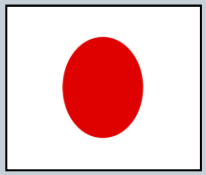
NEWS:
Nuclear Emulsions for Wimp Search

NATALIA DI MARCO
LABORATORI NAZIONALI DEL GRAN SASSO- INFN

ON BEHALF OF THE ***NEWS COLLABORATION***

Italy
- Napoli University "Federico II"
- LNGS – INFN
- Bari University
- Roma University "La Sapienza"

Japan
- Nagoya University
- Chiba University

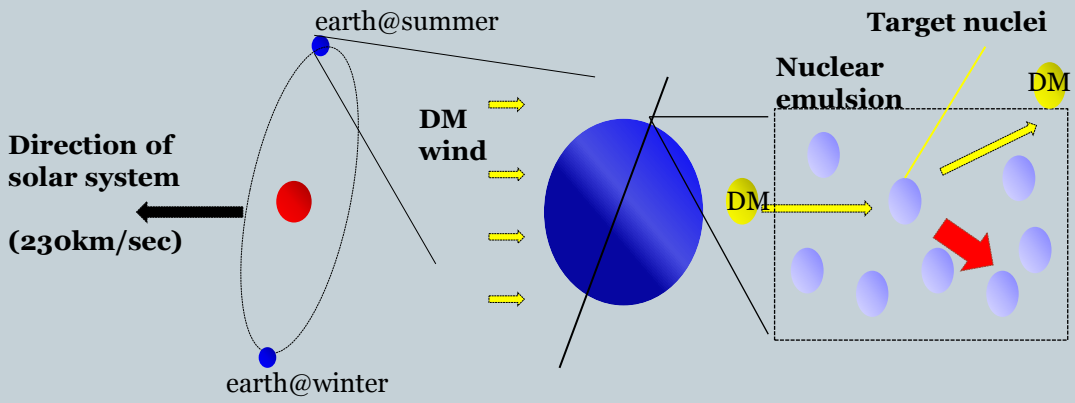


Russia
- JINR Dubna
- Moscow State University
- Lebedev Physical Institute

Turkey
- METU, Ankara

Directional DM searches

D. N. Spergel, Phys. Rev. D37 (1988)

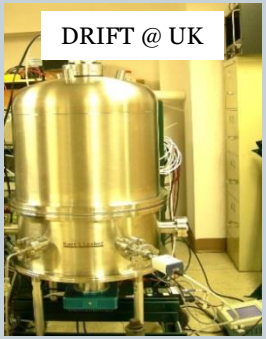


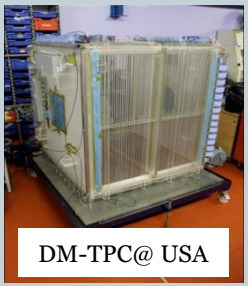
- Solar system movement in the galaxy → WIMP Flux not isotropic @ Earth.
- Directional measurement as a strong signature and unambiguous proof of the galactic DM origin

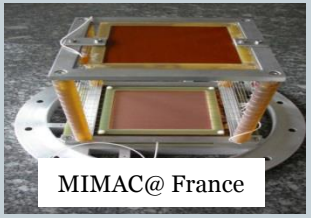
Current approach: low pressure gaseous detector

- Targets: CF_4, CF_4+CS_2, CF_4 + CHF_3
- Recoil track length O(mm)
- Small achievable detector mass due to the low gas density

⇒Sensitivity limited to spin-dependent interaction







The NEWS idea

Use solid target:

- Large detector mass
- Smaller recoil track lenght O(100 nm)

Nuclear Emulsion based detector acting both as target and tracking device

NIT: Nano Imaging Tracker , AgBr crystal size ~ 40 nm

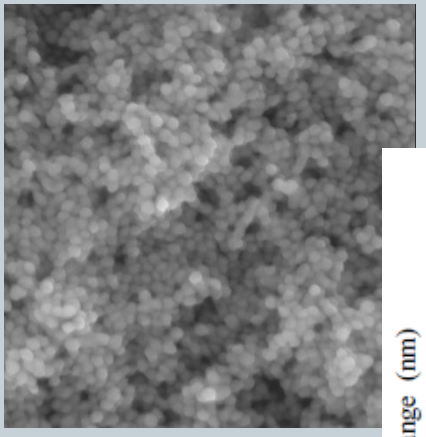
Natsume et al, NIM A575 (2007) 439

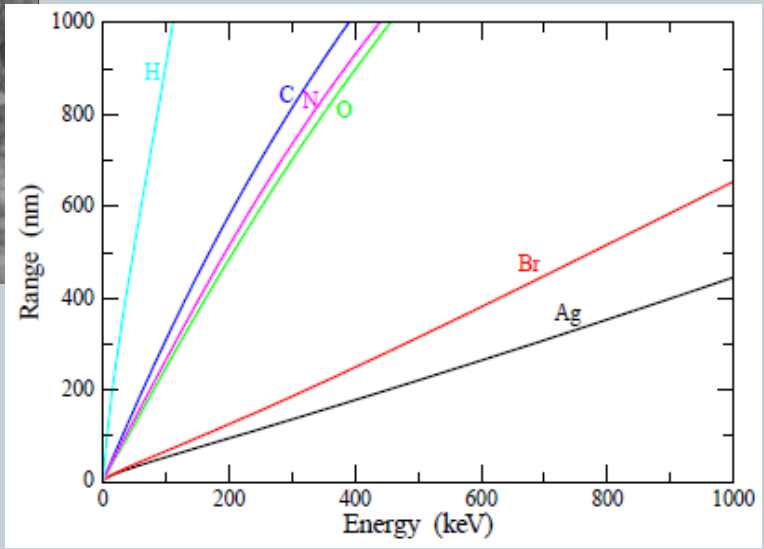
Constituent	Mass Fraction
AgBr-I	0.78
Gelatin	0.17
PVA	0.05

(a) Constituents of nuclear emulsion

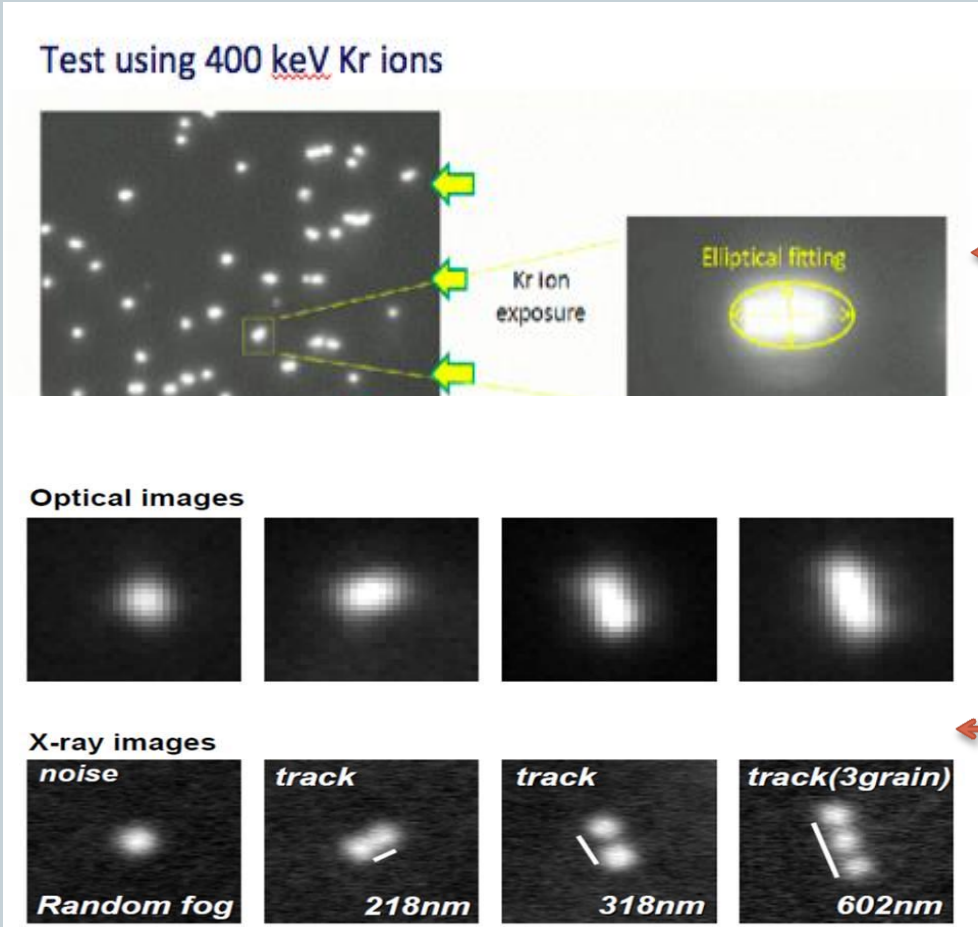
Element	Mass Fraction	Atomic Fraction
Ag	0.44	0.12
Br	0.32	0.12
I	0.019	0.003
C	0.101	0.172
O	0.074	0.129
N	0.027	0.057
H	0.016	0.396
S	0.003	0.003

(b) Elemental composition



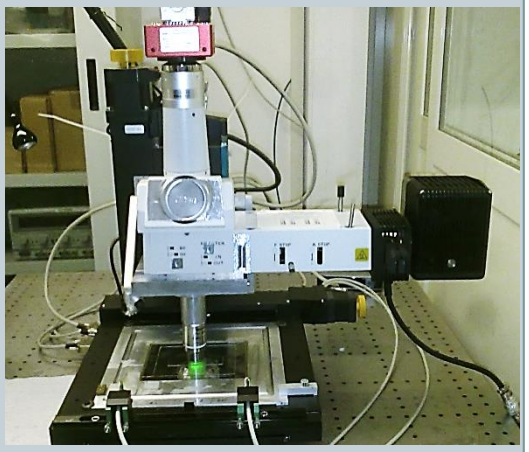


Read-out of submicrometric tracks



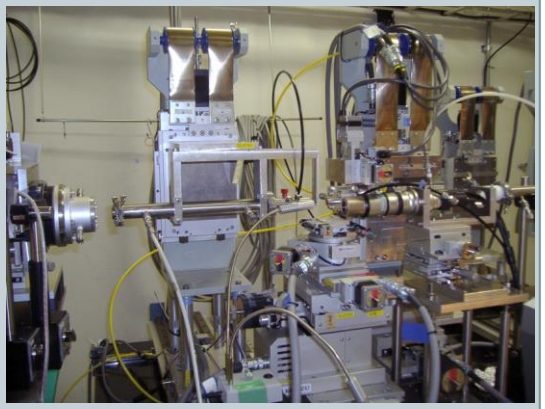
1) Signal preselection

Resolution: 200 nm
Speed: ~20 mm²/h



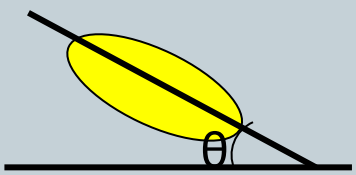
2) Signal confirmation

Resolution: 30 nm
Speed:
~ (200μm)²/100 s

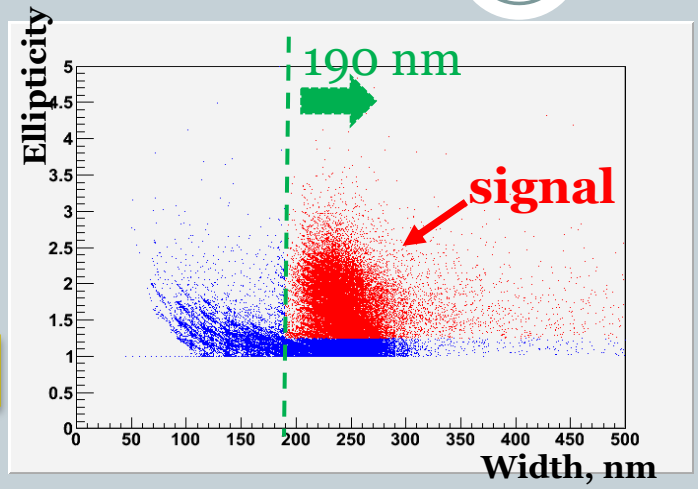


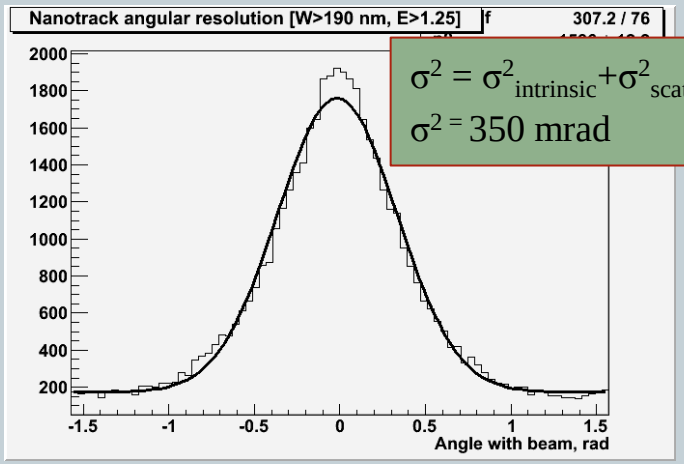
Read-out of submicrometric tracks

80 keV C ions



Direction detected!

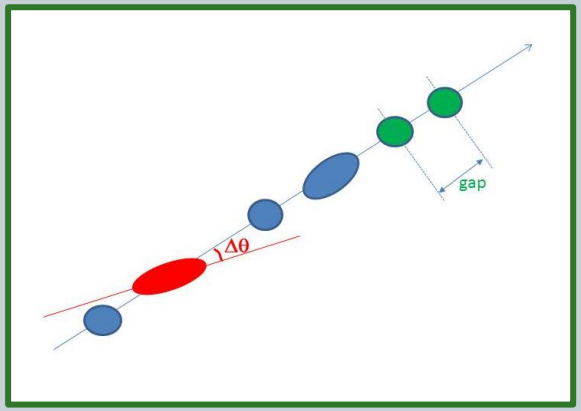


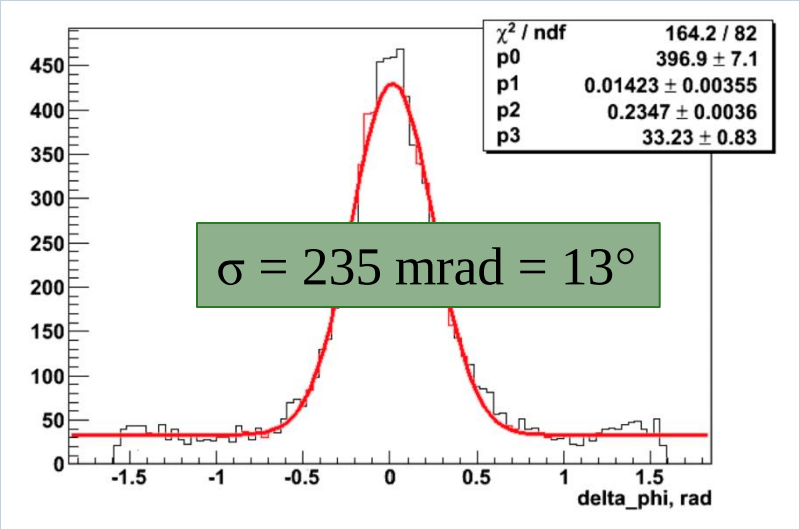


$\sigma^2 = \sigma^2_{intrinsic} + \sigma^2_{scattering}$

$\sigma^2 = 350$ mrad

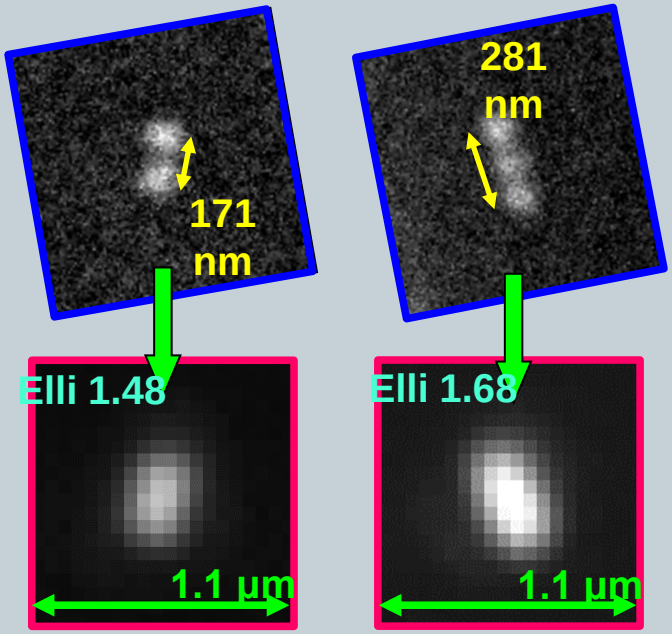
Neutron test Beam

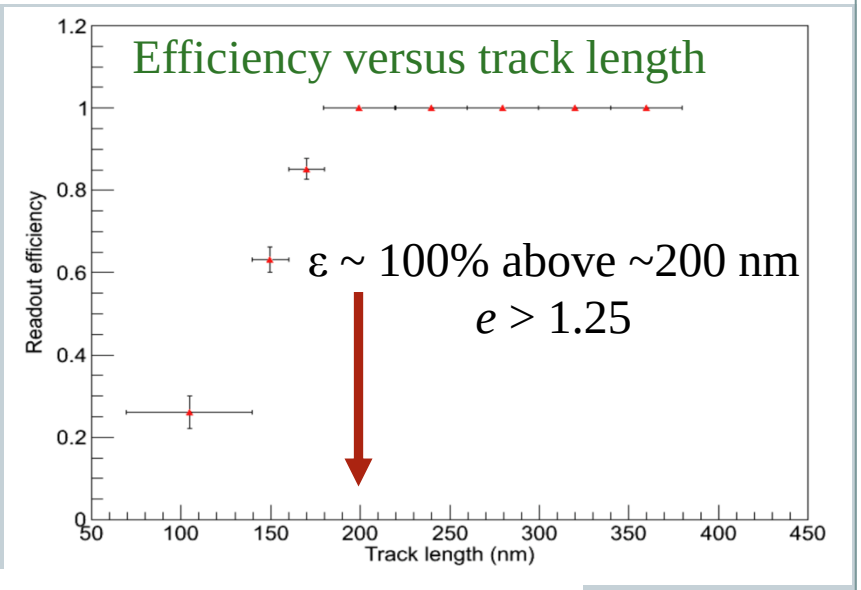


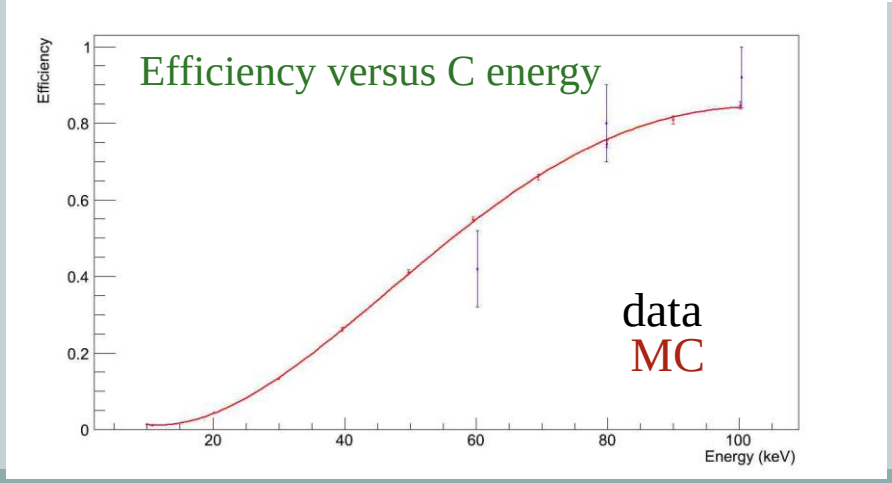


$\sigma = 235$ mrad $= 13°$

Read-out of submicrometric tracks

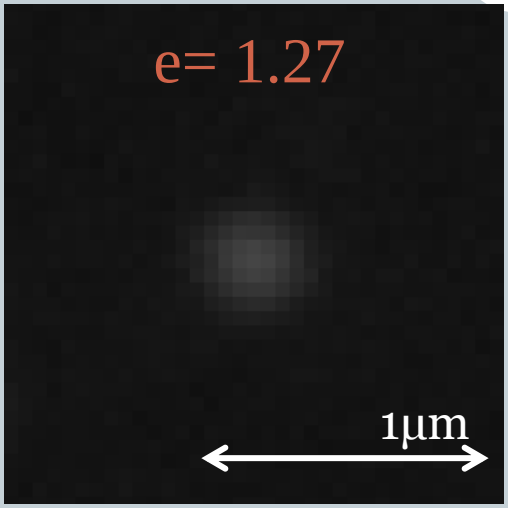


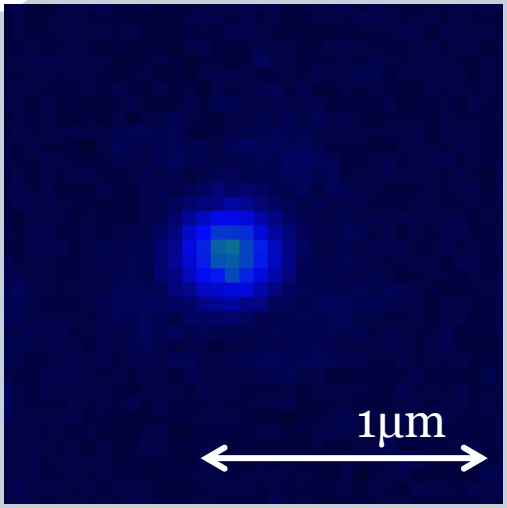




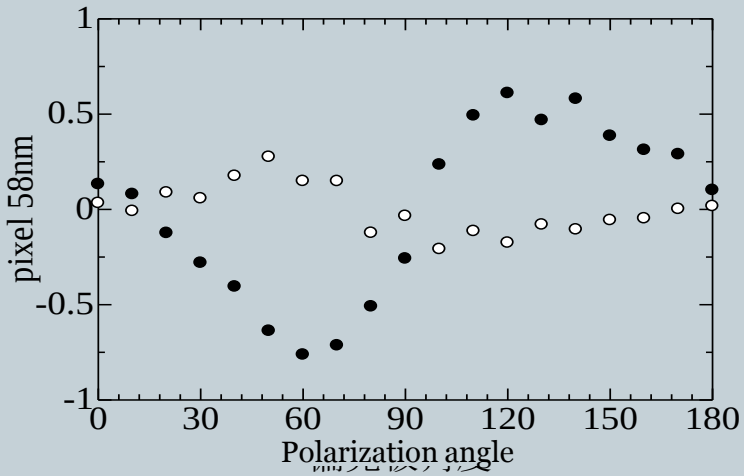
Read-out of submicrometric tracks

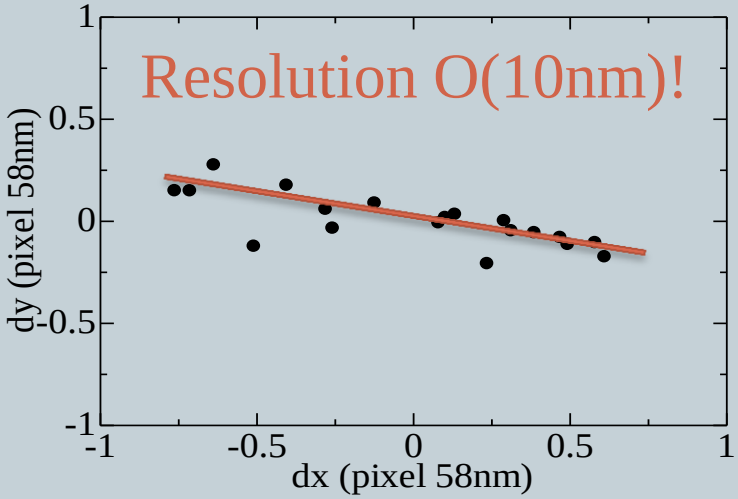
1) Signal preselection: optical microscope + shape analysis





2) Signal confirmation: optical microscope + polarized light





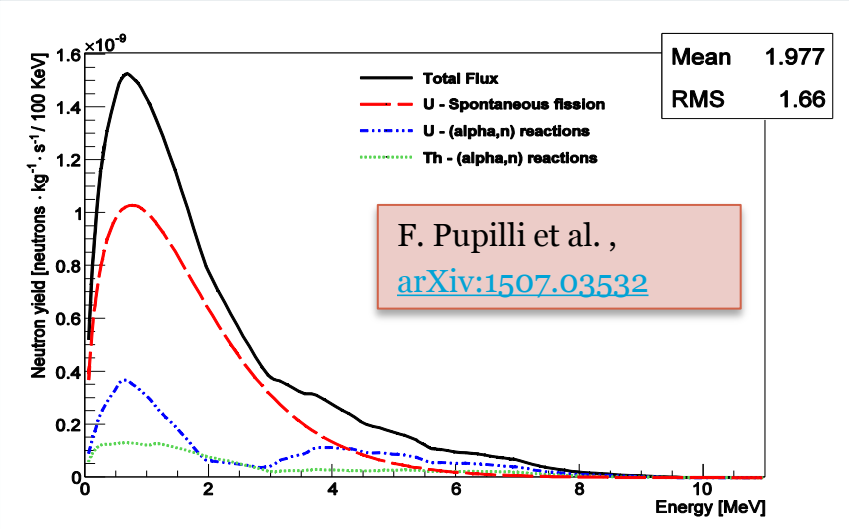
Expected Background

- Environmental radioactivity
- Radon and its progeny
- Cosmic rays
- Neutrons from natural fission, (a,n) reactions and from cosmic ray muon spallation and capture
- Radioimpurities in detector or shielding components

Intrinsic Neutron Yield

Intrinsic radioactive contaminant contribution have been estimated @LNGS using:

1. Inductively Coupled Plasma Mass Spectrometry (ICP-MS) (Chemistry Service)
2. g-spectrometry with Ge detector @ STELLA Facility (SubTErranean Low Level Assay)



Threshold [nm]	Fraction
50	0.100
100	0.075
150	0.060
200	0.052

Table 6: Fraction of detectable neutron-induced recoils as a function of the read-out threshold.

Activity measured with ICP-MS:
^{238}U: 23±7 mBq/kg
^{232}Th: 5.1±1.5 mBq/kg

SOURCES-based simulation:
1.2 n/kg/year

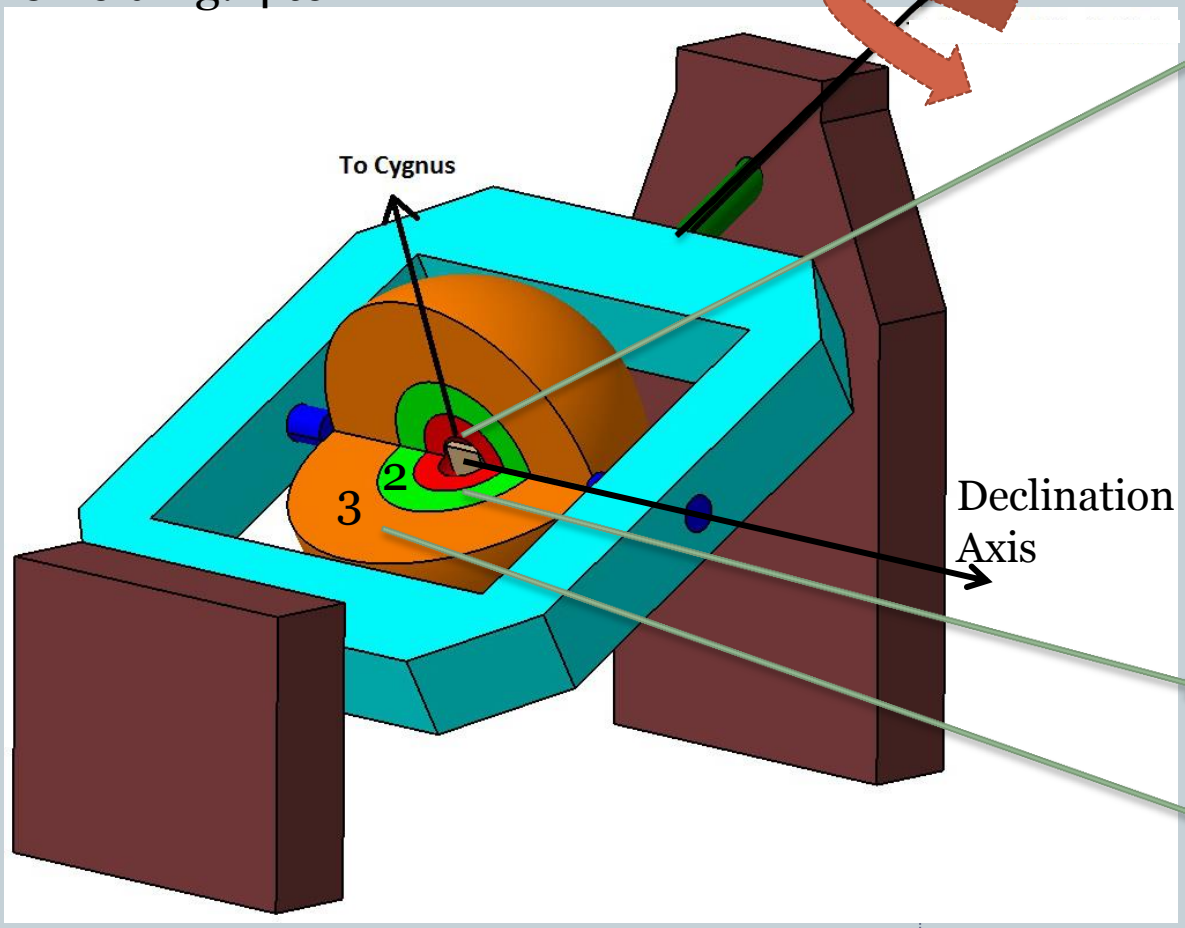
G4-based MC:
20.4% of neutrons interact producing nuclear (56%), proton (44%) and a (0.2%) recoils

Cut on the track lenght:

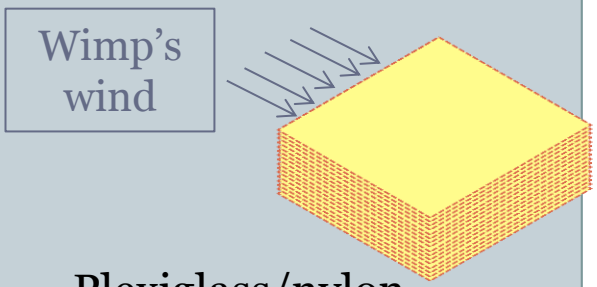
- 5%÷10% of the intrinsic neutron flux contributes to the background
- A further reduction of 70% can be achieved exploiting the directionality information (-1 <F < 1) → **0.02 ÷ 0.03 n/year/Kg**

Experimental Set-UP

Target: 1 Kg of NIT
Shielding: 4 ton



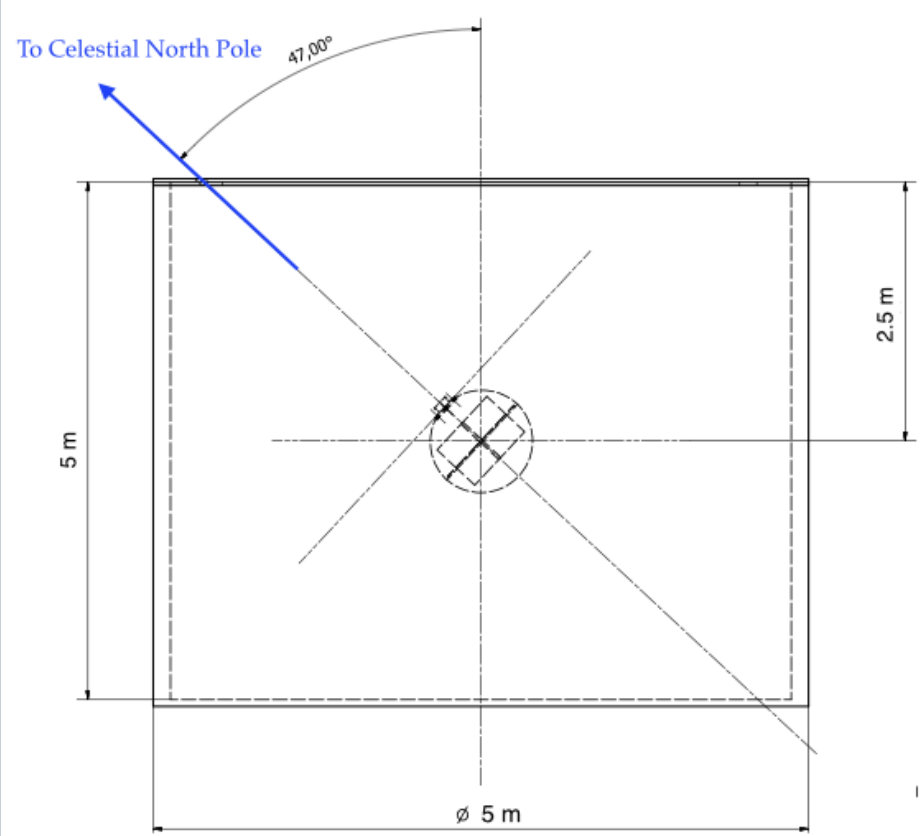
1. Internal phere: 30 cm diameter, holding the target.
   1 kg: 100, 50 μm thick, NIT films
   25 x 25 x 0.5 cm^3
   + OPERA-like films

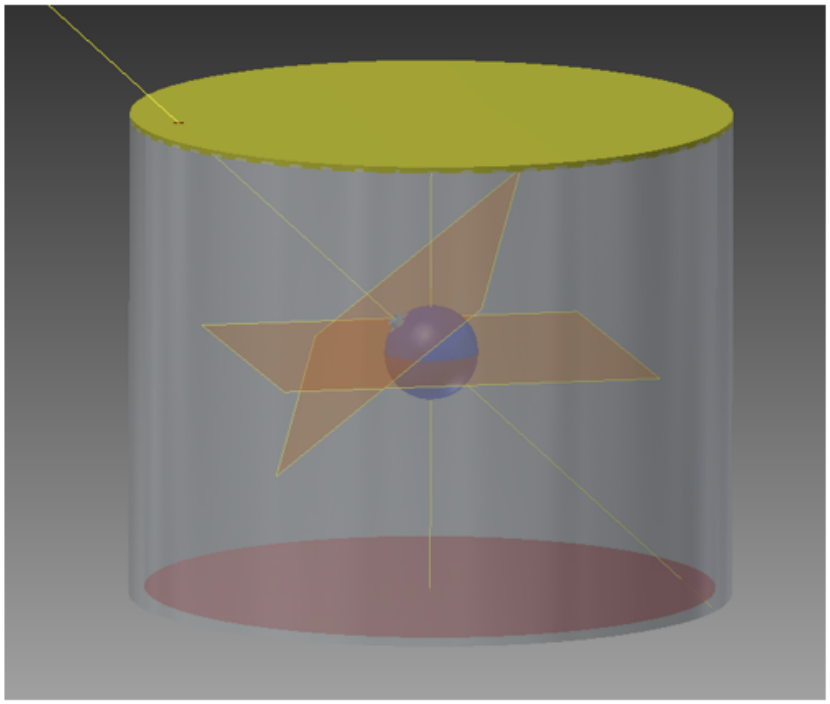


1. Plexiglass/nylon sphere: sealed from air and flushed with HP N_2
2. External sphere: 50 cm thick PE shielding

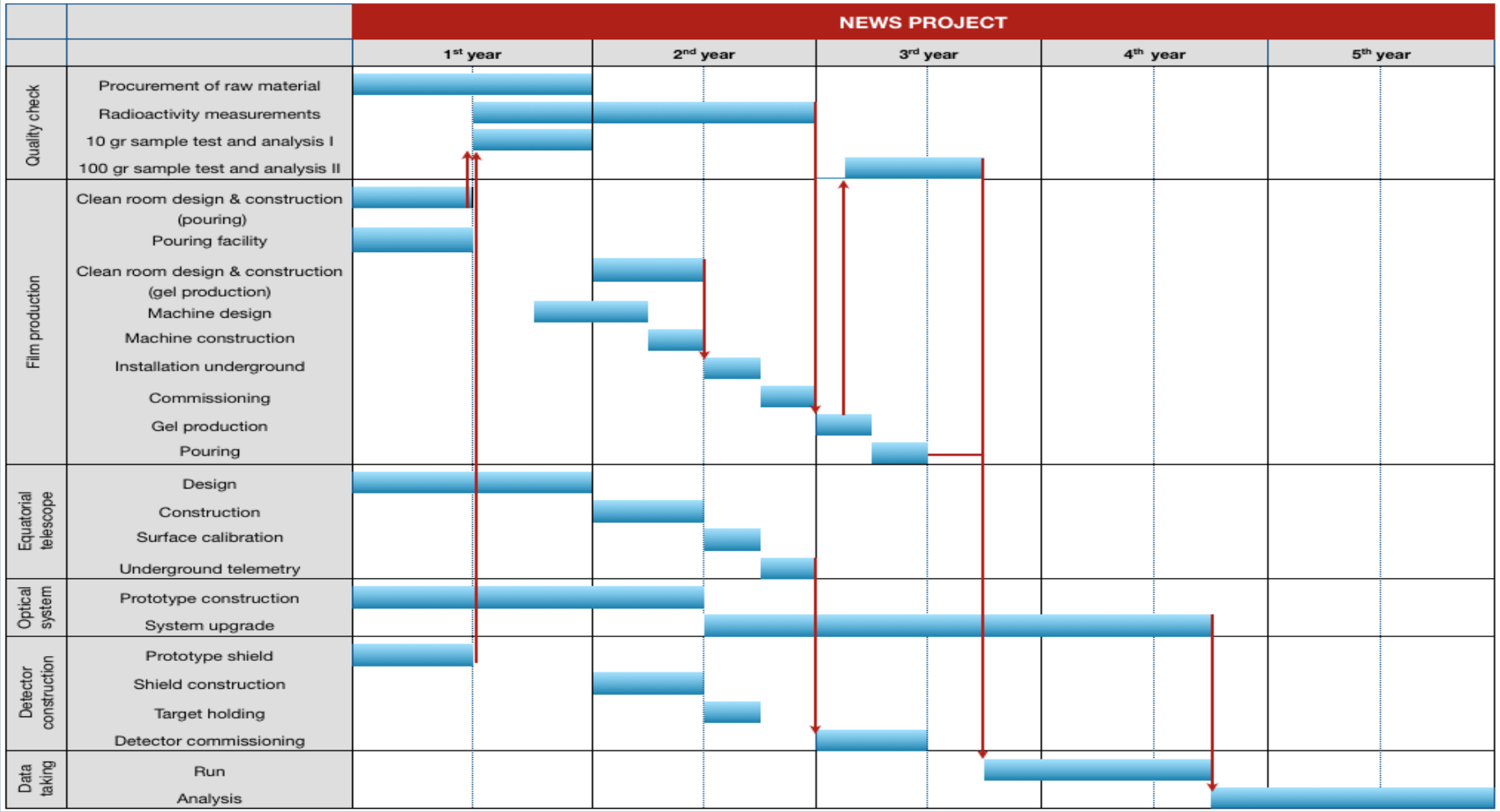
Experimental Set-UP

- Water Option

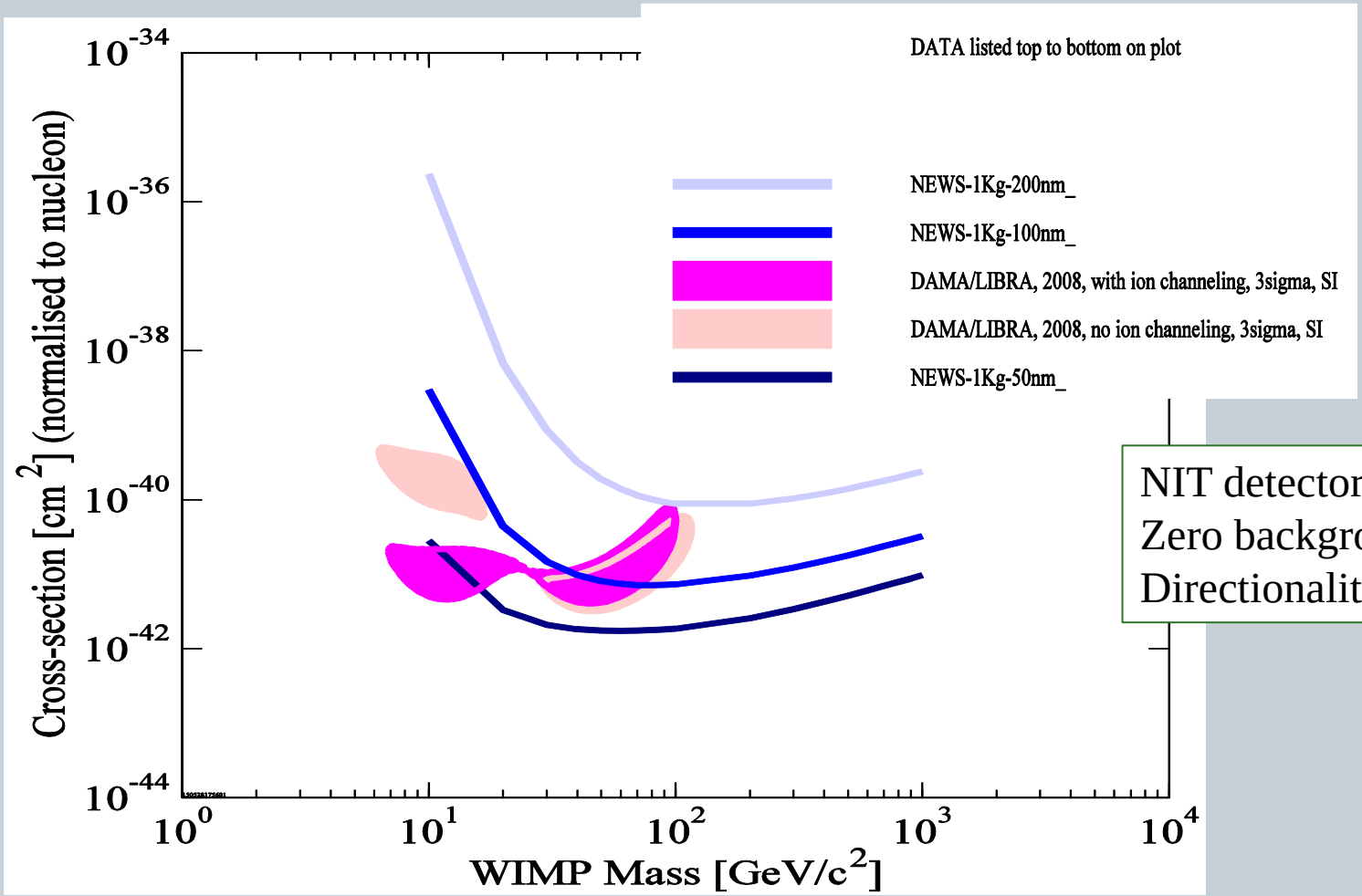




Schedule for 1 Kg Pilot Experiment



Physics Reach



NIT detector: 1 kg x 1 year
Zero background hypothesis
Directionality not included

Conclusions

A novel approach for **directional Dark Matter searches** is proposed in NEWS

- ✓ Novel nuclear emulsion technique with nanometric spatial resolution
- ✓ The use of a solid target would allow to explore the low cross section sector in the phase space indicated by recent direct search experiments but using a complementary an powerful approach
- ✓ Breakthrough in optical microscope readout technologies
- ✓ Current level of neutron background from intrinsic radioactivity allows the design of ~ 10 kg detector
- ✓ Prepare a kg scale (pilot) experiment soon (2018) as a demonstrator of the technology and the first spin-independent search of this kind
- ✓ Letter of Intent submitted to INFN

Thanks for your attention!

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

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55 physicists

backup

Directional DM searches

Depending on the unknown WIMP-nucleon cross section, directional detection may be used to : exclude Dark Matter, discover galactic Dark Matter with a high significance or constrain WIMP and halo properties.

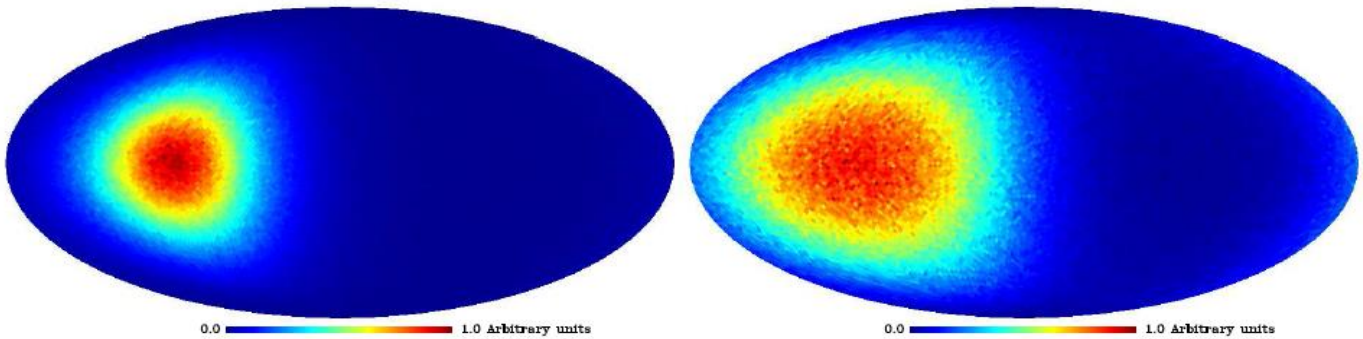
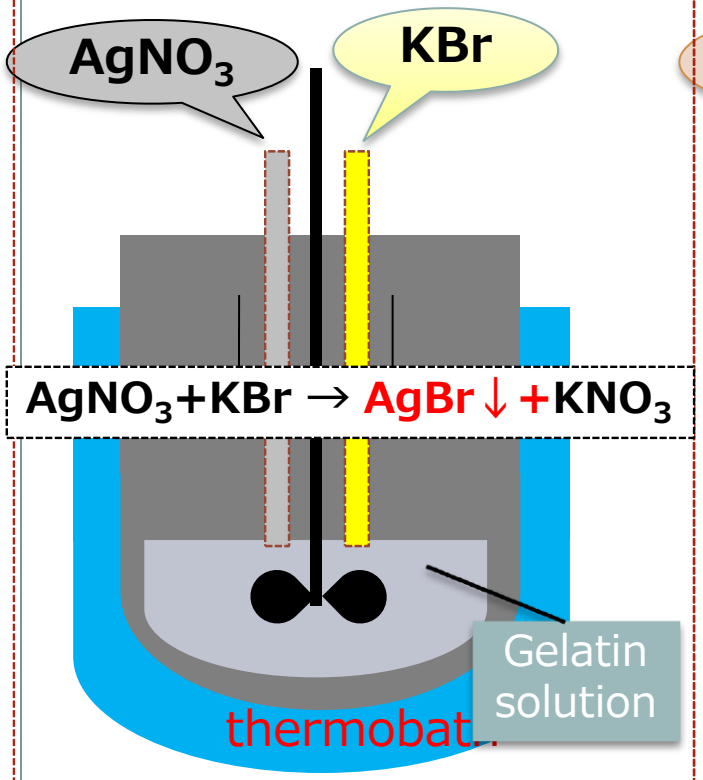


Figure 1. (Left) : WIMP flux for an isothermal spherical halo. (Right) WIMP-induced recoil distribution. Recoils maps are produced for a ^{19}F target, a 100 GeV.c^{-2} WIMP and considering recoil energies in the range 5 keV $\leq E_R \leq$ 50 keV. Figures extracted from [12].

F. Mayet, J.Phys.Conf.Ser. 469 (2013) 012013

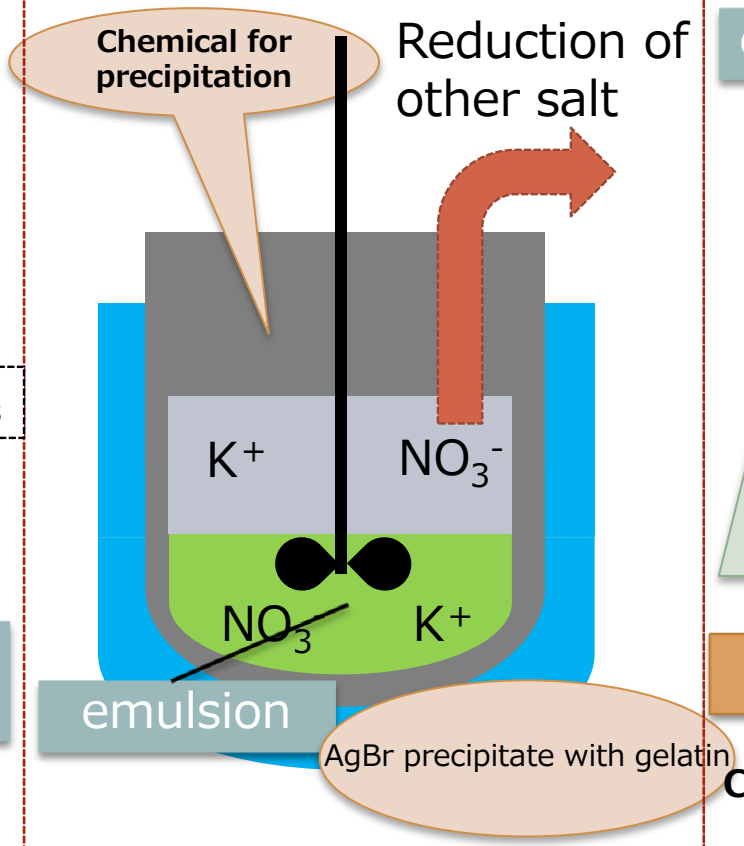
Production Process

Crystal formation

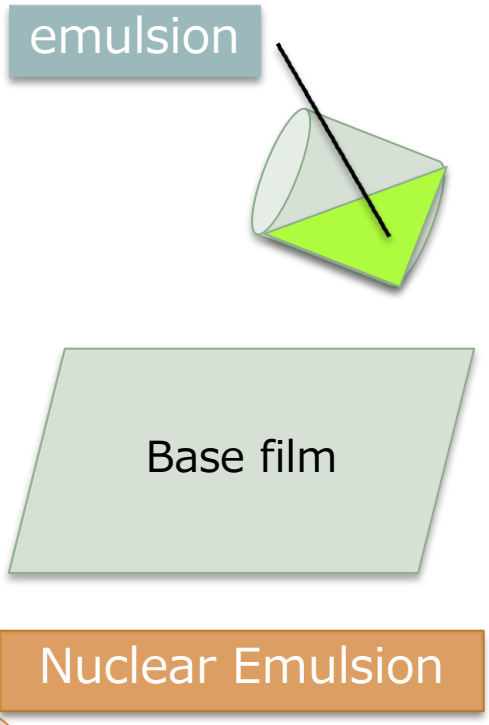


Control the AgBr crystal size
Temperature, insertion speed
Concentration of chemical, pAg control, rotation speed
etc.

wash/salt reduction



Apply



Control of dry condition

Temperature, humidity, Thickness etc.

PRODUCTION IN NAGOYA

Emulsion Production

Addition of $AgNO_3$ and NaBr

$AgNO_3 + NaBr \rightarrow AgBr + NaNO_3$

control of AgBr crystal size, density

Desalination

Reduction of Na^+, NO_3^-

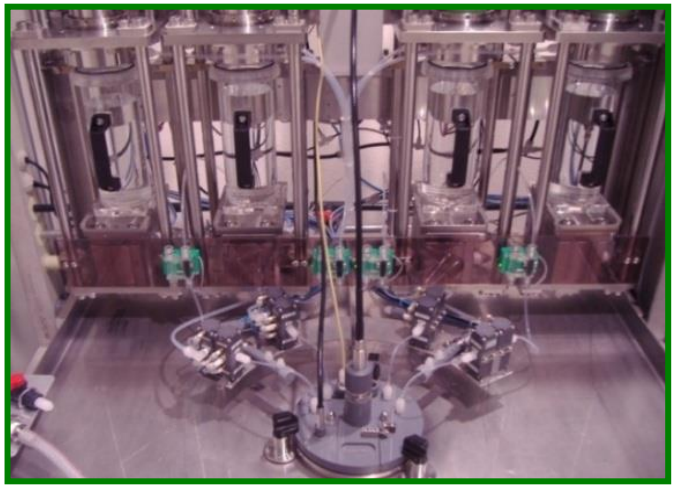
Sensitization

Au+ S sensitization

→tuning of the sensitivity

(grains/microns at given dE/dx)

Nuclear Emulsion Production

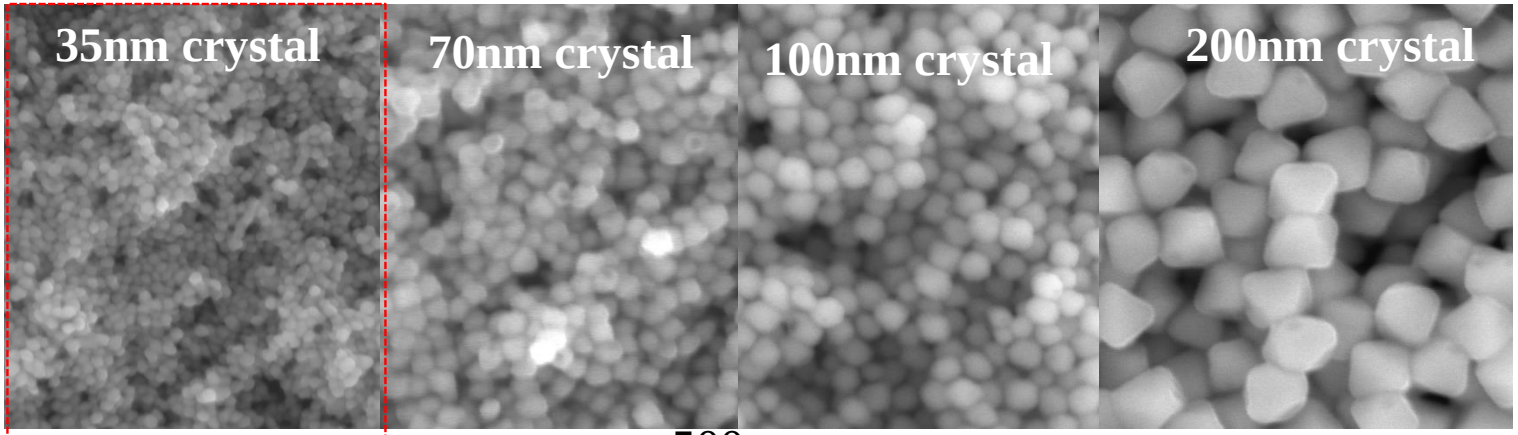


Mr. Kuwabara
FujiFilm Engineer

Production time: 4h ~100g/batch
⇒ ~1 kg/week detector production

For dark matter

Natsume et al, NIM A575 (2007) 439

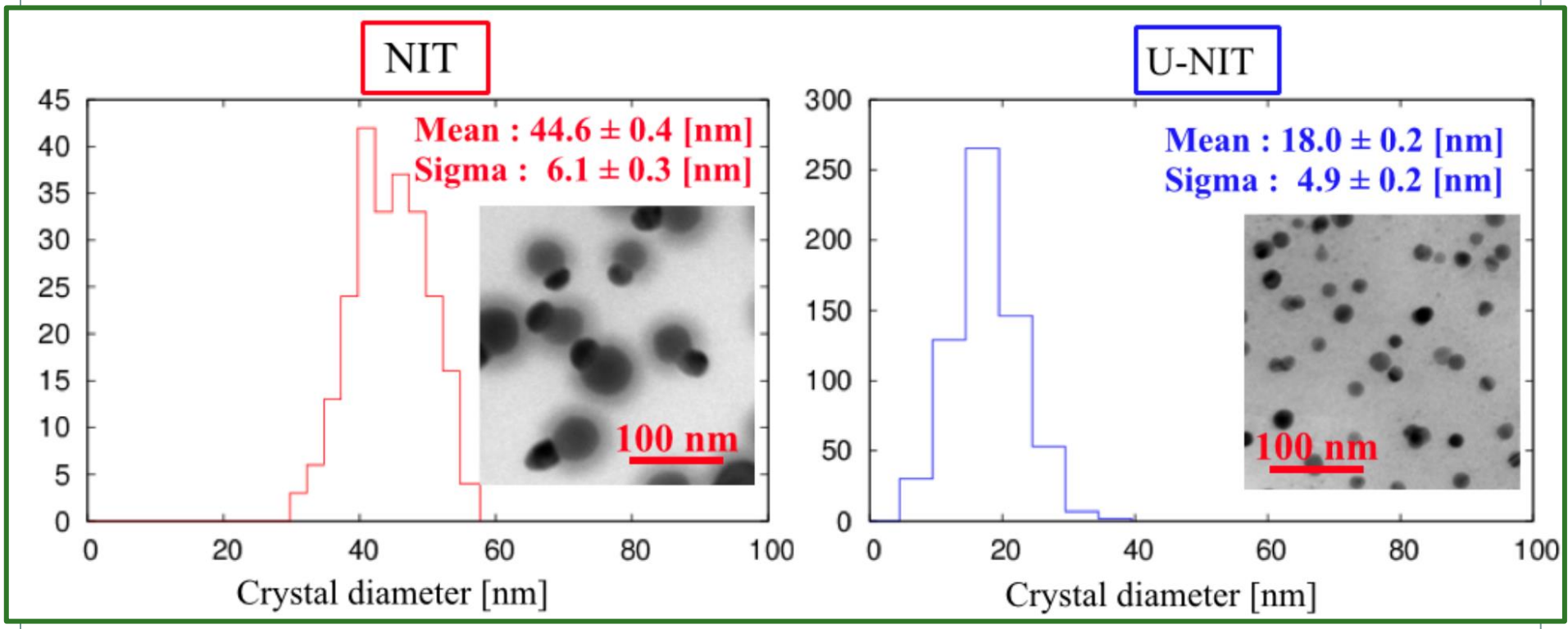


500nm

Size

R&D

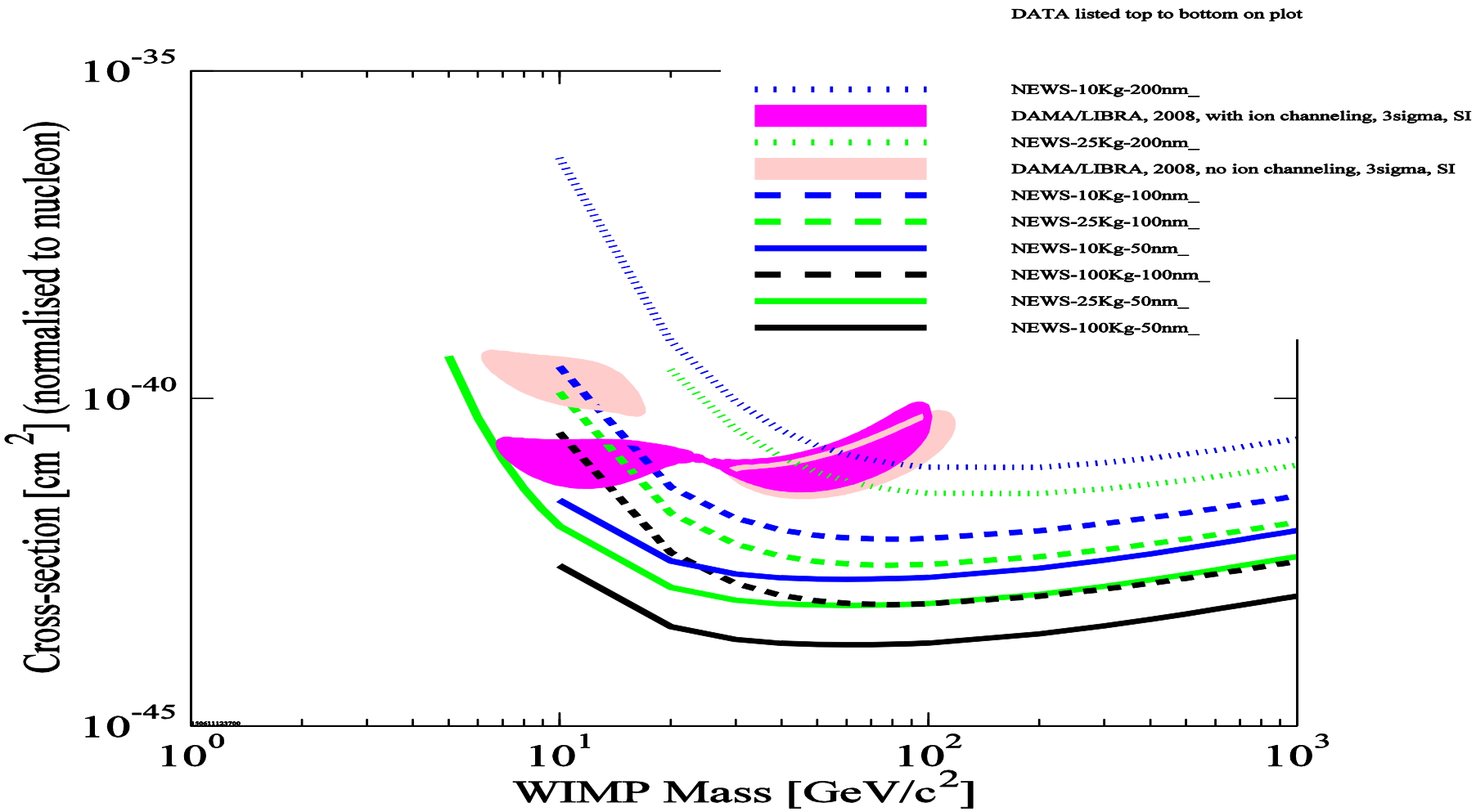
ULTRA-NANO IMAGING TRACKER



	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

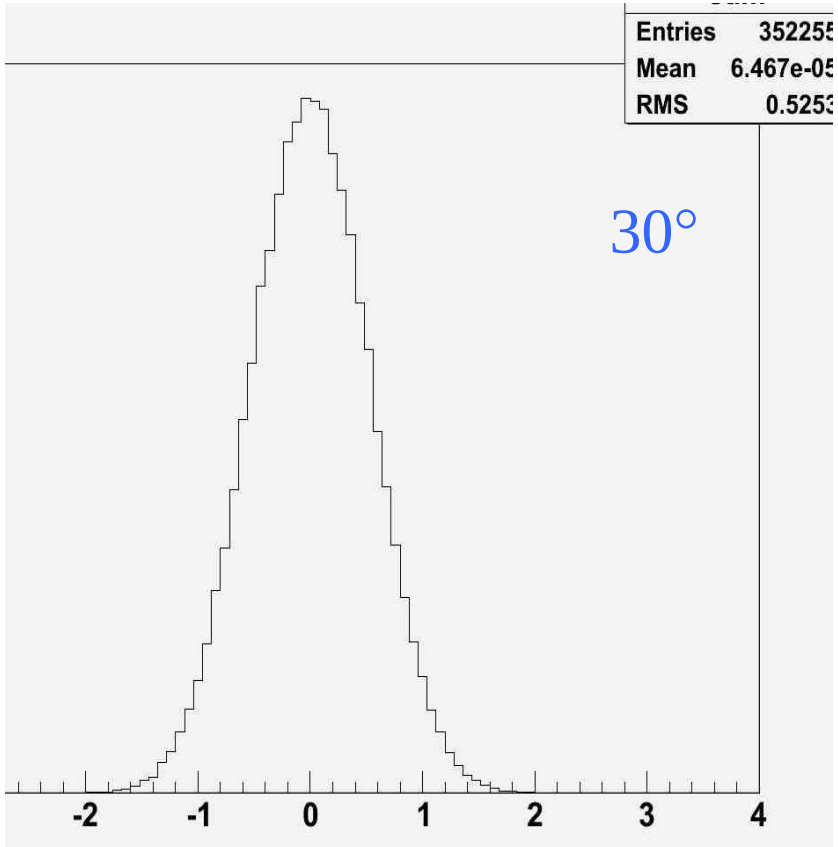
Physics Reach



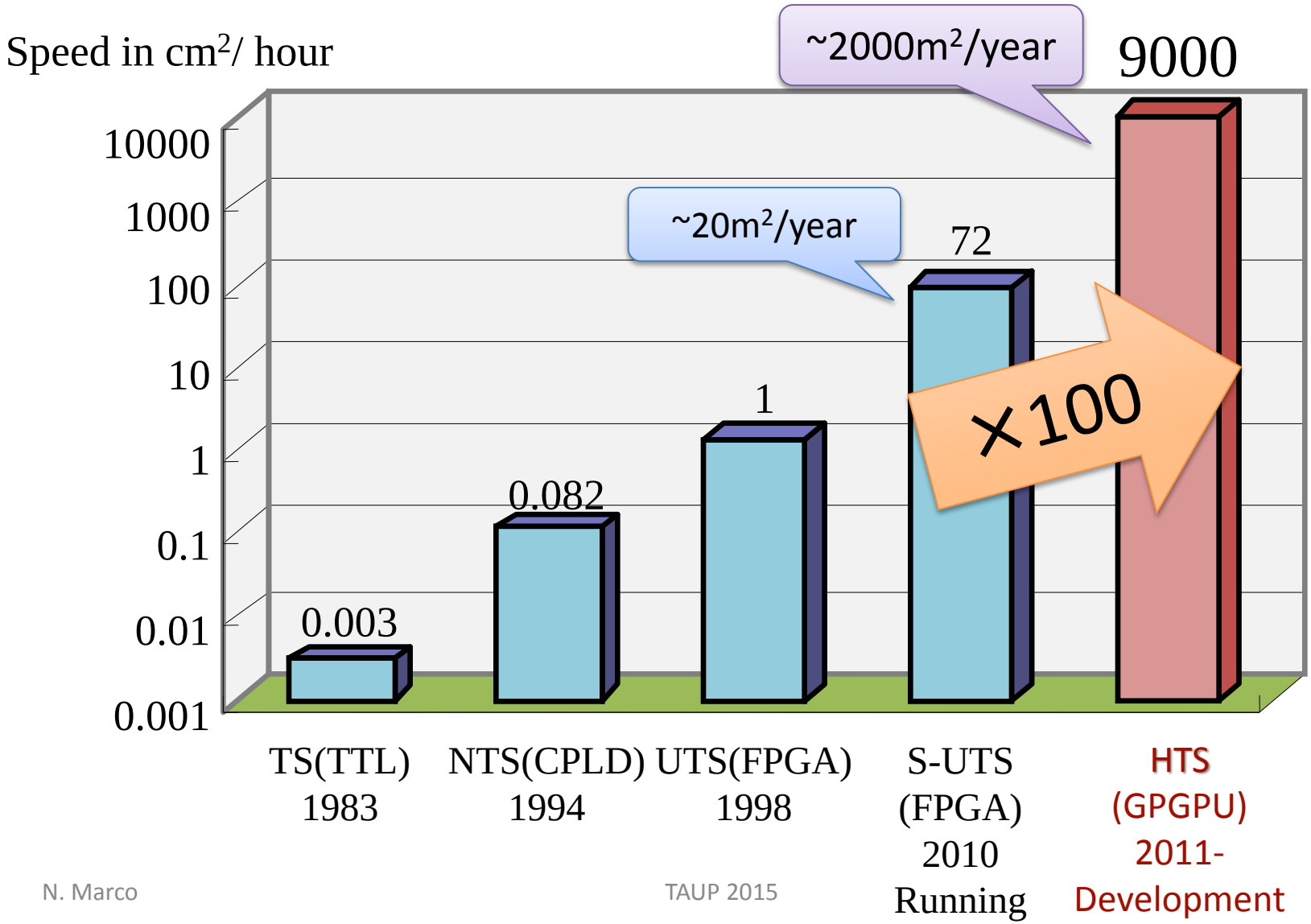
Expected angular distribution

example with M = 25 GeV

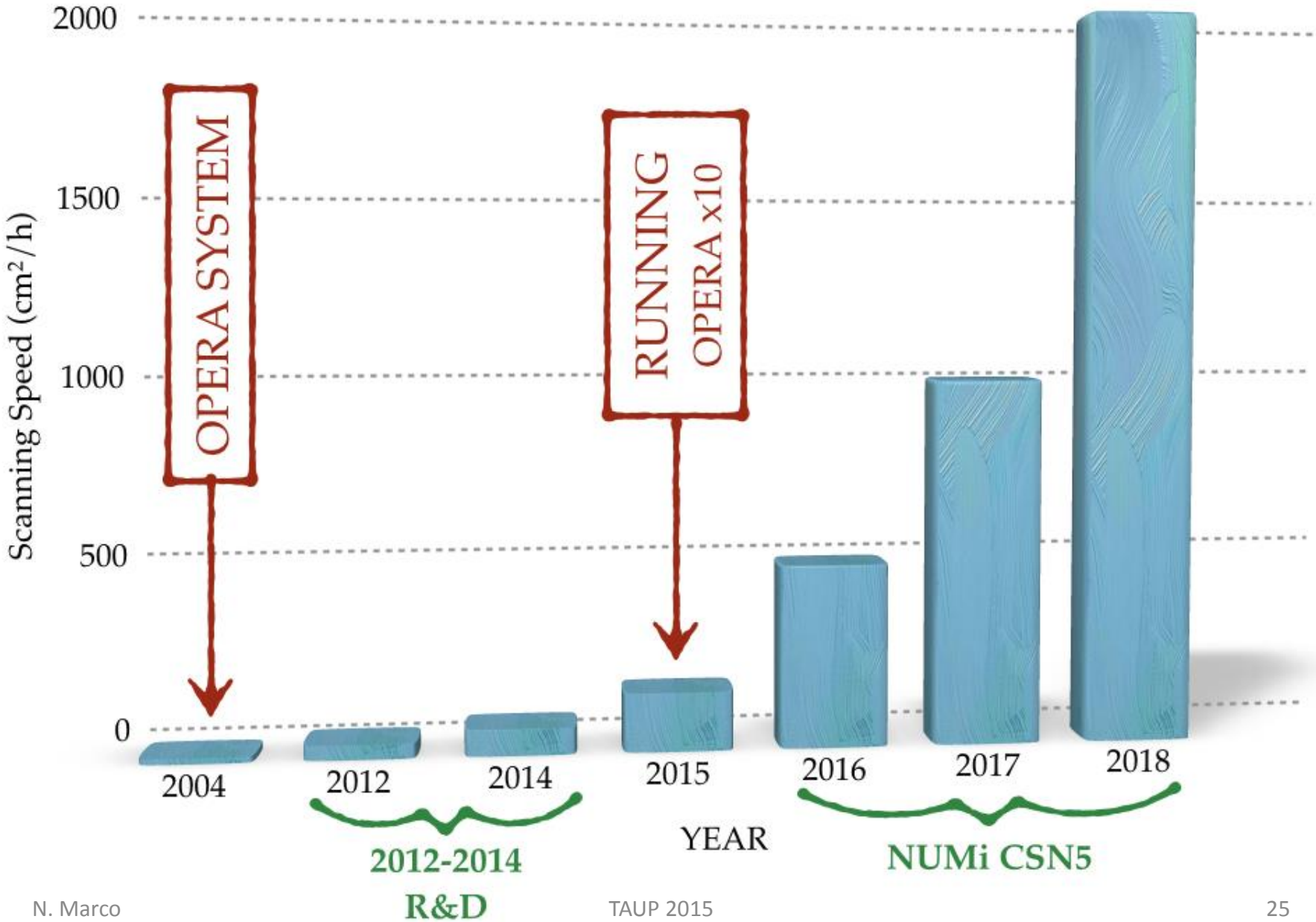
- Range > 150 nm



Evolution of the scanning speed

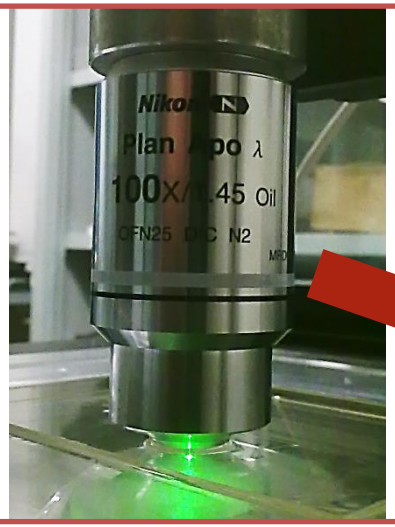


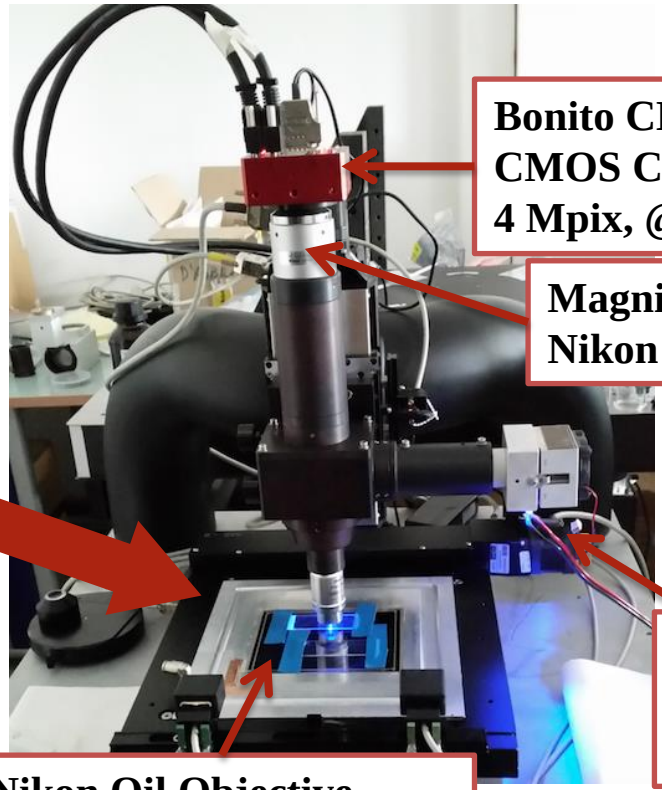
TECHNOLOGY DEVELOPMENT @ INFN



Optical Microscope Read-out: Step 1

100x objective lens with high N.A.





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

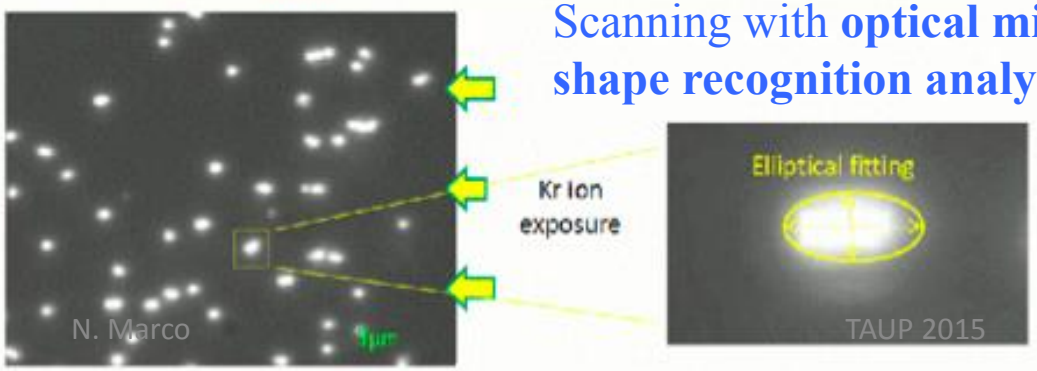
Magnifying lens, Nikon VM C-2.5x

100W Halogen Lamp

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

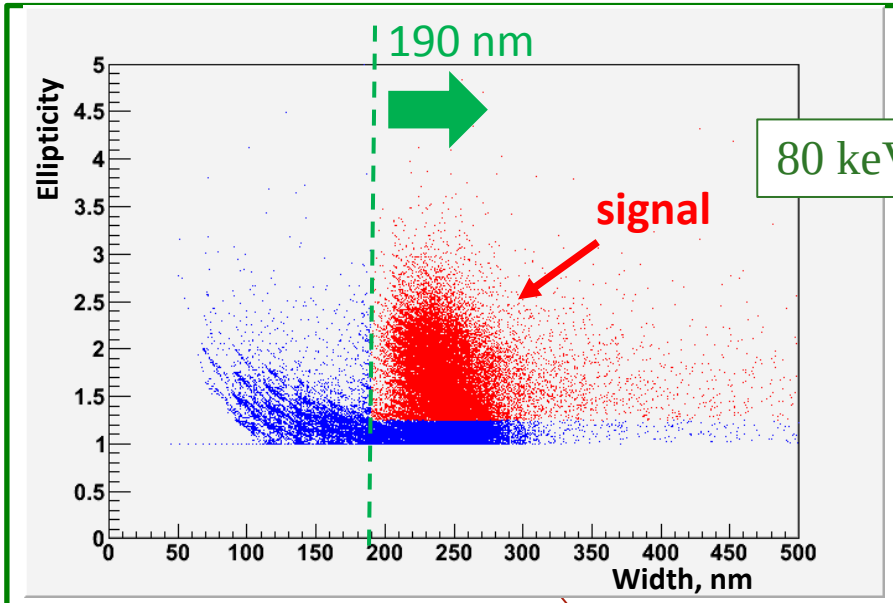
Nikon Oil Objective 100x, 1.45 N.A., Plan Apo

Test using 400 keV Kr ions

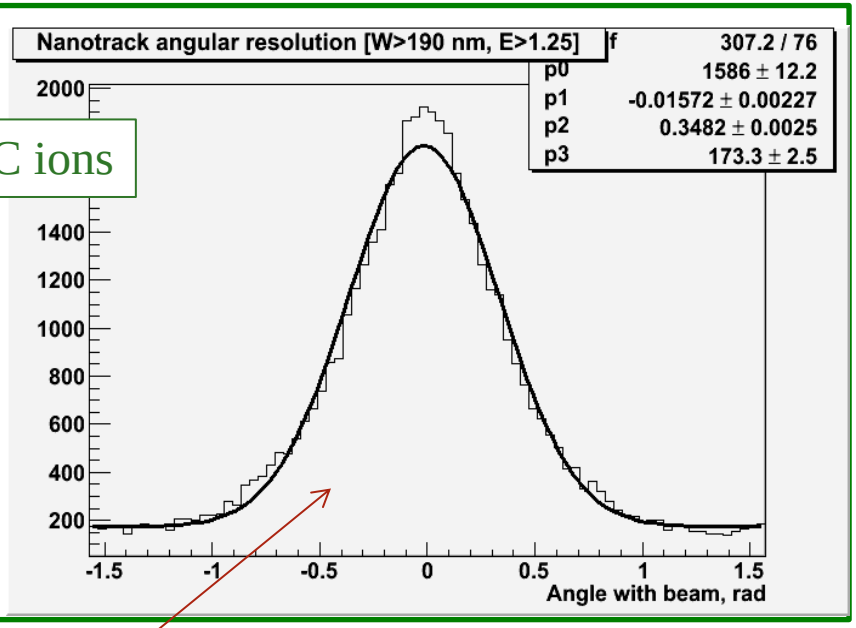


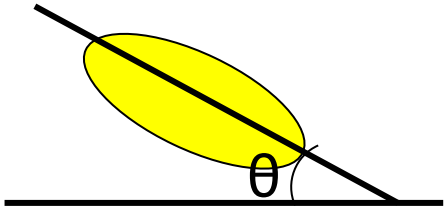
Scanning with **optical microscope** and **shape recognition analysis**

Selection Of C Ion Tracks With Shape Analysis



80 keV C ions





Direction detected!

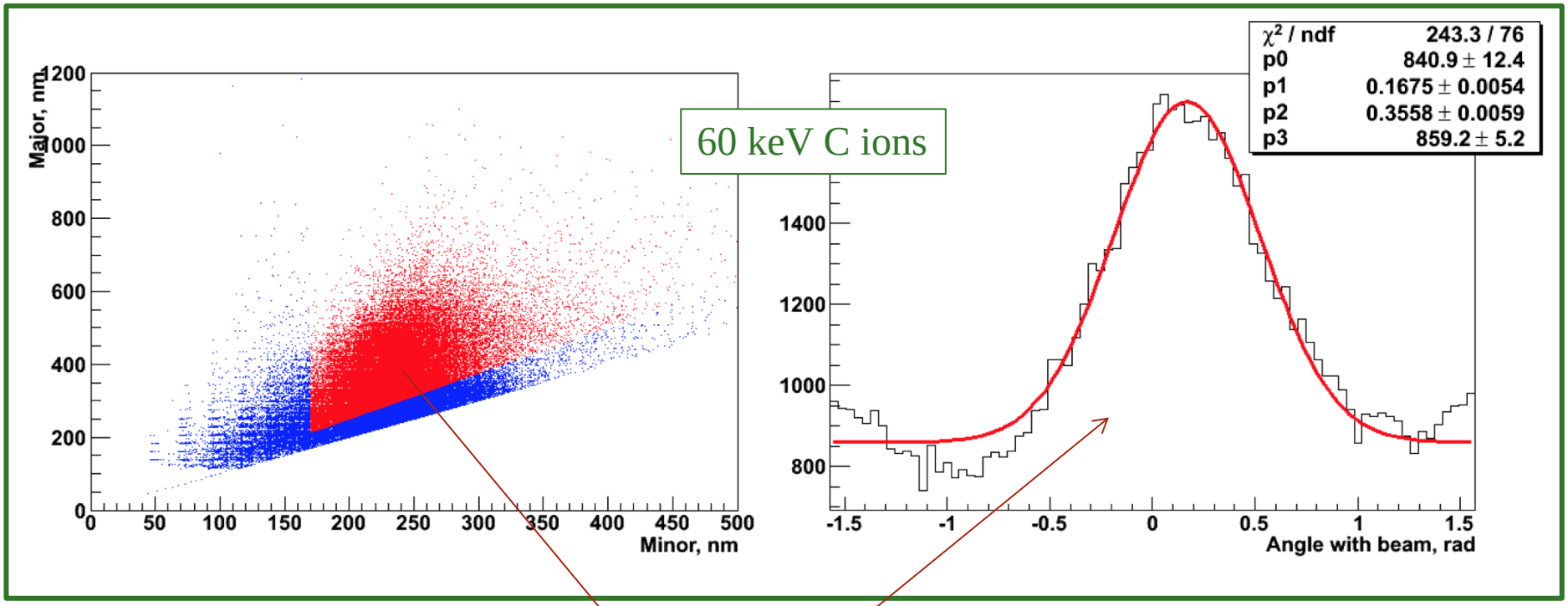
Signal selection:

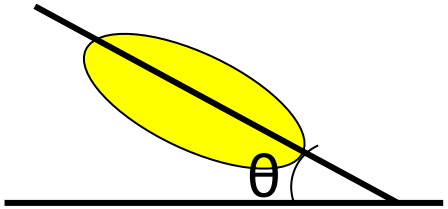
- Major/minor>1.25
- width > 190 nm

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

$$\sigma^2 = 350 \text{ mrad}$$

Selection Of C Ion Tracks With Shape Analysis





Direction detected!

Signal selection:

- Major/minor>1.25
- minor > 170 nm

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

$$\sigma^2 = 360 \text{ mrad}$$

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

NEUTRON TEST BEAM @ FNS (JAPAN)

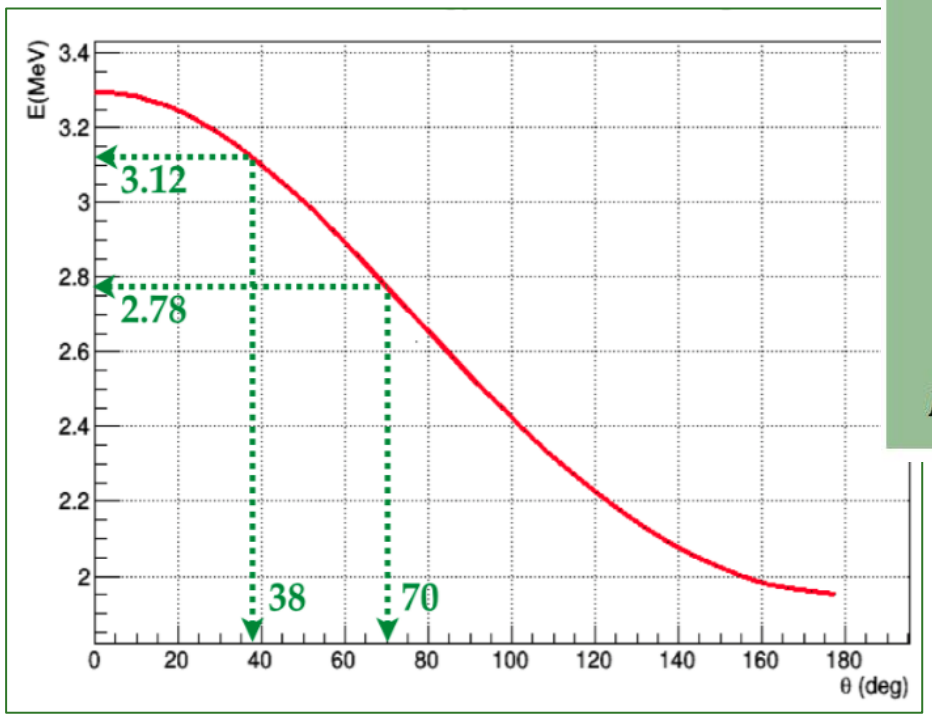
Japan Atomic Energy Research Institute

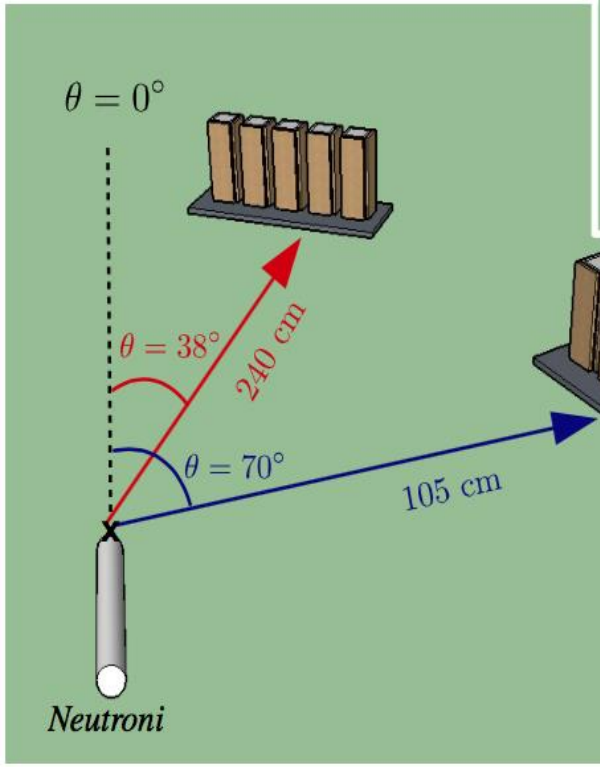
Emitted neutron energy

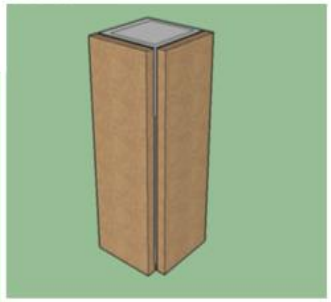
$\Theta_n = 38°$
$E_n = 3.12\ MeV$

$\Theta_n = 70°$
$E_n = 2.78\ MeV$

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



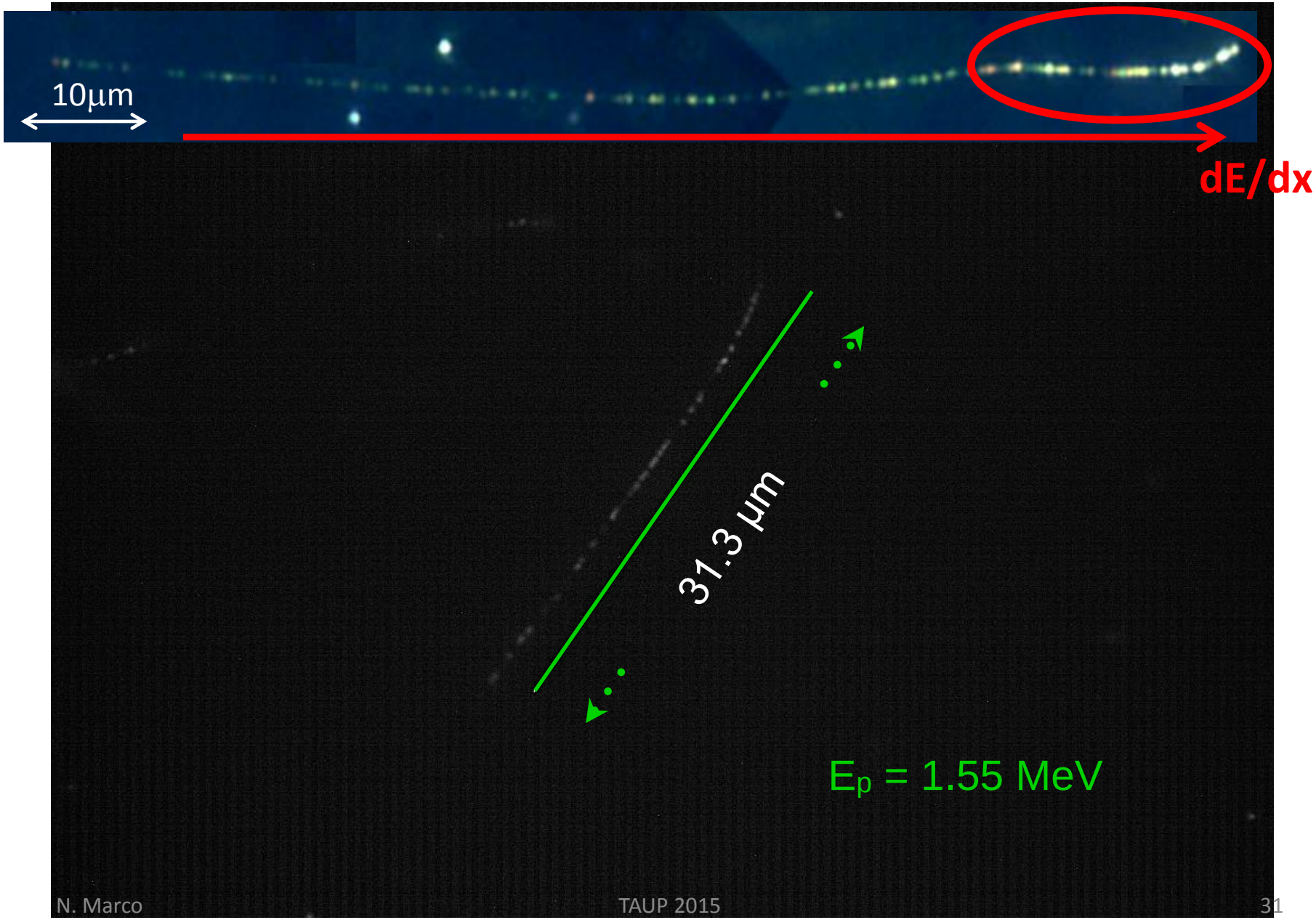




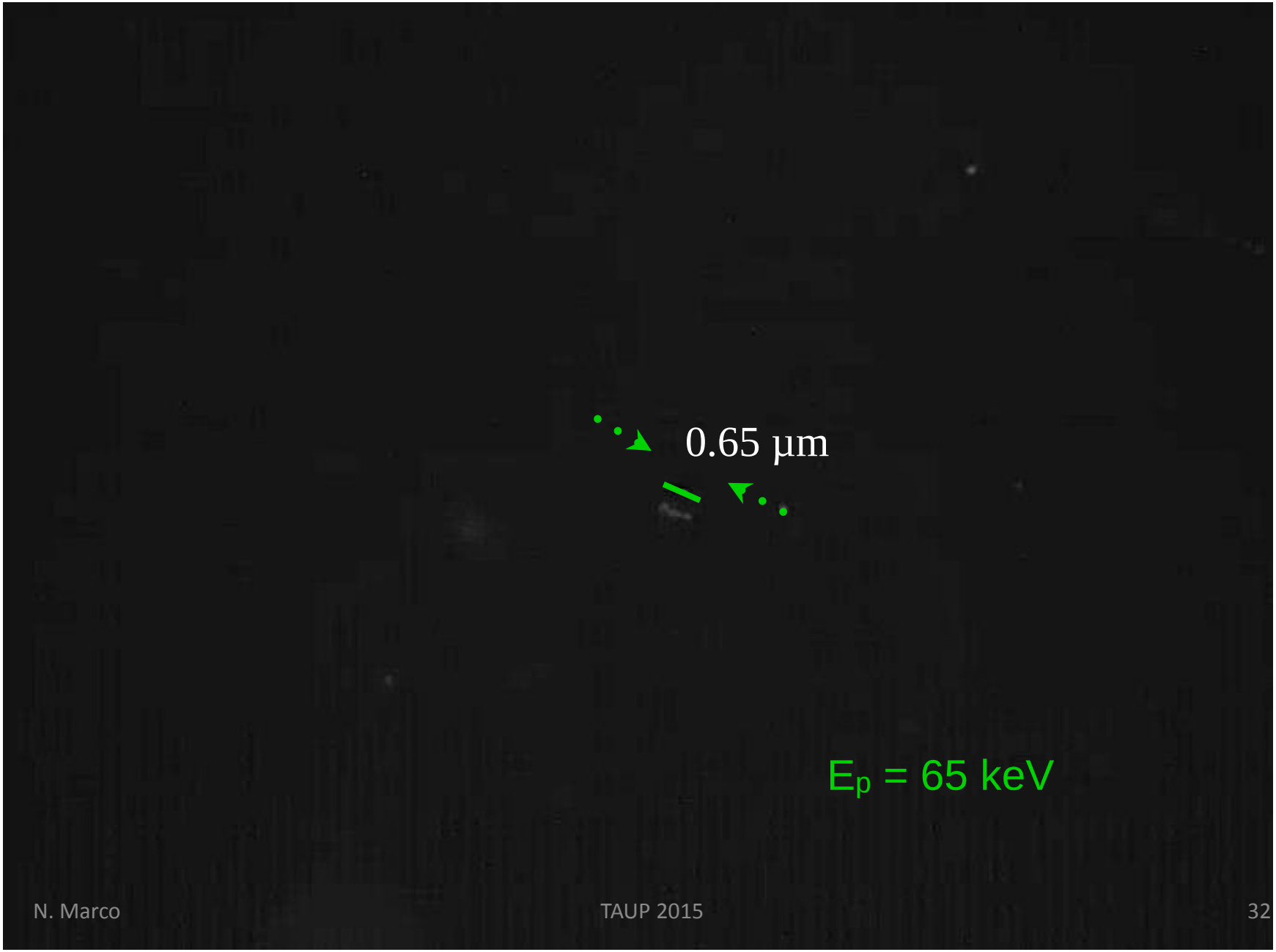
Emitted neutron energy

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

Neutron Test Beam Analysis

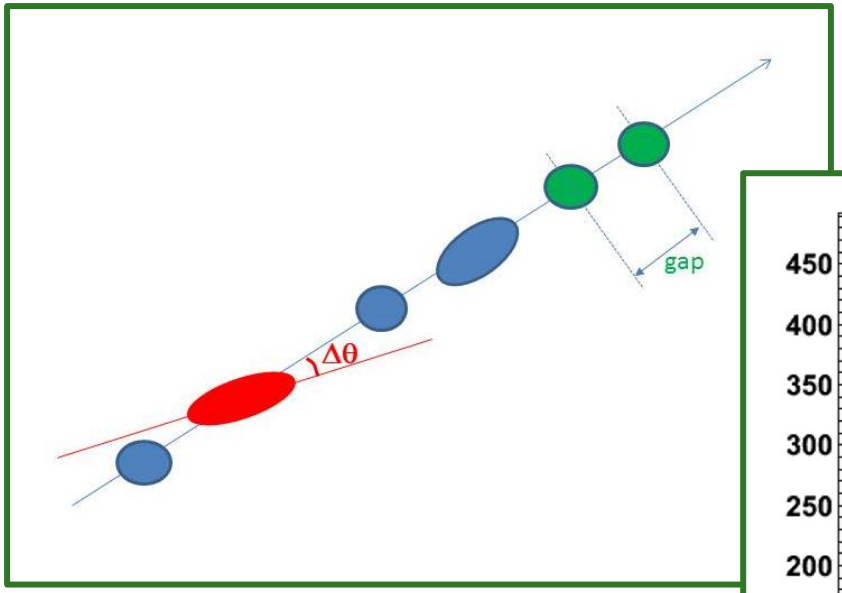


Neutron Test Beam Analysis

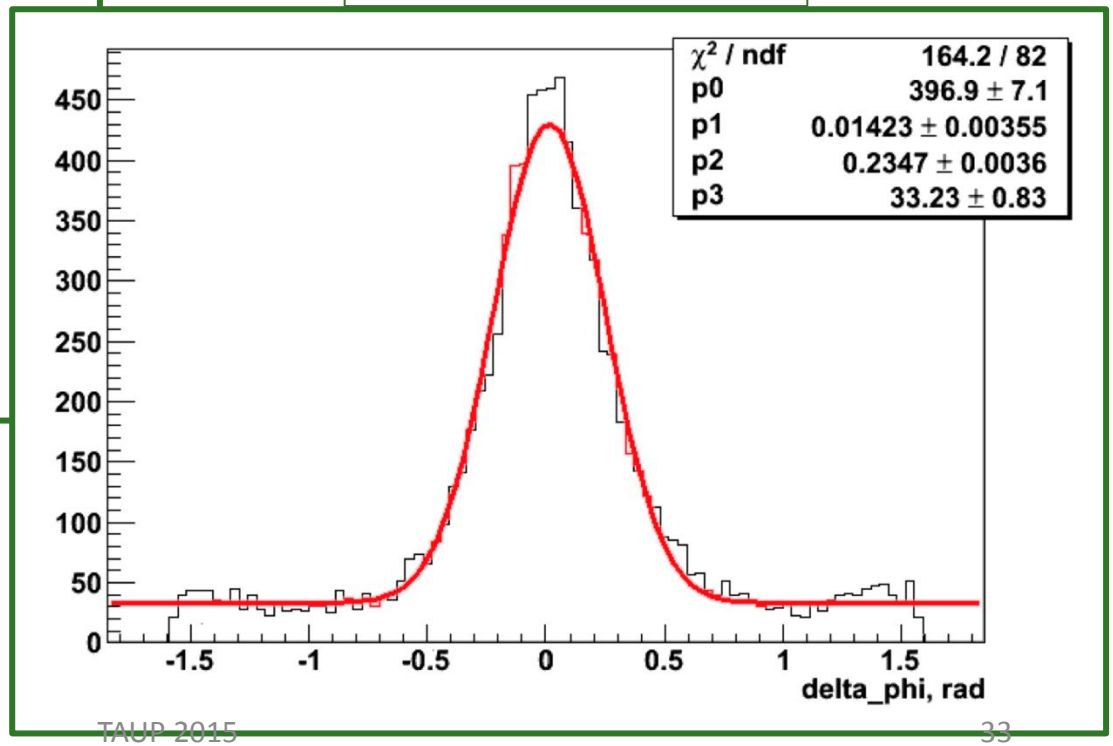


Intrinsic Angular Resolution

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



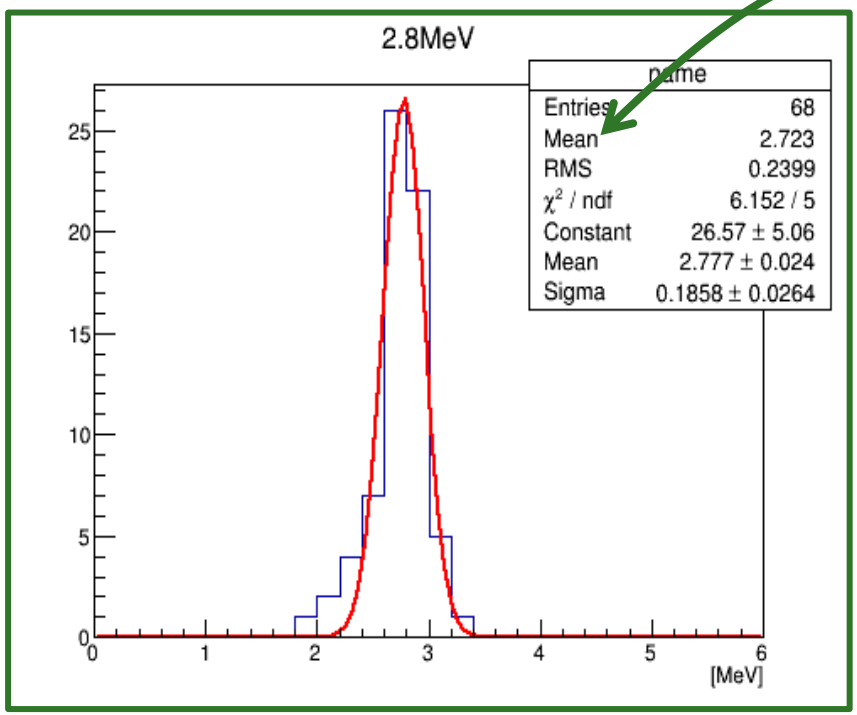
σ = 235 mrad = 13°



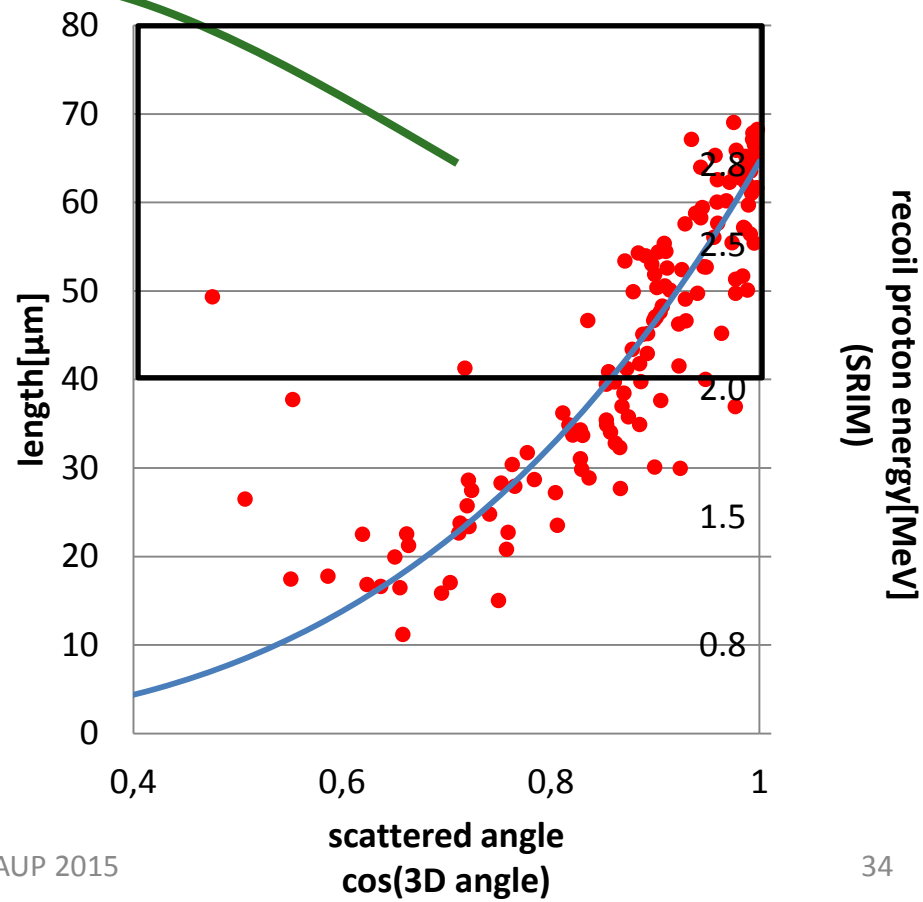
2.8 MeV Neutron Energy Measurement

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

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

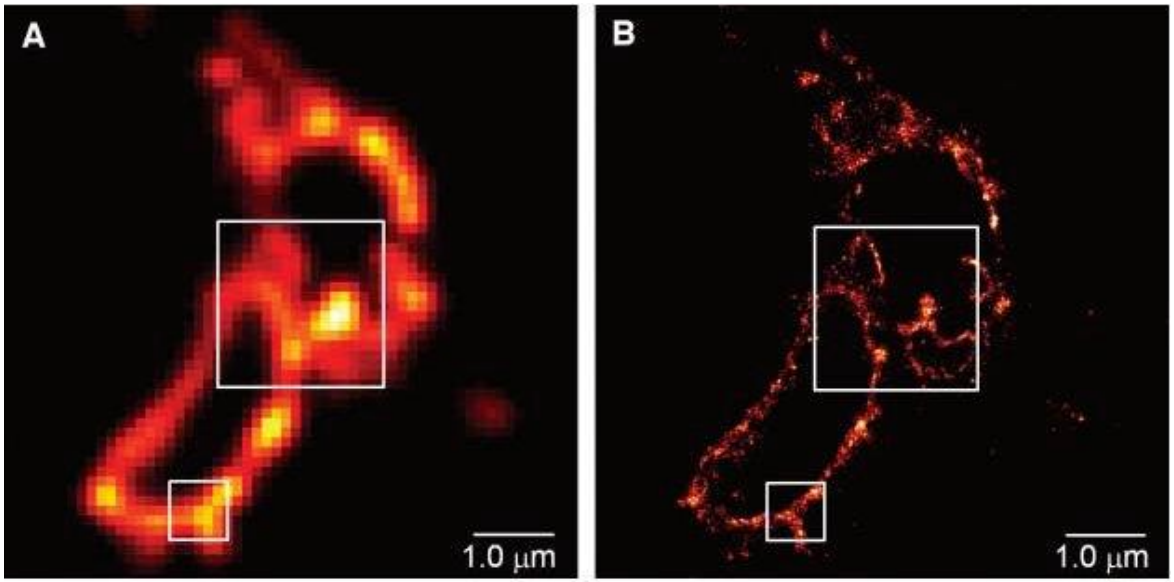


neutron energy
2.8±0.2MeV
resolution(σ/E) = 7%



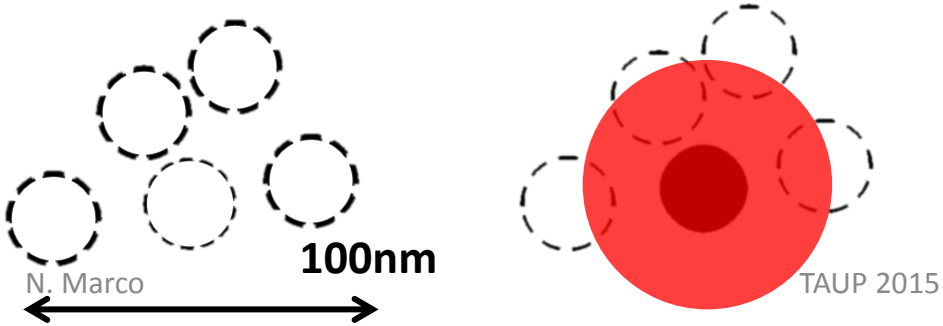
Imaging Beyond Optical Resolution: 2014 Nobel Prize In Chemistry

COS-7 cell optical images



Fluorescent molecule

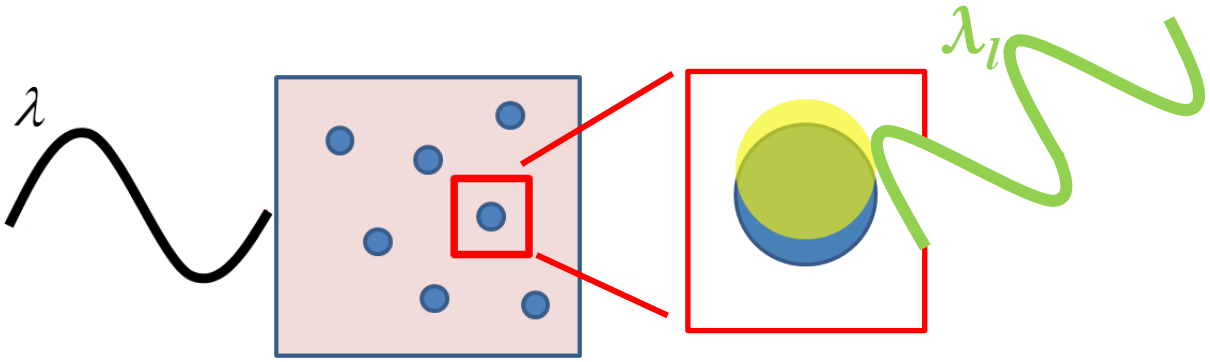
Eric Betzig *et al.*, Science 313, 1642 (2006)



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 of inside metal**

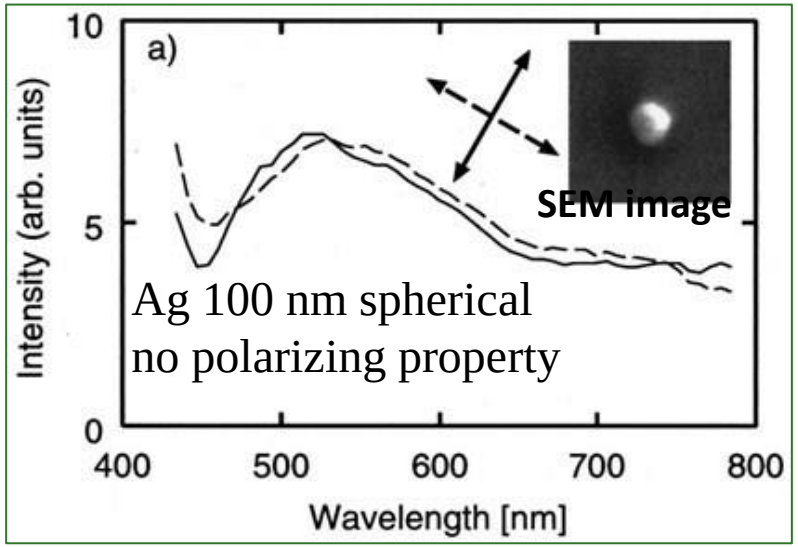
$$E_l = \frac{3\varepsilon_d(\lambda)}{\varepsilon_m(\lambda)+2\varepsilon_d(\lambda)} E_0$$

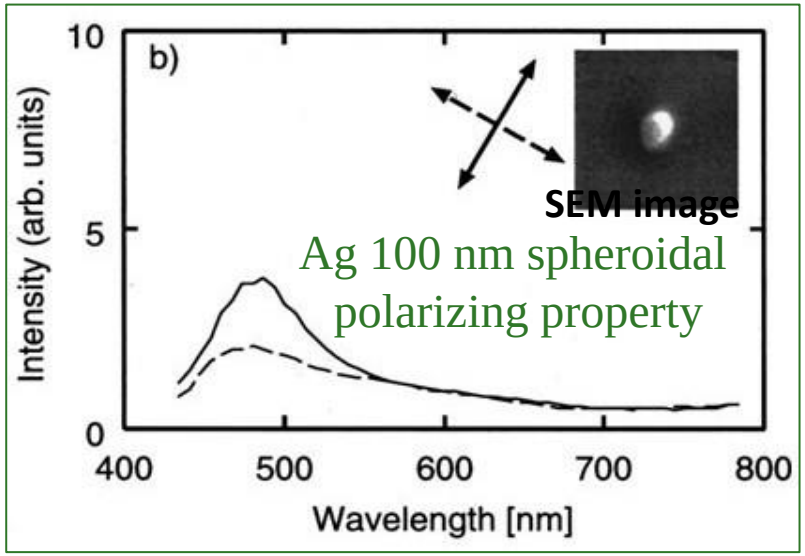
$$\varepsilon_m(\lambda_l)+2\varepsilon_d(\lambda_l) \approx 0$$

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)

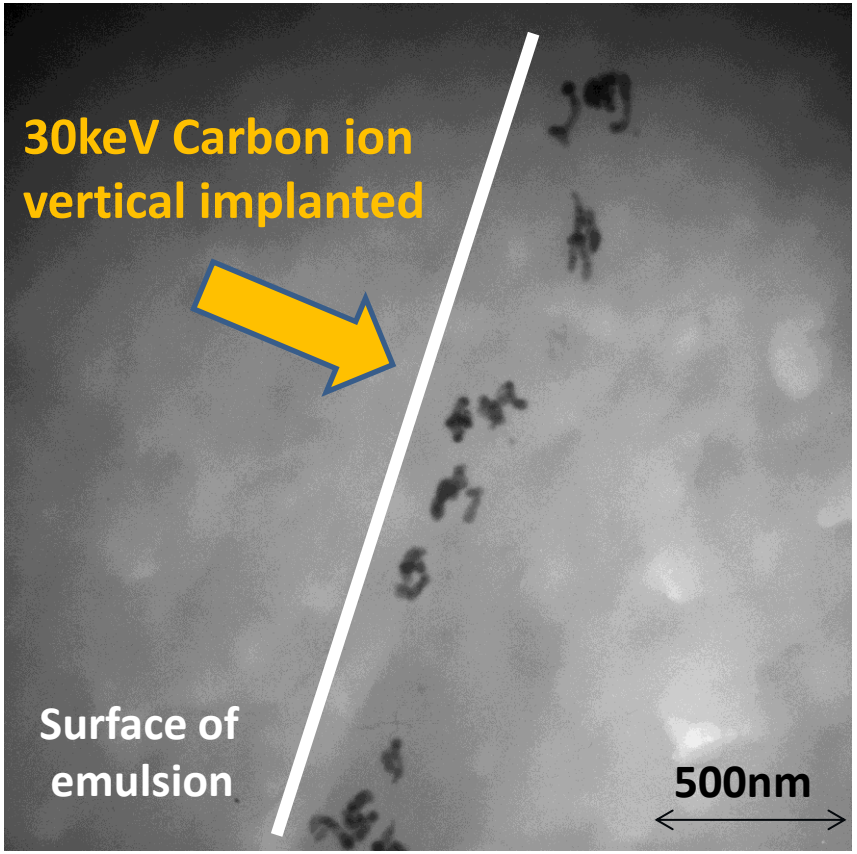




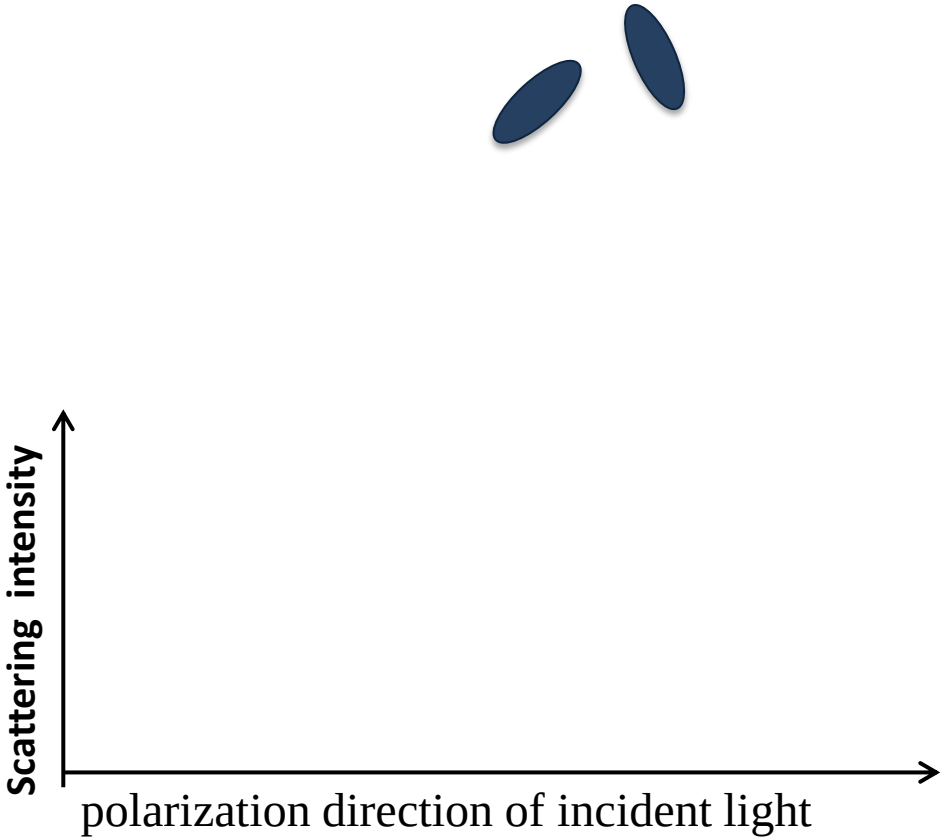
The polarization dependence of the resonance frequencies strongly reflects the shape anisotropy

Silver Grains Building Up Tracks

TEM image of Carbon track after development



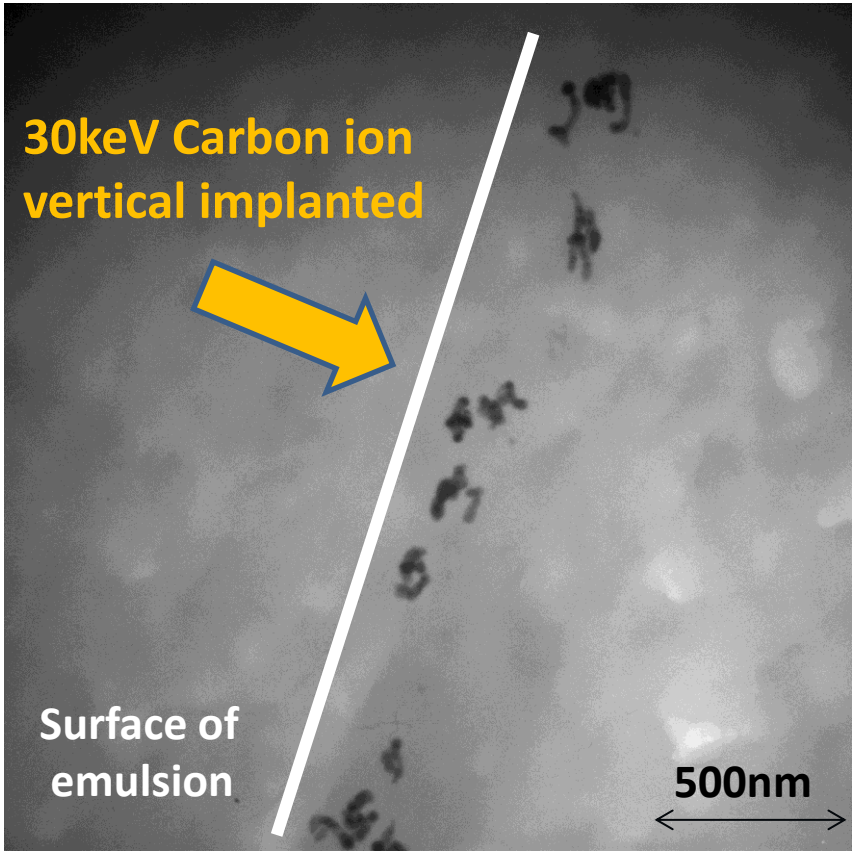
Shape different from each other



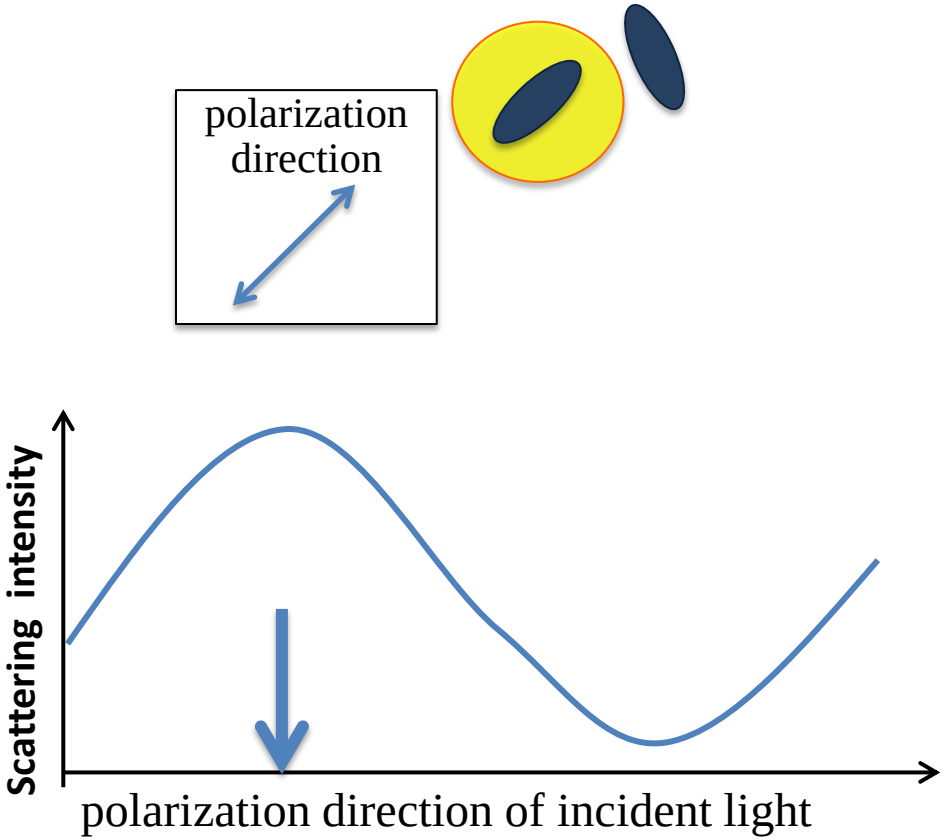
Optical response strongly depends
on the polarization of incident light

Silver Grains Building Up Tracks

TEM image of Carbon track after development



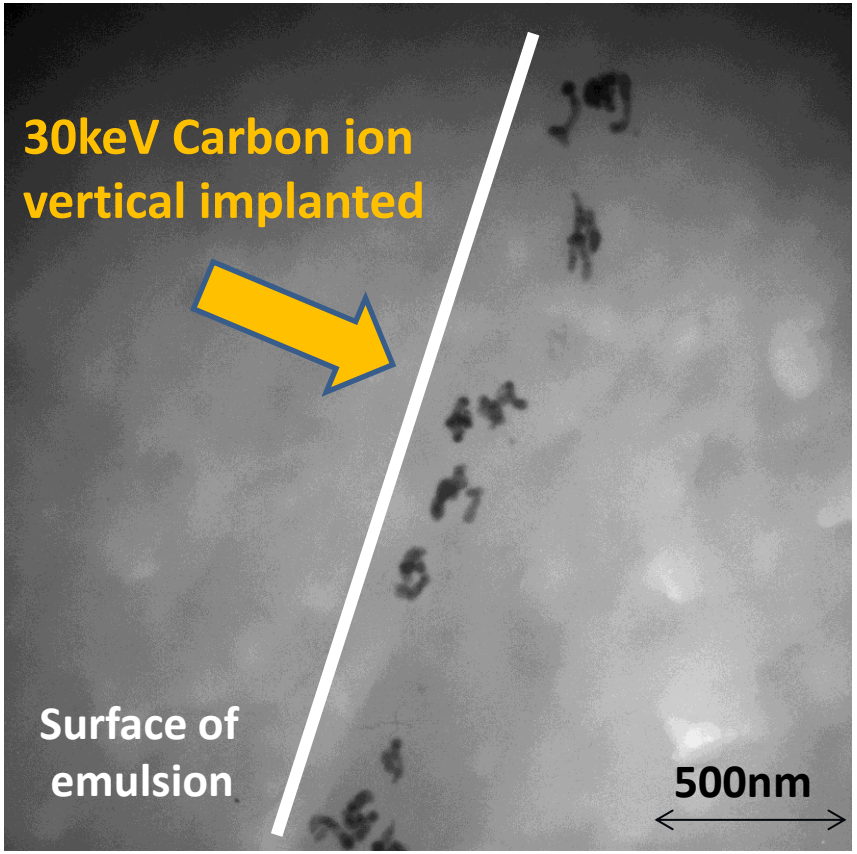
Shape different from each other



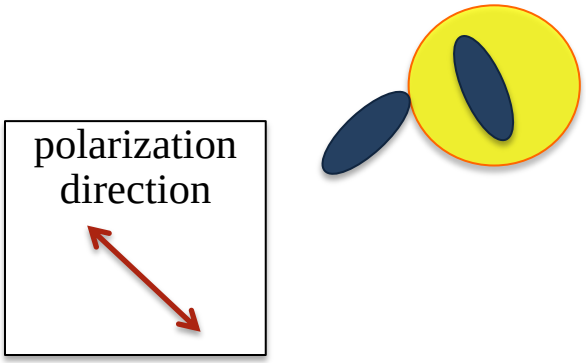
Optical response strongly depends on the polarization of incident light

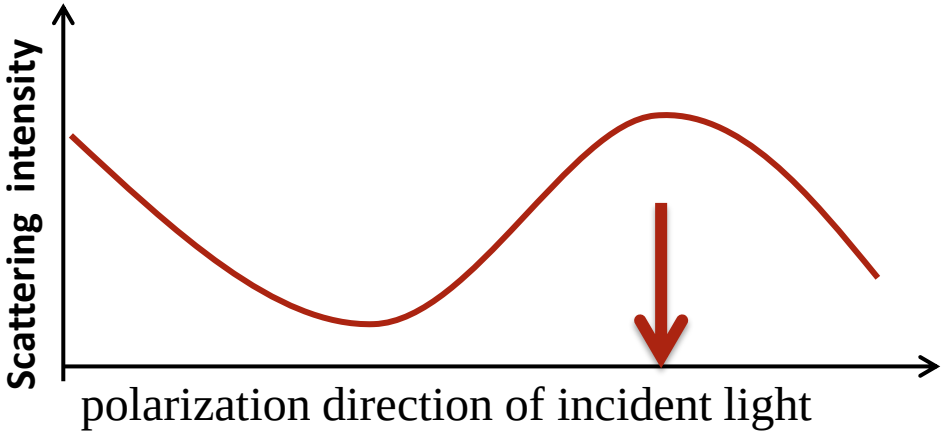
Silver Grains Building Up Tracks

TEM image of Carbon track after development



Shape different from each other

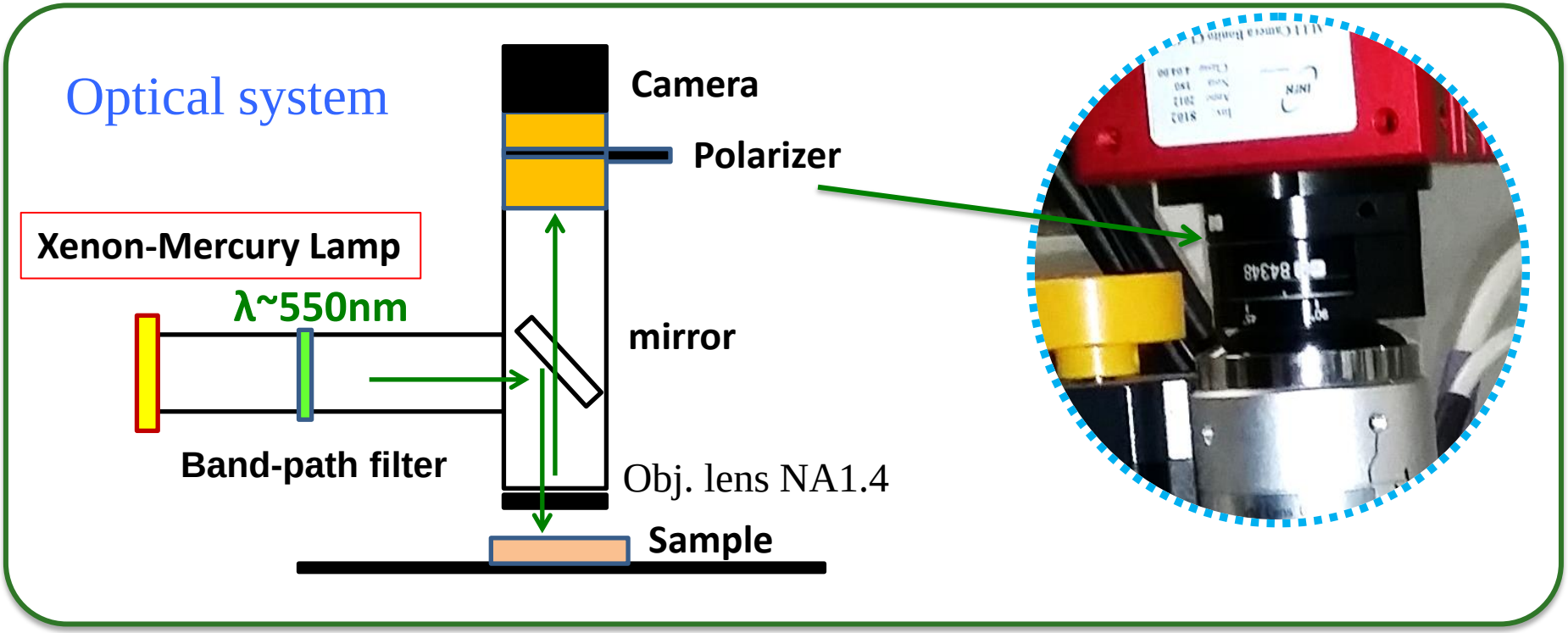




Optical response strongly depends on the polarization of incident light

MICROSCOPE UPGRADE

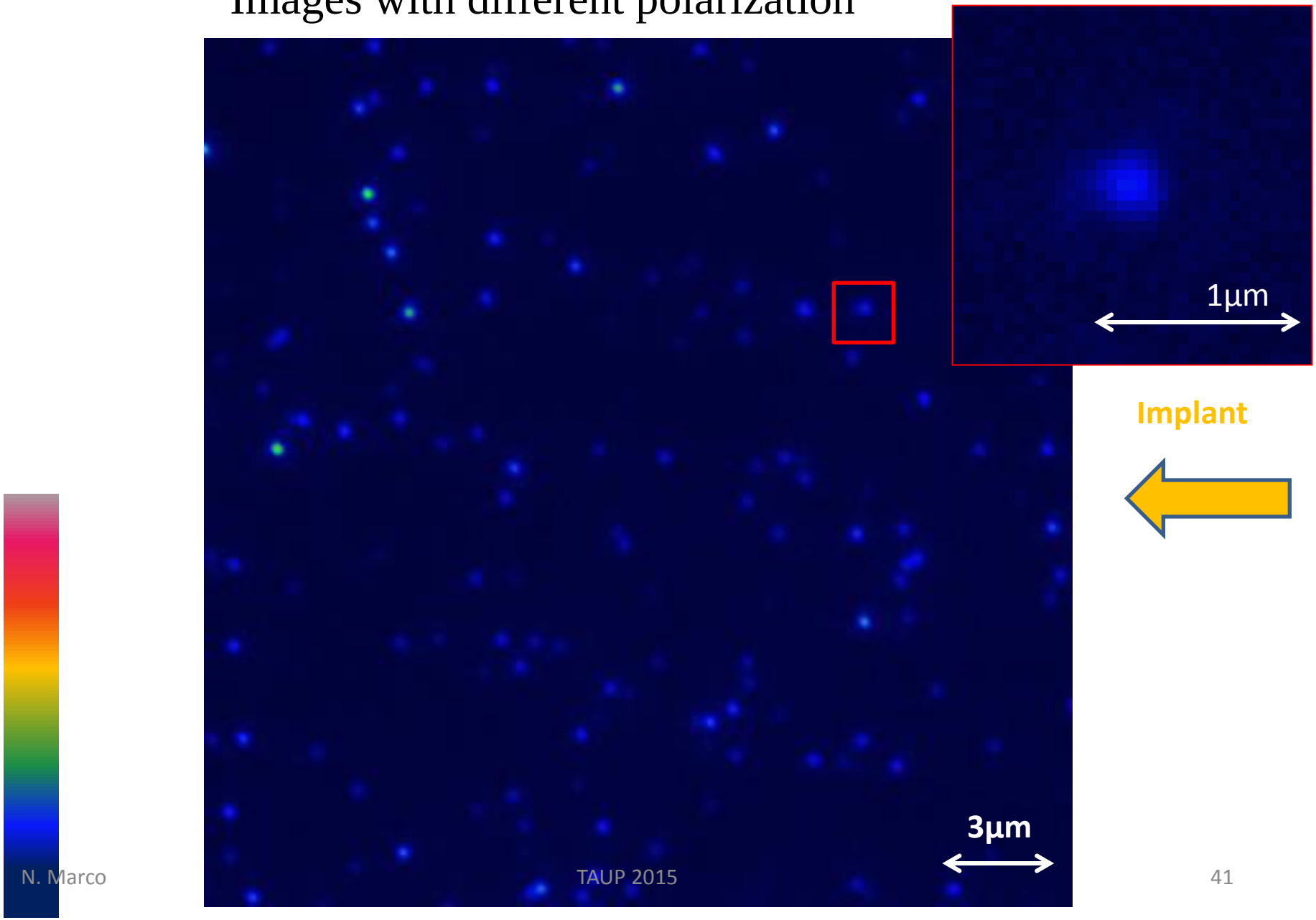
polarizer below the camera, rotated to charge polarization



Rotate by 180° with 10° steps
change the direction of polarization and measure the track

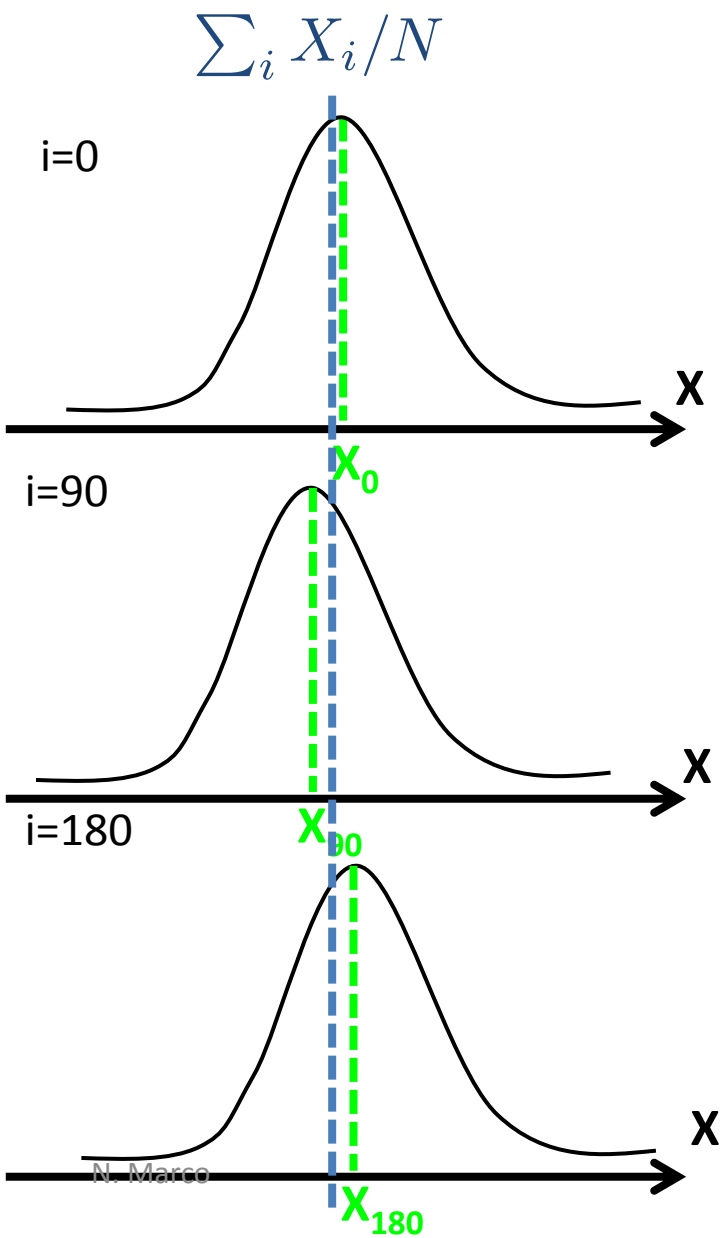
Measurements With Resonance Effect

Images with different polarization



Measurements With Resonance Effect

Evaluation of the position accuracy with a single grain



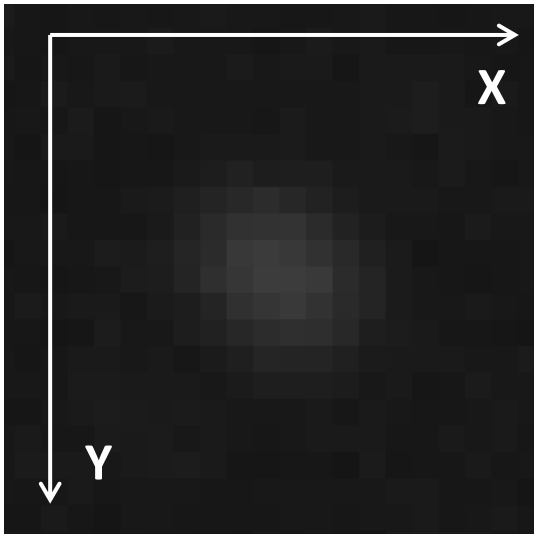
polarization angle i

$i \in \{0, \pi/18, \pi/9, \cdots, \pi\}$

(X_i, Y_i) cluster position

$dX_i = X_i - \sum_i X_i/N$

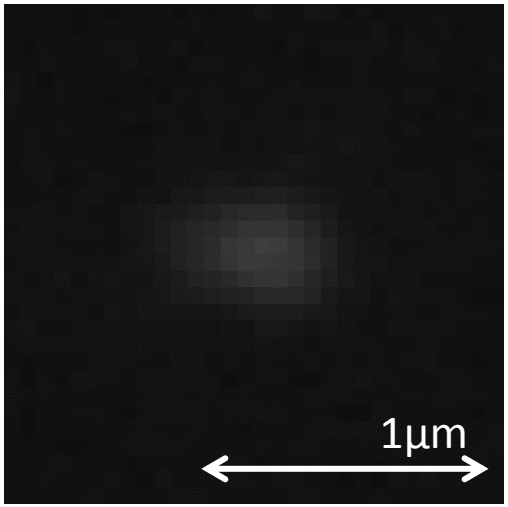
$dY_i = Y_i - \sum_i Y_i/N$

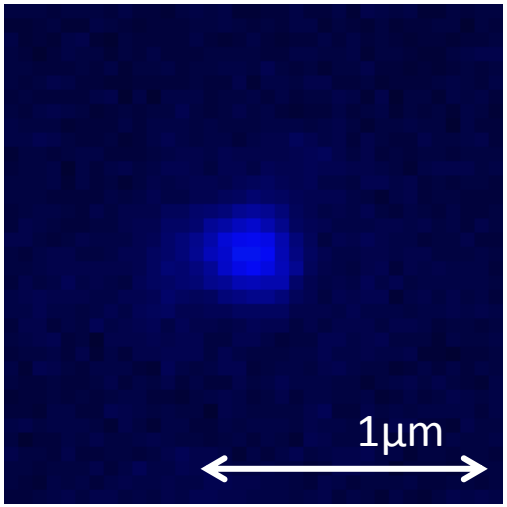


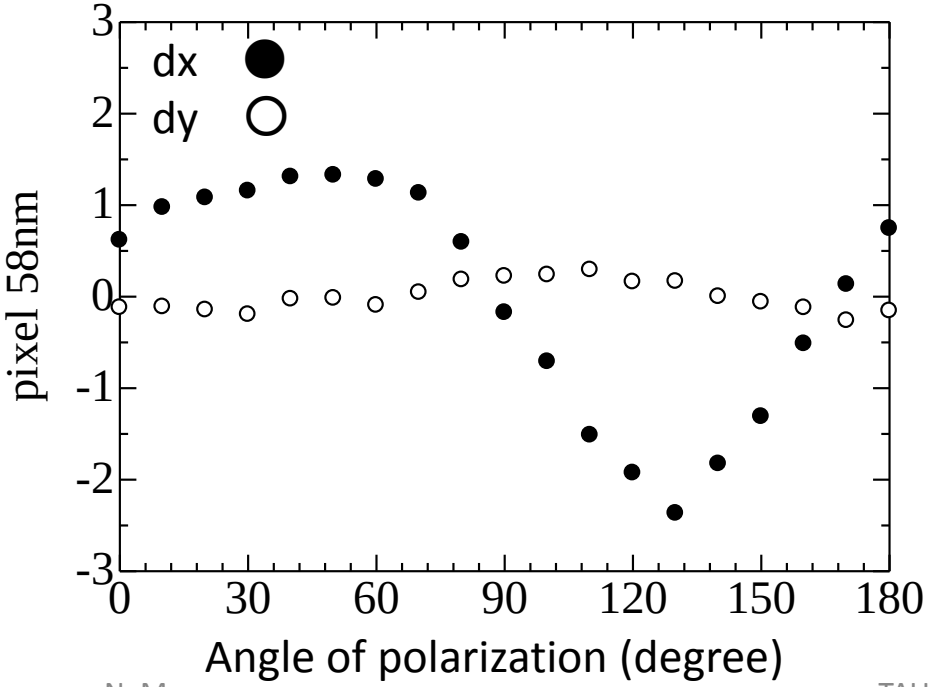
A Track Made Of Two Grains

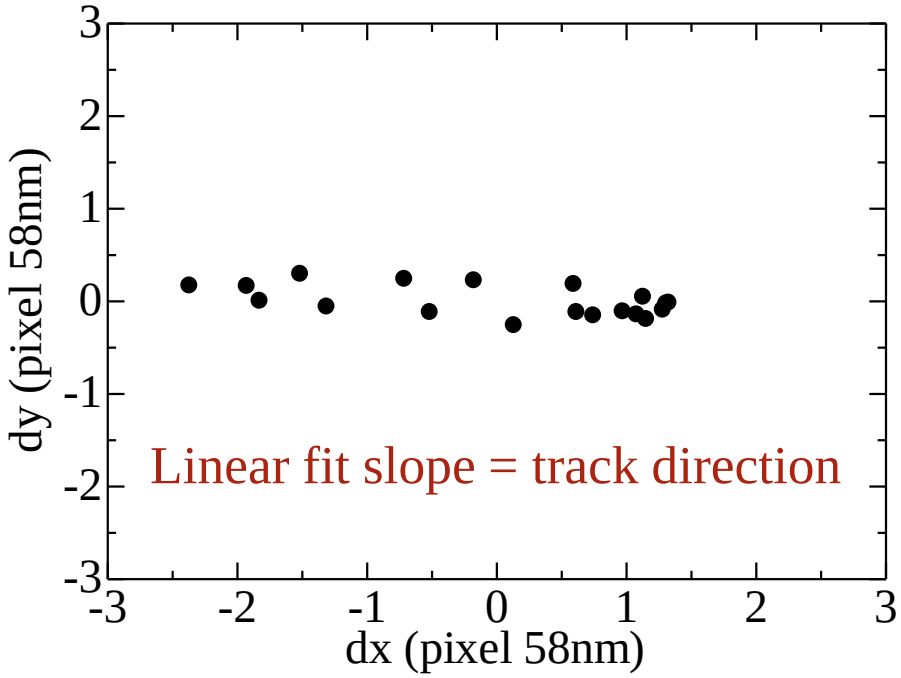
e = 1.49
without polarizer

Track validated by
elliptical shape analysis



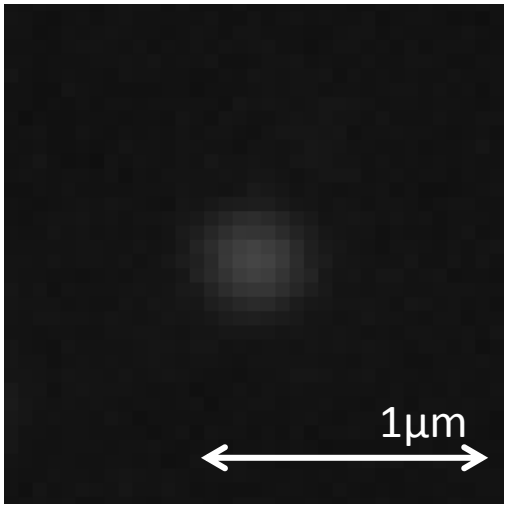


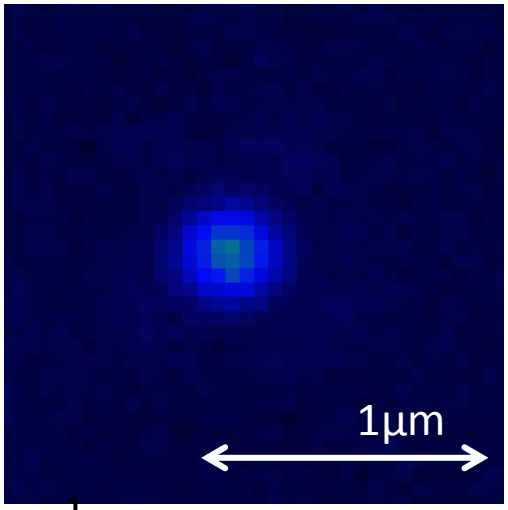


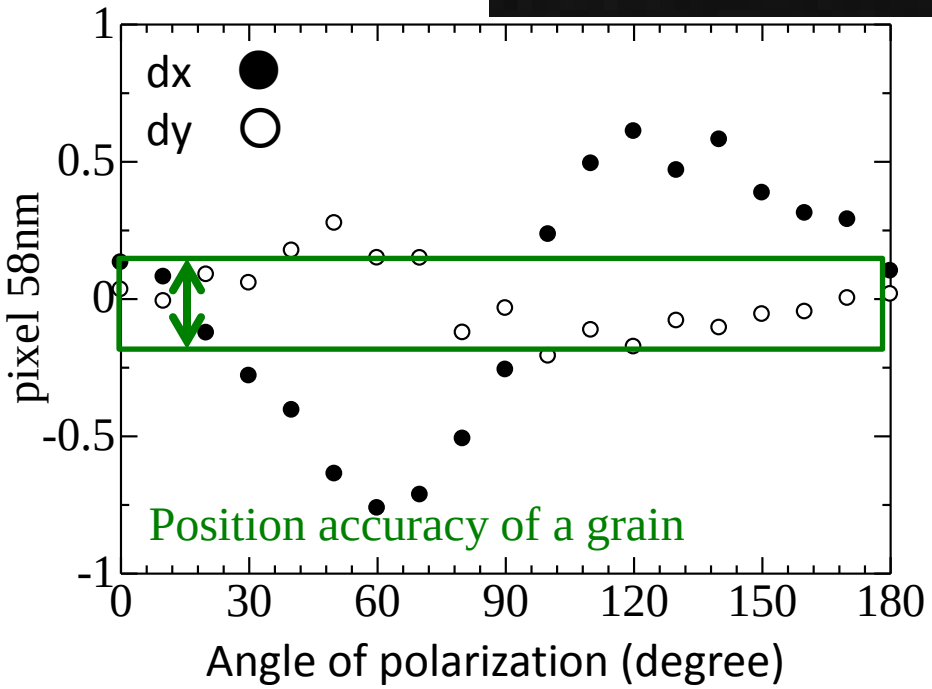


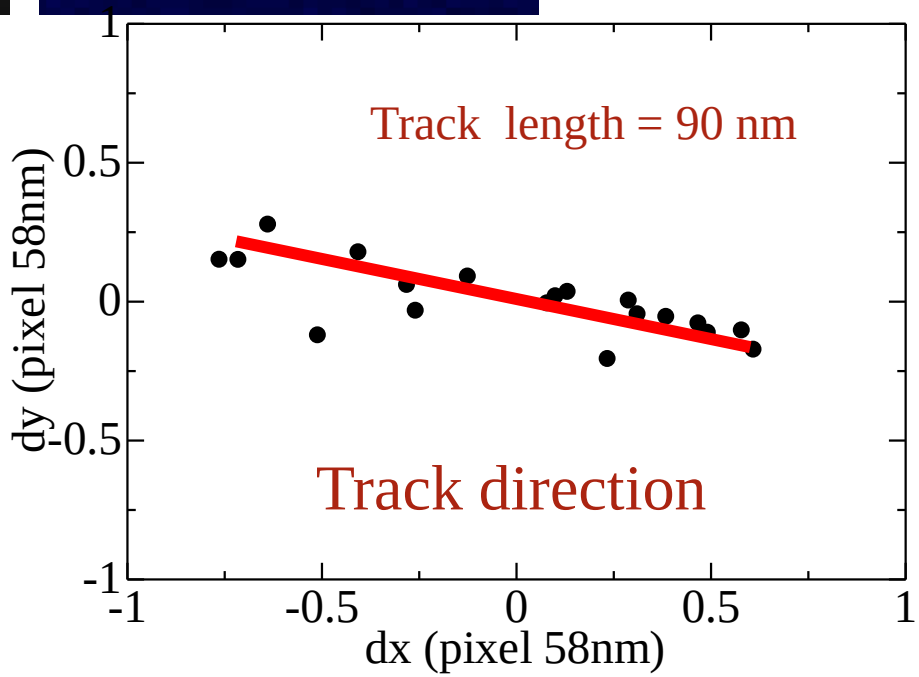
A Two-Grains Track

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



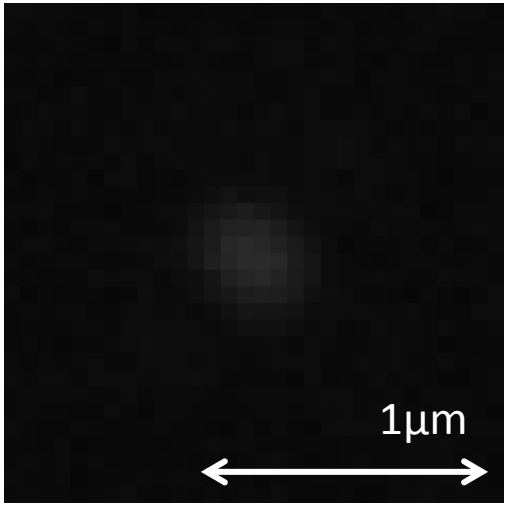


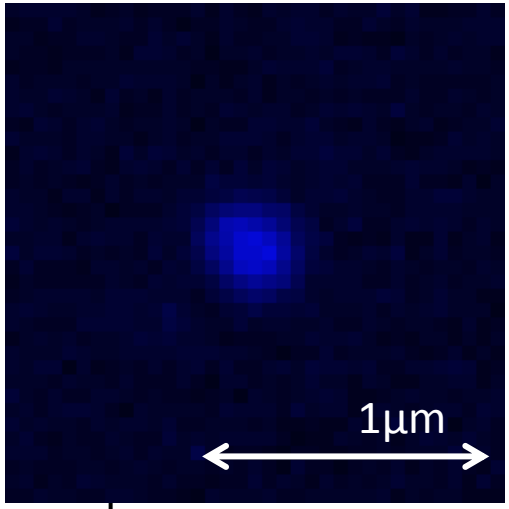


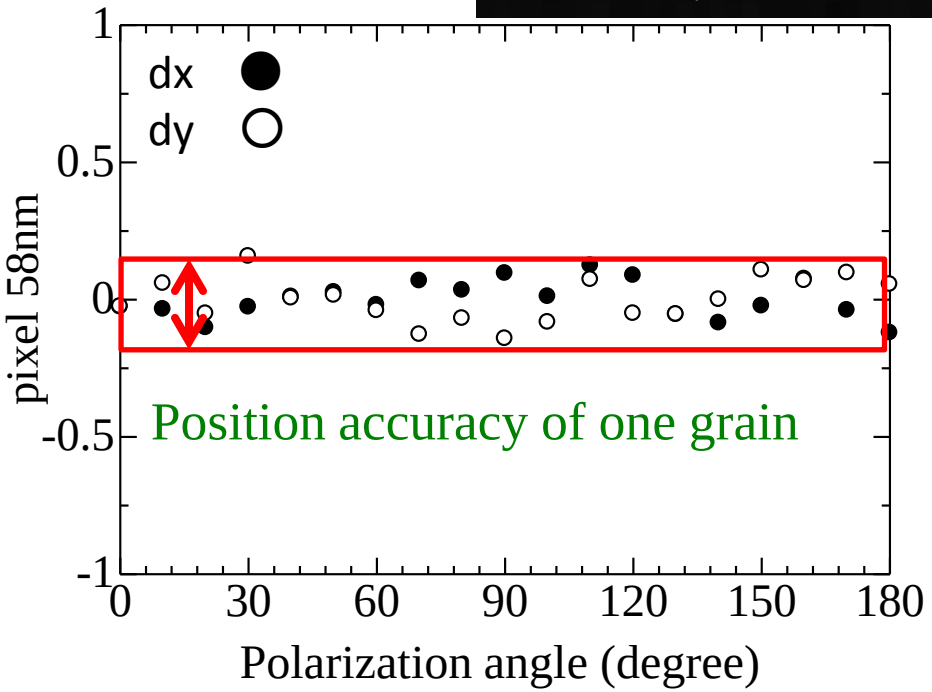


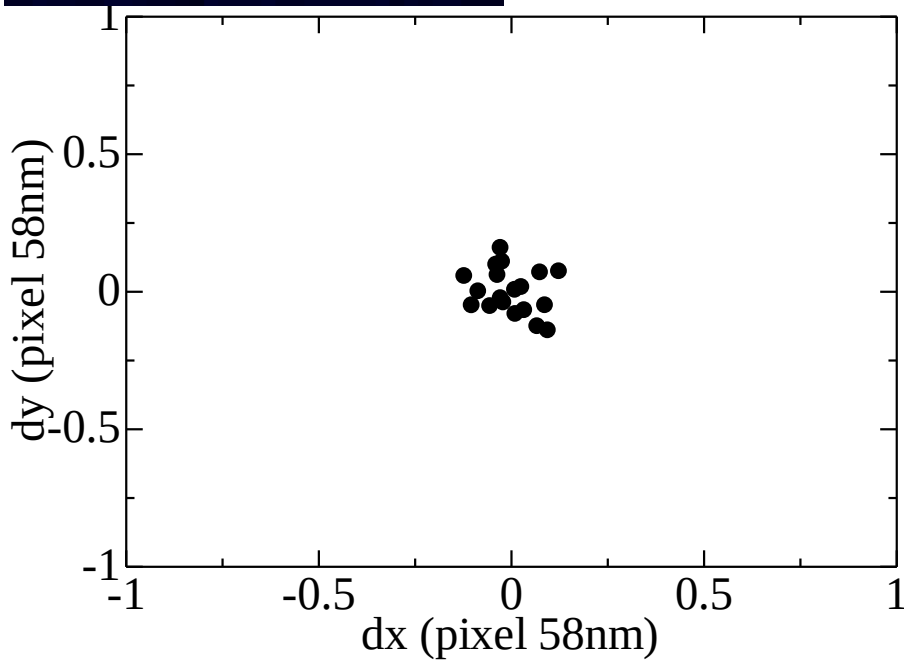
Single Grain For Accuracy Evaluation

Ag 60nm

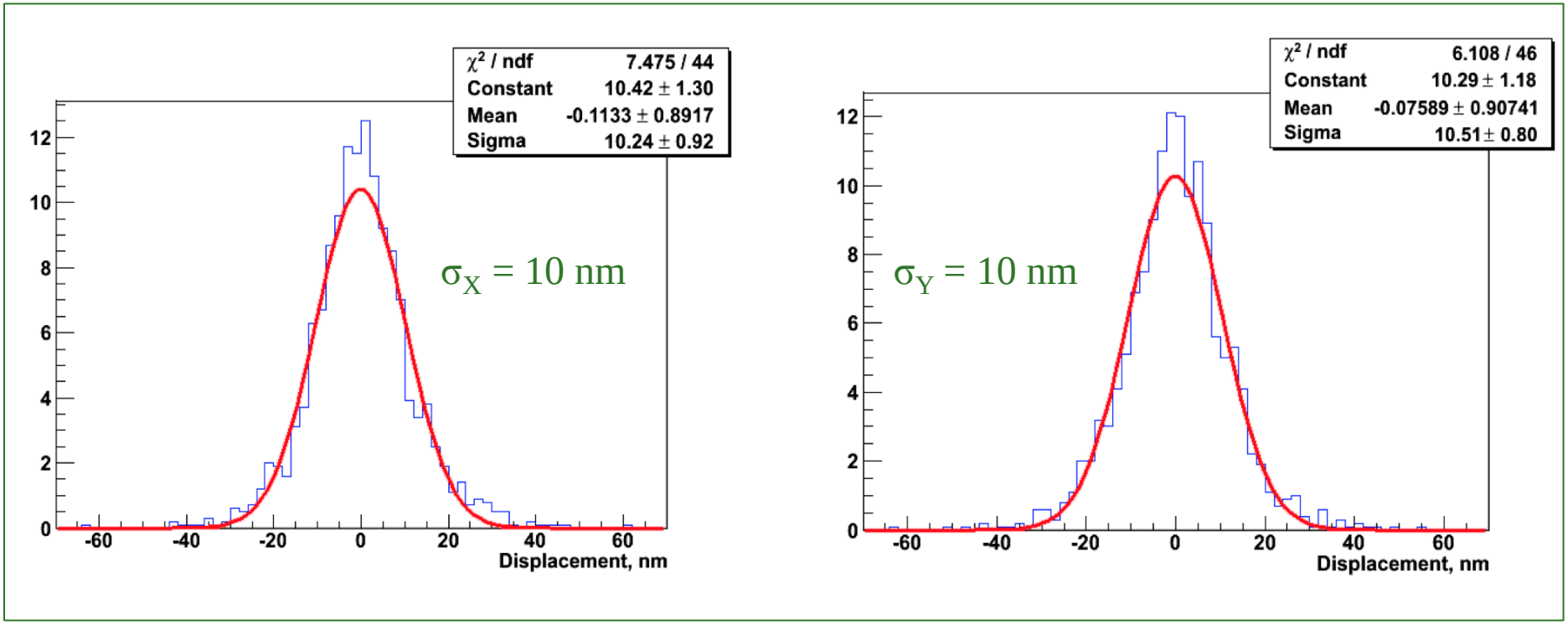








Position Accuracy

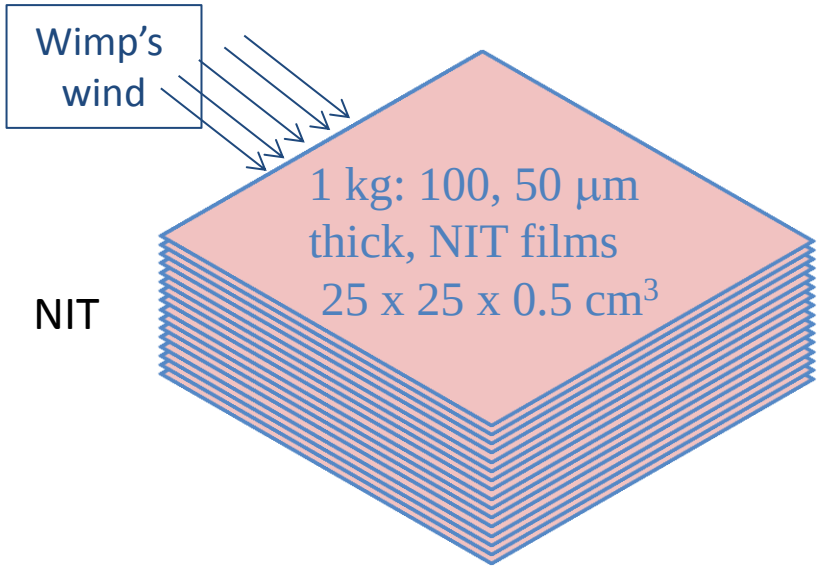


(pixel size 28 nm)

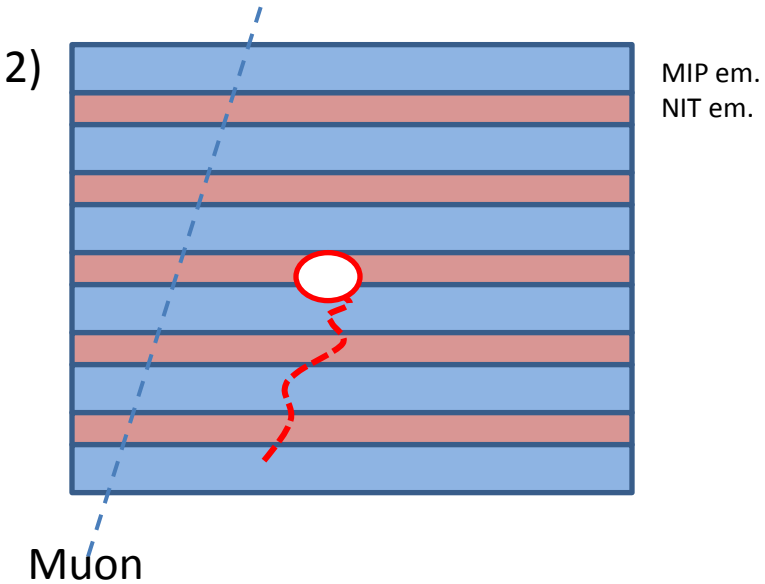
Unprecedented accuracy of 10 nm achieved on both coordinates
Breakthrough

Target options

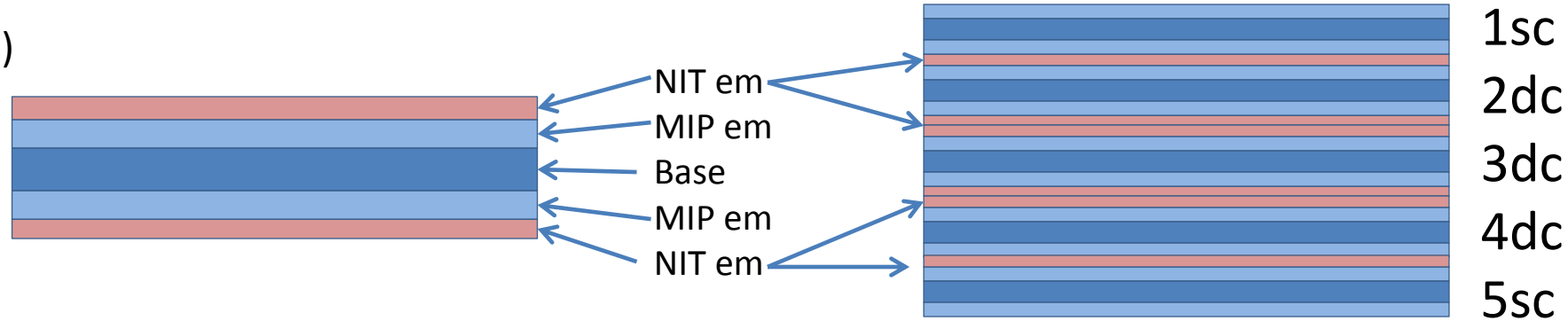
1)



2)



3)



Equatorial Telescope

- Mechanics:

  2 motorized axes (Polar and Declination) equipped with precise encoders for position monitoring. (Final precision 1°)

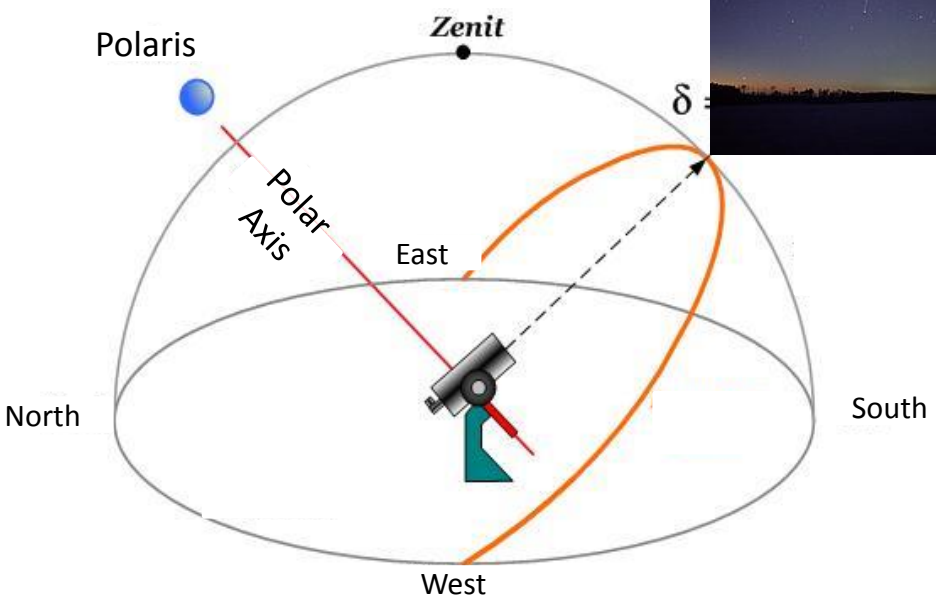
- Surface Calibration
  1. Follow the position of a star in the Cygnus constallation; measure position parameters in order to apply corrections to mechanics and electronic system.
  2. Use throughout the whole day to study systematic effects.

- Underground installation

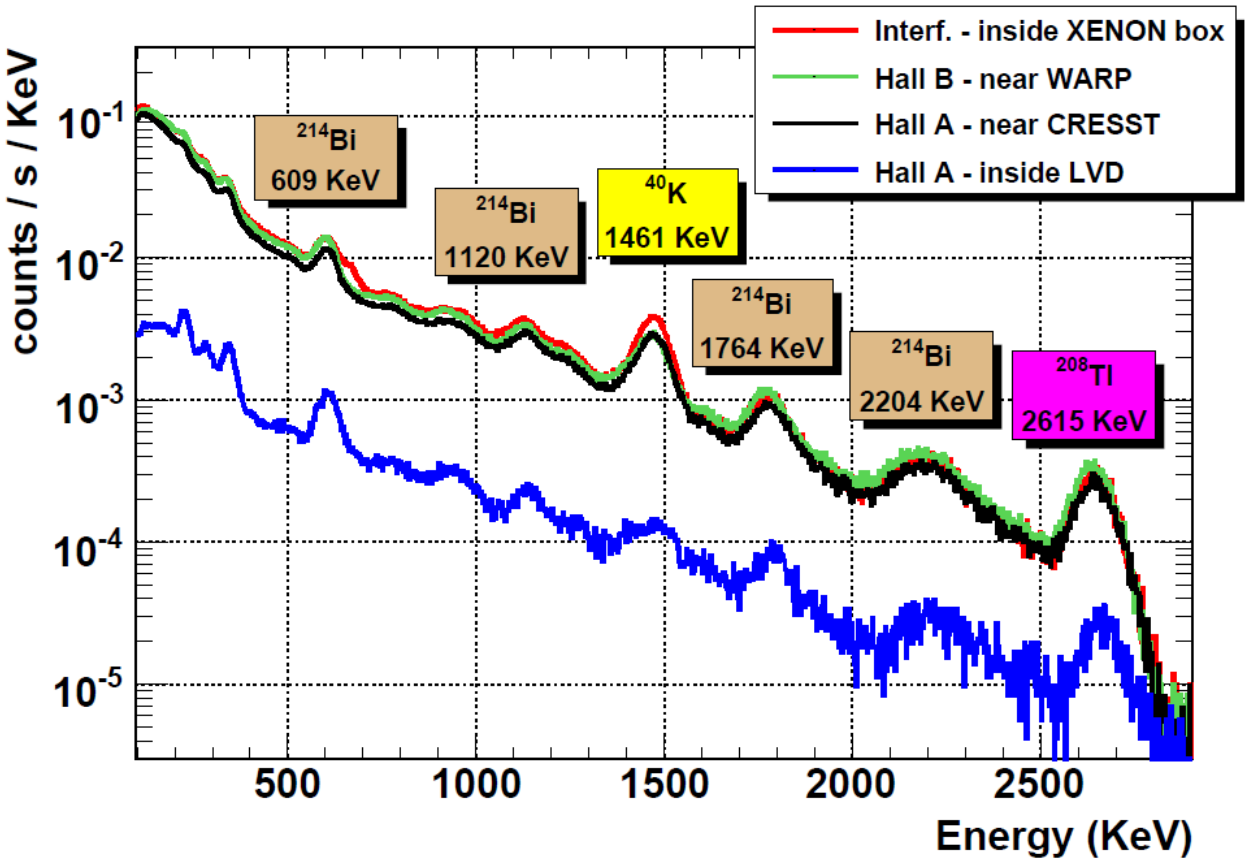
  Align the mount using existing high precision reference points.

- Materials

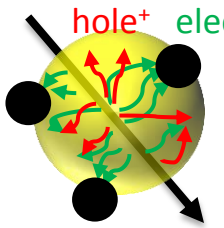
screening of all the materials used in the telescope is foreseen in order to evaluate their intrinsic radioactivity.



γ background

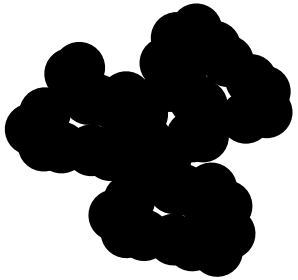


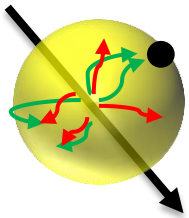
Electron rejection power



Signal event (recoiled nuclei)

- de/dx : 100~1000 keV/μm



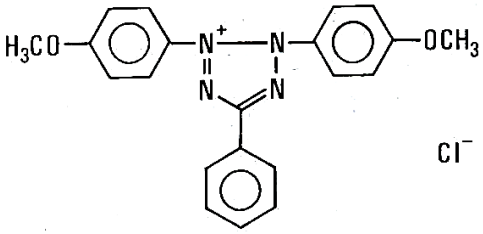


Background event (electron)

- de/dx : 1~10 keV/μm

A rejection power O(10^6) is needed:

- Chemical treatment (Tetrazolium-compounds)
- Cryogeny
- Discrimination in the read-out phase



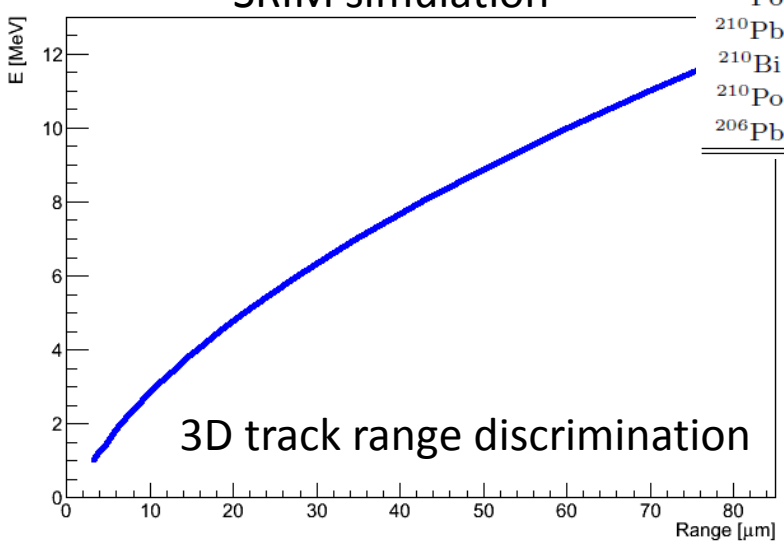
α particles

Sources: 238U, 232Th chains and 222Rn

Parent	Daughter	Decay Mode	Energy [MeV]	Half Life
^{238}U	^{234}Th	α	**4.27**	4.47×10^{9} yr
^{234}Th	^{234}Pa	β	0.273	24.1 d
^{234}Pa	^{234}U	β	2.20	6.70 hr
^{234}U	^{230}Th	α	**4.86**	2.45×10^{5} yr
^{230}Th	^{226}Ra	α	**4.77**	7.54×10^{4} yr
^{226}Ra	^{222}Rn	α	**4.87**	1.60×10^{3} yr
^{222}Rn	^{218}Po	α	**5.59**	3.82 d
^{218}Po	^{214}Pb	α	**6.12**	3.10 min
^{214}Pb	^{214}Bi	β	1.02	26.8 min
^{214}Bi	^{214}Po	β	3.27	19.9 min
^{214}Po	^{210}Pb	α	**7.88**	0.164 ms
^{210}Pb	^{210}Bi	β	0.0635	22.3 yr
^{210}Bi	^{210}Po	β	1.43	5.01 d
^{210}Po	^{206}Pb	α	**5.41**	138 d
^{206}Pb				stable

Parent	Daughter	Decay Mode	Energy [MeV]	Half Life
^{232}Th	^{228}Ra	α	**4.08**	1.41×10^{10} yr
^{228}Ra	^{228}Ac	β	0.0459	5.75 yr
^{228}Ac	^{228}Th	β	2.12	6.25 hr
^{228}Th	^{224}Ra	α	**5.52**	1.91 yr
^{224}Ra	^{220}Rn	α	**5.79**	3.63 d
^{220}Rn	^{216}Po	α	**6.40**	55.6 s
^{216}Po	^{212}Pb	α	**6.91**	0.145 s
^{212}Pb	^{212}Bi	β	0.570	10.6 hr
^{212}Bi	^{212}Po	β 64.06%	2.25	60.6 min
	^{208}Tl	α 35.94%	**6.21**	
^{212}Po	^{208}Pb	α	**8.96**	299 ns
^{208}Tl	^{208}Pb	β	5.00	3.05 min
^{208}Pb				stable

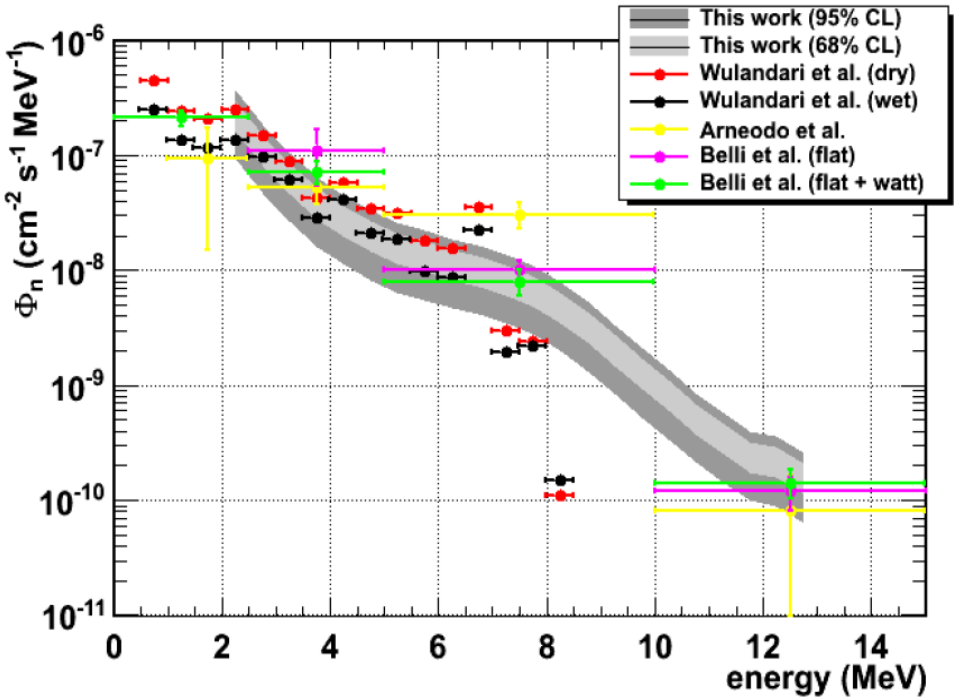
SRIM simulation



3D track range discrimination

Neutron production throught (α,n) reactions

Environmental neutron flux



Light materials are effective moderators for fast neutrons: 50 cm of polietilene (**PE, C2H4**) → reduction in the neutron flux of a factor O(10^4)

The opportunity to add a thin (1÷2 cm) layer of **Cadmium** to capture thermalised neutrons is under study.

Intrinsic neutron yield

The intrinsic emulsion radioactivity is responsible of an irreducible neutron yield through (α, n) and 238 U spontaneous fission reaction

Intrinsic radioactive contaminant contribution have been estimated @LNGS using:

1. Inductively Coupled Plasma Mass Spectrometry (ICP-MS) (Chemistry Service)
2. γ-spectrometry with Ge detector @ STELLA Facility (SubTErranean Low Level Assay)

Nuclide	Contamination [10^{-9} g g^{-1}]	Activity [mBq kg^{-1}]
AgBr-I		
^{232}Th	1.0	4.1
^{238}U	1.5	18.5
Gelatin		
^{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

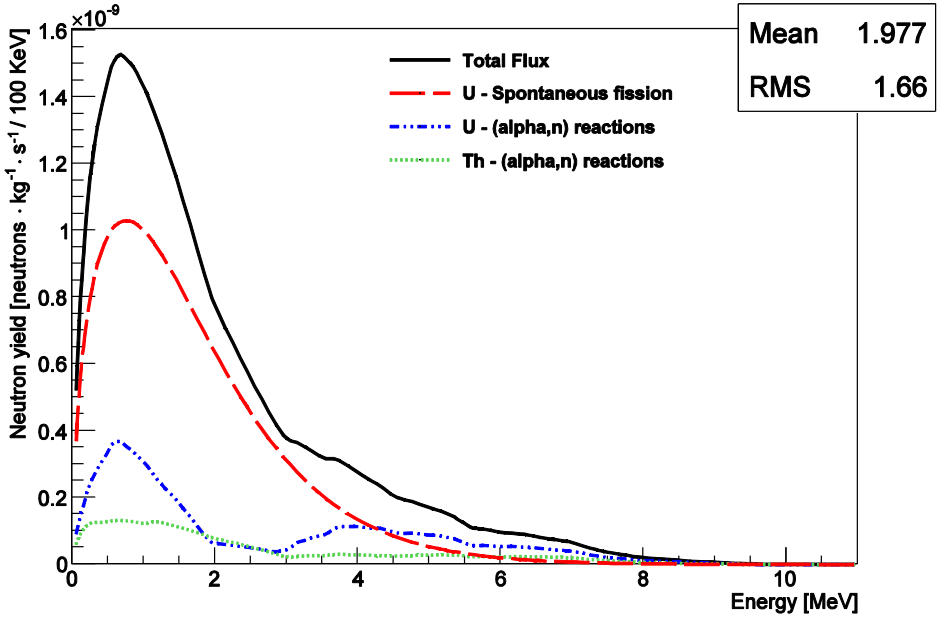
Table 4: Results obtained by ICP-MS in terms of contamination and activity for the different constituents of the nuclear emulsion. The estimated uncertainty is 30%. The upper limits on PVA are evaluated at 95% CL.

1) ICP-MS:
238U: 23±7 mBq/kg
232Th: 5.1±1.5 mBq/kg

Intrinsic neutron yield

Process	SOURCES simulation [kg^{-1} y^{-1}]	Semi-analytical calculation [kg^{-1} y^{-1}]
(α, n) from ^{232}Th chain	0.12	0.10±0.03
(α, n) from ^{238}U chain	0.27	0.26±0.08
Spontaneous fission	0.79	0.8±0.3
Total flux	1.18	1.2±0.4

F. Pupilli et al. , *Intrinsic neutron background of nuclear emulsions for directional Dark Matter searches*, to be submitted to Astrophysical Journal



Intrinsic neutron yield

GEANT4 simulation:

20.4% of neutrons interact producing nuclear (56%), proton (44%) and α (0.2%) recoils

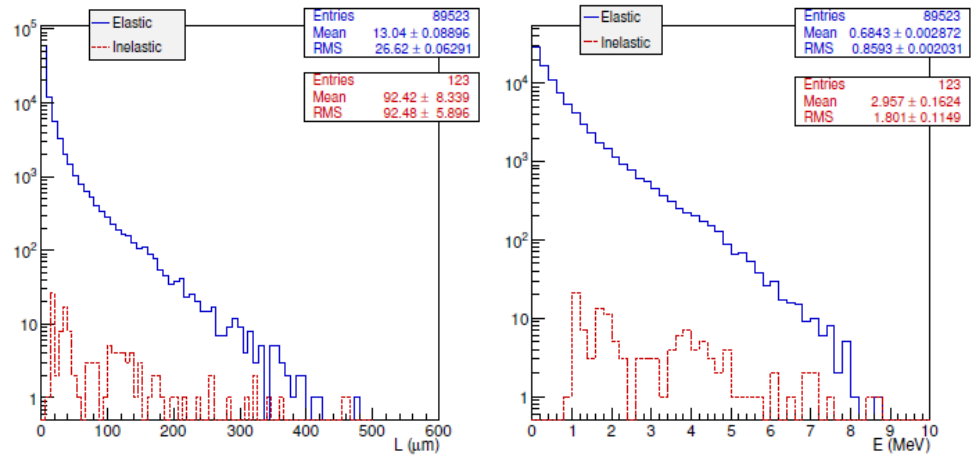


Figure 2: Track length (left) and energy spectrum (right) for proton recoils produced by elastic (blue curve) and inelastic (red curve) processes.

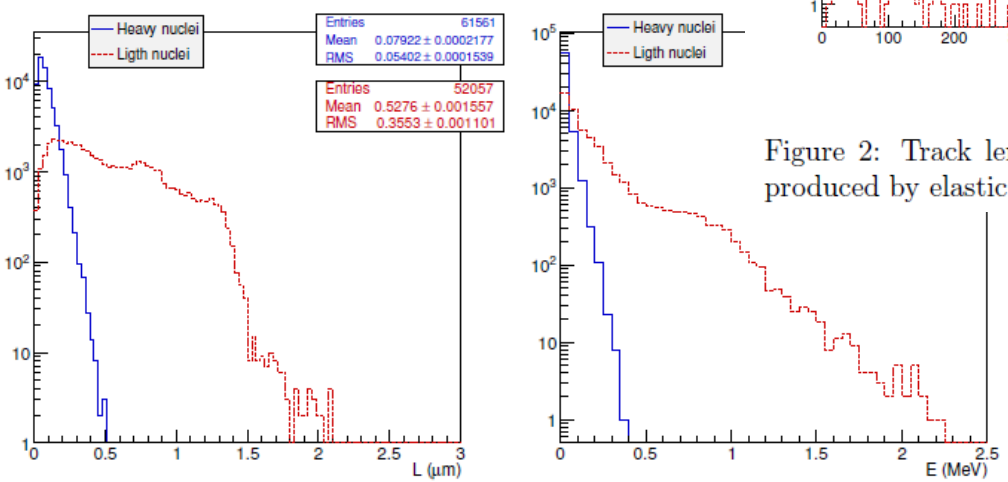


Figure 3: Track length (left) and energy spectrum (right) for heavy (blue curve) and light (red curve) nuclei.

Intrinsic neutron yield

Threshold [nm]	Fraction
50	0.100
100	0.075
150	0.060
200	0.052

Table 6: Fraction of detectable neutron-induced recoils as a function of the read-out threshold.

- 5%÷10% of the intrinsic neutron flux contributes to the background
- A further reduction of 70% can be achieved exploiting the directionality information ($-1 < \Phi < 1$)

→ 0.02 ÷ 0.03 n/year/Kg