# THE NEWSdm EXPERIMENT FOR DIRECTIONAL DARK MATTER SEARCHES

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# NEWSdm COLLABORATION

Nuclear Emulsion WIMP Search directional measurement

**81 physicists**
**23 institutes**

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

**JAPAN**
Chiba, Nagoya, Toho, Tsukuba

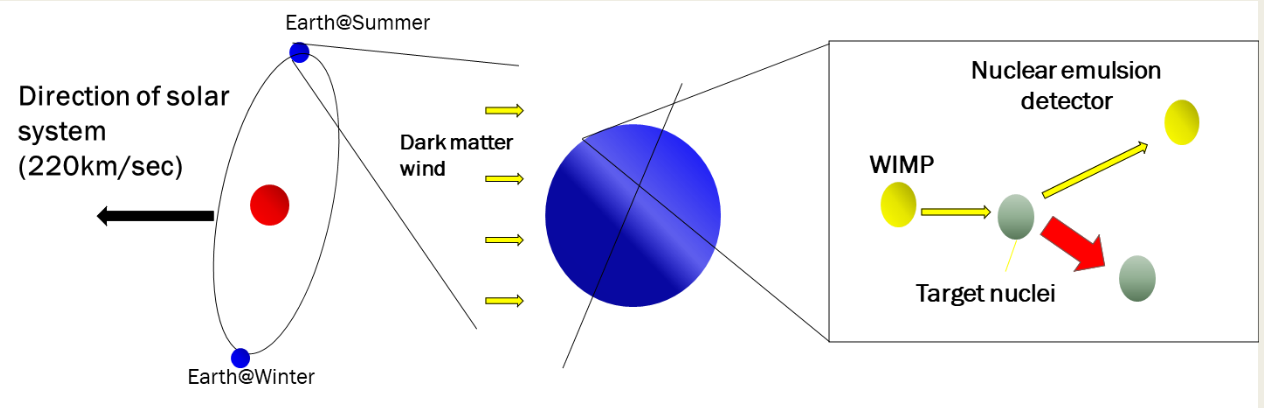
**SOUTH KOREA**
Gyeongsang University

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

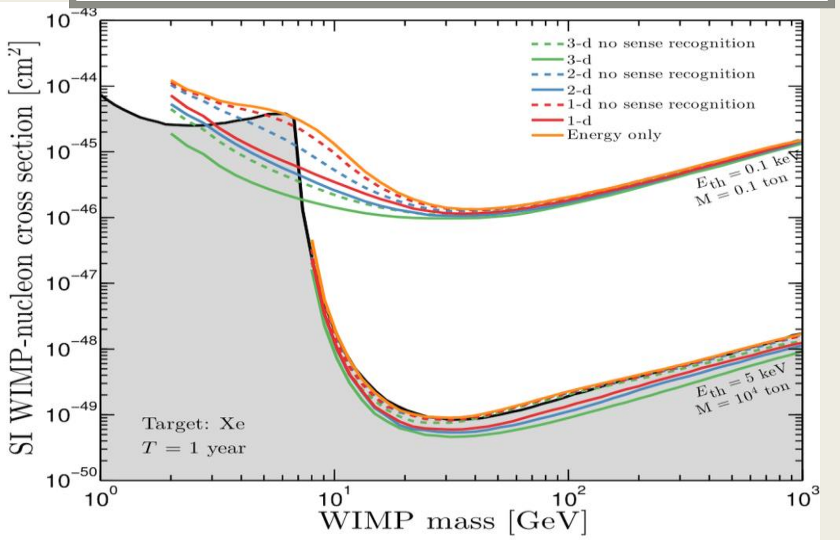
**TURKEY**
METU Ankara

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

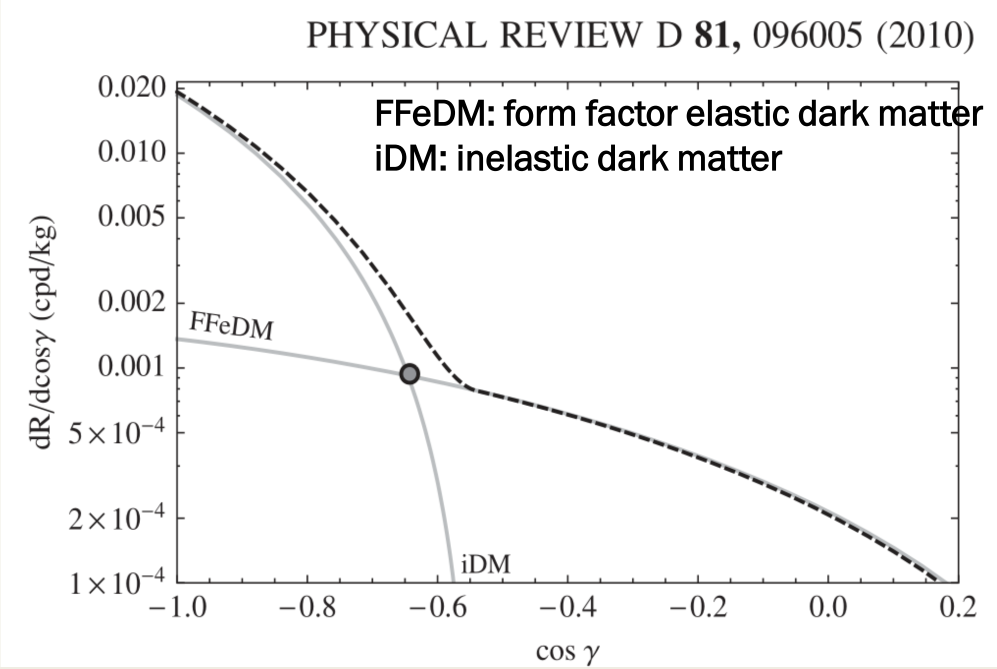
# Advantage of DM directionality knowledge



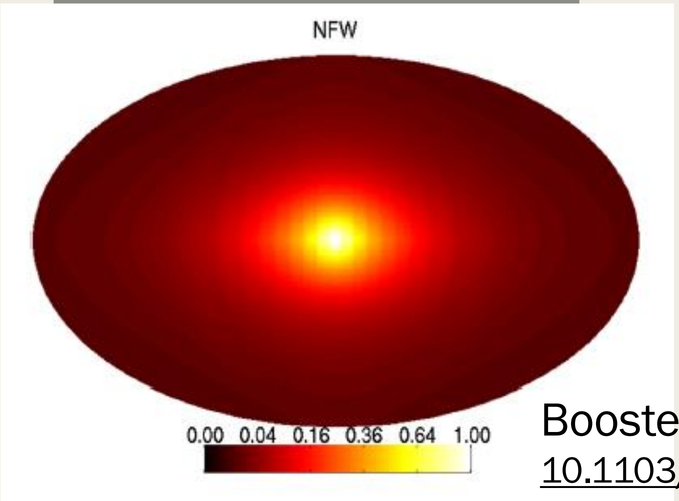

## Overcoming the Neutrino Floor




Physics Reports 627 (2016) 1



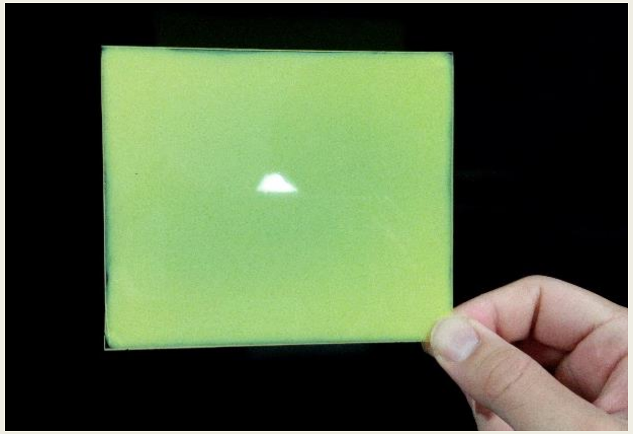

## Directional property

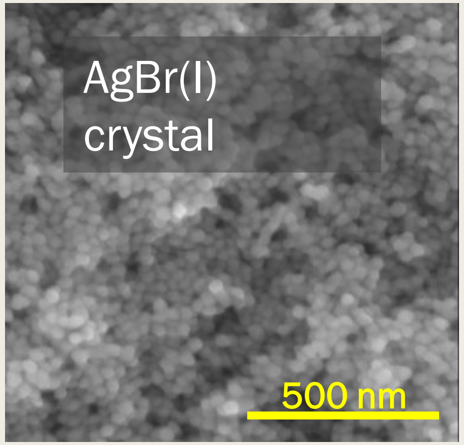



Boosted dark matter

10.1103/PhysRevLett.126.091804

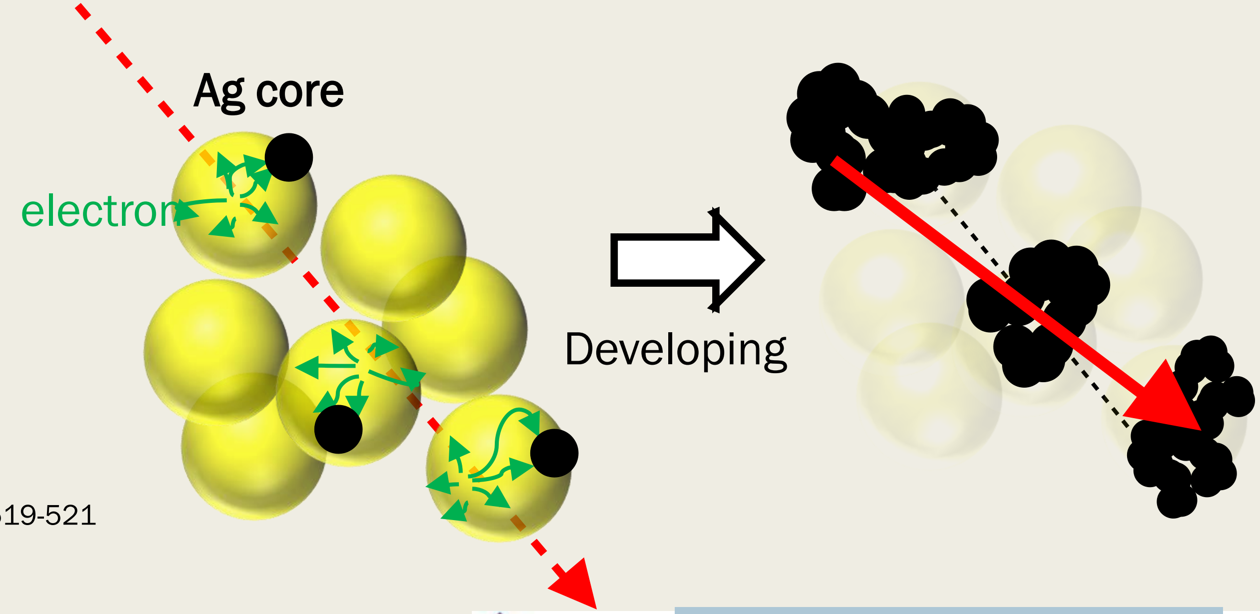
# Nano Imaging Tracker (NIT) developed for NEWSdm






Density : 3.1 ± 0.1 g/cm3
Crystal size : 20÷80 nm (tunable)

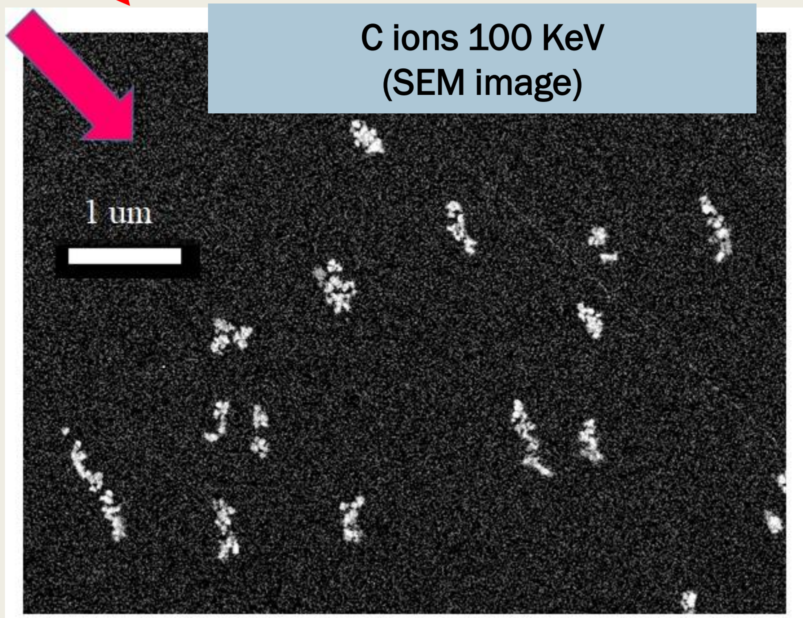
NIM A Nucl. Inst. Meth. A 718 (2013) 519-521
PTEP (2017)063H01



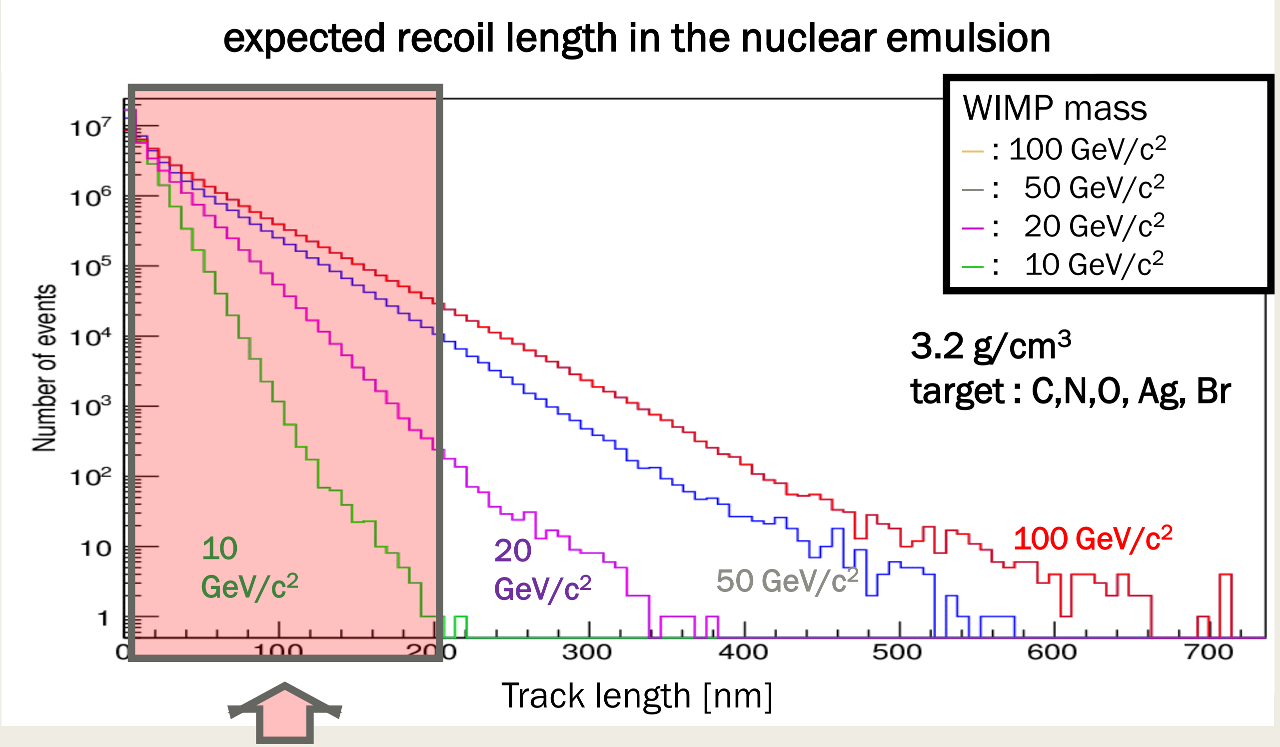

| Group | | Mass fraction | Atomic Fraction |
|---|---|---|---|
| Heavier DM | Ag | 0.44 | 0.10 |
| Heavier DM | Br | 0.32 | 0.10 |
| Heavier DM | I | 0.019 | 0.004 |
| Lighter DM | C | 0.101 | 0.214 |
| Lighter DM | O | 0.074 | 0.118 |
| Lighter DM | N | 0.027 | 0.049 |
| neutron | H | 0.016 | 0.410 |
| | S, Na + others | ~ 0.001 | ~ 0.001 |

**Solid-state detector**
**Density: 3.1 g/cm$^3$**

**High-speed volume analysis for nanometric tracks is required**

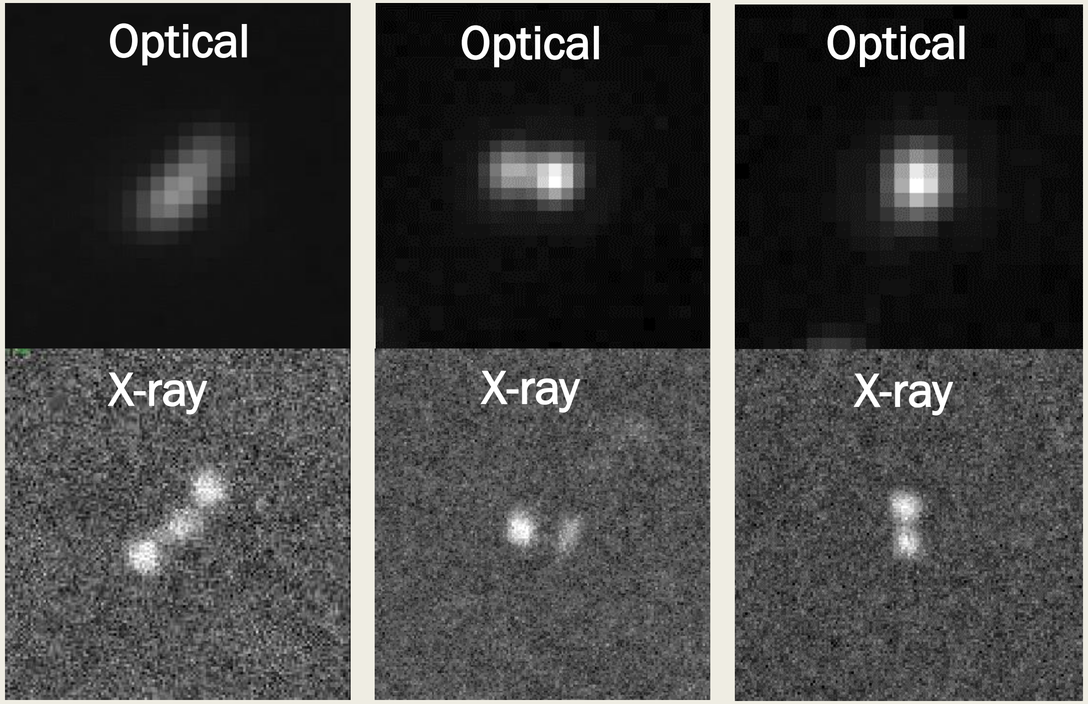


# Directional detection challenge




Inaccessible due to diffraction limit

400 keV Kr ion

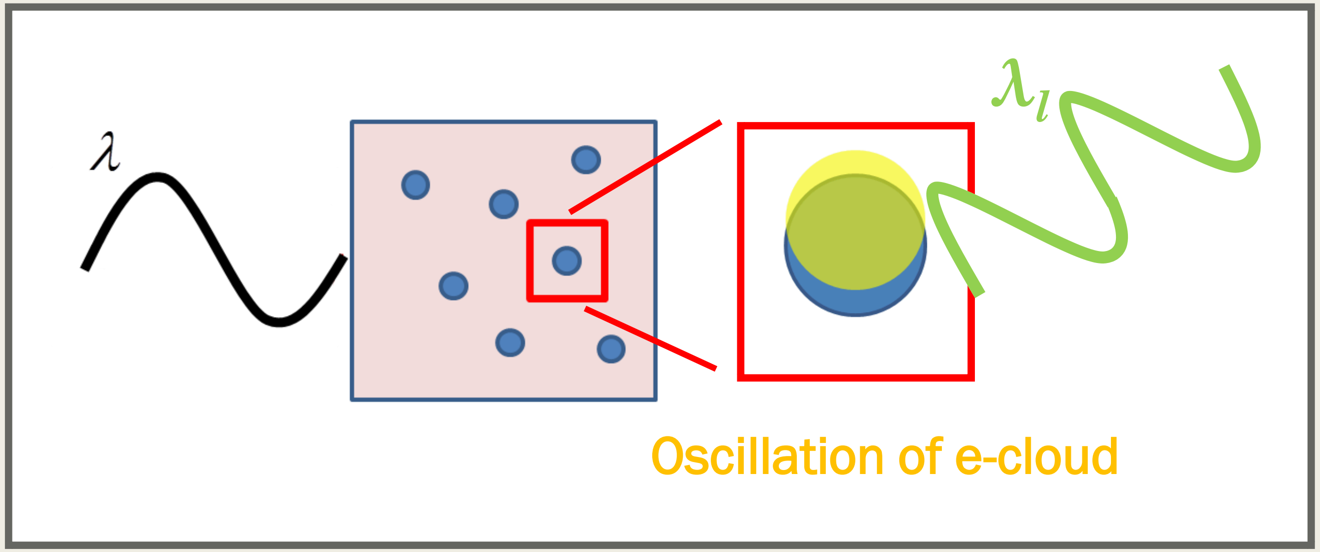


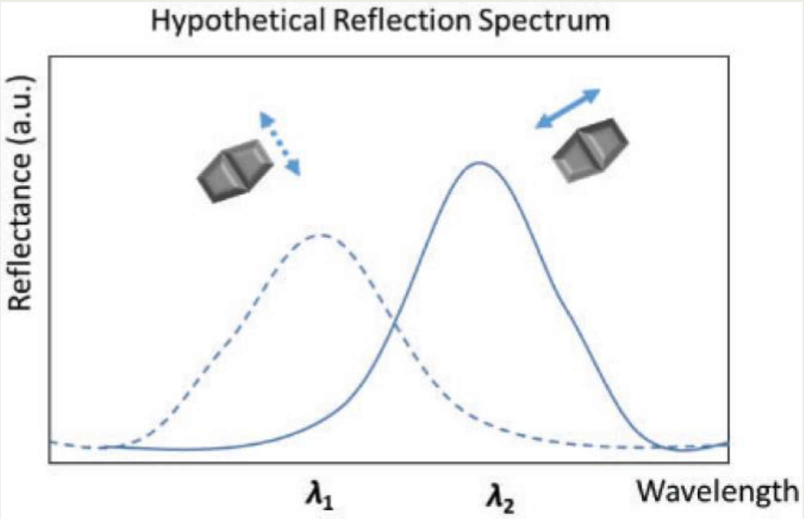

L = 380 nm L = 265 nm L = 160 nm

Need super-resolution to measure tracks shorter than 200 nm

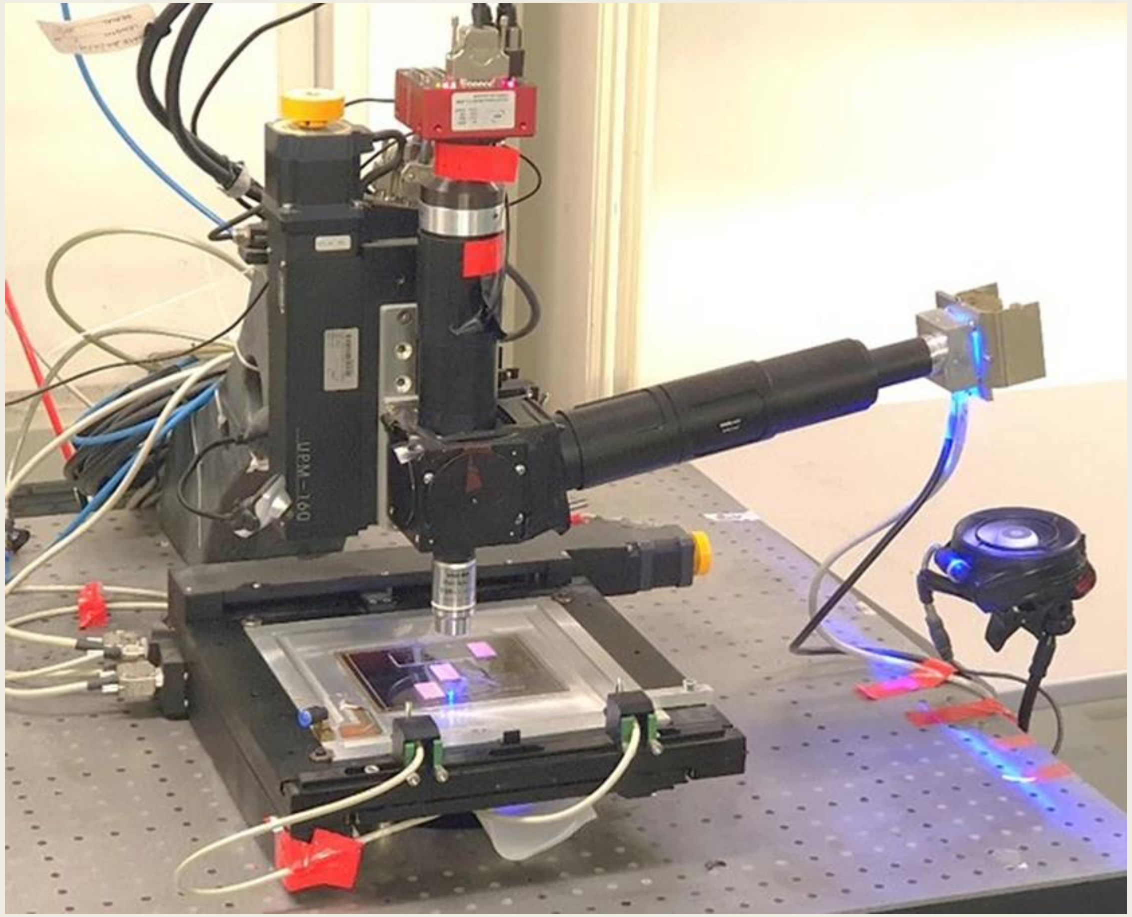
# Optical readout beyond the diffraction limit

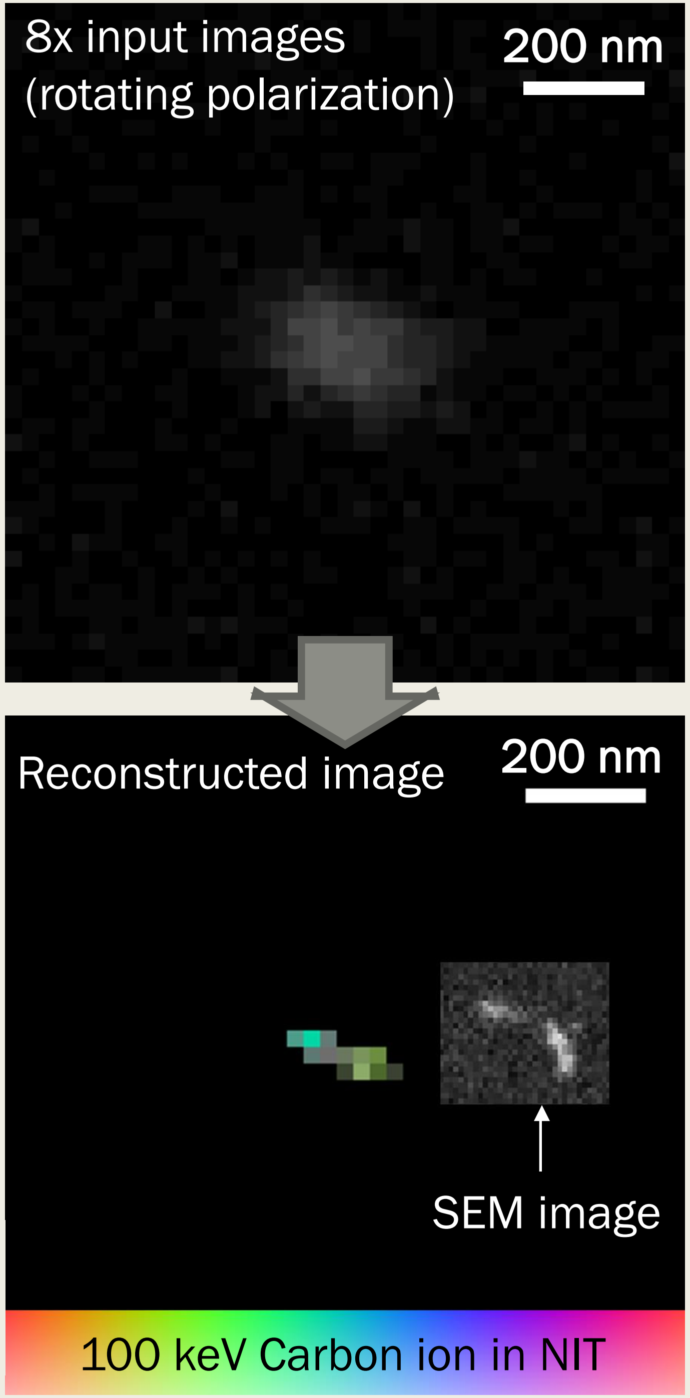
- Super-resolution idea: use the **plasmon resonance** effect to overcome the diffraction limit:
  - *generated by a light wave trapped within conductive nanoparticles smaller than the wavelength of light*
  - *resonant frequency strongly depends on the composition, size, geometry, dielectric environment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



# LSPR-based super-resolution imaging based on join deconvolution set of 8 polarized images

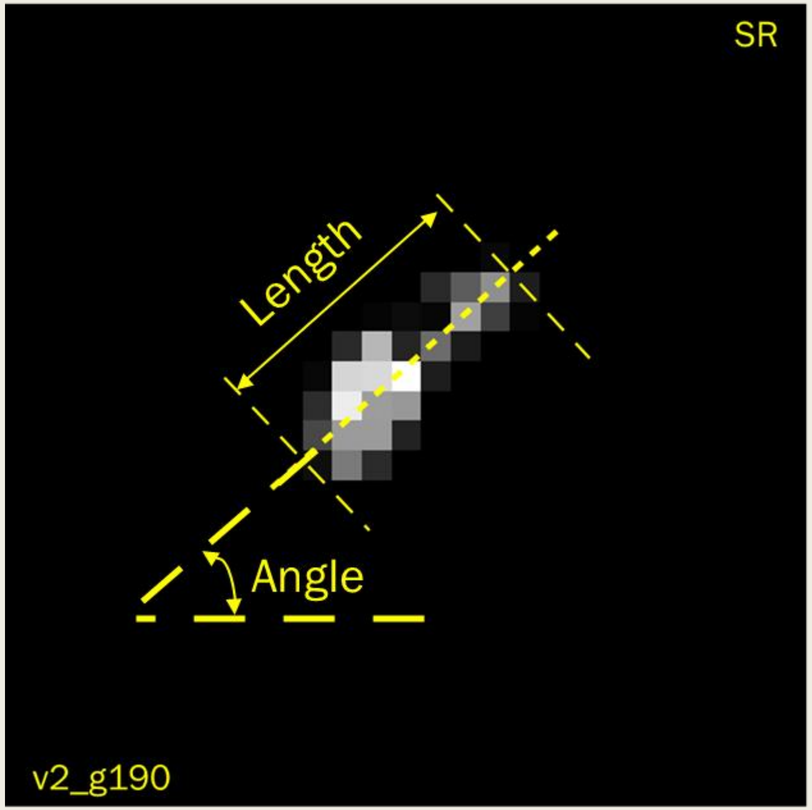


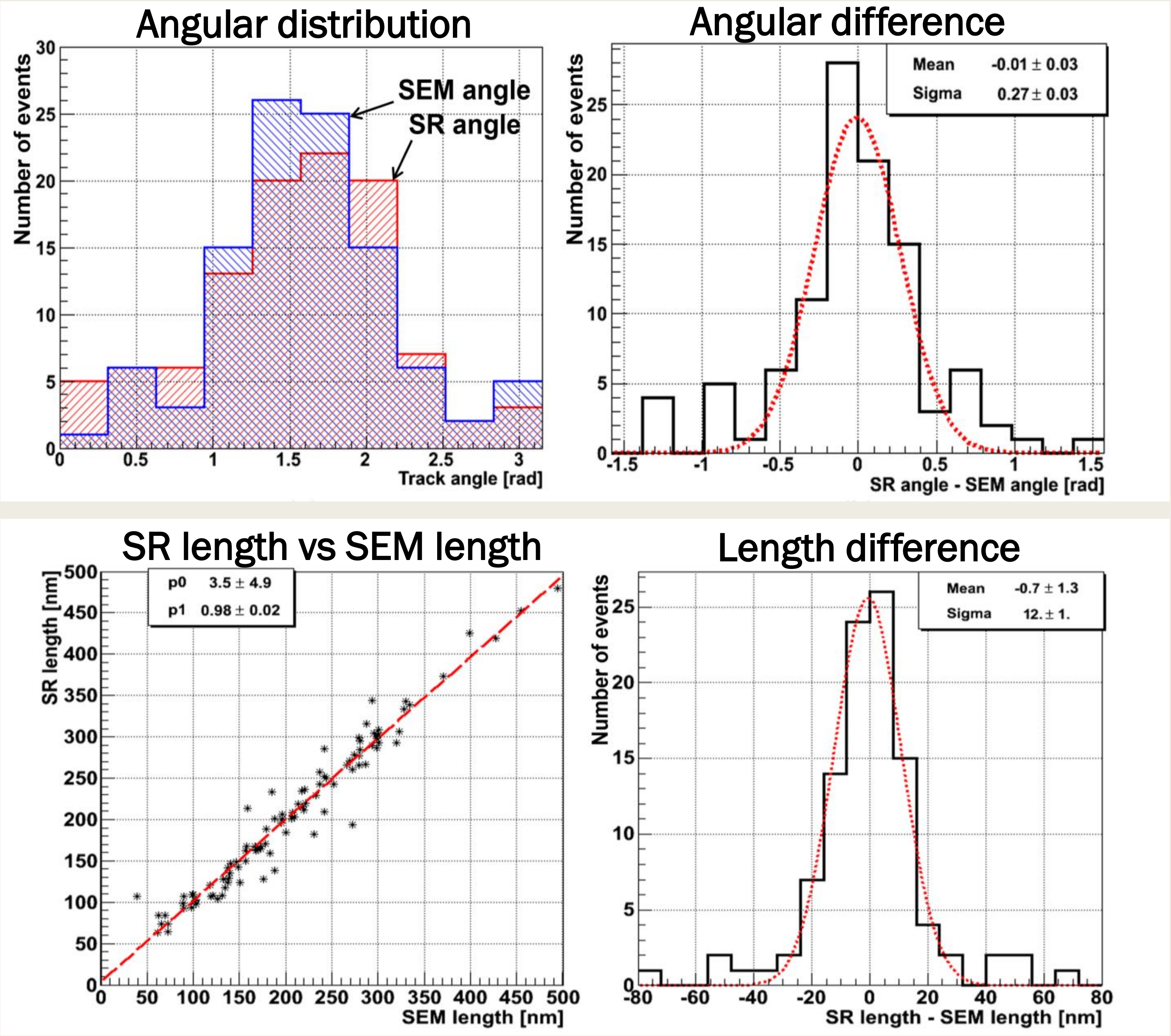



Event 2-162

**Alexandrov, A.,** ***et al.*** **Super-resolution high-speed optical microscopy for fully automated readout of metallic nanoparticles and nanostructures.**
***Sci Rep*** **10, 18773 (2020). https://doi.org/10.1038/s41598-020-75883-z**

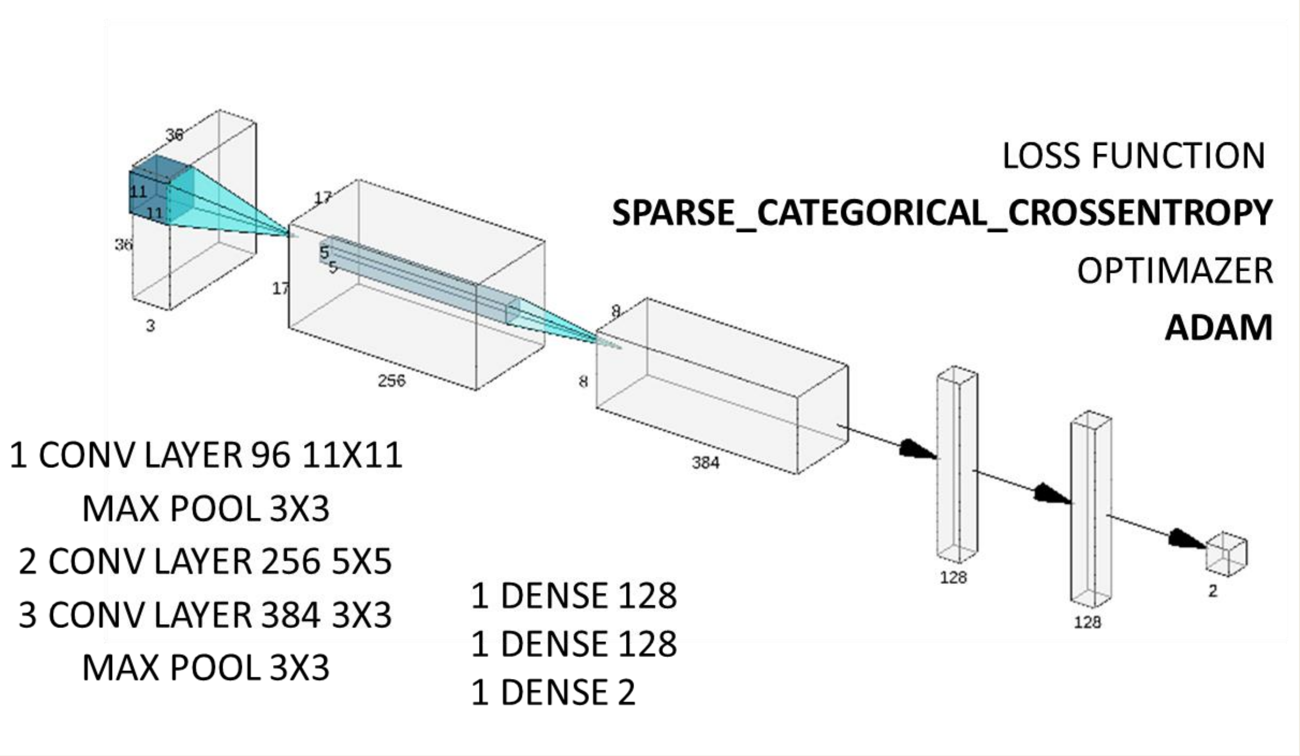
# Joint Image Deconvolution - Comparison with SEM

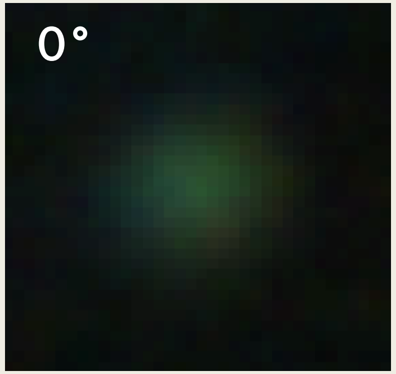


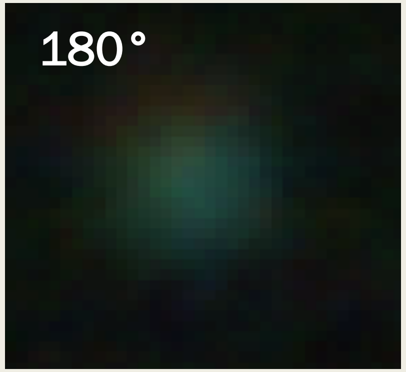




**Angular resolution: 270 ± 30 mrad**
**Length accuracy: 12 ± 1 nm**
**Spatial resolution: ~ 60 nm**
**NIT granularity: 71 nm**

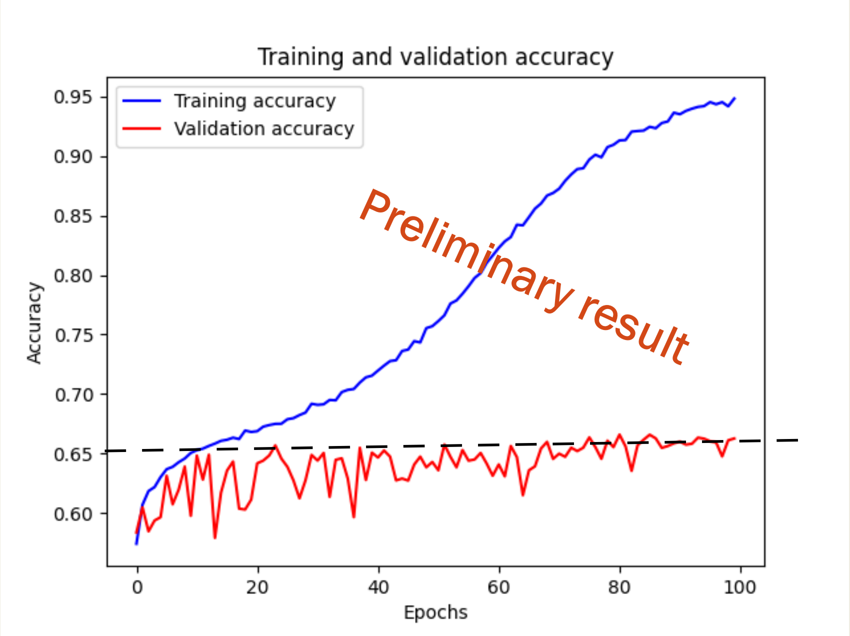
# Sense recognition with color
## Machine Learning approach




Carbon ion 100 keV




Sense prediction accuracy = 65%

# Backgrounds

External (with 1 m HDPE shielding @LNGS)

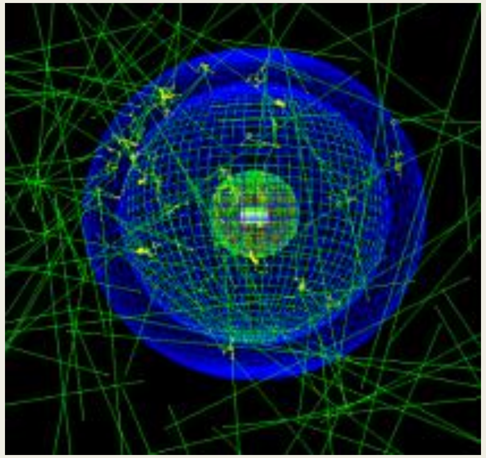
| Source | Rate $[10\ \mathrm{kg} \times \mathrm{y}]^{-1}$ |
|---|---|
| Environmental gammas | $(1.97 \pm 0.17) \times 10^4$ |
| Environmental neutrons | $\mathcal{O}(10^{-2})$ |
| Cosmogenic neutrons | $1.41 \pm 0.14$ |

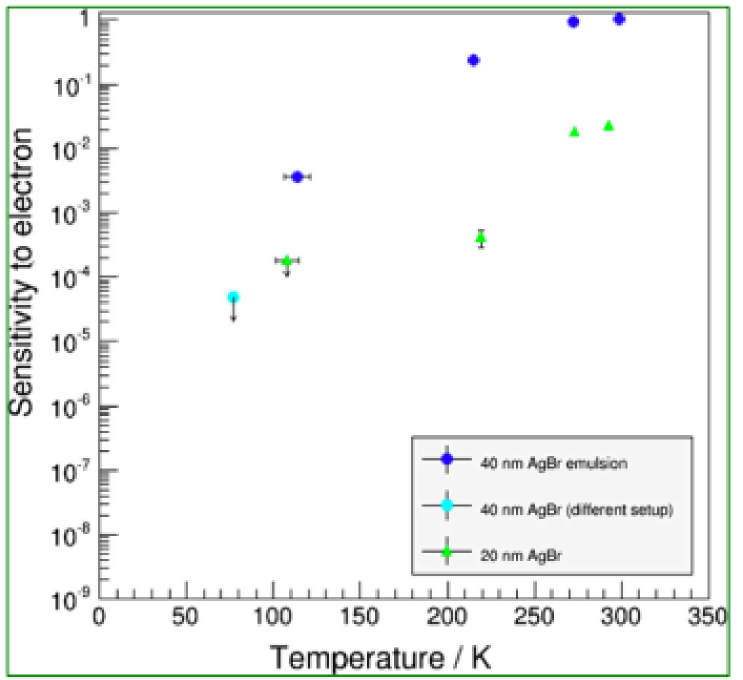
Intrinsic (Astropart. Phys.. 80 (2016) 16–21)

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

Additional **level arms** being quantified:

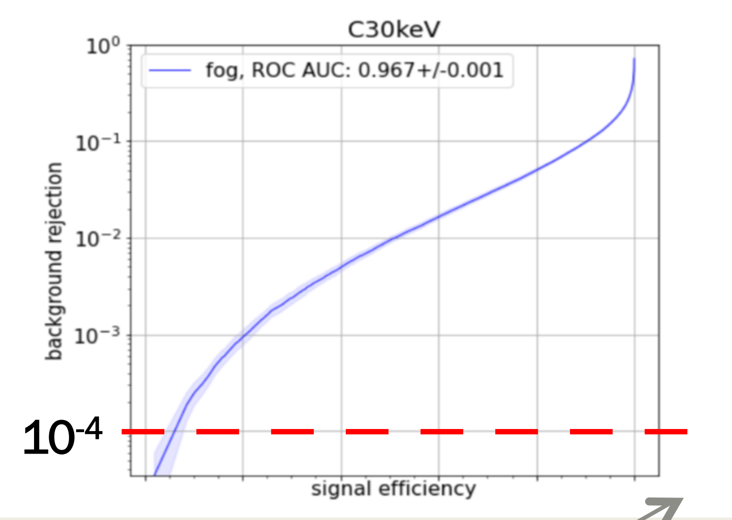
- Dedicated chemical treatments
- Reduced sensitivity to electrons at low temperatures ($10^{-4}$@77K)
- Electron response to polarized light scattering ($10^{-3}$-$10^{-4}$)
- Plasmon wavelength difference for electron and ion tracks ($10^{-3}$-$10^{-4}$)
- Replace the gelatin with synthetic polymers (final choice)

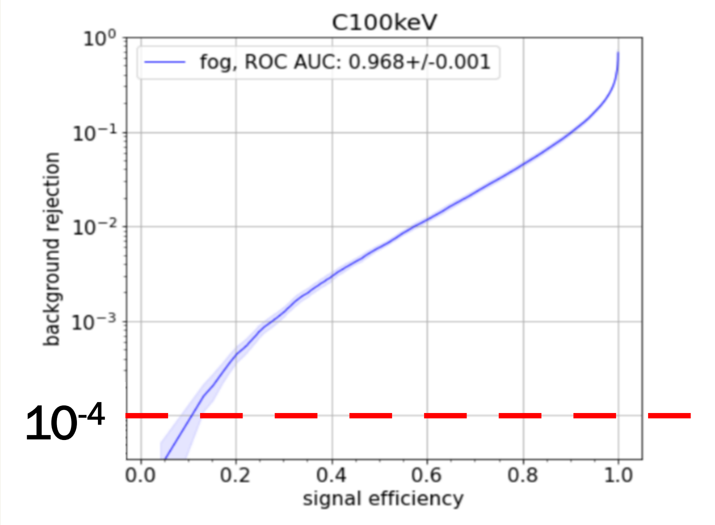




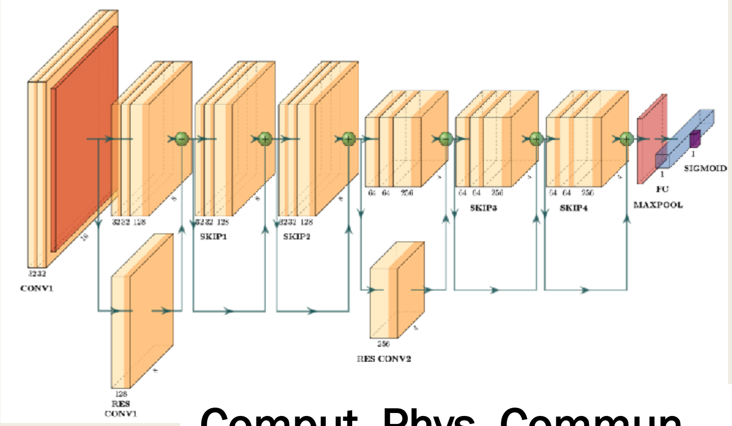

*NIM A 845 (2017) 373*

# Background reduction: Machine Learning approach



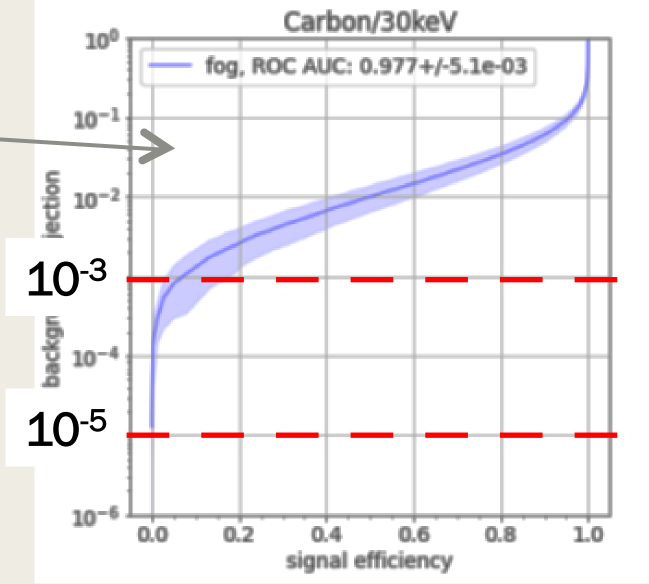

Schematic view of the CNN architecture

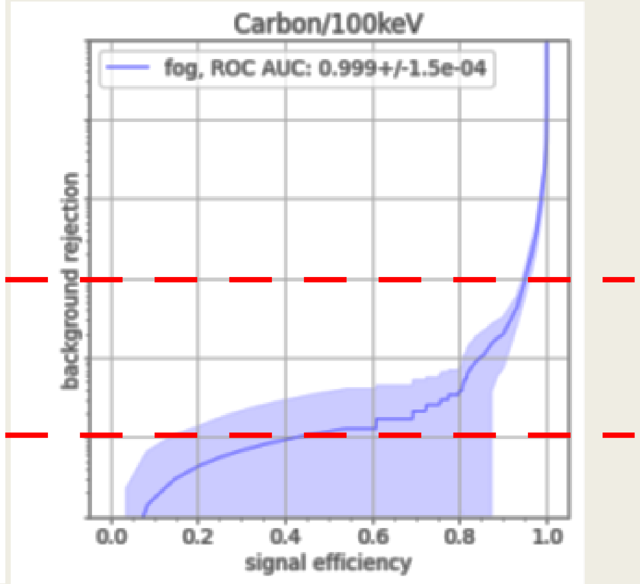



Comput. Phys. Commun. 275 (2022) 108312

Only polarization data

Only colour data

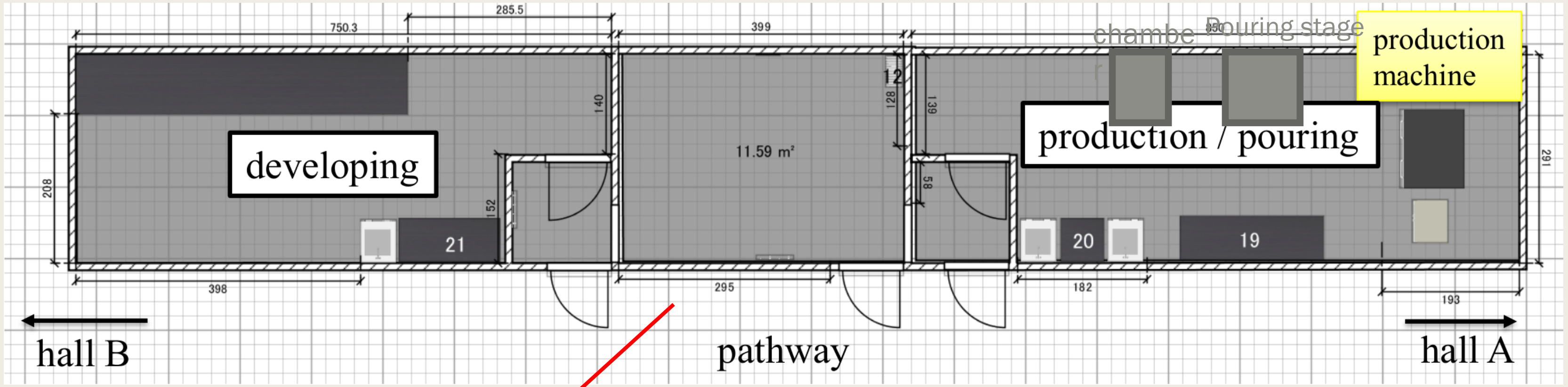


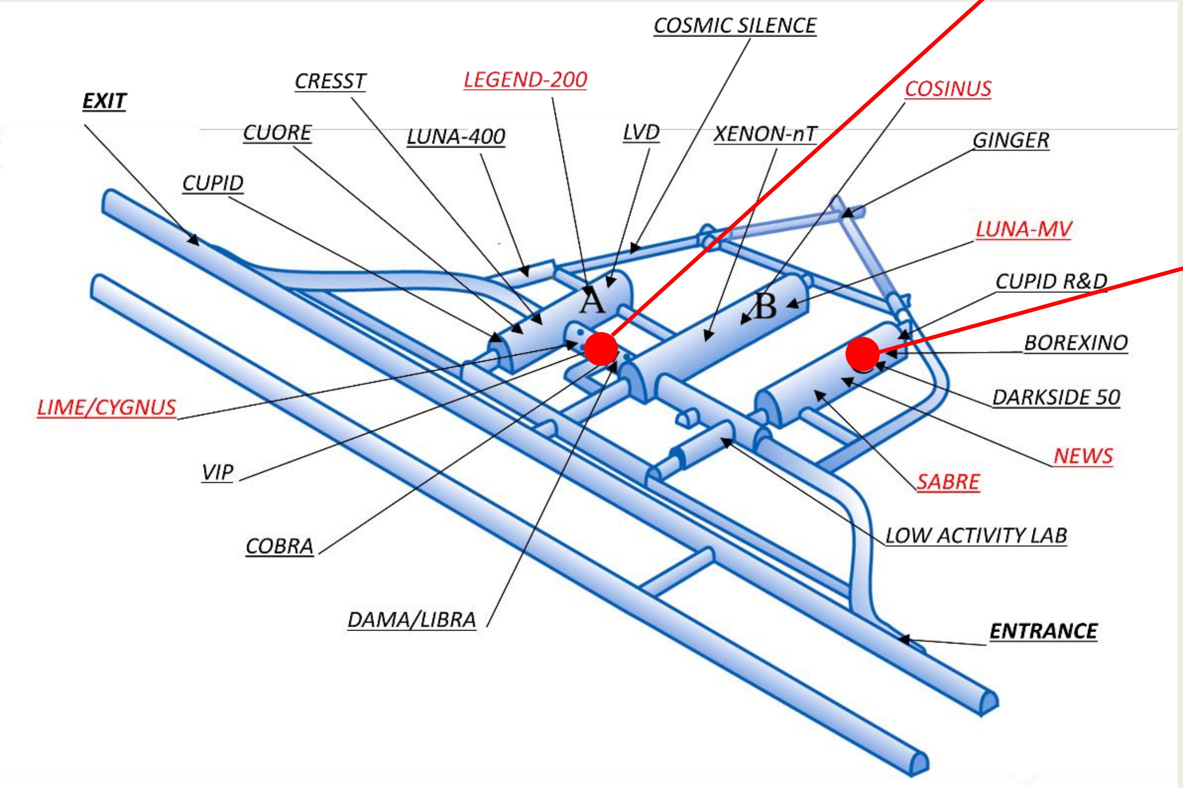




Background reduction factor and efficiency for different thresholds on ML probability-like output on **validation** data

# NEWSdm underground facility and detector

Hall F




Hall C

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

# 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

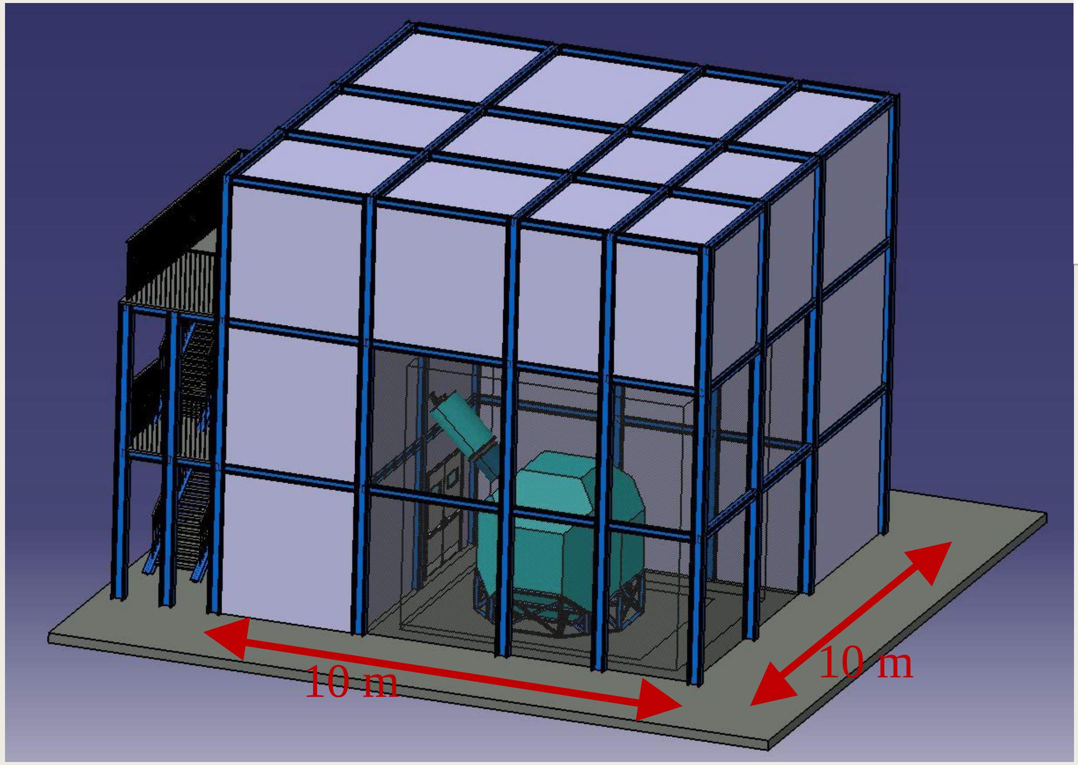
*Development room*

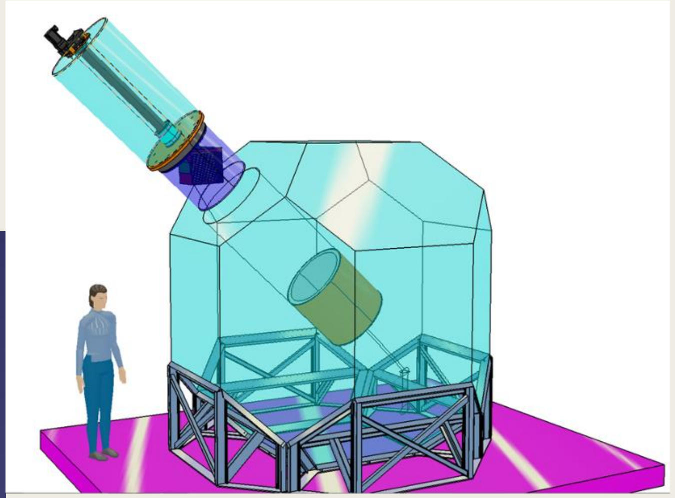

*Gel production room*

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

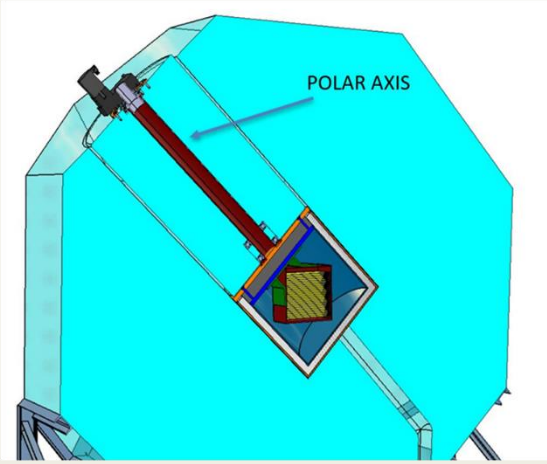
# Future facility for NEWSdm: 10kg and beyond

Emulsion facility and shielding with an equatorial telescope

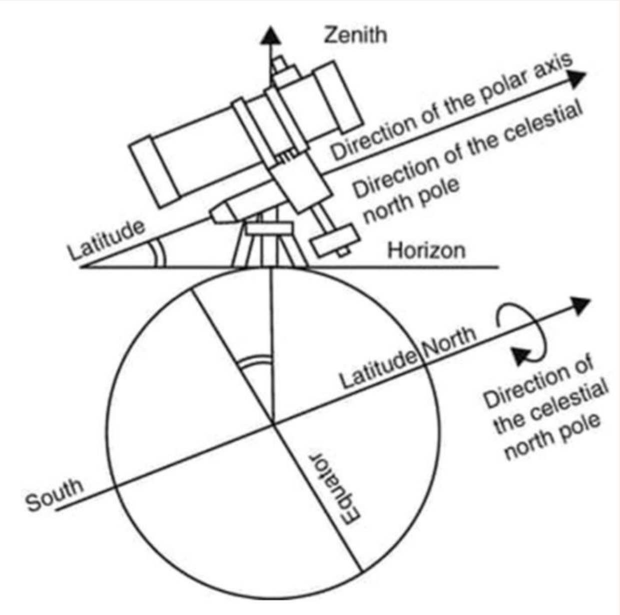


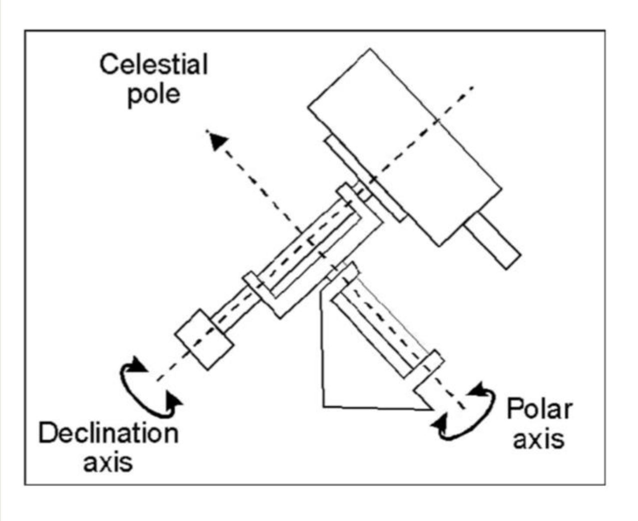



(a)



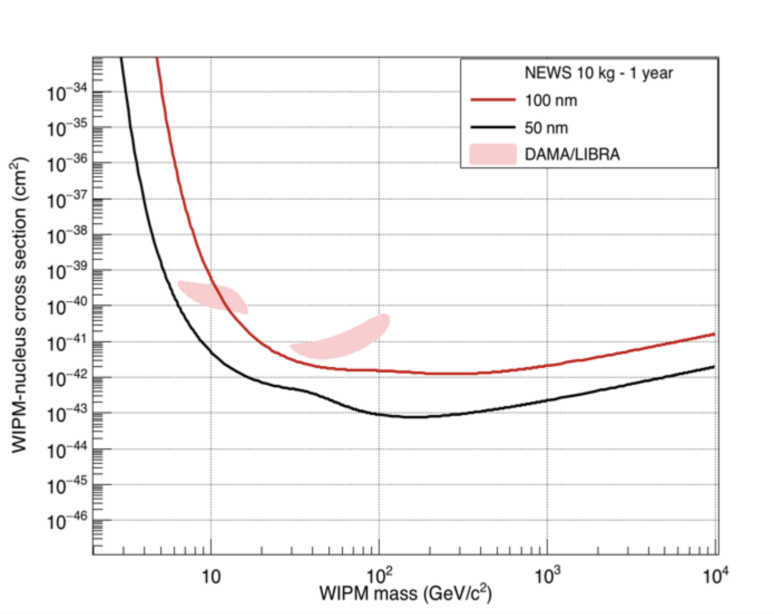

(b)



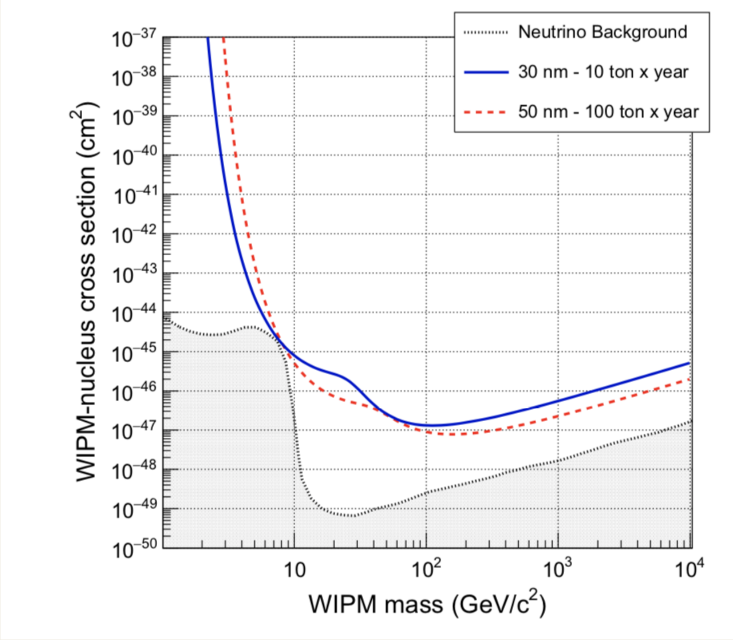



# NEWSdm intermediate and final goals

- 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
- Fist BDM directional measurement
- 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*

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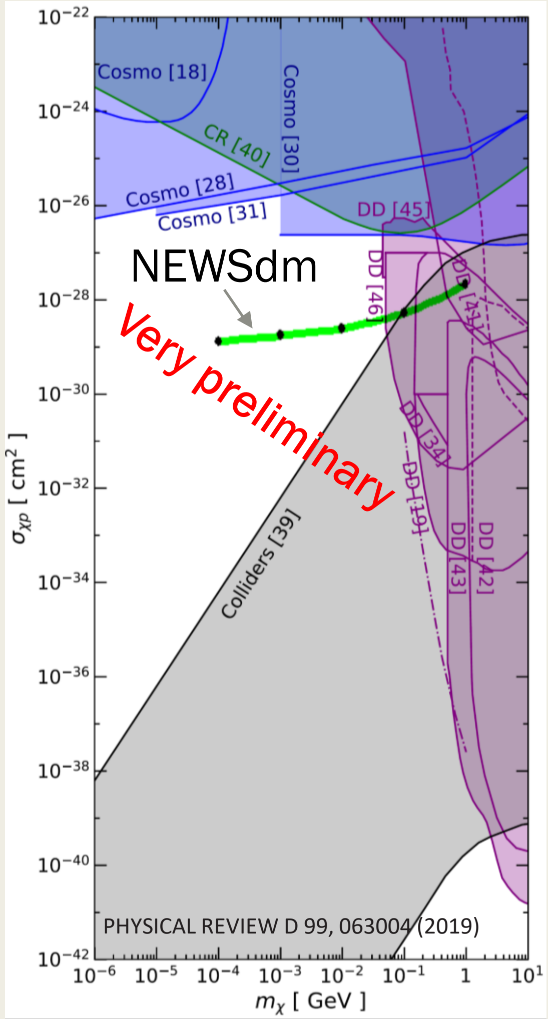


*Sensitivity to Boosted DM, H+C recoils >100 nm, Sea Level,10 kg year exposure*

# THANK YOU FOR ATTENTION!

Andrey ALEXANDROV (on behalf of the NEWSdm collaboration)

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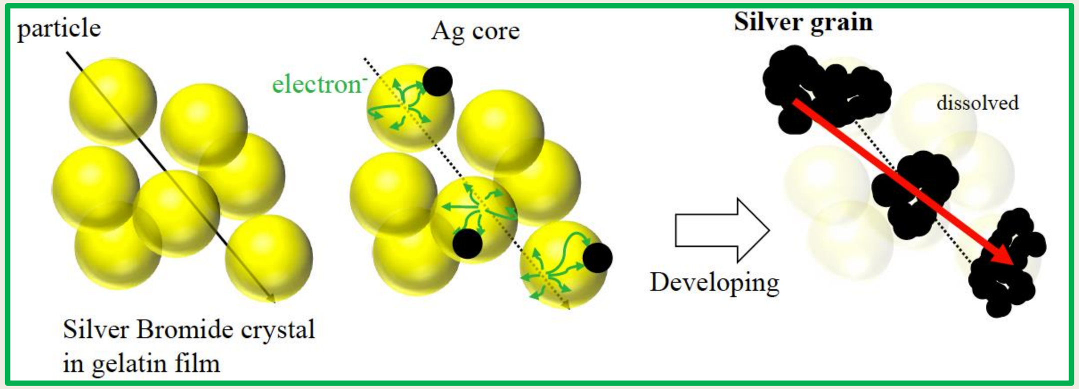
andrey.alexandrov@cern.ch

# BACKUP SLIDES

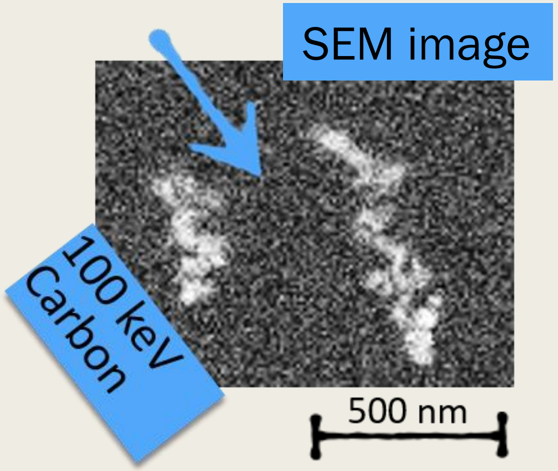
# NIT: Nano emulsion Imaging Trackers

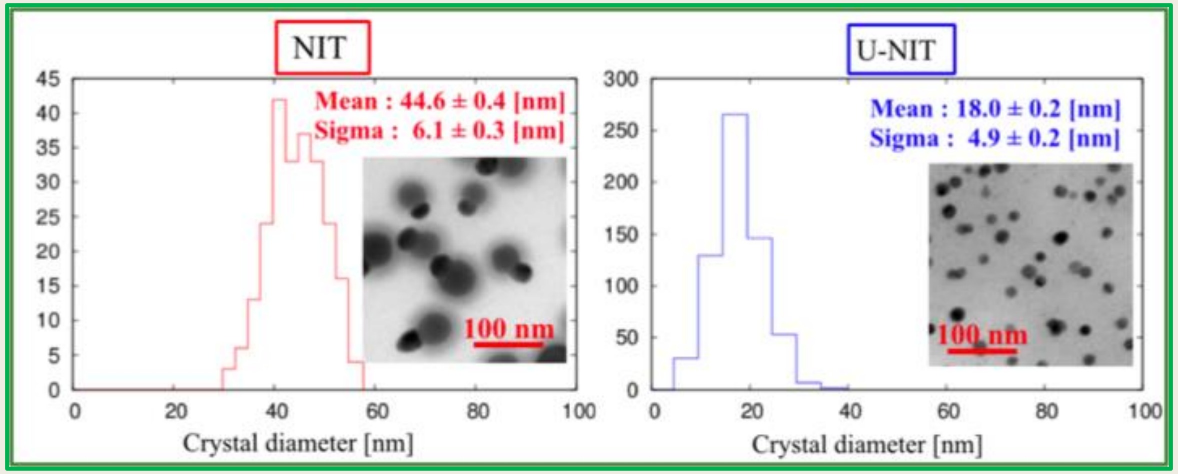



A long history, from the discovery of the Pion (1947) to the discovery of $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode (OPERA, PRL 115 (2015) 121802)

- 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



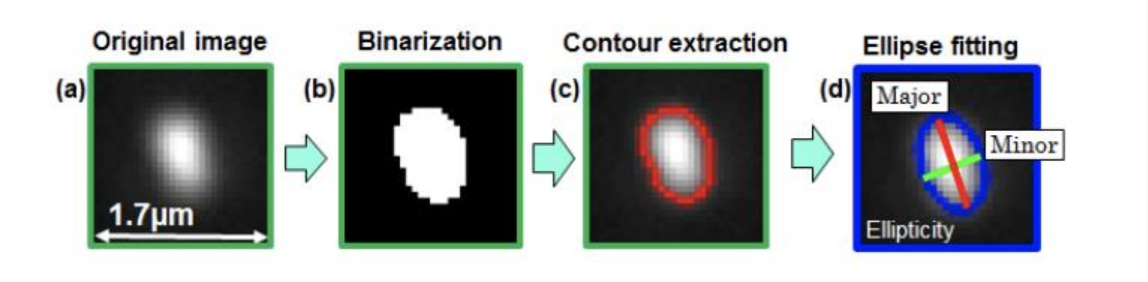

NIT granularity: 71 nm

U-NIT granularity: 40 nm

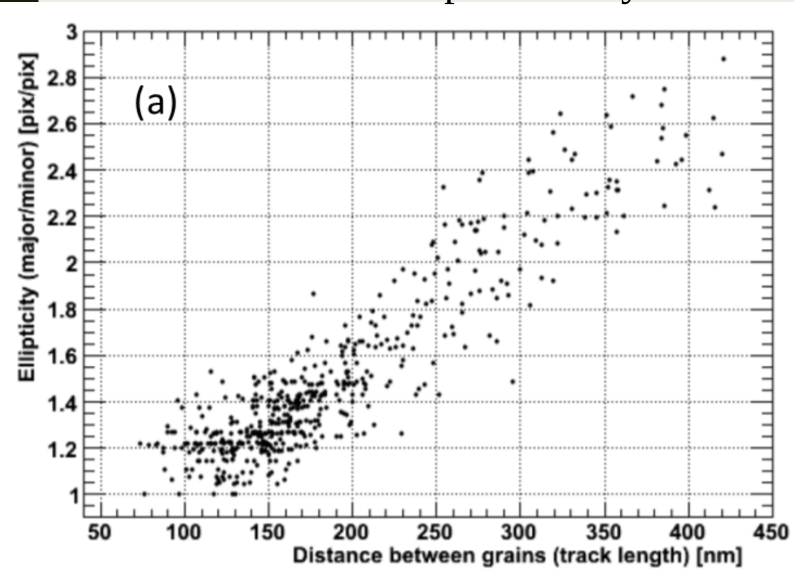
# Shape analysis

PTEP (2019) 063H02

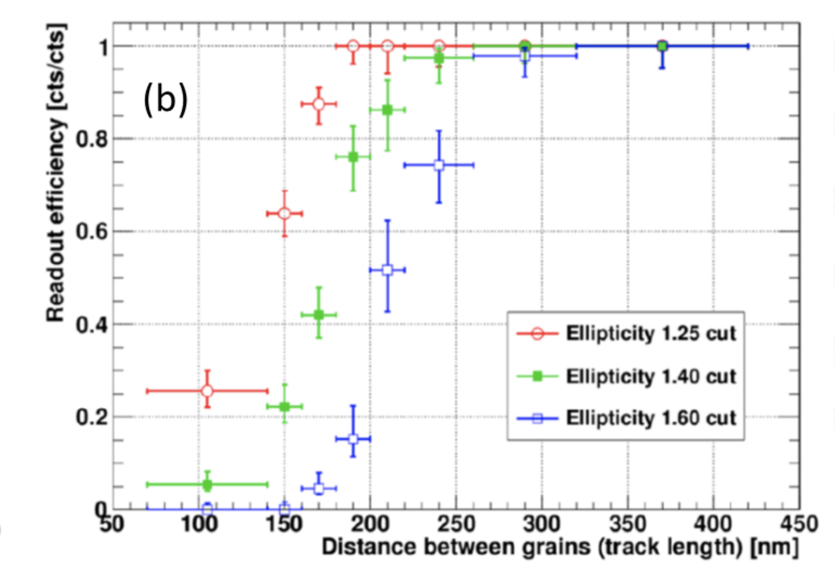
- Elliptical fit to measure the shape anisotropy



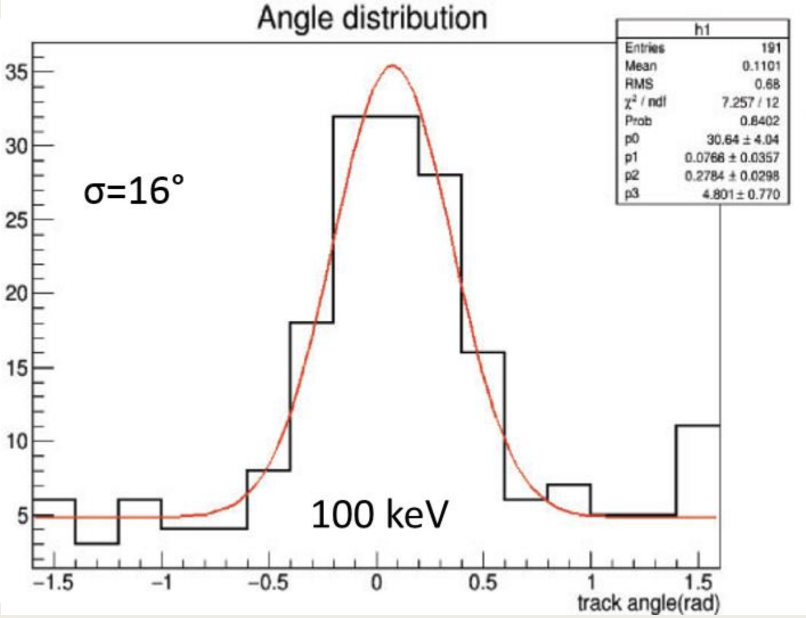

Correlation between track lengths measured by X-ray microscopy and ellipticity obtained with optical analysis




Correlation between readout efficiencies and track lengths for different ellipticity thresholds

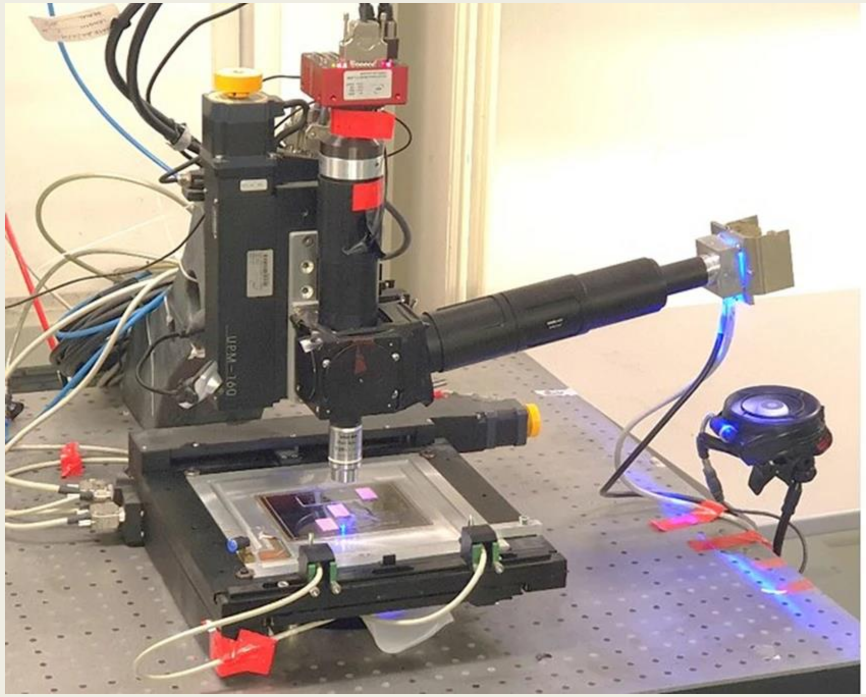


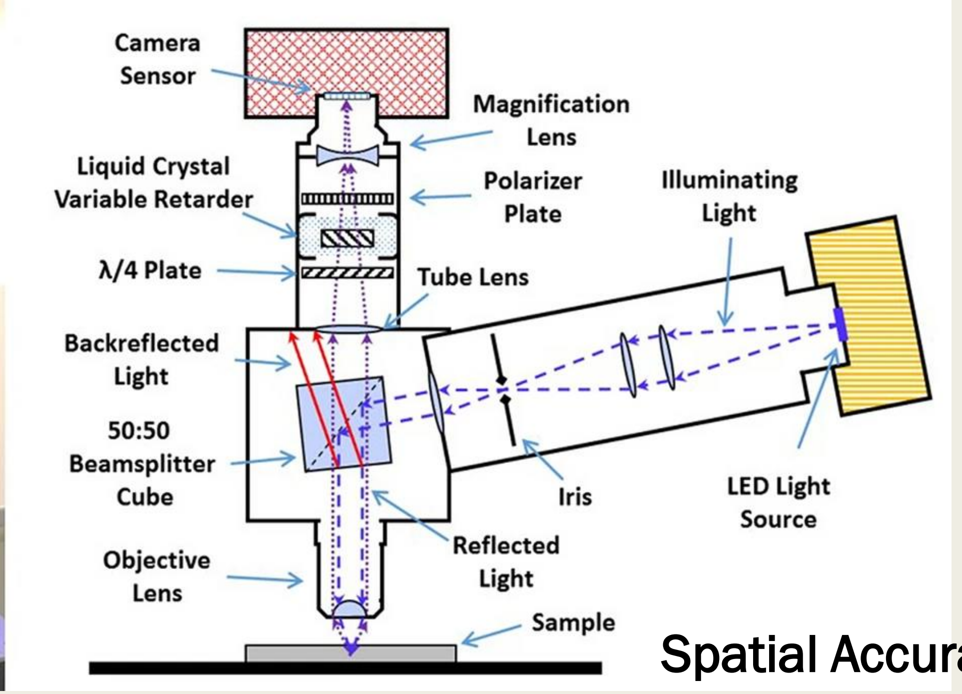

100 keV Carbon



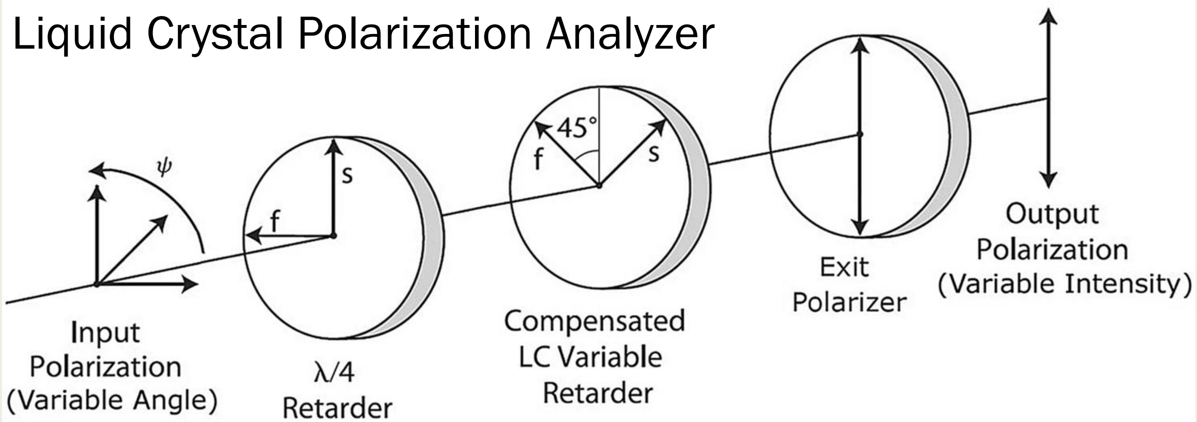
# Super-resolution microscope

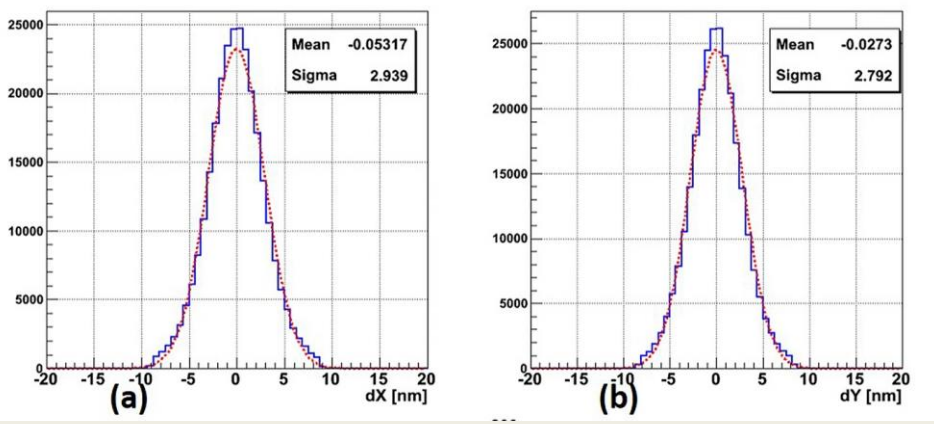
Sci. Rep. **10** (2020) 18773

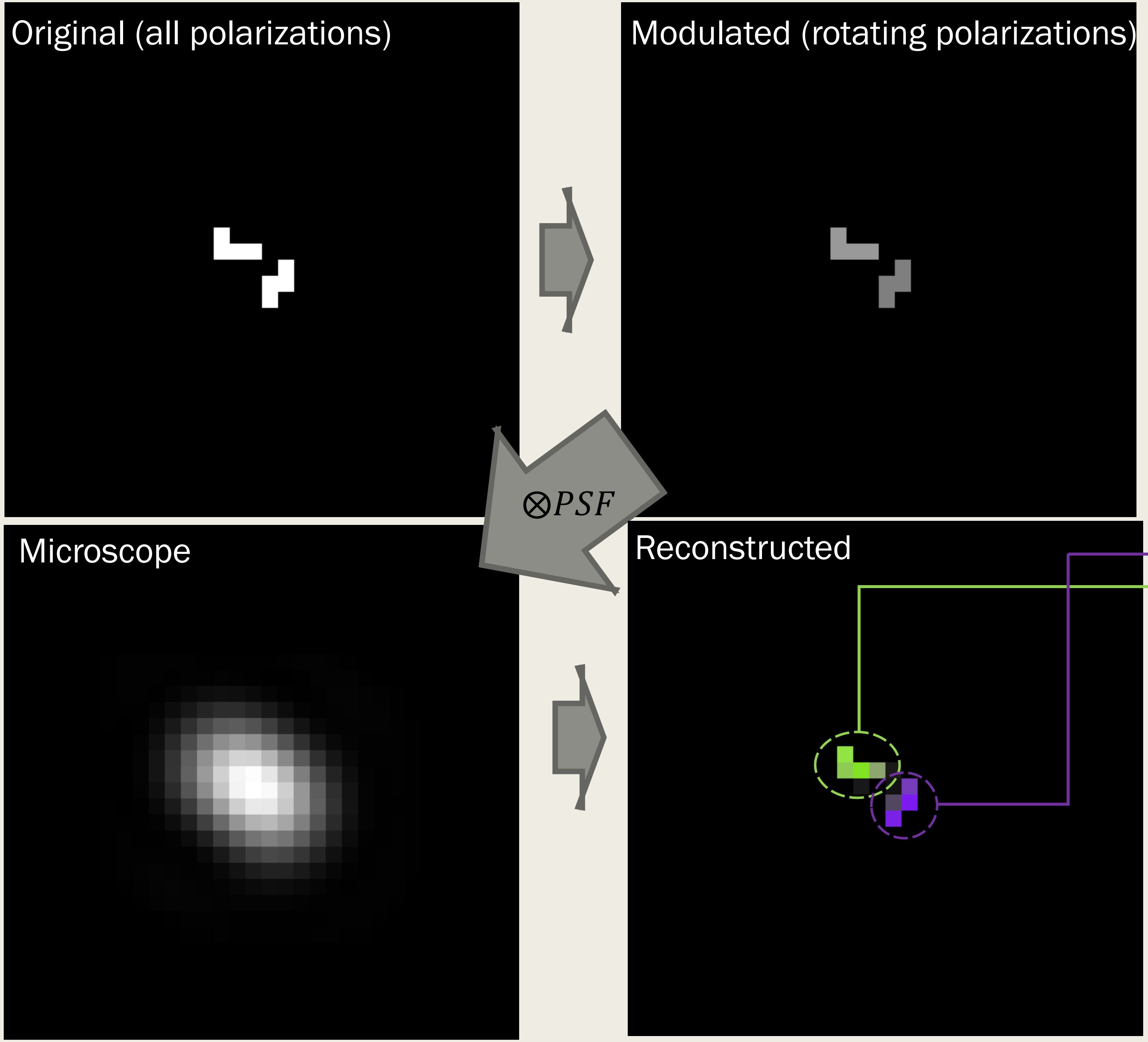





Spatial Accuracy = 3 nm



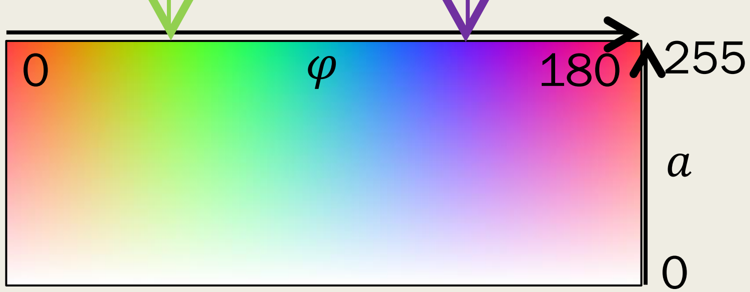






Modulate the intensity of each pixel in the image:

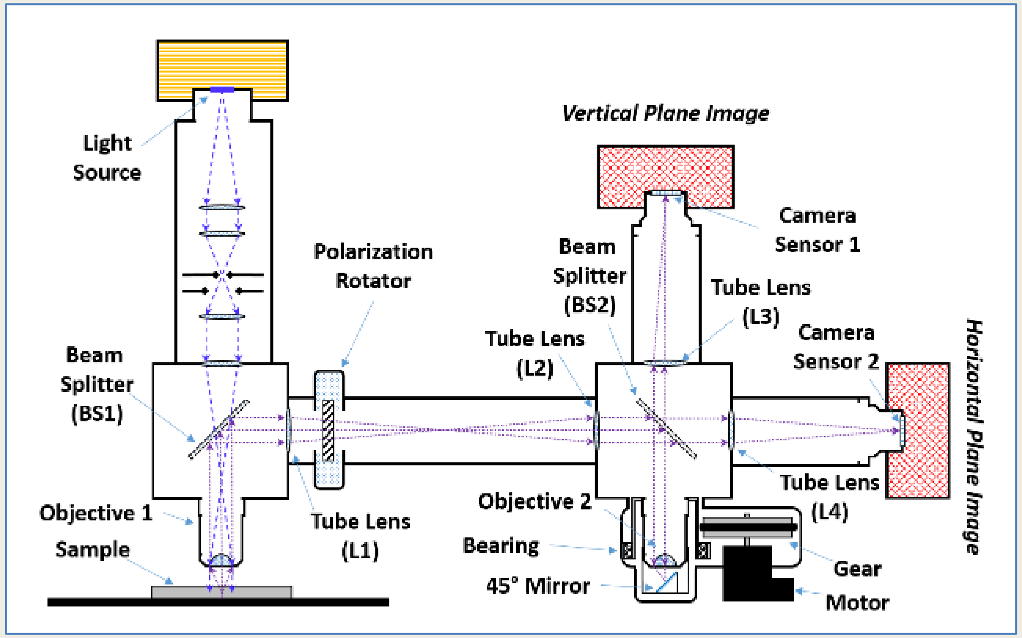
$$I_\theta = a\cos[2(\theta - \varphi)] + b$$

$\theta$ – polarization angle
$\varphi$ – pixel “phase”,
$b$ – pixel brightness mean,
$a$ – pixel brightness change amplitude

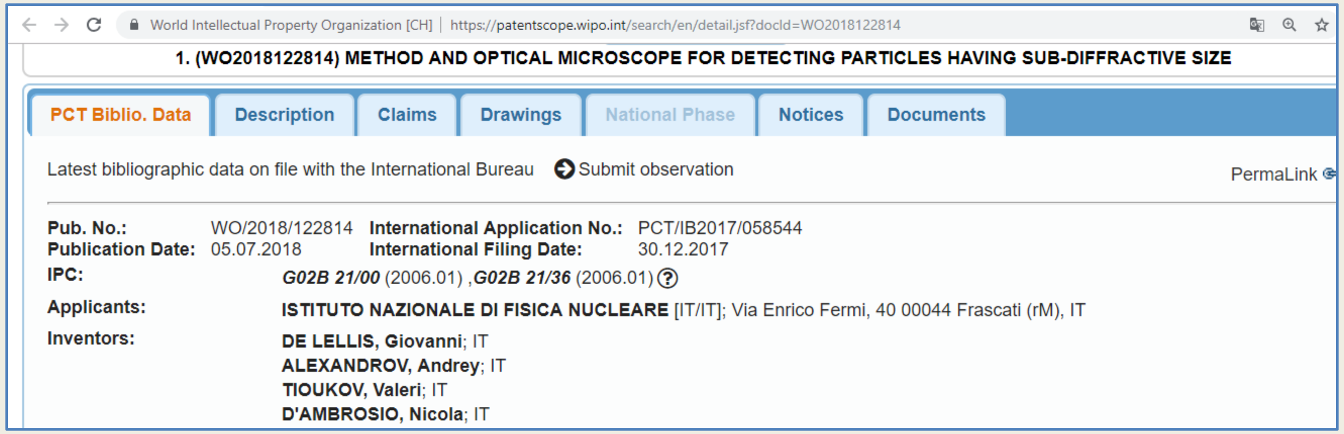



$a + b = pixel\ brightness$
$a = pixel\ color\ saturation$
$\varphi = pixel\ color$

# Measurement in 3D




International Patent No. WO/2018/122814

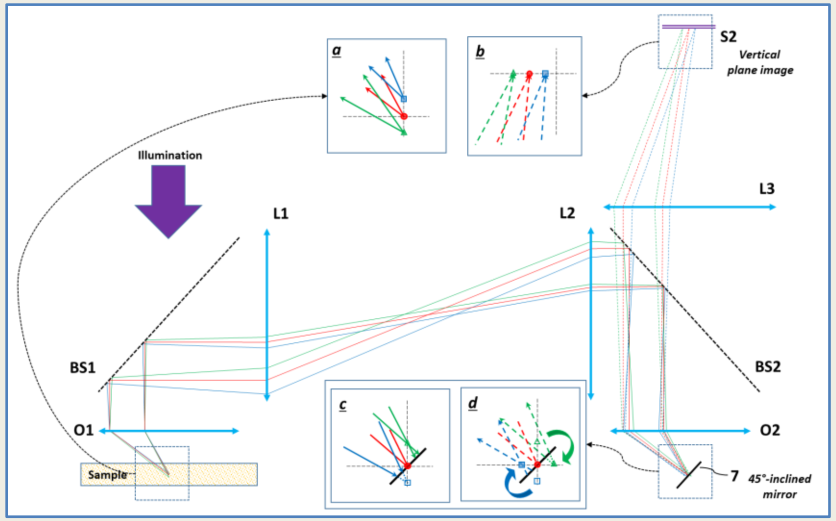

World Intellectual Property Organization [CH] | https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2018122814

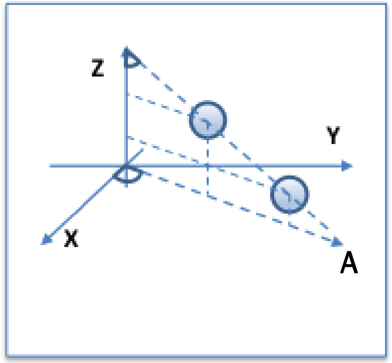
1. (WO2018122814) METHOD AND OPTICAL MICROSCOPE FOR DETECTING PARTICLES HAVING SUB-DIFFRACTIVE SIZE

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

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

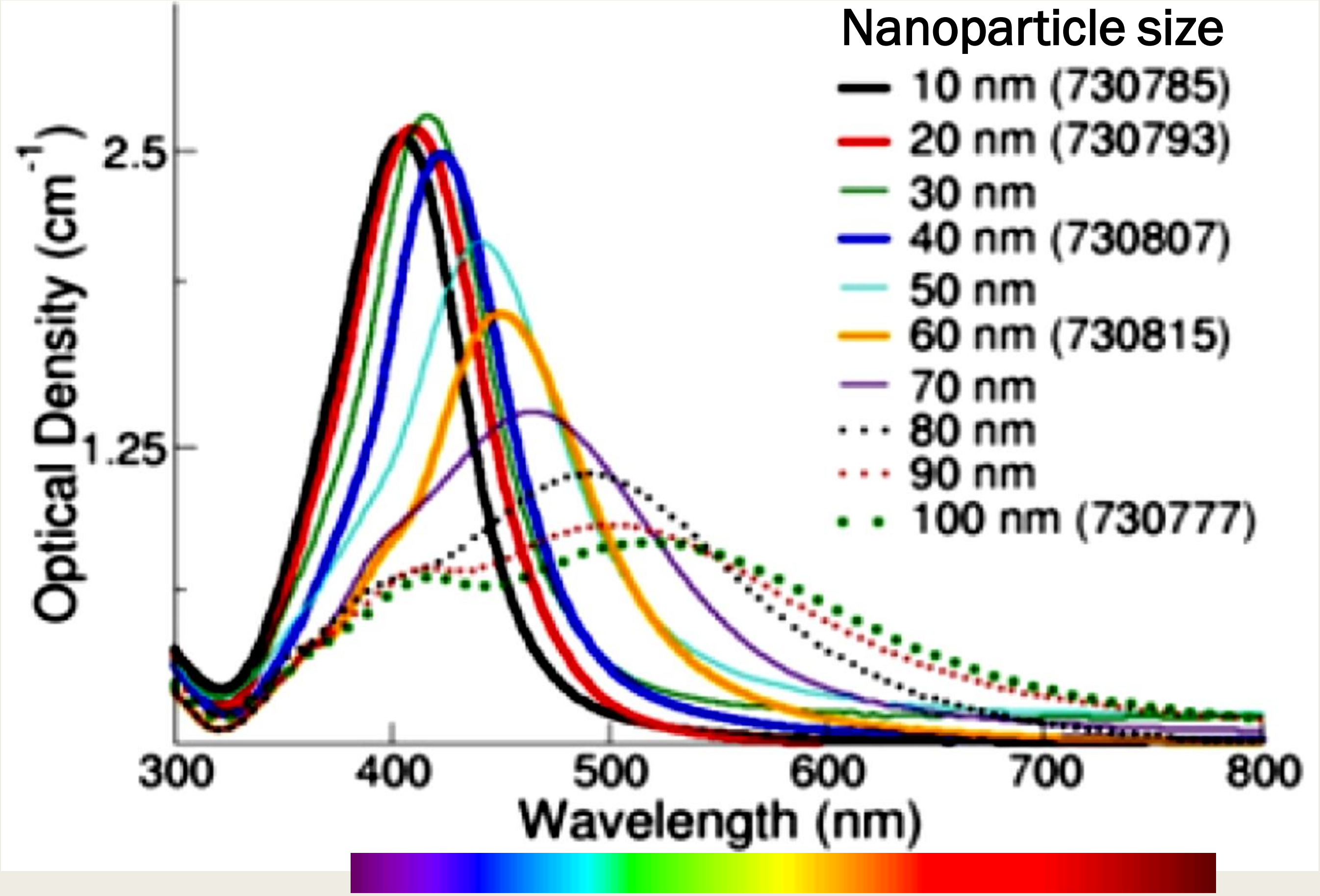
**Pub. No.:** WO/2018/122814 **International Application No.:** PCT/IB2017/058544
**Publication Date:** 05.07.2018 **International Filing Date:** 30.12.2017
**IPC:** *G02B 21/00* (2006.01) ,*G02B 21/36* (2006.01)
**Applicants:** **ISTITUTO NAZIONALE DI FISICA NUCLEARE** [IT/IT]; Via Enrico Fermi, 40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

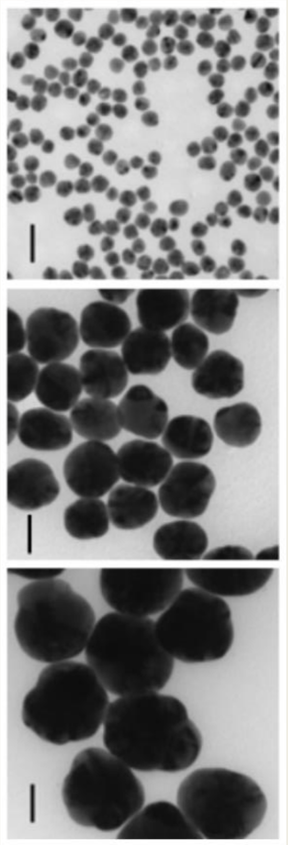


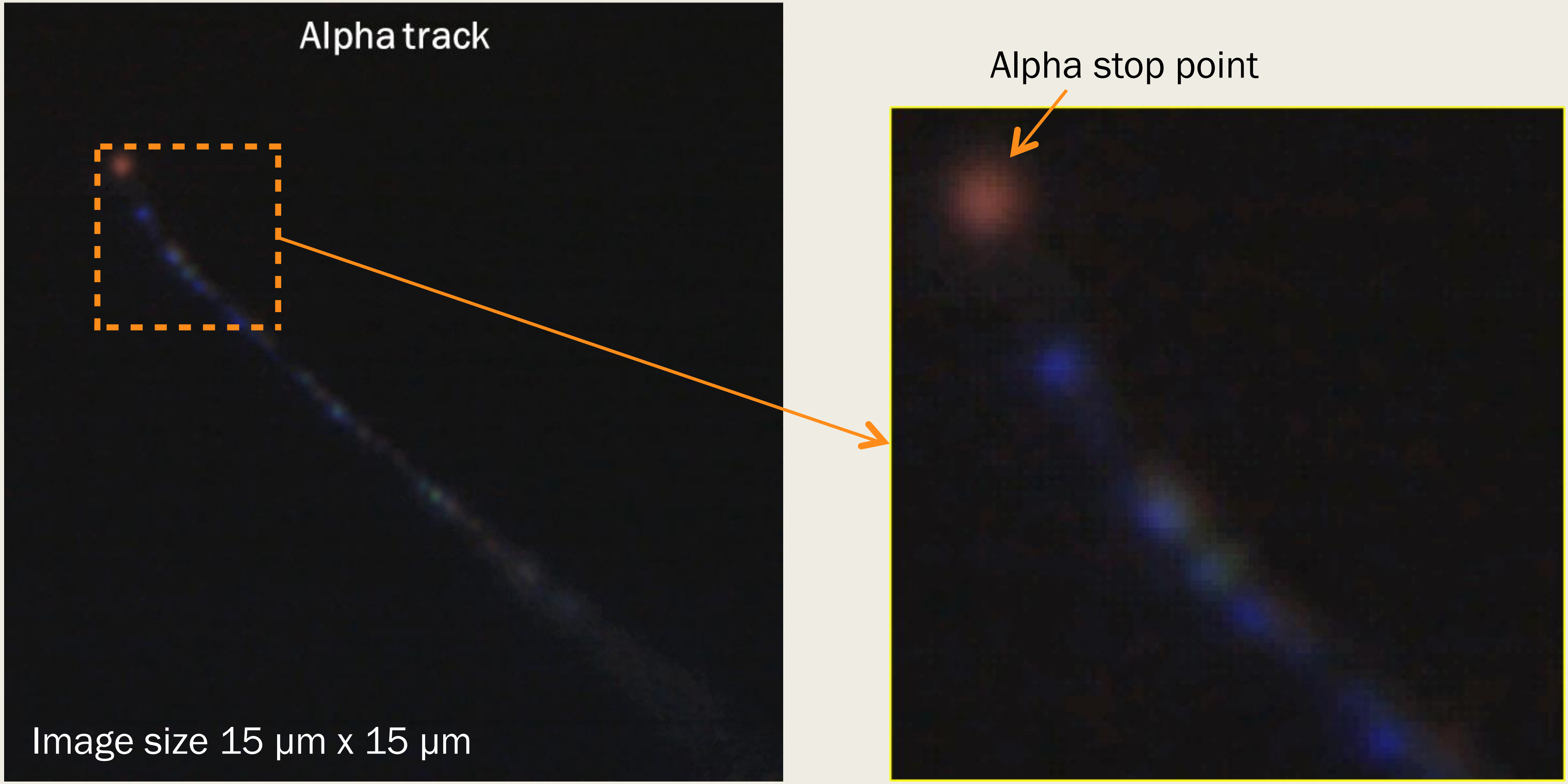

Two focal planes:
Horizontal: XY
Vertical: ZA

# Plasmon resonance wavelength dependency

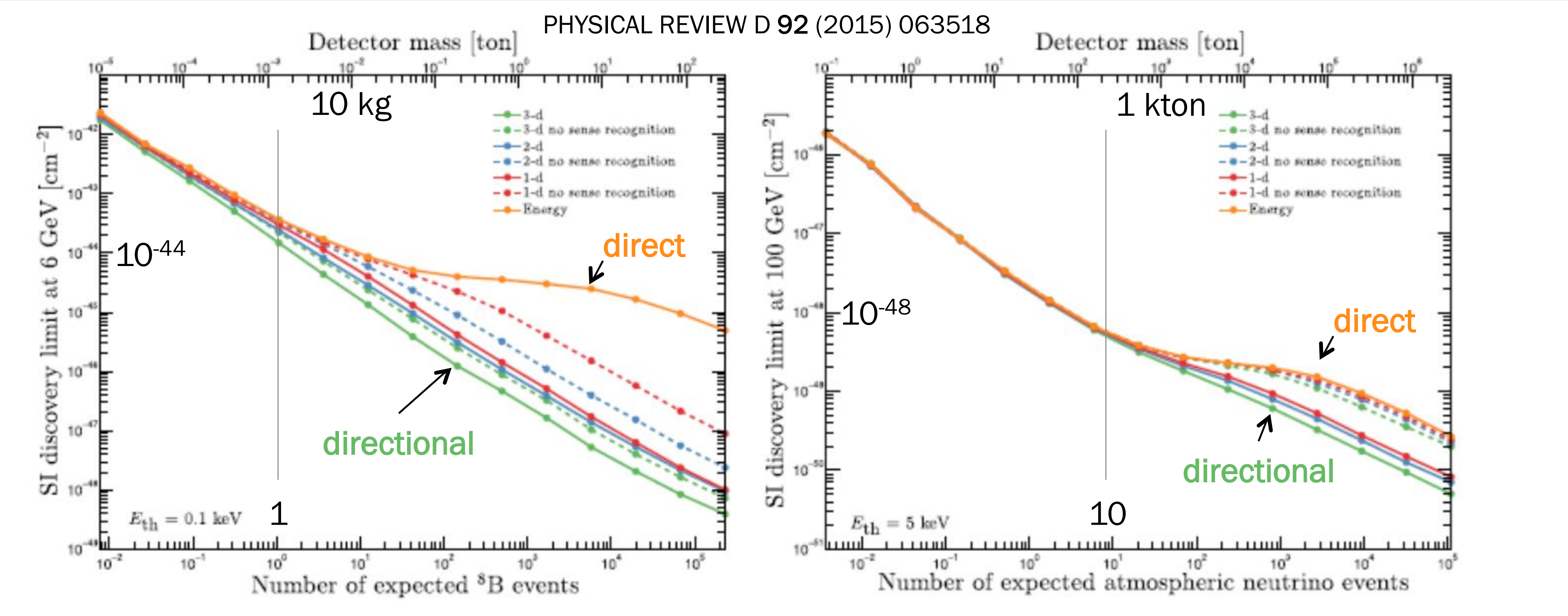


# Plasmon response for ion tracks



# Importance of the directional detection



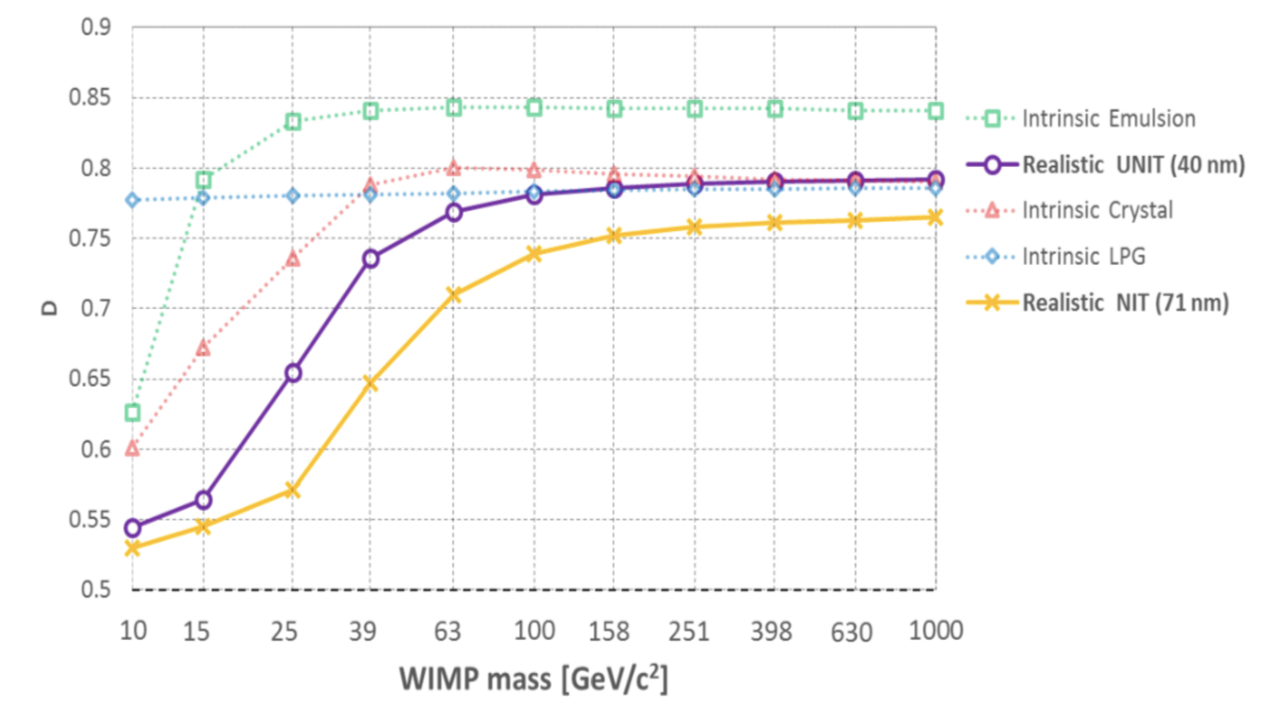

Need 3D with sense recognition for best results!

# 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-cos$\vartheta$ 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*

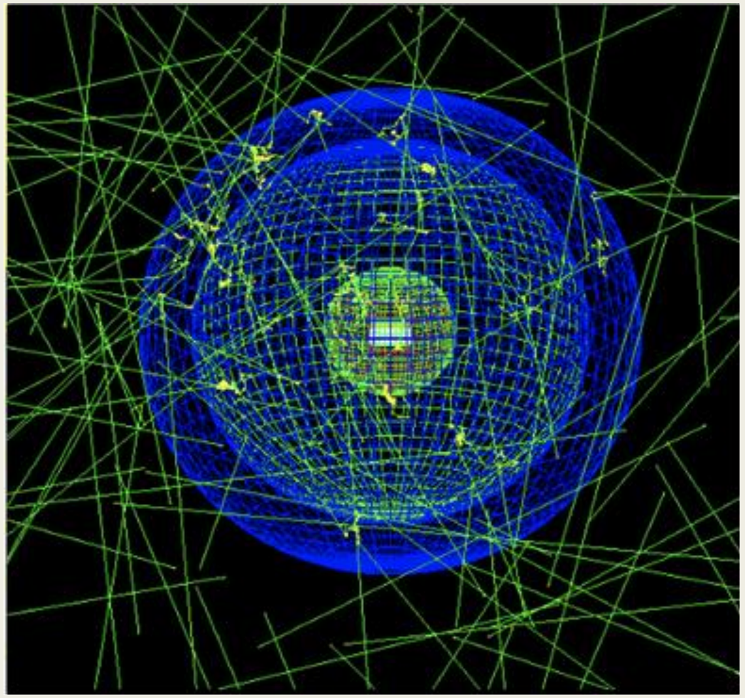
# Shield simulation

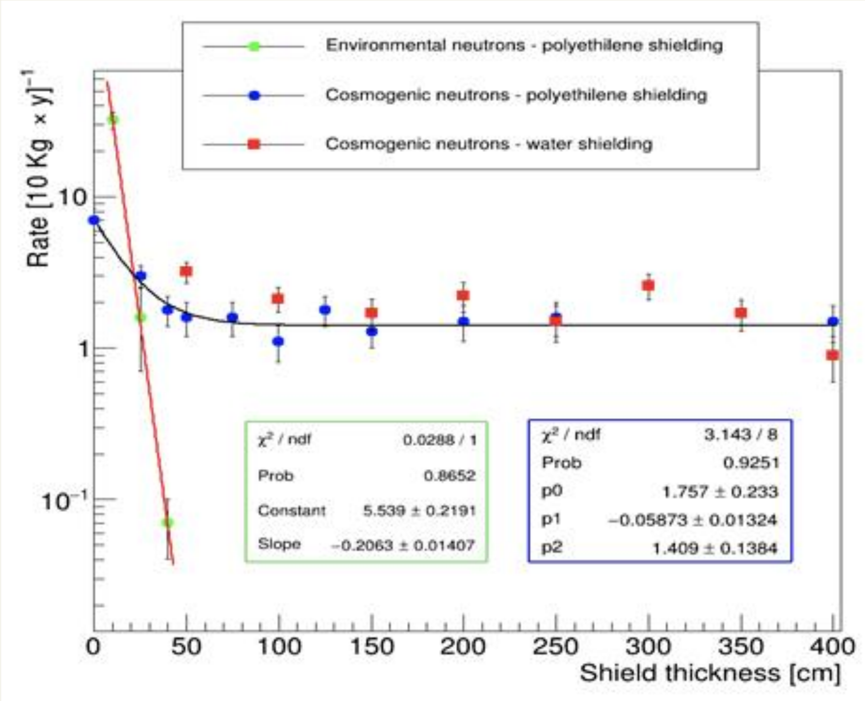
Optimisation of the shield with Geant4 simulation to reduce:

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

| 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 | $1.41 \pm 0.14$ |

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






Astroparticle Physics 80 (2016) 16–21

Intrinsic neutron background of nuclear emulsions for directional Dark Matter searches

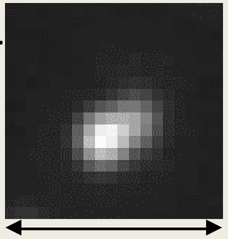
# Data analysis flow for test run

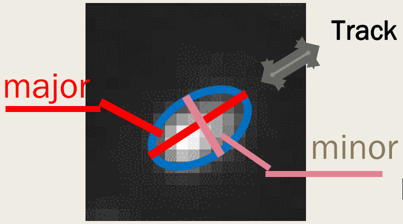
Automatic readout
1st trigger

Elliptical shape trigger

Requirement

- High speed scanning
- Low energy threshold
- Single noise (fog) reduction



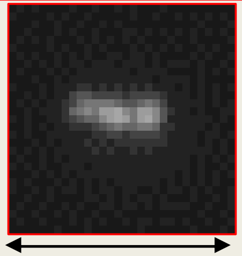

CNO : > 30 keV

Electron efficiency: 0.05

CNN
(machine learning )

≧ 3 grain track recognition

- Candidate selection and narrow down the number of event
- Image feature extraction




**Training sample :**
**neutron induce recoil nuclei @AIST (880keV, -50℃)**

Manual check

**Confirmation**
Electron rejection power :
**$10^{-4}$ @ room temperature**
**$10^{-6}$ @ -50℃**

**Current Selection**



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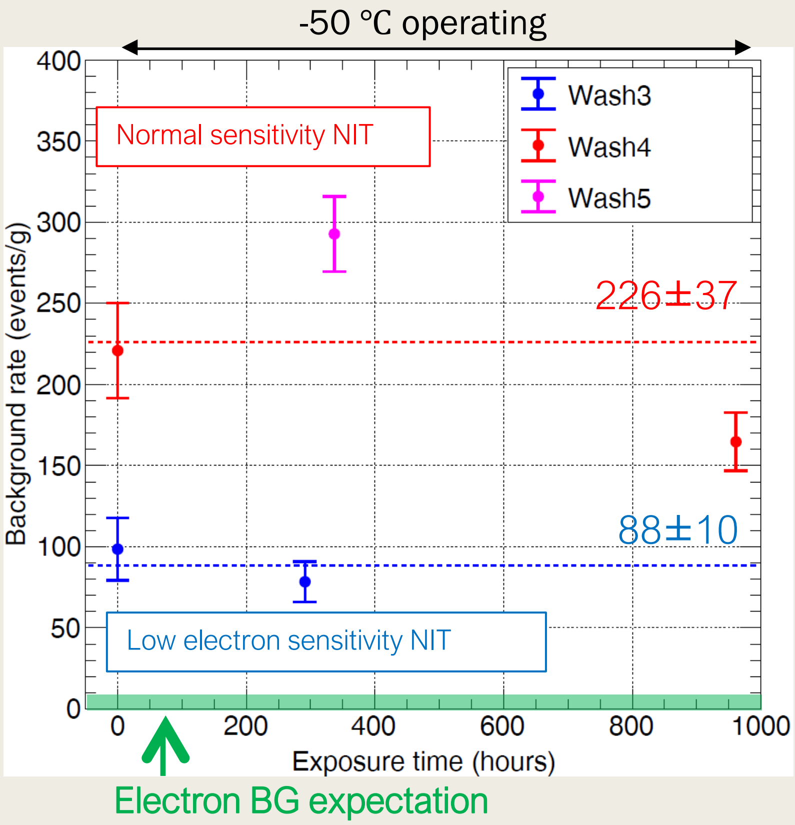
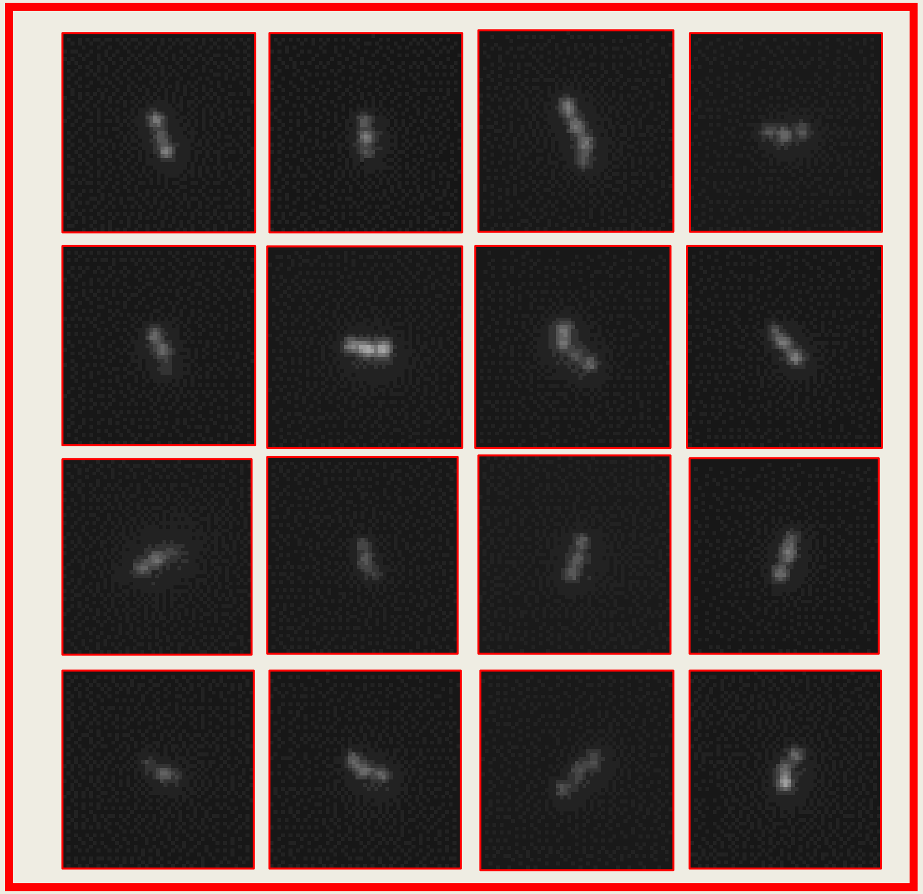
# Underground BG run status




Example of Selected candidate events



Current Selection
→Strict selection of signal-like events