NEWSdm experiment

Directional Dark Matter Search with Super-high resolution Nuclear Emulsion

Tatsuhiro NAKA

KMI, Nagoya University

on behalf of NEWSdm collaboration

Feb., 18-20 (presentation 18th), 2019 KMI2019 @ ES hall, Nagoya University

Dark Matter in our galaxy

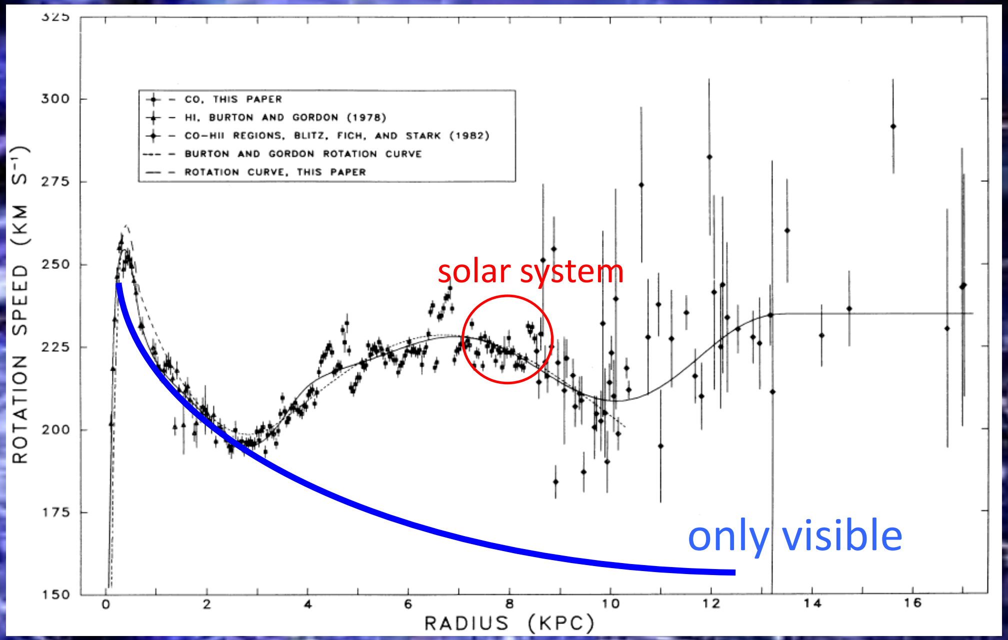
Center of galaxy

Local dark matter density : 0.4 +- 0.1 GeV/cm^3

- ✓ **Independent value 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)**

Solar system

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



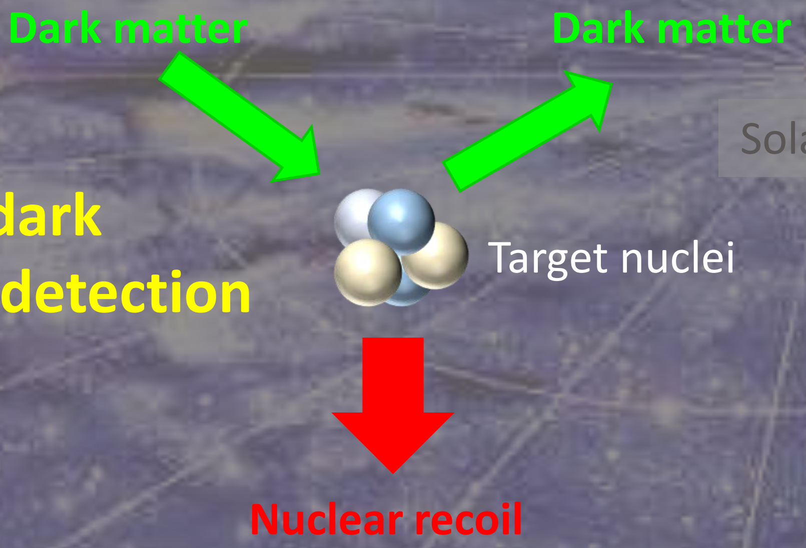
Astrophys. J. 295: 422-436, 1985

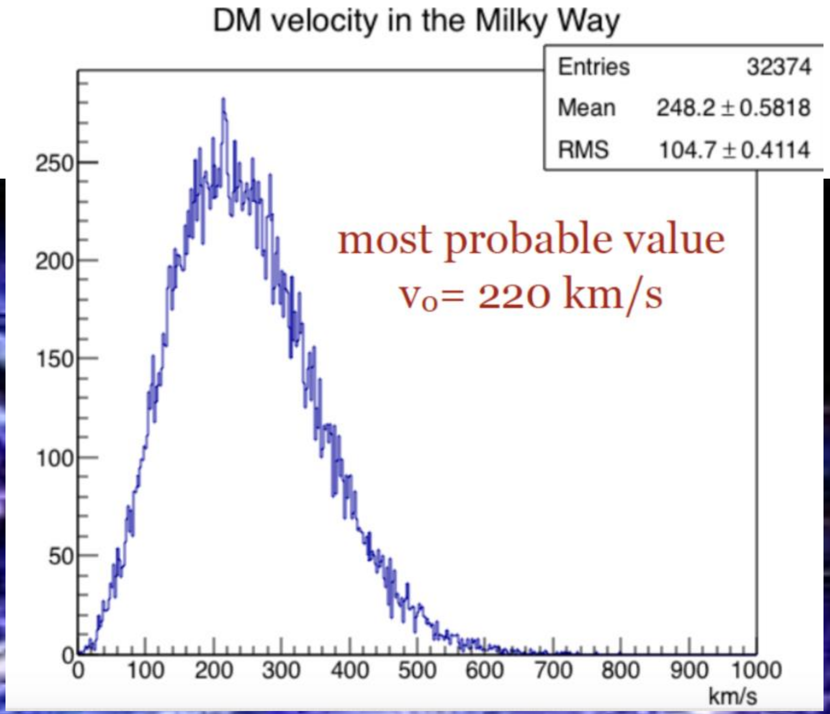
Direct Dark Matter Search

Standard dark matter model

- ☐ Maxwell-Bolzman distribution
- ☐ Weakly interaction with standard particles
- ☐ Nuclear recoil signal

WIMP dark matter detection



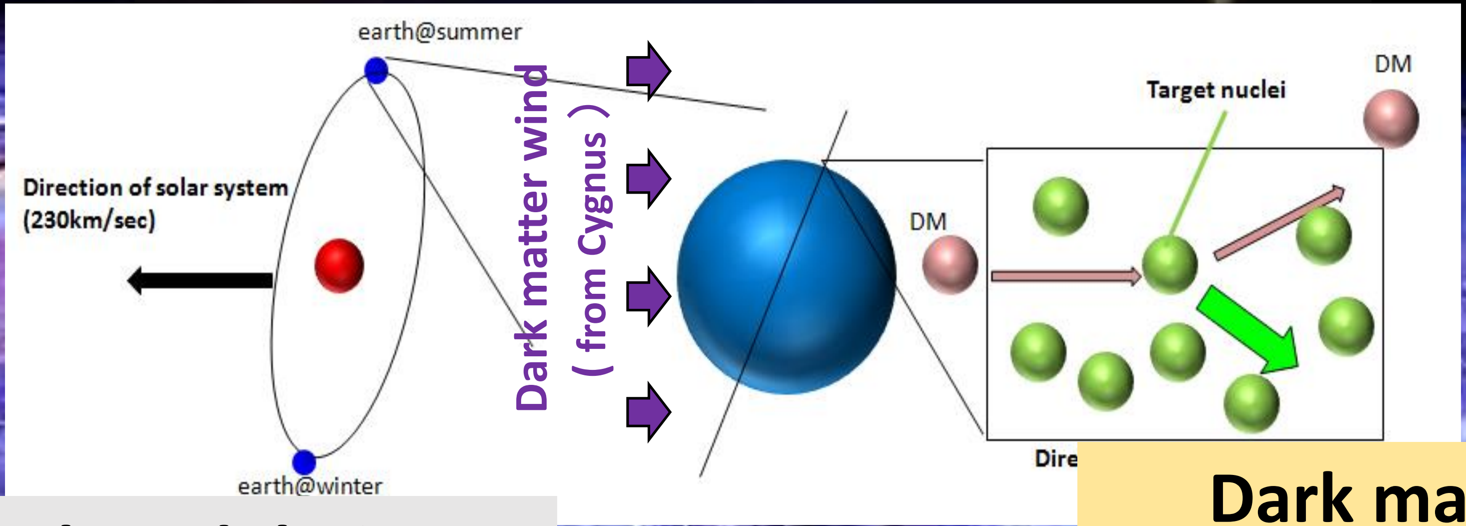


$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{\rho_\chi}{m_\chi}\int_{v_{min}}^{v_{max}} \mathrm{d}^3v\ f(\vec{v})v\frac{\mathrm{d}\sigma(\vec{v},E_R)}{\mathrm{d}E_R}$$

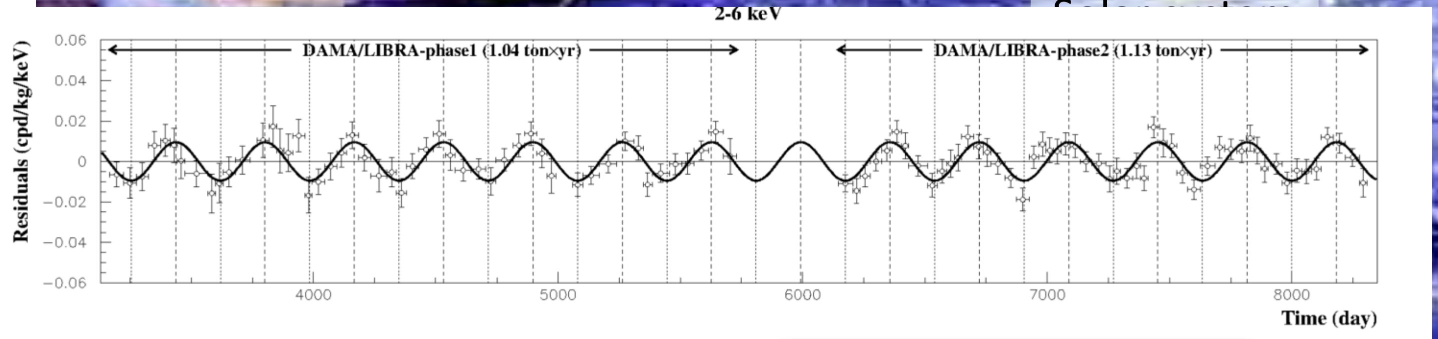
- **How to interact with standard particles**
- **Spin-dependent or independent ?**
- **Material dependence**
- **Velocity distribution**

Direct Dark Matter Search

Direct dark matter search

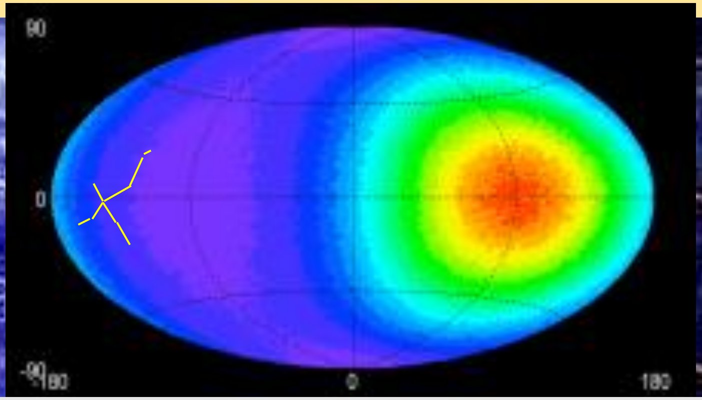


Annual modulation



- DAMA/LIBRA : 2.46 ton・y, 12.9σ
- (Nucl. Phys. At. Energy 19 (2018) 307-325)
- Some groups : no significant observation

Dark matter wind



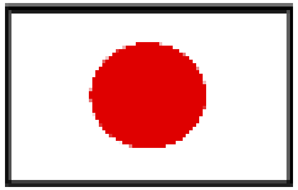
- ☐ Anisotropic signal for angular distribution
- ☐ Actively observation with lower statistics
- ☐ Currently technical R&D is needed

NEWSdm experiment
[Nuclear Emulsion for WIMPs Search – directional measurement]

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

<u>LOI under review by the LNGS science committee</u>

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



Chiba
Nagoya

METU Ankara

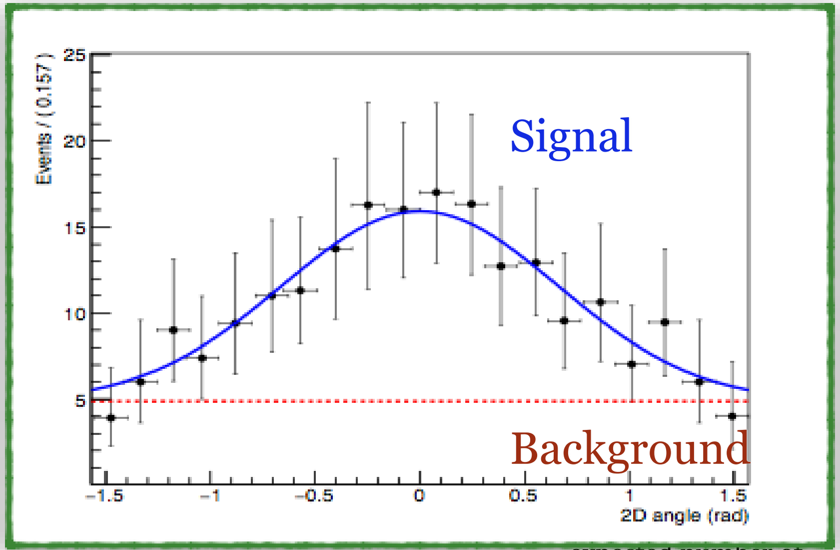
Bari
GSSI
LNGS
Napoli
Roma

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

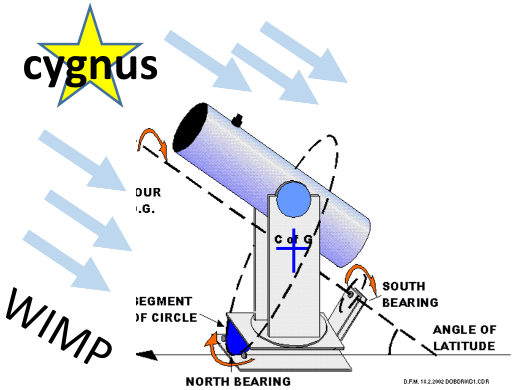
Gyeongsang

https://arxiv.org/abs/1604.04199

Potential of Directional Sensitive Search



N. Agfanova *et al.* (NEWSdm collaboration)
Eur. Phys. J. C (2018) 78: 578



expected number of WIMP events

expected number of background events

signal pdf

background pdf

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

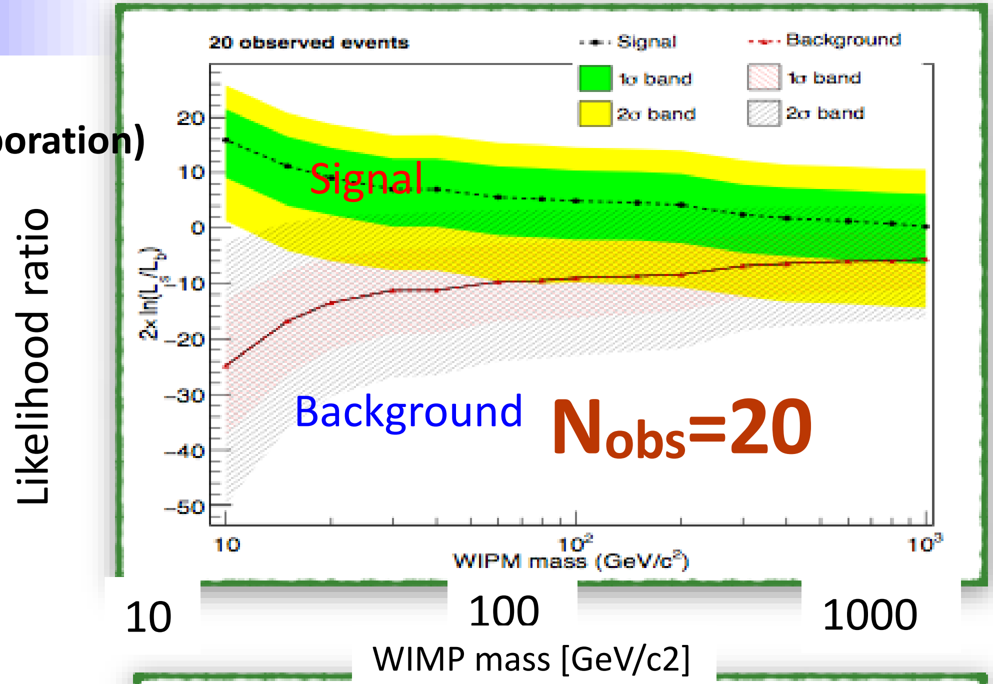
total number of observed events

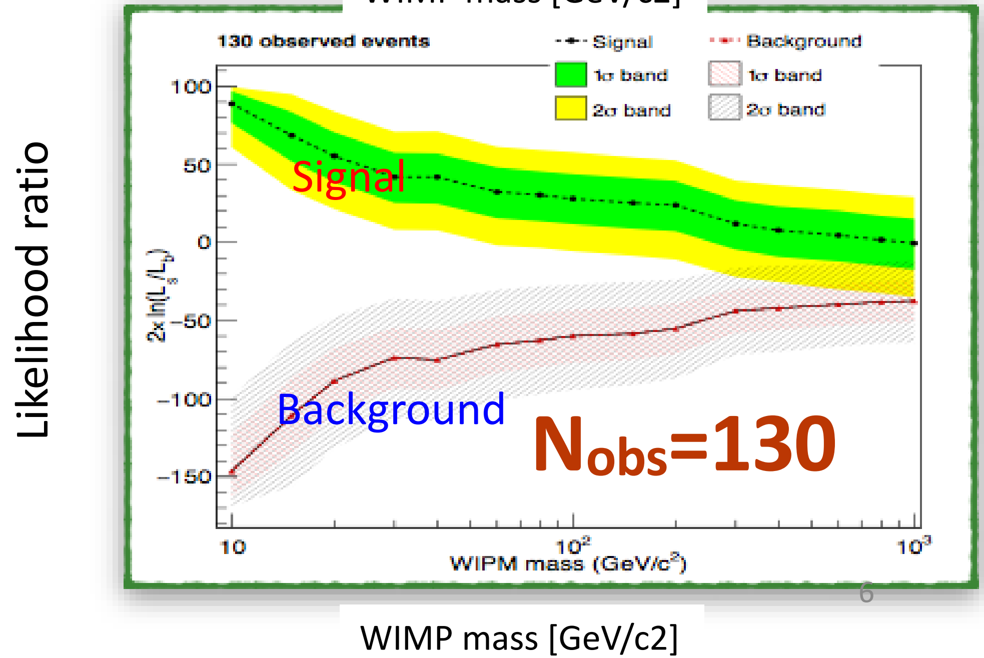
set of observables

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

Gain of 100 times

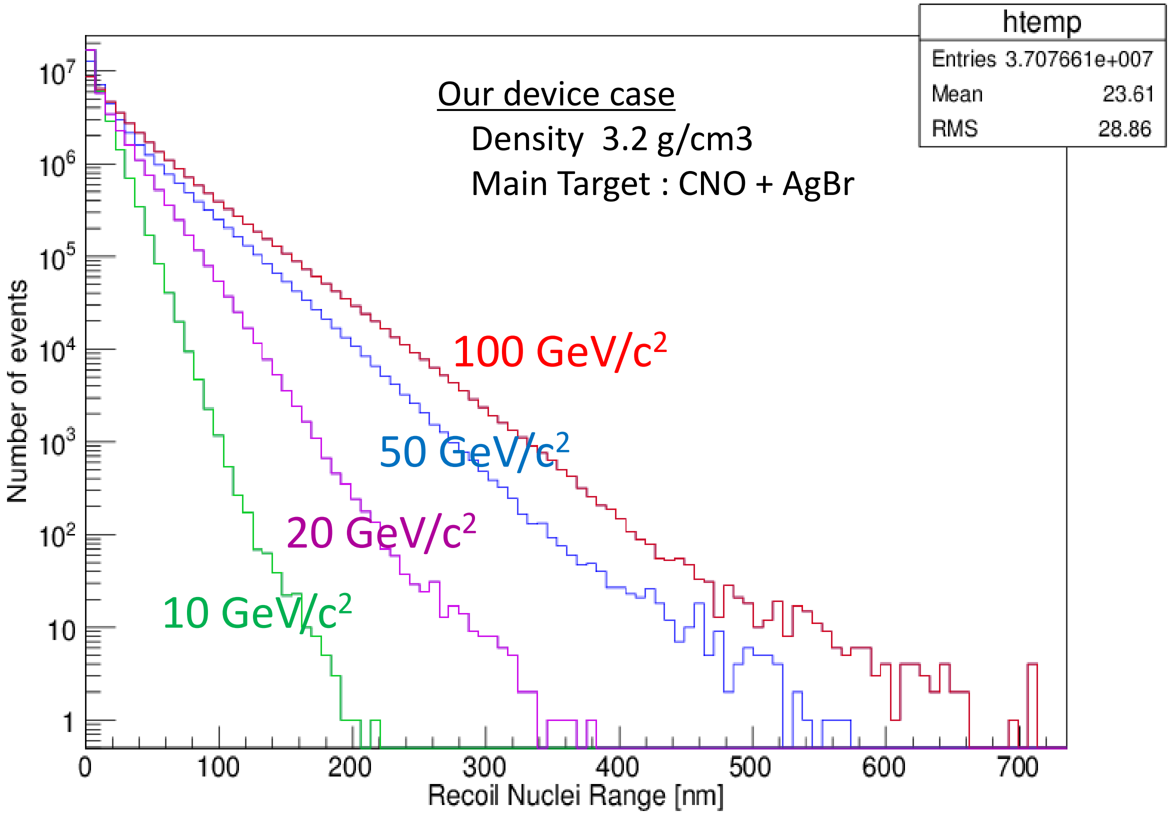
<u>Annual modulation : Several 1000 events</u>





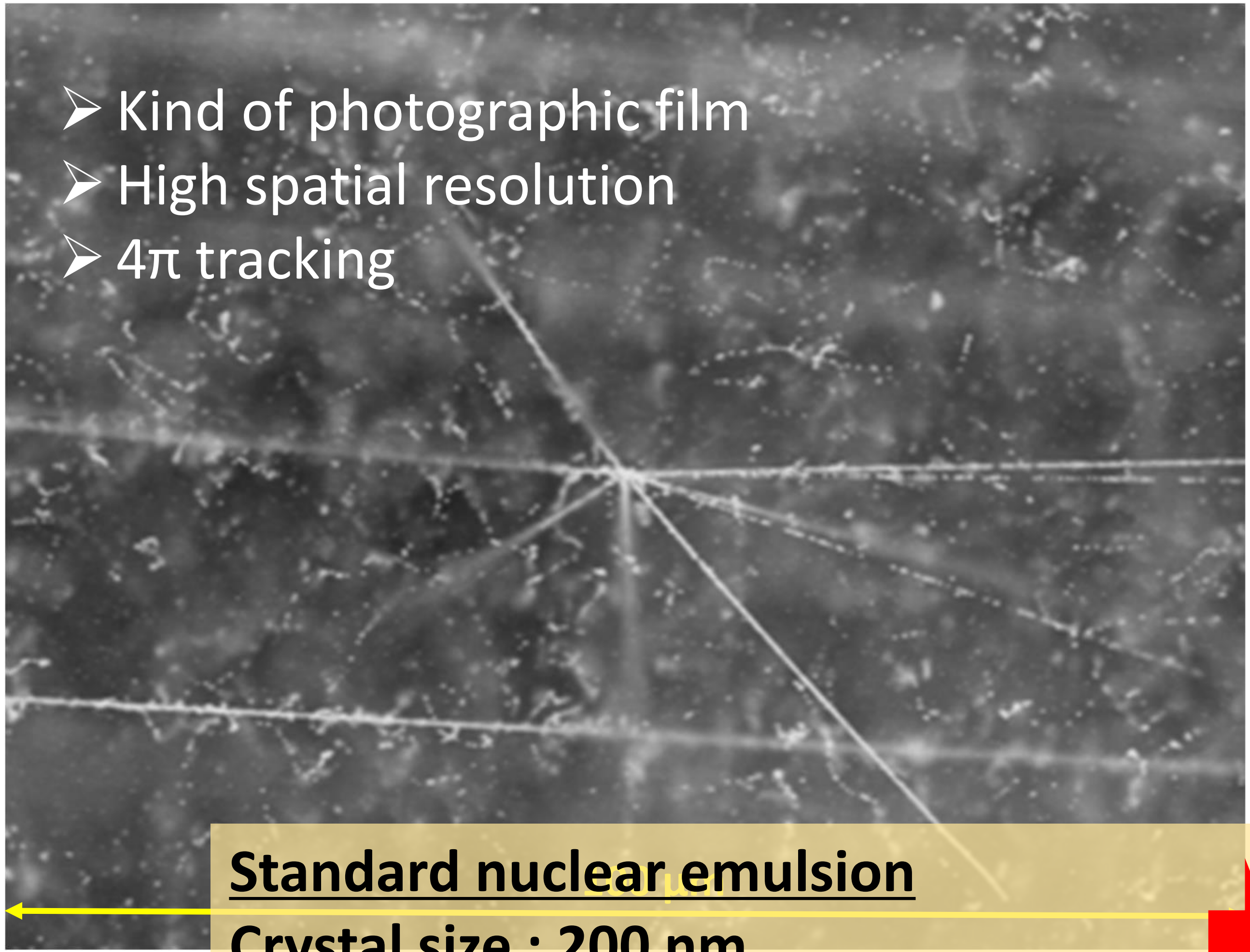
R&D Challenges for NEWSdm project

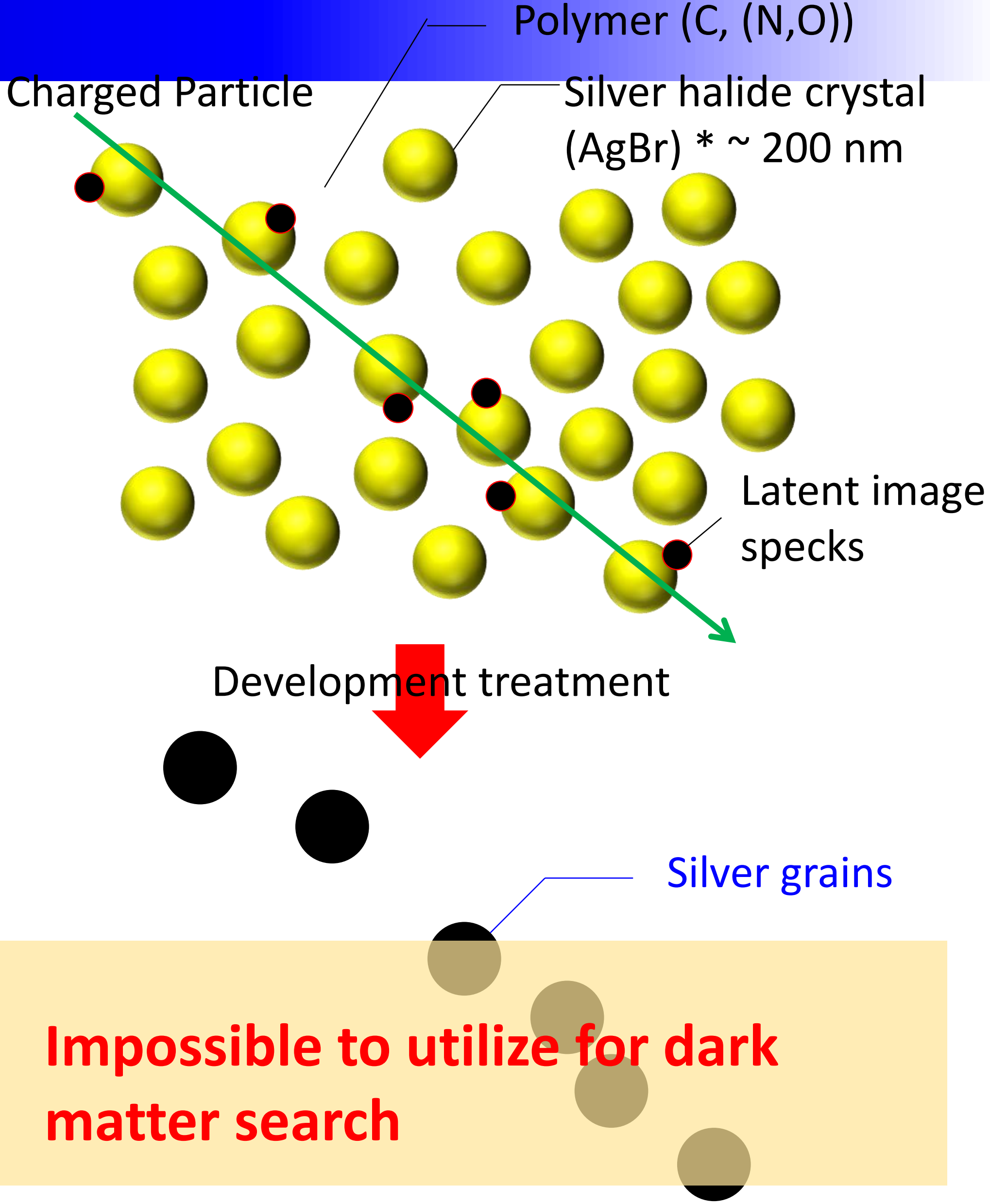
- Super-high resolution device using capability of detecting nano-scale tracl
- Readout technologies for such very short length tracks
- Understanding and rejection of backgrounds



Nuclear Emulsion Device

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



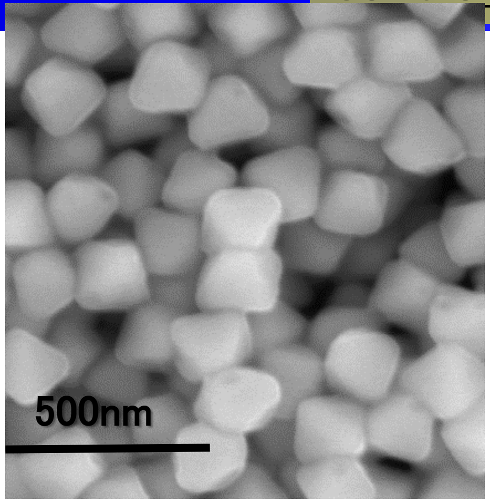


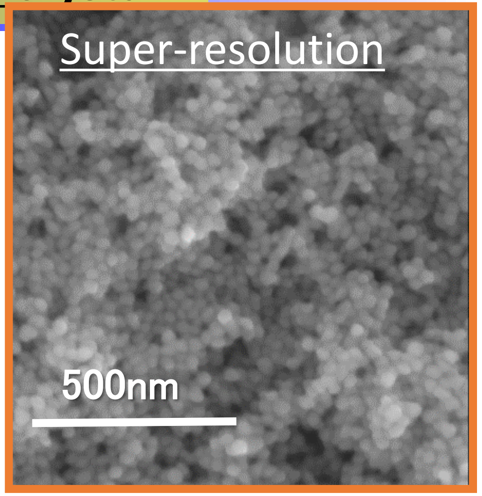
Standard nuclear emulsion
Crystal size : 200 nm
Detectable track length : > O(1) μm

Impossible to utilize for dark matter search

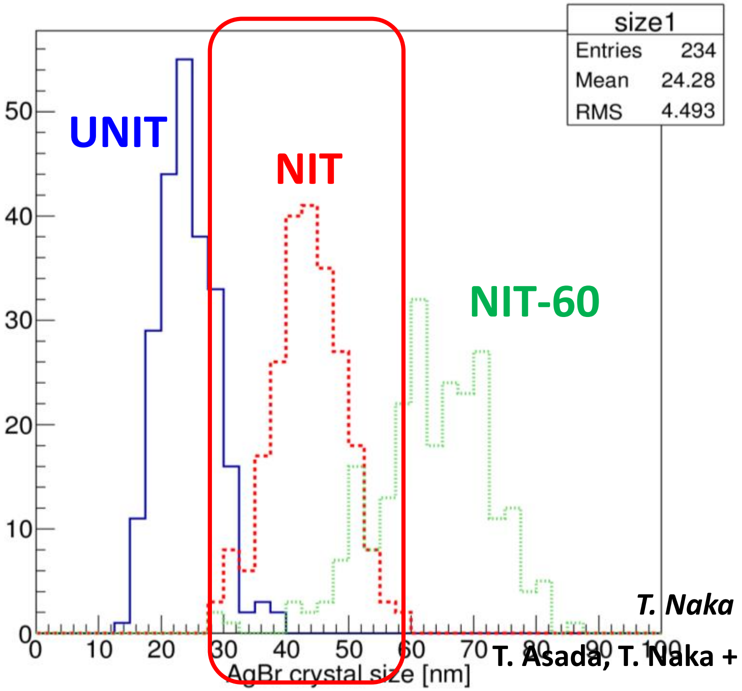
Nano Imaging Tracker(NIT)

Controlled AgBr crystal





・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.



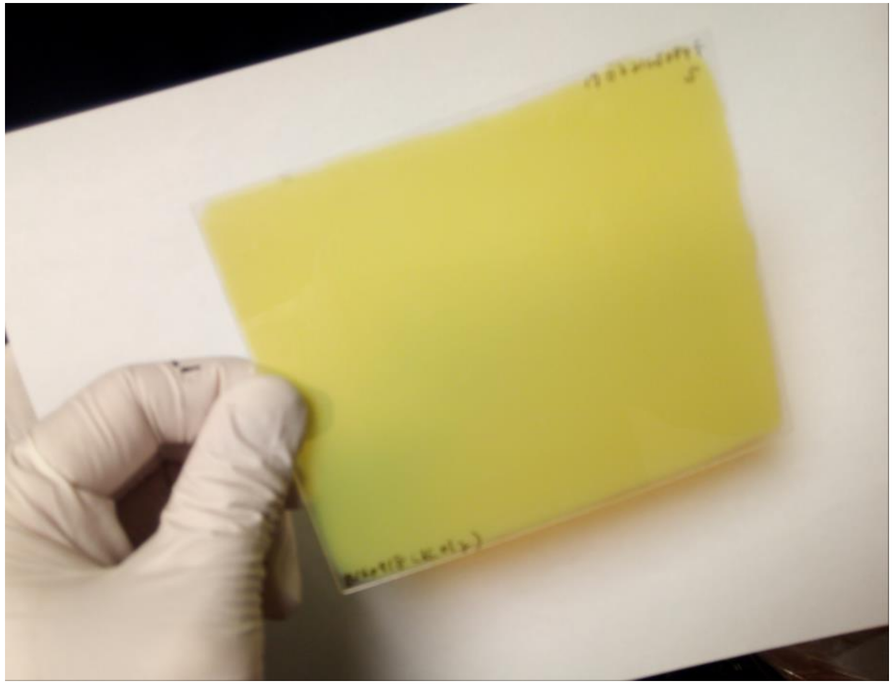
Current standard Device :
Nano Imaging Tracker [NIT]
crystal size : 44 nm

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

Low-velocity ion tracking with sub-micron length

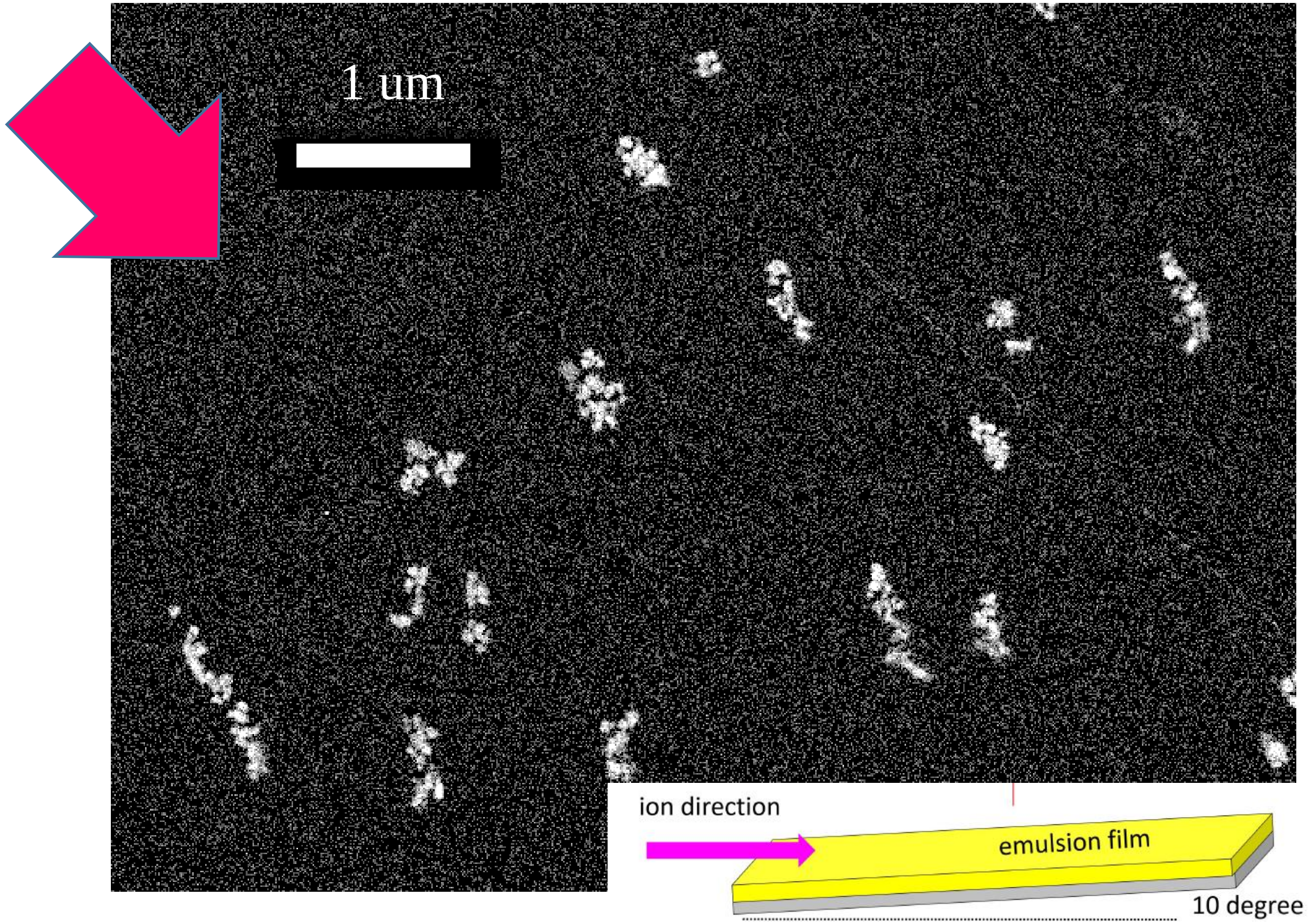
Can use ion implantation as calibration source

- Mono energy (±0.1 keV)
- Good direction uniformity (<10 mrad)
- Now, C from CO_2・Ar, Kr

(various kind ions are also possible)

Low velocity ion created by an ion-implantation system at Nagoya University

SEM image of low-velocity Carbon ion (100keV)

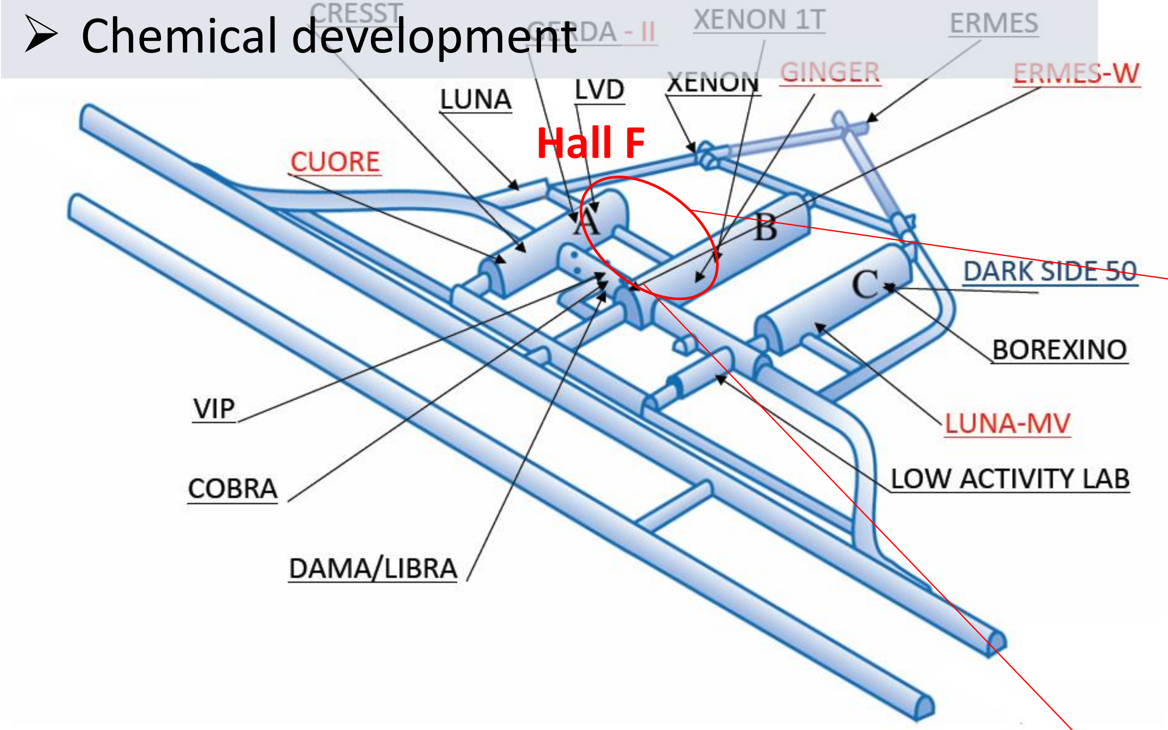


AgBr crystal has good sensitivity for Carbon ions (100 % consistent detection possibility)

Underground laboratory at LNGS

New Underground facility concept

- Device self-production in underground
- Film making
- Chemical development



Exposure site

Device Production facility

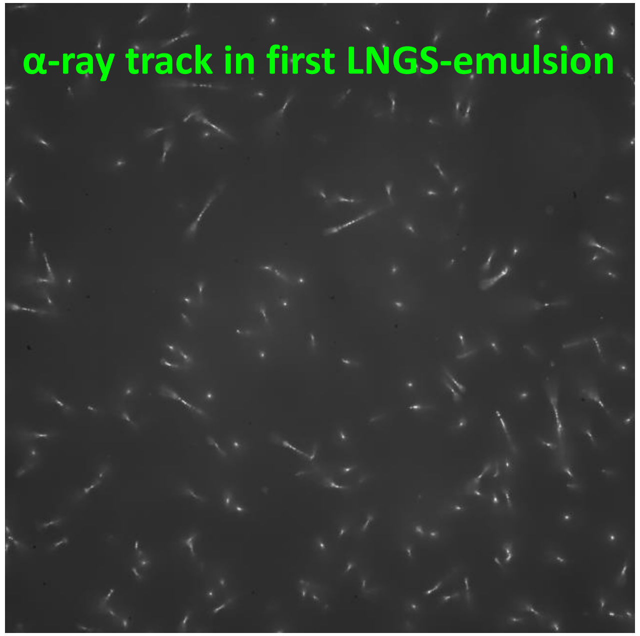
New production machine

New Underground emulsion facility

Feb. 2018 ~ : started construction and commissioning of the production machine at Nagoya (⇒ transported to LNGS from Sep. 2018)

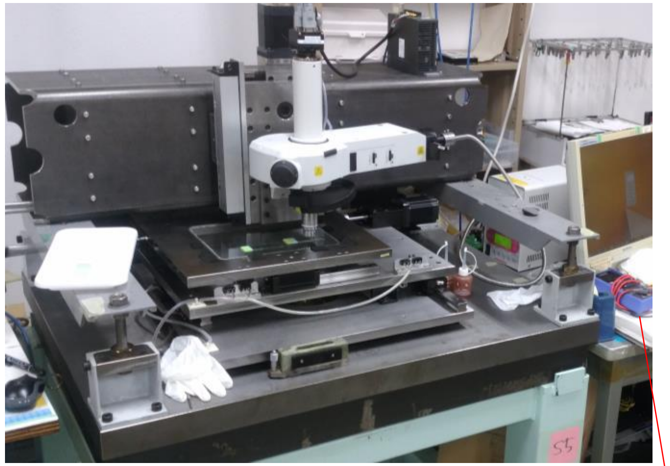
Feb. 2019 ~ : Started test production first time at underground
+ clean room and other infrastructure are on constructing

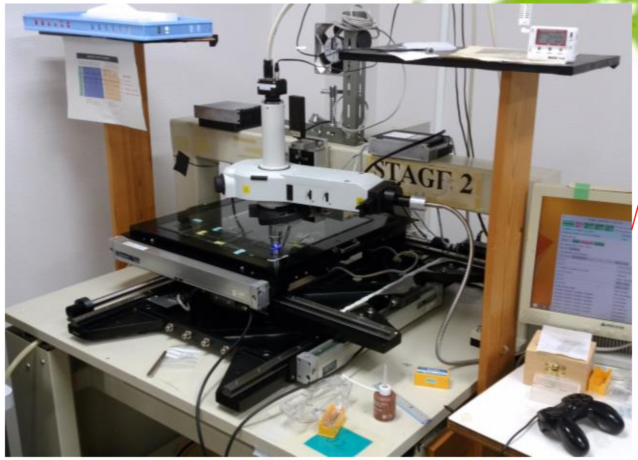
Up to April : overall confirmation of underground emulsion facility with clean room

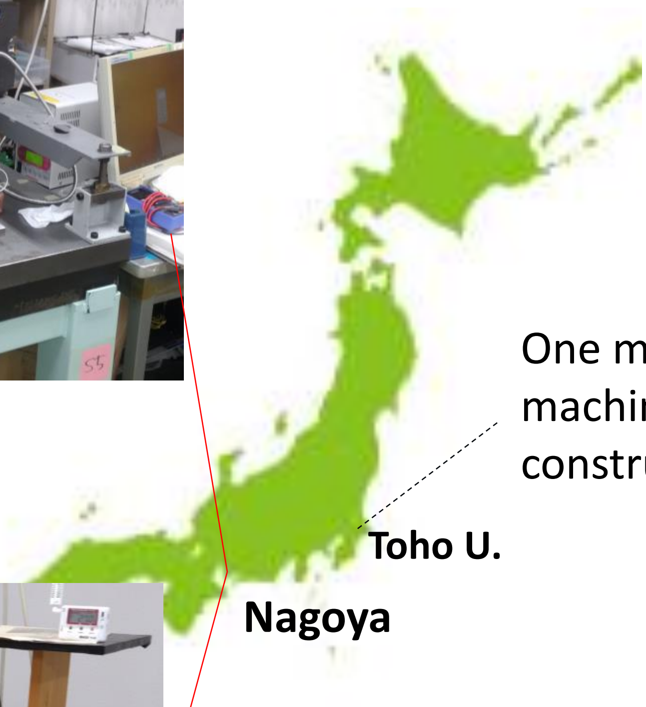


First production in LNGS succeeded !!

Readout technologies



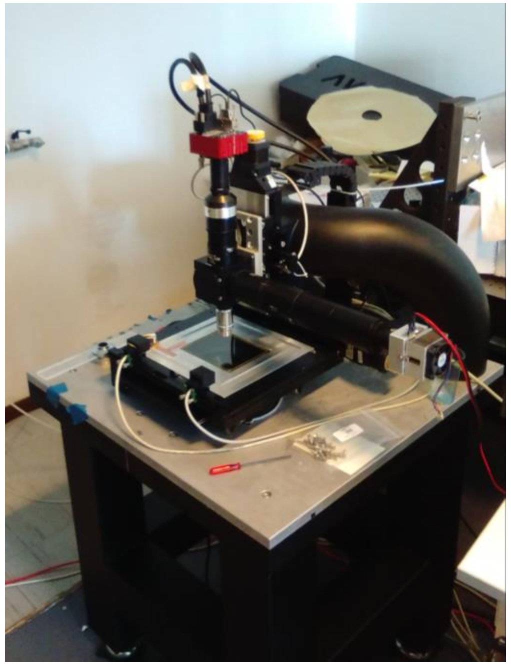




One more machine will be constructed

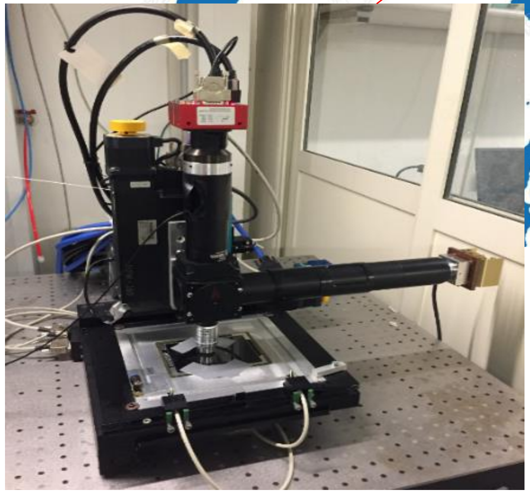
Toho U.

Nagoya



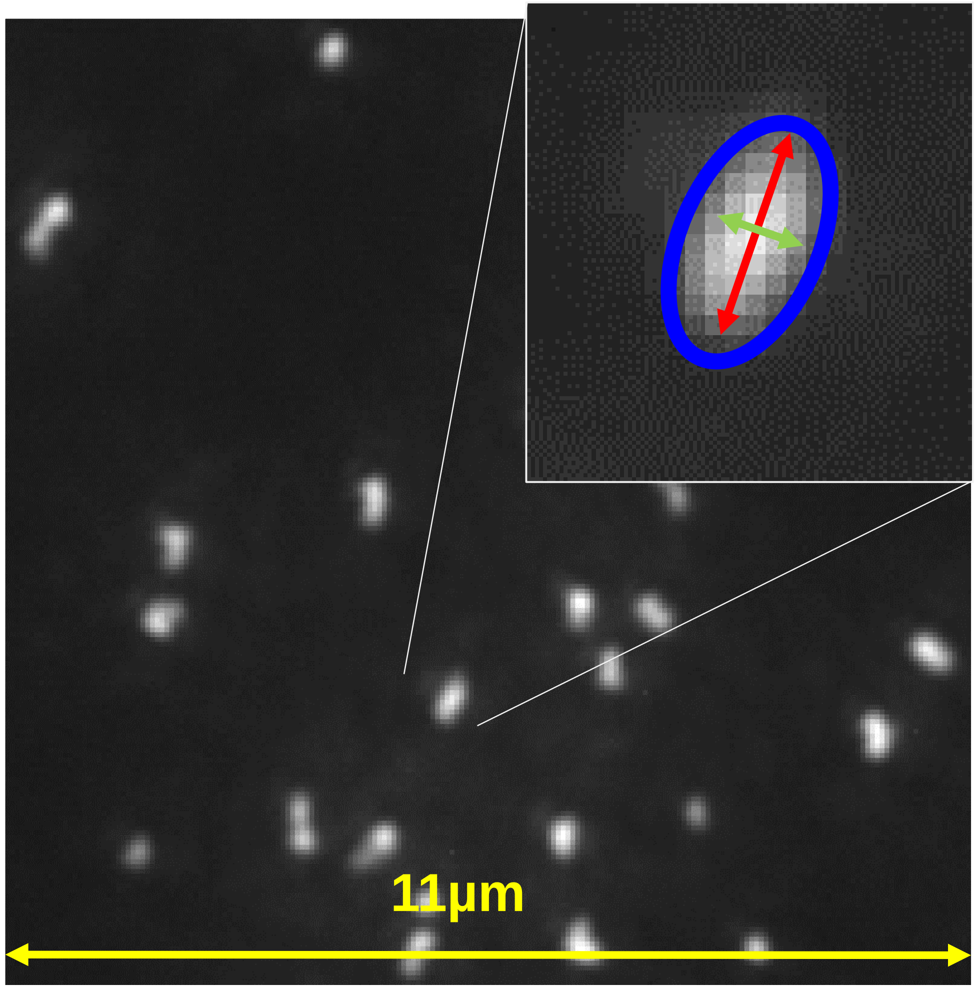
LNGS

Napoli

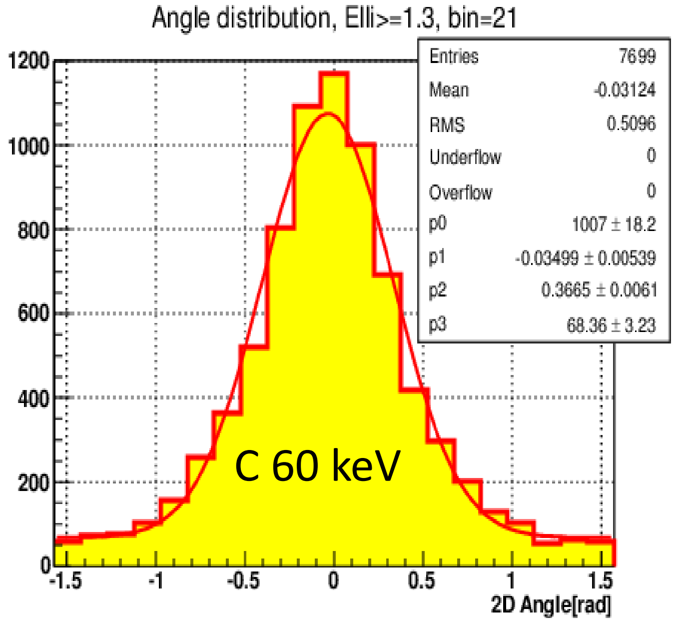


x 2

Sub-micron length track readout capability

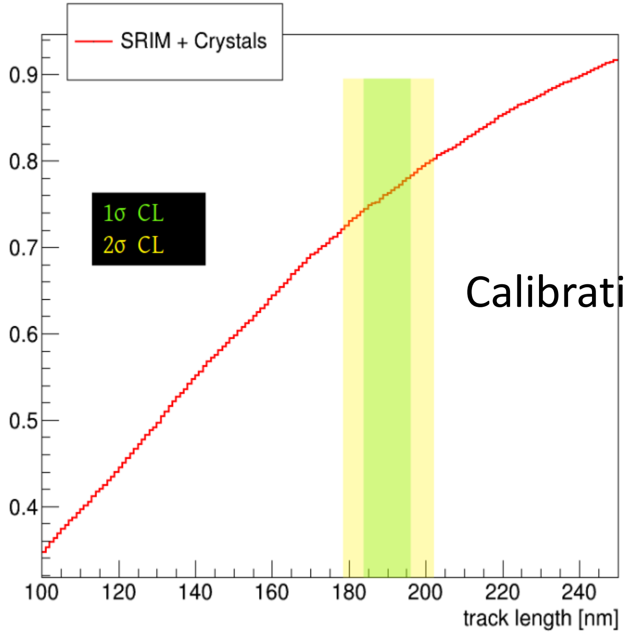


Cleary observed angular distribution
⇒ angular resolution ~ 30 deg.



Direction sensitive track length threshold in this algorithm
⇒ > ~ 190 nm

Energy threshold
> ~ 60 keV (eff. ~ 10 % ⇒ to be improve by upgrade optical condition)

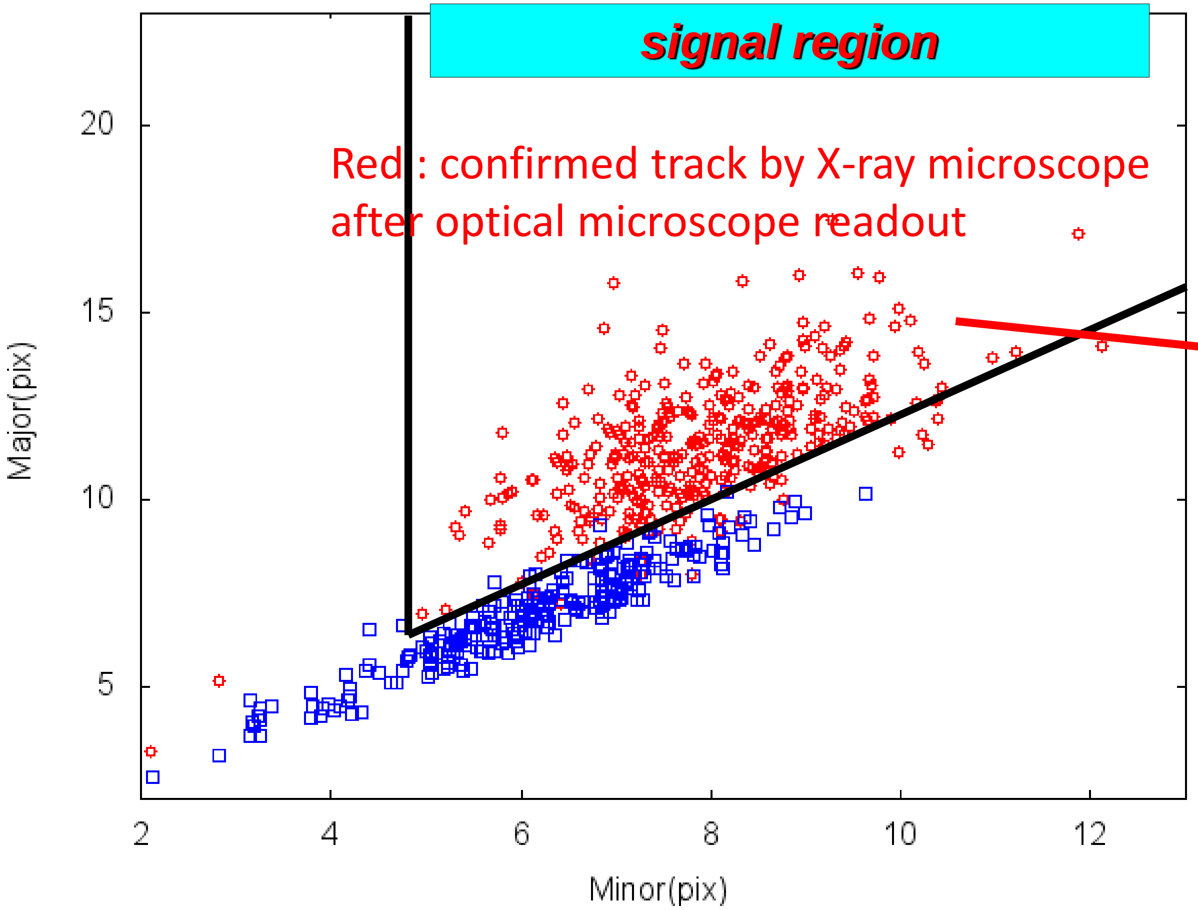


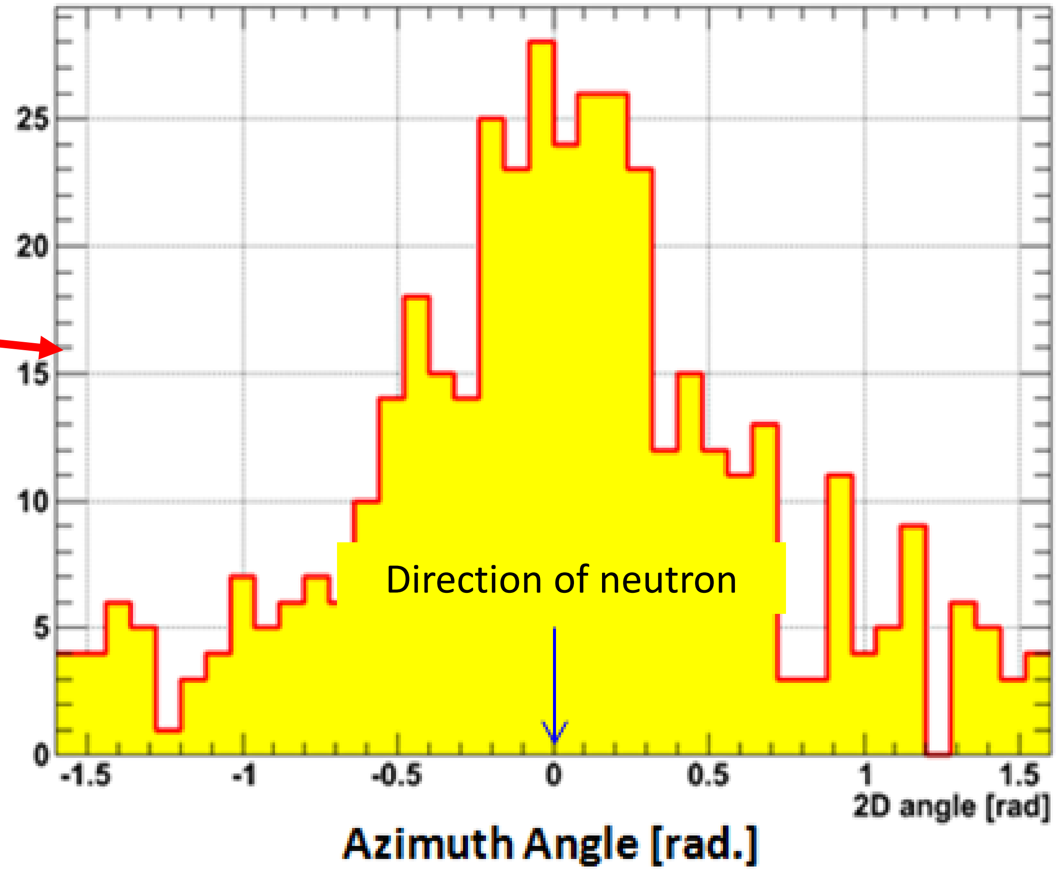
Calibration

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

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

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





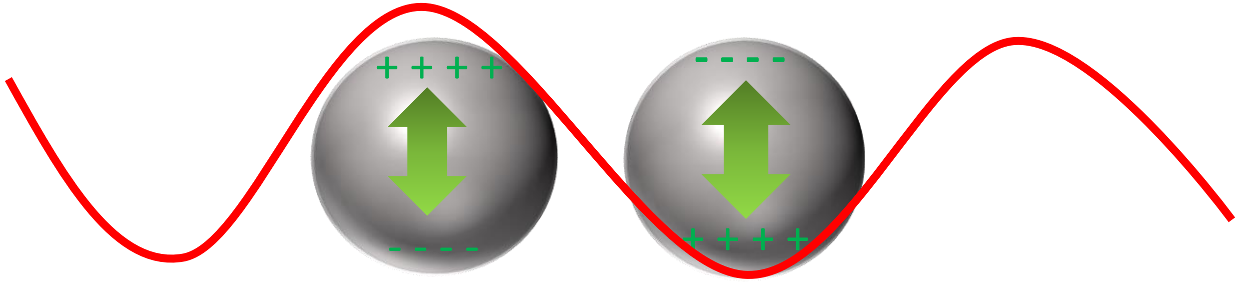
Mostly detected target was Br recoil [< 200 keV]

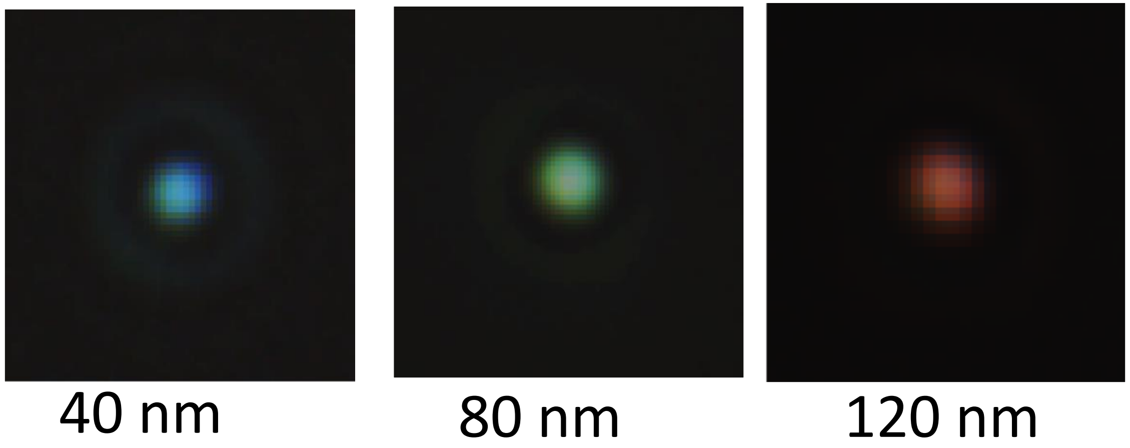
Now on studying CNO recoil demonstration due to 565 keV (Li-p nuclear fission reaction)

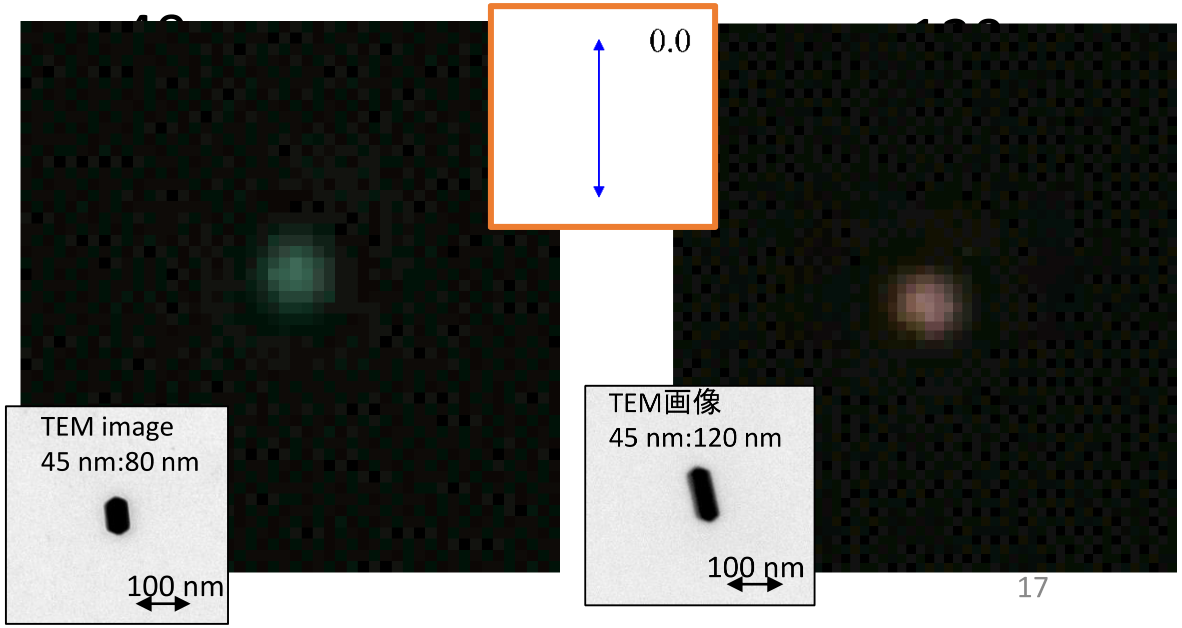
Localized Surface Plasmon Resonance (LSPR)

Silver-nano particle

Localized Surface Plasmon Resonance





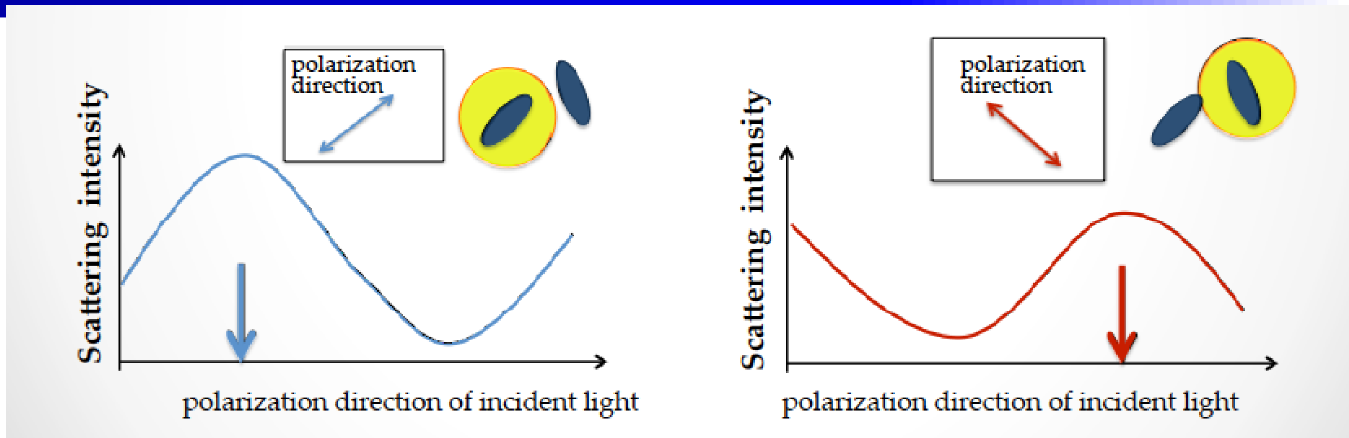


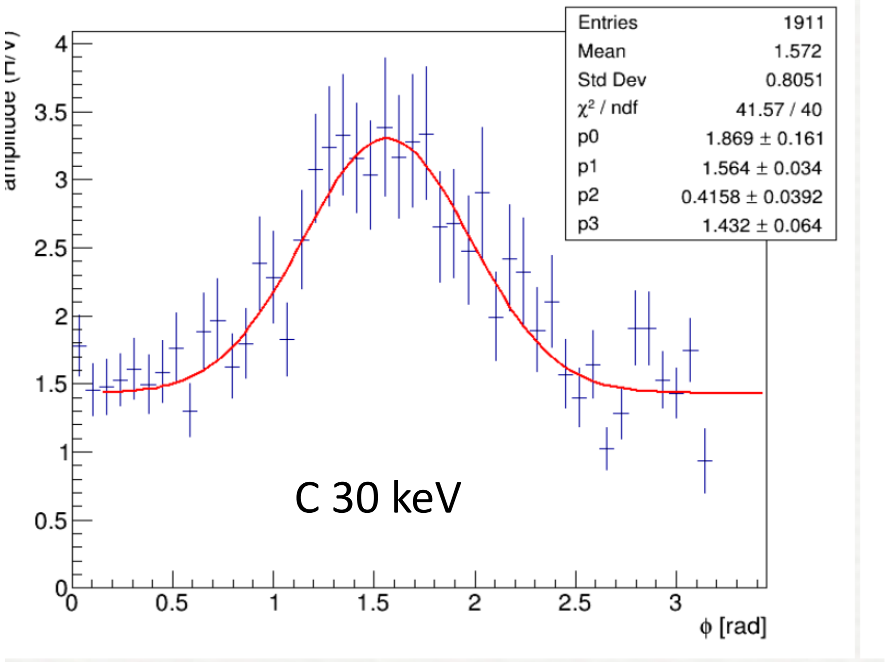
silver nano particle

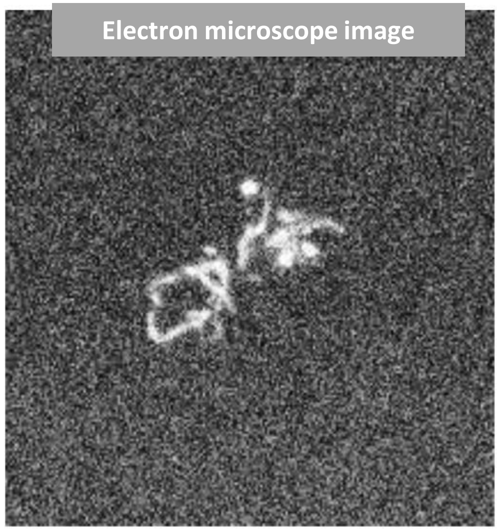
$$p = 4\pi\varepsilon_m a^3 \frac{\varepsilon_1(\lambda) - \varepsilon_m(\lambda)}{\varepsilon_1(\lambda) + 2\varepsilon_m(\lambda)} E_0$$

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

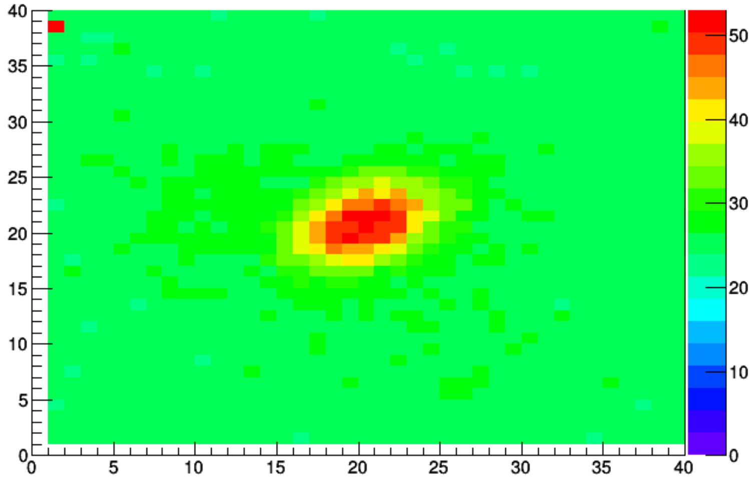
Super-resolution analysis using LSPR information

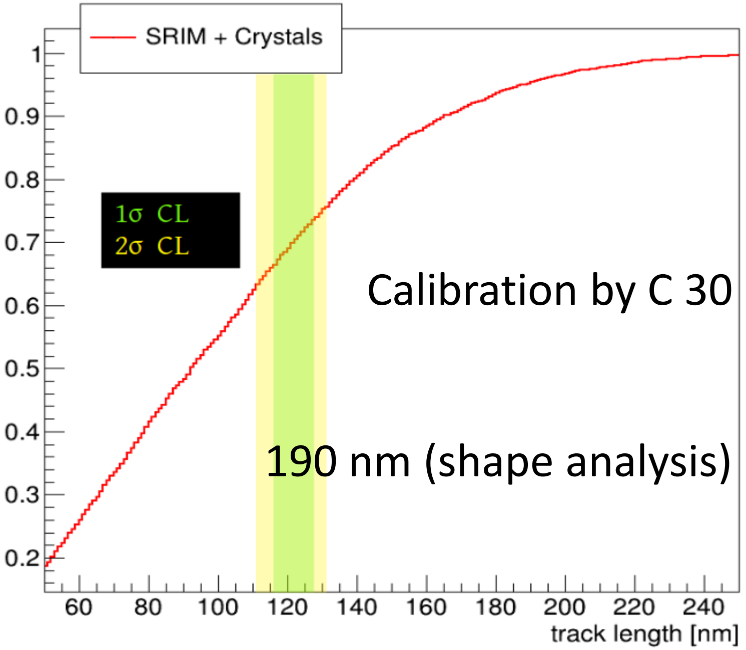






Polarization light dependence





Calibration by C 30 keV

190 nm (shape analysis) → 120 nm

Shift of barycenter is important information for nano-scale structure

Optical microscope system and analysis flow

Standard optical microscope scanning [on going]

Current Speed : ~30 g/year

- Elliptical event selection
- Roughly event selection with high speed
- On-line event analysis

~ 100 g/month scale (~ kg/y)

~ kg /month scale (~ 10 kg/y)

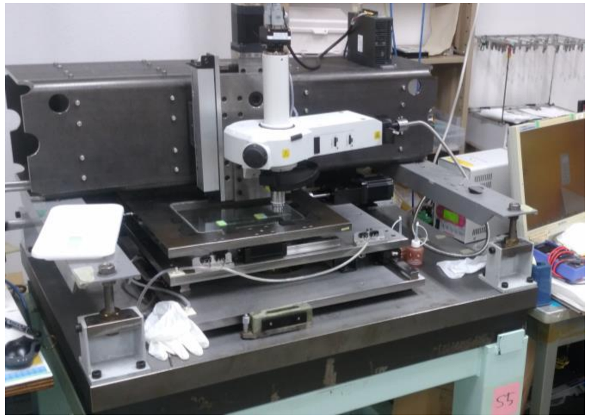
T. Katsuragawa *et al.*, JINST 12, T04002(2017)

Phase contrast imaging [will be newly installed]

10^7 events/month

- Phase contrast imaging
- Contaminated dust discrimination

No on comissionig

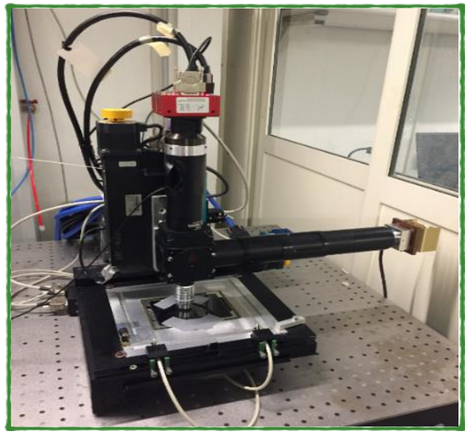


LSPR analysis [under studying]

10^5 events/month

- Super-resolution : ~10 nm
- Spectrum analysis
- Machine learning

Yandex@Russia, Napoli



Further new analysis [under studying]

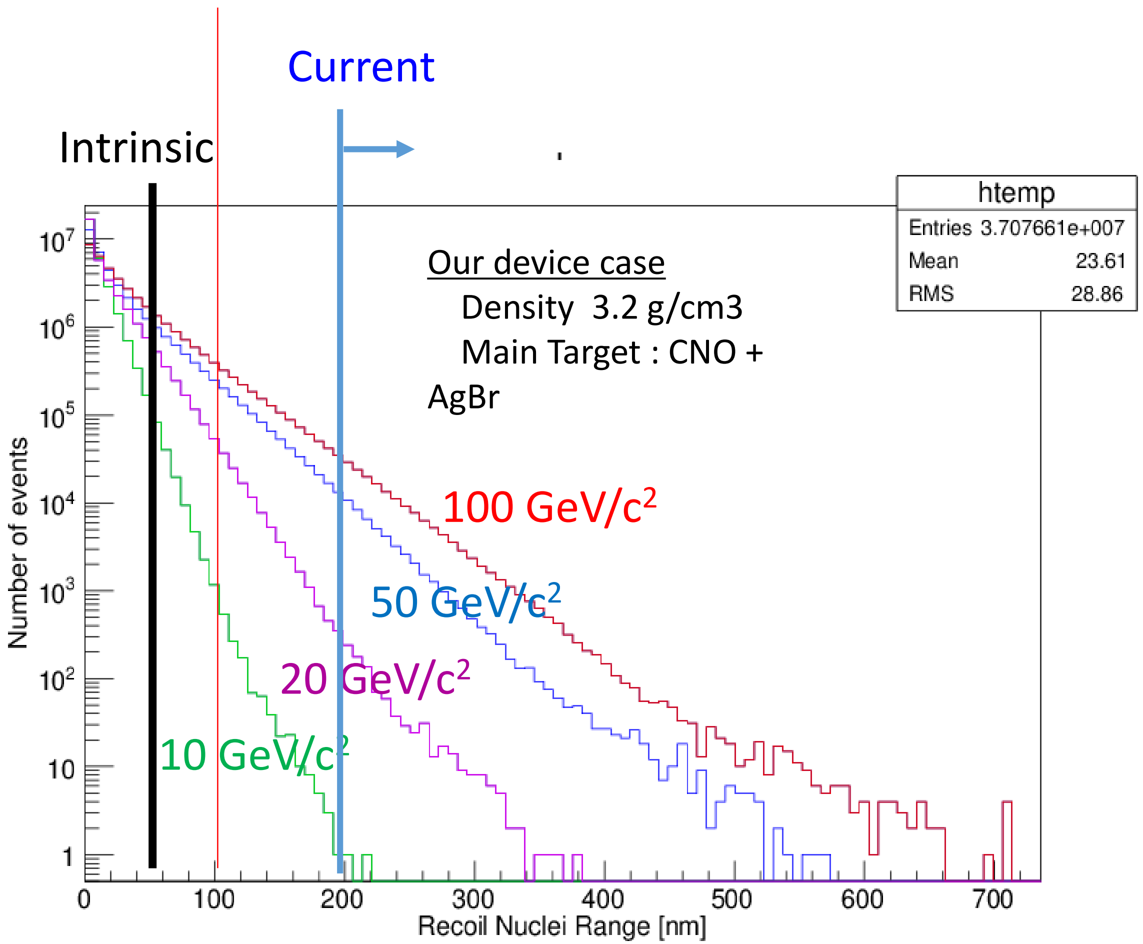
~10^3 events/month

- 3D super-resolution analysis with plasmonics
- Destructive analysis using oxidation method
- Expansion method

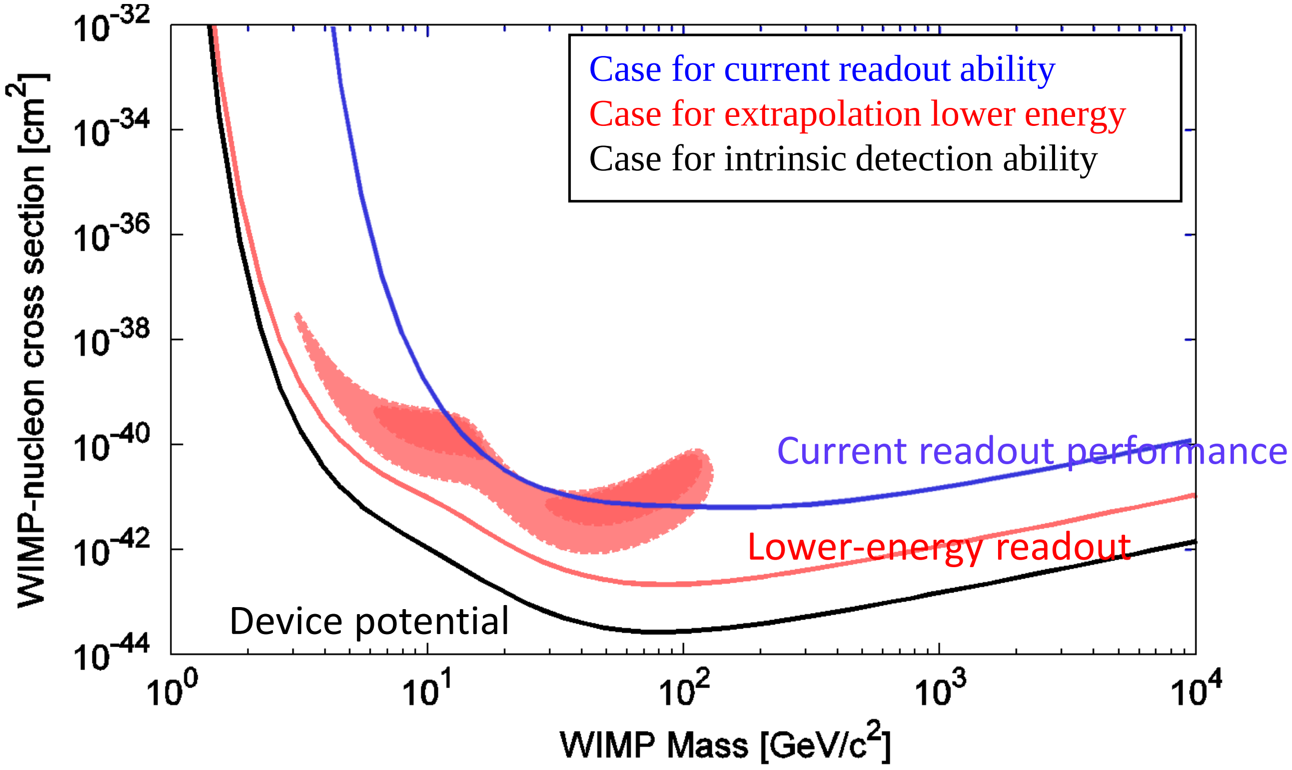
Cutting-edge technologies will be installed

Dark matter sensitivity

Demonstrated new tech.



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



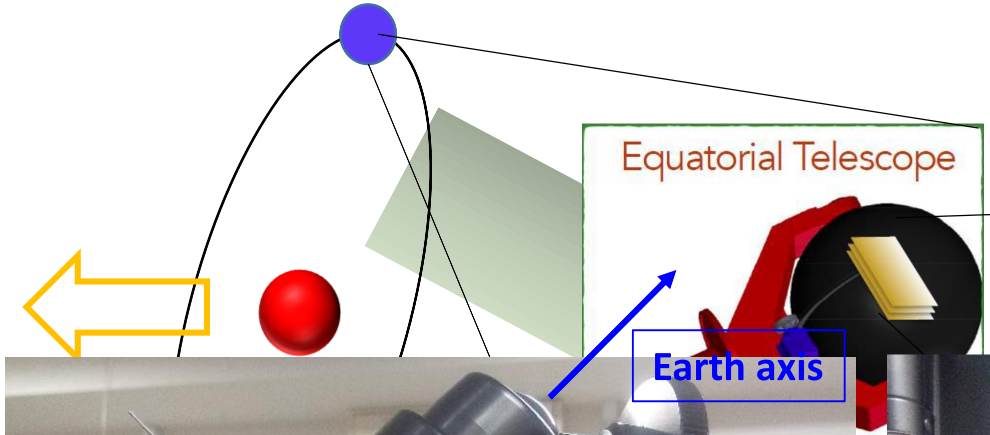
NIT detector / CNO sensitive / no Bkg no directionality
Simulation limit is “energy > 5 keV for all atoms (SRIM limit)”
& “Sensitivity > 0.1 % (Simulation statistics limit;10 event)”

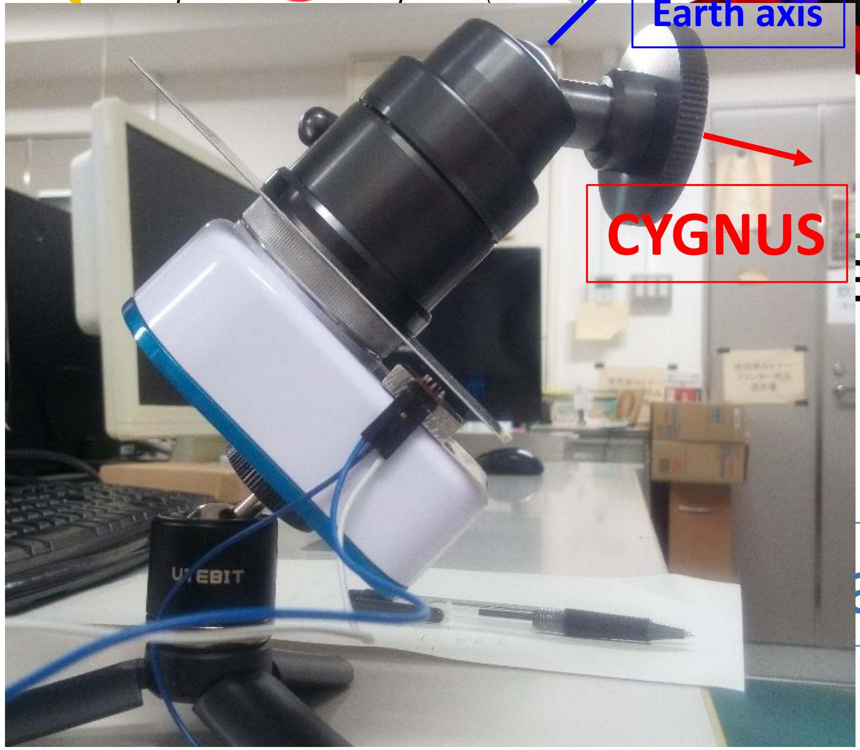
Device intrinsic potential : 10 keV of C recoil (> ~ 10% eff. and 45 ° angl. Res.

Understanding of backgrounds

	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 Phase contrast imaging Plasmonic analysis and image processing Machine learning Chemical treatment	Under studying (at least > 10^6 or more, in principle it should not be background)

Concept of NEWSdm experiment





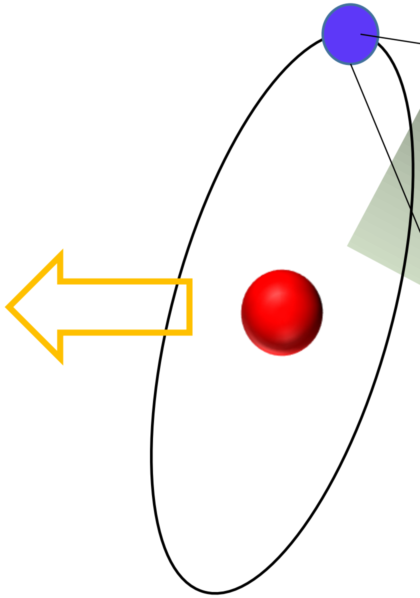
Device self-production

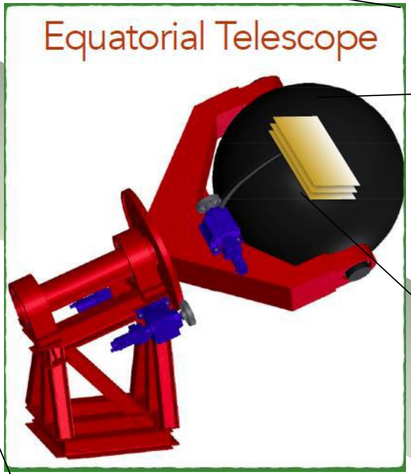
Surface laboratory

analysis

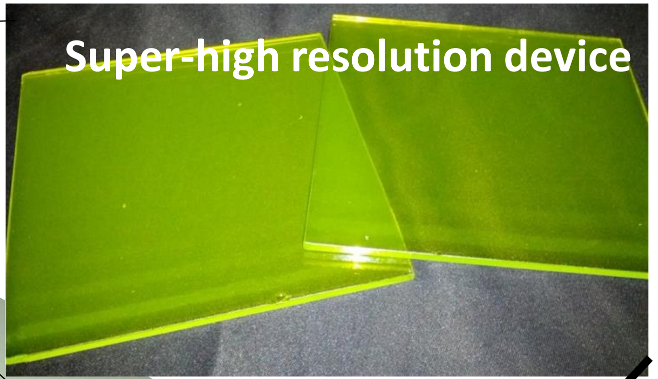
Using microscope techniques

Concept of NEWSdm experiment





Device self-production



Surface laboratory

exposure using telescope

Chemical development treatment

Underground laboratory

Readout + analysis
Using microscope techniques

Conclusion

- Direct dark matter search is very important method to directly understand what dark matter is
- Direction sensitive search is new promising method as next generation method to more understand dark matter property
- Nano Imaging Tracker is first solid detector to detect 100 nm length nuclear recoil as tracks
- NEWSdm experiment is under preparing and doing R&D for large scale directional dark matter search at LNGS, Italy

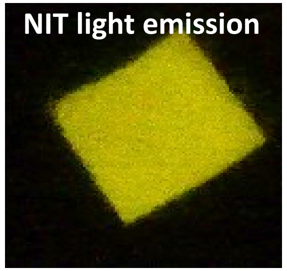
* Technical Design Report will be prepared in this year.

- Such unique technologies are interesting not only WIMP search, but beam experiment, neutrino experiment, neutron detector and any other detector applications.

Detector Application

[Scintillation light emission]

- ✓ High emission efficiency
  → possibility as scintillator
- ✓ Study for fundamental mechanism of AgBr nano crystal



T. Shiraishi, H. Ichiki, TN al., accepted (2019)

low-velocity heavy particle detector

- ✓ Exotic heavy low-velocity particle (e.g., monopole)
- ✓ Medical therapy
- ✓ Energy loss mechanism

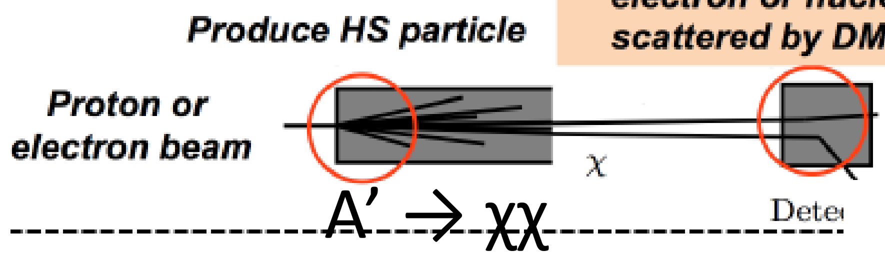
[Neutron detector]

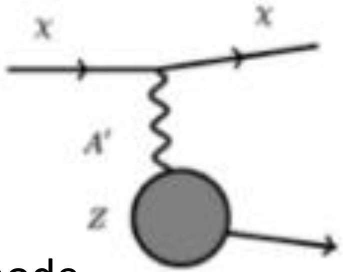
- ✓ Environment neutron measurement with direction information
- ✓ Low-energy (sub-MeV, UCN) neutron detector

NEWSdm Application

Hidden sector

Scattering technique, electron or nuclei scattered by DM

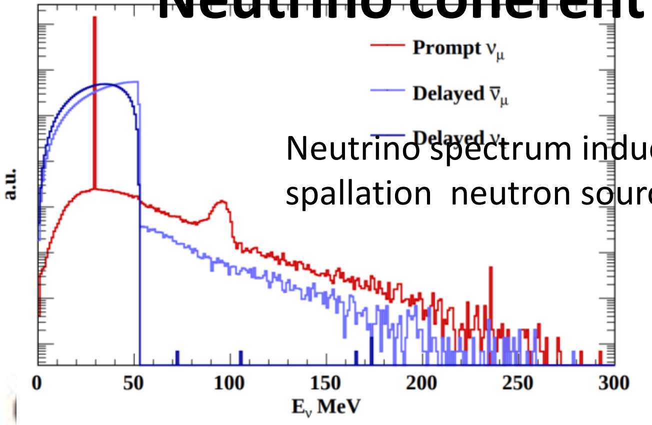




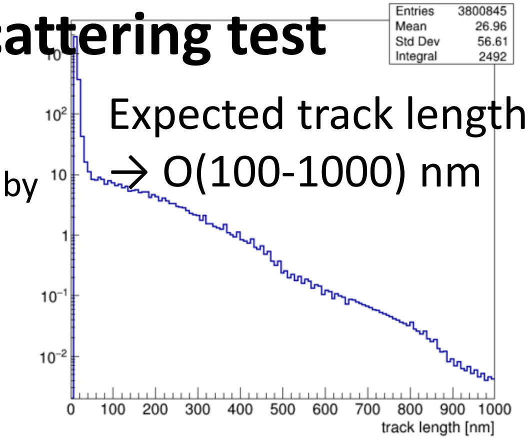
e.g., : SHiP-NEWSdm collaboration

Coherent scattering mode

Neutrino coherent scattering test



Neutrino spectrum induced by spallation neutron source



Expected track length
→ O(100-1000) nm

- ✓ Demonstration of neutrino floor for dark matter search
- ✓ High precision Demonstration using weak interaction of Dark matter search