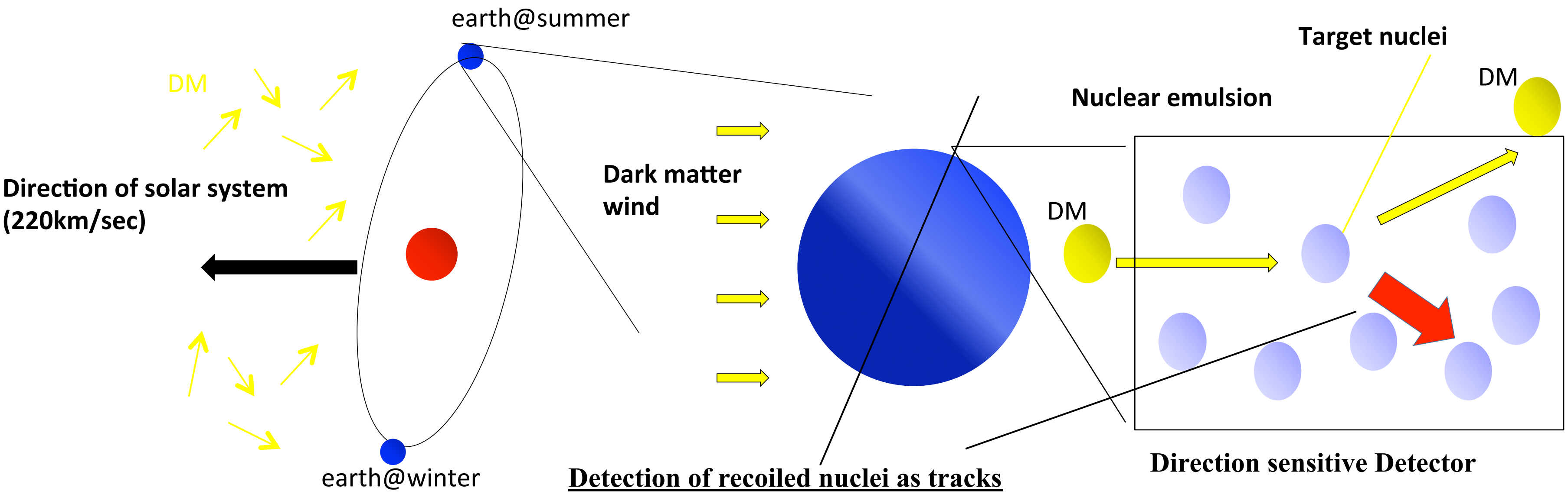
NUCLEAR EMULSIONS FOR WIMP SEARCH NEWS

Giovanni De Lellis
Università "Federico II" and INFN Napoli

- A novel approach to WIMP search
- A dark matter telescope based on nuclear emulsions

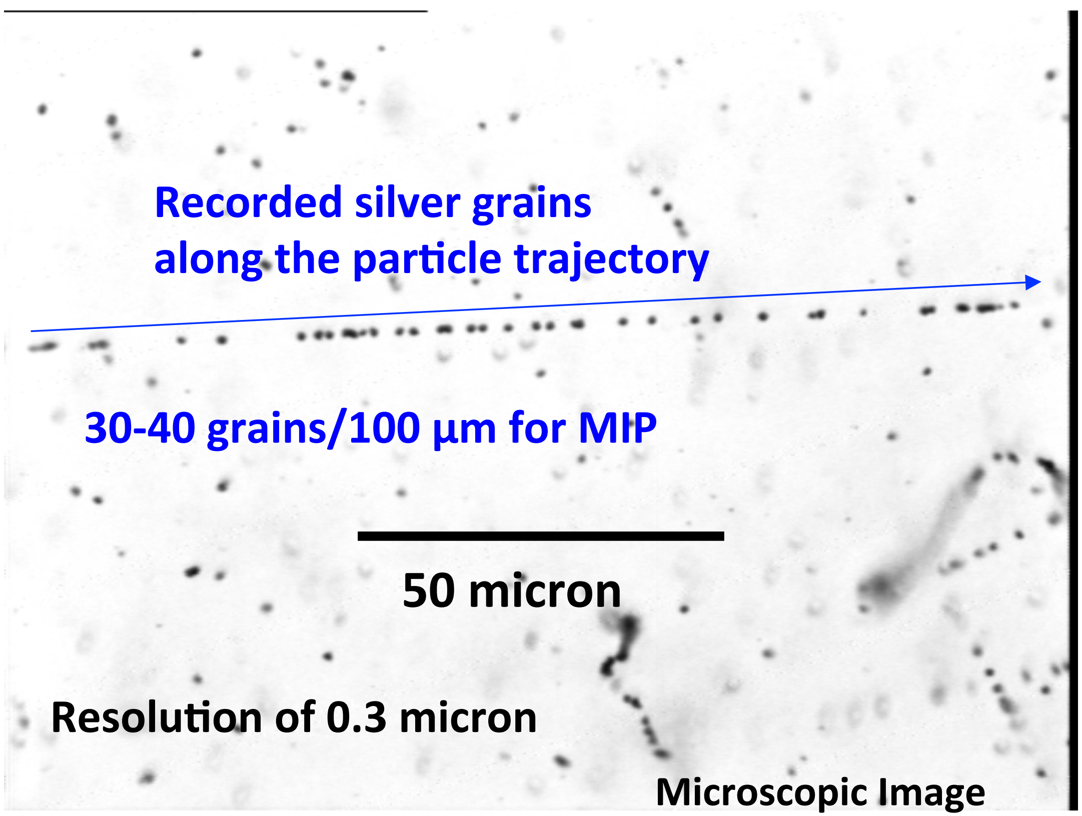
Directional signature in the Wimp Search

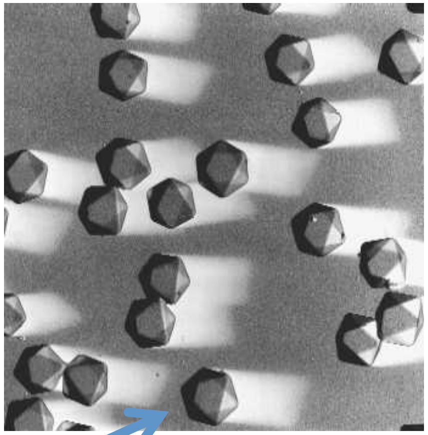


- Solar system movement in the galaxy → WIMP flux **not isotropic @ Earth**.
- Directional measurement as a **strong signature** and unambiguous proof of the galactic DM origin
- Nuclear emulsions is a solid detector → high sensitivity with a compact detector
- Challenge: very short recoil track lengths, O(100 nm)

Nuclear emulsions as sensitive media for charged particles

After the passage of charged particles through the emulsion, a latent image is produced
The emulsion chemical development makes Ag grains visible with an optical microscope





AgBr crystal, size 0.2-0.3 μm
is the "standard" detection element

Nuclear emulsions

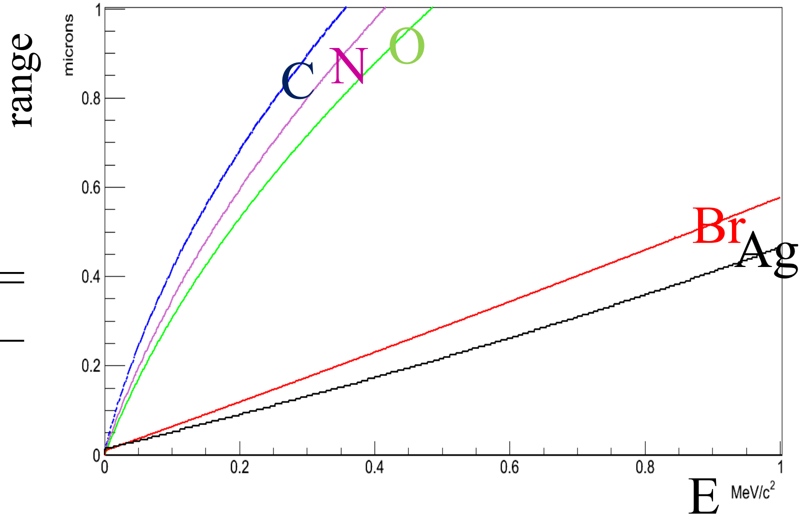
AgBr-I: sensitive elements
Organic gelatine: retaining structure
PVA to stabilise the crystal growth

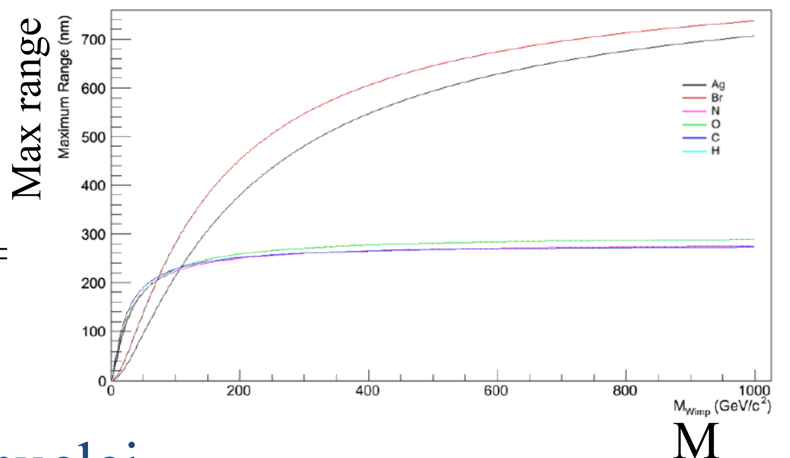
Constituent	Mass Fraction
AgBr-I	0.78
Gelatin	0.17
PVA	0.05

(a) Constituents of nuclear emulsion

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



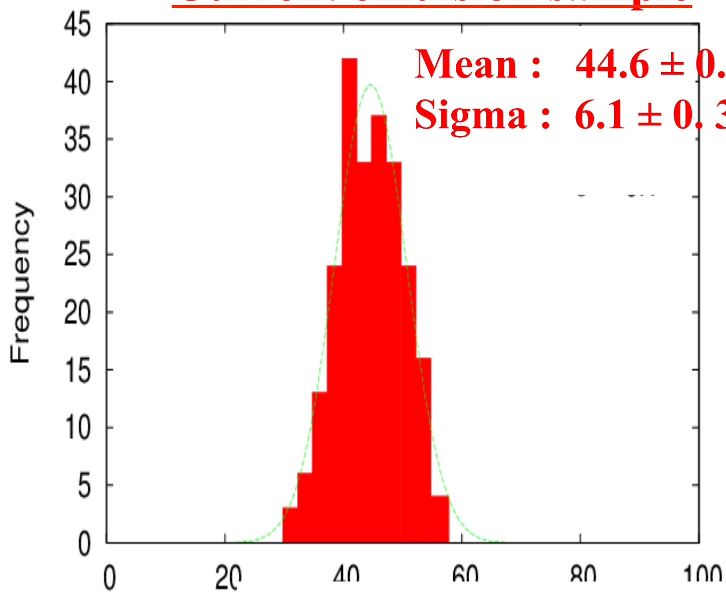


Both light and heavy nuclei

(Ultra-) Nano Imaging Tracker

NIT

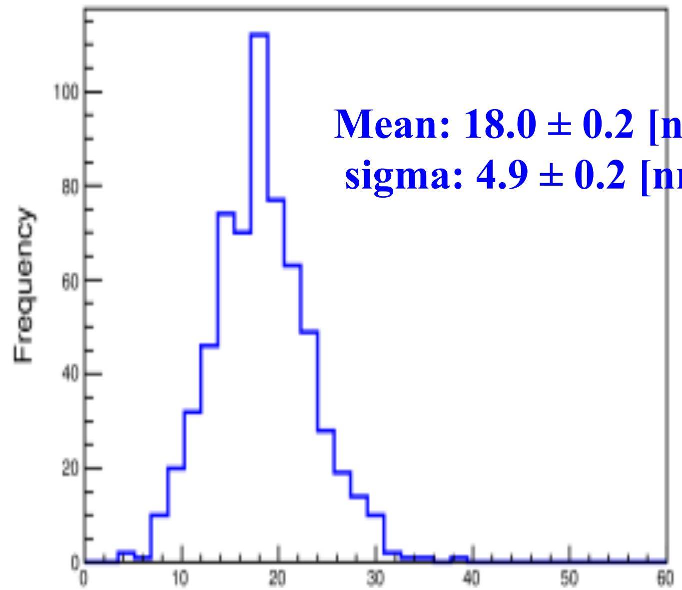
Current emulsion sample



Crystal diameter [nm]

U-NIT

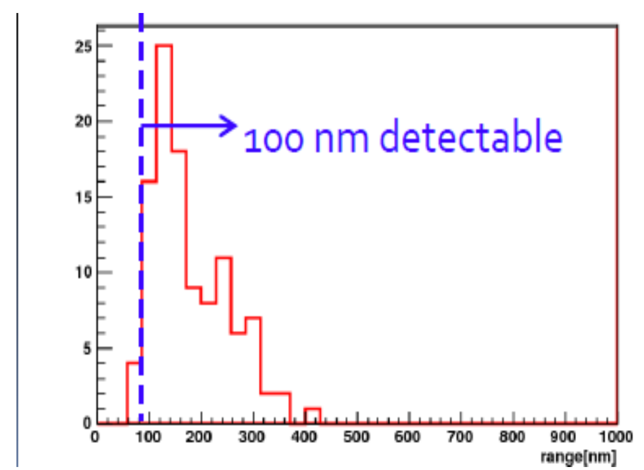
Finest grain emulsion



Crystal diameter [nm]

	NIT	U-NIT
AgBr density	12 AgBr/μm	29 AgBr/μm

Range threshold	Carbon Energy
200 nm	75 keV
100 nm	35 keV
50 nm	15 keV

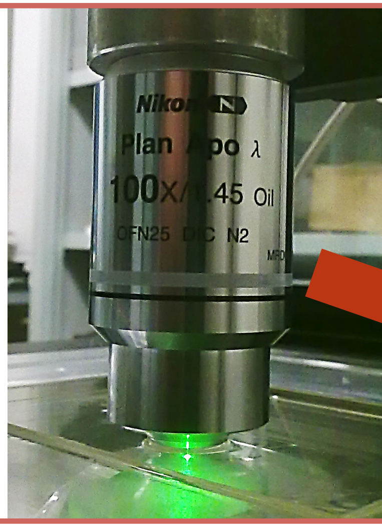


Detect tracks when their lengths become comparable/shorter than the optical resolution

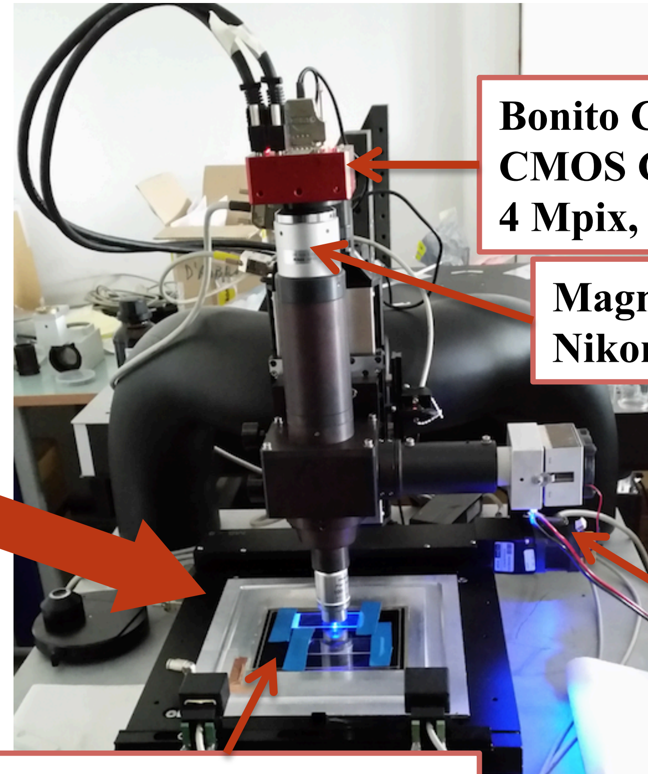
- Optical microscopes
  - Pros: Fast scanning profiting of the improvements driven by the OPERA experiment, dedicated measurement stations in each lab
  - Cons: Resolution with “standard” technologies ~ 200 nm
- X-ray microscopes
  - Pros: High resolution ~ 50 nm or better
  - Cons: extremely slow and not convenient (need an external lab)

Optical Microscope Read-out: Step 1

100x objective lens with high N.A.



Resolution: 28 nm/pixel
View Size: 65.2 x 48.3 µm²



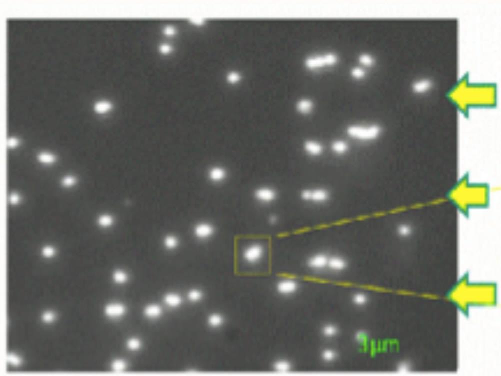
Bonito CL/CMC-4000
CMOS Camera
4 Mpix, @100 fps

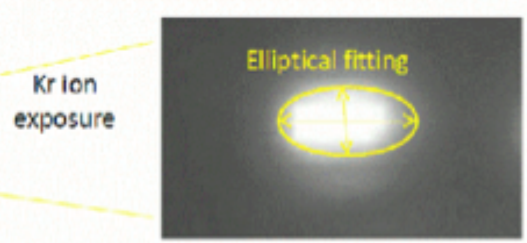
Magnifying lens,
Nikon VM C-2.5x

100W
Halogen
Lamp

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

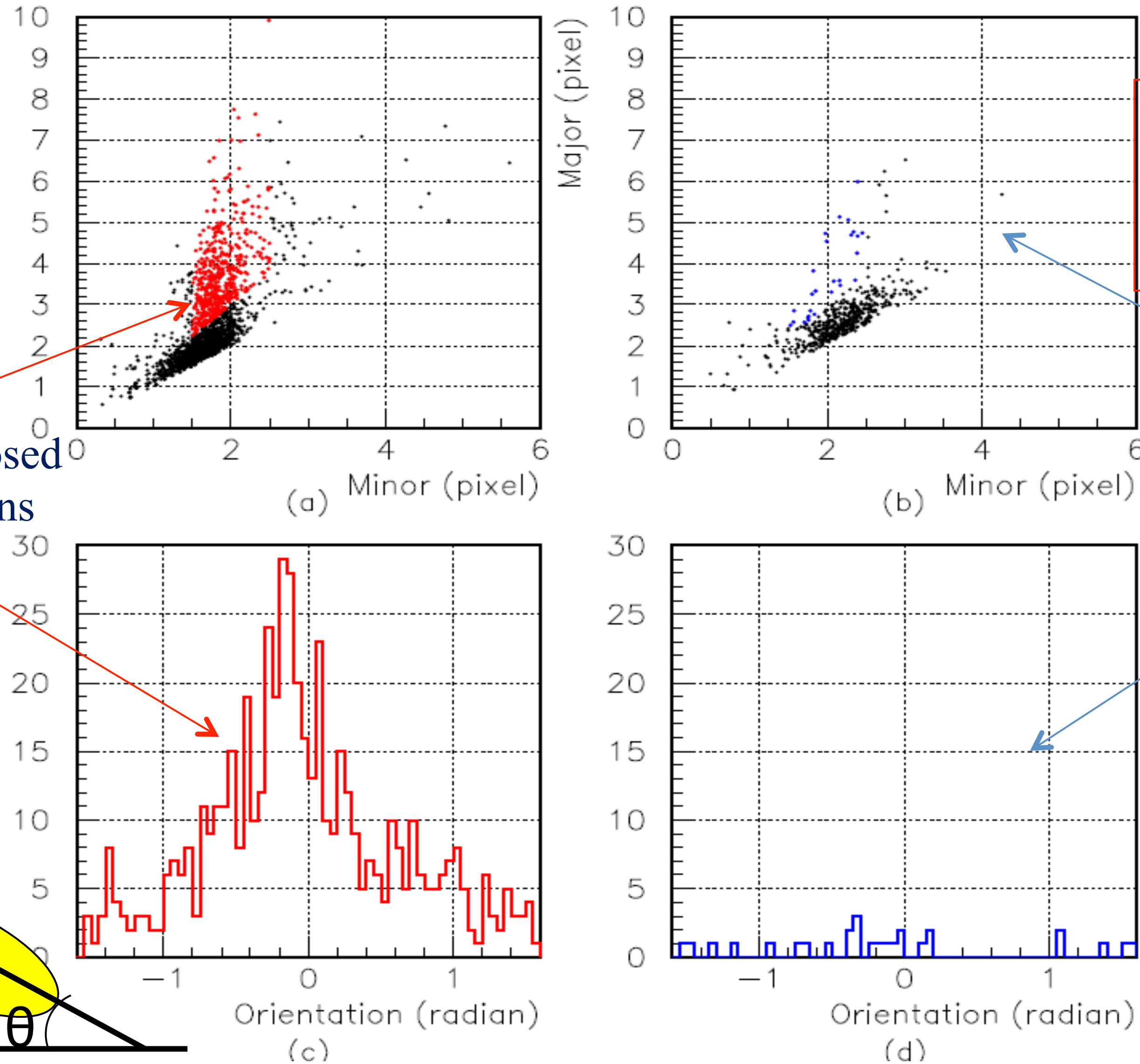
Test using 400 keV Kr ions





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

Selection of Kr ion tracks with shape analysis



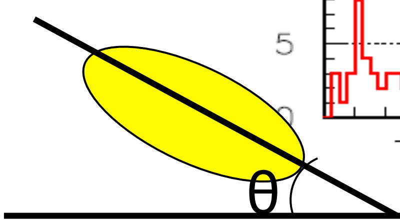
Major/minor>1.5

1.4<minor <2.6

pixel > 40

Film exposed to Kr ions

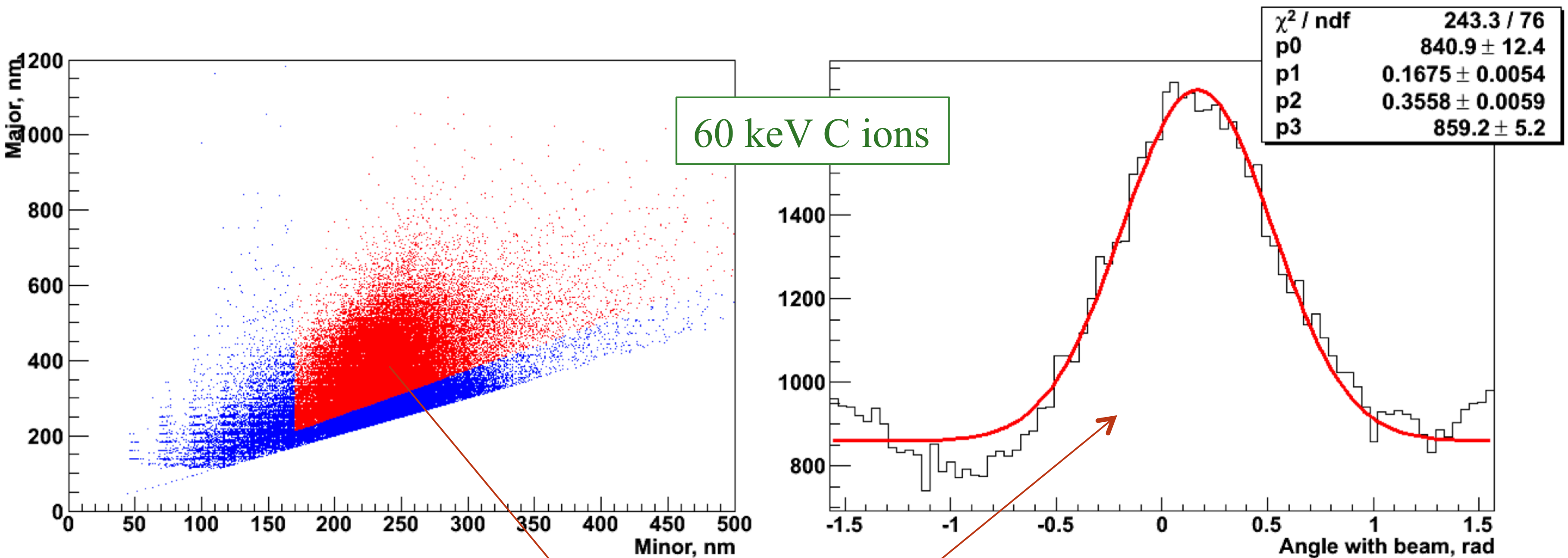
Reference film (unexposed)



Direction detected!

NIM A680 (2012) 12-17

Selection Of C Ion Tracks With Shape Analysis

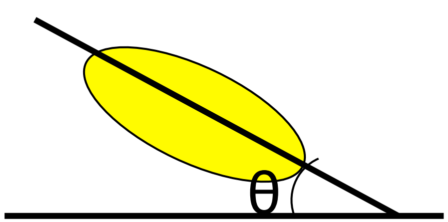


Signal selection:

- Major/minor>1.25
- minor > 170 nm

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

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



Direction detected!

Intrinsic Angular resolution As a By-Product of the Neutron Studies

NEUTRON TEST BEAM @ FNS (JAPAN)

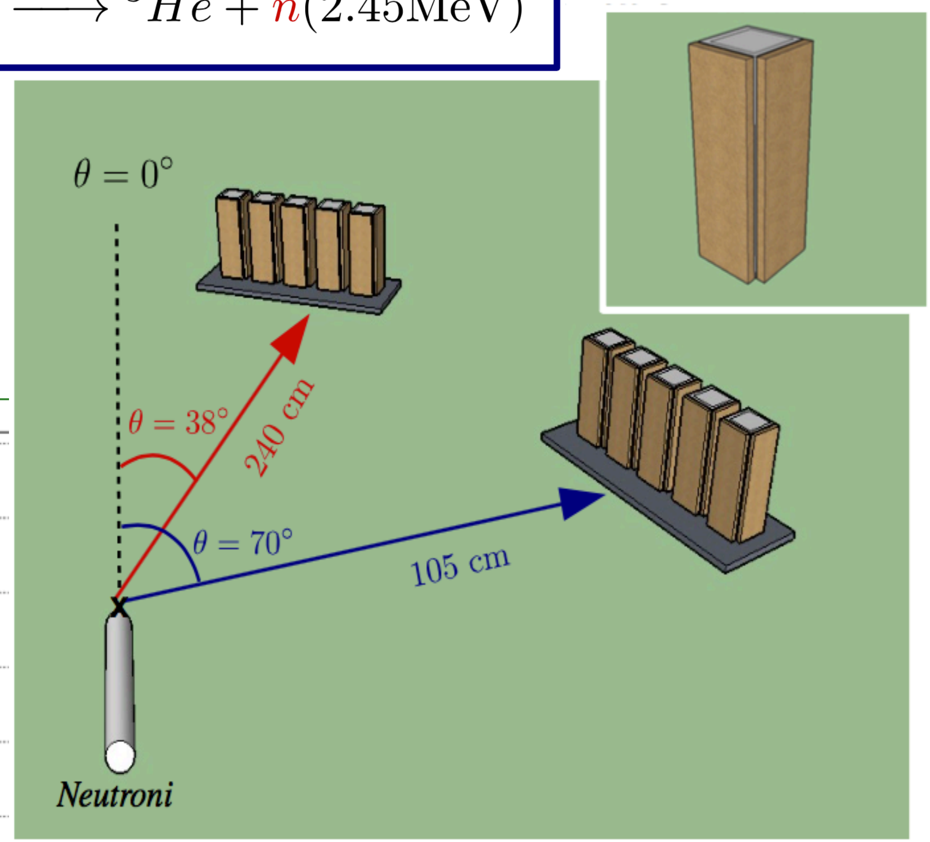
Japan Atomic Energy Research Institute

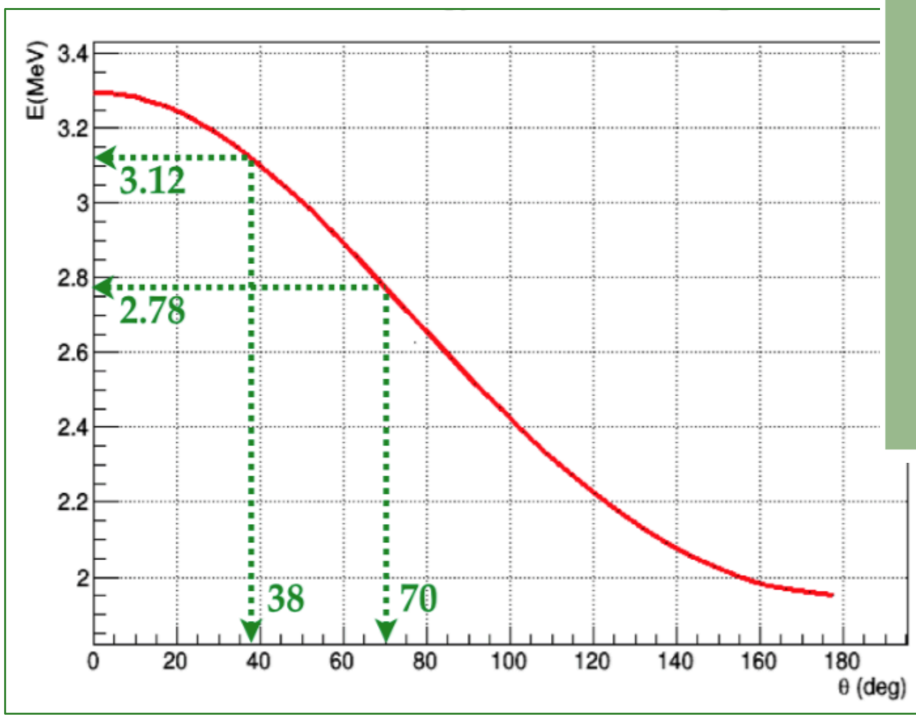
Emitted neutron energy

$\Theta_n = 38°$
$E_n = 3.12\ MeV$

$\Theta_n = 70°$
$E_n = 2.78\ MeV$

$$D + D \xrightarrow{50\%} {}^3He + n(2.45\text{MeV})$$

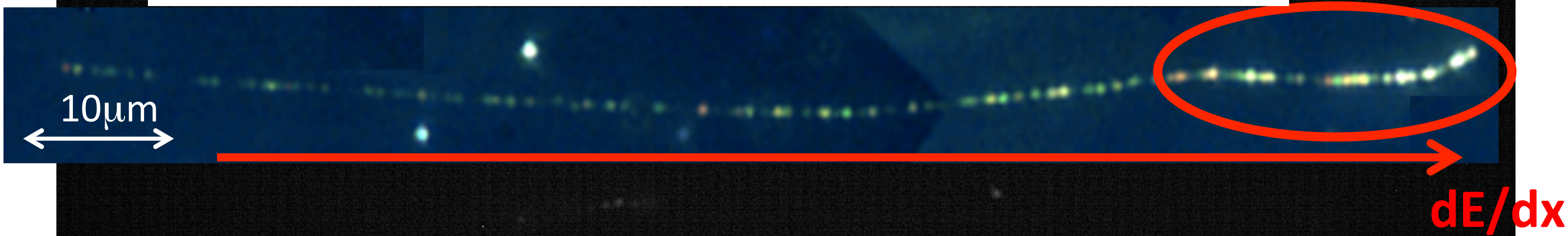




Emitted neutron energy

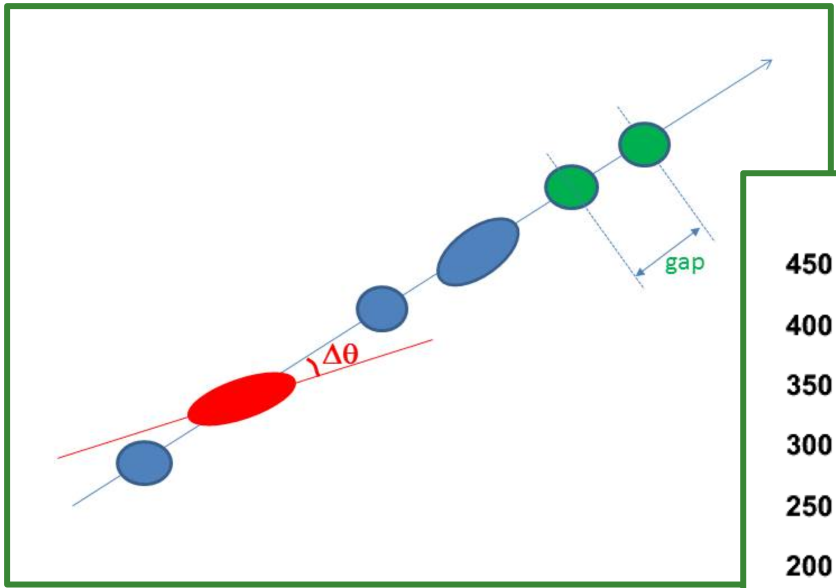
$$E_n = \frac{E_i}{8}\left(\sqrt{2 + \frac{19.6}{E_i(MeV)} + \cos^2\theta_n} + \cos\theta_n\right)^2$$

Neutron test beam analysis

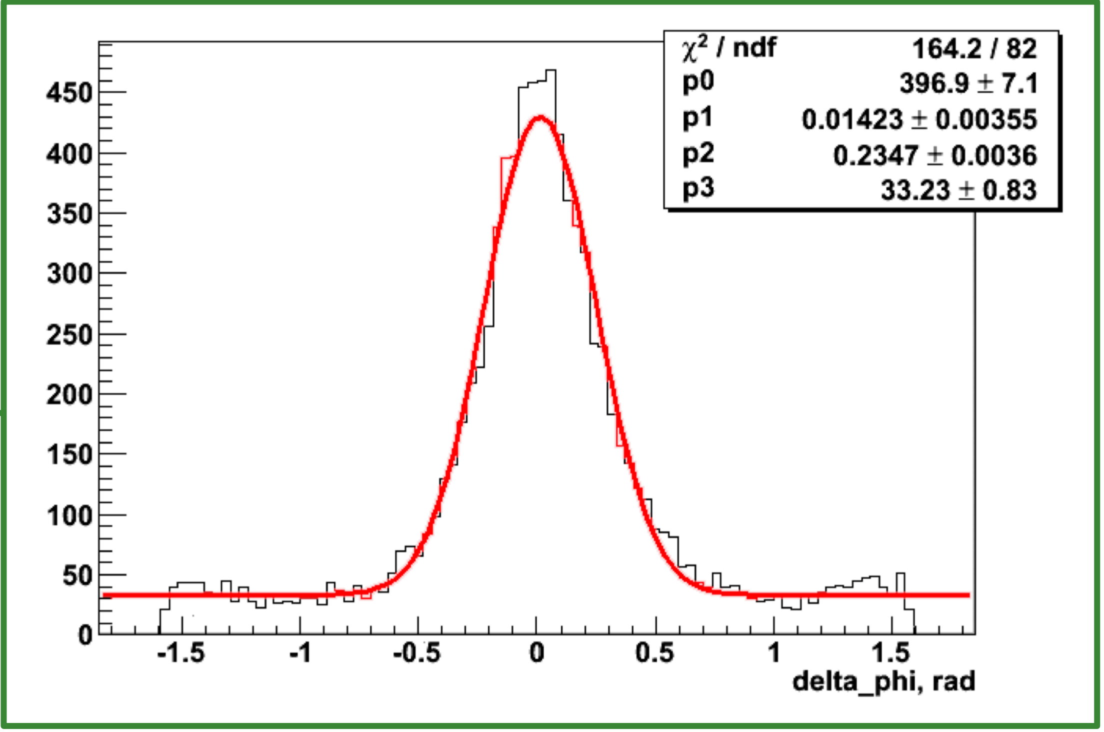


INTRINSIC ANGULAR RESOLUTION

- Neutron test Beam sample (FNS exposure)
- Compare clusters with elliptical (e > 1.1) shape with the proton recoil direction
- Scattering contribution negligible



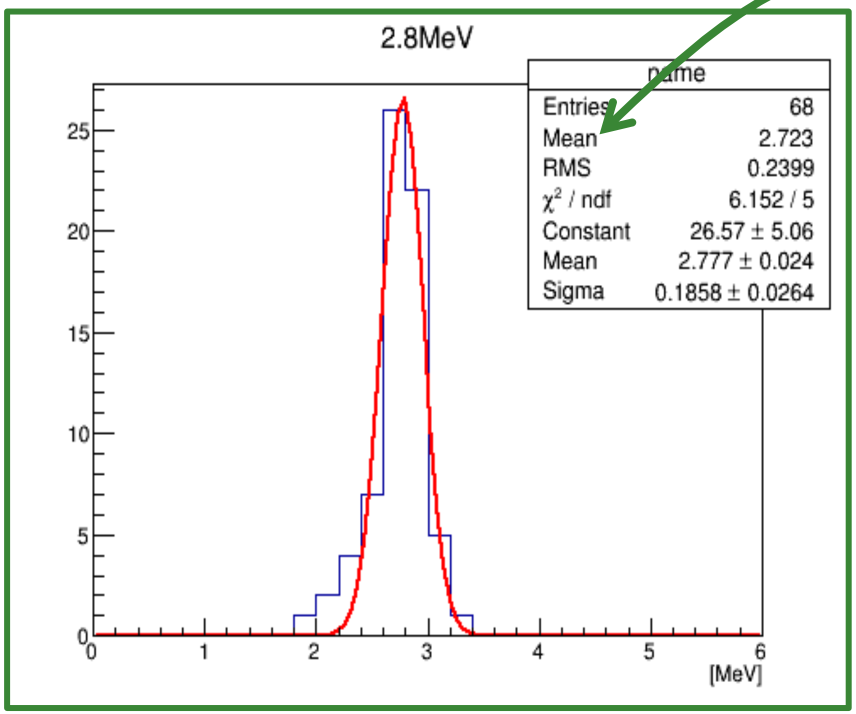
σ = 235 mrad = 13°



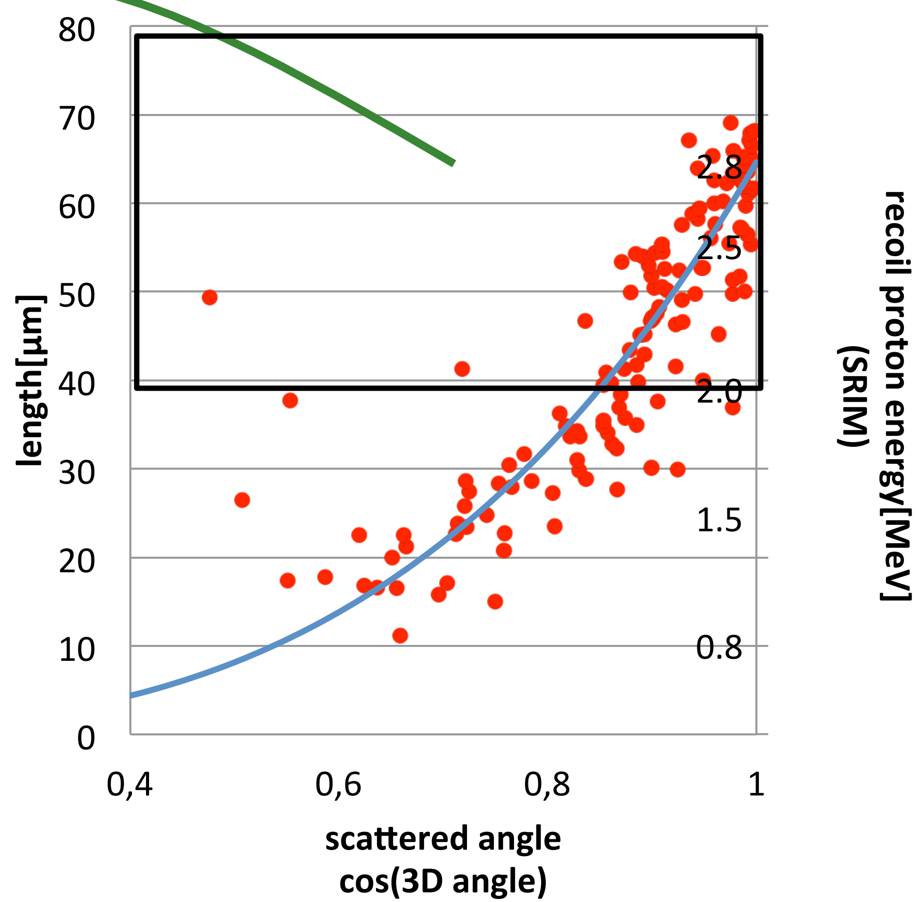
2.8 MeV Neutron Energy Measurement

- Measurement of track length and angle
- Proton energy using the energy-range relation (SRIM)
- → Neutron energy

$E_n = E_p / \cos^2\vartheta$



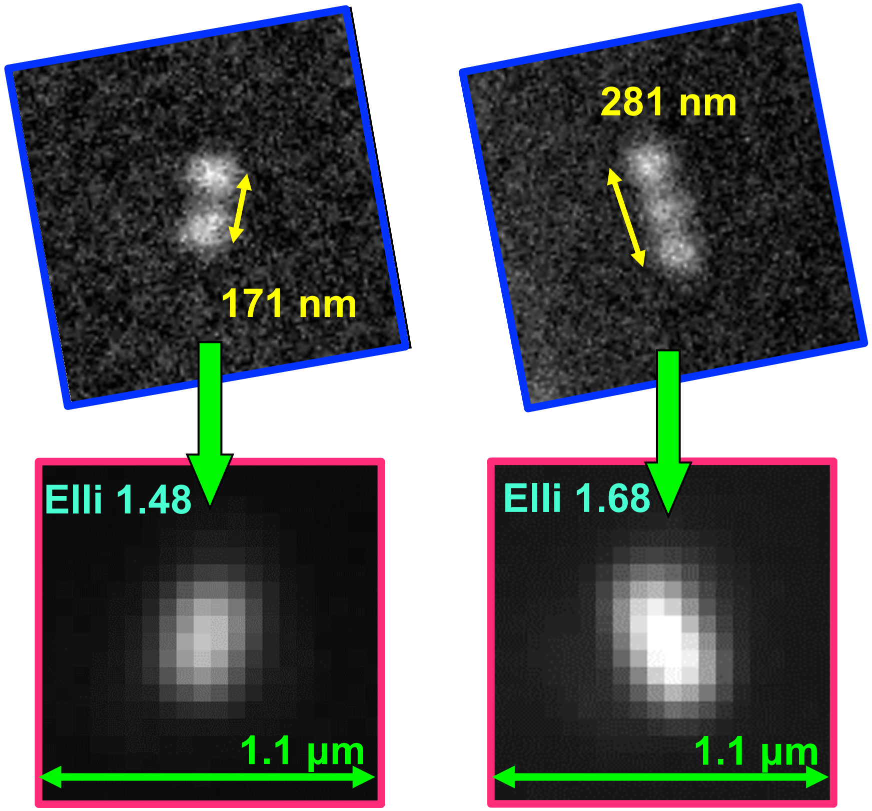
neutron energy
2.8±0.2MeV
resolution(σ/E) = 7%



EFFICIENCY EVALUATION

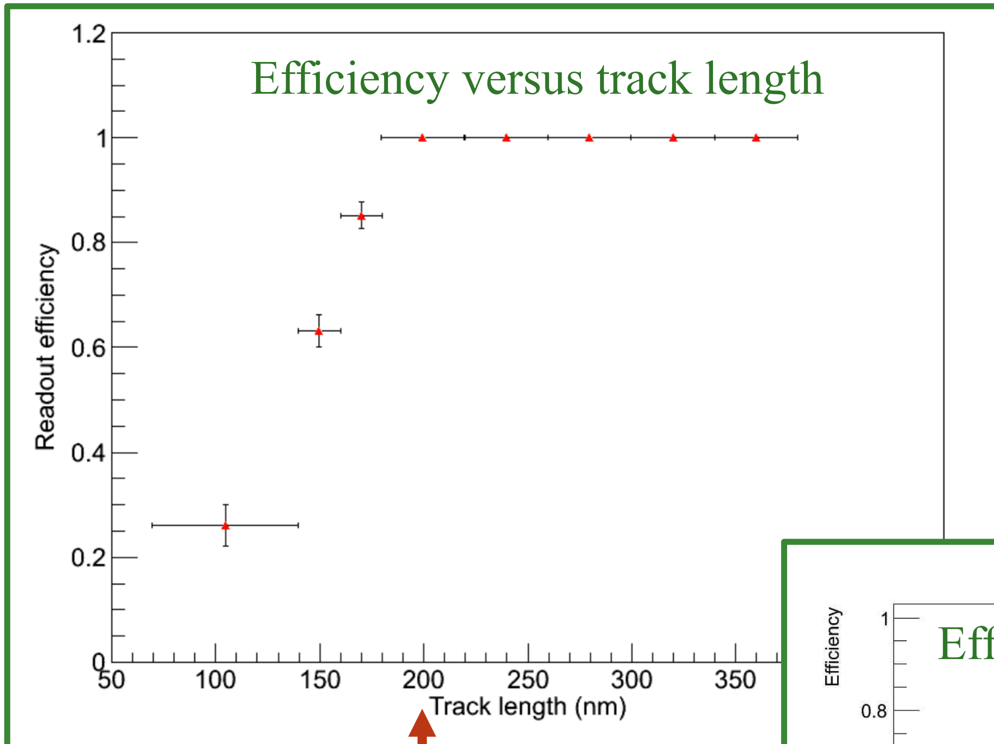
- Implantation: 60÷100 keV C-ions
- Emulsion sample: 40nm-crystal
- Scan with X-ray microscope & select candidates
- Scan with Optical microscope by a pin-point check & Elliptical fit

X-ray MS
- 10.83nm / pix
- 2048 x 2048 pix CCD

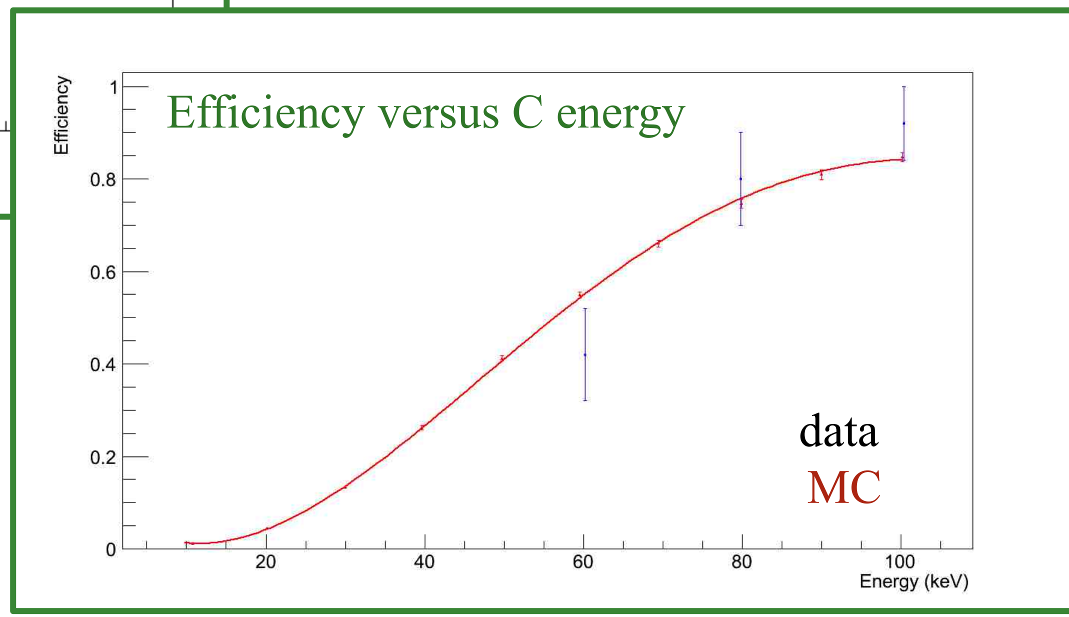


X-ray microscope: ~50 nm resolution and readout speed ~ (200μm)^2/100 s

EFFICIENCY EVALUATION



ε ~ 100% above ~200 nm
e > 1.25



BEYOND OPTICAL RESOLUTION

X-ray microscope

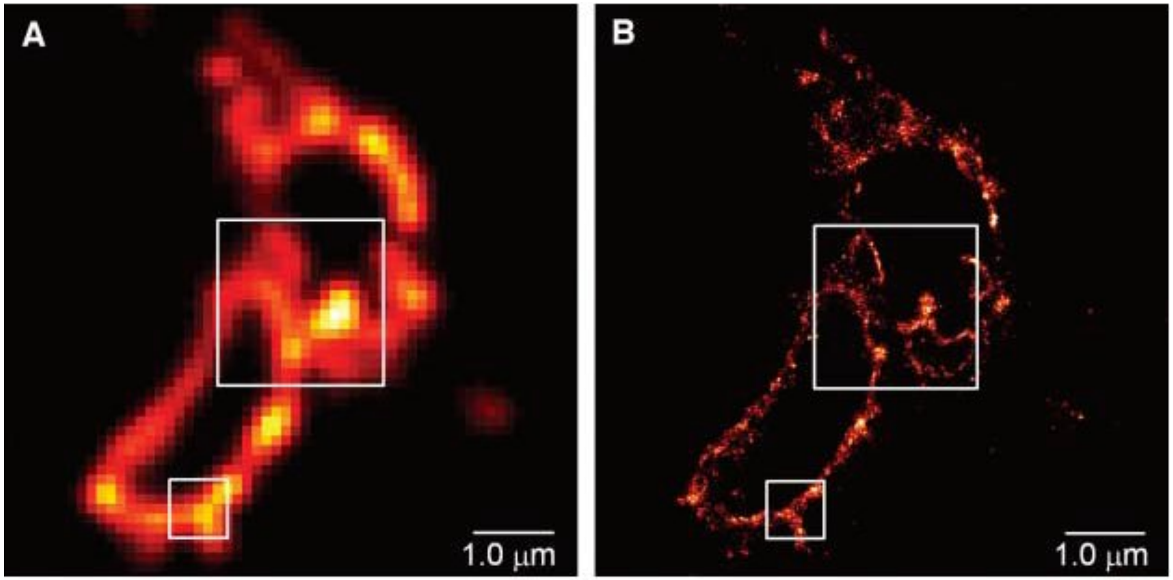
- Slow analysis speed
- Need of external X-ray guns

Optical microscope

- New technologies

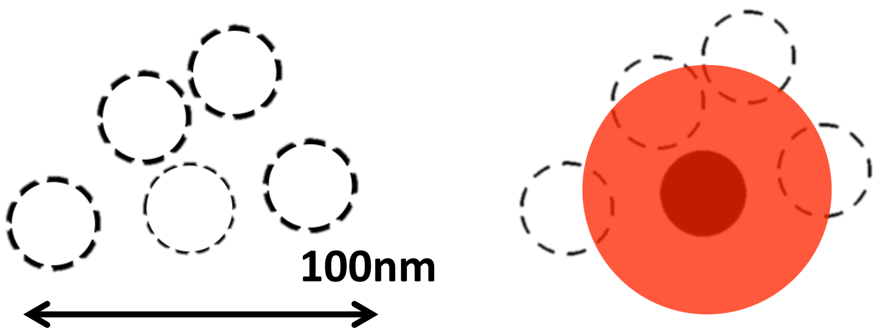
Imaging beyond the optical resolution: 2014 Nobel Prize in Chemistry

COS-7 cell optical images



Eric Betzig *et al.*, Science 313, 1642 (2006)

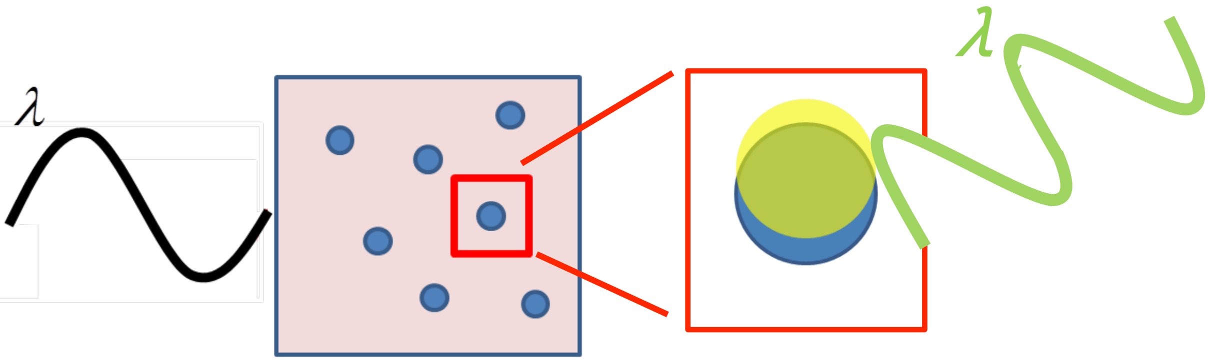
Fluorescent molecule



Using fluorescence

Optical resolution ~10 nm

Resonant Light Scattering From Ag Nanoparticles



Nano-metal in medium ε_d

Oscillation of e-cloud

E_l **intensity**

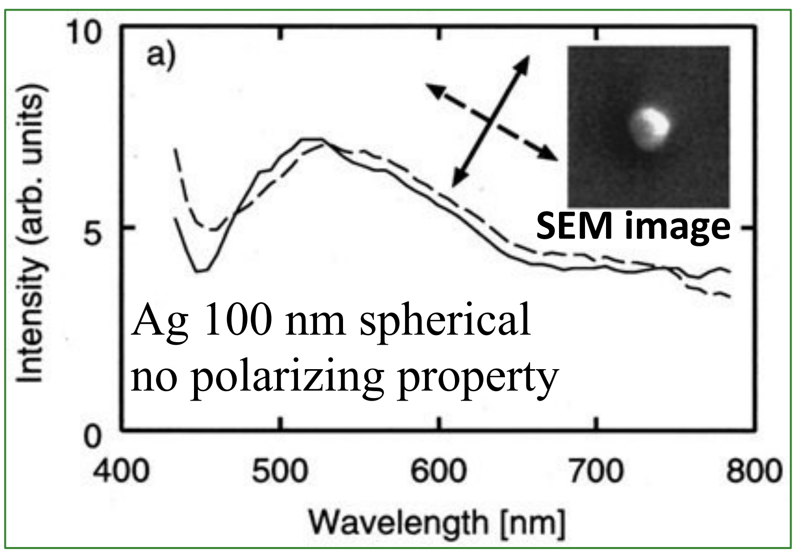
$$E_l = \frac{3\varepsilon_d(\lambda)}{\varepsilon_m(\lambda) + 2\varepsilon_d(\lambda)} E_0$$

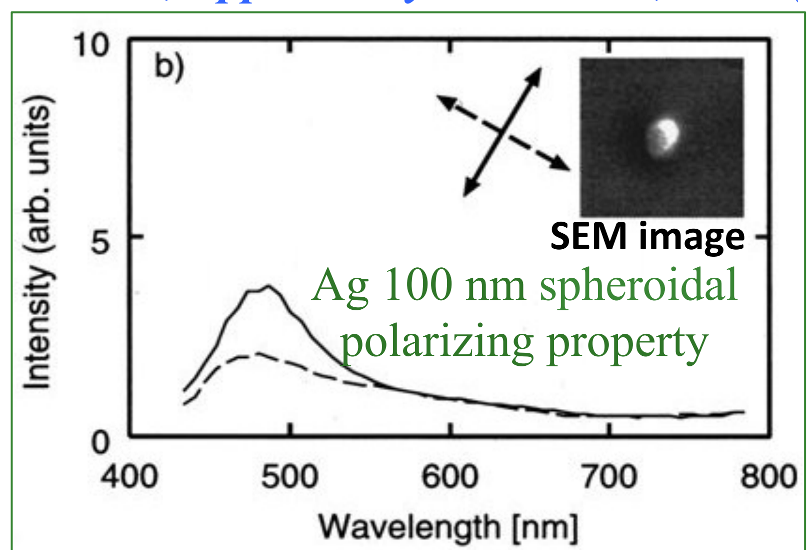
$$\varepsilon_m(\lambda_l) + 2\varepsilon_d(\lambda_l) \approx 0$$

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)

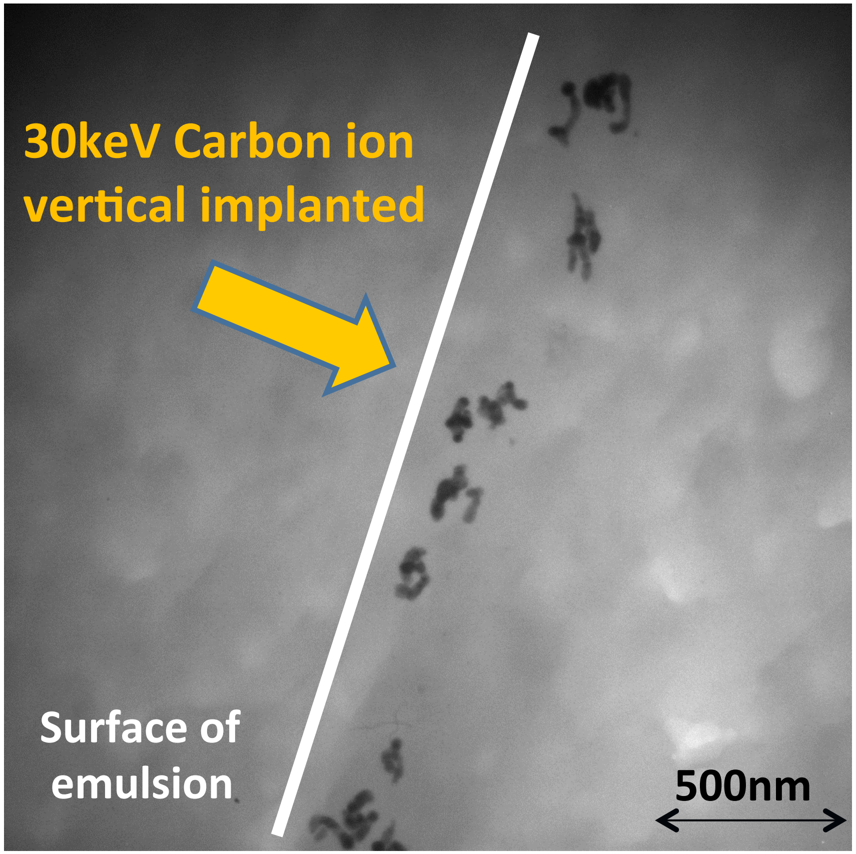




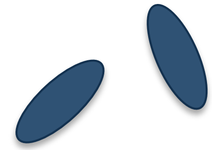
The polarization dependence of the resonance frequencies strongly reflects the shape anisotropy

SILVER GRAINS BUILDING UP TRACKS

TEM image of Carbon track after development



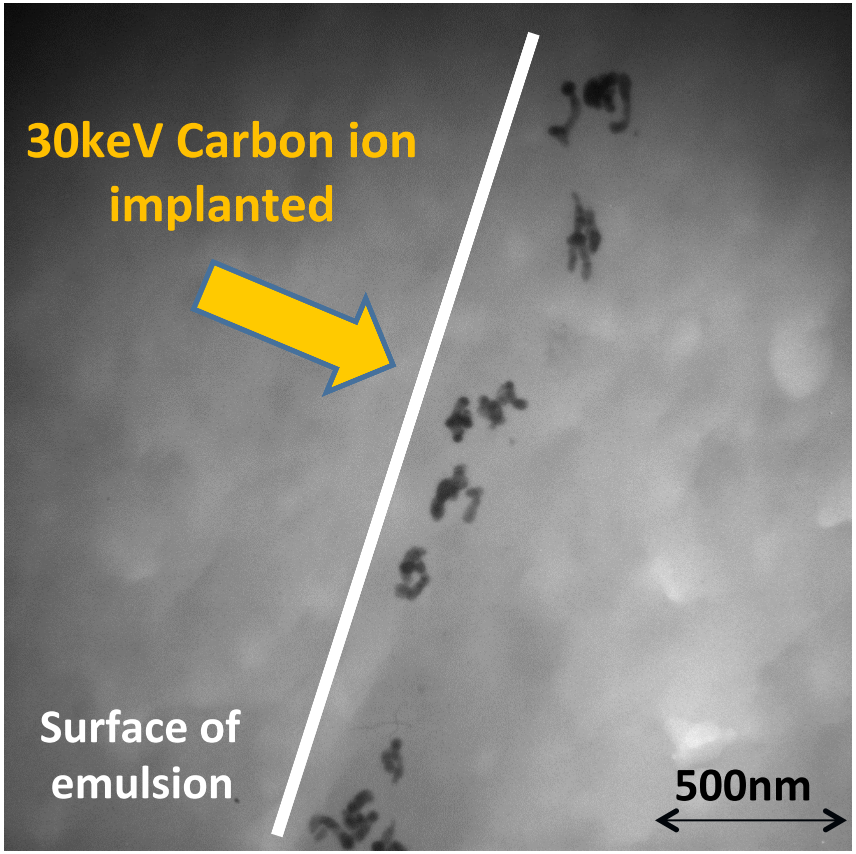
Shape different from each other



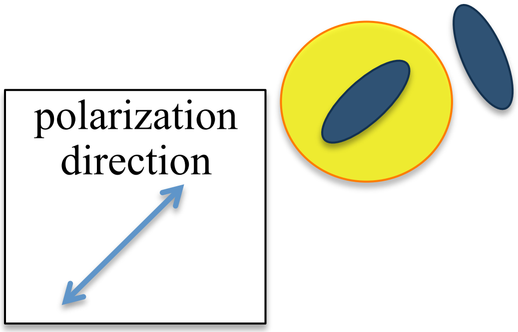
Optical response strongly depends on the polarization of incident light

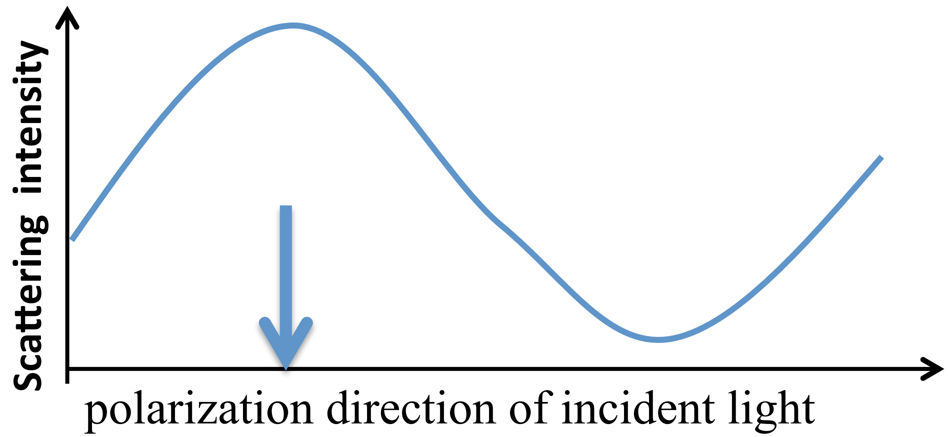
SILVER GRAINS BUILDING UP TRACKS

TEM image of Carbon track after development



Shape different from each other

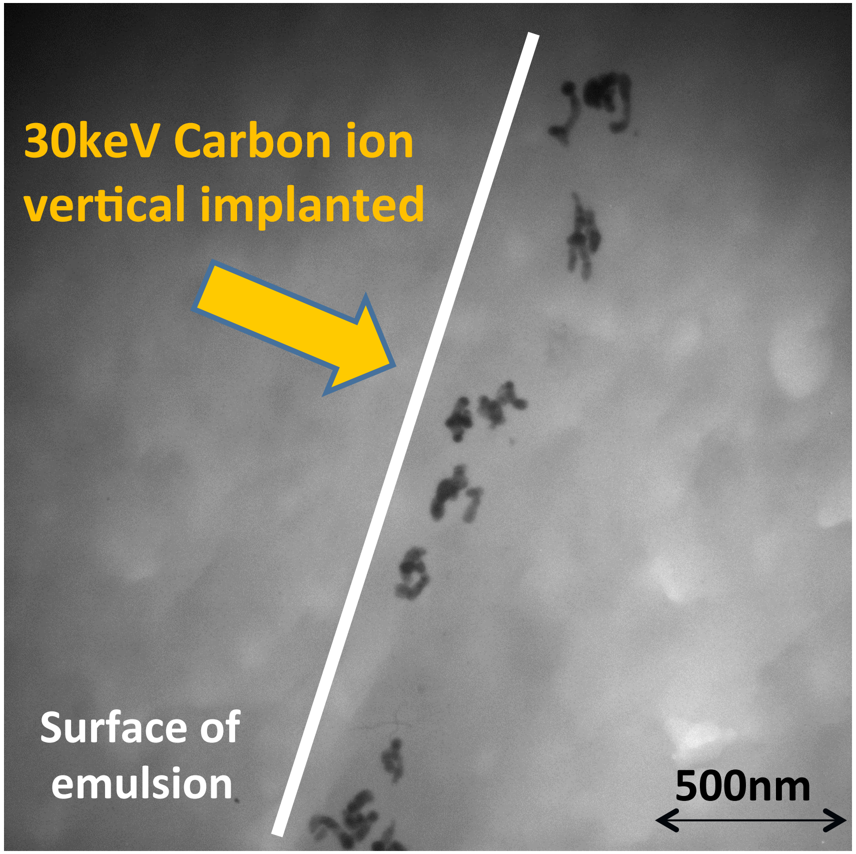




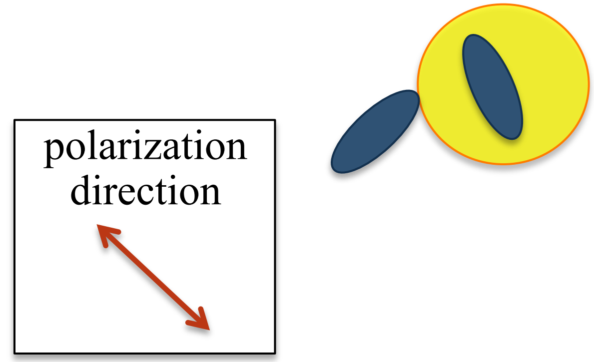
Optical response strongly depends
on the polarization of incident light

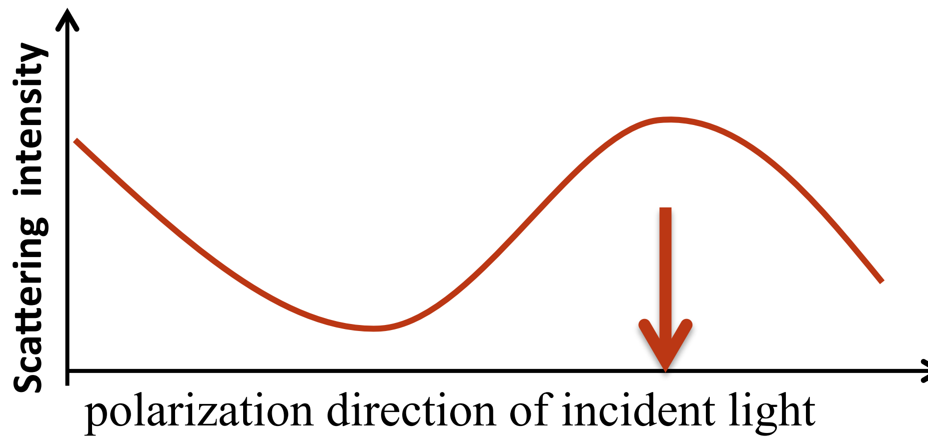
Silver Grains Building Up Tracks

TEM image of Carbon track after development



Shape different from each other



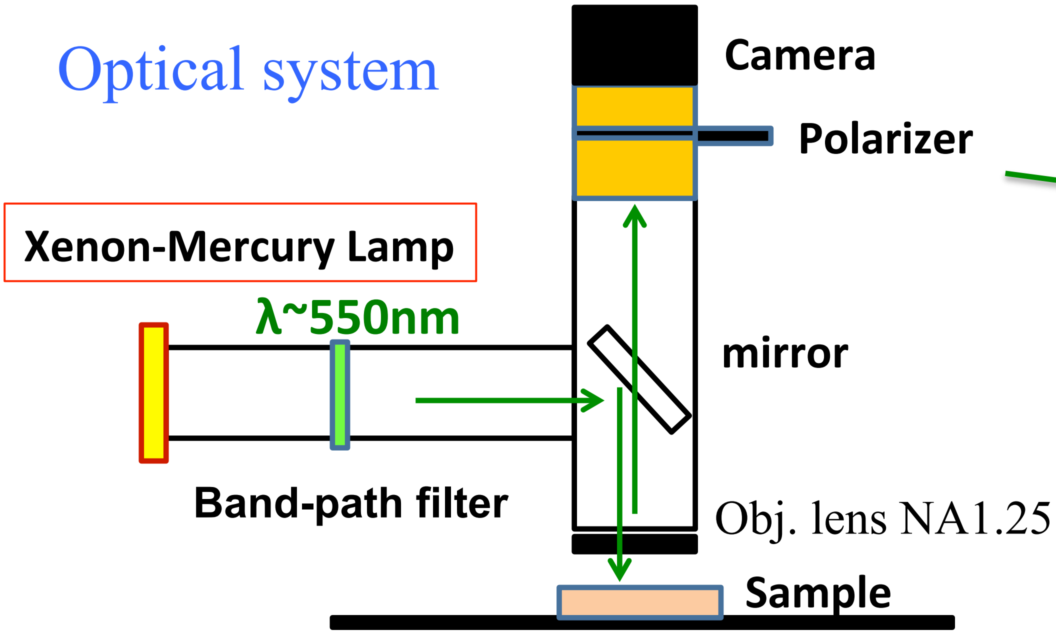


Optical response strongly depends
on the polarization of incident light

Microscope upgraded

polarizer below the camera, rotated to charge polarization

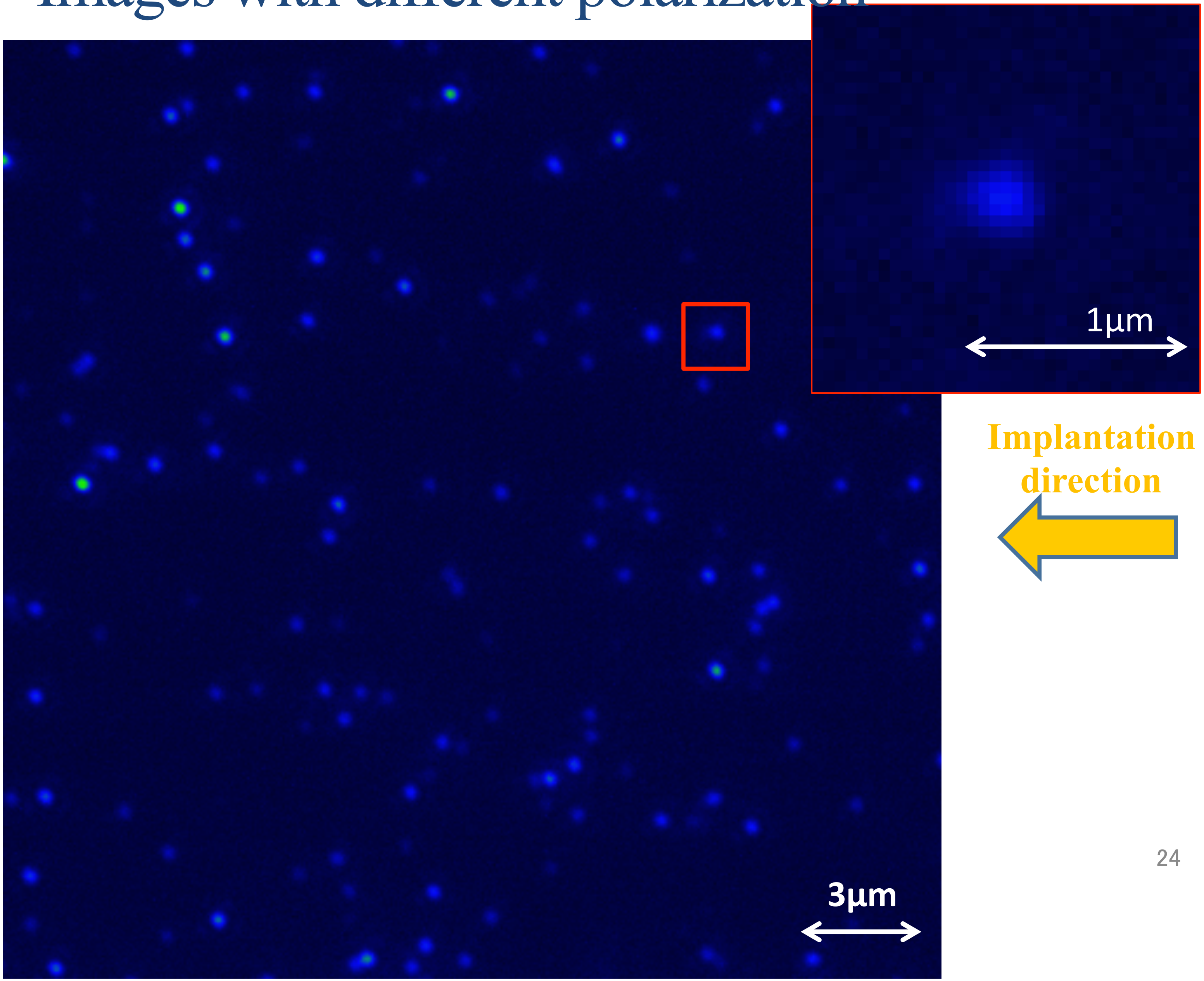
Optical system



Rotate by 180° with 10° steps

change the direction of polarization and measure the track

Measurements with plasmon resonance effect
Images with different polarization

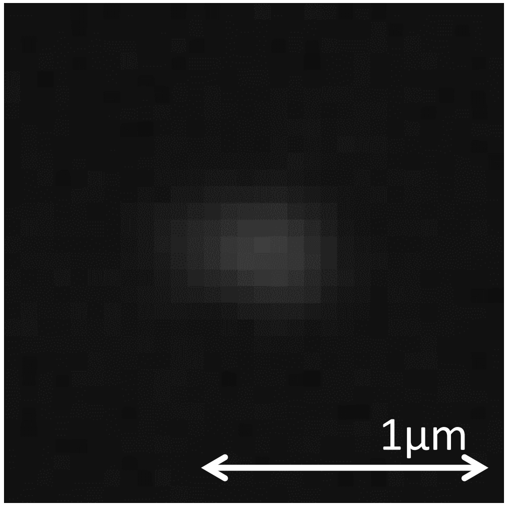


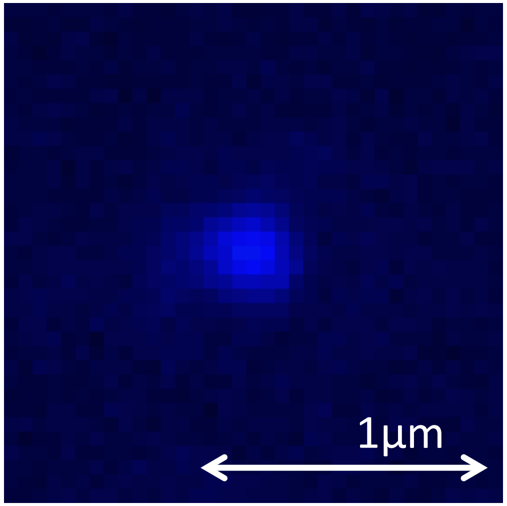
Implantation direction

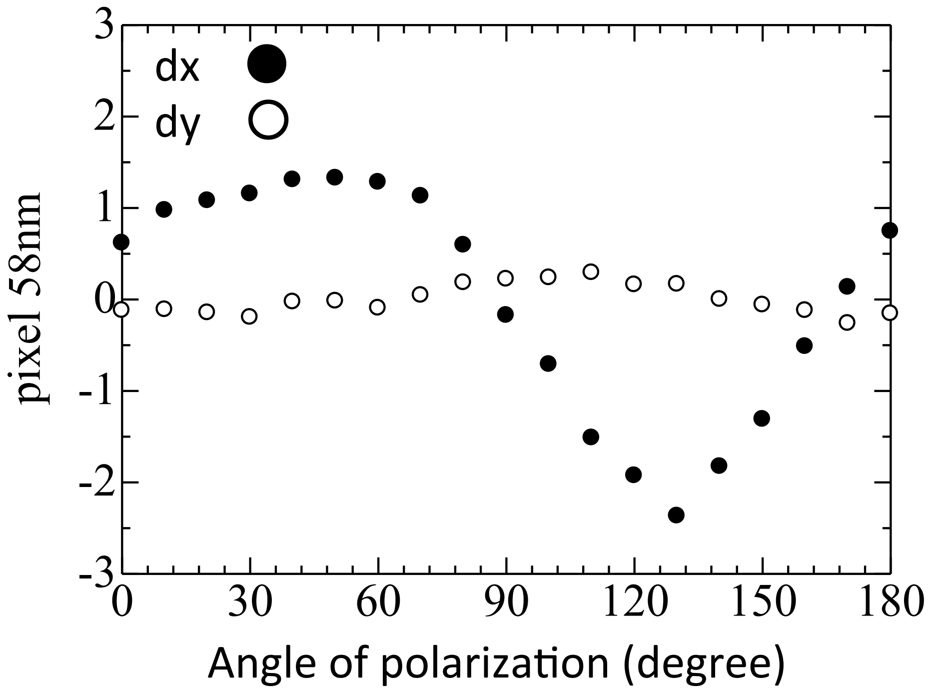
A Track Made Of Two Grains

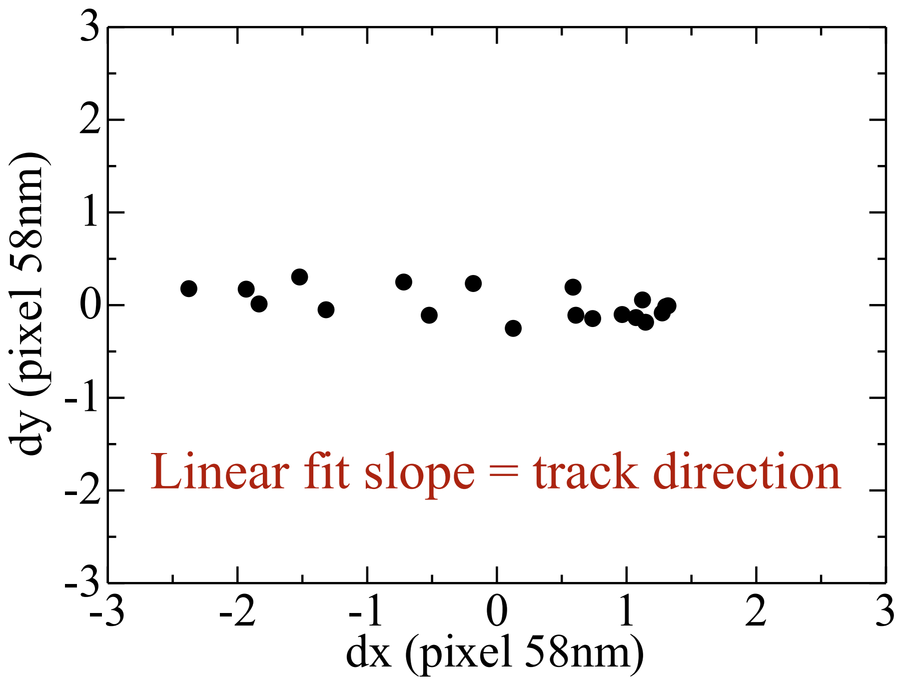
e = 1.49
without polarizer

Track validated by
elliptical shape analysis



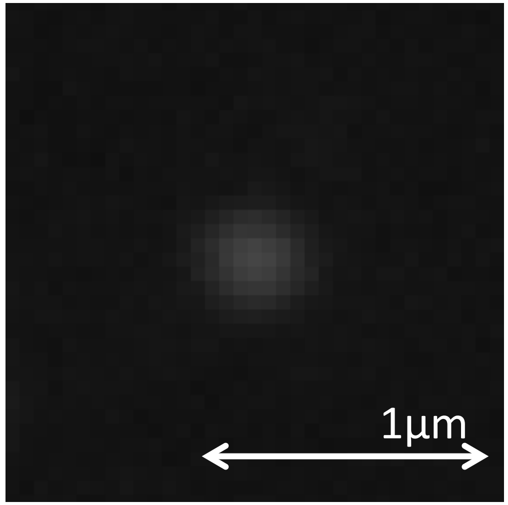


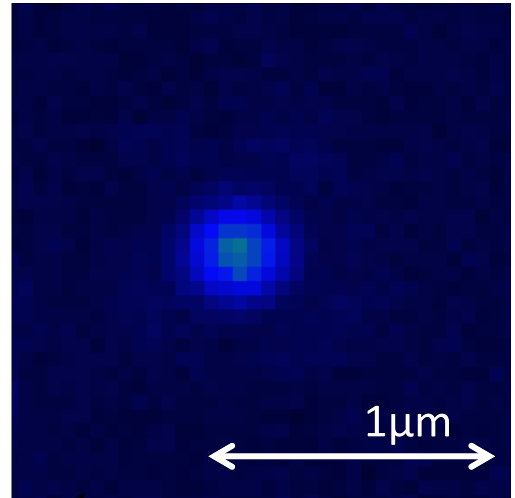


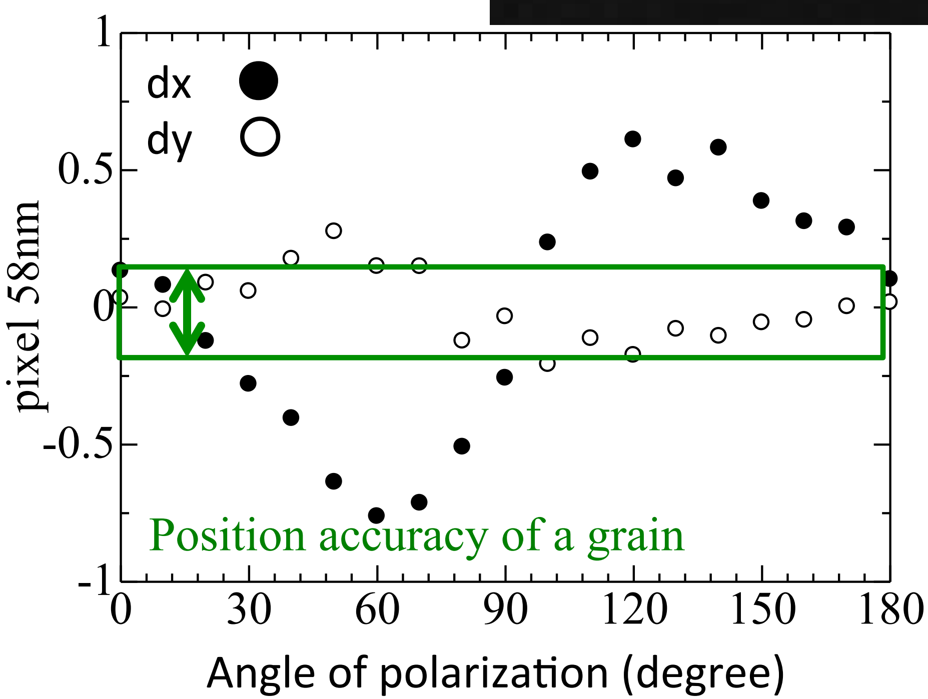


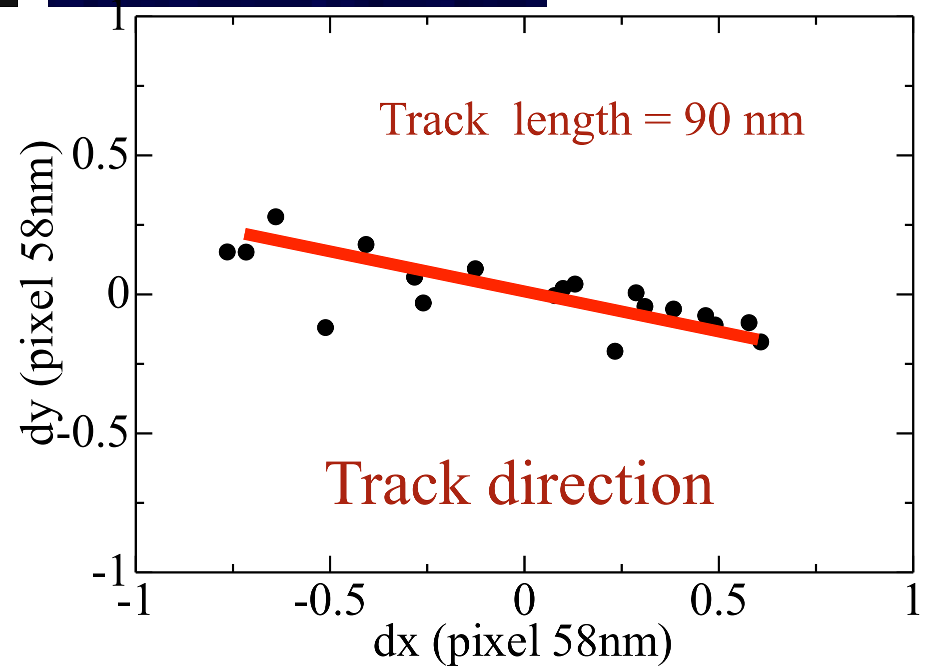
A Two-Grains Track

e = 1.27
without polarizer
Discarded by
ellipticity cut (1.4)



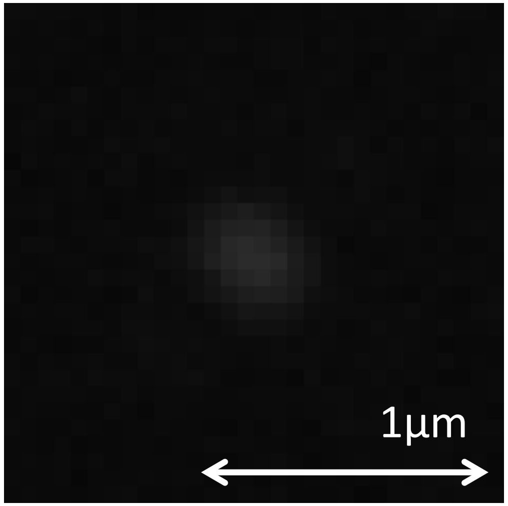


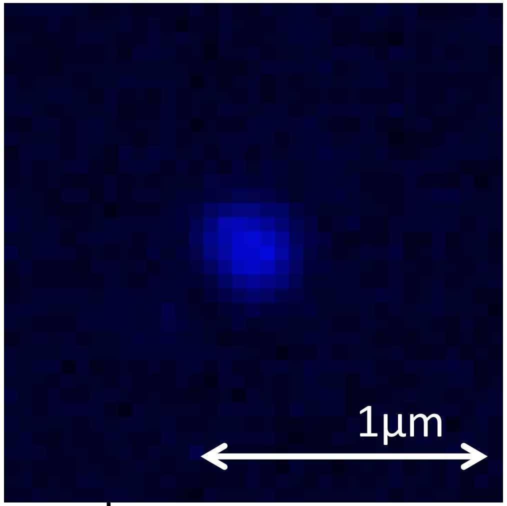


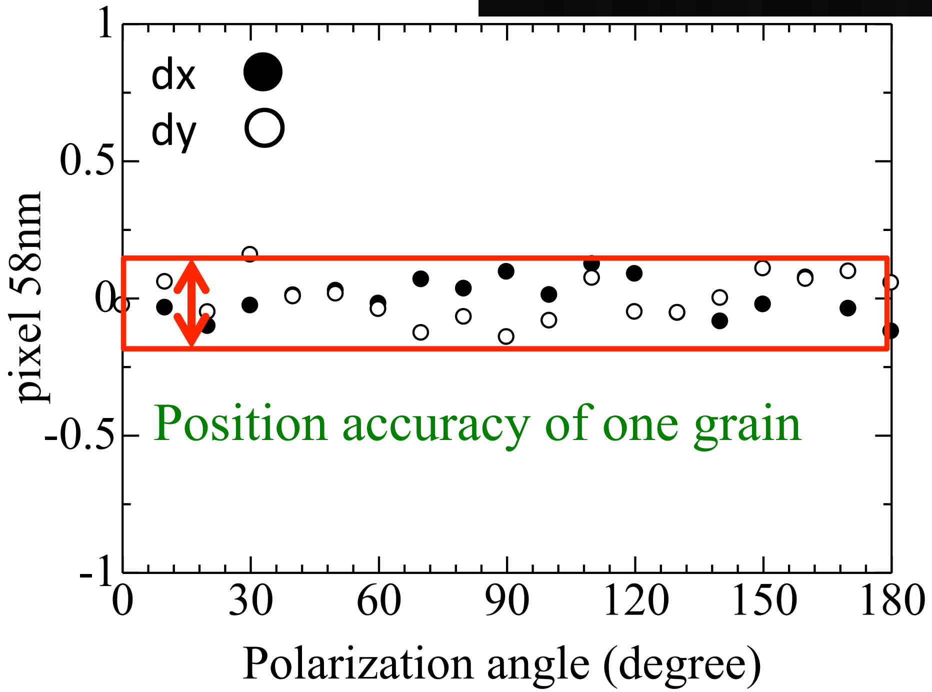


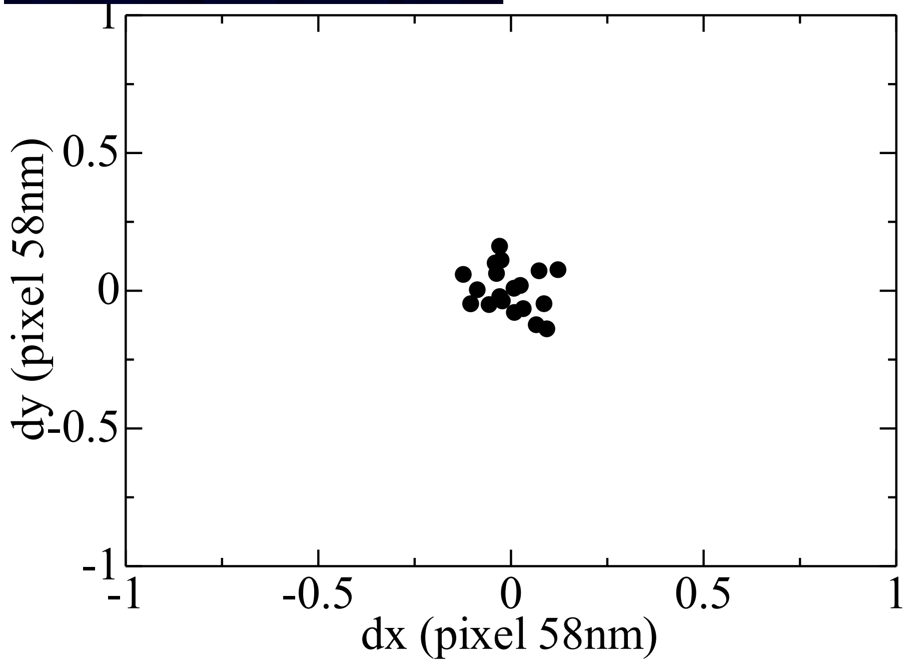
SINGLE GRAIN FOR ACCURACY EVALUATION

Ag 60nm

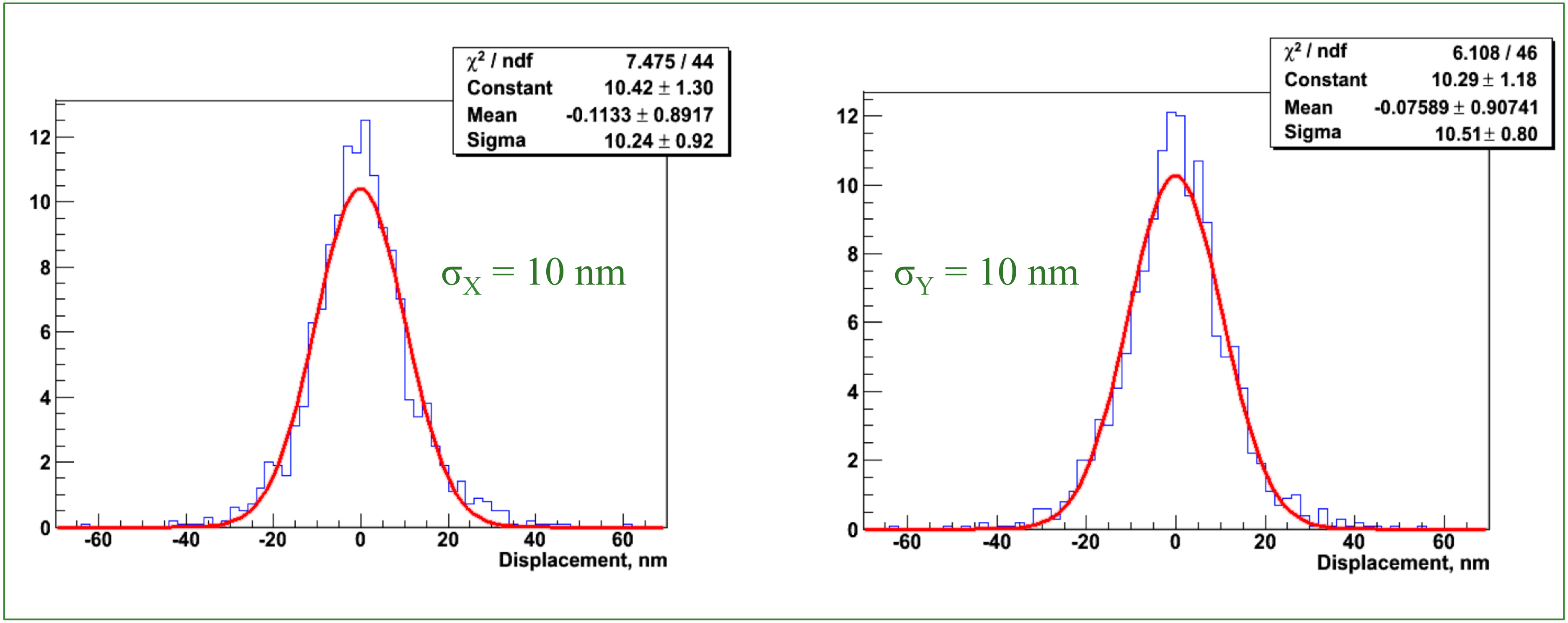








Position Accuracy



(pixel size 28 nm)

Unprecedented accuracy of 10 nm achieved on both coordinates

Breakthrough

Background Study

Measurement Of Intrinsic Radioactivity: Neutrons

Nuclide	Contamination [ppb]	Activity [mBq/Kg]
Gelatine		
^{232}Th	2.7	11.0
^{238}U	3.9	48.1
PVA		
^{232}Th	< 0.5	< 2.0
^{238}U	< 0.7	< 8.6
AgBr-I		
^{232}Th	1.0	4.1
^{238}U	1.5	18.5

Constituent	Mass Fraction
AgBr-I	0.78
Gelatin	0.17
PVA	0.05

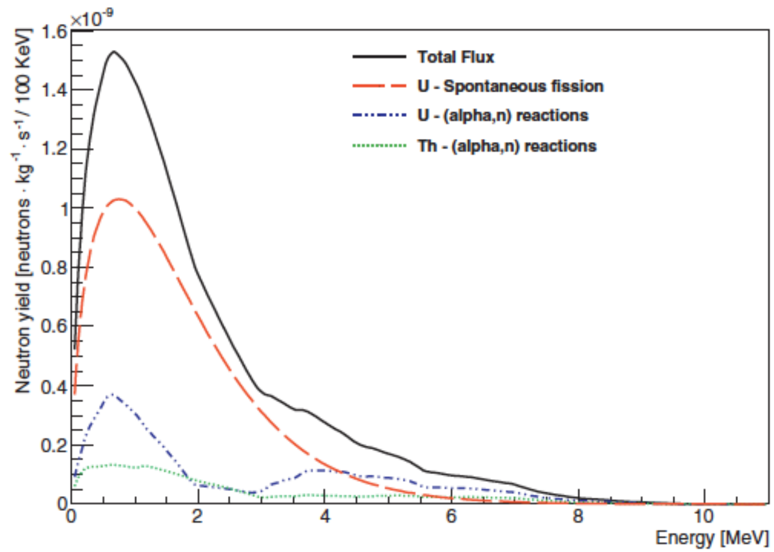
(a) Constituents of nuclear emulsion

^{238}U: 1.87 ppb (23.1 mBq/kg)
^{232}Th: 1.26 ppb (5.1 mBq/Kg)

Process	SOURCES simulation [kg^{-1} y^{-1}]	Semi-analytical calculation [kg^{-1} y^{-1}]
(α, n) from ^{232}Th chain	0.12 ± 0.04	0.11 ± 0.03
(α, n) from ^{238}U chain	0.27 ± 0.09	0.26 ± 0.08
Spontaneous fission	0.8 ± 0.3	0.8 ± 0.3
Total flux	1.2 ± 0.4	1.2 ± 0.4

$$\varepsilon \simeq 5\% \rightarrow 0.06 \div 0.11\, n/(kg \cdot year)$$

Astroparticle Physics 80 (2016) 16–21



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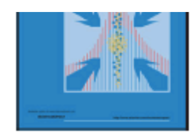


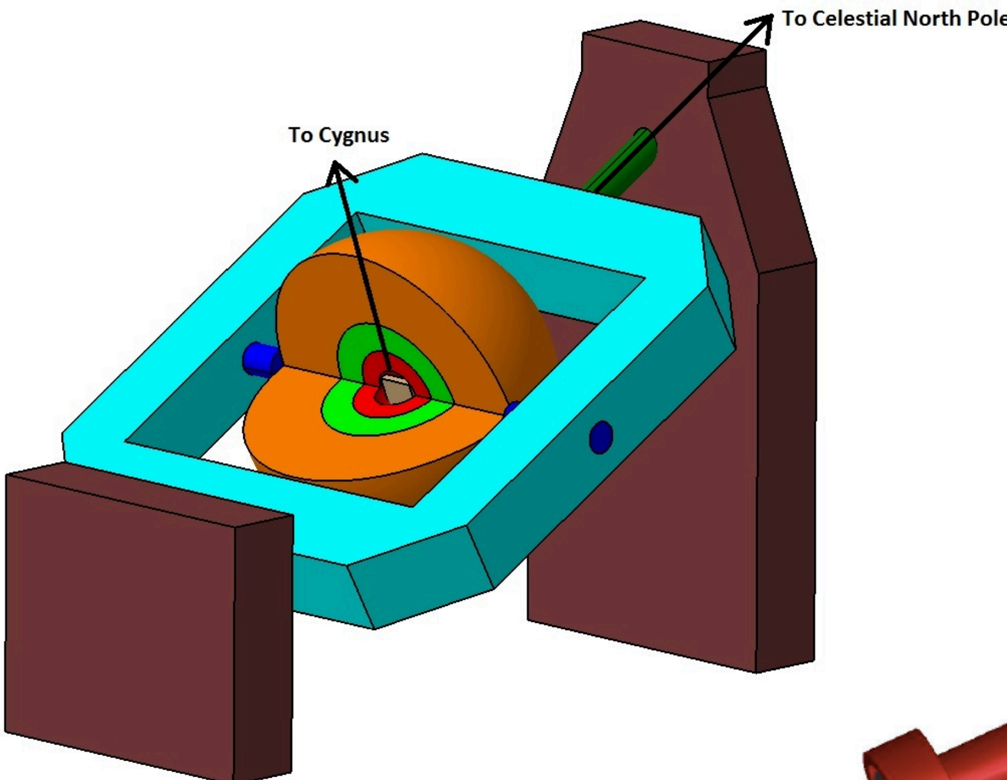
Intrinsic neutron background of nuclear emulsions for directional Dark Matter searches

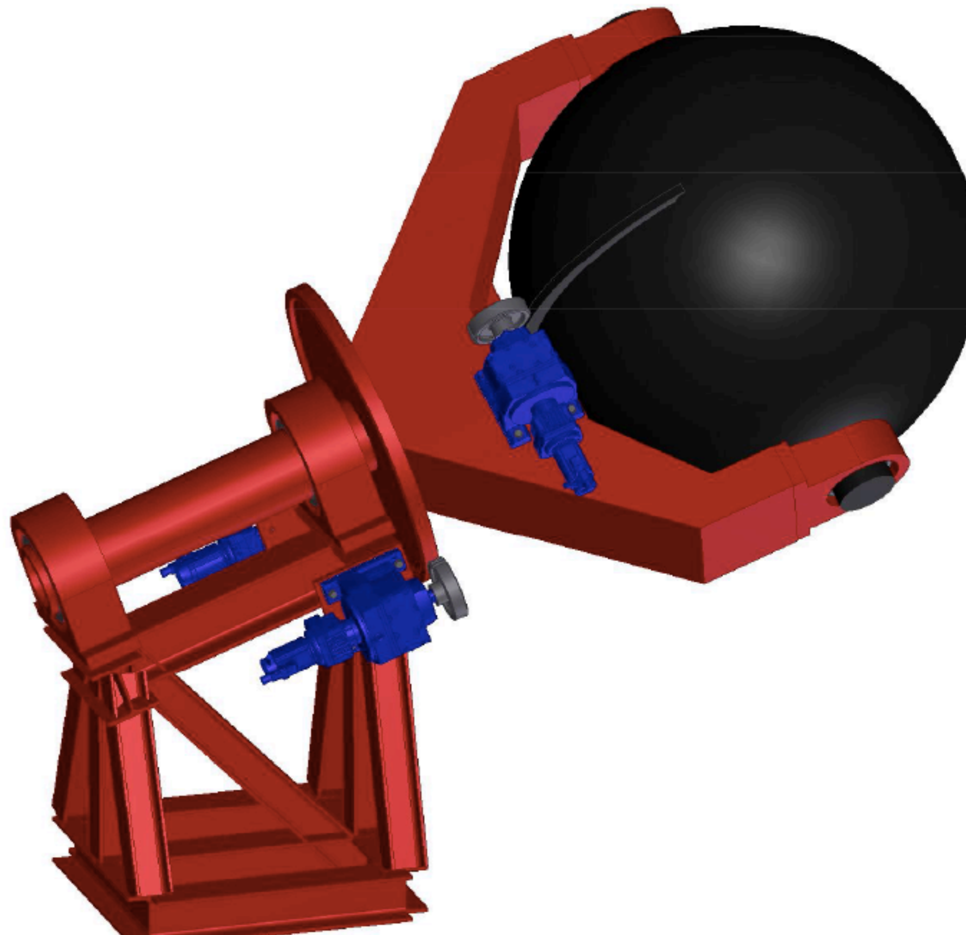
CrossMark

Facility And Detectors At LNGS

Experimental Set-Up With Equatorial Telescope

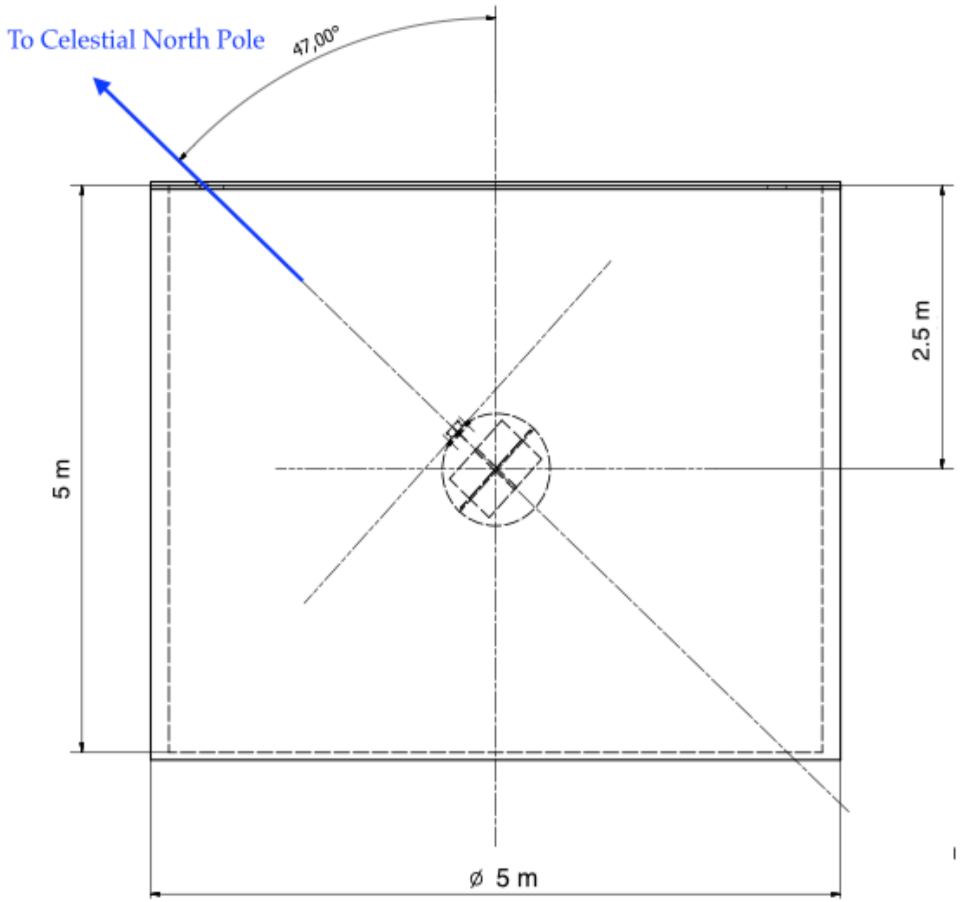
OPTION 1: polyethylene shielding

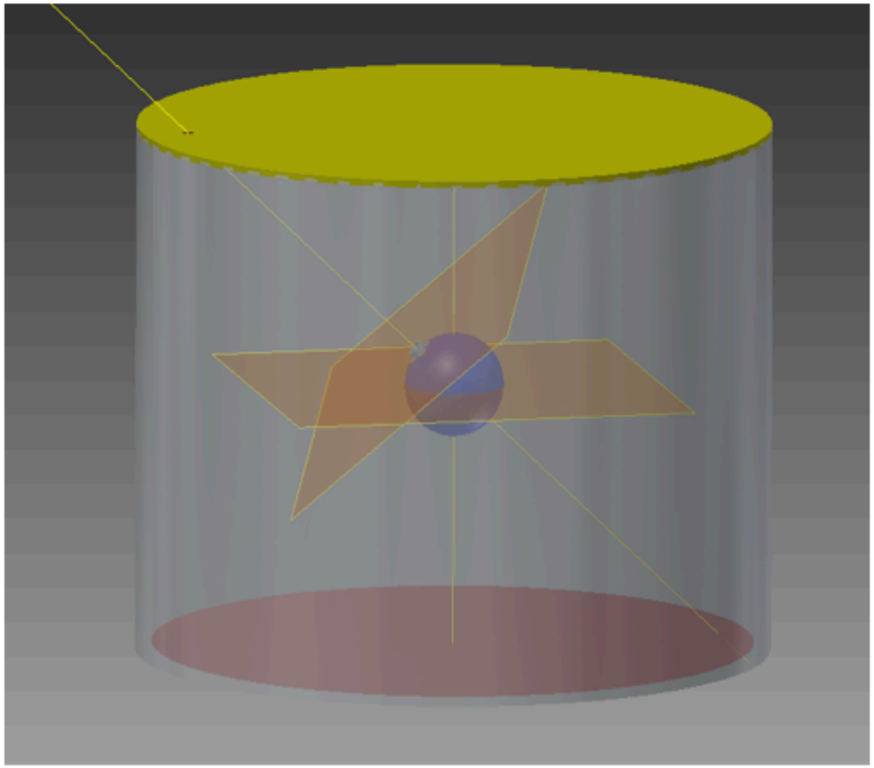




Experimental Set-Up With Equatorial Telescope

OPTION 2: water shielding





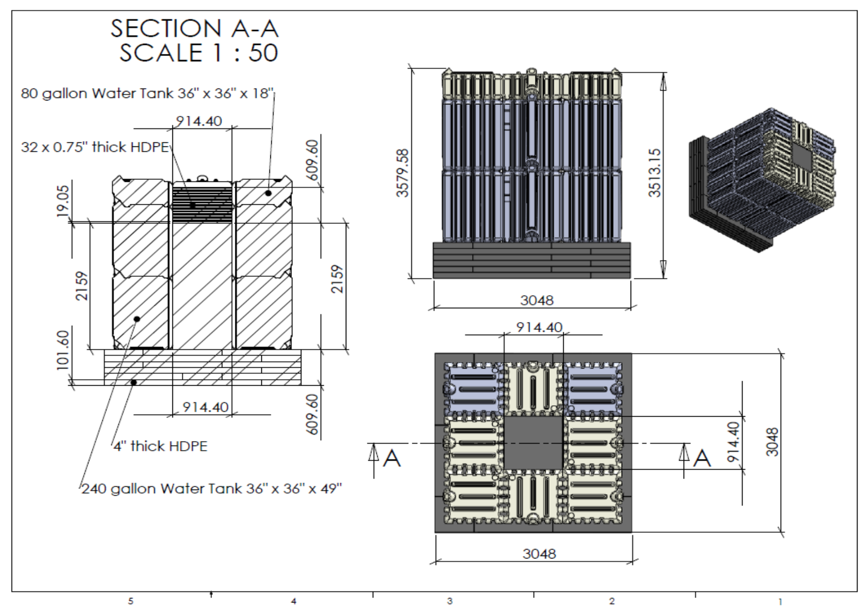
Set-up for a test

Control the background with a small scale detector

DarkSide-10 shield

Water Tanks

- Empty space in the center (2 big tanks equivalent) for detector installation
- Tanks to be filled with demineralized water

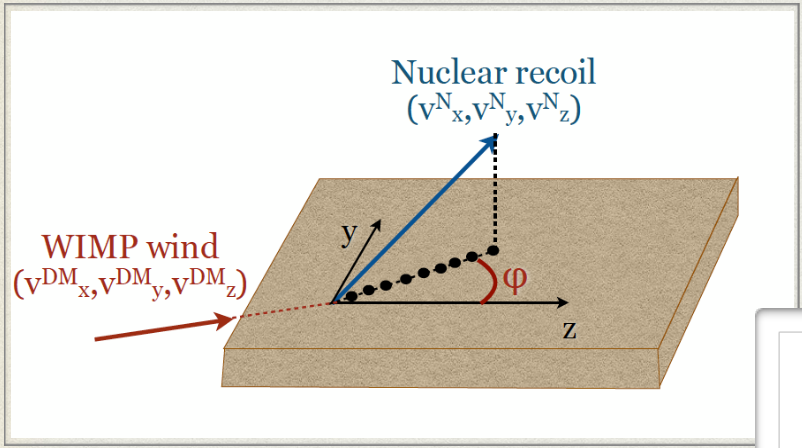


Sensitivity

2D RECOIL ANGLE

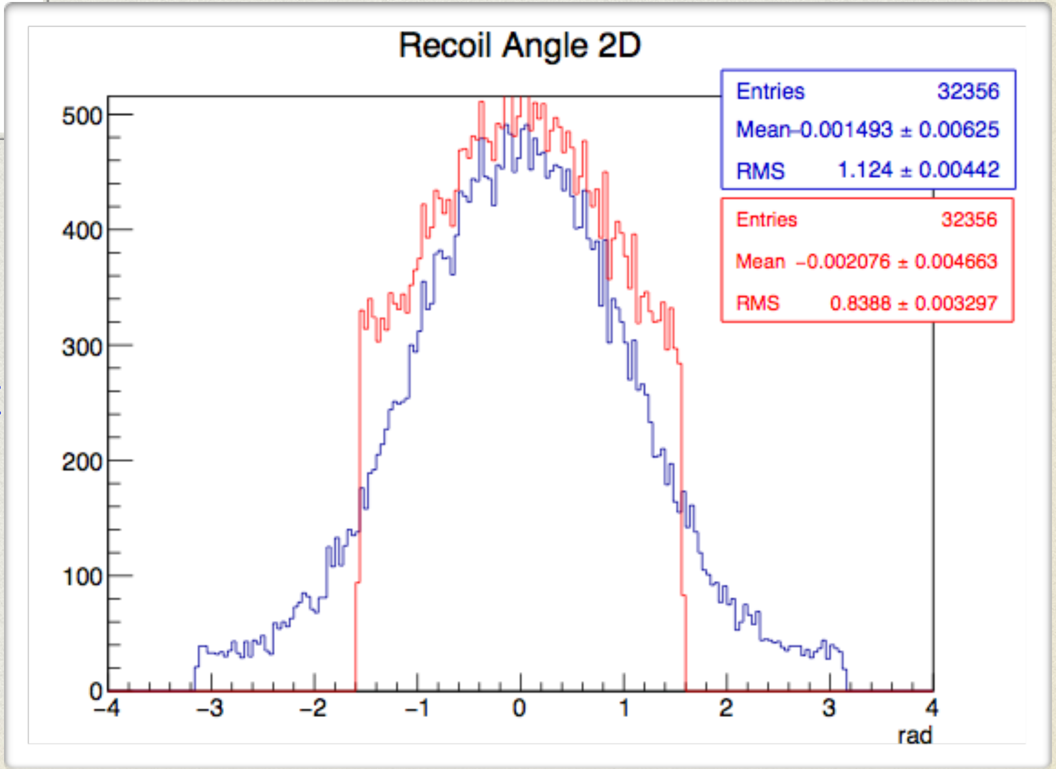
Assume 2D angle

Working on 3D angle measurement

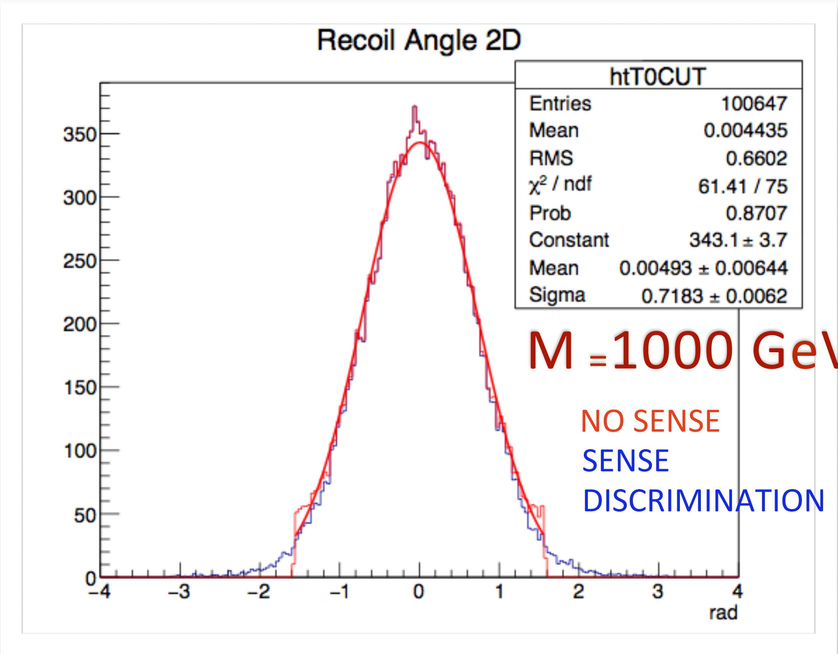


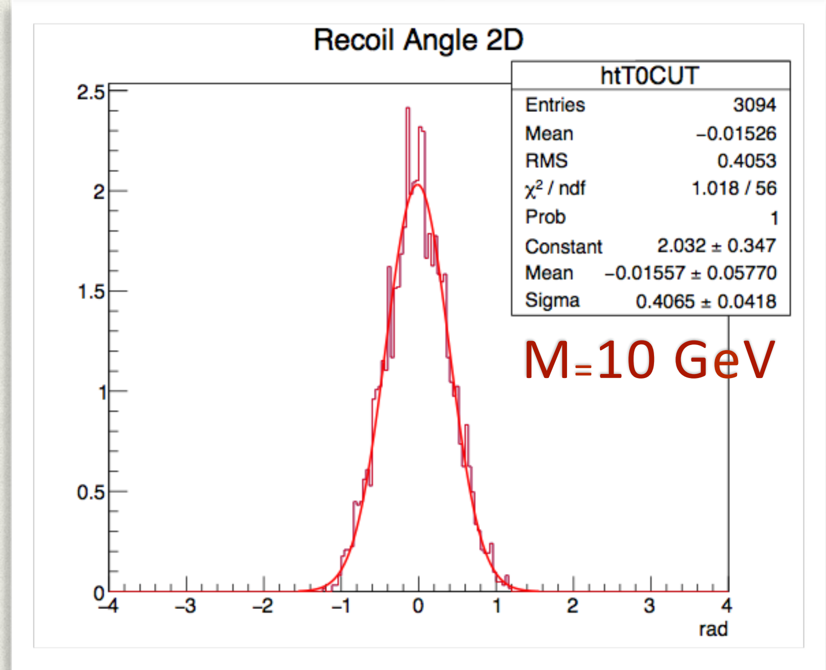
SENSE DISCRIMINATION

NO SENSE DISCRIMINATION



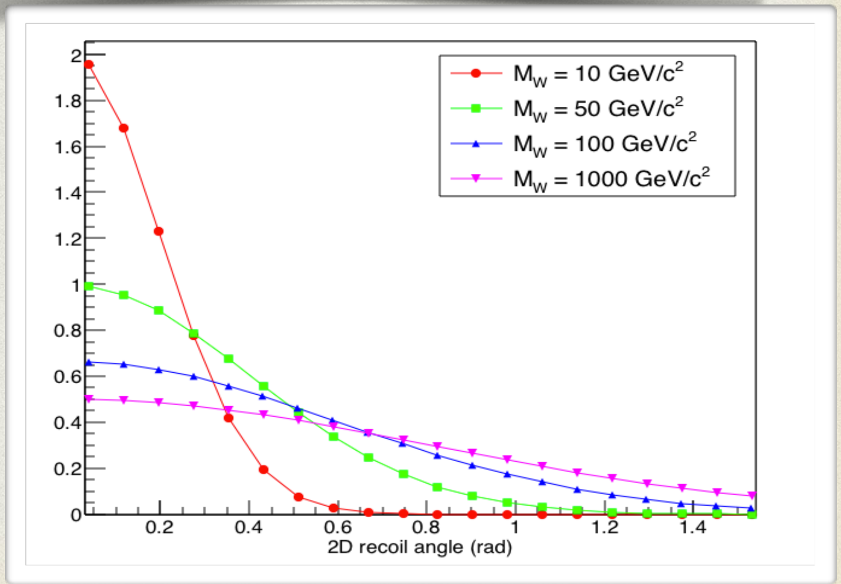
2D RECOIL ANGLE (Threshold: 100 nm)





The directionality depends on the WIMP mass

The lighter the WIMP, the stronger the angular anisotropy



LIKELIHOOD METHOD

expected number of WIMP events

expected number of background events

signal pdf

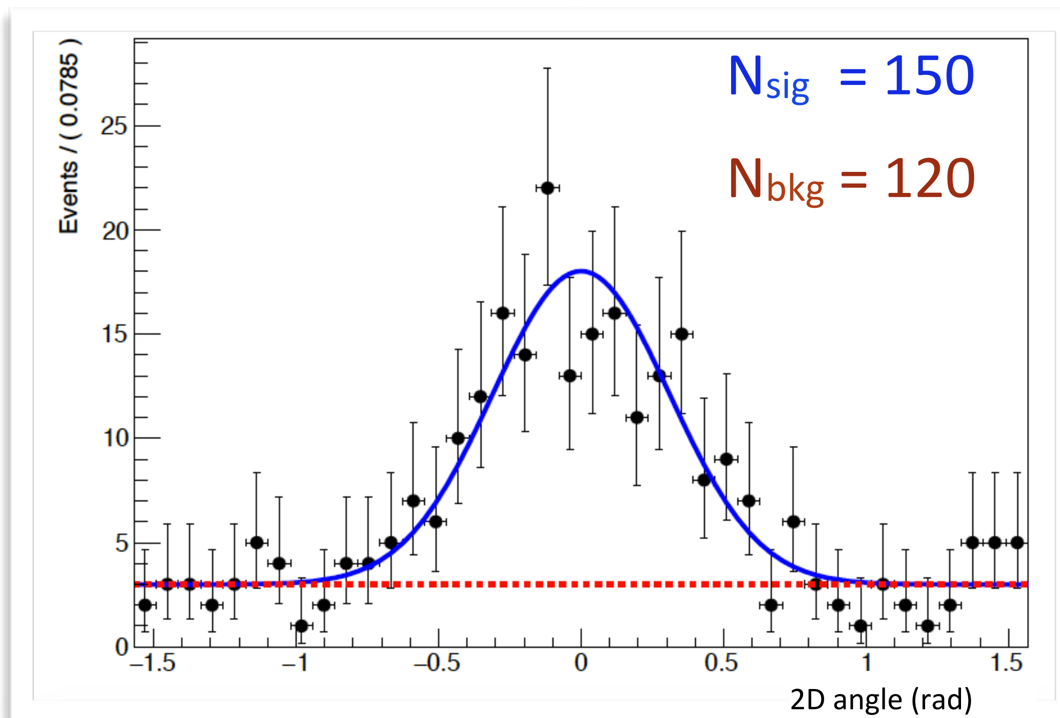
background pdf

$$\mathscr{L}(\sigma_{\chi-n}, R_b) = \frac{(\mu_\chi + \mu_b)^N}{N!} e^{-(\mu_\chi+\mu_b)} \times \prod_{i=1}^{N} [\mu_\chi f_\chi(\vec{q}_i; t_i) + \mu_b f_b(\vec{q}_i)]$$

total number of observed events

set of observables

- Observable: 2D recoil angle
- Signal: Gaussian (sigma dependent on M)
- Background: isotropic

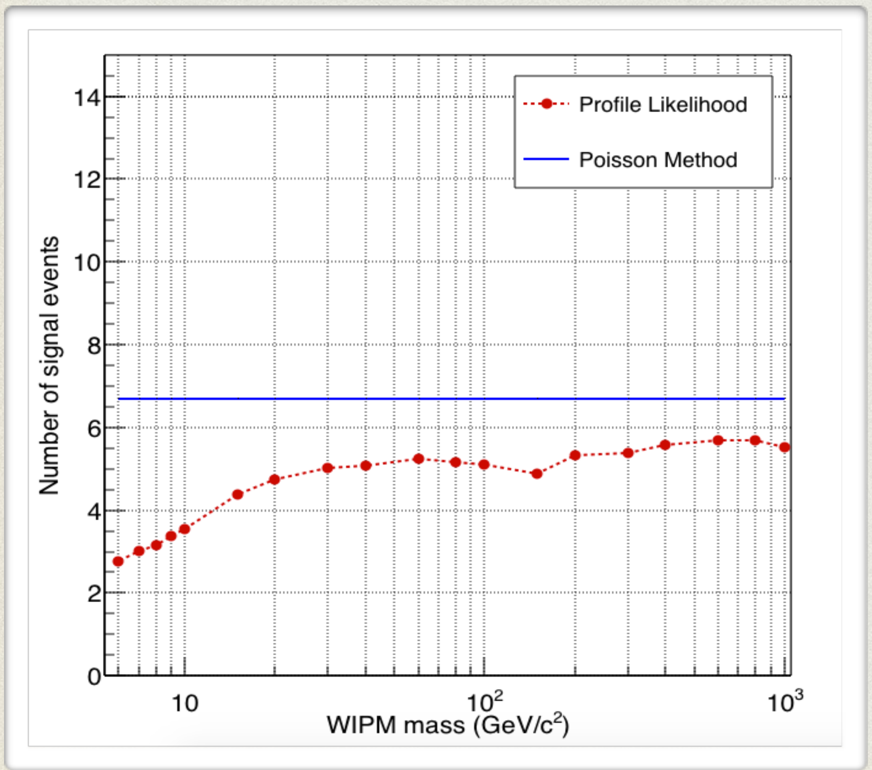


implementation with ROOSTATS libraries (Cern)

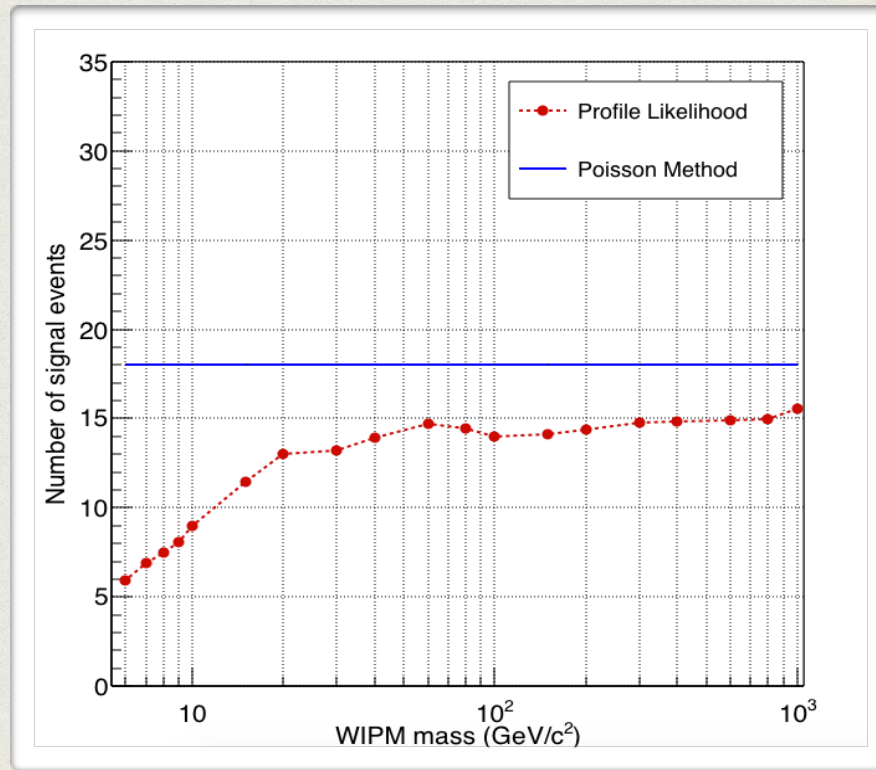
Upper limit on number of signal events

Exposure = 100 kg year
Threshold = 100 nm

- $N_{background} = 10$

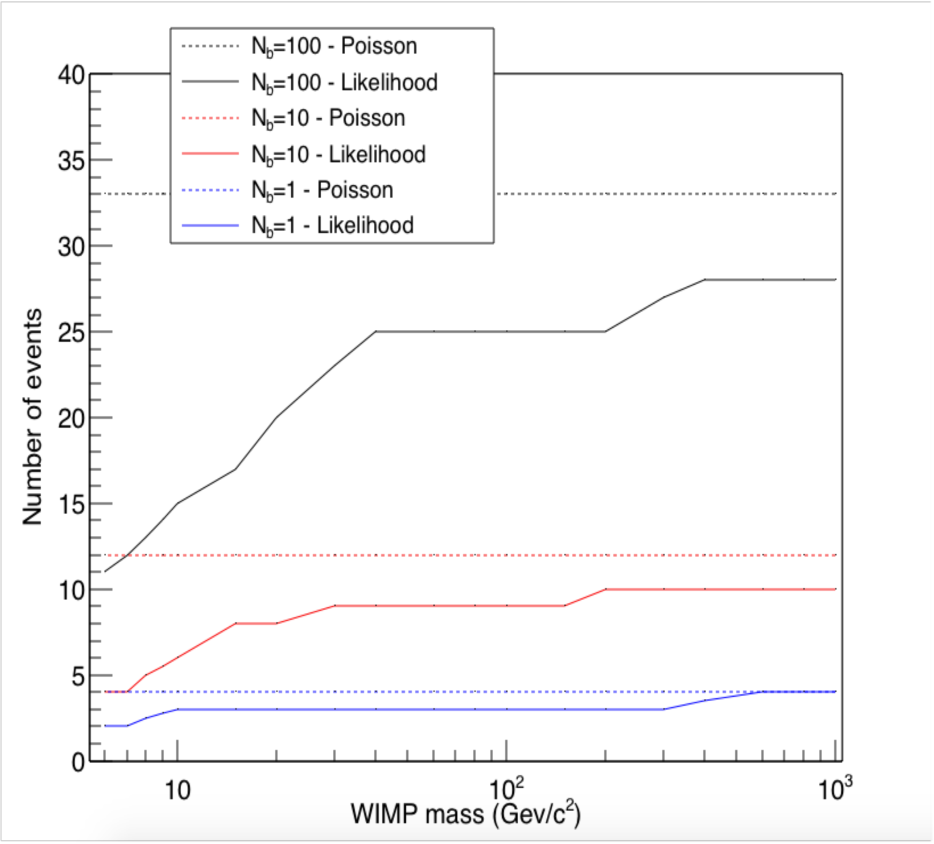


$N_{background} = 100$

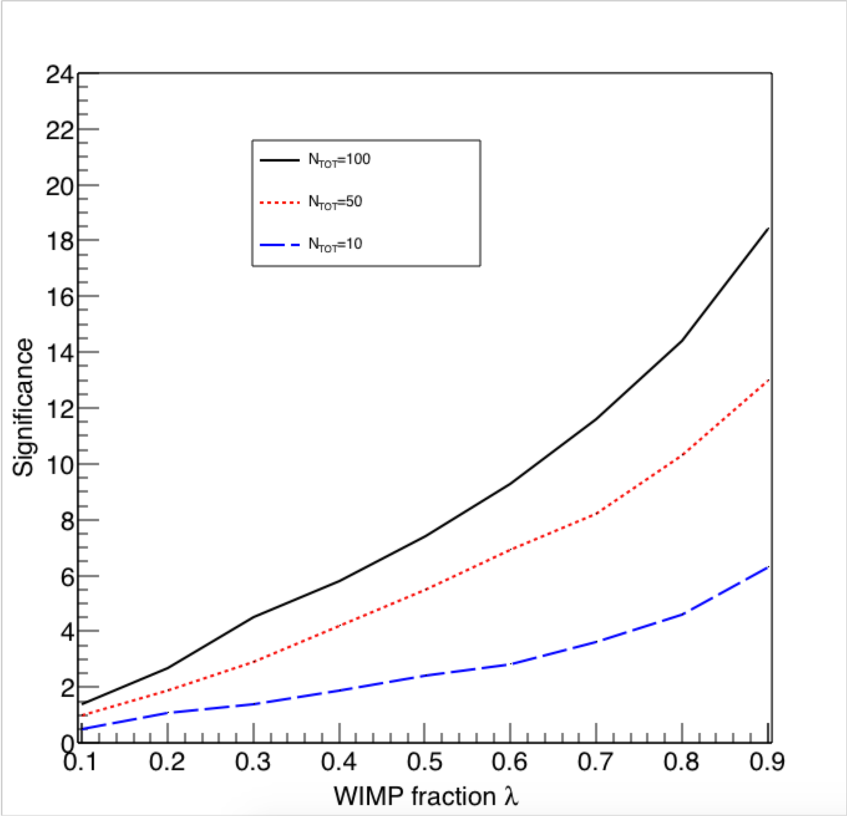


SIGNIFICANCE

- 3 sigma significance

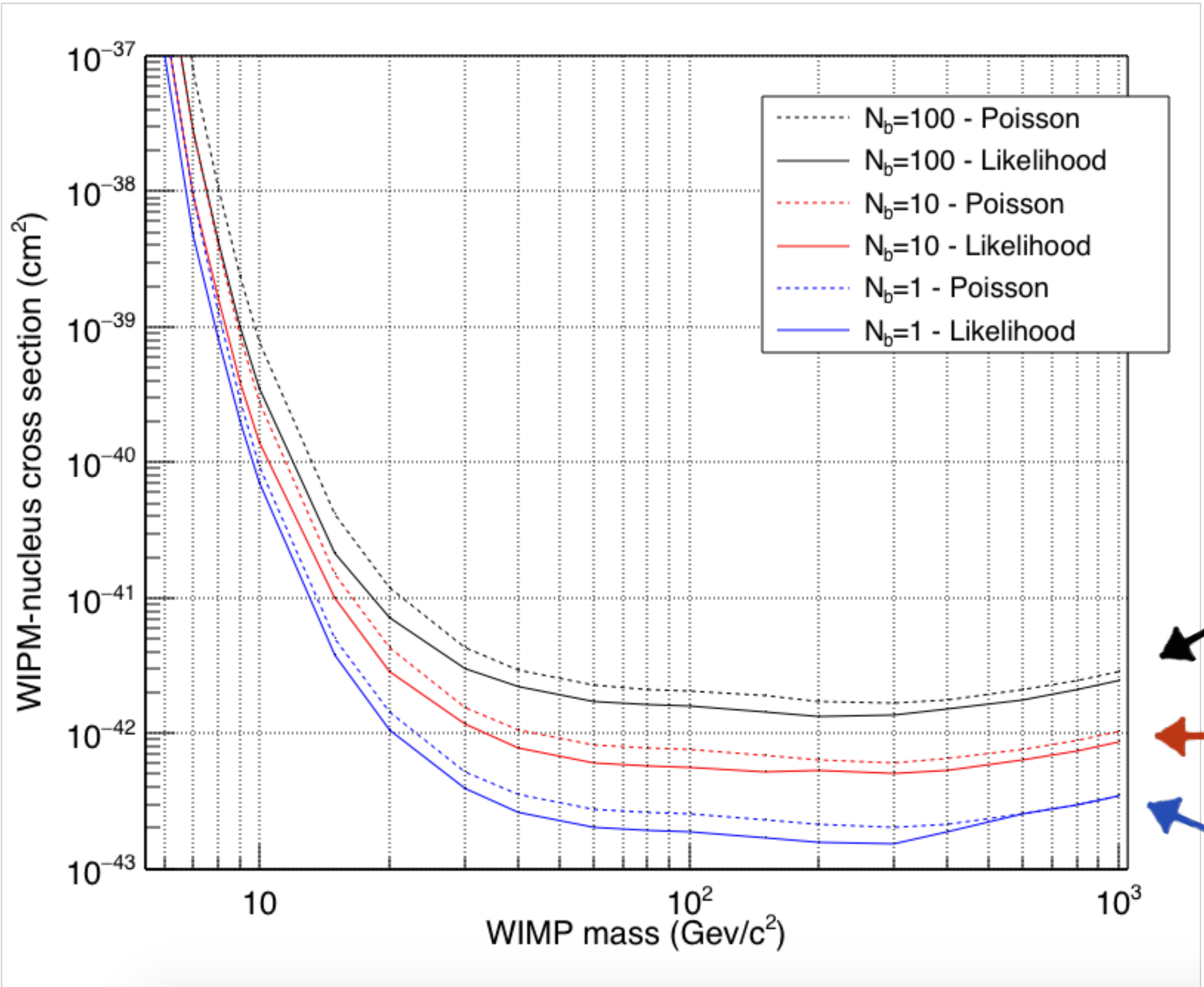


- Effect of signal purity in the data



- $\lambda = N_{sig} / (N_{sig}+N_{bkg})$
- N_{tot} = 10, 50, 100

3σ DISCOVERY REGION



Exposure = 100 kg years

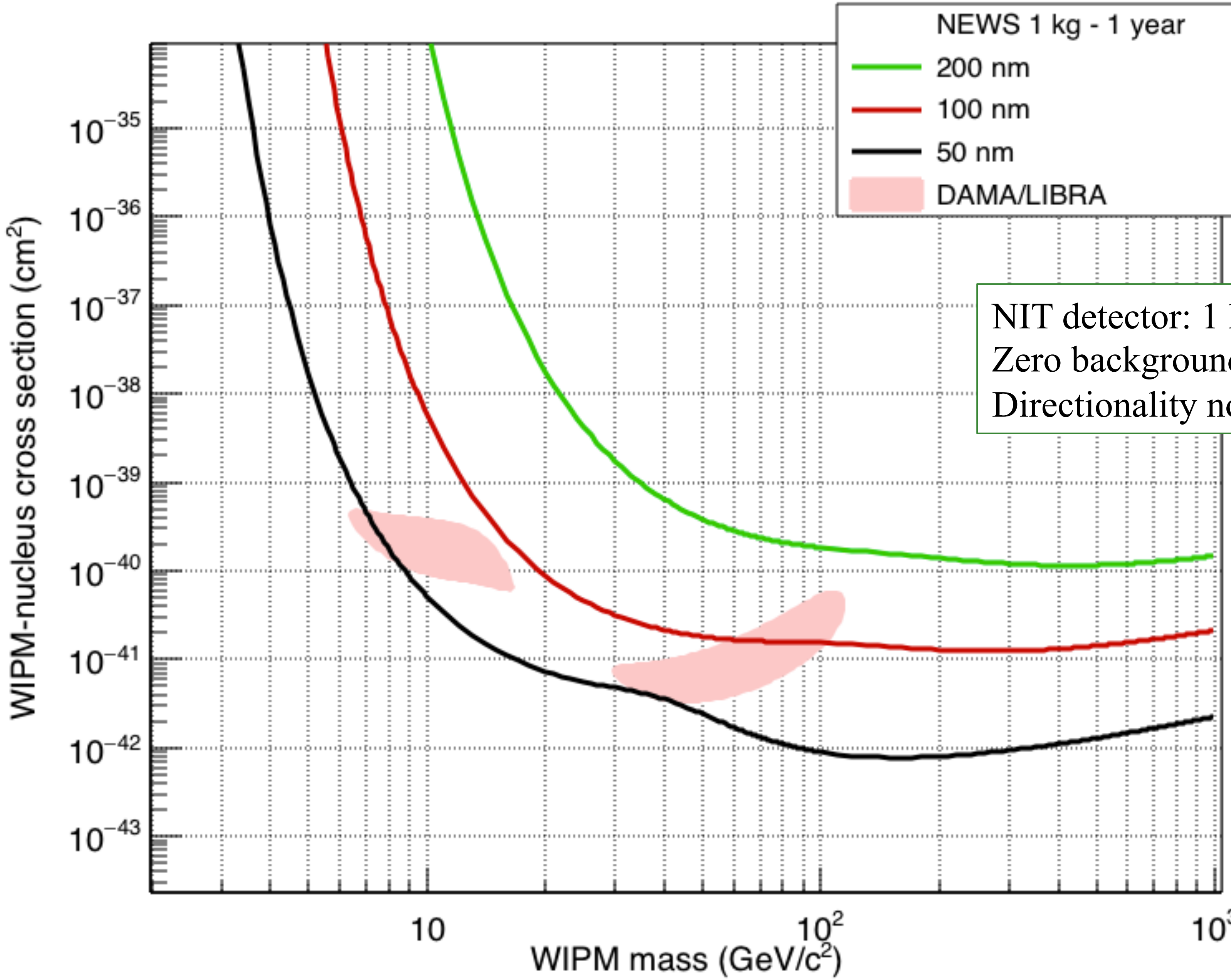
Threshold = 100 nm

N_b=100

N_b=10

N_b=1

SENSITIVITY: THRESHOLD EFFECT



NIT detector: 1 kg year
Zero background
Directionality not included

LNGS-LOI 48/15 UNDER REVIEW BY THE LNGS SCIENTIFIC COMMITTEE

NEWS: Nuclear Emulsions for WIMP Search
Letter of Intent
(NEWS Collaboration)

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Conclusion And Perspectives

- Nuclear emulsions with nanometric grains open the way for a directional dark matter search with high sensitivity
- Breakthrough in readout technologies for optical microscopes are two-fold
  - No need for X-ray confirmation (much faster and convenient)
  - Push the track length threshold down (higher sensitivity)
- Neutron background from intrinsic radioactivity negligible up to ~ 10 kg year
- Prepare a kg scale (pilot) experiment as a demonstrator of the technology and the first spin-independent search of this kind
- Letter of Intent submitted to LNGSC
- INFN funded the R&D phase till the TDR (expected in Summer 2017)
- Funds from JSPS (Japan)