Identification of nuclear recoils in a gas TPC with optical readout

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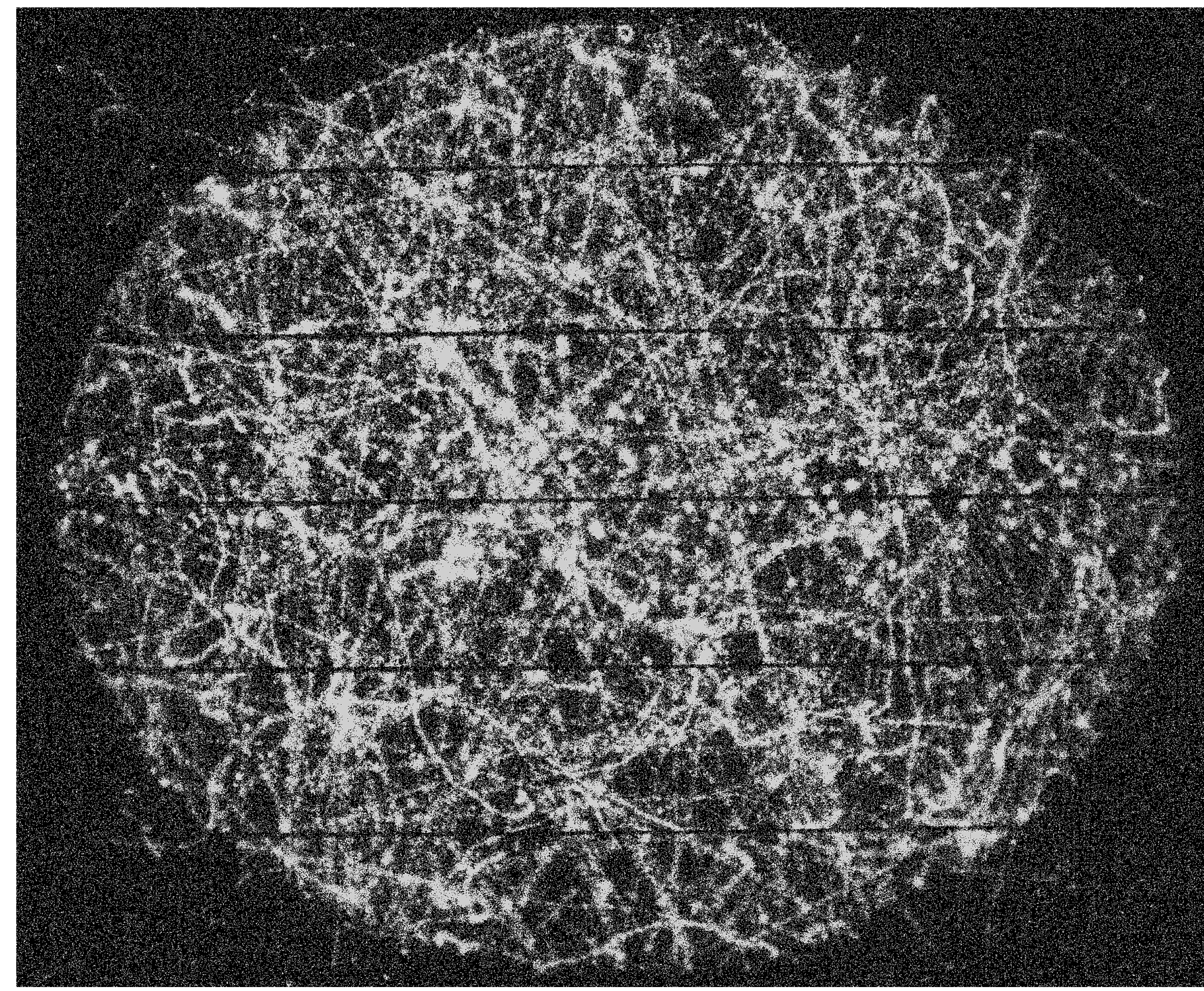
RD51 Workshop on Gaseous Detector Contributions to PID
16-17 February 2021 (remote-only)

CYGNO project

- The aim of CYGNO project is the development and realisation of a GEM-based Optically Readout Time Projection Chamber for the study of rare events with energy releases in the range 1-100 keV.

- Expected performance is:
  - High detection efficiency down to 1 keV;
  - Directionality at 10 keV;
  - Background rejection below 10 keV;



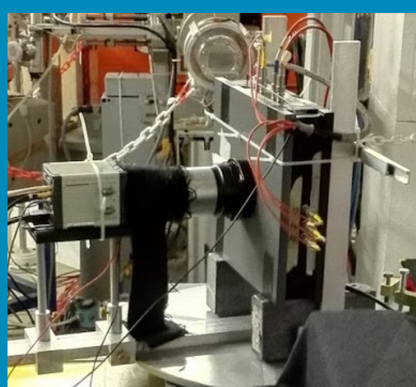
- Main ideas of the technology are:
  - He/CF_4 based gas target (atmospheric pressure);
  - GEM amplification stage;
  - Combined optical readout CMOS + PMT;

Project phases

PHASE 0: R&D

PHASE 1: ~1M³ DEMOSTRATOR

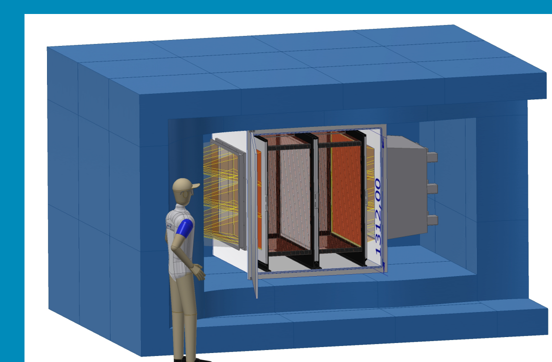
2018	2019	2020	2021/22	2023
@ ROMA1/LNF	@ LNF	@ LNF/LNGS	@ LNF/LNGS	@ LNGS
ORANGE	LEMON	LIME	Construction & test	Installation & commissioning



- 1 cm drift

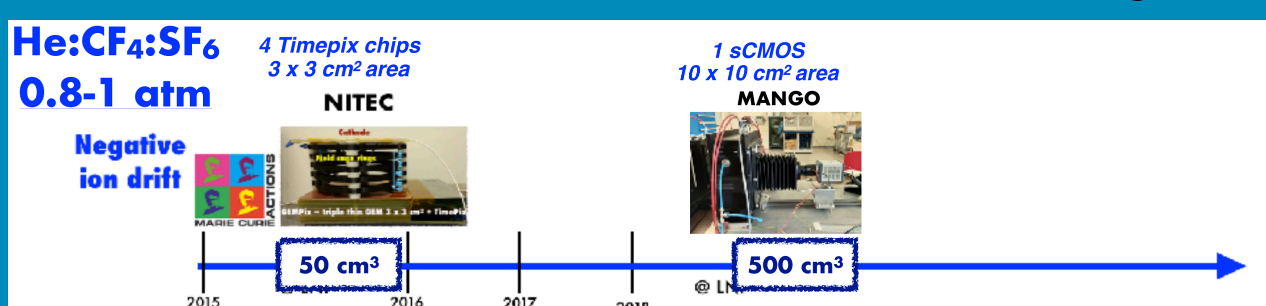
- 3D printing
- 20 cm drift

- 50 cm drift
- underground tests
- shielding



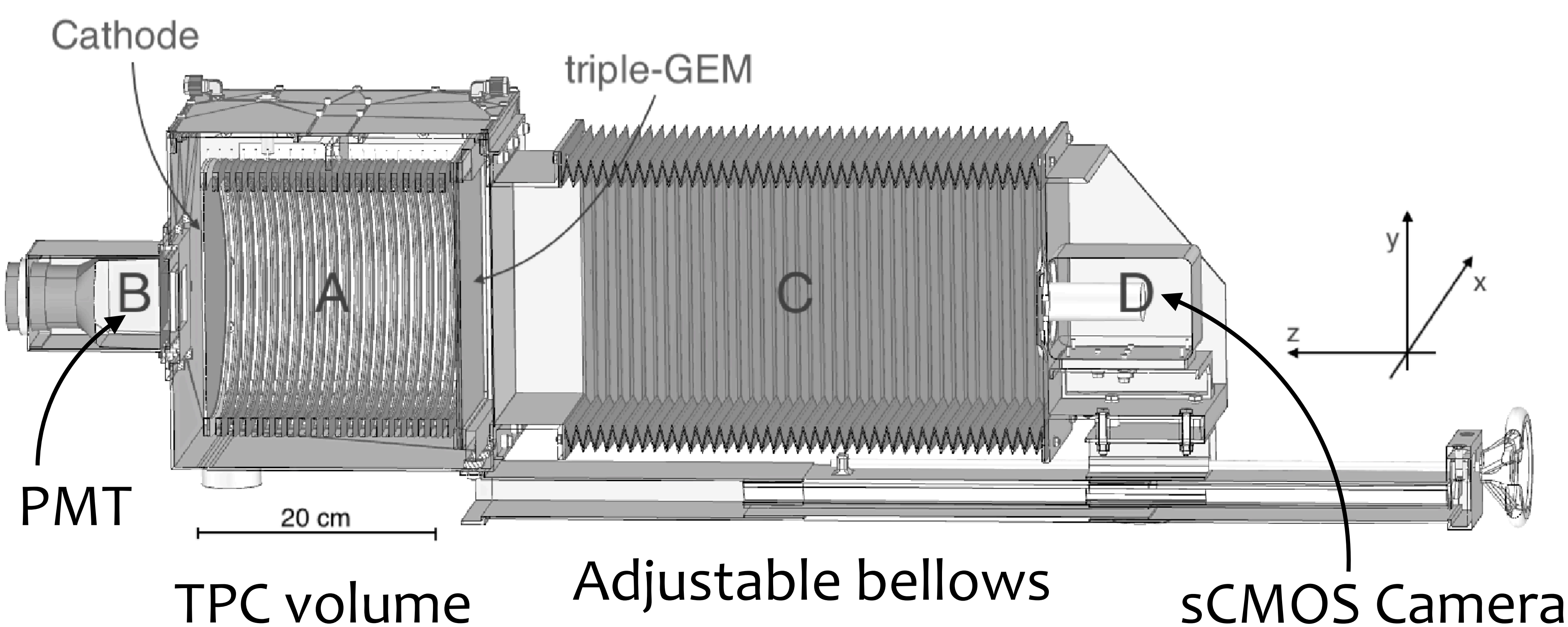
- background
- materials test
- gas purification
- scalability
- reliability

CYGNUS 30-100 m³



LEMON / LIME prototypes

- Lemon (Lime), prototypes of CYGNO, developed and operated at LNF
  - TPC with with 20 (50) cm drift space
  - Triple GEM (20 x 24 cm^2) in the TPC anode to amplify ionization charge
  - Optical readout of light emitted in the GEM through a CMOS camera
    - 2048 x 2048 pixels (2304 x 2304)
    - 1 pixel ~ 125 x 125 μm^2
    - noise ~ 2 (1) photons / pixel
  - PMT on the cathode side (trigger)



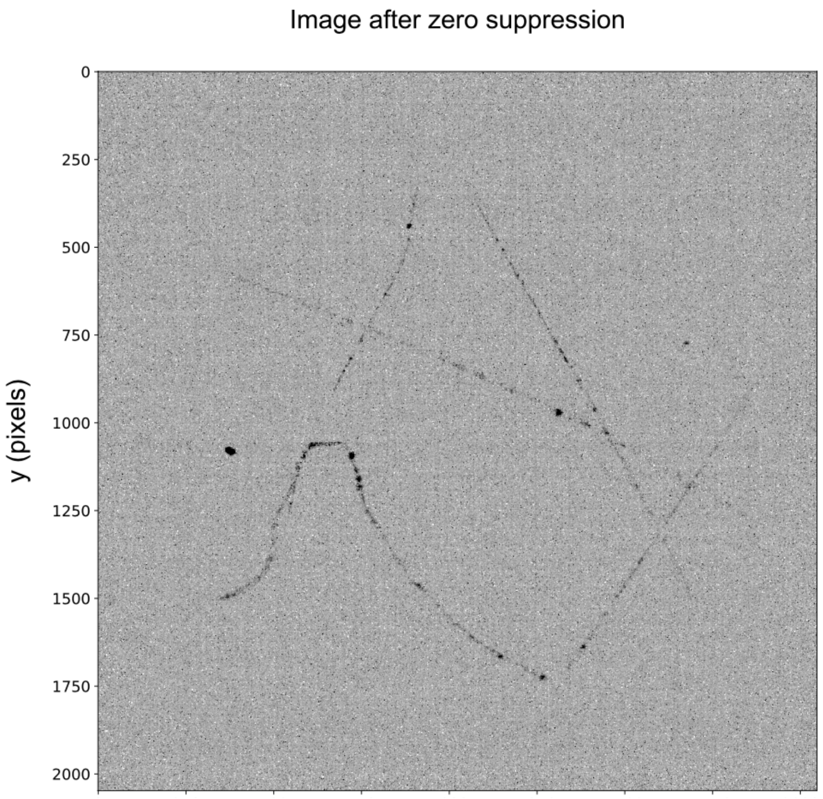
LEMON

Types of runs

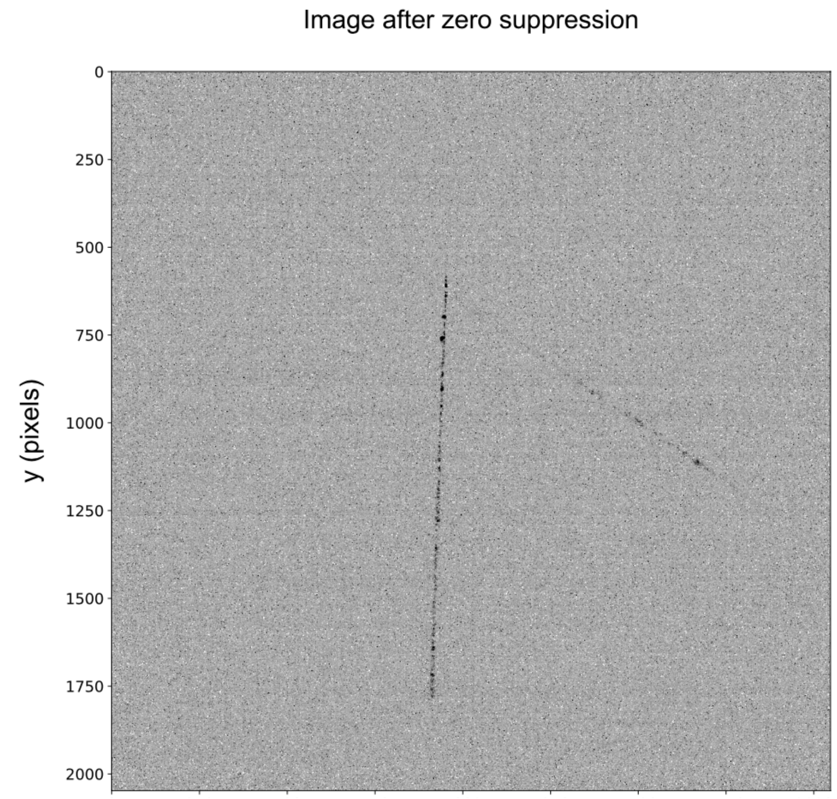
- Runs for Noise measurement: HV lowered to 300 V
  - 2D pedestal map and noise map
- Runs without sources:
  - characterization of ambient background (mostly cosmic rays)
- Runs with ^{55}Fe source:
  - X-rays with energy 5.9 keV: calibration of energy scale and re-assesment of the energy resolution
- Runs with AmBe source (3.5 x 10^3 MBq):
  - photons with E = 59 keV
  - photons with E = 4.4 MeV
  - **neutrons with kinetic energy [1-10] MeV from α-Be interaction => main source of nuclear recoils**

Example images

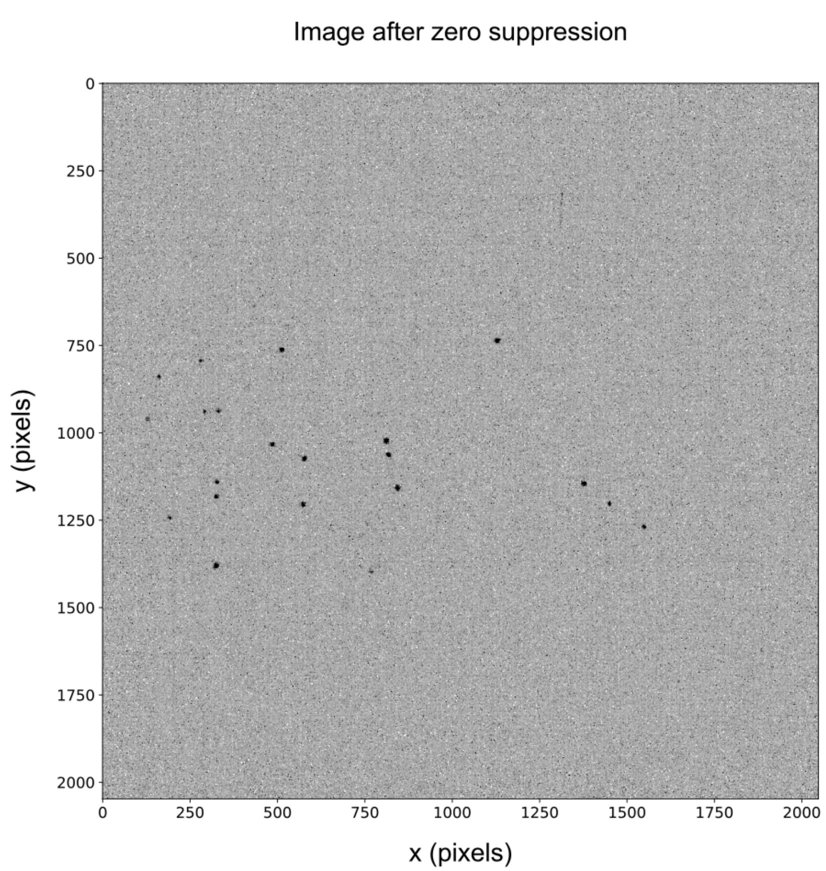
muons
natural radioactivity



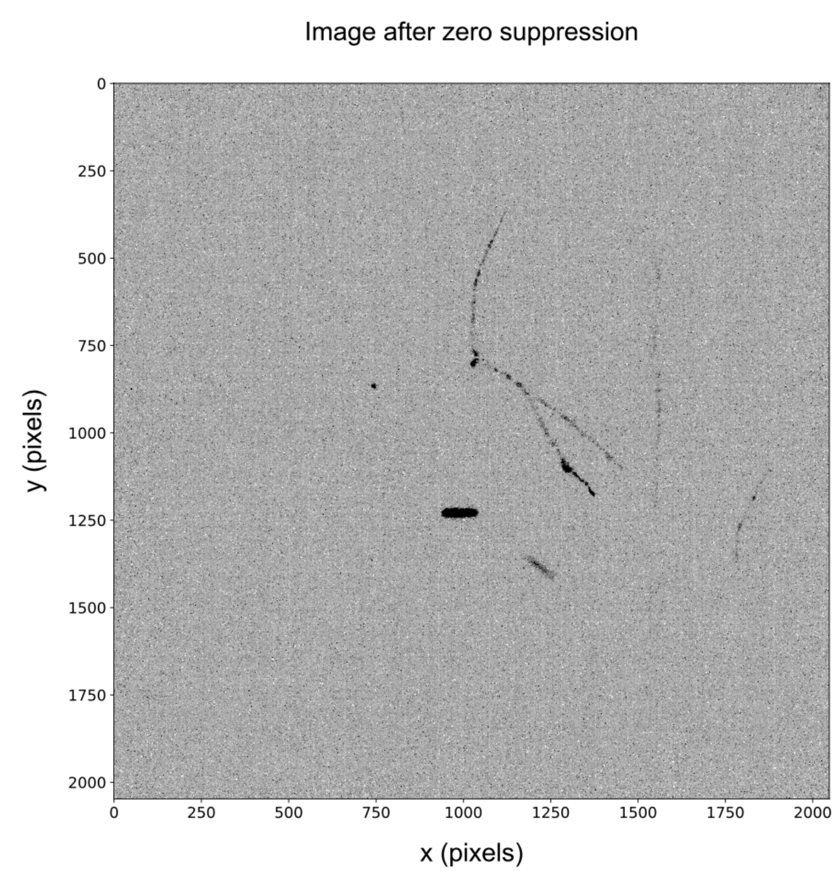
muons



X-rays spots
from ^{55}Fe



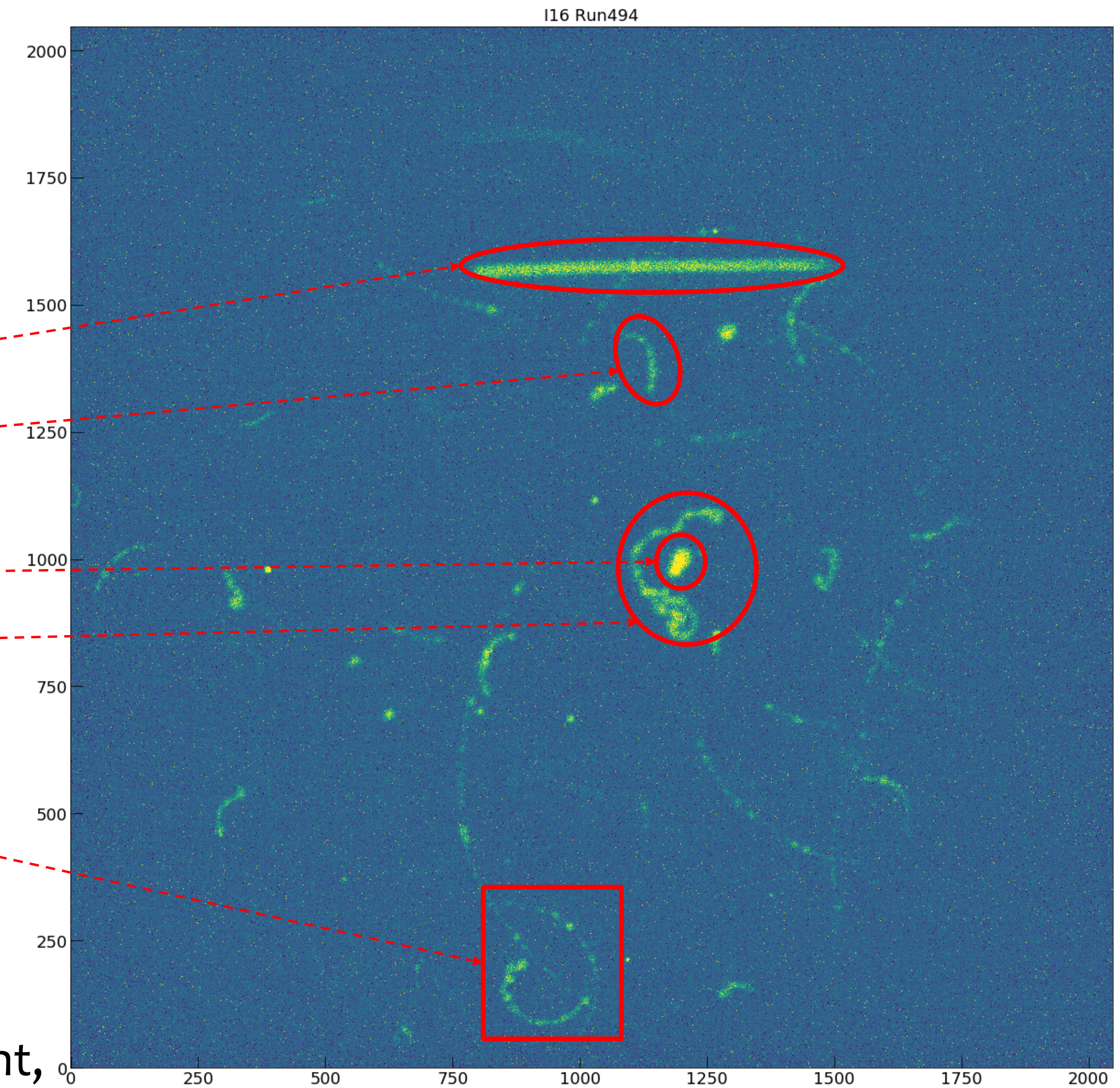
natural radioactivity
energetic nuclear recoil



Example image

This image is an example of what we can have using a specific source and what we need to identify:

- Brighter and long tracks;
- Lighter tracks;
- Brighter and rounded tracks;
- Close tracks;
- Overlapped tracks;
- etc..



The conditions are very different from the real experiment, where it is expect only few natural radioactivity background and the signal which are **short** and **curvy** tracks.

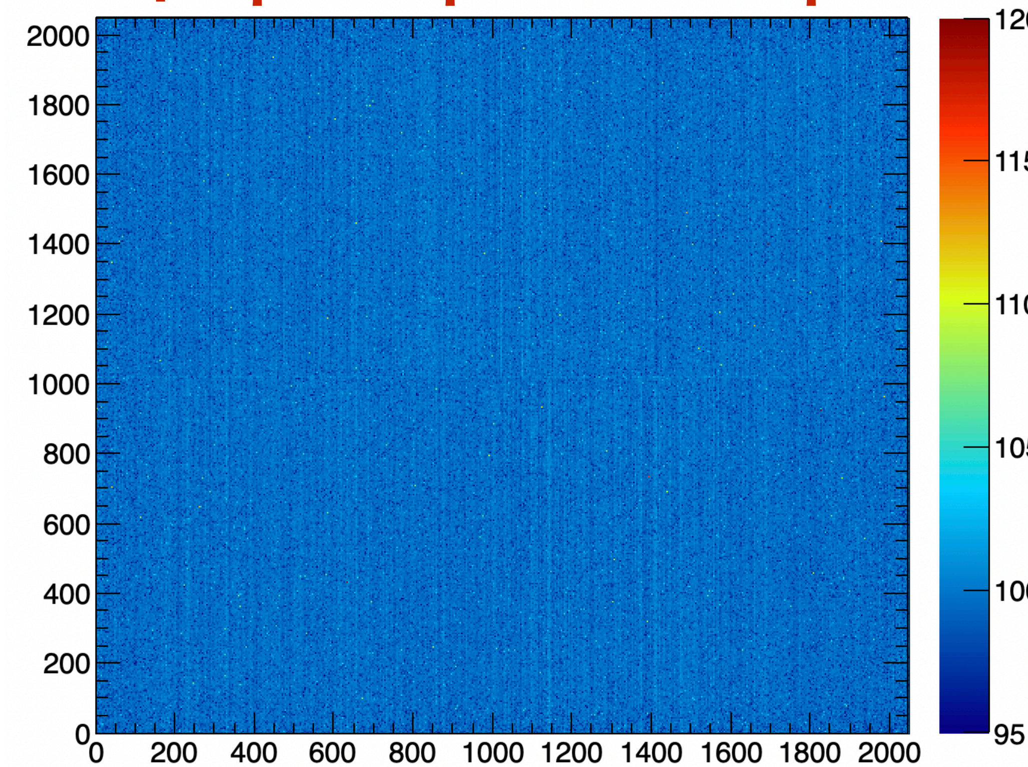
Noise Zero-Suppression

- Noise measured with runs with HV=300 V
- Found to be equivalent to runs in complete dark (camera with its own cap)

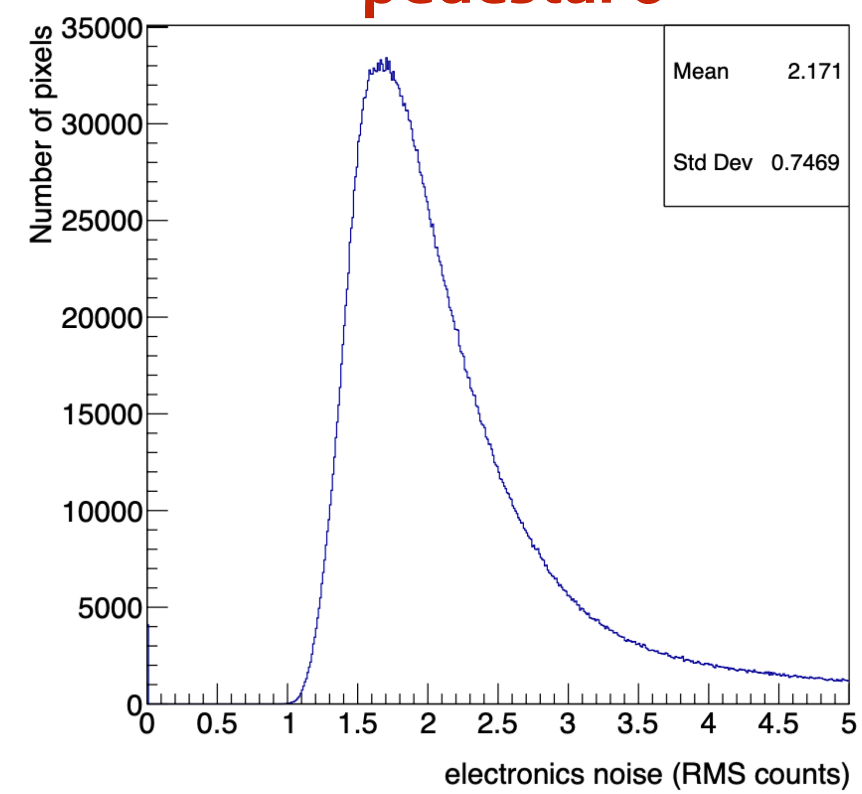
- Pedestal (CMOS sensor baseline) is subtracted pixel-by-pixel
- Zero-suppression to clean sensor noise: $A_i - P_i < 1.3\sigma_i$
  - σ mode = 1.7 photons

- Noise was found to evolve with time. Weekly pedestal runs taken to track:
  - pedestal and standard deviation evolution

4M pixel - pedestal map

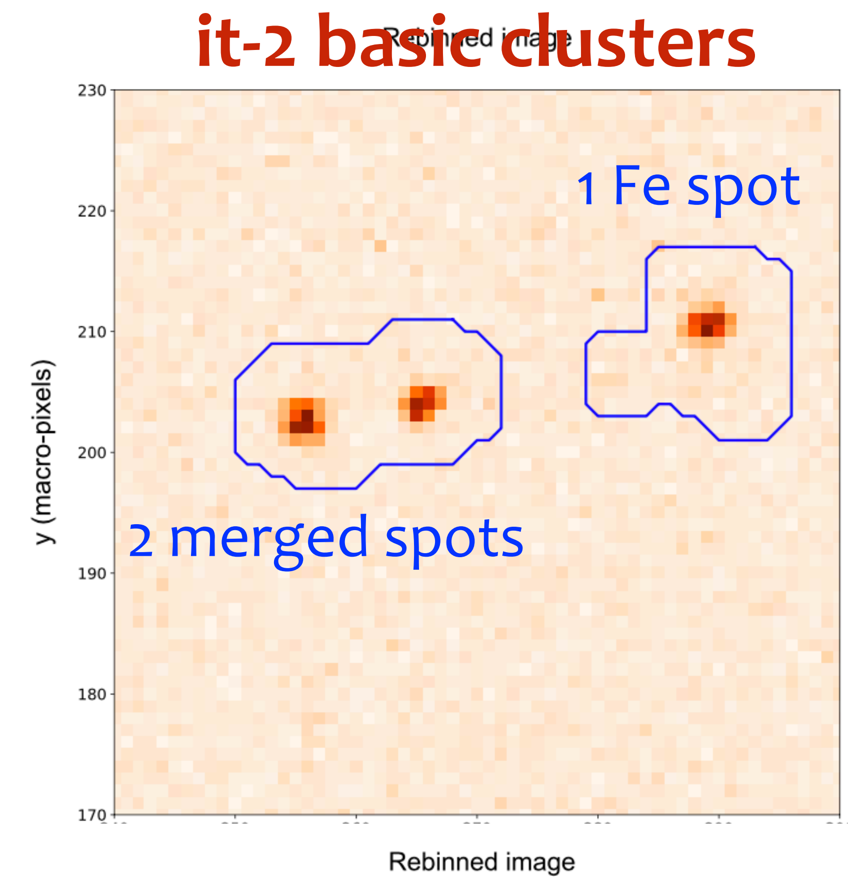


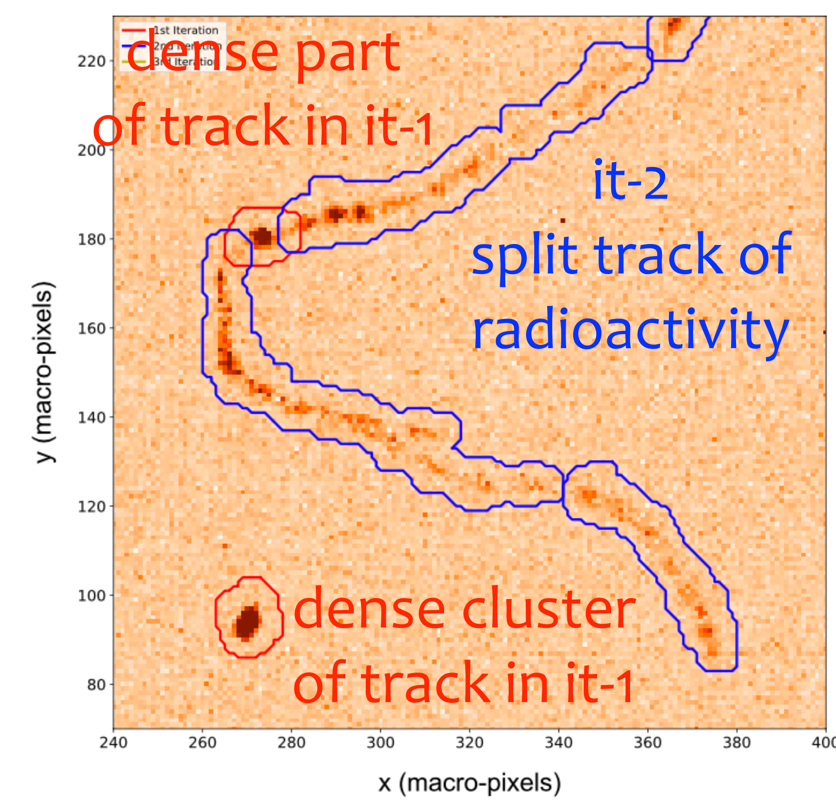
pedestal σ



Basic Clustering

- iDBSCAN: an application of DBSCAN with these peculiarities
  - 3D phase space: 2D spatial coordinates (x,y) + pixel intensities
    - => clusters together neighbor pixels, but “weighting” more pixels with higher light
  - iterative procedure:
    1. parameter set to efficiently cluster very intense energy deposits
       - targets energetic α’s, NRs
    2. remove the clustered pixels, run again with another parameter set
       - targets less intense deposits (most of ^{55}Fe and track pieces go here)
    3. remove again clustered pixels, run again with a loose parameter set
       - target fake clusters from random combinatorics
- **Run on 4x4 rebinned image for CPU-time**





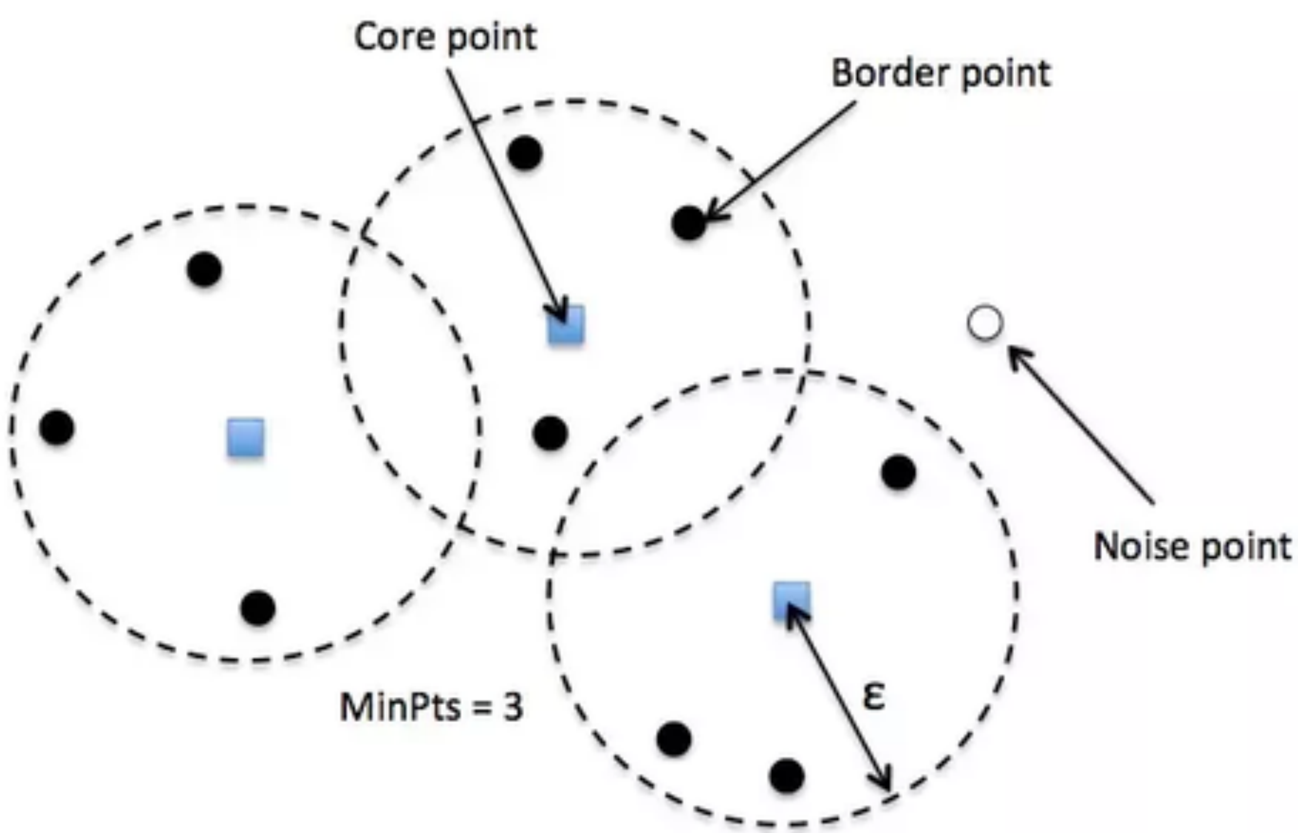
Example of DBSCAN

DBSCAN divides a dataset into subgroups of high density regions using two parameters: epsilon (**ε**) and minimum amount of points required to form a cluster (**minPts**).

Core point – a point that has at least a minimum number of other points (minPts) within its ε radius;

Border point – a point is within the ε radius of a core point BUT has less than the minimum number of other points (minPts) within its own ε radius;

Noise point – a point that is neither a core point or a border point.



Super Clustering

- Need of something that joins pieces for cosmics / longer tracks
- Use full-resolution to be sensitive to gradients of clusters in zones of local minima of the energy release along the path

- **chosen Morphological Geodesic Active Contours (GAC):**
  - able to follow kinks and change from convex -> concave shape along track
  - very efficient in zones of low information
  - can shrink efficienty along the crest of the cluster (300 iterations)

- An "old" algorithm, but with recent developments:
  - Kass, Witkin, Terzopoulos *Snakes: Active contour models.* Int J Comput Vision 1, 321–331
  - Caselles, Kimmel and Sapiro, 1997 *Geodesic Active Contours* Int. J. Comput. Vis. 22 61–79
  - Márquez-Neila, Baumela and Alvarez, 2014 *A morphological approach to curvature-based evolution of curves and surfaces*, IEEE Trans. Pattern Anal. Mach. Intell. 36 2–17

Following gradients

- The supercluster is a deformable spline which is sensitive mainly to the gradient (in intensity) of the image, with a weight which considers the continuity and the smoothness of the contour

$$||\nabla(N_{ph})|| = \sqrt{\left(\frac{\partial N_{ph}}{\partial x}\right)^2 + \left(\frac{\partial N_{ph}}{\partial y}\right)^2},$$

gradient in intensity

$$\theta = \tan^{-1}\left(\frac{\partial N_{ph}}{\partial y} / \frac{\partial N_{ph}}{\partial x}\right).$$

gradient in direction

- superclustering is a minimization of the “energy” along the boundary curve C

$$E(\mathcal{C}) = \int_0^1 g(N_{ph})(\mathcal{C}(p)) \cdot |\mathcal{C}_p| dp,$$

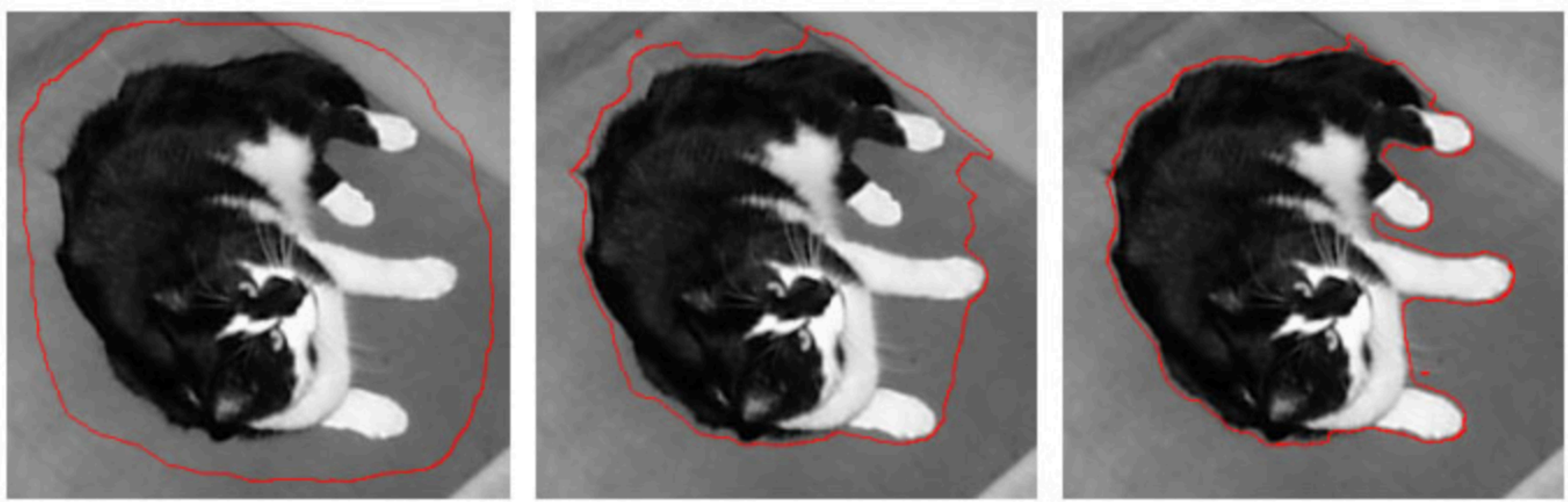
- the “stopping function” g defines where the edge is located, and it is purely geometrical (geodesic)

$$g(N_{ph}) = \frac{1}{\sqrt{1 + \alpha|\nabla G_\sigma * N_{ph}|}},$$

- some additional constrain is used to ensure the smoothness of the contour, especially to follow patterns which turn from convave to convex

Iterative algorithm

- It starts from the whole pictures, then iteratively shrinks

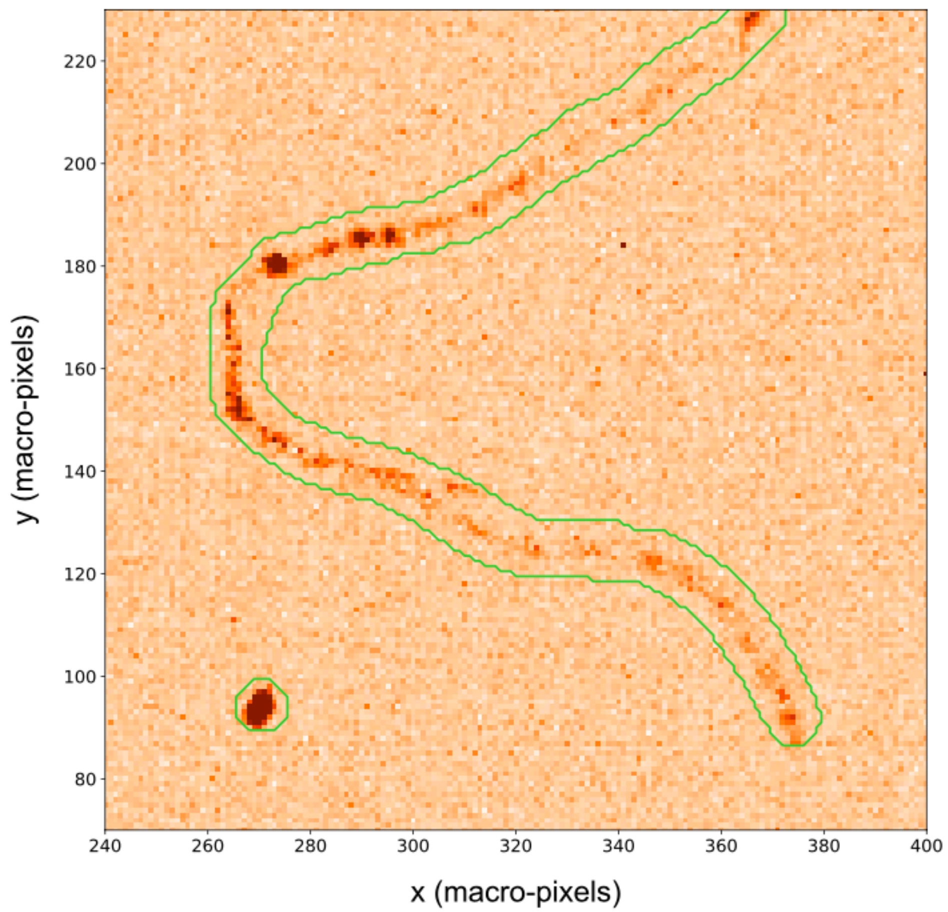


10^{th} iteration 50^{th} iteration 300^{th} iteration

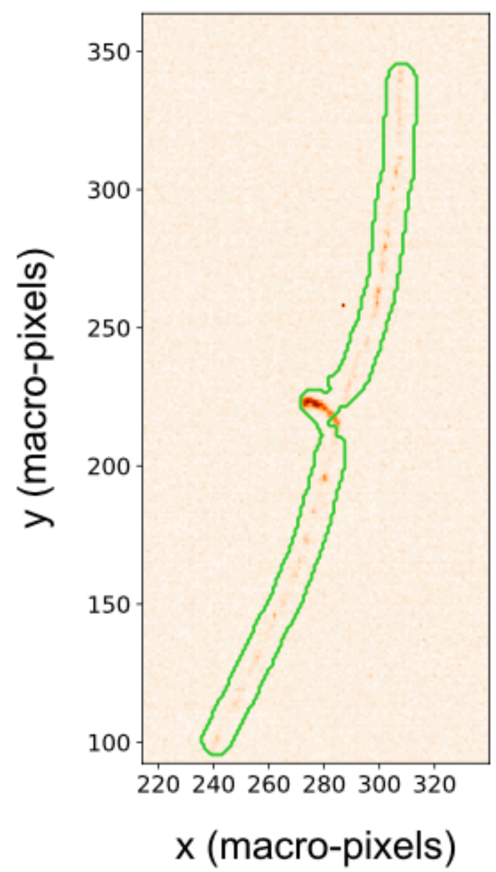
- the number of iterations depend on many details: smoothness of the contour, contrast, noise, etc.
  - some multi-dimensional optimization is needed for a given case
- All reconstruction (RAW input, zero-suppression, basic clusters, super clusters, calculation of cluster shapes, ROOT output) takes **~1s / image**

supercluster examples (LEMON)

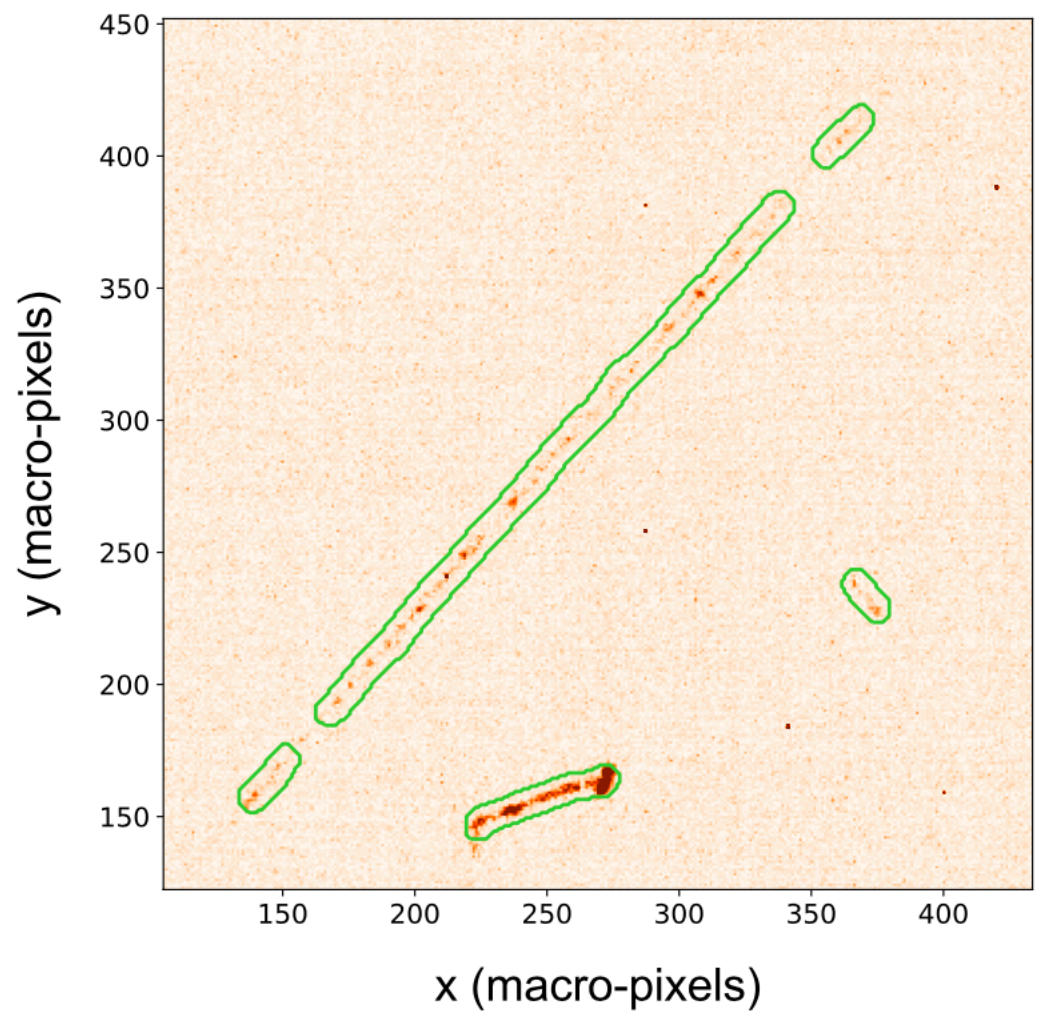
dense+faint regions joined



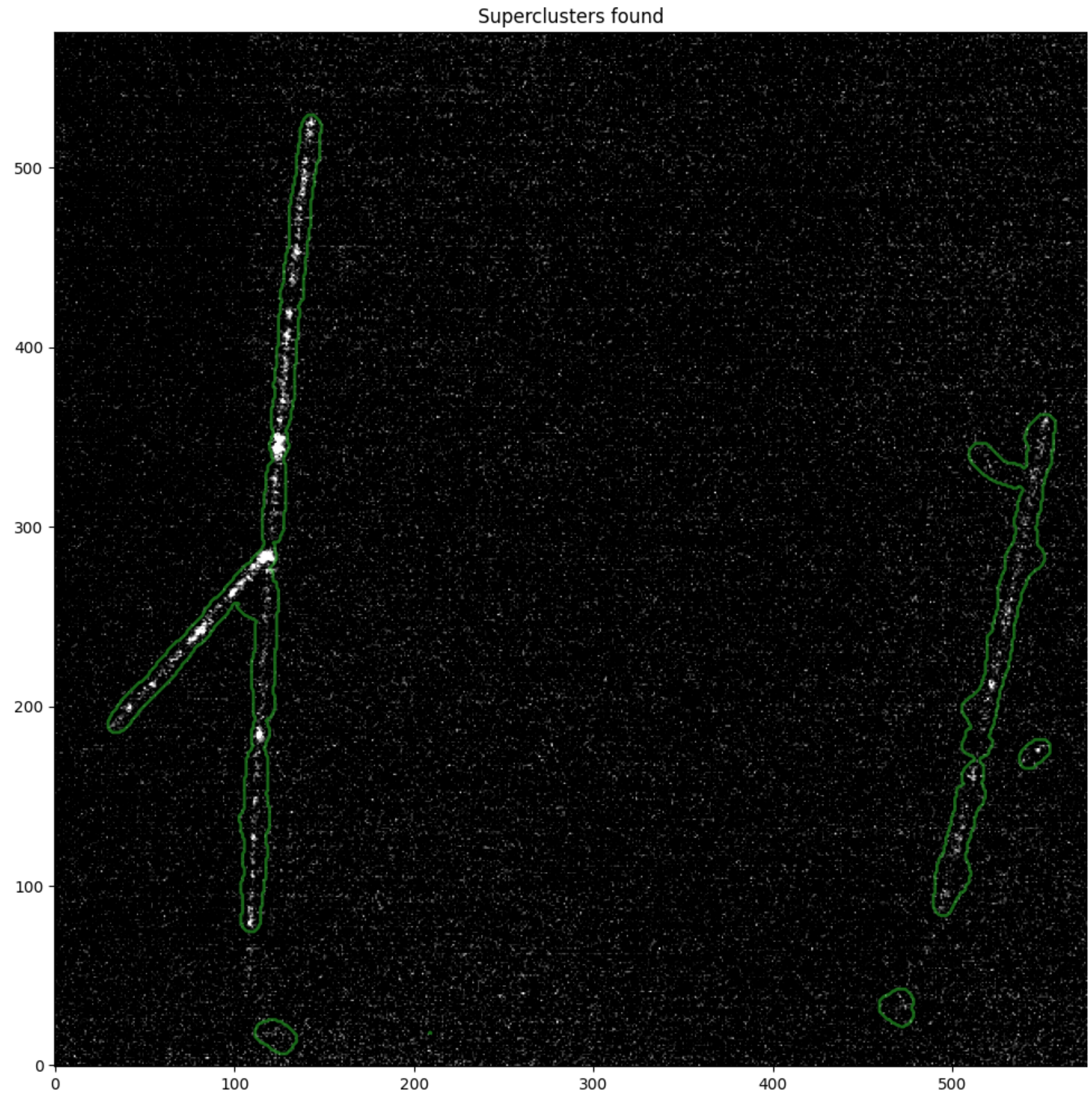
long track + δ ray

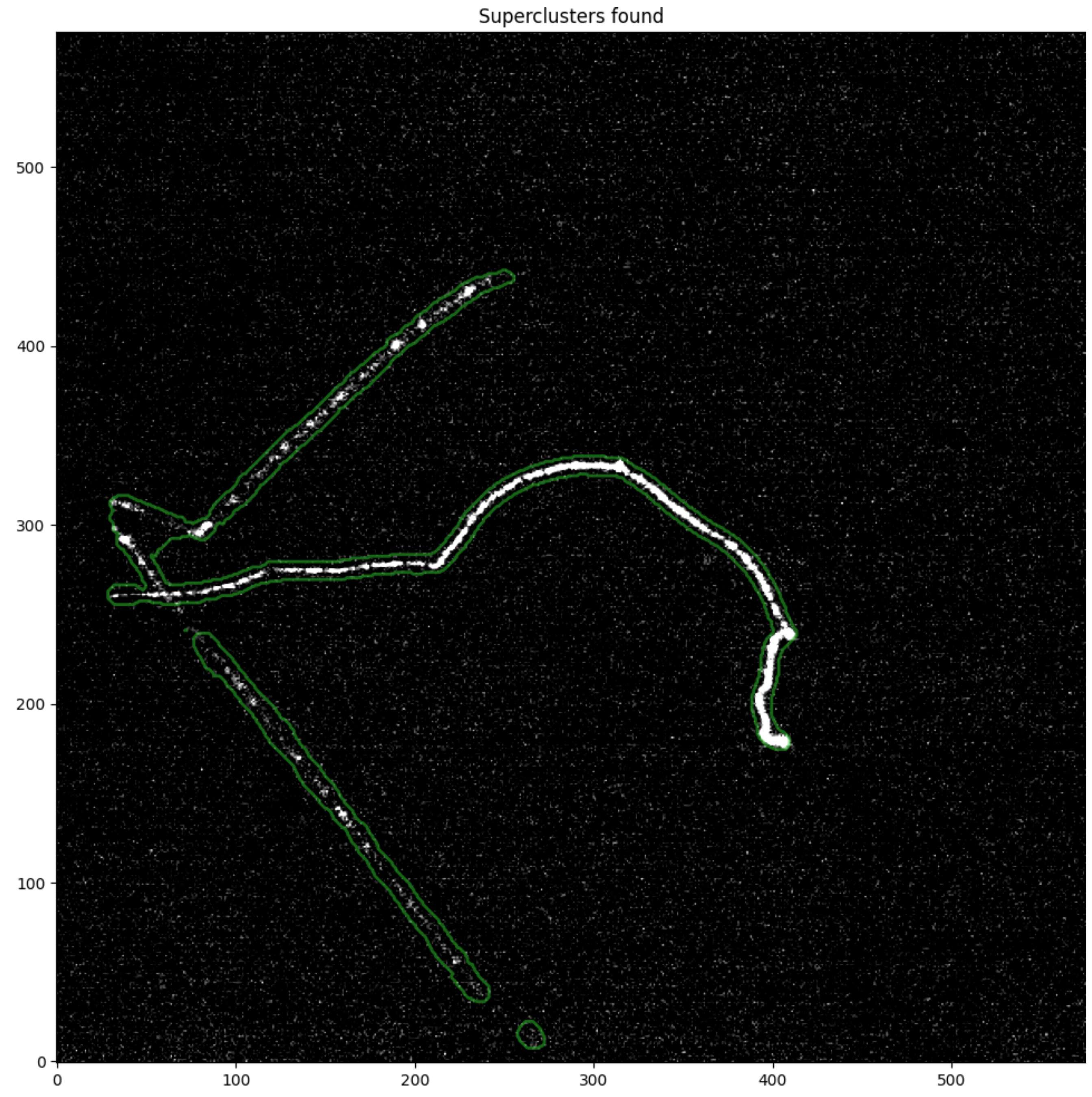


long muon track + probable α

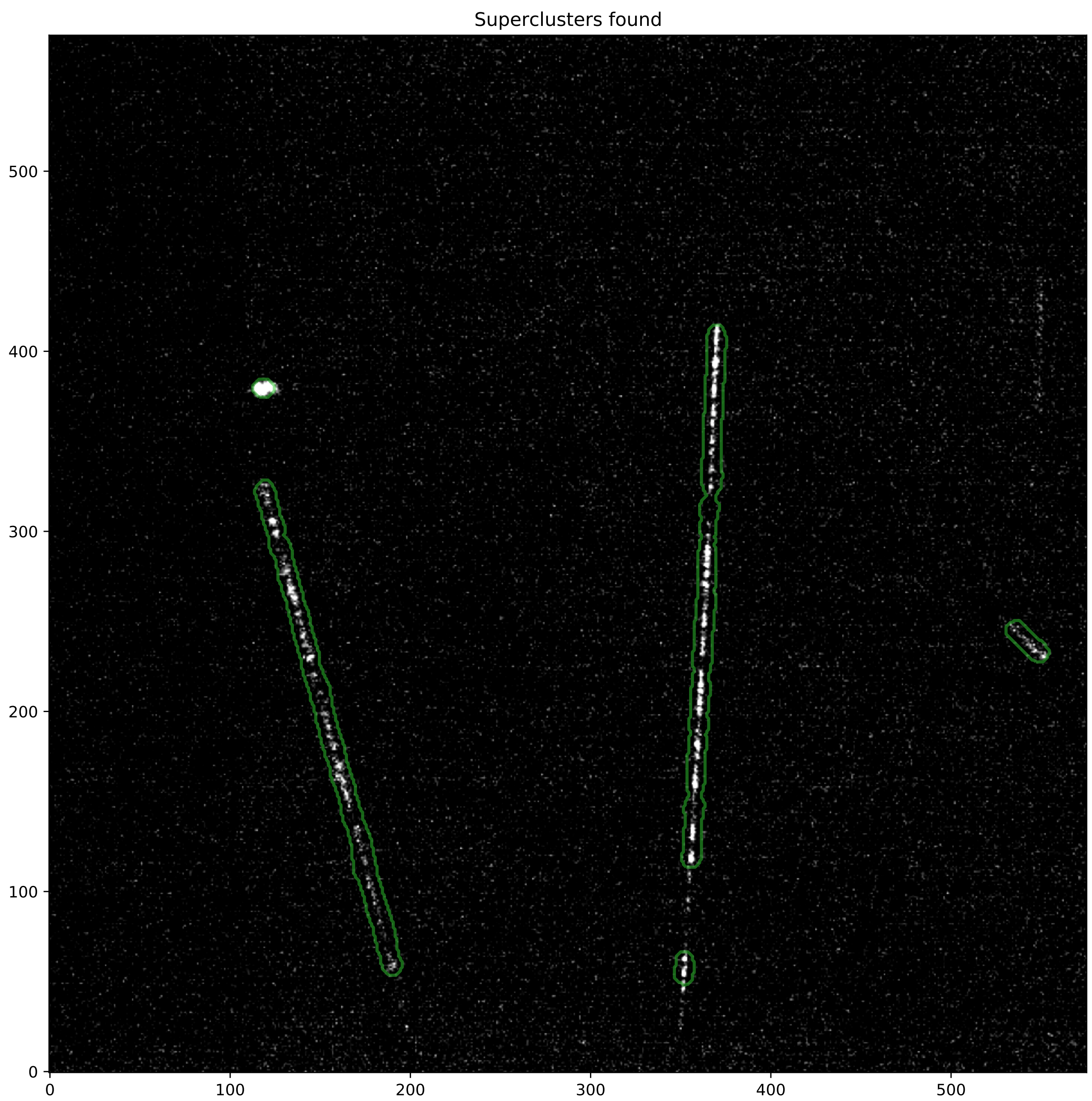


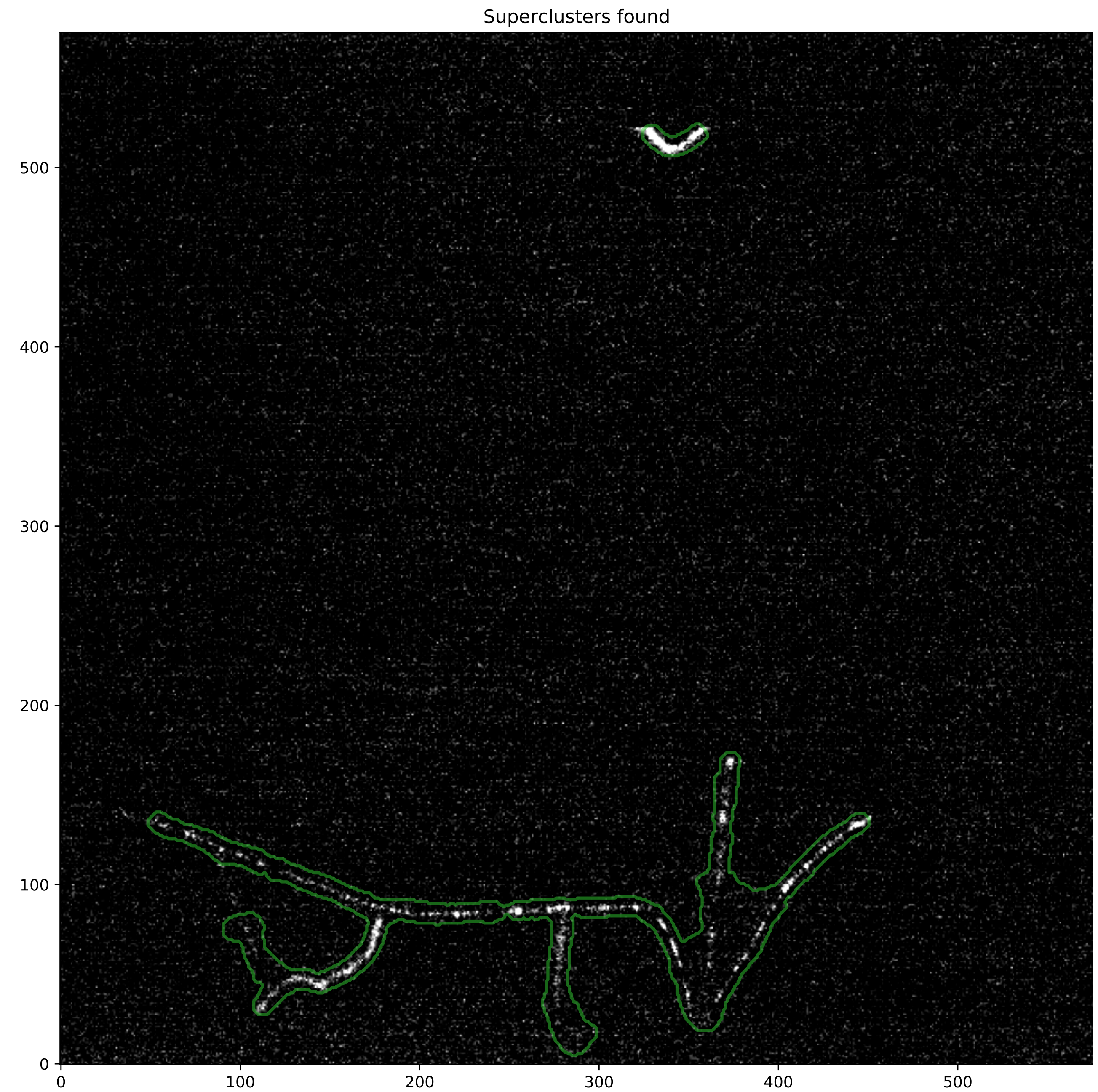
Supercluster examples (LIME)



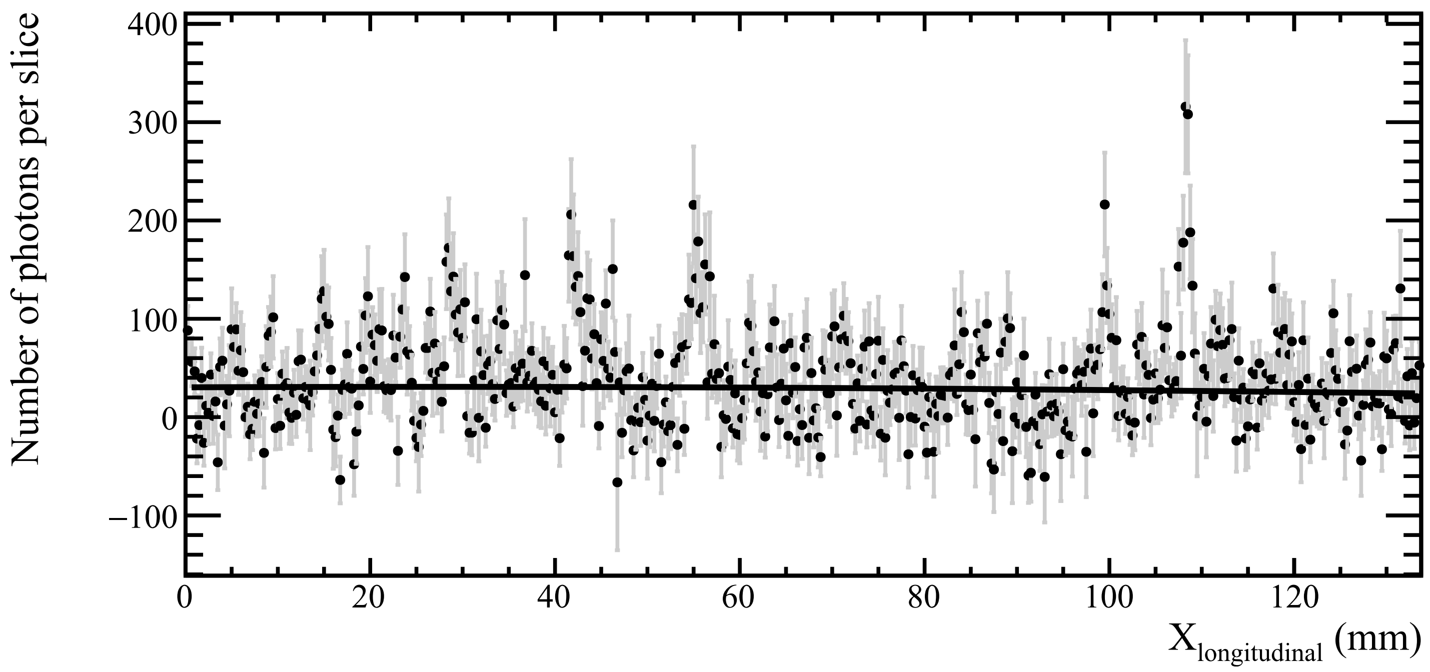


Supercluster examples (LIME)

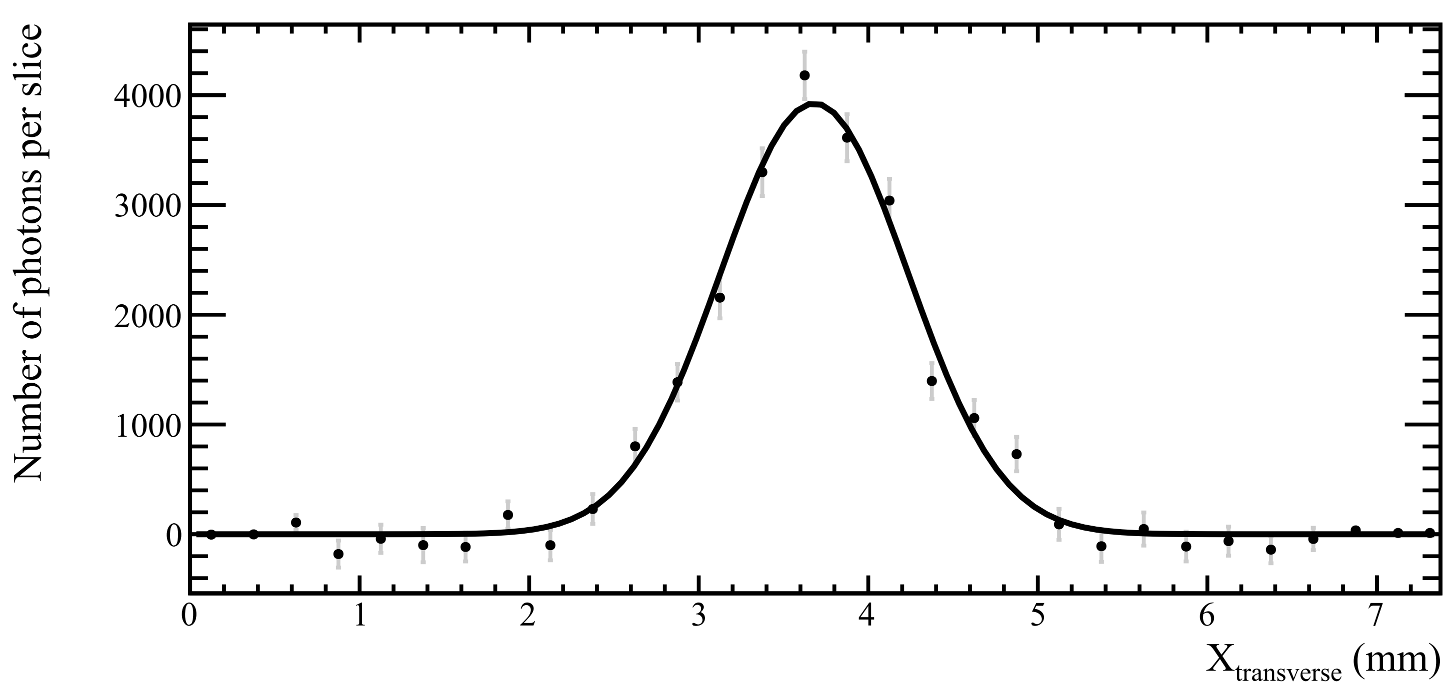




Profiles along the track



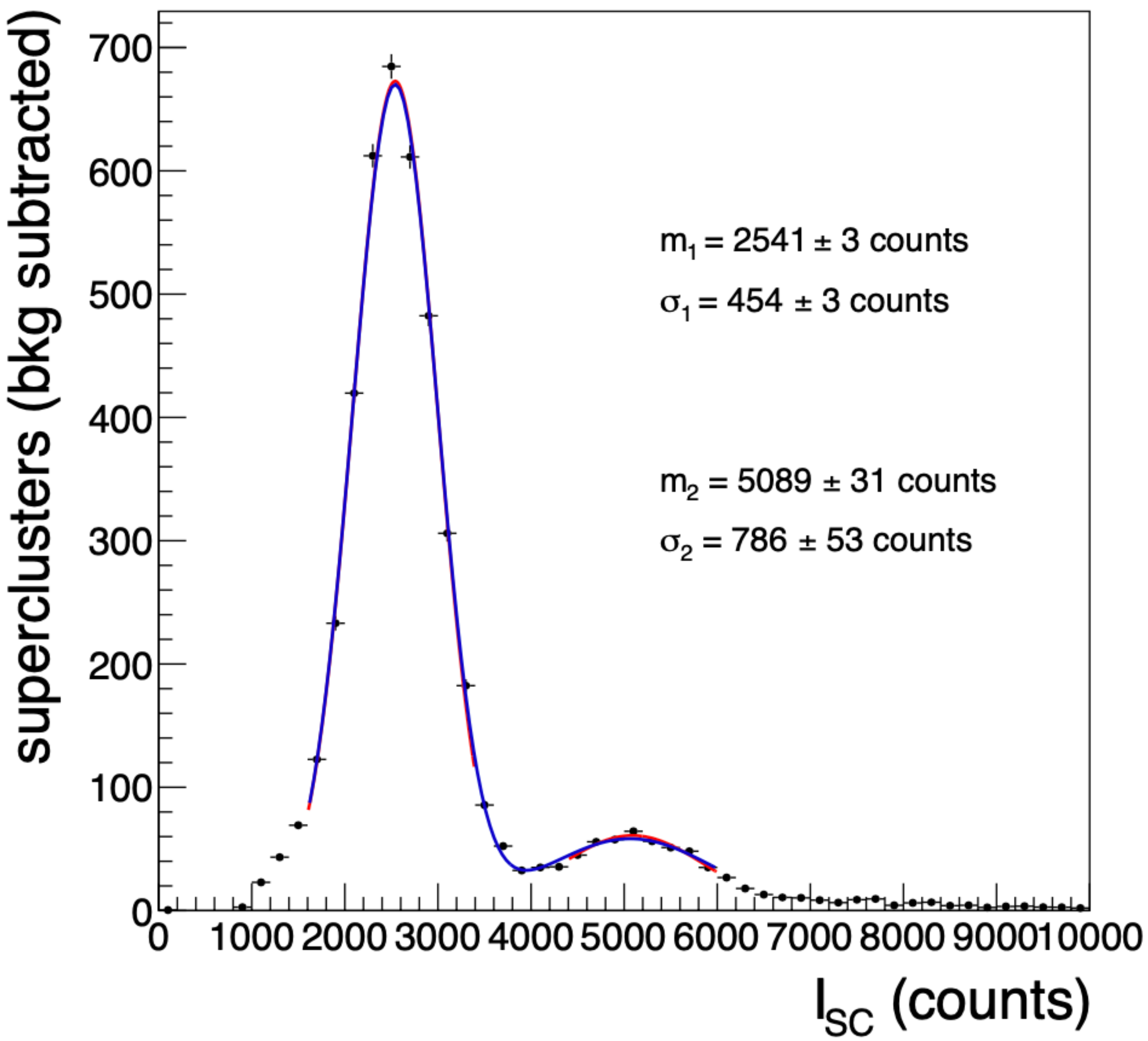
Following the track pattern, the single clusters of energy deposition are visible



Clear profile in the transverse direction

Energy scale calibration

- The visible energy of the clusters is calibrated using the average photon counts in clusters reconstructed in ^{55}Fe (E=5.9 keV)



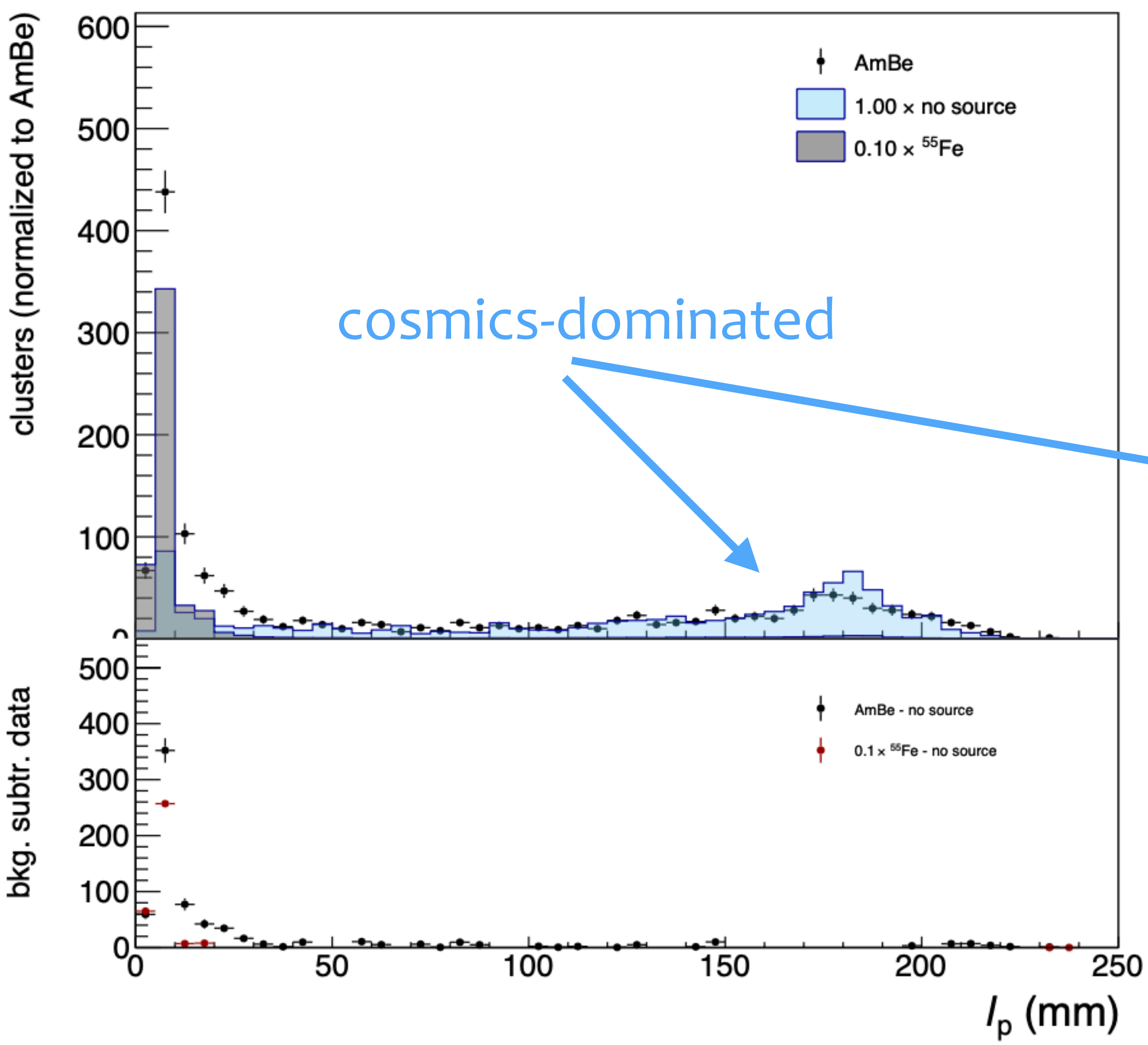
~2500 photons/cluster

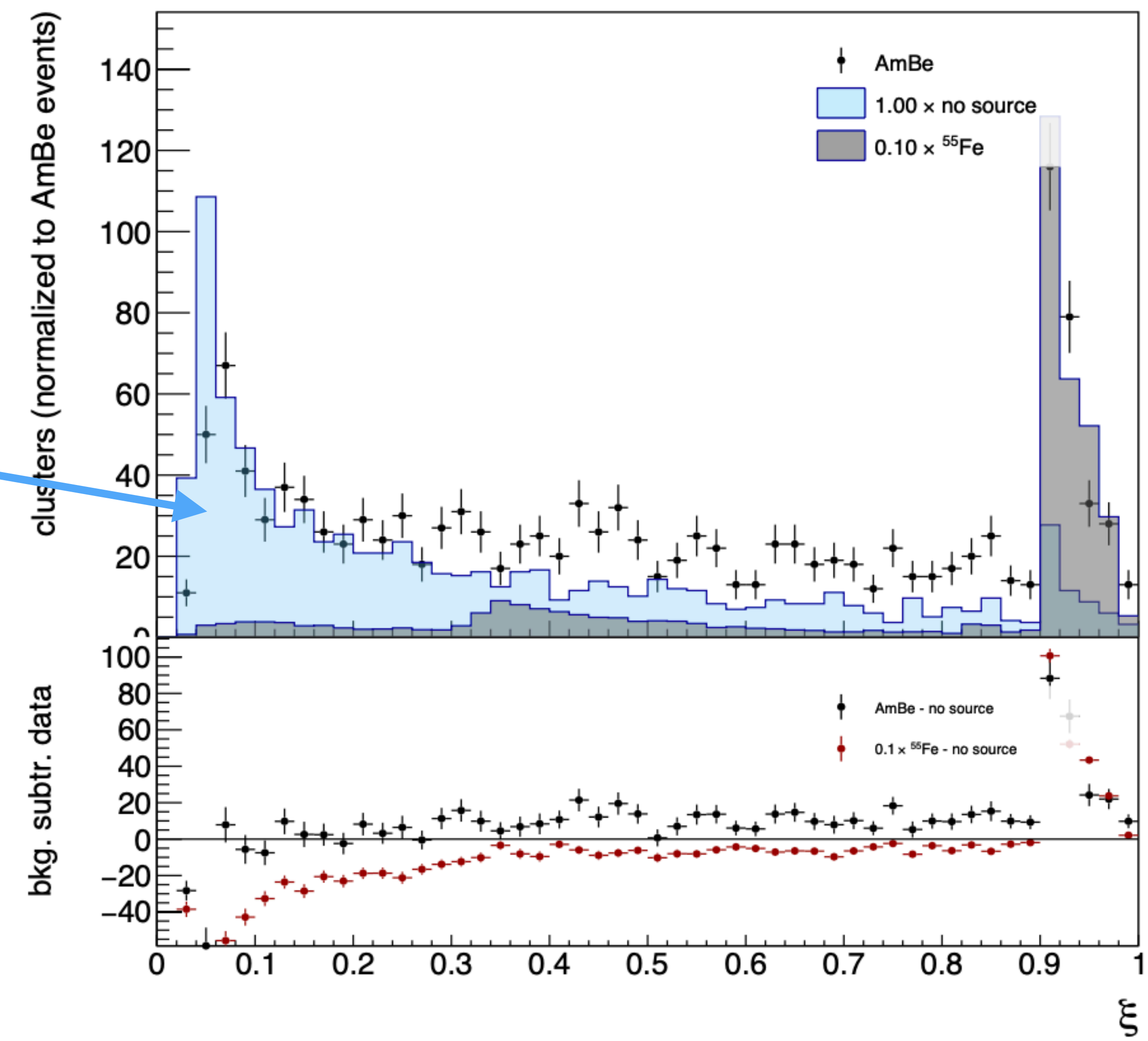
average σ(E)/E ~ 18%

~10% of merged spots clearly separated

Cluster shapes

- Easy handles to reject the ubiquitous background from cosmic rays:
  - long (l_p>13 cm) and "slim" (low aspect ratio: ξ = width / length)





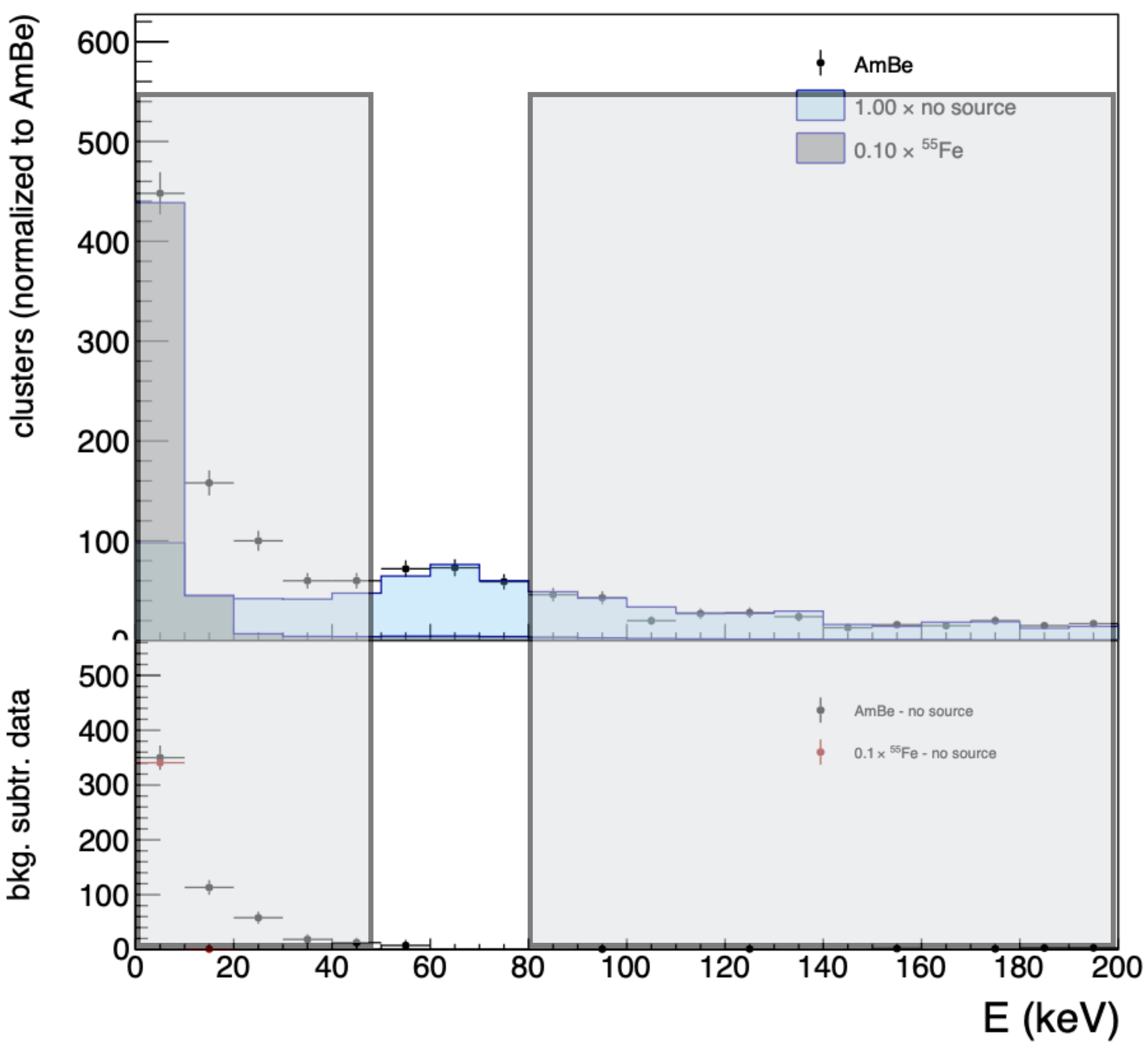
track length l_p **track aspect ratio ξ**

Background normalization

- No-source runs are used to get the templates of any variable to statistically subtract cosmics background from runs with source
- First, normalize the cosmic templates to the same live-time (40ms * N_{frames})
- ~OK, apart a small PMT-trigger bias:
  - in AmBe runs: recoils + cosmics present
  - in no-source runs: only cosmics present
  - => PMT triggers more frequently on cosmics in no-source runs than in AmBe runs for the same live-time (40 ms)
- Find a control region pure in cosmics in both AmBe and no-source runs (CR)
  - Energy 50<E<80 keV (2.3 keV / cm), long and slim tracks
- Compute trigger scale factor SF:

$$\varepsilon_{SF} = \frac{N_{CR}^{AmBe}}{N_{CR}^{no-source}}. \quad \sim 75\%$$

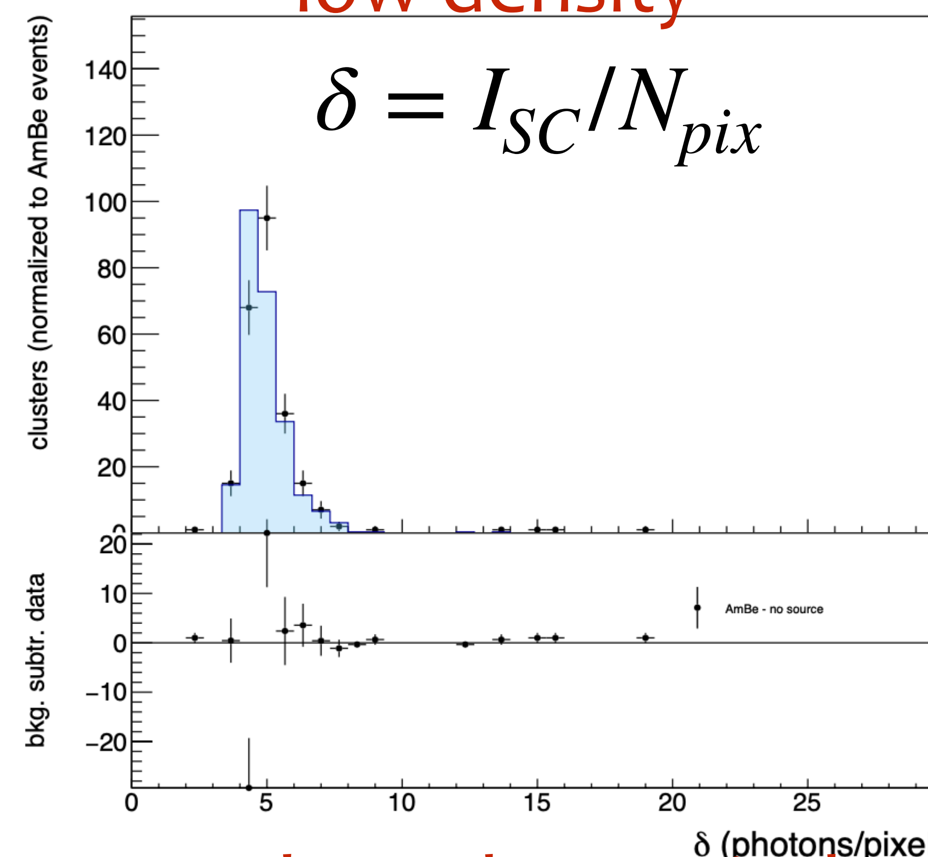
Cosmics control region



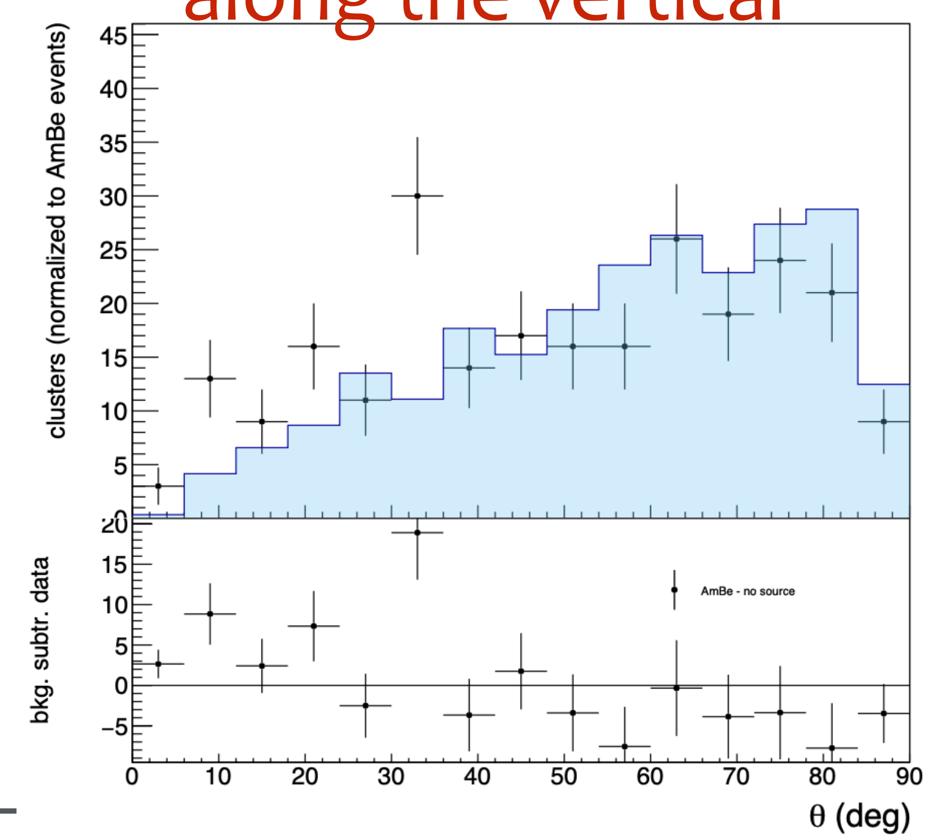
energy region for an expected
~2.3 keV/cm
energy release

low density

$$\delta = I_{SC}/N_{pix}$$

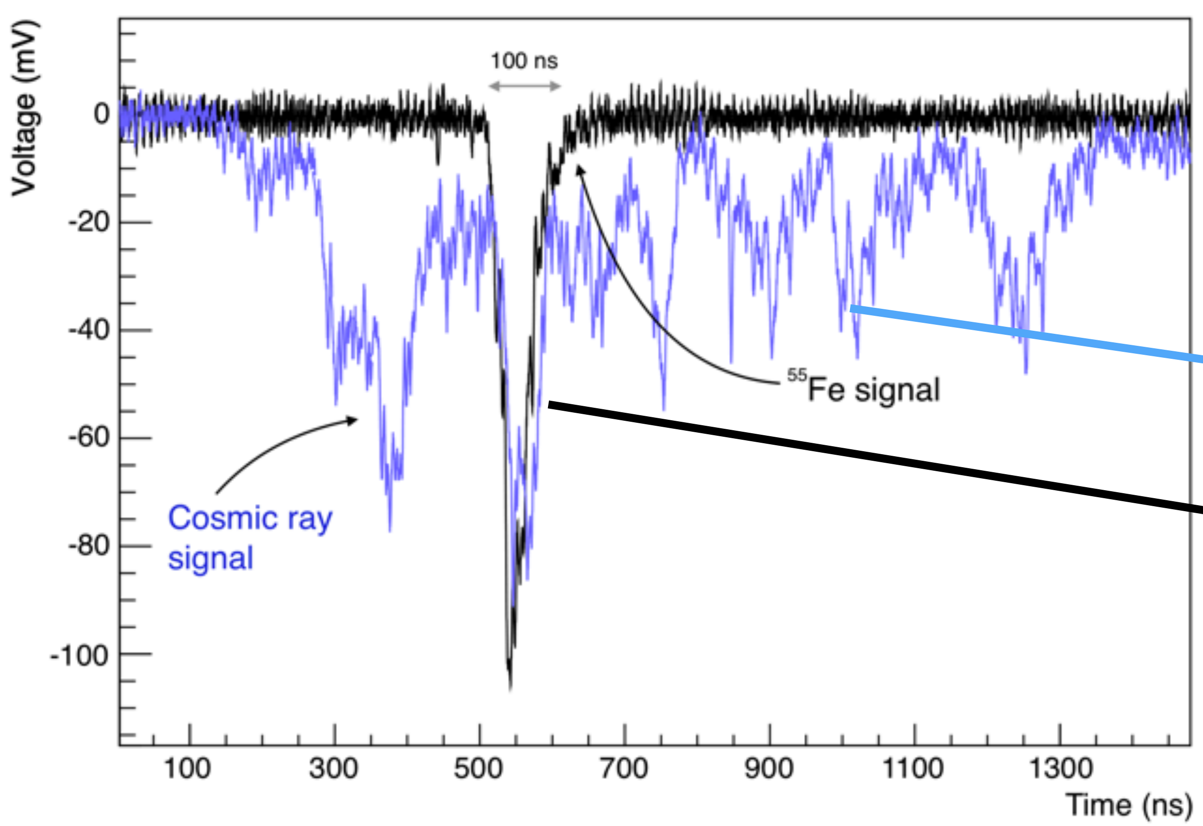


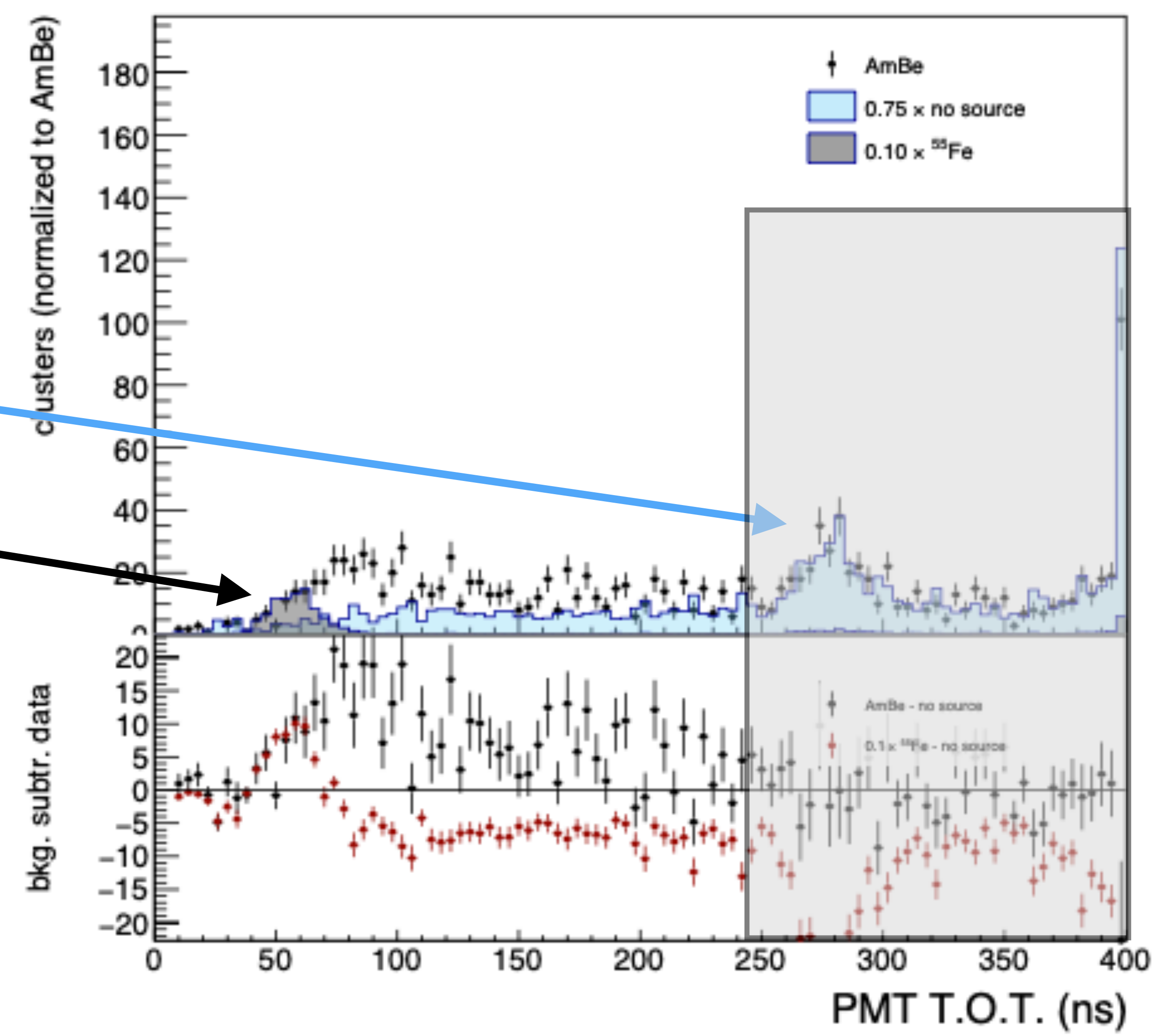
along the vertical



Further μ-rejection using PMT

- Residual background from cosmic rays with small pieces of tracks not joined by the supercluster can be still discriminated using the **time information**
- a muon track inclinated wrt the x-y plane produces clusters that arrive to the PMT at different times => broad waveform => large Time Over Threshold (TOT)



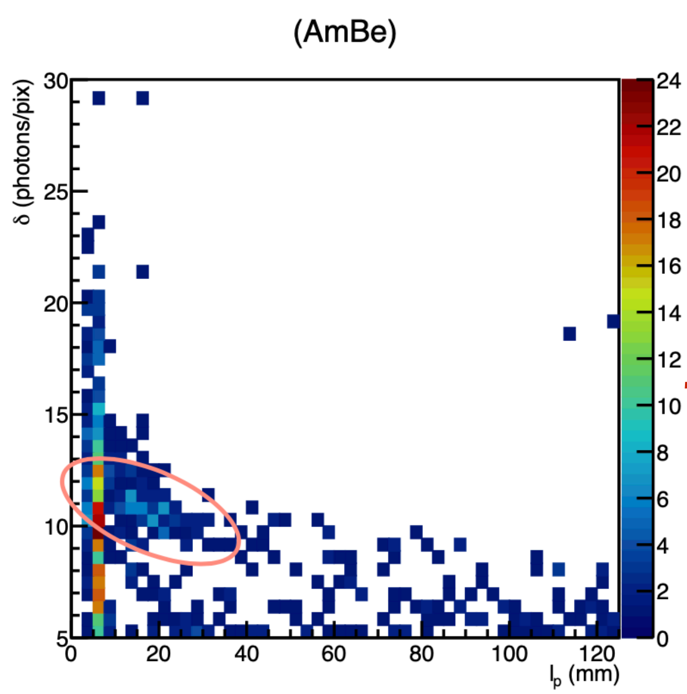


TOT < 250ns:

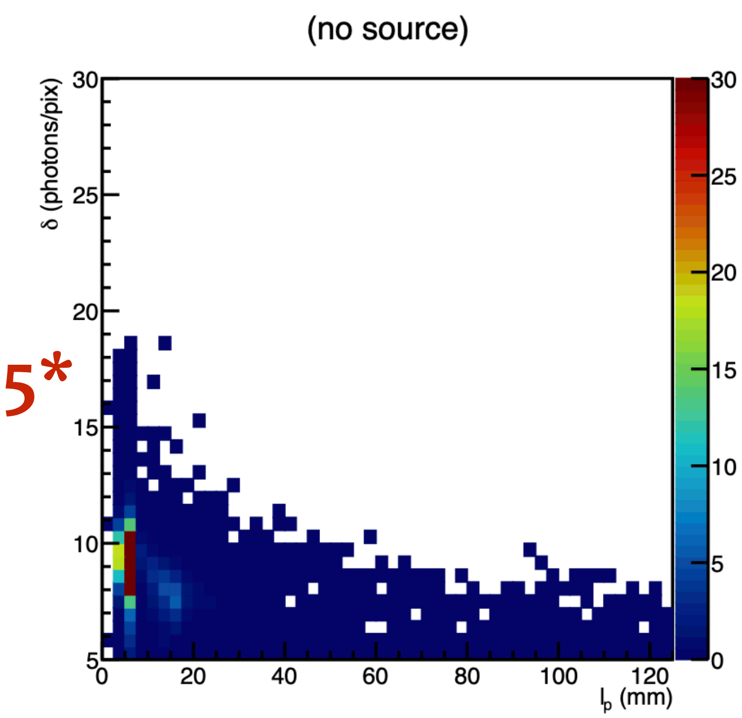
- keeps 98% of Fe/AmBe signals
- rejects ~20% of residual cosmics background

59 keV AmBe γ's

- Another visible candle are recoils induced by 59 keV photons from AmBe
- expected to be medium density, not-spot-like clusters
- This component is clearly visible only in the AmBe runs (after comsic-background subtraction) in the δ vs l_p plane



- 0.75*



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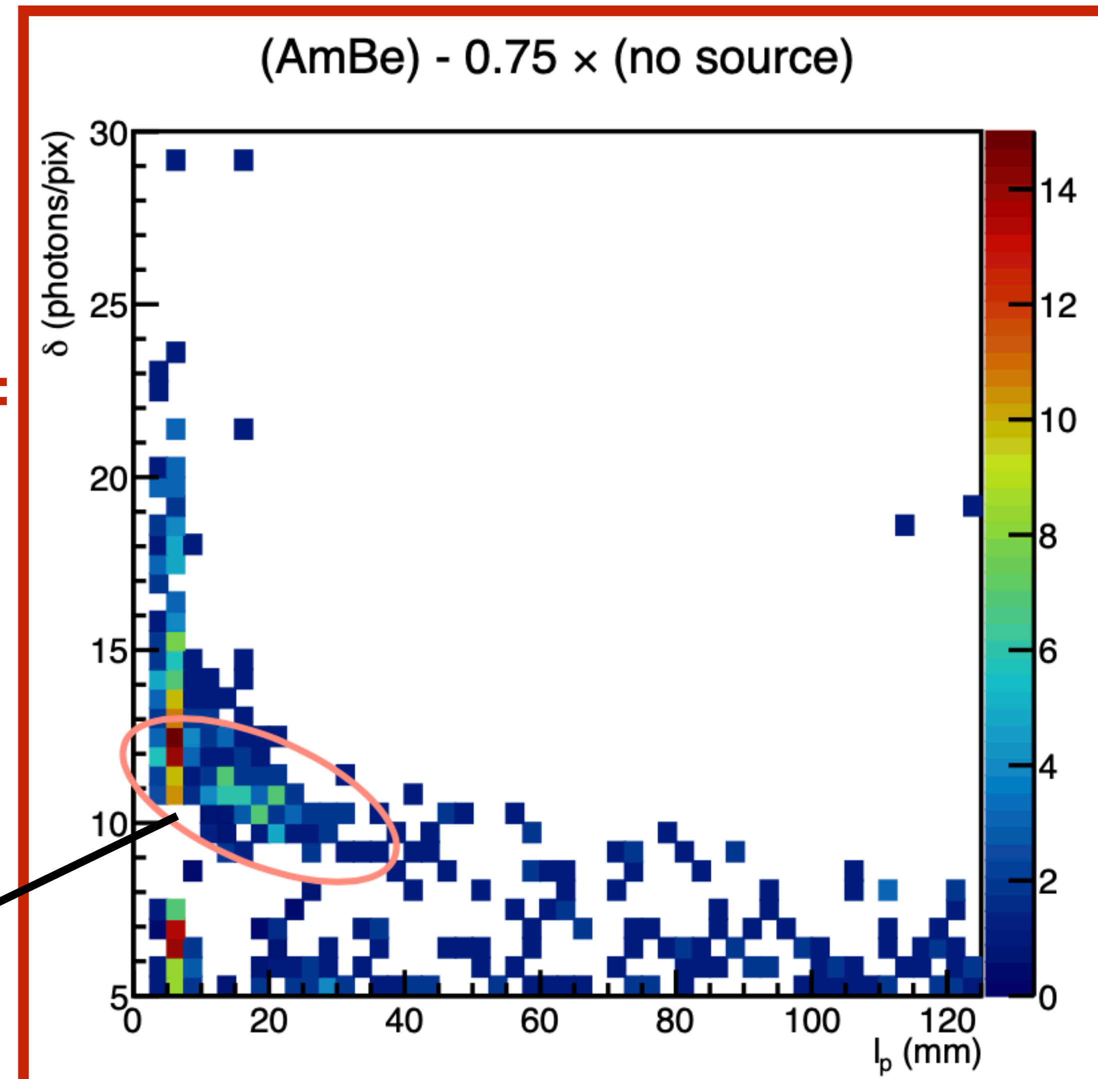
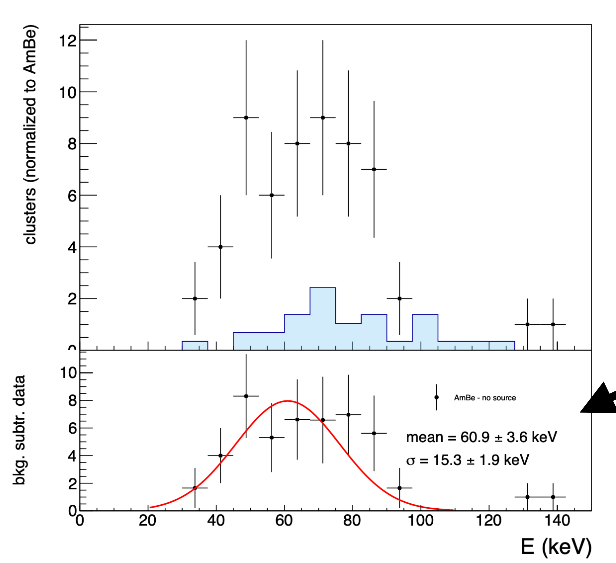
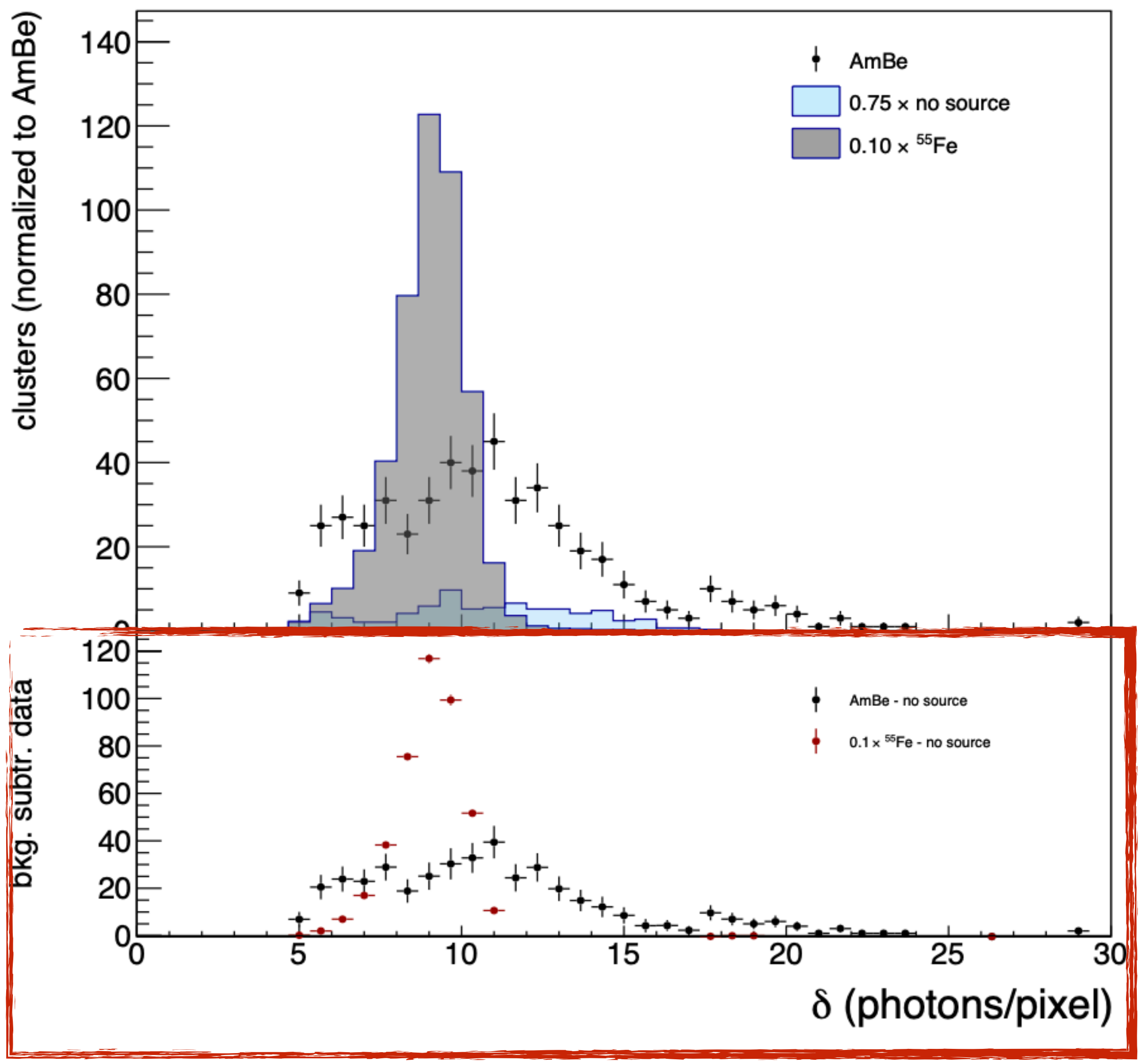




cluster density

- Cluster density $\delta = I_{SC}/N_{pix}$ used as main discriminating variable



After the dedicated bkg-normalization and bkg-subtraction shows 2 populations in AmBe:

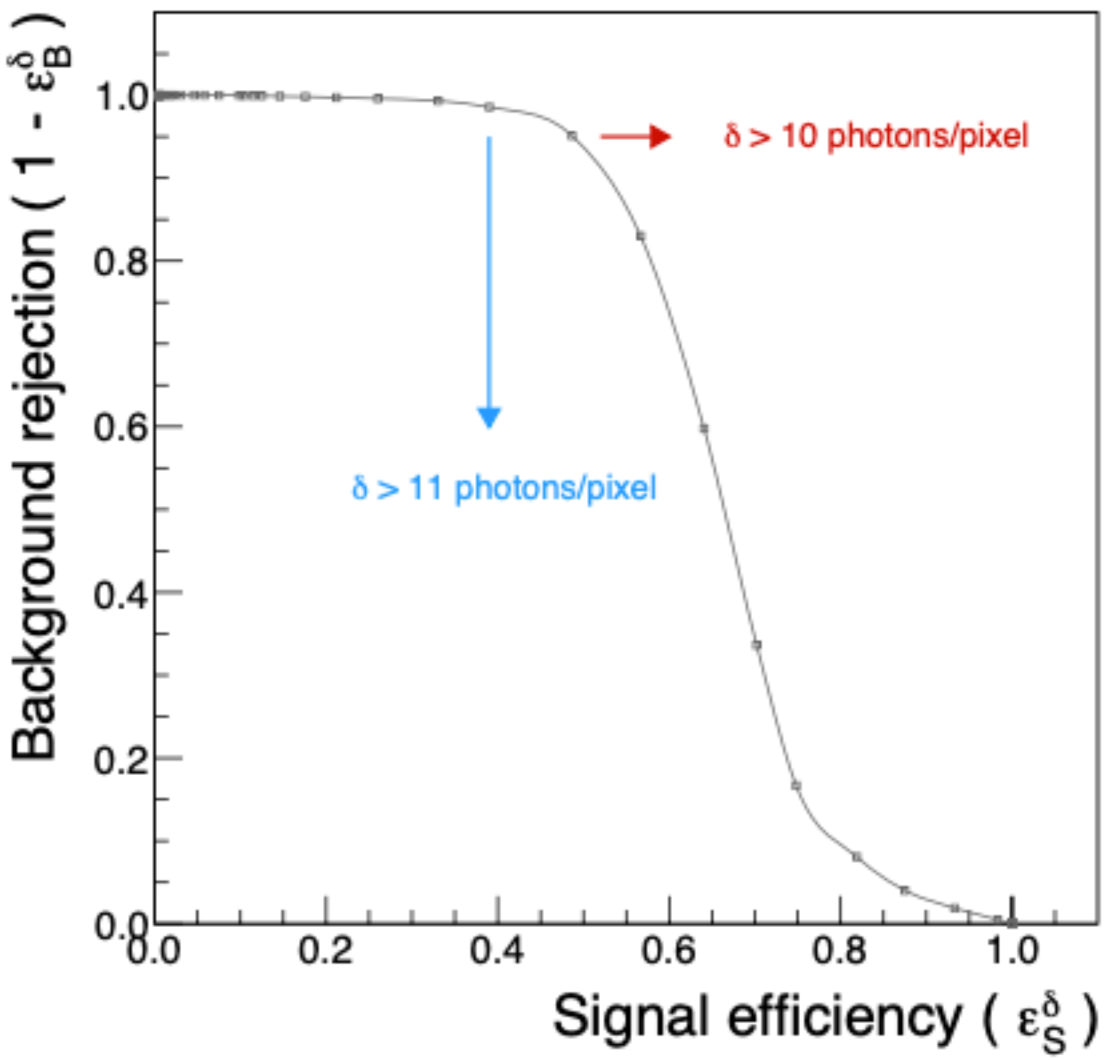
around δ~10 and ~17

preselection+ sliding threshold on this variable is used to give signal identification results: ε_S vs $(1-\varepsilon_B)$

N.B.1 cosmics background not of interest for underground CYGNO

=> concentrate on electron recoils from Fe rejection (so at fixed E=5.9 keV)

Nuclear recoils identification



ROC curve (S efficiency vs B rejection) for the selection on δ

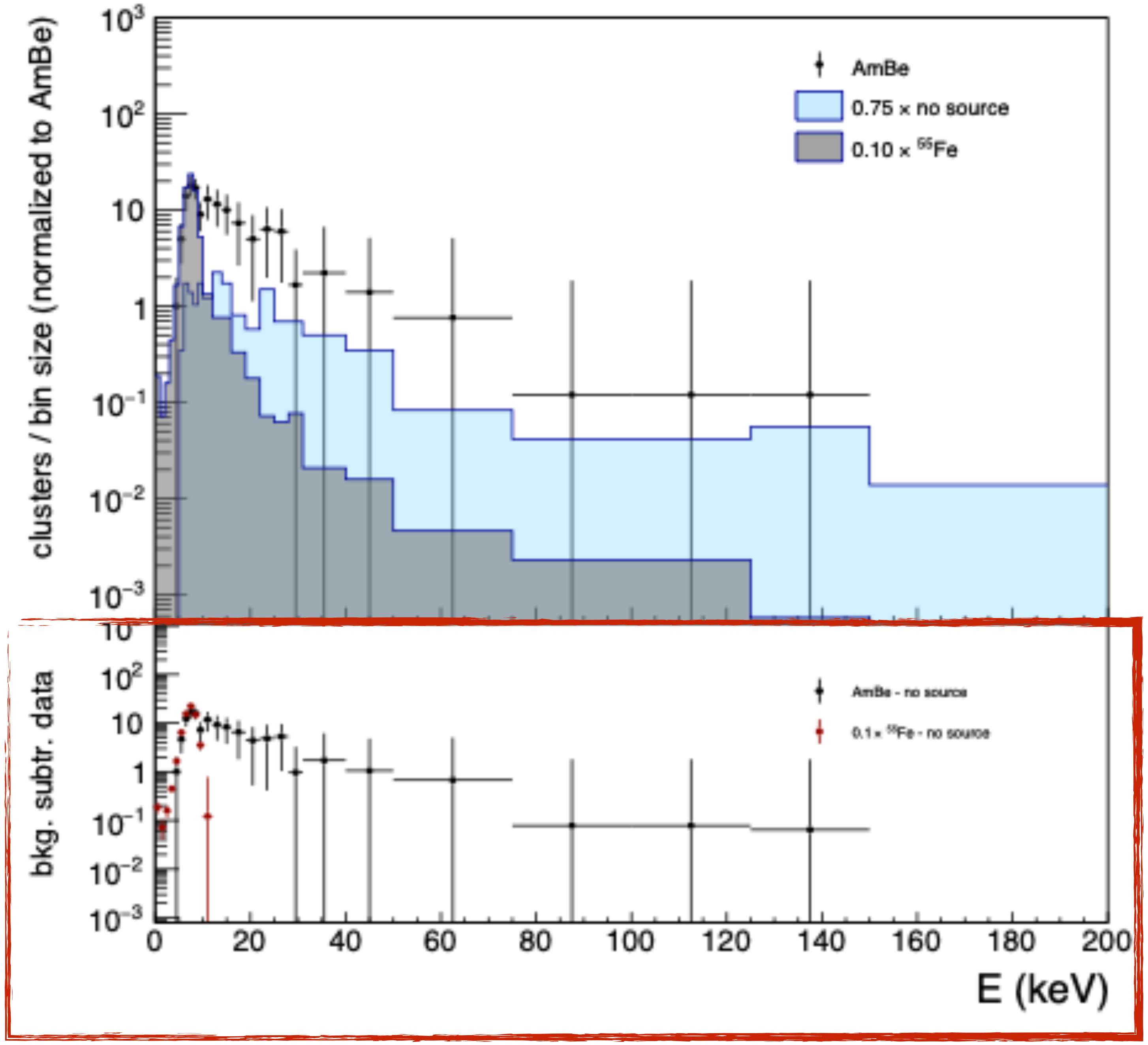
Full efficiency is the product of pre-selection (mostly cosmics rejection) efficiency and δ selection.

Two reference selections: **50% and 40% efficient on signal** => correspond to **96.5% and 99.2% background rejection**

working point	Signal efficiency			Background efficiency		
	ε_S^{presel}	ε_S^{δ}	ε_S^{total}	ε_B^{presel}	ε_B^{δ}	ε_B^{total}
WP_{50}	0.98	0.51	0.50	0.70	0.050	0.035
WP_{40}	0.98	0.41	0.40	0.70	0.012	0.008

Nuclear recoils spectrum

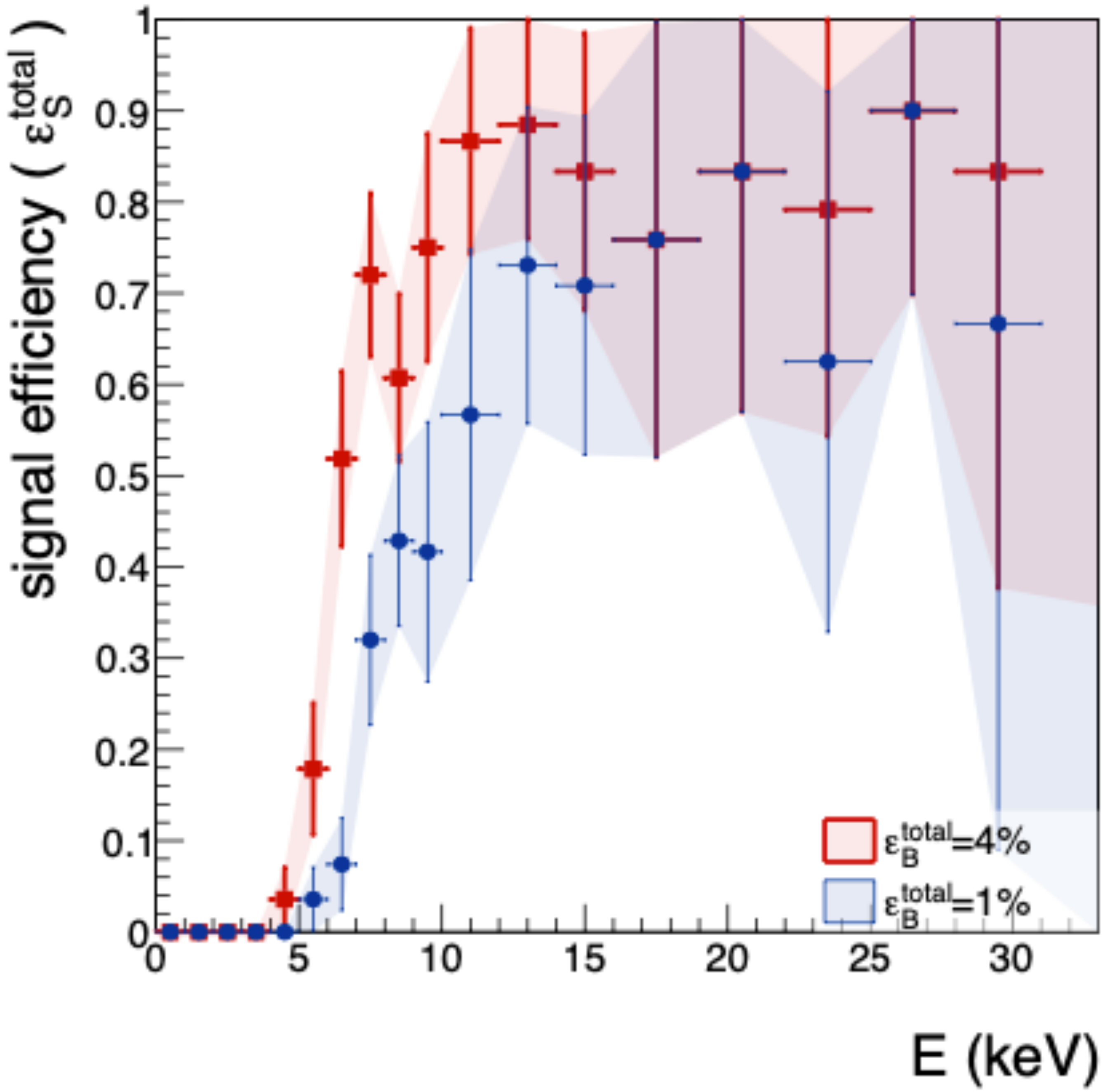
Spectrum after full WP50 selection



Most of the nuclear recoil candidates have a visible energy E<20 keV

Tails up to ~100 keV

Differential signal efficiency



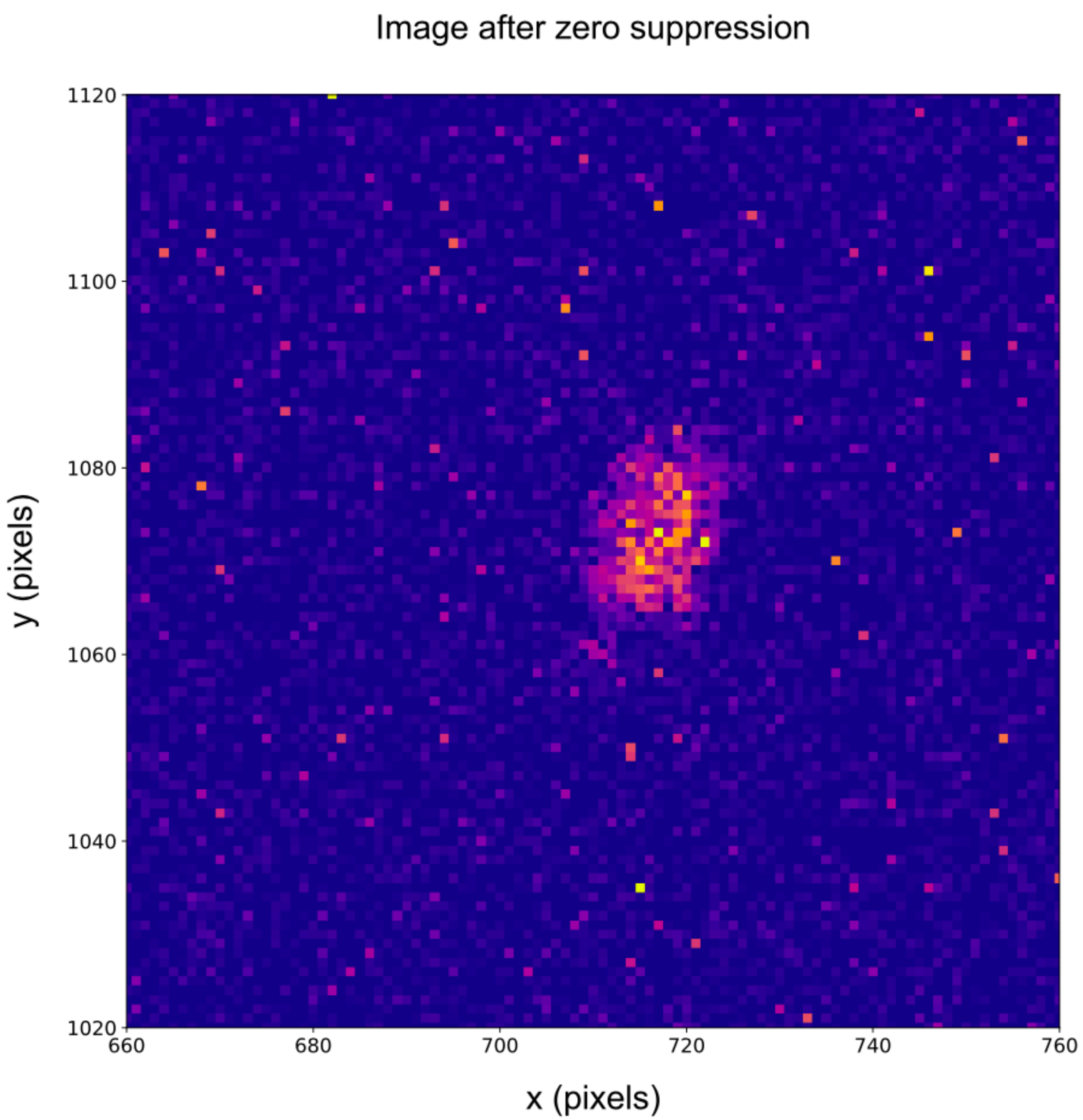
Background-subtracted energy spectrum before and after the density selection allows to compute signal efficiency vs E

Done for the 2 fixed rejection working points for 5.9 keV electron recoils:

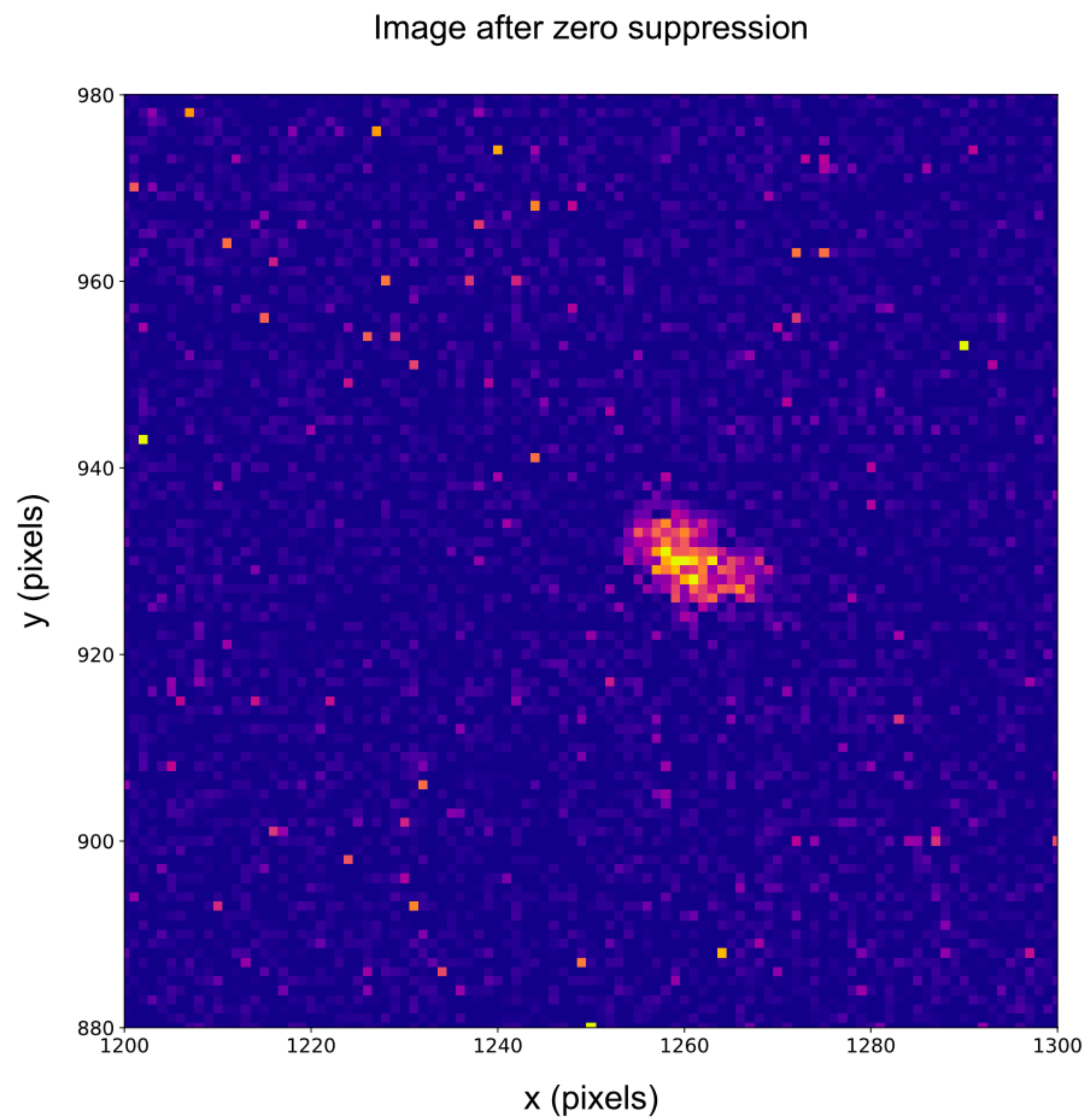
- $\varepsilon_S \approx 40\%$ for E<20 keV
- $\varepsilon_S \approx 14\%$ for 5<E<10 keV

Examples of 2 low-E NRs

- Two selected NR candidates with E<6 keV



E=5.2 keV



E=6.0 keV

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Measurement Science and Technolog

Meas. Sci. Technol. **32** (2021) 025902 (20pp)

https://doi.org/10.1088/1361-6501/abbd1

Identification of low energy nuclear recoils in a gas time projection chamber with optical readout

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Received 24 July 2020, revised 21 September 2020
Accepted for publication 30 September 2020
Published 1 December 2020

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Conclusions

- implemented a reconstruction algorithm which is efficient in a wide range of energies and track patterns
- tested on calibration events (^{55}Fe, 59 keV photons, cosmic rays, nuclear recoils)
- nuclear recoil efficiencies for high rejection of 6 keV electron recoil:
  - $\varepsilon_S \approx 40\%$ for E<20 keV
  - $\varepsilon_S \approx 14\%$ for 5<E<10 keV

- Next developments in the pattern recognition:
  - particle identification using cluster 3D properties
  - 3D reconstruction using information from PMT (z-coordinate)

- A lot of work ongoing on the HW side, and on simulation of signals and backgrounds towards installation under Gran Sasso

The End