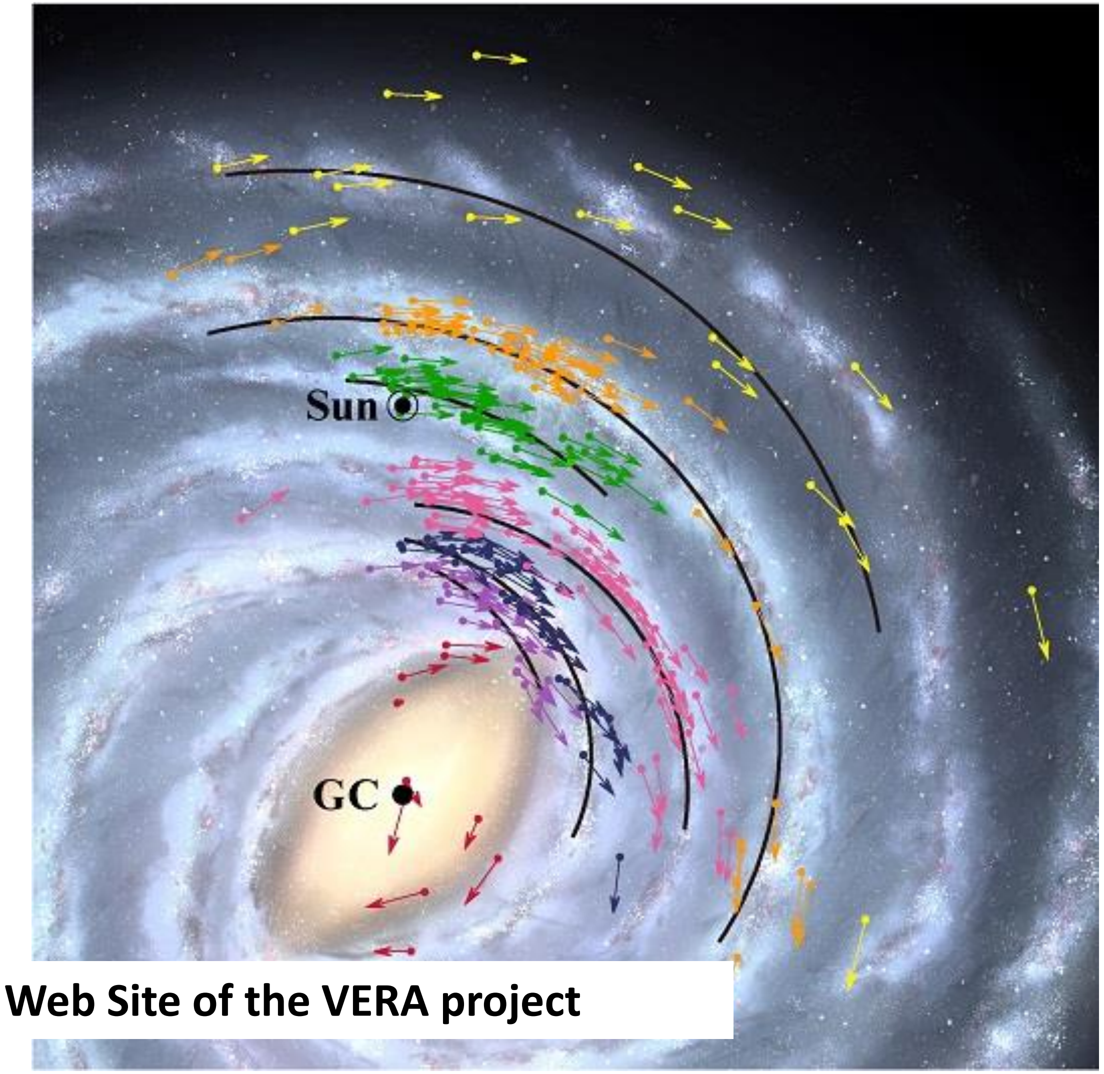
原子核乾板による方向に感度を持つ暗黒物質探索実験

東邦大学
中　竜大
NEWSdm collaboration

第2回　新学術「地下宇宙」若手研究会 2021.11.25@ 神戸大学

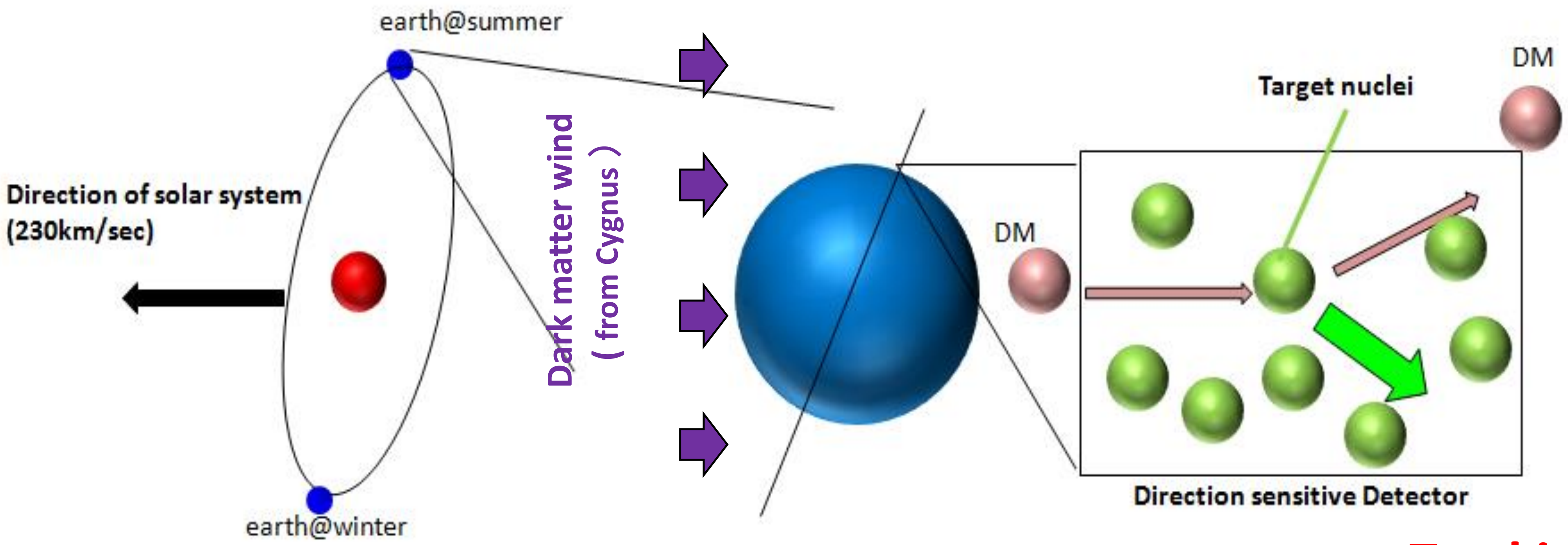
Dark matter in the Milky Way galaxy



From Web Site of the VERA project

- Local dark matter density : 0.3-0.5 GeV/cm^3
- Dark matter flux : O(10^5~10^6) /cm^2/s on the earth @ 10-100 GeV /c2 dark matter
- Astrophysical information is always anisotropic.
- Uncertain astrophysical assumption (e.g., velocity distribution, density profile)

Direction sensitive dark matter search



Counting, energy **<u>+ Tracking</u>**

Advantage of “Tracking ”

Diverse information to only calorimetric data.

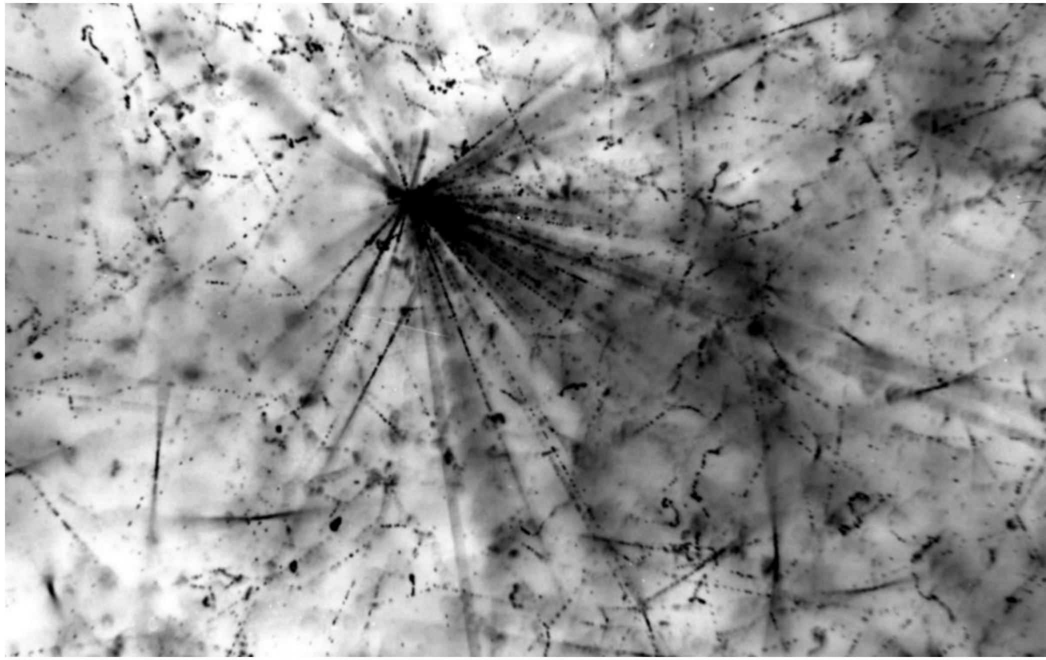
1. Direction

   ➡ identification of the source

2. topological information

   ➡ character of reaction or particle itself

3. Background discrimination

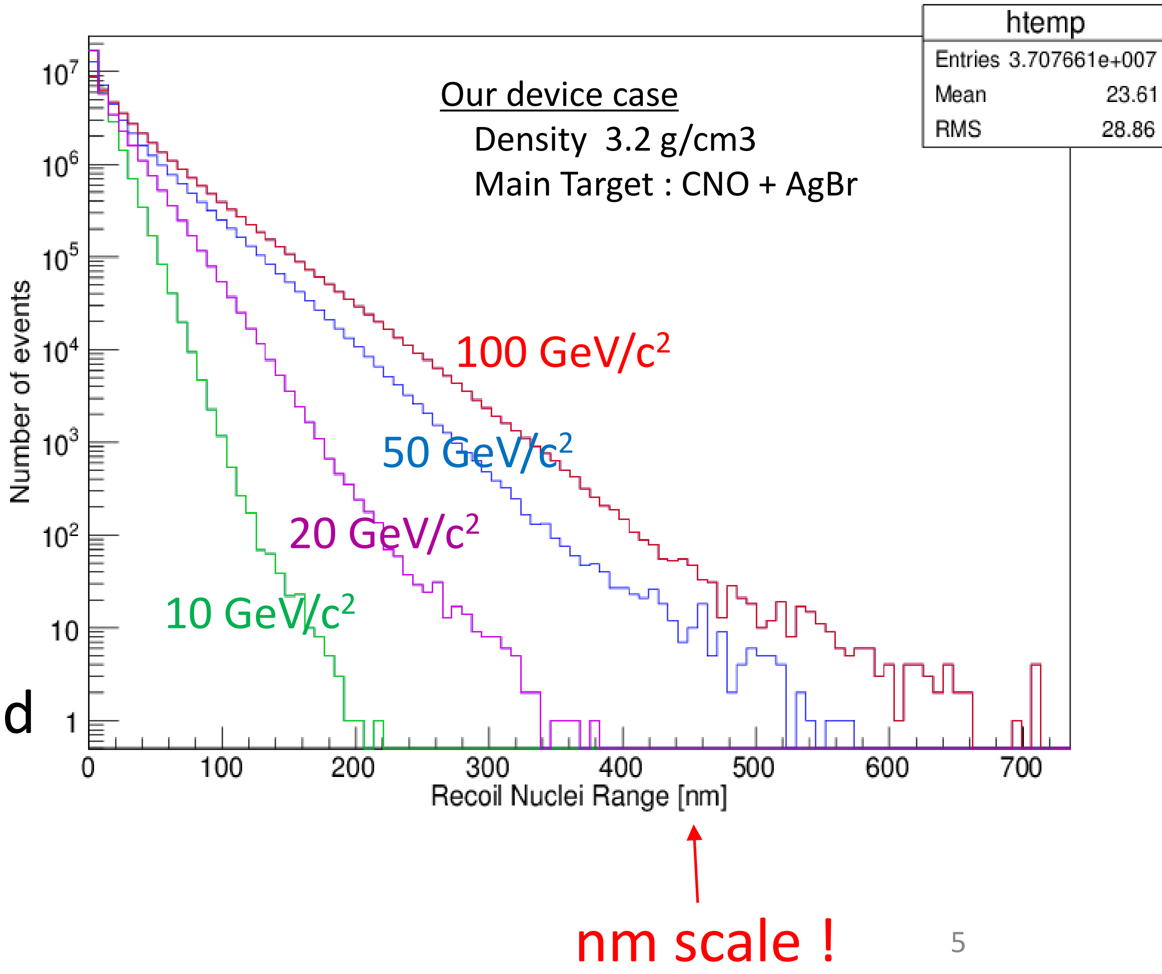


Technical Difficulties for solid (or liquid) detector

- ➢ New technical challenge ; Obtaining the direction information in nm scale

- ➢ Confirmation of the scalability and stability (production, cost, quality) for such new technologies

- ➢ Low-background or understanding the background



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

Chiba
Nagoya
Toho

METU Ankara

Bari
GSSI
LNGS
Napoli
Roma

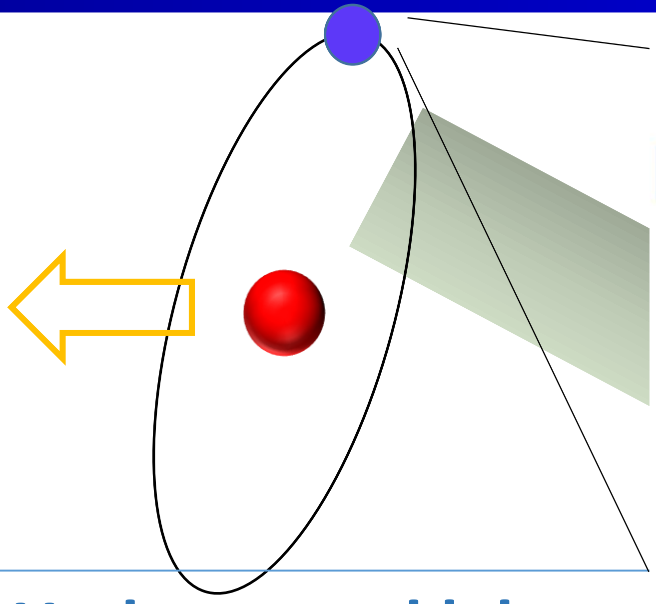
LPI RAS Moscow
JINR Dubna
SINP MSU Moscow
INR Moscow
Yandex School of Data Analysis

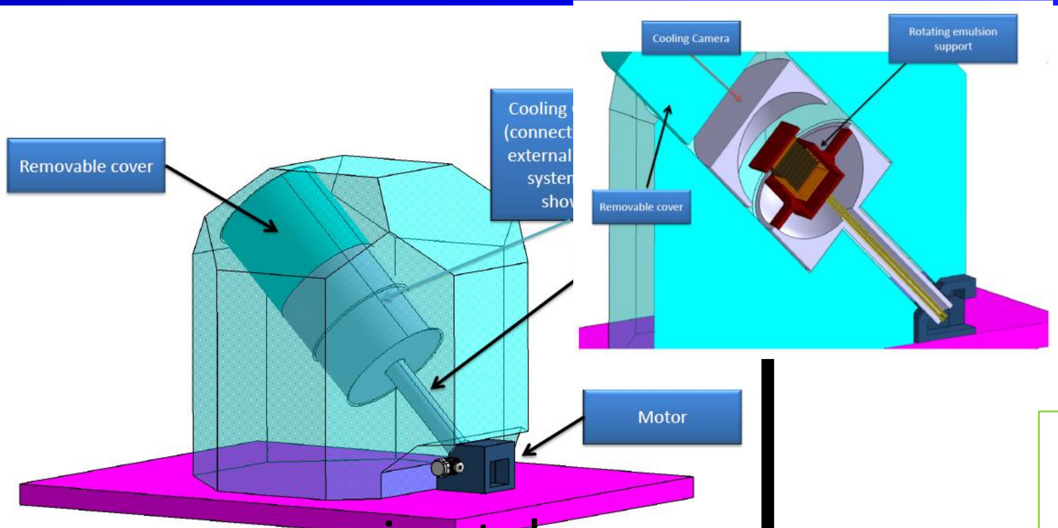
Gyeongsang

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

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

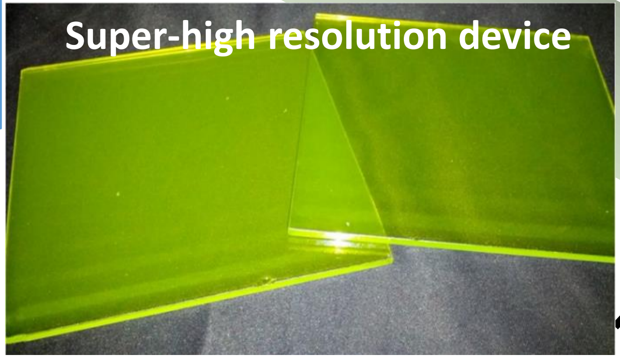
Concept of NEWSdm experiment using very high resolution nuclear emulsion





exposure using telescope

Underground laboratory
[Gran Sasso (LNGS)]



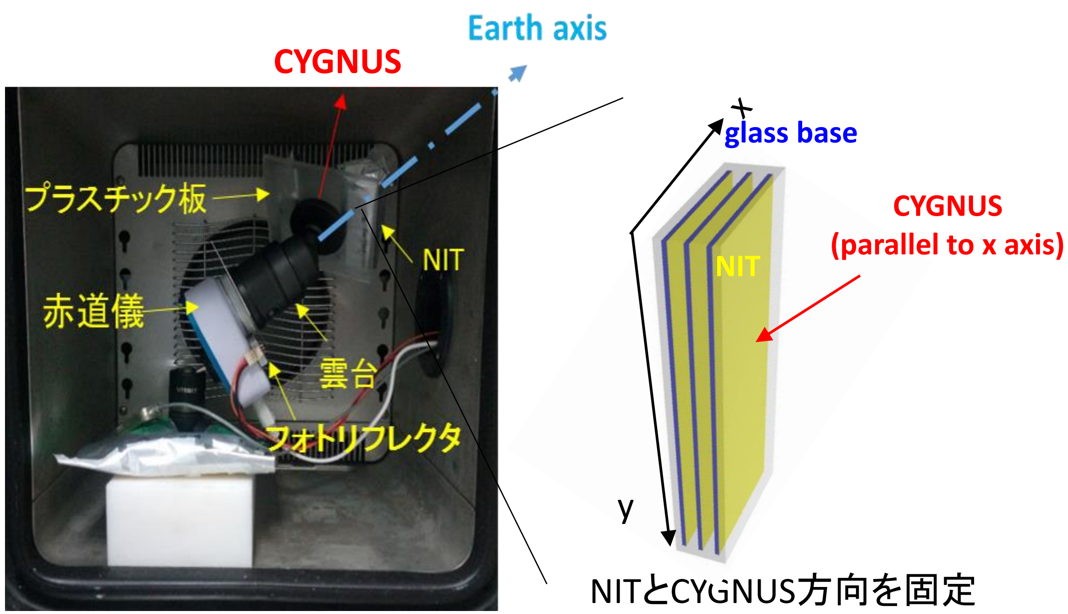
Surface laboratory
[Nagoya, Toho + Napoli, LNGS]

Readout + analysis
Using microscope techniques

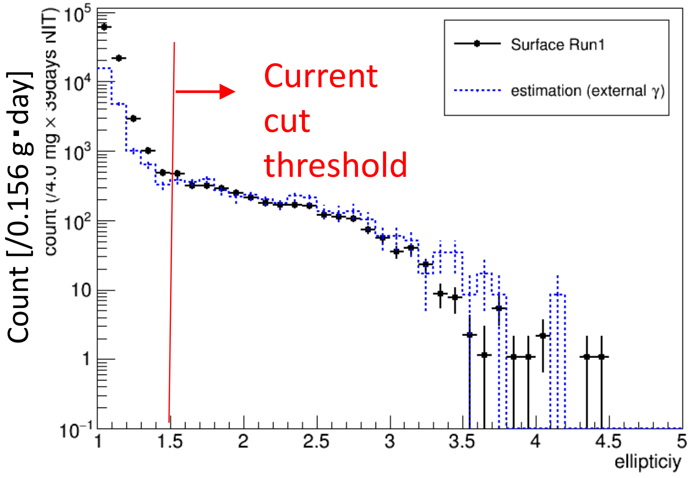
2019-2020 : 地上ランによるdark matter 方向感度実験は試験済み
⇒ 本格的な地下実験へ

Demonstration of directional search at surface laboratory

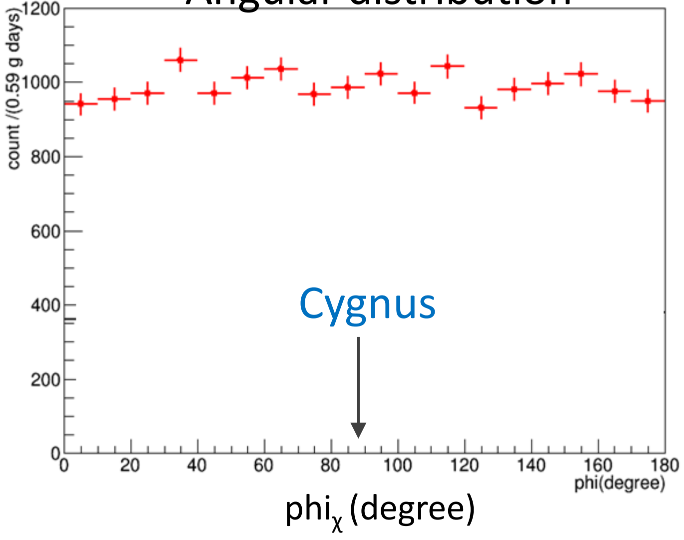
(2021物理学会春季大会 報告 [梅本])



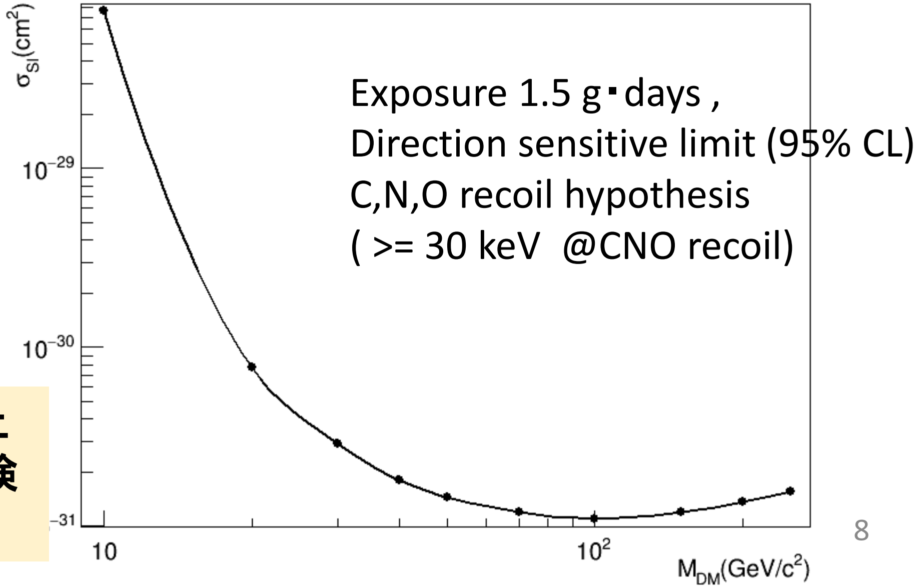
Environment γ-ray dominated



Angular distribution

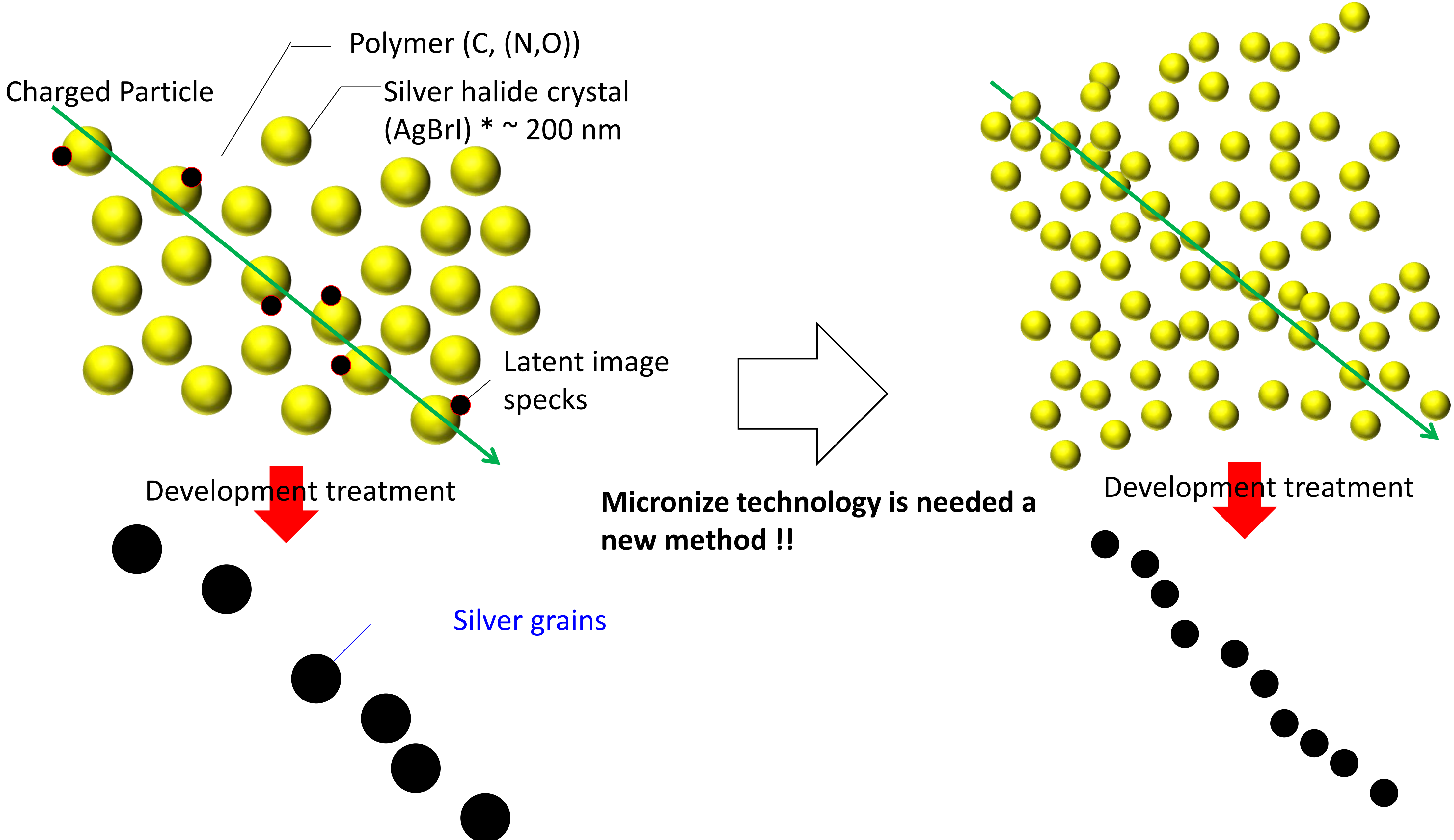


Angular distribution for CNO recoil due to neutron of 880 keV at AIST

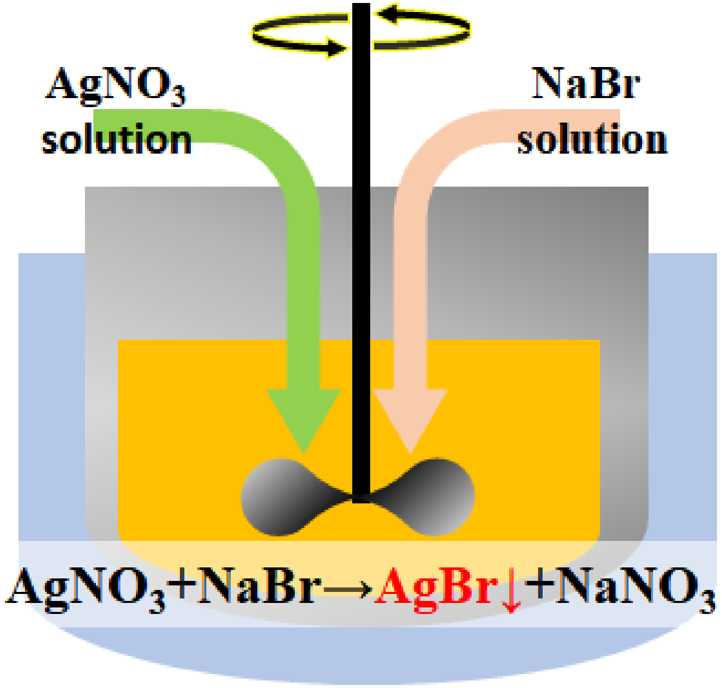


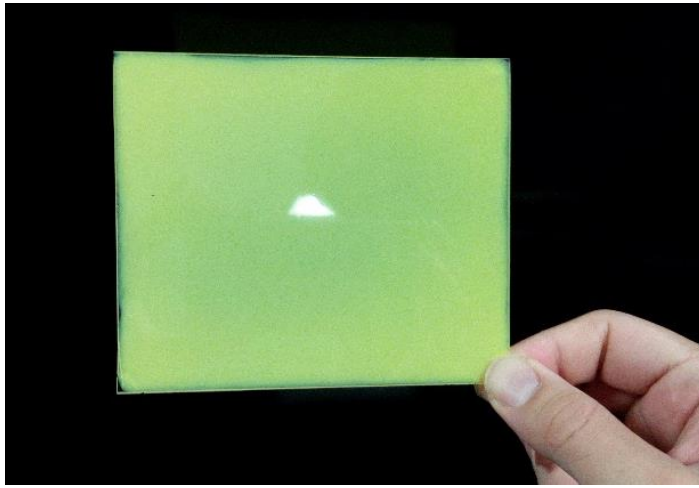
中性子による30 keV 以上の反跳CNO原子核の方検出の実証

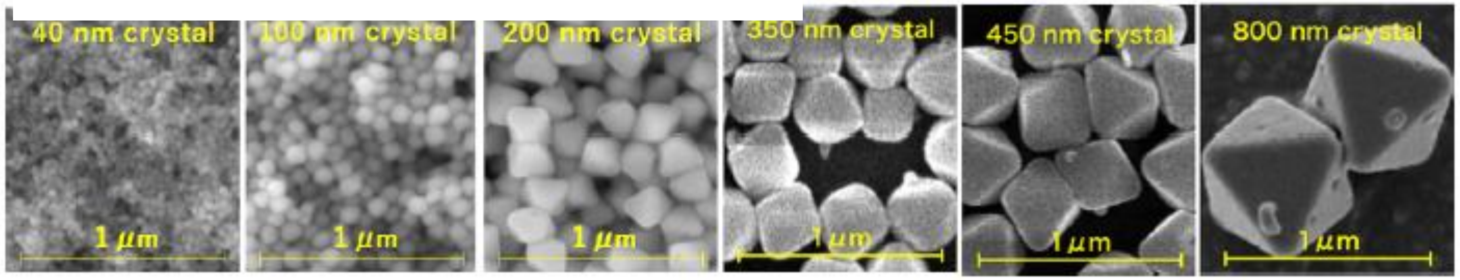
Concept of super-high resolution



Super-fine grained nuclear emulsion



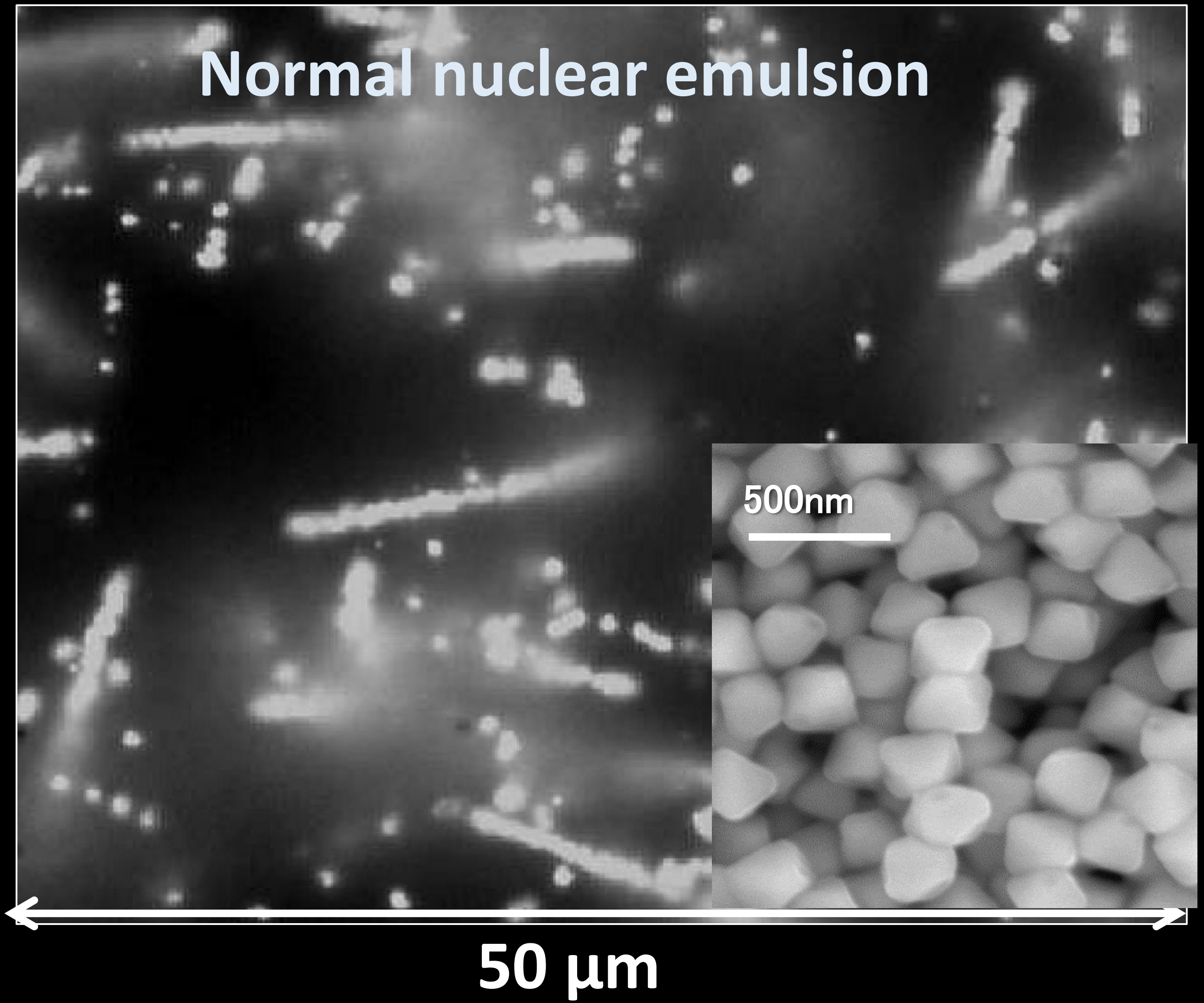


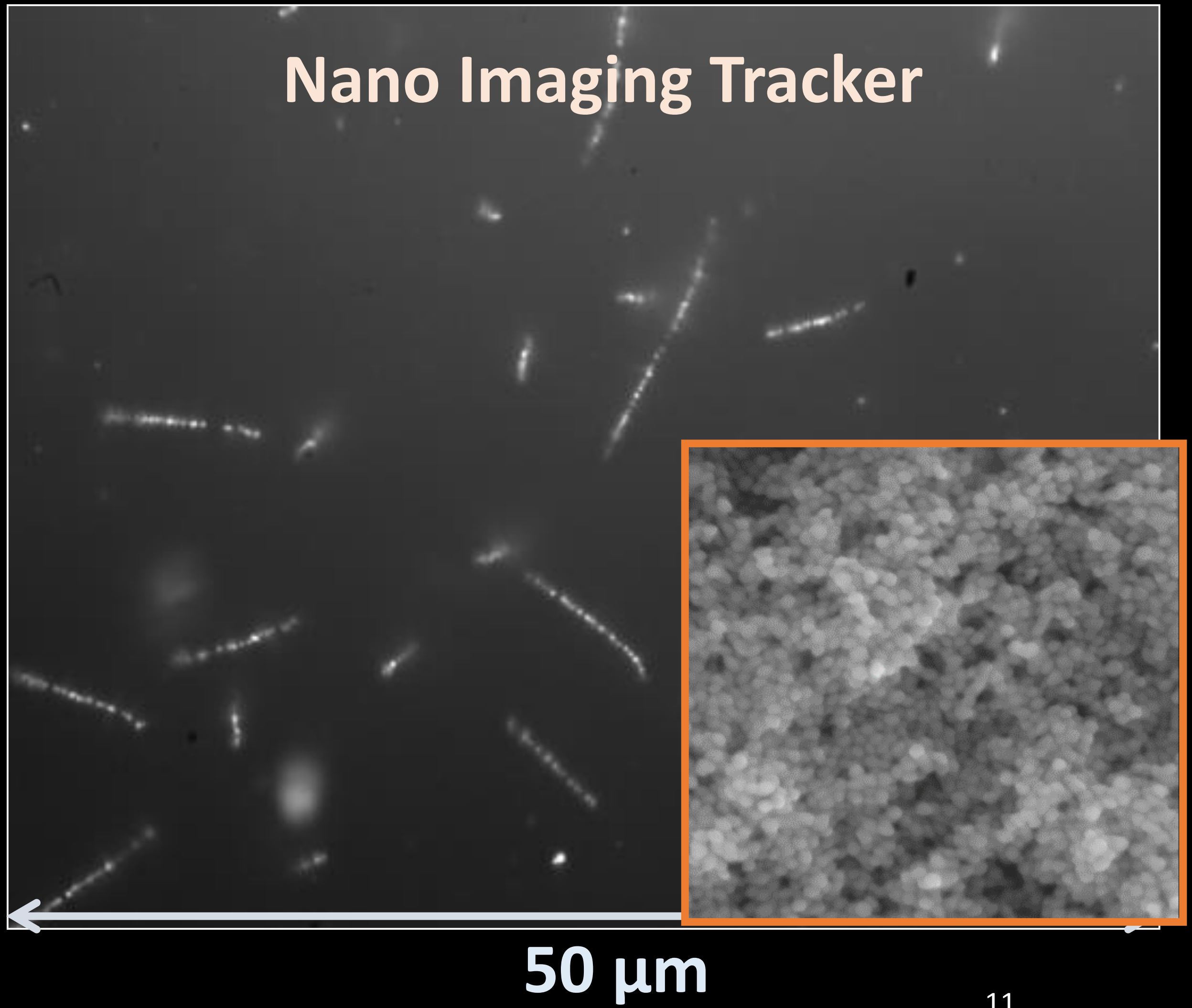


High ← Spartial resolution → Low

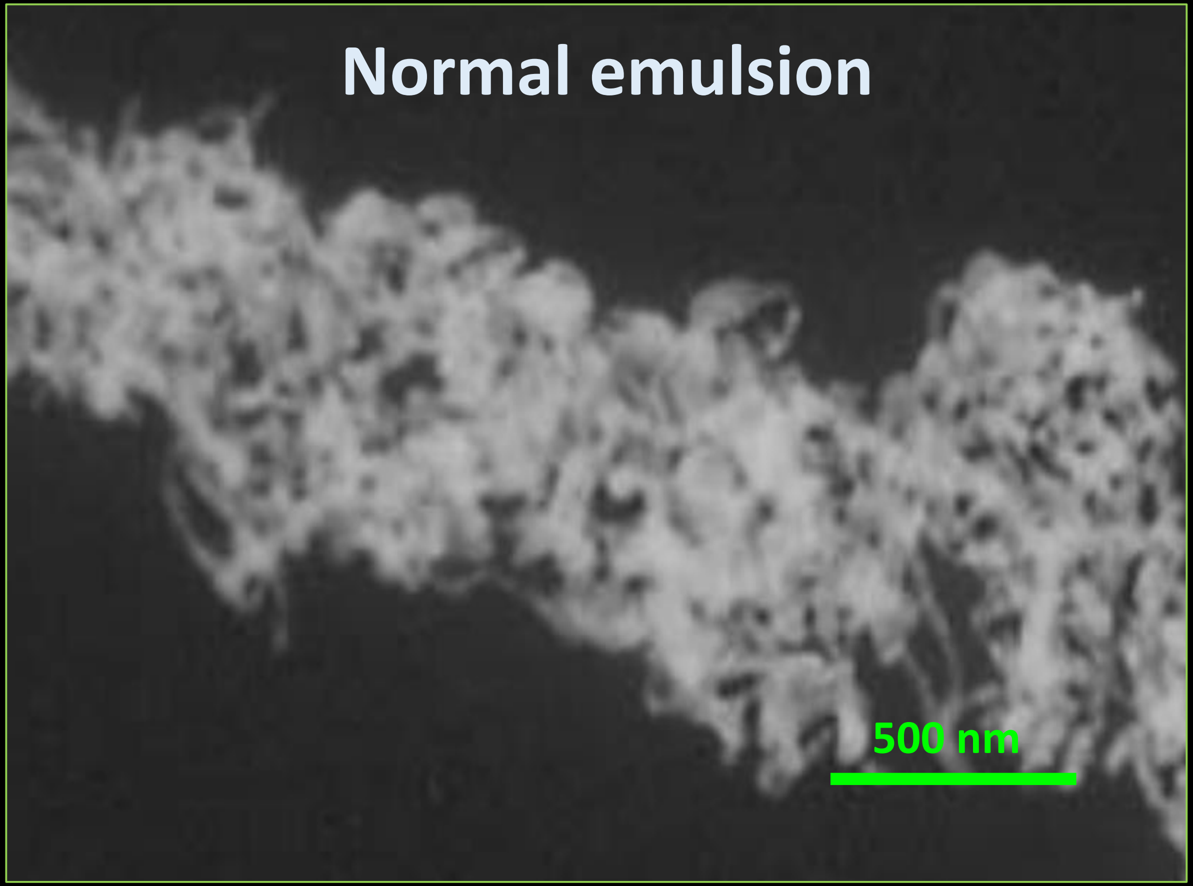
Dark matter detection

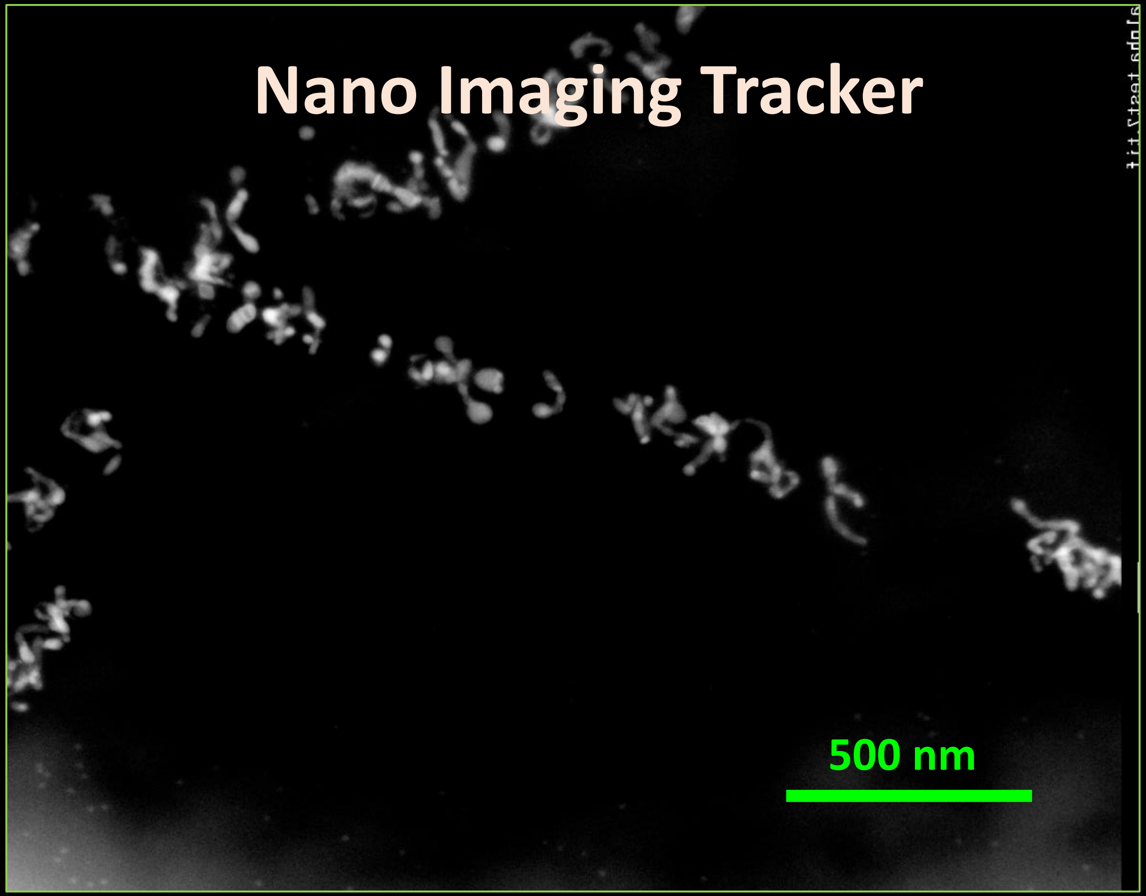
Comparison of alpha-ray tracks between normal emulsion and Nano Imaging Tracker





Case of electron microscope image



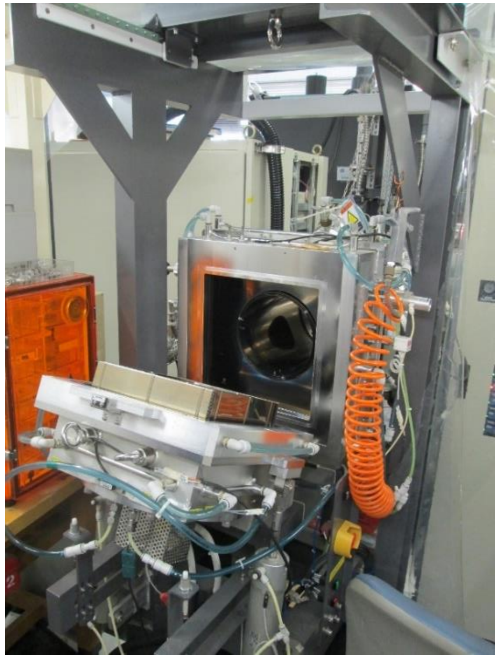


Low-velocity ion tracking

- Mono energy (±0.1 keV)
- Good direction uniformity (<10 mrad)
- C,N,O, Kr + H (Kanagawa)
- (various kind ions are also possible)

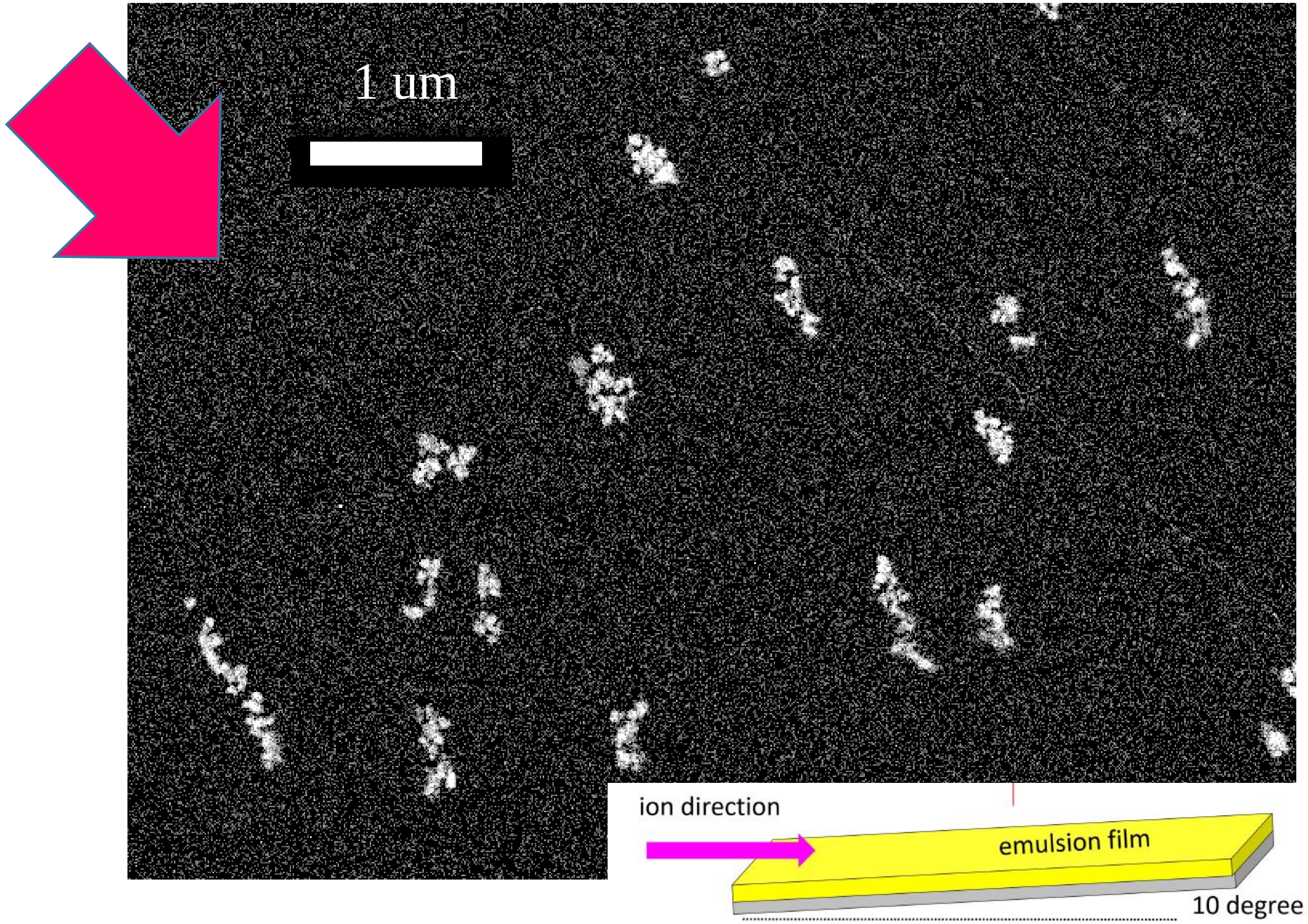
Ion-implantation system

@ Nagoya u.



@ Kanagawa u.

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

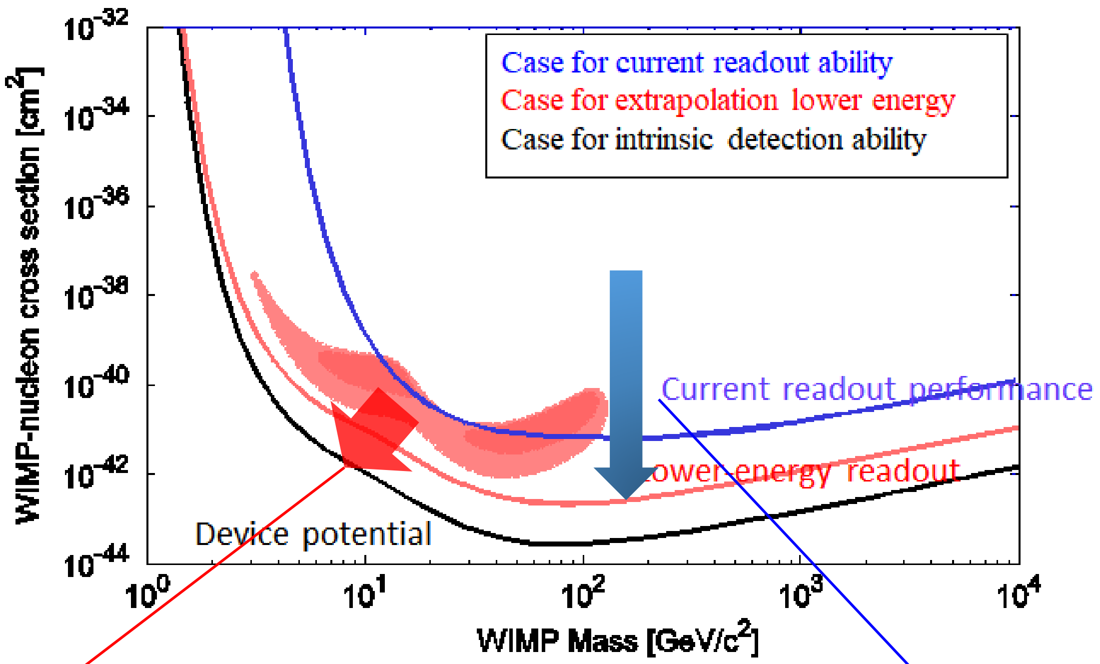


Elemental composition of NIT

	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

Heavier DM (Ag, Br, I)
Lighter DM (C, O, N)
neutron (H)

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



Proton recoil
- **Neutron measurement**
- Lower-mass dark matter search

低閾値化
- Finer grain emulsion
- Super-resolution imaging

Now on progress

低バックグラウンド化
- ☐ 低BGデバイス
- ☐ AgBr(I)感度特性
- ☐ 事象解析の高度化

高速読み取りシステム
- 高効率事象トリガー
- 読み取り装置高速化＋増設

Data taking machine in Japan

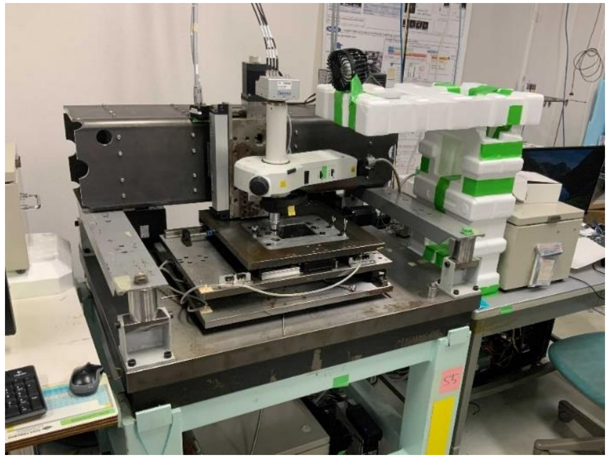
PTS-2 @ Nagoya

- Data analysis R&D
- Quality check of device

⇩

Surface run data analysis

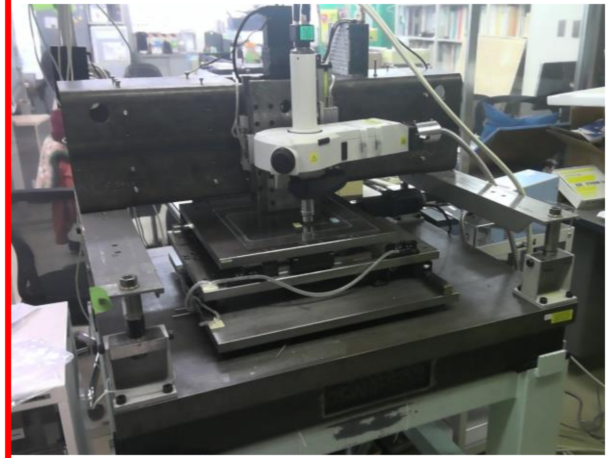
PTS-3 @ Nagoya



- R&D for Higher speed scanning system
- Quality check of device

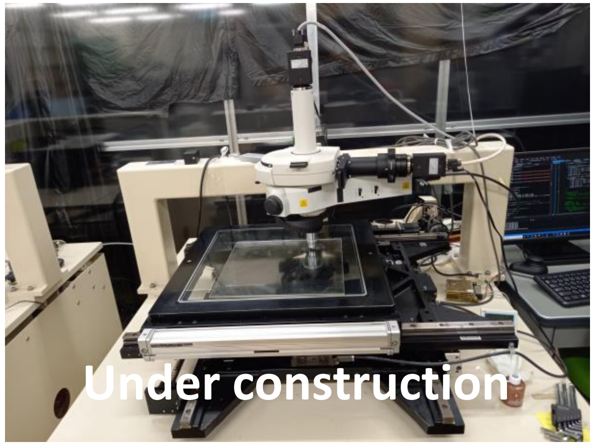
Underground run data taking

PTS-4 @ Toho



- Same scanning speed design with PTS-3
- Run data analysis
- Sub-MeV neutron measurement

C-PTS @ Toho



For color analysis

立ち上げ当初
(2013-2015)

~ 3g/y/machine

・データ取得＋画像処理の効率化
・有効領域拡大

~40 g/y/machine

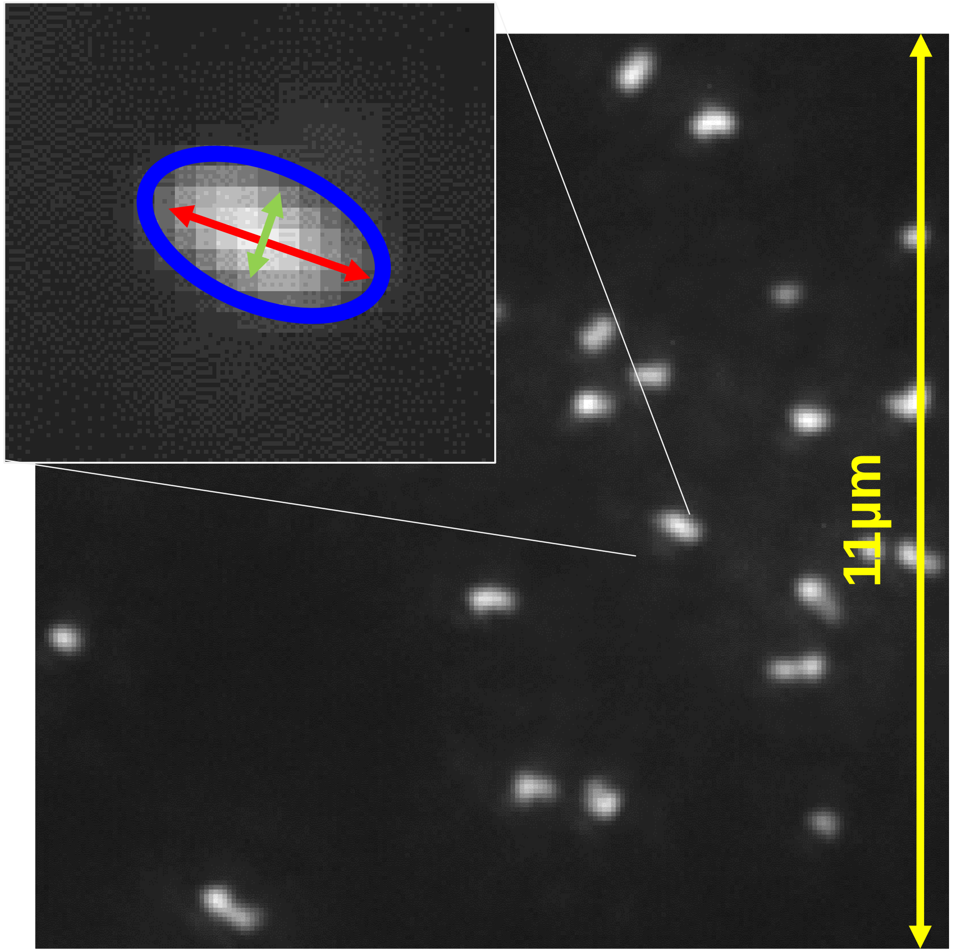
高速撮像スピードカメラ
~ 100g/y/machine

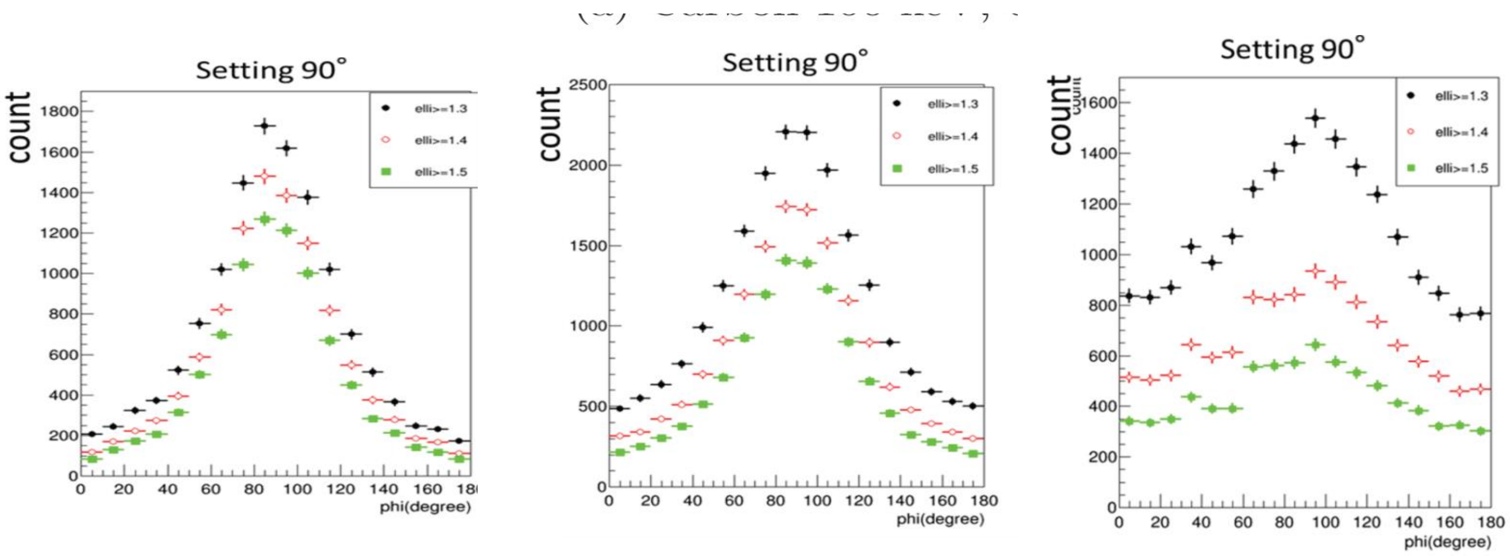
~100 g/y/machine

低倍率化
高視野化
高効率ステージ駆動

> 1 kg /y/total machine

Angular resolution for low-velocity ions





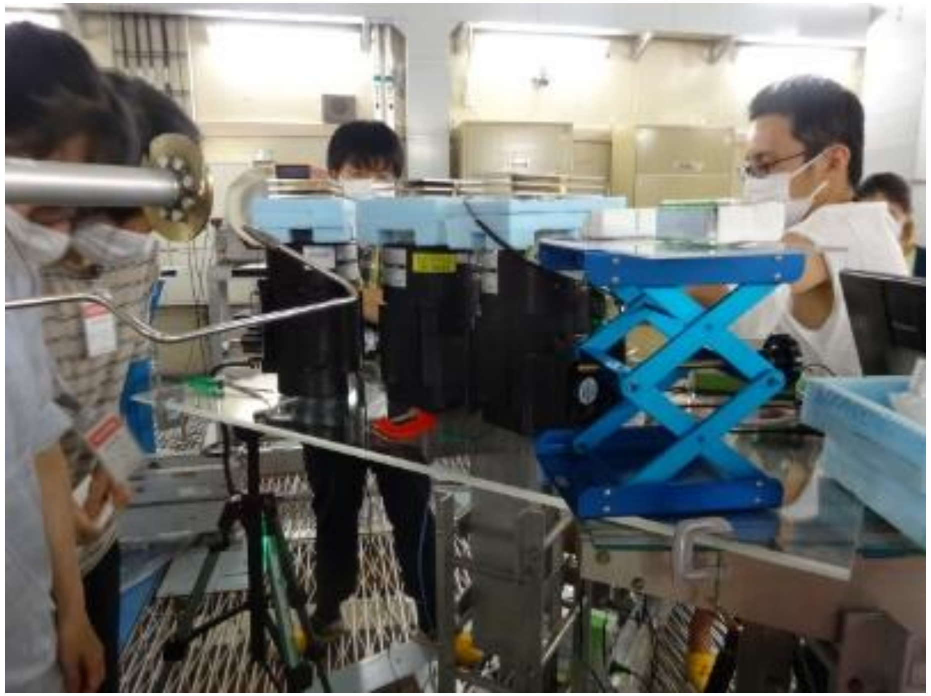
	Carbon 100 keV	Carbon 60 keV	Carbon 30 keV
phi =90° beam 認識効率/角度分解能	25.3±0.1(%) 27 ±3 (°)	12.0±0.1(%) 33 ± 3(°)	4.3 ± 0.1(%) 52 ± 3(°)
phi =135° beam 認識効率/角度分解能	24.6±0.1(%) 28 ±2 (°)	11.9±0.1(%) 34 ± 2(°)	5.0 ±0.1(%) 56 ± 3(°)
phi =180° beam 認識効率/角度分解能	22.5±0.1(%) 32 ±3 (°)	11.7±0.1(%) 35 ± 3(°)	4.0 ±0.1(%) 59 ± 2(°)

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

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

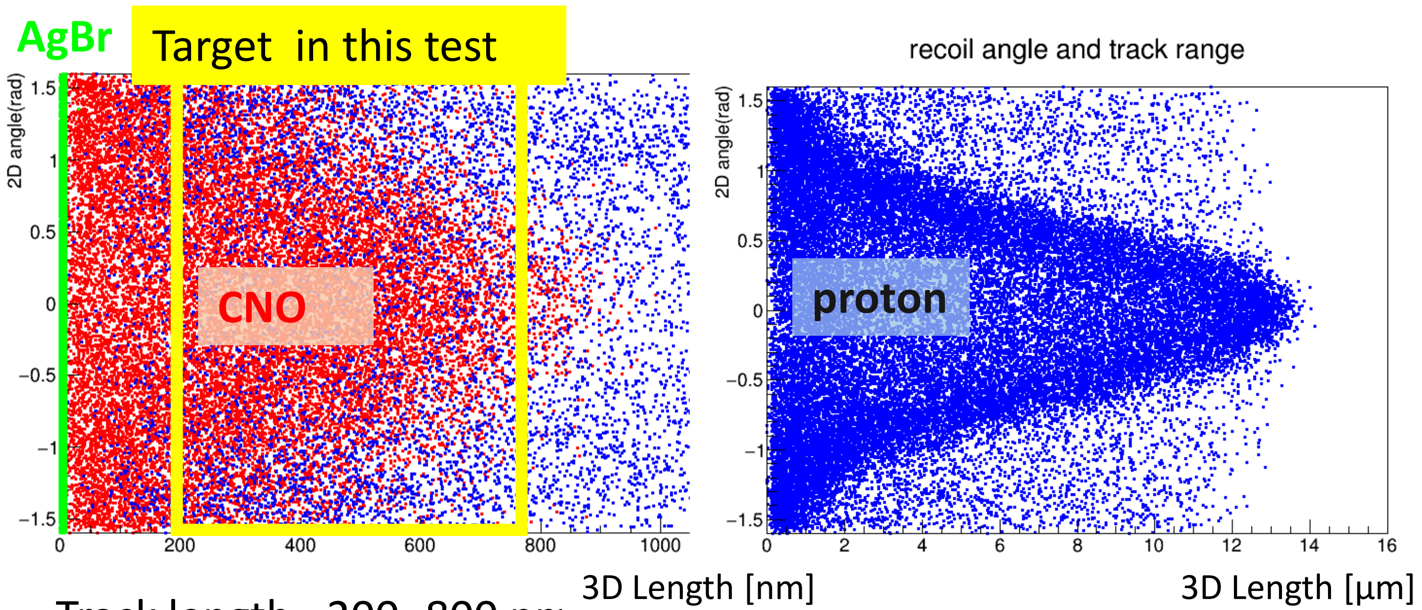
梅本篤宏　博士論文（2020）

中性子による反跳原子核検証 @産総研、中性子標準場



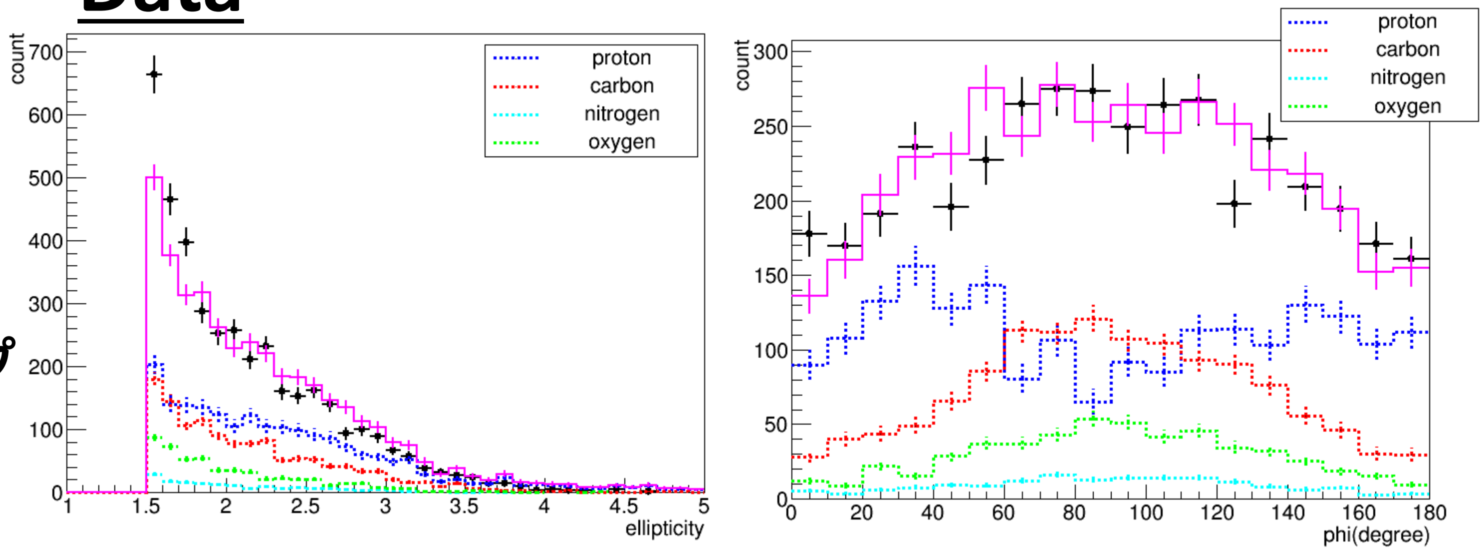
中性子による反跳原子核検出性能の較正

- ■ **産業技術総合研究所・中性子標準場グループ**
- ■ **T(p,n) 反応　 880keV**

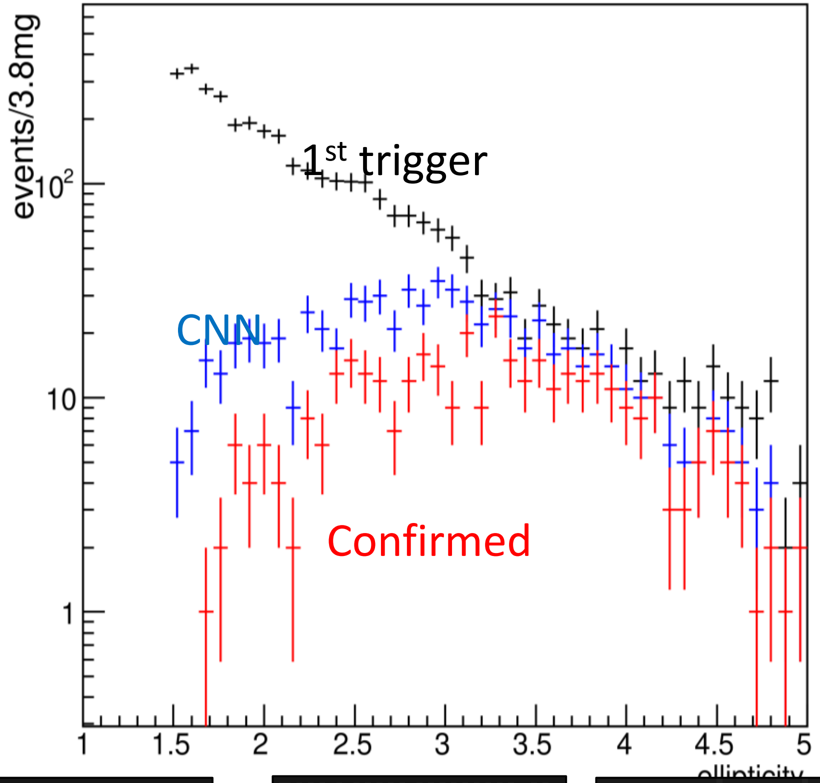


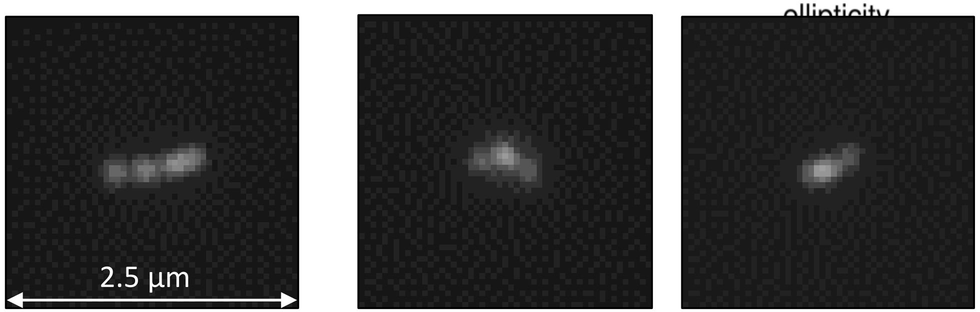
Track length : 200 -800 nm
Recoil energy @CNO : 30- 250 keV
H: 5-150 keV

Data

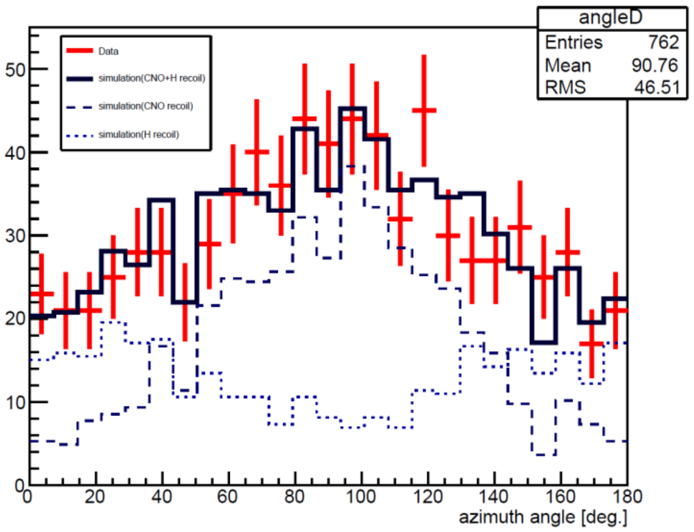


Neutron recoil detection (preliminary)

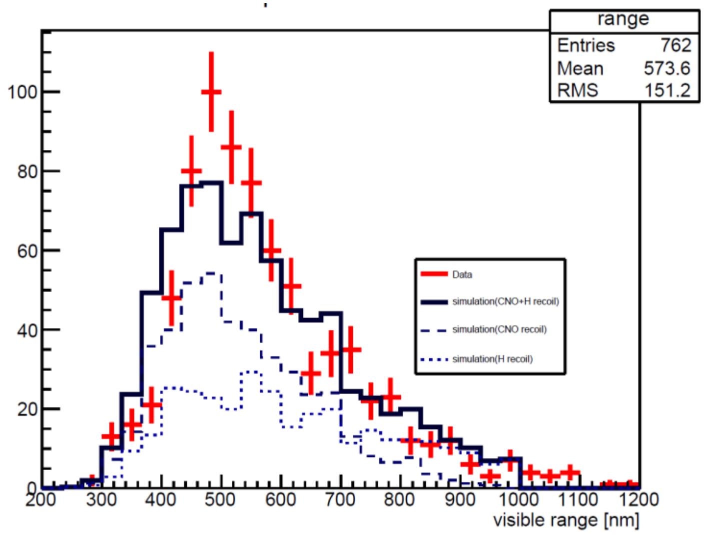




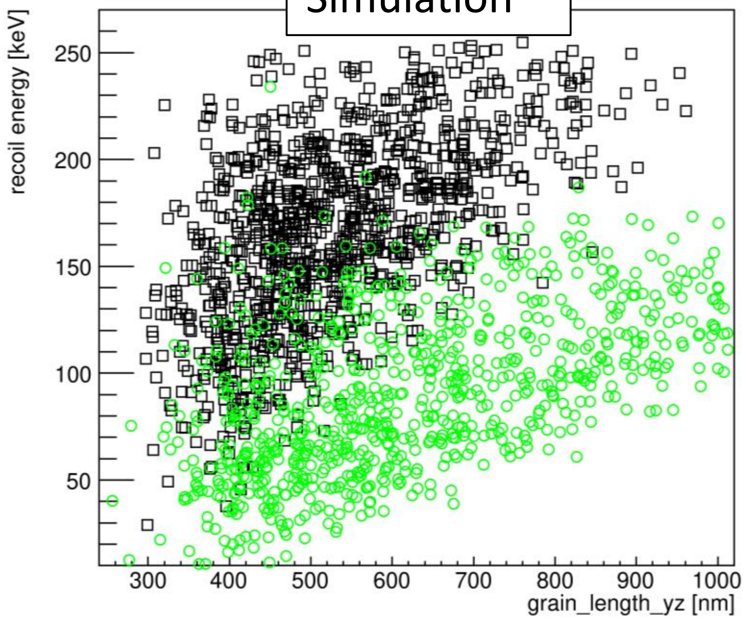
角度分布



飛程分布



Simulation



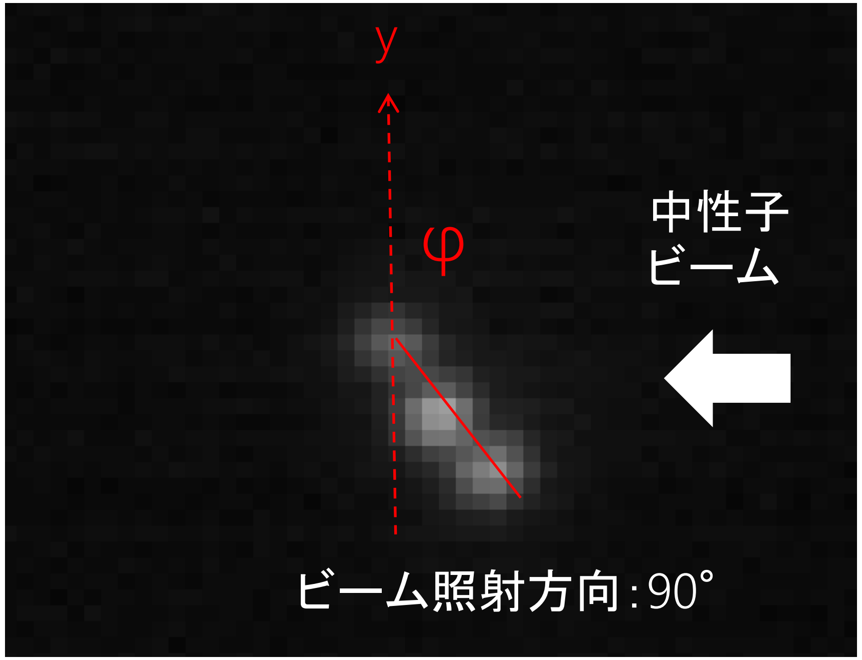
CNO recoil : 50 -250 keV
H recoil : 5- 150 keV

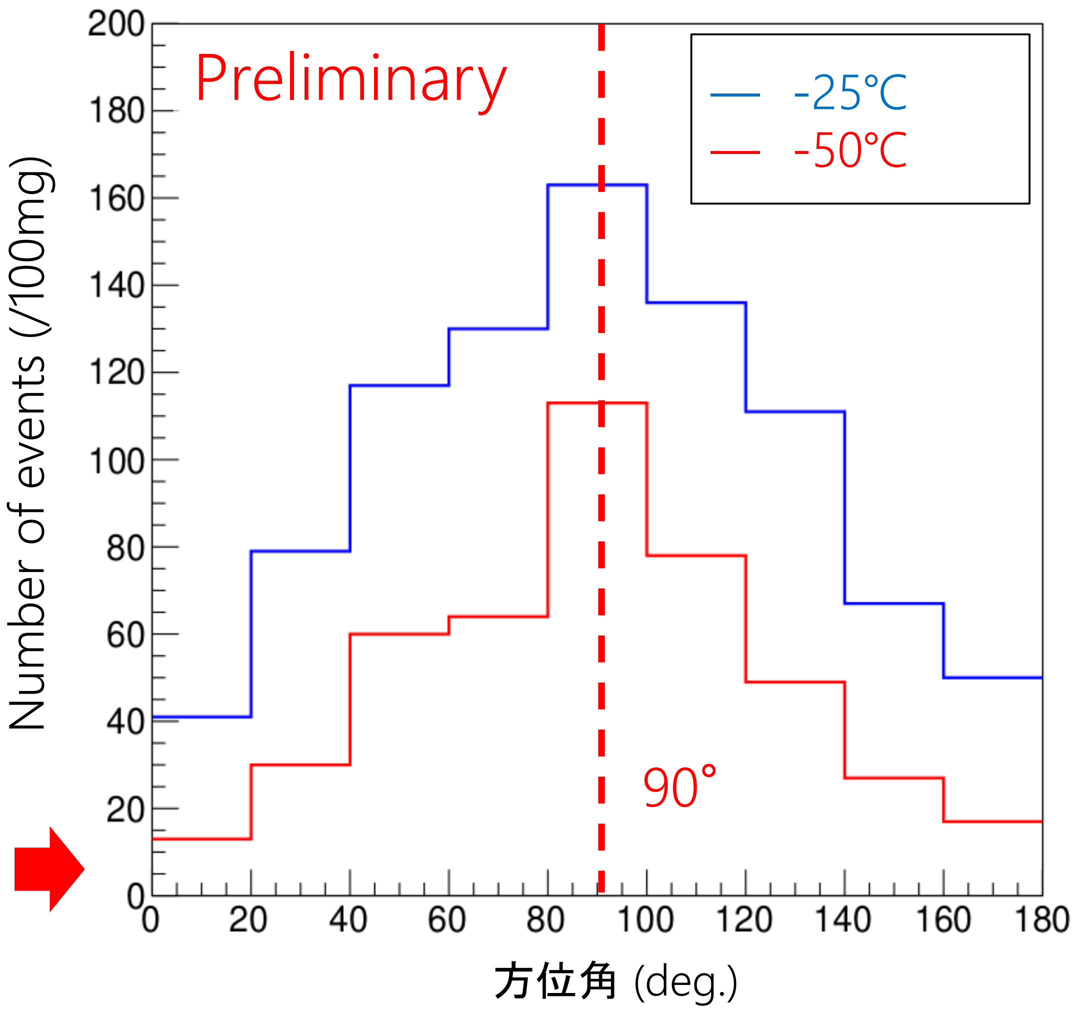
Electron event leakage : ~ 10%

Data, simulation ともupdate中
⇒ DM sensitivity 評価へ

Temperature Dependence

低温デバイス感度較正

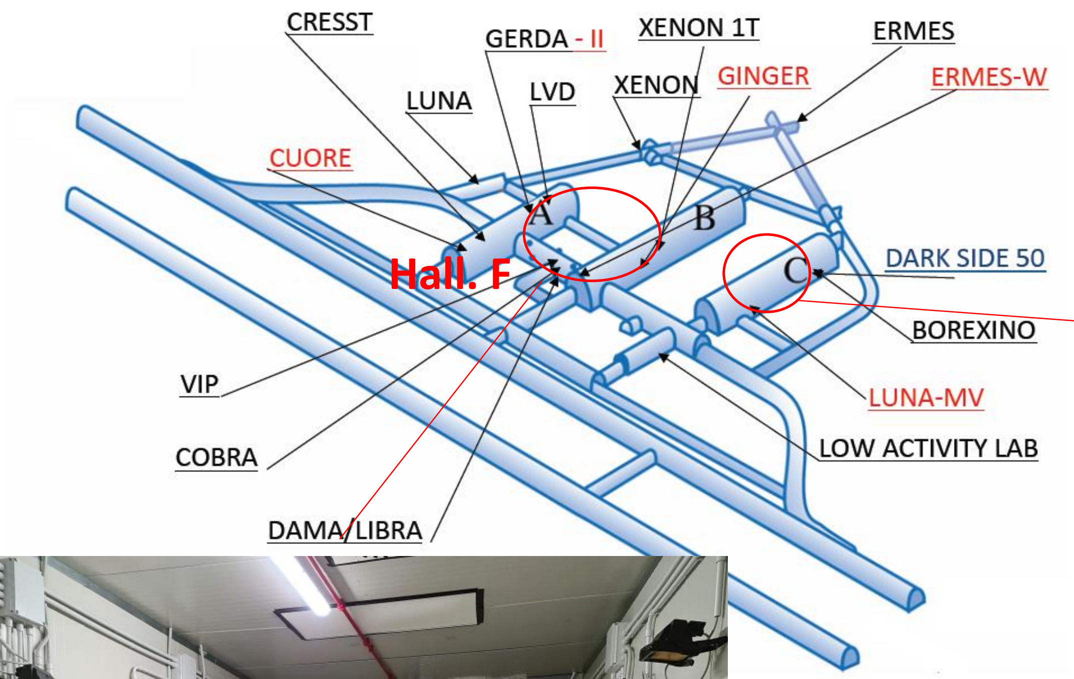




-50℃照射でも期待通りビーム方向のピークを検出できることを初めて確認した。

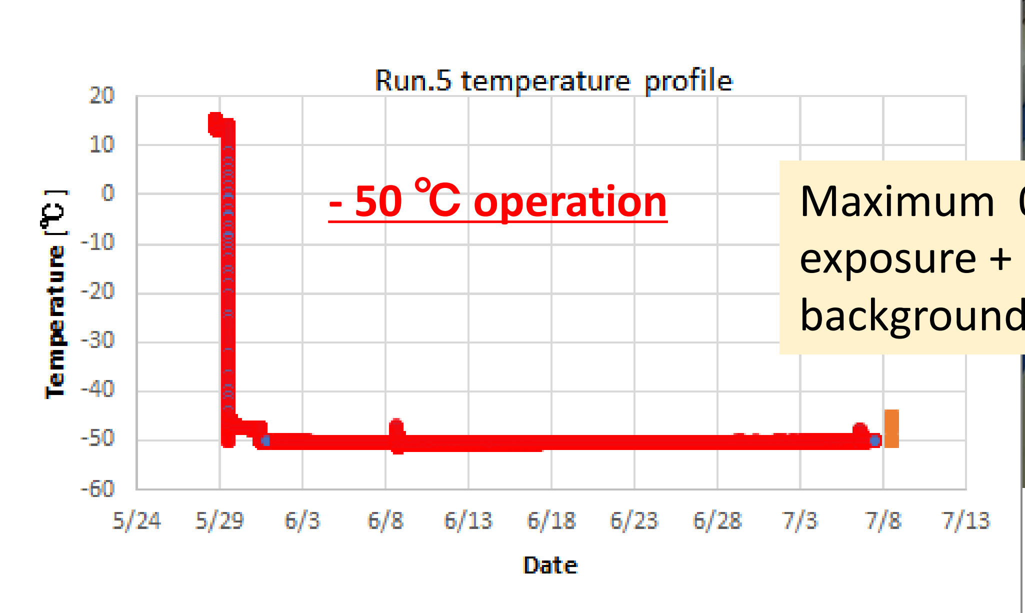
2021物理学会秋季大会（大島）

Underground Activity @LNGS



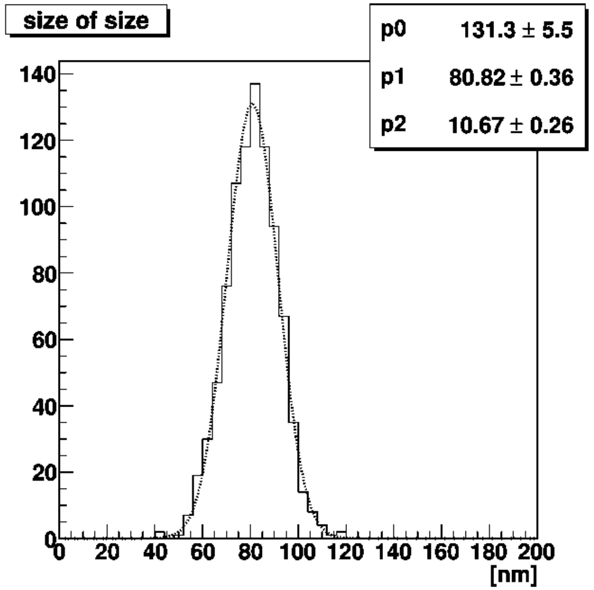
Device handling facility

- Device self-production
- Clean room
- Chemical development



Maximum 0.16 kg・day exposure + several background run

Device production@ LNGS



Handling in the clean room

Device production

De-ionizing process

Filtering process

Pouring on the plate

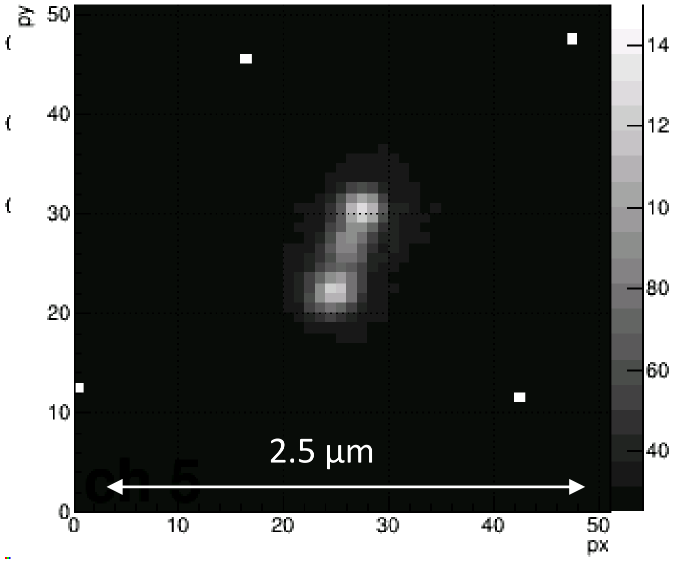
(Device production → Pouring on the plate: **No sensitivity**)

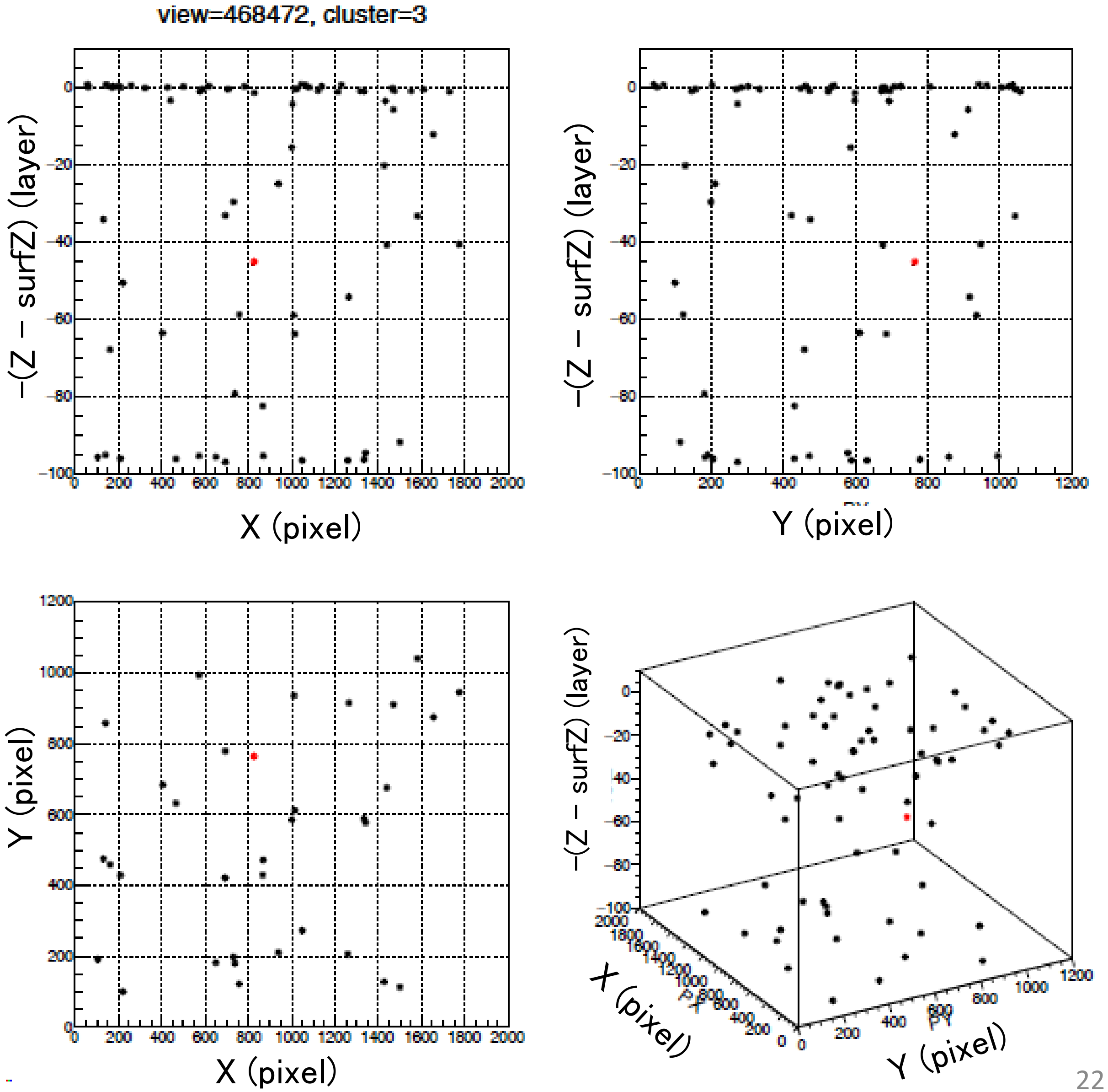
Install the shield before dry

Dry and run in the shield

ViewID=468472, ClID=3

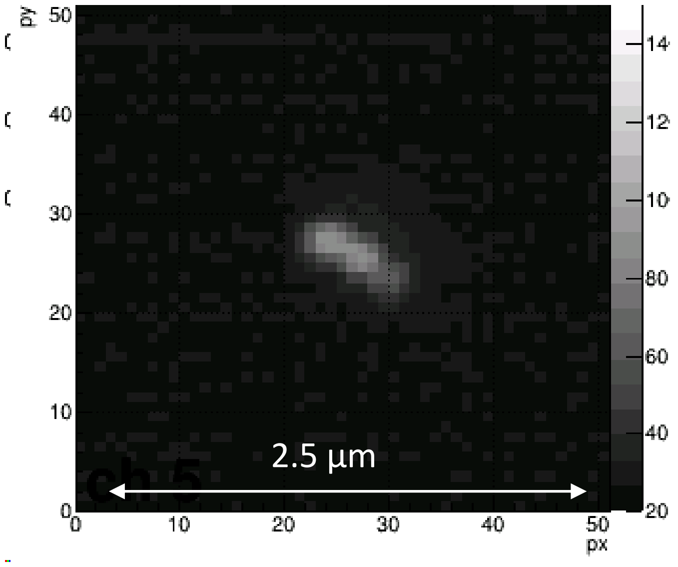
Red : the event, Black : the other clusters

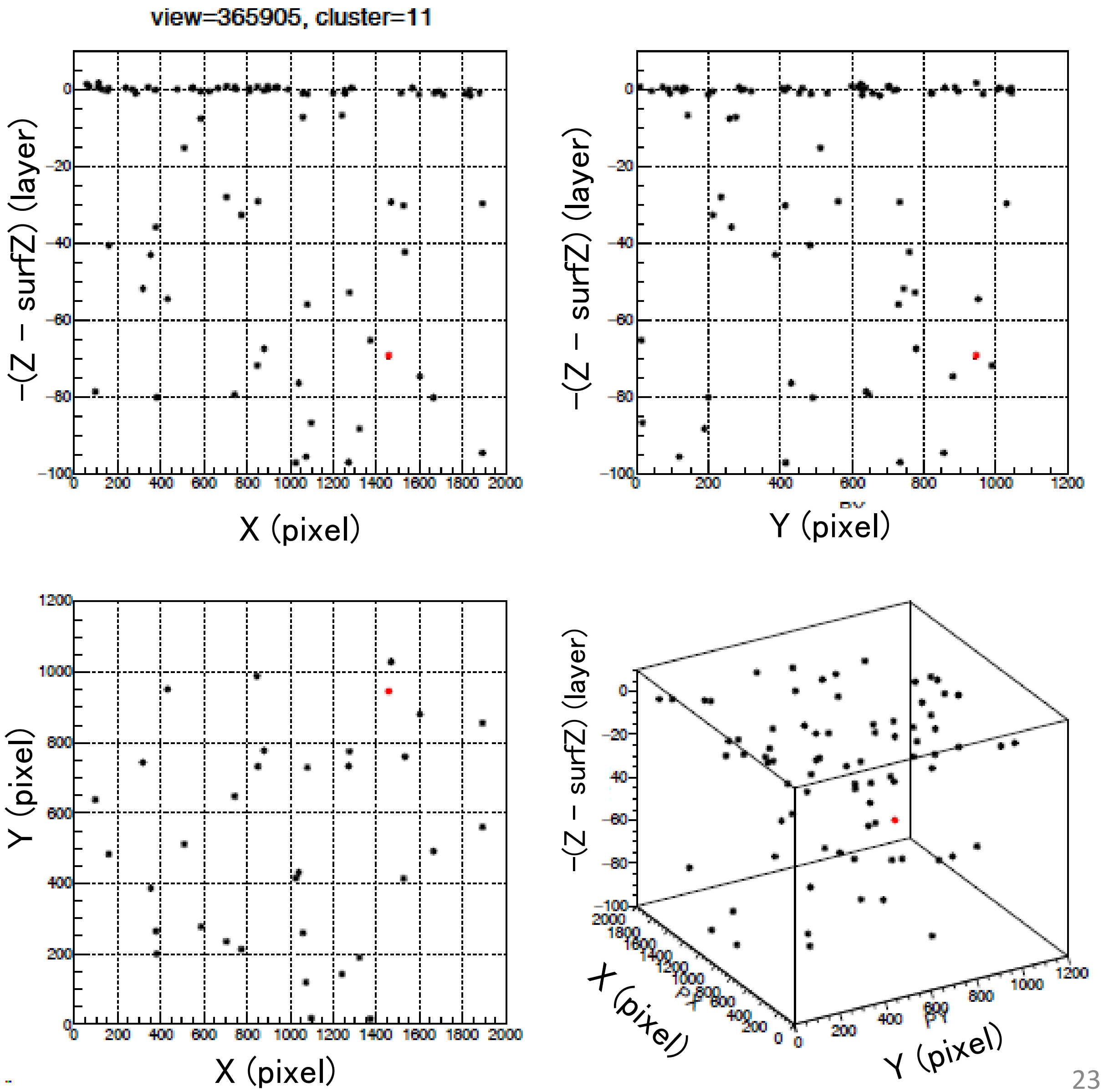


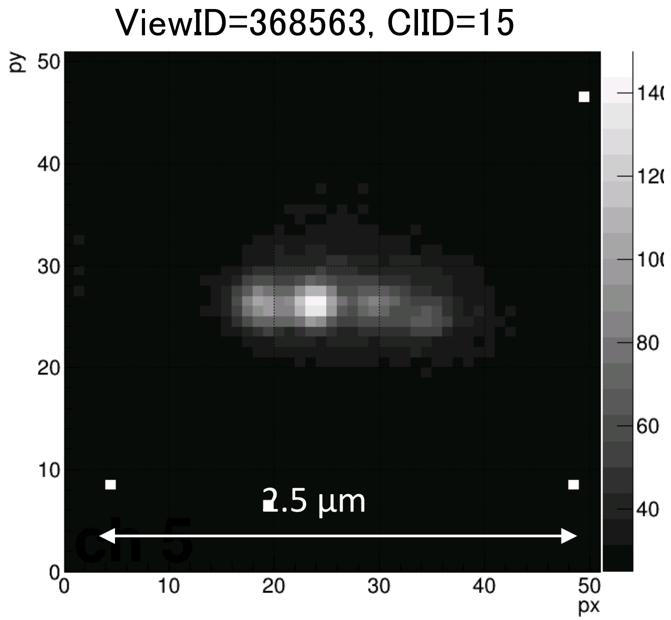


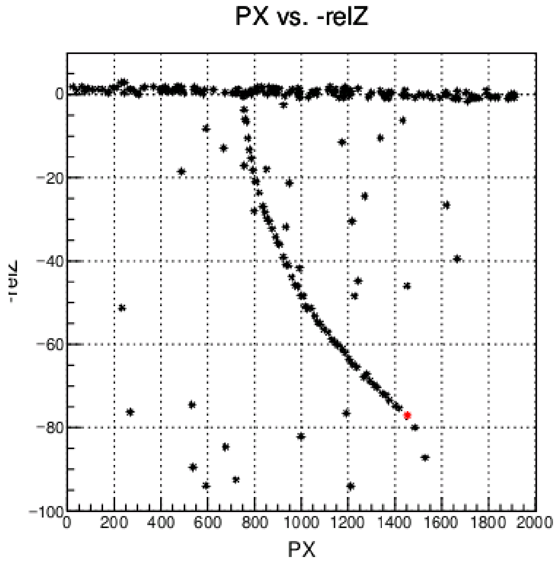
ViewID=365905, ClID=11

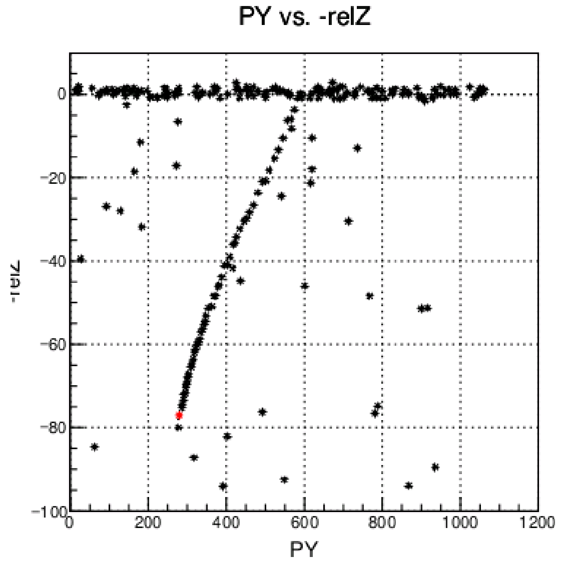
Red : the event, Black : the other clusters

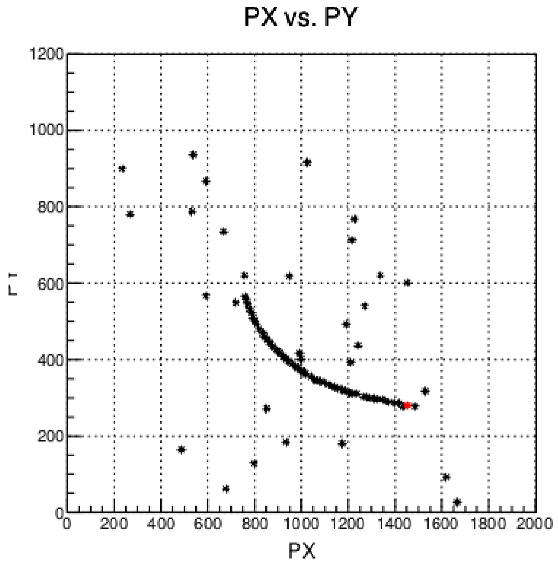


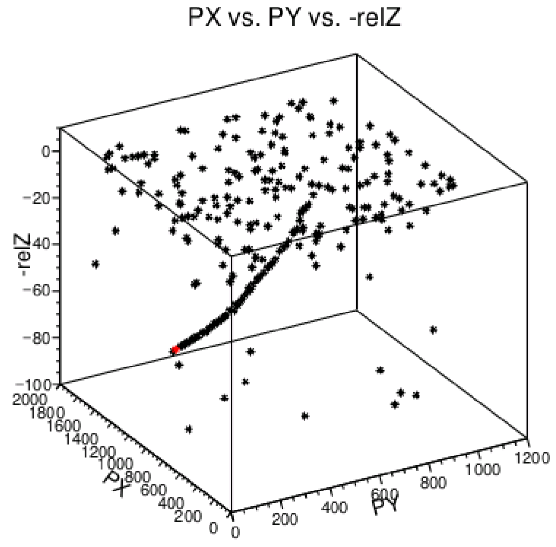



ViewID=368563, ClID=15
py
px
2.5 μm


PX vs. -relZ
PX


PY vs. -relZ
PY


PX vs. PY
PX


PX vs. PY vs. -relZ
-relZ
PX
PY

α-ray

Background analysis

Electron source expectation [/kg/day]		
	Surface run (2019)	underground run condition (2021)
Environmental (in shield)	(5+-1)E+5	~ 300
Base plate	(8 +- 2)E+5	~ 700
C-14	(1.1 +- 0.4)E+5	(1.1 +- 0.4)E+5
μ induce electron	~ 2E+6	~ 20

→ <u>ー50℃の状態で3桁以上の除去</u>

O(10) /kg/day程度まで低減

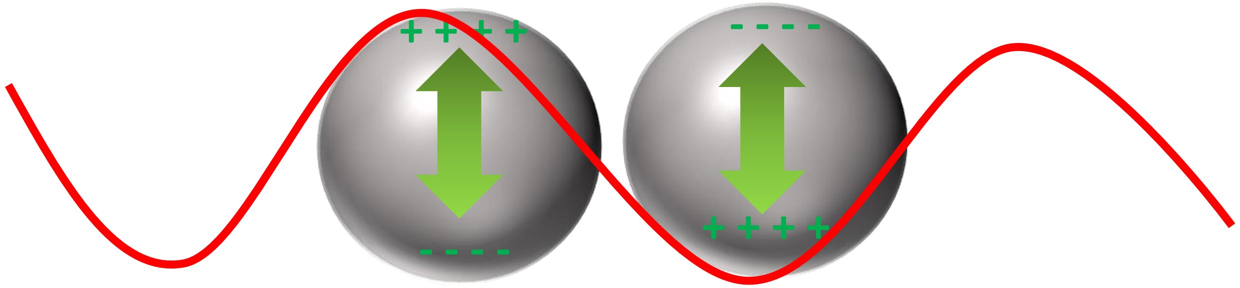
※ Background sourceの理解は、引き続き精査中

↑ **Surface runと同じ解析をした場合**

- **ランごとのデータクオリティ評価と事象頻度の比較**
- **MLのトレーニングデータセットの依存性**
- **飛跡の幾何学情報も含めてたバックグラウンドの詳細な理解**

局在表面プラズモン共鳴
(Localized Surface Plasmon Resonance: LSPR)

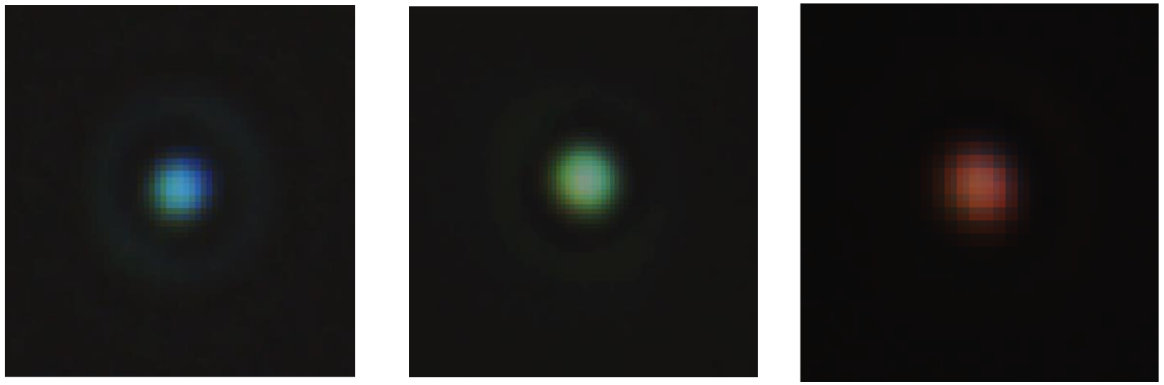
Dipole-moment of free electron in the nano metaric particle



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

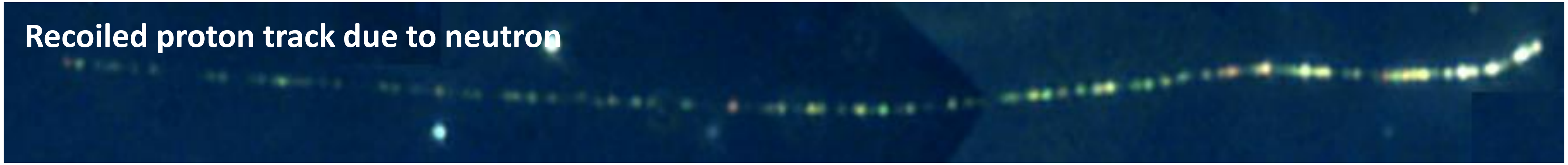
$$\boxed{\varepsilon_1(\lambda_l) + 2\varepsilon_m(\lambda_l) \approx 0}$$

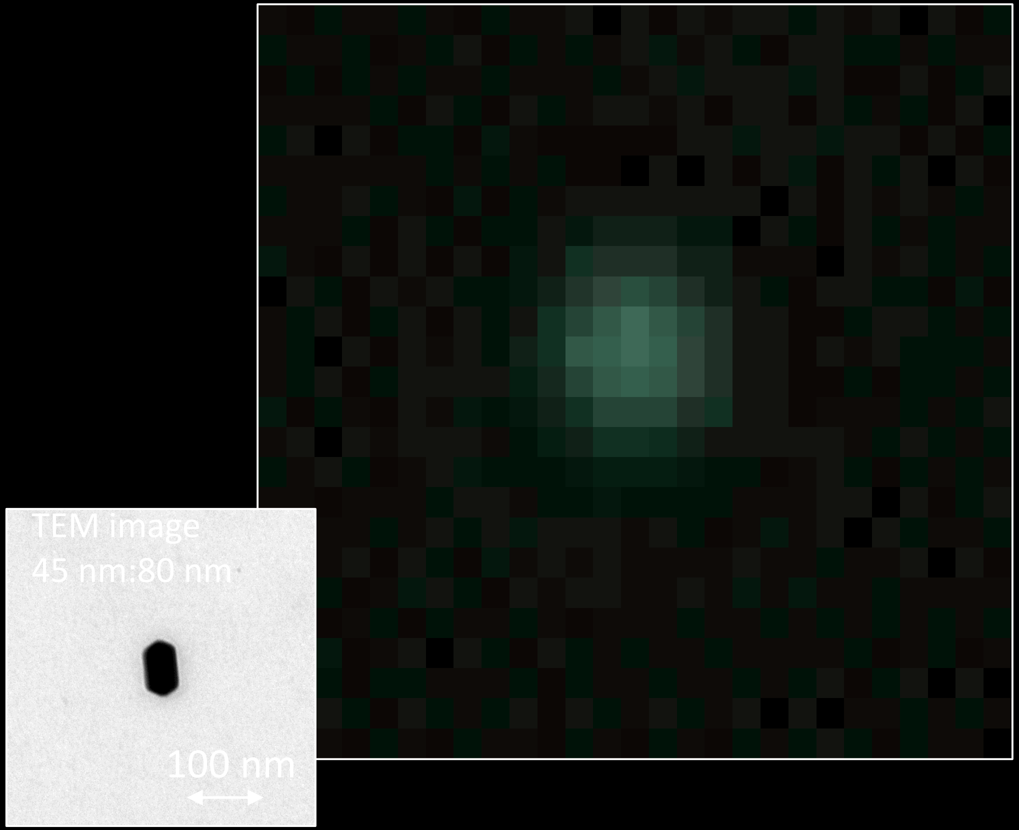
銀のナノ粒子におけるLSPR共鳴波長

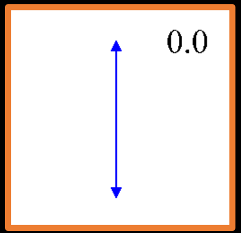


40 nm　80 nm　120 nm

- ✓ 数10nmの銀粒子における共鳴波長は可視光波長
- ✓ 共鳴波長は、サイズや形状に強く依存する
- ✓ 共鳴効果からナノスケール情報を取得




TEM image
45 nm:80 nm
100 nm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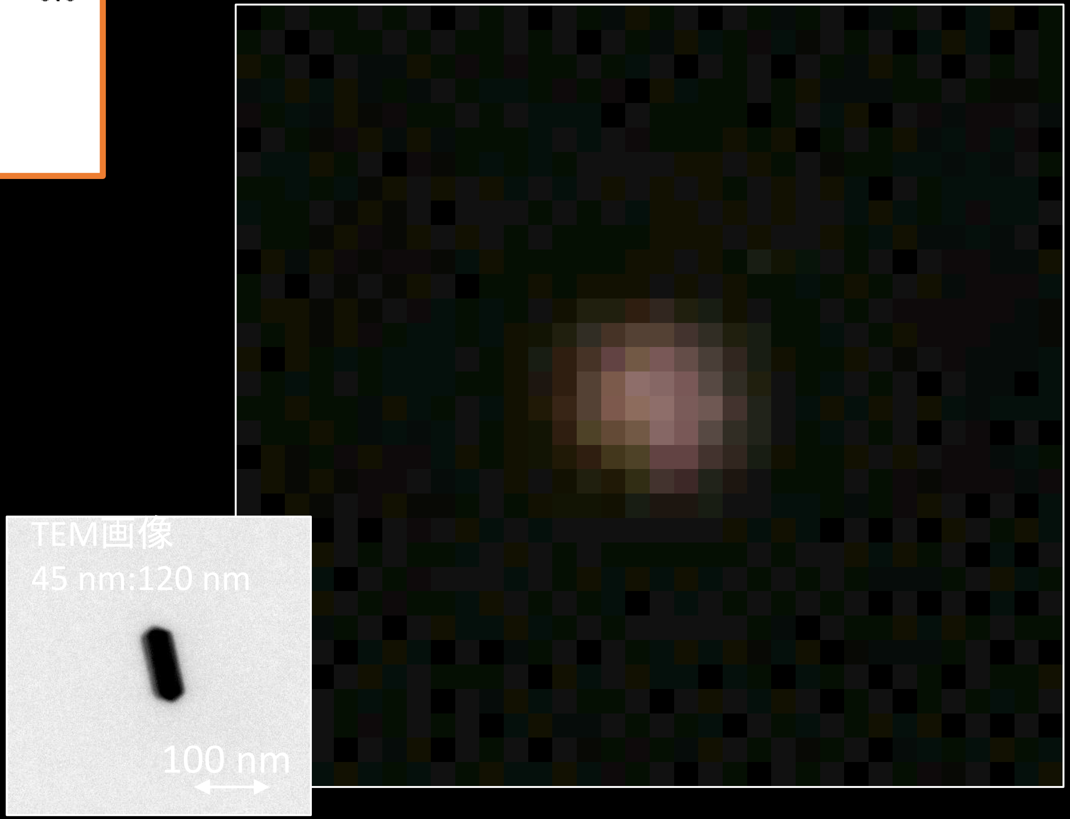
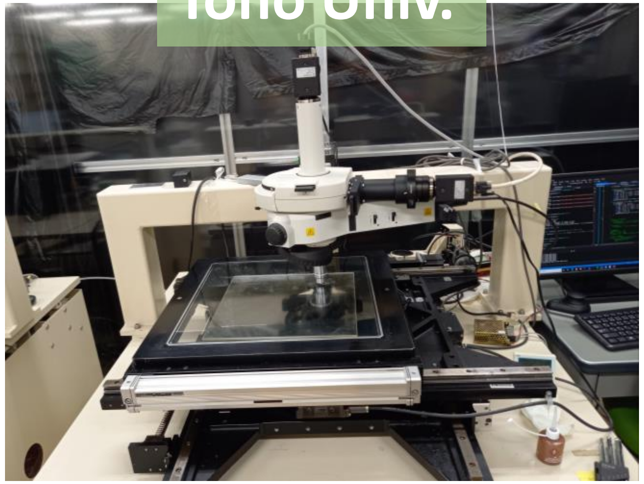
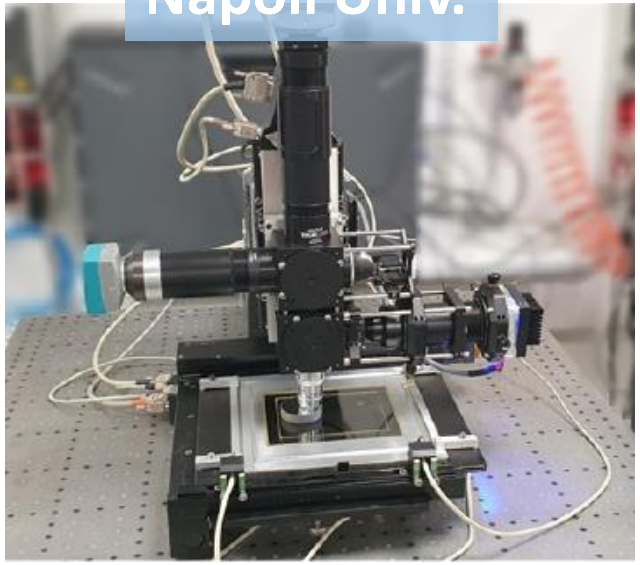

TEM画像
45 nm:120 nm
100 nm

Analysis using the effect due to the plasmon

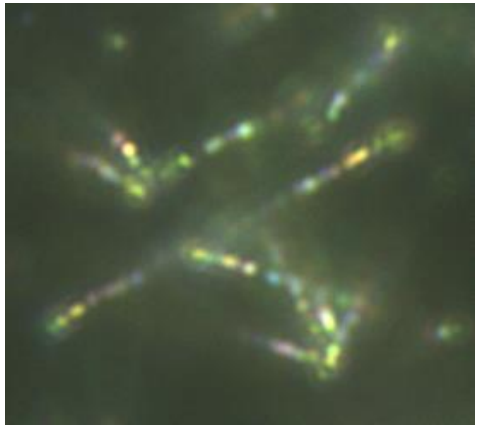
Toho Univ.



Napoli Univ.



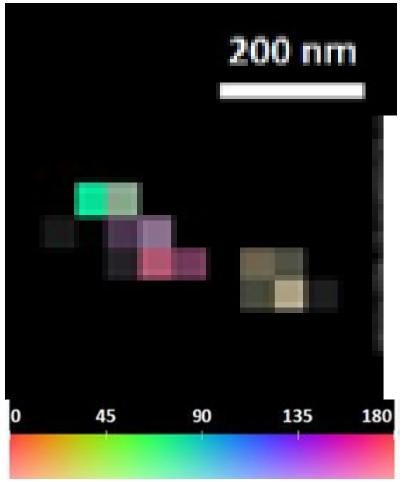
■ Color spectrum for particle ID



Color + ML

Color information due to LSPR of silver grain

■ Super-resolution imaging

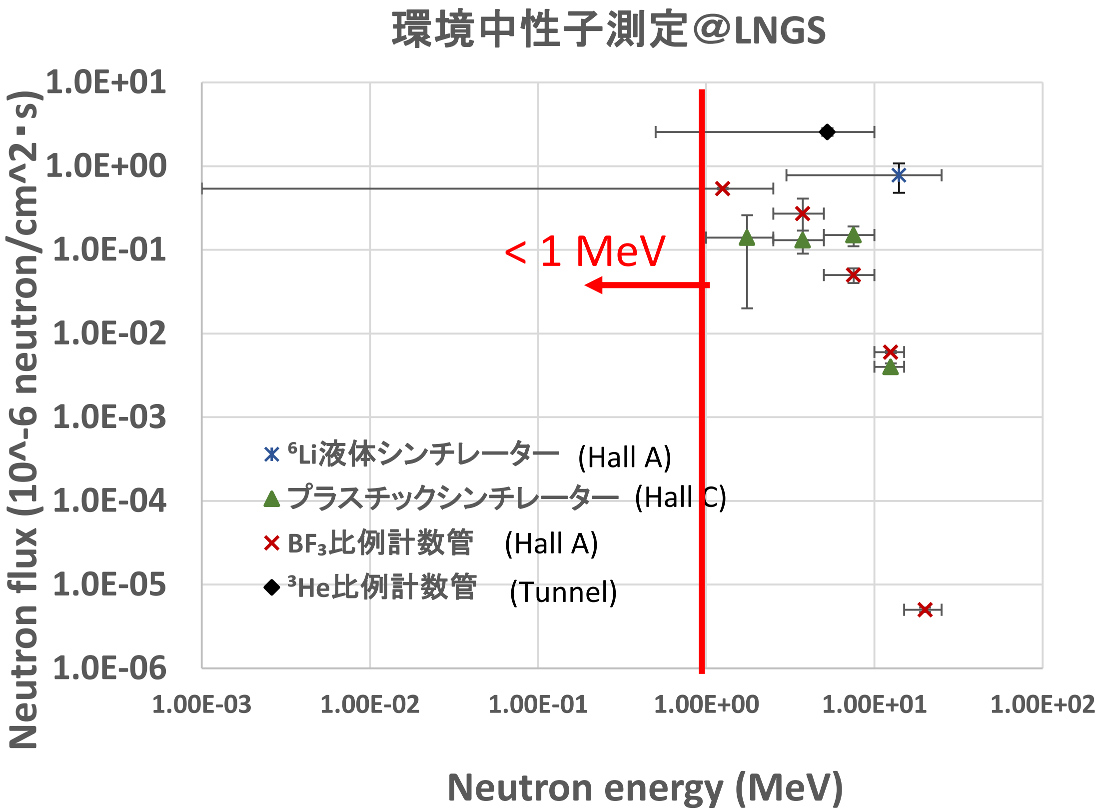


Color + polarization + ML

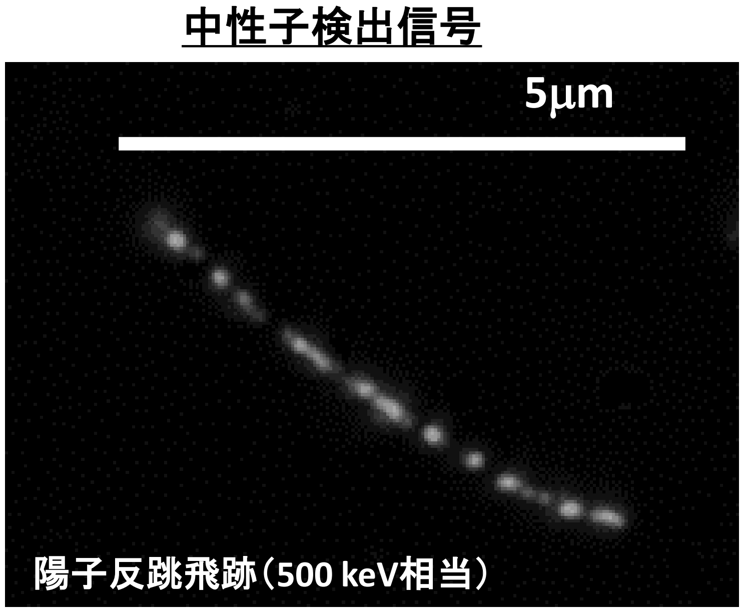
Super resolution corresponding to electron microscope

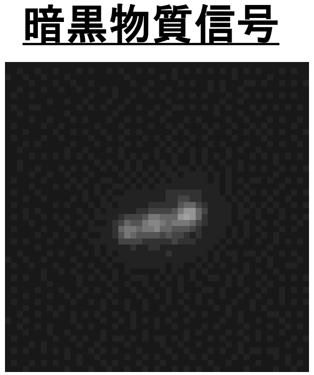
Neutron measurement

Sub-MeV neutron measurement in the underground (or surface) with direction sensitivity



No precise data for sub-MeV region for flux, spectrum and direction !!





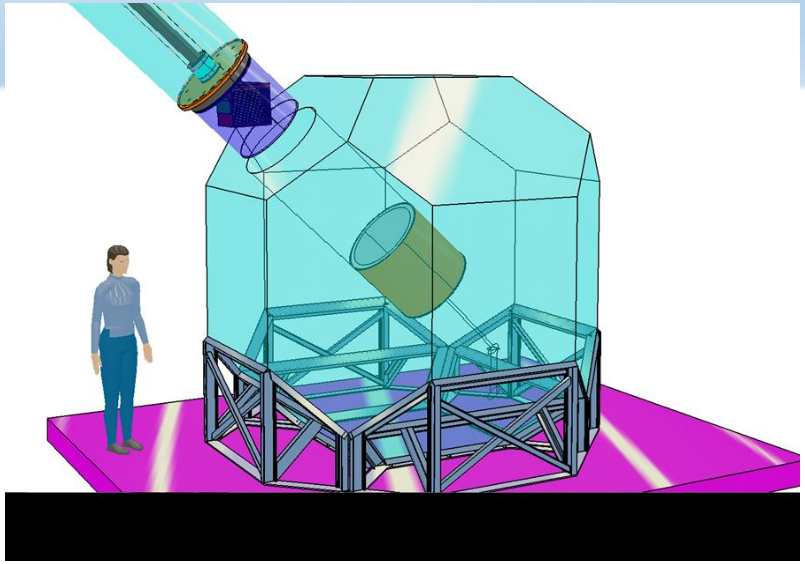
C(N,O) 反跳飛跡
(60-100 keV相当)

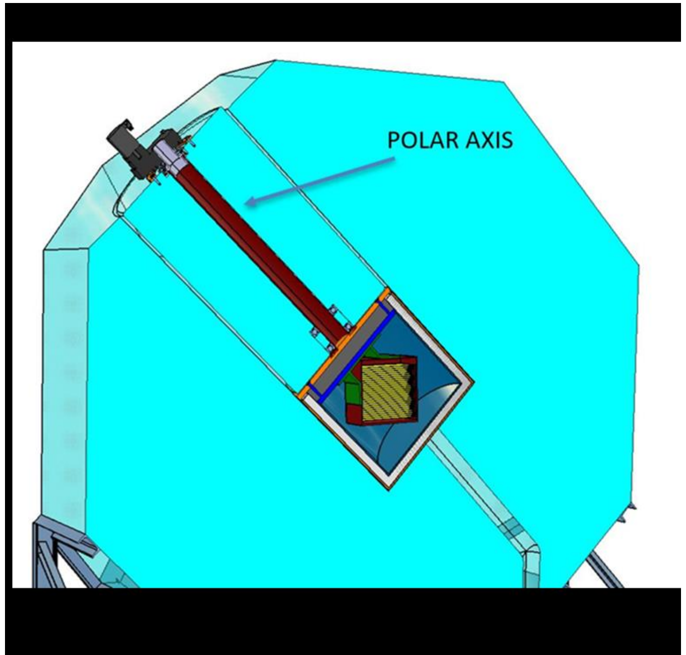
T. Shiraishi *et al.*, PTEP Volume 2021, Issue 4, April 2021, 043H01

> 200 keV以上のproton recoilにおいては現状background free

Conclusion

- 超高分解能原子核乾板によるナノトラッキング技術を用いた暗黒物質の方向感度探索実験を推進中
- デバイス＋読み取り･解析の基盤構築ができ、段階的な観測実験を進行中
- 地上実験の方向感度探索実験による実証試験⇒LNGSでのバックグラウンドランの実施（現在、解析を進行中）
- データ解析による信号理解と低バックグラウンド化に向けたR&Dを並行して推進中
- sub-MeV帯の中性子測定実験を準備中 (12月からLNGS地上ラン開始）





2021~： バックグラウンドランデータ解析とバックグラウンドの理解
低バックグラウンド化技術の検証

2022~： スケールの拡大と感度の向上･赤道儀を用いた本格的DMラン