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

Tatsuhiro Naka

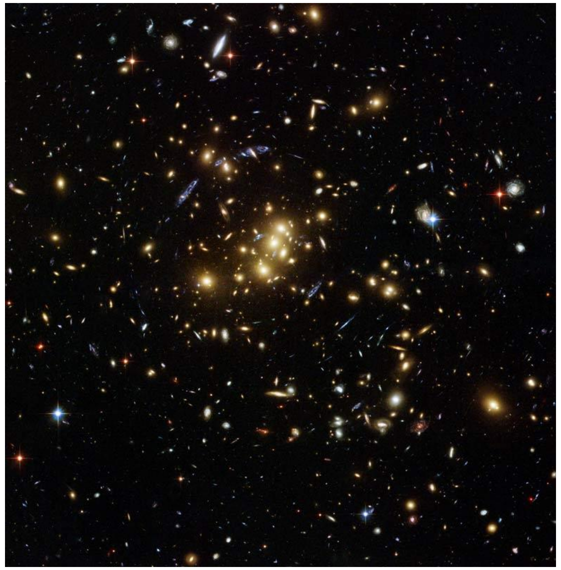
Nagoya University@Japan

On behalf of NEWSdm collaboration

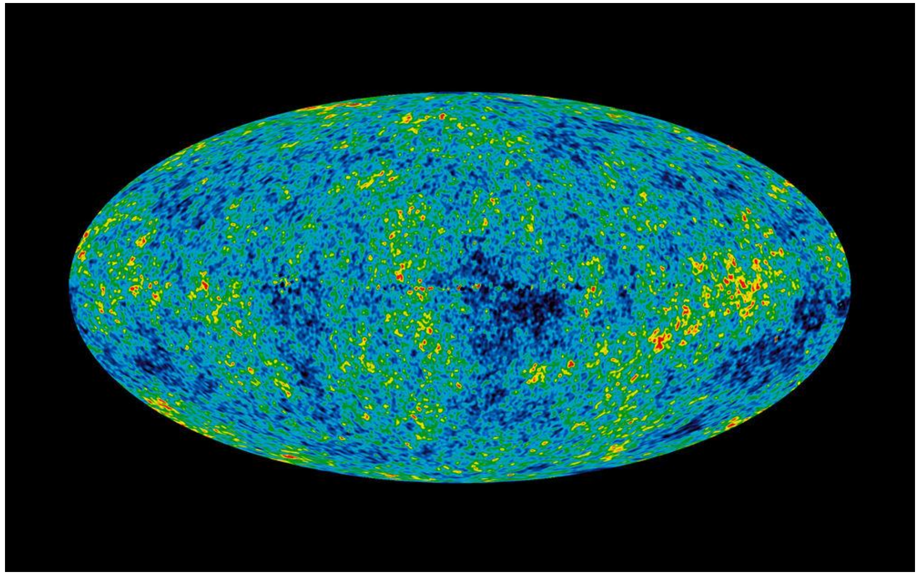
small

Scale of Universe

large

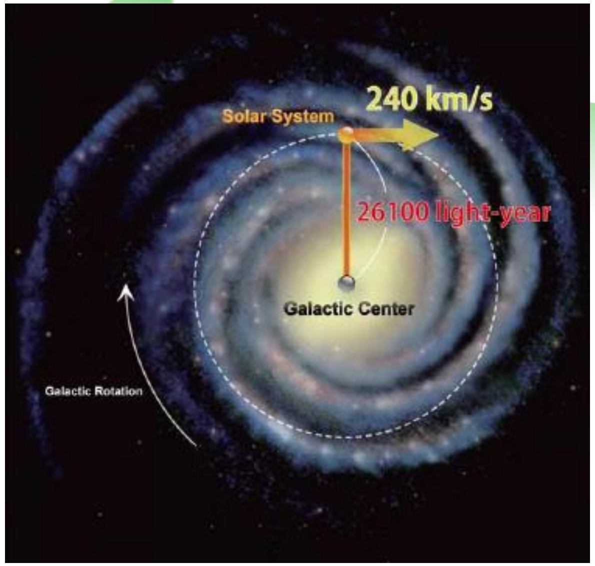


Glavitation Lensing

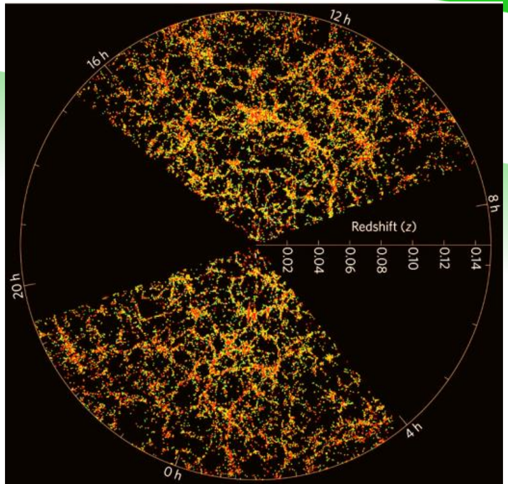


Cosmic Microwave Background (CMB)

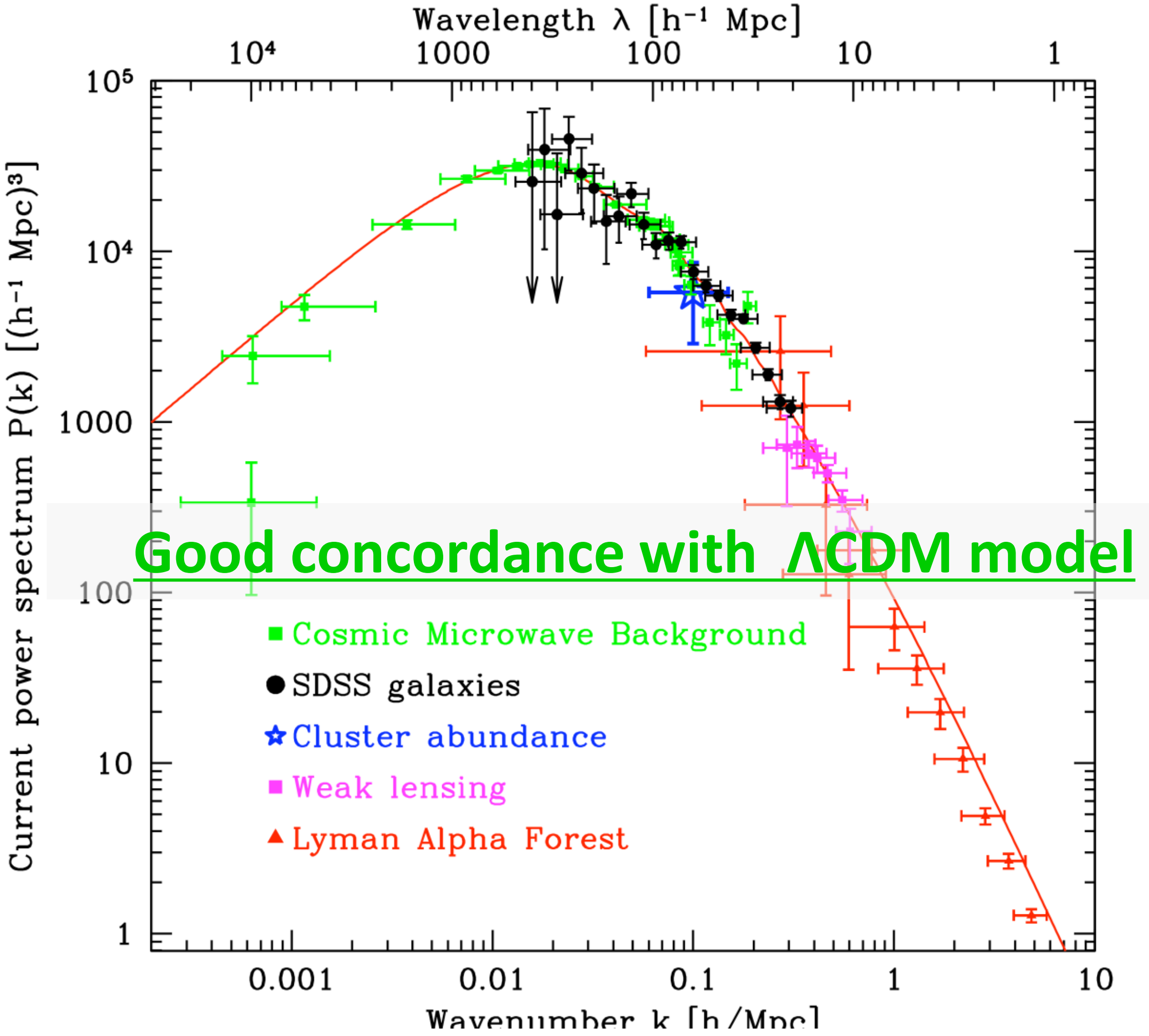
Rotation velocity of galaxy



Structure formation

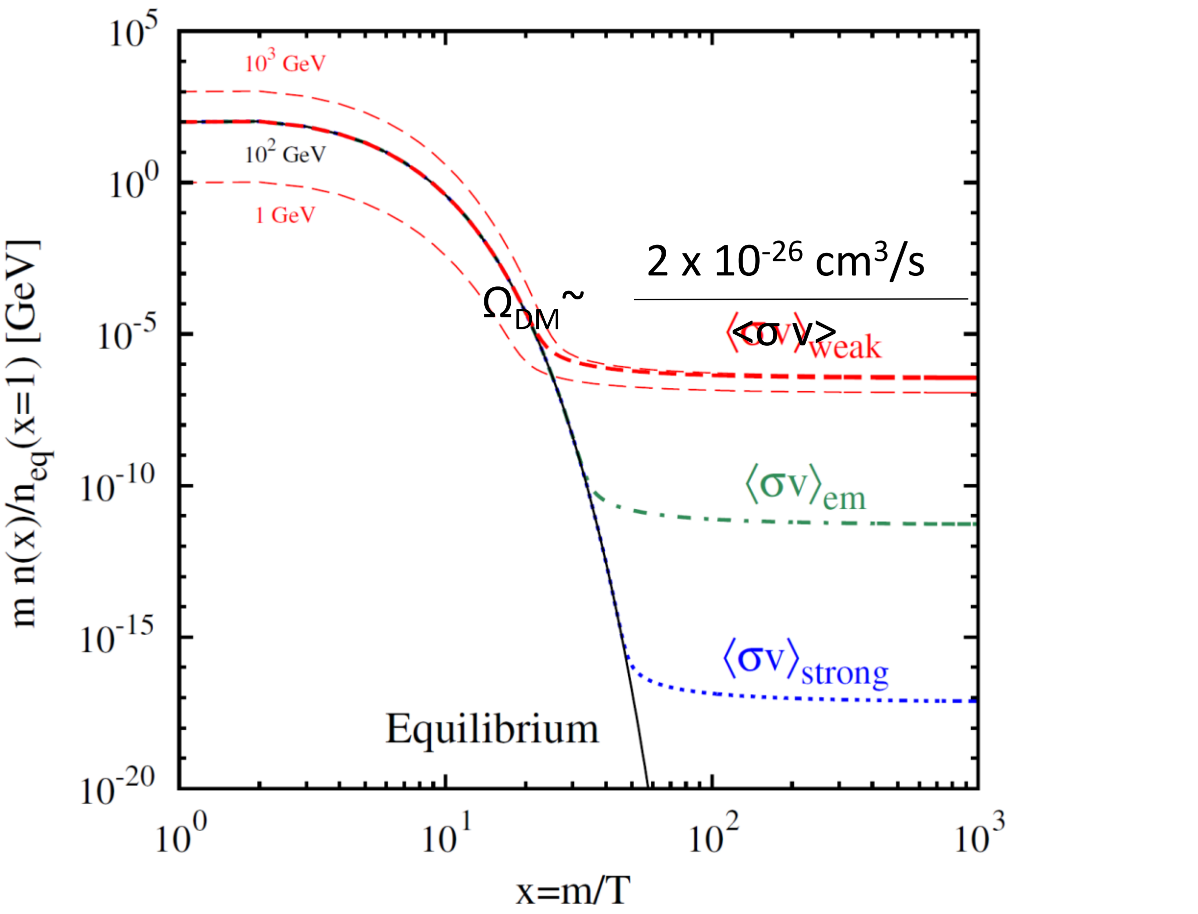


Cold Dark Matter



Good concordance with ΛCDM model

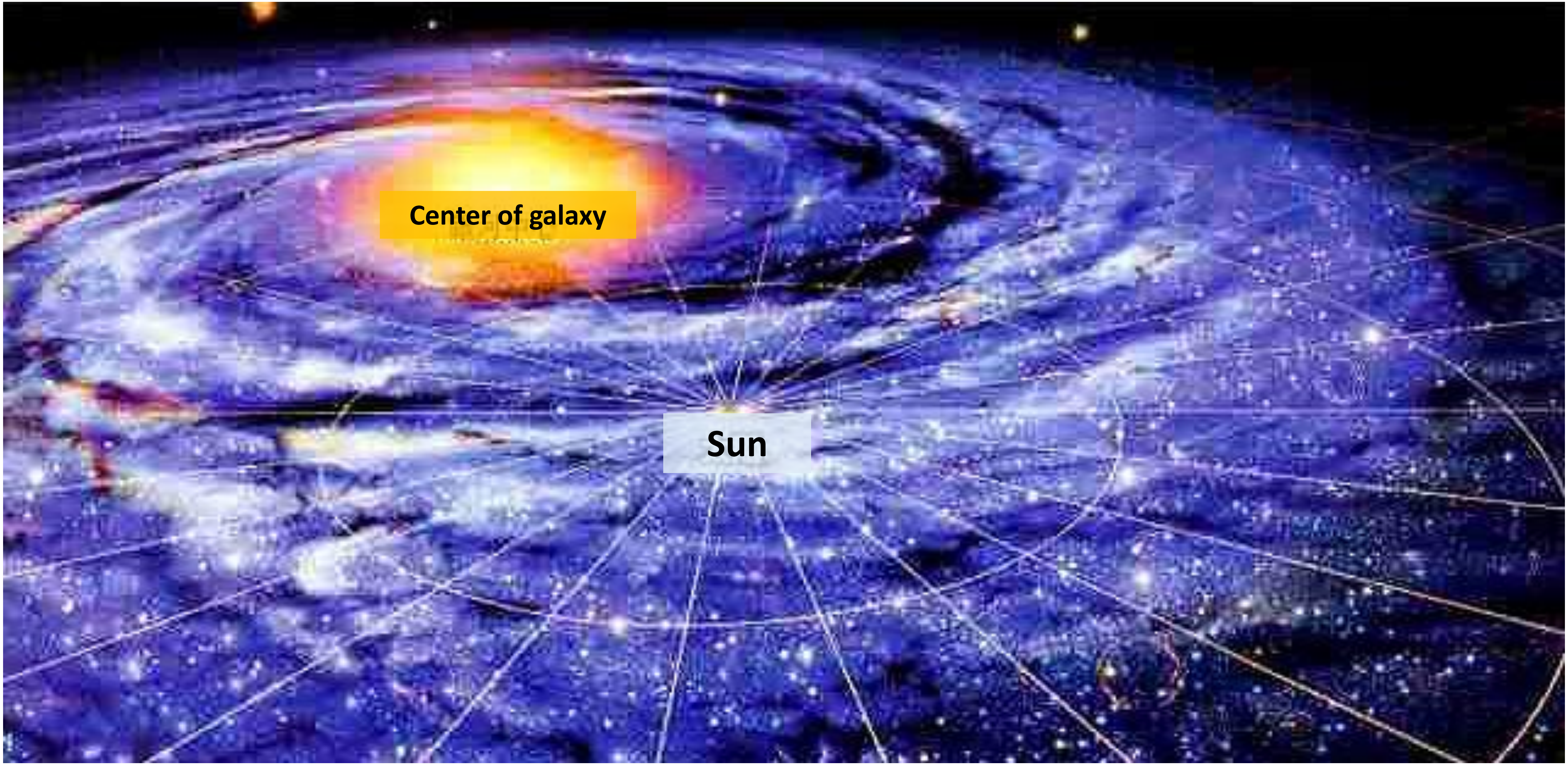
large — Scale — small

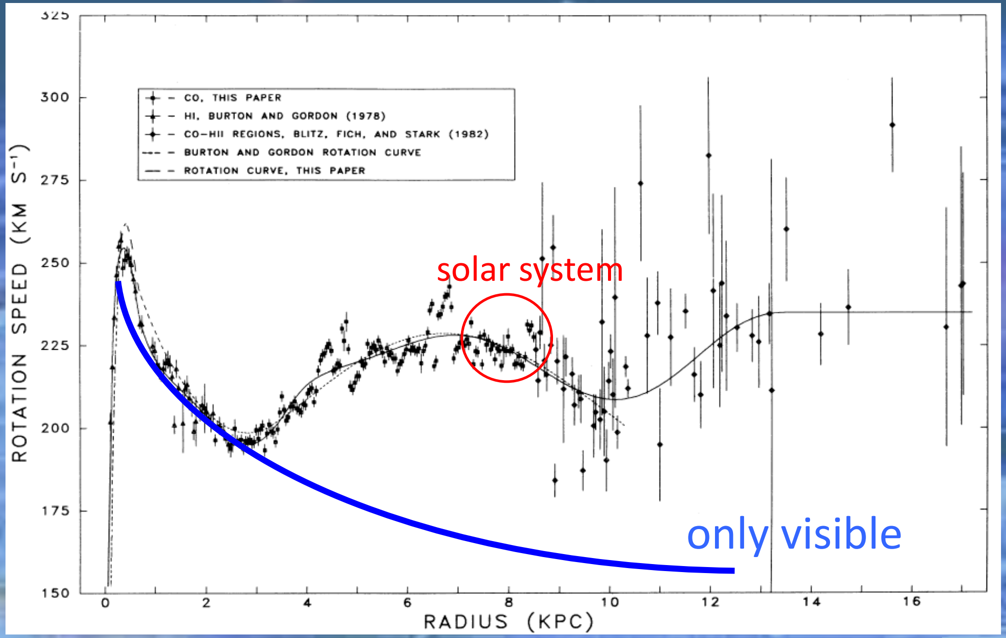


$\Omega_{DM} \sim \frac{2 \times 10^{-26}\ cm^3/s}{\langle\sigma v\rangle}$

Phys. Rev. D 86, 023506(2012)

Weakly Interacting Massive Particle (WIMP) scenario is very promising candidate.


Center of galaxy
Sun

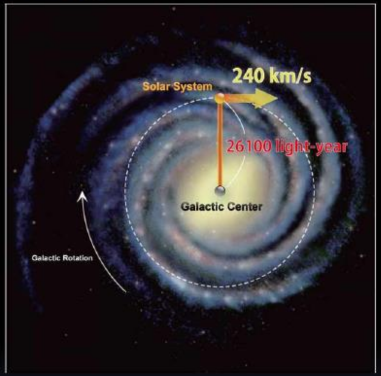


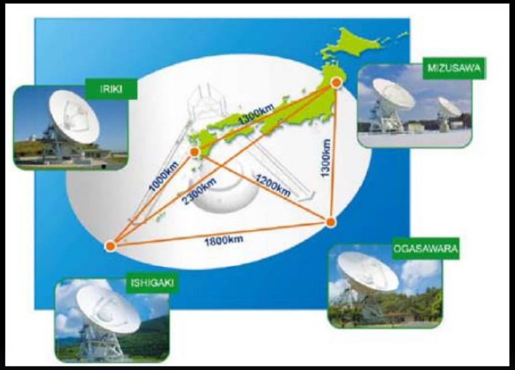
Astrophys. J. 295: 422-436, 1985

Sun

VERA

high precision measurement of rotation for Milkyway Galaxy





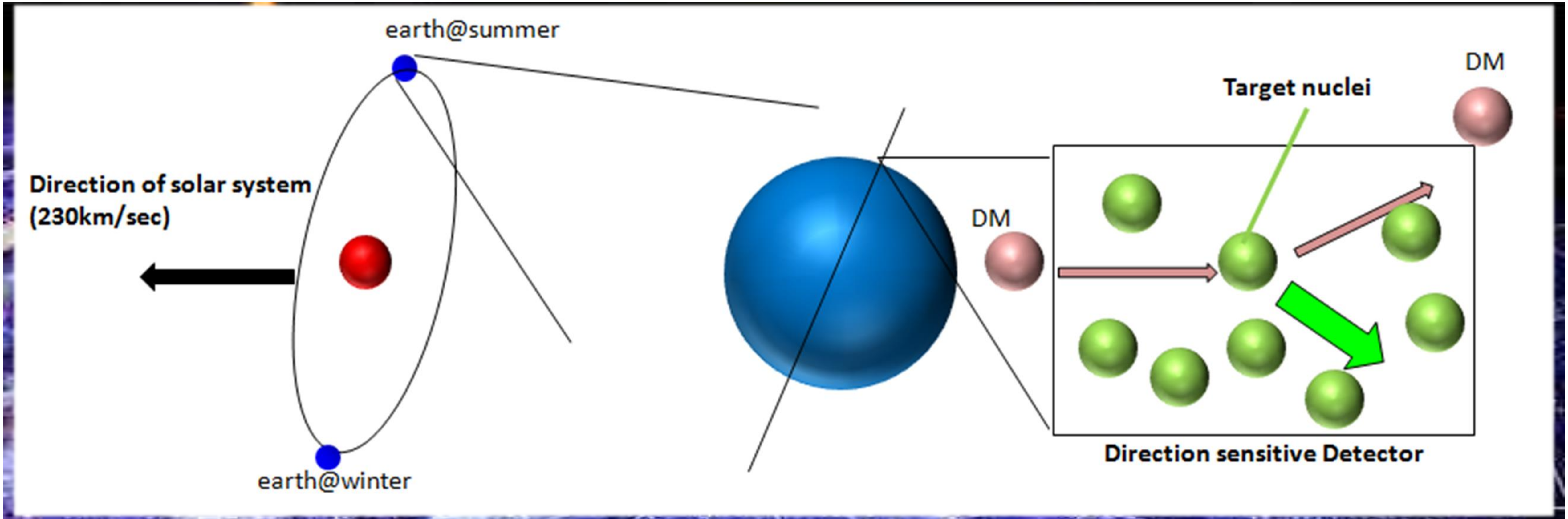
High precision measurement project of rotation velocity of Milkyway galaxy (measurement by the trigonometric parallax)

220 km/sec ⇒ 240 +- 14 km/sec around solar system (8kpc)

Local dark matter density : 0.3-0.5 GeV/cm^3

- ✓ This value is independent on dark matter model
- ✓ Very much mount of DM is condensed in the halo because mean dark matter density in the universe is ~ 1.4 keV/cm^3 (27 % of critical density ratio)

Dark matter flux on the earth ~ 100000 /cm^2/sec @ 100 GeV/c^2 dark matter

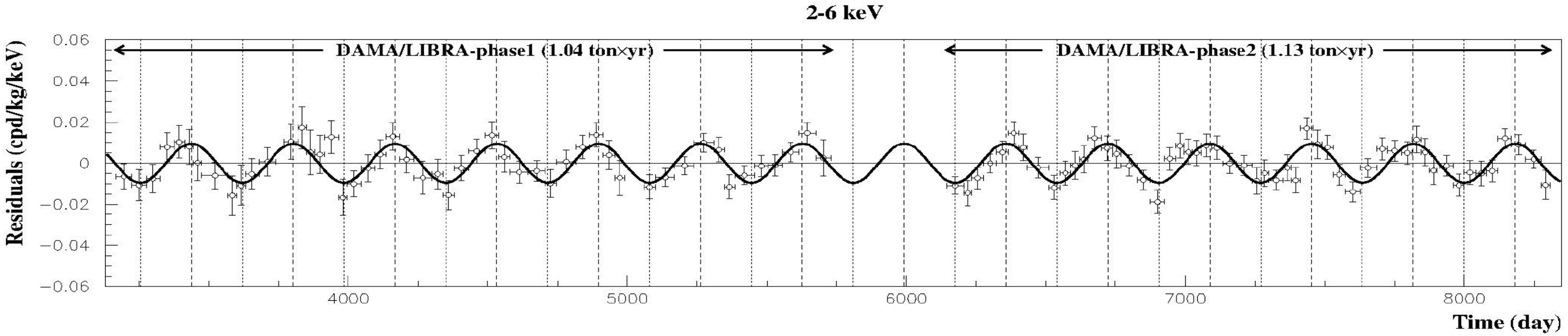


Velocity of dark matter < 1000 km/sec → low-energy frontier physics

Model Independent DM Annual Modulation Result

experimental residuals of the single-hit scintillation events rate vs time and energy

DAMA/LIBRA-phase1+DAMA/LIBRA-phase2 (2.17 ton × yr)



Absence of modulation? No

- 2-6 keV: χ^2/dof=199.3/102 ⇒ P(A=0) =2.9×10^{-8}

Fit on DAMA/LIBRA-phase1+ DAMA/LIBRA-phase2

Acos[ω(t-t_0)] ;
continuous lines: t_0 = 152.5 d, T = 1.00 y

2-6 keV

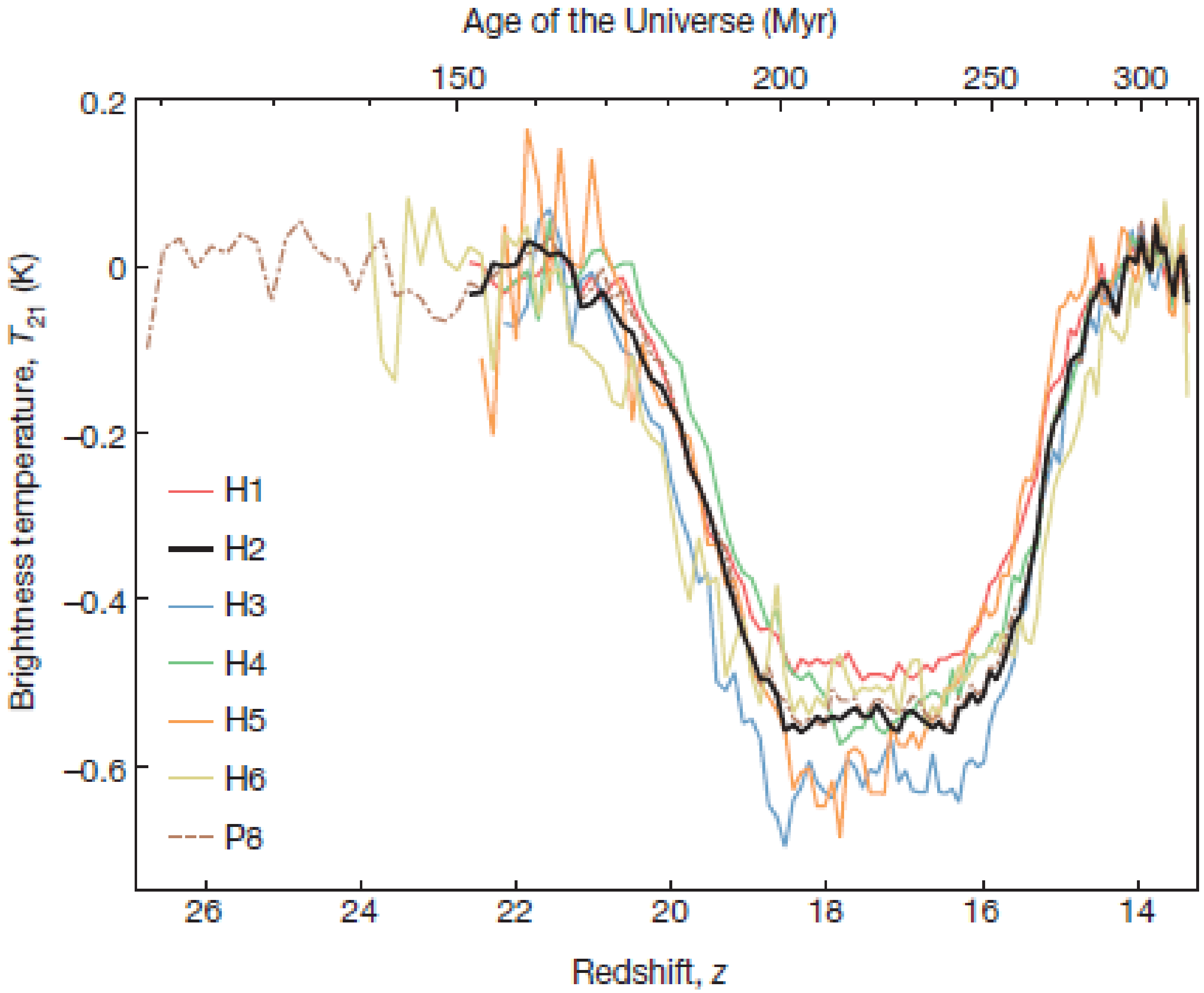
A=(0.0095±0.0008) cpd/kg/keV

χ^2/dof = 71.8/101 **11.9σ C.L.**

The data of DAMA/LIBRA-phase1 +DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 11.9 σ C.L.

R. Bernabei (DAMA/LIBRA), LNGS Scientific Committee Meeting, 26–27 March 2018

Strong absorption of H 21 cm line

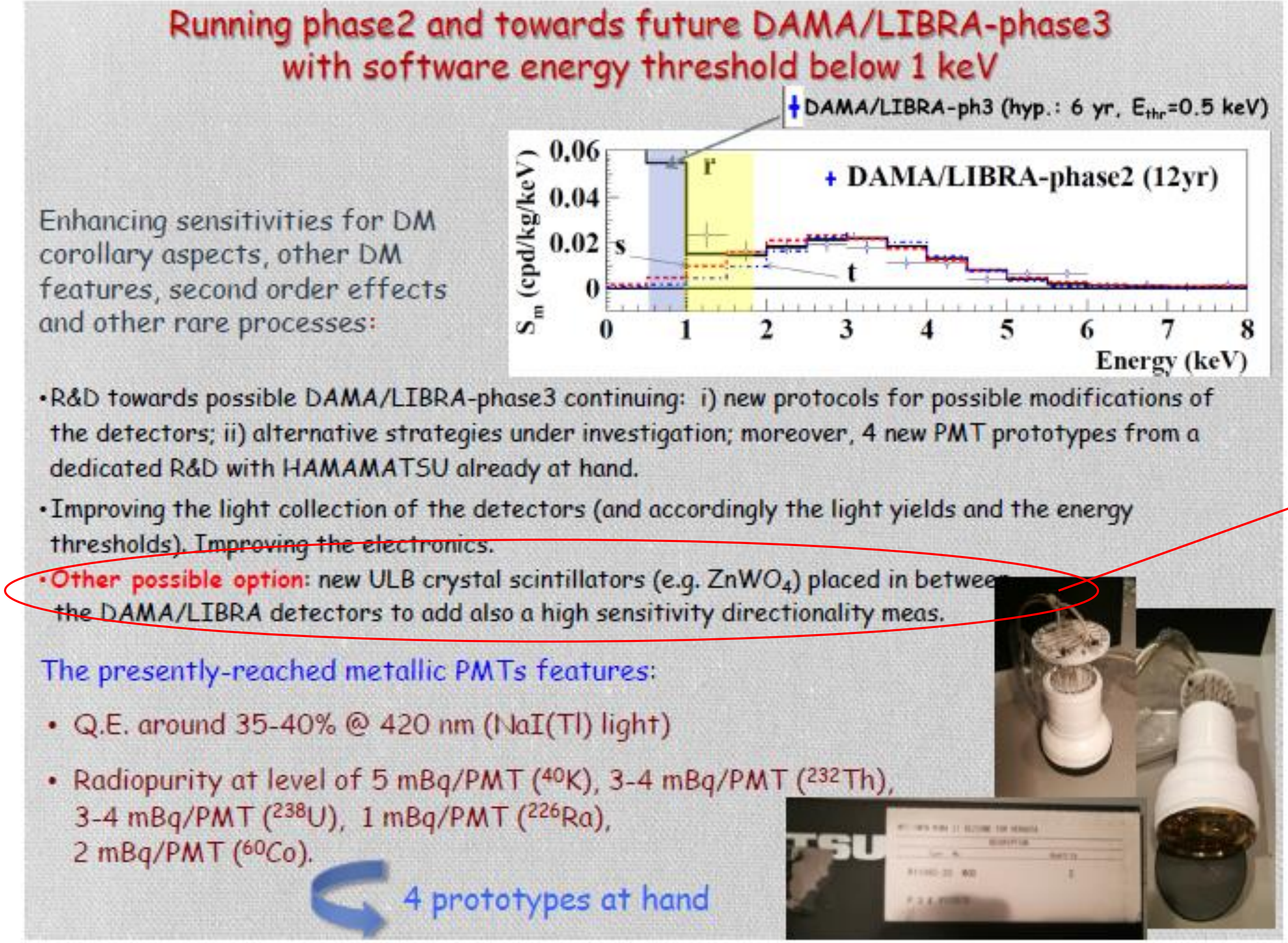


Nature : doi:10.1038/nature25792

High strong absorption of H21 cm line in the red

Baryo-DM cross section > ~10^{-43} cm^2

Nature: doi:10.1038/nature25791



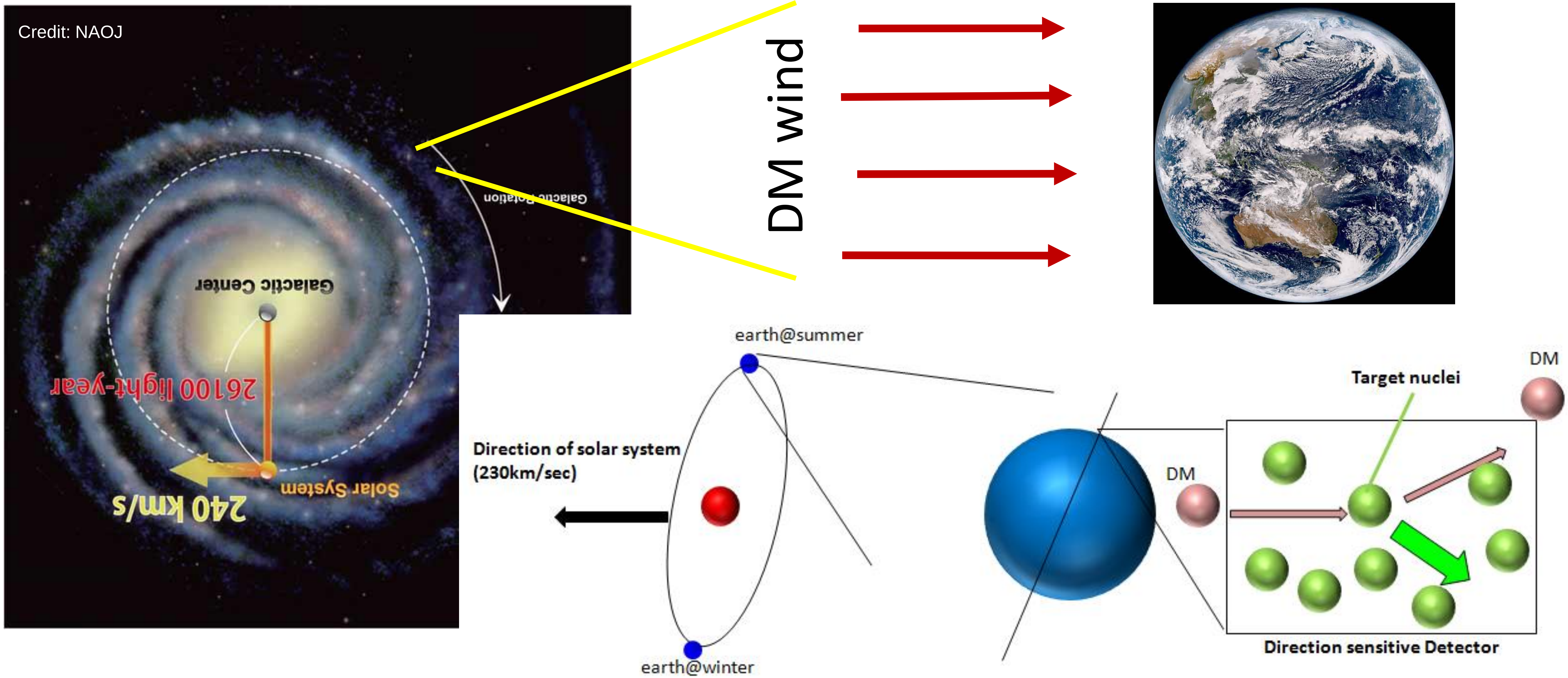
Directional information!!

ZnWO4 scintillator (not demonstrated yet for low-energy recoil)

Other Idea by solid detector or high dense gas
- Carbon nanotube + TPC
- Collumner recombination

→ not demonstrated yet

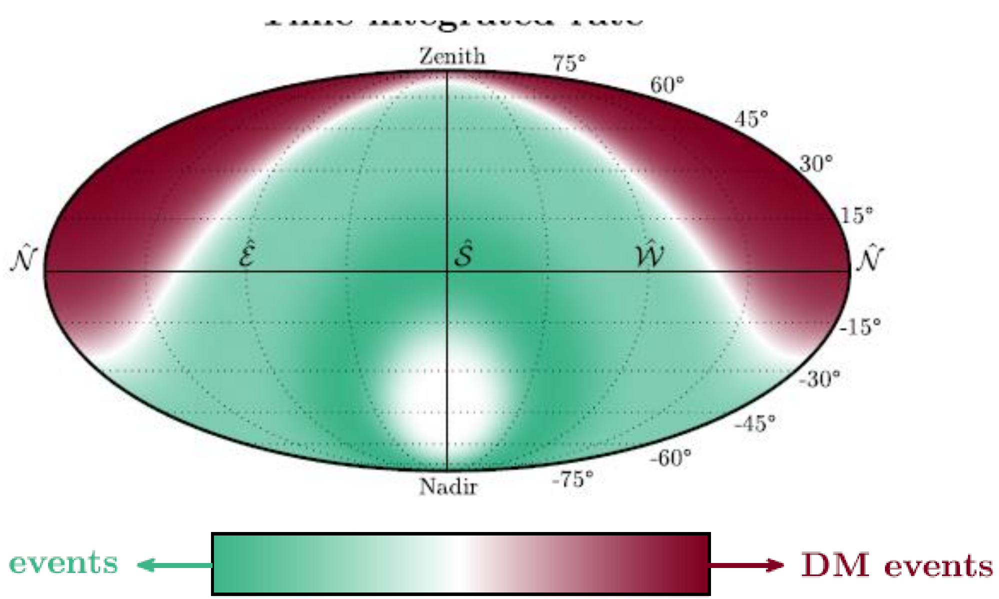
Direction Sensitive Dark Matter Search



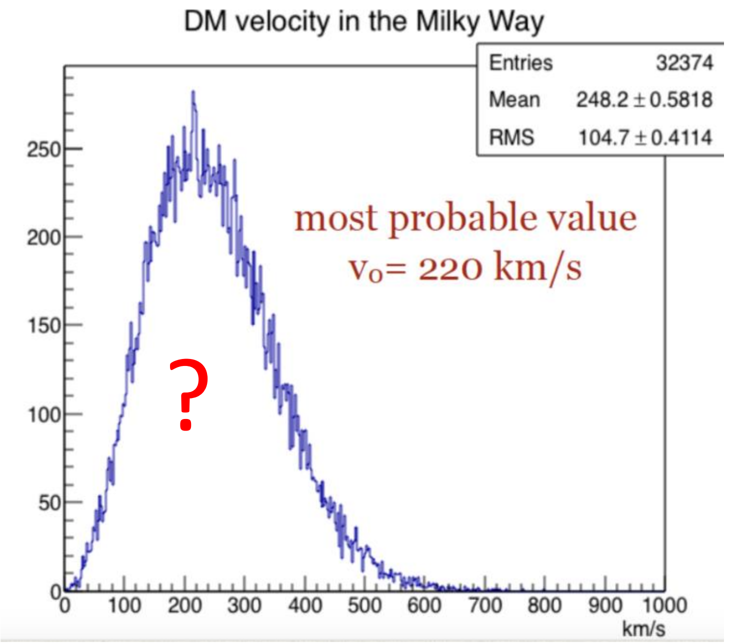
⇒ new systemic search with “ new degree of freedom”

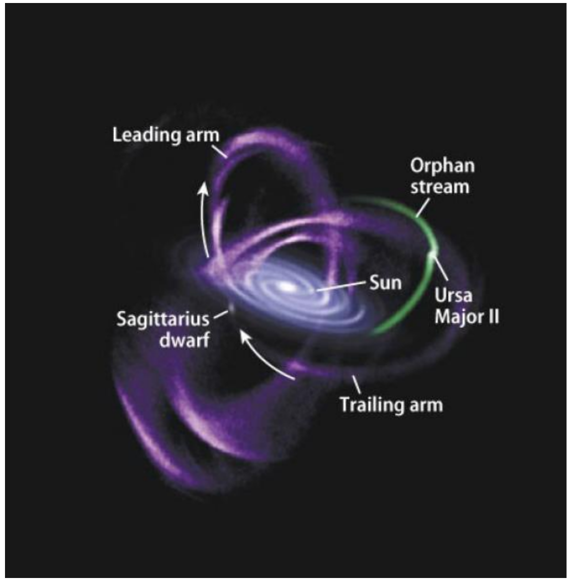
Information from directional search

Beyond neutrino background floor



Phys. Rev. D. 96, 083011 (2017)





☑Does DM have really Maxwellian ?

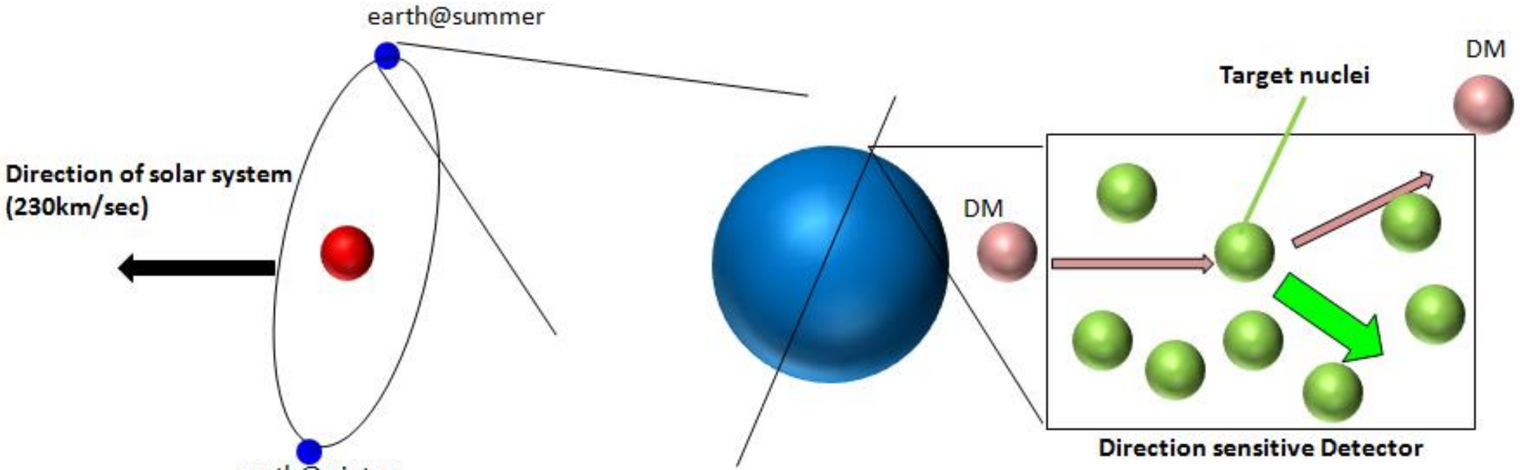
☑Dark matter flow ?

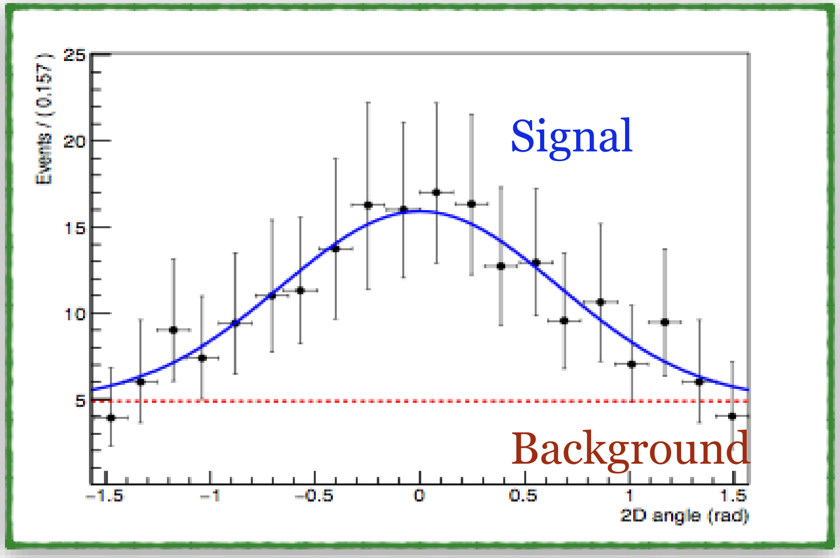
e.g., C. O'Hare and A. Green, Phys. Rev. D 90, 123511 (2014)

☑Anisotropic distribution?

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

Directional Dark Matter Search



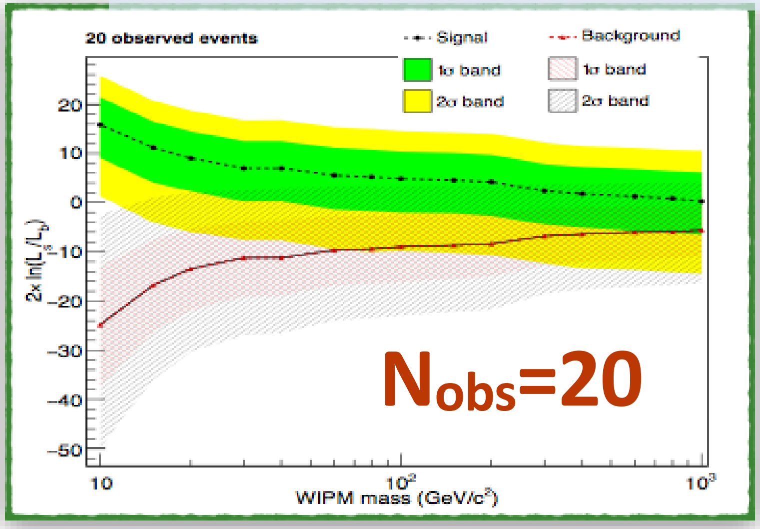


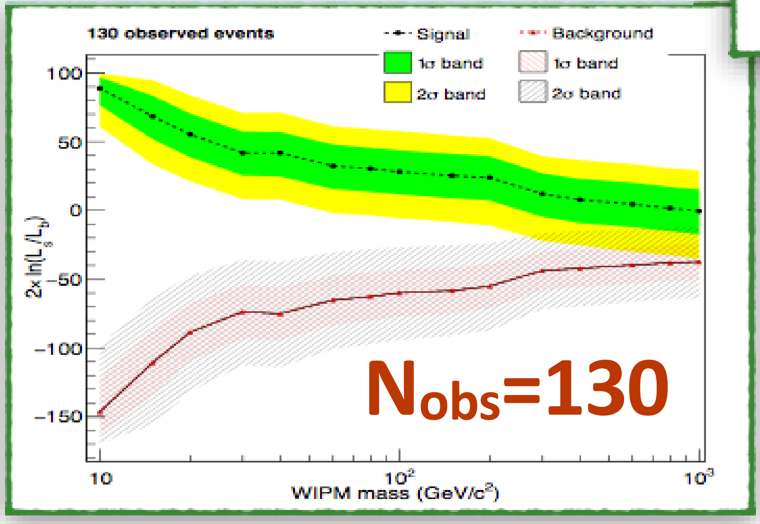
expected number of WIMP events; expected number of background events; signal pdf; background pdf

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

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 !!

arXiv:1705.00613 [astro-ph.CO]

Challenge for Direction Sensitive Dark Matter technologies

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

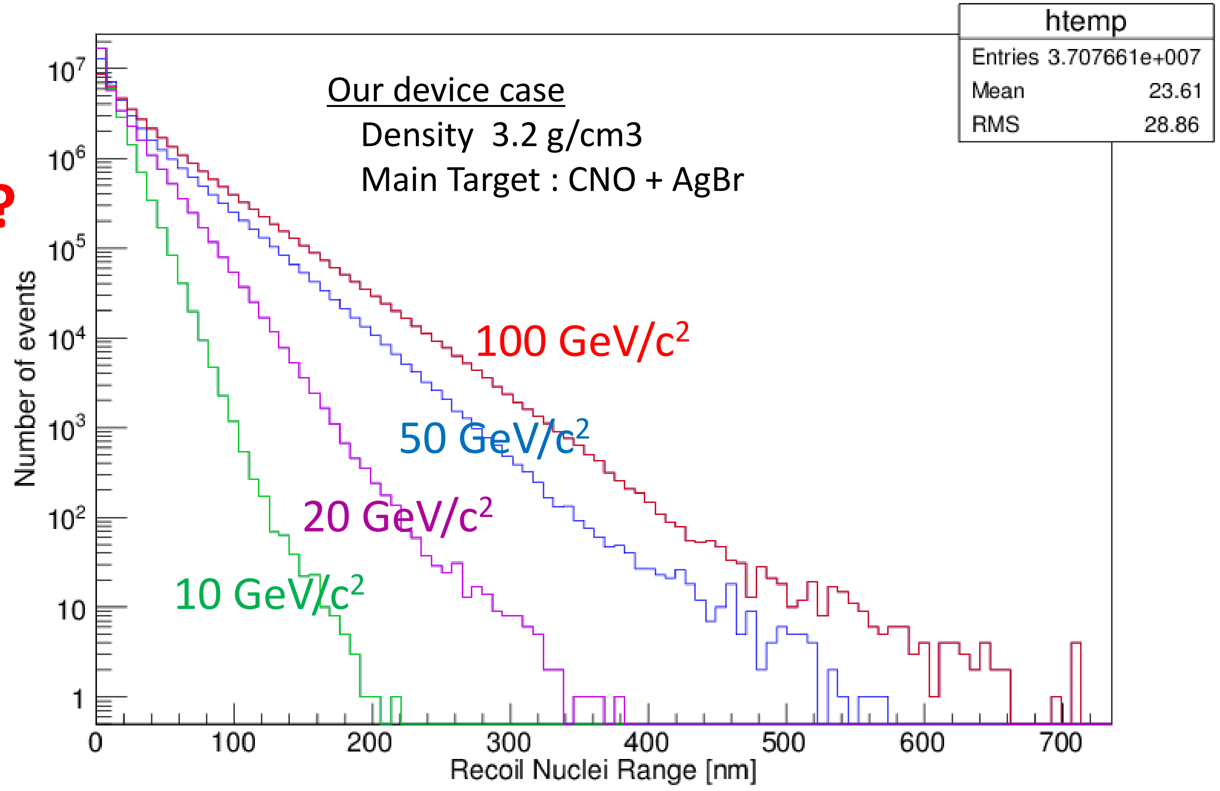
- **Track length of recoiled nuclei < ~ 1 μm**
- **Angular dispersion due to straggling ~ 25deg.**

As dark matter detector ･･

☑ low-background

☑ scalability

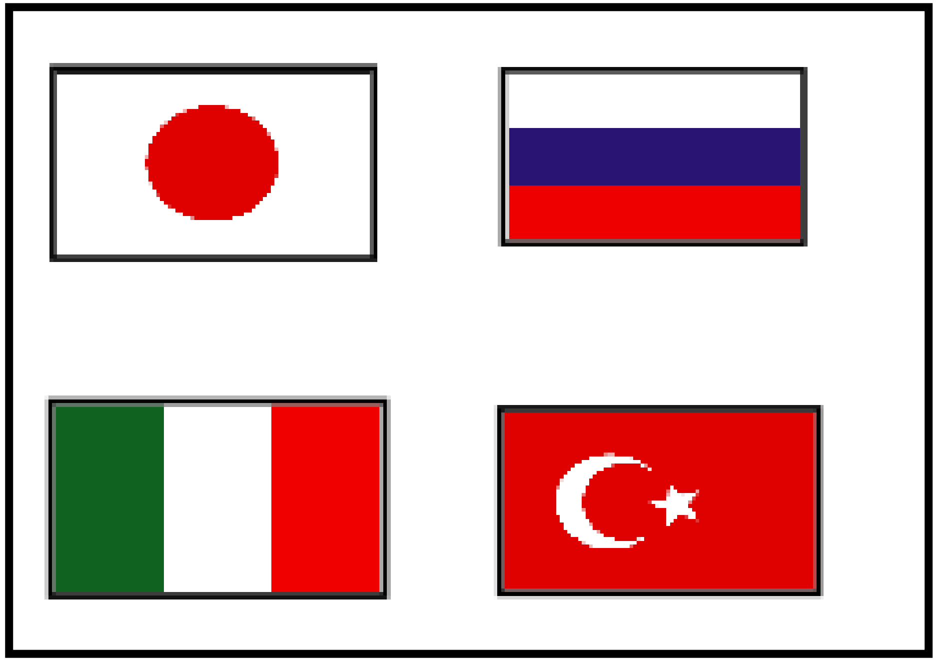
New technical challenge !!



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

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)

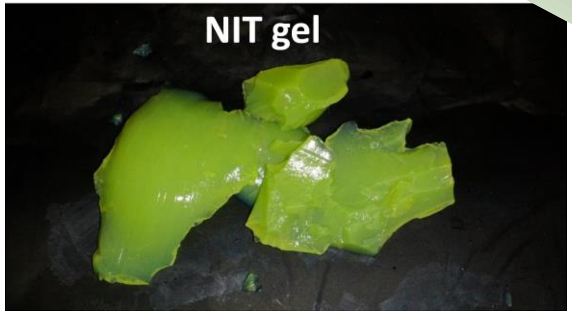
2015: Submitted LOI to
LNGS science committee

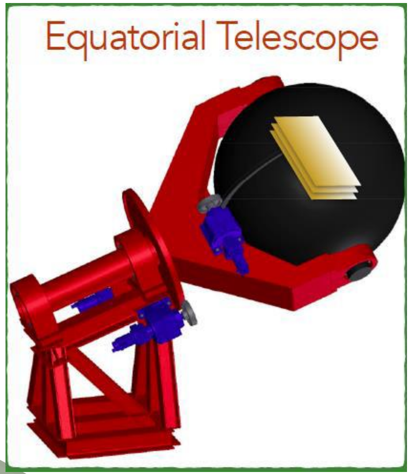
NEWSdm experimental strategies

Underground laboratory (LNGS). In future, multi-site observation (e.g., LNGS and SNOLAB)

Device self-production

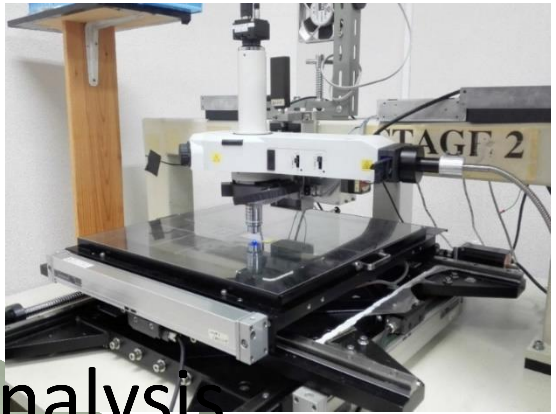
Super-high resolution device





Exposure +
chemical development

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

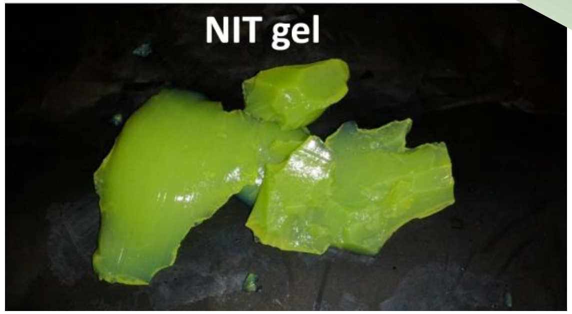


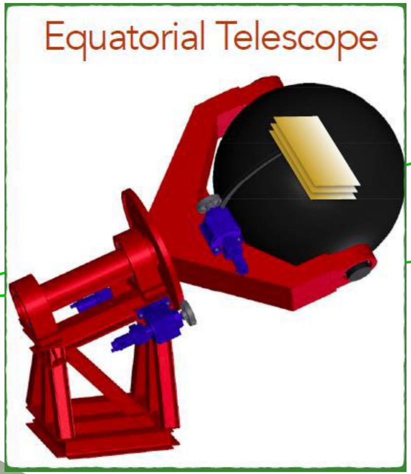
Readout + analysis
R&D on going

NEWSdm experimental strategies

Device self-production

Super-high resolution device





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

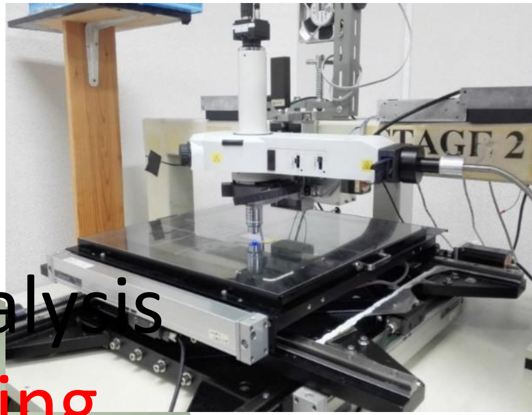
Exposure +
chemical development

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

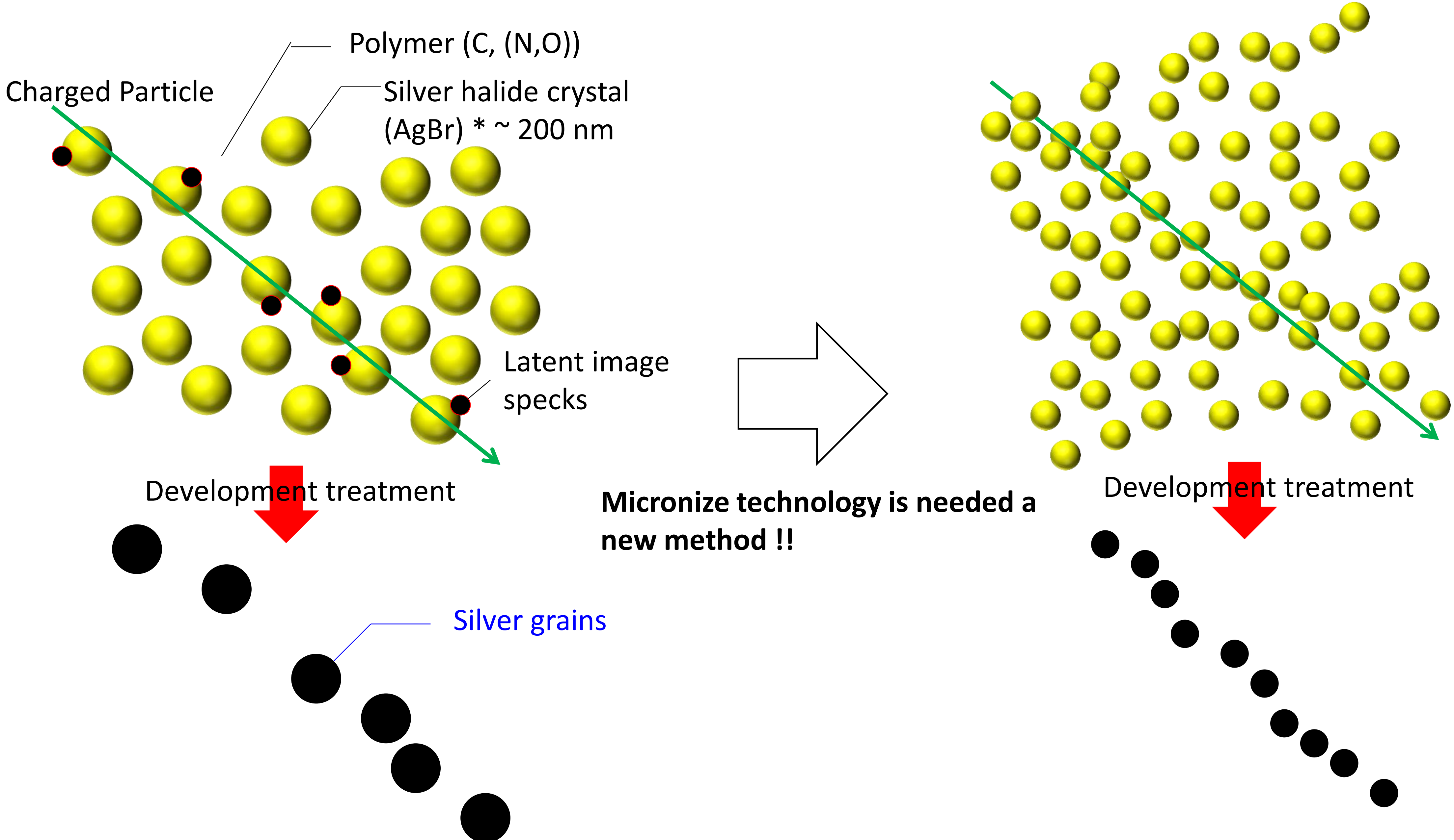
- **High speed scanning**
- **Super-high resolution microscopy**
- **Cutting-edge technologies for optics**

Readout + analysis

R&D on going



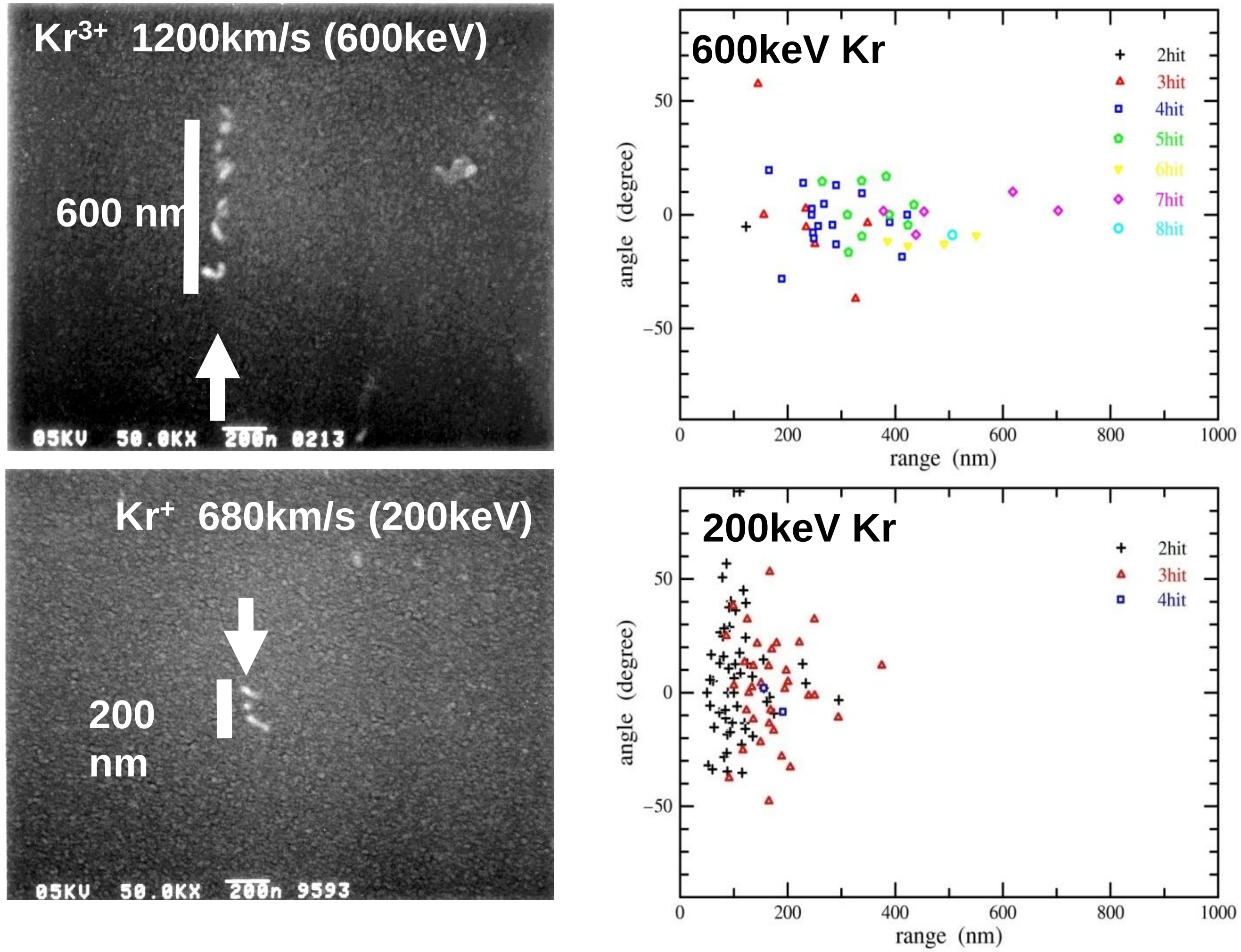
Concept of super-high resolution



Micronize technology is needed a new method !!

First demonstration of detection of submicron tracks

SEM (Scanning Electron microscope) observation



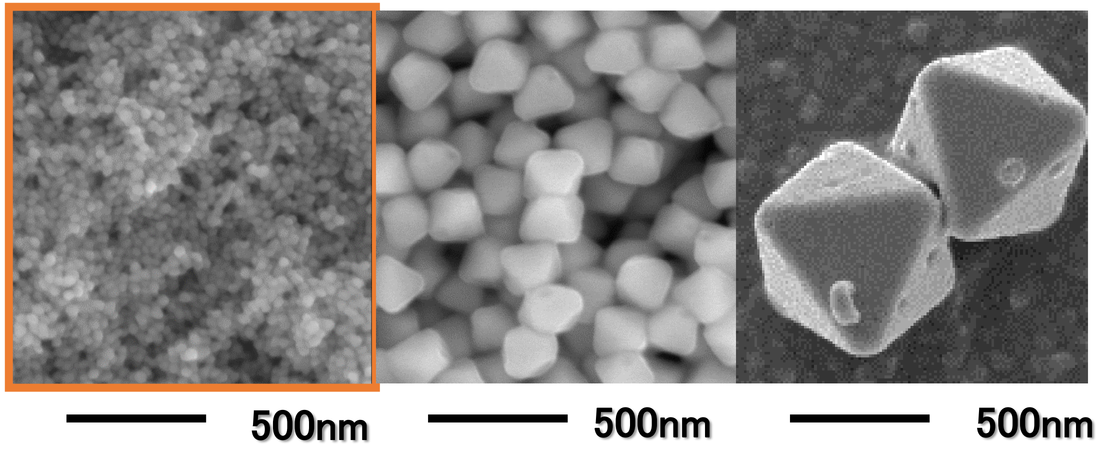
Natsume et al,. **NIM** A575 (2007) 439

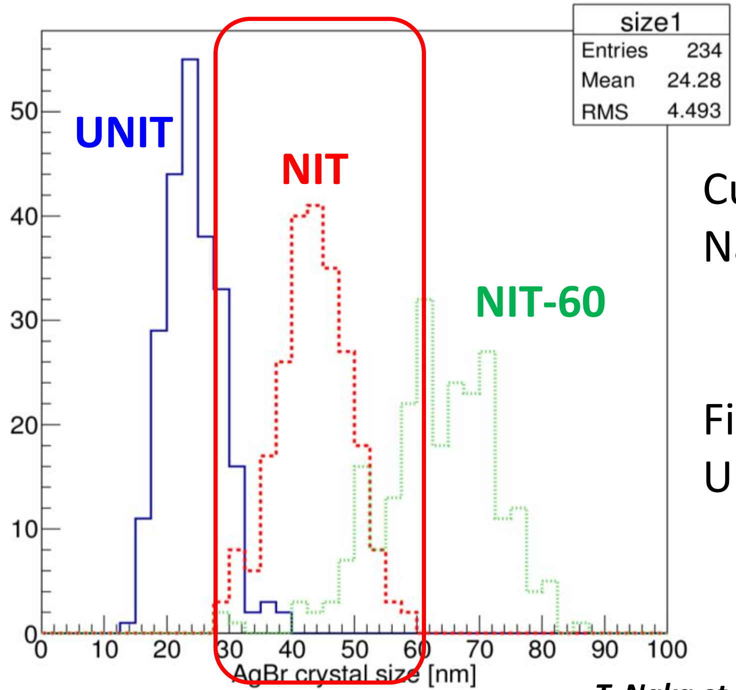
Device self-production

- 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

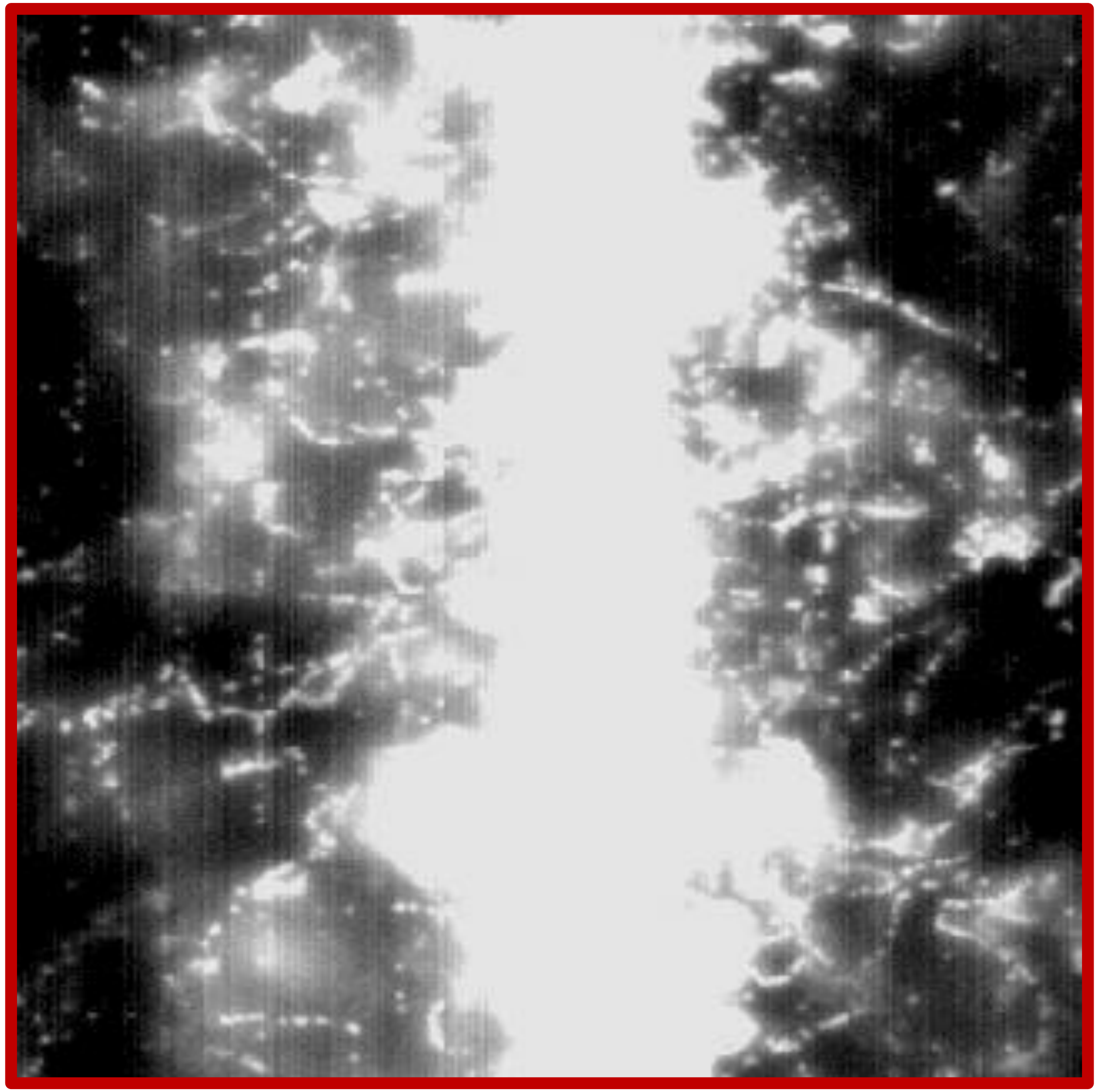
T. Naka et al., Nucl. Inst. Meth. A 718 (2013) 519-521

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

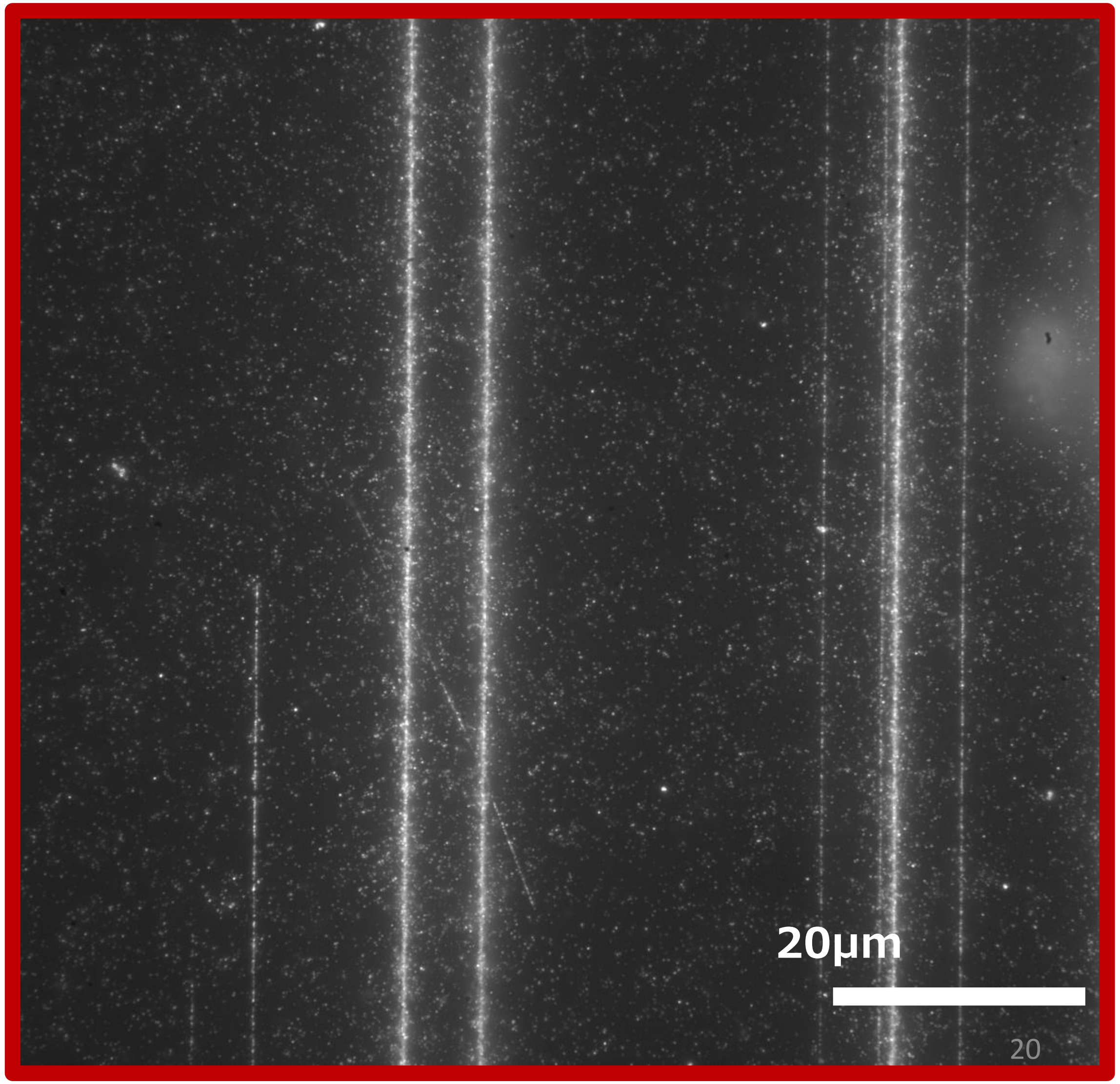
Pb 150GeV/n beam (exposed at CERN)

* Optical microscope image

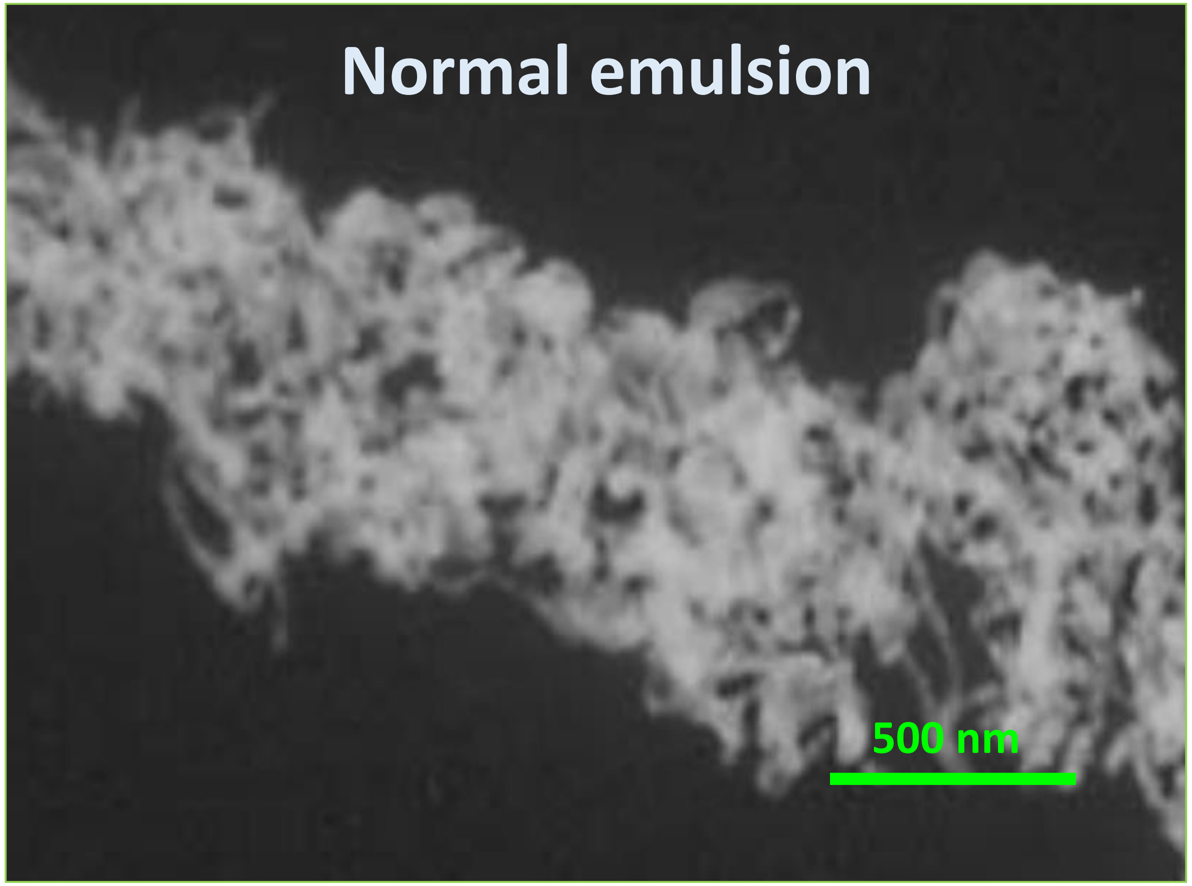
Normal emulsion

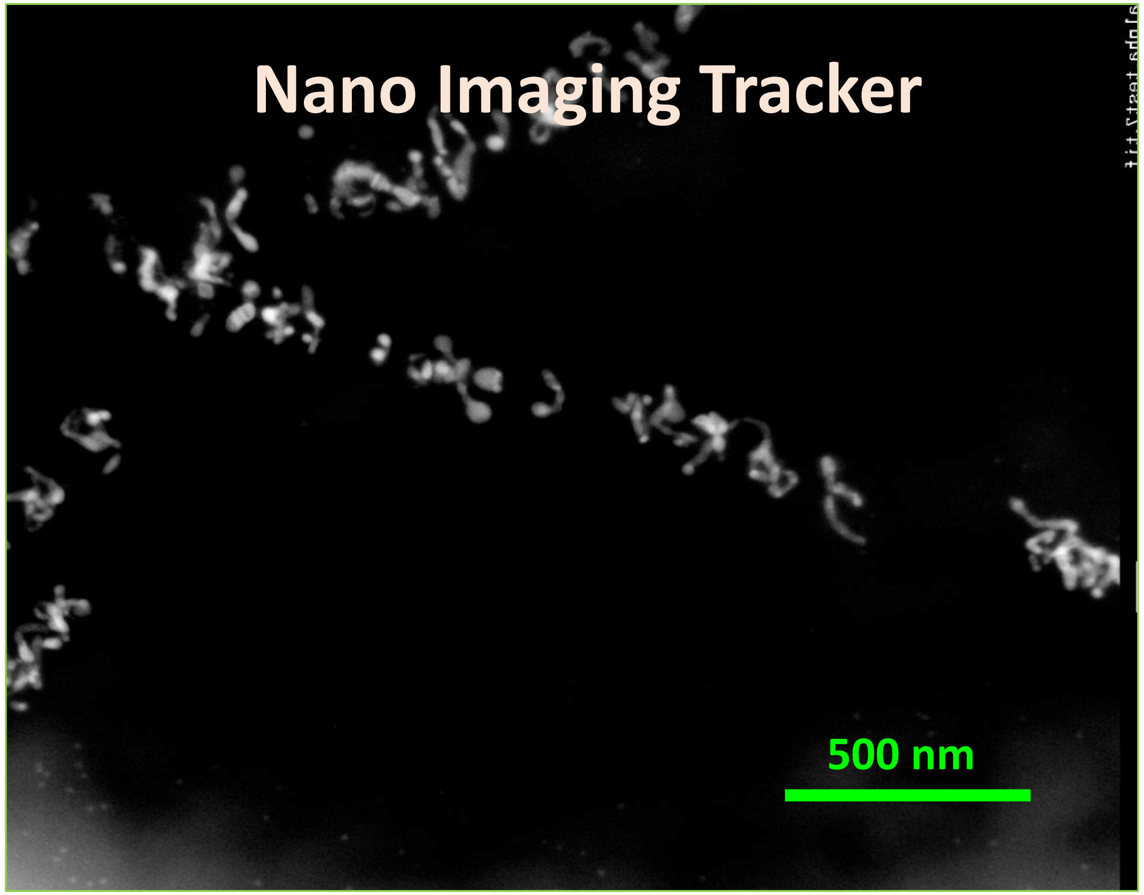


Nano Imaging Tracker

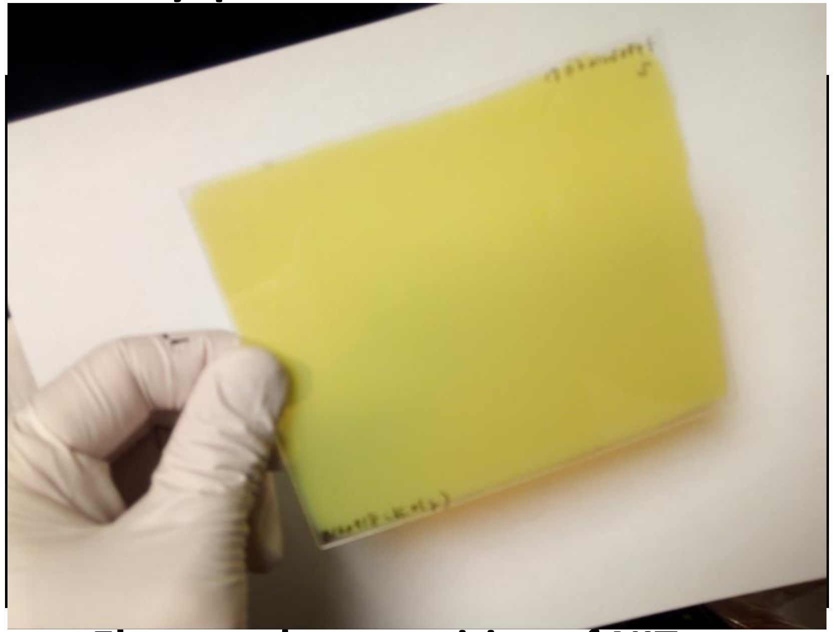


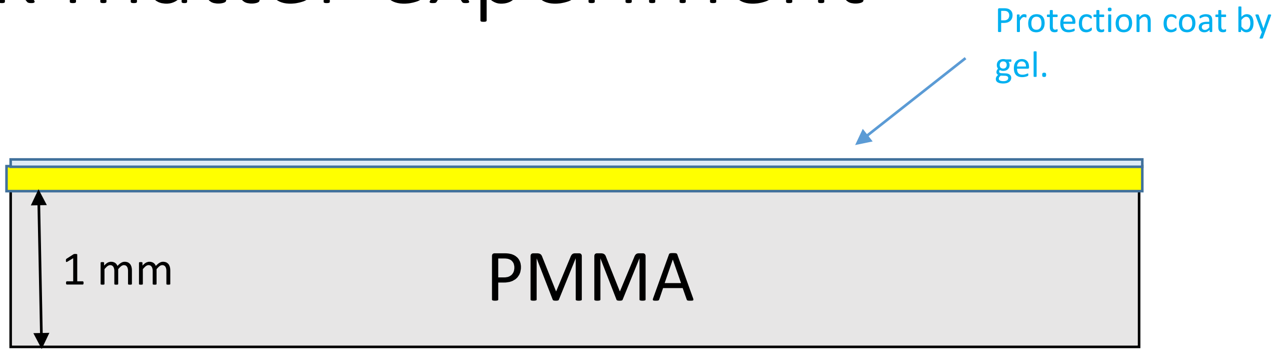
Case of electron microscope image





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:

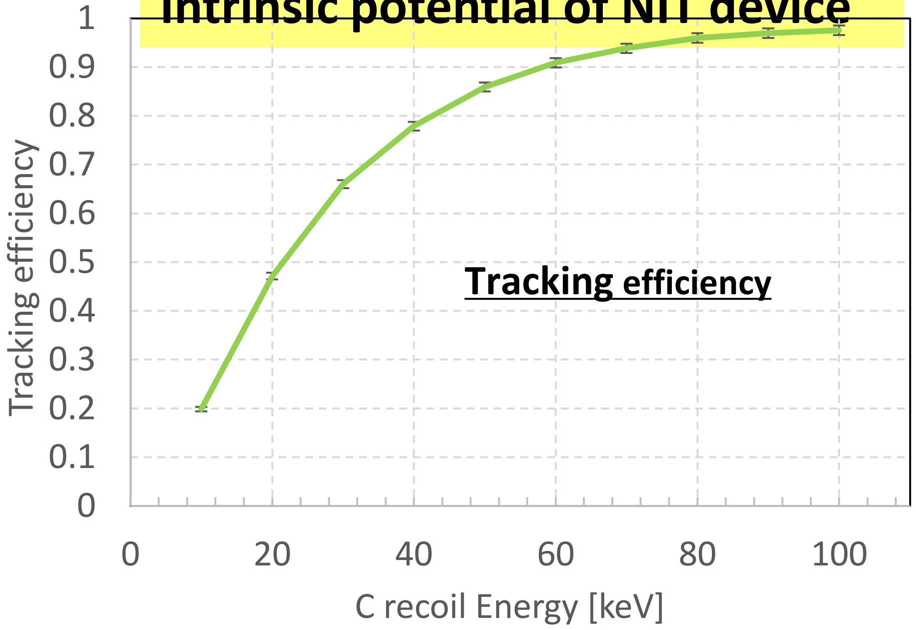
~ 1.2 /kg/y (by SOURCE simulation)

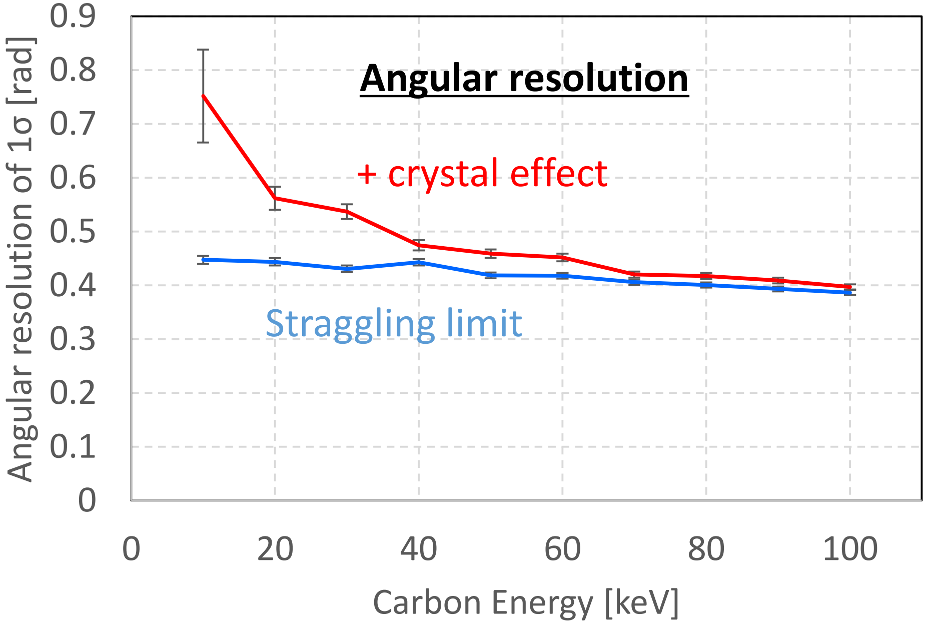
⇒ ~ 0.1 /kg/y (> 100 nm nuclear recoil)

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

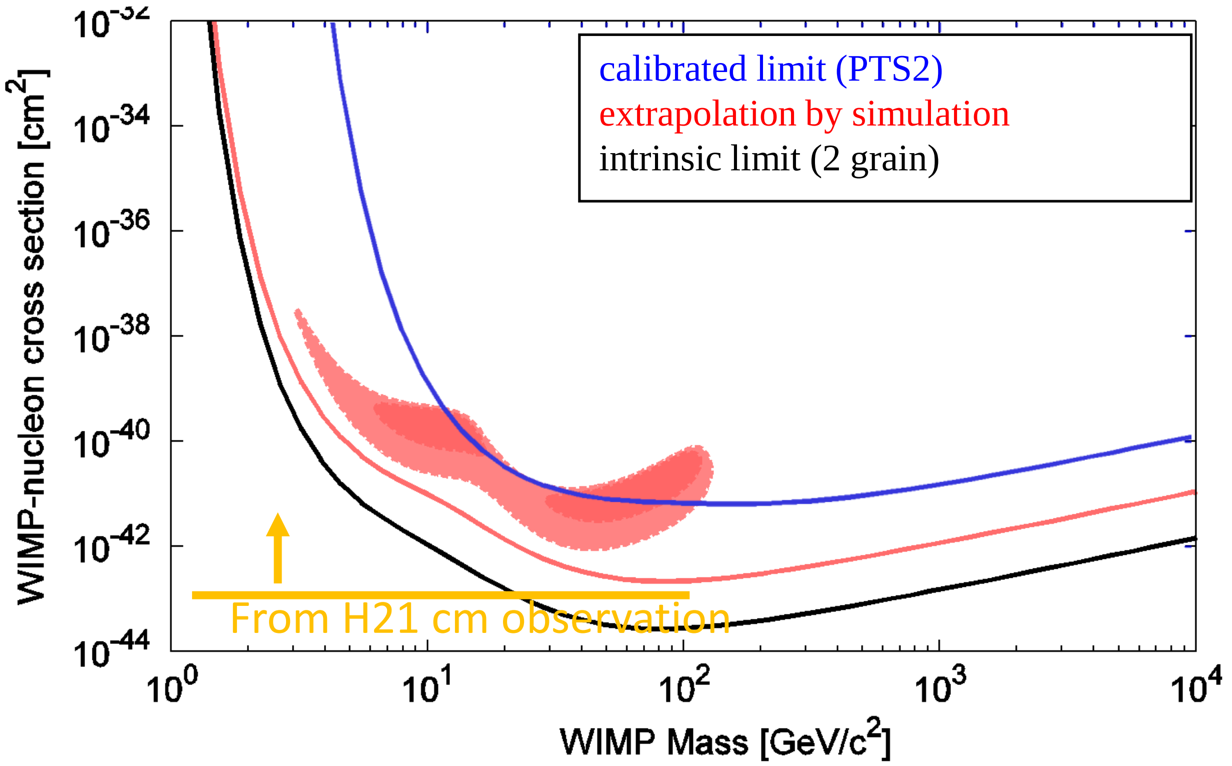
NIT emulsion potential

Intrinsic potential of NIT device





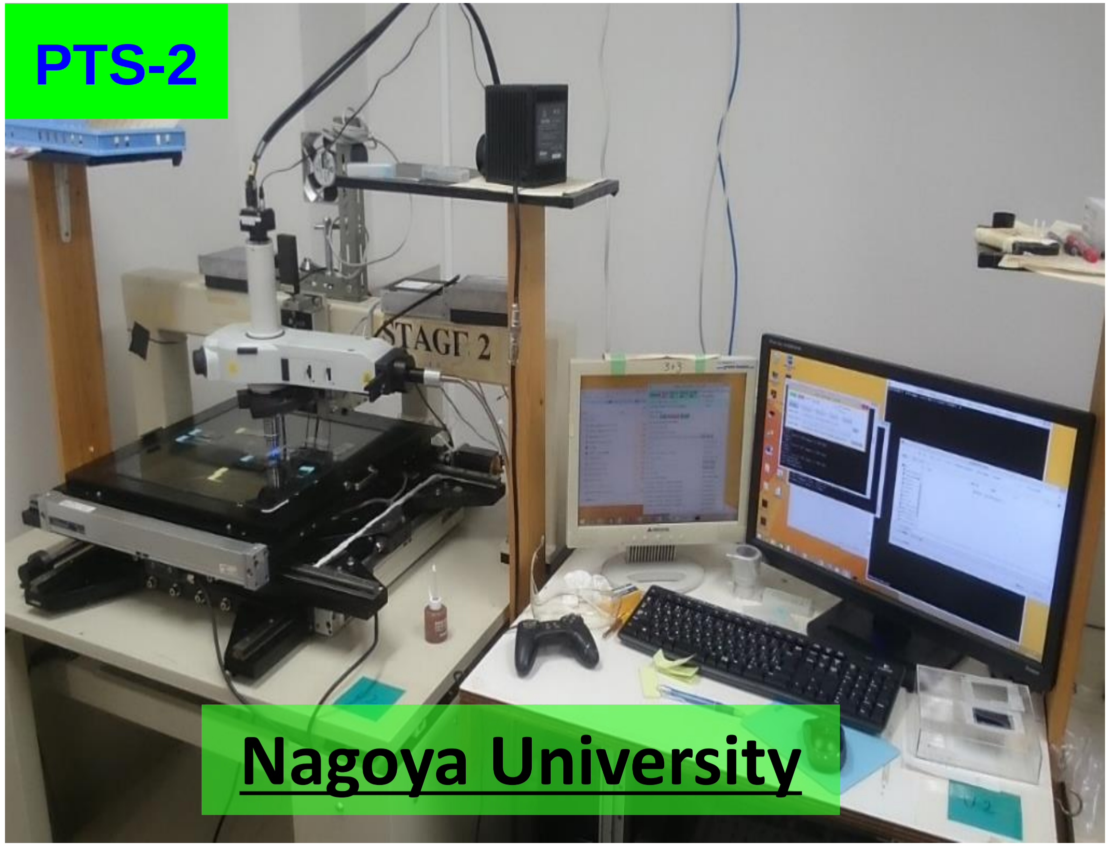
10 kg·year simulated sensitivity [90 % C.L.] + zero BG

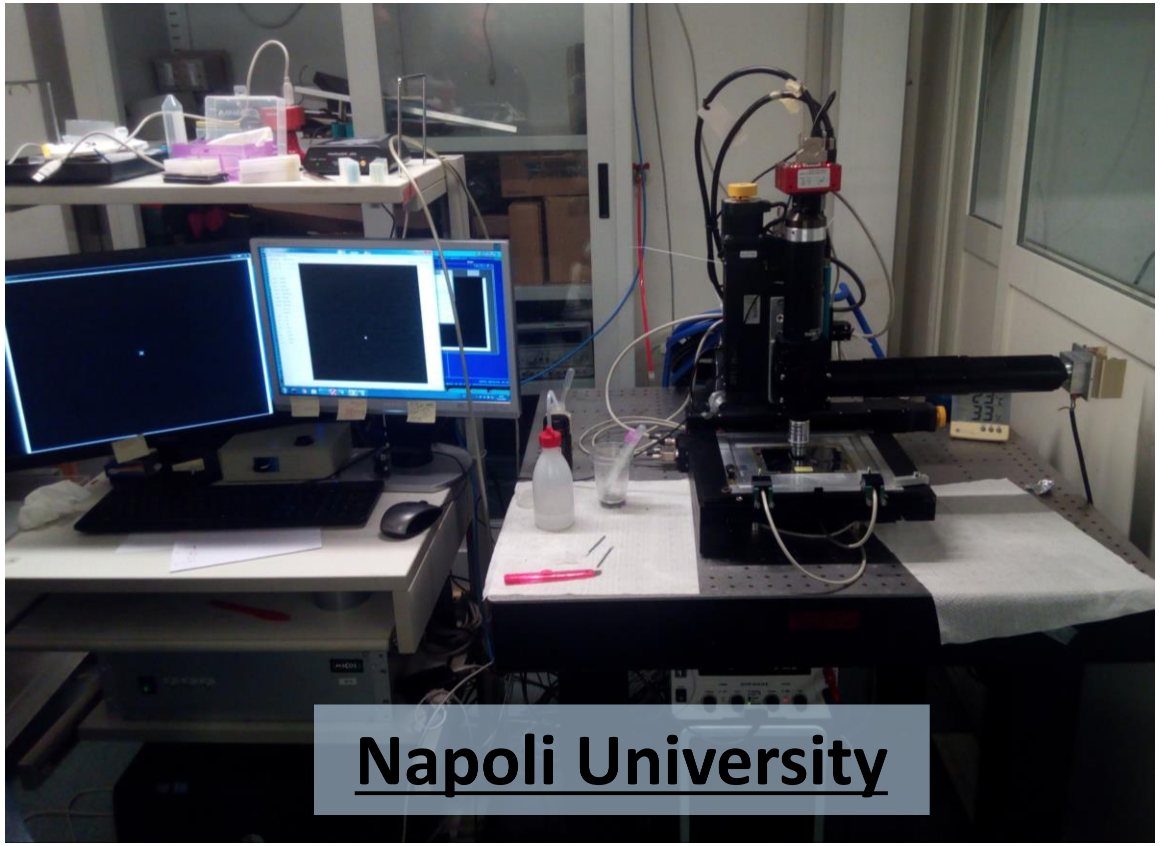


NIT detector / CNO sensitive / no Bkg no directionality
Simulation limit is “energy > 5 keV for all atoms (SRIM limit)”
& “Sensitivity > 0.1 % (Simulation statistics limit;10 event)”

Development of New Readout System

Prototype R&D system @Nagoya and Napoli



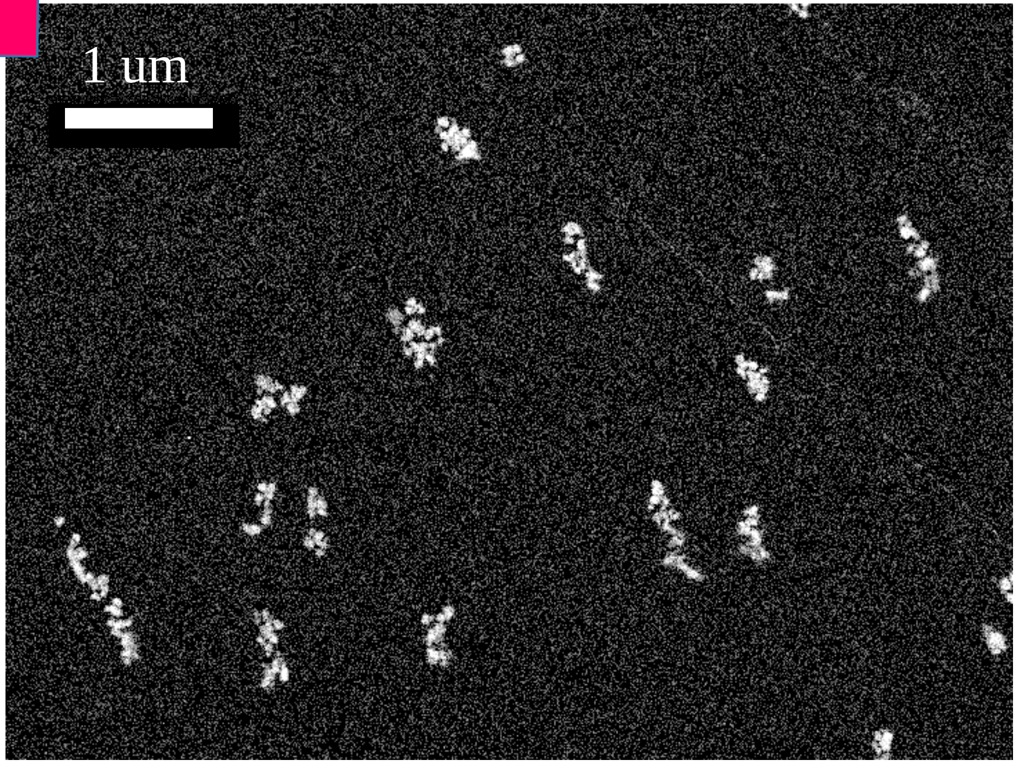


Low-velocity ion tracking

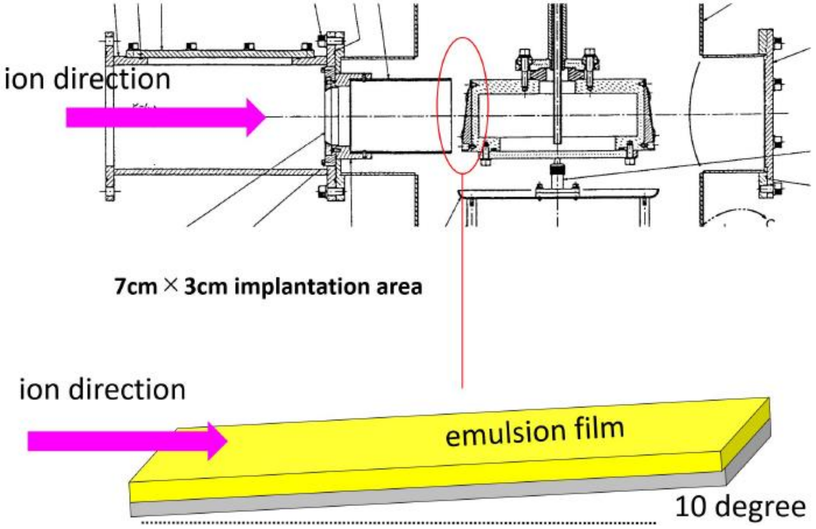
Can use ion implantation as calibration source

- 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

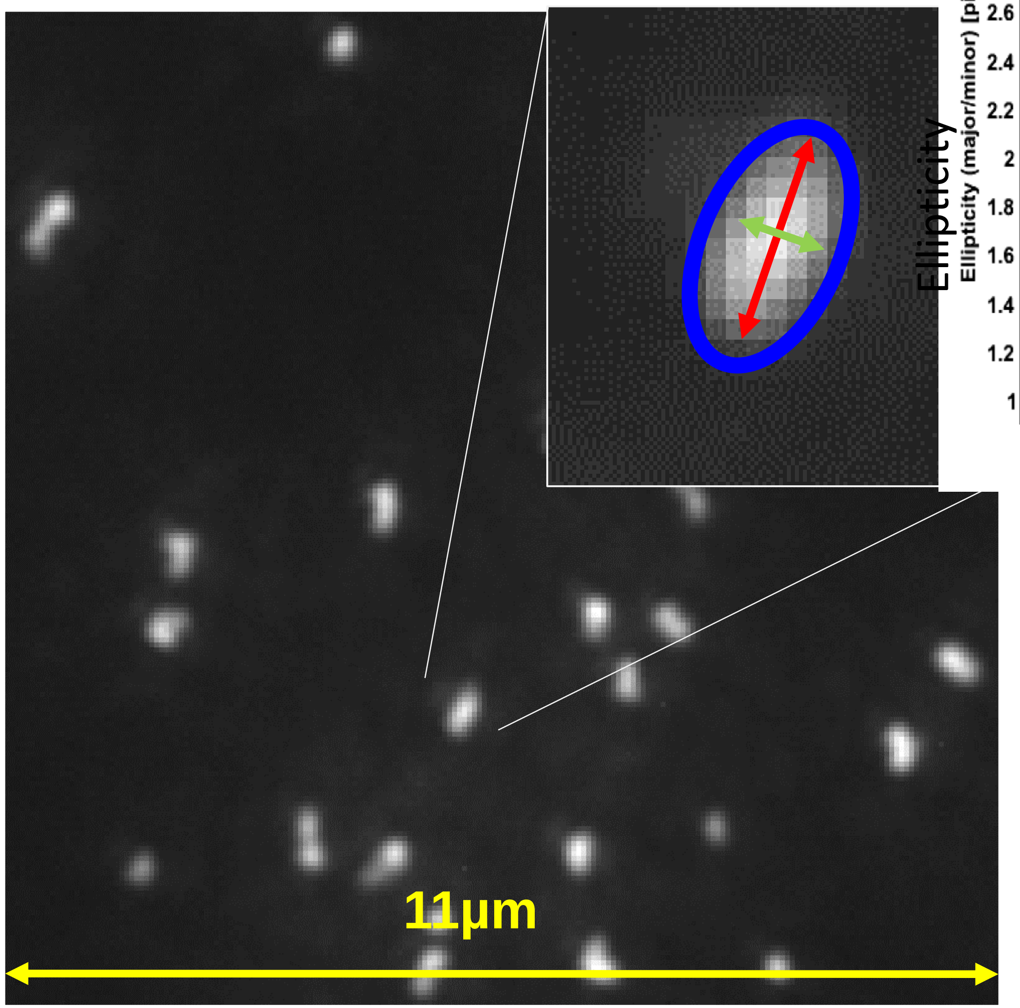


Side view of io



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

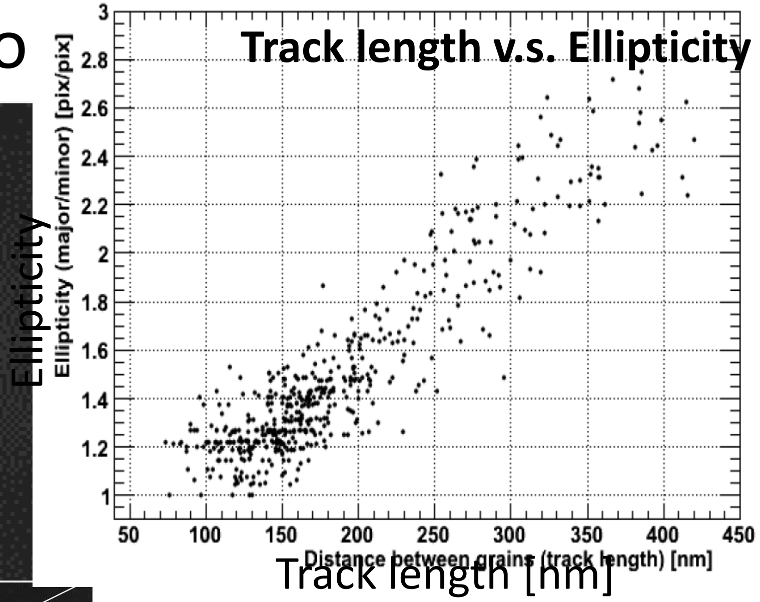
Candidate selection method using epi-illuminated optical microsco

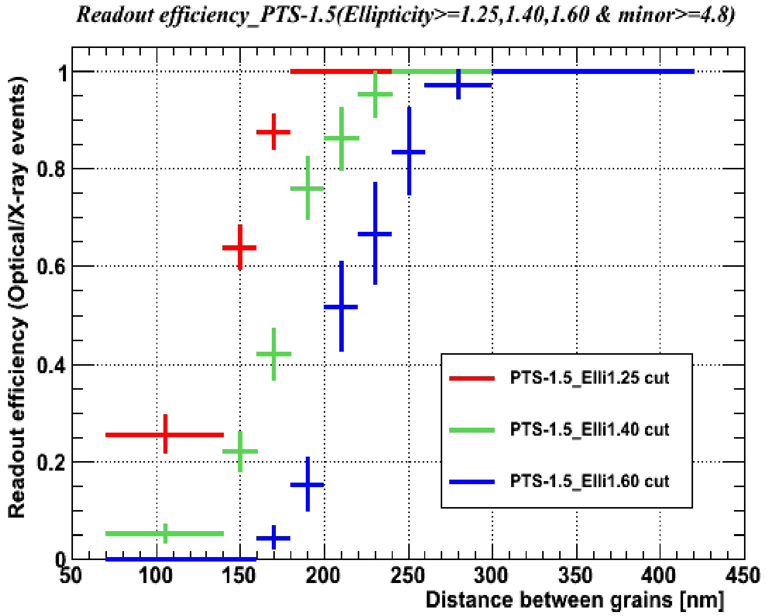


K. Kimura and T. Naka, Nucl. Inst. Meth. A 680 (2012) 12-17

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

Performance using only elliptical shape analysis

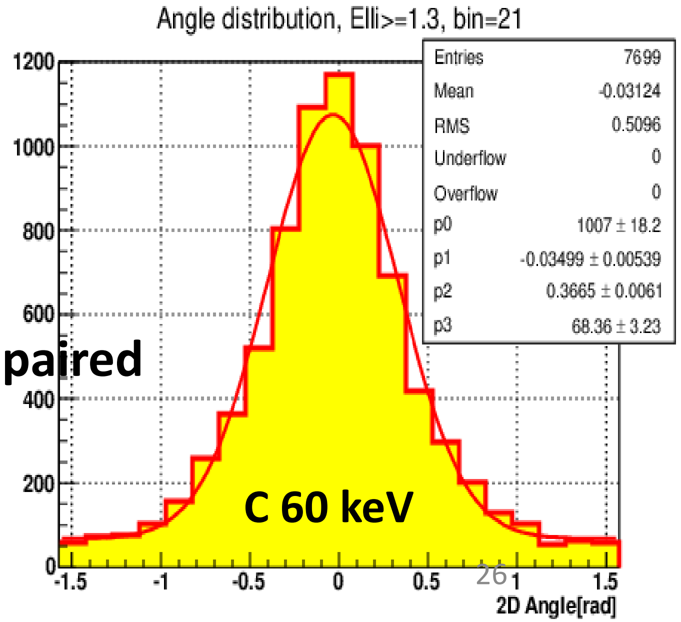


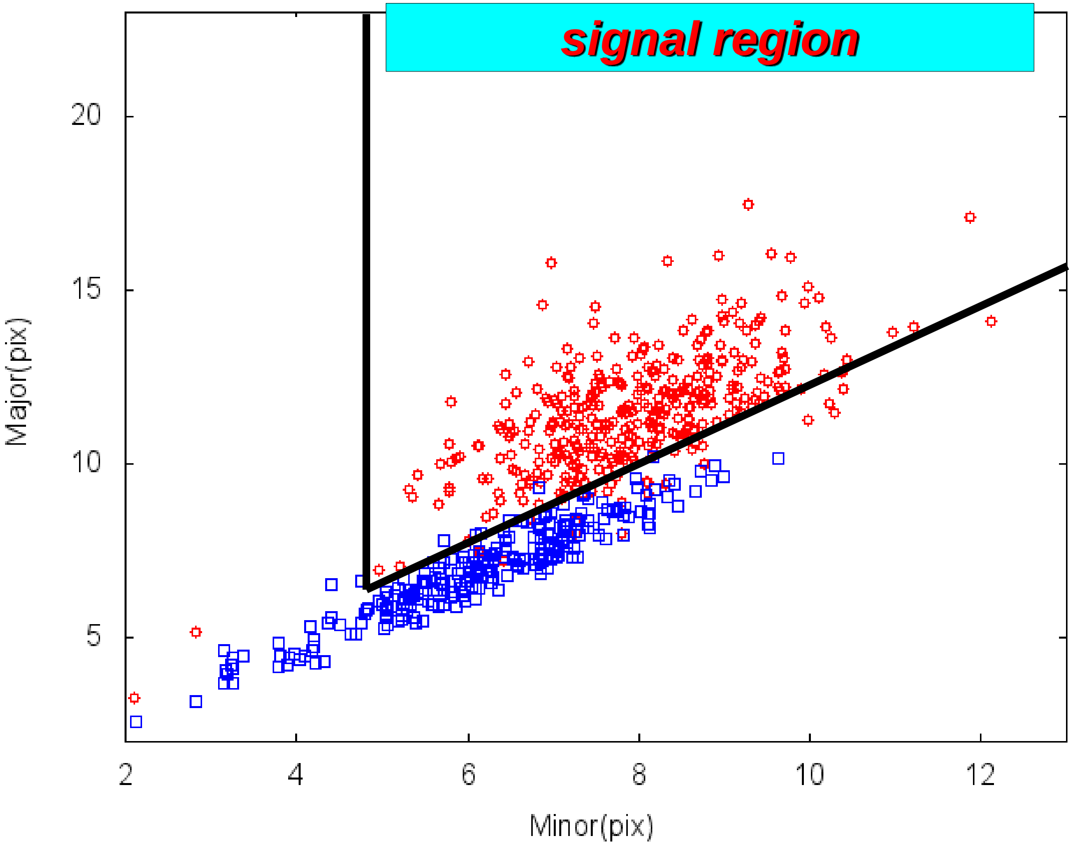


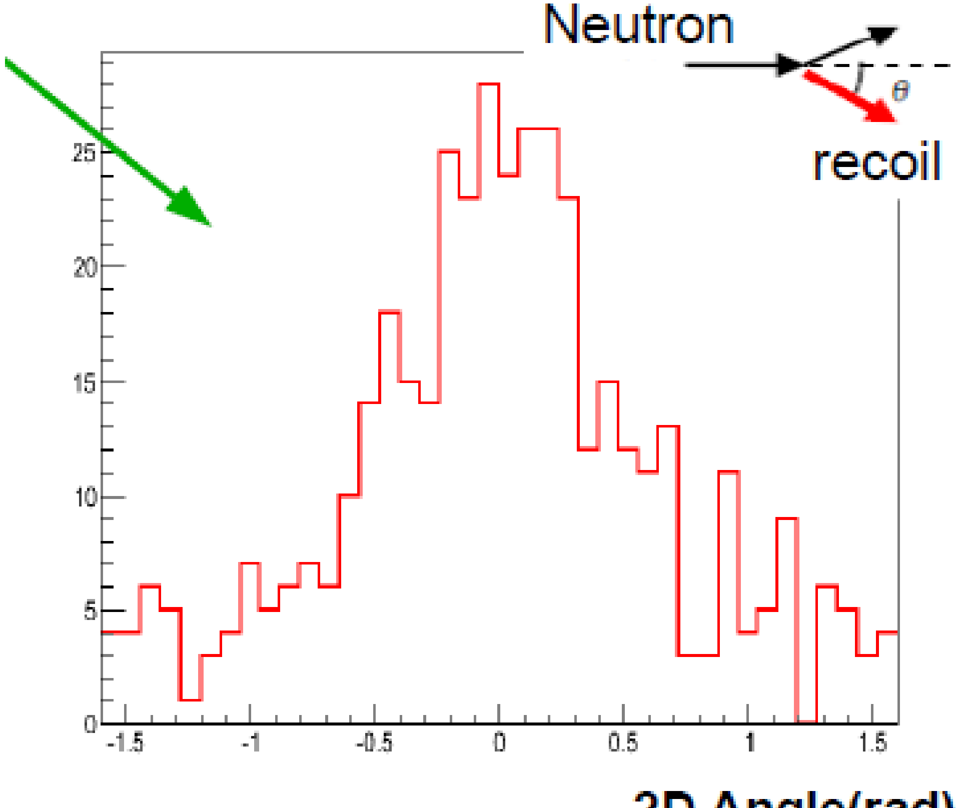
Current microscope has the potential to select > 100 nm length tracks

Direction sensitive eff.:
~30 % @60 keV
→ readout loss ~ 10 % or less
⇒ current efficiency is limited by optical contrast loss : to be repaired
Angular resolution :
~30 deg. @60 keV

Lower energy calibration is under studying.



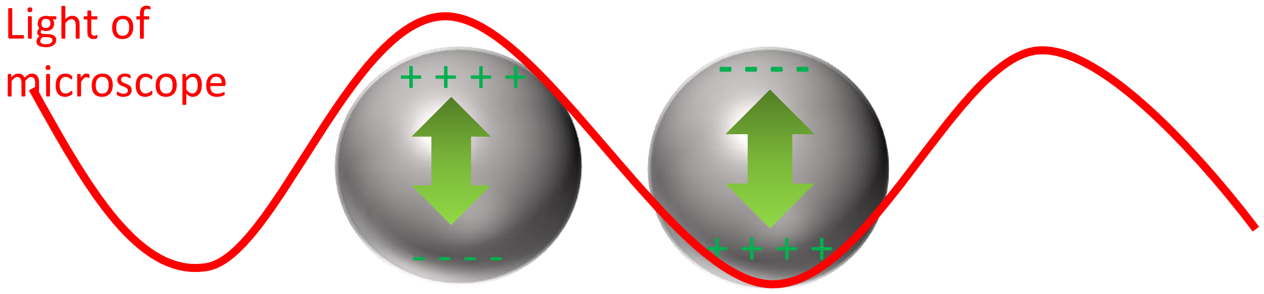

signal region
Major(pix)
Minor(pix)
20
15
10
5
2
4
6
8
10
12


Neutron
θ
recoil
2D Angle(rad)
25
20
15
10
5
0
-1.5
-1
-0.5
0
0.5
1
1.5

[redacted]

Localized Surface Plasmon Resonance (LSPR)

Localized Surface Plasmon Resonance

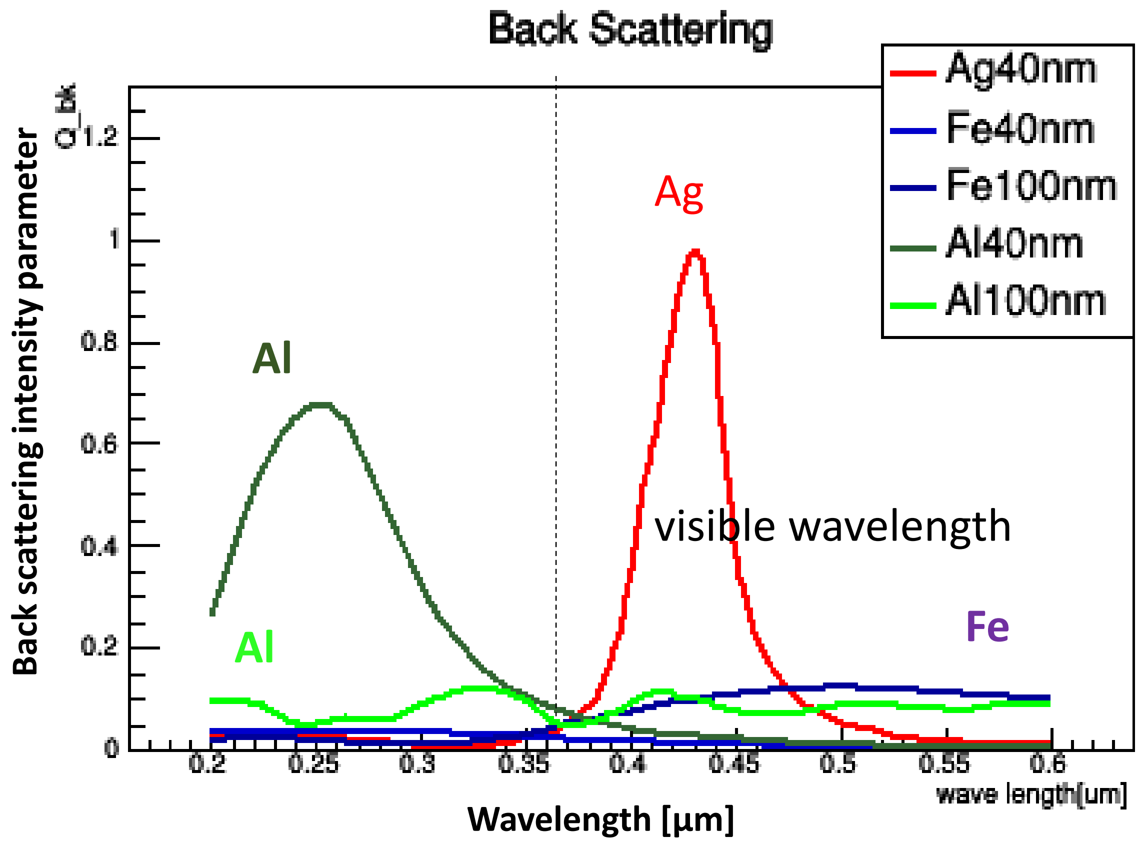


silver nano particle

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

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

Resonance condition

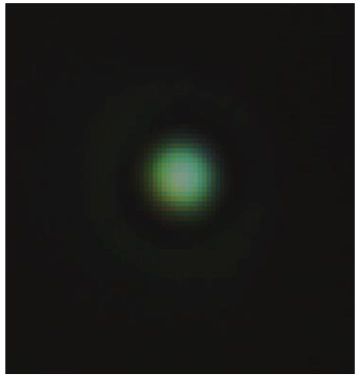


- Resonance effect due to coupling with the free electron and light of optical microscope
- Resonance wavelength depends on the crystal size
- Polarization angle dependence of resonance wavelength reflect the shape of nano-scale structure

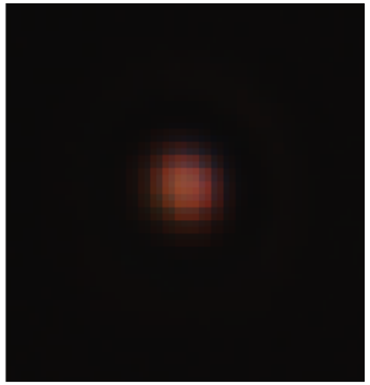
Optical response due to LSPR

<u>Silver-nano particle</u>

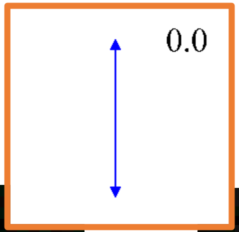
40 nm

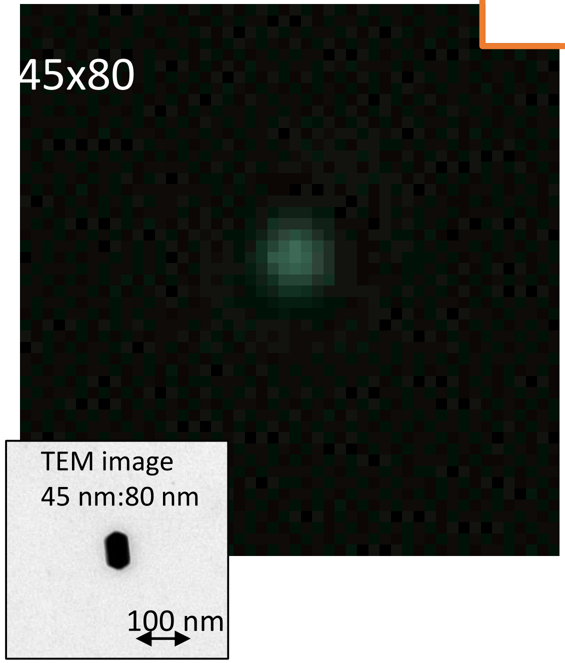


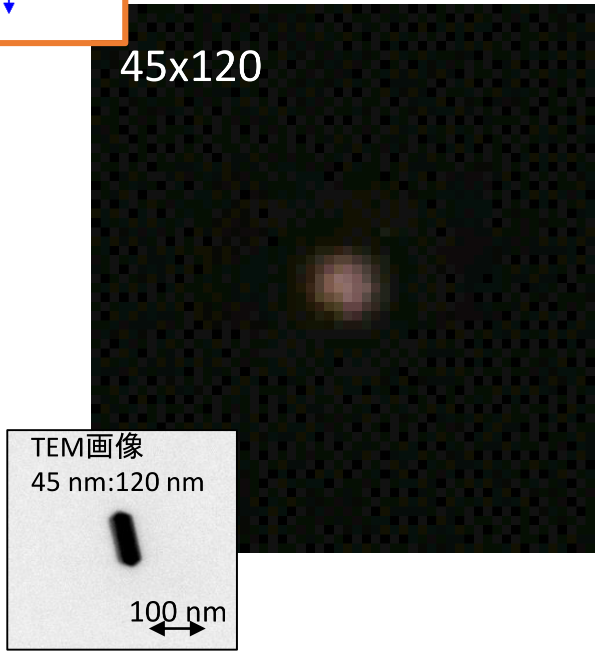
80 nm



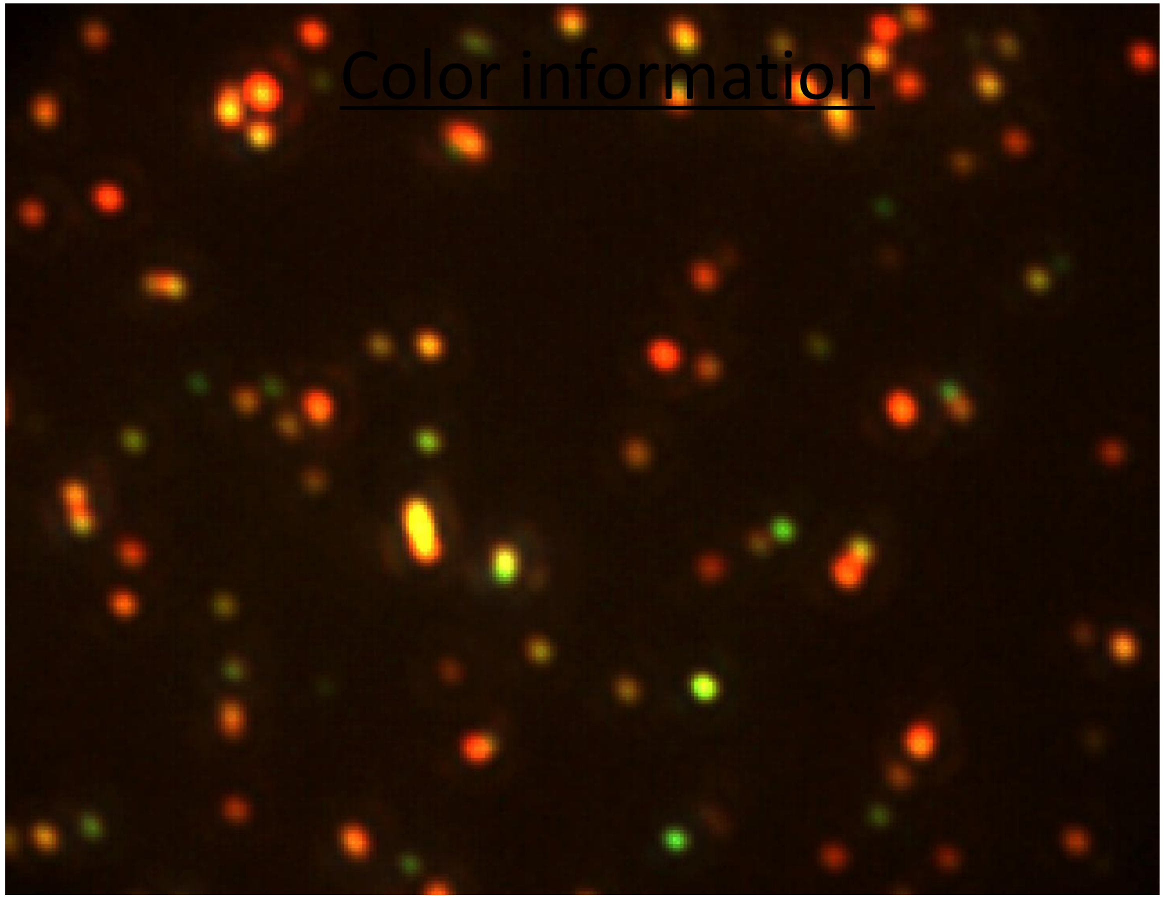
120 nm

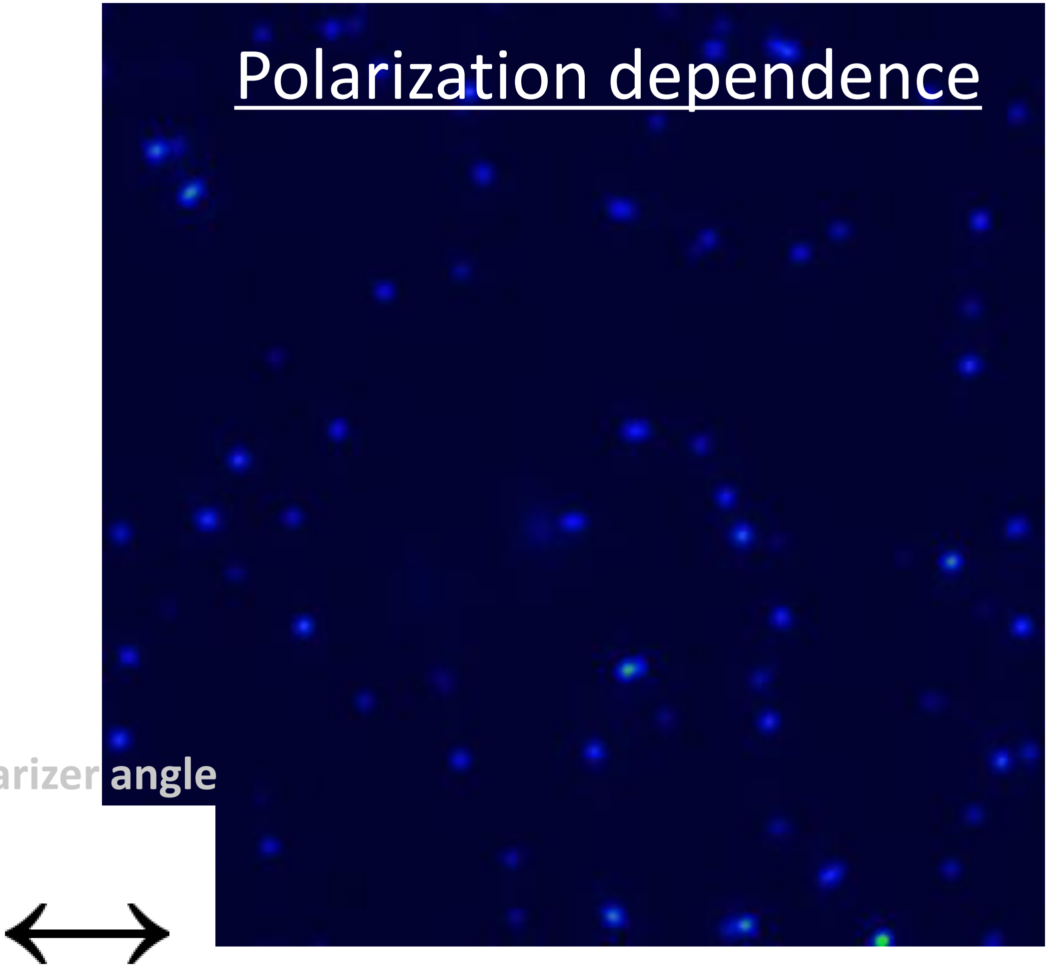






Optical response due to the Plasmon resonance for the developed silver grains for the NIT



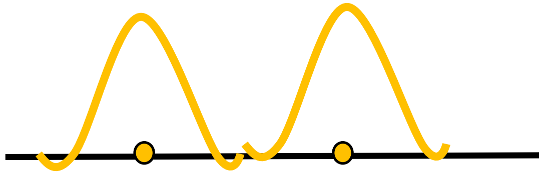


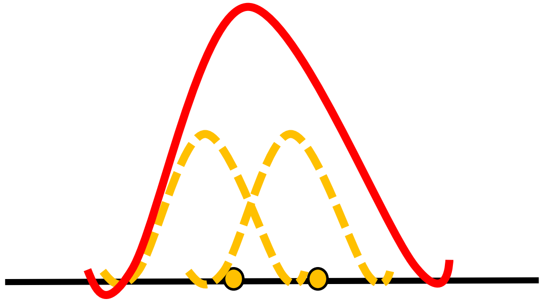
2014 Nobel Prize in Chemistry

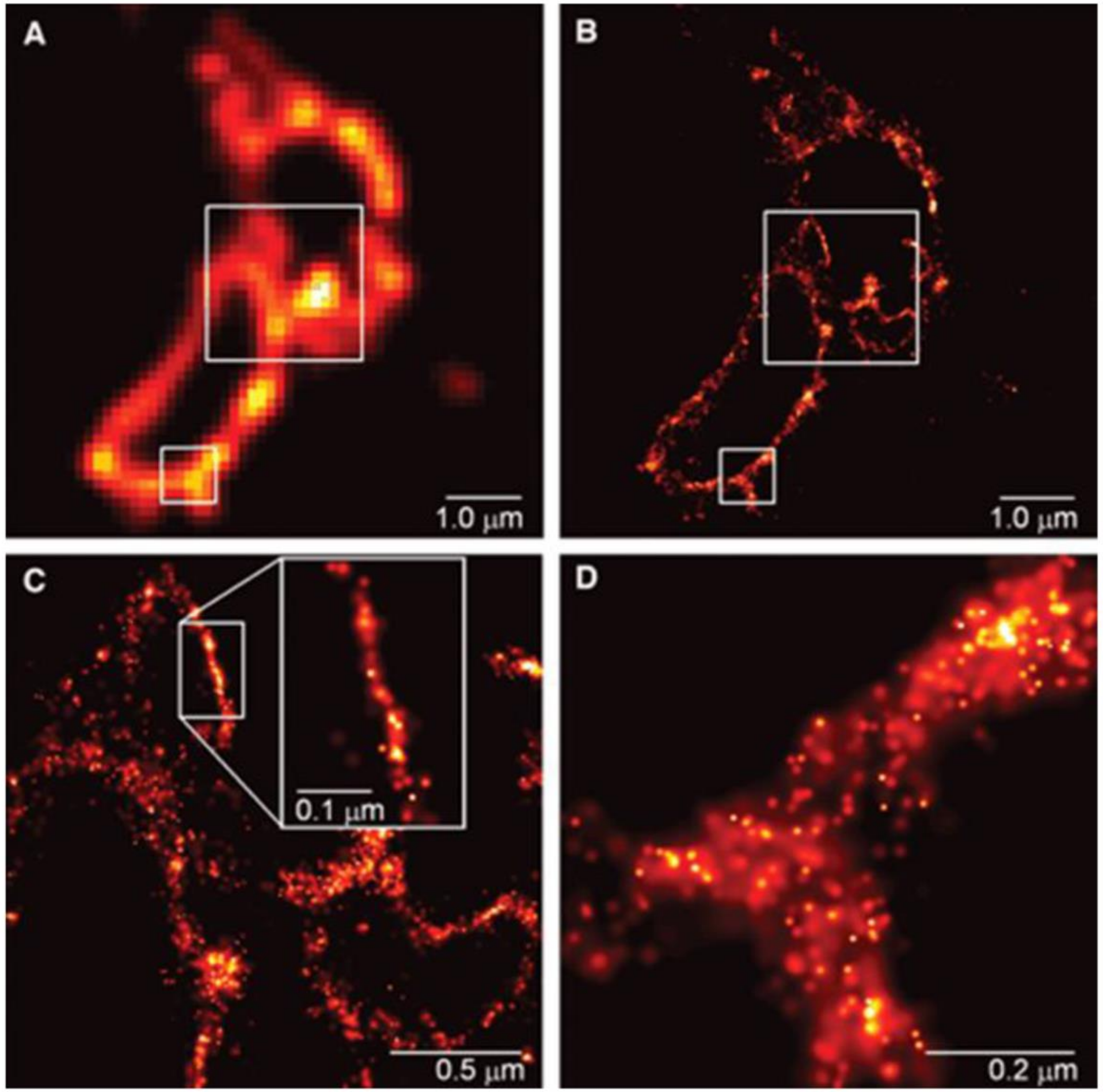
The Nobel Prize in Chemistry 2014 was awarded jointly to Eric Betzig, Stefan W. Hel William E. Moerner *"for the development of super-resolved fluorescence microscop*

- **Beyond diffraction limit concept**

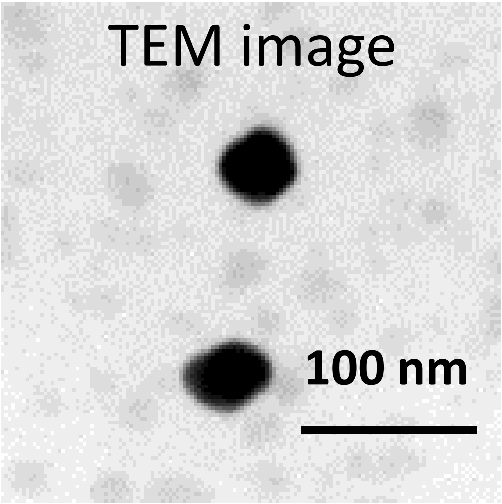
e.g., STED、STORM

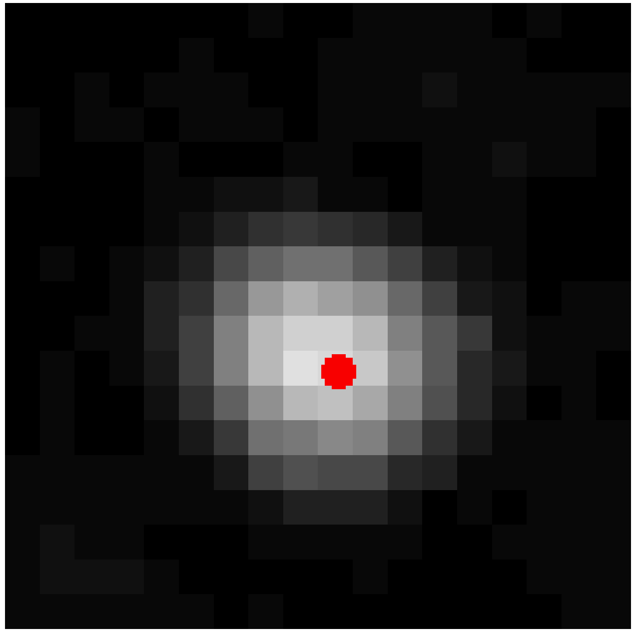


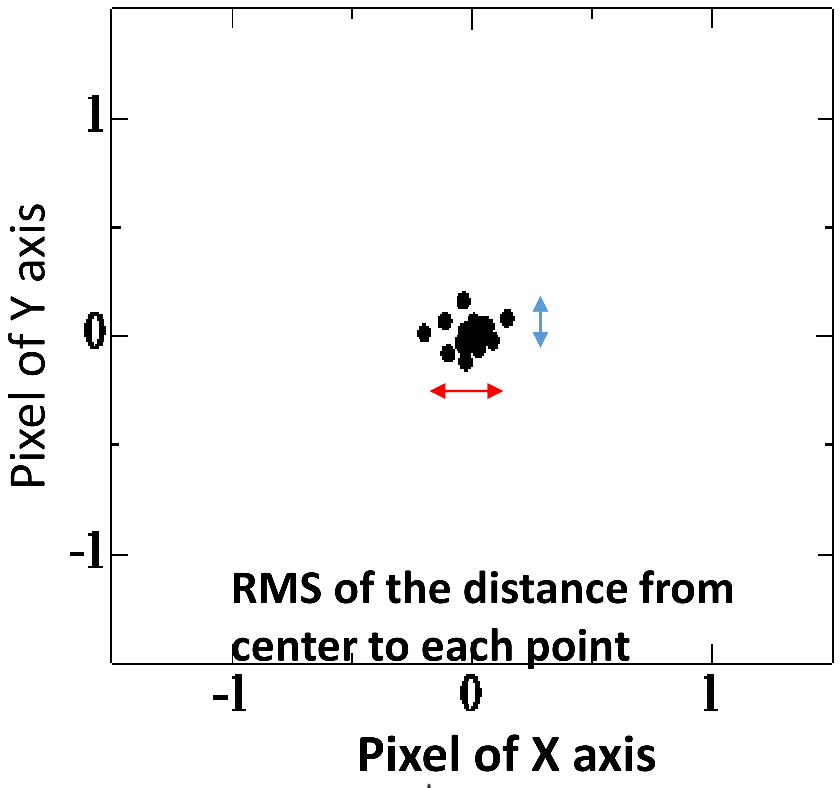


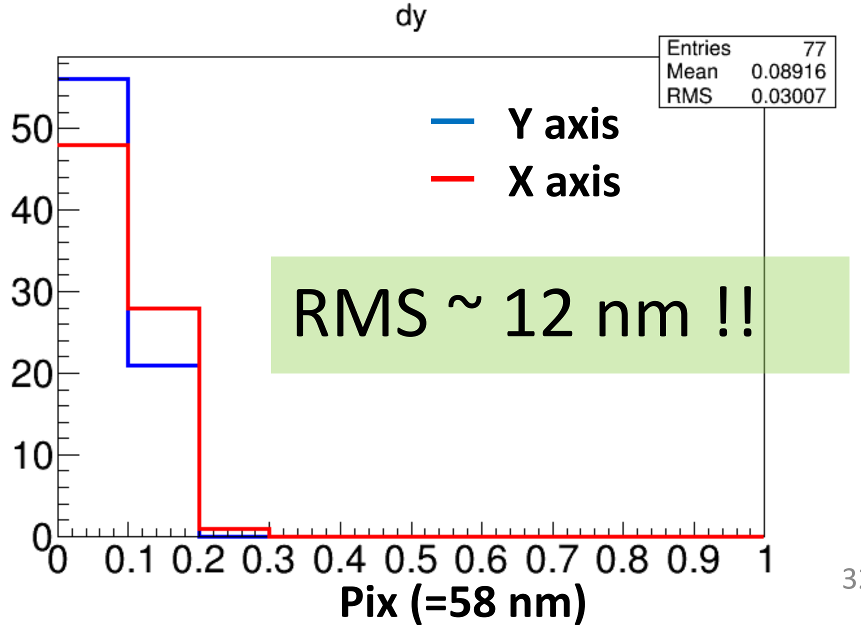


First demonstration





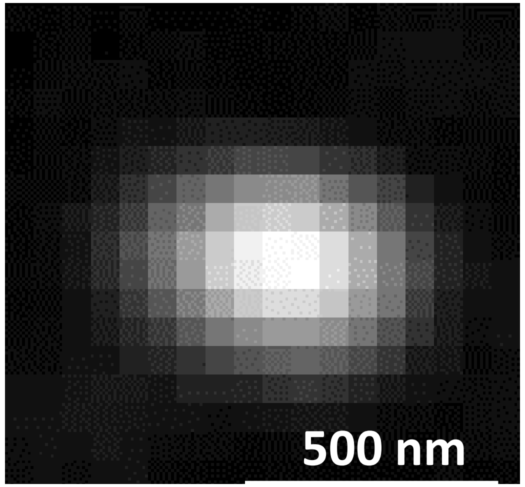




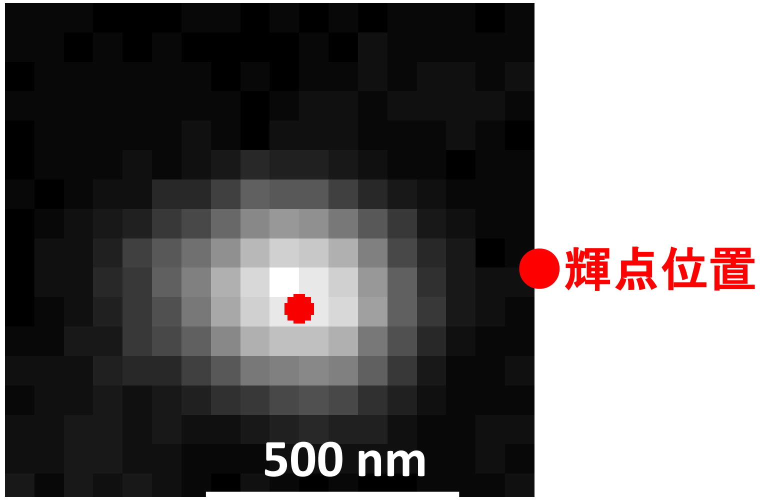
- **Calibration of position accuracy ~ spatial resolution using single Ag nano particle**

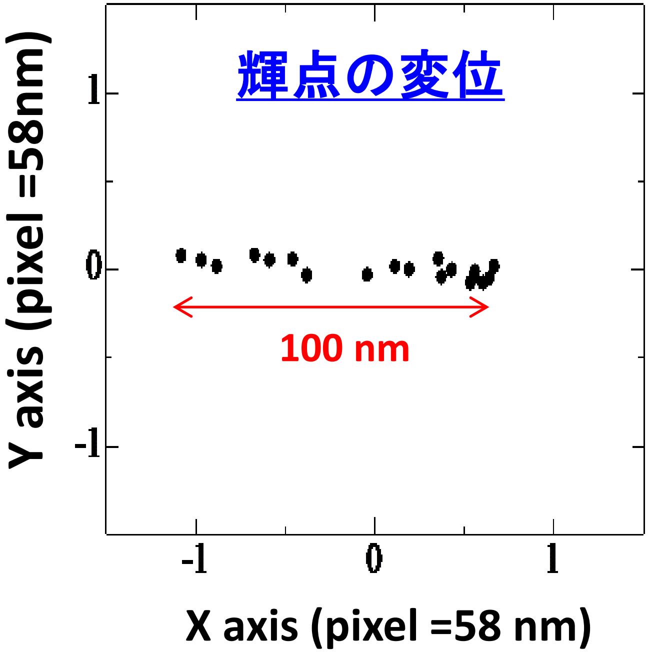
Demonstration of tracking to very short length tracks

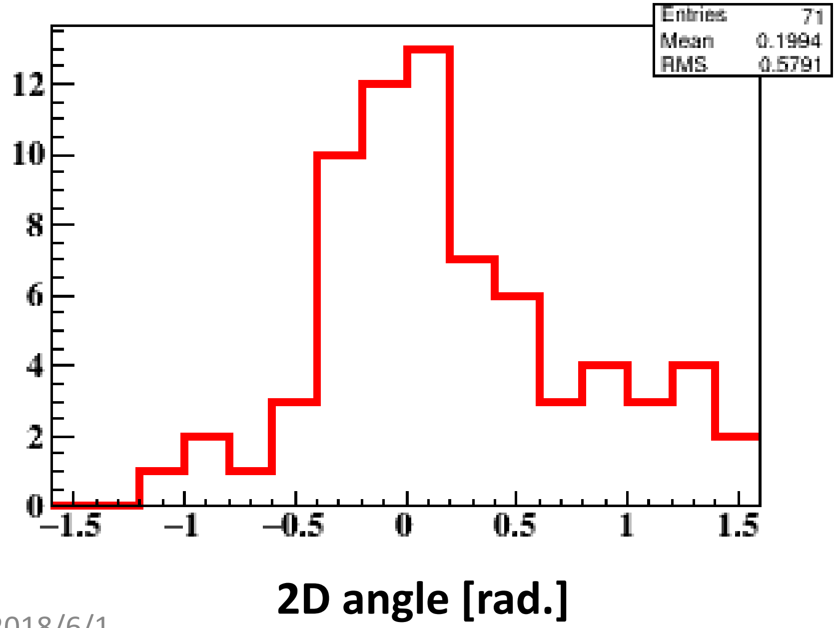
Carbon 100 keV　通常観察（λ=550 nm）



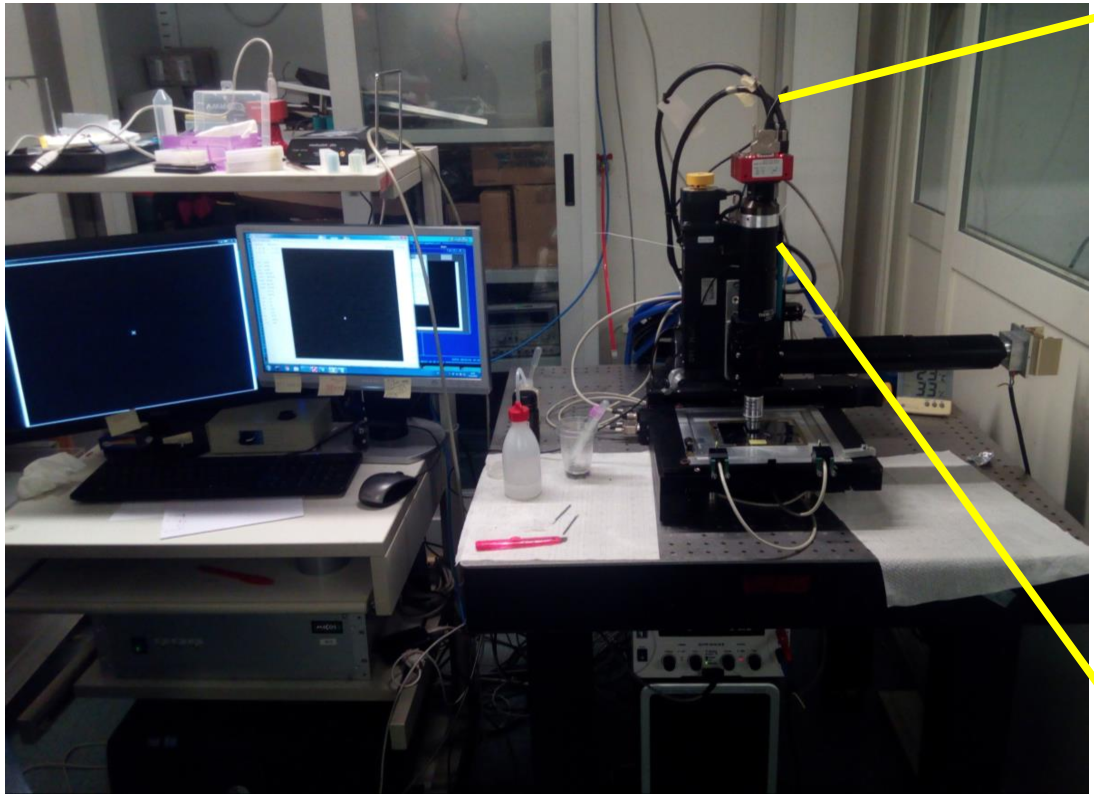
偏光観察（λ=550 nm + 偏光子回転）



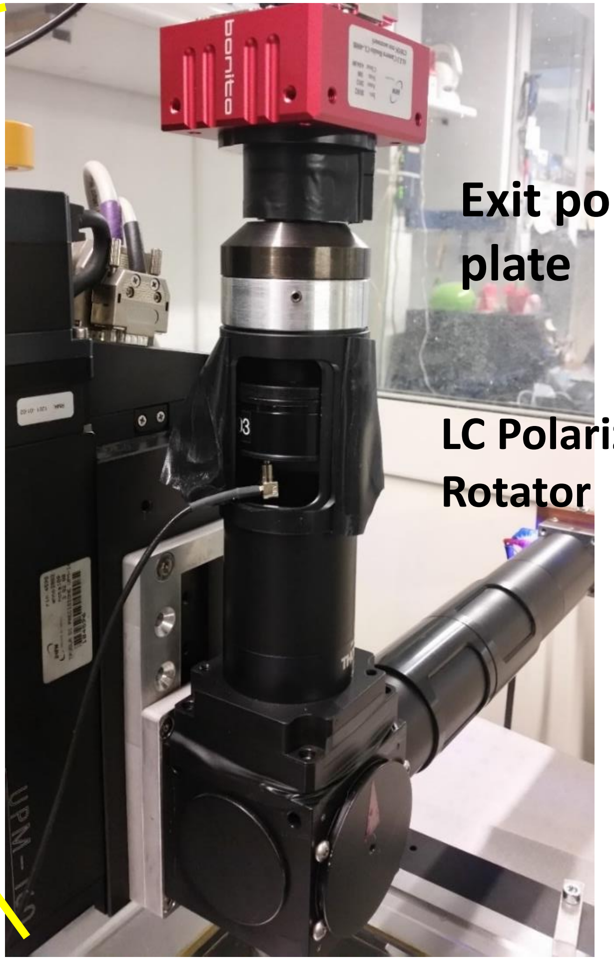




New plasmon nano-tracking system [prototype]

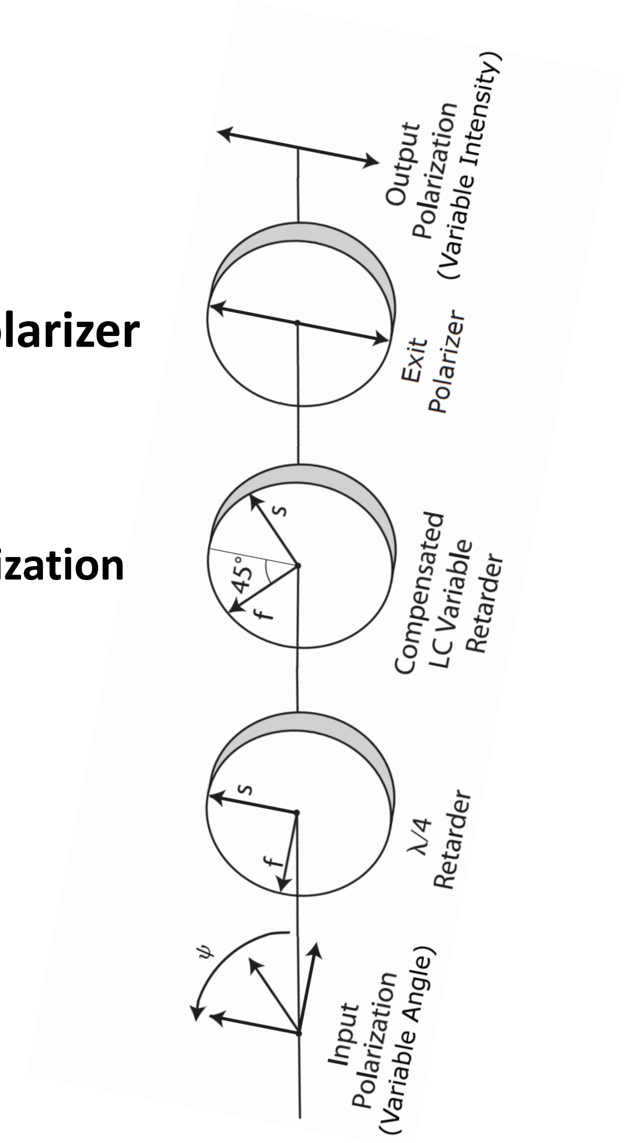


New epi-illuminated optical microscope system
@ Napoli University, Italy

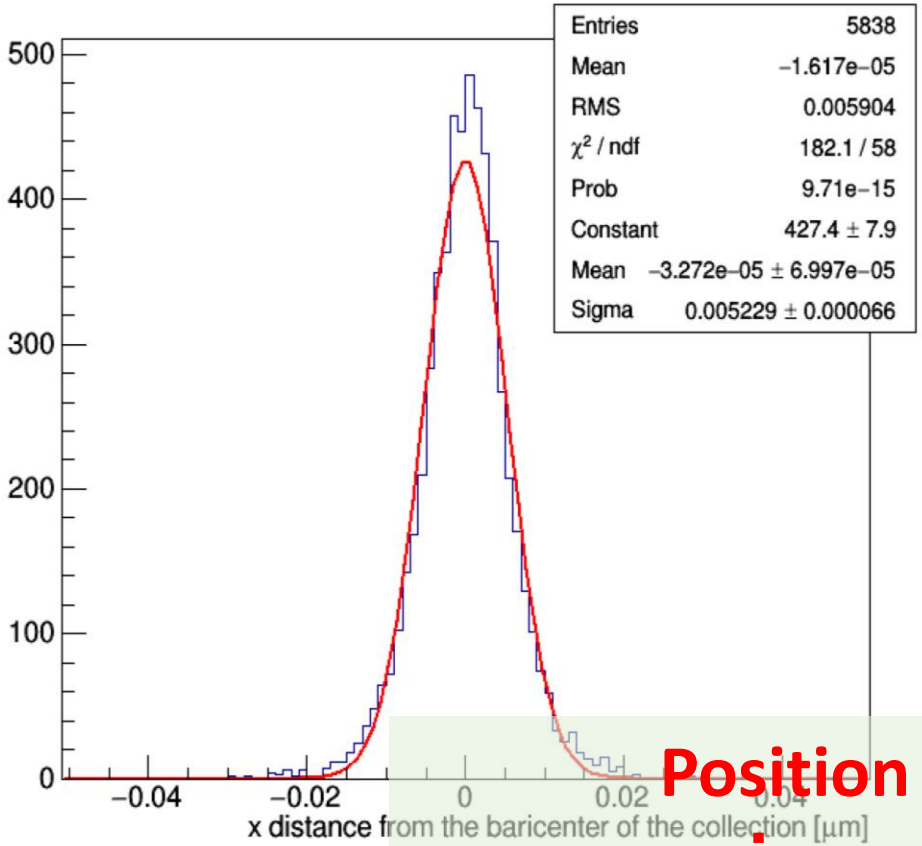


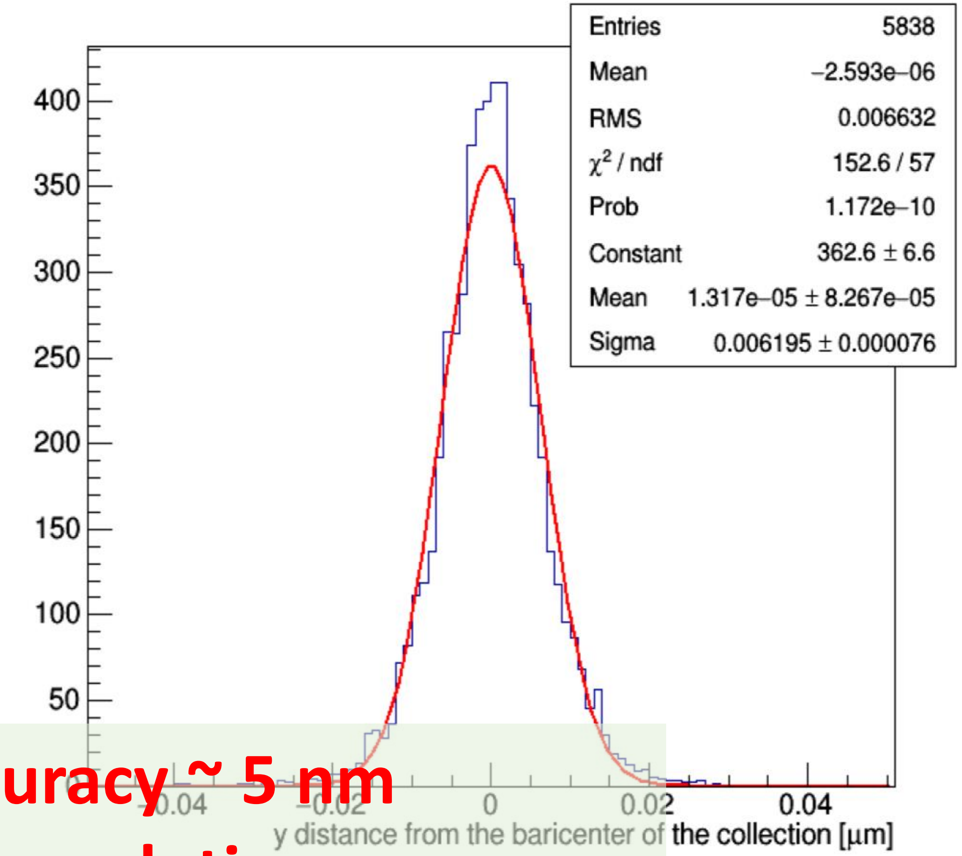
Exit polarizer plate

LC Polarization Rotator



Position accuracy for the plasmonic readout system



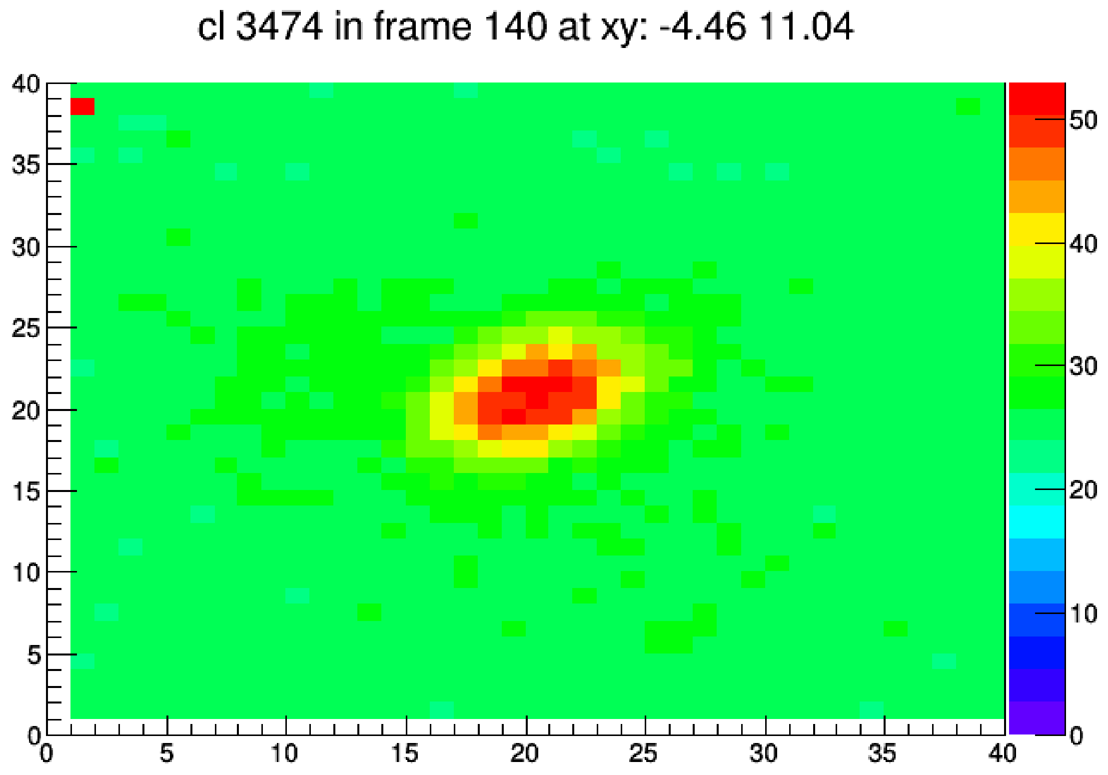


Position accuracy ~ 5 nm

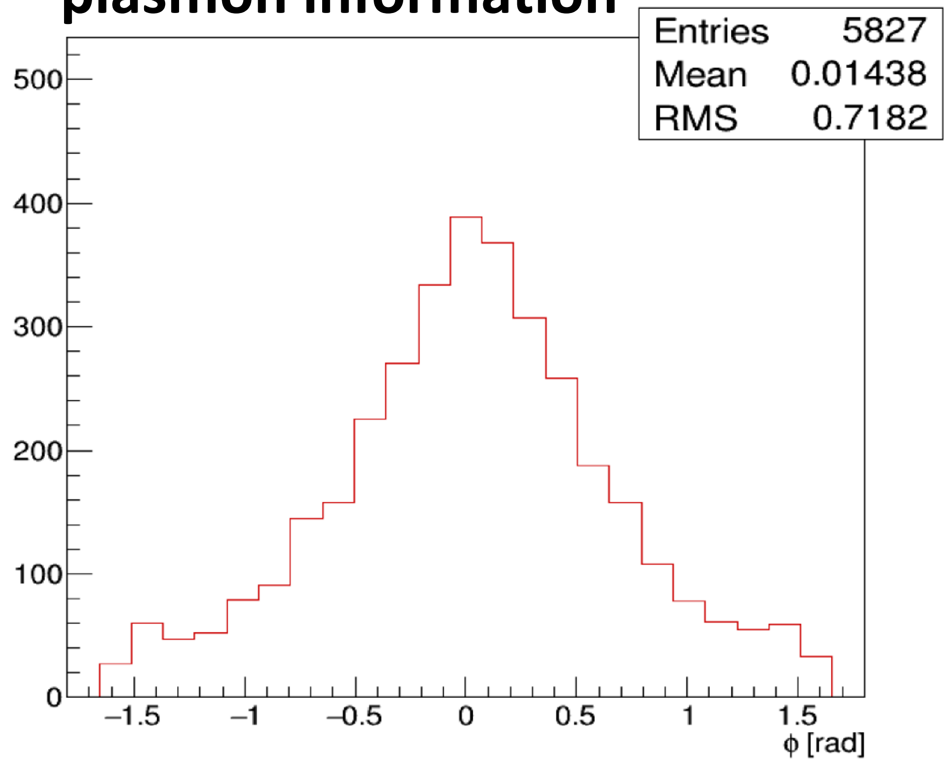
≒spatial resolution

※usual optical resolution > ～200nm

Automatic analysis system for the plasmonics



Angular distribution using only plasmon information



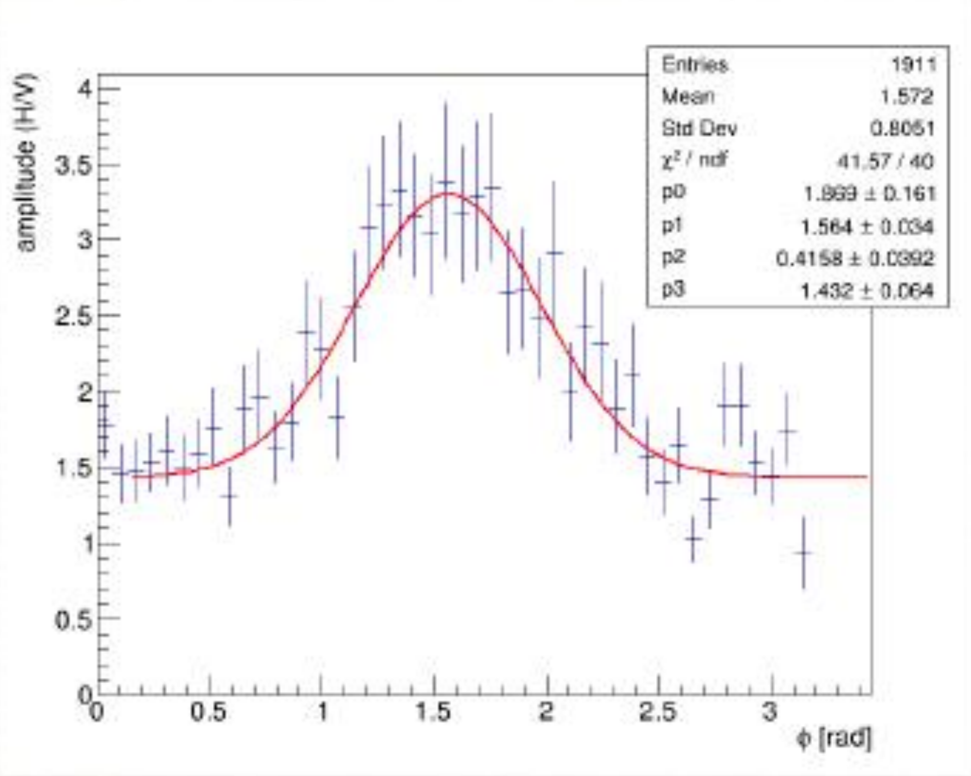
Demonstration of the direction sensitivity have been done .

Plasmon Analysis Updates

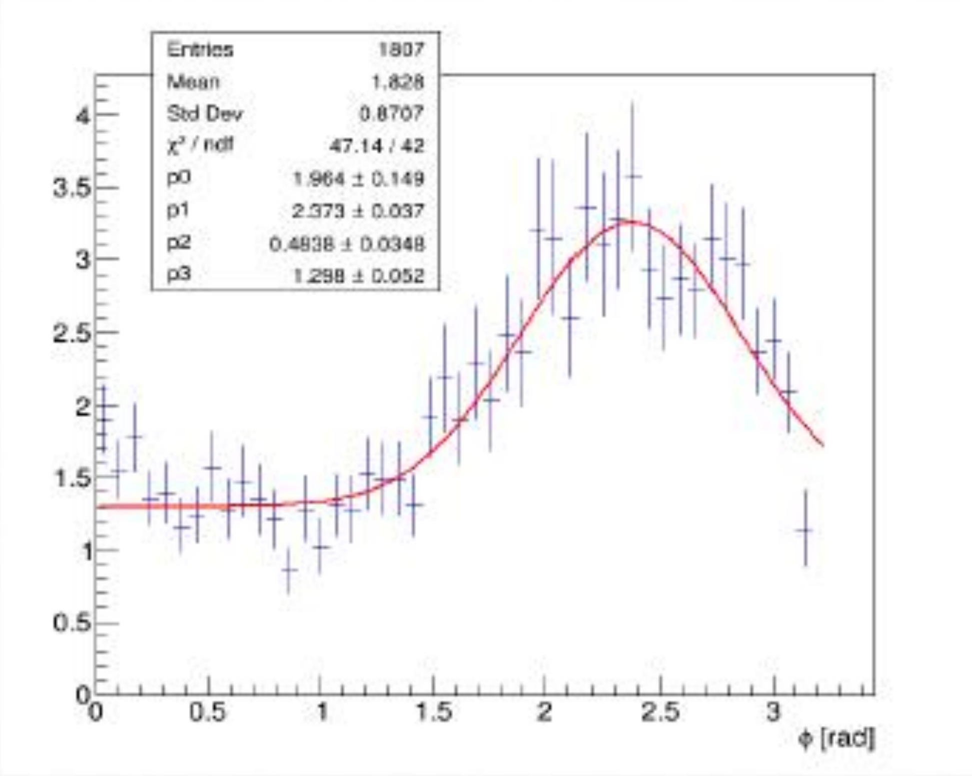
Preliminary

PDF Ratio between C 30 keV ion horizontal samples and vertical sample

Expected: 90° - Measured: 90°



Expected: 135° - Measured: 136°



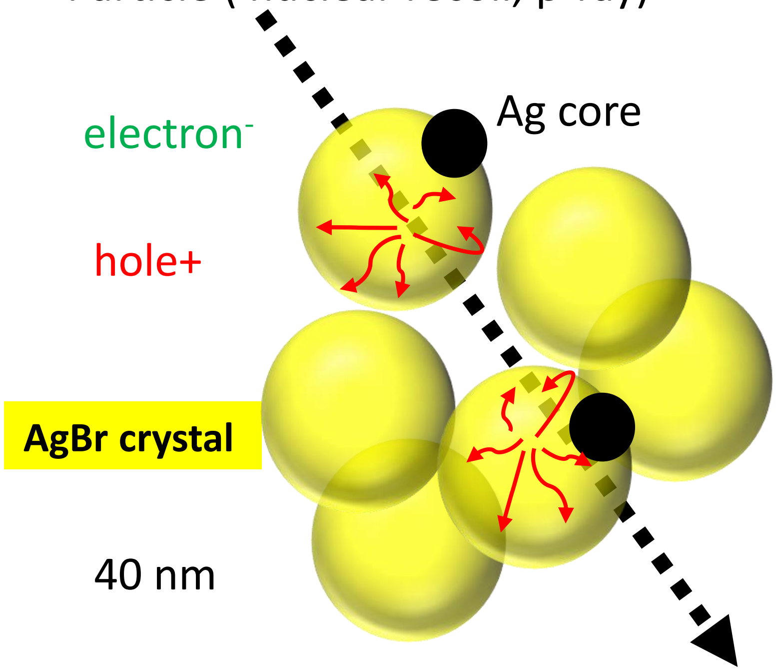
V. Gentile's slide in this meeting

Further new technlogies

- color information
- 3D nano-tracking
- Multi-variant analysis
- Machine learning
- Phase information
- Scintillation information from NIT emulsion

Quite new readout information and technologies with cutting-edge optics and technologies

β-ray event rejection potential



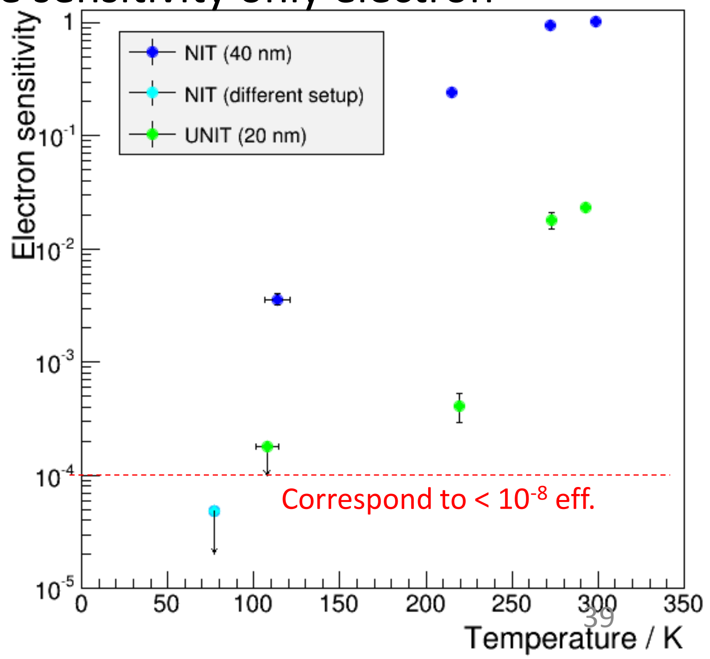
- **☐ Cryogenic crystal effect**
  - crystal quantum efficiency is drastically decrease by lower temperature
  - nuclear recoil is not by the thermal spike

⇒ 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)

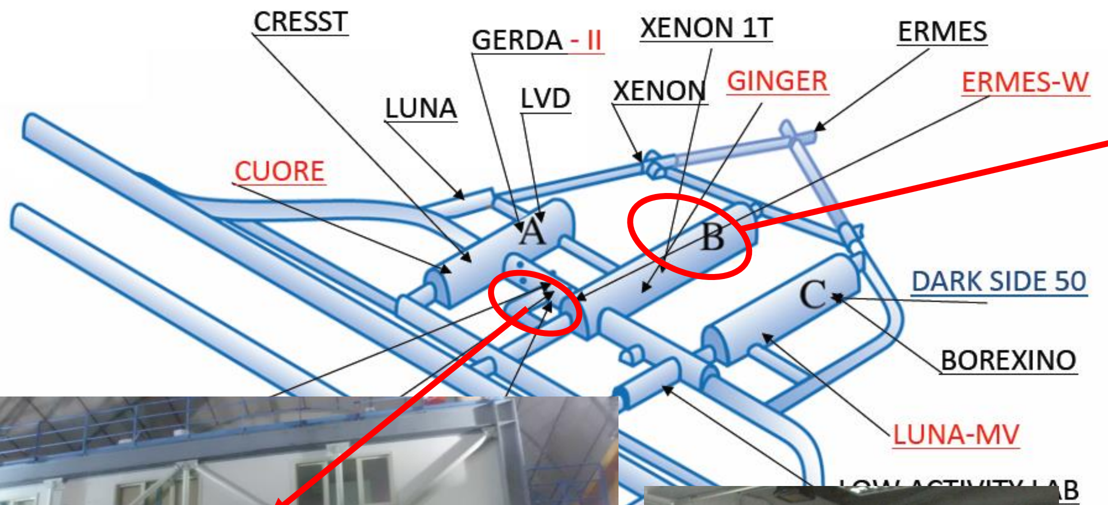


As potential, > 10^9 rejection power is expected by combination of some techniques

⇒ Now, constructing the calibration system in the LNGS

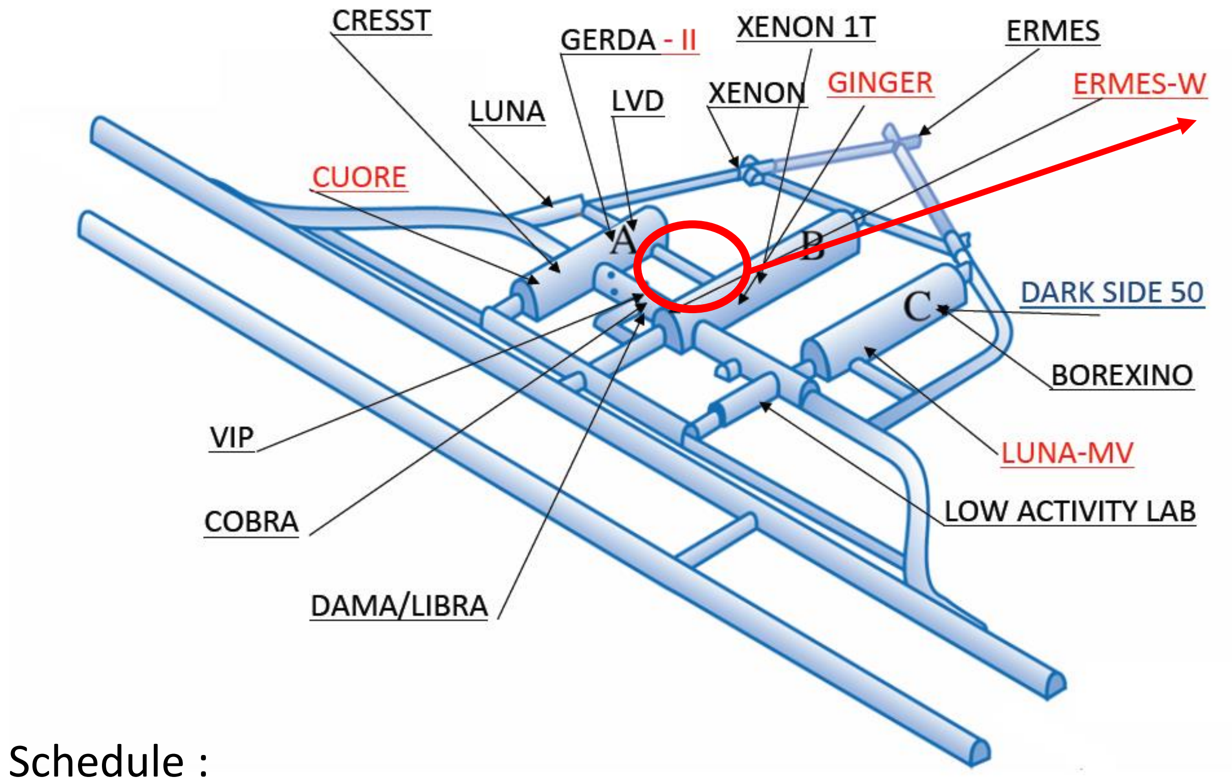
Pilot-run environment and shield

Gran Sasso underground laboratory, Italy



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

New site for NEWSdm experiment at LNGS



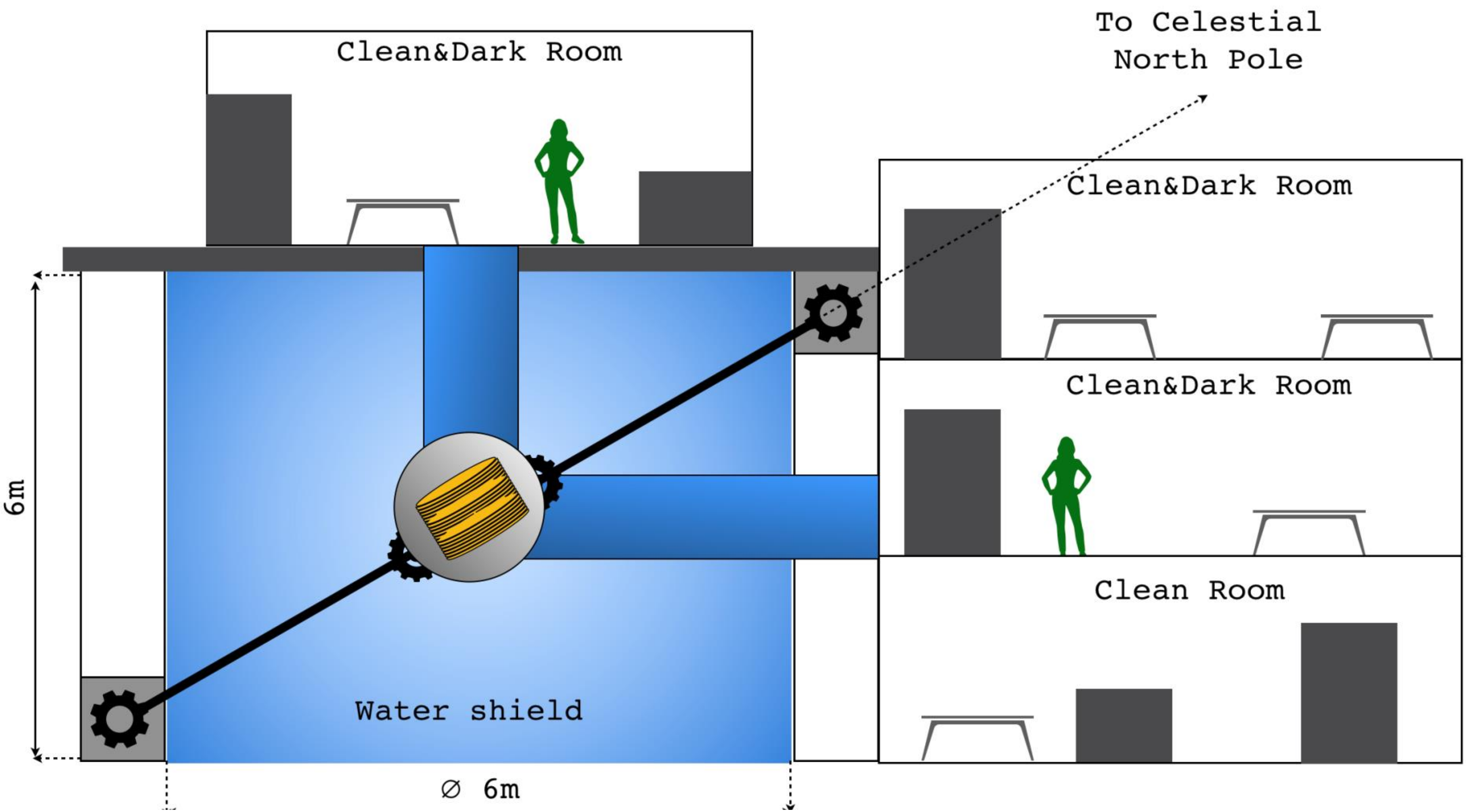
Schedule :

~ Dec. 2017 : construction of the hall

~ April. 2018 : construction of inside the hall and infrastructure

May – August , 2018 : install the new emulsion production machine

~ Sep., 2018 : commissioning of facility and background run



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

Conclusion

- **Dark matter is one of the most important subject in nature science**
- **ΛCDM model is concordance in cosmology, and CDM as WIMP is very promising candidate**
- **Recent observation (e.g., DAMA/LIBRA, H21cm) may have proof that non-zero DM-baryon interaction (around 10^{-42} cm^2)**
- **Super-fine grained nuclear emulsion (Nano Imaging Tracker : NIT) is the highest resolution detector in the world, and very promising detector for direction-sensitive dark matter detection**
- **NEWSdm project is very unique experiment toward directional dark matter search**
- **Quite new technologies continue producing as "nano-tracking technologies"**

Low-energy frontier will be very interesting from now, not only high energy physics