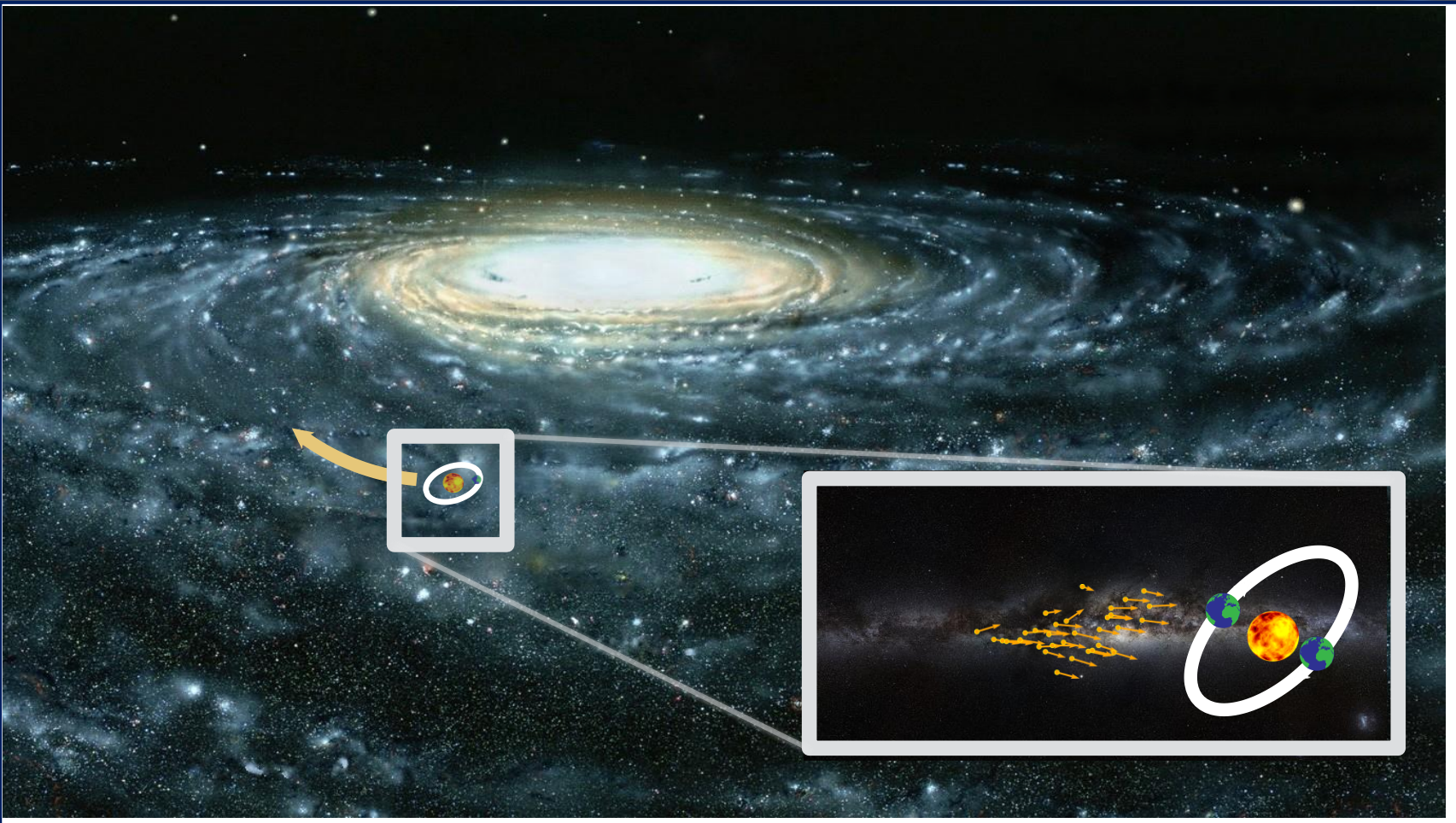
THE CYGNO EXPERIMENT

Davide Fiorina

Gran Sasso Science Institute & INFN LNGS

On behalf of the CYGNO collaboration

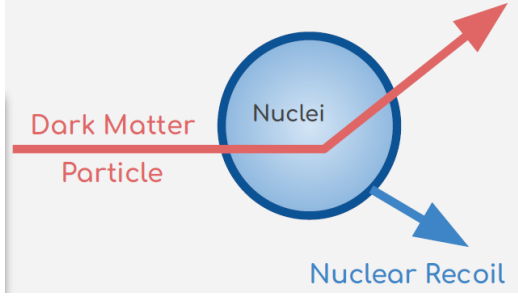
It’s a Dark Universe



Assumption

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

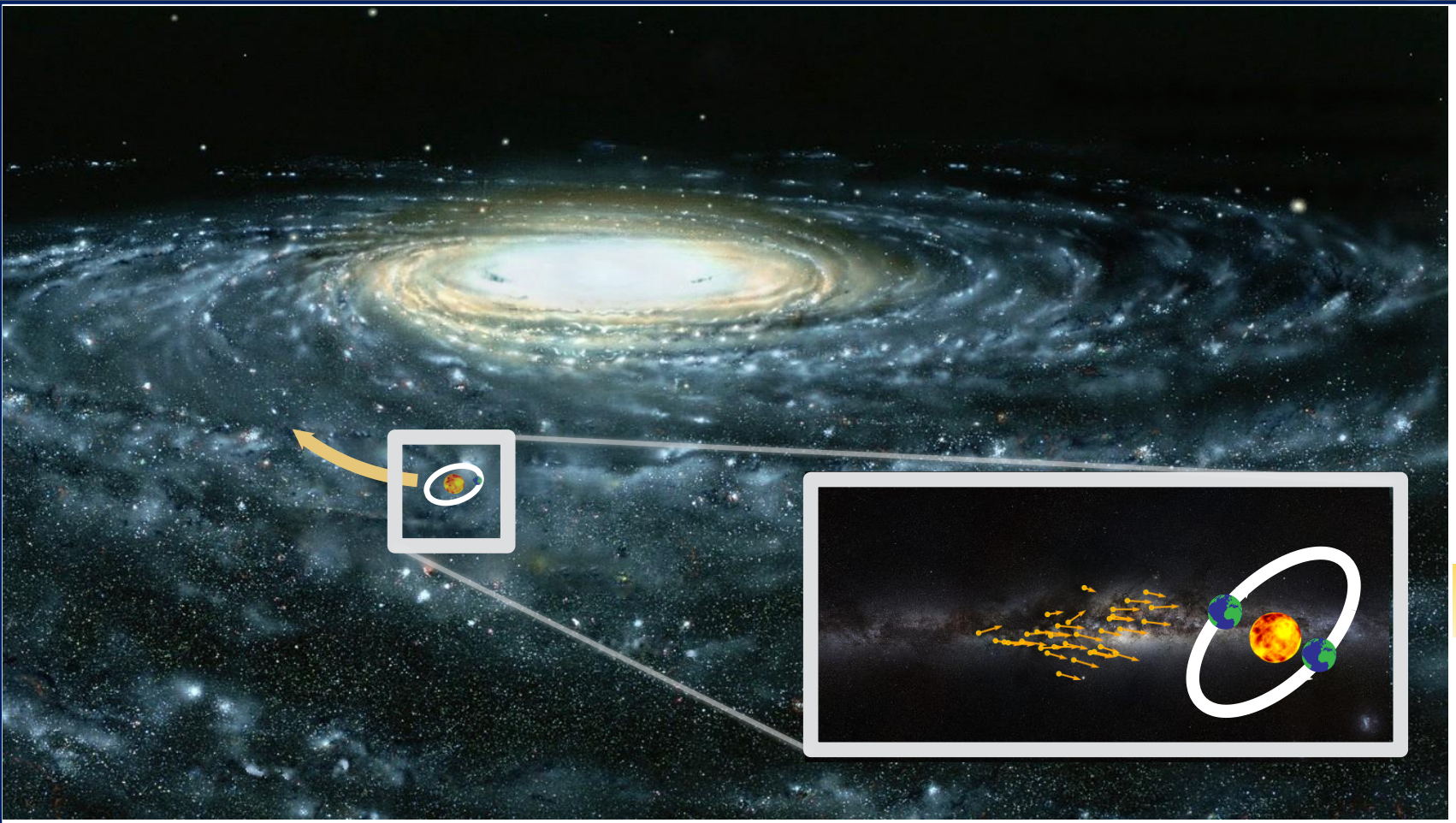
- $SM + \chi \rightarrow SM + \chi$
- **Direct detection** of nuclear recoil



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

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

It’s a Dark Universe



Assumption

→ Dark Matter is made of
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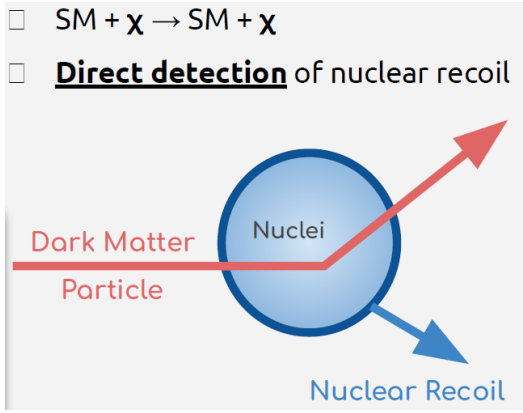


Directionality of the DM flux

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

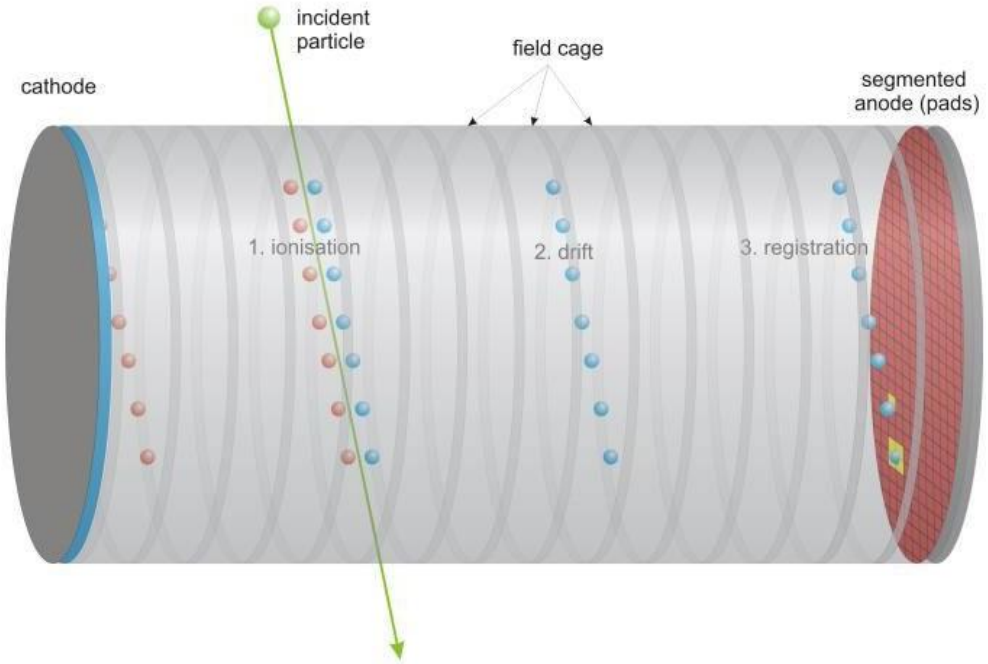
ENERGY → Excess would result in **falling exponentials**.

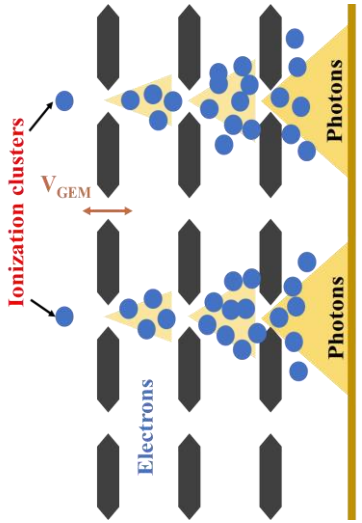
TIME → Results in a **few % annual modulation.**

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

CYGNO paradigm

He/CF_4 60/40





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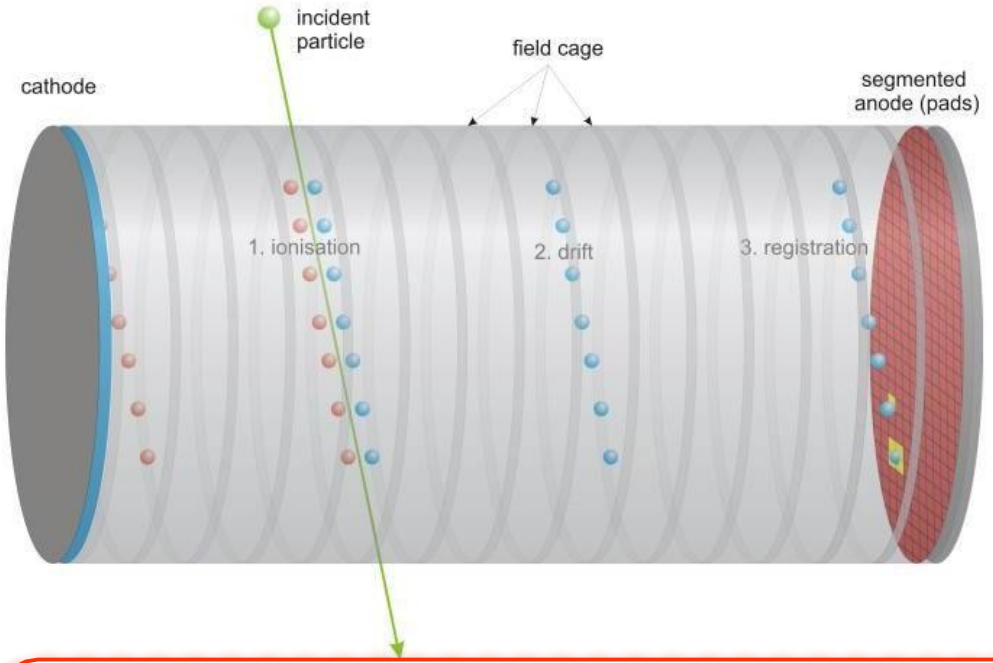
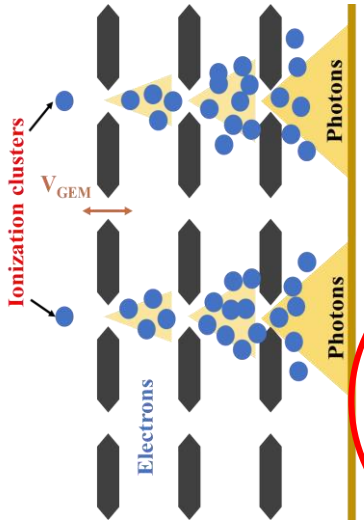
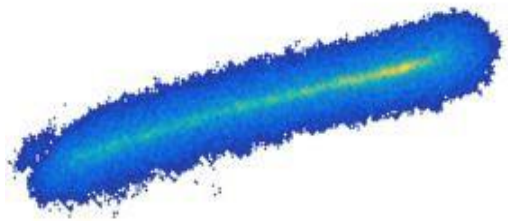




With the high granularity of the camera, we measure **energy** + **X & Y coordinates**



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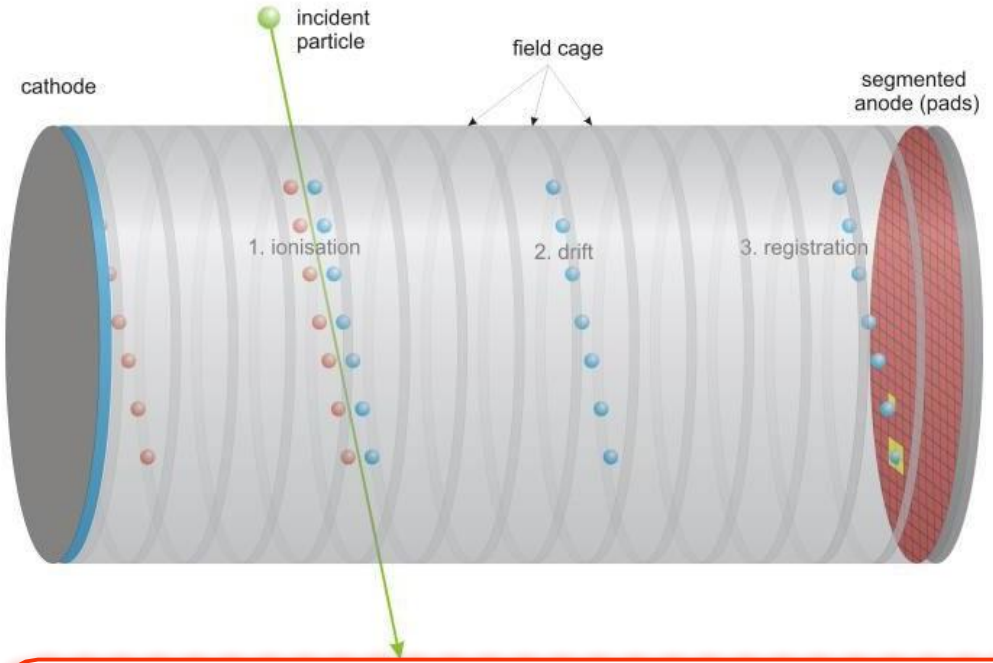

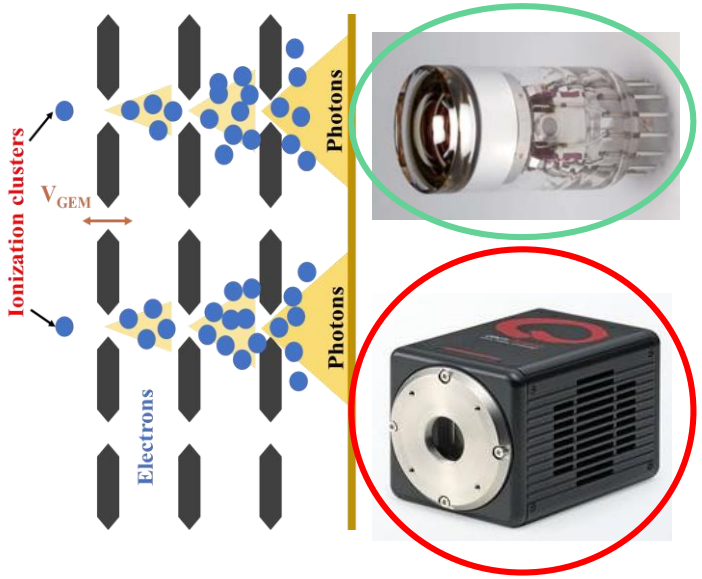

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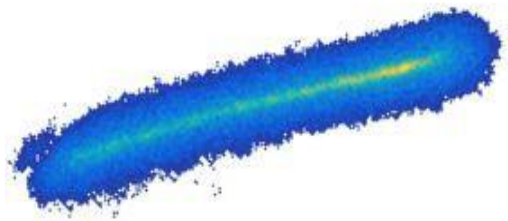
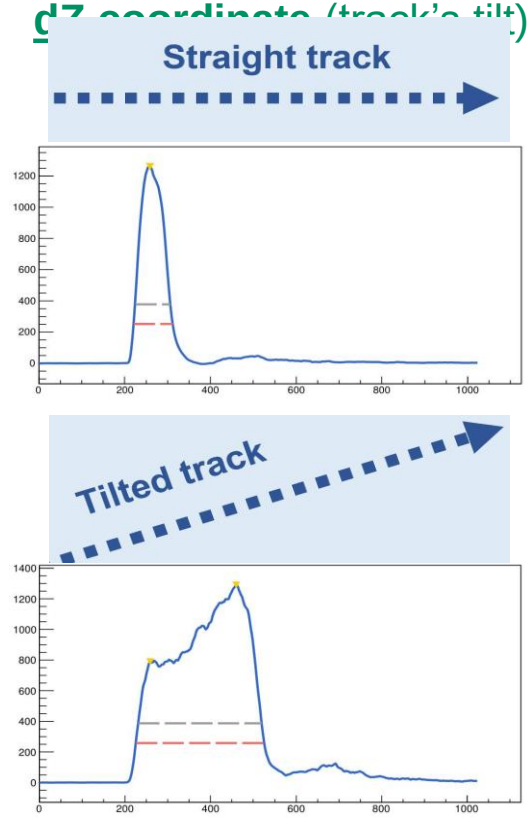


1.Independent **energy** measurement.

2.Electrons **times of arrival**

⇒

dZ coordinate (track's tilt)



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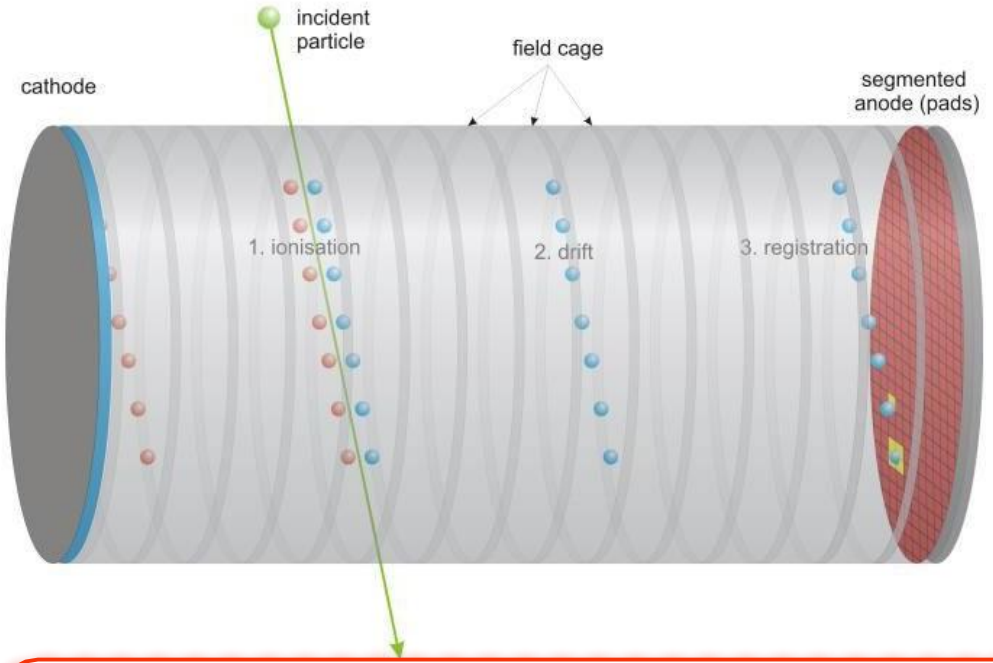

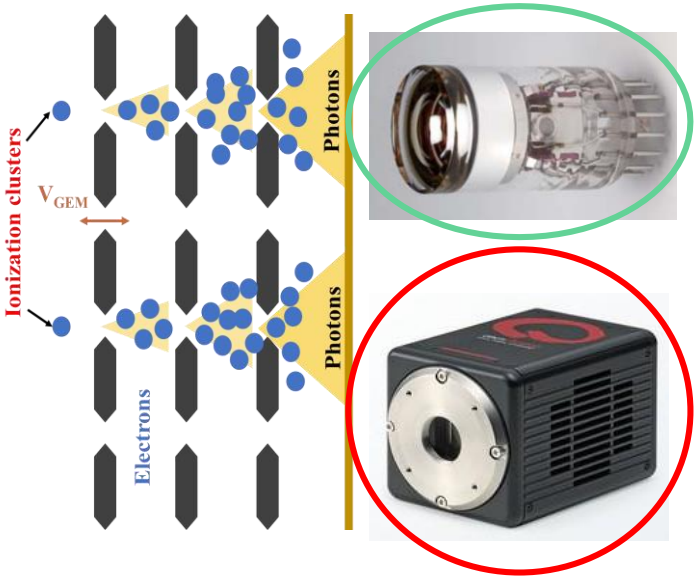

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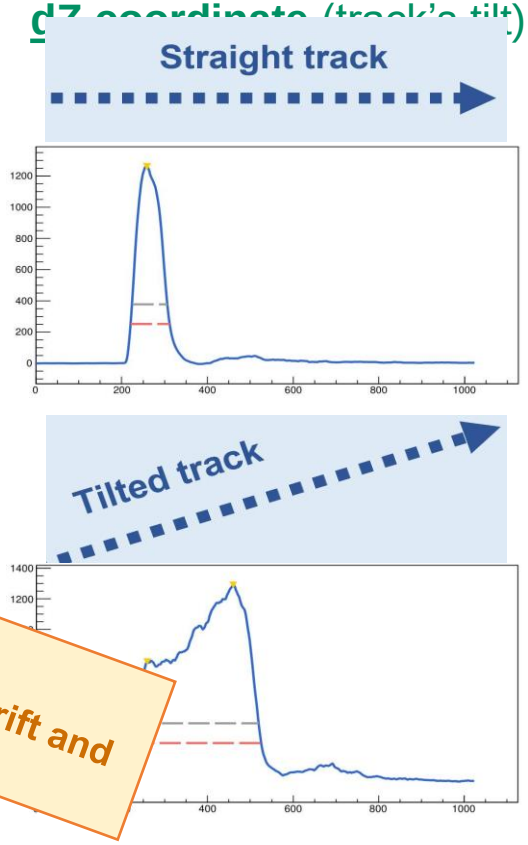

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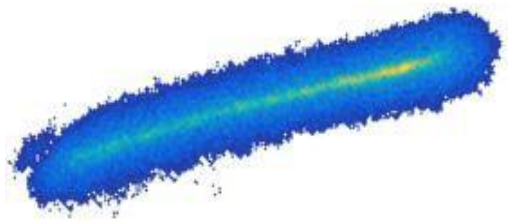
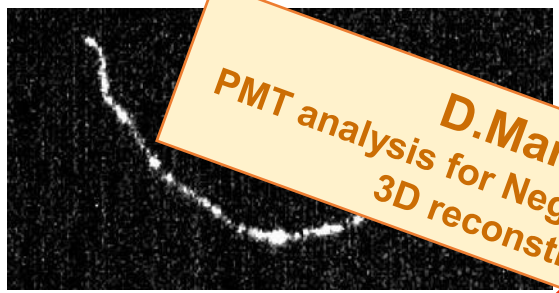
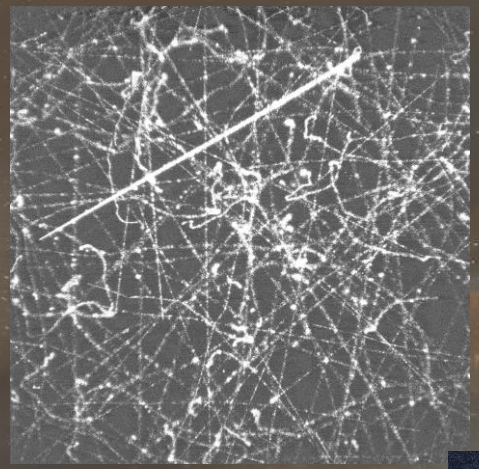
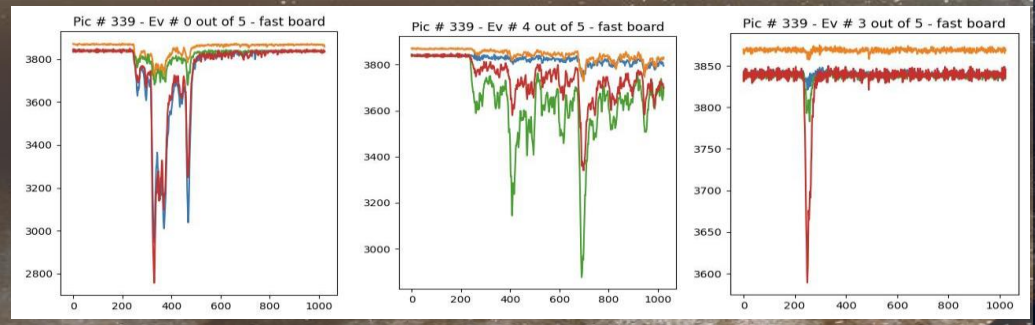


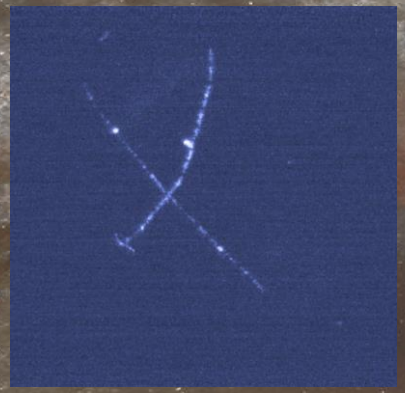


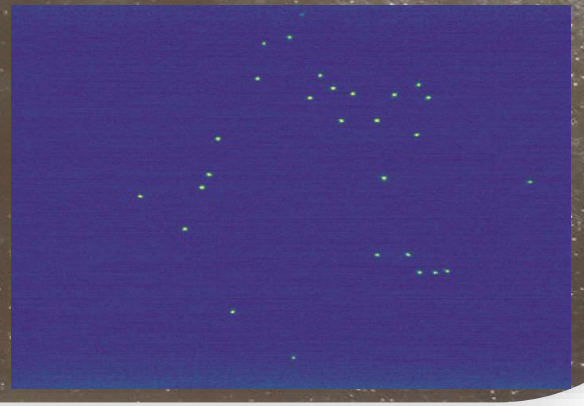
D.Marques
PMT analysis for Negative Ion Drift and 3D reconstruction

Detector PoV









CYGNO roadmap

PHASE 0: R&D and prototypes

2015/16 ROMA1 → 2017/18 LNF → 2019/24 LNF/LNGS

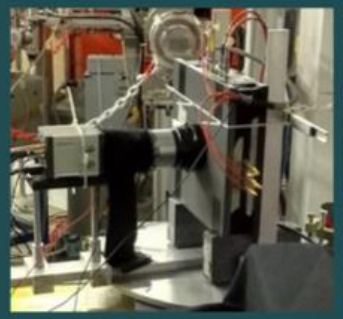
PHASE 1: 1 m³ Demonstrator

2024/27 LNF/LNGS

PHASE 2: 30 m³ Experiment

2027… LNGS

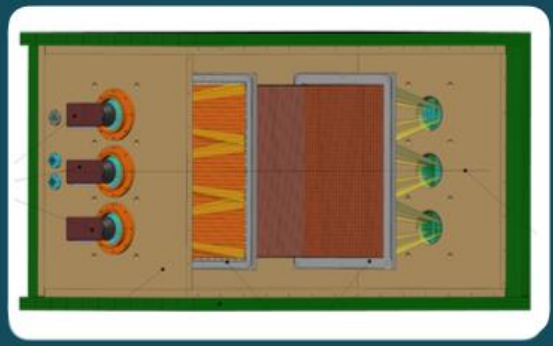
ORANGE → LEMON → LIME → CYGNO_04 → CYGNO_30



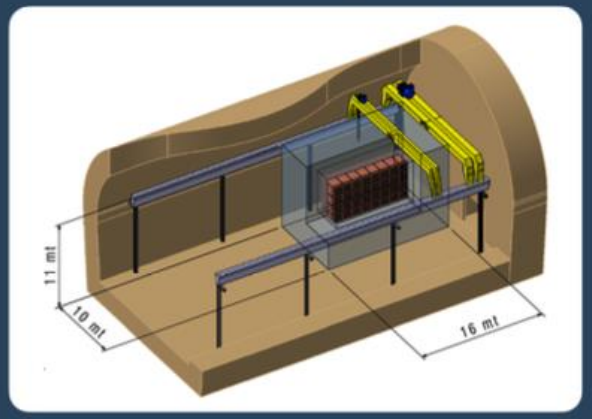
- 1 cm drift

- 3D printing
- 20 cm drift

- 50 cm drift
- underground tests
- shielding

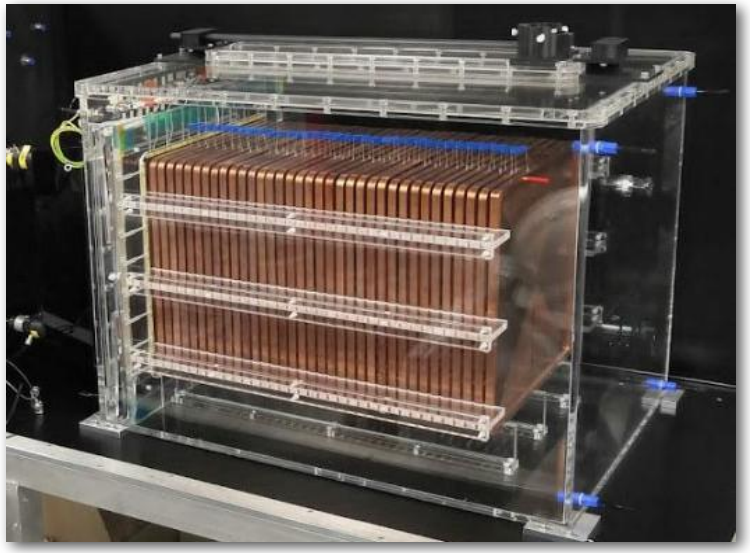


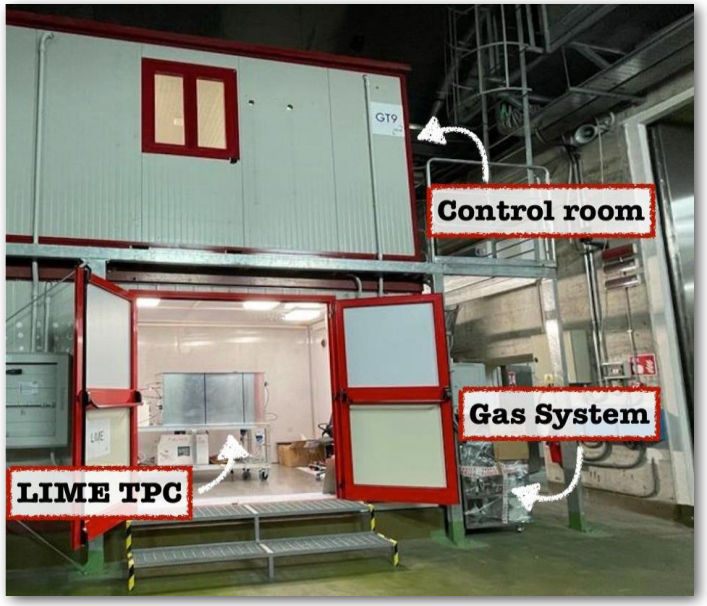
- background
- materials test, gas purification
- scalability



- Physics research

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)

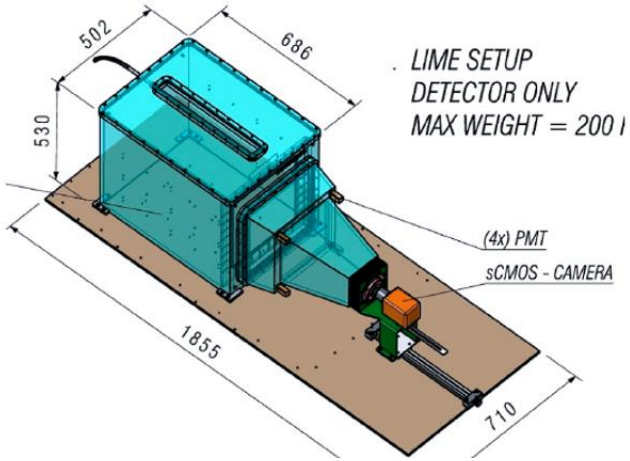
Work at 910 mbar (atmospheric)
- He/CF4 60/40 in recirculation mode (5+20 L/h fresh+recirculated)
- Oxygen+Nitrogen+Radon filters

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

$$\sigma_T \propto \sqrt{z}$$

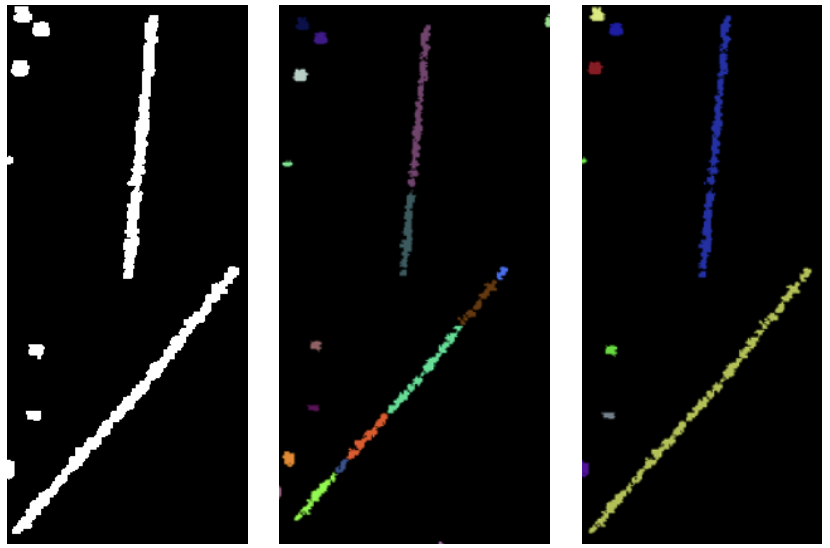


LIME – Long Imaging ModulE

Reconstruction:

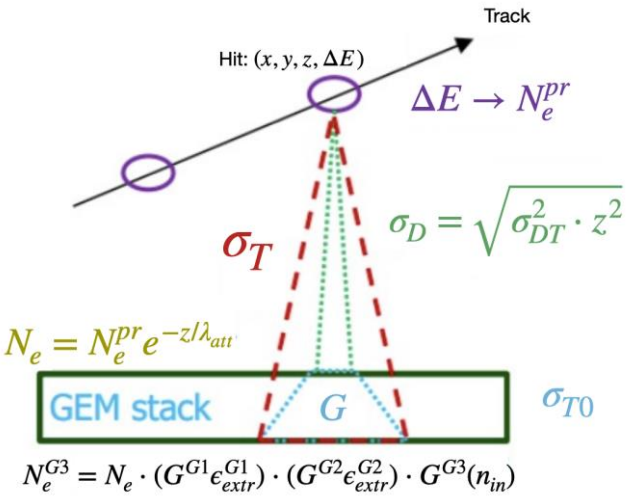
Directional iDBSCAN to detect cosmic-ray tracks for the CYGNO experiment – IOPscience
A density-based clustering algorithm for the CYGNO data analysis - IOPscience

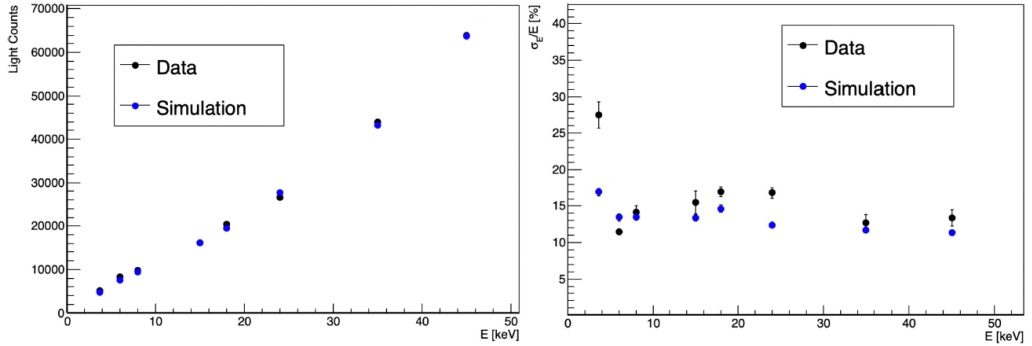
- Based on the iDBscan algorithm + Directional cluster search

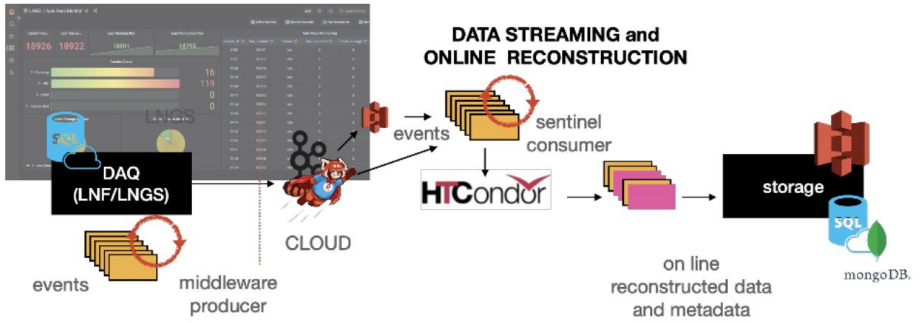


Digitization:

- 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)

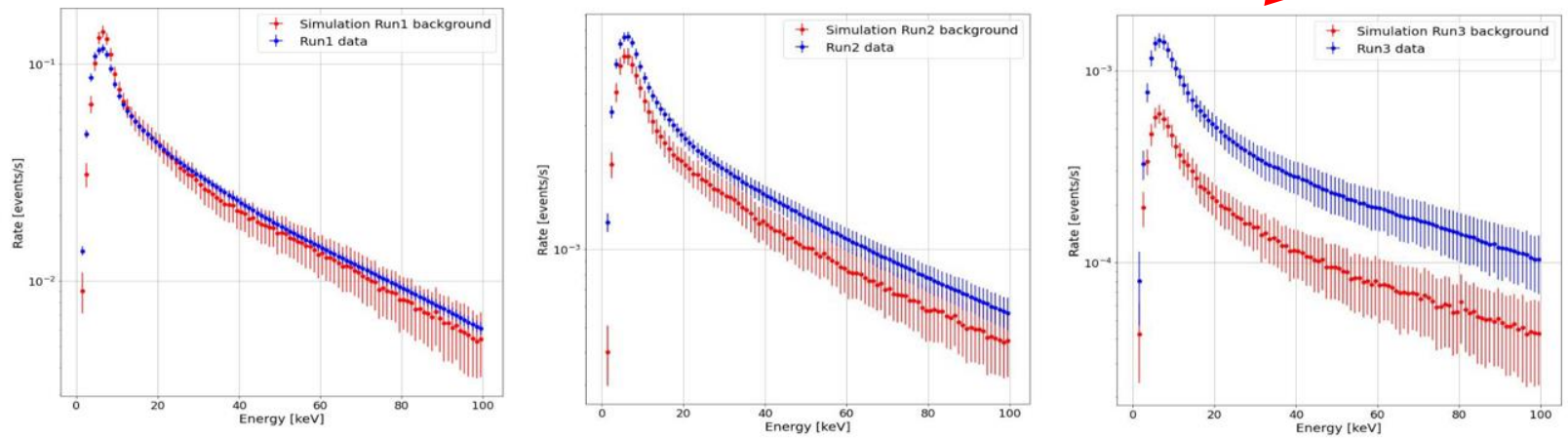
- Beta tester of the INFN-Cloud project
- Data streamlined on cloud, where it is reconstructed and stored
- **Thoughput ≈ 3 Mb/s**
- **Reconstruction queue 40CPUs**

LIME performance

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

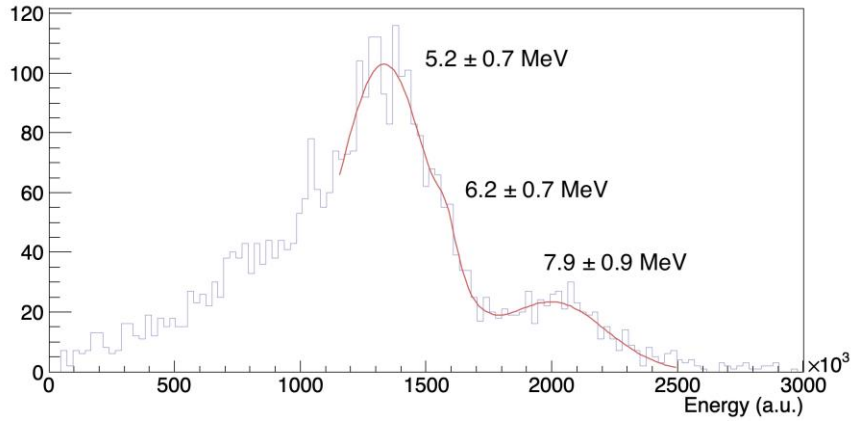
Phase	Shielding	GEM V [V]	# pictures	Live time [s]	Rate PMTs [Hz]
Run 1	None	420	285665	175627	30
Run 2	4 cm Cu	440	297992	191382	3.5
Run 3	10 cm Cu	440	171579	191471	1.6
Run 4	+40 cm H2O	Great external neutron suppression ⇒ *Under analysis…*			

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



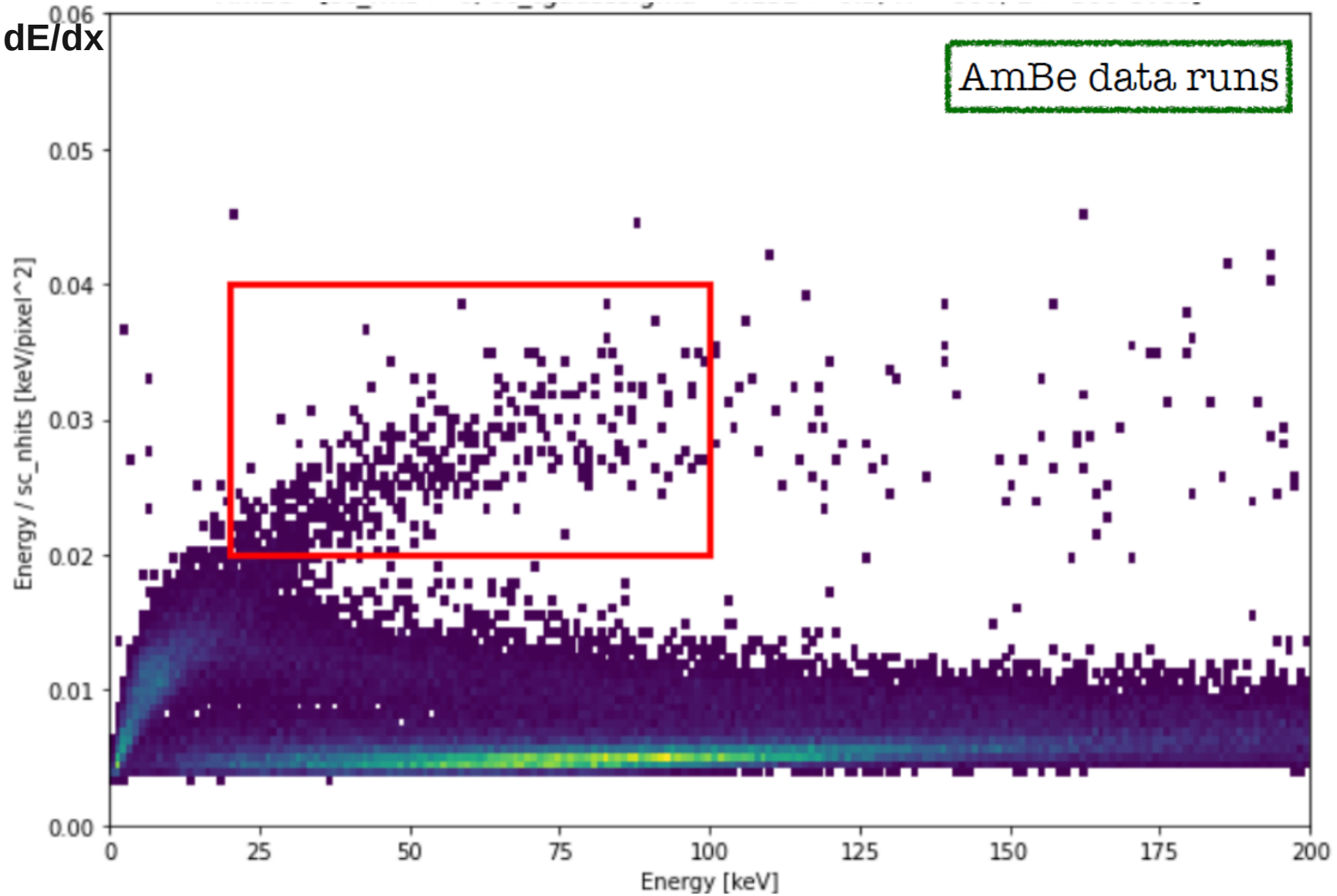
External background consistent with MC
With increasing shield, we highlight a non-expected background.

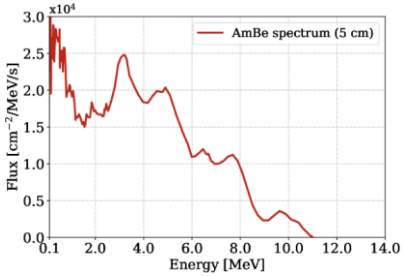
Main Suspect:
Alpha Contamination by Radon



Background Rejection

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





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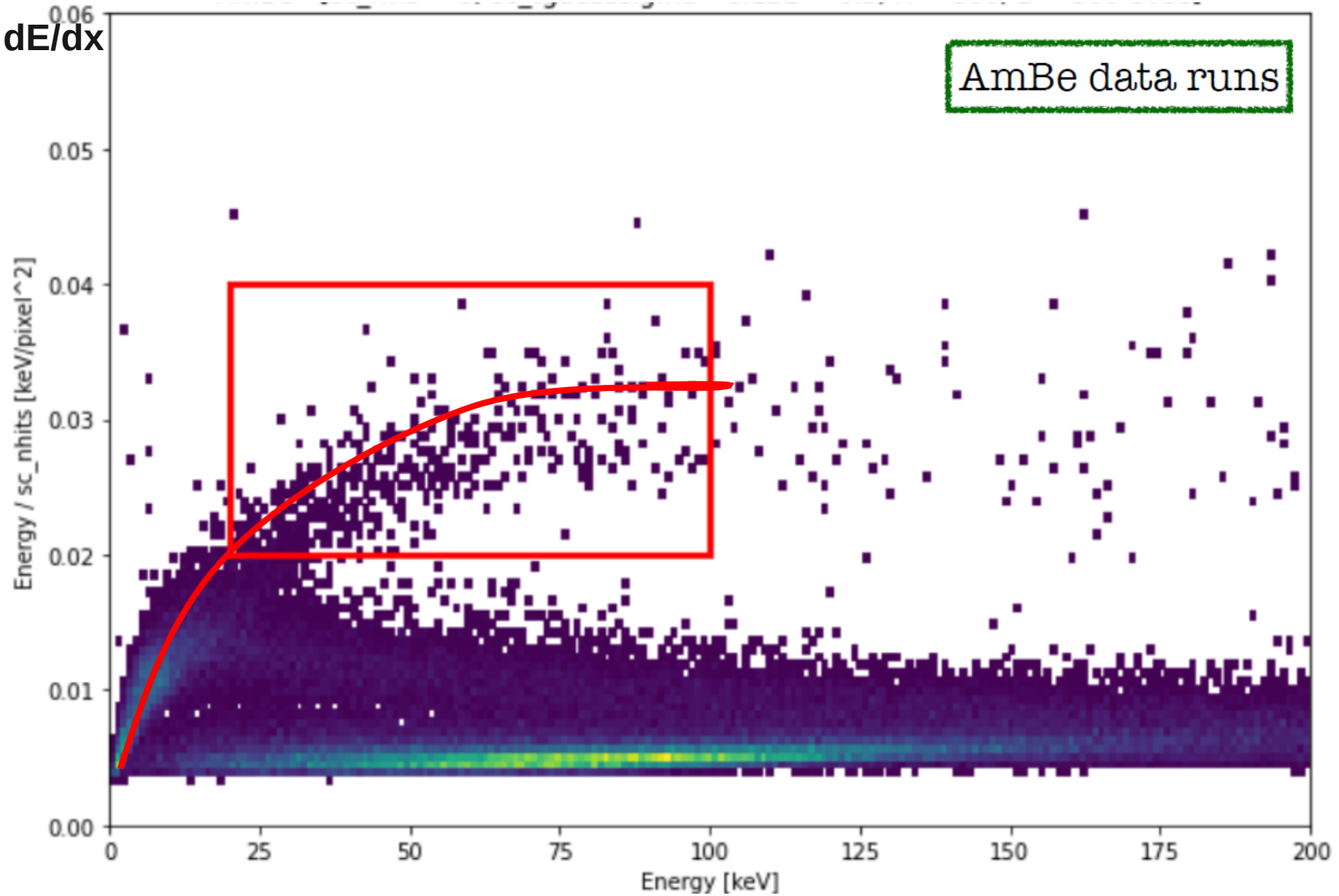
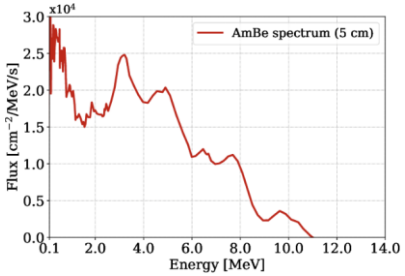
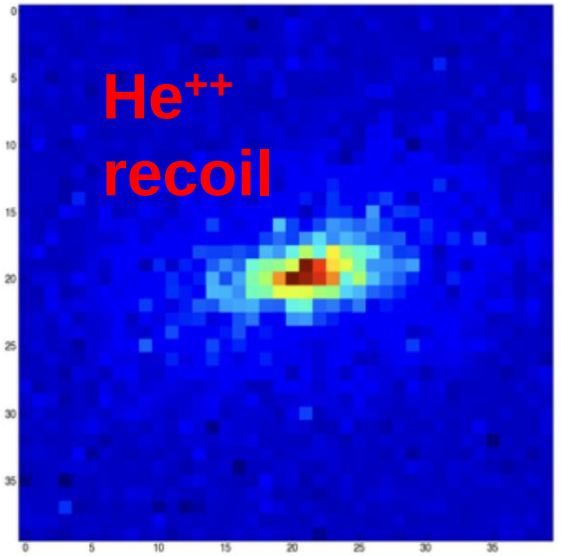




Nuclear Recoils



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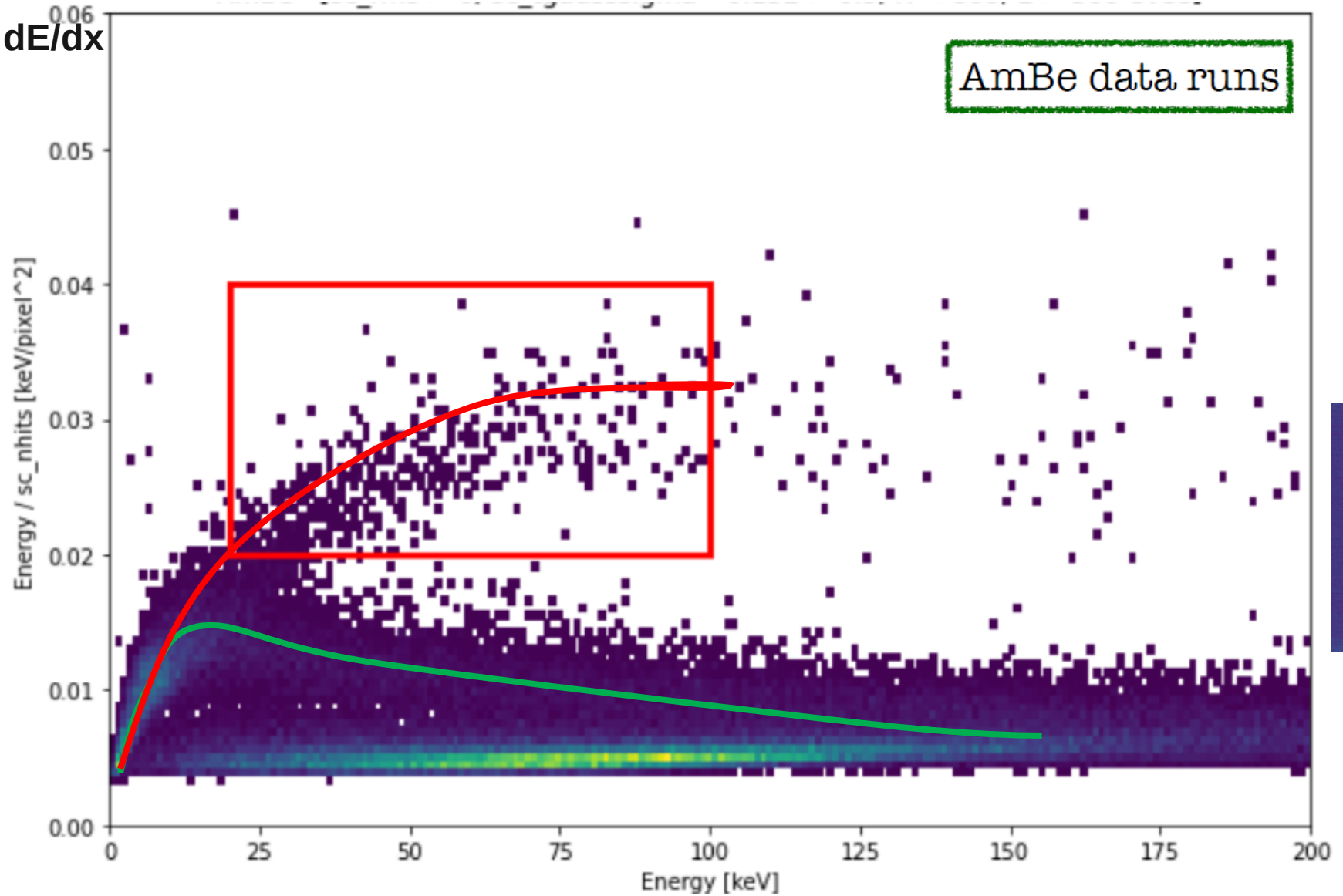
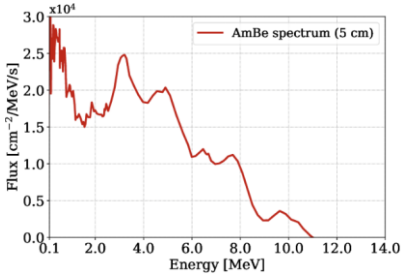
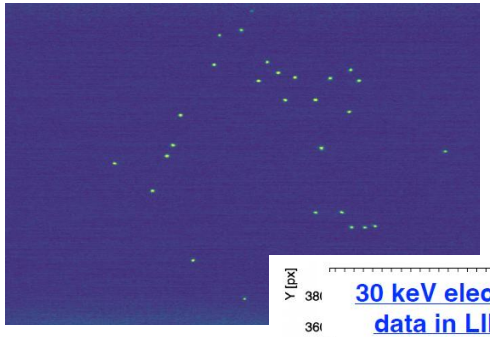
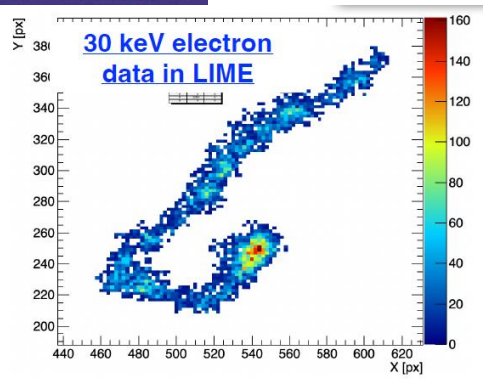




Electron Recoils

Nuclear Recoils





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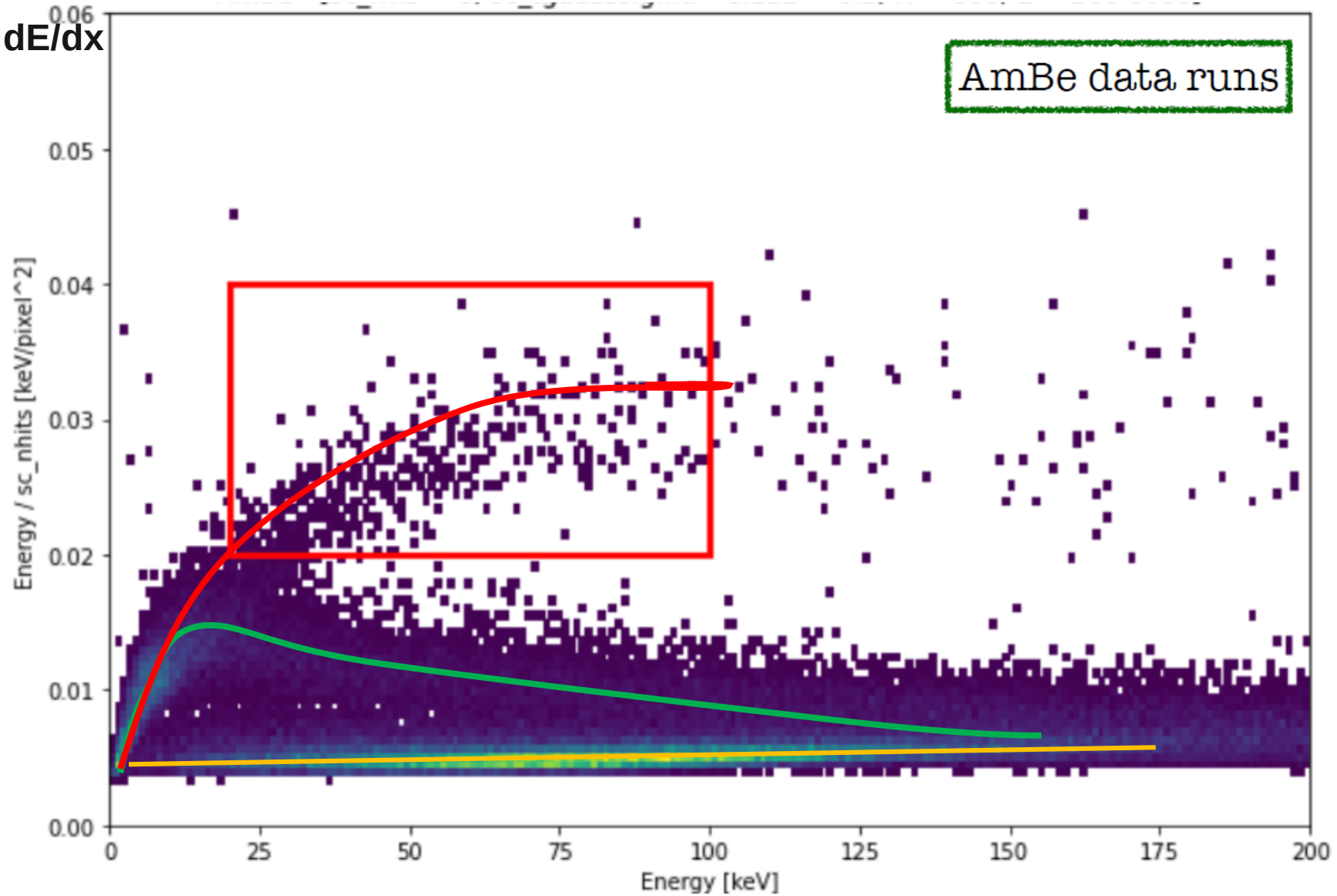
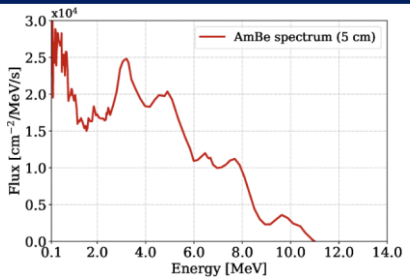


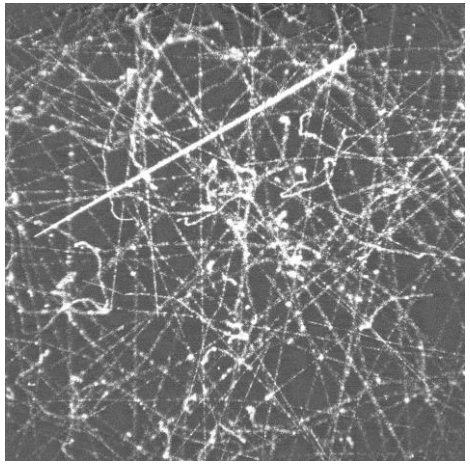


MIP

(muons and high energy electrons)

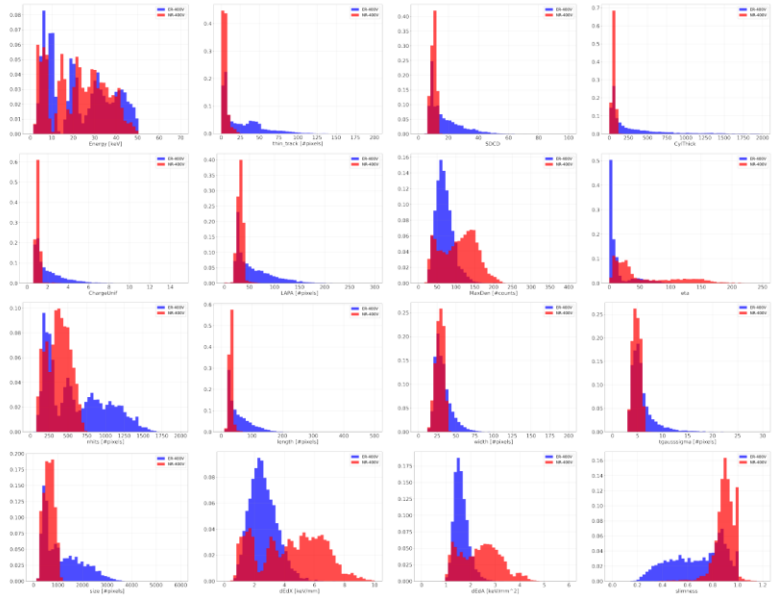
Electron Recoils

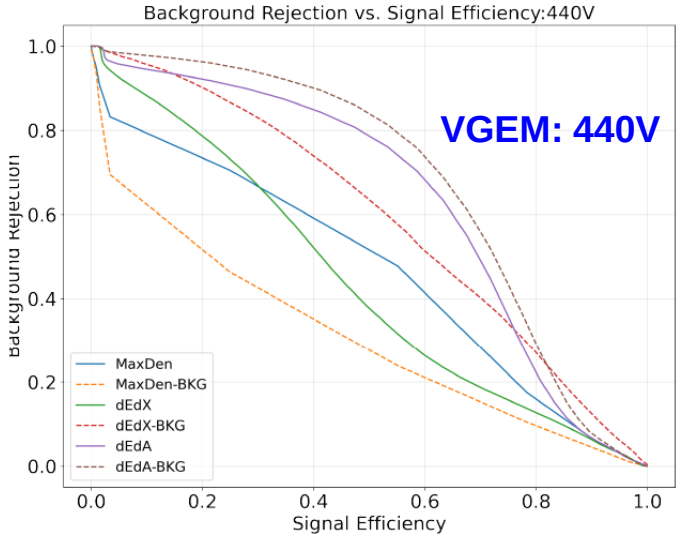
Nuclear Recoils

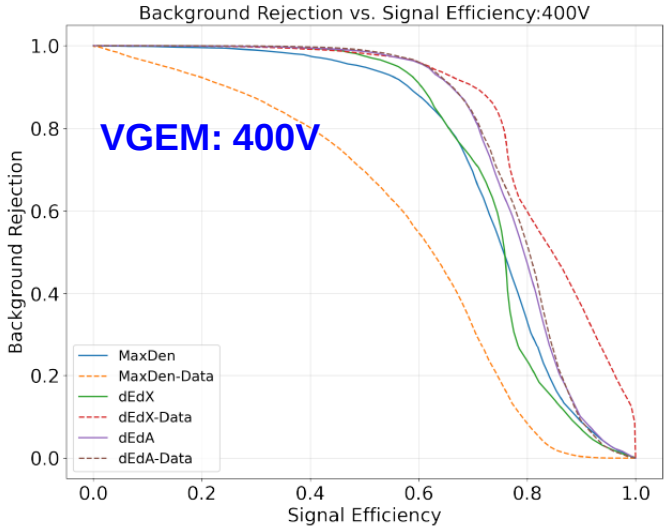


Background rejection

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







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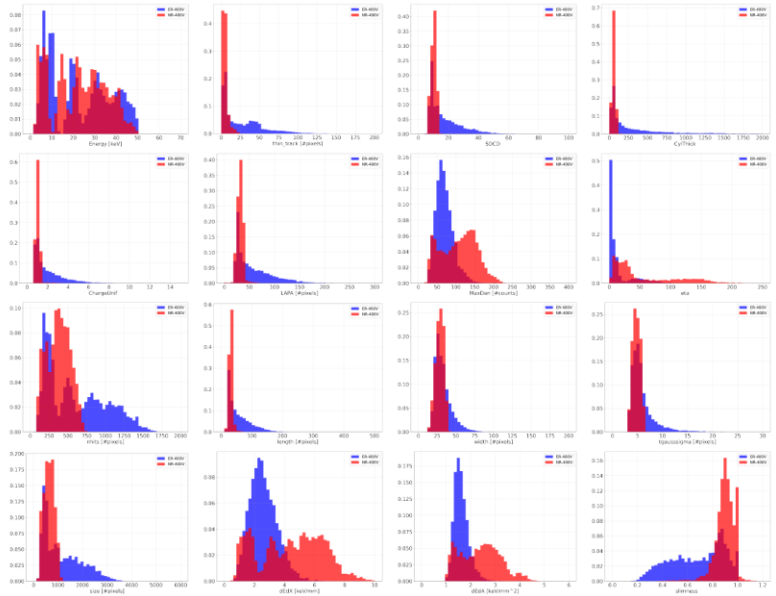
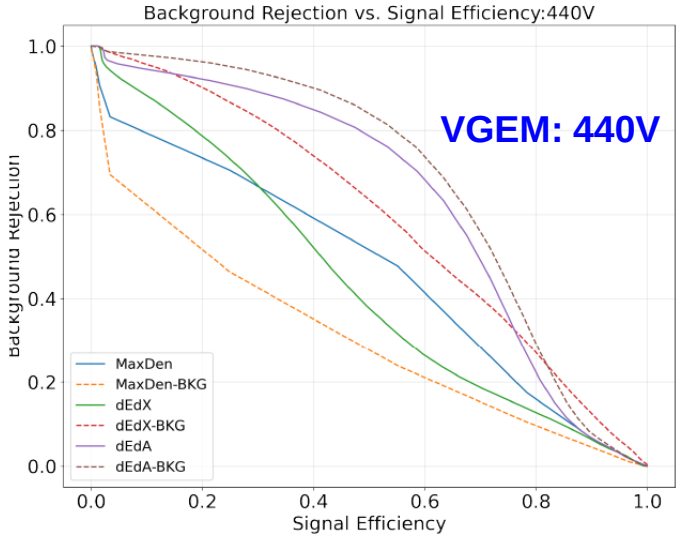
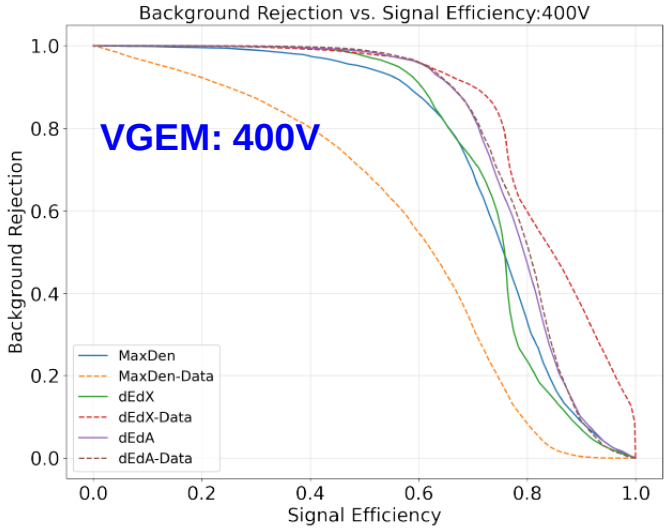






G. Dho

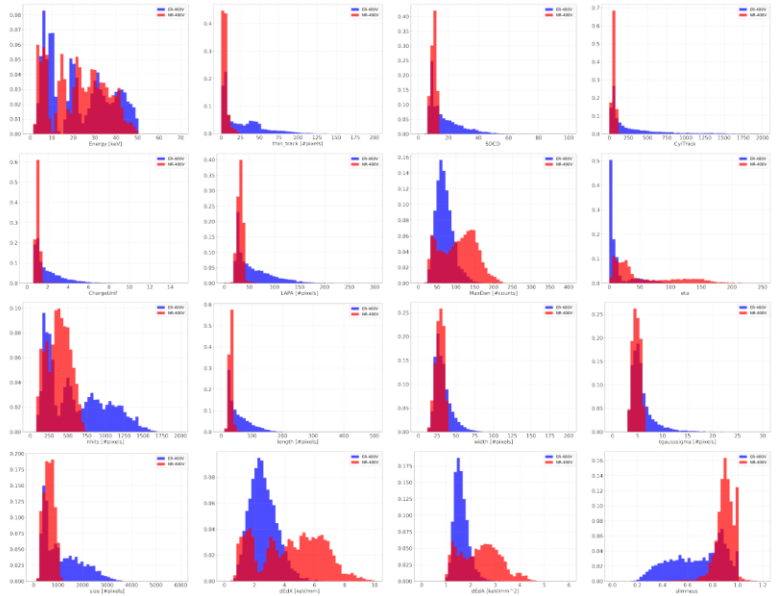
Impact of a strong electric field below the GEM on light yield and saturation in a He:CF4 based Time Projection Chamber

Saturation is clearly present in LIME!

And it affects the ER/NR discrimination

Background rejection

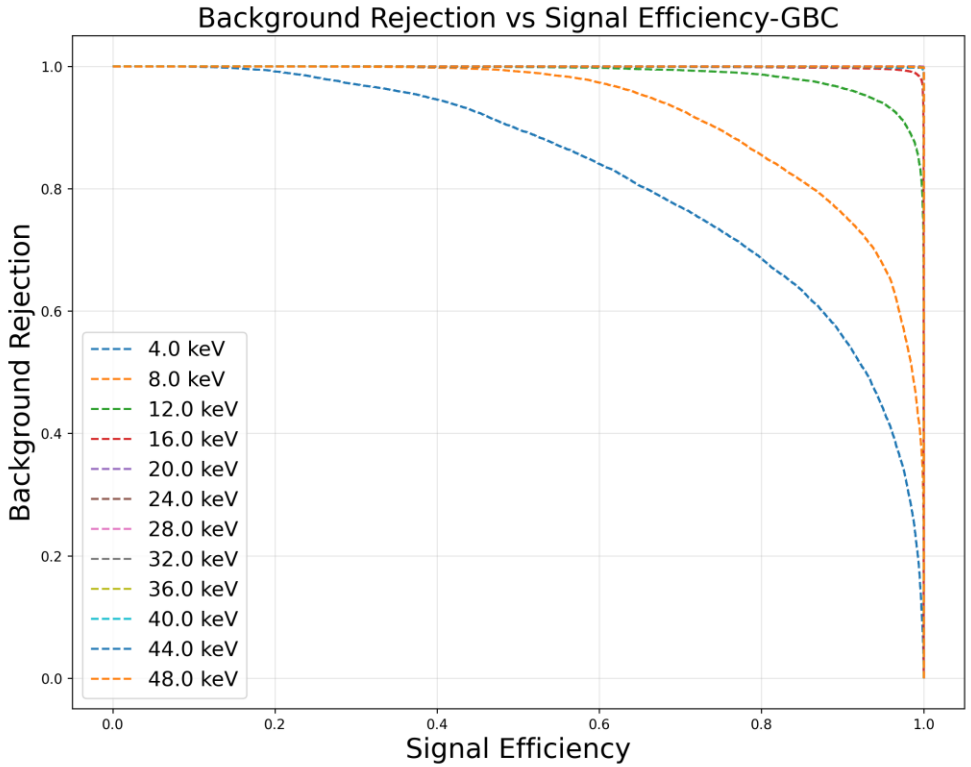
We have access to many variables related to the signal shape!

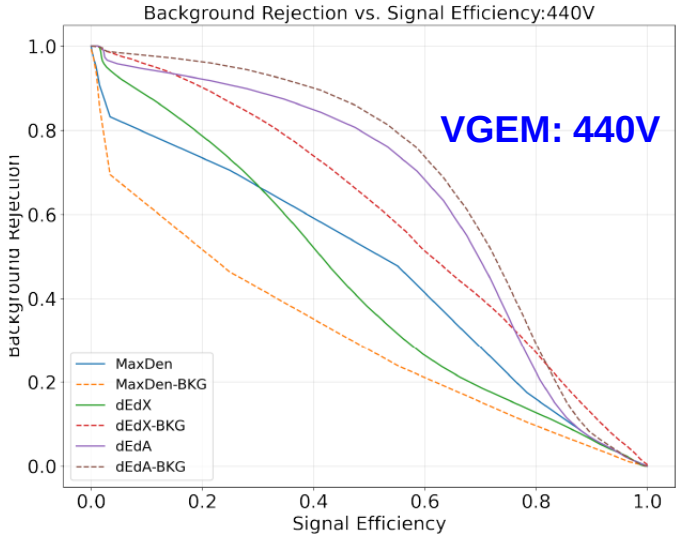


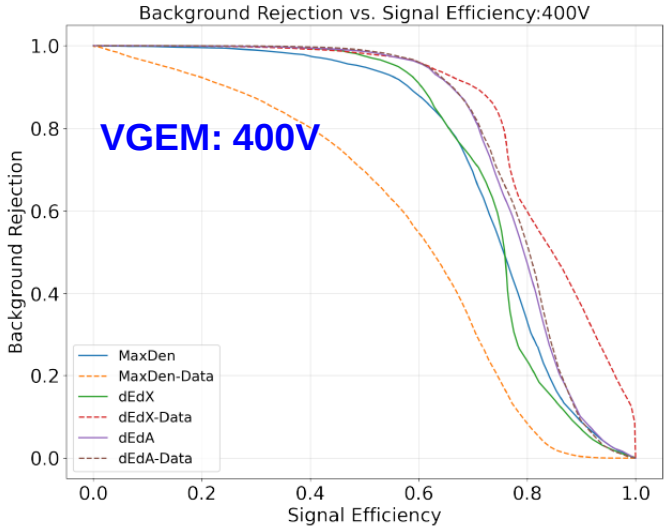
Convolution Neural Network

Atul Prajapati Thesis

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







G. Dho

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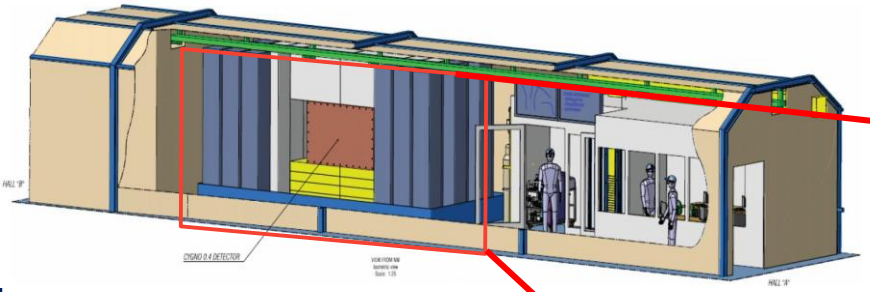
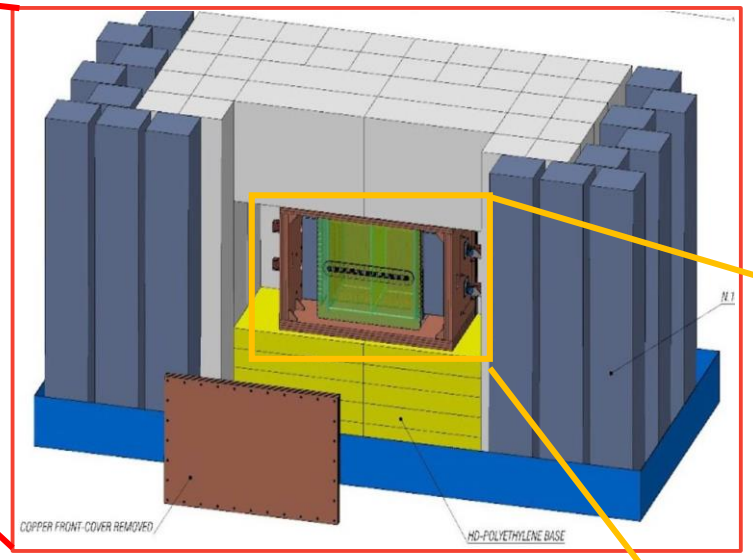
CYGNO_04

Scalability of the Technology

Radiopure materials

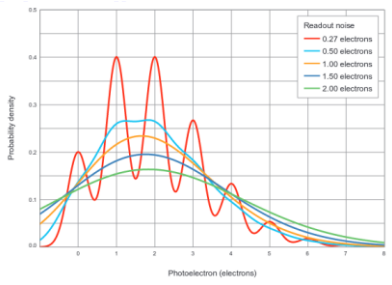


LNGS Hall F



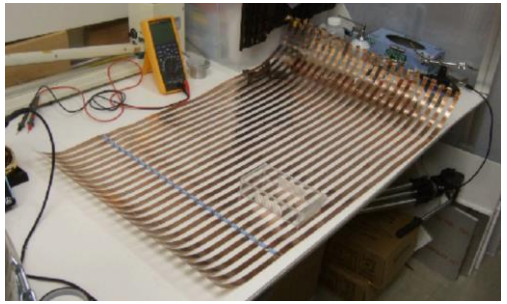
0.4m3 common cathode TPC

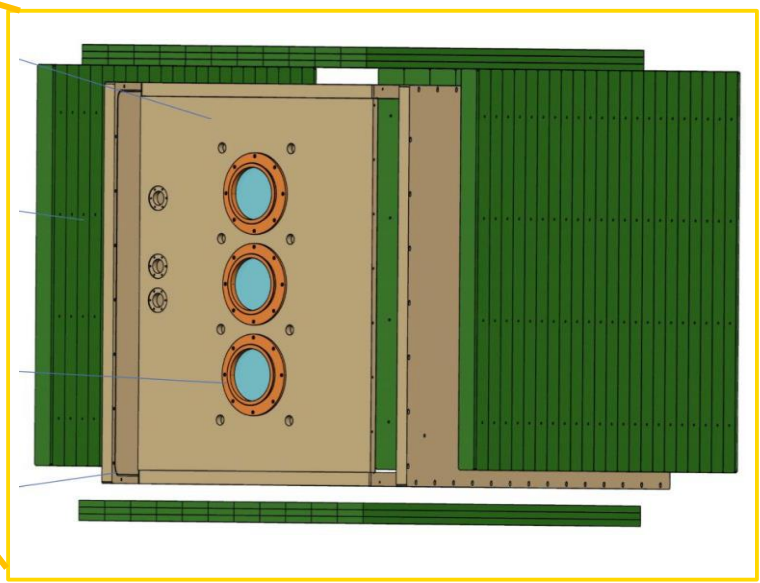
- 3 ORCA QUEST2 (next-gen) per side
- 8 PMTs per side
- 4+6cm copper shielding (radiopure+trad
- 40cm of water



Throughput expected ≈20Mb/s
Computational resources very demanding

Feasibility for a larger scale detector based on multiple CYGNO_04 modules

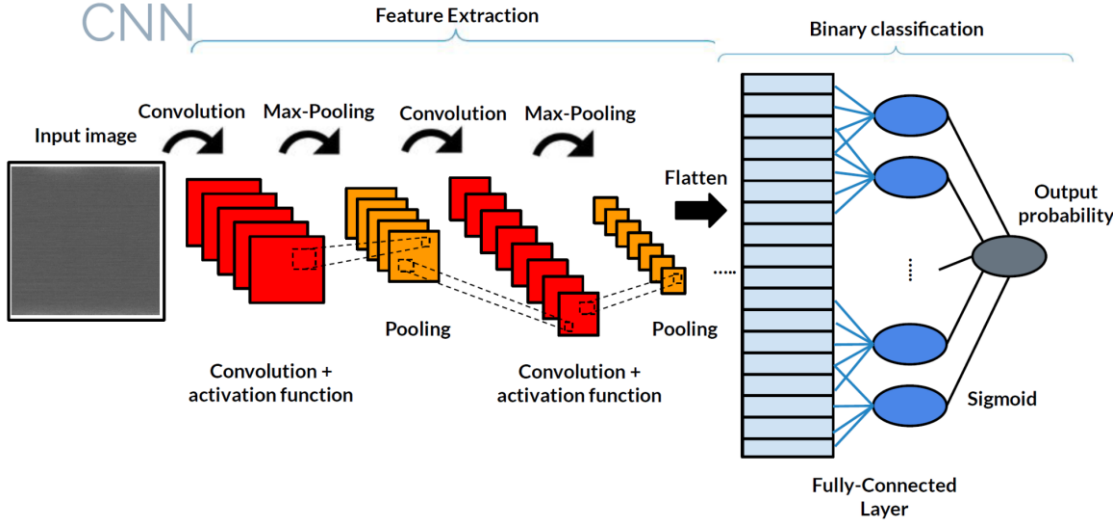




CYGNO_04 TDAQ

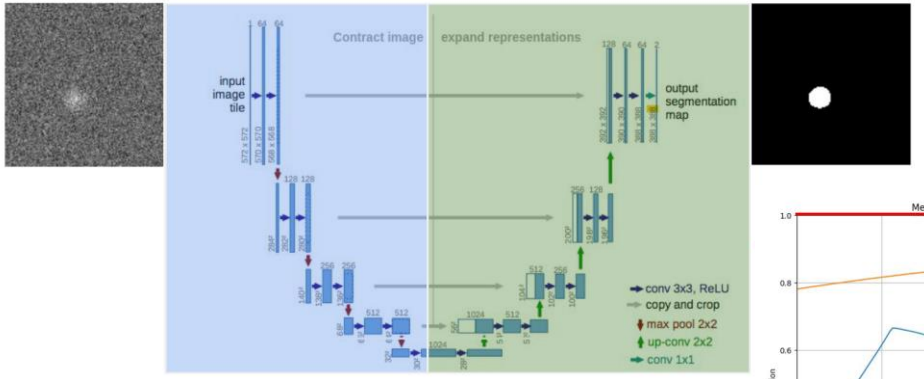
1° Level Trigger -Trained CNN classificator

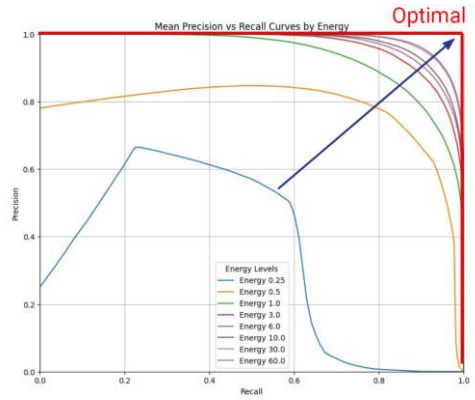
Individuate for every image if it contains signals or not



2° Level Trigger+Reco – U-Net CNN

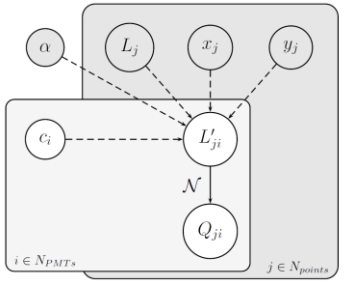
→ Signal/Noise classification on the pixels basis





3° Level PMT association – Bayesian FIT

Associate each PMT waveform to the correct camera cluster



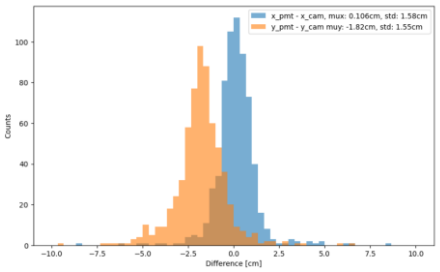
LIME tested

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

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).
  - Through nuclear recoil direction, solar neutrinos can be discriminated, and unambiguous confirmation of DM is possible.
  - Acceptable Solar neutrino (CNO cycle) for CYGNO_30 (S.Torelli thesis)
- 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

R&D activities ongoing

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

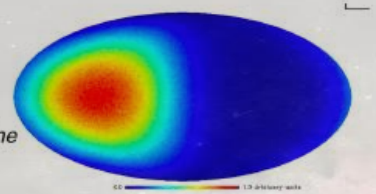
Capability to reject isotropy

Dive into the Neutrino Fog

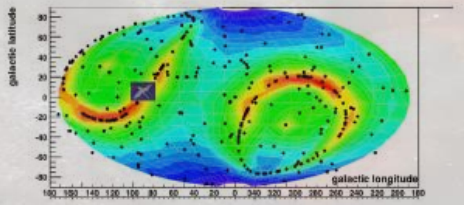
A. M. Green et. al, Astropart. Phys. 27 (2007) 142

WIMP signal (recoil map)

Angular distribution of Fluorine recoils [5;50] keV

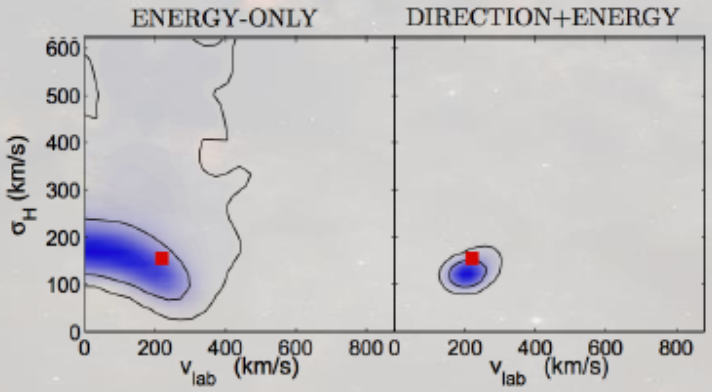


Background



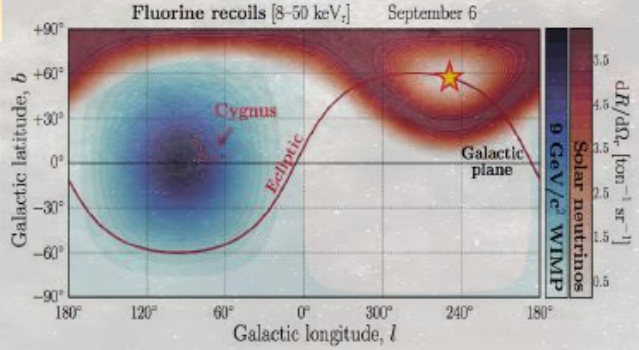
Directionality of the DM flux

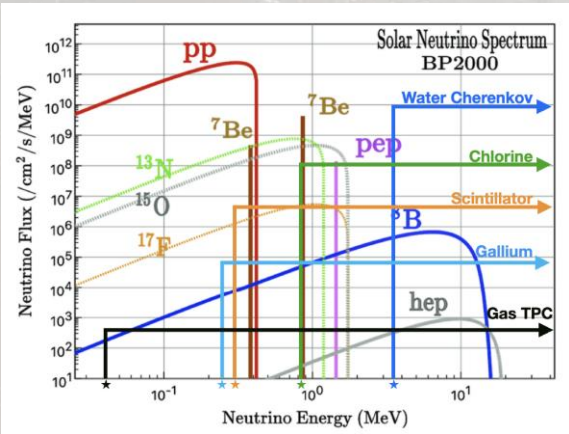
Phys.Rept. 627 (2016) 1-49



Capability to identify Solar neutrinos

e-Print: 2102.04596





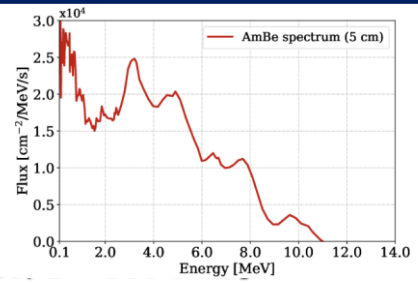
This is the only generic and unambiguous terrestrial signature of DM that results solely from the assumption that we live inside a DM halo.

The future of directional searches, Ciaran O’Hare

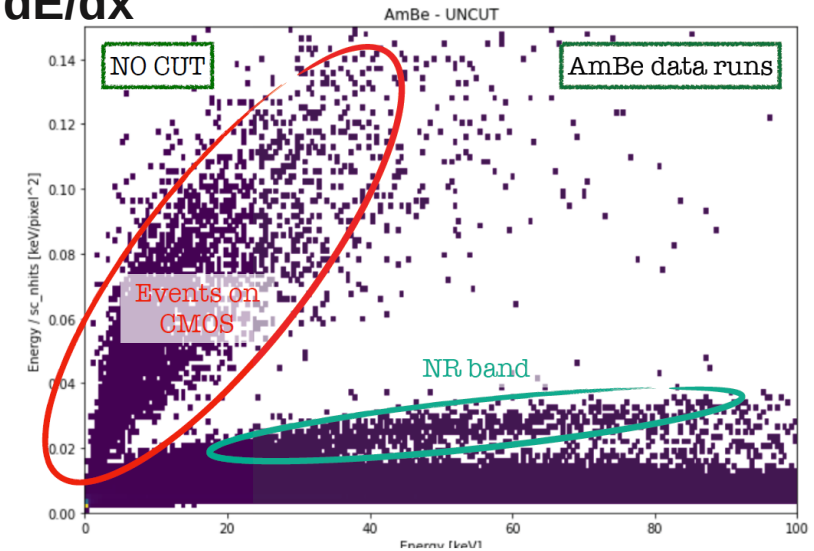
[2408.03760] Feasibility of a directional solar neutrino measurement with the CYGNO/INITIUM experiment (arxiv.org)

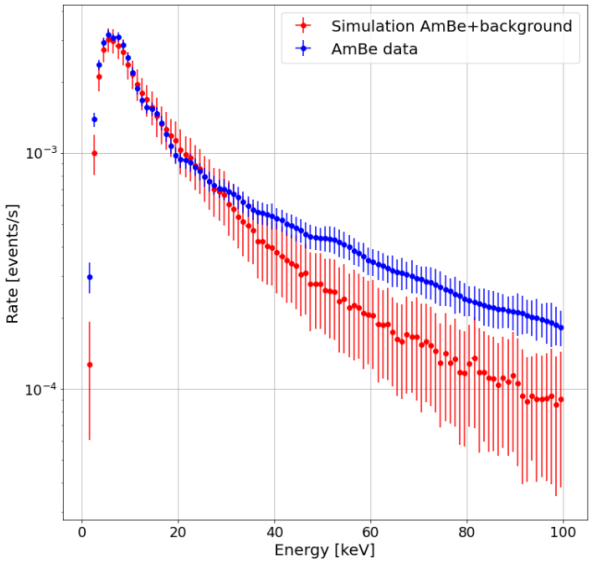
Background Rejection

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

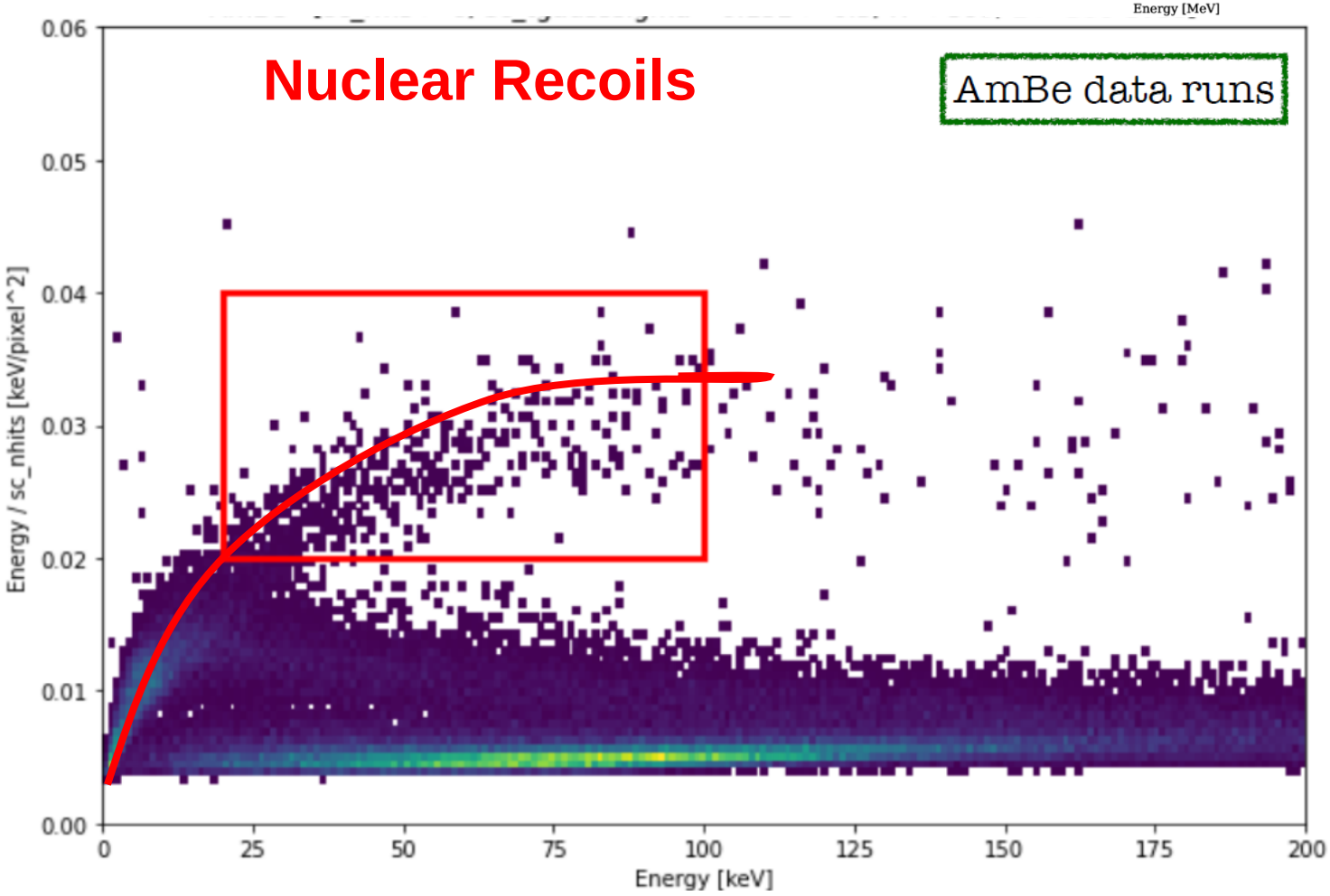


dE/dx





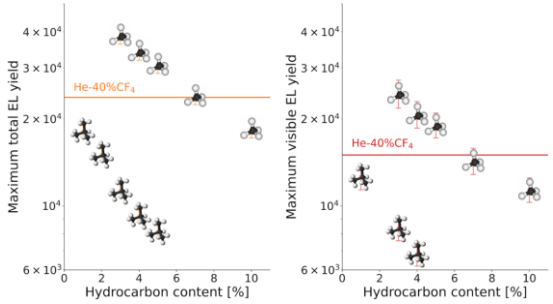
Simulation of AmBe gamma spectrum is correctly reproduced when background does not dominate

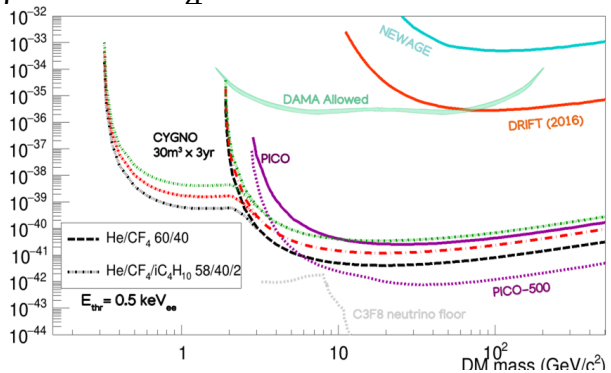


R&D activities

Hydrogen Rich Gas

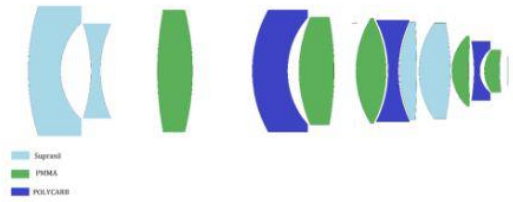
- Add hydrogen-rich gas is under study to gain sensitivity to lower DM masses iC_4H_{10} and CH_4 with <10% concentration





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!**