超微粒子原子核乾板を用いたグランサッソ研究所での地下環境中性子測定

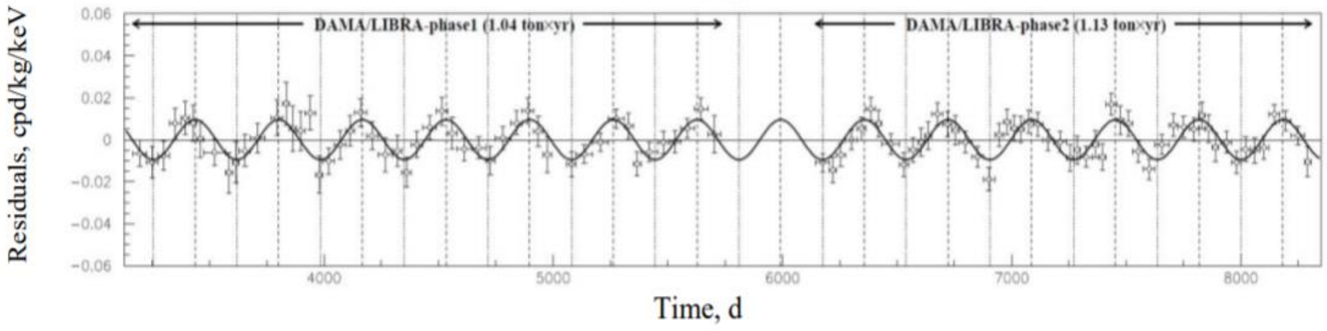
<u>白石 卓也</u> – 神奈川大学

On the behalf of the NEWSdm collaboration

DAMA信号の検証として

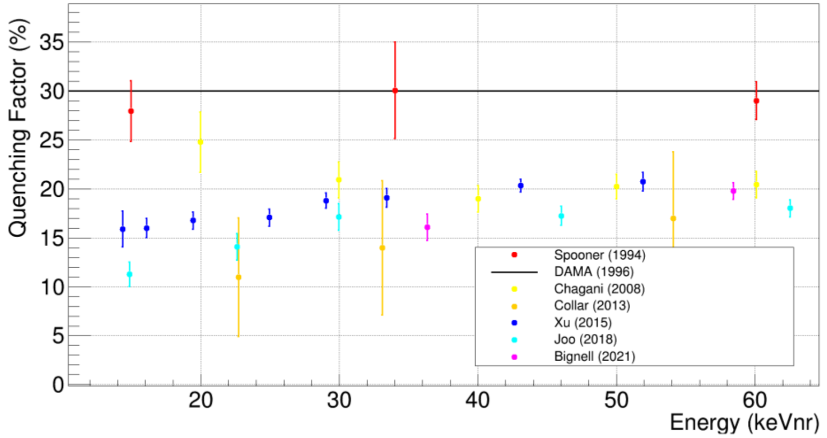
➢ DAMA実験の主張する信号：　2 – 6 keVee

22 years annual modulation



R. Bernabei et al., *Nucl. Phys. At. Energy* **19**, 307 (2018)

➢ 多くの実験がNa quenching ~20% と報告

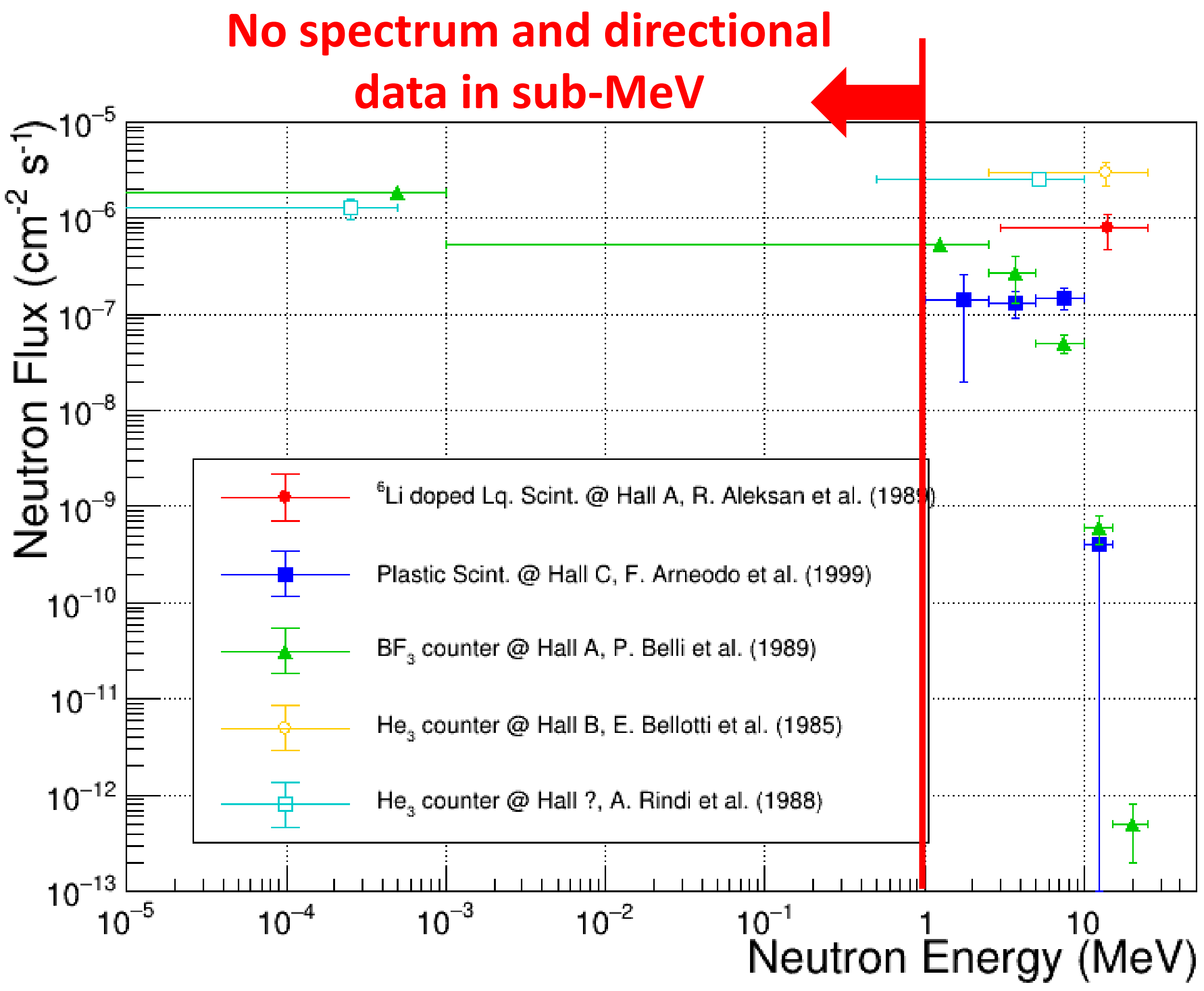


D. Cintas et al, J. Phys.: Conf. Ser. **2156**, 012065 (2021)

DAMA信号を中性子によるNa反跳と仮定すると、中性子エネルギーは　80 – 250 keV

→ DAMA信号の検証のためには、sub-MeV帯を含めたスペクトル測定が必要！

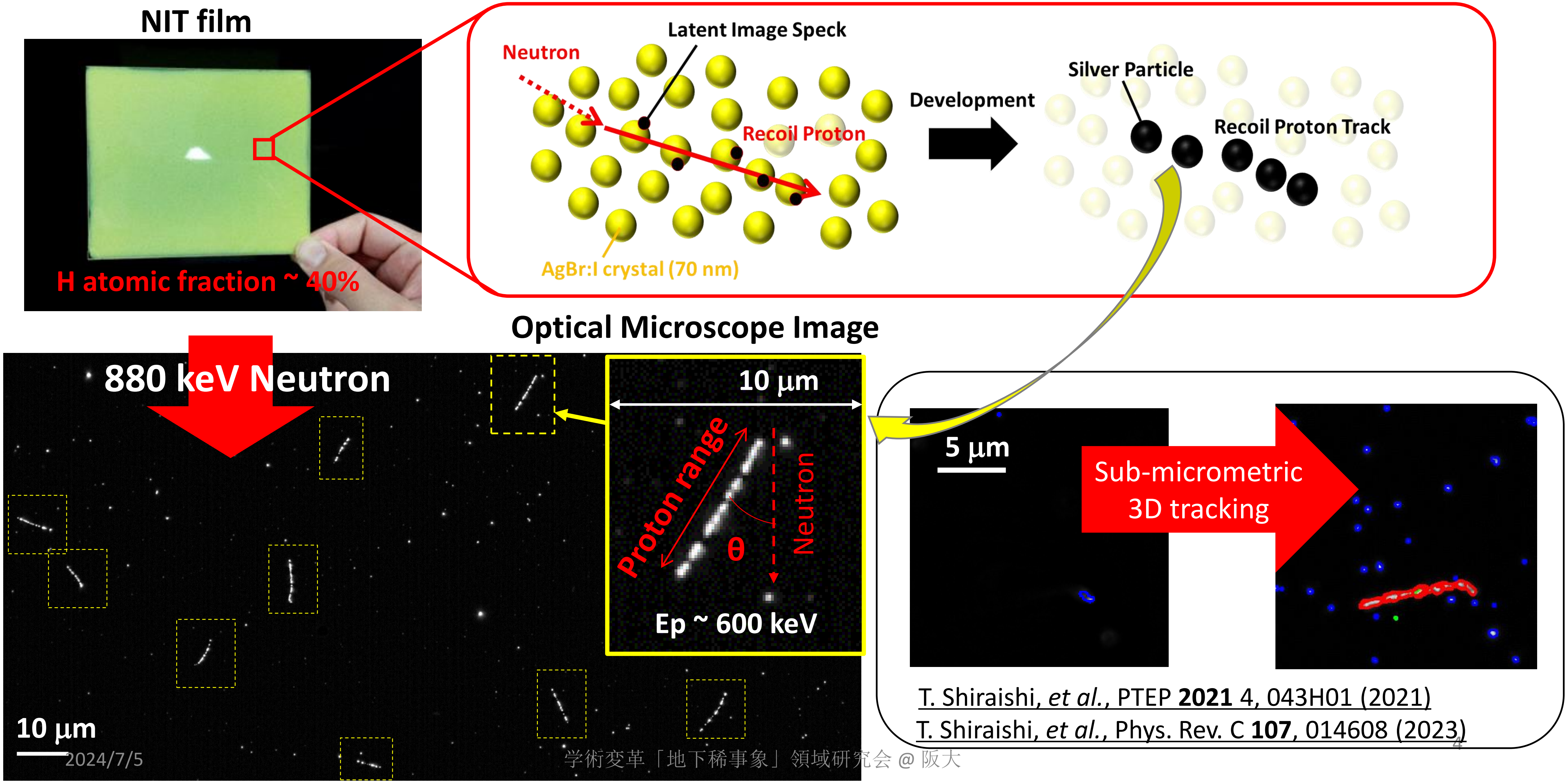
Environmental Neutron Measurement @LNGS



H. Wulandari et al., Astropart. Phys. **22** (2004) 313.

- ほとんどが減衰材＋熱中性子捕獲を使っている
  → 検出器自体のエネルギー分解能がない
  → 減衰材による不定性
- 角度分布は不明
- 測定ごとに異なる
  →場所や、雨季/乾季の岩石中の水分量の変化が影響？

Neutron Detection Principle by Nano Imaging Tracker (NIT)



T. Shiraishi, *et al.*, PTEP **2021** 4, 043H01 (2021)

T. Shiraishi, *et al.*, Phys. Rev. C **107**, 014608 (2023)

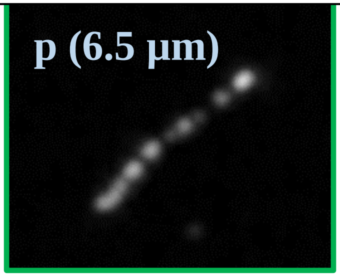
Neutron Detection Methods for Various Energies

Neutron Energy

meV (thermal neutron) — 100 keV (~ 1 μm) — Sub-GeV –

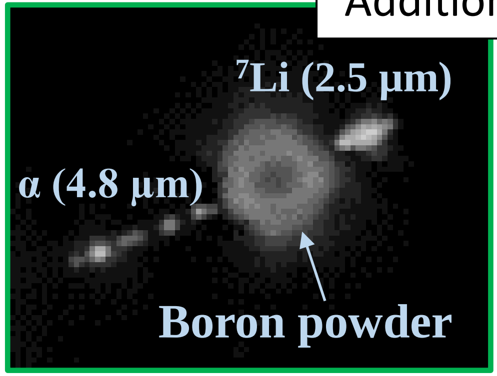
Neutron Capture

Self-contained target

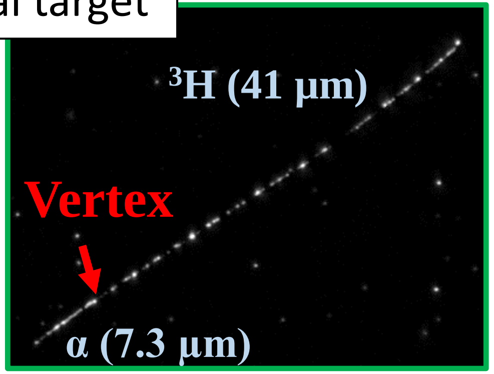


n + ^{14}N → p + ^{14}C + 0.62 MeV
2 barn @ 26meV

Additional target

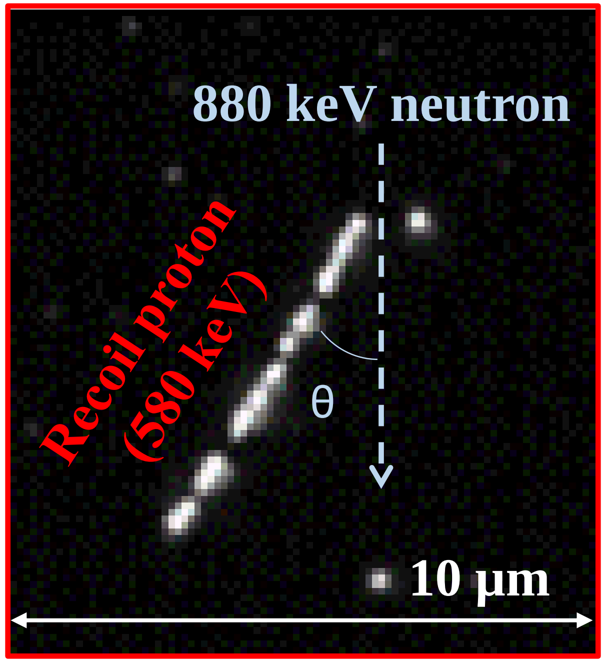


n + ^{10}B → α + ^{7}Li + 2.31 MeV
4000 barn @ 26meV

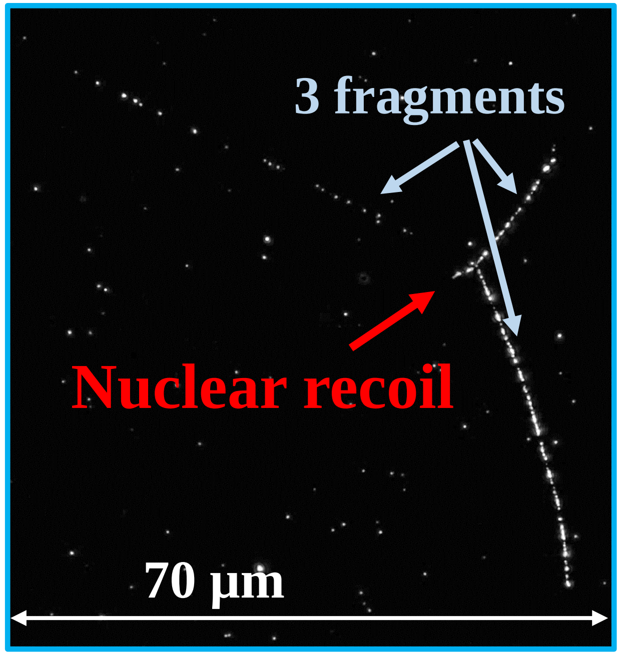


n + ^{6}Li → α + ^{3}H + 4.78 MeV
950 barn @ 26meV

Proton Elastic Scattering



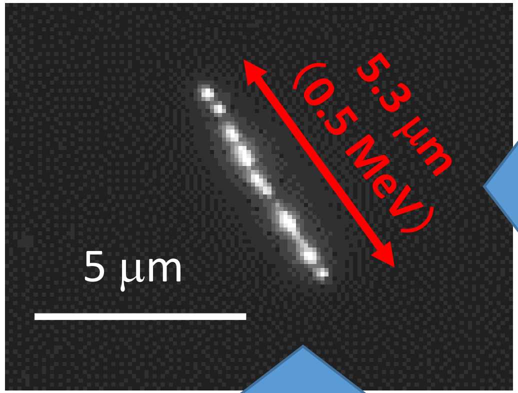
Deep Inelastic Scattering



反跳エネルギーと方向が測定可能

Background of Neutron Measurement

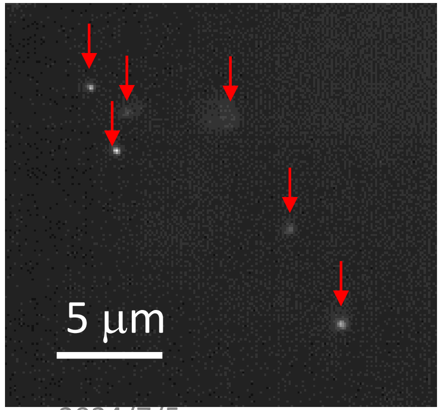
Recoil proton signal



Topological or Range cut

Clearly distinguishable

γ-ray (β-ray)

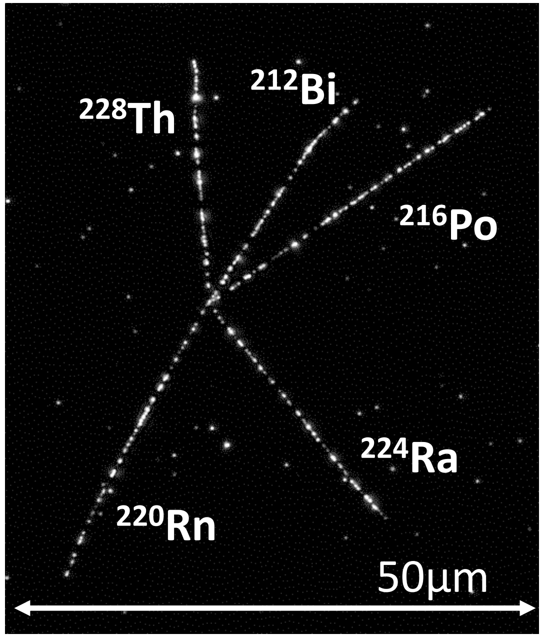


Exposed 5x10^7 γ-ray/cm^2 from ^{241}Am and ^{60}Co (5 years accumulation of environmental γ-ray)

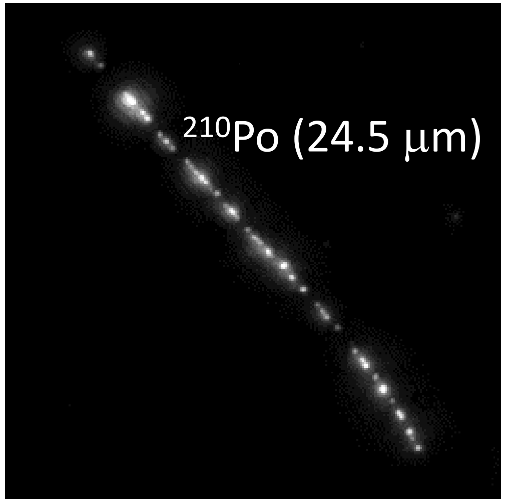
✓ **Environmental γ-rays cannot become background**

α-ray

Th star (^{228}Th → ^{208}Pb)



Single-α in U series

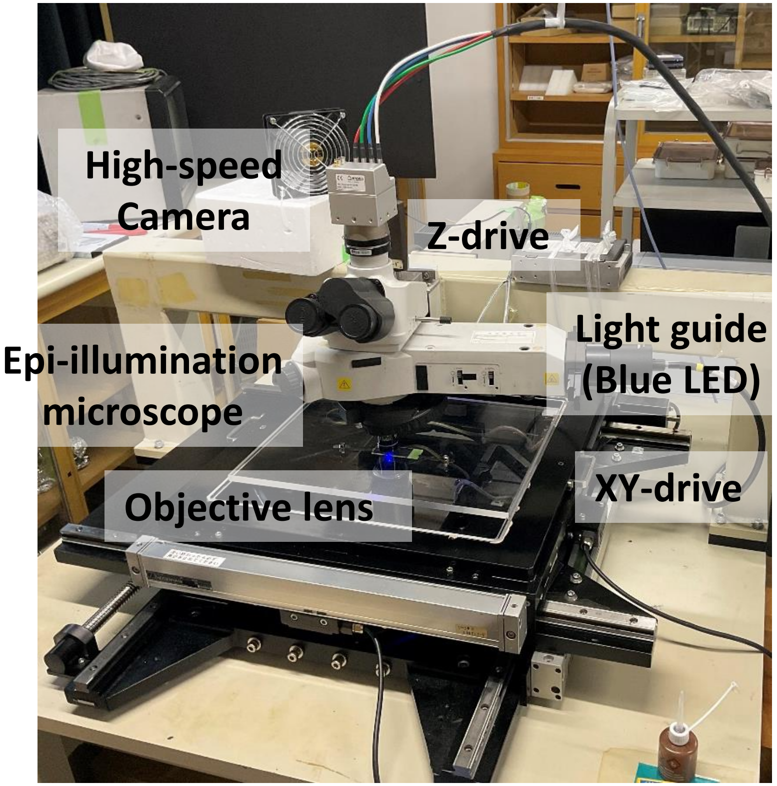


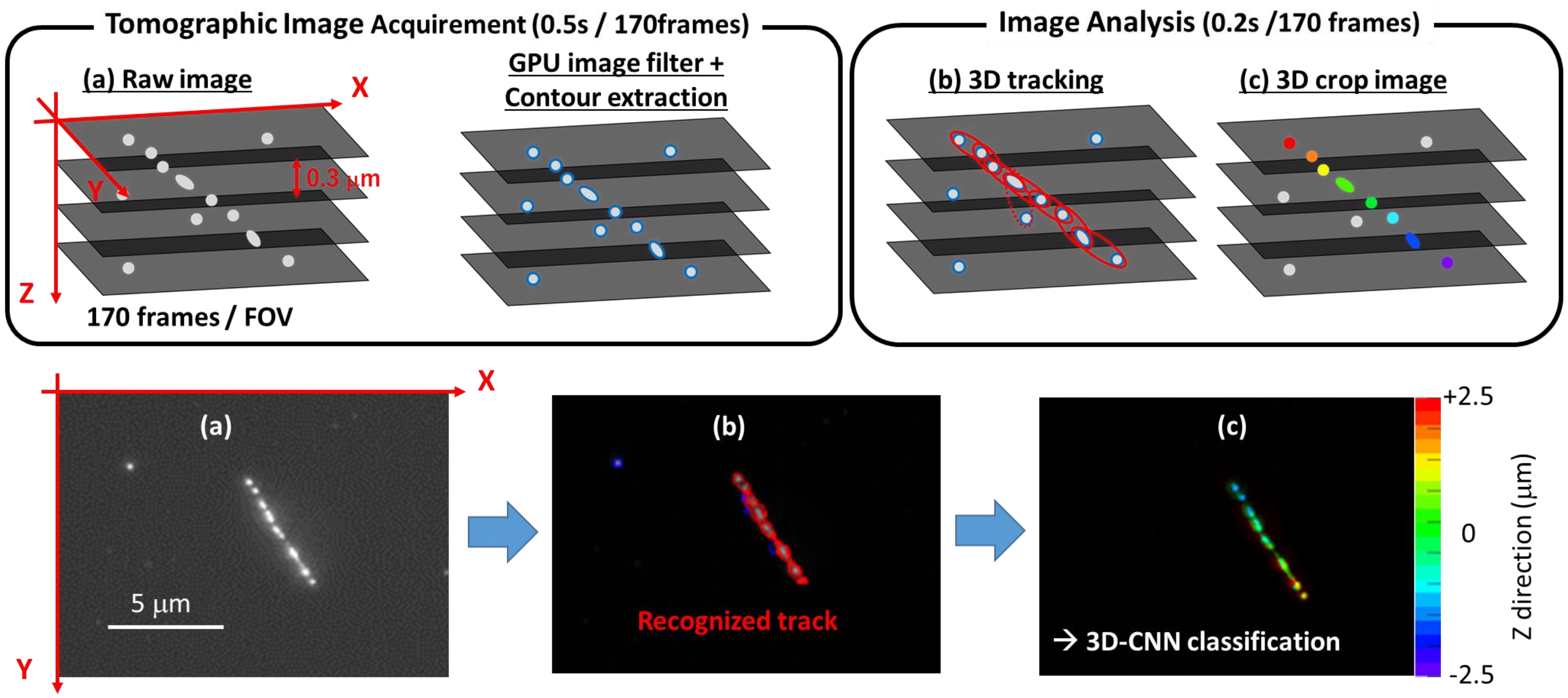
✓ **There is no background in sub-MeV region**
(2 - 14 μm → 0.25 - 1 MeV in proton energy)

✓ **MeV region can be analyzed excluding single-α (especially ^{210}Po peak around 24 μm)**

High-speed Readout and 3-dimensional Tracking

神奈川大学で開発した新規ステージ



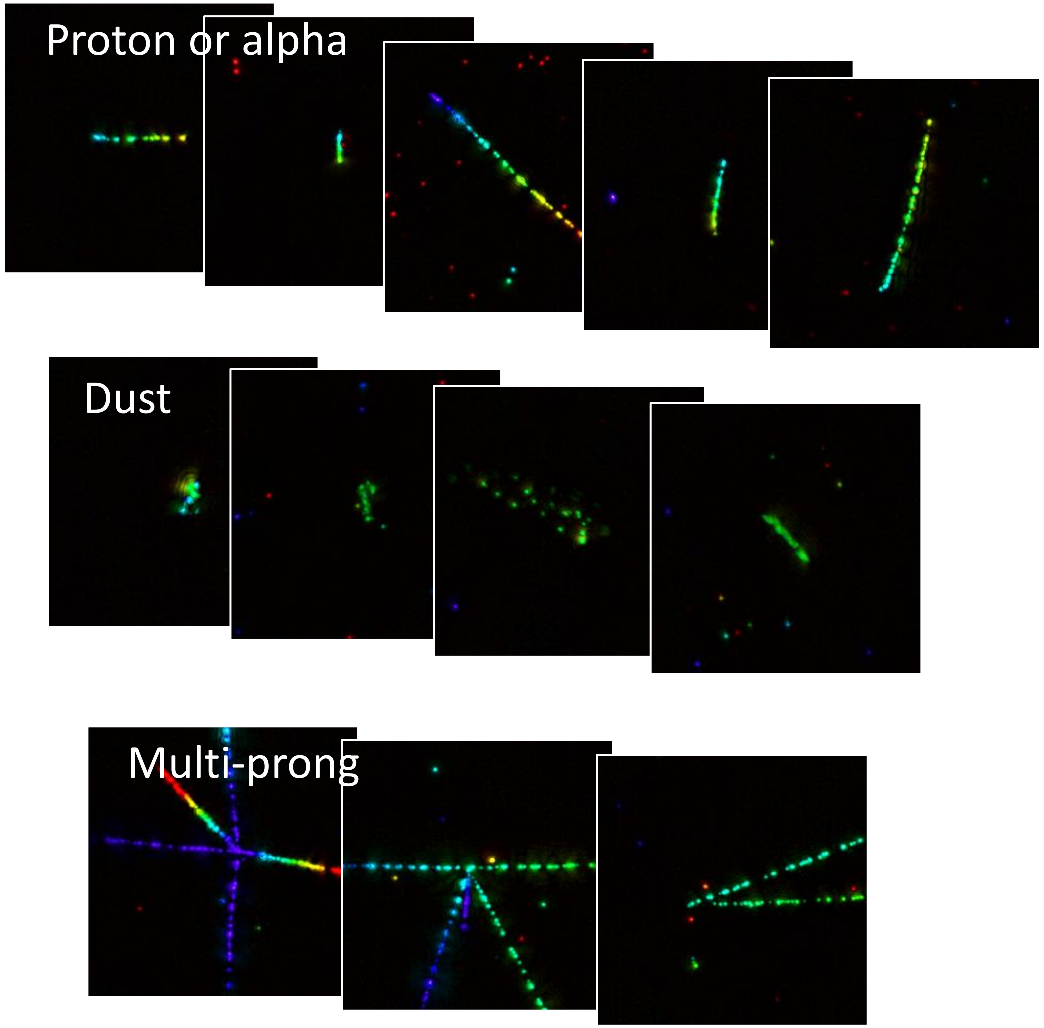


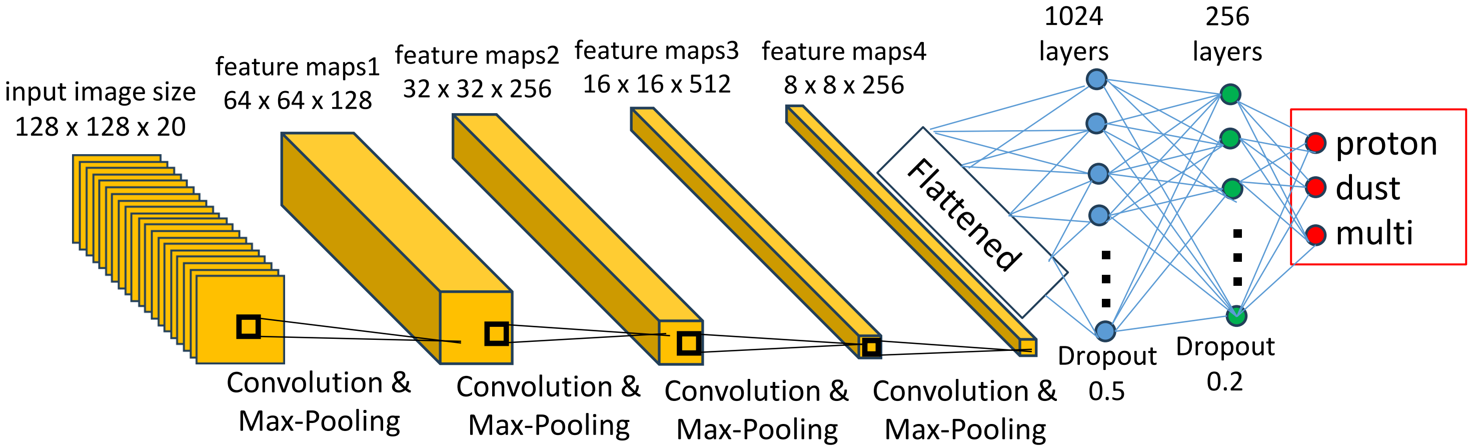
検出閾値1μm（100 keV相当）で 1台あたり 0.8 kg/yearの解析速度を達成

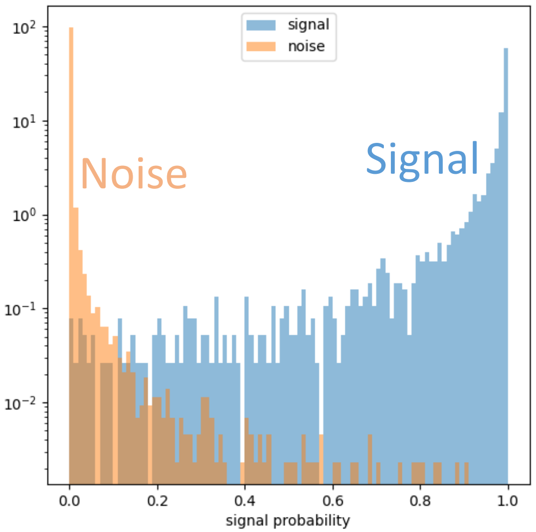
日本では4台が稼働中

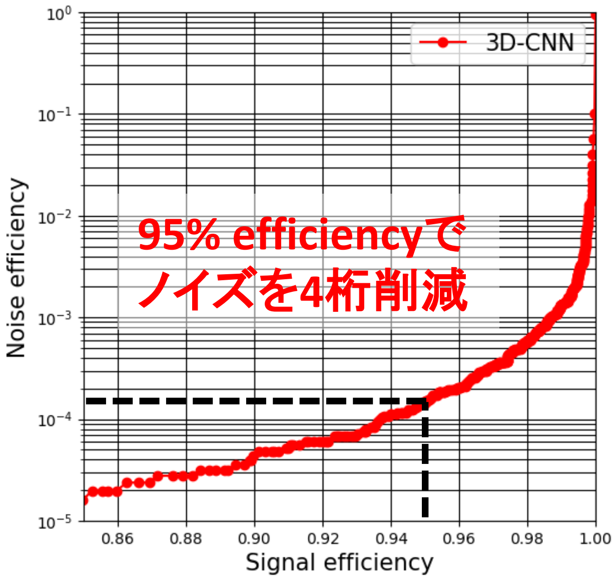
3D Convolutional Neutral Network（3D-CNN）

Training Samples

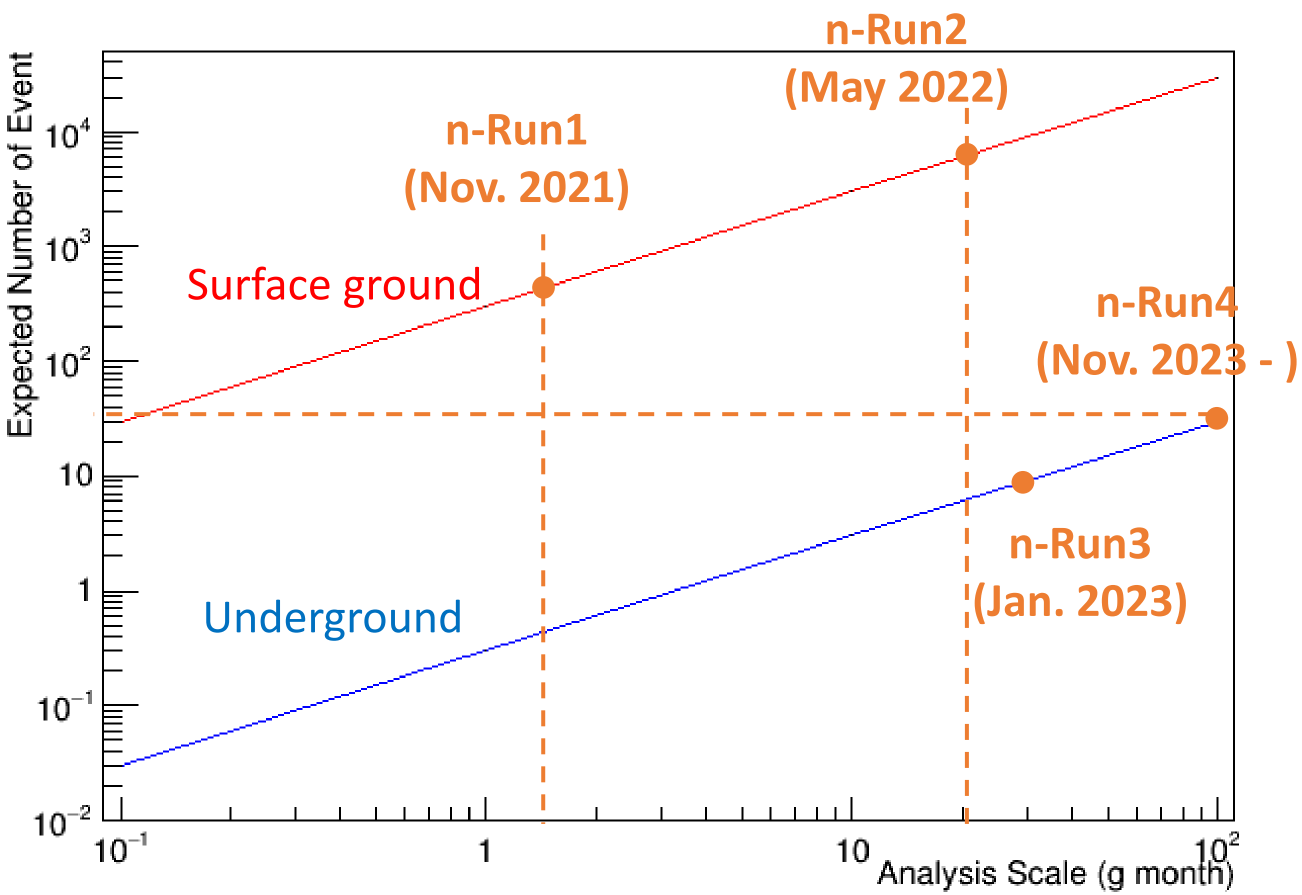


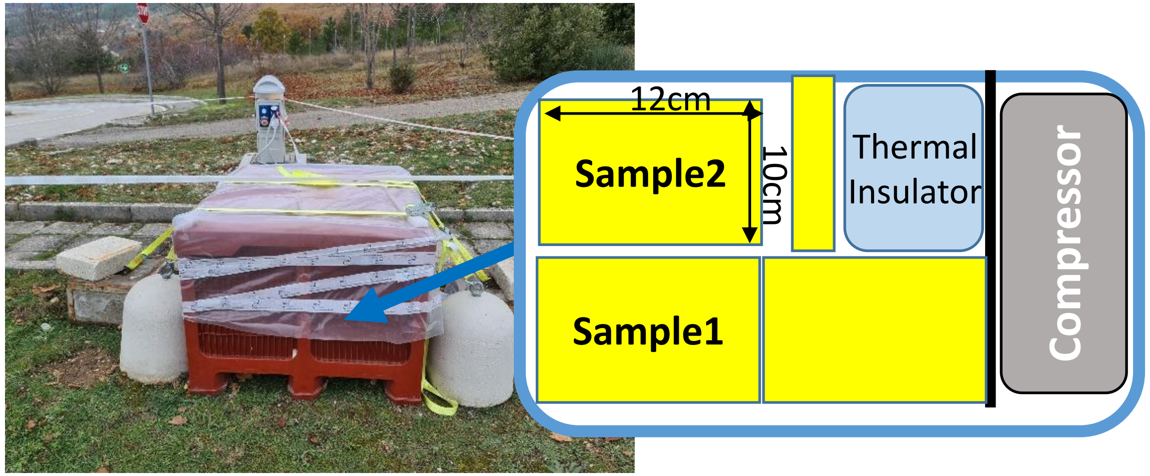






Environmental Neutron Measurement by NIT @ LNGS

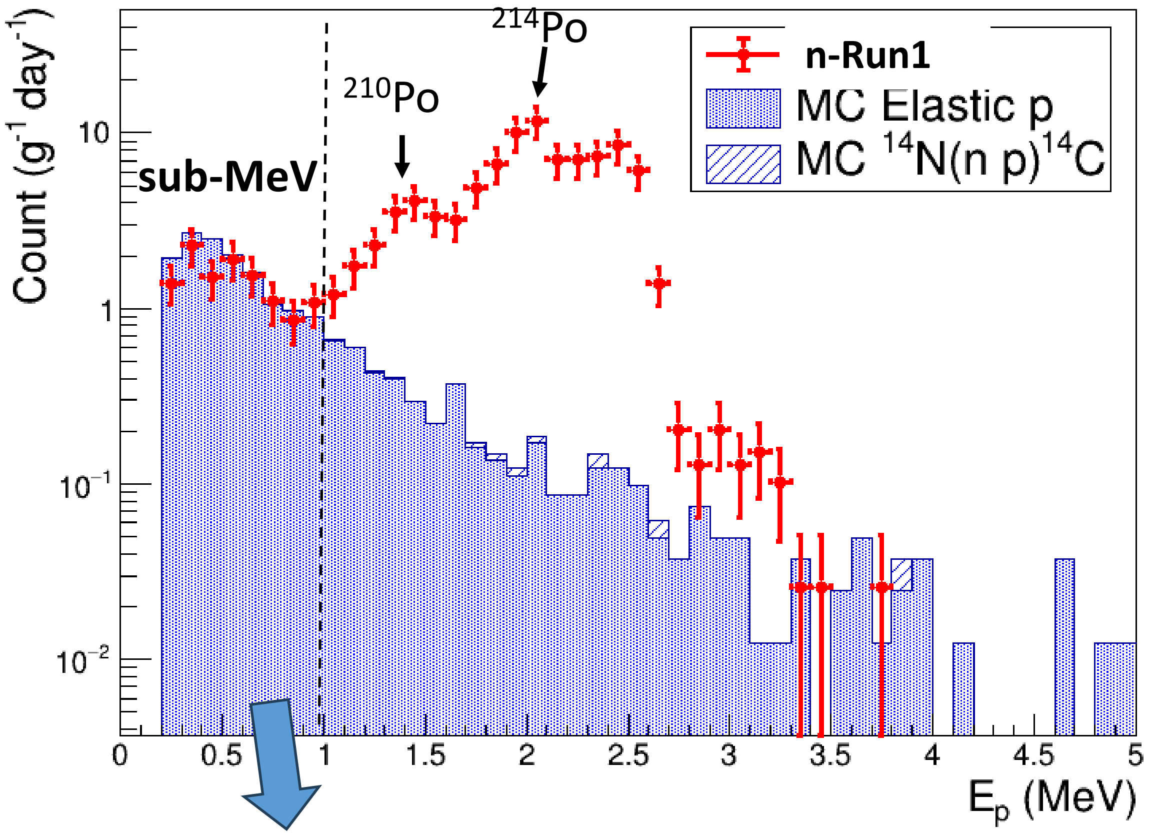


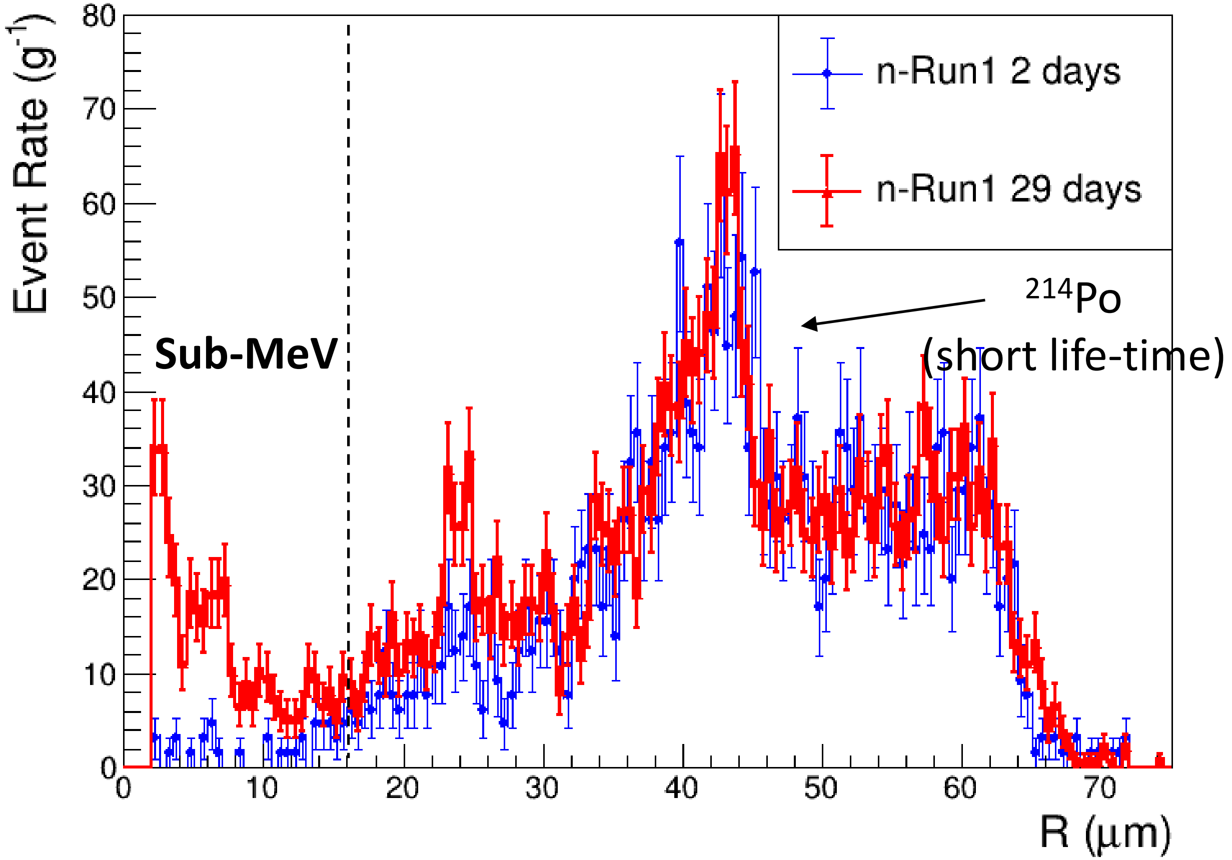


✓ **Without shielding!**

because of no sensitivity to muon and gamma

n-Run1 Result





Neutron Flux [0.25 ~ 10 MeV]

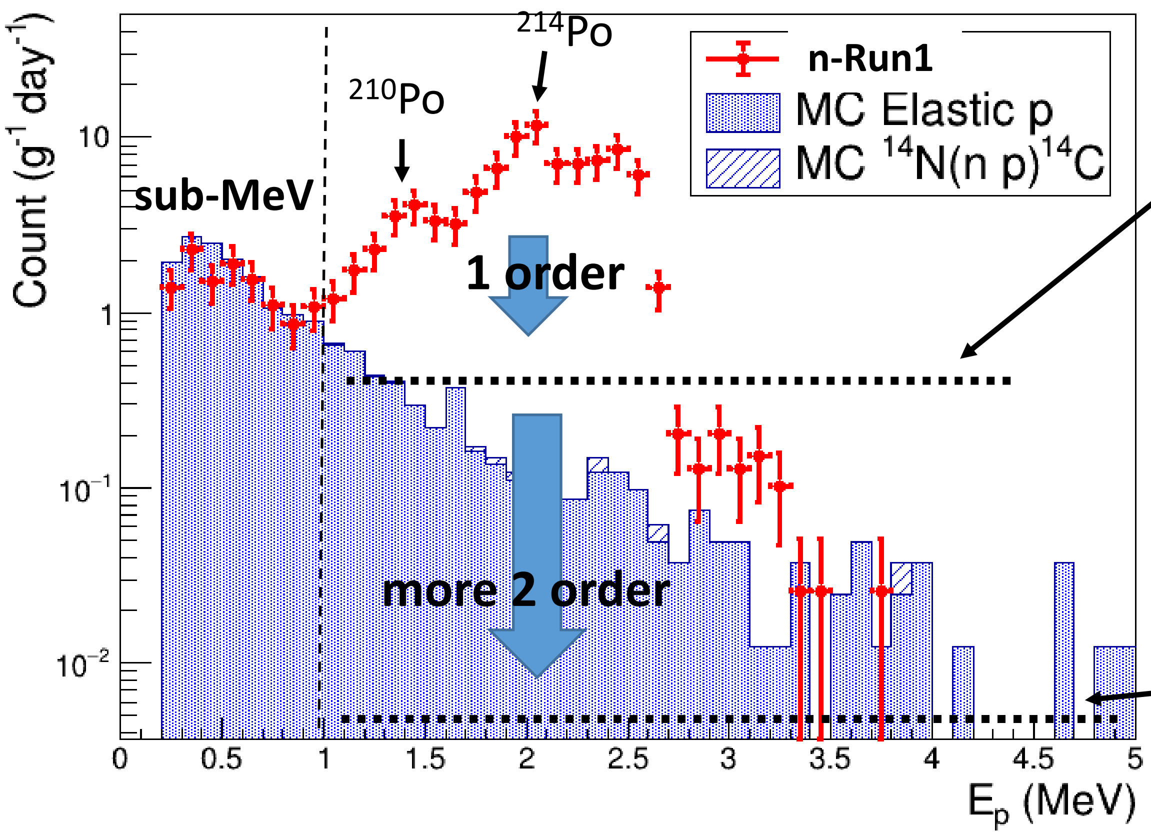
PARMA model : $9.0 \times 10^{-3}\ cm^{-2}\ s^{-1}$

Data : $(8.4 \pm 1.8) \times 10^{-3}\ cm^{-2}\ s^{-1}$

T. Shiraishi, *et al.*, Phys. Rev. C **107**, 014608 (2023)

Reduction of ^{214}Po Contamination at Drying

Proton Energy



Hall F (NEWSdm facility)

n-Run2, n-Run3 (climatic chamber)

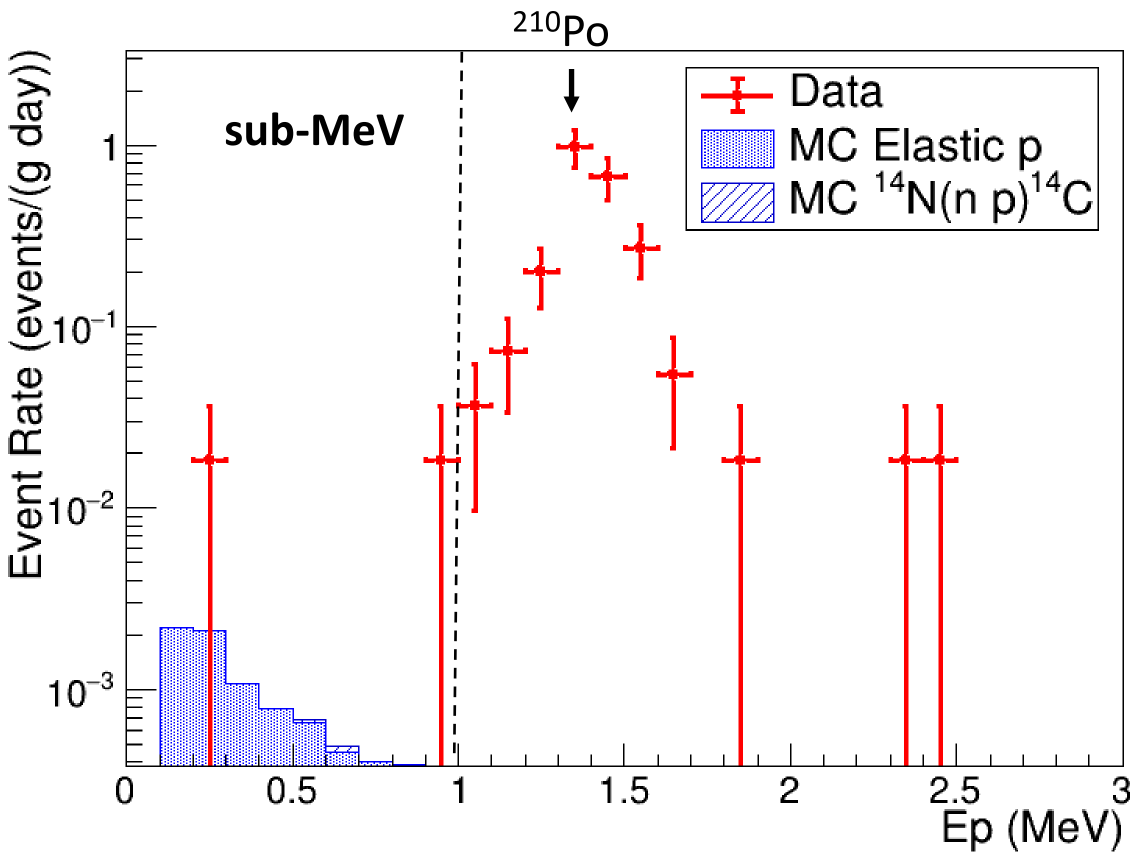
n-Run1 (granite table)

n-Run4 (Radon free room, CR1 @ Hall C)

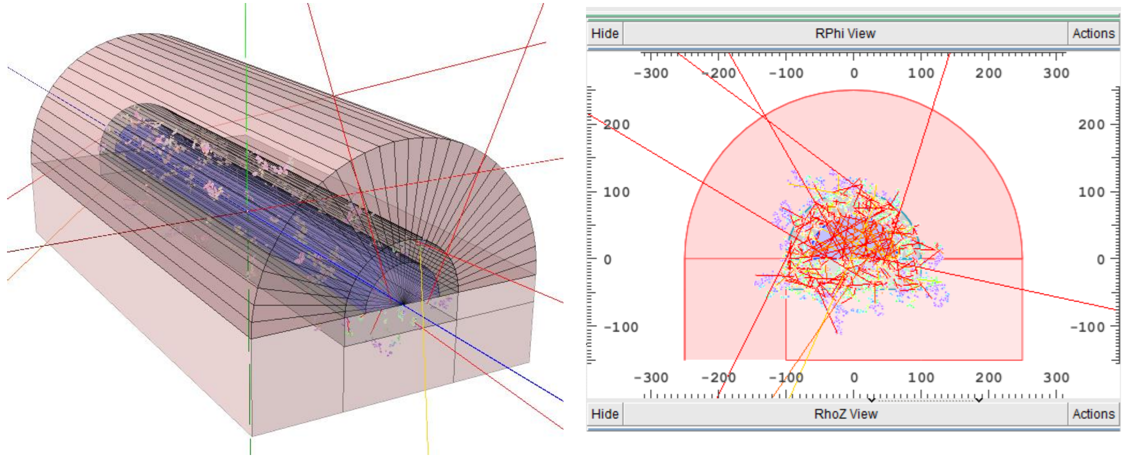
n-Run4 Result (100 g*month scale run)

Very Preliminary

1.9 g*month分の解析結果



MC Simulation using NeuCBOT and GEANT4



岩石中のU, Th系列の(α n)反応と自発核分裂を考慮

H. Wulandari et al., Astropart. Phys., 22, 313-322 (2004)

✓ 今のところsub-MeV帯は予測と無矛盾

- 地下中性子測定には少なくとも10 g*month スケールのNIT解析が必要

→ 秋の物理学会までに残りを解析する予定

Summary

→ T. Shiraishi, *et al.*, PTEP **2021** 4, 043H01 (2021)

- NIT解析用にのサブミクロン精度の3次元トラッキング技術を開発
  - 1μm (100 keV) 閾値で1台あたり 0.8 kg/year の解析速度を達成
  →今後さらに 1.5 kg/year までアップグレードする予定
  - 3D-CNNによる自動事象分類
- LNGS研究所での中性子測定
  - Surface run (n-Run1, nRun2)
    - Sub-MeV帯の中性子スペクトル・方向測定に成功 → T. Shiraishi, *et al.*, Phys. Rev. C **107**, 014608 (2023)
    - MeV帯において、サンプル製造時の^{214}Po混入が分かった
      → 乳剤塗布時のラドン混入を抑えることで3桁減らすことに成功
  - Underground run (n-Run3, nRun4) ongoing
    - 100 g*month スケールでのNIT解析によって、広いエネルギー範囲での地下中性子スペクトル測定を目指す
    - 実験場所や岩盤中の水分による中性子スペクトルへの影響の調査、未知事象の探索を行う

中性子スペクトル測定技術の応用

PHYSICAL REVIEW C **107**, 014608 (2023)

Environmental sub-MeV neutron measurement at the Gran Sasso surface laboratory with a super-fine-grained nuclear emulsion detector

T. Shiraishi,[1,*] S. Akamatsu,[1] T. Naka,[1,2] T. Asada,[3,4] G. De Lellis,[3,5] V. Tioukov,[5] G. Rosa,[6] R. Kobayashi,[7] N. D'Ambrosio,[4] A. Alexandrov,[3,5] and O. Sato[8]
[1]*Department of Physics, Toho University, Chiba J-274-8510, Japan*
[2]*Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, Aichi J-464-8602, Japan*
[3]*Universitá degli studi di Napoli "Federico II", Napoli I-80126, Italy*
[4]*Laboratori Nazionali del Gran Sasso - INFN, L'Aquila I-67100, Italy*
[5]*Istituto Nazionale di Fisica Nucleare, Napoli I-80126, Italy*
[6]*Sezione INFN di Roma, Roma I-00185, Italy*
[7]*Graduate School of Science, Nagoya University, Aichi J-464-8602, Japan*
[8]*Institute of Materials and Systems for Sustainability, Nagoya University, Aichi J-464-8602, Japan*

(Received 22 September 2022; accepted 29 November 2022; published 10 January 2023)

イタリア・グランサッソ研究所での
sub-MeV帯中性子スペクトル測定

波及

応用物理学会プレスリリース
（2022年9月）

工学

- 核融合反応の理解
- 中性子ラジオグラフィ

名古屋大学工学研究科
（富田英生氏）

- マイクロイオンビーム
  - がん治療
  - 元素マッピング

理化学研究所仁科センター
（池田時浩氏）

医療

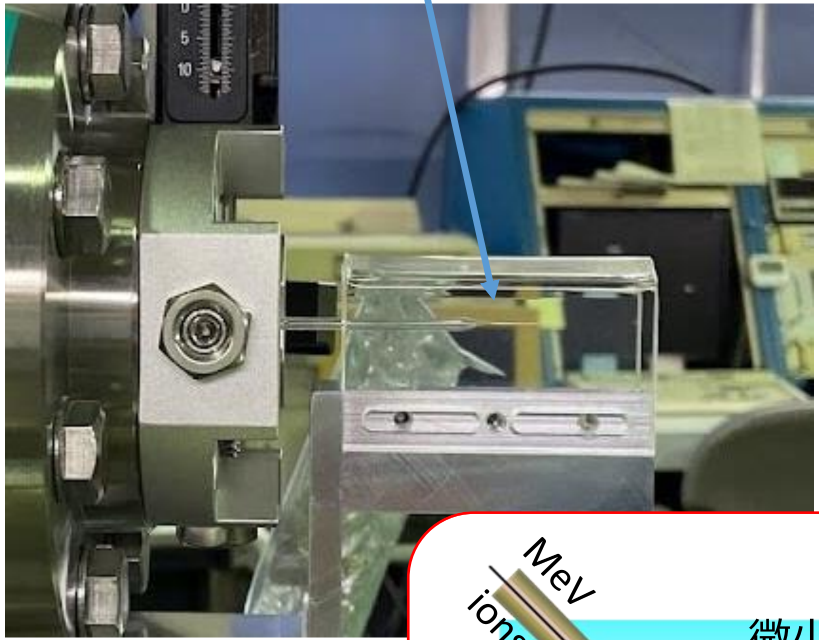
- BNCTの基礎研究
- 重粒子線治療における吸収線量分布

名古屋陽子線治療センター
（木村充宏氏）

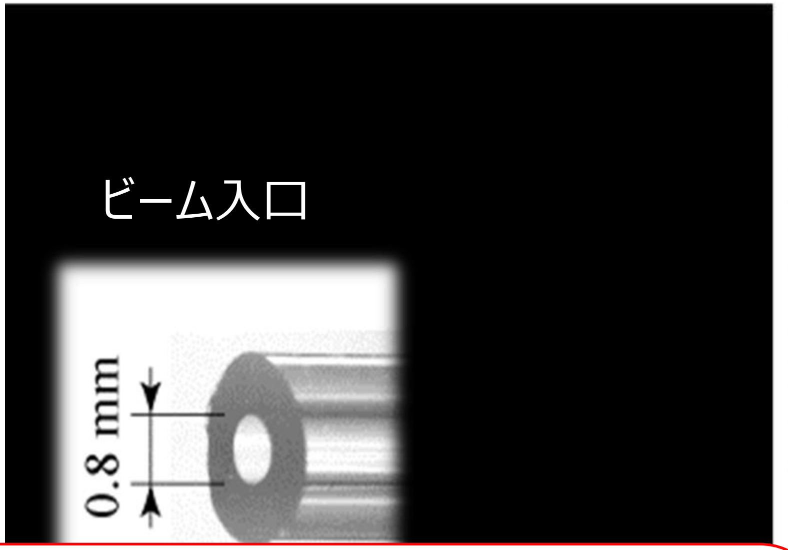
大気取り出しMeVマイクロイオンビームの研究（理化学研究所との共同研究）

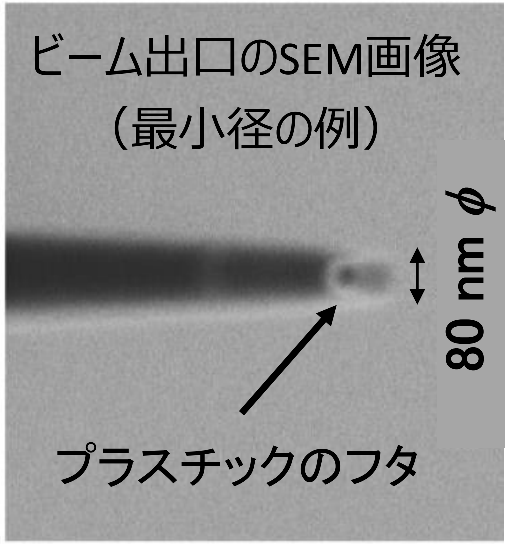
T. Ikeda, Quantum Beam Sci.4, 22 (2020).

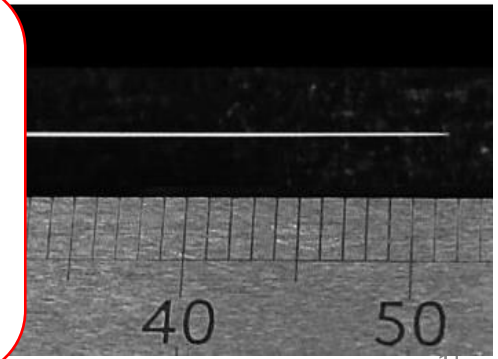
ガラスの針でビームをμmまで絞る

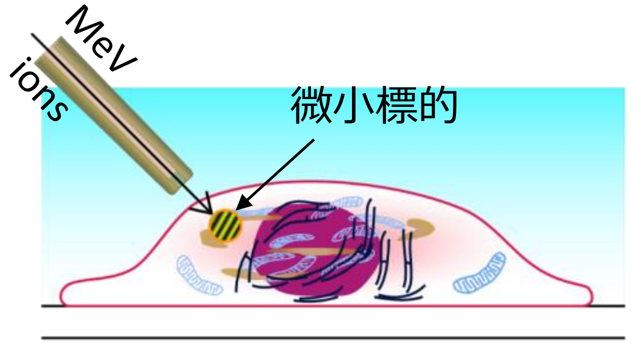


ガラスキャピラリーによるマイクロイオンビームの生成



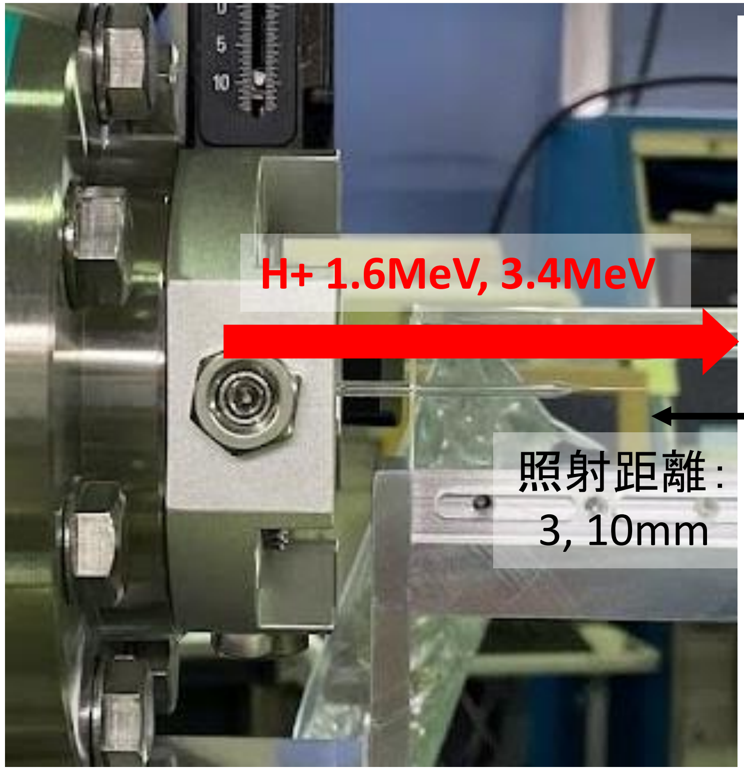


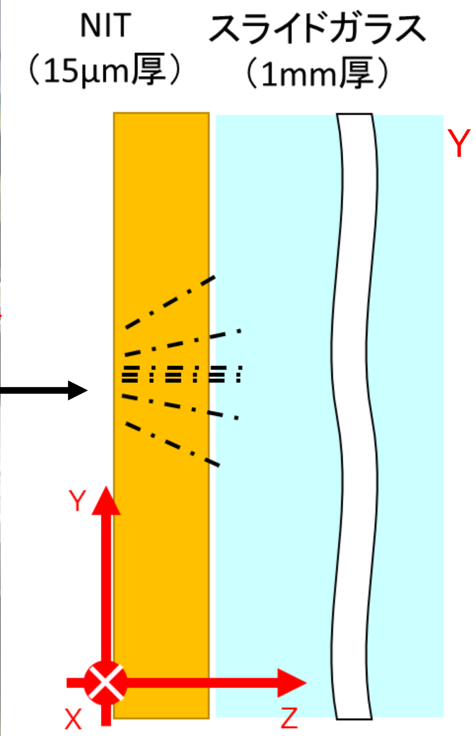




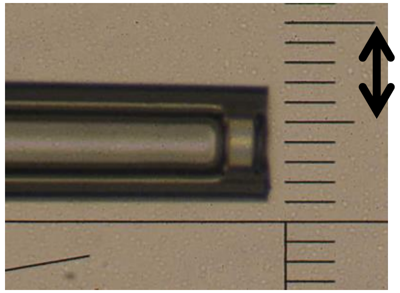
・細胞照射
・器官の一部を狙った照射
・元素マッピング（μ-PIXE）
などへの応用が期待

マイクロイオンビームの照射





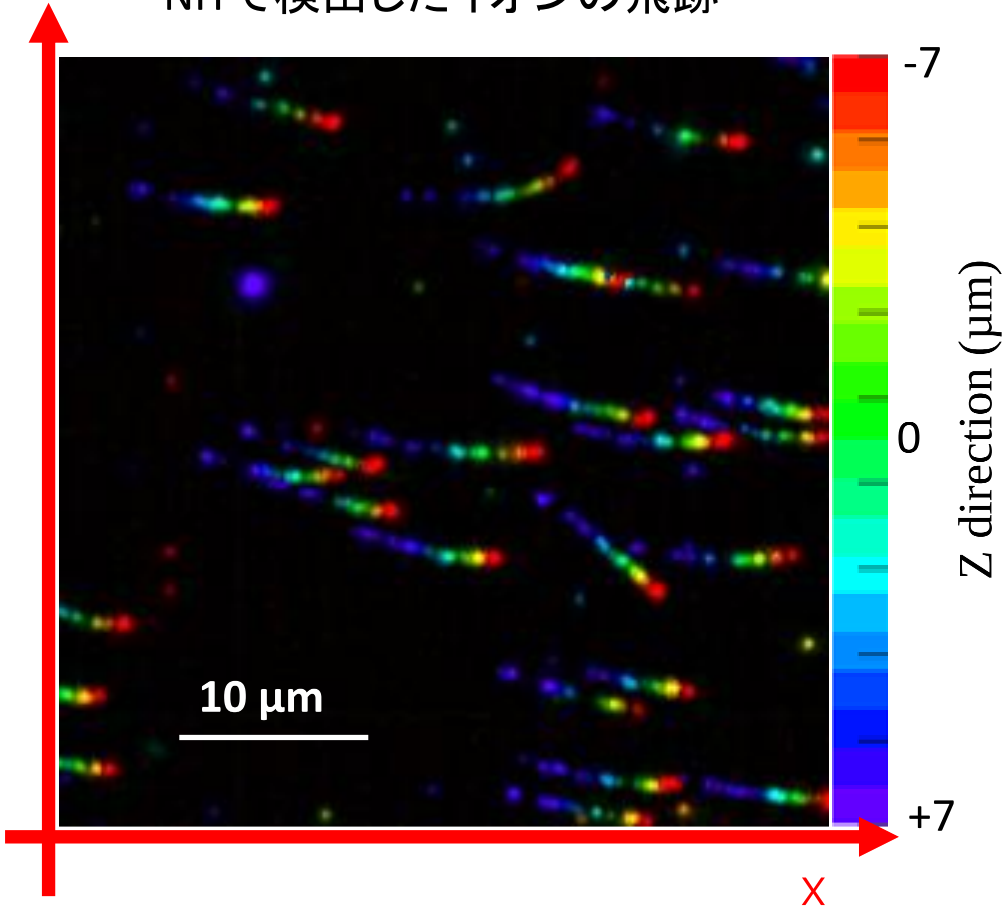
実際に使用した
キャピラリーの先端
No. 901d



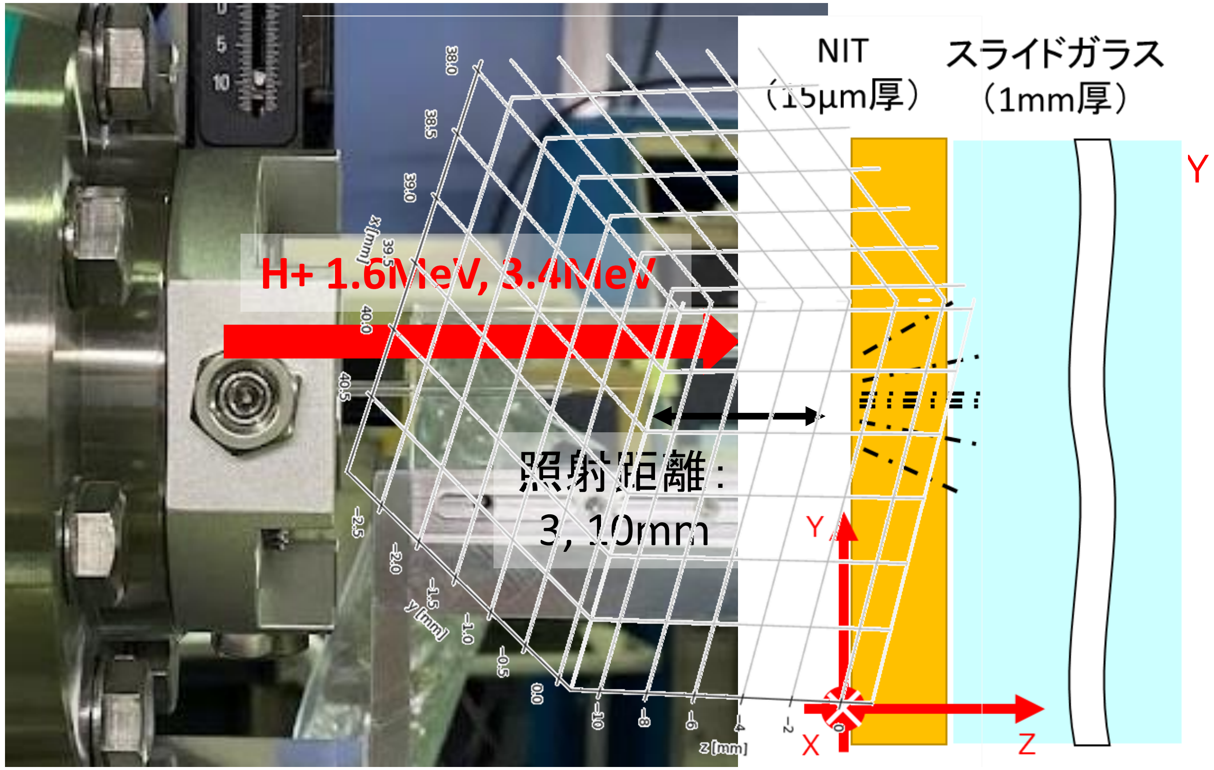
100um

フタ　50µmΦ
30µm厚

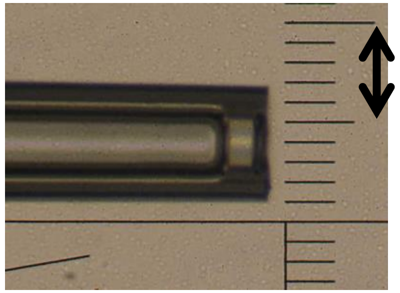
NITで検出したイオンの飛跡



マイクロイオンビームの照射



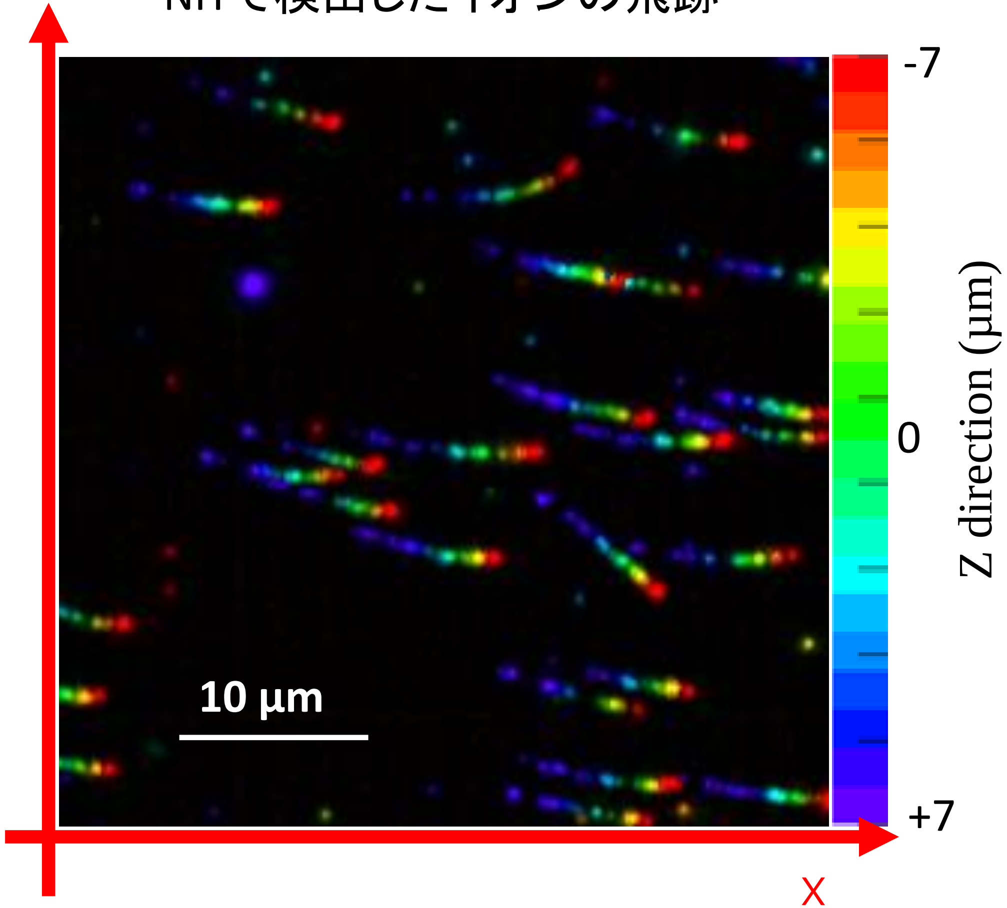
実際に使用した
キャピラリーの先端
No. 901d



100um

フタ 50μmΦ
30μm厚

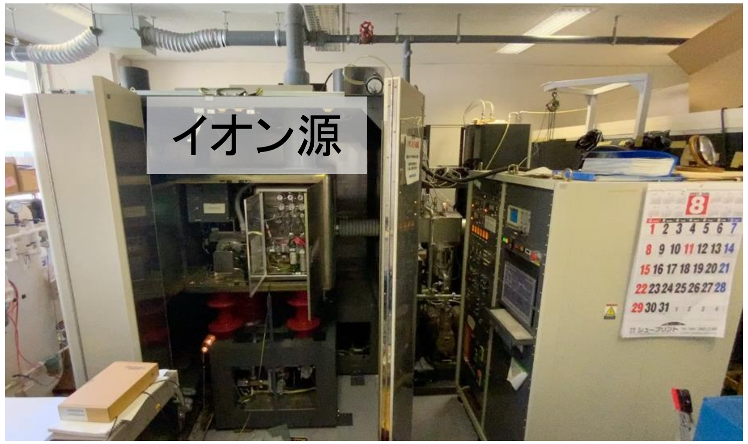
NITで検出したイオンの飛跡

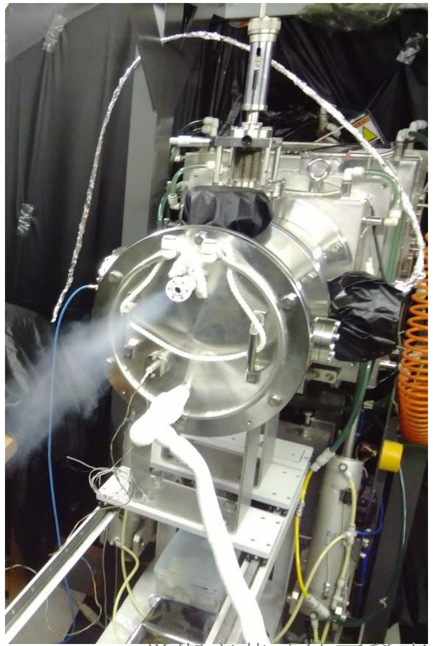


研究室保有の加速器 （神奈川大学星野研）

低速イオン注入装置
加速電圧 : 5 ~ 200 kV
照射温度 : –196 ~ 1000 ℃
ビーム電流 : 10 pA ~ 100 μA

1MVタンデム型ペレトロンイオン加速器
加速電圧 : 0.5 - 1 MV
検出器 : 表面障壁型Si半導体検出器 x 2
元素分析 : RBS-channeling, PIXE, 核反応, ERDA、…



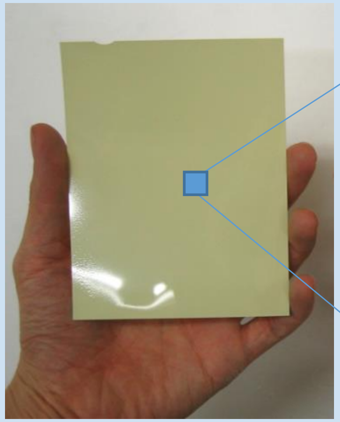


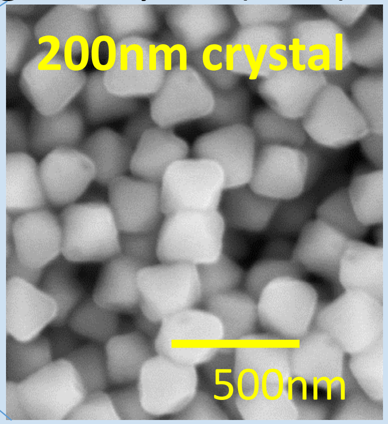
Backup

Comparison of Nuclear Emulsion

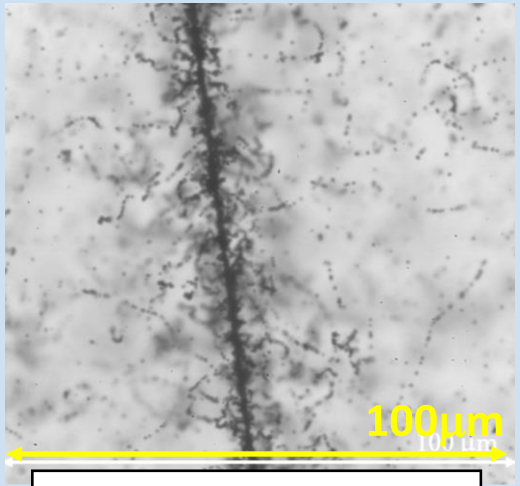
OPERA type

AgBr:I crystal (SEM)

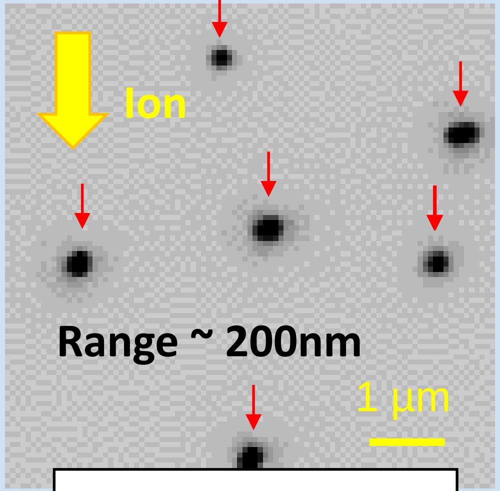




Optical microscope image



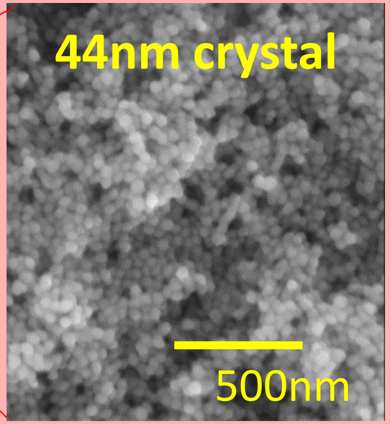
500MeV/n Fe ion



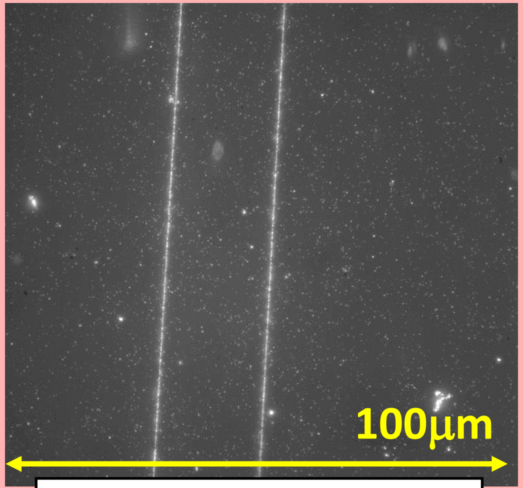
60keV C ion

Nano Imaging Tracker (NIT) type

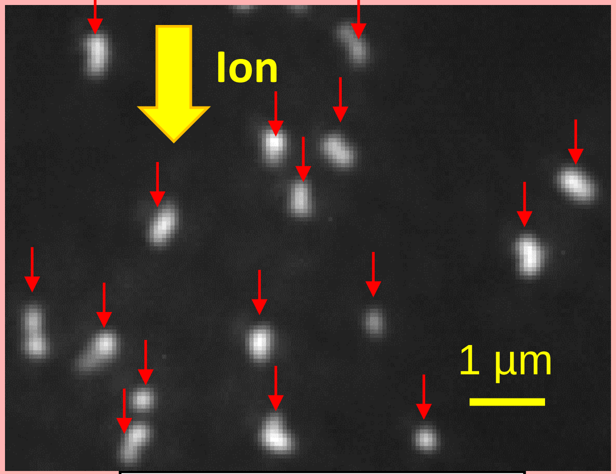
AgBr:I crystal (SEM)



Optical microscope image



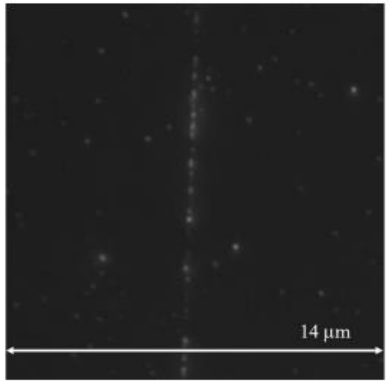
500MeV/n Fe ion



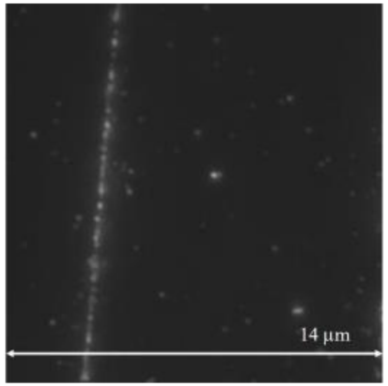
60keV C ion

High Energy Ion Track in NIT

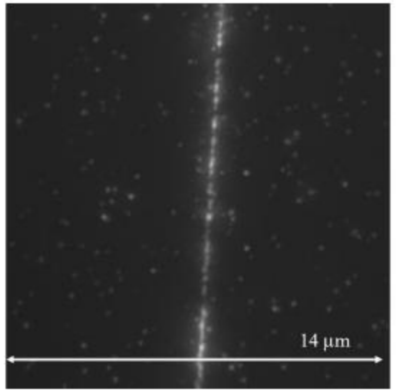
C 290 MeV/n



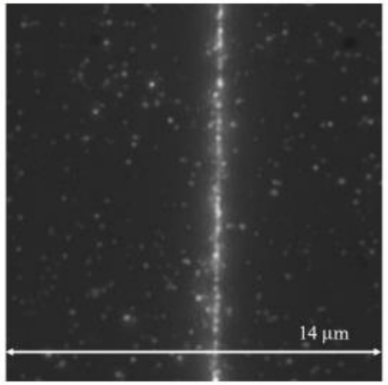
Ar 500 MeV/n



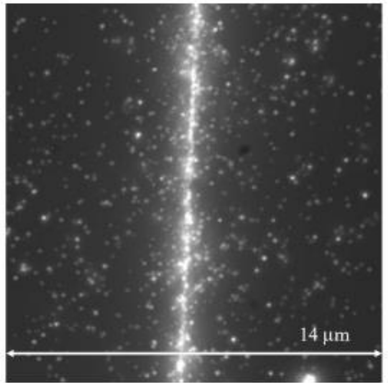
Fe 500 MeV/n



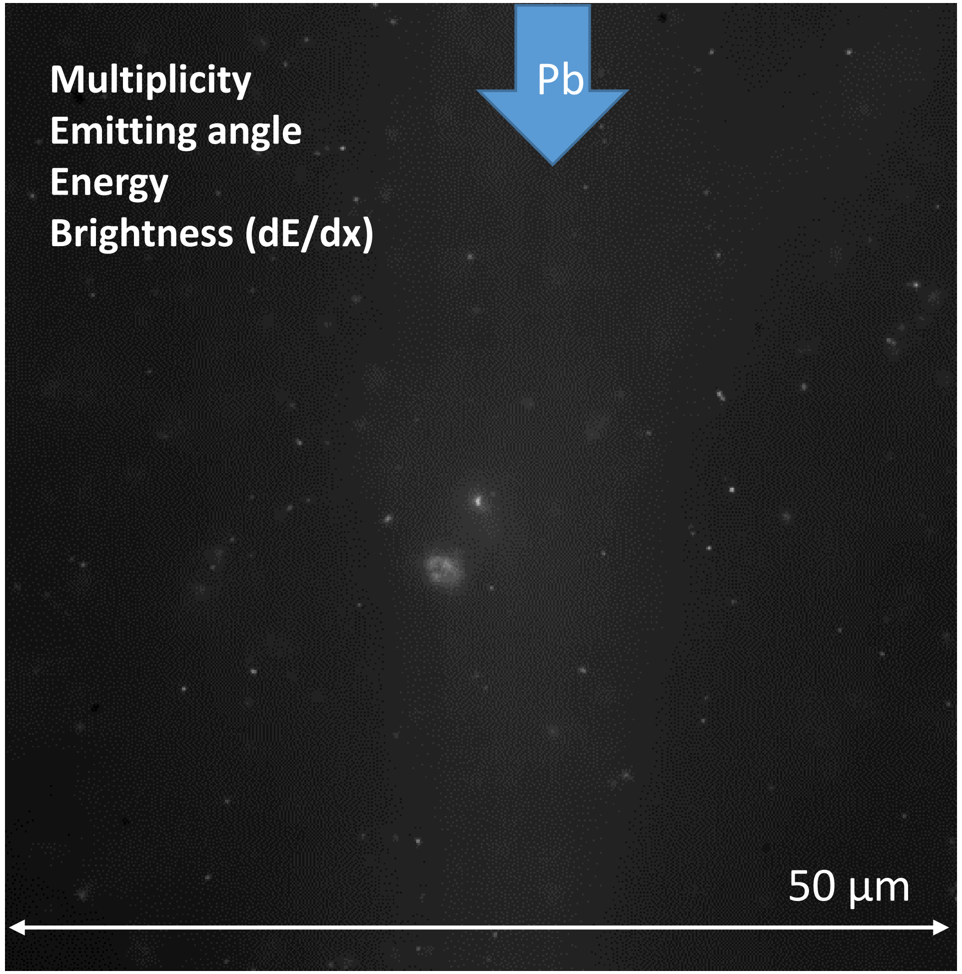
Xe 150 GeV



Pb 150 GeV



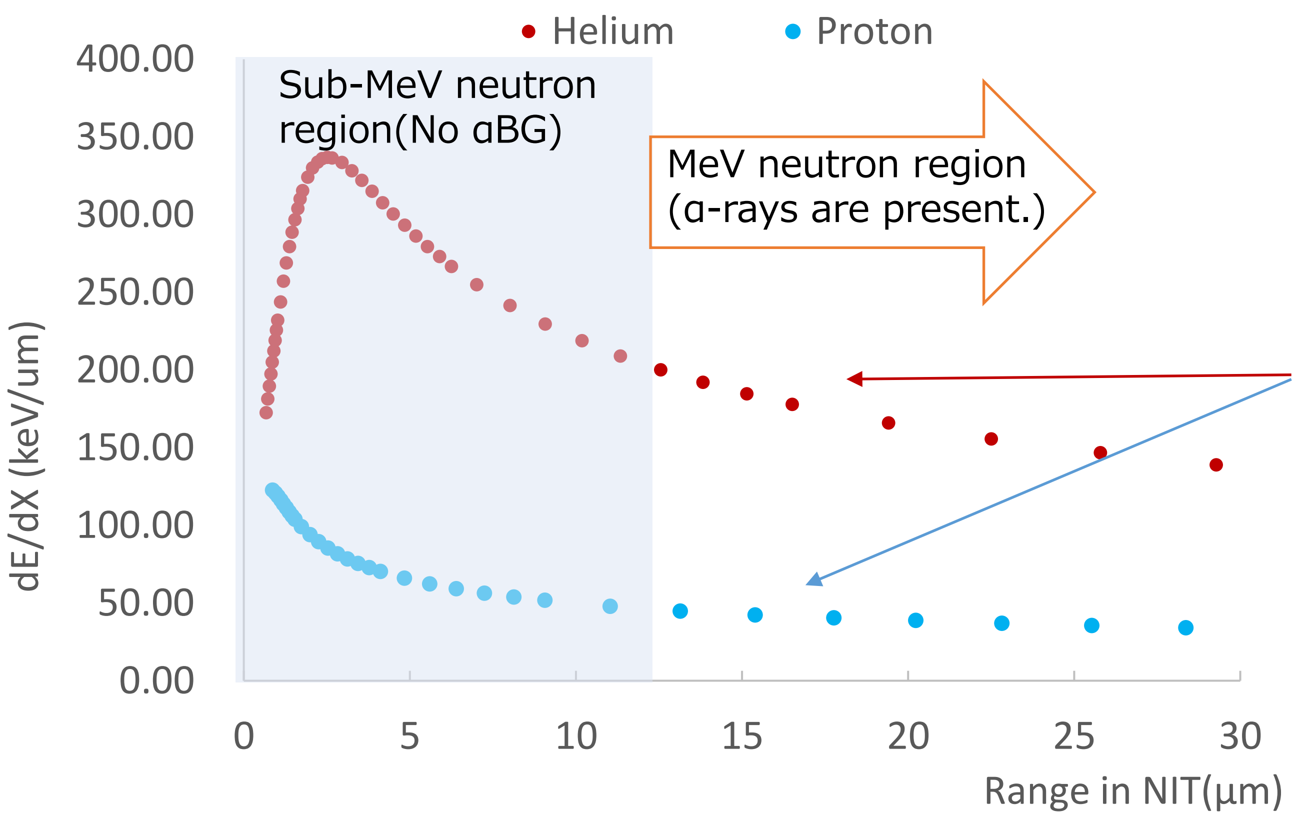
Spallation of 150 GeV Lead Beam



For p-α discrimination

Reported by Akamatsu

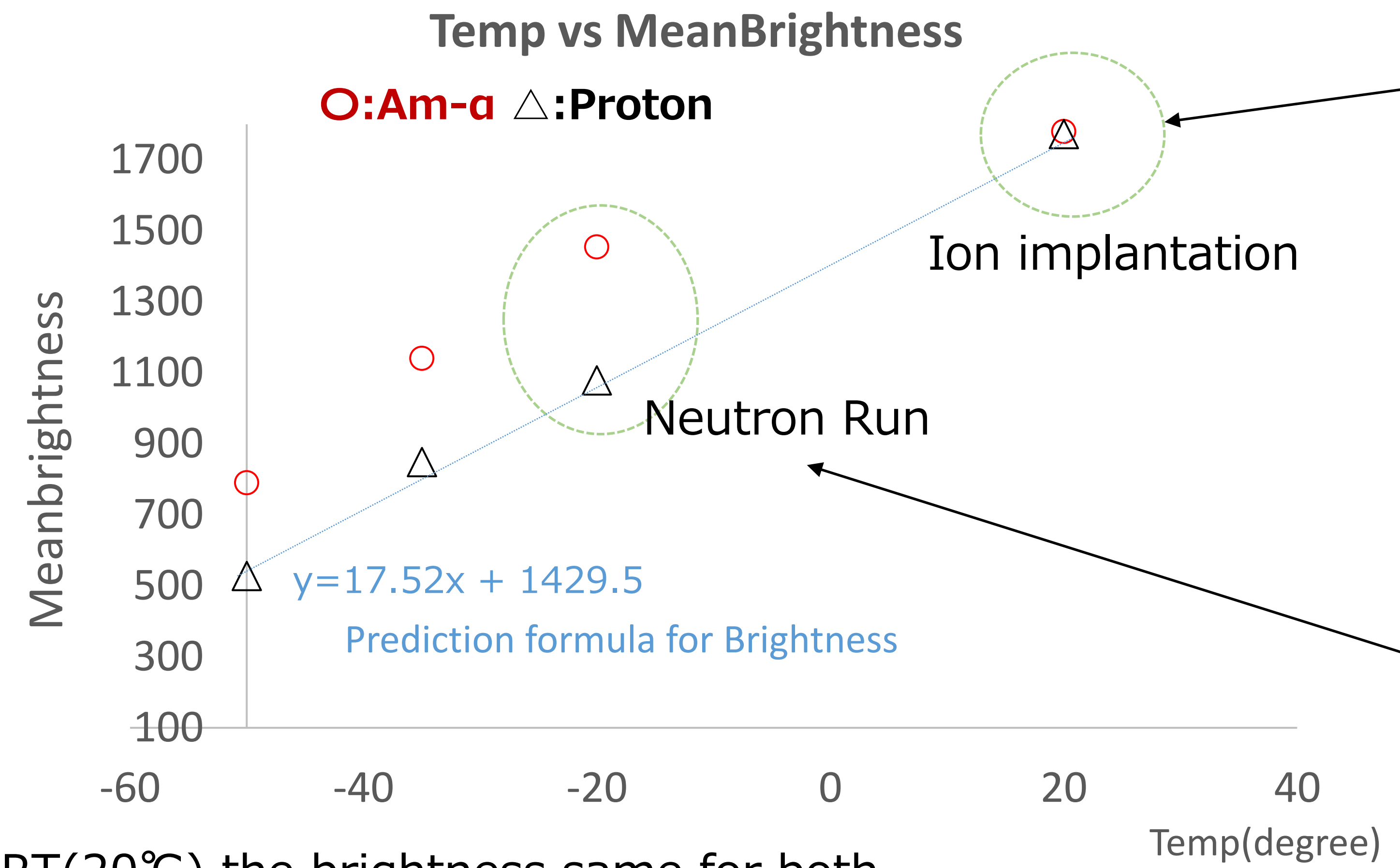
We tried to identify Alpha and Proton using differences in dE/dX.

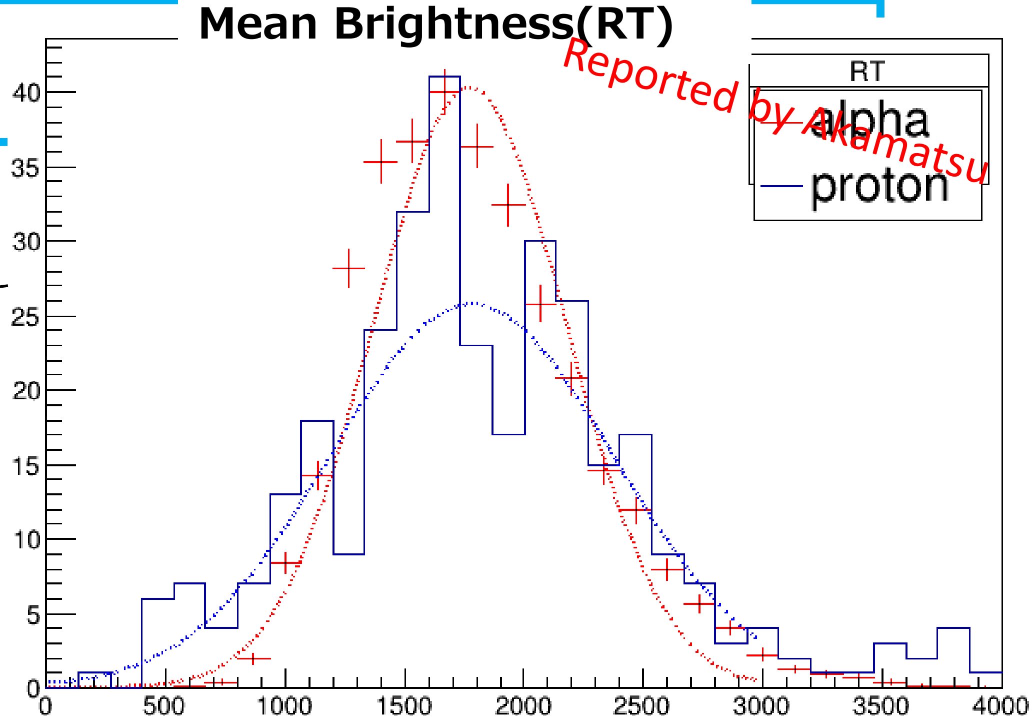


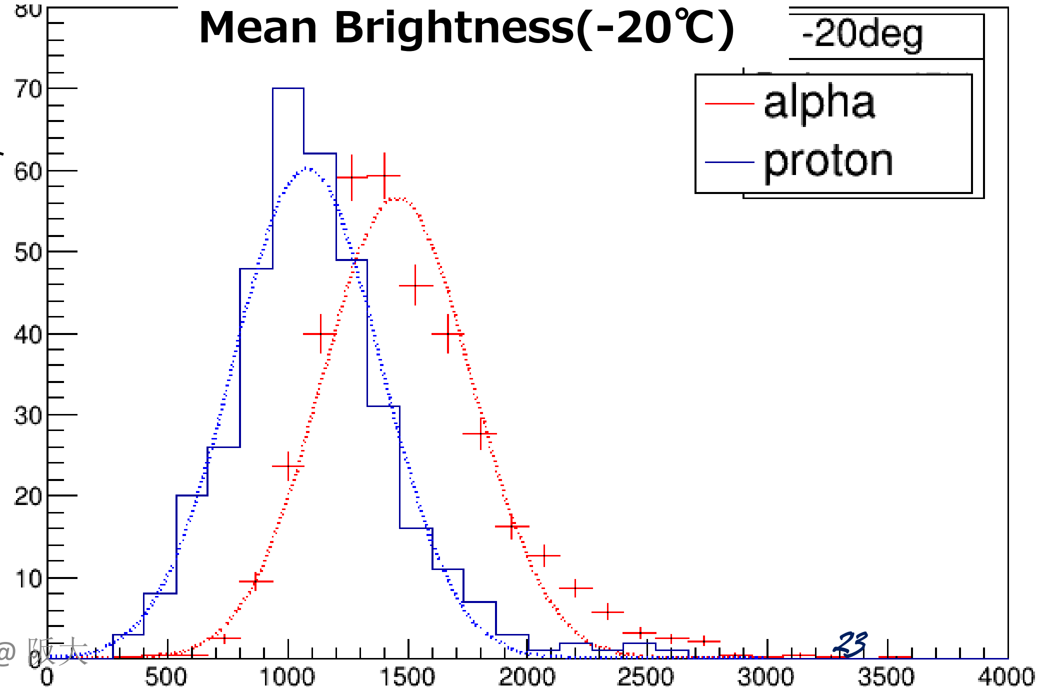
Do differences in dE/dX show up in the brightness of the track?

➢241Am-α (@Toho)and 252Cf neutron (@AIST) were exposed at different temperatures and the brightness of the track was compared.

p-ɑ discrimination







RT(20℃),the brightness same for both.

➢Can't be separated by brightness

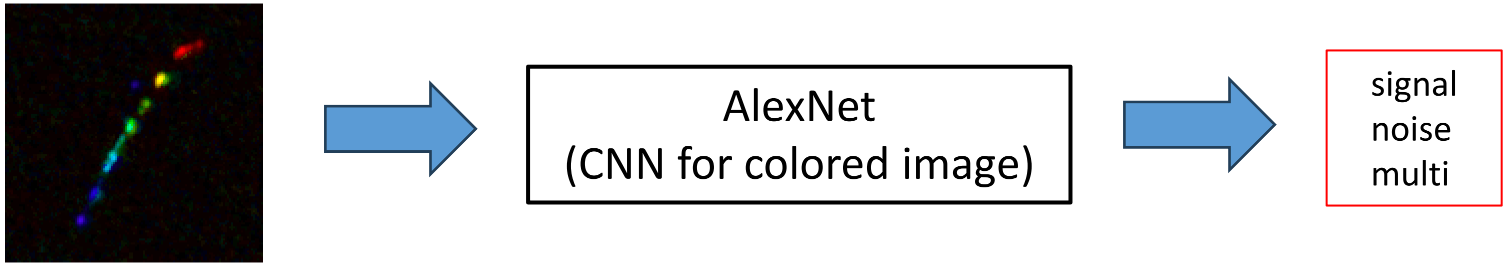
Below -20℃, the Brightness of ɑ is higher than that of proton.

➢There is a difference in brightness distribution.

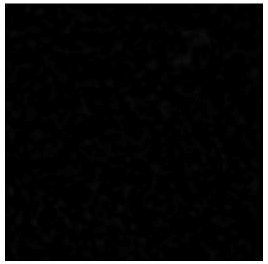
Can be statistically separated.

CNN upgrade (3D-CNN)

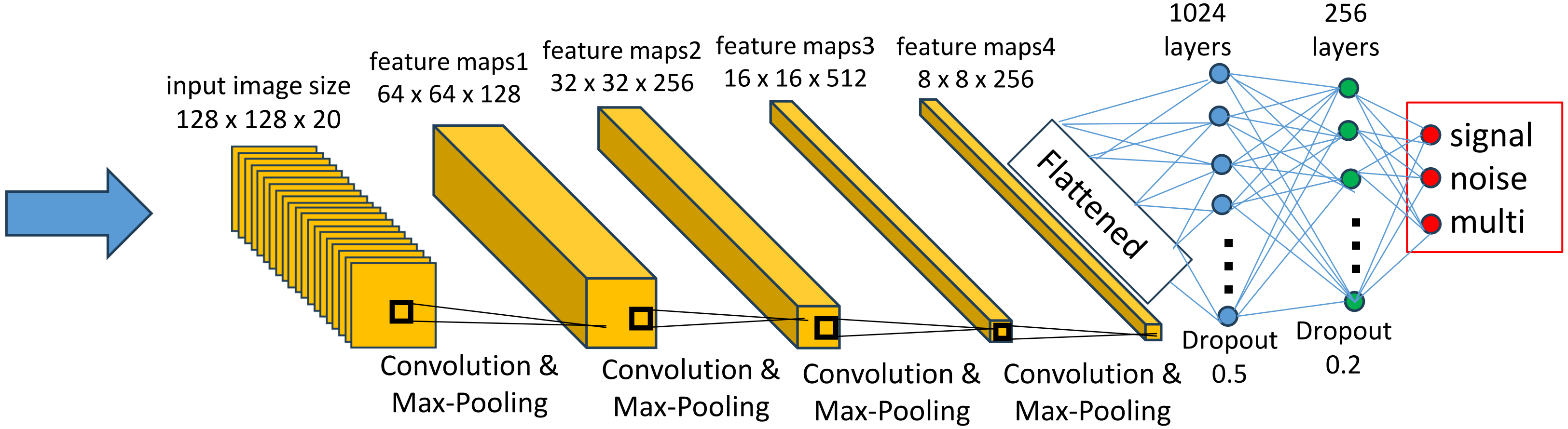
2D projected image
(128 x 128 x 3)



3D image
(128 x 128 x 20)



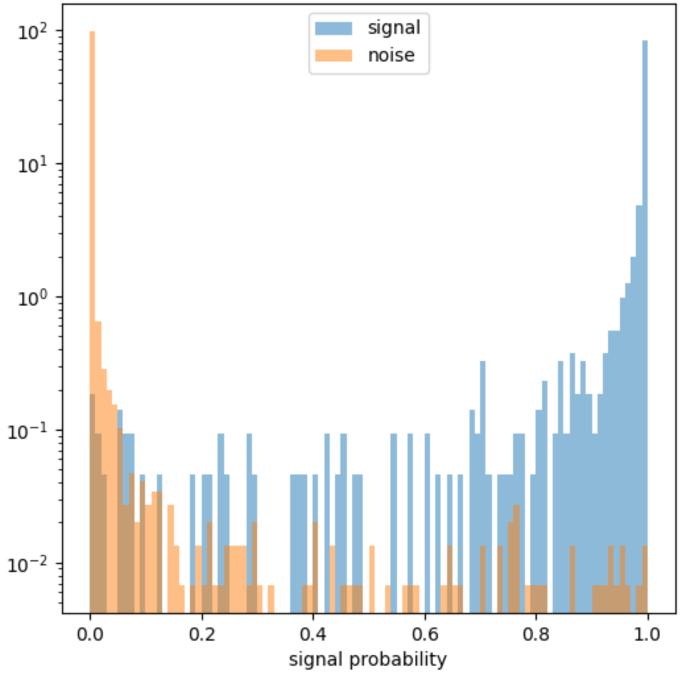
Custom 3D-CNN Network



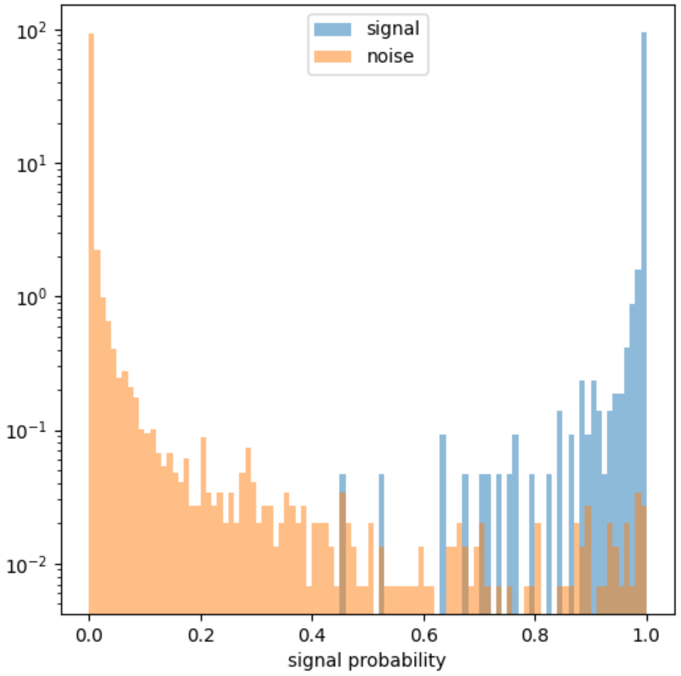
CNN upgrade (3D-CNN)

- Signal
  - AIST 880keV neutron
- Noise
  - n-Run4 0day

CNN w/ 2D projected image



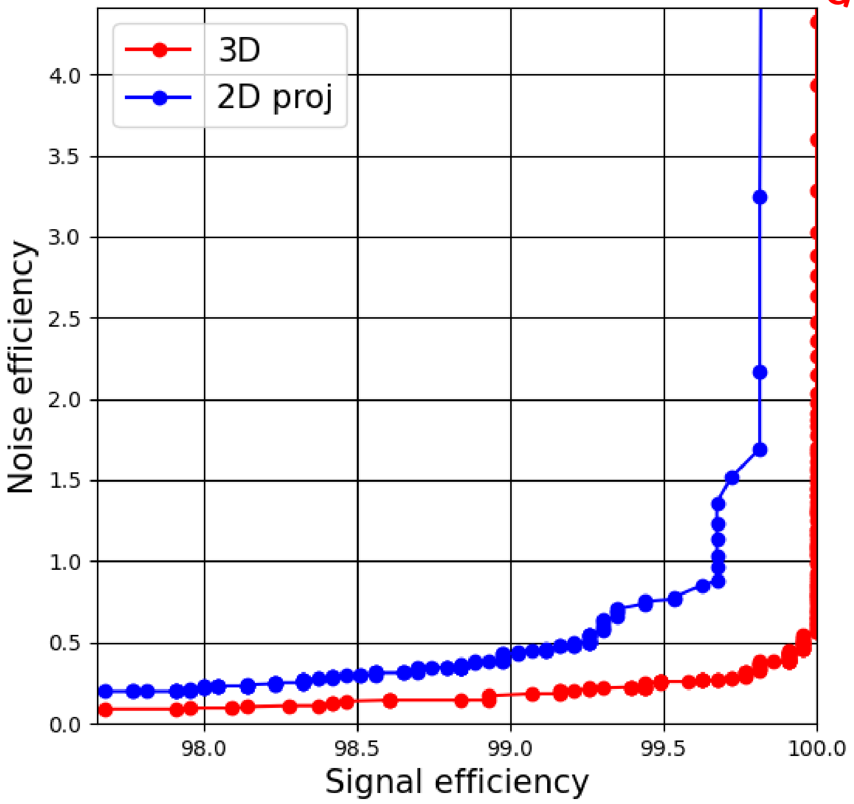
3D-CNN



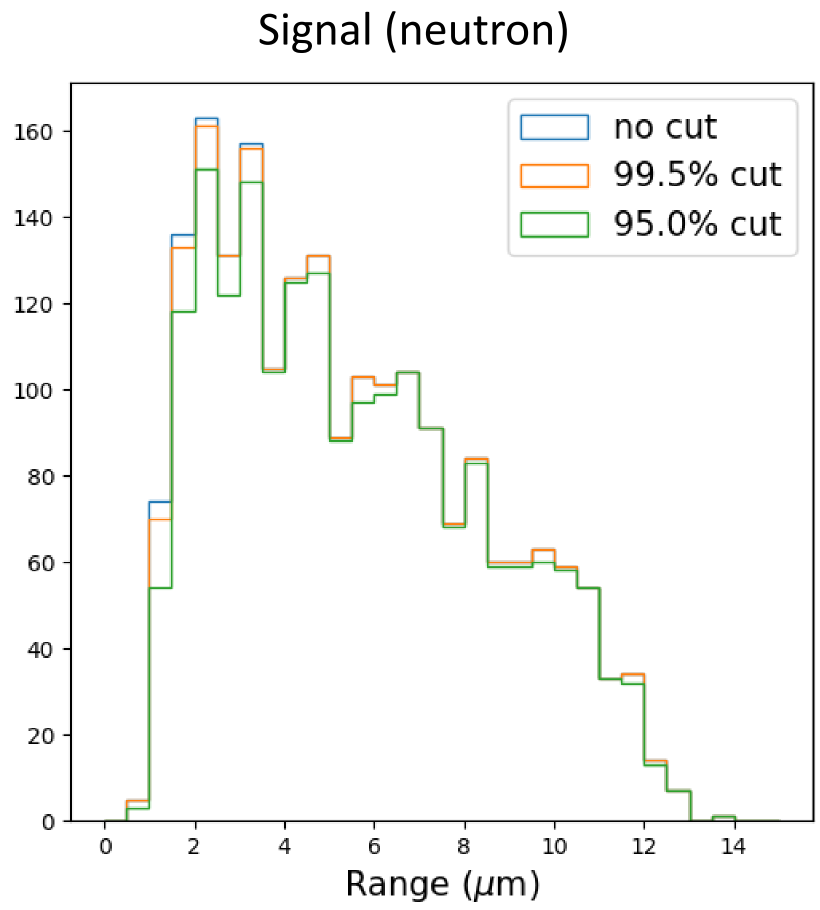
*still optimizing parameters…

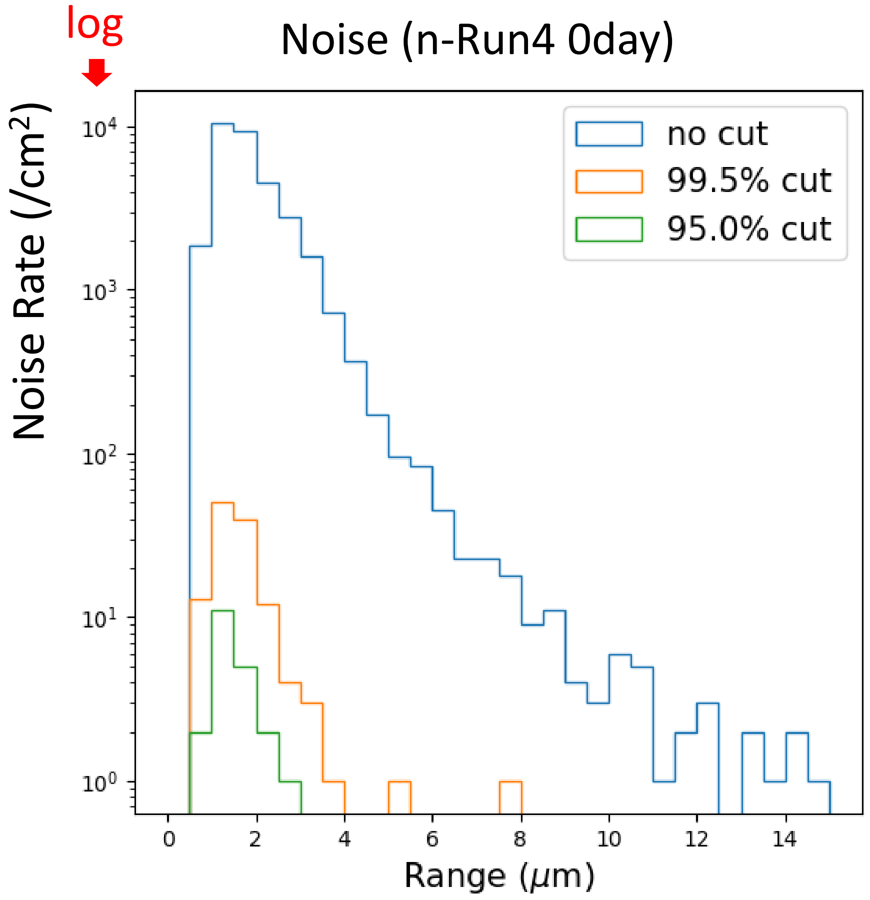
S/N curve

Preliminary



Effect for Range Distribution by 3D-CNN Cut



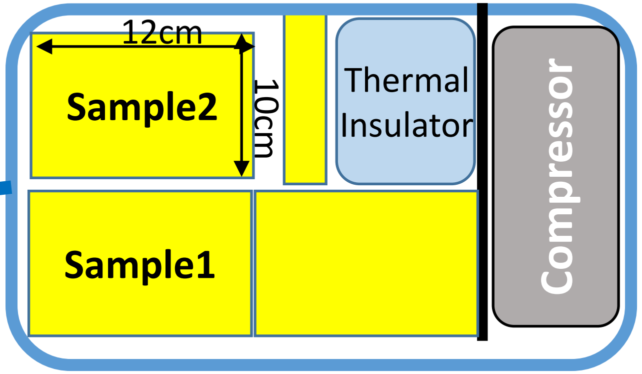


1st Surface Run (n-Run1) for Environmental Neutron Measurement @ LNGS

Motivation

- Demonstration of spectrum measurement for environmental neutron and CR-DM search
- There is no detailed data in the sub-MeV region even on the surface

Refrigerator Box

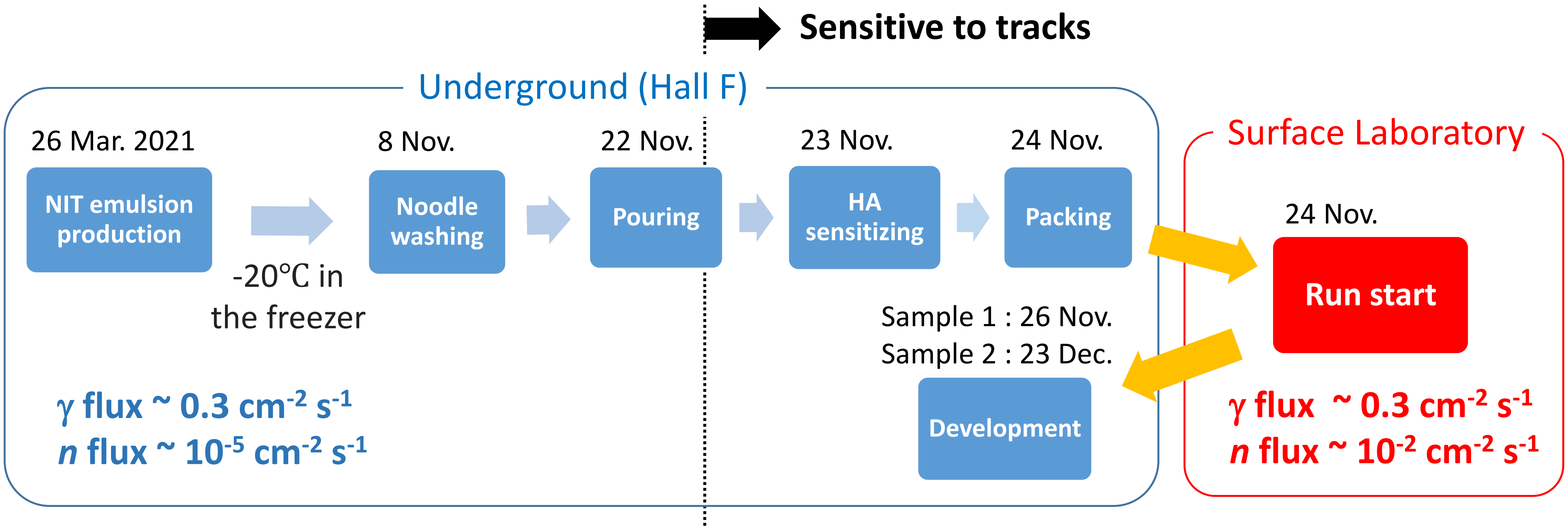


n-Run1 Setup

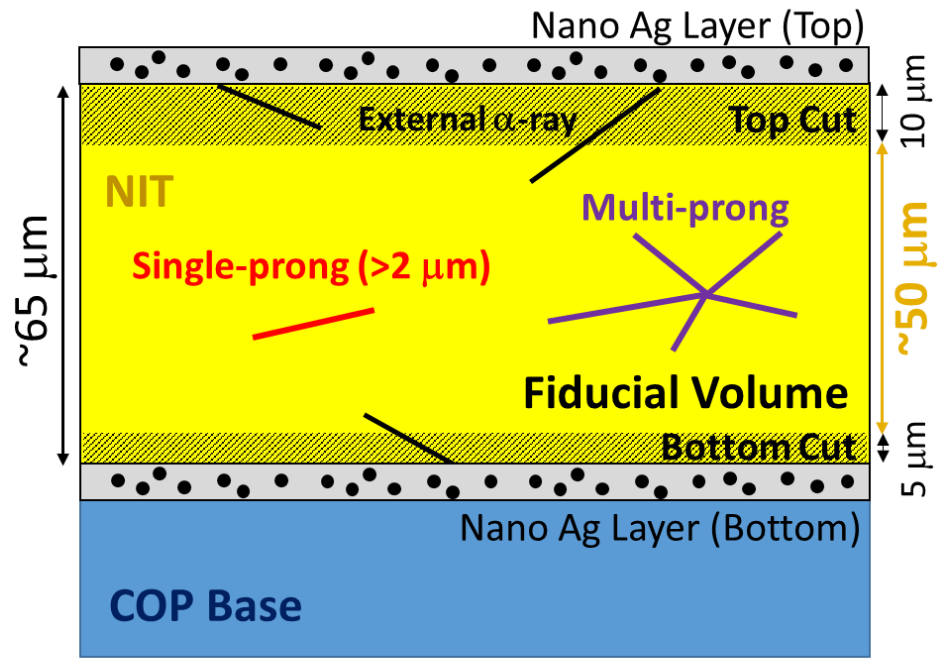
	Sample 1	Sample 2
Surrounding environment	Portable freezer box (outdoor)	
Altitude	1400 m	
Expected angle-integrated flux of atmospheric neutron in 0.25 – 10 MeV (assumed water fraction in ground as 20%) [13, 14]	$9.0 \times 10^{-3}\ n/(\mathrm{cm}^2\ \mathrm{s})$	
Operation temperature	-20 °C	
Run start 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)	0.65	1.35

* Recoil protons are accumulated $O(2)$ events /(g month) on the surface

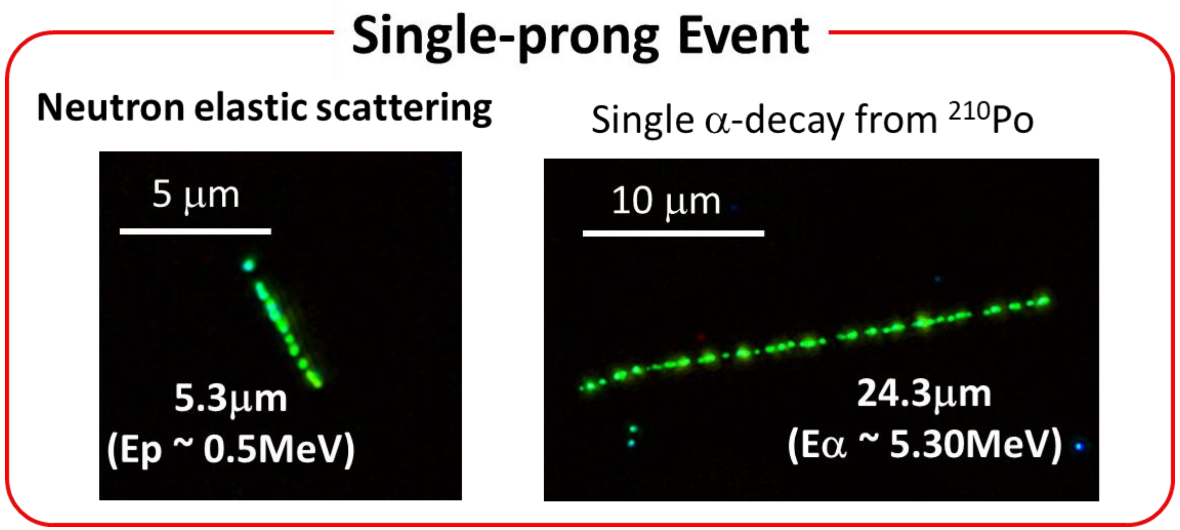
Sample preparation procedure for n-Run1

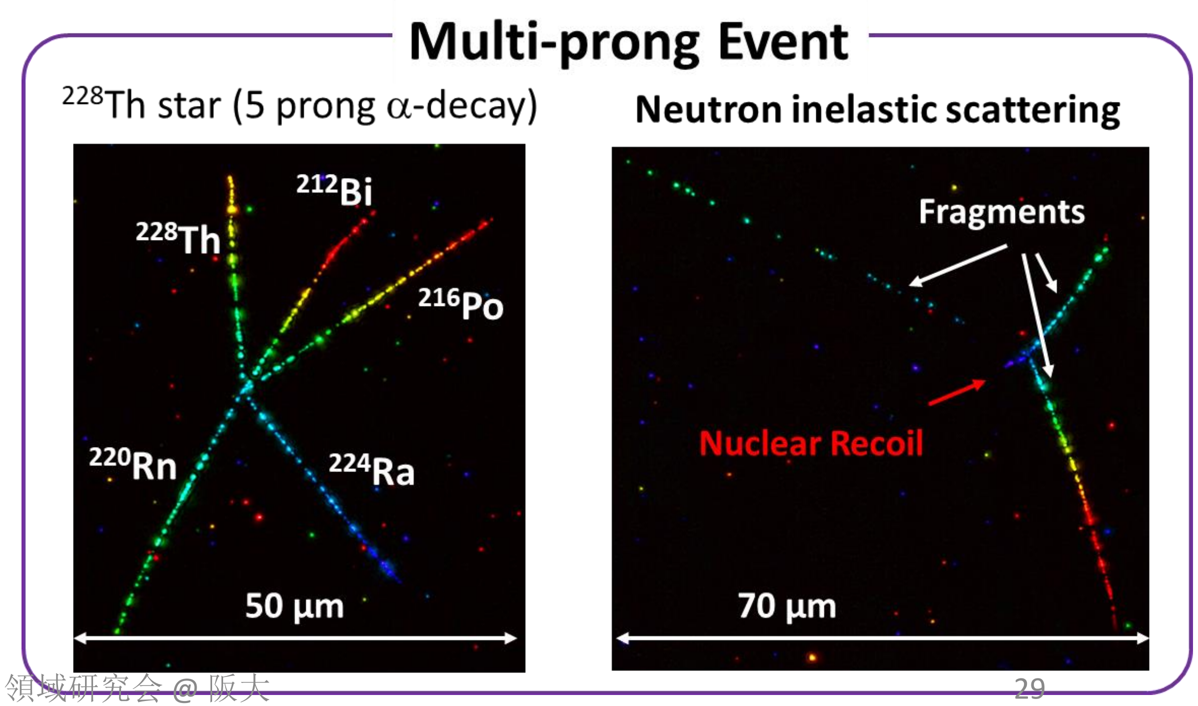


Event Classification



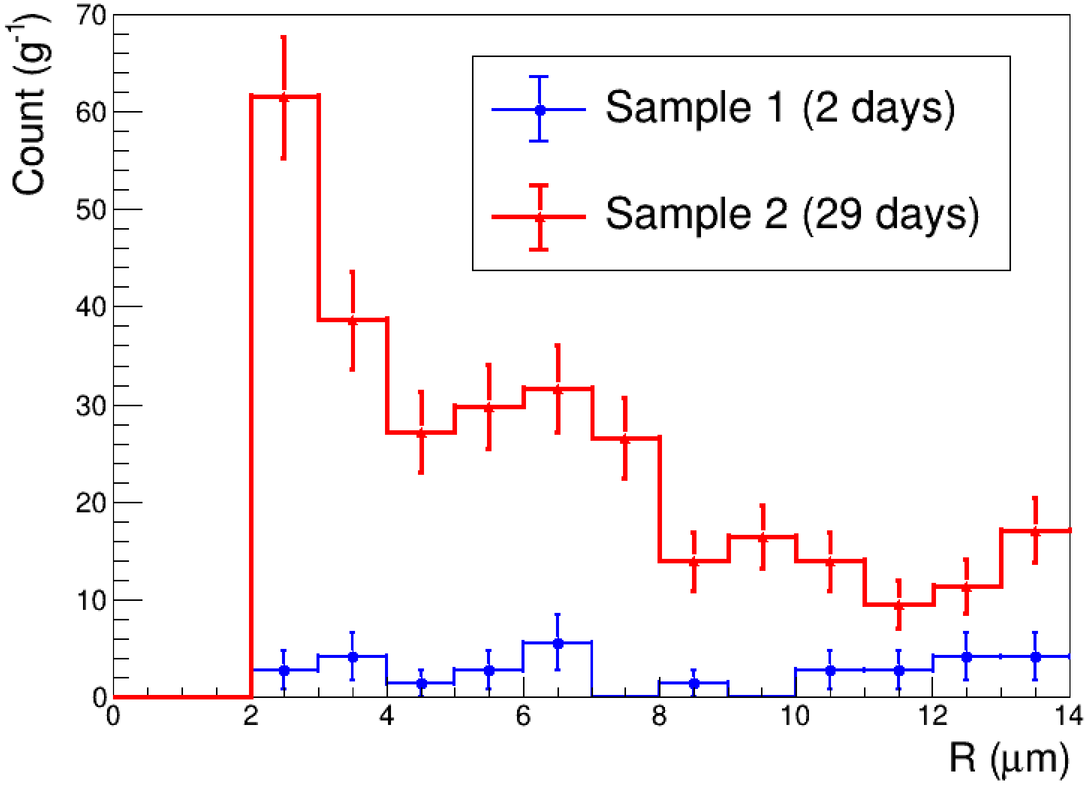
- External α-rays are excluded by fiducial volume cut, then events are topologically classified to **Single-prong** and **Multi-prong**
- **Unfortunately, n-Run1 samples accumulated a lot of Radon daughters, we focused on sub-MeV region (2~14μm → 0.25~1MeV) of Single-prong event to analyze with background free**





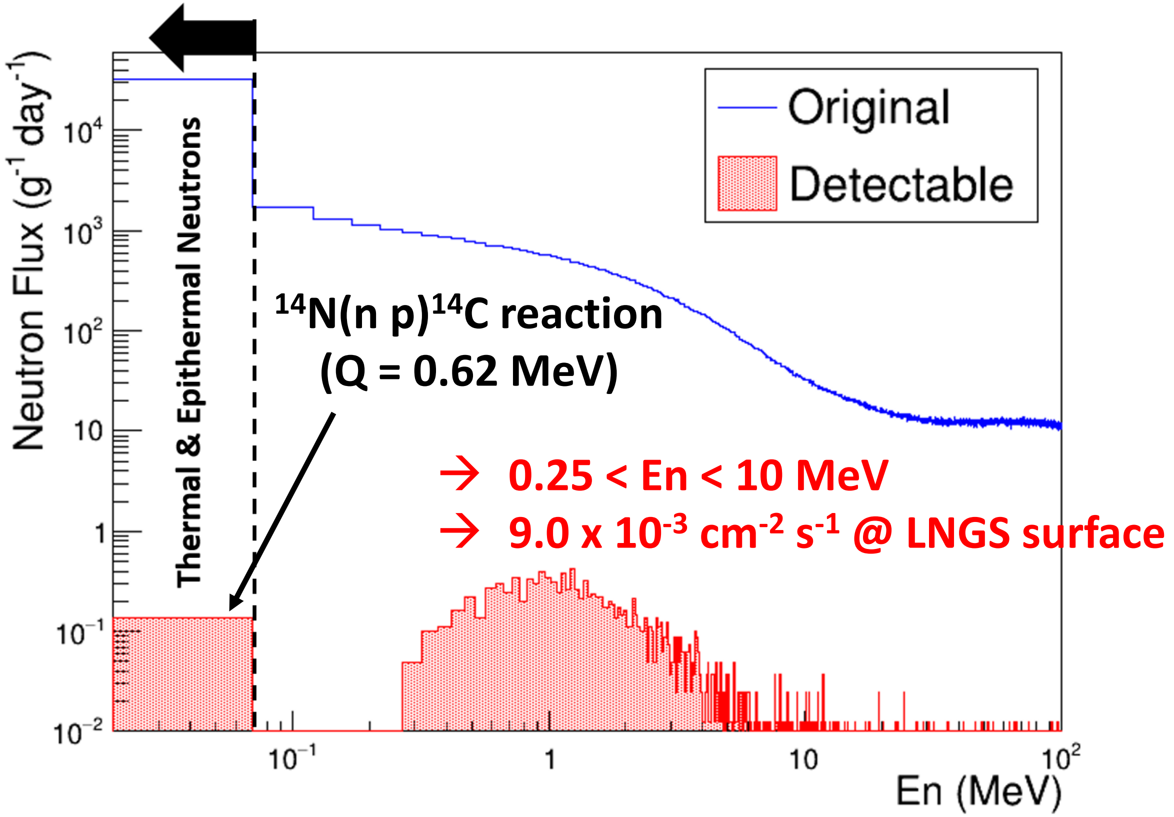
Single-prong Analysis Result (n-Run1)

Range spectrum of Single-prong signal



✓ **Observed signal increase consistent with environmental neutron signal**

Detectable neutron spectrum with 2 < R < 14 μm
(0.25 < Ep < 1 MeV)



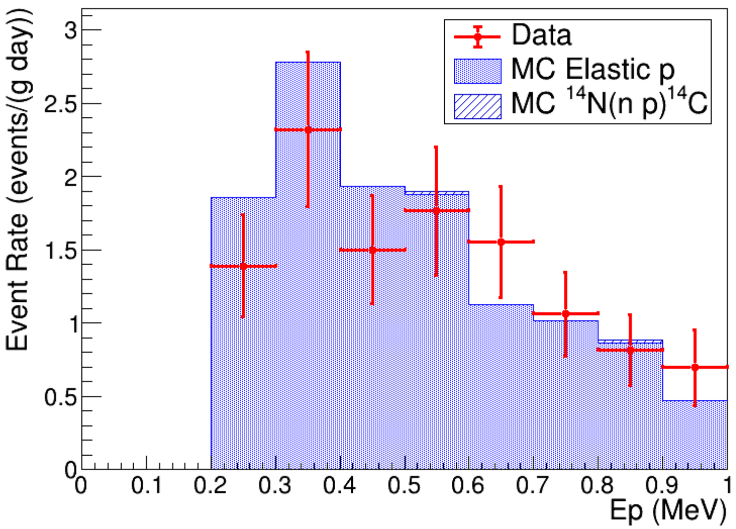
Assumed neutron spectrum expected by PARMA model

T. Sato, PLOS ONE **10**, e0144679 (2015)

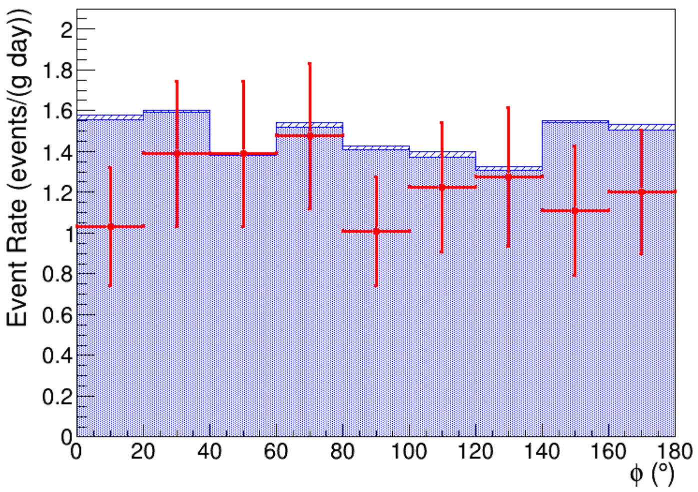
T. Sato, PLOS ONE **11**, e0160390 (2016)

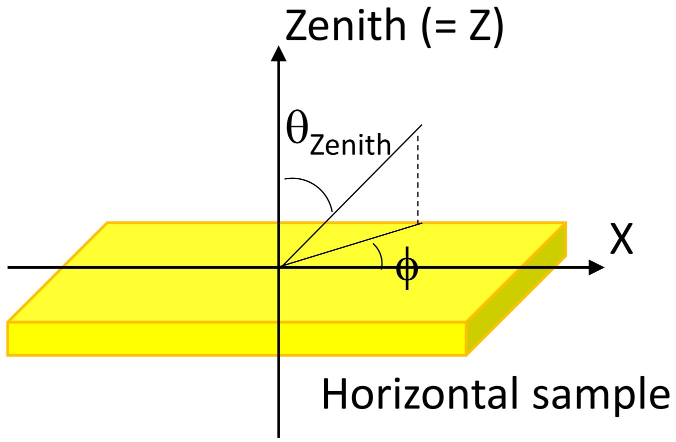
Data/MC Comparison (n-Run1)

Proton Energy

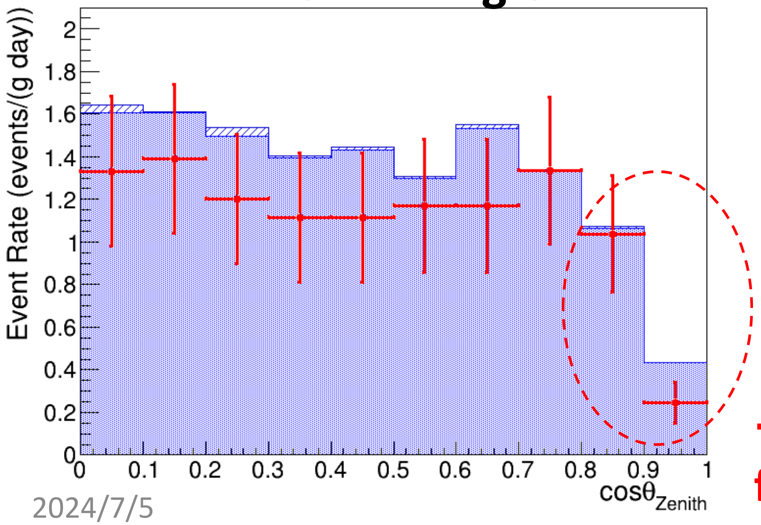


Plane Angle





Zenith Angle



→ **Due to low efficiency for vertical**

Number of Events

MC : 11.9±0.5 event/g/day

Data : 11.1 ± 0.6(stat.) ± 2.4(sys.) event/g/day

Neutron Flux [0.25 ~ 10 MeV]

PARMA model : $9.0 \times 10^{-3}\ cm^{-2}\ s^{-1}$

Data : $(8.4\pm1.8) \times 10^{-3}\ cm^{-2}\ s^{-1}$

T. Shiraishi, *et al.*, Phys. Rev. C **107**, 014608 (2023)

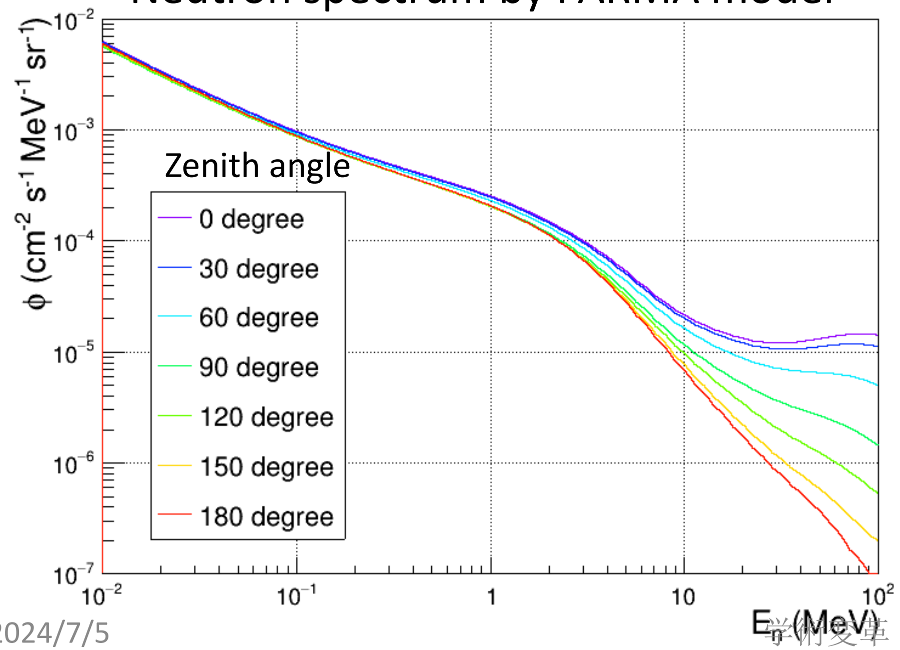
Simulation Normalization

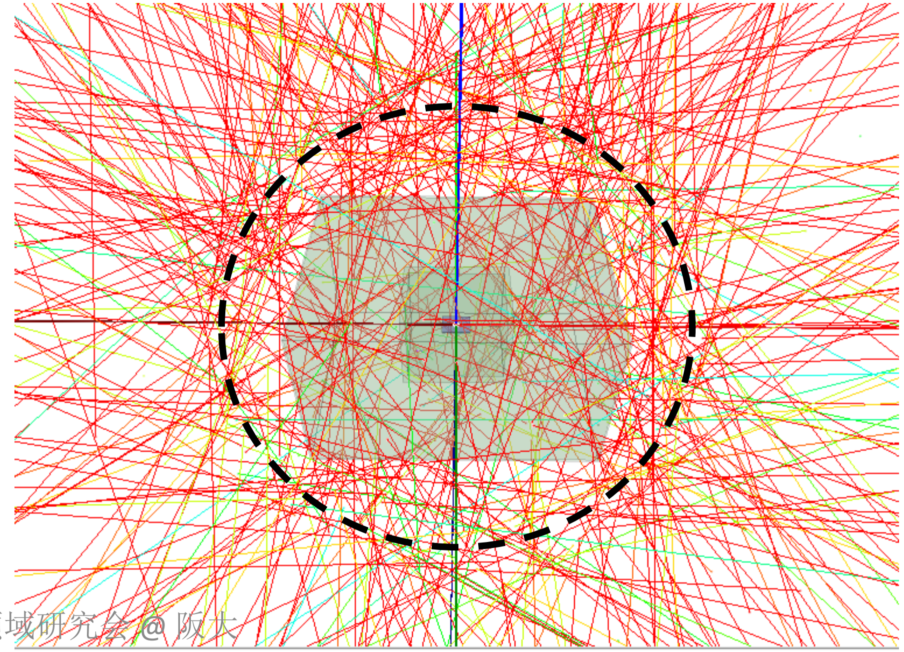
- Neutrons are generated from outside the container considering spectrum and angular distribution predicted by PARMA model
- To estimate geometrical efficiency, at first, generated geantinos and counted them entering to the NIT, then normalized the neutron flux

Previous (@ PRC paper)
- geantinos were generated uniform distribution

Current
- geantinos were generated same as neutron angular distribution

Neutron spectrum by PARMA model



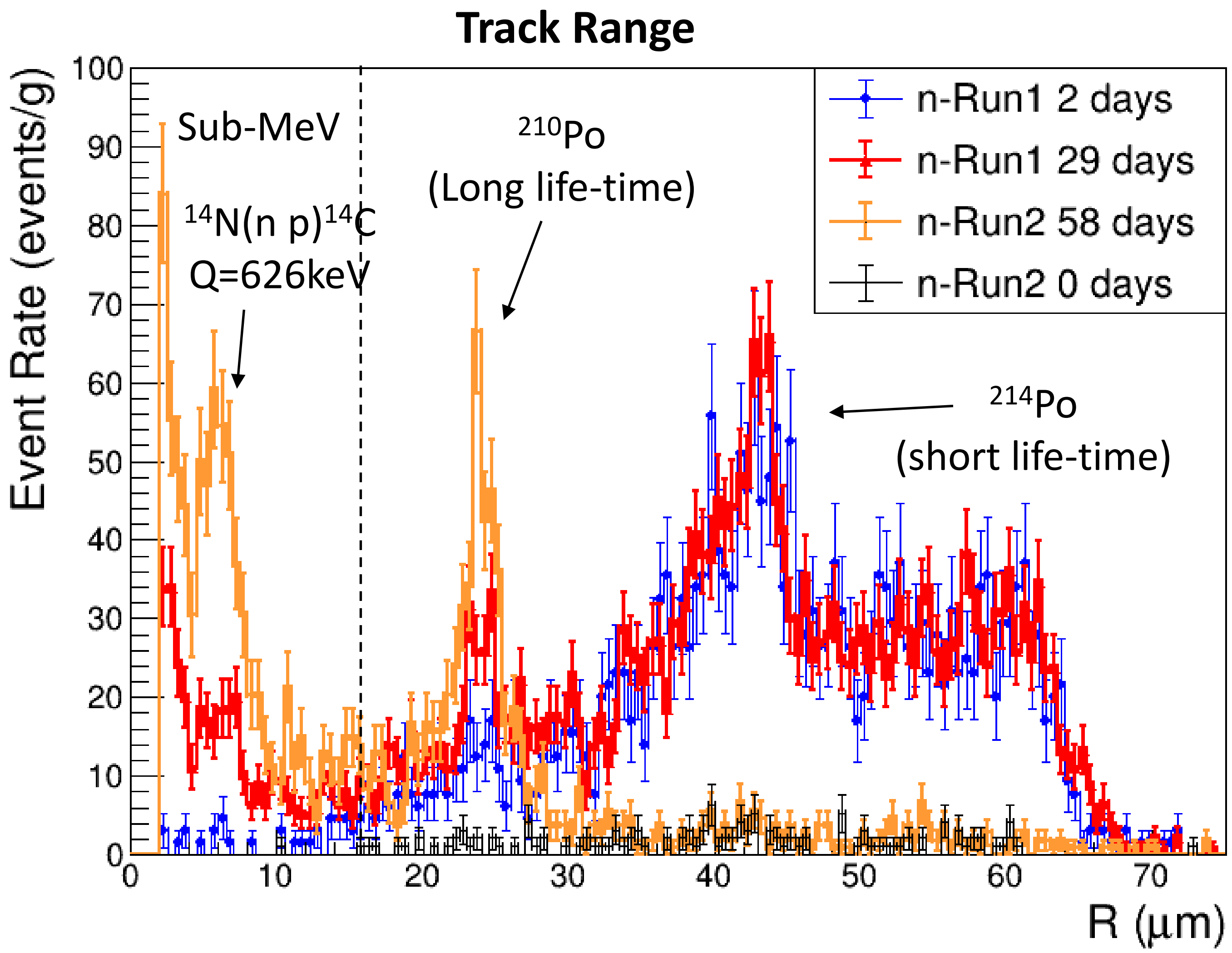


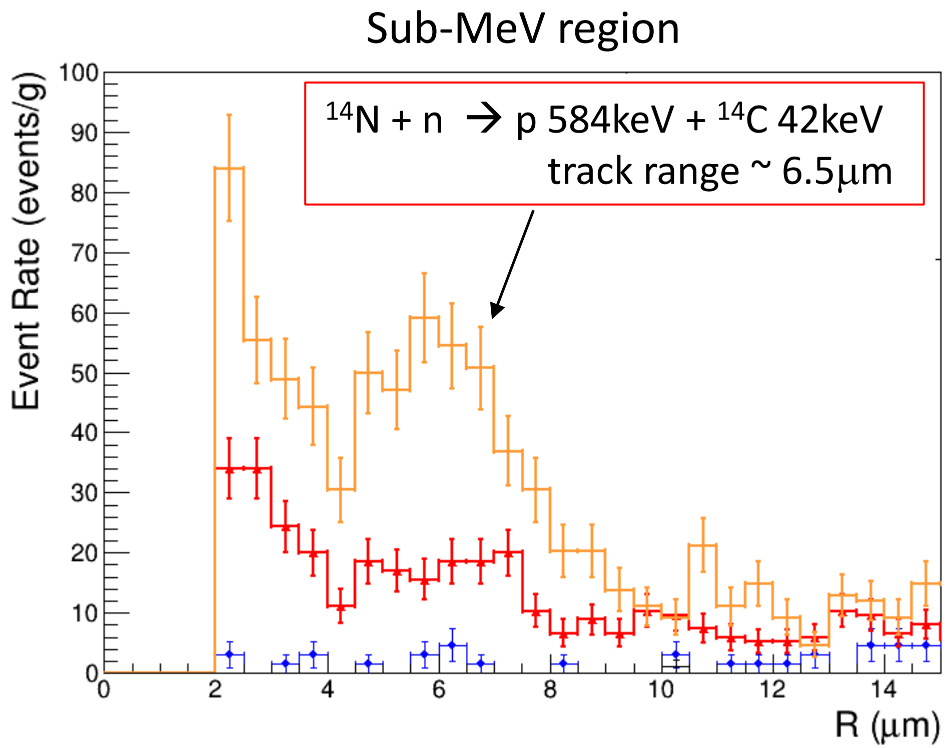
2nd Surface Neutron Run (n-Run2)

	Condition	Exposure Time on Surface (day)	Analyzed Mass (g)	Average Rainfall in Assergi (mm/day)
n-Run1 (Run start from 24 Nov. 2021)	Dried on granite table Run @ -20℃	2	0.65	4 **
		29	1.35	4 **
n-Run2 (Run start from 25 May 2022)	Dried in chamber Run @ -15℃	0	0.95	---
		58	1.08	1.4

** Estimation from Nov. – Dec. 2022 data

n-Run1 and n-Run2 Result



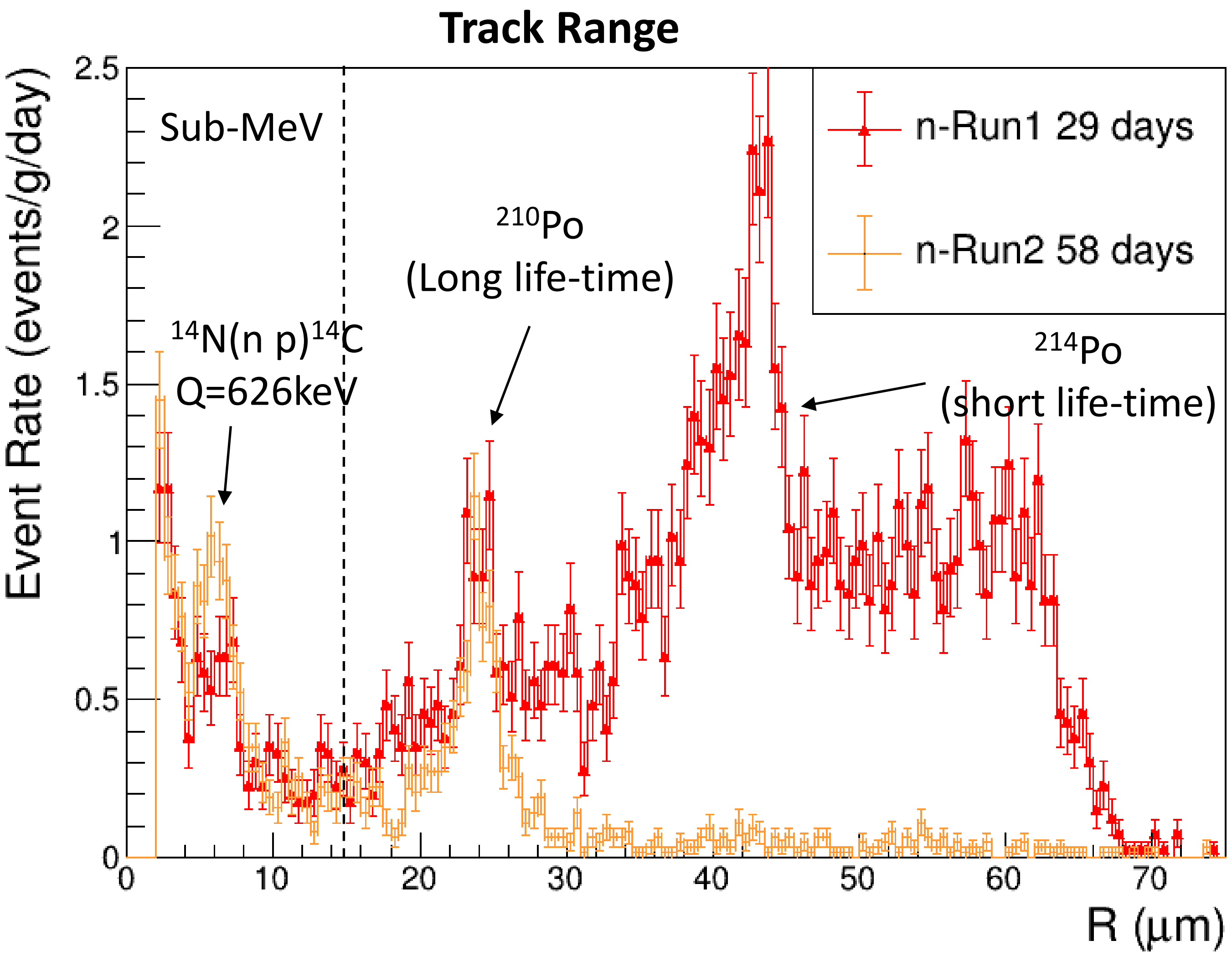


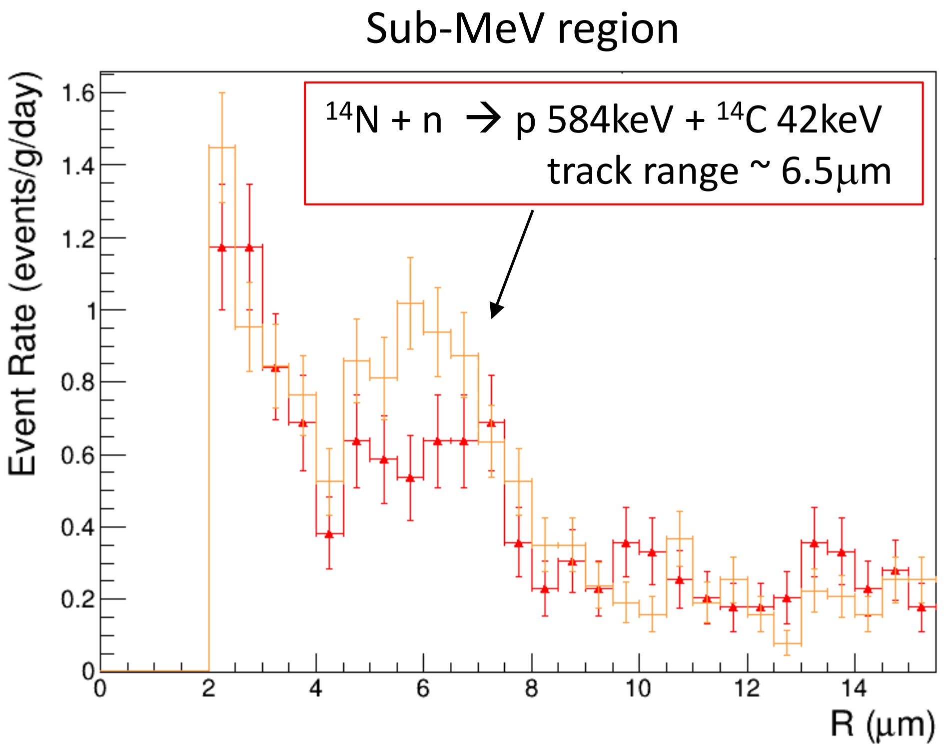
- ✓ **As expected**
  - ✓ **sub-MeV signal increase**
  - ✓ **^{210}Po-alpha increase**
  - ✓ **Offset background in MeV decrease**

Thermal neutron signal can be seen significantly

→ Thermalized due to surrounding materials? or attenuation by water contained in rock was suppressed?

n-Run1 and n-Run2 Result





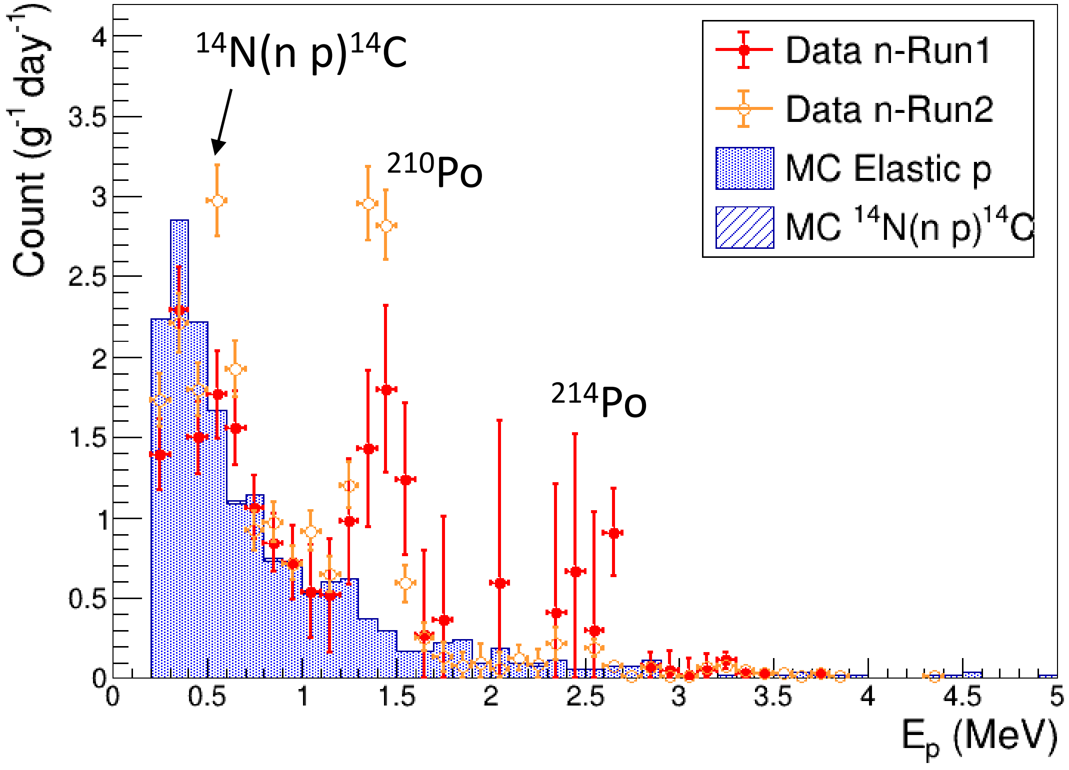
- ✓ **As expected**
  - ✓ **sub-MeV signal increase**
  - ✓ **^{210}Po-alpha increase**
  - ✓ **Offset background in MeV decrease**

Thermal neutron signal can be seen significantly

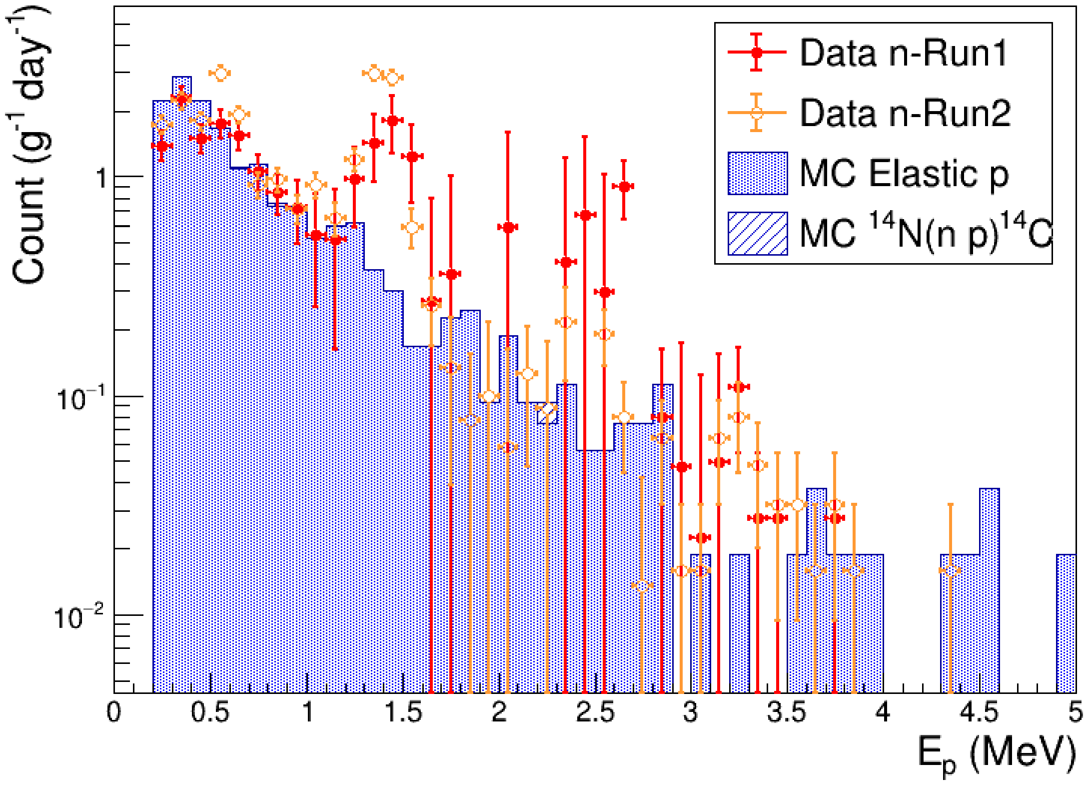
→ Thermalized due to surrounding materials? or attenuation by water contained in rock was suppressed?

Surface Run Result (*after reference subtraction)

Proton energy spectrum (linear scale)



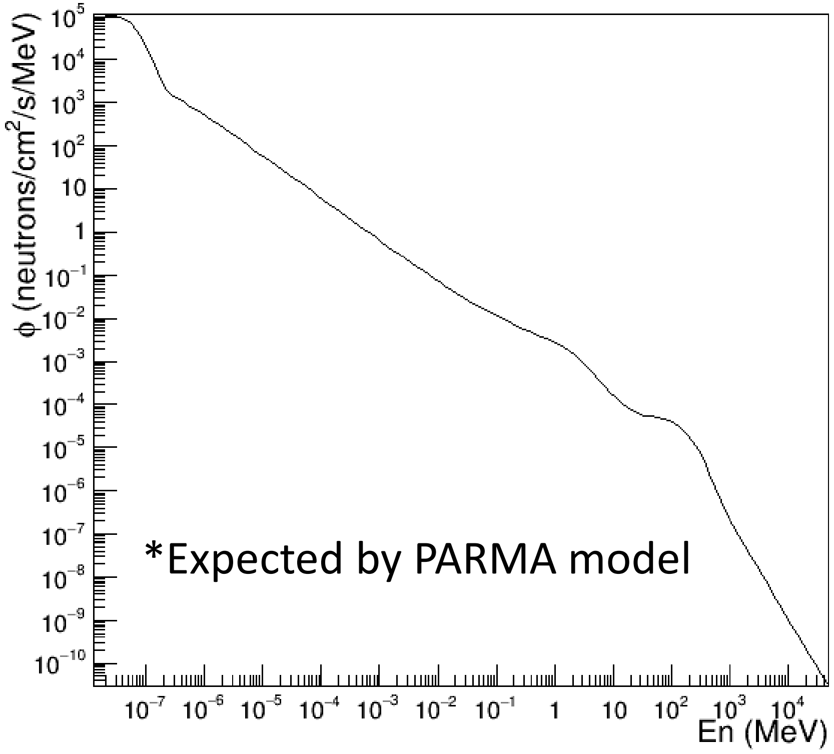
(log scale)



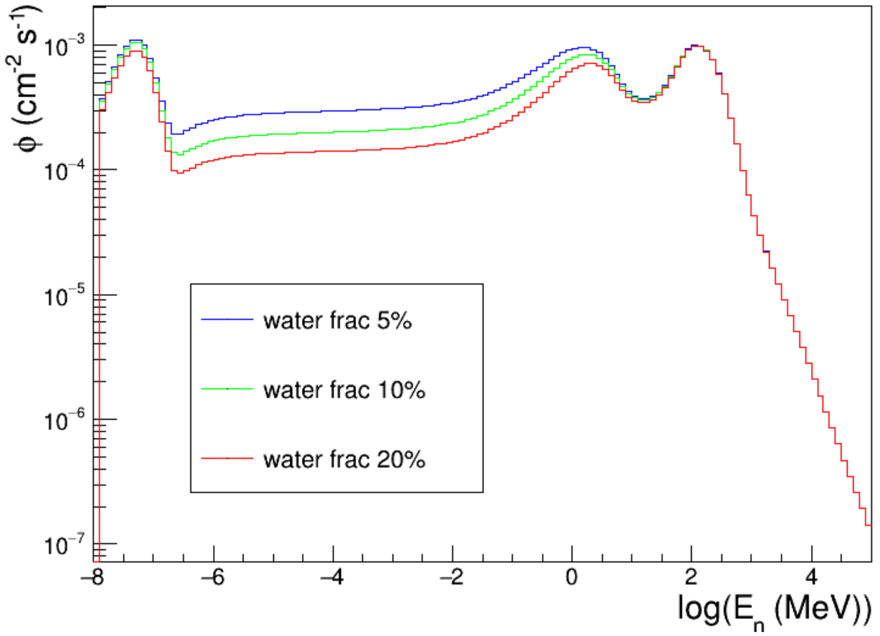
✓ Reduced offset background makes MeV spectrum similar to the simulation

Neutron Flux

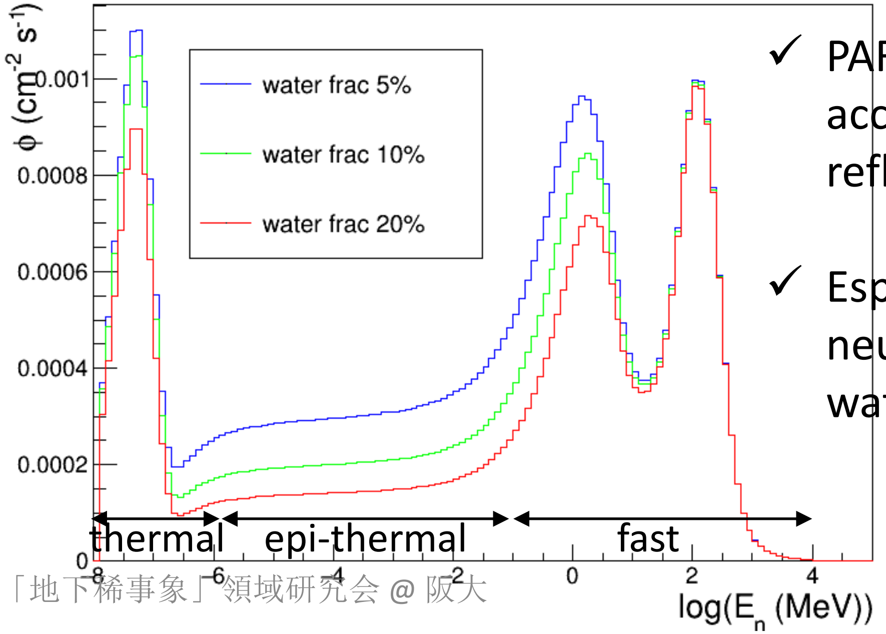
Angle-integrated neutron flux on LNGS surface
with water fraction in rock = 20%



Log



Linear



- ✓ PARMA model take into account the neutron reflection by surface ground
- ✓ Especially, epi-thermal neutrons flux depends on water fraction in rock

Underground Neutron Sources

- (α n) reaction in the rock by ^{238}U, ^{232}Th(, ^{235}U)

H. Wulandari et al., Astropart. Phys., 22, 313-322 (2004)

Table 3
^{238}U and ^{232}Th activities in LNGS rock

Hall	Activities (ppm)	
	^{238}U	^{232}Th
A	6.80 ± 0.67	2.167 ± 0.074
B	0.42 ± 0.10	0.062 ± 0.020
C	0.66 ± 0.14	0.066 ± 0.025

Table 2
Chemical composition of LNGS rock

$\rho = 2.71\ g/cm^3$

Element	C	O	Mg	Al	Si	K	Ca
% Weight	11.88	47.91	5.58	1.03	1.27	1.03	30.29

- Spontaneous fission of ^{238}U

Estimate myself using NeuCBOT and GEANT4 simulation

- μ spallation
  →Negligible in <10MeV region at LNGS underground

J.M. Carmona et al., Astropart.Phys. 21 (2004) 523-533

μ spallation

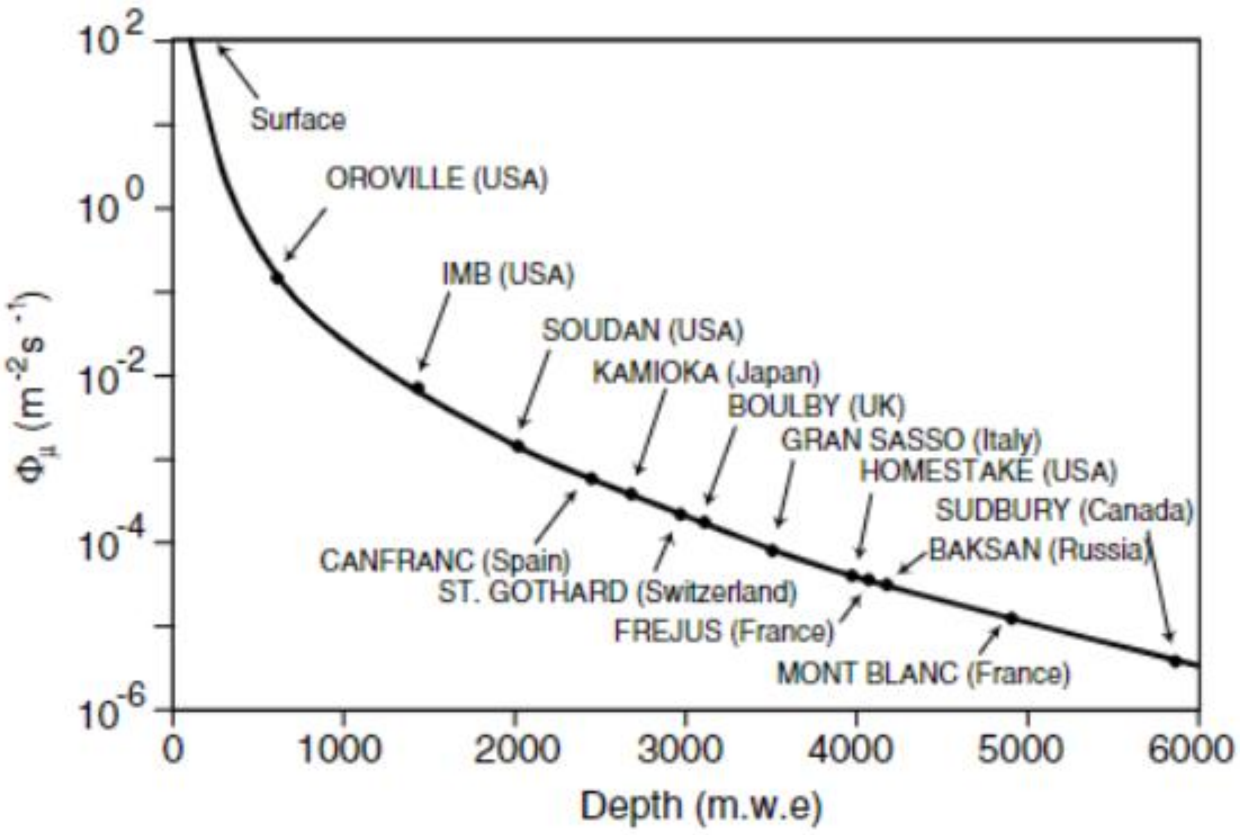
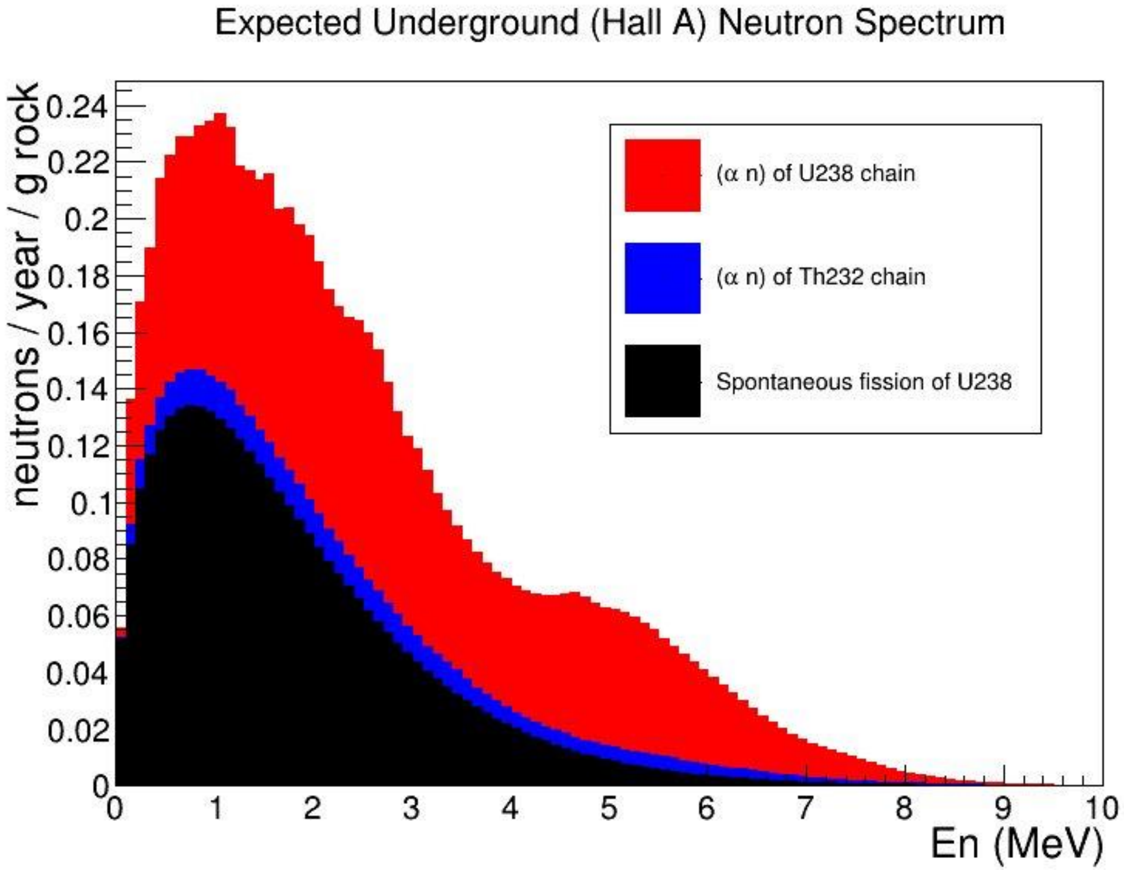


Fig. 1. Dependence of muon flux with depth, showing the location of the Canfranc Underground Laboratory with respect to other underground facilities.

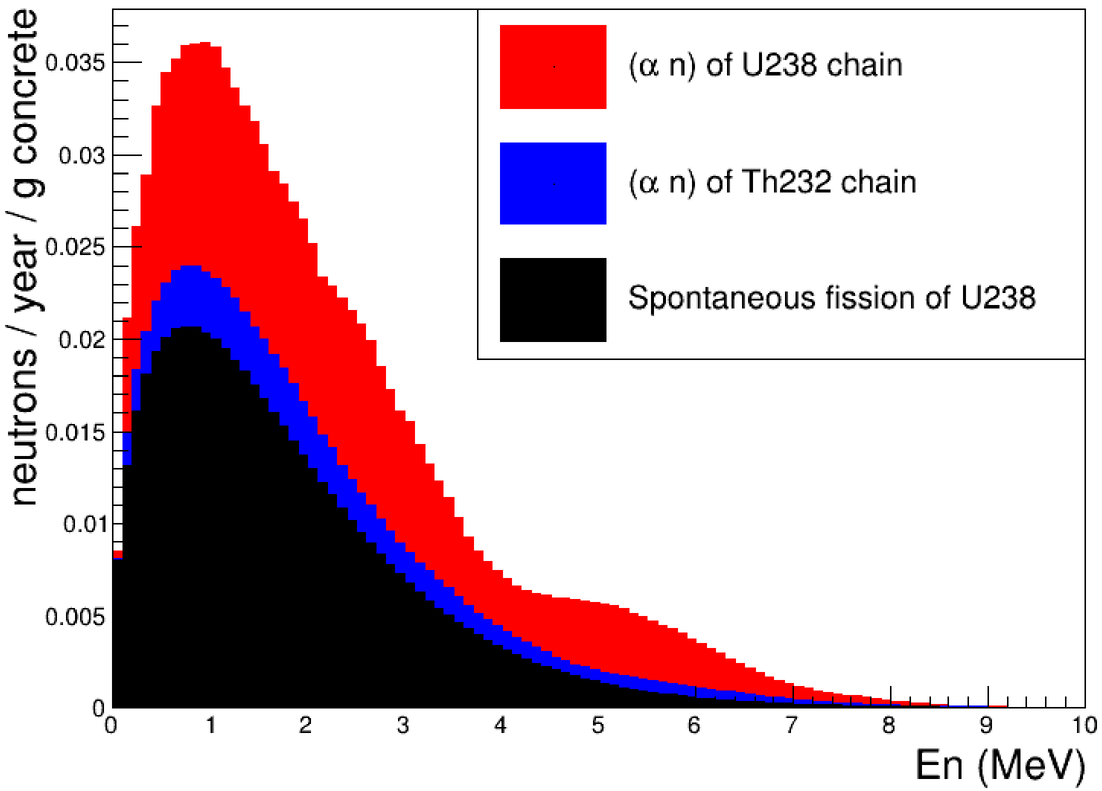
Underground muon rate is
about 6 order less than Surface

Almost negligible

neucbotでの計算



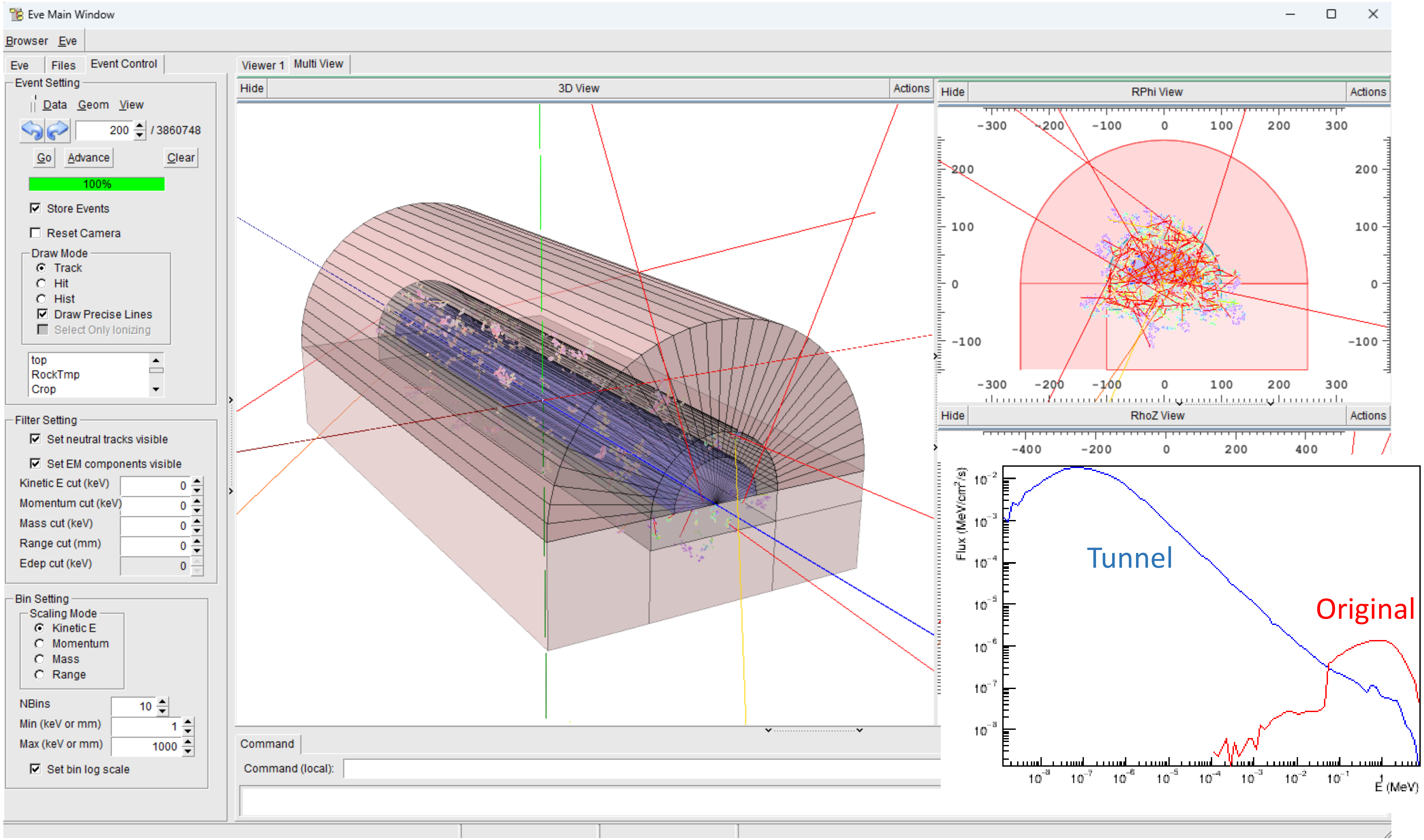
(左)岩石中での中性子エネルギー分布



(右)コンクリート中での中性子エネルギー分布

(αn) ^{238}U : 4.12091 neutrons / year / g
(αn) ^{232}Th : 0.557193 Fission : 3.45455

(αn) ^{238}U : 0.42034 neutrons / year / g
(αn) ^{232}Th : 0.112956 Fission : 0.533423

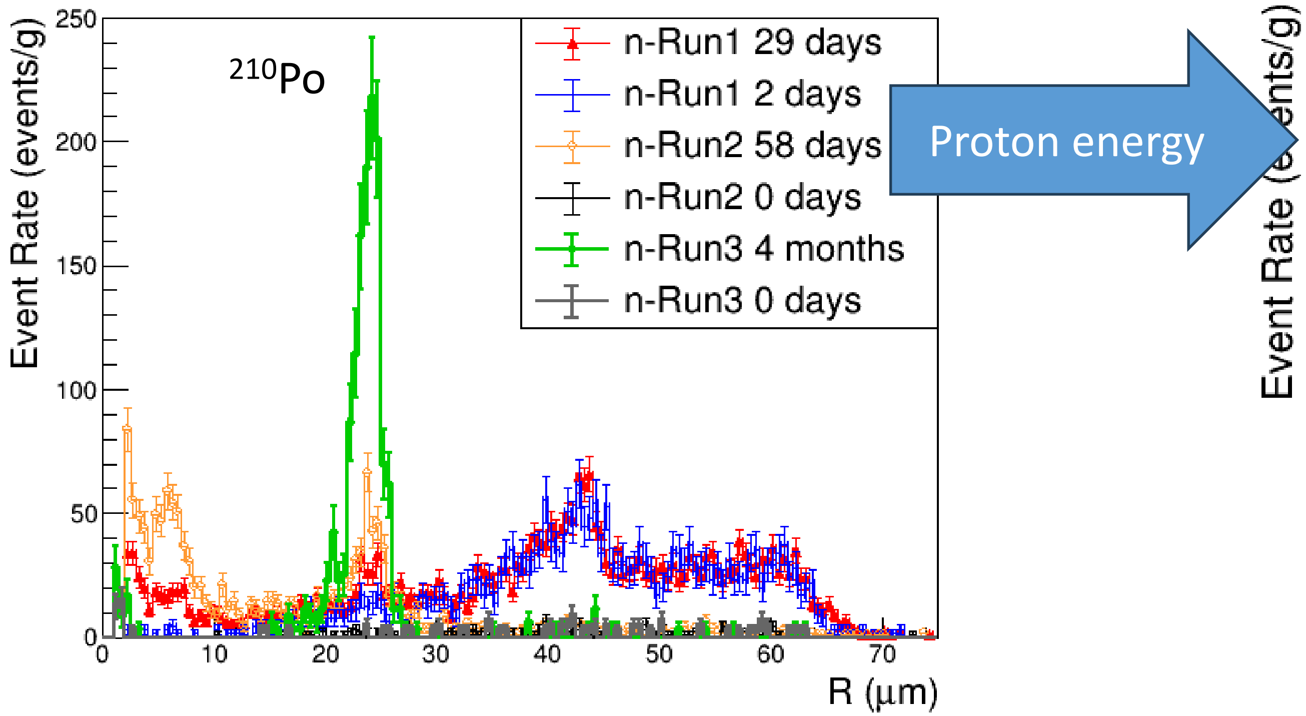

Eve Main Window
Browser Eve
Eve Files Event Control
Event Setting
Data Geom View
200 / 3860748
Go Advance Clear
100%
Store Events
Reset Camera
Draw Mode
Track
Hit
Hist
Draw Precise Lines
Select Only Ionizing
top
RockTmp
Crop
Filter Setting
Set neutral tracks visible
Set EM components visible
Kinetic E cut (keV)
Momentum cut (keV)
Mass cut (keV)
Range cut (mm)
Edep cut (keV)
Bin Setting
Scaling Mode
Kinetic E
Momentum
Mass
Range
NBins
Min (keV or mm)
Max (keV or mm)
Set bin log scale
Viewer 1 Multi View
Hide 3D View Actions
Hide RPhi View Actions
Hide RhoZ View Actions
Command
Command (local):
Flux (MeV/cm²/s)
E (MeV)
Tunnel
Original

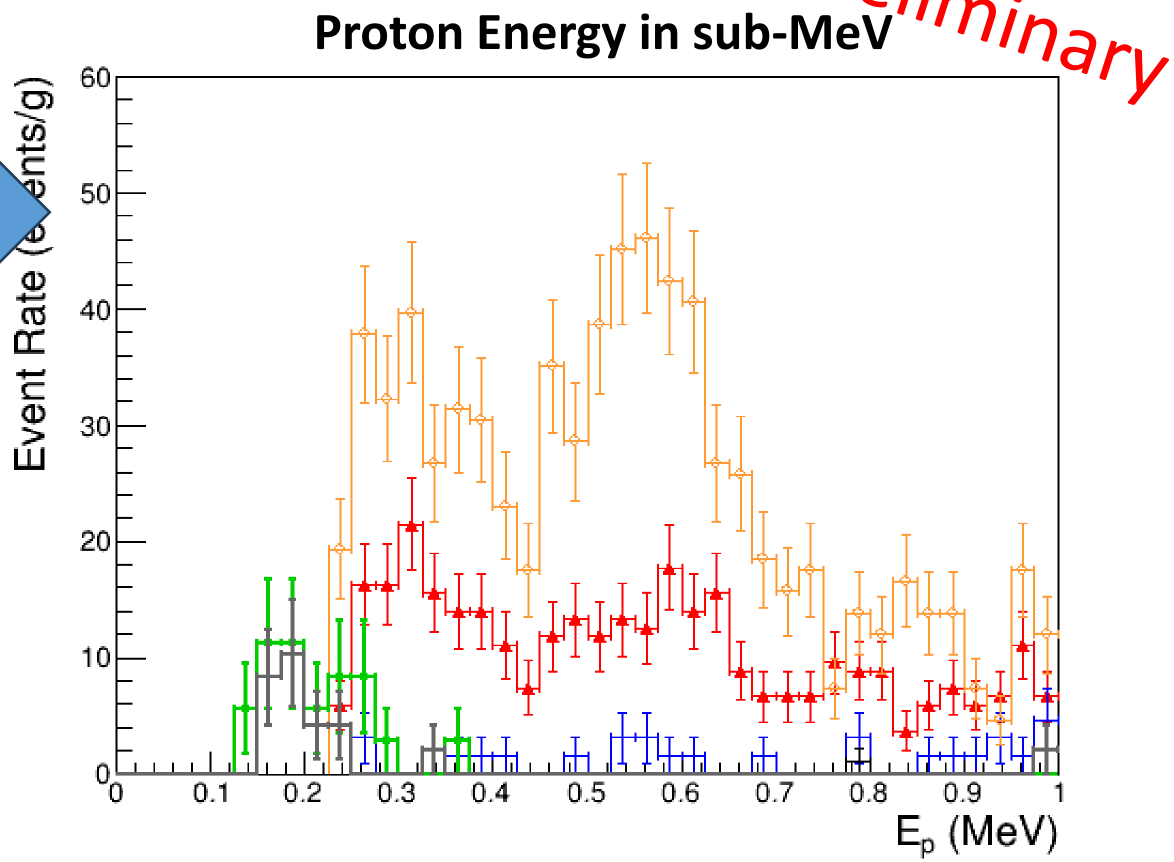
Neutron Run Go to Underground

	Installed Place	^{214}Po contamination (/g)	Exposure Time (days)	Experimental Scale (g*month)	Analyzed Scale (g*month)	Proton Energy Threshold (keV)
n-Run1 (Nov. 2021 -)	Surface ground	O(1000)	29	2	1.3	250
n-Run2 (May 2022 -)	Surface ground	O(100)	58	20	2.1	250
n-Run3 (Jan. 2023 -)	Underground Hall C & F	O(100)	120	30	1.4	100
n-Run4 (Nov. 2023 -)	Underground Hall C	O(1)	120	100	1.9 Ongoing	100

地下中性子測定には少なくとも10 g*monthスケールのNIT解析が必要

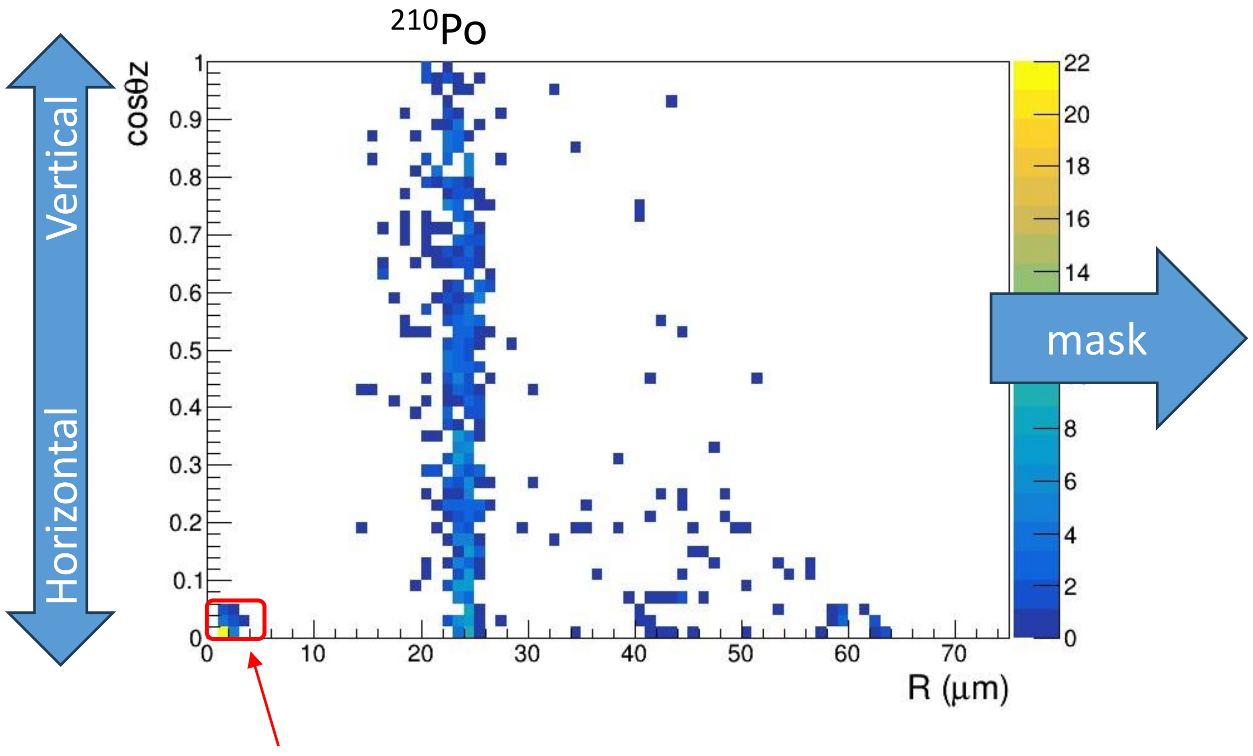
n-Run3 (Underground) Result



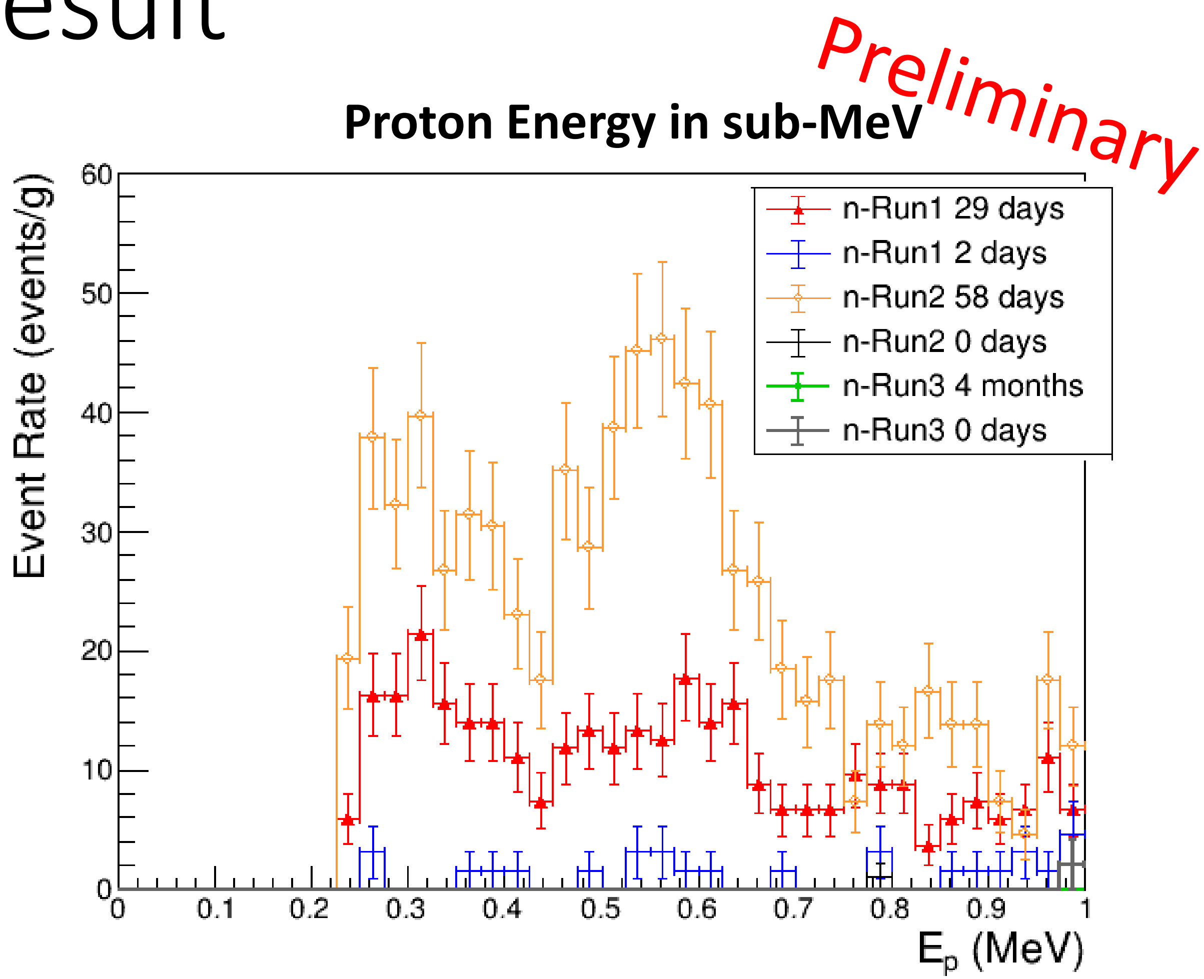


- ✓ Sub-MeV neutron signal clearly decreased because of underground
- ✓ There are time-independent signal-like tracks below 300 keV
  → **Non-physical events**

n-Run3 (Underground) Result



Mask cosθz < 0.05 && range < 3μm

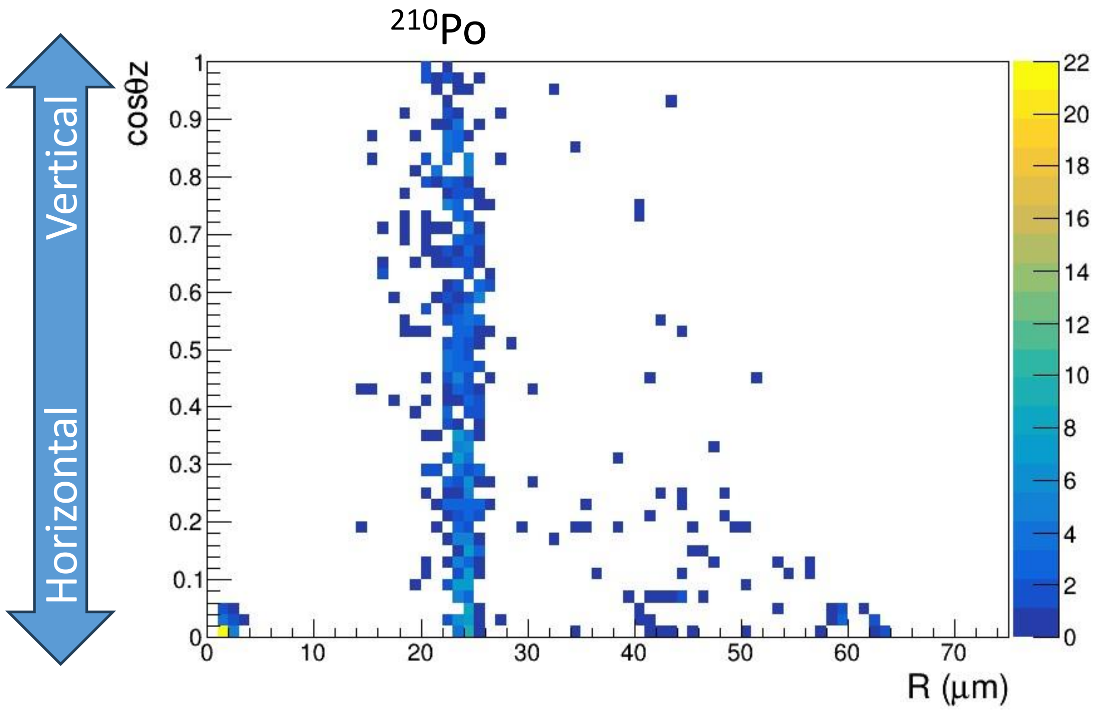


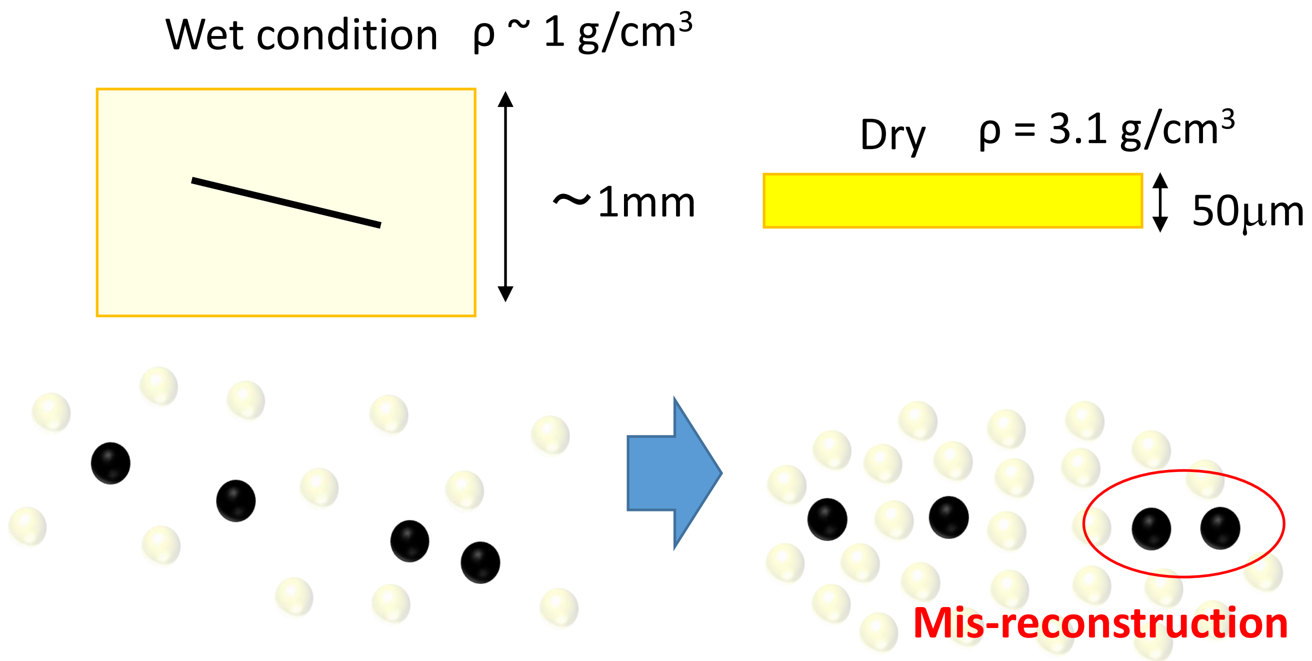
✓ If we avoid low energy & horizontal angle region, there is no excess in sub-MeV region

→ **Neutron flux < 4.2 x 10^{-5} cm^{-2} s^{-1} (90% C.L.)**

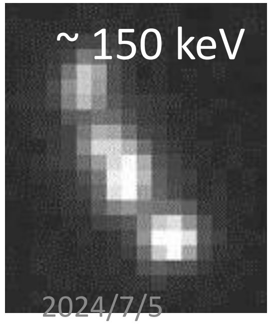
*Assume neutron spectrum same as surface

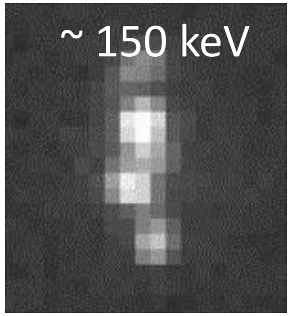
n-Run3 (Underground) Result





Signal-like tracks found below 300 keV are all horizontal!



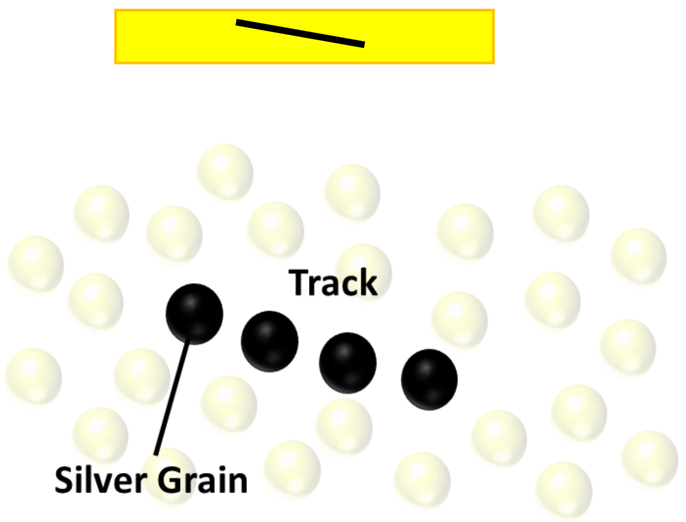


- Mis-reconstruction of α-track from ^{214}Po accumulated at wet condition?

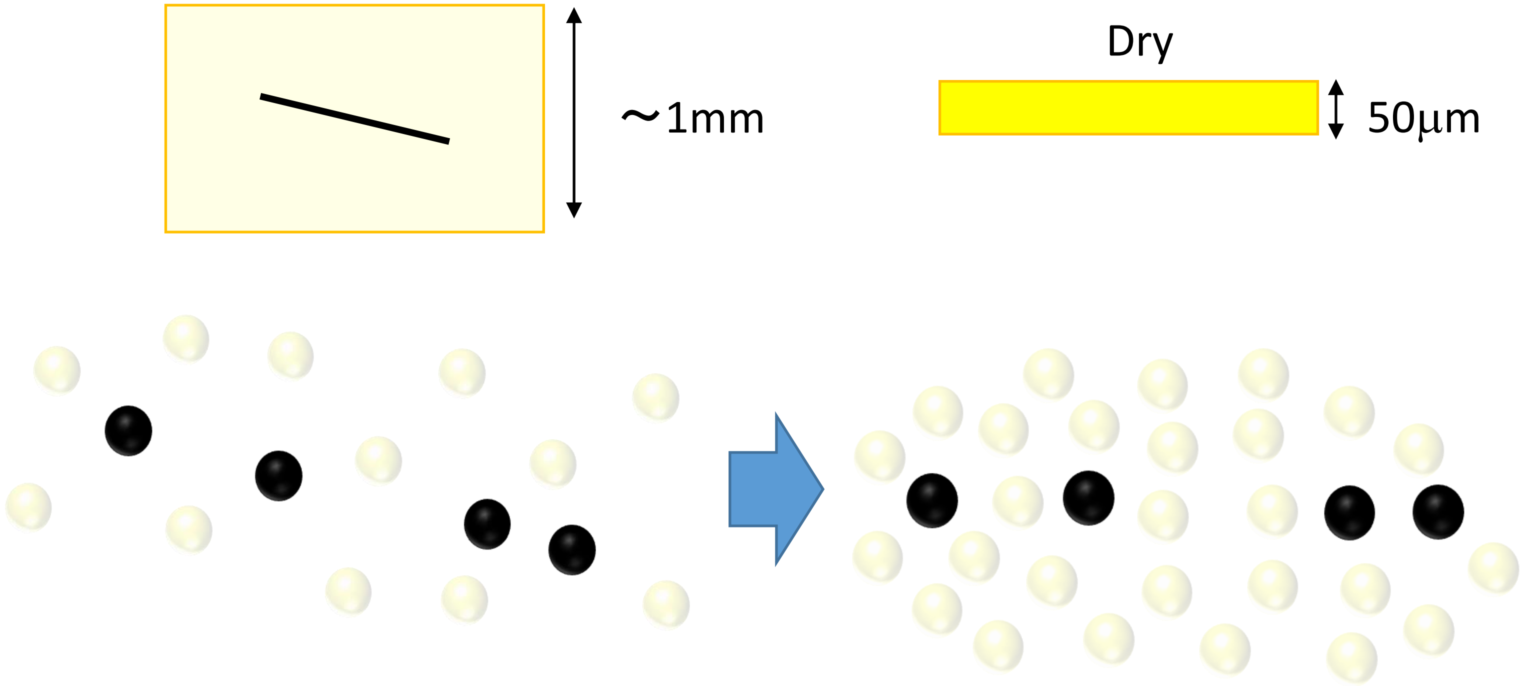
→ Should be checked by next n-Run4 (low ^{214}Po contamination)

α-ray accumulation in drying condition

After dry $\rho = 3.1\ g/cm^3$



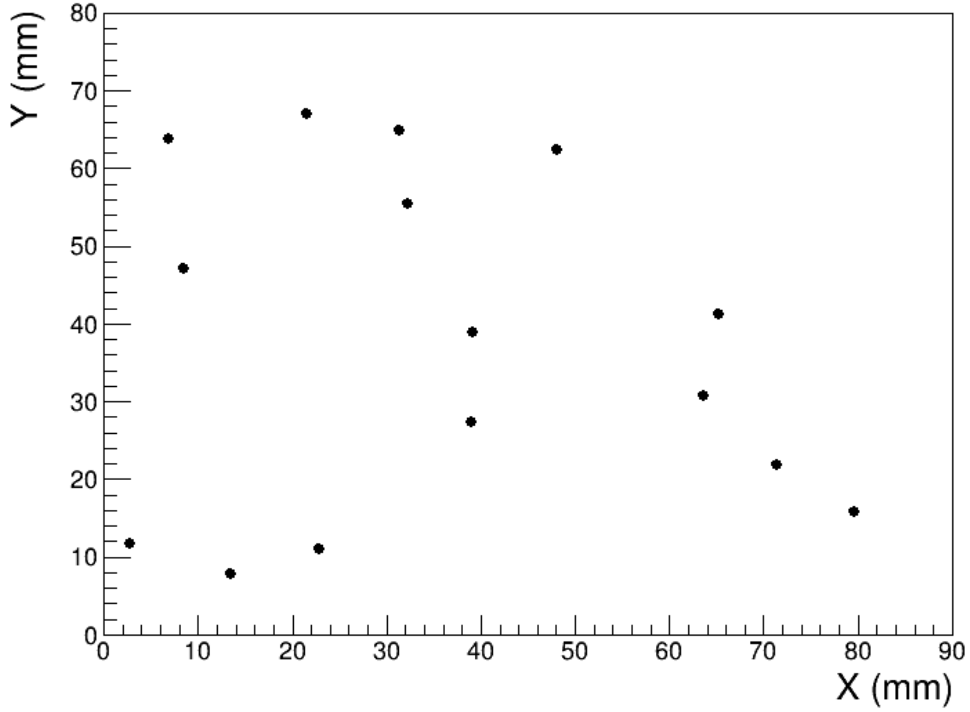
Wet condition $\rho \sim 1\ g/cm^3$

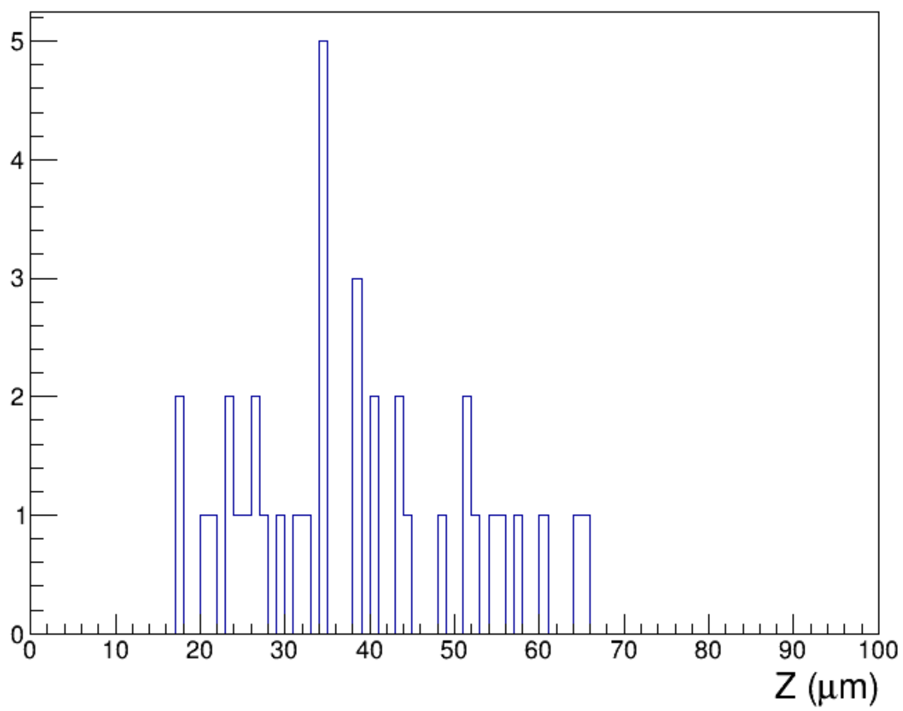


If α-ray create tracks at wet condition, tracks become **longer & darker & horizontal** because of

- Low mass density
- Low crystal density
- Shrink less than 1/10 thickness

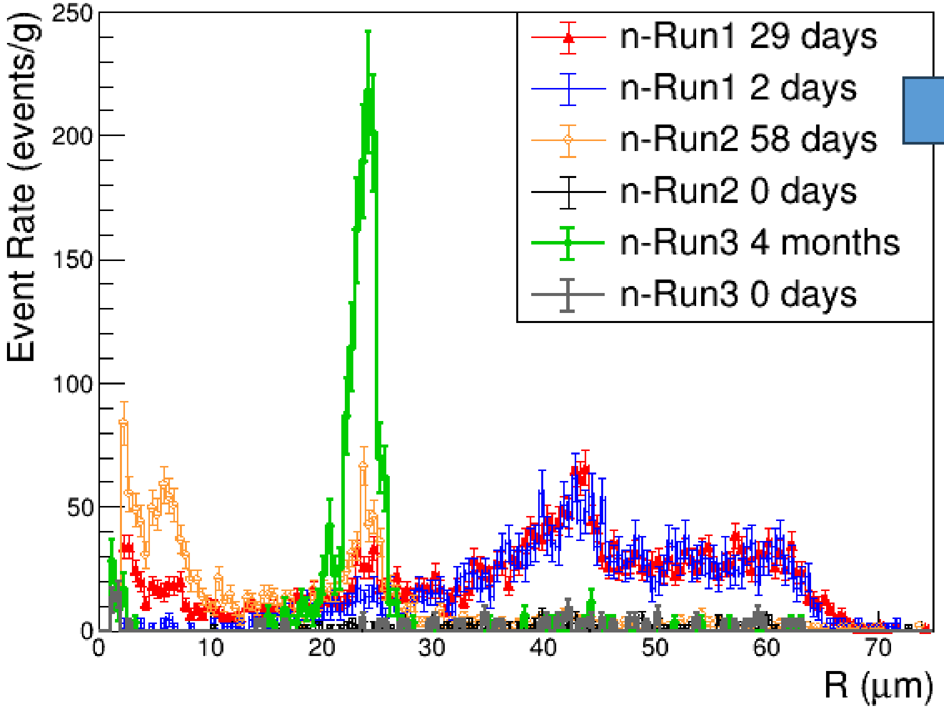
Event map of range < 3μm in n-Run3





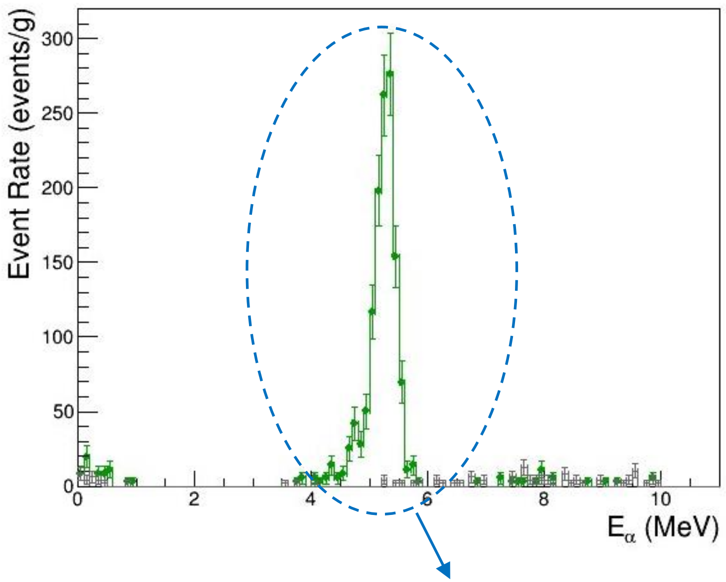
n-Run3 α-ray Analysis

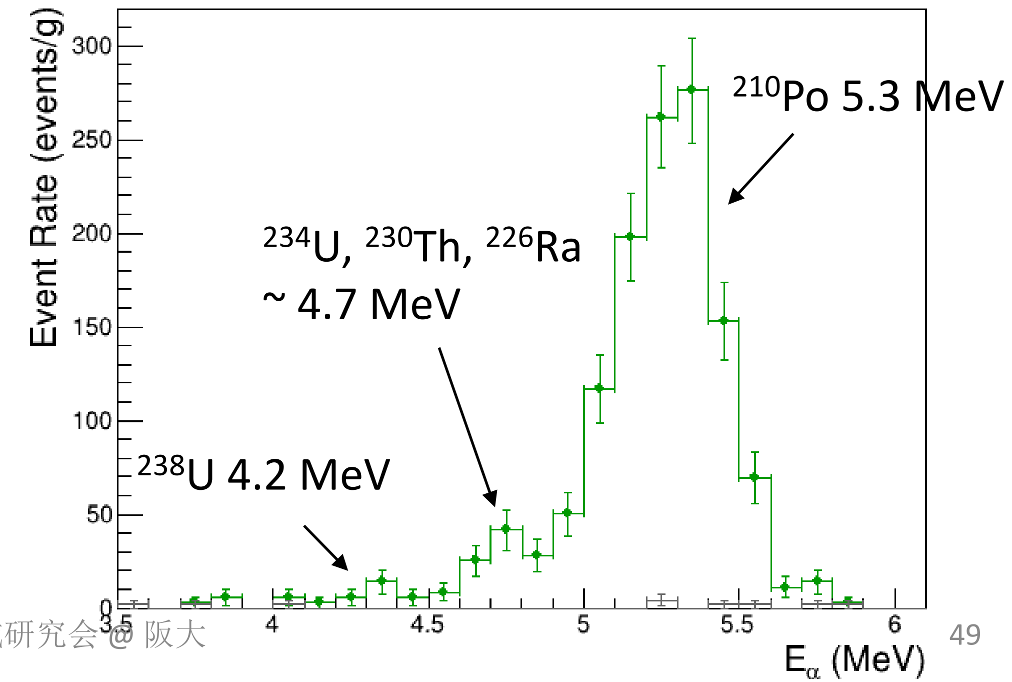
Range distribution



α energy

n-Run3 4 month



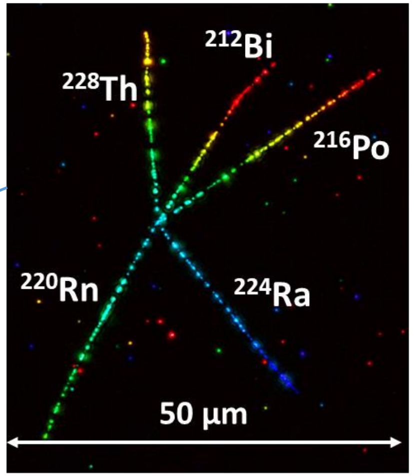


Intrinsic α Activity

F. Pupilli et al, Astropart. Phys. A **80**, 16 (2016))

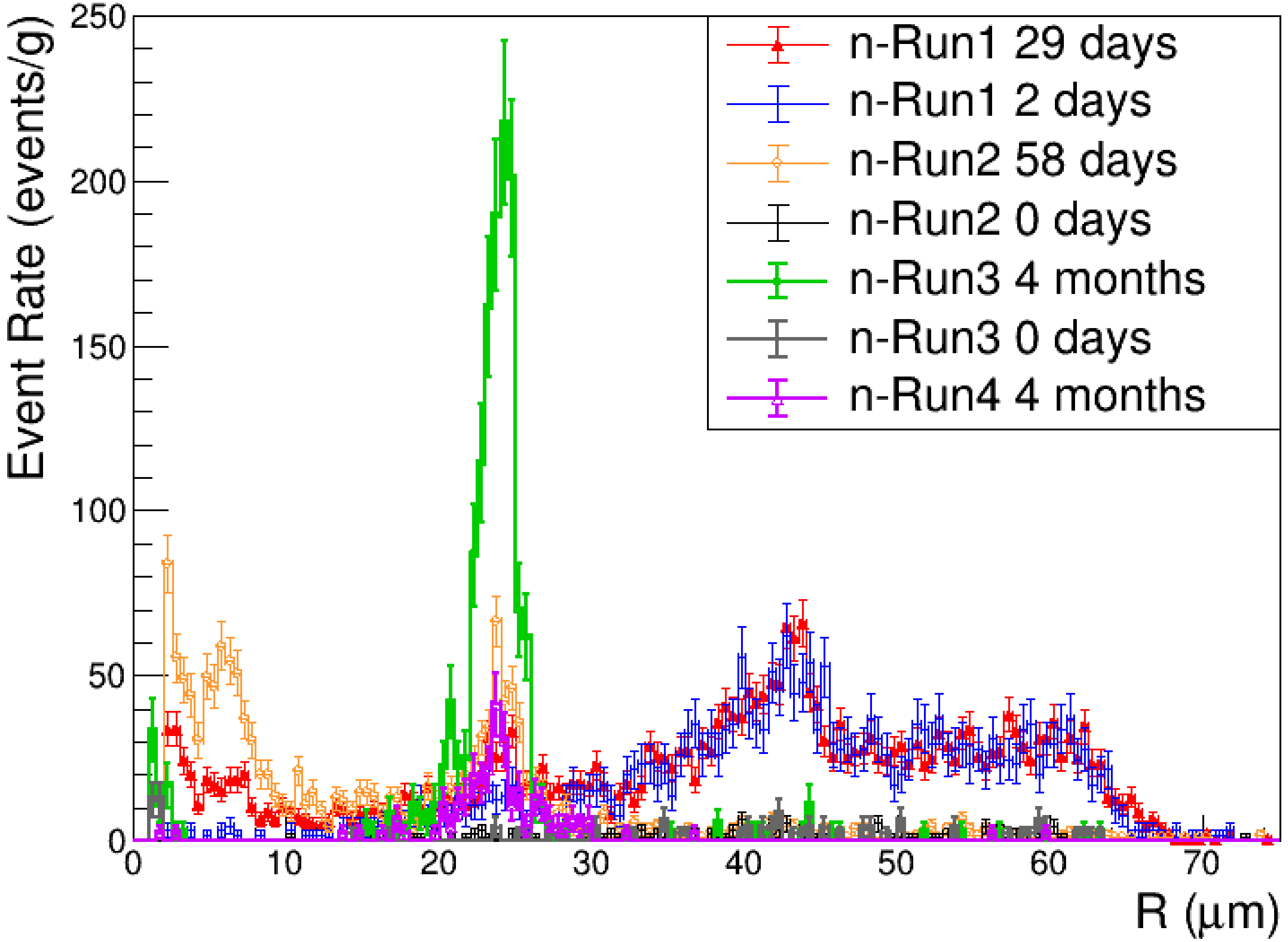
α Multiplicity	γ-ray measurement by Ge detector (mBq/kg)	n-Run1 (mBq/kg)	n-Run3 (mBq/kg)	n-Run4 (mBq/kg)
5 (^{228}Th to ^{208}Pb)	**6.0±0.6 (^{228}Th)**	**5.6±2.0**	**5.9±1.2**	**2.3±0.7**
1 (^{238}U)	**0.8±0.2 (^{226}Ra)**	**Not measured**	**3.2±0.5**	
1 (^{234}U&^{230}Th&^{226}Ra)	**2.4±0.2 (^{226}Ra)**	**Not measured**	**10±1**	
1 (^{210}Po)	**0.8±0.2 (^{226}Ra) +^{222}Rn contamination**	**54±7**	**118±6**	**23±2**

^{228}Th star (5 prong α-decay)



Assume radiative equilibrium

^{210}Po seems to be increased from n-Run1



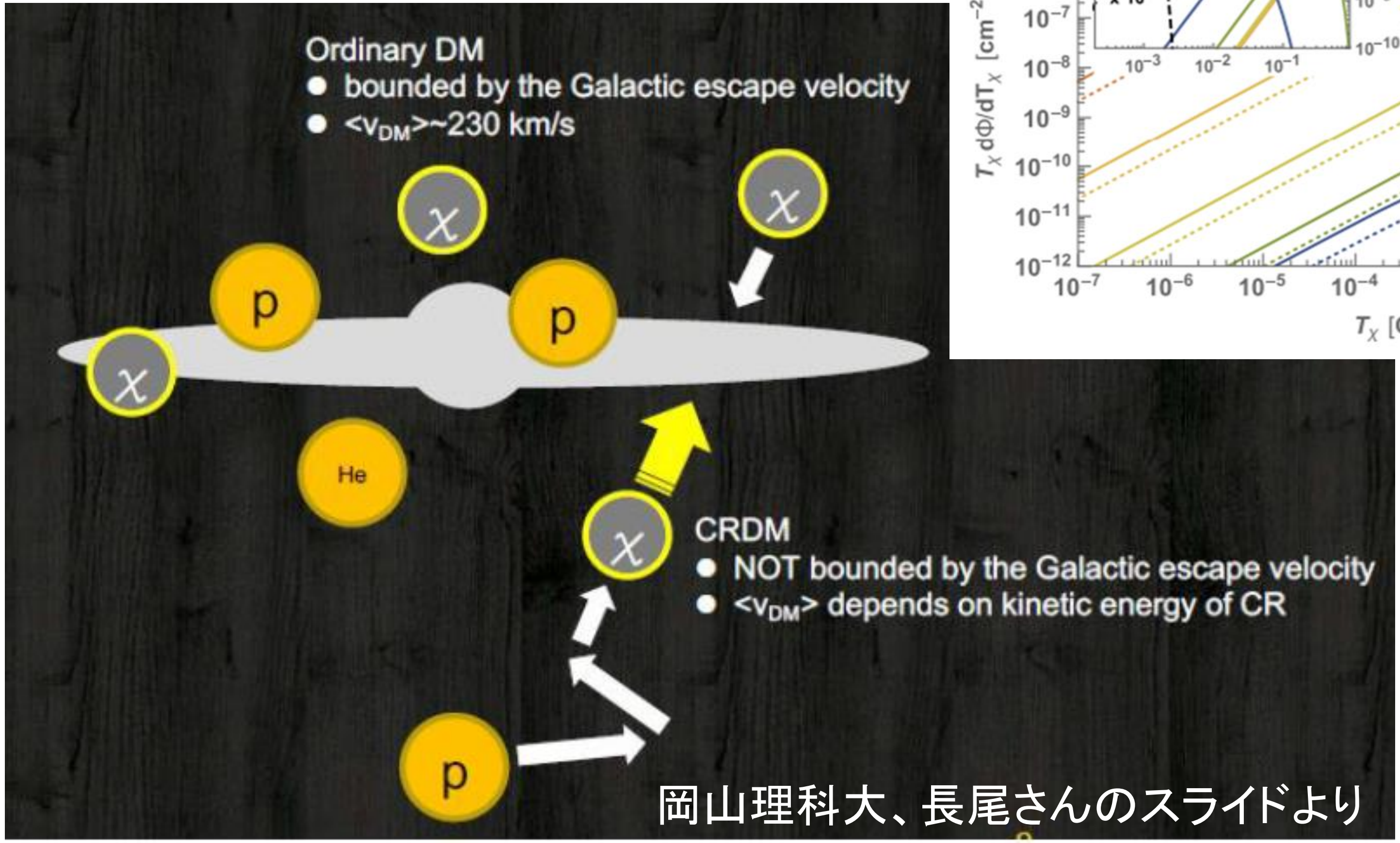
Event Rate (events/g)
250
200
150
100
50
0
0
10
20
30
40
50
60
70
R (μm)
n-Run1 29 days
n-Run1 2 days
n-Run2 58 days
n-Run2 0 days
n-Run3 4 months
n-Run3 0 days
n-Run4 4 months

Boosted Dark Matter

Natural idea in WIMP model !

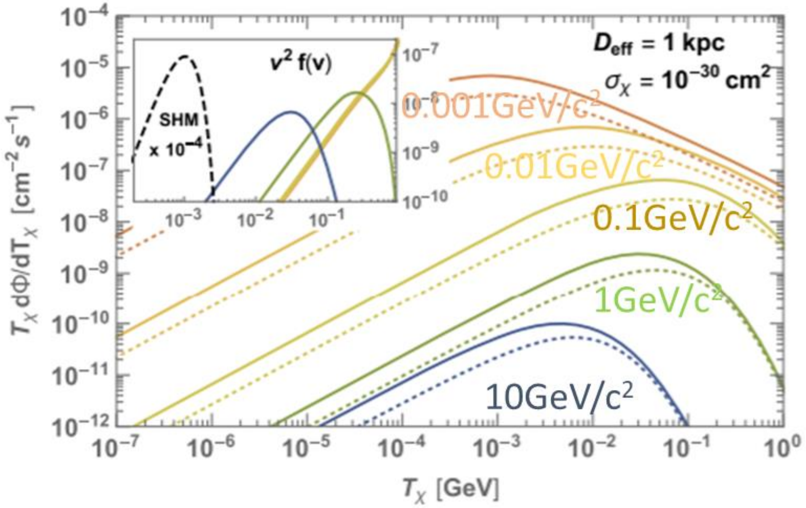
Cosmic Ray boosted Dark Matter (CRDM)

- WIMPs can be accelerated by interstellar cosmic-ray

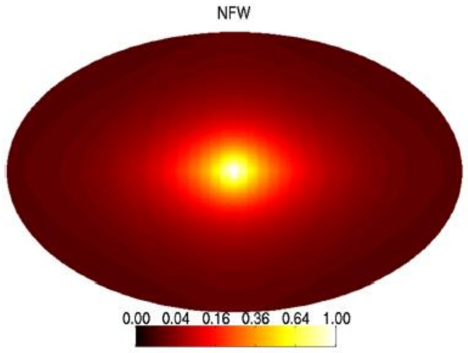


岡山理科大、長尾さんのスライドより

Energy Spectrum of CRDM

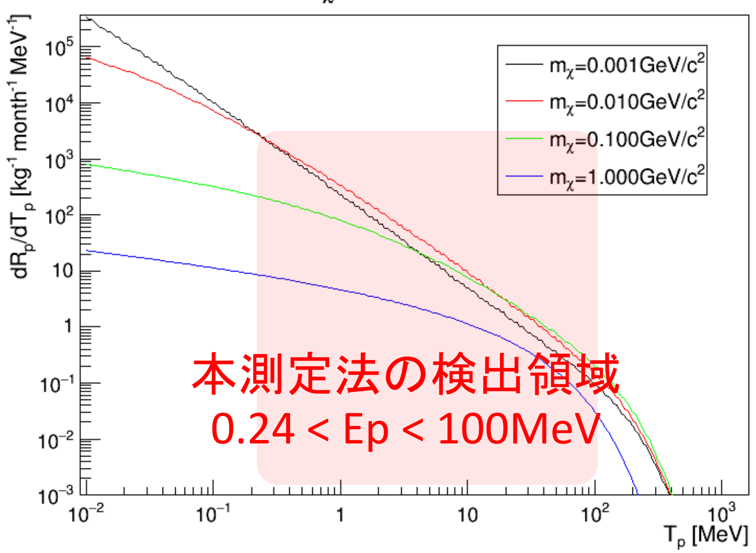


Directional distribution of CRDM to the galactic center



Recoil proton spectrum in NIT by CRDM

Deff=1kpc, $\sigma_\chi=10^{-26}$cm^2, NIT 1kg month



- 10.1103/PhysRevLett.122.171801
- 10.1103/PhysRevLett.126.091804

Diurnal Effect

https://doi.org/10.1103/PhysRevLett.126.091804

Directional distribution of BDM to the galactic center

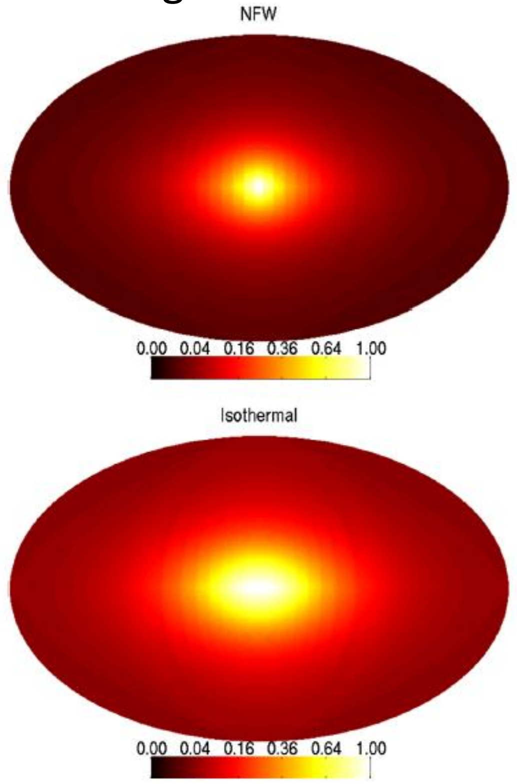


FIG. 1. Relative sky maps of CRDM fluxes in the Galactic coordinates with amplitude in the GC direction set to unity. The upper and lower panels are for the NFW and Isothermal DM density profiles, respectively.

- Because BDM flux depends on Cosmic Ray and DM density, it comes a lot from the galactic center
- In case of large cross section, because the rotation of the Earth changes the distance of BDM penetrating the Earth, its attenuation causes diurnal modulation.
- **Directional sensitivity can strongly claim the evidence for BDM**

Diurnal modulation of BDM arrival flux

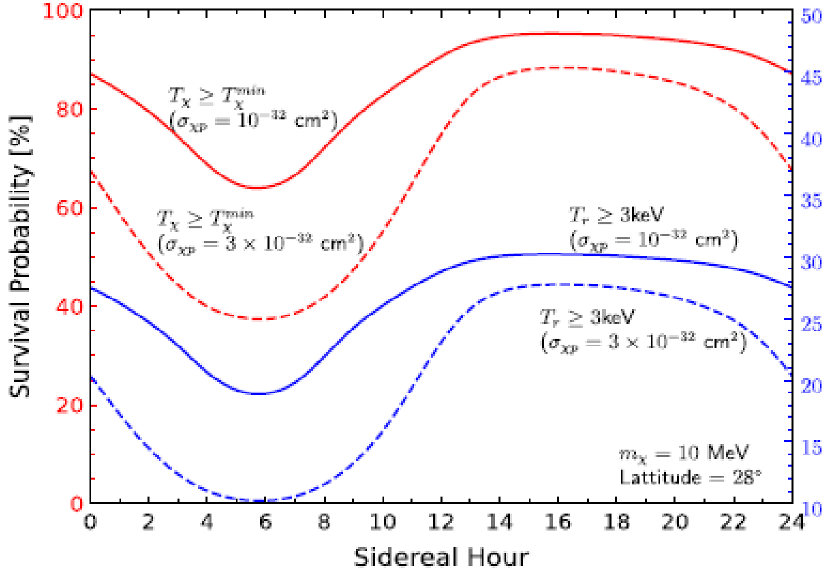


FIG. 4. The survival probability of CRDM arriving at an underground lab at latitude 28°N and a depth of 2 km vs the sidereal hour relative to the number of DM particles arriving at the Earth for two different cross sections $\sigma_{\chi p} = 1(3) \times 10^{-32}$ cm^2. The red curves correspond to the total CRDM arriving at the detector with $T_\chi \geq T_\chi^{\min}$, and the blue curves are those above the detector threshold ($T_r > 3$ keV for a liquid xenon detector).

Boosted Dark Matter (BDM, or CRDM)

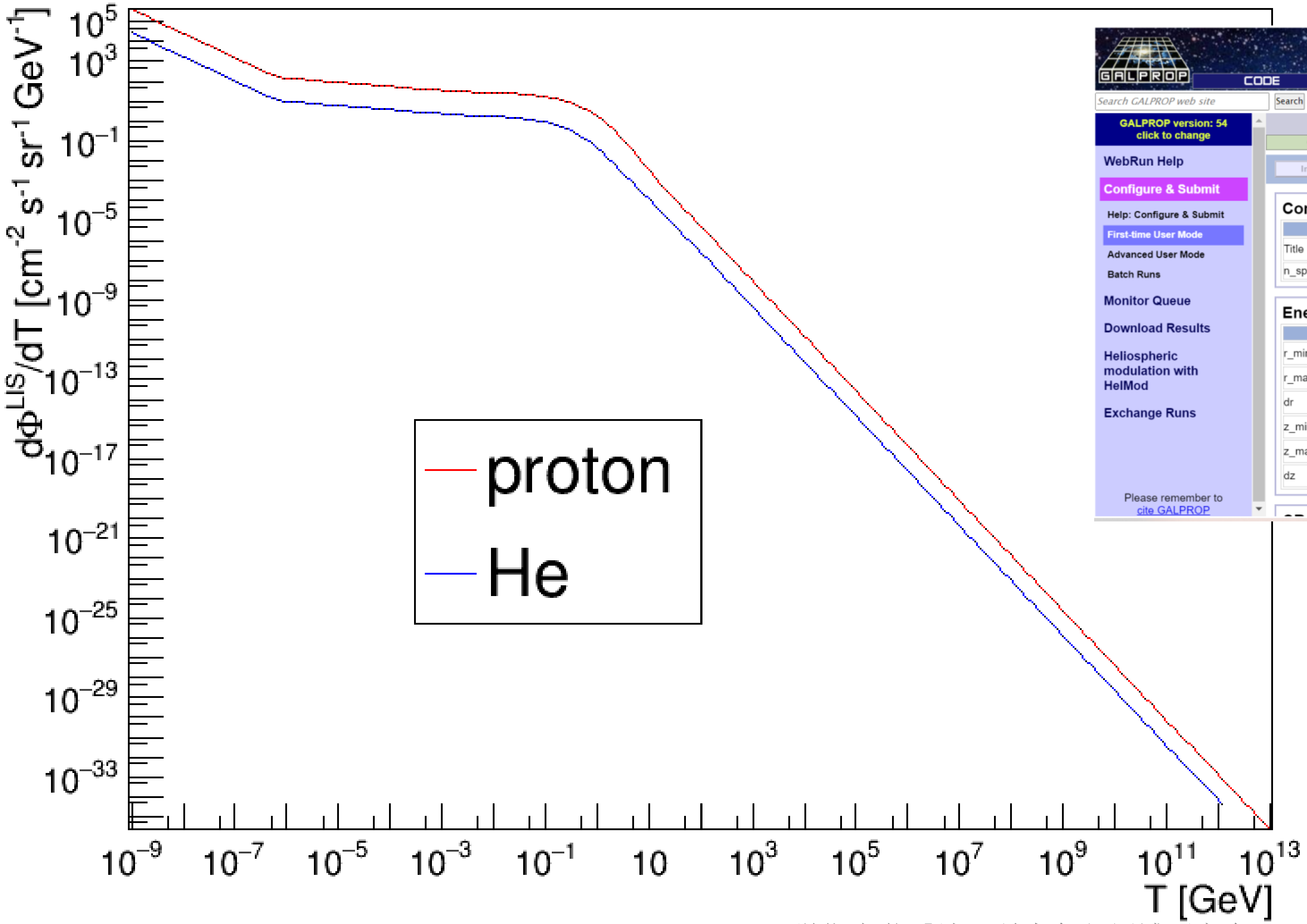
- BDM is low mass and fast ($\beta > 10^{-1}$) because of the CR acceleration mechanism
  - de-Broglie wave : 0.1 ~ 10 fm
    → It isn't coherent scattering with the whole nucleus?
  - Form factor is probably not followed R. Helm's formula (assumed $qR << 1$)
    → Dipole form : $F(Q^2)=1/(1+Q^2/\Lambda^2)$ is currently used (Λ_p~ 770MeV, Λ_{He}~ 410MeV)
  - Considering recoil energy, light target (e.g. H, He) has more advantageous?
- Directionality from the galactic center is important
- Strong rejection power for the EM component is needed

NIT

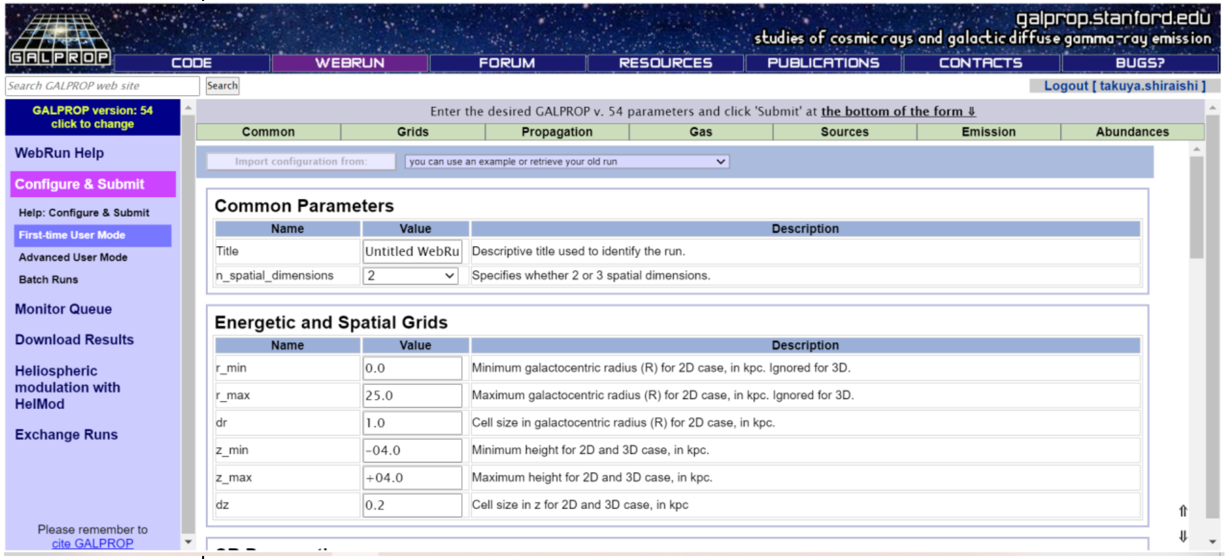
- Contained light target (H)
- High directional accuracy
- Background free in analysis of recoil proton more than sub-MeV

Interstellar CR Flux ($d\Phi^{LIS}/dT$)

CR flux (GALPROP model)



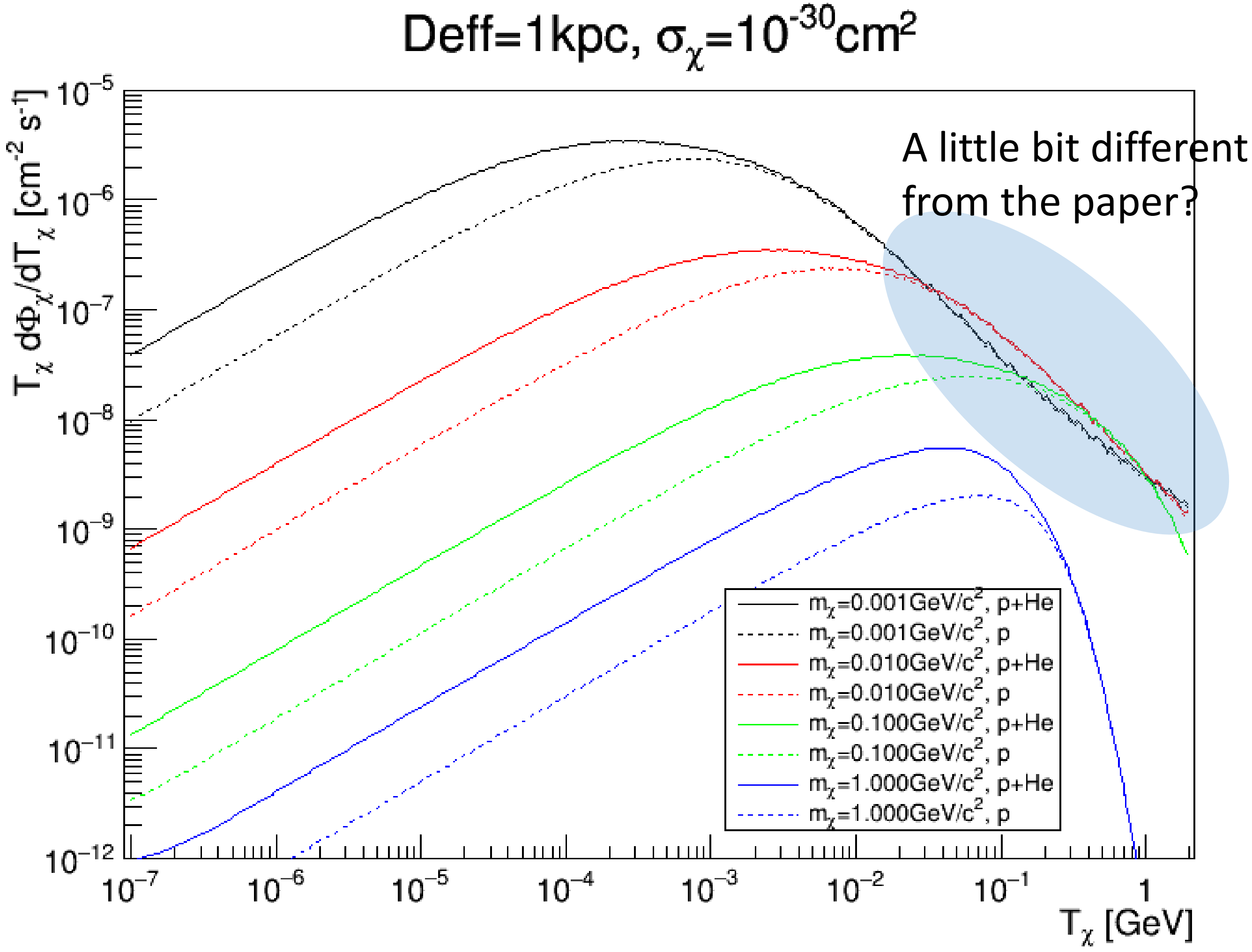
https://galprop.stanford.edu/index.php



H and He spectrum can be obtained from WEBRUN of GALPROP website

https://doi.org/10.1103/PhysRevLett.122.171801

BDM Spectrum



$$\frac{d\Phi_\chi}{dT_\chi} = D_{\rm eff}\frac{\rho_\chi^{\rm local}}{m_\chi} \times \sum_i \sigma_{\chi i}^0 G_i^2(2m_\chi T_\chi)\int_{T_i^{\rm min}}^{\infty} dT_i \frac{d\Phi_i^{\rm LIS}/dT_i}{T_\chi^{\rm max}(T_i)}. \qquad (8)$$

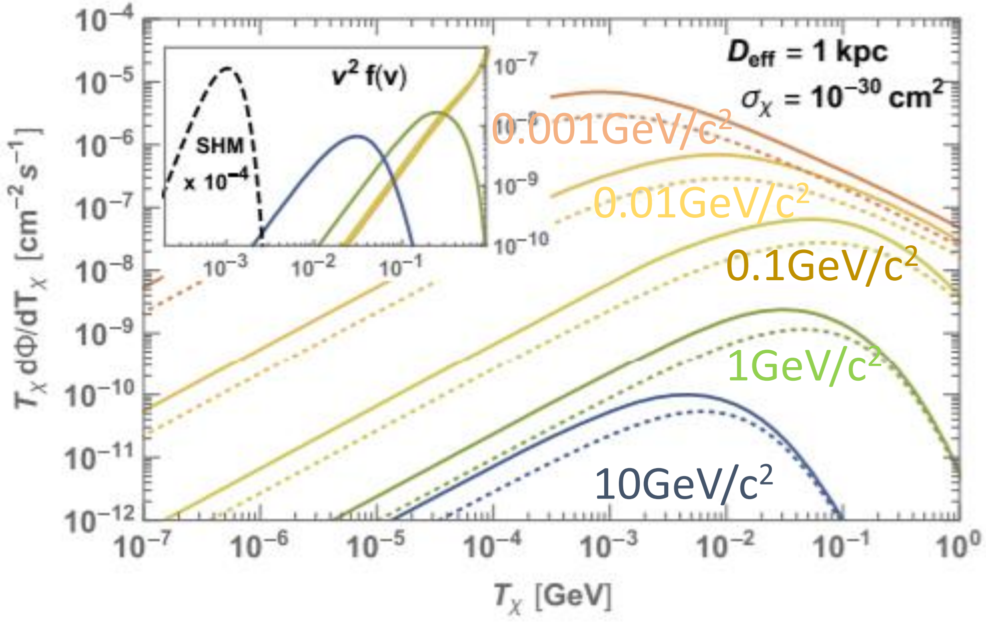
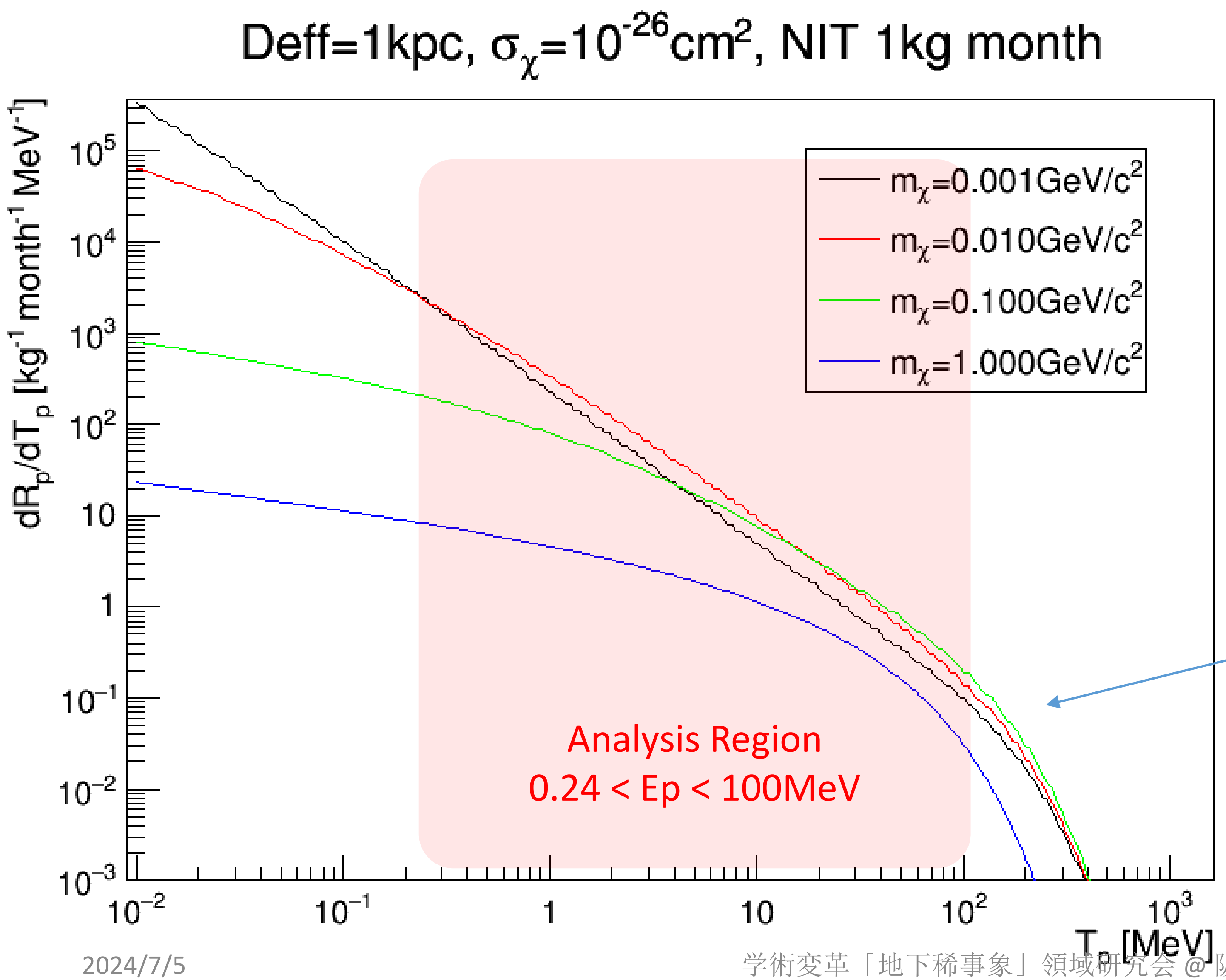


FIG. 1. Expected flux of CRDM for different DM masses m_χ = 0.001, 0.01, 0.1, 1, 10 GeV (from top to bottom). Dotted lines show the contribution from CR proton scattering alone. The flux is directly proportional to the effective distance $D_{\rm eff}$ and the elastic scattering cross section σ_χ, chosen here as indicated. (Inset) Compares the corresponding 1D velocity distributions $f(v)$, in units where $c = 1$, to that of the standard halo model (SHM) (dashed line).

Recoil Proton Spectrum in NIT by BDM

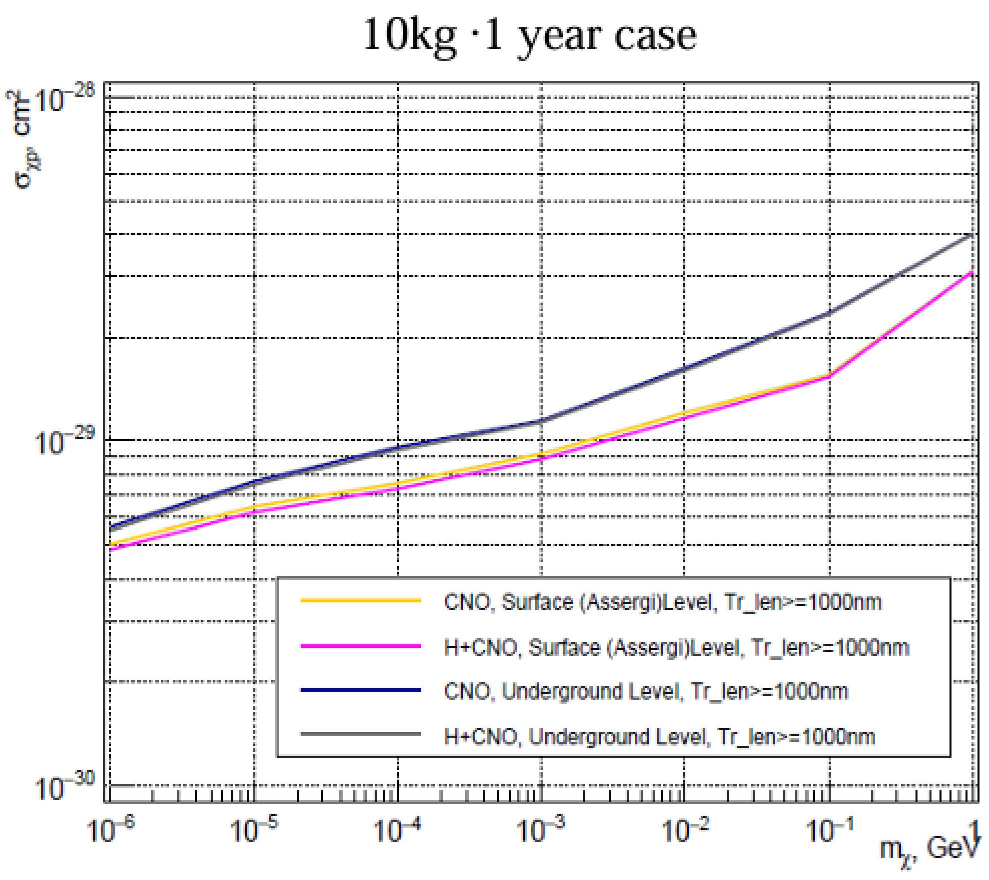


Nuclear recoil rate by CRDM

$$\frac{d\Gamma_N}{dT_N} = \sigma^0_{\chi N} G_N^2(2m_N T_N) \int_{T_\chi(T_\chi^{z,\mathrm{min}})}^{\infty} \frac{dT_\chi}{T_{r,N}^{\max}(T_\chi^z)} \frac{d\Phi_\chi}{dT_\chi}. \quad (14)$$

- ✓ Drastically decrease from Ep> 100 MeV (due to CR spectrum?)
- ✓ MeV region is reasonable

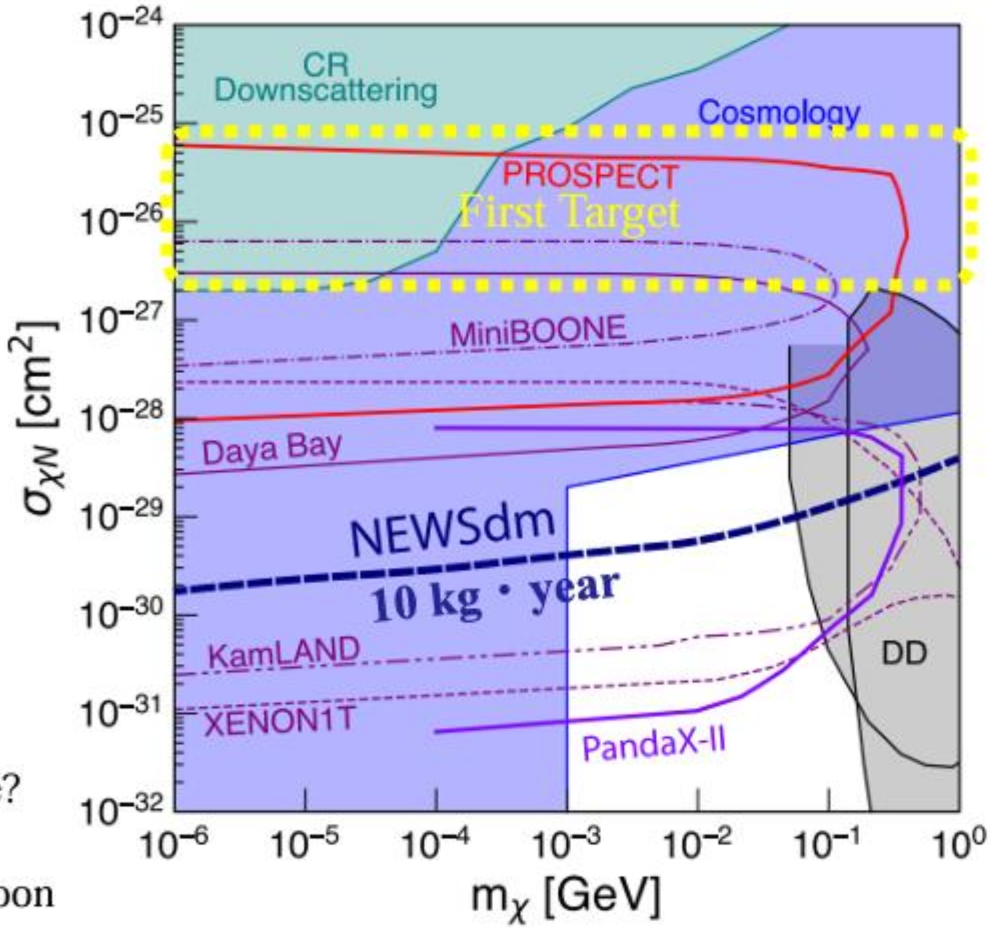
CRDM search



- Higher cross section region is also important in CRDM
- Scattering in the rock can disturb directional search
- Surface exposure has higher background, especially cosmic-ray induced background such as neutron, proton and muon.
- In emulsion case, targeting only long CNO recoil may be a good strategy for CRDM
  - >1um CNO: 400keV/um or more
  - alpha Bragg peak: <300keV/um
  - proton Bragg peak: <100keV/um
  - <u>Alpha insensitive emulsion is already verified</u>

CRDM search

- Nov-Dec 2023
- First trial of CRDM search
- very low sensitivity emulsion→ p, α free?
- Equatorial mount
- Analysis will start soon



N.Y. Agafonova et al JCAP07(2023)067

Calibration with ion implantation system

Accelerators in our laboratory

<u>Low Velocity Ion Implantation</u>

Acceleration Voltage : 5 ~ 200 kV

Temperature : –196 ~ 1000℃

Ion : H, He, B, C, N, O, F, Si, P, Ar, Ti, Fe, Co, Ge, Kr, Xe, CO, CD_4, ...

Valence : 1, 2, 3, (4)

Beam current : 10 pA ~ 100 μA

<u>1MV Tandem Pelletron Ion Accelerator</u>

Acceleration Voltage : 0.5 - 1 MV

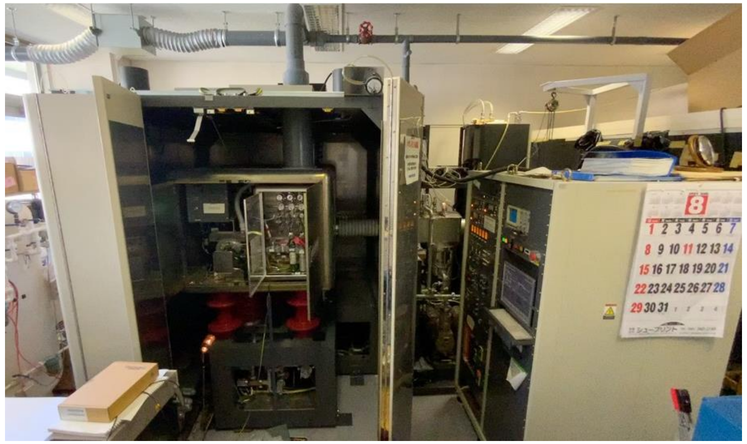
Ion : He^{++}, H, Li, B, C, O, Si, Ni, Cu, ...

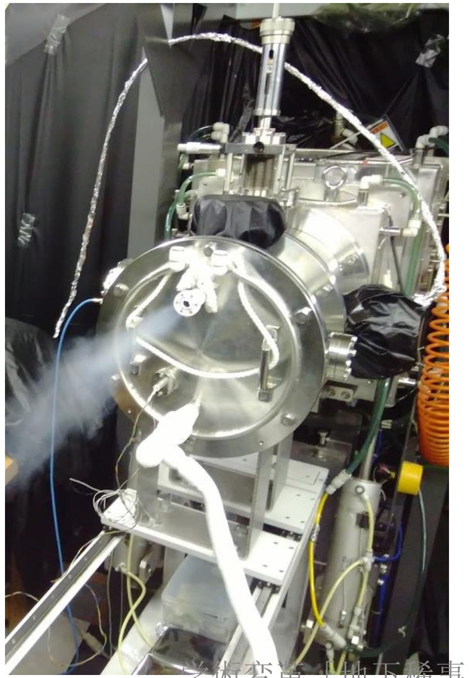
Valence : 1, 2, ???

Detector : Si semiconductor detector x 2

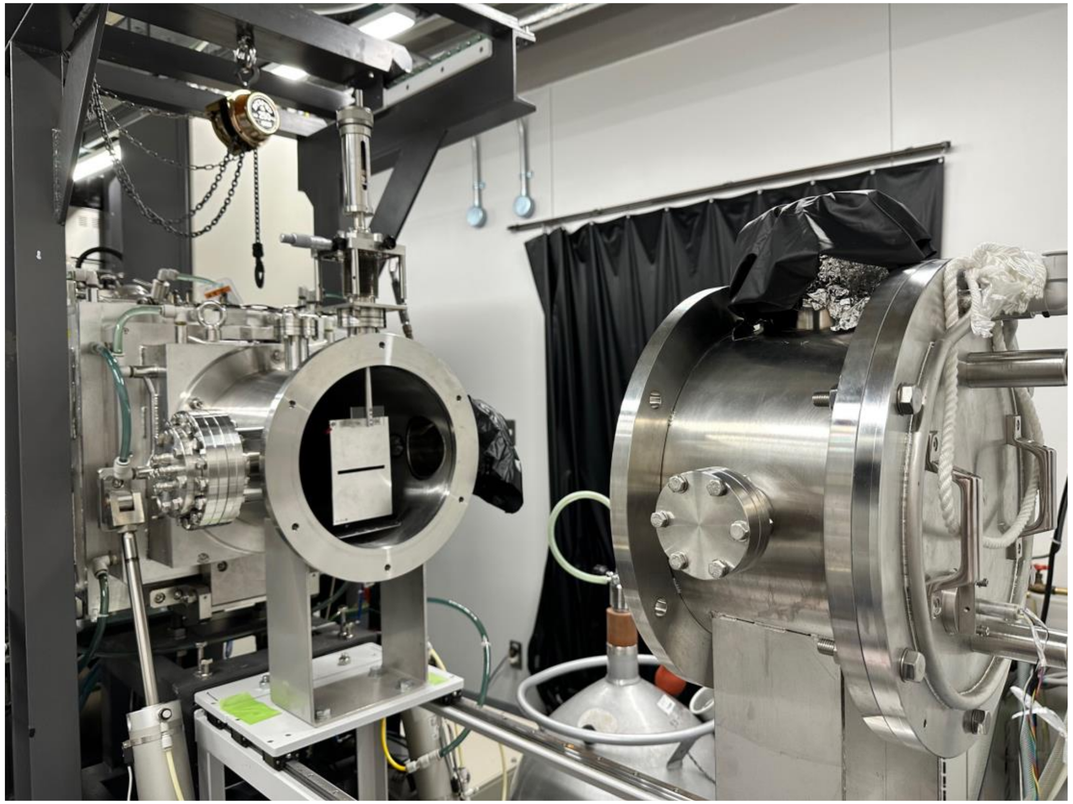
Beam size : ϕ 2 mm

Analysis : RBS-channeling, PIXE, Nuclear Reaction, ERDA

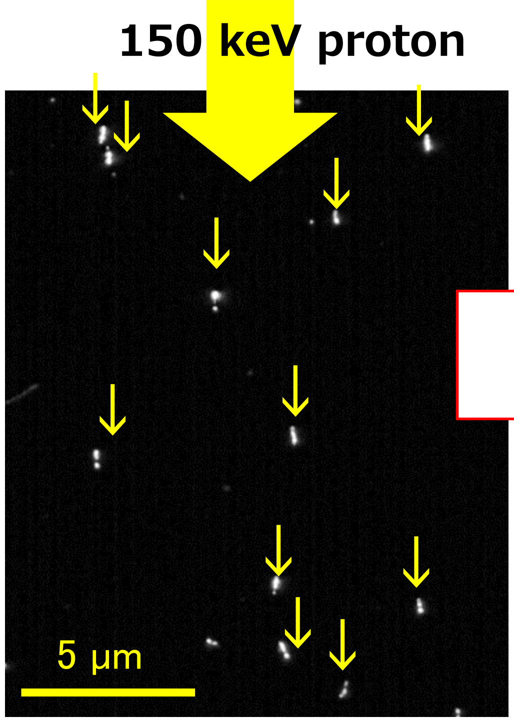




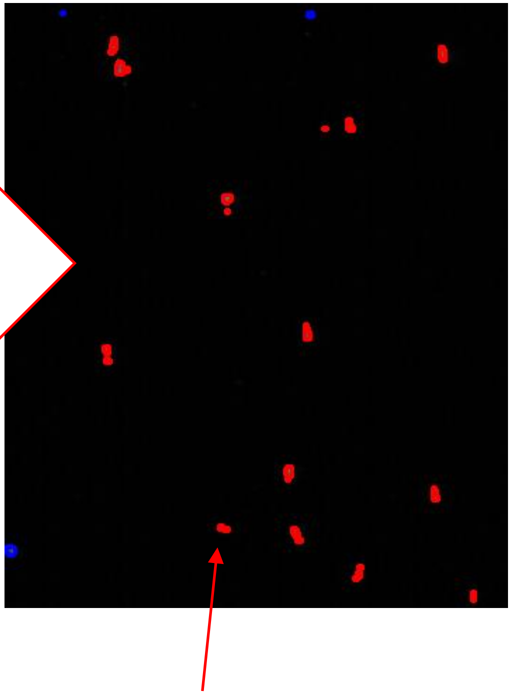
Detecting directly exposed protons



Ion implanter @ Kanagawa Univ.

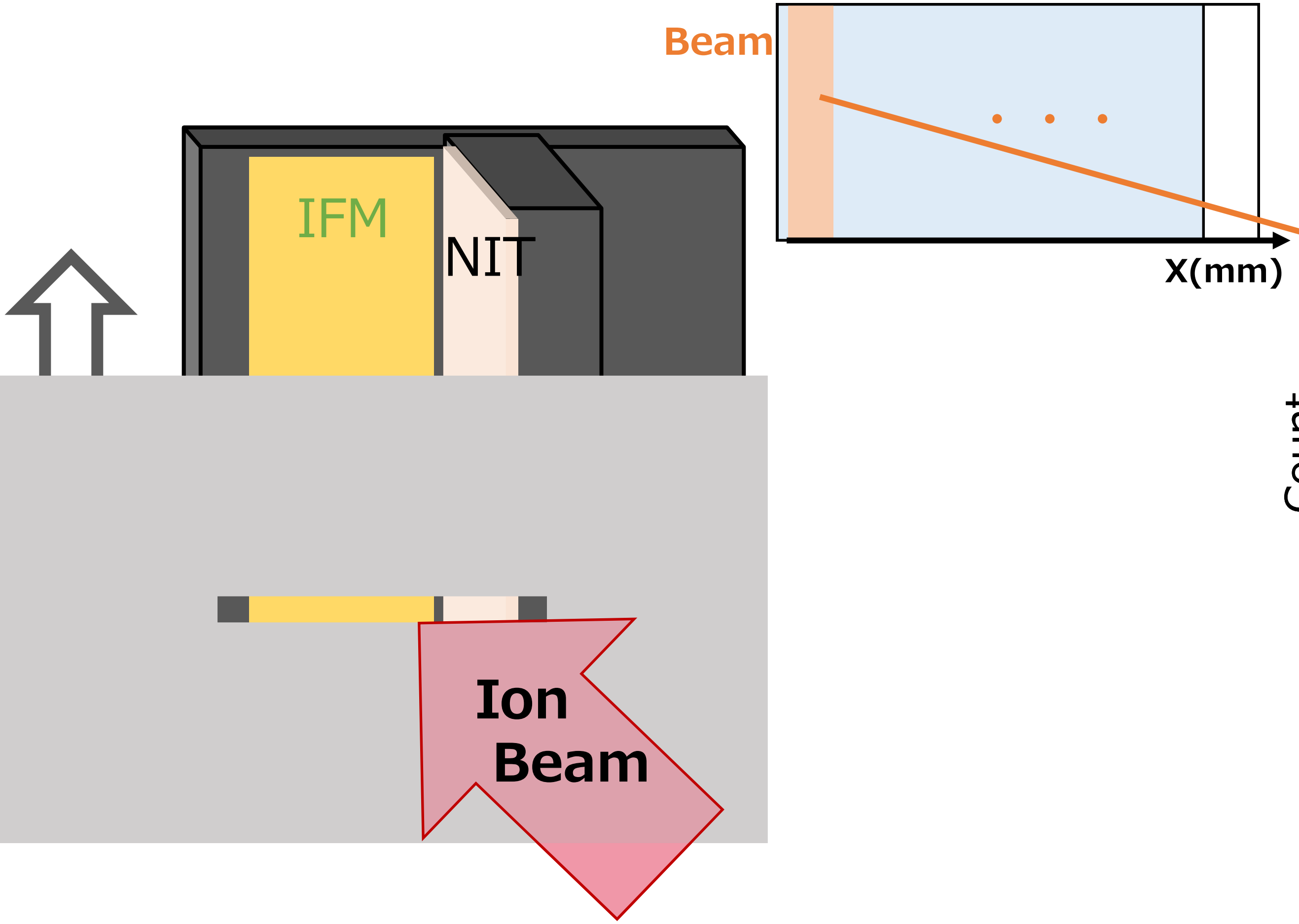


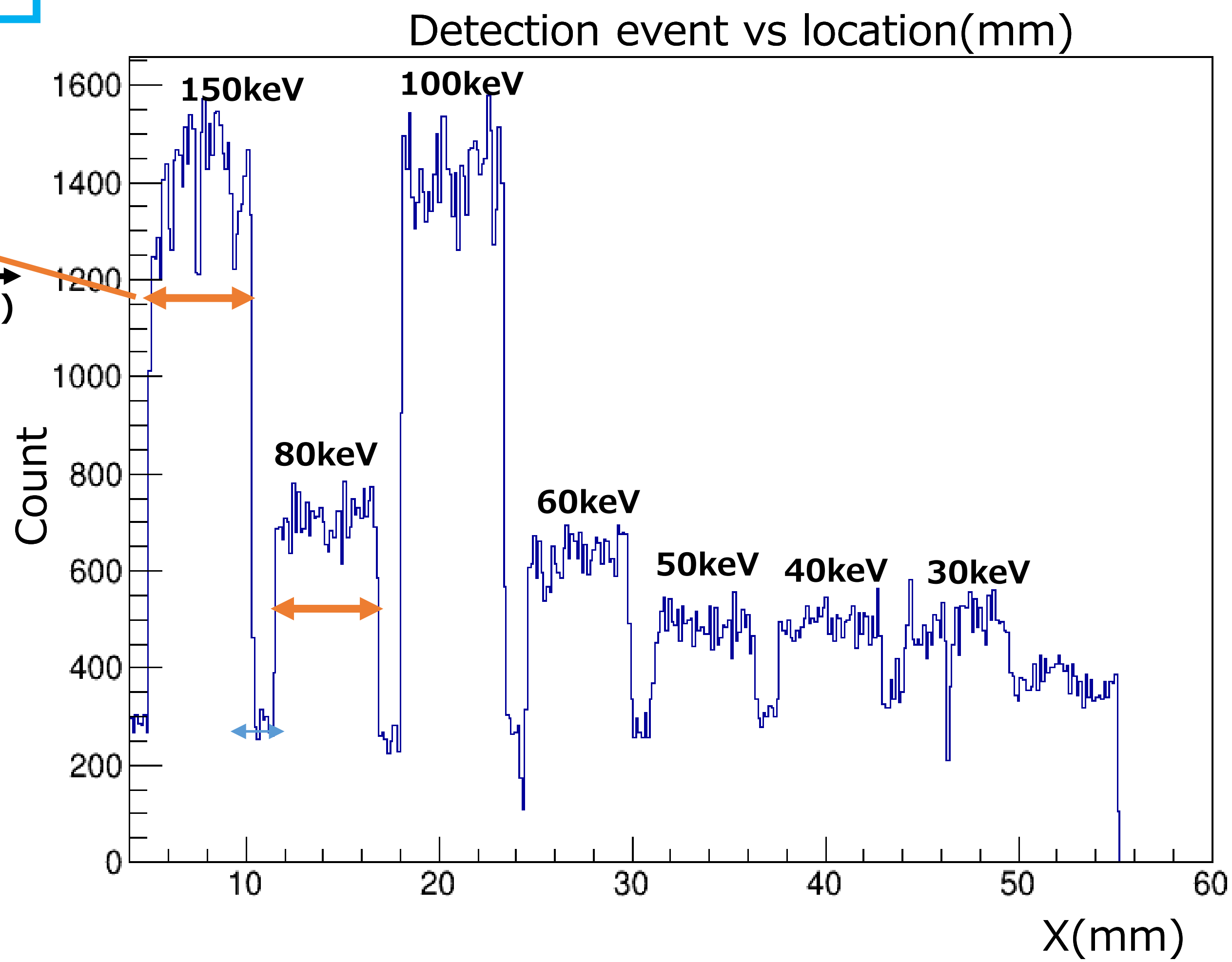
Automated detection



Recognized tracks

Detecting directly exposed protons



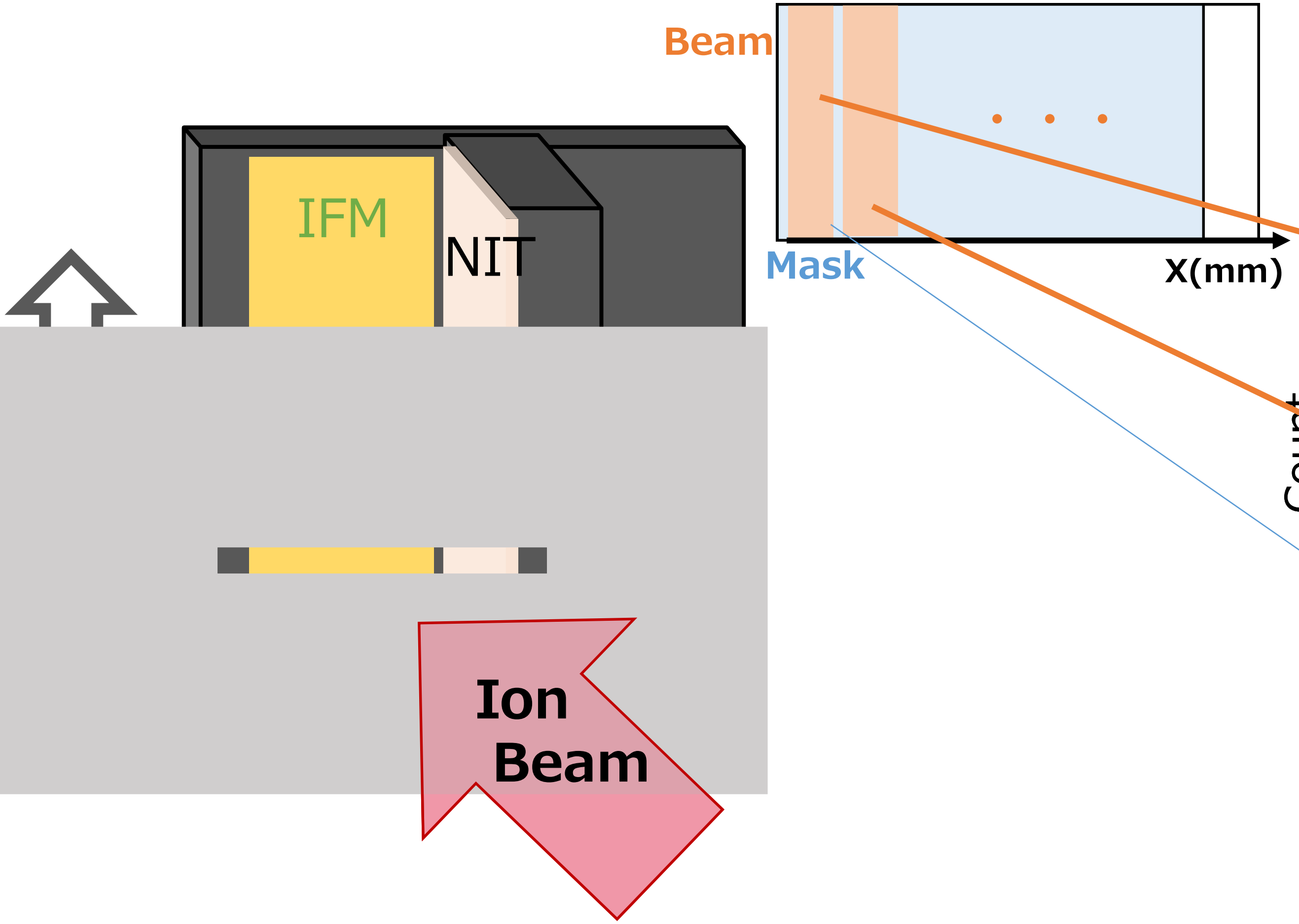


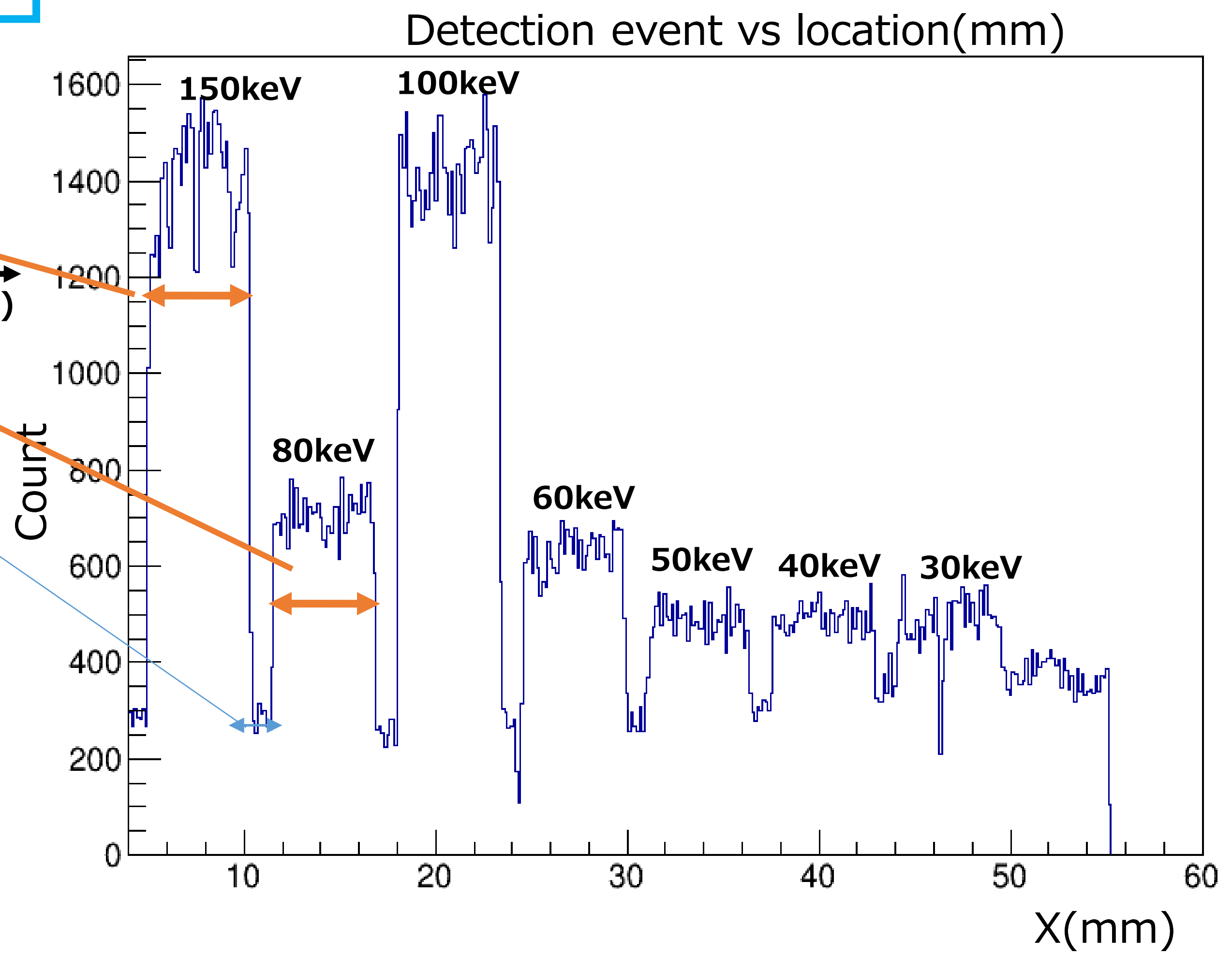
Ion exposure ➡ Move the plate up ➡ Ion exposure with different energy ・・・

➢One sample is exposured with protons of multiple energies.

・Beam areas and Mask areas are created.

Detecting directly exposed protons





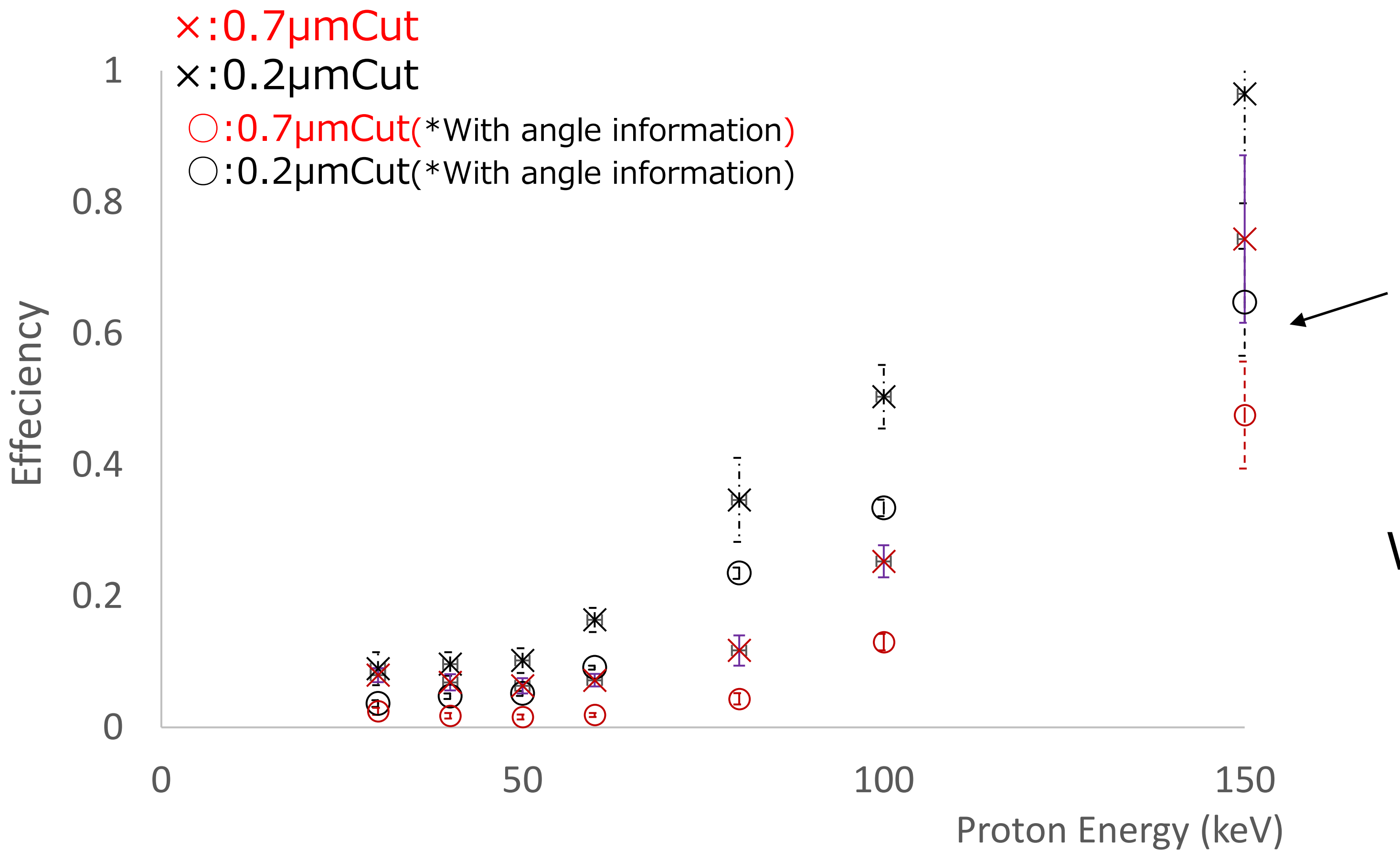
Ion exposure ➡ Move the plate up ➡ Ion exposure with different energy ・・・

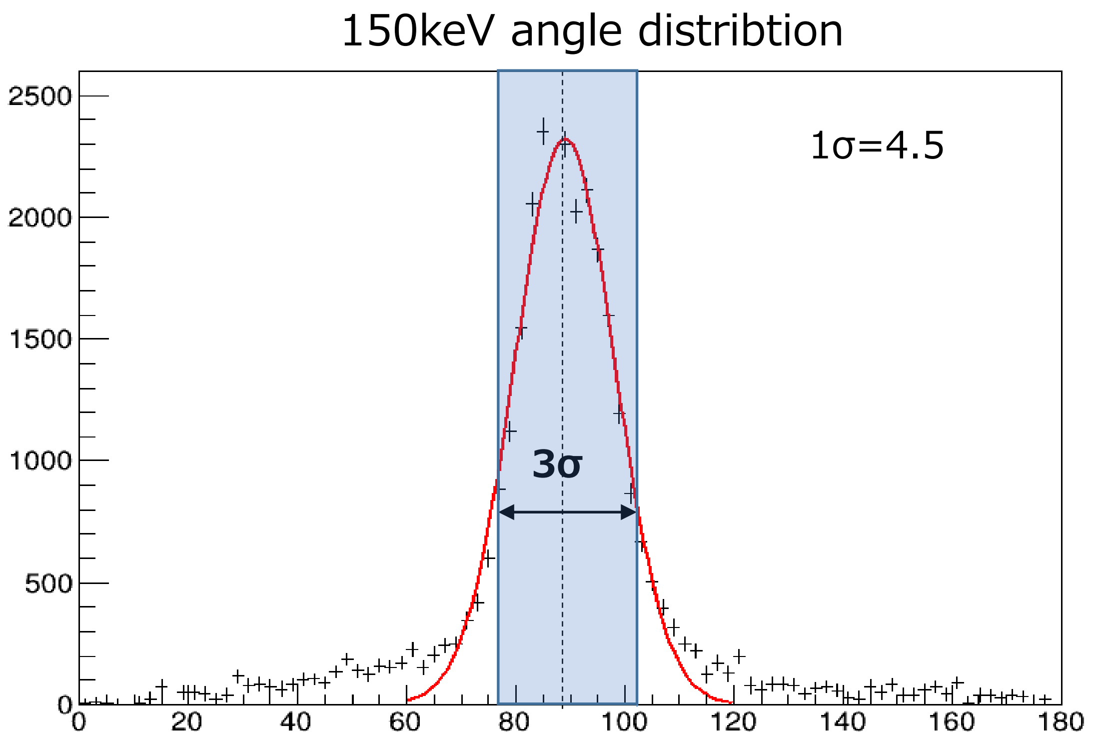
➢One sample is exposured with protons of multiple energies.

・Beam areas and Mask areas are created.

Detecting directly exposed protons

Efficiency=
(#of detection@NIT)/(#of deteciotn@IFM)



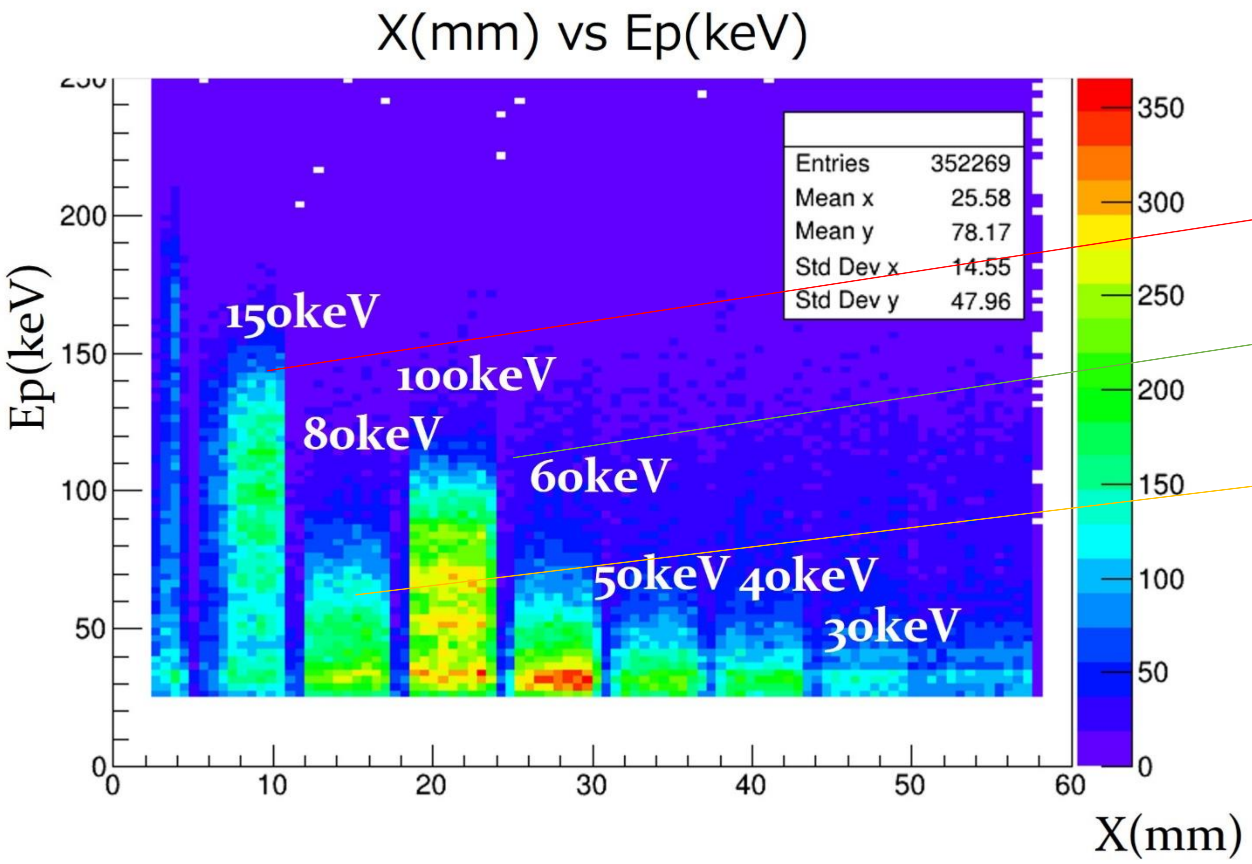


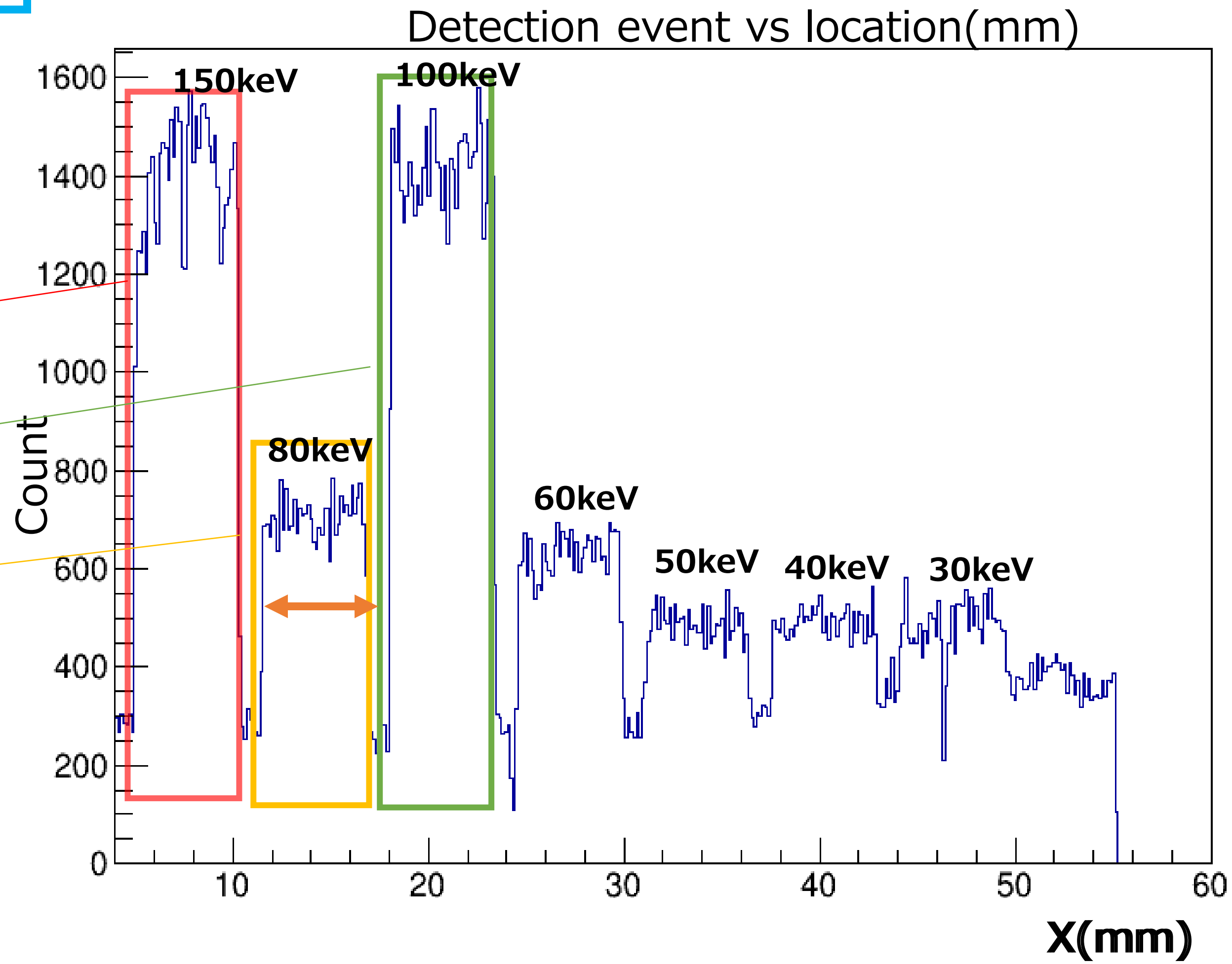
With angle information

- The angle distribution is Gaussian-fitted, and only components with angles within 3σ of it are considered as detection events.

*With angle information: Gaussian fit results for angle distribution
Number of components with angles within 3σ

Detecting directly exposed protons





Ion exposure ➡ Move the plate up ➡ Ion exposure with different energy ・・・

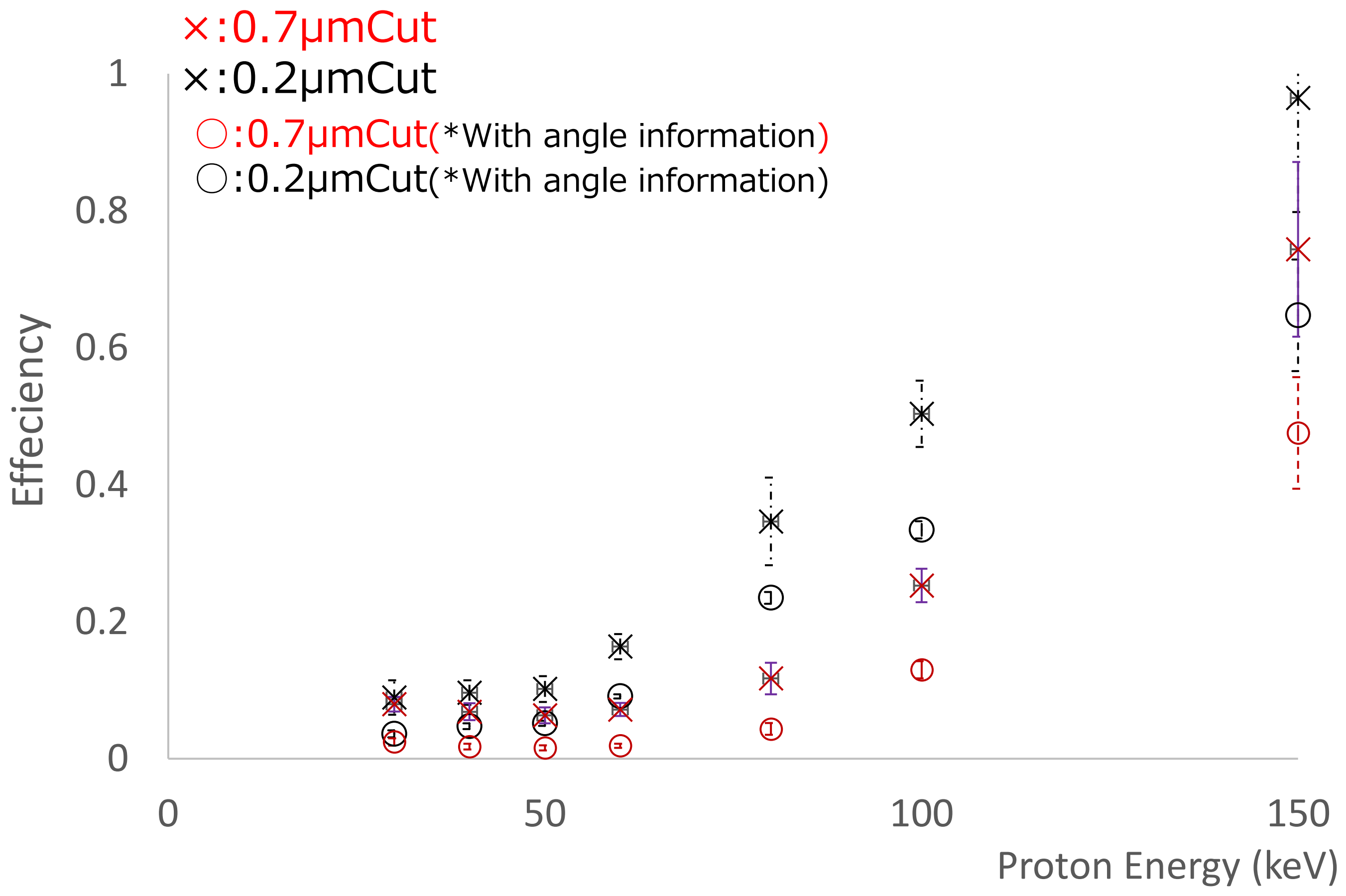
➢One sample is exposured with protons of multiple energies.

・Beam areas and Mask areas are created.

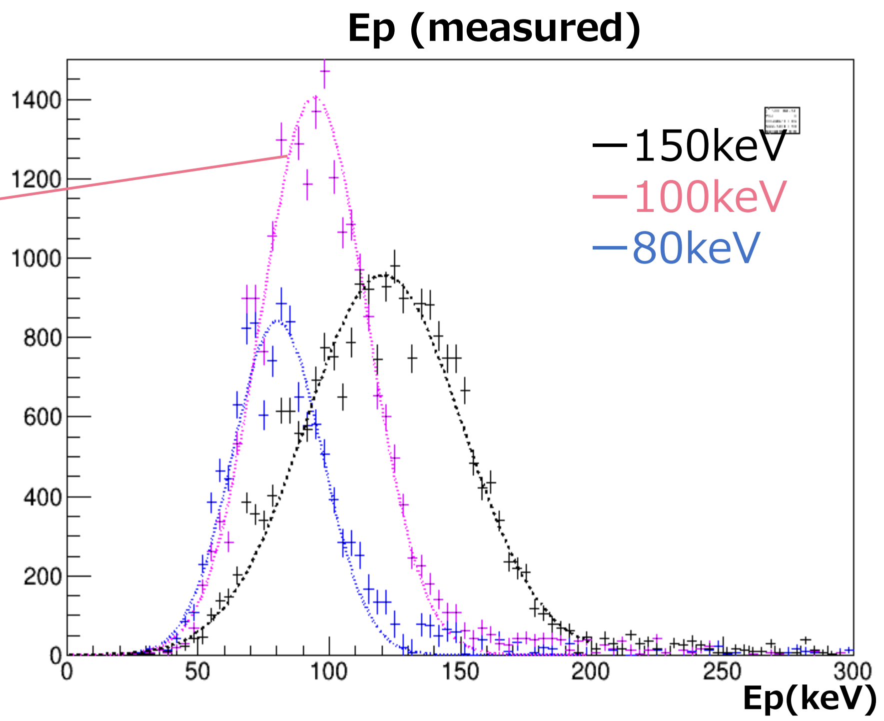
・The correlation between irradiation energy and irradiation position is also visible.

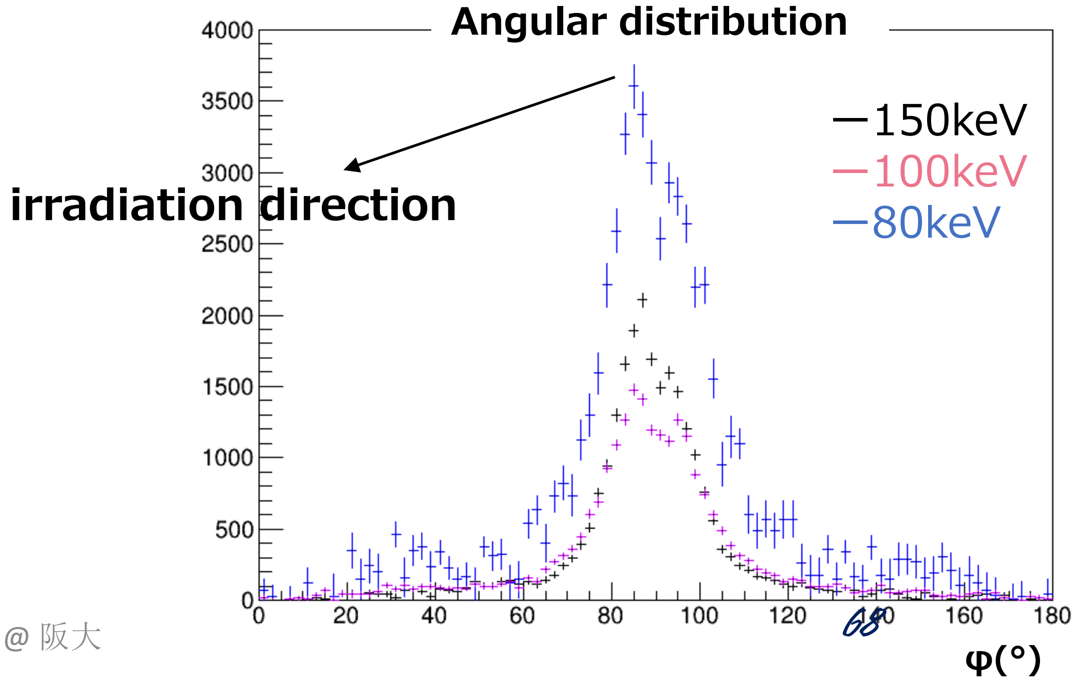
Detecting directly exposed protons

Efficiency= (#of detection@NIT)/(#of deteciotn@IFM)



Energy resolution 47%(@100keV)

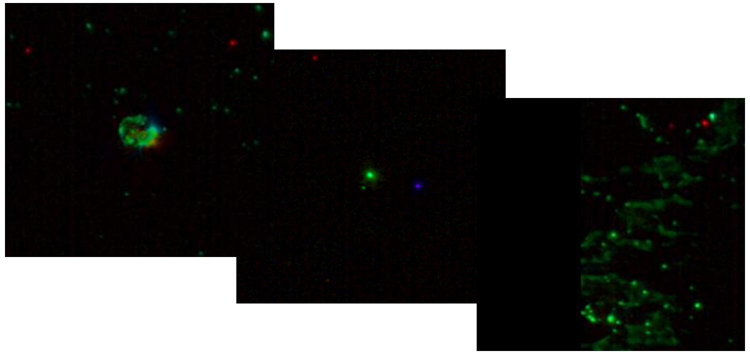




*With angle information: Gaussian fit results for angle distribution
Number of components with angles within 3σ

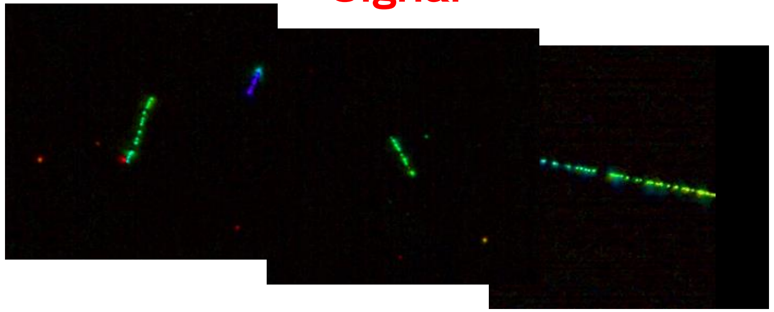
Implementing CNNs to improve efficiency of analysis

Noise



- γ-ray exposeured sample
- n-Run2 sample

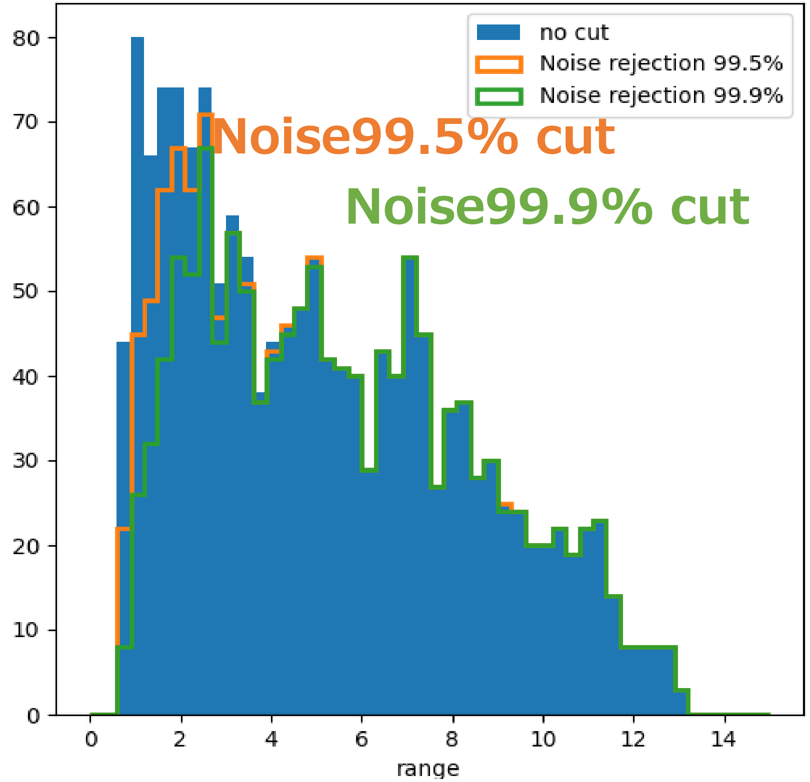
Signal



- Neutron exposured sample
- n-Run2 sample

Recoil proton tracks selected from880 keV neutron beam samples were automatically classified using CNN.

Results the signal classified using the learning model.

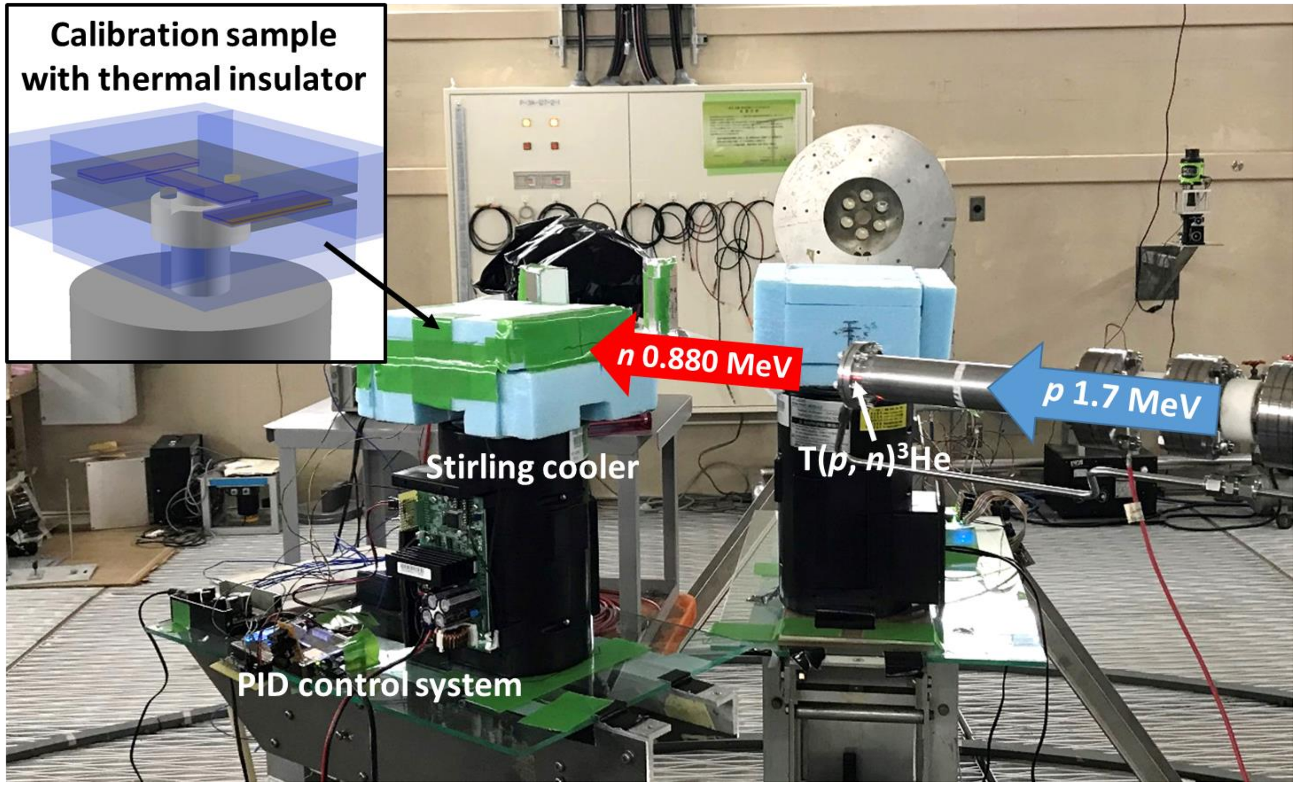


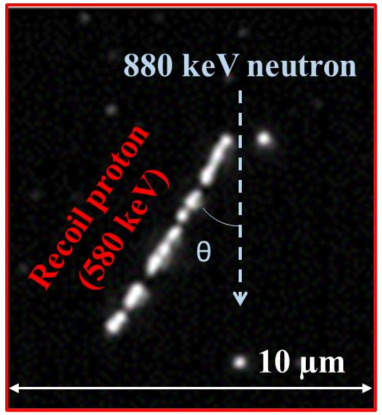
The selection accuracy is 20-50% at around 1 μm, and almost 100% at 2 μm and above.

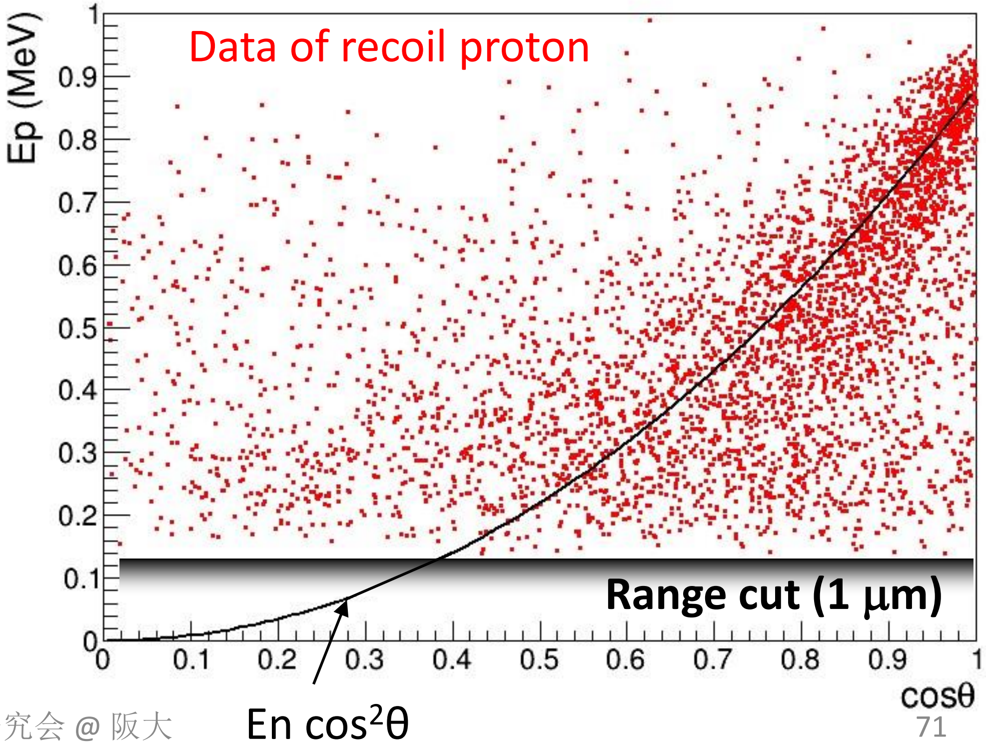
Monochromatic Neutron Calibration

Calibration with Monochromatic Sub-MeV Neutron

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



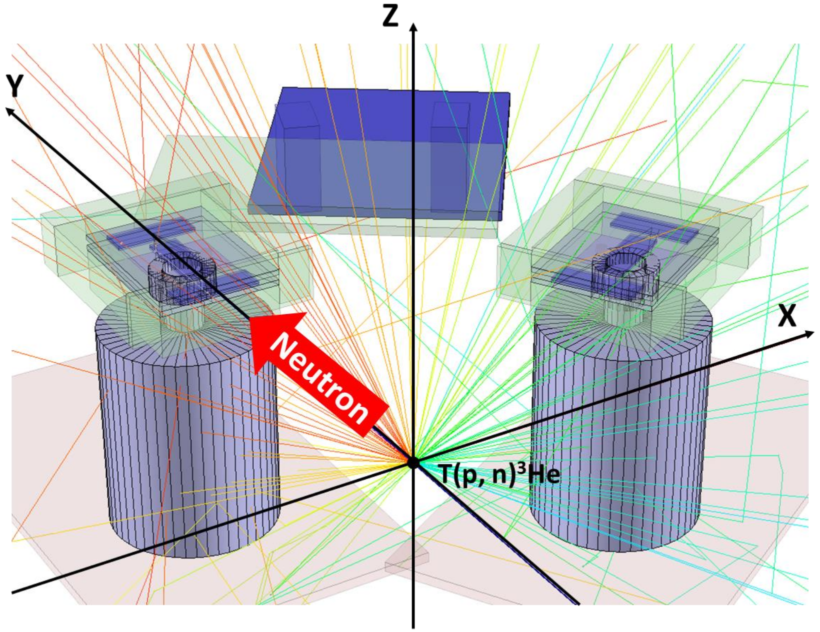




Exposed 7.9 hours with a stable temperature at -26℃

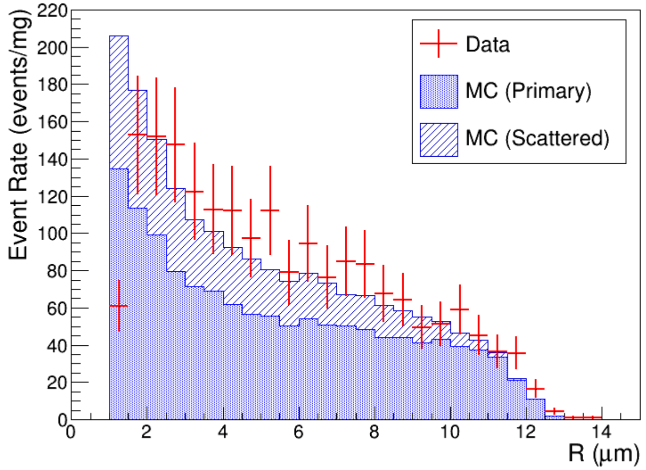
Calibration – Comparison with Simulation

GEANT4 simulation

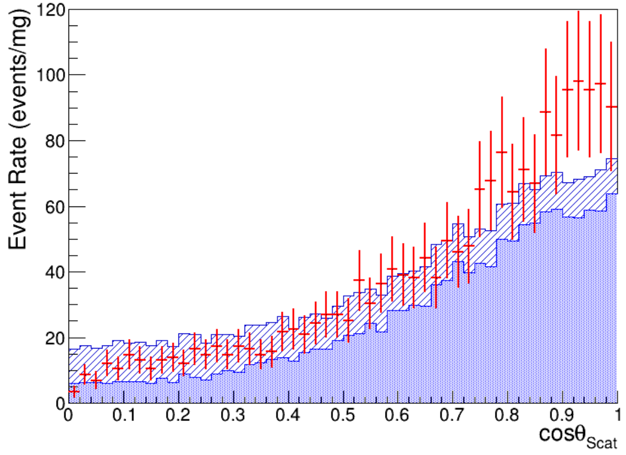


*Color corresponding to neutron energy

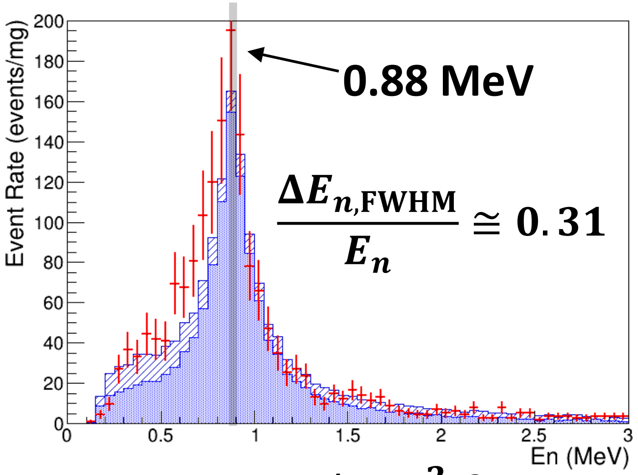
Proton Range



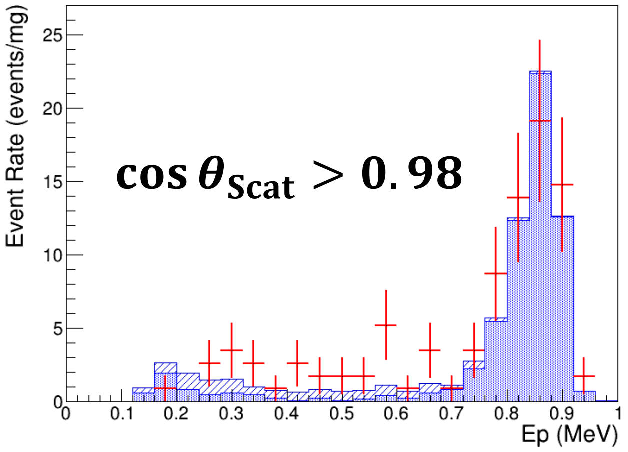
Scattering Angle



Neutron Energy



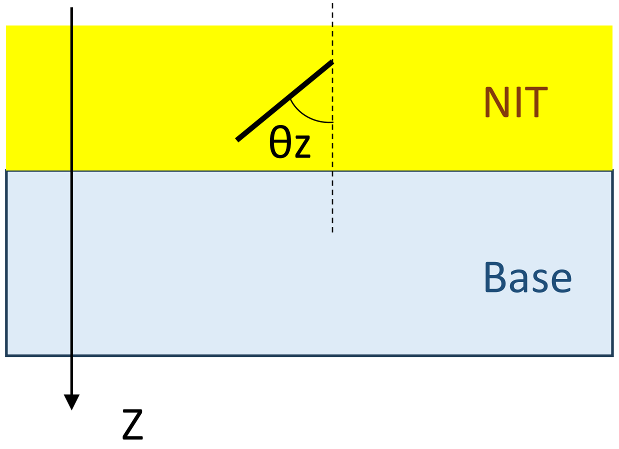
Proton Energy of Head-on Collision

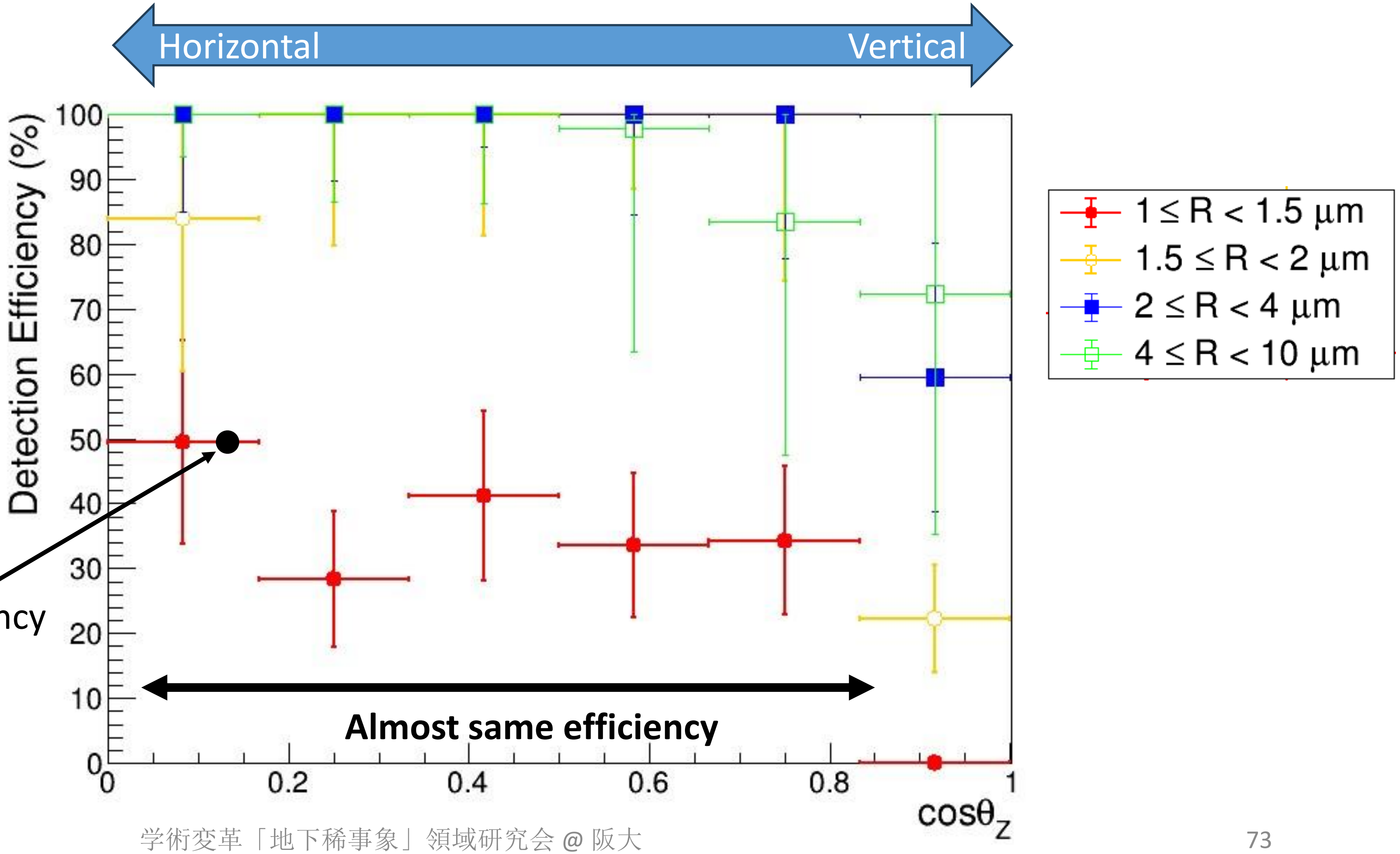


$$E_n = E_p / \cos^2\theta$$

- ✓ **Detected recoil protons are almost good agreement with kinematical expectation**
- ✓ **Detection efficiency for R < 1.5 μm seems to be not 100%**

Calibration – Angular and Range Dependency of Detection Efficiency

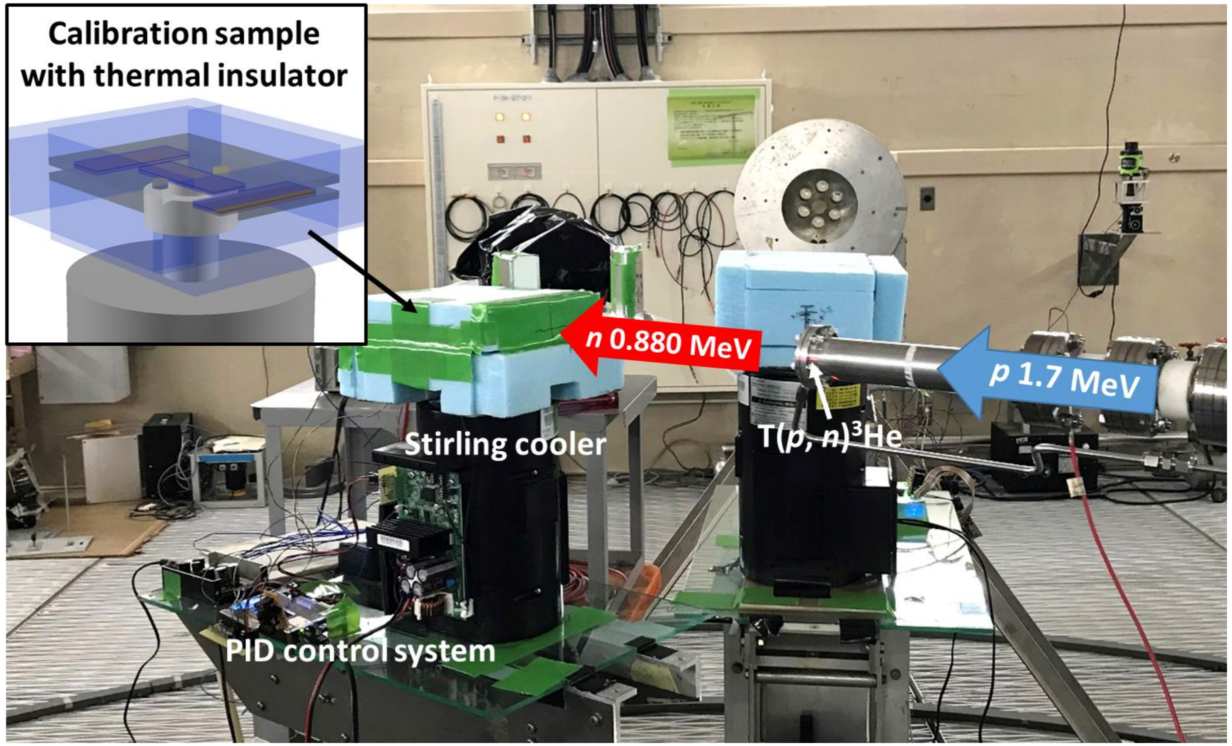




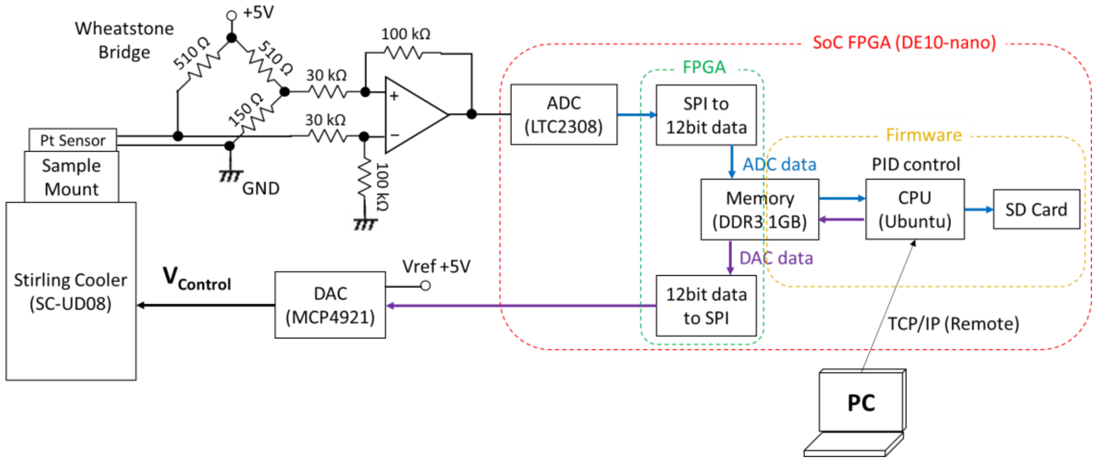
Horizontal 150 keV proton efficiency
~ 50% from ion implantation

Calibration with Monochromatic Sub-MeV Neutron

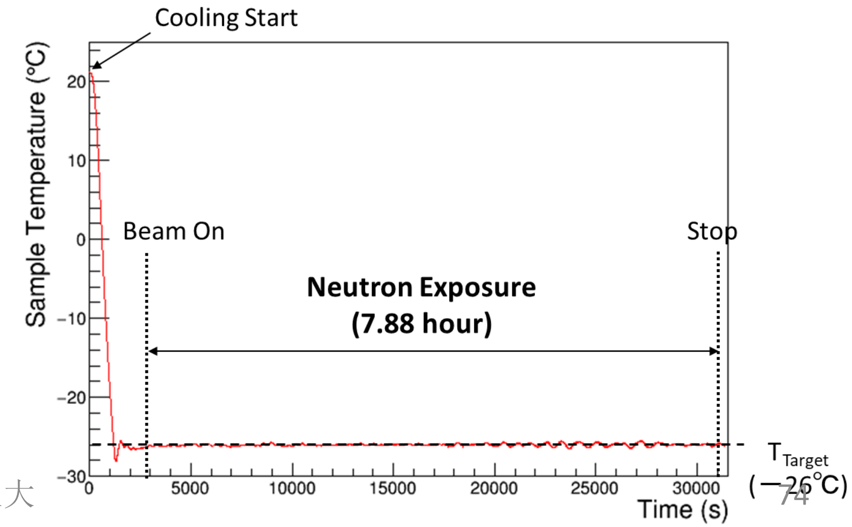
Monochromatic 880 keV neutron exposure at AIST



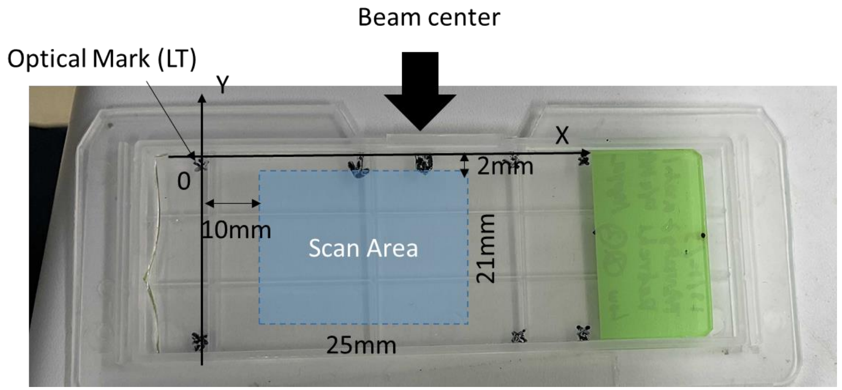
PID control system

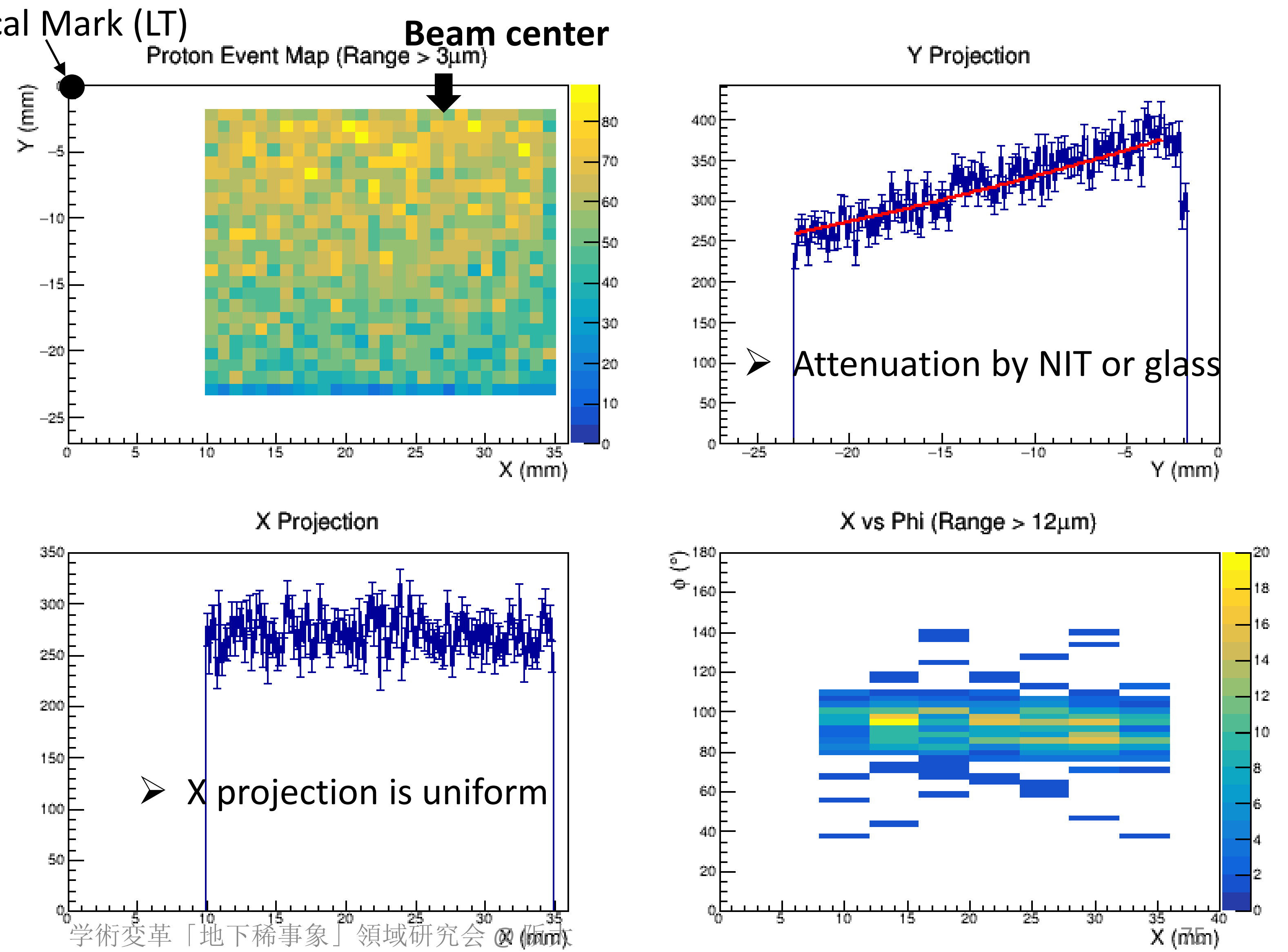


Sample temperature profile



Analysis of 880keV Sample



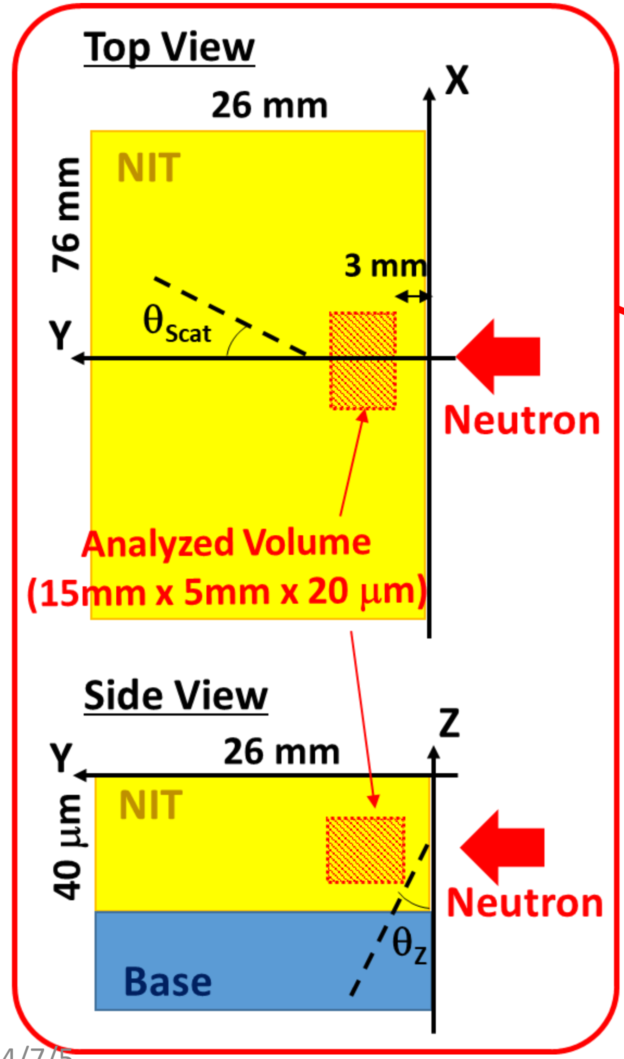


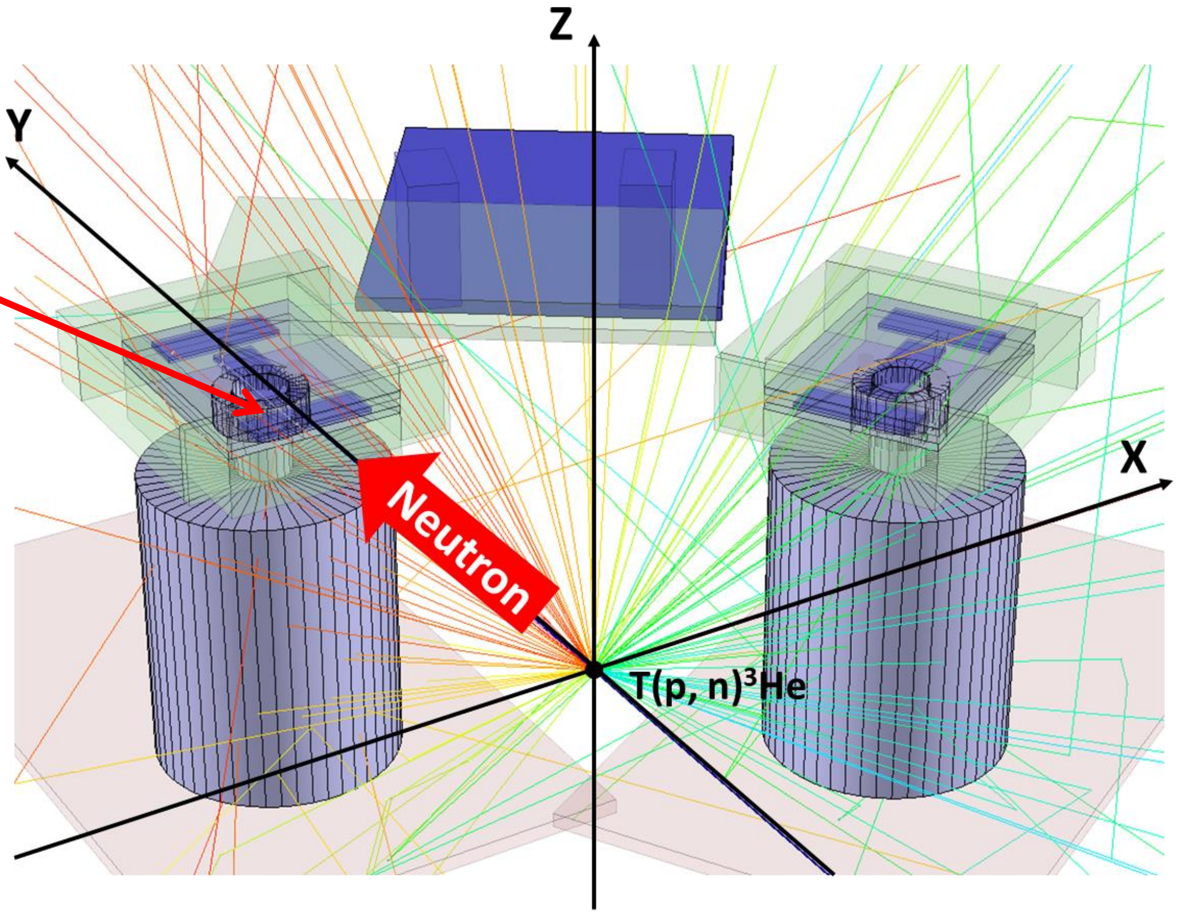
Simulation

Neutron Scattering Model:
- G4HadronElasticPhysicsHP
- G4HadronPhysicsShielding

Electromagnetic Model:
- G4EmLivermore

- Tracking step for recoil proton: 0.1μm
- Angular dependency of Energy and Flux in T(p, n)^{3}He reaction is considered

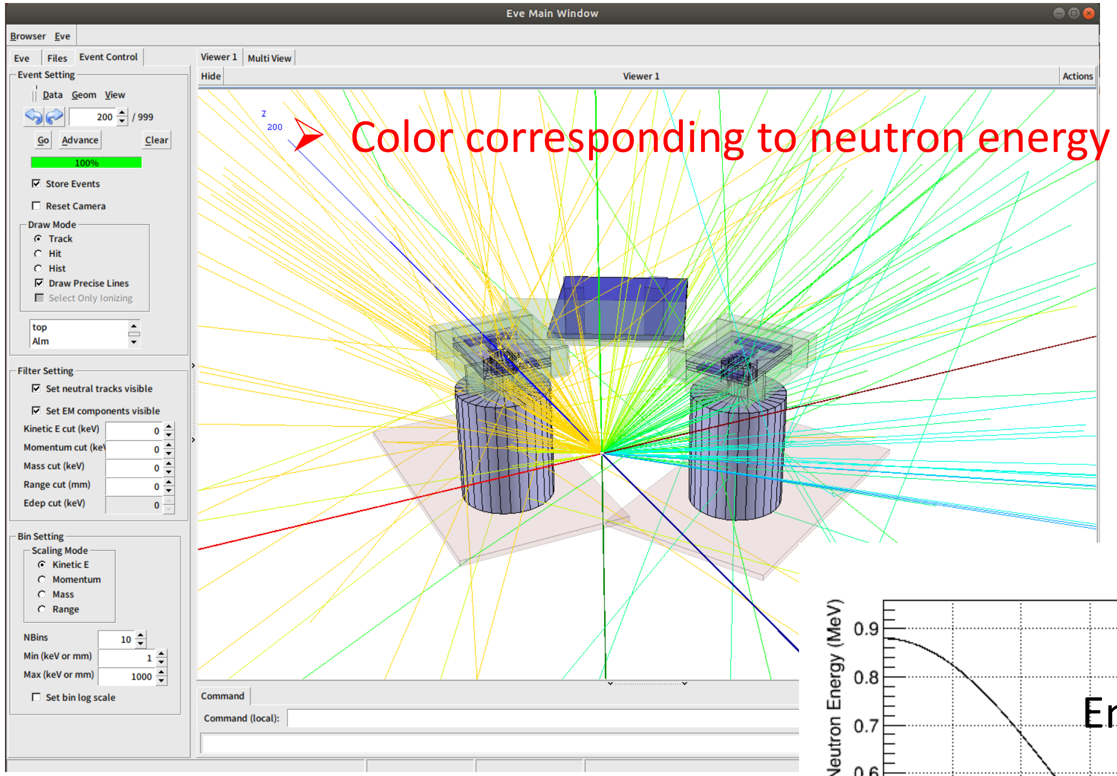


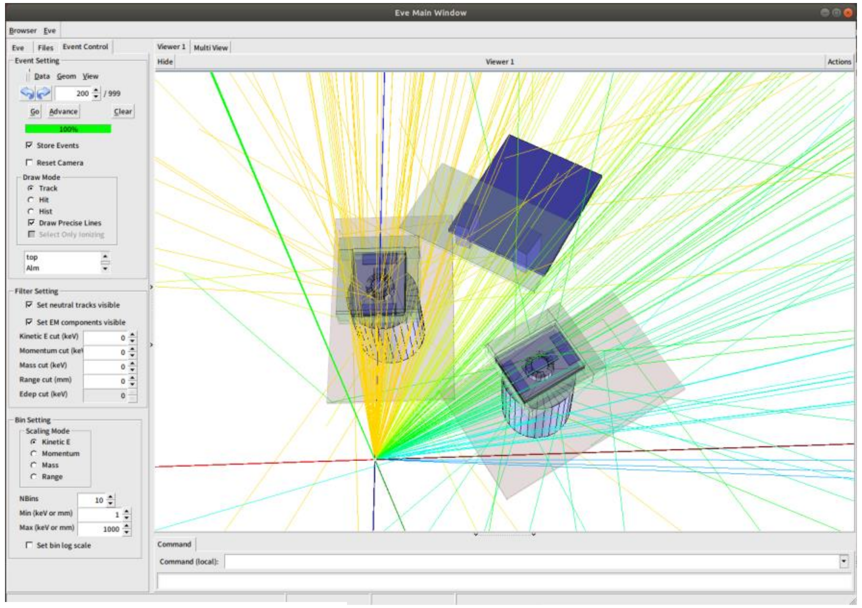


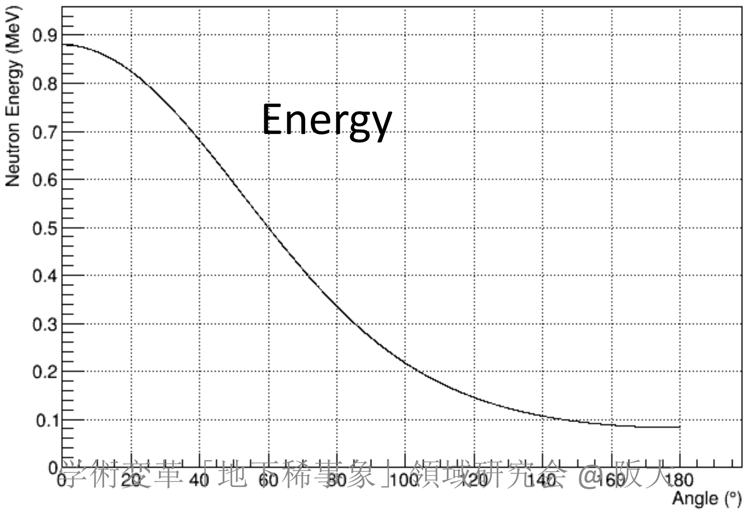
*Line color corresponding to neutron energy

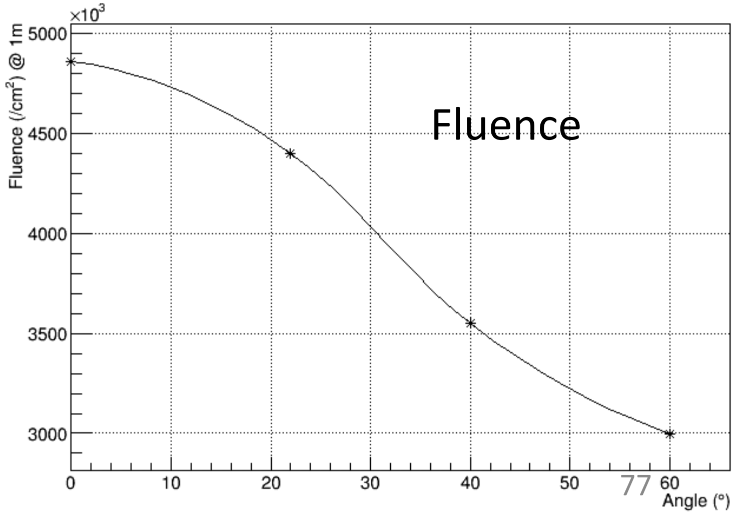
Simulation of Neutron Exposure

Considering energy and fluence for each angle

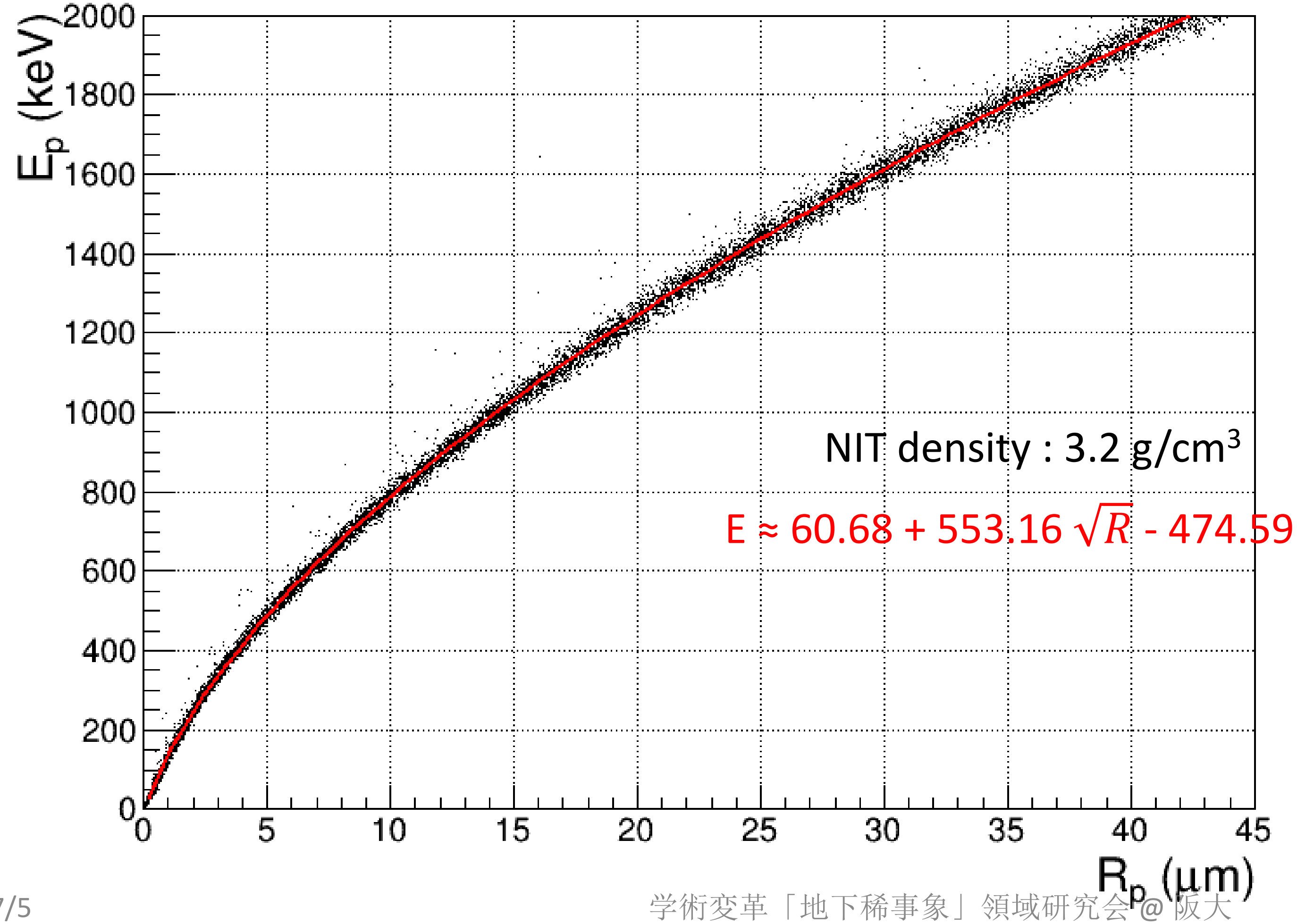








Correlation of Proton Energy and Range in NIT (GEANT4)

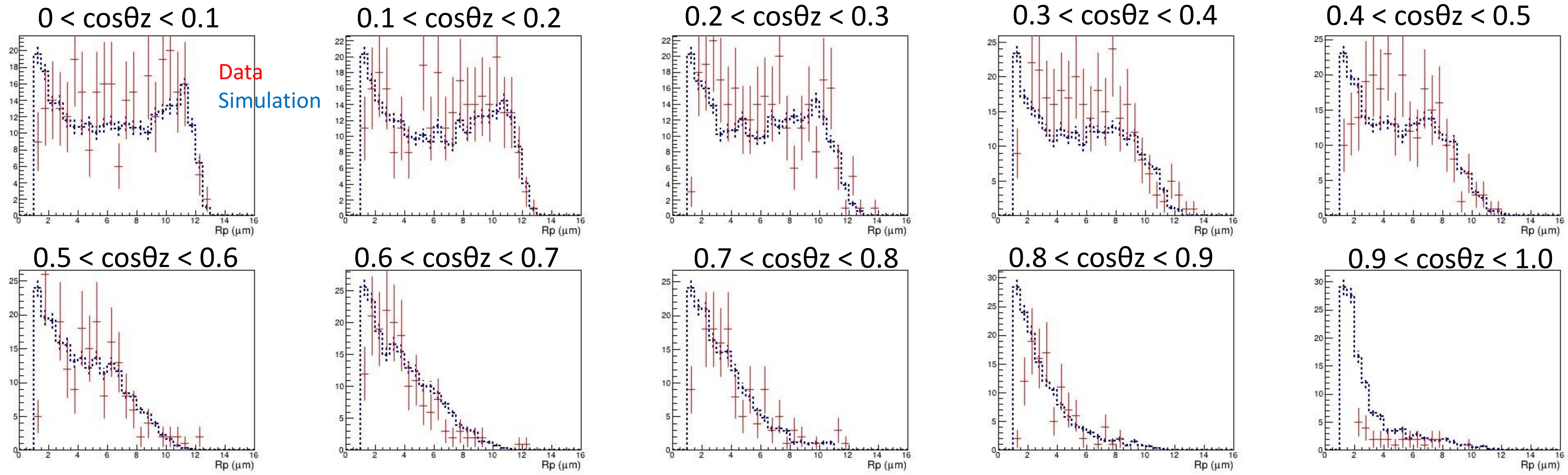


NIT density : 3.2 g/cm^3

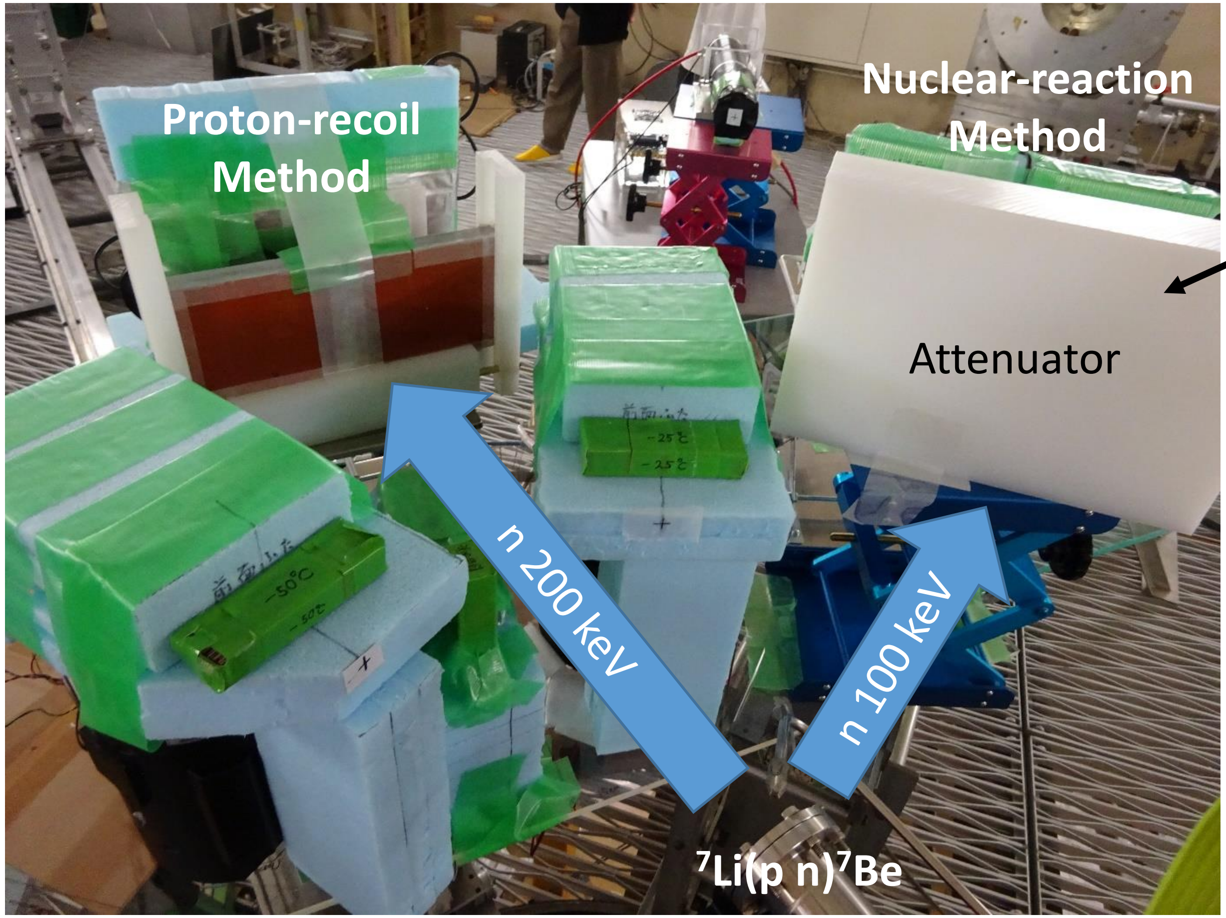
$E \approx 60.68 + 553.16\sqrt{R} - 474.59\sqrt[3]{R}$ (keV)

Angular dependency

AIST 2019 : 880keV neutron sample



Neutron Exposure from $^{7}Li(p\ n)^{7}Be$@ AIST 25 Aug. 2022



Behind the attenuator

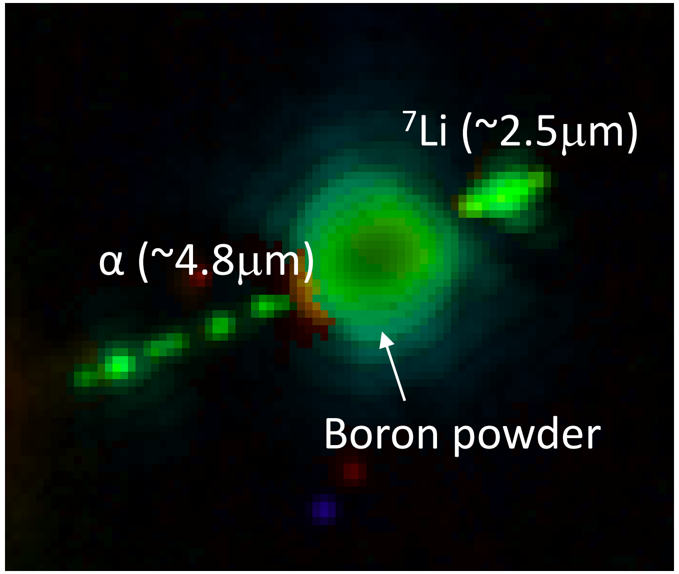
Following nuclear reactions occurred after attenuation

① $n + {}^{10}B \rightarrow \alpha + {}^{7}Li + 2.31MeV$

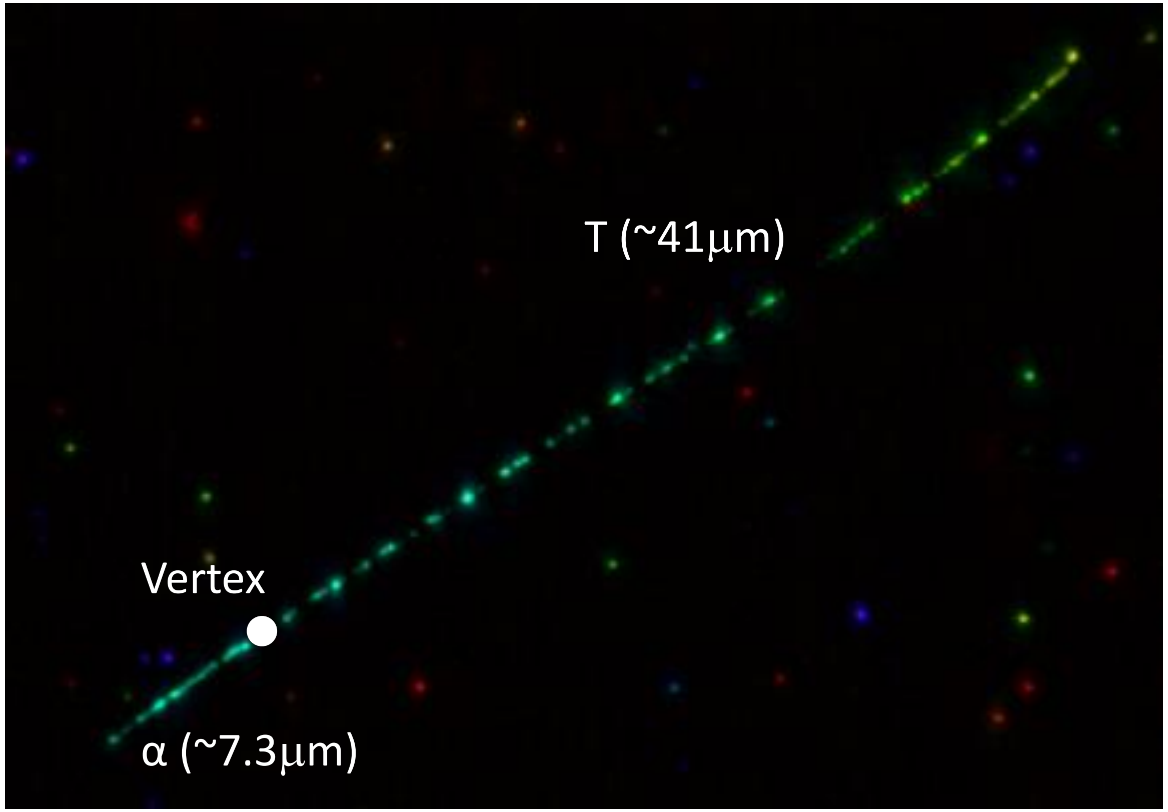
② $n + {}^{6}Li \rightarrow \alpha + T + 4.78MeV$

Detected event in Boron or Lithium contained sample

① n + ^{10}B → α + ^{7}Li + 2.31MeV

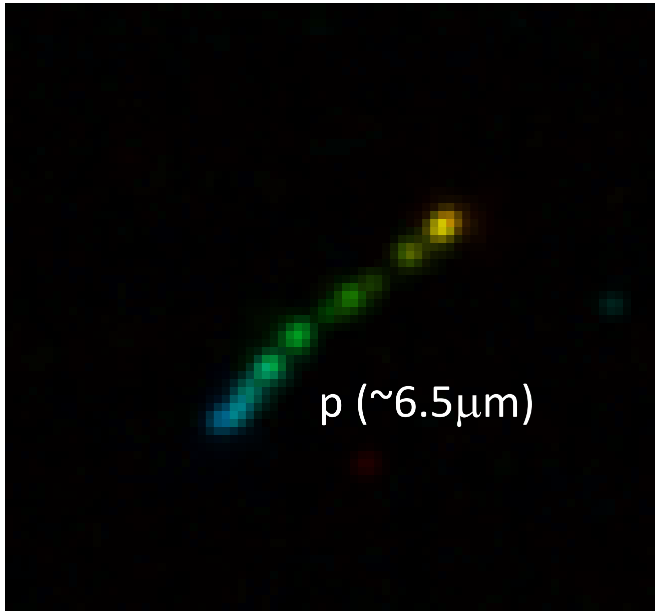


② n + ^{6}Li → α + T + 4.78MeV



Detected event in Boron or Lithium contained sample

③ n + ^{14}N → p + ^{14}C + 0.62MeV

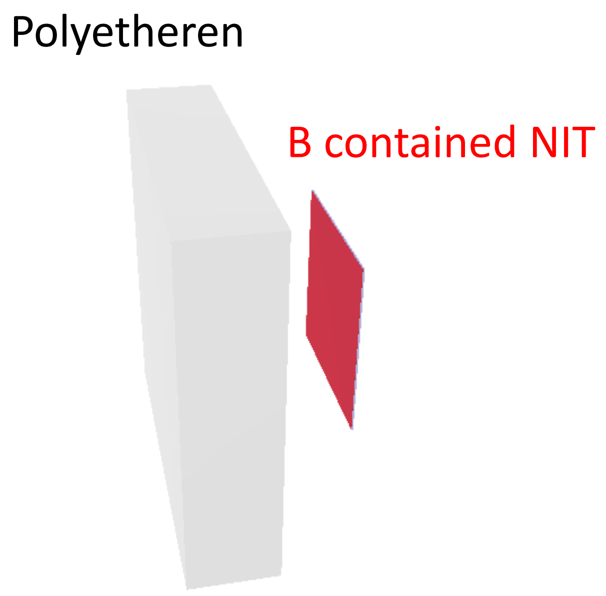


There are too many events around 6.5 μm…

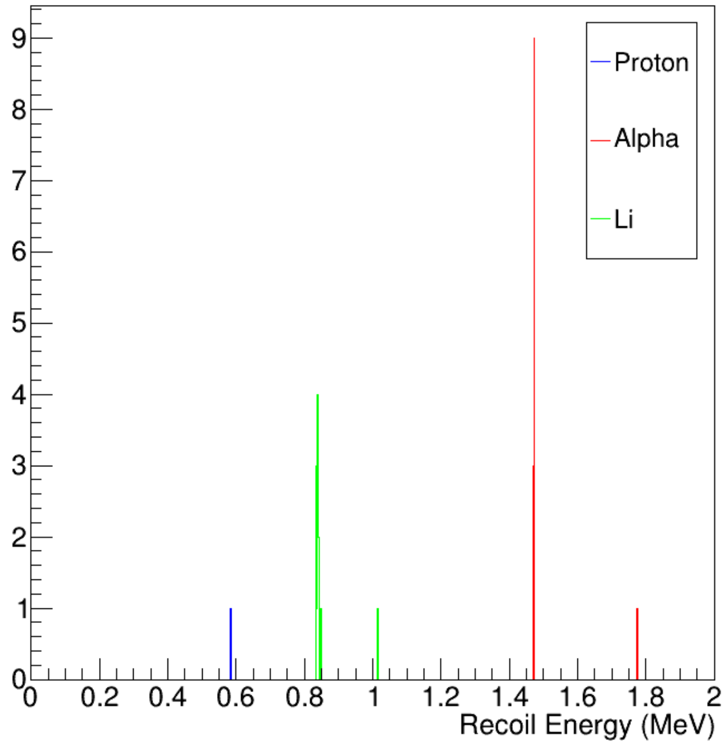
Atom	Mass fraction	Mol / Ag mol		σ @ 1eV
N	3.74%	0.694	^{14}N 99.6%	0.3 barn
B	0.042%	0.01	^{10}B 20%	620 barn

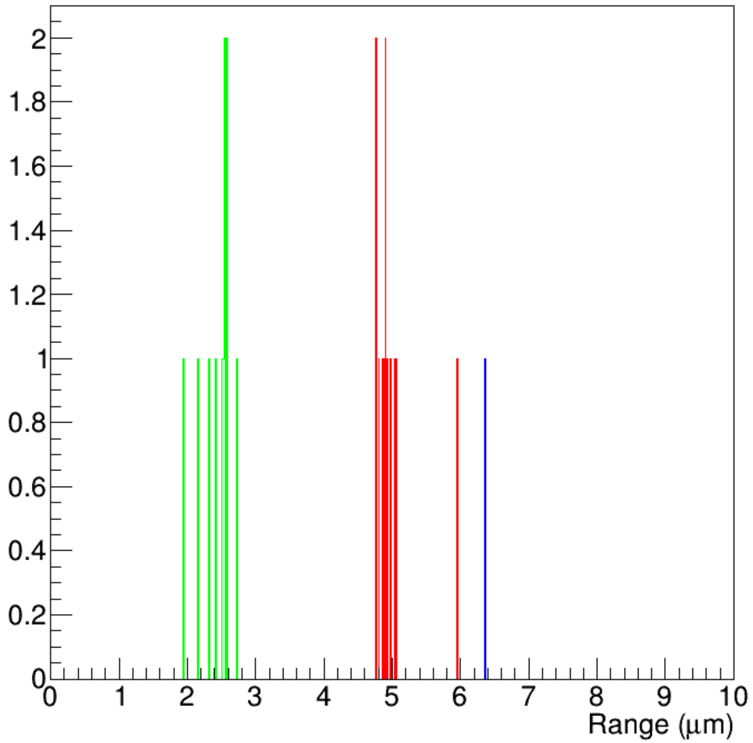
Expectation of event rate:

$$\text{event(N/B)} \sim \frac{0.694}{0.01} \times \frac{0.996}{0.2} \times \frac{0.3}{620} = 0.17$$



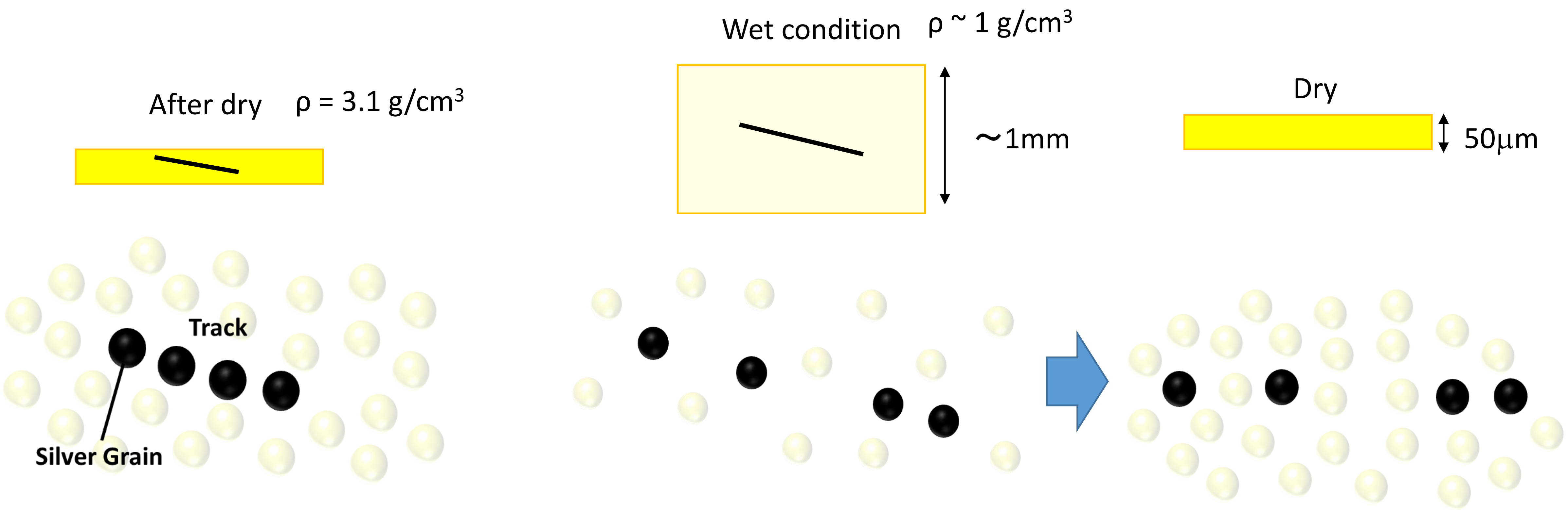
Simulation in B contained NIT





Calibration of α-ray detection

α-ray accumulation in drying condition



If α-ray create tracks at wet condition, tracks become **longer & darker & horizontal** because of

- Low mass density
- Low crystal density
- Shrink less than 1/10 thickness

Alpha-ray Counting Rate

Sample	Condition	Analyzed mass (g)	# of internal event (/g)	# of top α (/cm²)
Run16 ID1 Aside	Dry in Rn free room (shielded)	0.24	4 +- 4	0.9 +- 0.2
Run16 ID1 Bside		0.47	4 +- 3	1.1 +- 0.2
Run16 ID2 Aside	Dry in Rn free room (no-shielded)	0.50	8 +- 4	0.3 +- 0.1
Run16 ID2 Bside		**Not yet scanned**		
Run15 ID3 Aside	Dry in Rn free room + Hall F (35min)	0.27	4 +- 4	0.5 +- 0.2
Run15 ID3 Bside		0.38	3 +- 3	1.1 +- 0.2
Run15 ID5 Aside	Dry with buffer box in Rn free room	0.58	43 +- 9	0.4 +- 0.1
Run13 ID11	N_2 purged dry	0.16	< 14 (90% C.L.)	0.1 +- 0.1
Run13 ID8 (Same as **n-Run2**)	Chamber dry	0.08	650 +- 90	50 +- 3
Run7	Chamber pre-dry and dried in shield	0.44	220 +- 20	11.0 +- 0.5
n-Run1	Granite table	0.65	2200 +- 60	280 +- 6

Tested in CR1 Rn free room (Hall C)

→ 2 orders less than n-Run2 (Chamber dry)

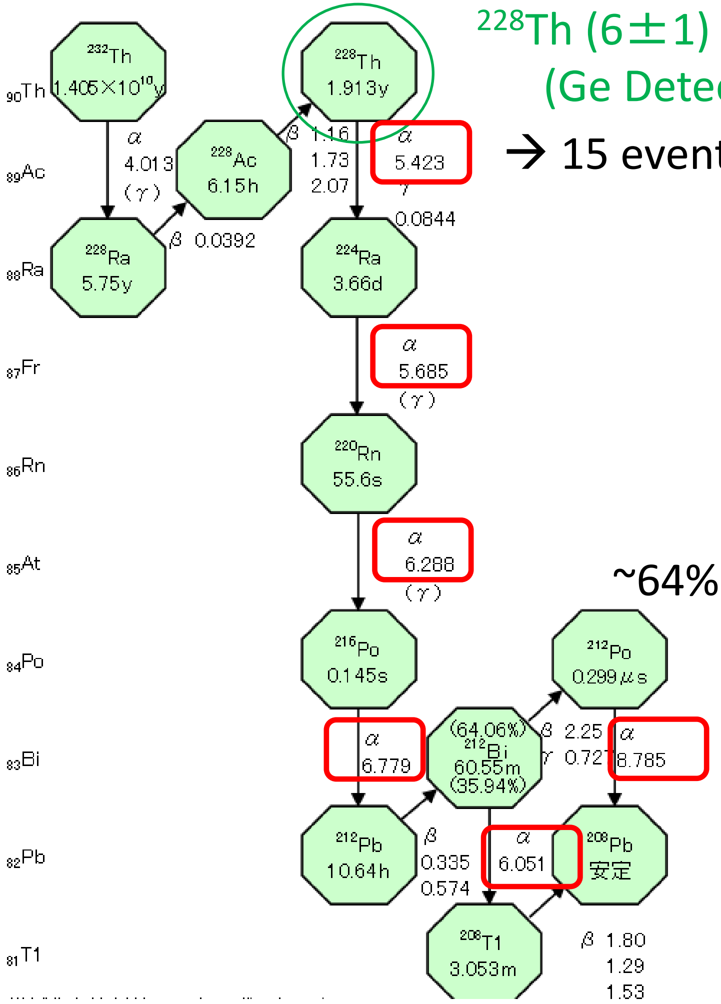
→ 3 orders less than n-Run1

Almost thin & horizontal tracks

Calibration of alpha-ray Energy (E_α) by Th star

Th Decay Chain

Suggested by Valeri

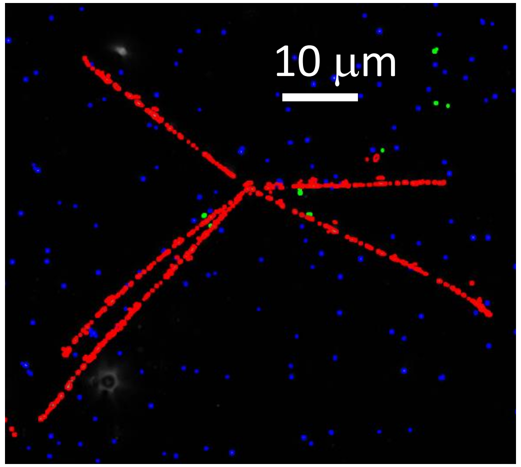


^{228}Th (6±1) mBq/kg
(Ge Detector)

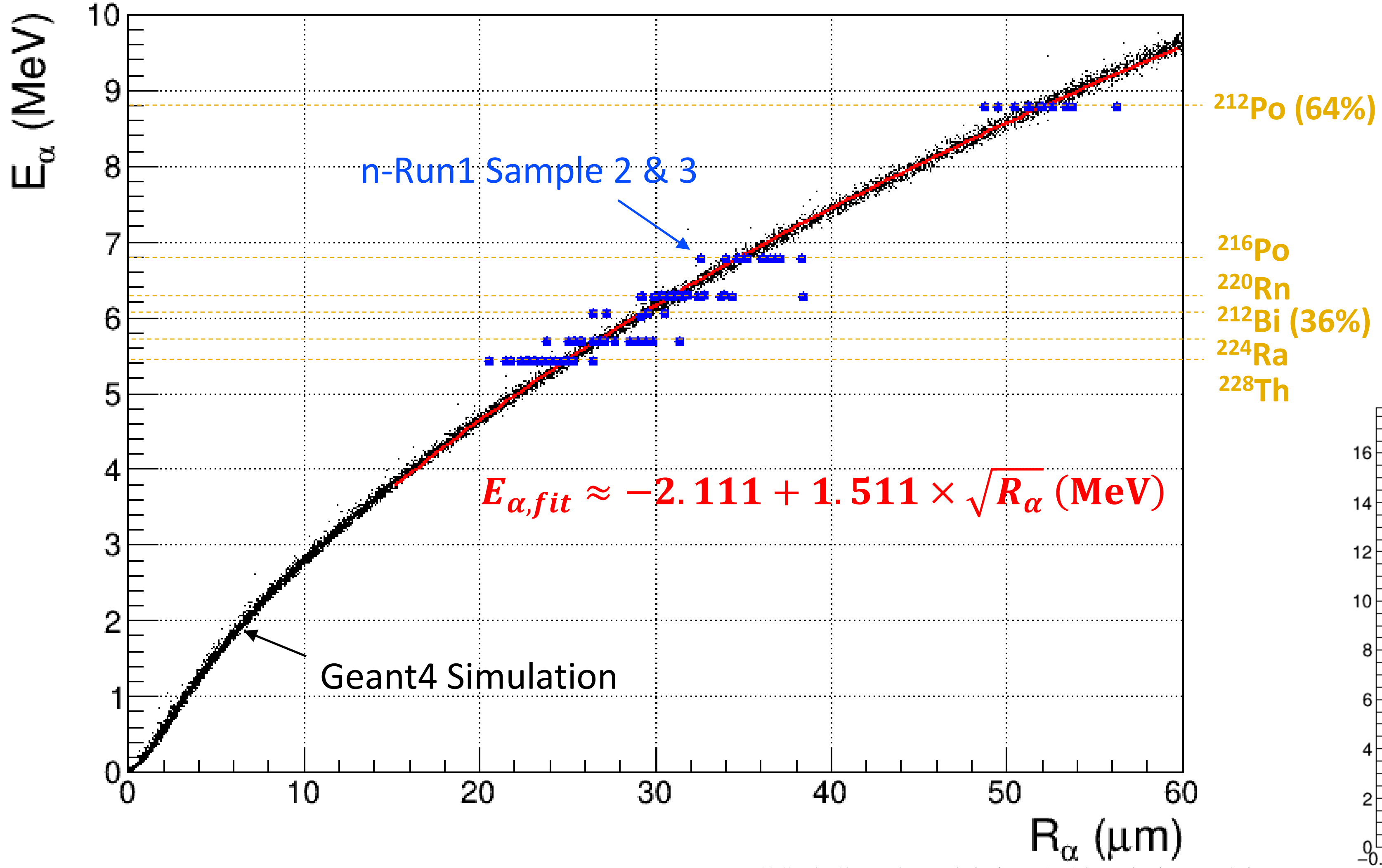
→ 15 events/(g 28day)

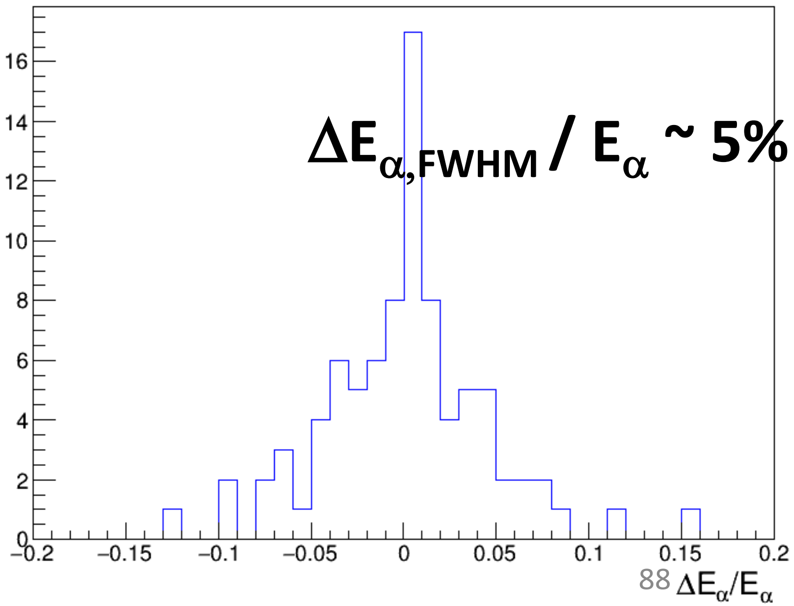
2002年アイソトープ手帳

- Th star event is useful for calibration of run condition, such as brightness or E-R relation
- It should be accumulated during run, and 5 prong event can be identified as ^{228}Th to ^{208}Pb
  - 5.423, 5.685, 6.288, 6.779, [8.785 or 6.051] MeV



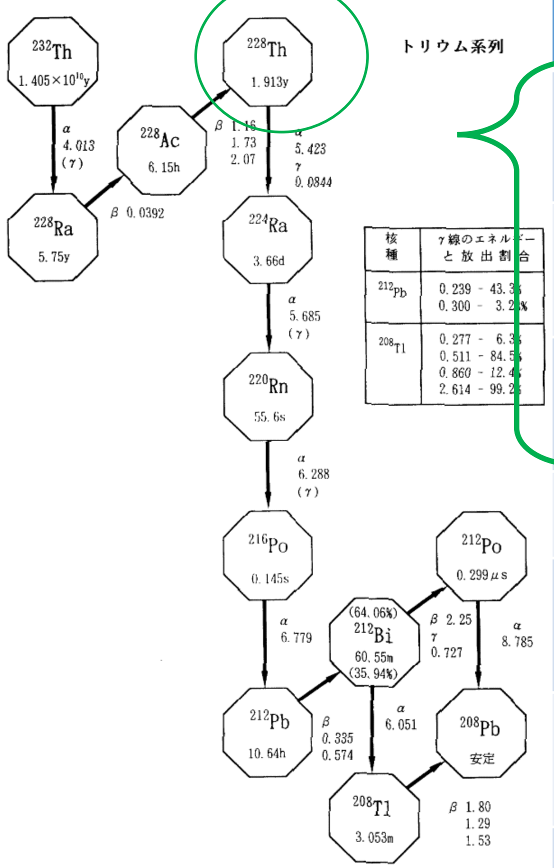
α-energy calibration with Th star



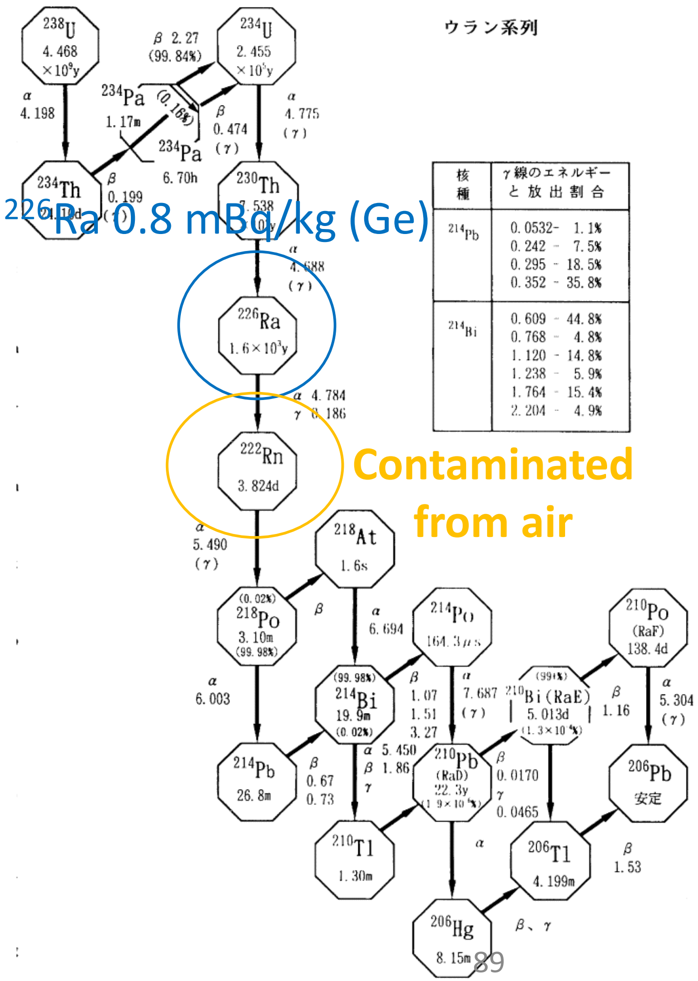


Concerning the excess in MeV region
- Understanding for ^{210}Po contamination -

^{228}Th (6±1) mBq/kg
(Ge Detector)



Multiplicity of α in 1event	Expected number of event (31day * 0.71g)	Number of event from Data
5 (^{228}Th to ^{208}Pb via ^{212}Po)	6.4 (Ge)	5
5 (^{228}Th to ^{208}Pb via ^{208}Tl)	3.6 (Ge)	3
4 (^{224}Ra to ^{208}Pb via ^{212}Po or ^{208}Tl)	~1 (Ge)	1
4 (^{226}Ra to ^{214}Bi)	1.5 (Ge)	2
3 (^{222}Rn to ^{214}Bi)	~0.1 (Ge) +^{222}Rn contaminated	3
1 (^{238}U, ^{234}U, ^{230}Th)	respectively 1.5 (Ge)	Respectively < 3
1 (^{210}Po)	1.5 (Ge) +^{222}Rn contaminated	80?

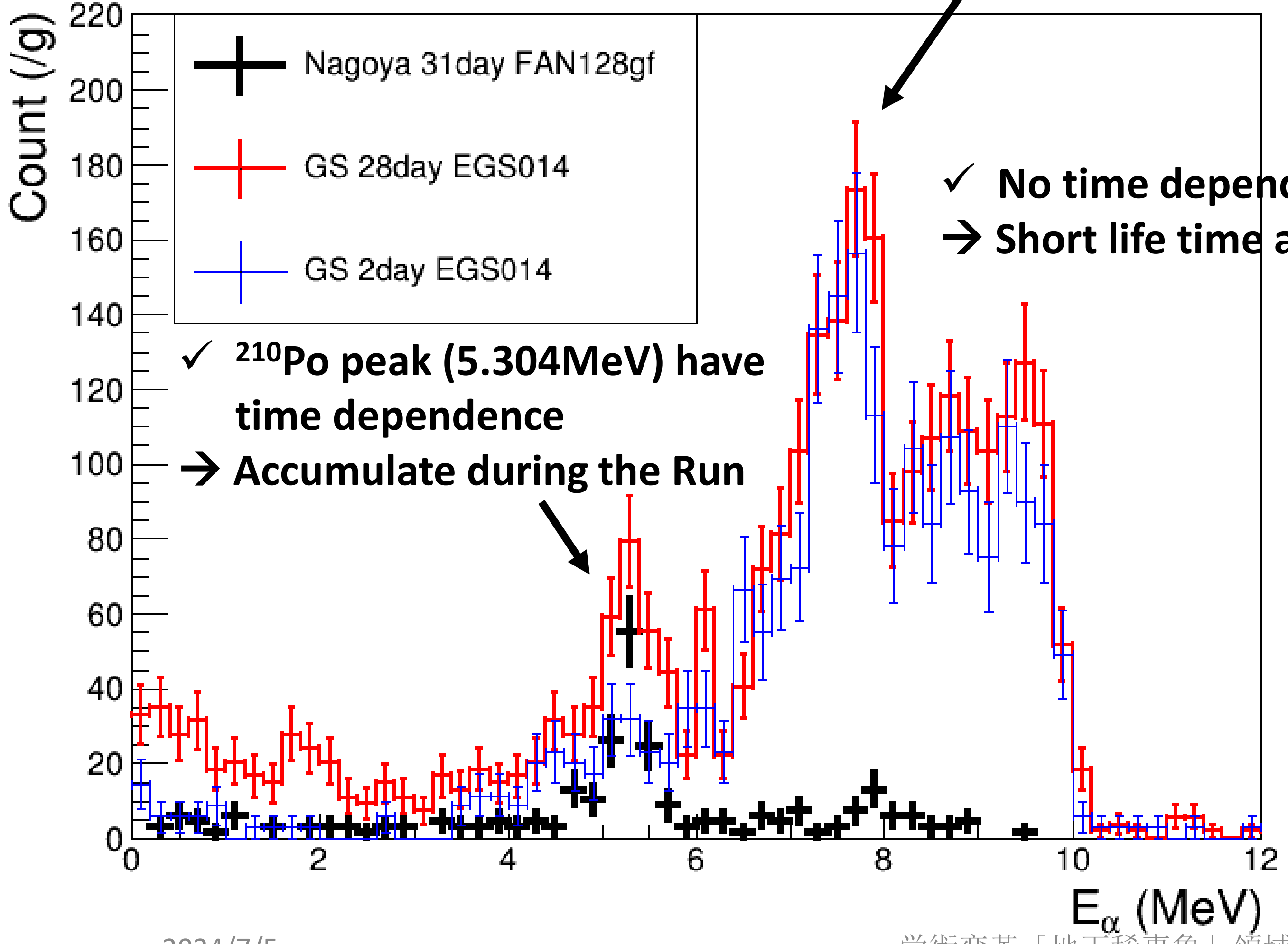


^{226}Ra 0.8 mBq/kg (Ge)

Contaminated from air

Eα Spectrum

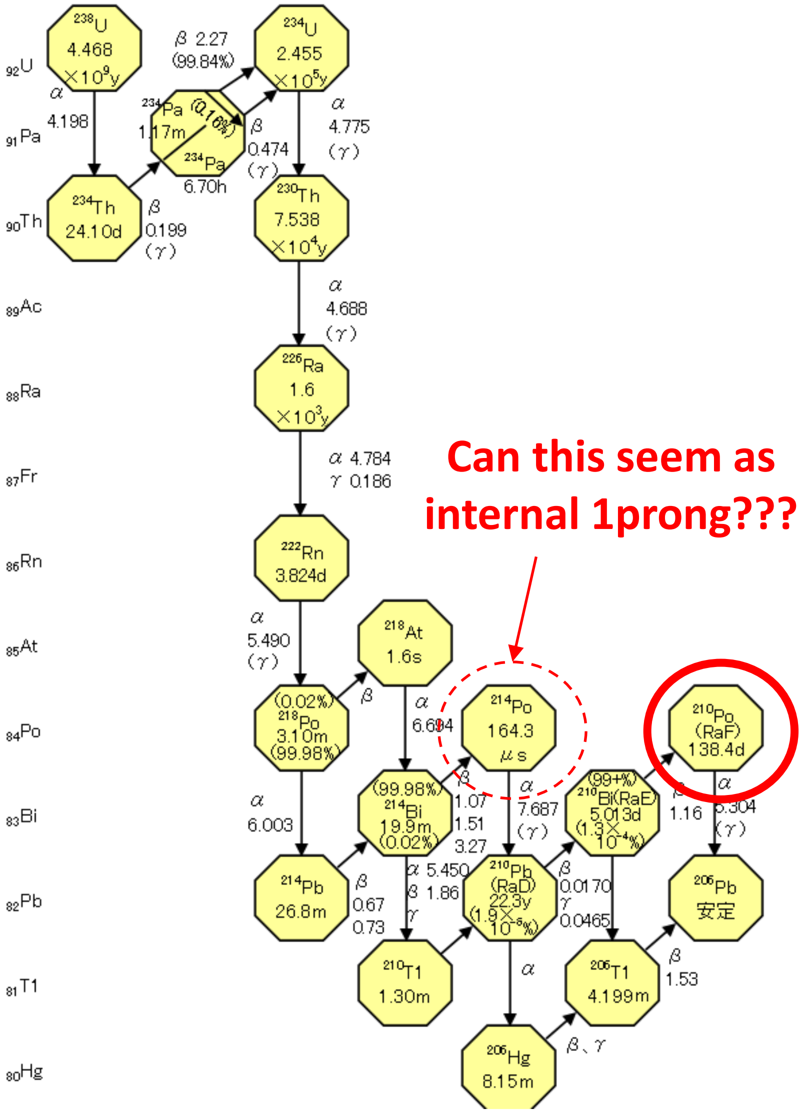
^{214}Po peak (7.687MeV) ???
→ ^{214}Po should be 3prong!



✓ ^{210}Po peak (5.304MeV) have time dependence
→ Accumulate during the Run

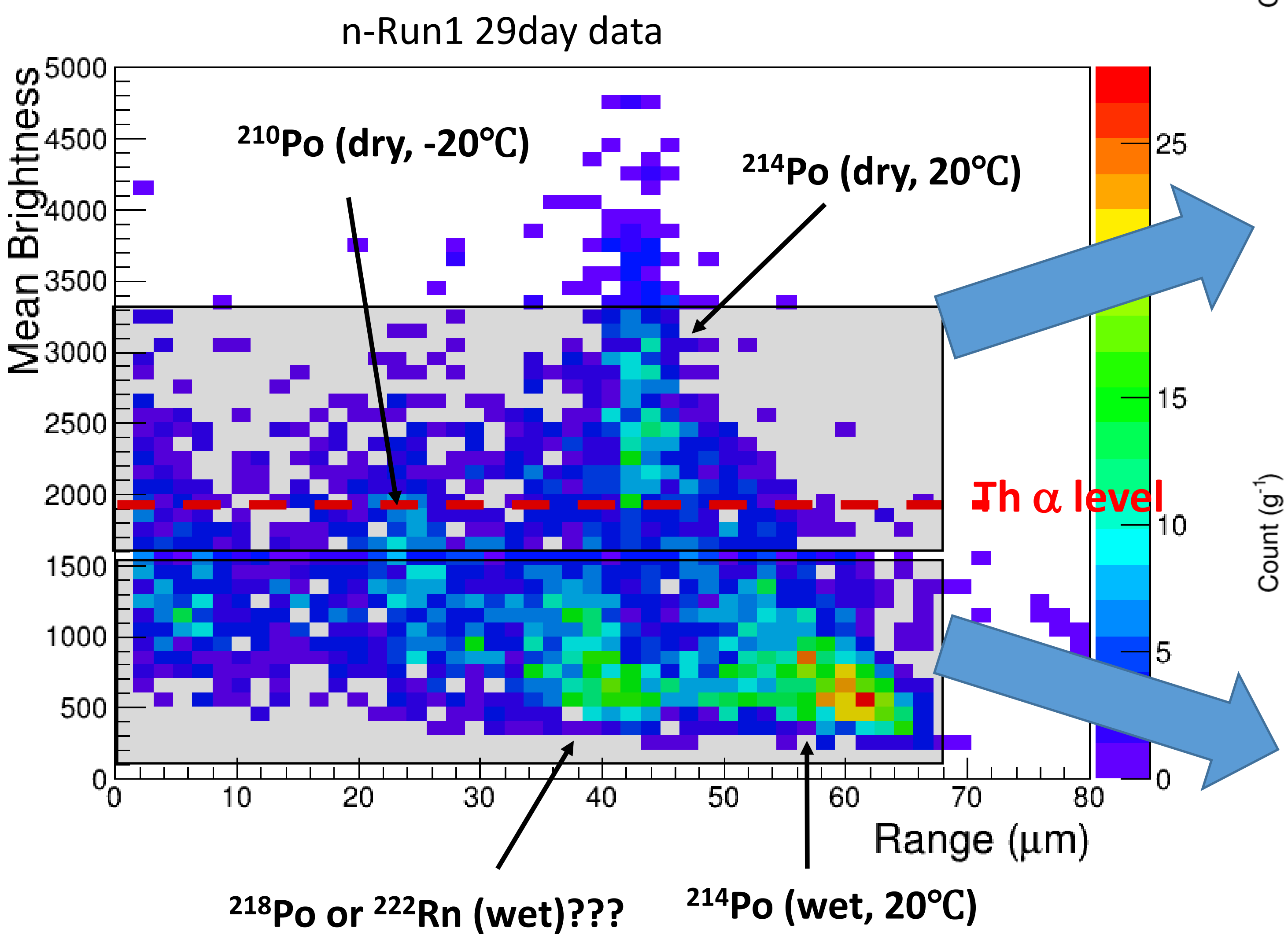
✓ No time dependence excess
→ Short life time alpha decay?

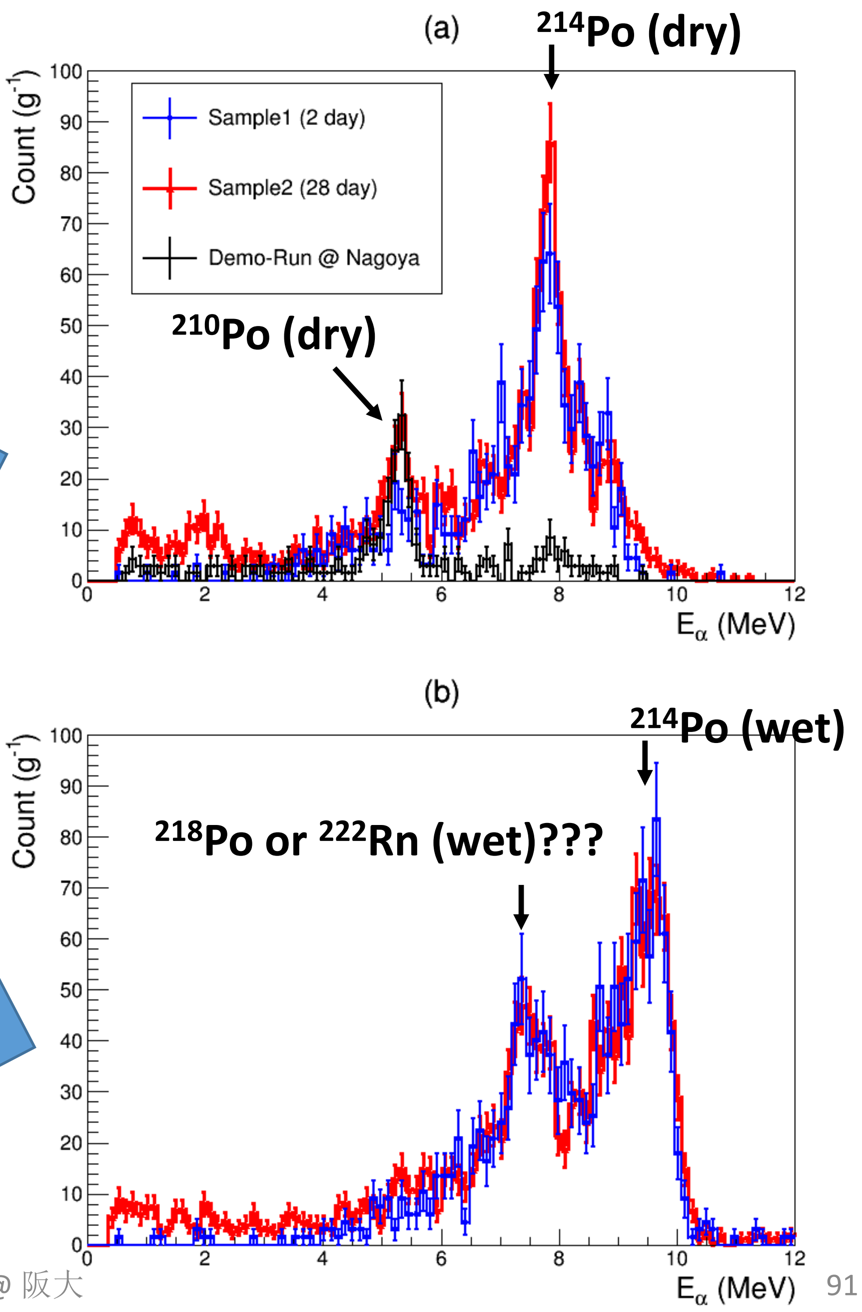
U decay chain

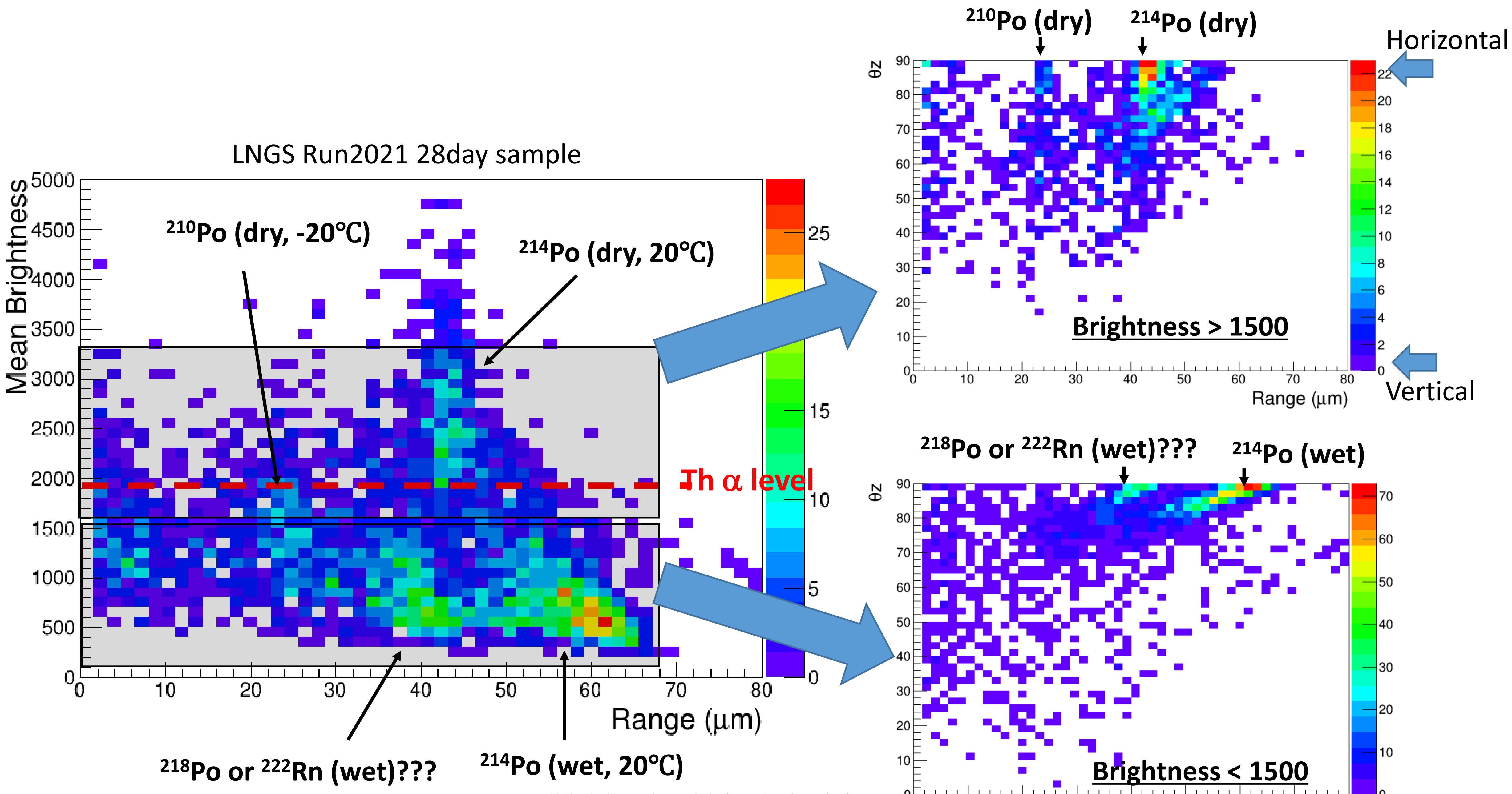


Can this seem as internal 1prong???

2002年アイソトープ手帳


n-Run1 29day data
Mean Brightness
Range (μm)
^{210}Po (dry, -20℃)
^{214}Po (dry, 20℃)
Th α level
^{218}Po or ^{222}Rn (wet)???
^{214}Po (wet, 20℃)


(a)
^{214}Po (dry)
Sample1 (2 day)
Sample2 (28 day)
Demo-Run @ Nagoya
^{210}Po (dry)
Count (g^{-1})
E_α (MeV)
(b)
^{214}Po (wet)
^{218}Po or ^{222}Rn (wet)???
Count (g^{-1})
E_α (MeV)

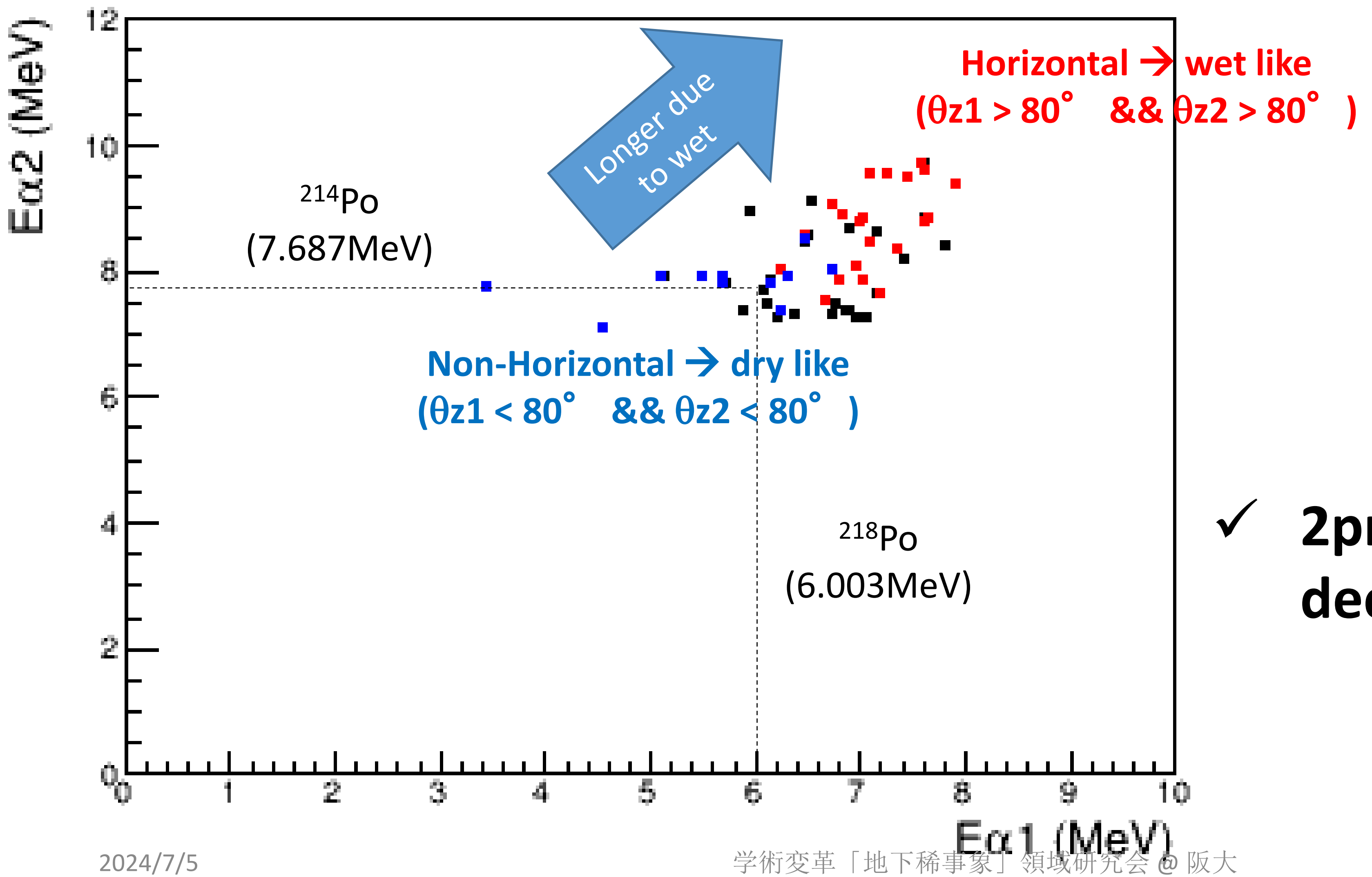

LNGS Run2021 28day sample
Mean Brightness
Range (μm)
^{210}Po (dry, -20℃)
^{214}Po (dry, 20℃)
Th α level
^{218}Po or ^{222}Rn (wet)???
^{214}Po (wet, 20℃)
^{210}Po (dry)
^{214}Po (dry)
Horizontal
Vertical
θz
Brightness > 1500
^{218}Po or ^{222}Rn (wet)???
^{214}Po (wet)
Brightness < 1500

2prong Anomaly

Multiplicity	# of event from 2day sample (/g)	# of event from 28day sample (/g)
3 (^{222}Rn to ^{210}Pb)	**3 +- 3**	**6 +- 3**
2	**72 +- 14**	**83 +- 11**
1 (>30μm ^{214}Po like)	**1770 +- 70**	**2470 +- 60**

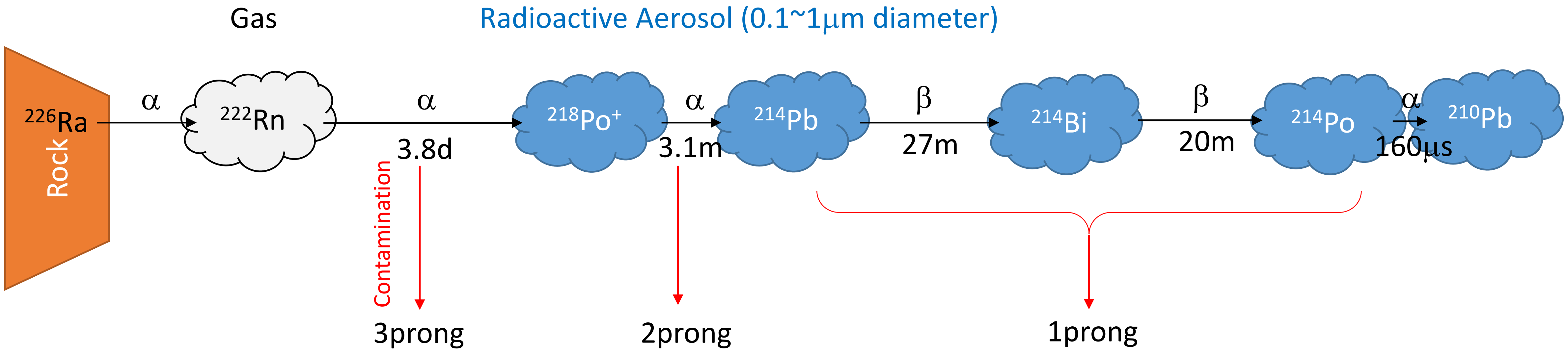
- 3prong is too few if we assume as contamination of ^{222}Rn
- 2prong/1prong ratio ~ 4%
- 2prong cannot be explained by ^{222}Rn contamination
- **Why 2prong detected such too many?**

2prong Analysis



✓ **2prong is likely double α-decay of ^{218}Po and ^{214}Po**

Can these be explained by Radioactive Aerosol?



Why is 3prong too few from data???

✓ ^{218}Po is known to be injected up to a few μm depth in Silicon or Cupper

	2prong/1prong ratio
Rough expectation by contamination of Radioactive Aerosol	**6.6% (from life time ratio)**
Data (GS 2day sample)	**4.1%**
Data (GS 28day sample)	**3.3%**

Intrinsic Activity (Chamber dry & Underground)

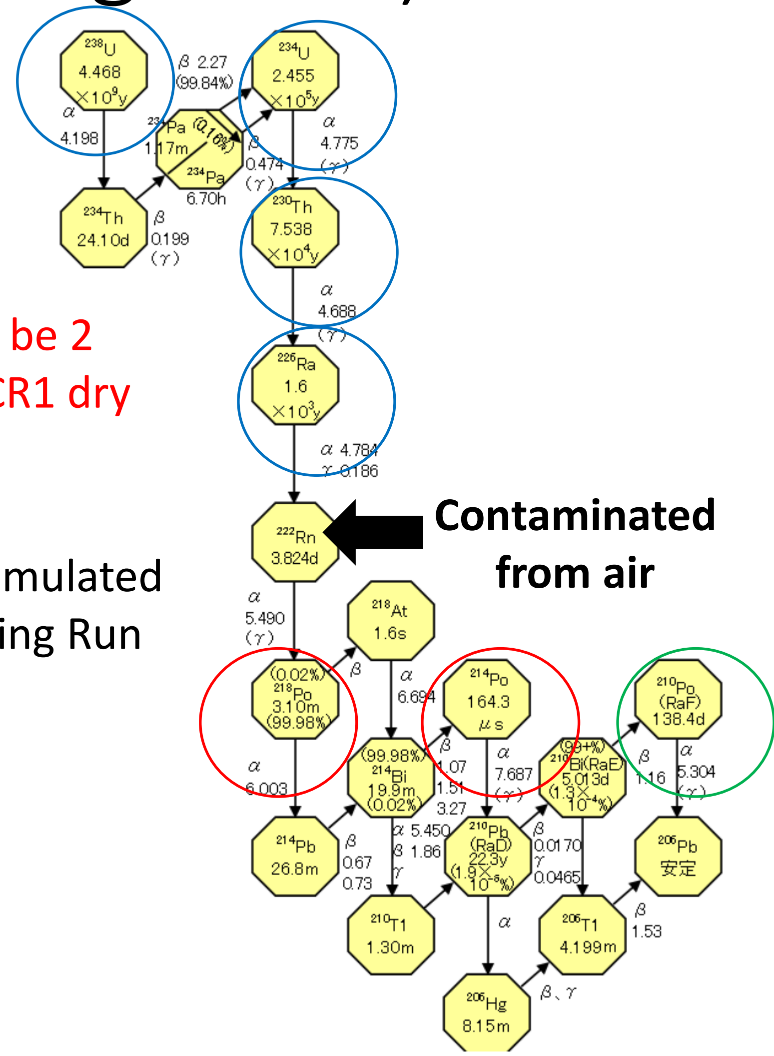
n-Run3 4 month sample

α source	Energy (MeV)	Event Rate (events/g/4month)	Total Activity (mBq/kg)
^{218}Po, ^{214}Po (Rn short decay)	6.003, 7.687	50 +- 12	
^{210}Po (Rn long decay)	5.304	1138 +- 56	10.97 +- 0.54
^{234}U, ^{230}Th, ^{226}Ra	4.775, 4.668, 4.784	103 +- 17	10.0 +-1.6
^{238}U	4.198	33 +- 10	3.2 +- 0.9

Confirmed to be 2 orders less by CR1 dry

Accumulated during Run

These activities are almost 3.3 mBq/kg respectively



According to Fabio's paper (Astropart. Phys. A **80**, 16 (2016)),
^{226}Ra activity is 2.4 mBq/(1kg high deionized gelatin) → 0.8 mBq/(1kg NIT)

Because of radiative equilibrium, ^{234}U, ^{230}Th, ^{226}Ra, ^{238}U should be same activity

内部バックグラウンド の測定
[Ge測定@LNGS]

	P-6405 (従来型)	P-6406 (高脱イオン化)	AgBr･I (from KBr)	AgBr･I (from NaBr)
Sample weight (measuring time)	119.6 g (568107 sec : ~7 days))	492.13 g (825660 sec : ~10 days)	148.9 g (1657796 sec : ~ 20 days)	302.6 g (1158142 sec: ~13 days)
Type of Ge detector	GePV	GeMPI2	GeCris	GeCris
Ra-228 [mBq/kg]	30 +- 10	< 1.3	< 52	< 12
Th-228 [mBq/kg]	50 +- 10	20 +- 2	< 3.8	< 5.5
Ra-226 [mBq/kg]	19 +- 7	2.4 +- 0.6	< 25	< 8.9
Th-234 [mBq/kg]	< 340	< 79	< 3300	< 220
Pa-234m [mBq/kg]	< 640	< 44	< 2000	< 590
U-235 [mBq/kg]	< 19	< 1.8	< 35	< 9.2
K-40 [mBq/kg]	1400 +- 200	< 8.7	98000 +- 9000	50 +- 20
Cs-137 [mBq/kg]	< 4.5	2.2 +- 0.5	< 22	< 6.3
Co-60 [mBq/kg]	< 2.9	-	< 22	-
Ag-108m [mBq/kg]	-	-	67 +- 9	49.3 +- 3.9
Ag-110m [mBq/kg]	-	-	4540+- 230	2960 +- 150

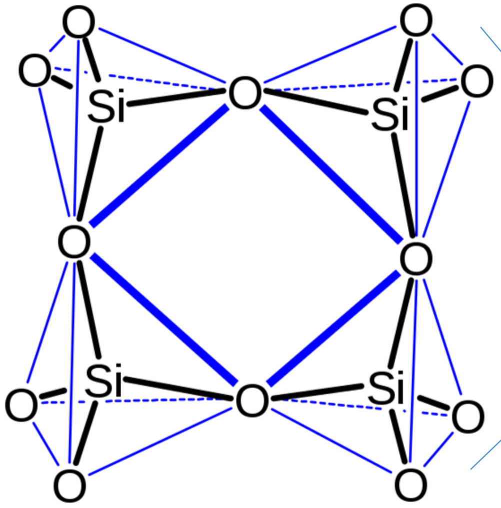
1/100 以下

1/2000 以下

現状、この組み合わせが最も低バックグラウンド

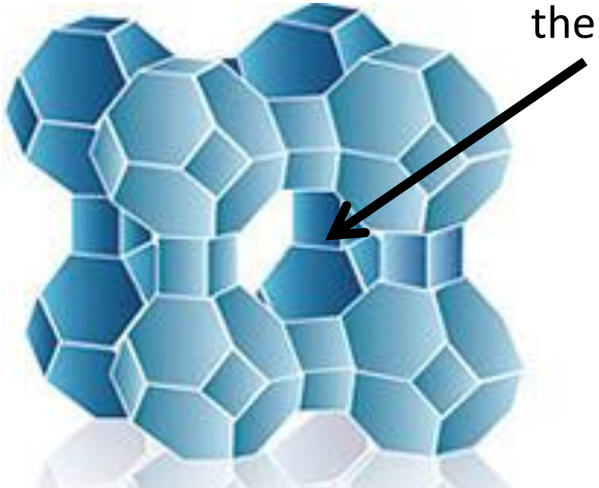
Radon filtering

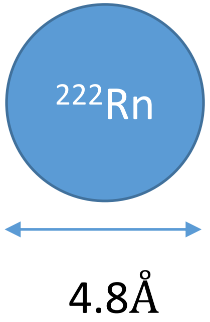
Zeolite (Molecular Sieve) as Radon Filter



Zeolite

This hole can capture the large atom





Hole Size: 3Å(K ion), 4Å(Na ion), 5Å(Ca ion)

→ 3Å and 4Å types are usually used for water absorption in some gases

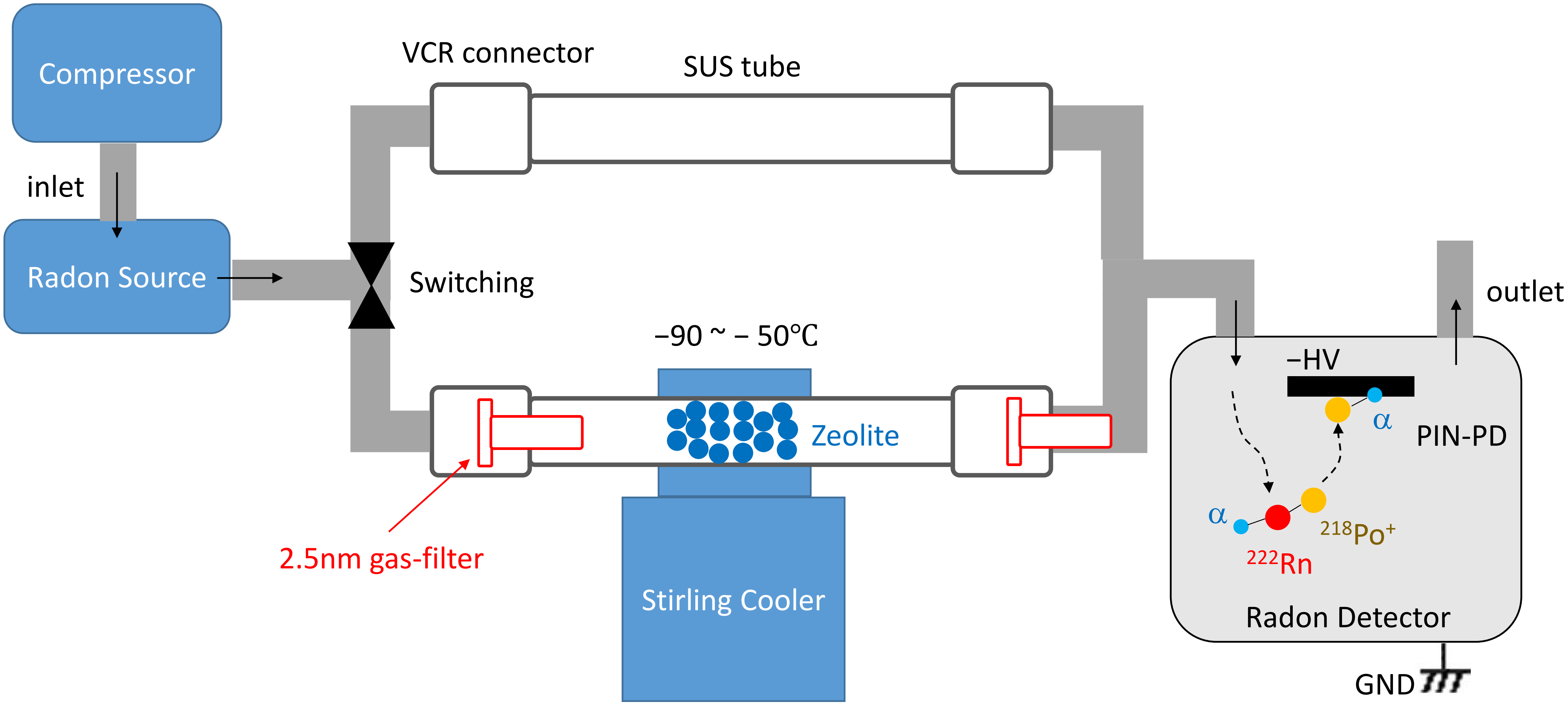
→ 5Å type can be used for Radon absorption at low temperature (-90 ~ -50 °C)

→ However, commercial products cannot be used because they emit radon from themselves.

→ **Dr. Ogawa, an expert who has participated in SK and XMASS experiments**, provided us a very clean zeolite

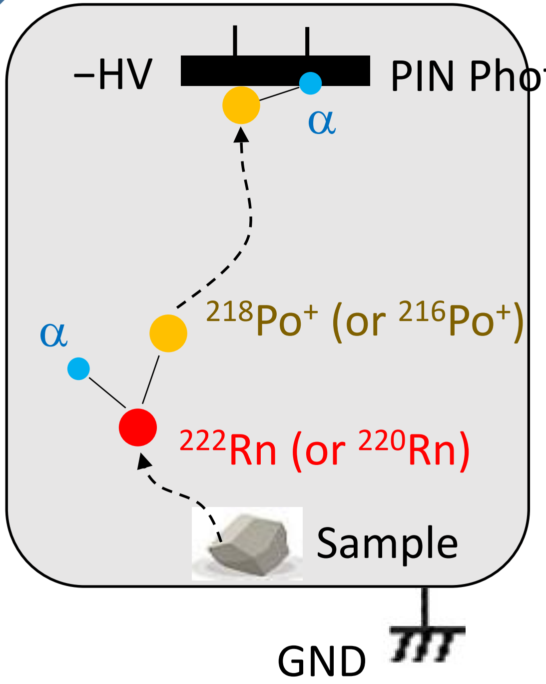
Wikipedia

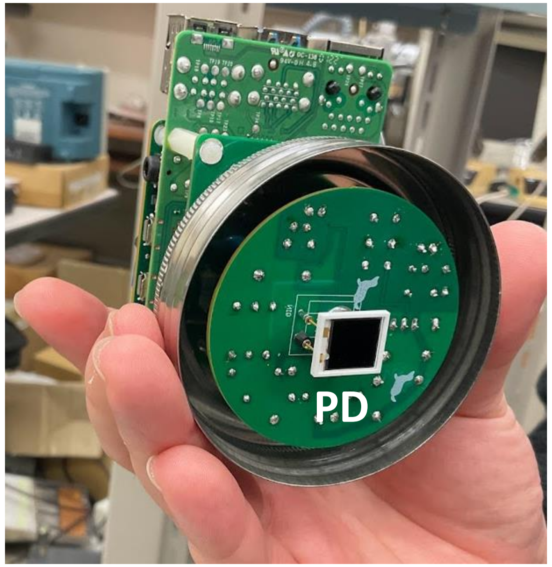
Concept of Radon Filtering System



Portable Radon Detector Kit

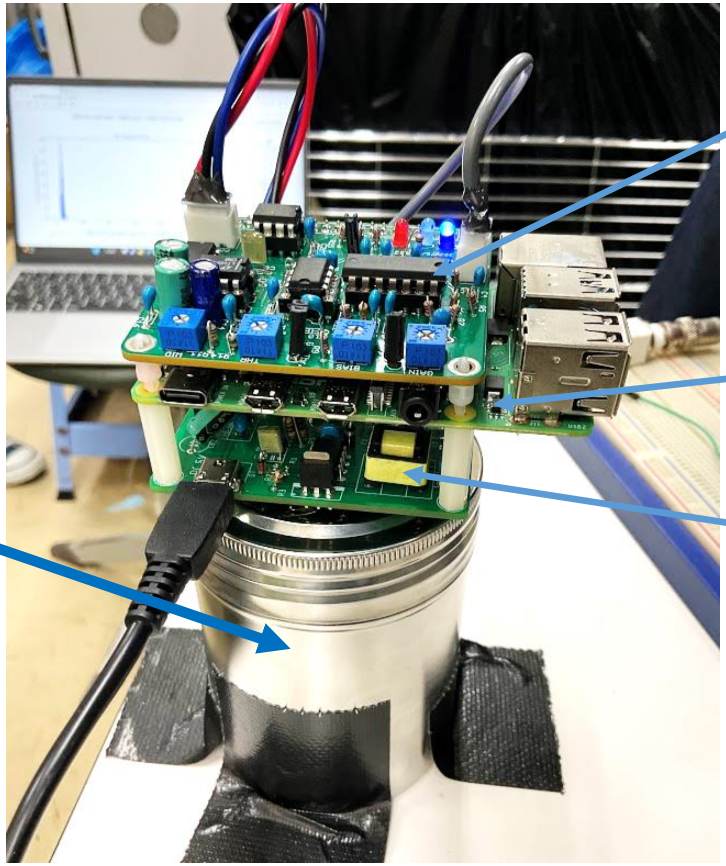
Electrostatic collection method





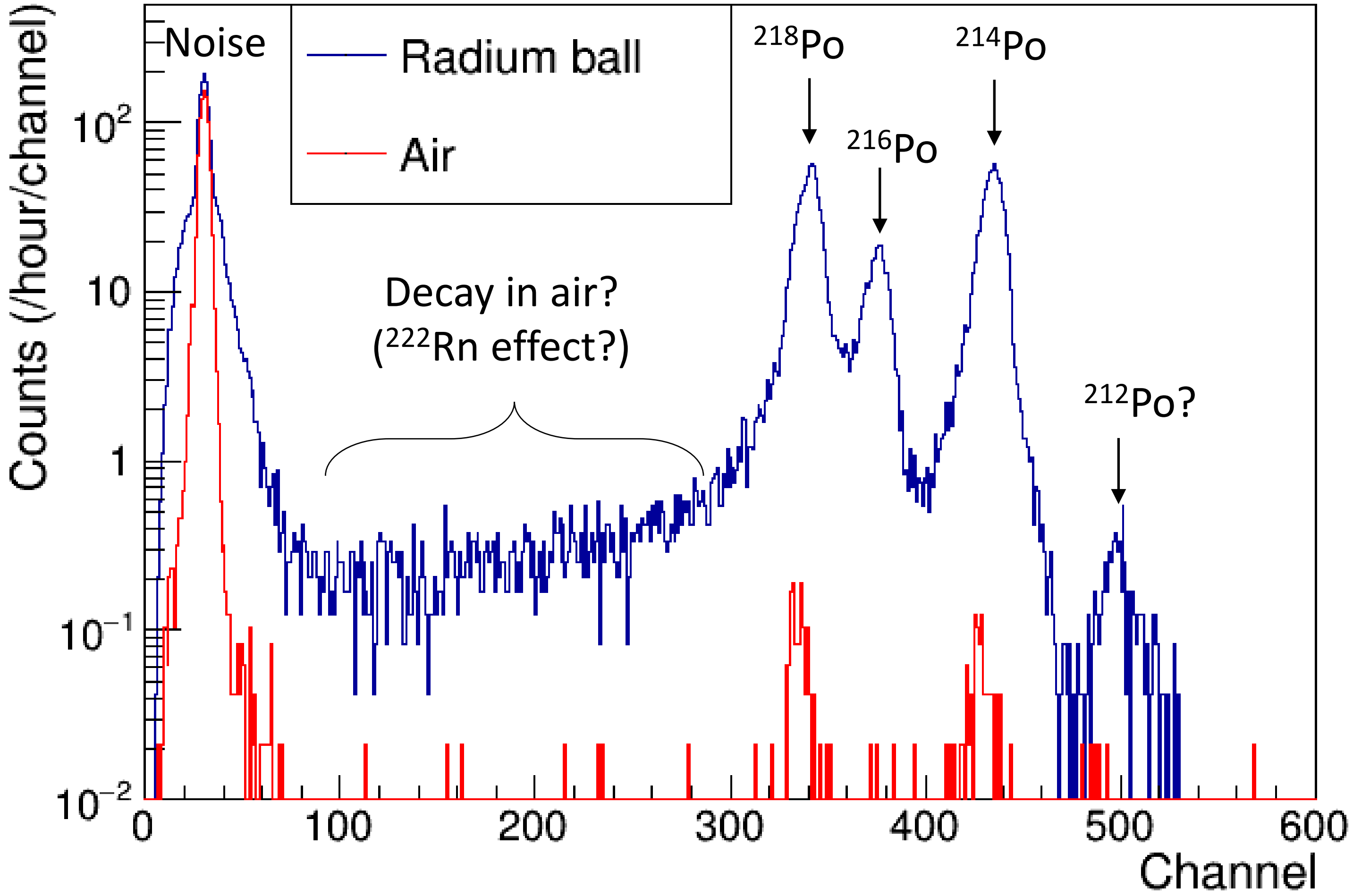
Daughters of ^{222}Rn and ^{220}Rn can be detected
→ ^{218}Po, ^{214}Po (U series)
→ ^{216}Po, ^{212}Bi, ^{212}Po (Th series)

Dr. Miake (Tsukuba Univ.) provided us the detection techniques for radon daughters



✓ 2 detectors were constructed

Radon Measurement Test

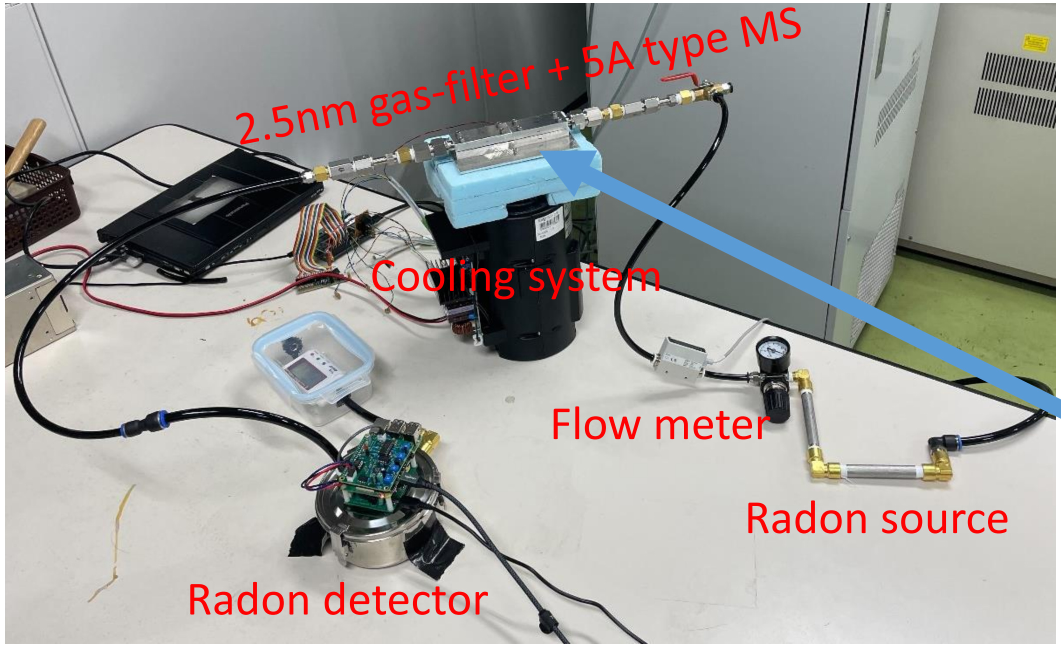


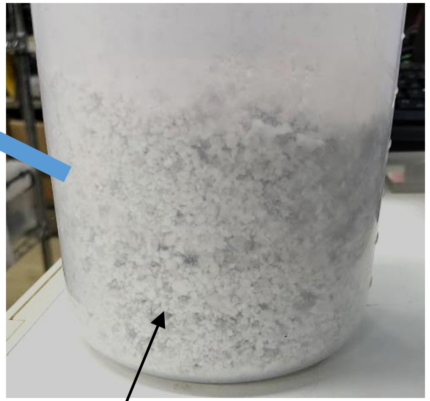
Current Status

We are now evaluating NAS clean (2.5nm semiconductor gas-filter)

→ Next step, install the Zeolite

- Remove small fragments with 0.6mm Sieve
- Fill zeolite to SUS tube
- N2 purge
- Baking @ 200 – 300 °C to remove water





fragments with
a few mm size

<u>Evaluation items</u>

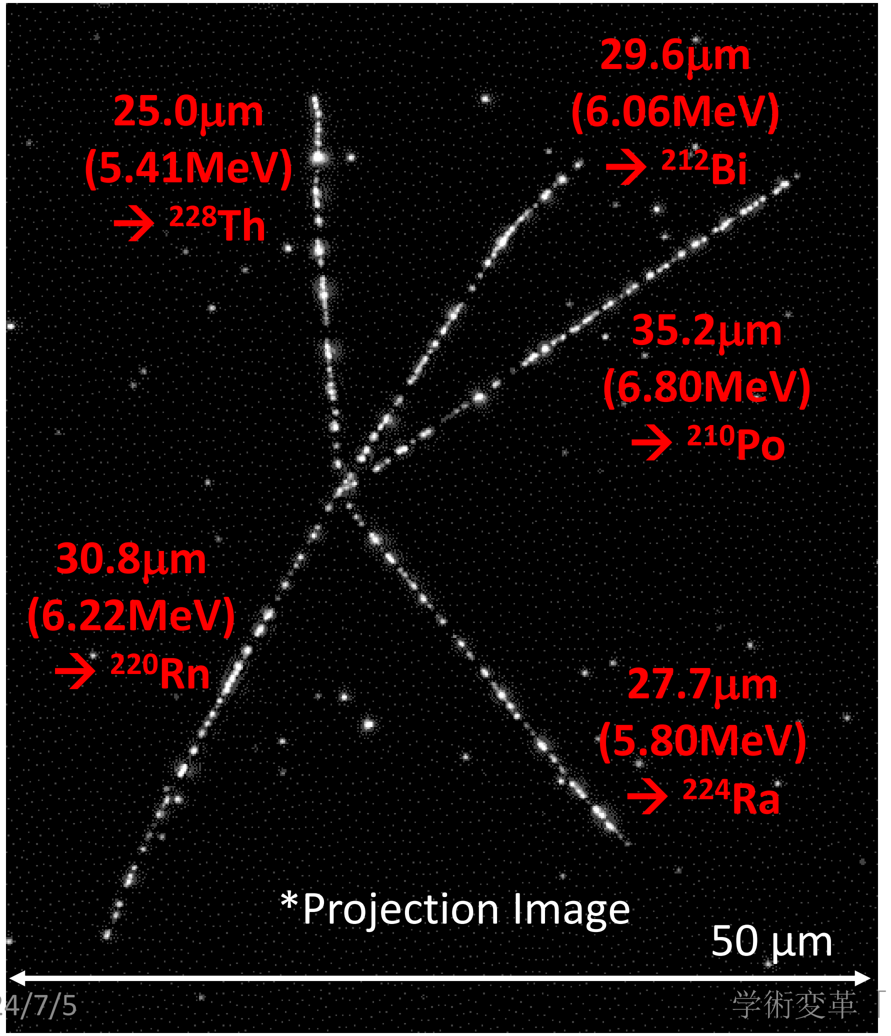
- ➢ Radon filtering efficiency
- ➢ Air flow rate
- ➢ Expiry date

After performance evaluation
→ Transport Rn filtering system to LNGS

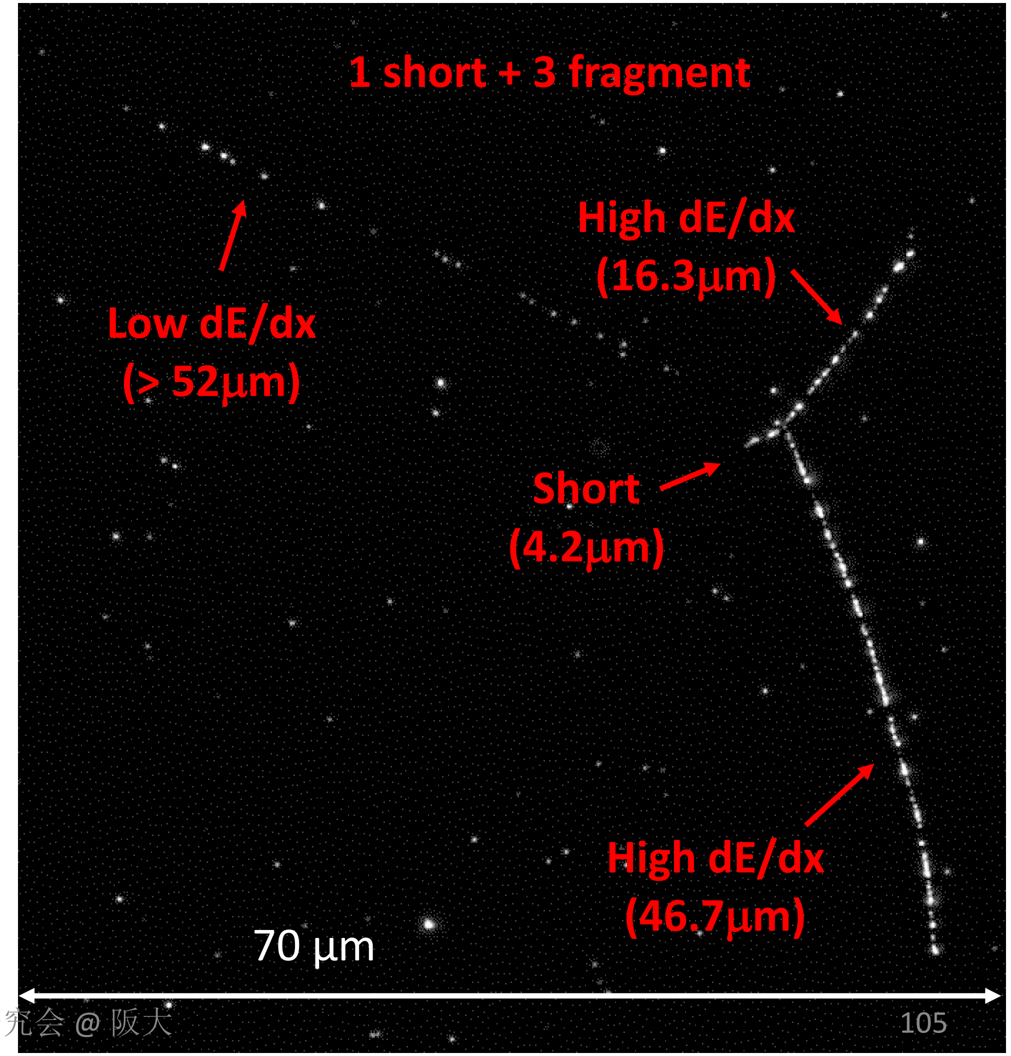
Multi-prong Neutron Inelastic Scattering

Actual Multi-prong Events from n-Run1

Th Star event
(5-prong α-decay from ^{228}Th to ^{208}Pb)

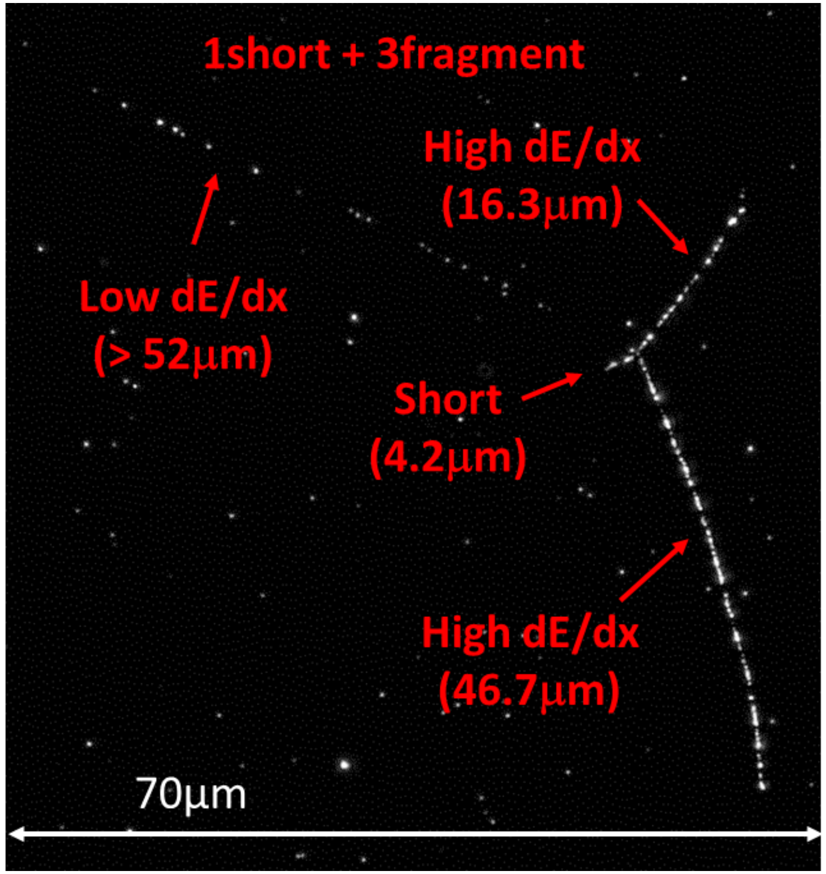


Deep Inelastic Scattering by neutron



Multi-prong Analysis

We found 17 events/(0.65g*28day) with multiplicity >= 3 after excluding α-decay

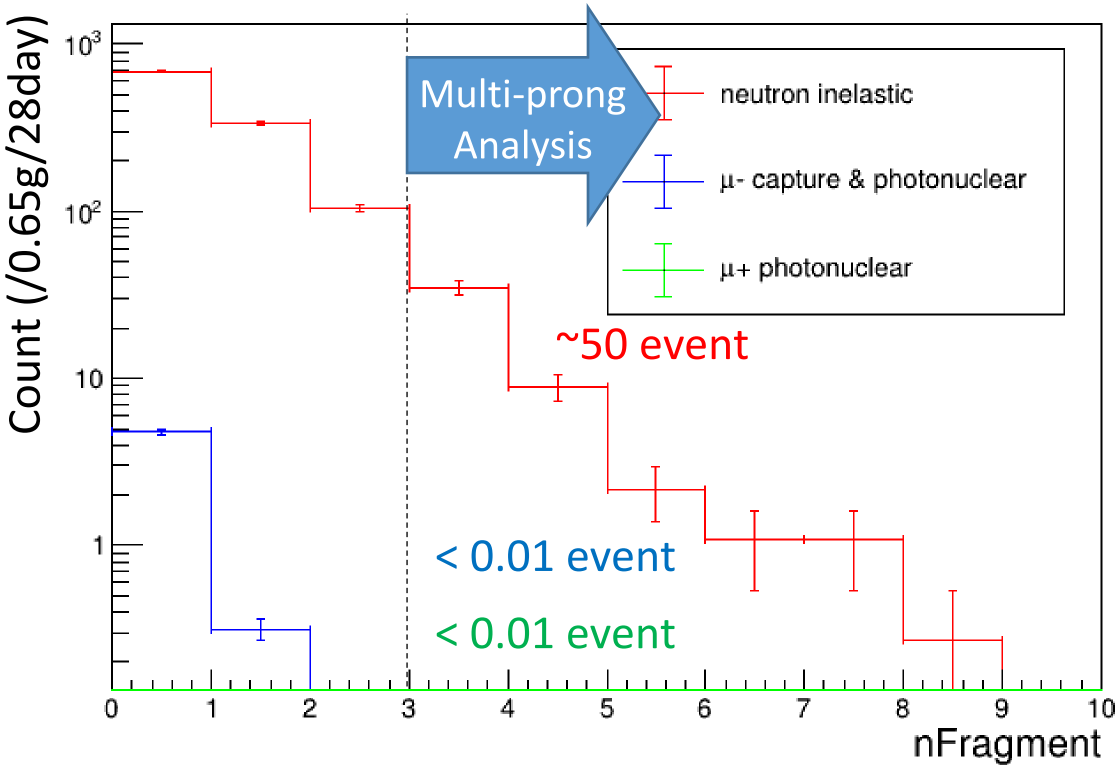


*Projection Image

Candidates

- μ spallation (photo-Nuclear)
- μ^- capture ($p + \mu^- \rightarrow n + \nu_\mu$: CC weak interaction)
  $N(Z, A) + \mu^- \rightarrow N'(Z-1, A)^* + \nu_\mu$
  $N'(Z-1, A)^* \rightarrow N'(Z-??, A-??) + (n + p + \alpha \ldots)$
- Neutron inelastic scattering

Rough estimation of the number of fragments by Geant4

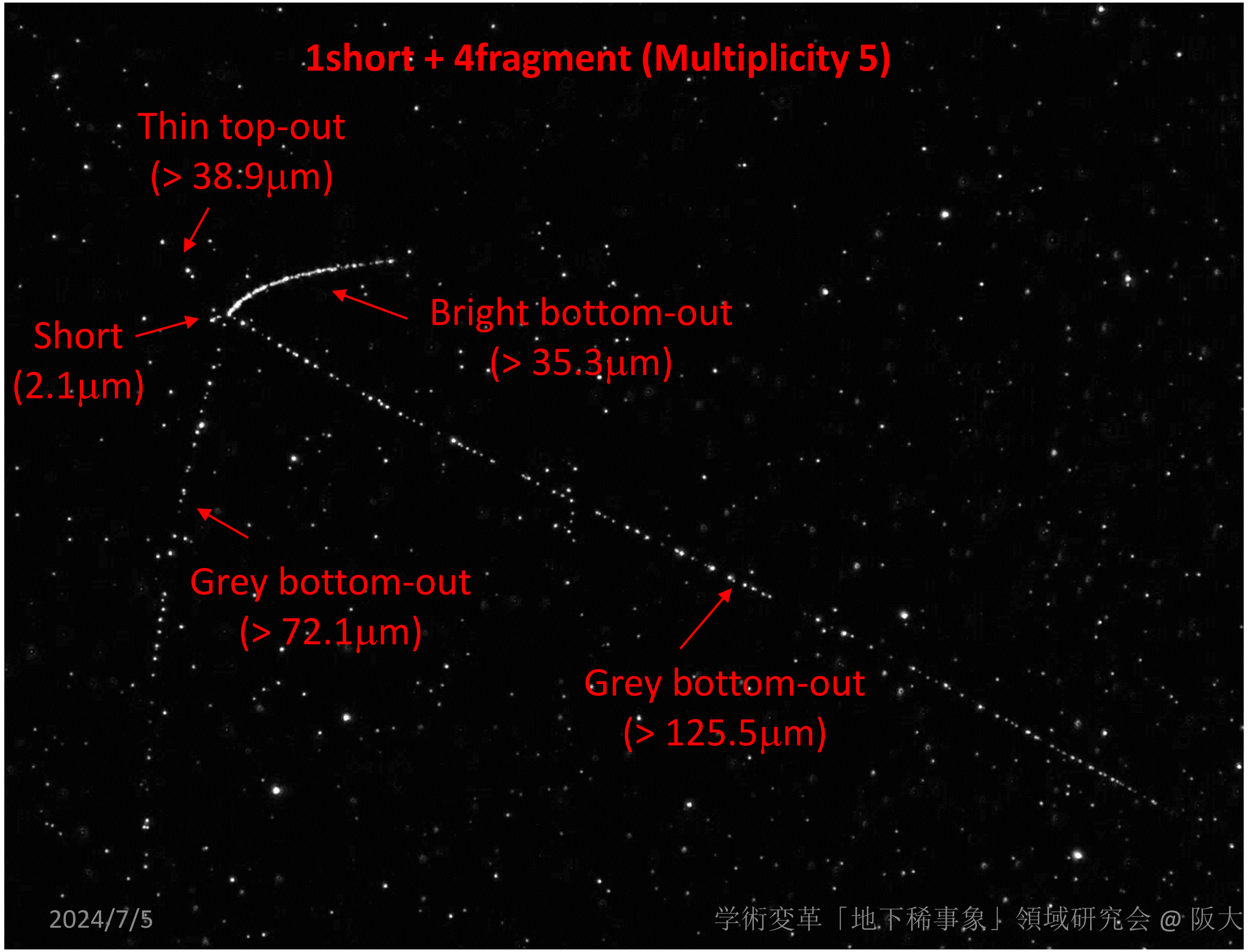


More likely neutron inelastic scattering!

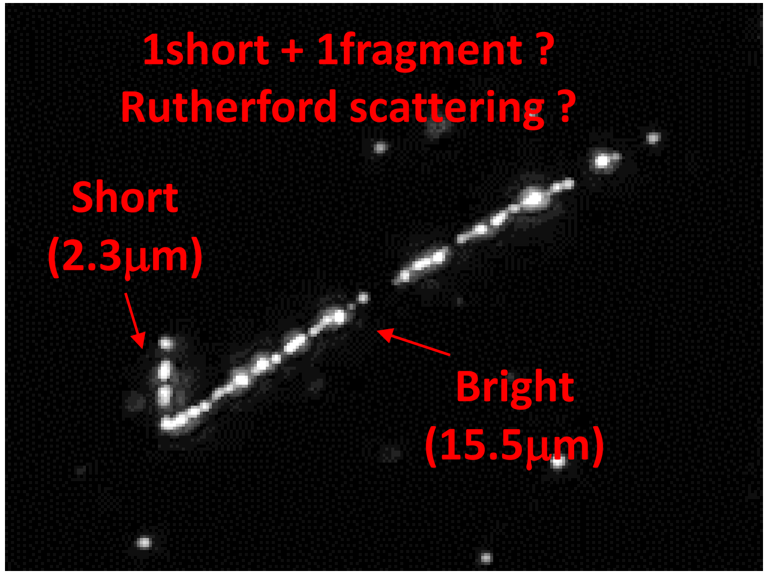
Interesting Multi-prong Event from 28day sample

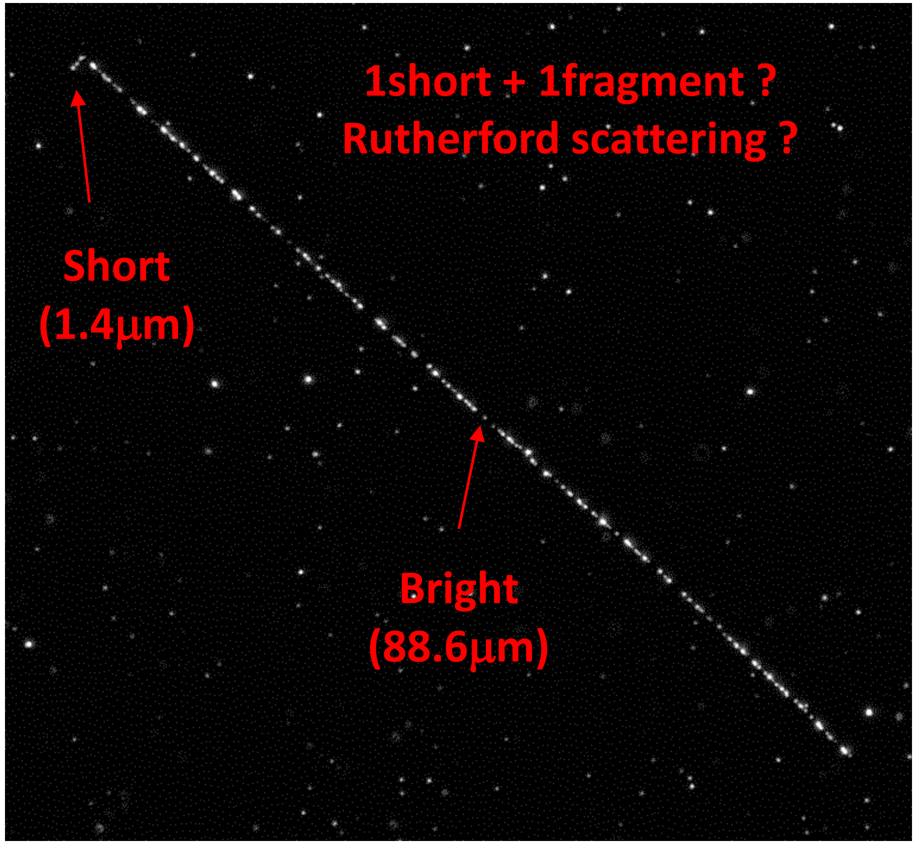
Projected Image

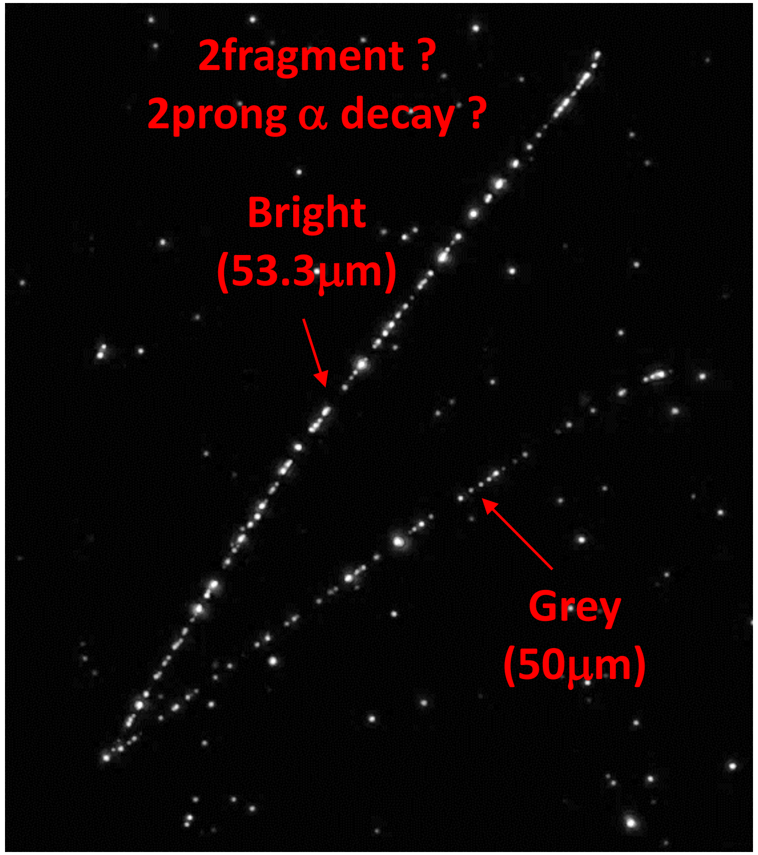
What is this ???



Kink and 2prong Events are Excluded in Current Analysis



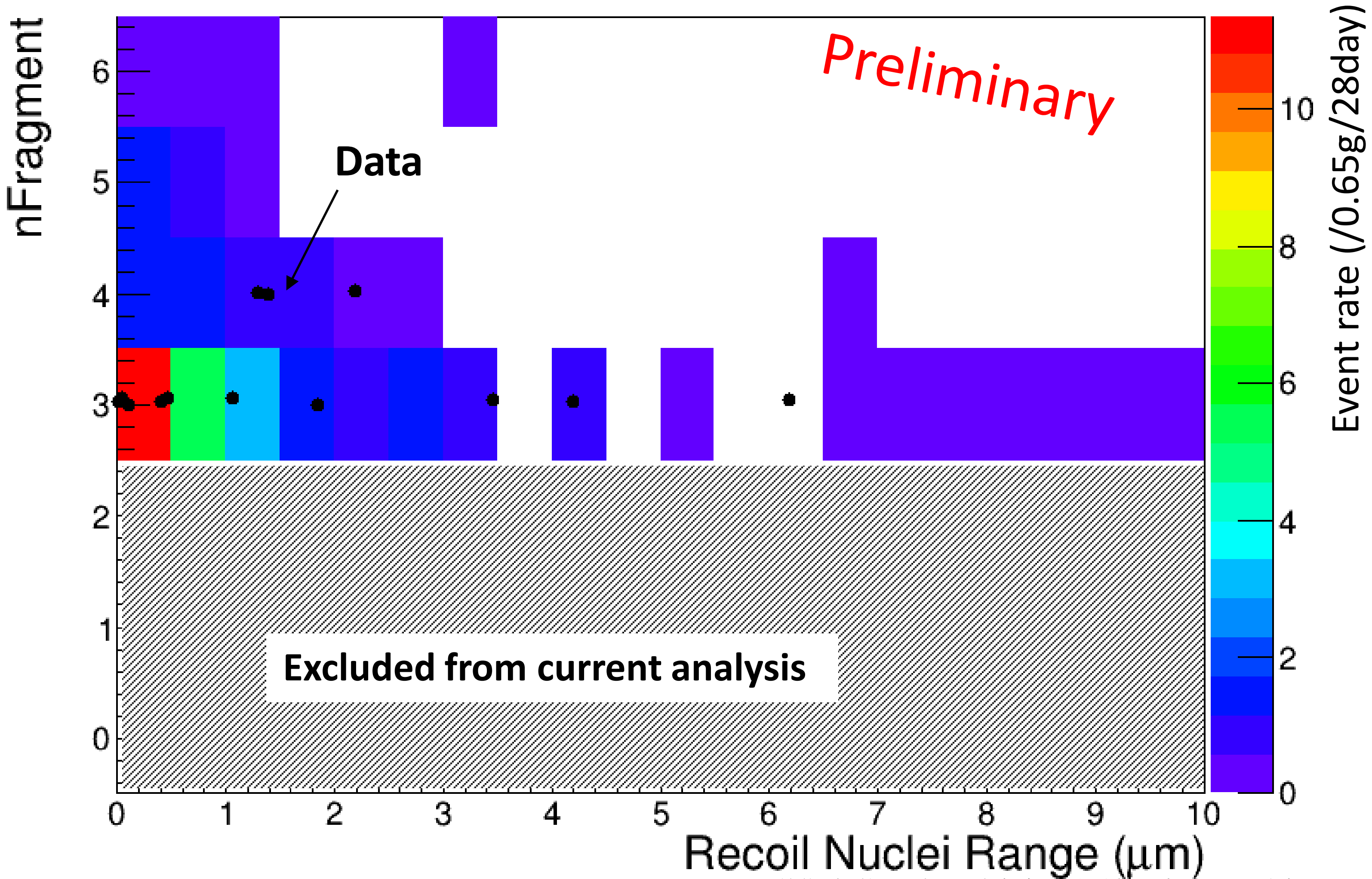




- Although I feel there are many kink and 2prong events, they are rejected in current analysis because they might be Rutherford scattering or 2prong of α-ray
- They might be included after reduction of MeV excess

Topological Analysis of Neutron Inelastic Scattering

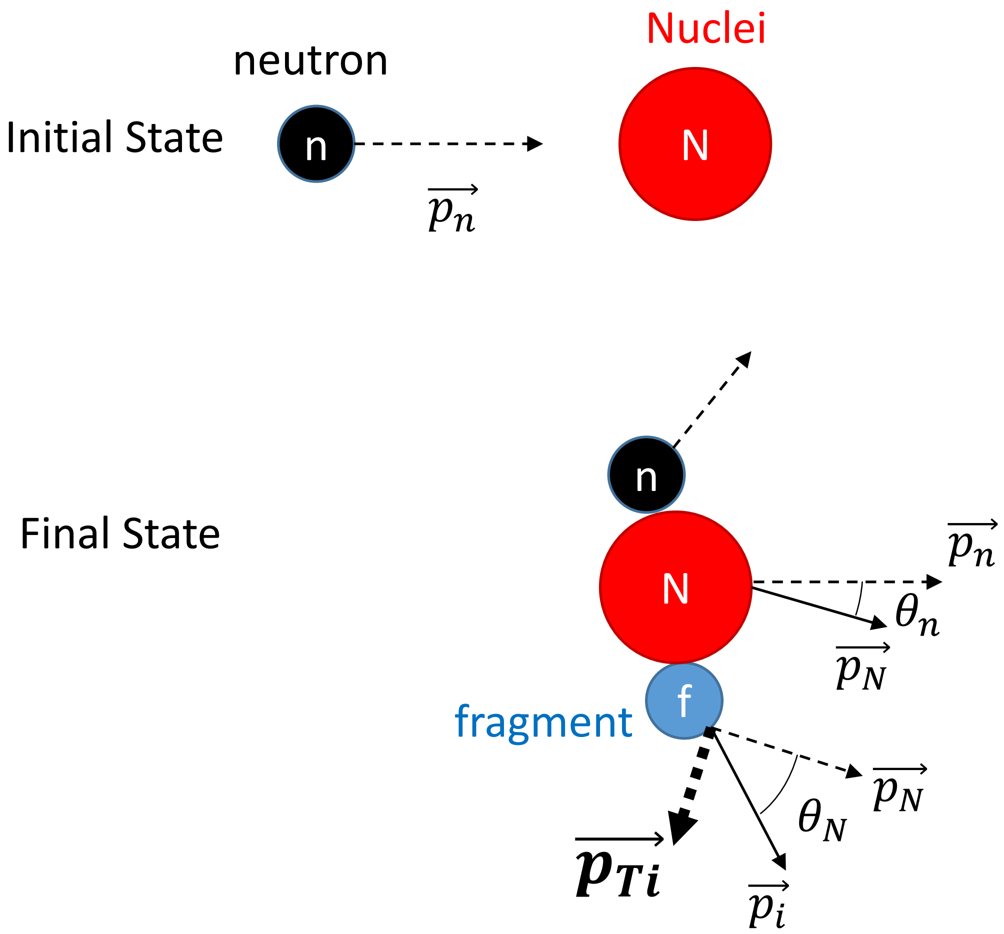
Comparison of Simulation and Data



- ✓ **Data is topologically similar to Simulation?**
  - ➢ Geant4 probably has big systematic errors for nFragment because there are no data.

- ☐ For more detail kinematical analysis, Fragment's Angle, Range (Energy), and Brightness (dE/dx) should be used.

Kinematics of Neutron Inelastic Scattering (Suggested by Gianni and Sato-san)



$\overrightarrow{p_n}$: Neutron initial momentum
$\overrightarrow{p_N}$: Recoil Nuclei momentum
$\overrightarrow{p_i}$: Fragment momentum

If assume $\overrightarrow{p_N} \approx \overrightarrow{p_n}$, transverse momentum ($p_T$) balance can be calculated

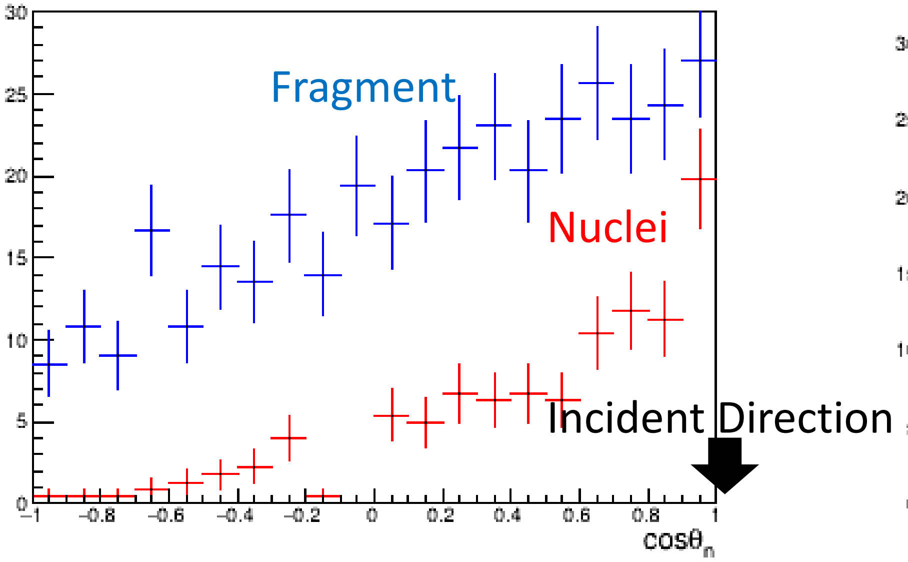
Transverse momentum (p_T) should be a good kinematical parameter because it is Lorenz invariant!

$$\boldsymbol{p_T\ Vector\ Sum} \equiv \left|\sum_i \overrightarrow{\boldsymbol{p_{Ti}}}\right|$$

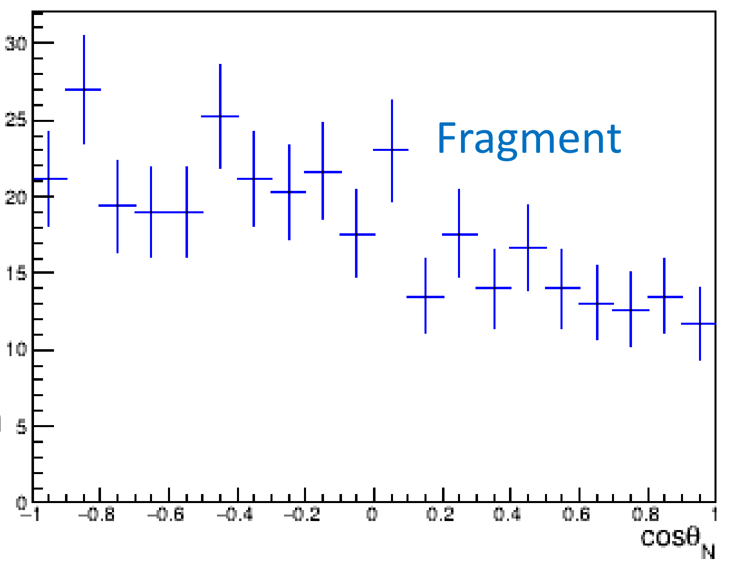
- Trying to calculate kinematical parameter on the MC-base…

- p_T Vector Sum cannot be 0 due to:
    1. Cannot include p_T of recoil Nuclei
    2. Missing p_T by neutron

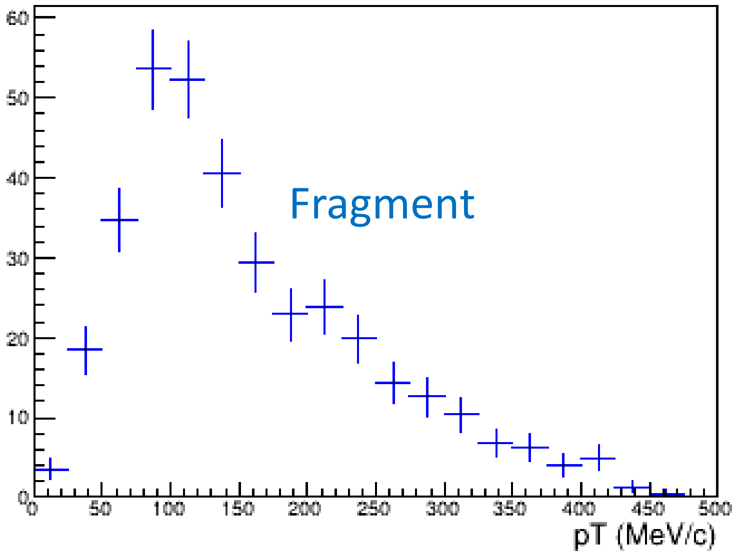
Relative angle to incident neutron



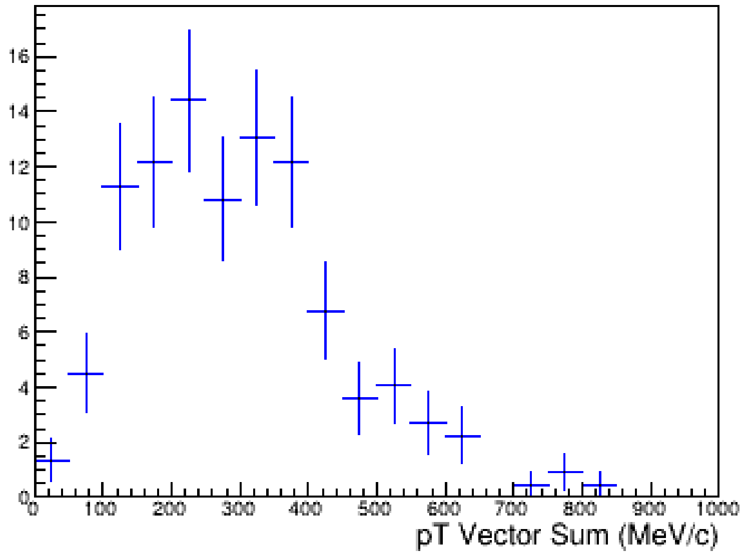
Relative angle to recoil nuclei

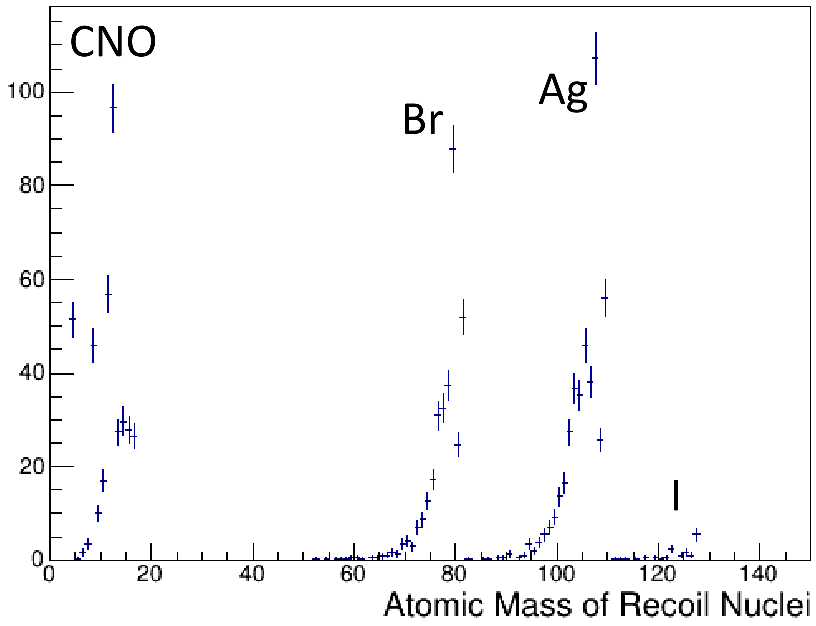


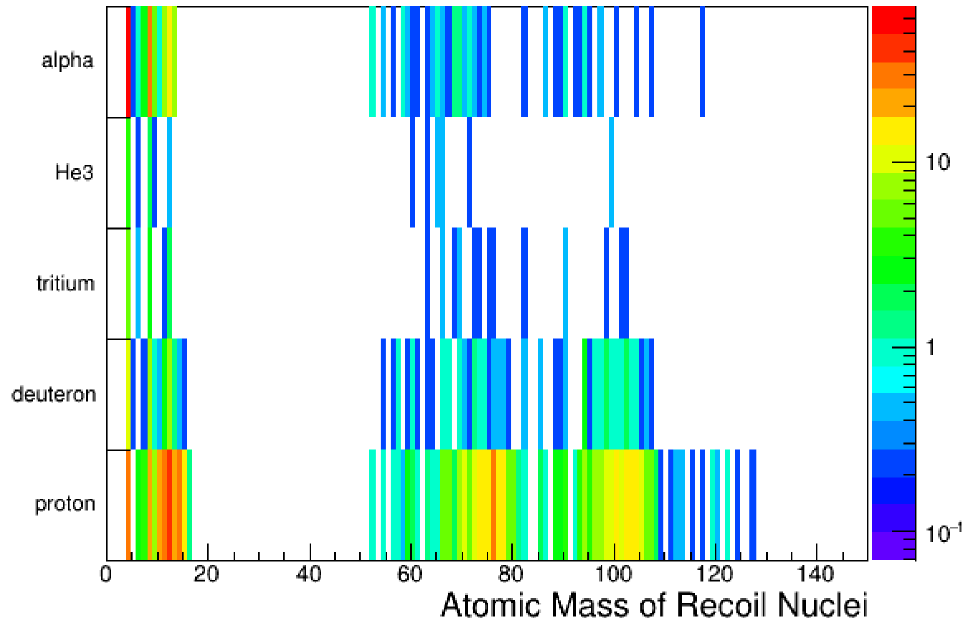
Relative p_T to recoil nuclei

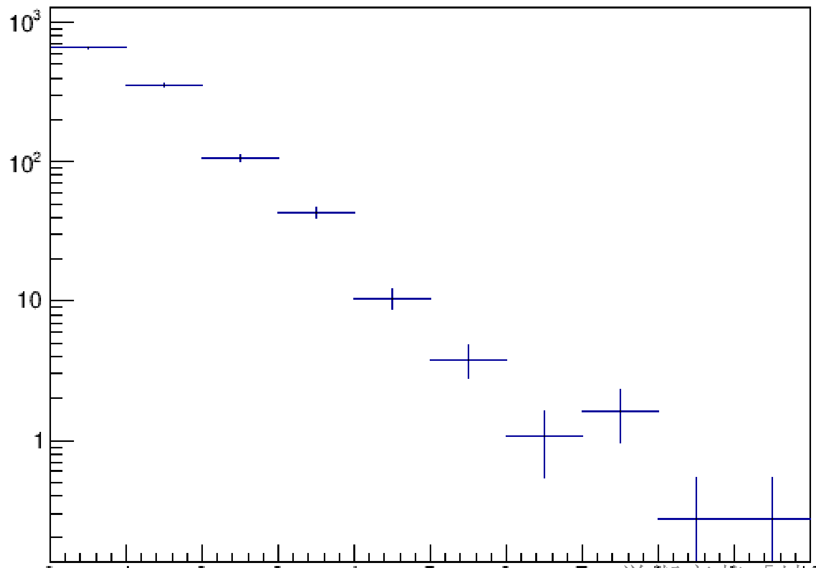


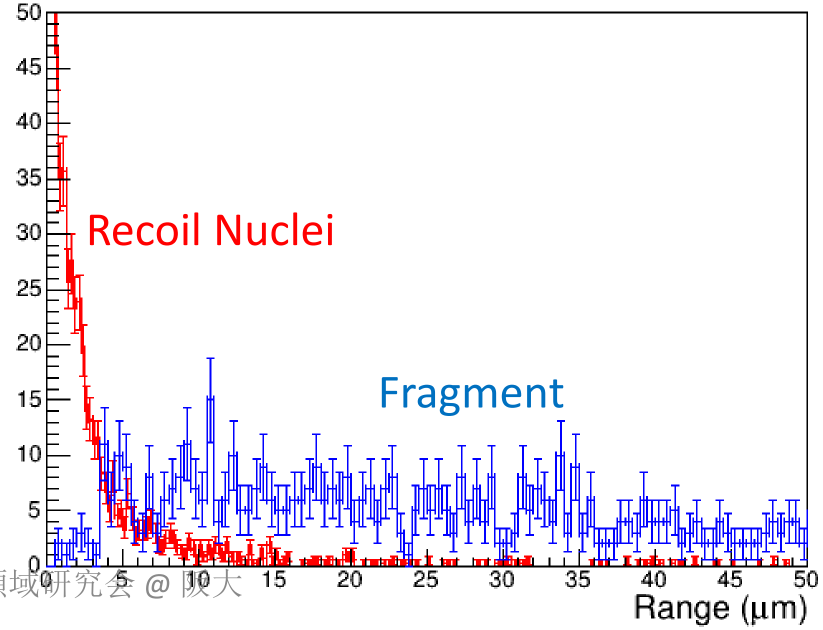
Vector sum of relative p_T to recoil nuclei




CNO
Br
Ag
I
Atomic Mass of Recoil Nuclei

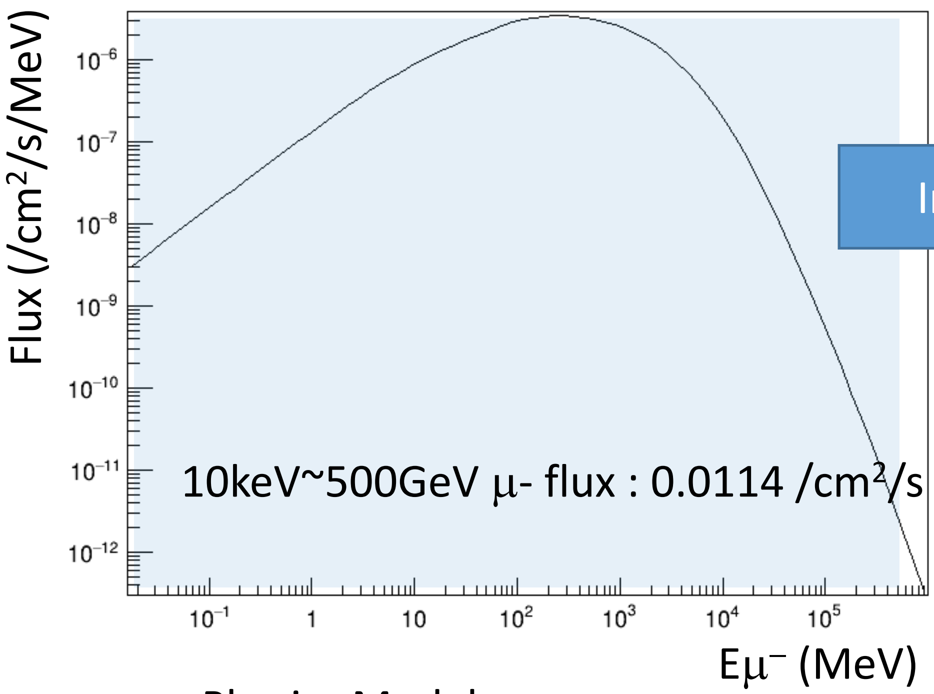

alpha
He3
tritium
deuteron
proton
Atomic Mass of Recoil Nuclei


nFragment


Recoil Nuclei
Fragment
Range (μm)

Muon Simulation in NIT

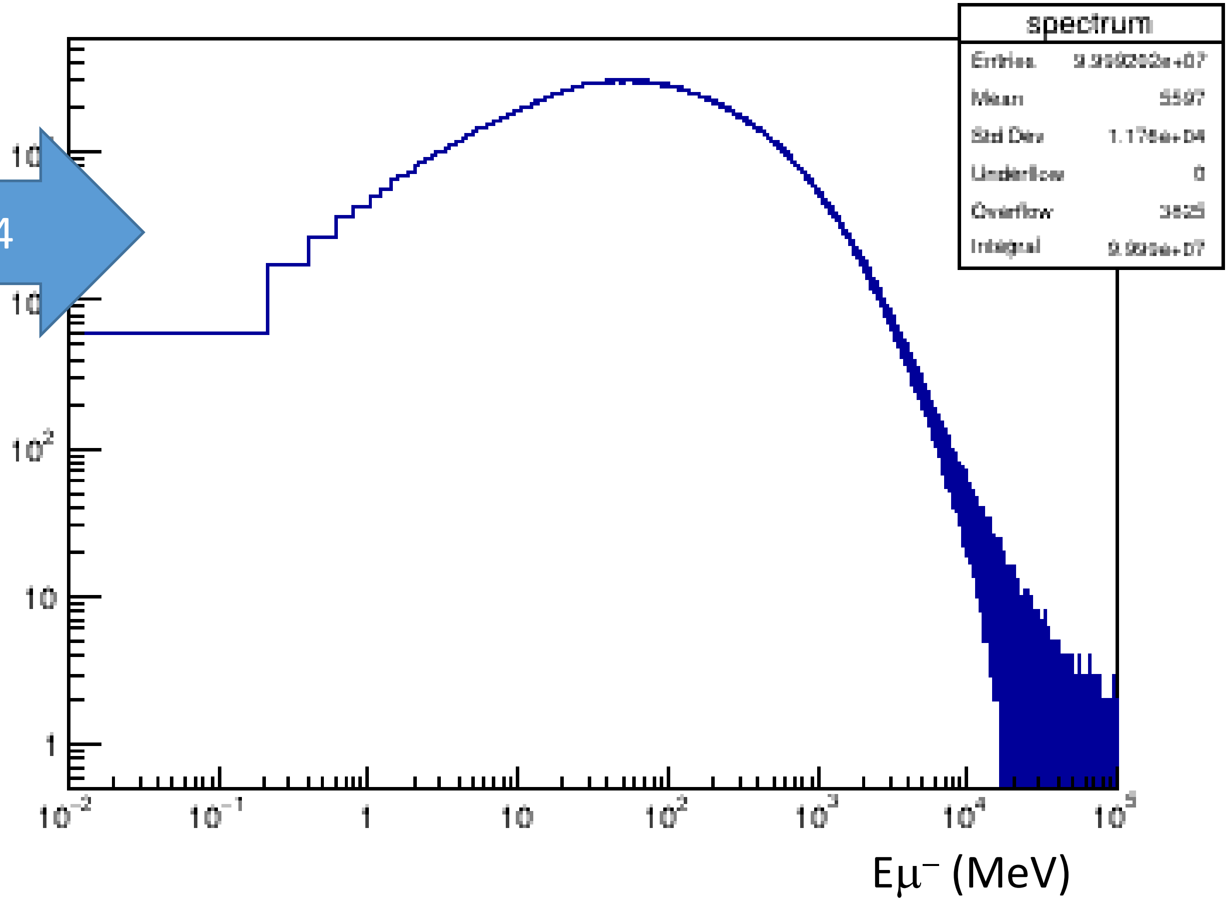
EXPACS (PARMA model) @ LNGS



10keV~500GeV μ- flux : 0.0114 /cm^2/s

Input to Geant4

Simulation μ^- Spectrum



Physics Model

Muon Photo-Nuclear Interaction

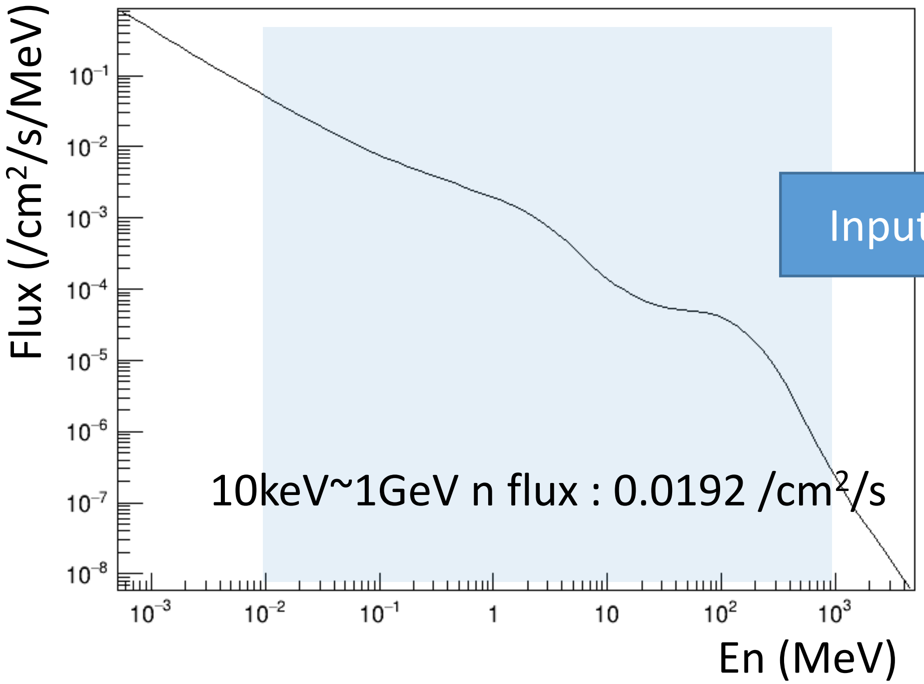
Muon Capture

Radioactive Decay

Livermore for EM

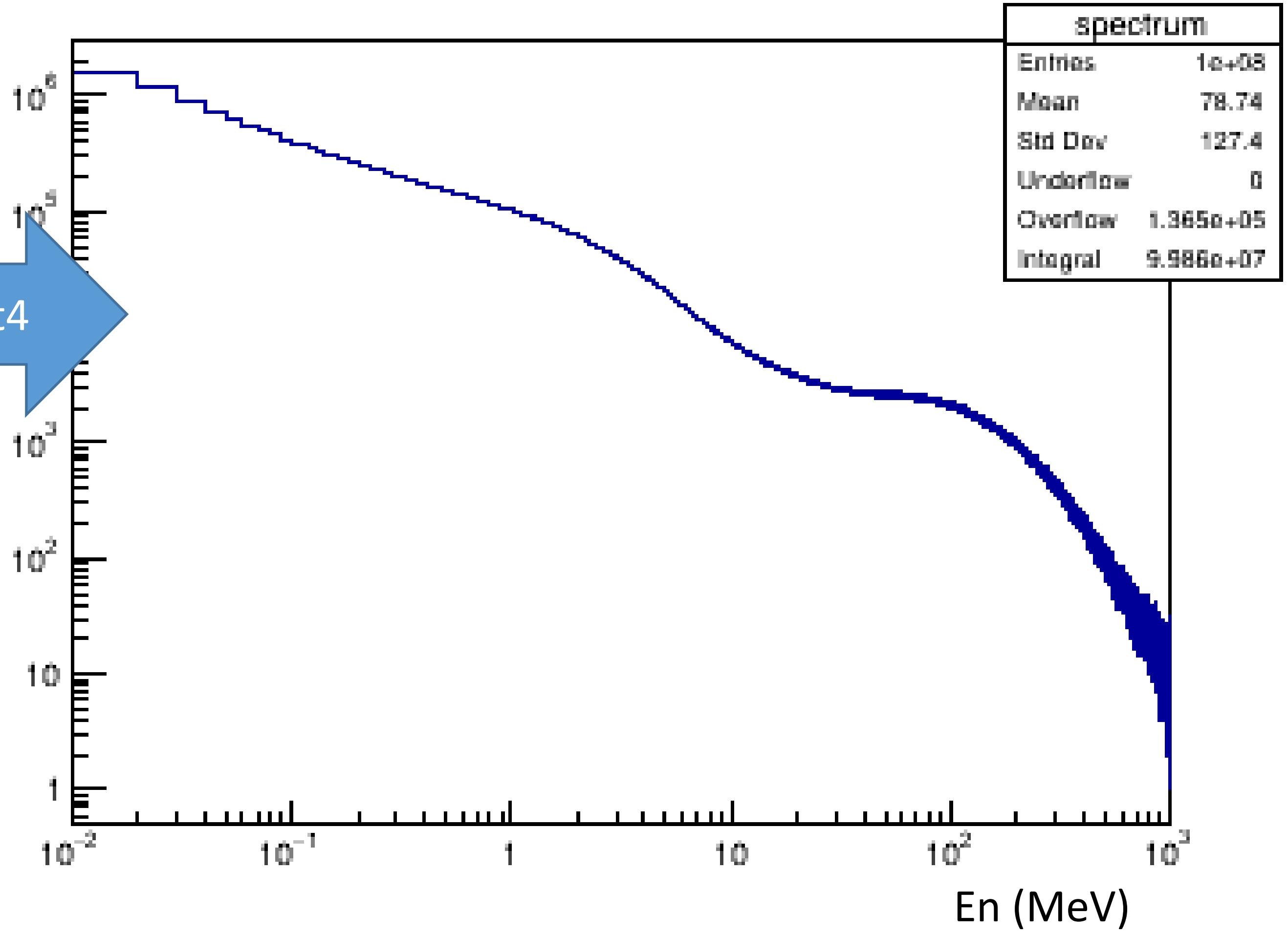
Neutron Simulation in NIT

EXPACS (PARMA model) @ LNGS



Input to Geant4

Simulation Neutron Spectrum



<u>Neutron Physics Model</u>

Elastic : NeutronHPElastic

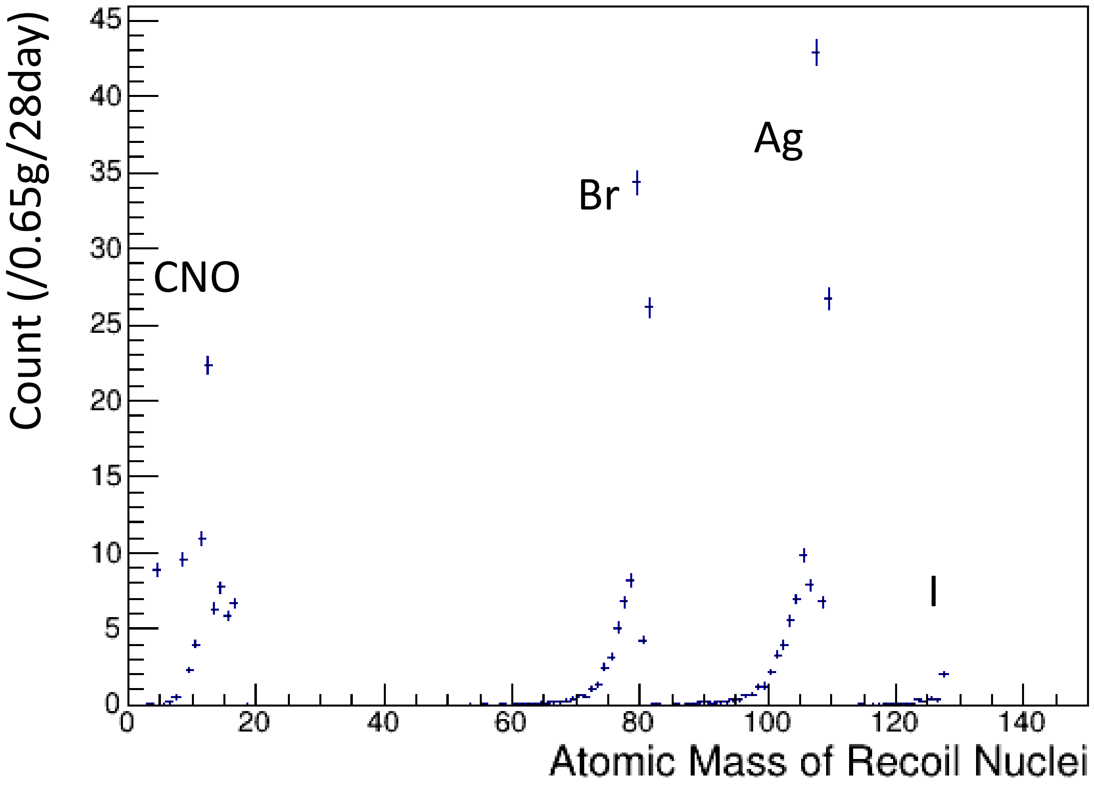
Inelastic : NeutronHPInelastic

EM : Livermore

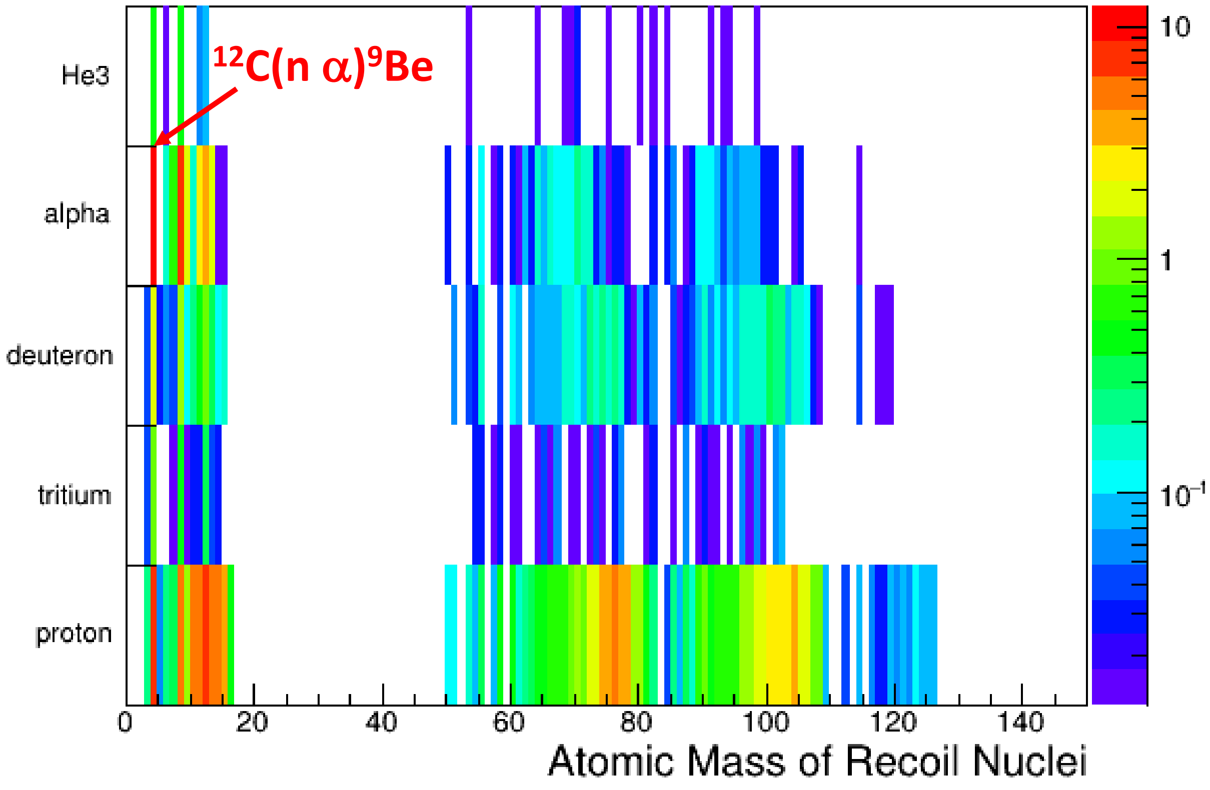
Neutron Inelastic Simulation in NIT

Extract only "Inelastic" of neutron physics process

Atomic Mass of Recoil Nuclei

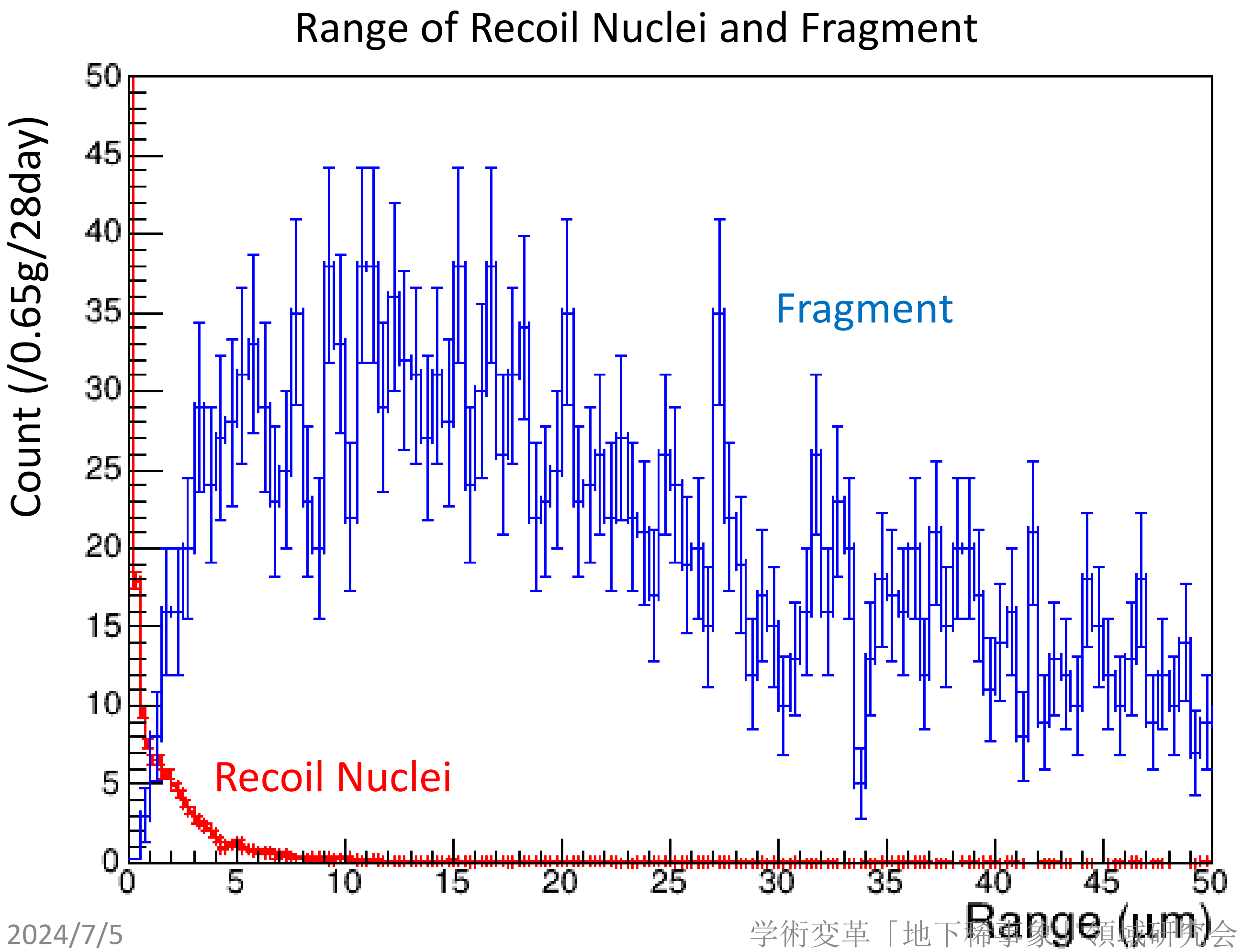


Atomic Mass of Recoil Nuclei vs Fragment particles



Neutron Inelastic Simulation in NIT

Extract only “Inelastic” of neutron physics process



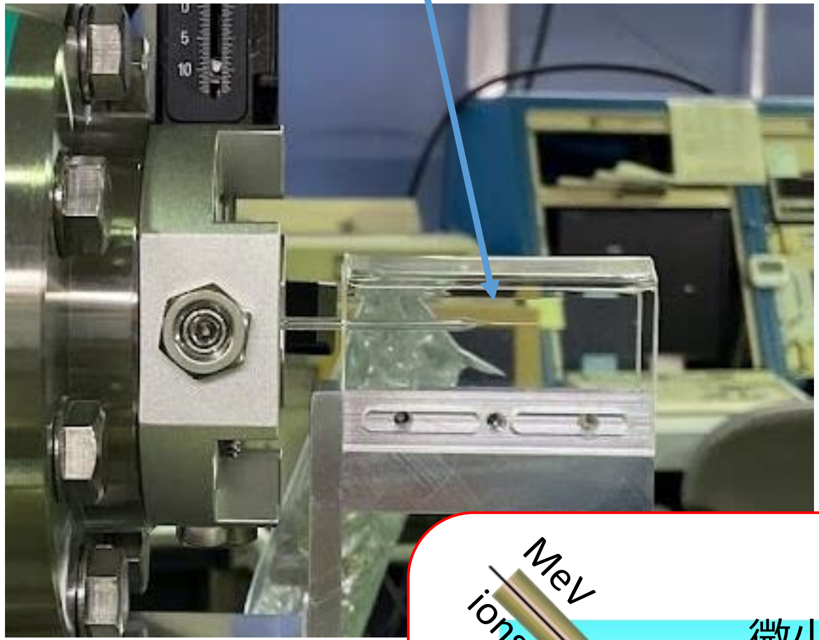
- ✓ Recoil nuclei, almost CNO, is up to 10 μm in maximum
- ➢ We identified shortest track with less than 10 μm as recoil nuclei, and remained tracks as fragments

マイクロイオンビームの研究

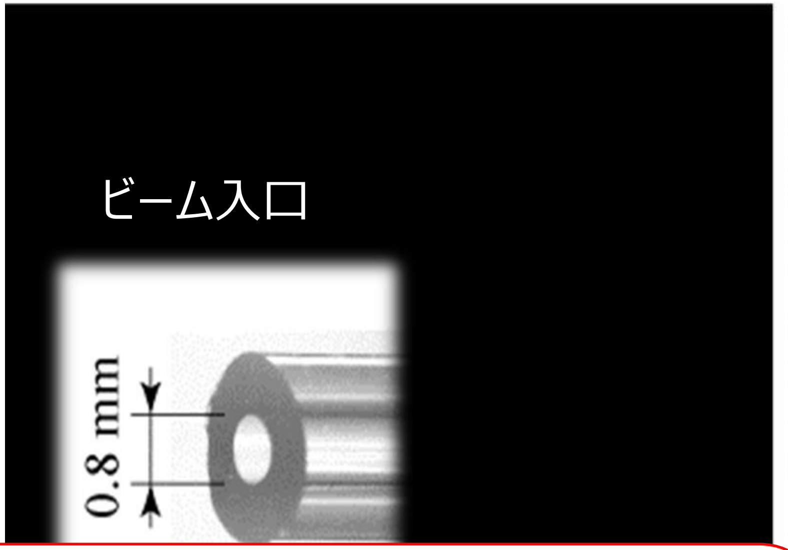
大気取り出しMeVマイクロイオンビームの研究（理化学研究所との共同研究）

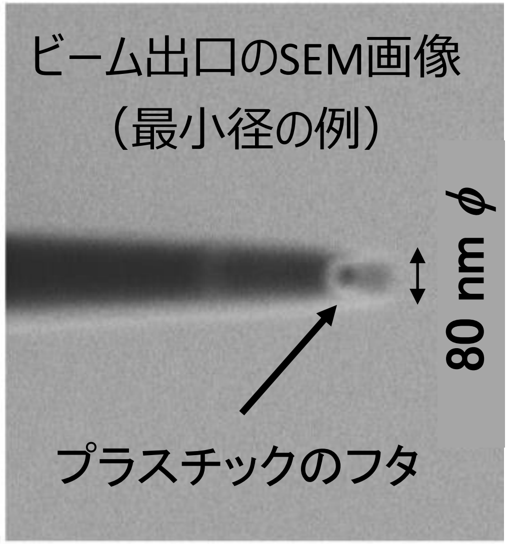
T. Ikeda, Quantum Beam Sci.4, 22 (2020).

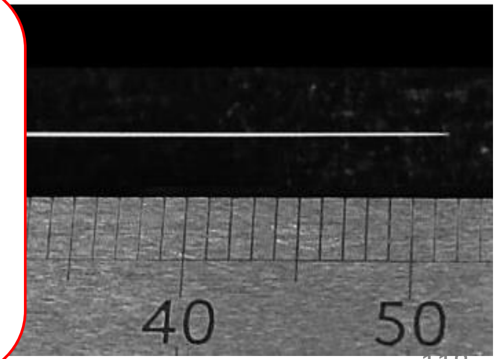
ガラスの針でビームをμmまで絞る

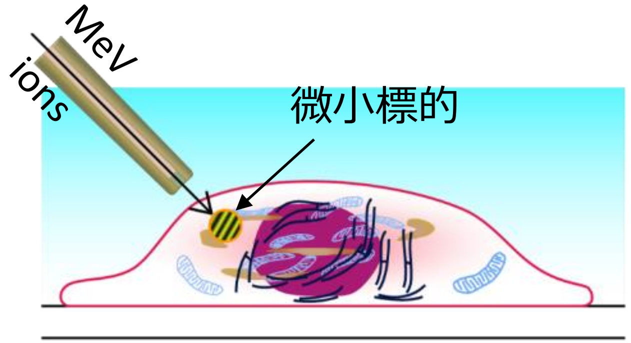


ガラスキャピラリーによるマイクロイオンビームの生成





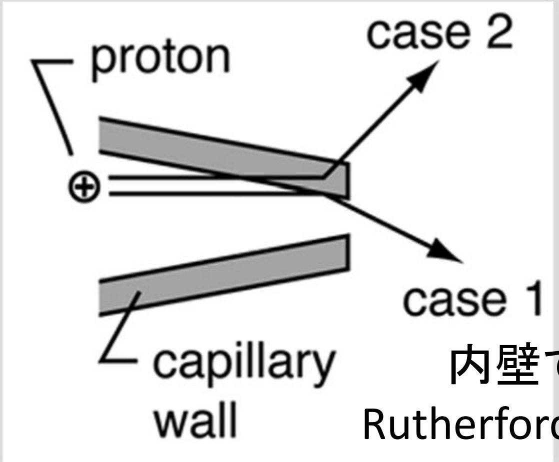




・細胞照射
・器官の一部を狙った照射
・元素マッピング（μ-PIXE）
などへの応用が期待

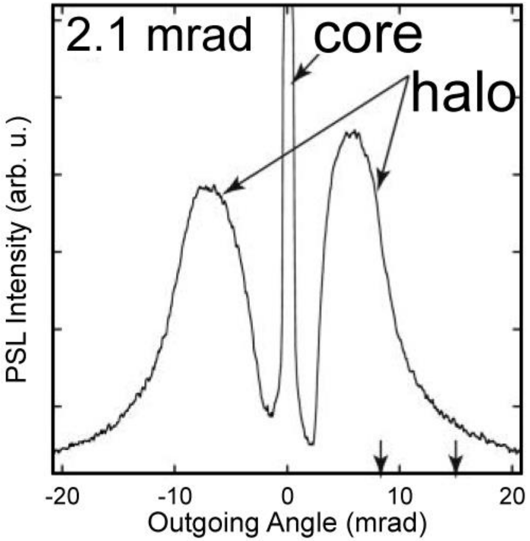
マイクロイオンビームの先行研究

内壁を貫通



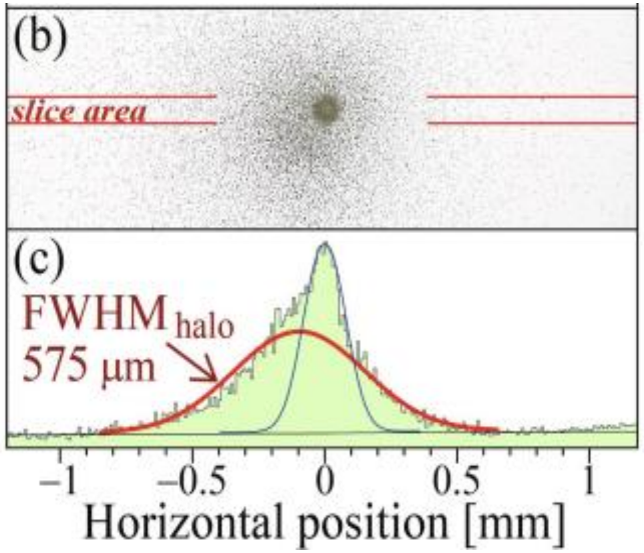
内壁で
Rutherford散乱

シミュレーションでの予測



Hasegawa *et al*., J. Appl. Phys. 110, 044913 (2011).

CR-39を用いたビームプロファイル測定



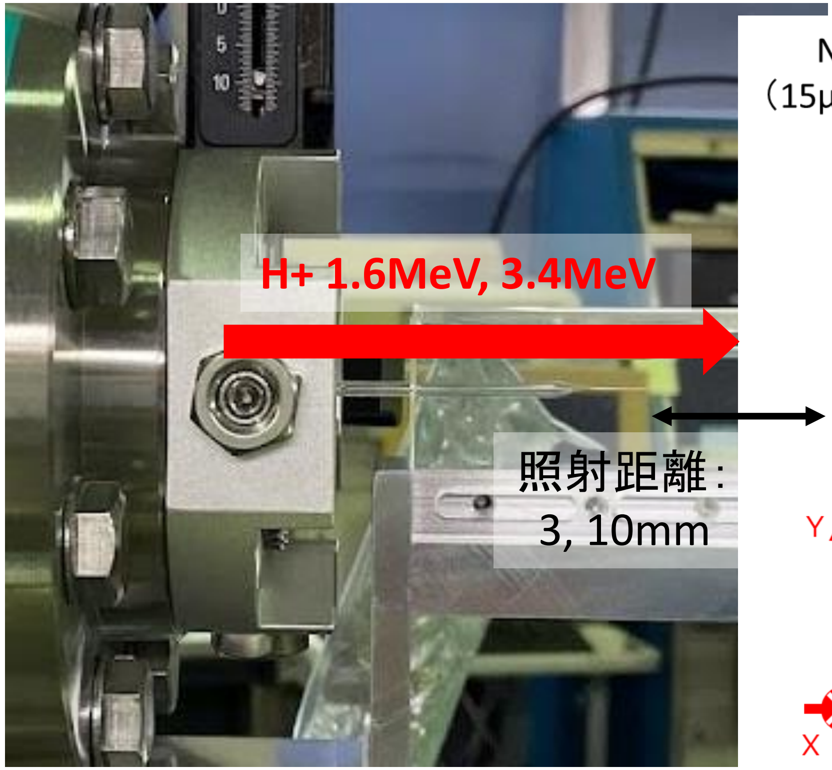
T. Ikeda, Quantum Beam Sci.4, 22 (2020).

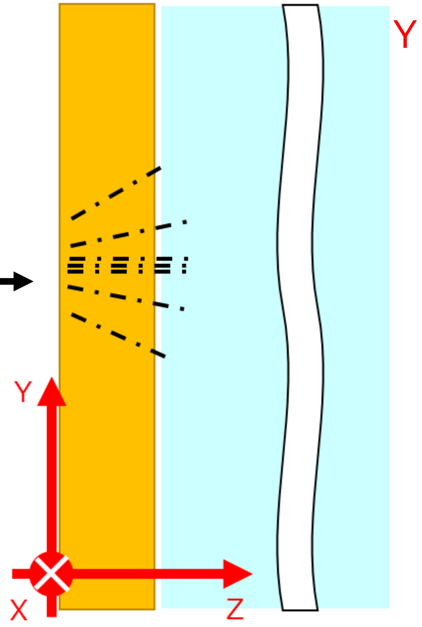
※実際には大気取り出しのためのフタがあるためさらに複雑

実験の目的
・キャピラリー出口でのイオンの振る舞いを明らかにする
→ 各イオンの軌道情報が必要

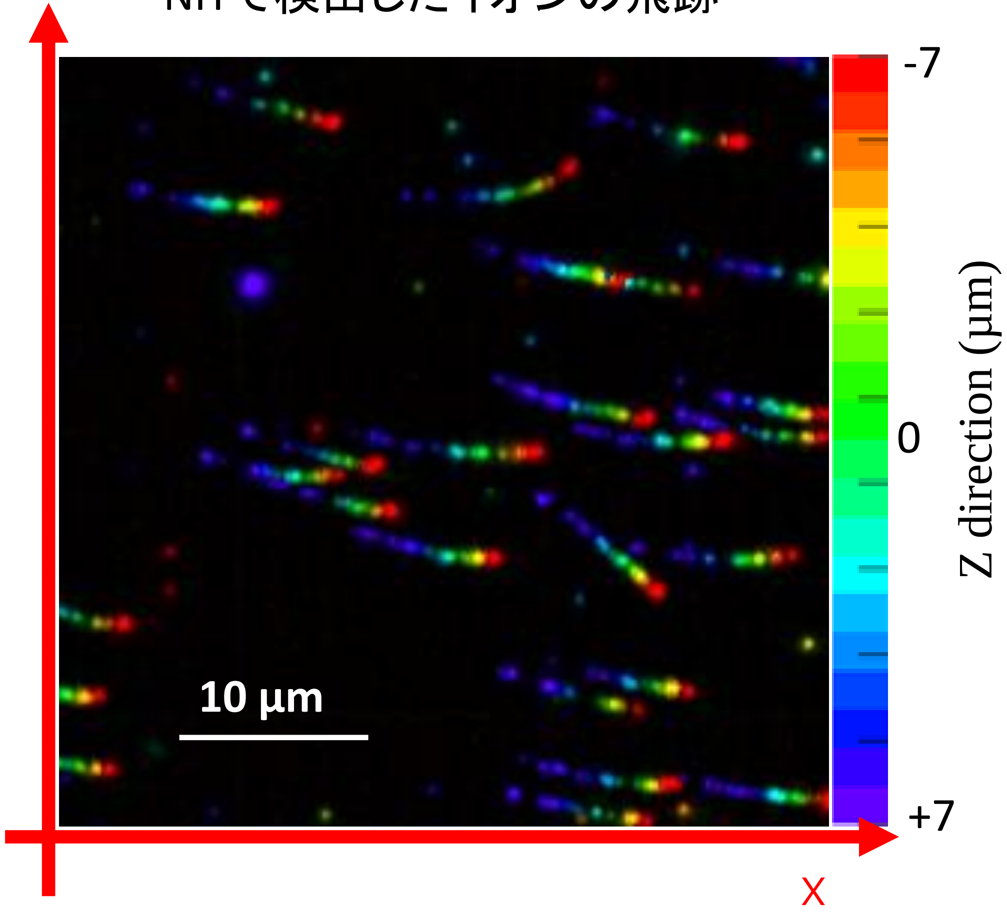
課題点
・3次元のイオンの軌道が不明
・高密度照射に対して弱い
・エネルギーその相関が薄い

マイクロイオンビームの照射

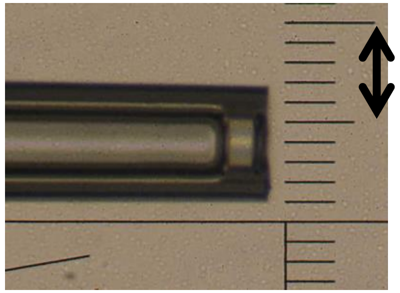




NITで検出したイオンの飛跡

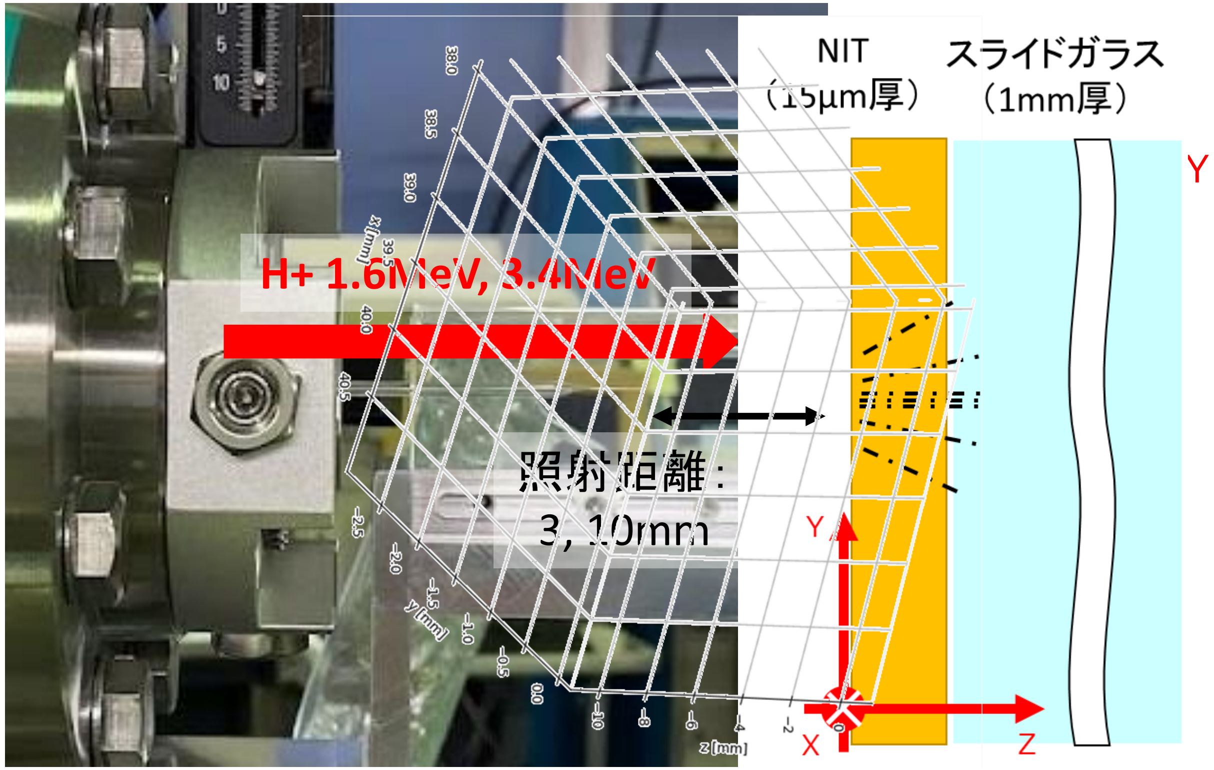


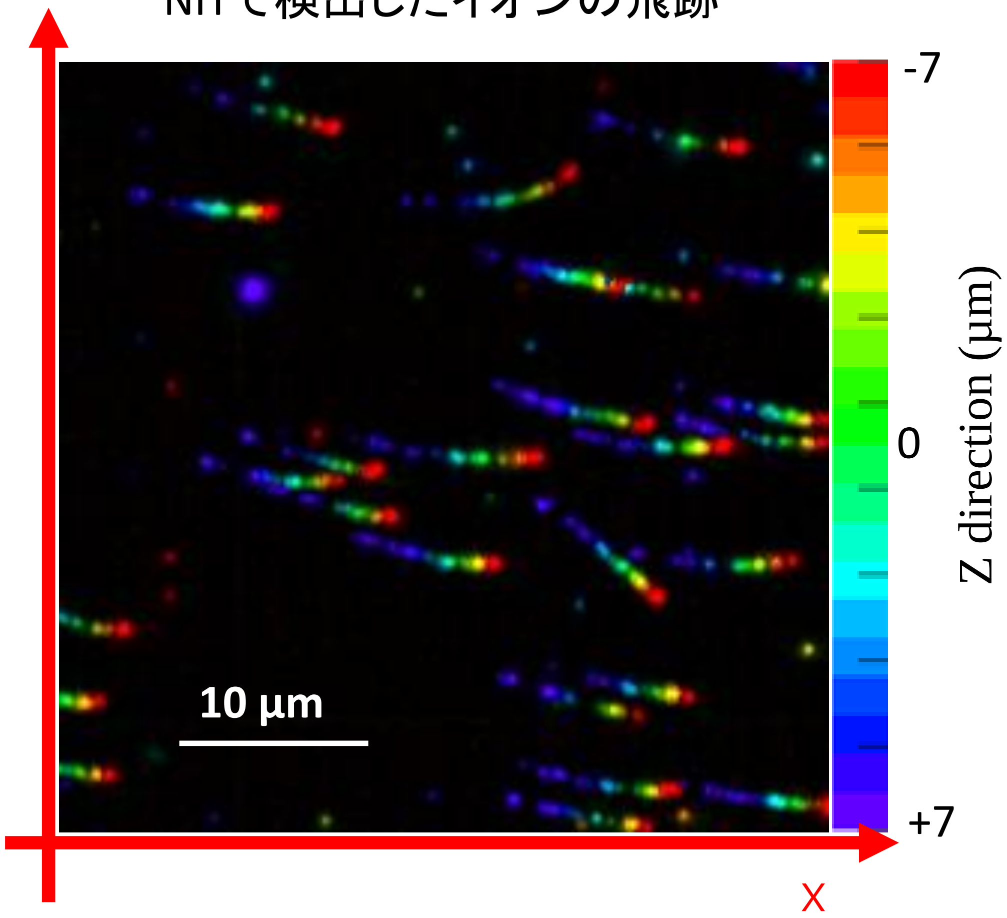
実際に使用した
キャピラリーの先端
No. 901d



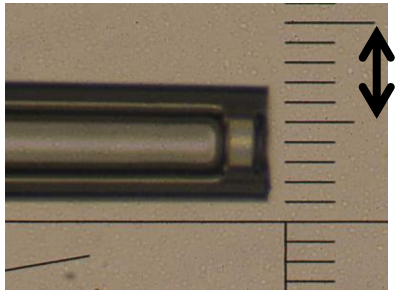
フタ　50µmΦ
30µm厚

マイクロイオンビームの照射





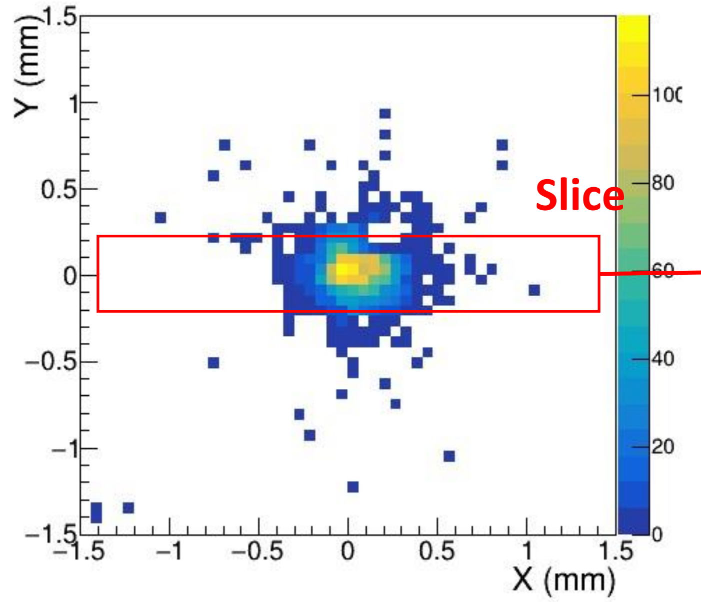
実際に使用した
キャピラリーの先端
No. 901d

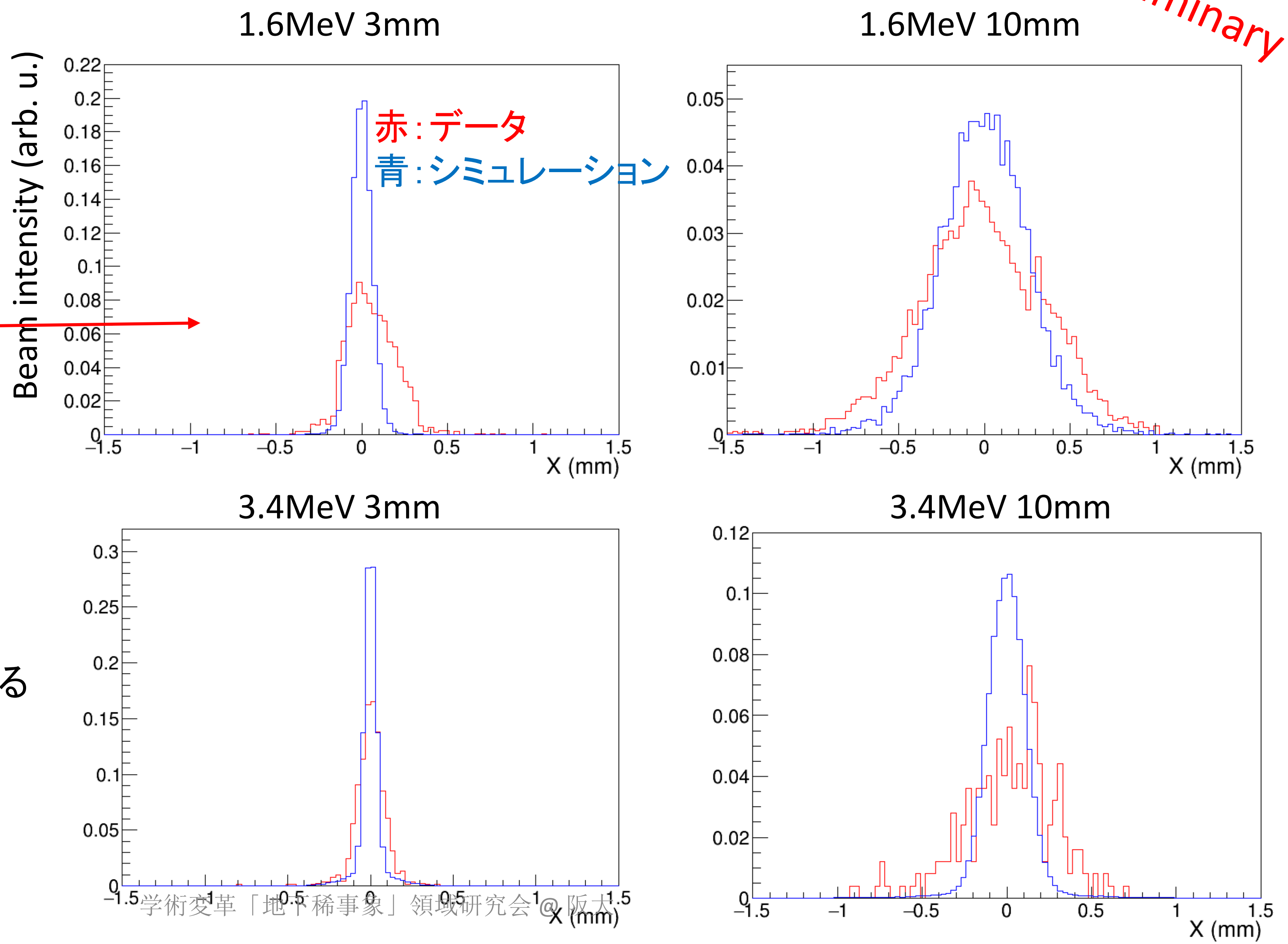


100um

フタ 50μmΦ
30μm厚

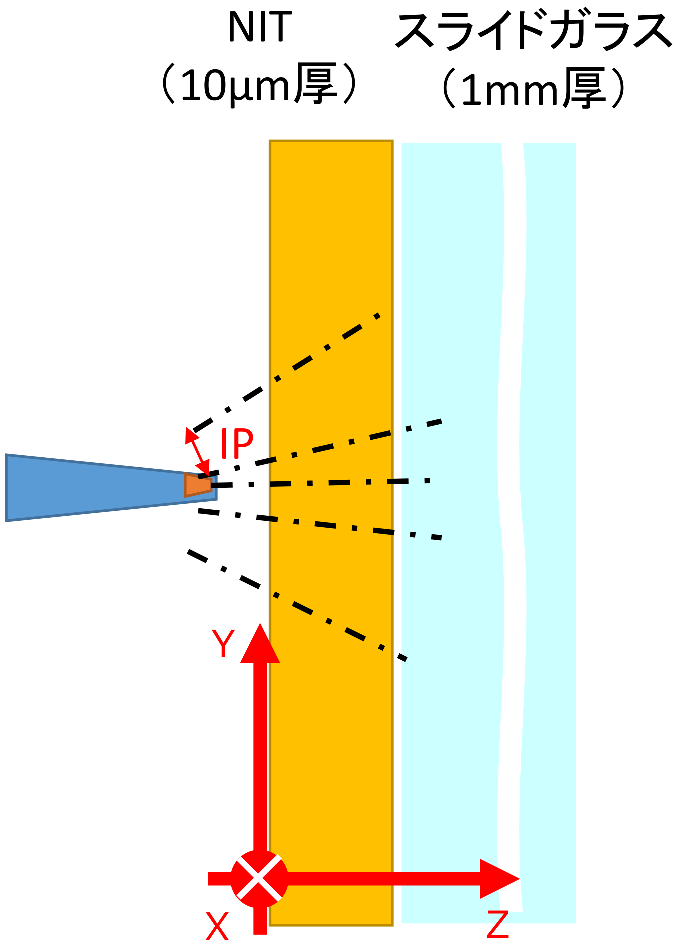
ビームプロファイル

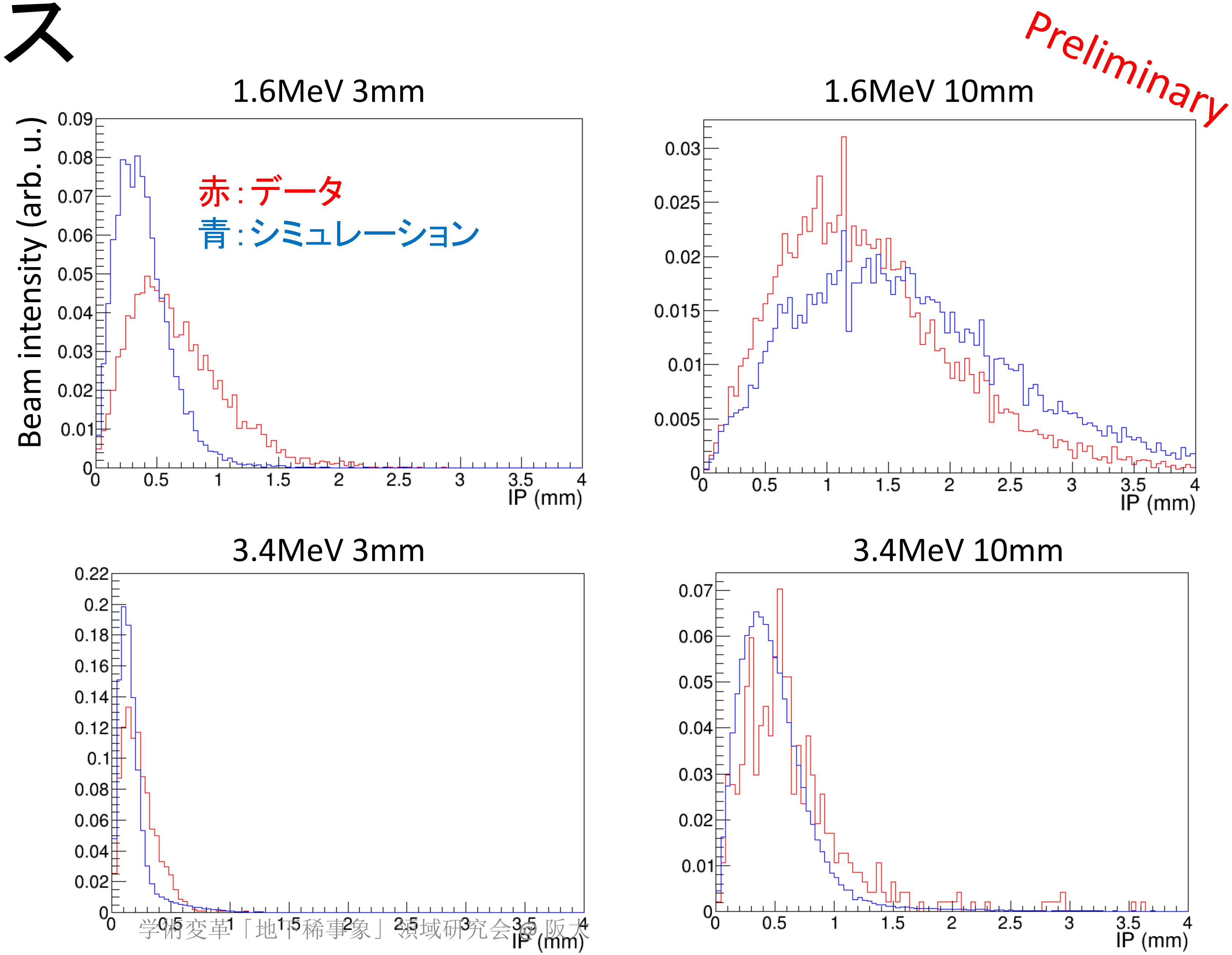




✓ データが少し広がって見える
- 測定精度？
- Halo成分
- ビーム形状？

バックトレース


NIT
（10µm厚）
スライドガラス
（1mm厚）
IP
Y
X
Z


Preliminary
1.6MeV 3mm
1.6MeV 10mm
3.4MeV 3mm
3.4MeV 10mm
赤 : データ
青 : シミュレーション
Beam intensity (arb. u.)
IP (mm)