# The nuclear emulsions workflow

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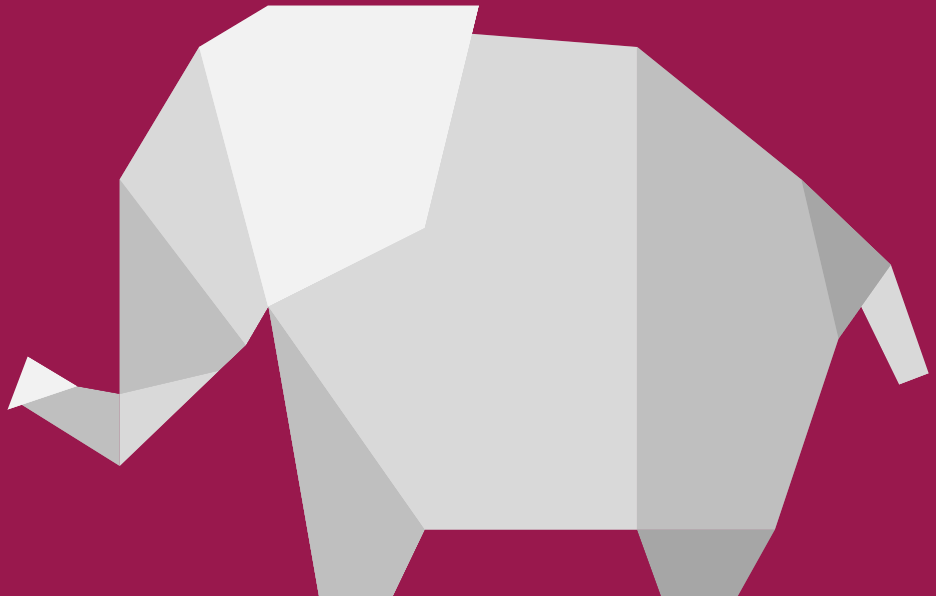
1. The detection principles and chemical treatments
2. Tracks reconstruction and analysis
3. NIT

# The Nuclear Emulsions: detection principles and chemical treatments



# Nuclear Emulsion chemical composition

- Standard emulsions composition: AgBr + gelatin
- Gelatine provides a 3D substrate to locate the crystals of silver halide and prevent them to migrate during the chemical development: keep the original position

## OPERA films

| Element | Mass fraction |
|---|---|
| Ag | 0.3834 |
| Br | 0.2786 |
| I | 0.0081 |
| C | 0.13 |
| N | 0.0481 |
| O | 0.1243 |
| H | 0.024 |
| S | 0.001 |
| Si | 0.001 |
| Na | 0.001 |
| K | 0.0005 |

**Grain dimension:** $\sim 200$ **nm**

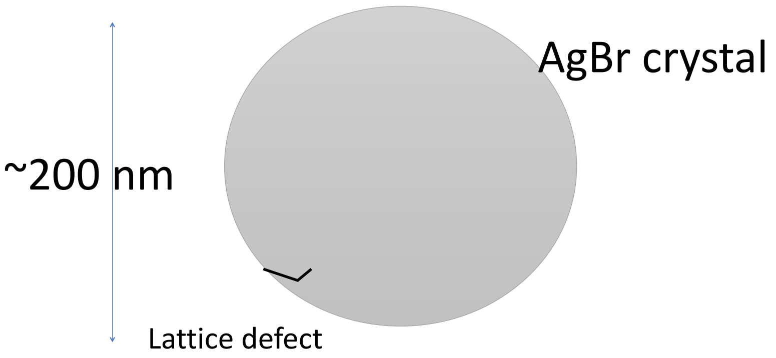
## Nano Imaging Tracker (NIT)

| Constituent | Mass Fraction | |
|---|---|---|
| AgBr-I | 0.78 | → sensitive elements |
| Gelatin | 0.17 | → retaining structure |
| PVA | 0.05 | → to stabilise the crystal growth |

| Element | Mass Fraction | Atomic Fraction |
|---|---|---|
| Ag | 0.44 | 0.10 |
| Br | 0.32 | 0.10 |
| I | 0.019 | 0.004 |
| C | 0.101 | 0.214 |
| O | 0.074 | 0.118 |
| N | 0.027 | 0.049 |
| H | 0.016 | 0.410 |
| S | 0.003 | 0.003 |

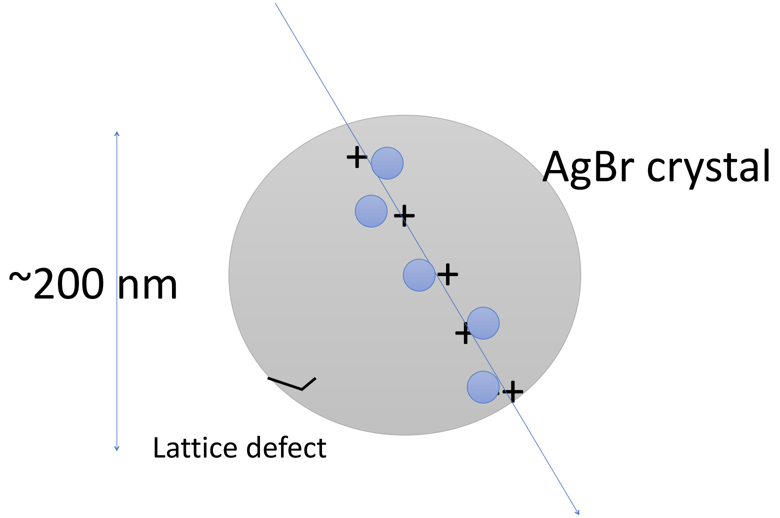
**Grain dimension after development:** $\sim 20-45$ **nm**

# Detection principle



# Detection principle

1. Ionization induced by a particle
   - 2.6 eV band gap



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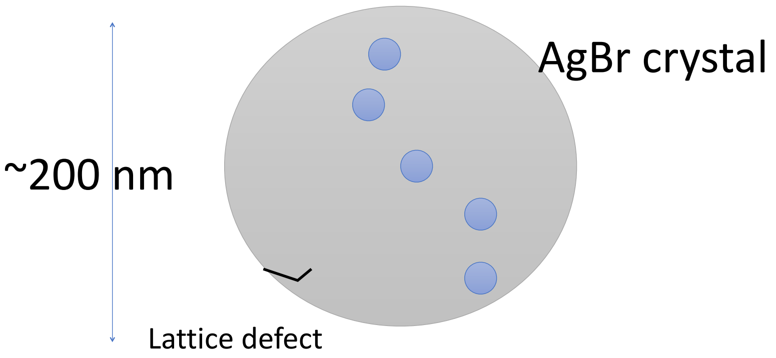

# Detection principle

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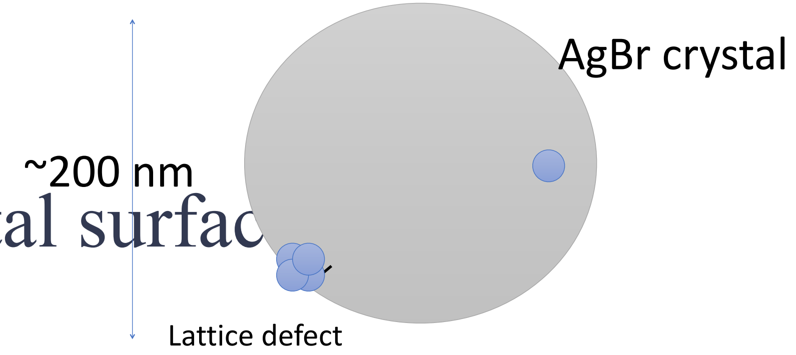
   - Attract interstitial silver ions
   - Produce a “latent image” = $Ag_n$



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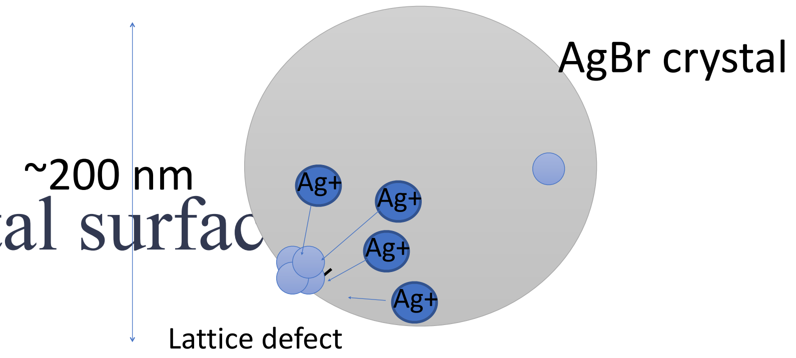

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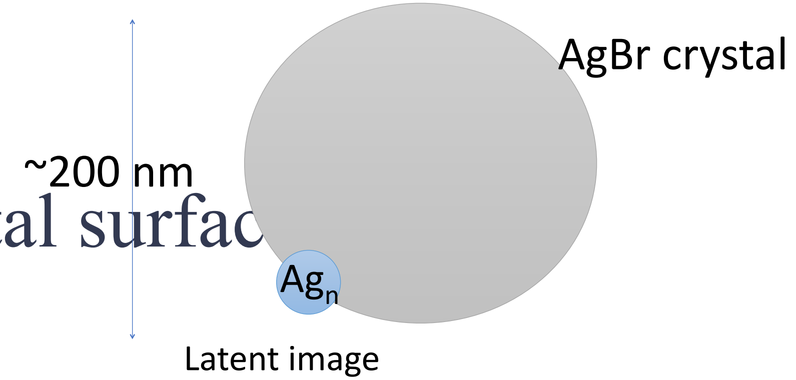

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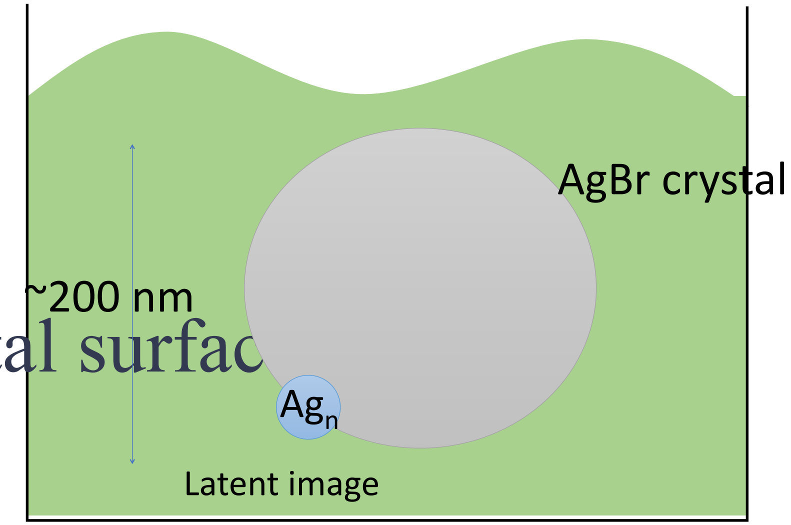
3. Chemical amplification of signal
   - Development →silver filaments
   - $10^7$ - $10^8$ amplification



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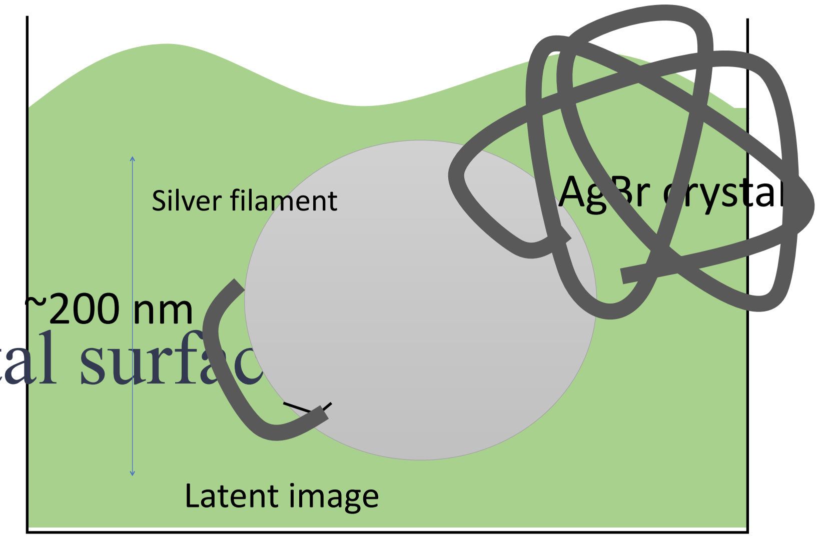

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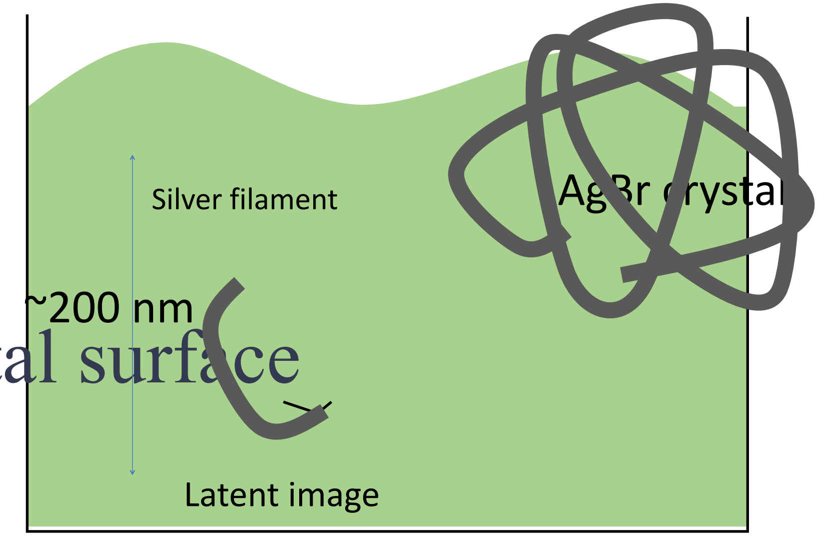

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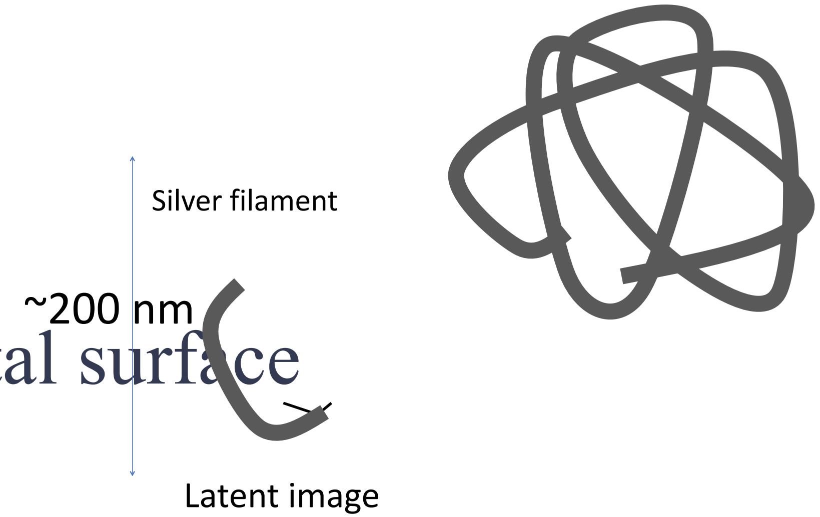
5. Observe it at optical microscopes



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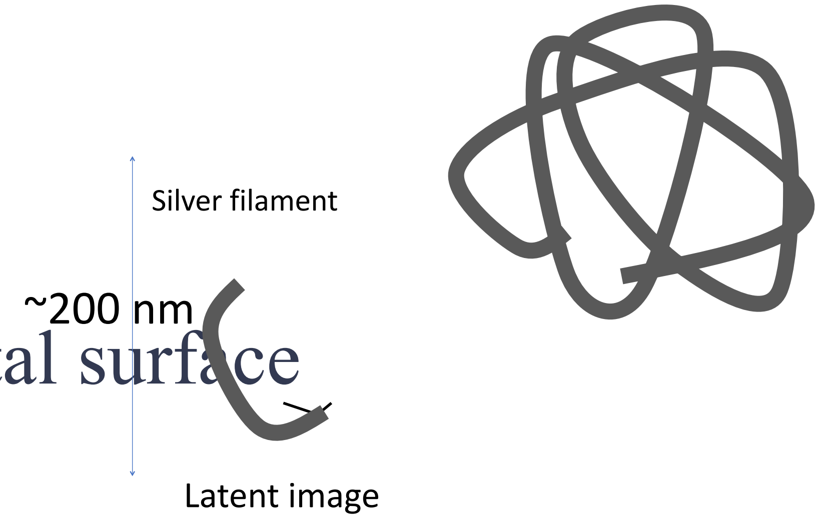
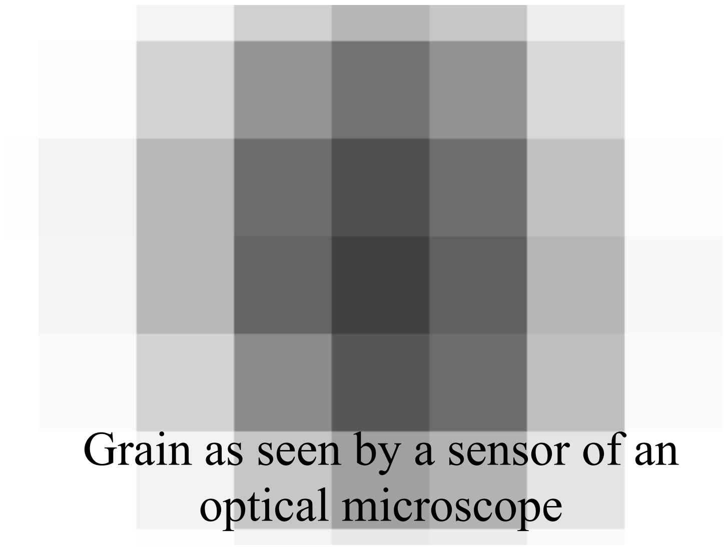


Grain as seen by a sensor of an optical microscope

# Film production

1 


Control of AgBr crystal size, density

# Film production

1

Control of AgBr crystal size, density

2

**Desalination**

Reduction of Na, $NO_3$

# Film production

1

Control of AgBr crystal size, density

2

**Desalination**

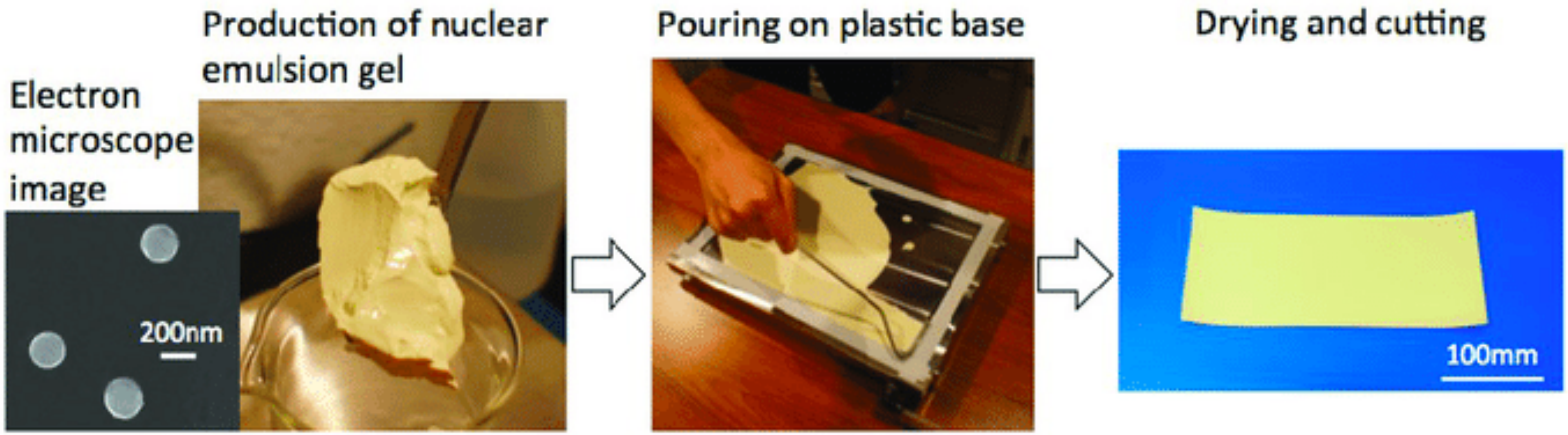
Reduction of Na, $NO_3$

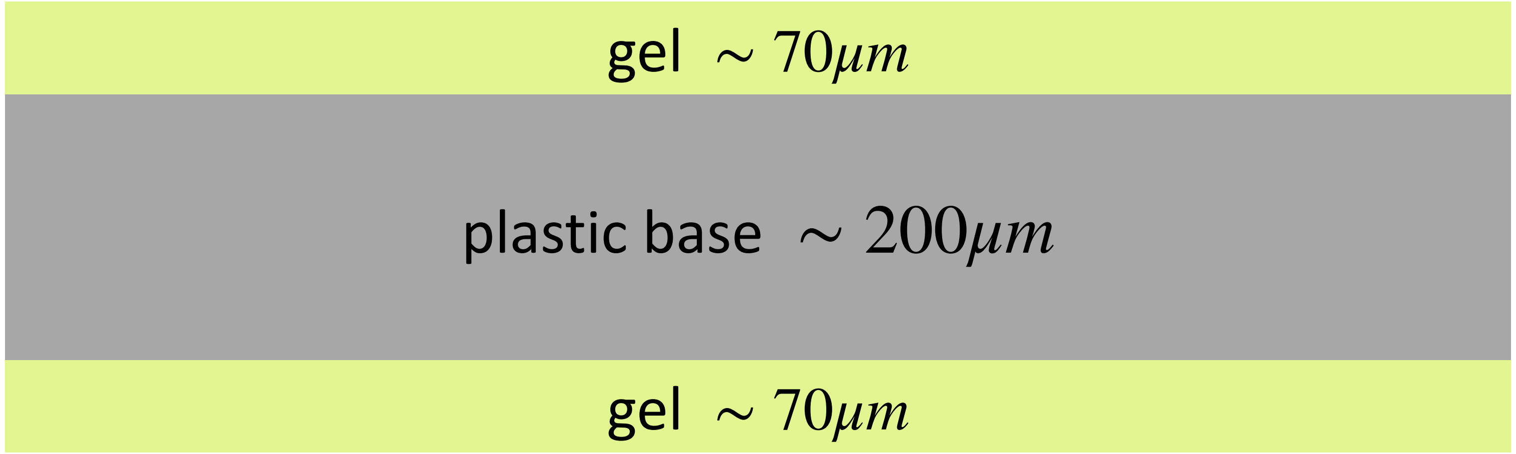
3

**Sensitization**

Au+S sensitization
→ tuning of the sensitivity (grains/μm at a given dE/dx)

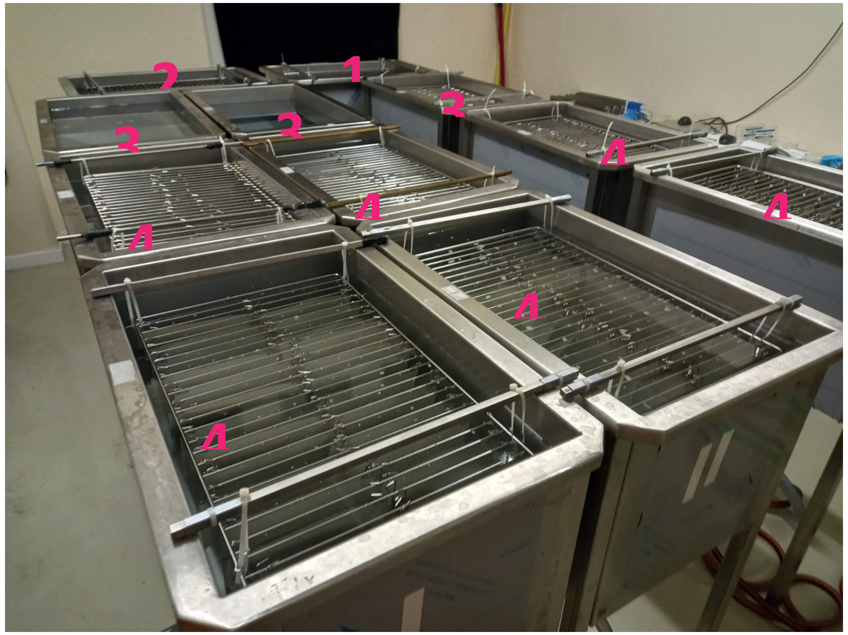
# Film production



# Nuclear emulsions development

1. Development
2. Stop
3. Fix
4. Wash
5. Glycerine
6. Dry

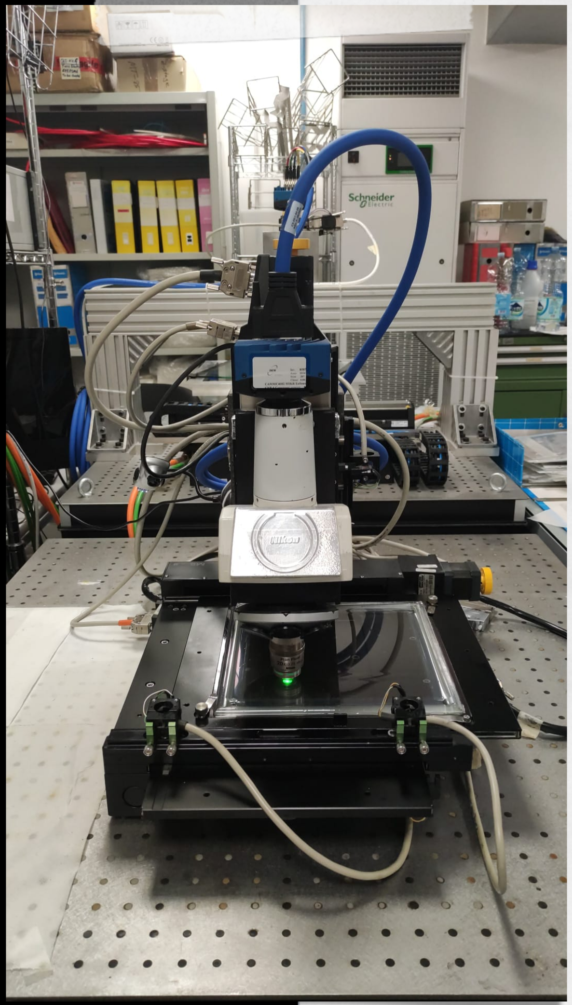


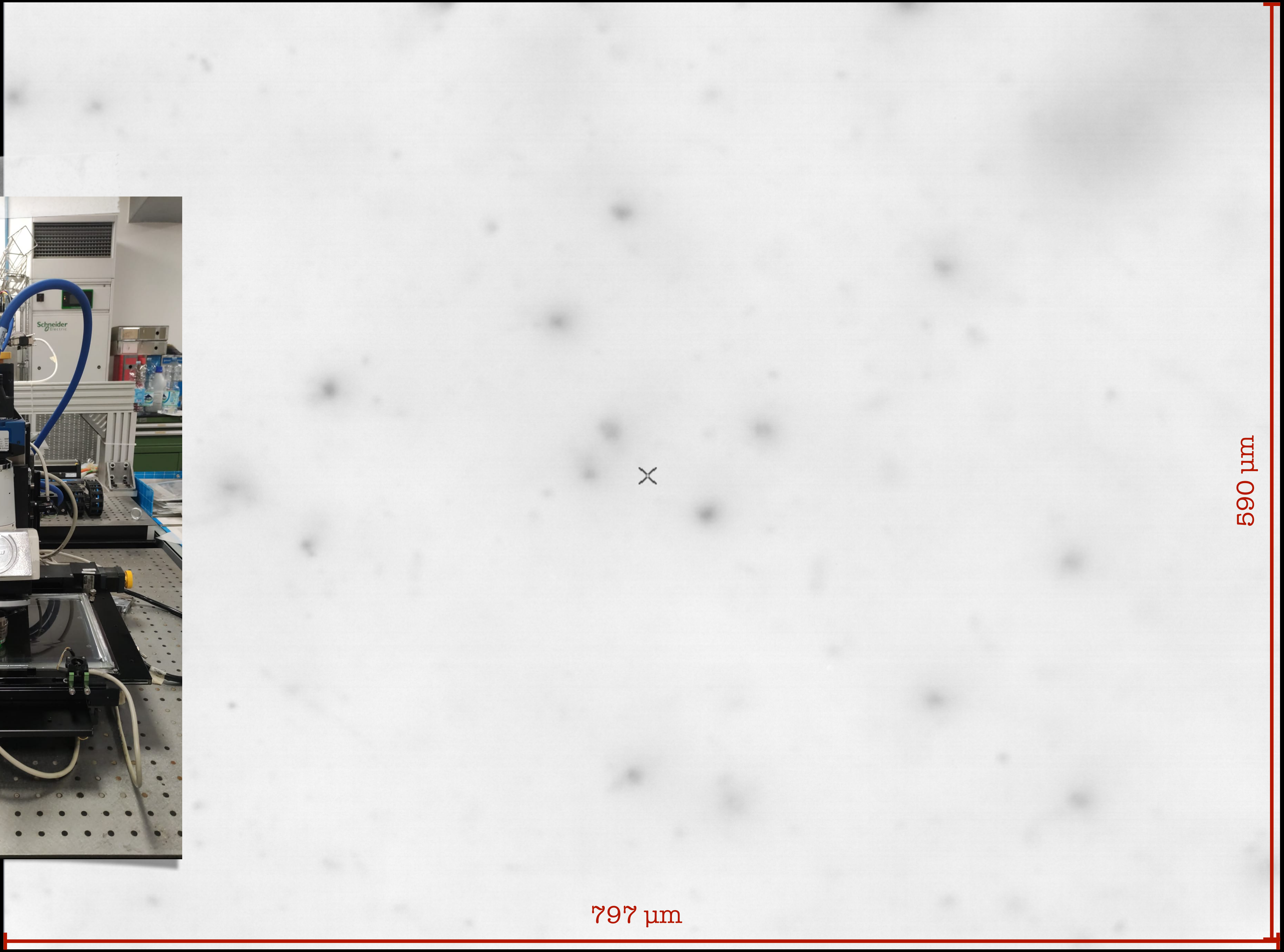
**Total time: about 2 days**

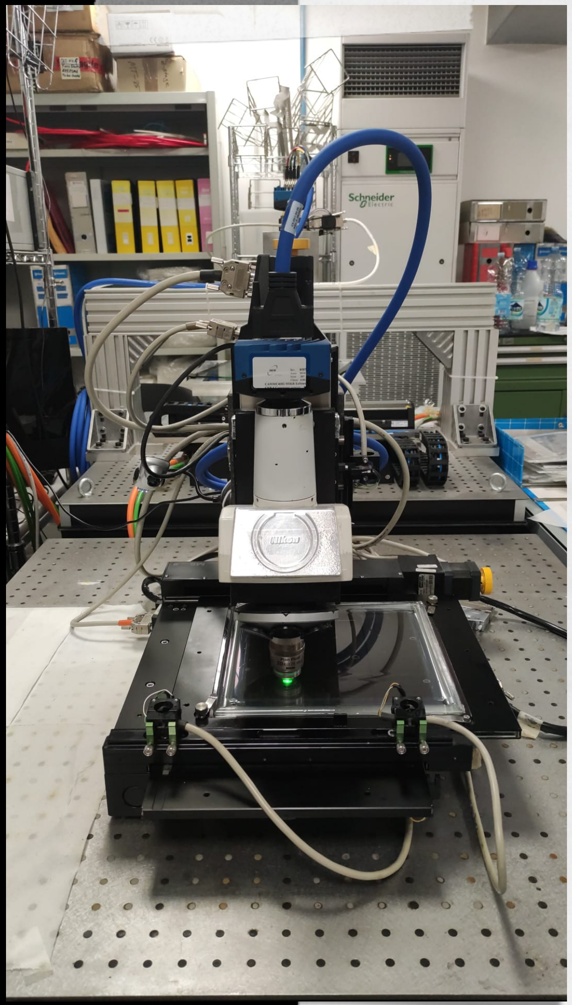
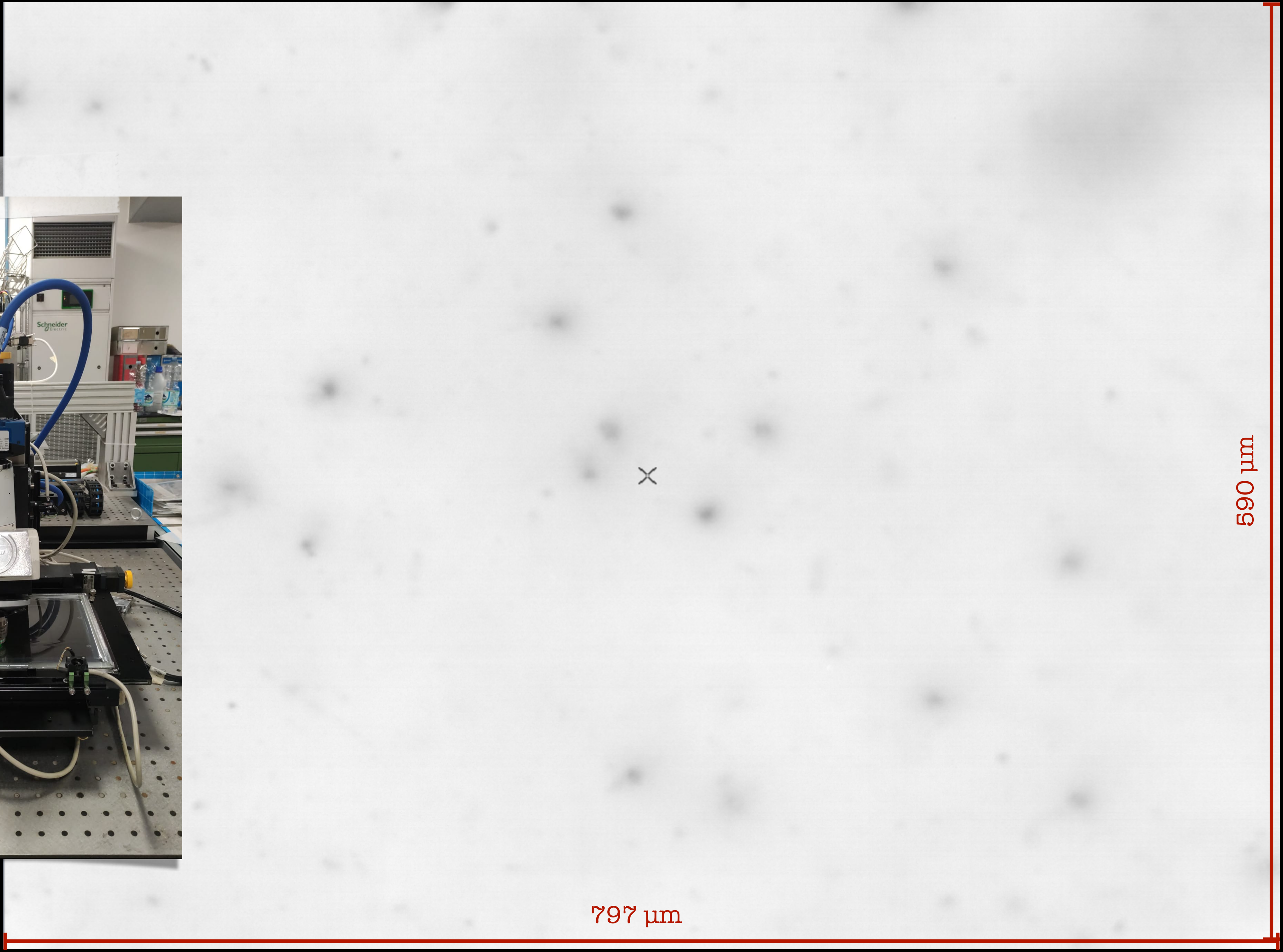
# The Nuclear Emulsions: track reconstruction


797 µm
590 µm

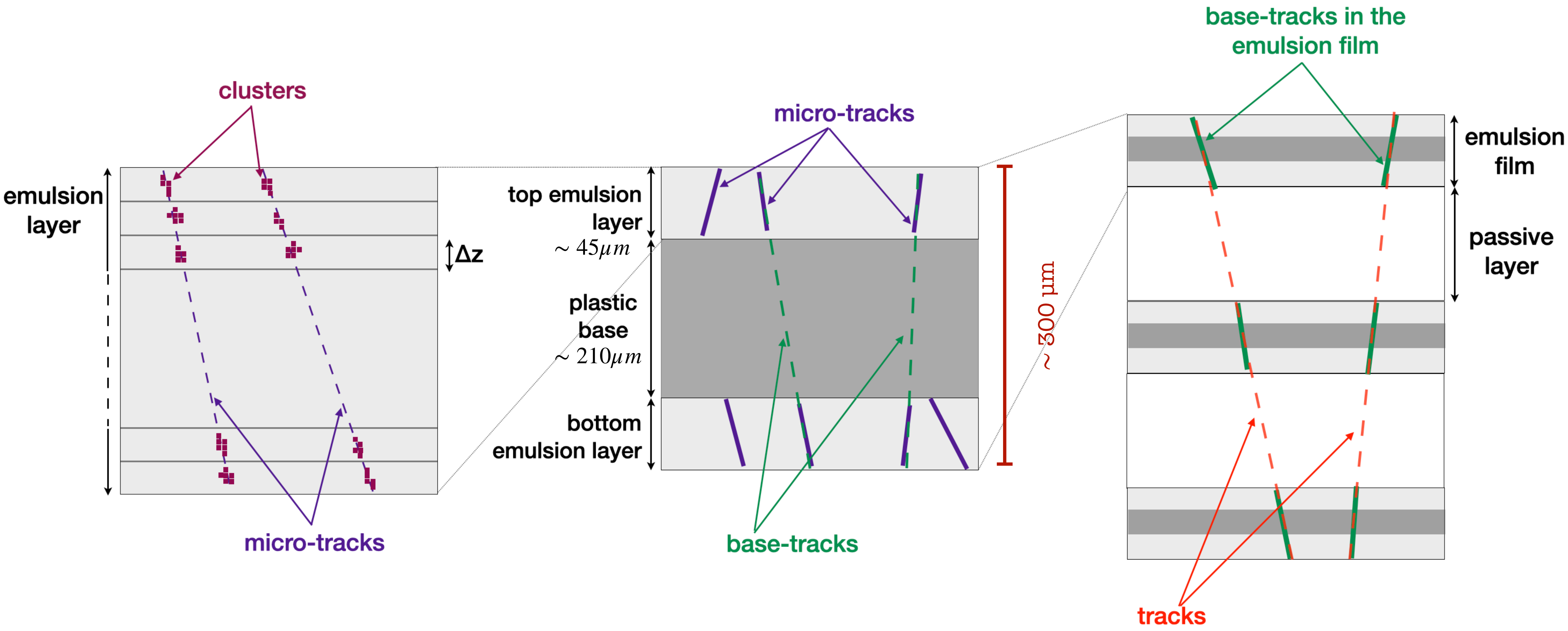

797 µm
590 µm


Schneider


797 µm
590 µm

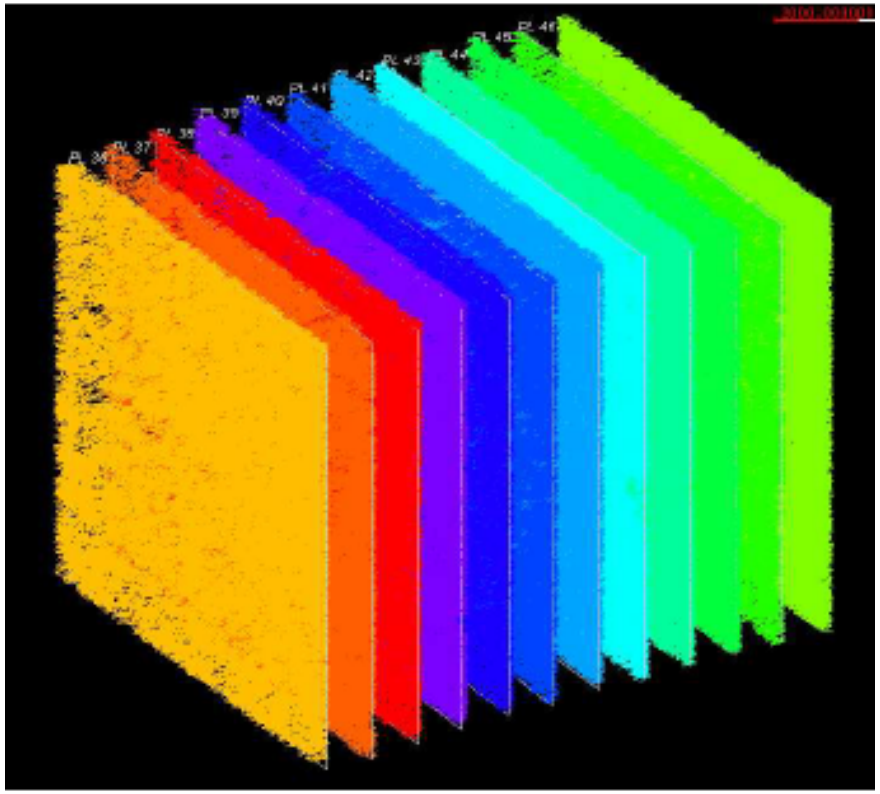


797 µm
590 µm

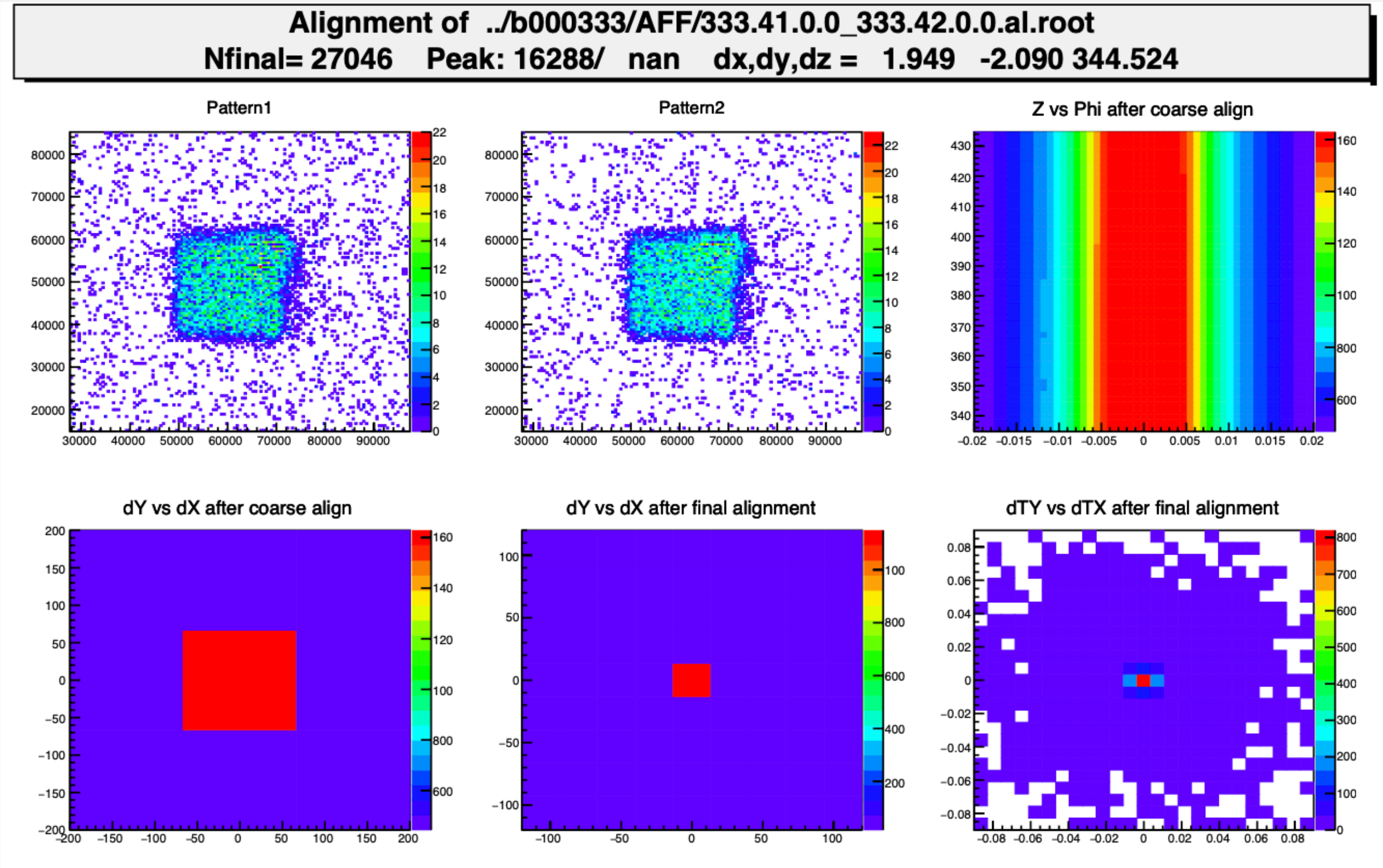
# ECC tracks' reconstruction



# Nuclear emulsion films alignment

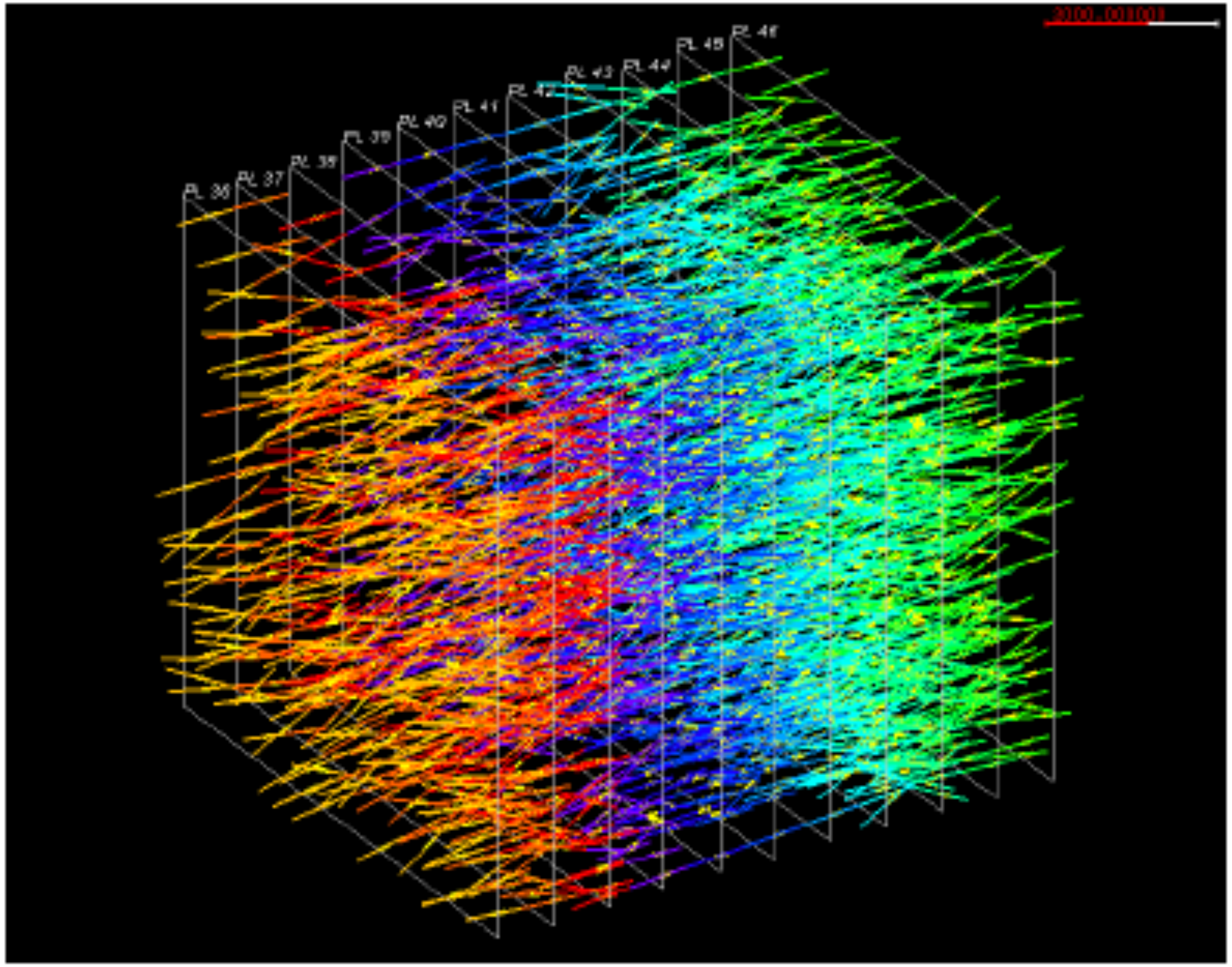
- **STEP 1**: align couples of consecutive plates (~3 interactions with more stringent parameters)





# Nuclear emulsion films alignment

- Residual (small) misalignment are present in the global reconstruction
- **STEP 2**: re-alignment of the whole stack, taking into consideration long tracks to improve the global alignment
- Final tracks reconstruction



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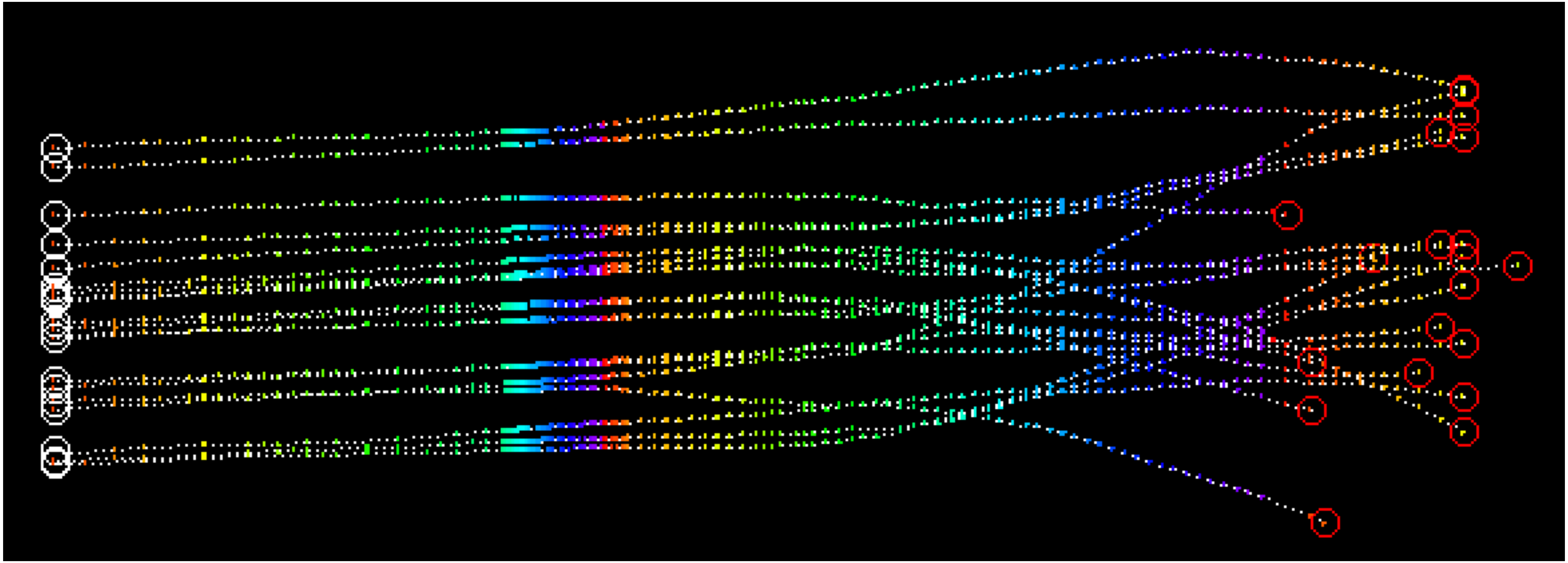
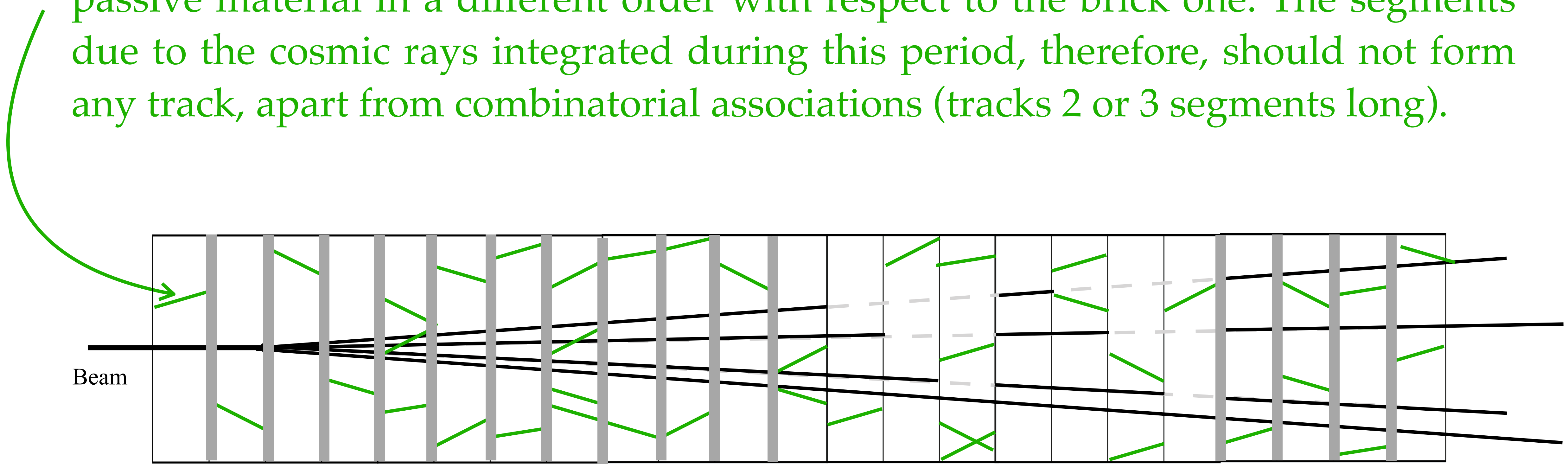


EXAMPLE OF LONG TRACKS (NSEG>100) TAKEN FROM GSI3 **DATA**

# Background I (random base tracks)

Nuclear emulsions integrate cosmic rays since their production up to their development

Before and after brick assembling nuclear emulsions are are are piled up without passive material in a different order with respect to the brick one. The segments due to the cosmic rays integrated during this period, therefore, should not form any track, apart from combinatorial associations (tracks 2 or 3 segments long).




Passive material not to scale

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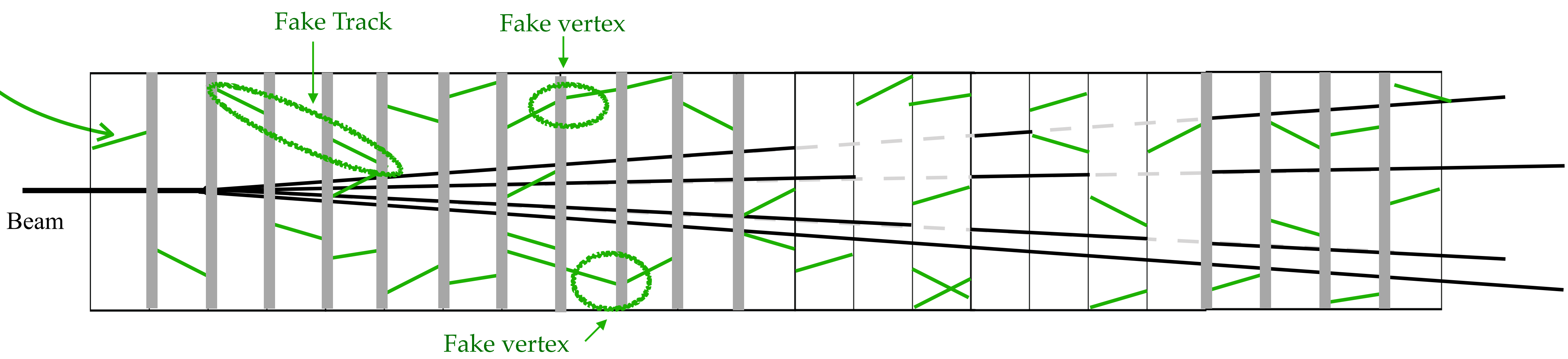
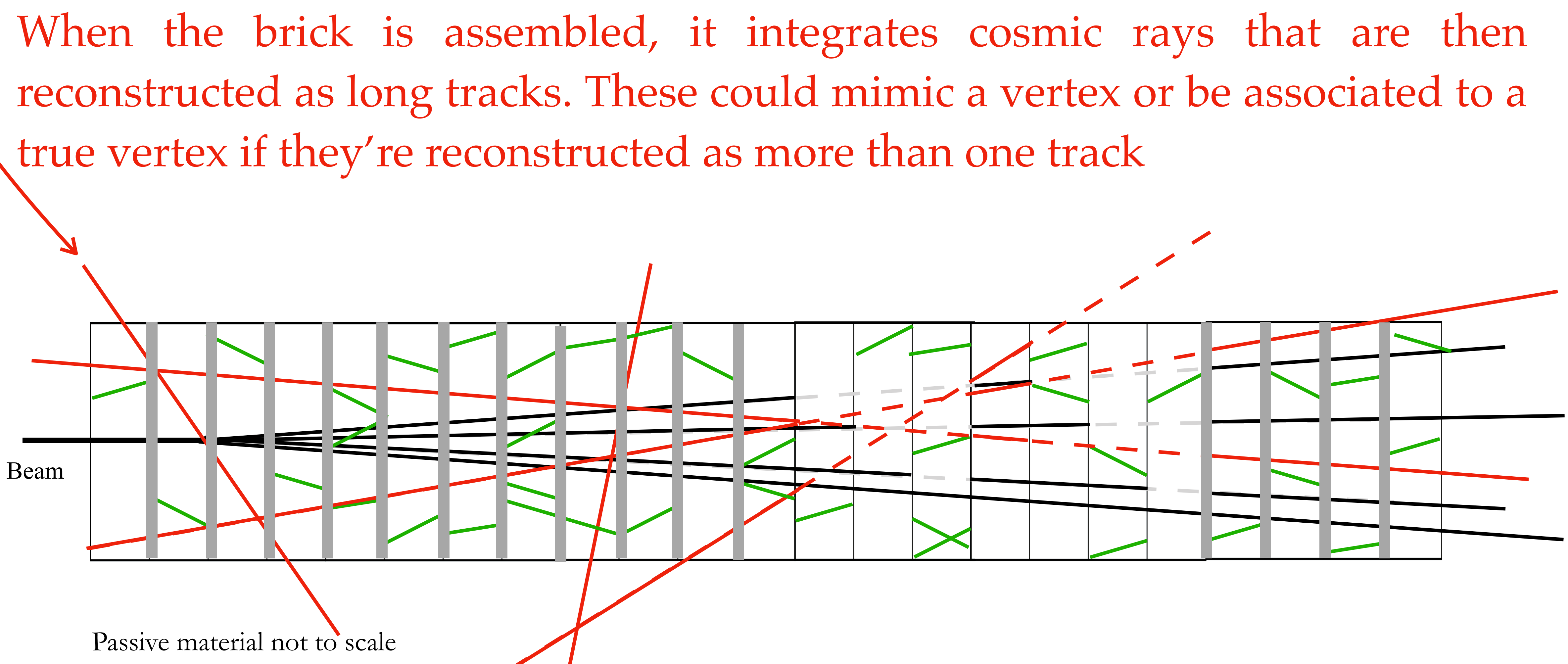



Passive material not to scale

# Background II (long cosmic rays)

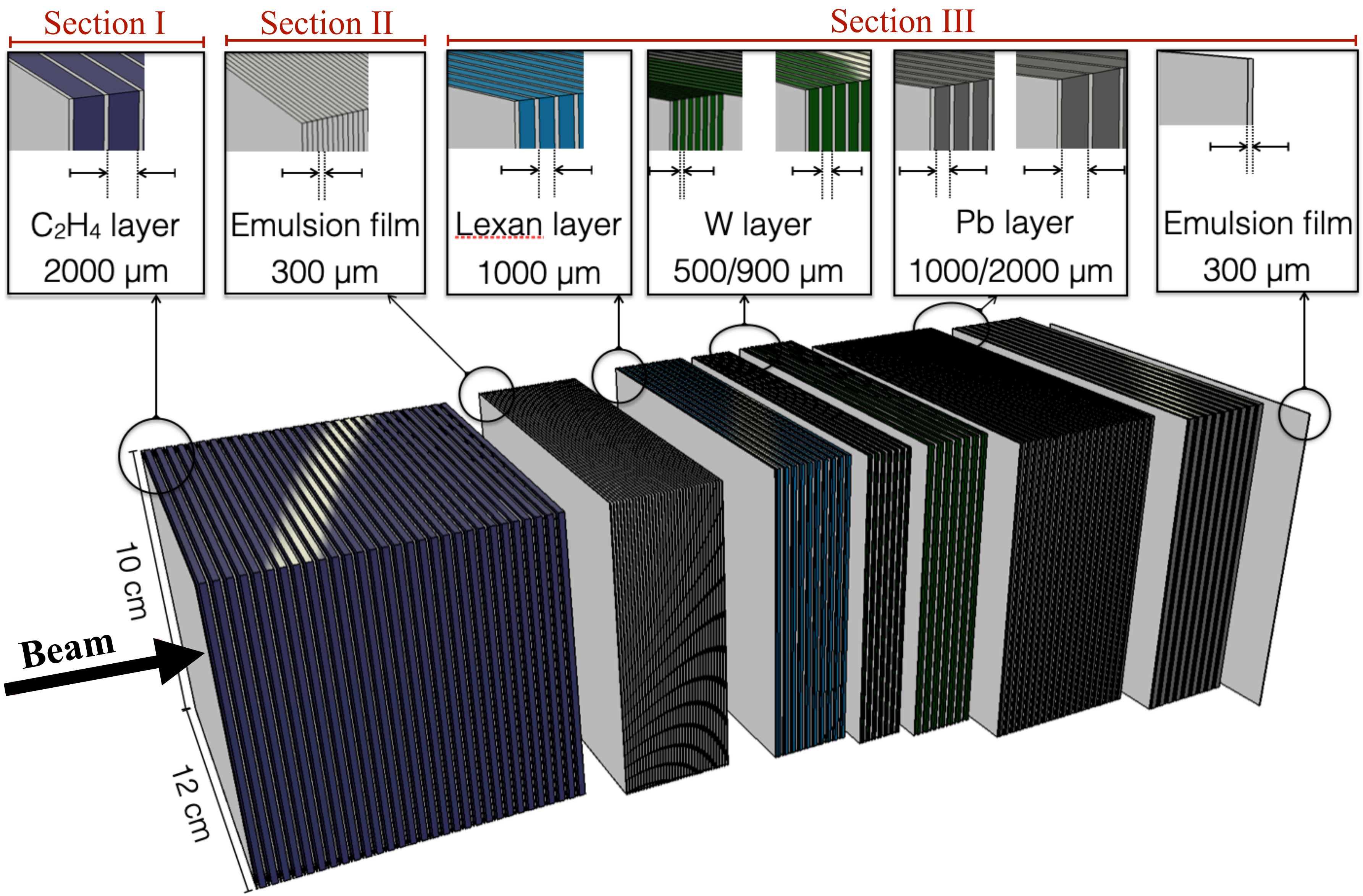
Nuclear emulsions integrate cosmic rays since their production up to their development

When the brick is assembled, it integrates cosmic rays that are then reconstructed as long tracks. These could mimic a vertex or be associated to a true vertex if they're reconstructed as more than one track




Passive material not to scale

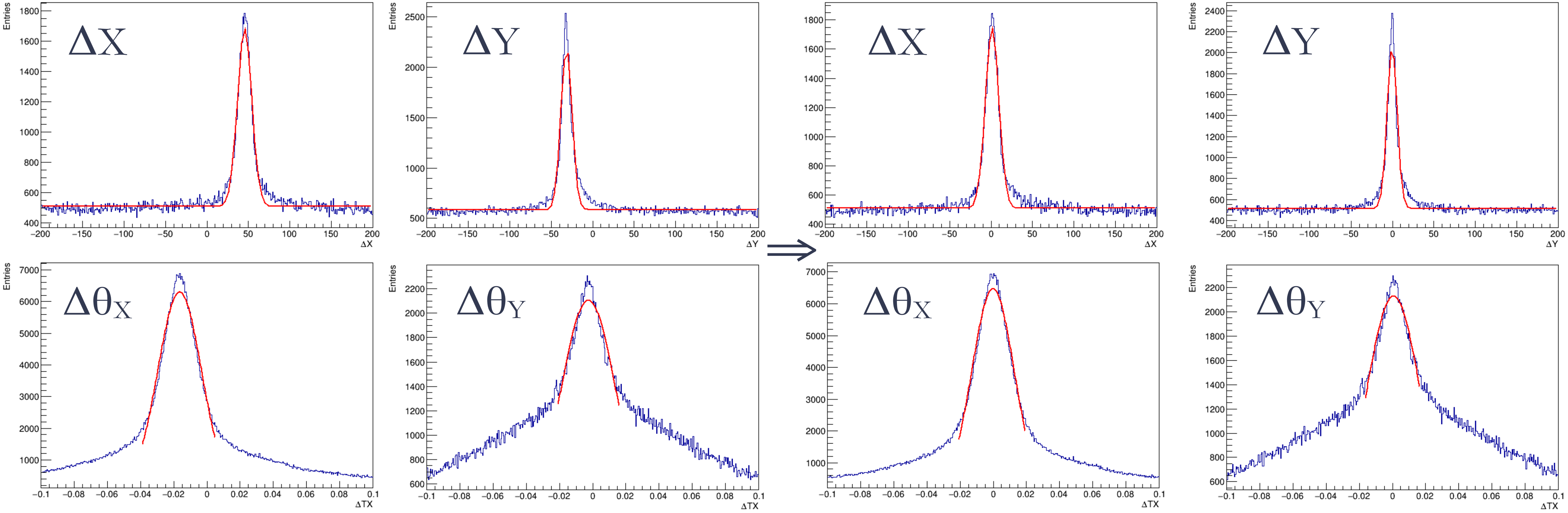
# Detector Structure



# Merging procedure between different sections

- Each section is characterised by its own parameters (material density, thickness…): tracking algorithm applied to each section separately → Different reference systems for each section
  - Optimised procedure to put tracks in the same reference system
  - Improved final XY shift + rotation to correct the offsets

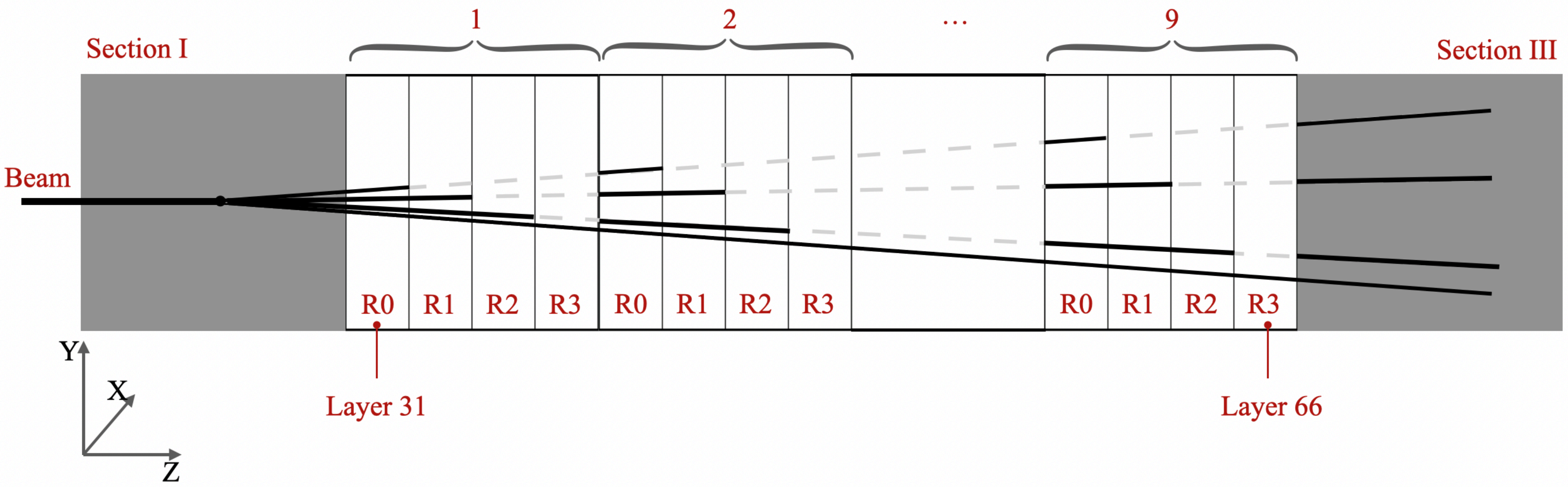
**Before corrections** **After corrections**




EXAMPLE TAKEN FROM GSI3 DATA S1→S2

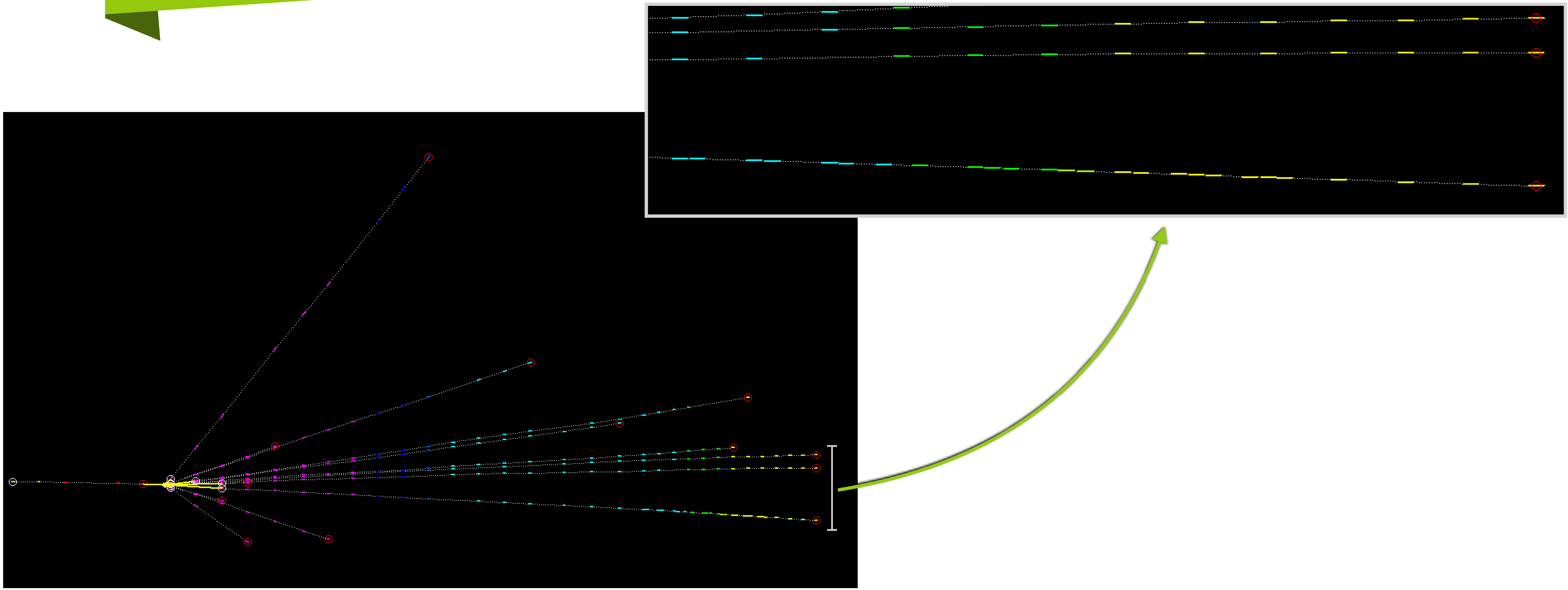
# Charge measurement

- Nuclear emulsion response is proportional to the energy loss of particles over a certain dynamic range: grain density is proportional to the particle's specific ionization
- Highly ionizing particles saturate nuclear emulsion's response
- A procedure based on different thermal treatments can extend the dynamical range of the emulsions to overcome the saturation effects
- Each thermal treatment erase totally or partially the track's segments, depending on its ionization



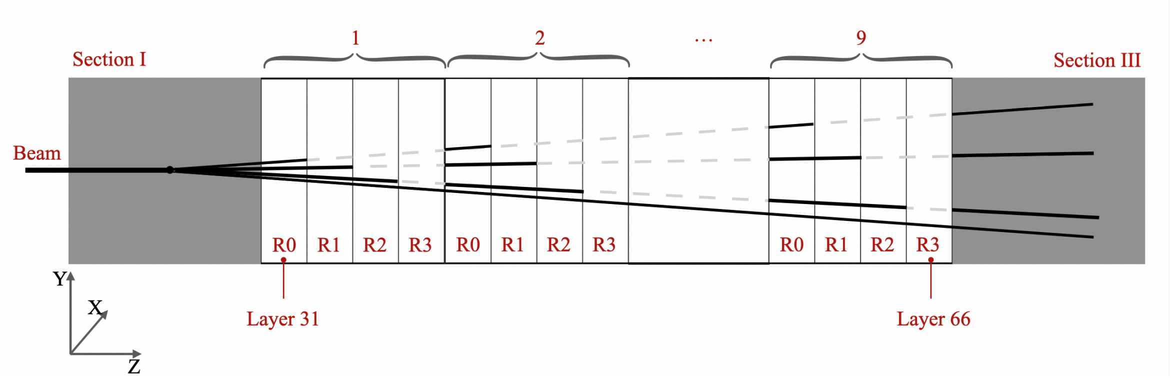

- **R0:** Not thermally treated
- **R1:** 24 h at **T1=28°C** and RH = 95%
- **R2:** 24 h at **T2=34°C** and RH = 95%
- **R3:** 24 h at **T3=36°C** and RH = 95%

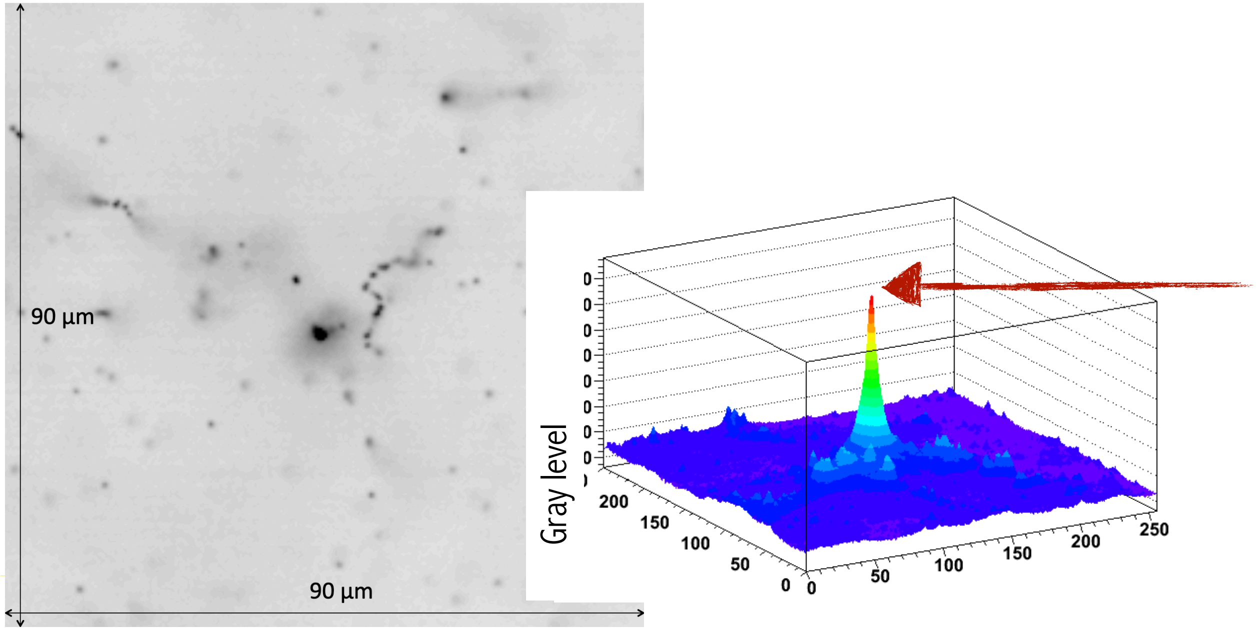
# Study of interactions



Example of Vertex taken from GSI3 data

# Charge identification with Nuclear Emulsions spectrometer




For each track the following variables are evaluated:

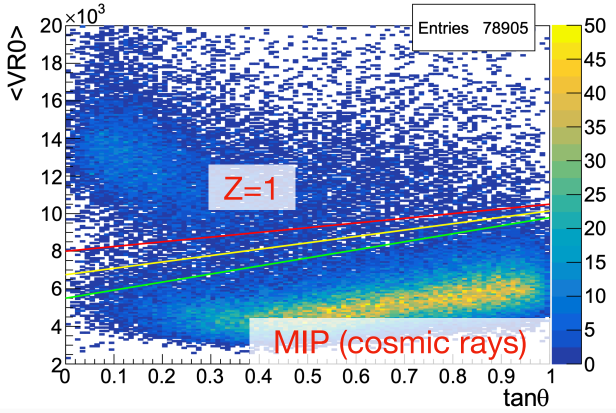
- tanθ: the tangent of the inclination of most upstream fitted track segment w.r.t. the Z axis
- NRx: the number of segments belonging to the track for each set of thermal treatments *Rx*, with $x \in \{0,1,2,3\}$
- VRx: for each segment, a variable named "volume" is defined as the sum of the pixel brightness and expressed in arbitrary units related to particles' ionisation
- $\langle \text{VRx} \rangle = \dfrac{\sum_{NRx} VRx}{NRx}$

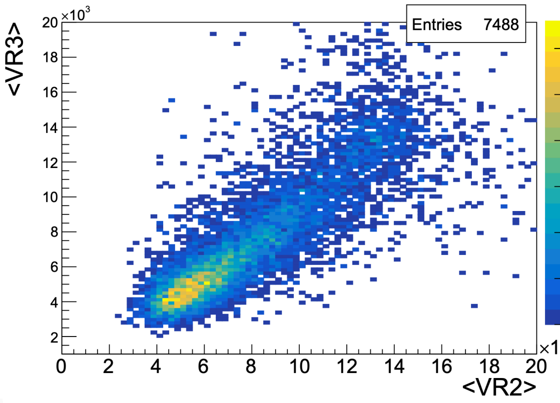
# Charge identification with Nuclear Emulsions spectrometer

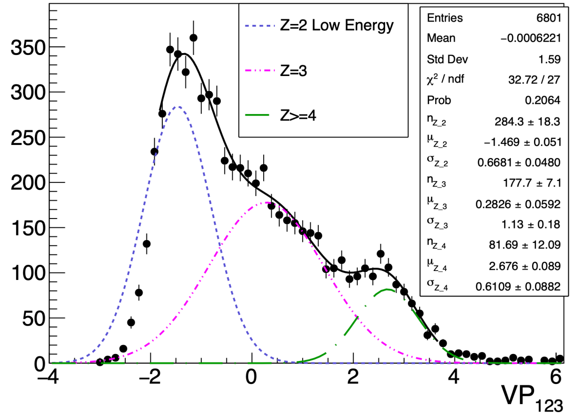
Two complementary methods:

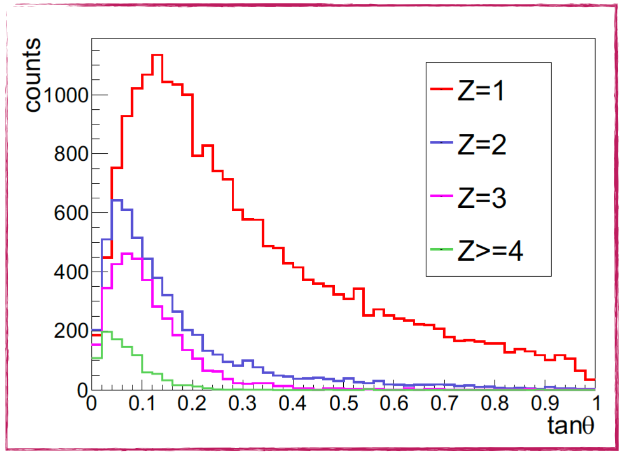
- Cut based-analysis to distinguish cosmic rays, Z=1 and Z=2 (high energy) fragments
- Principal Component Analysis to separate Z=2 (low energy), Z=3 and Z≥4 fragments

O@200MeV/n on $C_2H_4$



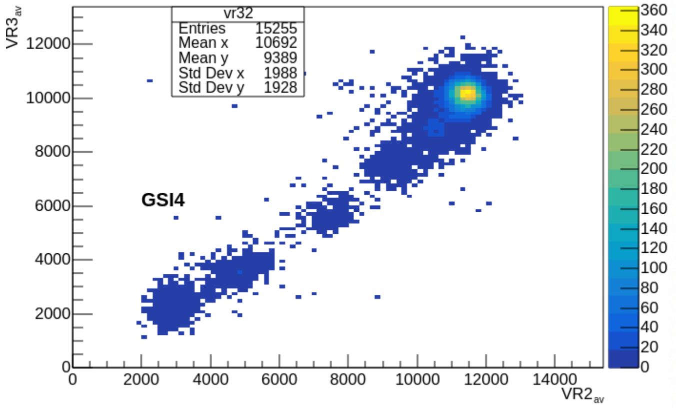



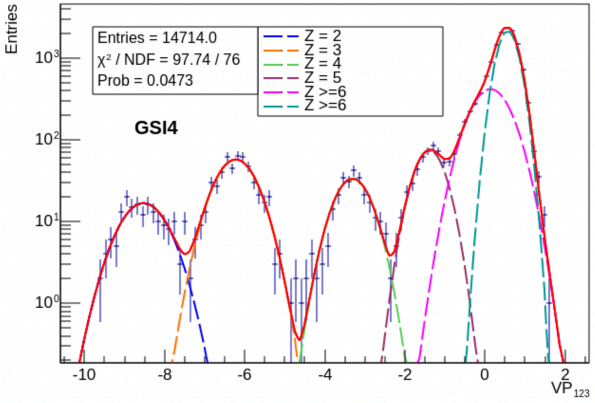




G. Galati doi.org/10.1515/phys-2021-0032

O@400MeV/n on $C_2H_4$

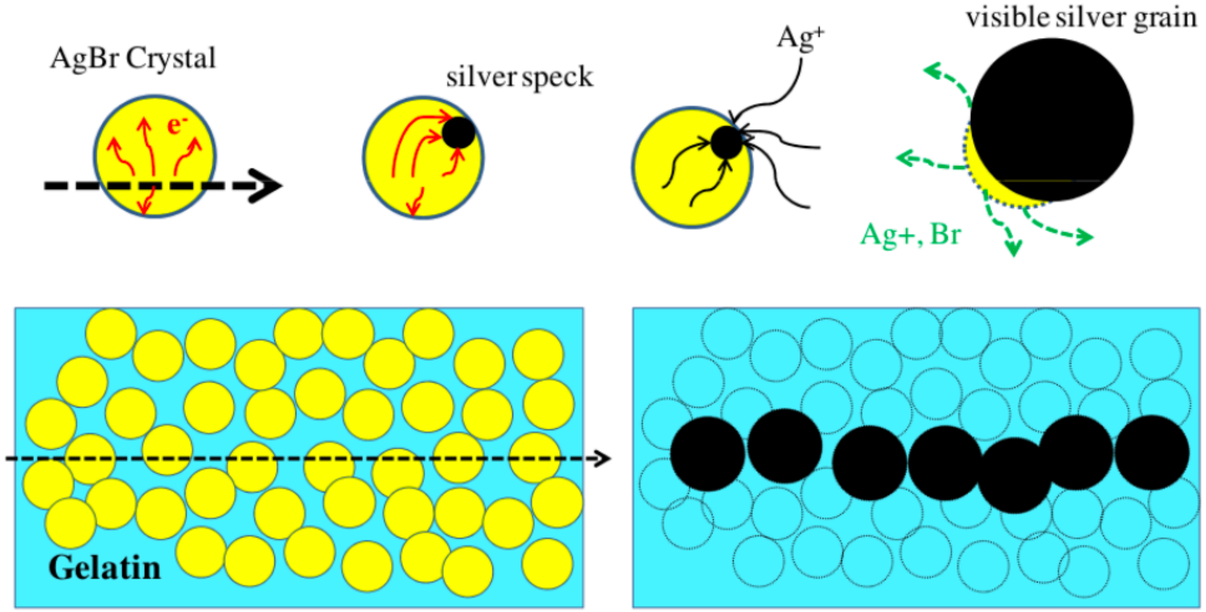



paper to be published soon!

# NIT:
# NANO IMAGING TRACKERS

# Nano Imaging Tracker (NIT)

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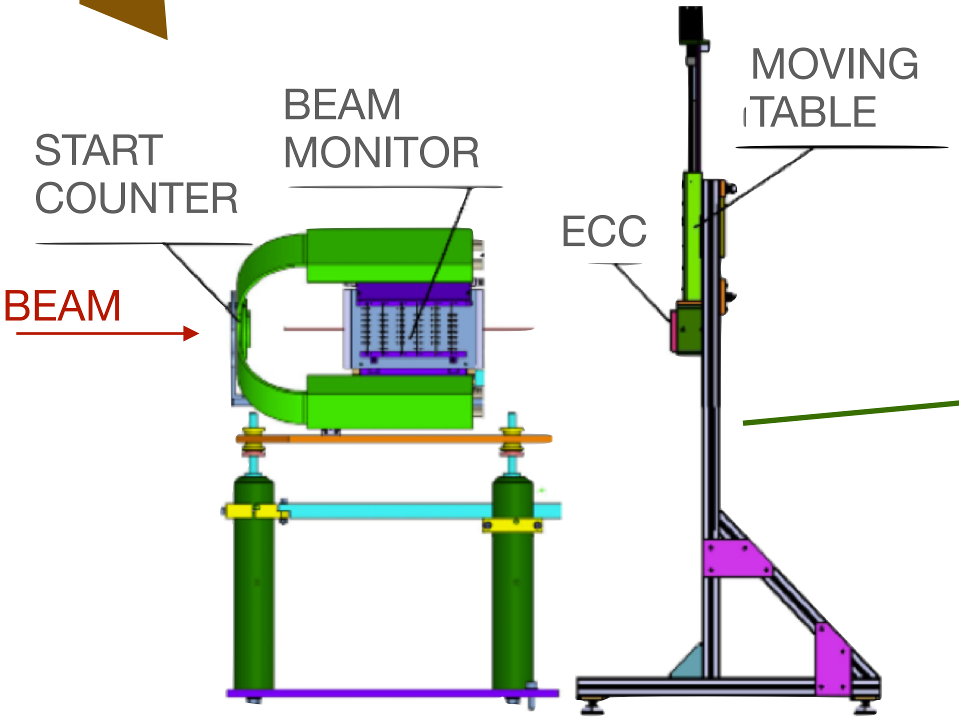
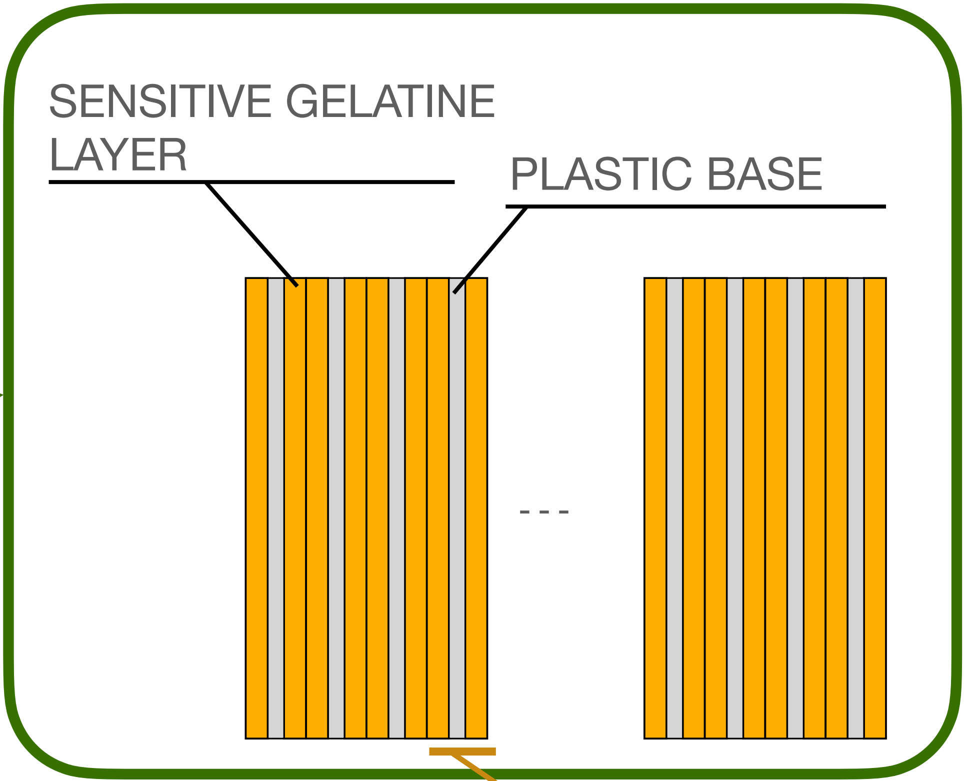
heavy nuclei (Ag, Br, I)

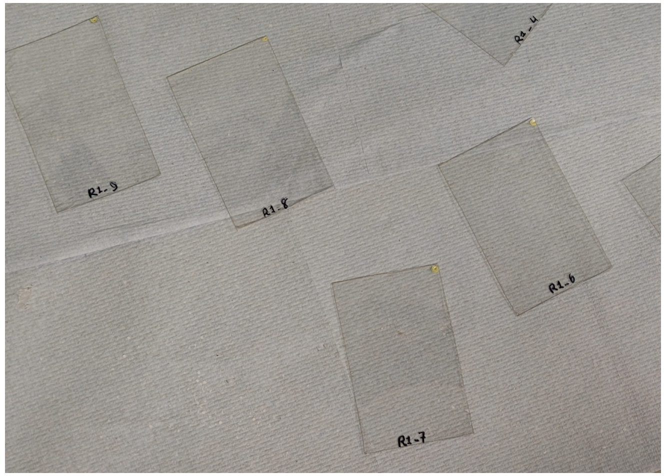
light nuclei (C, O, N, H, S)

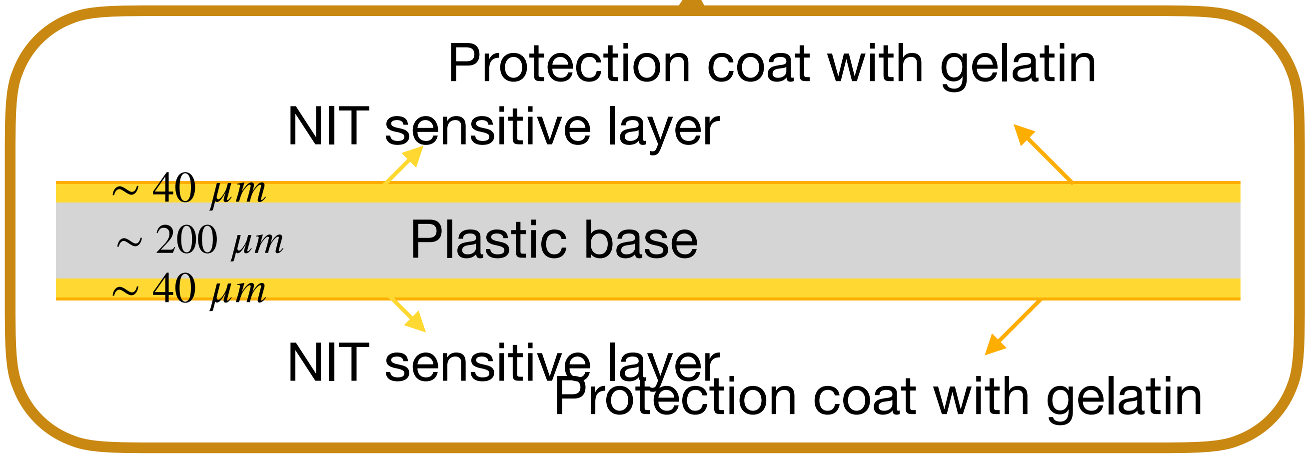
- Grain size ~70nm
- Typical distance between the centers of two sensitive elements is 71 nm, corresponding to about 350 sensitive elements per $1\mu m^3$

# Experimental set-up



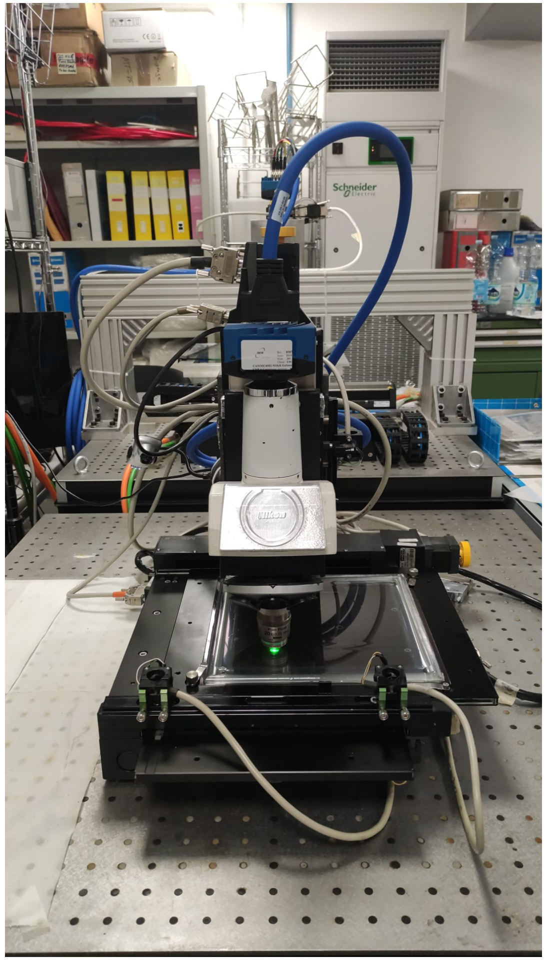





# New microscope R&D

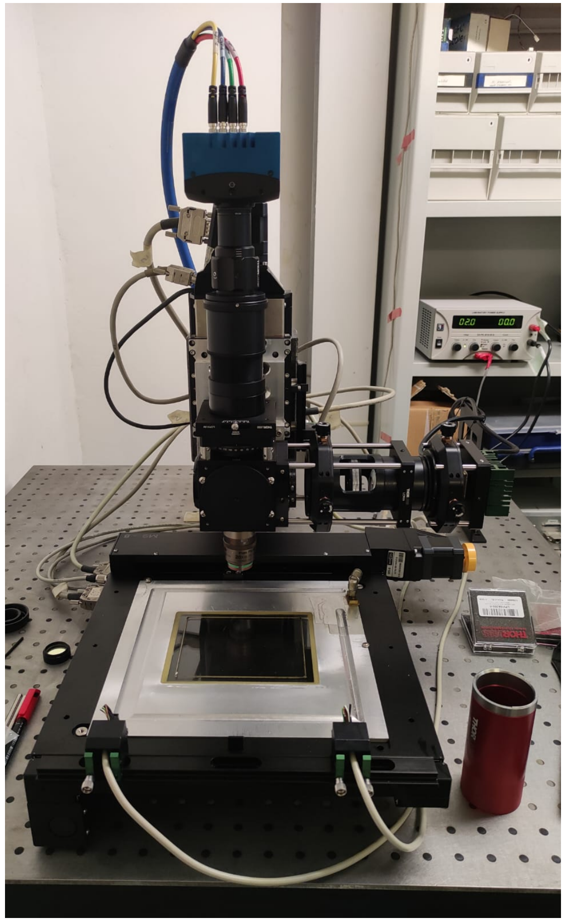
## Standard FOOT microscope

- Standard nuclear emulsions
- (grain size = 200 nm)
- Works in **transmission**
- 20x objective
- Z Step = 1.75 µm
- Scan both sides
- Scanning speed: 20cm²/h
- Small grains **not** visible

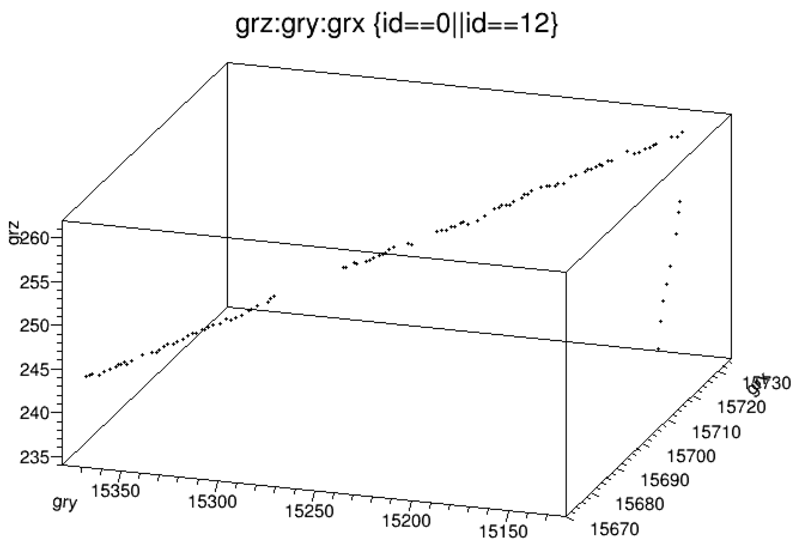


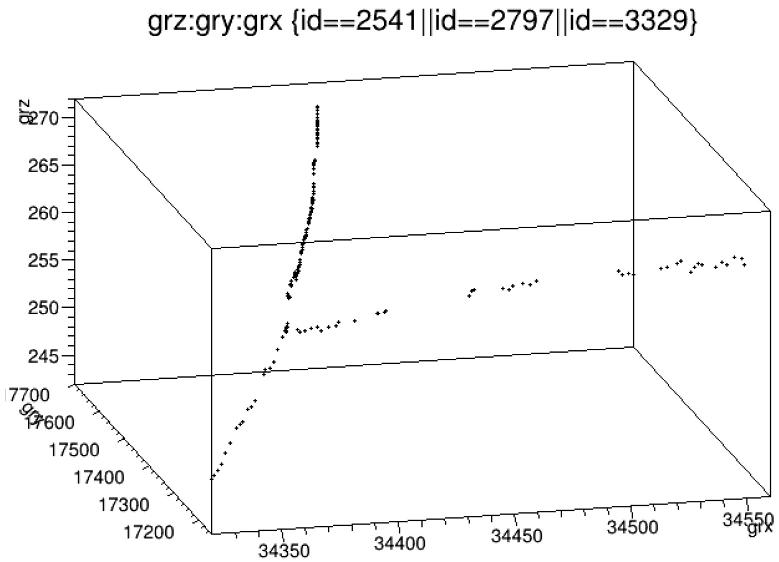
## New FOOT microscope

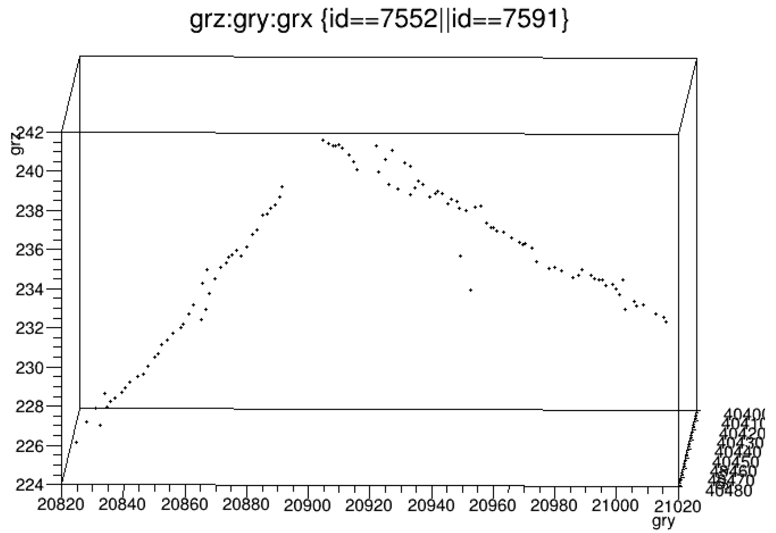
- NIT (grain size = 70 nm)
- Works in **reflection**
- 20x/40x objective + **adjustable** magnifying lens
- Intermediate Z step
- Scanning speed: 3cm²/h
- Possible to scan both sides
- Blue light → plasmonic resonance

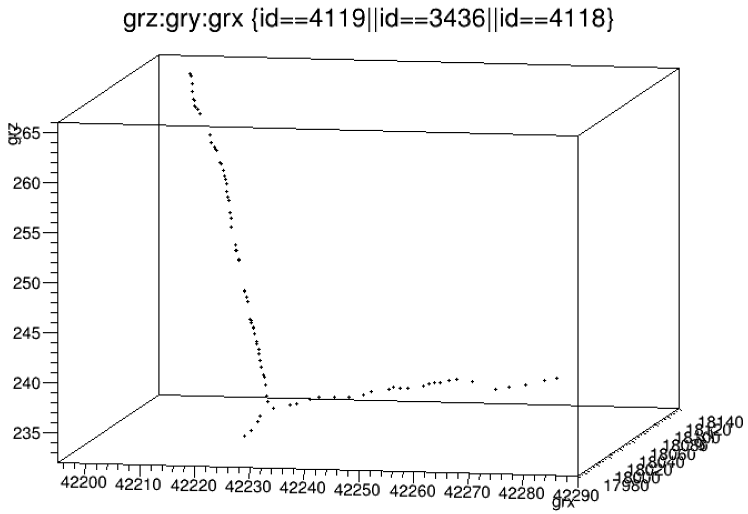


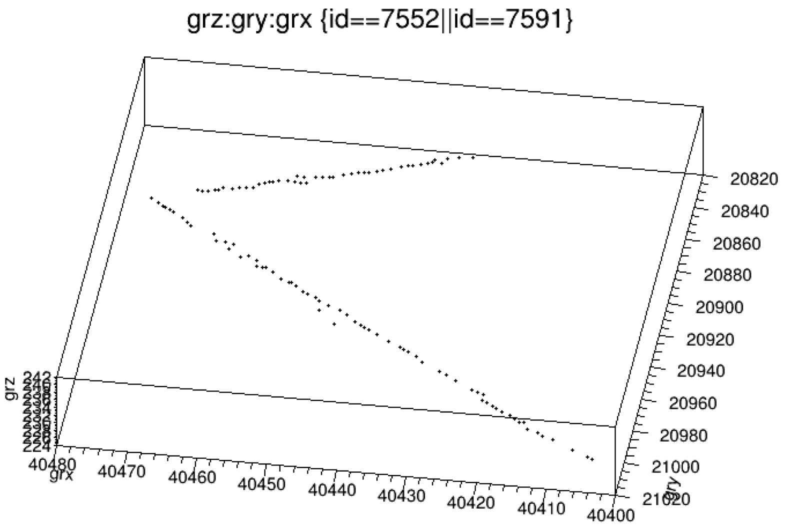
# NIT Preliminary Results

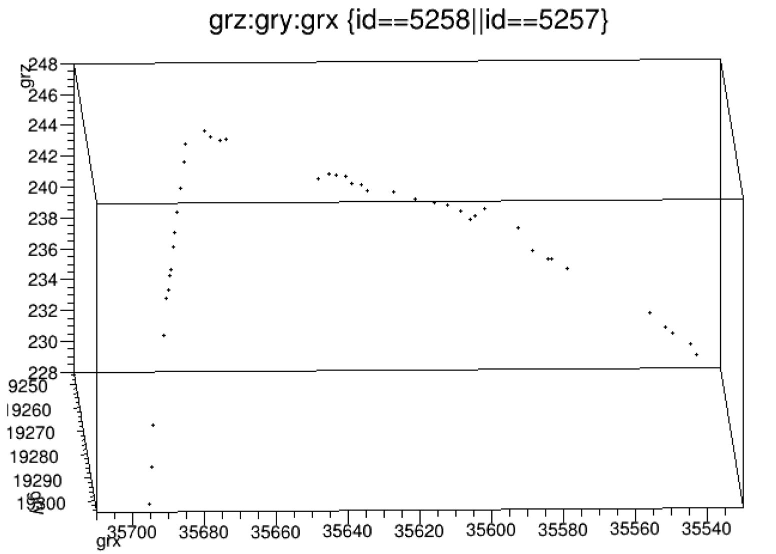


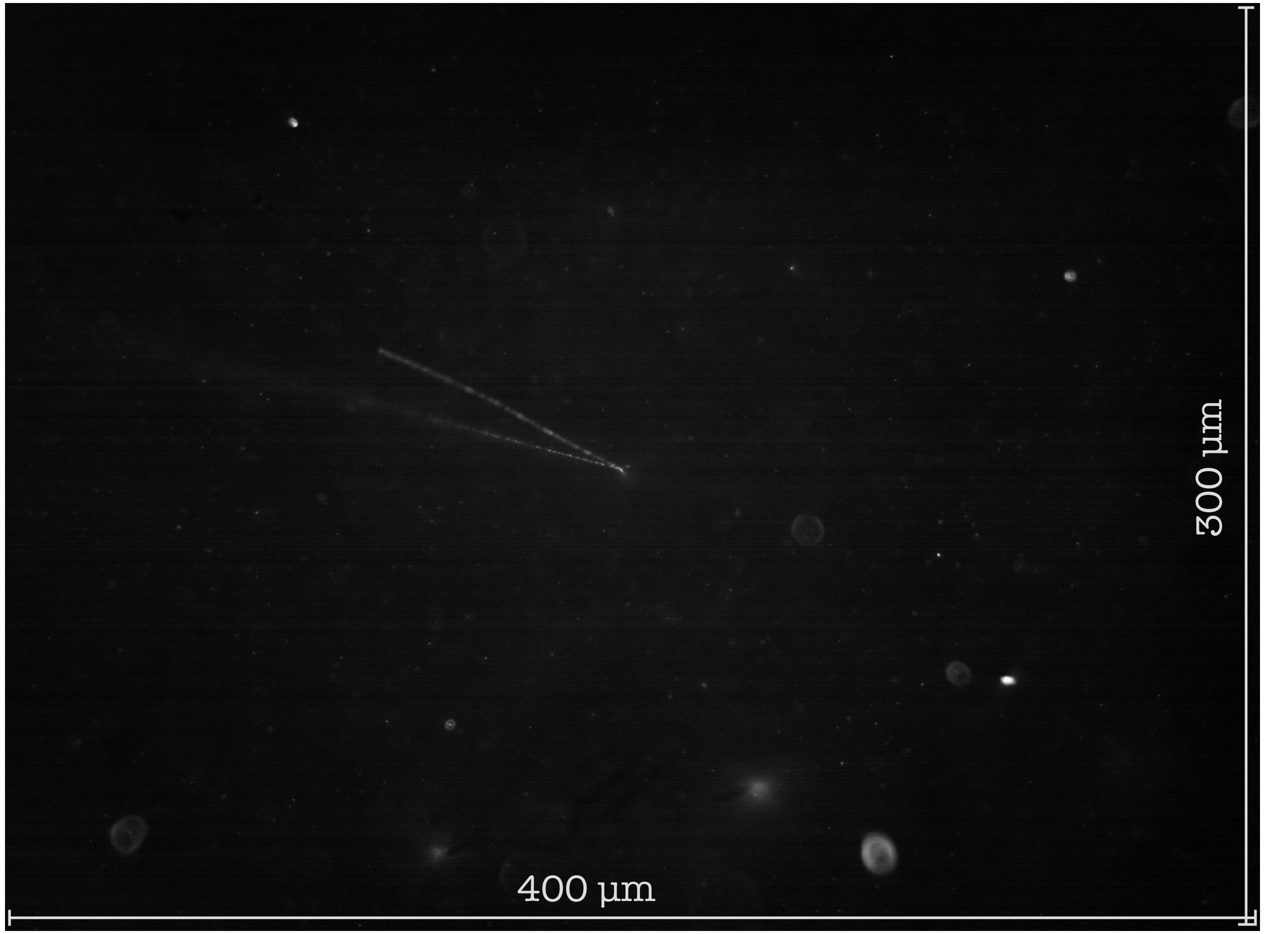



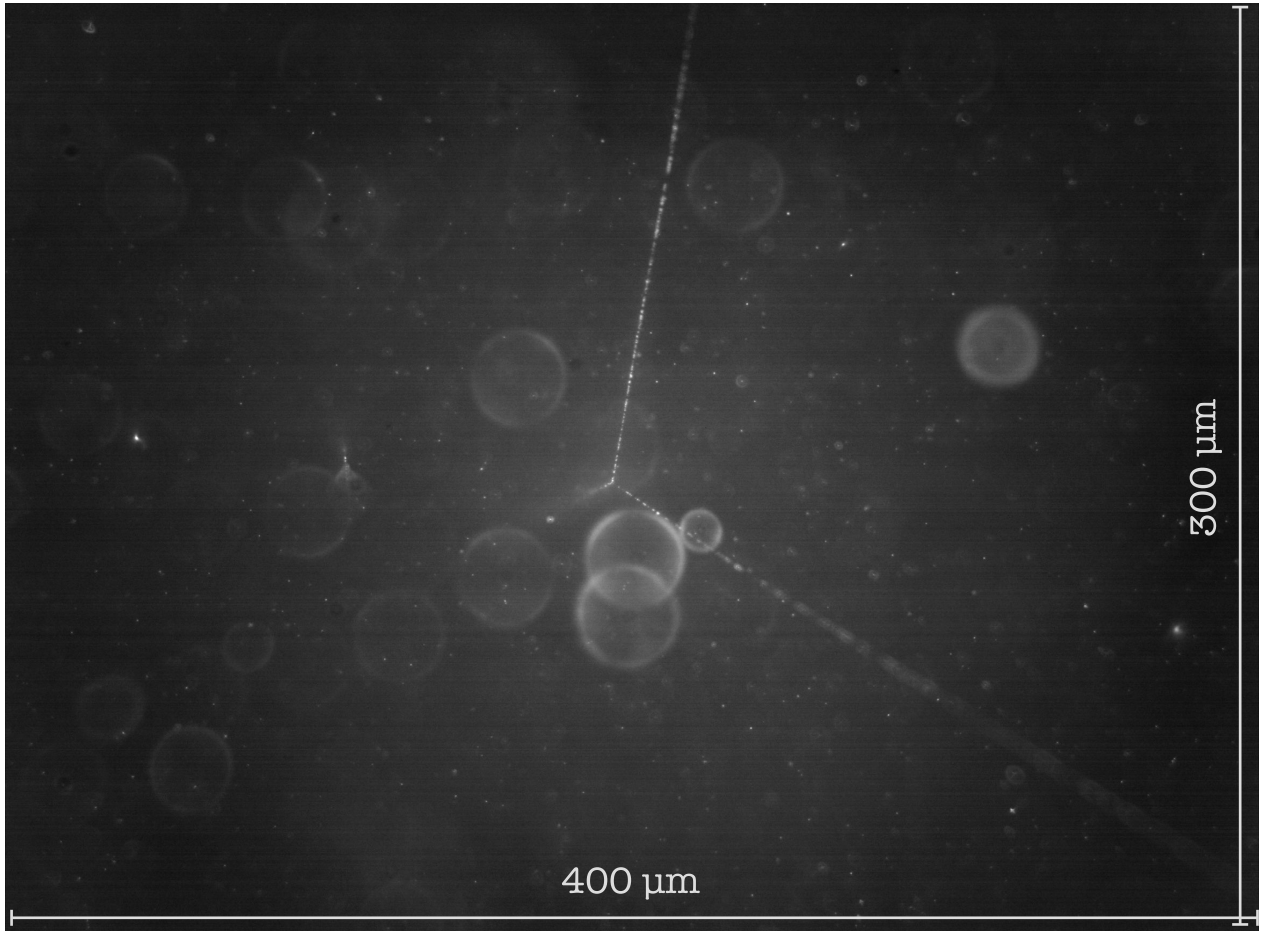



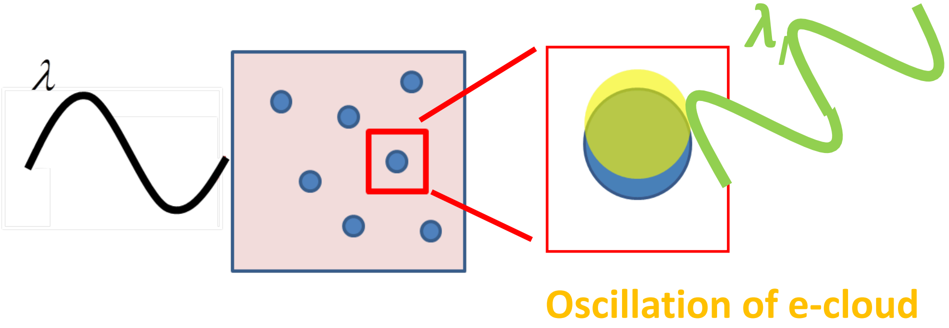
# NIT Preliminary Results



# Next step? Resonant Light Scattering

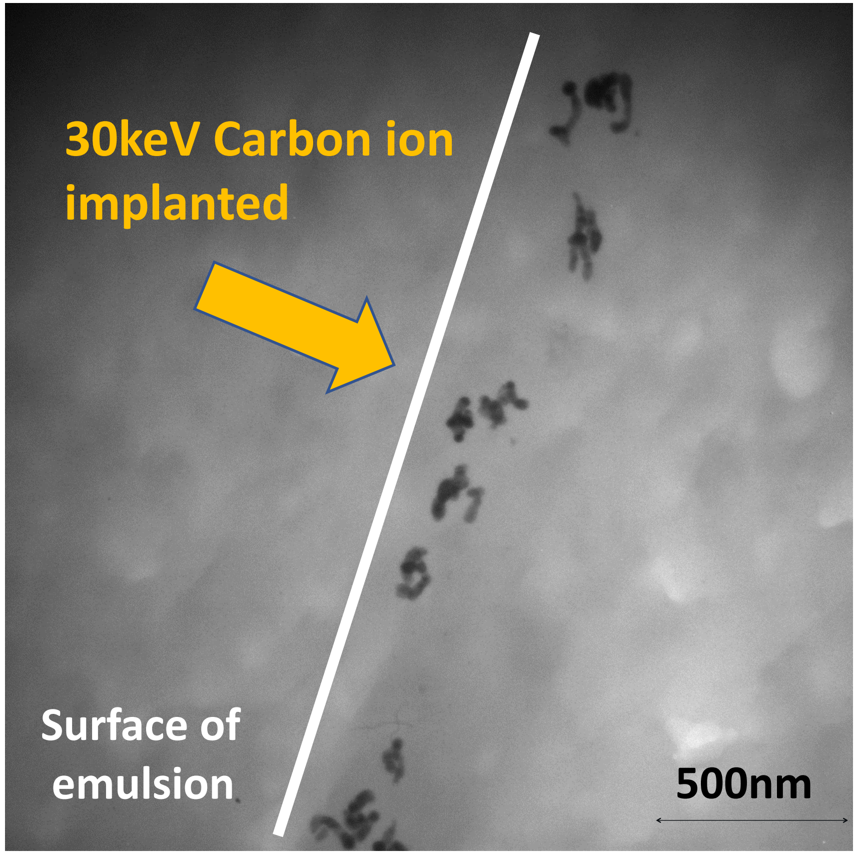
- Occurring when the light is scattering off a nanometric metallic (silver) grain dispersed in a dielectric medium (Applied Phys Letters 80 (2002) 1826)
- Sensitive to the shape of nanometric grains: when silver grains are **not spherical**, the resonant response depends on the polarization of the incident light.
- Each grain is emphasized at different polarization values



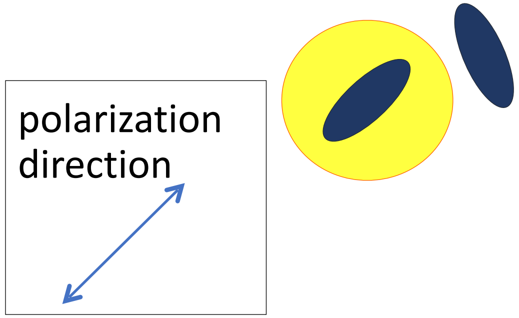

- Taking multiple measurements over the whole polarization range produces a displacement of the barycenter of the cluster
- Measure the displacement of cluster barycentre as a function of polarization angle (dx, dy)

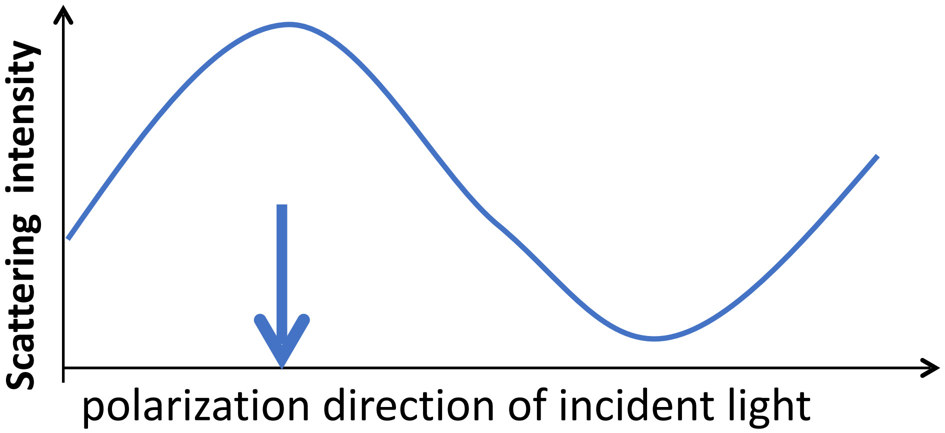
# Beyond the limits of diffraction with Plasmon Analysis

**TEM image of Carbon track after development**




Different orientation

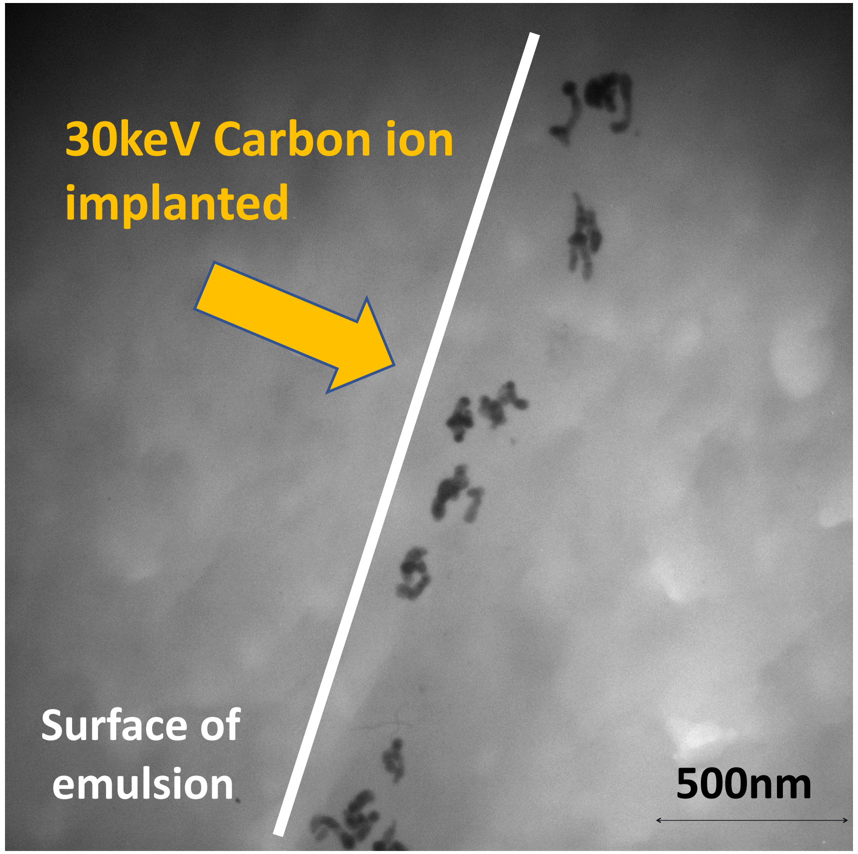


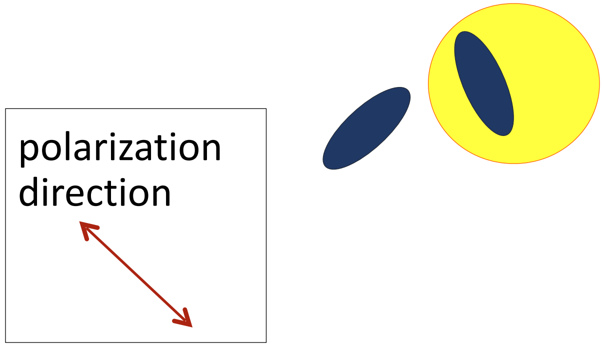

Optical response strongly depends on the polarization of incident light

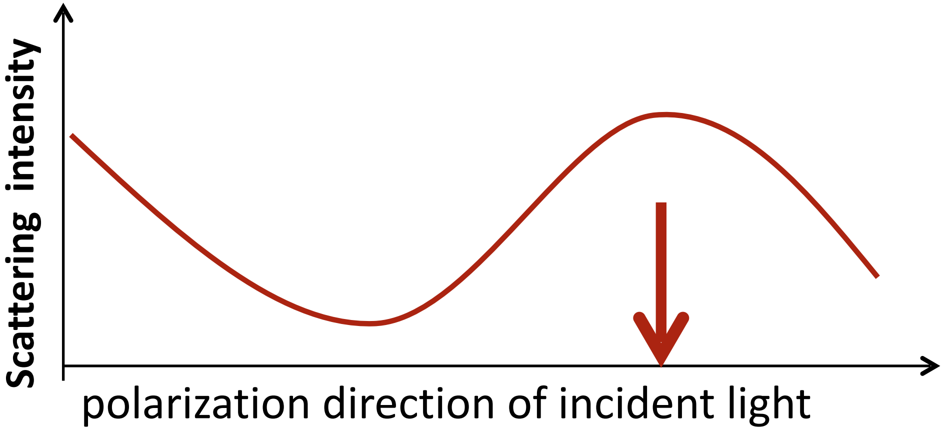
# Beyond the limits of diffraction with Plasmon Analysis

**TEM image of Carbon track after development**




Different orientation



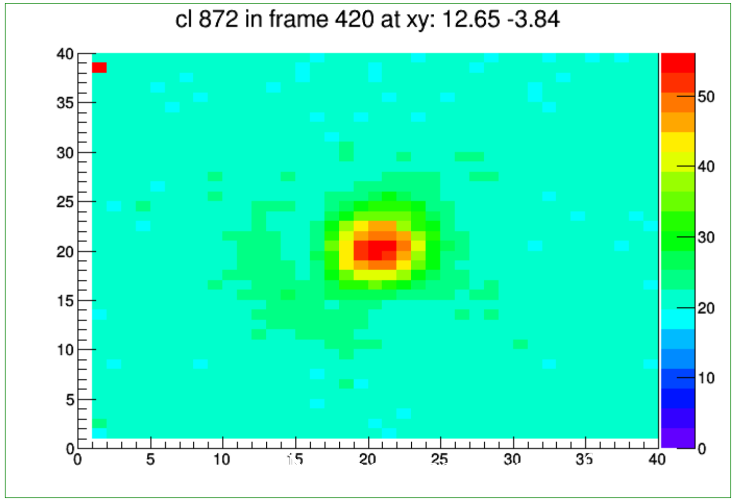



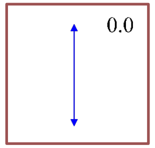

Optical response strongly depends on the polarization of incident light

# Beyond the limits of diffraction with Plasmon Analysis

## Background grain

Barycenter of the cluster

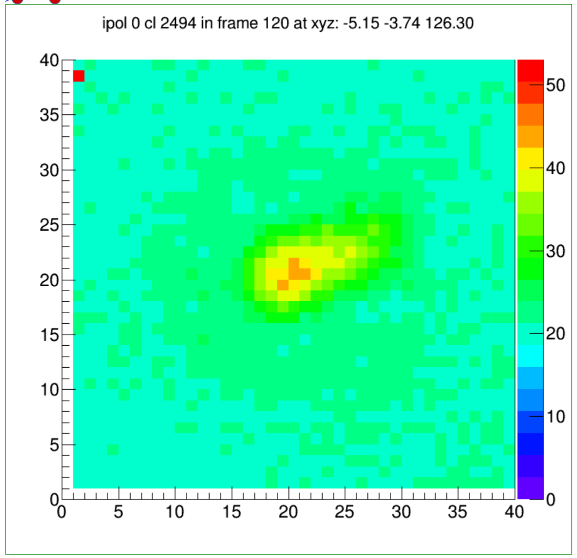


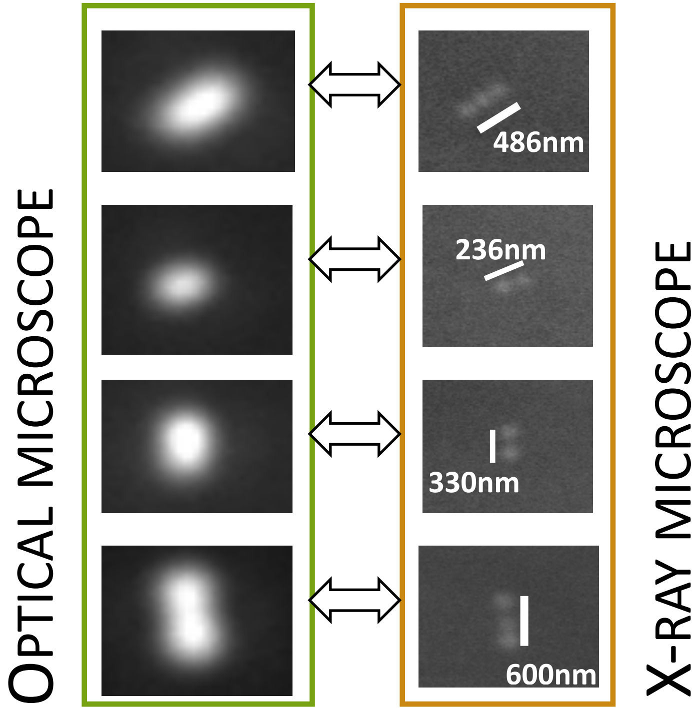



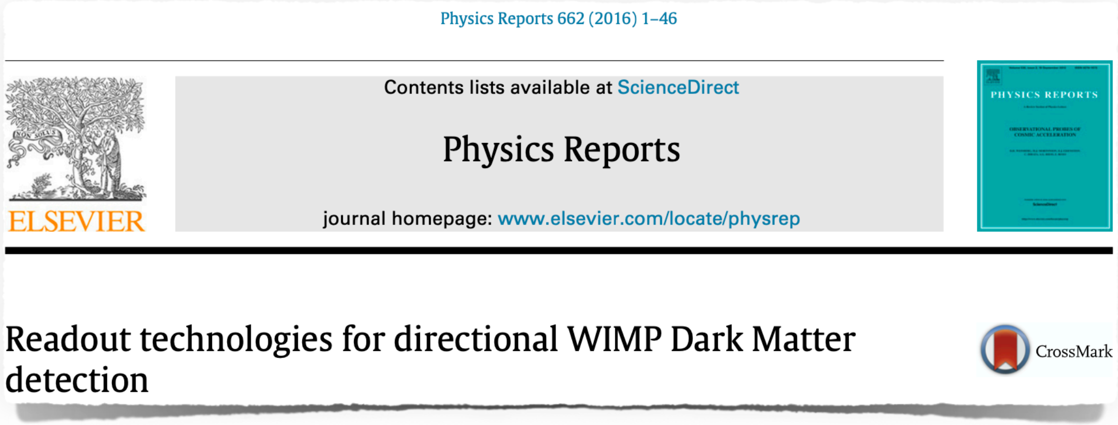

Polarization angle

## Signal-like events (100keV C ion)

Max barshift

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Readout technologies for directional WIMP Dark Matter detection

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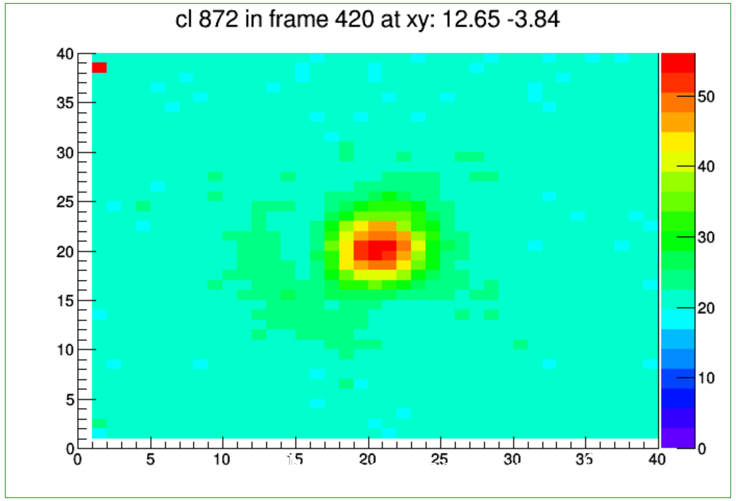
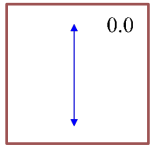
# Beyond the limits of diffraction with Plasmon Analysis

Background grain

Barycenter of the cluster

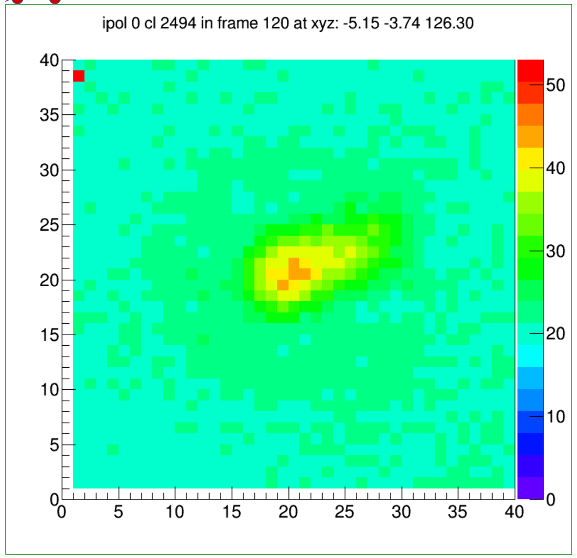


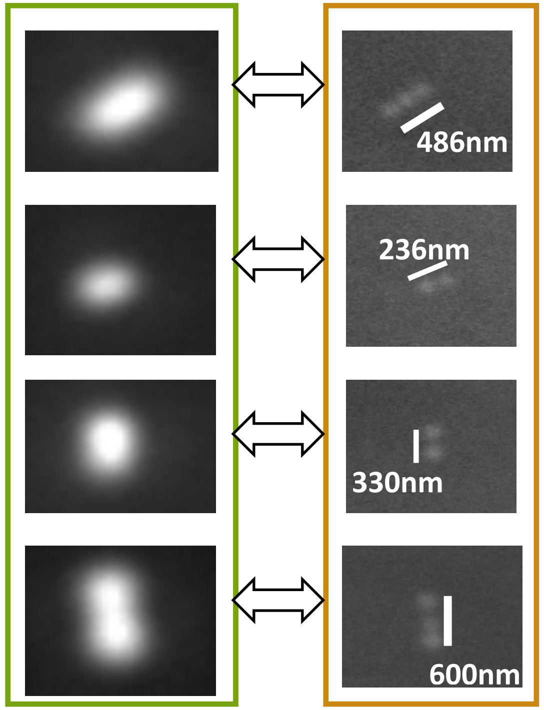

Polarization angle

Signal-like events (100keV C ion)

Max barshift




OPTICAL MICROSCOPE




X-RAY MICROSCOPE

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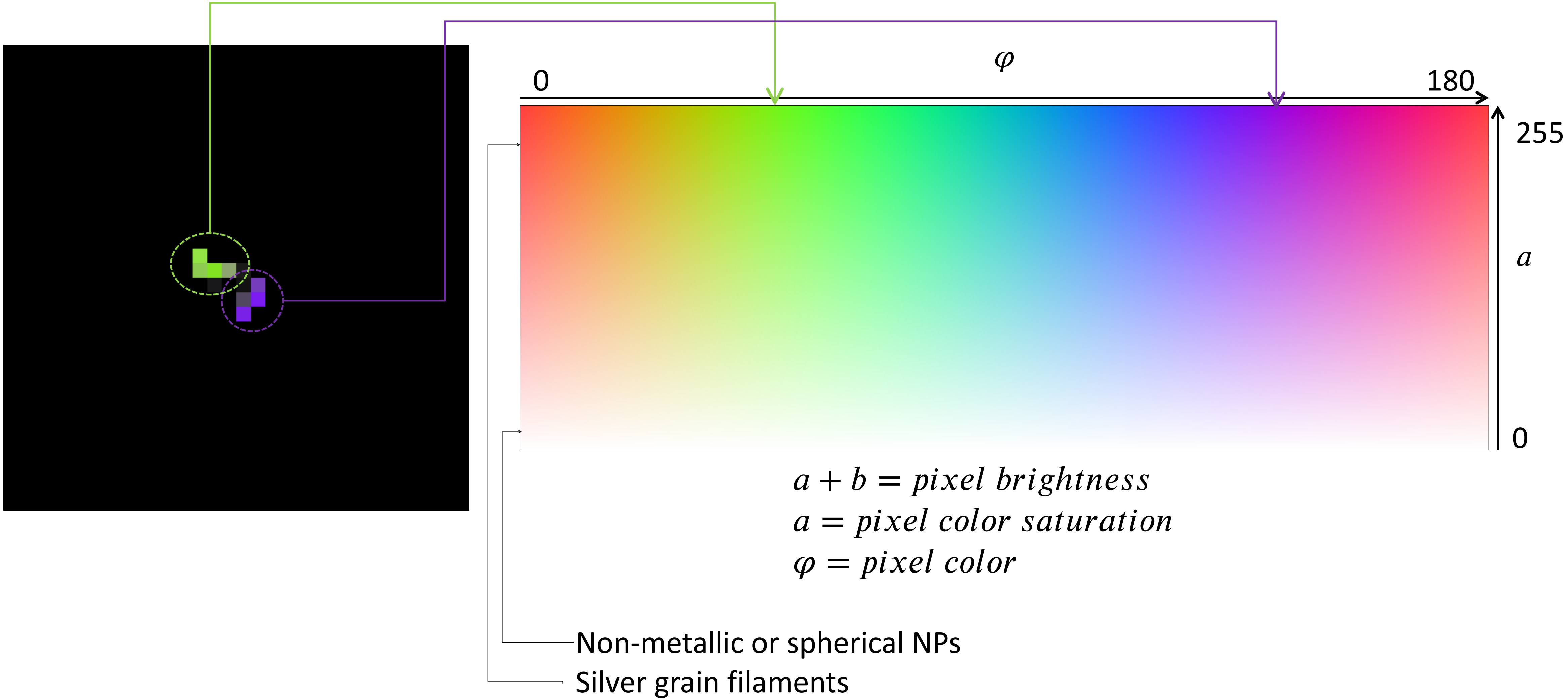
# Color representation

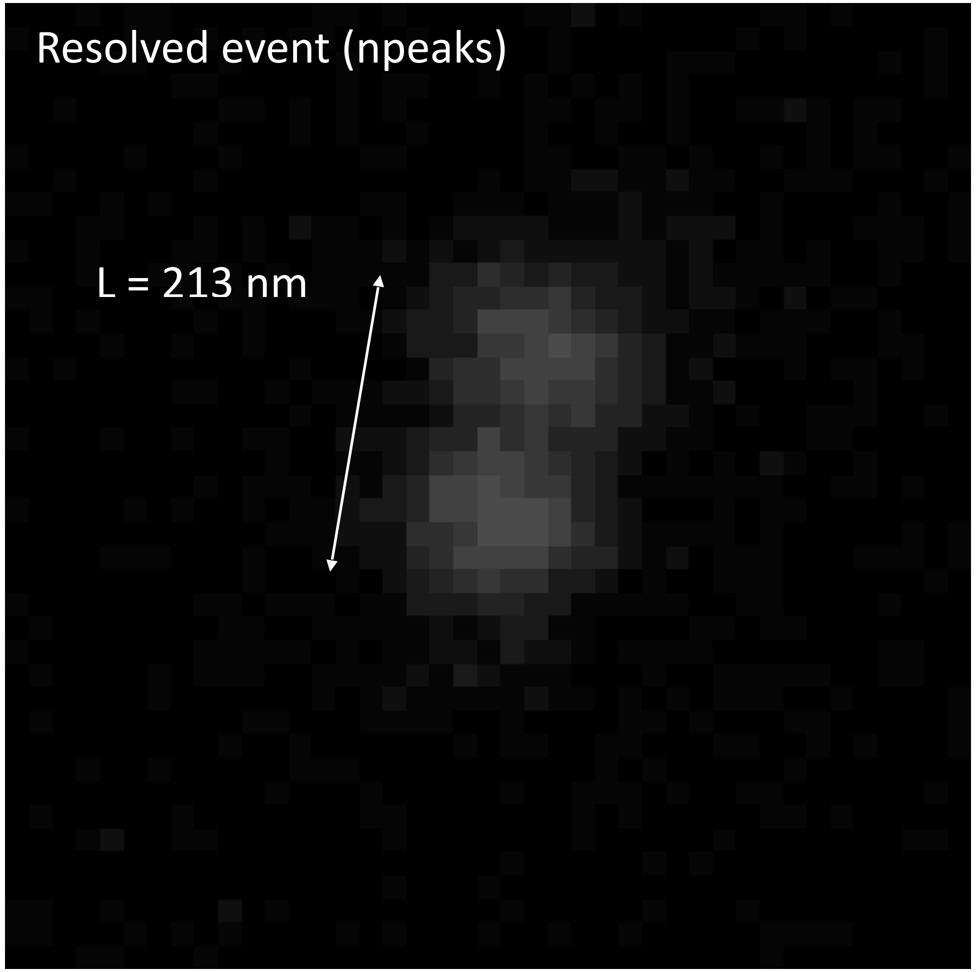


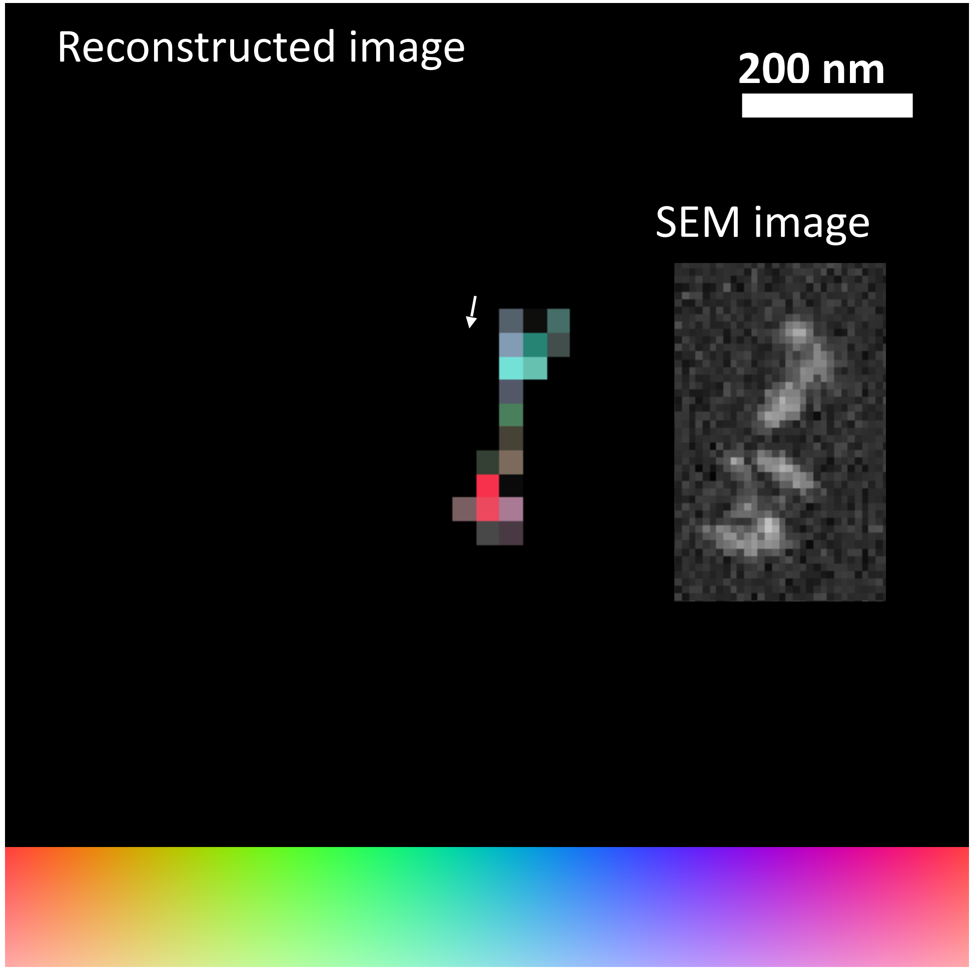

$a + b = pixel\ brightness$

$a = pixel\ color\ saturation$

$\varphi = pixel\ color$

# Color representation



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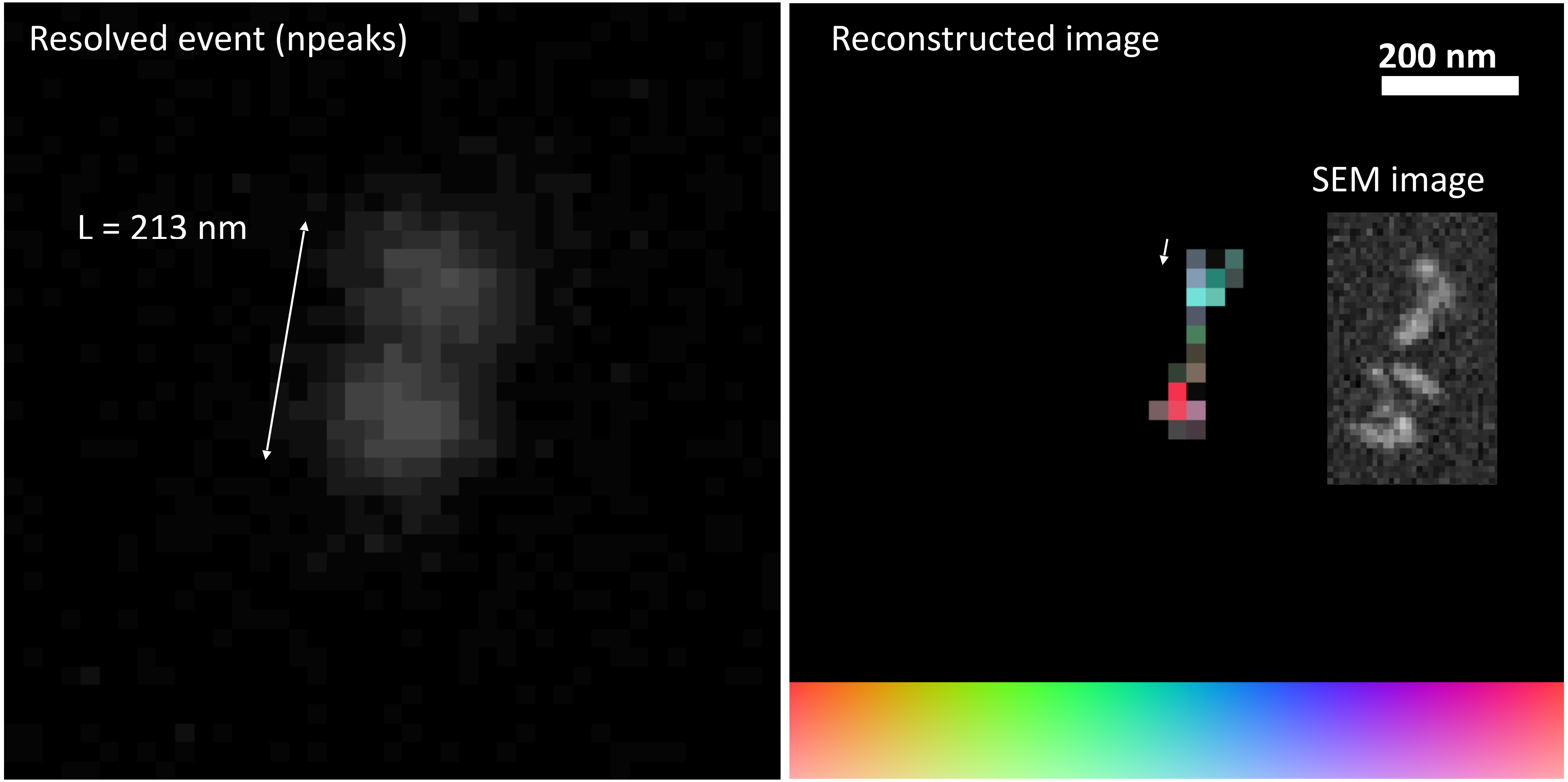

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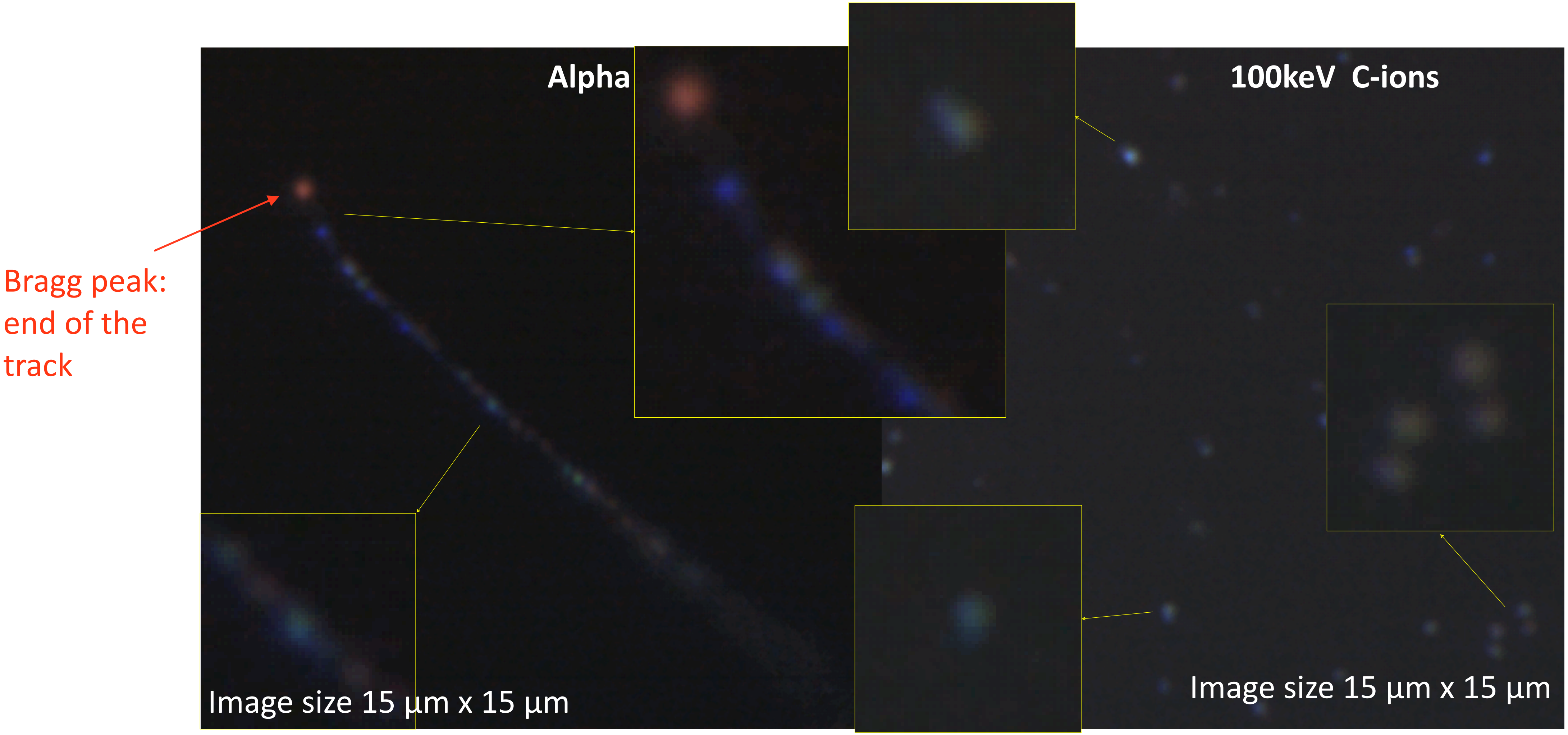

# Color representation