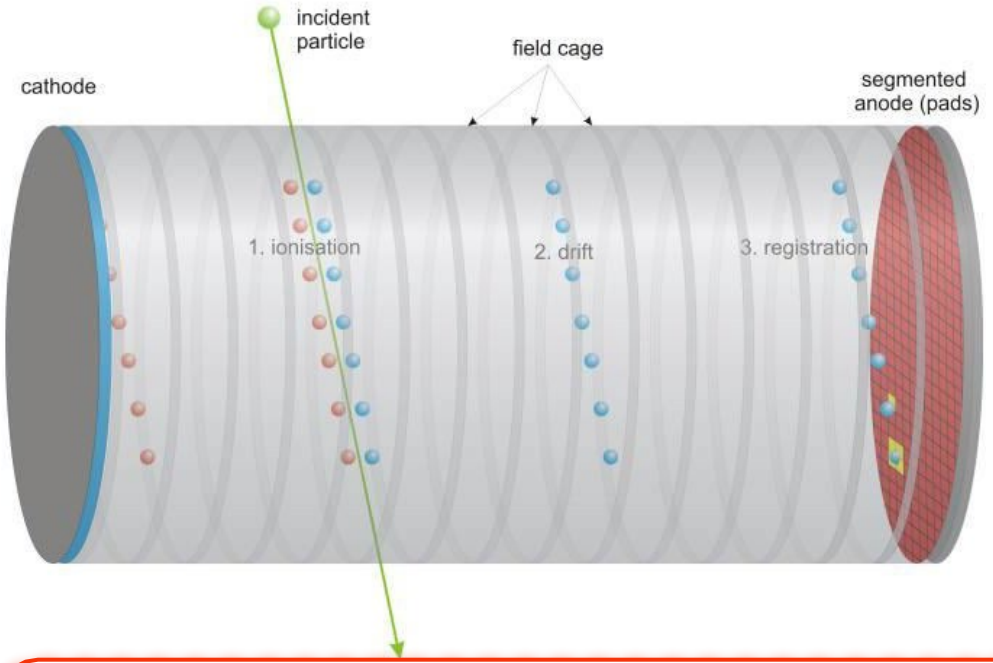
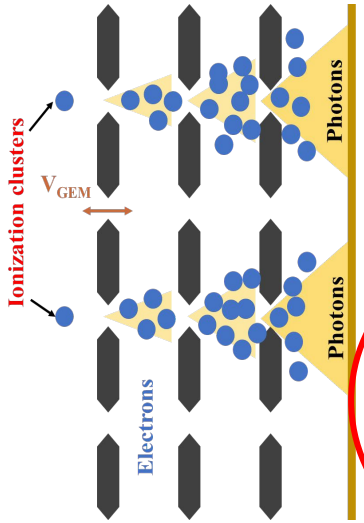
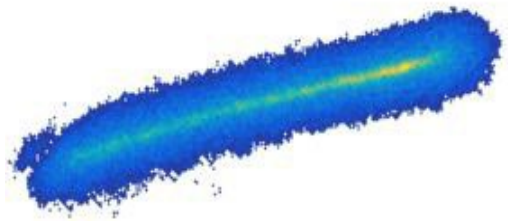




With the high granularity of the camera, we measure **energy** + **X & Y coordinates**



Absolute Z measurement $\sigma_T \propto \sqrt{z}$

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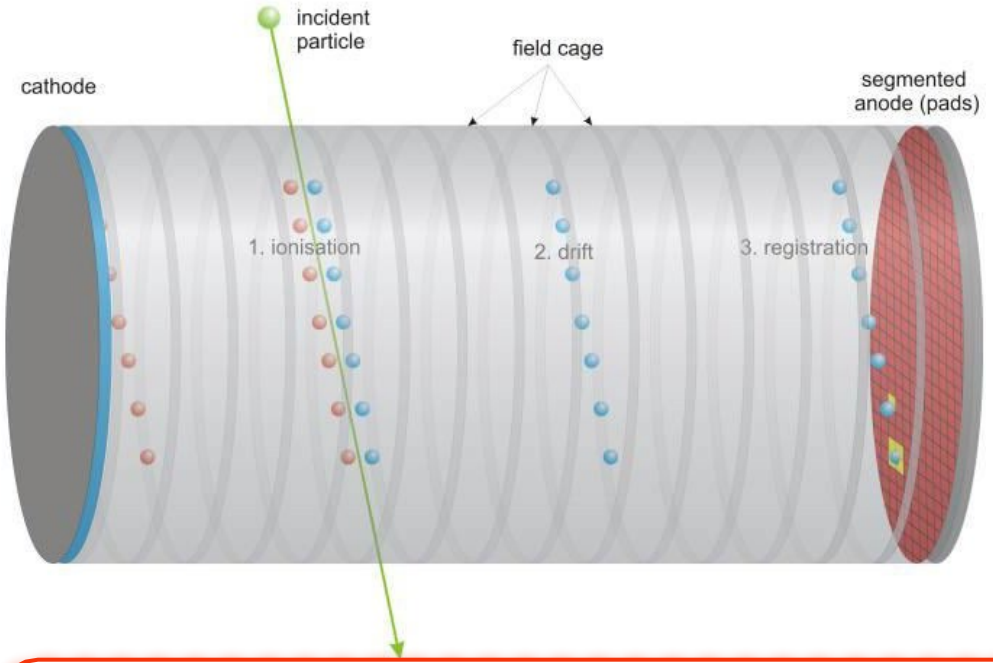

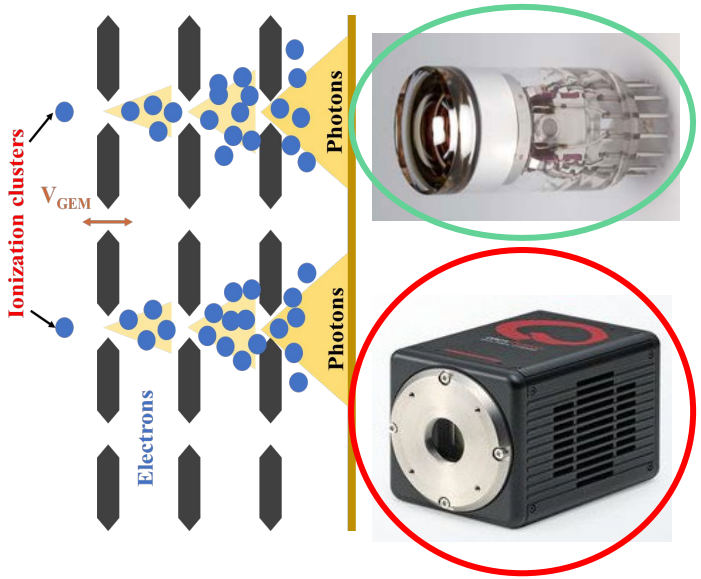

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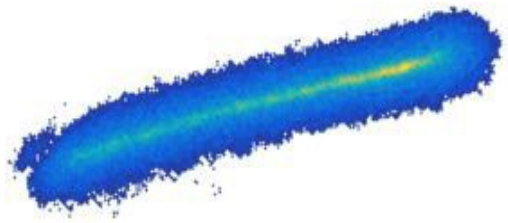
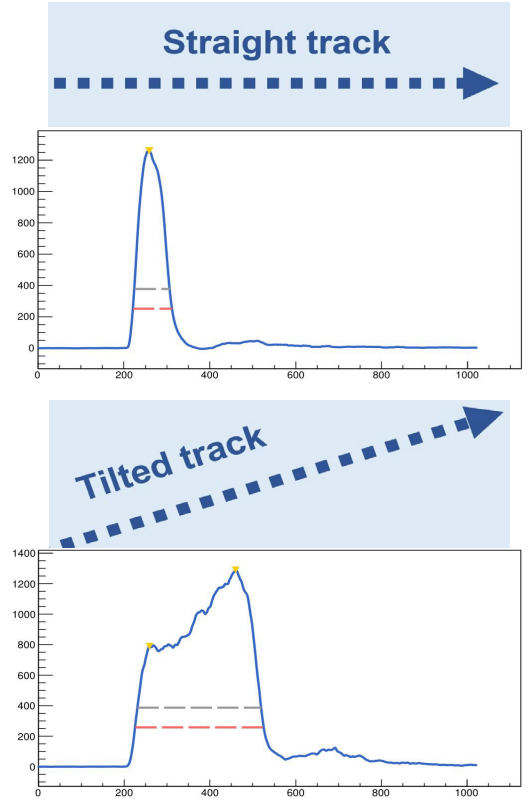


Absolute Z measurement $\sigma_T \propto \sqrt{z}$

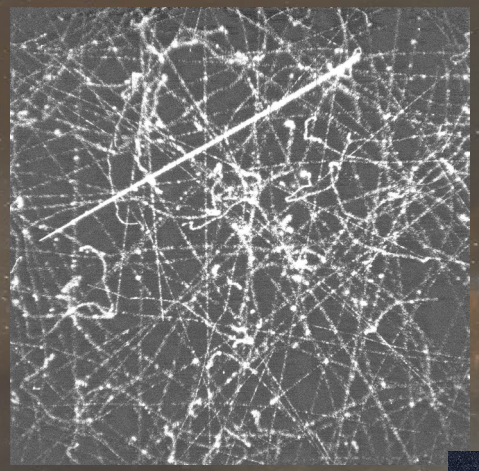
ΔZ of the track

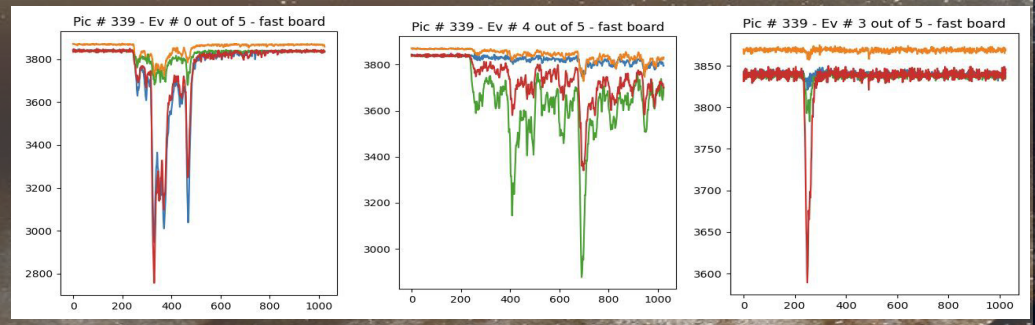
1.Independent **energy** measurement.

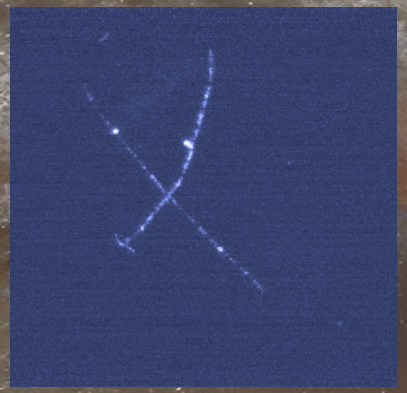
2.Electrons **times of arrival** ⇒ **dZ coordinate** (track's tilt)

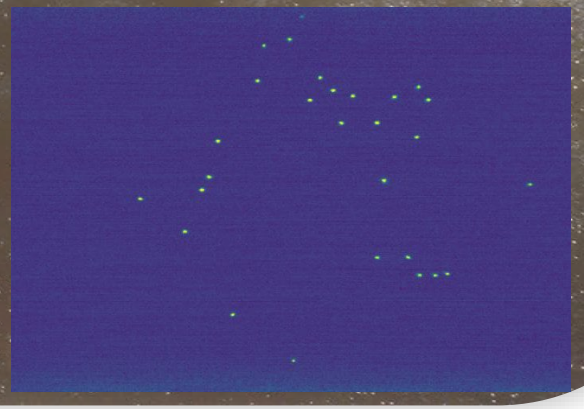


Detector PoV









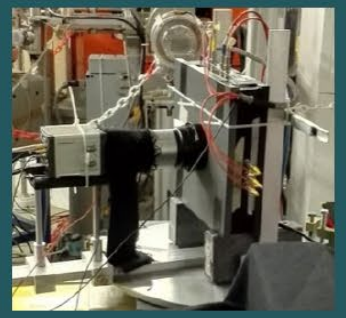
CYGNO roadmap

The CYGNO Experiment

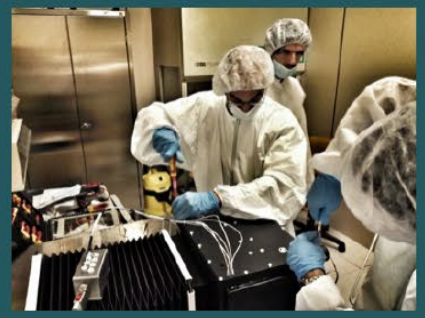
PHASE 0: R&D and prototypes

2015/16 ROMA1 → 2017/18 LNF → 2019/25 LNF/LNGS

ORANGE → LEMON → LIME



- 1 cm drift



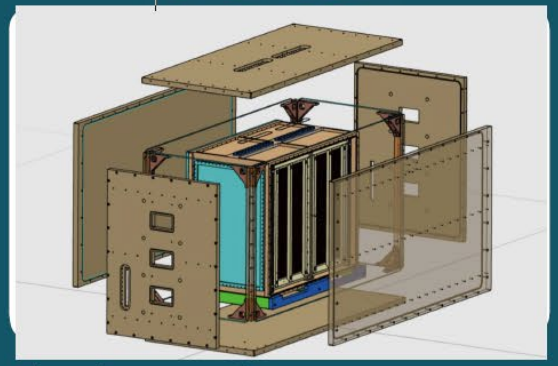
- 3D printing
- 20 cm drift

- 50 cm drift
- underground tests
- shielding

PHASE 1: 1 m³ Demonstrator

2026/28 LNF/LNGS

CYGNO_04

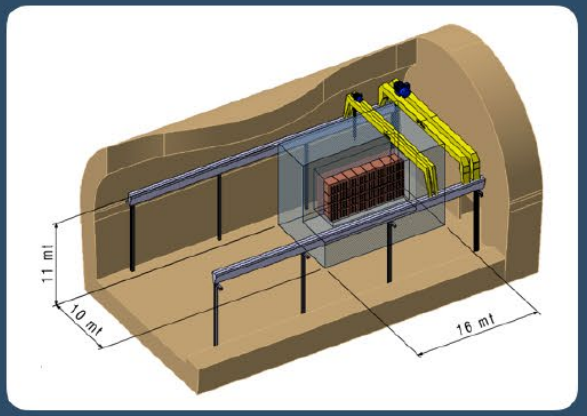


- background
- materials test, gas purification
- scalability

PHASE 2: 30 m³ Experiment

2029… LNGS

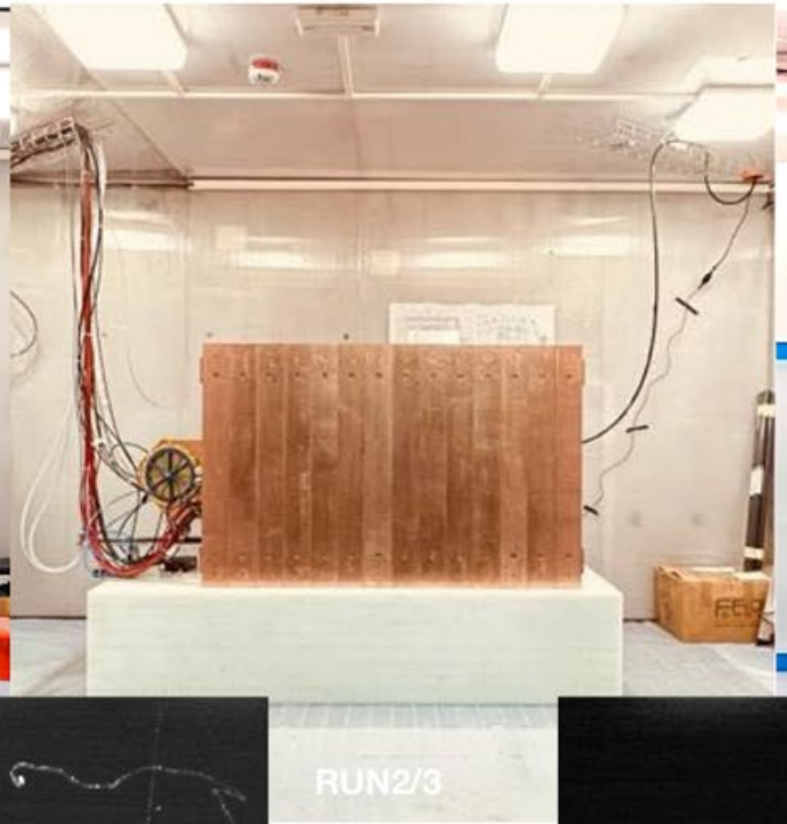
CYGNO_30



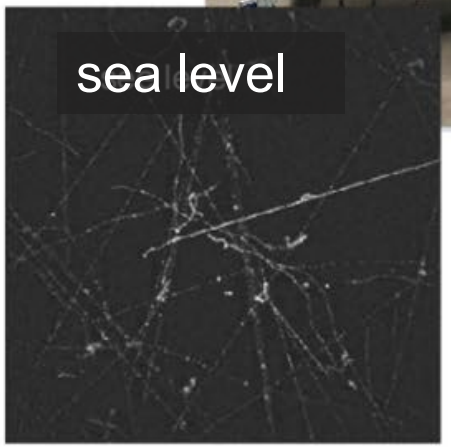
- Physics research

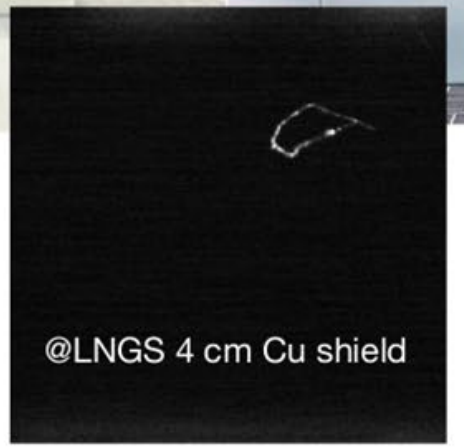
LIME Underground Runs

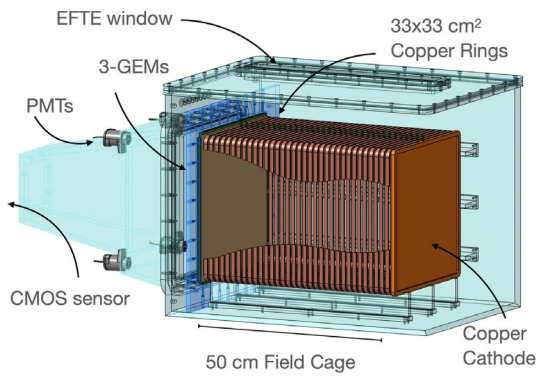

RUN1


RUN2/3


RUN4

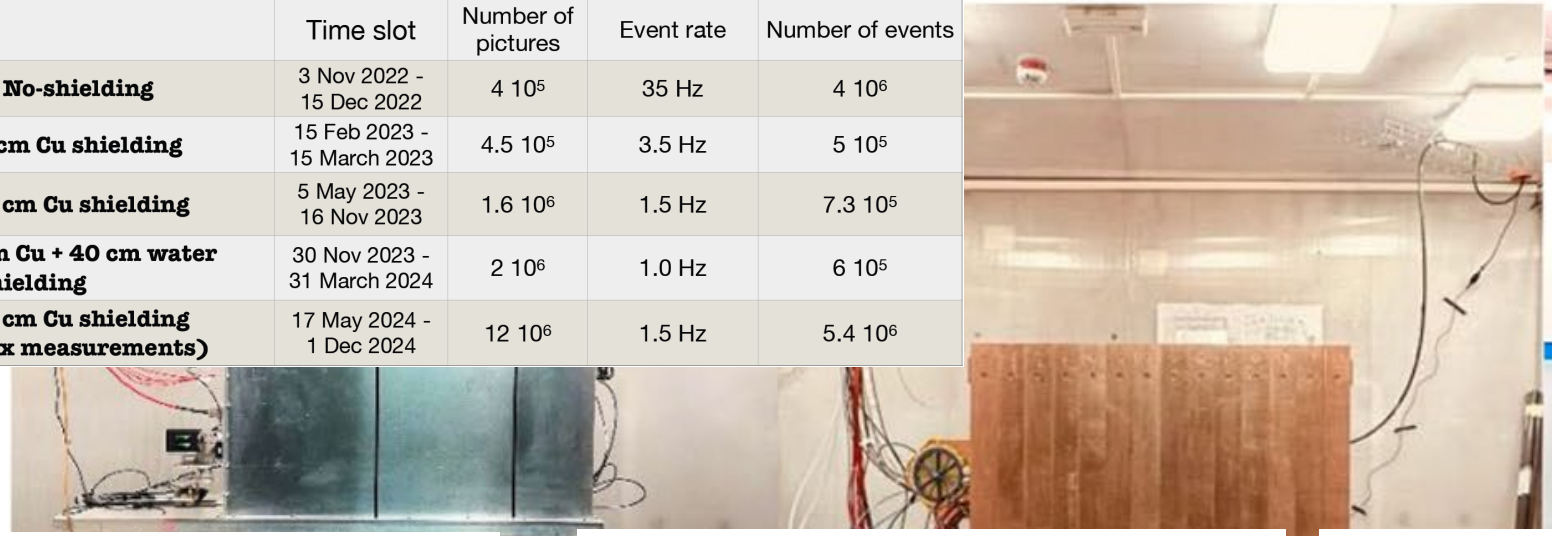


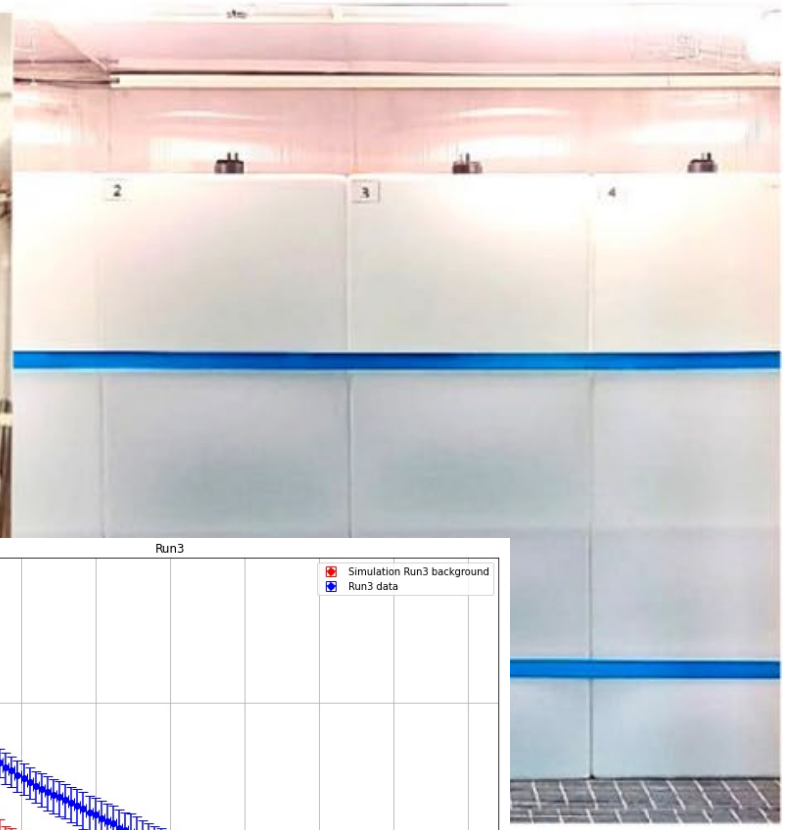


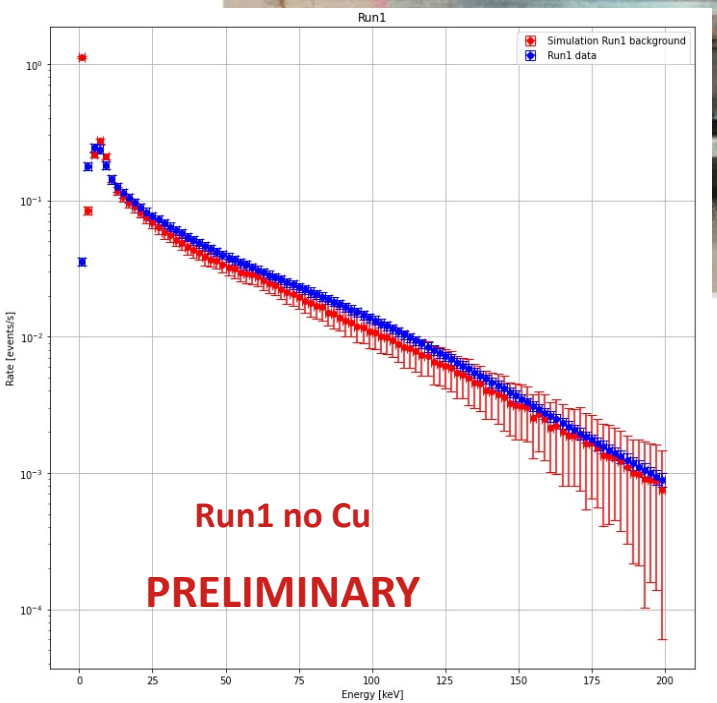


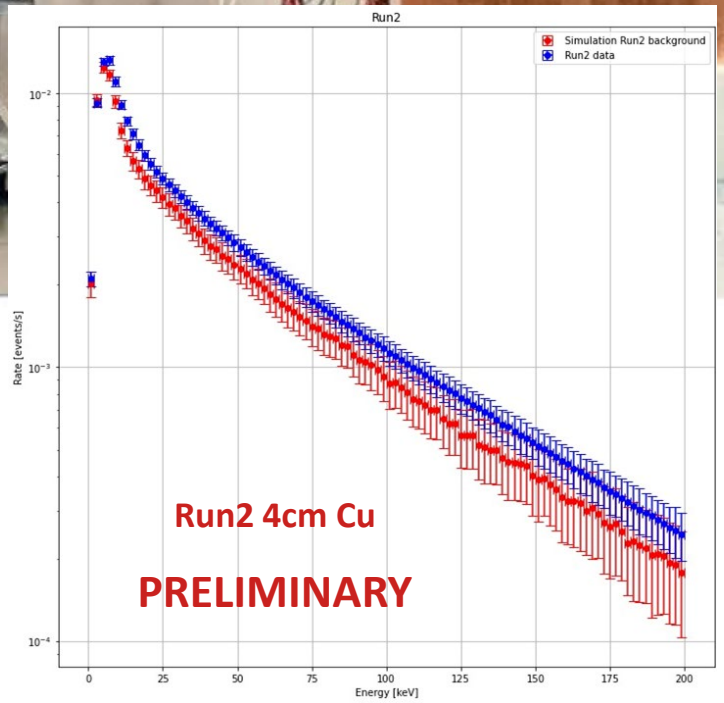
LIME Underground Runs

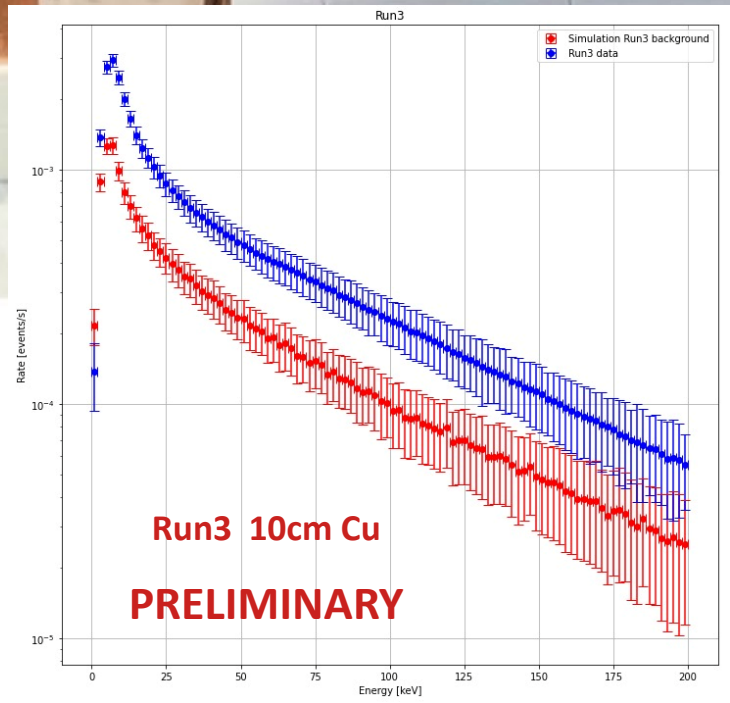
	Time slot	Number of pictures	Event rate	Number of events
RUN 1: No-shielding	3 Nov 2022 - 15 Dec 2022	4 10^5	35 Hz	4 10^6
RUN 2: 4 cm Cu shielding	15 Feb 2023 - 15 March 2023	4.5 10^5	3.5 Hz	5 10^5
RUN 3: 10 cm Cu shielding	5 May 2023 - 16 Nov 2023	1.6 10^6	1.5 Hz	7.3 10^5
RUN 4: 10 cm Cu + 40 cm water shielding	30 Nov 2023 - 31 March 2024	2 10^6	1.0 Hz	6 10^5
RUN 5: 10 cm Cu shielding (neutron flux measurements)	17 May 2024 - 1 Dec 2024	12 10^6	1.5 Hz	5.4 10^6





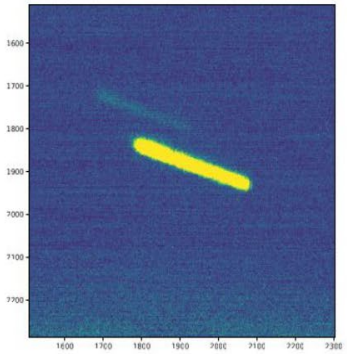


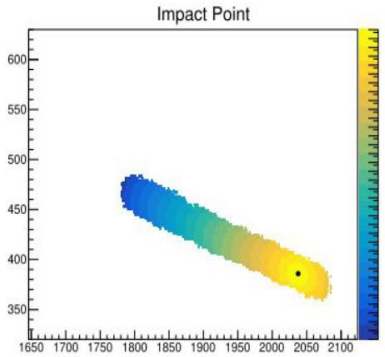


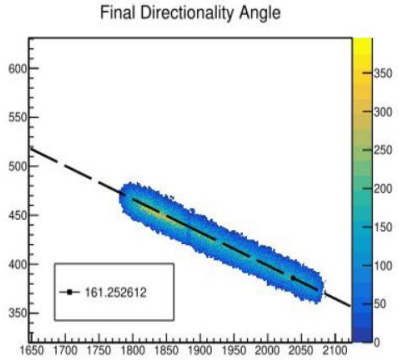


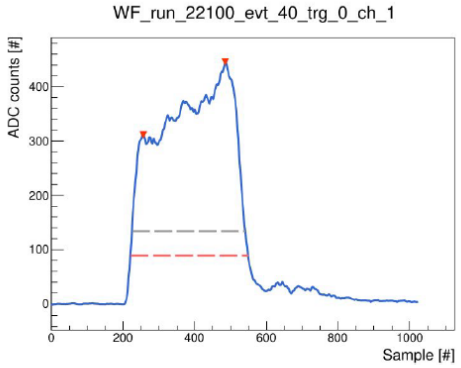
Internal contamination detected

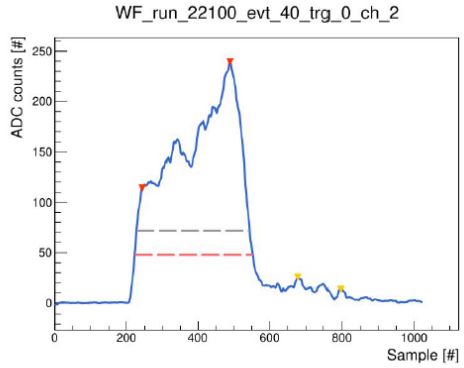
3D reconstruction

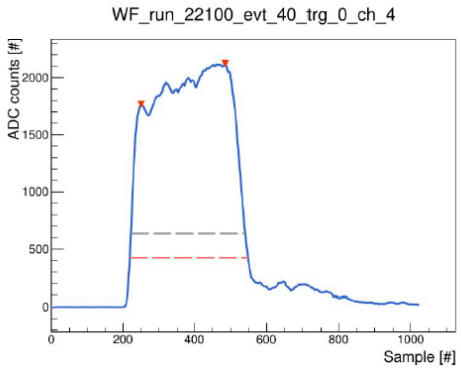


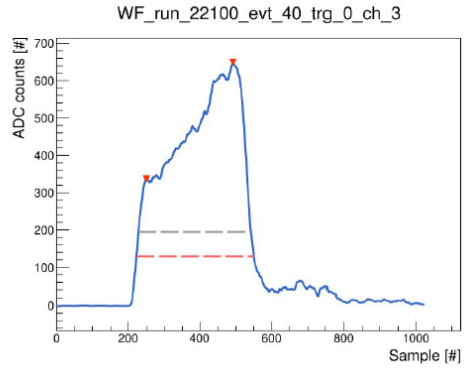












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- **Precision of ~1 cm**

Bayesian network 3D event reconstruction in the Cygno optical TPC for dark matter direct detection

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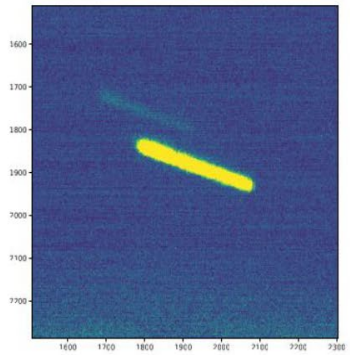
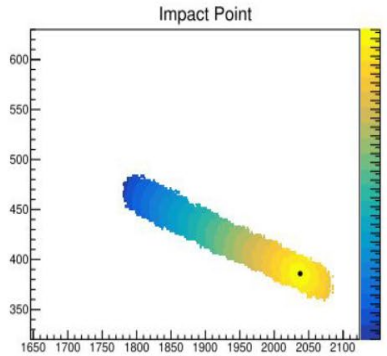
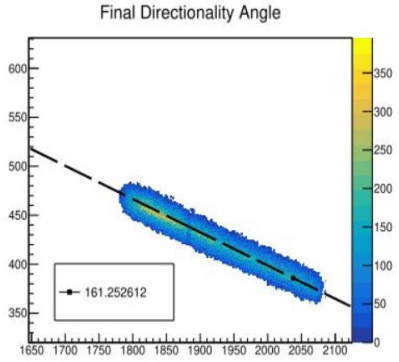
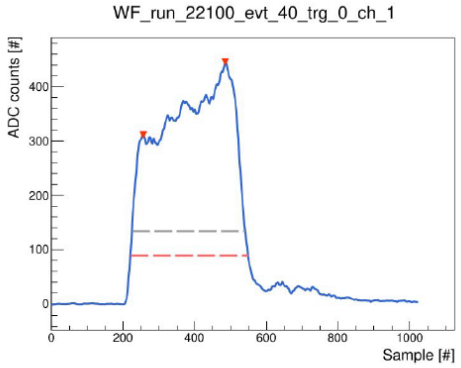
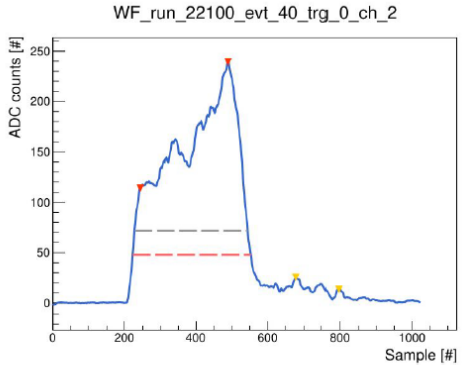
3D reconstruction

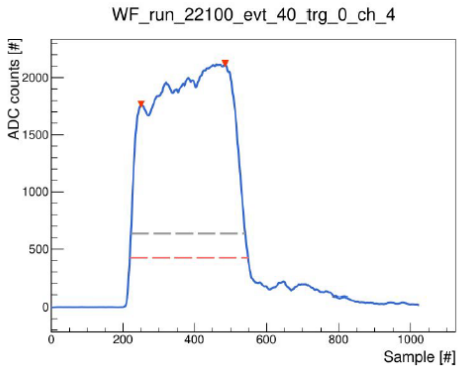


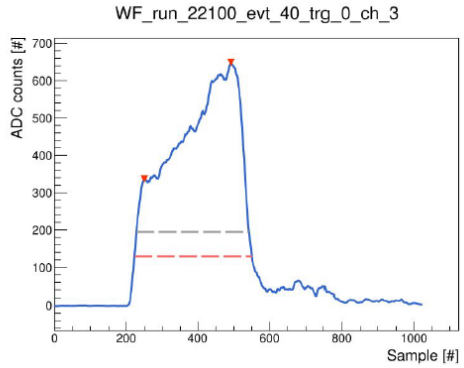












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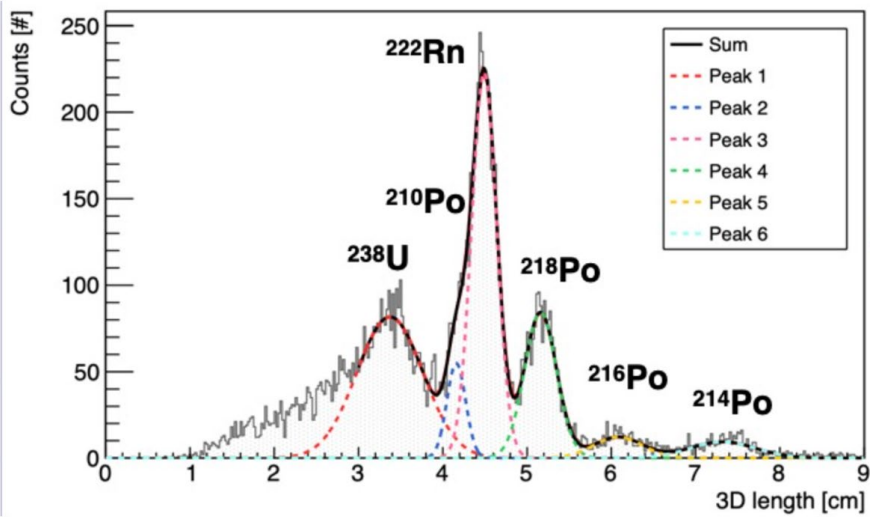
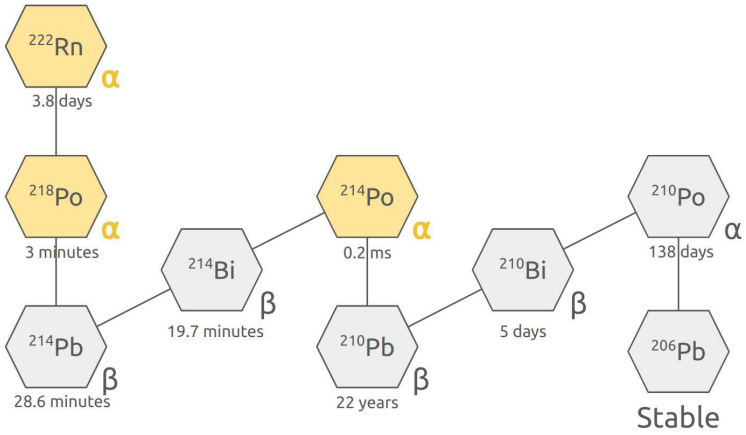
[Bayesian network 3D event reconstruction in the Cygno optical TPC for dark matter direct detection]

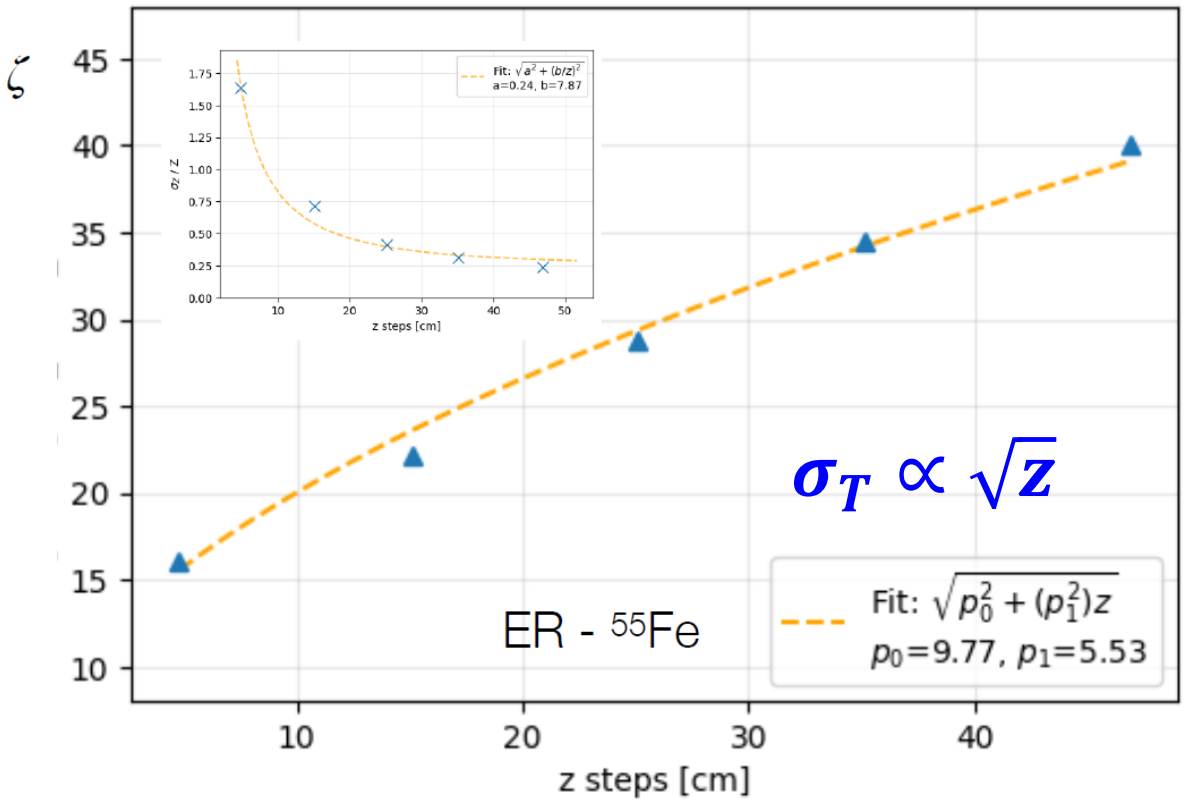


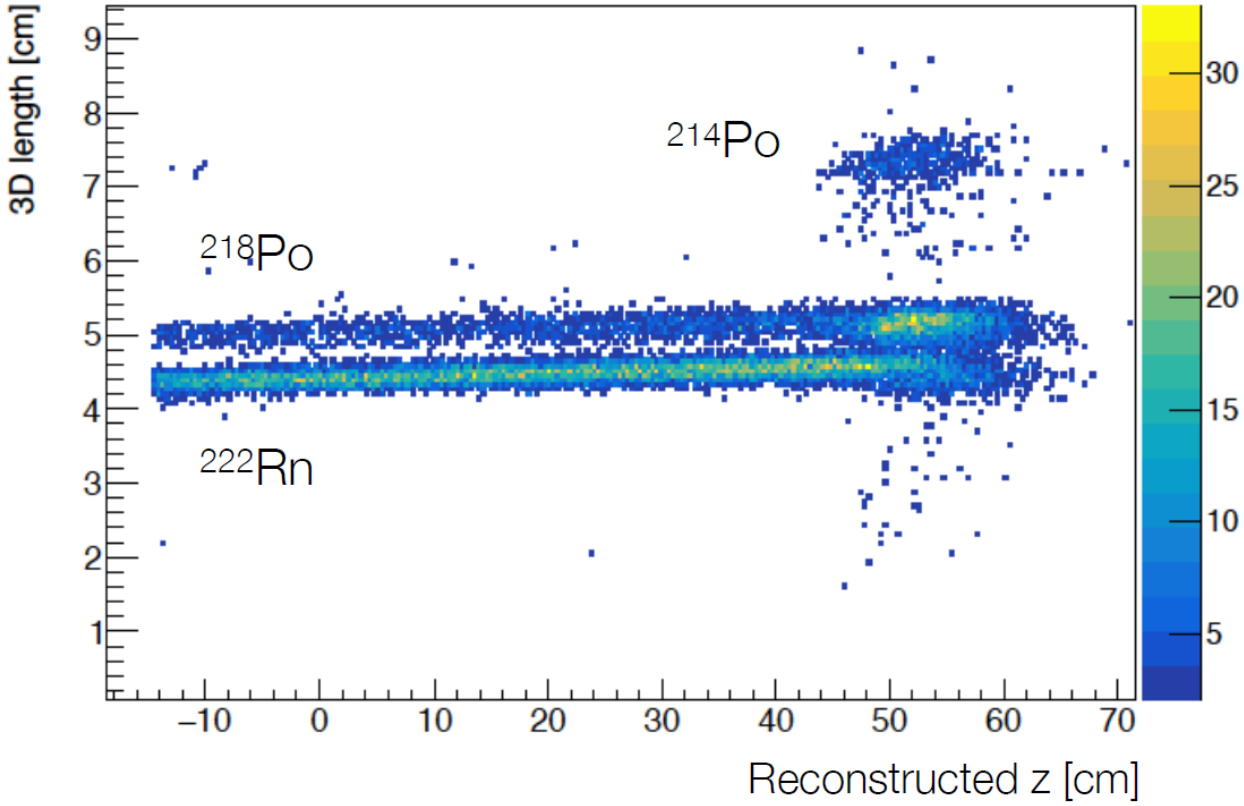
Full 3D reconstruction of alpha enables radon progeny spettroscopy



Z reconstruction

- To develop tools to evaluate the absolute z of low-energy ER, we use ^{55}Fe events;
- Several variables spot-shape were studied, and the most effective resulted that takes into account the distribution of the hits within the spot.



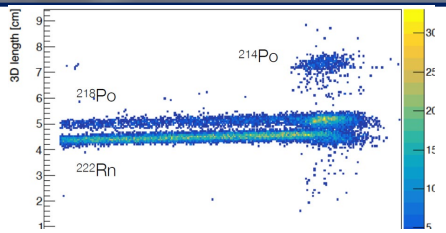


David Marques (GSSI) - PhD thesis

3D fiducialization

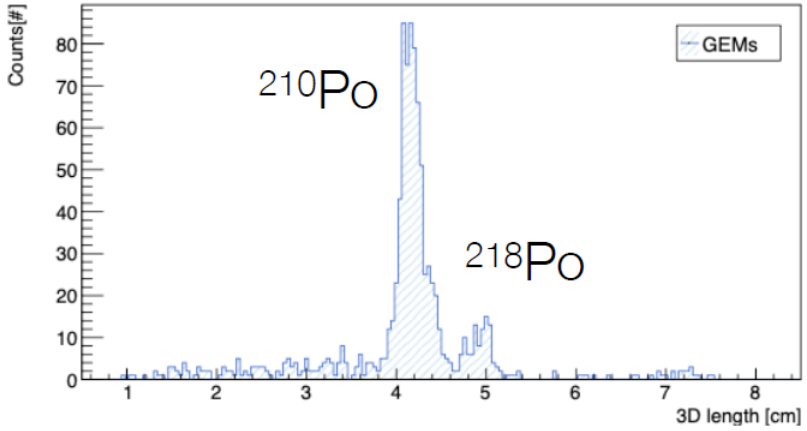
By reconstructing the 3D positions of the alphas, we can separate the contributions of

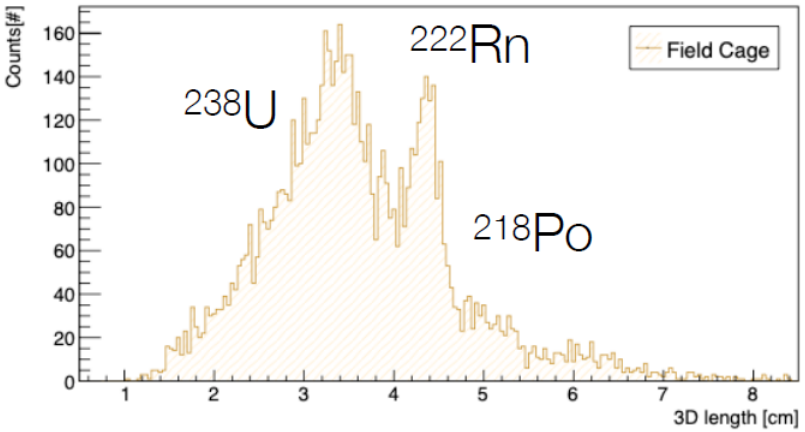
- ^{222}Rn chain (gas and cathode)
- ^{238}U and ^{232}Th chains as found in the GEM and Field Cage copper by HPGe

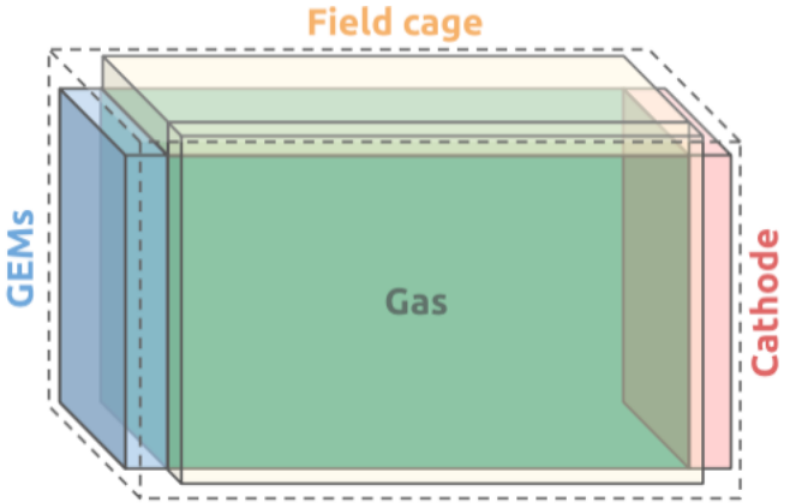


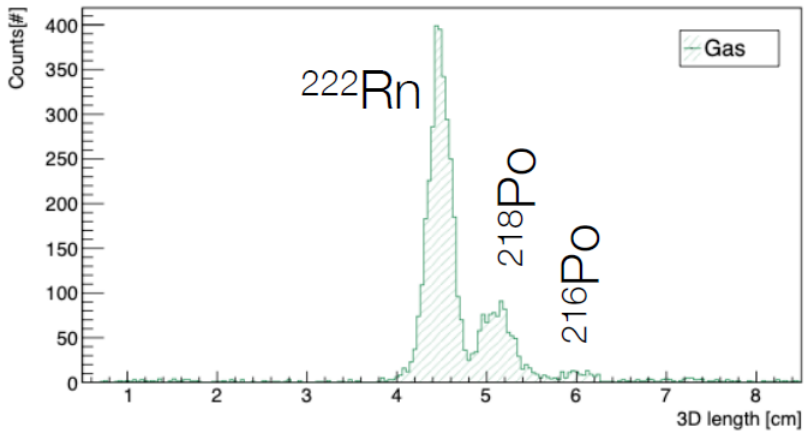
^{232}Rn chain

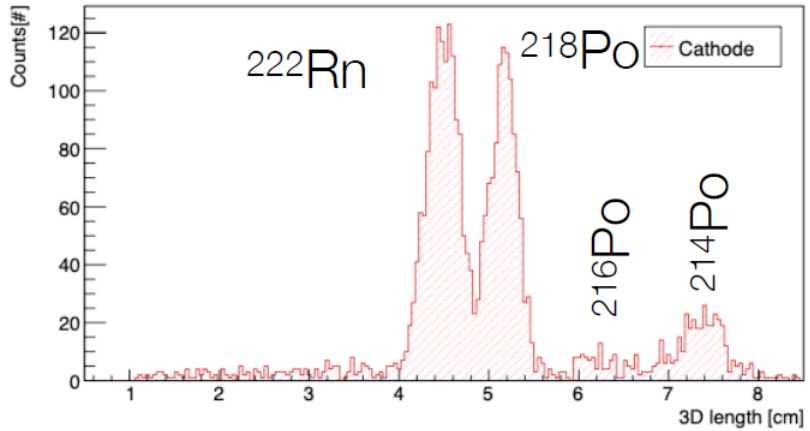
^{238}U and ^{232}Th chains











David Marques (GSSI) - PhD thesis

Radon progeny Nuclear Recoil

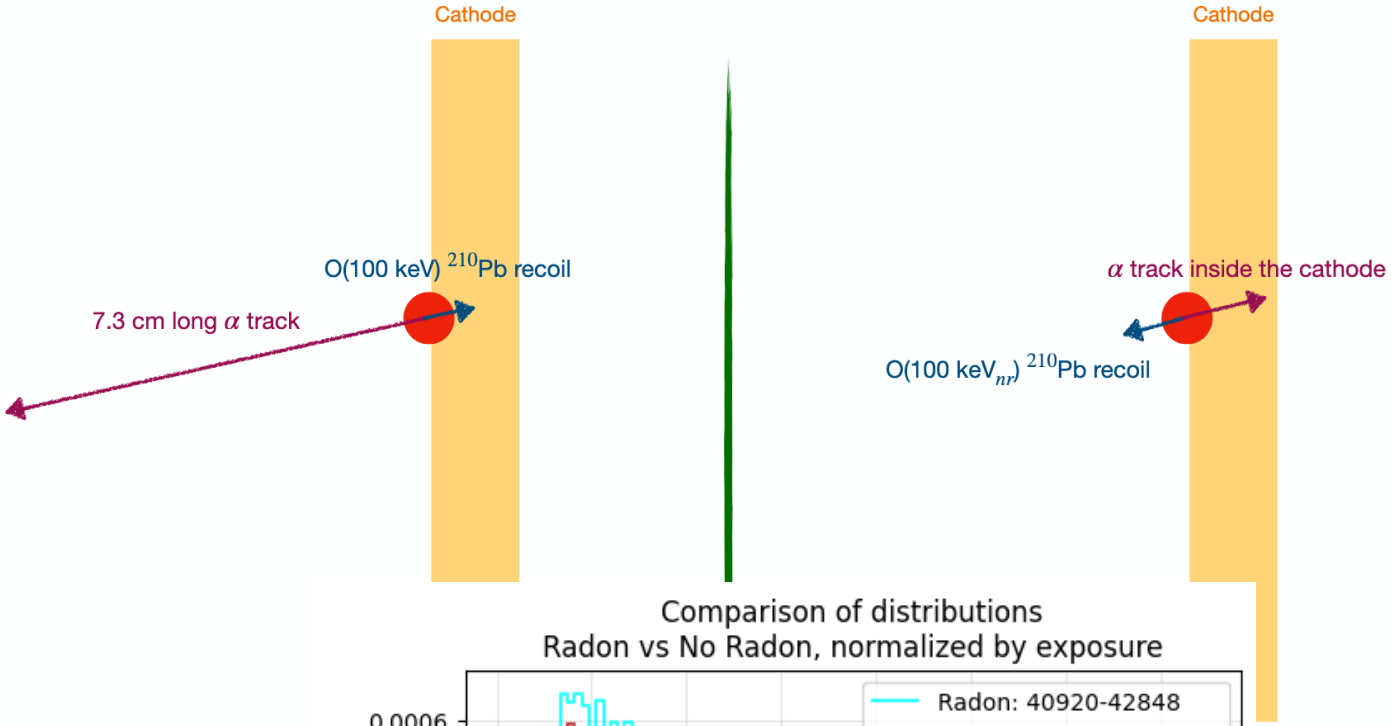
First detection of radon progeny recoil tracks by MIMAC

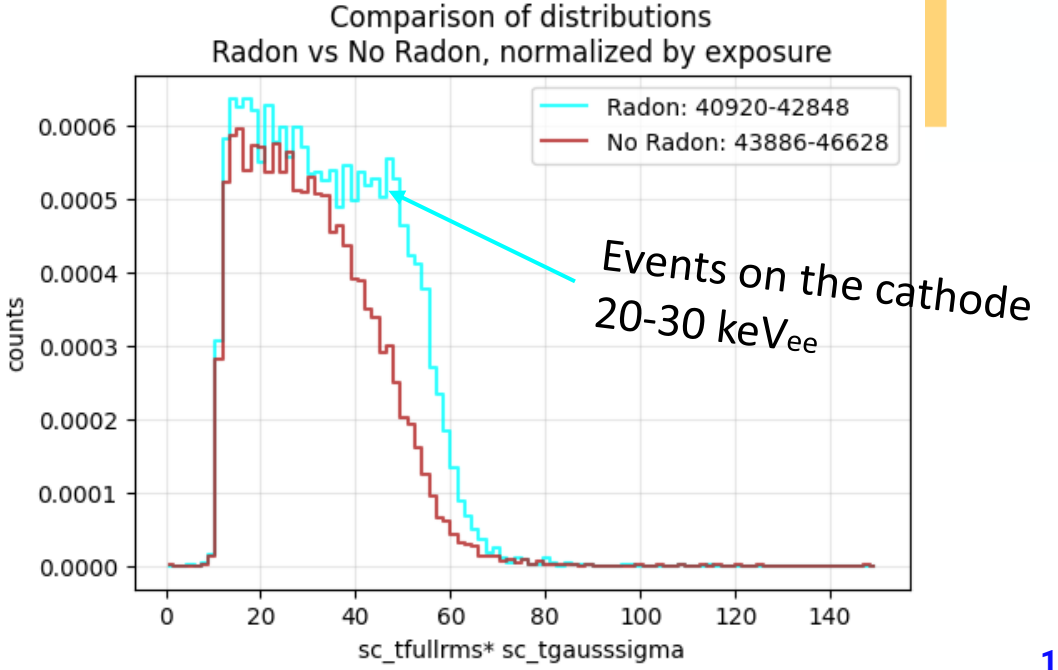
Q. Riffard, D. Santos, O. Guillaudin, G. Bosson, O. Bourrion, J. Bouvier, T. Descombes, C. Fourel, J.-F. Muraz, L. Lebreton · Show full author list

Published 30 June 2017 · © 2017 IOP Publishing Ltd and Sissa Medialab
Journal of Instrumentation, Volume 12, June 2017
Citation Q. Riffard *et al* 2017 *JINST* **12** P06021
DOI 10.1088/1748-0221/12/06/P06021

MIMAC paper: 10.1088/1748-0221/12/06/P06021

Parent	$T_{1/2}$	Mode	$E^{kin}_{\alpha/\beta\,max}$ [MeV]	Daughter	E^{kin}_{recoil} [keV]	E^{ioni}_{recoil} [keVee]
From ^{222}Rn						
^{222}Rn	3.8 days	α	5.489	^{218}Po	100.8	38.23
^{218}Po	3.1 min	α	6.002	^{214}Pb	112.3	43.90
^{214}Pb	27 min	β^-	1.024	^{214}Bi	-	-
^{214}Bi	20 min	β^-	3.272	^{214}Po	-	-
^{214}Po	164 µs	α	7.687	^{210}Pb	146.5	58.78
^{210}Pb	22 years	β^-	0.064	^{210}Bi	-	-
^{210}Bi	5 days	β^-	1.163	^{210}Po	-	-
^{210}Po	138 days	α	5.304	^{206}Pb (stable)	103.7	40.28

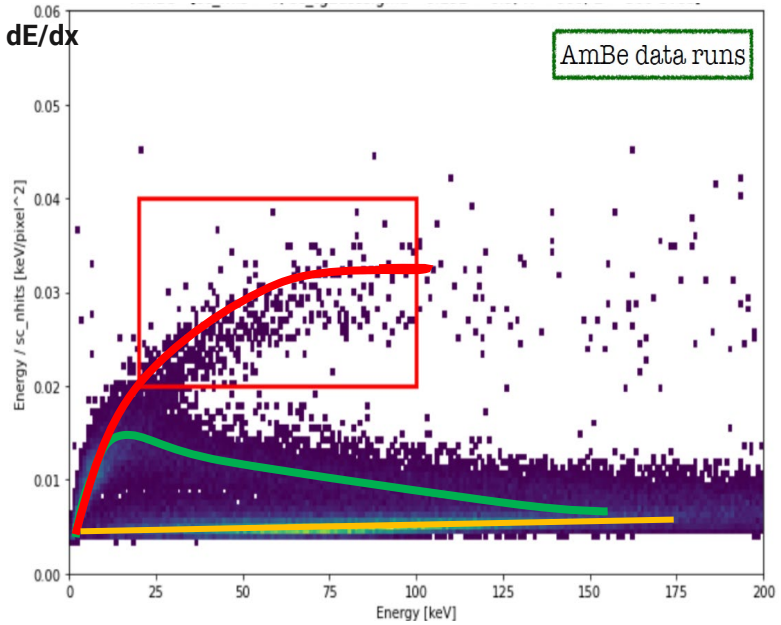




- 10%-20% Quenching Factor for Pb at the 150 keV energy, we should expect 15-30 keVee
- The identification of this dangerous background component will allow us to reject it
- **Analysis currently Ongoing!**

NR-ER discrimination

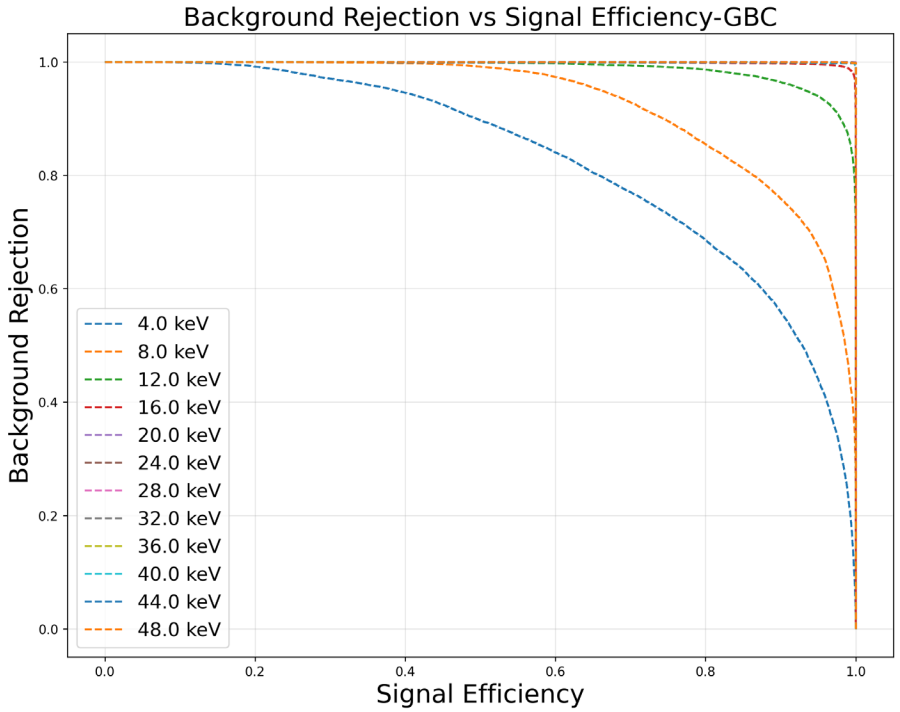
We have access to many variables related to the signal shape!



Convolution Neural Network

Atul Prajapati Thesis

- Training on **MC** using multiple shape variables
- Promising results beyond traditional analysis



NR-ER discrimination

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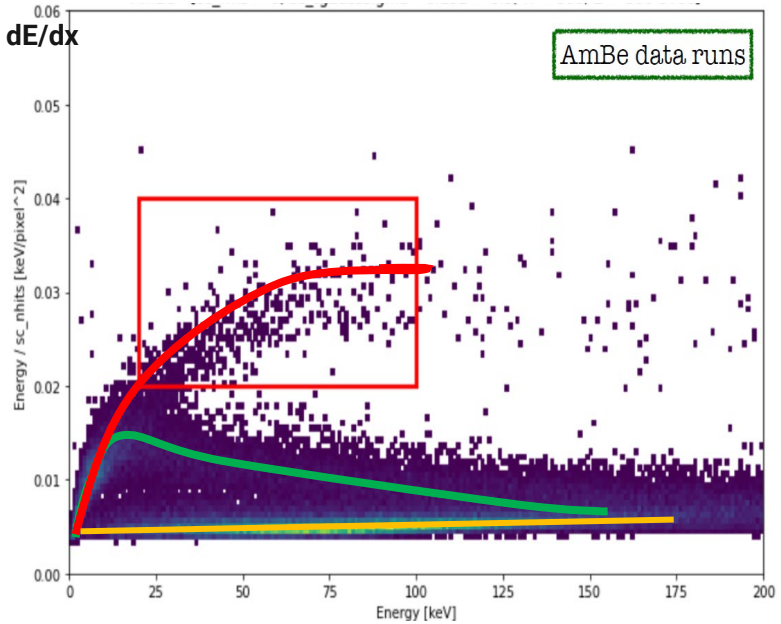

Convolution Neural Network

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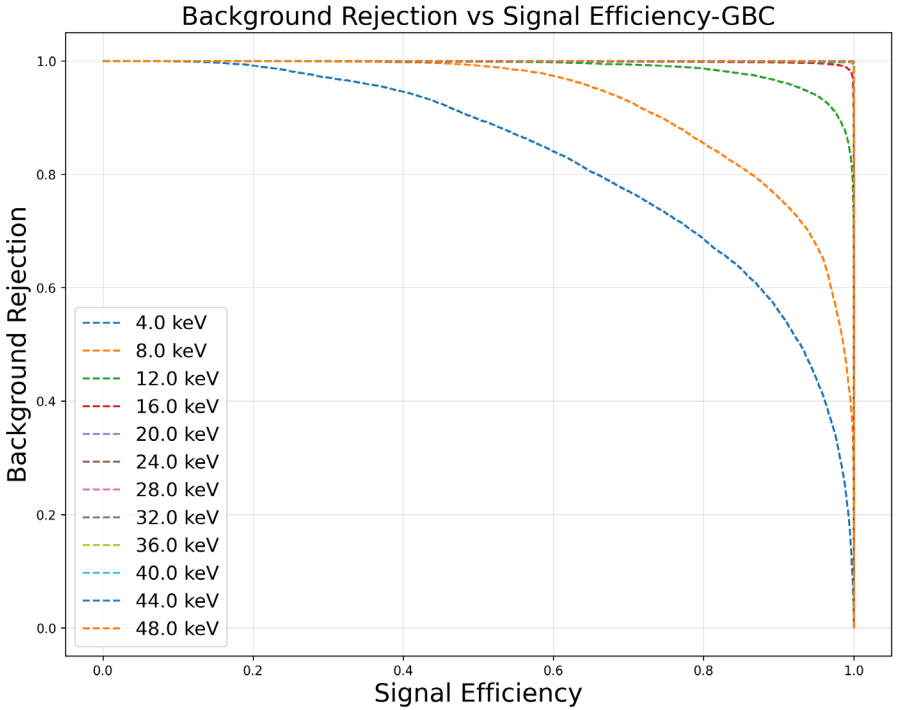
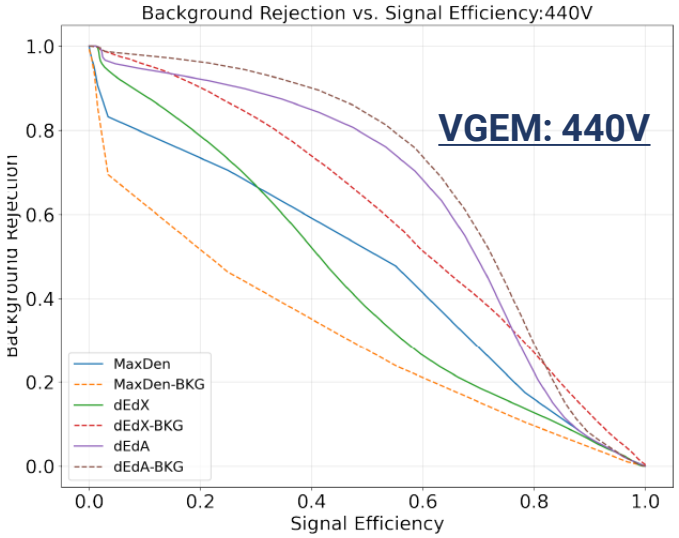
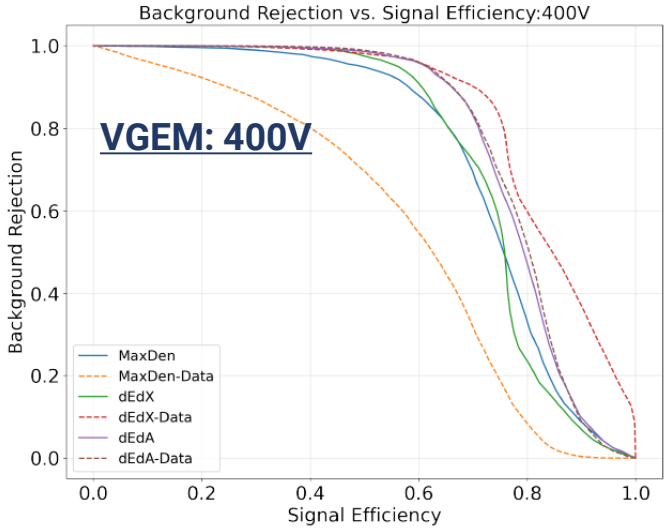






Saturation is clearly present in LIME!

And it affects the ER/NR discrimination

Modeling the light response of an optically readout GEM based TPC for the CYGNO experiment

2406.05713

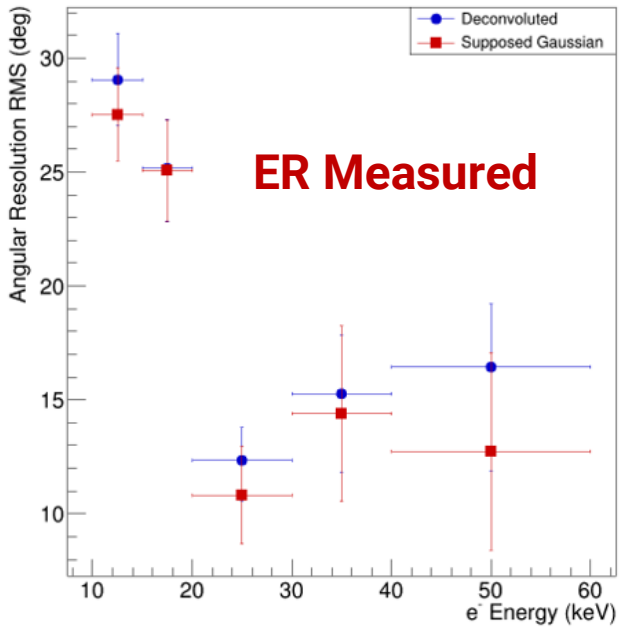
Fernando Dominques Amaro[1], Rita Antonietti[2,3], Elisabetta Baracchini[4,5], Luigi Benussi[6], Stefano Bianco[6], Campagnola[6], Cesidio Capoccia[6], Michele Caponero[6,9], Gianluca Cavoto[7,8], Igor Abritta Costa[6], Antonio Emiliano Dané[6], Melba D'Astolfo[4,5], Giorgio Dho[6], Flaminia Di Giambattista[4,5], Emanuele Di Marco[7], D'Imperio[7], Joaquim Marques Ferreira dos Santos[1], Davide Fiorina[4,5], Francesco Iacoangeli[7], Zahoor Ul Herman Pessoa Lima Júnior[4,5], Ernesto Kemp[10], Francesca Lewis[8], Giovanni Maccarrone[6], Rui Daniel Pas Robert Renz Marcelo Gregorio[11], David José Gaspar Marques[4,5], Luan Gomes Mattosinhos de Carvalho[1] Mazzitelli[6], Alasdair Gregor McLean[11], Pietro Meloni[2,3], Andrea Messina[7,8], Cristina Maria Bernardes M Rafael Antunes Nobrega[12], Igor Fonseca Pains[12], Matteo Pantalena[8], Emiliano Paoletti[6], Luciano Passa Fabrizio Petrucci[2,3], Stefano Piacentini[4,5], Davide Piccolo[6], Daniele Pierluigi[6], Davide Pinci[7a], Atul Praj Francesco Renga[7], Rita Joana Cruz Roque[1], Filippo Rosatelli[6], Alessandro Russo[6], Sabrina Salamino[8], Saviano[6,13], Federico Francesco Scamporlino[8], Angelo Serrecchia[8], Pedro Alberto Oliveira Costa Silva[1], Curwen Spooner[11], Roberto Tesauro[6], Sandro Tomassini[6], Samuele Torelli[4,5], and Donatella Tozzi[7,8]

[Modeling the light response of an optically readout GEM based TPC for the CYGNO experiment]

Enhancing the light yield of He:CF_4 based gaseous detector

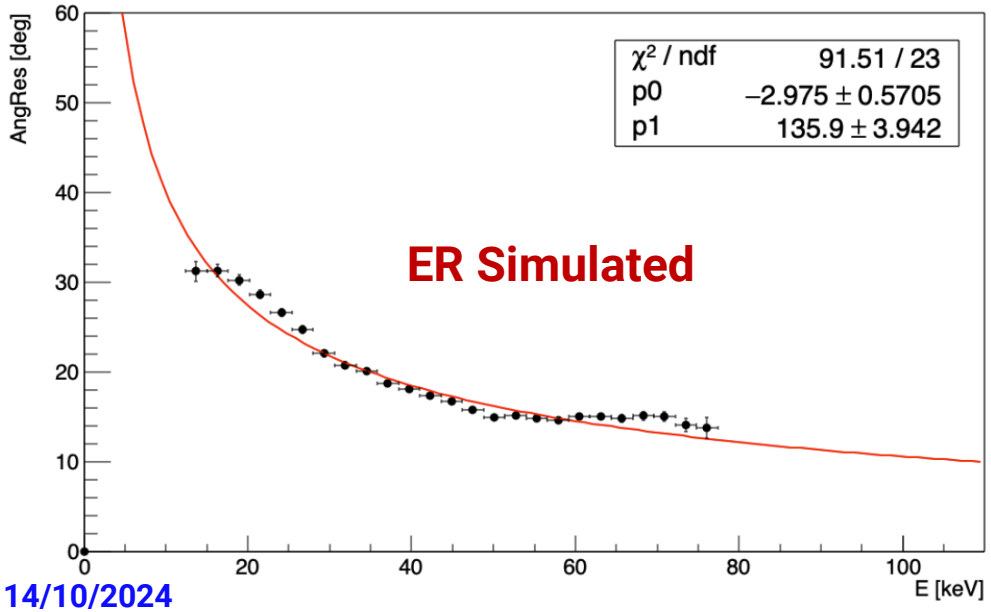
Fernando Domingues Amaro[1], Rita Antonietti[2,3], Elisabetta Baracchini[4,5], Luigi Benussi[6], Stefano Bianco[6], Roberto Campagnola[6], Cesidio Capoccia[6], Michele Caponero[6,7], Danilo Santos Cardoso[8], Luan Gomes Mattosinhos de Carvalho[9], Gianluca Cavoto[10,11], Igor Abritta Costa[6], Antonio Croce[6], Emiliano Dané[6], Giorgio Dho[4,6,a], Flaminia Di Giambattista[4,5], Emanuele Di Marco[11], Melba D'Astolfo[4,5], Giulia D'Imperio[11], Davide Fiorina[4,5], Francesco Iacoangeli[11], Zahoor ul Islam[4,5], Herman Pessoa Lima Júnior[4,8], Ernesto Kemp[12], Giovanni Maccarrone[6], Rui Daniel Passos Mano[1], Robert Renz Marcelo Gregorio[13], David José Gaspar Marques[4,5], Giovanni Mazzitelli[6], Alasdair Gregor McLean[13], Andrea Messina[10,11], Pietro Meloni[2,3], Cristina Maria Bernardes Monteiro[1], Rafael Antunes Nobrega[9], Igor Fonseca Pains[9], Emiliano Paoletti[6], Luciano Passamonti[6], Fabrizio Petrucci[2,3], Stefano Piacentini[4,5], Davide Piccolo[6], Daniele Pierluigi[6], Davide Pinci[11], Atul Prajapati[4,5], Francesco Renga[11], Rita Joana da Cruz Roque[1], Filippo Rosatelli[6], Alessandro Russo[6], Joaquim Marques Ferreira dos Santos[1], Giovanna Saviano[6,14], Pedro Alberto Oliveira Costa Silva[1], Neil John Curwen Spooner[13], Roberto Tesauro[6], Sandro Tomassini[6], Samuele Torelli[4,5]

Angular Resolution

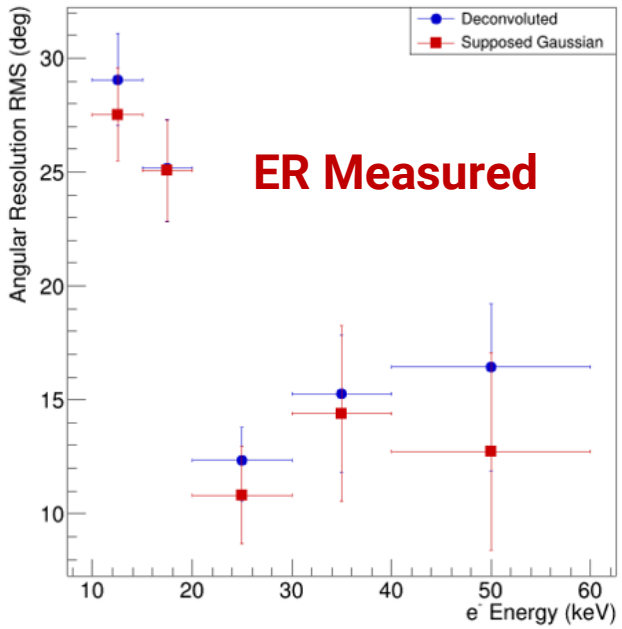


ER angular resolution

- Measured by 90Sr electrons irradiation
- Good match with Simulated data



Angular Resolution



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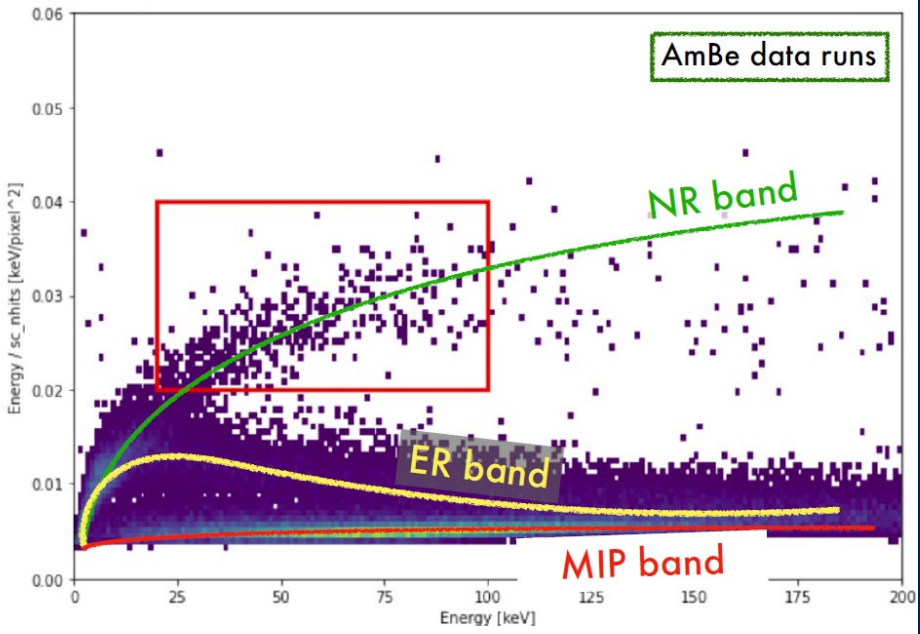
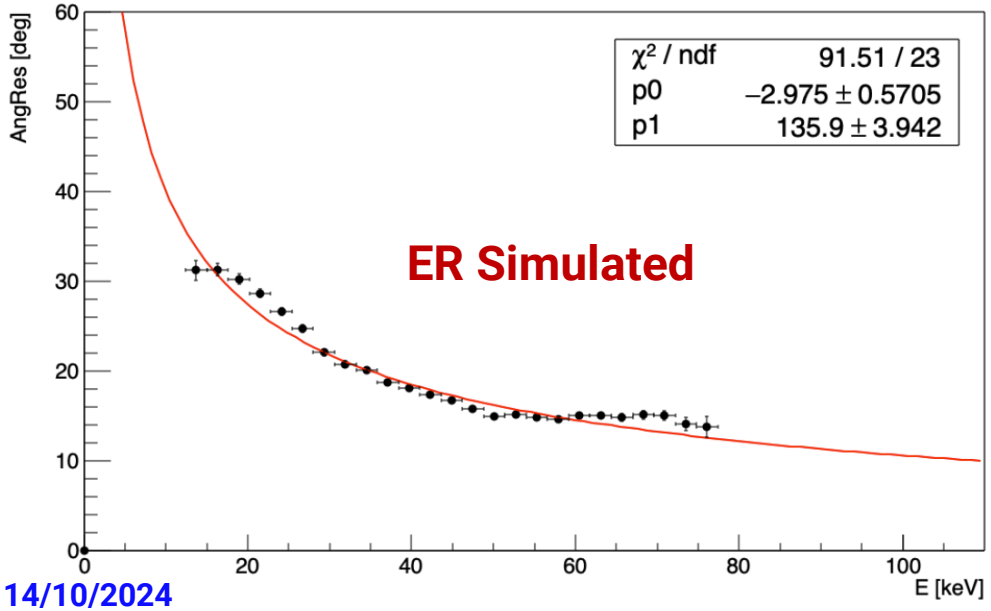
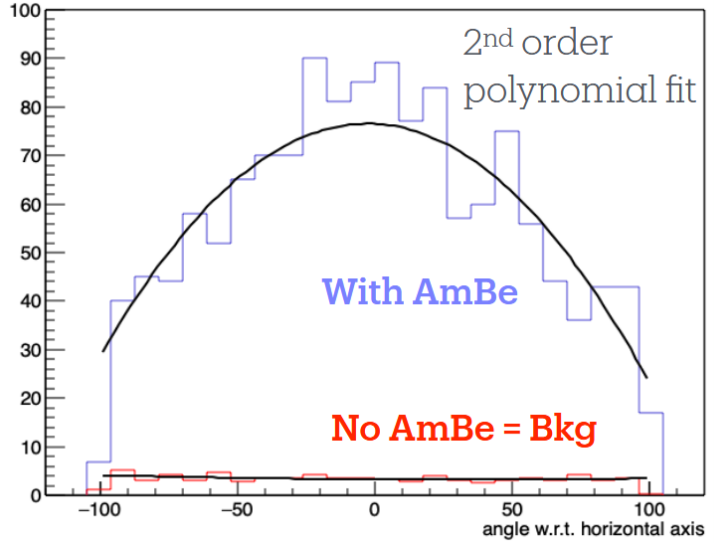




NR angular resolution

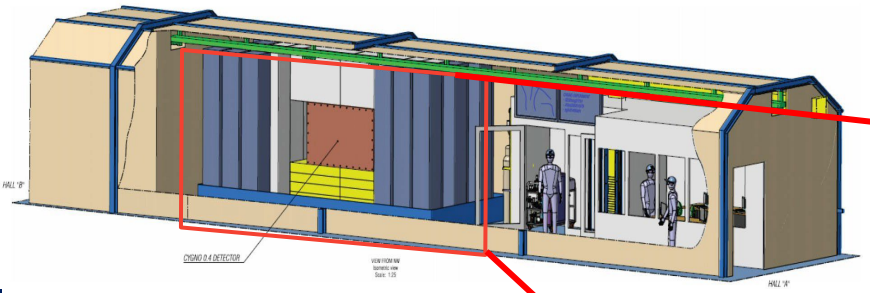
- Estimated via naive assumption on AmBe neutron source data taking
- Estiamted 45° RMS (>20 keVee)
  - Upper Limit!



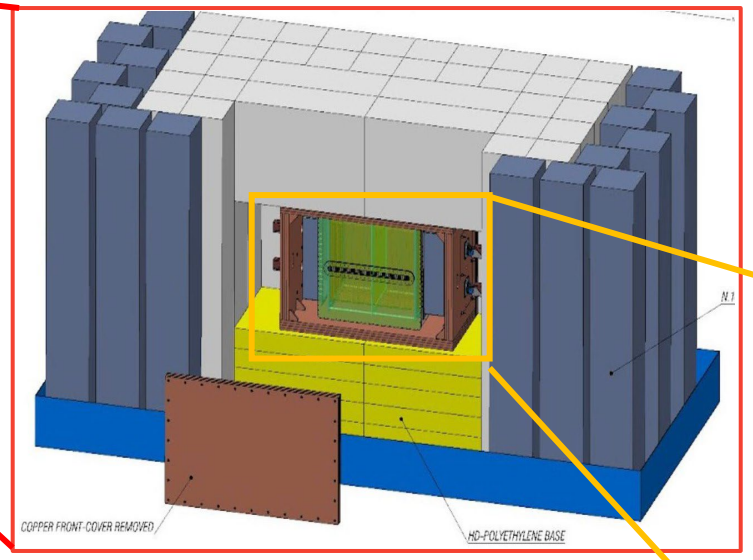
CYGNO_04

Scalability of the Technology

Radiopure materials

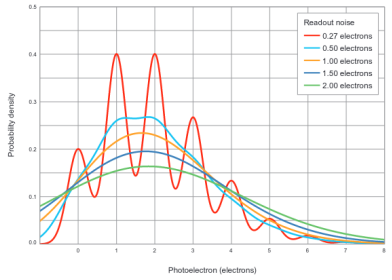


LNGS Hall F

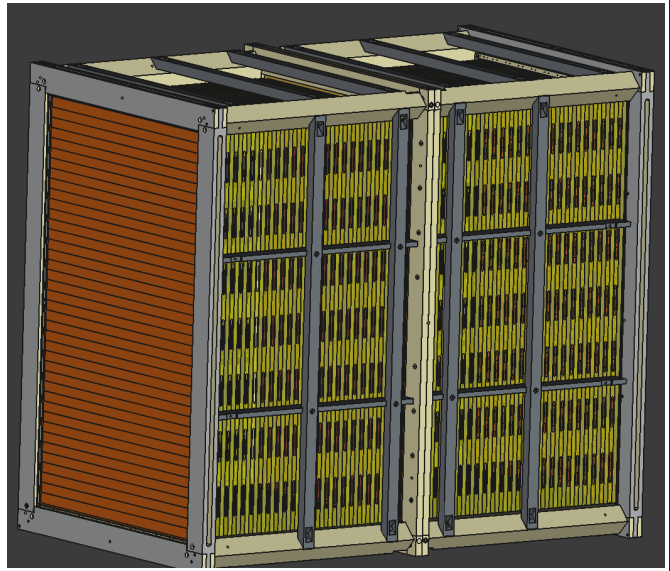


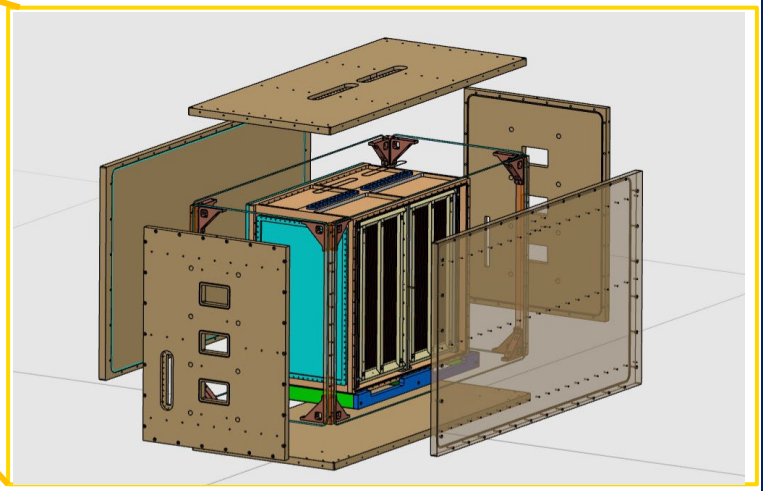
0.4m3 common cathode TPC

- 3 ORCA QUEST2 (next-gen) per side
- 8 PMTs per side
- 4+6cm copper shielding (radiopure+traditional)
- 40cm of water



Feasibility for a larger scale detector based on multiple CYGNO_04 modules





Throughput expected ≈20Mb/s
Computational resources very demanding

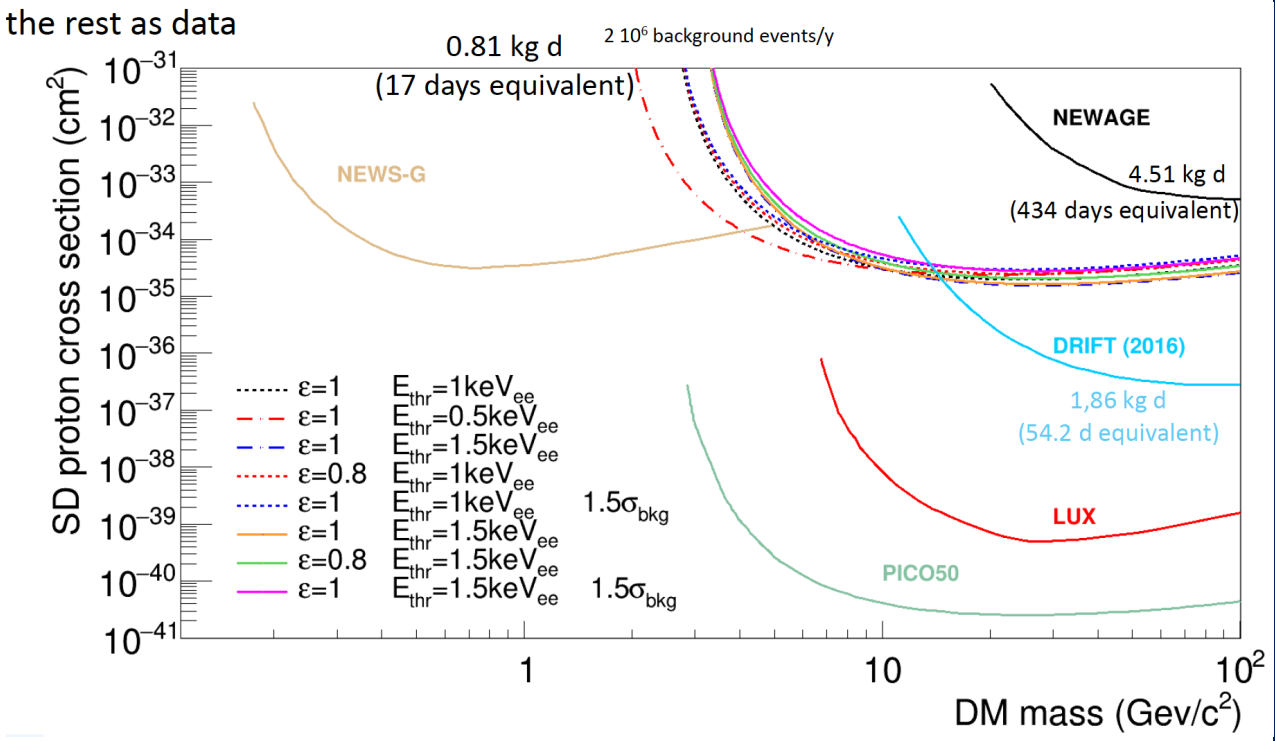
→ Triggerless data selection with ML on GPU

Expected Limits

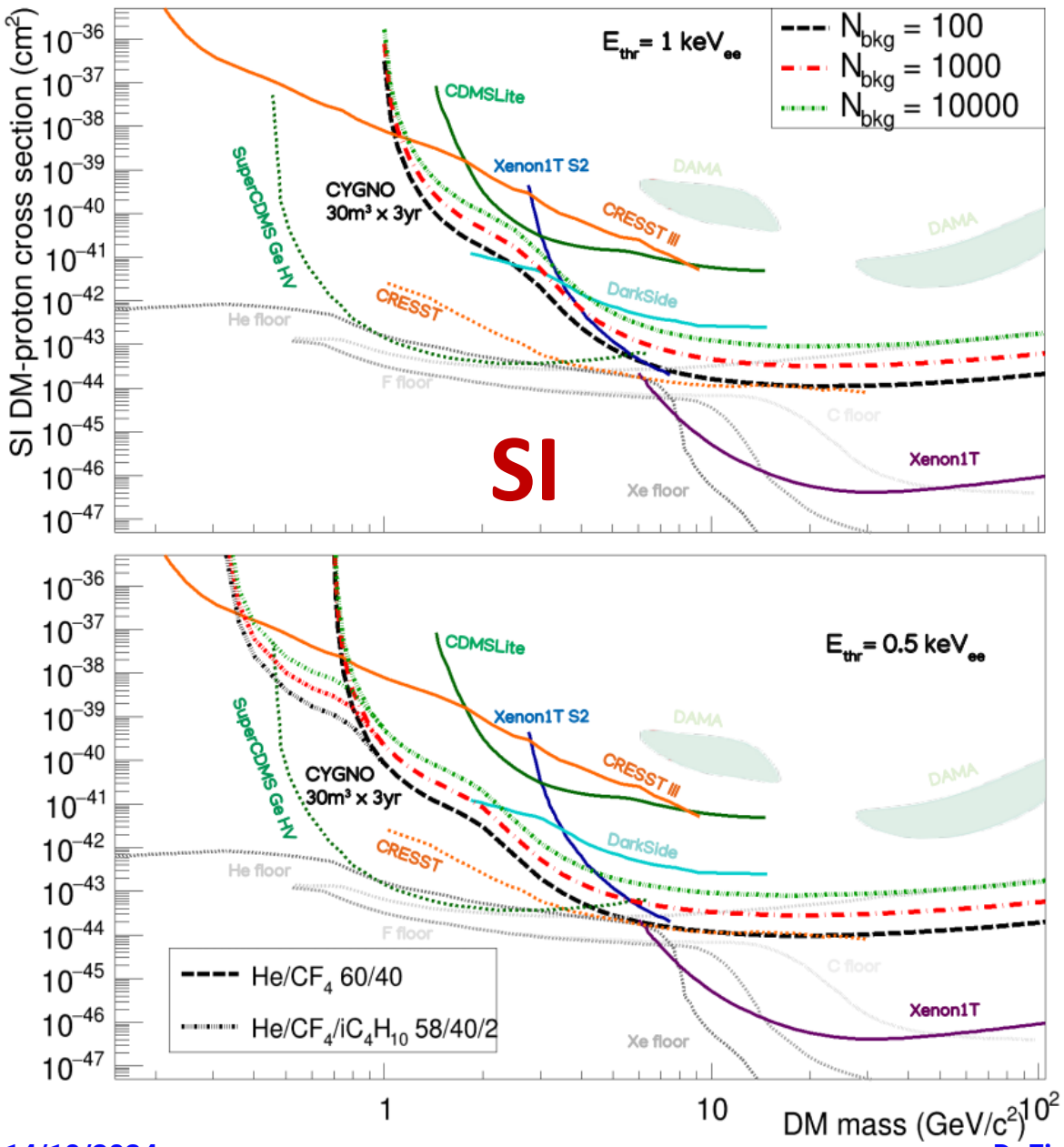
LIME naive limits with a subsample of 17 days

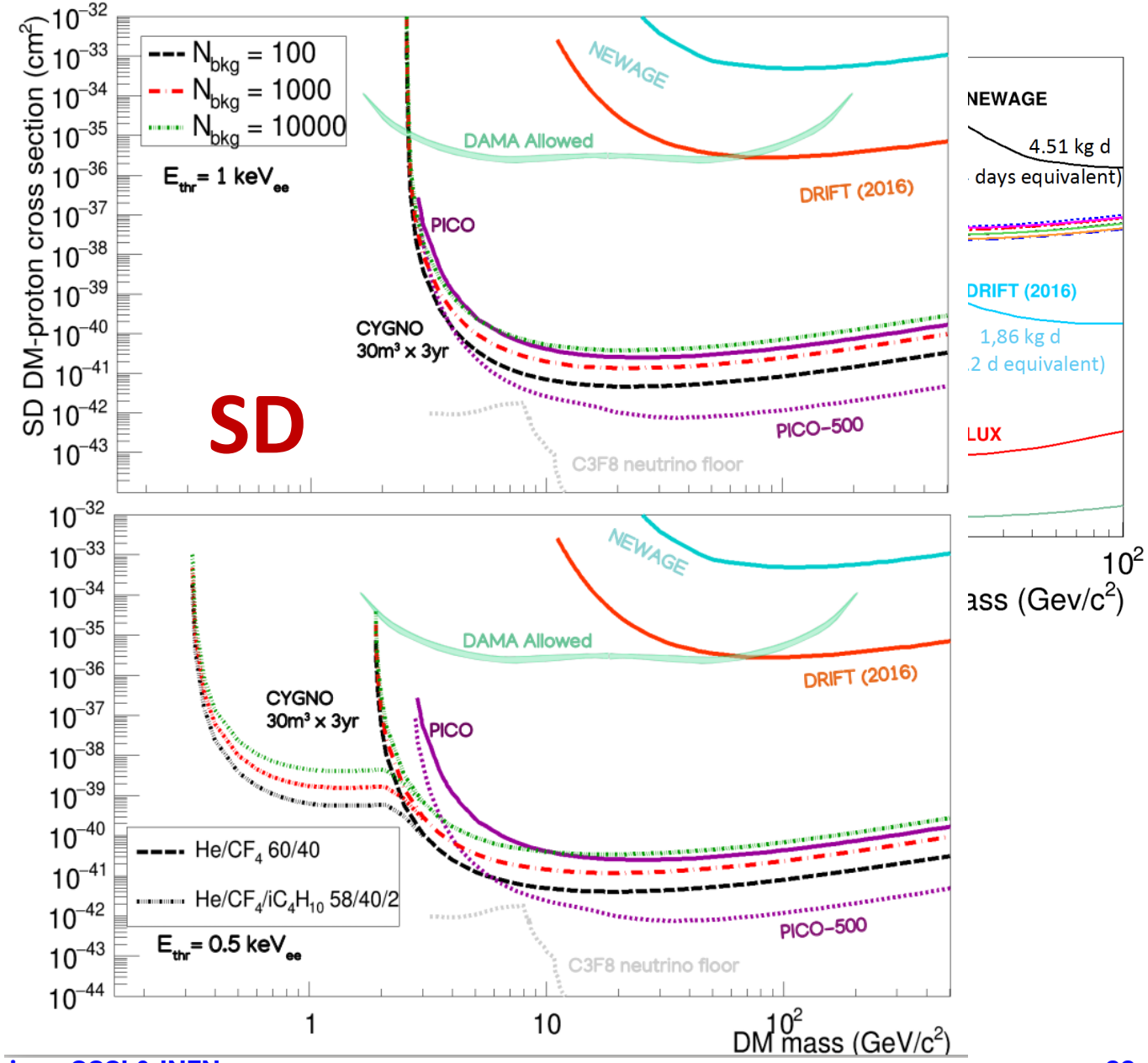
- Not a radiopure detector
- No solid background model
- No Directionality

→ **A detector not designed for physics is competitive with the only other directional detector.**



Expected Limits

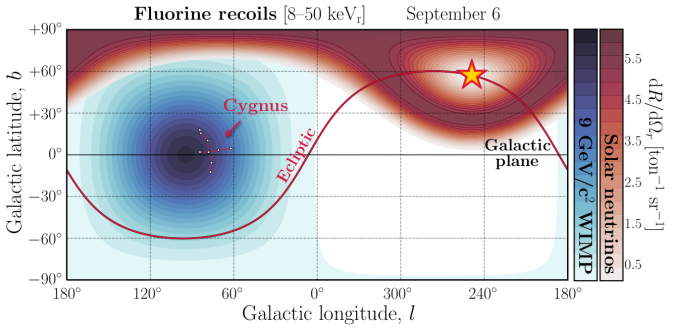


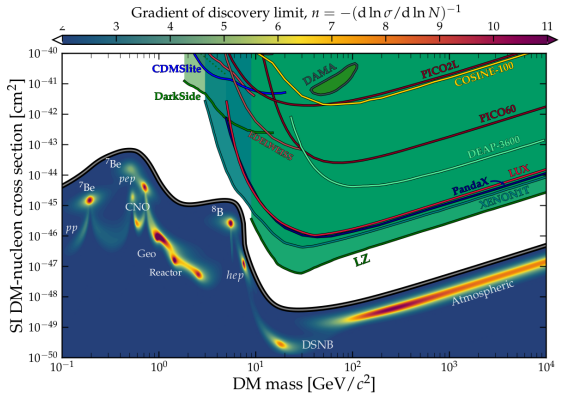


Conclusion

The CYGNO collaboration is developing a high-precision triple-GEM TPC at atmospheric pressure with optical readout.

- The main focus is the **directional direct search** of DM WIMP-like particles in the low mass range (0.5-10 GeV) with a threshold of 0.5 keV_{ee}.
  - Directionality provides a unique handle to confirm the presence of the Galactic dark matter halo.
  - Isotropic Background rejection
  - Operations beyond Neutrino Fog





- LIME demonstrated the feasibility of such a detector for **rare event search,** validating our **MC chain**
- CYGNO04 will prove the scalability of our detector model for a larger project starting in the **first trimester of 2026**

Experiment	Where	Amplification + Readout	Gas Pressure [mbar]	Volume [L]	Energy Thr [keV_{ee}]	Active Mass [gr]
DRIFT	UK	MWPC	55	800	20	33
NEWAGE	Japan	1 GEM +muPIC	100	37	20	11.5
MIMAC	France	Micromegas	50	5.8	2	1.2
D3	Australia	2 GEM + pixelated RO	1000	40	5	60
CYGNO	Italy	3 GEMs + sCMOS + PMT	900	400	1	600

BACKUP

It's a Dark Universe

Energy, Time, and other widely used methods are <u>not enough</u> to prove that an eventual signal is a Dark Matter signal

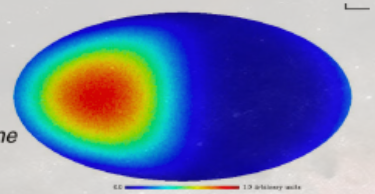
Capability to reject isotropy

Dive into the Neutrino Fog

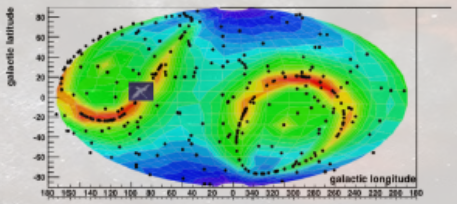
A. M. Green et. al, Astropart. Phys. 27 (2007) 142

WIMP signal (recoil map)

Angular distribution of Fluorine recoils [5;50] keV

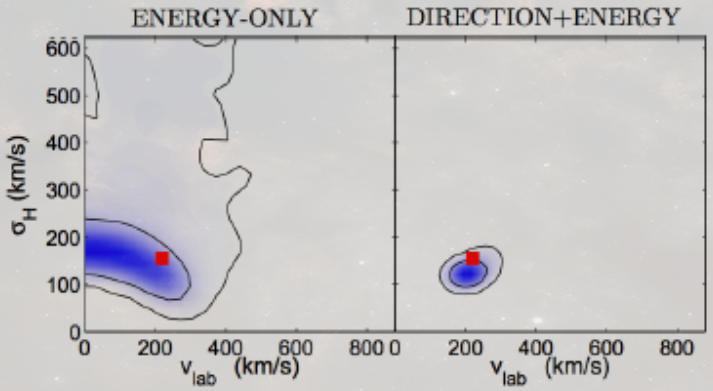


Background



<u>Directionality of the DM flux</u>

Phys.Rept. 627 (2016) 1-49

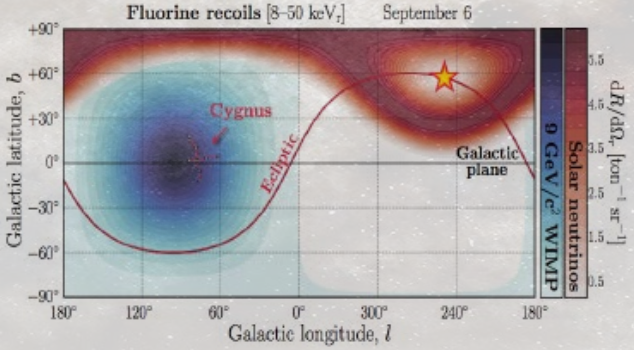


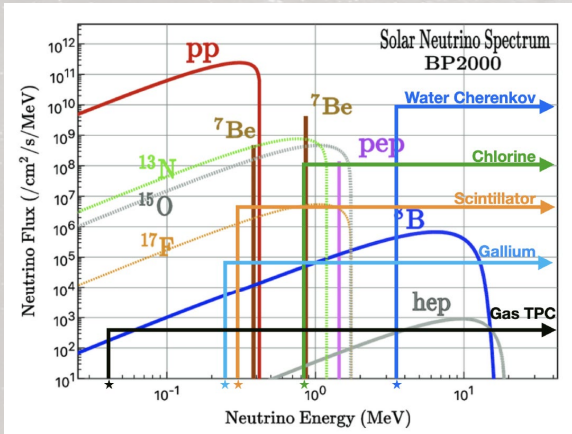
This is the only generic and unambiguous terrestrial signature of DM that results solely from the assumption that we live inside a DM halo.

<u>The future of directional searches, Ciaran O'Hare</u>

Capability to identify Solar neutrinos

e-Print: 2102.04596

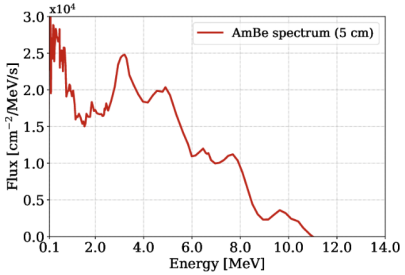


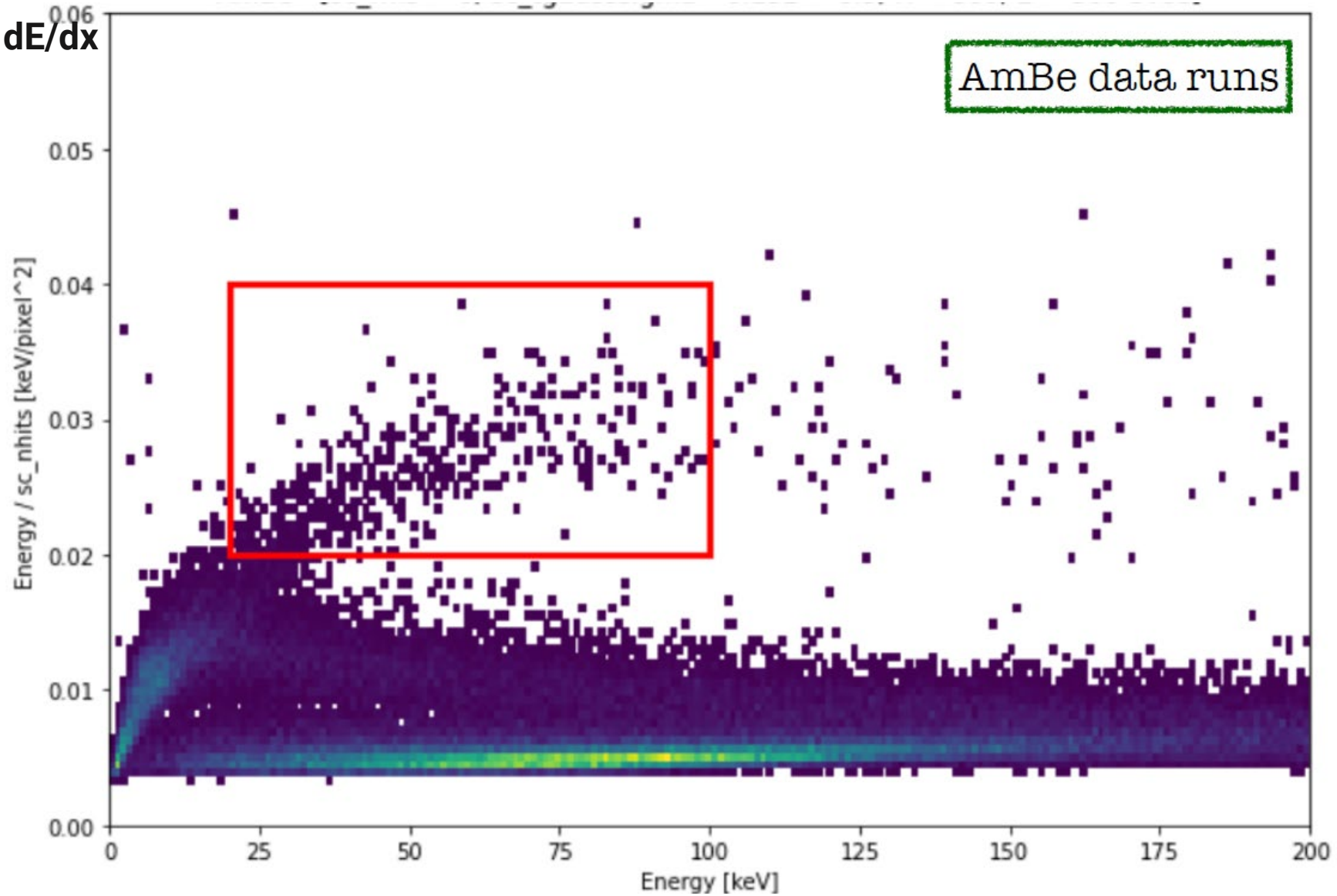


[2408.03760] Feasibility of a directional solar neutrino measurement with the CYGNO/INITIUM experiment (arxiv.org)

Background Rejection

Data taking with Americium-beryllium source → Neutrons to induce Nuclear Recoil signals





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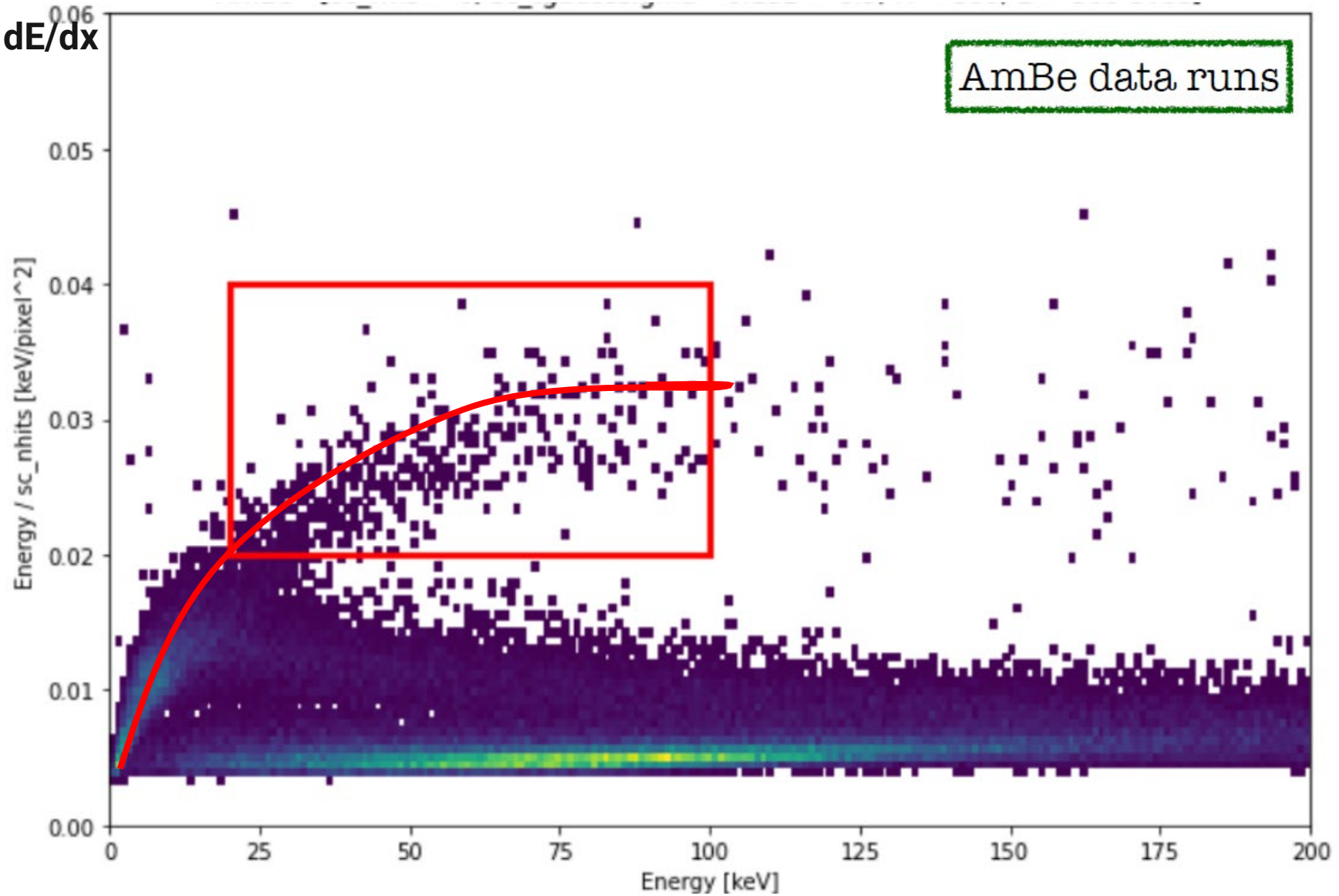
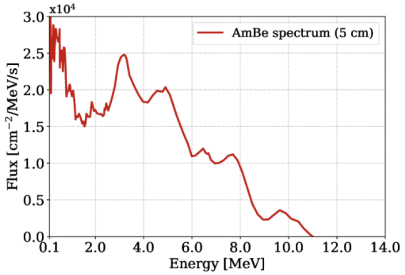
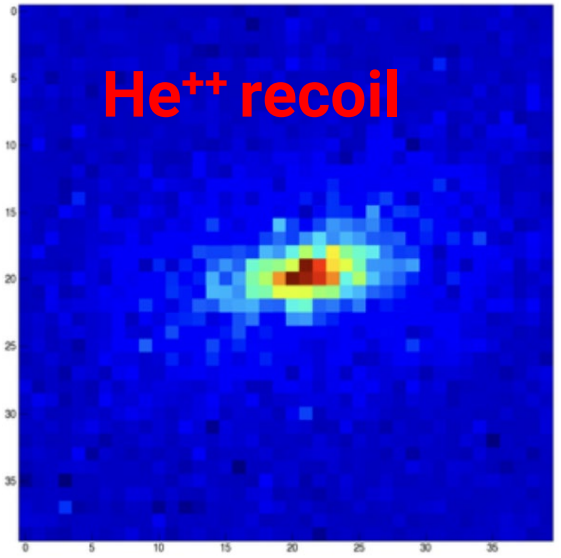


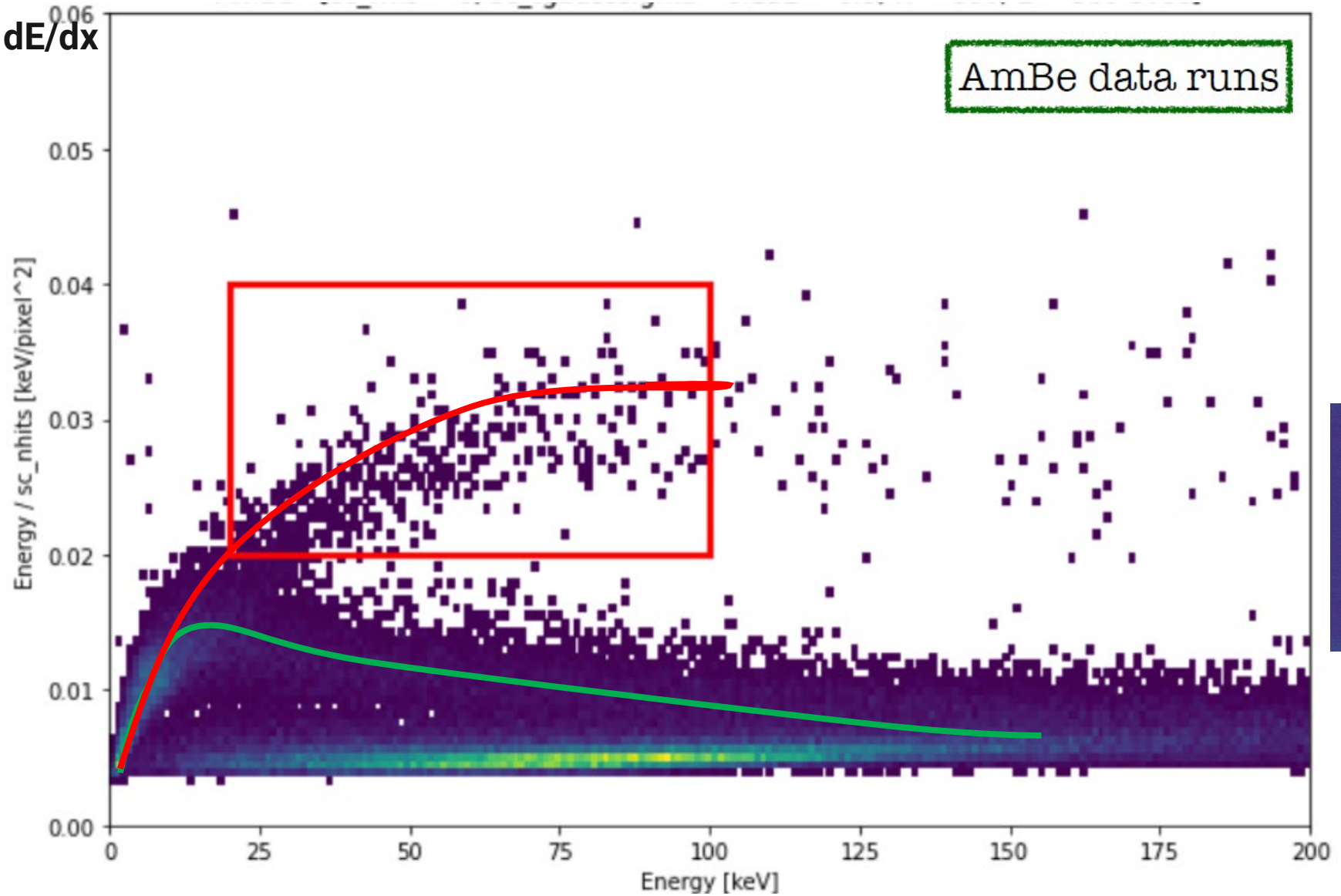


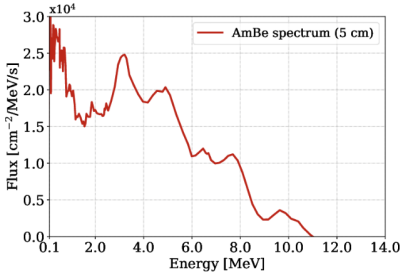
Nuclear Recoils



Background Rejection

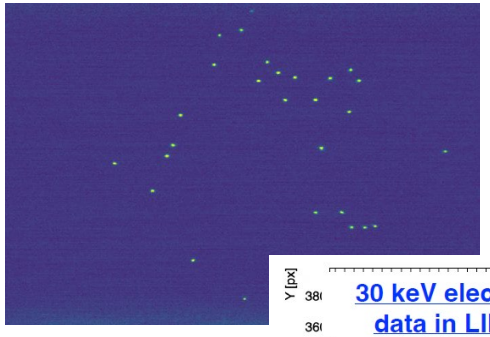
Data taking with Americium-beryllium source → Neutrons to induce Nuclear Recoil signals

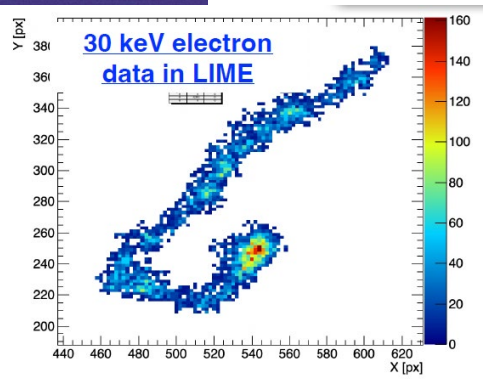




Electron Recoils

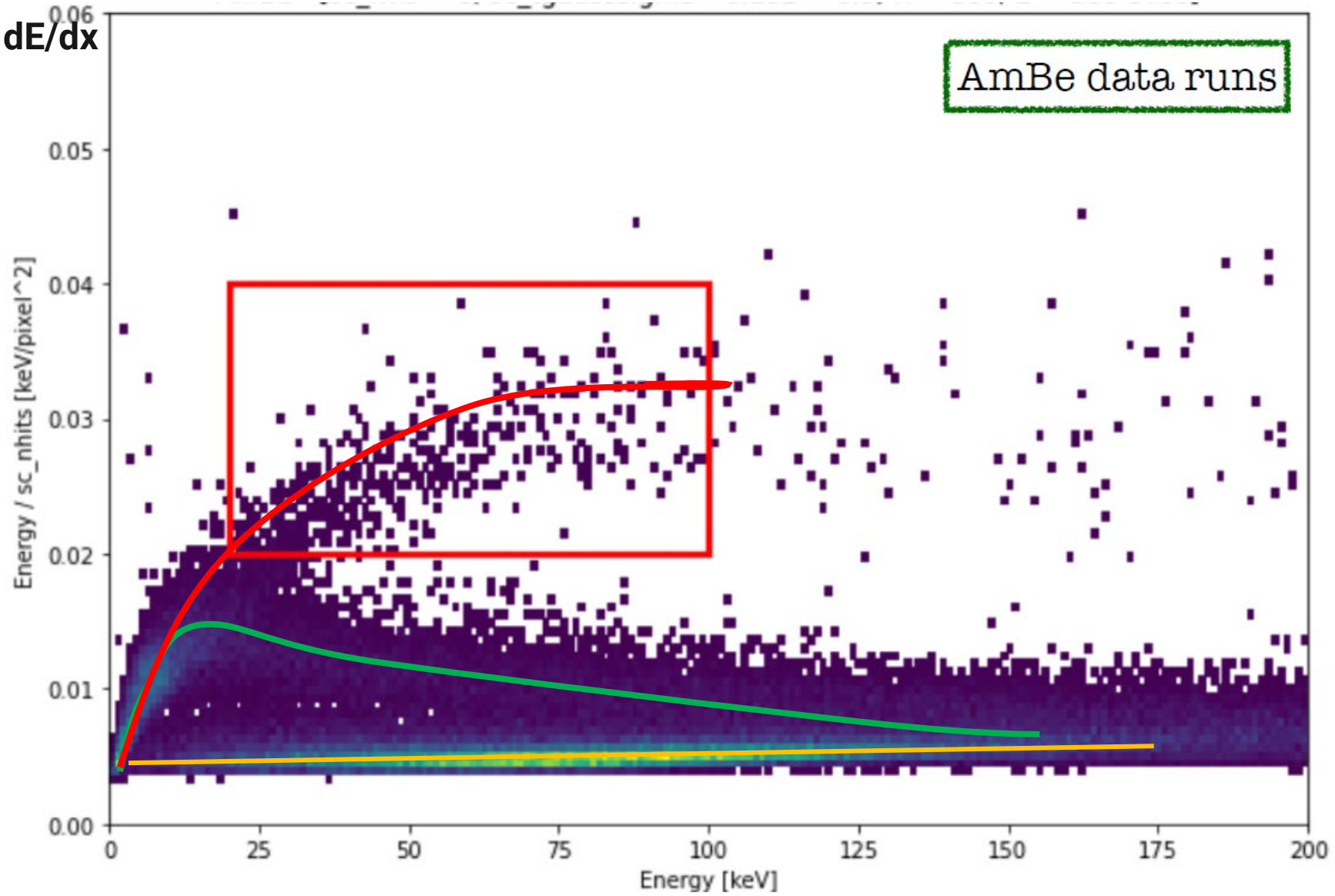
Nuclear Recoils

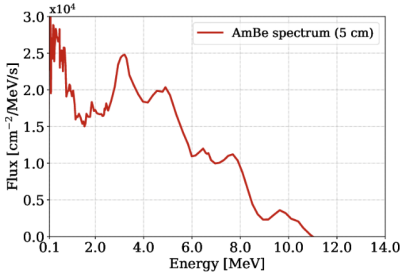




Background Rejection

Data taking with Americium-beryllium source → Neutrons to induce Nuclear Recoil signals



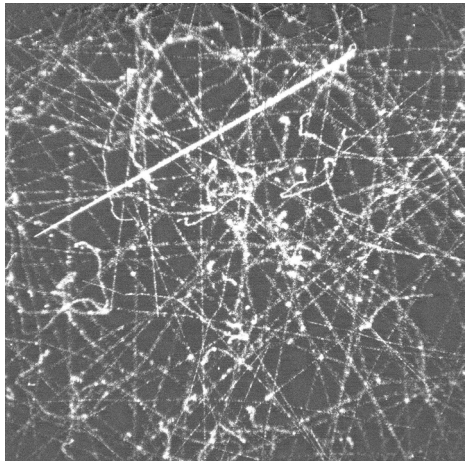


MIP

(muons and high energy electrons)

Electron Recoils

Nuclear Recoils



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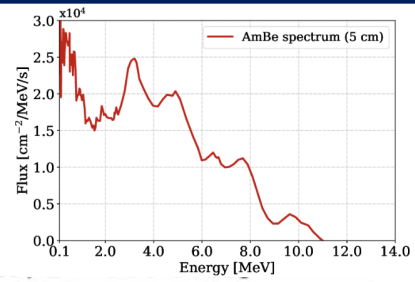
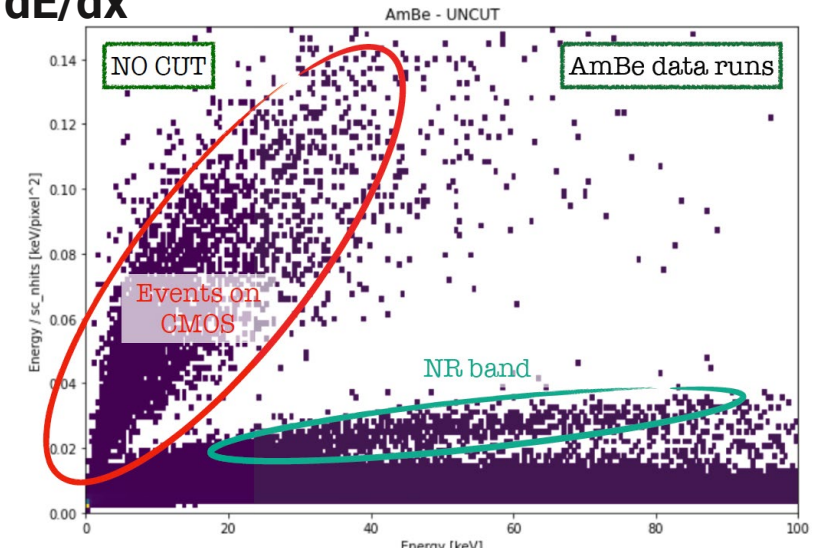
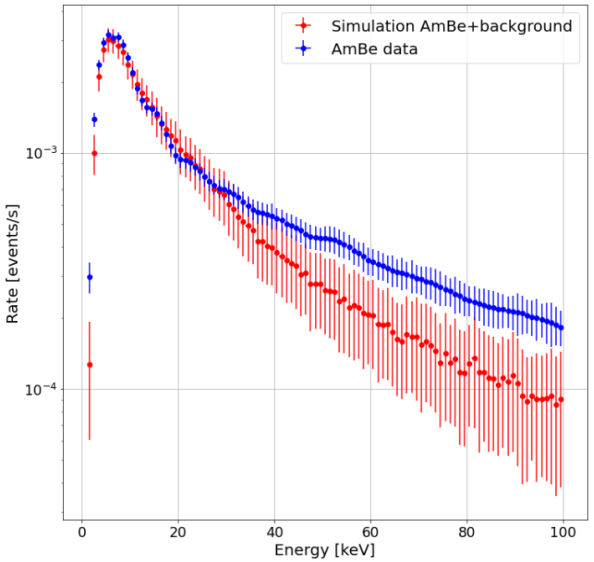
Data taking with Americium-beryllium source → Neutrons to induce Nuclear Recoil signals

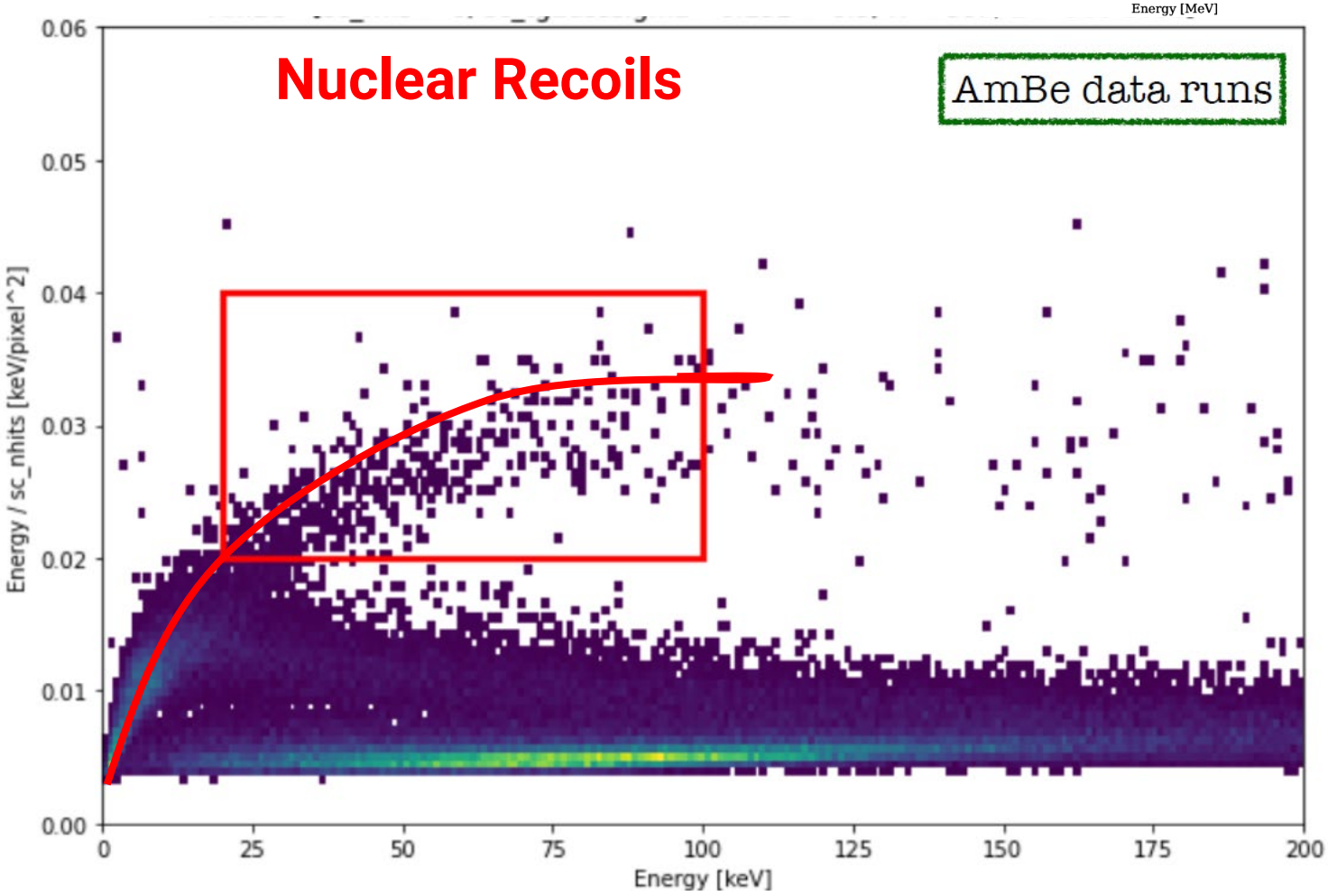


dE/dx





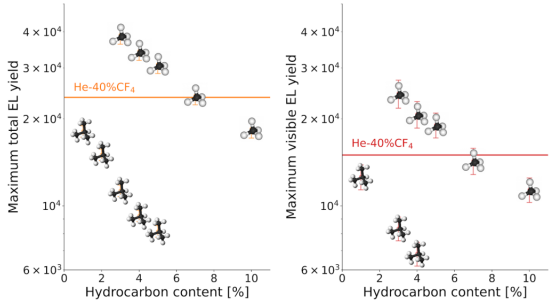
Simulation of AmBe gamma spectrum is correctly reproduced when background does not dominate

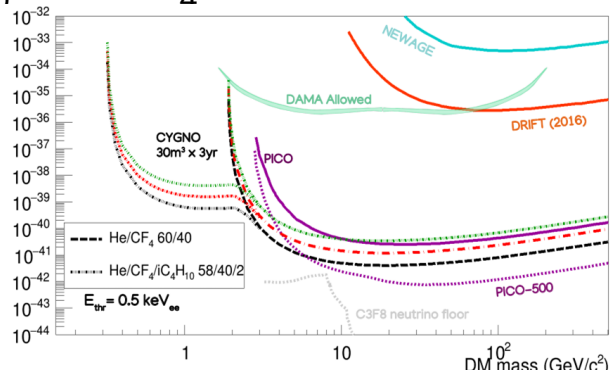


R&D activities

Hydrogen Rich Gas

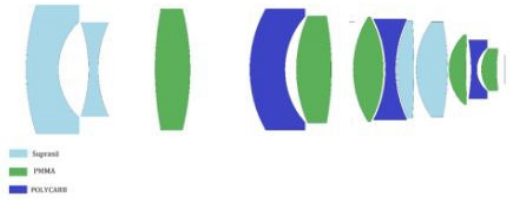
- Add hydrogen-rich gas is under study to gain sensitivity to lower DM masses iC_4H_{10} and CH_4 with <10% concentration





Low radioactivity Lens

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



Feasibility study for low radioactivity lens

Enhanced Light Yield

[2406.05713] Enhancing the light yield of He:CF$_4$ based gaseous detector (arxiv.org)

G. Dho

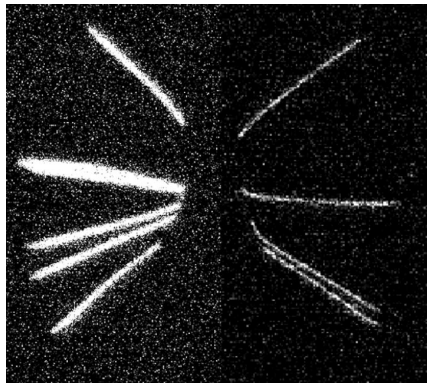
Impact of a strong electric field below the GEM on light yield and saturation in a He:CF4 based Time Projection Chamber

Negative Ions SF_6

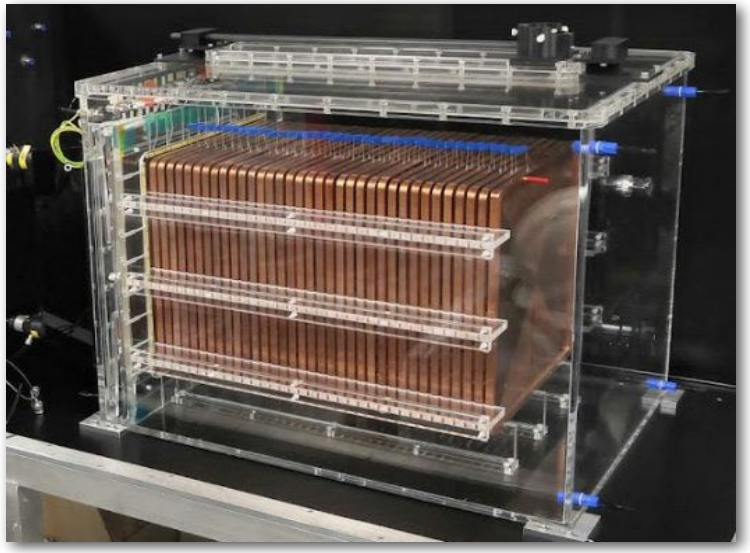
He:CF4:SF6 (59,39.4:1.6)

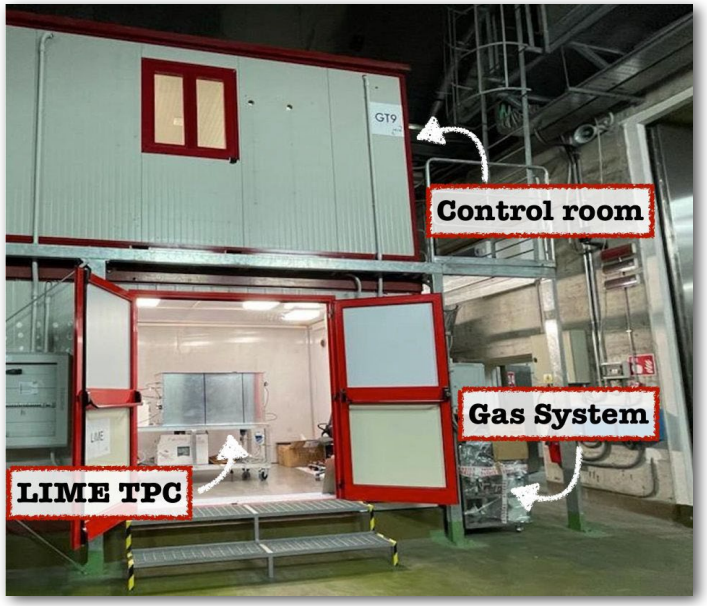
Reduce diffusion during drift by adding SF_6 (thus negative ions) to the gas mixture.

→ **Operation at 900mbar!**



LIME – Long Imaging ModulE





50L single-side TPC
Commissioning done in LNF in 2021/22

33x33 cm^2 standard triple GEM
- D/T1/T2: 500/2/2 mm – 1/2.5/2.5 kV/cm
- VGEM: 440V

Imaging:
- ORCA FUSION camera 2304x2304 pixel granularity 155 x 155 um^2
- 4 PMTs on the four edges
- Schneider Xenon lens (F=0.95, f=25.6mm)

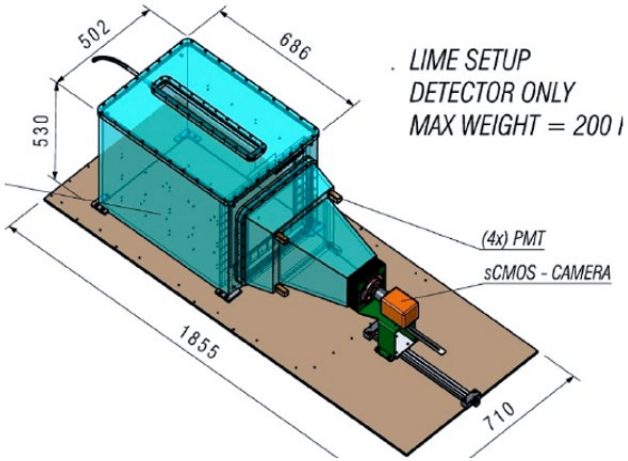
Work at 910 mbar (atmospheric)
- He/CF4 60/40 in recirculation mode (5+20 L/h fresh+recirculated)
- Oxygen+Nitrogen+radon filters

DAQ based on MIDAS
- Single USB 3.1 readout from camera
- Fast+slow VME ADCs for PMTs waveforms

Trigger
- >2 PMT over the threshold (FPGA-based)
- Save 300ms exposed camera picture

55Fe source stability/calibration
- At different drift distances
- Standard candle for intrinsic working parameters

$$\sigma_T \propto \sqrt{Z}$$

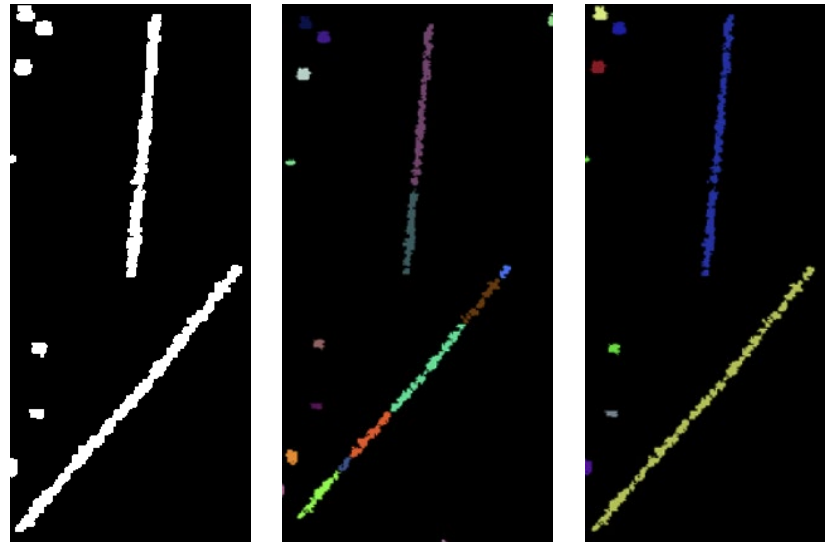


LIME – Long Imaging ModulE

Reconstruction:

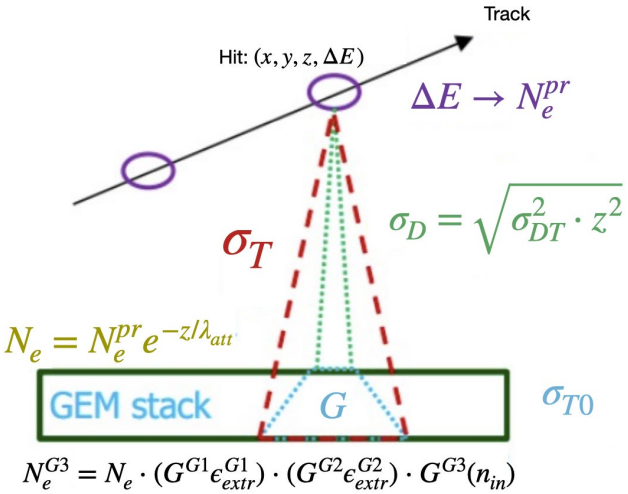
Directional iDBSCAN to detect cosmic-ray tracks for the CYGNO experiment – IOPscience
A density-based clustering algorithm for the CYGNO data analysis - IOPscience

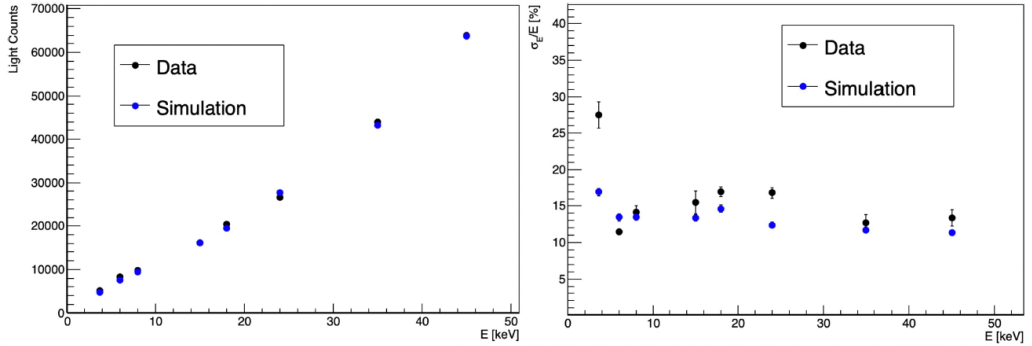
- Based on the iDBscan algorithm + Directional cluster search

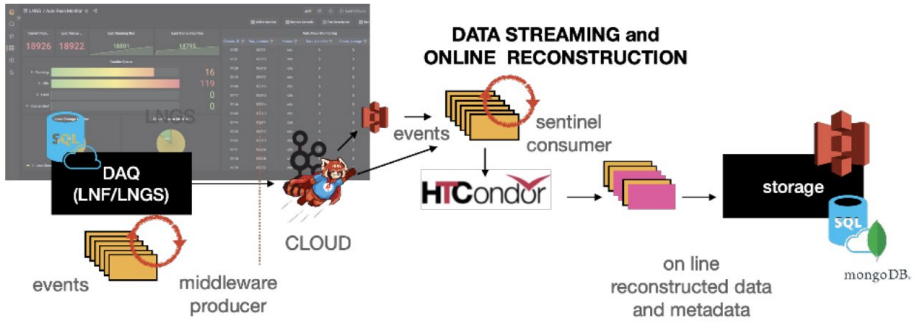


Digitization:

- Fast simulation to mimic the response function without a full simulation







CYGNO data managing

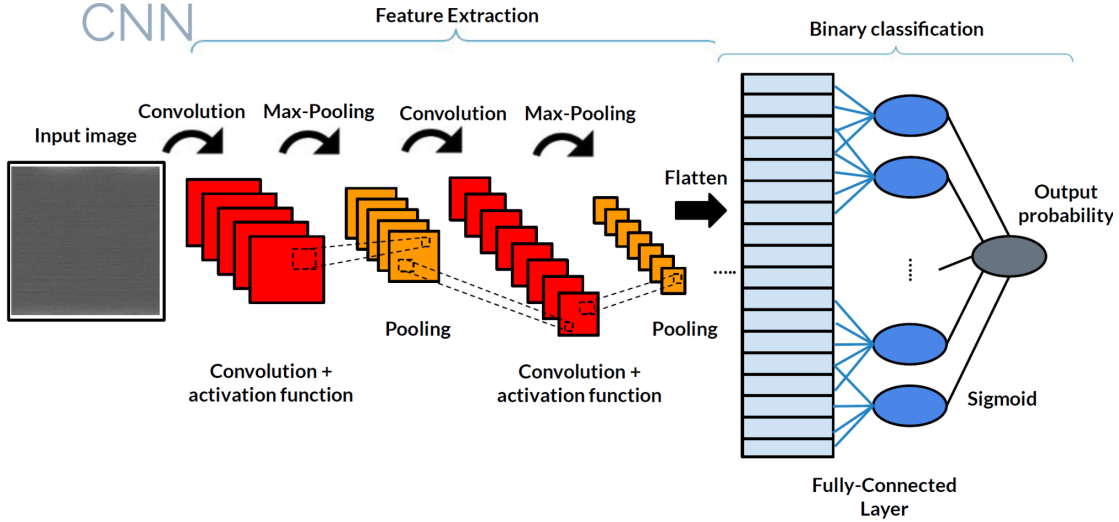
Data handling of CYGNO experiment using INFN-Cloud solution (epj-conferences.org)

- Beta tester of the INFN-Cloud project
- Data streamlined on cloud, where it is reconstructed and stored
- **Thoughput ≈ 3 Mb/s**
- **Reconstruction queue 40CPUs**

CYGNO_04 TDAQ

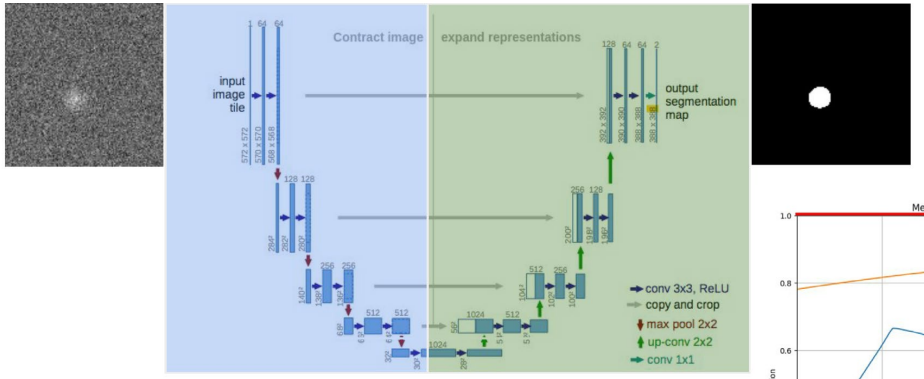
1° Level Trigger -Trained CNN classificator

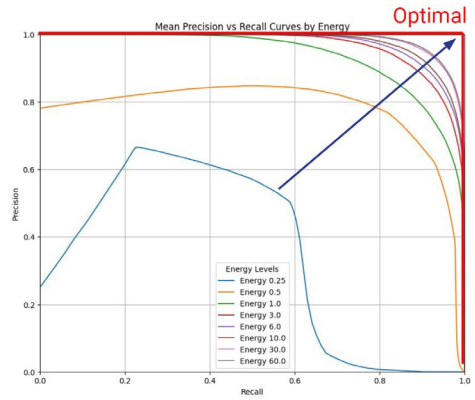
Individuate for every image if it contains signals or not



2° Level Trigger+Reco – U-Net CNN

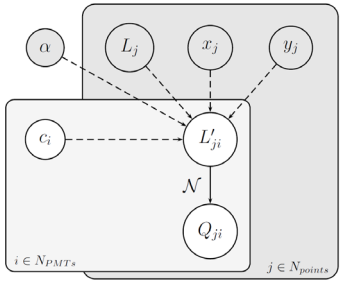
→ Signal/Noise classification on the pixels basis





3° Level PMT association – Bayesian FIT

Associate each PMT waveform to the correct camera cluster



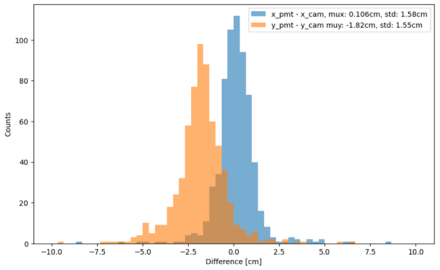
LIME tested

Fixed x_j, y_j, L_j !

$$p(\{x_{ij}\}\,|\,\theta) = \prod_{j=1}^{N_{points}} \prod_{i=1}^{4} \mathcal{N}(\{x_{ij}\}\,|\,L'_{ij}(\theta))$$

With:

- $L'_{ji} = c_i \frac{L_j}{R_{ij}^{\alpha}}$
- $R_{ji} = \sqrt{x_{ji}^2 + y_{ji}^2 + z^2}$
- $\alpha = 4$



1to1 association

$\sigma_{X/Y} \approx 1.5$cm

Expected Pipeline for commissioned CYGNO_04

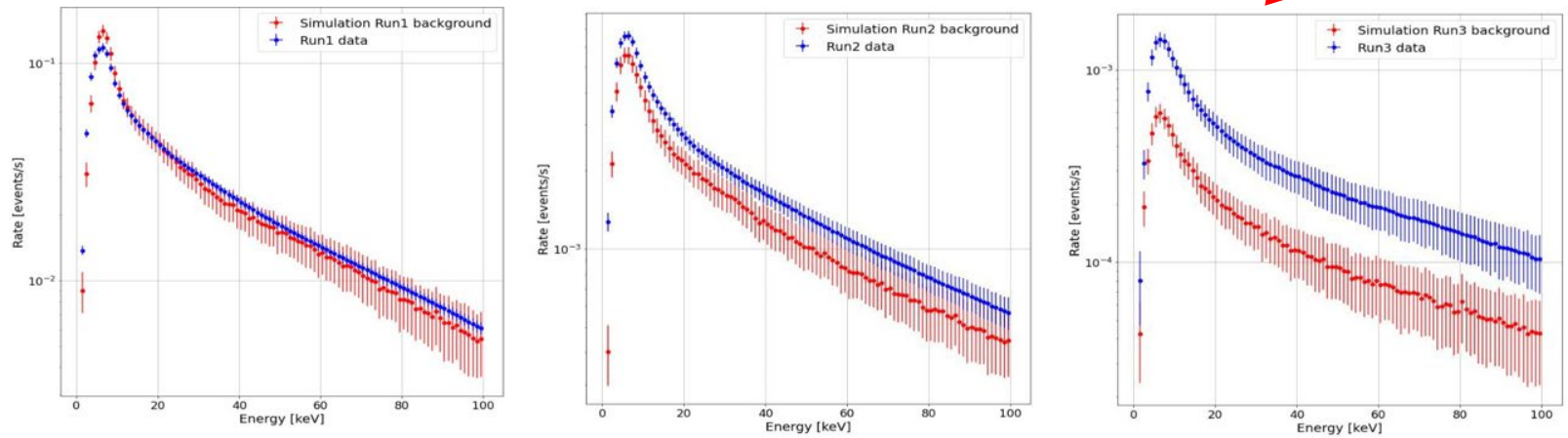
- Reduce throughput
- Imporved reconstruction performance
- Possible automatic 3D reco

LIME performance

- **Prove we can operate such a detector underground**
- **Study and improve out MC chain**

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

Run1 ***Run2 - Run3*** ***Run4***



Main Suspect:
Alpha Contamination by r adon

External background consistent with MC
With increasing shield, we highlight a non-expected background.