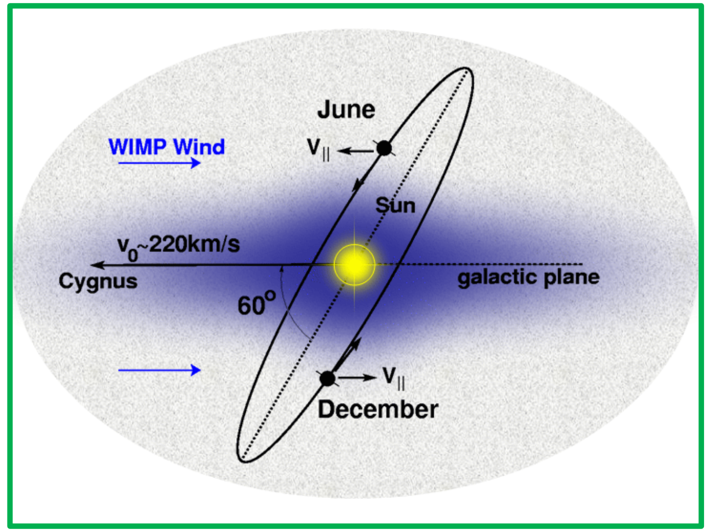
Fully-automated nanometric optical microscopy for dark matter discovery

A. Alexandrov[1], N. D'Ambrosio[2], G. De Lellis[1] and V. Tioukov[1]
[1]INFN sezione di Napoli,
[2]Laboratori Nazionali d Gran Sasso

This R&D is being carried out within the NEWSdm Collaboration

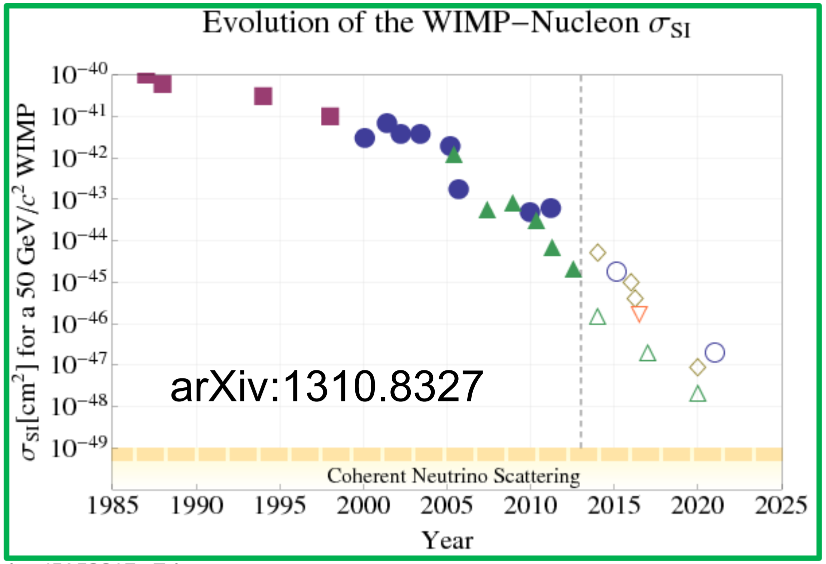
Power Of Directionality

- Impinging direction of DM particle is (preferentially) opposite to the velocity of the Sun in the Galaxy, i. e. from Cygnus Constellation



- Unambiguous proof of the galactic origin of Dark Matter

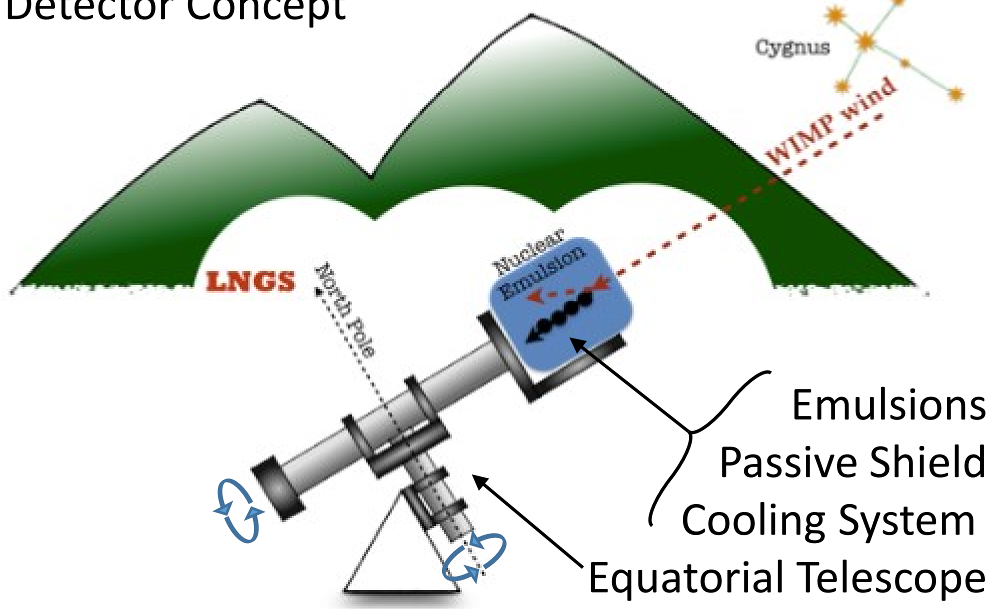
- Unique possibility to overcome the "neutrino floor", where coherent neutrino scattering creates an irreducible background



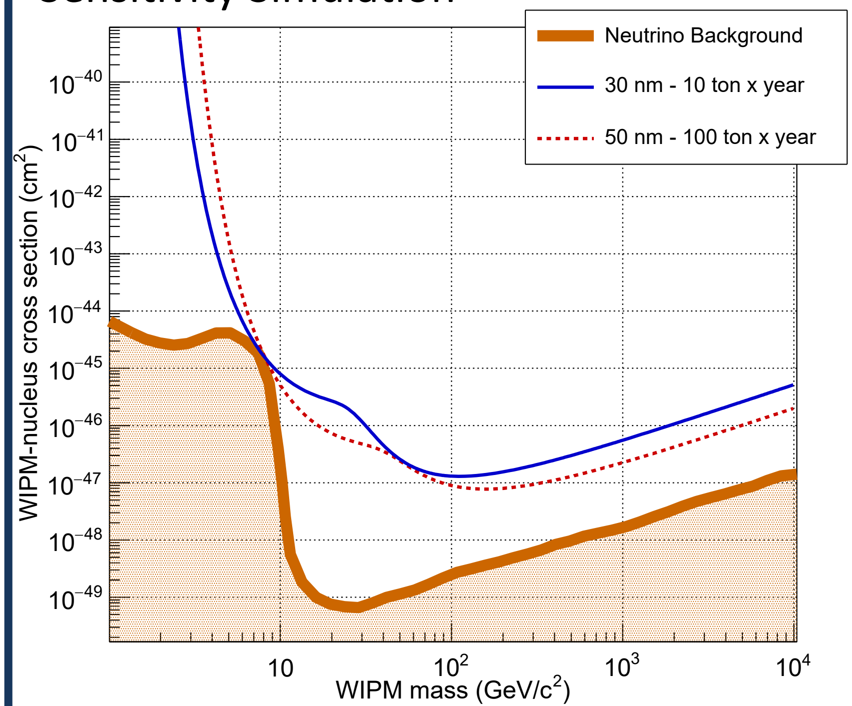
Nuclear Emulsion WIMP Search directional measurement

http://news-dm.lngs.infn.it

Detector Concept



Sensitivity Simulation



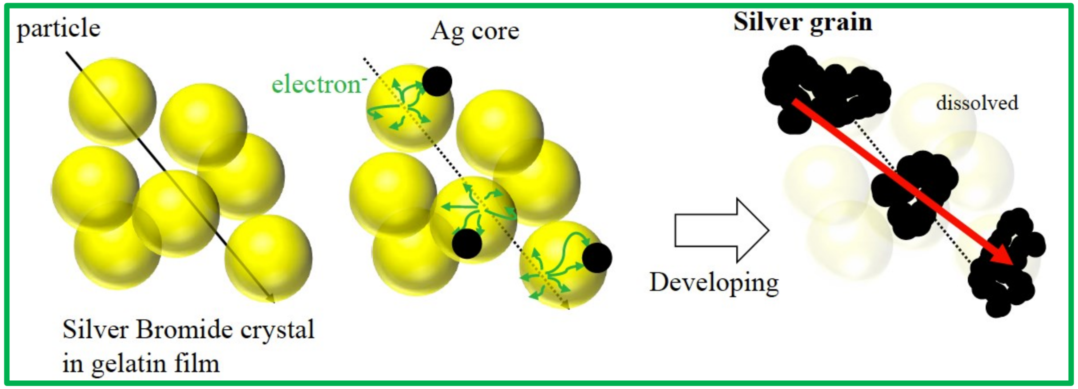
The neutrino bound is reached with:

- 10 ton x year exposure if 30 nm threshold
- 100 ton x year exposure if 50 nm threshold

Challenge for readout speed

Challenge for readout resolution

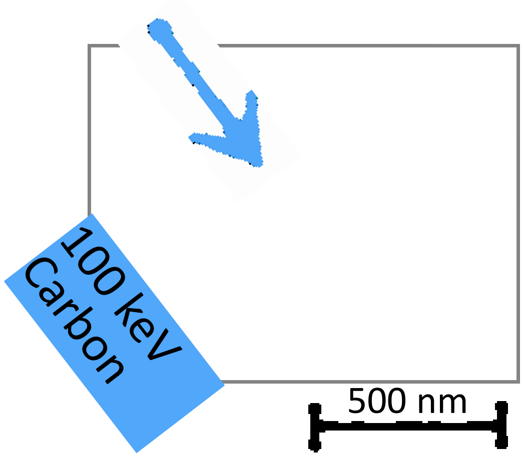
NIT: Nano emulsion Imaging Trackers

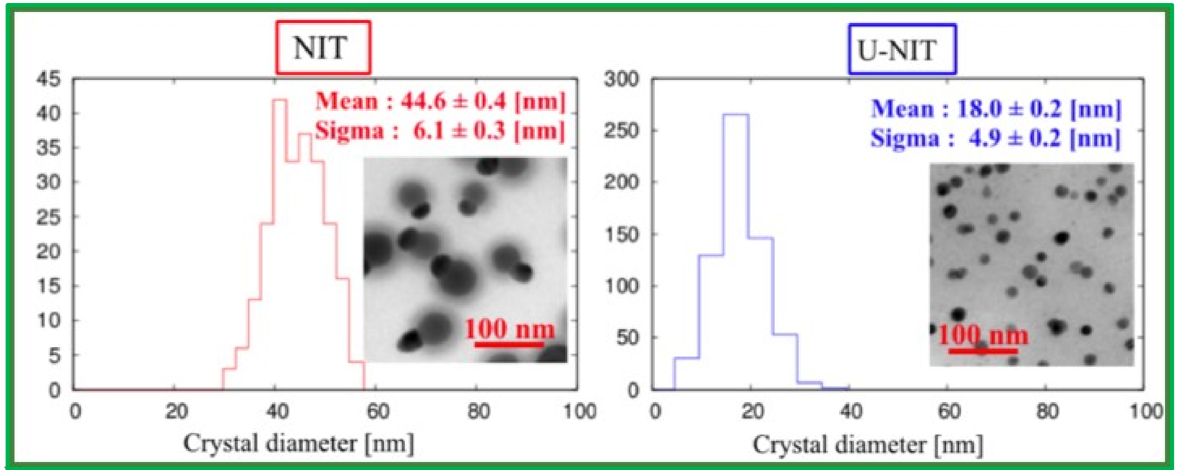


A long history, from the discovery of the **Pion (1947)** to the discovery of $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode (**OPERA, PRL 115 (2015) 121802**)

- Nuclear emulsions: AgBr crystals in organic gelatine
- Passage of charged particle produce *latent image*
- Chemical treatment make Ag grains visible

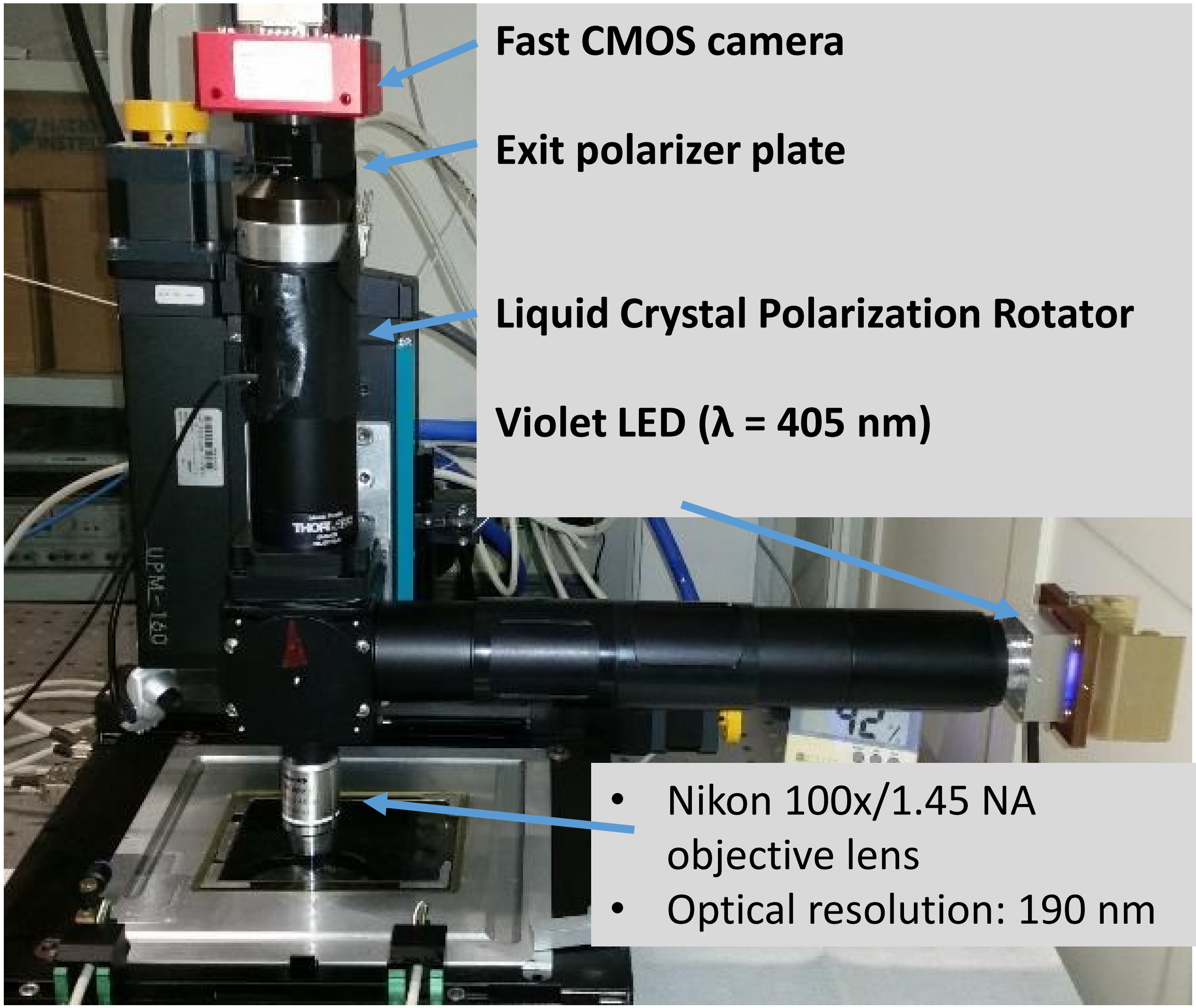
- New kind of emulsion for DM search
- Smaller crystal size





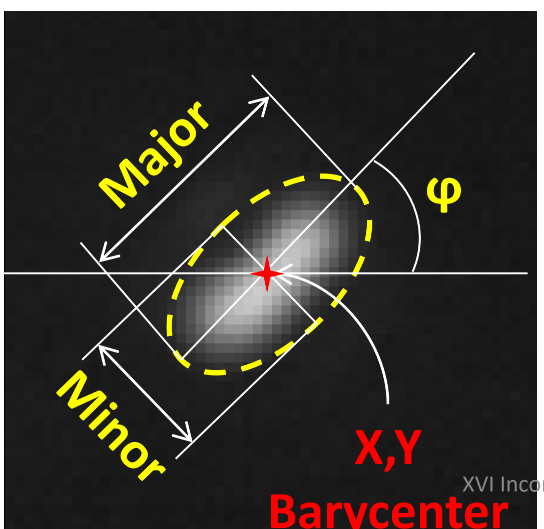
Optical scanning system prototype

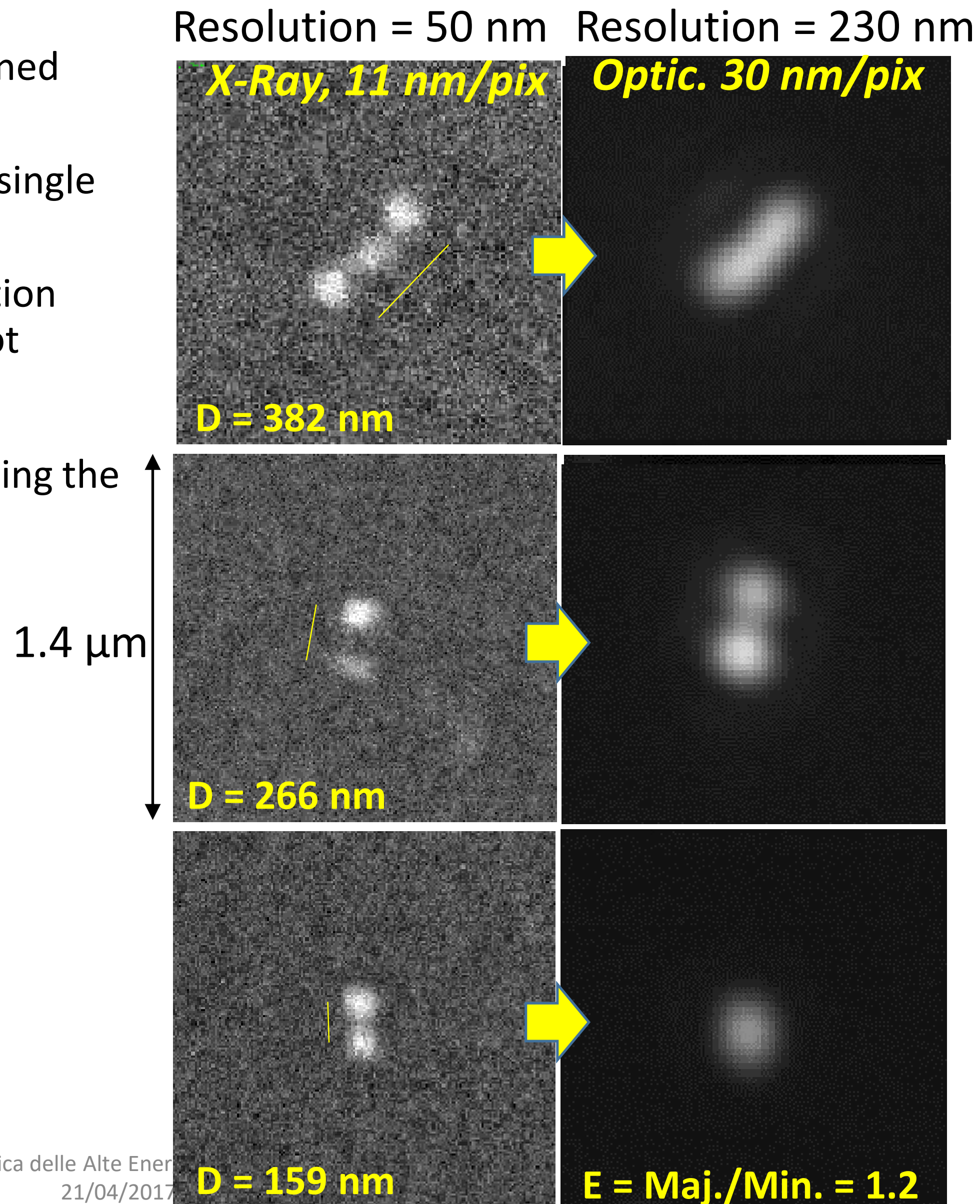
Designed and assembled in Naples for studies of the plasmon resonance phenomenon



Diffraction Limit and Shape Analysis

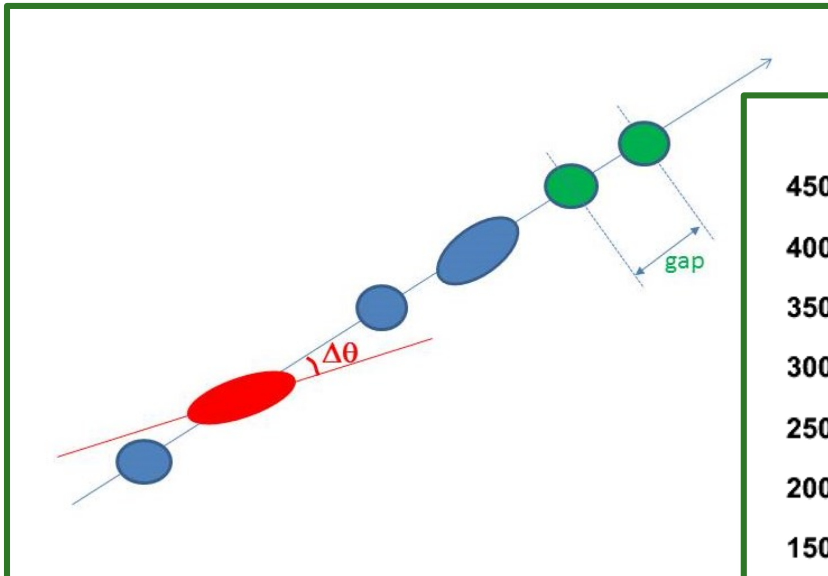
- A track is a sequence of close and aligned grains (at least 2)
- Resolve a track = distinguish it from a single grain
- Grains are closer than the mic. resolution (200 nm) -> not resolved -> single spot
- Add more pixels = make it smoother
- Infer the presence of a track by analyzing the spot's shape!
- Single grain = round spot
- Ellipticity = Major/Minor



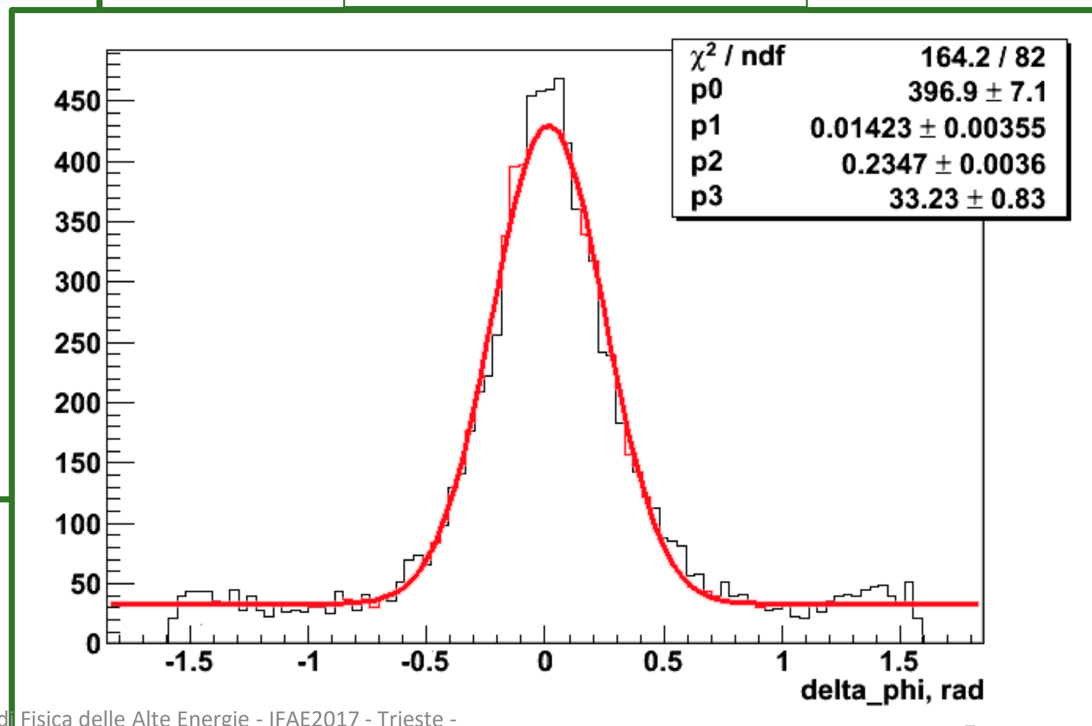


Grain Shape Analysis
Intrinsic Angular Resolution

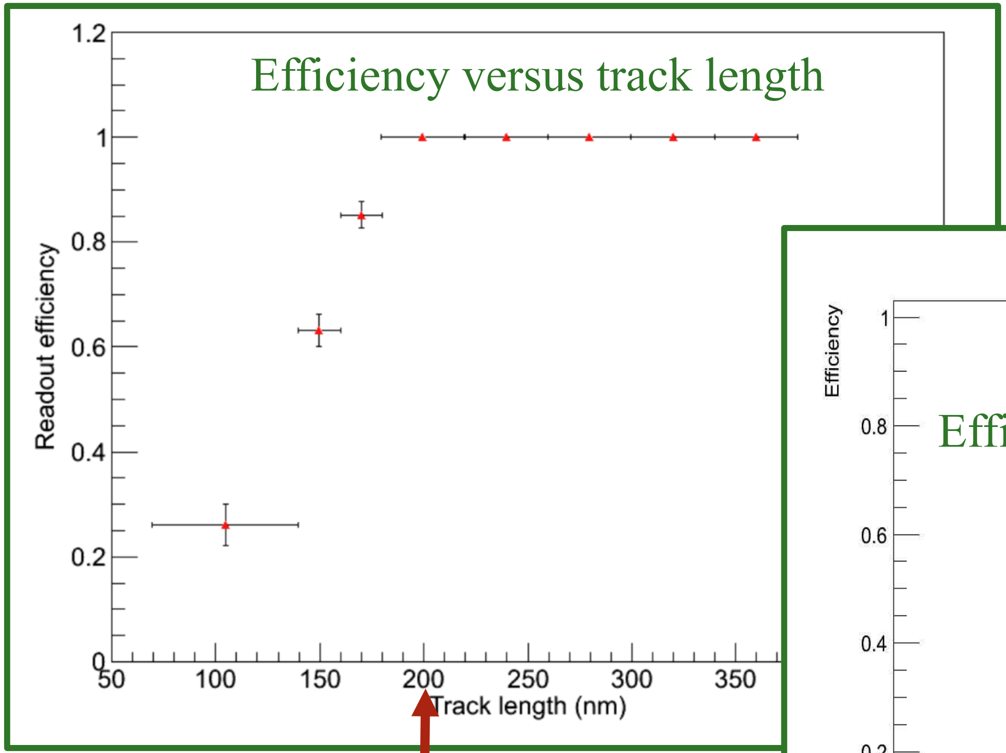
- Neutron test Beam sample (FNS exposure)
- Compare clusters with elliptical (e > 1.1) shape with the proton recoil direction
- Scattering contribution negligible

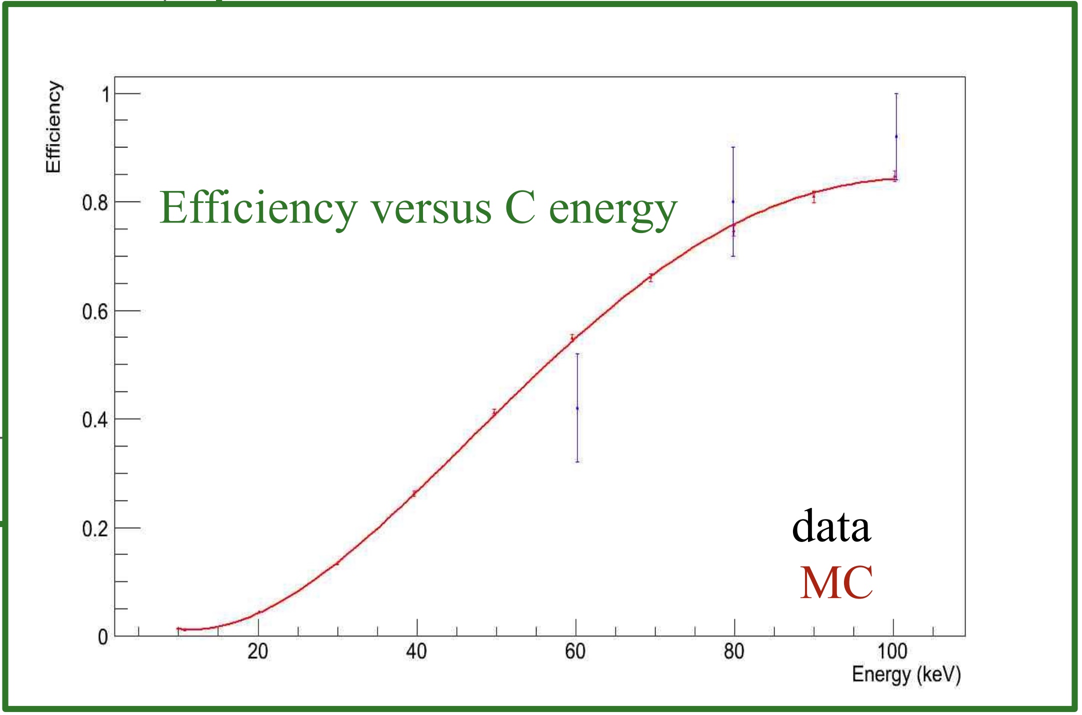


σ = 235 mrad = 13°



Grain Shape Analysis Efficiency Evaluation



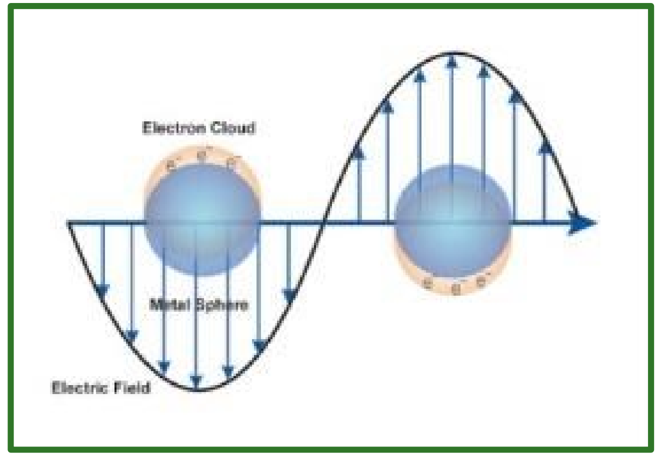


ε ~ 100% above ~200 nm
$e > 1.25$

New technology to overcome limitations of the shape analysis method

Localized Surface Plasmon Resonance

The LSPR is a coherent, collective spatial oscillation of the conduction electrons in a metallic nanoparticle, which can be directly excited by near-visible light.

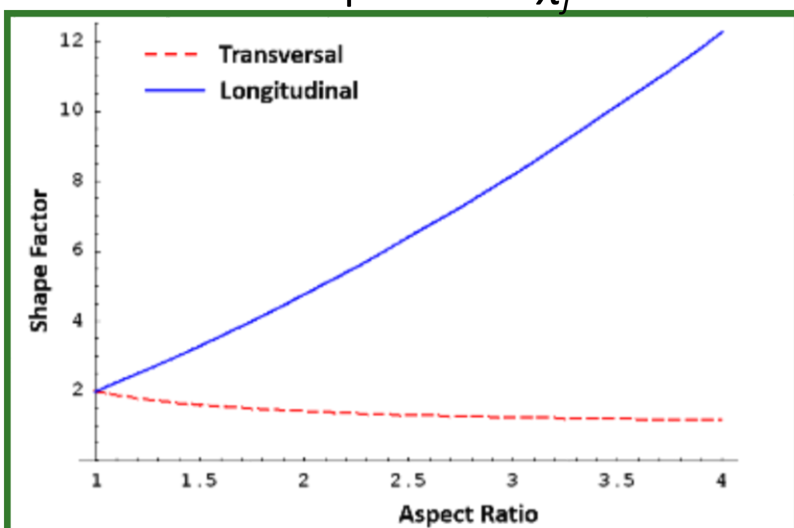


Light scattering cross-section:

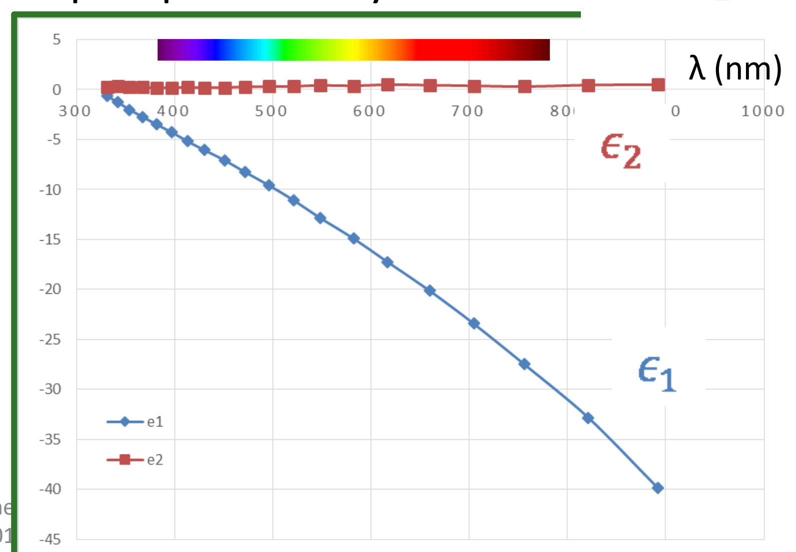
$$\sigma_{sc} = \frac{8\pi^3 V^2 \epsilon_m^2}{3\lambda^4} A_j \frac{(\epsilon_1 - \epsilon_m)^2 + \epsilon_m^2}{\left(\epsilon_1 + \chi_j \epsilon_m\right)^2 + \epsilon_2^2}$$

Resonance condition: [redacted]

Shape-factor χ_j

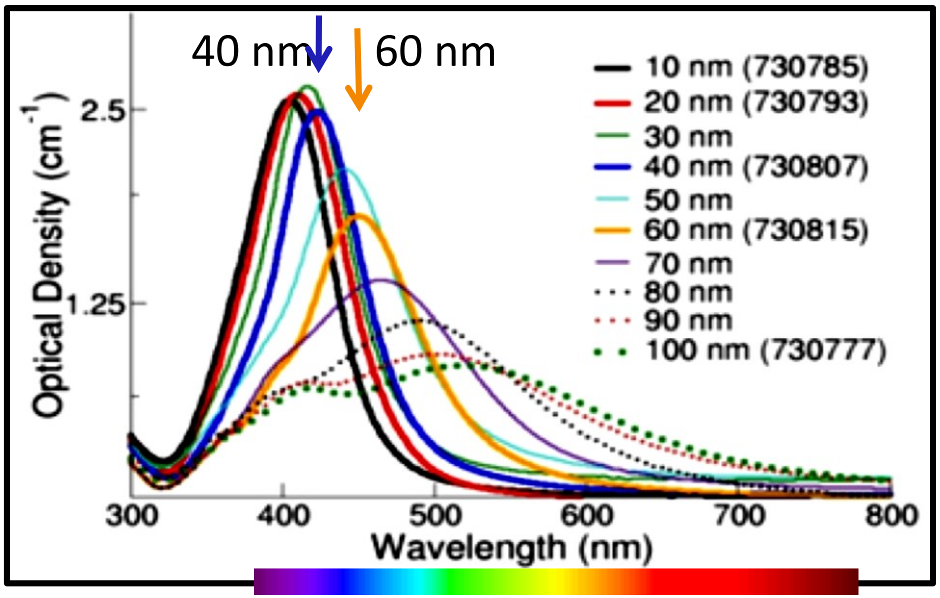


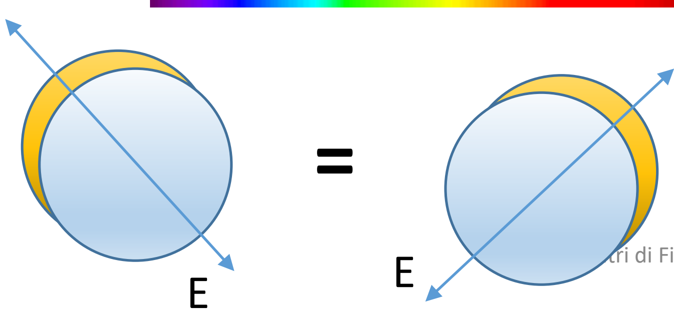
Complex permittivity of silver: $\epsilon = \epsilon_1 + i\epsilon_2$



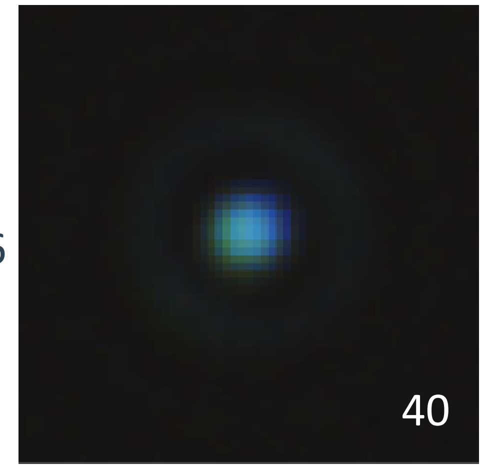
LSPR in emulsion

Silver Nanospheres

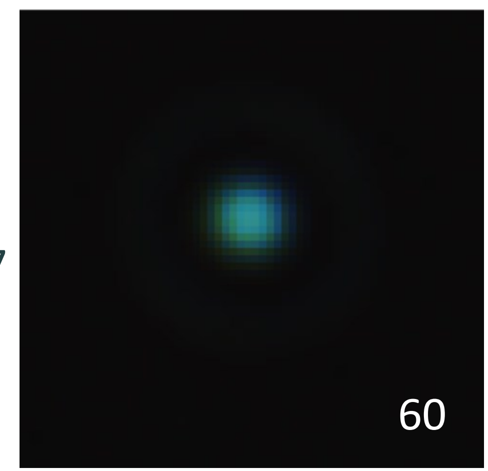




40 nm
Peak = 415 nm
RGB = 42,68,86
0.488,0.791,1

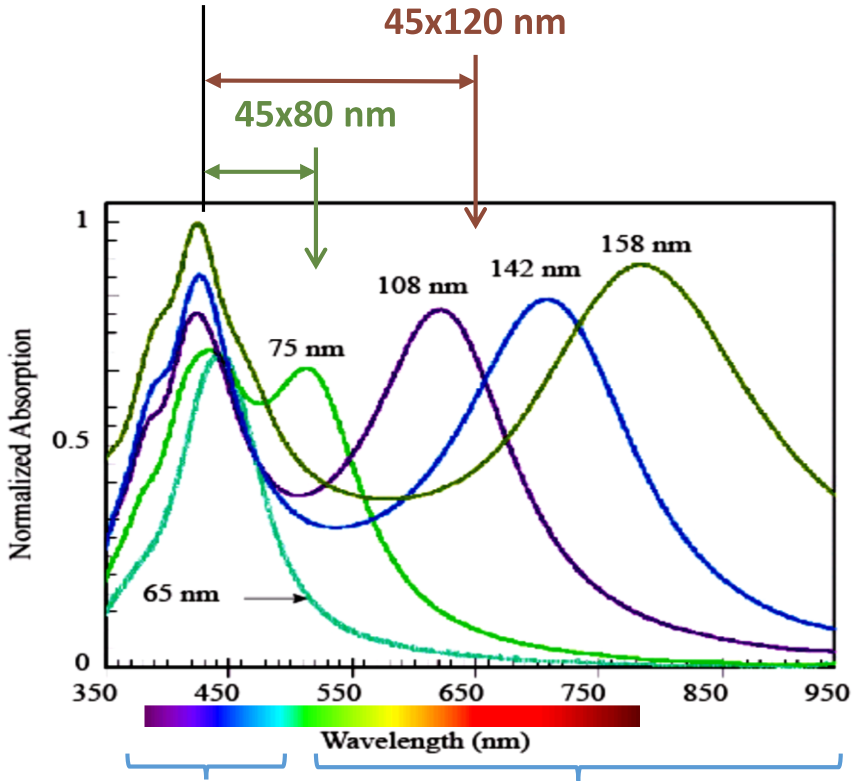


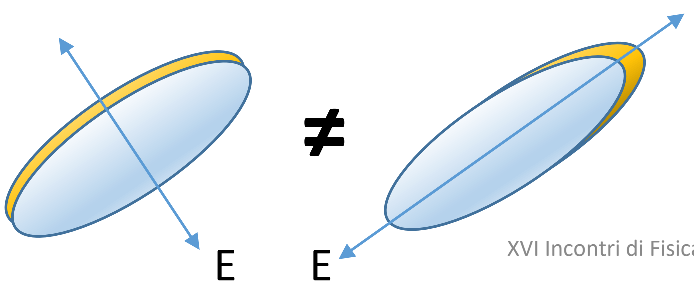
60 nm
Peak = 440 nm
RGB = 35,65,67
0.522,0.97,1



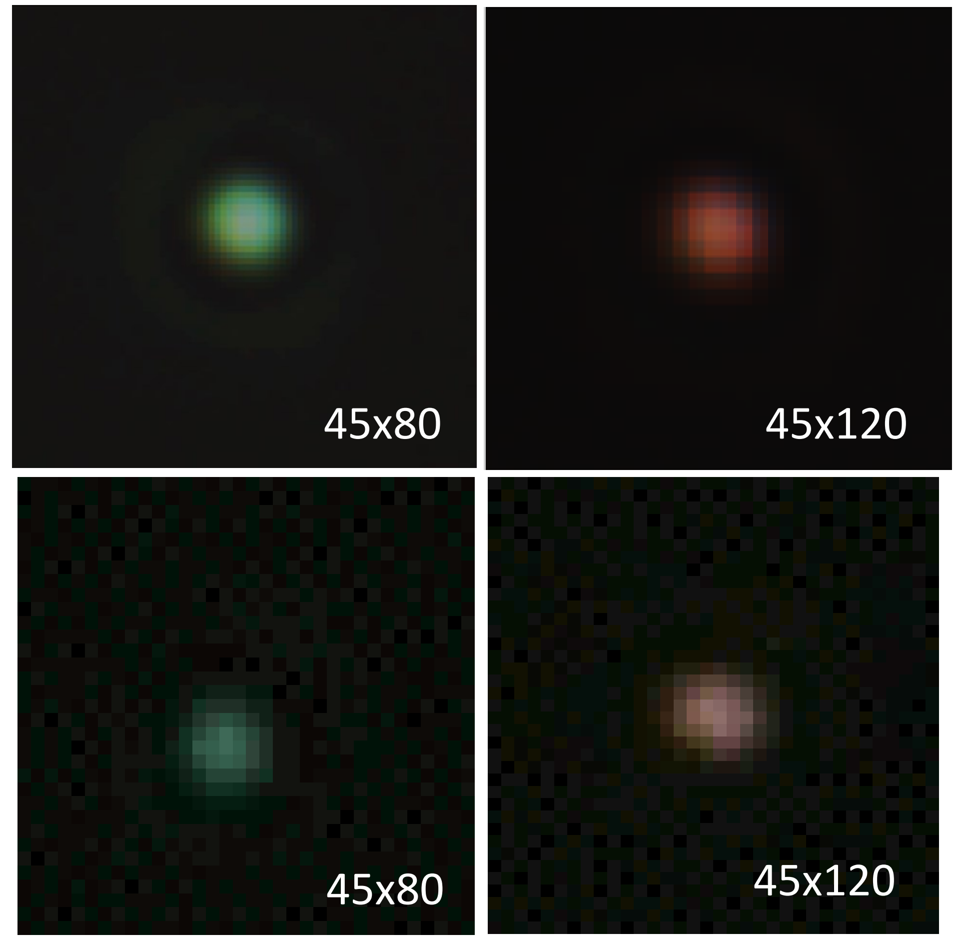
LSPR in emulsion

Silver Nanorods



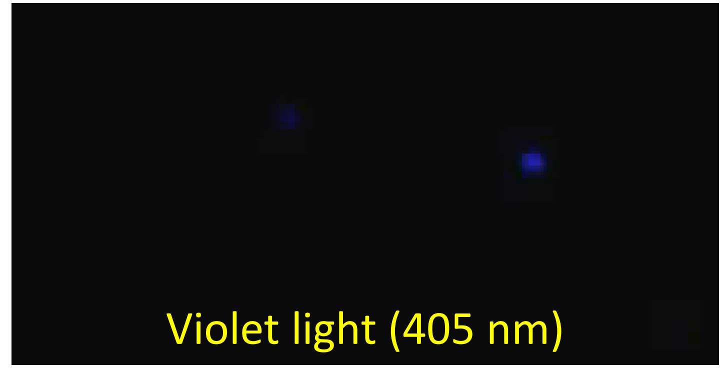


45x80 nm	**45x120 nm**
Peak = 520 nm	Peak = 650 nm
RGB = 57,71,60	RGB = 78,62,52
0.803,1,0.845	1,0.795,0.667



Changing the polarization angle

LSPR as a measurement instrument

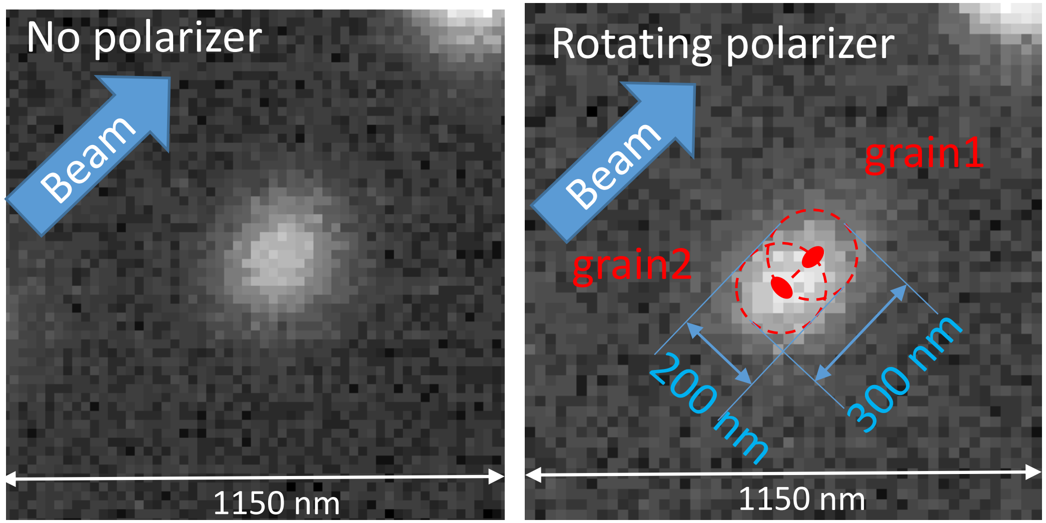


- With a monochromatic illumination or a band-pass color filter grain images start to disappear when the LSP resonance wavelength is outside the chosen wavelength range
- LSPR is a powerful instrument to manipulate grain image color and brightness
- Developed grains show form of randomly oriented filaments
- Analyzing the intensity profile of the scattered light for various polarization angles it becomes possible to isolate the position of each unresolved grain within a track

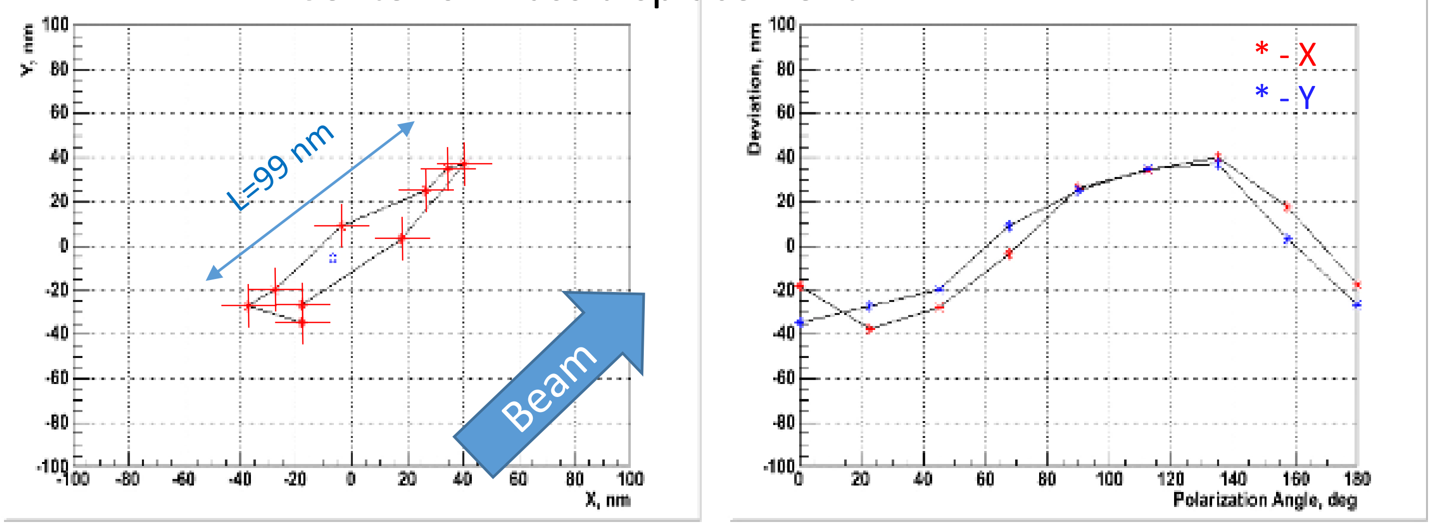
Track reconstruction with Plasmon Analysis

- Grains are too close to be resolved (d=99 nm)
- A single elliptical cluster is seen without the polarizer
- The mass center of the track starts to "oscillate" with the rotation of polarizer

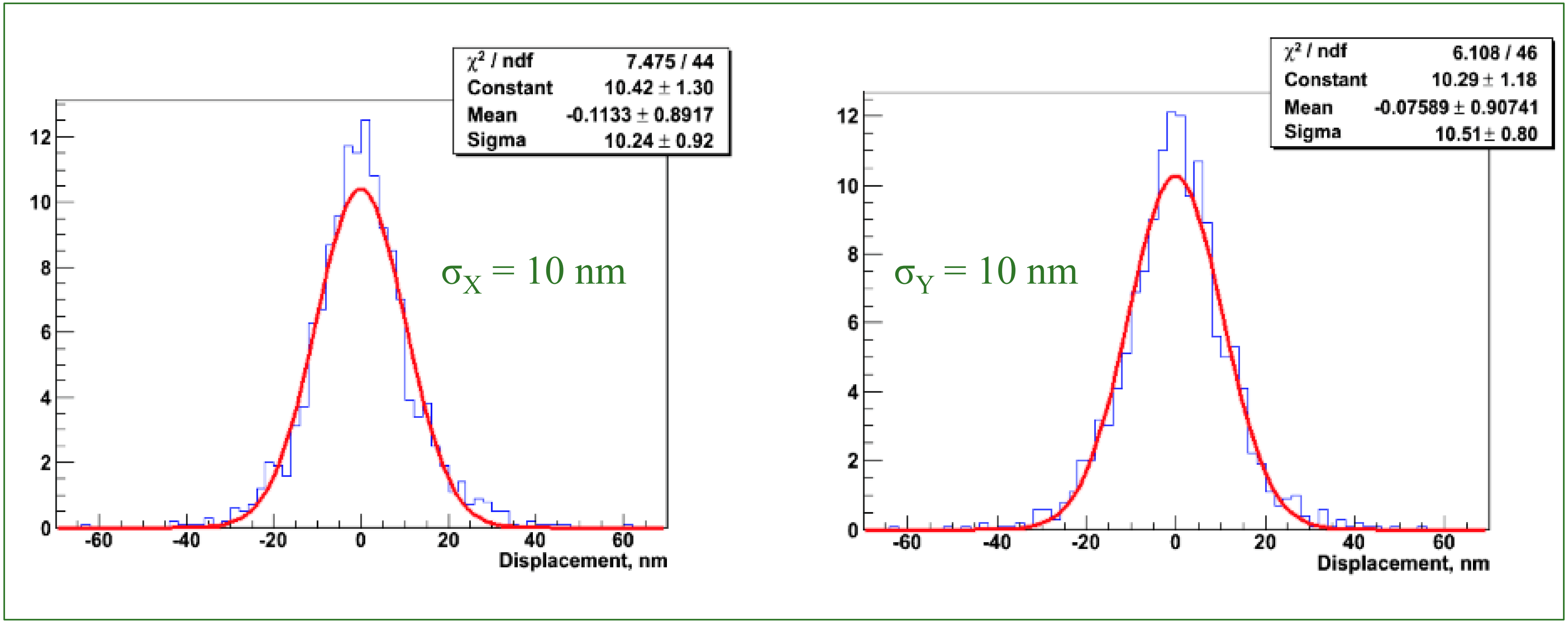
A track made of two grains



Center of mass displacement



POSITION ACCURACY



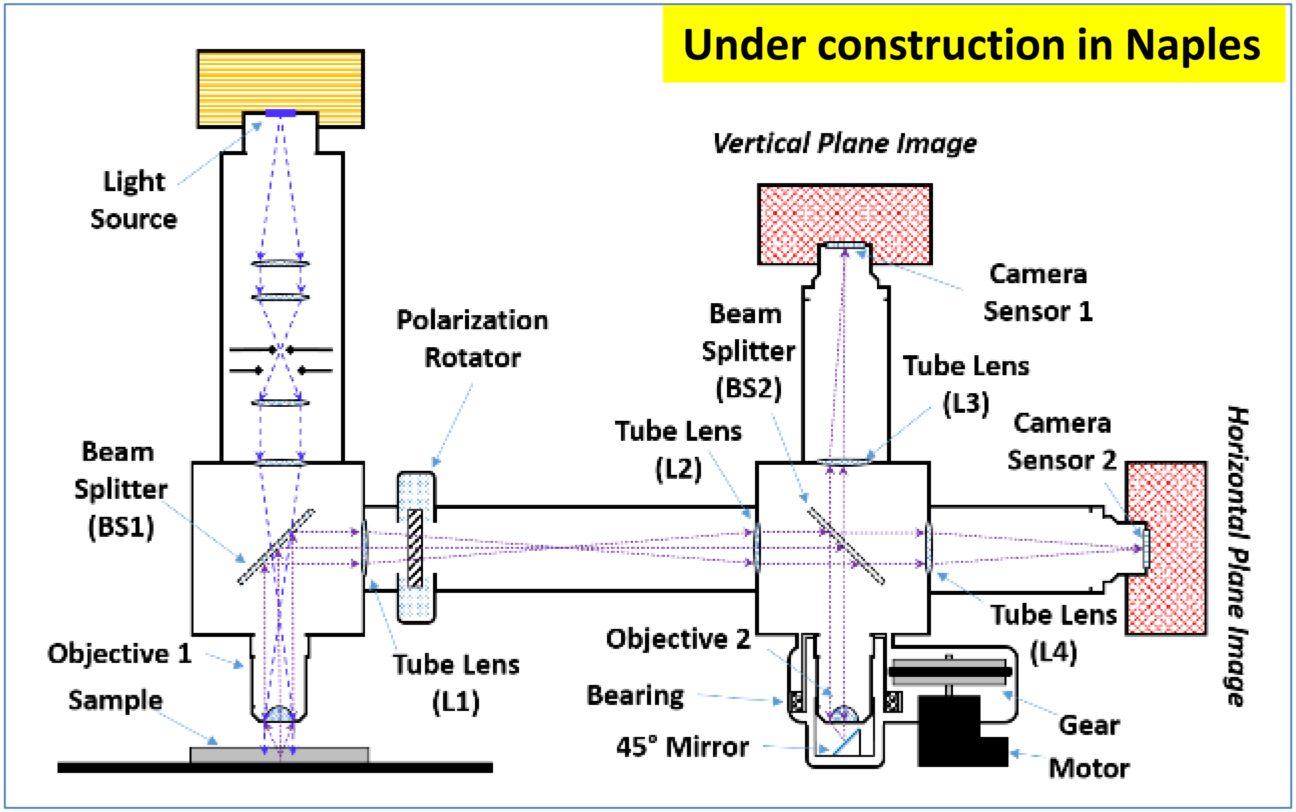
(pixel size 28 nm)

Accuracy of 10 nm on both coordinates

Allows reconstruction:

- 100 nm long tracks in NIT emulsions (11 grains/μm)
- 40-50 nm long tracks in U-NIT emulsions (29 grains/μm)

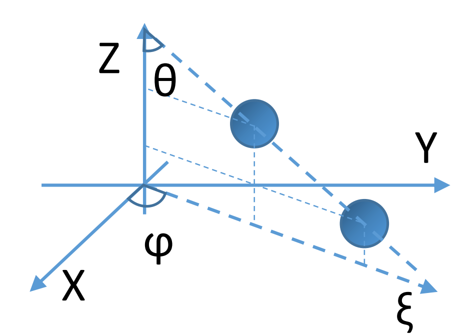
3D NANOMETRIC READOUT



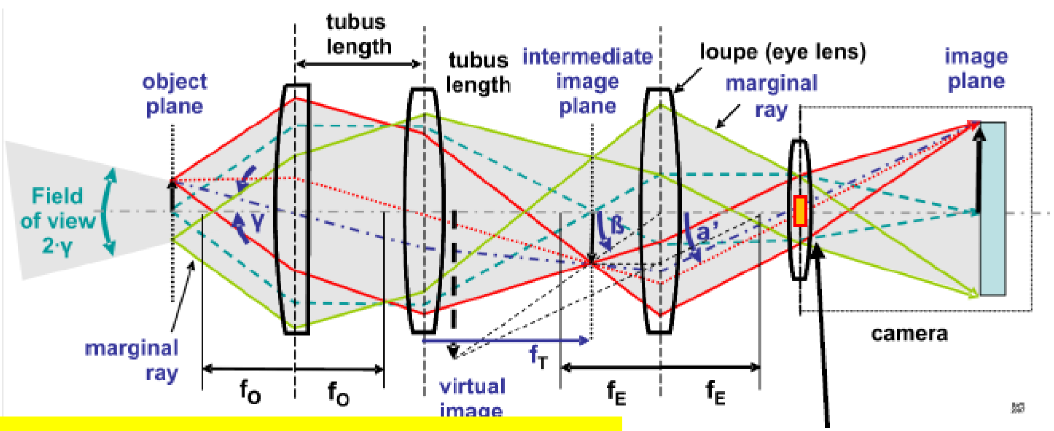
Patented within INFN
in December 2016
N. 102016000132813

Inventors:
A. Alexandrov,
N. D'Ambrosio,
G. De Lellis,
V. Tioukov

- Perform plasmon analysis in horizontal plane
  - Measure φ angle
- Rotate mirror to make the vertical plane coincide with the prediction's direction (φ)
- Perform plasmon analysis in vertical plane
  - Measure θ angle
  - Measure 3D length



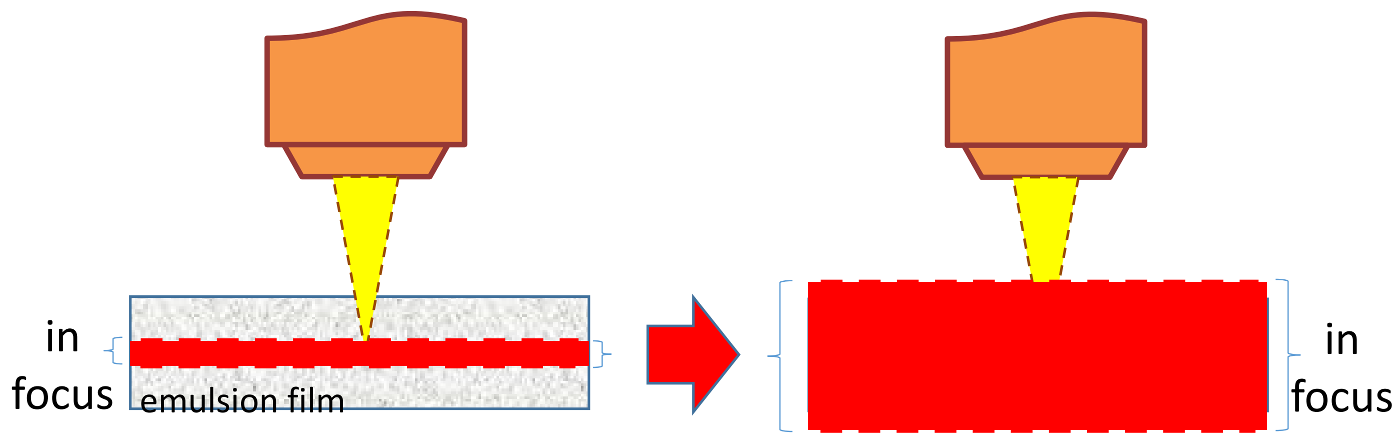
Depth-of-Field expansion



Under construction in Naples

$$DoF = \frac{\lambda}{2\,n\left(1-\sqrt{1-\left(\frac{NA}{n}\right)^2}\right)}$$

The depth of field is about 200-250 nm for 100x/1.45 NA oil objective lens at 405 nm



Need several steps along the vertical axis to analyze the entire depth

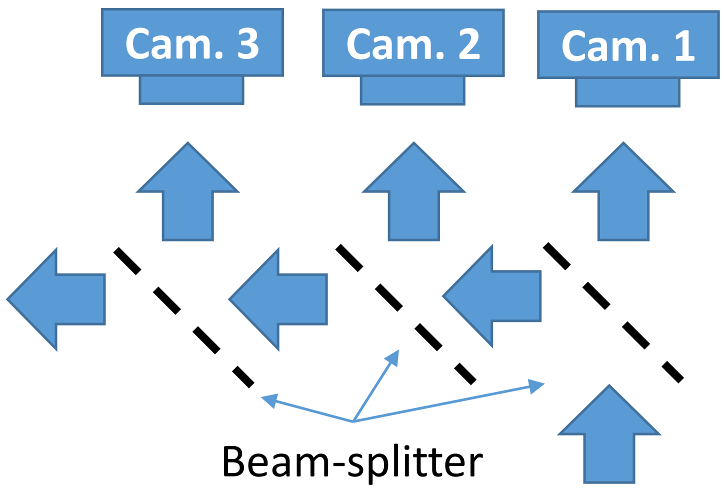
The entire depth can be analyzed in a single step

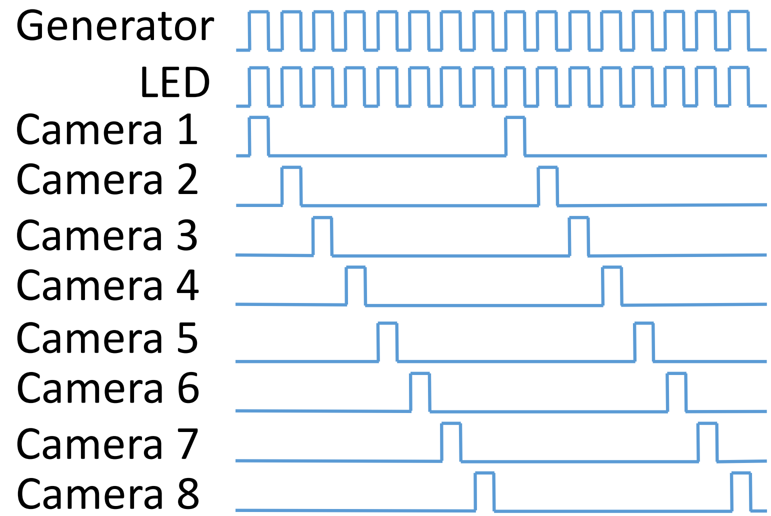
Depth-of-Field expansion

- Immediate improvement (use existing HW)
  - 100x/1.49NA objective, 4M camera @ 563 fps
  - Stop&Go: ~2.3 kg/year/microscope
- Short-term improvement (HW upgrade required)
  - 60x/1.49NA objective, 25M camera @ 90 fps (this HW already exist)
  - Stop&Go: ~11 kg/year/microscope
- Long-term improvement (R&D required)
  - 60x/1.49NA objective, 25M camera @ 90 fps (or faster)
  - Illumination system (more light yield, stroboscopic)
  - Multiple camera readout is possible
  - Fast XY stage (exist, allowing 5-6 cameras)
  - Continuous Motion: up to 70 kg/year/camera/microscope

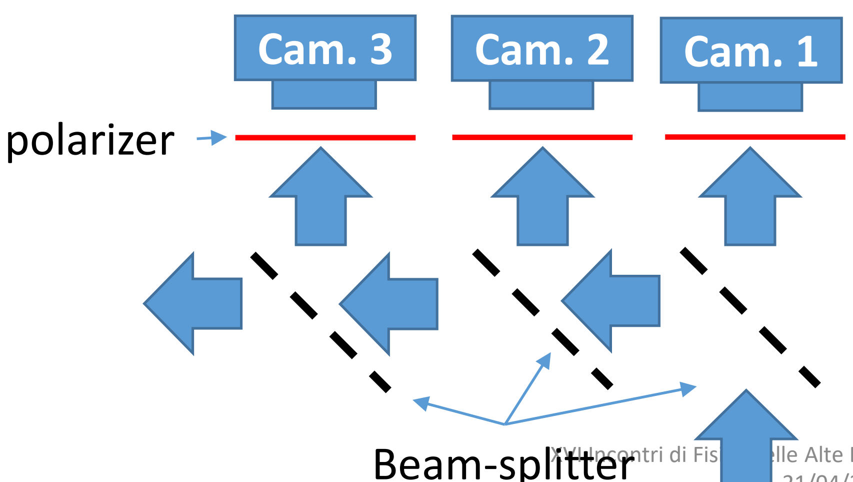
Multicamera readout

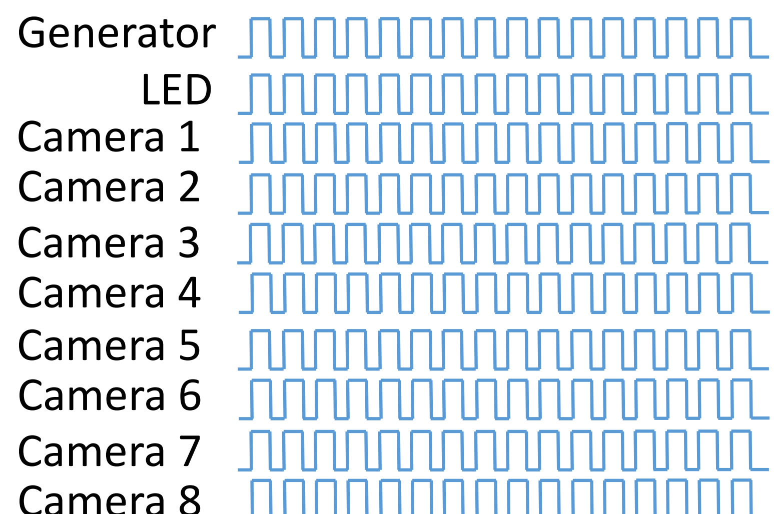
Consecutive configuration (for shape analysis)





Parallel configuration (for plasmon analysis)





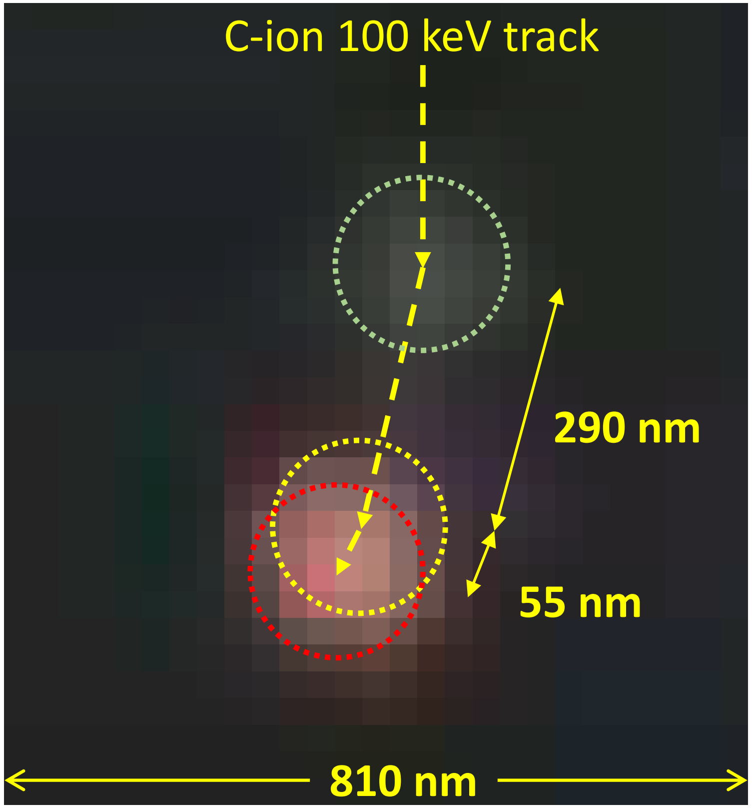
NEWSdm readout strategy

- **1st pass:** Prediction selection with fast 2D microscopes
  - Low magnification but high NA optics (60x/1.49 NA)
  - DoF expansion
  - Grain shape analysis
  - 2D plasmon analysis with multi-camera readout
- **2nd pass:** Prediction check with high-precision 3D microscopes
  - 3D plasmon analysis
  - Multi-camera readout for accuracy improvement

This strategy allows analyzing large emulsion volumes with highest resolution in shortest possible time:
Need about 15 microscopes to analyze a 1 ton detector in 1 year.
Within INFN OPERA laboratories there are 31 microscopes.

Multi-wavelength Plasmon Resonance Analysis

- LSP Resonance wavelength is another source of information
- Depends on grain's size and shape
- Larger energy loss -> more latent images produced -> larger and longer grains -> red shift of the resonant wavelength
- Expect more red at track's stopping point
- Head-tail discrimination!



Conclusions

- The 10 nm accuracy of the Plasmon Resonance analysis enables reconstruction of 100 nm long tracks in NIT and 50 nm in U-NIT emulsions
- Extension of the Plasmon Resonance Analysis to the multi-wavelength domain enables head-tail discrimination
- The novel microscope design can perform the plasmon resonance analysis in both horizontal and vertical planes allowing a full 3D reconstruction of a recoil track with a nanometric accuracy
- The DoF expansion technique allows readout of a ton-scale detector in one year using just 10-20 microscopes
- Reported techniques will pave the way to scale the NEWSdm experiment to the ton-scale, towards the neutrino floor and the DM discovery

Thank You!

Backup

Nuclear emulsions

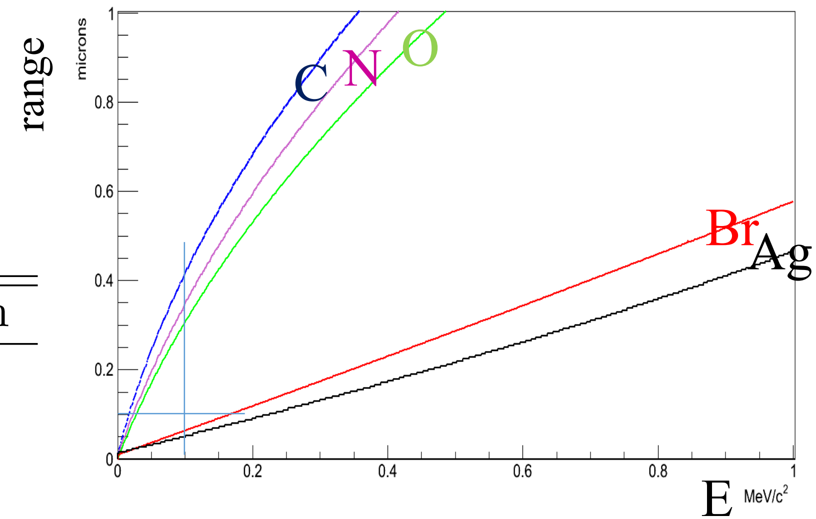
AgBr-I: sensitive elements
Organic gelatine: retaining structure
PVA to stabilise the crystal growth

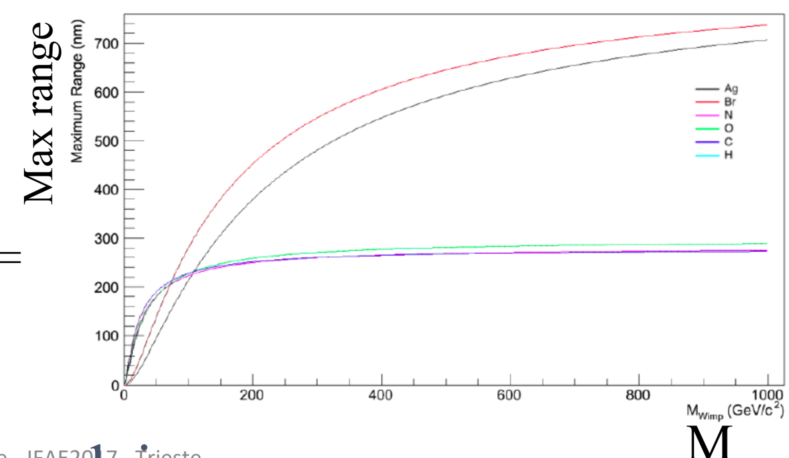
Constituent	Mass Fraction
AgBr-I	0.78
Gelatin	0.17
PVA	0.05

(a) Constituents of nuclear emulsion

Element	Mass Fraction	Atomic Fraction
Ag	0.44	0.12
Br	0.32	0.12
I	0.019	0.003
C	0.101	0.172
O	0.074	0.129
N	0.027	0.057
H	0.016	0.396
S	0.003	0.003

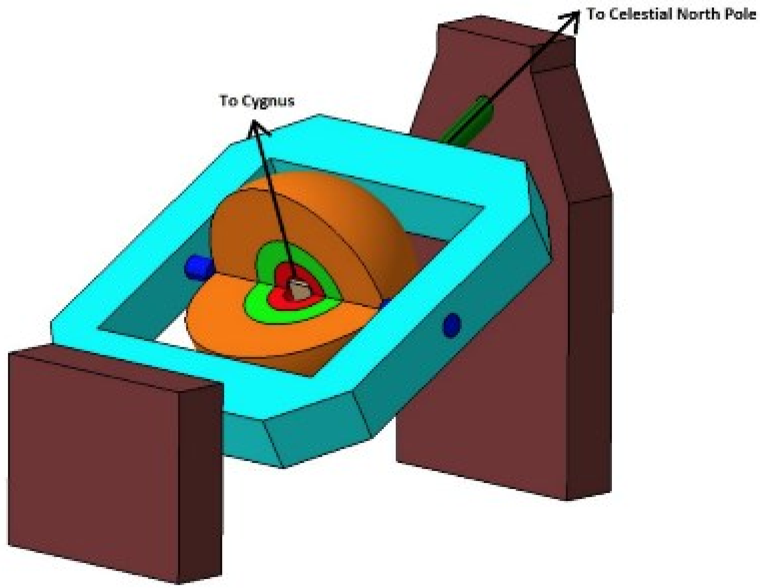
(b) Elemental composition

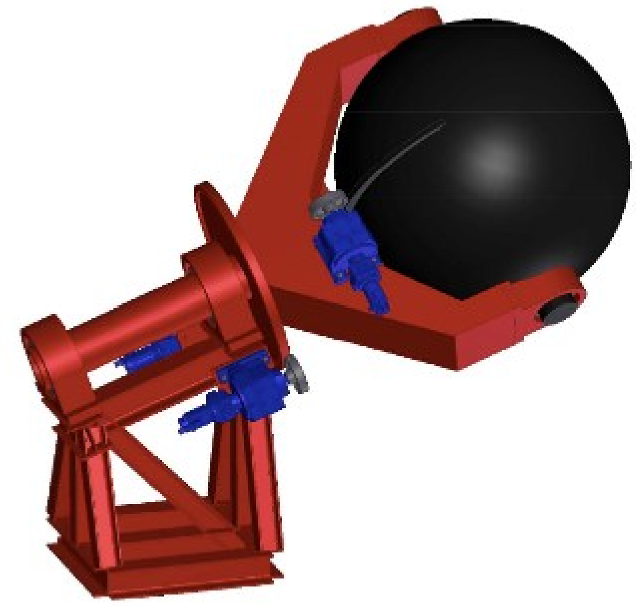


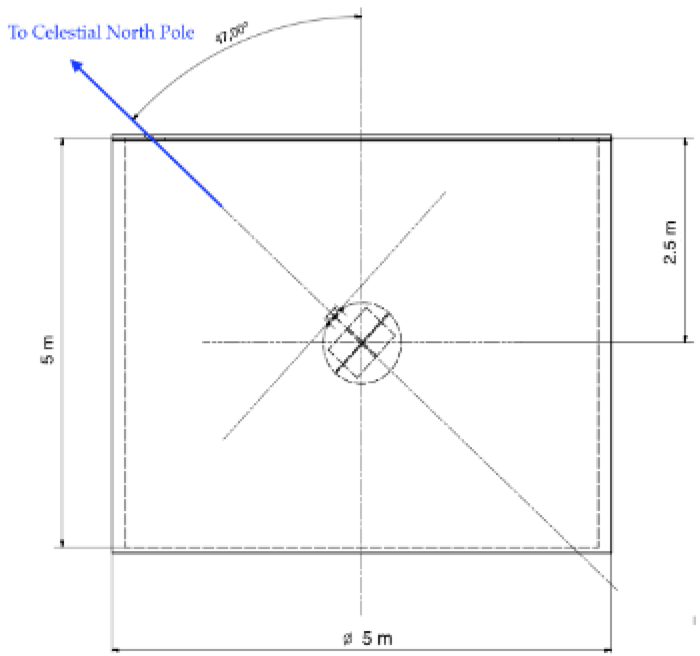


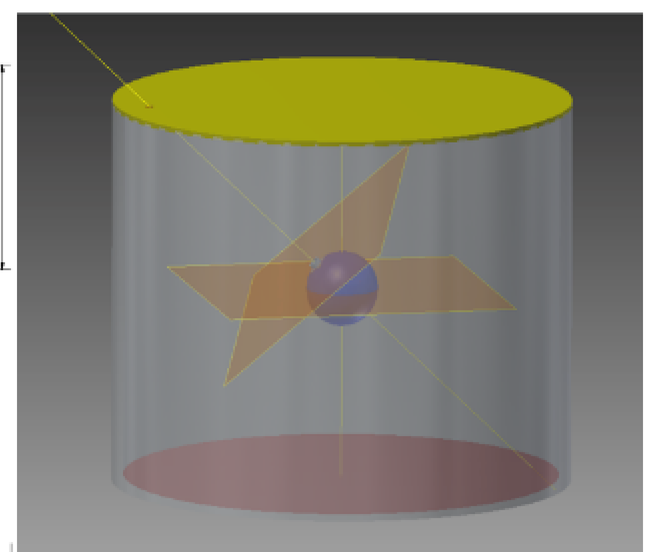
Both light and heavy nuclei

Experimental setup options with the equatorial telescope

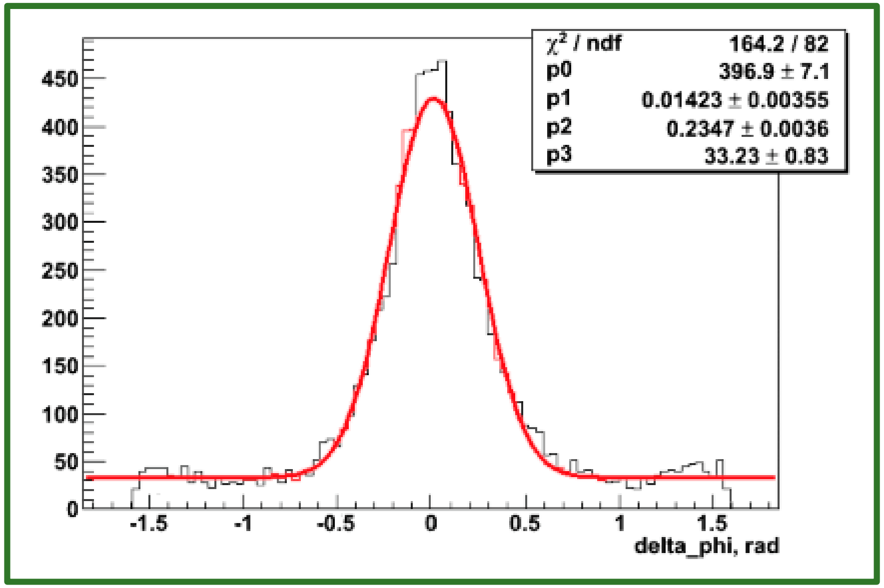


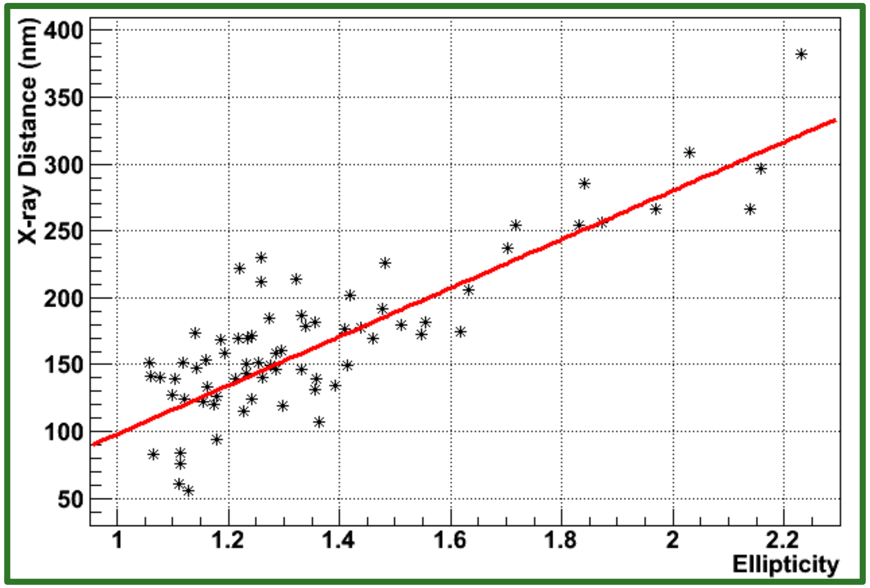






Grain Shape Analysis





- Angular resolution
  - Ions (C100, Kr400)
  - Intrinsic (inside proton tracks)
- Efficiency and length limit
  - X-ray sample