Toho University

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

Direction sensitive dark matter search with nuclear emulsions

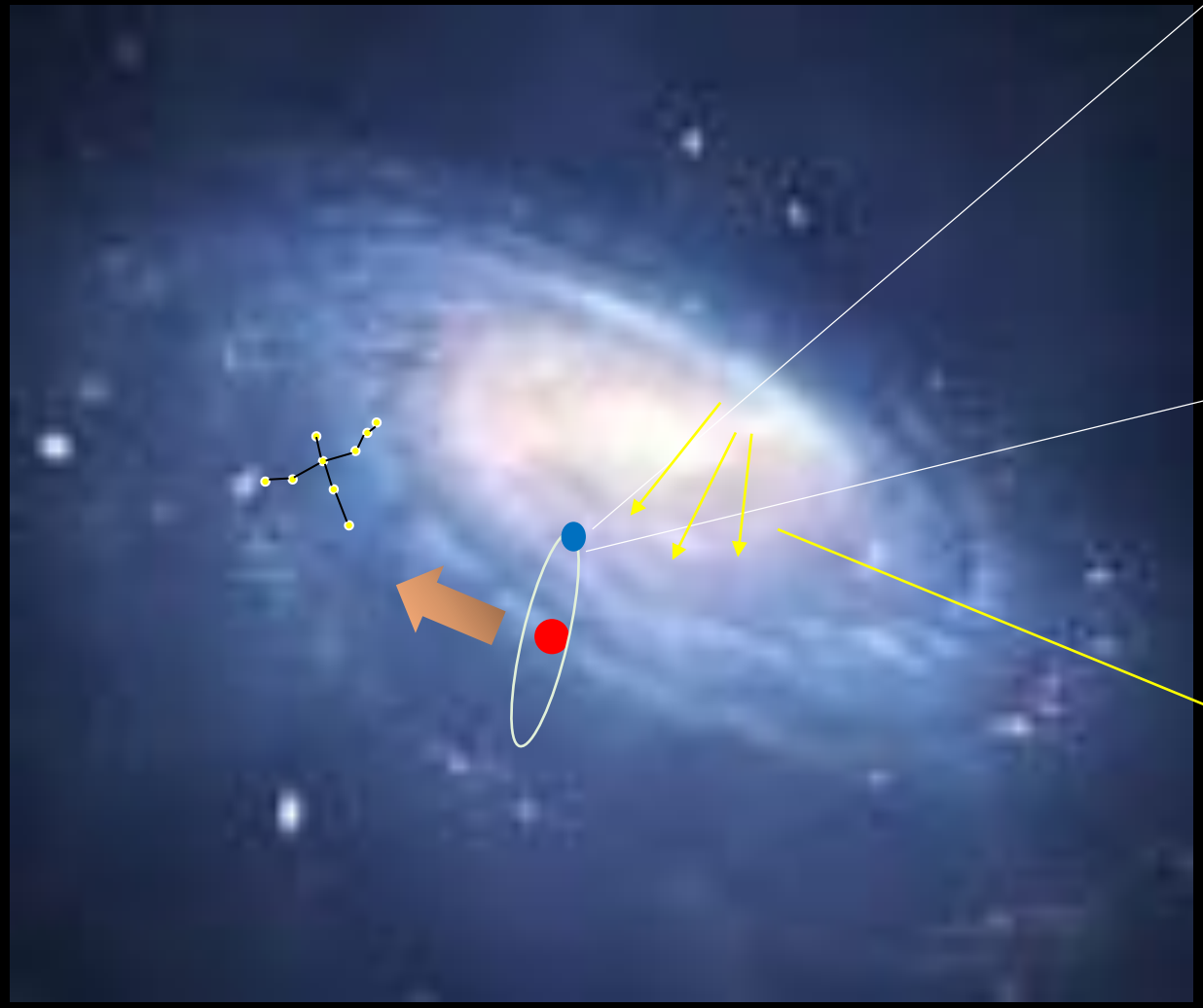
Tatsuhiro NAKA

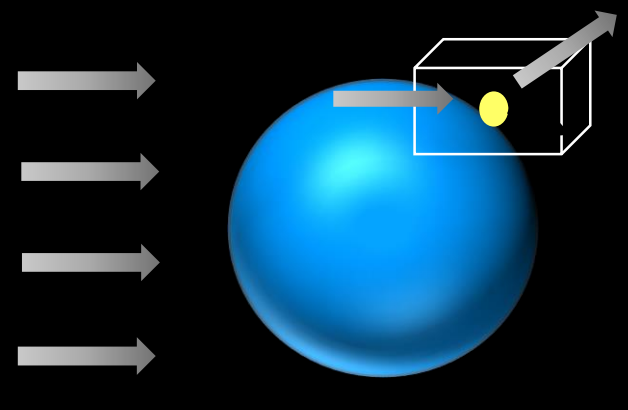
Toho University

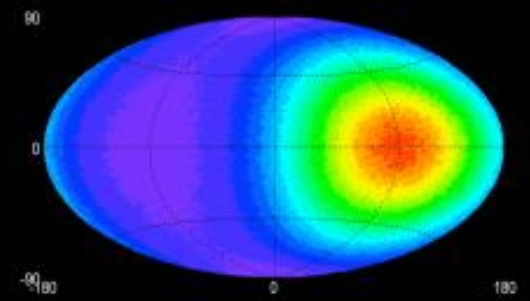
(KMI, Nagoya Univ.)

on behalf of NEWSdm collaboration

Advantage of Directionality for dark matter detection

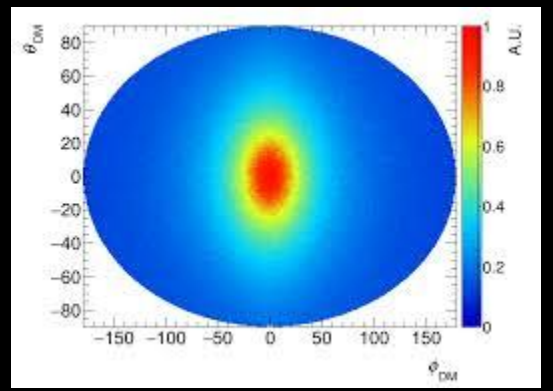






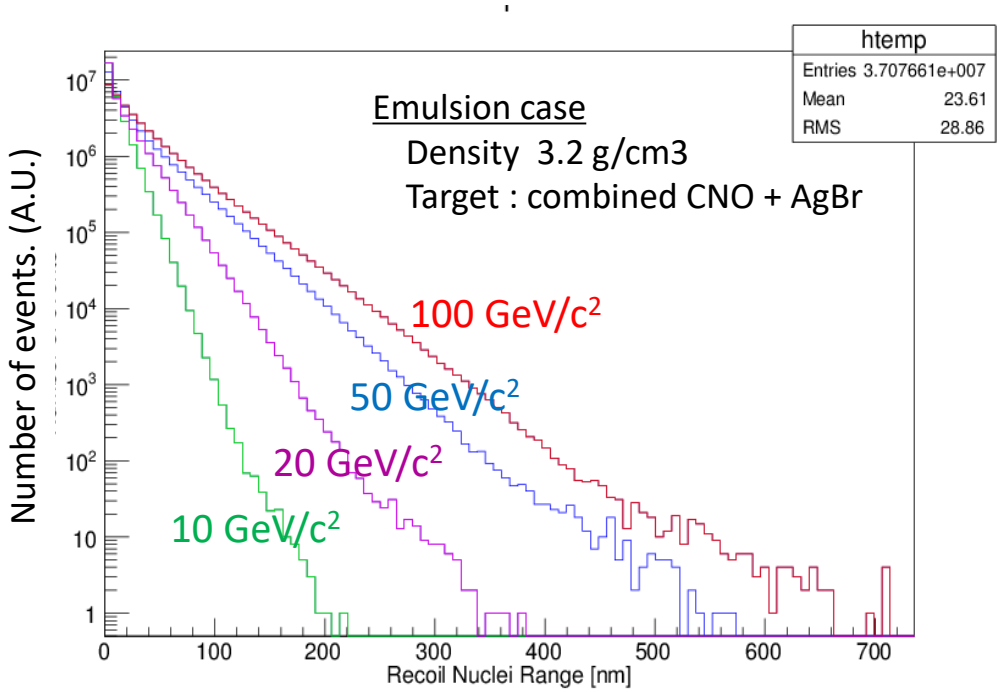
- More reliable evidence for dark matter with distribution model in the halo
- Background discrimination for isotropic component and/or different distribution

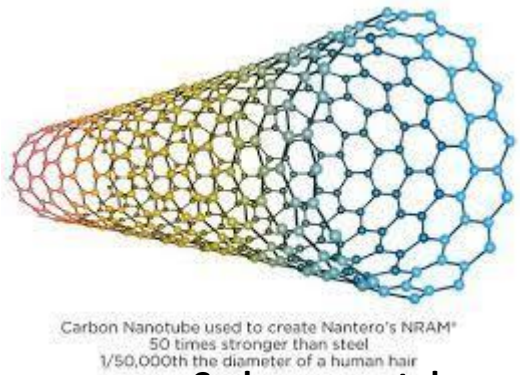
Galactic excess
e.g., cosmic-ray boosted DM,
dark particle by annihilation or decay



Keiko I. Nagao *et al* JCAP07(2023)061

Direction Sensitivity for solid detector

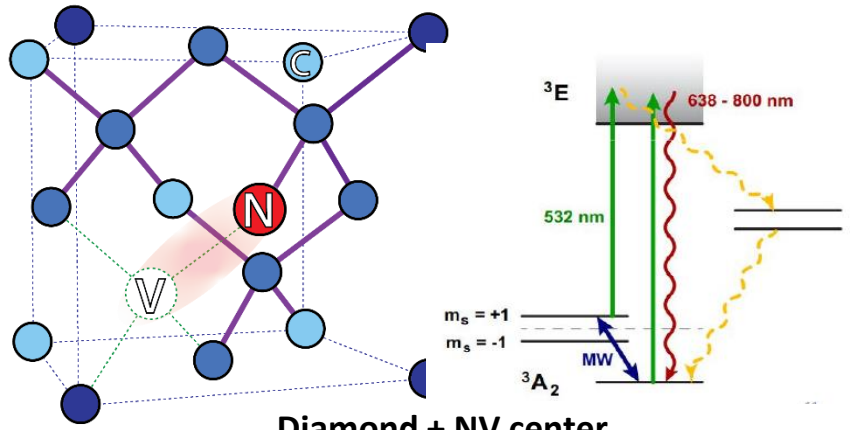




Carbon nano tube

[Requirement]

- Super high resolution
- Intrinsic structure and response depending on the track direction with nm scale
- Scalability and low-background

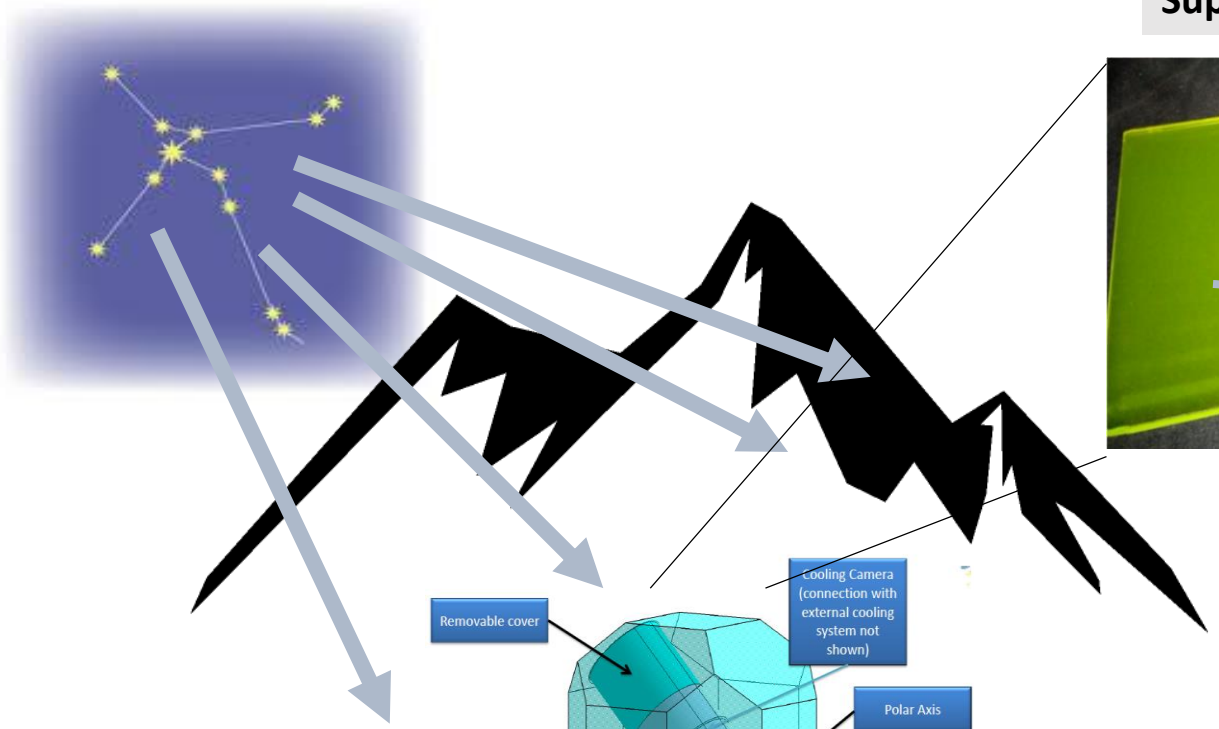


Diamond + NV center

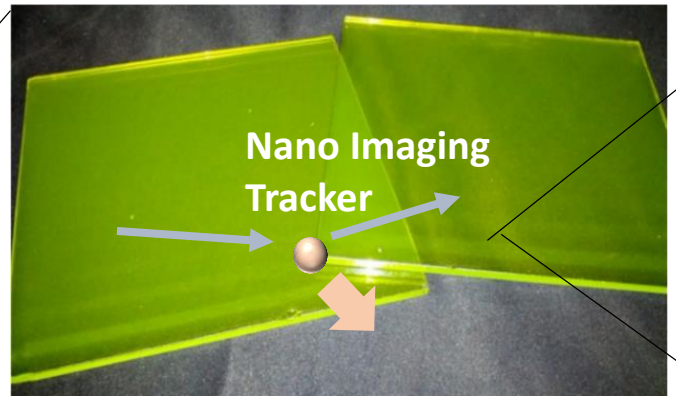
NEWSdm experiment

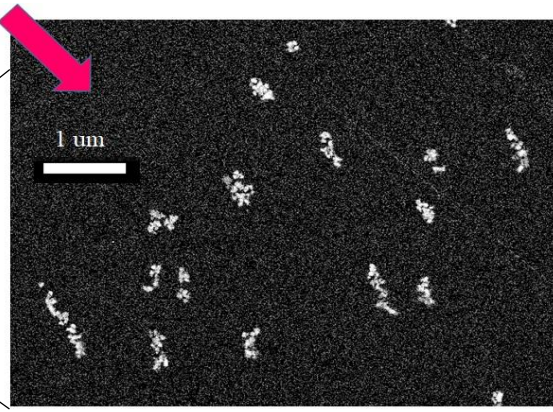
Collaborated by 5 counties, 14 institutes

Direction Sensitive Dark Matter Search with Super-high resolution nuclear emulsion



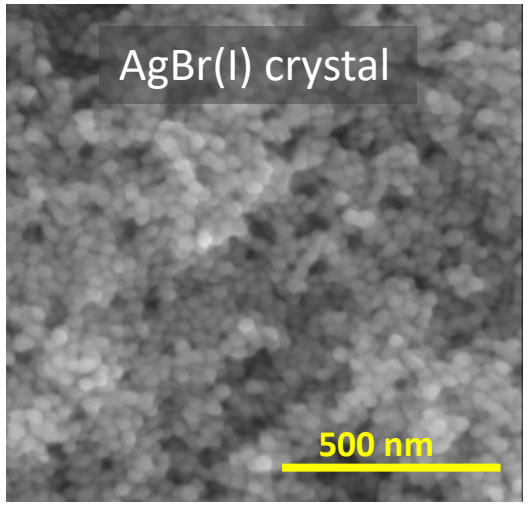
Super-resolution nuclear emulsion and sub-micron tracking

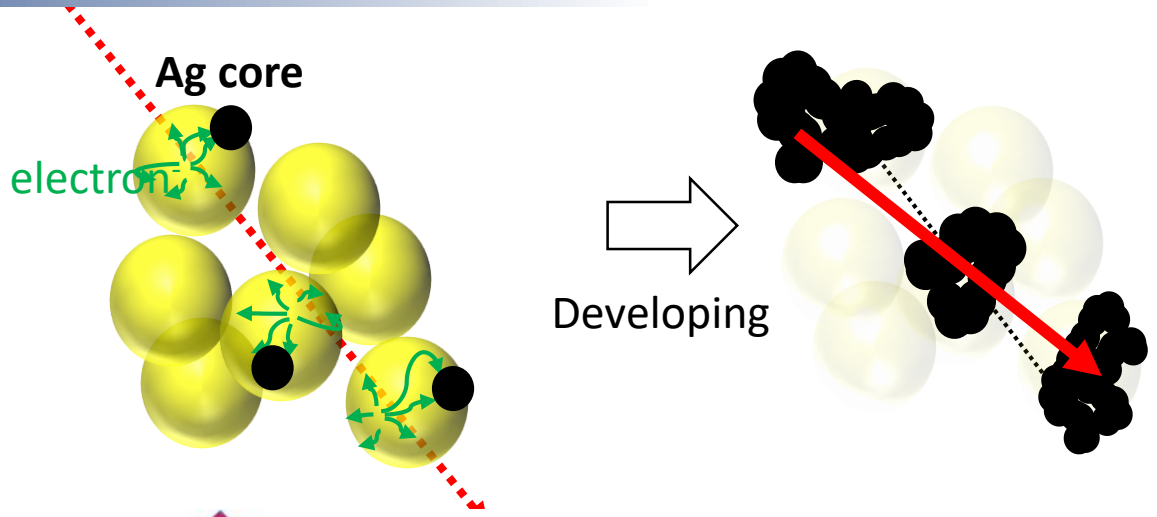


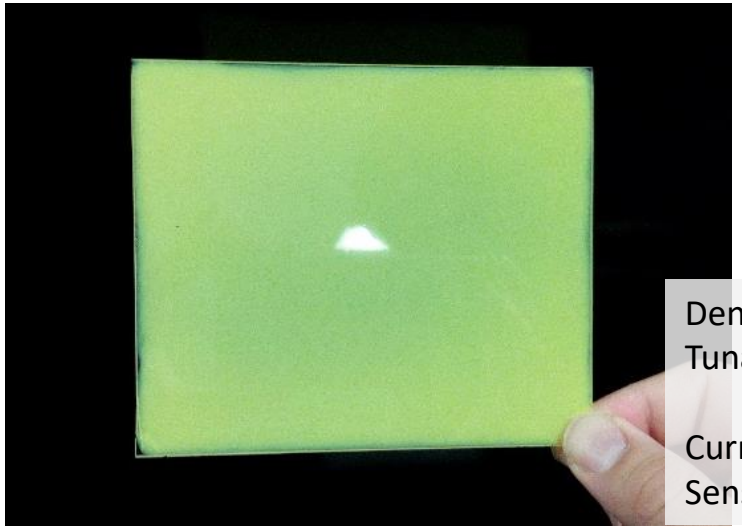


Super fine-grained nuclear emulsion [Nano Imaging Tracker : NIT]

TN et al., NIM A Nucl. Inst. Meth. A 718 (2013) 519-521
T. Asada, TN et al., , PTEP (2017)063H01

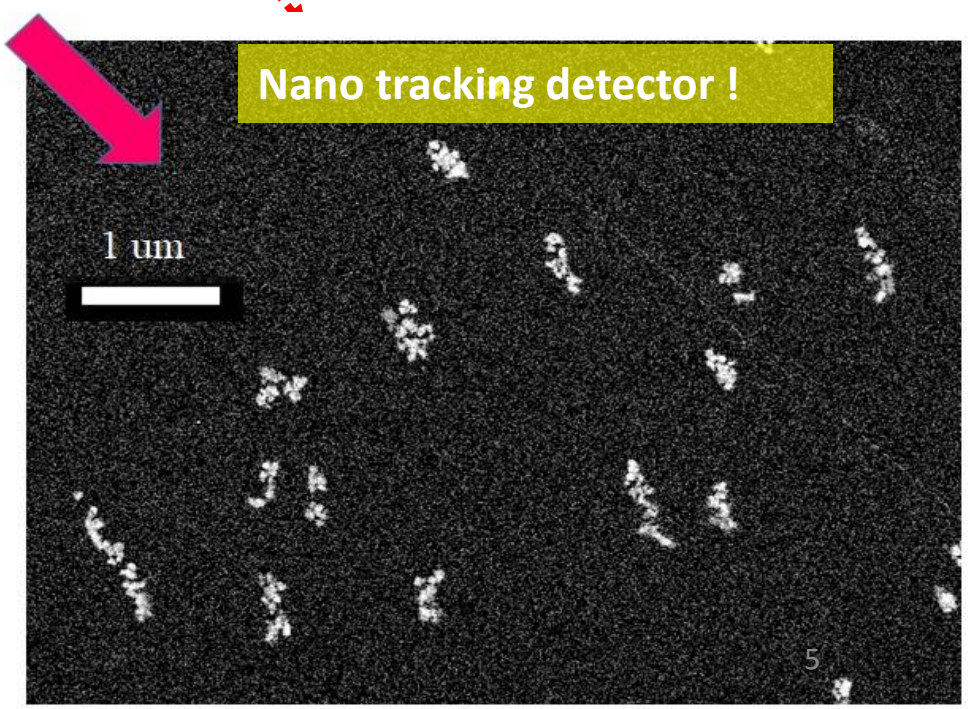






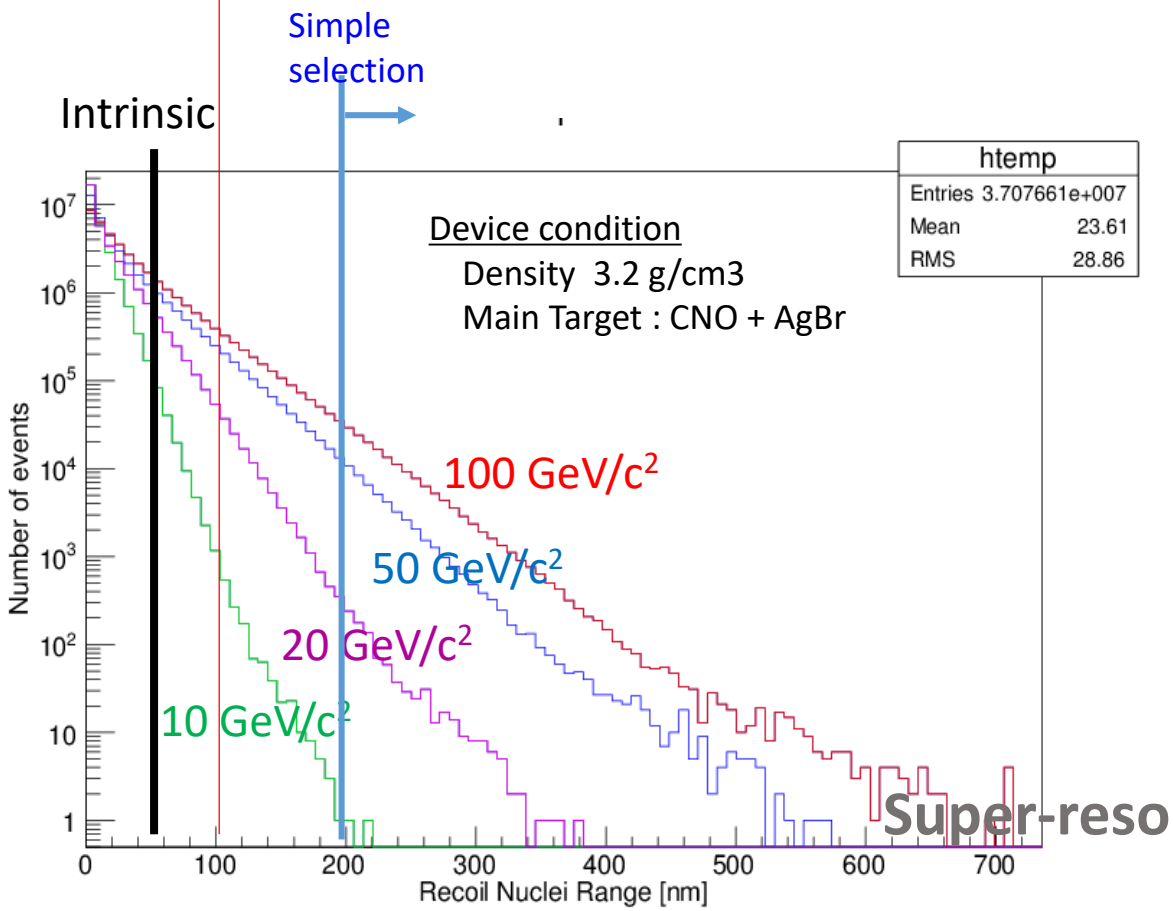
Density : 3.1 ± 0.1 g/cm3
Tunable Crystal size : > 20 nm

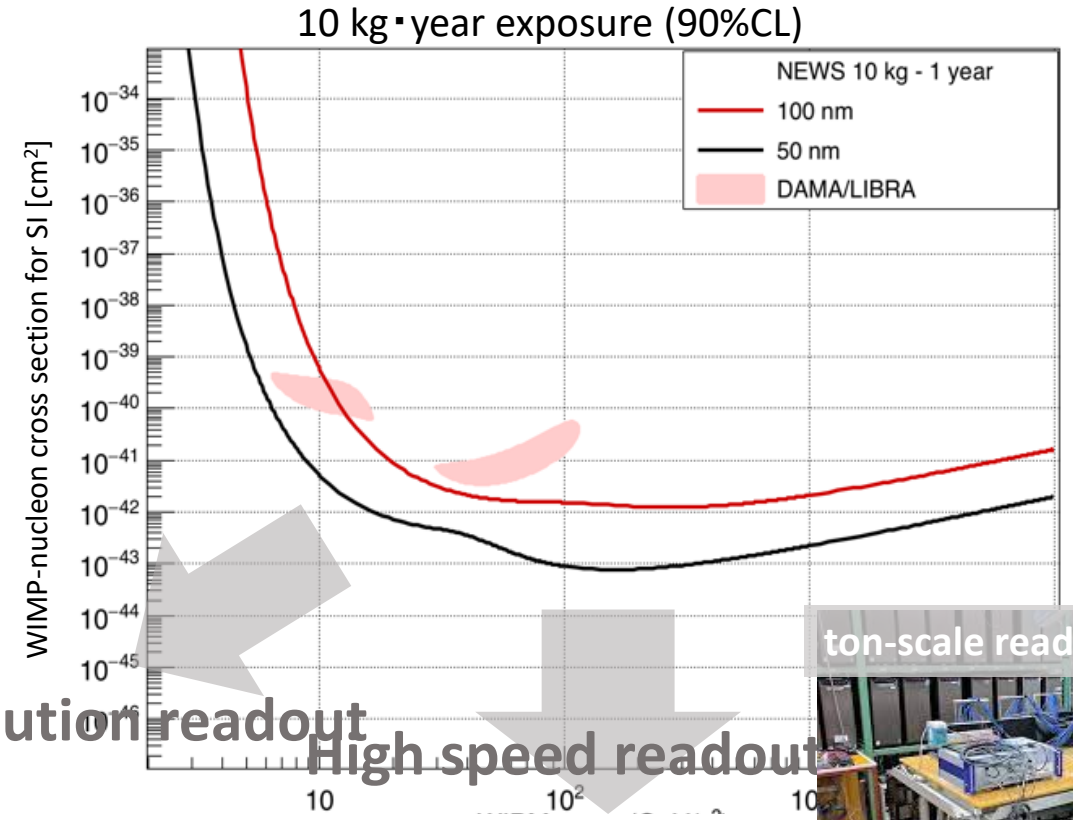
Current standard type : 70 +- 10 nm
Sensitization : Halogen-Accepter (HA) with Na_2SO_3



Dark matter sensitivity potential

readout upgraded





Super-resolution readout

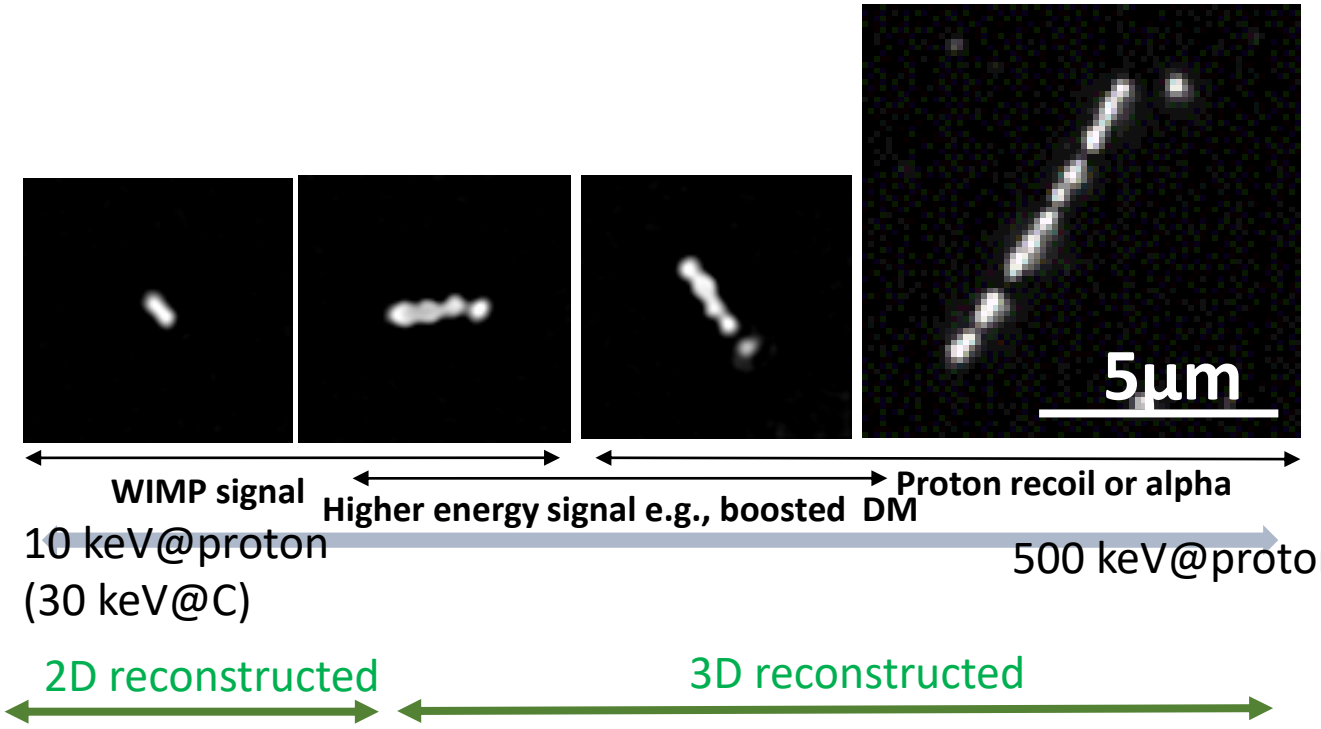
High speed readout

ton-scale readout system

PTEP, 2017 10, 103H01

Readout System

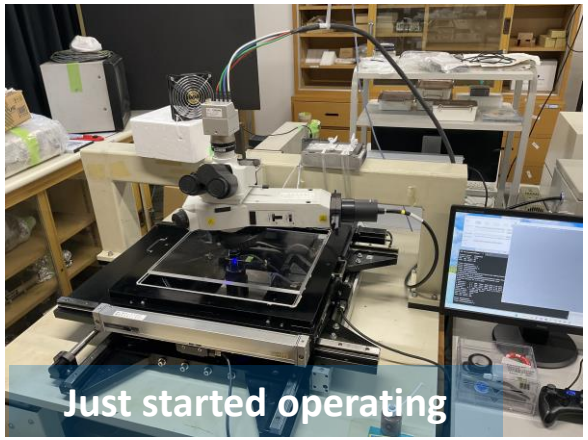
T. Shiraishi, TN *et al.*, PTEP, 4, 043H01 (2021)
A. Umemoto, TN *et al.,* PTEP 10, 103H02 (2020)
Y. Katsuragawa, TN *et al.,* JINST 12(2017)T04002
M. Kimura and TN, Nucl. Inst. and Meth. A 680 (2012)



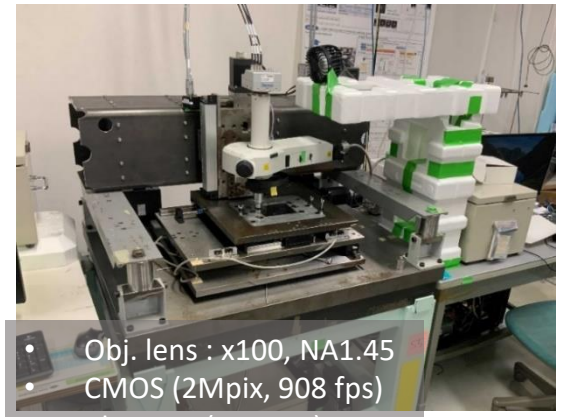
Readout System

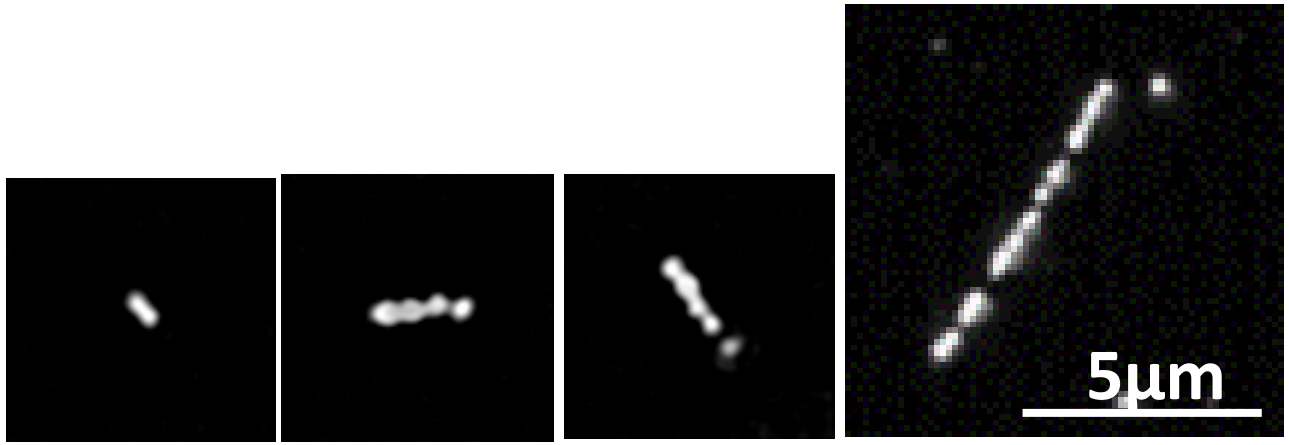
T. Shiraishi, TN *et al.*, PTEP, 4, 043H01 (2021)
A. Umemoto, TN *et al.*, PTEP 10, 103H02 (2020)
Y. Katsuragawa, TN *et al.*, JINST 12(2017)T04002
M. Kimura and TN, Nucl. Inst. and Meth. A 680 (2012)

PTS-2 @ Kanagawa U.

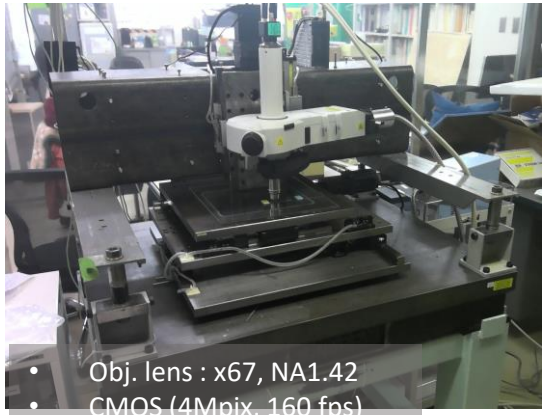


PTS-3 @ Nagoya





PTS-4 @ Toho



PTS-5 @ Nagoya

2D reconstructed

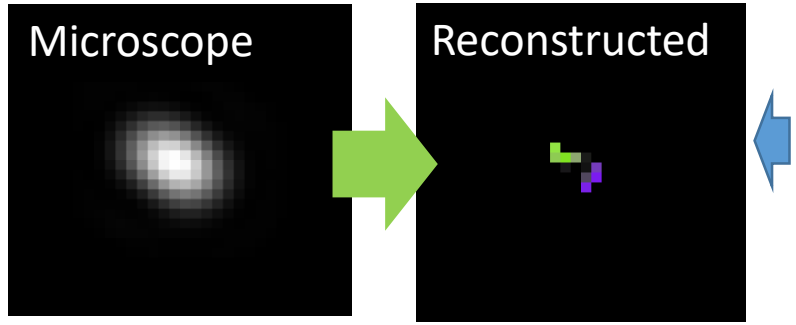
~ 0.4 kg/year/machine
(100 times improved
from pilot machine)

3D reconstructed

~ 1.2 kg/year/machine

Track selection procedure

LSPR (plasmonic response)
+ super resolution



Scientific Reports volume 13, Article number: 22813 (2023)

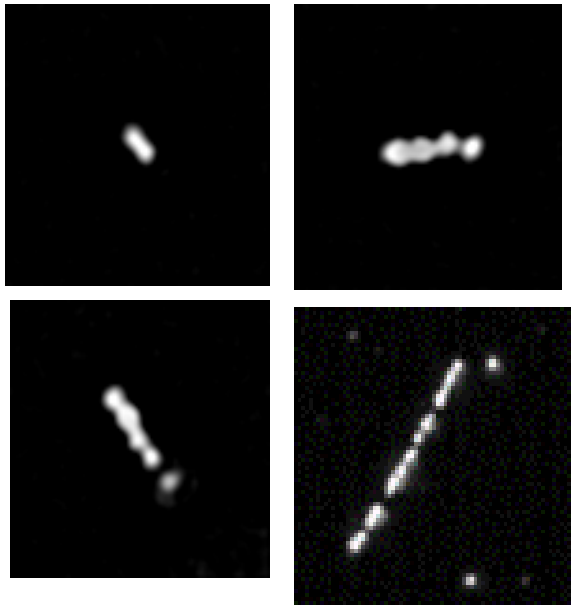


Image data
3D position data
Elliptical fitting data
Brightness

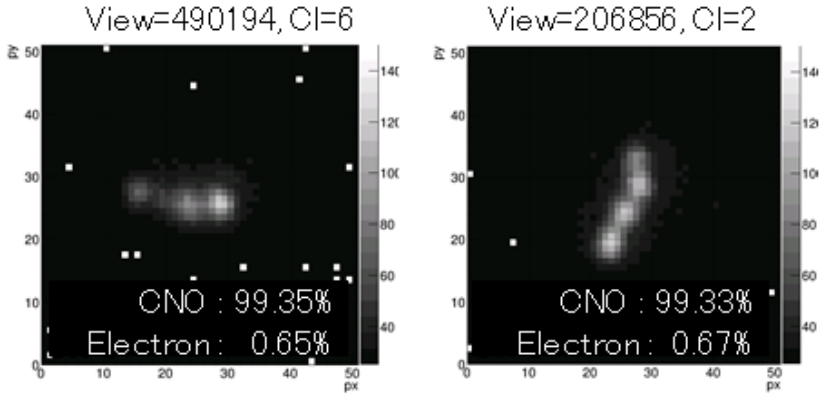
Nucl. Inst. Meth. A 680 (2012) 12-17

JINST 12 T04002 (2017)

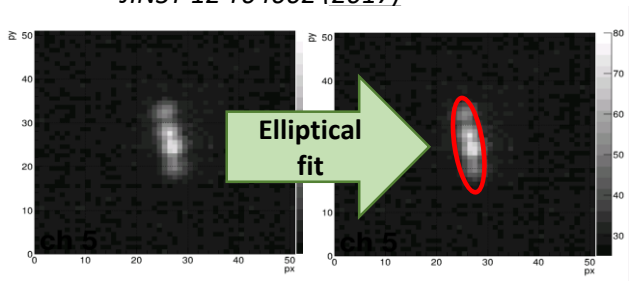
R < 0.3 µm

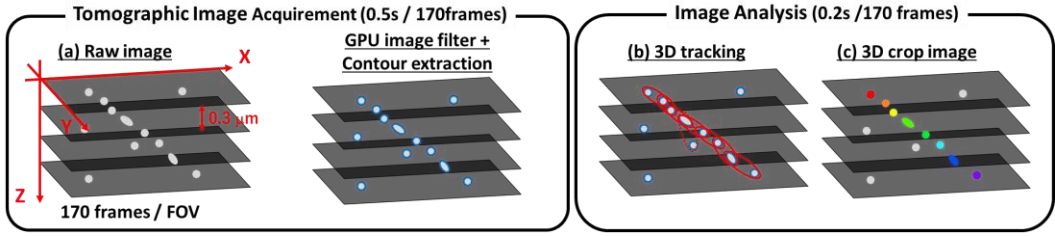
R > 0.3 – 1.0 µm

CNN

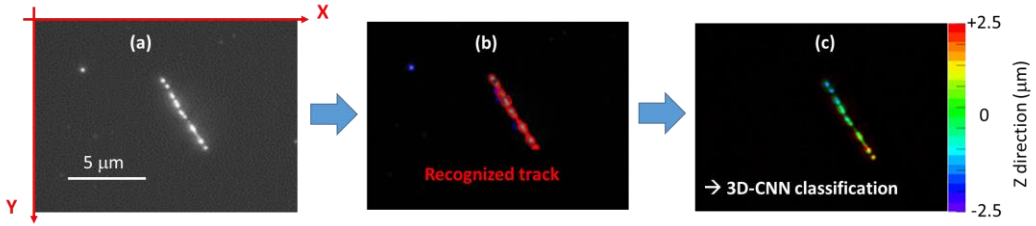


R > 1µm





3D reconstruction



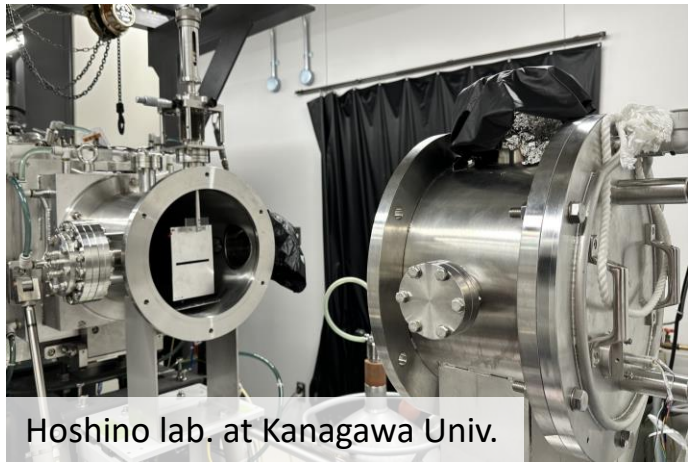
PTEP 2021 (2021) 4, 043H01

+ CNN selection (on going)

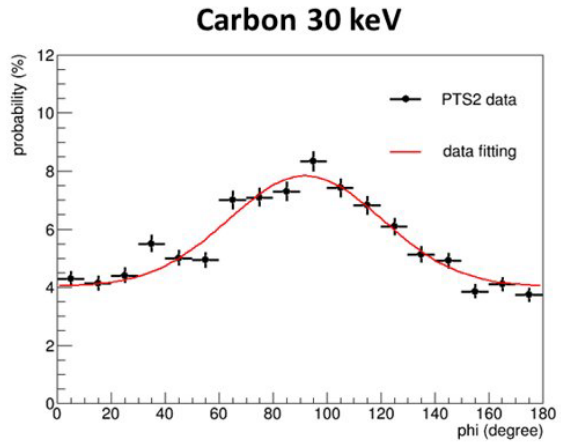
Direction sensitivity checks

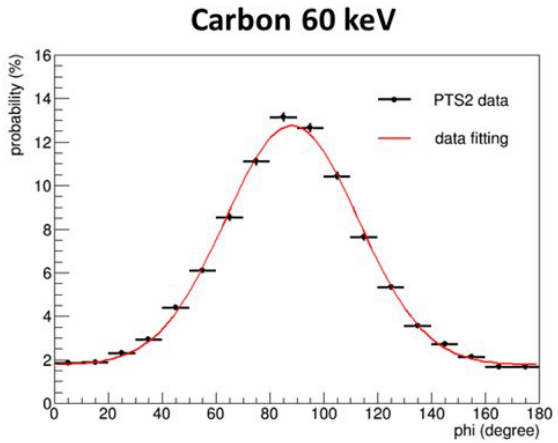
■ Ion-implantation

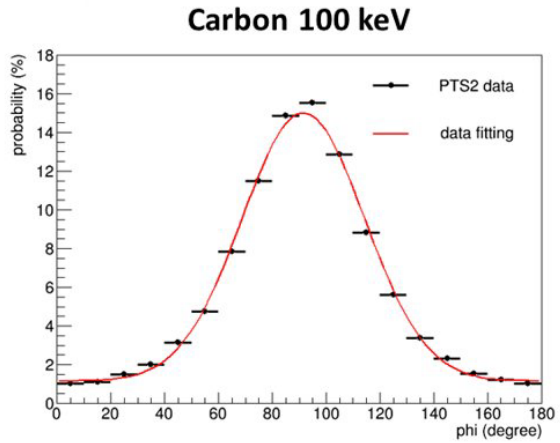
IMASS at Nagoya Univ.

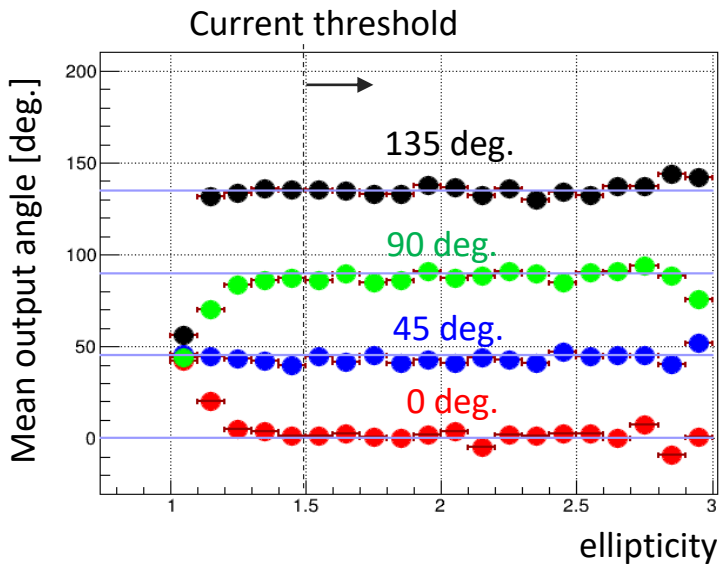


Hoshino lab. at Kanagawa Univ.



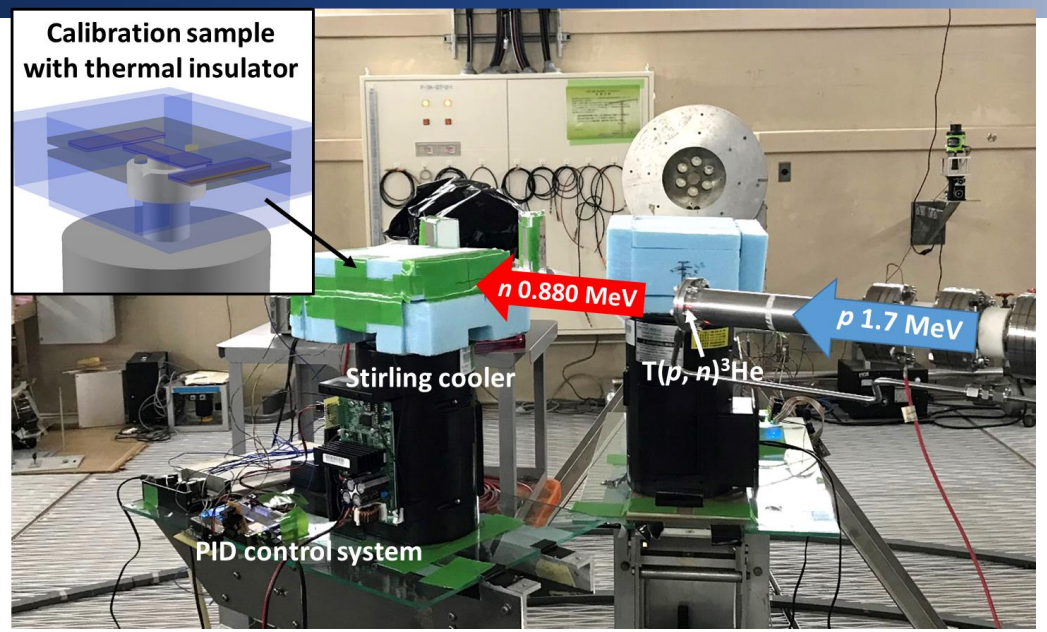




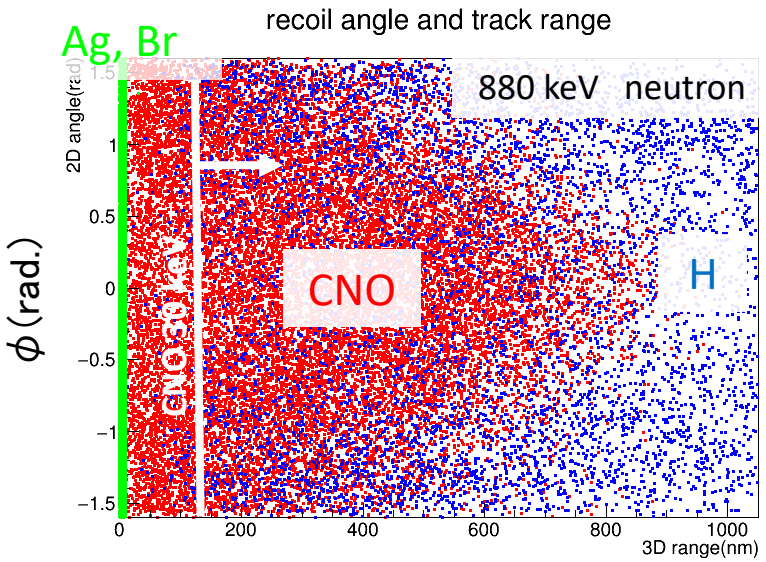


Energy of Carbon	Angular resolution [deg.]
100 keV	32 +- 3
60 keV	35 +- 3
30 keV	59 +- 2

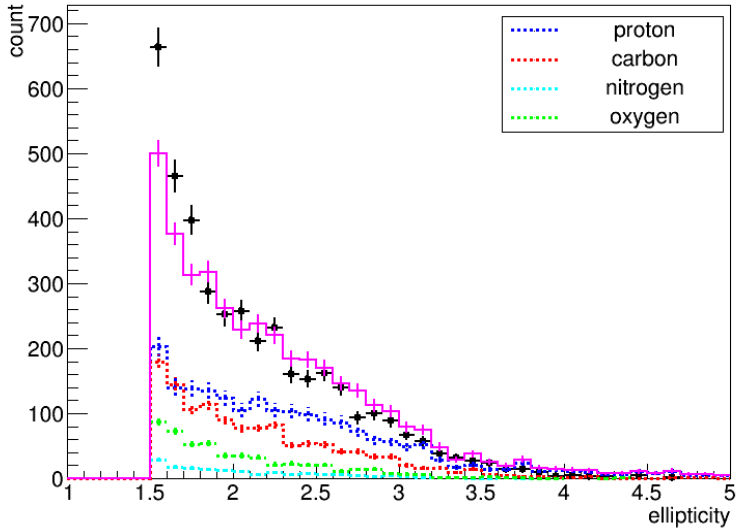
Nuclear recoil detection by neutron



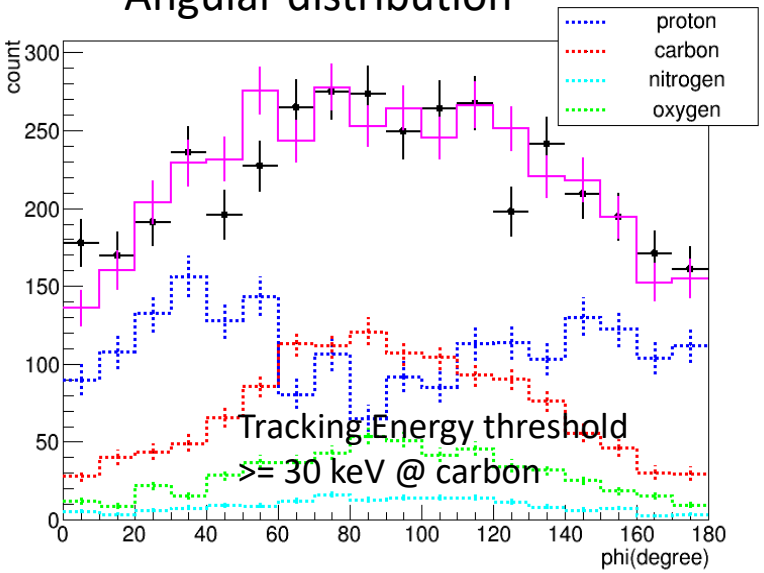
- Neutron source due to nuclear fission reaction at AIST is very useful calibration source for directly detection of nuclear recoil, not only ion-implantation system.
- Detection of nuclear recoil tracks are demonstrated
- The performance for any experiment condition such as temperature, device sensitivity control etc. is investigated.



Ellipticity scpectrum

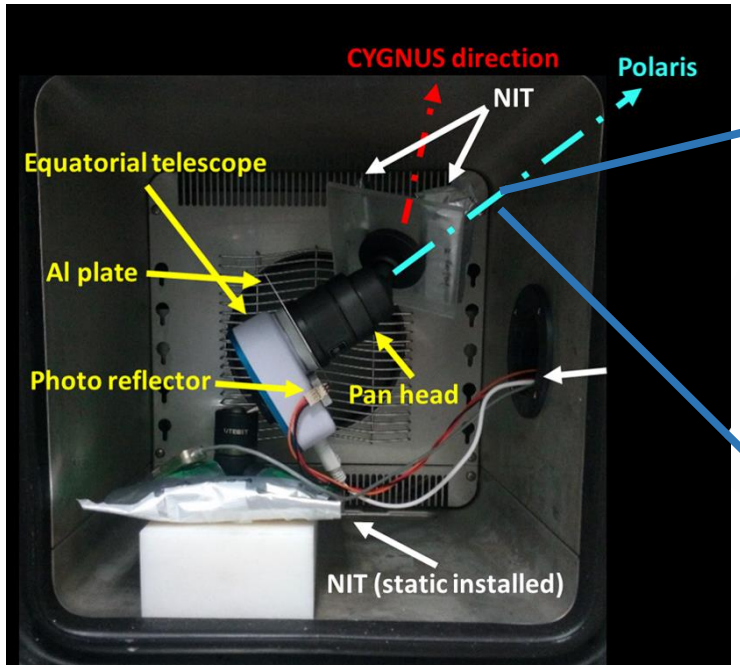


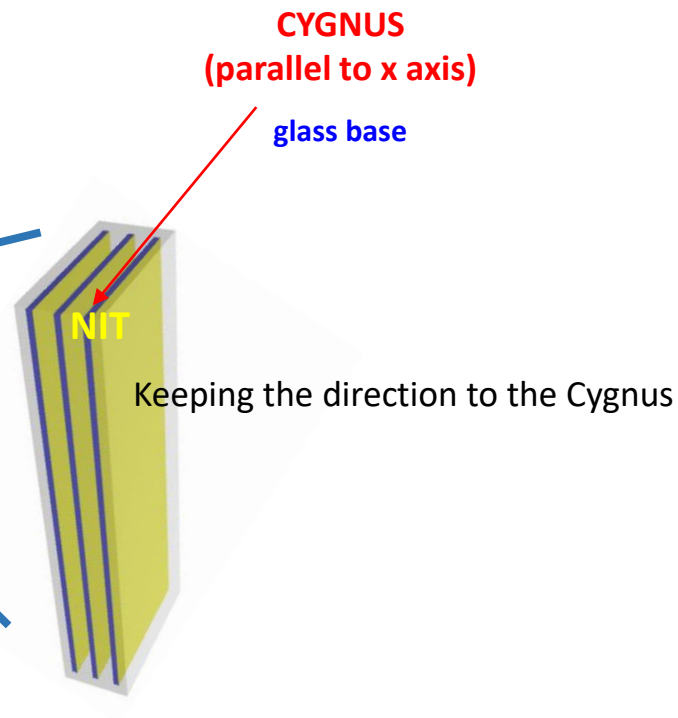
Angular distribution



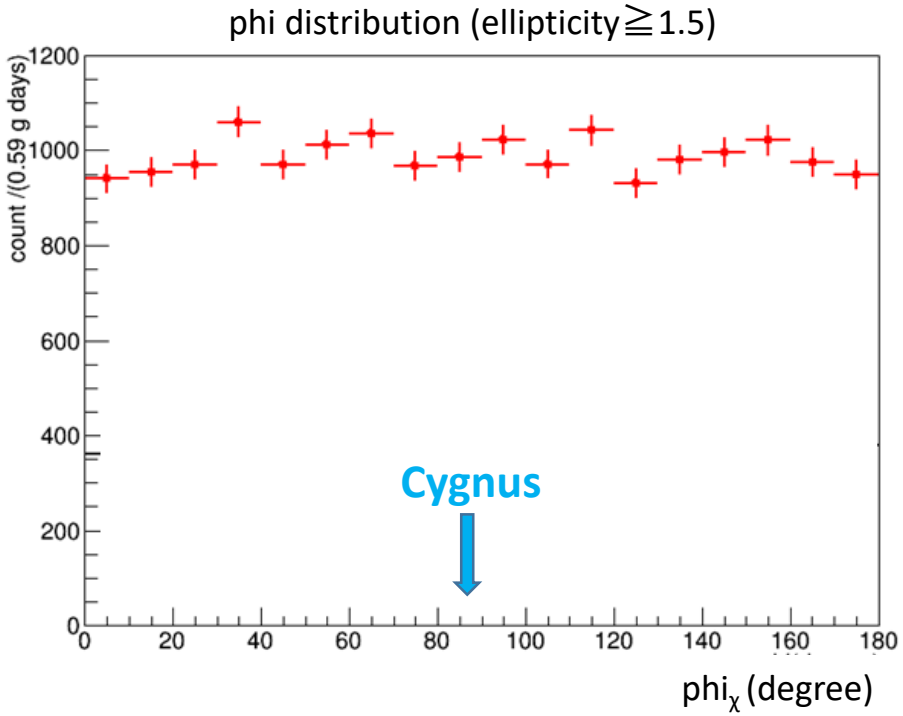
Demonstration of directional DM search [surface run @ Nagoya University]

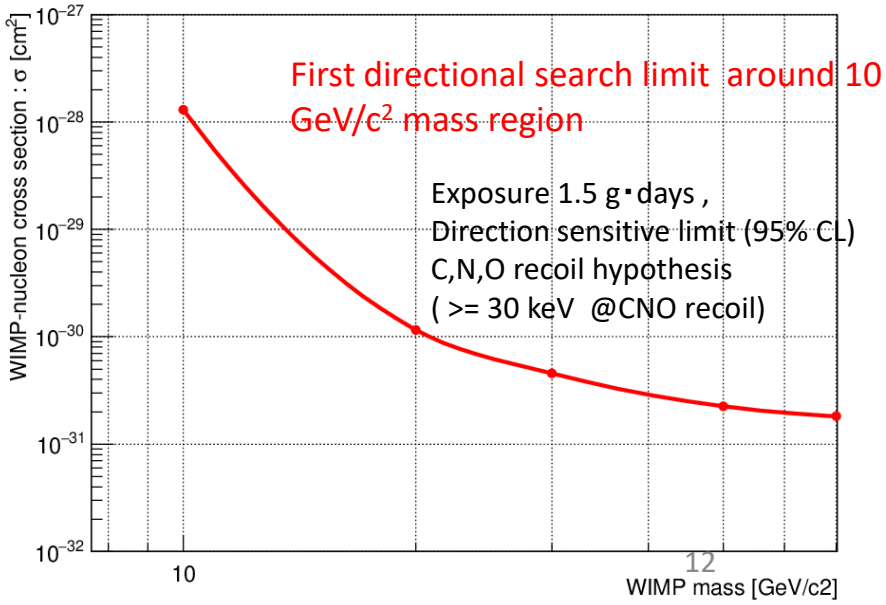
Technical test at surface lab.





Keeping the direction to the Cygnus





- First demonstration of solid tracking detector and directly tracking analysis
- Directional search around 10 GeV/c^2 region is first in the world

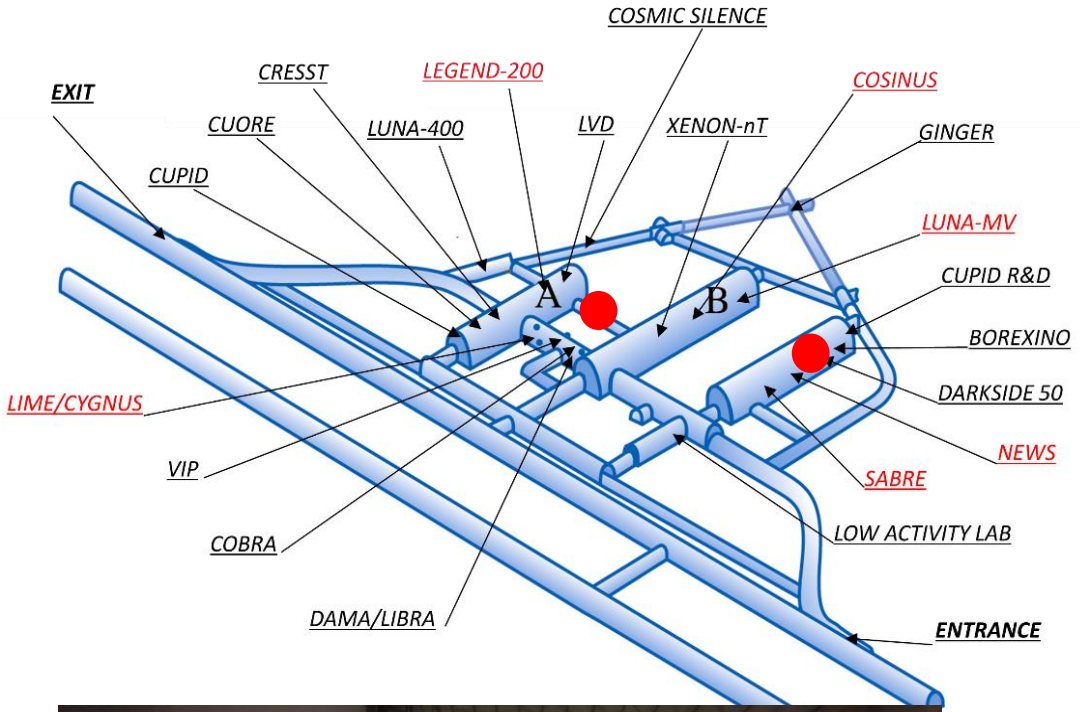
Underground activities at LNGS

Hall F :

- Device self-production with clean room (ISO class.6)
- Device handling and chemical treatment

Hall C :

- Exposure area with shield and device cooling system

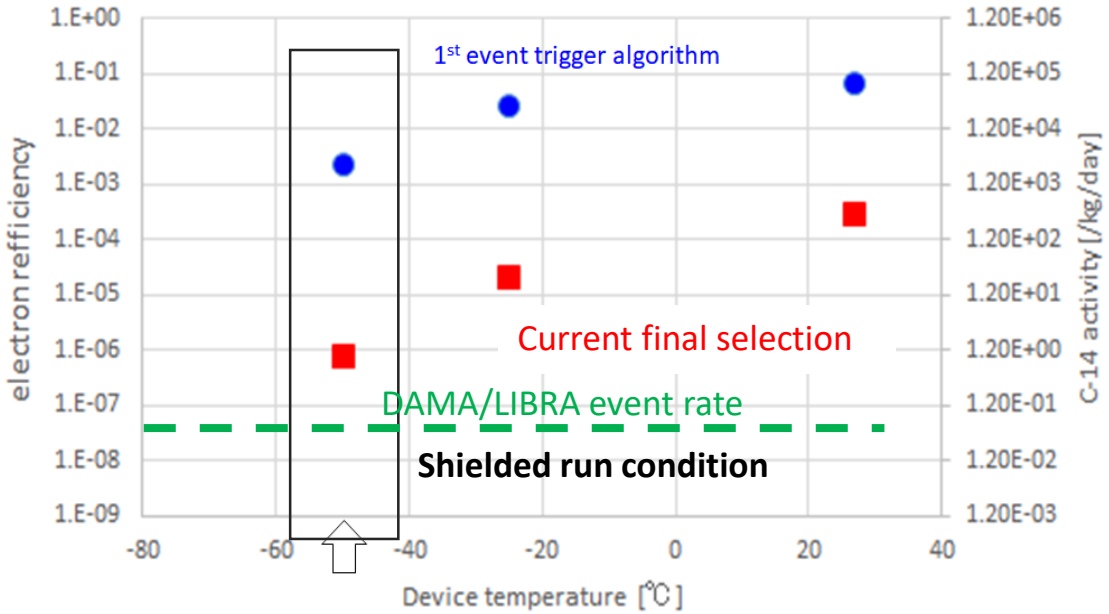


Technical run at Hall.C

[Intrinsic radioactivity in the device]

	Activity [mBq/kg]
U-238	42
Th-232	7-21
K-40	40-130
Ag-108m	50
C-14	24000

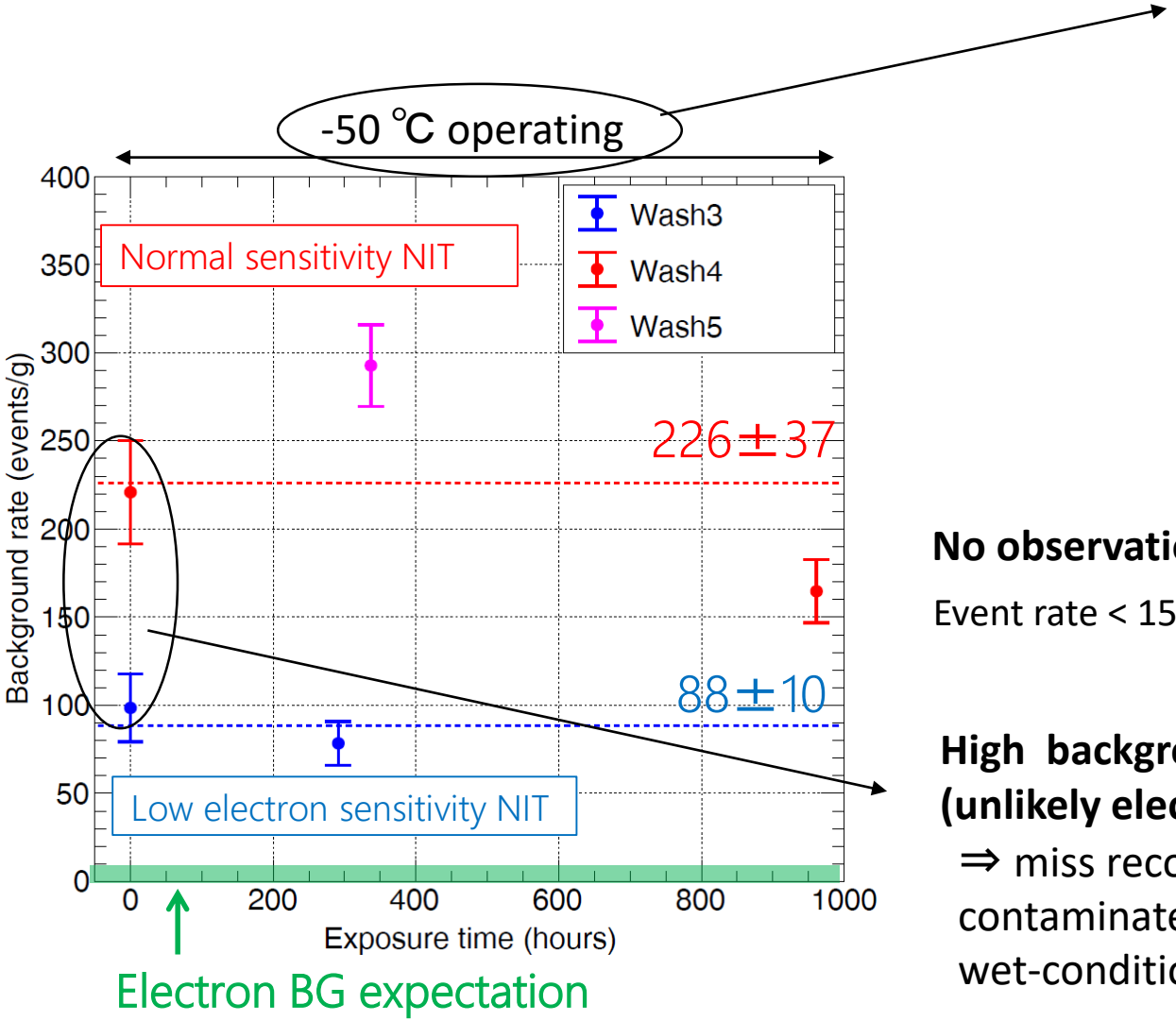
Temperature dependence for electron efficiency

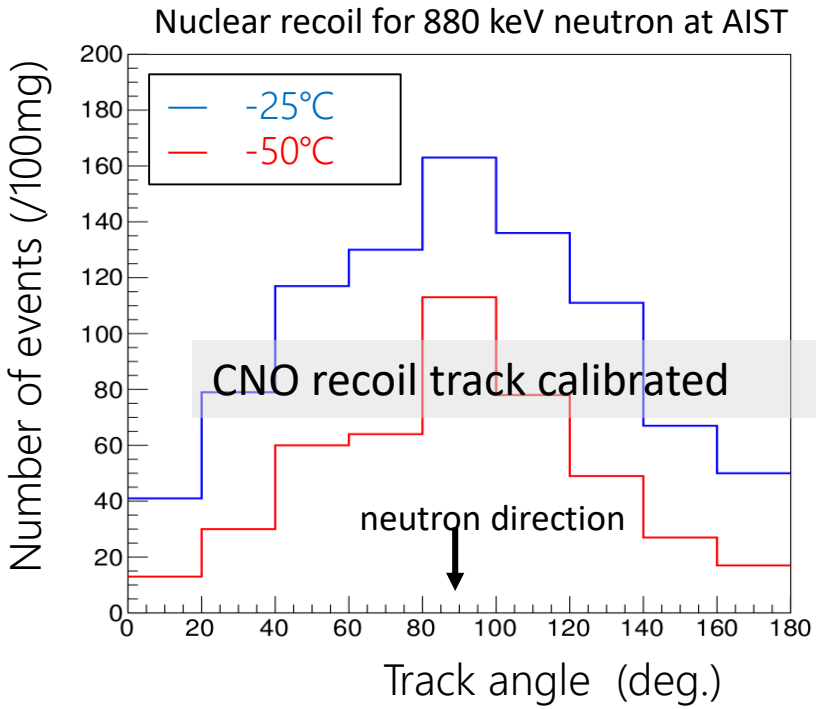


- Low-temperature operation to keep the emulsion stability
- Electron background rejection using temperature dependence of sensitivity for the energy deposition

	Flux @ underground	Event rate for current selection condition [/kg/day] outside the shield	Event rate for current selection condition [/kg/day] w/ shield
μ	**~10^{-8} /cm²/s**	**< 1 x 10^{-2}**	**< 1 x 10^{-2}**
Environment γ-ray	**0.38 /cm²/s**	**~ 1.8 x 10^{5}**	**< 100**
C-14 (intrinsic)		**~100**	**~100**
Neutron	**~10^{-6} /cm²/s**	**< 0.1**	**< 10^{-3}**

Underground BG run status





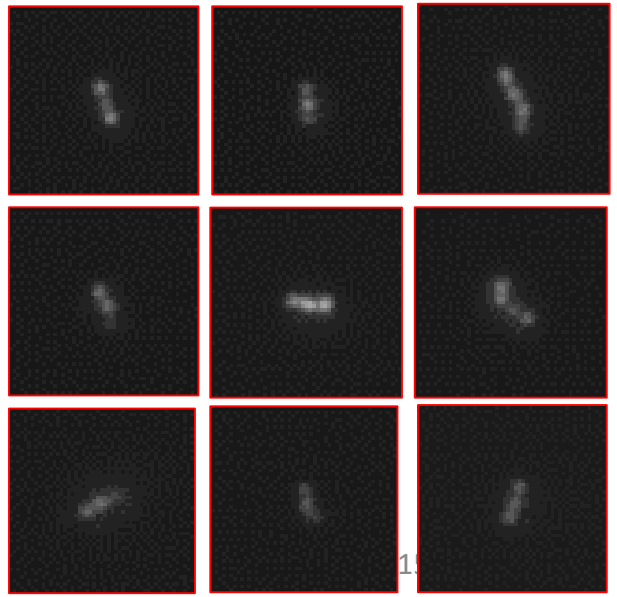
No observation with time dependent signal

Event rate < 1510 events/kg/day (95%CL)

Preliminary

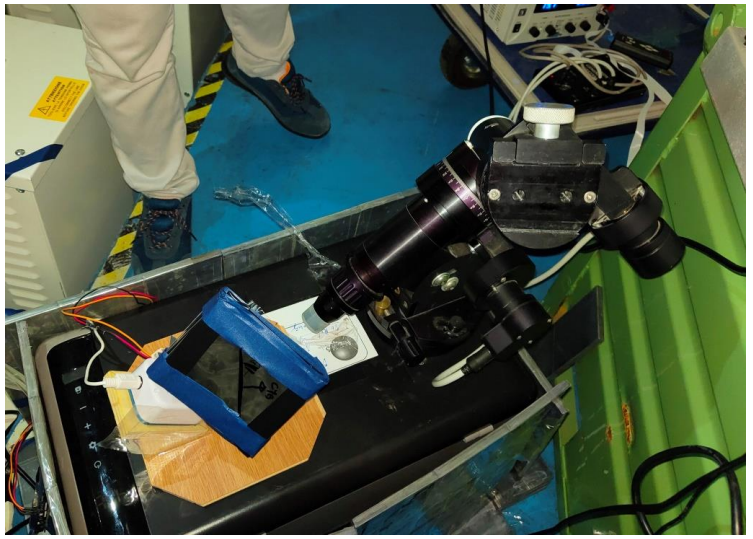
High background contamination (unlikely electron BG)

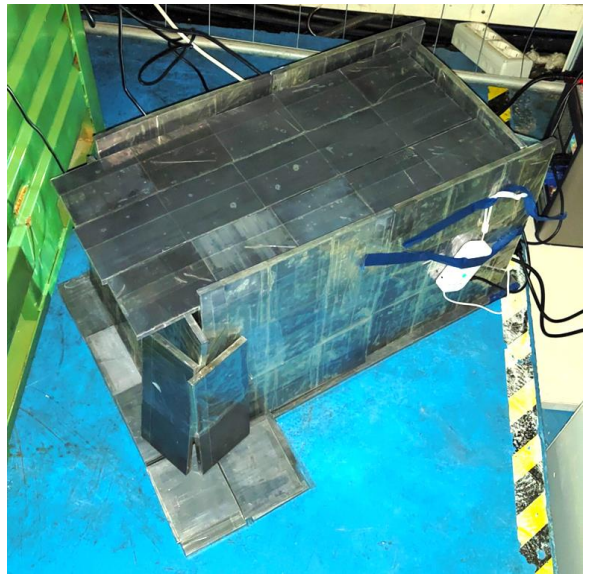
⇒ miss reconstructed α-ray BG contaminated and emitted in the wet-condition are suspected.

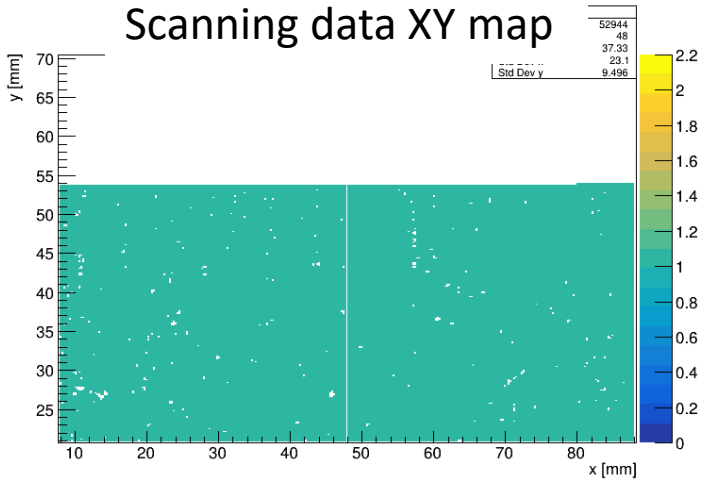


Current activities for lower BG condition and telescope run

On going the BG investigation in the Rn free clean room at Hall.C





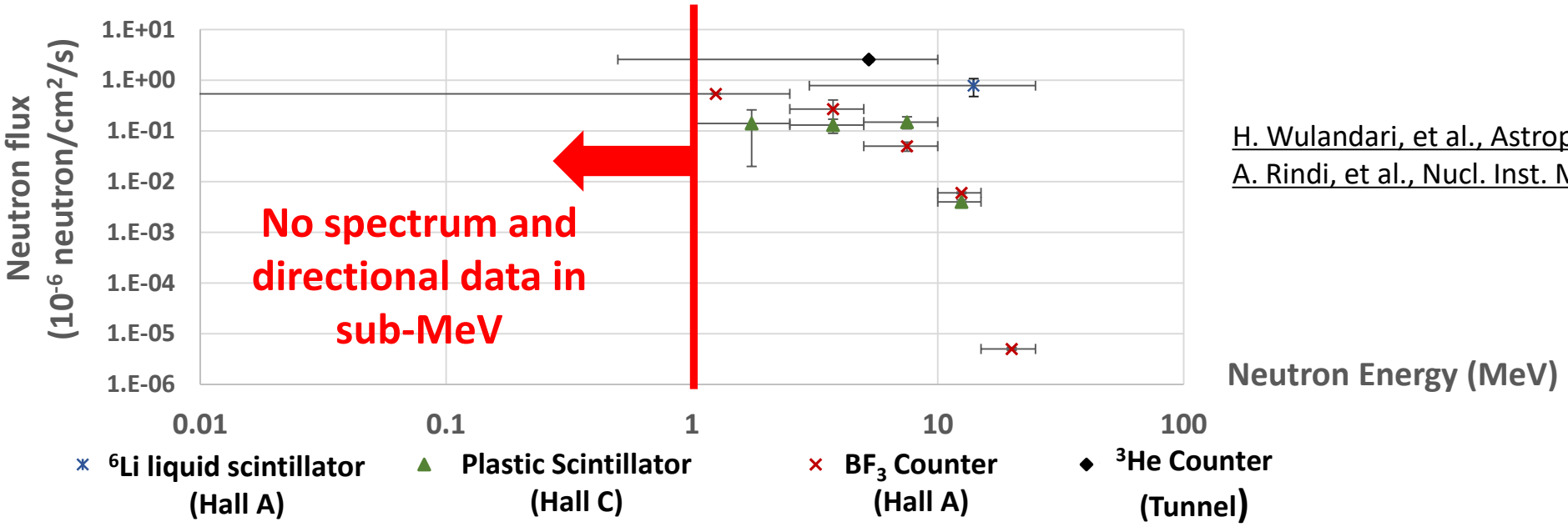


Operation temperature : -15℃
Shield condition : 2cm Pb

Total exposure : ~ 0.1 kg▪day

Data taking is on going

Environmental Neutron Measurement @LNGS

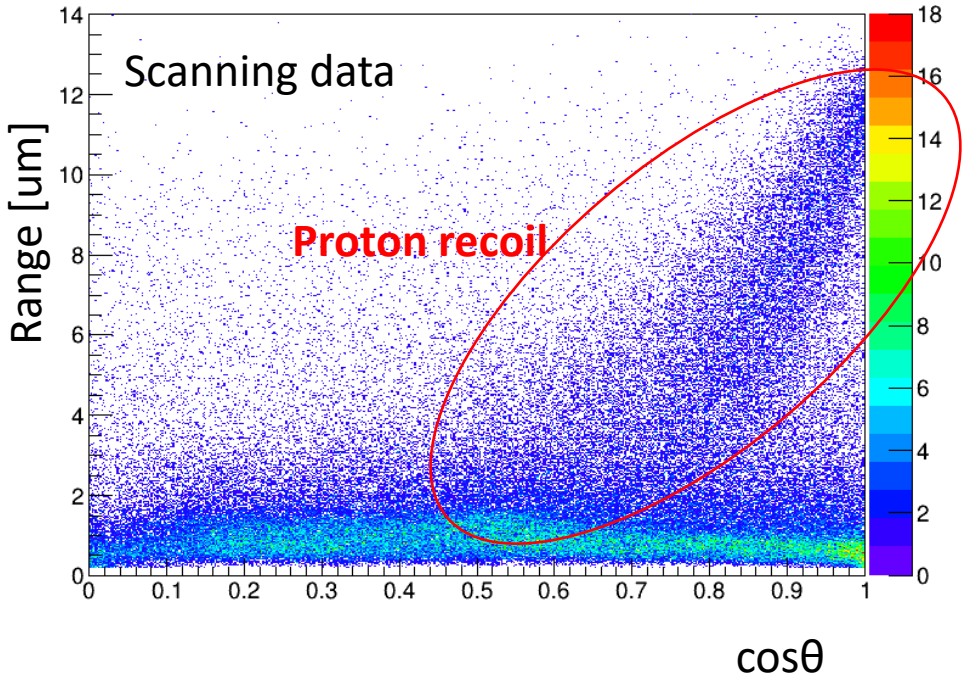


H. Wulandari, et al., Astropart. Phys. **22** (2004) 313.
A. Rindi, et al., Nucl. Inst. Meth. A, **272** (1988) 871.

Neutron Detector	Energy Range	γ-ray rejection power	Energy Resolution	Directionality
Liquid Scintillator	1MeV – 100MeV	Bad	Good	None
BF_3 , ^3He Proportional Counter	Thermal – 20MeV	Good	None	None
Proton-recoil Proportional Counter	10keV – 2MeV	Bad	Good	None
Nano Imaging Tracker (NIT)	Thermal & 100 keV –	Good	Good	Good

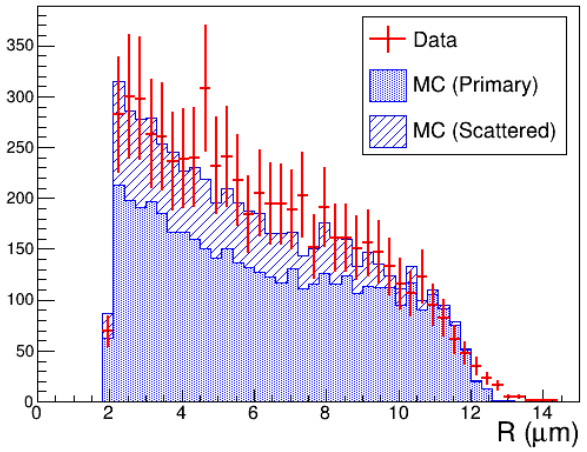
Calibration with Monochromatic Sub-MeV Neutron

Monochromatic 880 keV neutron exposure from T(p n)^{3}He reaction at AIST

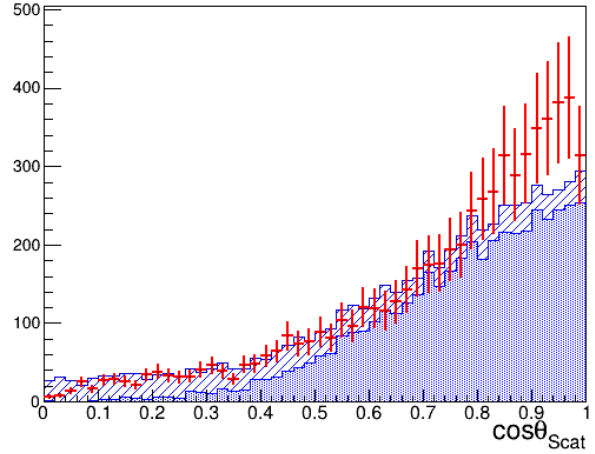


✓ **Detected recoil protons are almost good agreement with kinematical expectation**

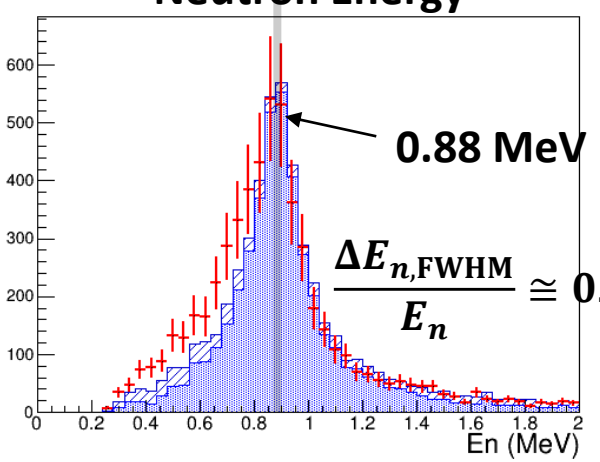
Proton Range



Scattering Angle

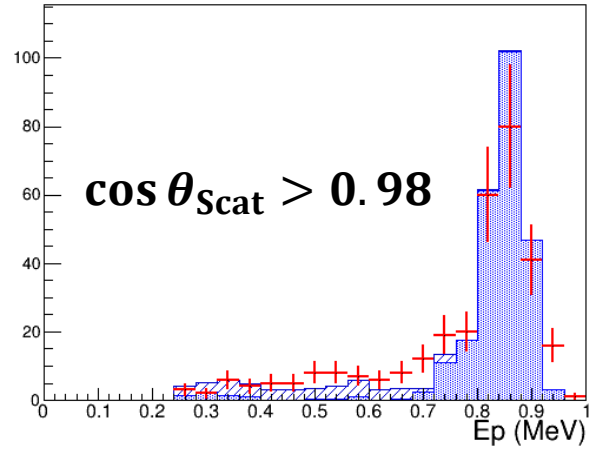


Neutron Energy



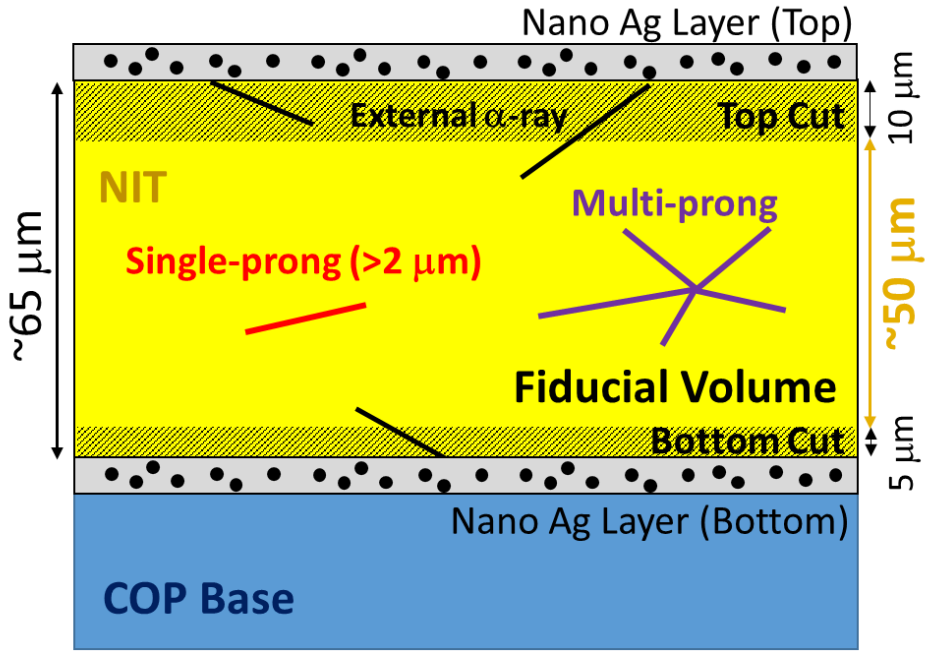
$$\frac{\Delta E_{n,\mathrm{FWHM}}}{E_n} \cong 0.31$$

Proton Energy of Head-on Collision



$$E_n = E_p / \cos^2\theta$$

Event Classification

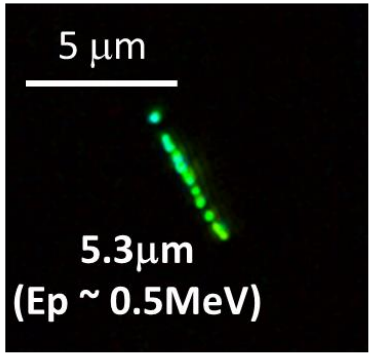


- External α-rays are excluded by fiducial volume cut, then events are topologically classified to **Single-prong** and **Multi-prong**

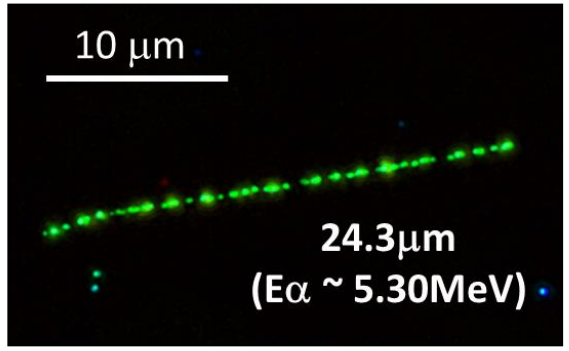
- **Focused on sub-MeV region (2~14μm → 0.25~1MeV) of Single-prong event to analyze with background free**

Single-prong Event

Neutron elastic scattering



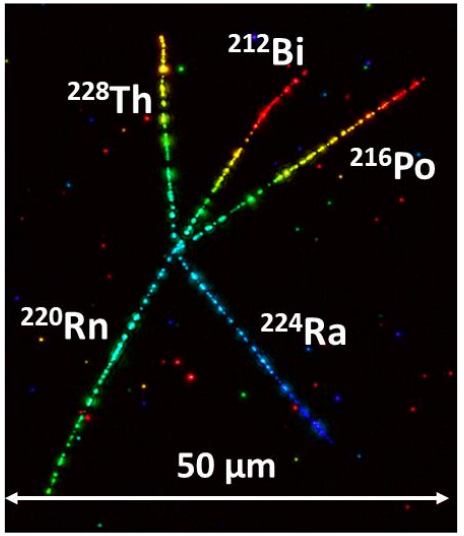
Single α-decay from ^{210}Po



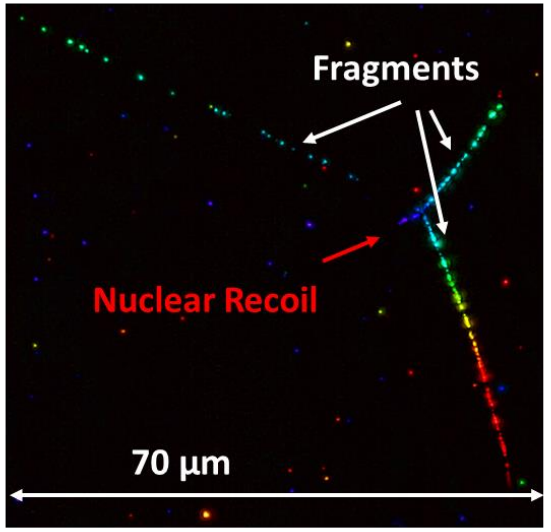
*** Recently, event selection threshold was improved 2μm → 1μm**

Multi-prong Event

^{228}Th star (5 prong α-decay)

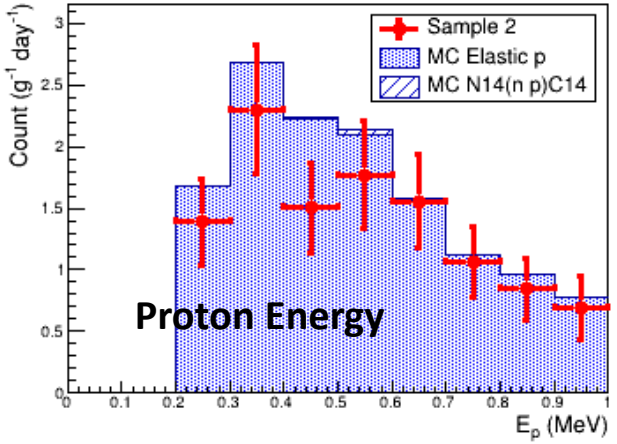


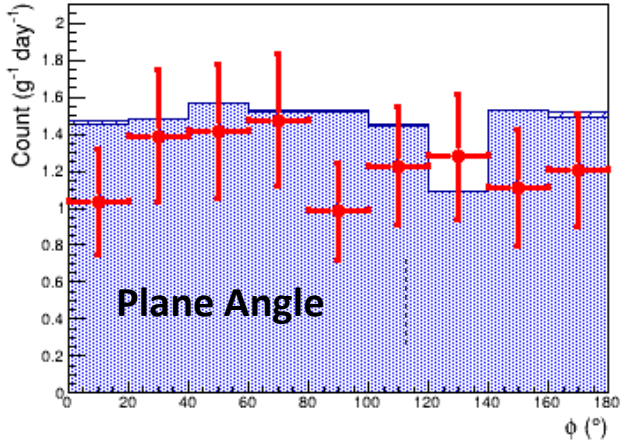
Neutron inelastic scattering

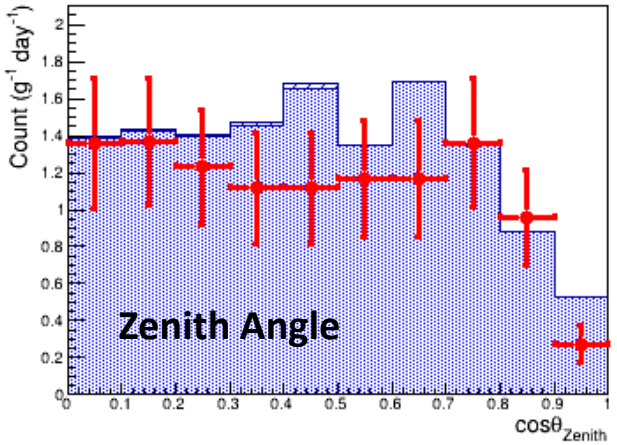


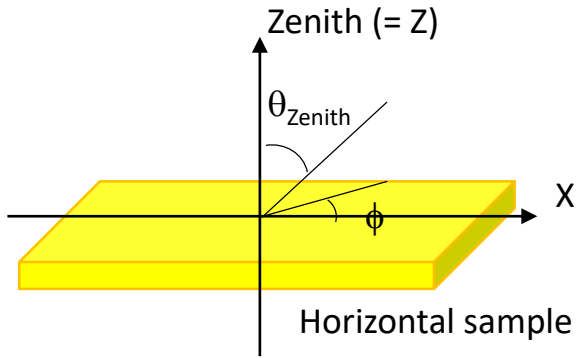
Demonstration of directional neutron measurement with sub-MeV scale

	Sample 1	Sample 2
Surrounding environment	Portable freezer box (outdoor)	
Altitude	1400 m	
Expected angle-integrated flux of atmospheric neutron in 0.25 – 10 MeV (assumed water fraction in ground as 20%)[12]	9.0×10^{-3} cm^{-2} s^{-1}	
Operation temperature	−20 °C	
Run start date	24 Nov. 2021	
Preparation time in underground (days)	2	2
Exposure time (days)	2	29
Installation direction	Horizontal	
Analyzed area (cm^2)	46.7	99.4
Analyzed mass (g)	0.67	1.40









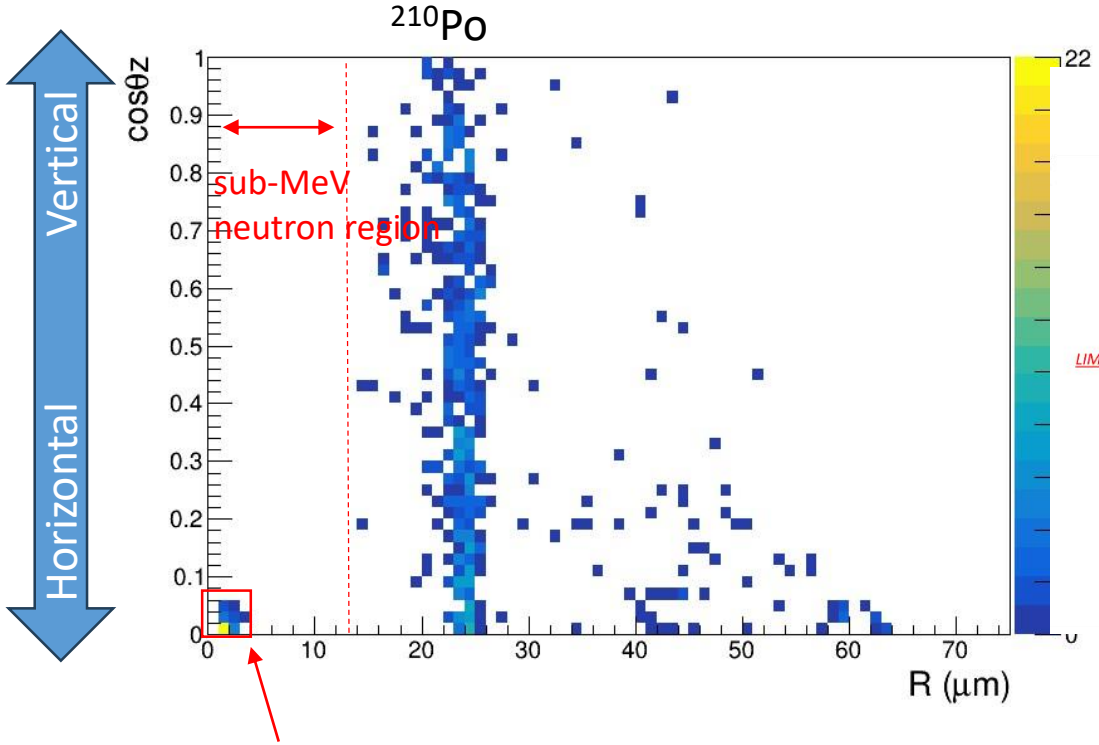
Number of Events [Flux in 0.25 ~ 10 MeV]

Data : 11.1±2.5 event/g/day

⇒ (7.4±1.7) x 10^{-3} cm^{-2} s^{-1} **Phys. Rev. C 107, 014608 (2023)**

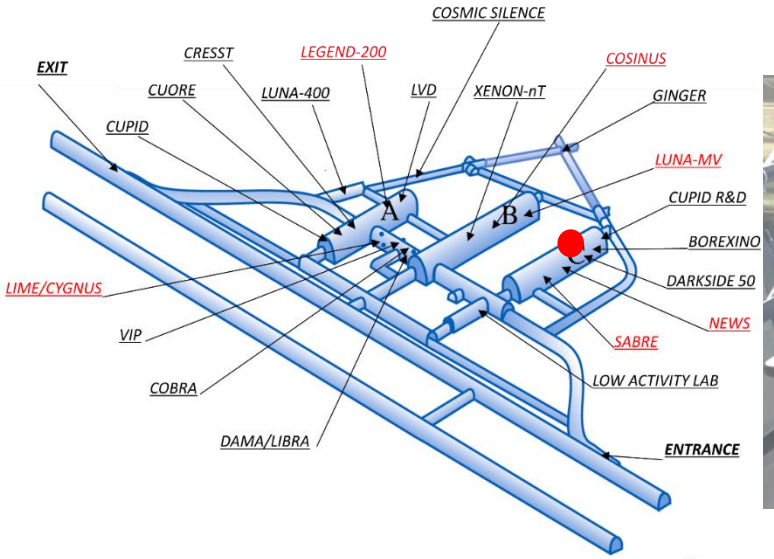
Underground Neutron measurement

~0.04 kg･day analyzed in the ~0.9 kg･day exposure device



Mask cosθz < 0.05 && range < 3μm

Backgrounds from α-ray before drying process of emulsion plate are expected.
⇒ To be investigated more.

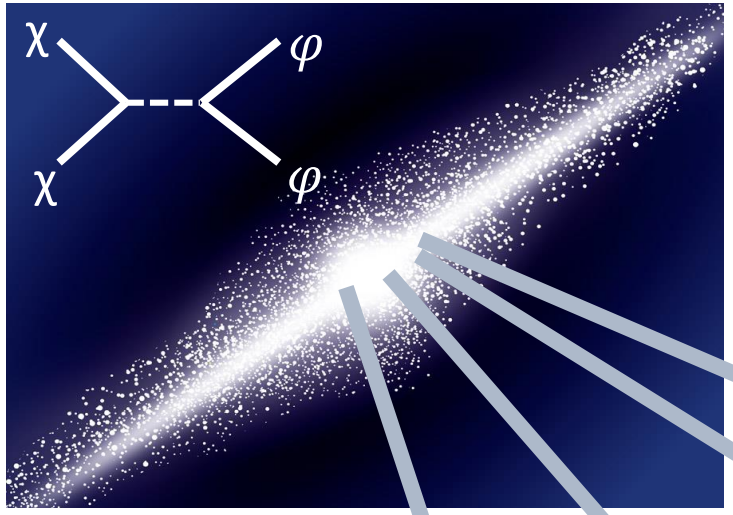


Hall.C exposure
[-15℃ operation]

Current underground neutron flux upper limit
< 4.5 × 10^{-5} /cm²/sec (90%CL) *Very Preliminary

Further exposure run is on going.

DM physics using low-energy (< 1MeV) proton recoil



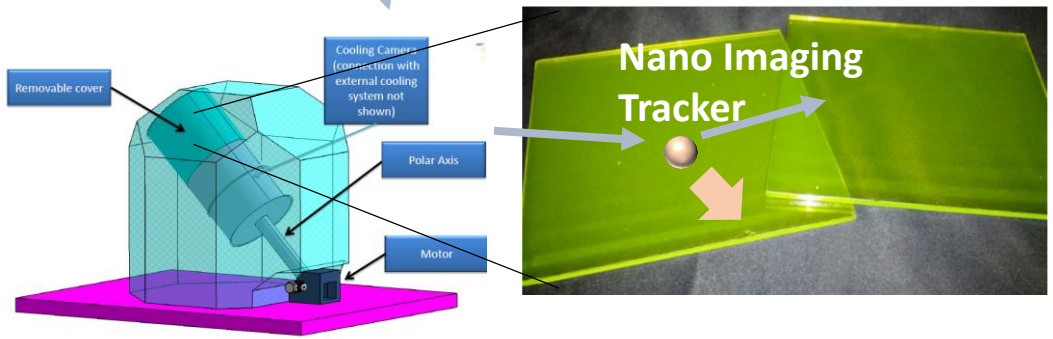
Low-mass dark particle search **with ~MeV scale**

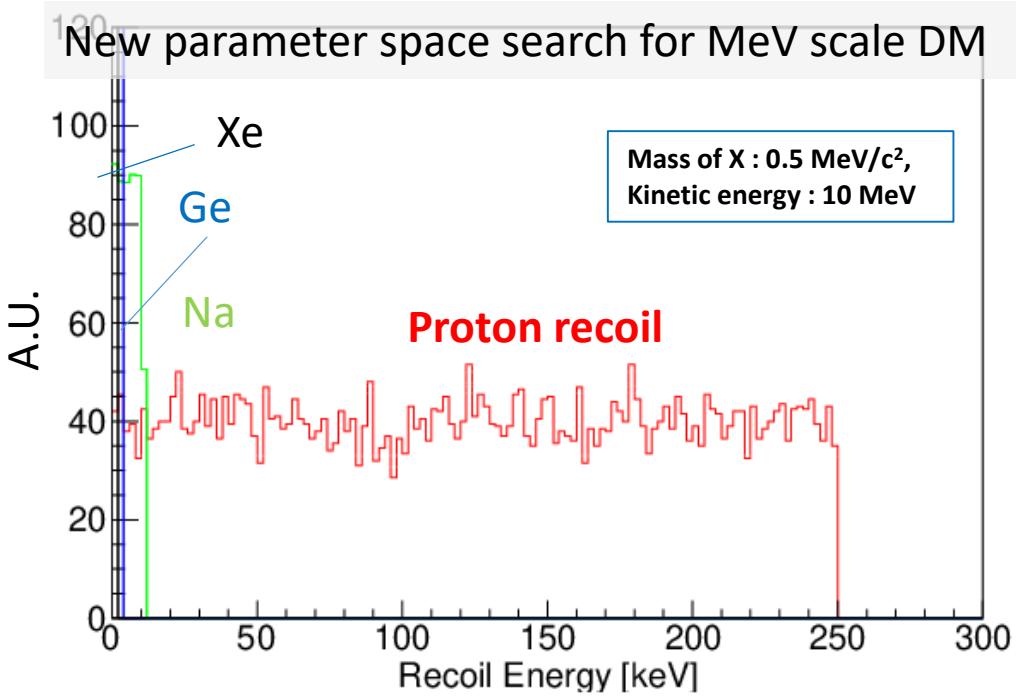
$\chi\chi \rightarrow \varphi\varphi$ [mainly from galactic center]

$\varphi + \mathrm{N} \rightarrow \varphi + N$ **Test of baryon interaction**

arXiv:1405.7370v4

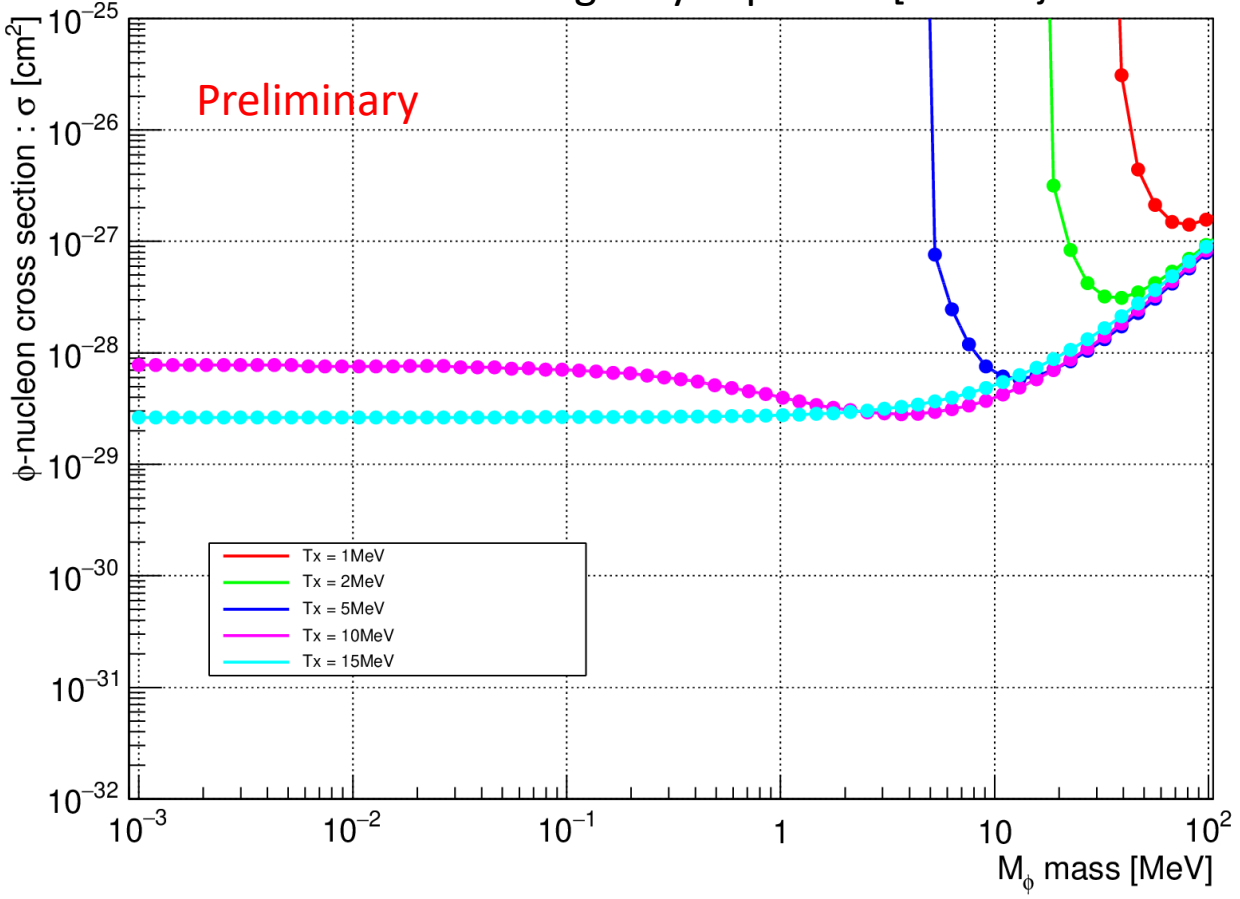
BDM flux on the earth $\phi \sim 1.6\ cm^{-2}s^{-1}\left(\frac{<\sigma v>}{5\times10^{-26}\ cm^3/s}\right)\left(\frac{5\ MeV/c^2}{M_1}\right)^2$





Expected sensitivity limit for emitted dark particle – nucleon cross section from GC

Expected sensitivity for neutron measurement condition with 1kg・day exposure [90%CL}



- The run with 1kg・day exposure are on going as neutron measurement (but not used the telescope yet).
  ⇒ Scanning will be started from next month.
- Further scale up experiment with telescope is now on preparing.
- Theoretical discussion is also on going, such as any specific particle physics model, validity for cosmology.

Conclusion

- Directional sensitive search for dark matter is important methodology for identification of dark matter behavior in the MW halo.
- Fine-grained nuclear emulsion is implementable tracking detector with capability of detecting nano-scale nuclear recoil tracks.
- Directional search with telescope on the surface lab. was demonstrated, and directional search around 10 GeV/c^2 mass range was carried out.
- NEWSdm experiment is on going at underground lab. of LNGS.
- Telescope run in underground have been started, and data taking is on-going.
- In parallel, direction sensitive neutron measurement around sub-MeV energy range is on-going.
  ⇒ surface run was done
  ⇒ underground run is on going (now is no background for > 1μm proton signal)
- New parameter space search for MeV scale dark sector using proton recoil is also on-going.