NAGOYA UNIVERSITY

KMI

素粒子宇宙起源研究機構

NEWS project

Hunting of directional dark matter with emulsions

~ Detector Technology~

Fundamental Particle Physics Laboratory
Graduate School of Science of Nagoya University
Division of Particle and Astrophysical Sciences

Tatsuhiro Naka

Nagoya University

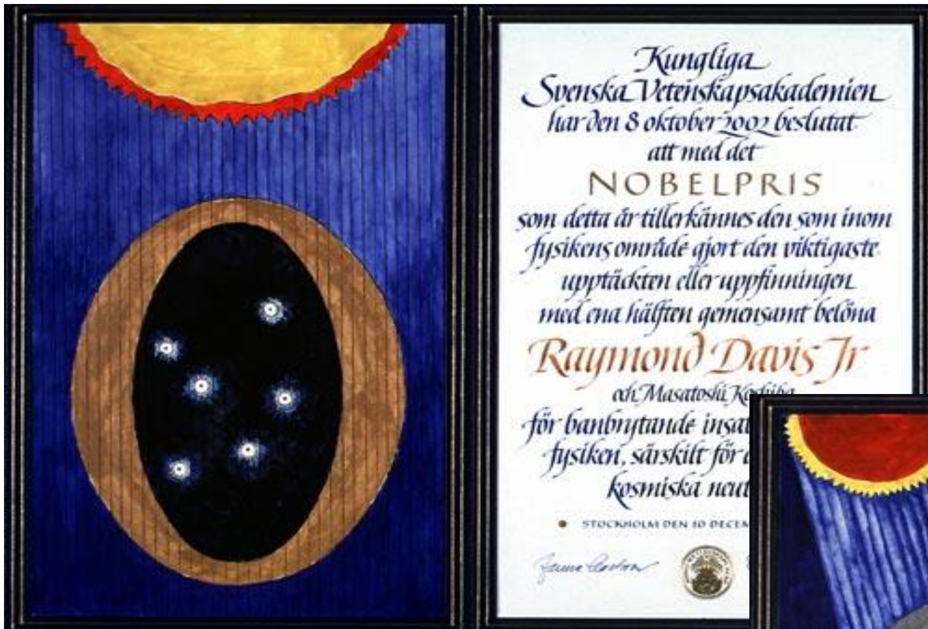
Kobayashi-Maskawa Institute, Japan

on behalf of the NEWS collaboration

NEWS seminar, 16 June, 2015@ University of Roma

Why is directionality?

<u>A certificate of merit of Novel Prize in 2002</u>



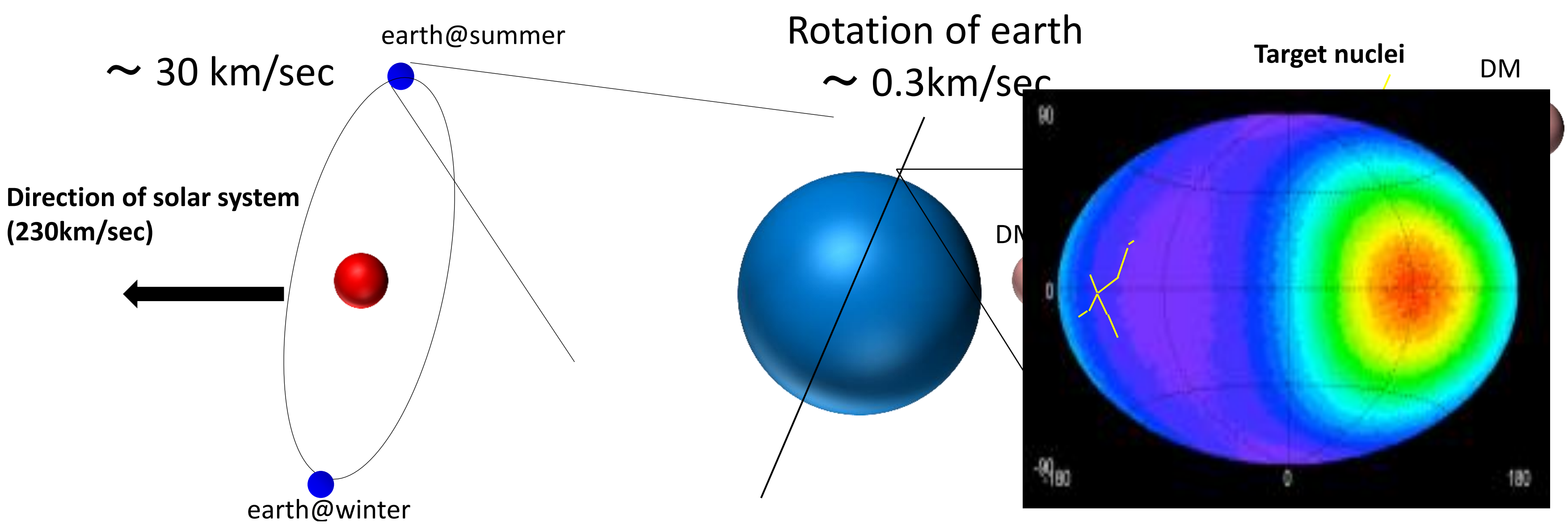
Prof. R. Davis Jr

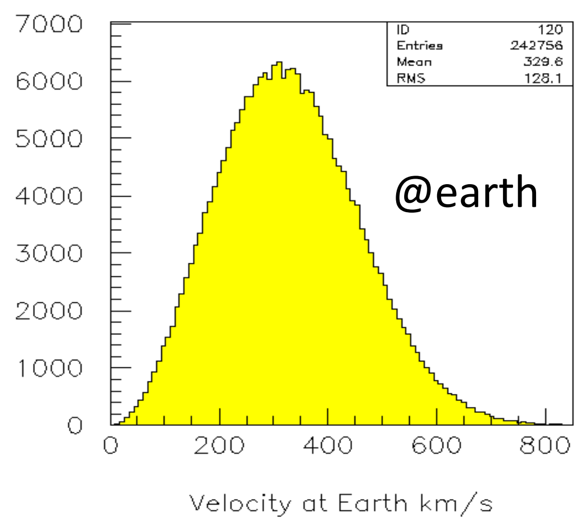
Current DM search motivation

Our motivation

Prof. M. Koshiba

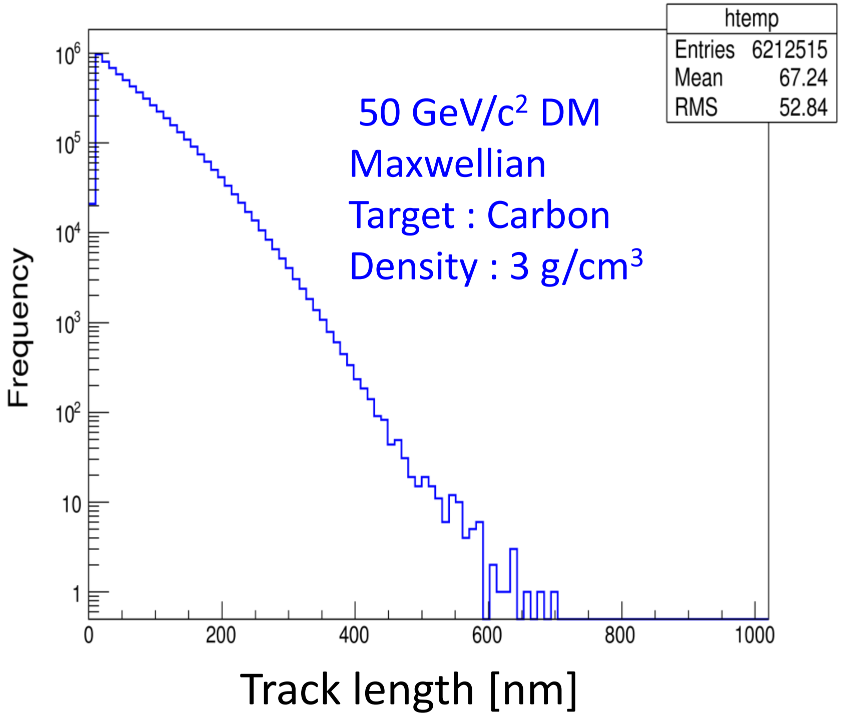
Directional Dark Matter Search





Dark Matter velocity distribution is assumed as Maxwellian.
(this is big assume itself)
⇒ velocity at earth frame is less than about 800 km/sec

Directional Dark Matter Search with Nuclear Emulsion



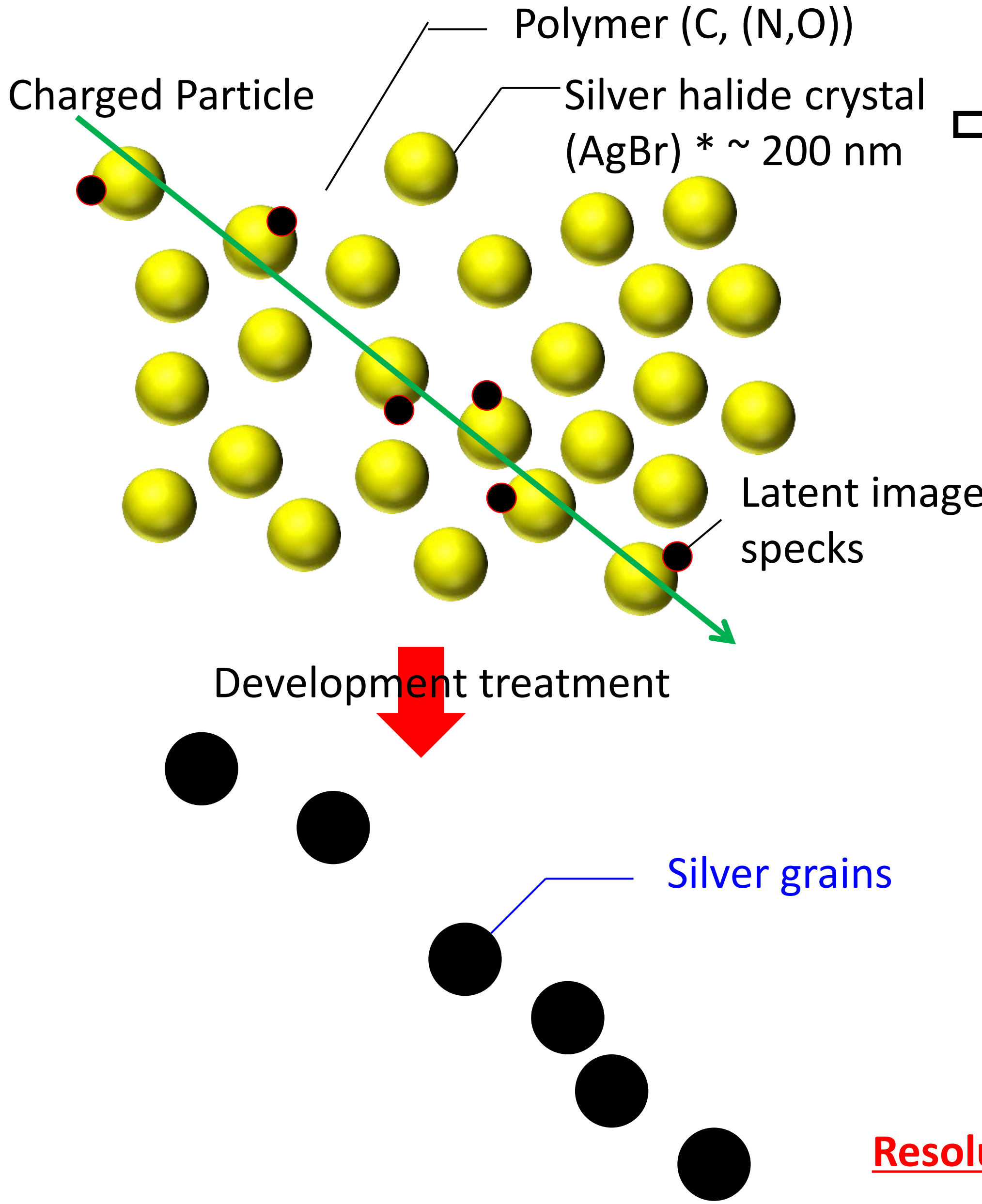
Required Detector Performance

- High spatial resolution
- enough angular resolution
- low-background
- scalability

⇩

Can the nuclear emulsion work as direction sensitive dark matter detector?

Detection Principle of emulsions detector



⇒ Semiconductor (VG ~ 2.7 eV)

- □ **Spatial resolution**
  ⇒ Crystal size and density
- □ **Angular Resolution**
  ⇒ crystal size

For example, in the case of usual type,

Crystal size : 200 nm (σ ~ 10 nm)
Density : 2.8 g/cm^3
(Vol. occupancy of crystal : 30 %)

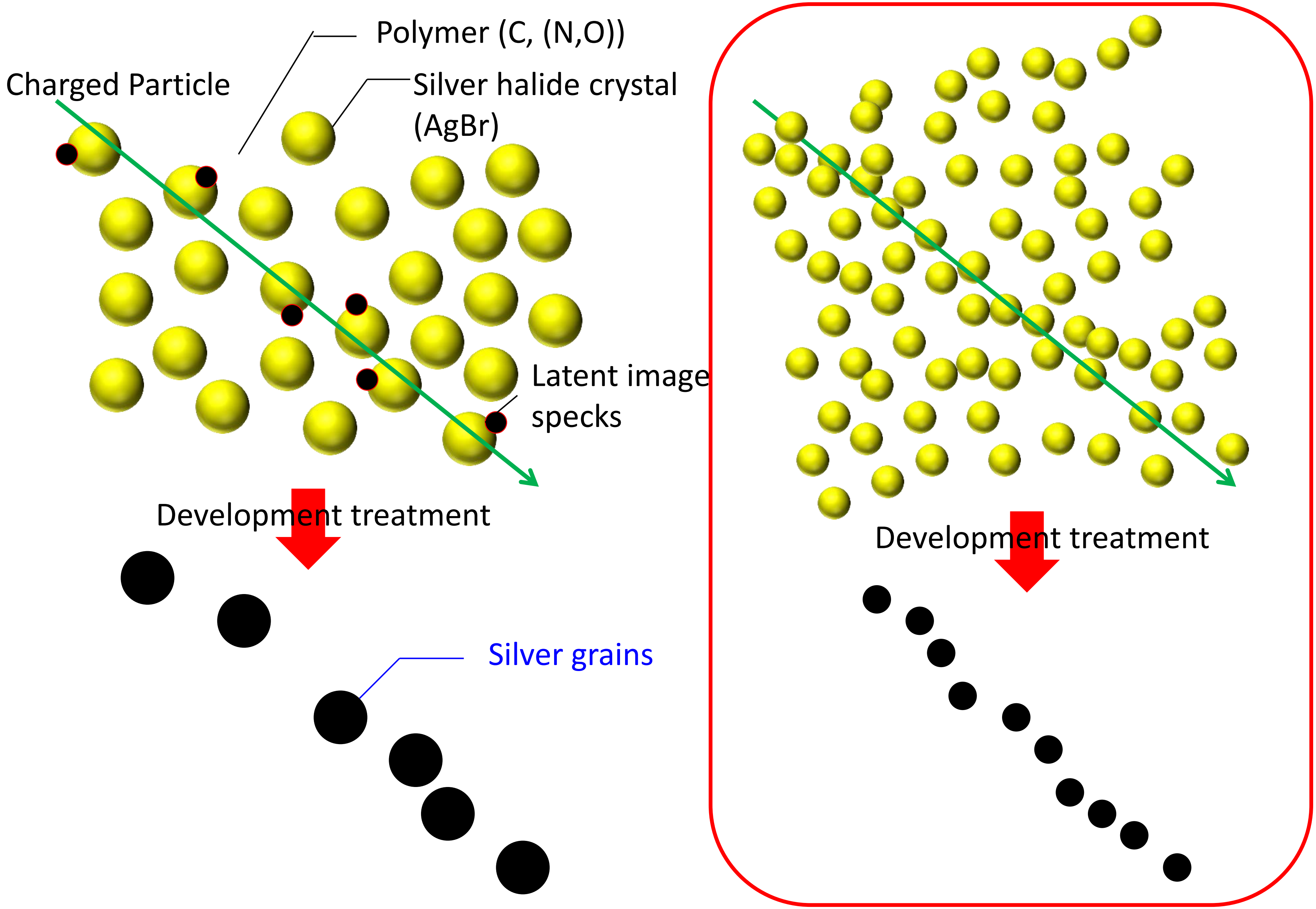
⇩

<u>2.4 crystals / μm</u>

Detectable more than μm order!!

<u>Resolution is poor yet for directional DM search.</u>

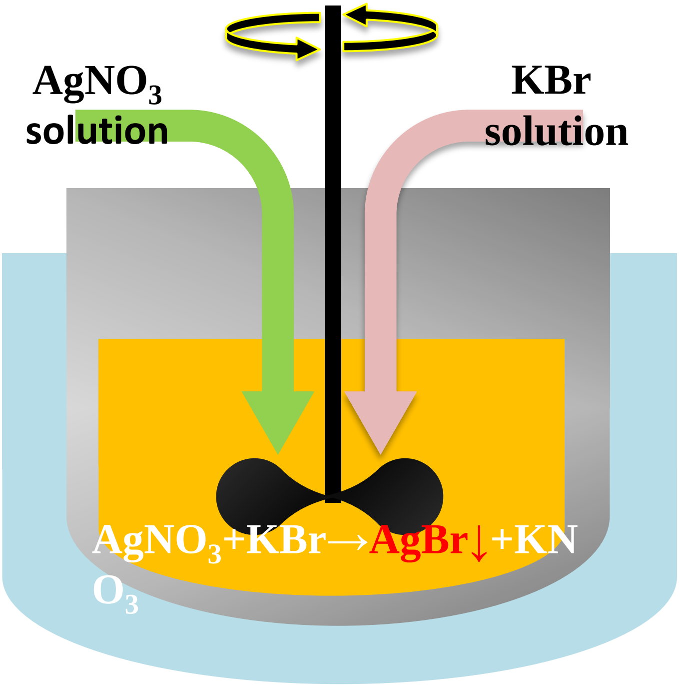
Higher resolution



Nuclear Emulsion Production for Dark Matter search

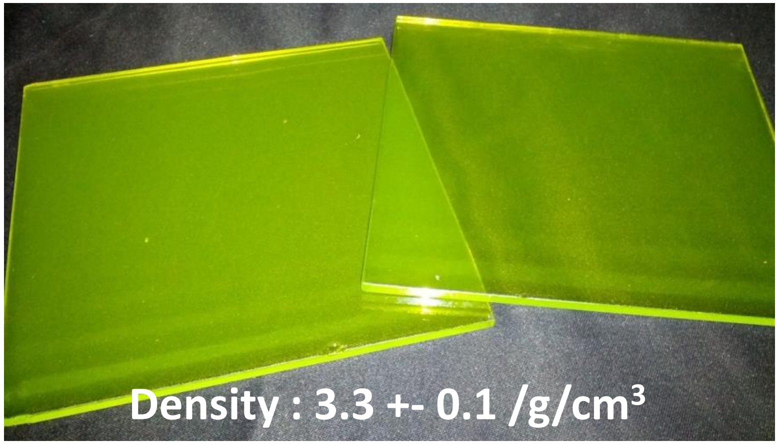
2008～ : start of discussion
2010. Apr.～ : Start of install of machine in Nagoya university
(2014～ : Install of larger scale machine)

- ☐ Development of new original device
- ☐ Elemental Study for detection mechanism
- ☐ Supply of emulsion device to the world



Production scale : 1 kg device/week
Production cost : 1 k EURO/device of kg
(60 % of all cost is $AgNO_3$)

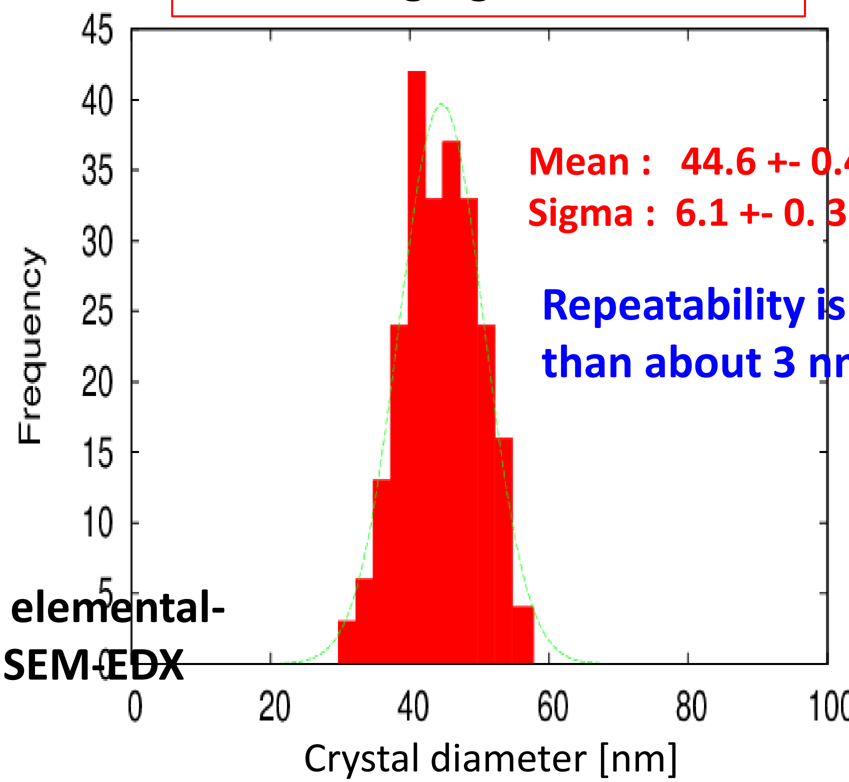
Fine-Grained Emulsion
[Nano Imaging Traker : NIT]



	Mass fraction
AgBr-I	0.78
Gelatin	0.17
PVA	0.05

	Weight occupancy
C	10.12
H	1.63
O	7.41
N	2.68
S	0.03
Ag	44.065
Br	32.190
I	1.875

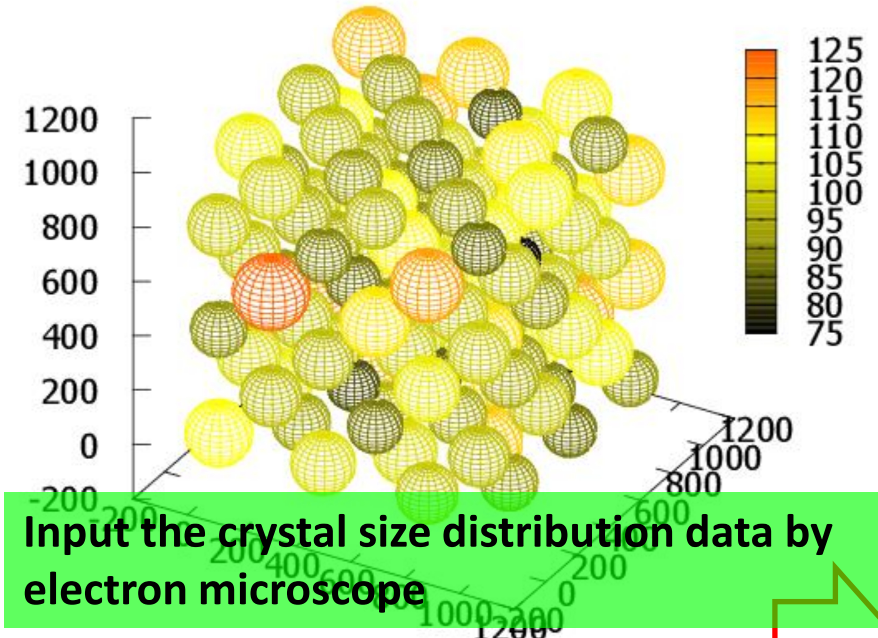
Nano Imaging Tracker; NIT



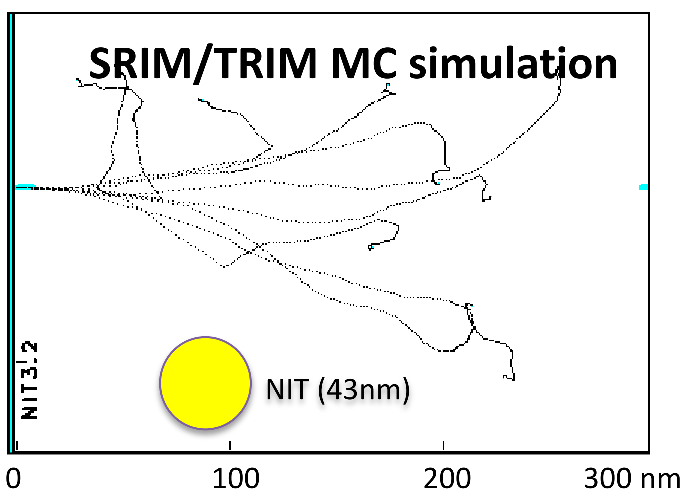
Repeatability is less than about 3 nm.

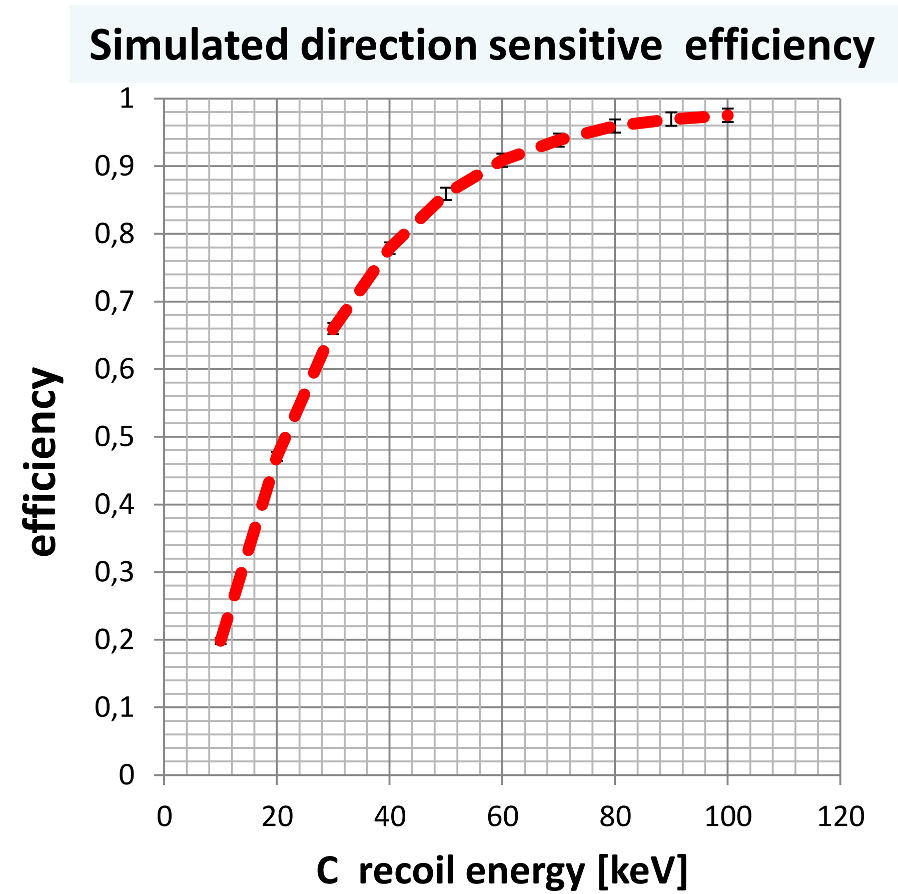
Measured by elemental-analyzer and SEM-EDX

New simulation for nuclear emulsion
[Intrinsic resolution with direction sensitivity]



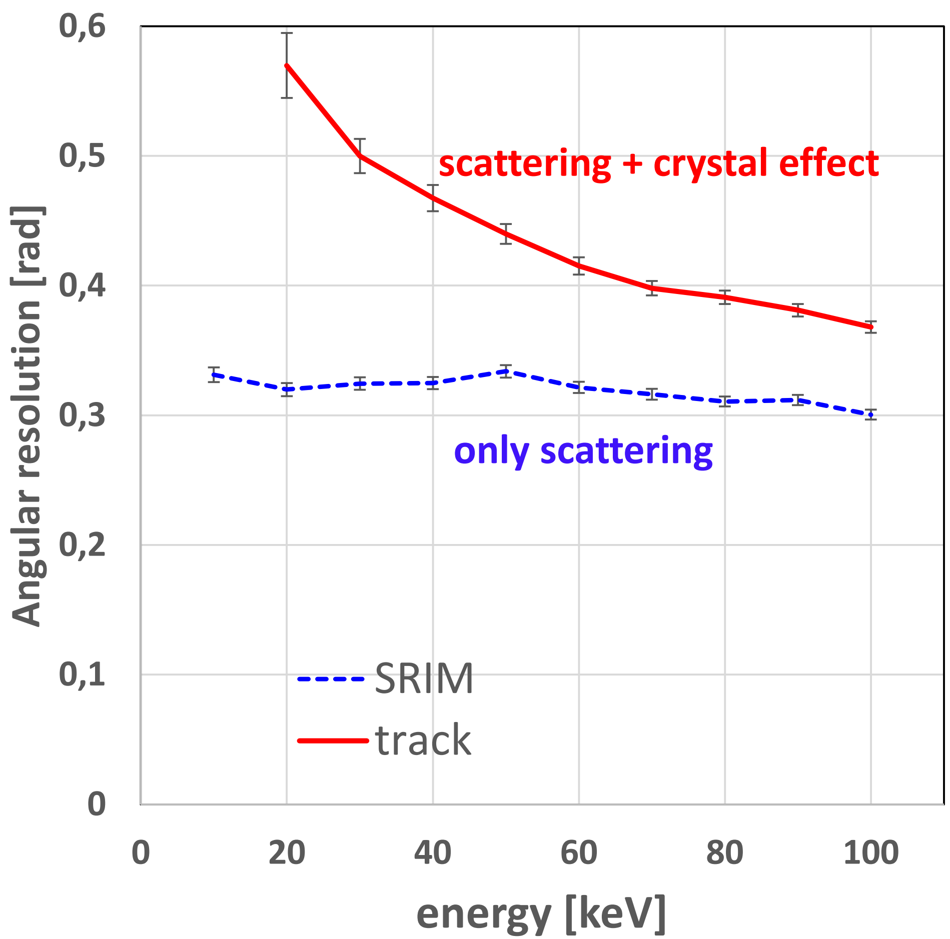
Input the crystal size distribution data by electron microscope

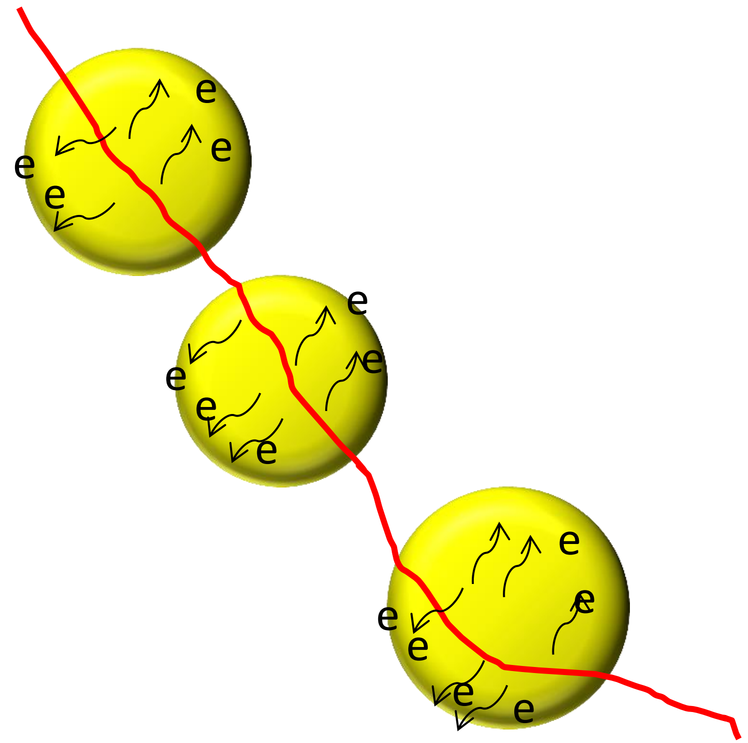




NIT has the potential of direction sensitivity to 10 keV for C recoil.

Potential of NIT
[Angular resolution]





Ionized electrons are closed in the crystal.
⇒ angular resolution is defined by scattering and crystal size effect

Scattering effect : ~ 300 mrad.
Intrinsic resolution : ~ 250 mrad (crystal size effect)

Readout Strategy

High-speed roughly Selection and screening

$\Rightarrow$ optical microscopy

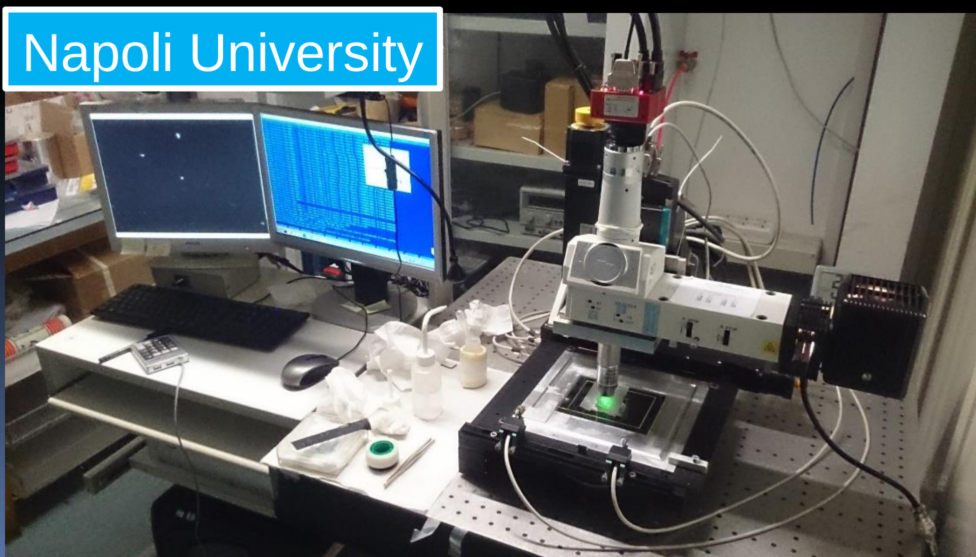
High precision analysis

Various new technology will be innovated

-Higher resolution microscopy
- nano-scale information
- 3D angle information
 etc.

Optical Readout Machine for shorter length tracks

Nagoya University



Napoli University

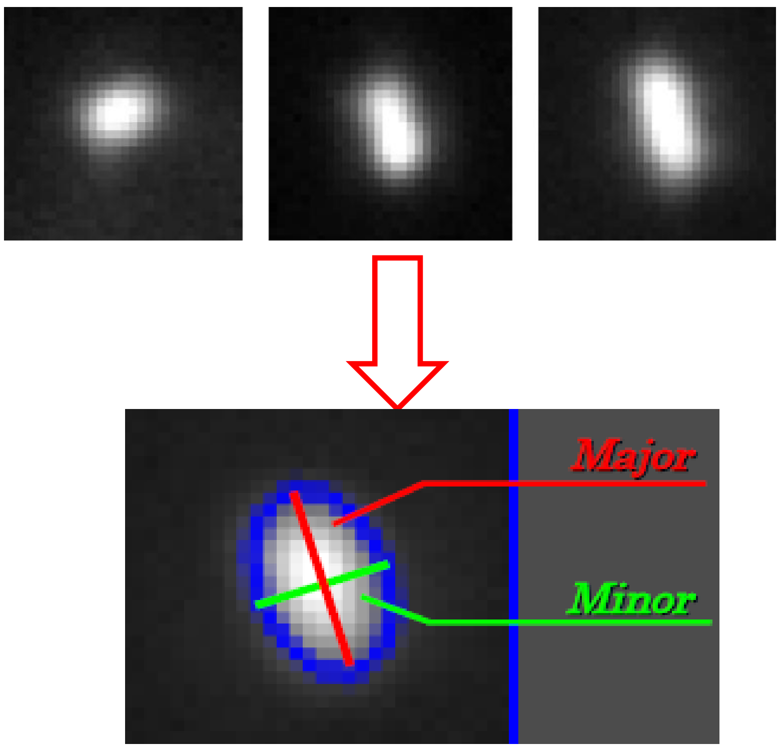
LNGS(Gran sasso)

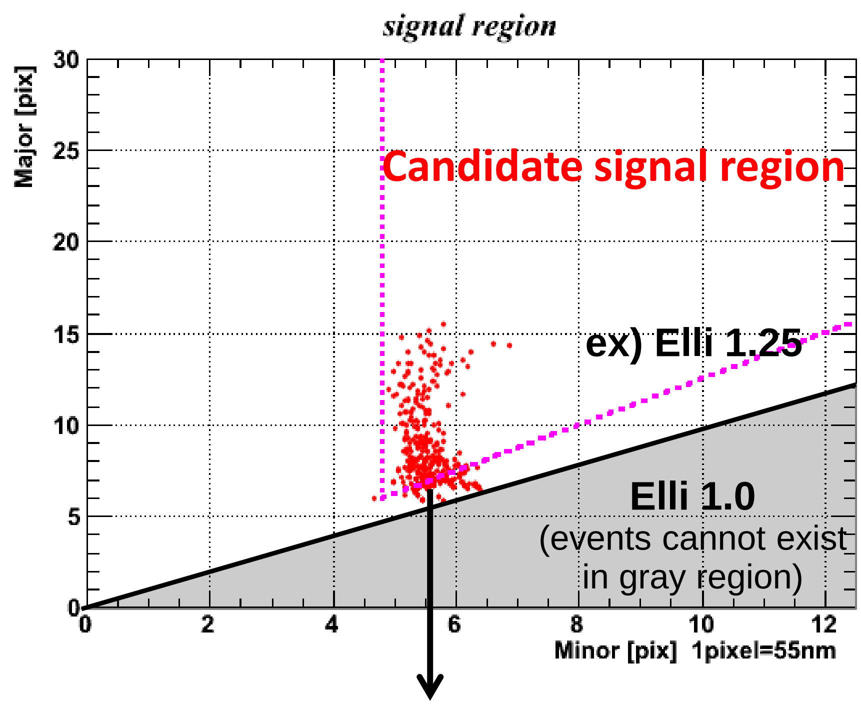
All systems are adopted the epi-illuminated optics.

Candidate selection for optical microscope system

Example of nuclear recoil signal

2D_Track length vs. Ellipticity





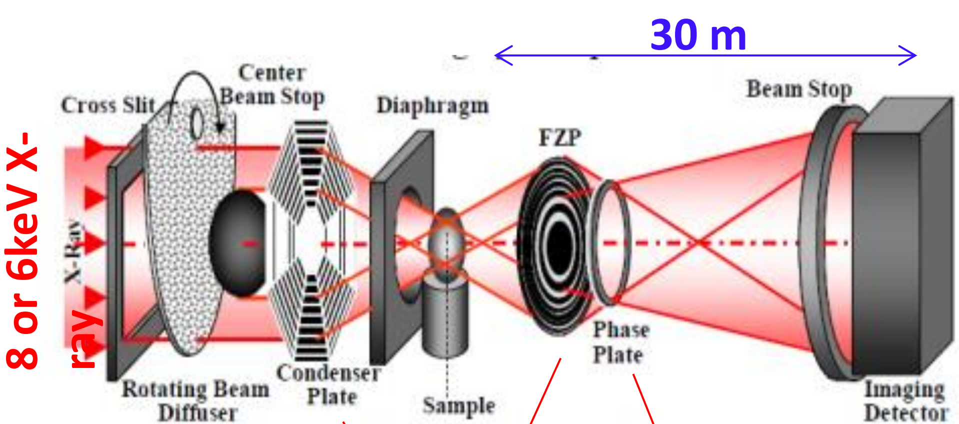
Current selection is used the simple elliptical shape

γ/β events are expected to be distributed around Ellipticity of one.

Another out put parameter
- **position information**
- **brightness**
- **area of signals**

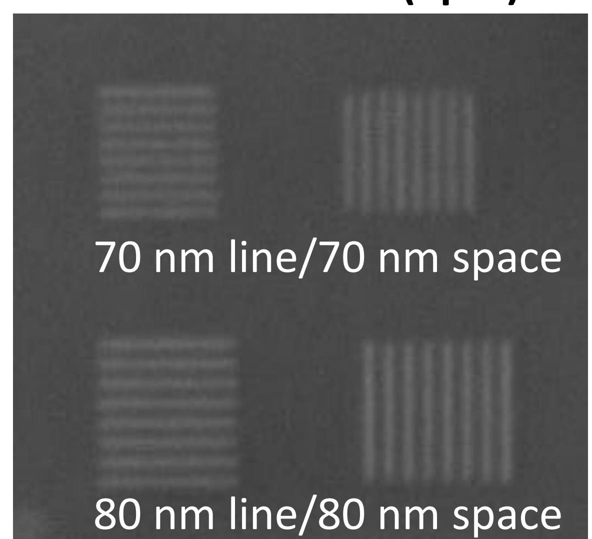
Hard X-ray microscope

SPring-8 @ Japan

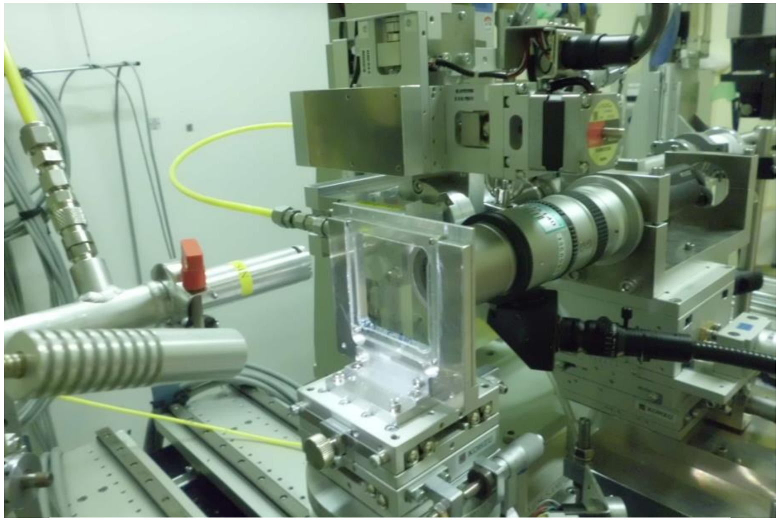


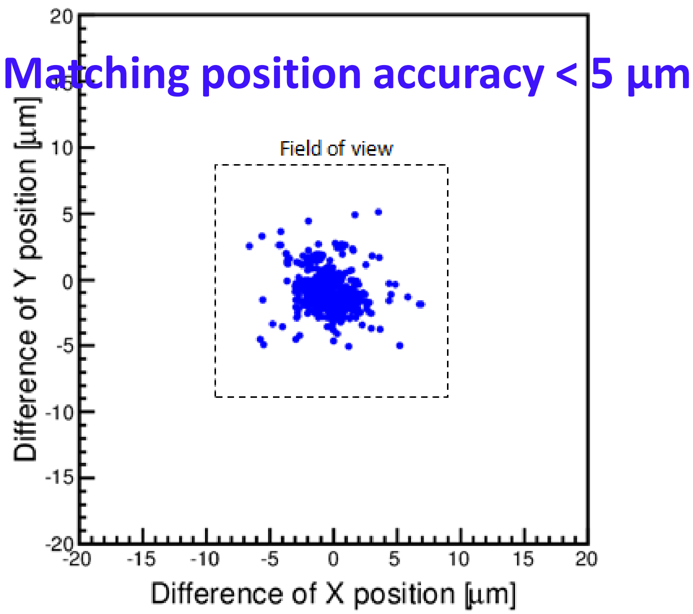
Zone plate
(outer most zone width of 50 nm)
Zernike phase plate

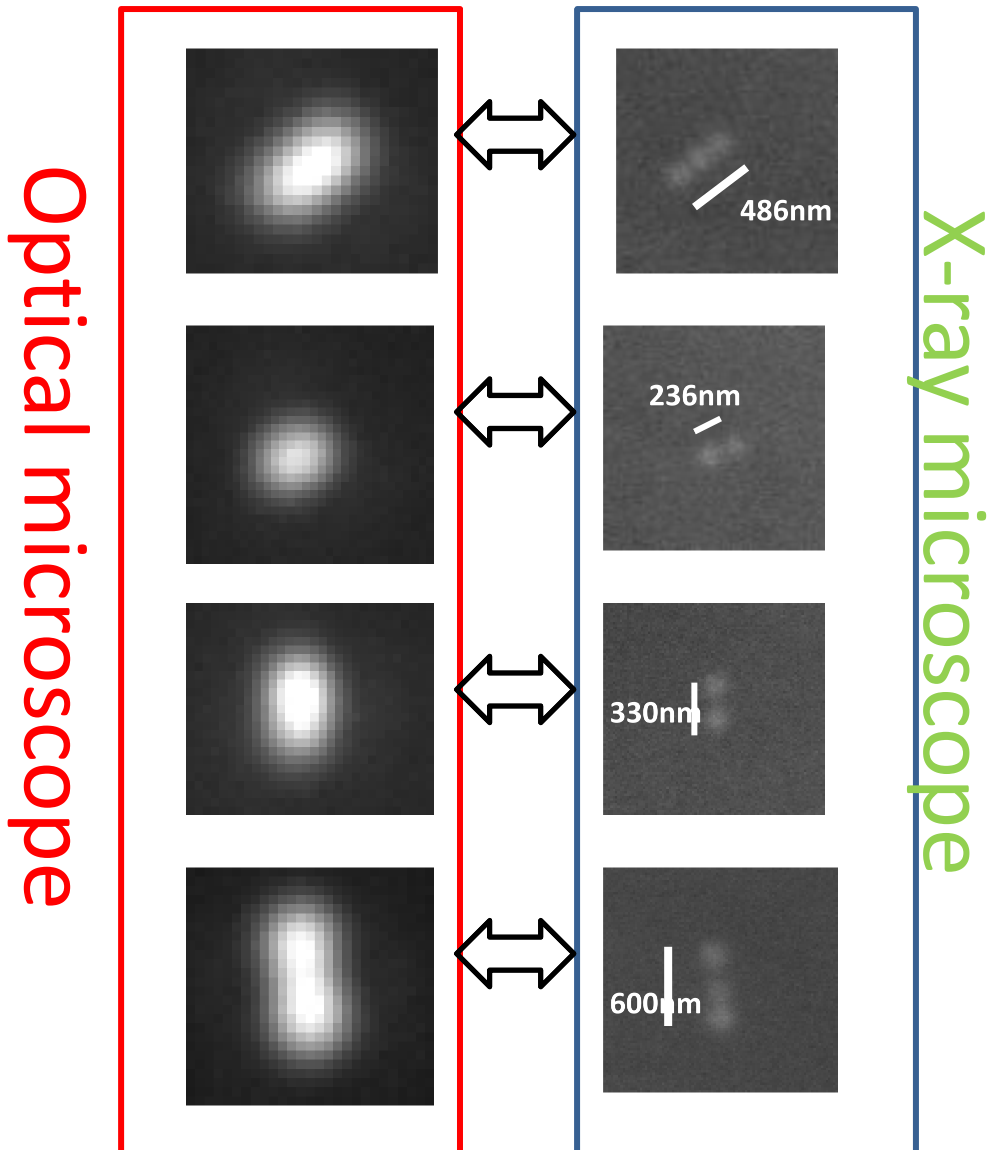
Ta 100 nm thickness pertarn on SiN membrane (2μm)



Maching of recoiled tracks between Optical and X-ray microscope



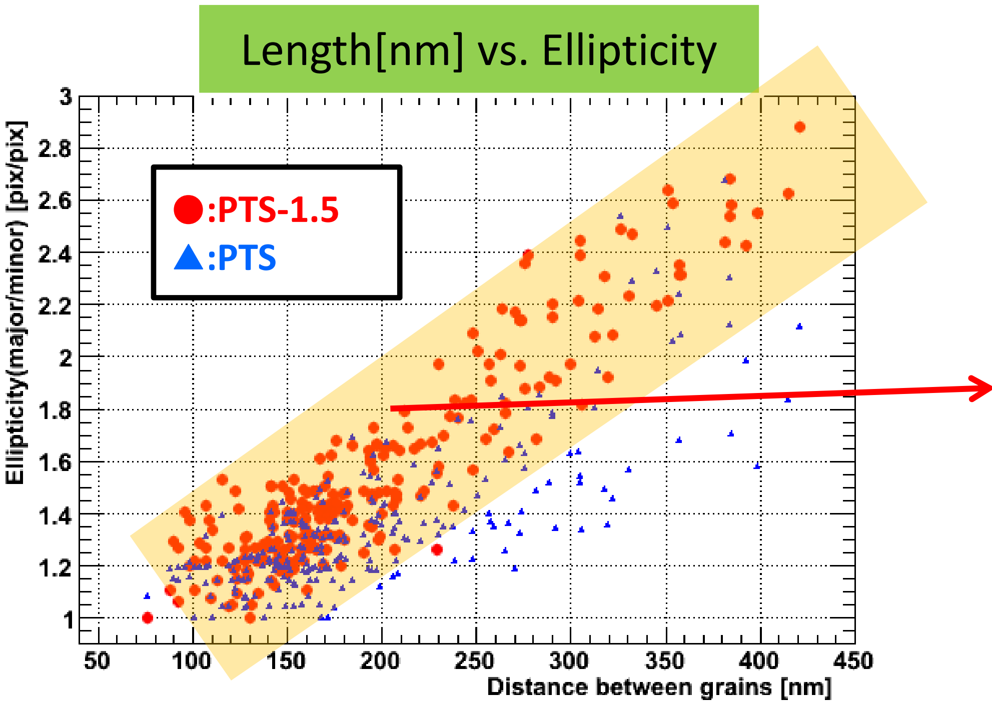


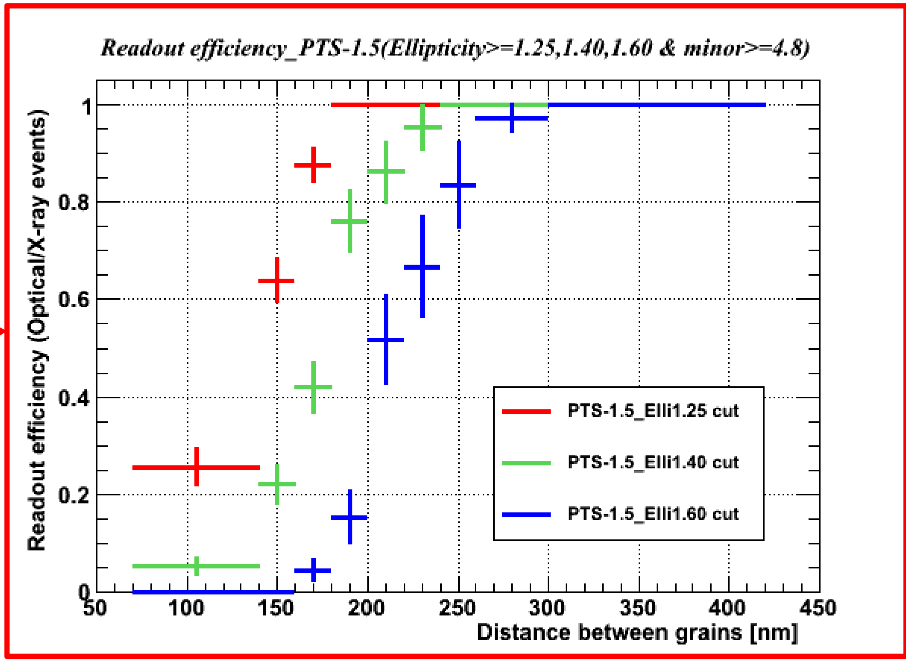


Maching efficnecy > 99 %

Imaging speed : 1000 events /days

Readout Efficiency dependence of ellipticity to real length





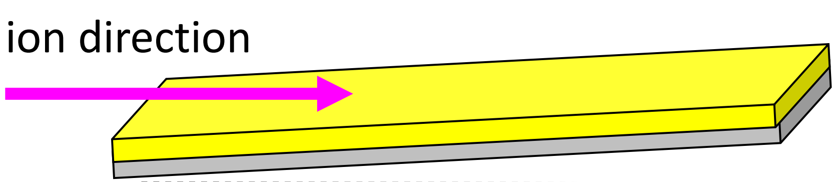
	PTS-1	PTS-1.5
N.A. of obj. lens	1.25	1.4
Wavelength	550 nm	450 nm
Optical resolution [measurement from PSF]	**315 nm**	**233 nm**

By high resolution setup, we can read out more than 100 nm length tracks.

Tracking Study
[Ion-implantation]

Type of gas : CO_2 ▪ Ar, Kr
Dose Intensity : > 1E+7 /cm^2
Accelerate Voltage : 10 -200 keV
(Higher energies can be exposed by control of ionic valence.)
Ex. 200 kV x Kr^{2+} = 400 keV Kr

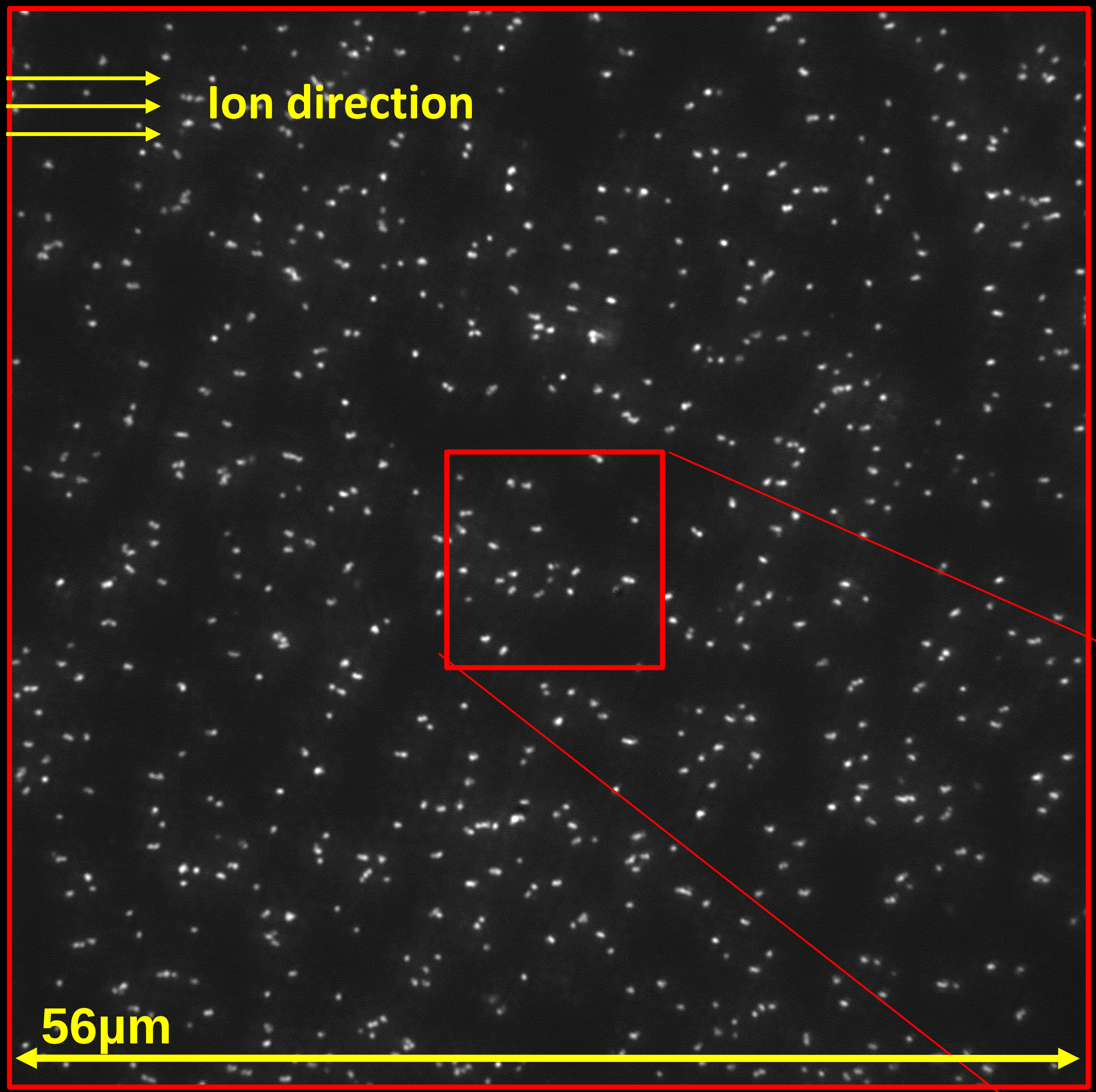
Exposure condition
Vacuum level : ~ 1E-7 torr
recorded area of film : surface

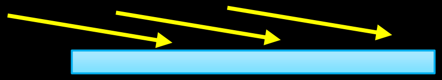


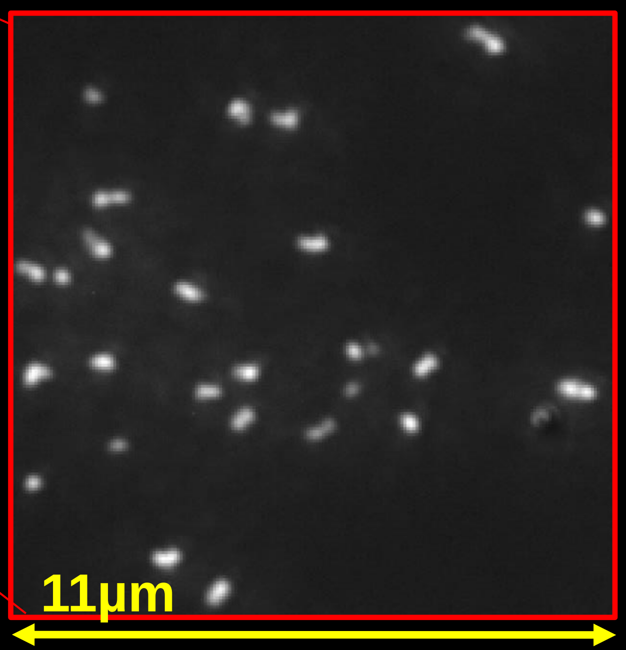
- ☐ monochromatic energy
- ☐ uniform direction (< 1 mrad.)

⇨ Detector performance [detection efficiency, angular resolution]

Actual image of tracks @Carbon 100 keV



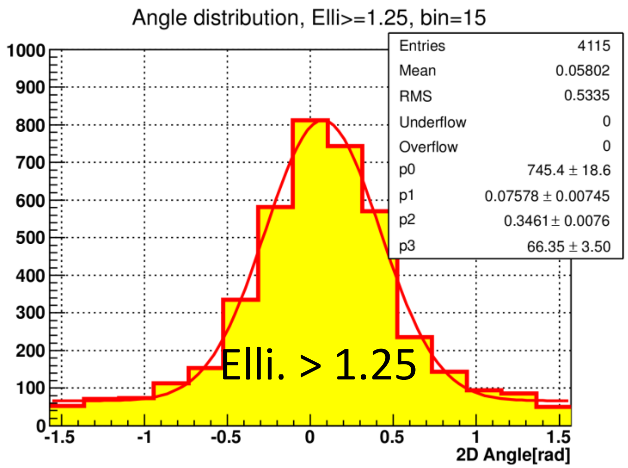


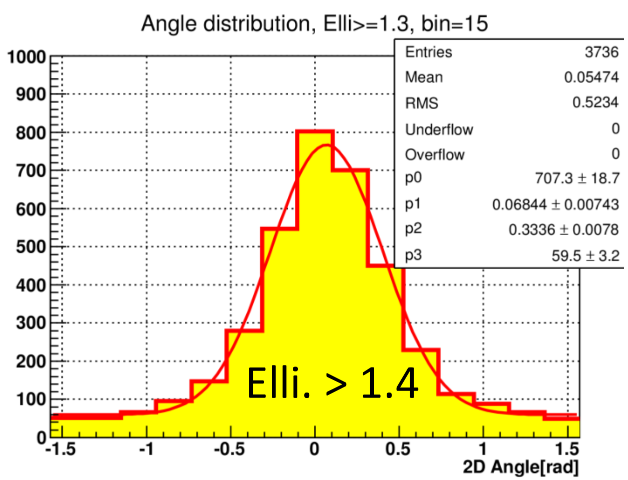


Blue

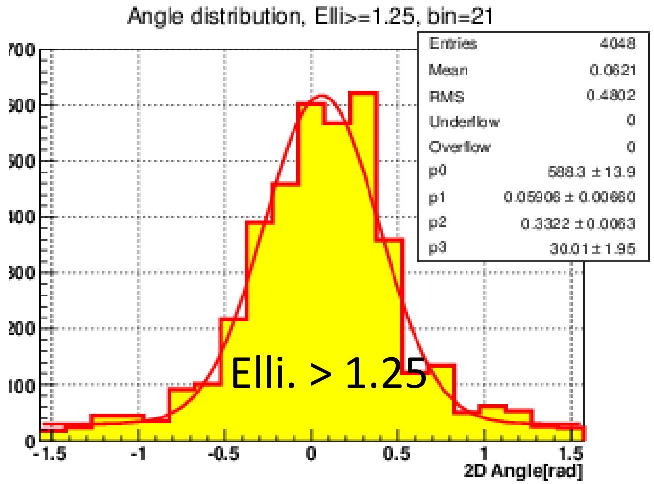
Angular distribution measured by optical microscope

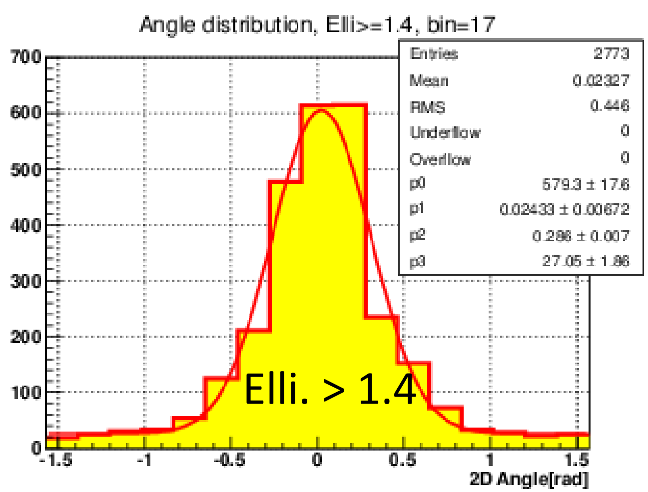
100 keV C



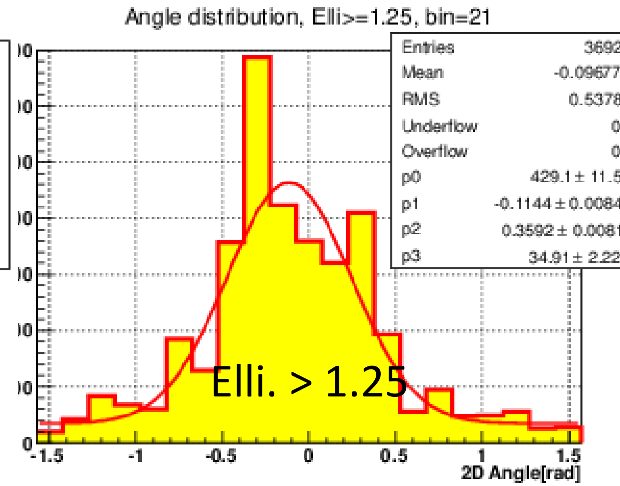


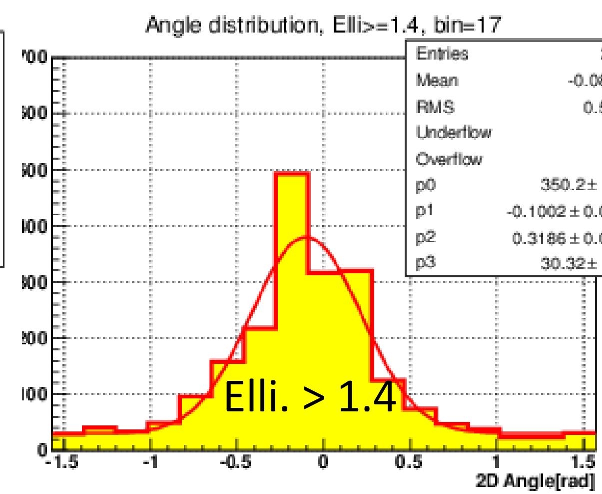
80 keV C



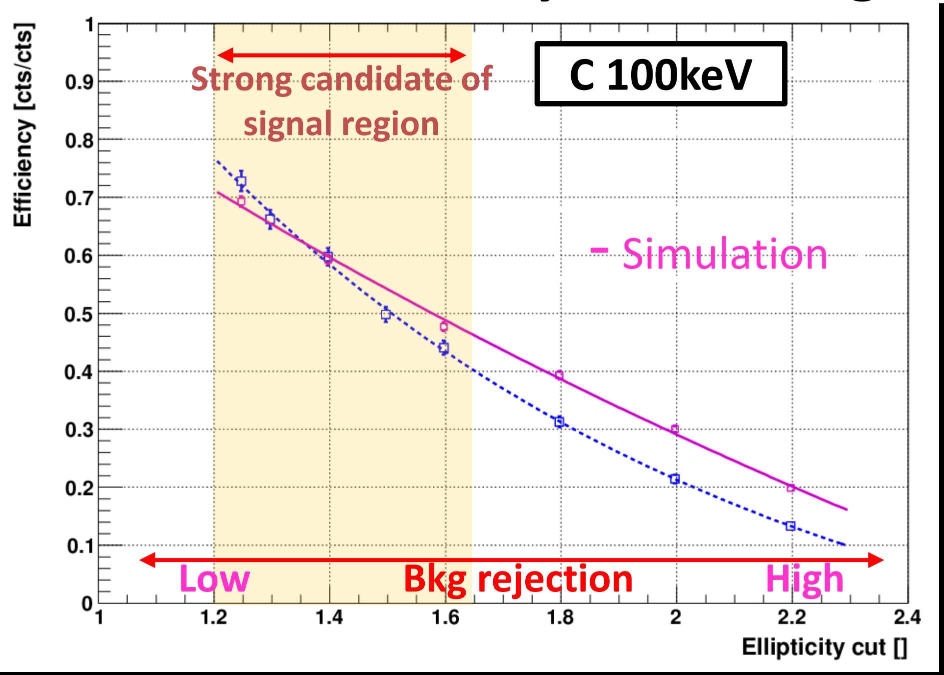


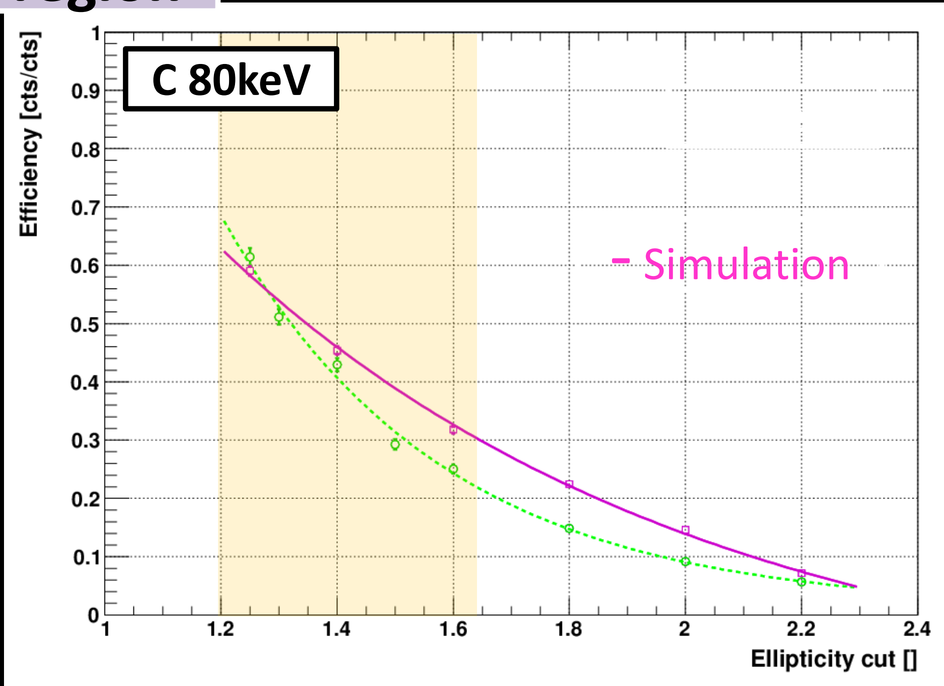
60 keV C



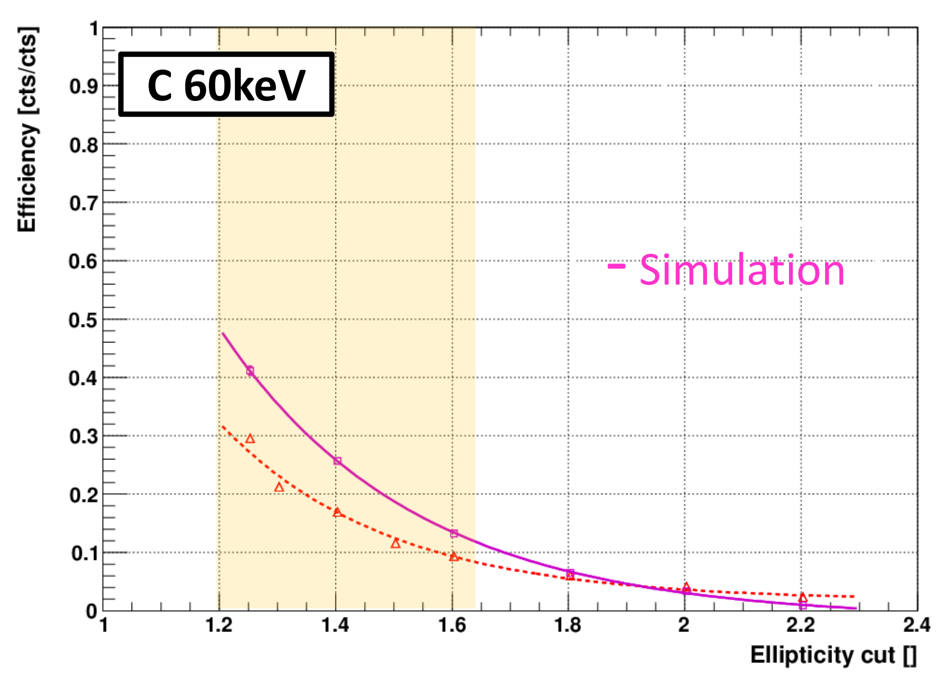


Detection efficiency for each signal region



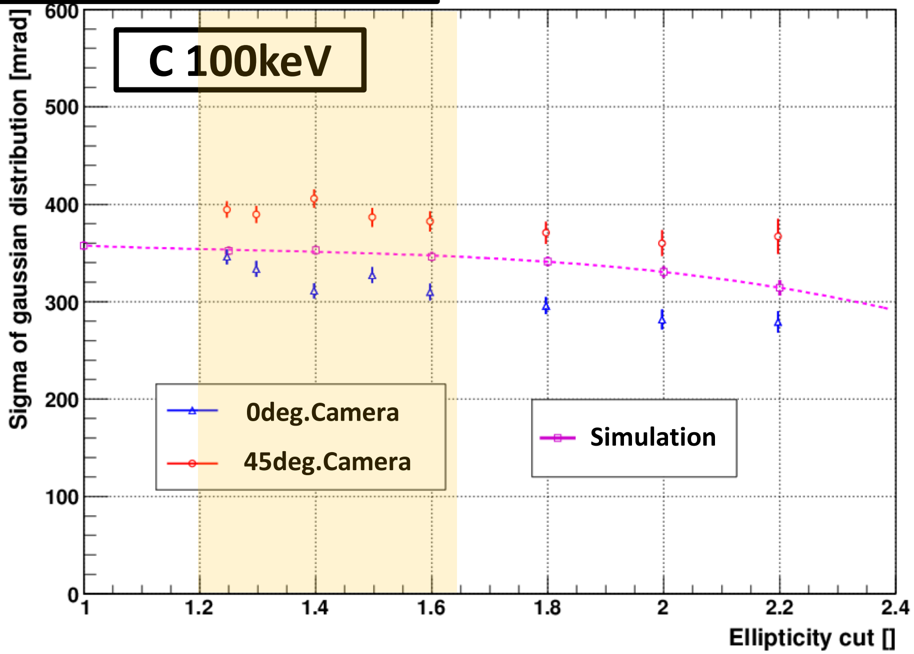


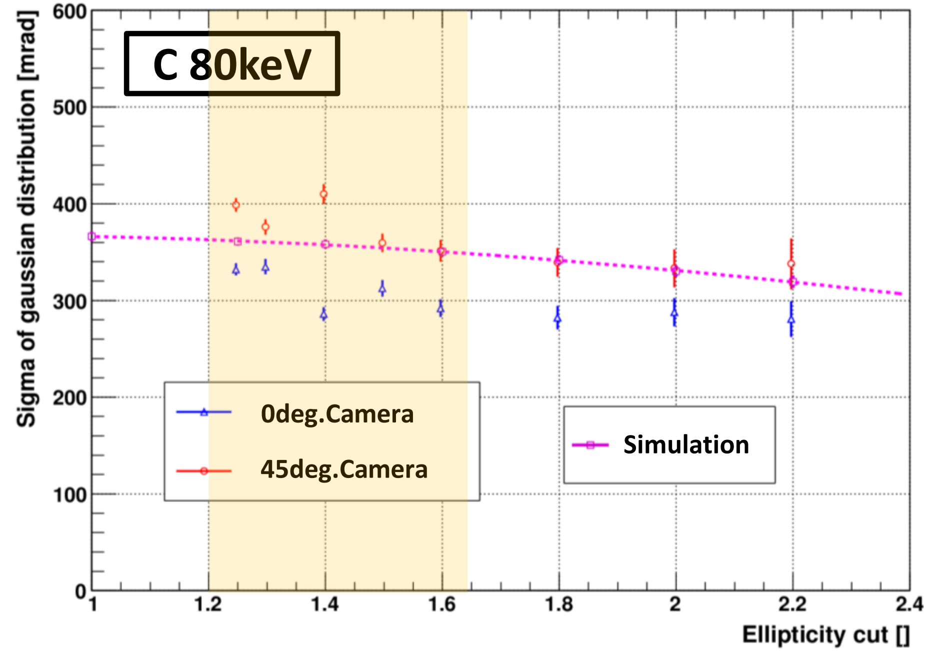
"Ellipticity cut" vs. "Efficiency"



Simulation was assumed 100 % quantum efficiency of crystal

Angular resolution

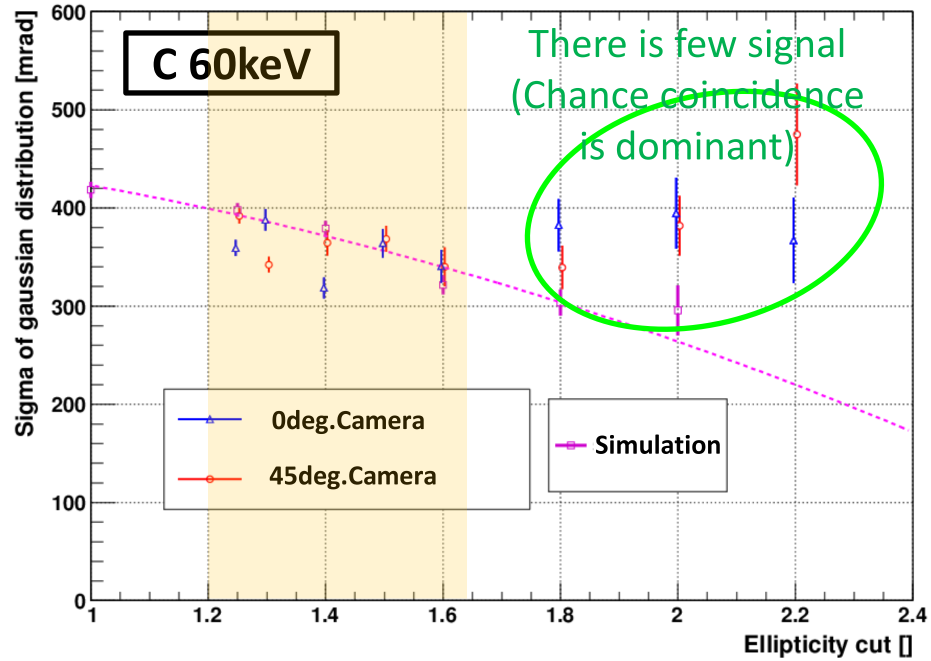




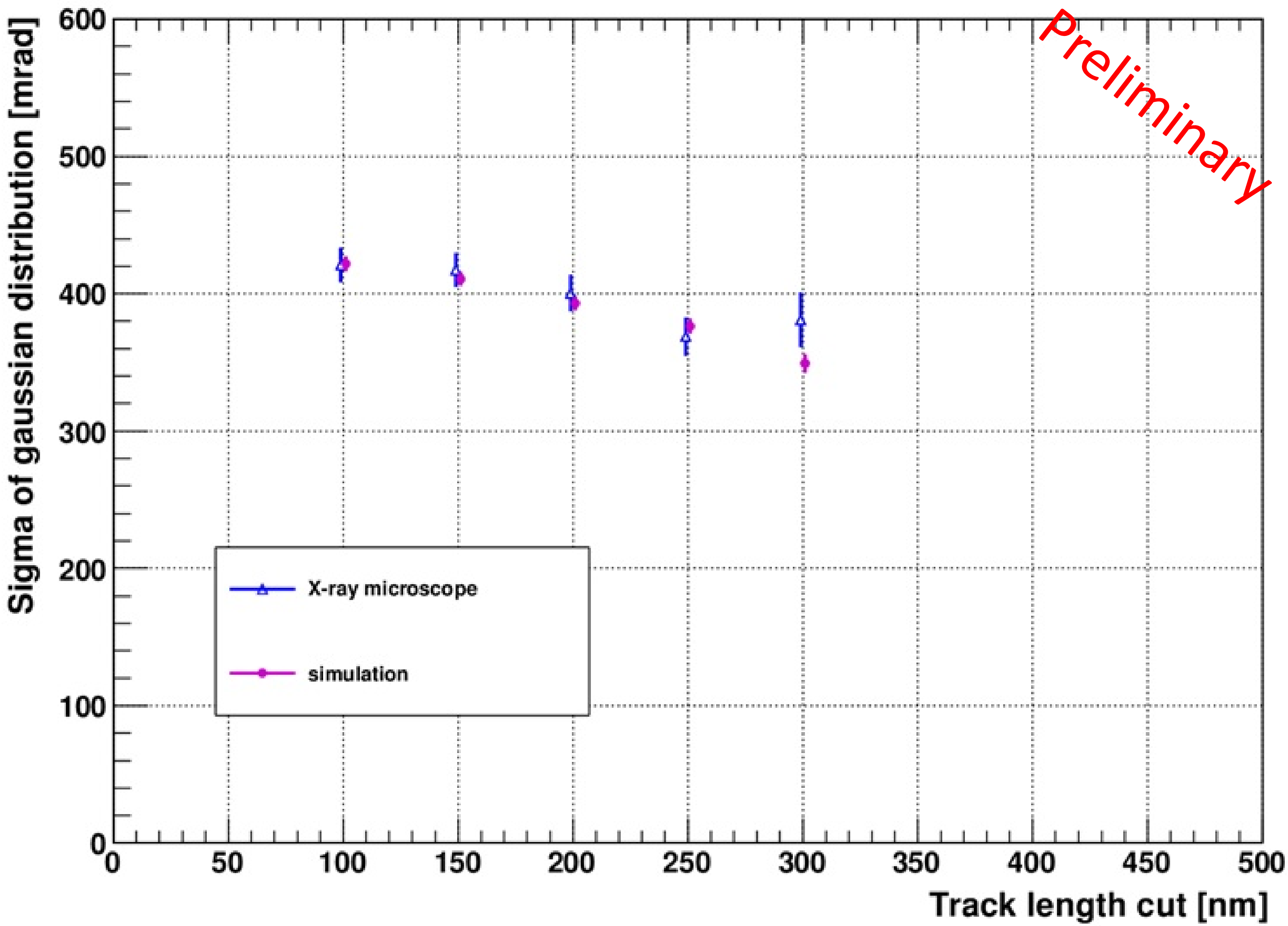
“Ellipticity cut”

vs.

“Sigma of Gaussian in angular distribution”

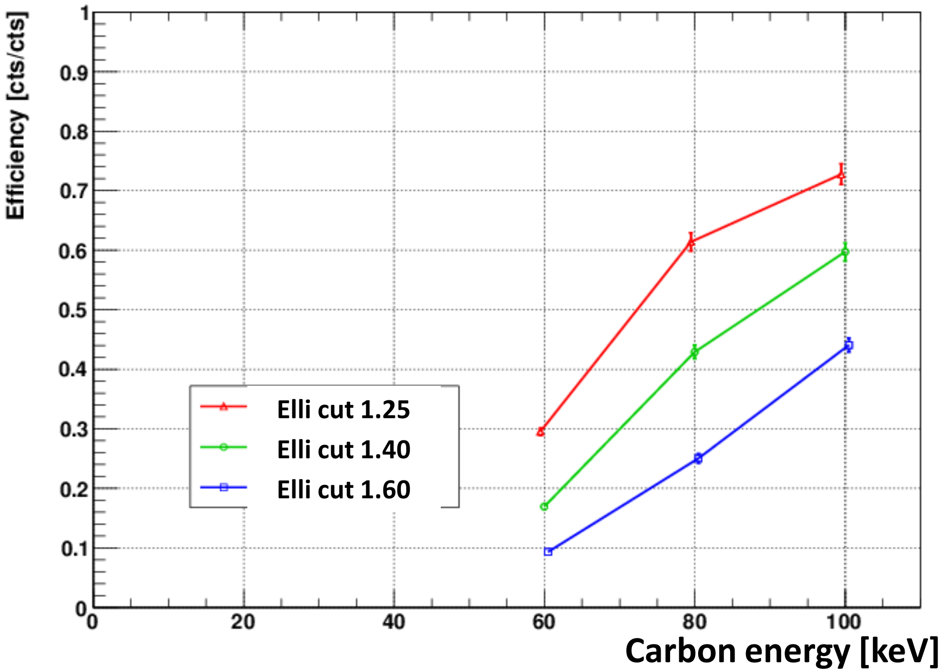


Comparison of angular resolution between X-ray measurement and simulation

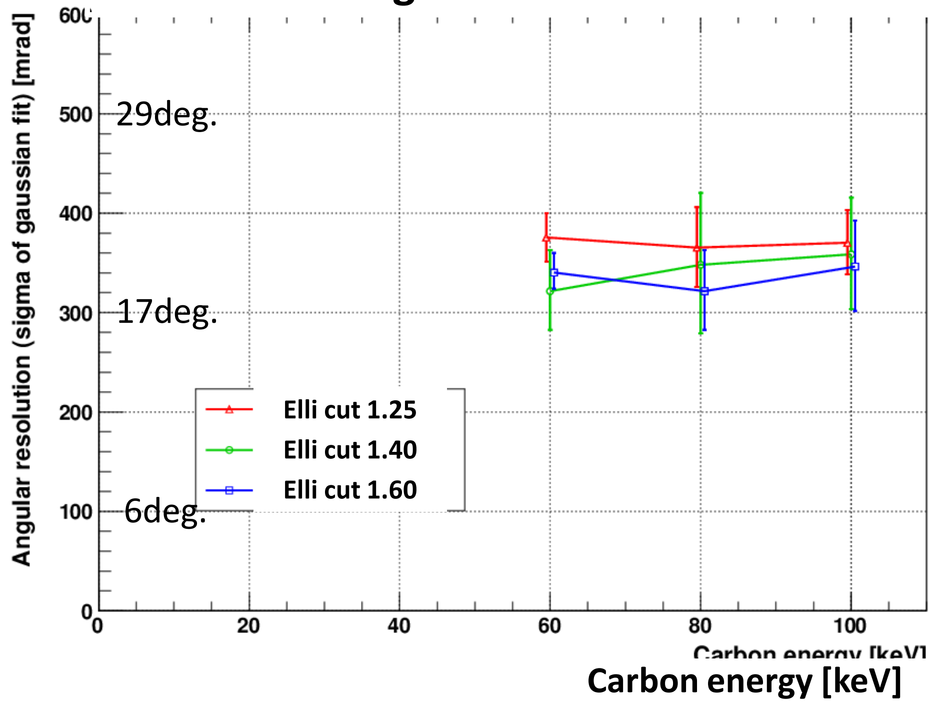


Result of performance [60 – 100 keV] [Ion-implant system]

Absolute efficiency with direction sensitivity



"Angular resolution"



Energy	Elli>1.4	Elli>1.25
100 keV	59.7 ± 1.5(stat) %	72.8 ± 1.7(stat) %
80 keV	42.9 ± 1.2(stat) %	61.4 ± 1.5(stat) %
60keV	16.9 ± 0.4(stat) %	29.5 ± 0.6(stat) %

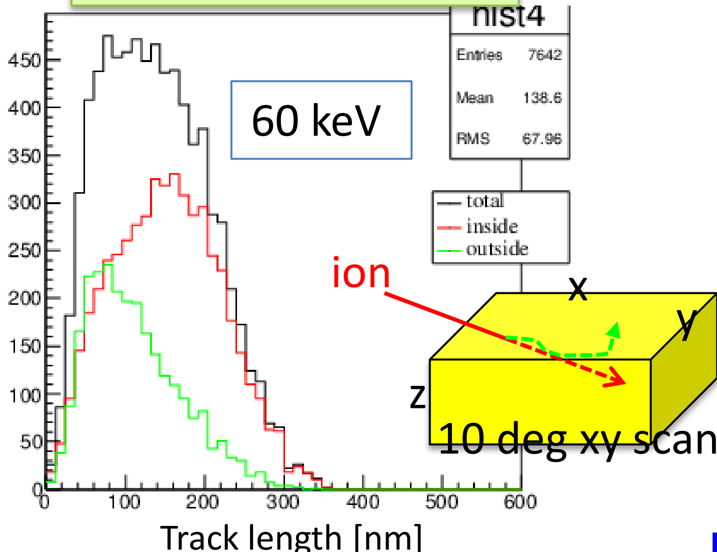
Systematic uncertainties have several % .

Angular resolution ~ 350 mrad.

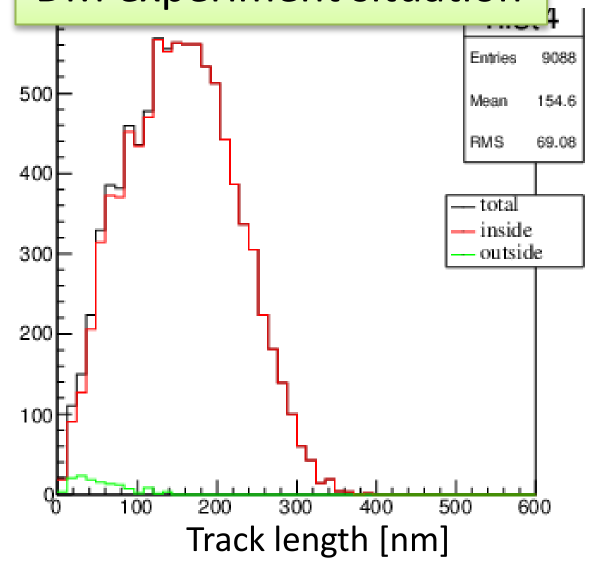
Angular resolution is top value to another directional DM detector.

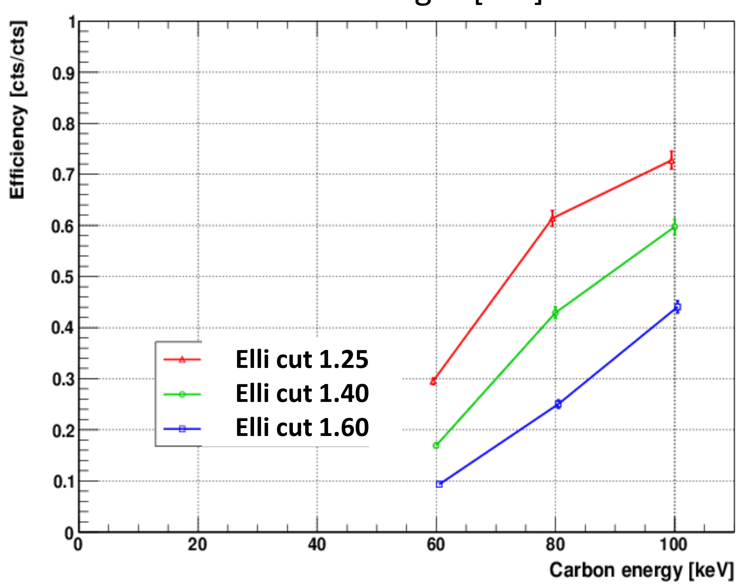
Correction of non-fiducial region effect

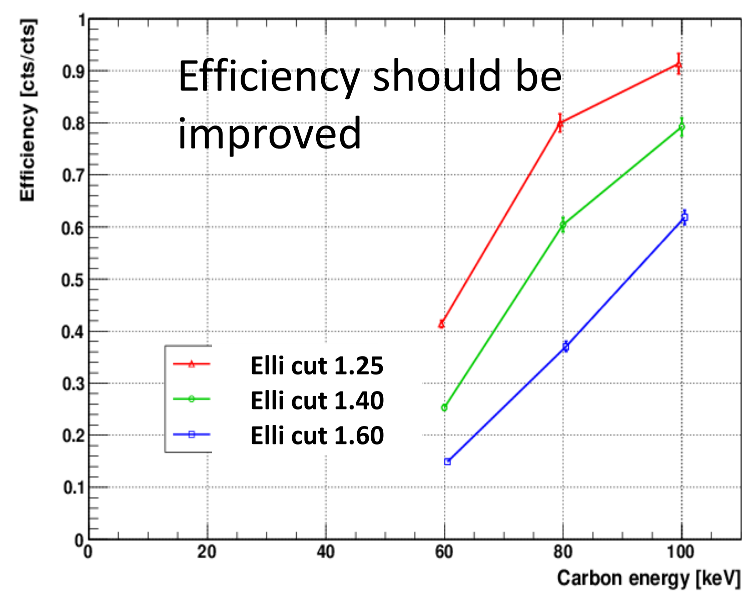
ion implant situation



DM experiment situation

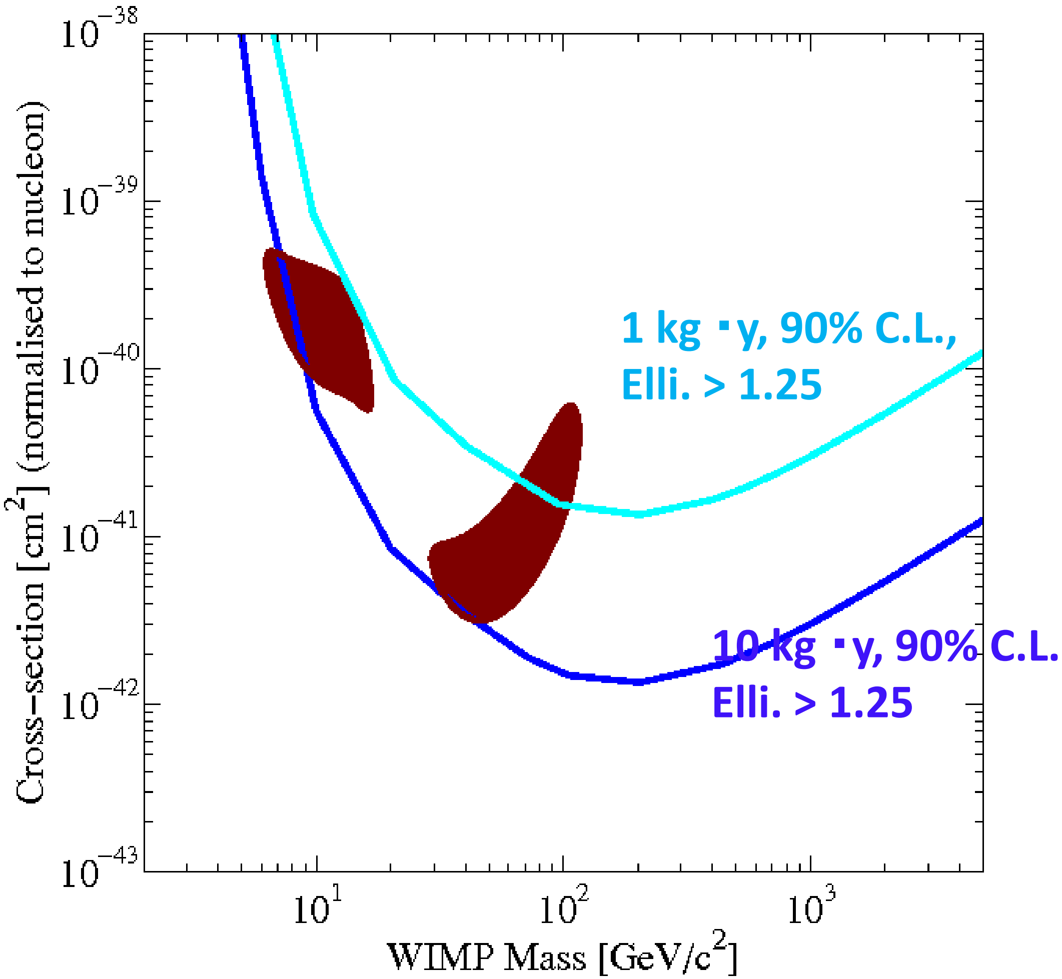






Current device was more than 40 % efficiency for 60 keV C recoil

Updated Spin-independent cross section limit [main target : CNO + Ag,Br]

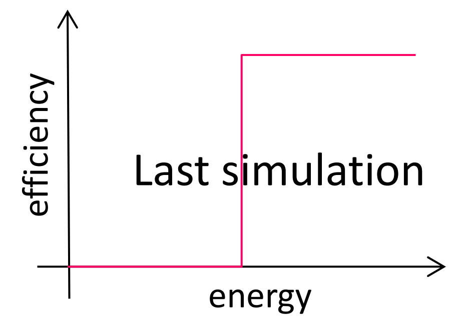


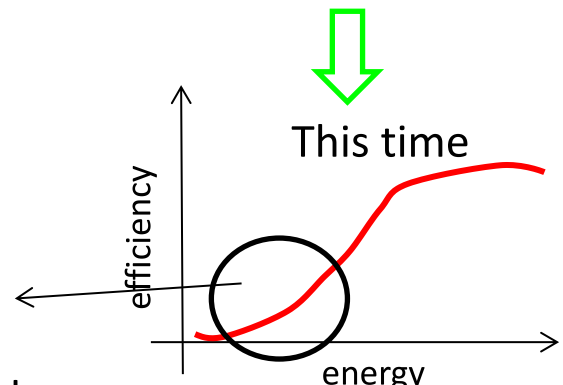
<u>Efficiency condition</u>

80% eff. @ 80 keV

40 % eff. @ 60 keV

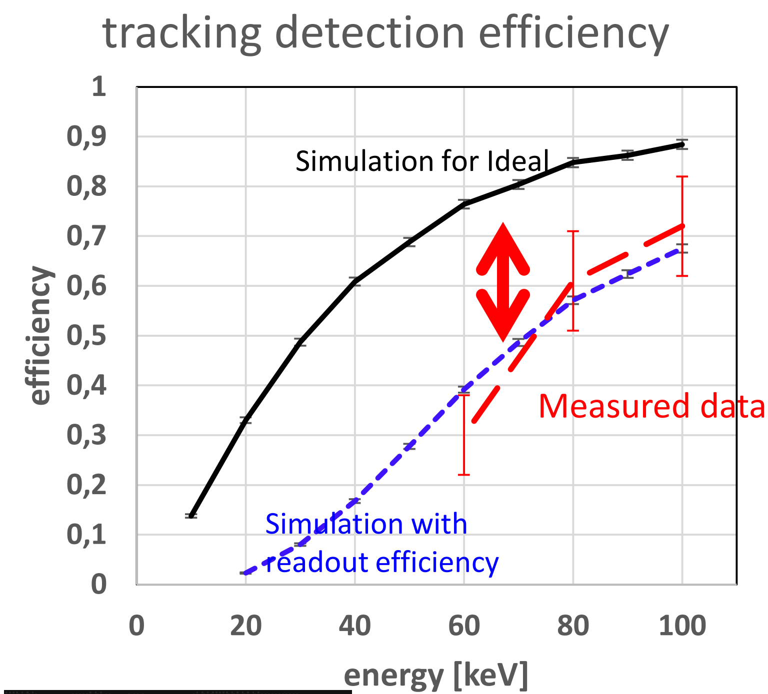
and lower energy efficiencies are extraporate using fitting function

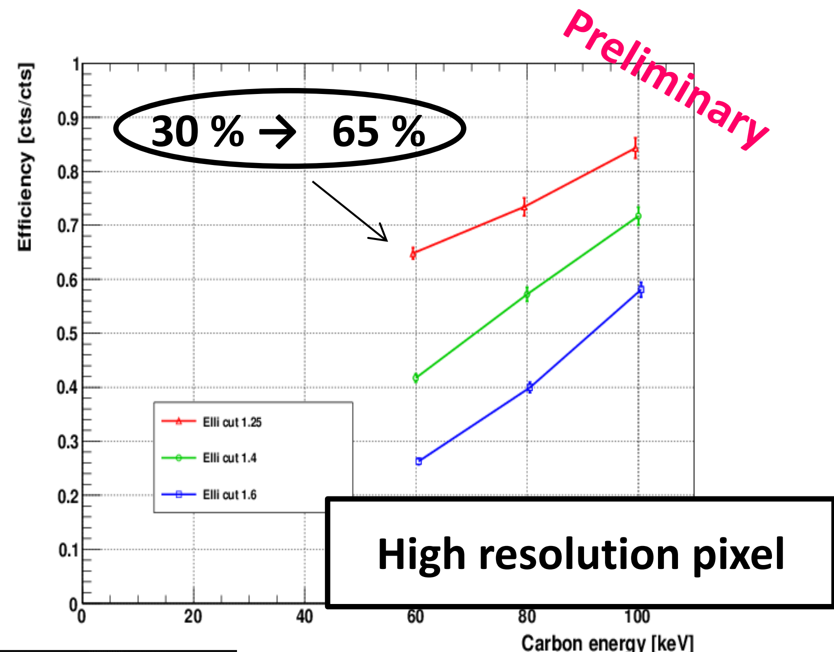


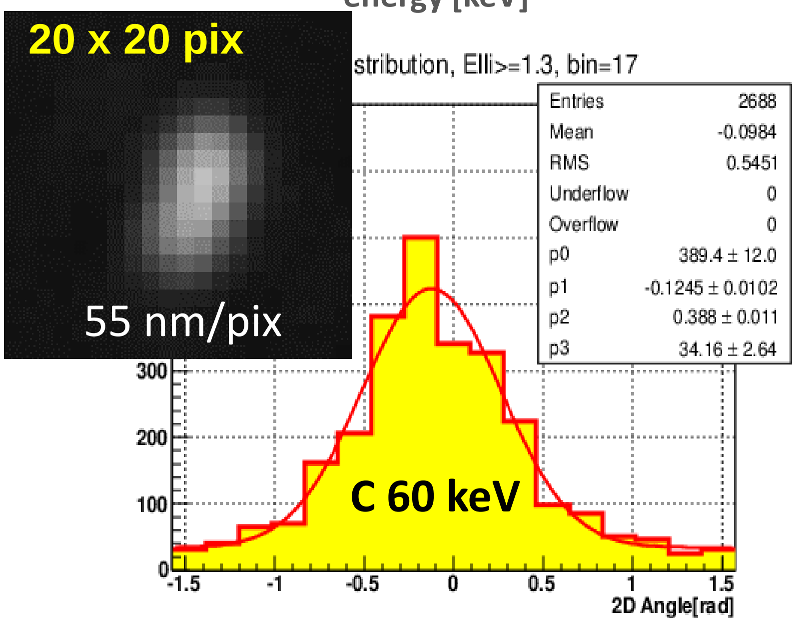


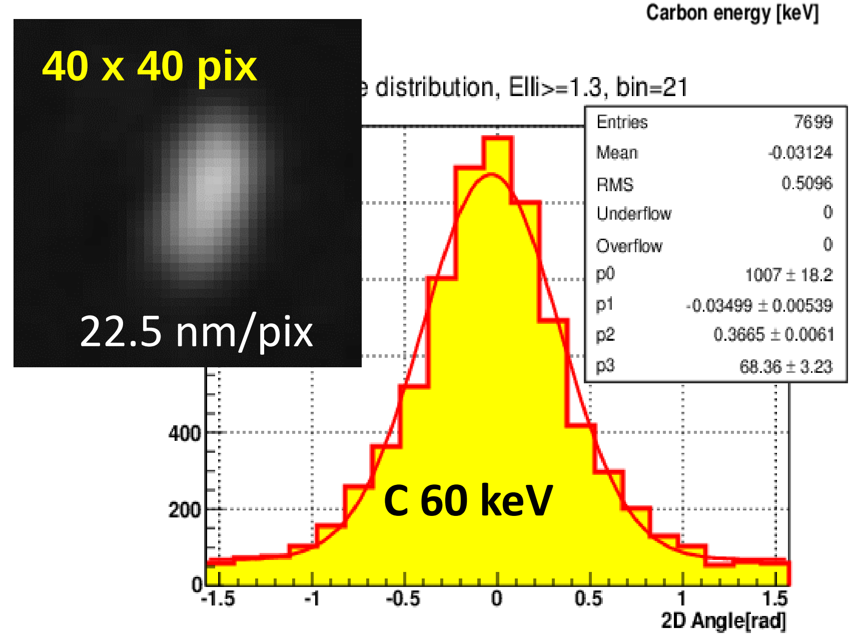
Non-zero efficiency is important because of exponential energy spectrum

Further improve of efficiency





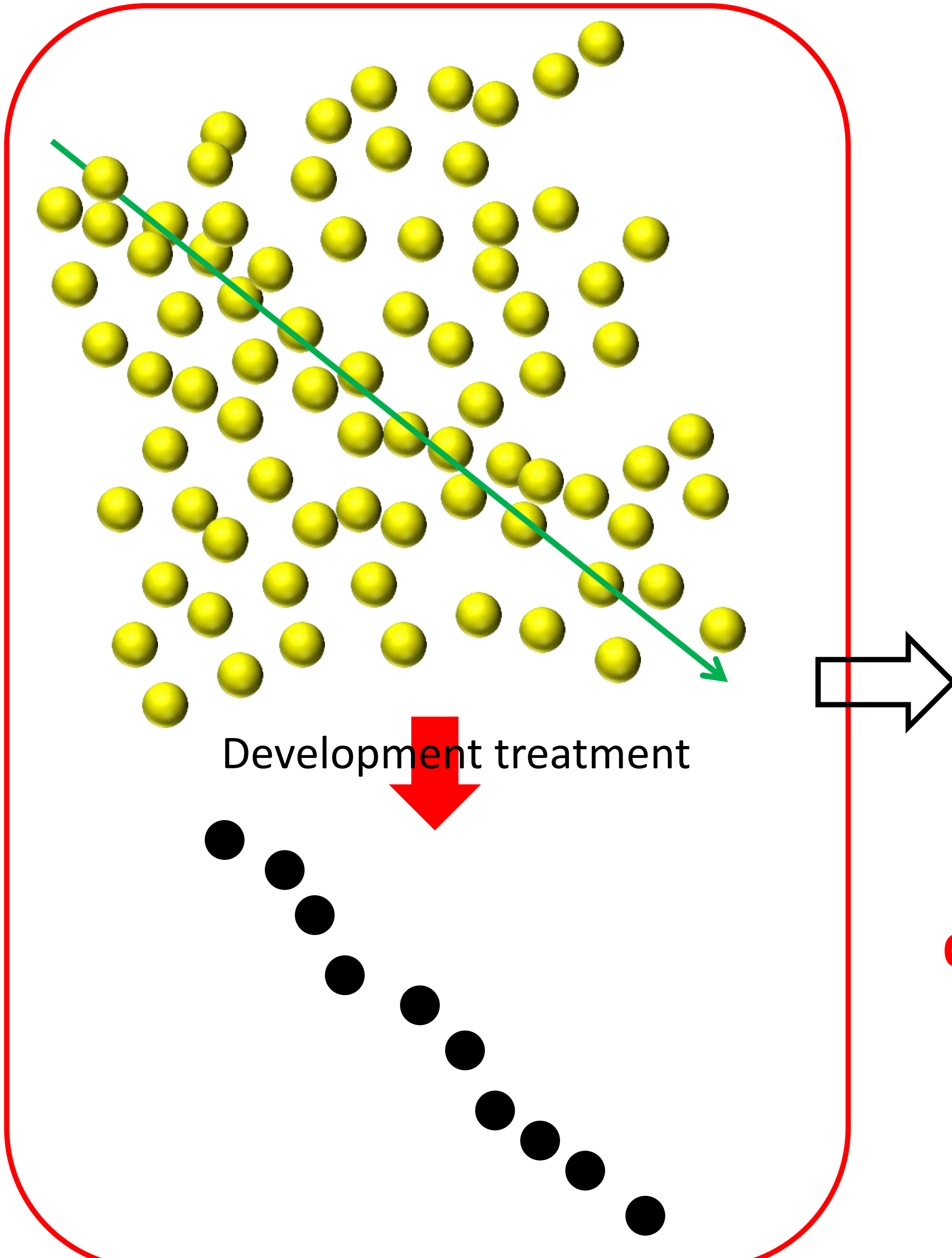




Another high precision analysis and lower background study

- Background discrimination
- signal confirmation
- lower background

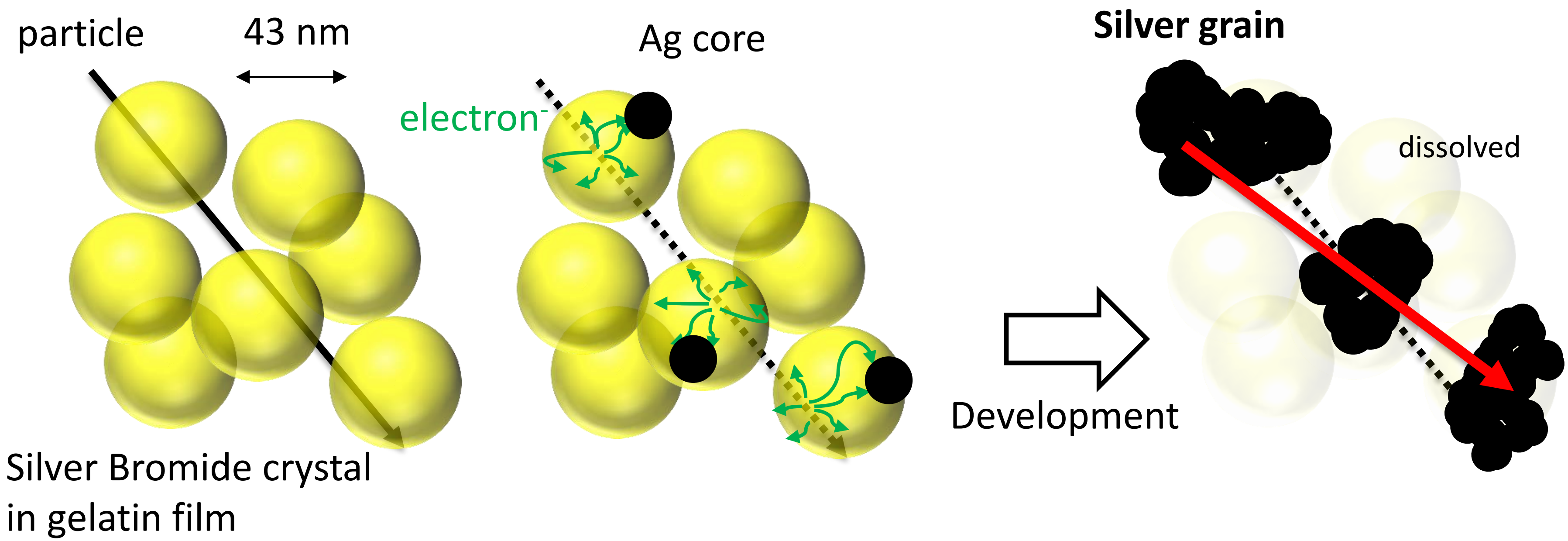
Higher resolution



This image is Not correct.
More complicated information are included.

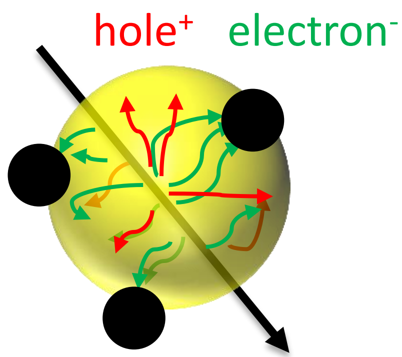
One silver grain is not just one grain !

Detection process of Emulsion

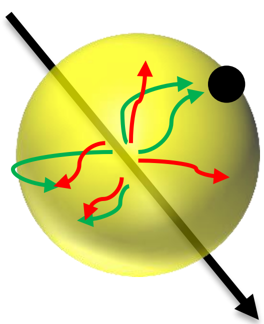


- ✓ **number of latent image specks is not always one, high dE/dx particles form two or more latent image specks .**
- ✓ **developed grains have filament sturucture**
- ✓ **latent image speck size due to low dE/dx particles tend to small**
- ✓ **another nose is not filament structure**

Kind of events source



- Signal event (recoiled nuclei)
  - de/dx : 100~1000 keV/um
  - Cores become strong(big) and many

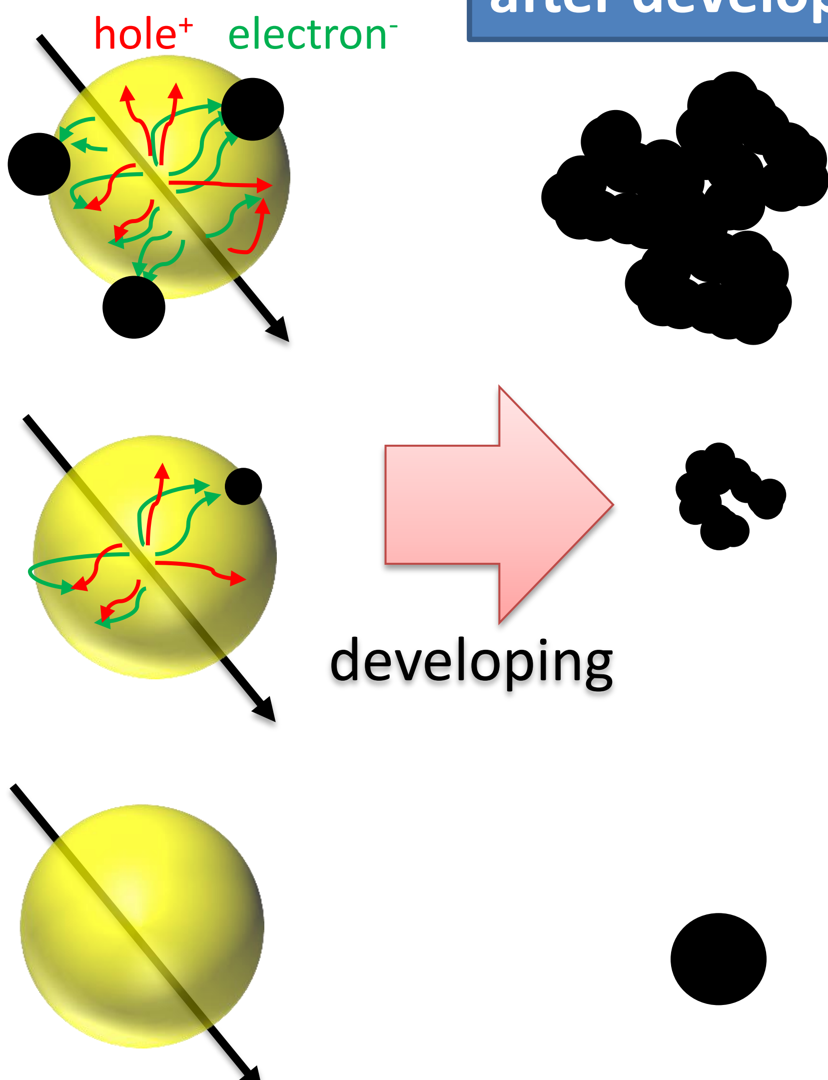


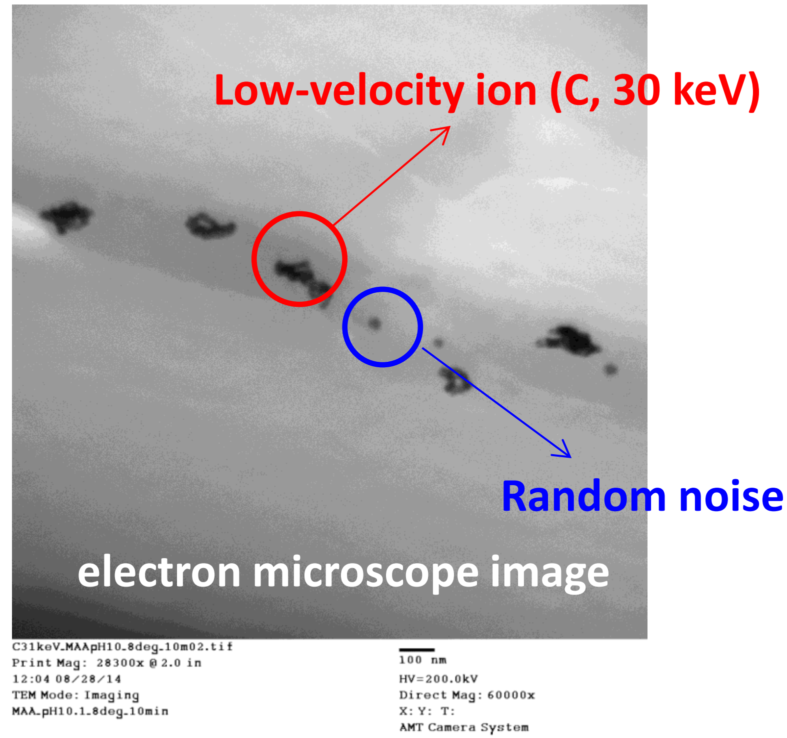
- Background event (electron)
  - de/dx : 1~10 keV/um
  - Cores become small and few

- Noise event (not from particle, unknown)
  - Core may be bigger than signal's one.

Additional Information

after developing

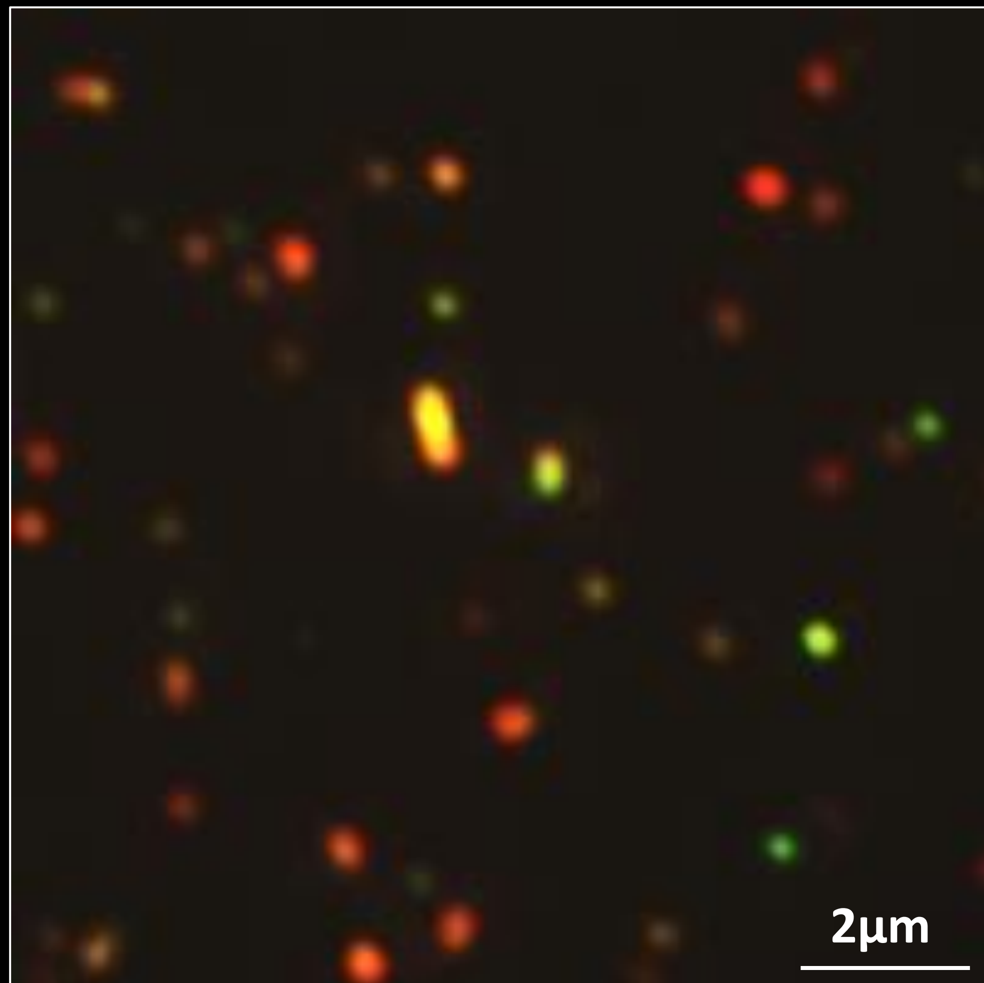




Nano-scale structure have very important information for distinguish of signal from noise

Plasmon resonance in emulsion

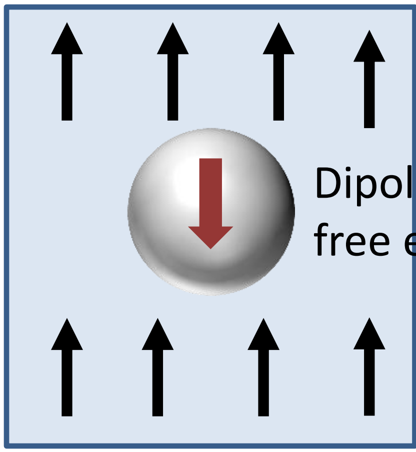
Using optical microscope , can see tracks are colorful!!



Carbon ion track after developing process

Taken by color camera (Halogen lamp λ = 300~3000nm)

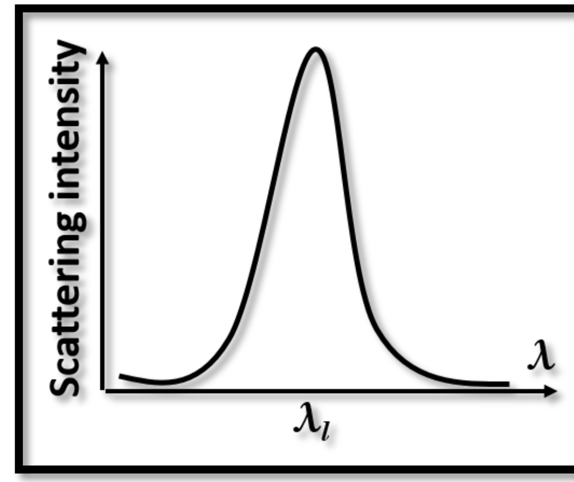
Plasmon resonance in nano-metaric particle



$$p = 4\pi\varepsilon_m a^3 \frac{\varepsilon_1(\lambda) - \varepsilon_m(\lambda)}{\varepsilon_1(\lambda) + 2\varepsilon_m(\lambda)} E_0$$

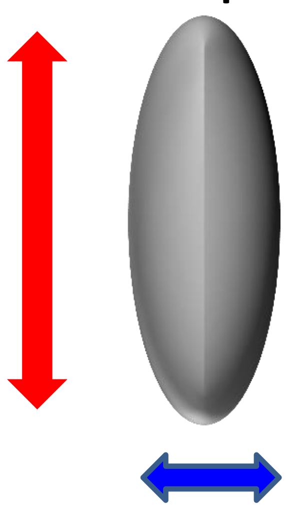
Dipole moment p for free electrons

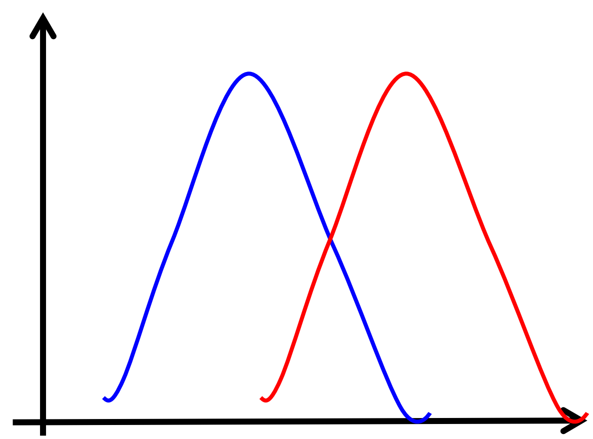
$$\varepsilon_1(\lambda_l) + 2\varepsilon_m(\lambda_l) \approx 0$$



λ_l has visible wave length for 40 – 100 nm Ag nano particle

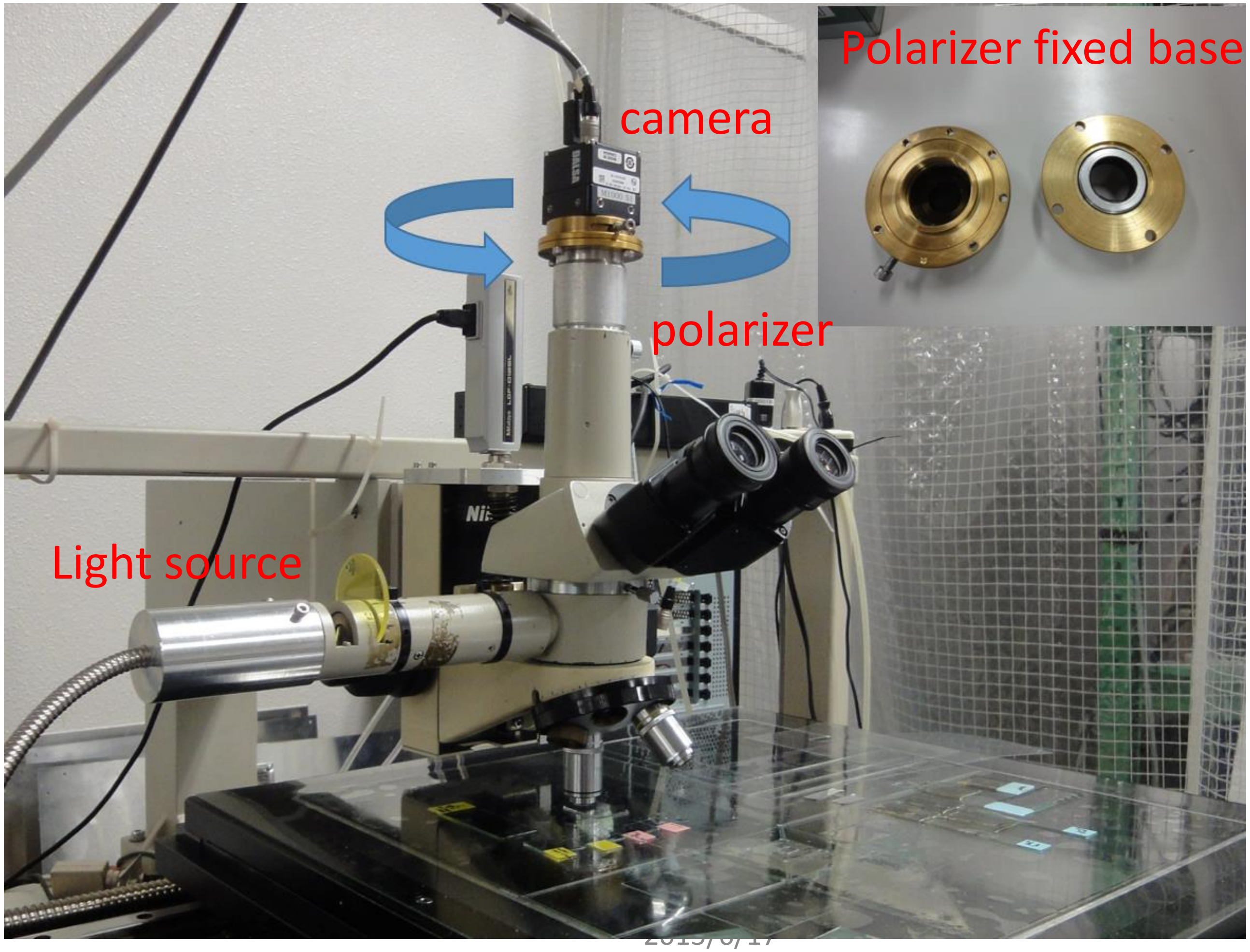
Polarized dependence



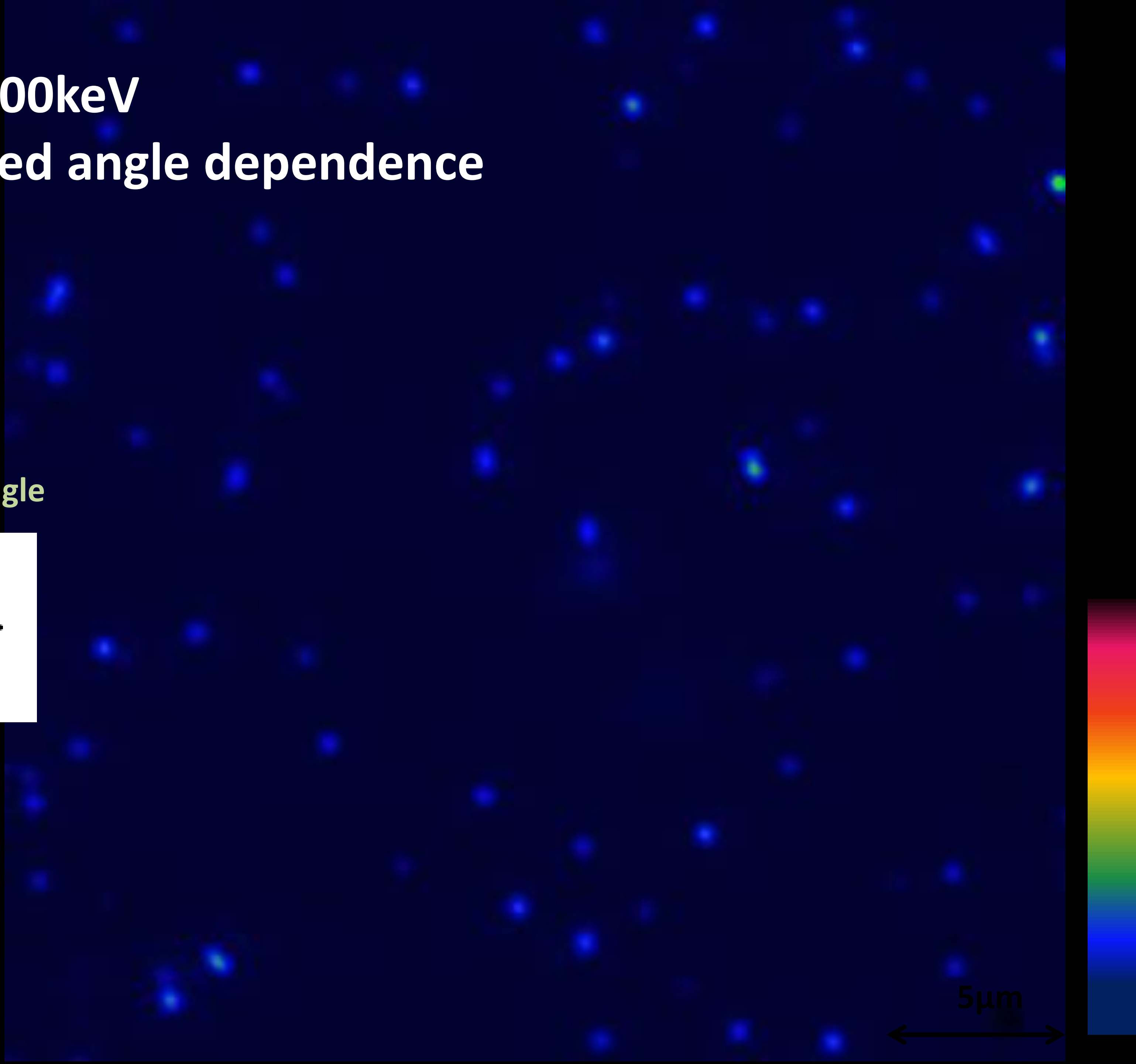


Polarization analysis

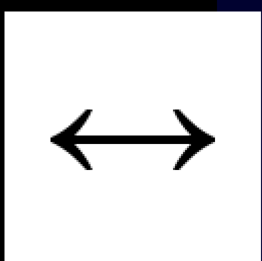
- develop the optical microscope that can do polarization analysis
- set a polarizer under the camera and rotate it



C ion 100keV
Polarized angle dependence

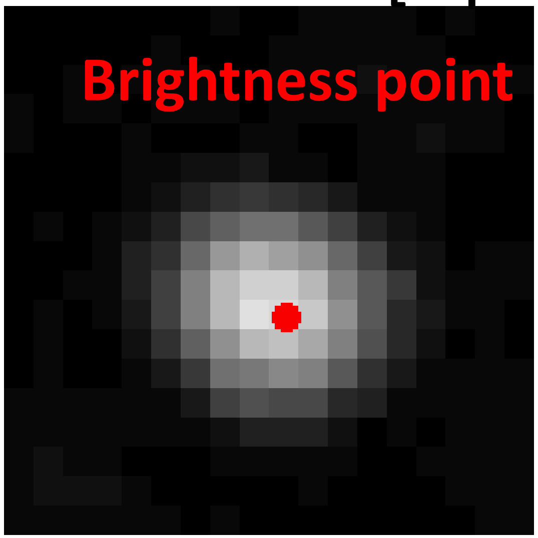


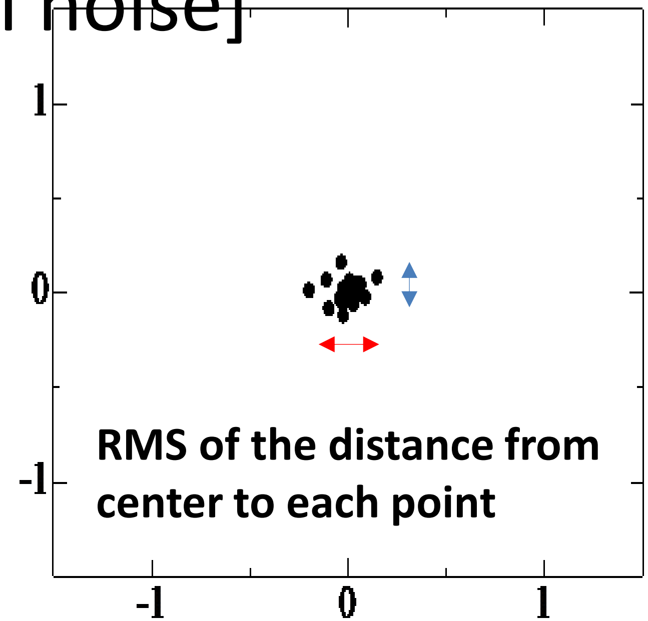
Polarizer angle



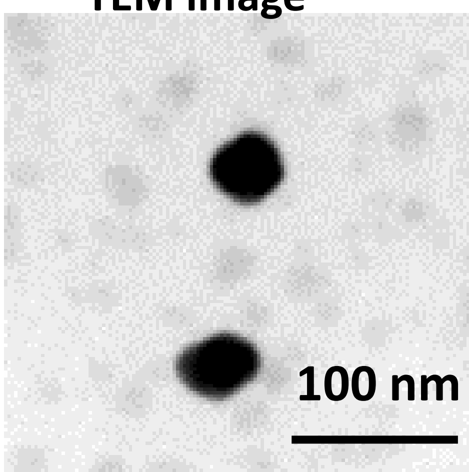
Super-high resolution technology
[spherical noise]

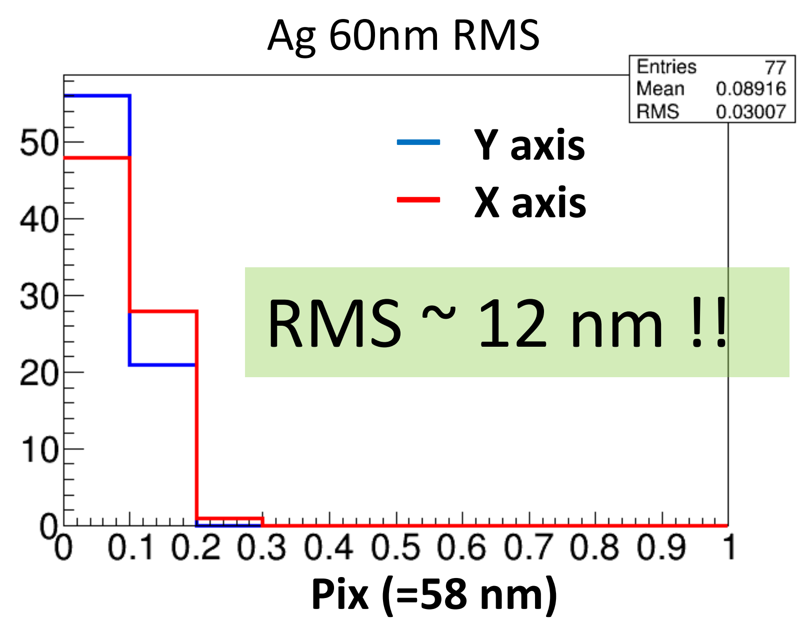
Ag cluster





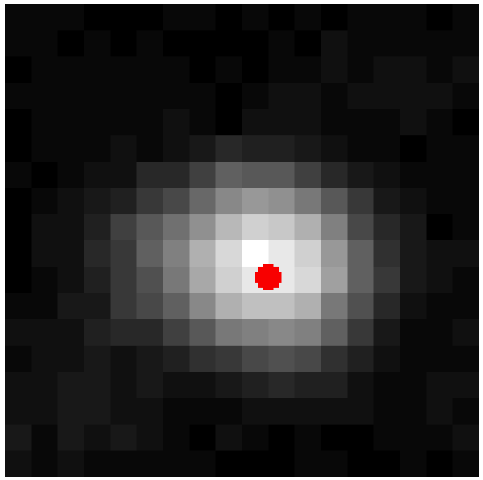
TEM image

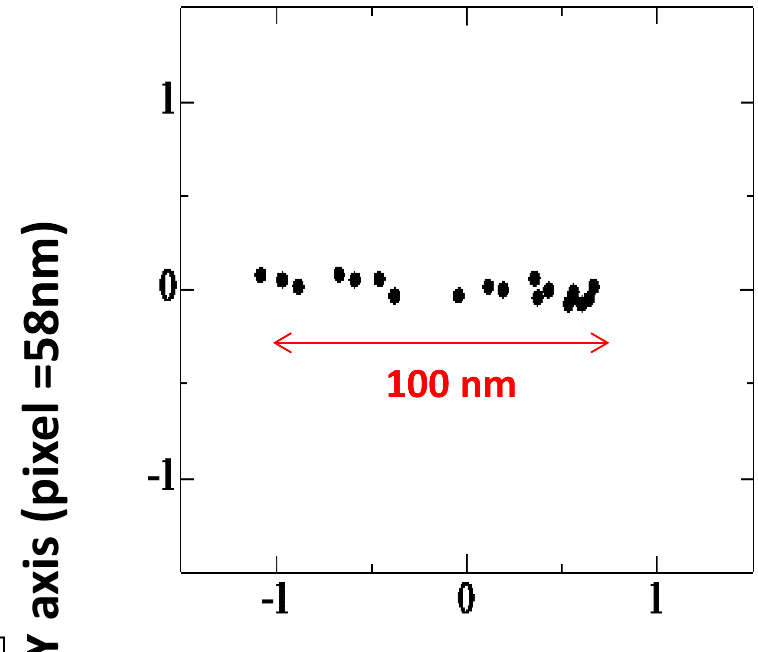


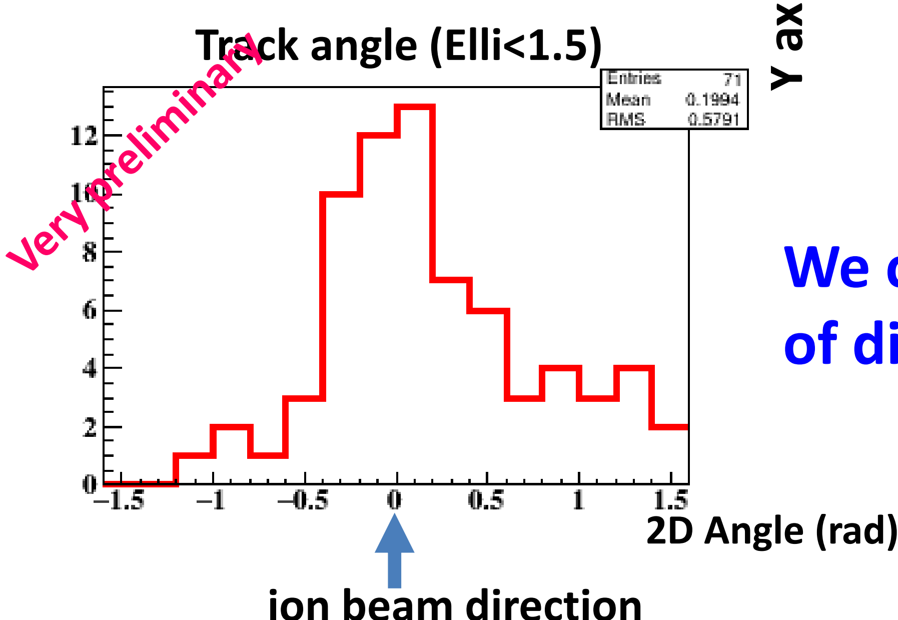


Super-high resolution technology [tracking]

Track candidate







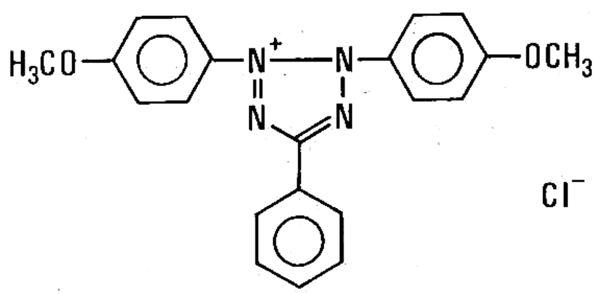
We could obtain the information of direction except shape analysis!

Background rejection

☐ Chemical control of quantum efficiency of AgBr crystal

✓ electron trap on the crystal
⇒ clearly separation between low dE/dx (γ・β-rays) and high dE/dx (nuclear recoil)
✓ development speed dependent on latent image speck size
⇒ separation as contrast or plasmon response

better than 1E-6 rejection power should be expected, at least from current study



2,3-di(methoxyphenyl)
-5-phenyltetrazolium

☐ Cryogenic device

✓utilize the temperature increase dependence between low-dE/dx and high dE/dx particle in low-temperature device
⇒ now on studing

Background rejection power and more realist achievable sensitivity will be shown in this year.

Summary

- ☐ **Nano Imaging Tracker (NIT) was developed in Nagoya University**
  → crystal size : 40 nm (3.3 g/cm^3)
- ☐ **Potential for NIT simulation with crystal effect**
  → it has direction sensitivity for more than 10 keV
  → angular resolution is better than 600 mrad. for more than 10 keV
- ☐ **Optical microscope ssystem + X-ray microscope analysis @ SPring-8 are aready running**
- ☐ **Low-velocity ion analysis using ion-implant system and optical microscopy**
  → improved to 65 % + 350 mrad. resolution by high resolution pixel analysis @ 60 keV C signal
  → Finally, about 70 % and 350 mrad ang. resolution is expected in dark matter search situation
  → Analysis data is consistent with simulation assume 100 % Q.E. of crystal

Lower energy performance study is now on going .

Background study

- Plasmon analysis was achieved 10 nm resolution analysis
  → shorter length event analysis, signal and noise discrimination
- Quantum efficiency control studies are on going
  → tetrazorium compound ; expected better than 10-6 rejection power
  → cryogenic device ; also better than 10-6 rejection power
  } Finally combined
- replace the gelatin to petroleum-derived polymer (e.g., PVA, PVP, btadien etc)