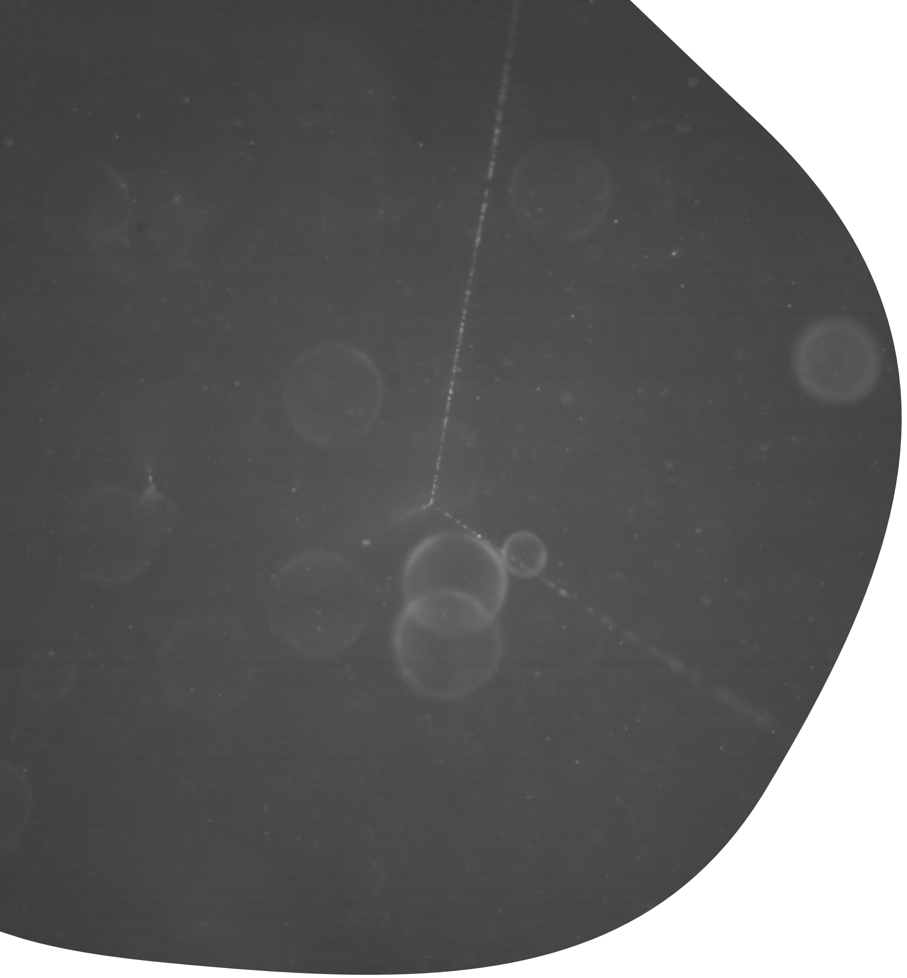

INFN
LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

An Innovative Method to Measure Target Fragmentation in Direct Kinematics with Nanometric Nuclear Emulsion

Nicola D'Ambrosio on behalf of DAMON collaboration

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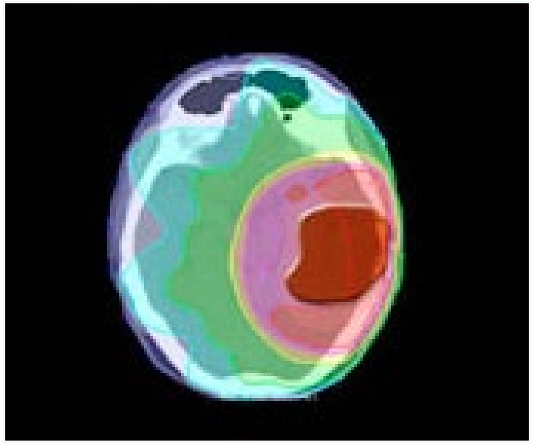
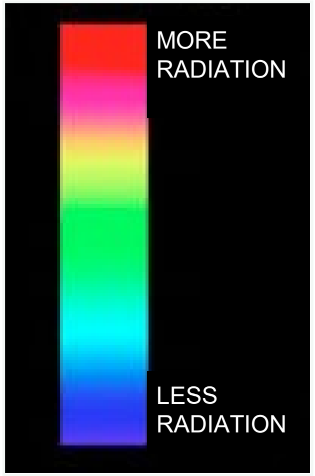
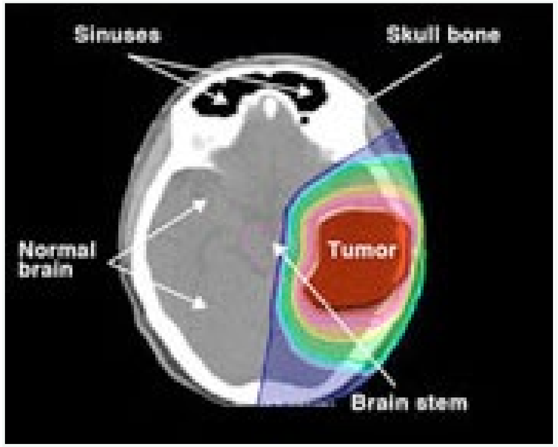
Nuclear Fragmentation in Proton Therapy

- Charged Particle therapy is a cancer treatment employing protons or ^{12}C beams
- Respect to conventional radio therapy it has favorable depth-dose profile (**Bragg Peak**) → precise dose localization for deep tumors



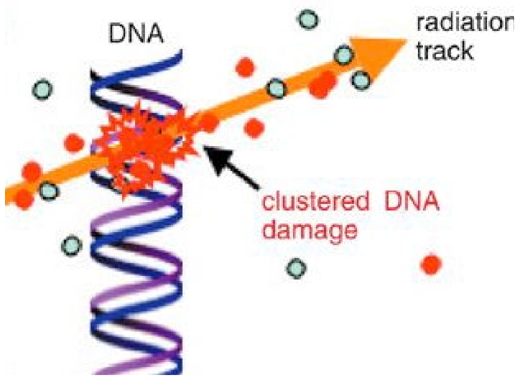




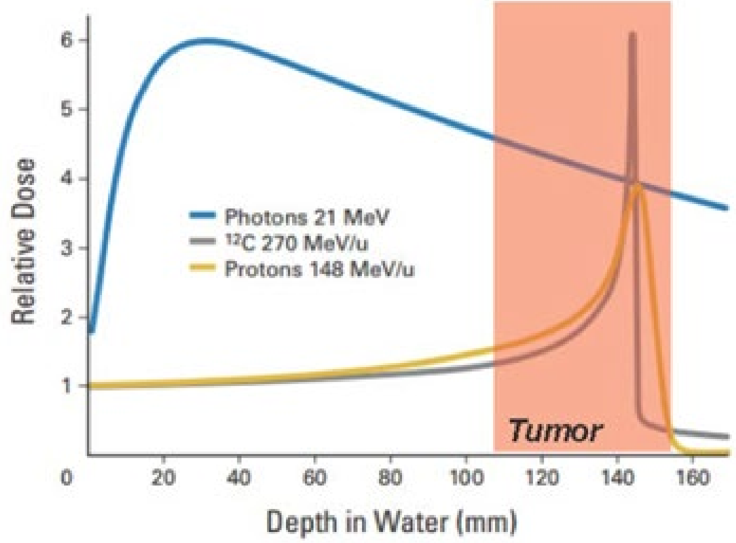
→CONVENTIONAL RADIOTHERAPY

→CHARGED PARTICLE THERAPY

- 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 experiment)



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



- The main experimental difficulty for a direct measurement of target fragmentation induced by a proton beam is the short range of produced fragments (≤100 μm)

- Fragments so short do not exit the target: **target and the tracking device should coincide**

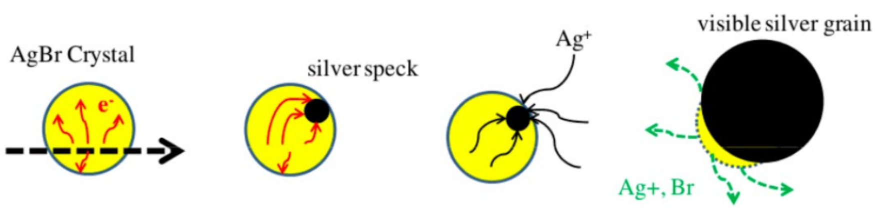
- **Very high resolution ->** use of novel kind of nuclear emulsion, called **Nano Imaging Tracker (NIT),** with grains at the nanometric scale allows to detect path lengths shorter than 100 nm

Nuclear Emulsion Films

- Large number of silver halide crystals (generally $AgBr$) dispersed in an organic gelatine binder

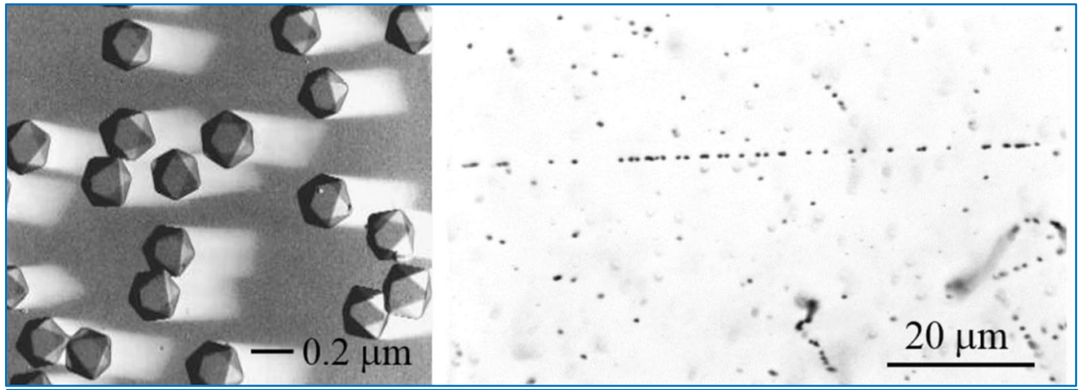
  Charged particle -> formation of the **latent image**:

$Ag^+ + e^- \rightarrow Ag$ Signal amplification with a reduction agent (chemical development)

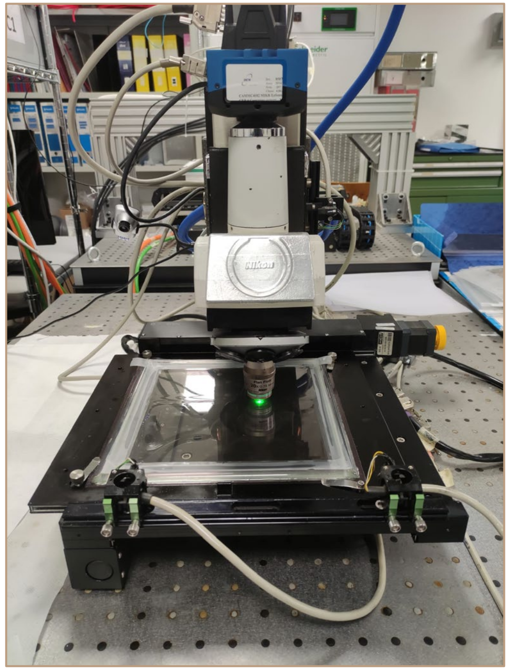


- Several **applications**:
  - HEP: **OPERA**, SND@LHC, FASER, DsTau…
  - Medical Physics: FOOT, DAMON, …
  - Muon Radiography…
- Features of OPERA-like emulsions:
  - average crystal diameter of 200 nm, a granularity of 1 μm and a sensitivity to MIPs of ~ 30 grains / 100 microns

Example of a track in a nuclear emulsion



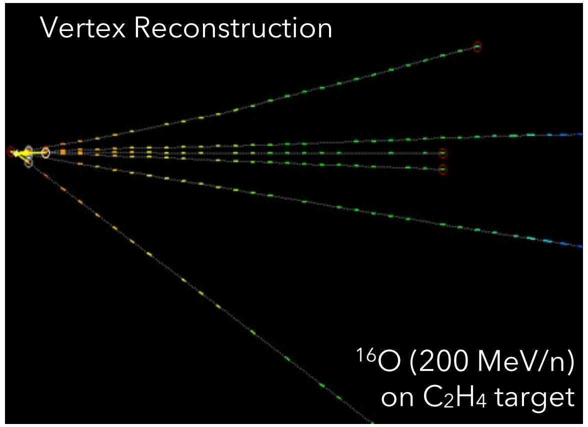
From: G. De Lellis et al., Journal of Instrumentation



Automated optical microscope for OPERA-like emulsion films

Scanning with automated optical microscopes

Offline track and event reconstruction

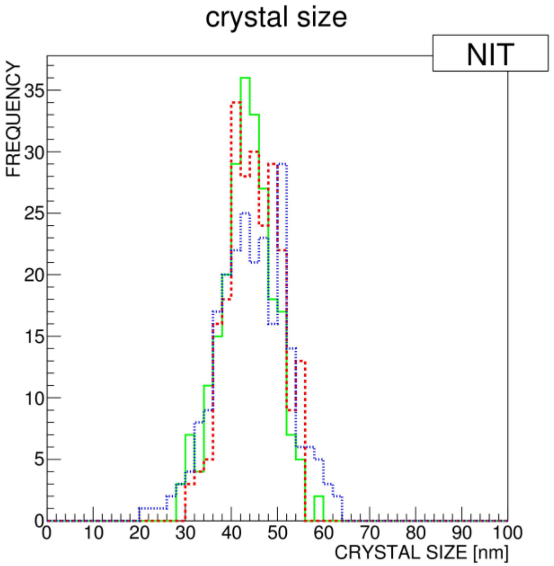


Nano Imaging Trackers (NIT)

- **Nano Imaging Trackers** (**NIT**) are a novel kind of nuclear emulsion films, with nanometric grains size, that 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 are in Nagoya (Japan) and at Laboratori Nazionali del Gran Sasso (LNGS, Italy)

Undeveloped NIT sample

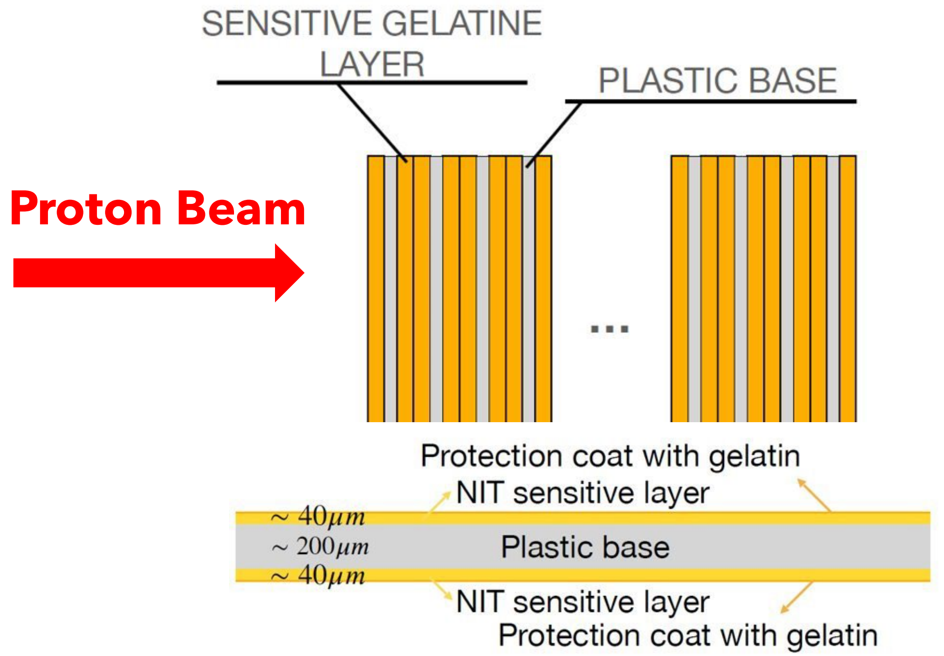
LNGS Gel Production Machine



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

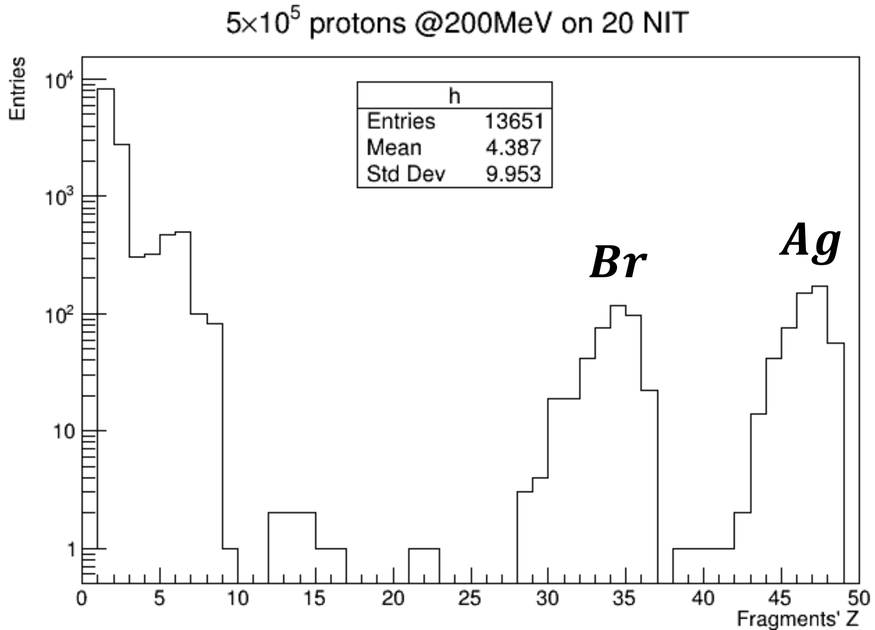
DAMON: A new approach to Target Fragmentation

- The **DAMON (Direct meAsureMent of target fragmetatiON)** 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**



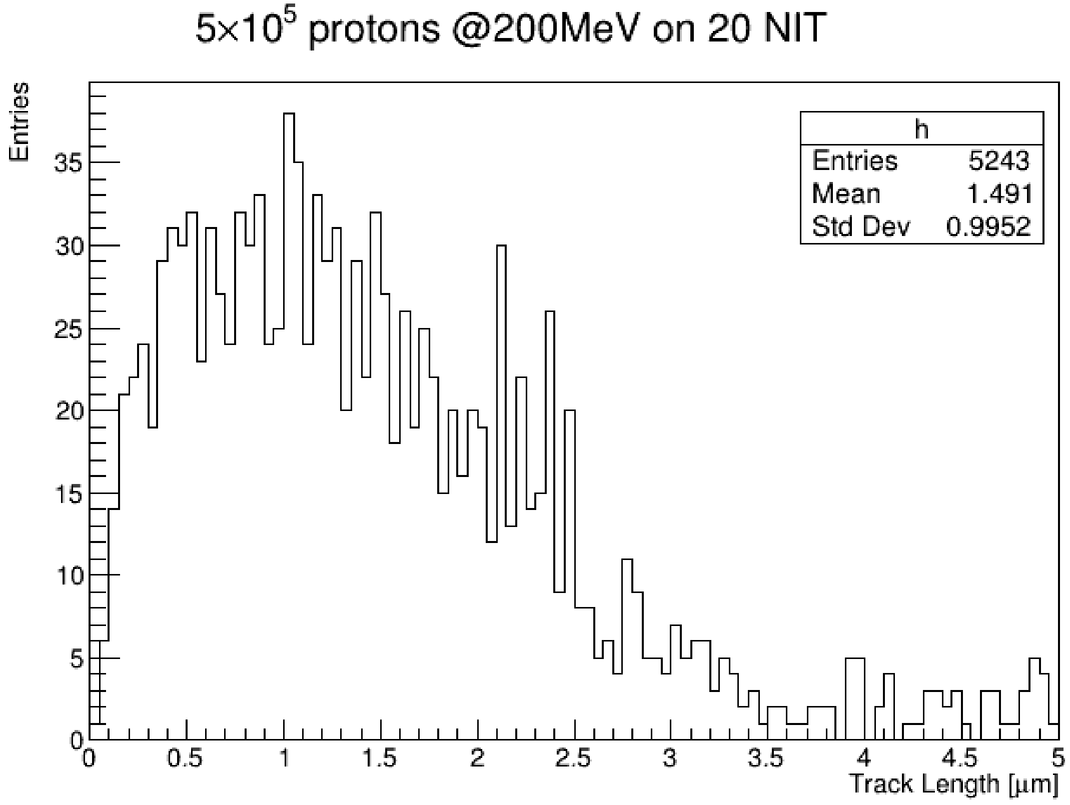
- Among all interactions (Geant4 Simulation):
  - ~38 % occur in the emulsion gel (C, O, H, N, Ag, Br)
  - ~62% occur in the plastic support (Polystirene, $(C_8H_8)_n$)

    (Less than 10% of interactions on Ag, Br)
- Typical energies of fragments, of the order of MeV, make them travel at least 300 nm → **detectable!**

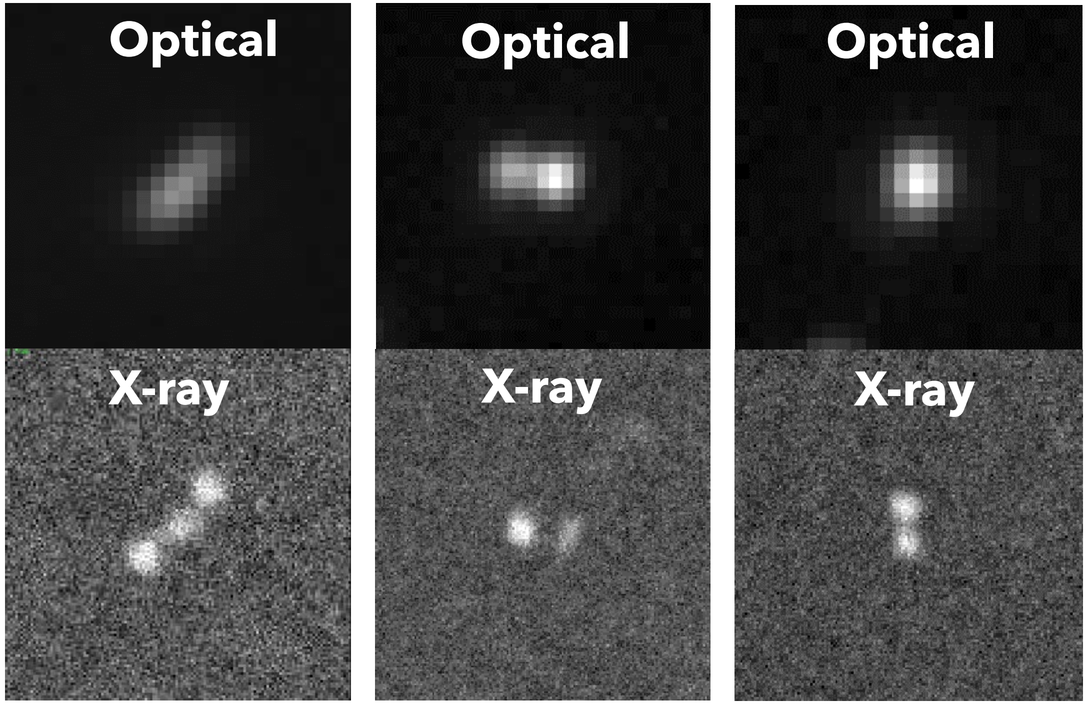


NIT Readout: Super Resolution

- 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 emplying an optical super-resolution microscope



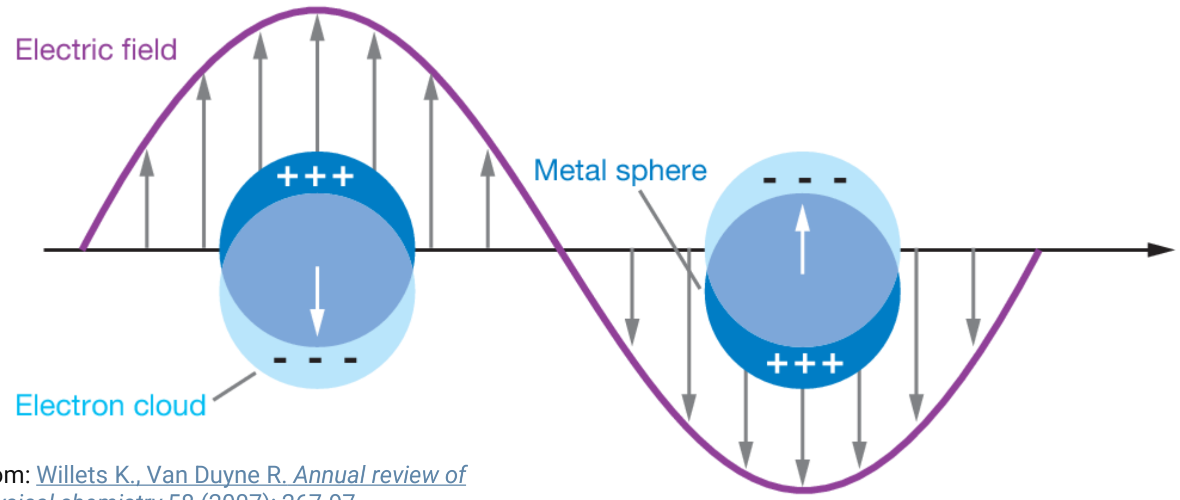
400 keV Kr ion in NIT



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

Localized Surface Plasmon Resonance

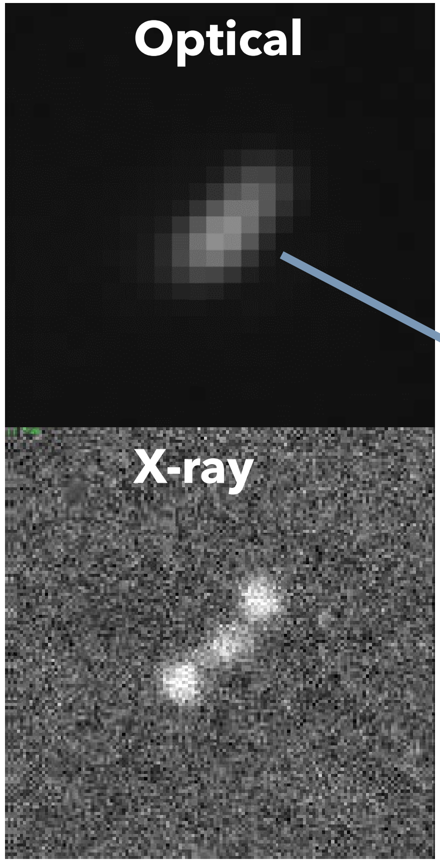
- Super-resolution is achieved by employing the **localized surface plasmonic resonance** (LSPR)
- Localized surface plasmons are non-propagating excitations of the conduction electrons of metallic nanostructures immersed in a dielectric → **silver grains in NIT exhibit LSPR at visible wavelengths**!



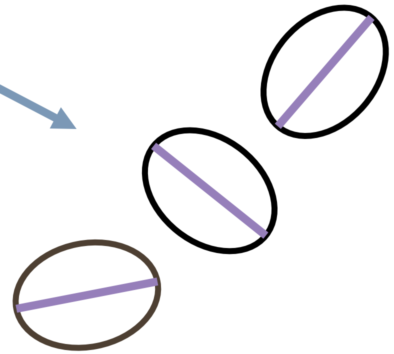
From: Willets K., Van Duyne R. *Annual review of physical chemistry* 58 (2007): 267-97

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

Resonance condition



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

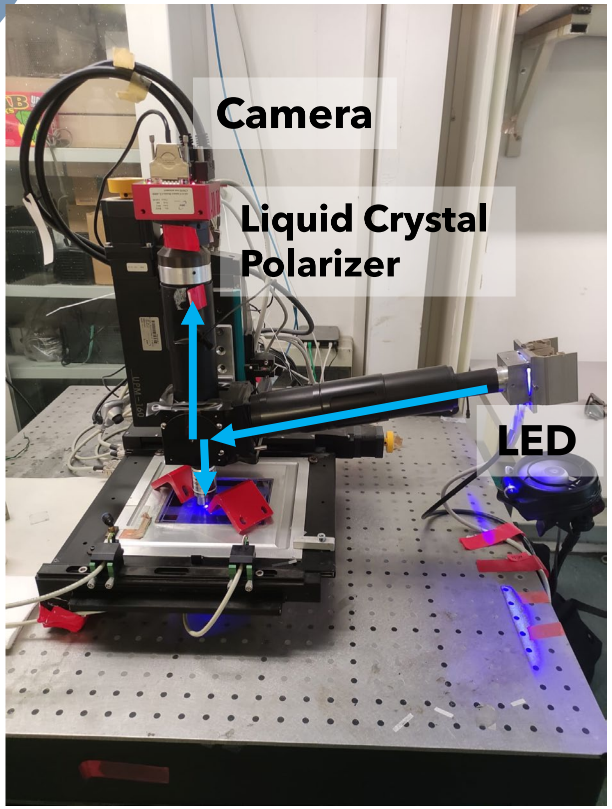


Maximum reflected light when E field is parallel to major axis → possible to resolve close structures!

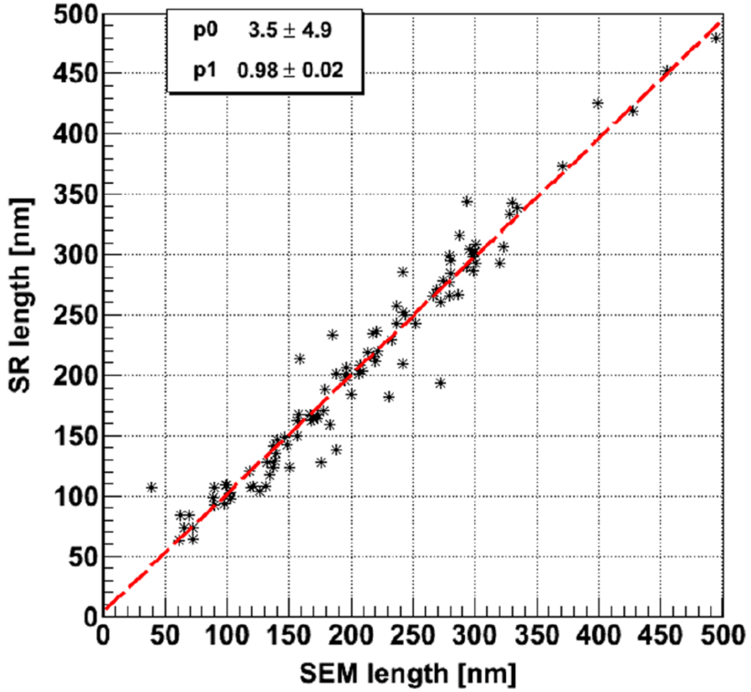
Super Resolution LSPR Optical Microscope

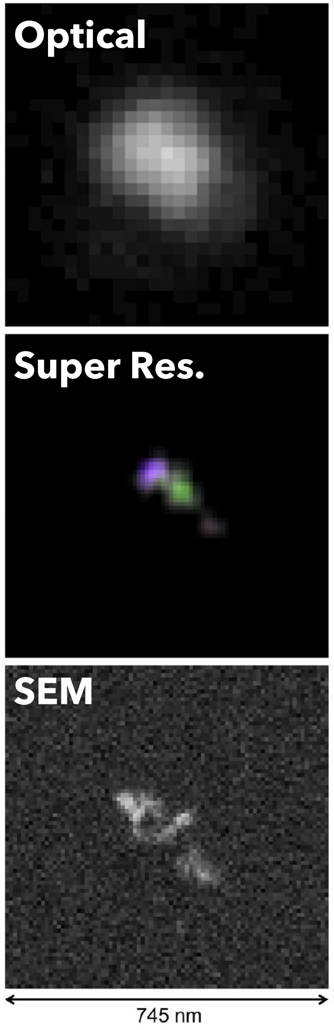
100 keV Carbon ion in NIT

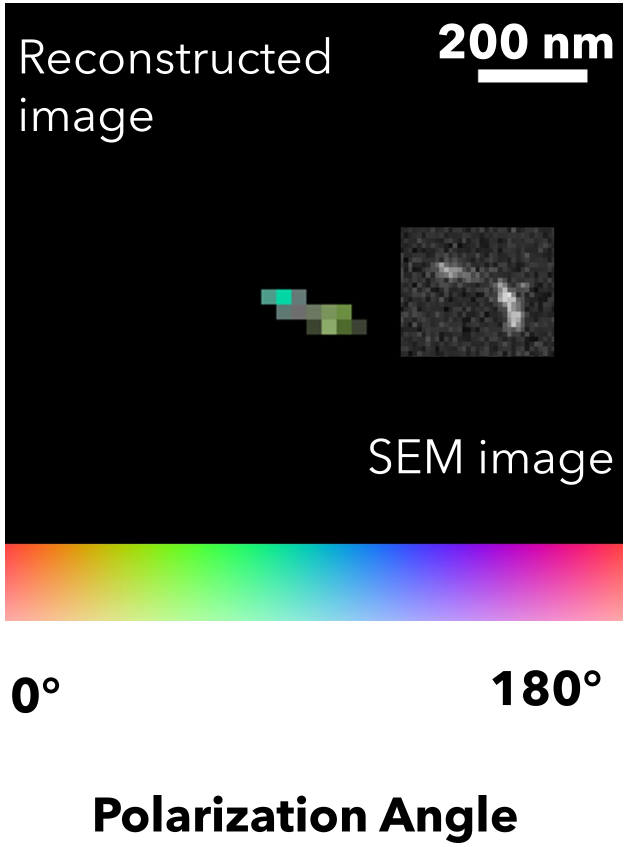
- 8x input images obtained with different polarizations (obtained with a liquid crystal polarizer)
- Tracks **down to 50 nm** have been reconstructed



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



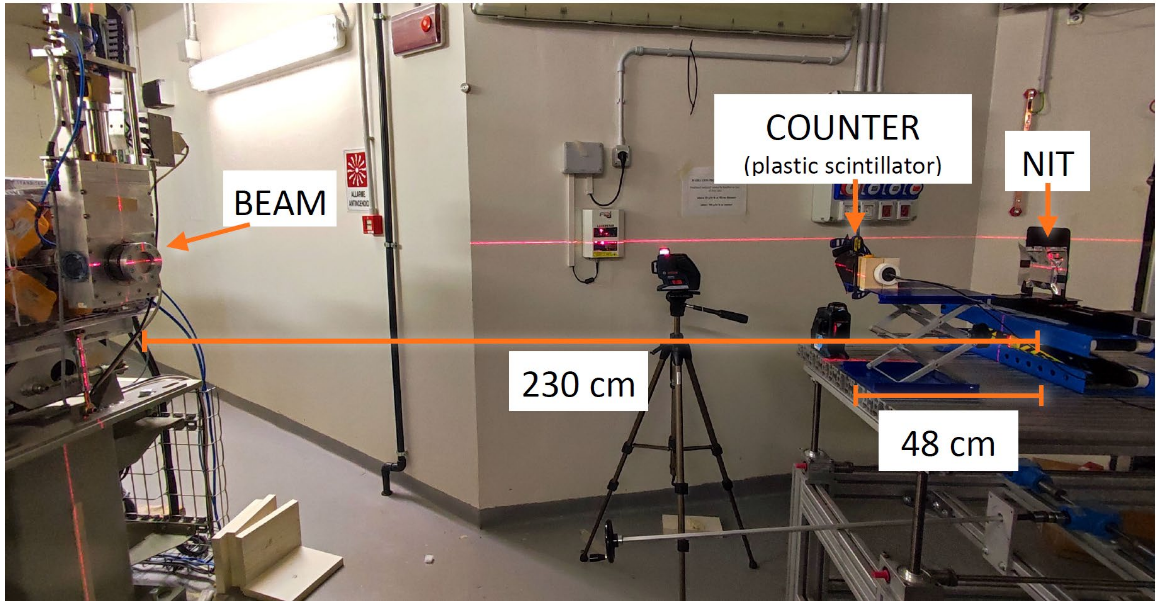


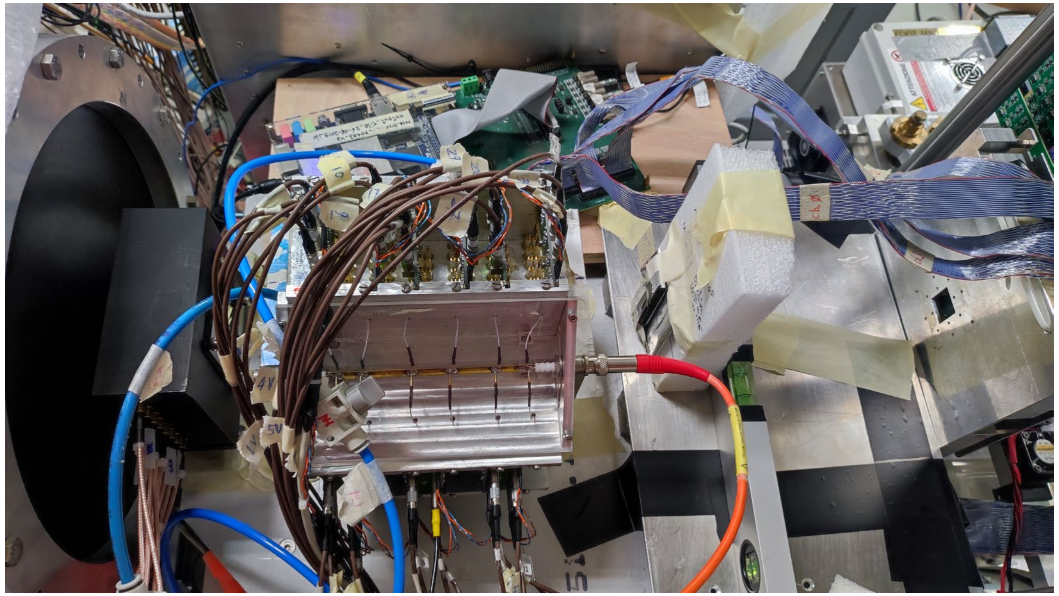


Experimental Campaigns

- Two preliminary exposures performed 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

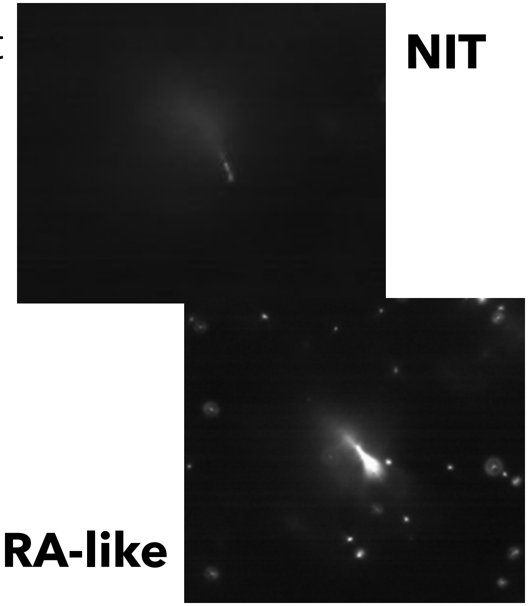
Trento Exposure: uniform density of 10^4 protons cm^{-2}





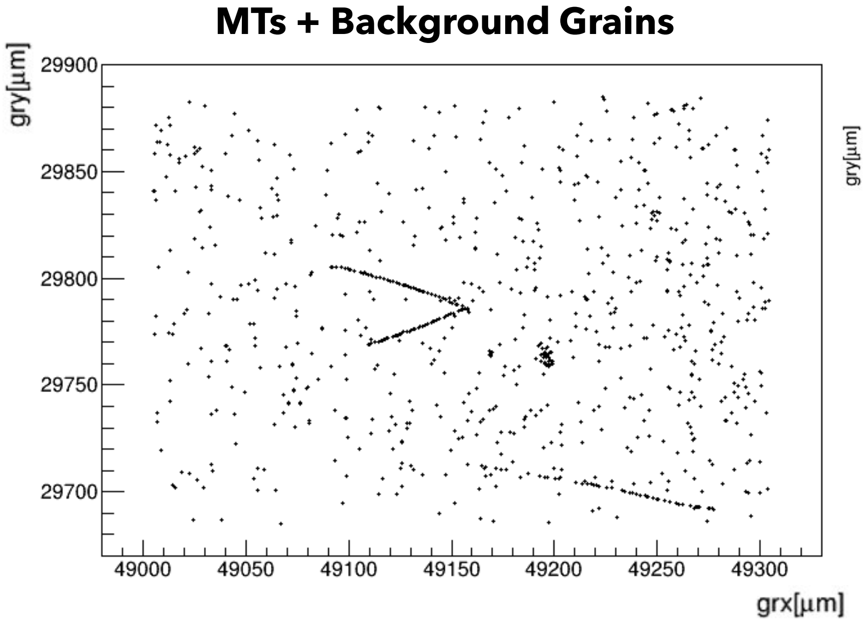
CNAO Exposure: single high intensity spot (10^7 protons)

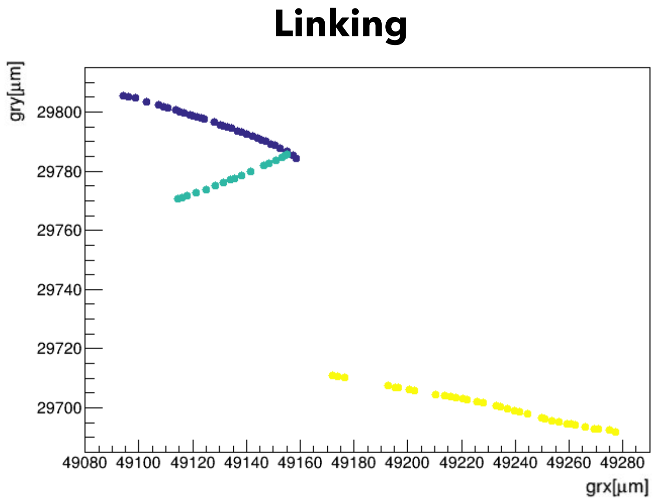
- Sensitivity test showed that current NIT are **not sensitive enough to reconstruct primary protons** above 70 MeV!
- Tests ongoing tuning emulsion components and with hybrid OPERA-NIT emulsion

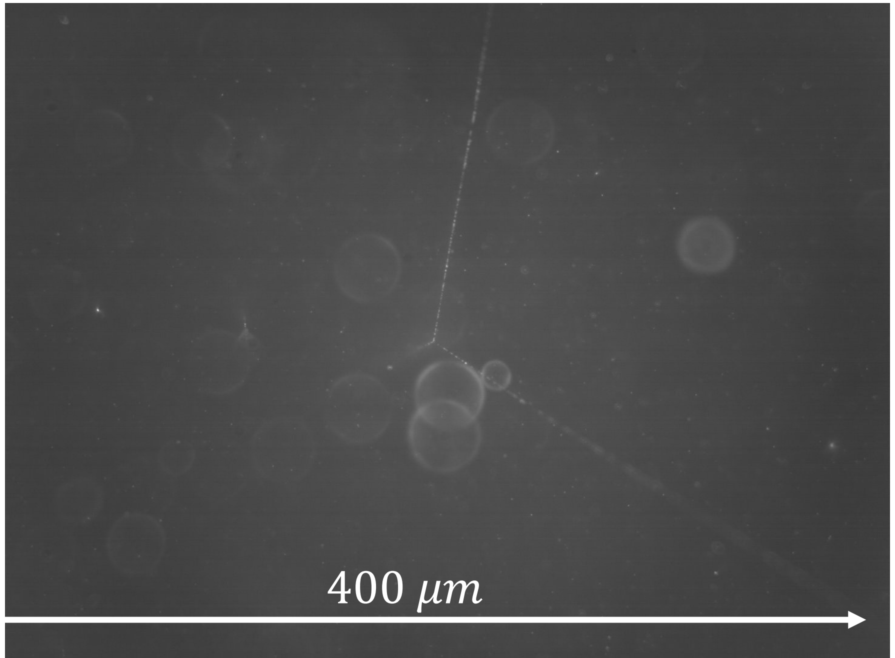


Offline Reconstruction Workflow

- After scanning, images are analyzed and 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…)







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

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 NIT components and production procedure to increase sensitivity
  - Optimization of Super Resolution system for analysis of NIT sample
  - Super Resolution scanning of reconstructed interactions and study of grain density for charge ID

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