33rd Rencontres de Blois on "Exploring the Dark Universe"
22-27 May 2022

Directional dark matter search with nuclear emulsions

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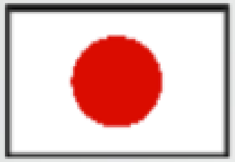
INFN Napoli

On behalf of NEWSdm collaboration

NEWSdm COLLABORATION

81 physicists
23 Institutes

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



JAPAN
Chiba, Nagoya, Toho

SOUTH KOREA
Gyeongsang University

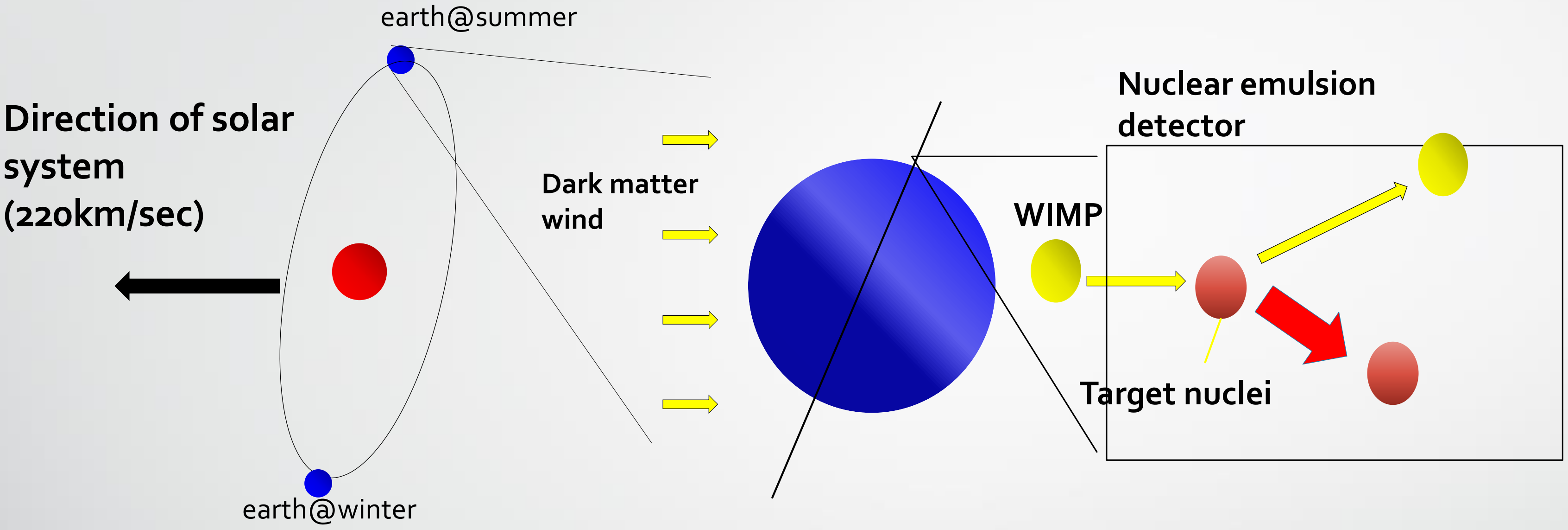
RUSSIA
LPI RAS Moscow
JINR Dubna
SINP MSU Moscow
INR Moscow
NUST MISiS Moscow
NRU HSE Moscow

TURKEY
METU Ankara

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

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

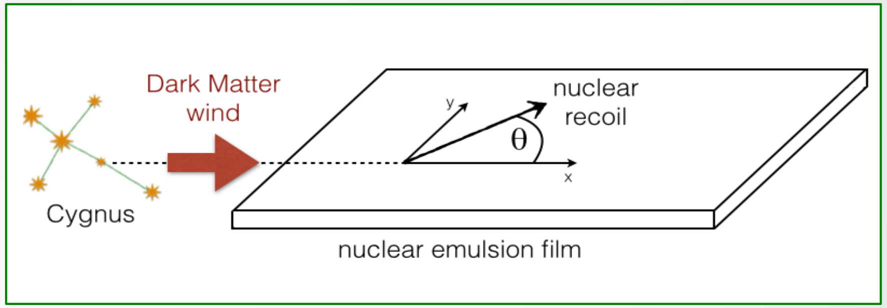
WIMP directional information

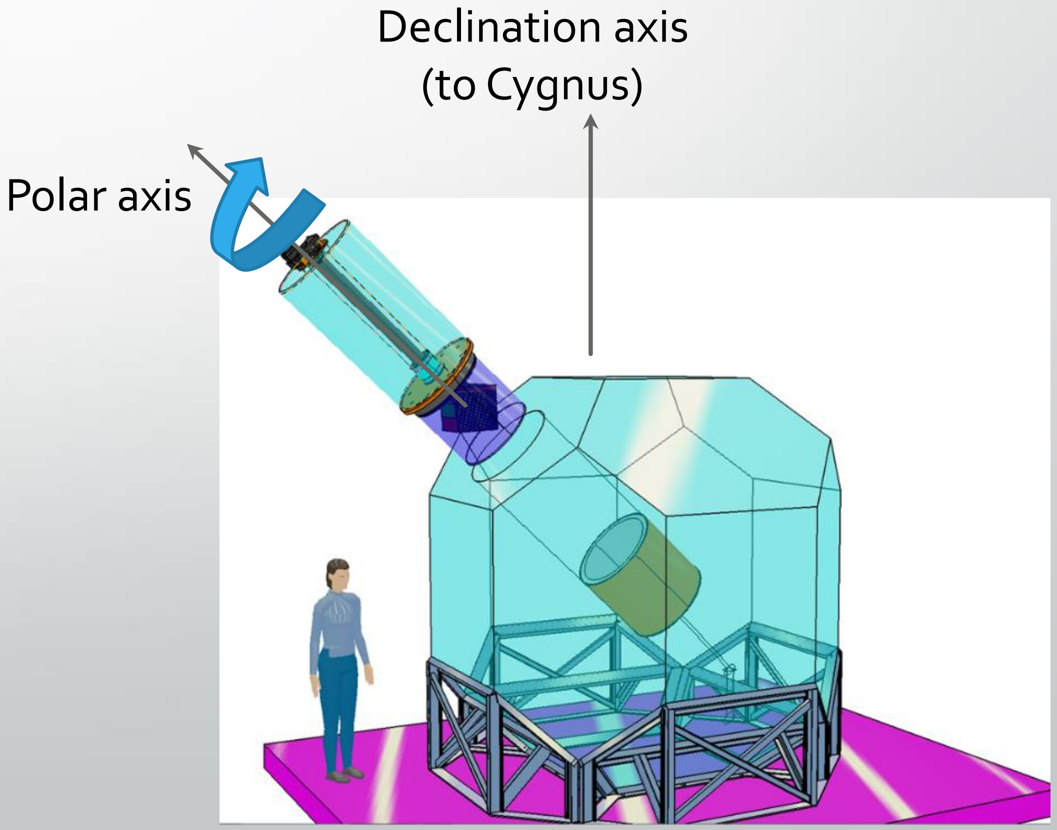


- Direction of the scattered nuclei has strong correlation with WIMP flux and provide a **strong signature** and unambiguous proof of the galactic DM origin
- **Nuclear Emulsion** is a high density solid state media – big mass with a compact detector is possible
- Unique possibility to overcome the "neutrino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

NEWSdm concept

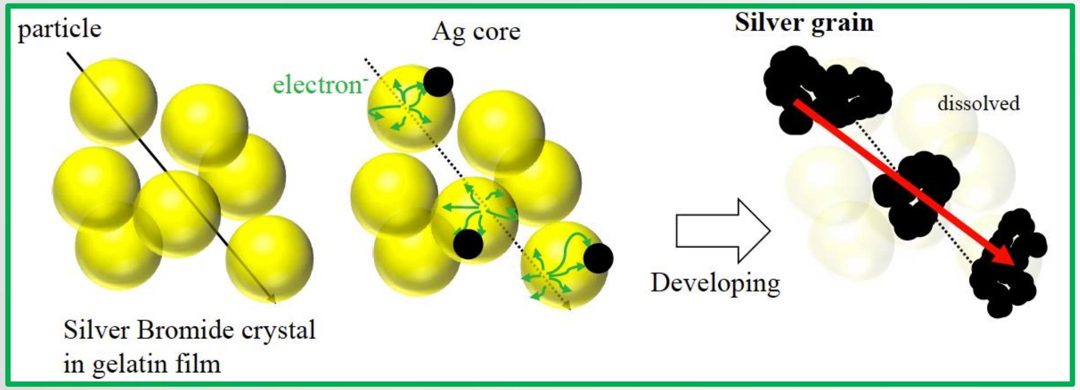
- **<u>Goal</u>**: detect the direction of **nuclear recoils**
- **<u>Target</u>**: nanometric emulsion films acting both as target and tracking detector
- **<u>Background reduction</u>:** neutron **shield** surrounding the target
- **<u>Fixed pointing</u>**: target mounted on **equatorial telescope** pointing to the Cygnus Constellation
- **<u>Location</u>**: underground lab (LNGS)





(a)

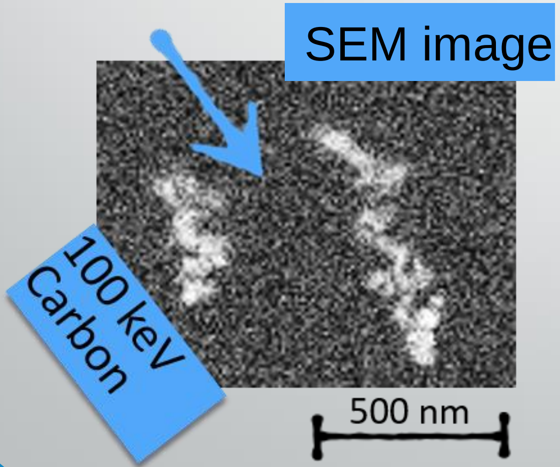
NIT: Nano emulsion Imaging Tracker

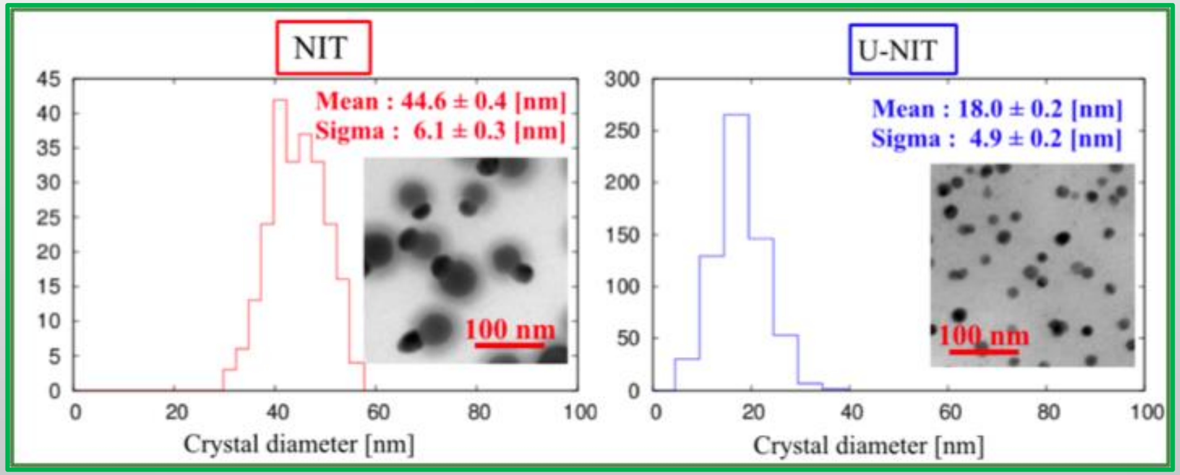


A long history, from the discovery of the **Pion (1947)** to the discovery of $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode (**OPERA, PRL 115 (2015) 121802**)

- 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

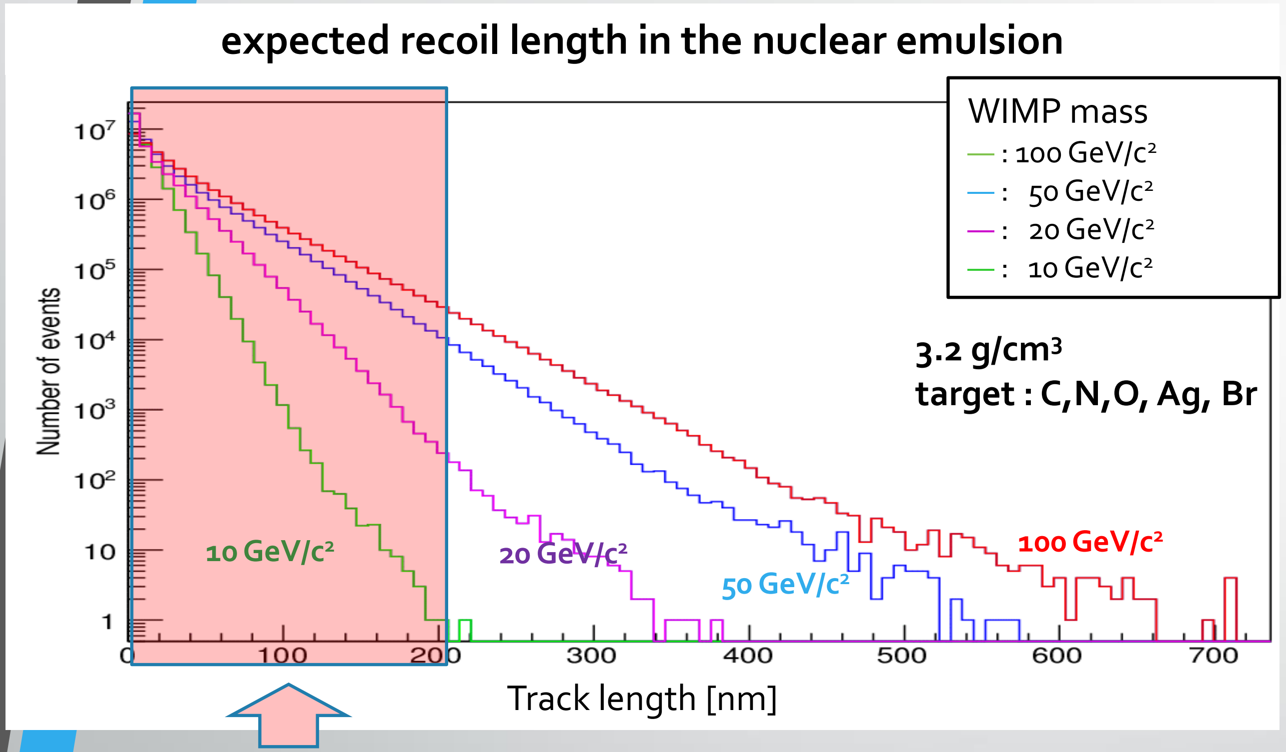




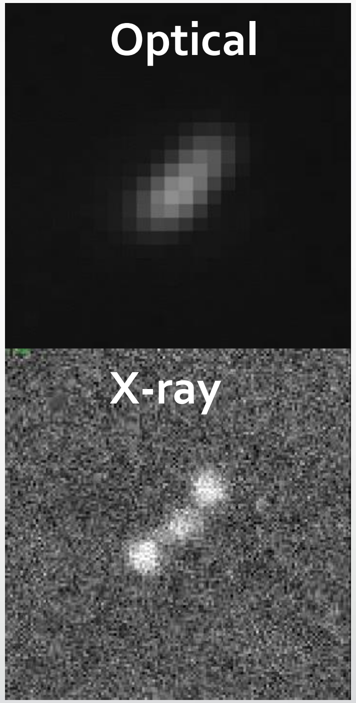
NIT granularity: 71 nm

U-NIT granularity: 40 nm

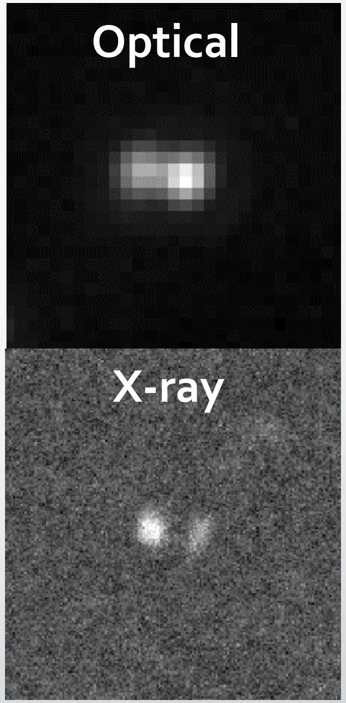
Direction detection challenge



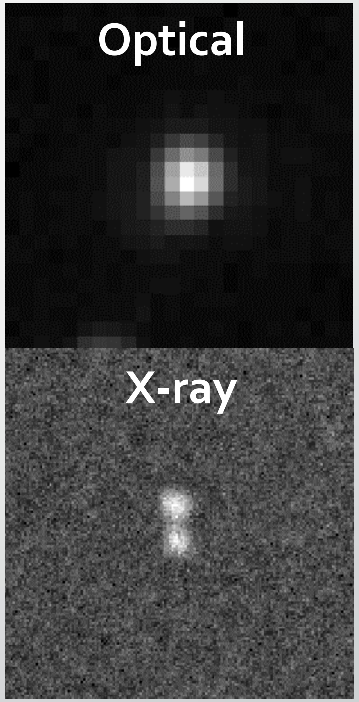
Inaccessible due to diffraction limit



L = 380 nm



L = 265 nm

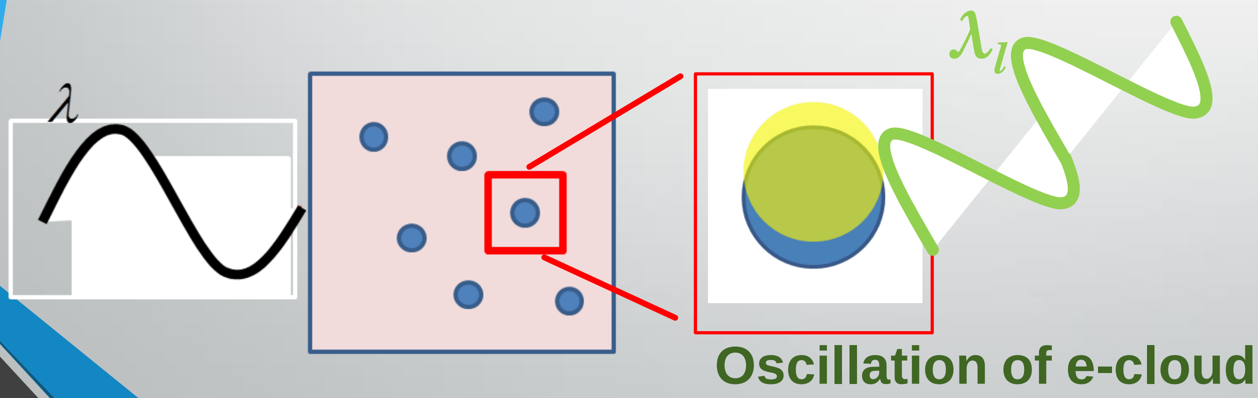


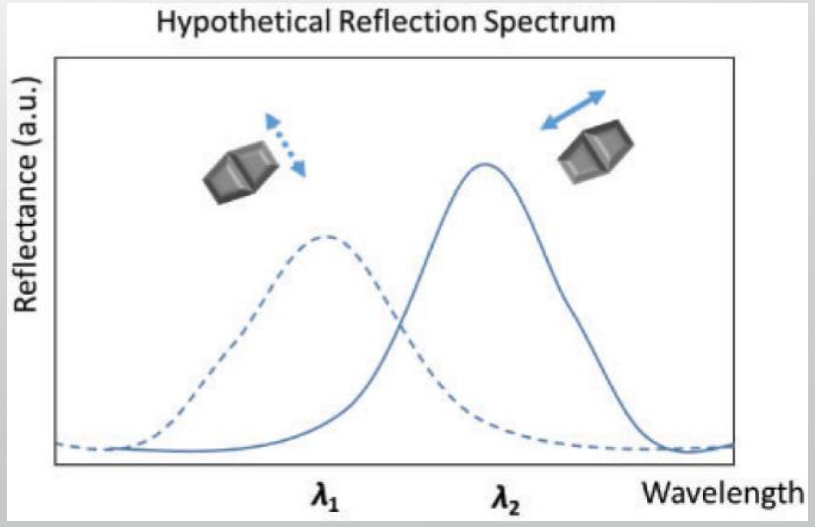
L = 160 nm

Need super-resolution to measure tracks shorter than 200 nm

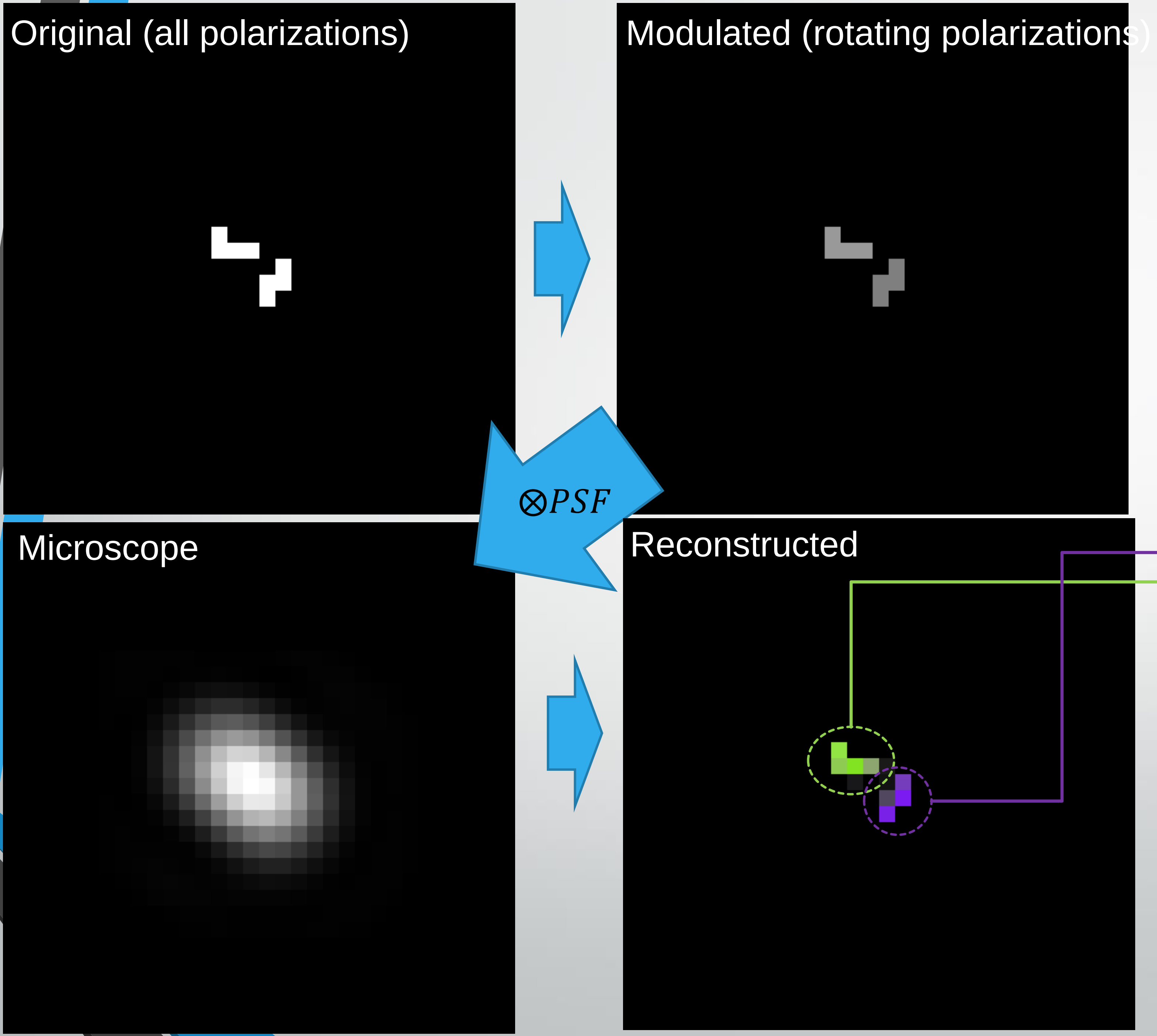
Optical readout beyond the diffraction limit

- 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**





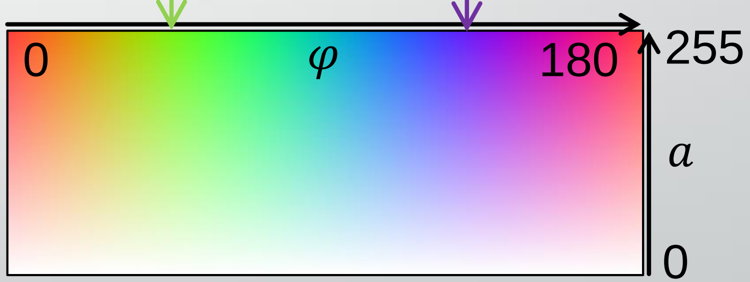
PTEP, Vol. 2019 Issue 62019, 063H02



Modulate the intensity of each pixel in the image:

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

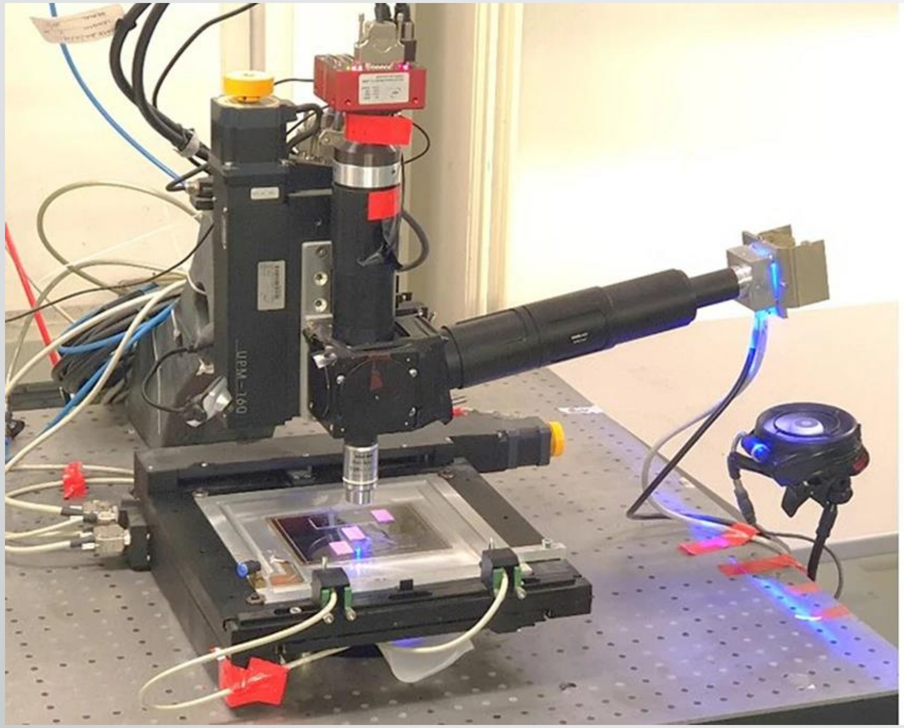
θ – polarization angle
φ – pixel “phase”,
b – pixel brightness mean,
a – pixel brightness change amplitude

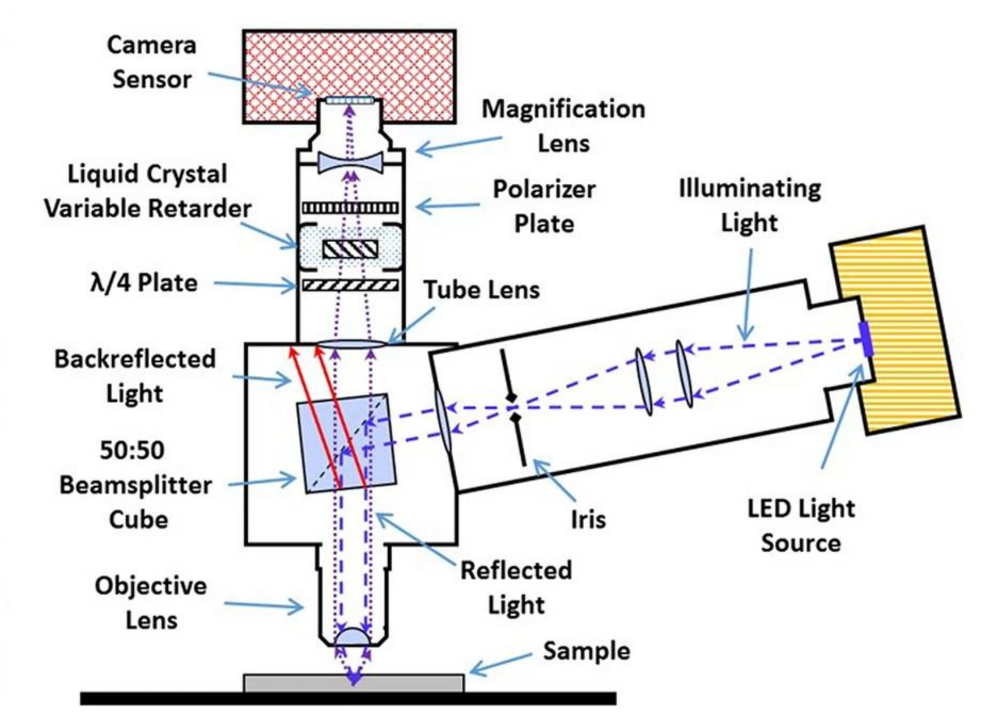


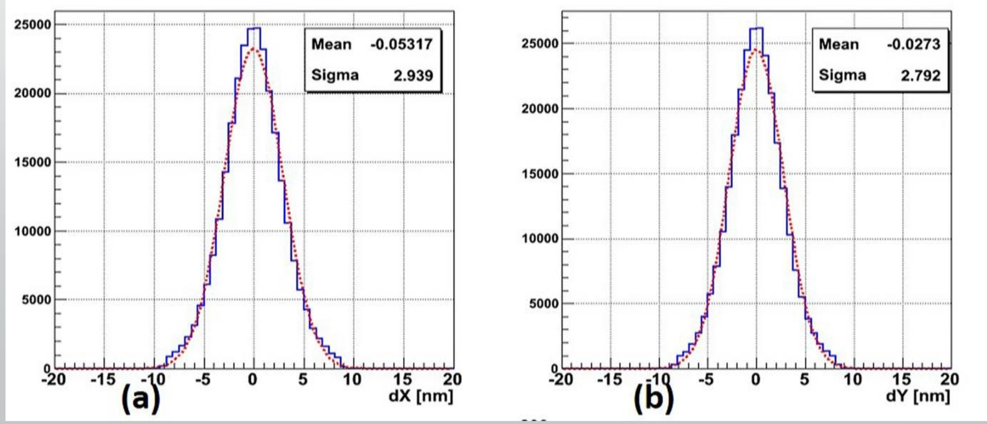
$a + b = pixel\ brightness$
$a = pixel\ color\ saturation$
$\varphi = pixel\ color$

Super-resolution microscope

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





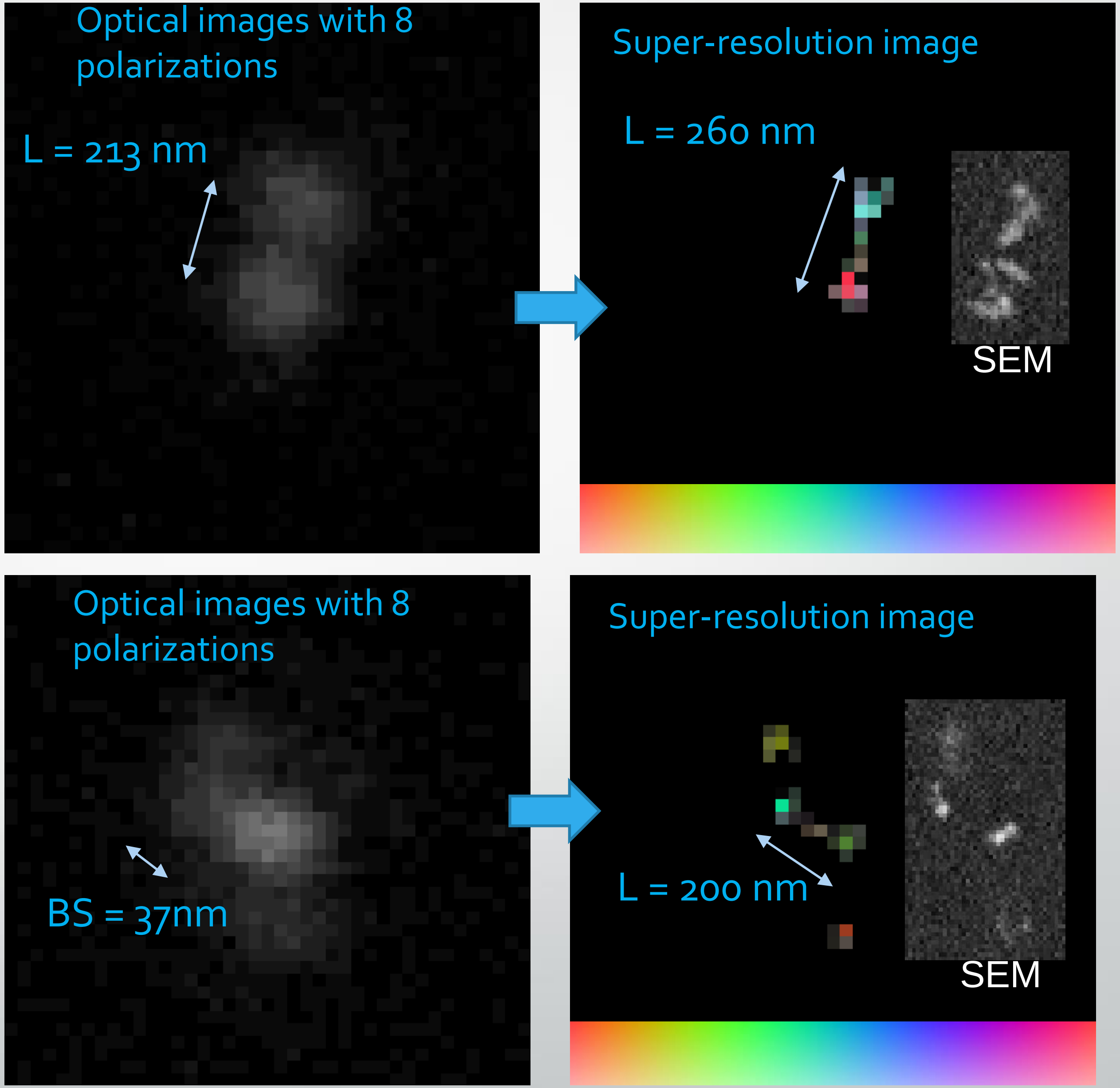


Field of view = 63 x 47 µm
(pixel size = 27 nm)

Spatial Accuracy = 3 nm

LSPR-based super-resolution imaging

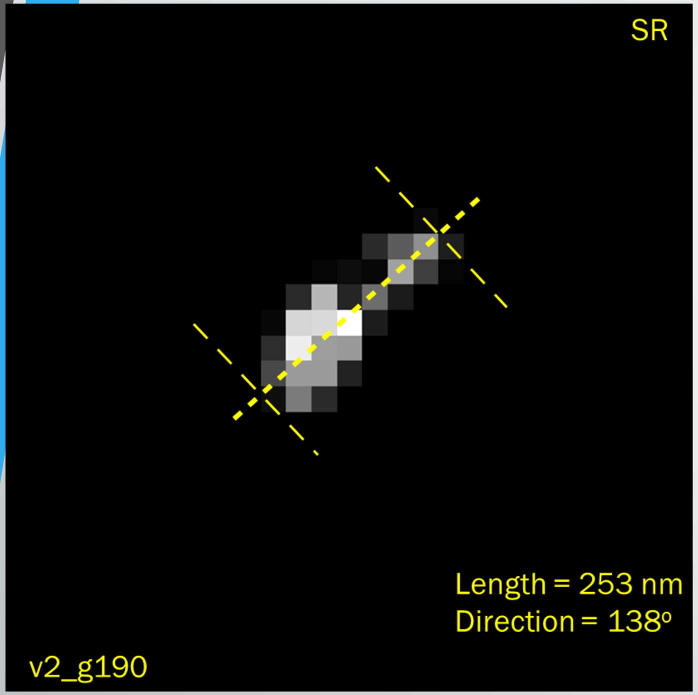
A super-resolution image is modelled as a set of brightness-modulated pixels, with each pixel being described with three parameters: average brightness, brightness change amplitude and brightness phase (the polarization angle at which the maximum pixel brightness is reached). With this image model a joint deconvolution of event images was performed

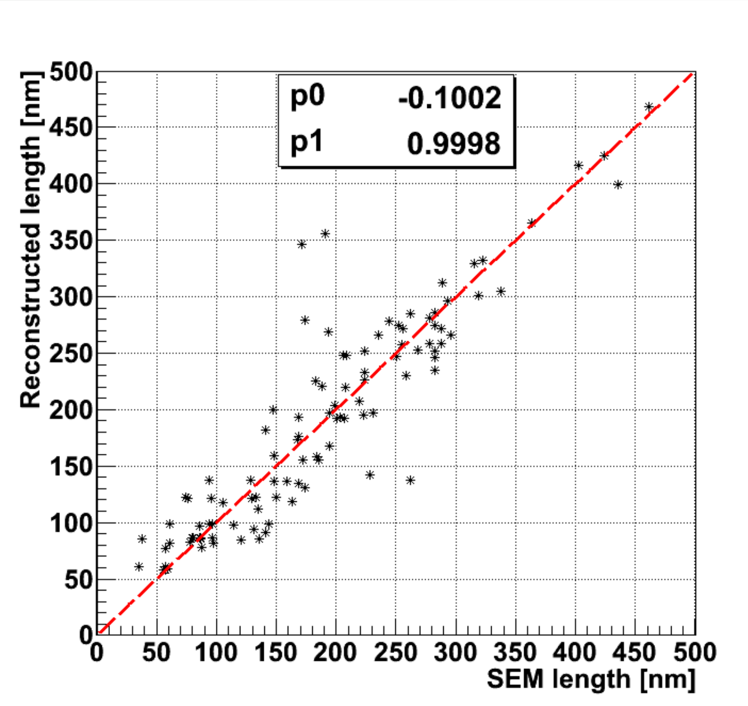


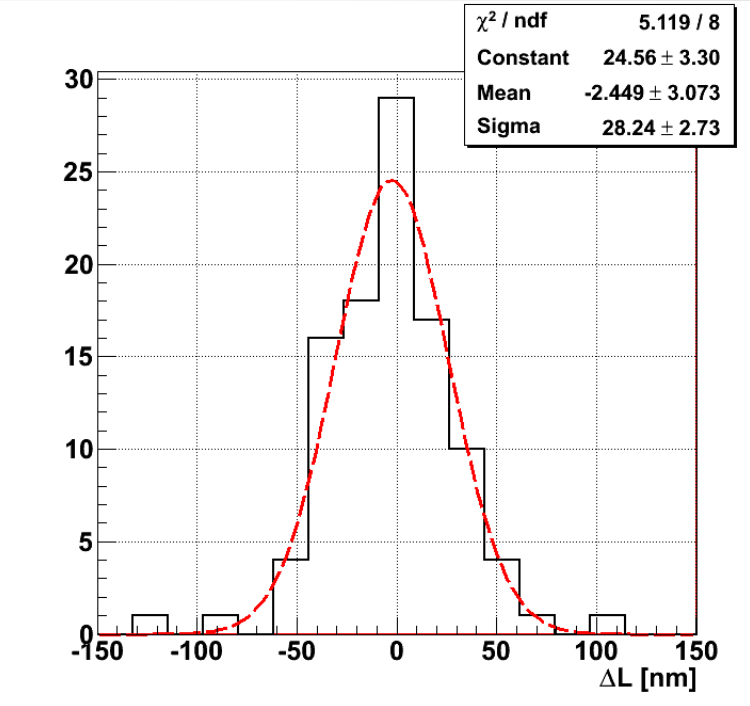
Alexandrov, A., *et al.* Super-resolution high-speed optical microscopy for fully automated readout of metallic nanoparticles and nanostructures. *Sci Rep* 10, 18773 (2020). https://doi.org/10.1038/s41598-020-75883-z

Joint Image Deconvolution

Event Length comparison with SEM





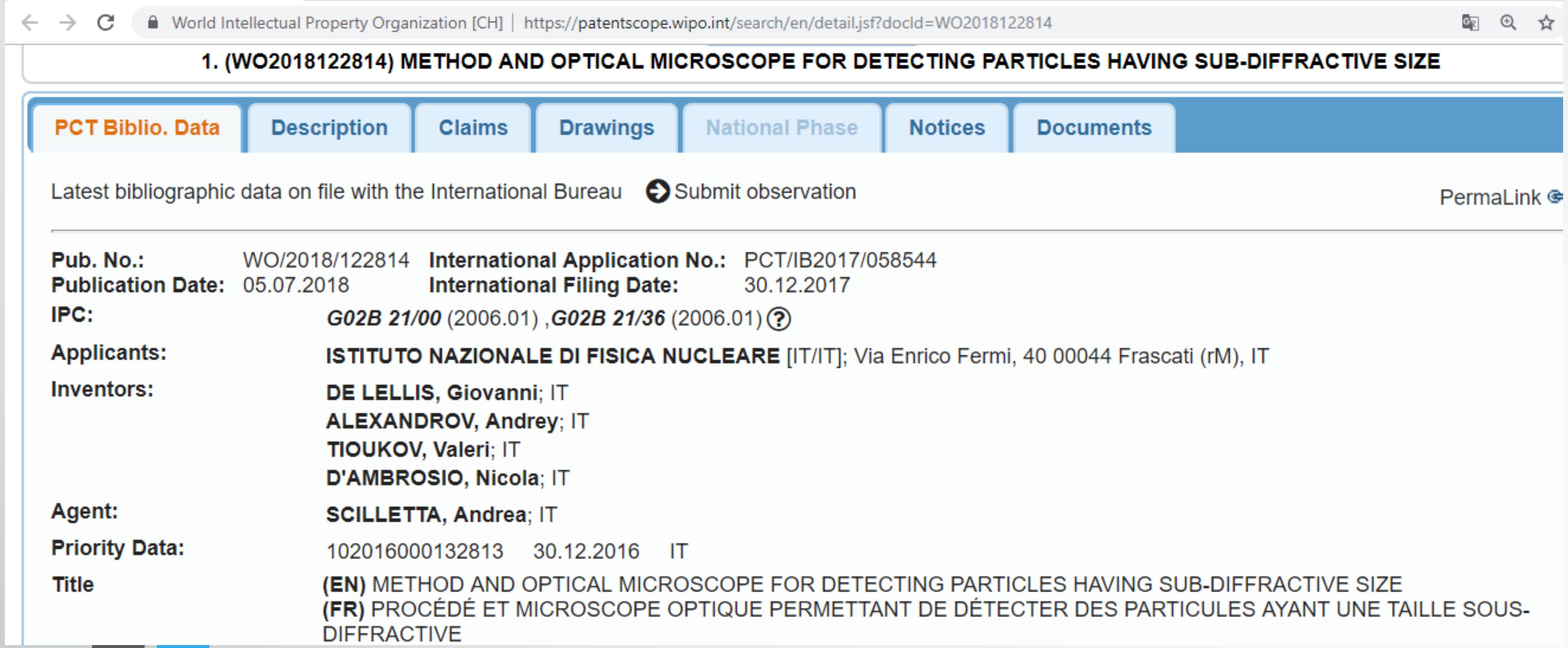


Length accuracy: 28 nm ≈ pixel size (27.5 nm)

Spatial resolution: 80 nm (Nyquist theorem)

Pearson Coefficient	Matched	Cross-test
Length	0.912	-0.009
Width	0.713	-0.007

Super resolution: 3-dimensions!



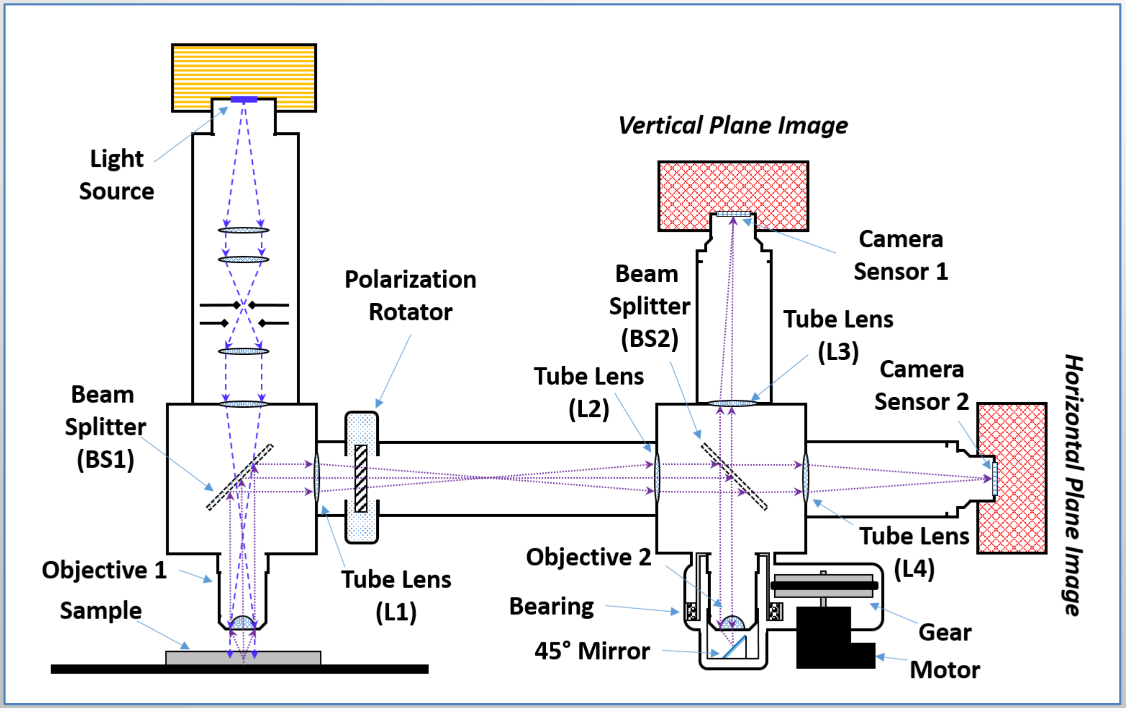
World Intellectual Property Organization [CH] | https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2018122814

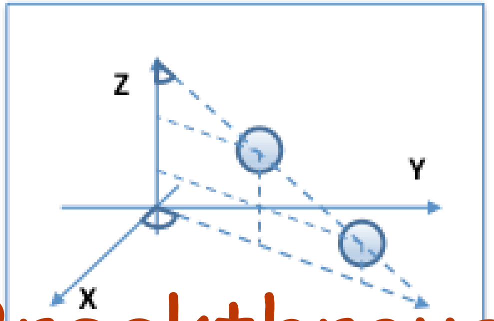
1. (WO2018122814) METHOD AND OPTICAL MICROSCOPE FOR DETECTING PARTICLES HAVING SUB-DIFFRACTIVE SIZE

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

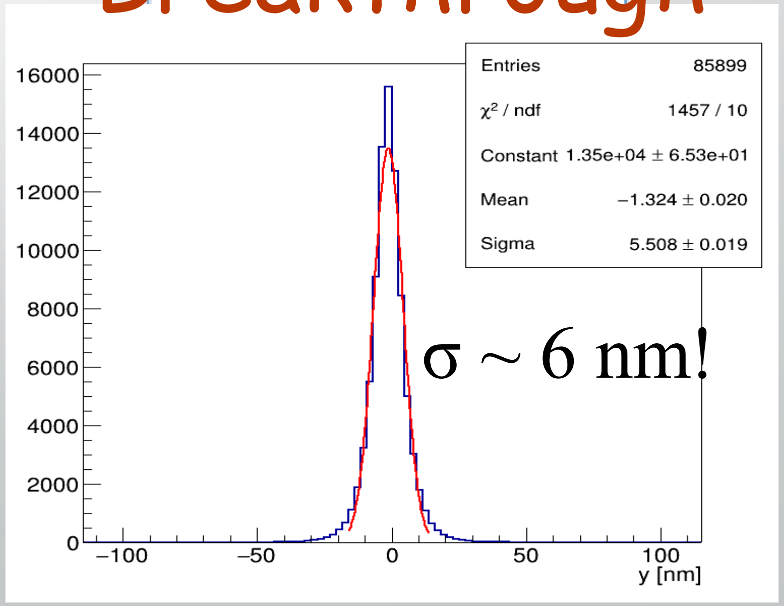
Latest bibliographic data on file with the International Bureau   Submit observation   PermaLink

Pub. No.:	WO/2018/122814
Publication Date:	05.07.2018
International Application No.:	PCT/IB2017/058544
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
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-DIFFRACTIVE





Breakthrough

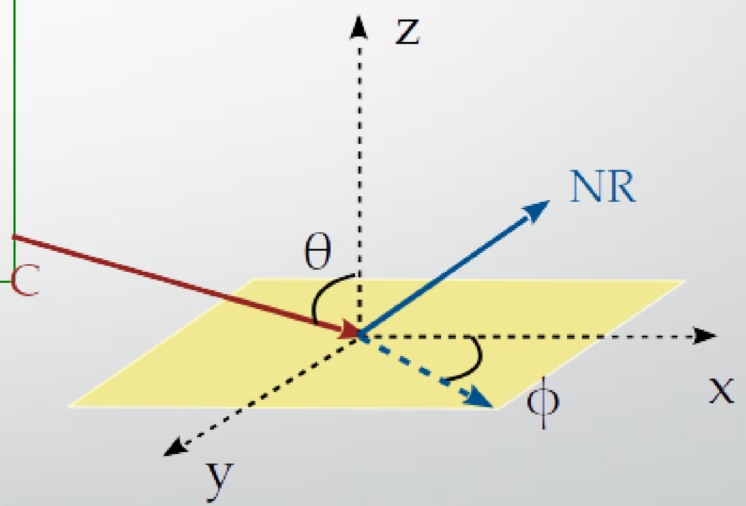


$\sigma \sim 6$ nm!

CARBON ION SAMPLES

Aim: plasmon analysis with C-Ion samples

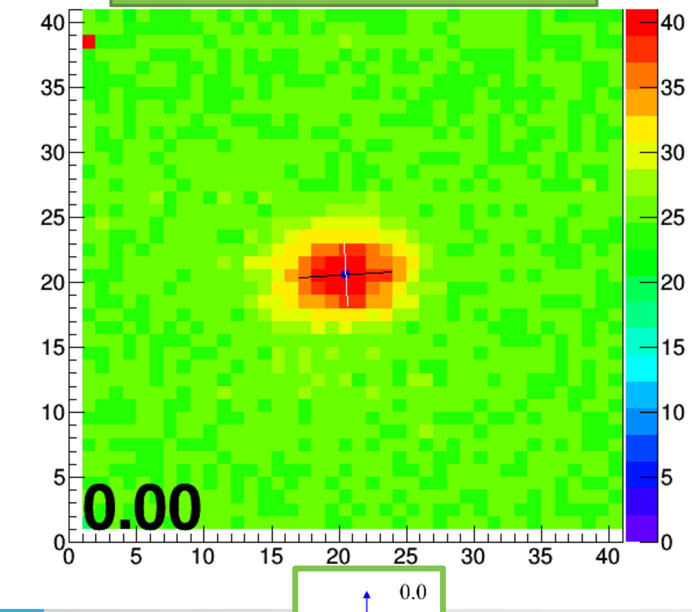
C-Ion samples (vacuum implantation)
100keV (Horizontal ~ 80°)
60keV (Horizontal ~ 80°)
30keV (Horizontal ~ 80°)
10keV (Vertical ~ 10°)



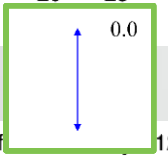
Horizontal exposures to produce nanotracks in NIT with a preferred direction (signal-like samples)
Vertical exposure to produce in most cases one grain in NIT with an isotropic direction (background-like sample)

Plasmon analysis of isolated grains

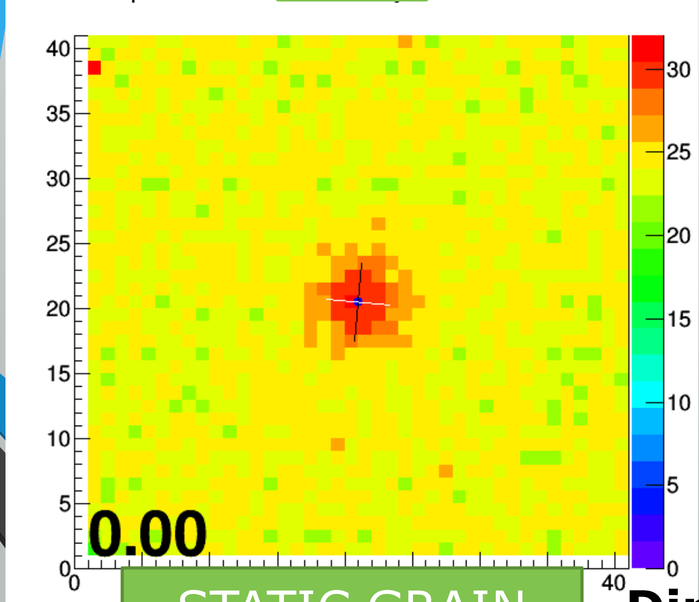
MOVING GRAIN



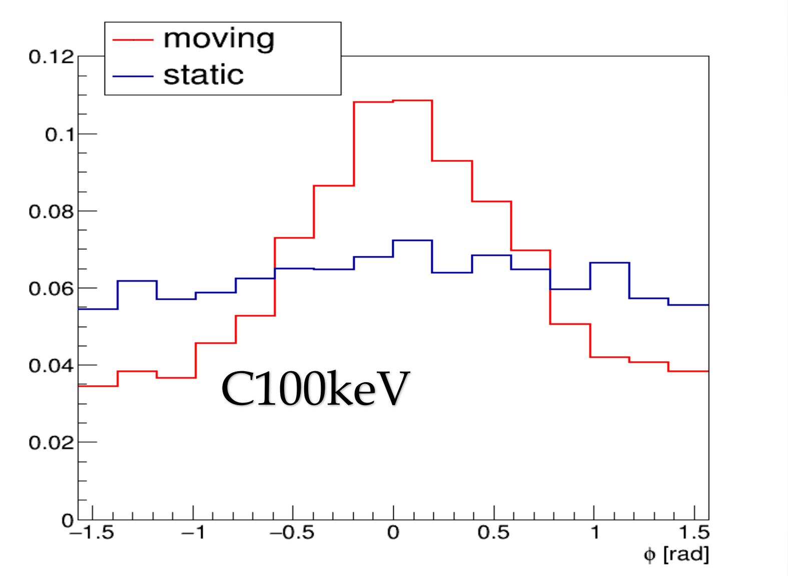
pol angle

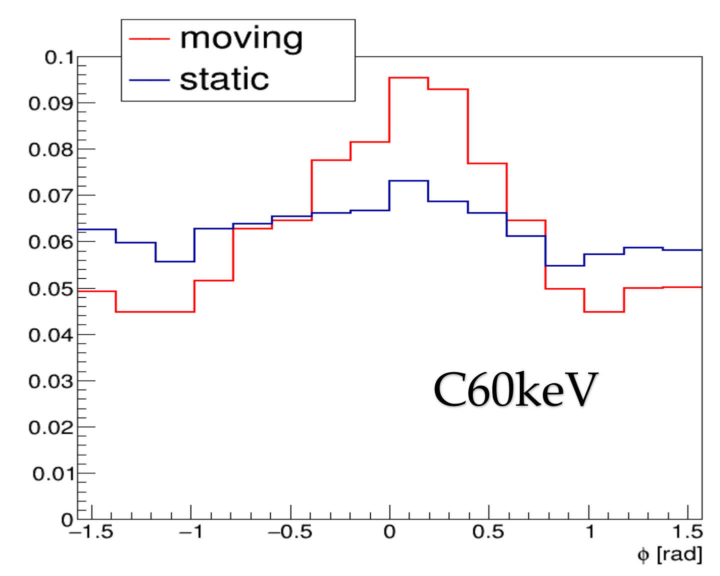


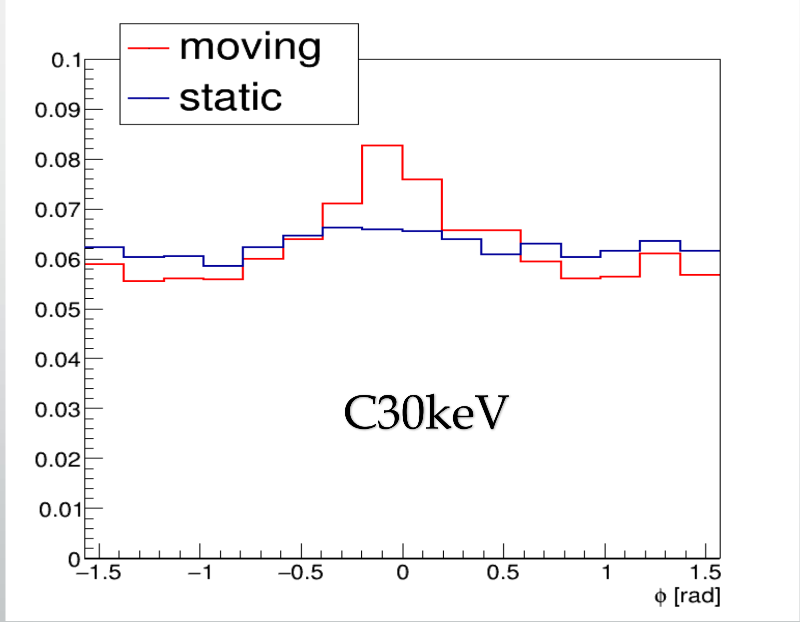
ipol 0 cl 508 in f 12.46 0.26 0.60

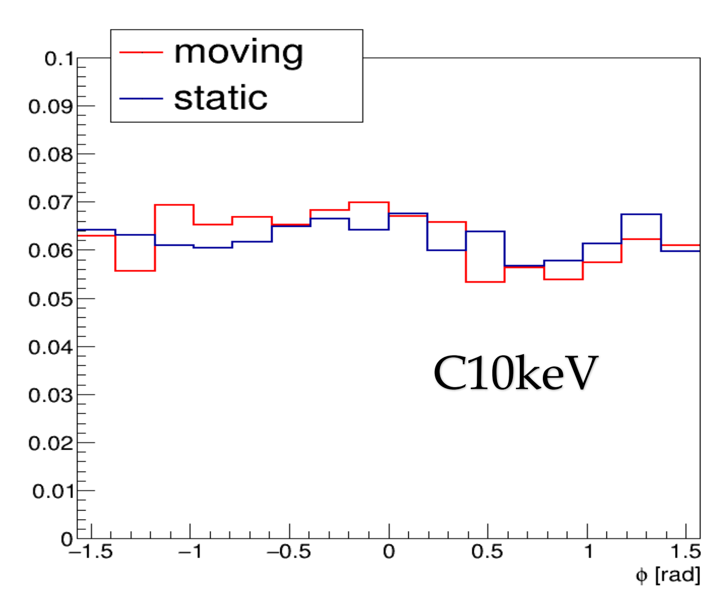


STATIC GRAIN





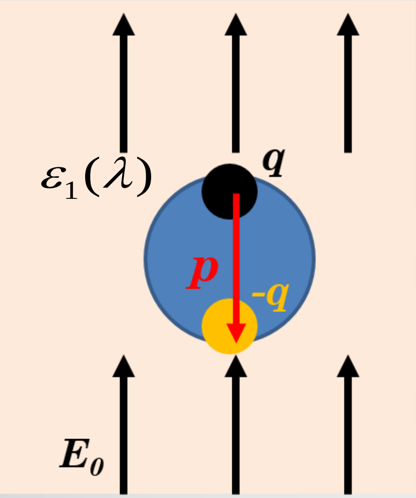




Directionality demonstrated with Carbon ions down to 30 keV

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

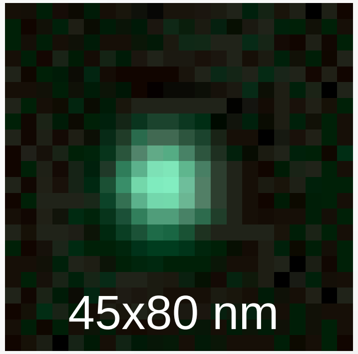
$$\varepsilon_1(\lambda_l) + 2\varepsilon_m(\lambda_l) \approx 0$$

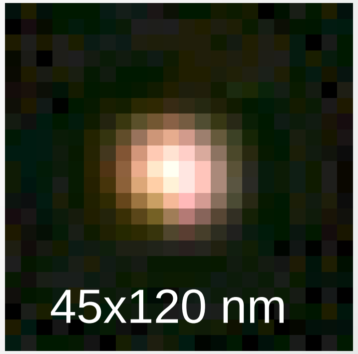
Appl. Phys. Lett. **80**, 1826 (2002)

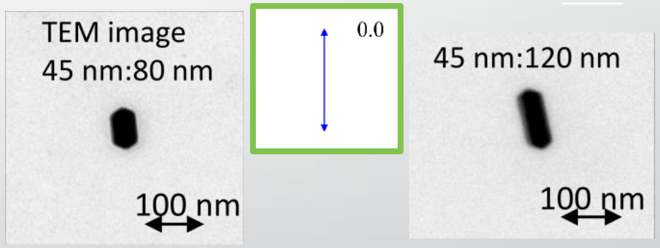
Ag grain size → resonance wavelength

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

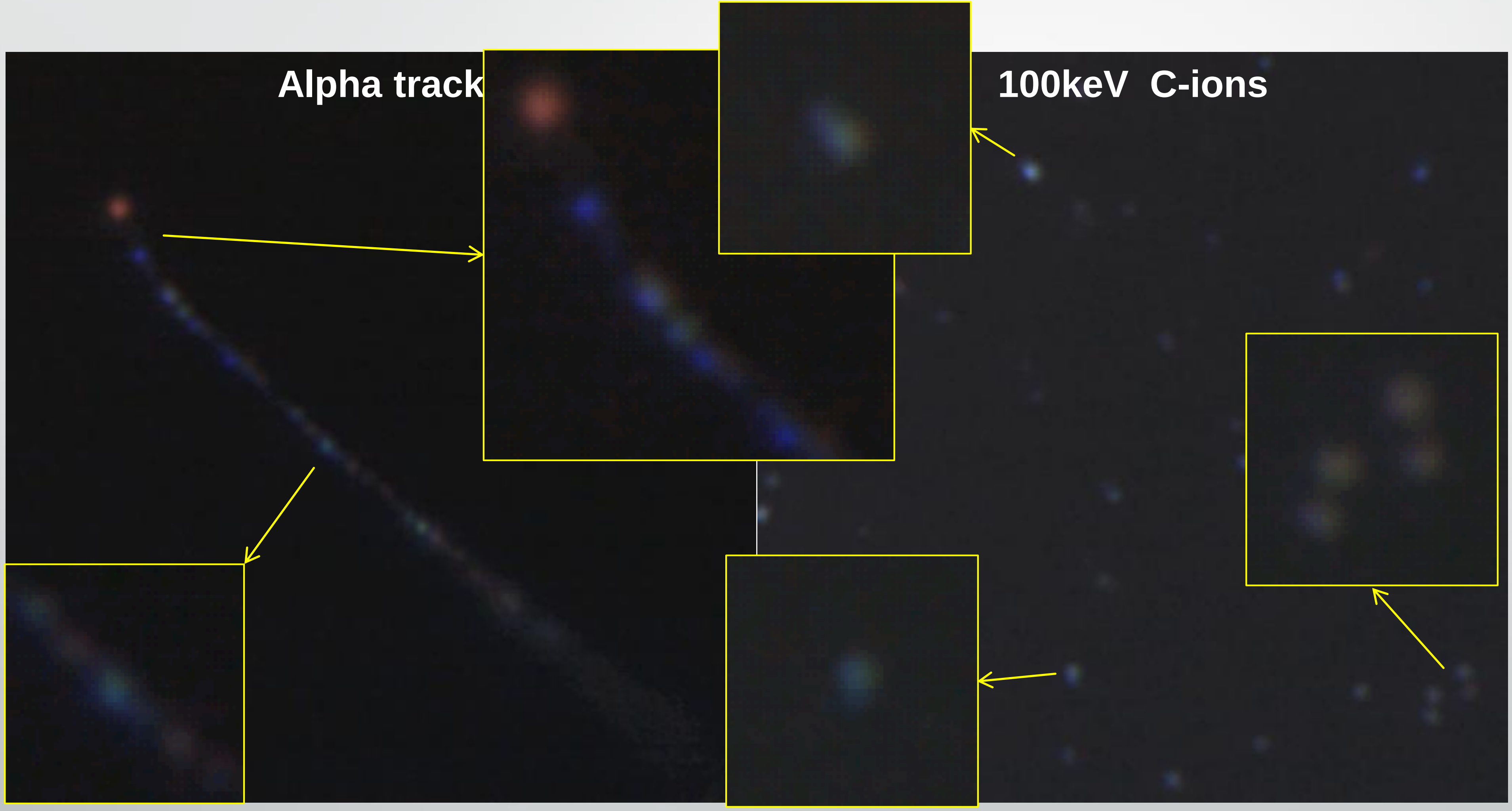


Image size 15 µm x 15 µm

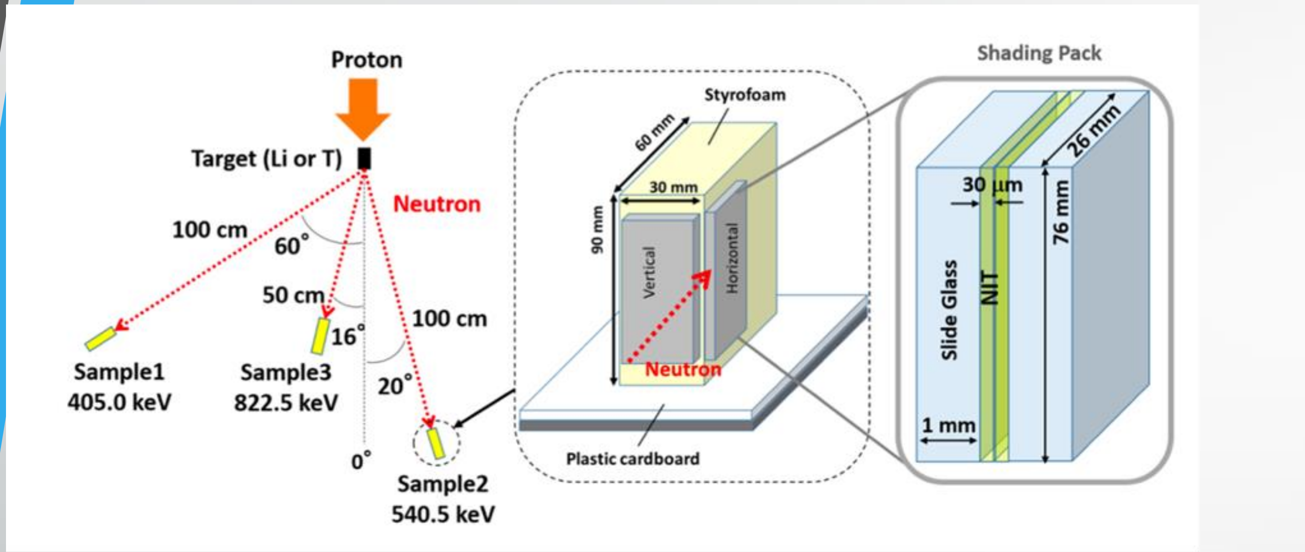
Image size 15 µm x 15 µm

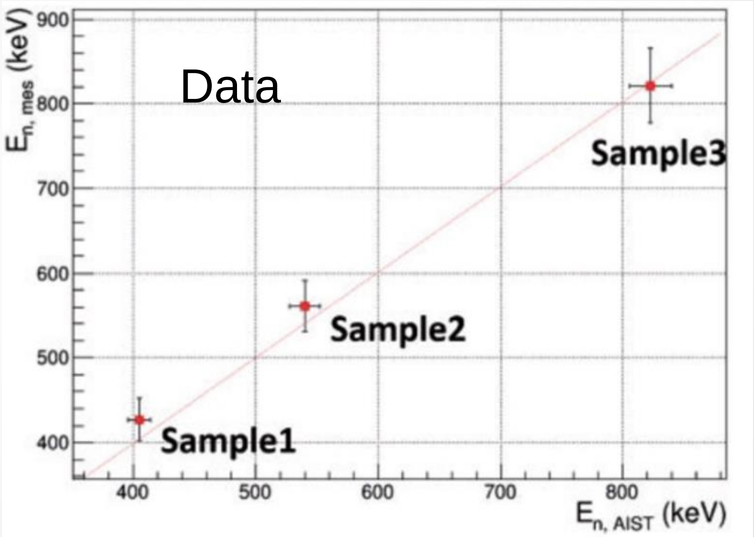
Head-tail discrimination!

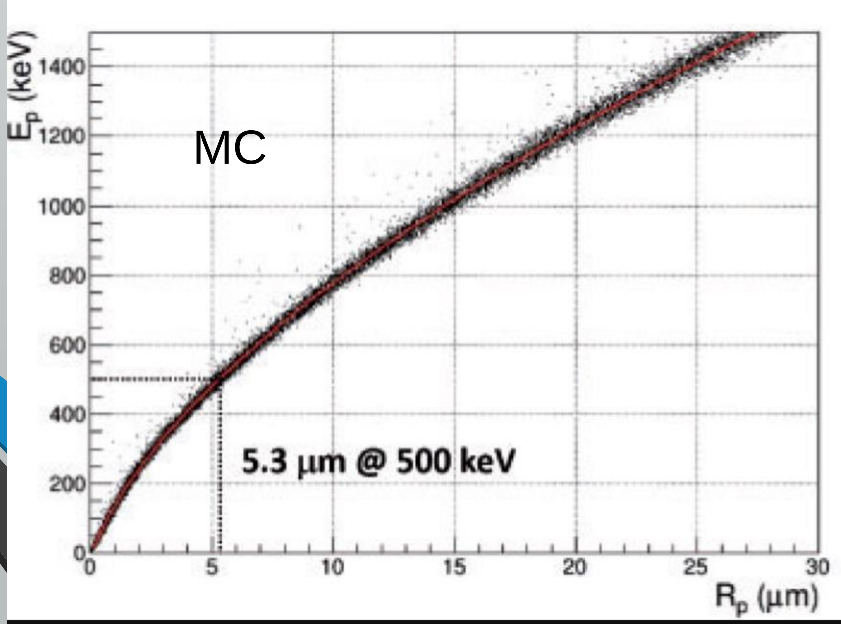
Sub-MeV neutron measurement calibration

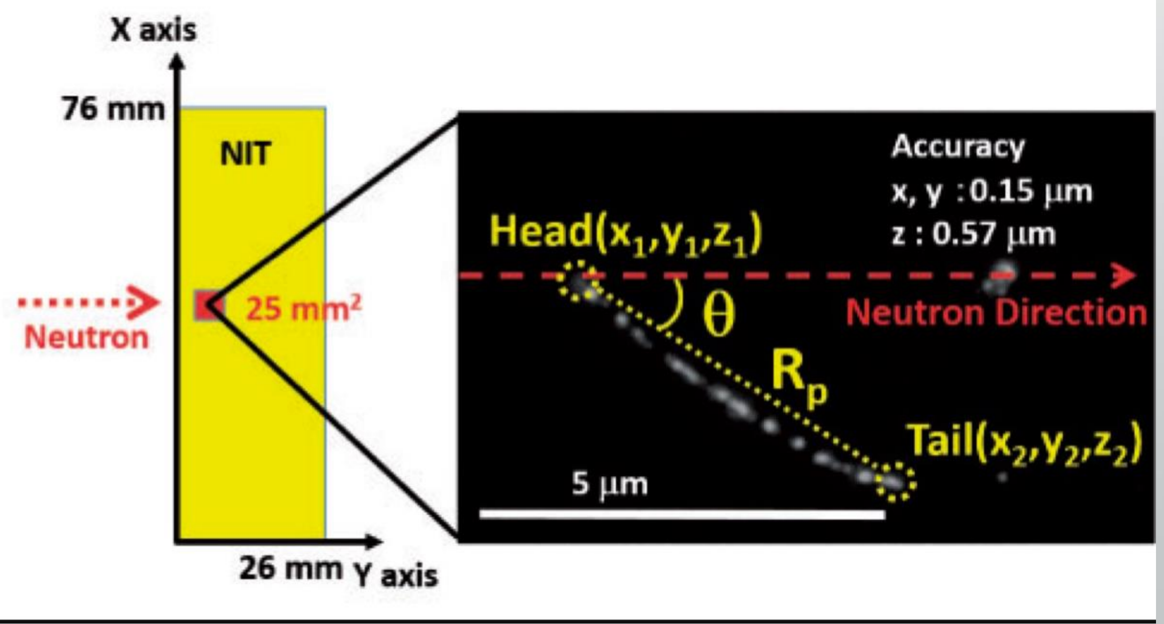
National Institute of Advanced Industrial Science and Technology, Tokyo, Japan

PTEP n. 4 (2021) 043H01, 10 Mar 2021 https://doi.org/10.1093/ptep/ptab030









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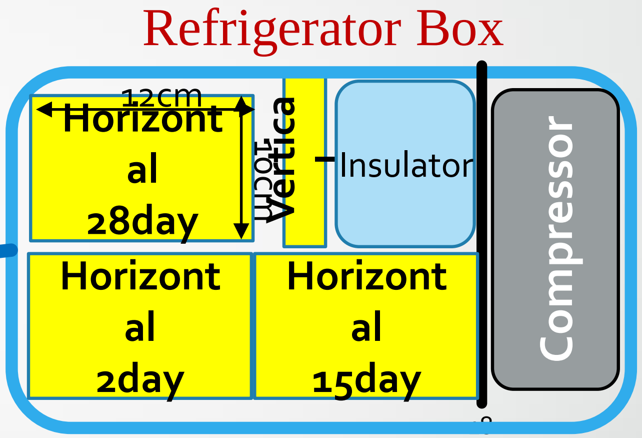
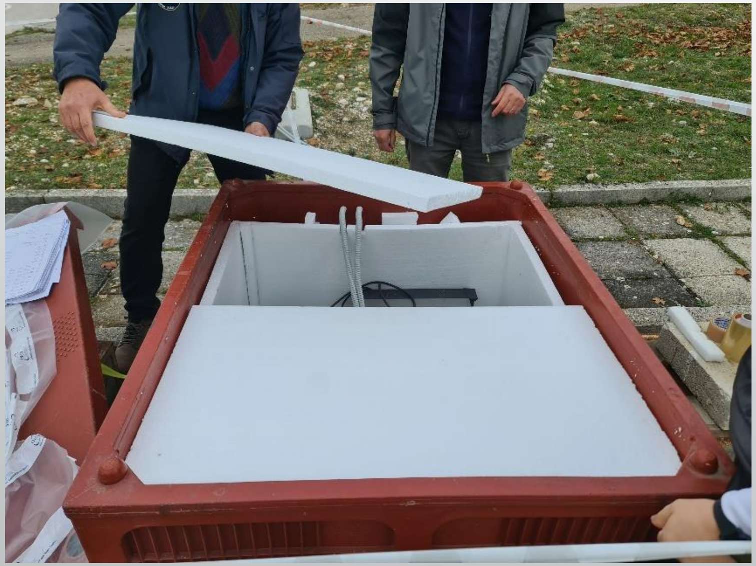
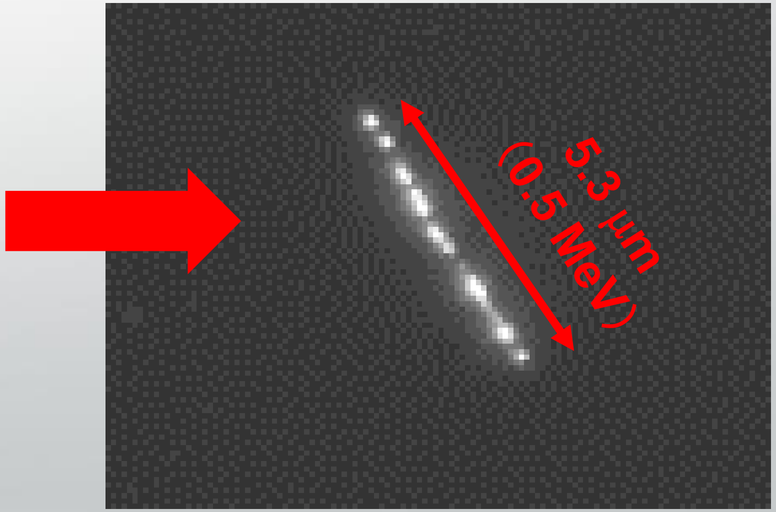
Neutron measurement at LNGS: first sub-MeV detection and first directional detection



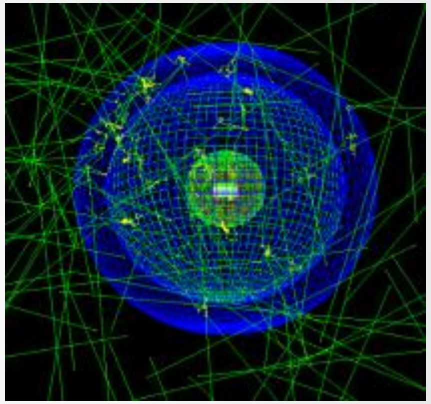




Backgrounds

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

Astropart. Phys.. 80 (2016) 16–21



External (with 1 m HDPE shielding @LNGS)

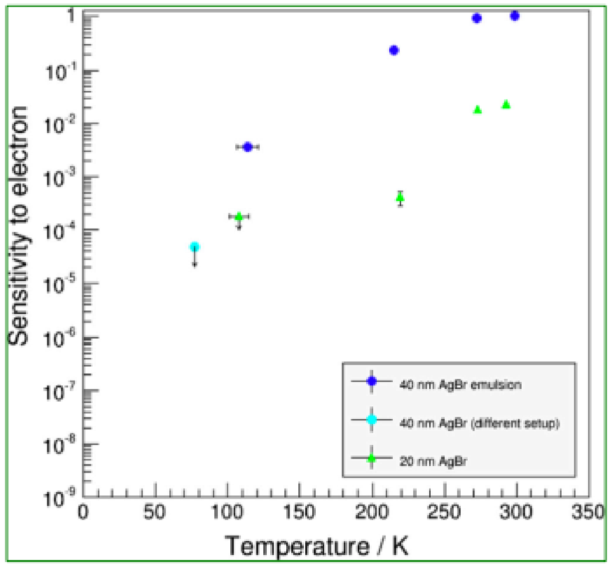
Source	Rate $[10\,\mathrm{kg} \times \mathrm{y}]^{-1}$
Environmental gammas	$(1.97 \pm 0.17) \times 10^{4}$
Environmental neutrons	$\mathcal{O}(10^{-2})$
Cosmogenic neutrons	1.41 ± 0.14

C14 and gamma;

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

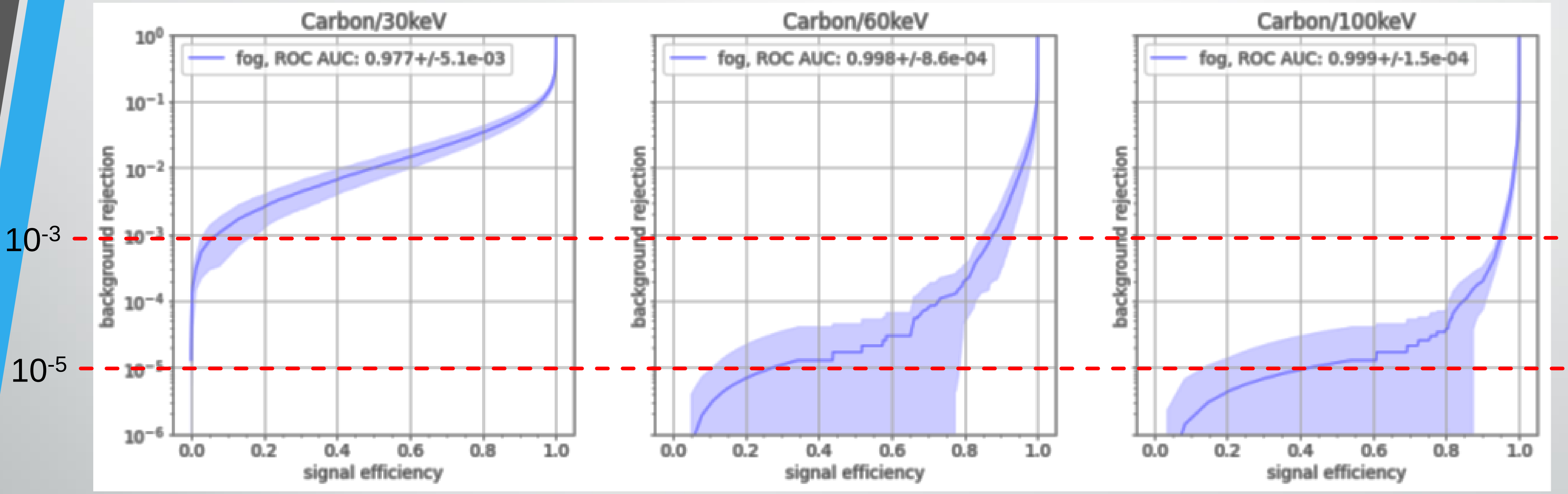
Additional **lever arms** being quantified:

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



NIM A 845 (2017) 373

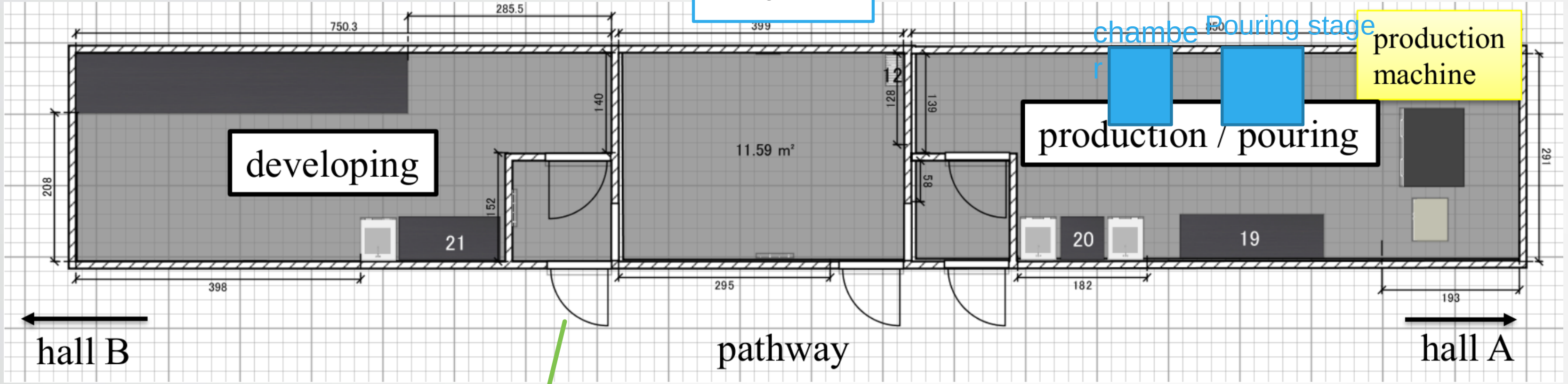
Background reduction: Machine Learning approach



Preliminary results

Only color images, no polarization information

Hall F


chambe
r
Pouring stage
production
machine
750.3
285.5
399
350
140
128
12
139
291
208
152
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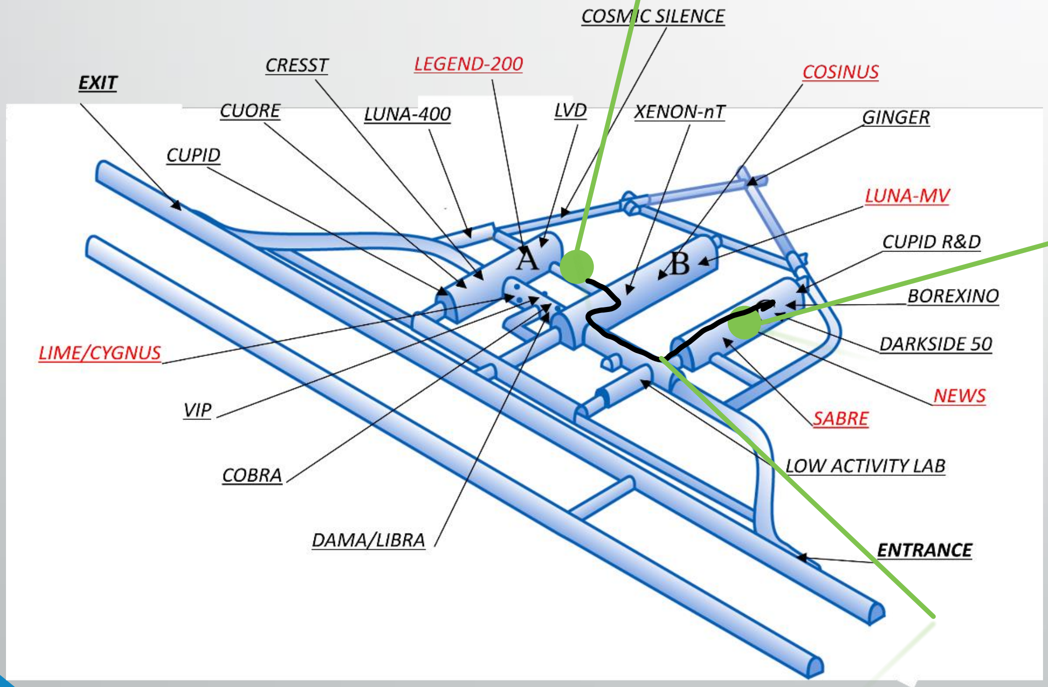
developing
11.59 m²
production / pouring
21
20
19
398
295
182
193
hall B
pathway
hall A


COSMIC SILENCE
EXIT
CRESST
LEGEND-200
COSINUS
CUORE
LUNA-400
LVD
XENON-nT
GINGER
CUPID
LUNA-MV
CUPID R&D
BOREXINO
DARKSIDE 50
LIME/CYGNUS
NEWS
VIP
SABRE
LOW ACTIVITY LAB
COBRA
DAMA/LIBRA
ENTRANCE
A
B

Hall C

Underground emulsion production facility @LNGS

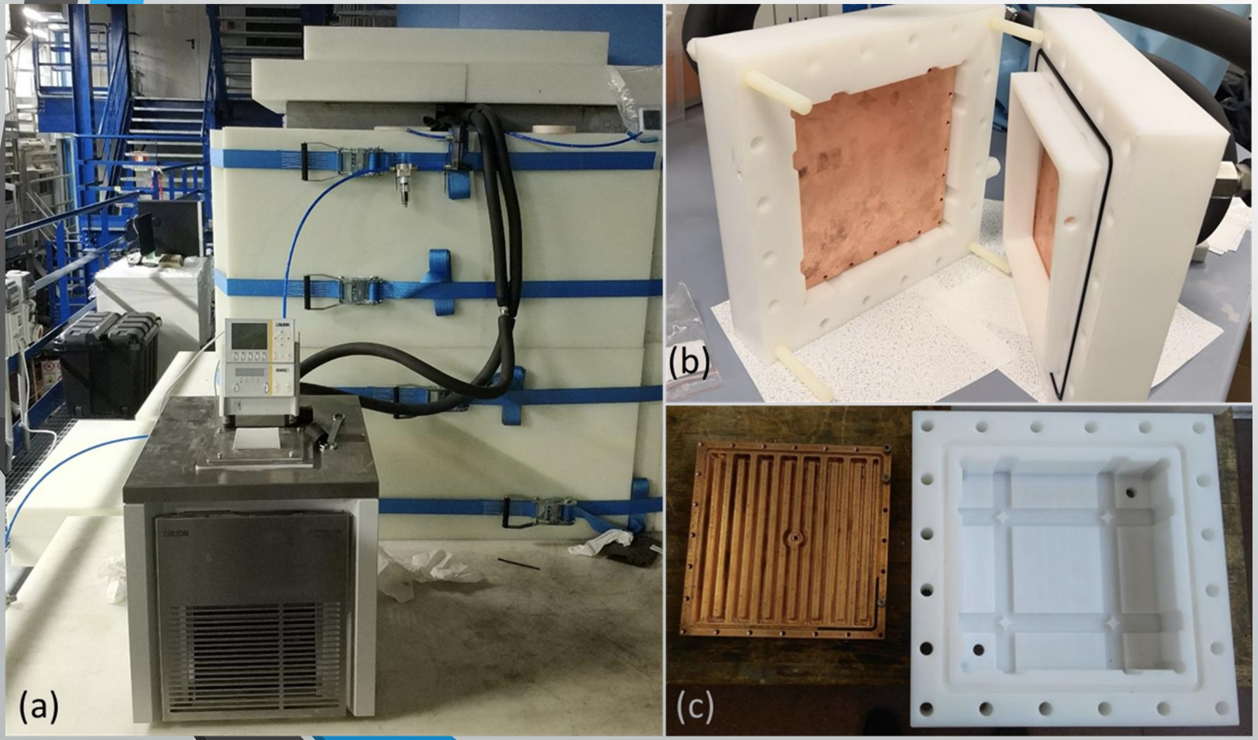
Fully operational since Dec-2020
Production capacity 100-200 g/day

NEWSdm: current setup

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

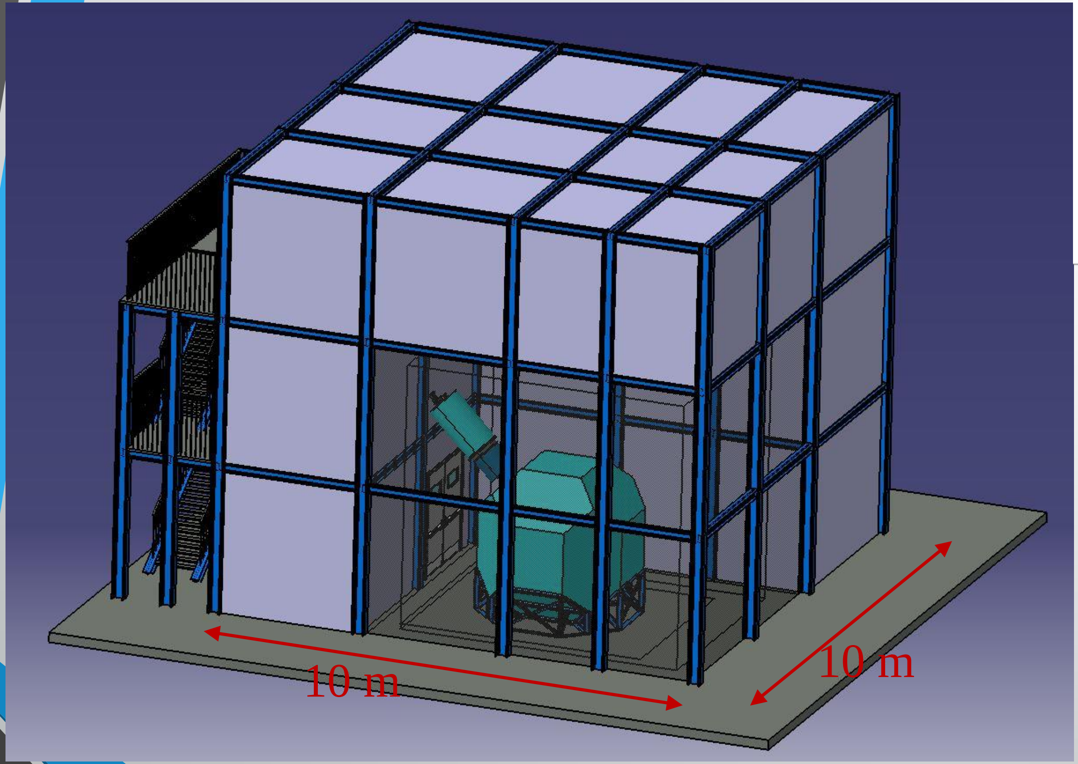
- Experimental setup in Hall C, close to Borexino
- Assembly of the setup in March 2021
- Test measurements ongoing

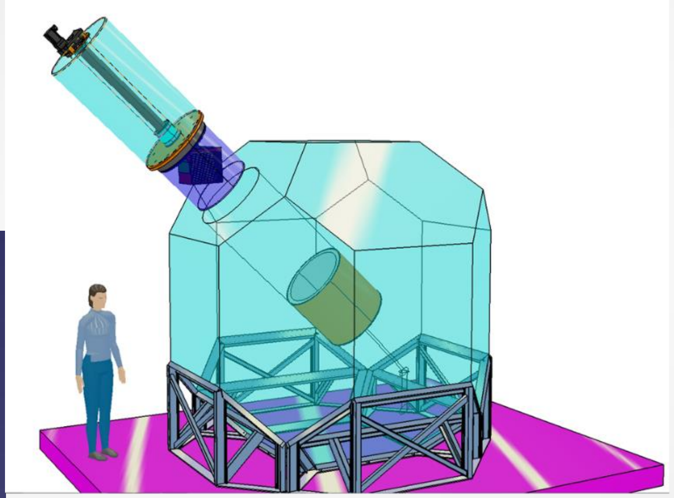
- Shielding: 10cmHDPE+10cm Pb+10cm HDPE



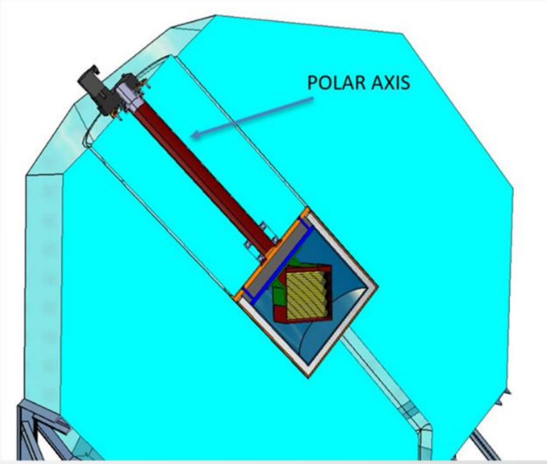
Future facility for NEWSdm: 10kg and beyond

Emulsion facility and shielding with an equatorial telescope

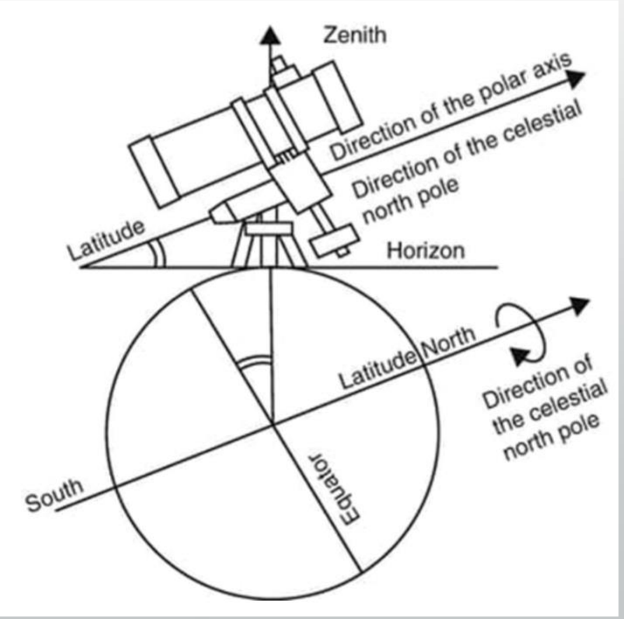


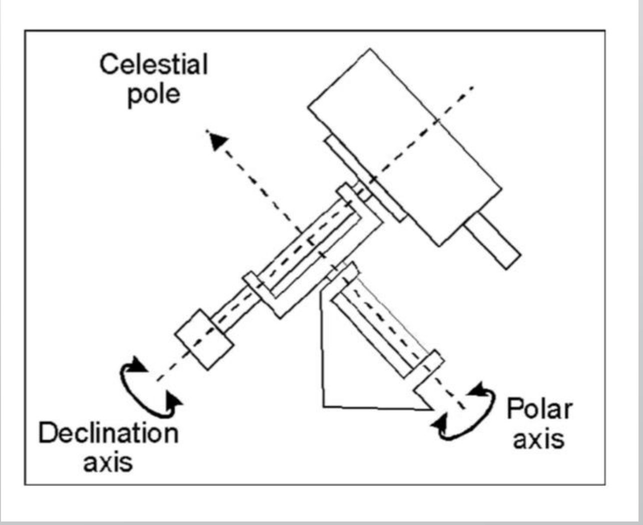


(a)

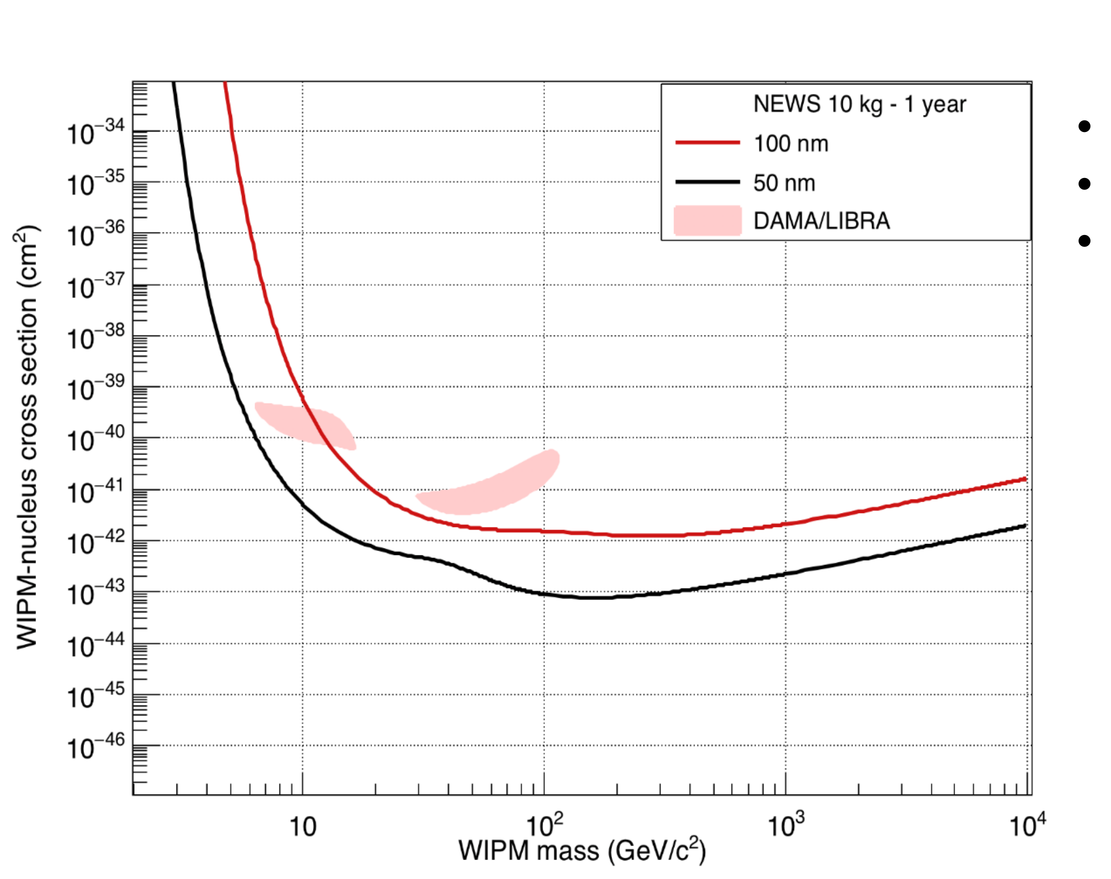


(b)





Sensitivity of a pilot experiment
10 kg scale



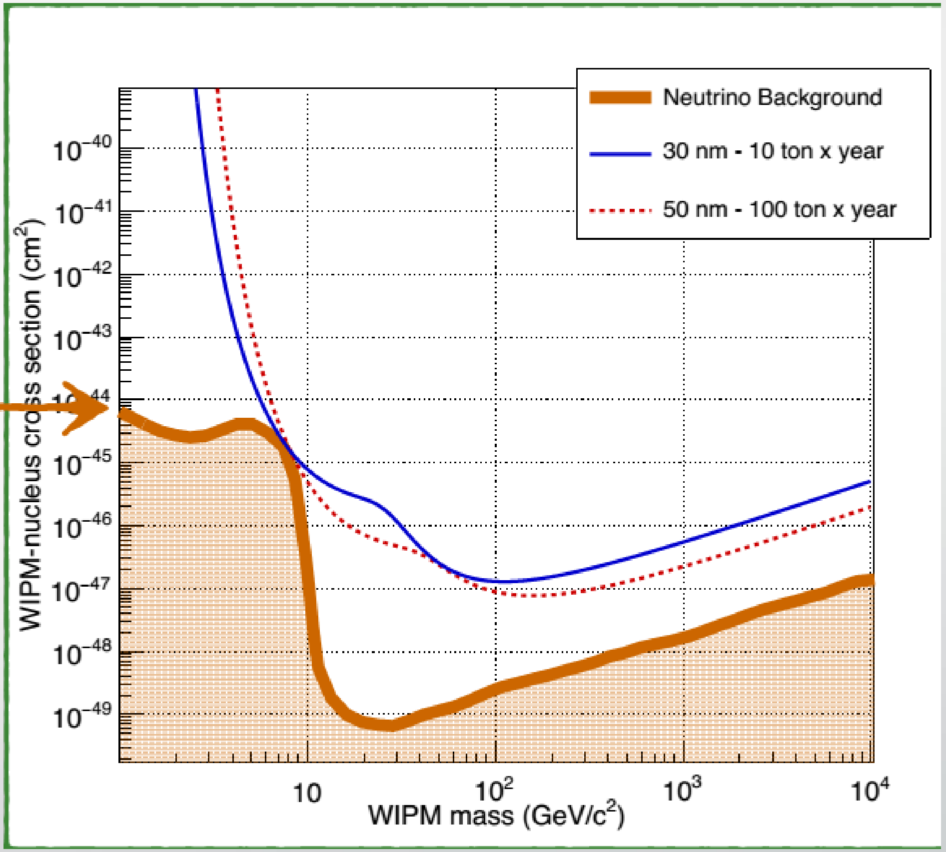
- 10kg x year experiment
- Zero background assumed
- Directionality not exploited

Towards Neutrino Floor

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

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

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-throw 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
- Near goal – few kg scale detector as technology demonstrator and for the first physics run
- By-products of NEWSdm R&D which has an intrinsic value:
  - New method for optical super-resolution
  - Neutron measurements in subMeV region with directionality

THANK YOU FOR ATTENTION!