NEWSdm

Nuclear **E**mulsions for **W**IMP **S**earch with **d**irectional **m**easurement

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On behalf of the NEWSdm Collaboration

CYGNUS 2019, Rome 2019 Jul 10th

NEWSdm COLLABORATION

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

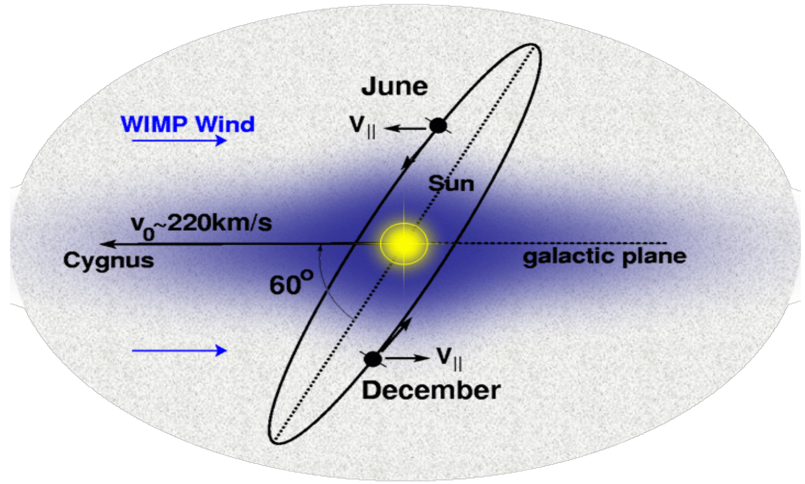
TURKEY
METU Ankara

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

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

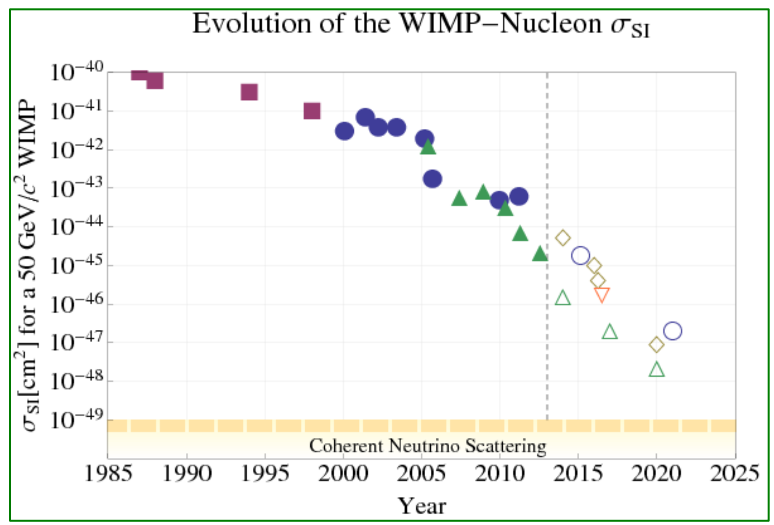
POWER OF DIRECTIONALITY

- Impinging direction of DM particle is (preferentially) opposite to the velocity of the Sun in the Galaxy, i.e. from Cygnus Constellation

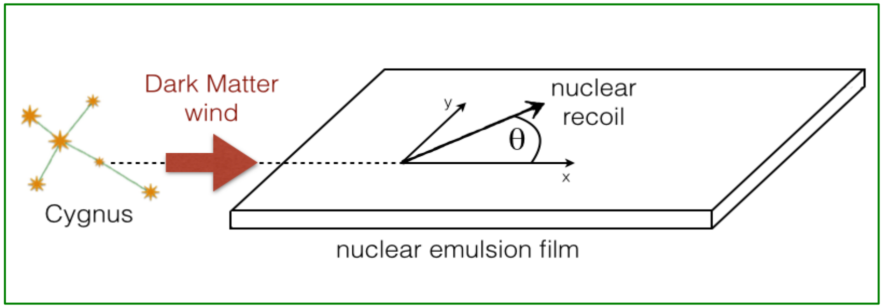


- Unambiguous proof of the galactic origin of Dark Matter

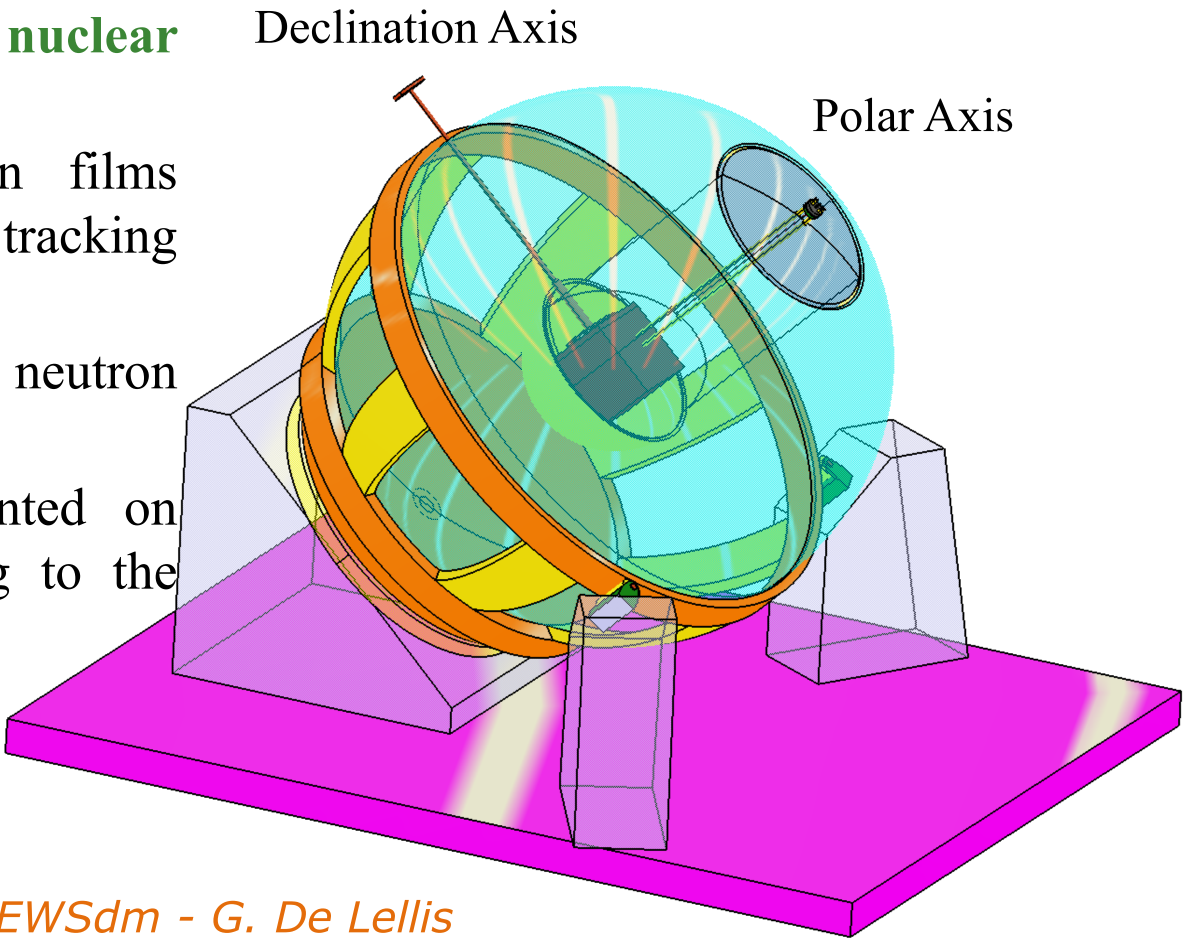
- Unique possibility to overcome the "neutrino floor", where coherent neutrino scattering creates an irreducible background



NEWSdm PRINCIPLE

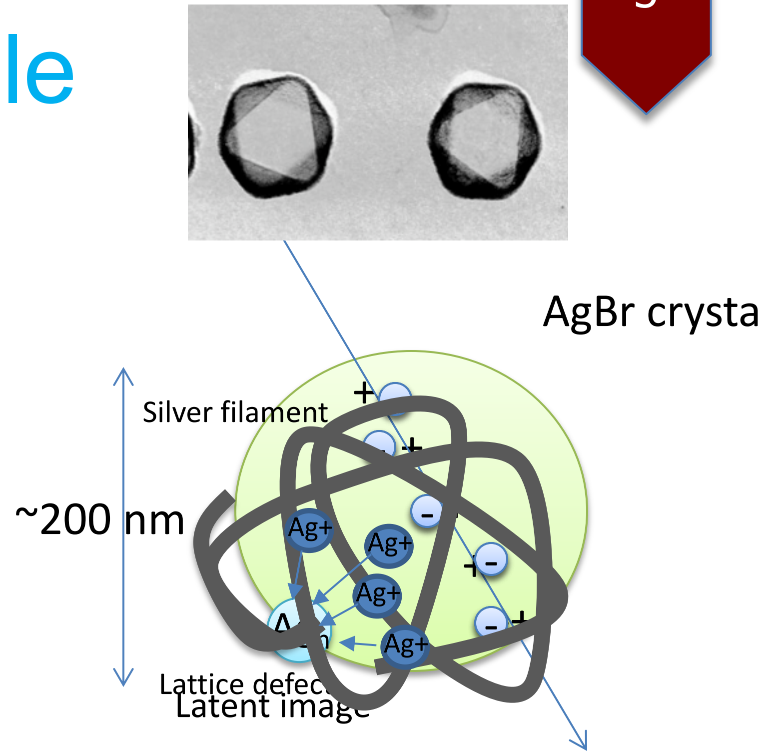


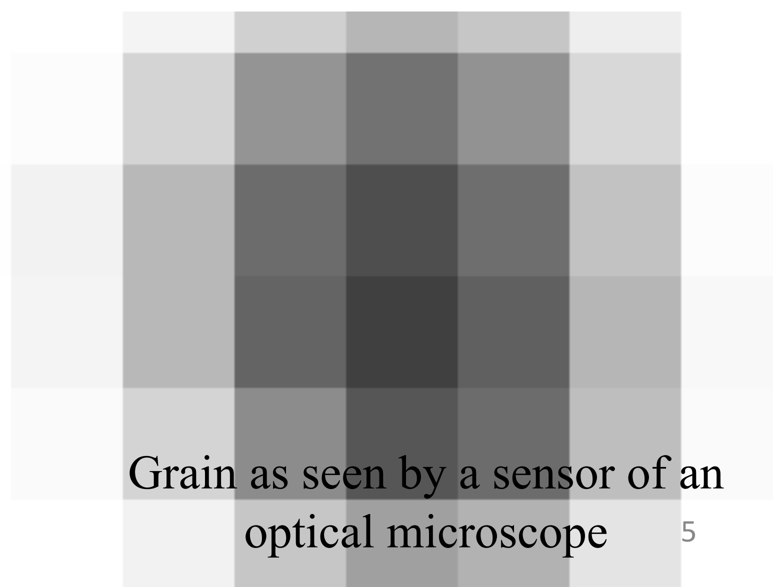
- **<u>Aim</u>**: detect the direction of **nuclear recoils**
- **<u>Target</u>**: nanometric emulsion films acting both as target and tracking detector
- **<u>Background reduction:</u>** neutron **shield** surrounding the target
- **<u>Fixed pointing</u>**: target mounted on **equatorial telescope**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

NIT EMULSIONS

Constituent	Mass Fraction
AgBr-I	0.78
Gelatin	0.17
PVA	0.05

(a) Constituents of nuclear emulsion

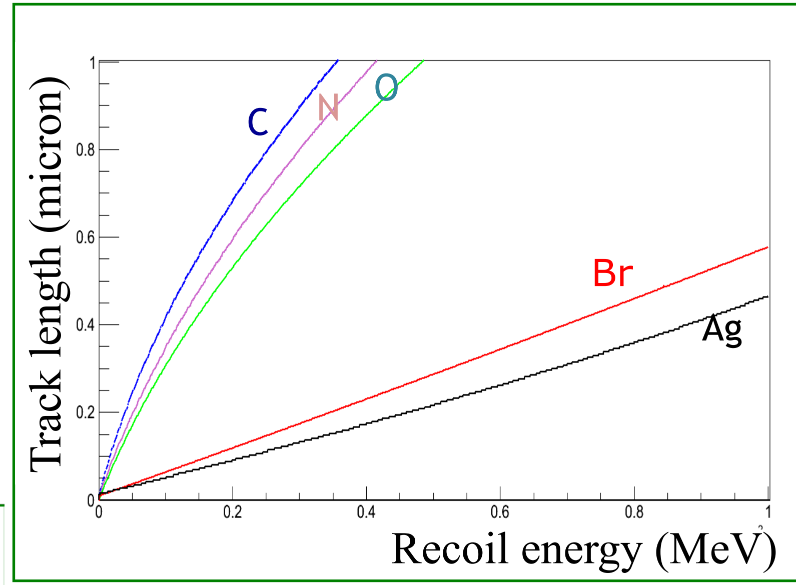
AgBr-I: sensitive elements
Organic gelatine: retaining structure
PVA to stabilise the crystal growth

heavy nuclei

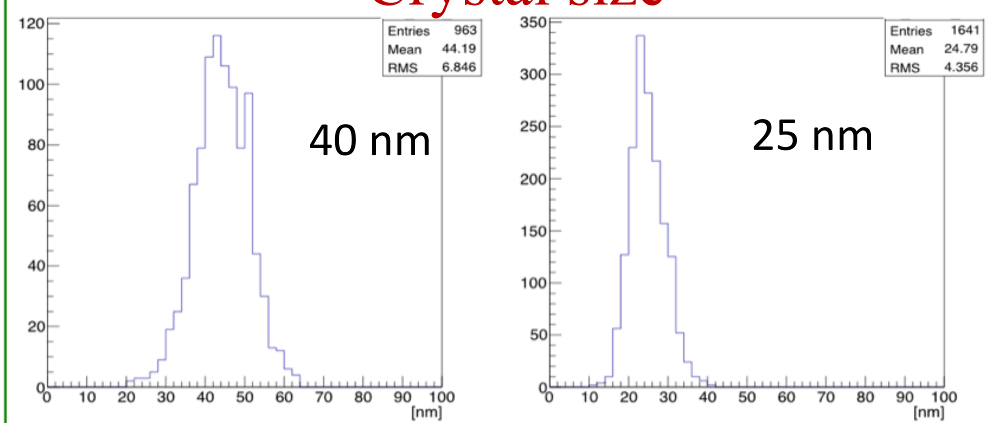
light nuclei

Element	Mass Fraction	Atomic Fraction
Ag	0.44	0.12
Br	0.32	0.12
I	0.019	0.003
C	0.101	0.172
O	0.074	0.129
N	0.027	0.057
H	0.016	0.396
S	0.003	0.003

(b) Elemental composition



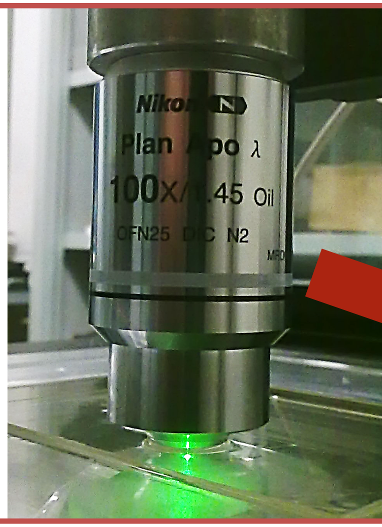
Crystal size



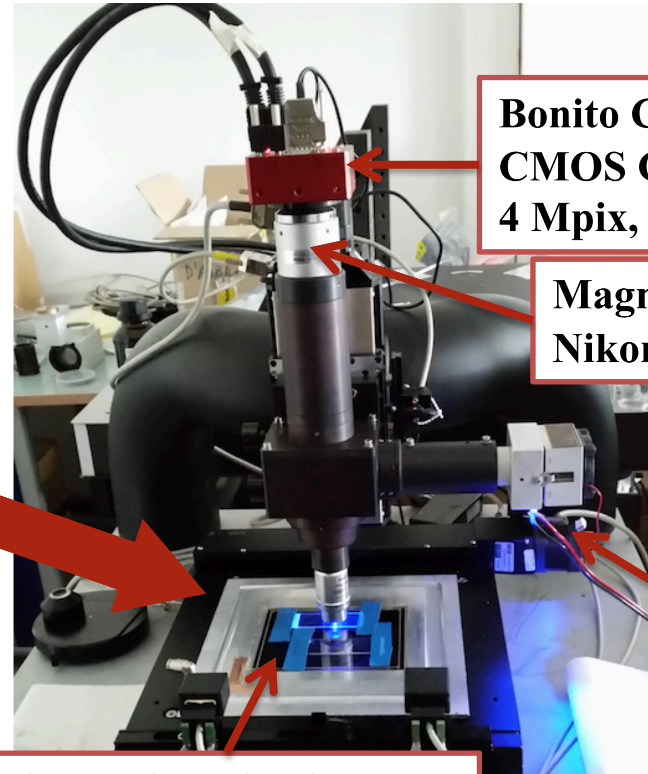
READOUT TECHNOLOGY

OPTICAL MICROSCOPE READ-OUT: STEP 1

100x objective lens with high N.A.



Resolution: 28 nm/pixel
View Size: 65.2 x 48.3 μm^2



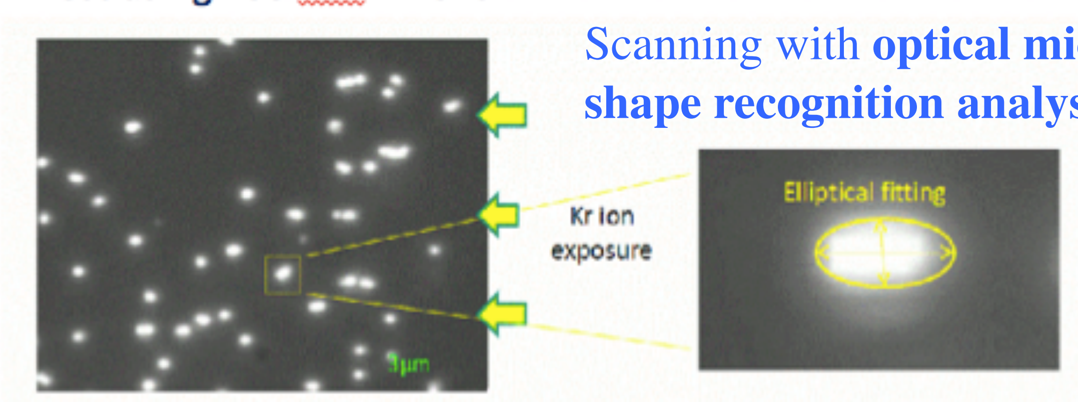
Bonito CL/CMC-4000 CMOS Camera 4 Mpix, @100 fps

Magnifying lens, Nikon VM C-2.5x

100W Halogen Lamp

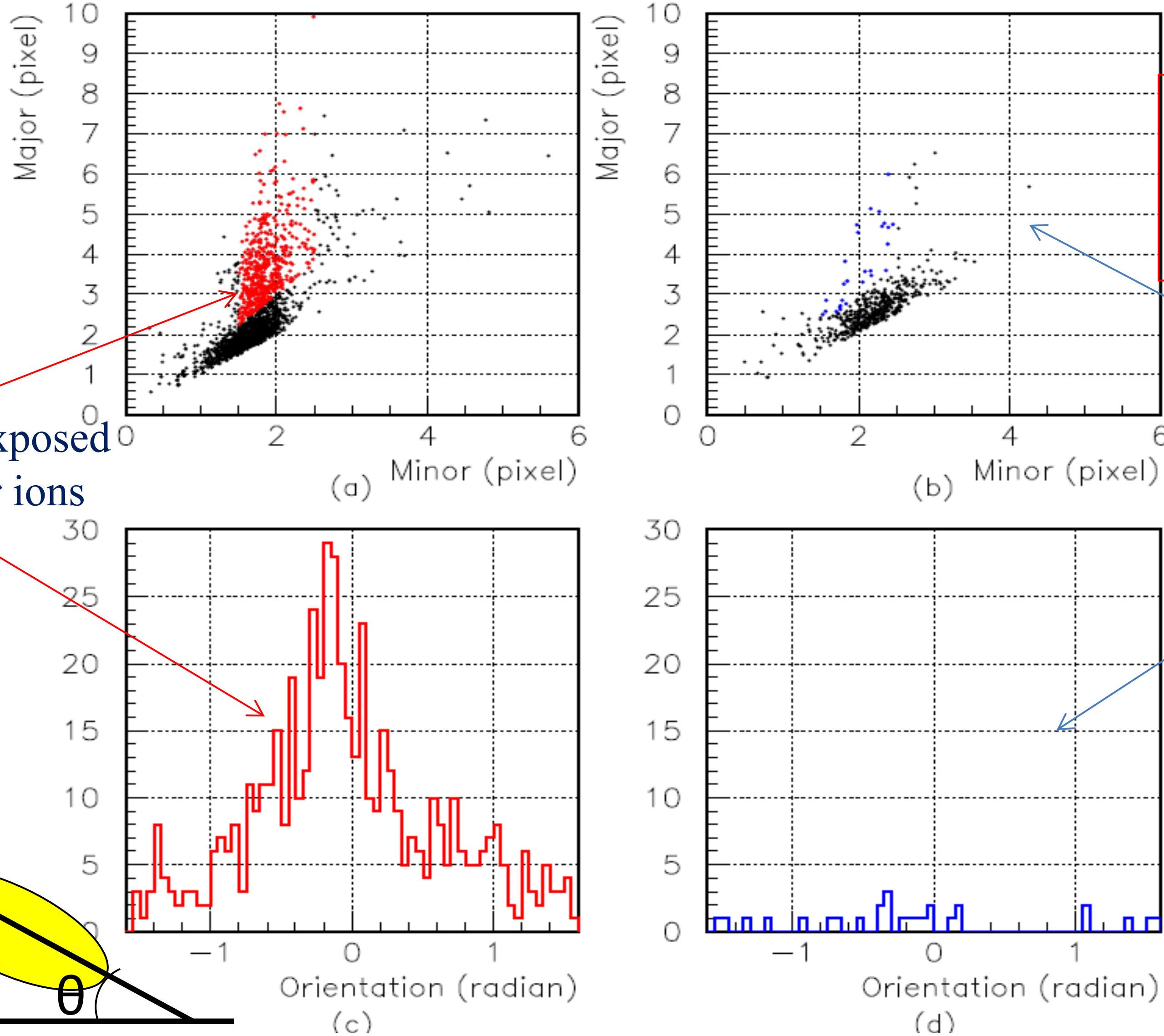
Nikon Oil Objective 100x, 1.45 N.A., Plan Apo

Test using 400 keV Kr ions



Scanning with **optical microscope** and **shape recognition analysis**

Selection of Kr ion tracks with shape analysis



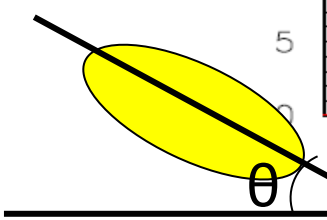
Major/minor>1.5

1.4<minor <2.6

pixel > 40

Film exposed to Kr ions

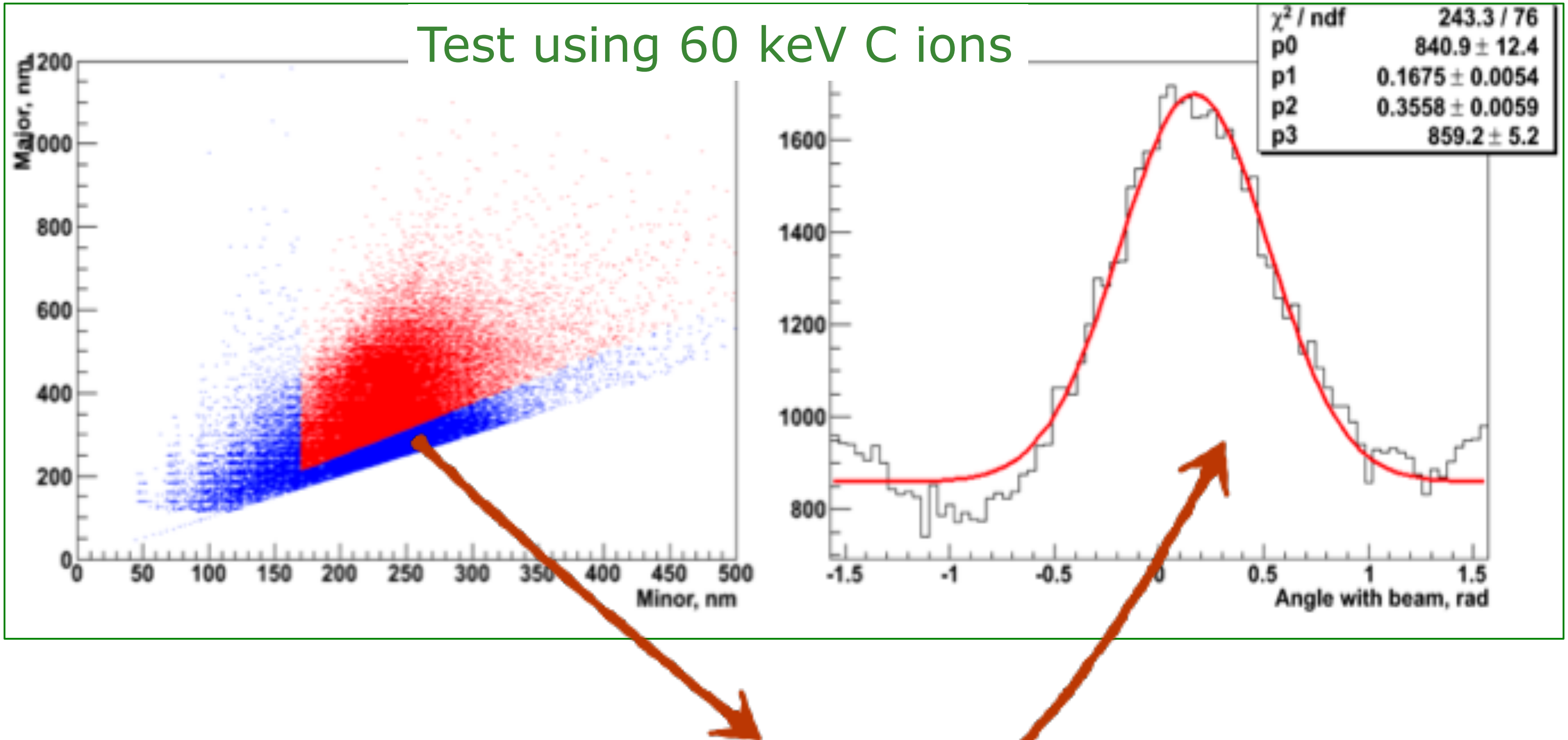
Reference film (unexposed)



Direction detected!

NIM A680 (2012) 12-17

TRACK SELECTION:Shape analysis



$$\sigma^2 = \sigma^2_{intrinsic} + \sigma^2_{scattering}$$

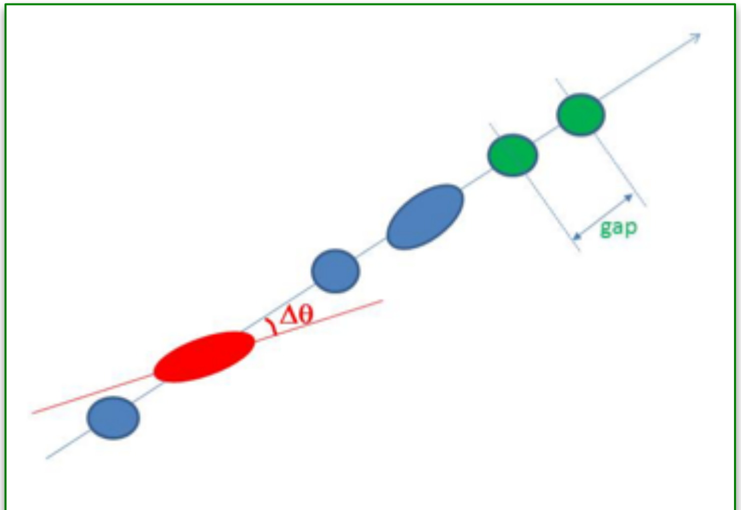
$$\sigma = 360 \text{ mrad}$$

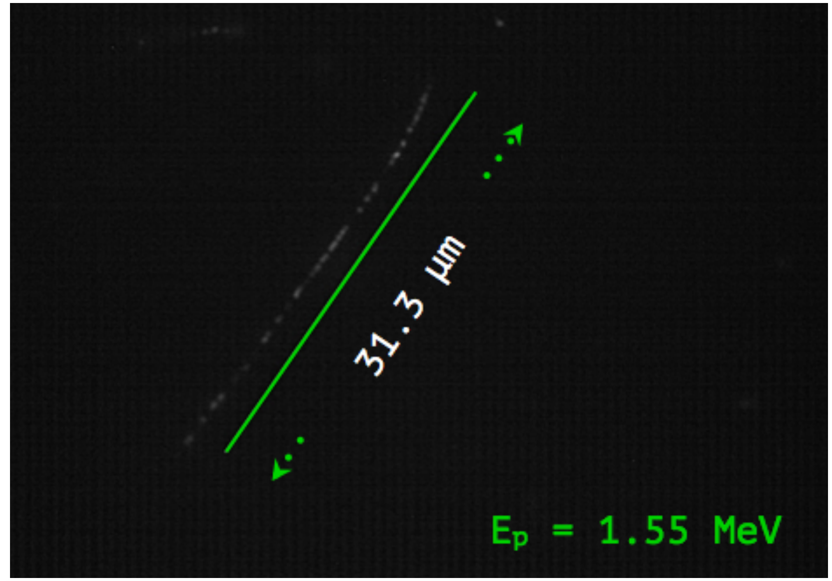
SIGNAL SELECTION

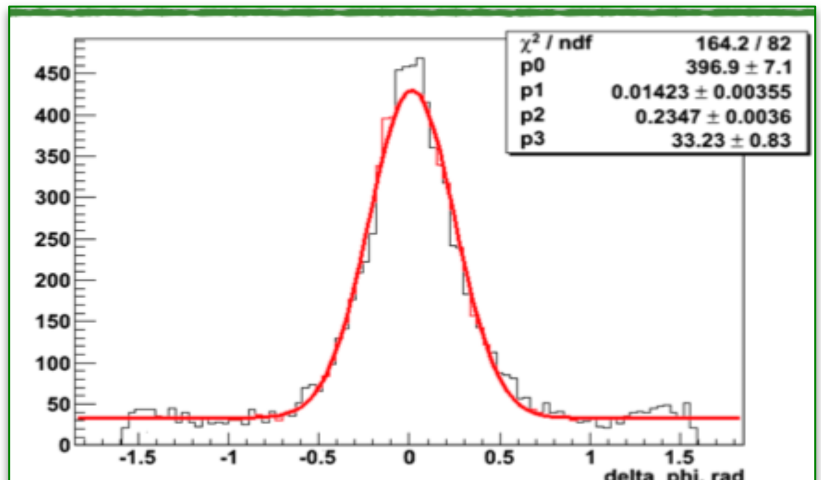
- Major axis/minor axis > 1.25
- minor axis > 170 nm

INTRINSIC ANGULAR RESOLUTION

- Neutron test beam sample: exposure at FNS facility (Japan)
- Compare clusters with elliptical (e > 1.1) shape with the proton recoil direction
- Scattering contribution negligible



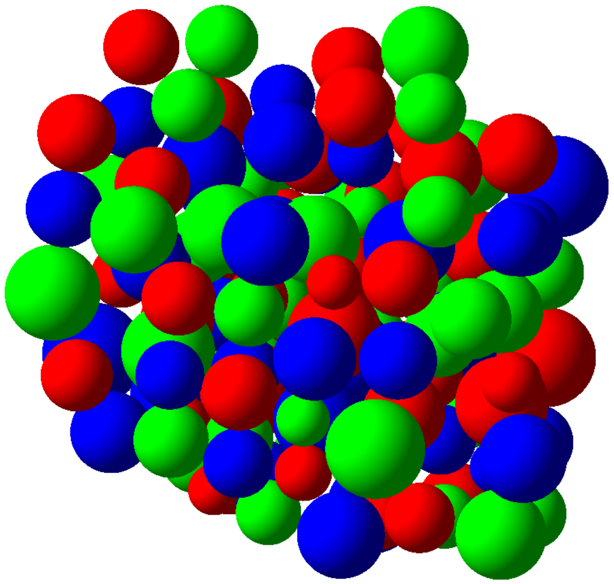




INTRINSIC ANGULAR RESOLUTION
σ = 235 mrad = 13°

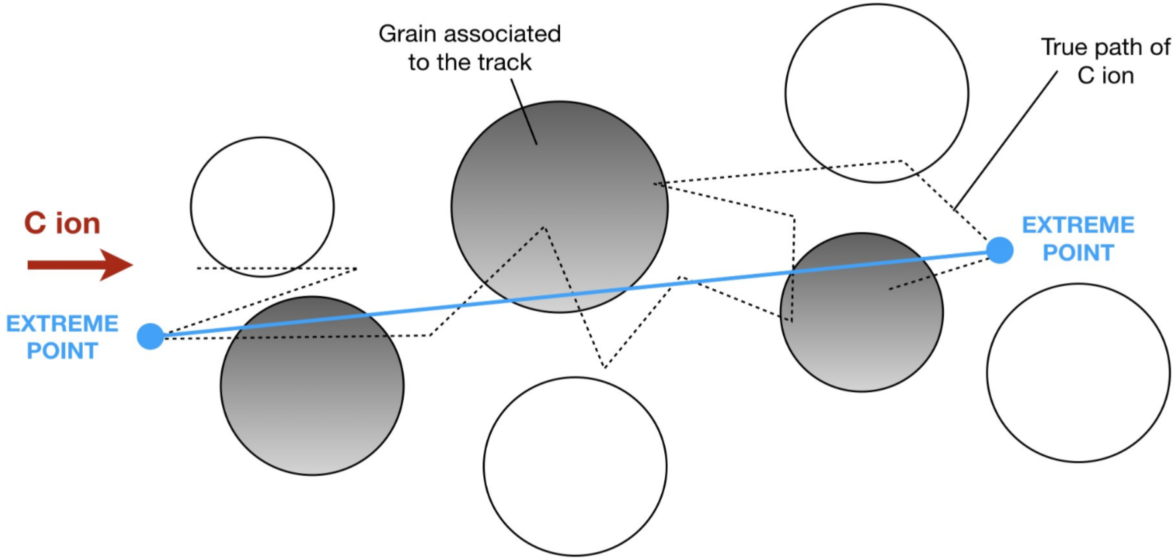
CRYSTAL MODEL

Simulation of crystals in NIT



Crystal radius gaussian (22.0, 3.4) nm
Volume occupancy ~45 %

Events generated by SRIM are translated in the crystal framework



STEP1: SHAPE ANALYSIS

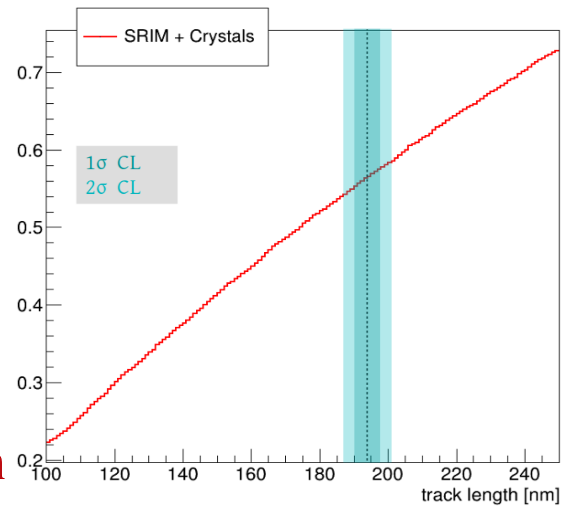
$$\epsilon_{sh} = \frac{N_{gaus}}{N_{gaus} + N_{flat}}$$

→

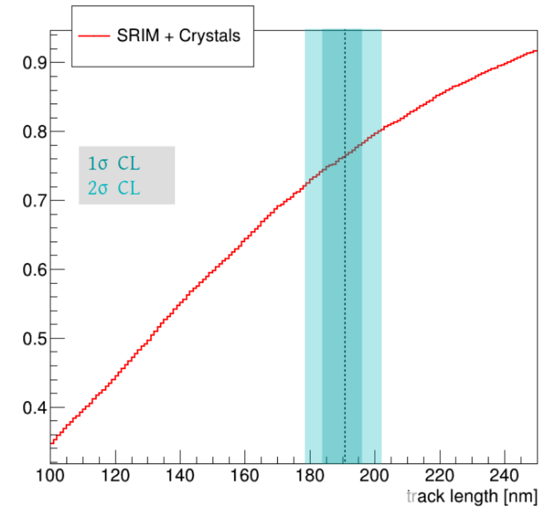
C100keV_H: 44%
C60keV_H: 24%

From the CDFs → track length threshold corresponding to the measured inefficiency

Track length threshold ~**190 nm**

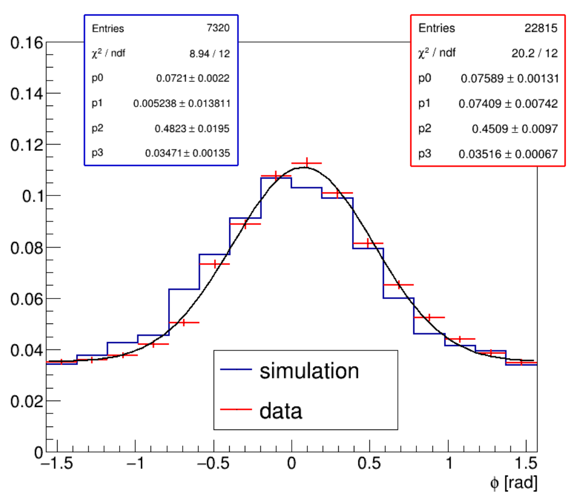


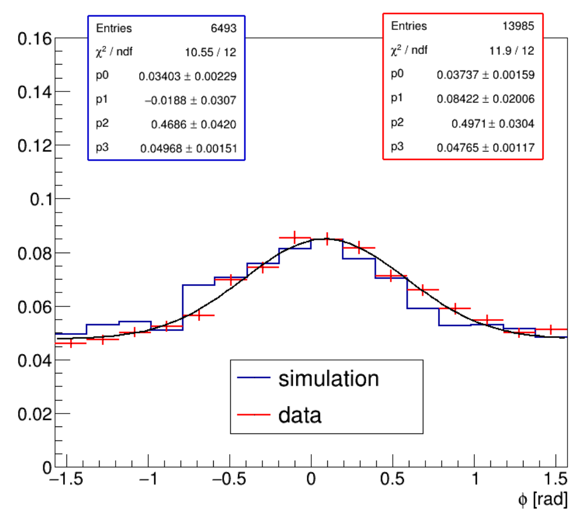
C100keV



C60keV

Data/MC comparison:
random direction for track lengths < 190nm





Technological Developments

SCIENTIFIC REPORTS

OPEN

A Novel Optical Scanning Technique with an Inclined Focusing Plane

Andrey Alexandrov[1,2,3,4], Giovanni De Lellis[1,2] & Valeri Tioukov[1]

Received: 9 August 2018

Accepted: 18 January 2019

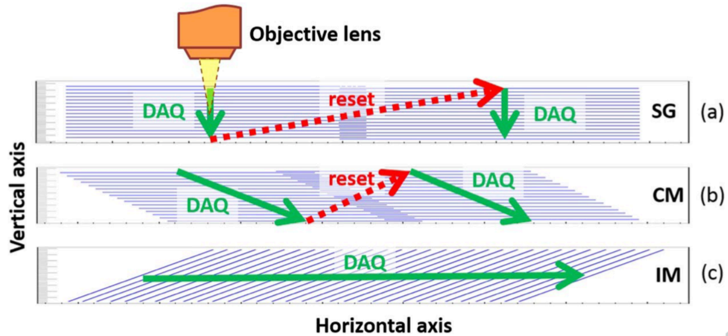
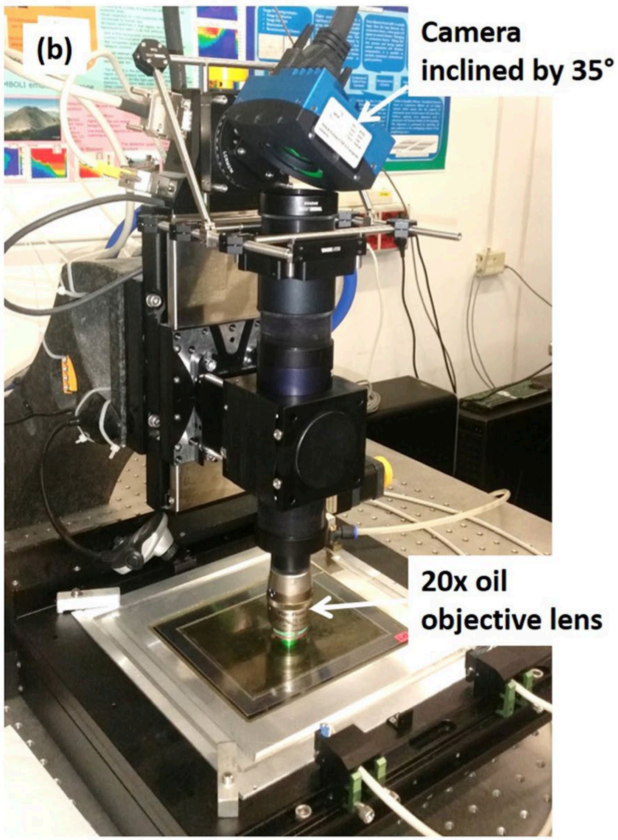
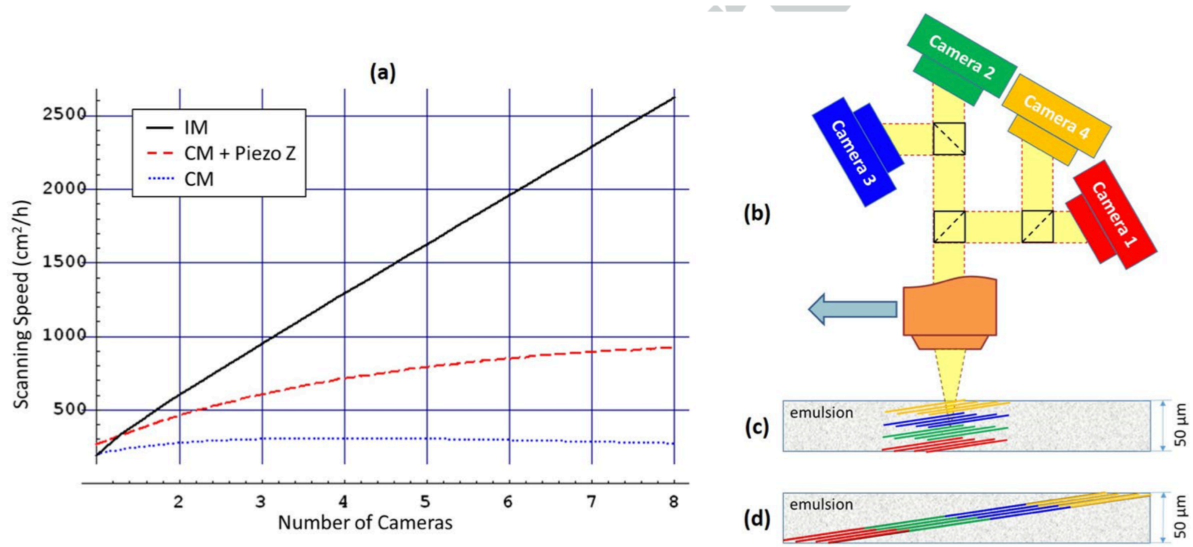


Figure 1. Illustration of (**a**) Stop&Go (SG), (**b**) Continuous Motion (CM) and (**c**) the proposed Inclined Motion (IM) scanning techniques.

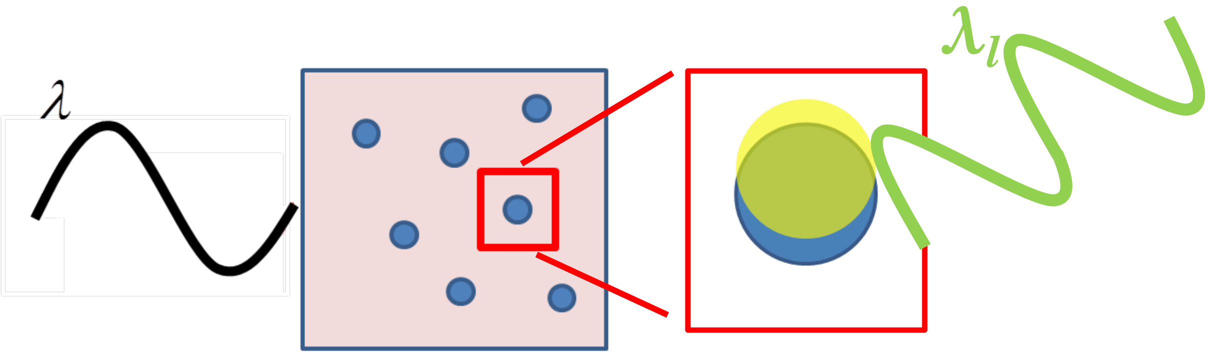


Nature Scientific Reports (2019) 9:2870



Beyond Optical Resolution: New Technologies

Resonant Light Scattering From Ag Nanoparticles



E_l intensity of inside metal

$$E_l = \frac{3\varepsilon_d(\lambda)}{\varepsilon_m(\lambda) + 2\varepsilon_d(\lambda)} E_0$$

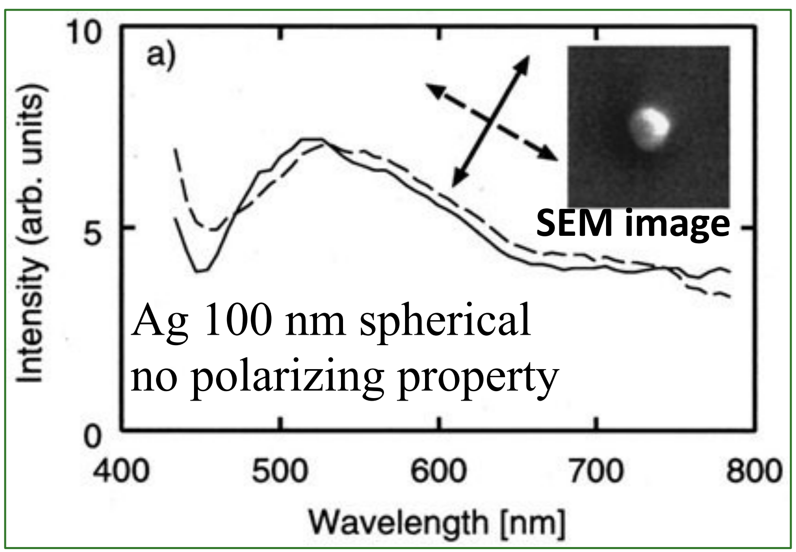
$$\varepsilon_m(\lambda_l) + 2\varepsilon_d(\lambda_l) \approx 0$$

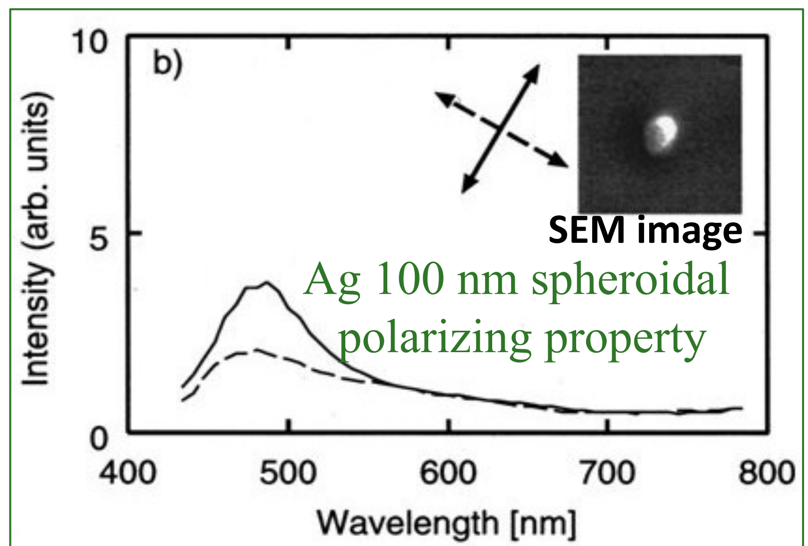
Nano-metal in medium ε_d **Oscillation of e-cloud**

E_l is resonance enhanced

Scattering spectrum depends on the light polarization and on the grain shape

H.Tamaru et al ., Applied Phys Letters 80, 1826 (2002)

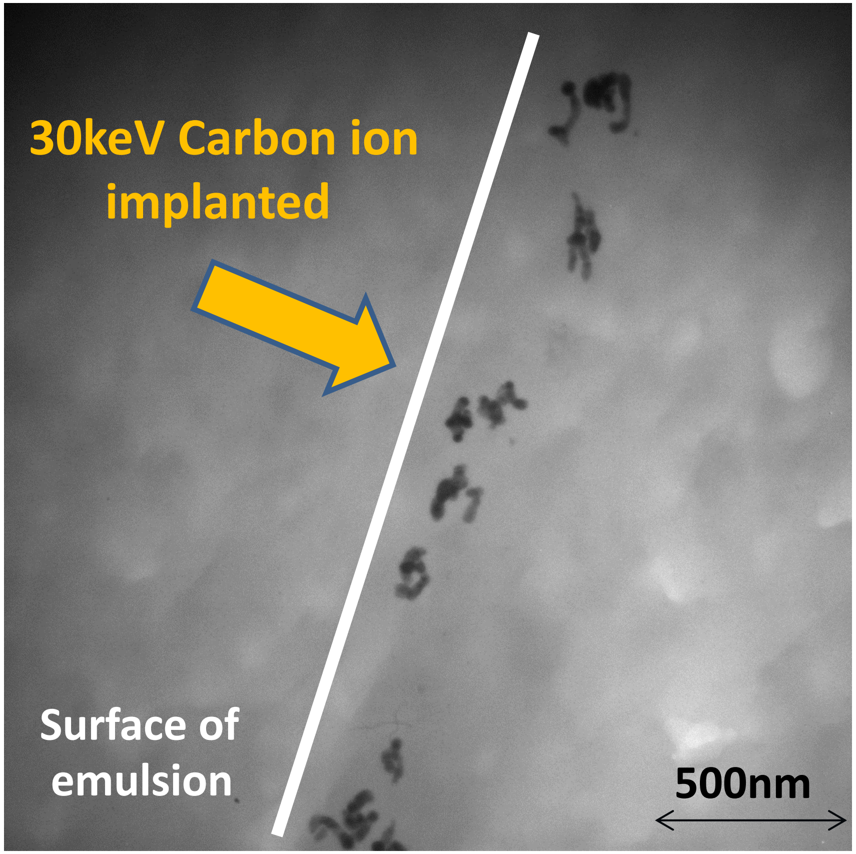




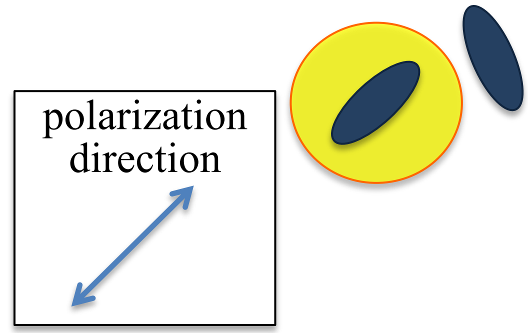
The polarization dependence of the resonance frequencies strongly reflects the shape anisotropy

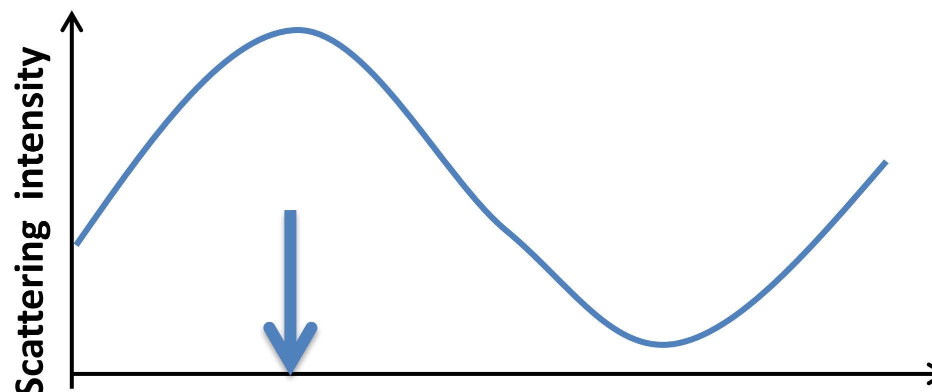
Resonant light scattering: silver grains

TEM image of Carbon track after development



Different orientation

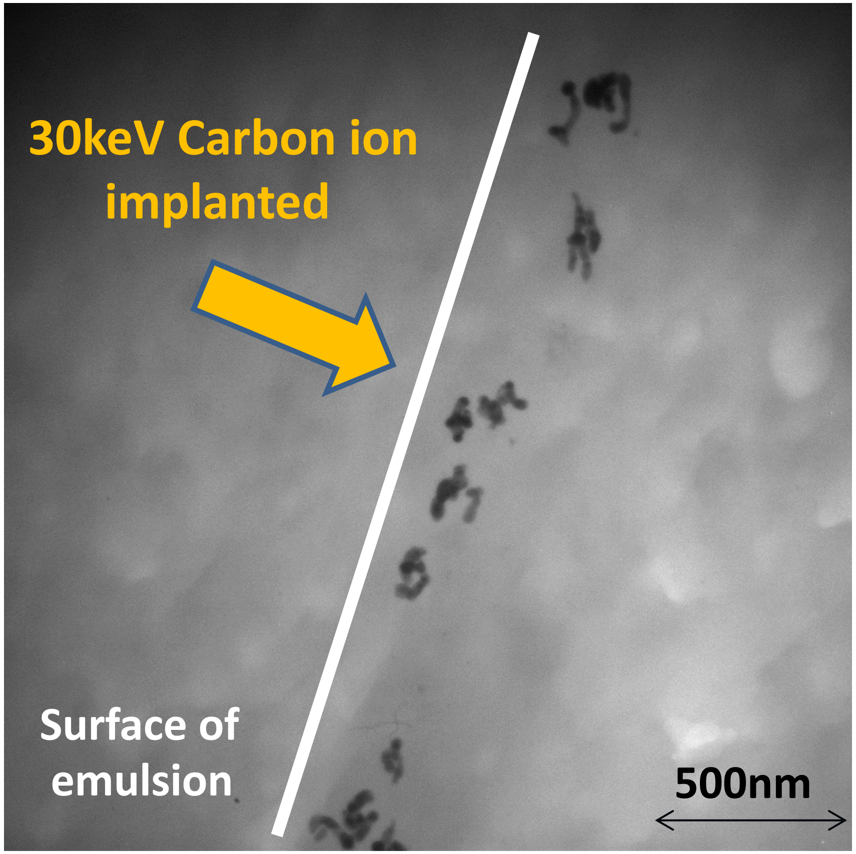




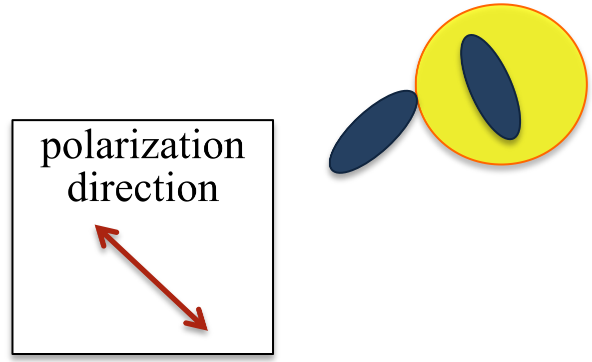
Optical response strongly depends on the polarization of incident light

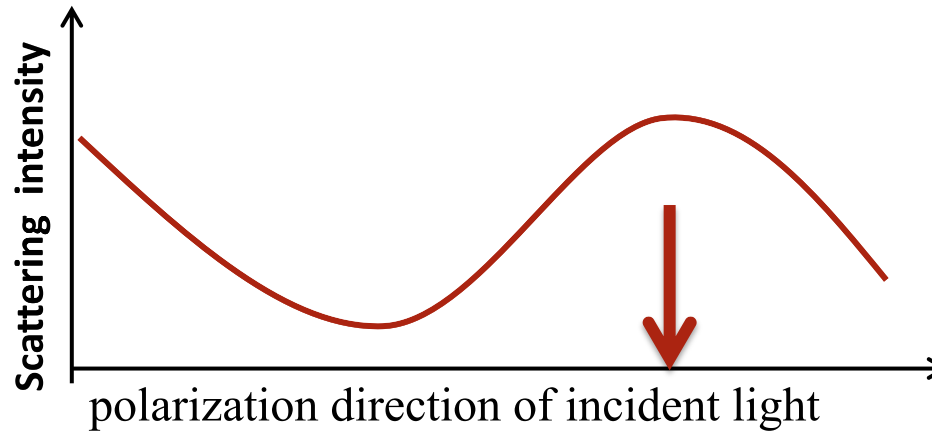
RESONANT LIGHT SCATTERING: SILVER GRAINS

TEM image of Carbon track after development



Different orientation





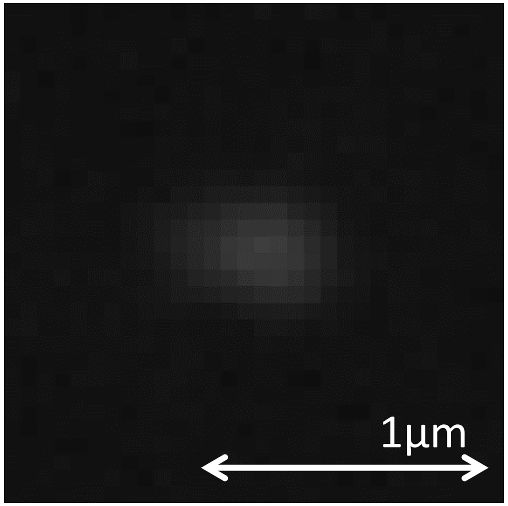
Optical response strongly depends on the polarization of incident light

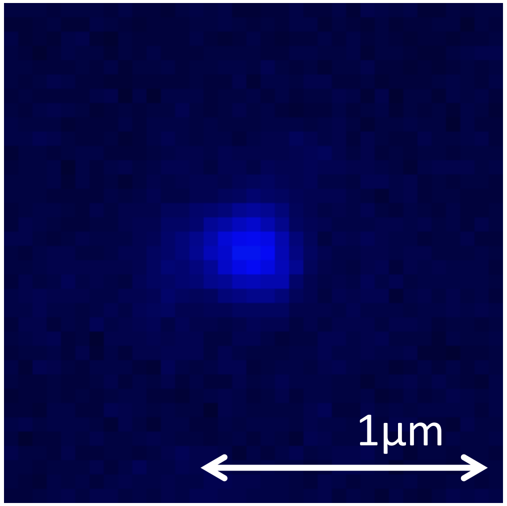
Published on PTEP (2019) 063H02

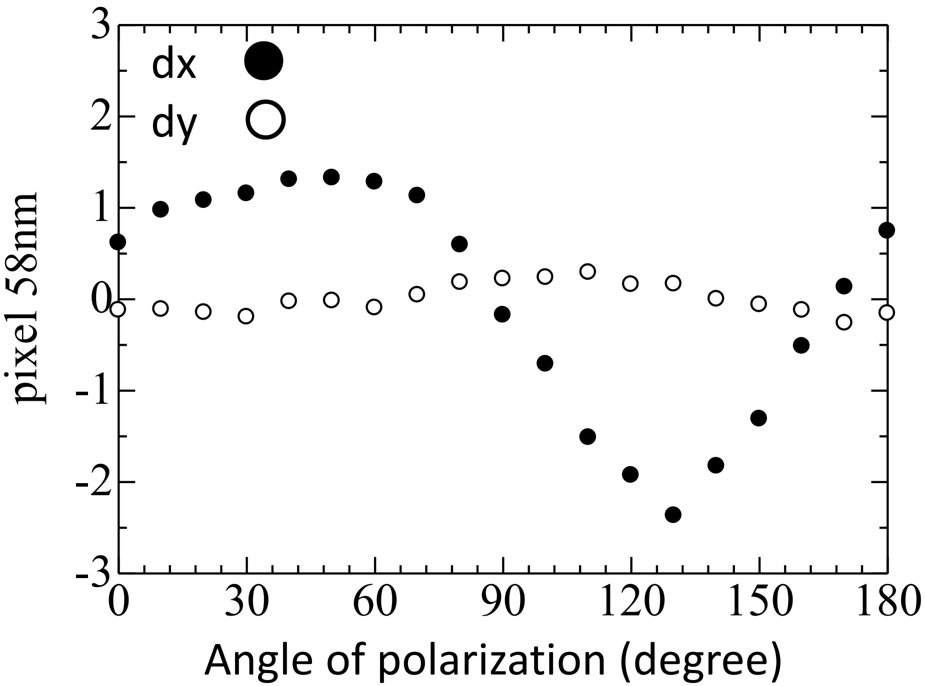
A TRACK MADE OF TWO GRAINS

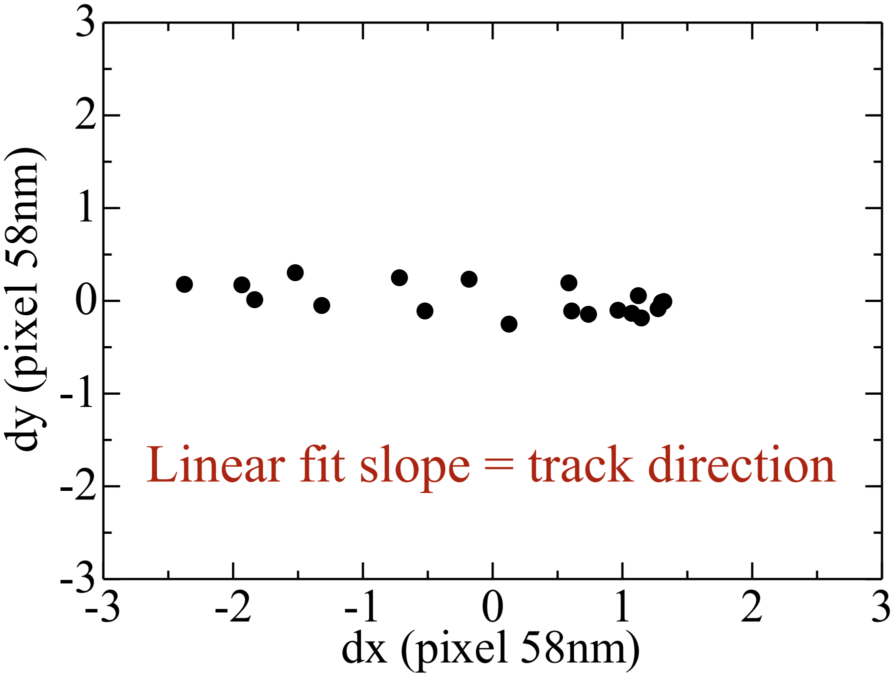
e = 1.49
without polarizer

Track validated by
elliptical shape analysis







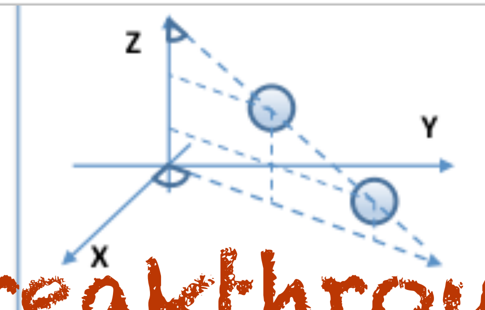


Published on PTEP (2019) 063H02

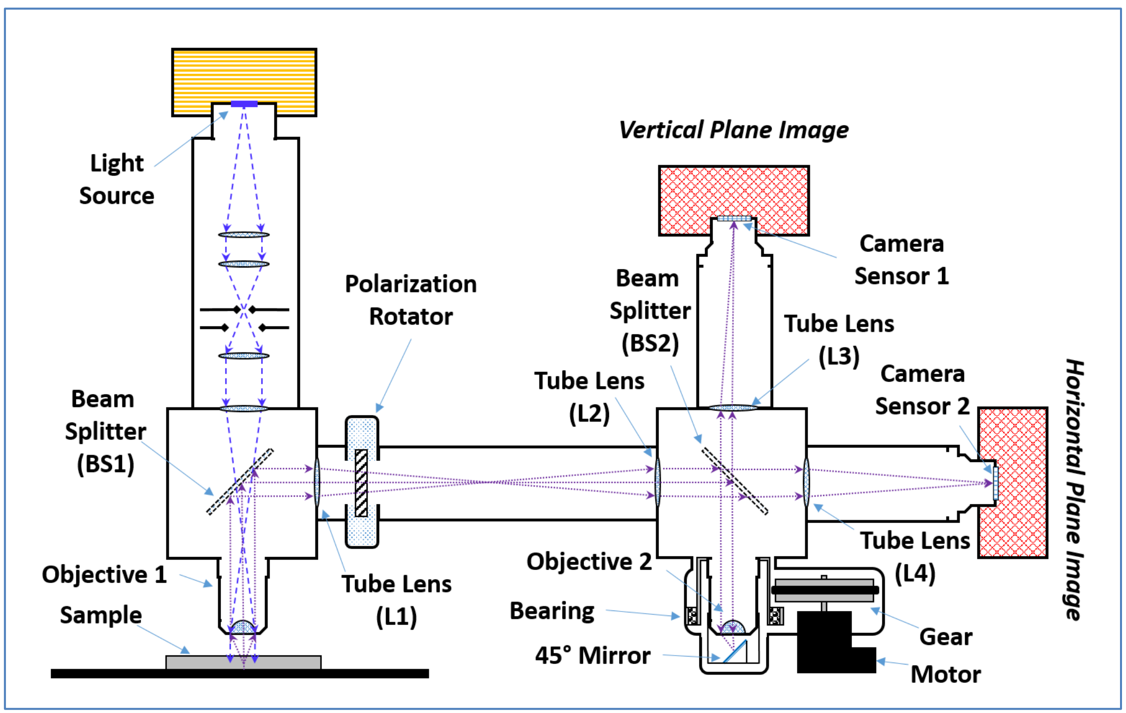
SUPER RESOLUTION MICROSCOPE WITH 3D RECONSTRUCTION

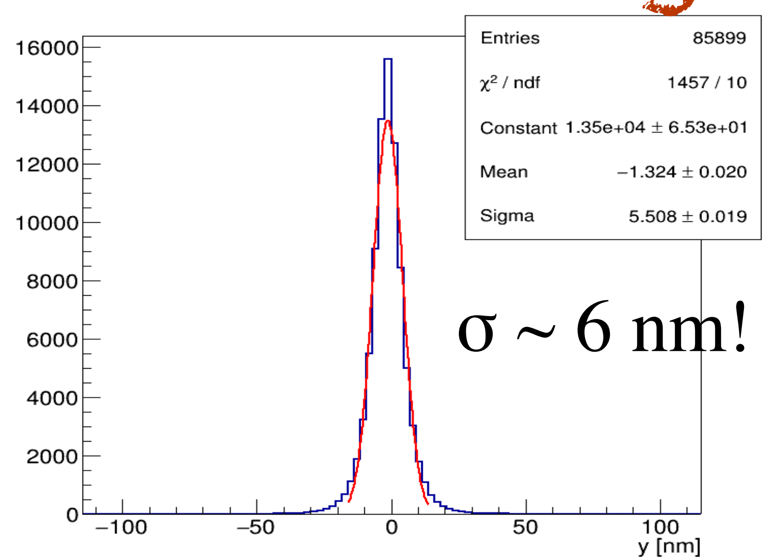
Int.Class	Appl.No	Title / Applicant	Ctr	PubDate / Inventor
	1. WO/2018/122814	METHOD AND OPTICAL MICROSCOPE FOR DETECTING PARTICLES HAVING SUB-DIFFRACTIVE SIZE	WO	05.07.2018
G02B 21/00	PCT/IB2017/058544	ISTITUTO NAZIONALE DI FISICA NUCLEARE		DE LELLIS, Giovanni

Optical microscope (100) for detecting particles having sub-diffractive size within a sample, comprising: a display system (50), having a first objective (01); a polarising device (6); an analyser system (60), having a second objective (02) and a reflection element (7), wherein an optical path between the first objective (01) and the secon objective (02) is divided into two identical parts symmetric with respect to a coupling plane; a sensor device (S2) configured to detect a plurality of beams correspondin to a plurality of polarisation configurations of the polarising device (6) that is reflected by the reflection element (7), thus acquiring a plurality of images; and one or mor processing units configured to perform a two-dimensional method of analysis of the plurality di acquired images.



Breakthrough





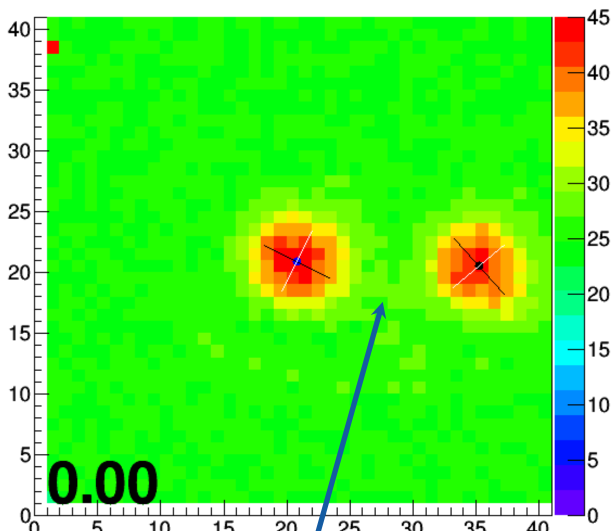
$\sigma \sim 6$ nm!

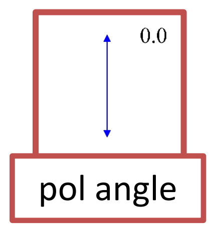
STEP2: PLASMON ANALYSIS

Data categories:

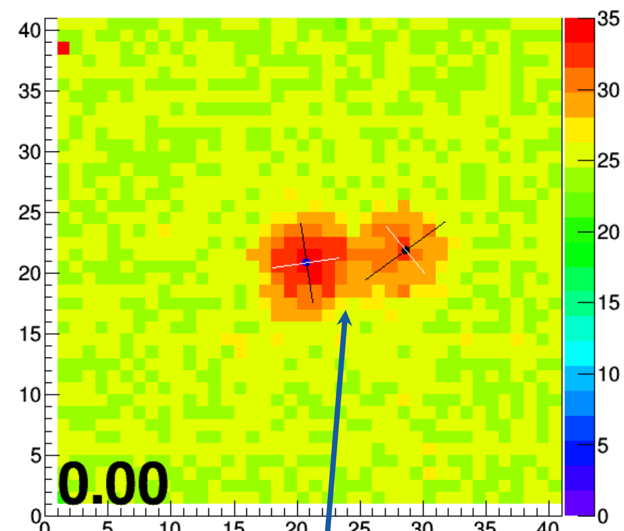
1. **Micro-tracks**: two or more grains aligned
2. **isolated** grains
   - Multi-grain clusters (≥ 2 brightness peaks) ⟶ microtracks
   - Moving grains ($\Delta s > \Delta s_{thr}$) ⟶ nanotracks
   - Static grains ($\Delta s < \Delta s_{thr}$) ⟶ background

MICROTRACKS





MULTI-GRAIN CLUSTERS

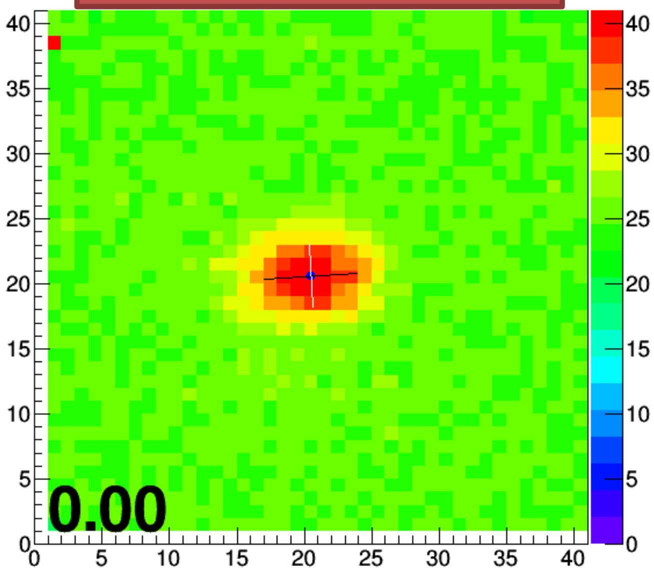


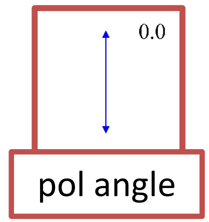
Empty space between two grains

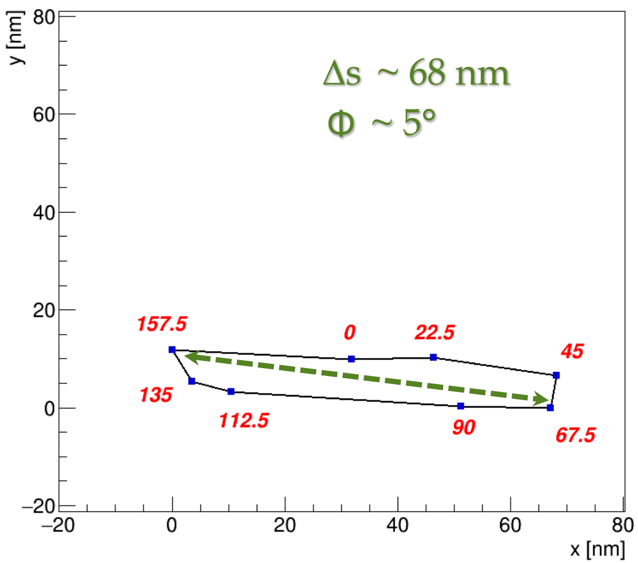
A single grain is reconstructed

STEP2: PLASMON ANALYSIS

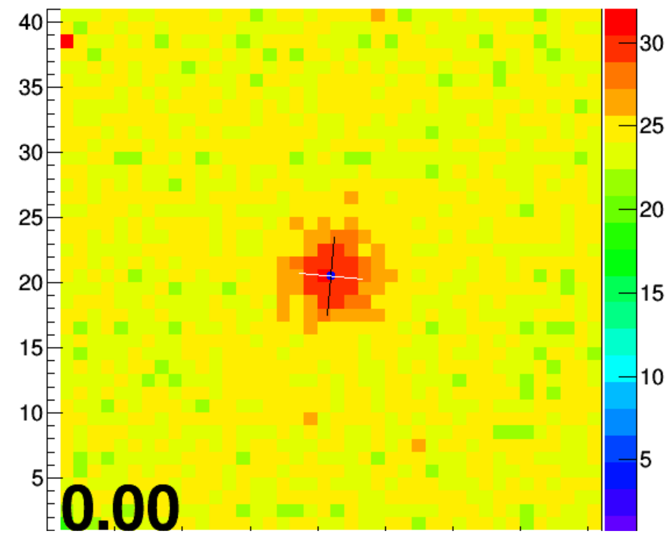
MOVING GRAIN

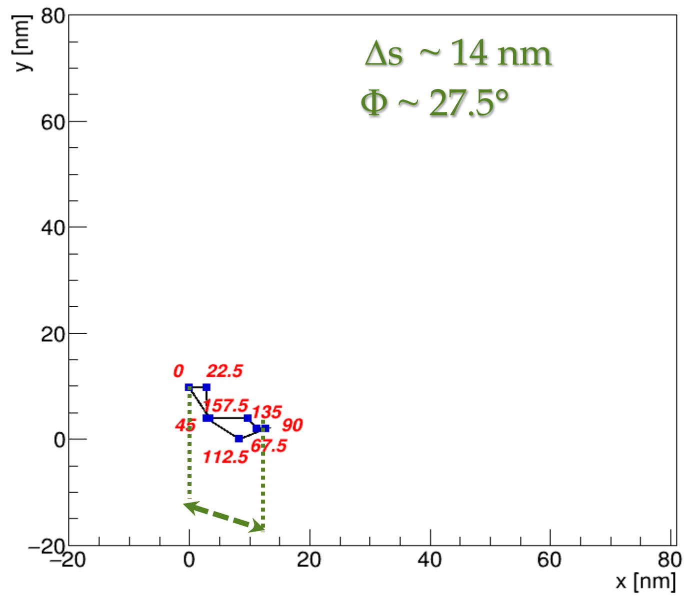






STATIC GRAIN

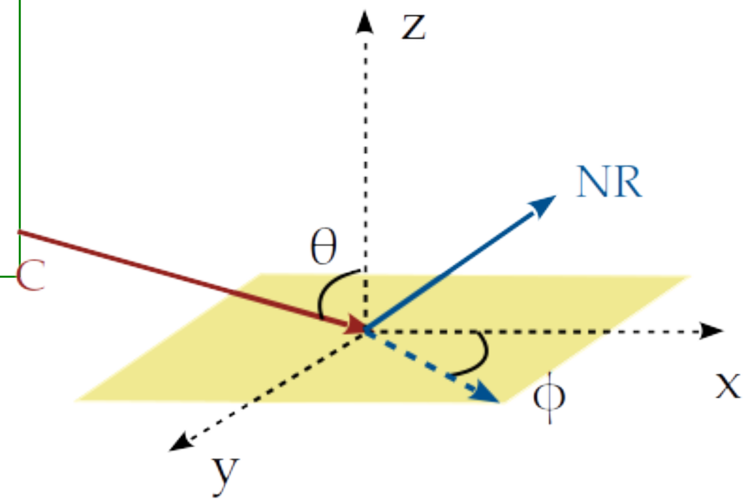




CARBON ION SAMPLES

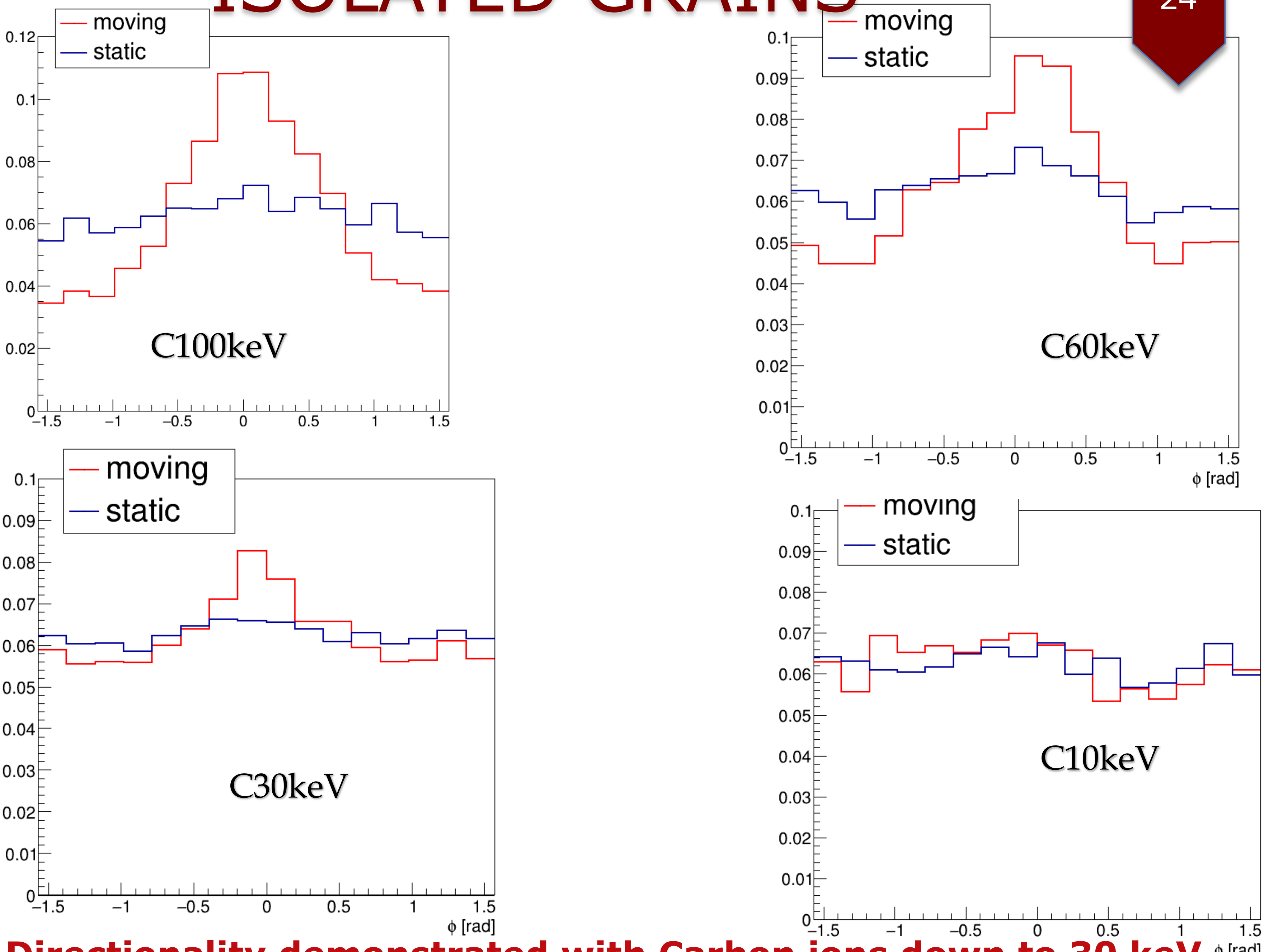
Aim: plasmon analysis with C-Ion samples

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)

ISOLATED GRAINS



Directionality demonstrated with Carbon ions down to 30 keV

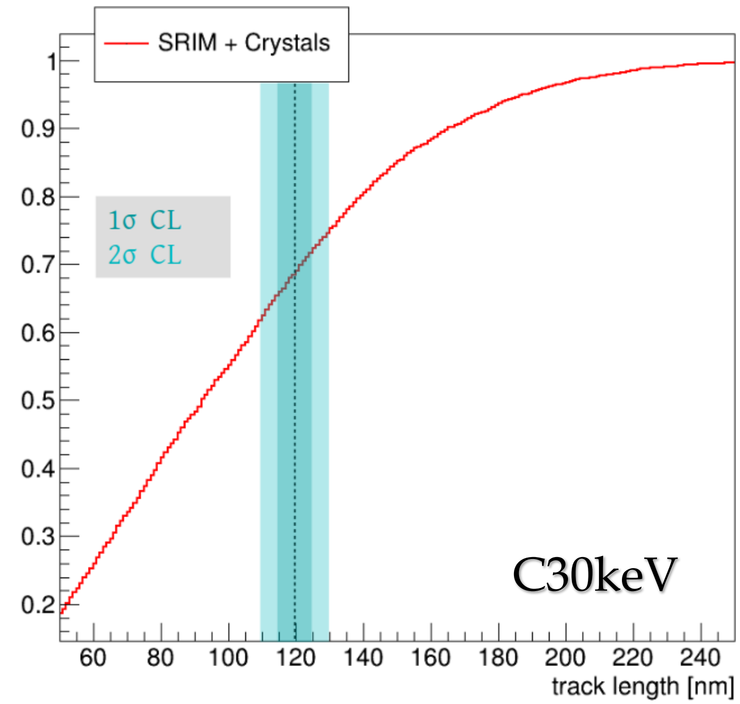
EFFICIENCY OF PLASMON ANALYSIS

$$\epsilon_{pl} = \frac{N_{multi-grain} + N_{moving}}{N_{tot}}$$

C100keV: 48 %
C60keV: 40%
C30keV: 31%

Plamon analysis essential for 30keV Carbon detection

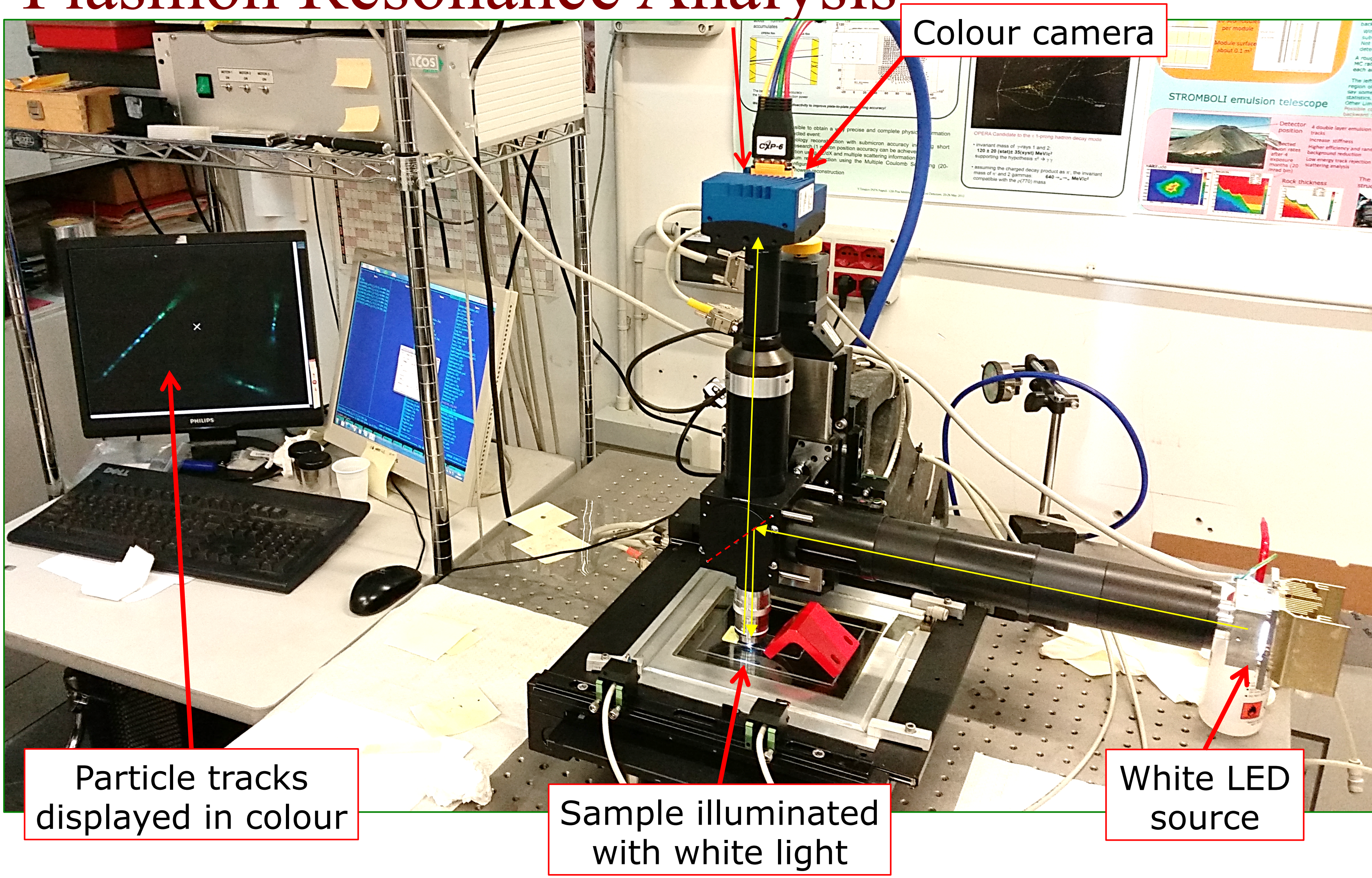
efficiency → track length threshold



track length threshold (120±5) nm

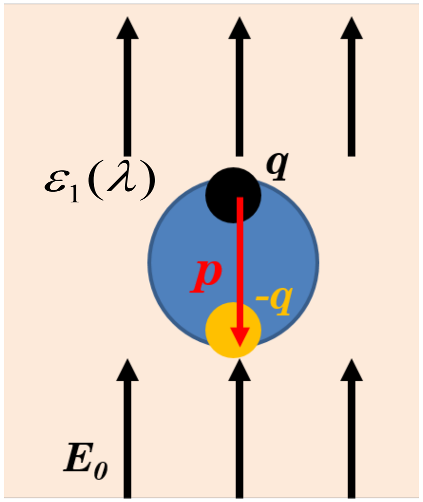
Further threshold lowering using U-NIT with larger granularity

Colour Camera and Extension of the Plasmon Resonance Analysis



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

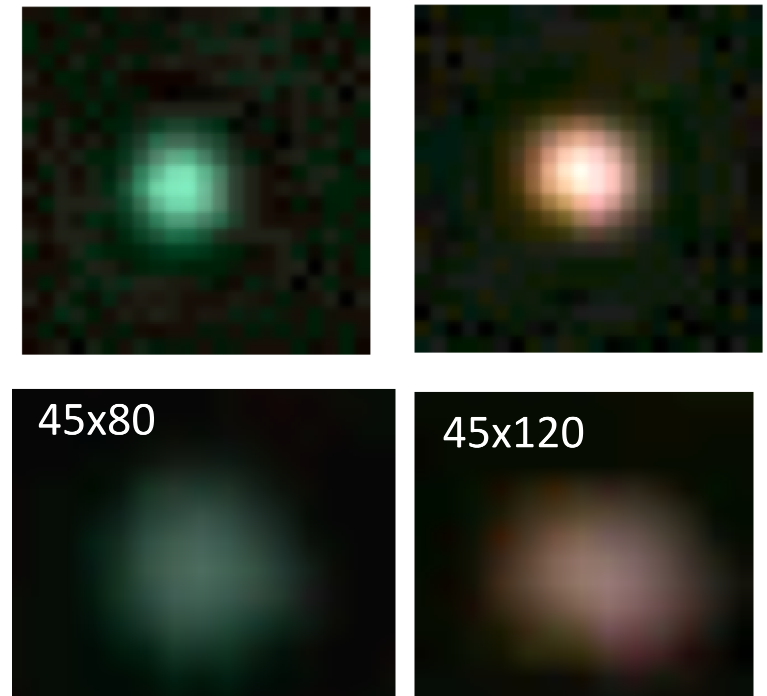
$$\varepsilon_1(\lambda_l) + 2\varepsilon_m(\lambda_l) \approx 0$$

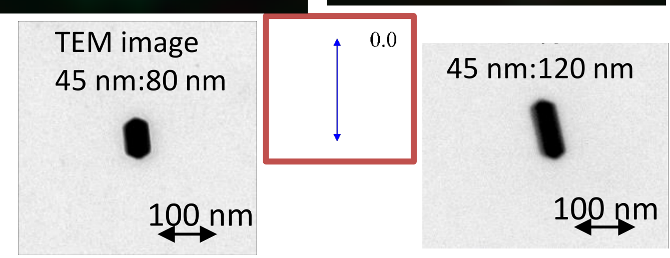
Appl. Phys. Lett. 80, 1826 (2002)

Ag grain size → resonance wavelength

Colored optical image of silver rod

*polarization rotating



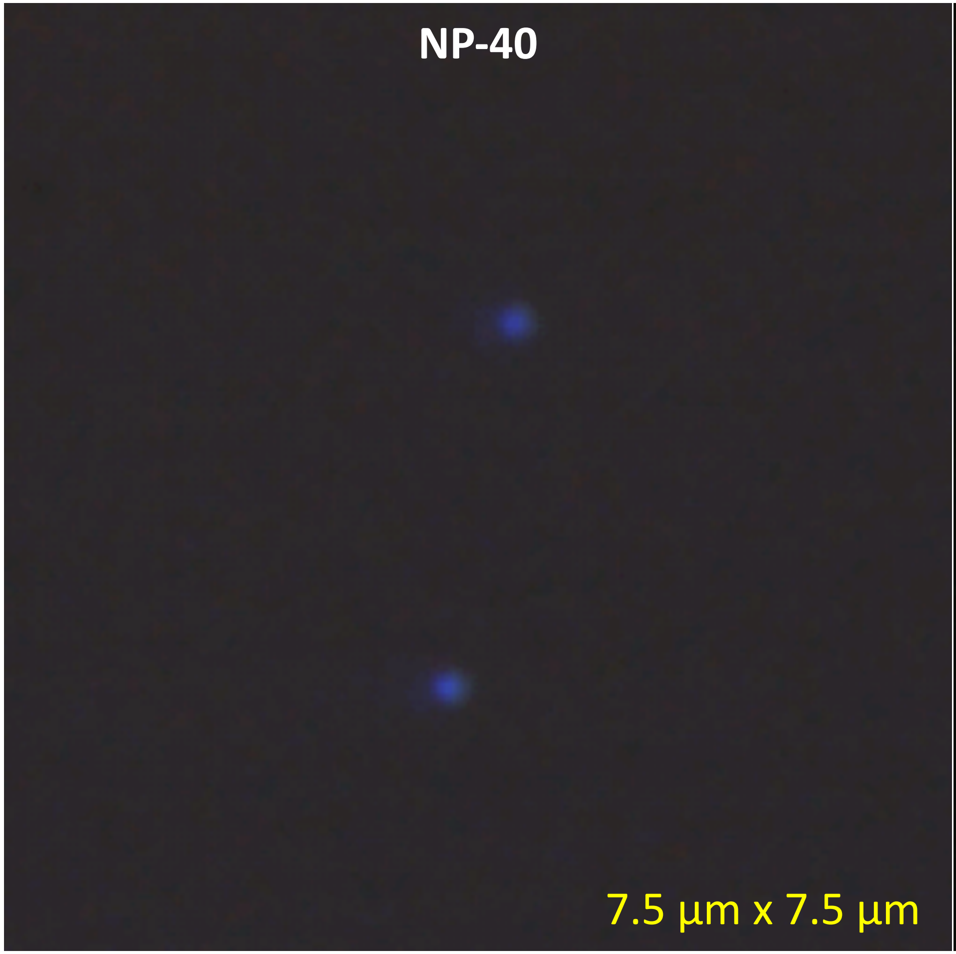


~45 nm : blue
~80 nm : green

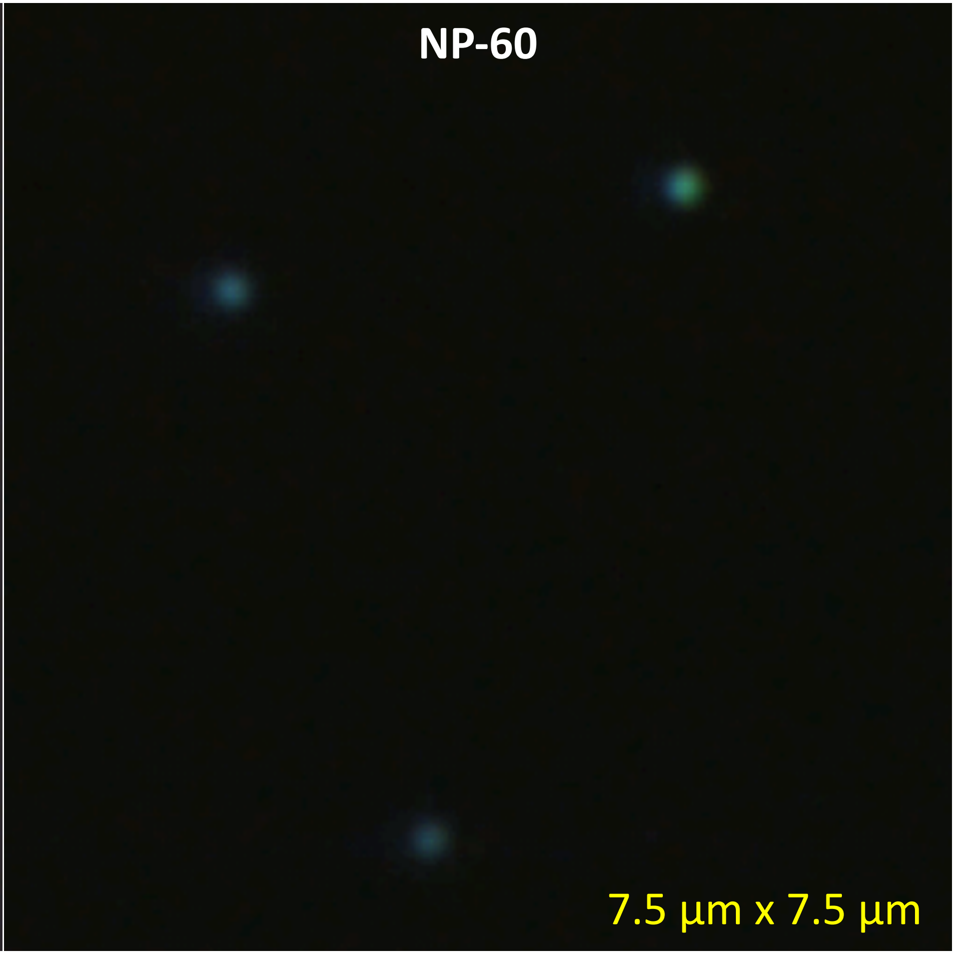
~45 nm : blue
~120 nm :orange–red

Silver Nanoparticles for calibration

40 nm diameter

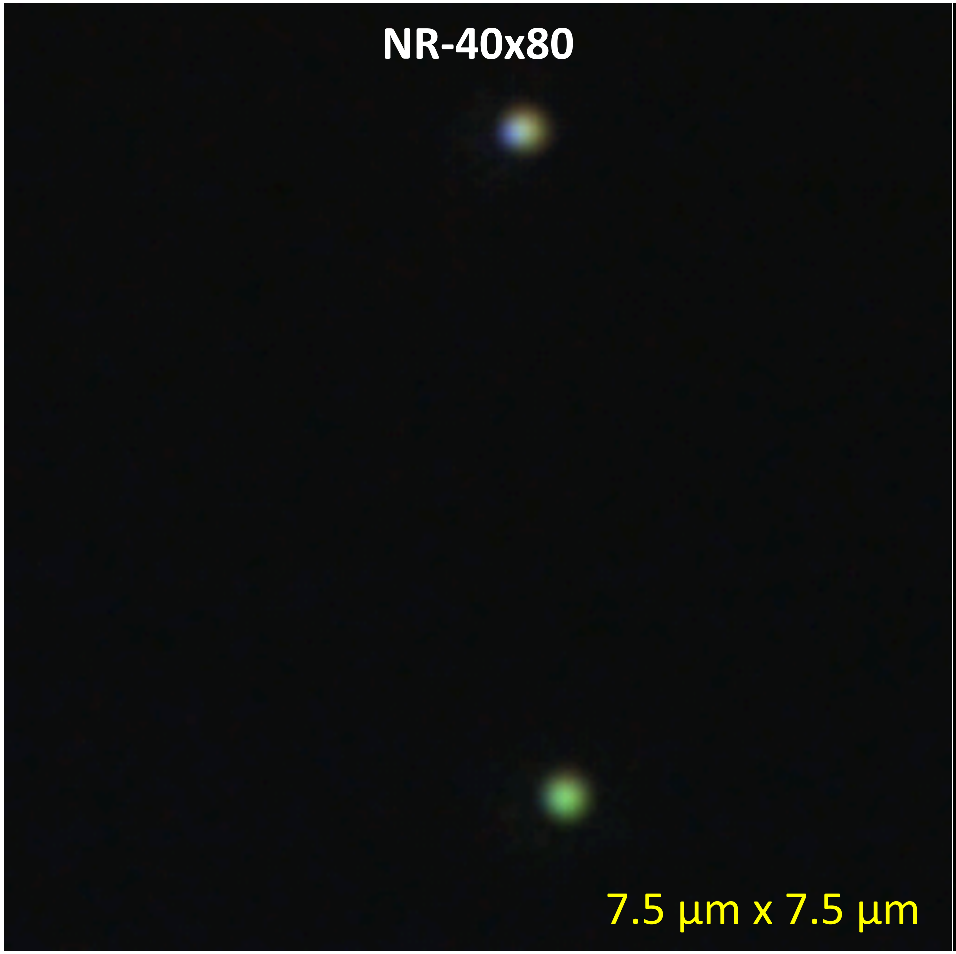


60 nm diameter

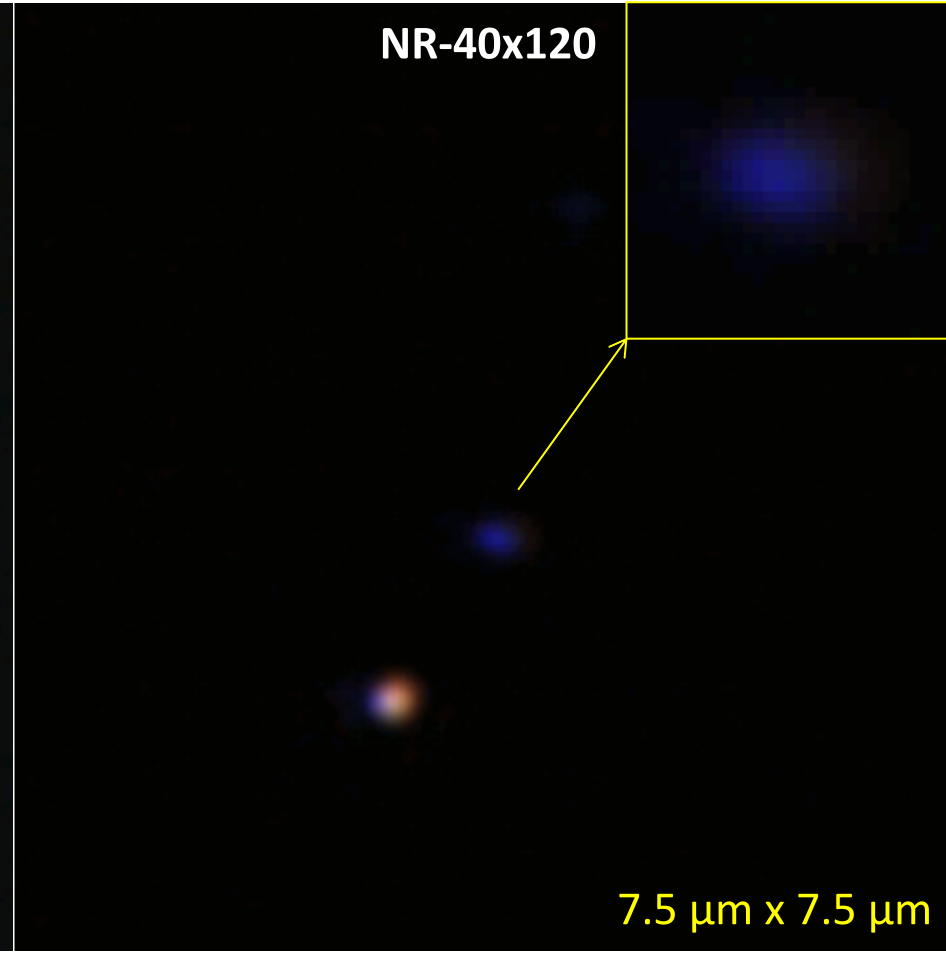


Silver Nanorods for calibration

40 nm diameter, 80 nm height



40 nm diameter, 120 nm height



Colour camera
Localized Surface Plasmon Resonance

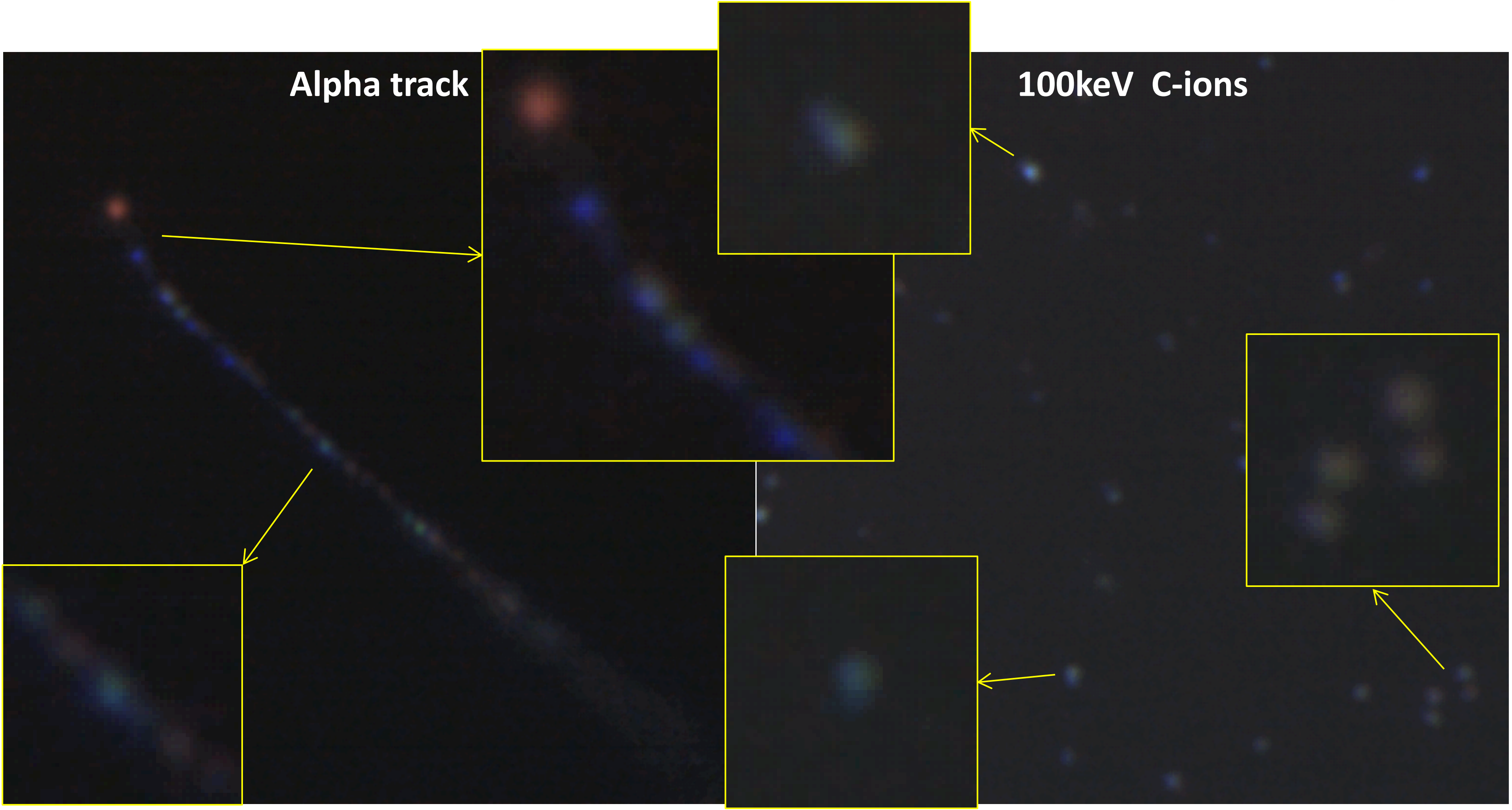


Image size 15 µm x 15 µm

Image size 15 µm x 15 µm

Head/tail discrimination!

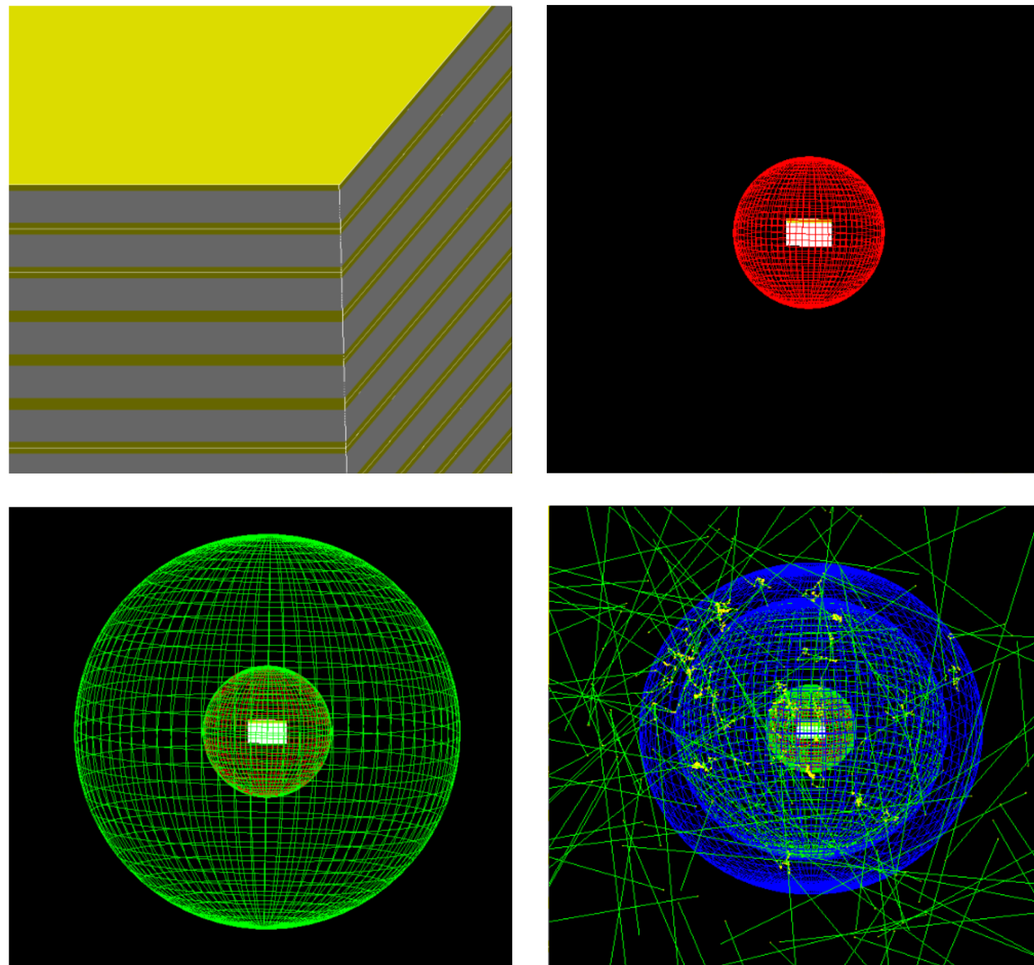
Background and analysis techniques

BACKGROUND SOURCES

EXTERNAL SOURCES

1) Environmental photons
2) Environmental neutrons
3) Cosmogenic neutrons

→ **GEANT4 SIMULATION**



INTRINSIC SOURCES

1) Radioactivity from ^{14}C
2) Intrinsic neutrons

Astroparticle Physics 80 (2016) 16–21

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropartphys

Intrinsic neutron background of nuclear emulsions for directional Dark Matter searches

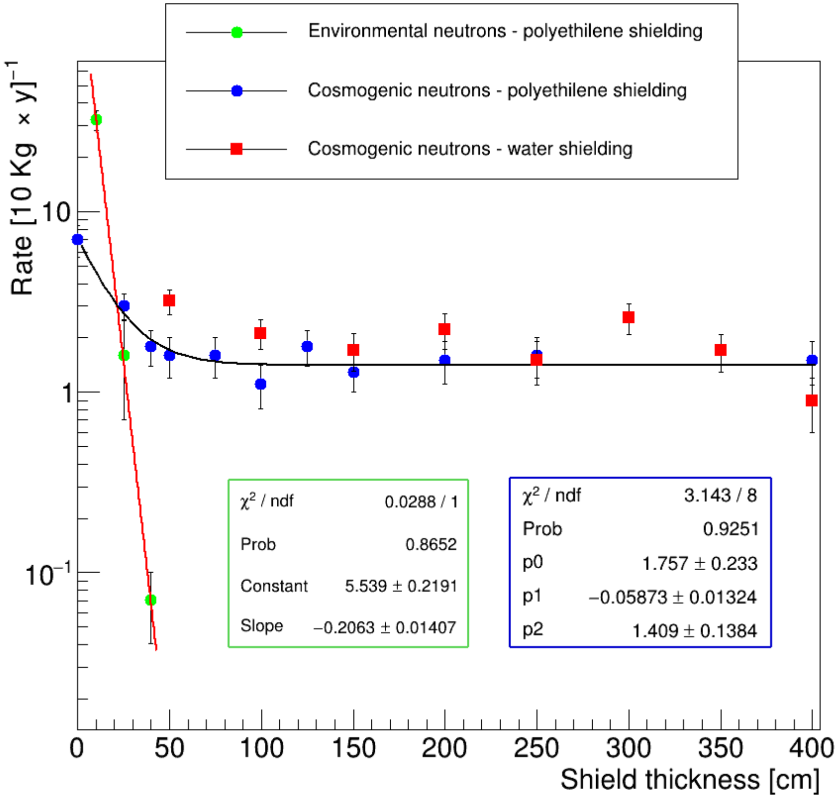
$\leq$ 1/10 kg year

without raw material pre-selection

EXTERNAL BACKGROUND

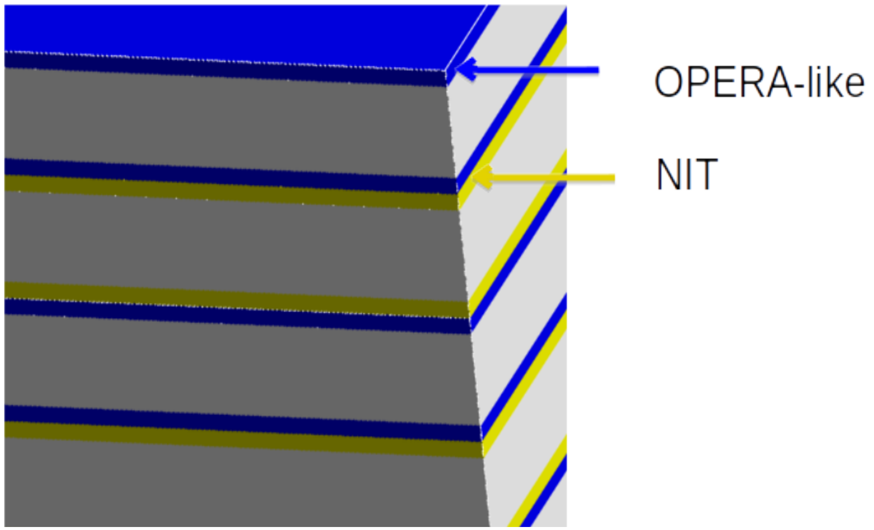
1 m of Polyethylene provides a nuclear induced recoil rate of about **1.4**

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



Further discrimination:
Use OPERA-like emulsions as veto

Topological identification



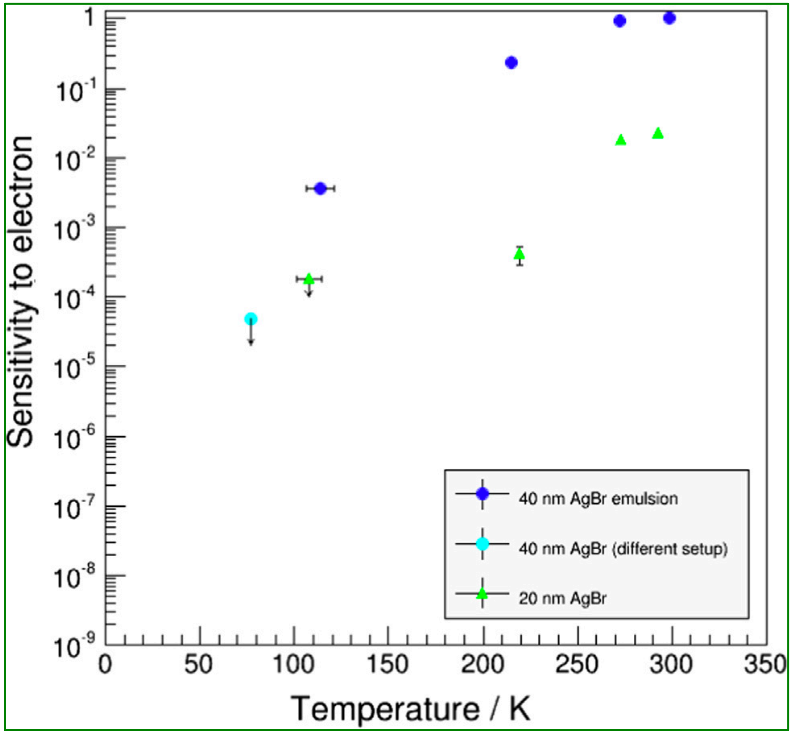
RADIOACTIVITY FROM ^{14}C

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

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

Additional **level arms** being quantified:

- Dedicated chemical treatments
- 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)



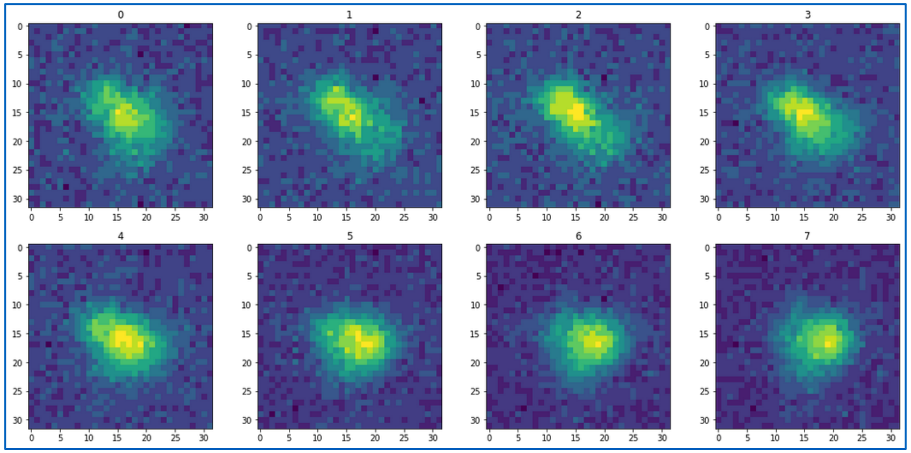
NIM A 845 (2017) 373

MACHINE LEARNING TECHNIQUES

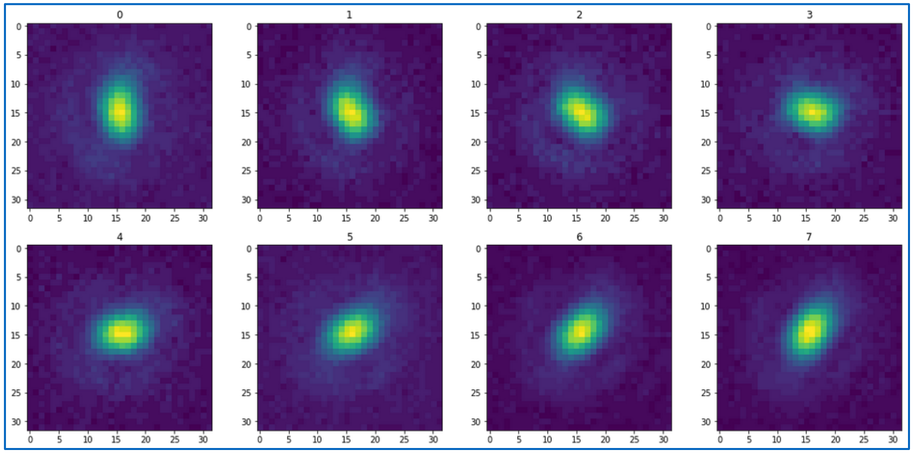
MACHINE LEARNING APPROACH

Experimental data

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

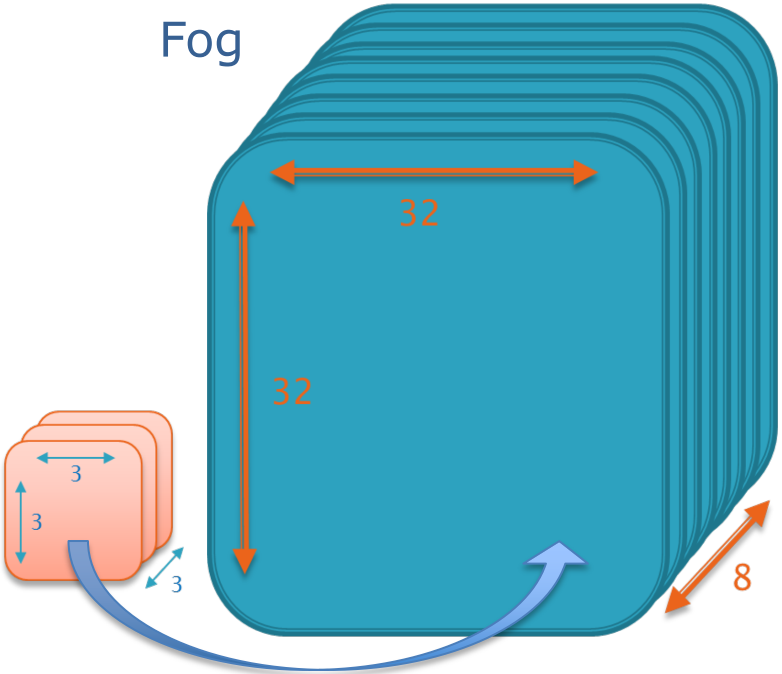


C100keV



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

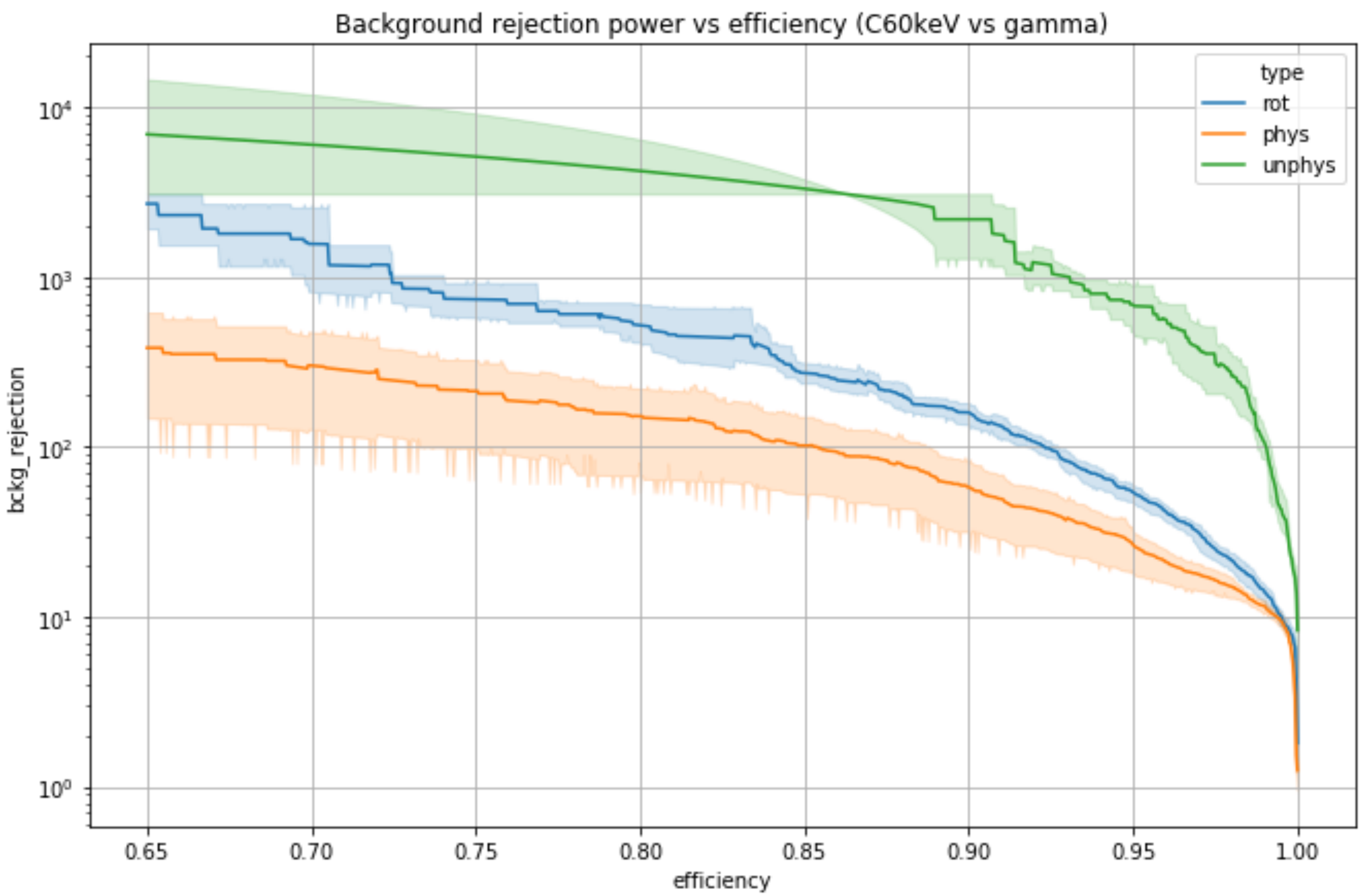


PRELIMINARY RESULTS

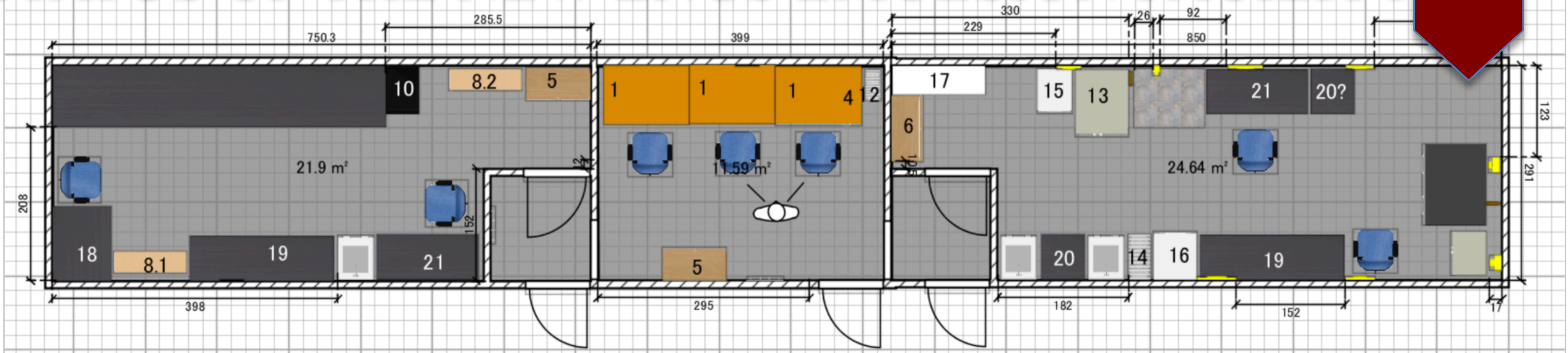
60keV Carbon VS gamma

Several approaches compared

- **Orange**: using only data far from the edge (currently limited statistics)
- **Blue:** increasing the above dataset by random rotation of images
- **Green**: adding edge part with silver nanoparticles

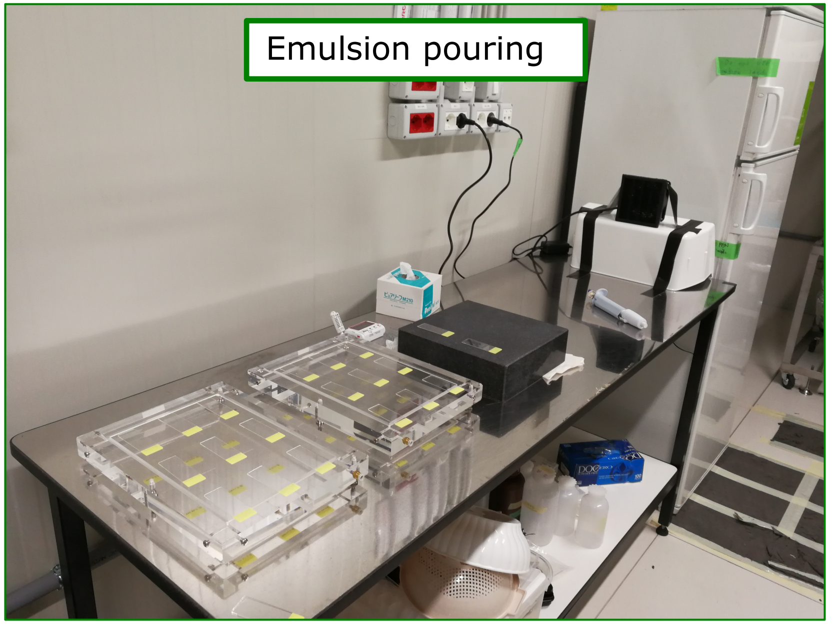


STATUS OF THE NEW LNGS EMULSION FACILITY



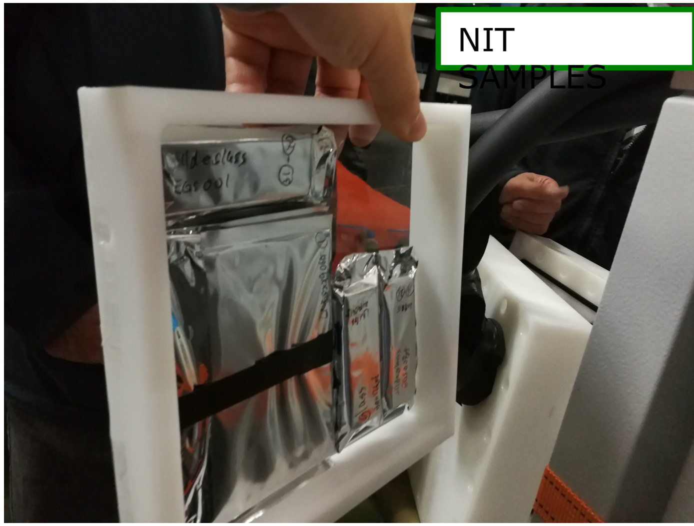
First test at LNGS

Emulsion Production at LNGS

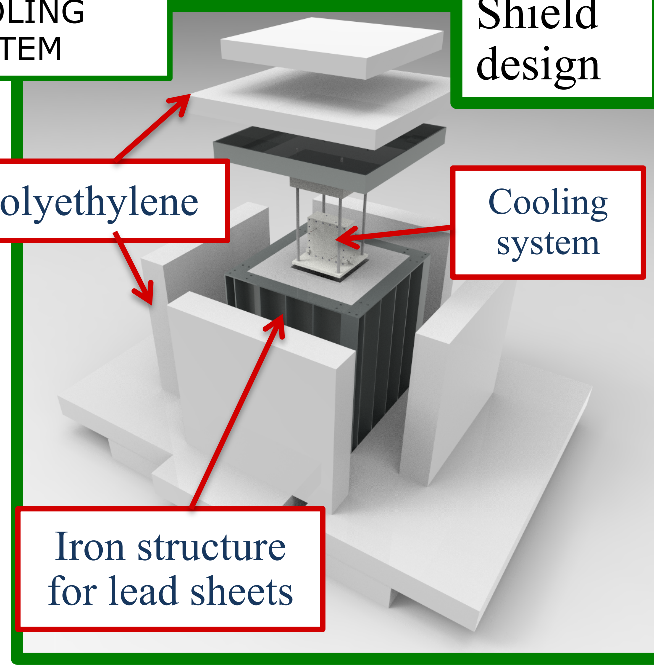


Current production rate
1kg per week

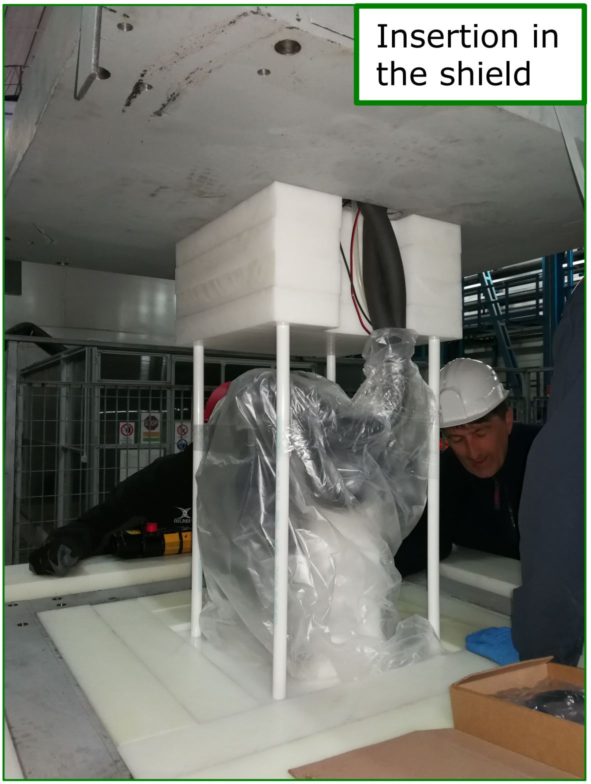
10g detector: checking the whole chain



COOLING SYSTEM



10g detector test

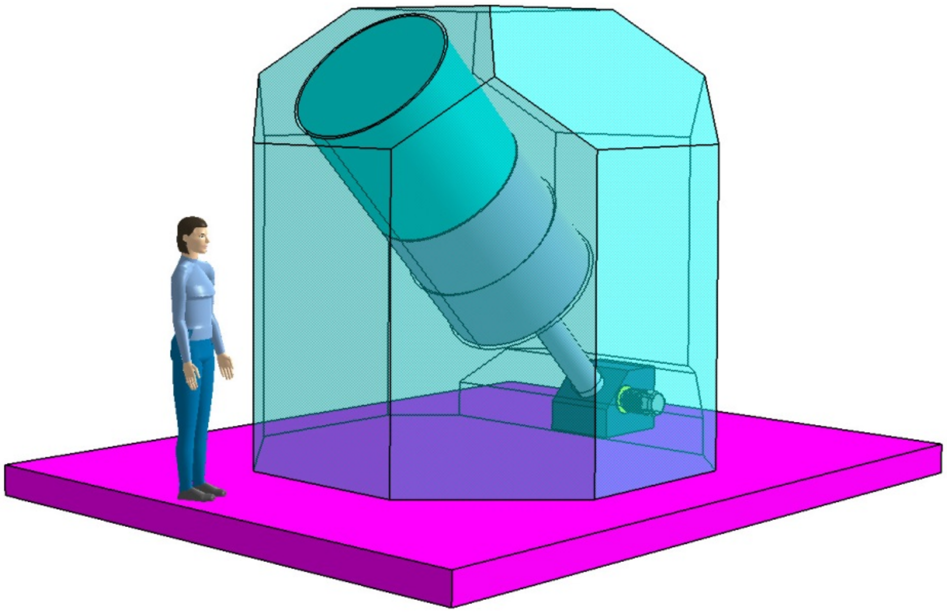


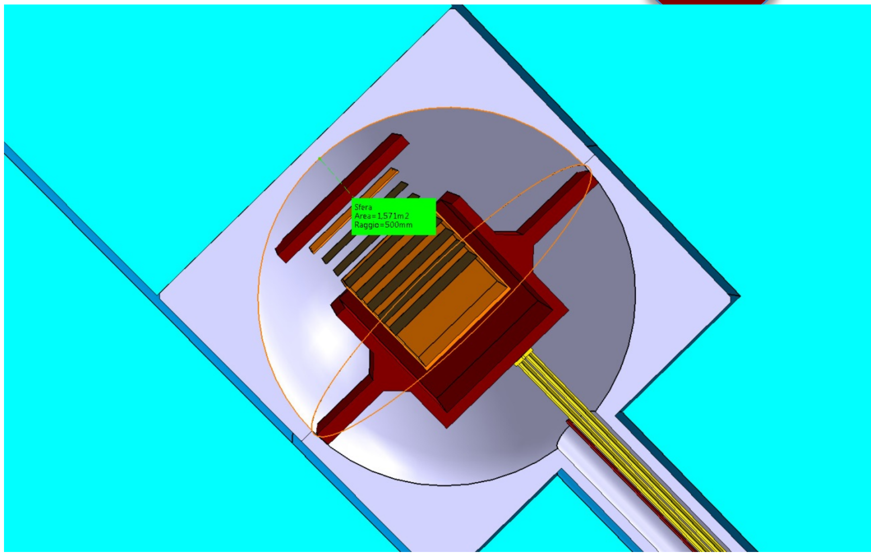
Insertion in the shield

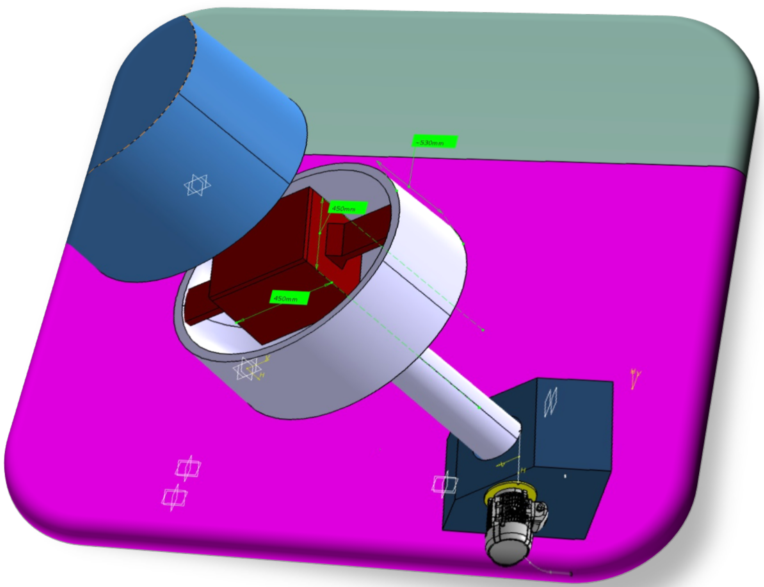
Connection with the cryostat

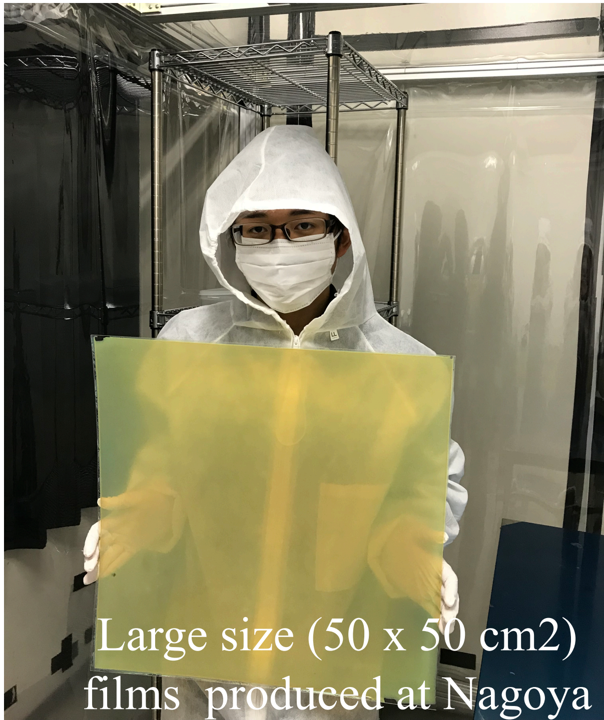
10g test started on 17th June
Extraction on 8th July

Designing a larger detector



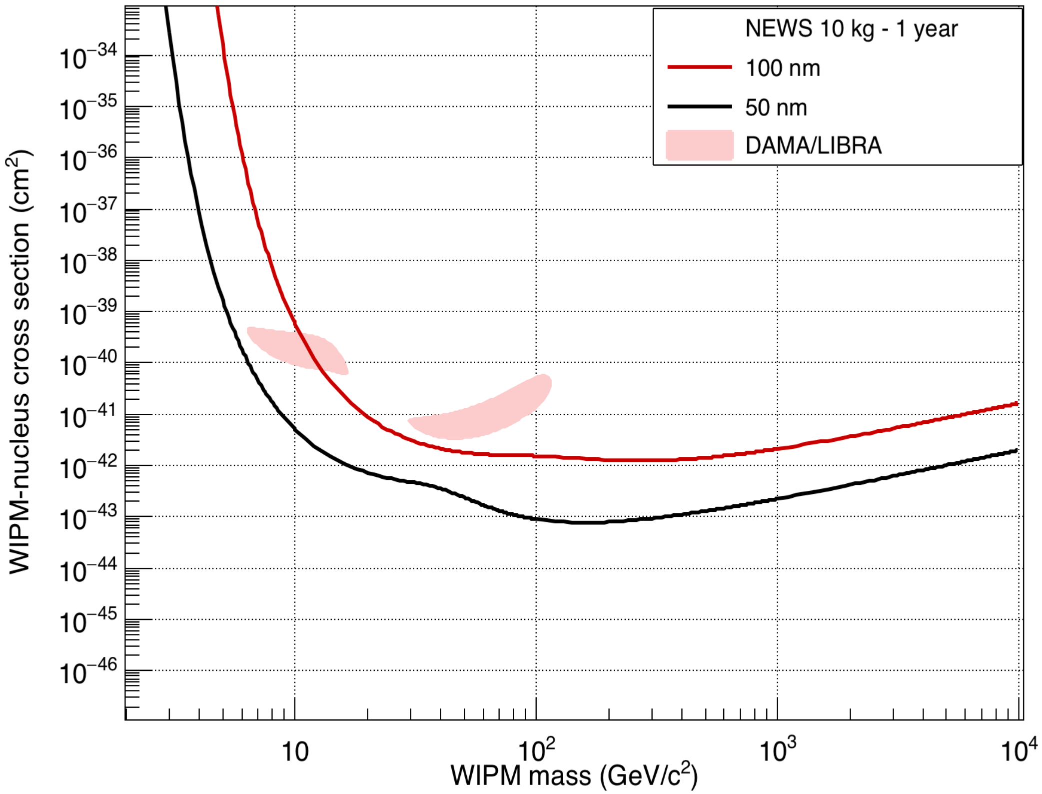






NEWSdm SENSITIVITY

SENSITIVITY OF A PILOT EXPERIMENT



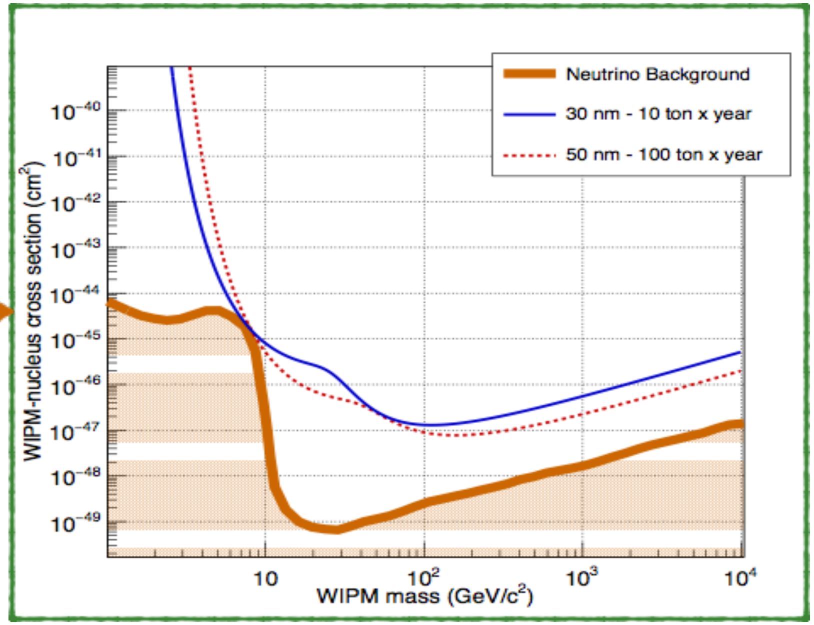
- 10kg x year experiment
- Zero background assumed
- Directionality not exploited

TOWARDS THE 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 And Perspectives

- Nuclear emulsions with nanometric grains pave the way for a directional dark matter search with high sensitivity
- Breakthrough in readout technologies provide 3D and head/tail discrimination with high sensitivity
- Neutron background from intrinsic radioactivity negligible up to ~ 10 kg year, without any care on the material choice
- Machine learning approach to handle the complexity of the information
- Experimental tests ongoing in Gran Sasso to reproduce the full analysis chain
- Prepare a few kg scale detector as a demonstrator of the technology and for the first physics run
- TDR in preparation