超微粒子原子核乾板による LNGS環境中性子測定

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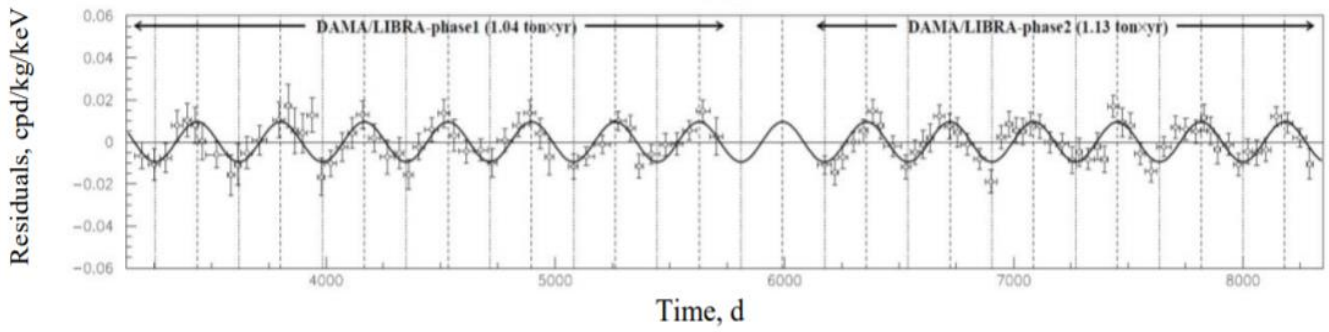
On the behalf of the NEWSdm collaboration

2024/2/7「第9回極低放射能技術」研究会 @ 横国大

DAMA信号の検証として

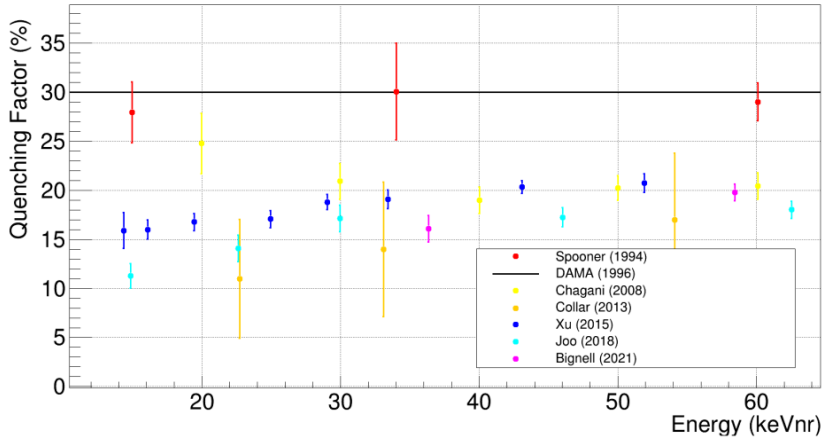
- DAMA実験の主張する信号： 2 – 6 keVee

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

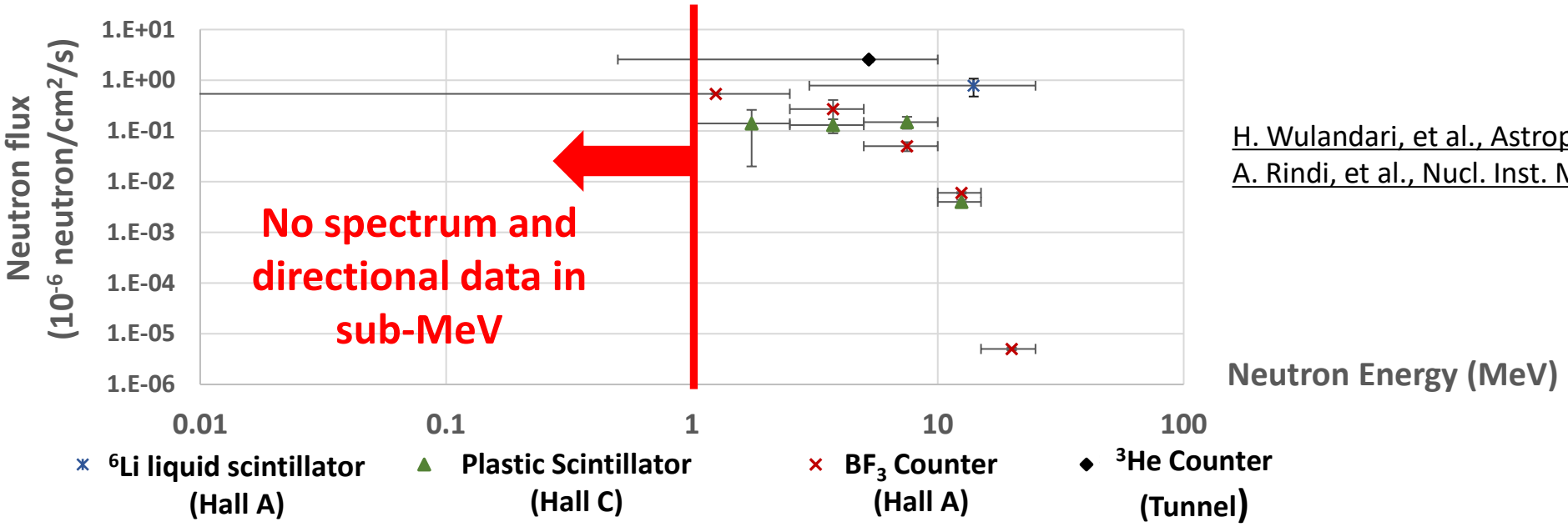


D. Cintas et al, J. Phys.: Conf. Ser. **2156**, 012065 (2021)

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！

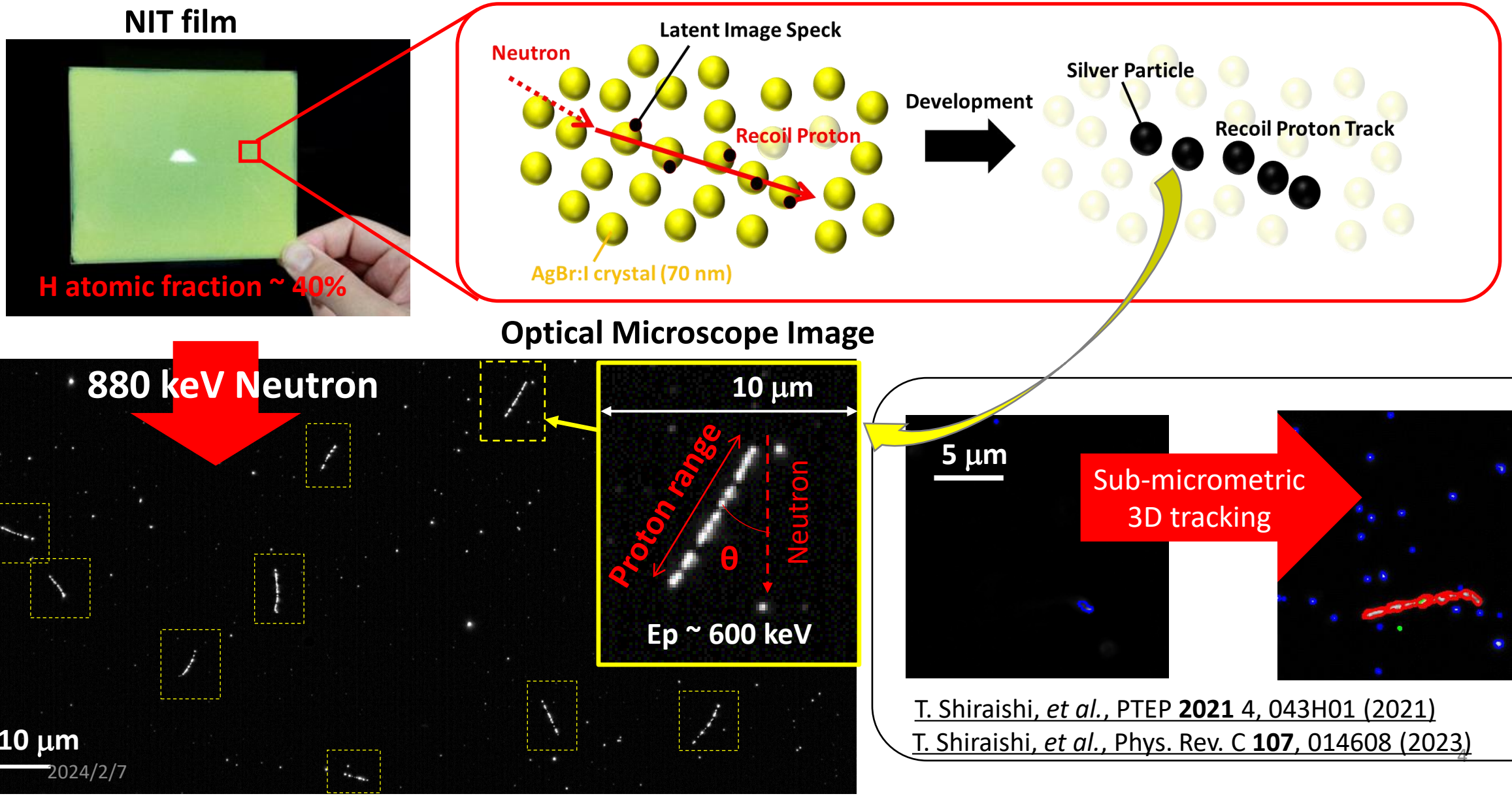
Environmental Neutron Measurement @LNGS



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

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

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)

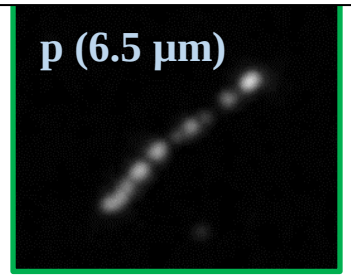
Neutron Detection Methods for Various Energies

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

Neutron Energy

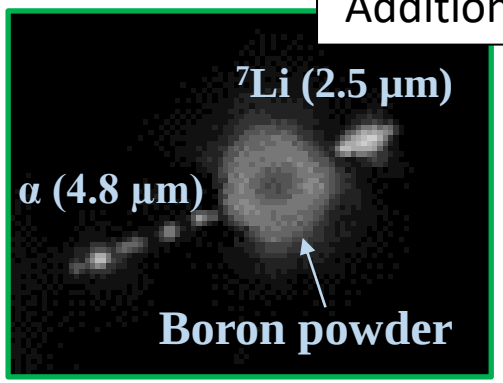
Neutron Capture

Self-contained target

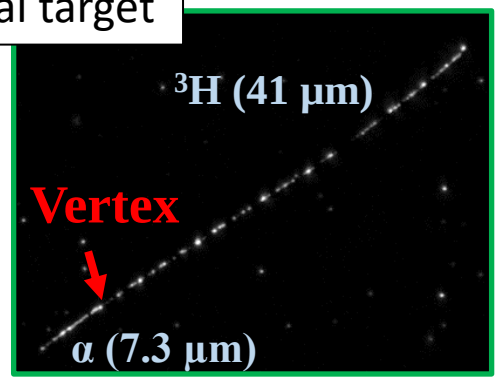


$n + {}^{14}N \rightarrow p + {}^{14}C + 0.62$ MeV
2 barn @ 26meV

Additional target

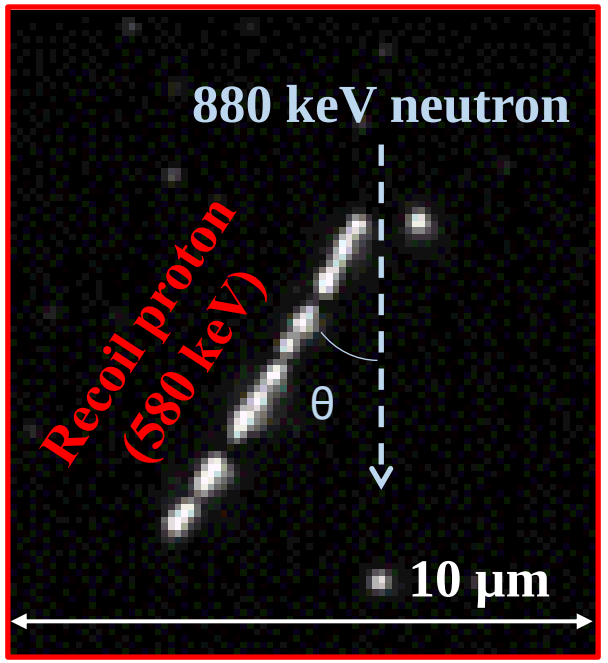


$n + {}^{10}B \rightarrow \alpha + {}^{7}Li + 2.31$ MeV
4000 barn @ 26meV

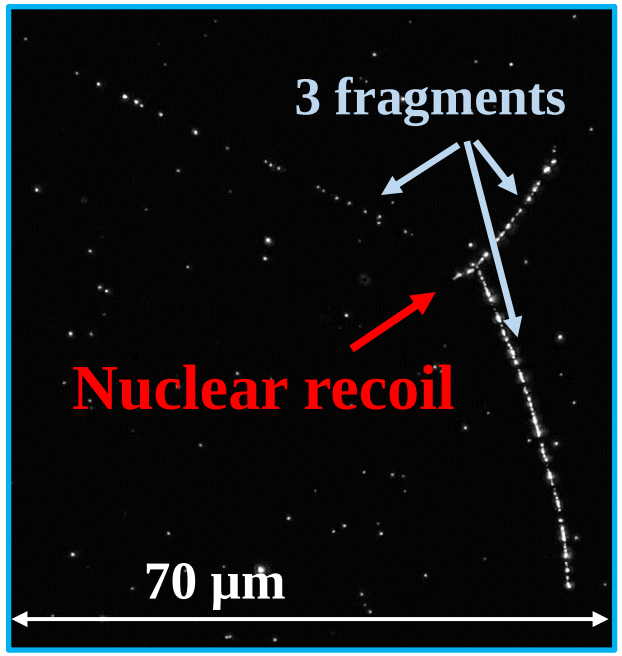


$n + {}^{6}Li \rightarrow \alpha + {}^{3}H + 4.78$ MeV
950 barn @ 26meV

Proton Elastic Scattering



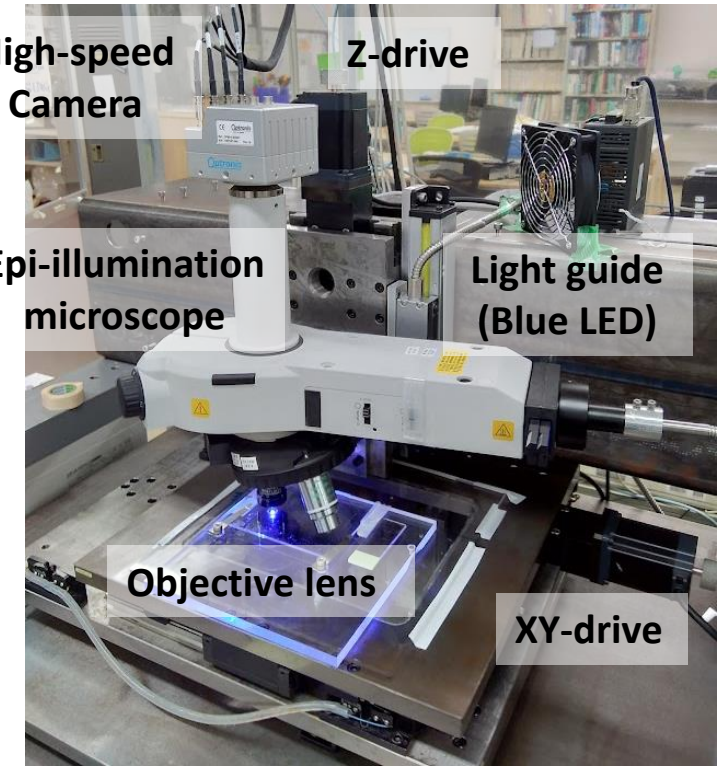
Deep Inelastic Scattering

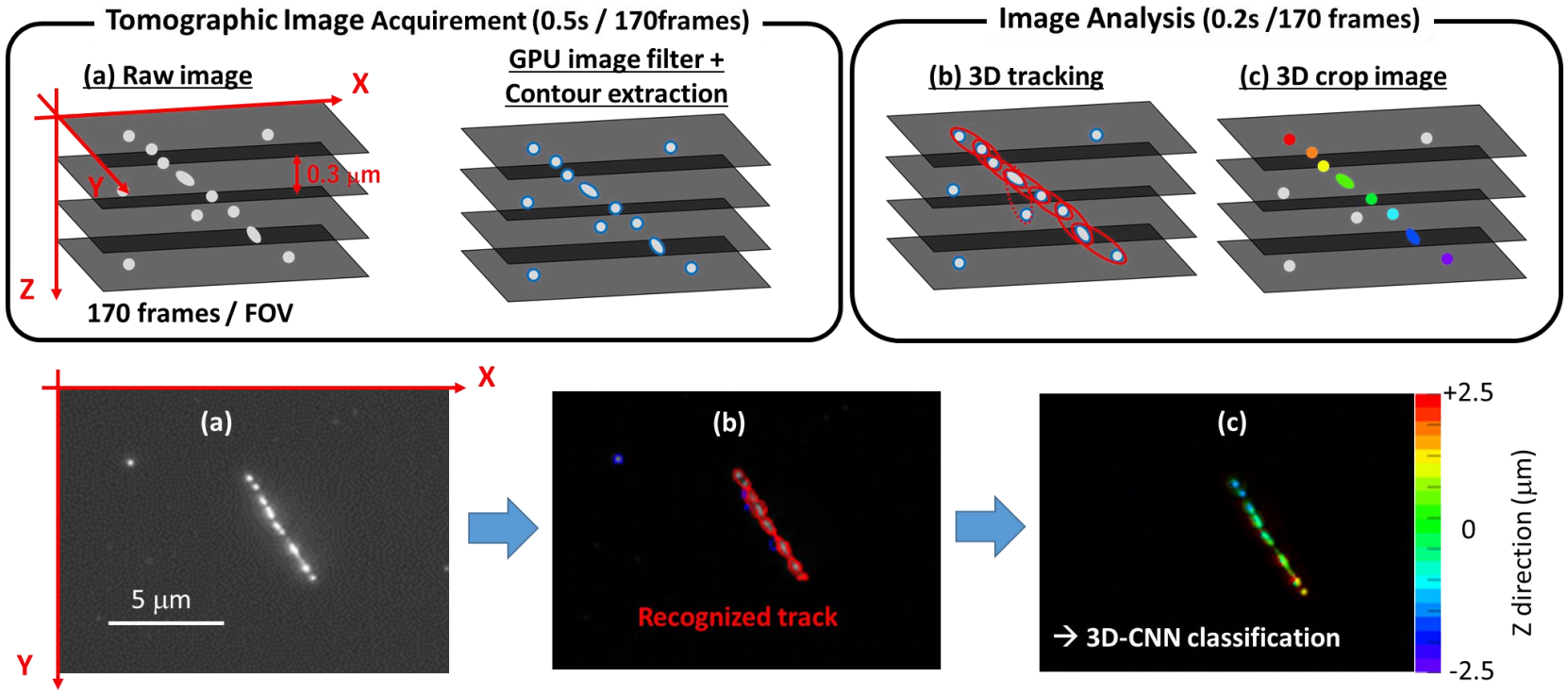


Reconstruct 3D trajectory with sub-micron accuracy
→ Capable to get position, energy and direction even in sub-MeV

High-speed Readout and Image Processes

PTS system @ Toho Univ.





Achieving 0.5 kg/year/machine with 1 μm range cut

Under constructing an upgraded PTS machine in Kanagawa Univ.

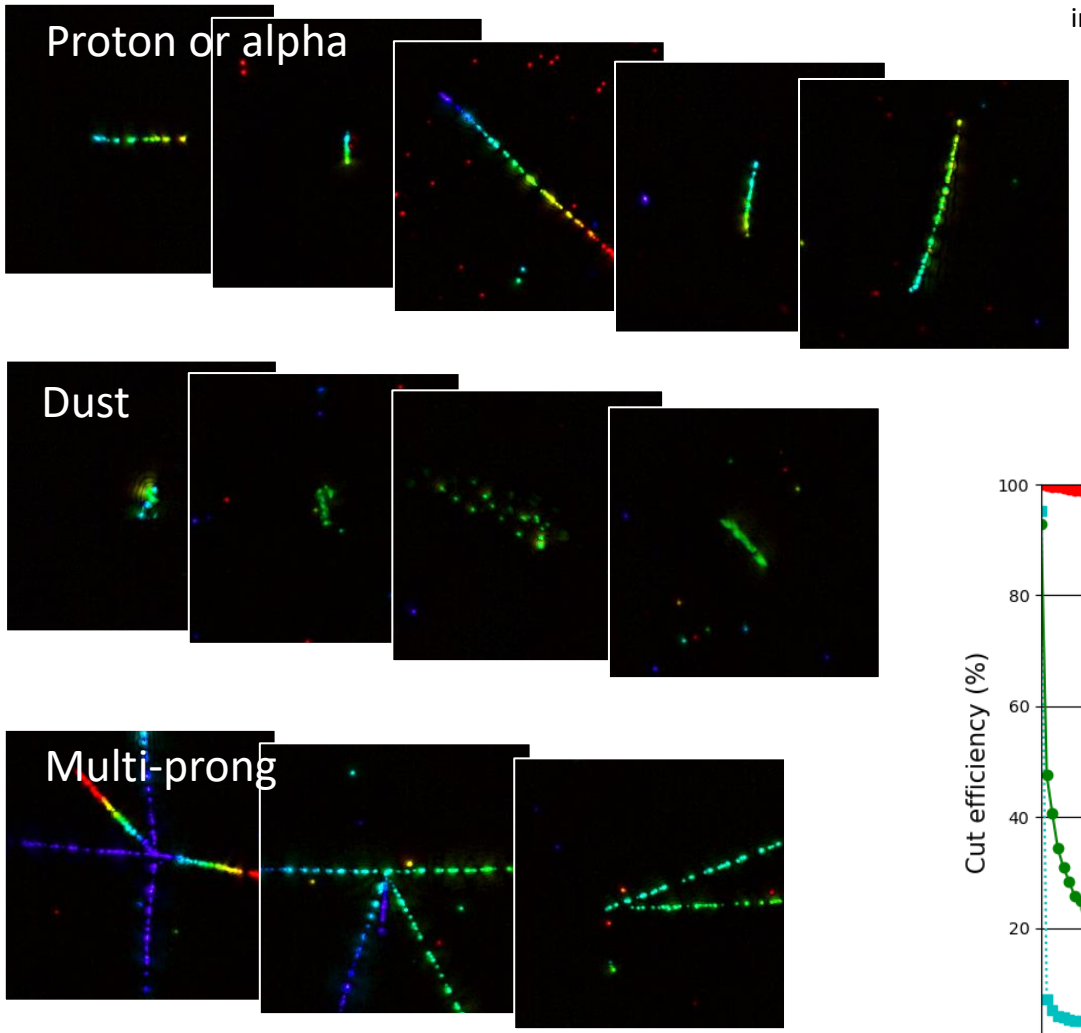
→ expected to be 1.5 kg/year/machine

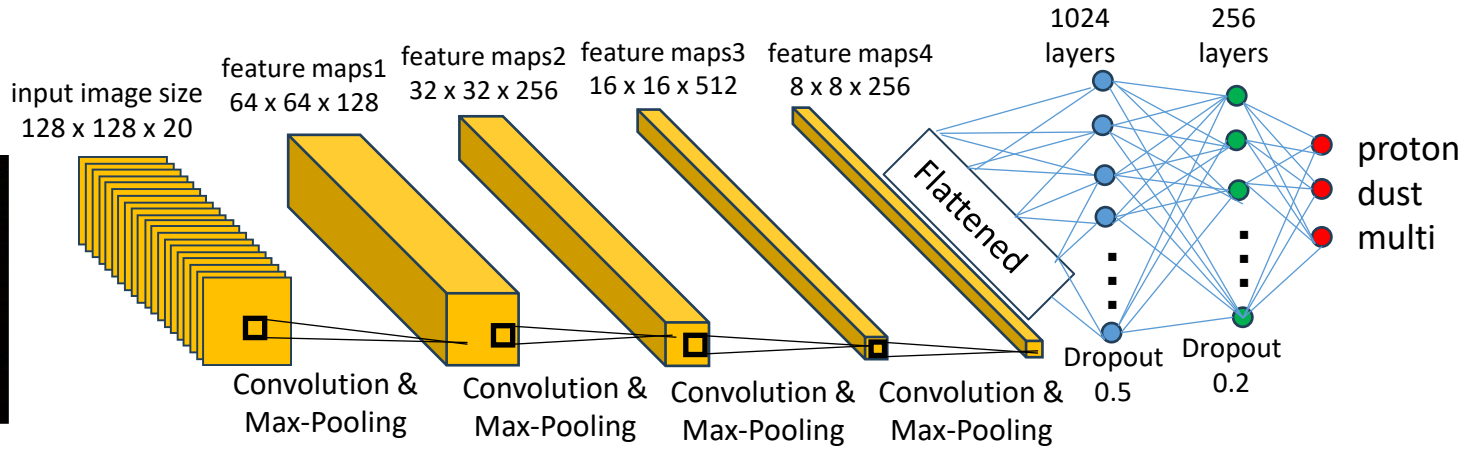
T. Shiraishi, *et al.*, PTEP **2021** 4, 043H01 (2021)

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

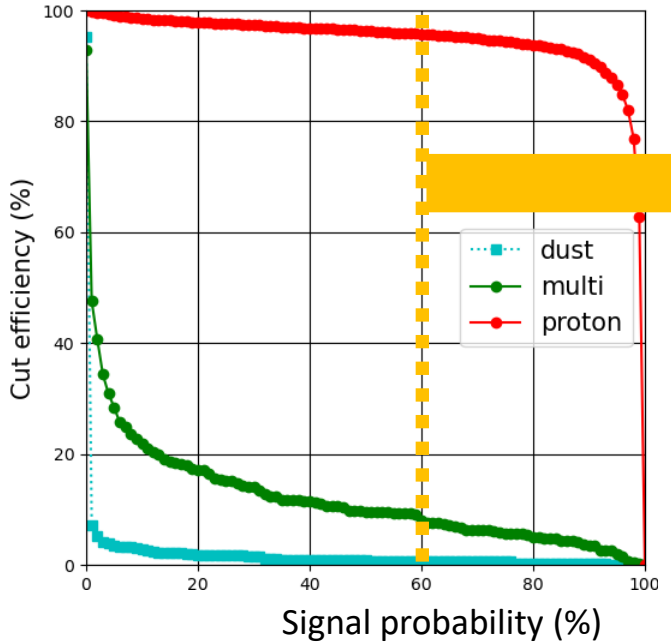
3D Convolutional Neutral Network

Training Samples

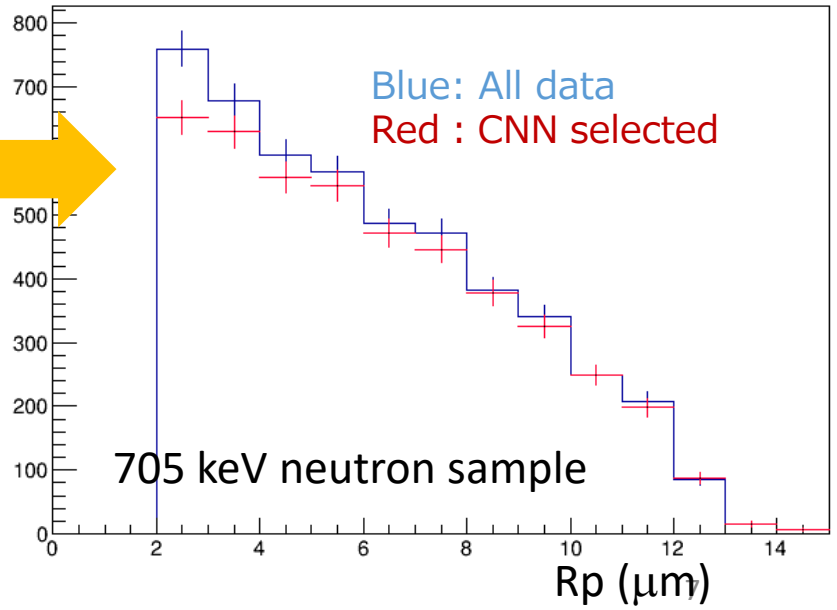




CNN cut efficiency

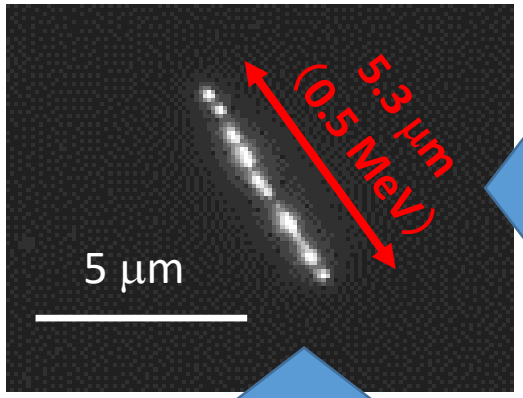


CNN selection effect



Background in Neutron Detection

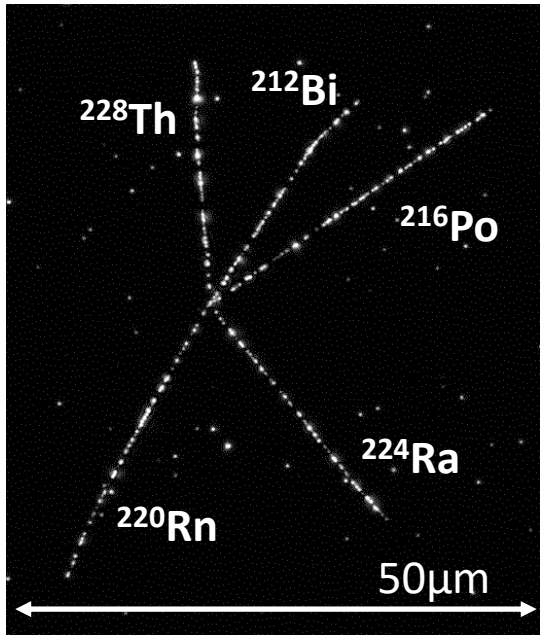
Recoil proton signal



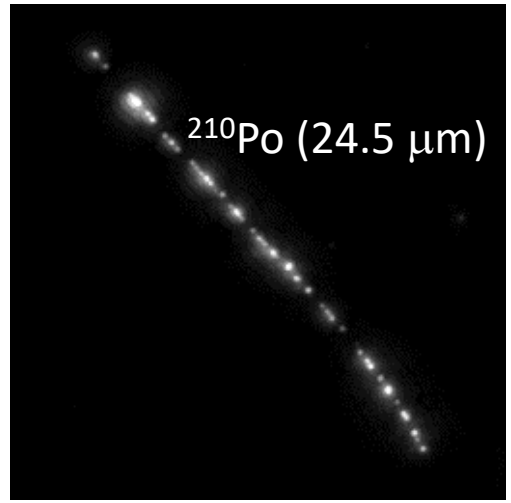
Topological or Range cut

α-ray

Th star (^{228}Th → ^{208}Pb)

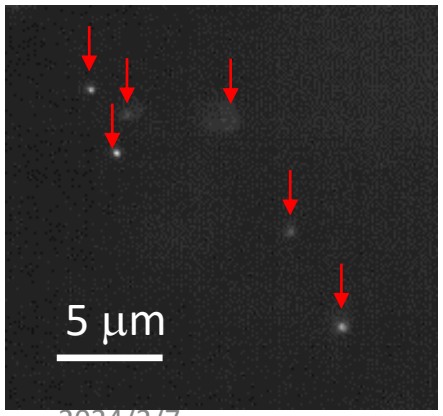


Single-α in U series



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)

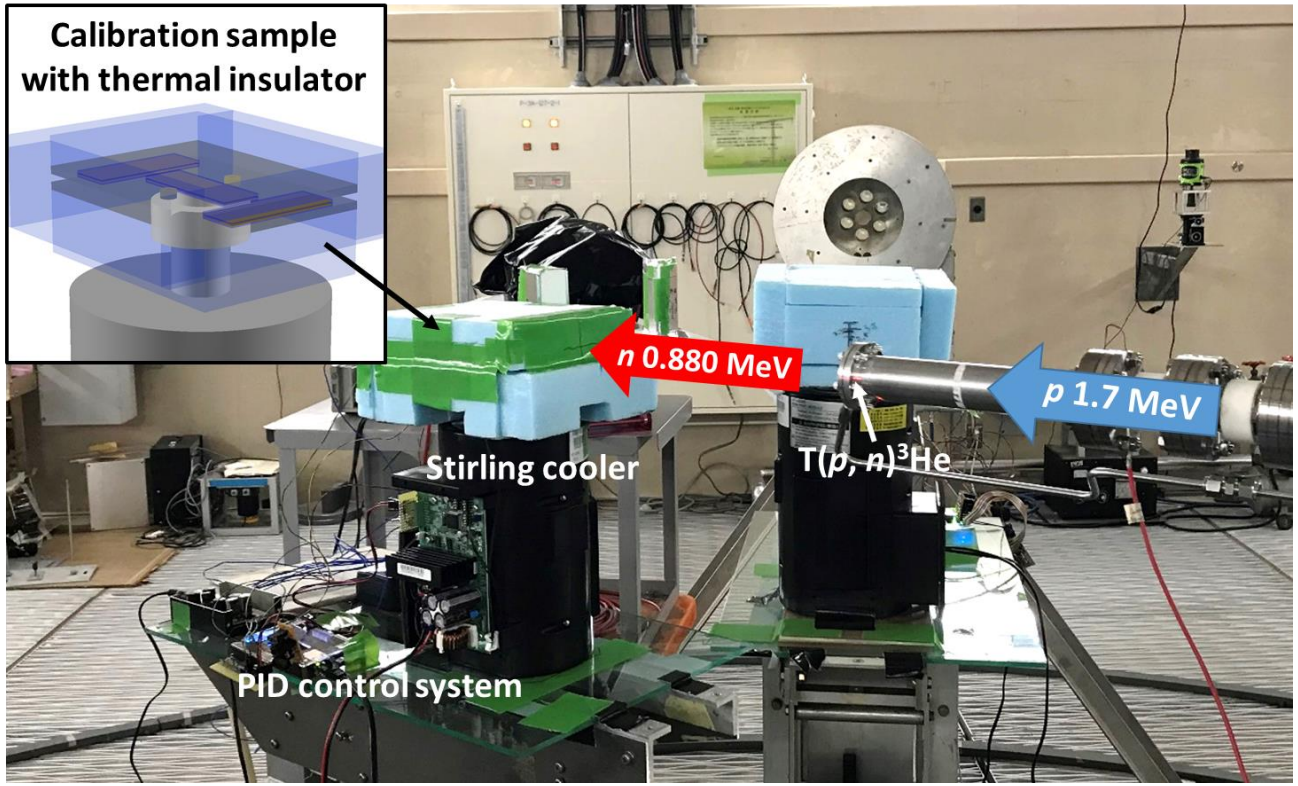
✓ **Environmental γ-rays cannot become background**

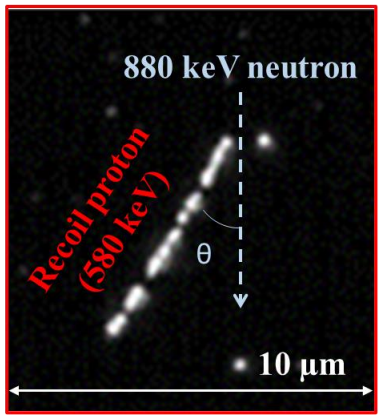
✓ **There is no background in sub-MeV region (2 - 14 μm → 0.25 - 1 MeV in proton energy)**

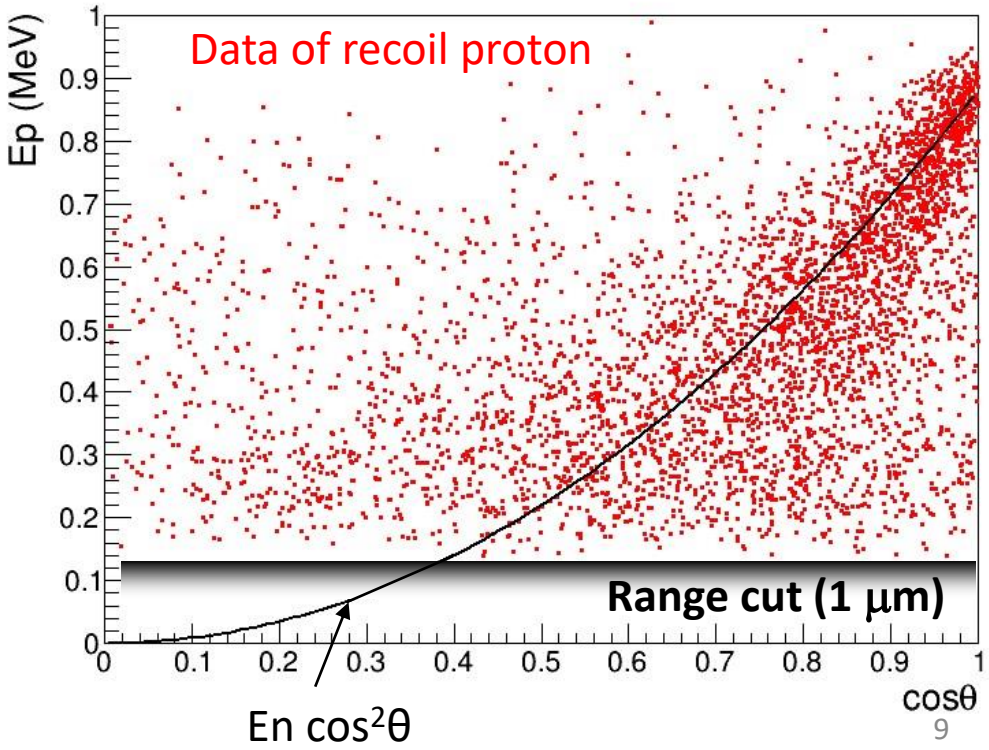
✓ **MeV region can be analyzed excluding single-α (especially ^{210}Po peak around 24 μm)**

Calibration with Monochromatic Sub-MeV Neutron

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



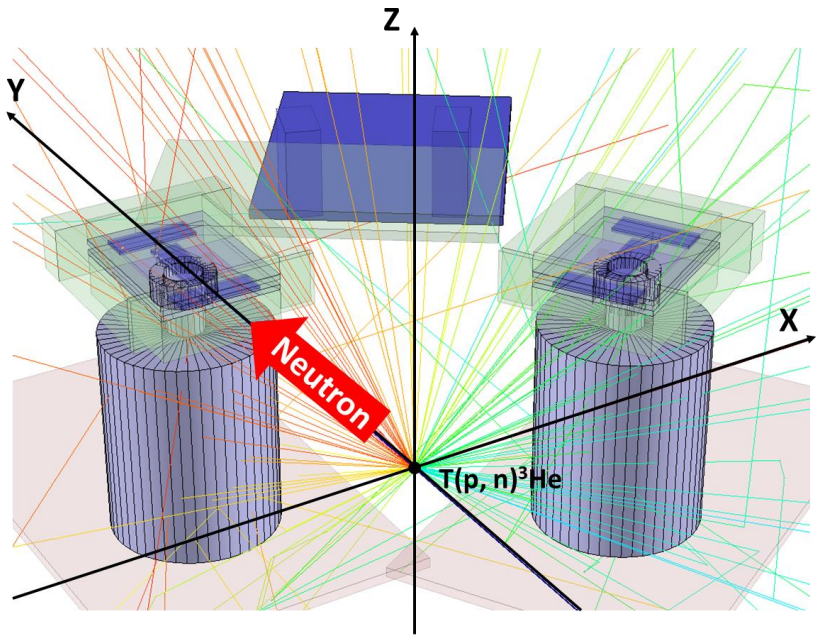




Exposed 7.9 hours with a stable temperature at -26℃

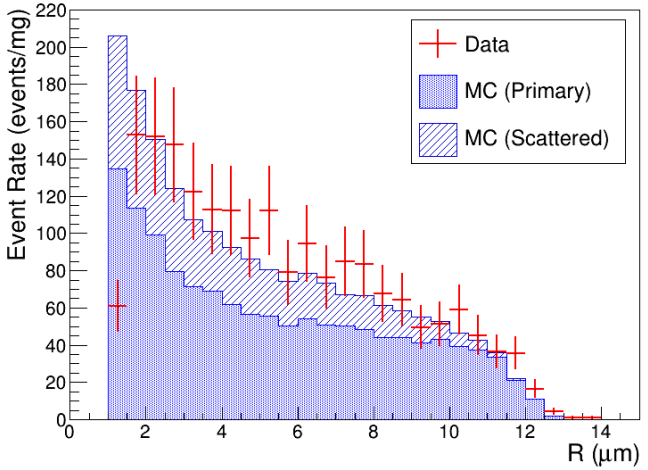
Calibration – Comparison with Simulation

GEANT4 simulation

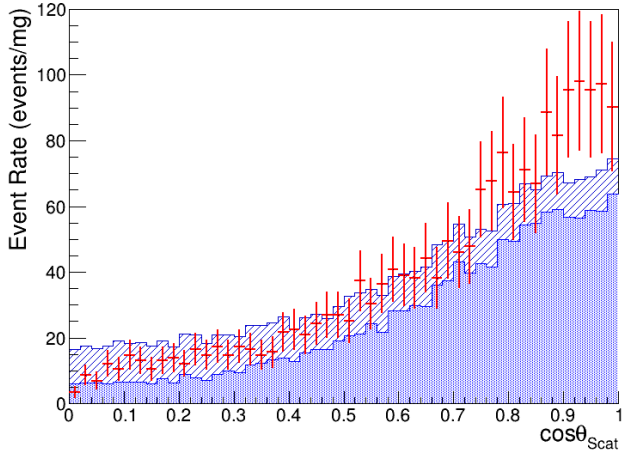


*Color corresponding to neutron energy

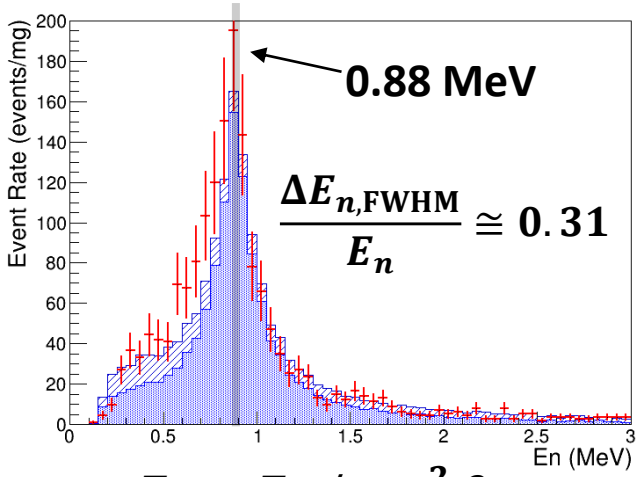
Proton Range



Scattering Angle

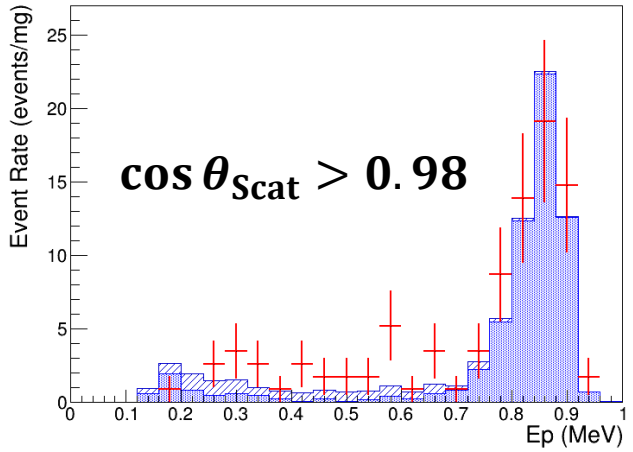


Neutron Energy



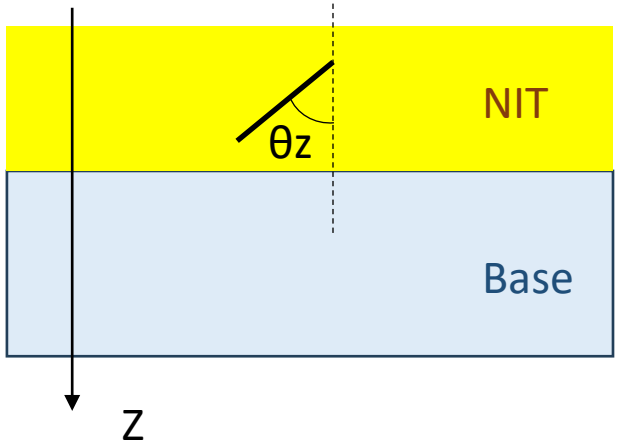
$E_n = E_p / \cos^2\theta$

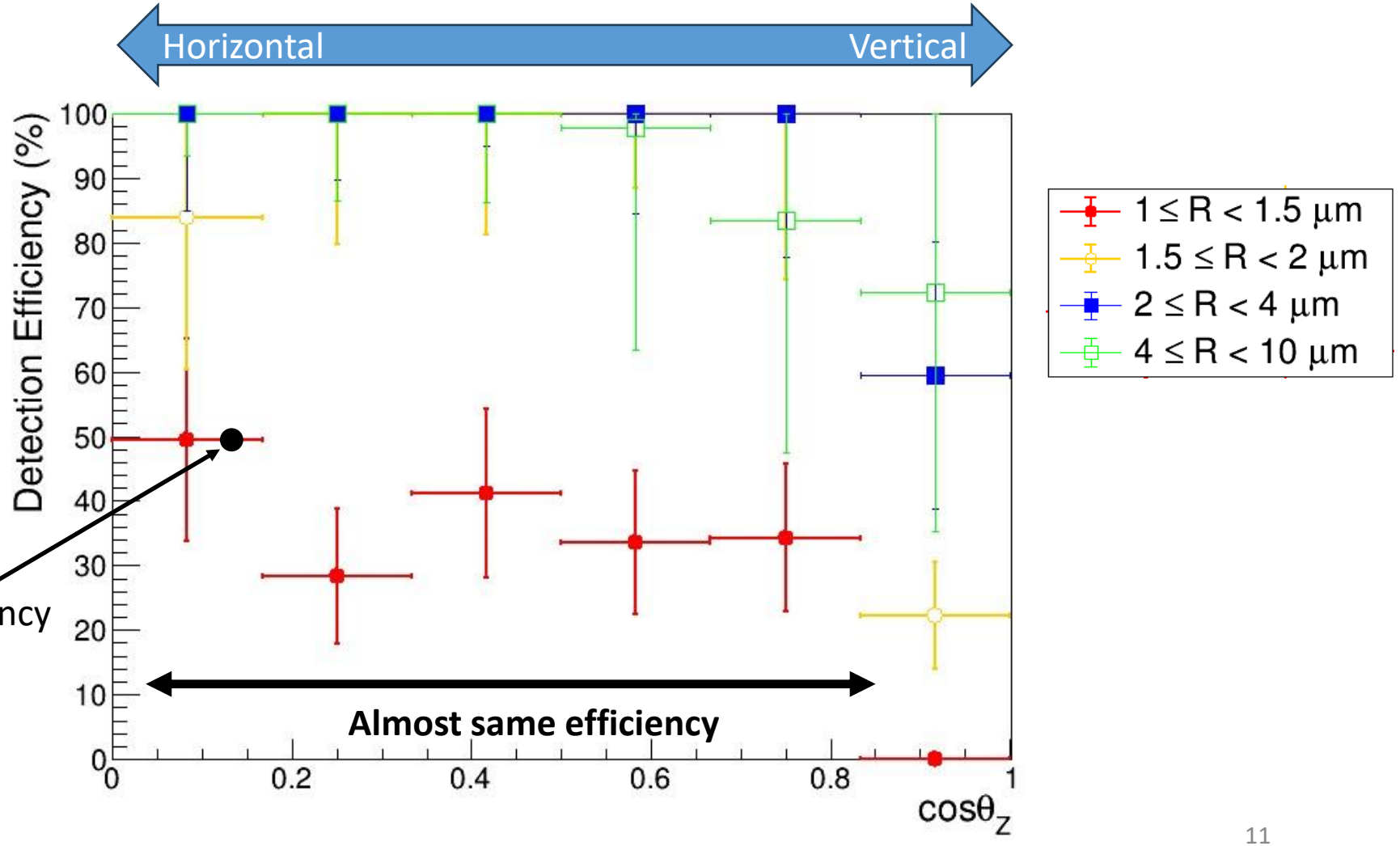
Proton Energy of Head-on Collision



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

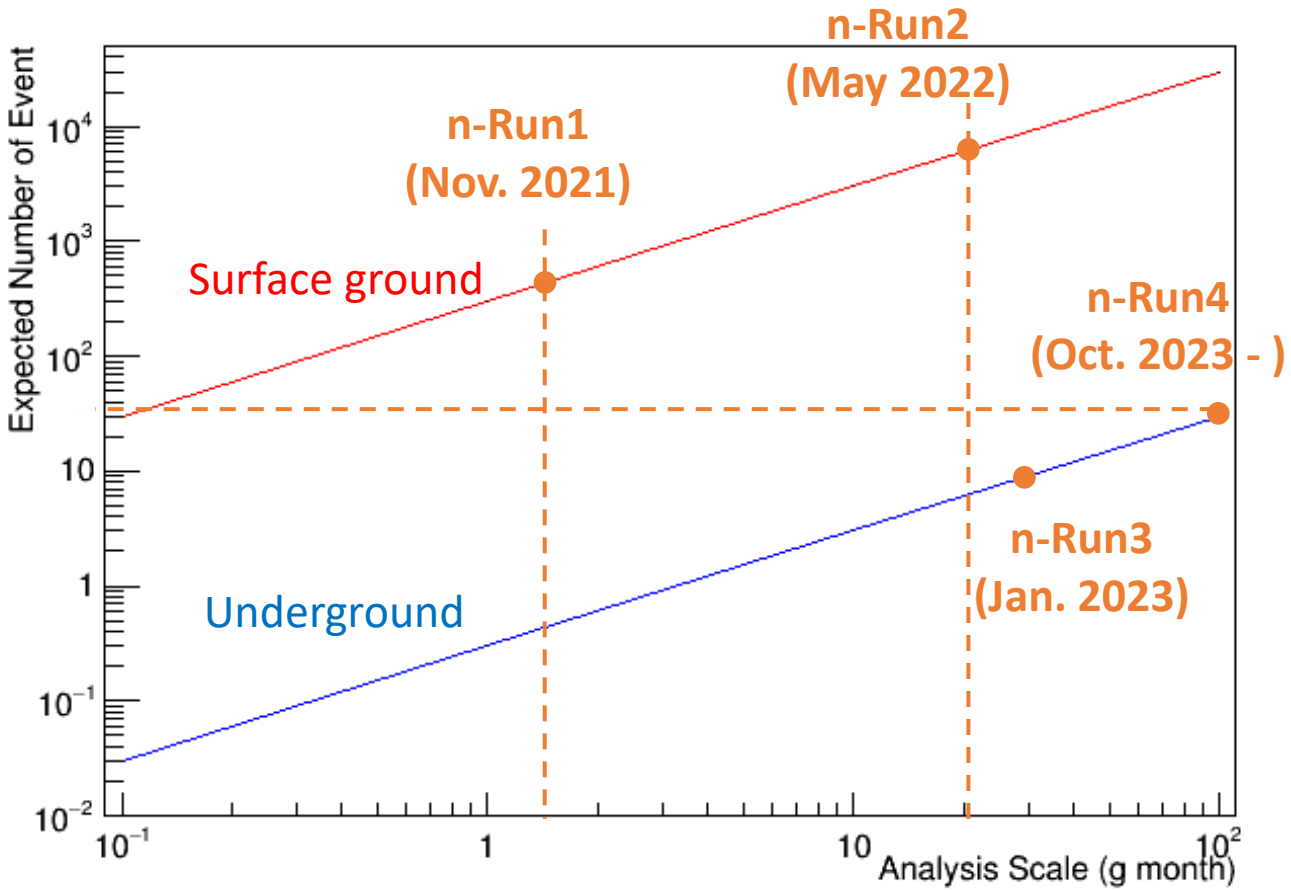
Calibration – Angular and Range Dependency of Detection Efficiency





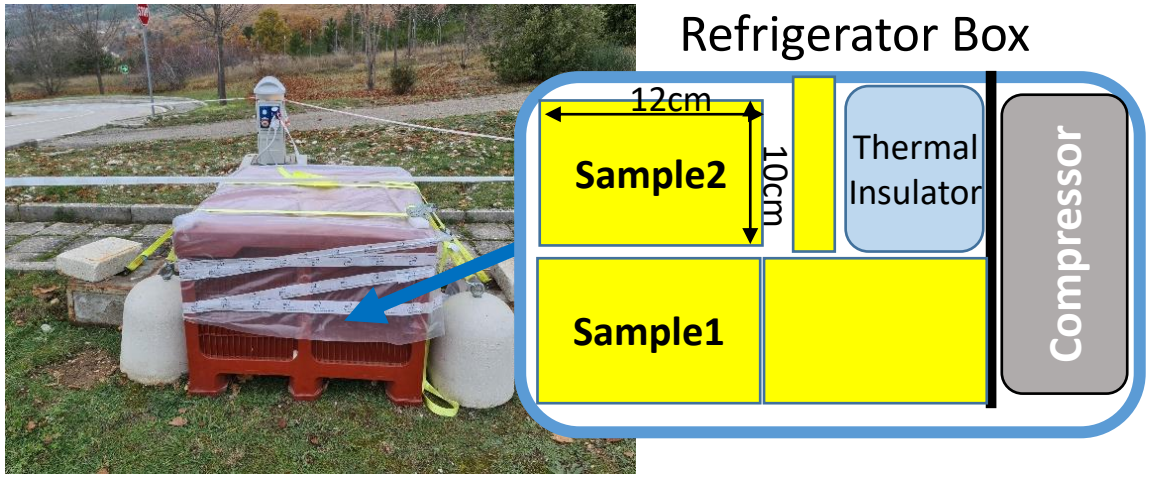
Horizontal 150 keV proton efficiency
~ 50% from ion implantation

Neutron Measurement by NIT @ LNGS



Motivation of Surface Run

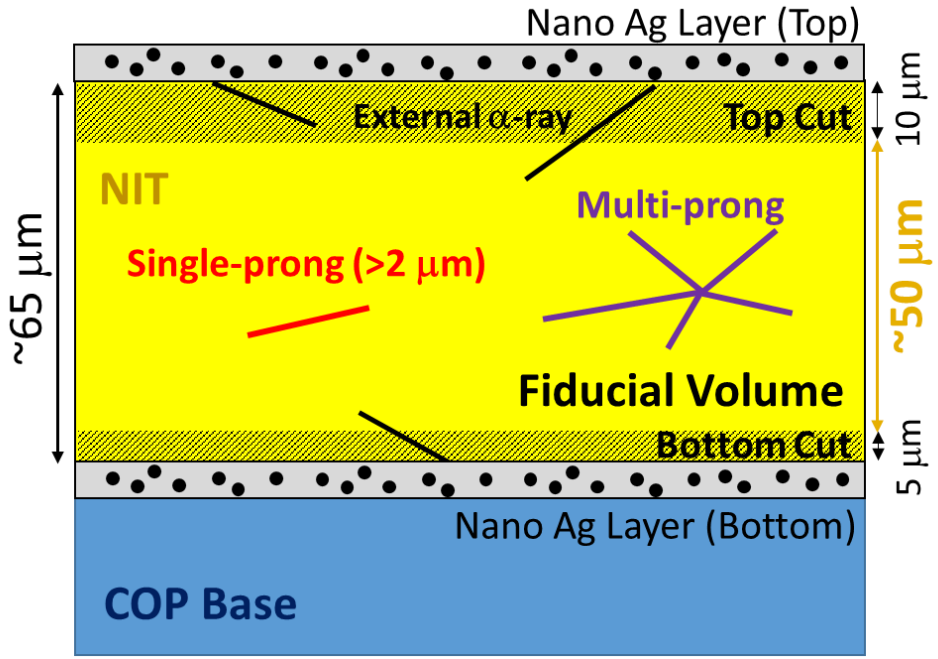
- Demonstration of spectrum measurement for environmental neutron and CR-DM search
- There is no detailed data in the sub-MeV region even on the surface ground



✓ **Without shielding!**

because there is no sensitivity for muon and gamma

Event Classification

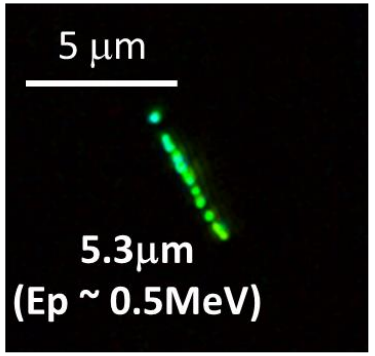


- External α-rays are excluded by fiducial volume cut, then events are topologically classified to **Single-prong** and **Multi-prong**

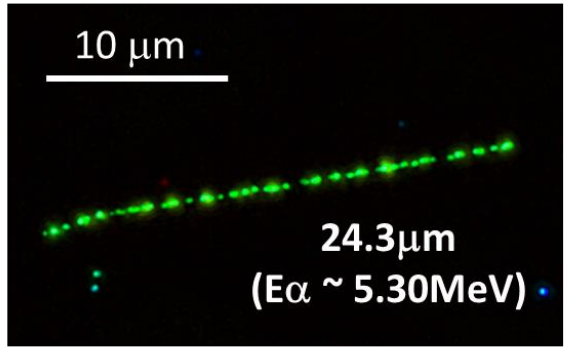
- **Unfortunately, n-Run1 samples accumulated a lot of Radon daughters, we focused on sub-MeV region (2~14μm → 0.25~1MeV) of Single-prong event to analyze with background free**

Single-prong Event

Neutron elastic scattering

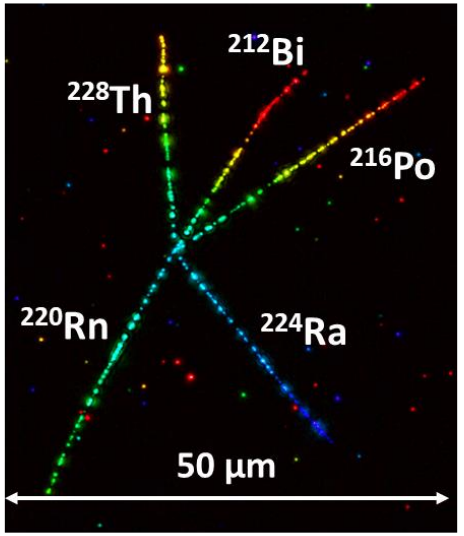


Single α-decay from ^{210}Po

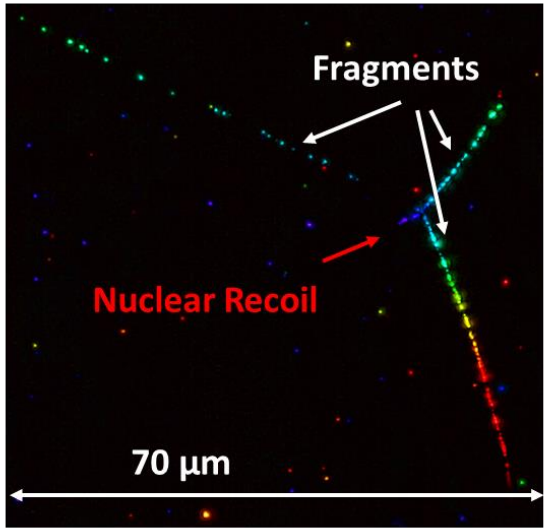


Multi-prong Event

^{228}Th star (5 prong α-decay)

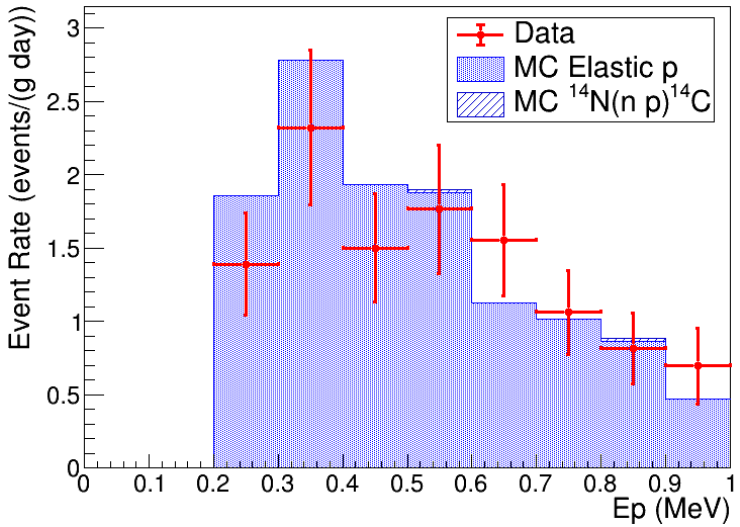


Neutron inelastic scattering

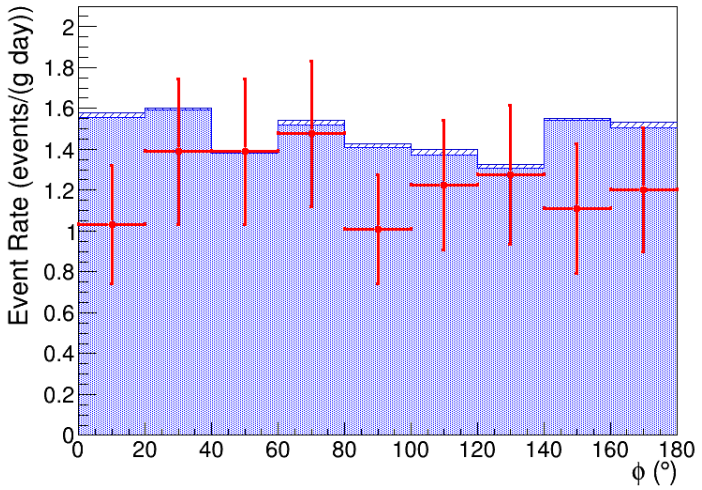


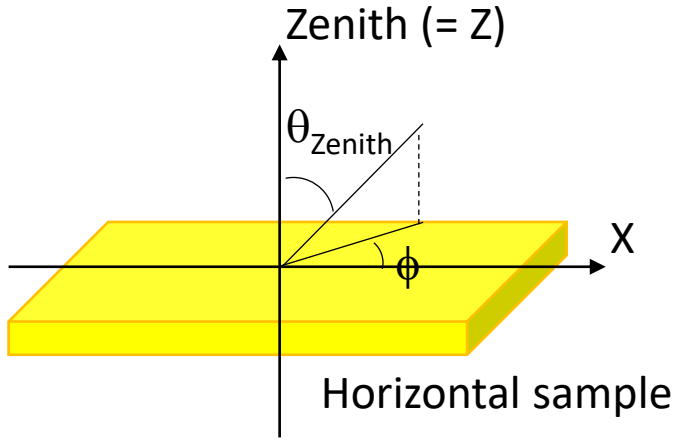
Data/MC Comparison (n-Run1)

Proton Energy

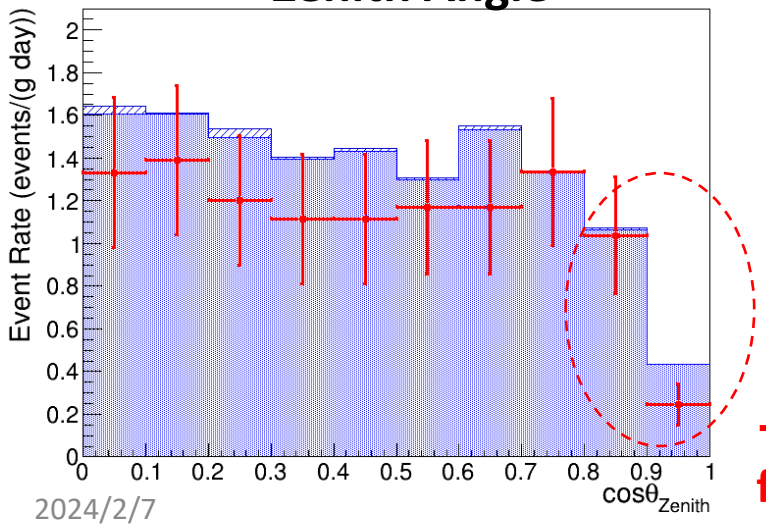


Plane Angle





Zenith Angle



Number of Events

MC : 11.9±0.5 event/g/day

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

→ **Due to low efficiency for vertical**

Neutron Flux [0.25 ~ 10 MeV]

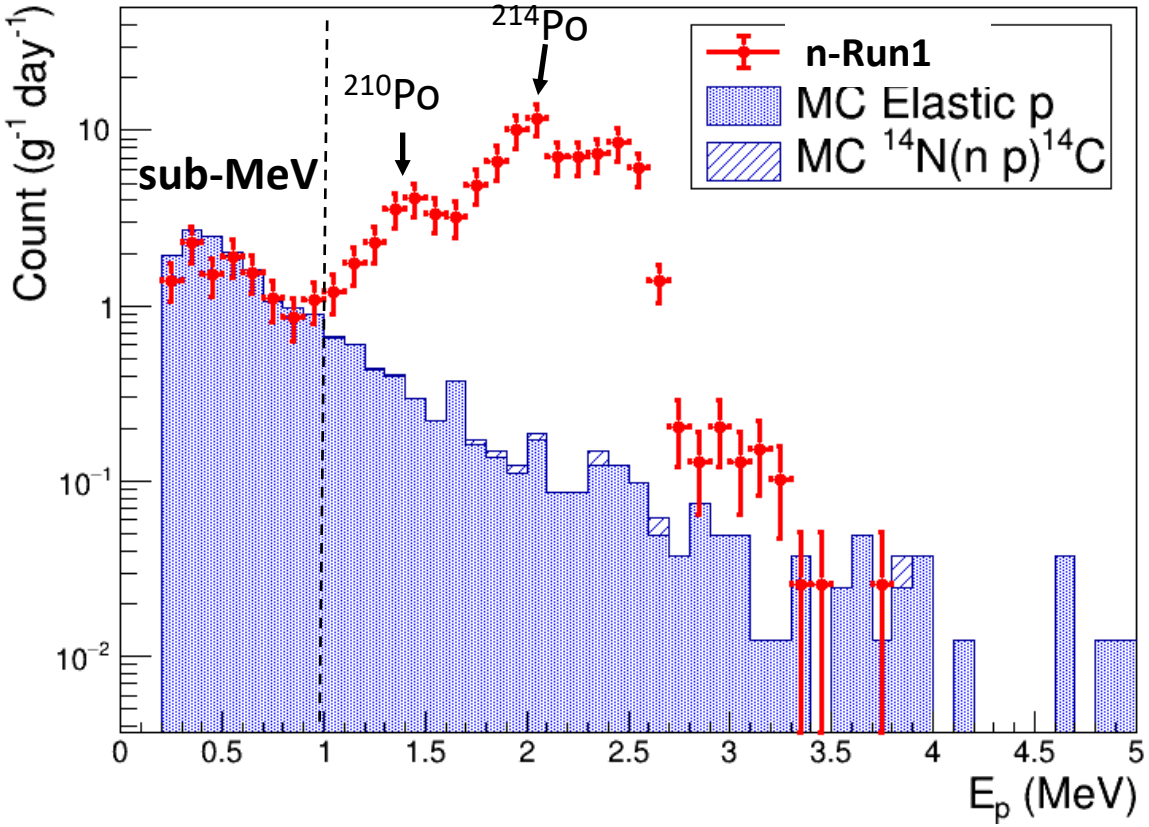
PARMA model : 9.0 x 10^{-3} cm^{-2} s^{-1}

Data : (8.4±1.8) x 10^{-3} cm^{-2} s^{-1}

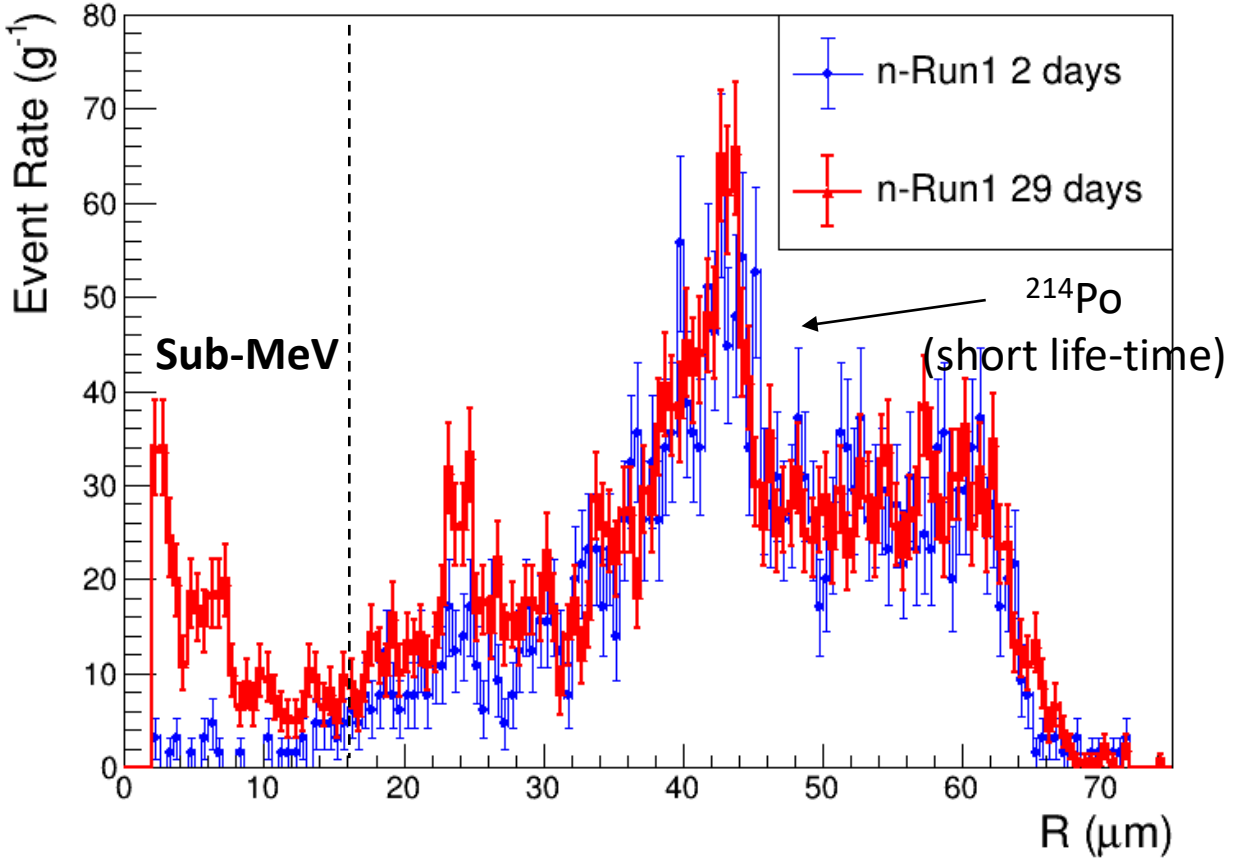
T. Shiraishi, *et al.*, Phys. Rev. C **107**, 014608 (2023)

MeV Region (n-Run1)

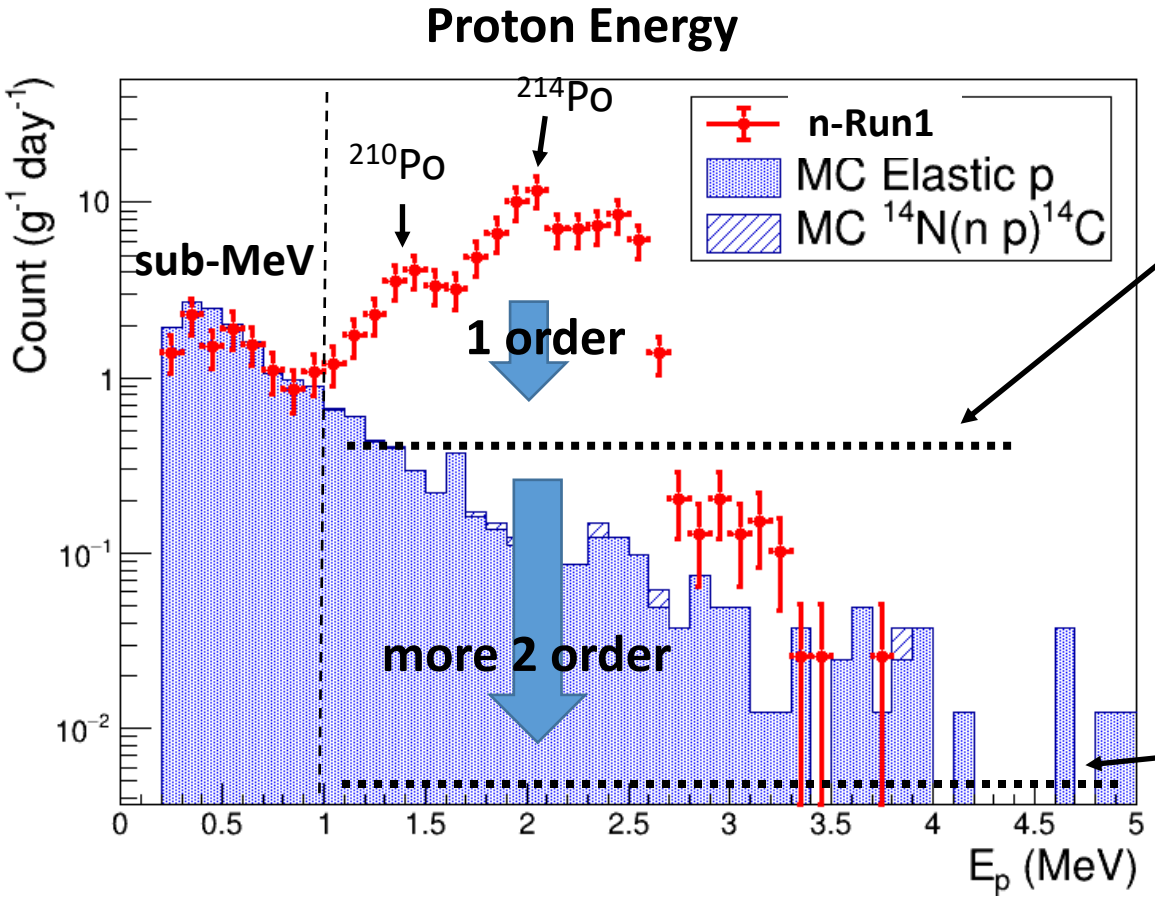
Proton Energy



Track Range



Reduction of ^{214}Po Contamination at Drying



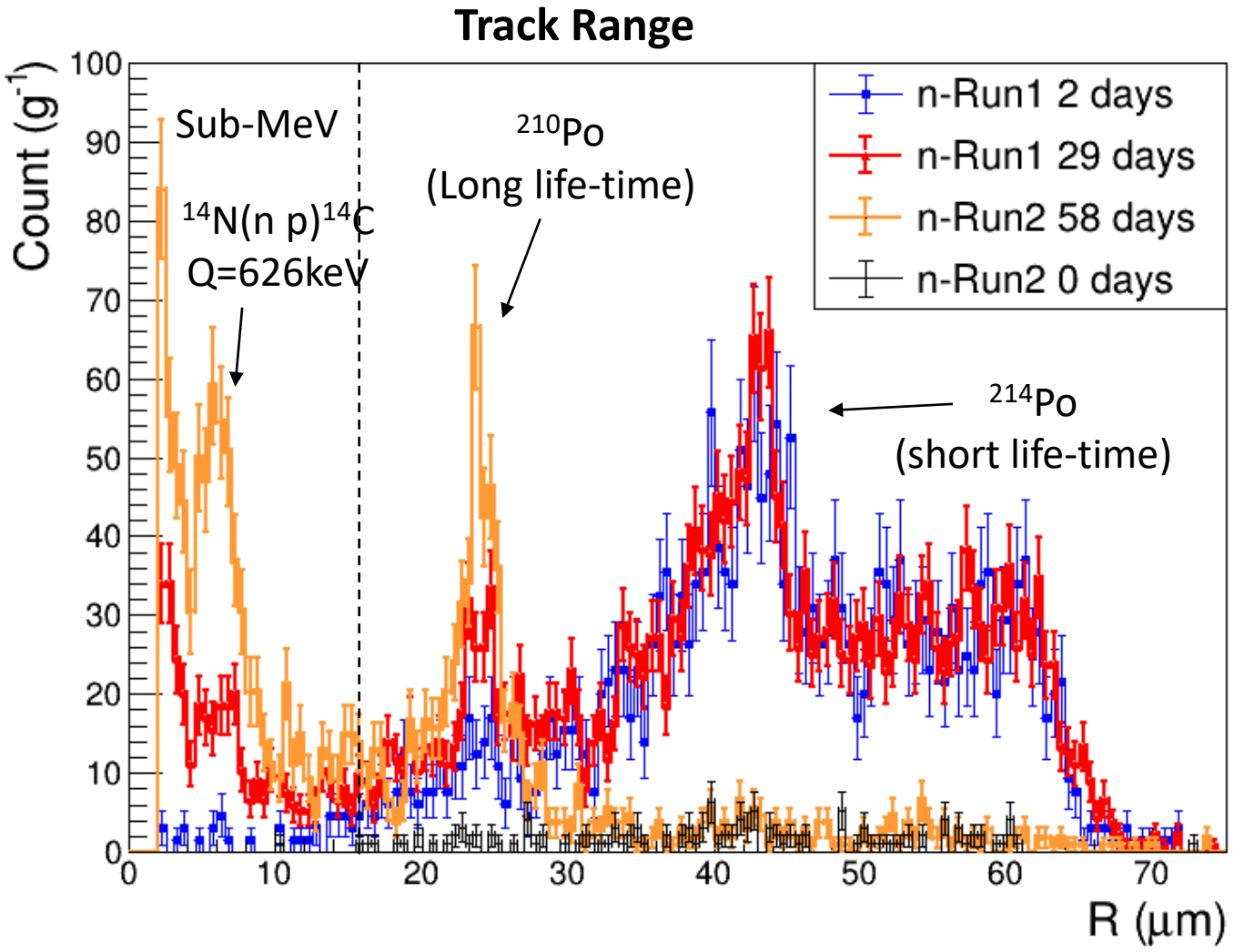
Hall F (NEWSdm facility)

n-Run2, n-Run3
(climatic chamber)

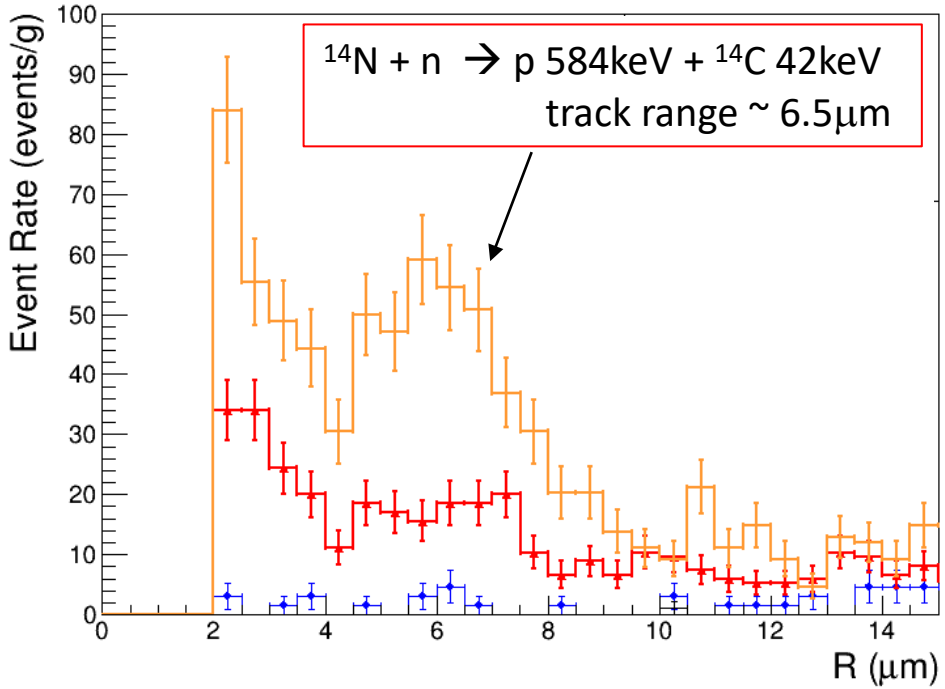
n-Run1
(granite table)

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

n-Run1 and n-Run2 Result



Sub-MeV region

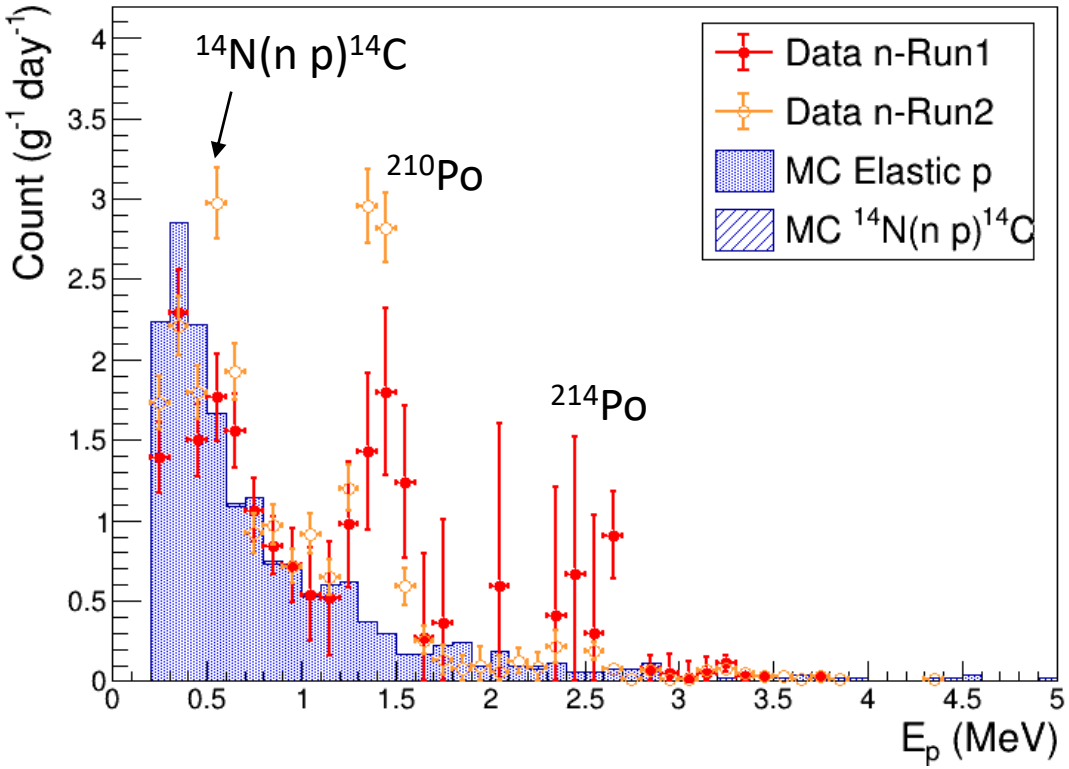


✓ **予想通り、**
- ✓ **sub-MeV 中性子信号と^{210}Po-αは時間に依存して増えた**
- ✓ **MeV領域のオフセットBG（^{214}Po-α）は減った**

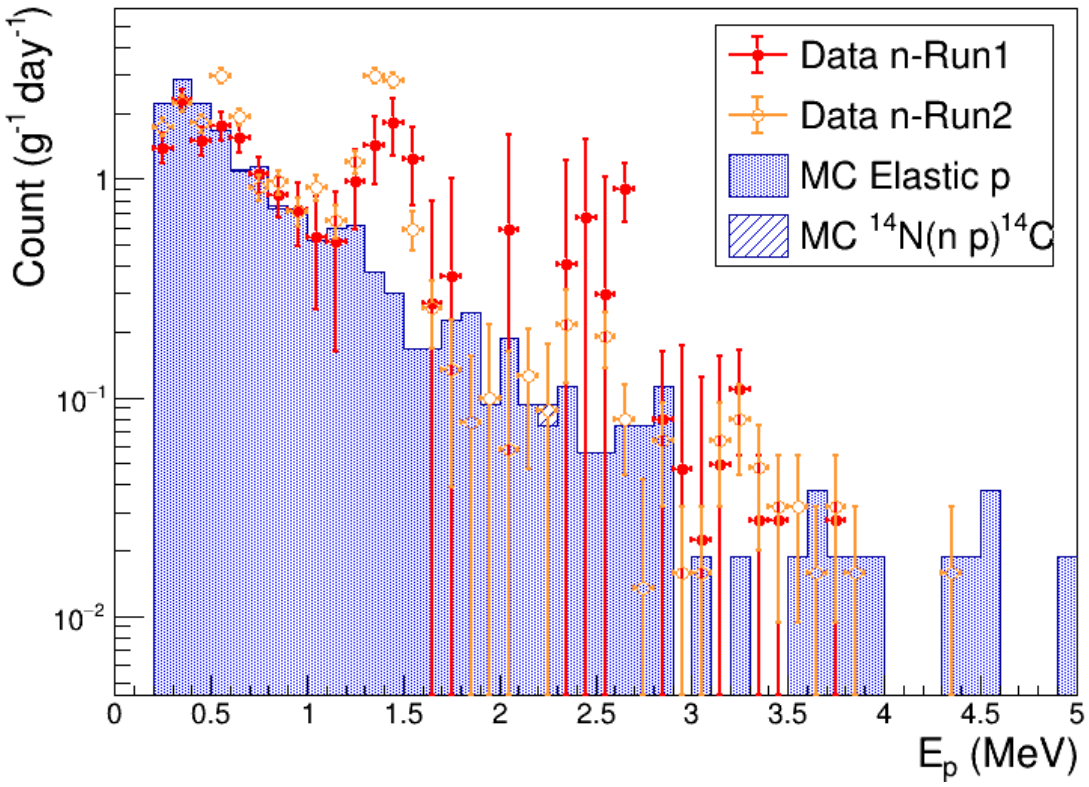
熱中性子信号がはっきり見えるようになった？
→周辺物質で熱化？
岩盤中の水分による減衰が抑制？

Surface Run Result (*after reference subtraction)

Proton energy spectrum (linear scale)



(log scale)



✓ オフセットBGを減らしたことにより、MeV領域のスペクトルがMCでの予想にかなり近づいた

Neutron Run Go to Underground

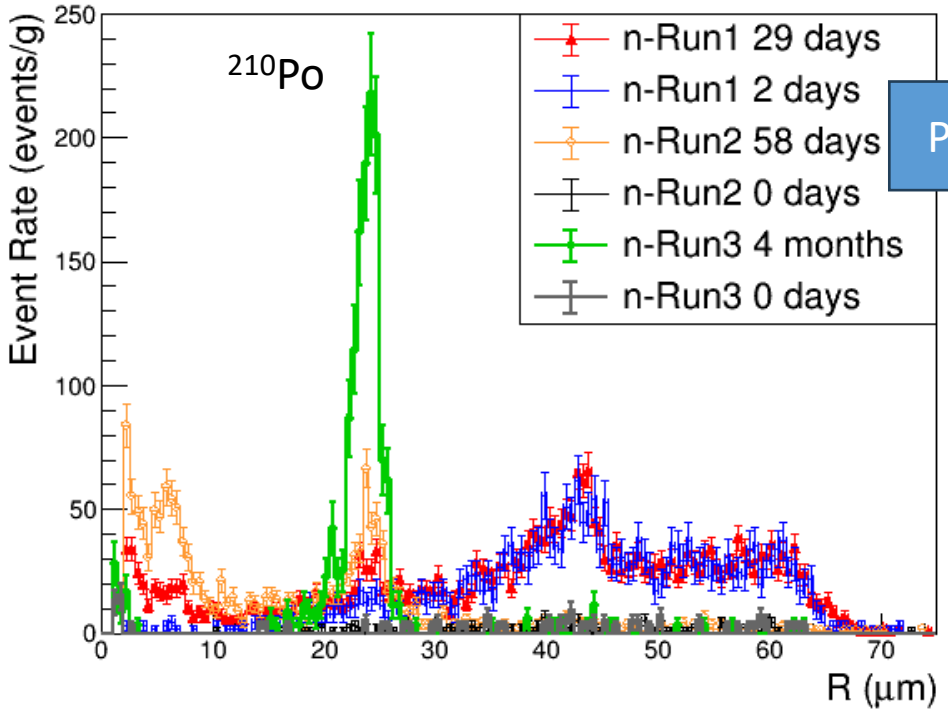
	Installed Place	^{214}Po contamination (/g)	Exposure Time (days)	Experimental Scale (g*month)	Analyzed Scale (g*month)	Proton Energy Threshold (keV)
n-Run1 (Nov. 2021 -)	Surface ground	O(1000)	29	2	1.3	250
n-Run2 (May 2022 -)	Surface ground	O(100)	58	20	2.1	250
n-Run3 (Jan. 2023 -)	Underground Hall C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

At least 10 g*month scale is needed for underground neutron measurement

n-Run3 (Underground) Result

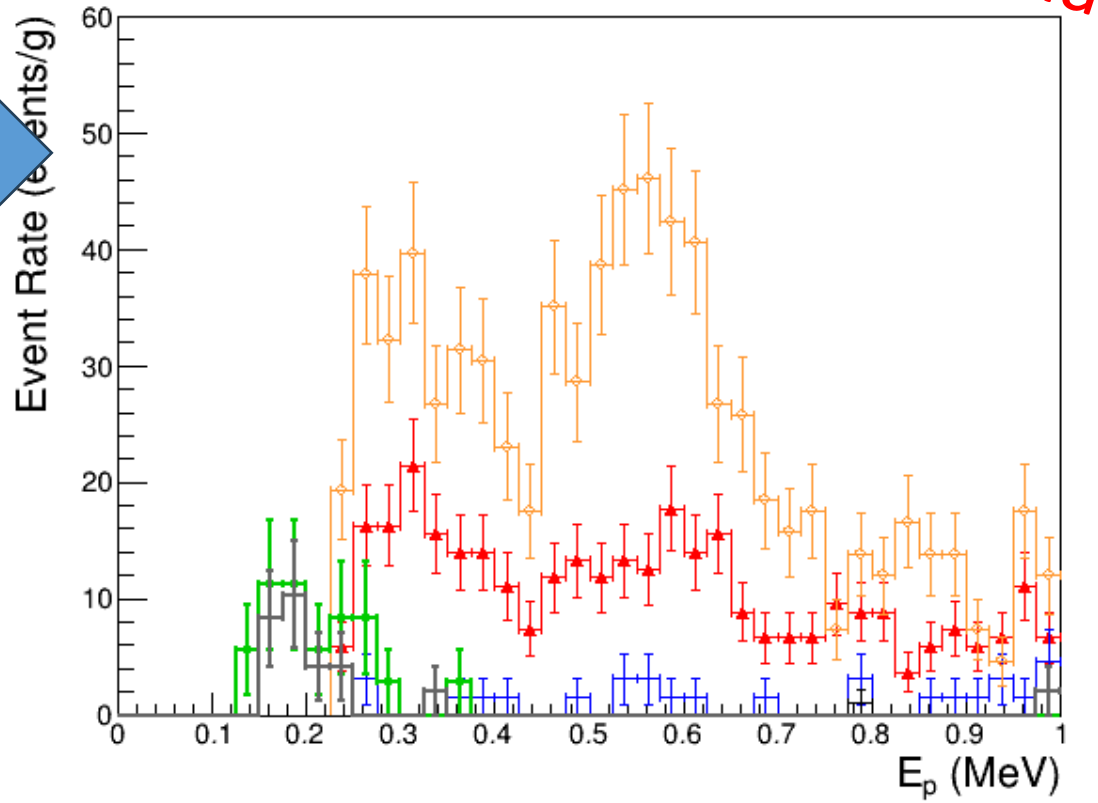
Preliminary

Track Range



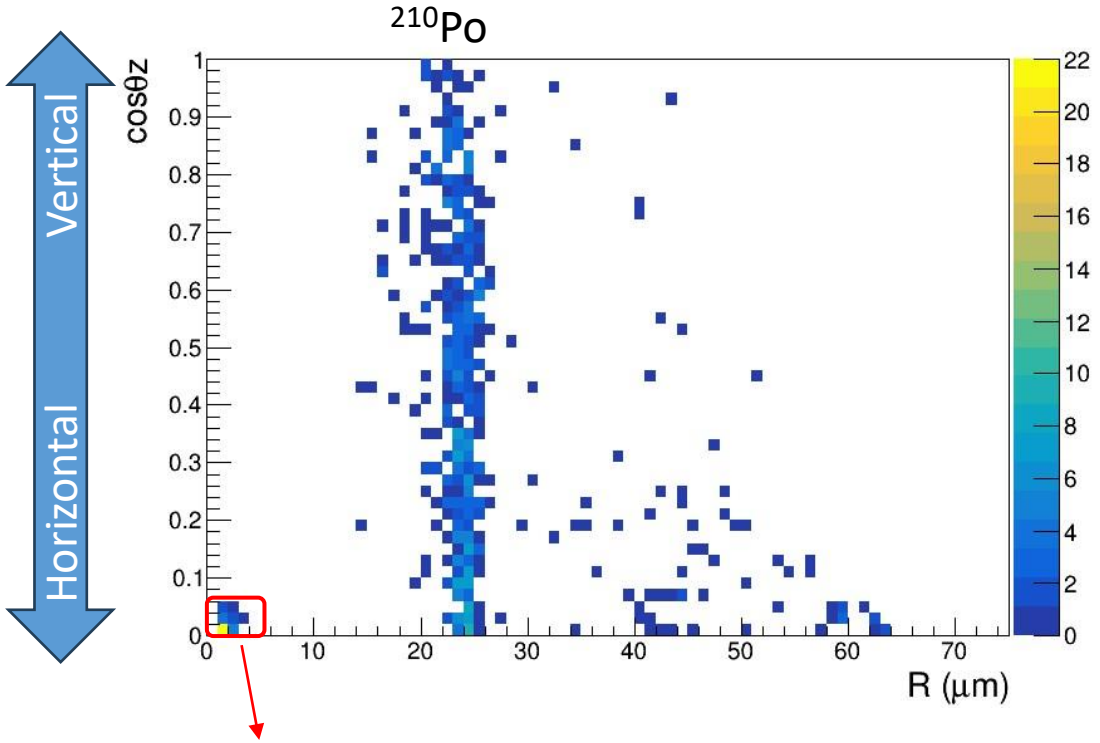
Proton energy

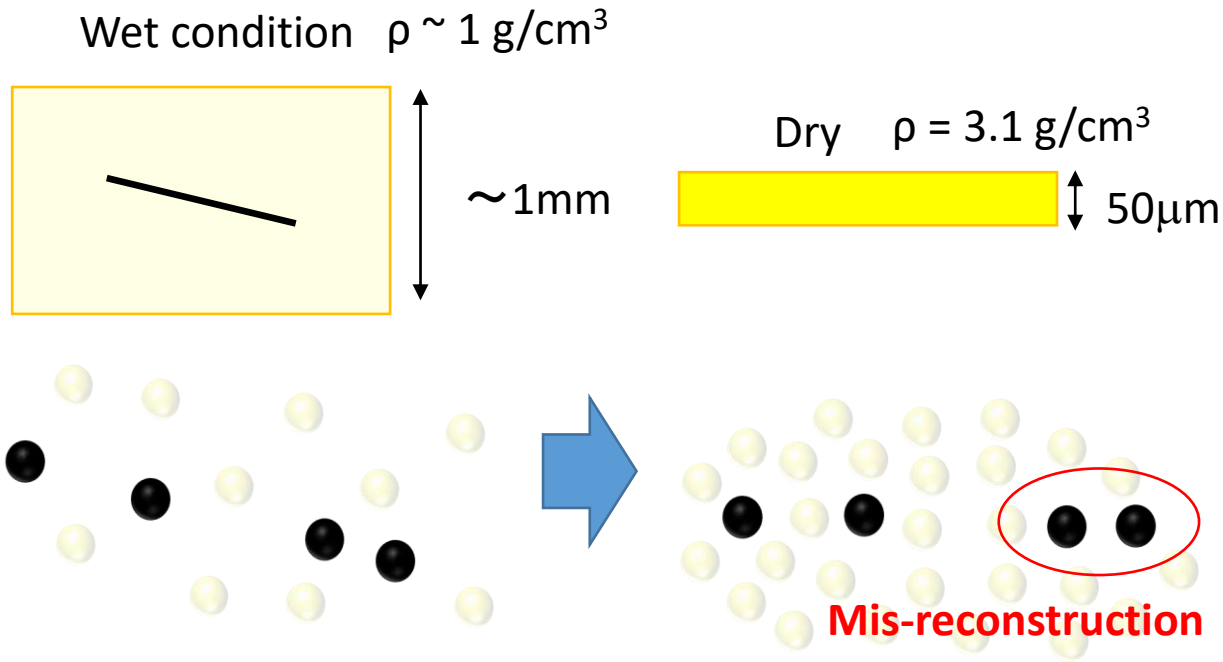
Proton Energy in sub-MeV



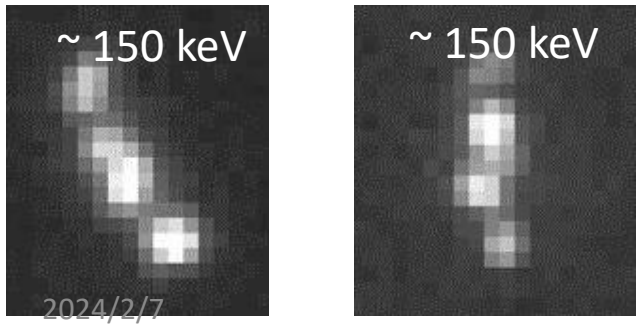
- ✓ 地下Runのため、sub-MeV帯の信号はかなり減ることを確認
- ✓ 300 keV 以下に時間依存のないオフセットBGあり
  →非物理事象

n-Run3 (Underground) Result





300 keV 以下のSignal-like はすべて水平な飛跡

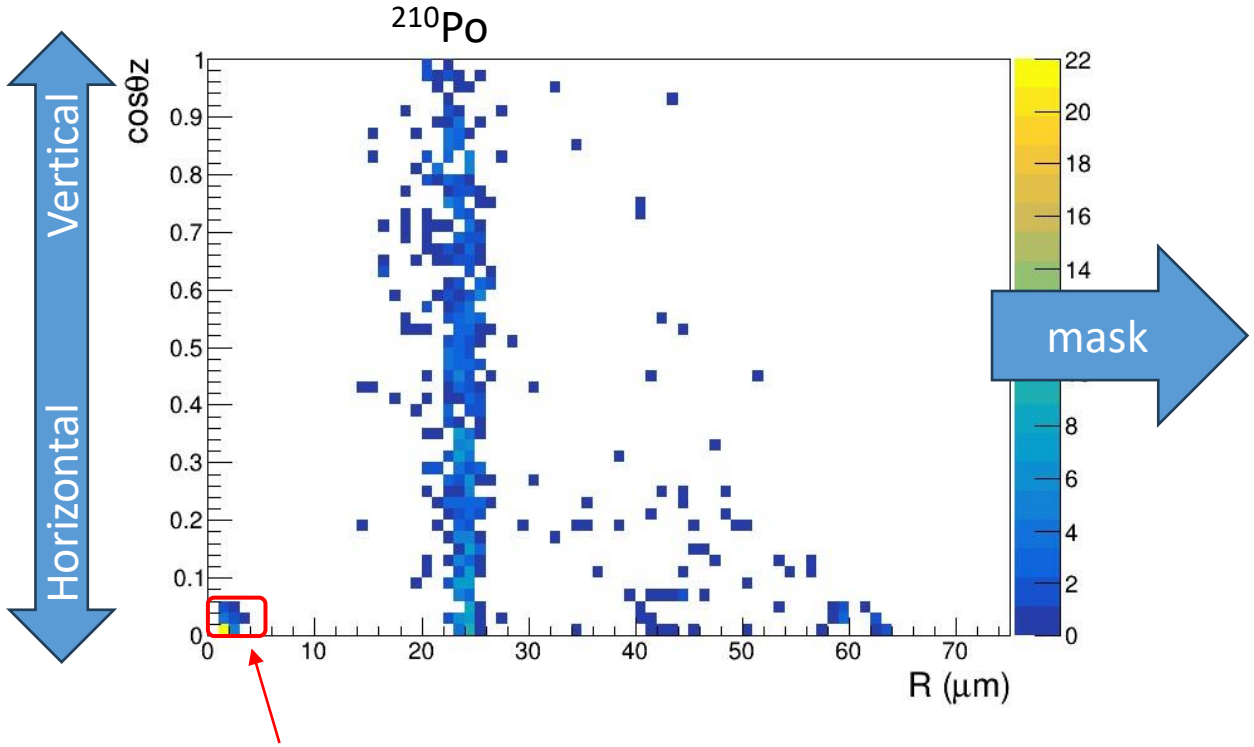


- 乳剤乾燥中に^{214}Po が混入すると、α線の一部を誤認する可能性？

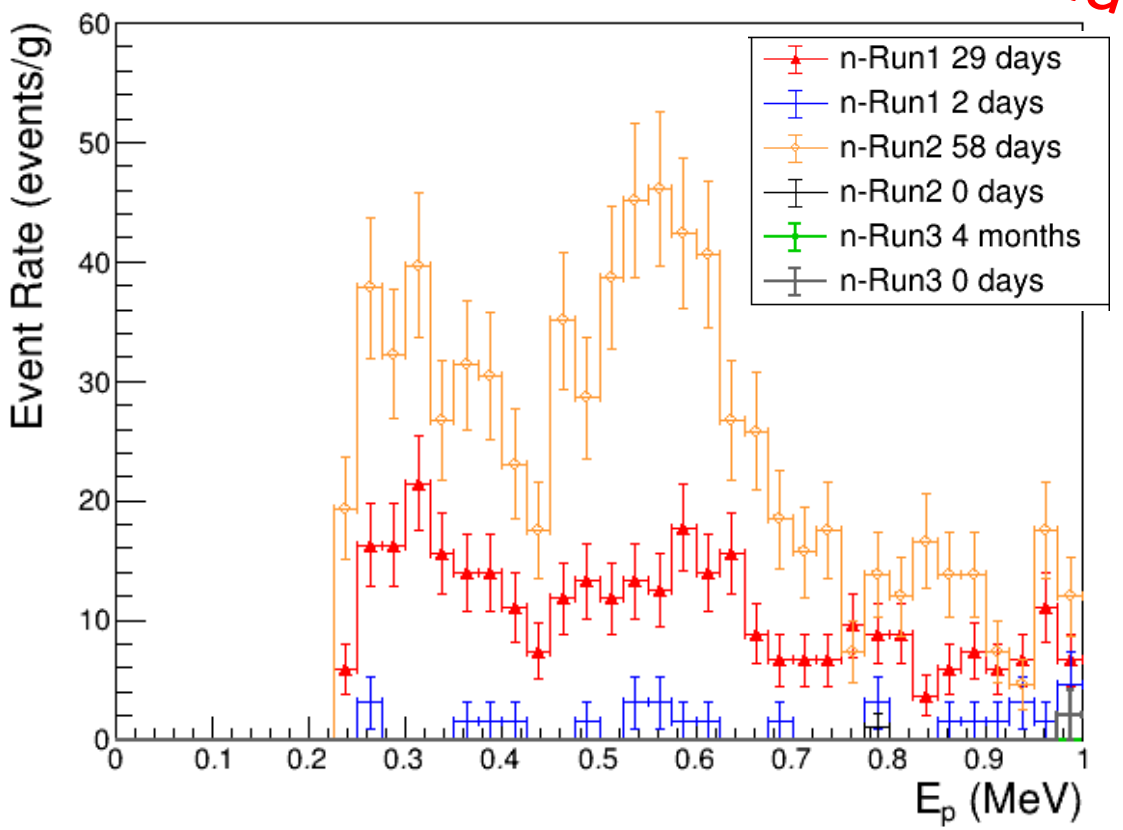
→ 現在設置中のn-Run4 (low ^{214}Po contamination)で確認する

n-Run3 (Underground) Result

Preliminary



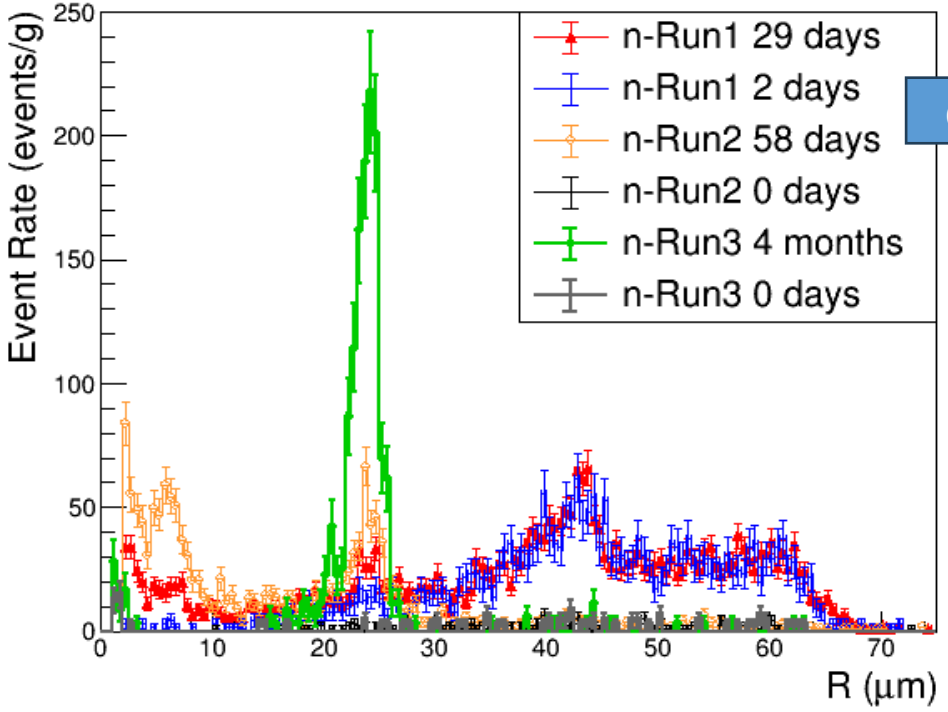
Mask cosθz < 0.05 && range < 3μm



✓ 低エネルギー&水平の領域を避ければ、sub-MeV帯にexcessはなし

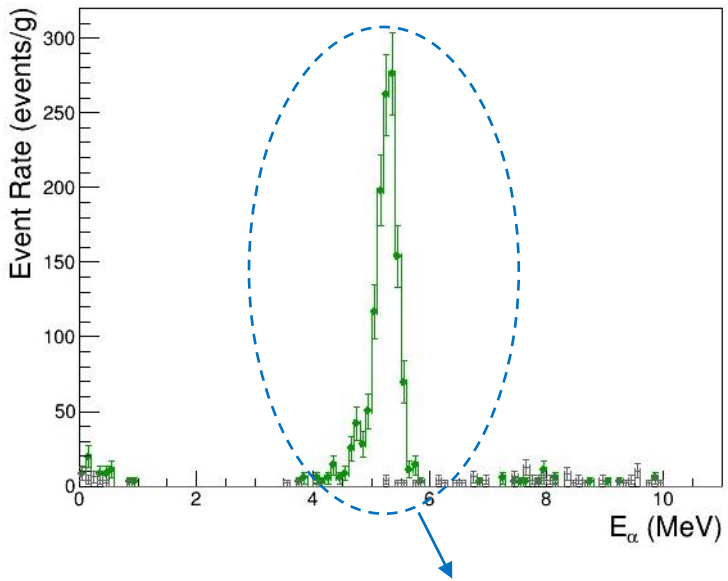
n-Run3 α-ray Analysis

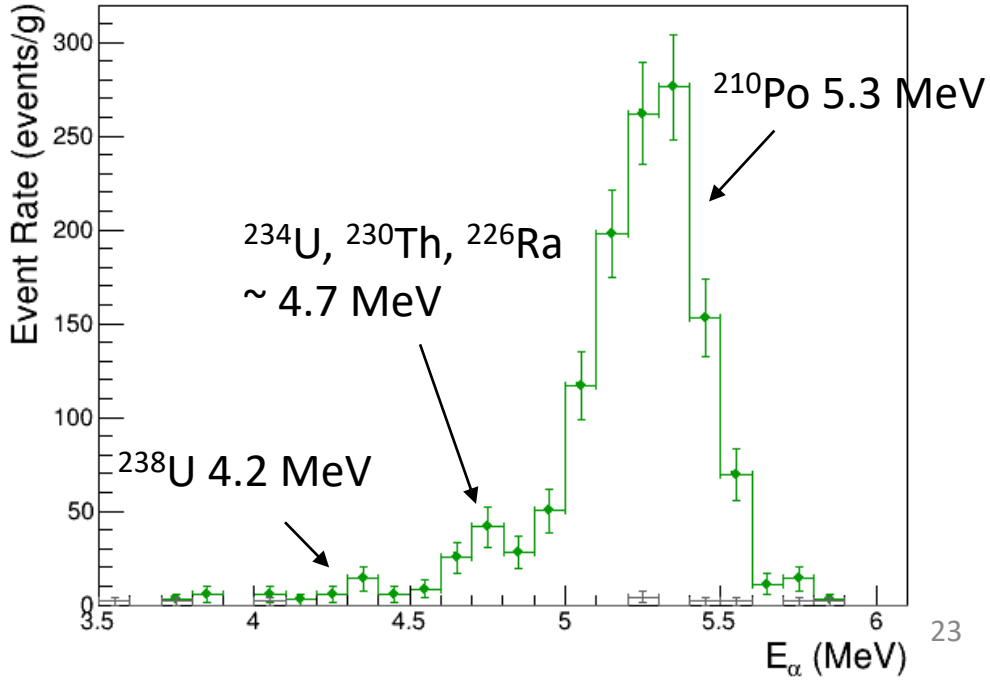
Range distribution



α energy

n-Run3 4 month

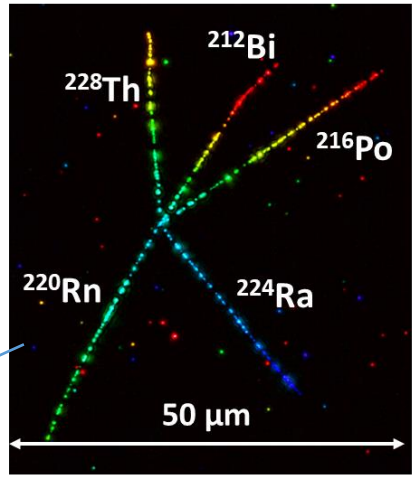




Intrinsic α Activity

α Multiplicity	Expected # of event by Ge detector (g^{-1} $month^{-1}$)	# of event from n-Run1 (g^{-1} $month^{-1}$)	# of event from n-Run3 (g^{-1} $month^{-1}$)
5 (^{228}Th to ^{208}Pb)	16±2 (Th)	15±5	15±3
1 (^{238}U)	2.1±0.5 (U)	---	8.4±1.4
1 (^{234}U, ^{230}Th, ^{226}Ra)	6.3±1.5 (U)	---	26±3
1 (^{210}Po)	2.1±0.5 (U) +^{222}Rn contaminated	165±16	790±23

^{228}Th star (5 prong α-decay)



γ-ray measurement by Ge detector
(^{228}Th: 6.0±0.6 mBq/kg)
(^{226}Ra: 0.8±0.2 mBq/kg)

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

Summary

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

- 3-dimensional sub-micrometric tracking technique has been developed for NIT analysis
  - Achieved 100 keV threshold analysis for recoil proton with 0.5 kg/year/machine

  →Analysis speed will be further upgraded to 1.5 kg/year/machine

- Neutron run in Gran Sasso
  - Surface run (n-Run1, nRun2)
    - Succeeded to measure neutron spectrum and direction → T. Shiraishi, *et al.*, Phys. Rev. C **107**, 014608 (2023)
    - ^{214}Po contamination problem was found in MeV region

      → **Solved by using radon free room at the sample preparation in current experimental scale**

  - Underground run (n-Run3, nRun4) Preliminary
    - Aiming 100 g*month scale to measure neutron spectrum
    - Unknown horizontal background were found in < 300 keV
      - Maybe mis-reconstruction of alpha accumulated at wet condition?
      - If we avoid this region, there is no signal in sub-MeV region as expected
    - n-Run4 with further 2 orders lower ^{214}Po contamination is now ongoing

Backup