DIRECTIONAL DARK MATTER SEARCH WITH NEWSDM

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NEWSdm COLLABORATION

Nuclear Emulsion WIMP Search directional measurement

81 physicists
23 institutes

JAPAN
Chiba, Nagoya, Toho, Tsukuba

RUSSIA
LPI RAS Moscow
JINR Dubna
SINP MSU Moscow
INR RAS Moscow
NUST MISiS Moscow
NRU HSE Moscow

ITALY
LNGS, GSSI
INFN: Napoli, Roma, Padova
Univ.: Napoli, Roma, Padova, Potenza, Benevento

SOUTH KOREA
Gyeongsang University

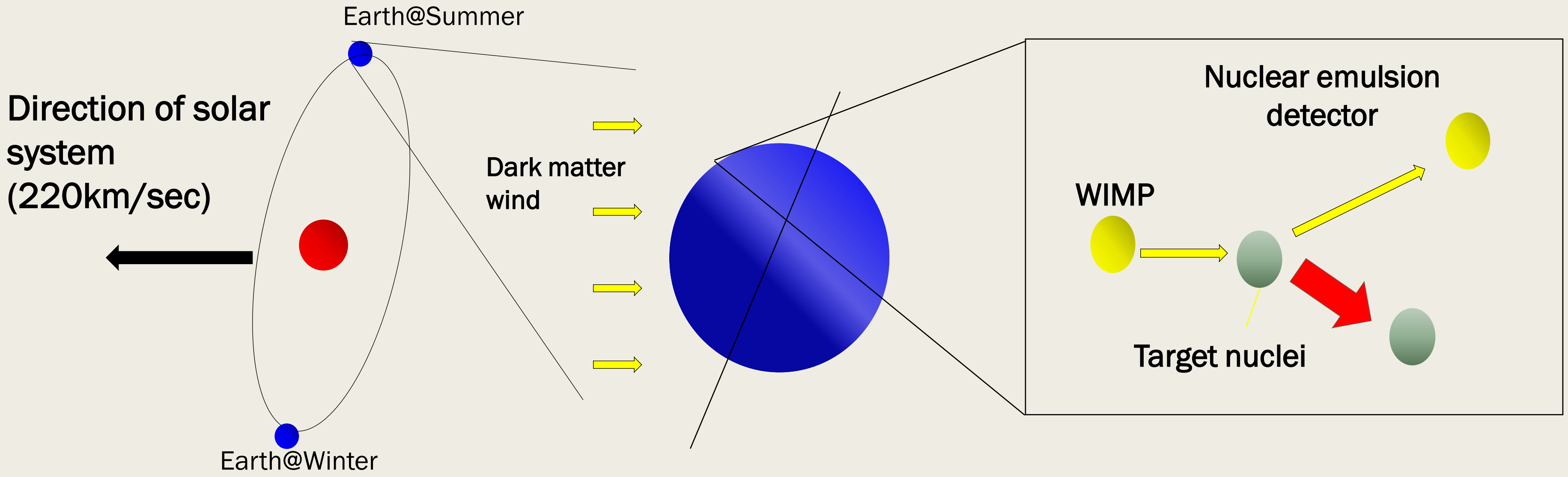
TURKEY
METU Ankara

Website: news-dm.lngs.infn.it
Letter of intent: https://arxiv.org/pdf/1604.04199.pdf

Outline

- Physics motivation
- Nano Imaging Trackers
- Super-resolution readout
- Machine learning techniques to nanometric image analysis
- Underground facility and current setup
- Conclusions: intermediate and final goals

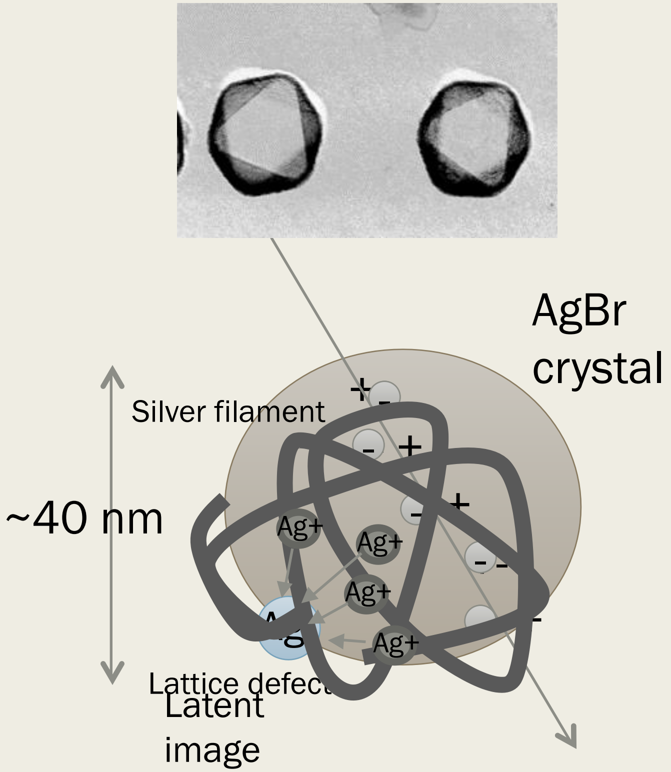
WIMP directional detection

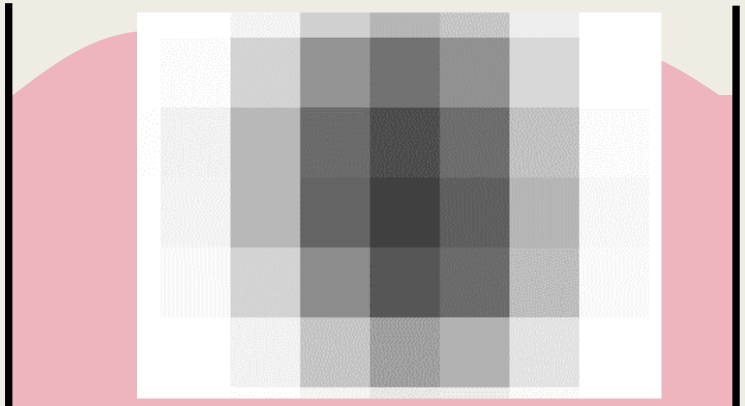


- Strong correlation between the direction of WIMP and scattered nuclei → **strong signature** and **unambiguous proof** of the galactic DM origin
- Unique possibility to overcome the “neutrino floor”, where coherent neutrino scattering creates an irreducible background
- **Nuclear Emulsion** is a high-density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

Detection principle

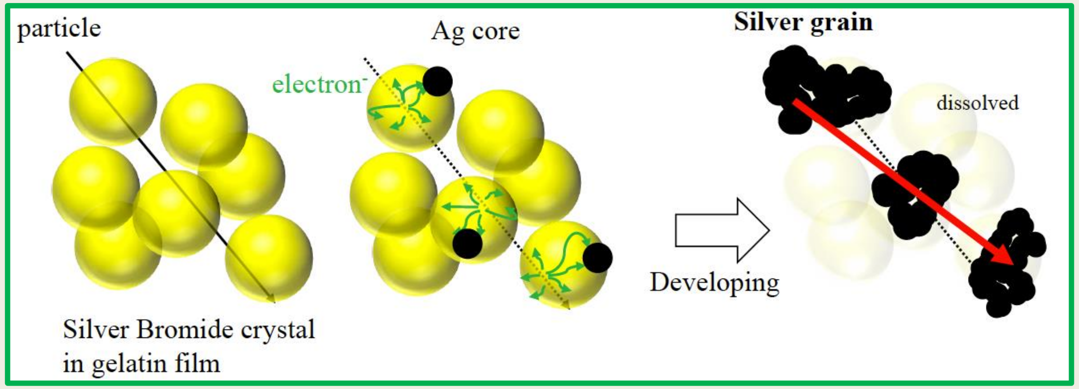
1. Ionization induced by a particle
   – *2.6 eV band gap*
2. Electrons trapped at a lattice defect on the crystal surface
   – *Attract interstitial silver ions*
   – *Produce a "latent image" = Ag_n*
3. Chemical amplification of signal
   – *Development → silver filaments*
   – *10^7 - 10^8 amplification*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





Grain as seen by a sensor of an optical microscope

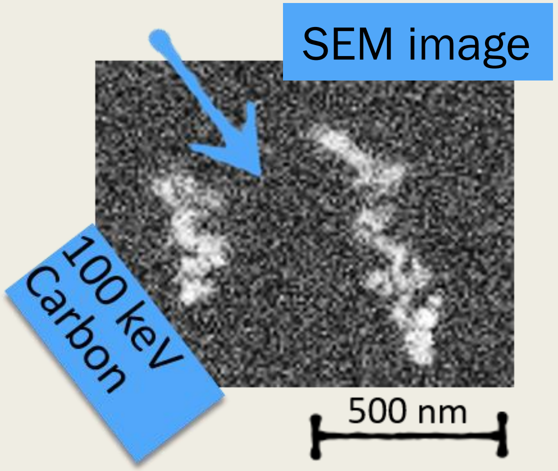
NIT: Nano emulsion Imaging Trackers

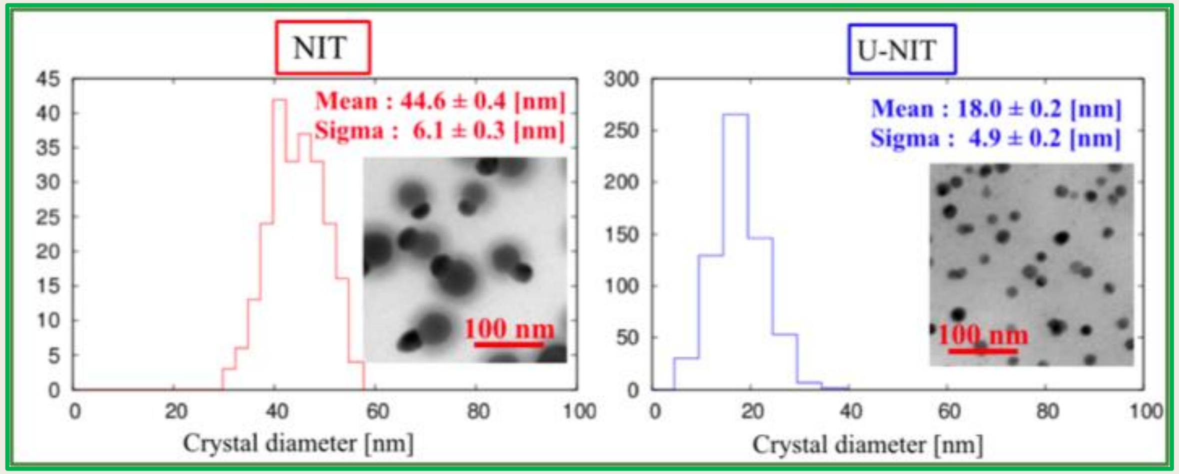


A long history, from the discovery of the Pion (1947) to the discovery of $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode (OPERA, PRL 115 (2015) 121802)

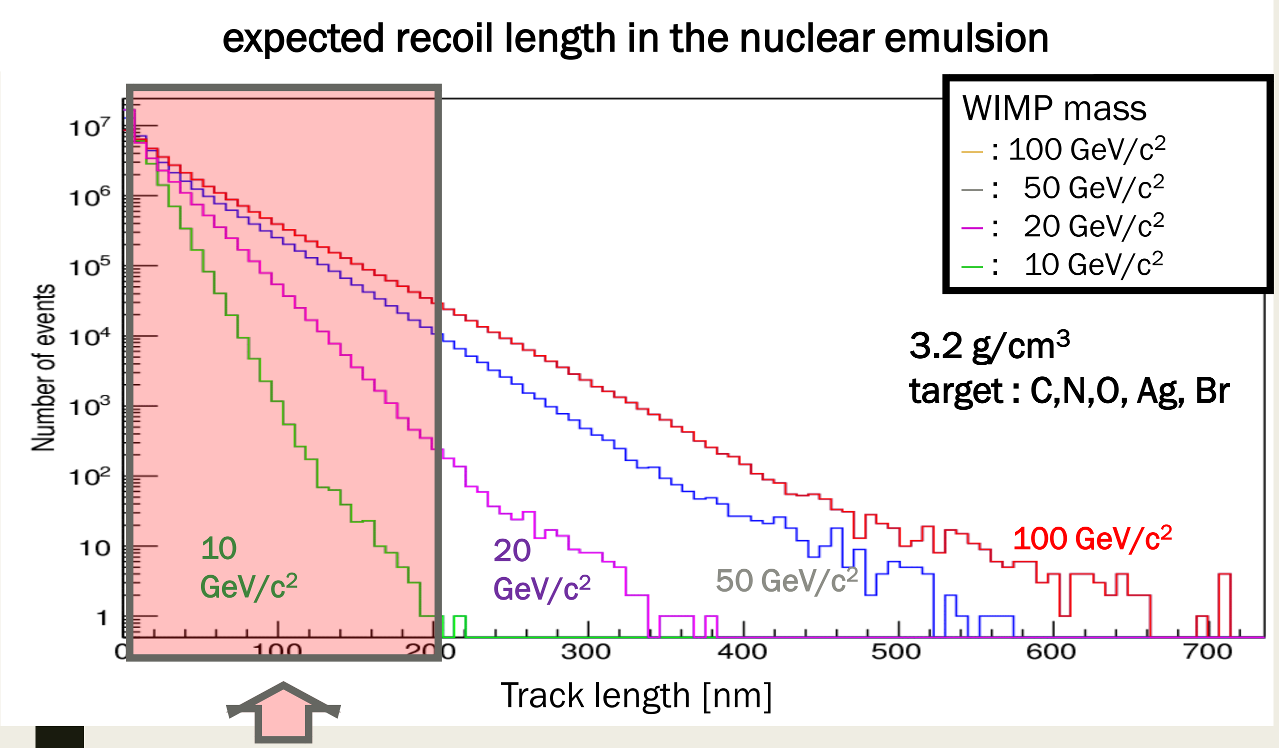
- Nuclear emulsions: AgBr crystals in organic gelatine
- Passage of charged particle produce *latent image*
- Chemical treatment make Ag grains visible

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

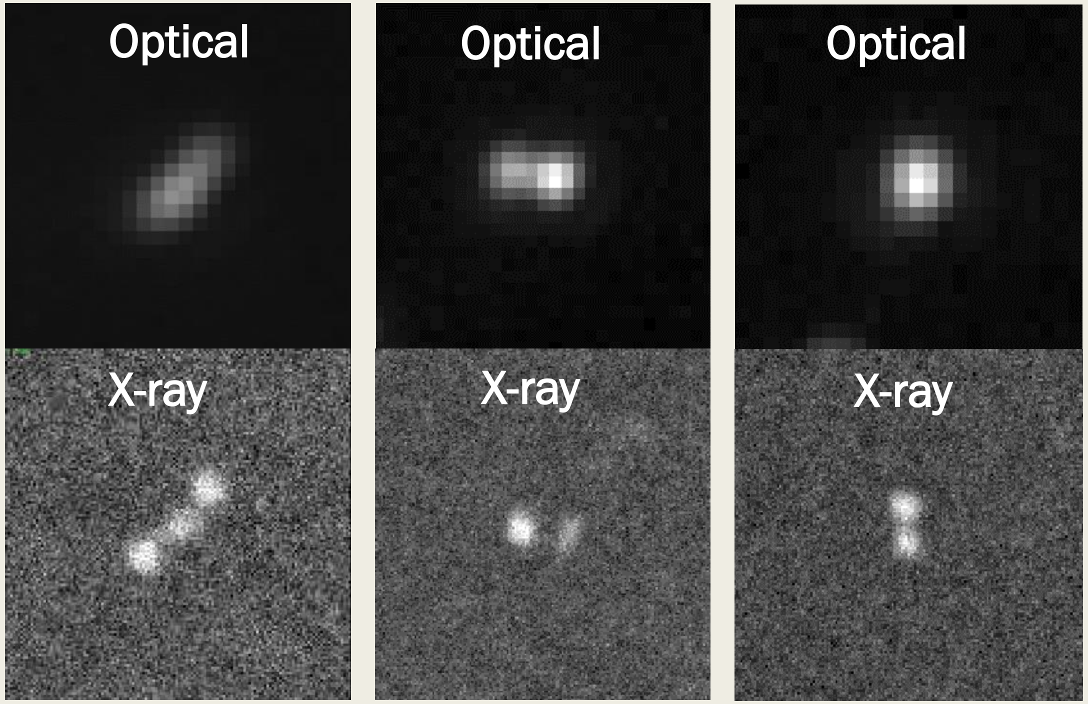




Directional detection challenge



Inaccessible due to diffraction limit



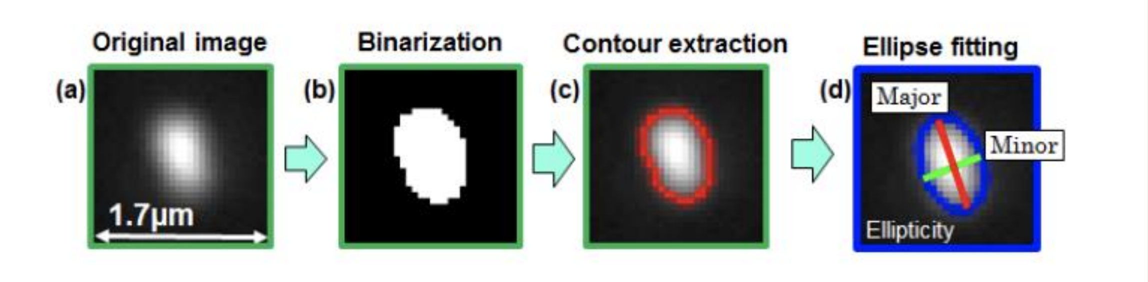
L = 380 nm L = 265 nm L = 160 nm

Need super-resolution to measure tracks shorter than 200 nm

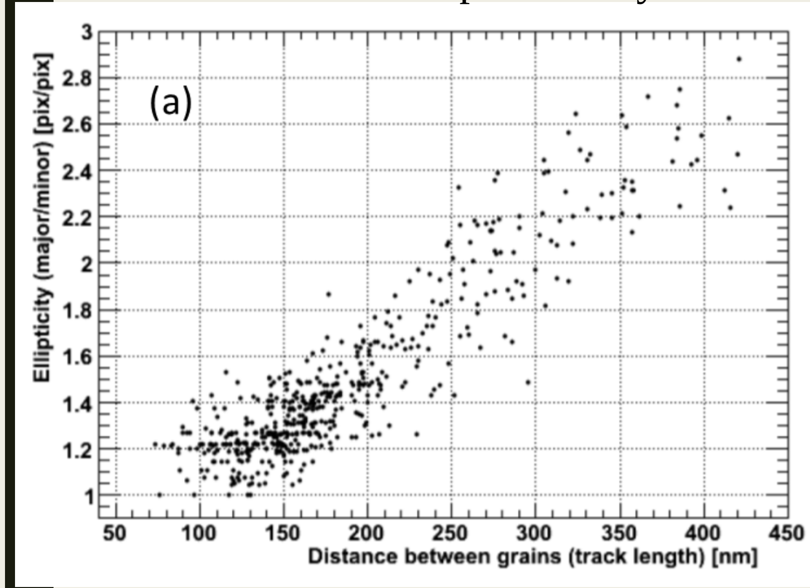
Shape analysis

PTEP (2019) 063H02

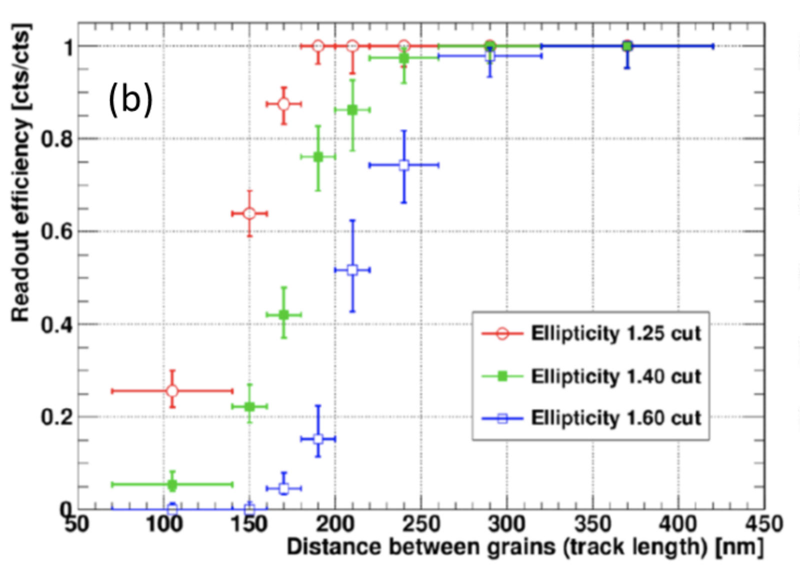
- Elliptical fit to measure the shape anisotropy



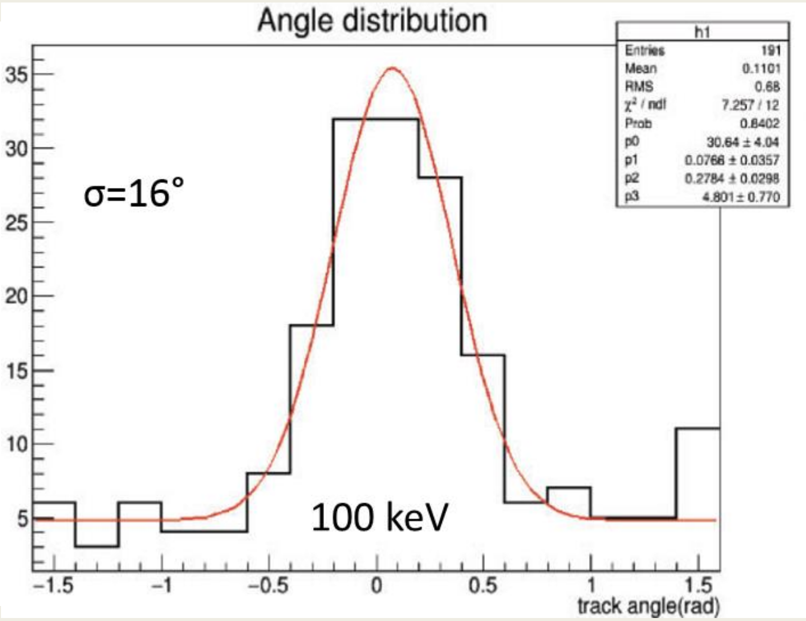
Correlation between track lengths measured by X-ray microscopy and ellipticity obtained with optical analysis



Correlation between readout efficiencies and track lengths for different ellipticity thresholds

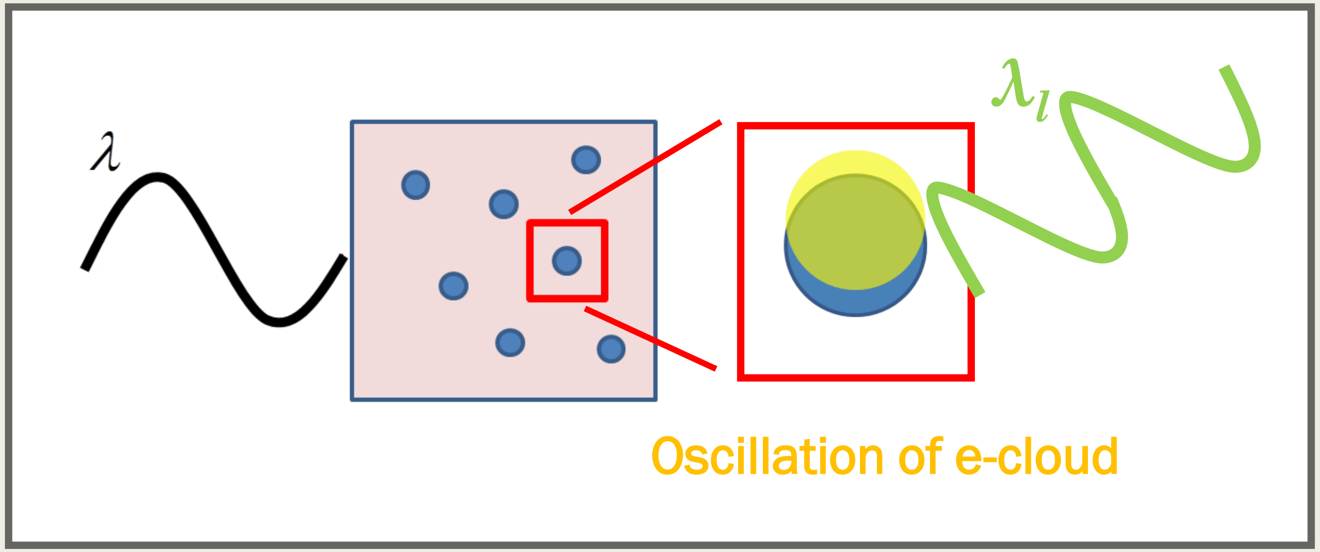


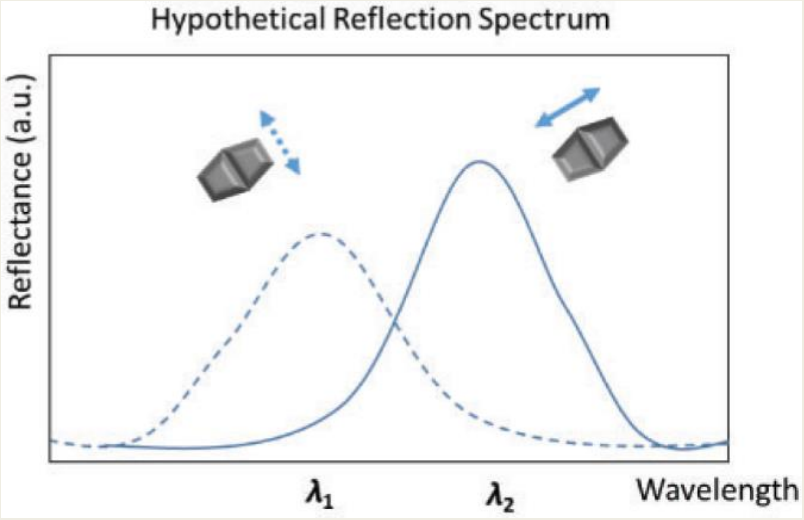
100 keV Carbon

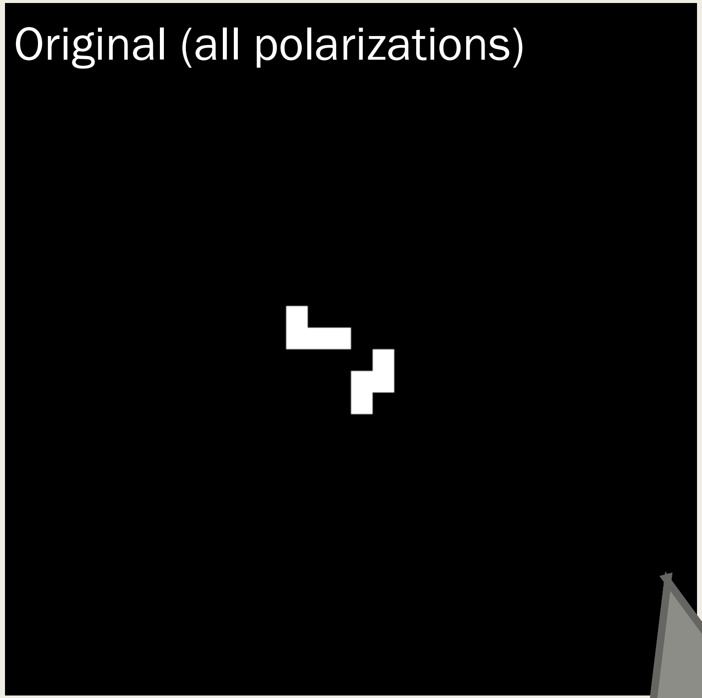


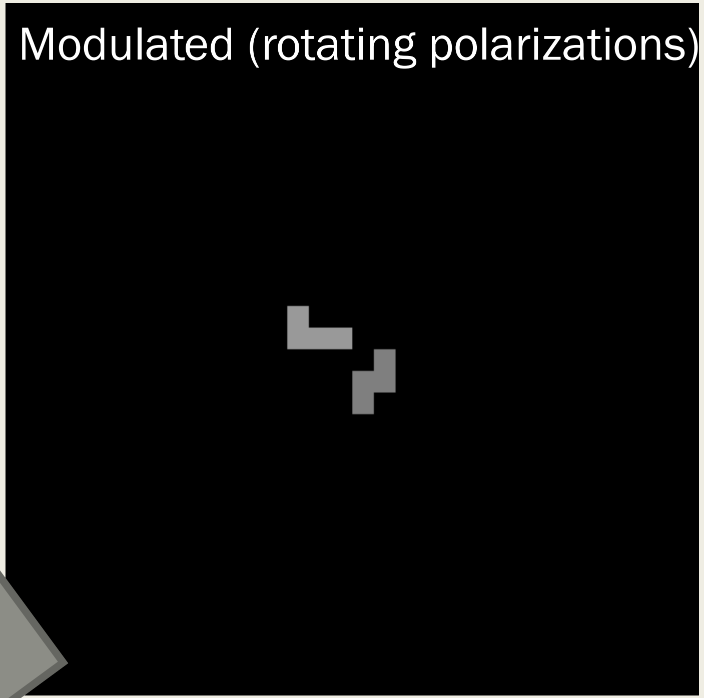
Optical readout beyond the diffraction limit

- Super-resolution 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***







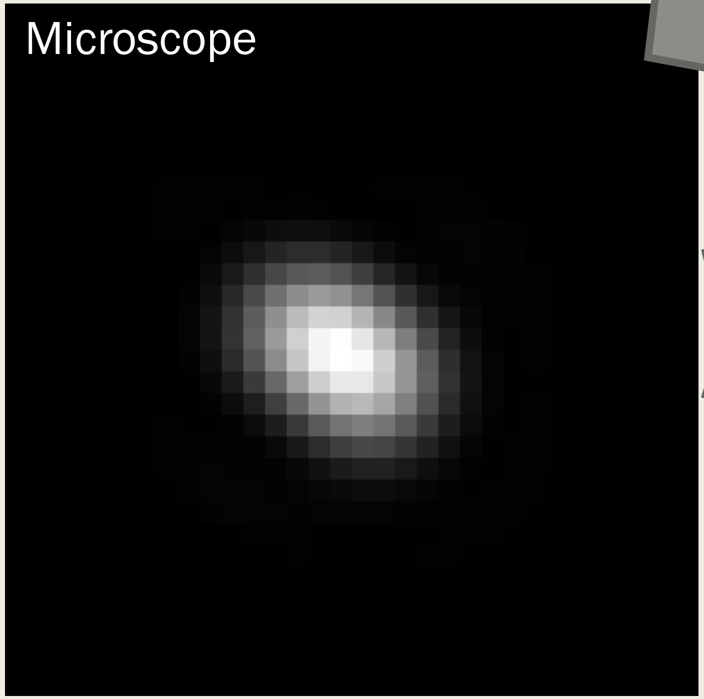


Modulate the intensity of each pixel in the image:

$$I_\theta = a\cos[2(\theta - \varphi)] + b$$

θ – polarization angle
φ – pixel “phase”,
b – pixel brightness mean,
a – pixel brightness change amplitude

$\otimes PSF$

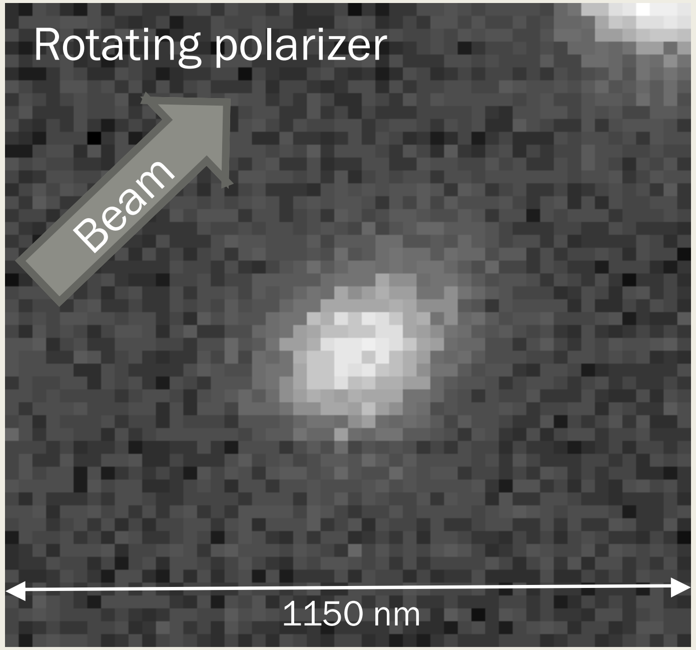


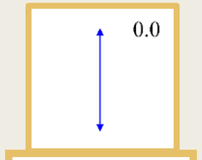
1. Barycenter shift analysis
2. Joint image deconvolution

Barycenter shift analysis

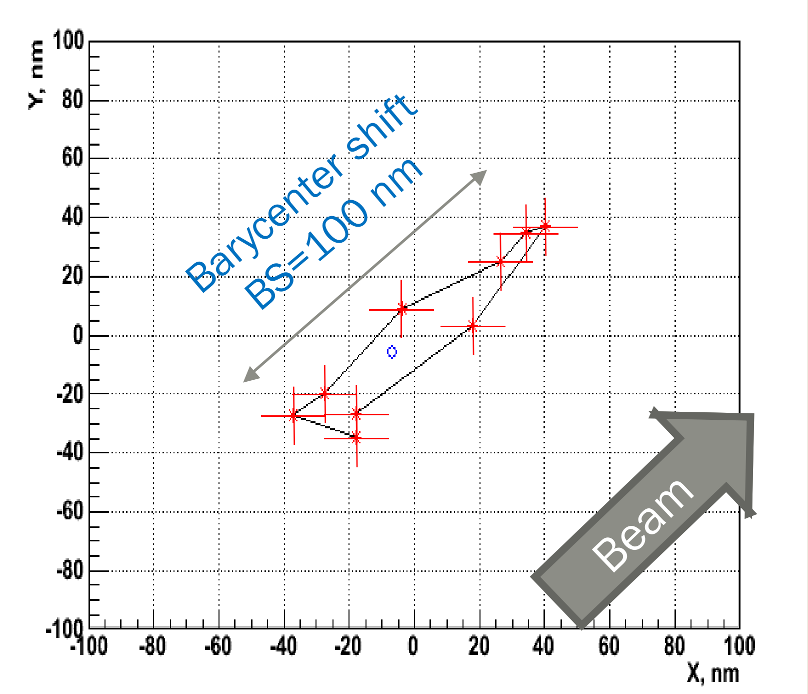
NIM A **824** (2016) 600–602

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

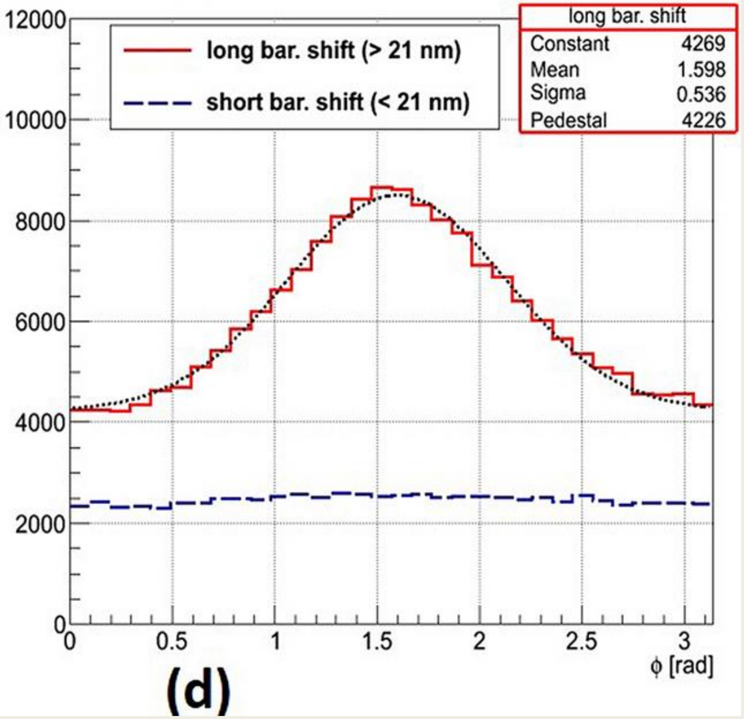




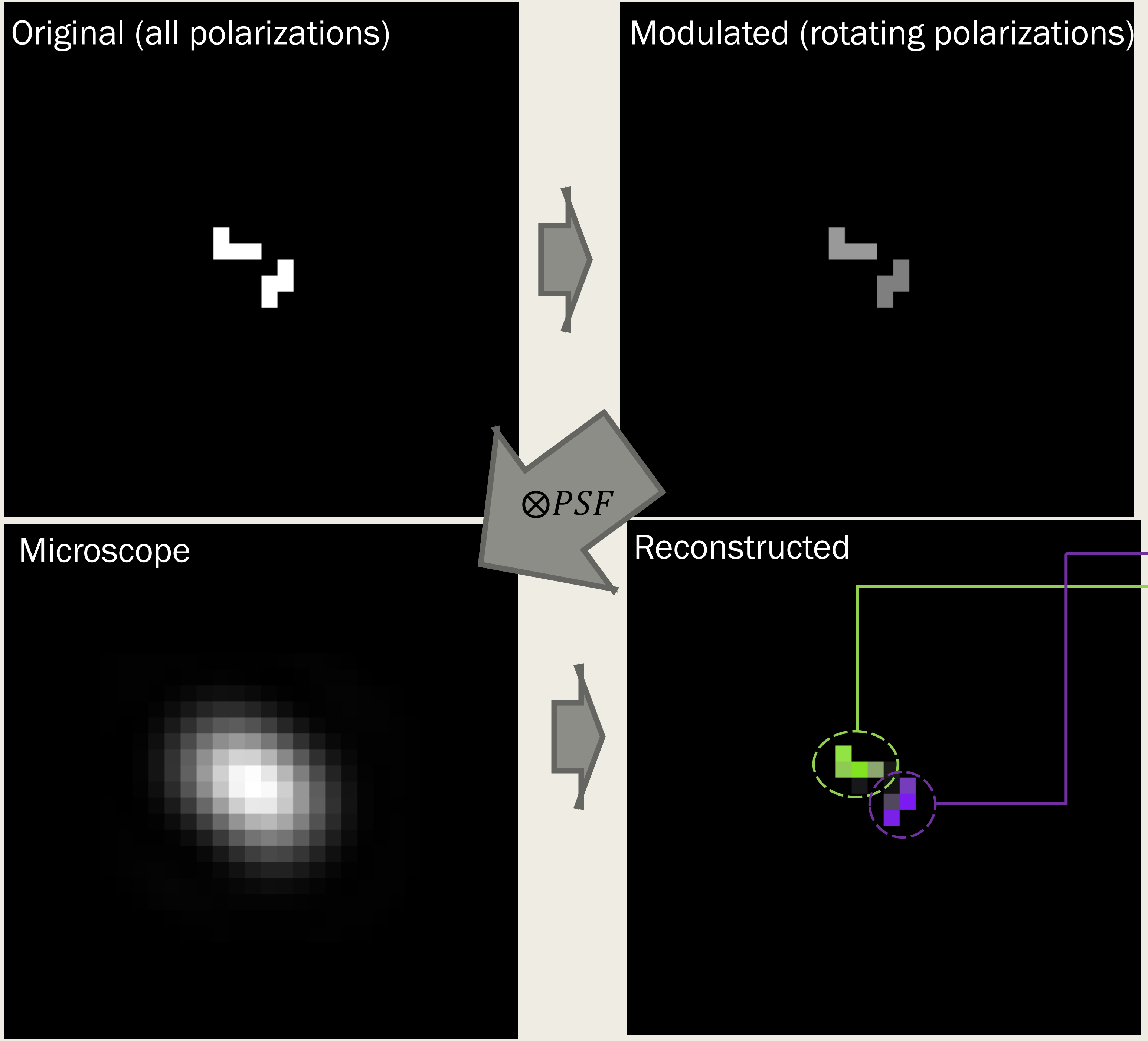
pol angle



Carbon ion
100 keV



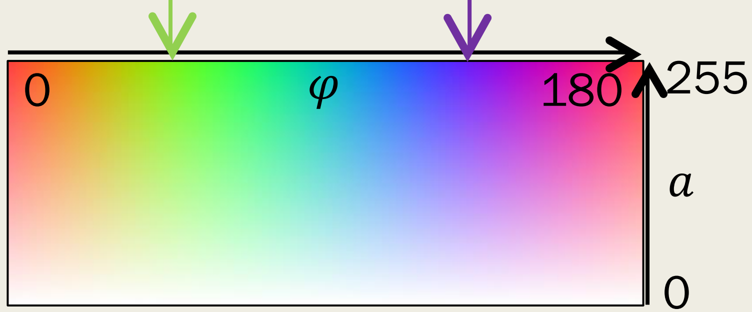
Carbon ions
60 keV



Modulate the intensity of each pixel in the image:

$$I_\theta = a\cos[2(\theta - \varphi)] + b$$

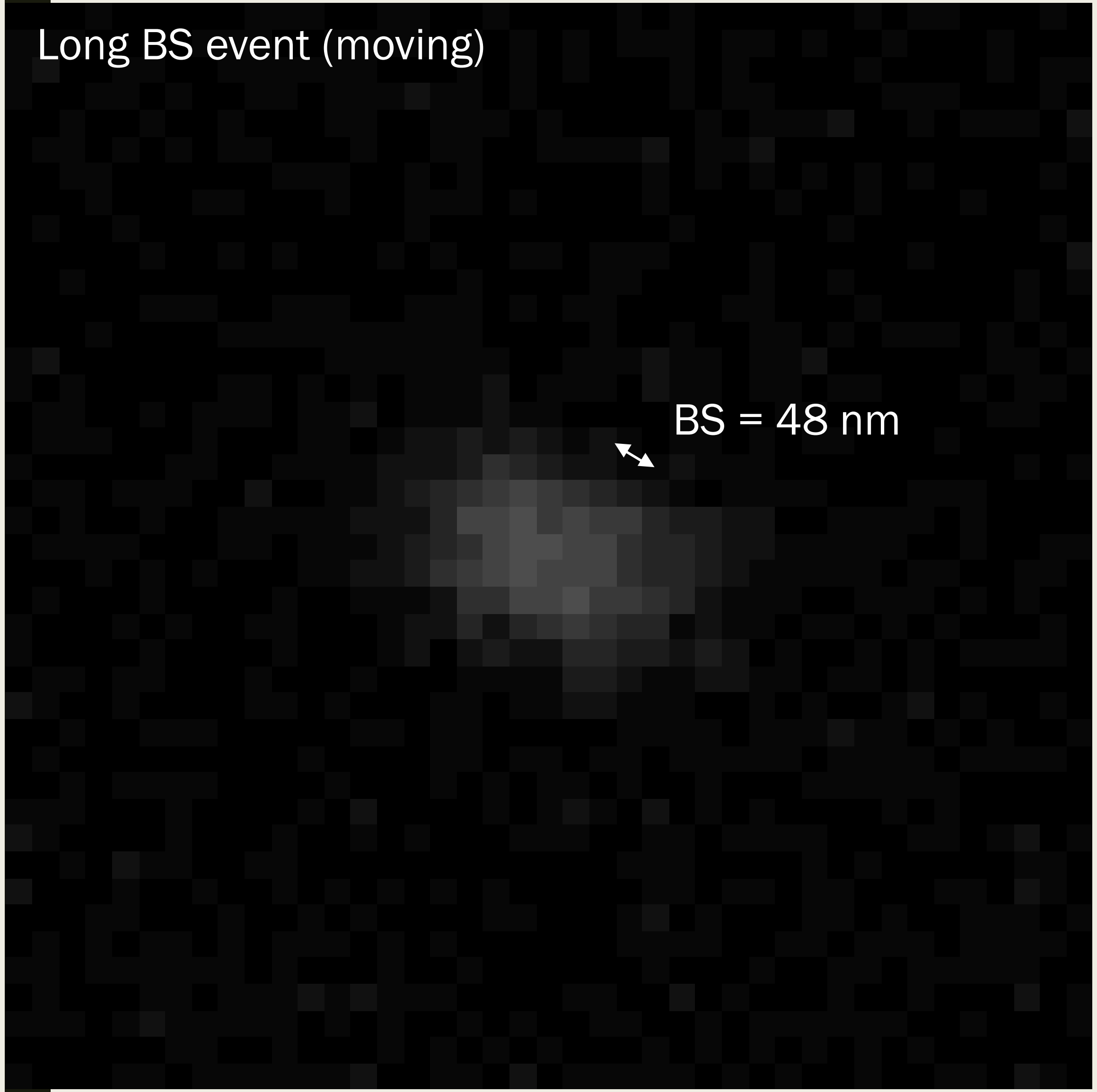
θ – polarization angle
φ – pixel “phase”,
b – pixel brightness mean,
a – pixel brightness change amplitude

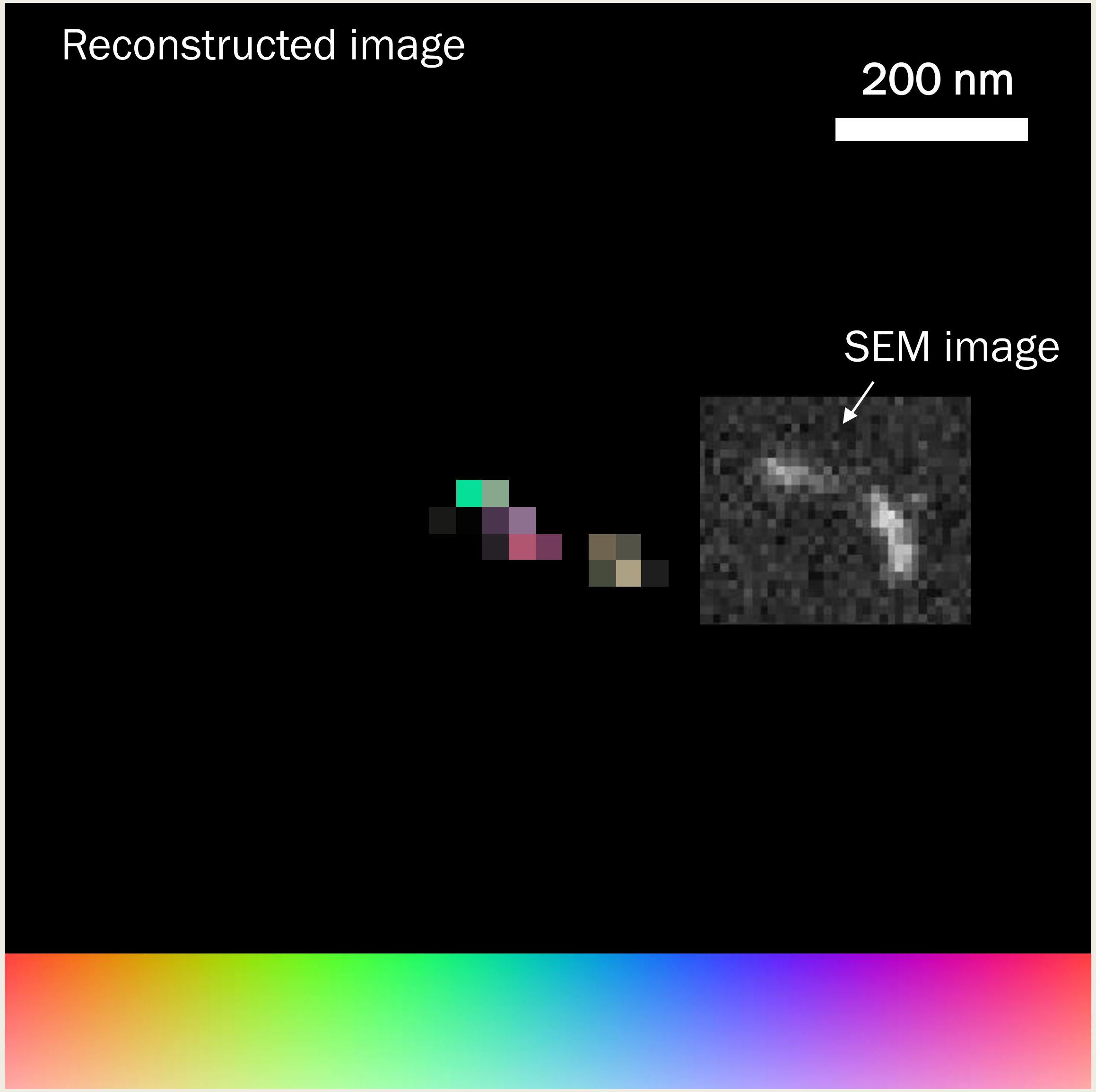


$a + b = pixel\ brightness$
$a = pixel\ color\ saturation$
$\varphi = pixel\ color$

Joint image deconvolution

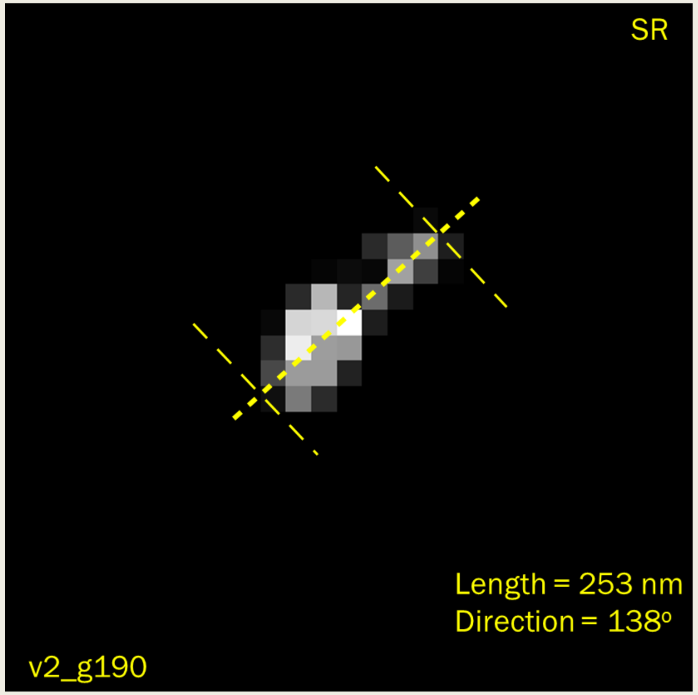
Sci. Rep. **10** (2020) 18773

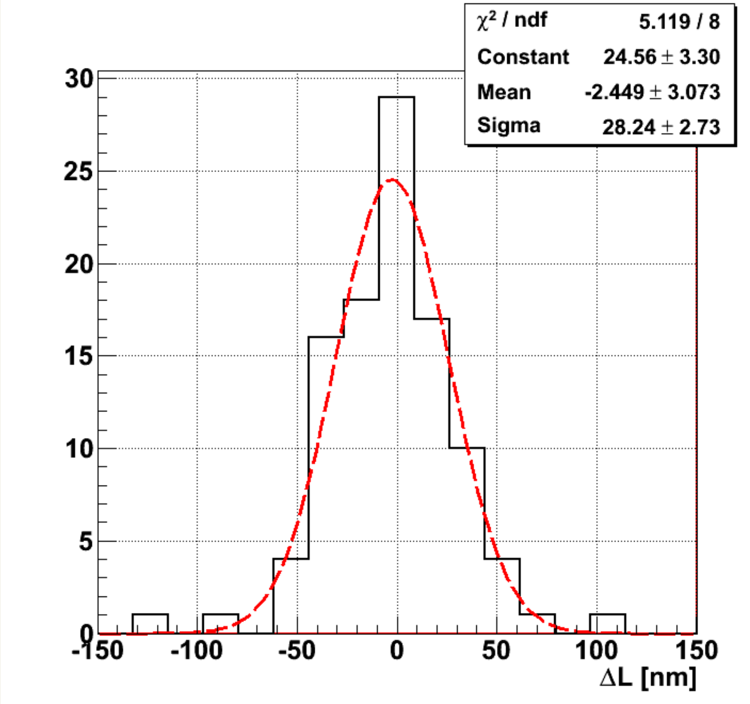


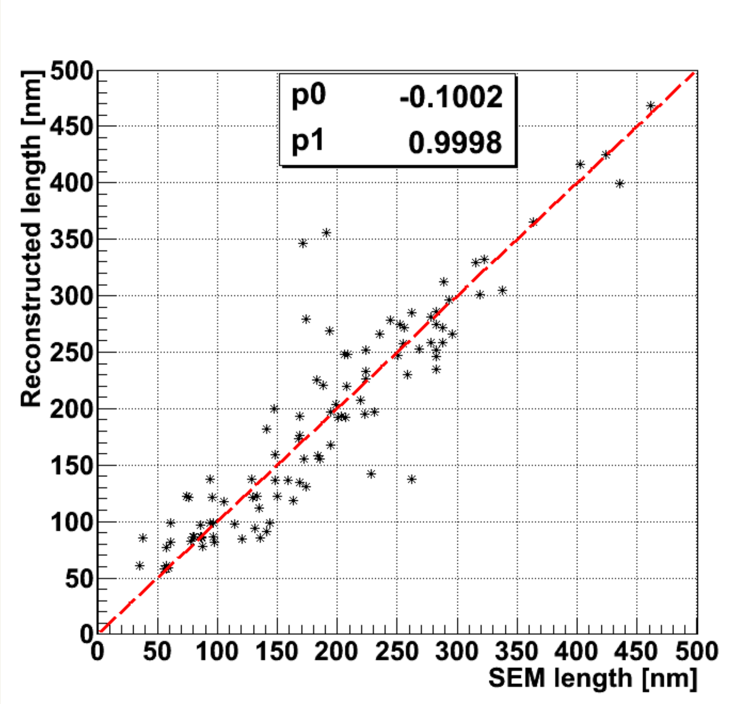


Joint Image Deconvolution

Event Length comparison with SEM







Length accuracy: 28 nm ≈ pixel size (27.5 nm)
Spatial resolution: 80 nm (Nyquist theorem)

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

Super-resolution microscope

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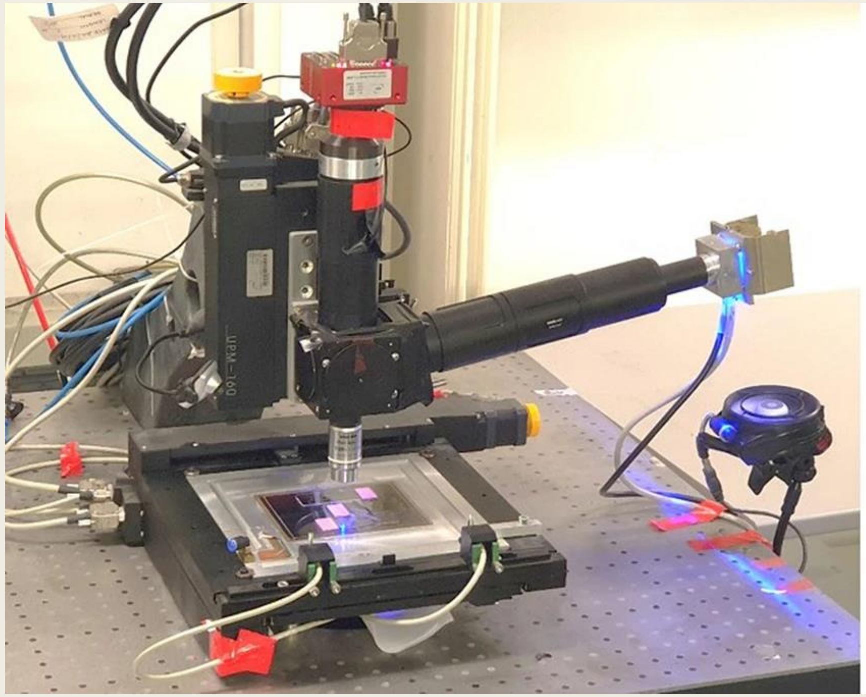
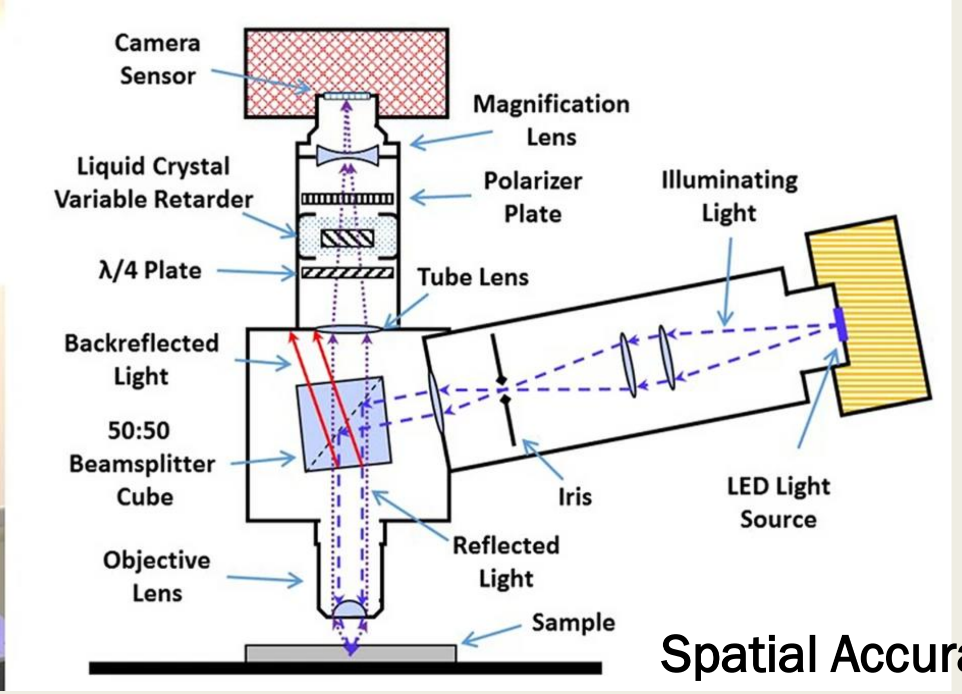
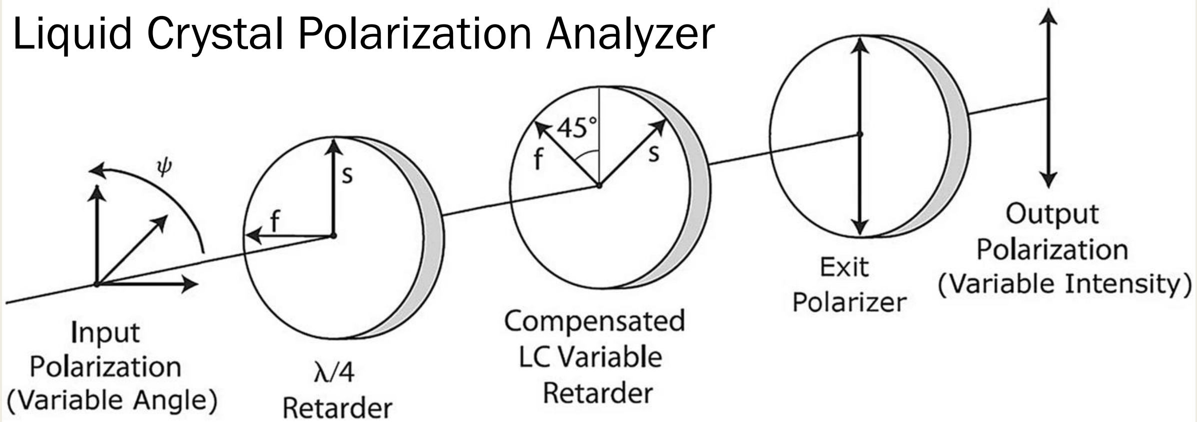
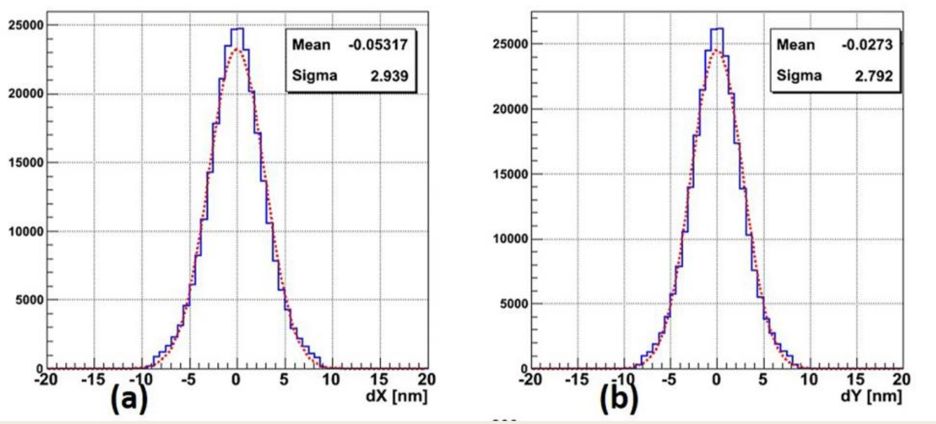


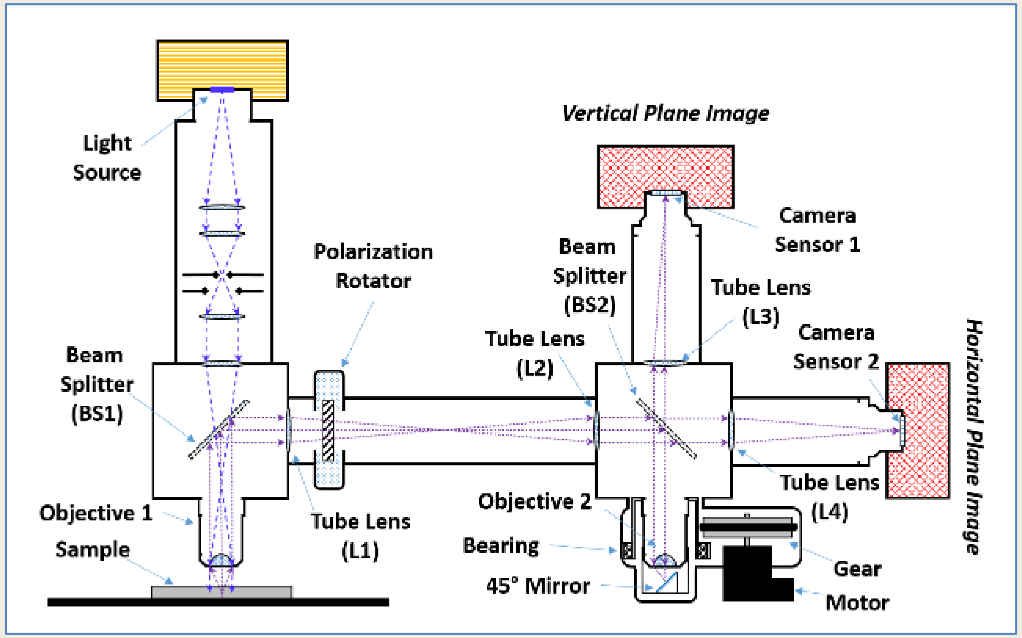


Spatial Accuracy = 3 nm

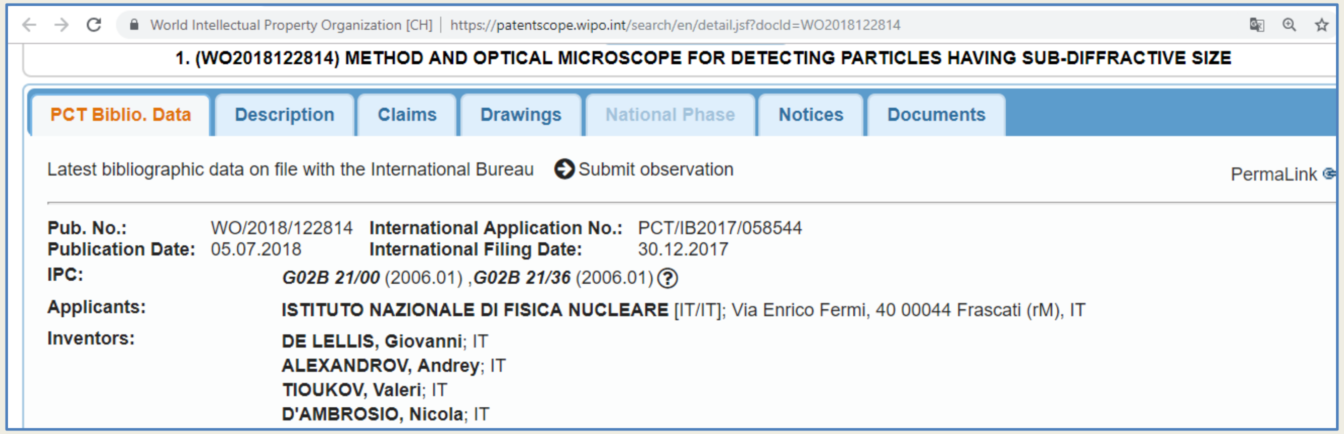




Measurement in 3D



International Patent No. WO/2018/122814



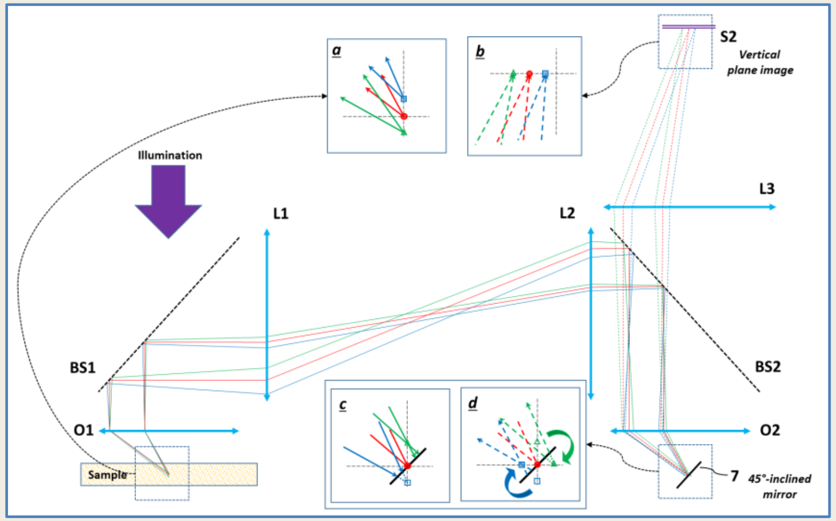
World Intellectual Property Organization [CH] | https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2018122814

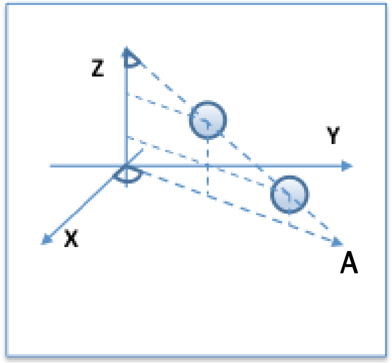
1. (WO2018122814) METHOD AND OPTICAL MICROSCOPE FOR DETECTING PARTICLES HAVING SUB-DIFFRACTIVE SIZE

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

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

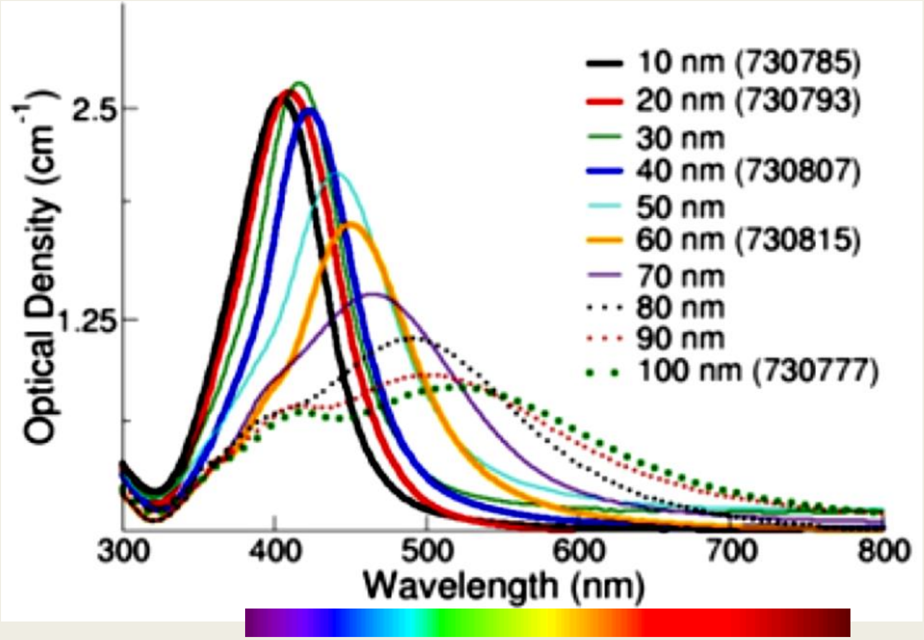
Pub. No.: WO/2018/122814 **International Application No.:** PCT/IB2017/058544
Publication Date: 05.07.2018 **International Filing Date:** 30.12.2017
IPC: *G02B 21/00* (2006.01) ,*G02B 21/36* (2006.01)
Applicants: **ISTITUTO NAZIONALE DI FISICA NUCLEARE** [IT/IT]; Via Enrico Fermi, 40 00044 Frascati (rM),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

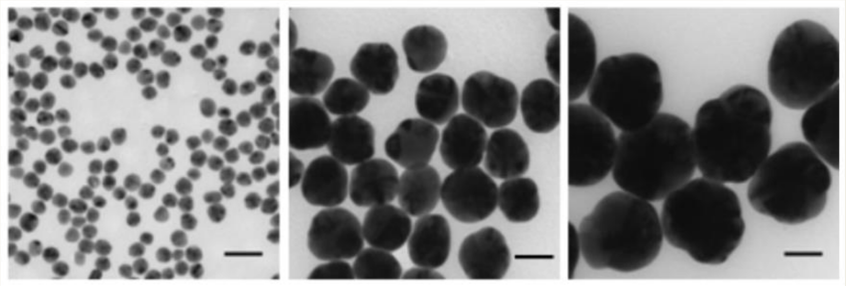




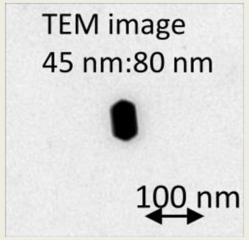
Two focal planes:
Horizontal: XY
Vertical: ZA

Plasmon resonance wavelength dependency



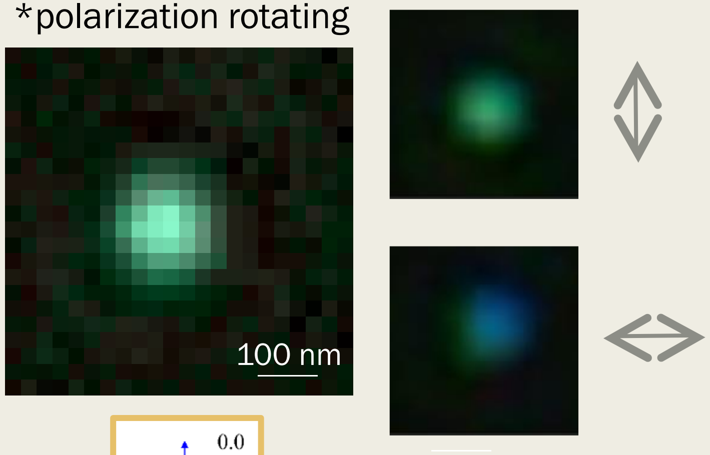


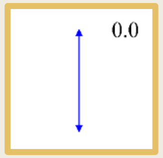
20 nm   60 nm   100 nm

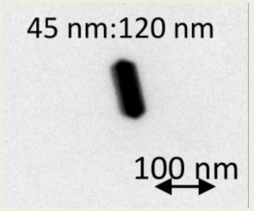


~45 nm : blue
~80 nm : green

*polarization rotating

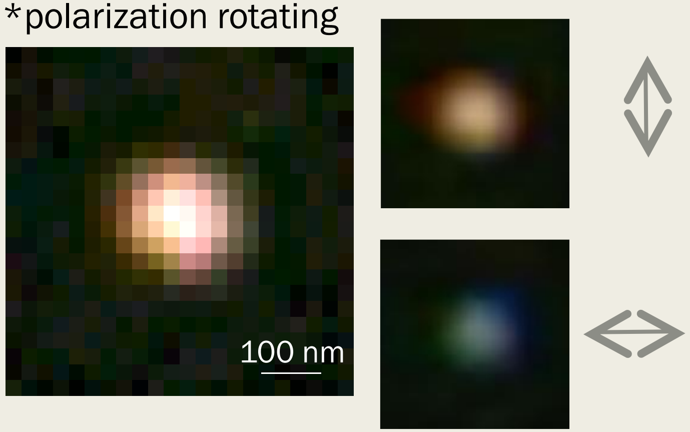




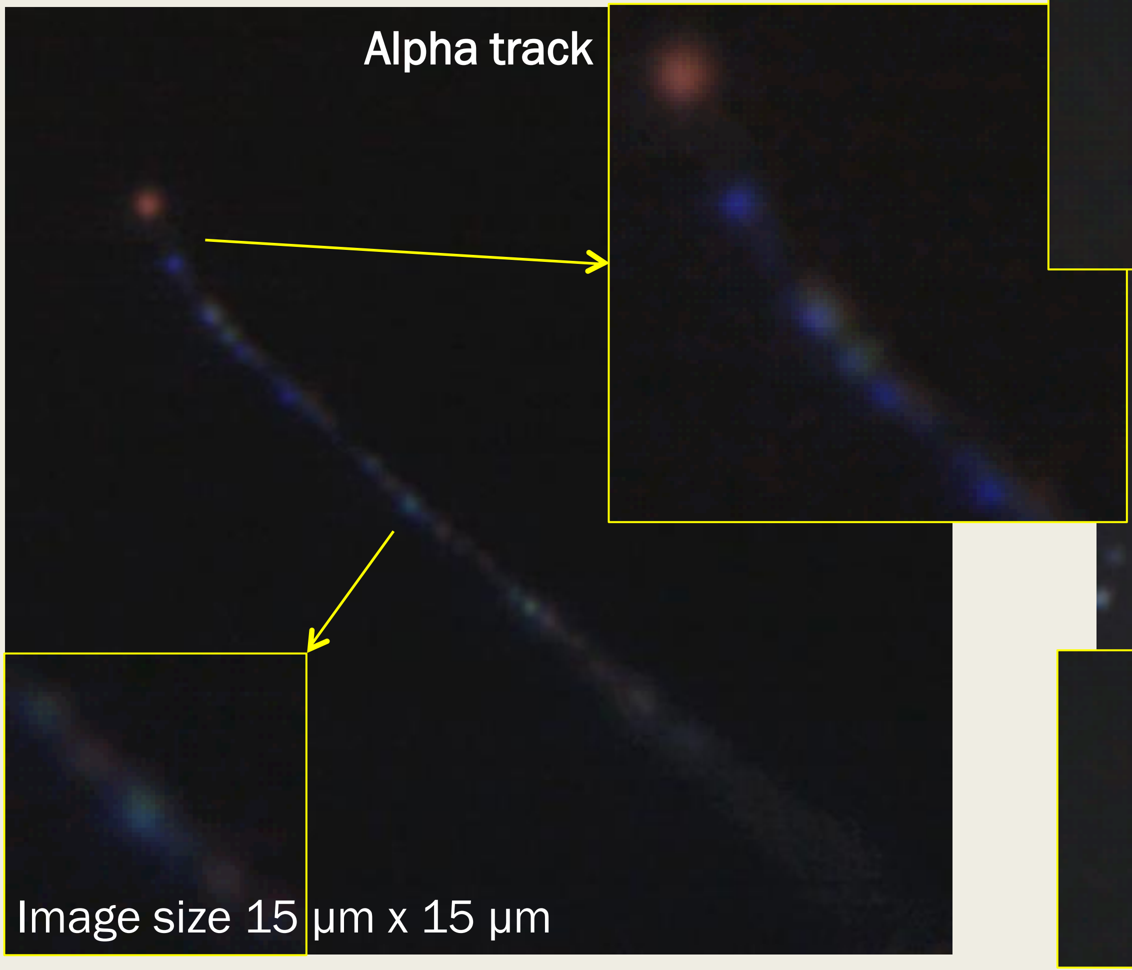


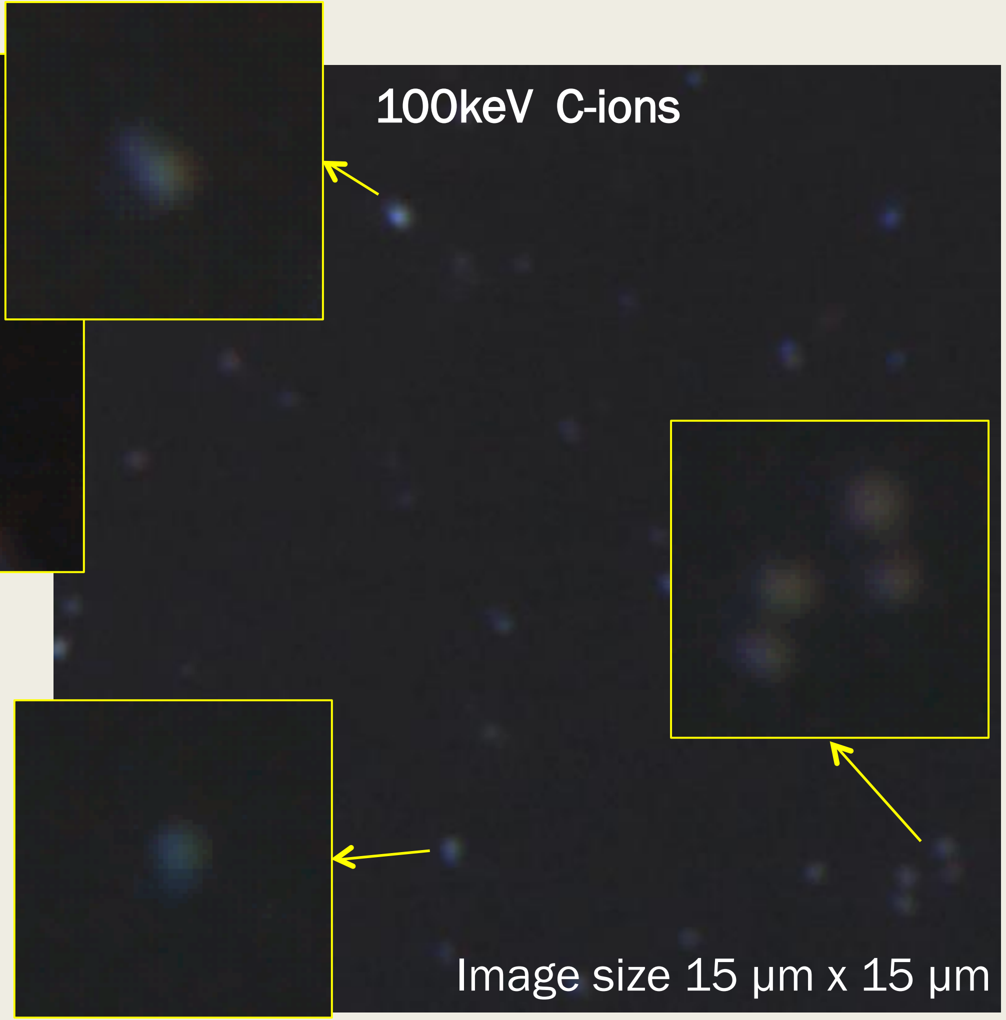
~45 nm : blue
~120 nm :orange

*polarization rotating



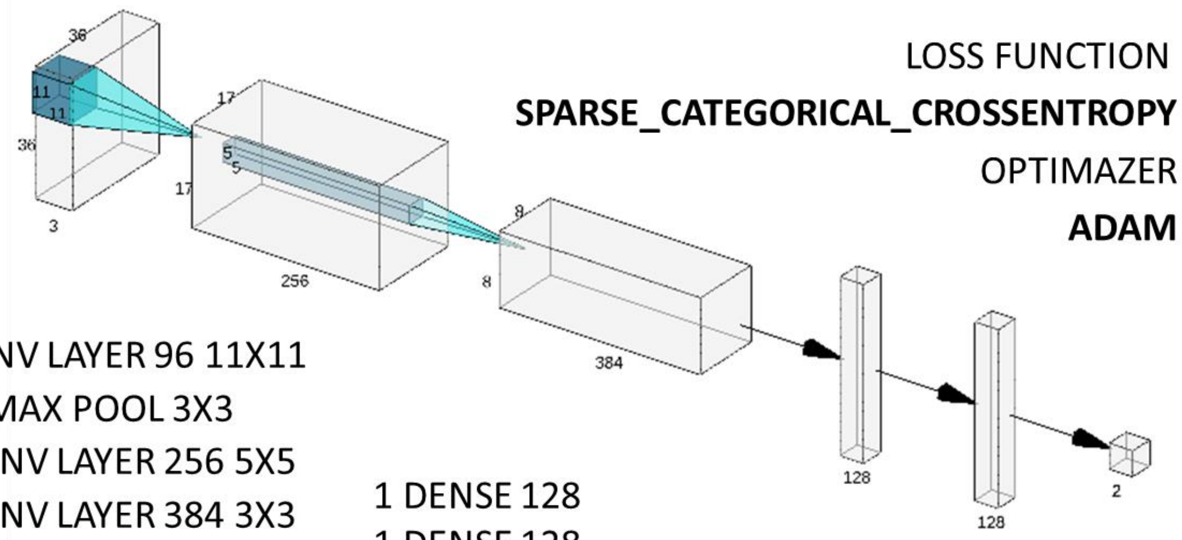
Plasmon response for α and C tracks





Sense recognition with color

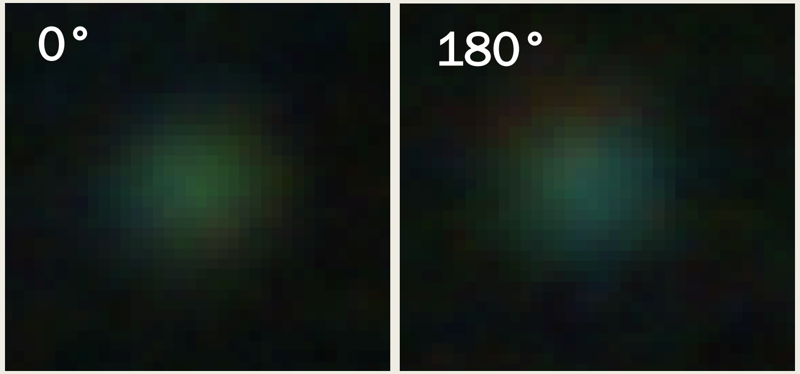
Machine Learning approach



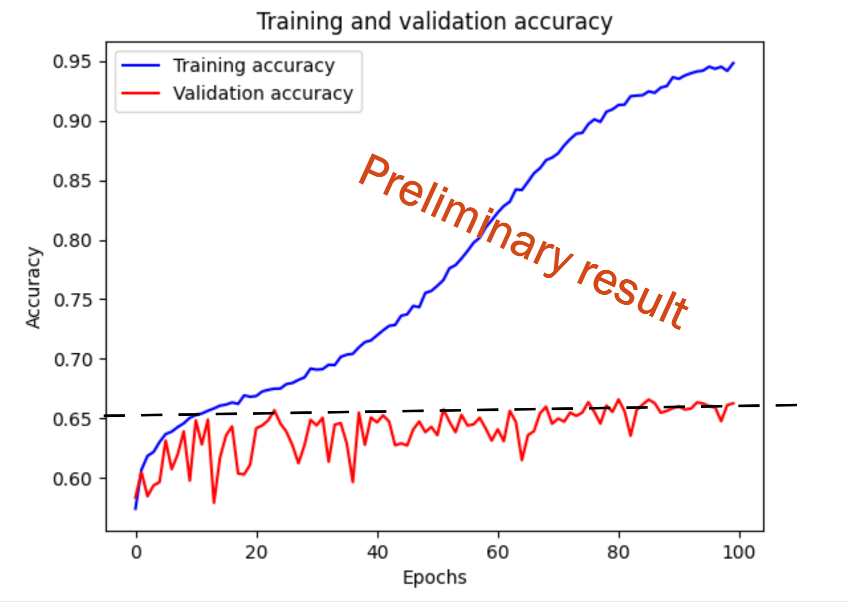
LOSS FUNCTION
SPARSE_CATEGORICAL_CROSSENTROPY
OPTIMAZER
ADAM

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



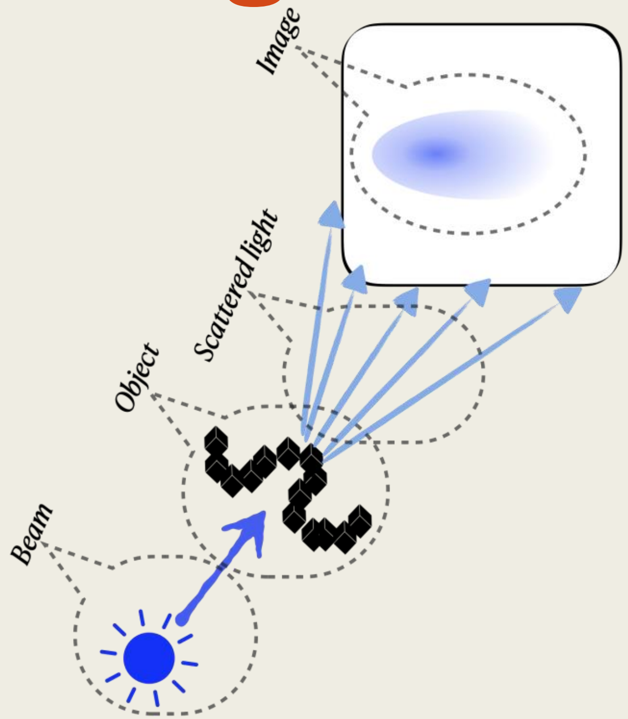
Carbon ion 100 keV



Sense prediction accuracy = 65%

Realistic simulation of nanoparticle images

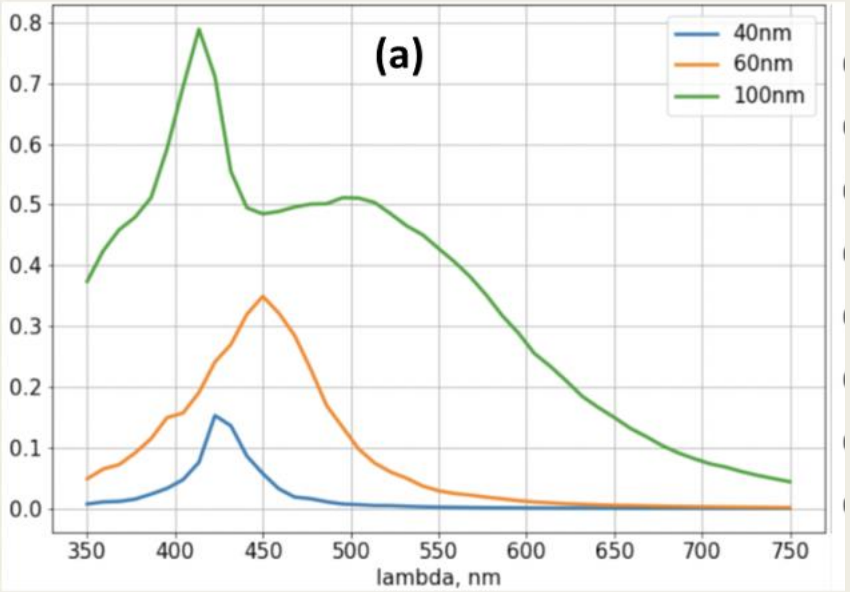
- Generate a 3D model of the object to be simulated (filaments, nano-particles)
- Use discrete dipole approximation to obtain optical images (ADDA, HoloPy)
- Tune the parameters and check the simulation by comparison with real samples



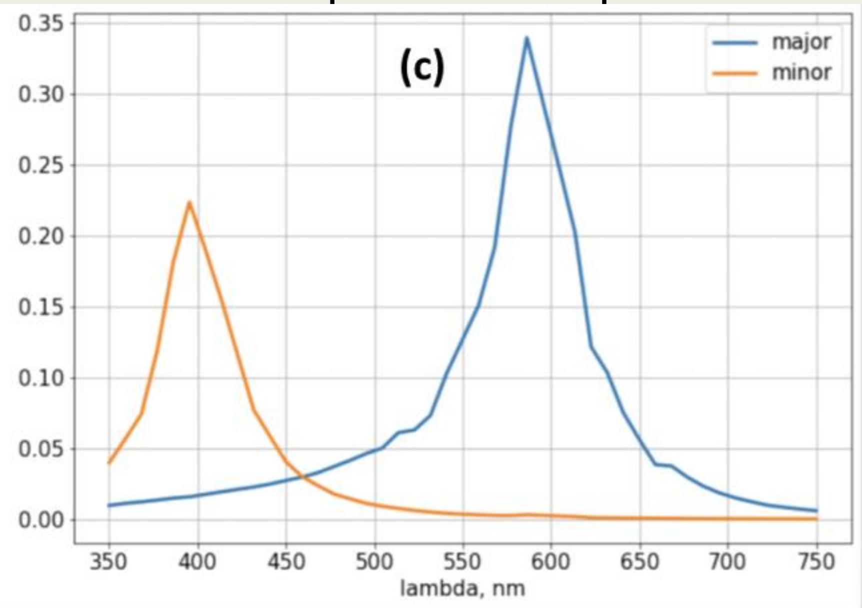
HoloPy: DDA for holography in Python https://github.com/manoharan-lab/holopy

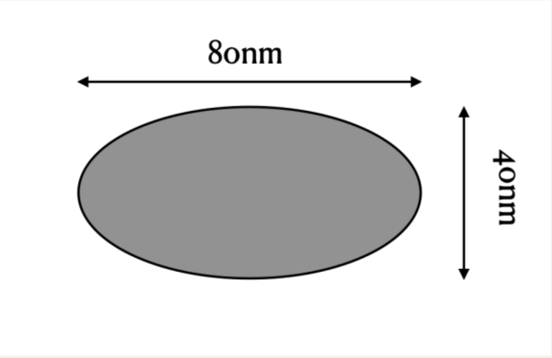
Use ADDA for scattering calculations: https://github.com/adda-team/adda

Silver spheres

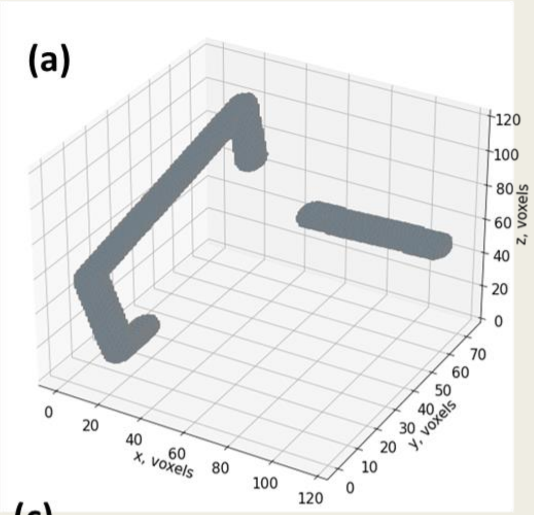


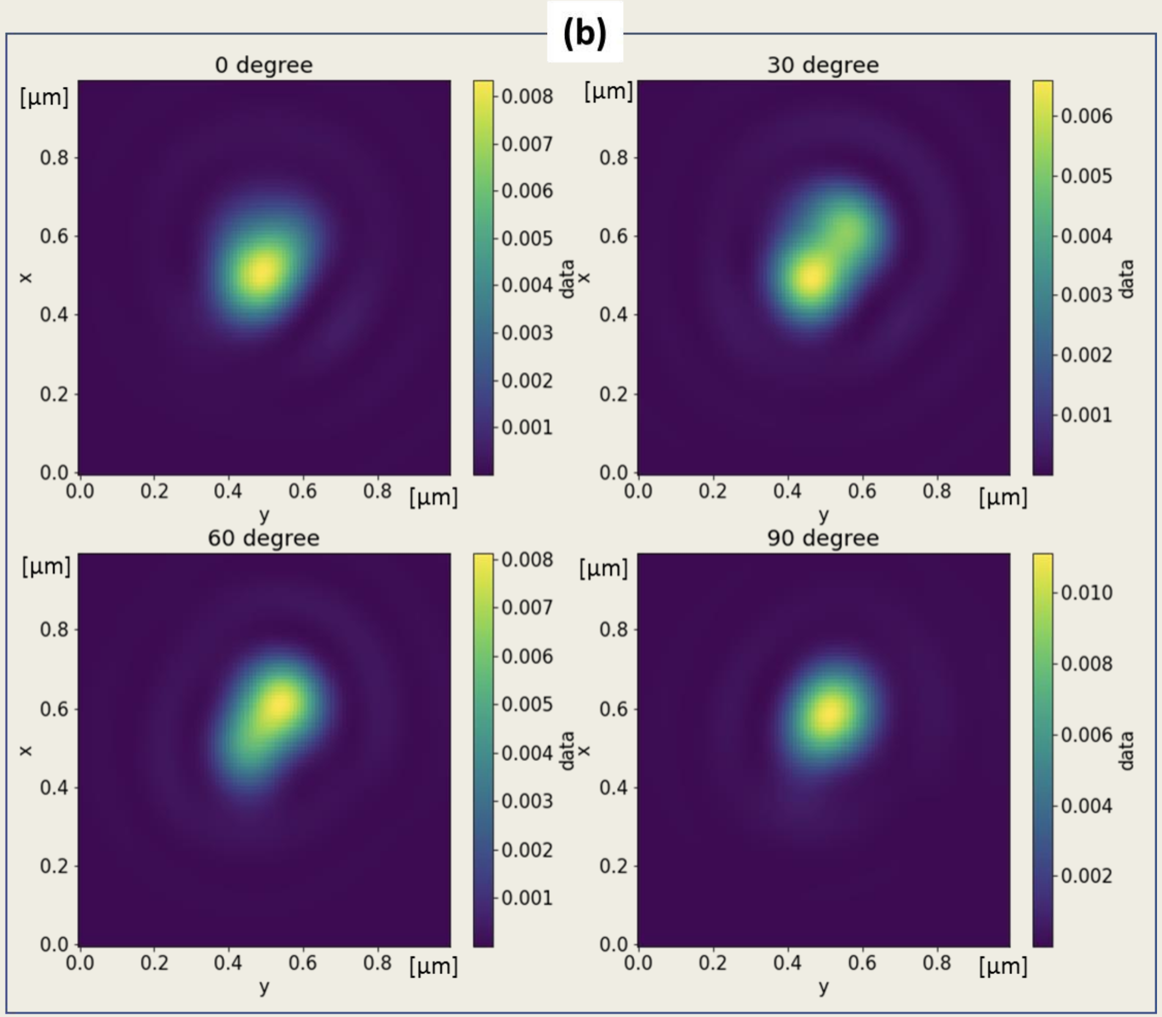
Silver ellipsoidal nanoparticle

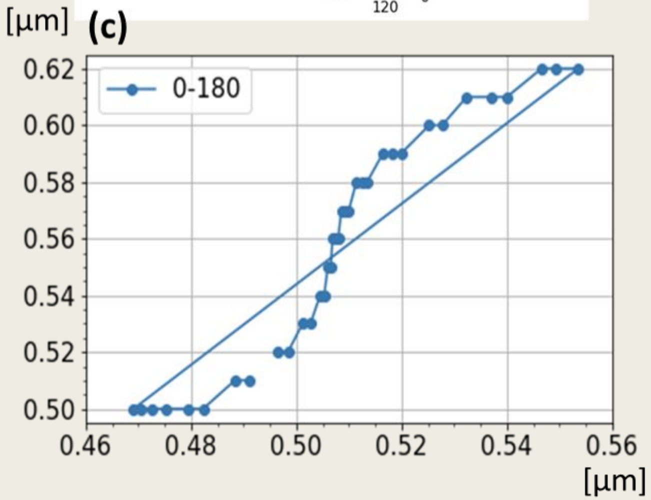




Simulation of two silver filaments





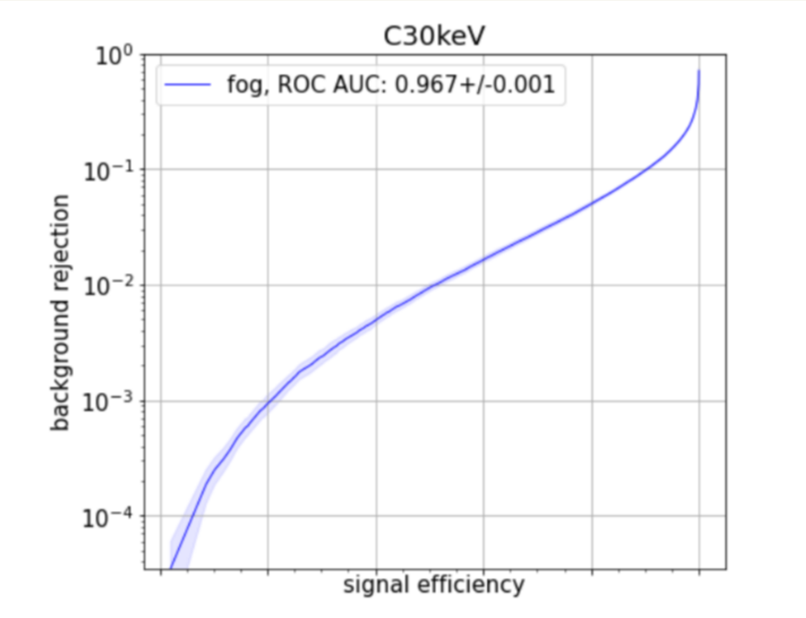


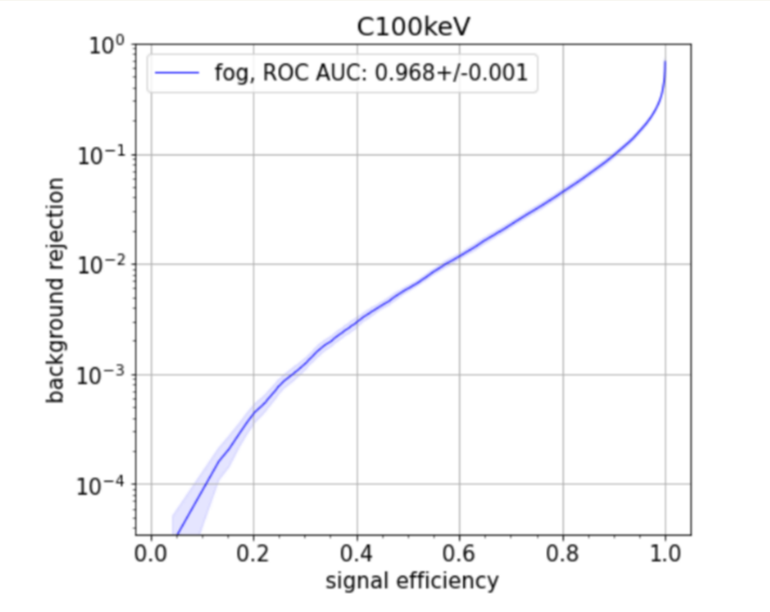
Background reduction: Machine Learning approach

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

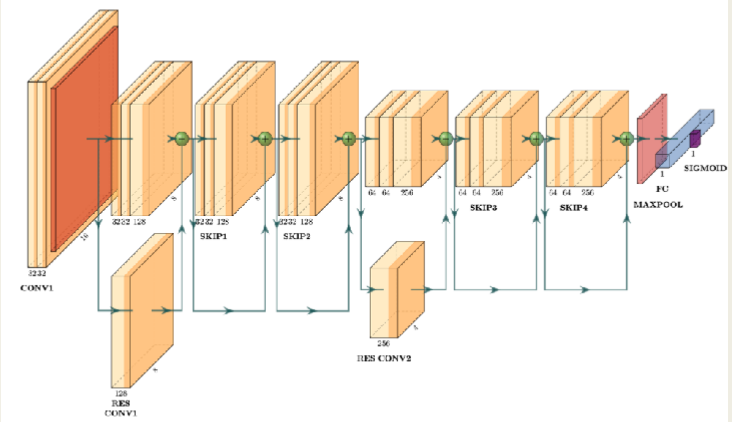
arXiv:2106.11995

Submitted to Comput. Phys. Commun.





Schematic view of the CNN architecture



	Barshift		NEWSnet		Shape analysis
	Validation	Test	Validation	Test	
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

- Fixed threshold to obtain efficiency similar to barshift
- Fog reduction is compared

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

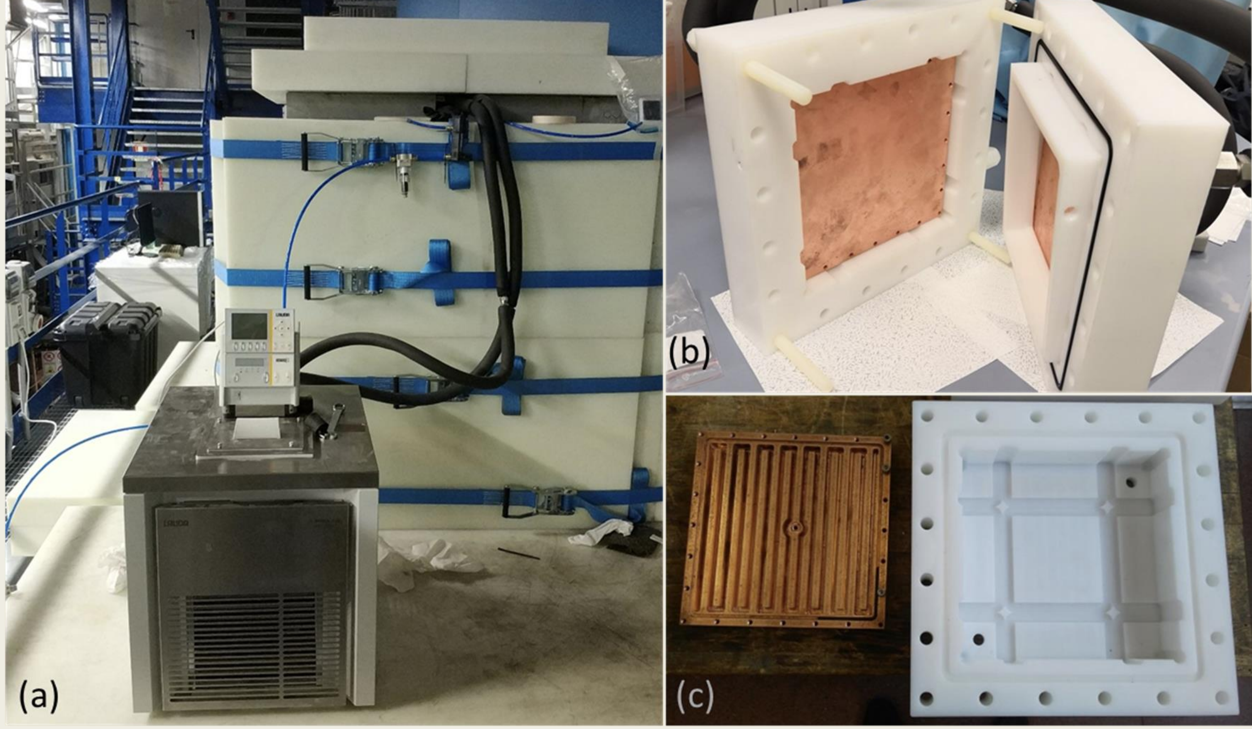
Gel production room

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

NEWSdm: current setup

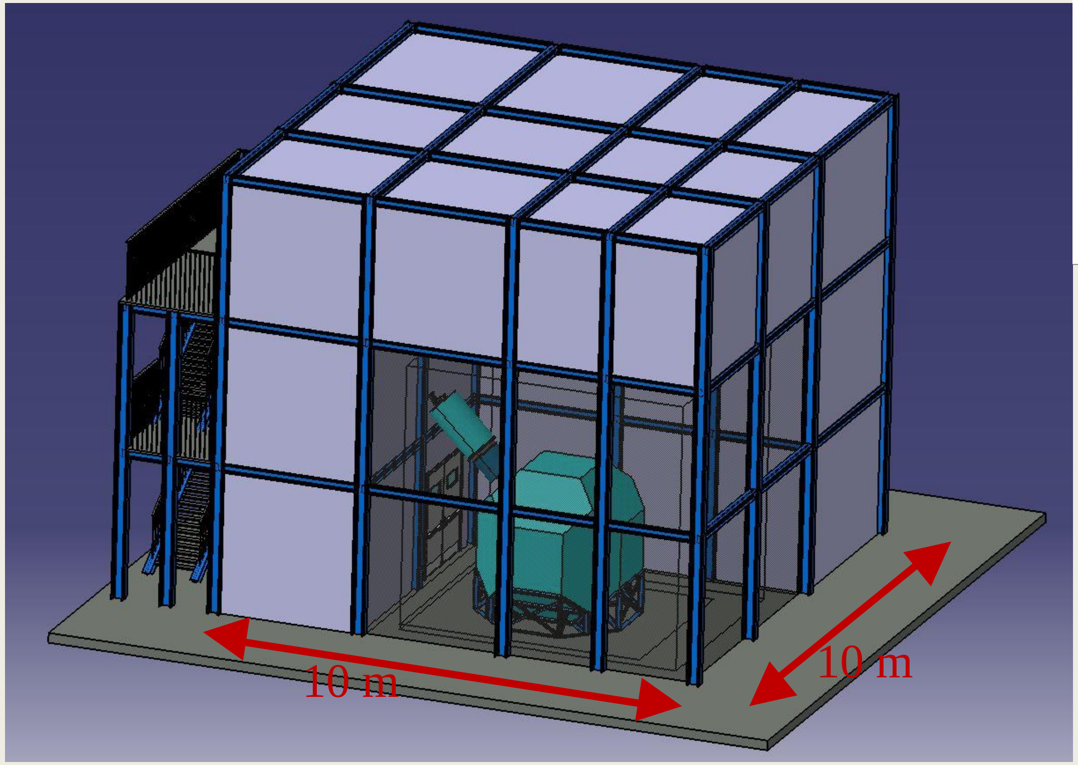
- Experimental setup in Hall C, close to Borexino
- Assembly of the setup in March 2021
- Test measurements ongoing

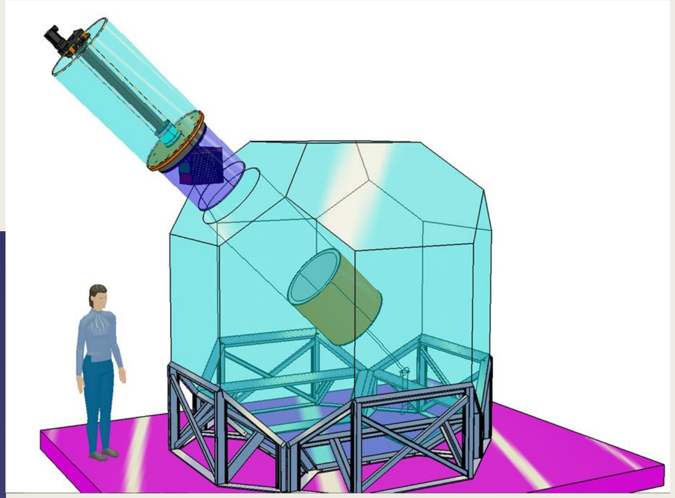
Mass	Exposure	Temp.	Shield
~10g	40days	-50°C	40cm PE + 10cm Pb



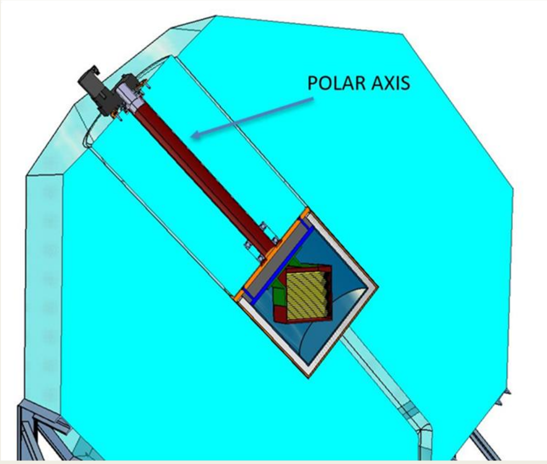
Future facility for NEWSdm: 10kg and beyond

Emulsion facility and shielding with an equatorial telescope

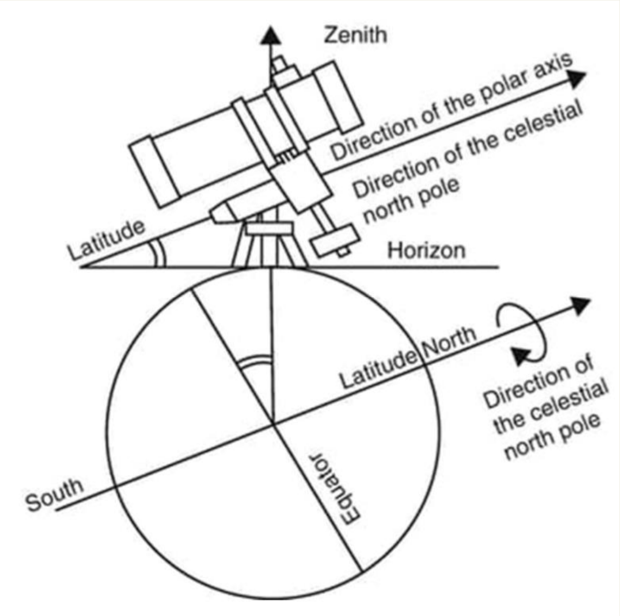


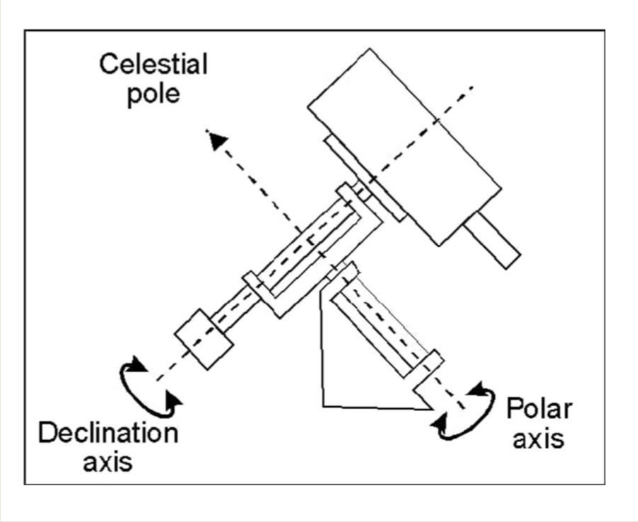


(a)



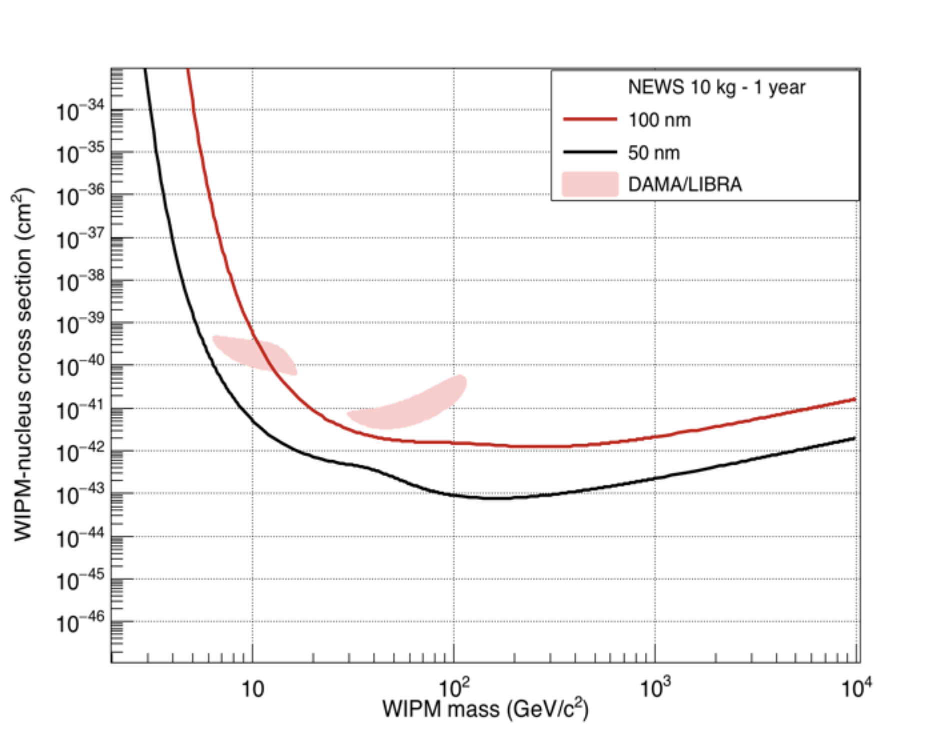
(b)



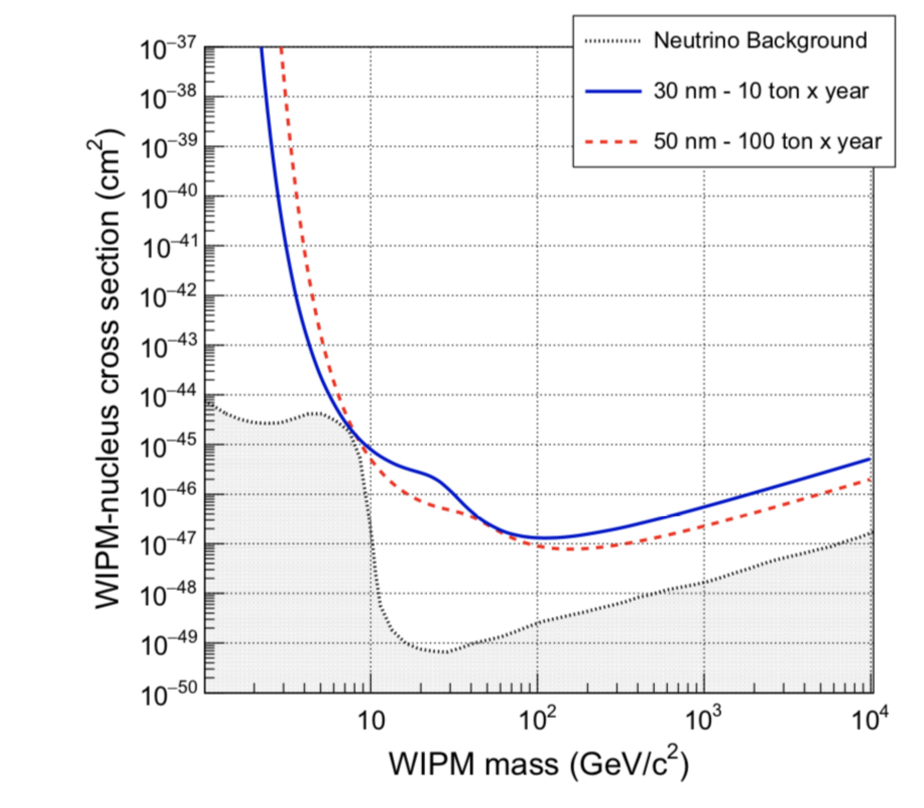


NEWSdm intermediate and final goals

- 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!

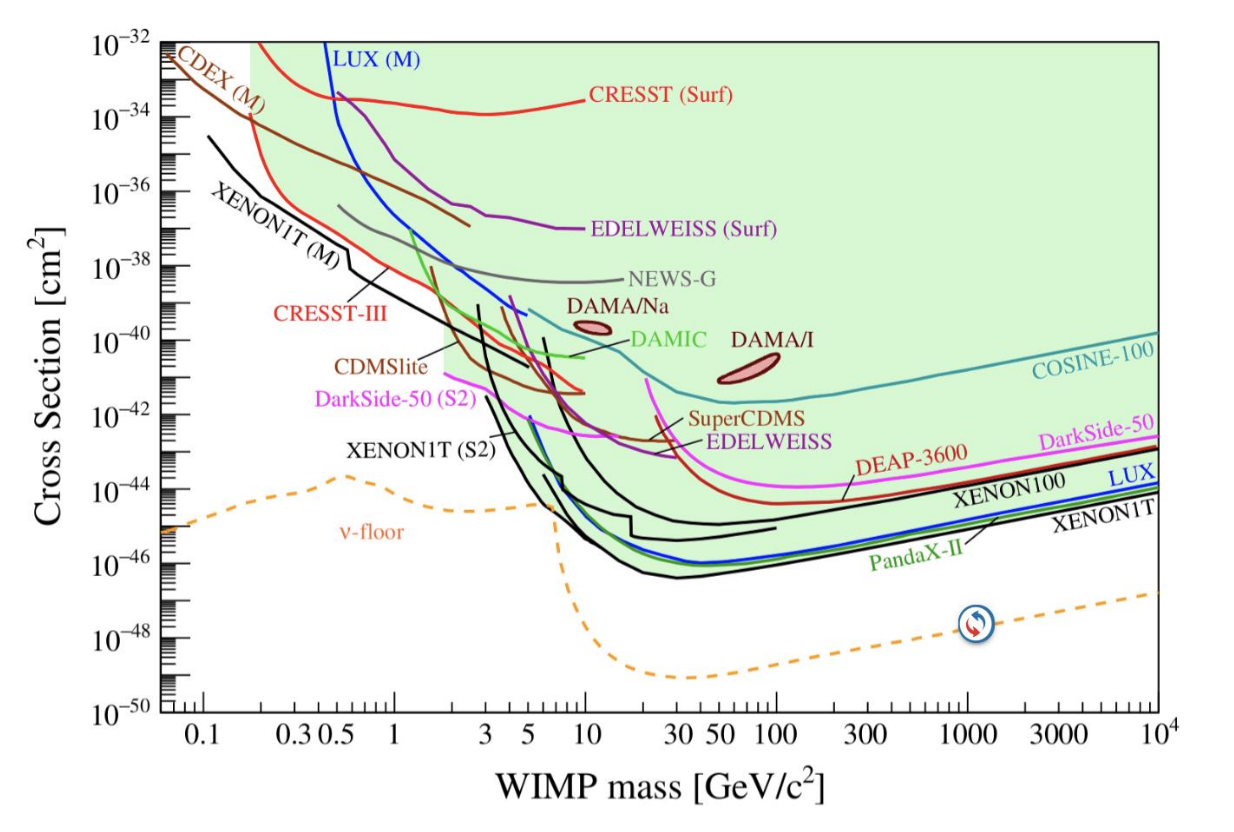
Andrey ALEXANDROV (On behalf of the NEWSdm collaboration)

andrey.alexandrov@na.infn.it

BACKUP SLIDES

Direct Dark Matter searches

- Current status of searches for spin-independent elastic WIMP-nucleus scattering assuming the standard parameters for an isothermal WIMP halo

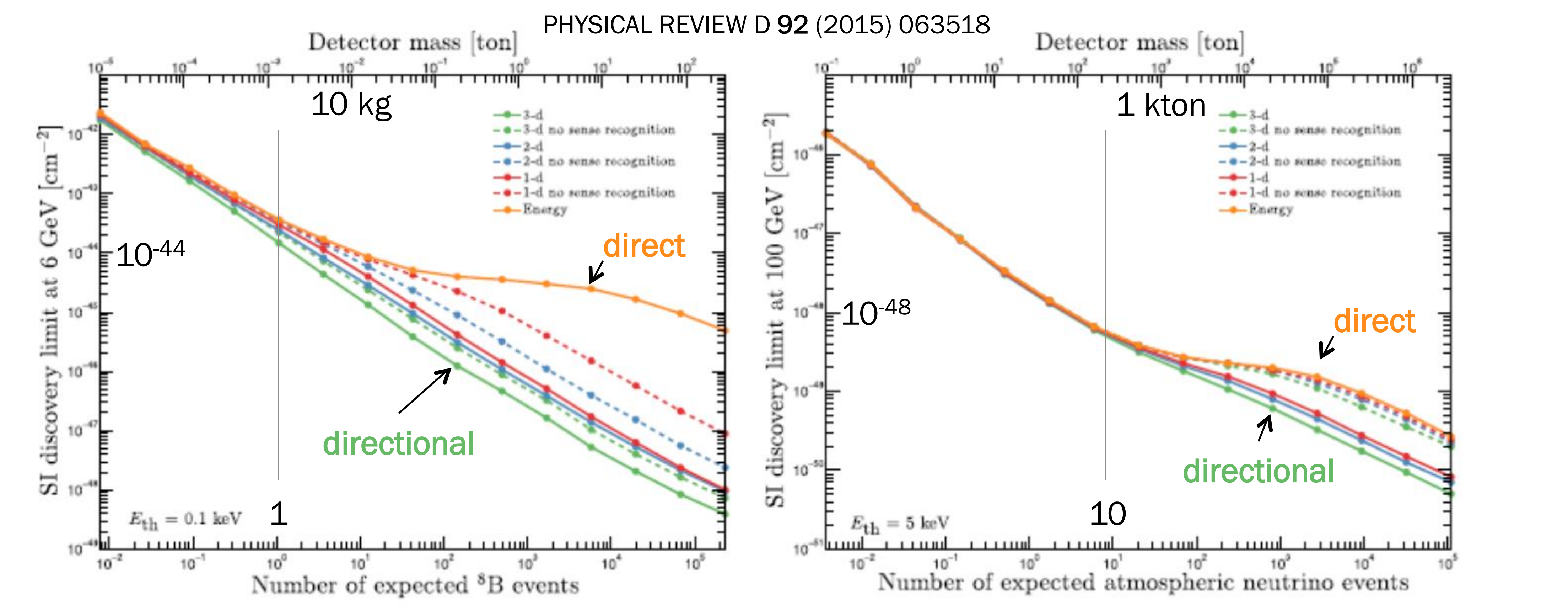


Direct Detection of Dark Matter – APPEC Committee Report

https://www.appec.org/wp-content/uploads/2021/04/appec_dm_report_2020_ga_approved.pdf

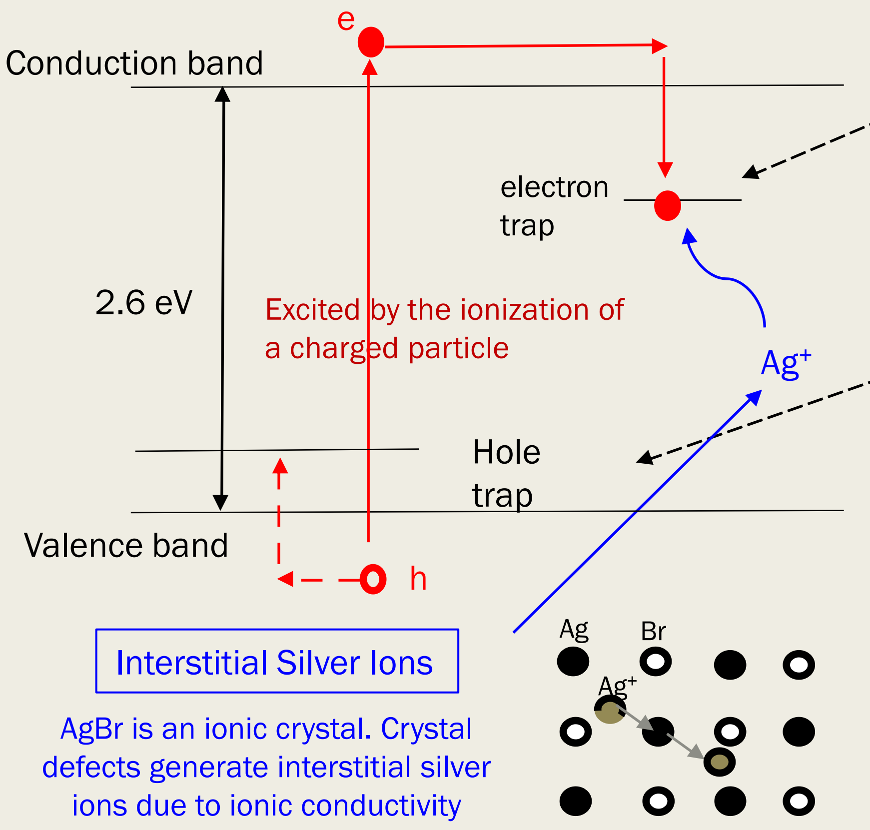
arXiv: 2104.07634

Importance of the directional detection



Need 3D with sense recognition for best results!

Nuclear emulsion: detection principle



Electron trap

- ☑ surface kink site
- ☑ artificially doped (e.g., AuS, S_2, Fe, ・・)
- ☑ crystal defect
- ☑ Ag_2 on P-center (positive kink site)

Hole trap

- ☑ Iodide doped
- ☑ Ag_2 on R-center (neutral kink site)

$$e^- + Ag^+ \rightarrow Ag$$
$$Ag + e^- + Ag^+ \rightarrow Ag_2$$
$$Ag_{n-1} + e^- + Ag^+ \rightarrow Ag_n$$

Latent image specks

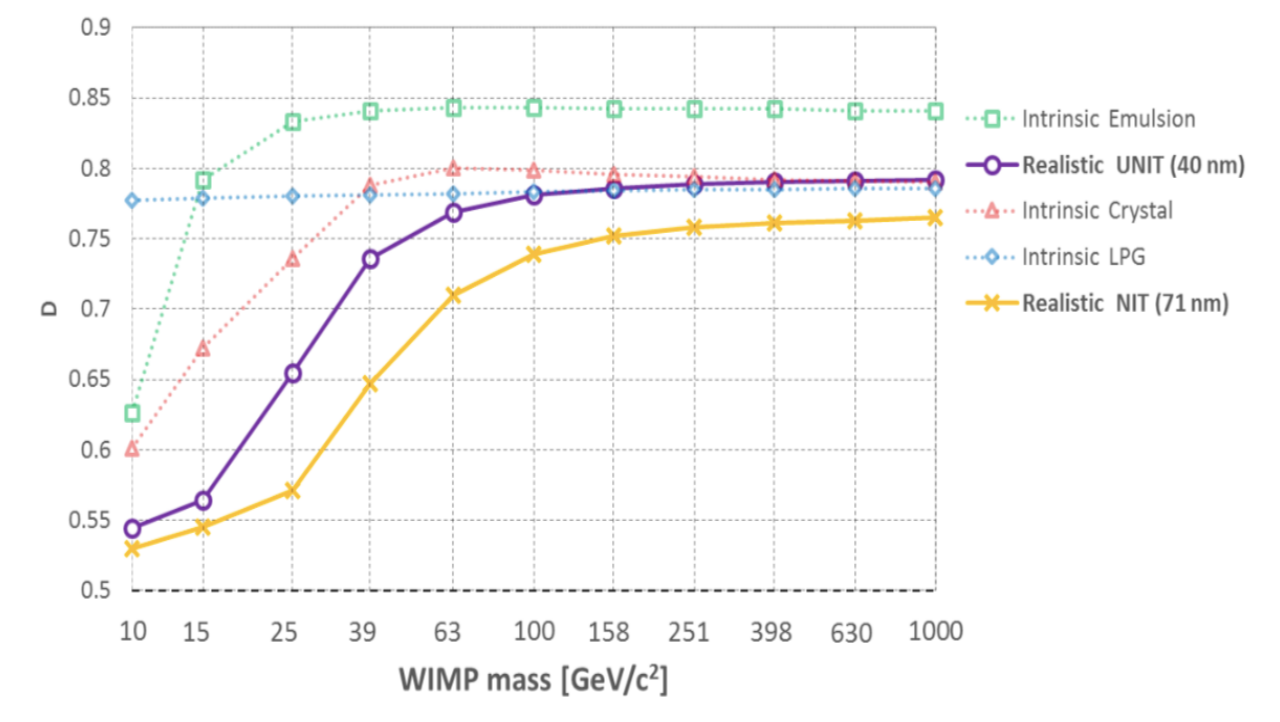
n >4 In standard photographic theory

Directionality preservation of nuclear recoils

- Performance in the measurement of the recoil direction and comparison with other techniques
- Simulation of nuclear emulsion granularity: volume filled with AgBr crystals described as spheres of diameters 44±7 nm for NIT, 25±4 nm for U-NIT

- Evaluation of energy-weighted cosine distribution

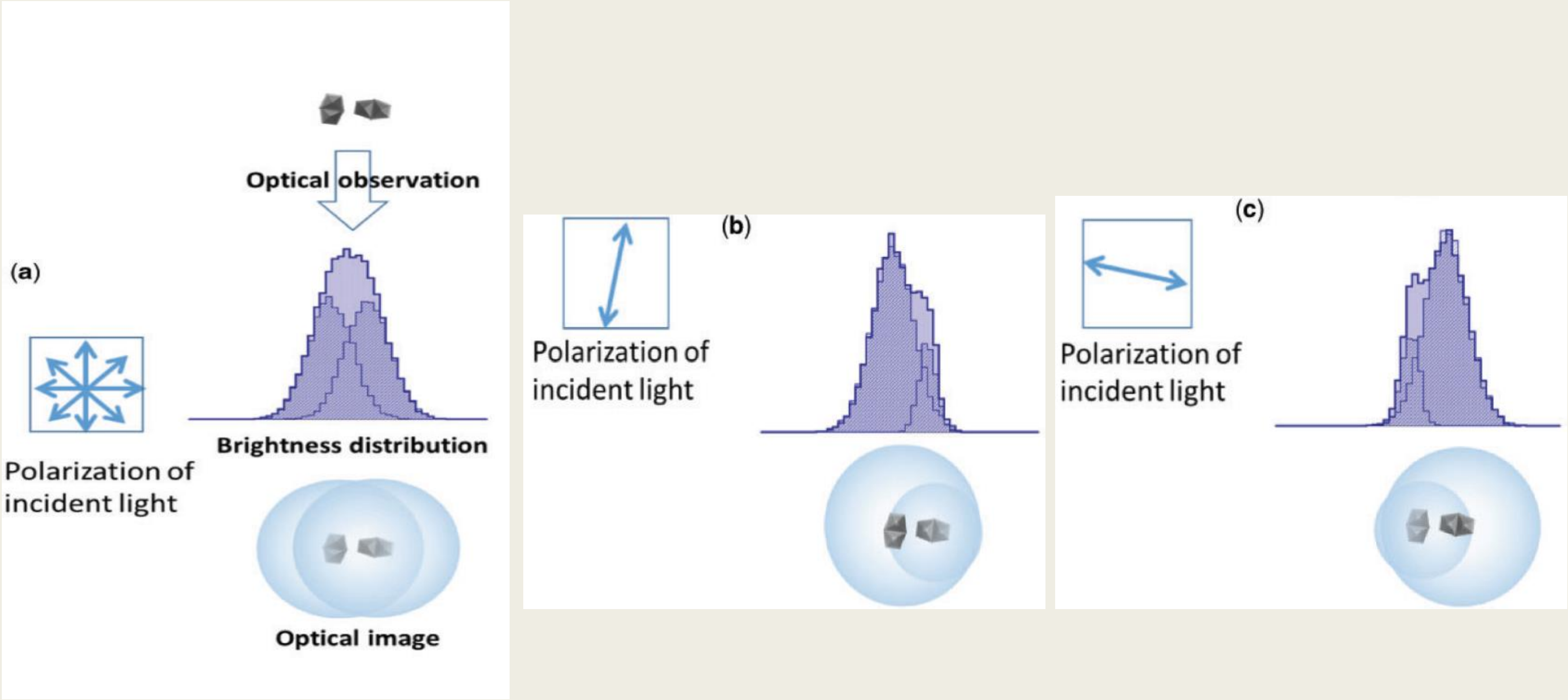
$$D = \frac{\sum_{i=0}^{N_{collisions}} \Delta E_i \cos\theta_i}{\sum_{i=0}^{N_{collisions}} \Delta E_i} = \frac{\langle \Delta E \cos\theta \rangle_{track}}{\langle \Delta E \rangle_{track}}$$



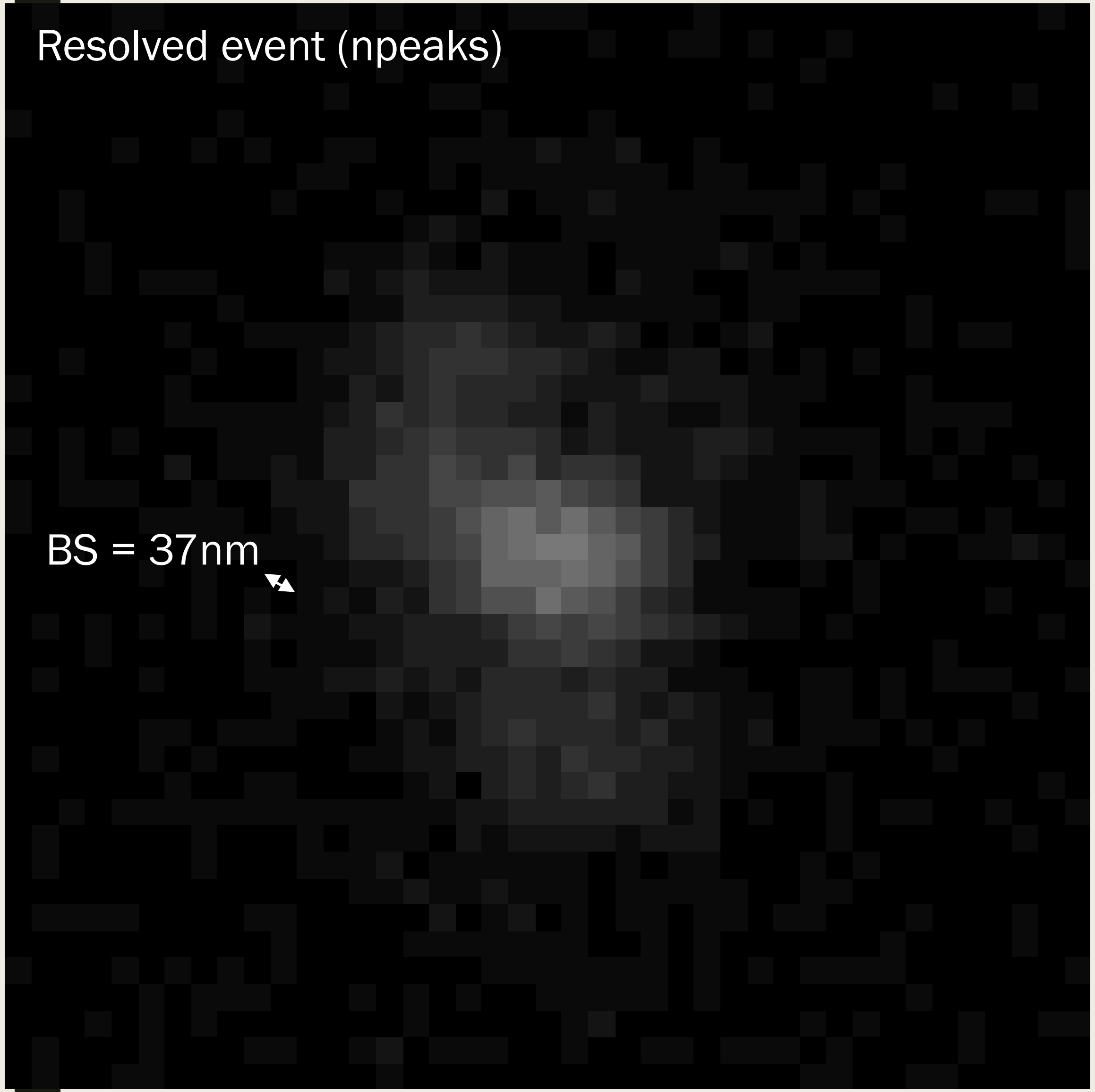
Realistic distribution of mean values of weighted-cosϑ for NIT and U-NIT, compared with other detectors

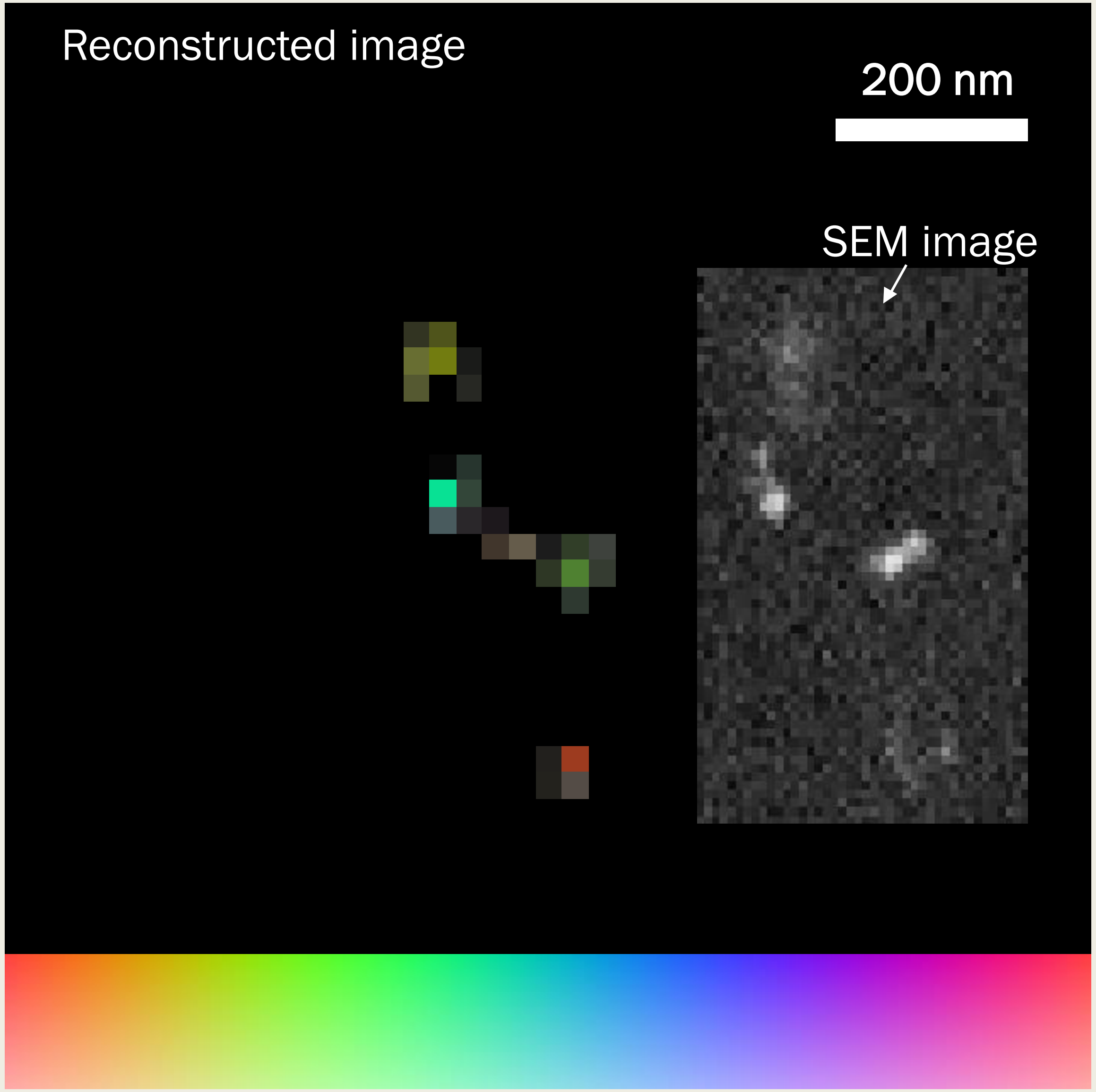
A. Alexandrov, G. De Lellis, A. Di Crescenzo, A. Golovatiuk and V. Tioukov, «Directionality preservation of nuclear recoils in an emulsion detector for directional dark matter search» JCAP 04 (2021) 047

Optical readout beyond the diffraction limit



PTEP, Vol. 2019 Issue 62019, 063H02

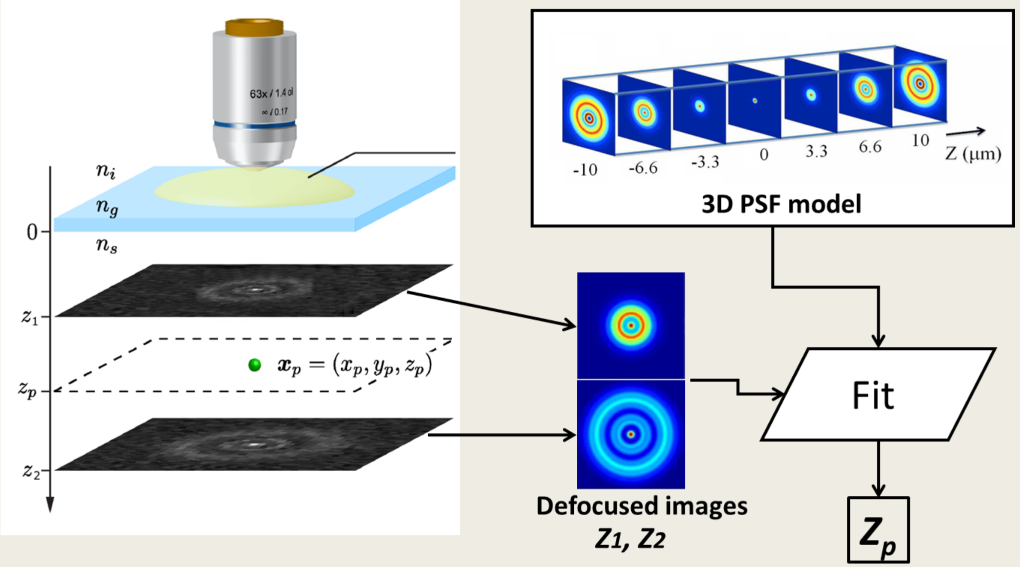


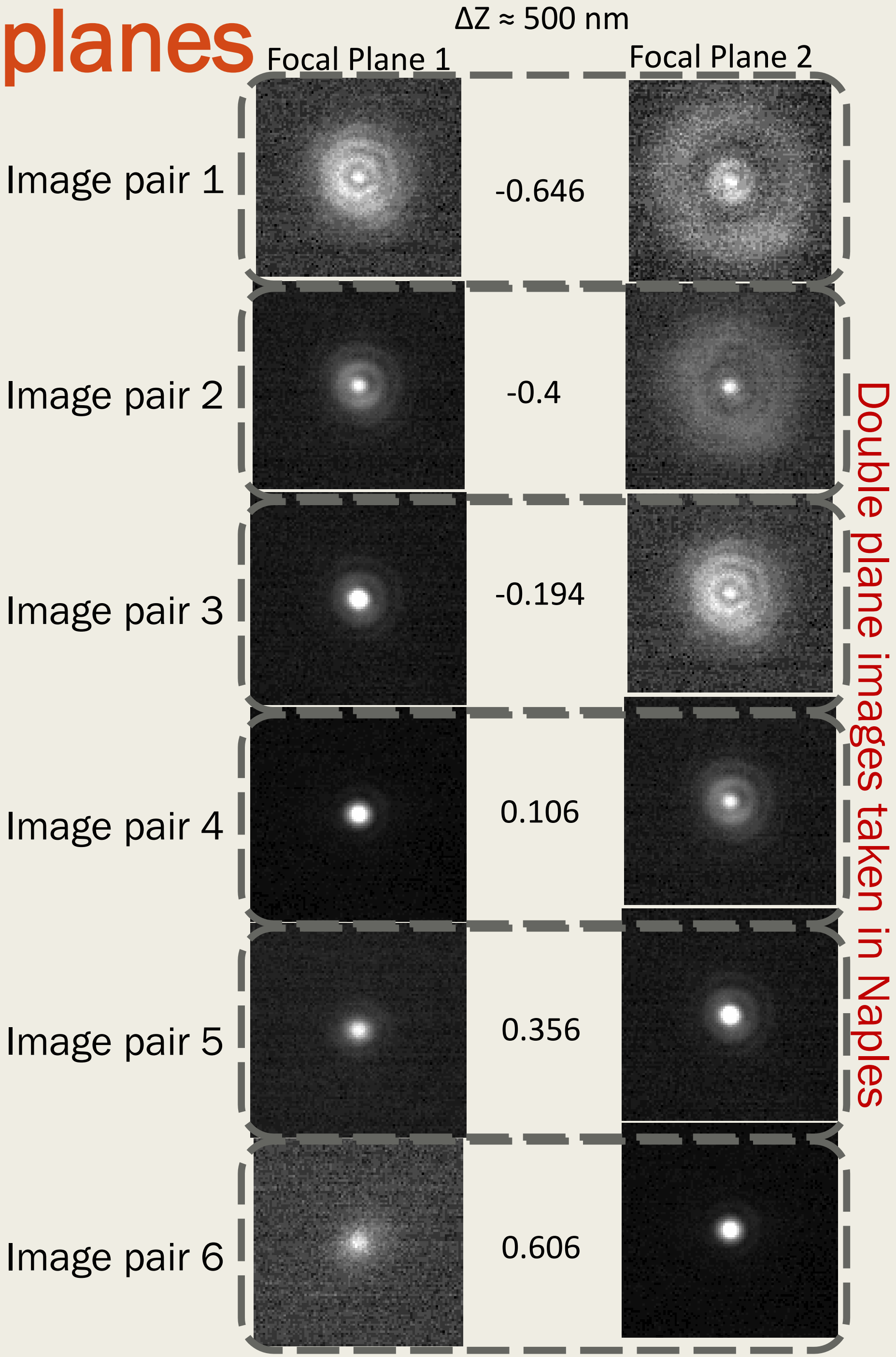


Grain v1_g192

Z reconstruction with two parallel planes

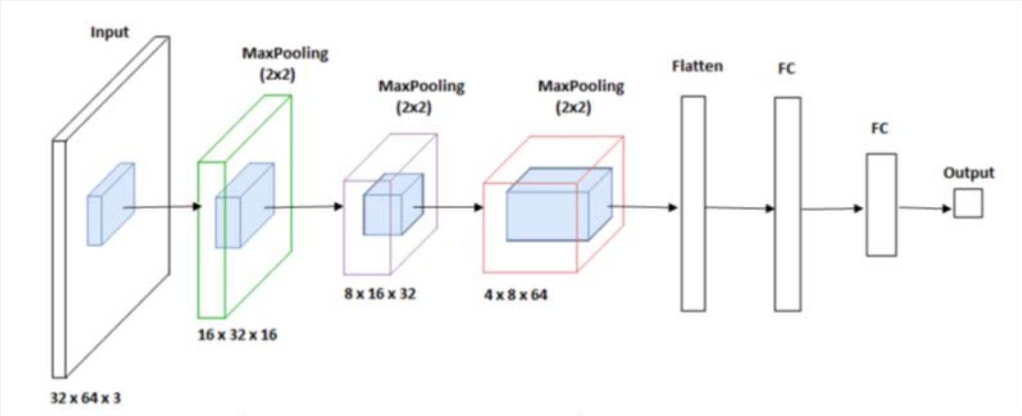
Biophys J. 95(12):6025-43 (2008)





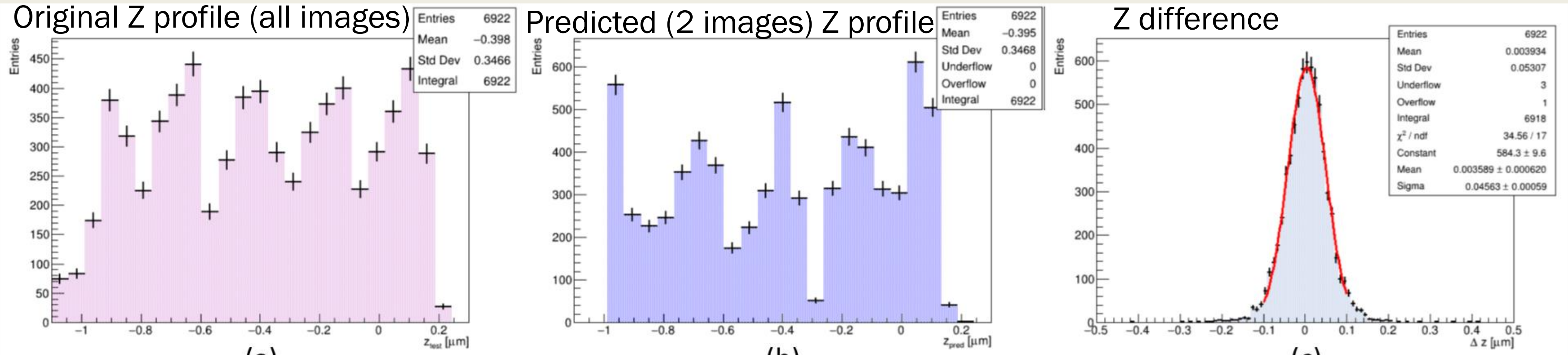
- Near the focal plane the PSF changes little => bad Z localization
- Out of focus the PSF starts to change rapidly: new rings of varying radii => fit improves => good Z localization
- <u>Idea:</u> with two focal planes separated by a small (~resolution) distance the object will always be out-of-focus at one of the planes

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

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

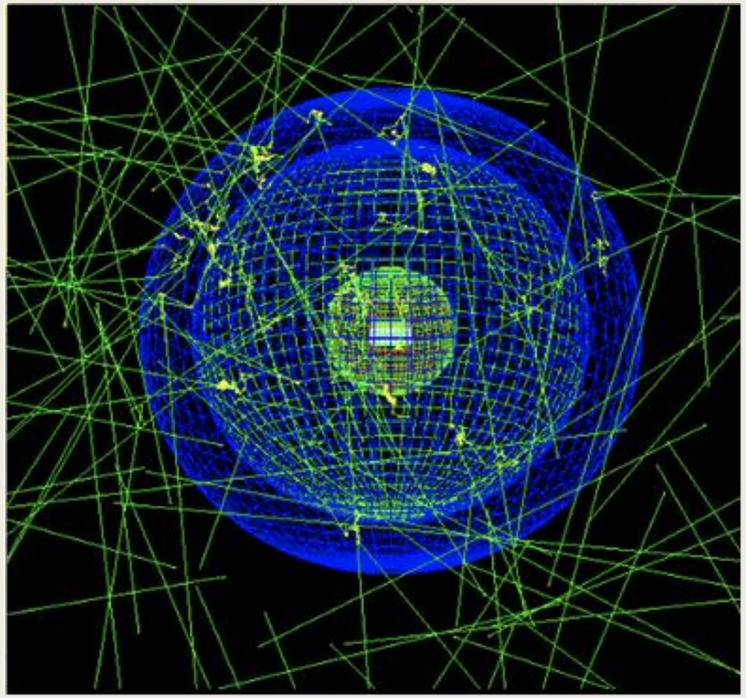
Shield simulation

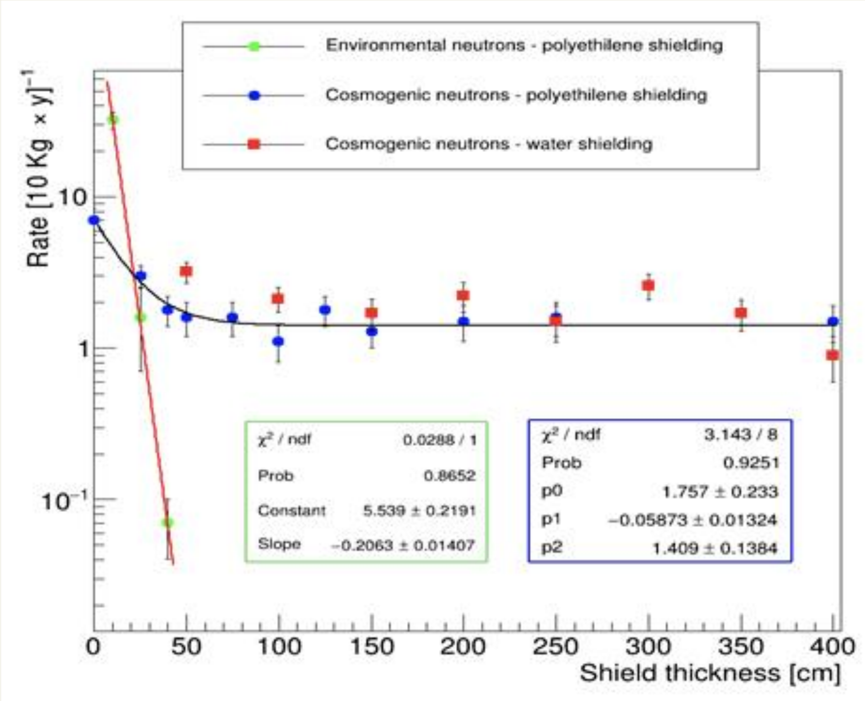
Optimisation of the shield with Geant4 simulation to reduce:

- neutrons from environmental radioactivity
- neutrons produced by cosmic muon spallation in the surrounding rock and in the shield itself
- Environmental gammas

Best configuration: 100 cm of polyethylene for a total neutron rate of ∽ 1.4 for an exposure of 10 kg year

Source	Rate $[10\,\mathrm{kg} \times\ \mathrm{y}]^{-1}$
Environmental gammas	$(1.97 \pm 0.17) \times 10^4$
Environmental neutrons	$\mathcal{O}(10^{-2})$
Cosmogenic neutrons	1.41 ± 0.14





Astroparticle Physics 80 (2016) 16–21

Intrinsic neutron background of nuclear emulsions for directional Dark Matter searches

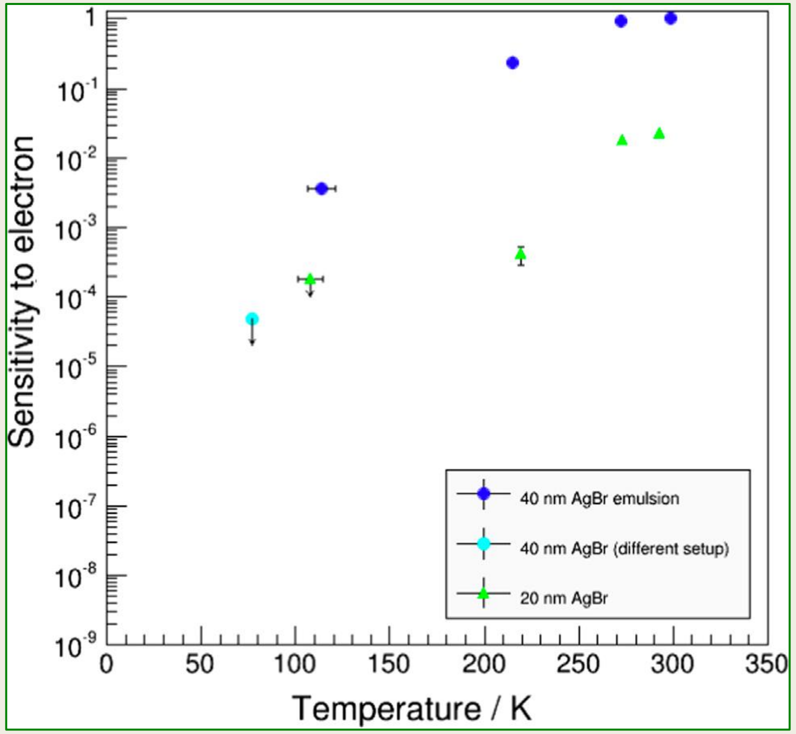
RADIOACTIVITY FROM 14C

Given the carbon content in the emulsion and the ^{14}C activity, beta-rays amount to $\sim 10^8$ per kg*year

Strong reduction factor: NIT emulsions insensitive to MIP and largely insensitive to electrons

Additional **level arms**:

- Reduced sensitivity to electrons at low temperatures
- Electron response to polarized light scattering
- Colour camera to distinguish nuclear recoils from electrons
- Replace the gelatine with synthetic polymers (final choice)



NIM A 845 (2017) 373