DIRECTIONAL DARK MATTER SEARCH WITH NUCLEAR EMULSION

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On behalf of the NEWSdm collaboration

NEWSdm COLLABORATION

Nuclear Emulsion WIMP Search directional measurement

75 physicists
14 Institutes

JAPAN
Chiba, Nagoya, Toho

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

ITALY
University and INFN Bari
LNGS, Gran Sasso
University and INFN Napoli
INFN Roma

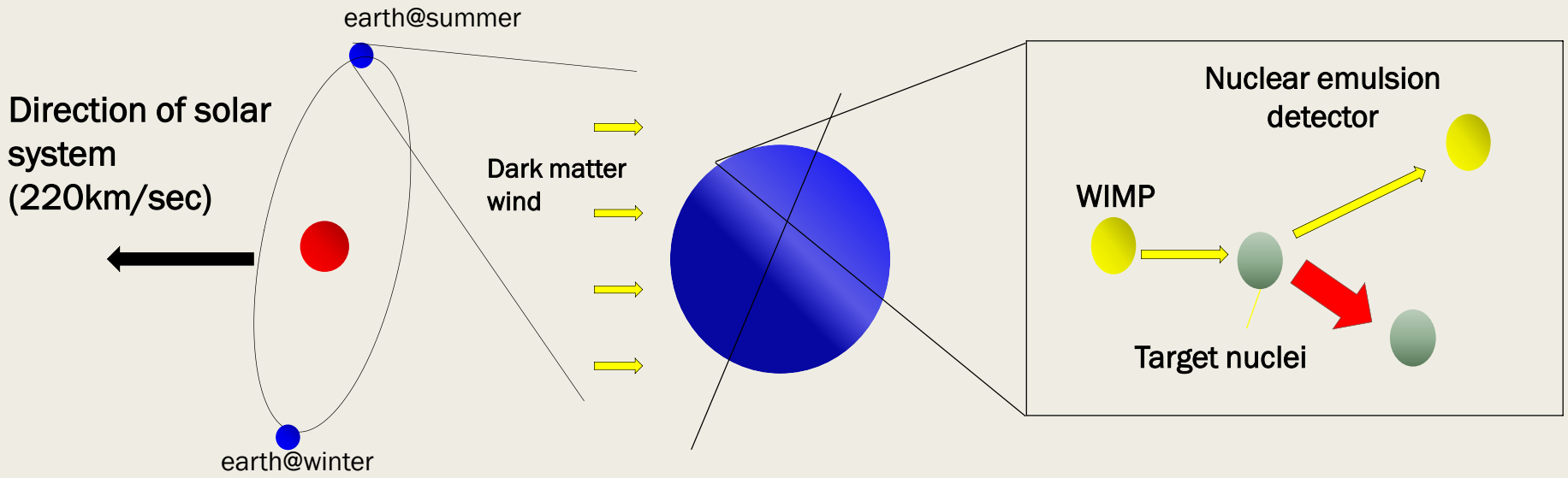
SOUTH KOREA
Gyeongsang University

TURKEY
METU Ankara

Website: news-dm.lngs.infn.it

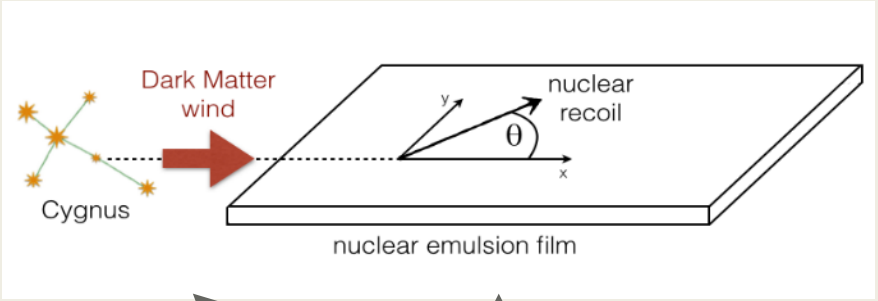
Letter of intent: https://arxiv.org/pdf/1604.04199.pdf

WIMP directional information

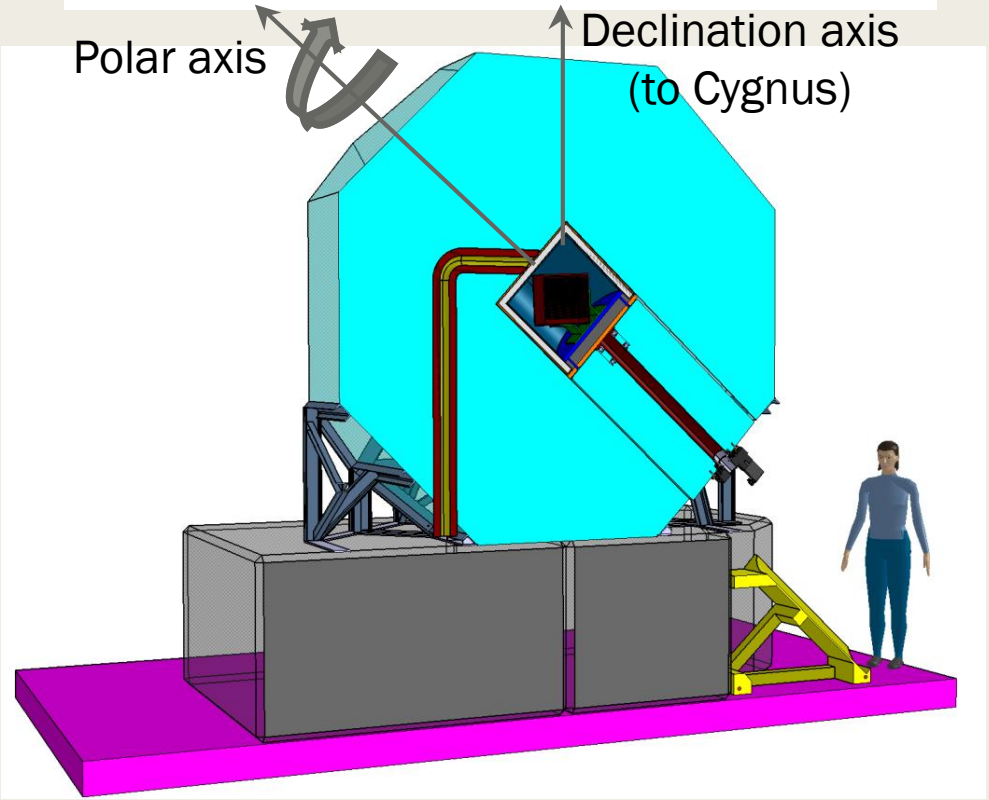


- Direction of the scattered nuclei has strong correlation with WIMP flux and provide a **strong signature** and unambiguous proof of the galactic DM origin
- Unique possibility to overcome the “neutrino floor”, where coherent neutrino scattering creates an irreducible background
- **Nuclear Emulsion** is a high density solid state media – big mass with a compact detector is possible

NEWSdm Principle

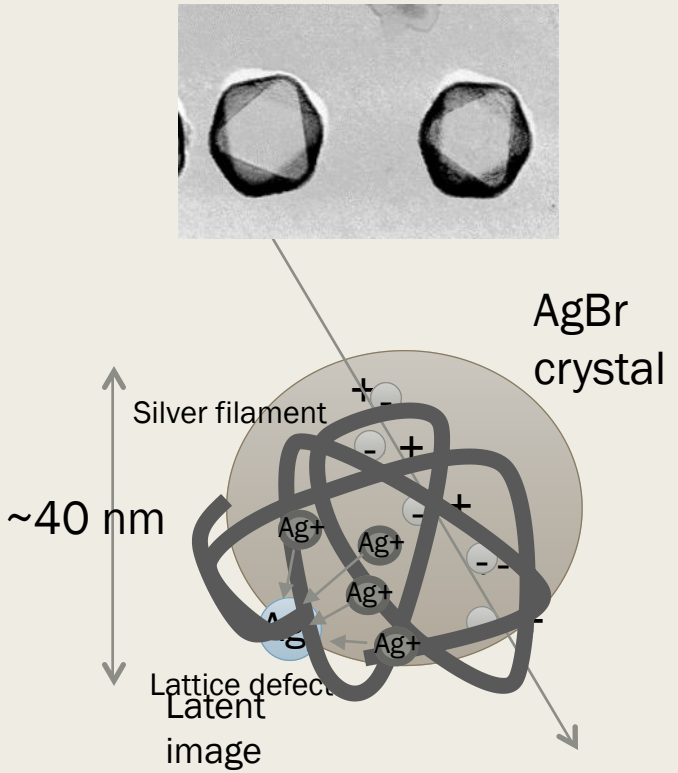


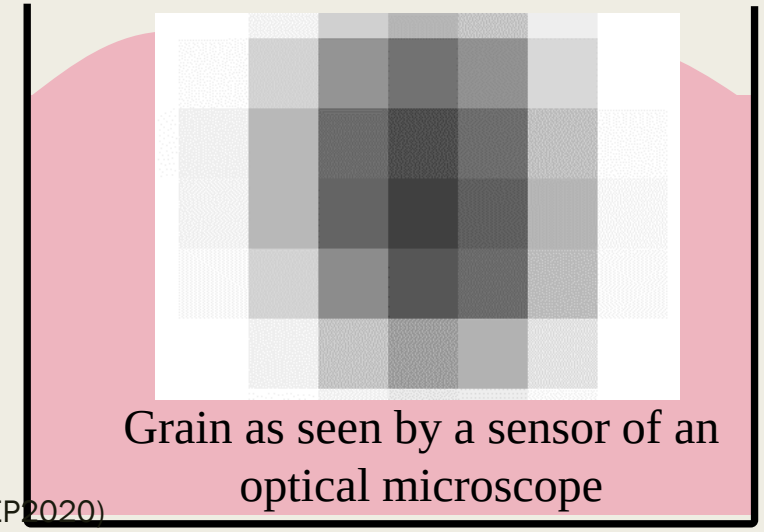
- **Goal**: detect the direction of nuclear recoils
- **Target**: nanometric emulsion films acting both as target and tracking detector
- **Background reduction**: neutron shield surrounding the target
- **Fixed pointing**: target mounted on equatorial telescope pointing to the Cygnus Constellation
- **Location**: Underground labs



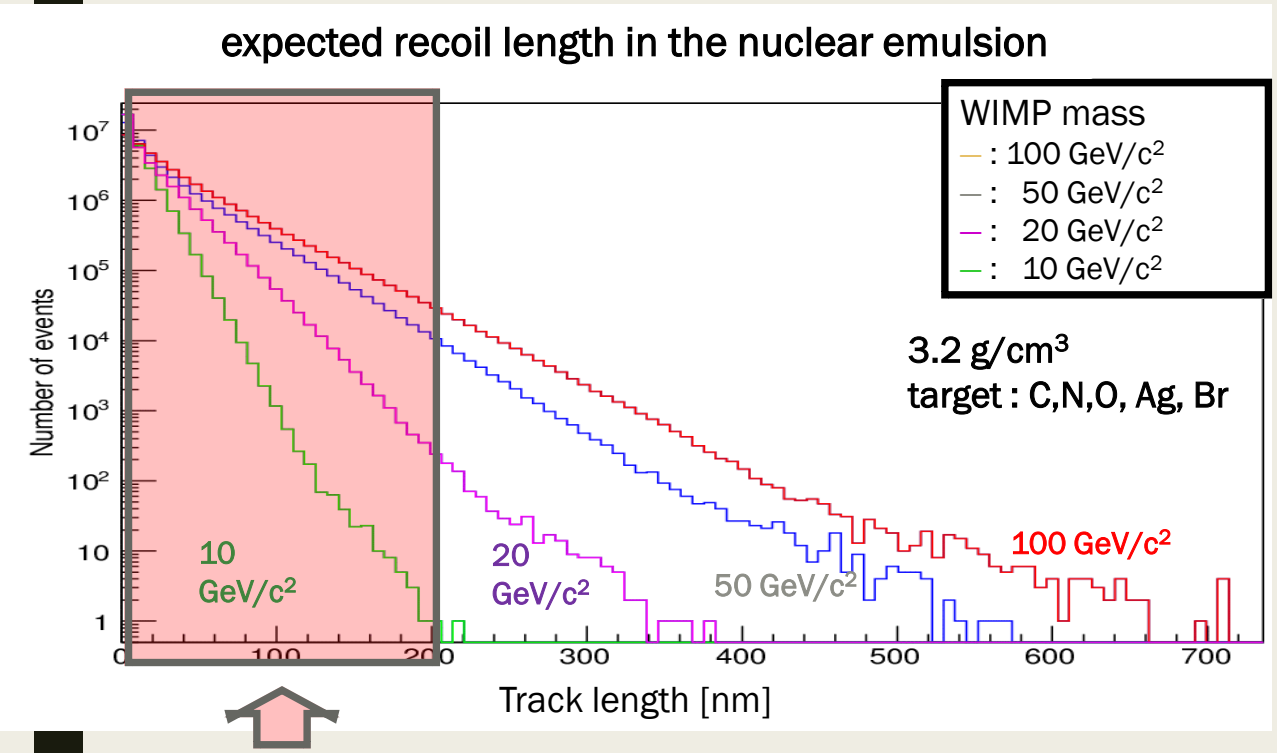
Detection principle

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

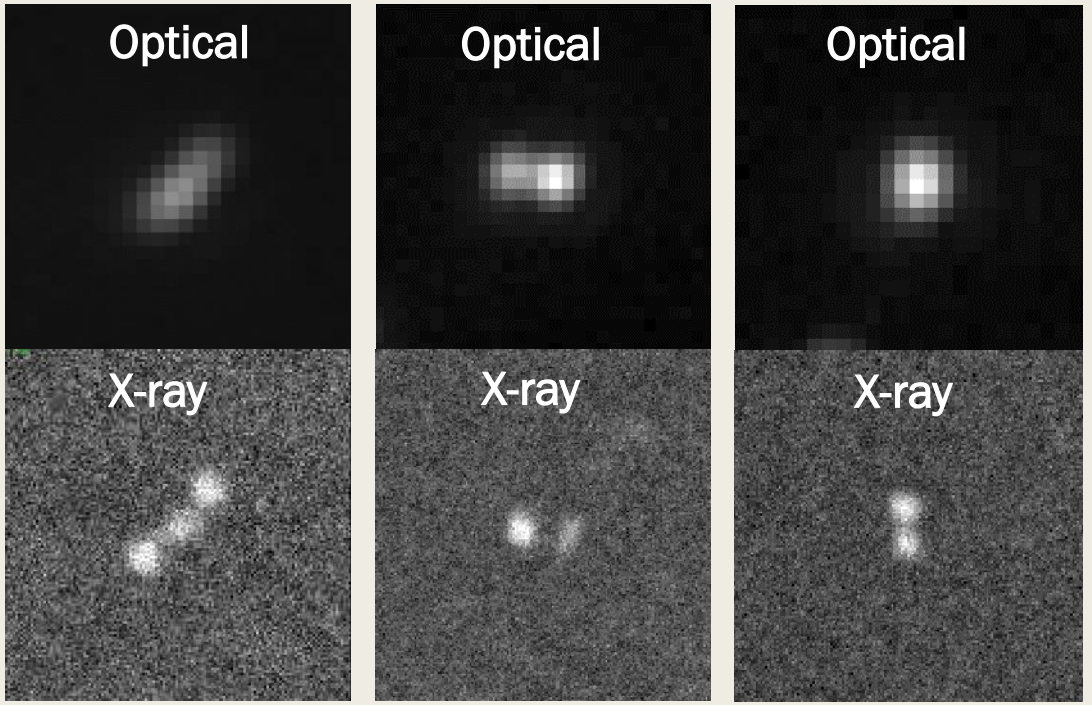



Grain as seen by a sensor of an optical microscope

Directional detection challenge



Inaccessible due to diffraction limit

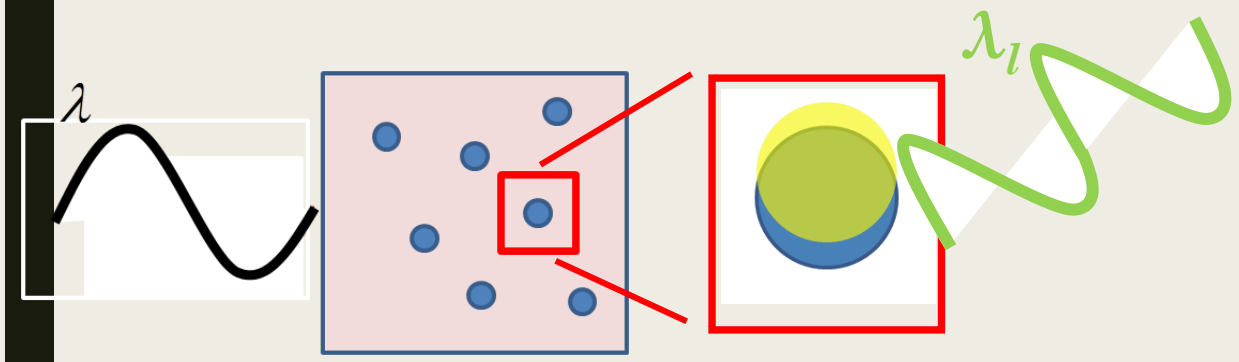


L = 380 nm L = 265 nm L = 160 nm

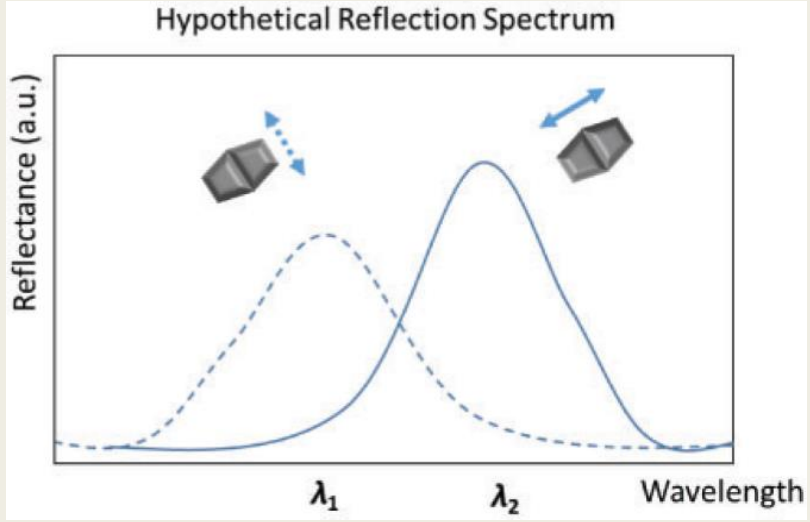
Need super-resolution to measure tracks shorter than 200 nm

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***

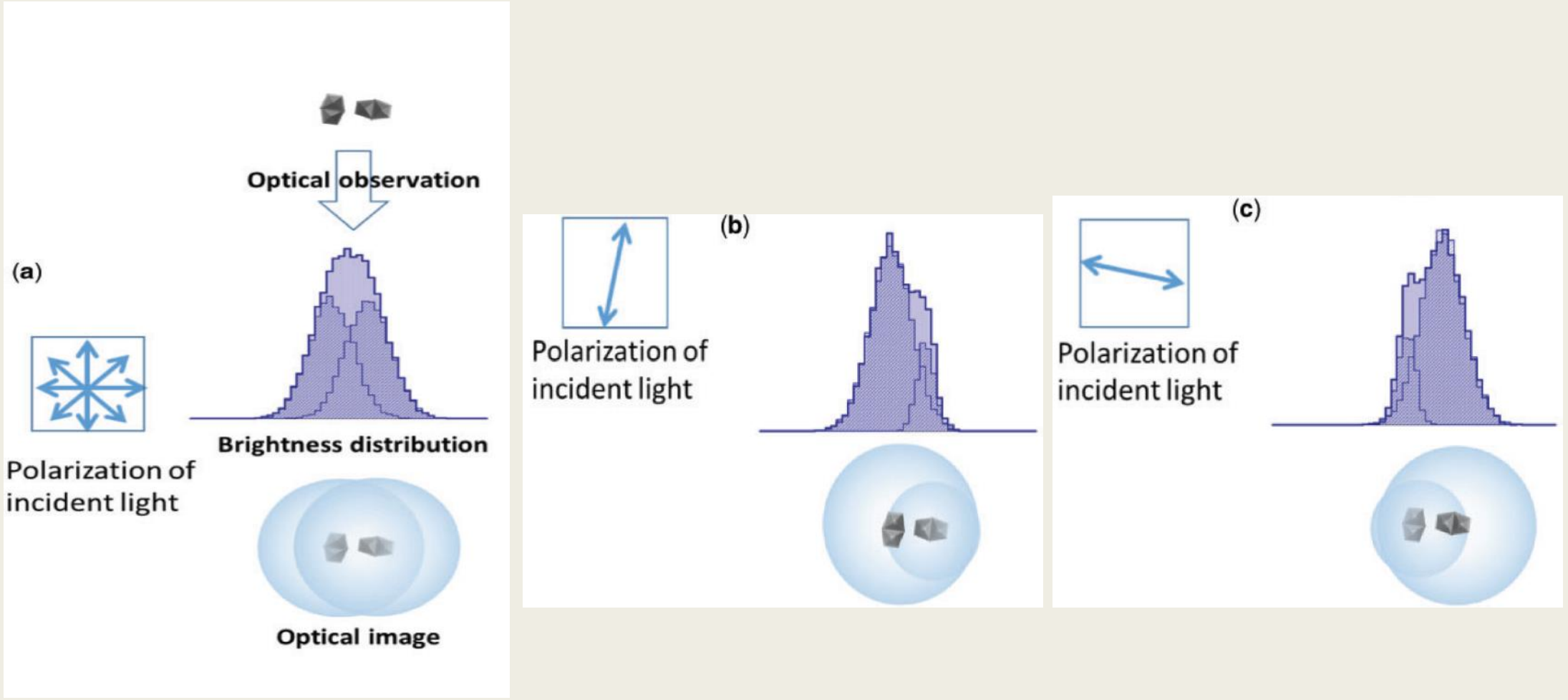


Oscillation of e-cloud



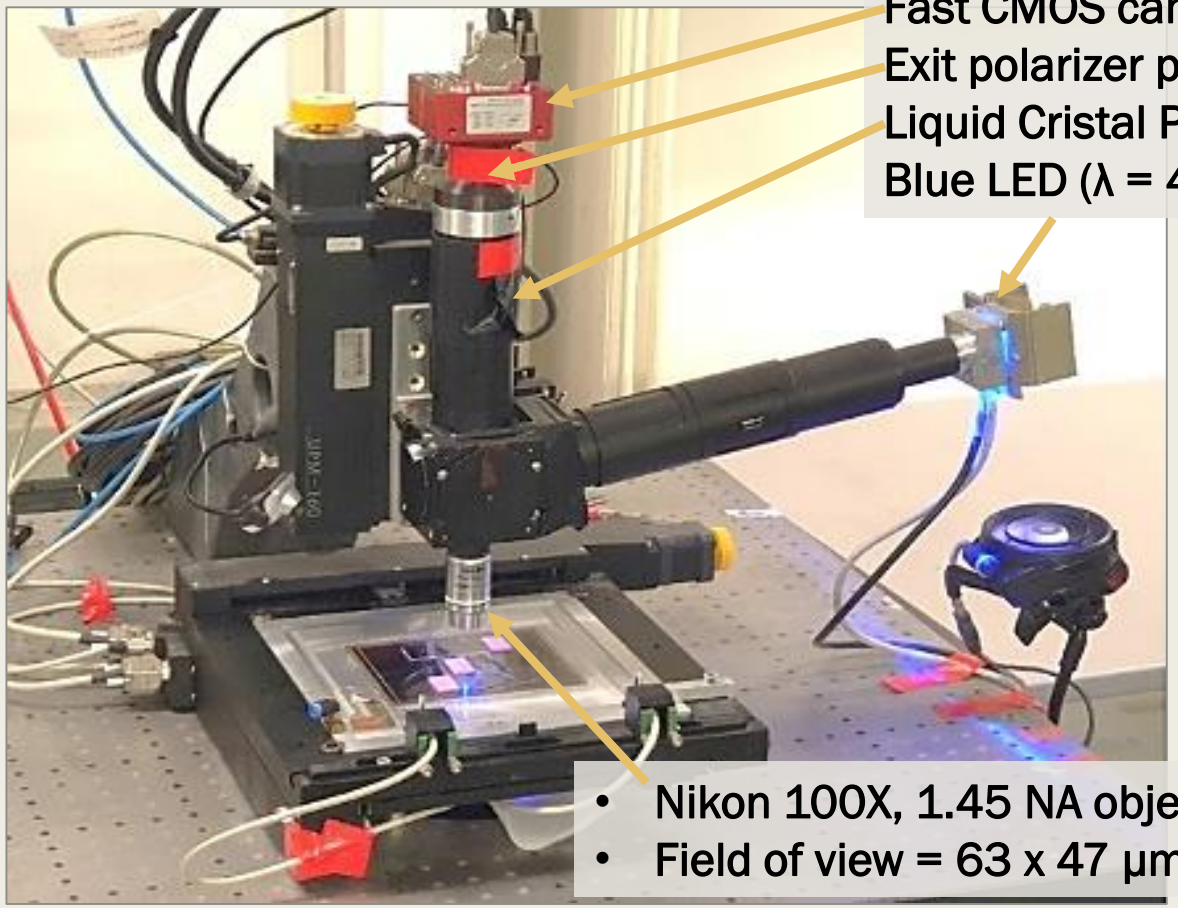
PTEP, Vol. 2019 Issue 62019, 063H02

Optical readout beyond the diffraction limit



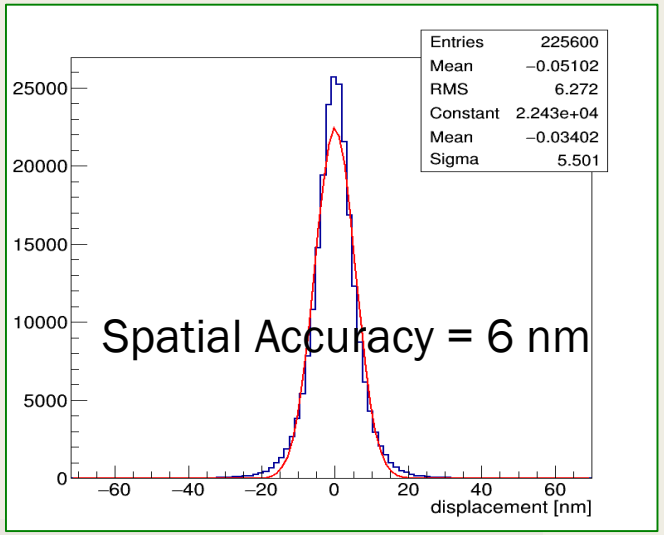
PTEP, Vol. 2019 Issue 62019, 063H02

Optical scanning system customized for plasmon



Fast CMOS camera
Exit polarizer plate
Liquid Cristal Polarization Rotator
Blue LED (λ = 460 nm)

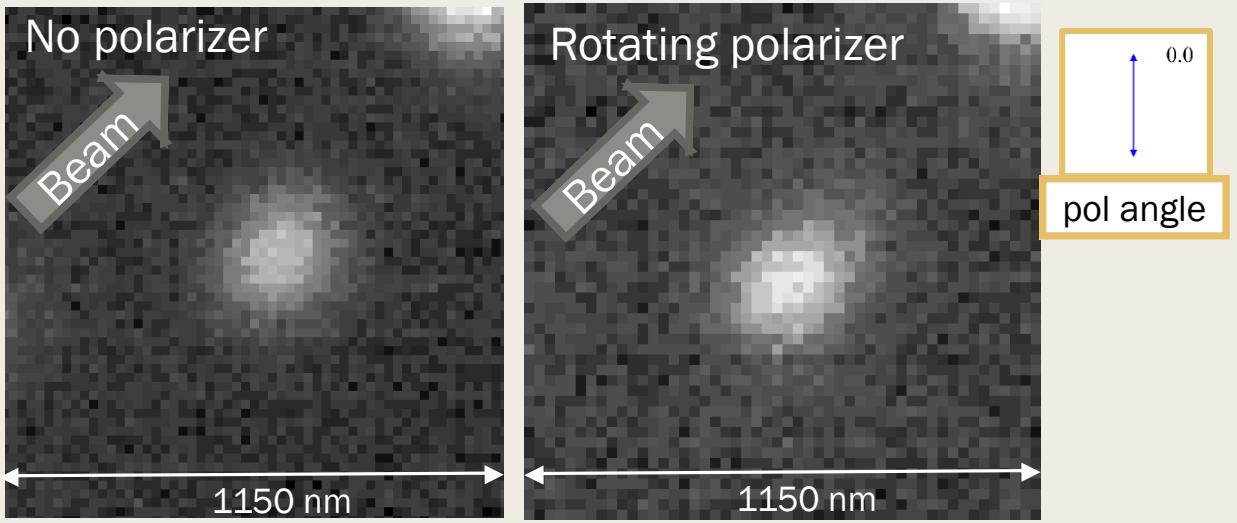
- Nikon 100X, 1.45 NA objective
- Field of view = 63 x 47 μm (pixel size = 27 nm)



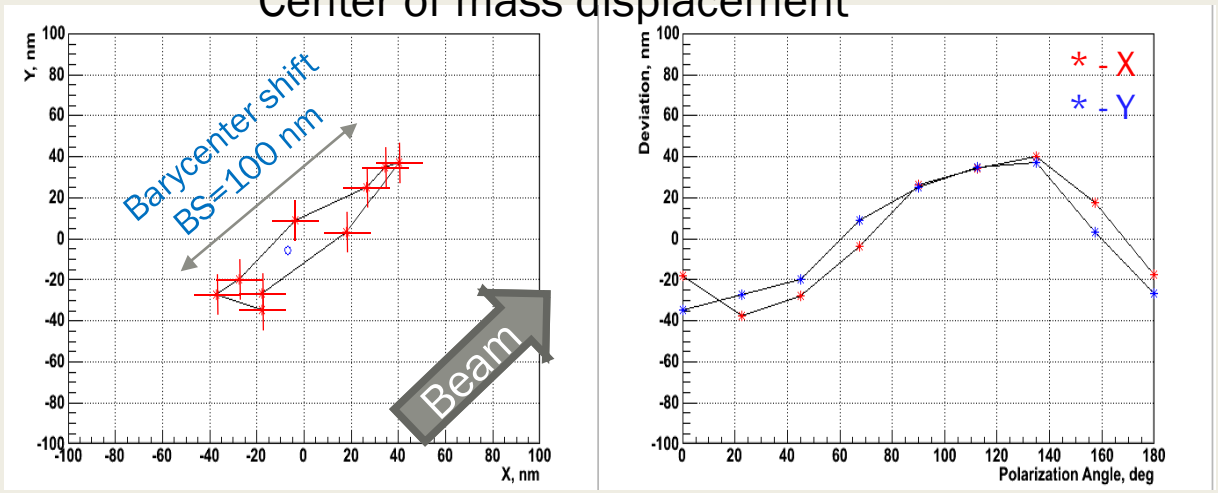
Super resolution: two-dimensions

- Grains are too close to be resolved (L=100 nm)
- A single elliptical cluster is seen without the polarizer
- The mass center of the track starts to “oscillate” with the rotation of polarizer

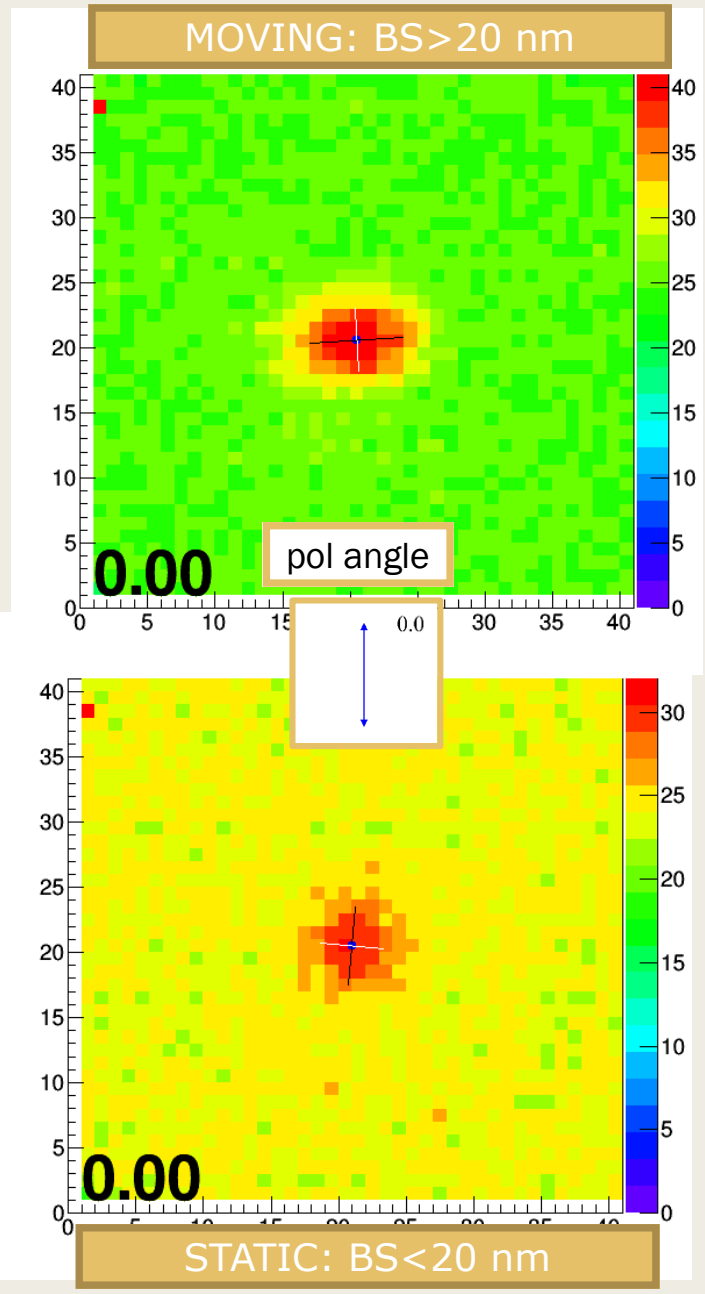
A track made of two grains

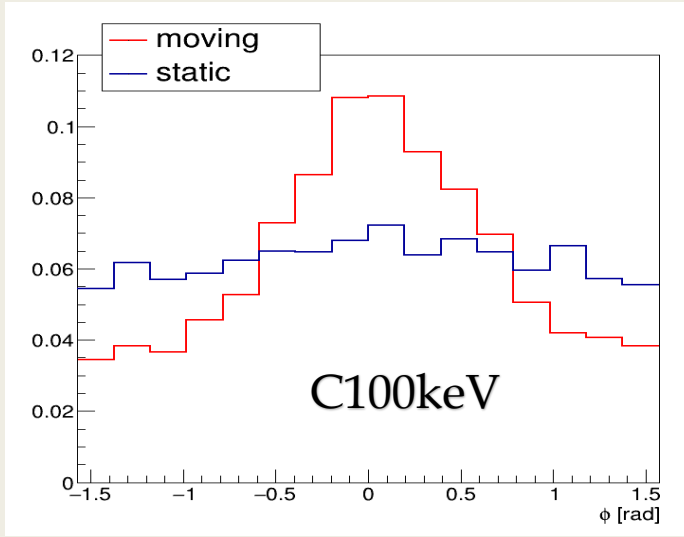


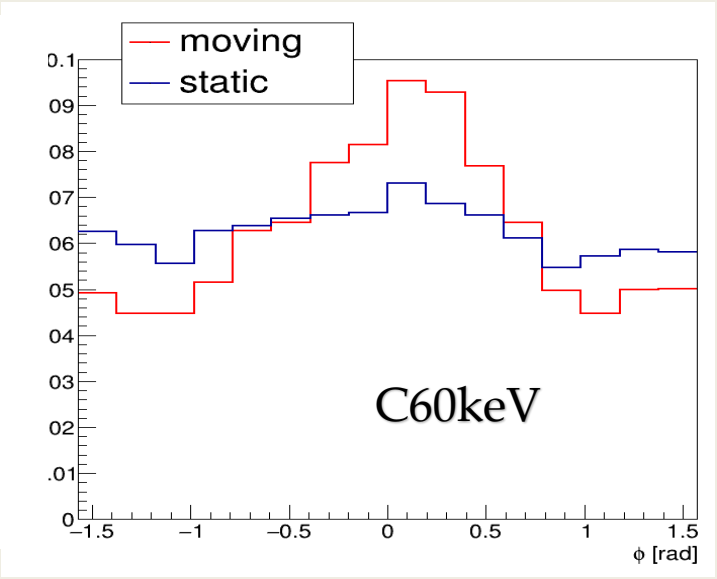
Center of mass displacement

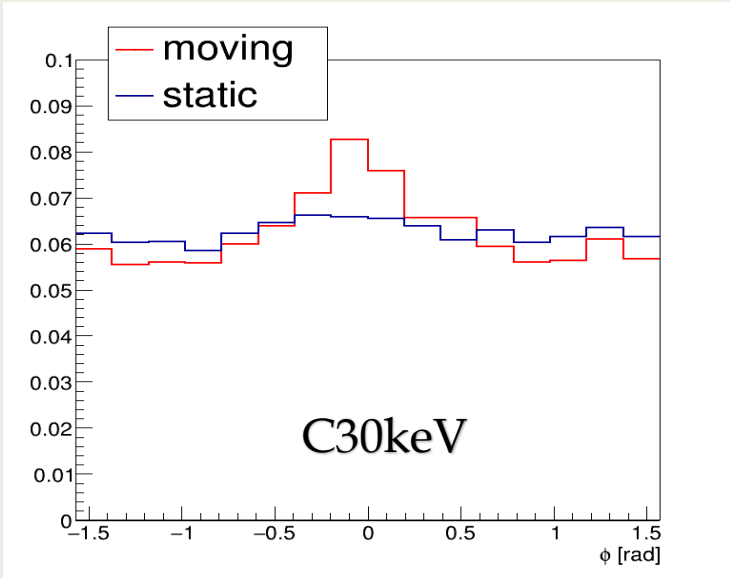


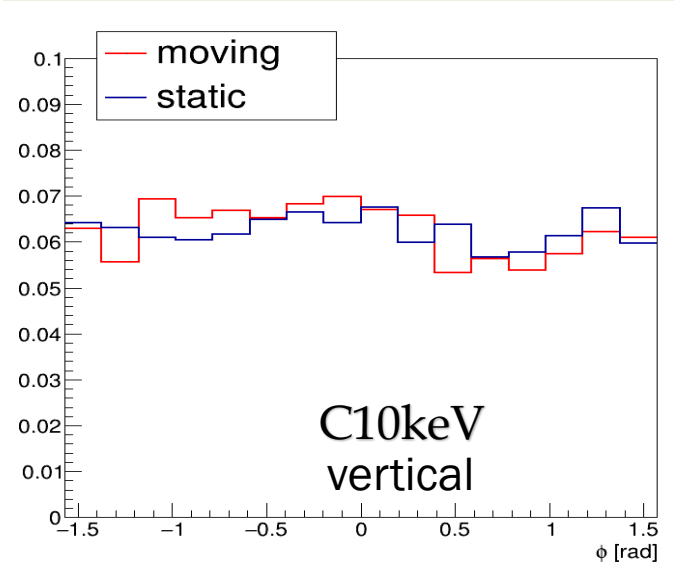
Plasmon analysis of isolated events











Directionality demonstrated with Carbon ions down to 30 keV

Super resolution: 3-dimensions!

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

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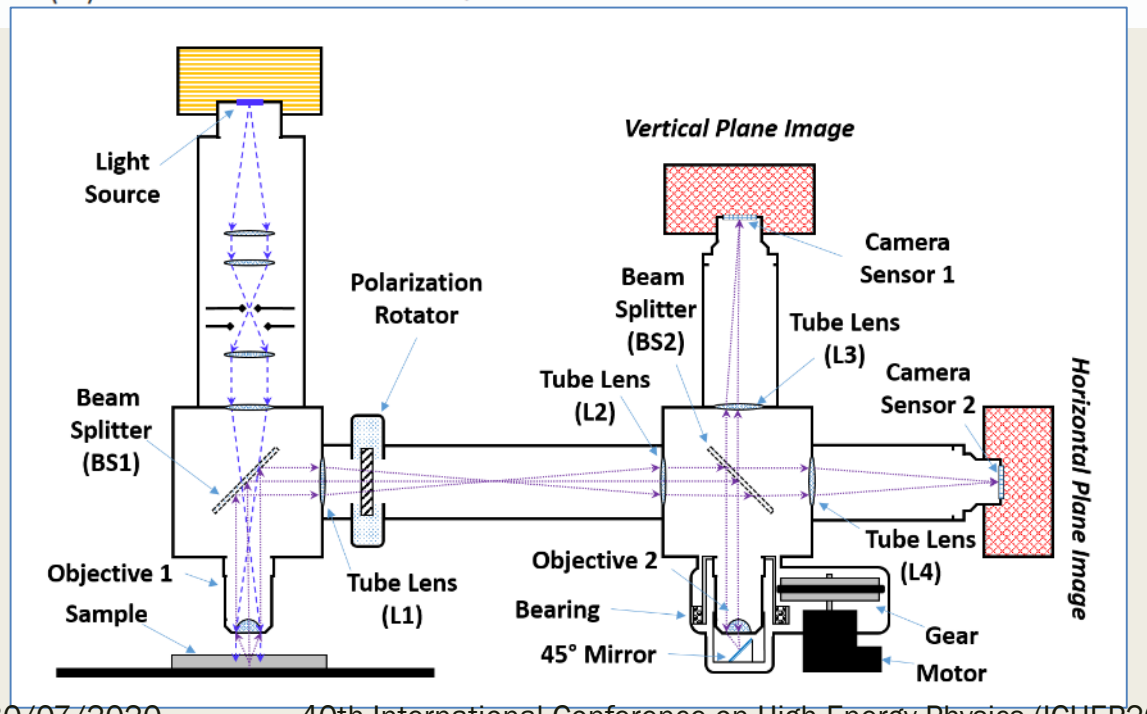
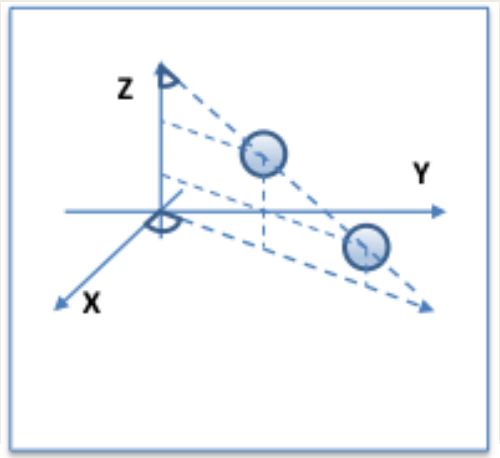
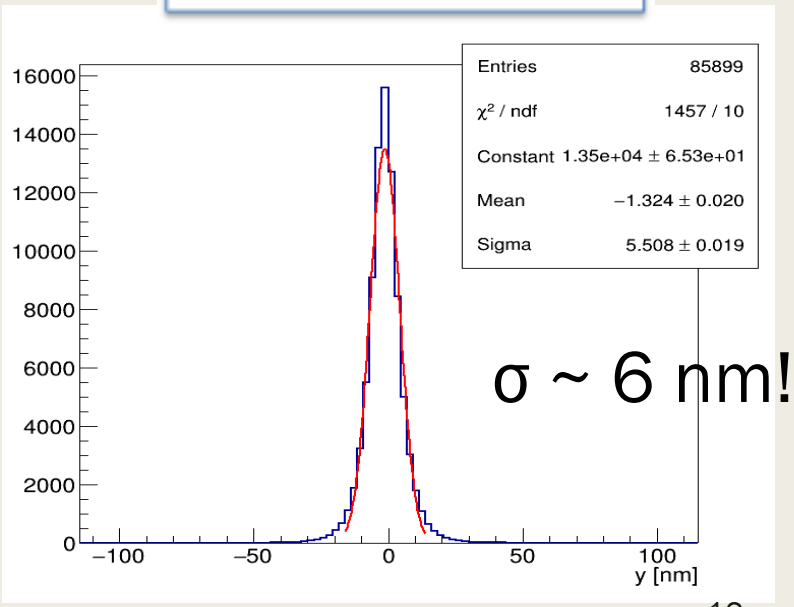
Agent: **SCILLETTA, Andrea**; IT

Priority Data: 102016000132813 30.12.2016 IT

Title **(EN)** METHOD AND OPTICAL MICROSCOPE FOR DETECTING PARTICLES HAVING SUB-DIFFRACTIVE SIZE
(FR) PROCÉDÉ ET MICROSCOPE OPTIQUE PERMETTANT DE DÉTECTER DES PARTICULES AYANT UNE TAILLE SOUS-



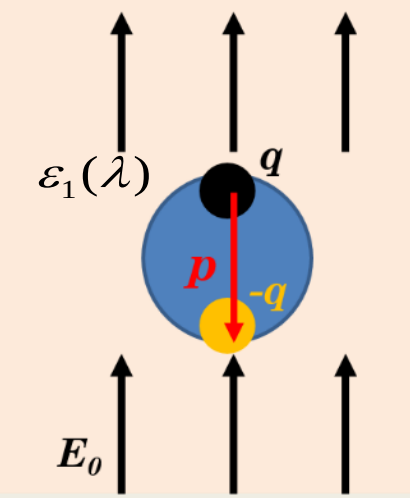




σ ~ 6 nm!

LSP (Localized Surface Plasmon) resonance

Annu. Rev. Phys. Chem. 58 (2007) 267-297



dipole in metallic particle

dipole moment

$$p = 4\pi\varepsilon_m a^3 \frac{\varepsilon_1(\lambda) - \varepsilon_m(\lambda)}{\varepsilon_1(\lambda) + 2\varepsilon_m(\lambda)} E_0$$

resonance

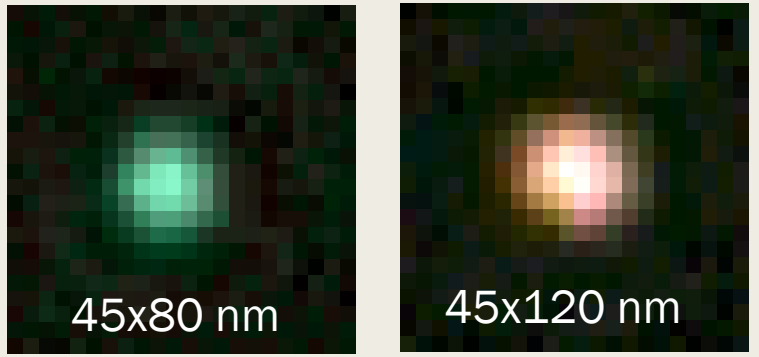
$$\varepsilon_1(\lambda_l) + 2\varepsilon_m(\lambda_l) \approx 0$$

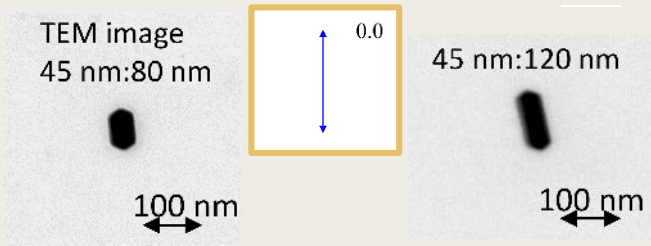
Appl. Phys. Lett. **80**, 1826 (2002)

Ag grain size ⟶ resonance wavelength

Colored optical image of silver rod

*polarization rotating





~45 nm : blue
~80 nm : green

~45 nm : blue
~120 nm :orange–red

LSP in the NIT emulsion

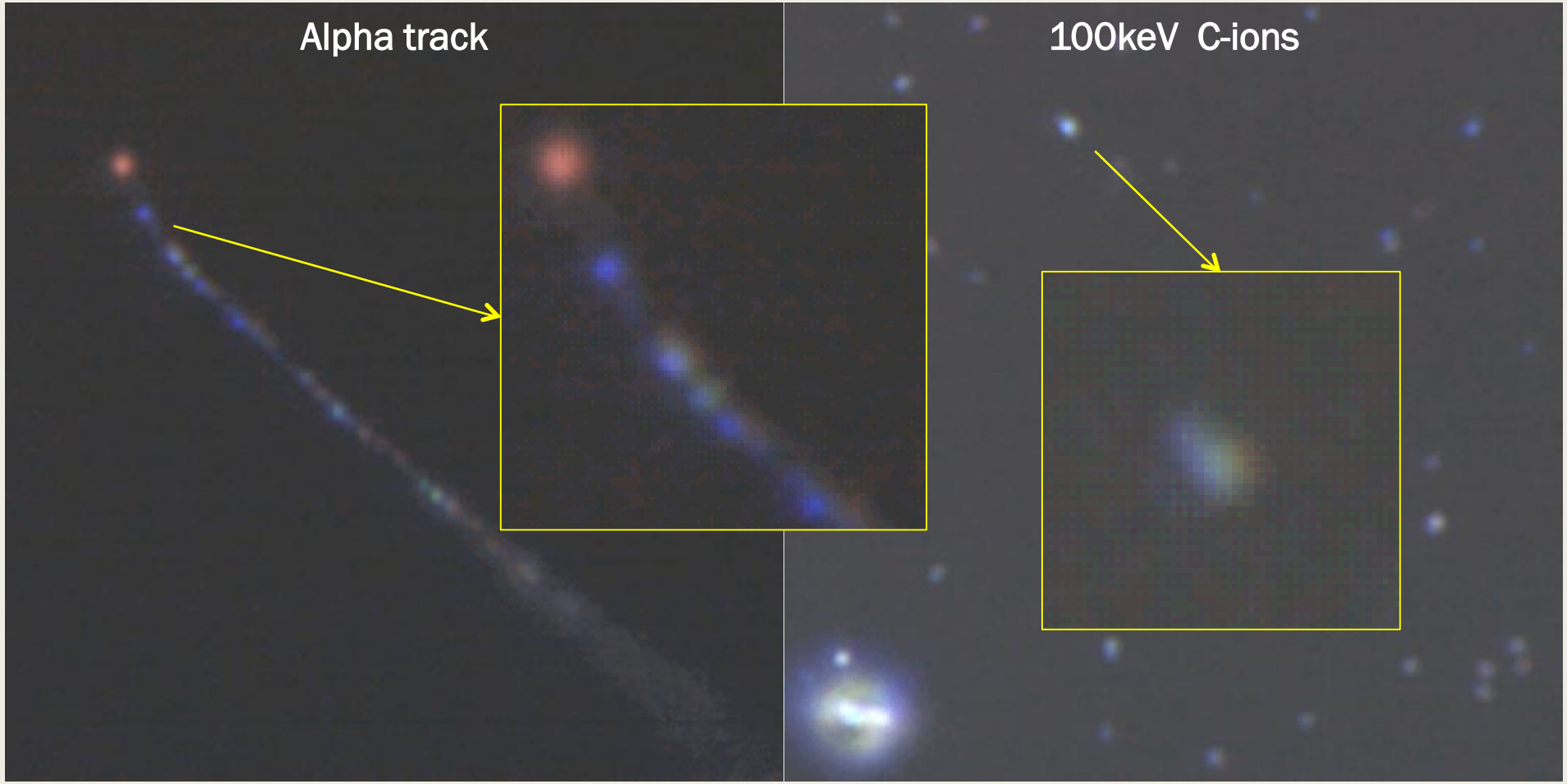


Image size 15 μm x 15 μm

Image size 15 μm x 15 μm

Head-tail discrimination!

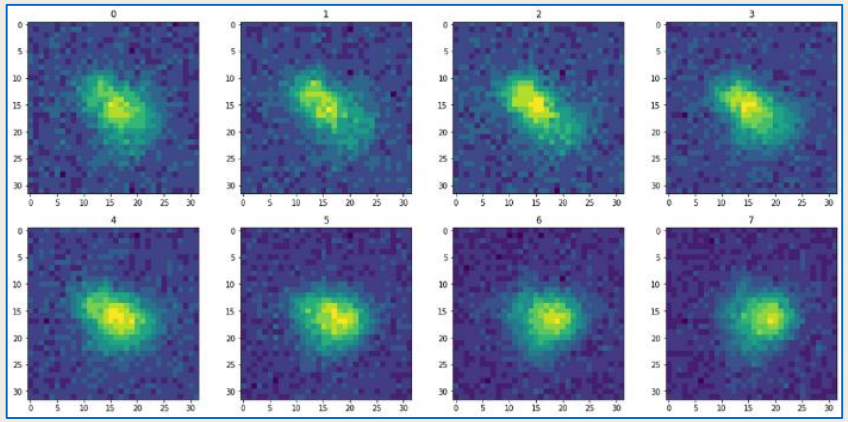
Machine Learning Approach

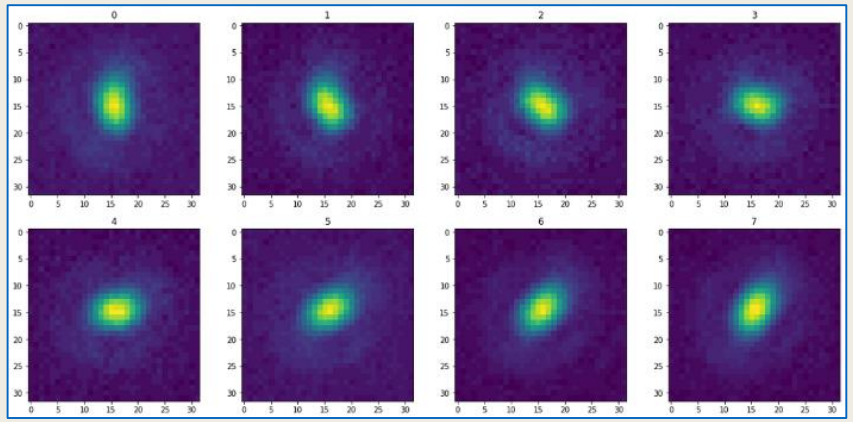
Experimental data

- **Signal:** samples exposed to C ions at different energies
- **Background:** gamma exposure, random fog

J. Phys.: Conf. Ser. (2020) 1525 012108

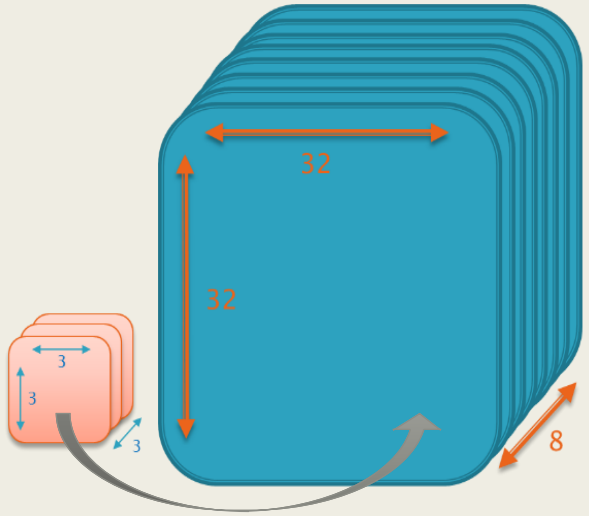
C100keV





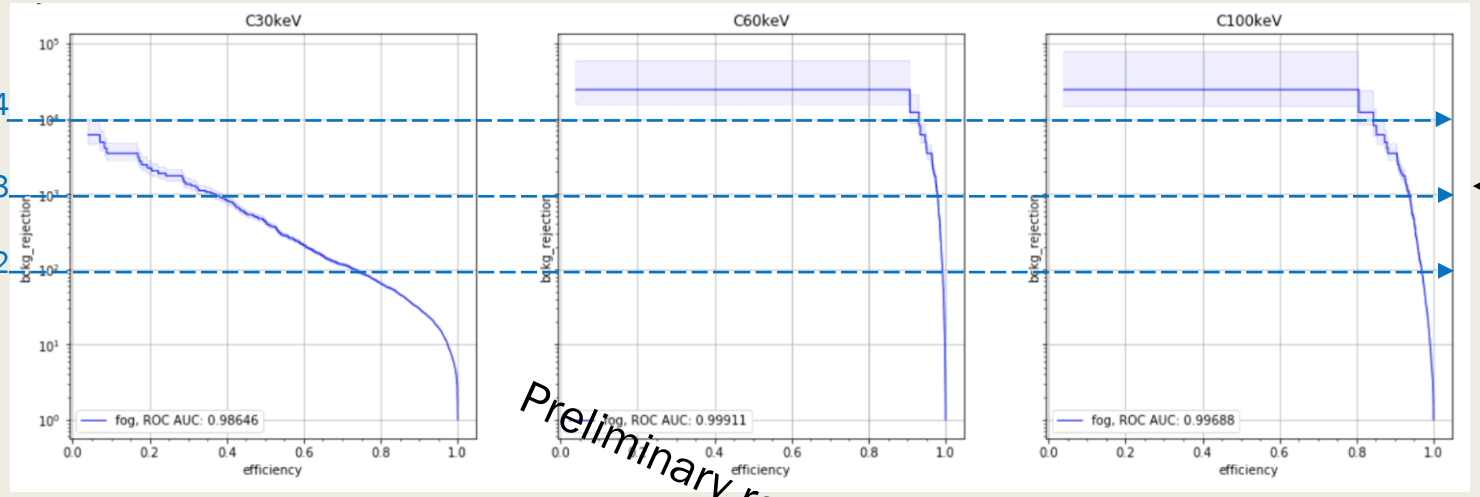
Fog

- 3D CONVOLUTIONAL NN: approach designed to work with images, capable of discovering complex features of images and gaining high performance
- Stacking together images for different light polarizations to obtain a 3D image



Machine Learning Analysis

Rejection power (against fog and dust)



10^4

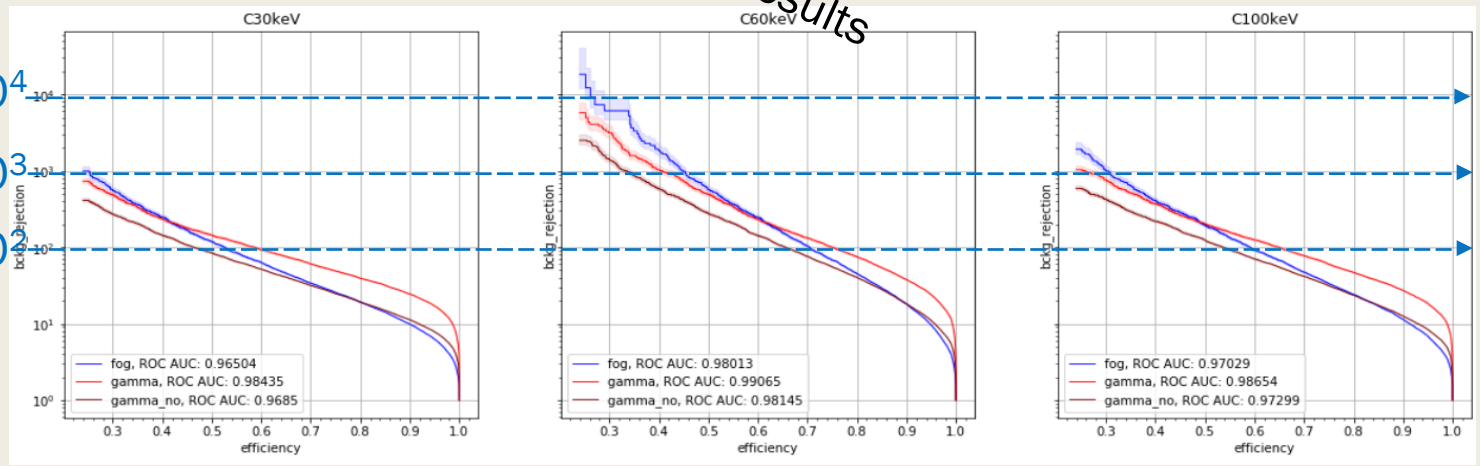
10^3

10^2

Color
(all polarizations)

Only color images, no polarization information

Preliminary results



10^4

10^3

10^2

Polarization
λ=460 nm

Only polarization, no color

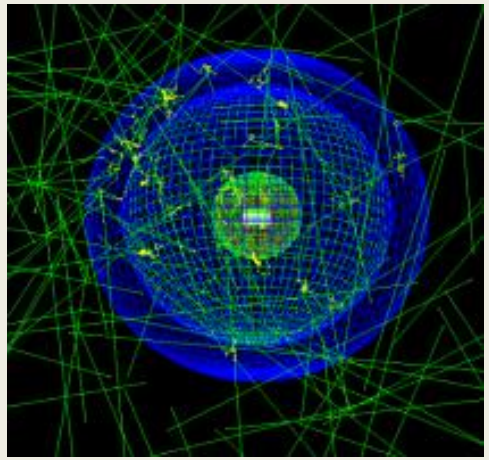
Next step: combine polarization and colour

Backgrounds

Intrinsic

Intrinsic Radioactivity	Rate [g × month]$^{-1}$	Rate [kg × year]$^{-1}$
Radiogenic neutrons	(5.0 ± 1.7) × 10^{-6}	0.06 ± 0.02
Intrinsic ß	33.7 ± 1.8	(4.04 ± 0.02) × 10^{6}

Astropart. Phys.. 80 (2016) 16–21



External (with 1 m HDPE shielding @LNGS)

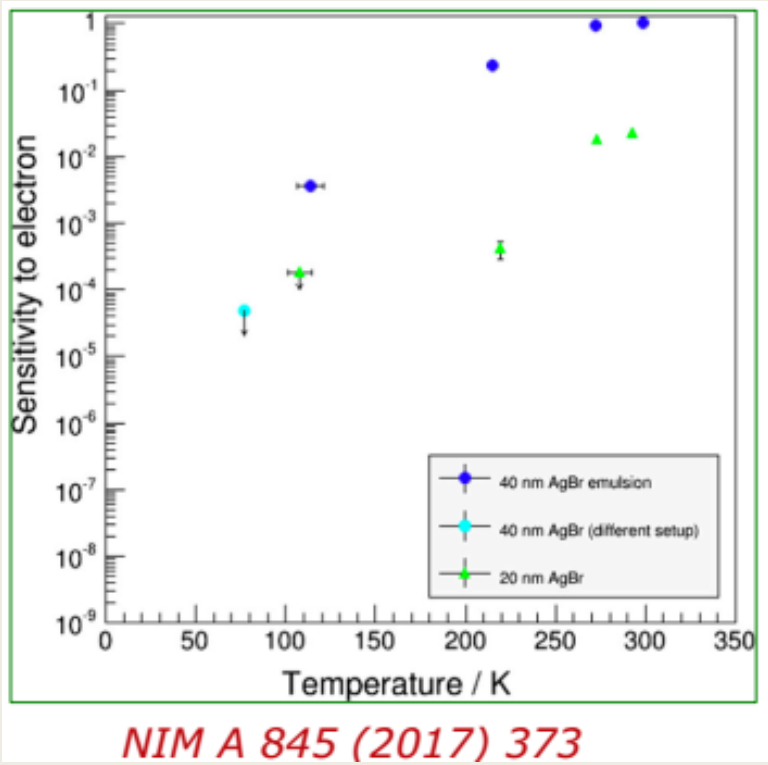
Source	Rate [10 kg × y]$^{-1}$
Environmental gammas	$(1.97 \pm 0.17) \times 10^4$
Environmental neutrons	$\mathcal{O}(10^{-2})$
Cosmogenic neutrons	1.41 ± 0.14

C14 and gamma;

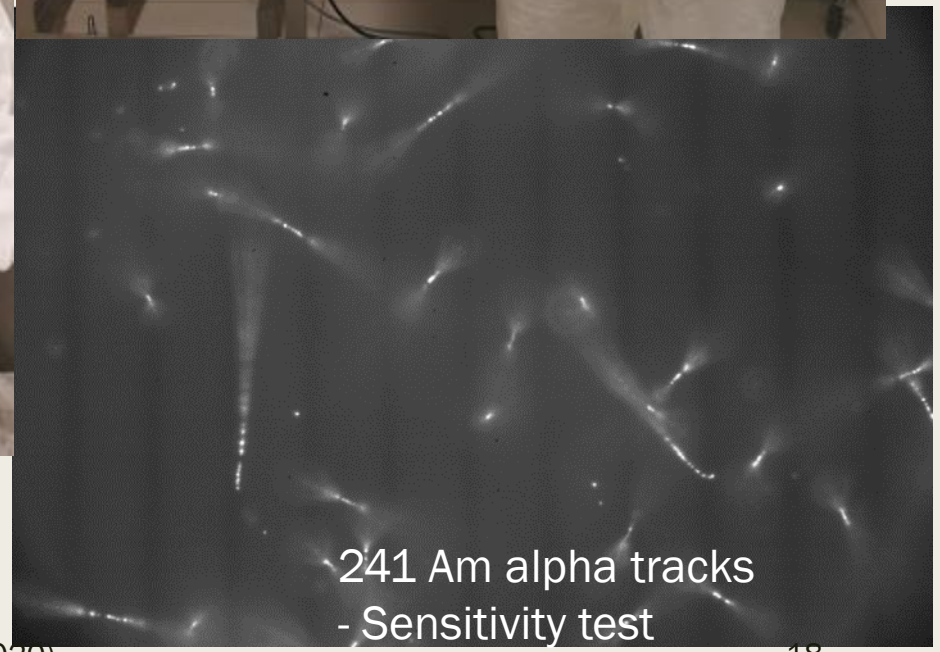
- **Strong reduction factor:** NIT emulsions insensitive to MIP and largely insensitive to electrons (~10^{-4})

Additional **level arms** being quantified:

- Dedicated chemical treatments
- Reduced sensitivity to electrons at low temperatures (10^{-4}@77K)
- Electron response to polarized light scattering (10^{-2}-10^{-3})
- Colour camera to distinguish nuclear recoils from electrons (10^{-3}-10^{-4})
- Replace the gelatin with synthetic polymers (final choice)
- Topological veto using MIP sensitive emulsions

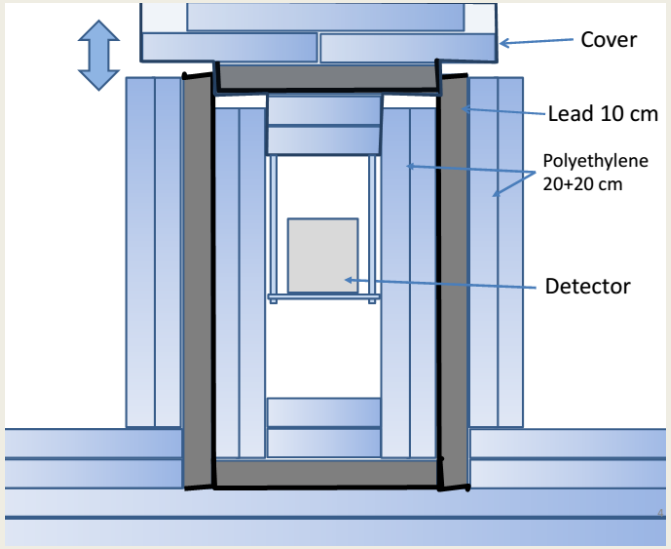


Underground emulsion production facility @LNGS

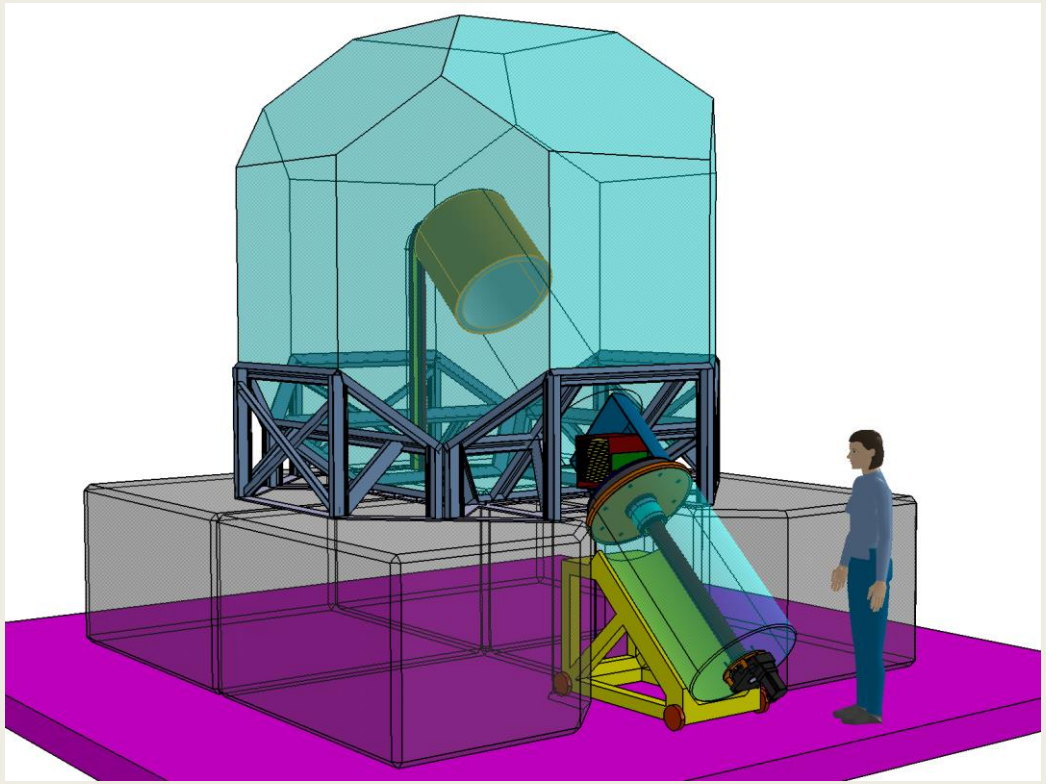


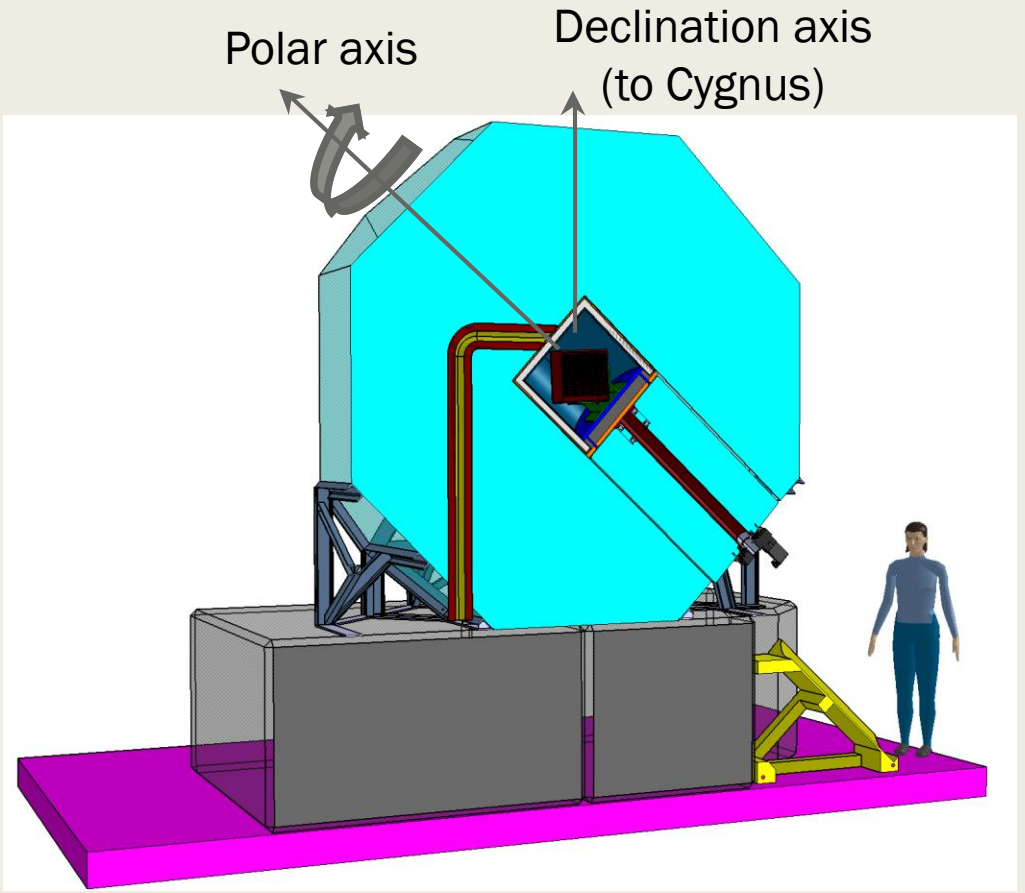
Fully operational since Feb-2019
Production capacity 100-200 g/day

Shielding prototype installed at LNGS hall B (for 10 g demonstrator run)

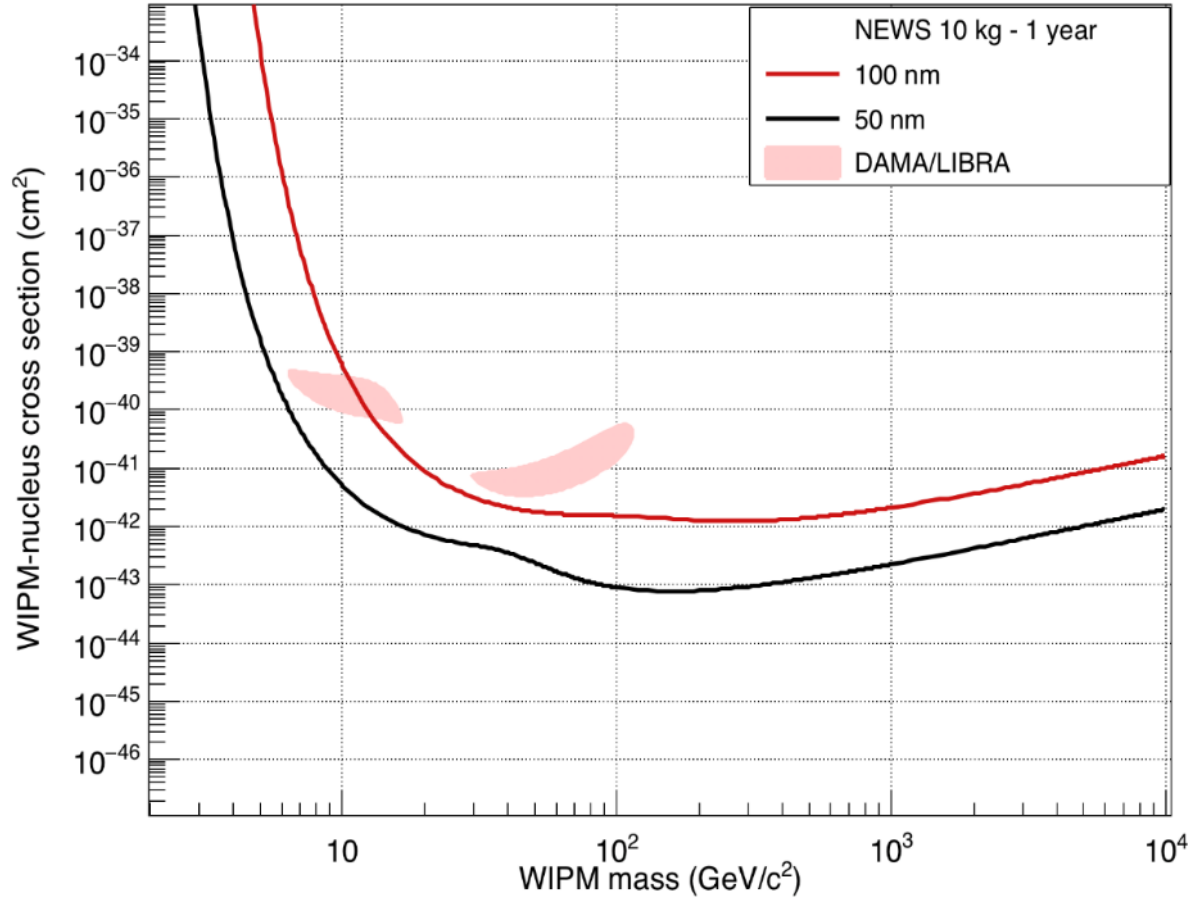


Equatorial telescope inside shielding (for 10-kg-scale physics run)





Sensitivity of a pilot experiment 10 kg scale



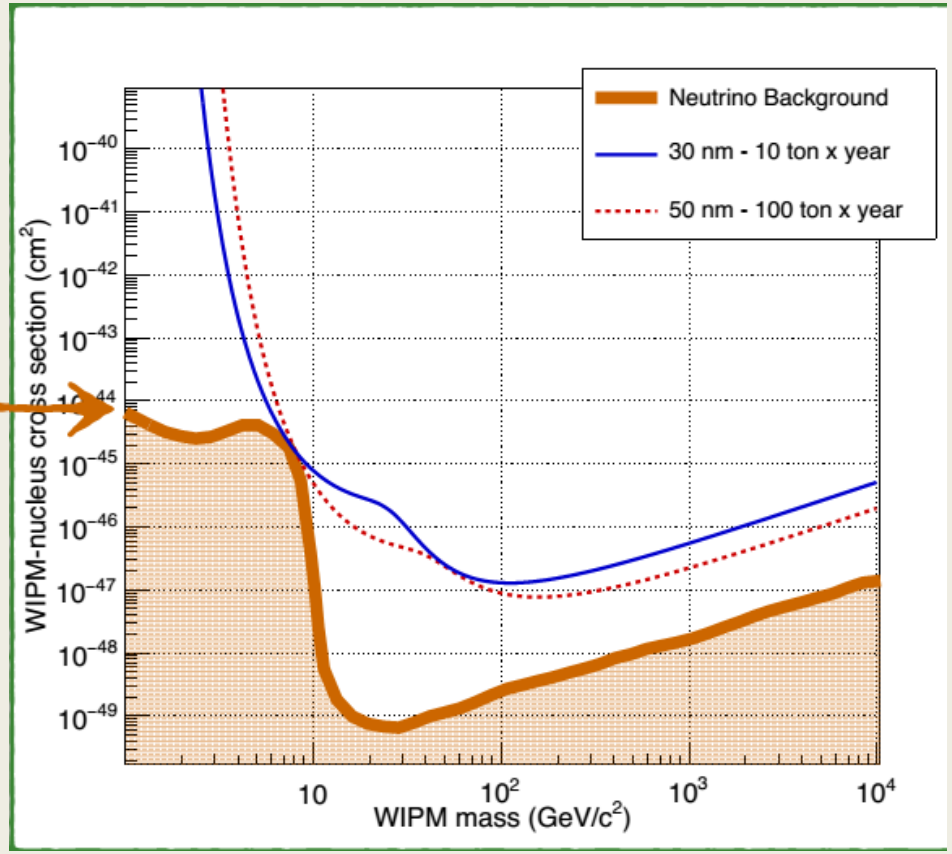
- 10kg x year experiment
- Zero background assumed
- Directionality not exploited

Towards Neutrino Floor

NEWSdm Collaboration
Eur.Phys.J. C78 (2018) no.7, 578

- Discrimination based on measurement of recoil direction
- Unique possibility to search for WIMP signal beyond “neutrino floor”

Neutrino coherent scattering indistinguishable from WIMP interactions
Phys.Rev.D89 (2014) no.2, 023524 (Xe/Ge target)



REQUIREMENTS

- Larger mass scale detector
- Reduction of track length threshold

The neutrino bound is reached with:
➞10 ton x year exposure if 30 nm threshold
➞100 ton x year exposure if 50 nm threshold

Conclusion

- Nano-grain emulsion based, high resolution detector for a directional Dark Matter search is under development
- Technological break-through for optical readout makes possible fast analysis of O(100nm) tracks: 2D and 3D super-resolution, head-tail, color information
- Machine learning approach to handle the data complexity
- Emulsion production underground is established, experimental tests ongoing to reproduce the full analysis chain
- Autumn 2020 run: 10 g detector as the technology demonstrator
- Future goal: ~10 kg scale detector for the first physics run
- TDR is under preparation

THANK YOU FOR ATTENTION!

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For further discussion:
Meeting ID: 960 6793 4407