NAGOYA UNIVERSITY

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

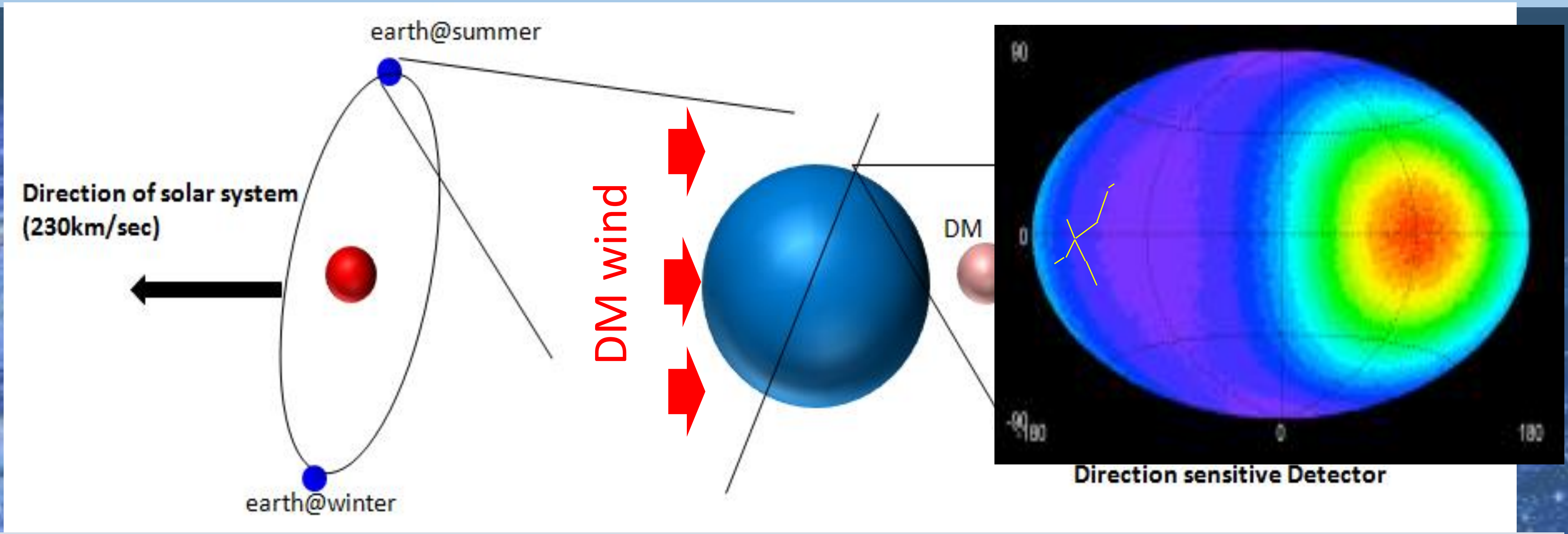
Direction Sensitive Dark Matter Search with Super-high Resolution Nuclear Emulsion

Tatsuhiro Naka

KMI, Nagoya University@Japan

on behalf of NEWSdm collaboration

7 July, 2018 ICHEP2018 @ Soul, South Korea



Direction sensitive search → new generation dark matter search experiment

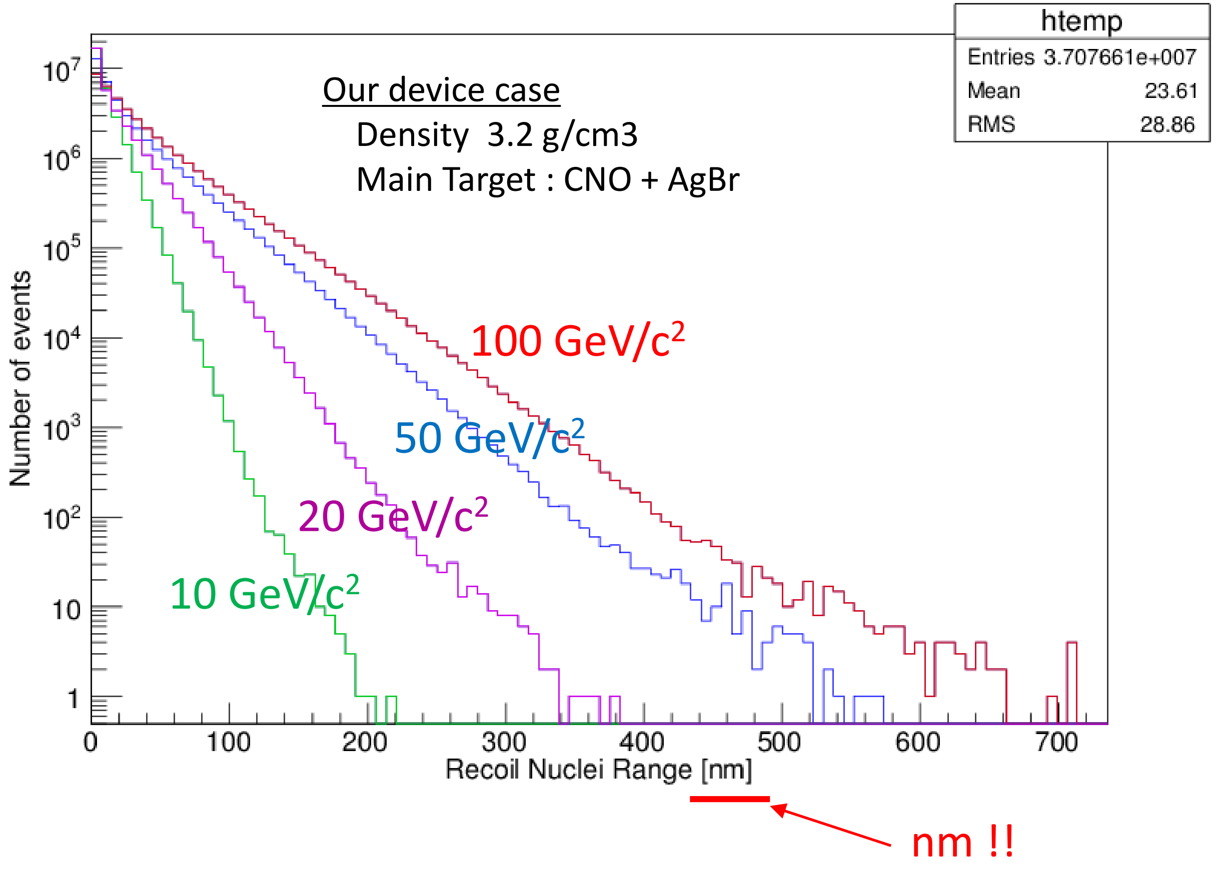
- Essentially new systematics, not only annual modulation
- It has 100 times gain statistically for required # of signal to annual modulation search
- Discrimination between neutrino and dark matter using angle information
- Dark Matte Astronomy (dark matter distribution)

Challenge for Direction Sensitive Dark Matter technologies

Can the solid (or liquid) detector have directional sensitivity to nuclear recoil signal due to WIMPs ? (currently gaseous detector is on studied)

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

New technical challenge !!

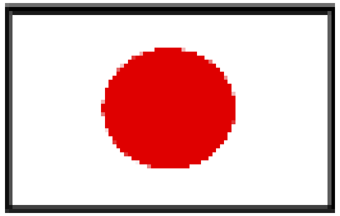


Low mass (~10 GeV/c2) search : light target + < 200 nm length
High mass (> 100 GeV/c2) search : heavy target + < ~700 nm

NEWSdm ~ **Nuclear Emulsions** for WIMP Search + directional measurement

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

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



Chiba
Nagoya

METU Ankara

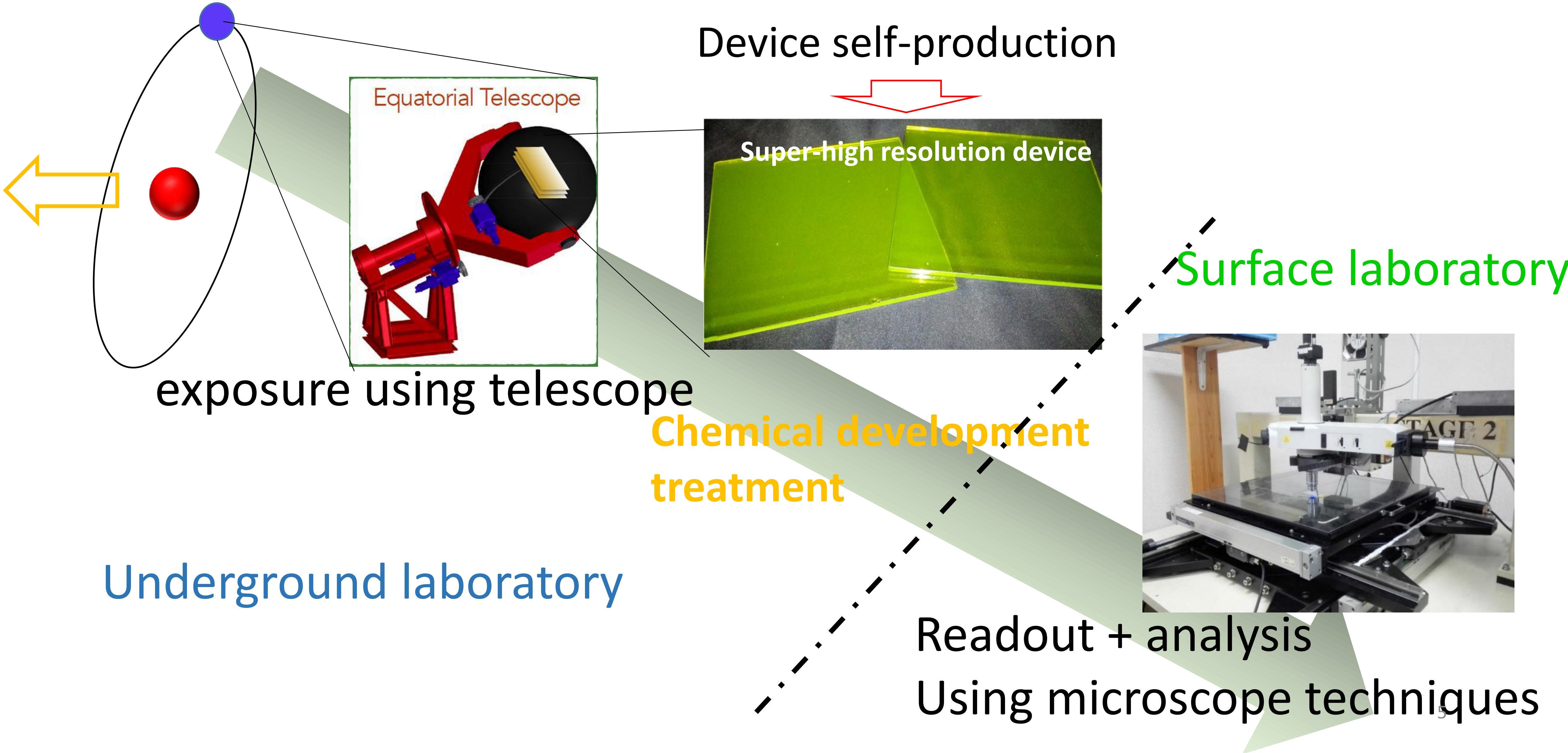
Bari
GSSI
LNGS
Napoli
Roma

LPI RAS Moscow
JINR Dubna
SINP MSU Moscow
INR Moscow
Yandex School of Data Analysis

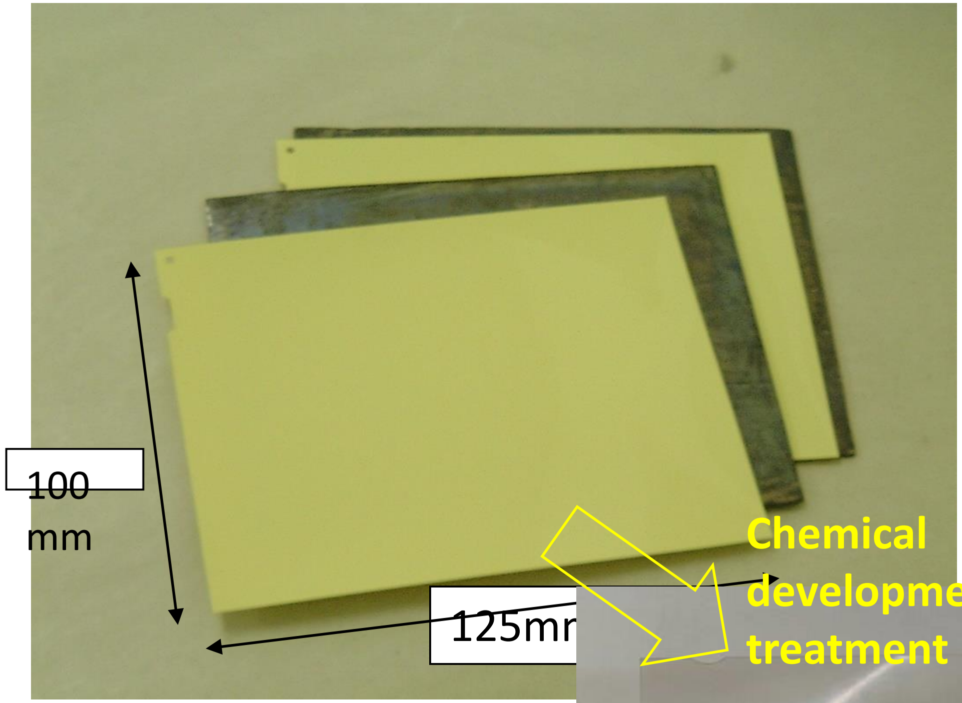
Gyeongsang

LOI under review by the LNGS scince committee
https://arxiv.org/abs/1604.04199

Concept of NEWSdm experiment

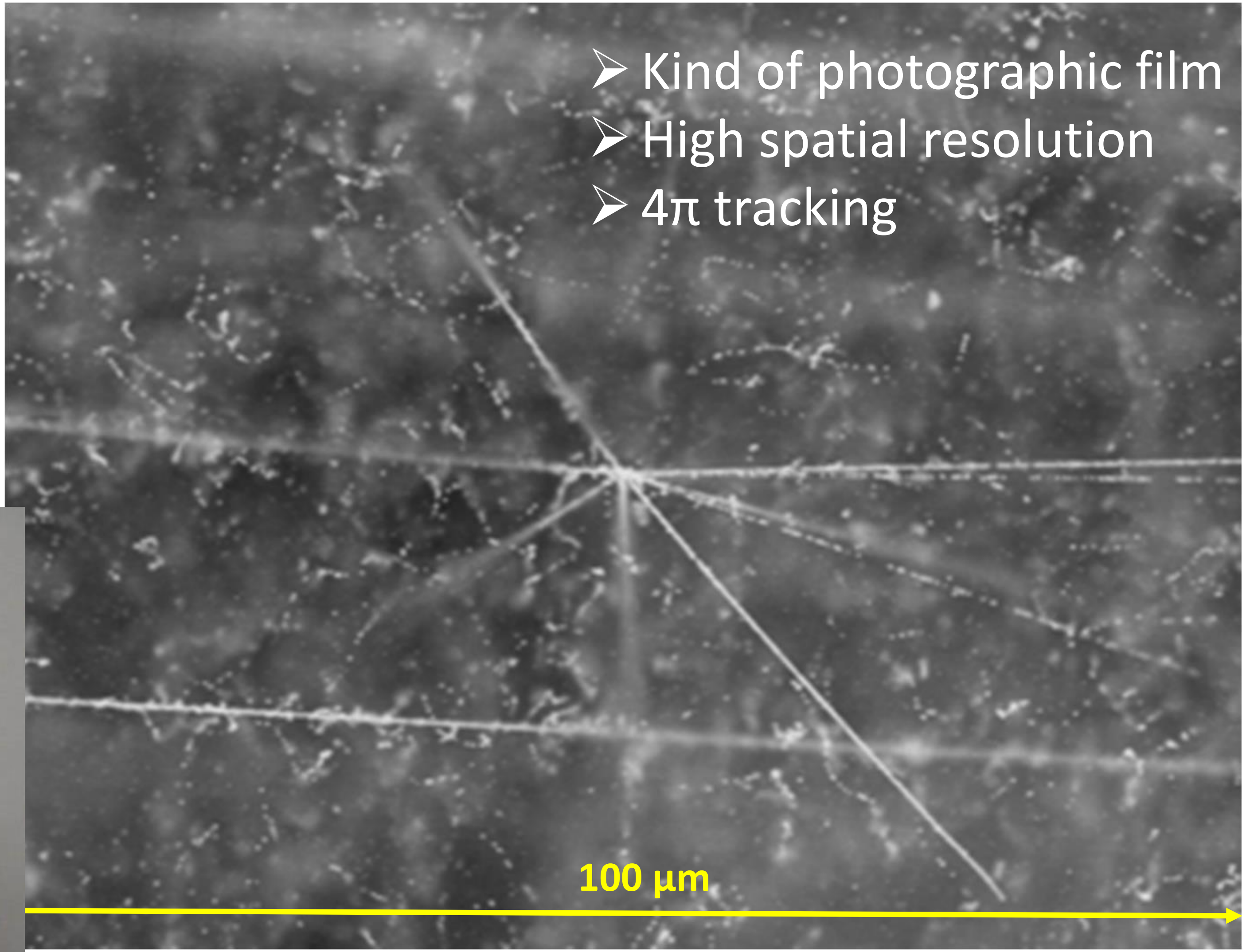


Nuclear Emulsion



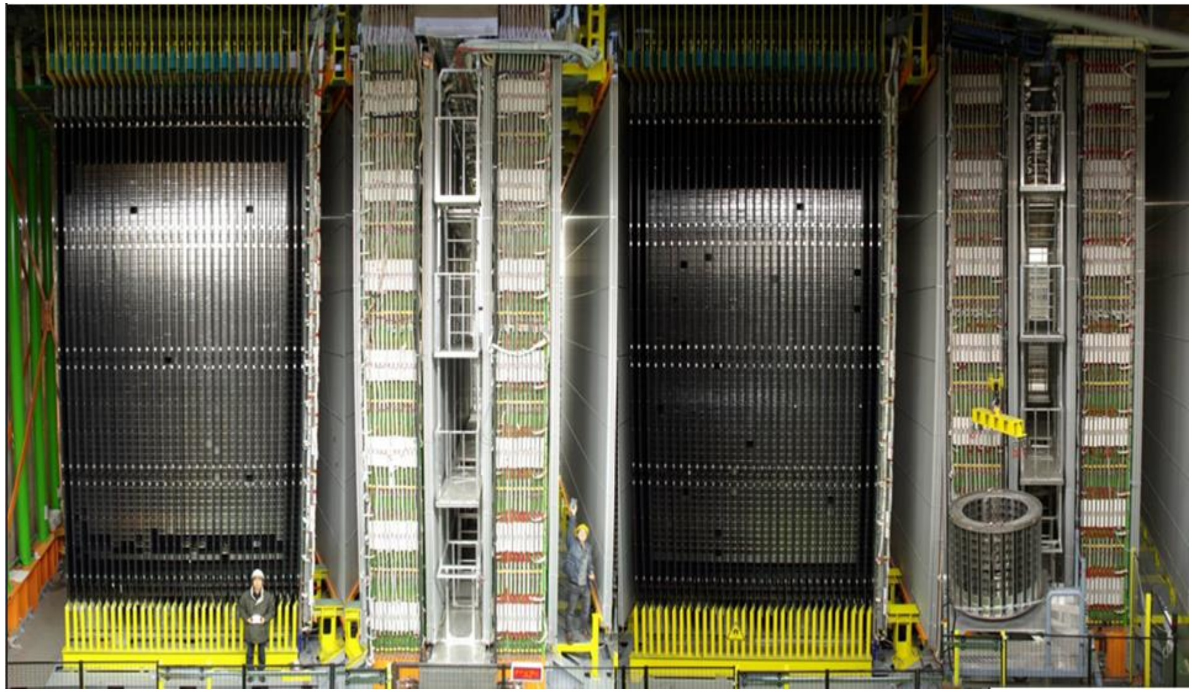
Chemical development treatment

Solid tracking detector :
Density ~ 3 g/cm^3



Latest nuclear emulsion experiment and readout

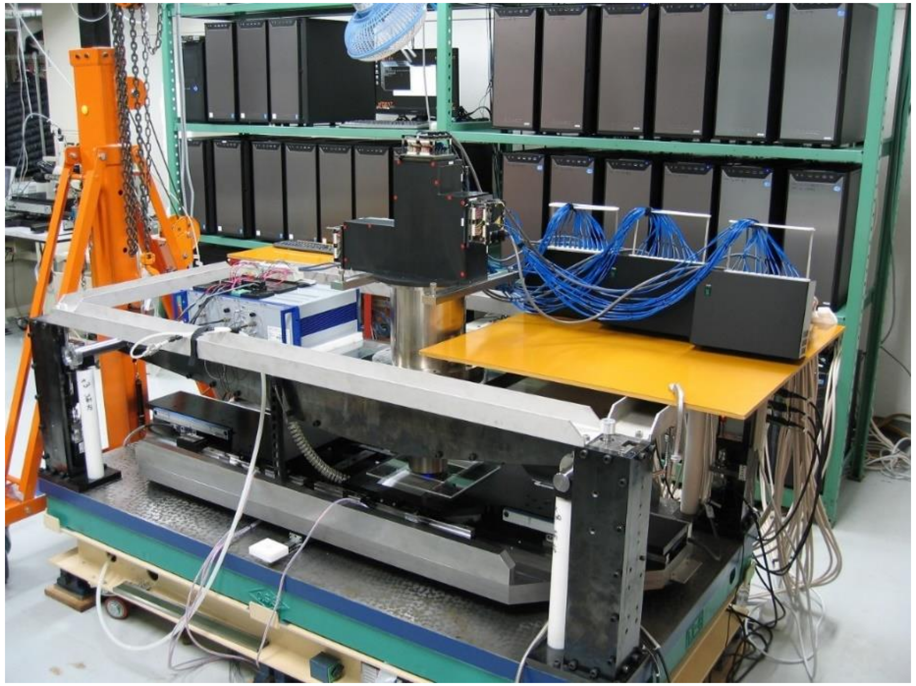
OPERA detector



20 m

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

Current highest speed readout system

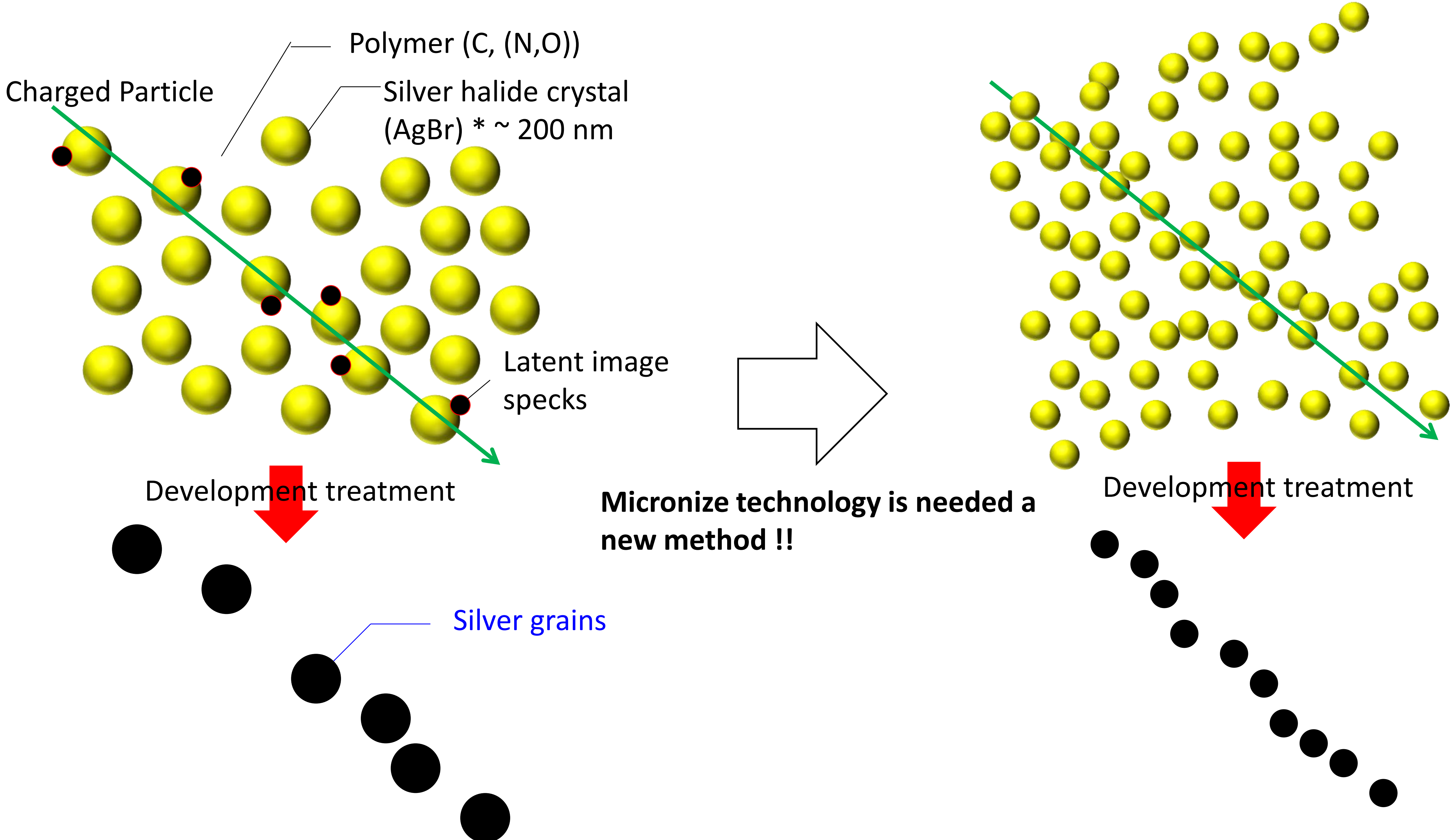


Scanning speed ~ several ton /year

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

It has good potential for ton scale experiment !

Concept of super-high resolution

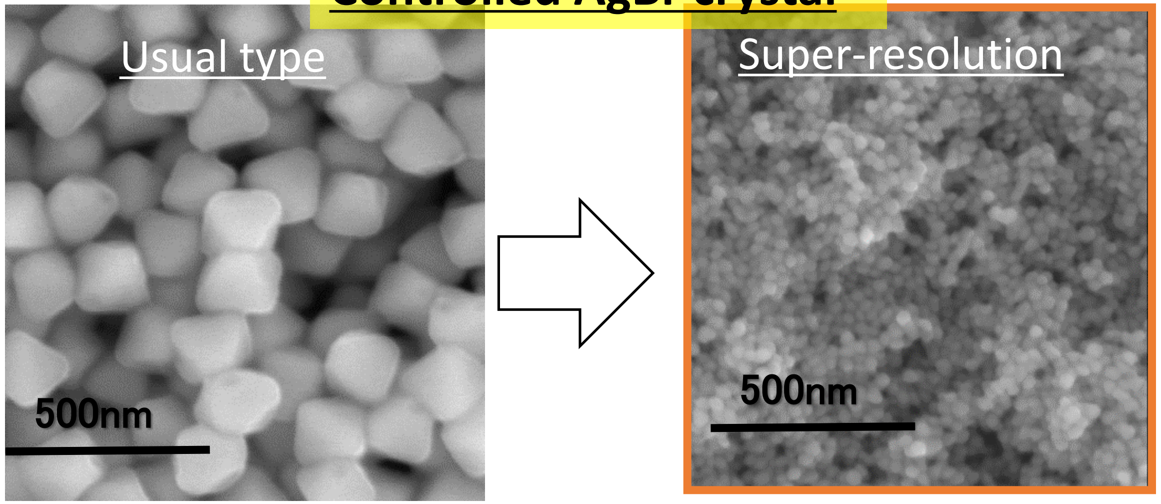


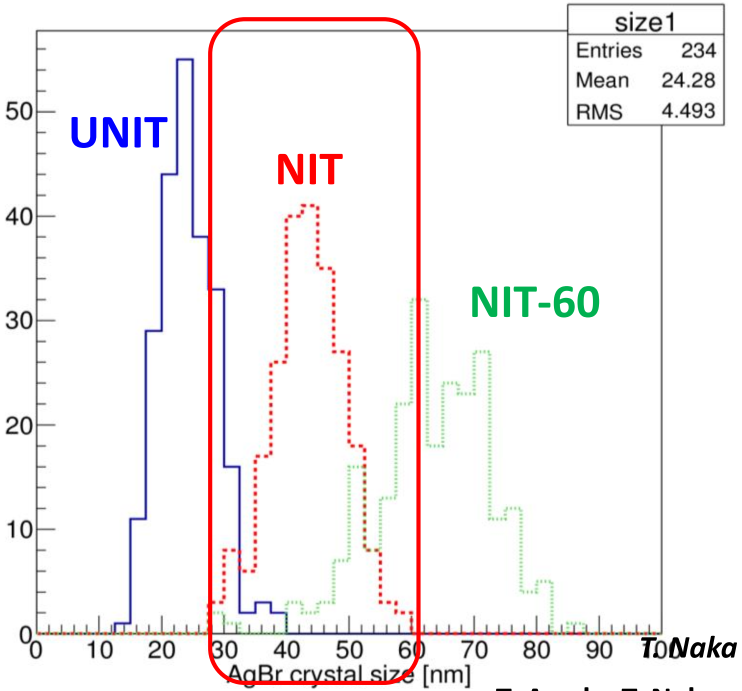
Self-production of Nano Imaging Tracker(NIT)

- 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





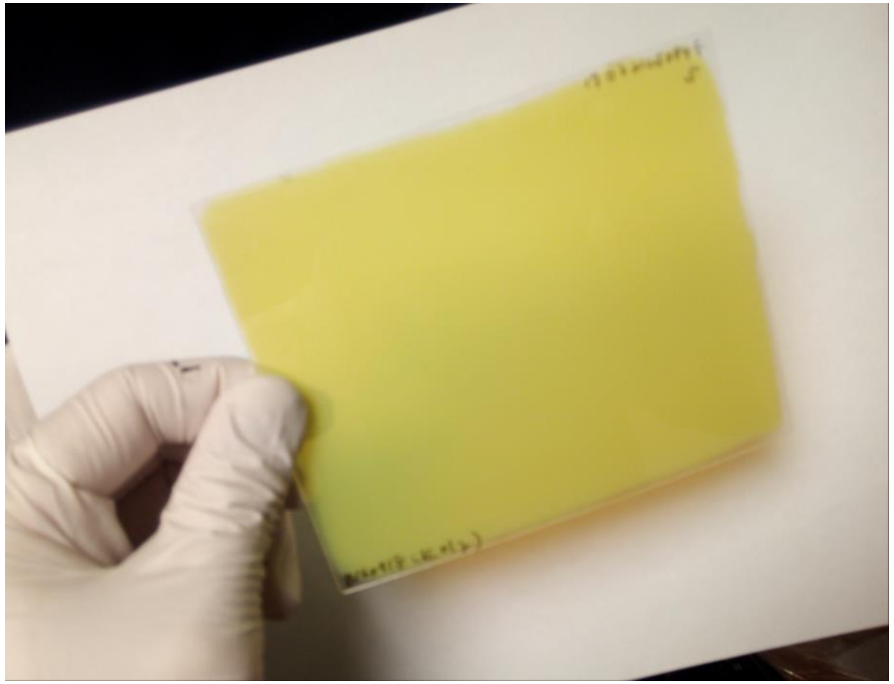
Current standard Device :
Nano Imaging Tracker [NIT]
crystal size : 44 nm

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 NIT film for dark matter experiment



Elemental composition of NIT

For high-mass DM s: Ag, Br, I

For low-mass DM: C, O, N, H, S, Na + others

	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]

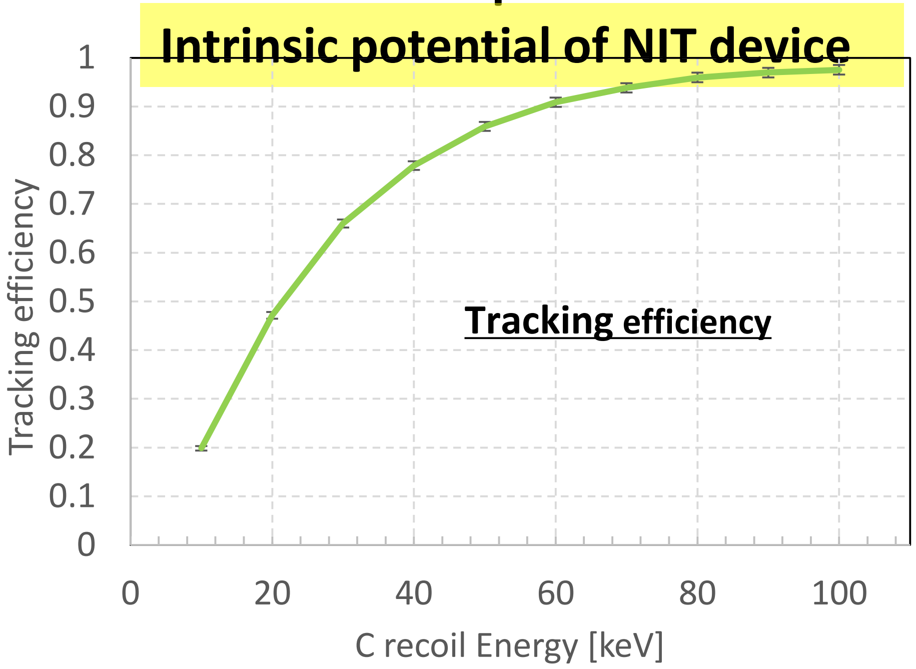
◆ Intrinsic neutron emission:

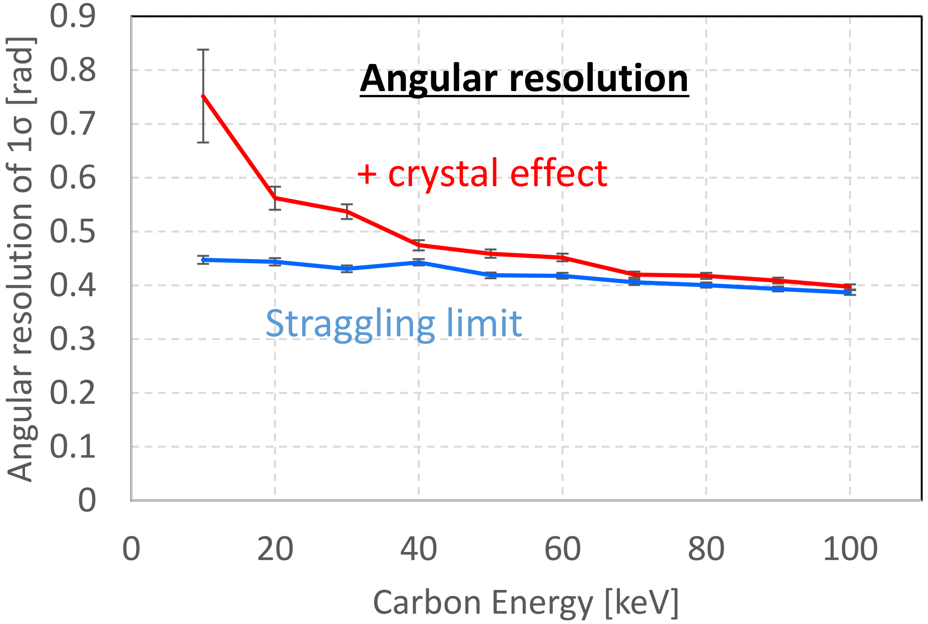
~ 1.2 /kg/y (by SOURCE simulation)

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

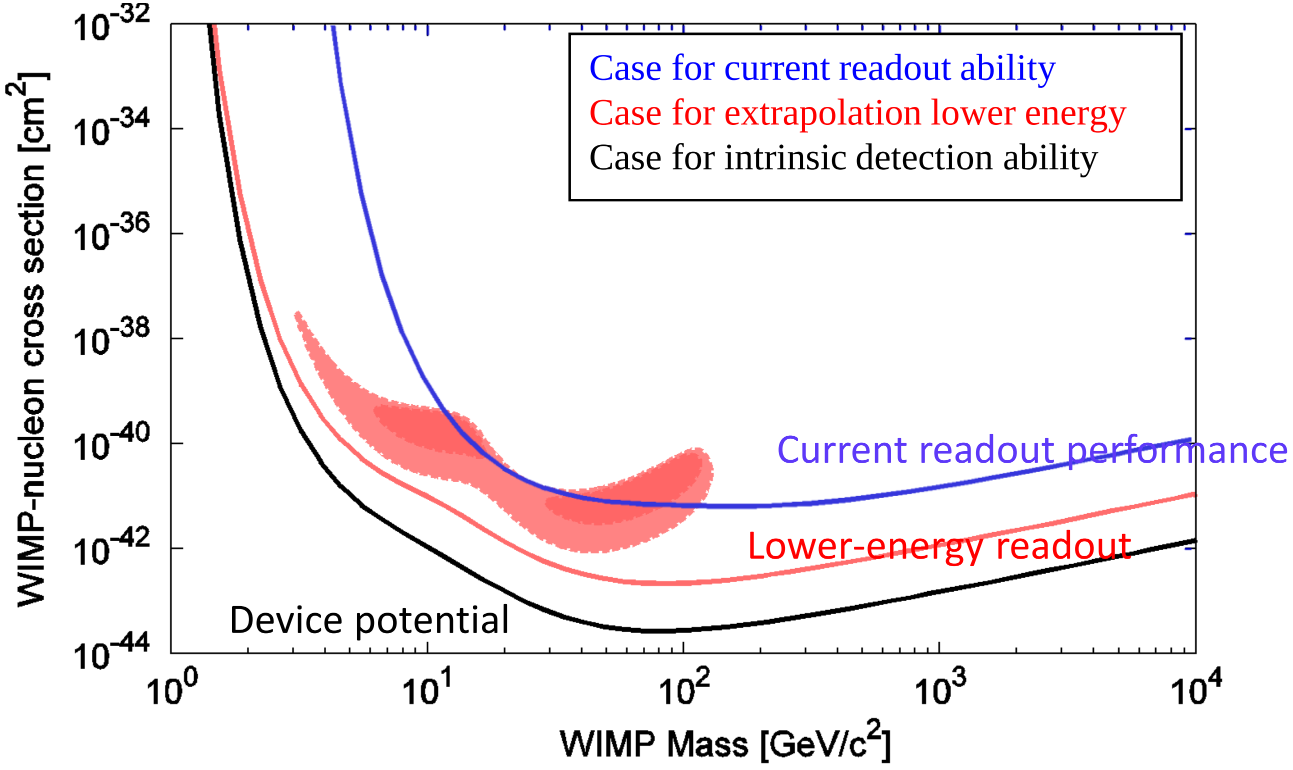
Detail shown in Astropart. Phys. 80 (2016)16-21

NIT device potential





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)"

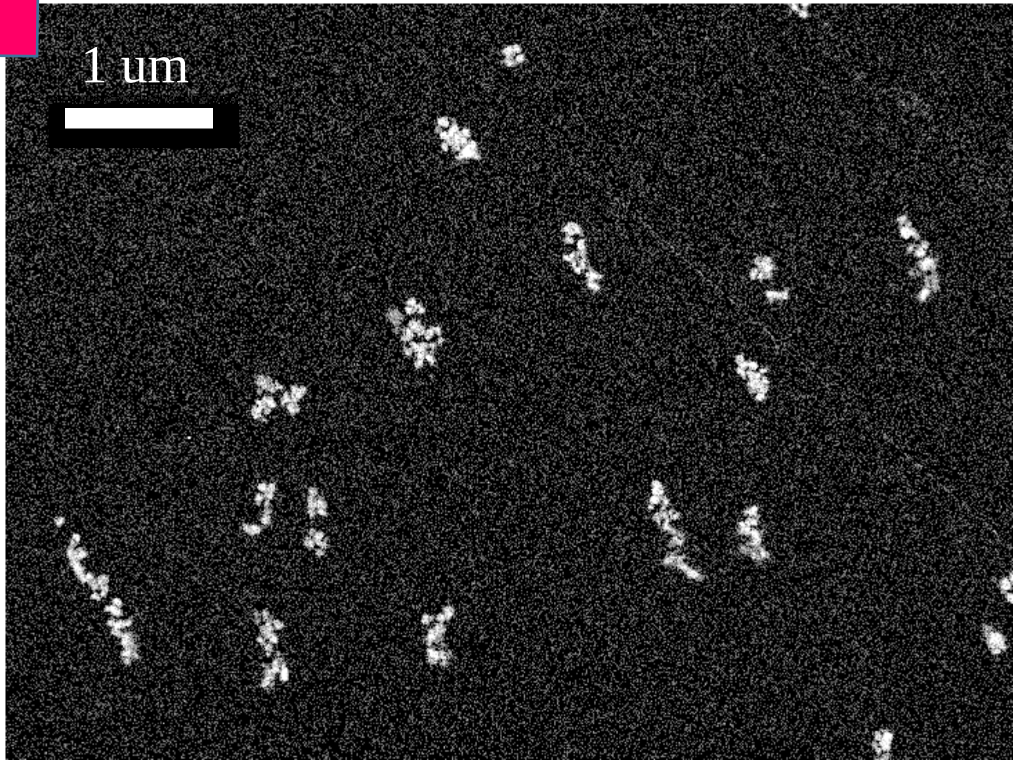
Device potential : 10 keV of C recoil (> ~ 10% eff. and 45° angl. Res.

Low-velocity ion tracking

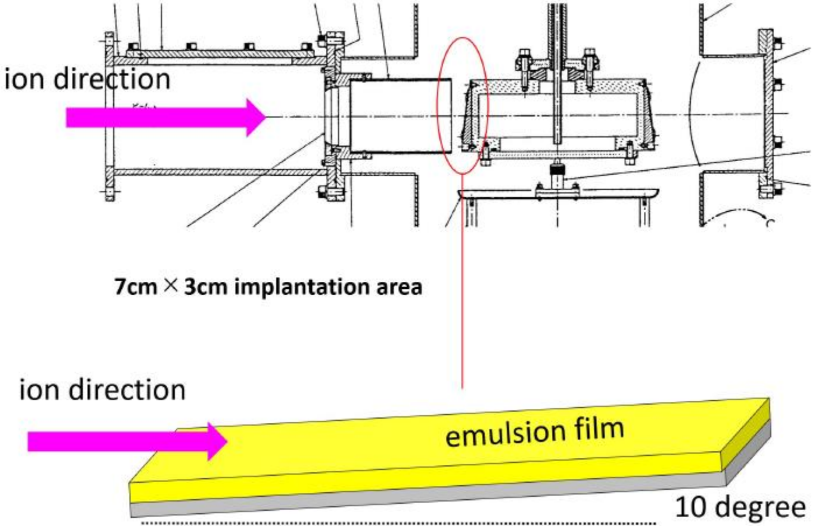
Can use ion implantation as calibration source

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

100 keV Carbon SEM image



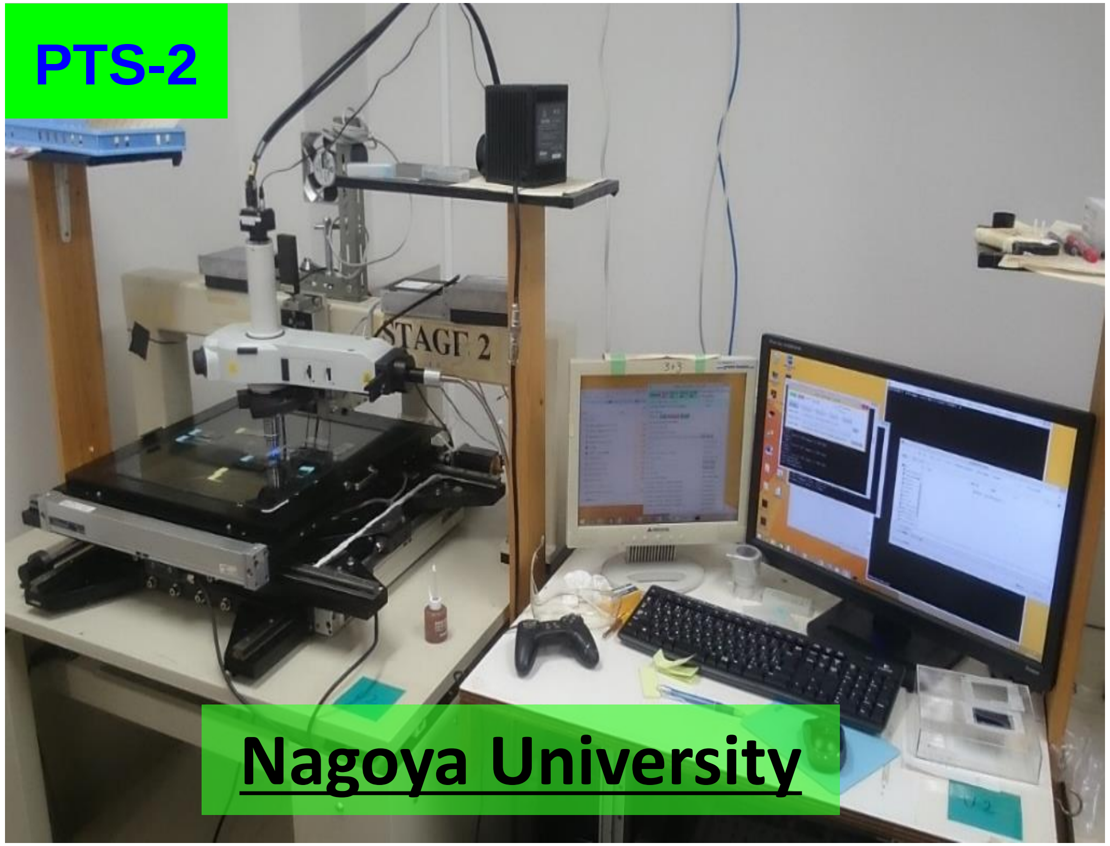
Side view of i

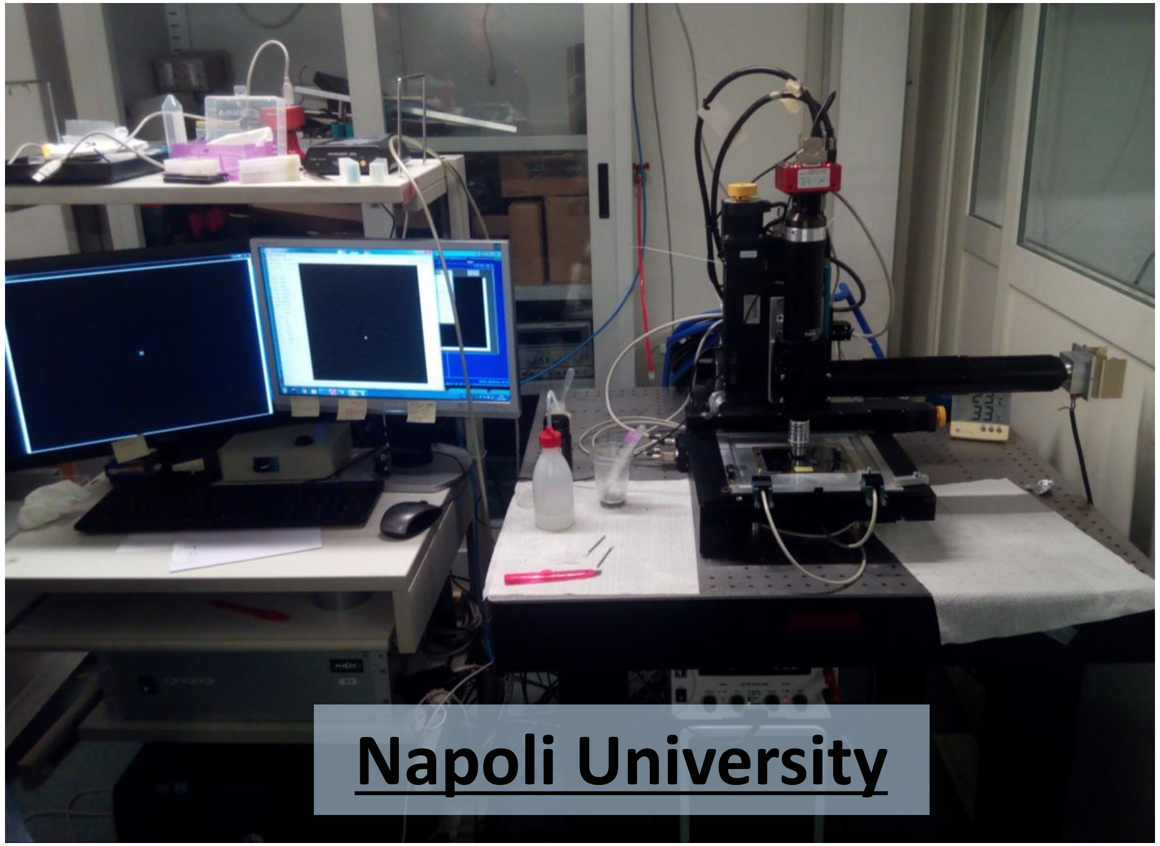


AgBr crystal has good sensitivity about Carbon (~ 100 % efficiency)

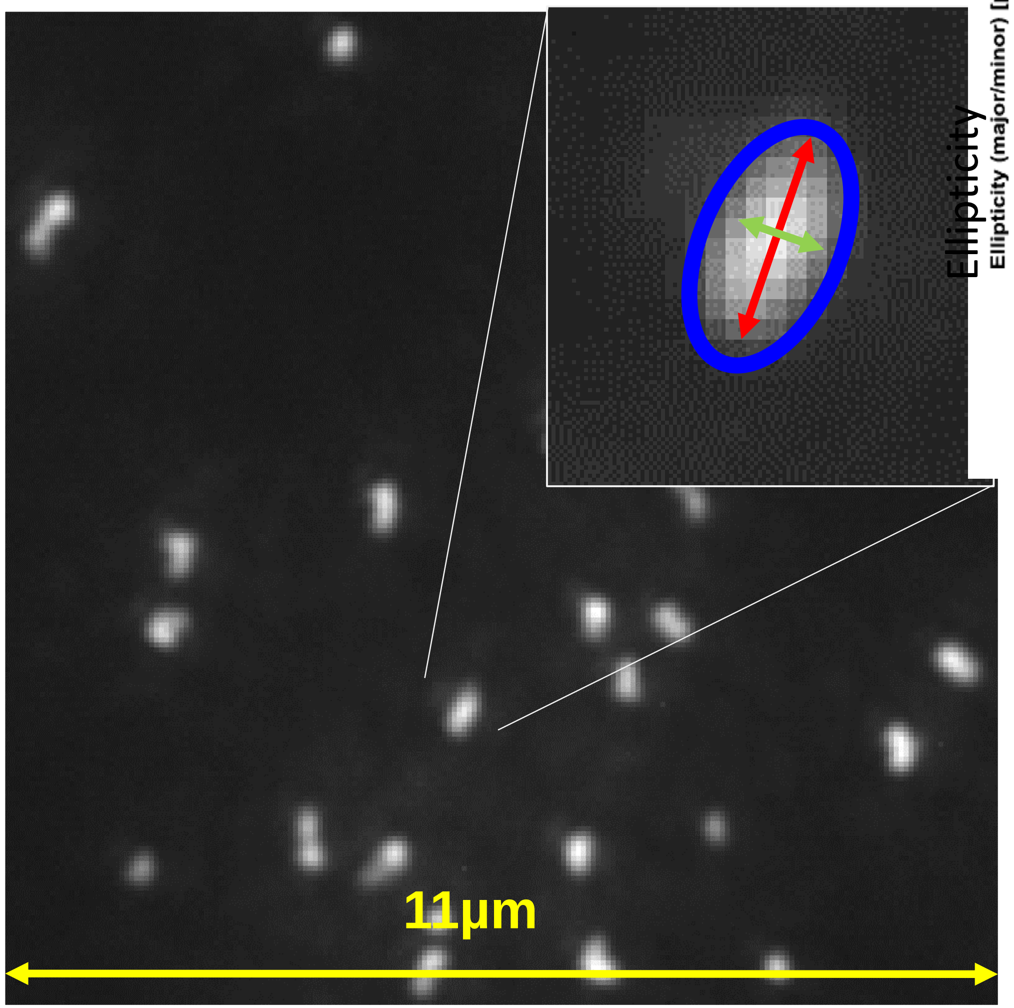
Development of New Readout System for nano-tracking

Prototype R&D system @Nagoya and Napoli





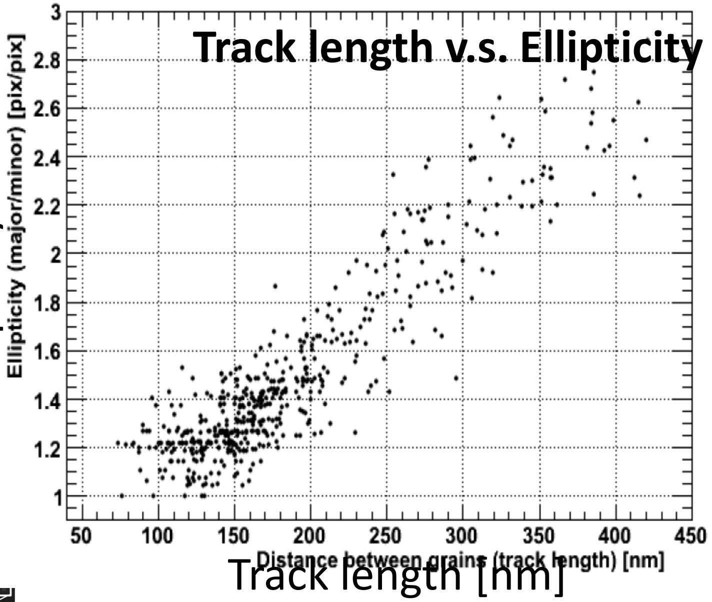
Candidate selection method using epi-illuminated optical microscop

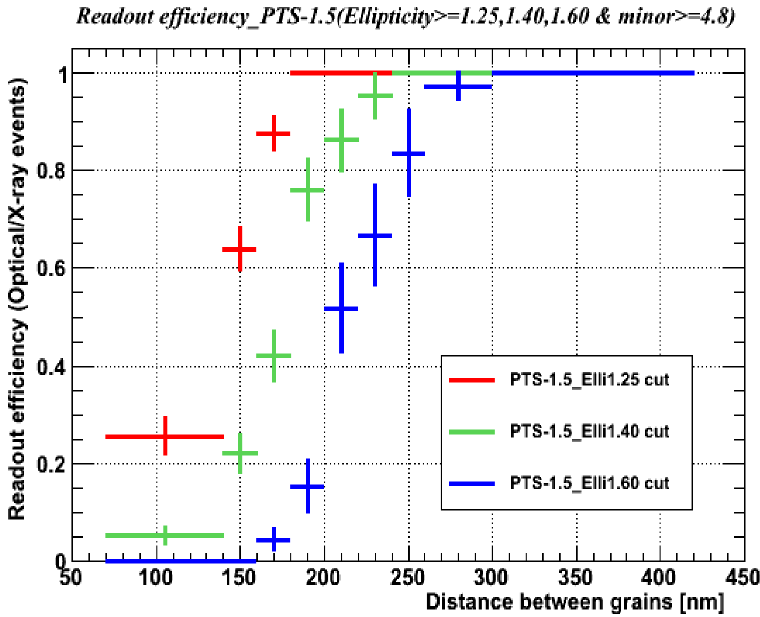


K. Kimura and T. Naka, Nucl. Inst. Meth. A 680 (2012) 12-17

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

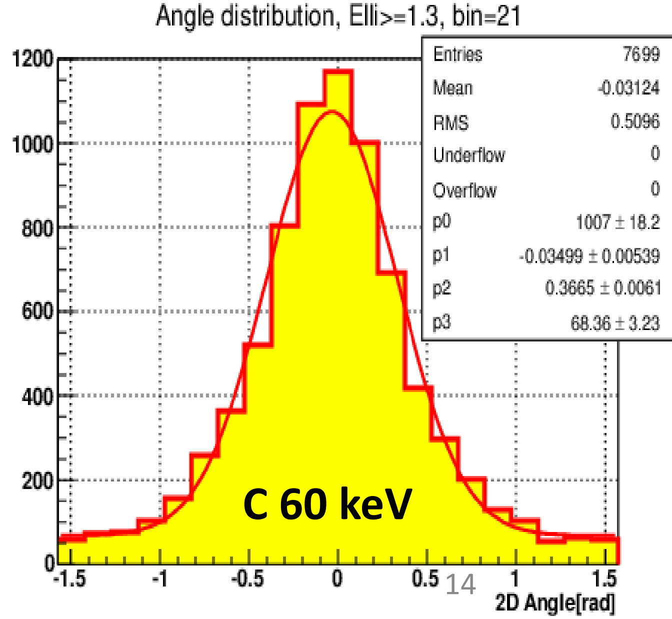
Performance using only elliptical shape analysis



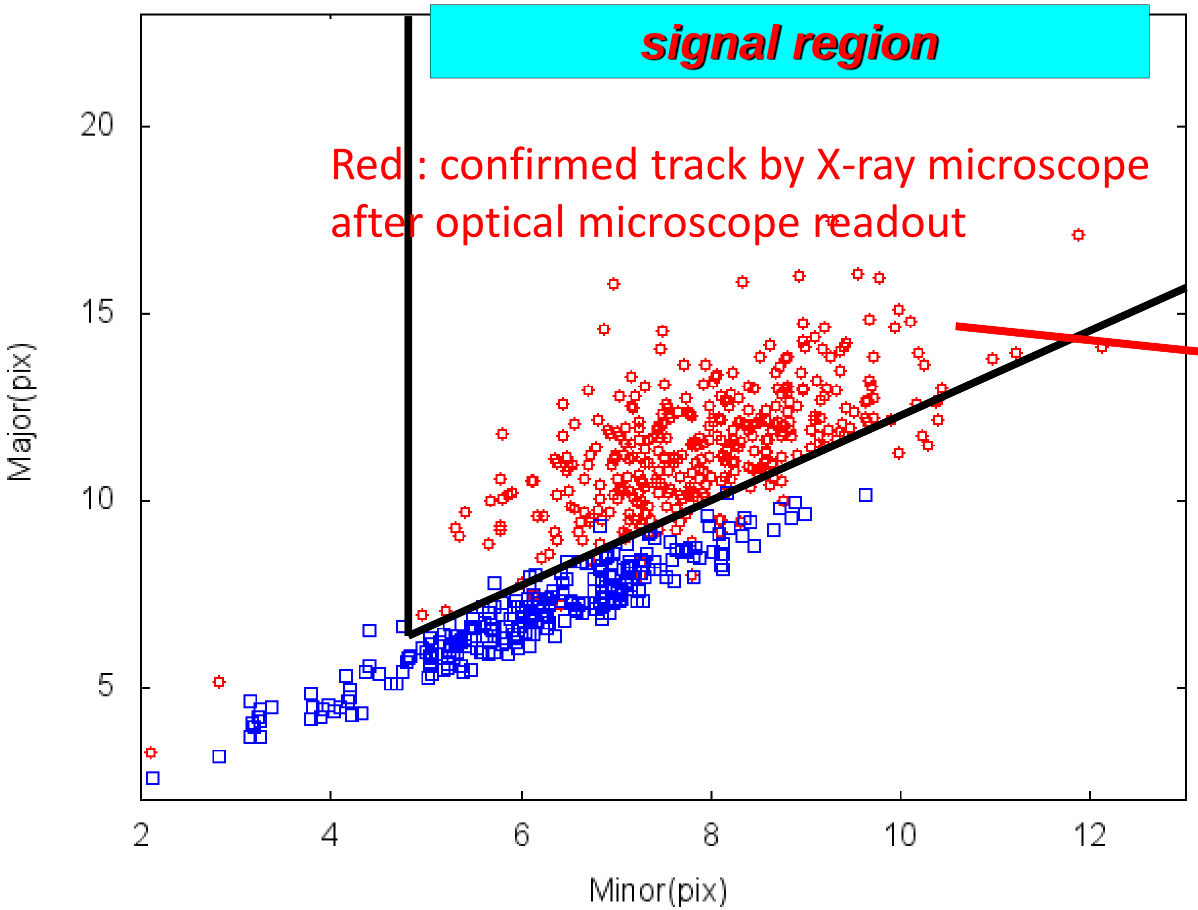


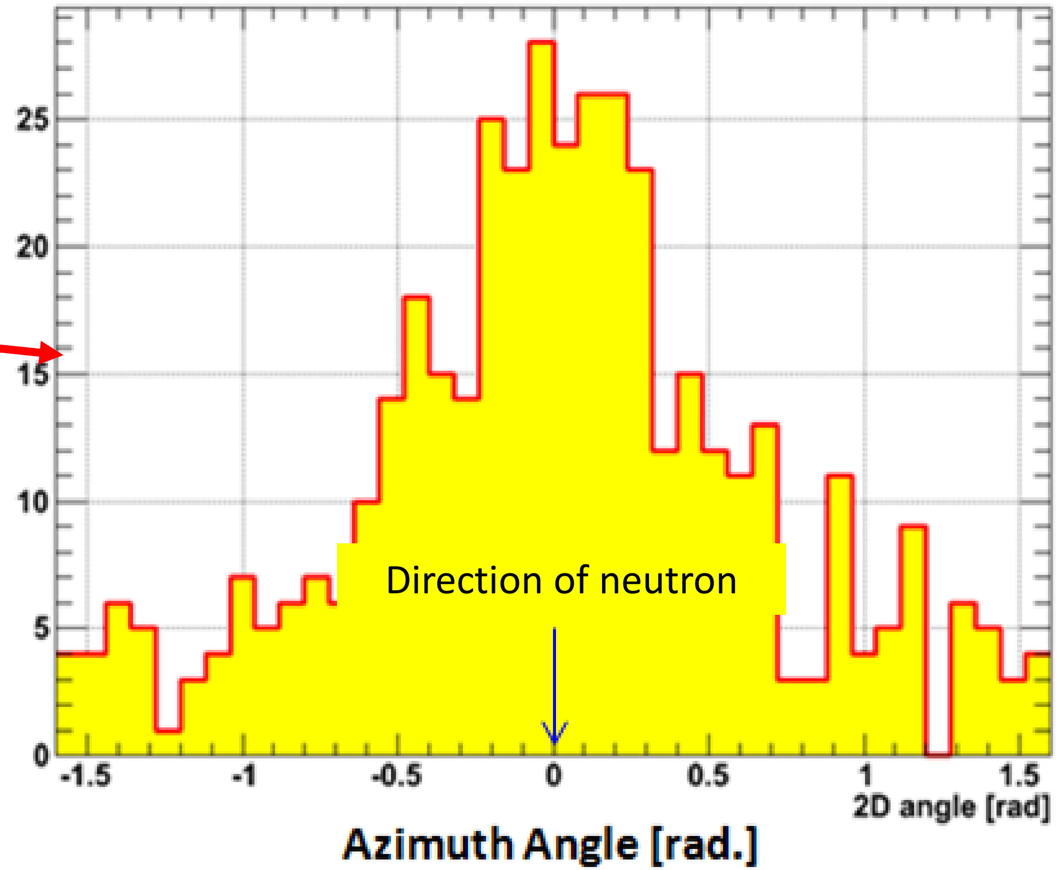
Current microscope has the potential to select > 100 nm length tracks

Direction sensitive eff. :
~30 % @60 keV
(Cullently limited by the optical condition ⇒ to be upgrade)
Angular resolution :
~30 deg. @60 keV
⇒ good compatibility to expectation by simulation



Demonstration of direction sensitive nuclear recoil detection due to 14.8 MeV neutrons





Mostly detected target was Br recoil [< 200 keV]

Now on preparing CNO recoil demonstration due to 565 keV (Li-p nuclear fission reaction)

Study of higher level event selection technique

- For Signal/Background discrimination
- For lower energy threshold

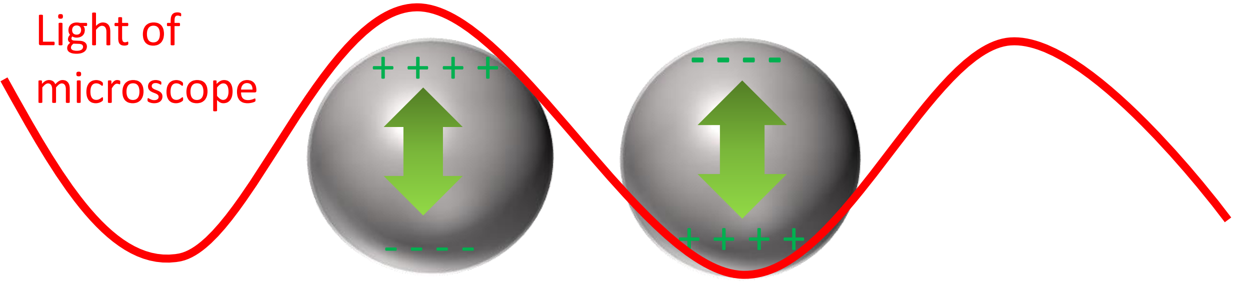
- Super-resolution microscopy
- X-ray microscope (TN et al., Rev Sci Instrum. 2015 86(7):073701)
- Machine learning
- Phase-difference imaging

etc.

Cutting-edge technologies for microscopy and image-processing

Localized Surface Plasmon Resonance (LSPR)

Localized Surface Plasmon Resonance



silver nano particle

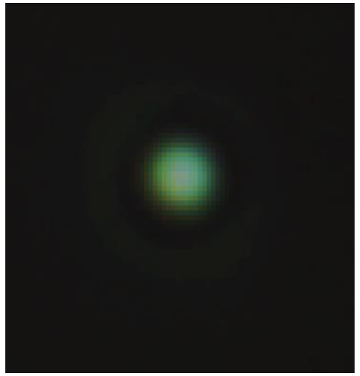
$$p = 4\pi\varepsilon_m a^3 \frac{\varepsilon_1(\lambda) - \varepsilon_m(\lambda)}{\varepsilon_1(\lambda) + 2\varepsilon_m(\lambda)} E_0$$

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

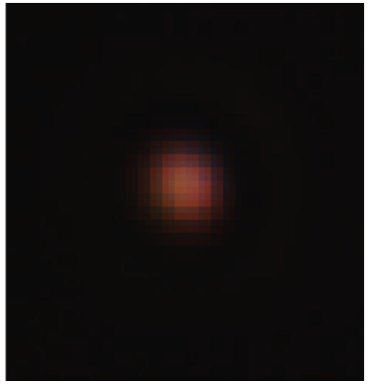
Plasmon Resonance condition

Silver-nano particle

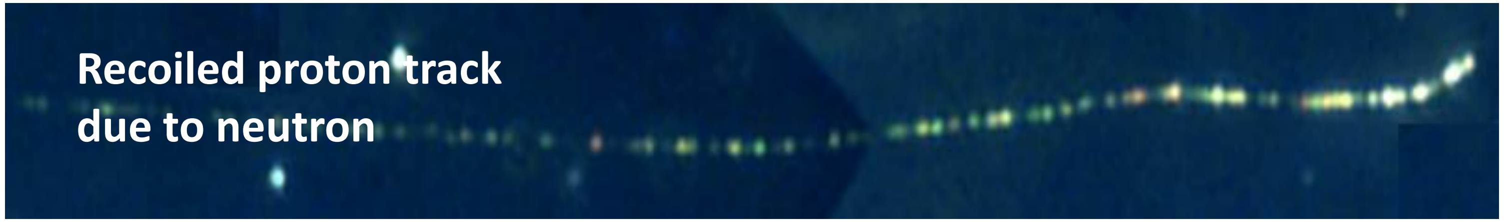
40 nm



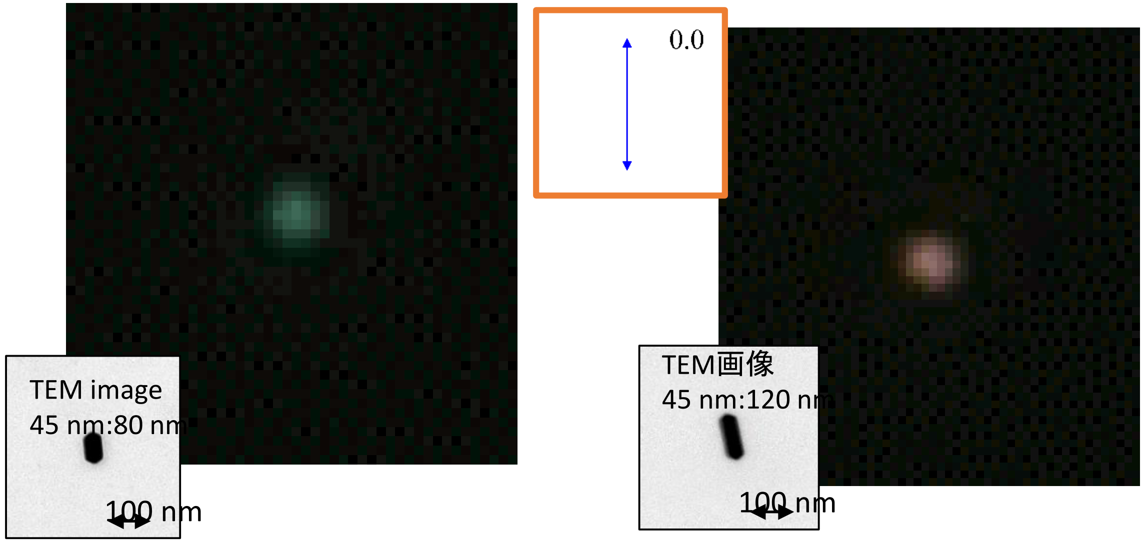
80 nm

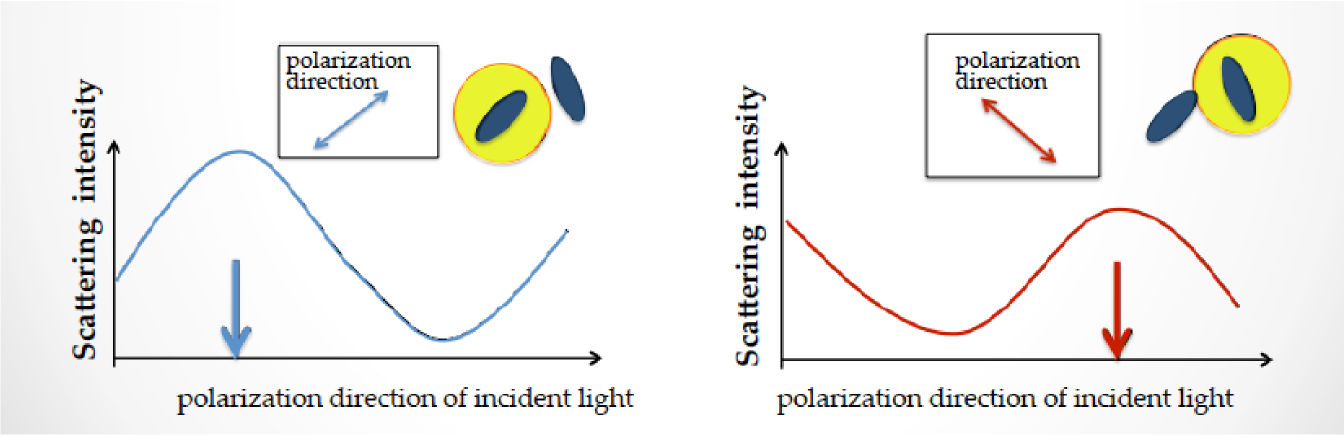


120 nm



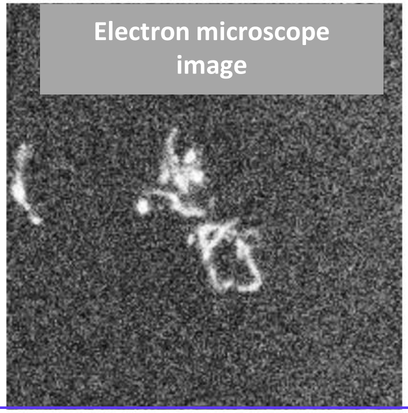
Concept of super-resolution microscopy using LSPR





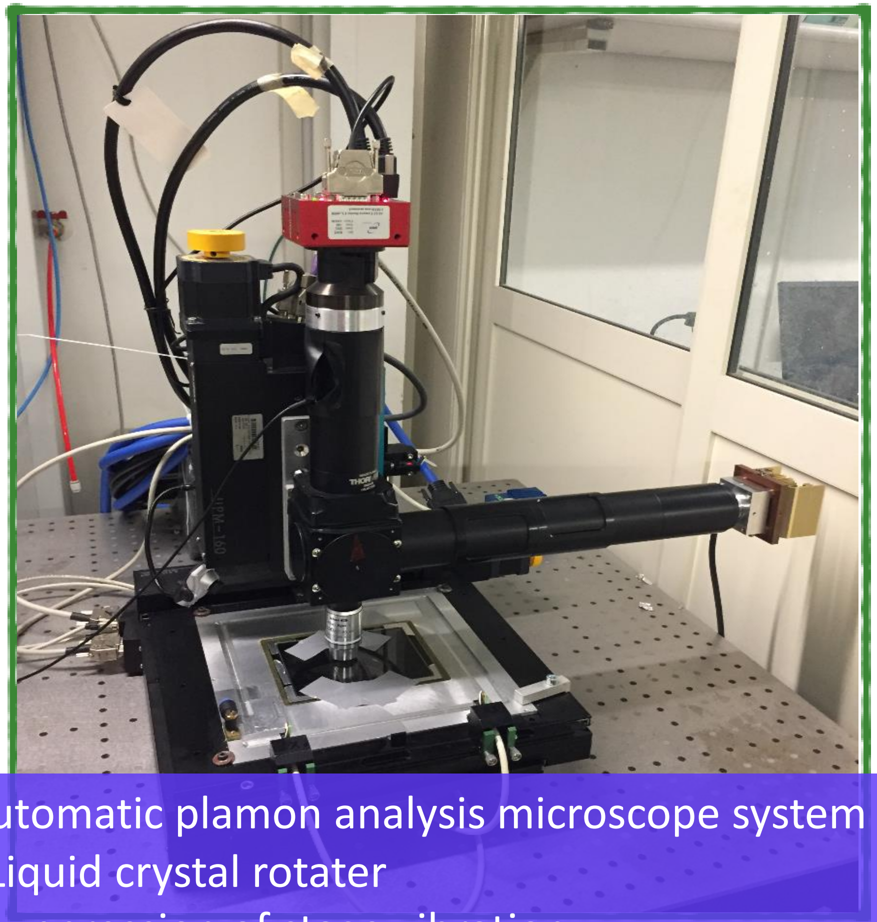
By combination both the wavelength shift and rotation of polarized angle, non-diffractive condition is realized.
optical resolution ≒position accuracy
(~ 10 nm or less)

- Dipole moment for non-spherical Ag nano particle depends on the polarization angle
- Resonance wavelength is shifted by that.

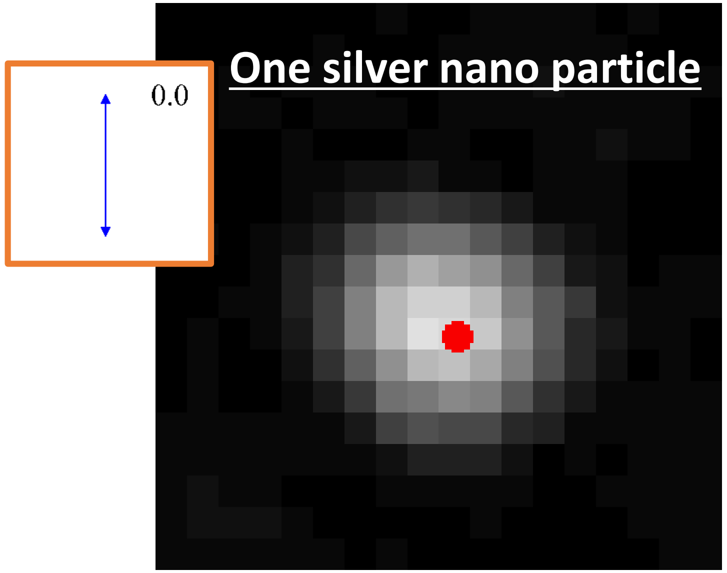


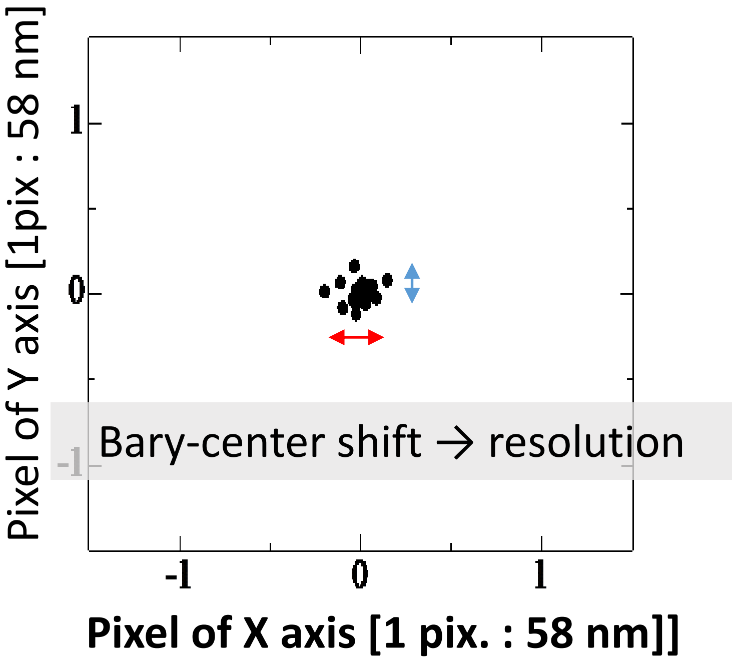
Developed silver grain such as the nuclear recoil has very complicated silver filametn structure
⇒ It's very good to realize above concept

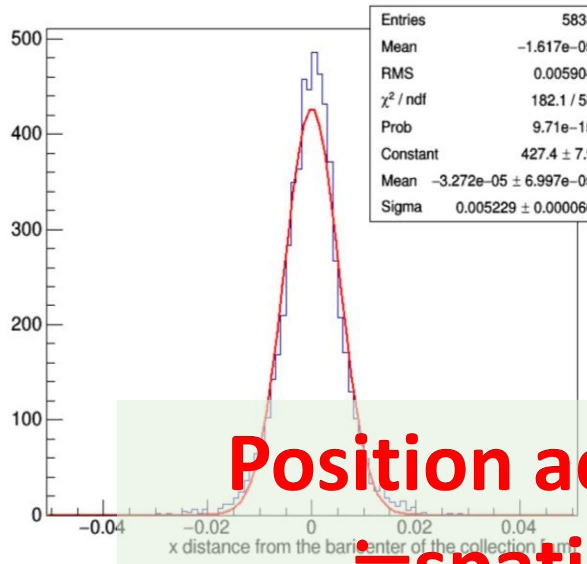
Resolution calibration

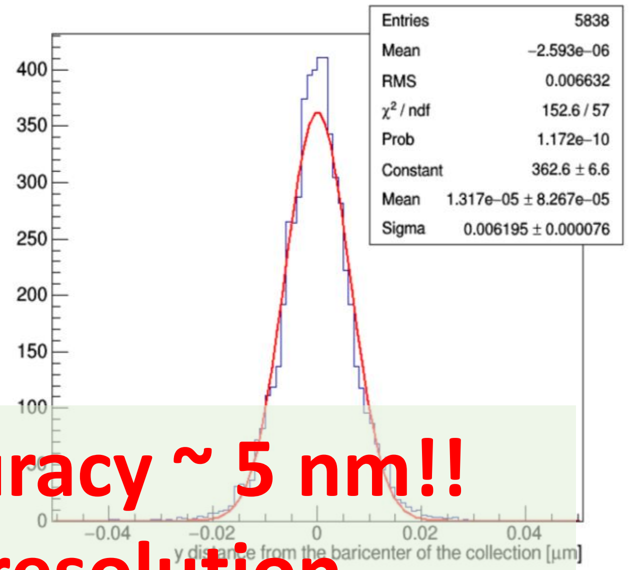


Automatic plamon analysis microscope system
・Liquid crystal rotater
・suppression of stage vibration
(・color imaging)
(・combine machine learning)



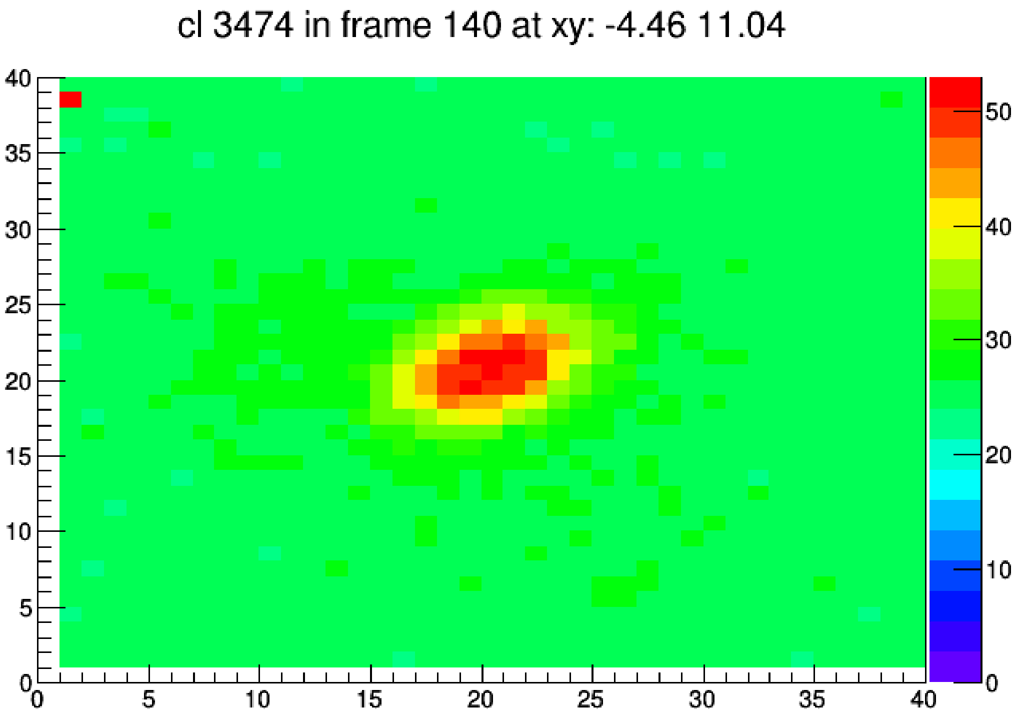






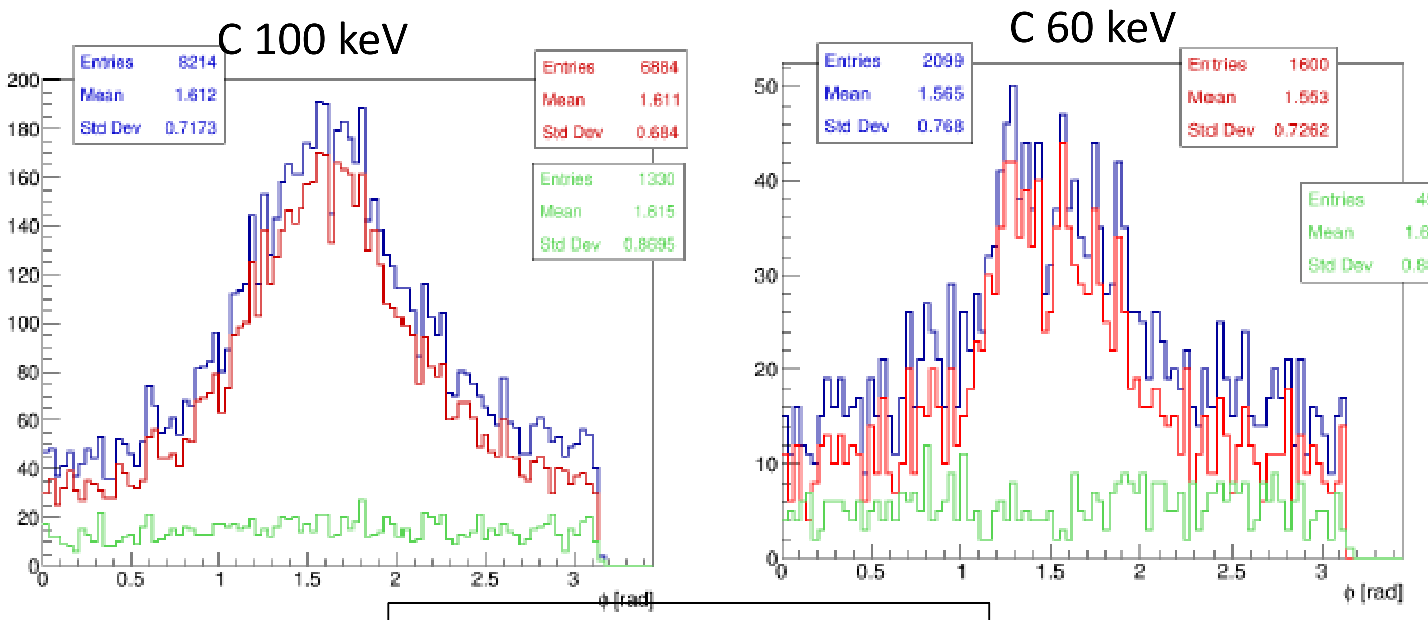
Position accuracy ~ 5 nm!!
≒spatial resolution

Readout study using the plasmonics information



Shift of barycenter is important information for nano-scale structure

Direction sensitivity using plasmon analysis

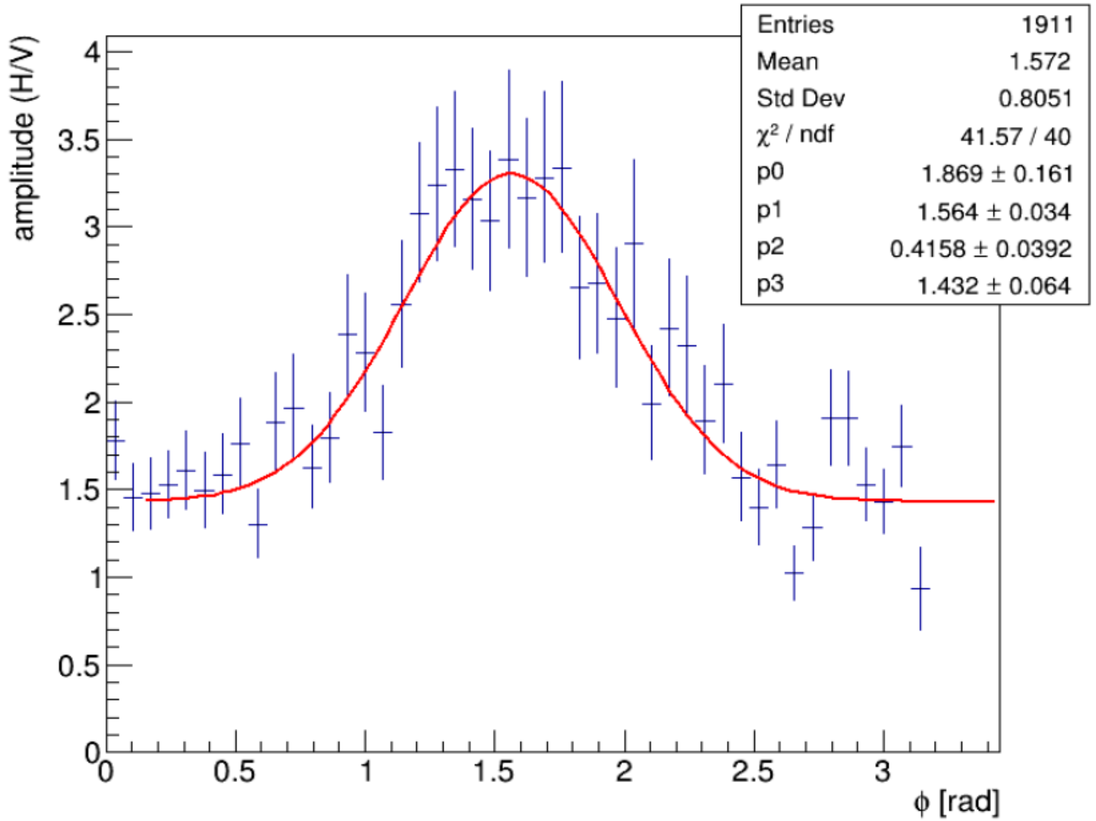


Blue : total
Red : Bari-center shift > 30 nm
Green : Bari-center shift < 30 nm

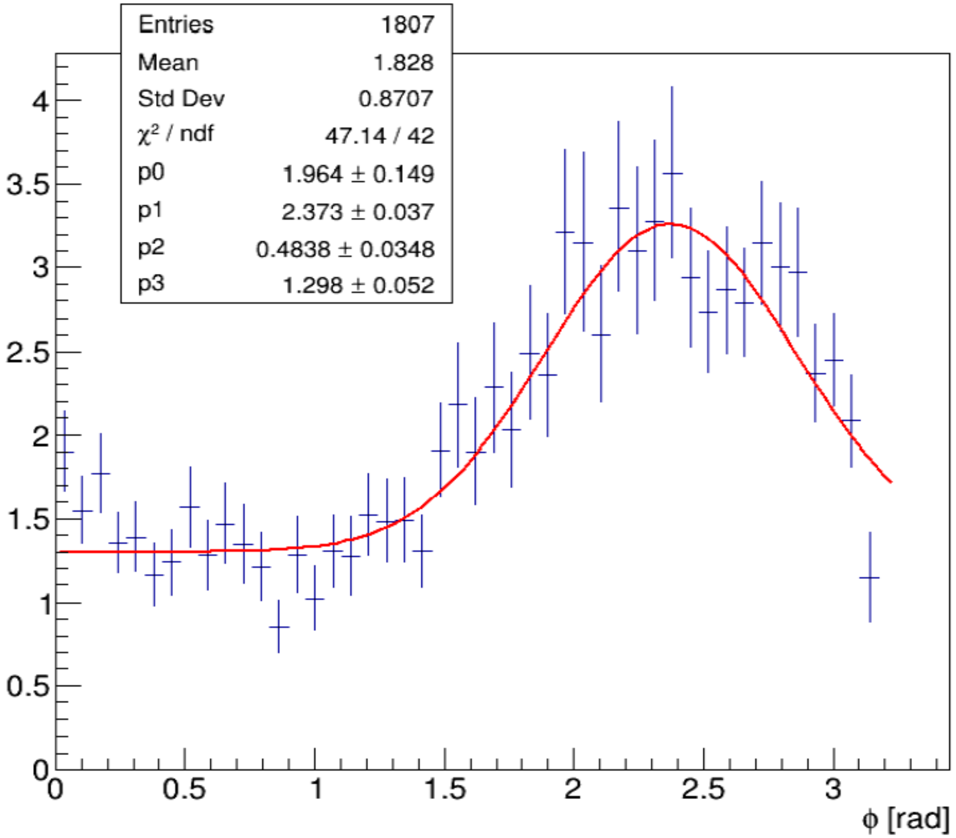
Demonstration of the direction sensitivity have been done .

Direction sensitivity of low-energy C ion [30 keV]

Expected : 90 ° -> Measured : 90°



Expected : 135 ° -> Measured : 136°



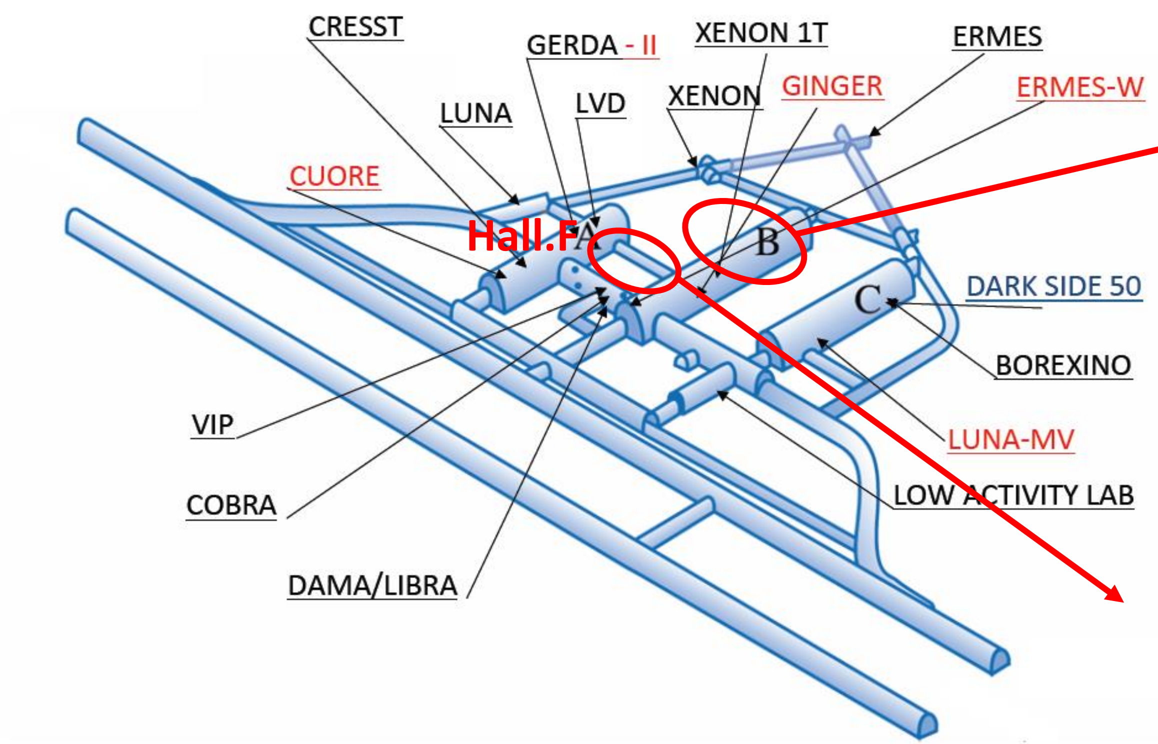
Indication :: low-mass dark matter (< 10 GeV/c2) can be seen with the direction !

Background studying

	Main source	Technologies	Expected rejection power or event rate
Physical BG			
Electrons	C-14 β Environment gamma	Crystal temperature dependence (*M. Kimura et al., NIM A 845 (2017) 373*) Crystal sensitivity control Image and plasmonic analysis	(> 10^6 or more rejection power (< O(1) /kg/day)) *now on studying
		Synthetic Polymer	> 10^3 or more
Neutron	Intrinsic (α, n)	-	~ 3 x 10^{-4} /kg/day or less Astropart. Phys. 80 (2016)16-21
	Environment	Water shield	< 1E-4/kg/day
Cosmic-ray	Recoiled nuclei	Coincidence with MIP sensitive emulsion	*on studying using simulation
	Spallation neutron	(under studying with simulation)	(~O(10^{-4}))/kg/day * now on study)
Nonphysical BG			
Contaminated dust	(under studying)	Clean room Plasmonic analysis and image processing Machine learning Chemical treatment	Under studying (at least > 10^6 or more, in principle it should not be background)

Test experiment Site

Gran Sasso underground laboratory, Italy



Exposure site

Device Production and handling facility

Now on constructing the device production facility at Hall.F, LNGS

⇨ Operation will be started in this October

Conclusion

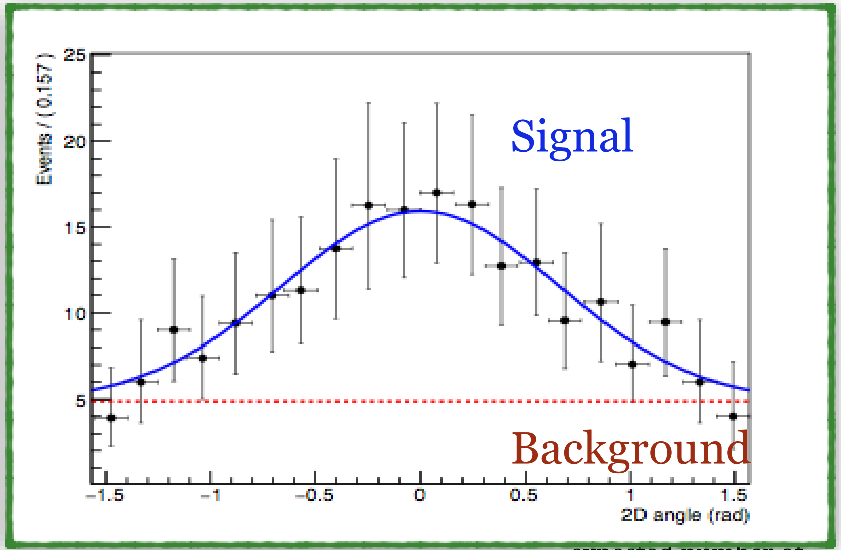
- **Directional sensitive search is new methodology to obtain new information for direct dark matter search**

- **Super-fine grained nuclear emulsion (Nano Imaging Tracker : NIT) have been firstly demonstrated to be able to detect the nuclear recoil as track.**

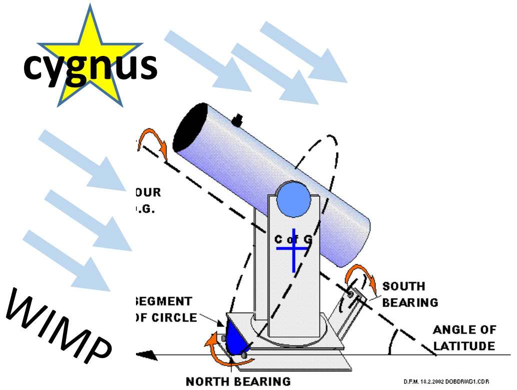
- **NEWSdm project is now on going as international experiment toward directional dark matter search in the LNGS**
  2018 : underground facility construction at LNGS
  2019 : TDR will be prepared and start the small scale experiment
  2020 - : preparation and run for larger scale experiment of ~ kg scale

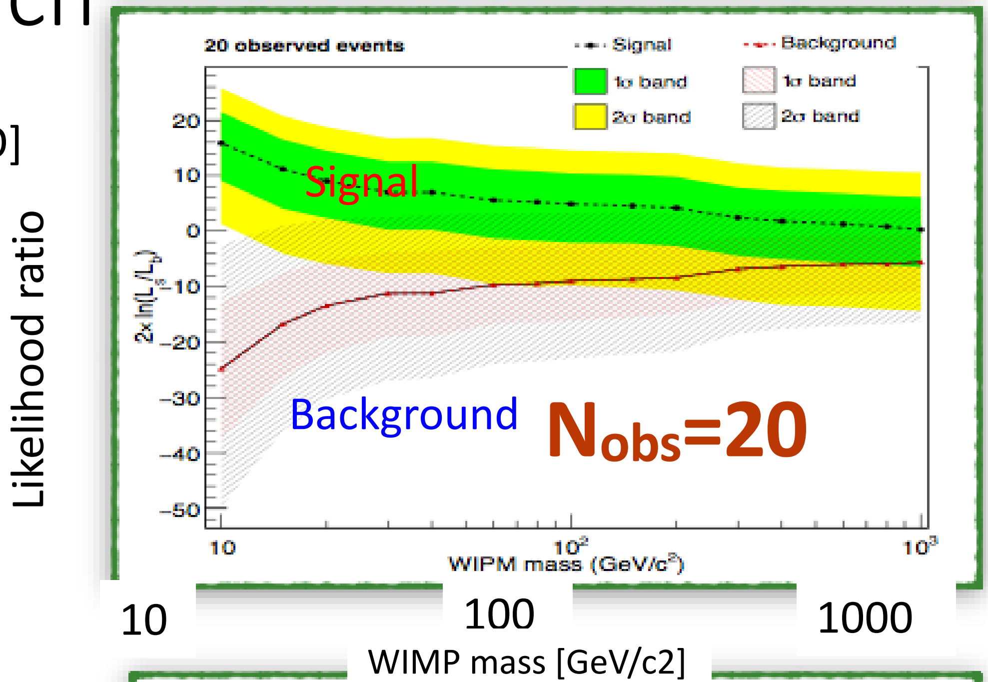
- **Background study and new readout technologies are now on progress**

Potential of Directional Sensitive Search



arXiv:1705.00613 [astro-ph.CO]





expected number of WIMP events

expected number of background events

signal pdf

background pdf

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

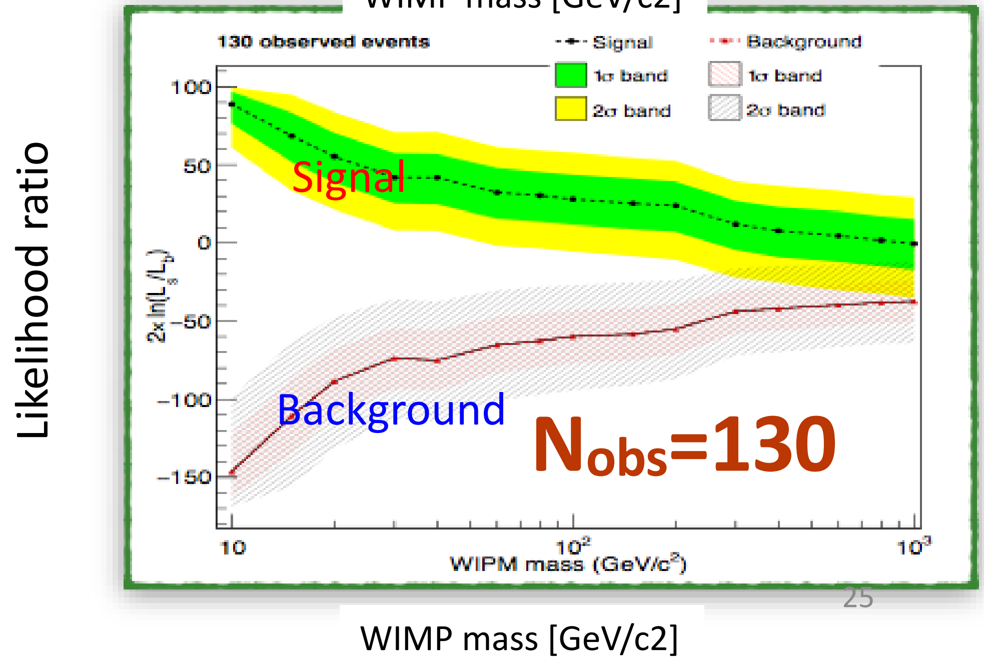
total number of observed events

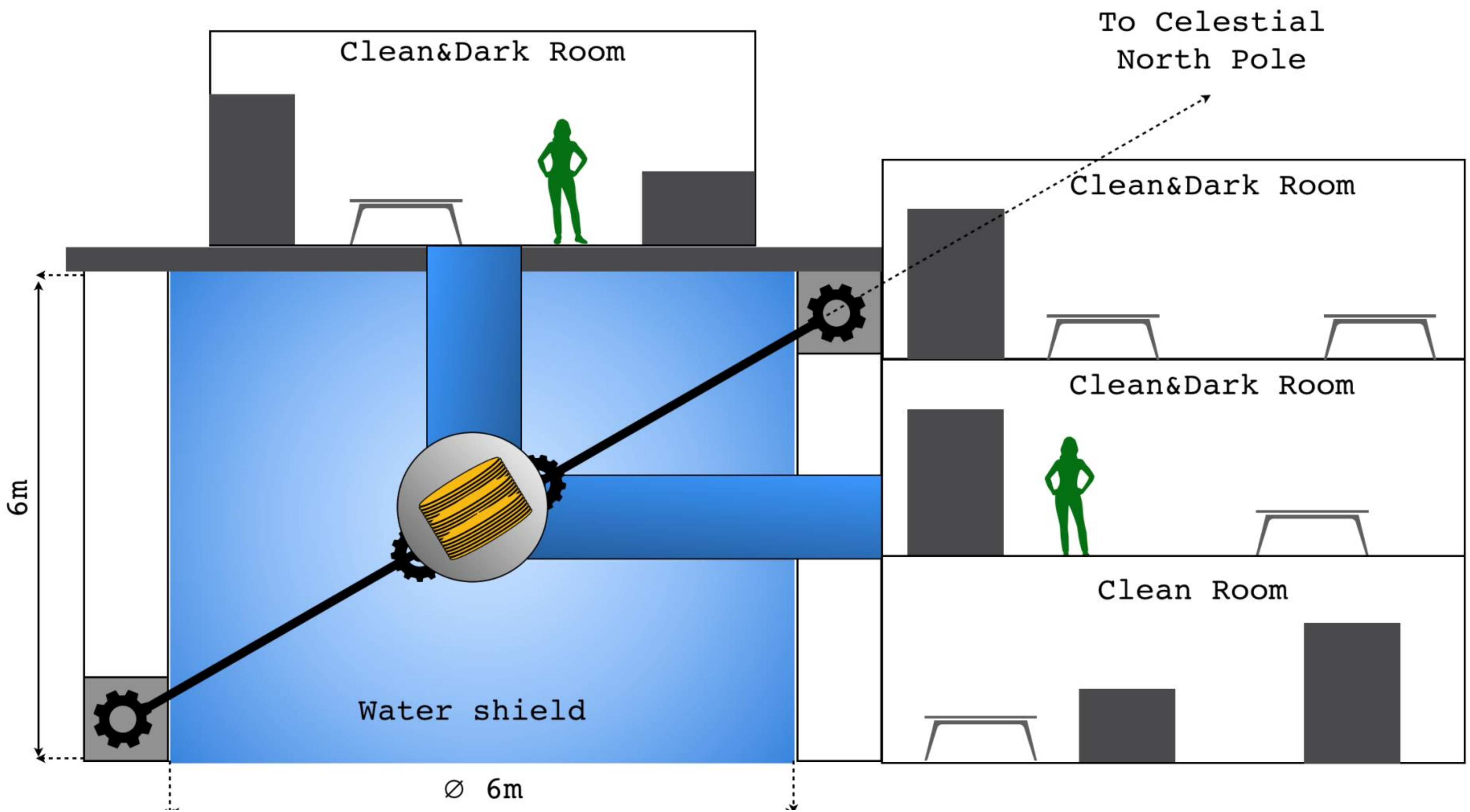
set of observables

<u>Direction information : Several 10 events</u>

Gain of 100 times

<u>Annual modulation : Several 1000 events</u>




Clean&Dark Room
To Celestial
North Pole
Clean&Dark Room
Clean&Dark Room
Clean Room
6m
Water shield
∅ 6m