NAGOYA UNIVERSITY

Kobayashi-Maskawa Institute
for the Origin of Particles and the Universe

NEWSdm
Direction Sensitive Dark Matter Search with Super-high Resolution Nuclear Emulsion

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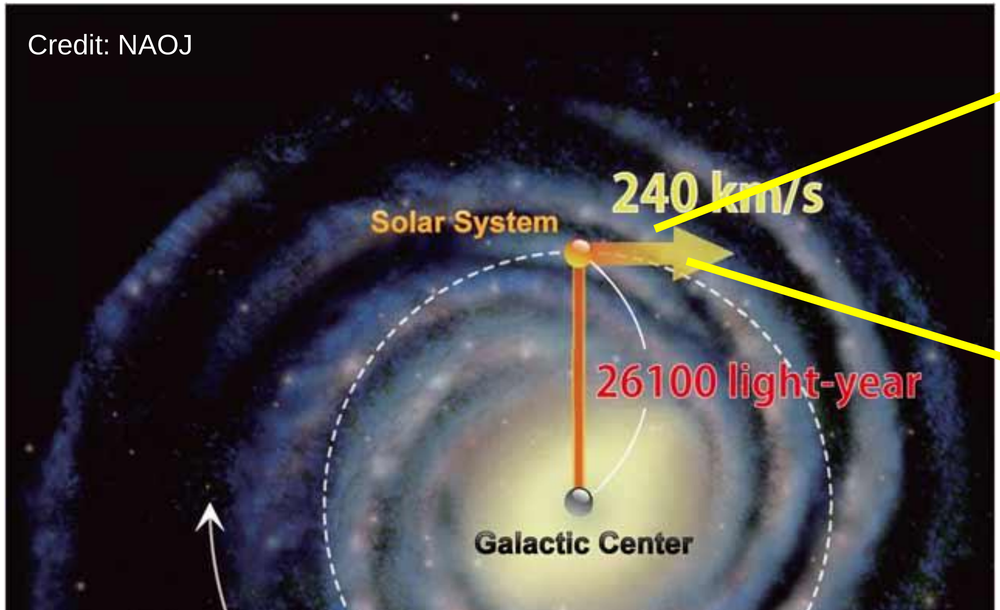
On behalf of NEWdm collaboration

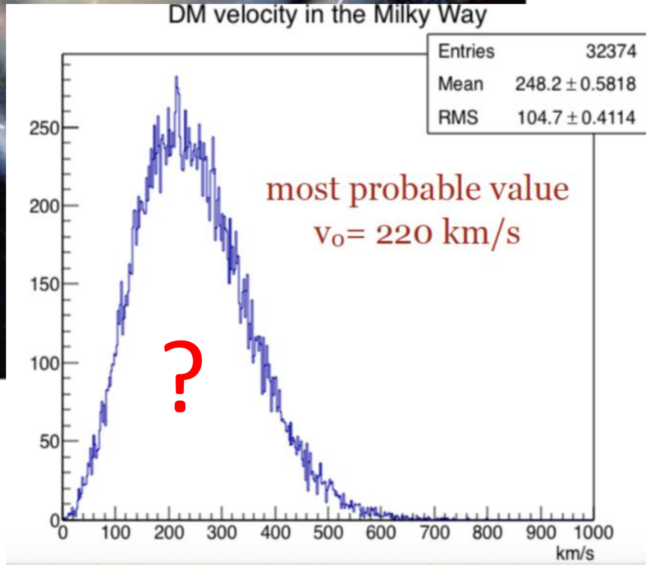
2017. 7.24-29 13th Rencontres du Vietnam Exploring the Dark Universe 2017 @ Quy Nhon, Vietnam

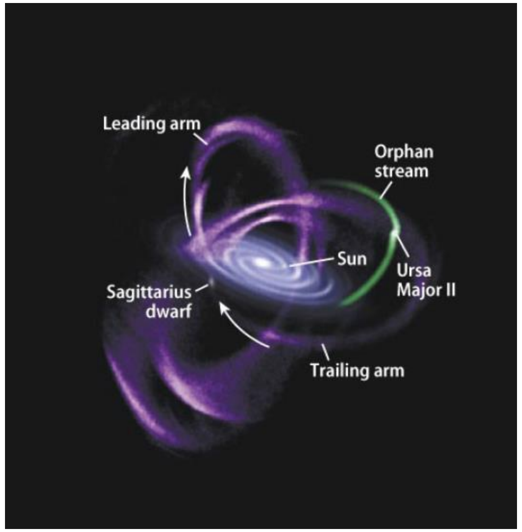
Direction Sensitive Dark Matter Search



Why do we need the directional sensitive detectors?

⇒ new systemic search " new degree of freedom"





Does DM have really Maxwellian ?

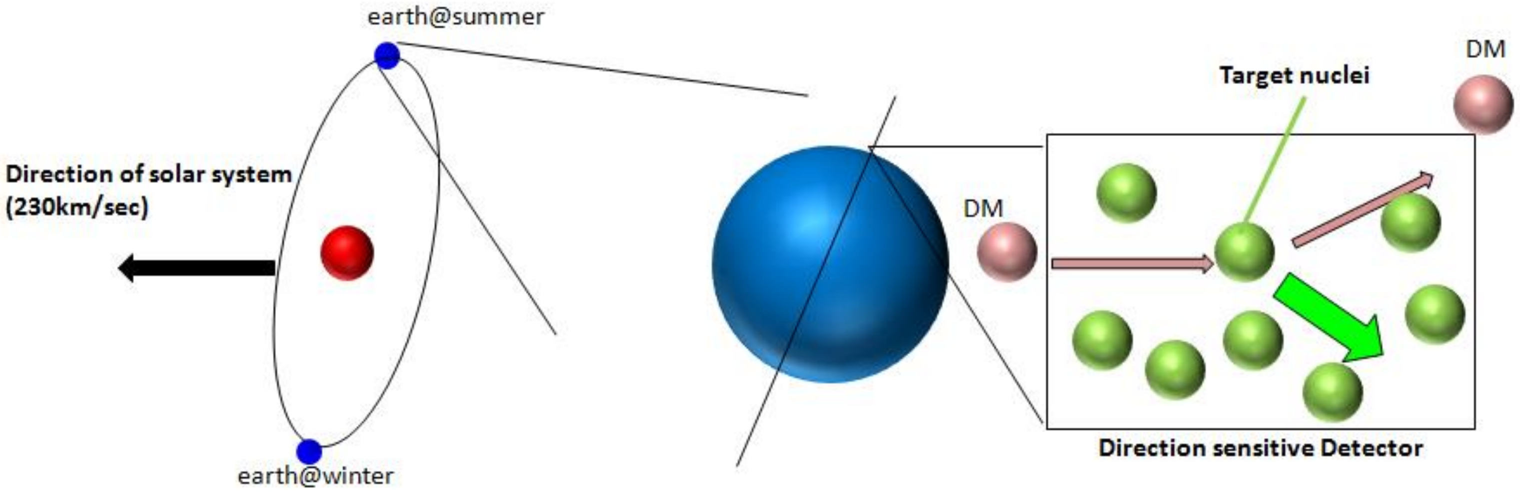
Dark matter flow ?

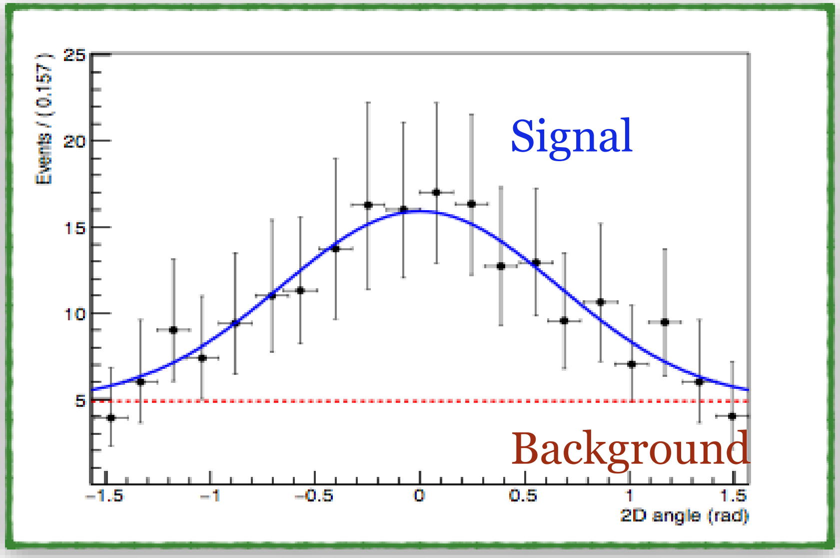
e.g., C. O'Hare and A. Green, Phys. Rev. D 90, 123511 (2014)

Anisotropic distribution?

F. S. Ling et al., JCAP 1002, 012 (2010)

Directional Dark Matter Search





expected number of WIMP events

expected number of background events

signal pdf

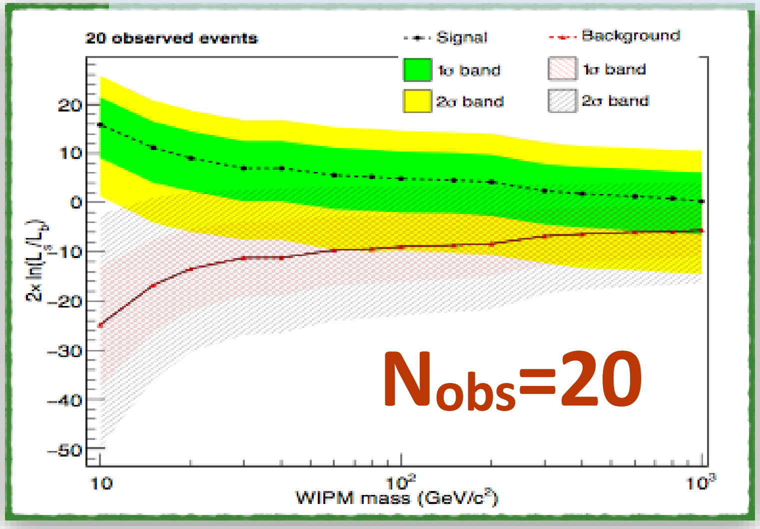
background pdf

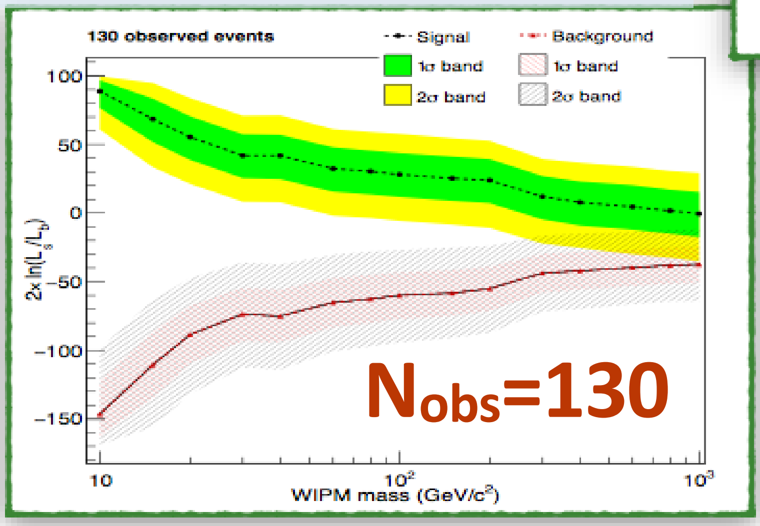
$$\mathscr{L}(\sigma_{\chi-n}, R_b) = \frac{e^{-(\mu_\chi+\mu_b)}}{N!} \times \prod_{i=1}^{N} [\mu_\chi f_\chi(\vec{q}_i; t_i) + \mu_b f_b(\vec{q}_i)]$$

total number of observed events

set of observables

Profile Likelihood ratio test using angular distribution





Achievement of ~ 100 times statistical gains to the annual modulation by the direction sensitivity !!

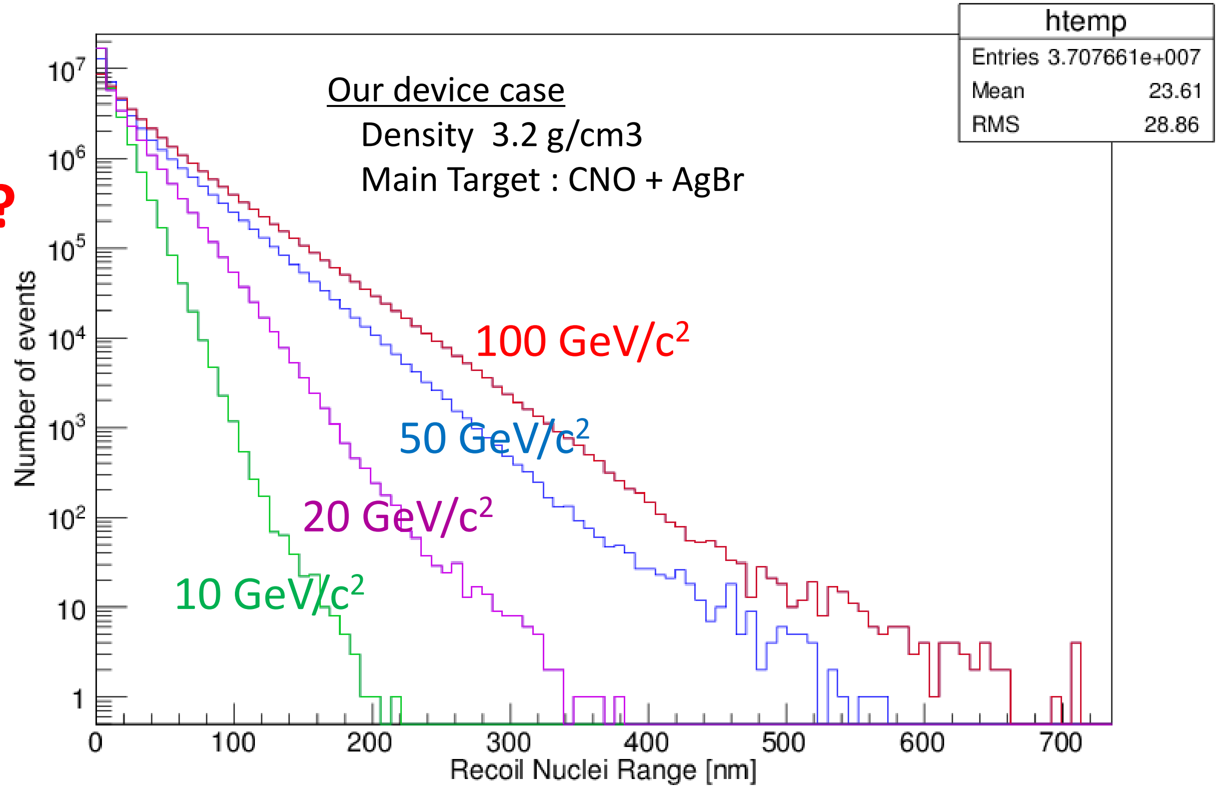
Challenge for Direction Sensitive Dark Matter technologies

Can the solid (or liquid) detector have directional sensitivity to nuclear recoil signal due to WIMPs ?

- **Track length of recoiled nuclei < ~ 1 μm**
- **Angular dispersion due to straggling ~ 25deg.**

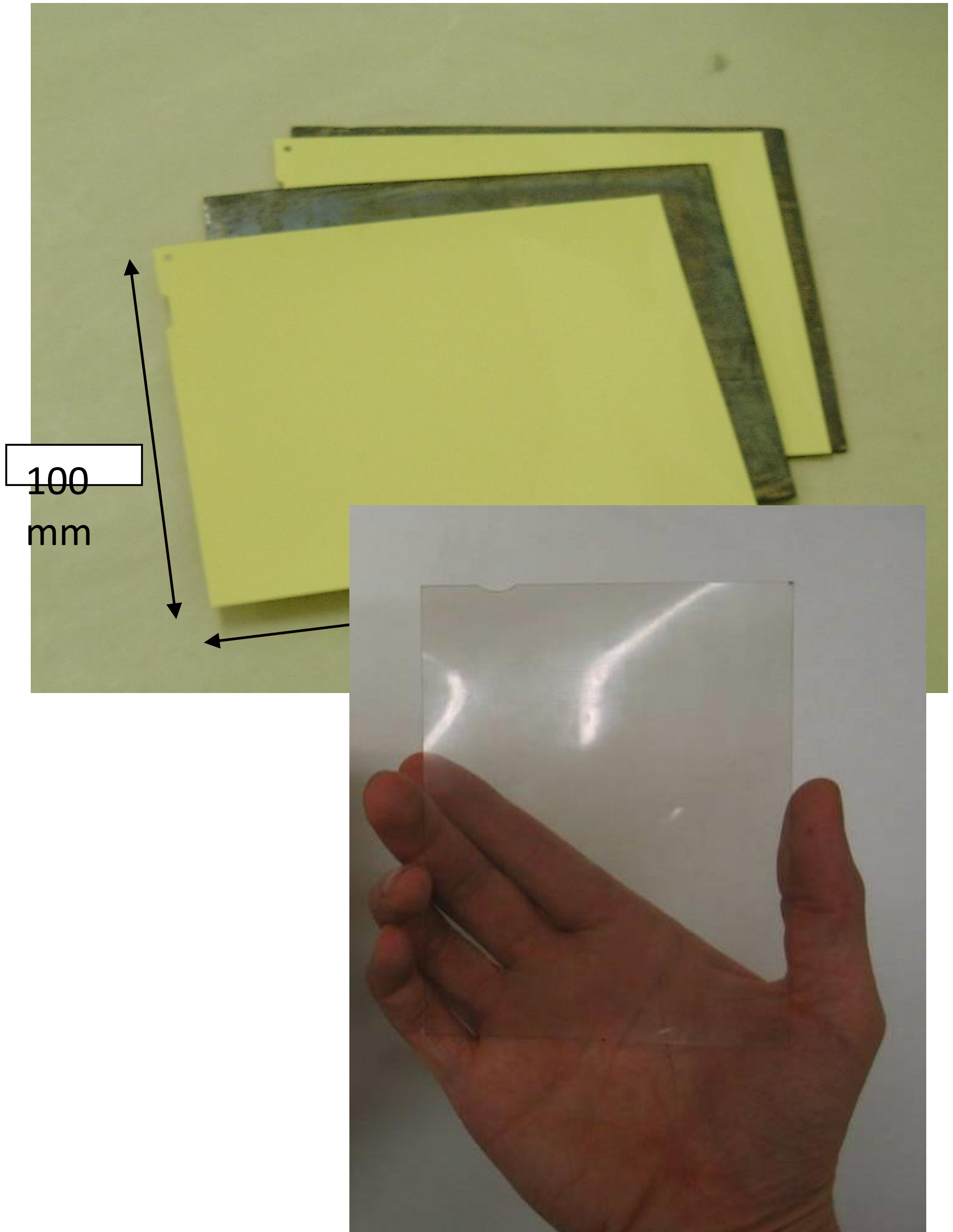
As dark matter detector ･･
- ☑ low-background
- ☑ scalability

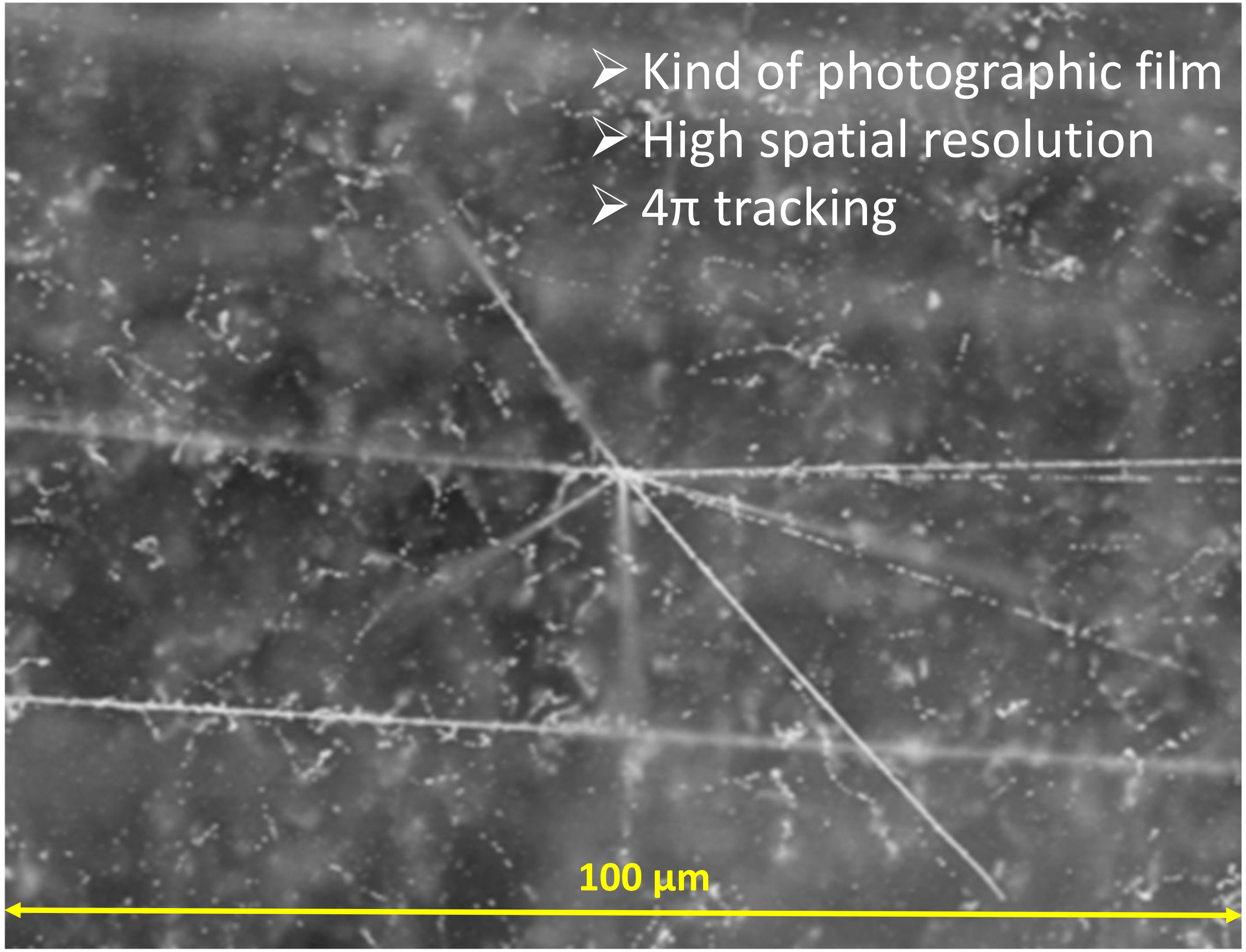
New technical challenge !!



Low mass (~10 GeV/c2) search : light target + < 200 nm length
High mass (> 100 GeV/c2) search : heavy target + < ~700 nm

Nuclear Emulsion

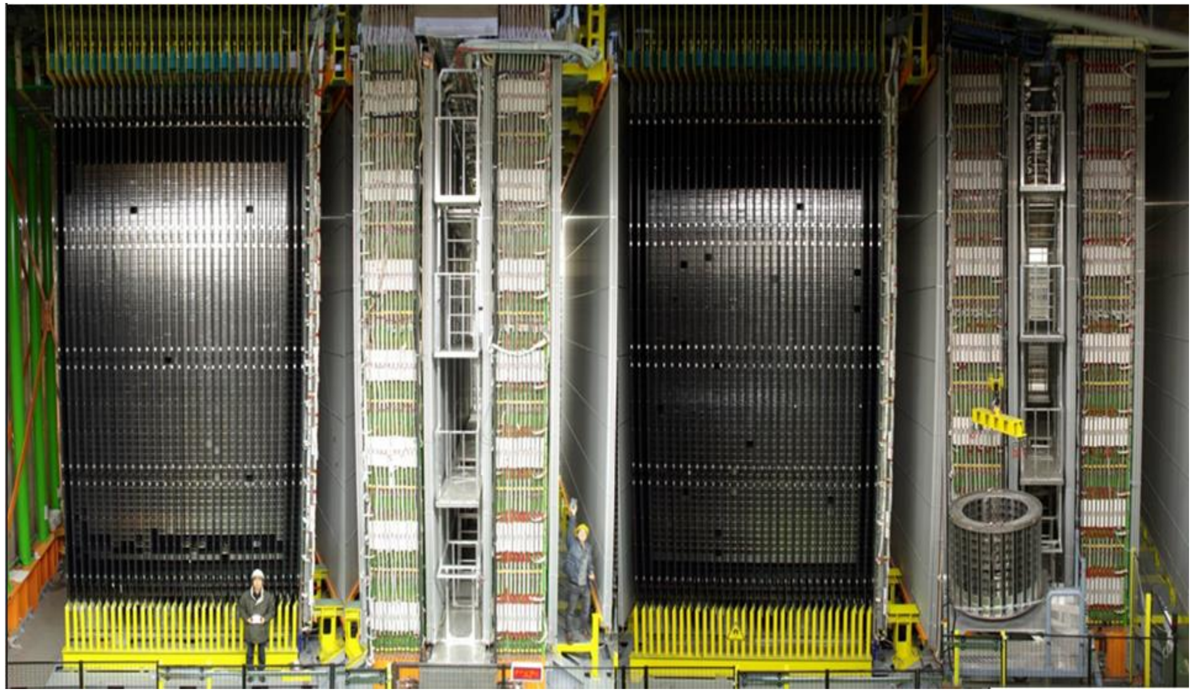




- Kind of photographic film
- High spatial resolution
- 4π tracking

Latest the nuclear emulsion experiment and readout

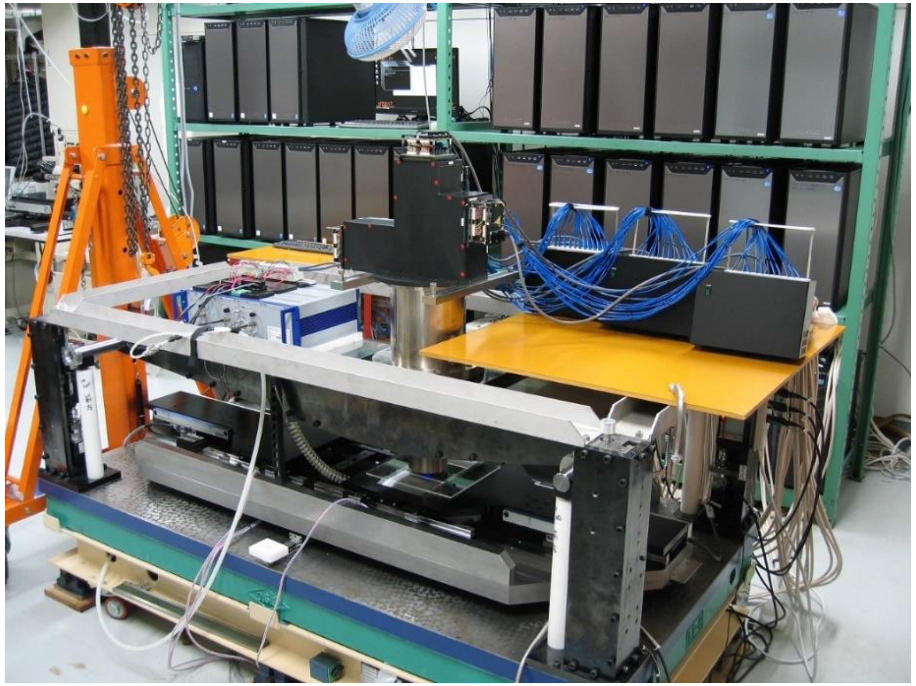
OPERA detector



20 m

Observed neutrino oscillation with
30 ton emulsion detector x 5 years (150 ton･year)
(Emulsions are 20 % volume in this picture)

Current highest speed readout system



Scanning speed ~ several ton /year

Ref : M. Yoshimoto el al., **arXiv:1704.06814 [physics.ins-det]**

NEWSdm ~Nuclear Emulsions for WIMP Search + directional measurement

http://news-dm.lngs.infn.it

Japan
Chiba
Nagoya

Russia
LPI RAS Moscow
JINR Dubna
SINP MSU Moscow

(Yandex)
⇒ computing science

Italy
Bari
LNGS
Naples
Rome

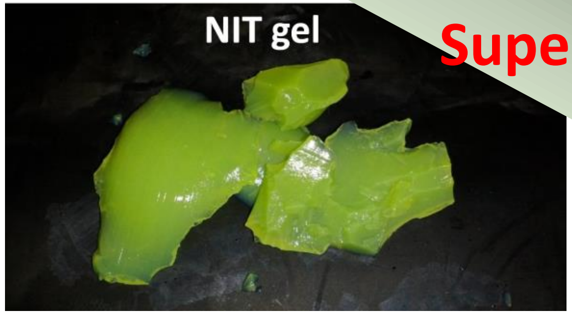
Turkey

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

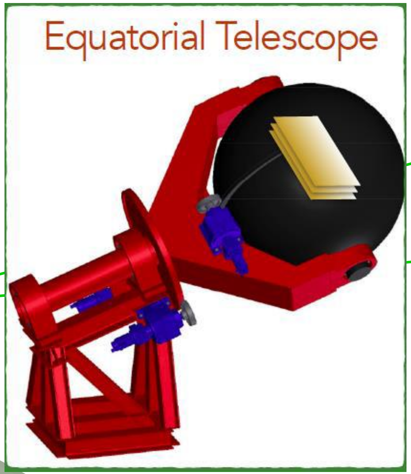
2015: Submitted LOI to
LNGS science committee

NEWSdm experimental strategies

Device self-production



Super-high resolution device



- low-background device
- Clean environment for the emulsion handling
- equatorial Telescope

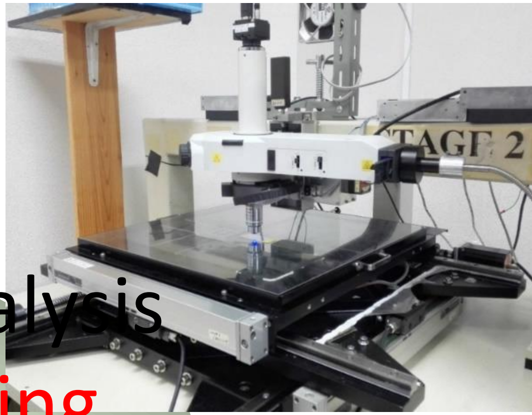
Exposure +
chemical development

- **Underground facility**
- **Run mounting the equatorial telescope**

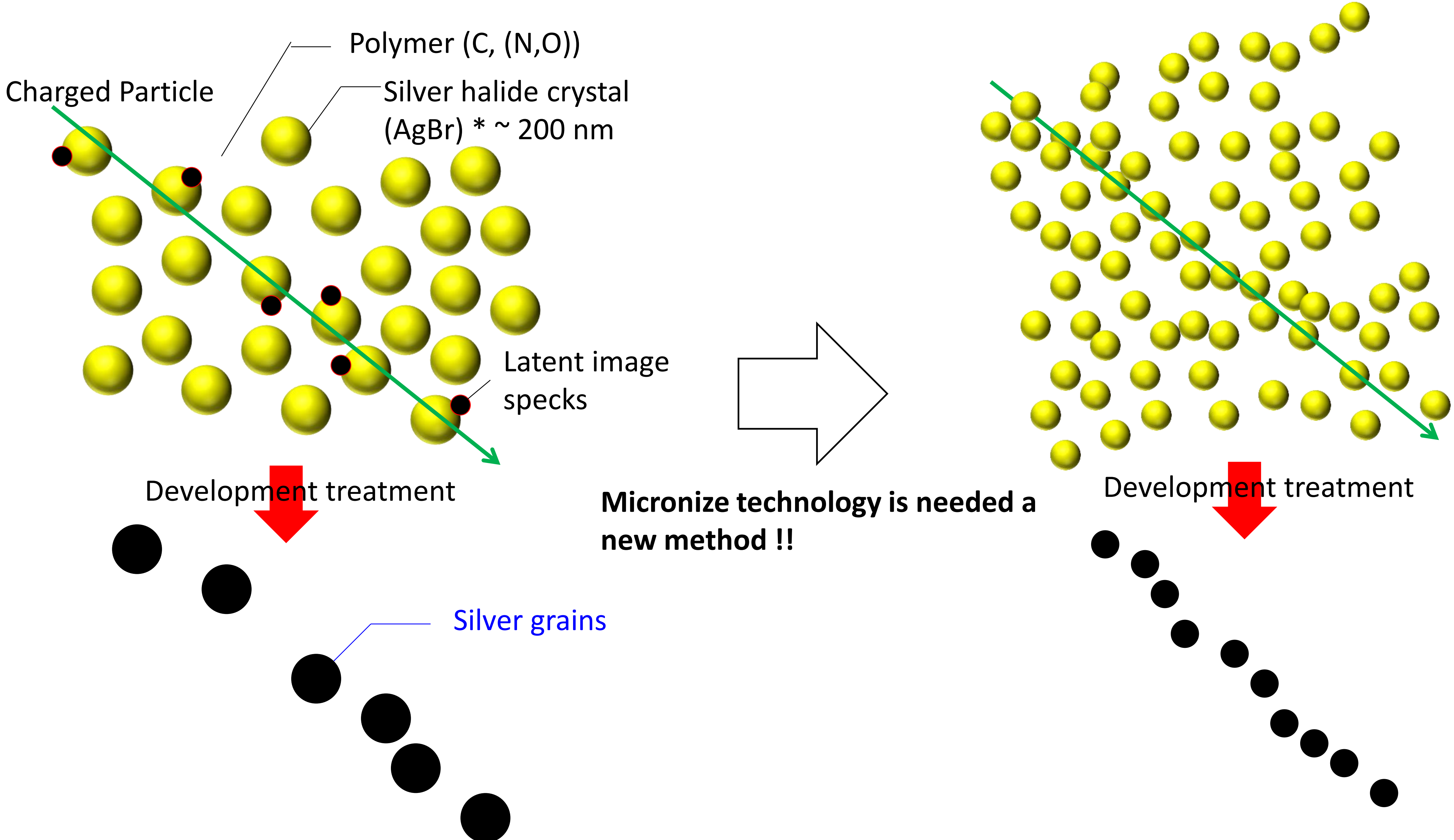
- **High speed scanning**
- **Super-high resolution microscopy**
- **Cutting-edge technologies for optics**

Readout + analysis

R&D on going



Concept of super-high resolution

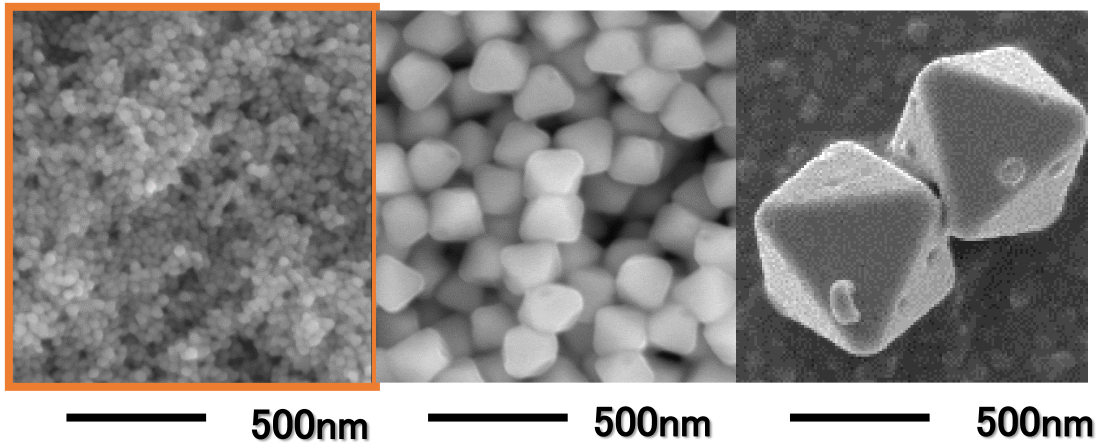


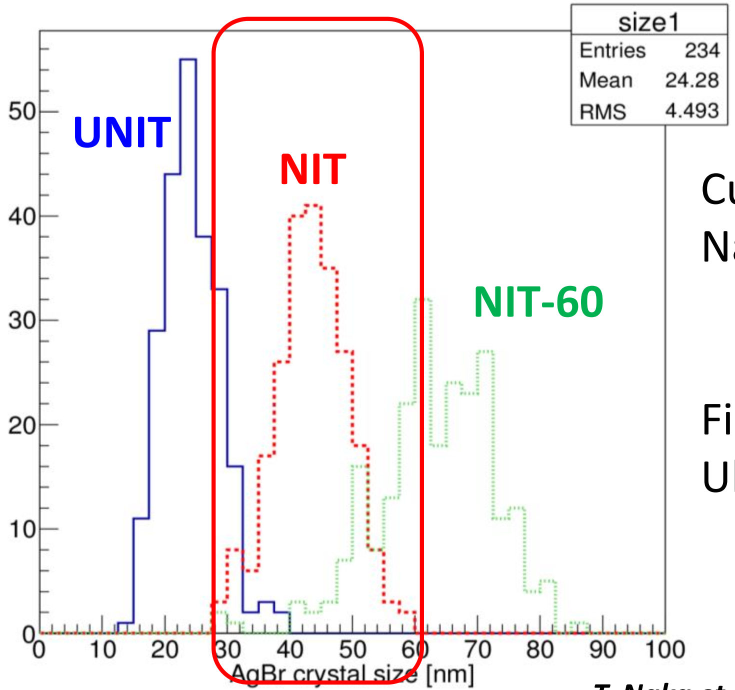
Device self-production

- Production time : 4-5 hours /batch
- One butch : ~ 100 g (+ 300 g)
  (there are 2 type machines)

⇒ kg scale production is possible using this machine.

Controlled AgBr crystal





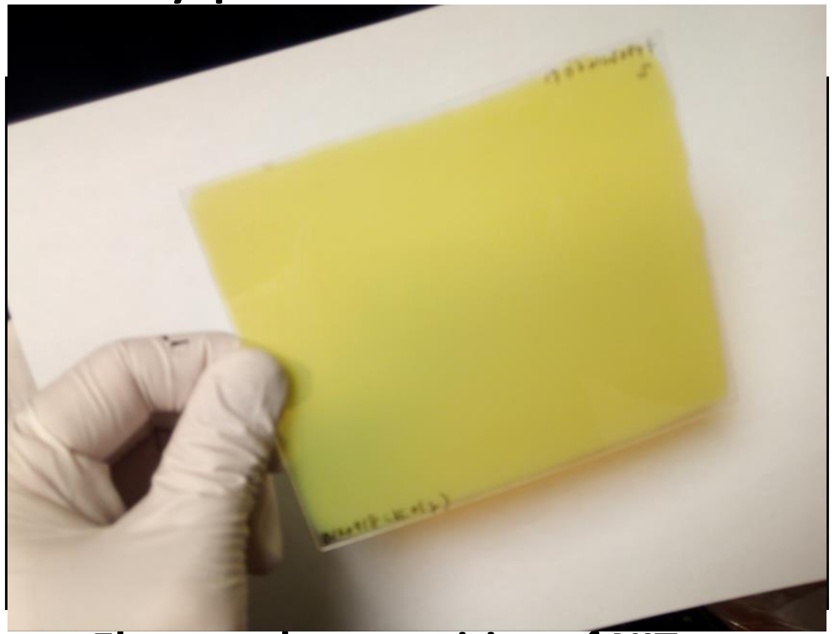
Current standard Device :
Nano Imaging Tracker [NIT]
crystal size : 44 nm

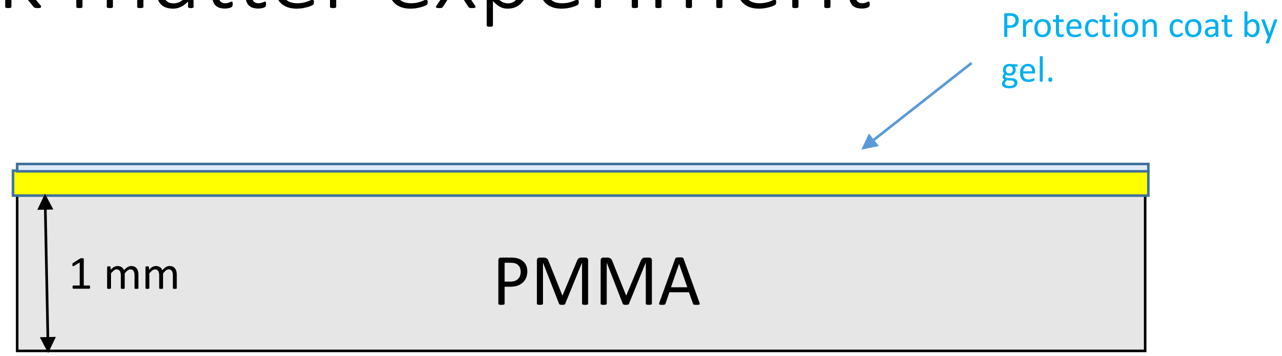
Finest grain emulsion :
Ultra-NIT [UNIT]
crystal size : 25 nm

T. Naka et al., Nucl. Inst. Meth. A 718 (2013) 519-521

T. Asada, T. Naka + , Prog Theor Exp Phys (2017) 2017 (6): 063H01

prototype film of NIT for dark matter experiment





Size : 10 x 12 cm^2
NIT layer thickness : ~ 50-70 μm
Base material : PMMA
(pre-treatment in Nagoya by ourselves)

Target mass ~2 g/film

Elemental composition of NIT

	Mass fraction	Atomic Fraction
Ag	0.44	0.10
Br	0.32	0.10
I	0.019	0.004
C	0.101	0.214
O	0.074	0.118
N	0.027	0.049
H	0.016	0.410
S, Na + others	~ 0.001	~ 0.001

◆ Intrinsic radioactivity :

U-238	Th-232	K-40	Ag-110m	C-14
27	6	35	(~400)	24000

[mBq/kg]

◆ Intrinsic neutron emission:

~ 1.2 /kg/y (by SOURCE simulation)

⇒ ~ 0.1 /kg/y (> 100 nm nuclear recoil)

Detail shown in Astropart. Phys. 80 (2016)16-21

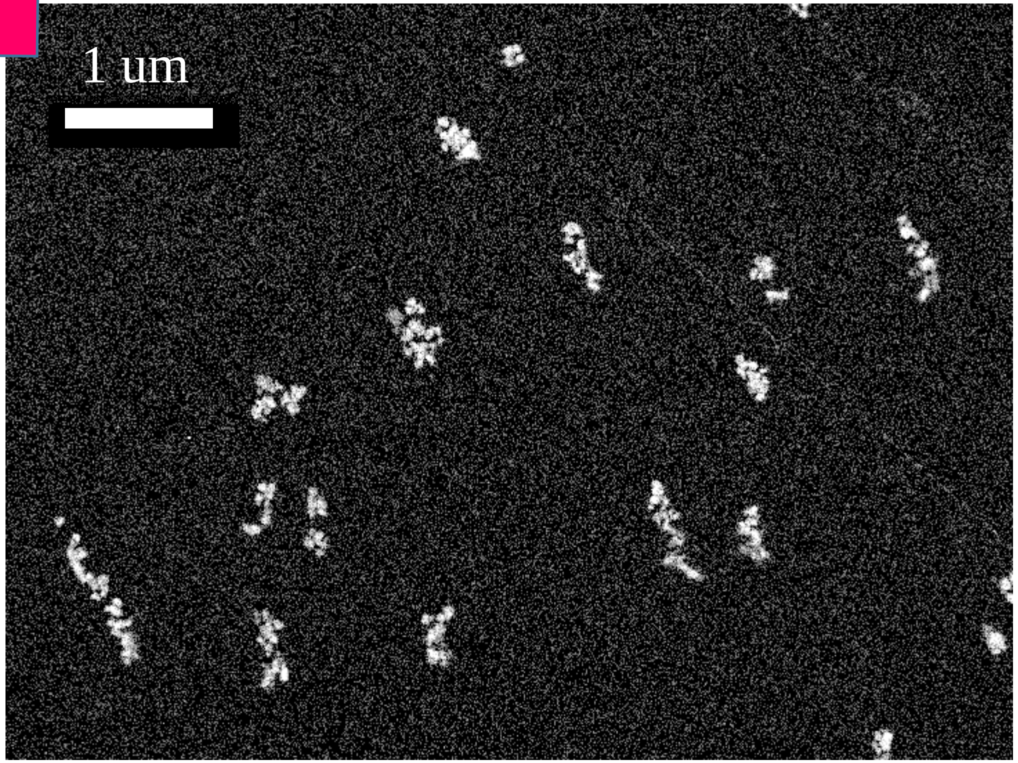
Low-velocity ion tracking

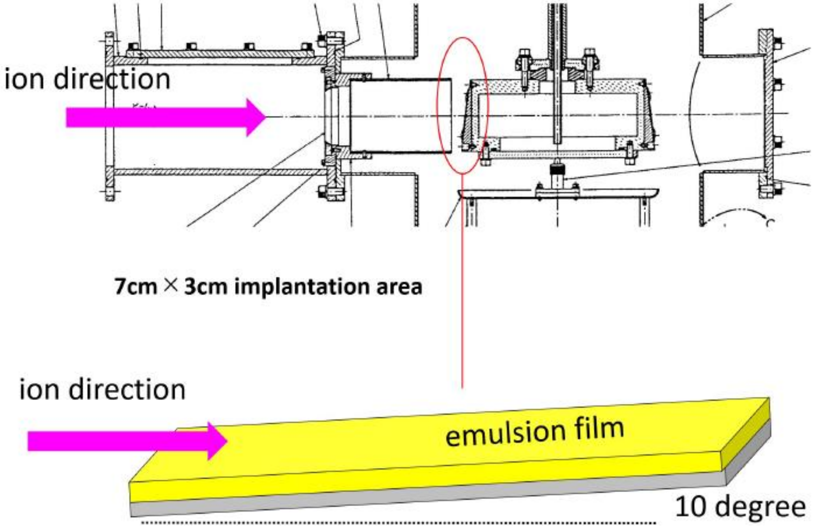
Can use ion implantation as calibration source

- Mono energy (±0.1 keV)
- Good direction uniformity (<10 mrad)
- Now, C from CO_2・Ar, Kr (but other various ion is possible)

Side view of i

100 keV Carbon SEM image

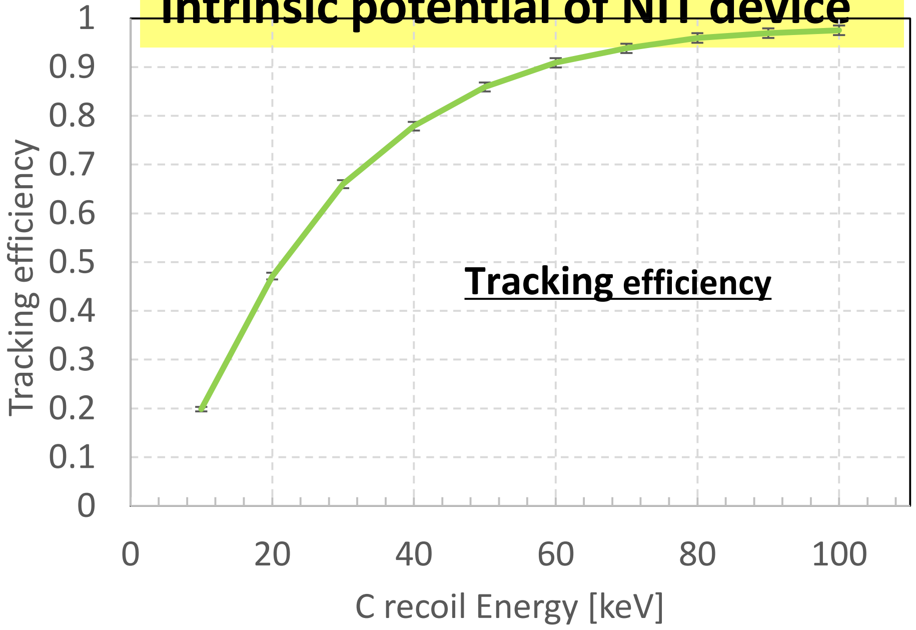


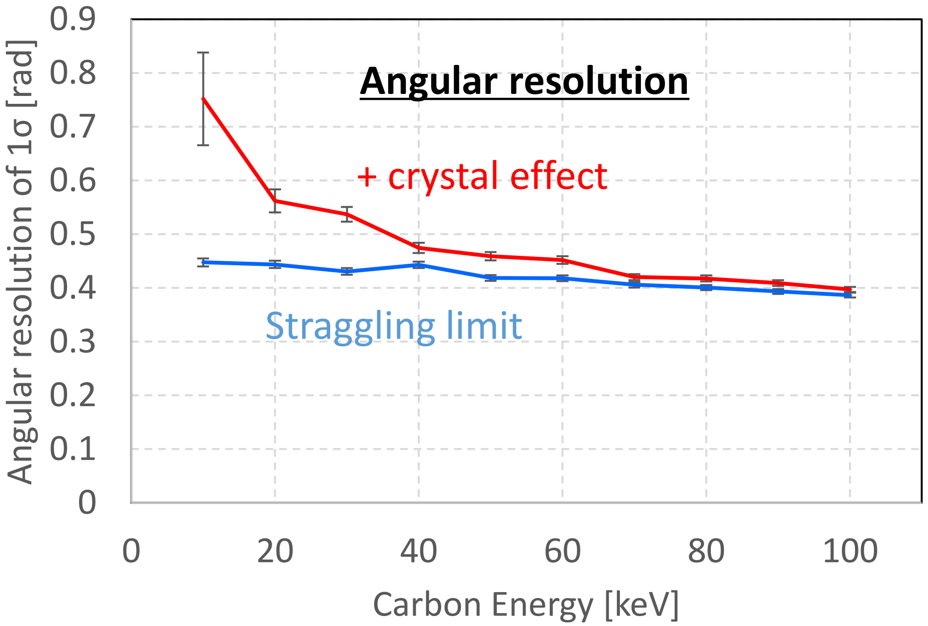


AgBr crystal has good sensitivity about Carbon (~ 100 % efficiency)

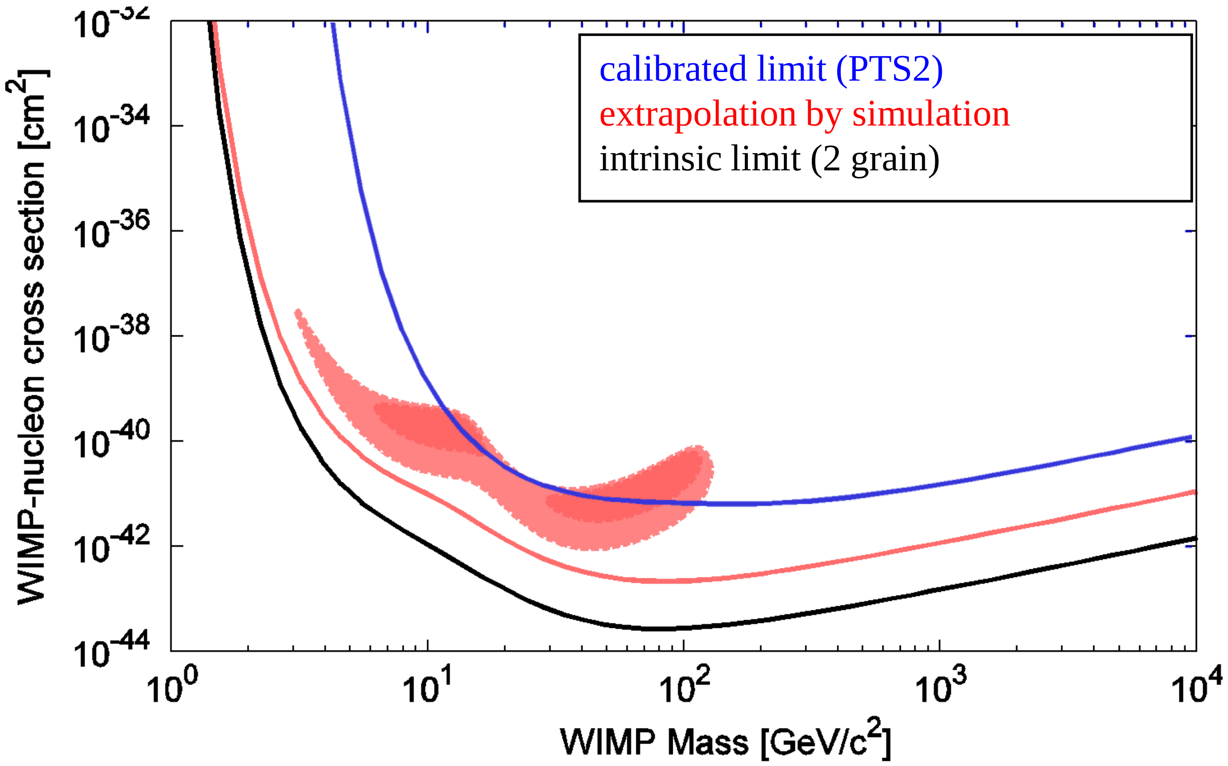
NIT emulsion potential

Intrinsic potential of NIT device





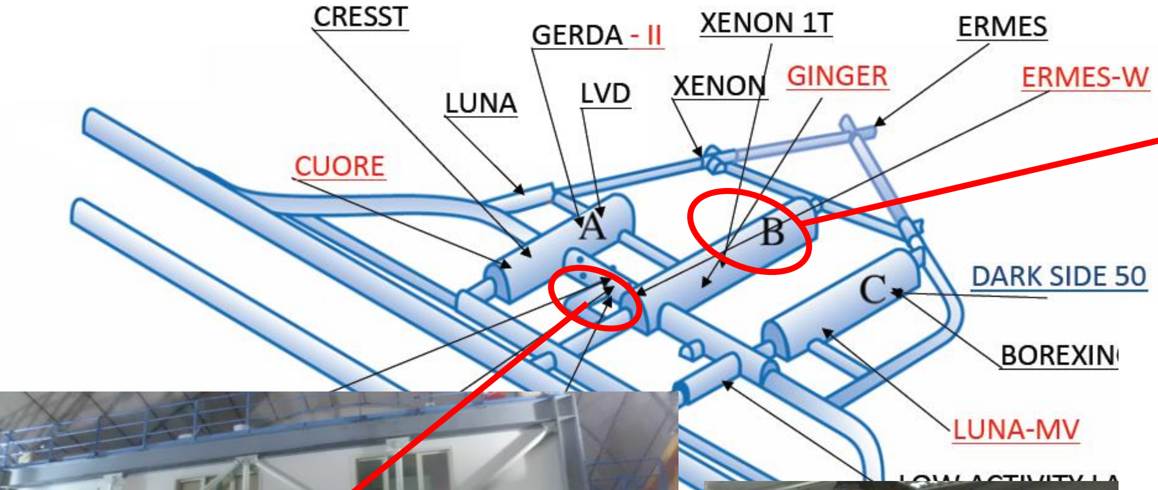
10 kg·year simulated sensitivity [90 % C.L.] + zero BG

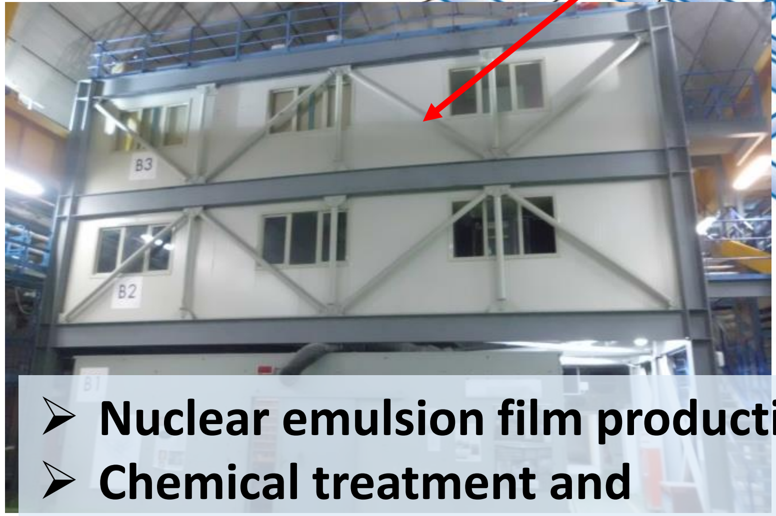


NIT detector / CNO sensitive / no Bkg no directionality
Simulation limit is “energy > 5 keV for all atoms (SRIM limit)”
& “Sensitivity > 0.1 % (Simulation statistics limit;10 event)”

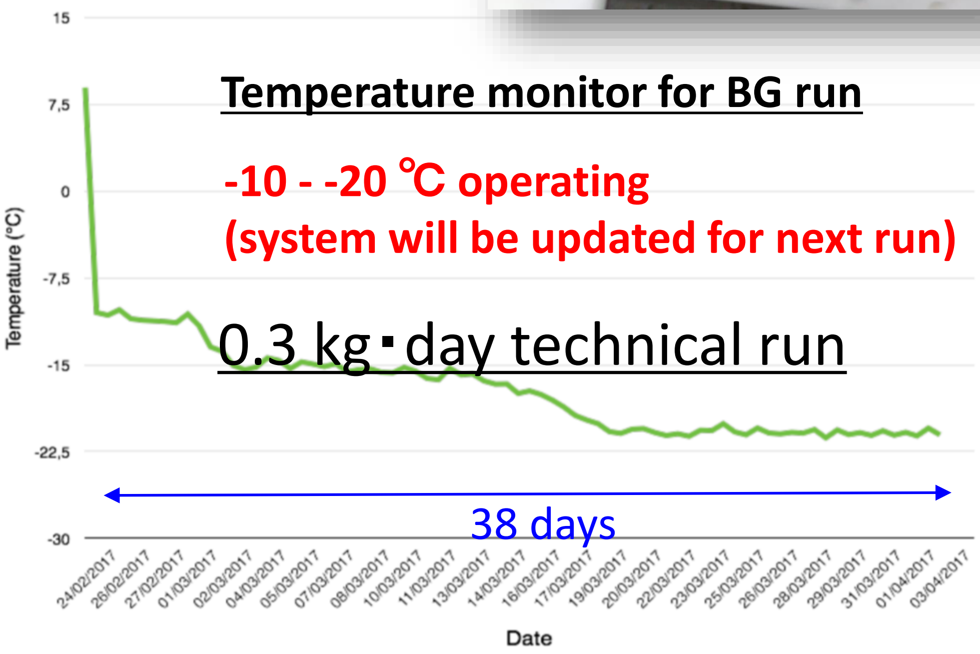
Pilot-run environment and shield

Gran Sasso underground laboratory, Italy





- Nuclear emulsion film production
- Chemical treatment and development
- Underground run



Temperature monitor for BG run

-10 - -20 ℃ operating
(system will be updated for next run)

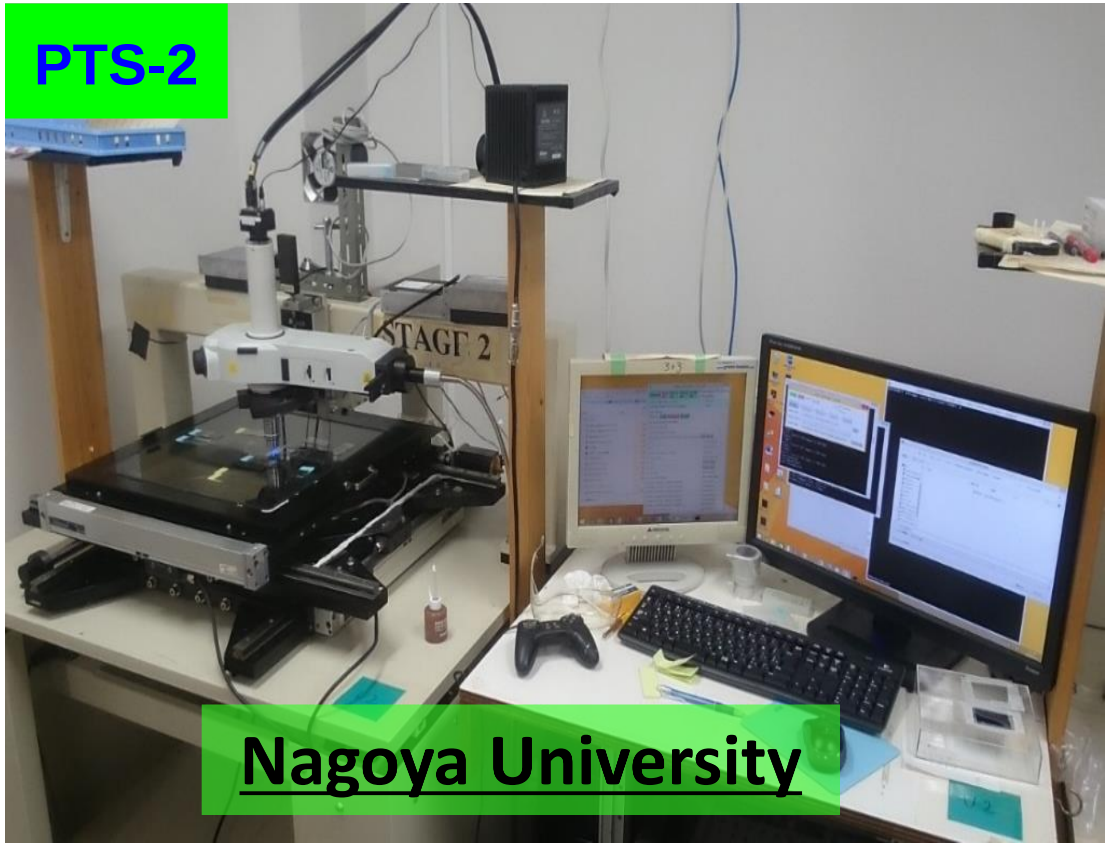
0.3 kg・day technical run

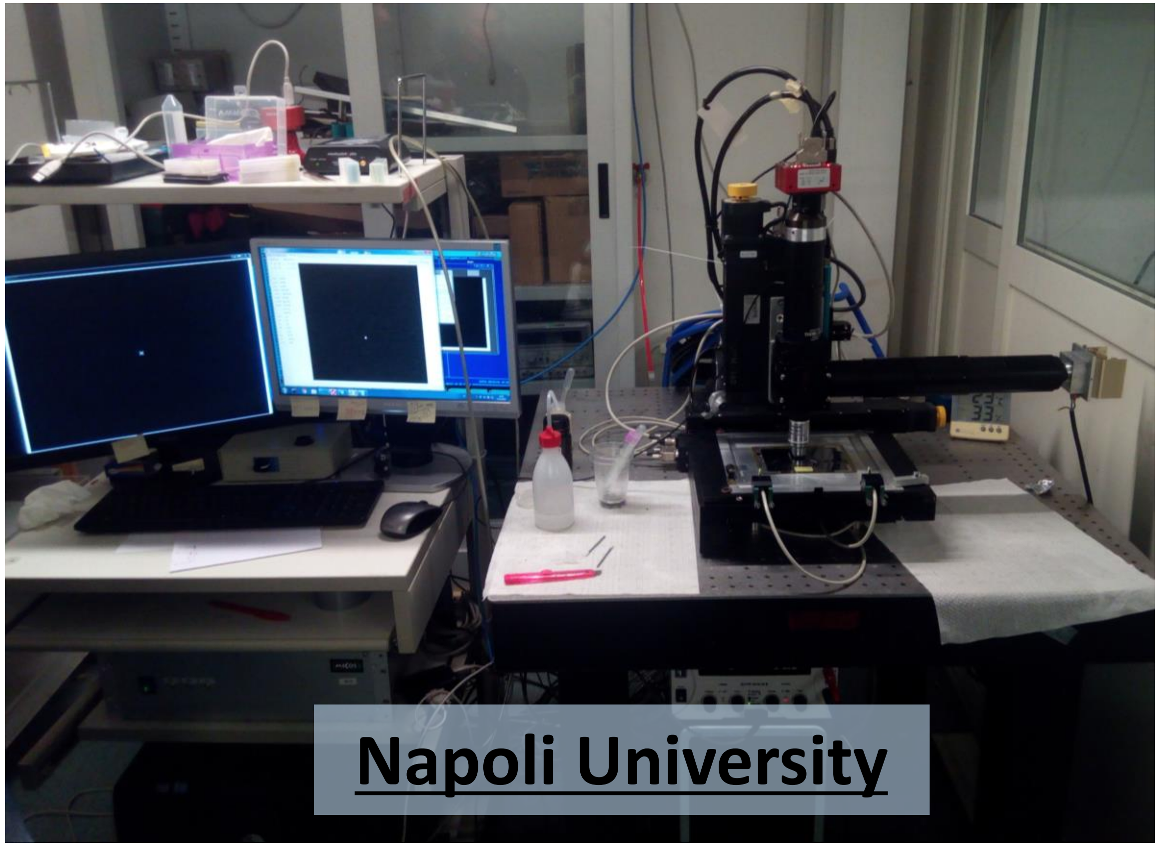
38 days

Readout R&D

Development of New Readout System

Prototype R&D system @Nagoya and Napoli





Readout concept

As the nuclear emulsion keep to record the track such as photographic film, we can read out anytime and by various technologies.

1st step : Roughly candidate selection by high speed scanning system
⇒ making the prediction for the position in the emulsion film

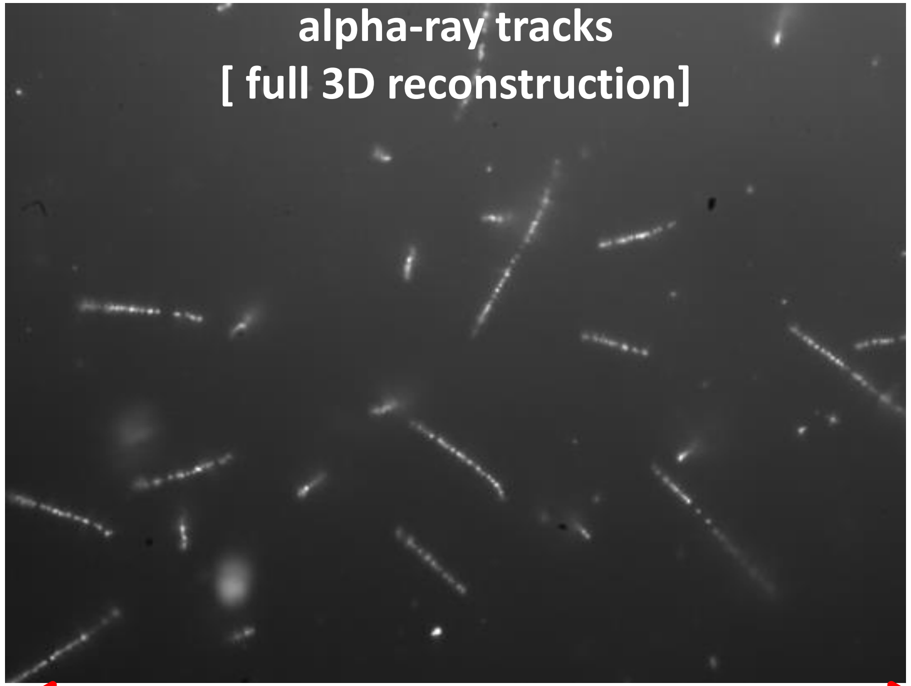
2nd or more step : Using the high-precision and super-high resolution microscope technologies

Nano-tracking prototype scanning system @Nagoya Univ.

Japanese prototype (PTS2)

Base on the epi-illuminated optical microscope

T. Katsuragawa et al, JINST 12 T04002 (2017)

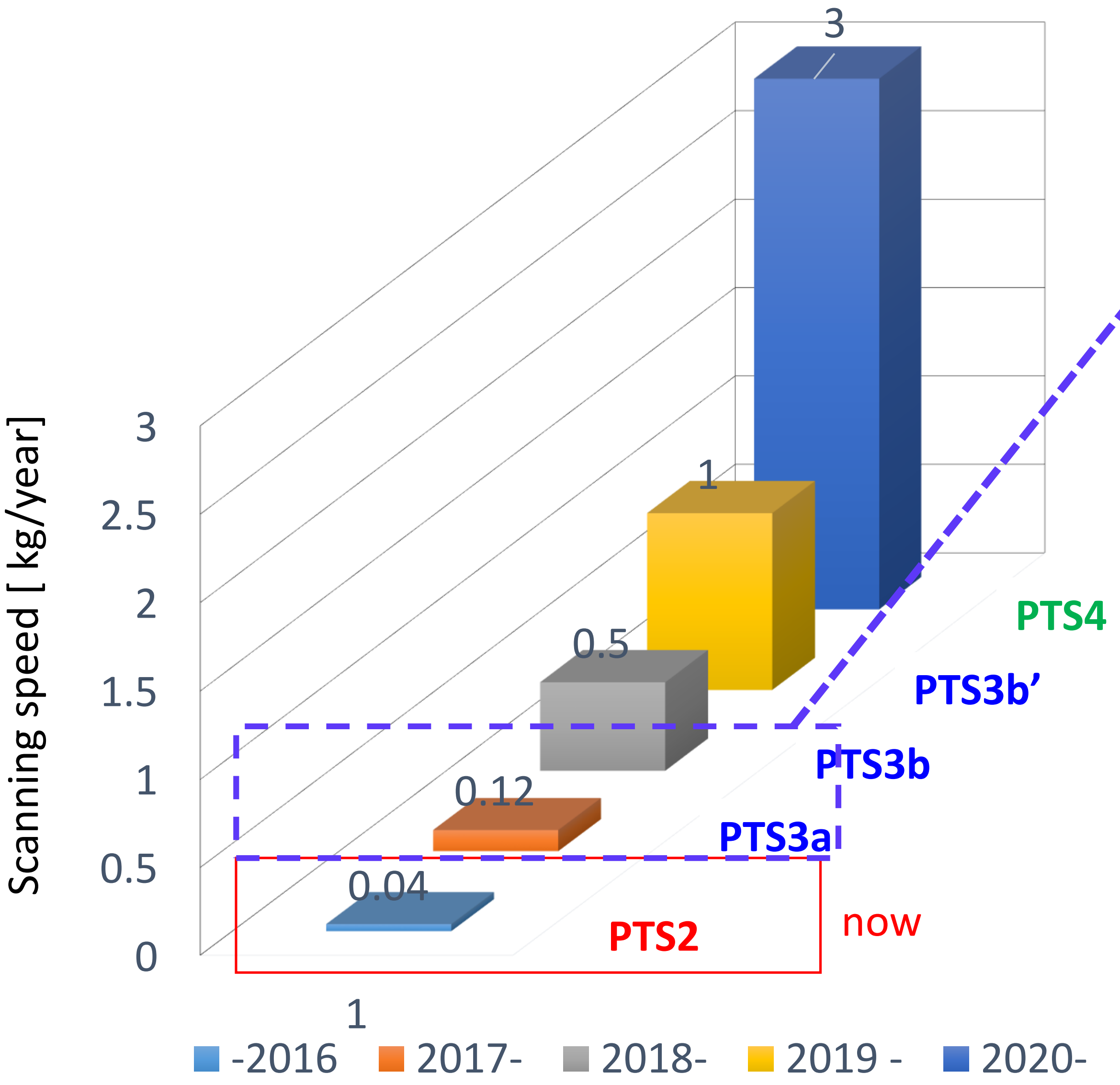


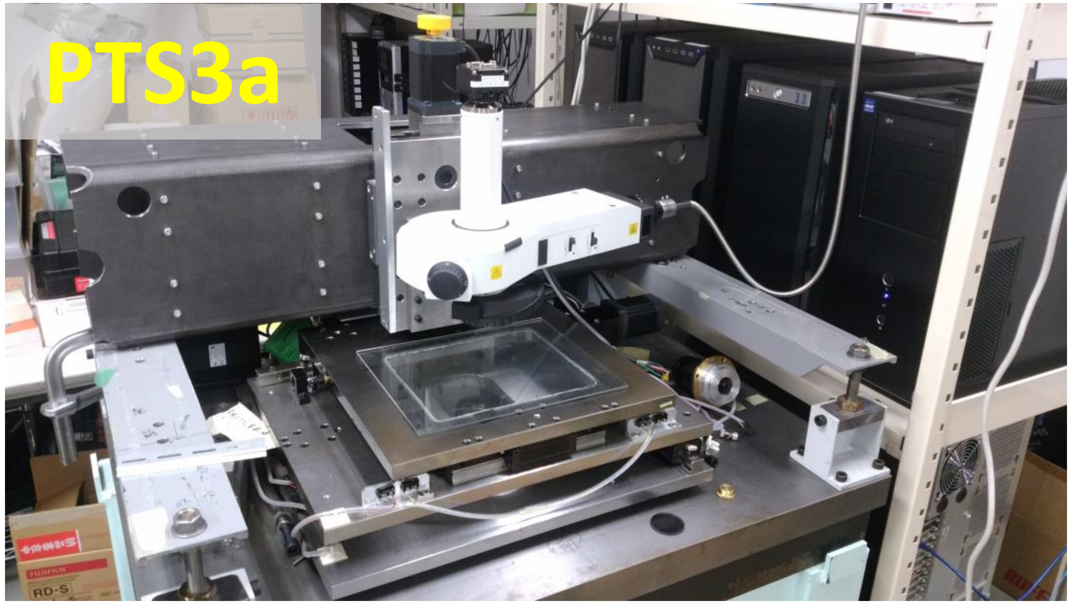
50 μm

Objective lens : Magnification 100x, N.A=1.45
CMOS camera: 2048 pix *2048pix , 180 fps
55 nm / pix
Light source : Hg/Xe lamp w/ λ~450 nm op filter
Spatial resolution : ~230 nm (measured)
Stage control : pulse motor

Scanning speed 1g NIT /10 days (upgrade soon)

Roadmap of scanning system for nano-scale tracking





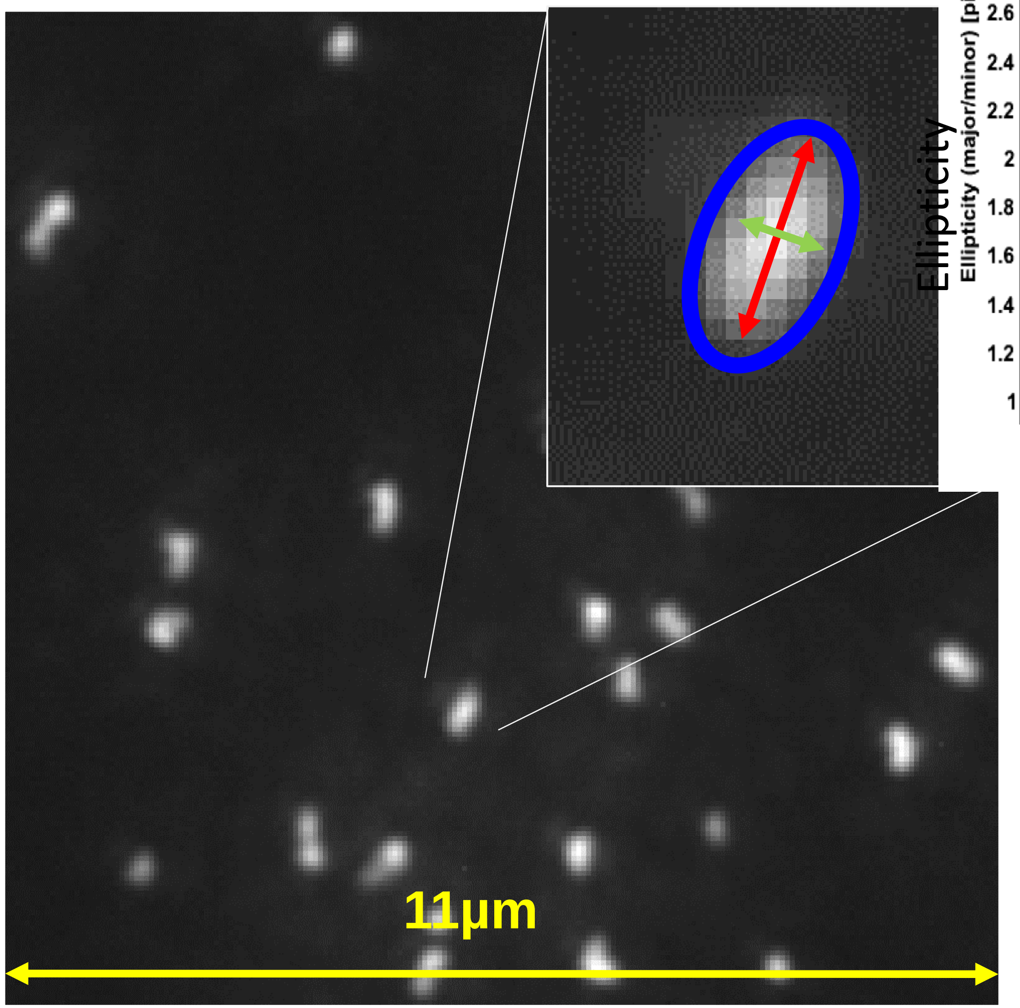
[PTS2] 40 g/y (current system)

[PTS3a] 120 g/y expected (x 3 higher than PTS2])
⇒ Wider FOV due to higher vision camera

[PTS3b] 500 g/y expected
⇒ PTS3a + large DOF system

[PTS3b', PTS4] 1000 - 3000 g/y expected
⇒ PTS3b + custom special lens, high framerate

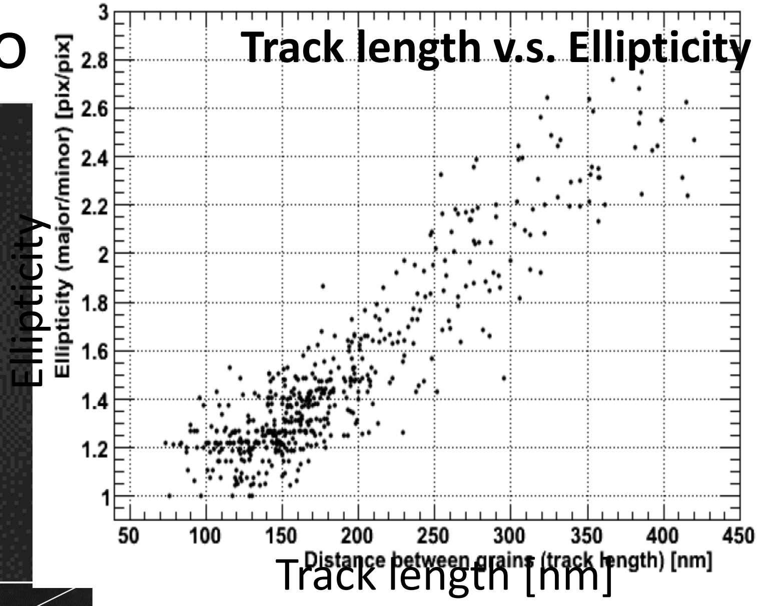
Candidate selection method using epi-illuminated optical microsco

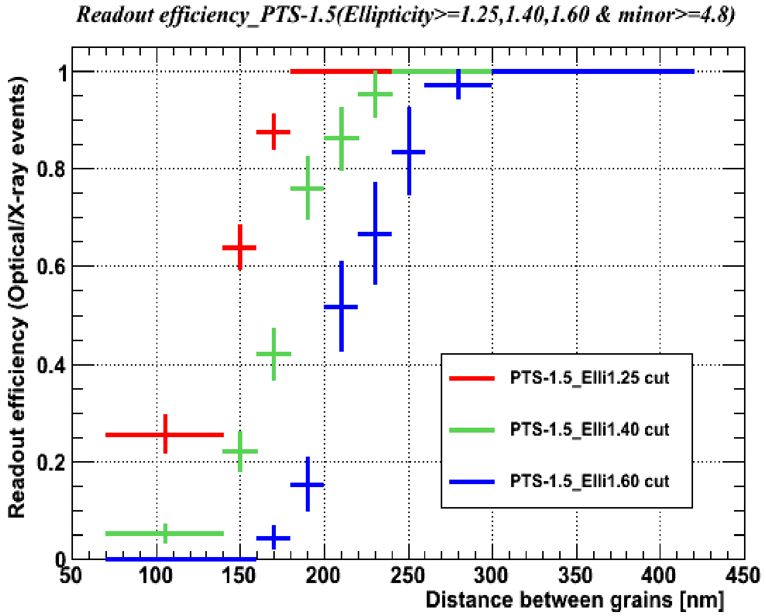


K. Kimura and T. Naka, Nucl. Inst. Meth. A 680 (2012) 12-17

T. Katsuragawa et al, JINST 12 T04002 (2017)

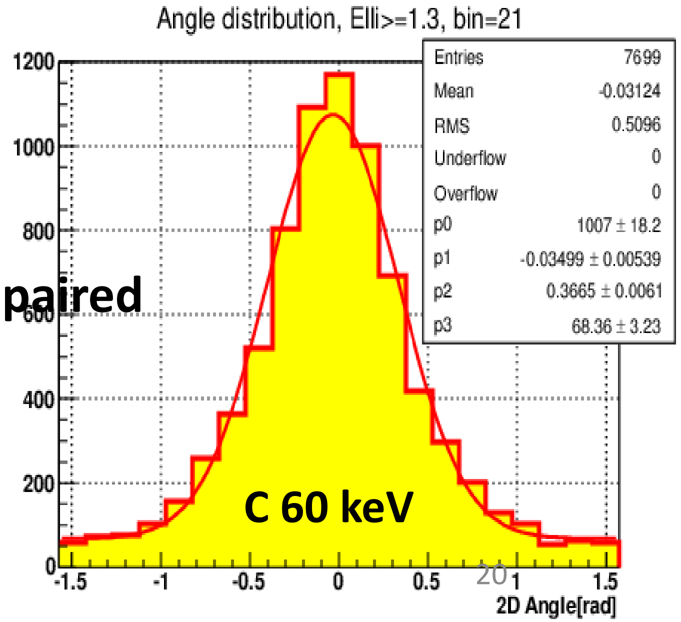
Performance using only elliptical shape analysis





Current microscope has the potential to select > 100 nm length tracks

Direction sensitive eff.:
~30 % @60 keV
⇒ current efficiency is limited by optical contrast loss : to be repaired
Angular resolution :
~30 deg. @60 keV



Lower energy calibration is under studying.

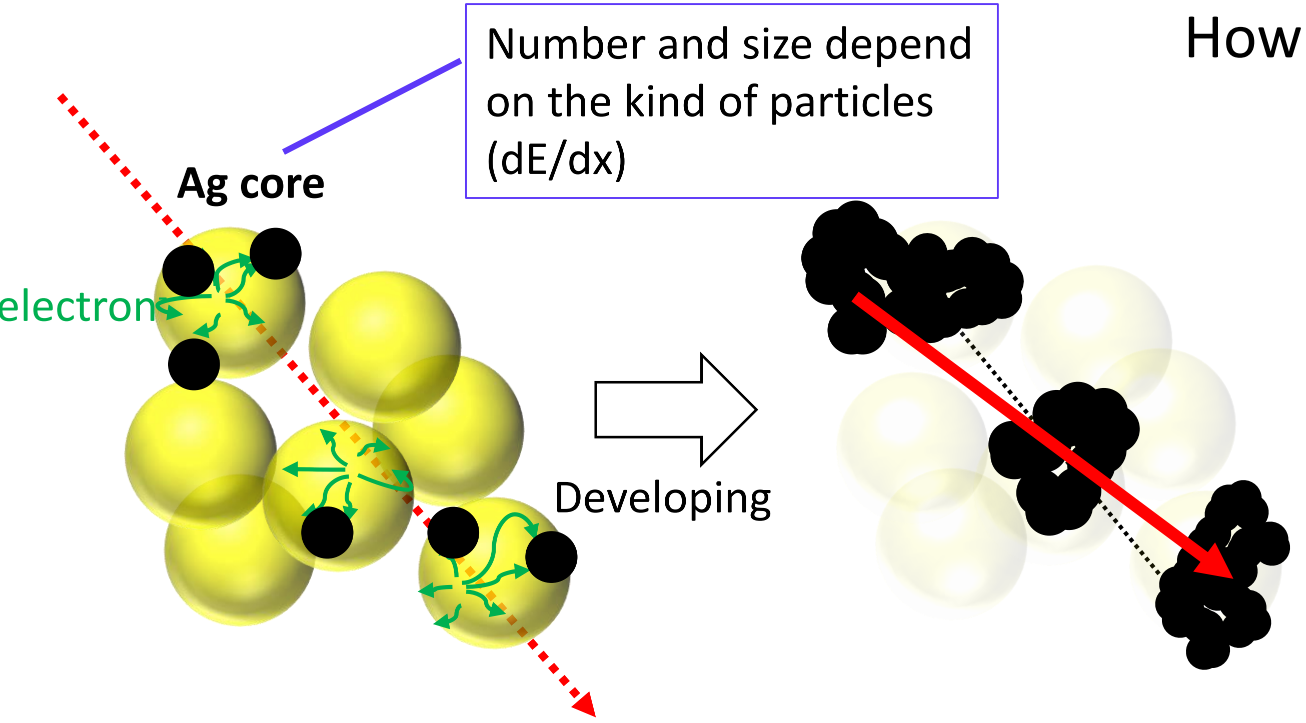
Readout concept

As the nuclear emulsion keep to record the track such as photographic film, we can read out anytime and by various technologies.

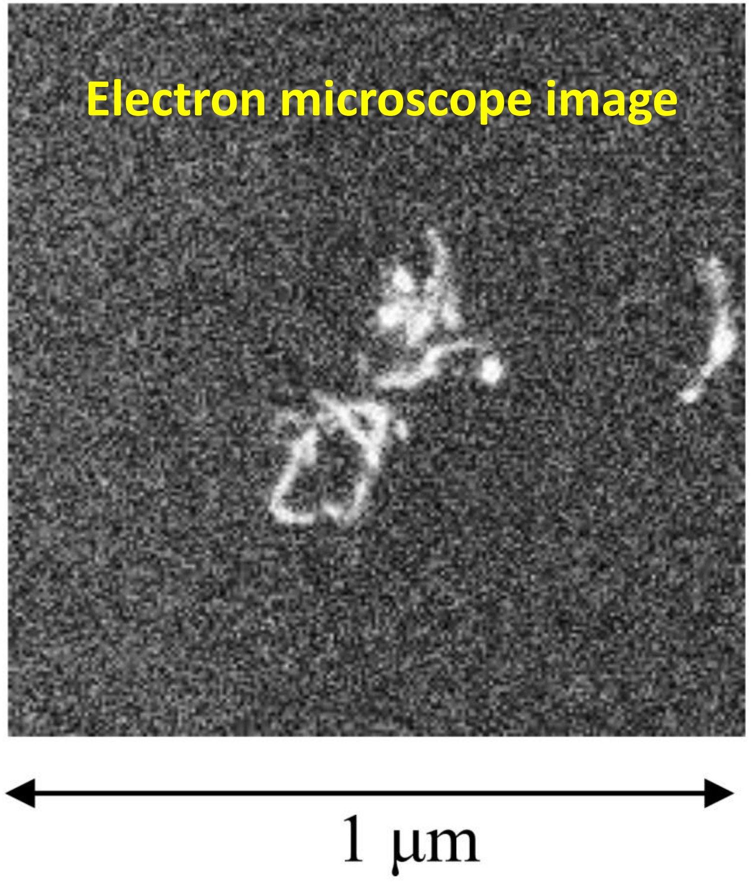
1^{st} step : Roughly candidate selection by high speed scanning system
⇒ making the prediction for the position in the emulsion film

2^{nd} or more step : Using the high-precision and super-high resolution microscope technologies

Concept of confirmation of signal



How do you confirm the signal from background?

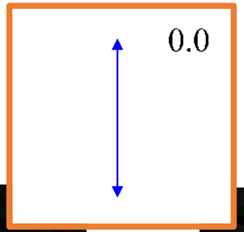


☑ complicate Ag filament structure ⇒ unique information as signal
☑ this structure depends on the dE/dx and controlled by the type of development treatment

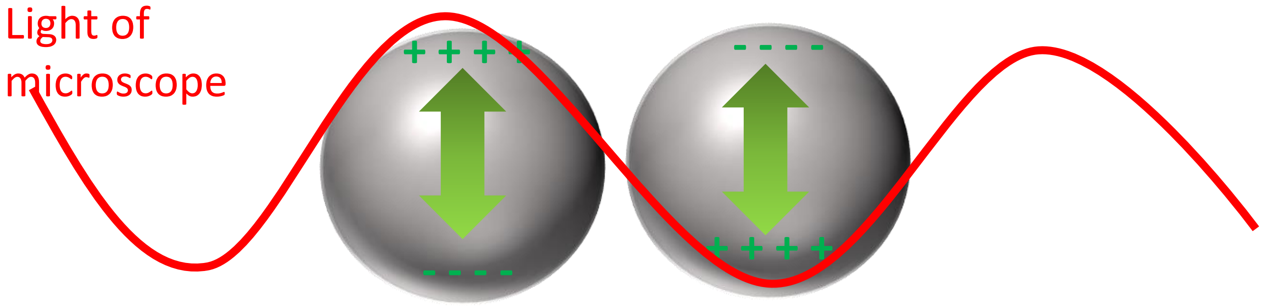
Output of such nano-scale information is critical point for the signal confirmation

Beyond optical resolution analysis

Concept of beyond optical resolution⇒ 2014 novel prize



Localized Surface Plasmon Resonance

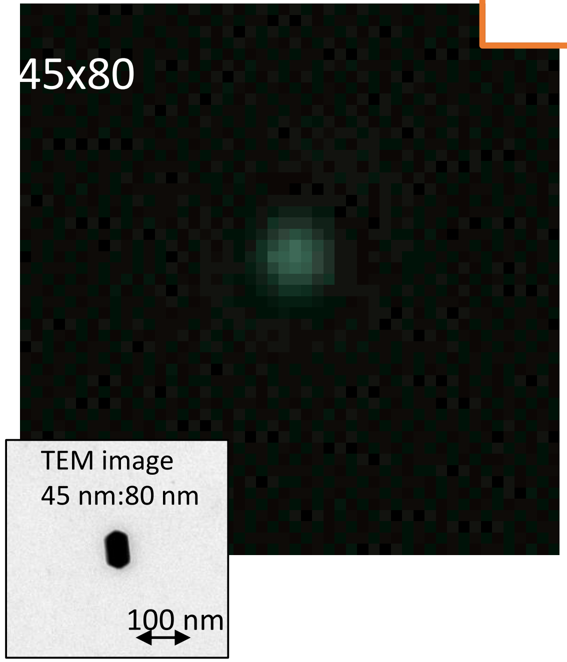


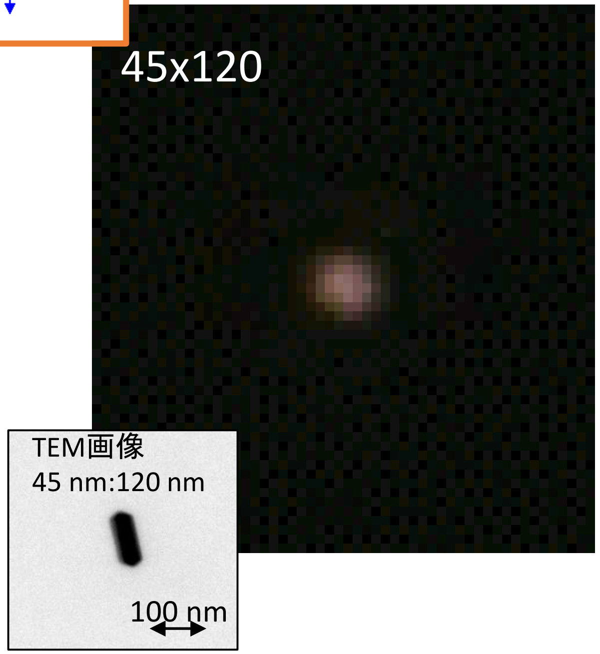
silver nano particle

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

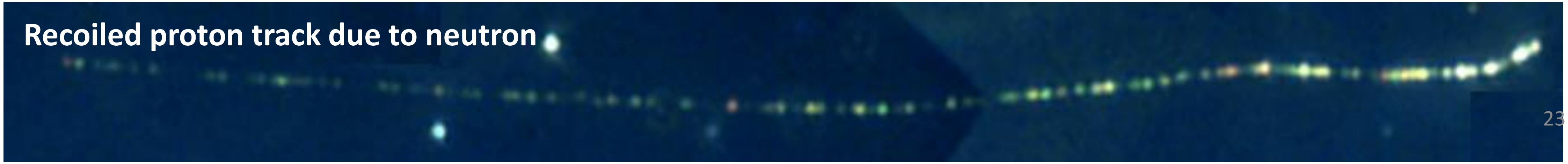
$$\boxed{\varepsilon_1(\lambda_l) + 2\varepsilon_m(\lambda_l) \approx 0}$$

Resonance condition

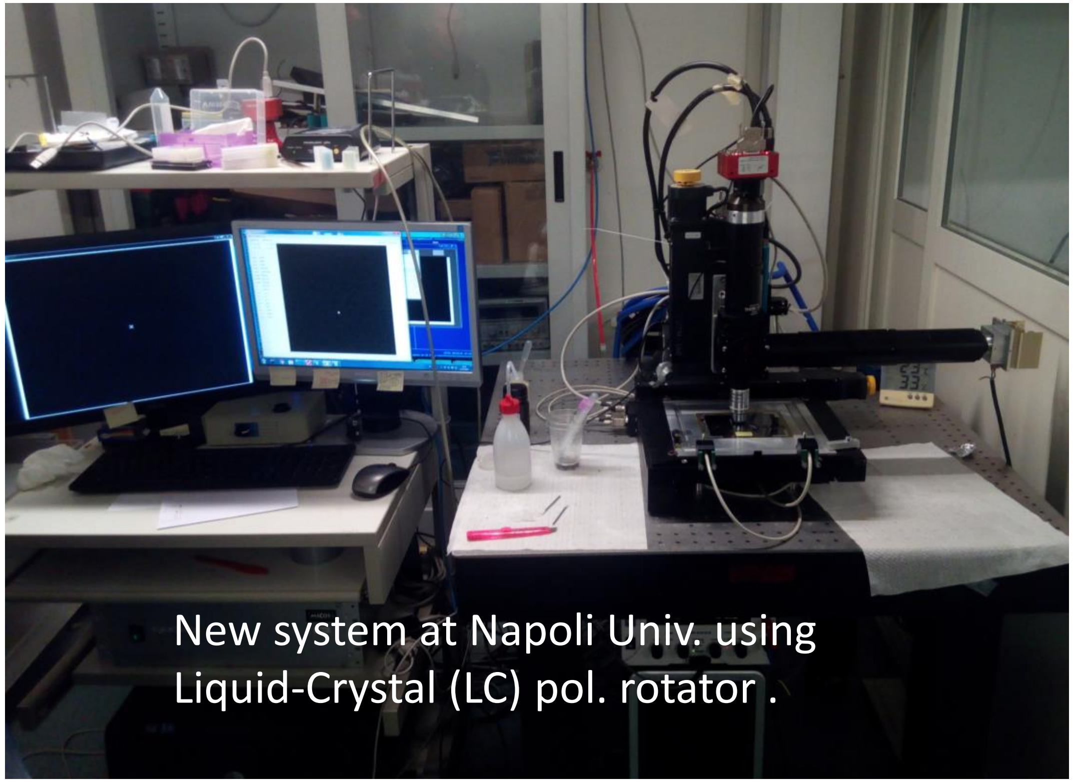




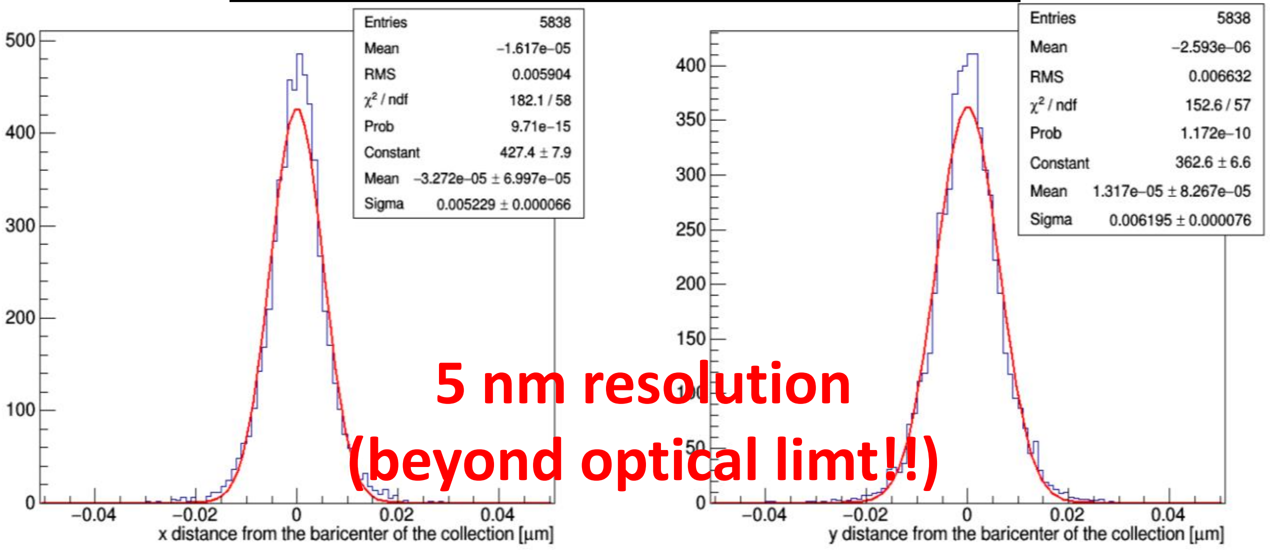
- Resonance effect due to coupling with the free electron and light of optical microscope
- Resonance wavelength depends on the crystal size
- Polarization angle dependence of resonance wavelength

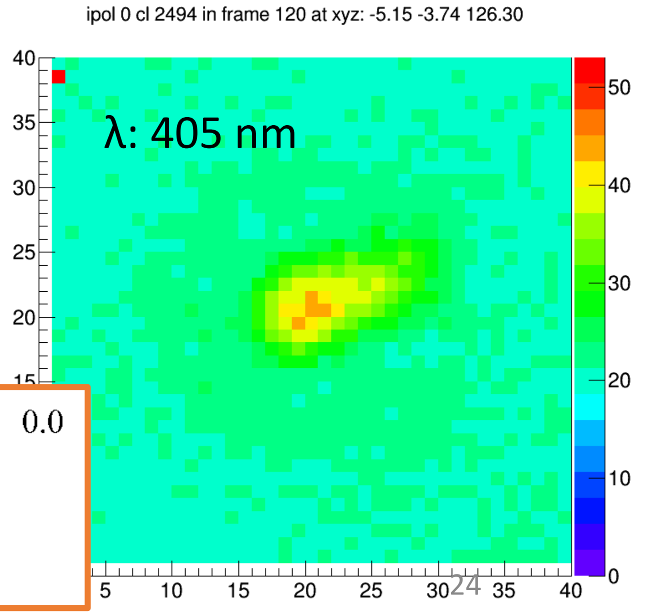


R&D of Super-high resolution tracking



Position resolution for X and Y direction



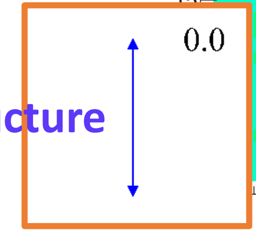


What should we see ?

- **polarization dependence**
- **wavelength dependence**

☑ **super-high resolution imaging**
☑ **back ground rejection + PID**

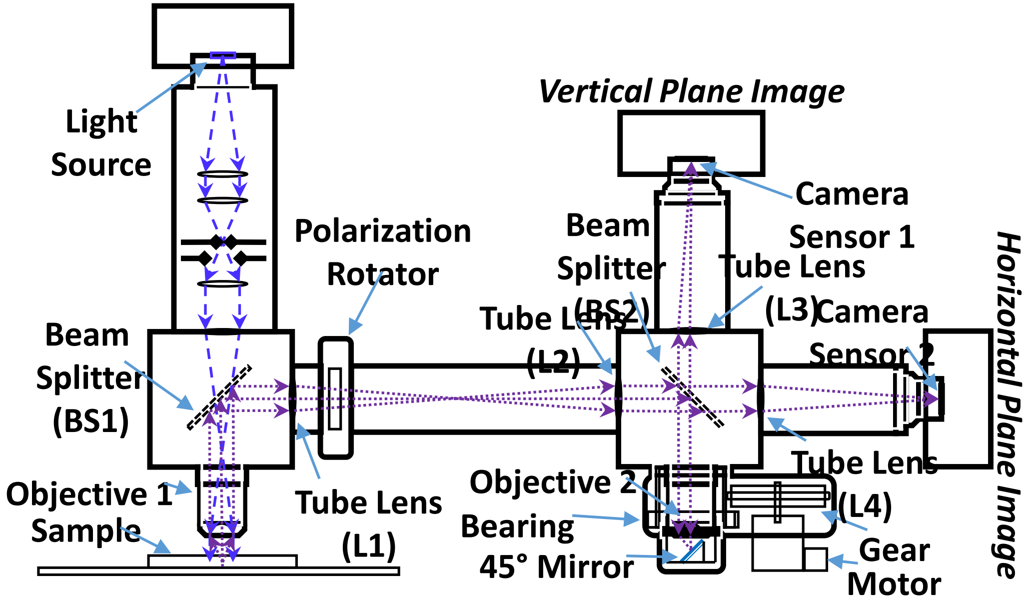
Due to the difference of nano scale structure of silver grains

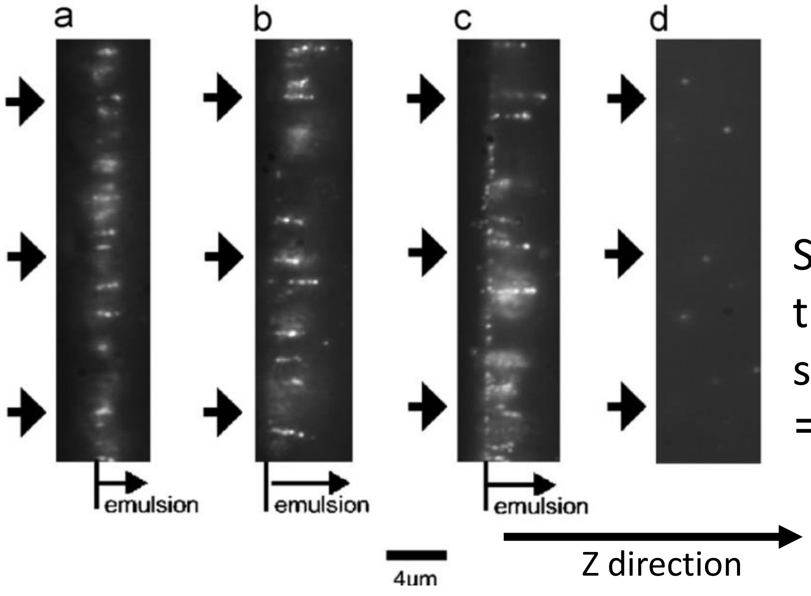


3D nano-track reconstruction system

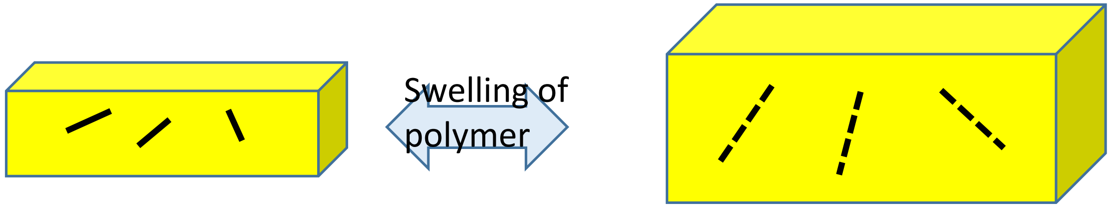
- Currently, resolution of Z direction is about 0.3 µm because of limitation due to optical rule
- By using the Plasmon response, it's possible to analysis beyond optical limitation for also Z direction
  ⇒ several 10 nm
- By combination with track expansion techniques, more high precision reconstruction should be possible

⇒ this will be very powerful signal confirmation from backgrounds





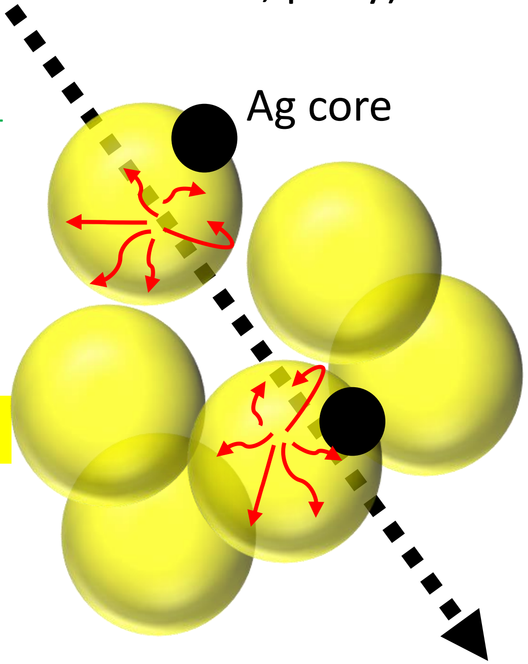
Submicron length tracks are elongated by swell of polymer
⇒ easy recognition



T. Naka *et al.*, Nucl. Inst. Meth. A 581 (2007)

Near future plan

β-ray event rejection potential



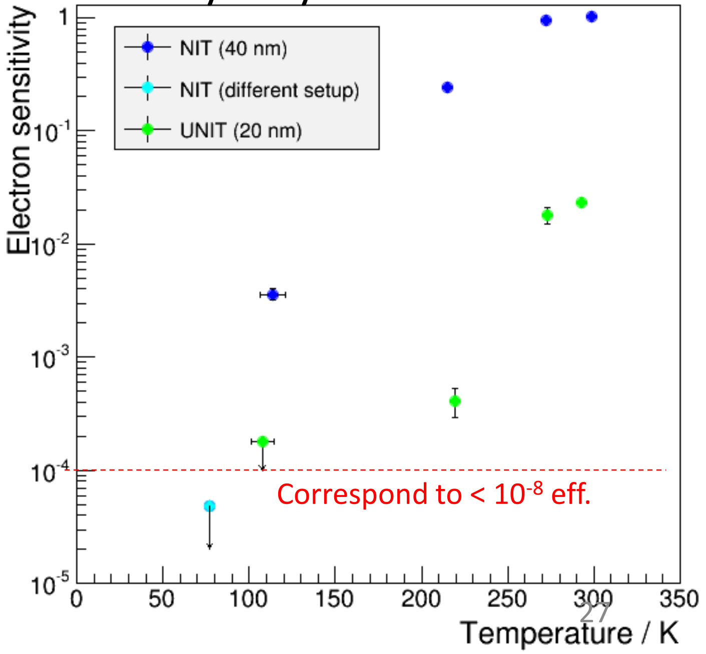
- ☐ Cryogenic crystal effect
  - crystal quantum efficiency is drastically decrease by lower temperature
  - nuclear recoil is not by the thermal spike

⇒ Powerful discrimination between nuclear recoil and electron
e.g.) expected BG signal eff. due to electron < 10^{-9} @80K

- ☐ Chemical treatment
  - Nuclear recoil can create enough number of e-h pair for the Ag core
  - Dopant in the AgBr crystal to suppress the sensitivity only electron

- ☐ Low background material
  - gelatin have high C-14 level
  - replacement to the synthetic polymer

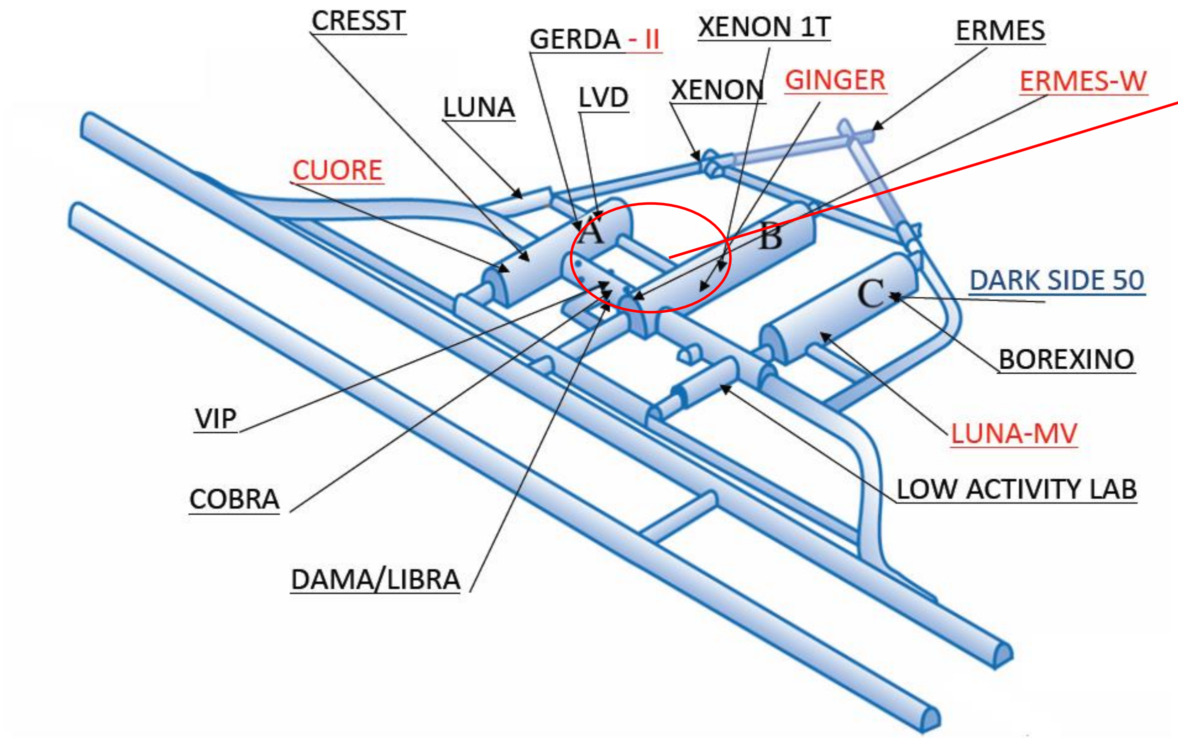
  ⇒ at least > 10^3 rejection
  (aleady measured byAMS)



As potential, > 10^9 rejection power is expected by combination of some techniques

⇒ Now, constructing the calibration system in the LNGS

New site and next subject



<u>New Facility optimized this experiment</u>

1. Clean room

2. Clean water

⇒ will be utilized Borexino's pure water

3. Emulsion self-production (new machine will be installed)

To do

- construction of calibration system
- direct measurement the environment radioactivity

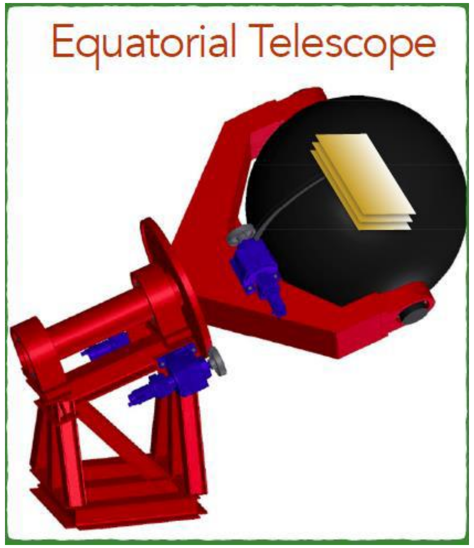
Future plan

2017 :

- **Data taking R&D**
- **More high precision calibration**
- **Understanding of background + analysis of technical run data**
- **construction of new under ground site**

2018 :

- **TDR submission to LNGS**
- **kg scale experiment design study**
- **construction of higher seed scanning system**
- **equatorial telescope**



2019 ~ :

- **physics run with > several 100 g experiment**
- **larger scale experiment study**

But, the schedule depends on the situation of background …

Summary

- **Directional sensitive dark matter detector give new information for us and enable high reliable measurements**
- **we propose a fine-grained nuclear emulsion (Nano Imaging Tracker: NIT) as super high resolution dark matter detector**
- **Already demonstrated about the capability of detecting the tracks with several 10 keV (> 100 nm)**
- **Readout system based on the optical microscope is constructed**

  - first trigger system using simple shape analysis is operating now

  - super-high resolution analysis system is under studying
- **Technical run have been carried out in the Gran Sasso laboratory with 0.3 kg･day exposure**

  ⇒ now, doing the data analysis and R&D

  ⇒ low-background study is also on going