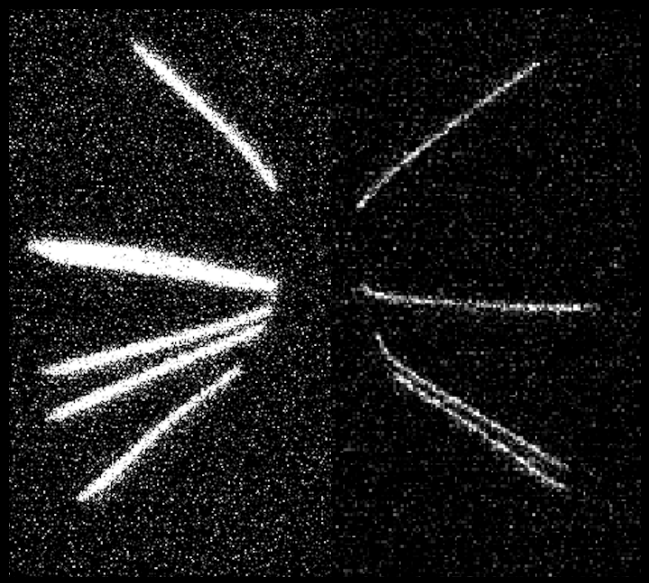
Elisabetta Baracchini

Gran Sasso Science Institute

Innovative means of operation of optical readout TPC



Fernando Domingues Amaro [1], Elisabetta Baracchini [2,3], Luigi Benussi [4], Stefano Bianco [4], Cesidio Capoccia [4], Michele Caponero [4,5], Danilo Santos Cardoso [6], Gianluca Cavoto [7,8], André Cortez [2,3], Igor Abritta Costa [9], Rita Joanna da Cruz Roque [1], Emiliano Dané [4], Giorgio Dho [2,3], Flaminia Di Giambattista [2,3], Emanuele Di Marco [7], Giovanni Grilli di Cortona [4], Giulia D'Imperio [7], Francesco Iacoangeli [7], Herman Pessoa Lima Júnior [6], Guilherme Sebastiao Pinheiro Lopes [9], Amaro da Silva Lopes Júnior [9], Giovanni Maccarrone [4], Rui Daniel Passos Mano [1], Michela Marafini [10], Robert Renz Marcelo Gregorio [11], David José Gaspar Marques [2,3], Giovanni Mazzitelli [4], Alasdair Gregor McLean [11], Andrea Messina [7,8], Cristina Maria Bernardes Monteiro [1], Rafael Antunes Nobrega [9], Igor Fonseca Pains [9], Emiliano Paoletti [4], Luciano Passamonti [4], Sandro Pelosi [7], Fabrizio Petrucci [12,13], Stefano Piacentini [7,8], Davide Piccolo [4], Daniele Pierluigi [4], Davide Pinci [7,*], Atul Prajapati [2,3], Francesco Renga [7], Filippo Rosatelli [4], Alessandro Russo [4], Joaquim Marques Ferreira dos Santos [1], Giovanna Saviano [4,14], Neil John Curwen Spooner [11], Roberto Tesauro [4], Sandro Tomassini [4] and Samuele Torelli [2,3]

This project has received fundings under the European Union's Horizon 2020 research and innovation programme from the European Research Council (ERC) grant agreement No 818744

Outline

- High precision imaging 3D optical readout TPC: the CYGNO experiment
- Reducing diffusion and improving tracking: negative ion drift operation
- Enhancing light yield: electroluminesce after the amplification stage

High precision imaging 3D optical readout TPC

The CYGNO experiment

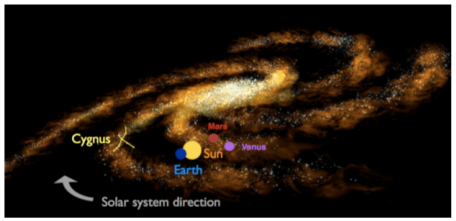
See F. Di Giambattista poster

CYGNO experiment

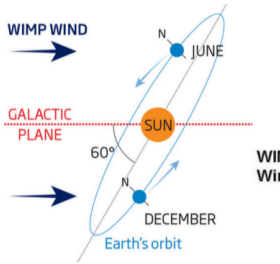
F. D. Amaro et al [CYGNO Collaboration], Instruments, Volume 6, Issue 1

CYGNO: high precision 3D TPC for directional Dark Matter searches and solar neutrino spectroscopy

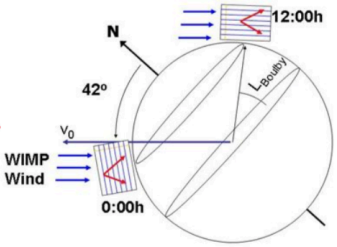
https://web.infn.it/cygnus/



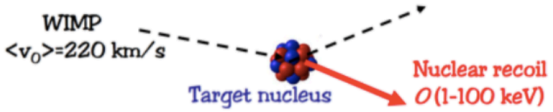
Our Galaxy



Solar system



Earth



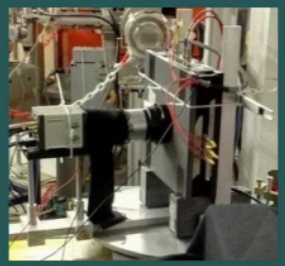
Detector target

PHASE 0: R&D and prototypes

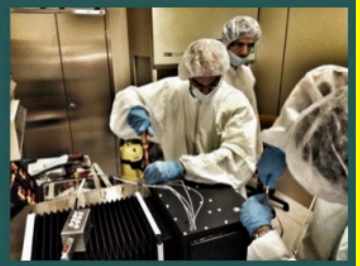
PHASE 1: O(1) m³ Demonstrator

PHASE 2: 30 m³ Experiment

2015/16 ROMA1	2017/18 LNF	2019/22 LNF/LNGS	2023/26 LNF/LNGS	2026.. LNGS
ORANGE	LEMON	LIME	CYGNO_04	CYGNO_30

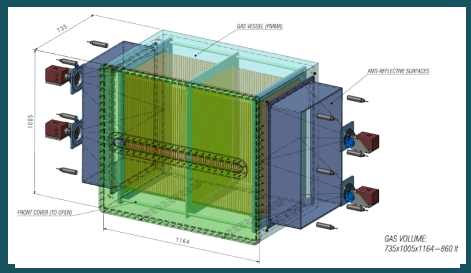


- 1 cm drift

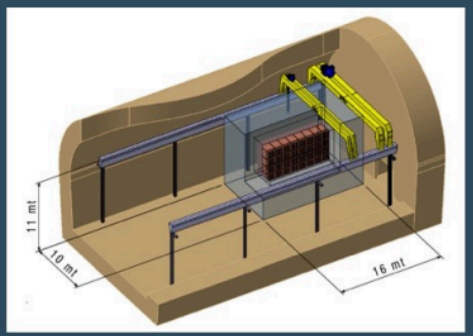


- 3D printing
- 20 cm drift

- 50 cm drift
- underground tests
- MC validation

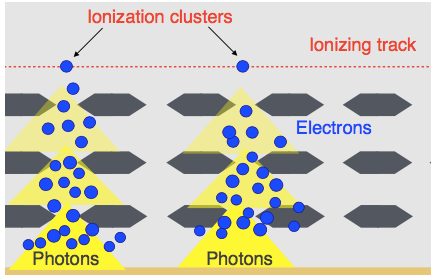


- background
- materials test, gas purification
- scalability

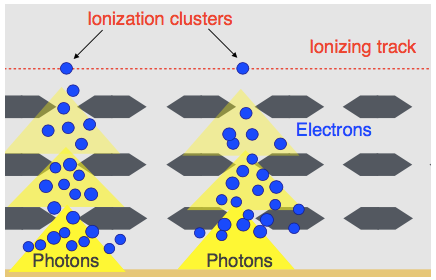


- Physics research

JINST 13 (2018) no.05, P05001



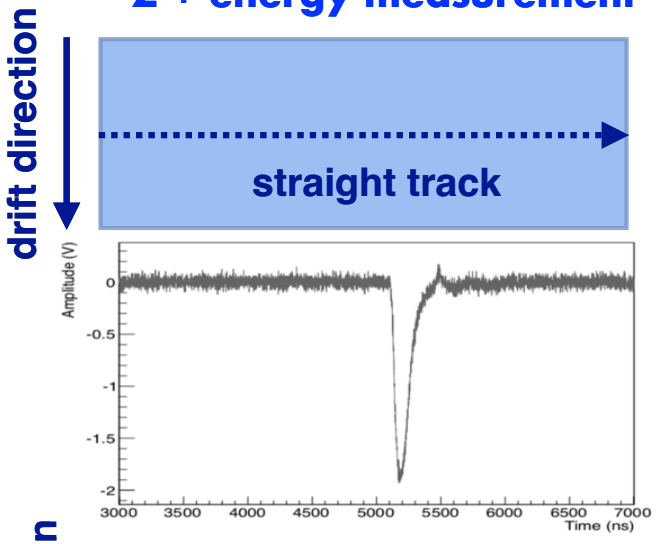
JINST 13 (2018) no.05, P05001

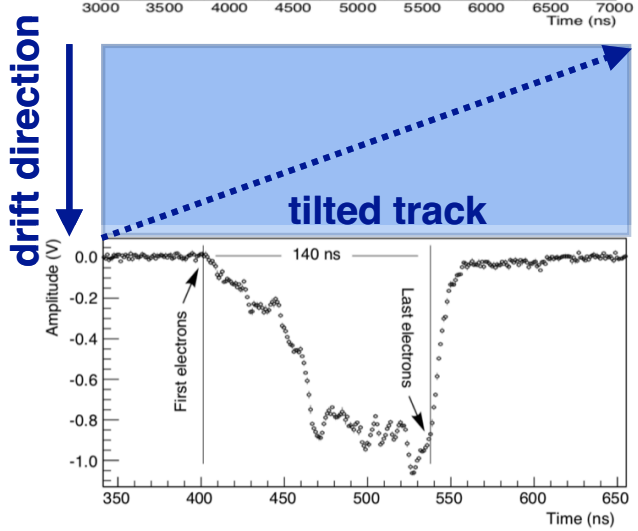


PMT:

integrated

Z + energy measurement





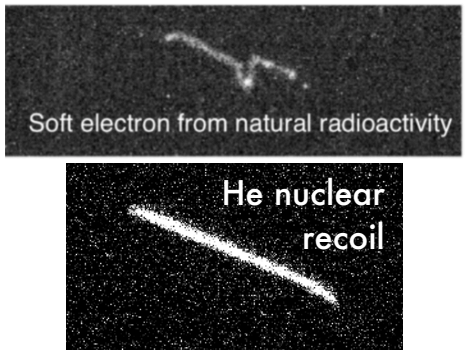
CYGNO :3D TPC with optical readout via PMT + sCMOS

JINST 13 (2018) no.05, P05001

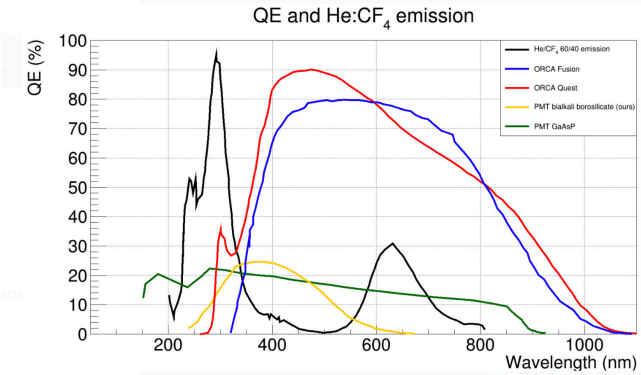
sCMOS:

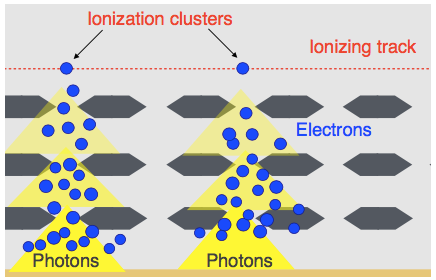
high granularity

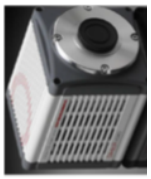
X-Y + energy measurements



- **1/3 noise w.r.t. CCDs**
- **Market pulled**
- **Single photon sensitivity**
- **Decoupled from target**
- **Large areas with proper optics**



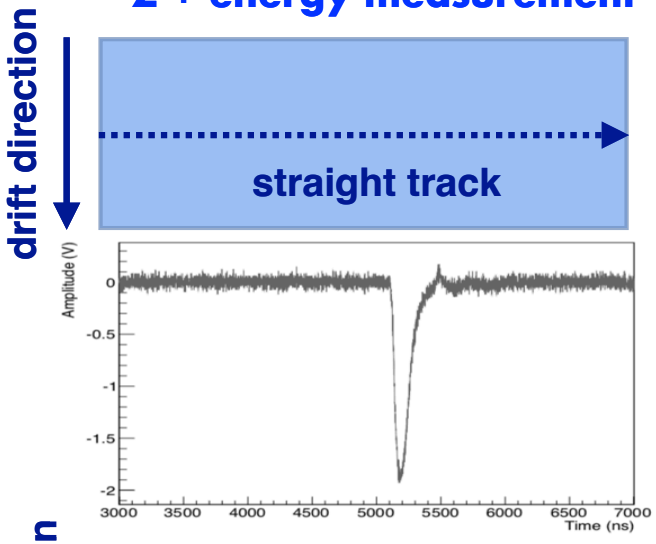


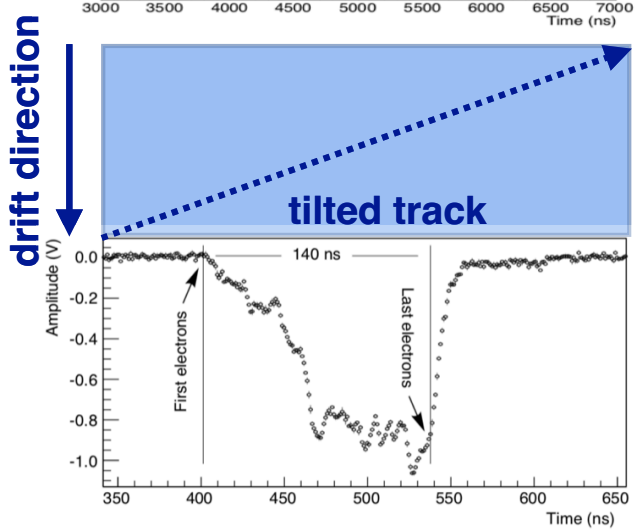


PMT:

integrated

Z + energy measurement





He:CF_4 @ 1 atm

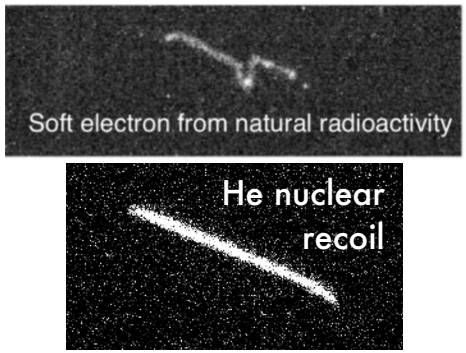
CYGNO :3D TPC with optical readout via PMT + sCMOS

JINST 13 (2018) no.05, P05001

sCMOS:

high granularity

X-Y + energy measurements



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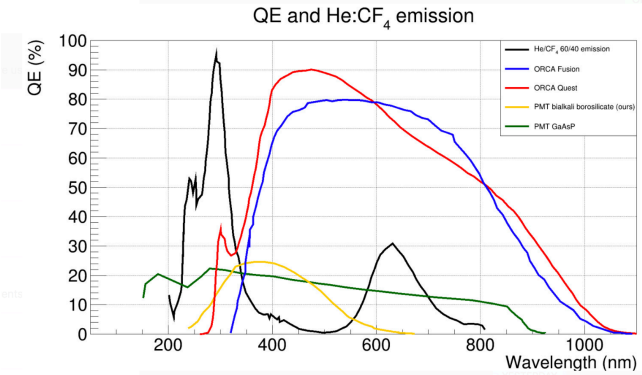
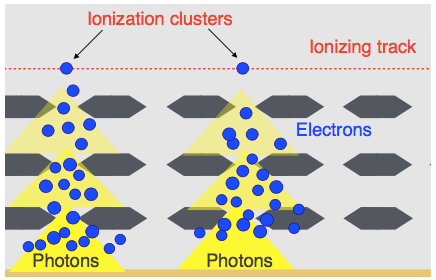
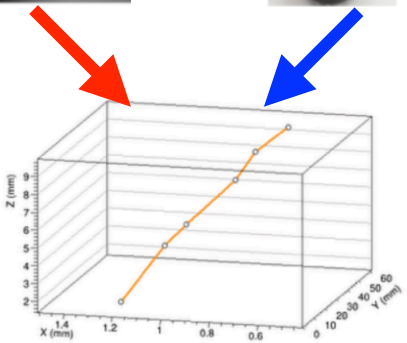


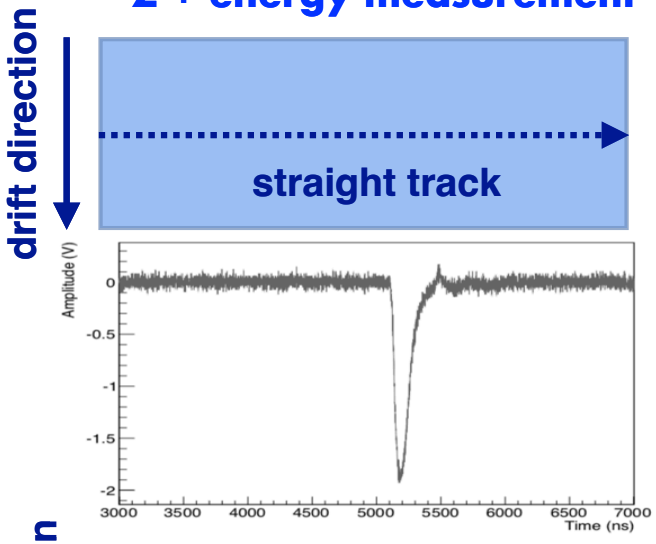


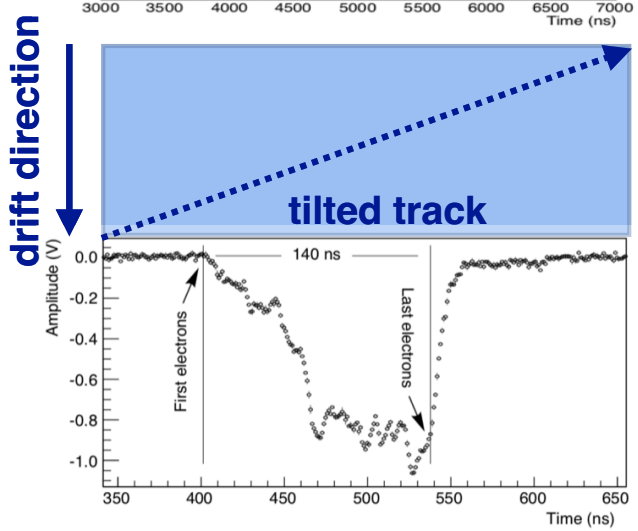


PMT:

integrated

Z + energy measurement





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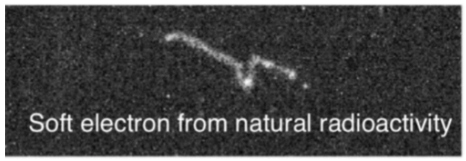

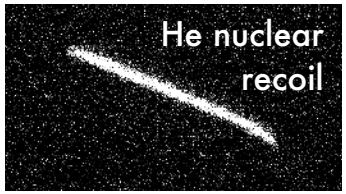

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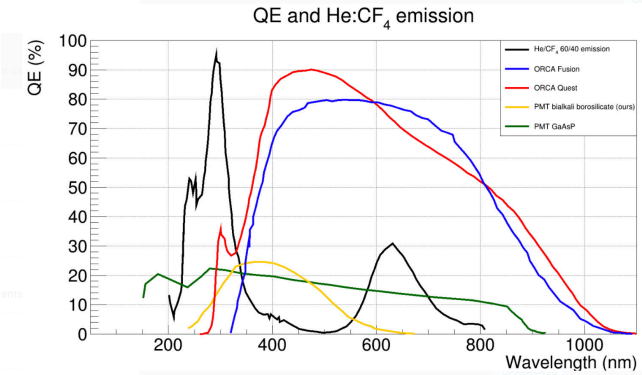
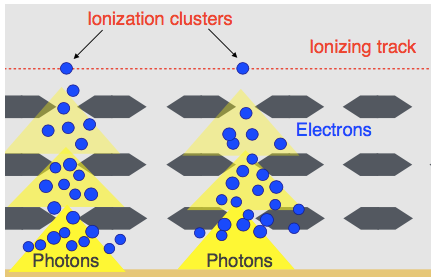
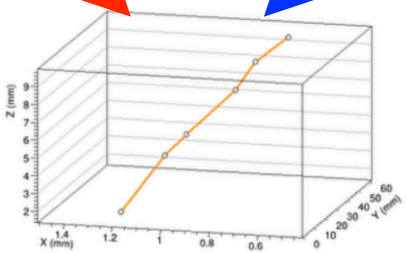




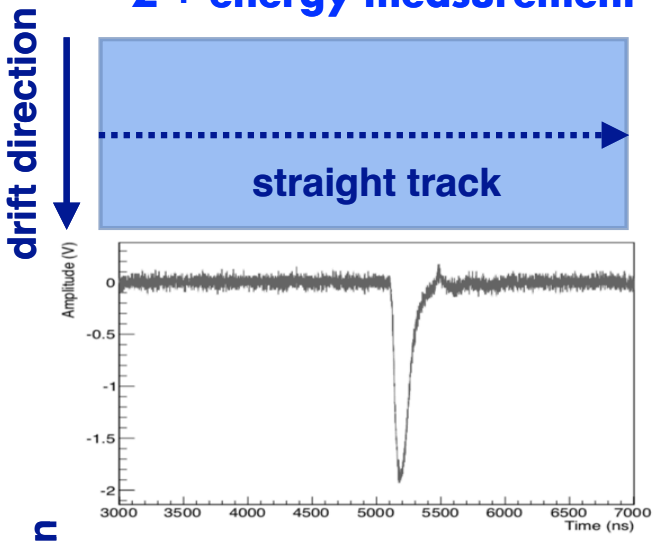


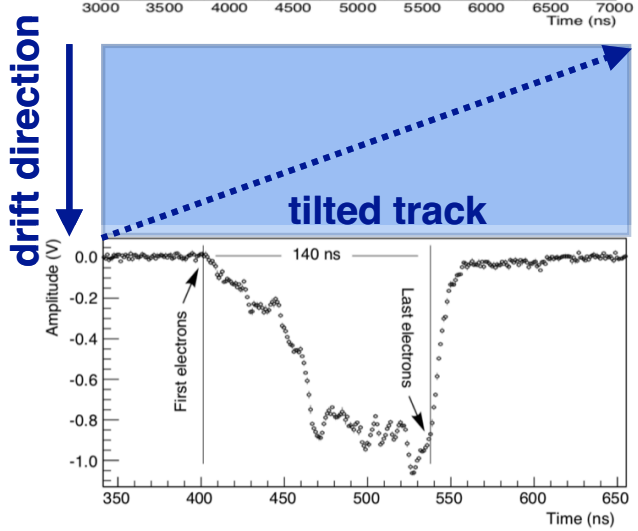
+ SF_6 for negative ion drift

PMT:

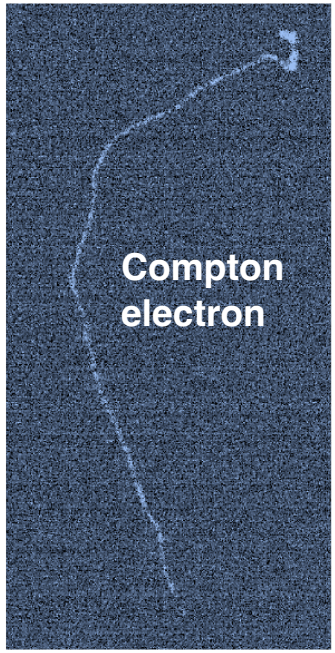
integrated

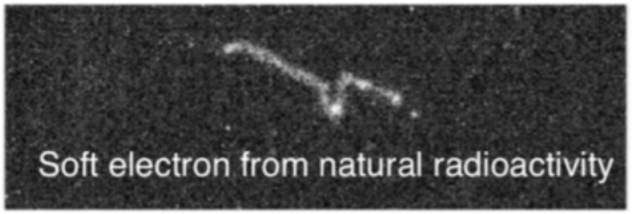
Z + energy measurement

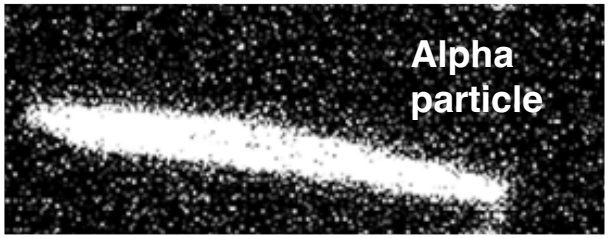


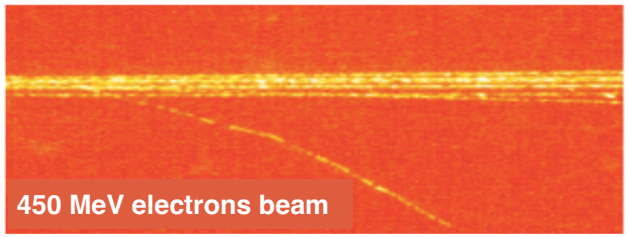


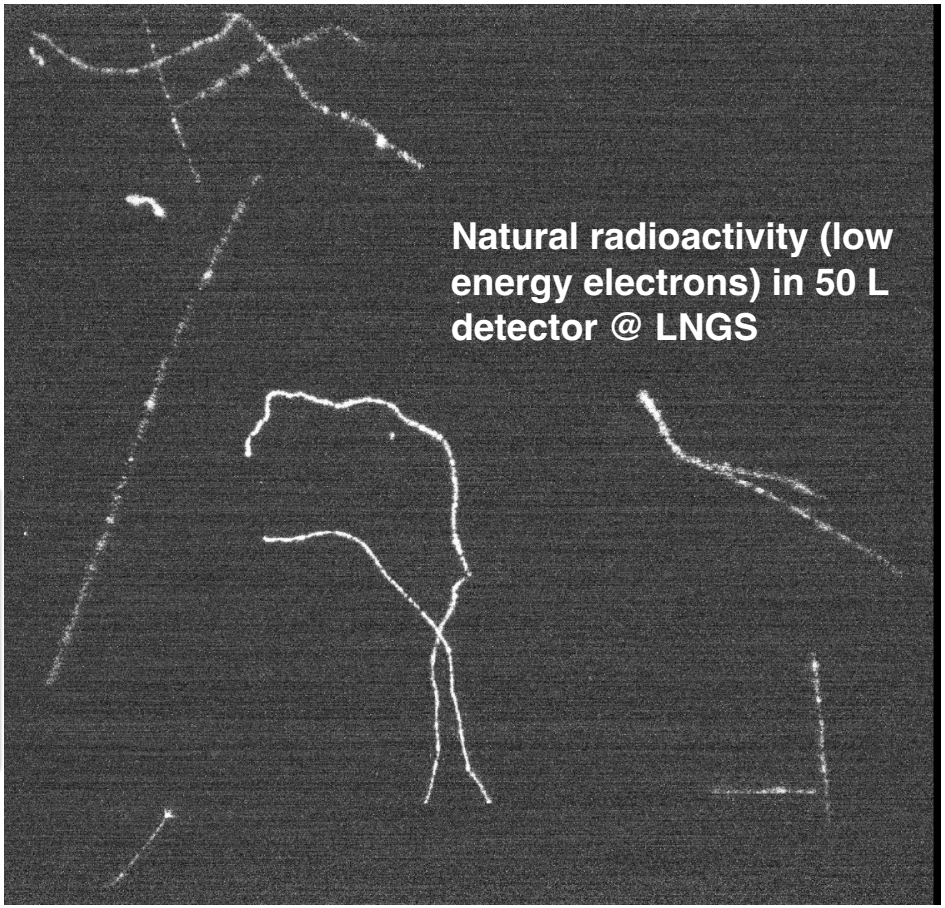
Imaging tracks with CYGNO

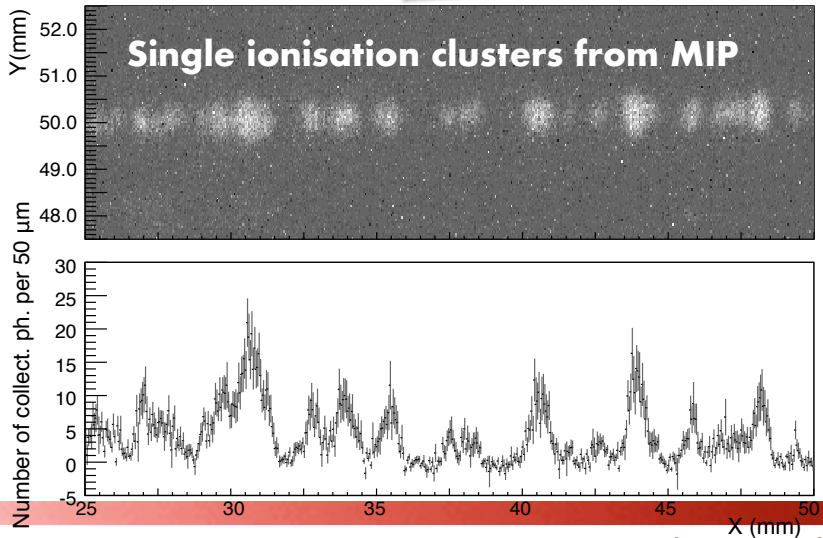


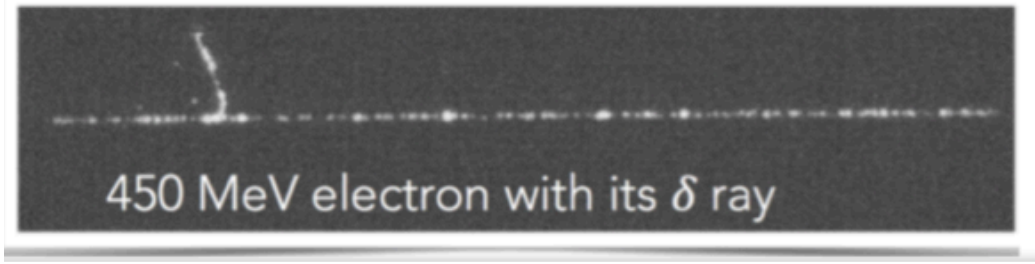








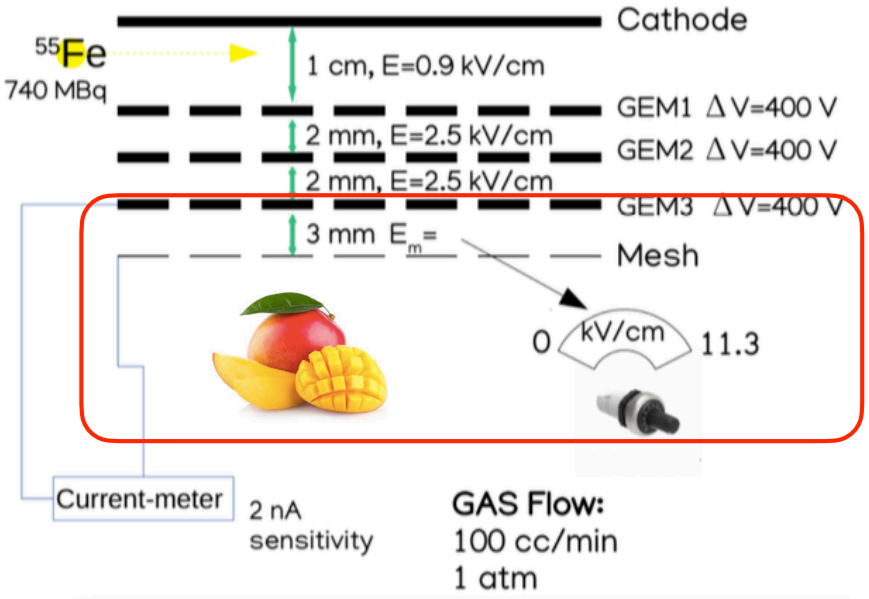




Enhanching light yield:

Electroluminescence after the amplification stage

Enhancing the light yield through electroluminescence



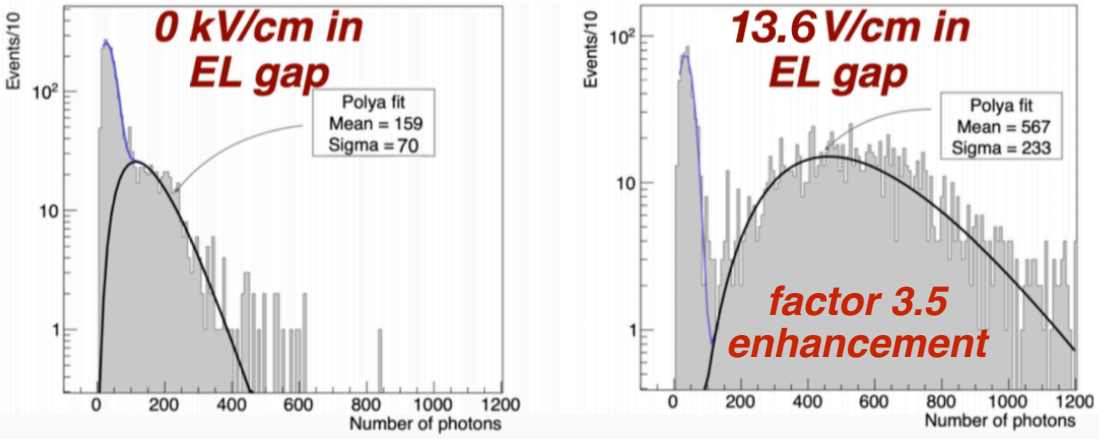
- Add a mesh (in a later stage a glass ITO) 3 mm after MANGO last GEM
- Apply a drift field between GEM and mesh (0-12 kV/cm)
- Electrons travelling in the GEM-mesh gap produce additional light with no (or relatively low) further ionisation

First evidence of luminescence in a He/CF_4 gas mixture induced by non-ionizing electrons

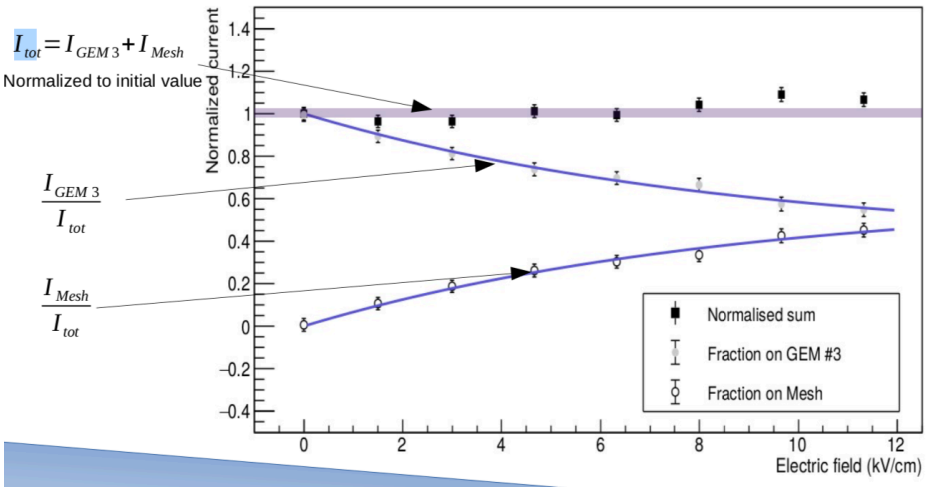
E. Baracchini (Gran Sasso), L. Benussi (Frascati), S. Bianco (Frascati), C. Capoccia (Frascati), M. Caponero (Frascati and ENEA, Frascati) et al. (Apr 22, 2020)

Published in: *JINST* 15 (2020) 08, P08018 • e-Print: 2004.10493 [physics.ins-det]

^{55}Fe light spectra



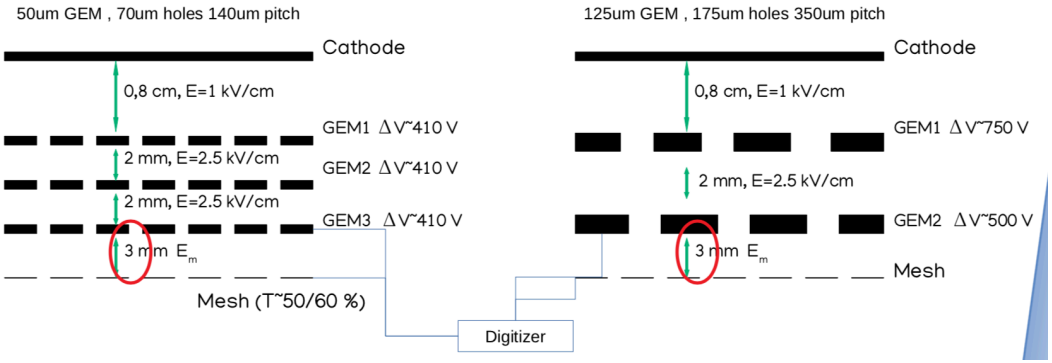
^{55}Fe GEM & mesh currents



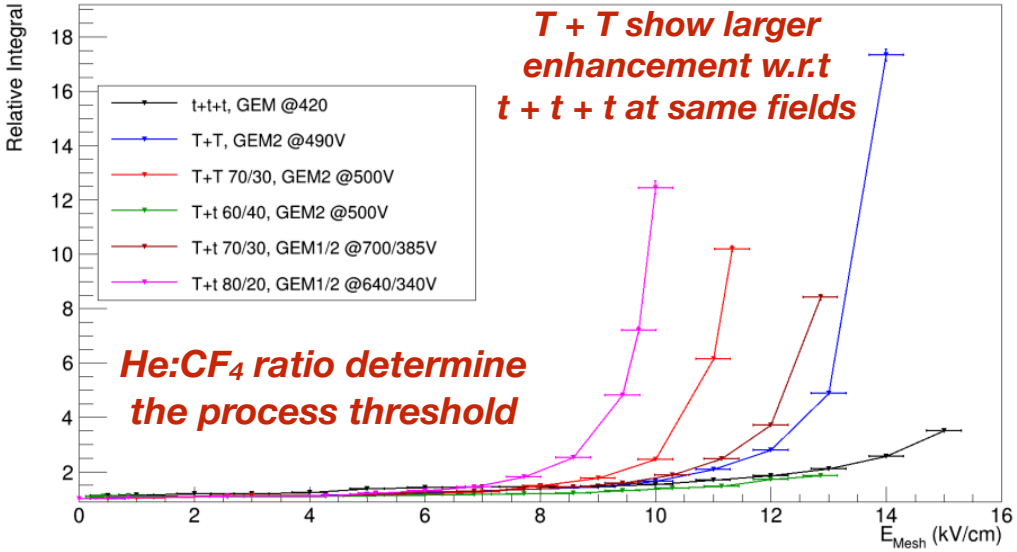
EL studies varying GEMs configuration & He:CF_4 ratio

Triple thin 50 um (t + t +t)

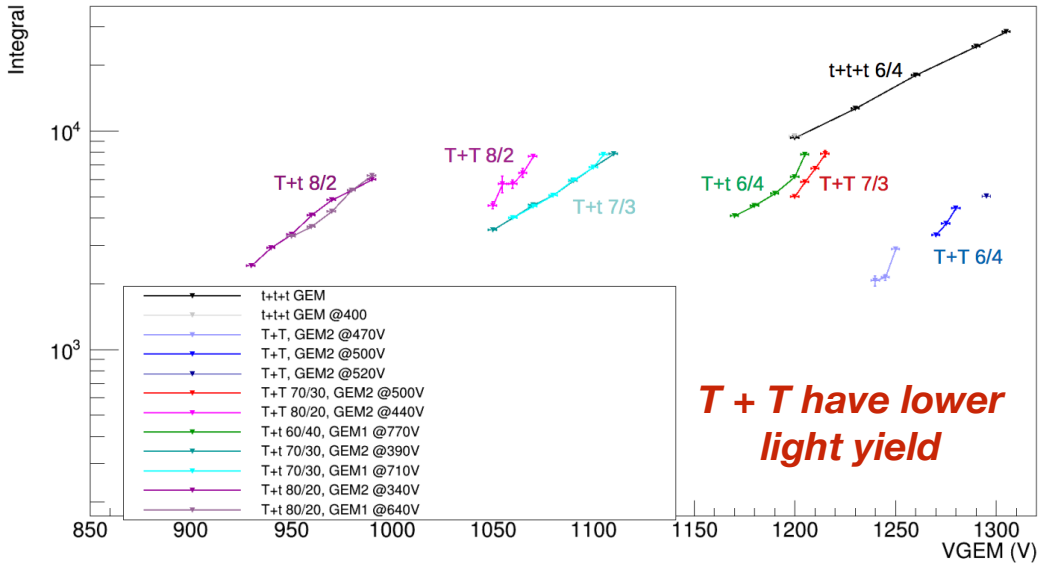
Double thick 125 um (T + T)



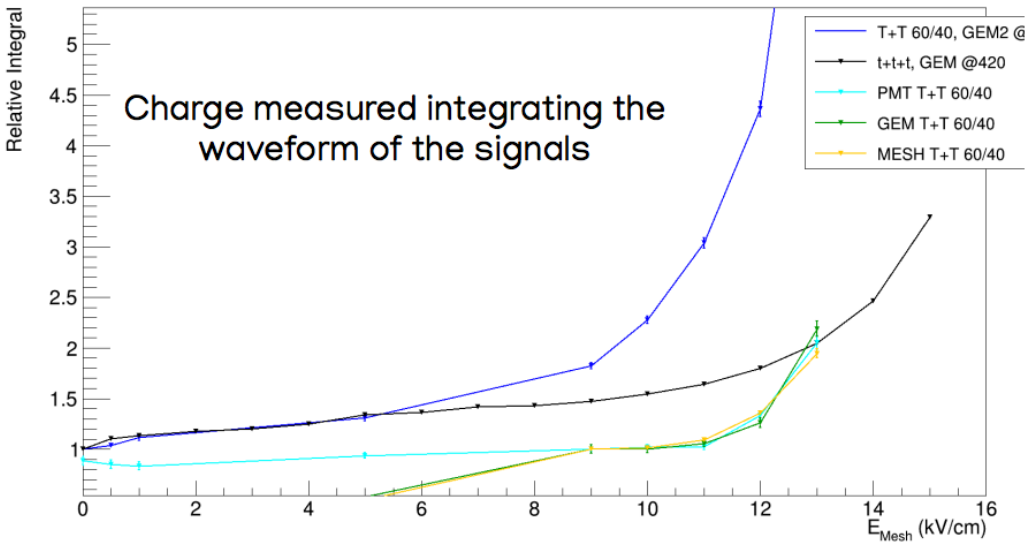
Relative light increase WITH EL



Light yield WITHOUT EL

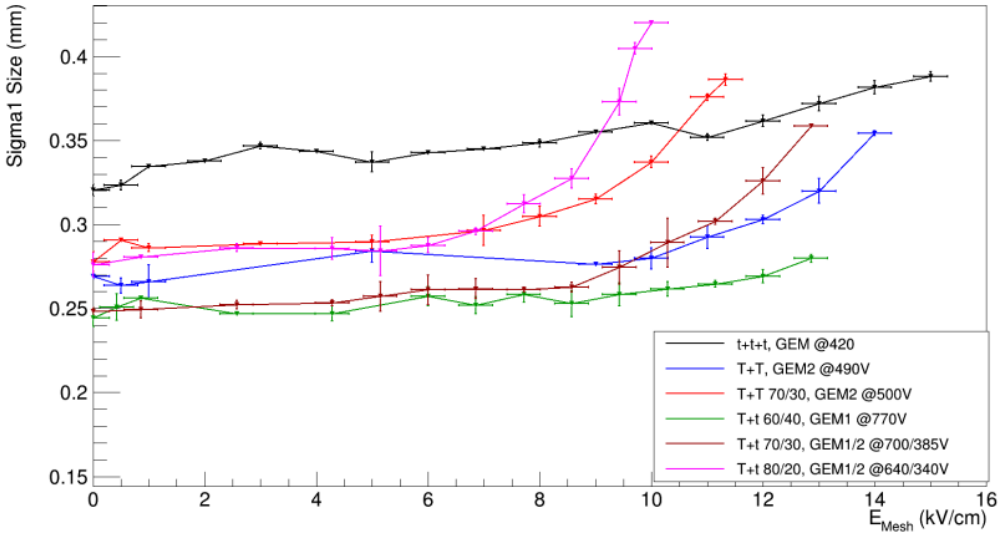


Light/charge comparison WITH EL



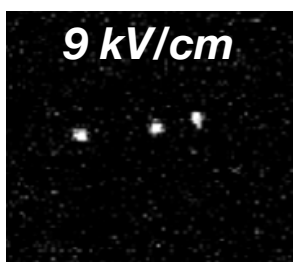
Energy and spot size (i.e. space) resolution with EL

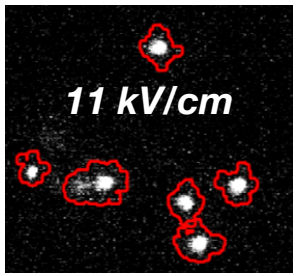
^{55}Fe spot size vs EL field



T + T displays better space resolution, but with larger He fraction degradates faster than t + t + t with raising fields

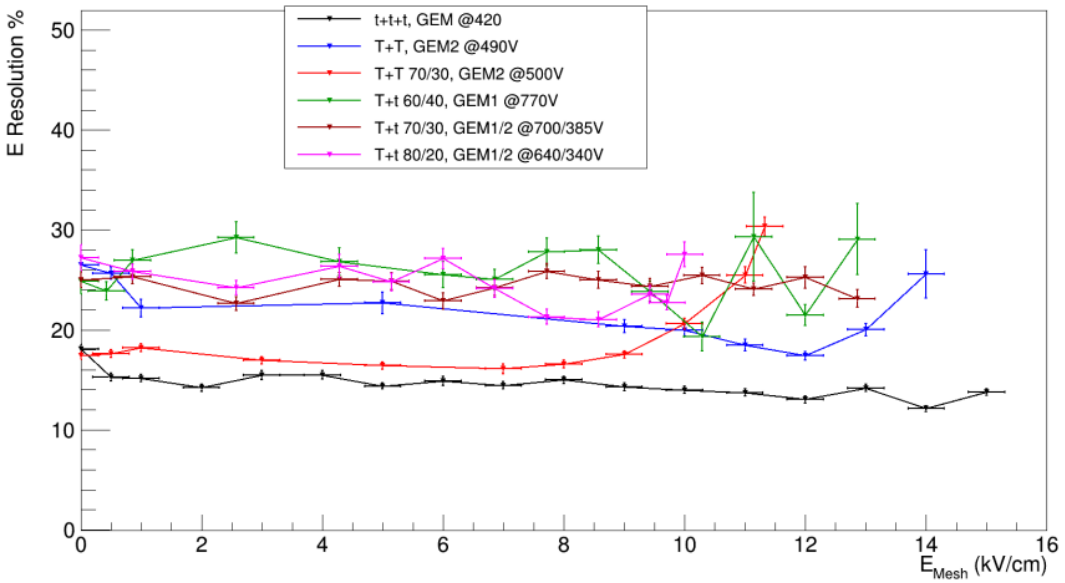
Iron looks like a round spot in our images: spot size is a measurement of the diffusion





T + T

^{55}Fe energy resolution vs EL field



t + t + t displays better energy resolution and no significant degradation is seen

Conclusions & outlook

- **High precision optical TPC with 3D tracking through PMT + sCMOS is a very promising technique:**
  - For directional Dark Matter searches and solar neutrino spectroscopy (see F. Di Giambattista poster)
  - For large field of view X-ray polarimetry detectors (see E. Baracchini poster)
  - For neutron spectroscopy (see F. Di Giambattista poster at NDRA 2022 Summer School)
  - Migdal effect measurement
  - ....
- **Alternative means of operation of TPC can significantly boost detection performances**
- **We demonstrated for the first time the possibility of achieving negative ion drift operation at atmospheric (mountain) pressure with an optical readout**
  - First ever detection of negative ion drift with PMT!
  - Significant reduction of diffusion observed with respect to He:CF_4 classic ED at same light yield
  - Systematic diffusion data acquired (last week…), analysis on going
  - Next steps: explore different ratios of same mixtures & lower energy threshold
- **We demonstrated for the first time electroluminescence of non-ionising electrons in He:CF_4**
  - Can be used to enhance light yield of several 3-10 factor without significant degradation of resolution
  - Systematic investigation of process dependence on GEM thickness & gas mixtures
  - Paper in preparation

Thanks for your attention!

An underground CYGNO surfer :D

**image acquired 10 days ago @ undergrond LNGS with LIME*

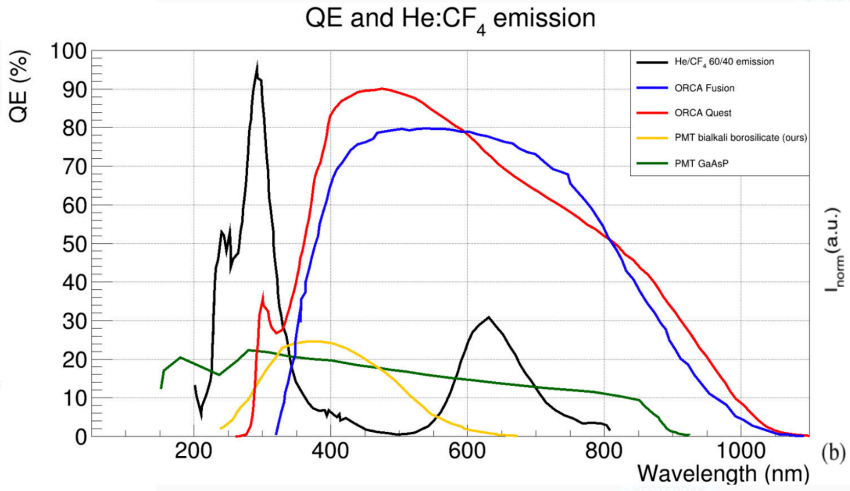
Backup slides

sCMOS characteristics & gas emission spectra

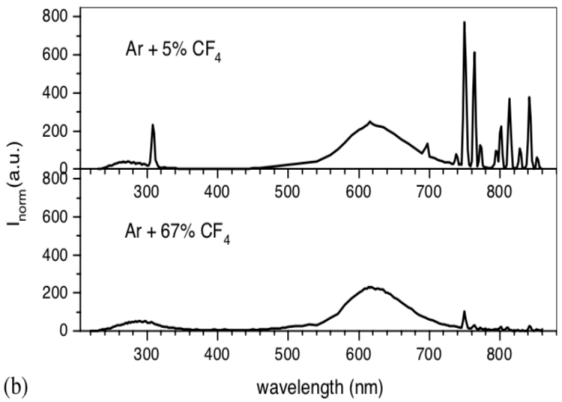
https://www.hamamatsu.com/eu/en/product/cameras/cmos-cameras.html

HAMAMATSU	# of pixels	pixel size [um²]	sensor area [cm²]	dynamic range	readout noise (fast scan)	Exposure time (fast)
Orca Flash	2048 x 2048	6.5 x 6.5	1.33 x 1.33	37000:1	1.4 (1.6) rms	33 (10) sus
Orca Fusion	2304 x 2304	6.5 x 6.5	1.498 x 1.498	21400:1	0.7 (1.4) rms	280 (17) us
Orca Quest	4096 x 2304	4.6 x 4.6	1.884 x 1.060	25900:1	0.27 (0.43) rms	200 (7.2) us

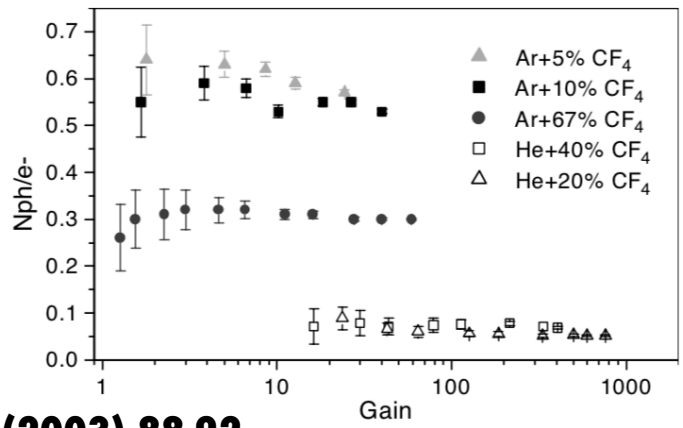
improving performances



Ar:CF_4 spectra



Ar:CF_4 & He:CF_4 photon production



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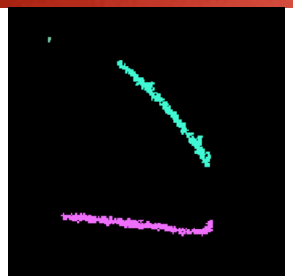
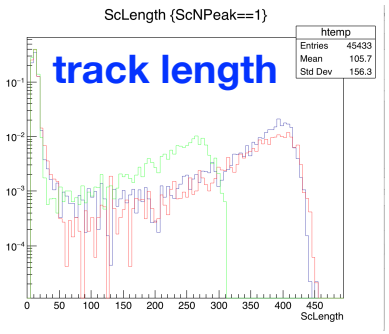
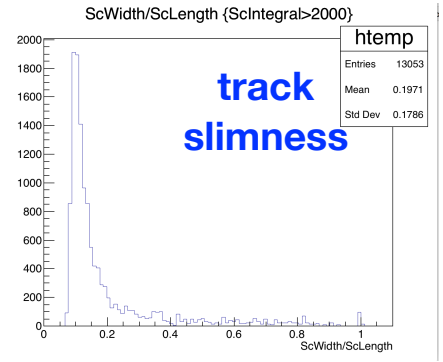
Data analysis strategy

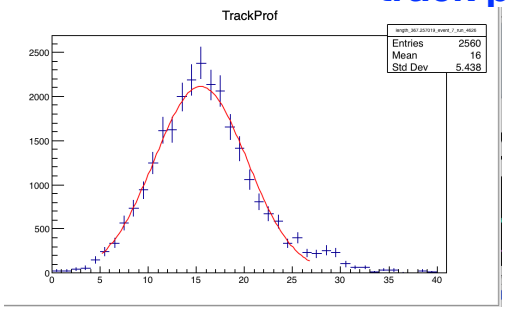


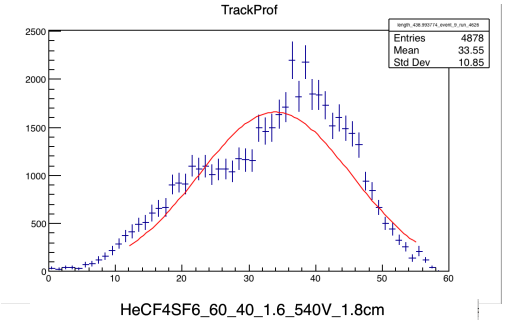
- Track reconstructed with CYGNO autumn2021 code
- Fit reconstructed tracks transverse profile
- Tracks selection:
  - track length > 150 (300) pixels (depending on source position)
  - track slimness < 0.3
  - # of peaks in the transverse profile == 1 (select single tracks)
  - Chi2/nDOF of transverse fit profile < 5 (remove additional multiple tracks)
- Sigma of track profile and track integral fitted with Gaussian to estimate diffusion and light yield

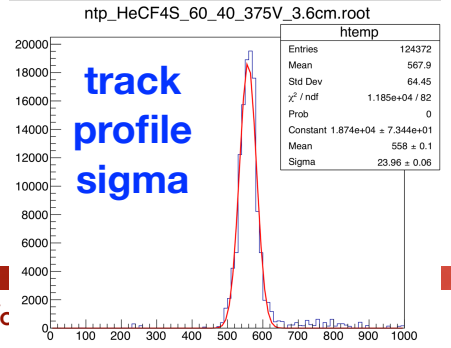


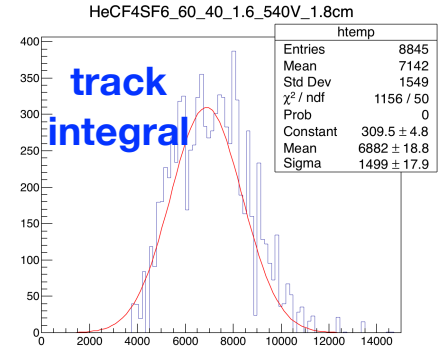


track profile





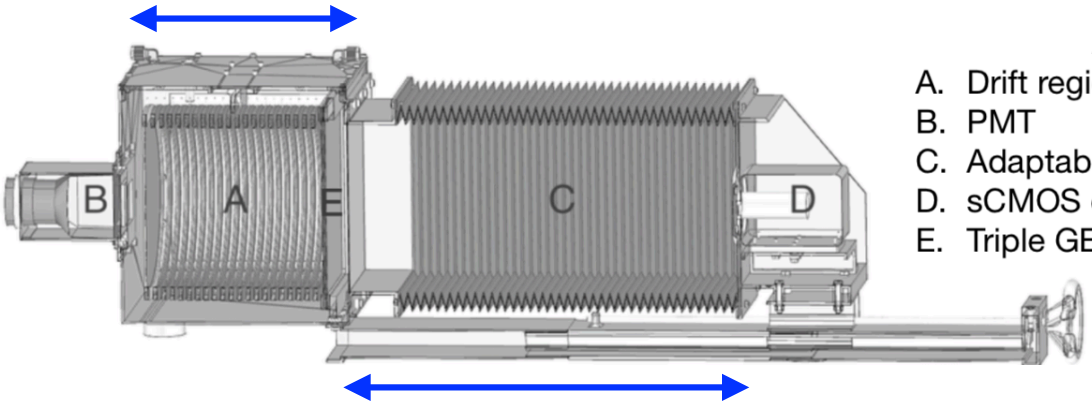




EL measurements in LEMON

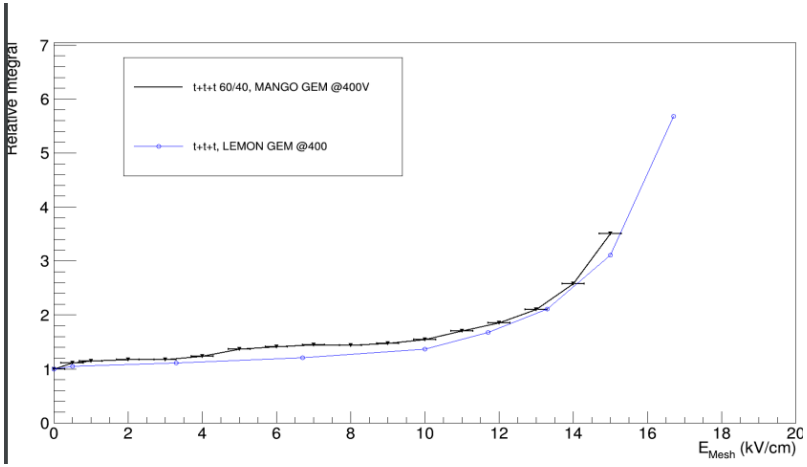
20 cm drift length

10 L active volume

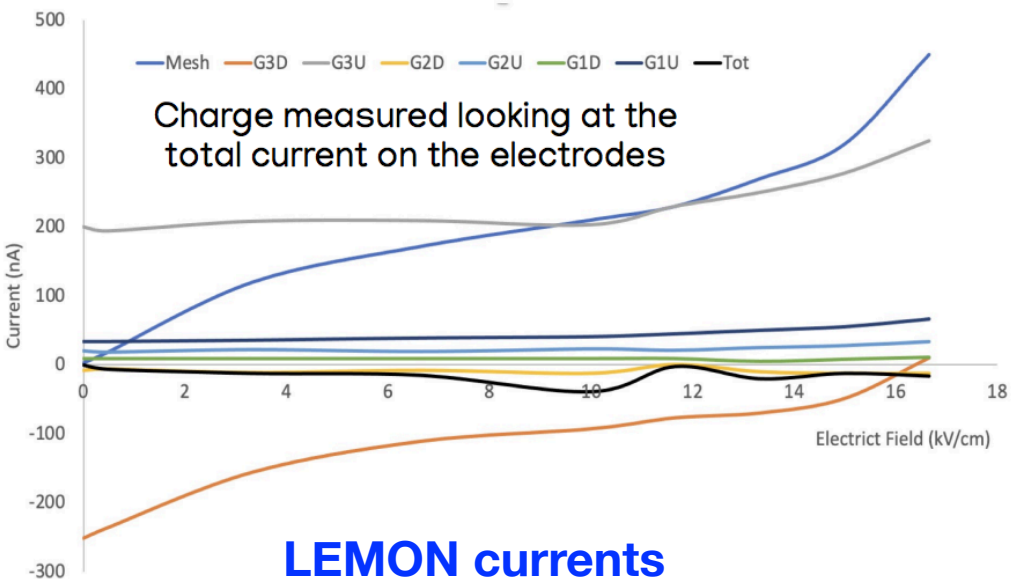


A. Drift region
B. PMT
C. Adaptable bellow
D. sCMOS camera
E. Triple GEM System

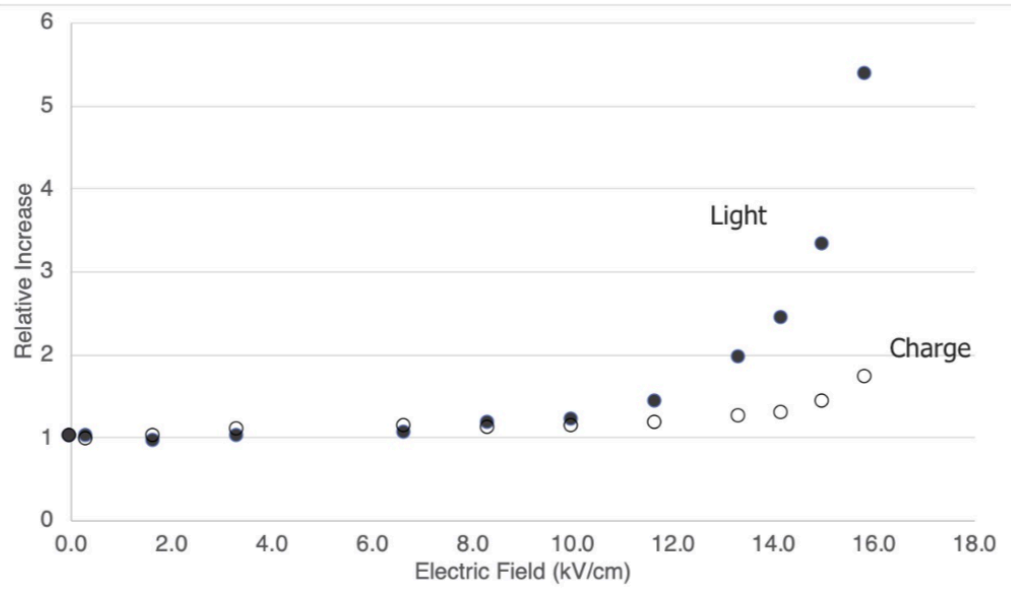
52.5 cm sCMOS distance *d* from GEMs



MANGO/LEMON consitency



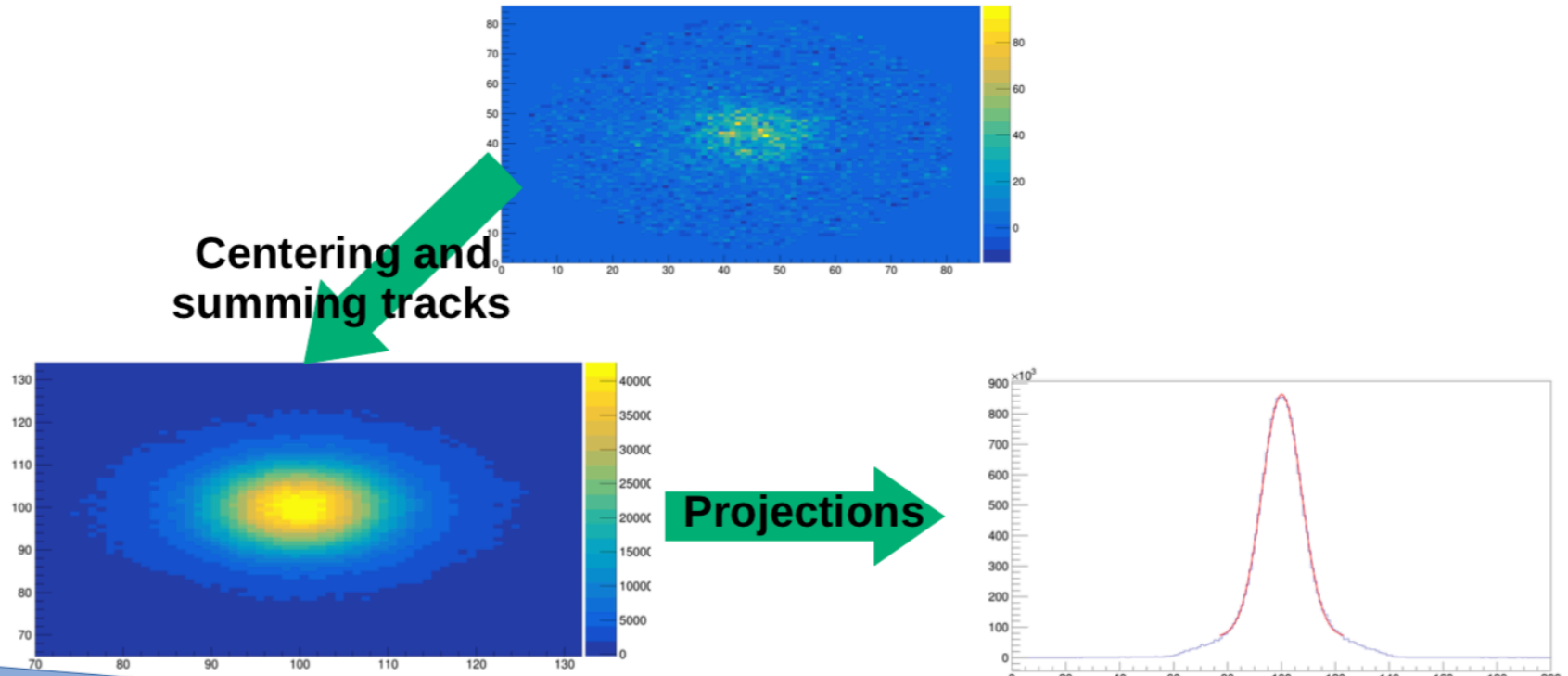
LEMON currents



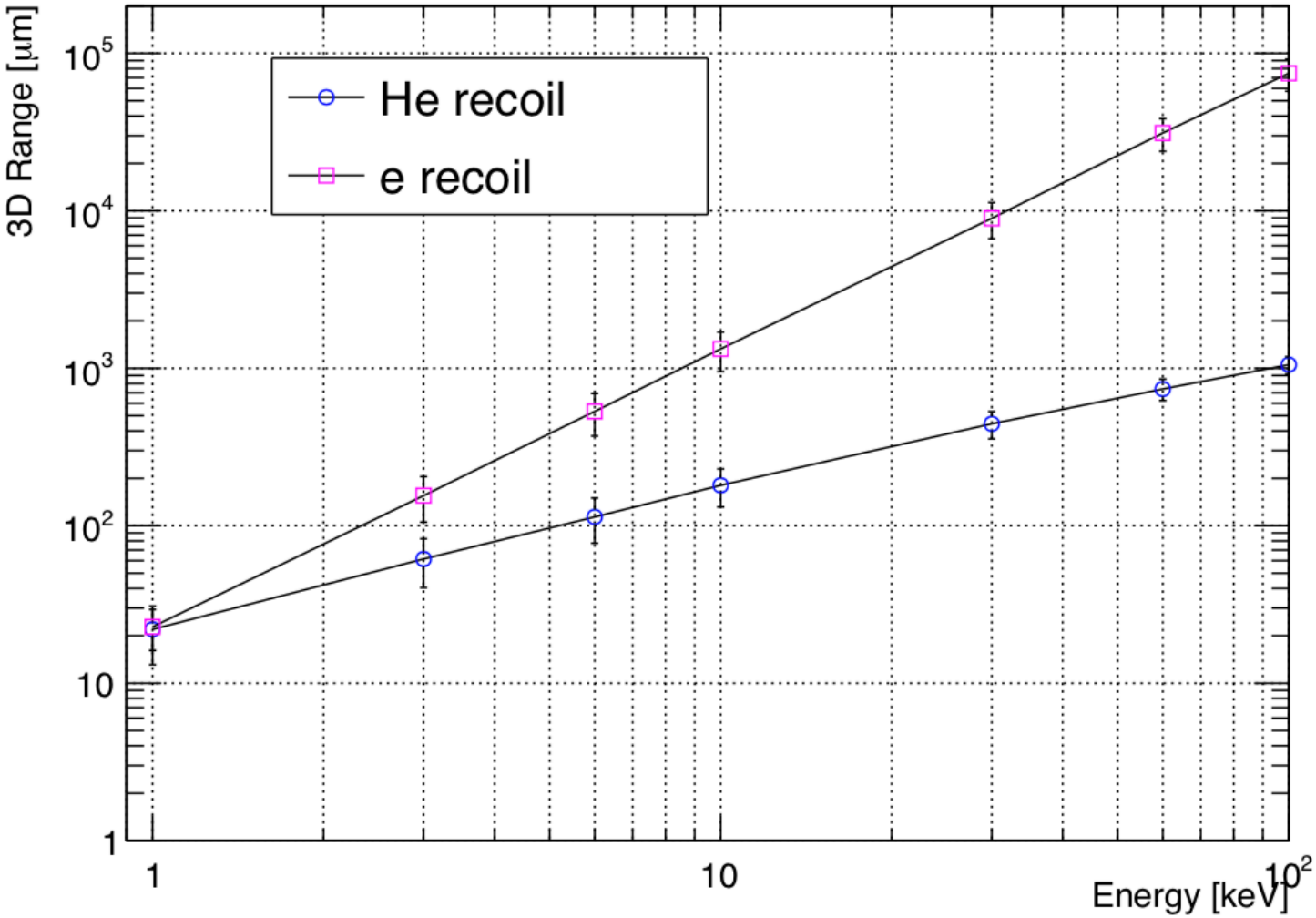
Spot size evaluation

Size Measurement

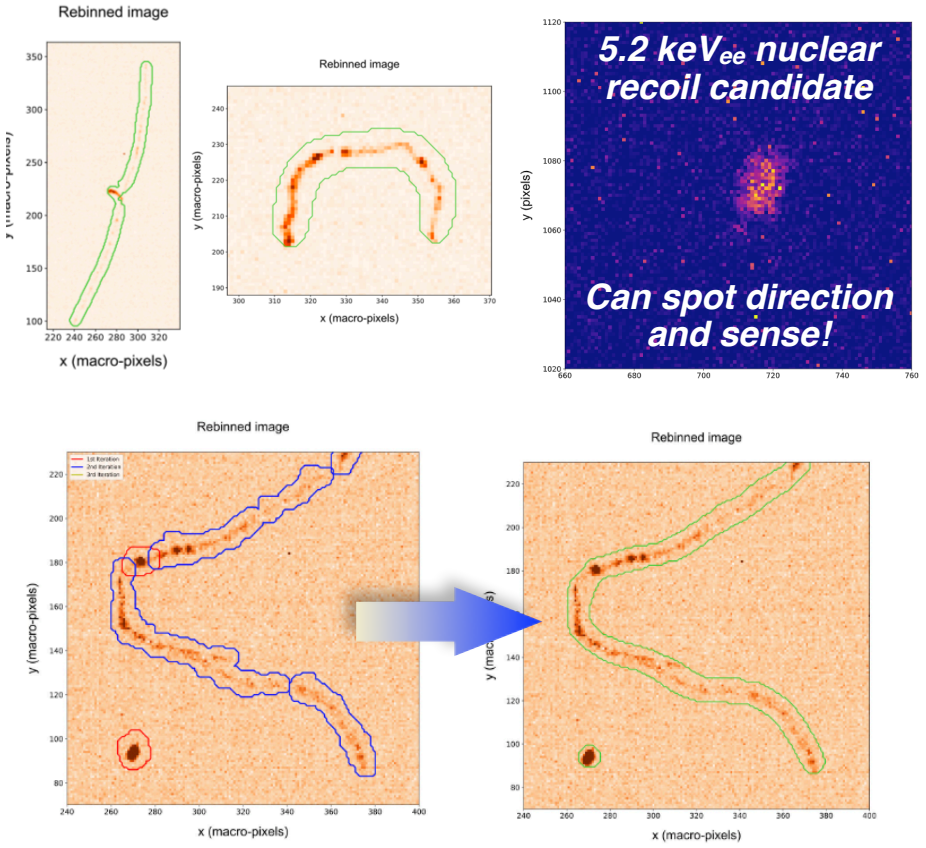
- To quantify the dimension of the spots, trying to be independent from the light output, all the spots are centred and summed and the sigma of the shape is fitted with a gaussian



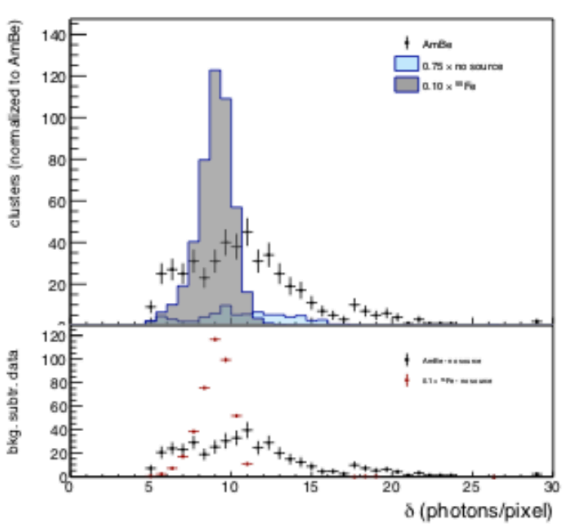
Range in He:CF_4 60:40 @ 1 bar

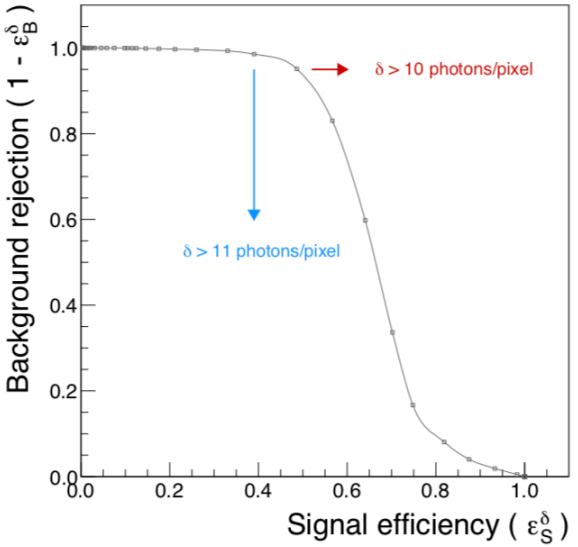


Response to AmBe source: low energy nuclear recoil & discrimination from ^{55}Fe



Reconstruction based on custom multiple iteration of IDBSCAN + morphological geodesic active contours (GAC)





40% nuclear recoil efficiency for energies < 20 keV$_{ee}$, with 99% ^{55}Fe events rejected

Signal efficiency			Background efficiency		
ε_S^{presel}	ε_S^{δ}	ε_S^{total}	ε_B^{presel}	ε_B^{δ}	ε_B^{total}
0.98	0.51	0.50	0.70	0.050	0.035
0.98	0.41	0.40	0.70	0.012	0.008

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