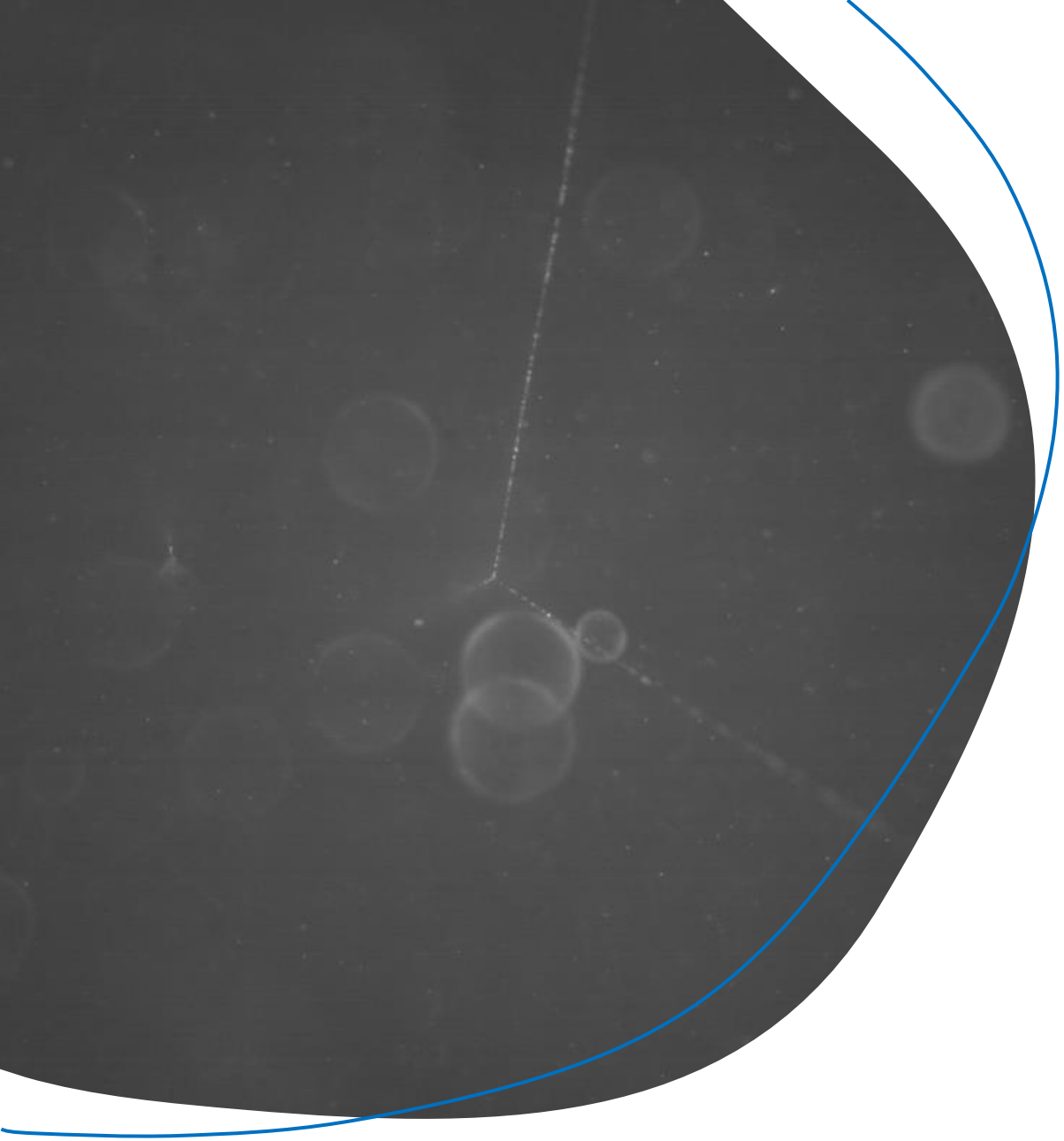


From Dark Matter Searches to Proton Therapy

Vincenzo Boccia on the behalf of the DAMON collaboration

(vincenzo.boccia@na.infn.it)

16TH PISA MEETING ON ADVANCED DETECTORS

Finanziato dall'Unione europea NextGenerationEU

Ministero dell'Università e della Ricerca

Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

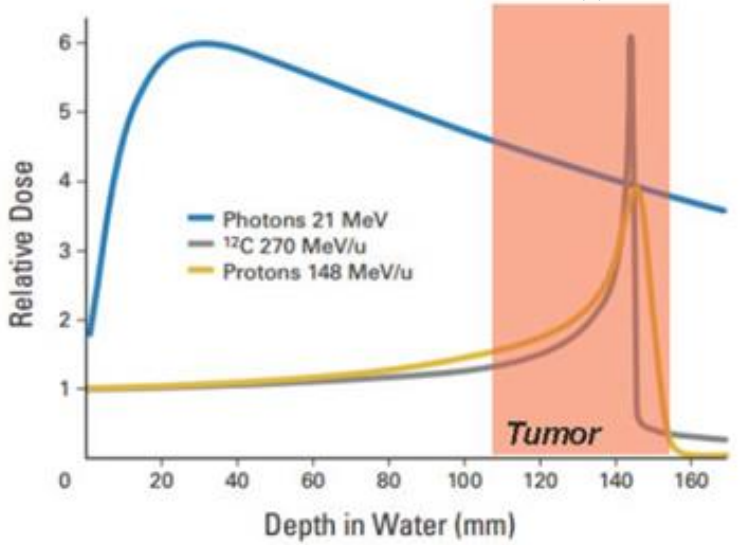
Outline

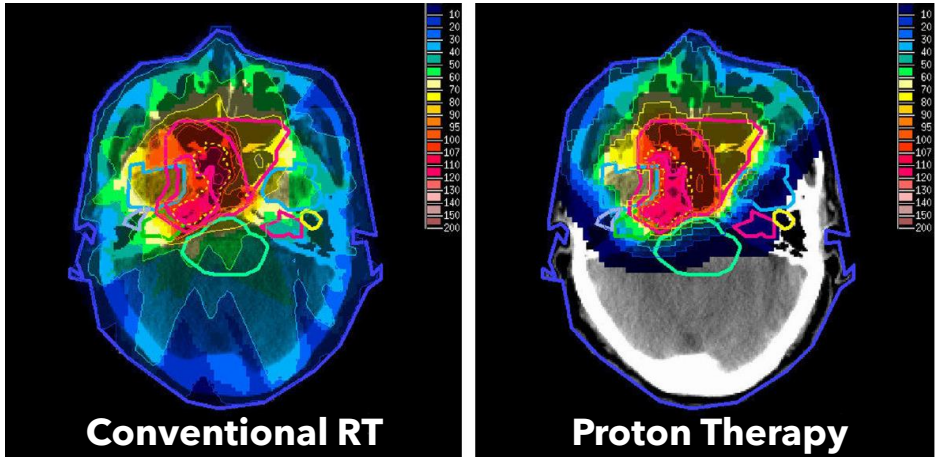
- The problem of target fragmentation in proton therapy
- Nano Imaging Trackers (NIT): a novel kind of nuclear emulsion film
- Direct meAsureMent of target fragmentation (DAMON): a new approach to measurements of proton-induced target fragmentation
- First results of the DAMON project

Nuclear Fragmentation in Proton Therapy

- Charged Particle therapy is a cancer treatment employing p or ^{12}C beams
- Favorable depth-dose profile (**Bragg Peak**) → precise dose localization for deep tumors

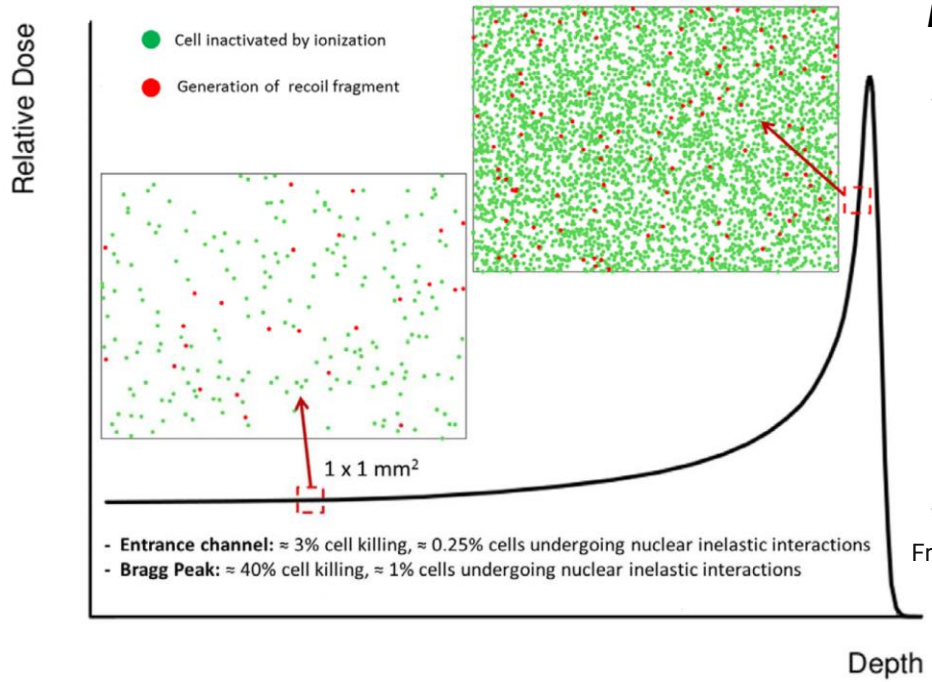
From: Dilmanian et al., Frontiers in Oncology 5(3), 2015





From: Taheri-Kadkhoda et al., Radiation Oncology 3:4, 2008

- In proton therapy, target fragmentation has a significant impact in the entrance channel, where healthy tissues are located
- Direct detection of target fragments is challenging: so far little data has been collected and only with inverse kinematics approaches (FOOT, Poster 263)



Expected Target Fragments' Ranges in H_20

Fragment	E (MeV)	LET ($keV/\mu m$)	Range (μm)
^{15}O	1.0	983	2.3
^{15}N	1.0	925	2.5
^{14}N	2.0	1137	3.6
^{13}C	3.0	951	5.4
^{12}C	3.8	912	6.2
^{11}C	4.6	878	7.0
^{10}B	5.4	643	9.9
^{8}Be	6.4	400	15.7
^{6}Li	6.8	215	26.7
^{4}He	6.0	77	48.5
^{3}He	4.7	89	38.8
^{2}H	2.5	14	68.9

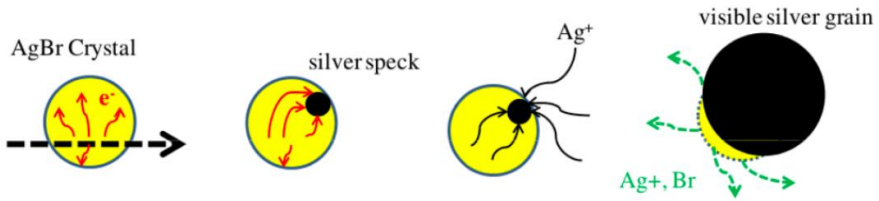
From: Tommasino F. and Durante *Cancers* **2015**, *7*(1), 353-381;

Nuclear Emulsion Films

- Large number of silver halide crystals (generally $AgBr$) dispersed in an organic gelatine binder
  - Formation of the **latent image**:

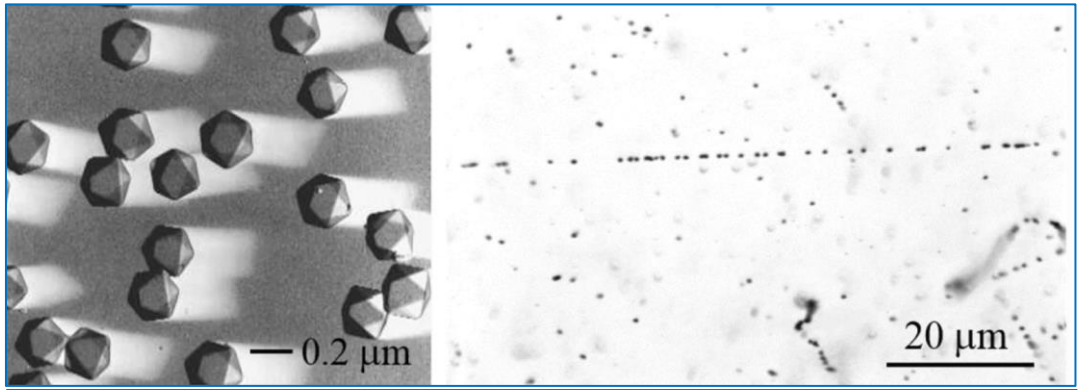
$$Ag^+ + e^- \rightarrow Ag$$

  - Signal amplification with a reduction agent (chemical development)

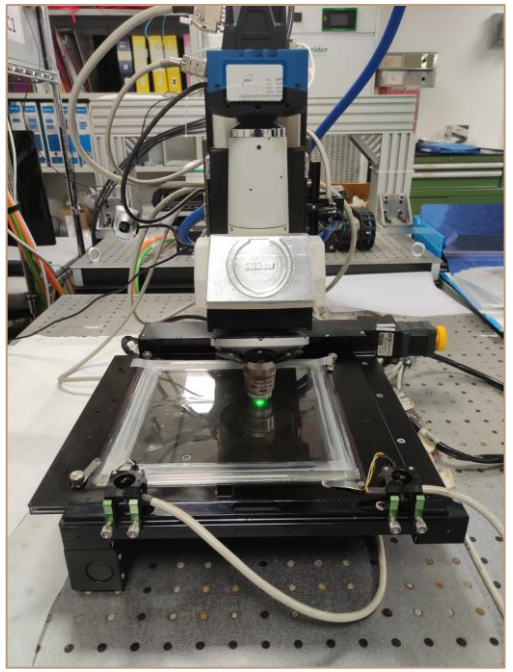


- Several **applications**:
  - HEP: **OPERA**, SND@LHC, FASER, DsTau…
  - Medical Physics: FOOT, DAMON, …
  - Muon Radiography…
- Features of OPERA-like emulsions:
  - average crystal diameter of 200 nm, a granularity of 1 μm and a sensitivity to MIPs of ~ 30 grains / 100 μm

Example of a track in a nuclear emulsion



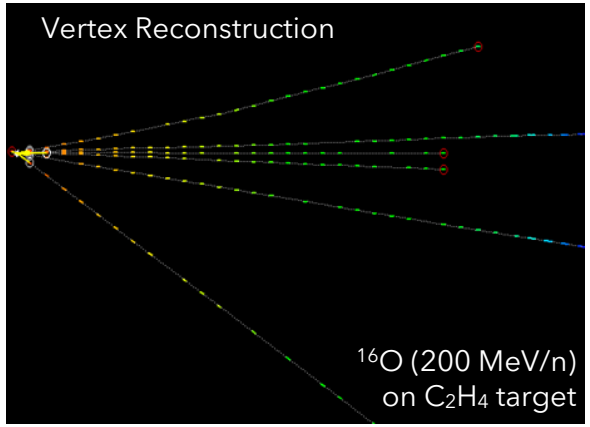
From: G. De Lellis et al., Journal of Instrumentation



Automated optical microscope for OPERA-like emulsion films

Scanning with automated optical microscopes

Offline track and event reconstruction



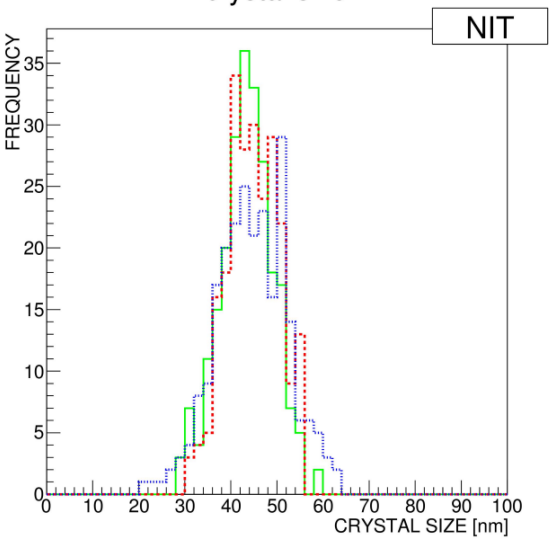
Nano Imaging Trackers (NIT)

- **Nano Imaging Trackers** (**NIT**) are a novel kind of fine grained nuclear emulsion films
- NIT were designed to achieve a directional direct detection of WIMP-induced nuclear recoils
- The expected nuclear recoil track lengths in NIT are of the order of **100 nm** → extremely high spatial resolution required
- New production method: finer AgBr crystals (tunable from **20 nm to 80 nm**) and dedicated low temperature development
- NIT production facilities in Nagoya (Japan) and Gran Sasso (LNGS, Italy)

LNGS Gel Production Machine

Undeveloped NIT sample

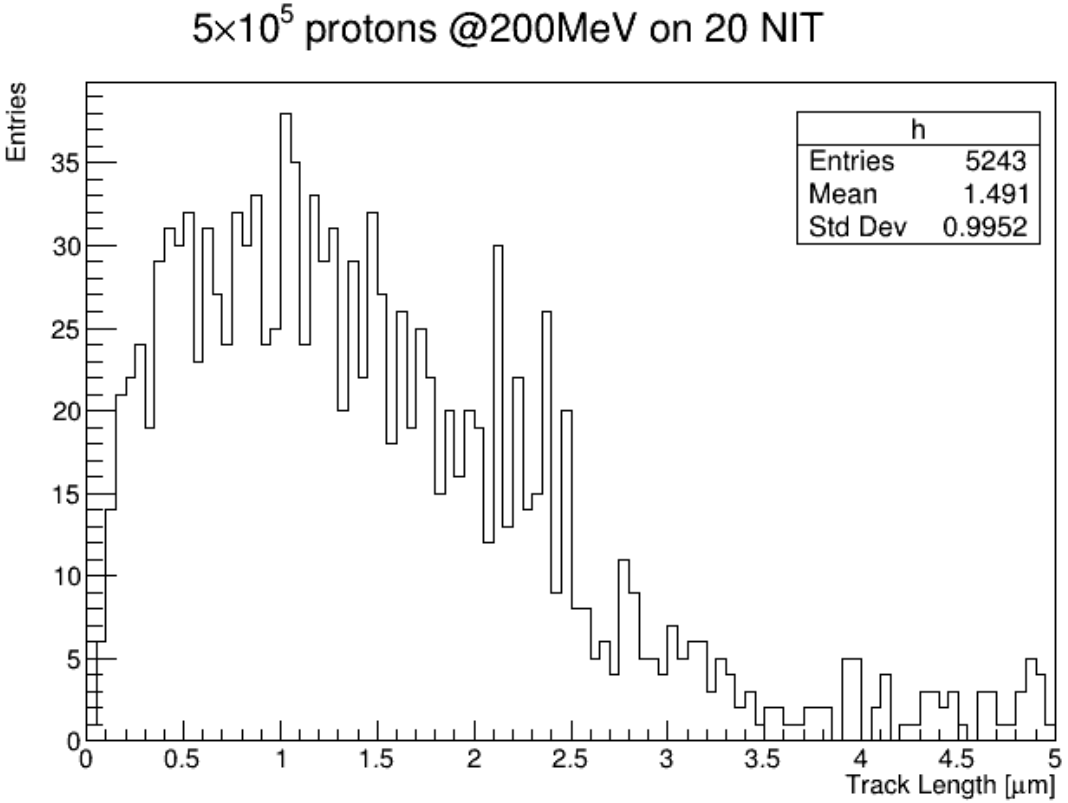
crystal size



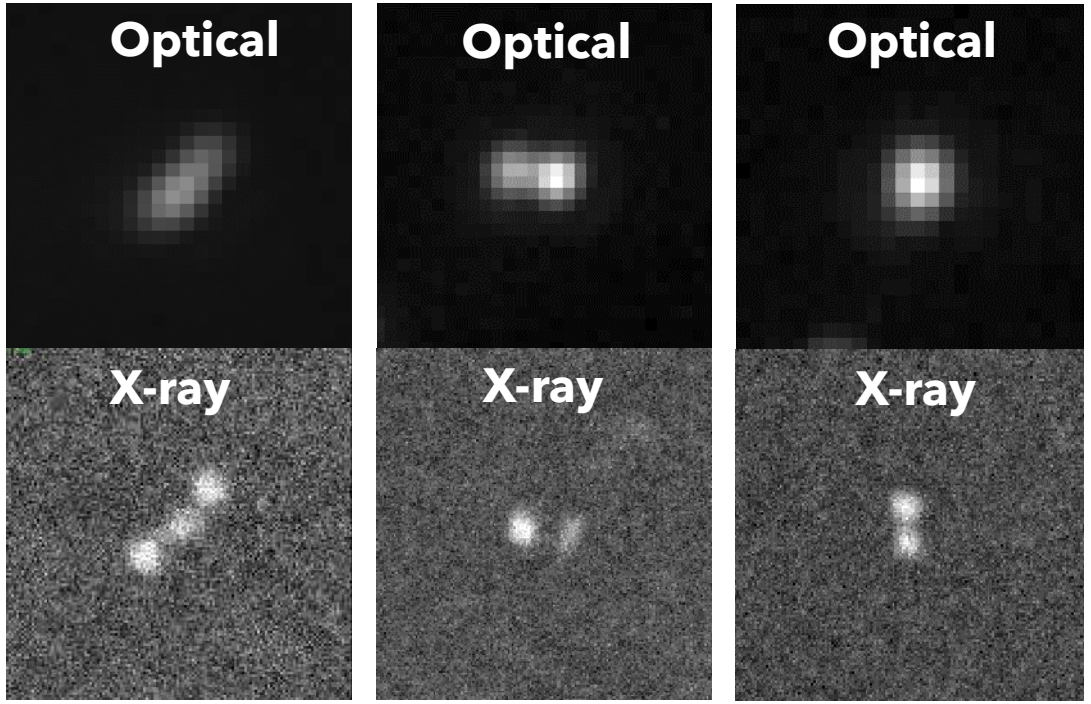
From: Asada T. et al. Prog. Theor. Exp. Phys. 2015

NIT Readout: Super Resolution

- Tracks shorter than $\sim 200\ nm$ can not be resolved due to the optical diffraction limit
  - About 10% of proton induced target fragments (200 MeV) are expected to have **track lenghts in NIT** $< 1\ \mu m$
- X-ray or Scanning Electron Microscope (SEM) cannot be employed on a large scale because of their **limited speed** → new approach employing an optical super-resolution microscope



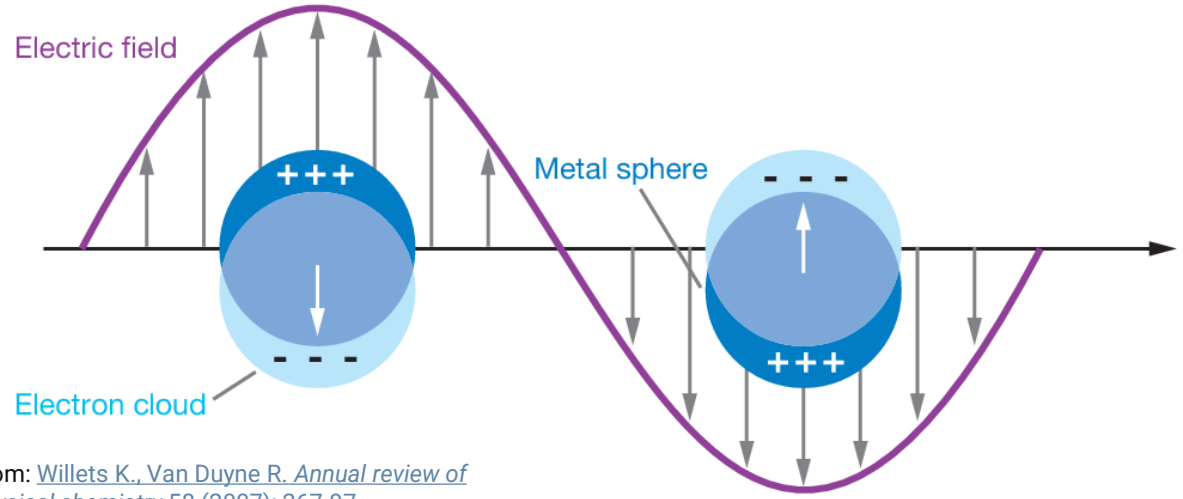
400 keV Kr ion in NIT



L = 380 nm **L = 265 nm** **L = 160 nm**

Localized Surface Plasmon Resonance

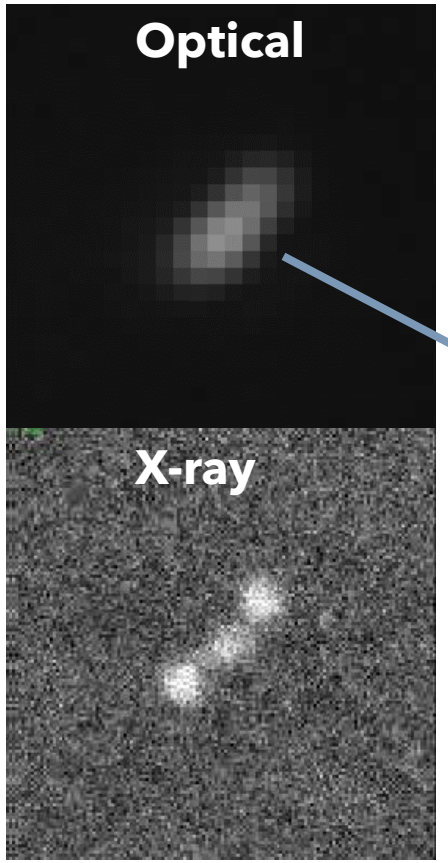
- Super-resolution is achieved by employing the **localized surface plasmonic resonance** (LSPR)
- Localized surface plasmons are non-propagating excitations of the conduction electrons of metallic nanostructures immersed in a dielectric → **silver grains in NIT exhibit LSPR at visible wavelengths**!



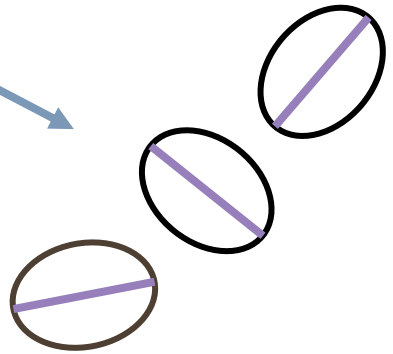
From: Willets K., Van Duyne R. *Annual review of physical chemistry* 58 (2007): 267-97

$$\alpha = 4\pi a^3 \frac{\varepsilon - \varepsilon_m}{\varepsilon + 2\varepsilon_m} \rightarrow \varepsilon = -2\varepsilon_m$$

Resonance condition



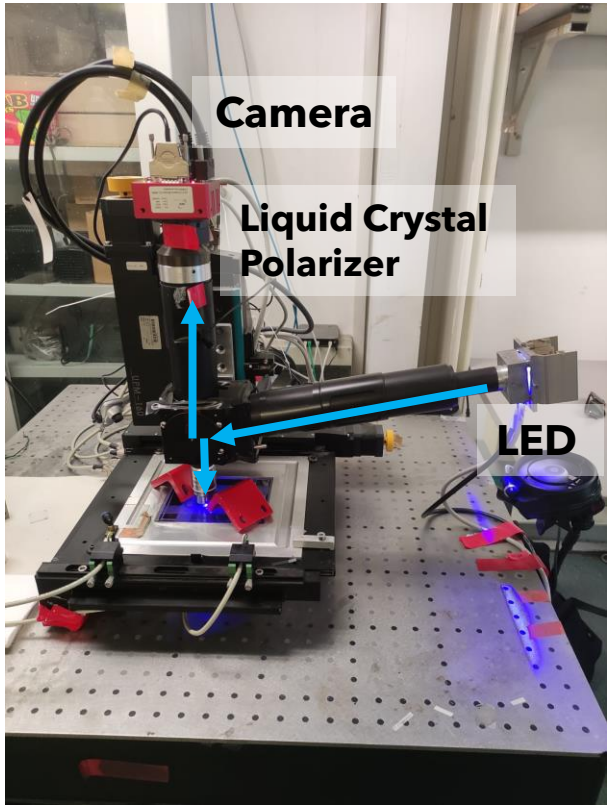
LSPR depends on the **shape** and **orientation** of the nanoparticle



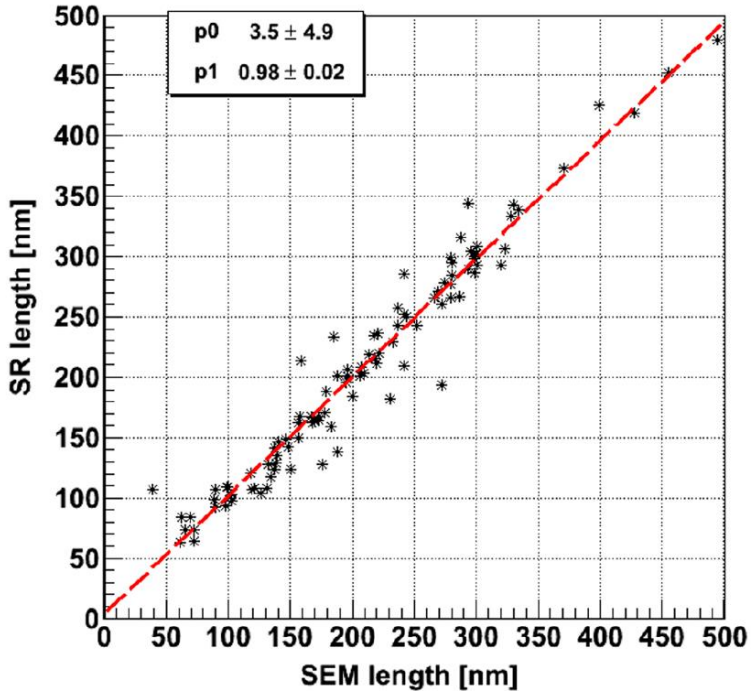
Maximum reflected light when E field is parallel to major axis → possible to resolve close structures!

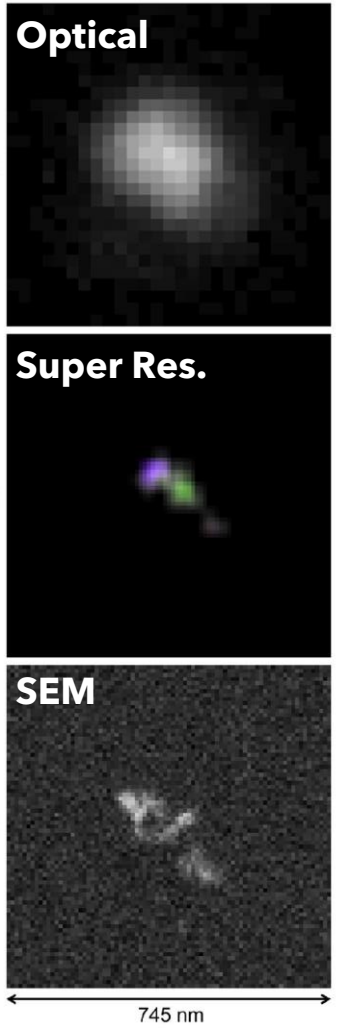
Super Resolution LSPR Optical Microscope

- 8x input images obtained with different polarizations (obtained with a liquid crystal polarizer)
- Tracks **down to 50 nm** have been reconstructed

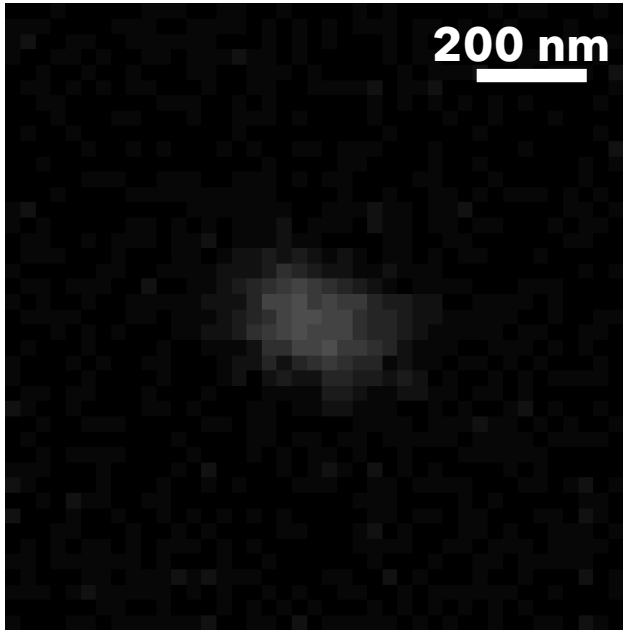


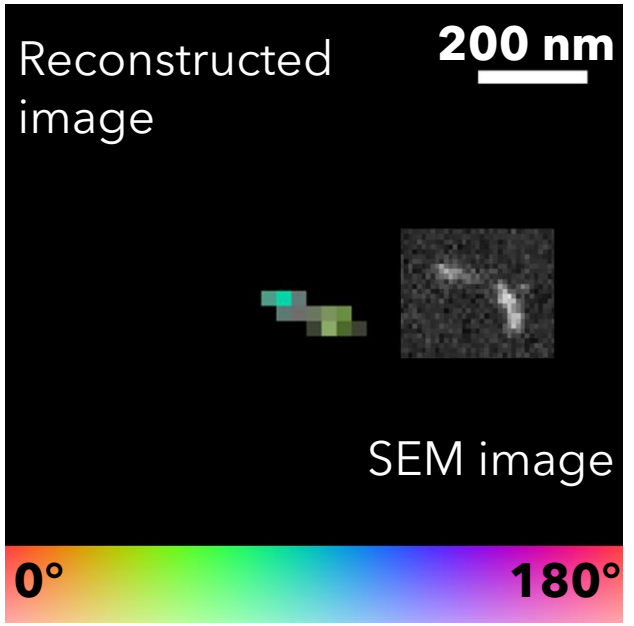
From: Alexandrov et al. Scientific Reports volume 13, Article number: 22813 (2023)





100 keV Carbon ion in NIT

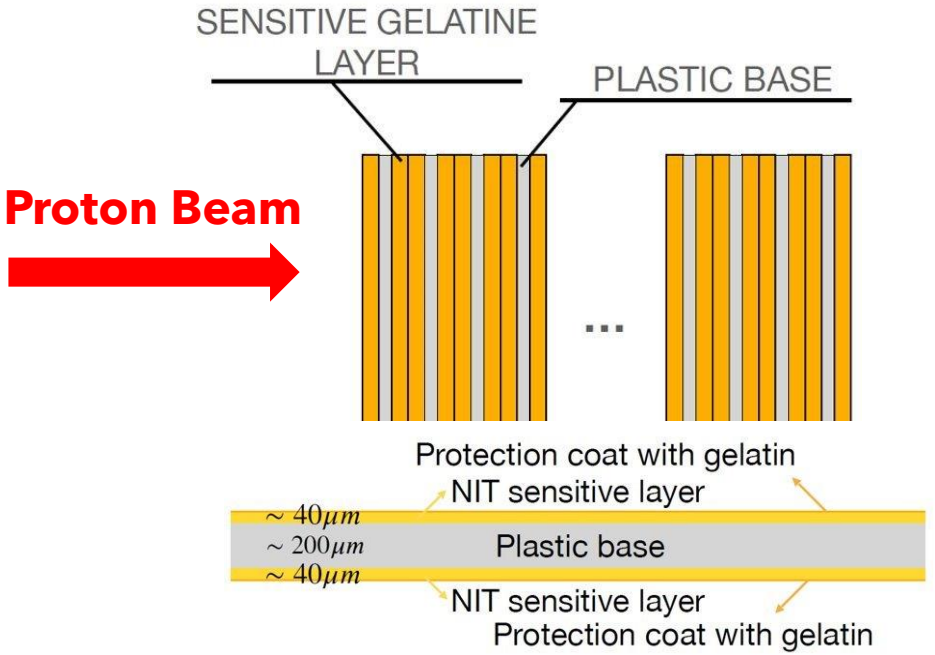


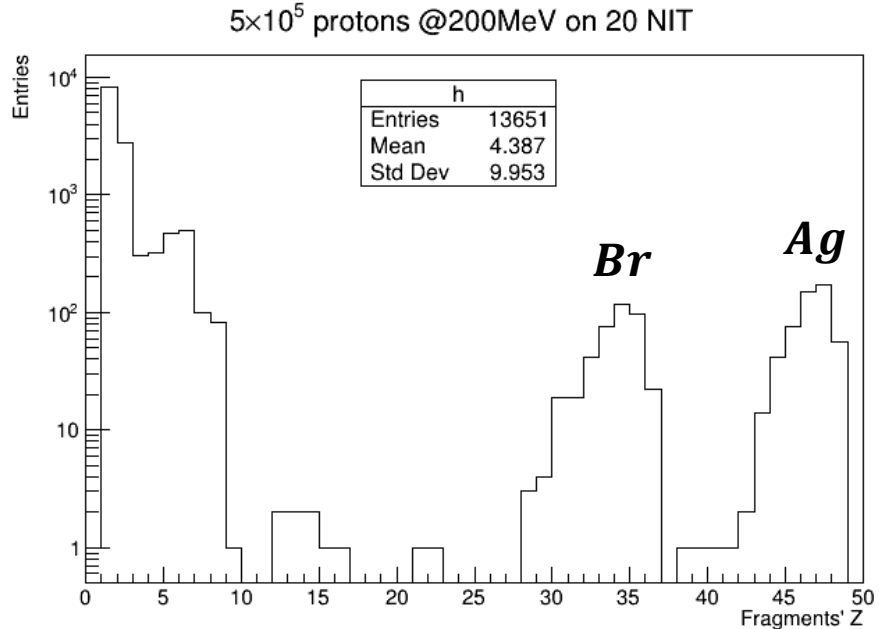


Polarization Angle

DAMON: A new approach to Target Fragmentation

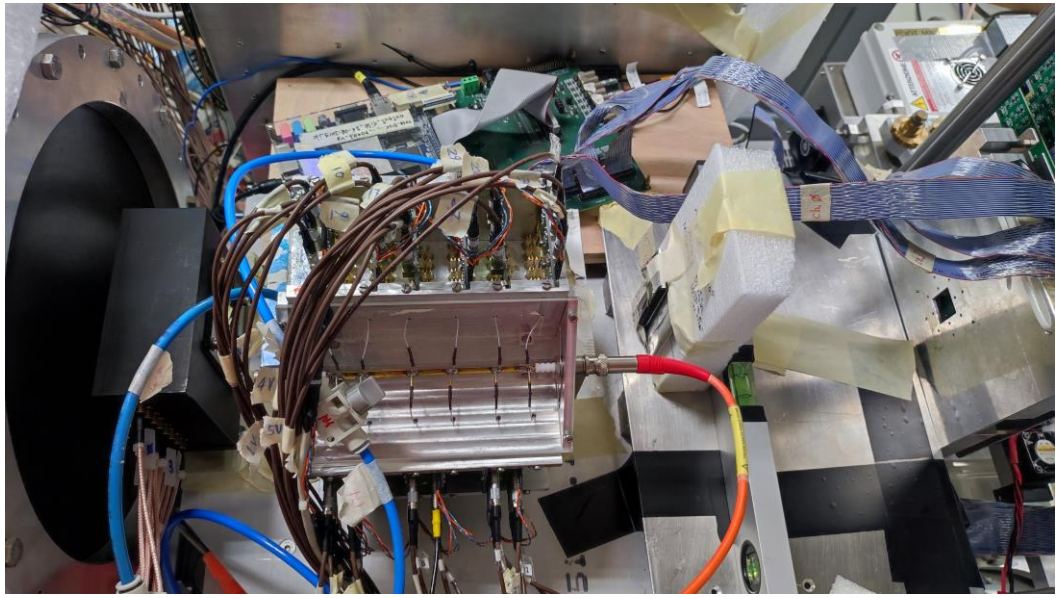
- The DAMON (Direct meAsureMent of target fragmentation) project (PRIN 2022) aims at measuring for the first time proton-induced target fragmentation in **direct kinematics**
- Direct detection of short fragments made possible by NIT **acting both as target and tracking devices**
- The estimated interaction probability for 200 MeV protons in a detector with 20 NIT is $\sim \mathbf{1\%}$
- Among all interactions (Geant4 Simulation):
  - ~38 % occur in the emulsion gel (C, O, H, N, Ag, Br)
  - ~62% occur in the plastic support (Polystirene, $(C_8H_8)_n$)
  - ~15% of interactions on Ag, Br
- Typical energies of fragments, of the order of MeV, make them travel at least 300 nm → **detectable!**





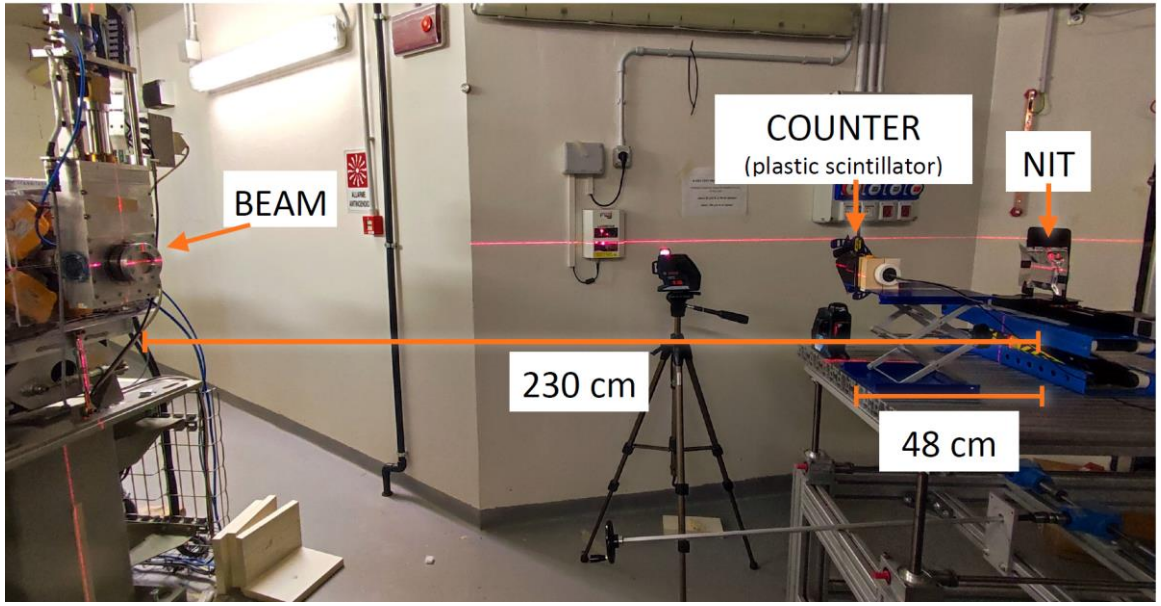
Experimental Campaigns

- Two exposures perfomed so far
  - **Pilot run** with an exposure of 19 NITs to 211 MeV protons at the Trento proton therapy center
  - Proton **sensitivity test** at CNAO (Pavia) to 70 MeV protons
- NIT samples were produced in LNGS and kept in a refrigerated box during transport to minimize thermal noise



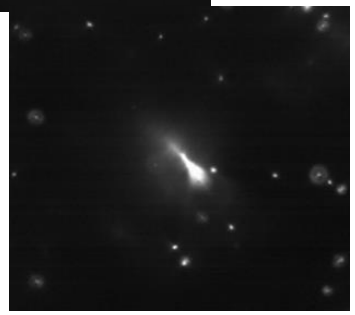
CNAO Exposure: single high intensity spot (10^7 protons)

Trento Exposure: uniform density of 10^4 protons cm^{-2}



- Sensitivity test showed that current NIT are **not sensitive enough to reconstruct primary protons** above $70\ MeV$!
- Tests ongoing with hybrid OPERA-NIT detectors

NIT



OPERA-like

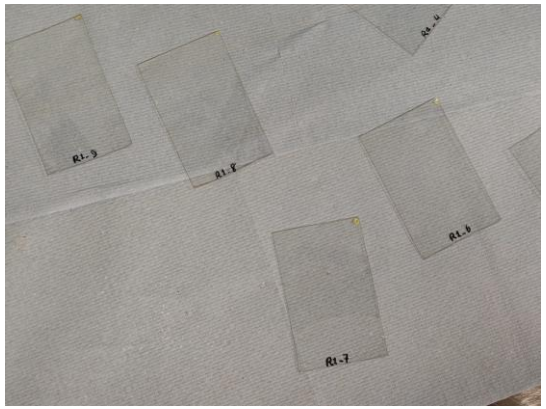
Pilot Run Readout

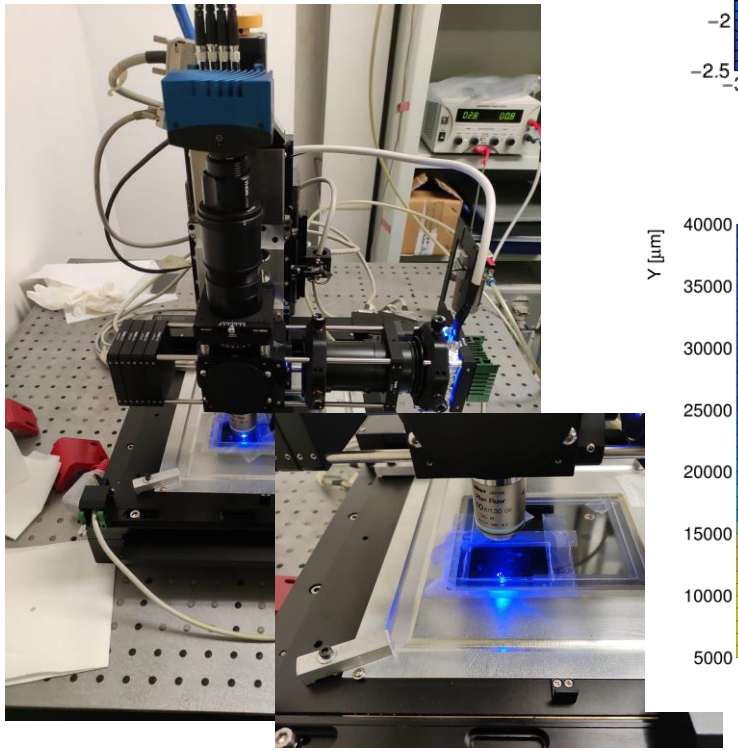
- Target density for the Pilot Run was 10^4 protons cm^{-2} → 5x5 grid for uniform exposure
- NIT size was ~ $6x4\ cm^2$ with two sensitive gelatine layers (~ 60 μm) deposited on both sides of a polystyrene support (~ 200 μm)
- Two step readout: **optical scan** and **SR scan**

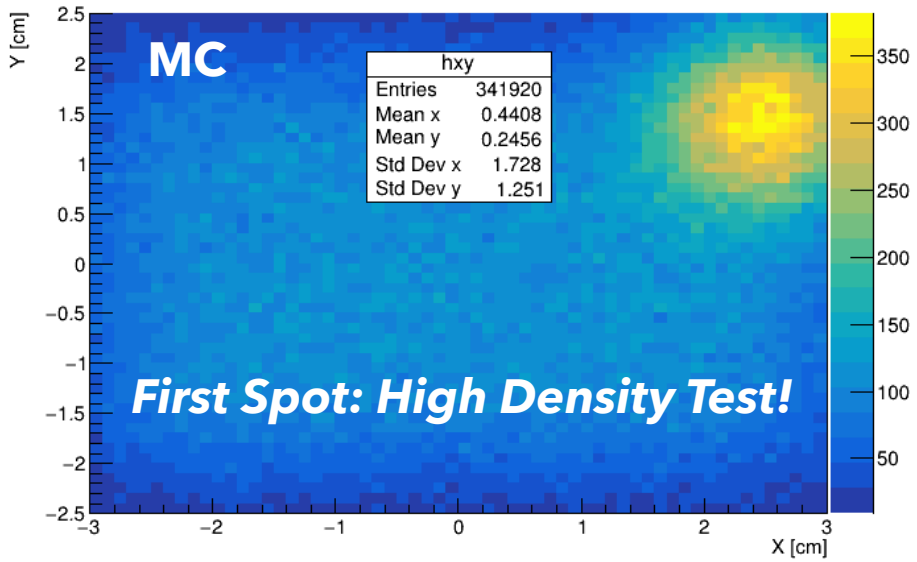
Fast Scan Features

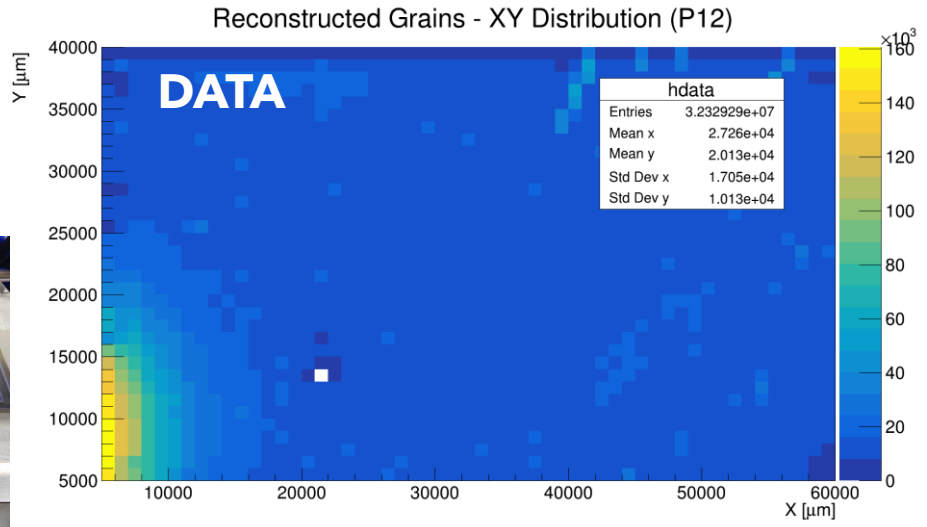
View Size	800x600 μm
Z step	0.75 μm
Scan Speed	~3 cm^2/h

Developed NIT samples





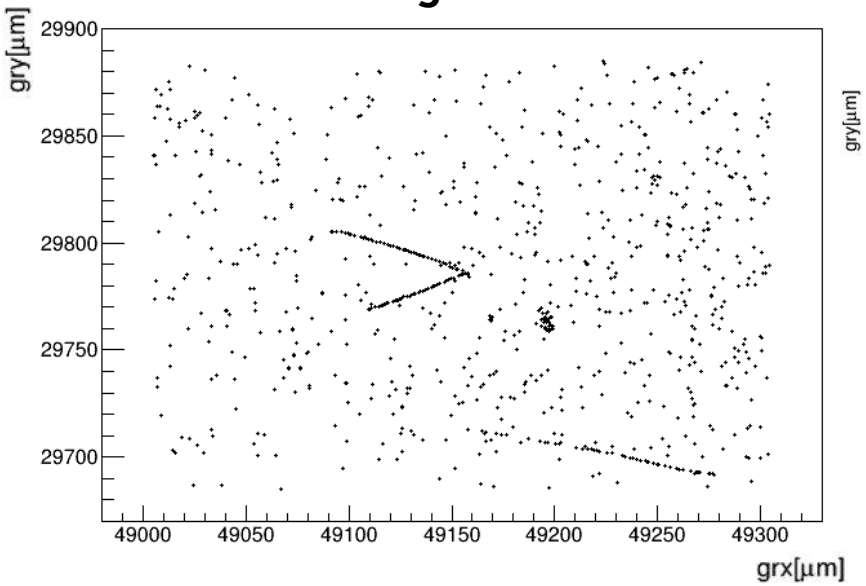




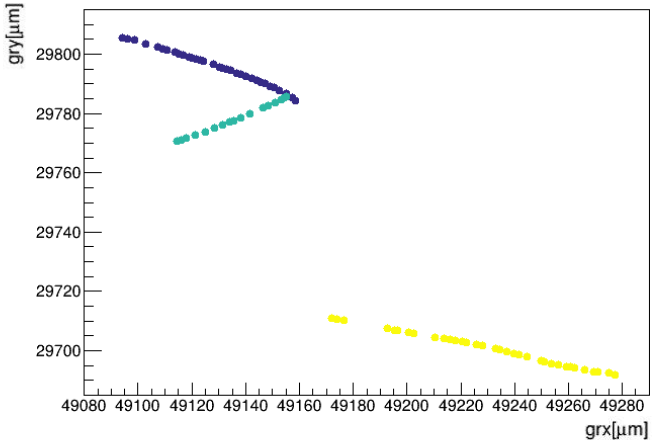
Offline Reconstruction Workflow

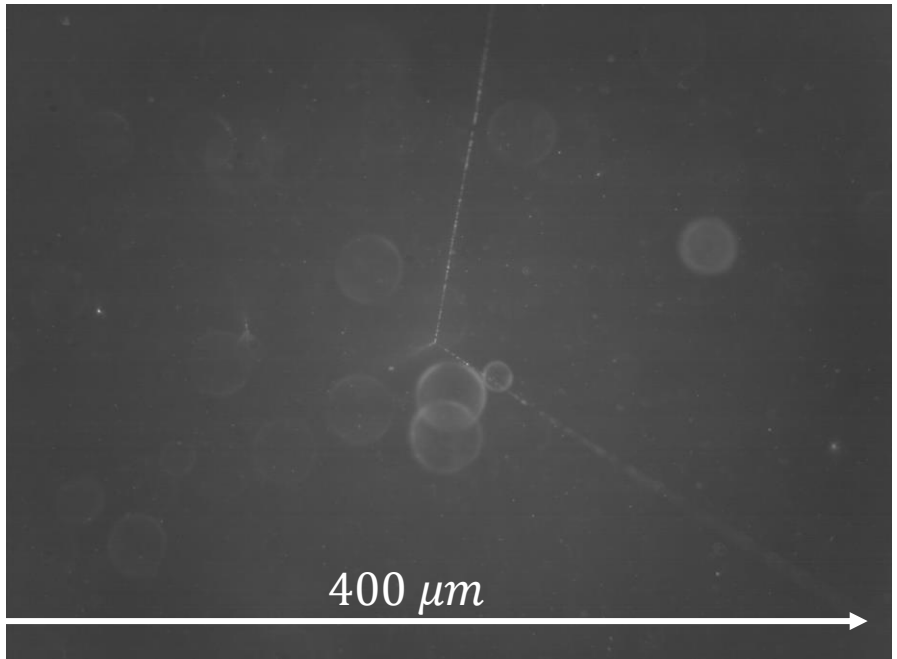
- After scanning, clusters are merged to reconstuct **grains**
- Aligned grains are linked together to form segments in a single layer called **micro-tracks (MTs)**
- Background grains can be isolated (thermal noise…) or clustered (film damage, dust specks…)

MTs + Background Grains



Linking + Cuts on Ngr

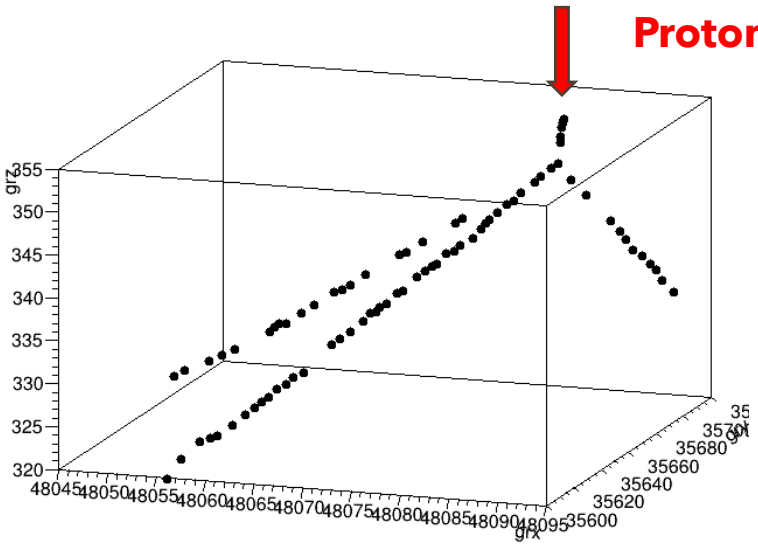




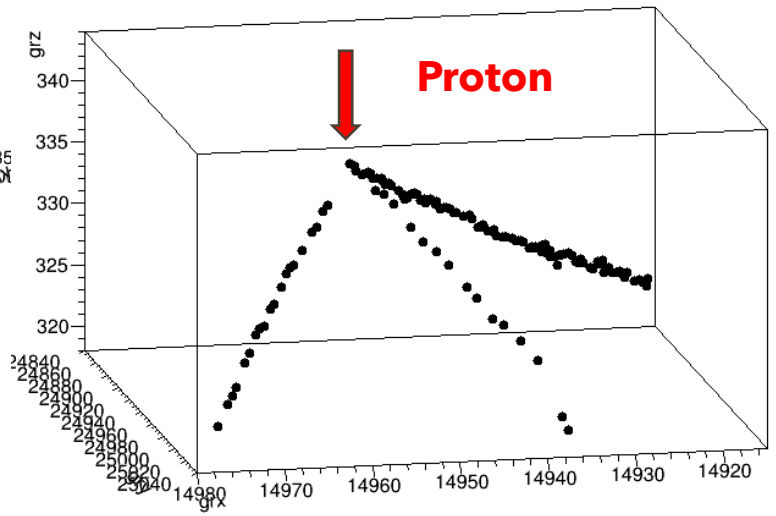
- Very **low background expected**:
  - Not sensitive to MIPs or primary protons
  - Environmental radioactivity (**mainly Radon** and Uranium/Thorium producing $\sim 20\ \mu m\ \alpha$ tracks)
- Vertex search
  - At least one secondary track longer than 25 μm required
  - Tracks shorter than 5 grains excluded to reduce background

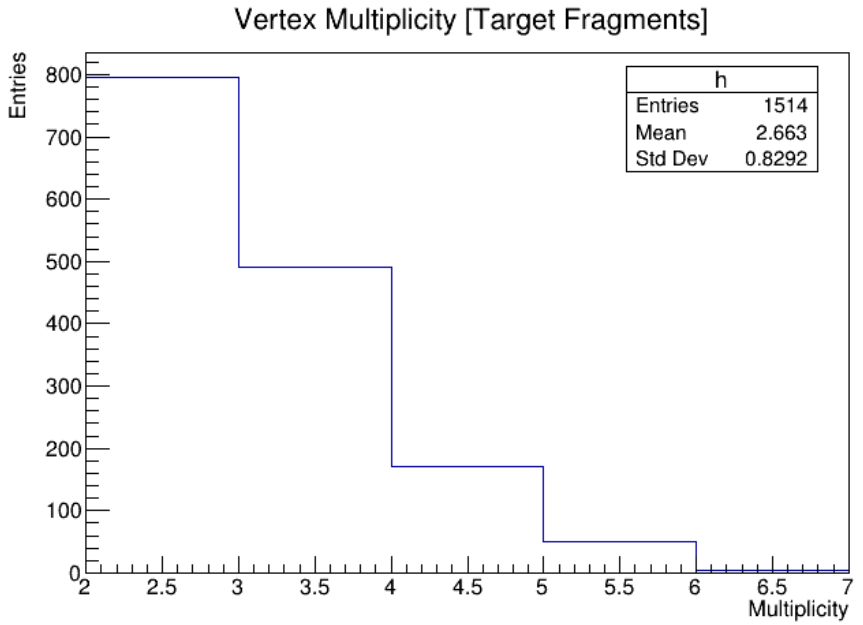
Results from Fast Scanning

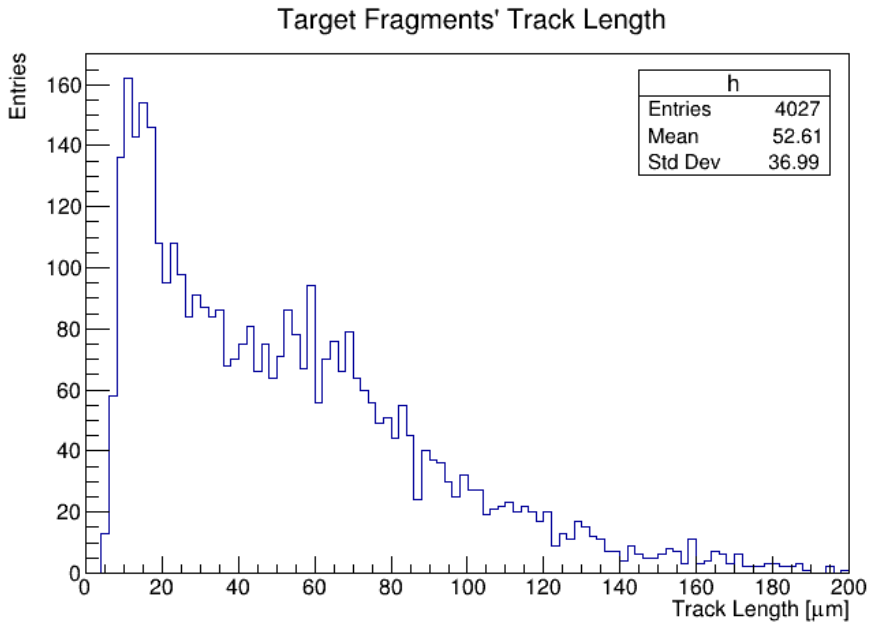
- After the Pilot Run, top-side scanning performed with the fast optical microscope
- About **1500 reconstructed interactions**
- Currently on-going: scanning of these fragmentation vertices with SR microscope



3D displays of reconstructed events



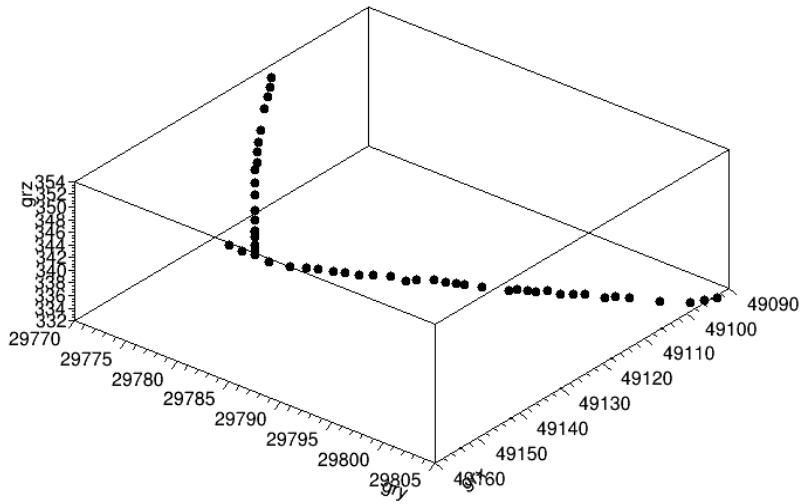


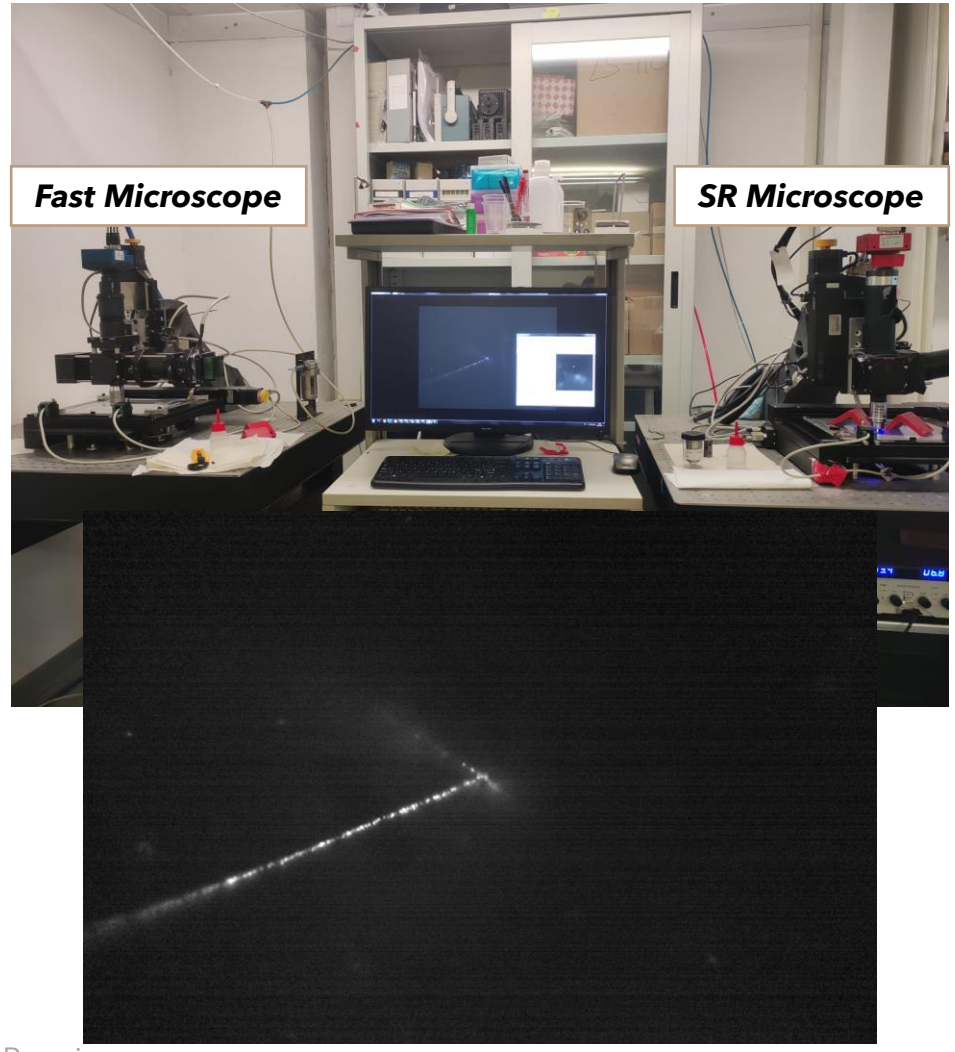


First Application of SR Microscope

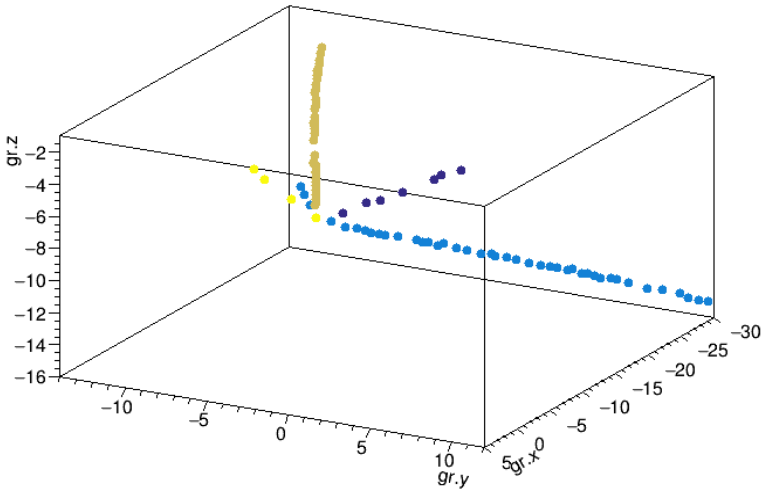
- Once a fragmentation interaction has been reconstructed, a second scan can be performed
- Fiducial marks have been used as reference system

Reconstruction after fast scan





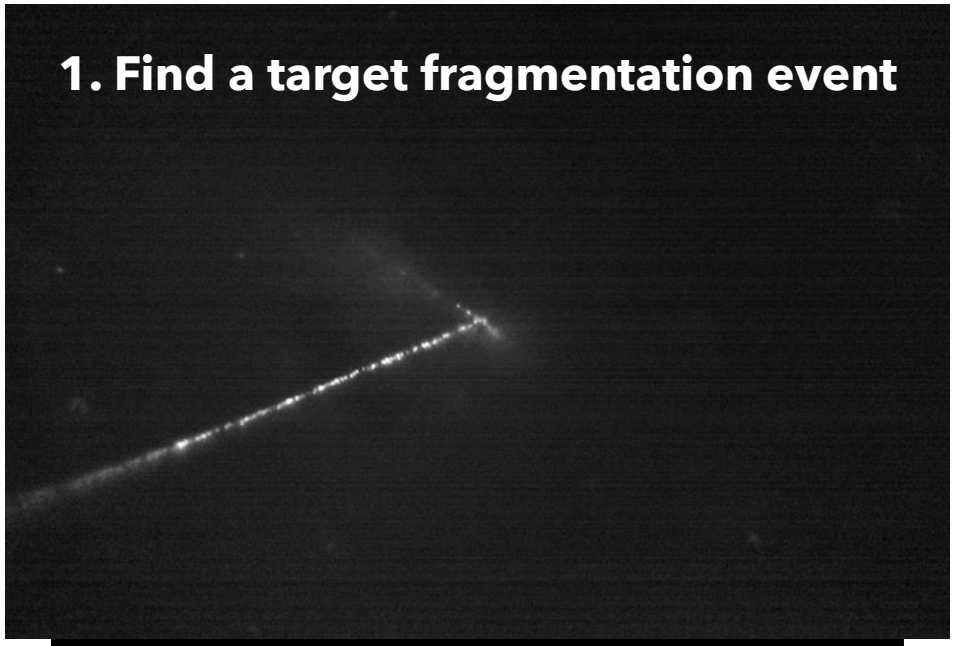
Reconstruction after second scan (no SR)



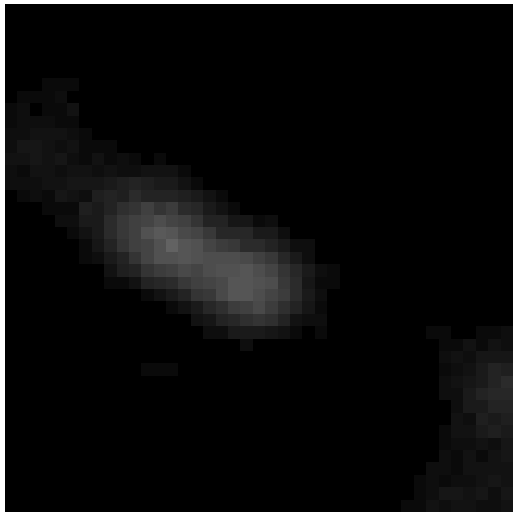
→ 3 shorter tracks are recovered during the second scan!

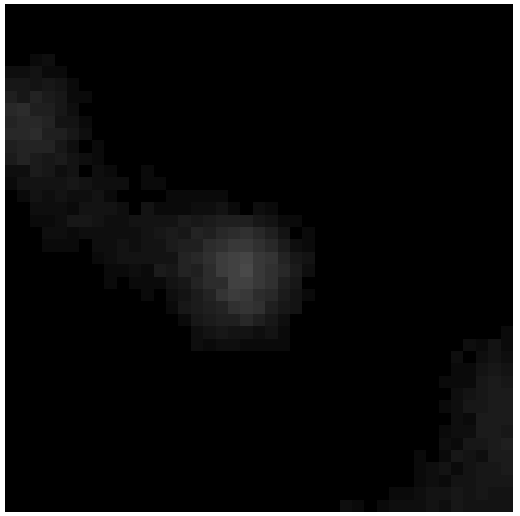
SR Workflow

1. Find a target fragmentation event



2. Perform scanning with 8 polarizations

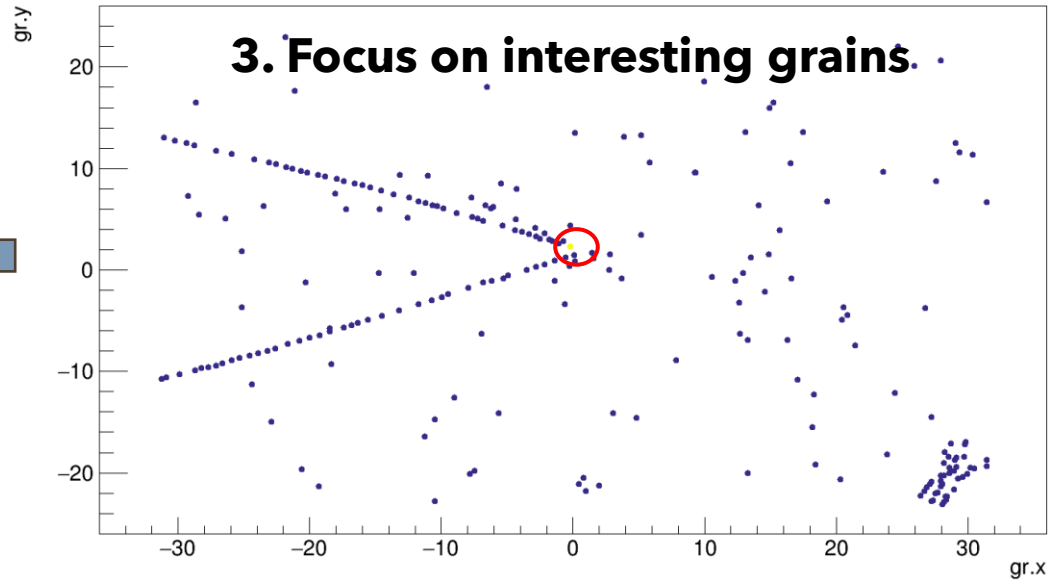




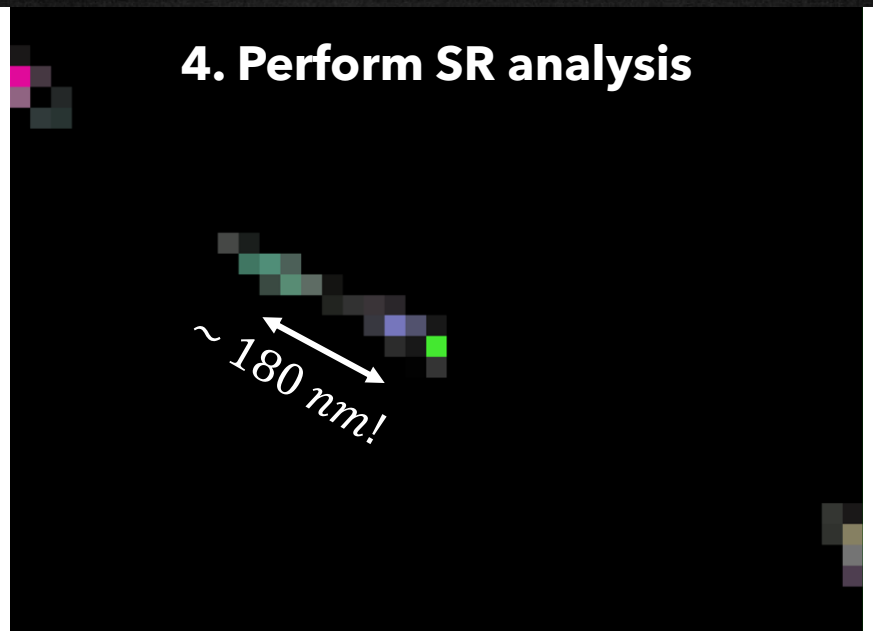
Polarization Angle $= 112.5°$

Polarization Angle $= 180°$

3. Focus on interesting grains



4. Perform SR analysis



Conclusions

- DAMON is a new experiment aiming at measuring proton induced target fragmentation in direct kinematics
- NIT are used both as target and tracking devices to achieve the needed spatial resolution
- Analysis of the Pilot Run: more than 1500 interactions identified via fast scanning!
- On-going
  - Optimization of SR system for current NIT sample
  - SR scanning of reconstructed interactions and study of grain density for charge ID

Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
INFN Istituto Nazionale di Fisica Nucleare
Università degli Studi di Napoli Federico II