NUCLEAR EMULSIONS FOR WIMP SEARCH WITH A DIRECTIONAL MEASUREMENT

EPS-HEP Conference, Jul 26th 2021

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NEWSdm Collaboration

80 scientists
14 Institutes

JAPAN
Chiba
Nagoya
Toho

RUSSIA
LPI RAS Moscow
JINR Dubna
SINP MSU Moscow
INR Moscow
Yandex School of Data Analysis

ITALY
LNGS
University and INFN Napoli
INFN Roma

SOUTH KOREA
Gyeongsang University

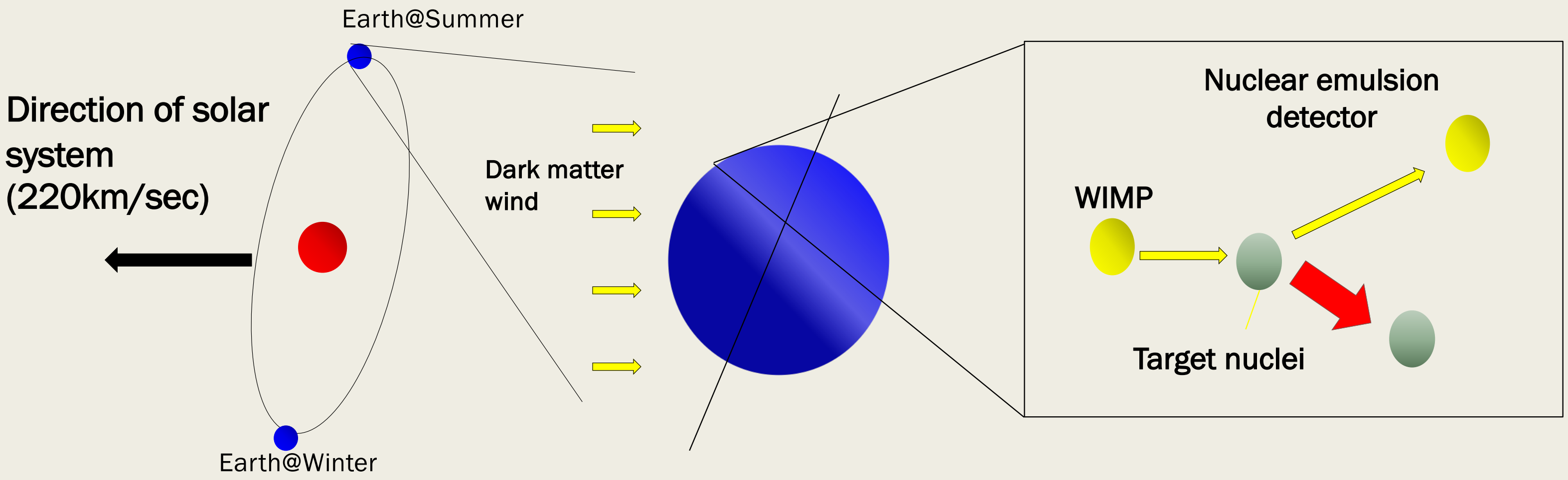
TURKEY
METU Ankara

Website: *news-dm.lngs.infn.it*

Outline

- Physics motivation
- Nano Imaging Trackers
- Super-resolution readout
- Machine learning techniques to nanometric image analysis
- Underground facility and current setup
- Neutron detection and measurements with an equatorial mount
- Conclusions

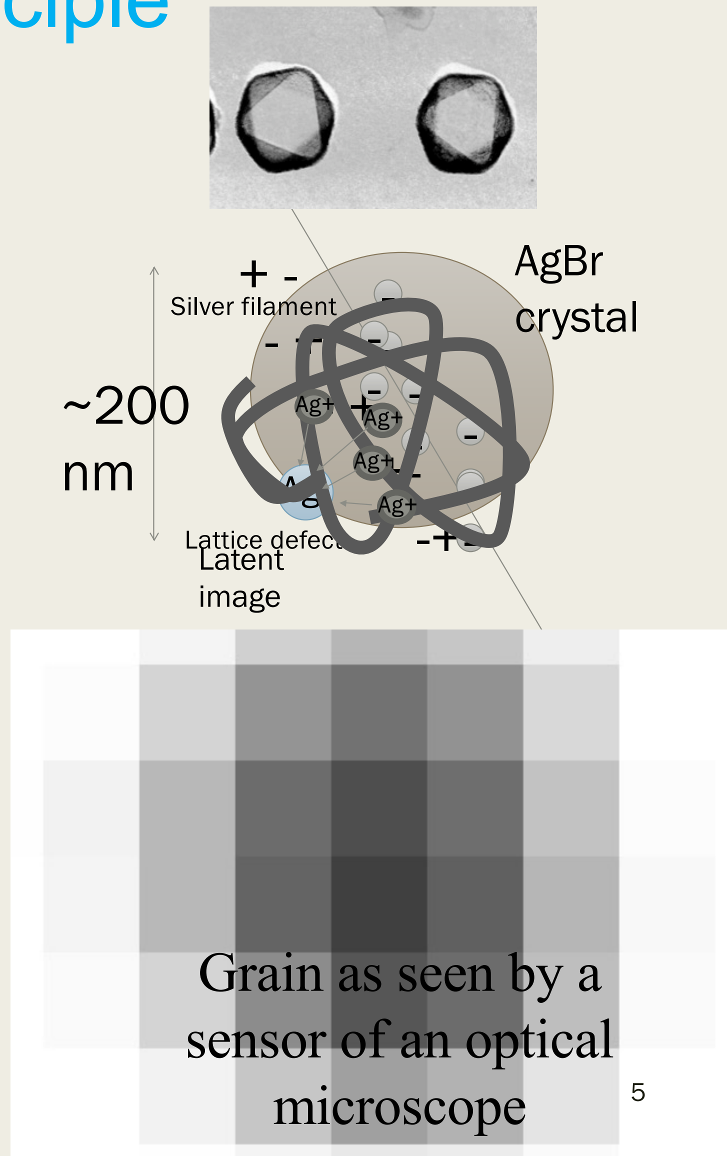
WIMP directional detection



- Strong correlation between the direction of WIMP and scattered nuclei → **strong signature** and **unambiguous proof** of the galactic DM origin
- Unique possibility to overcome the “neutrino floor”, where coherent neutrino scattering creates an irreducible background
- **Nuclear Emulsion** is a high-density solid-state medium → large mass with a compact detector

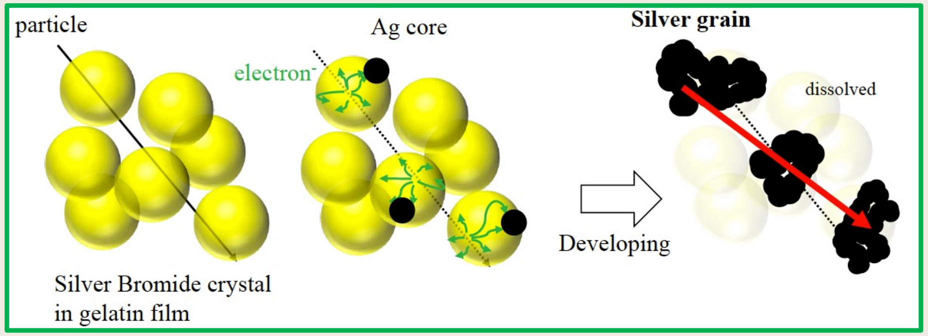
Nuclear emulsion: detection principle

1. Ionization induced by a particle
   - *2.6 eV band gap*
2. Electrons trapped at a lattice defect on the crystal surface
   - *Attract interstitial silver ions*
   - *Produce a "latent image" = Ag_n*
3. Chemical amplification of signal
   - *Development → silver filaments*
   - *10^7 - 10^8 amplification*
4. Dissolve crystals
5. Observe it at optical microscopes



Grain as seen by a sensor of an optical microscope

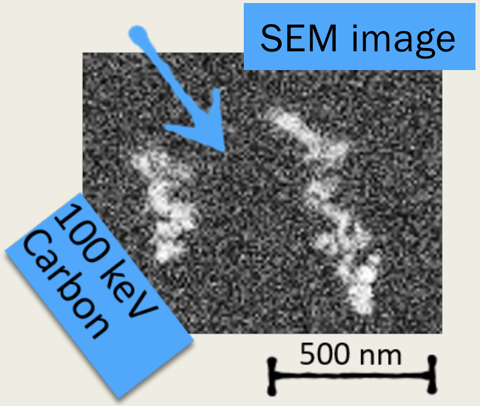
NIT: Nano emulsion Imaging Trackers

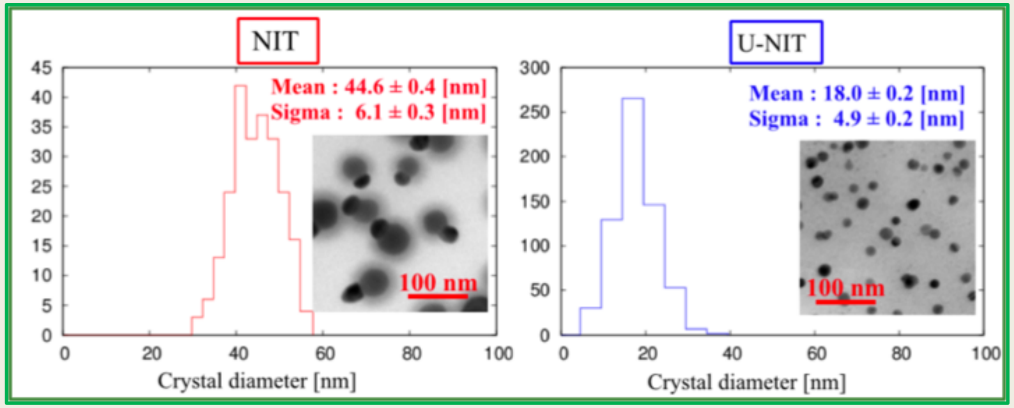


A long history, from the discovery of the Pion (1947) to the discovery of $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode (OPERA, PRL 115 (2015) 121802)

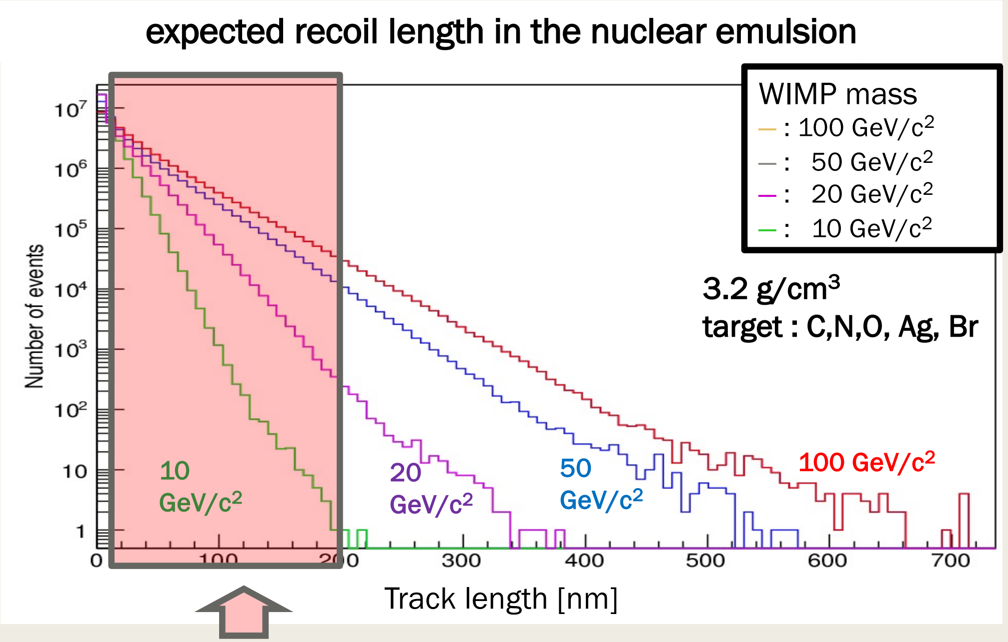
- Nuclear emulsions: AgBr crystals in organic gelatine
- Passage of charged particle produce *latent image*
- Chemical treatment make Ag grains visible

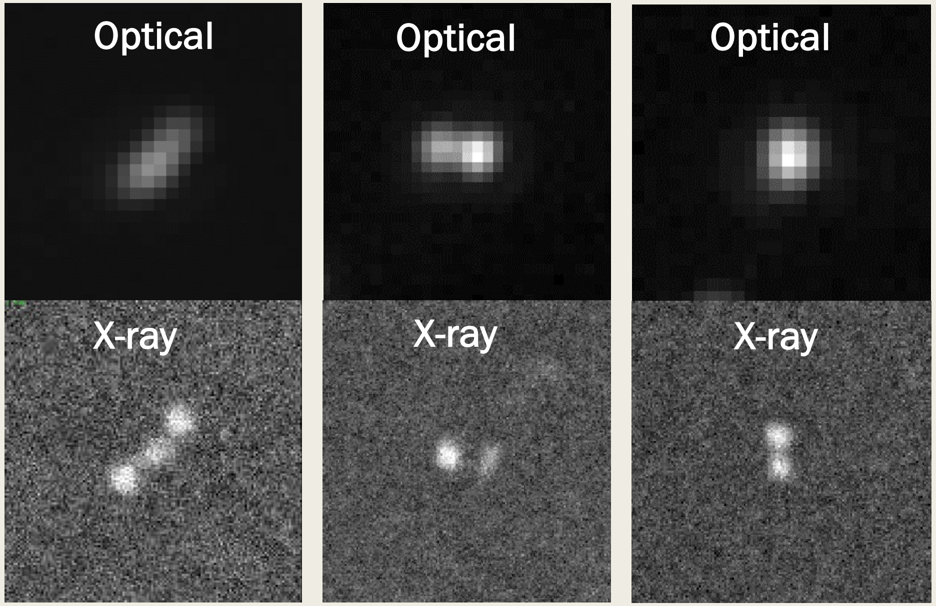
- New kind of emulsion for DM search
- Smaller crystal size





Track lengths of nuclear recoils vs WIMP mass





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

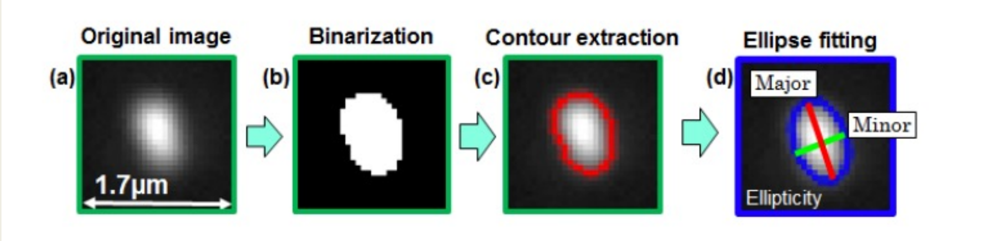
Inaccessible with standard optical techniques due to diffraction limit

Need super-resolution to measure tracks shorter than 200 nm

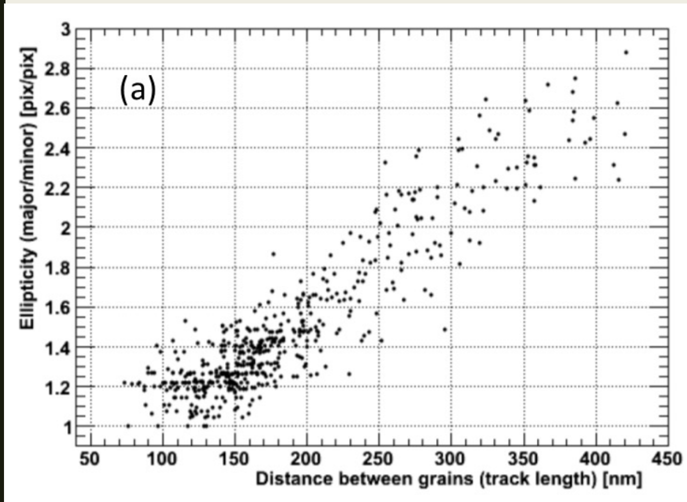
New optical techniques at the nanometric scale

Phase 1: shape analysis

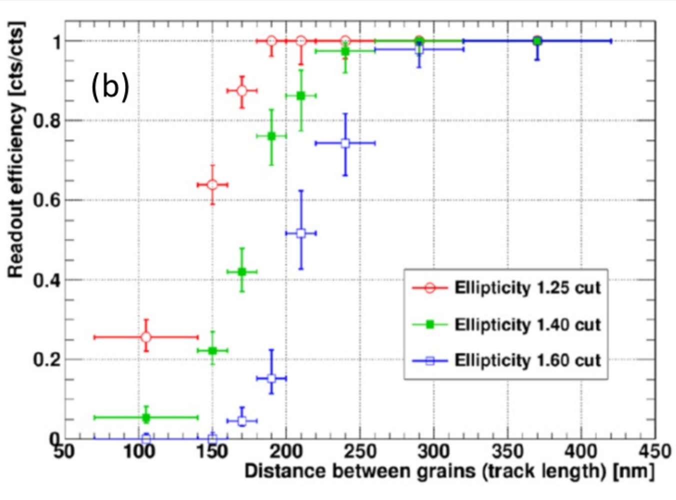
- Elliptical fit to measure the shape anisotropy



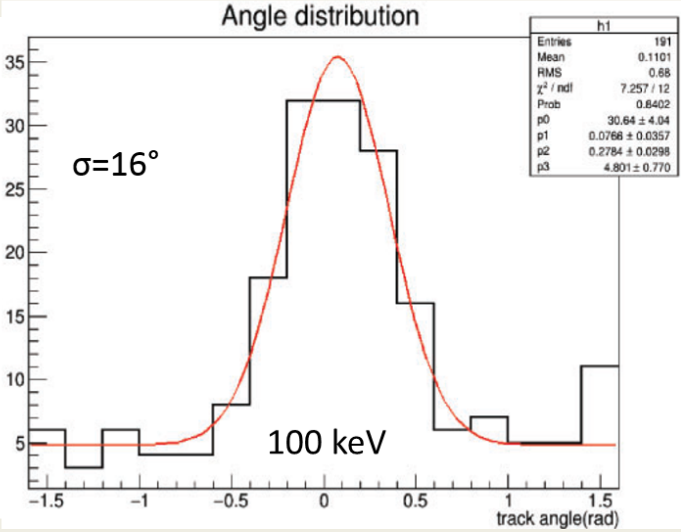
Correlation between track lengths measured by X-ray microscopy and ellipticity obtained with optical analysis



Correlation between readout efficiencies and track lengths for different ellipticity thresholds



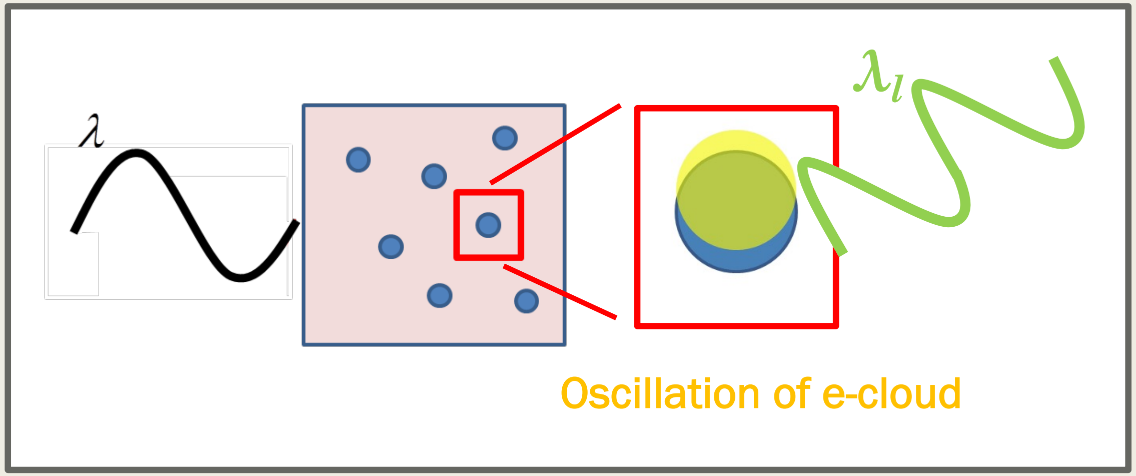
100 keV Carbon

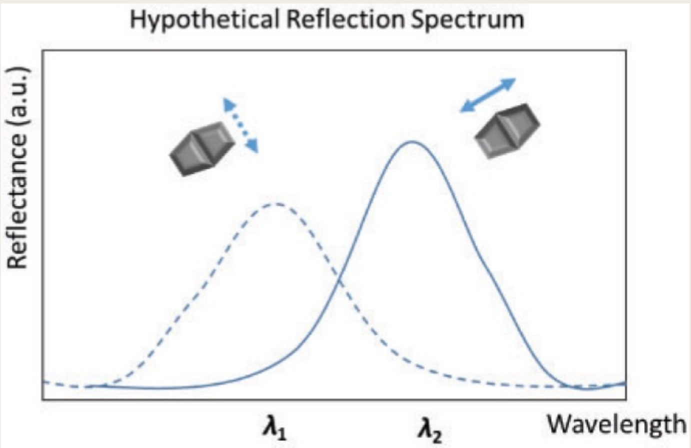


PTEP (2019) 063H02

Phase 2: optical readout beyond the diffraction limit

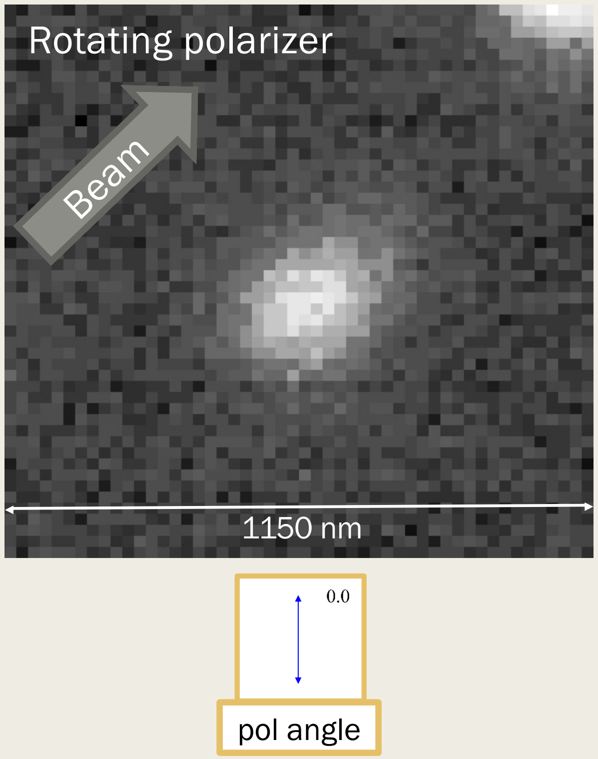
- Idea: use the **plasmon resonance** effect to overcome the diffraction limit:
  - *generated by a light wave trapped within conductive nanoparticles smaller than the wavelength of light*
  - *resonant frequency strongly depends on the composition, size, geometry, dielectric environment and distance between nanoparticles*
  - *occurs in the visible region for Ag and Au nanoparticles!*
  - *improve resolution by analyzing scattered light **polarization** and **spectrum***

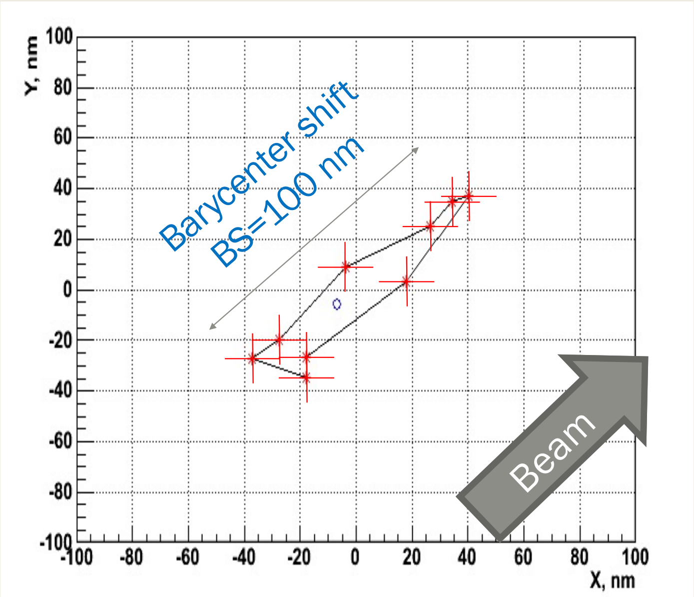




Super resolution: two-dimensions

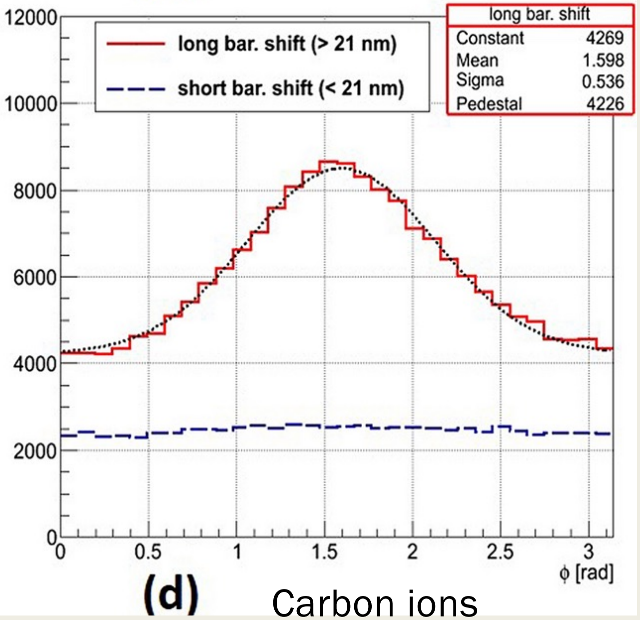
NIM A **824** (2016) 600–602





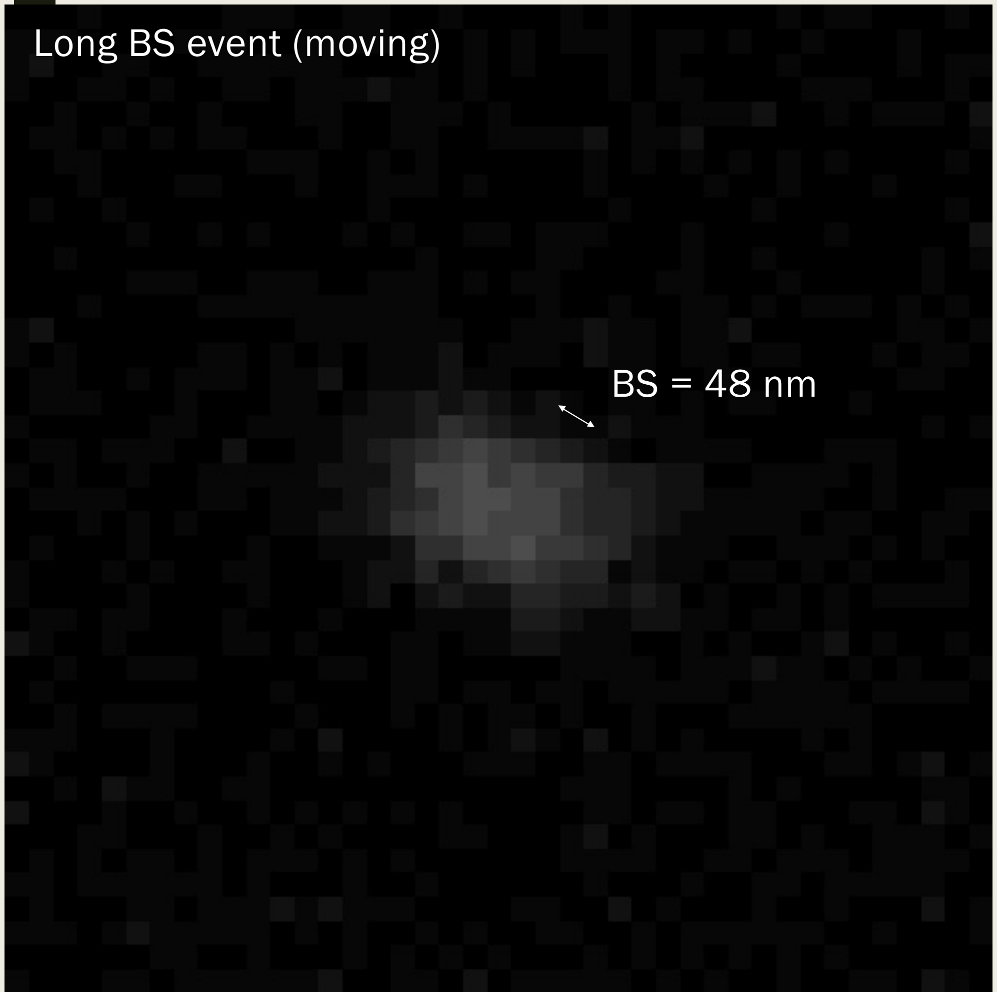
Carbon ion
100 keV

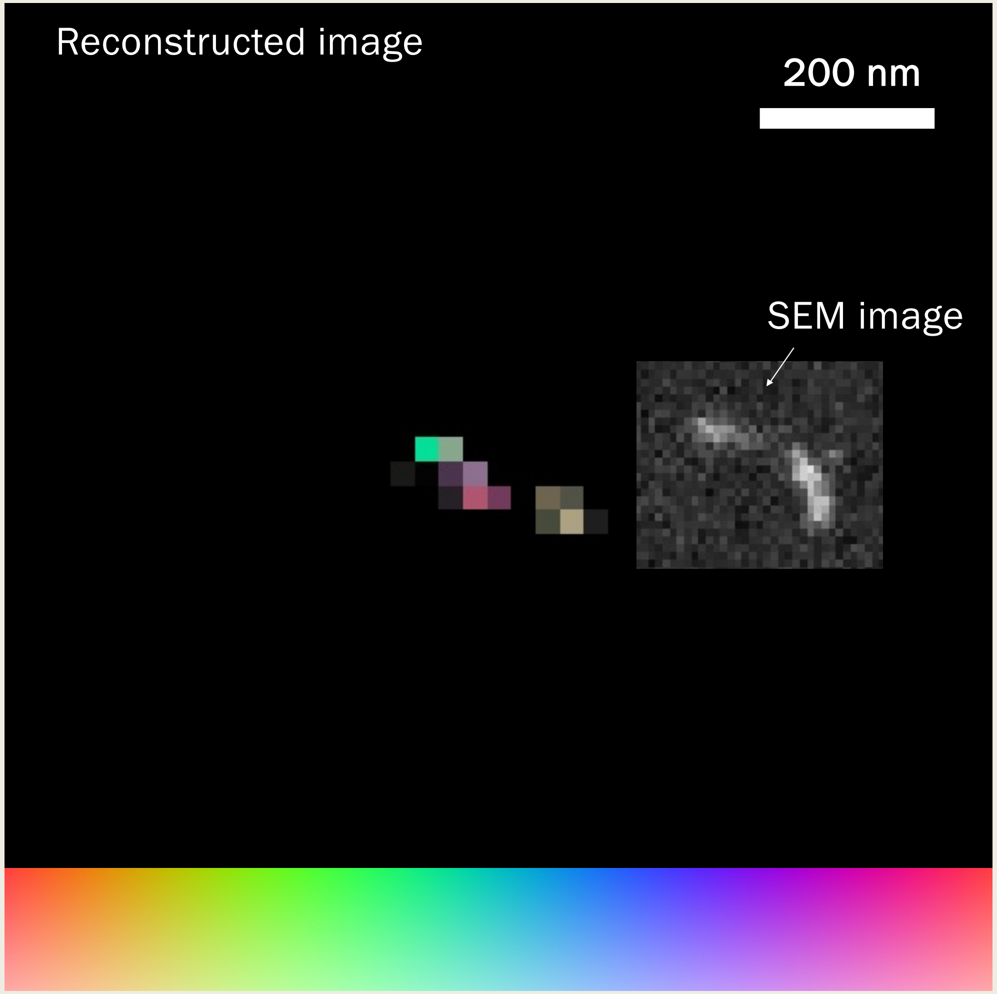
Sci. Rep. **10** (2020) 18773



Carbon ions
60 keV

Exploiting the plasmon resonance effect





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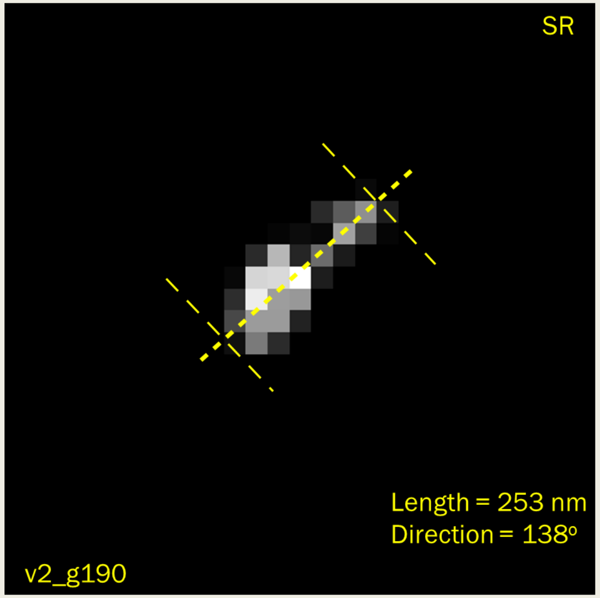
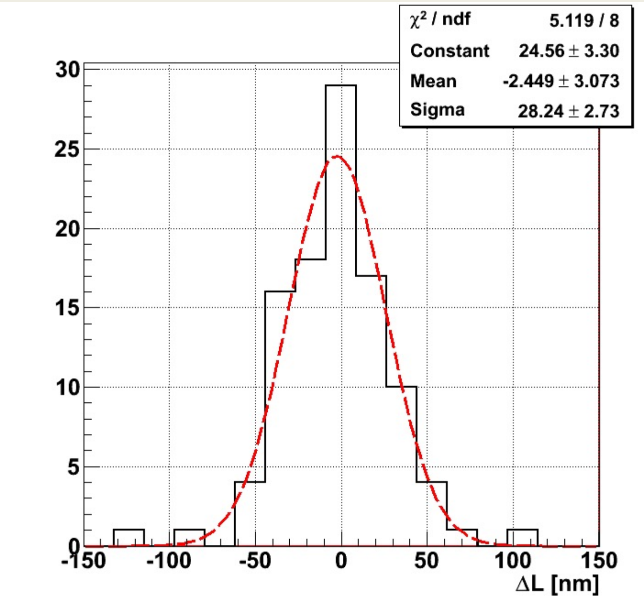
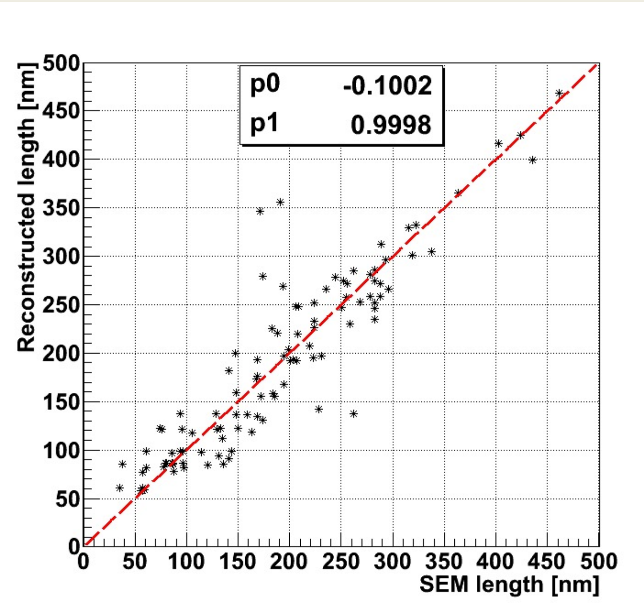
SR-SEM comparison: Event Length



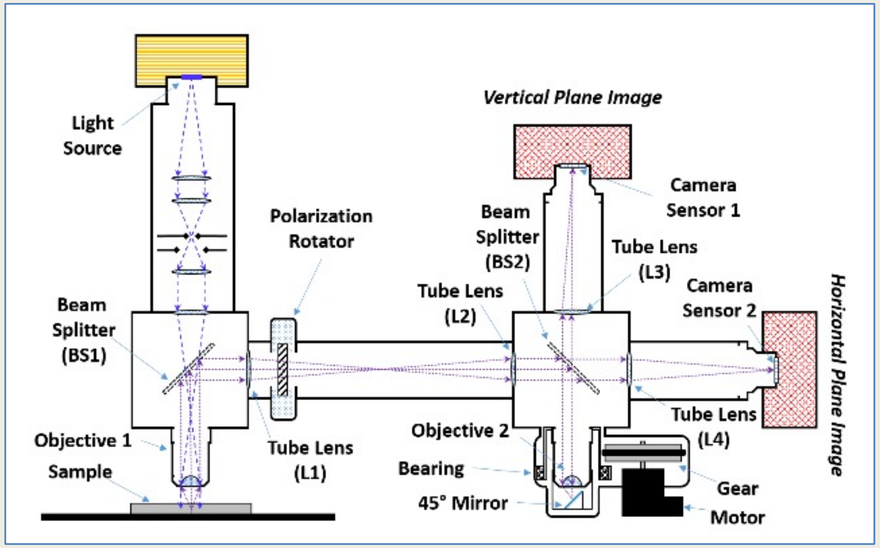




Accuracy: 28 nm ≈ pixel size (27.5 nm)
Resolution: 80 nm (Nyquist theorem)

Pearson Coefficient	Matched	Unmatched
Length	0.912	-0.009
Width	0.713	-0.007

3D measurement



International Patent No. WO/2018/122814

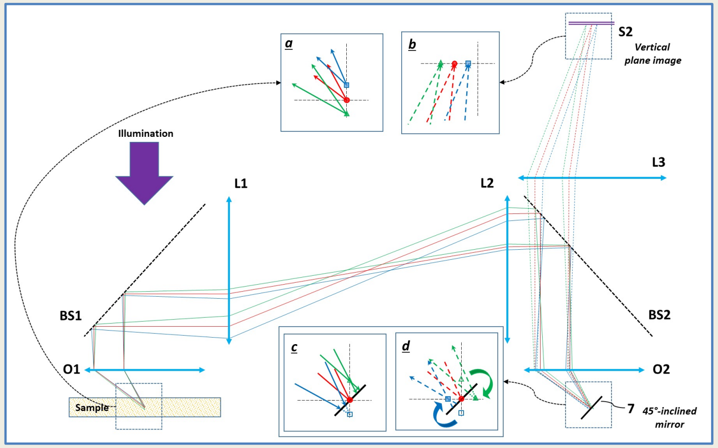
World Intellectual Property Organization [CH] | https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2018122814

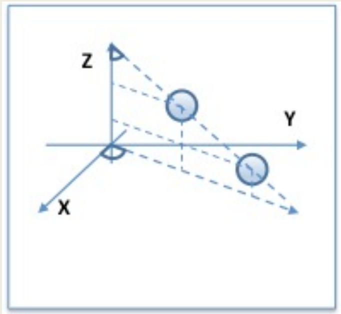
1. (WO2018122814) METHOD AND OPTICAL MICROSCOPE FOR DETECTING PARTICLES HAVING SUB-DIFFRACTIVE SIZE

PCT Biblio. Data | Description | Claims | Drawings | National Phase | Notices | Documents

Latest bibliographic data on file with the International Bureau Submit observation PermaLink

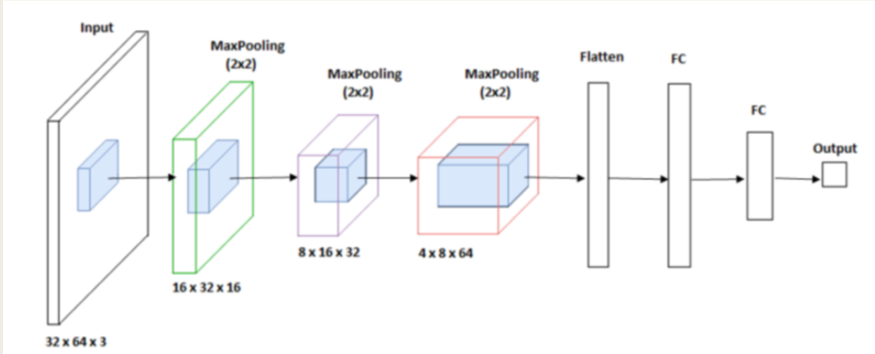
Pub. No.: WO/2018/122814 **International Application No.:** PCT/IB2017/058544
Publication Date: 05.07.2018 **International Filing Date:** 30.12.2017
IPC: *G02B 21/00* (2006.01) ,*G02B 21/36* (2006.01)
Applicants: **ISTITUTO NAZIONALE DI FISICA NUCLEARE** [IT/IT]; Via Enrico Fermi, 40 00044 Frascati (rM), IT
Inventors: **DE LELLIS, Giovanni**; IT
ALEXANDROV, Andrey; IT
TIOUKOV, Valeri; IT
D'AMBROSIO, Nicola; IT



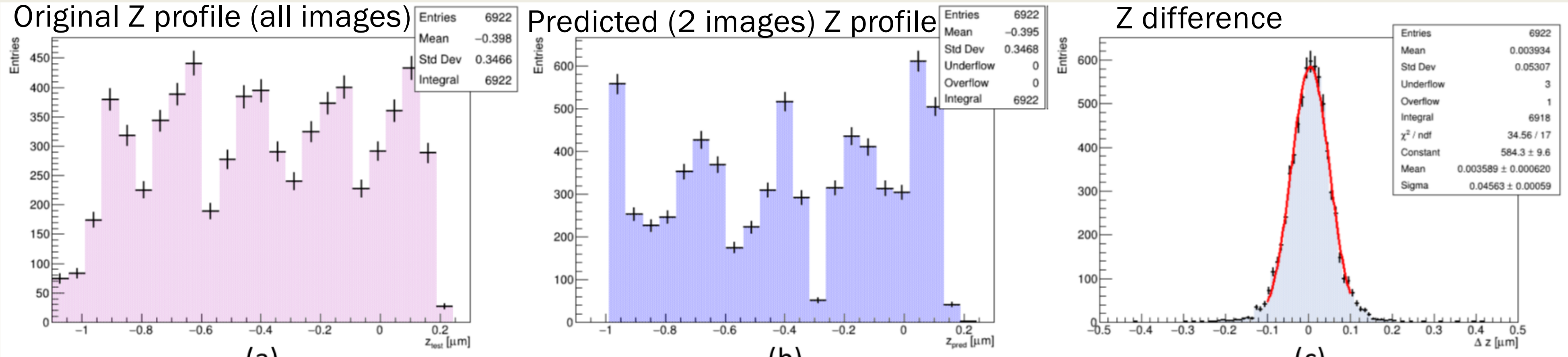


Z reconstruction with machine learning: Convolutional Neural Network

- Each event is a doublet of images plus the Z coordinate
- 2 images (500 nm apart) are merged in a single larger one
- The output is the estimated Z coordinate



Sampling step of 250 nm along Z

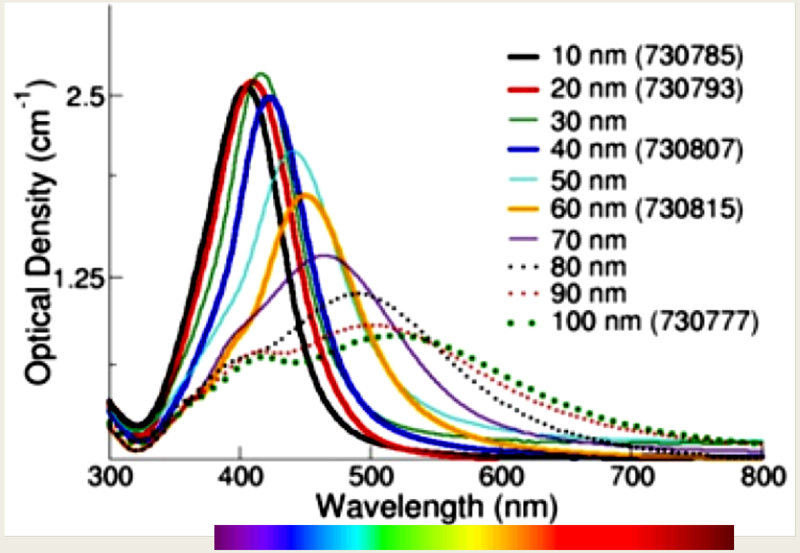


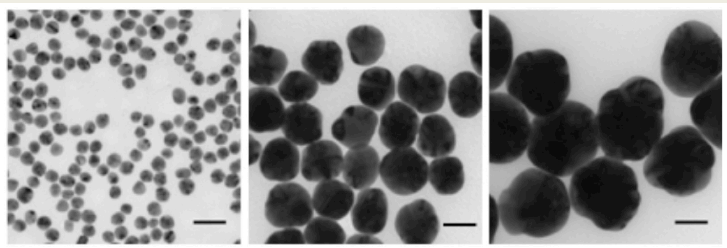
(a) (b) (c)

Depth of Field: $d_{\text{tot}} = \frac{\lambda \cdot n}{\text{NA}^2} + \frac{n}{\text{M} \cdot \text{NA}} e \approx 400\ nm$

Achieved accuracy ~ 46 nm
Improvement of one order of magnitude!

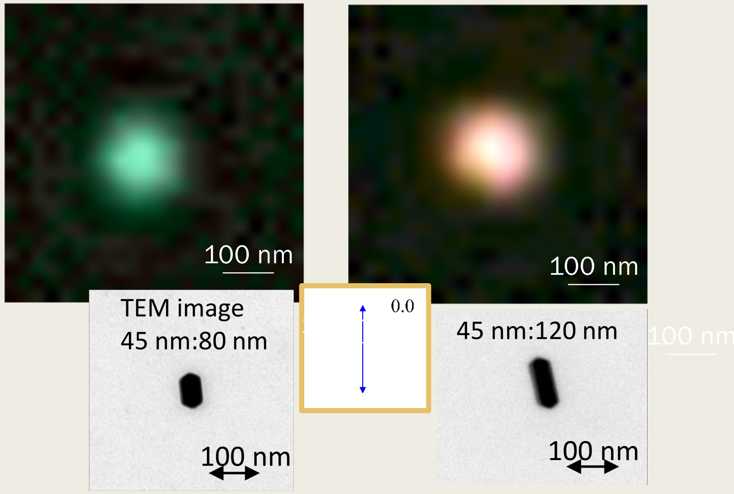
Wavelength dependency of plasmon resonance





20 nm 60 nm 100 nm

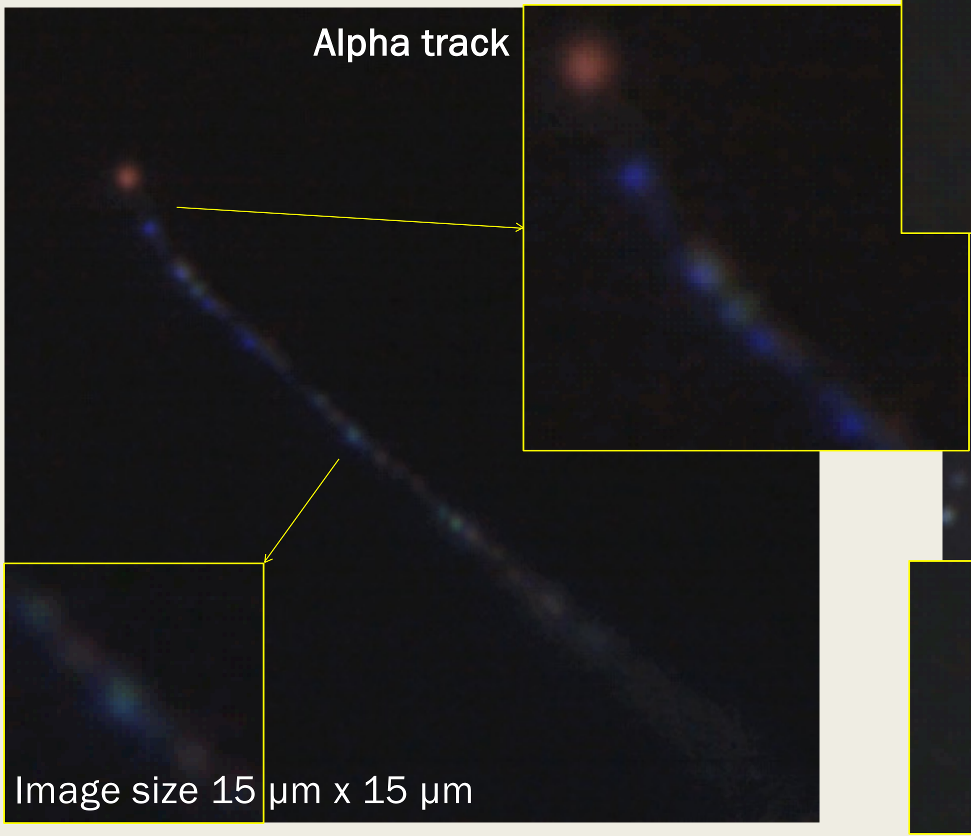
*polarization rotating

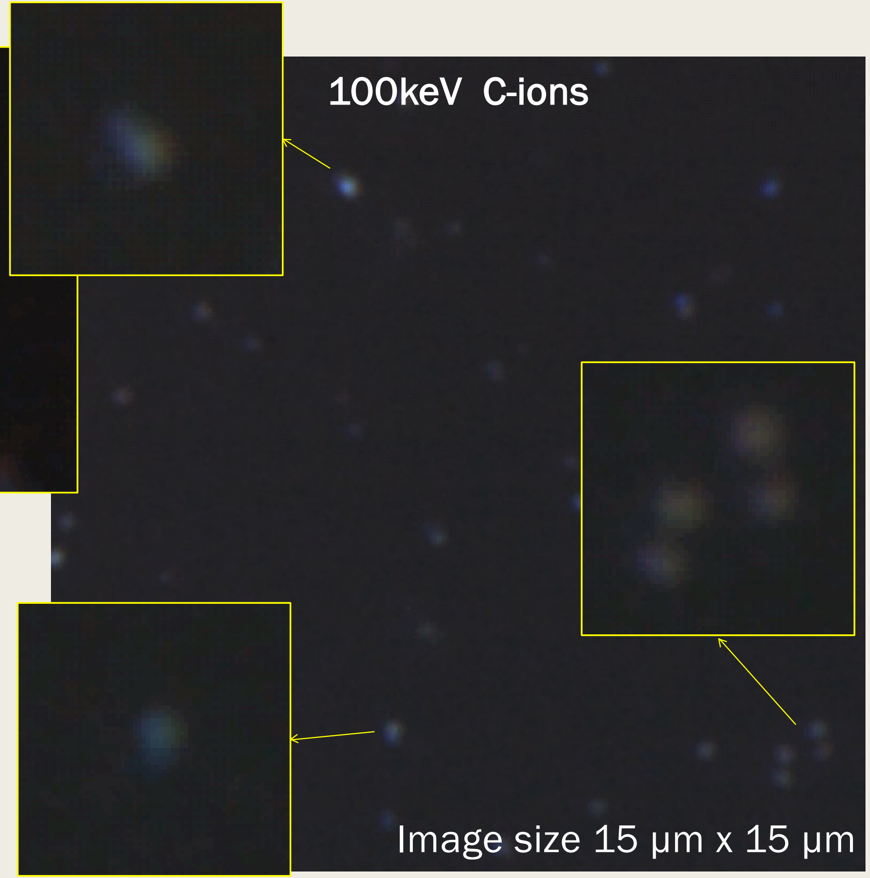


~45 nm : blue
~80 nm : green

~45 nm : blue
~120 nm :orange-red

Plasmon response for α and C tracks



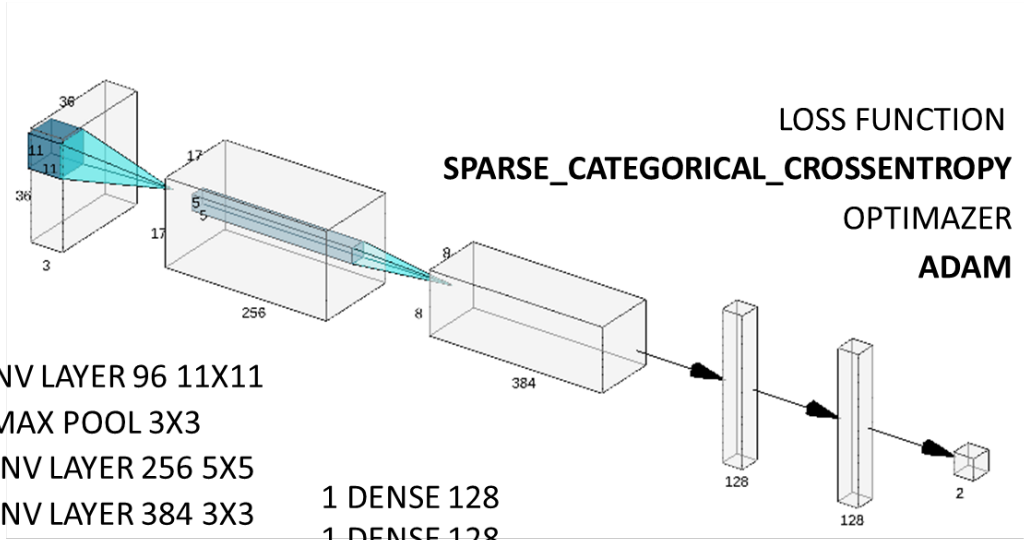


Master thesis

Marianna Fusco, Naples, 2021

Sense recognition with color

Machine Learning approach



LOSS FUNCTION

SPARSE_CATEGORICAL_CROSSENTROPY

OPTIMAZER

ADAM

1 CONV LAYER 96 11X11

MAX POOL 3X3

2 CONV LAYER 256 5X5

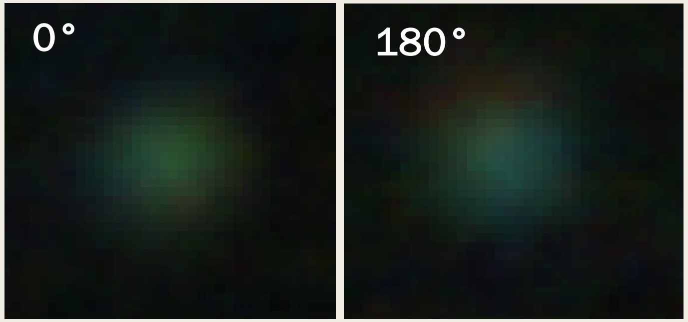
3 CONV LAYER 384 3X3

MAX POOL 3X3

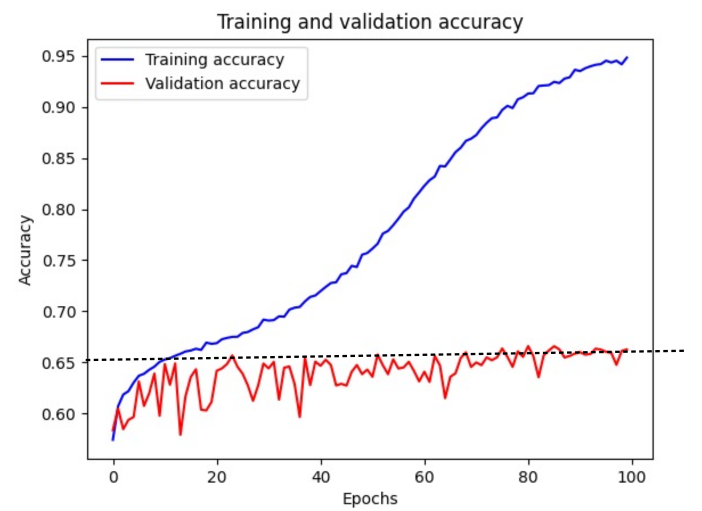
1 DENSE 128

1 DENSE 128

1 DENSE 2



Carbon ion 100 keV



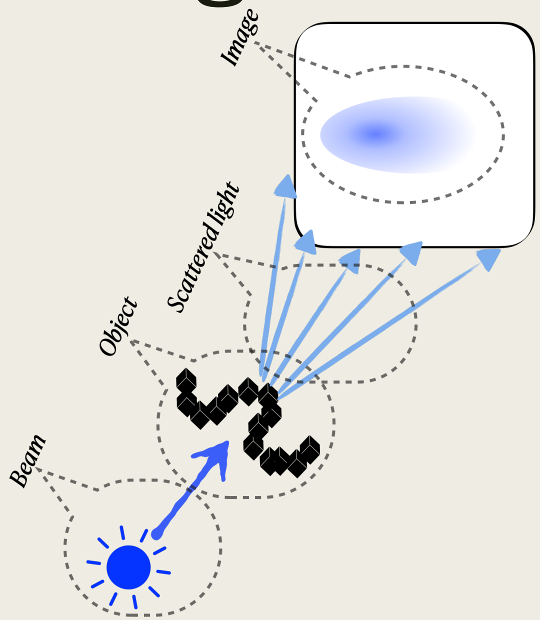
Sense prediction accuracy = 65%

Realistic simulation of images at the nanometric scale

Machine learning application for signal/noise discrimination

Realistic simulation of nanoparticle images

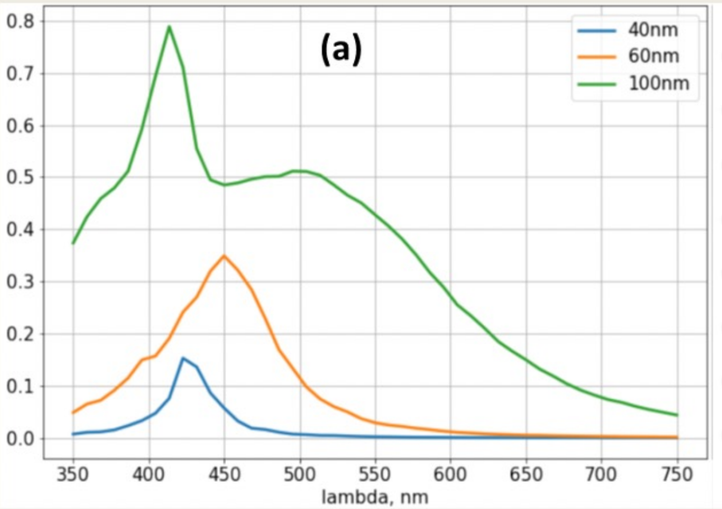
- Generate a 3D model of the object to be simulated (filaments, nano-particles)
- Use discrete dipole approximation to obtain optical images (ADDA, HoloPy)
- Tune the parameters and check the simulation by comparison with real samples



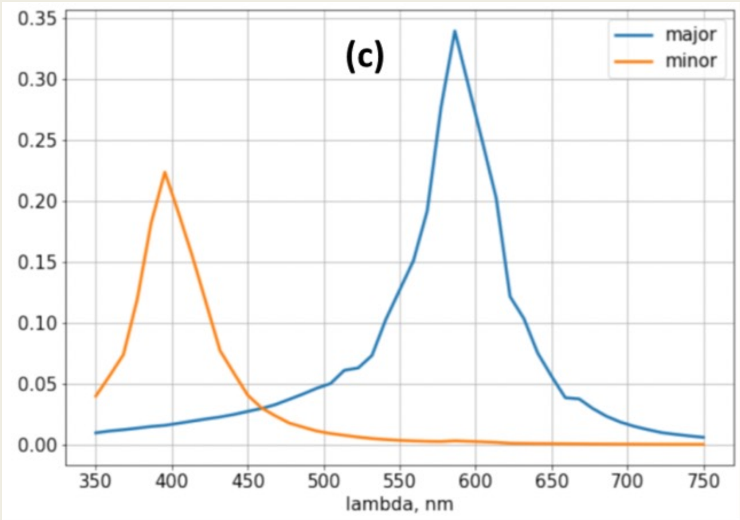
HoloPy: DDA for holography in Python https://github.com/manoharan-lab/holopy

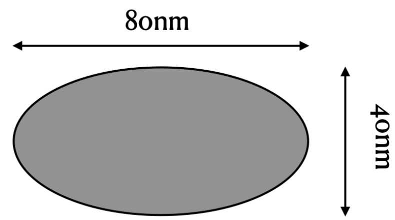
Use ADDA for scattering calculations: https://github.com/adda-team/adda

Silver spheres



Silver ellipsoidal nanoparticle





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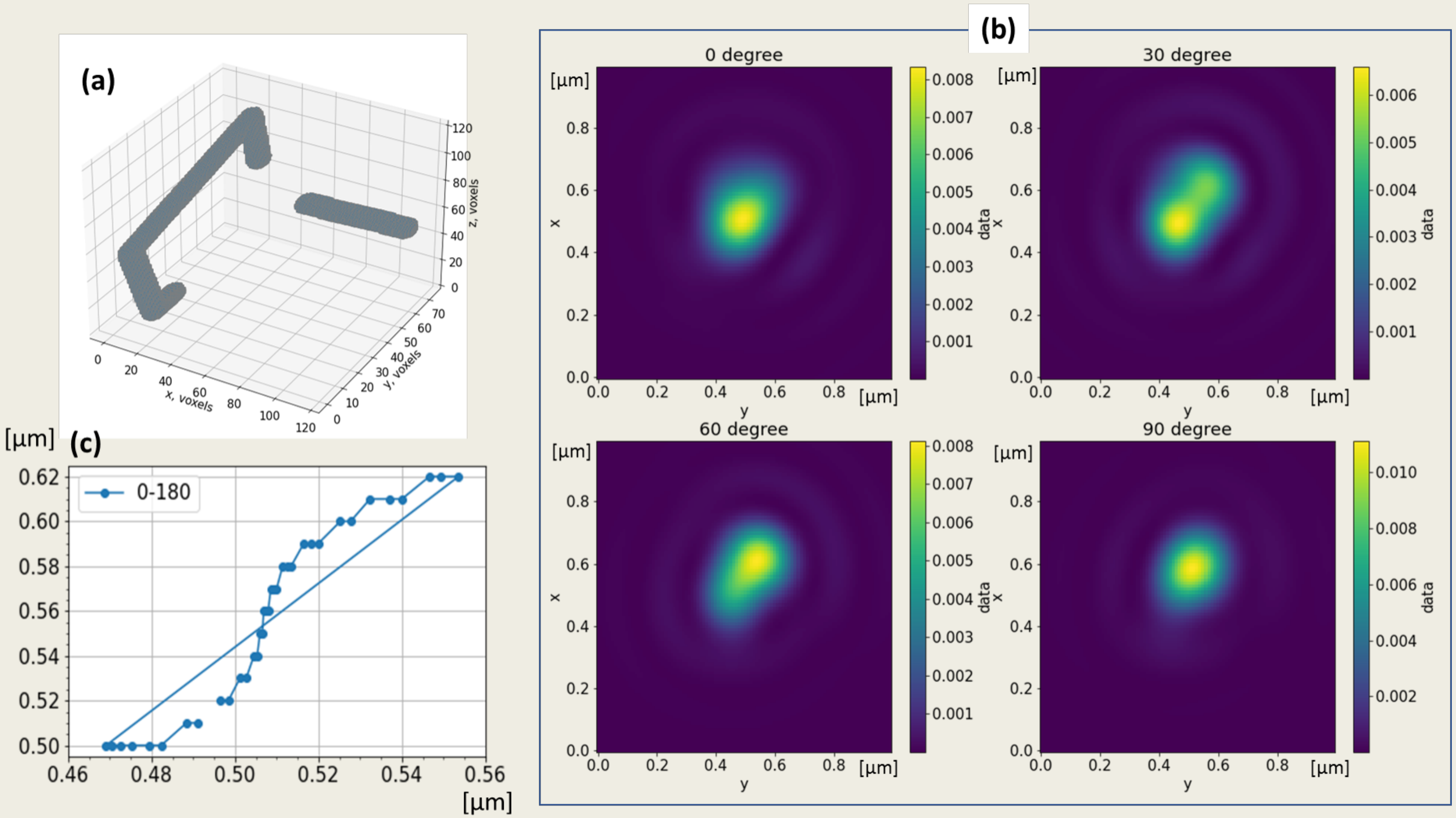
Simulation of two silver filaments



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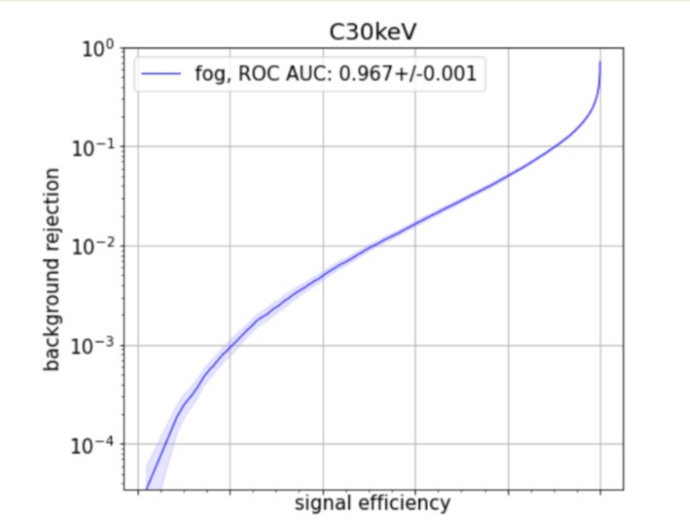
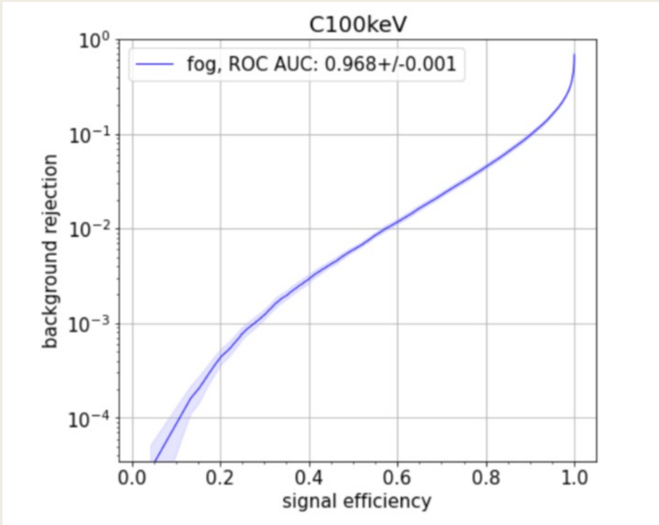
ML analysis results

https://arxiv.org/pdf/2106.11995.pdf

- Fog/dust reduction factor and efficiency for different thresholds on ML probability-like output on **validation** data





	Barshift Validation	Barshift Test	NEWSnet Validation	NEWSnet Test	Shape analysis
			Signal efficiency		
C30keV	$25.3 \pm 1.5\%$	$25.5 \pm 1.7\%$	$29.3 \pm 3.9\%$	$16.2 \pm 3.1\%$	$1.7 \pm 0.1\%$
C100keV	$38.0 \pm 1.8\%$	$38.2 \pm 1.2\%$	$36.5 \pm 3.4\%$	$37.4 \pm 3.3\%$	$29.7 \pm 0.7\%$
			Background rejection power		
Fog	0.32 ± 0.02	0.39 ± 0.02	$(2.4 \pm 0.74) \cdot 10^{-3}$	$(4.2 \pm 1.3) \cdot 10^{-4}$	0.01

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Emulsion facility and current setup underground

Emulsion facility at LNGS Hall F

- Work carried out in the facility:
  - Installation of containment vessels under the floor
  - Improvement of electric system
  - Installation of a thermostatic chamber
- Emulsion production machine
- Access to the emulsion facility since December 2020

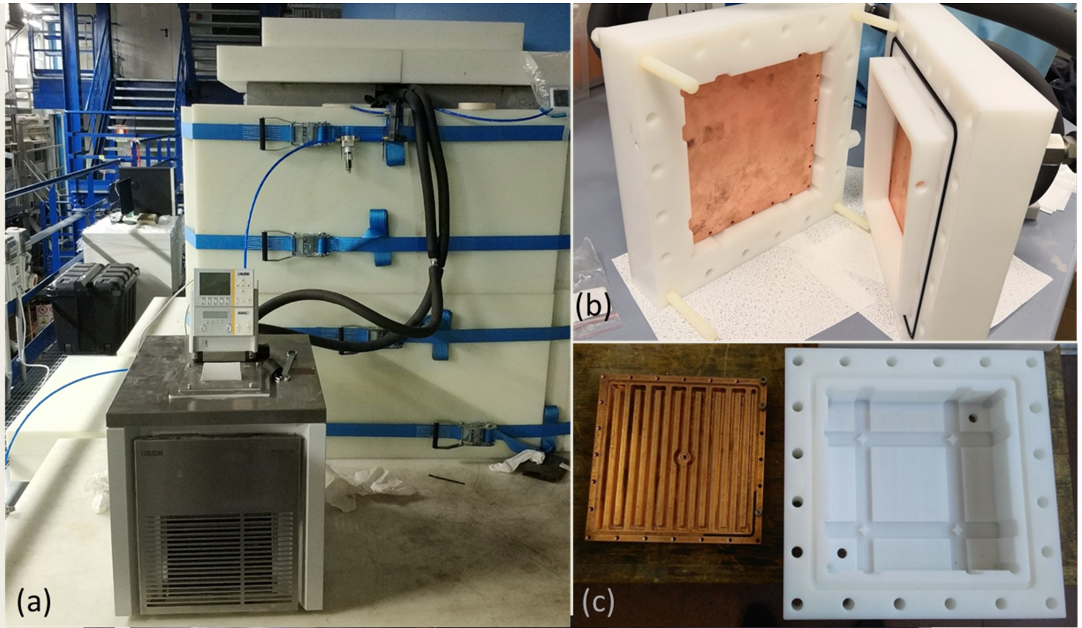
Development room

Gel production room

Gel production machine produced in Japan and certified compliant to EU safety

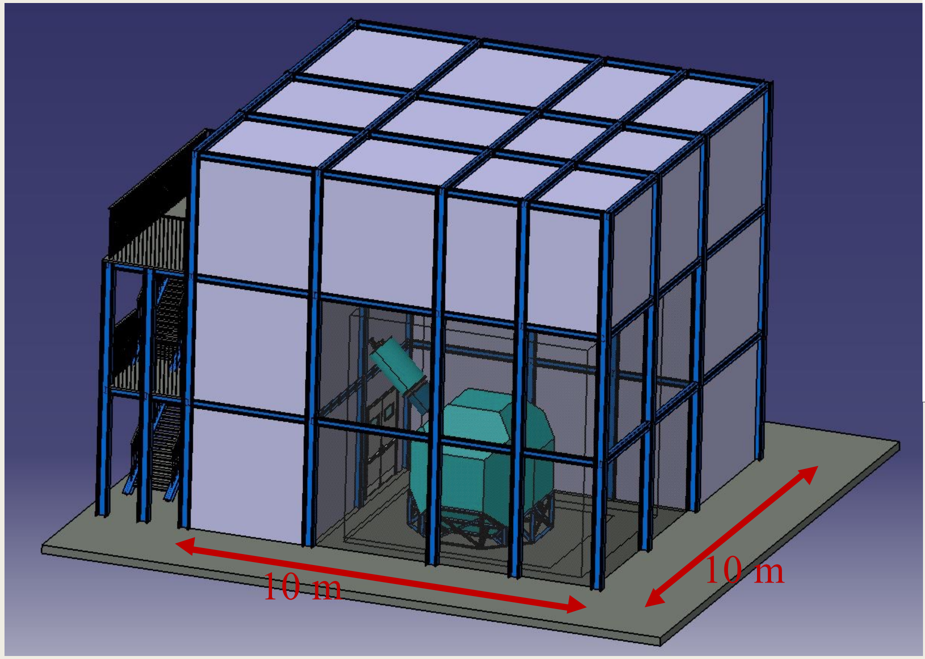
NEWSdm: current setup

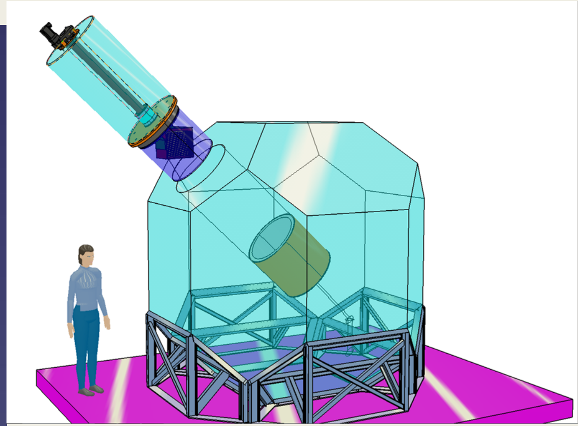
- Experimental setup in Hall C, close to Borexino
- Assembly of the setup in March 2021
- Test measurements ongoing



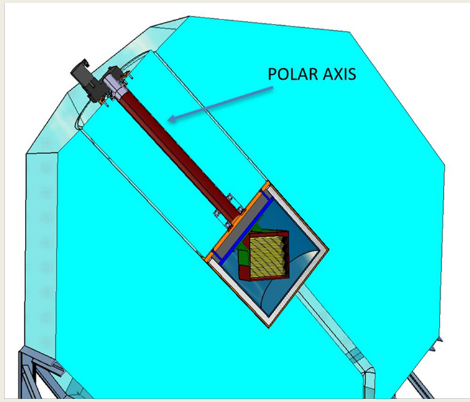
Future facility for NEWSdm: 10kg and beyond

Emulsion facility and shielding with an equatorial telescope

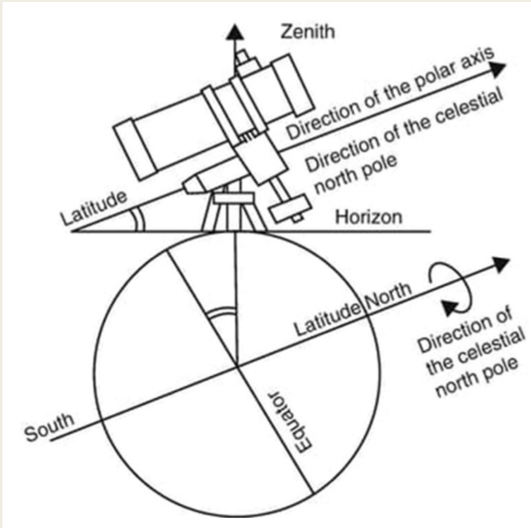


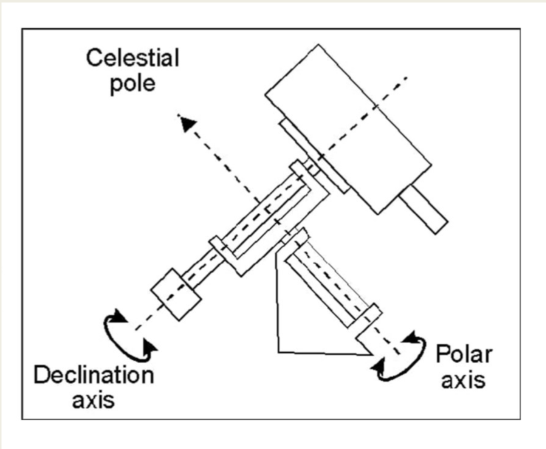


(a)



(b)

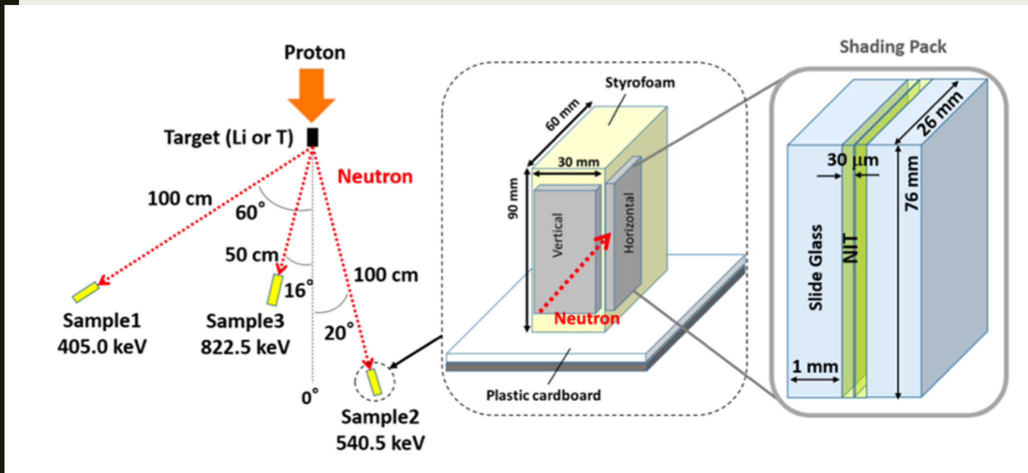




Additional data supporting the proof of concept

Sub-MeV neutron measurement

National Institute of Advanced Industrial Science and Technology, Tokyo, Japan

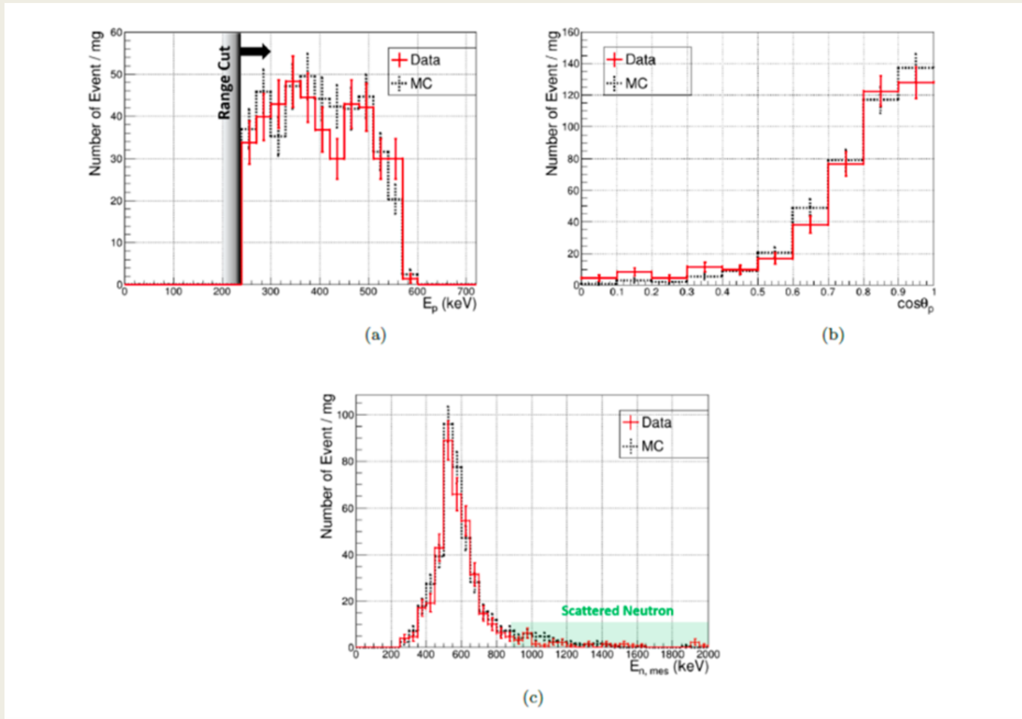


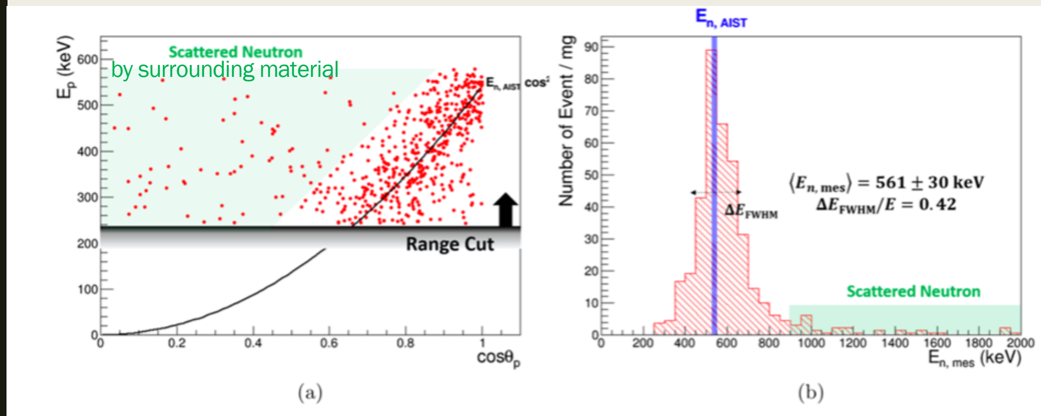
	Neutron source	Distance (cm)	Angle (degrees)	$E_{n,\mathrm{AIST}}$ (keV)	Flux (n cm^{-2} s^{-1})	Exposure time (hour)
Sample1	Li(p,n)Be	100	60	405.0 ± 9.3	361 ± 12	5.68
Sample2	Li(p,n)Be	100	20	540.5 ± 12.7	791 ± 26	5.68
Sample3	T(p,n)He	50	16	822.5 ± 16.7	908 ± 30	6.92

$$E_p = 41.6 + 527 \times R_p^{1/2} - 432 \times R_p^{1/3}.$$

$$E_{n,\mathrm{mes}} = \frac{E_p}{\cos^2\theta_p}.$$

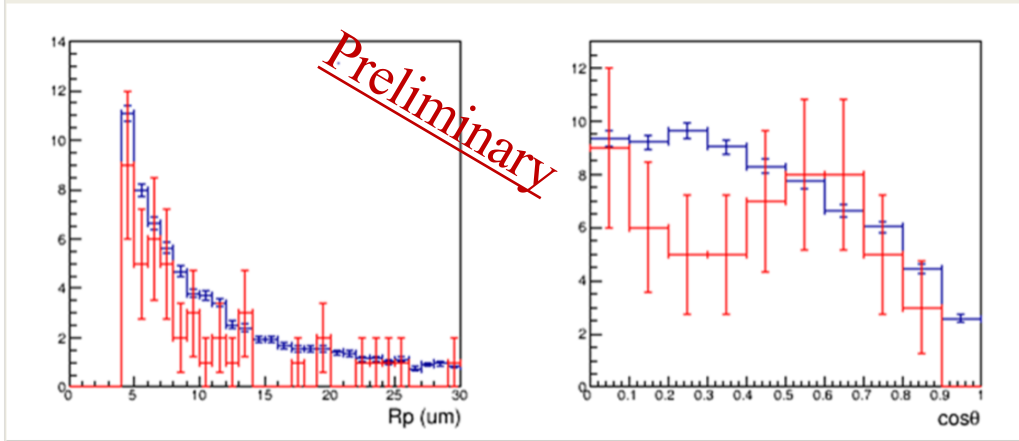
Analysis of sample2





PTEP n. 4 (2021) 043H01, 10 Mar 2021

Neutron measurement at LNGS surface



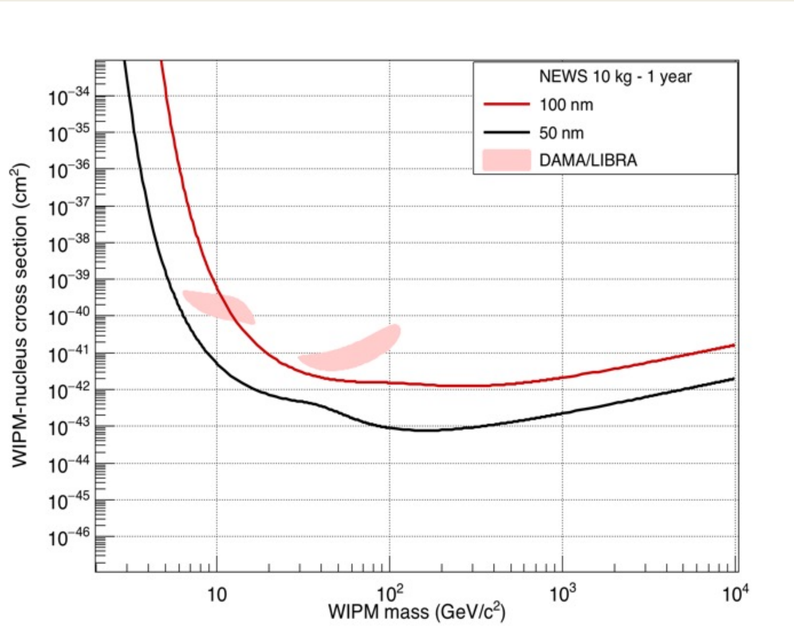
	Flux @0.4-1.0 MeV $[/cm^2/\mathrm{sec}]$
Data	$(1.0\pm0.2)\times10^{-3}$
Simulation	1.5×10^{-3}

- Explored energy range [0.4-1] MeV
- Upper bound (12.5 μm) for proton containment in the emulsion sensitive layer

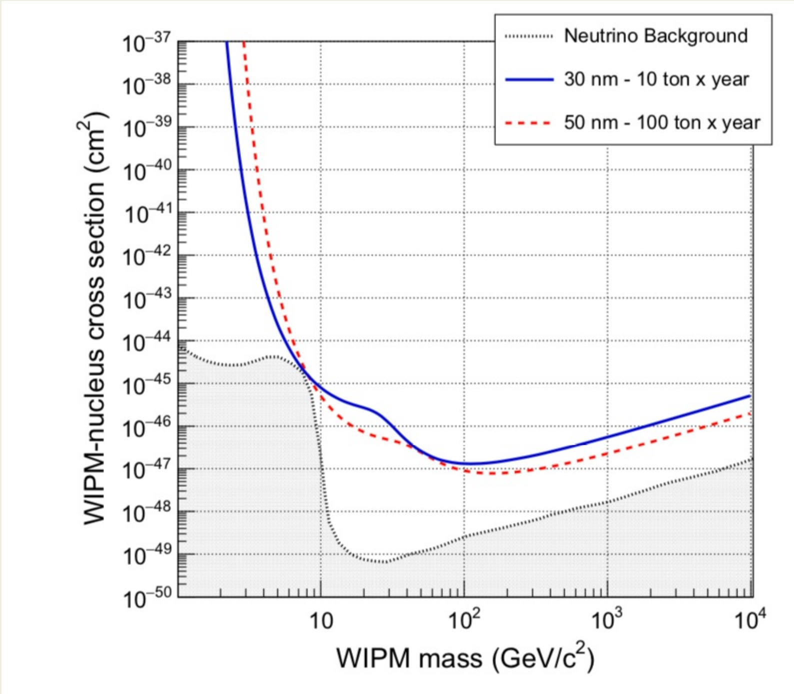
Exposure at 4º C, lasting for ~140 hours, equivalent to 3.2 g days

NEWSdm intermediate and final goals

- First **directional** dark matter detector with a 10 kg solid target
- Explore the DAMA region with a completely different technique based on the *visual* observation of recoil tracks in emulsion
- First high-sensitivity spin-independent measurement with a directional approach
- First step in the application of the emulsion technology, scalable to larger masses
- Longer term: overcome the neutrino floor



90% C.L. upper limits for the NEWSdm detector with an exposure of 10 kg year in the zero-background hypothesis



90% C.L. upper limits for the NEWSdm detector with an exposure of 10 ton year in the zero-background hypothesis

THANK YOU FOR ATTENTION!