Environmental neutron measurement at the Gran Sasso laboratory in the NEWSdm experiment

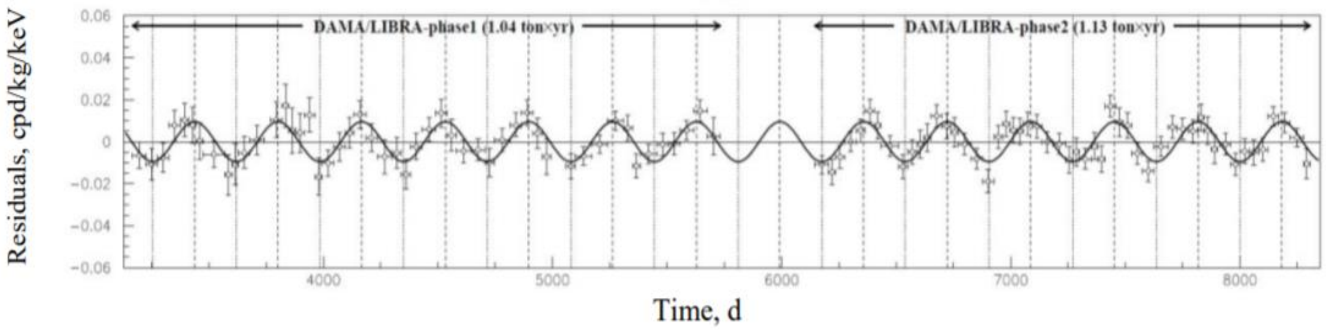
T. Shiraishi - Kanagawa Univ.
On the behalf of the NEWSdm collaboration

14 Dec. 2023   CYGNUS 2023 (Sydney)

For the Verification of DAMA Signal

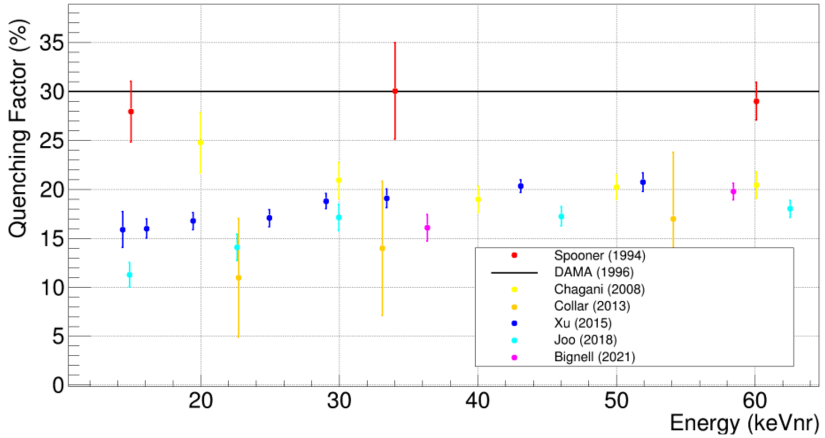
- DAMA claims signal around 2 – 6 keVee

22 years annual modulation



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

- Many experiments agree that quenching factor of Na is ~20%

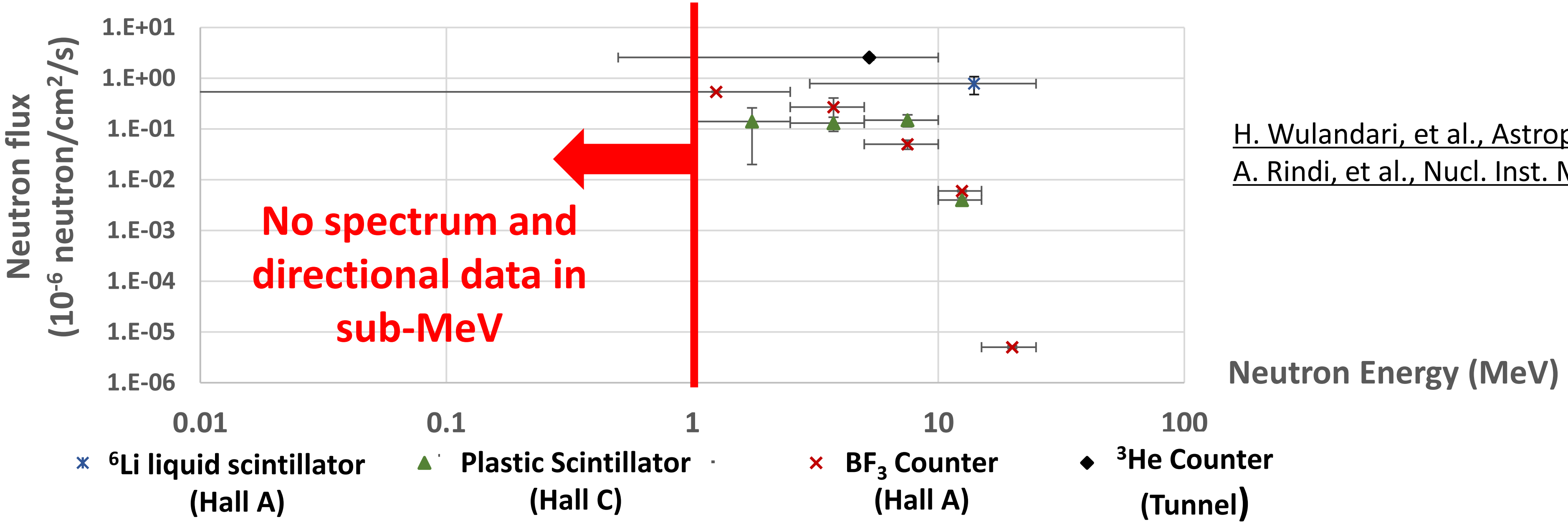


D. Cintas et al, J. Phys.: Conf. Ser. **2156**, 012065 (2021)

Assuming DAMA signal as neutron background, its energy corresponding to 80 – 250 keV

→ Neutron spectrum measurement including sub-MeV region is needed to verify the DAMA signal!

Environmental Neutron Measurement @LNGS



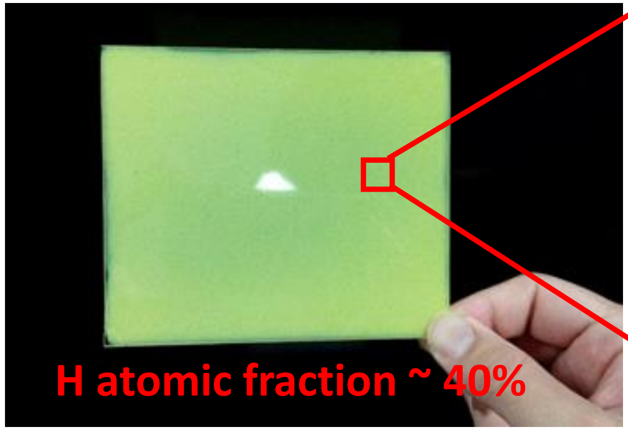
No spectrum and directional data in sub-MeV

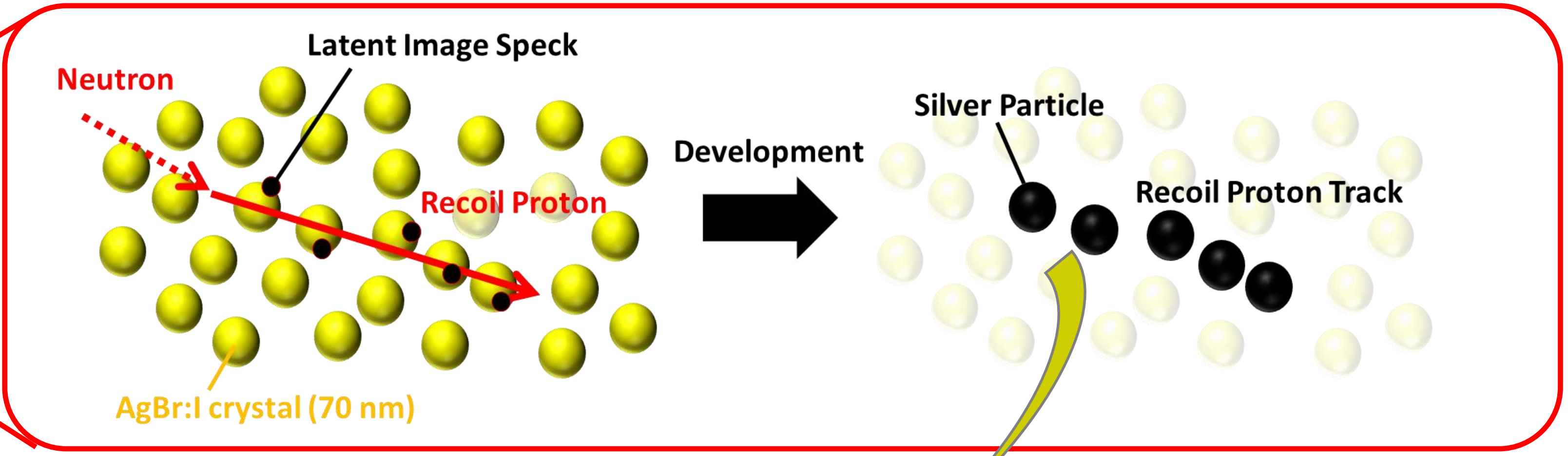
H. Wulandari, et al., Astropart. Phys. **22** (2004) 313.
A. Rindi, et al., Nucl. Inst. Meth. A, **272** (1988) 871.

Neutron Detector	Energy Range	γ-ray rejection power	Energy Resolution	Directionality
Liquid Scintillator	1MeV – 100MeV	Bad	Good	None
BF_3 ,^{3}He 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

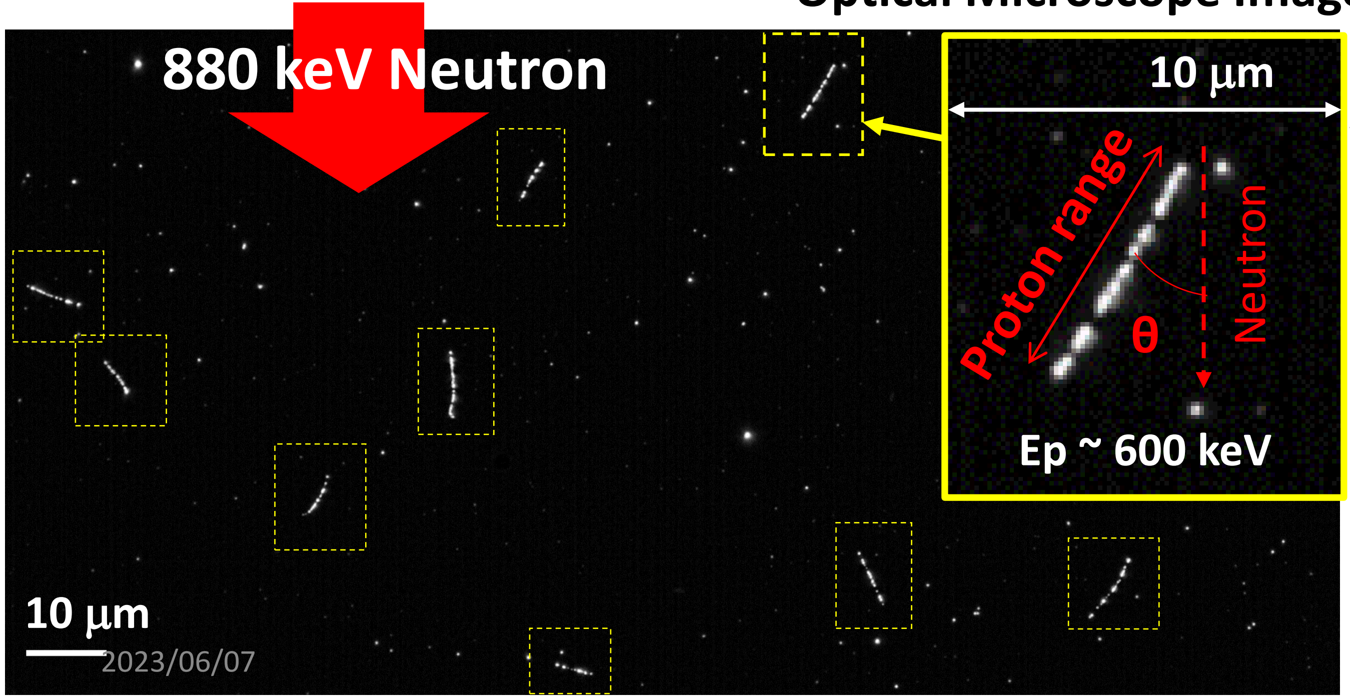
Neutron Detection Principle by Nano Imaging Tracker (NIT)

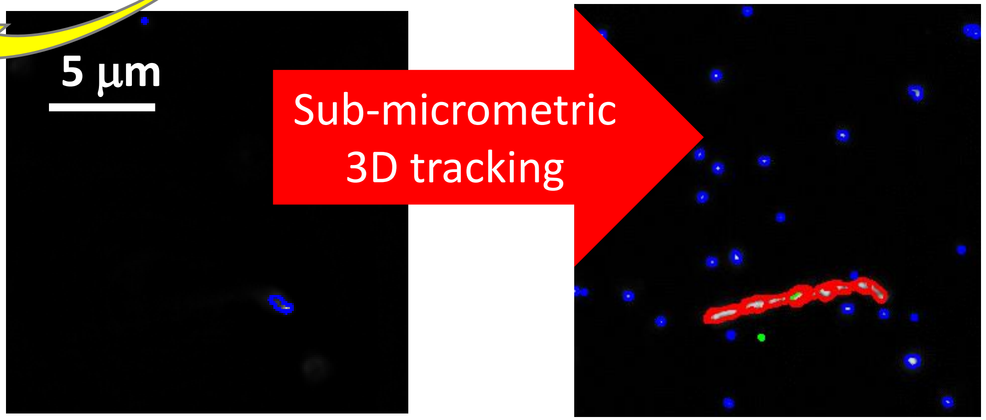
NIT film





Optical Microscope Image





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

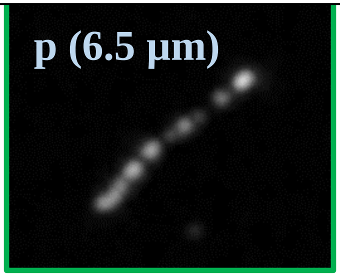
meV (thermal neutron) 100 keV (~ 1 µm) Sub-GeV –

Neutron Capture

Proton Elastic Scattering

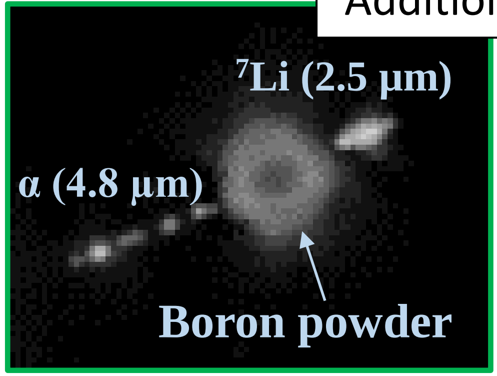
Deep Inelastic Scattering

Self-contained target

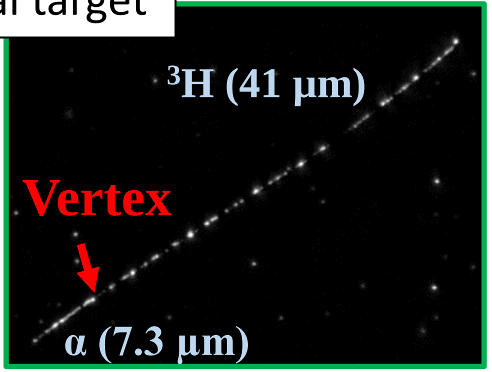


n + ^{14}N → p + ^{14}C + 0.62 MeV
2 barn @ 26meV

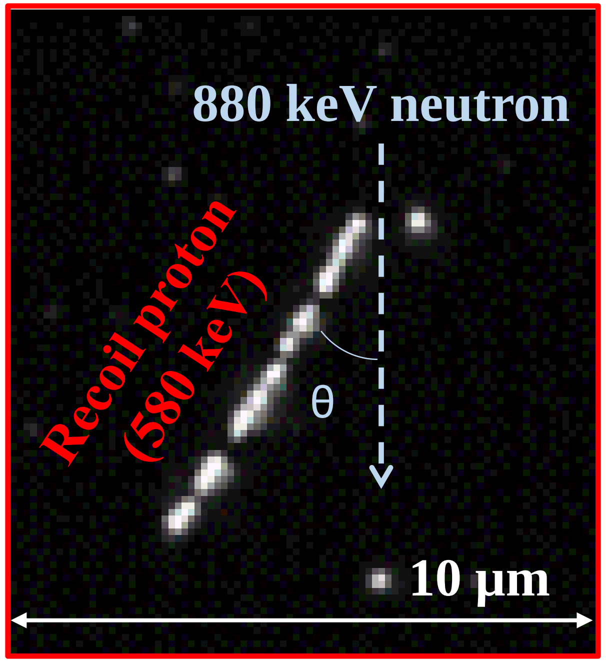
Additional target

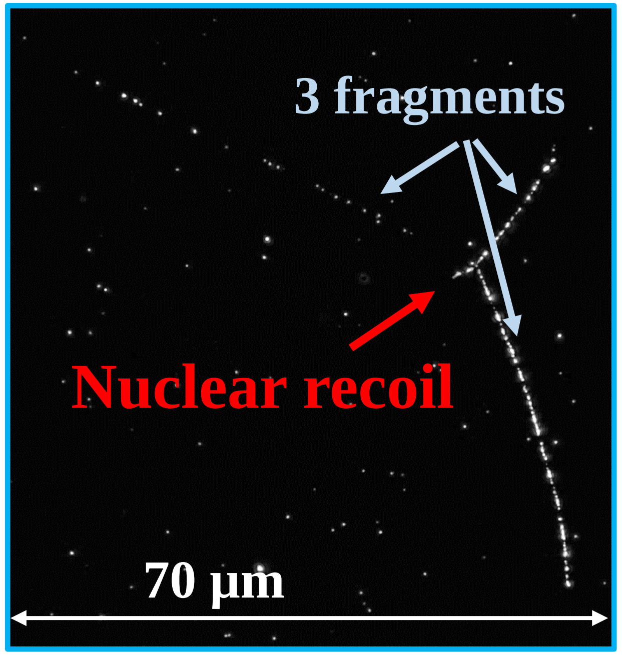


n + ^{10}B → α + ^{7}Li + 2.31 MeV
4000 barn @ 26meV



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

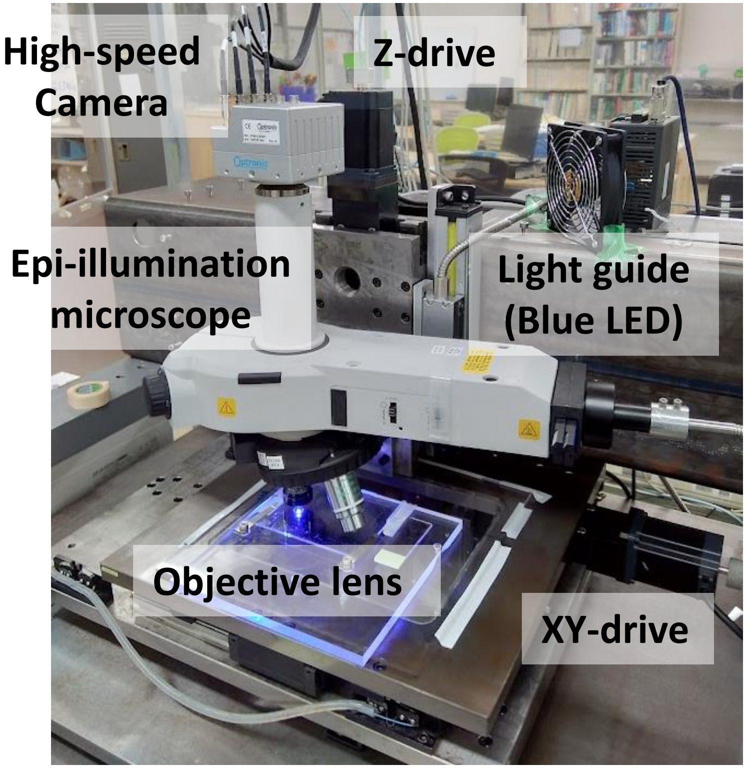


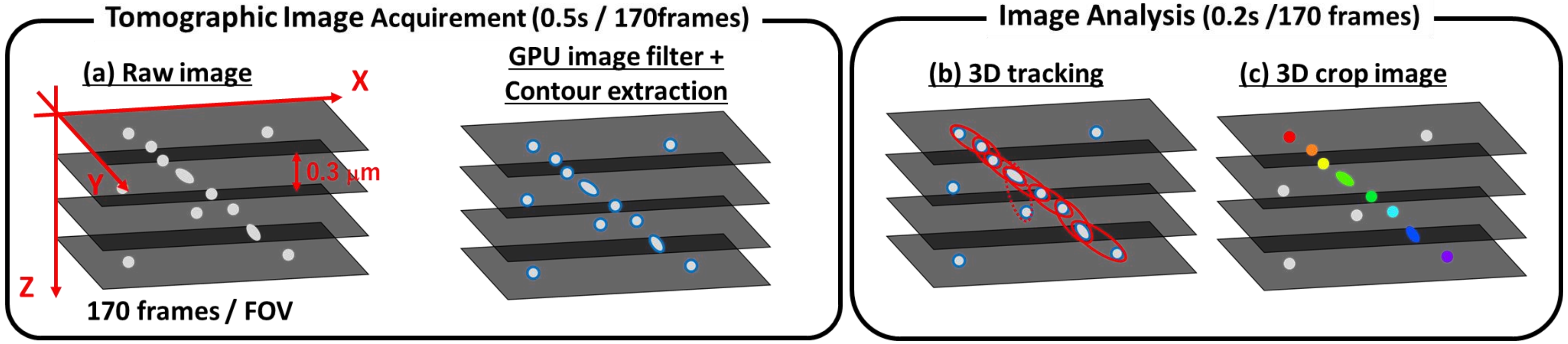


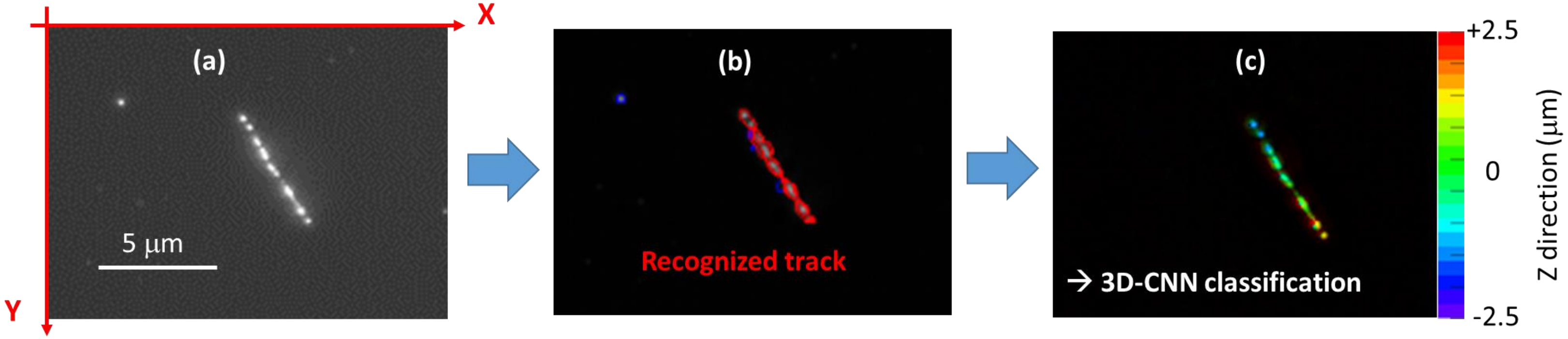
Reconstruct 3D trajectory with sub-micron accuracy
→ can obtain position, energy and direction

High-speed Readout and Image Processes

PTS system @ Toho Univ.







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

T. Shiraishi, *et al.*, PTEP **2021** 4, 043H01 (2021)
T. Shiraishi, *et al.*, Phys. Rev. C **107**, 014608 (2023)

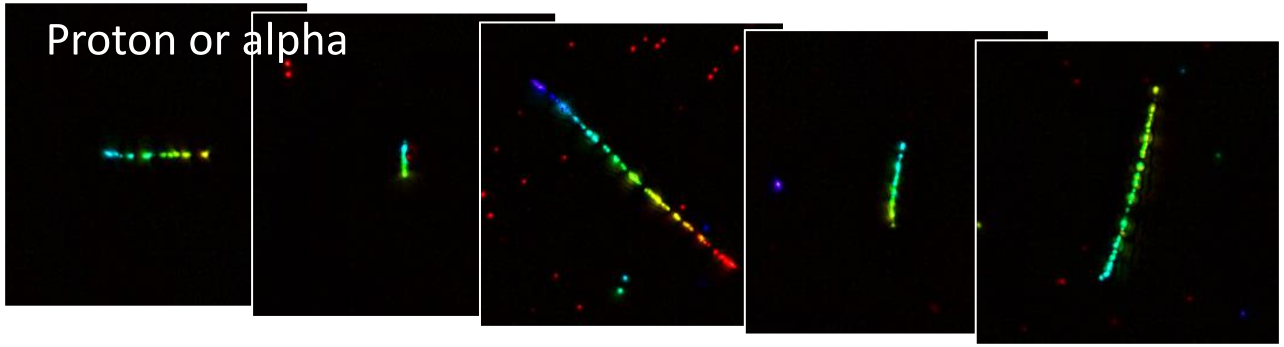
Under constructing an upgraded PTS machine in Kanagawa Univ.

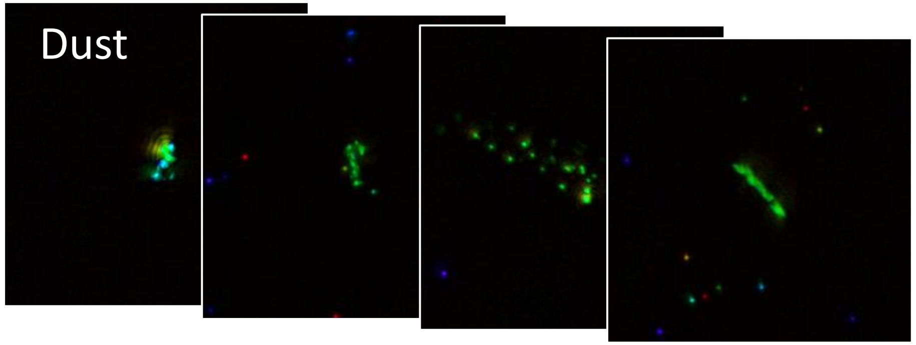
→ expected to be 1.5 kg/year/machine until Apr. 2024

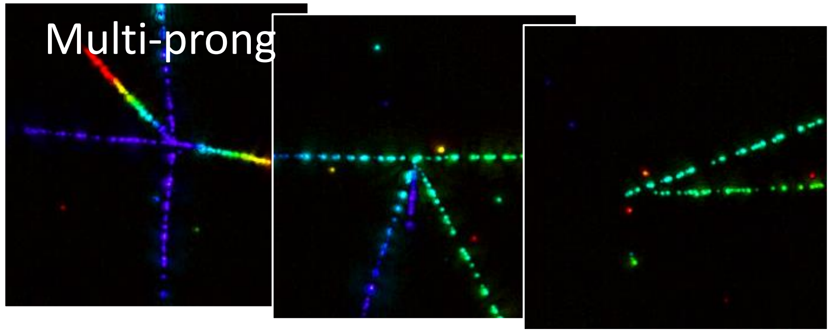
Convolutional Neural Network

*still using 2Dconv for 3D image ☹

Training Samples

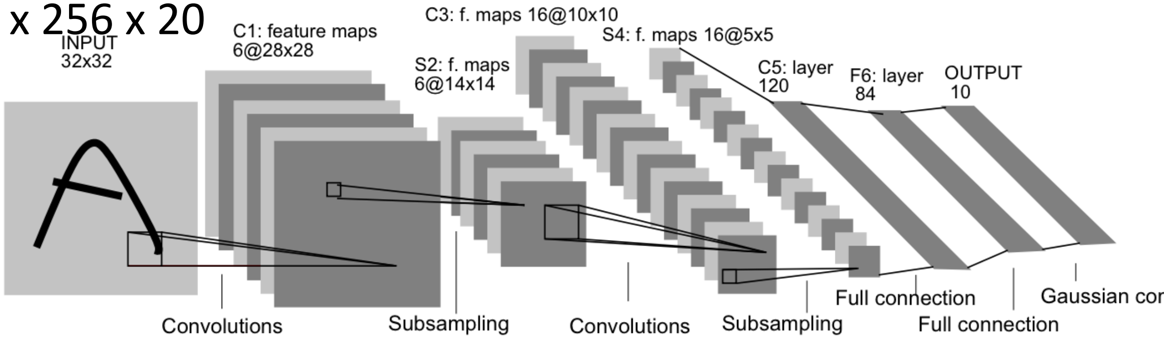

Proton or alpha


Dust


Multi-prong

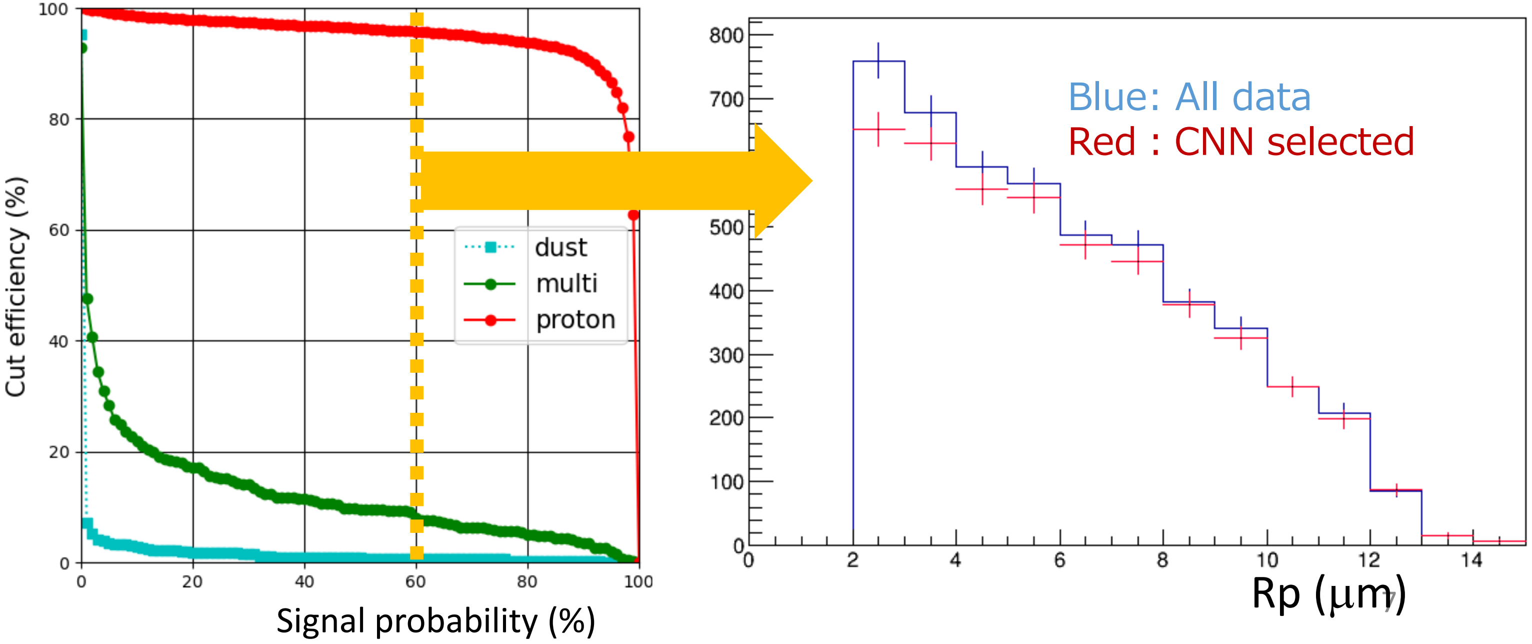
Input image size

256 x 256 x 20



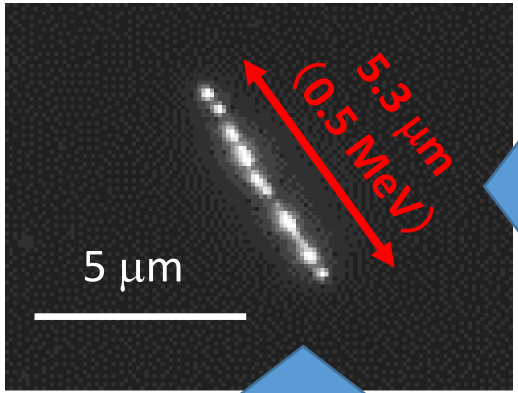
CNN cut efficiency

CNN selection effect (705 keV neutron sample)



Background in Neutron Detection

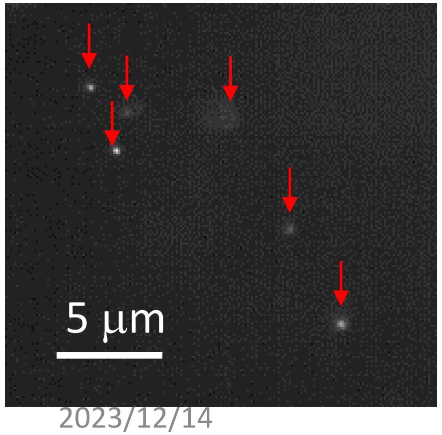
Recoil proton signal



Topological or Range cut

Clearly distinguishable

γ-ray (β-ray)

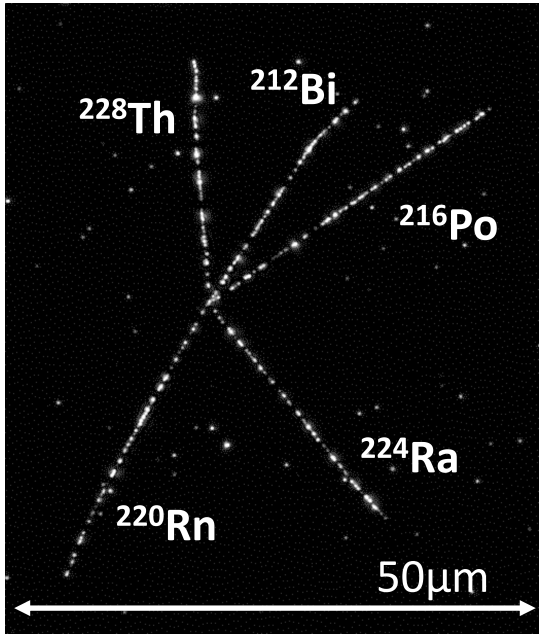


Exposed 5×10^{7} γ-ray/cm^{2}
from ^{241}Am and ^{60}Co
(5 years accumulation of
environmental γ-ray)

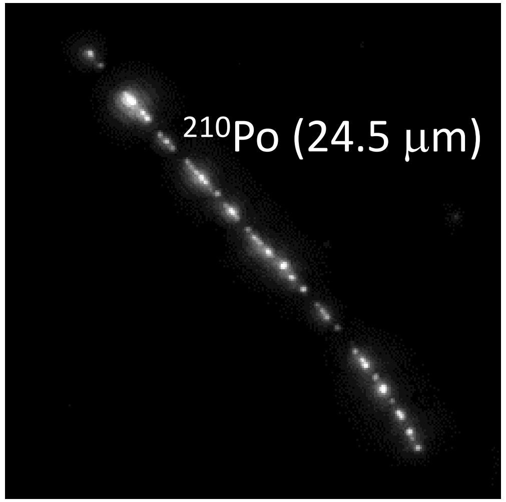
✓ **Environmental γ-rays cannot become background**

α-ray

Th star (^{228}Th → ^{208}Pb)



Single-α in U series

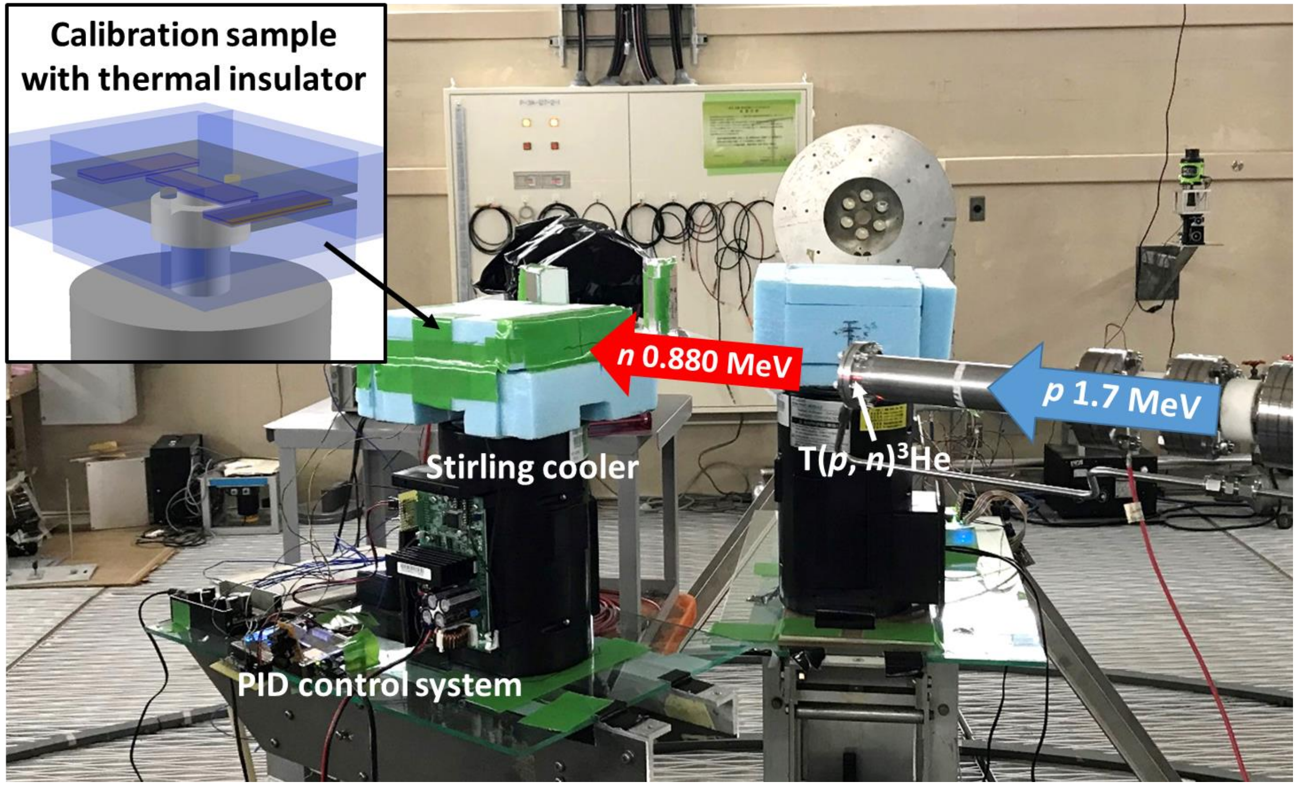


✓ **There is no background in sub-MeV region**
(2 - 14 μm → 0.25 - 1 MeV in proton energy)

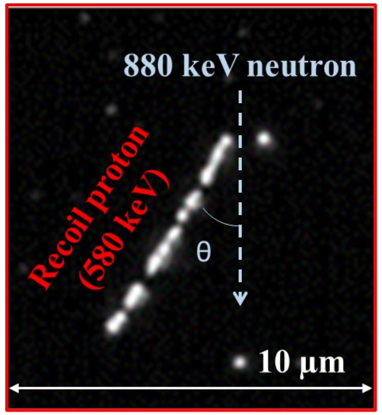
✓ **MeV region can be analyzed excluding single-α**
(especially ^{210}Po peak around 24 μm)

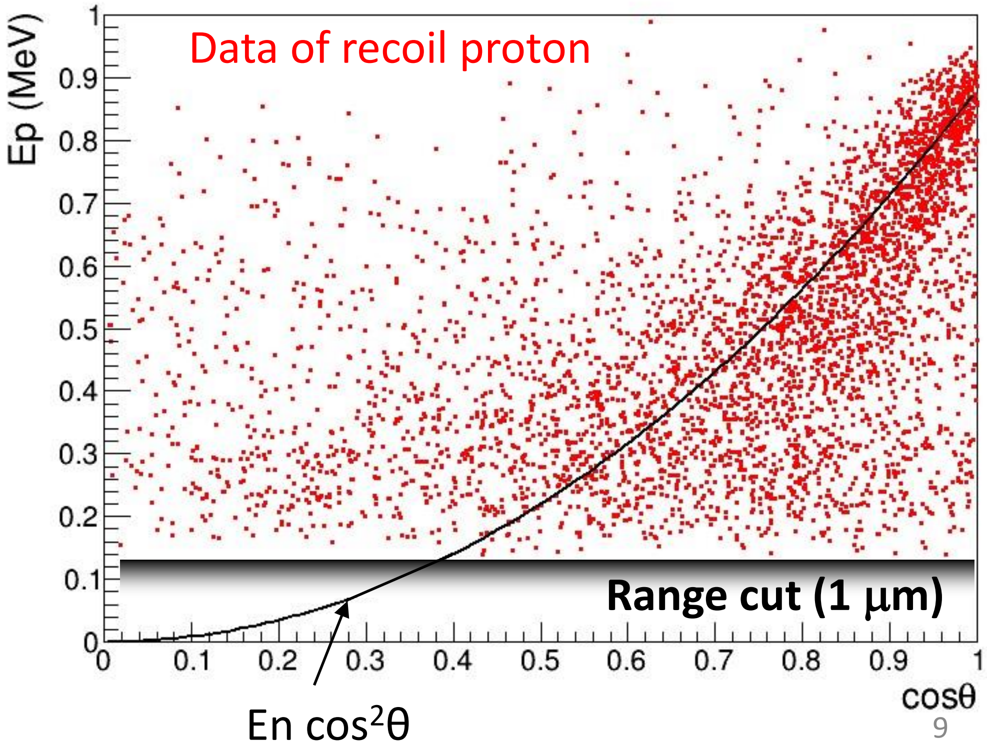
Calibration with Monochromatic Sub-MeV Neutron

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



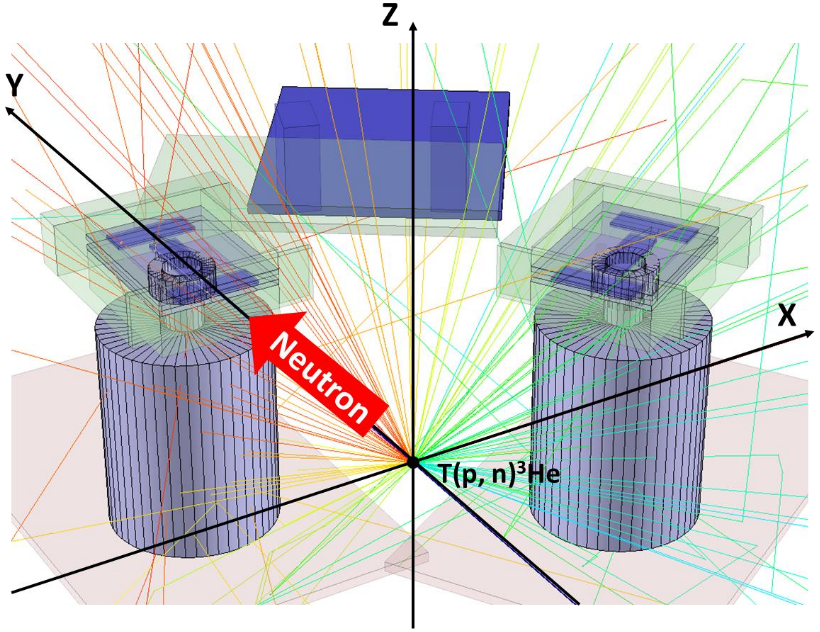
Exposed 7.9 hours with a stable temperature at -26℃





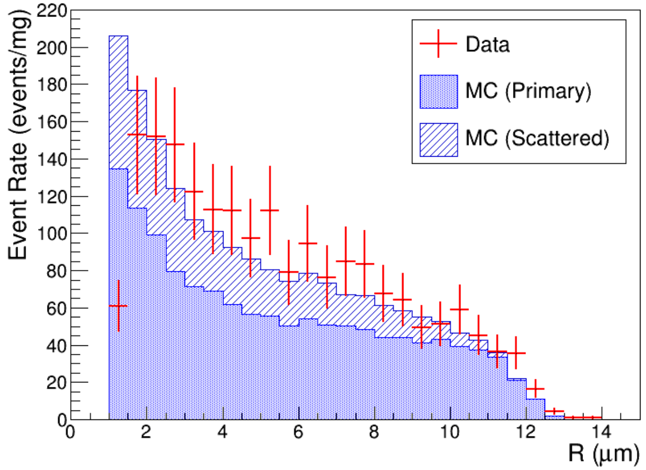
Calibration – Comparison with Simulation

GEANT4 simulation

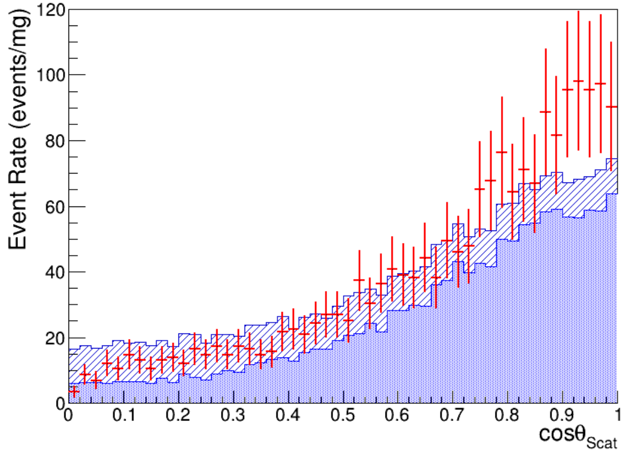


*Color corresponding to neutron energy

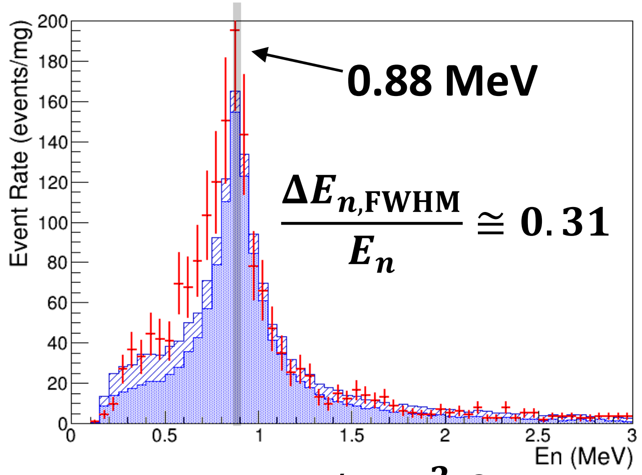
Proton Range



Scattering Angle



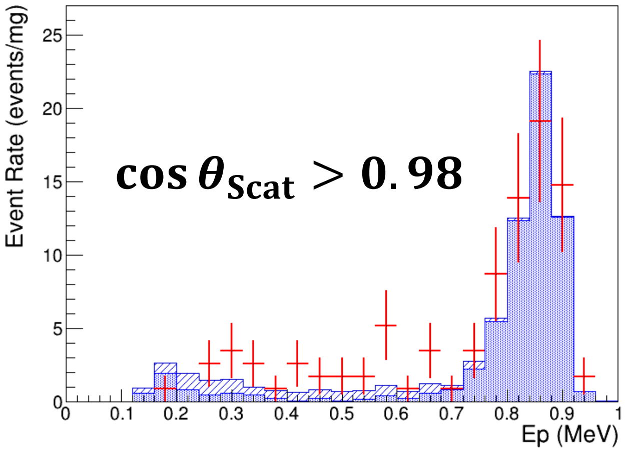
Neutron Energy



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

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

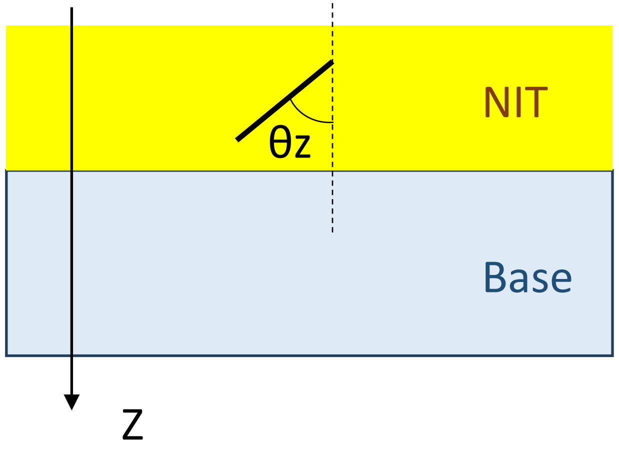
Proton Energy of Head-on Collision

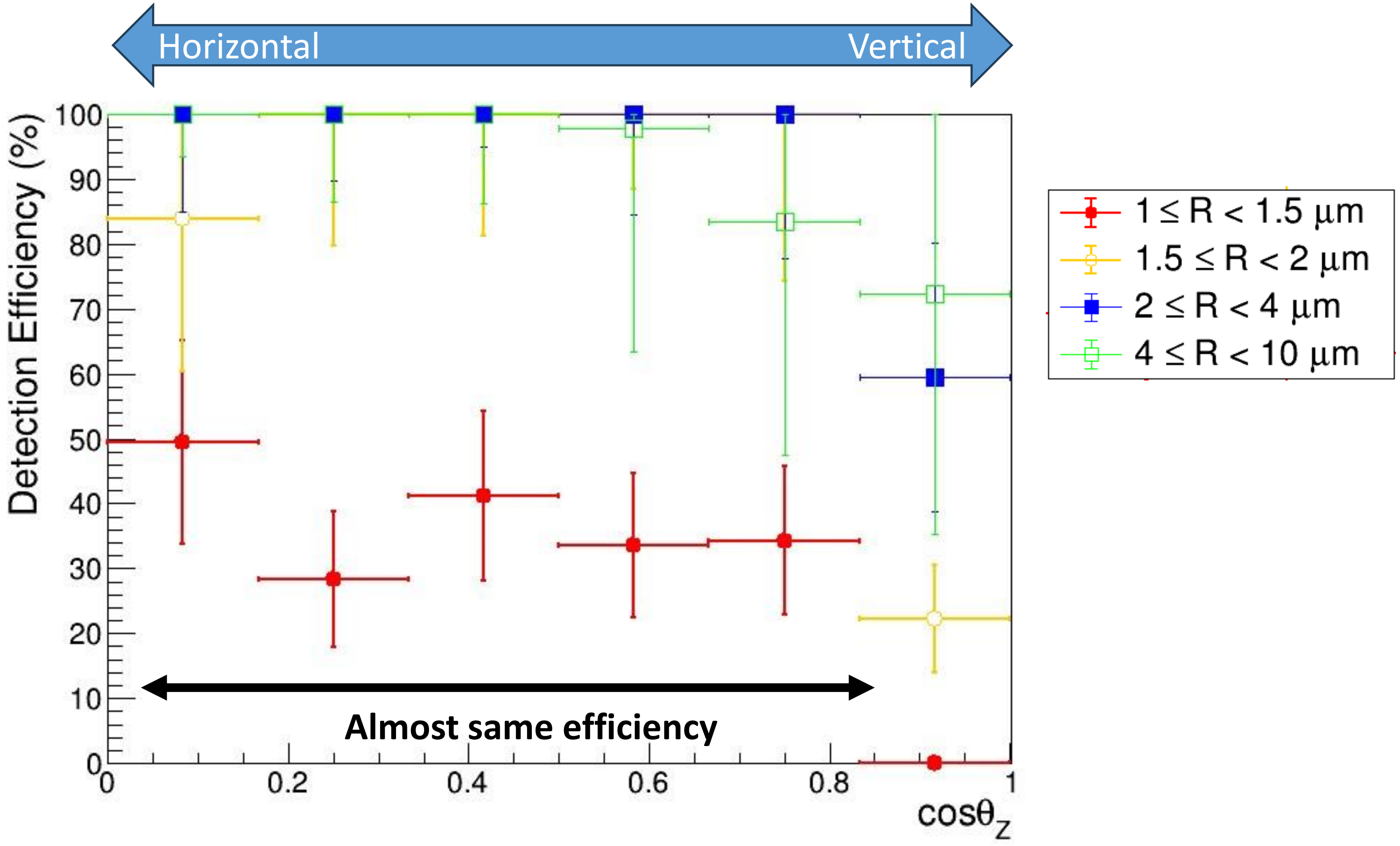


$$\cos\theta_{\mathrm{Scat}} > 0.98$$

- ✓ **Detected recoil protons are almost good agreement with kinematical expectation**
- ✓ **Detection efficiency for R < 1.5 µm (< 200 keV) is not 100%**

Calibration – Angular and Range Dependency of Detection Efficiency



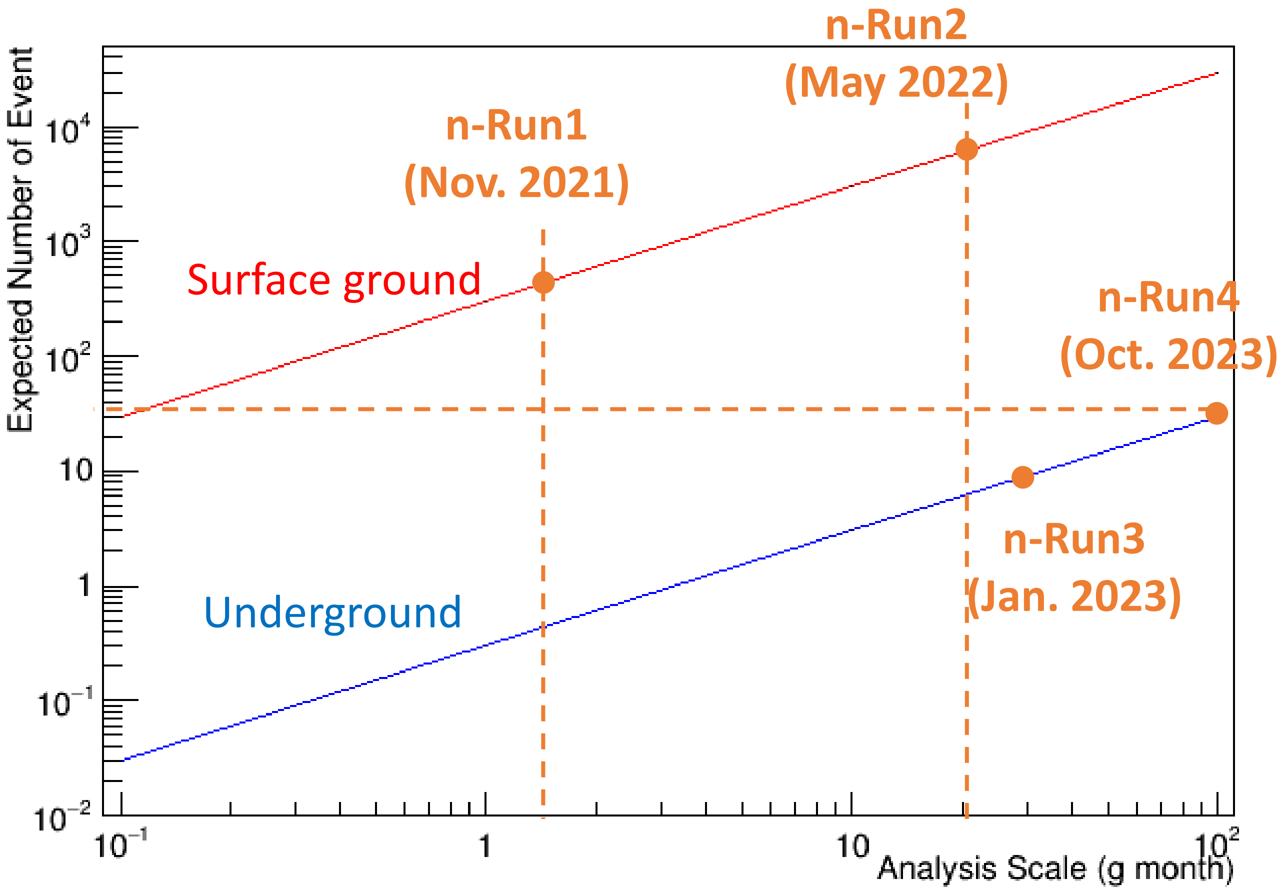


Horizontal

Vertical

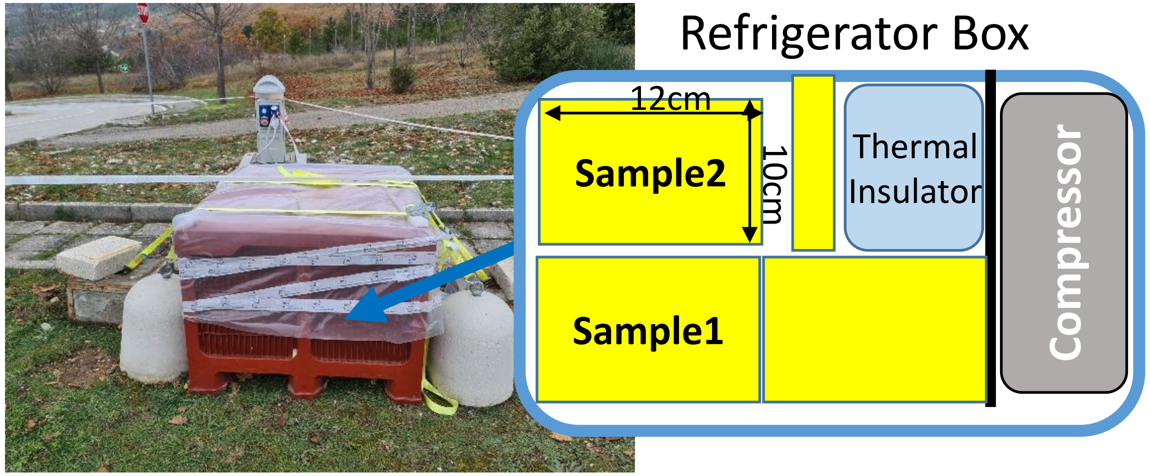
Almost same efficiency

Environmental Neutron Measurement by NIT @ LNGS



Motivation of Surface Run

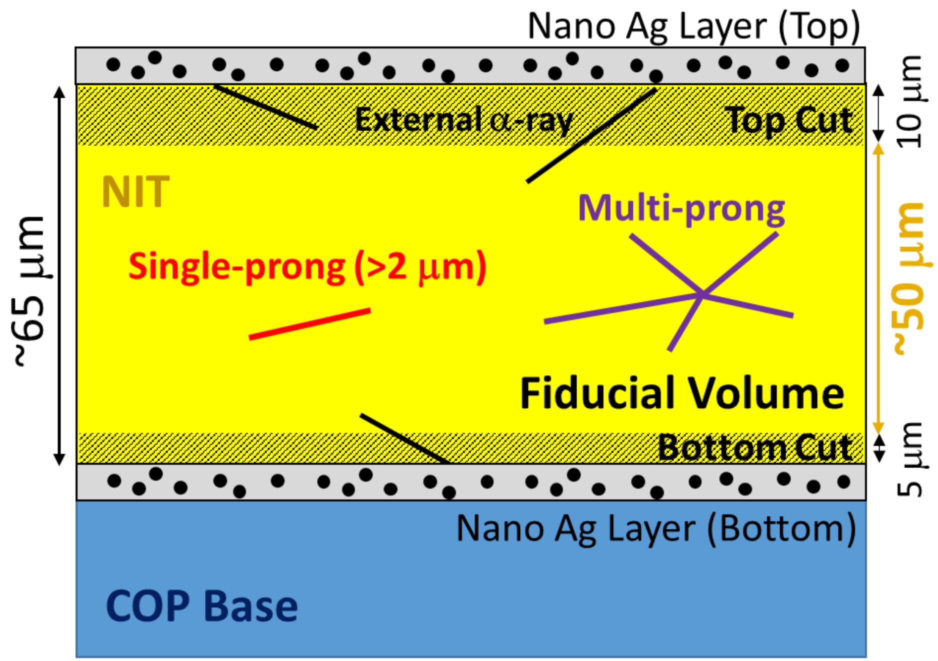
- Demonstration of spectrum measurement for environmental neutron and CR-DM search
- There is no detailed data in the sub-MeV region even on the surface ground



✓ **Without shielding!**

because there is no sensitivity for muon and gamma

Event Classification

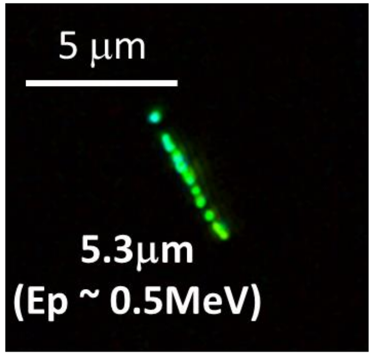


- External α-rays are excluded by fiducial volume cut, then events are topologically classified to **Single-prong** and **Multi-prong**

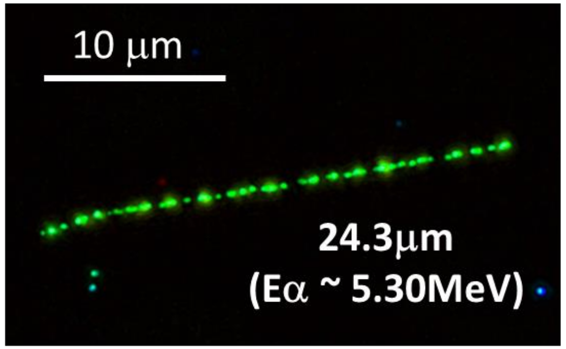
- **Unfortunately, n-Run1 samples accumulated a lot of Radon, we focused on sub-MeV region (2~14μm → 0.25~1MeV) of Single-prong event to analyze with background free**

Single-prong Event

Neutron elastic scattering

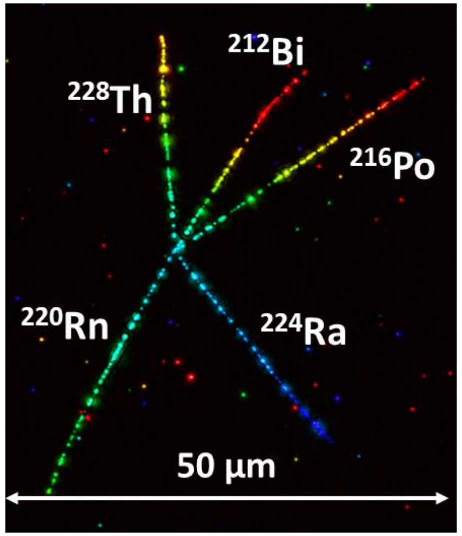


Single α-decay from ^{210}Po

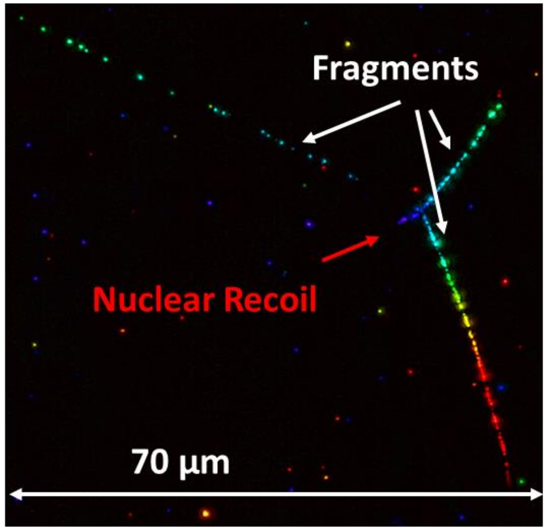


Multi-prong Event

^{228}Th star (5 prong α-decay)



Neutron inelastic scattering

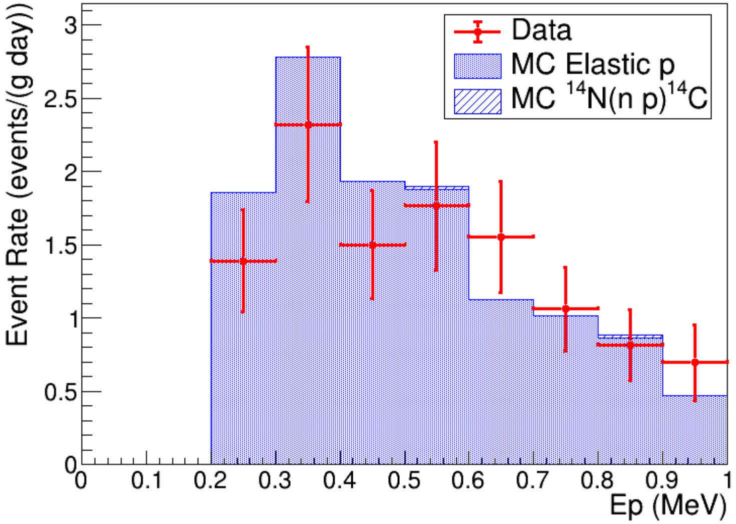


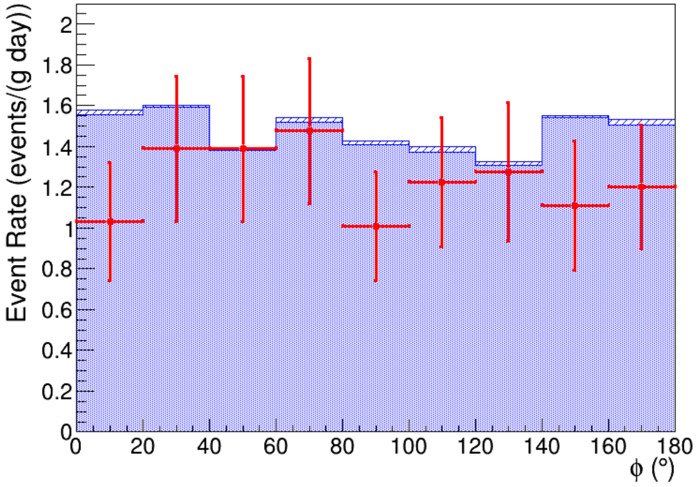
Data/MC Comparison (n-Run1)

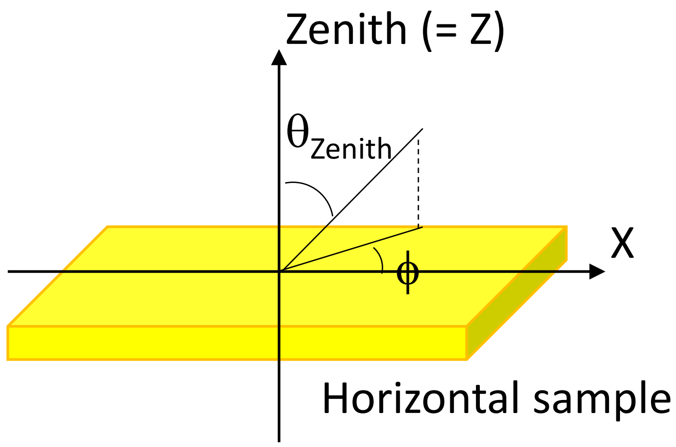
MC : Geant4 + PARMA model

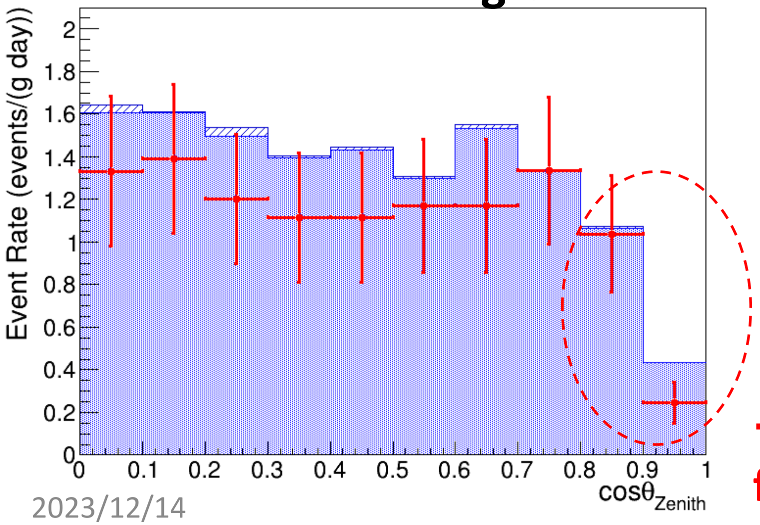
T. Sato, PLOS ONE **10**, e0144679 (2015)

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


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]

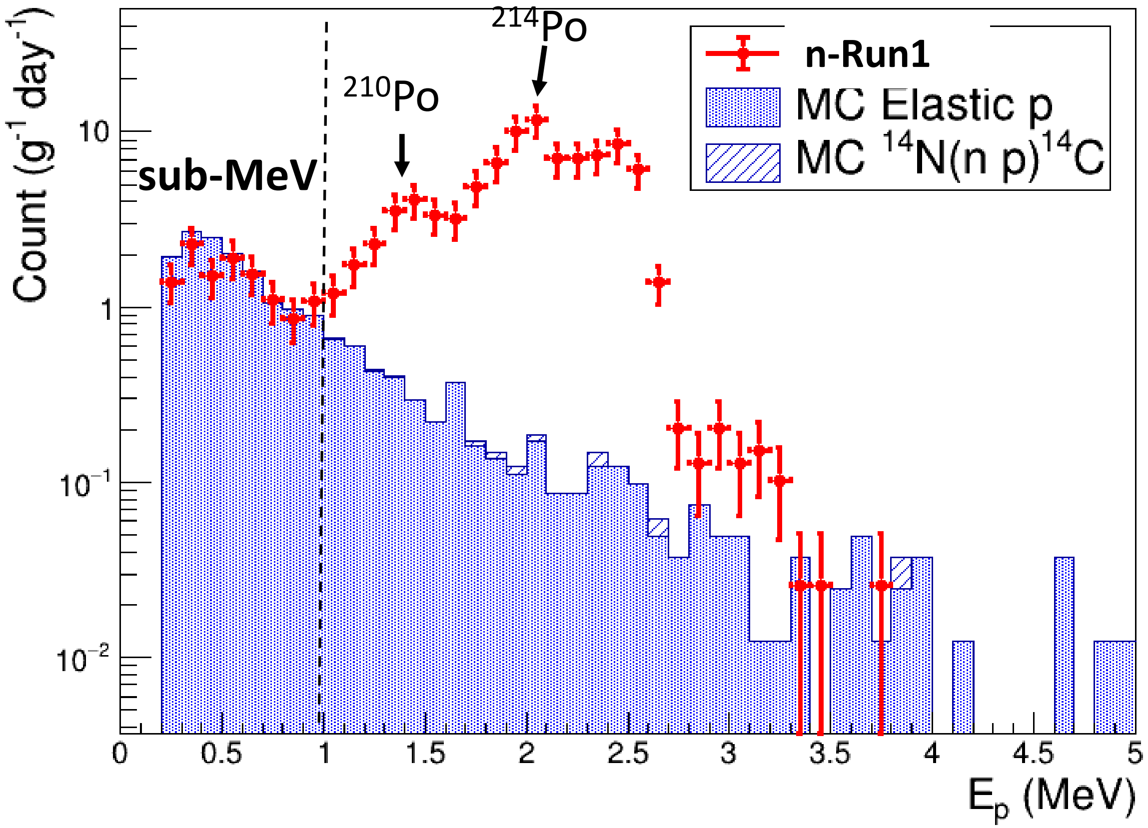
PARMA model : 9.0 x 10^{-3} cm^{-2} s^{-1}

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

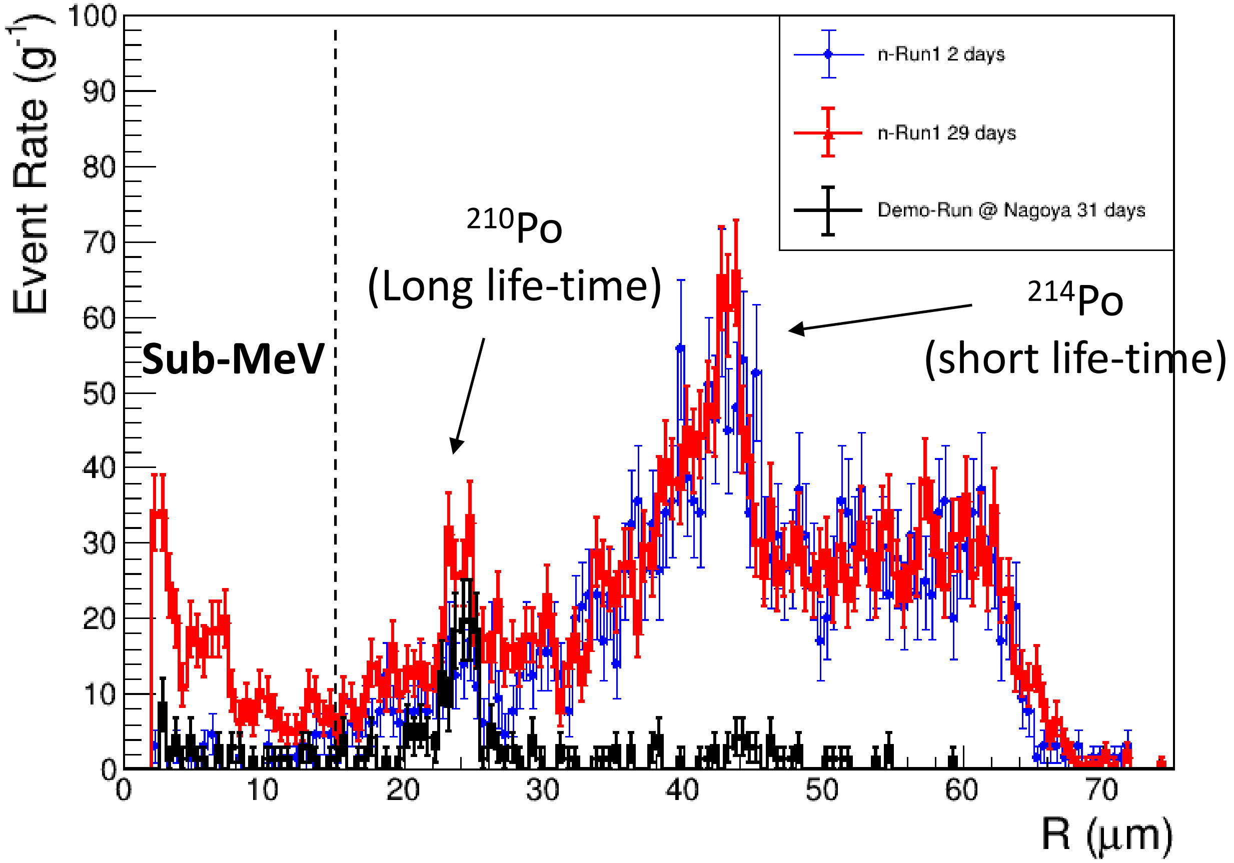
T. Shiraishi, *et al.*, Phys. Rev. C **107**, 014608 (2023)

MeV Region (n-Run1)

Proton Energy

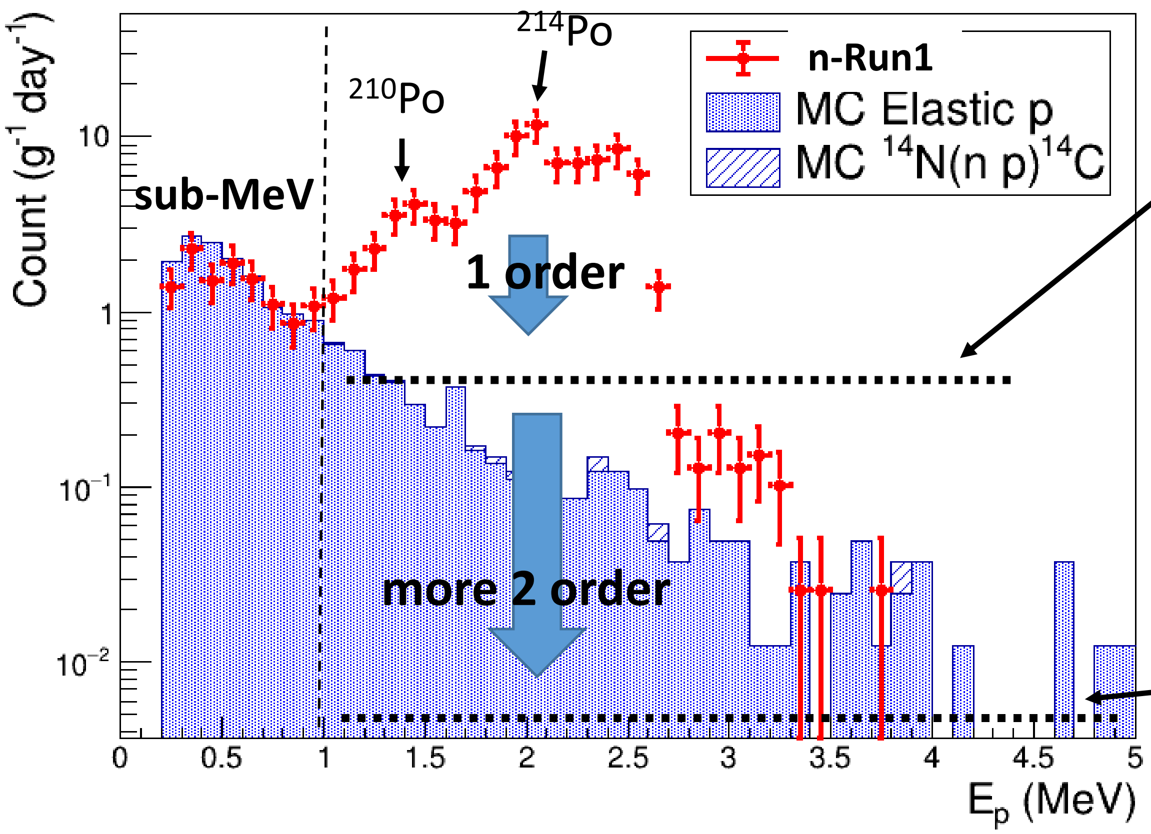


Track Range



Reduction of ^{214}Po Contamination at Drying

Proton Energy



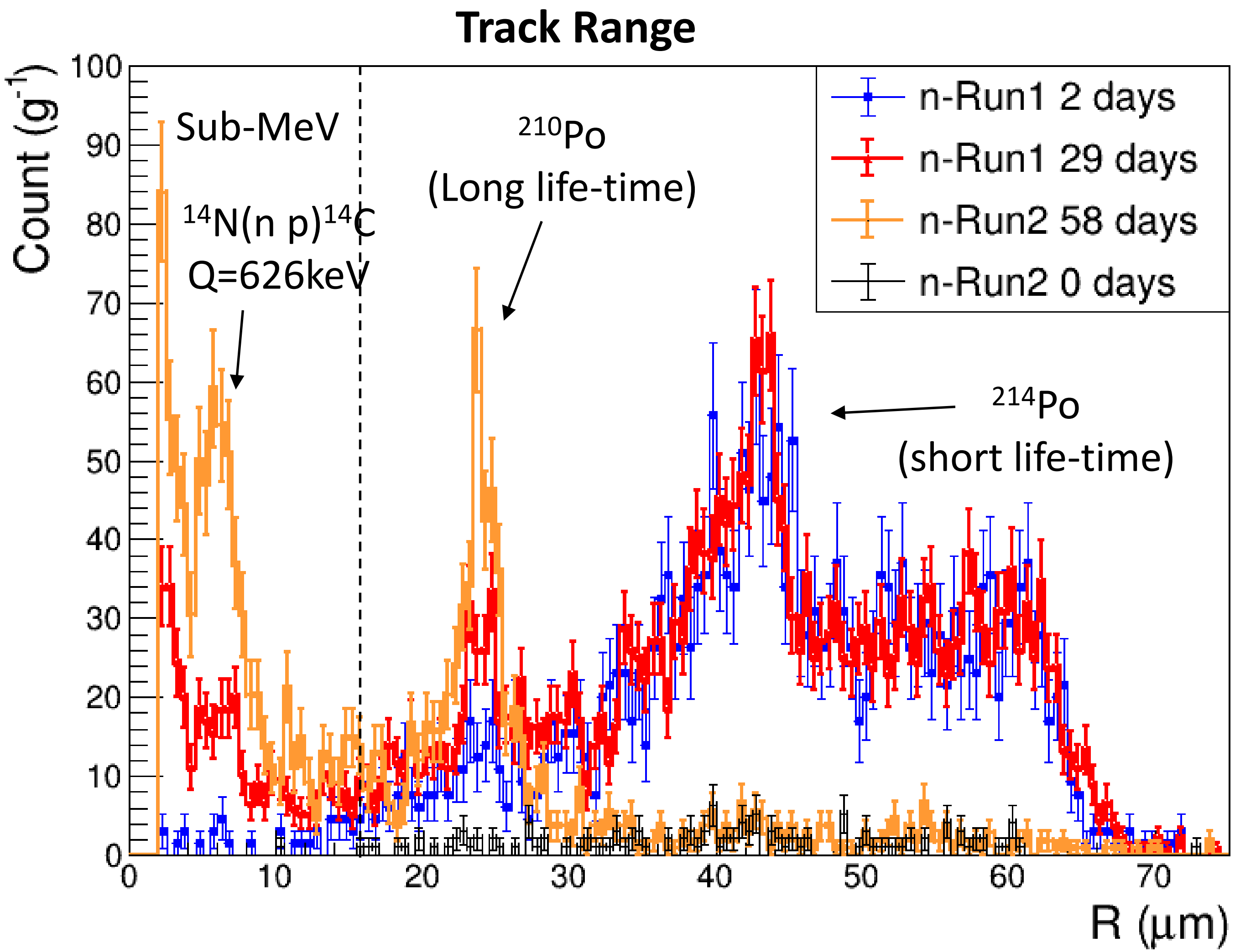
Hall F (NEWSdm facility)

n-Run2, n-Run3
(climatic chamber)

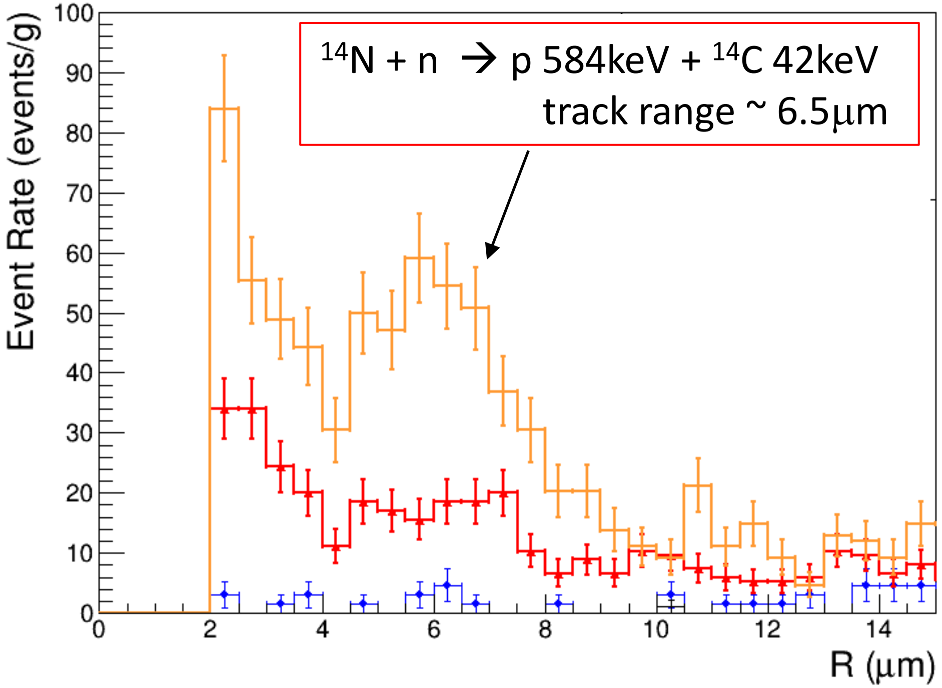
n-Run1
(granite table)

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

n-Run1 and n-Run2 Results



Sub-MeV region

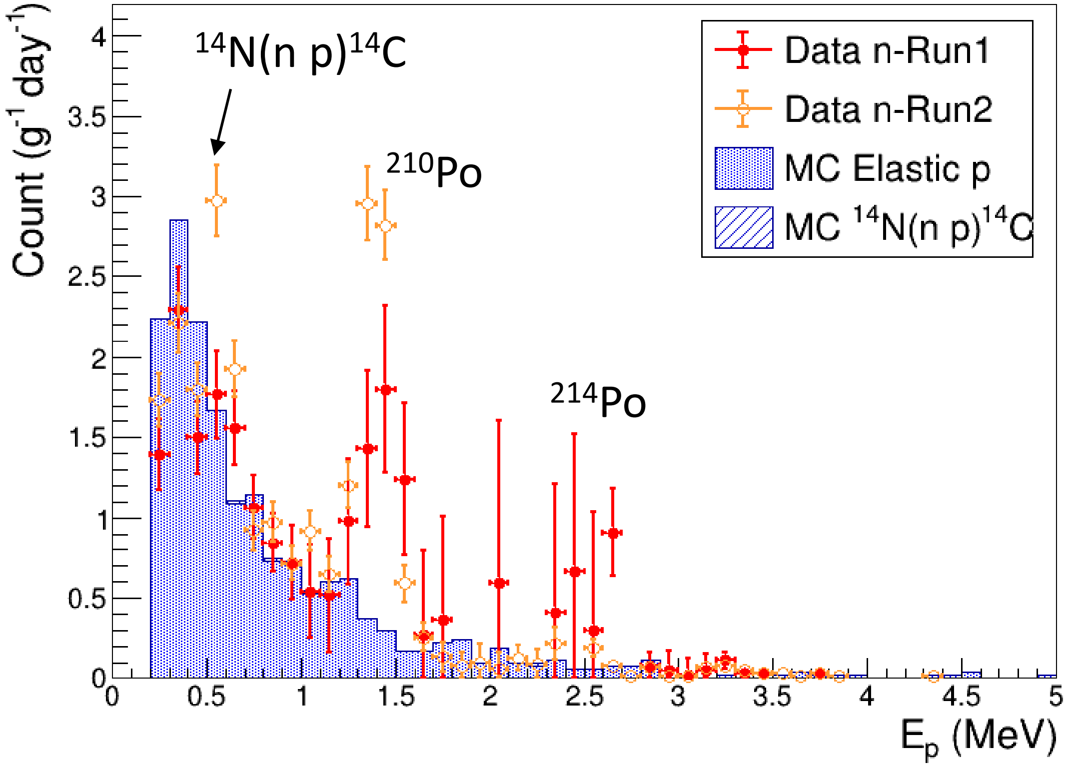


- ✓ **As expected**
  - ✓ **sub-MeV signal increase**
  - ✓ **^{210}Po-alpha increase**
  - ✓ **Offset background in MeV decrease**

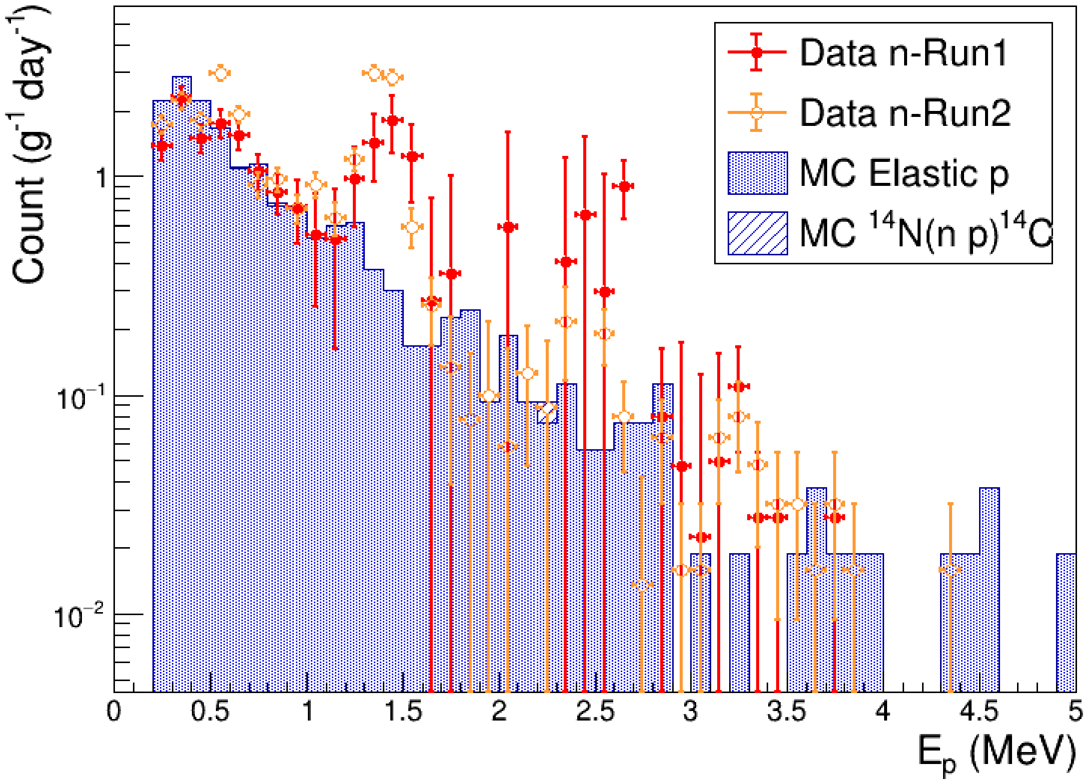
Thermal neutron signal can be seen significantly
→ Thermalized due to surrounding materials? or attenuation by water contained in rock was suppressed?

n-Run1 and n-Run2 Results (*after reference subtraction)

Proton energy spectrum (linear scale)



(log scale)



✓ Thanks to reduced ^{214}Po contamination, MeV spectrum close to the simulation

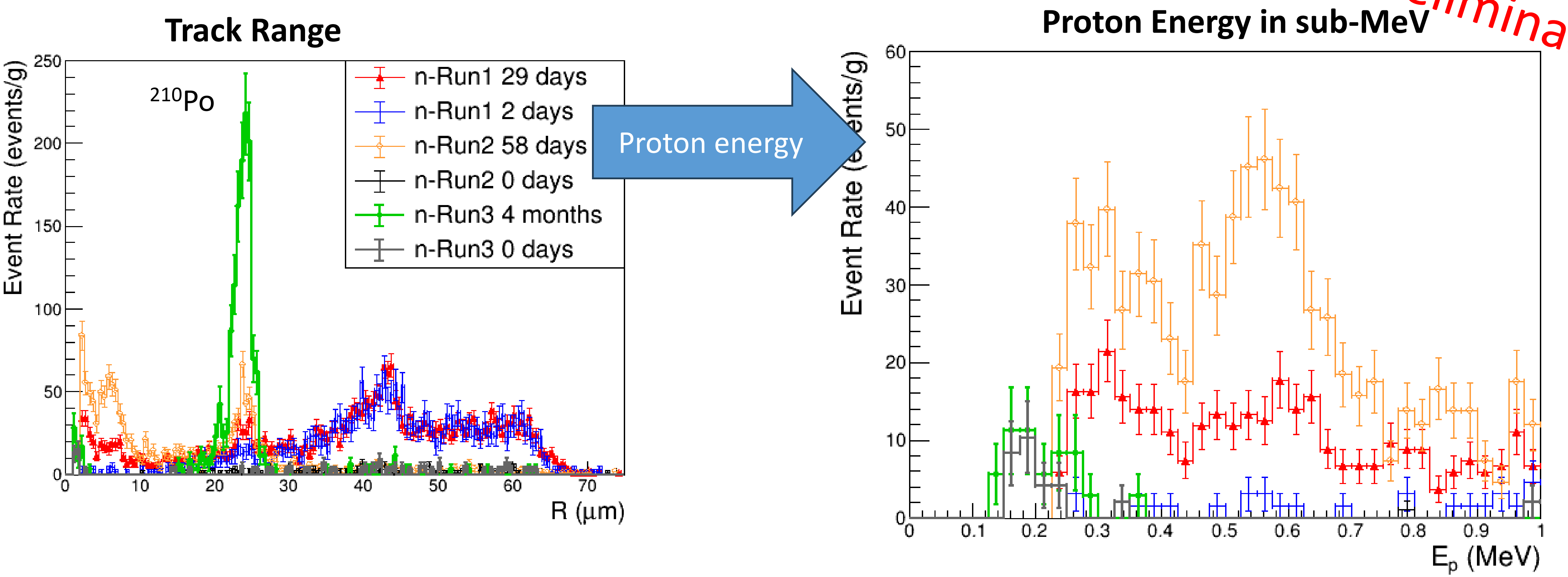
Neutron Run Go to Underground

	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) (using CR1)	120	100	--- Exposure ongoing	100

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

n-Run3 (Underground) Result

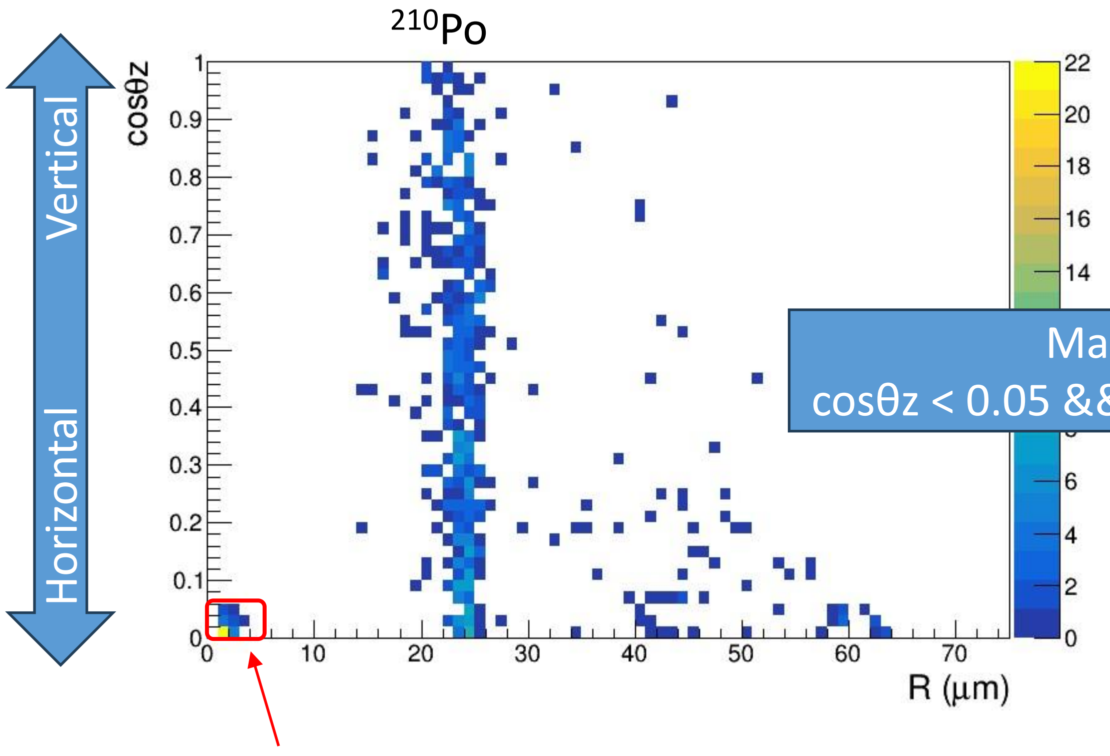
Preliminary



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

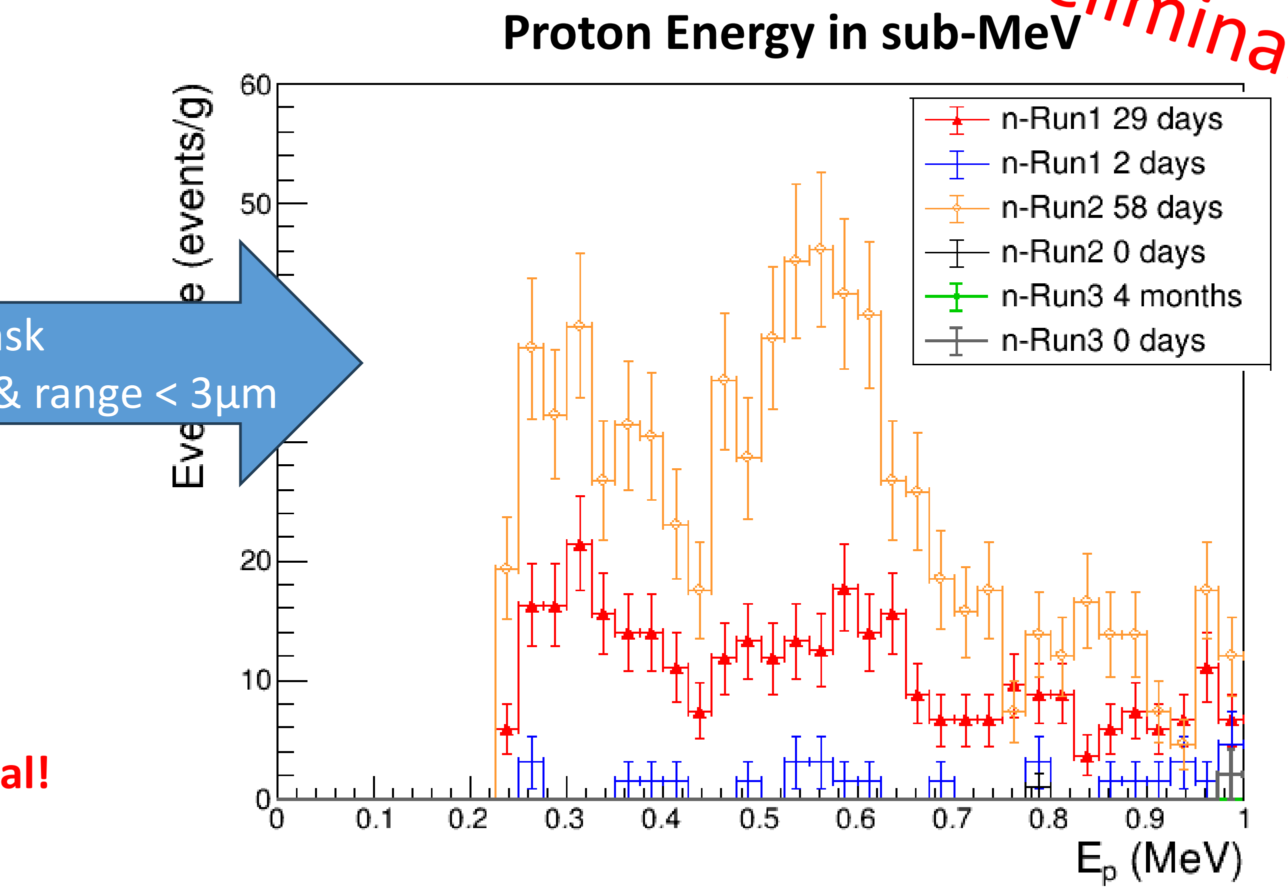
n-Run3 (Underground) Result

Preliminary

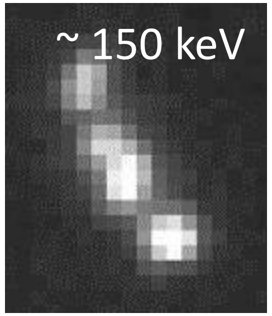


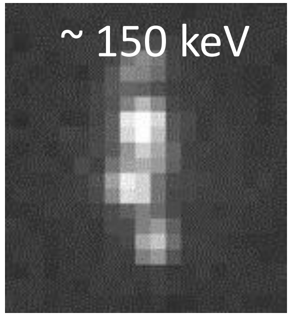
Mask

cosθz < 0.05 && range < 3μm



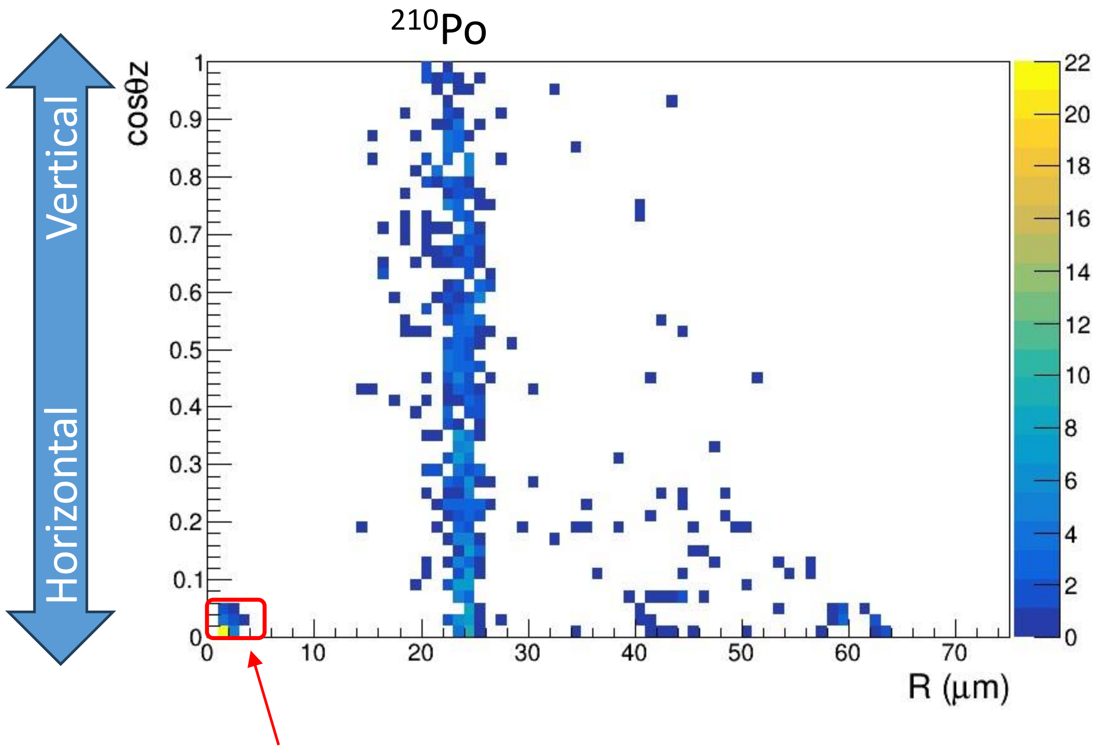
Signal-like tracks found below 300 keV are all horizontal!



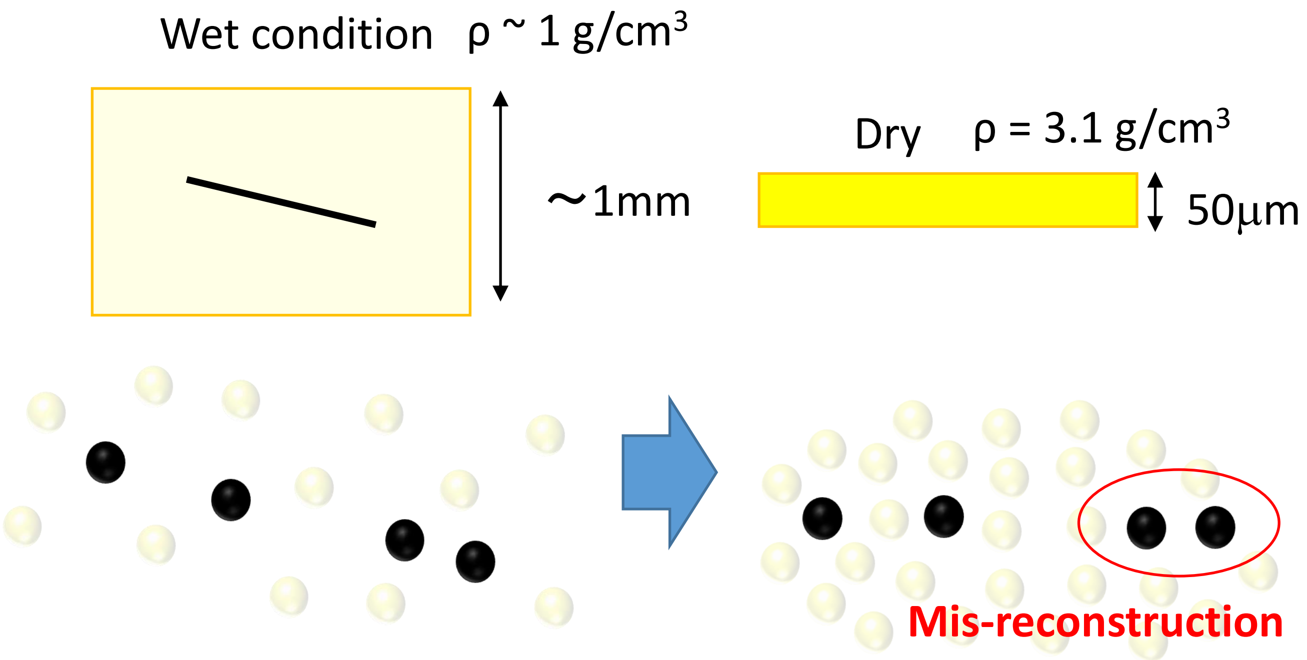


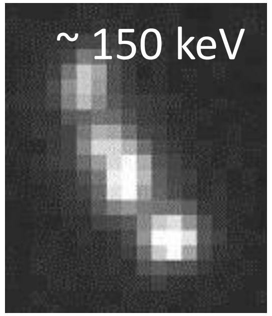
- ✓ **If we avoid low energy & horizontal angle region, there is no excess in sub-MeV region**

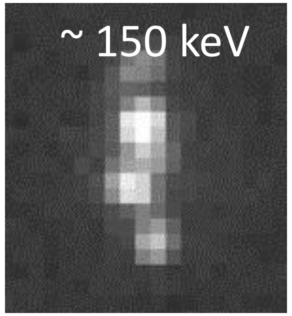
n-Run3 (Underground) Result



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





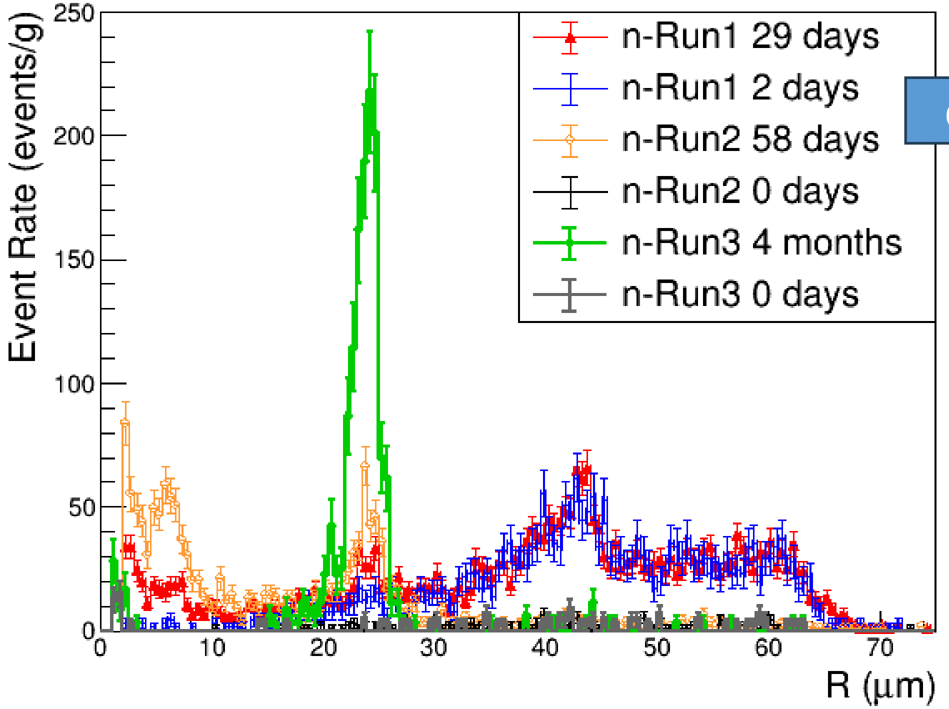


- Mis-reconstruction of α-track from ^{214}Po accumulated at wet condition?

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

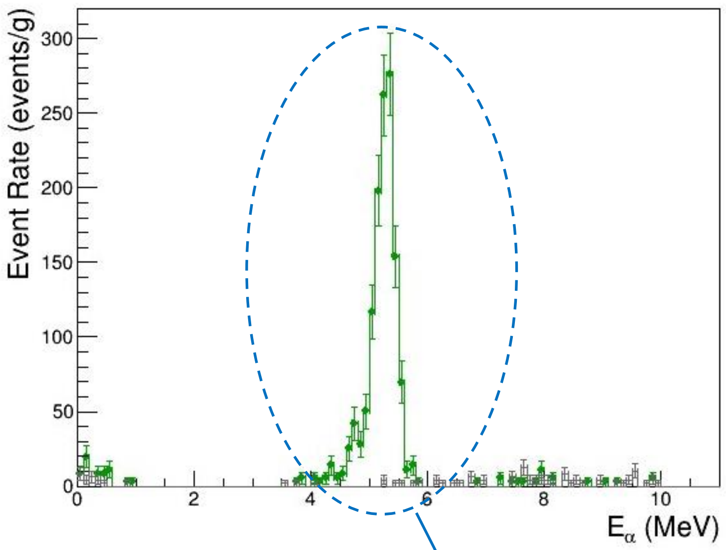
n-Run3 α-ray Analysis

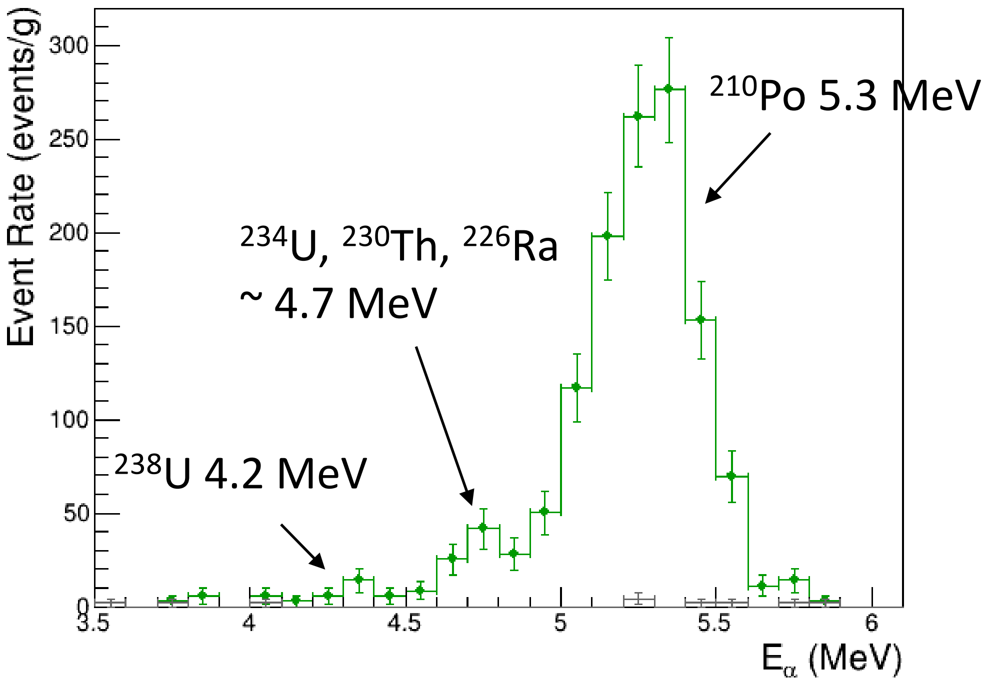
Range distribution



α energy

n-Run3 4 month

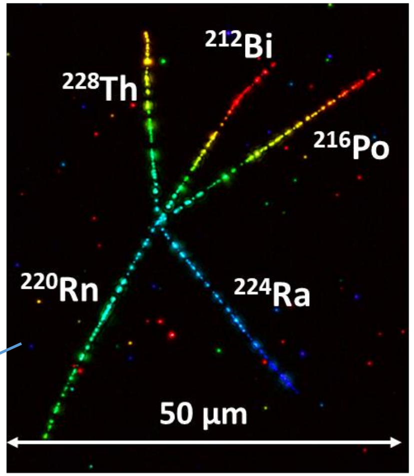




Intrinsic α Activity

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

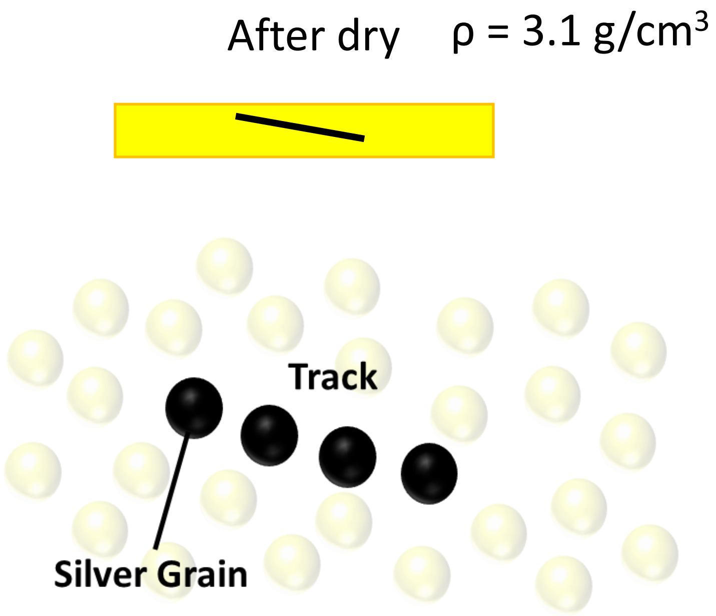
  →Analysis speed will be further upgraded to 1.5 kg/year/machine

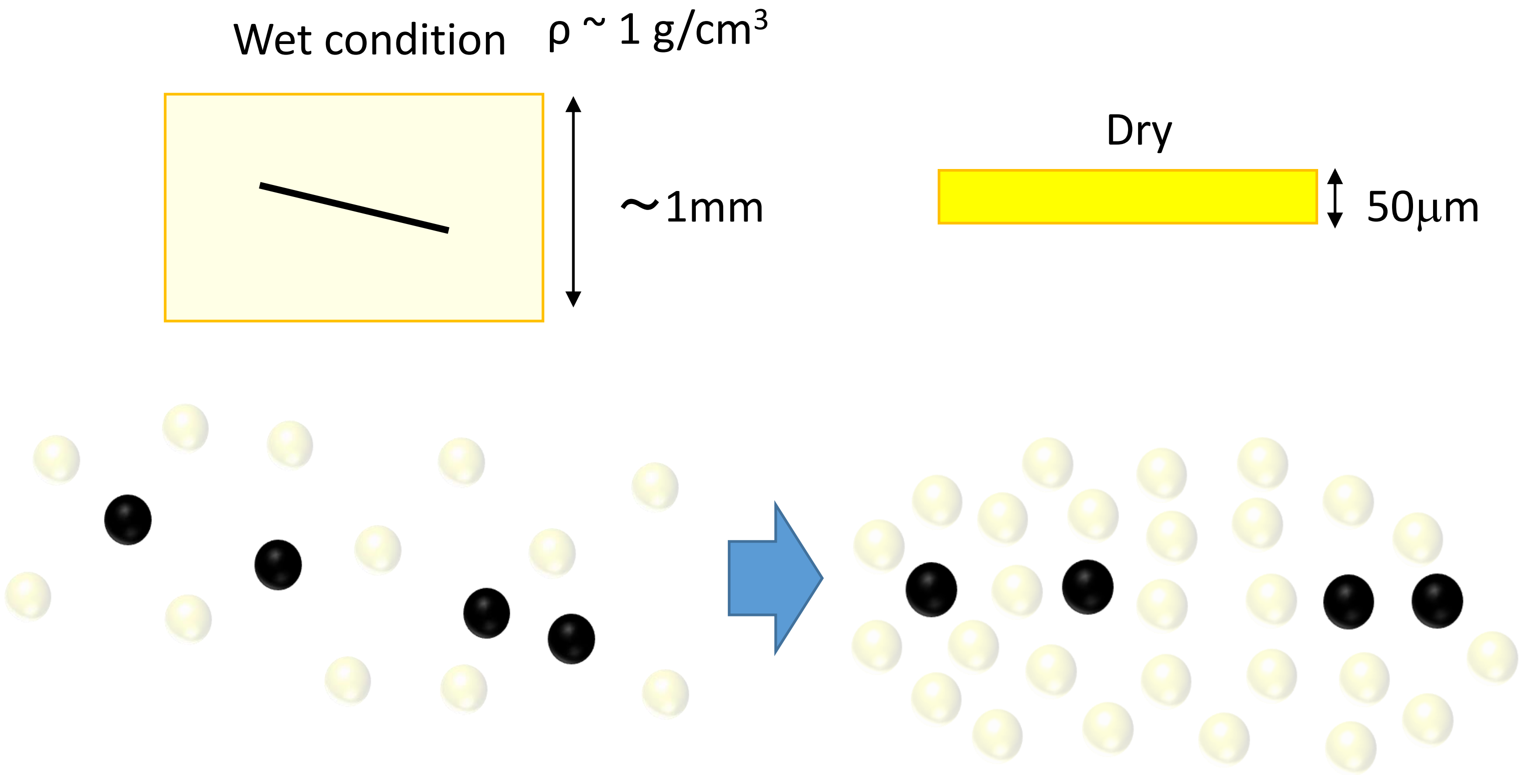
- Neutron run in Gran Sasso
  - Surface run (n-Run1, nRun2)
    - Succeeded to measure neutron spectrum and direction → T. Shiraishi, *et al.*, Phys. Rev. C **107**, 014608 (2023)
    - ^{214}Po contamination problem was found

      → **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 the begging of sample preparation?
      - 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

α-ray accumulation in drying condition





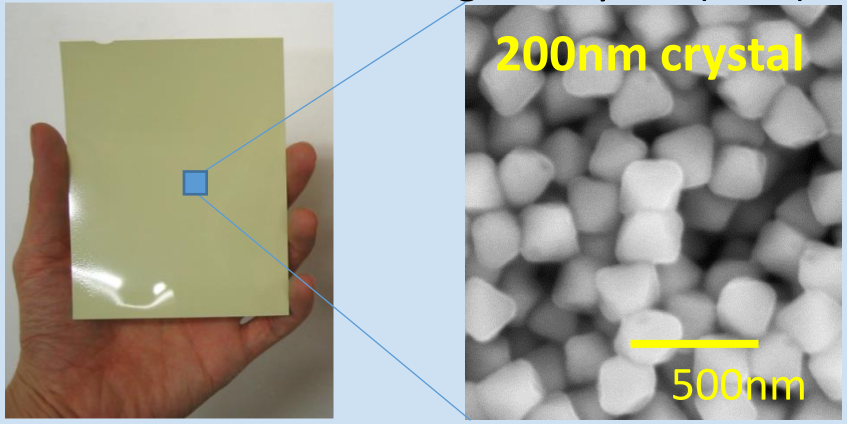
If α-ray create tracks at wet condition, tracks become **longer & darker & horizontal** because of

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

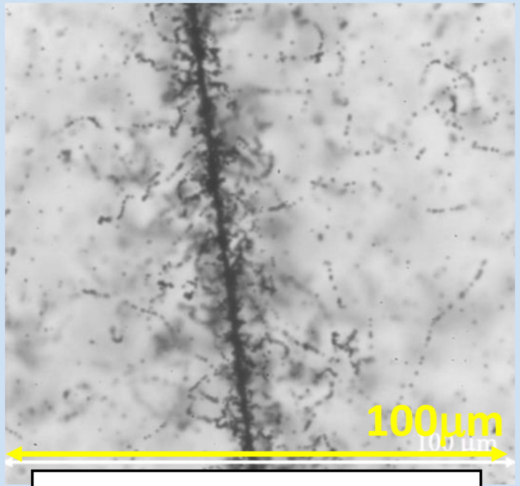
Comparison of Nuclear Emulsion

OPERA type

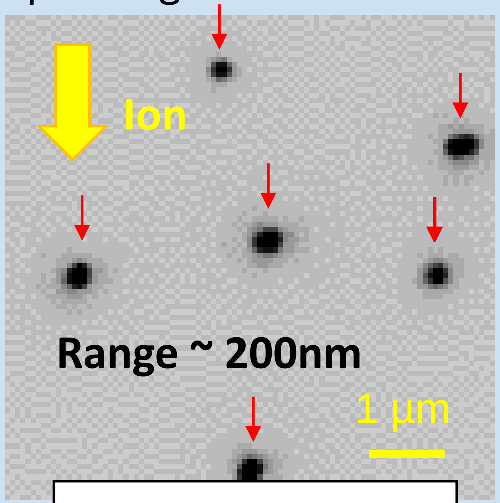
AgBr:I crystal (SEM)



Optical microscope image



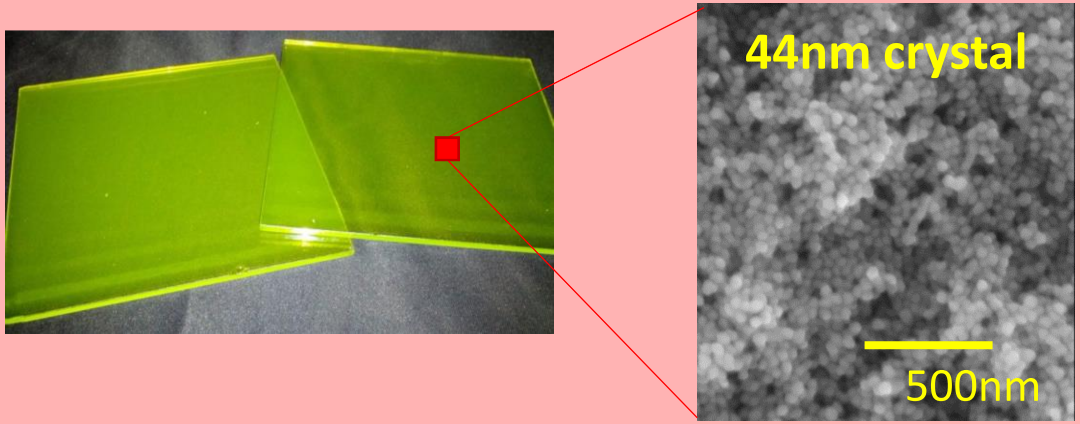
500MeV/n Fe ion



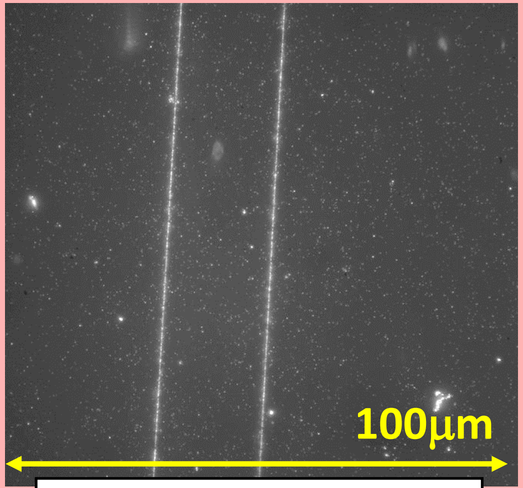
60keV C ion

Nano Imaging Tracker (NIT) type

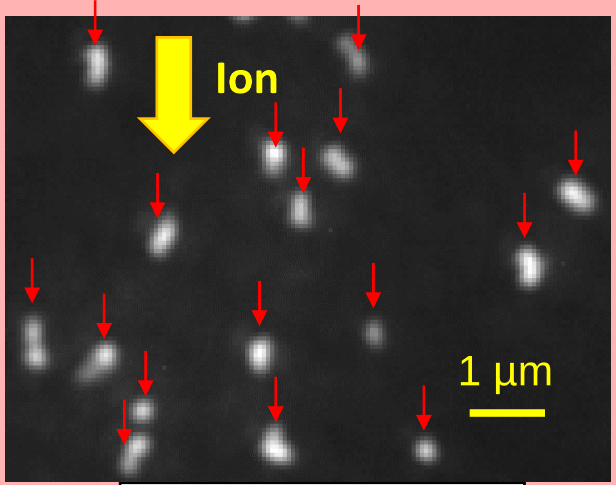
AgBr:I crystal (SEM)



Optical microscope image



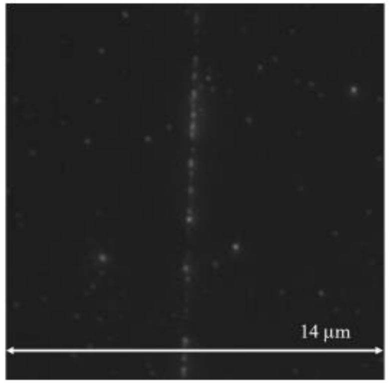
500MeV/n Fe ion



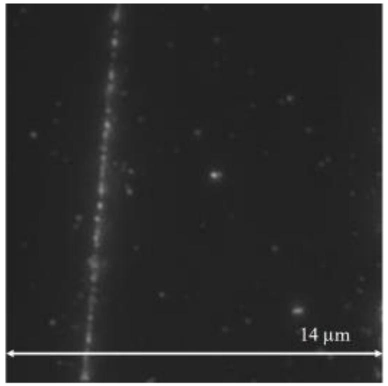
60keV C ion

High Energy Ion Track in NIT

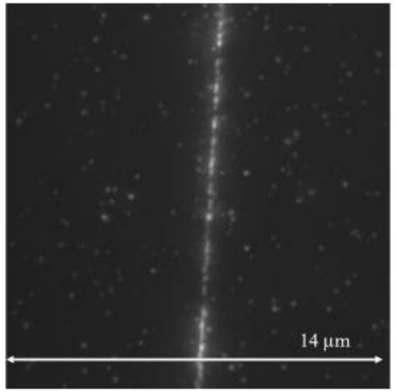
C 290 MeV/n



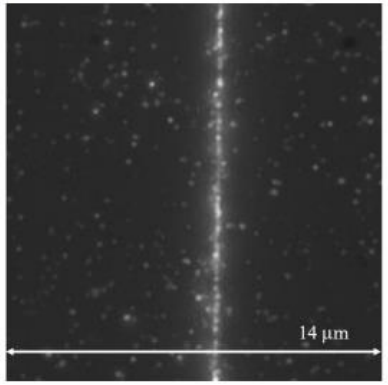
Ar 500 MeV/n



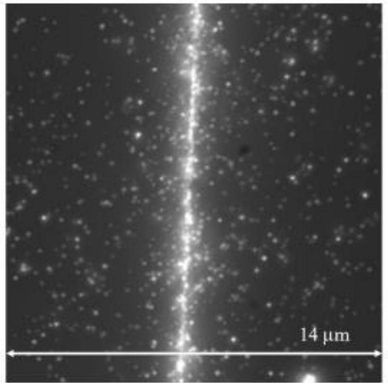
Fe 500 MeV/n



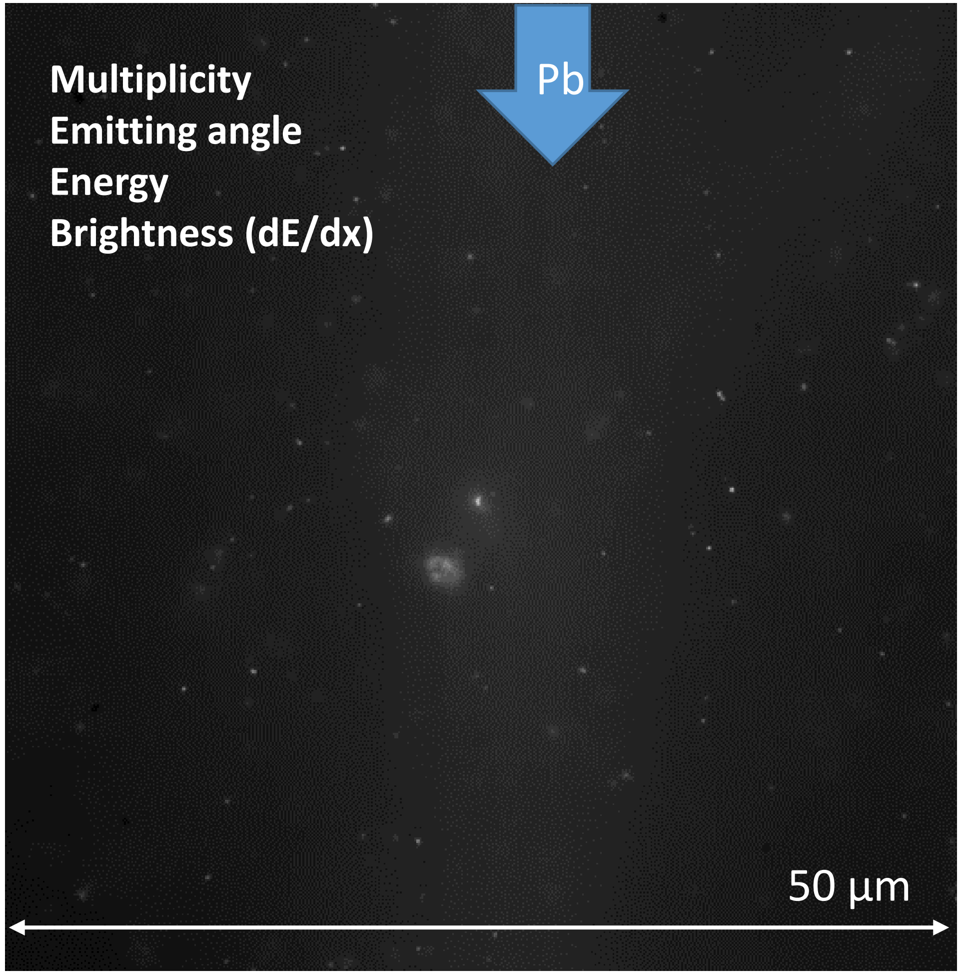
Xe 150 GeV



Pb 150 GeV



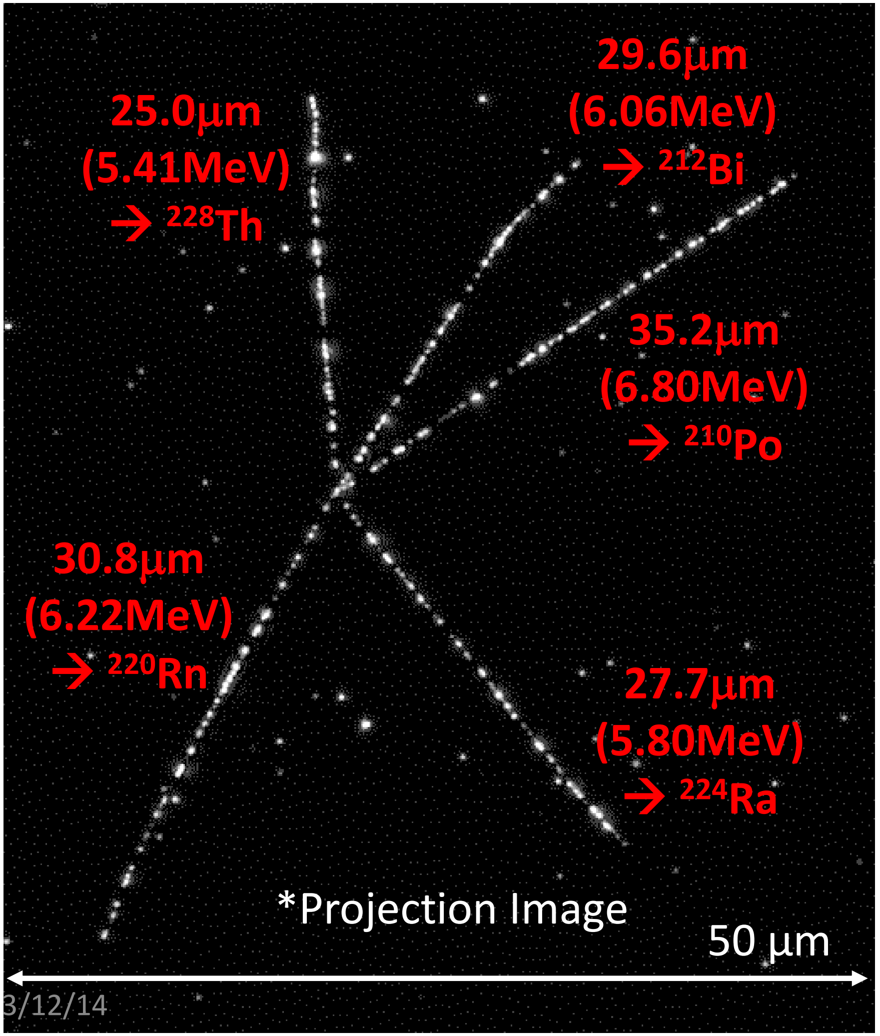
Spallation of 150 GeV Lead Beam



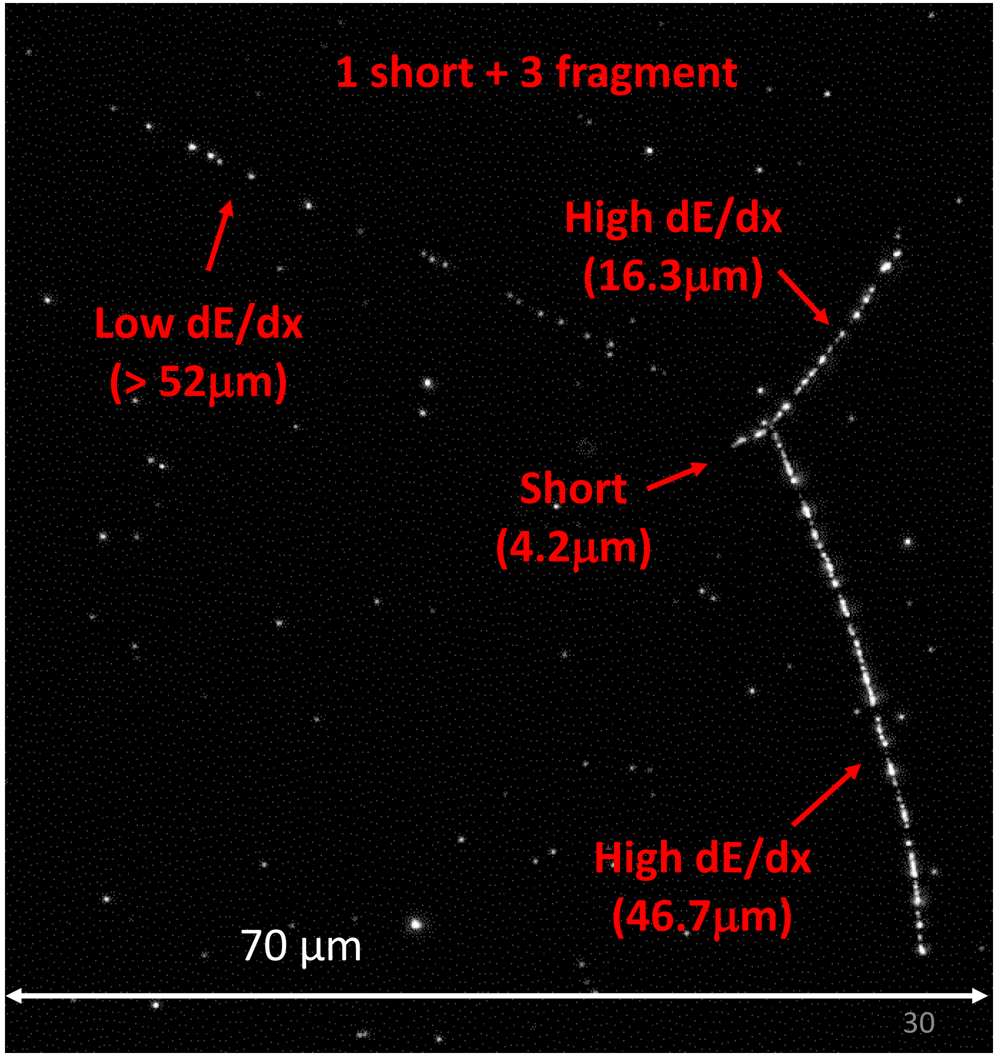
Multiplicity
Emitting angle
Energy
Brightness (dE/dx)

Actual Multi-prong Events from n-Run1

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

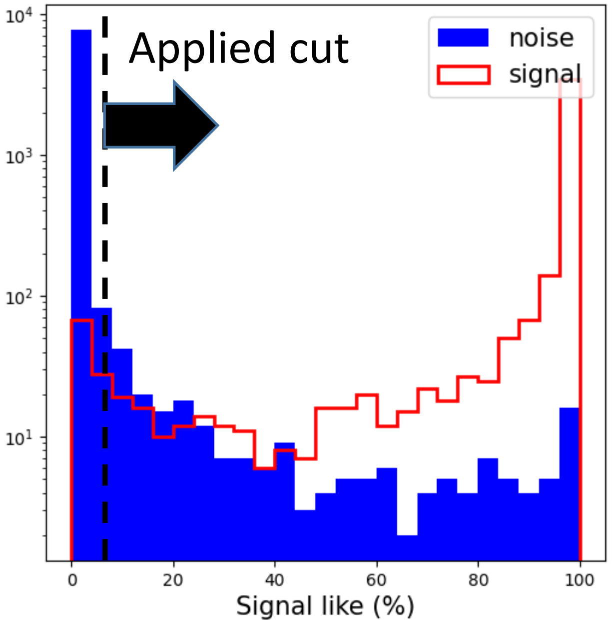


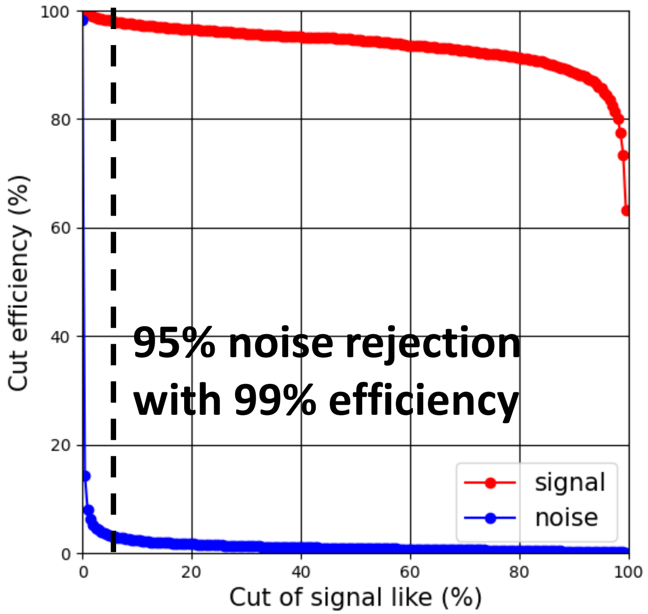
Deep Inelastic Scattering by neutron



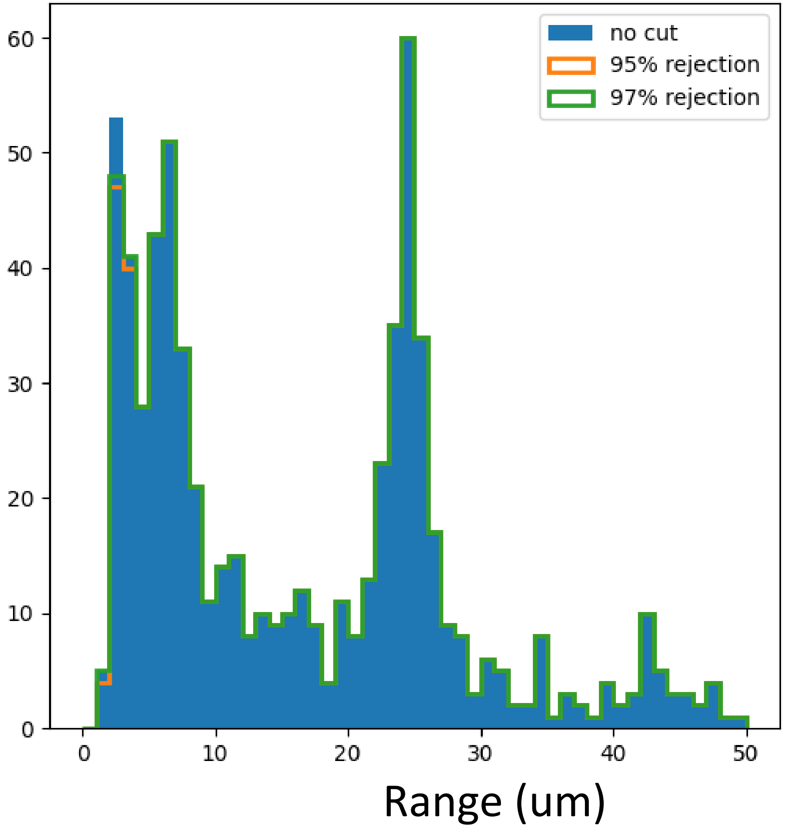
Analysis flow (n-Run2)

- Chain tracking (2um) → CNN (2um) → Manual check
  - CNN training sample
    - Signal
      - AIST 880keV neutron @ -26 deg. (EGS012 wash4)
      - n-Run2 2 month signal @ -15 deg. (EGS016)
    - Noise
      - n-Run2 2 month noise @ -15 deg. (EGS016)


Applied cut

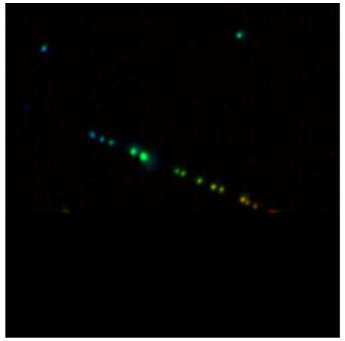

95% noise rejection with 99% efficiency

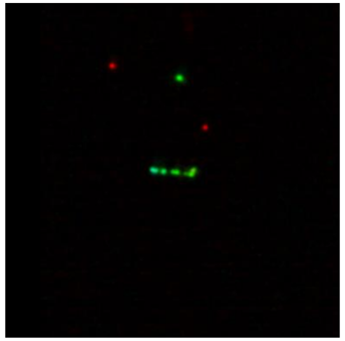
Effect of CNN cut to n-Run2 range distribution

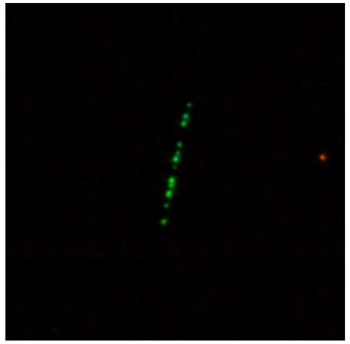


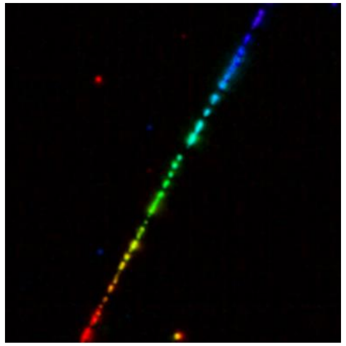
Classification

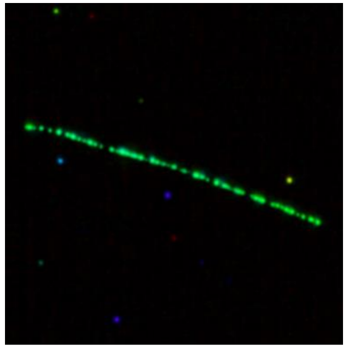
27 μm


signal

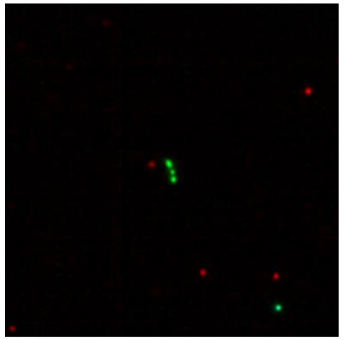

signal


signal

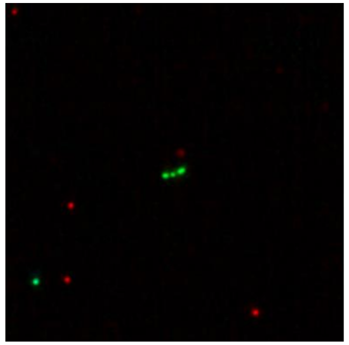

signal

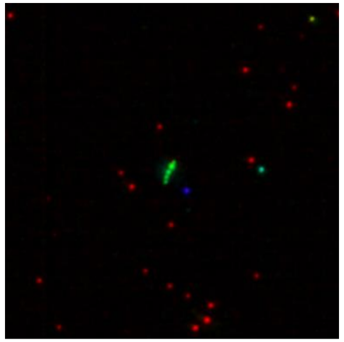

signal

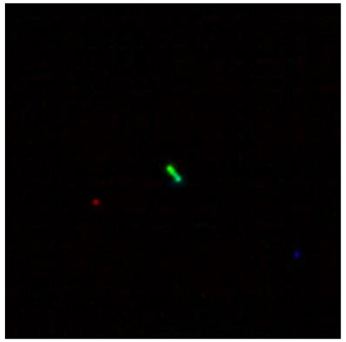
Signal
(R >= 3.5 μm)


short

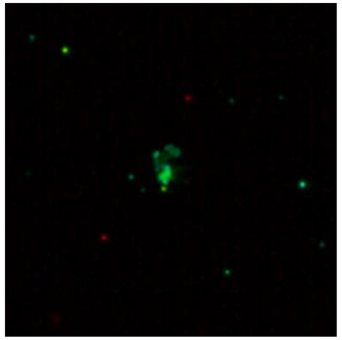

short

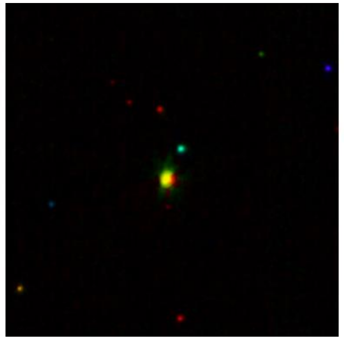

short

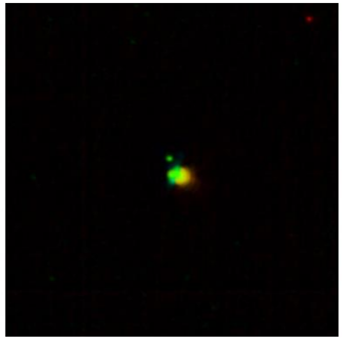

short


short

Signal
(1 <= R < 3.5 μm)


noise


noise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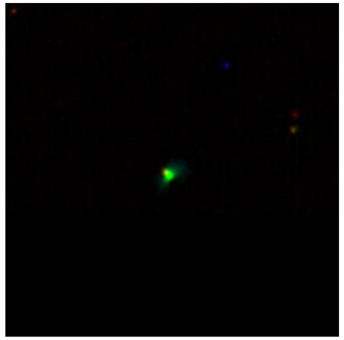
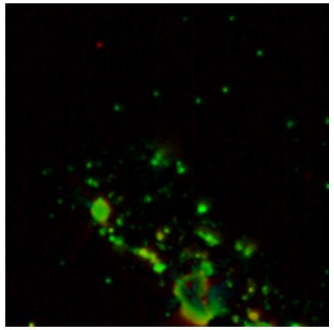

noise


noise

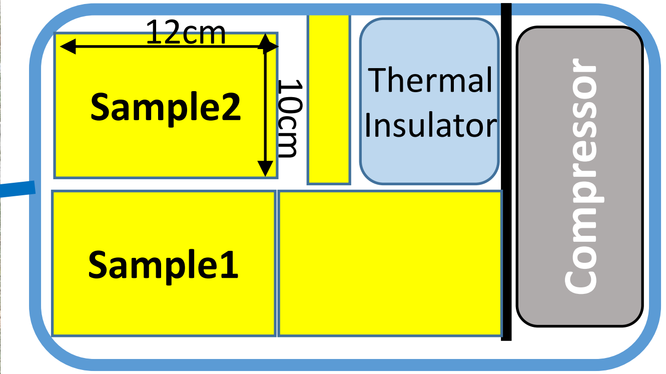
Noise

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



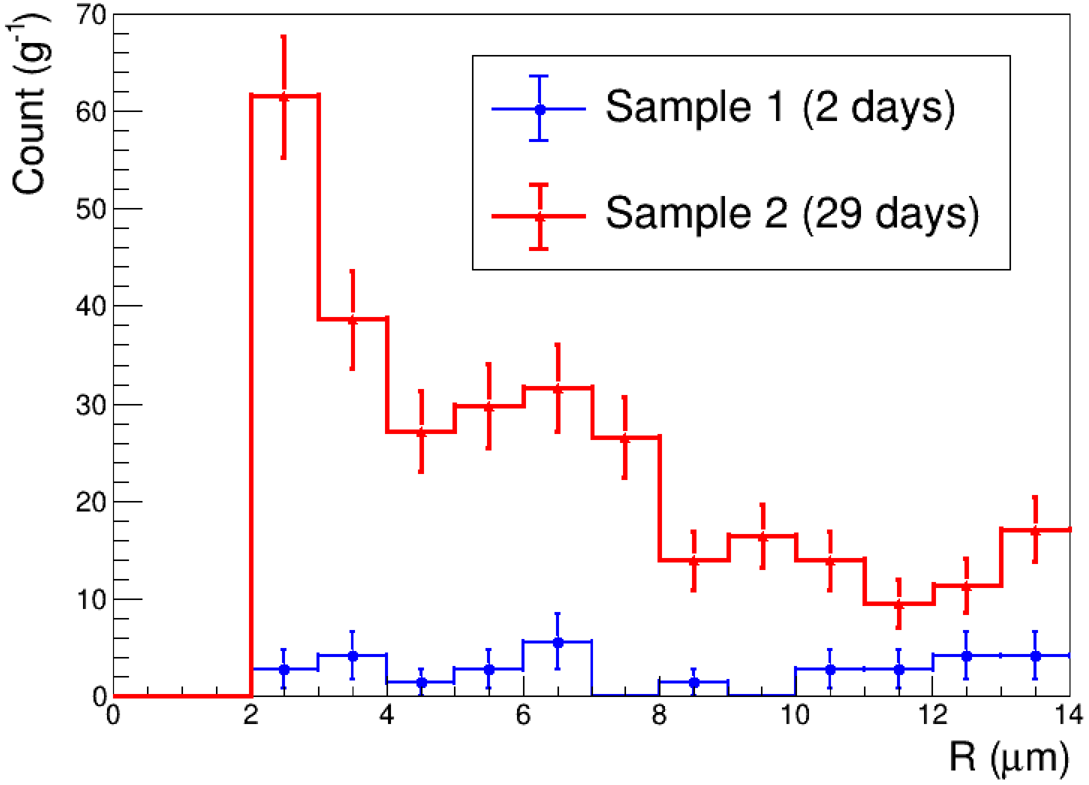
n-Run1 Setup

	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	$-20\ ^\circ\mathrm{C}$	
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

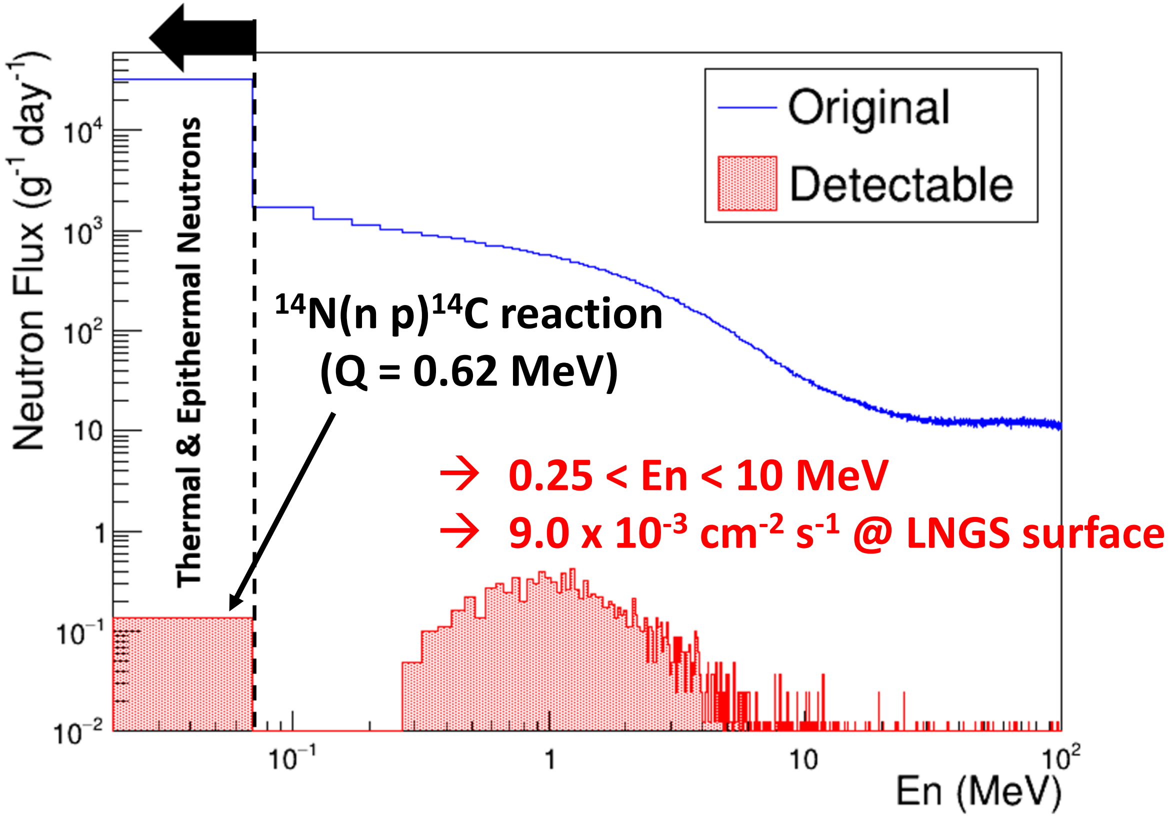
Single-prong Analysis Result (n-Run1)

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)



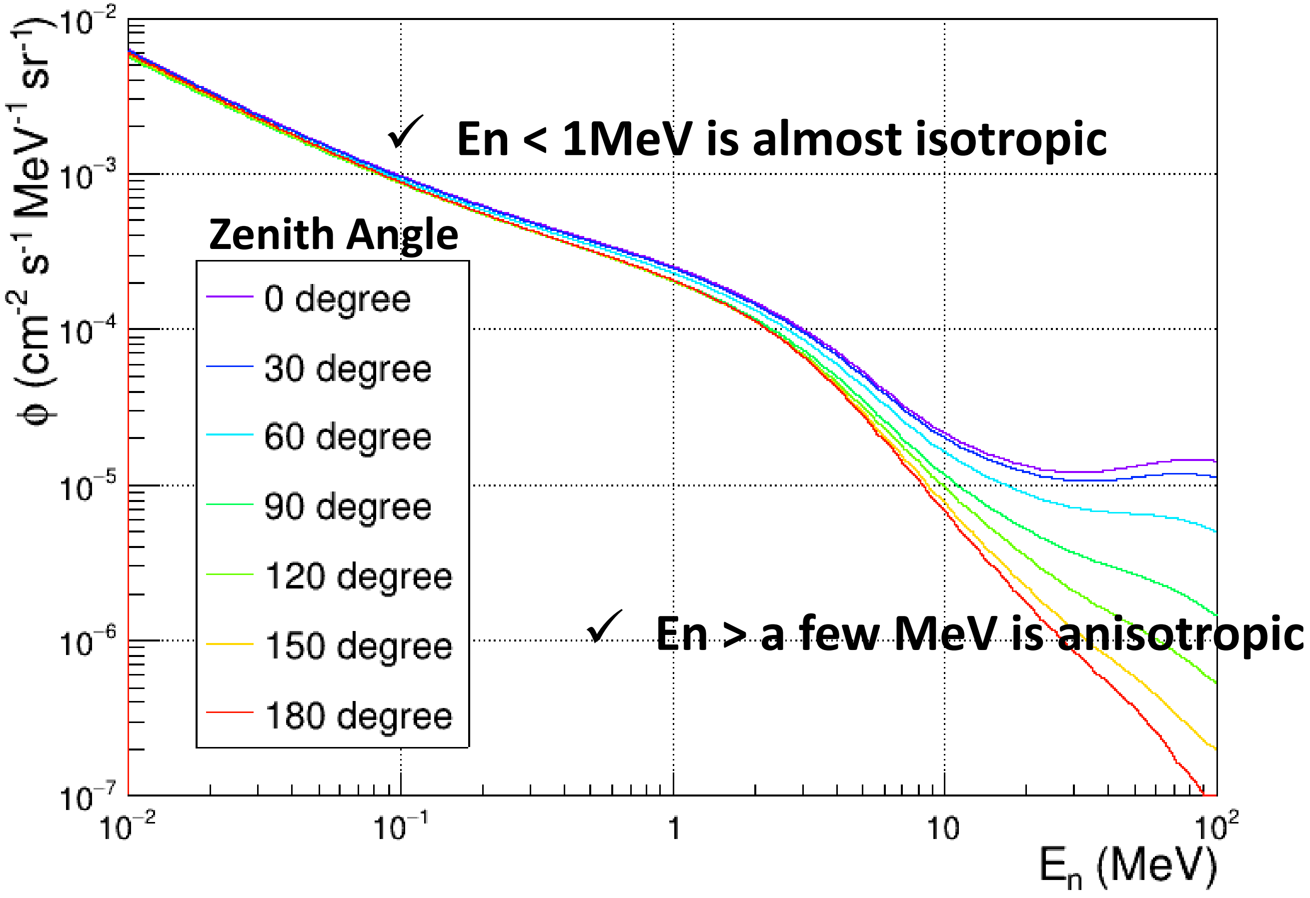
Assumed neutron spectrum expected by PARMA model

T. Sato, PLOS ONE **10**, e0144679 (2015)
T. Sato, PLOS ONE **11**, e0160390 (2016)

Simulation for Surface LNGS-run

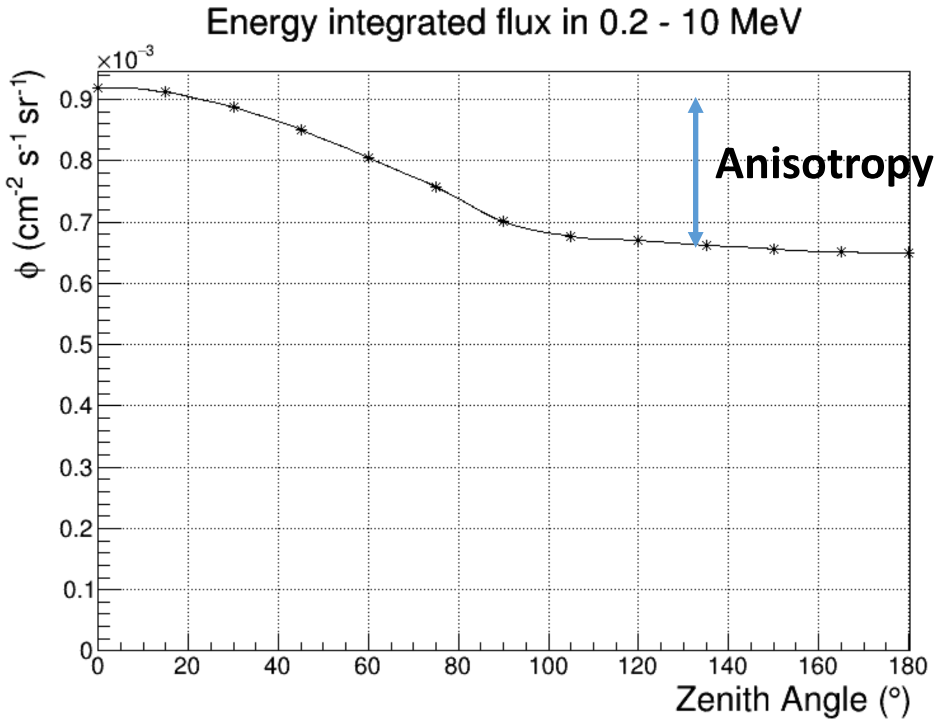
T. Sato, PLOS ONE **10**, e0144679 (2015)
T. Sato, PLOS ONE **11**, e0160390 (2016)

Zenith angular dependency of neutron spectra expected by PARMA model


✓ **En < 1MeV is almost isotropic**

✓ **En > a few MeV is anisotropic**

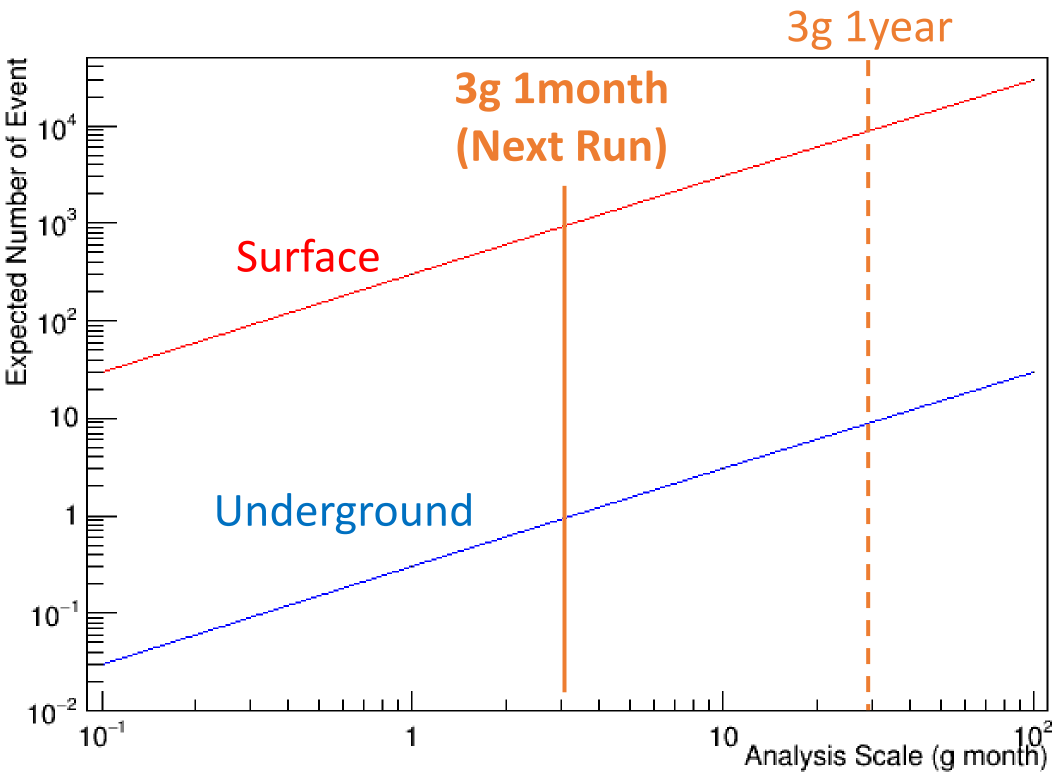
Conditions for PARMA model
Altitude : 1400 m.s.l.   Date : 1 Dec. 2021
Latitude : 42.5 deg   Longitude : 13.6 deg
Surrounding environment : Ground
Water fraction in ground : 20%


Energy integrated flux in 0.2 - 10 MeV

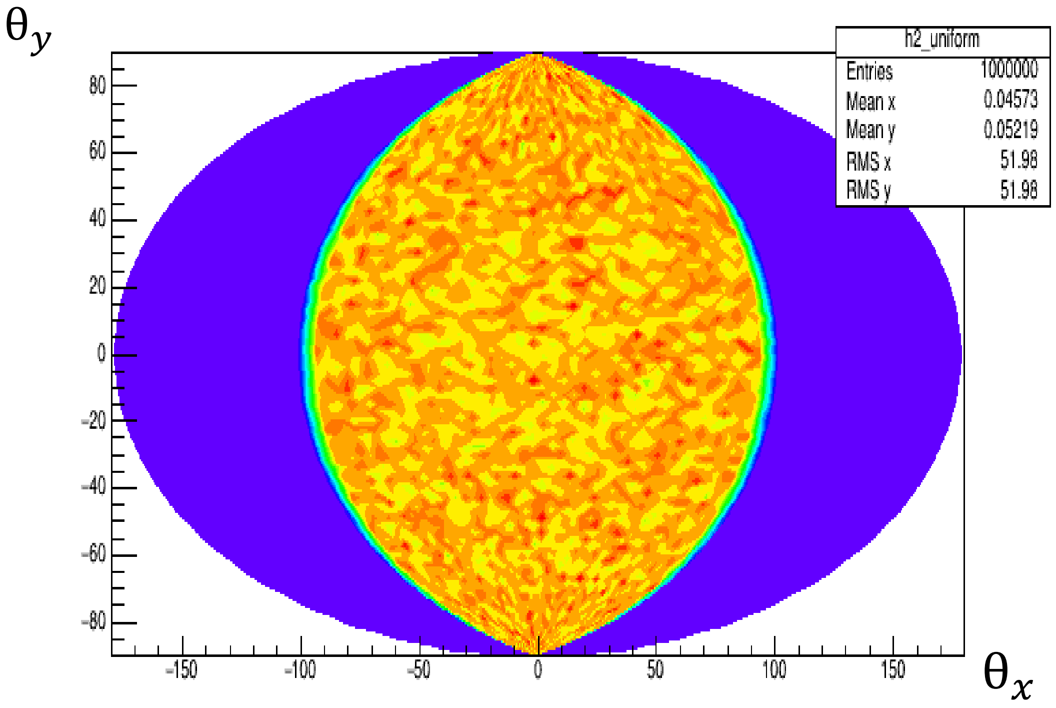
Anisotropy

Expected Result from Next Run

Analysis scale vs Expected neutron events



Expected Sky Map assuming the flat neutron angle



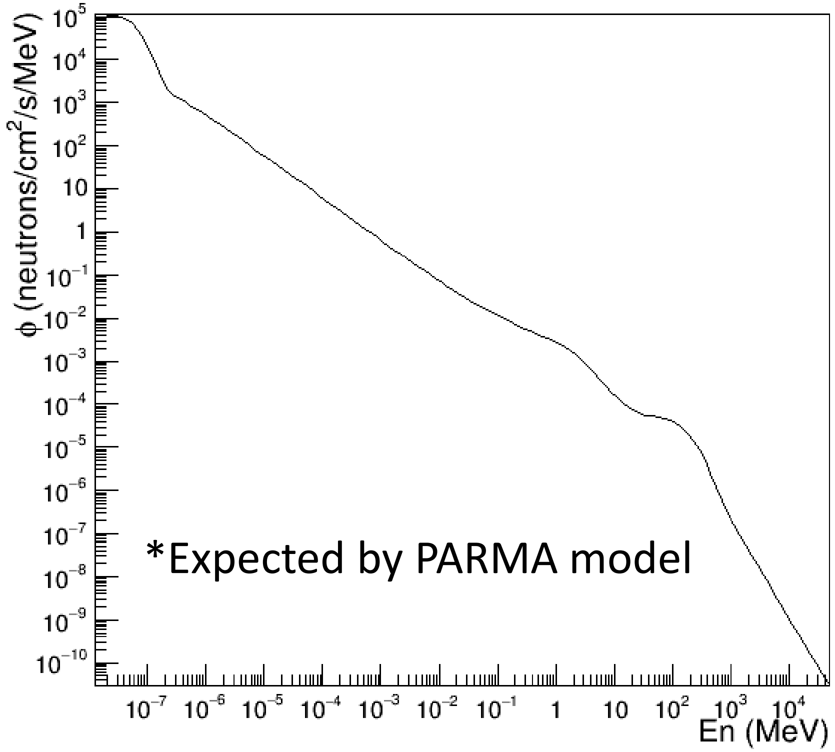
2nd Surface Neutron Run (n-Run2)

	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

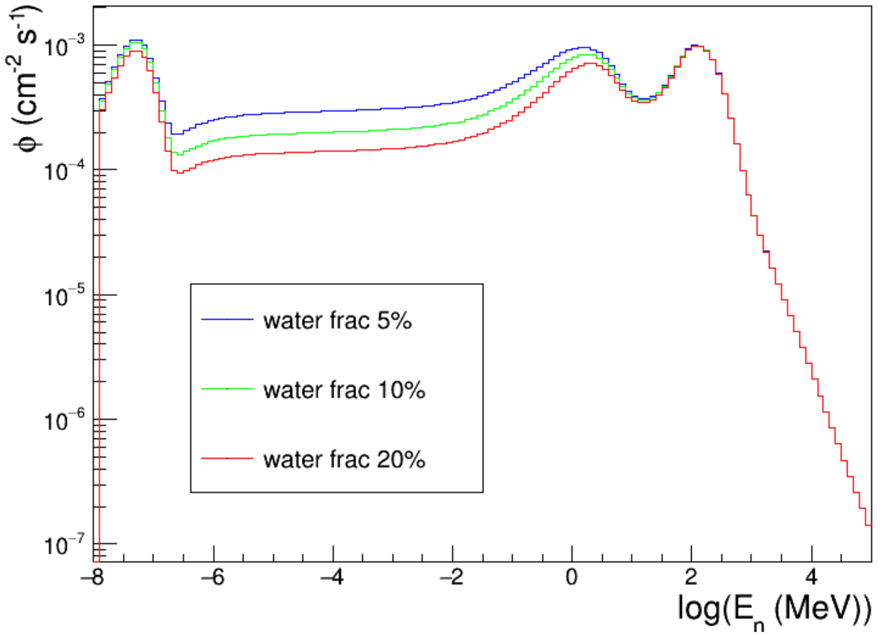
Neutron Flux

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

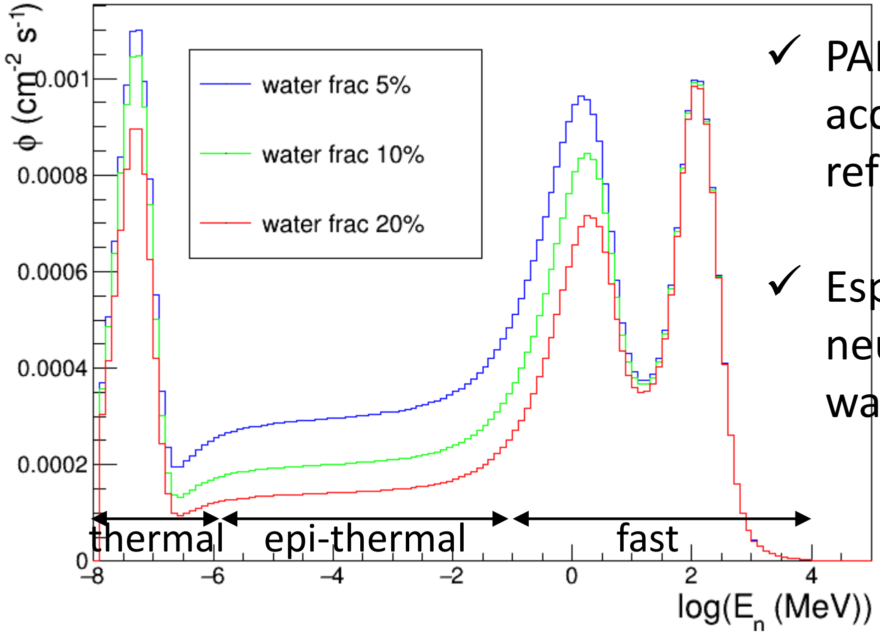


*Expected by PARMA model

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)

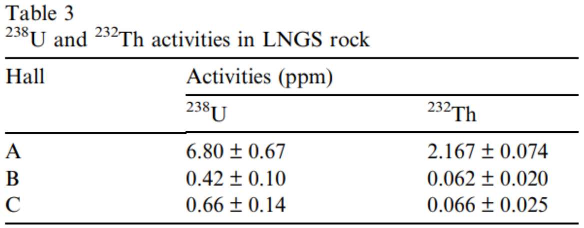


Table 3
^{238}U and ^{232}Th activities in LNGS rock

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

- Spontaneous fission of ^{238}U

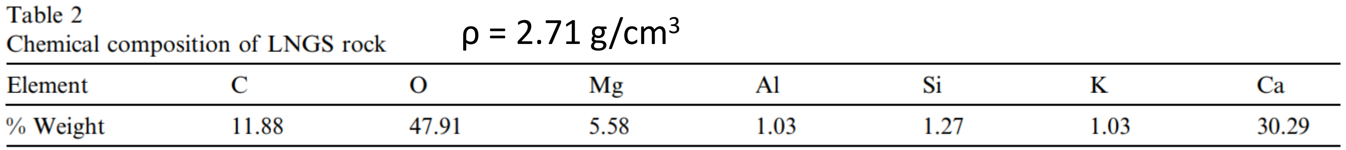


Table 2
Chemical composition of LNGS rock

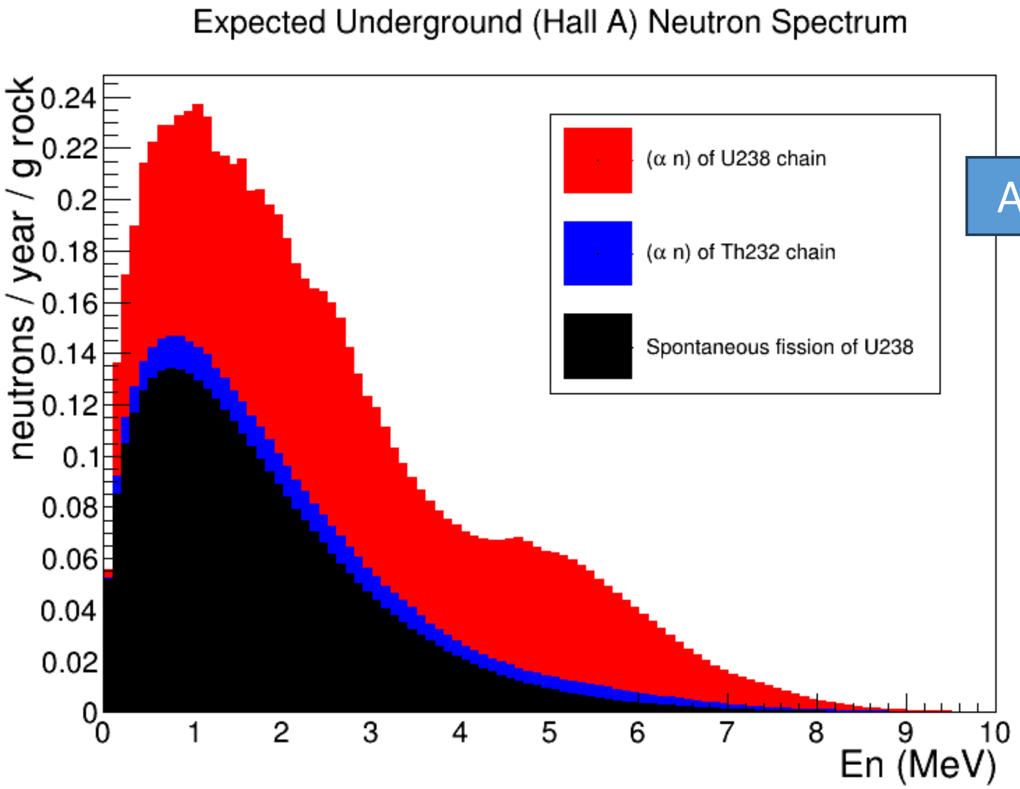
ρ = 2.71 g/cm^3

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

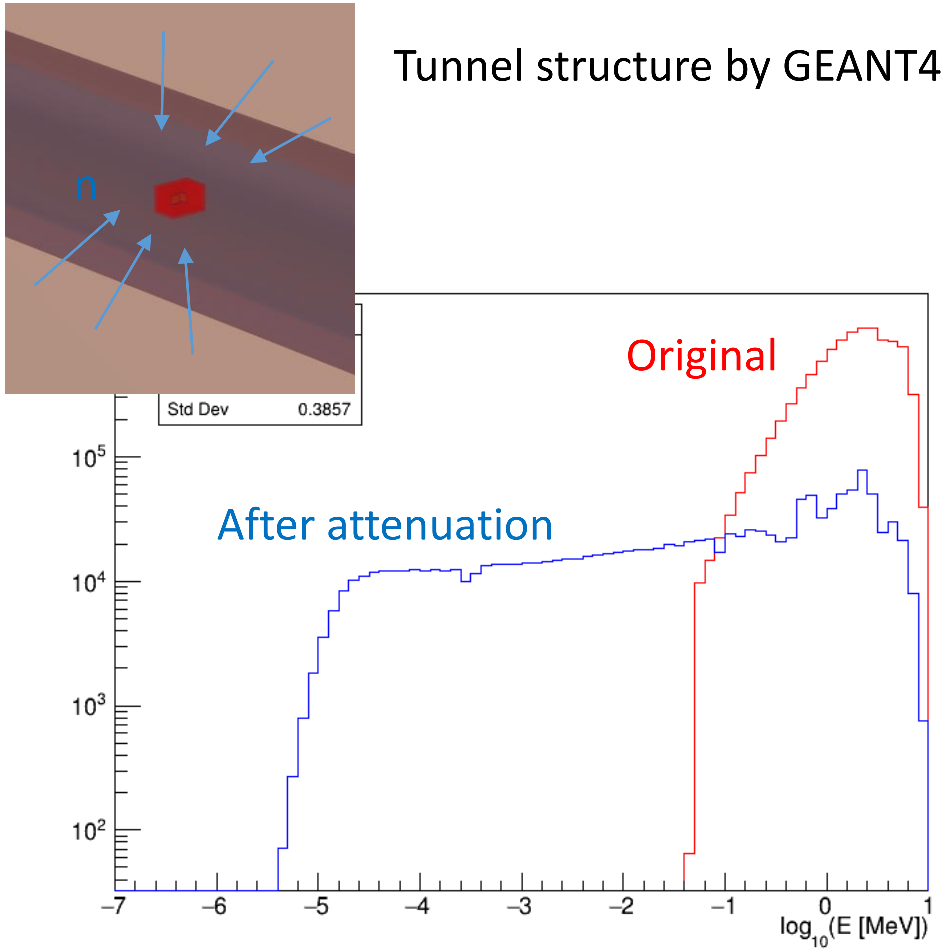
Estimate myself using NeuCBOT and GEANT4 simulation

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

Neutron Spectrum at LNGS Underground



Attenuation



Tunnel structure by GEANT4

Neutrons attenuated by water contained concrete
→Spectrum spread to thermal region

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

μ spallation

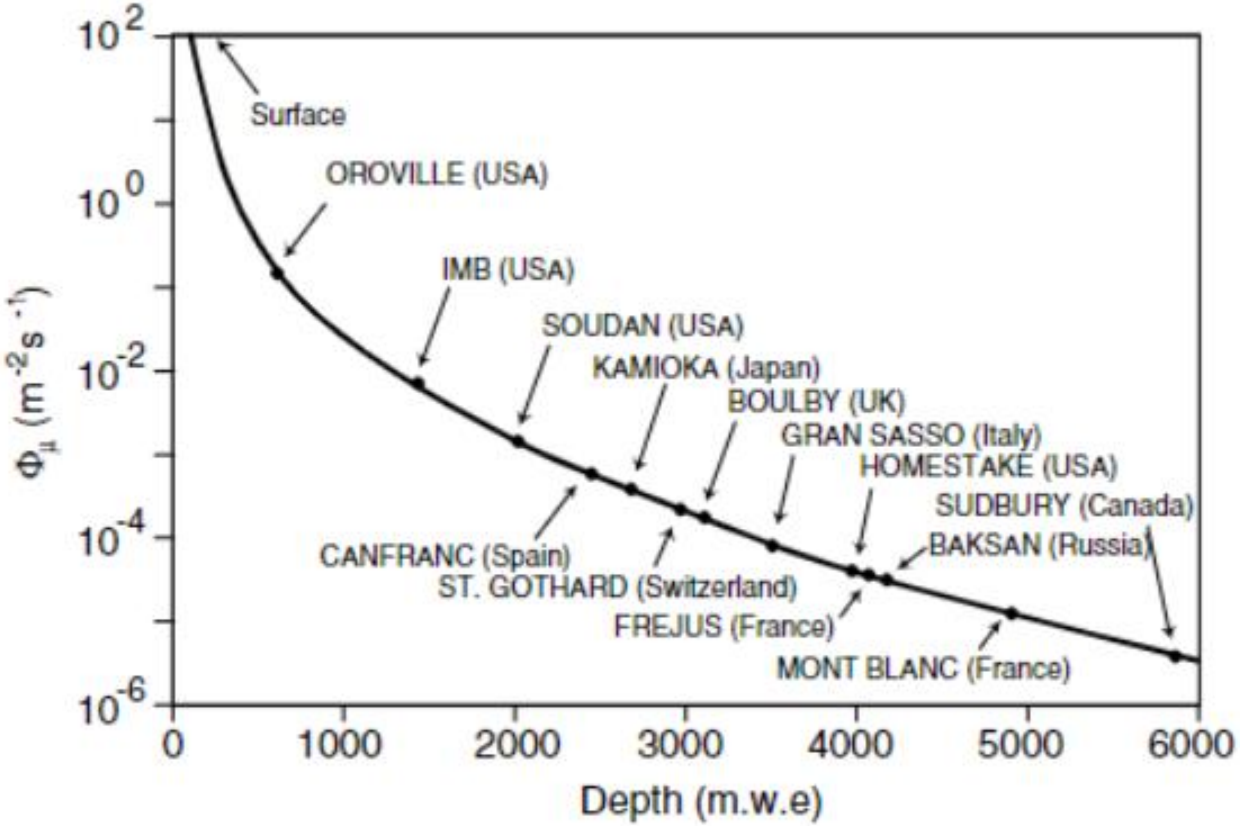


Fig. 1. Dependence of muon flux with depth, showing the location of the Canfranc Underground Laboratory with respect to other underground facilities.

Underground muon rate is about 6 order less than Surface

Almost negligible

Calibration with ion implantation system

Accelerators in our laboratory

Low Velocity Ion Implantation

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

1MV Tandem Pelletron Ion Accelerator

Acceleration Voltage : 0.5 - 1 MV

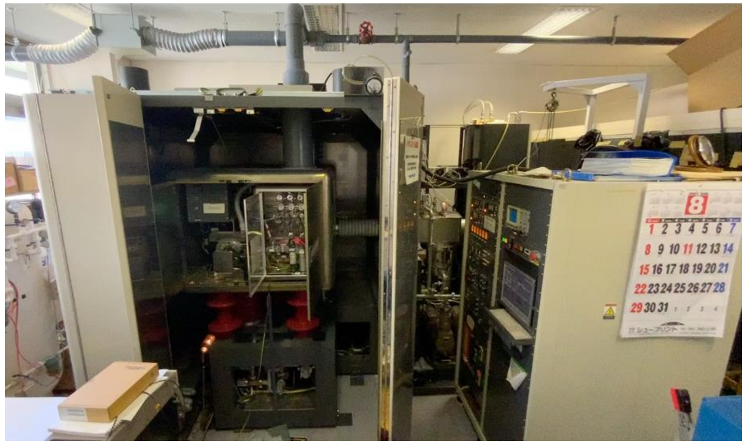
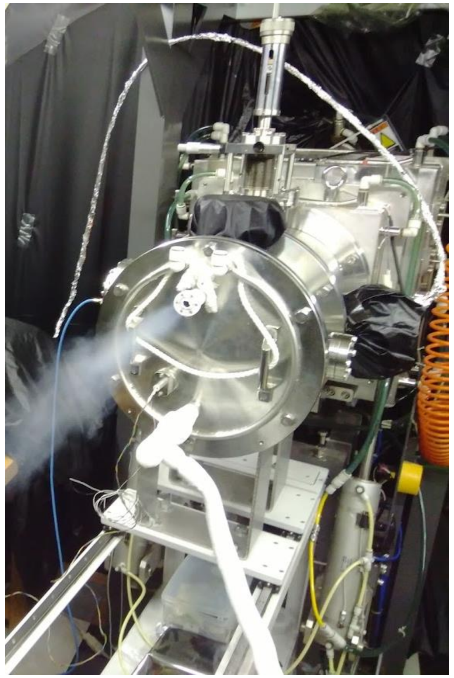
Ion : He^{++}, H, Li, B, C, O, Si, Ni, Cu, ...

Valence : 1, 2, ???

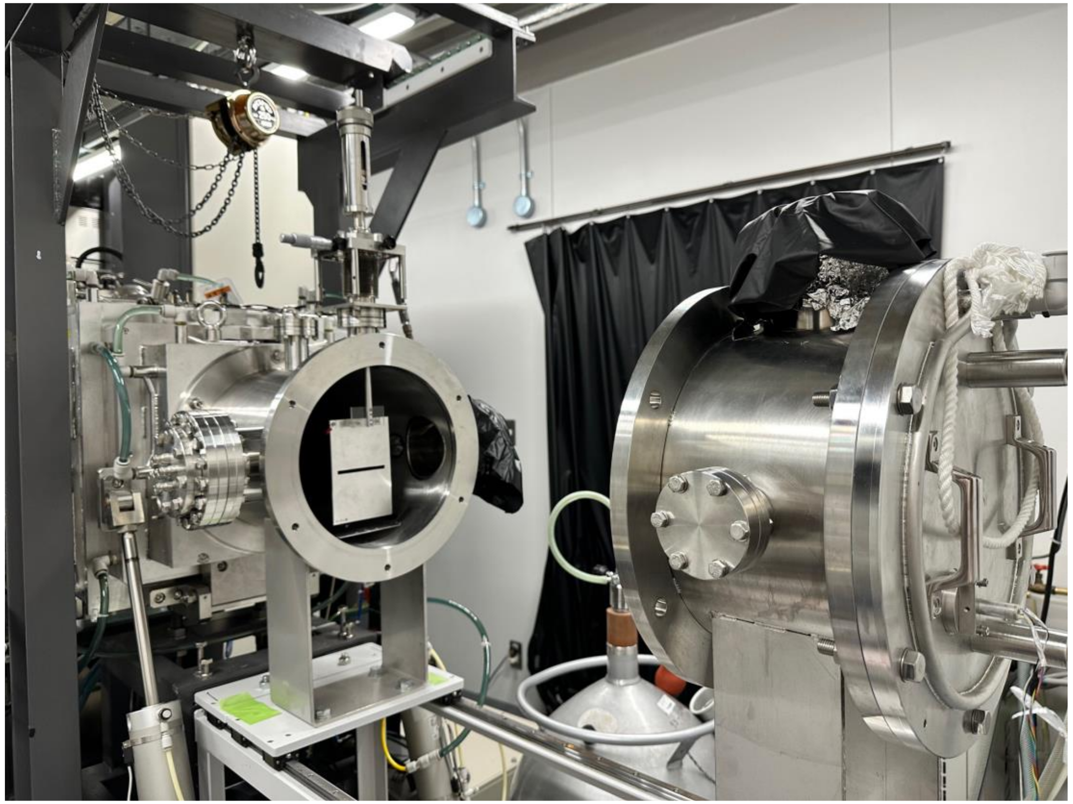
Detector : Si semiconductor detector x 2

Beam size : ϕ 2 mm

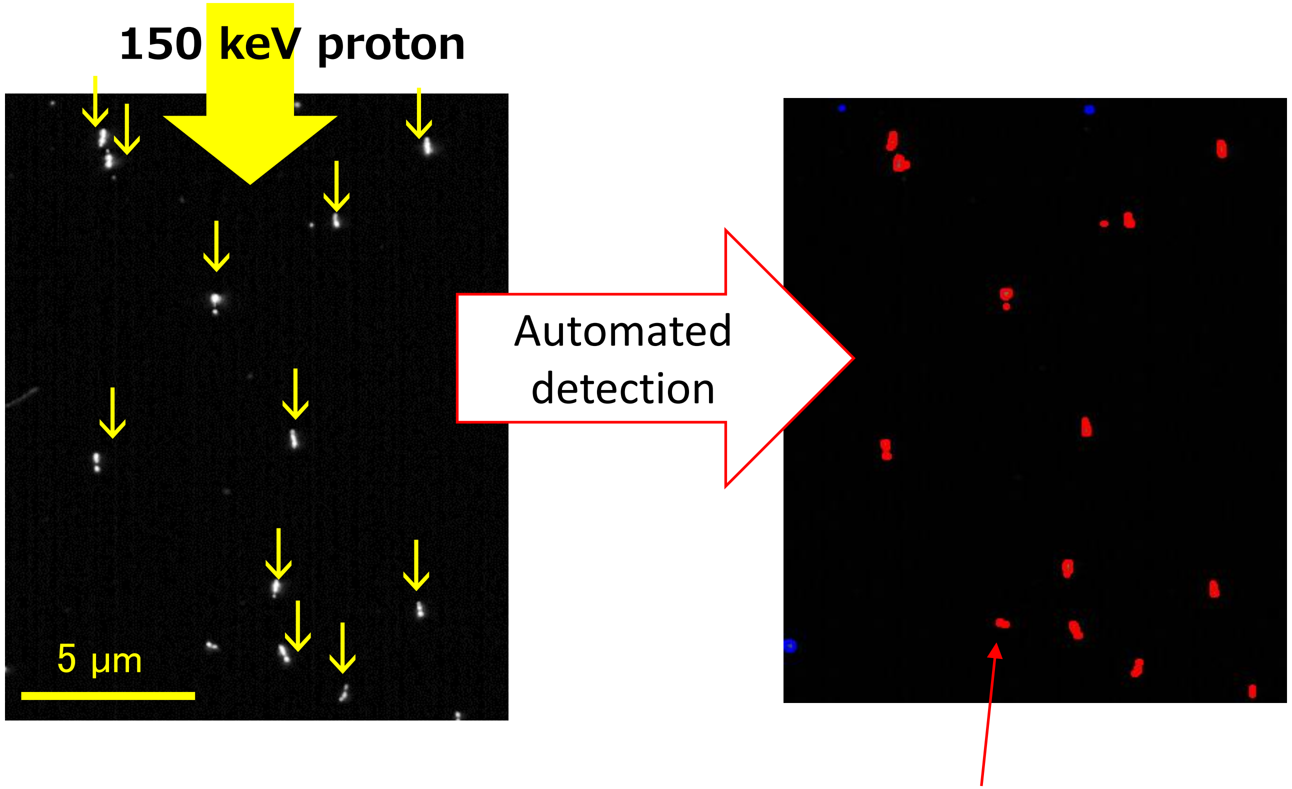
Analysis : RBS-channeling, PIXE, Nuclear Reaction, ERDA

Detecting directly exposed protons



Ion implanter @ Kanagawa Univ.

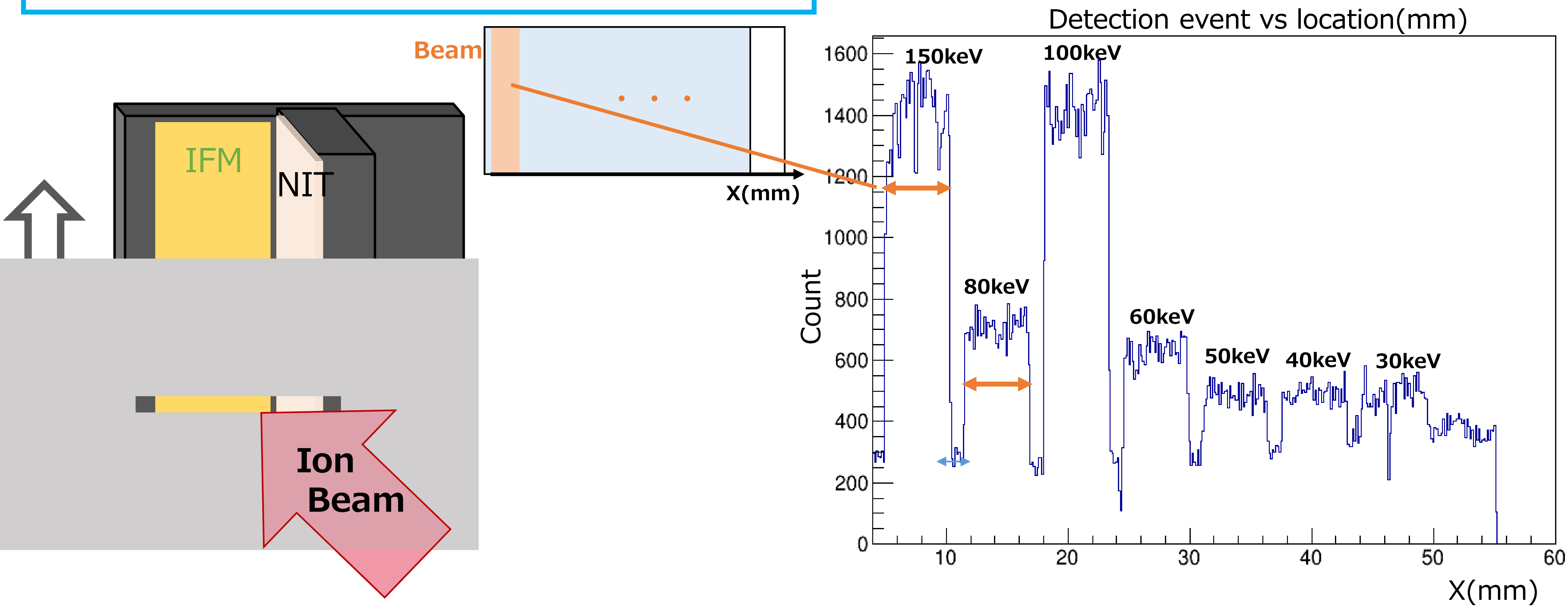


150 keV proton

Automated detection

Recognized tracks

Detecting directly exposed protons

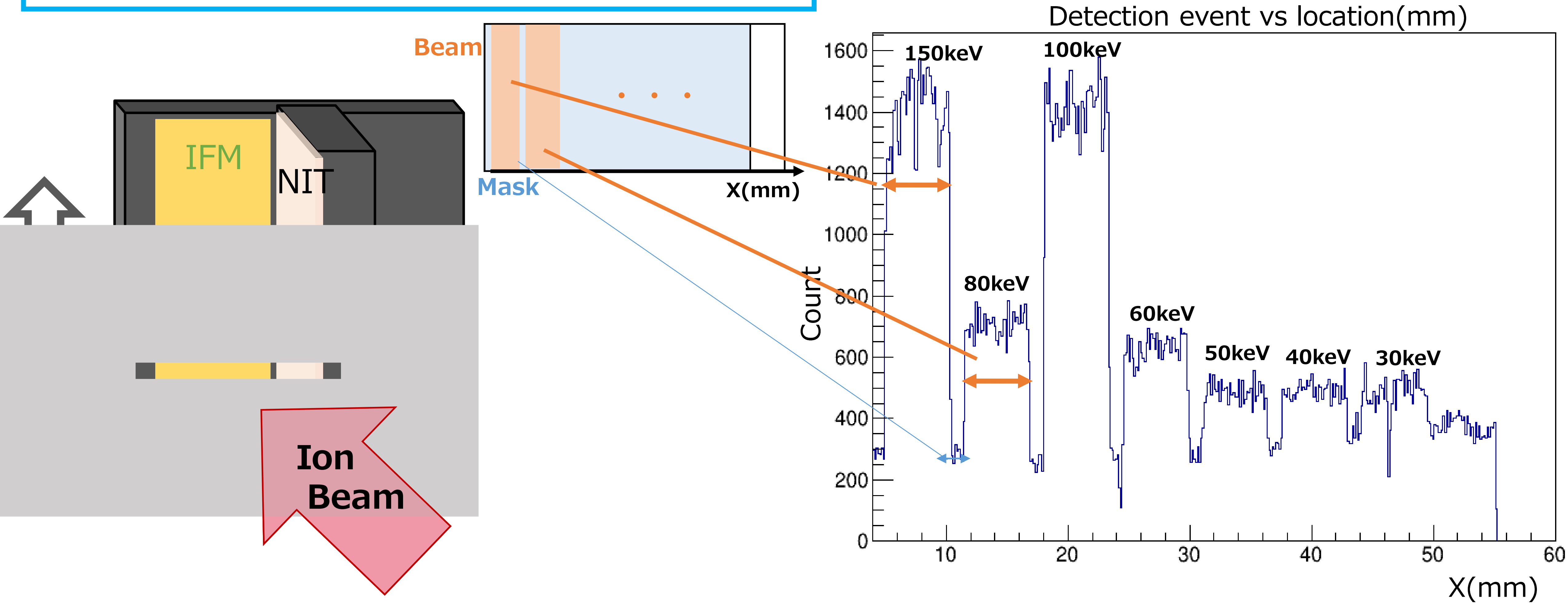


Ion exposure ➡ Move the plate up ➡ Ion exposure with different energy ・・・

➢One sample is exposured with protons of multiple energies.

・Beam areas and Mask areas are created.

Detecting directly exposed protons



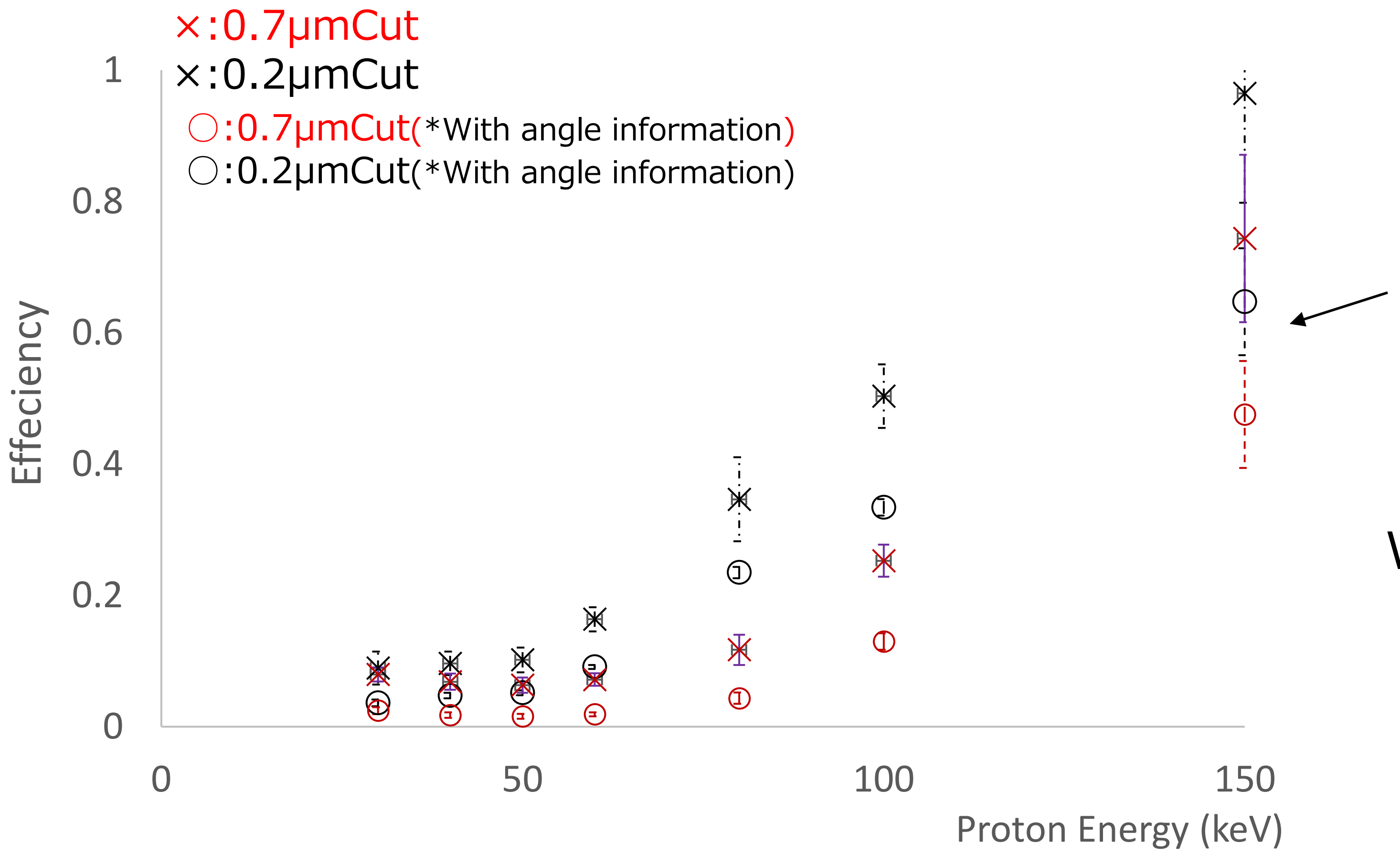
Ion exposure ➡ Move the plate up ➡ Ion exposure with different energy ・・・

➢One sample is exposured with protons of multiple energies.

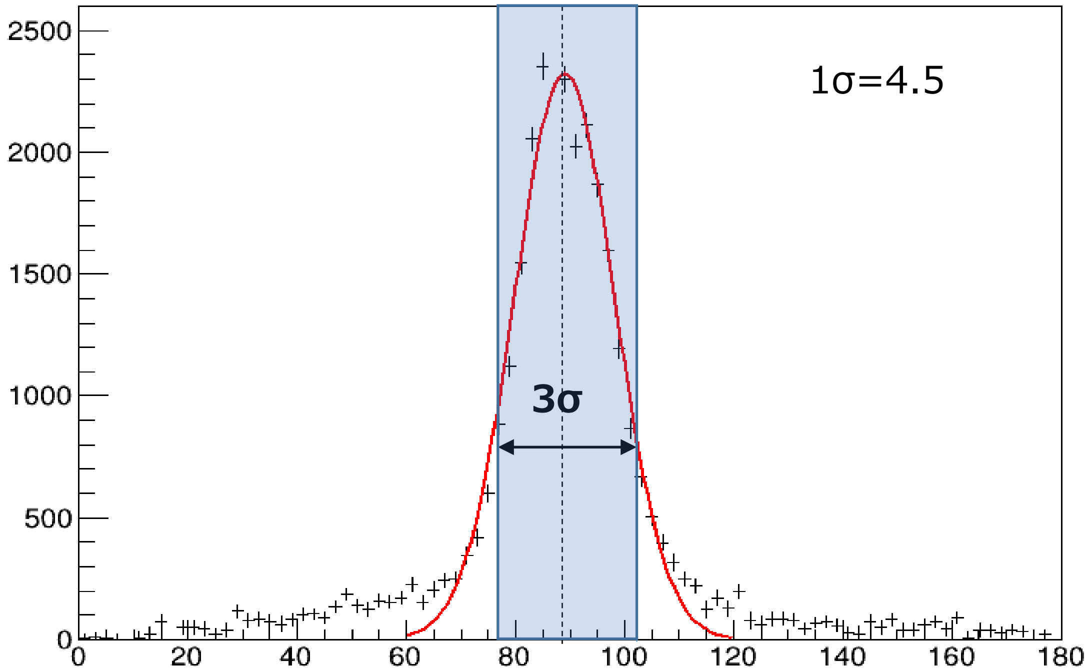
・Beam areas and Mask areas are created.

Detecting directly exposed protons

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



150keV angle distribtion

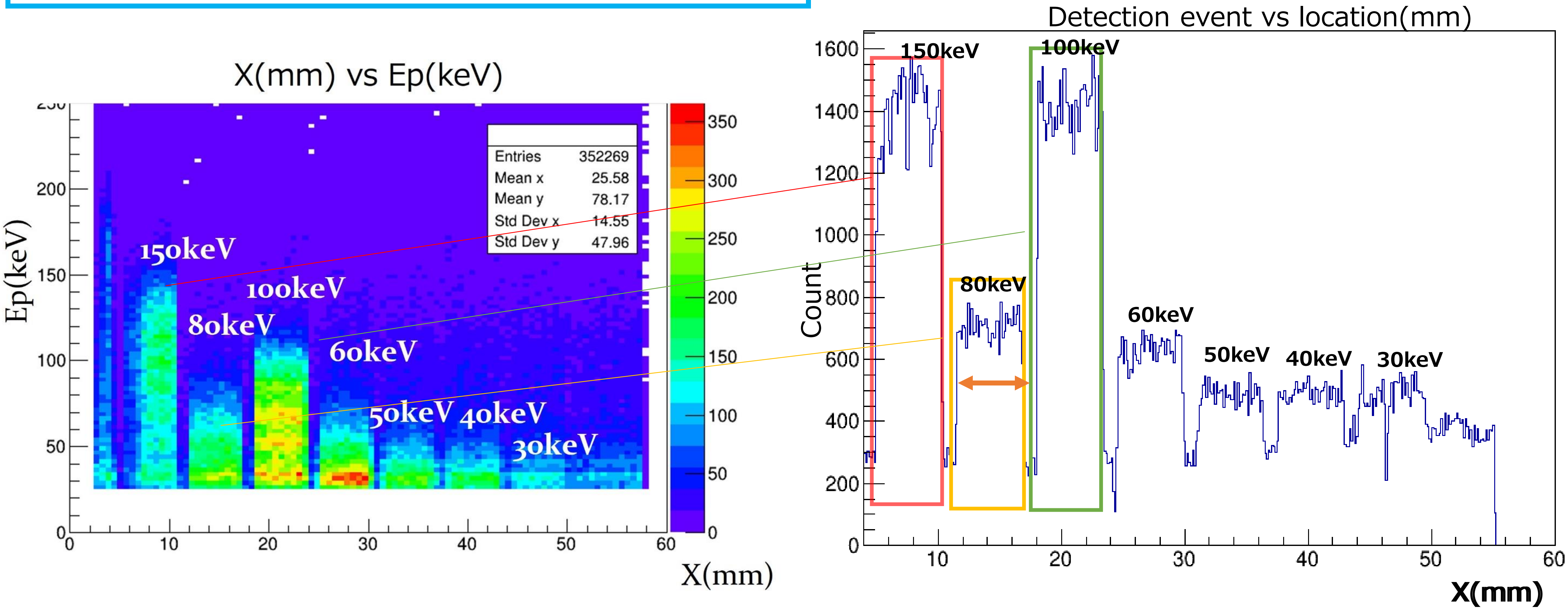


With angle information

- 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.

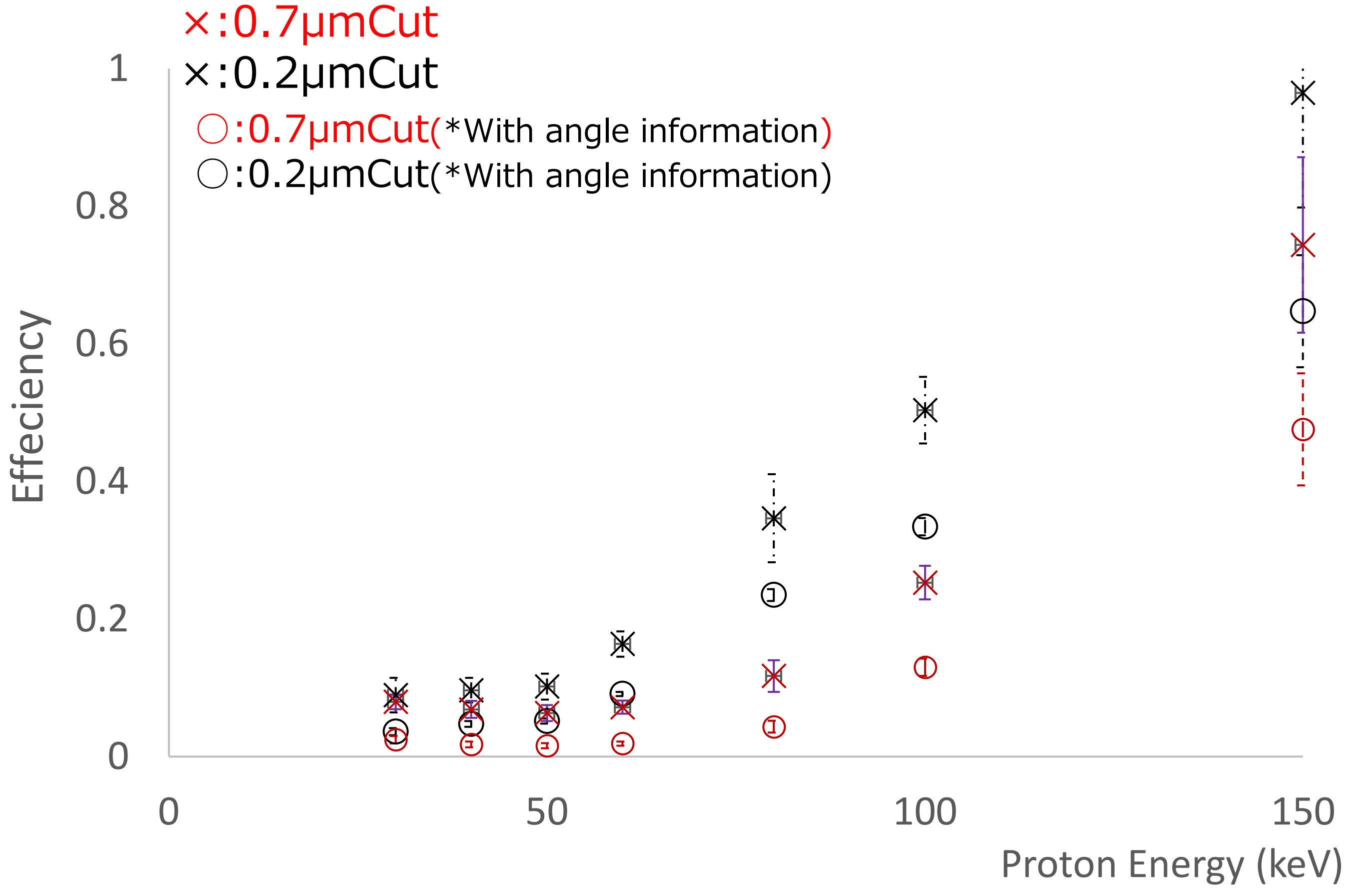
・Beam areas and Mask areas are created.

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

Detecting directly exposed protons

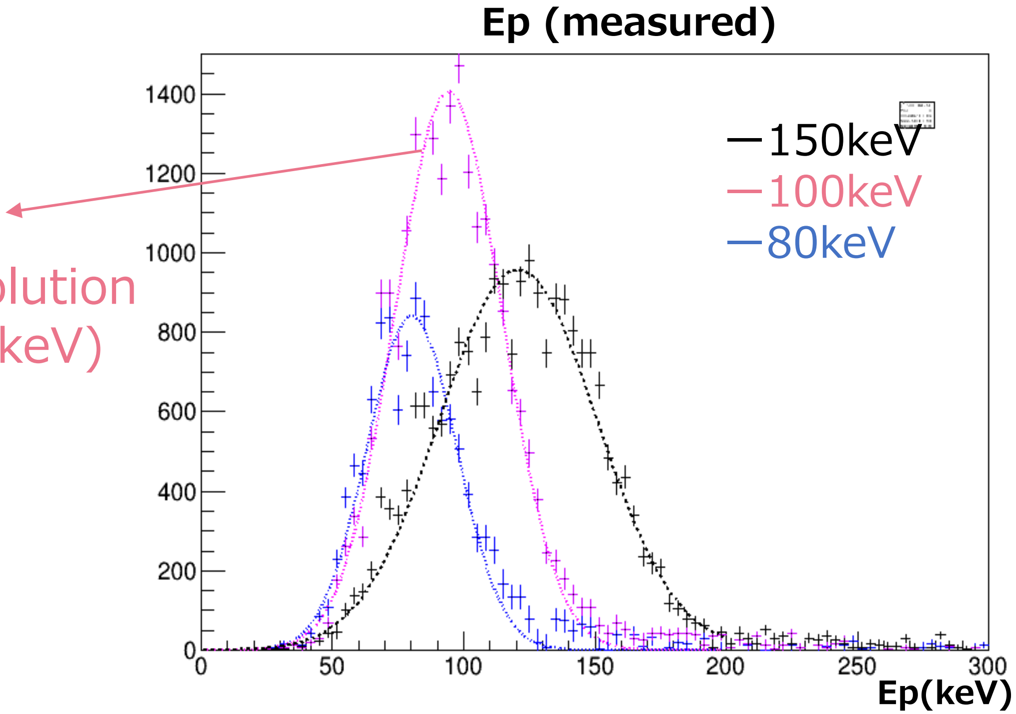
Efficiency=

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

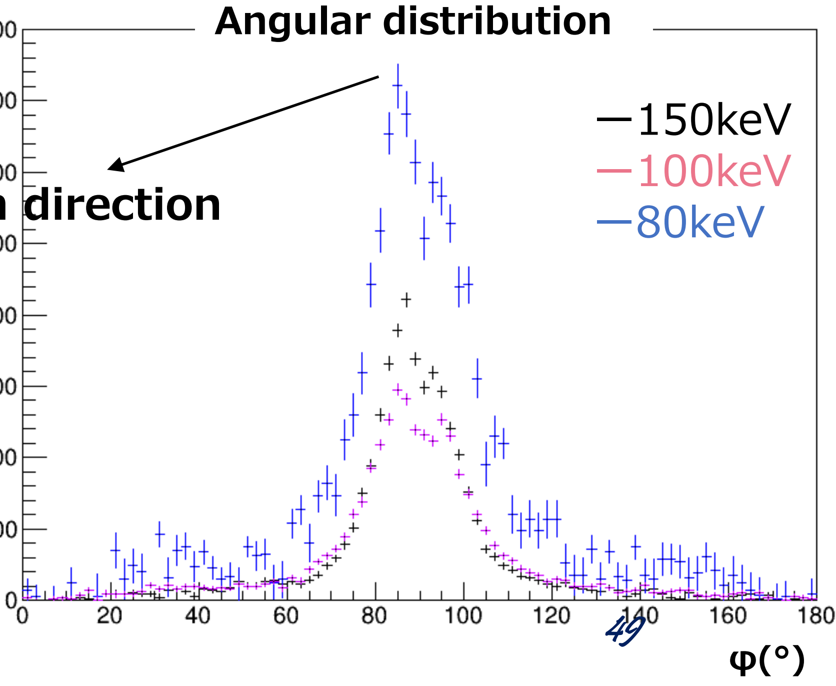


*With angle information: Gaussian fit results for angle distribution
Number of components with angles within 3σ

Energy resolution
47%(@100keV)

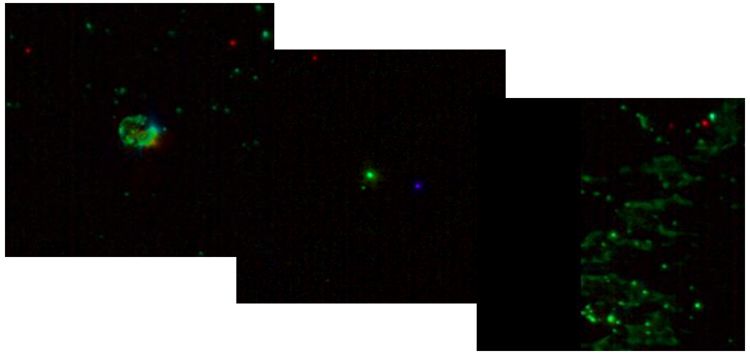


irradiation direction



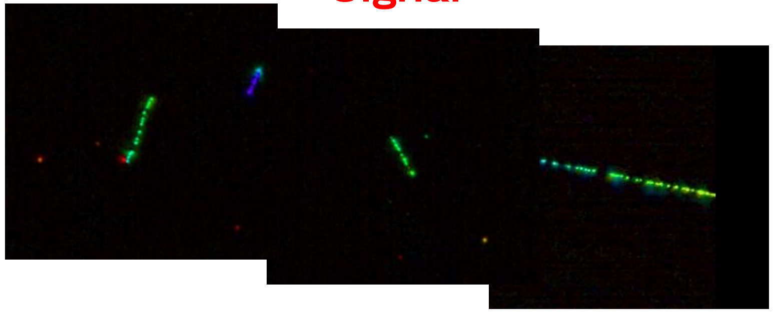
Implementing CNNs to improve efficiency of analysis

Noise



- γ-ray exposeured sample
- n-Run2 sample

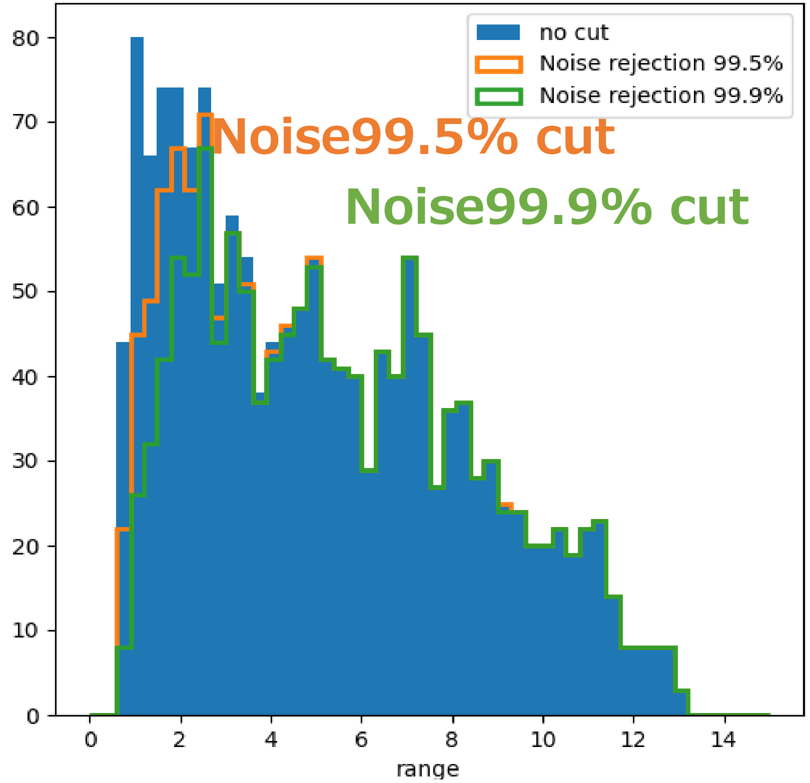
Signal



- 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.

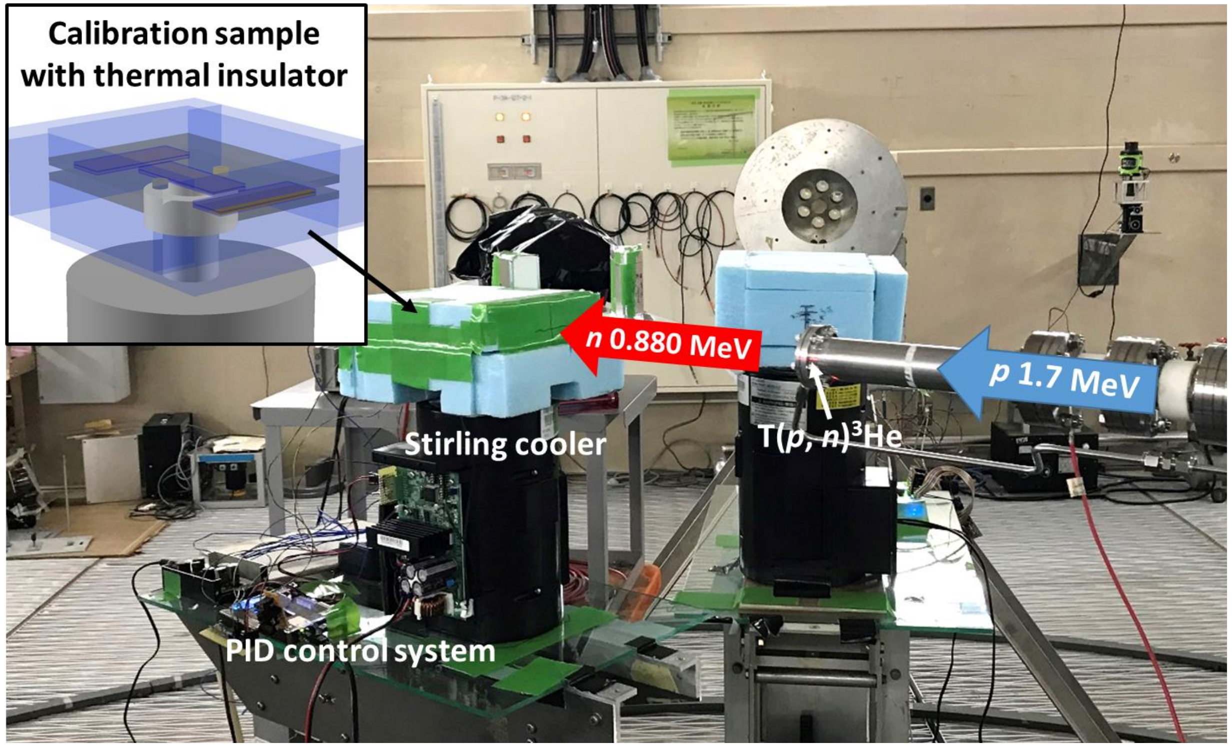


The selection accuracy is 20-50% at around 1 μm, and almost 100% at 2 μm and above.

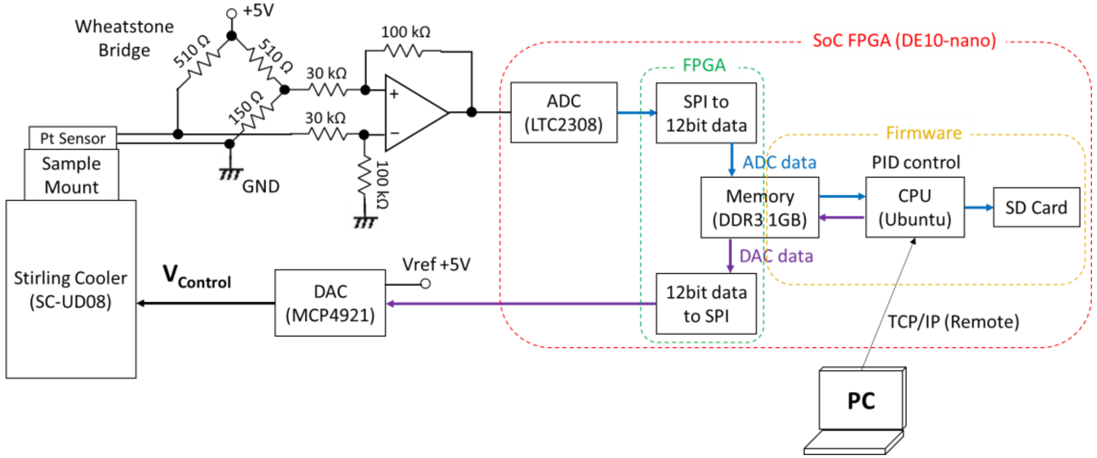
Monochromatic Neutron Calibration

Calibration with Monochromatic Sub-MeV Neutron

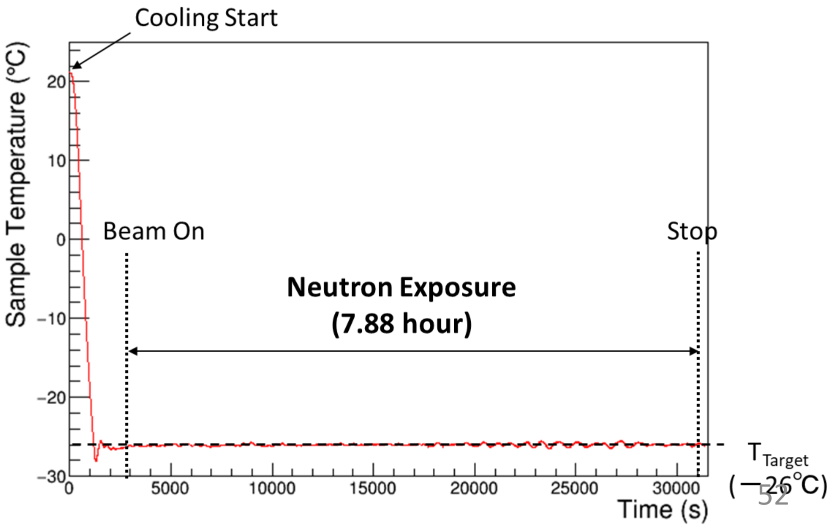
Monochromatic 880 keV neutron exposure at AIST



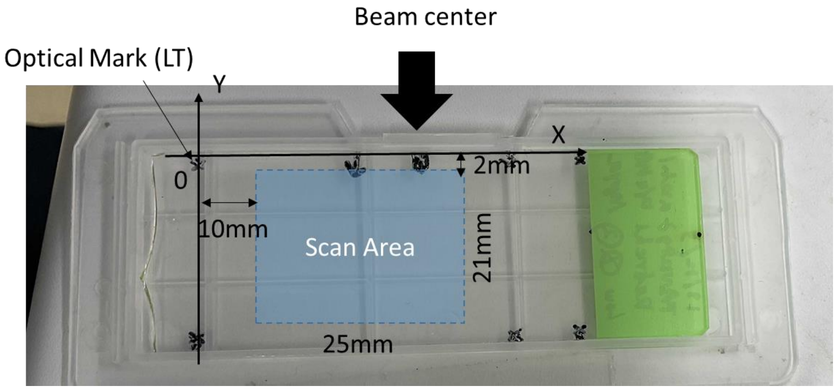
PID control system

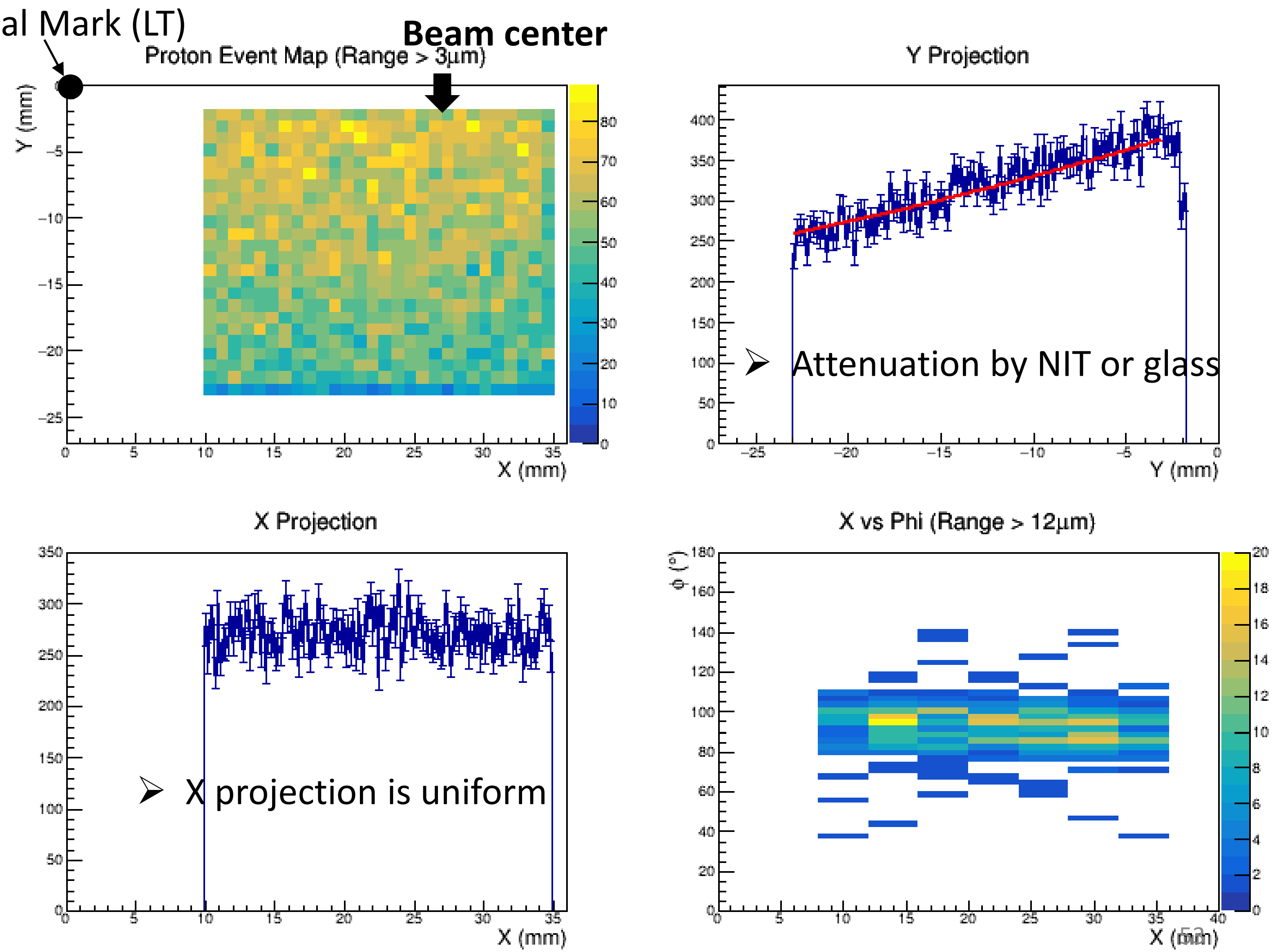


Sample temperature profile



Analysis of 880keV Sample





- Attenuation by NIT or glass
- X projection is uniform

Simulation

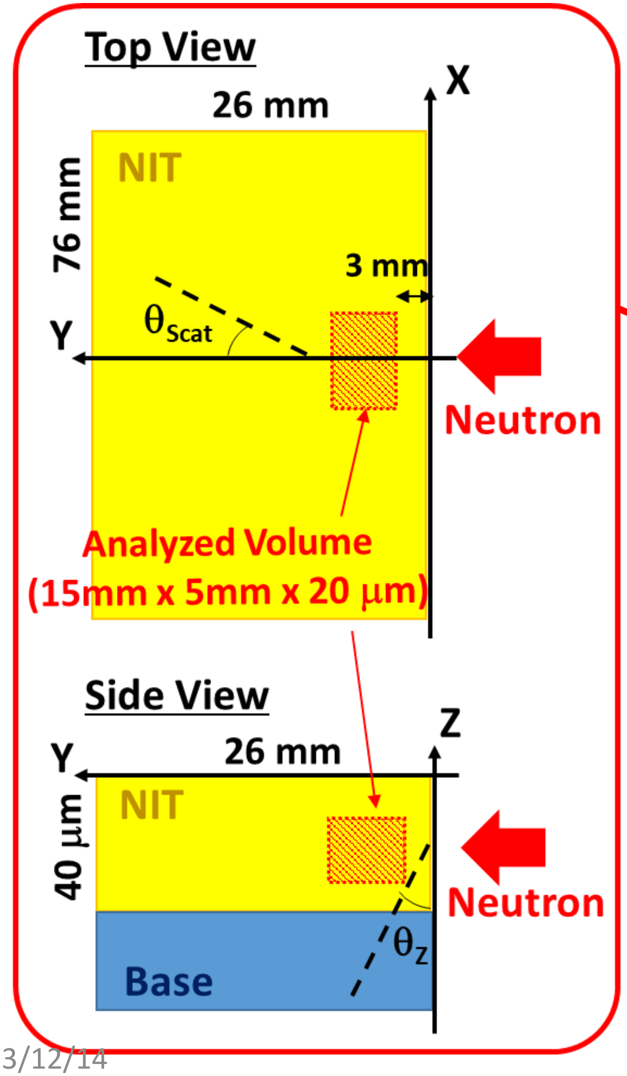
Neutron Scattering Model:

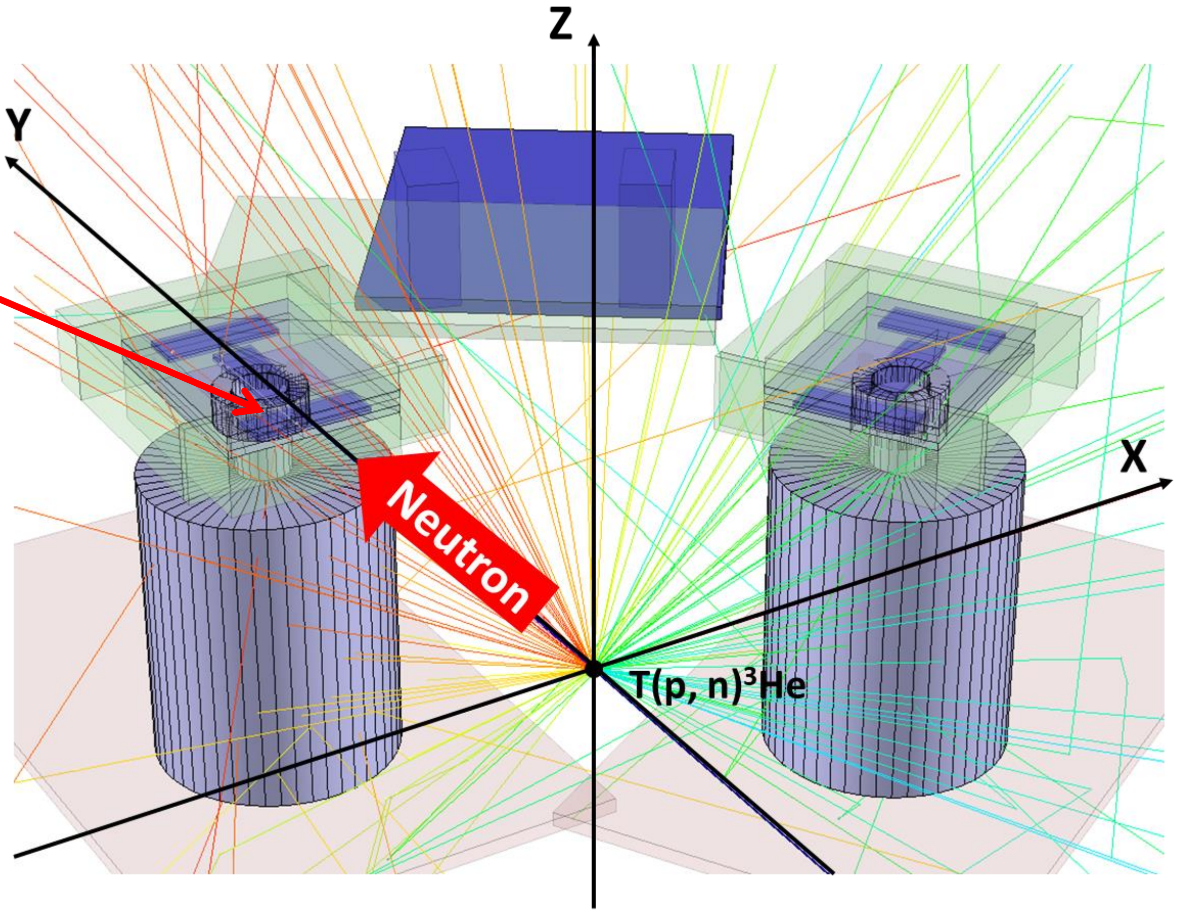
- G4HadronElasticPhysicsHP
- G4HadronPhysicsShielding

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

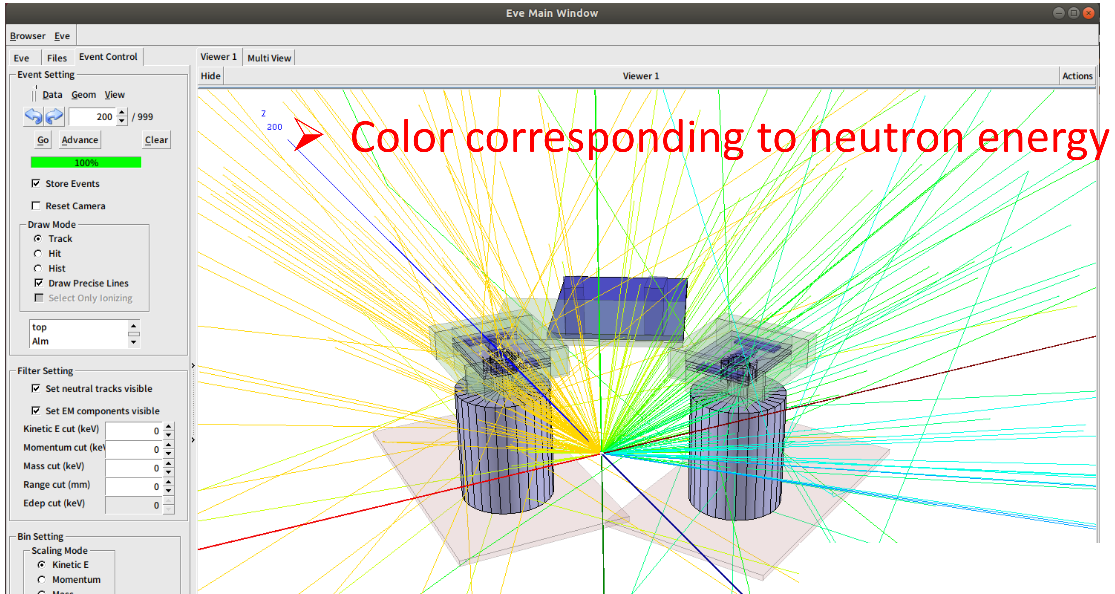




***Line color corresponding to neutron energy**

Simulation of Neutron Exposure

Considering energy and fluence for each angle

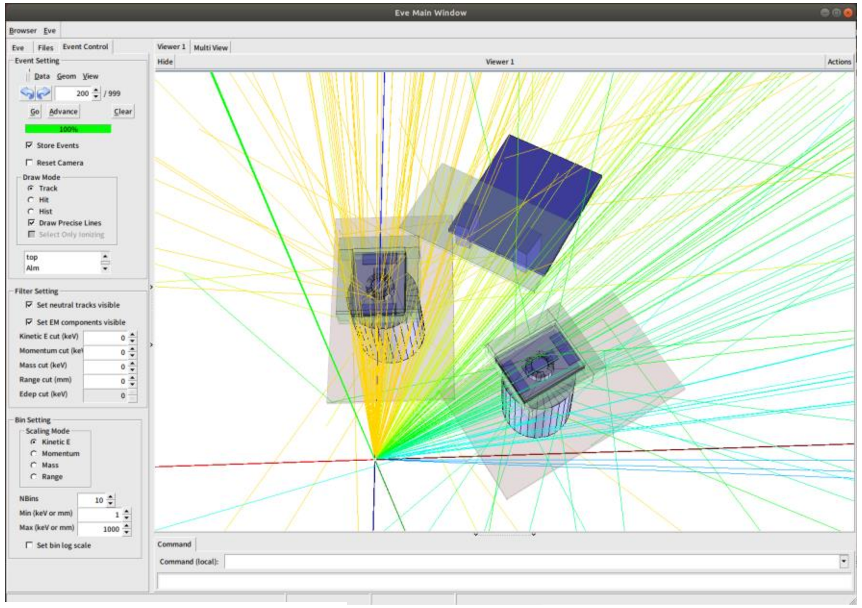


Event Setting
200 / 999
100%
☑ Store Events
☐ Reset Camera
Draw Mode
● Track
○ Hit
○ Hist
☑ Draw Precise Lines
☐ Select Only Ionizing
top
Alm

Filter Setting
☑ Set neutral tracks visible
☑ Set EM components visible
Kinetic E cut (keV) 0
Momentum cut (keV) 0
Mass cut (keV) 0
Range cut (mm) 0
Edep cut (keV) 0

Bin Setting
Scaling Mode
● Kinetic E
○ Momentum
○ Mass
○ Range
NBins 10
Min (keV or mm) 1
Max (keV or mm) 1000
☐ Set bin log scale

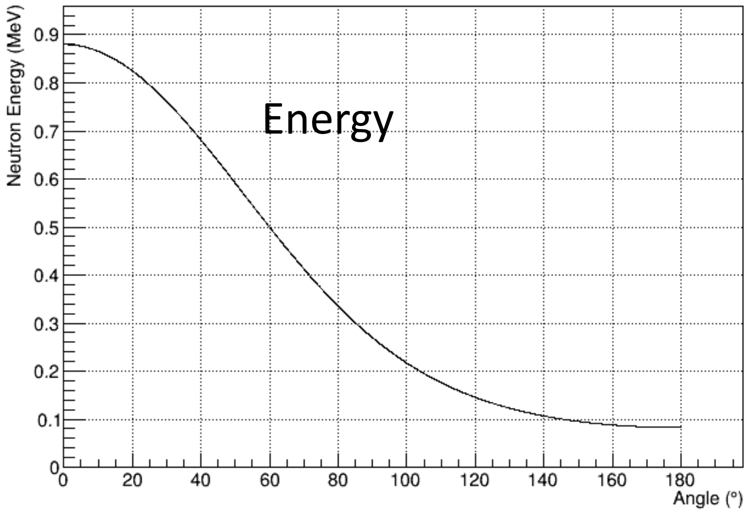
➤ Color corresponding to neutron energy



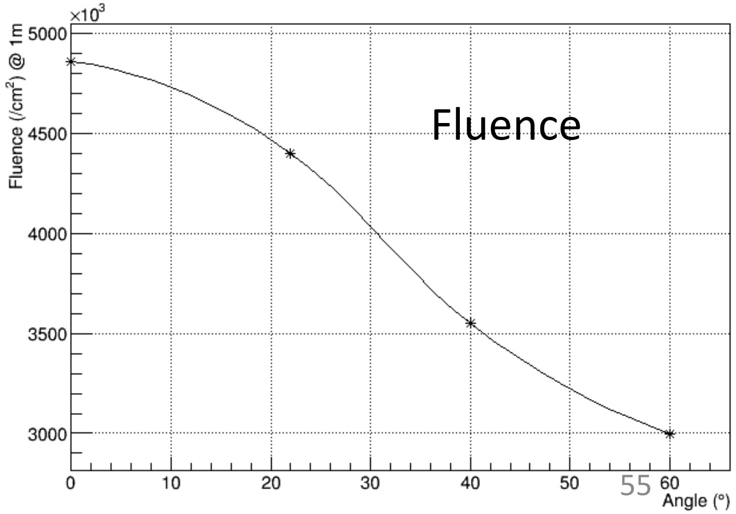
Event Setting
200 / 999
100%
☑ Store Events
☐ Reset Camera
Draw Mode
● Track
○ Hit
○ Hist
☑ Draw Precise Lines
☐ Select Only Ionizing
top
Alm

Filter Setting
☑ Set neutral tracks visible
☑ Set EM components visible
Kinetic E cut (keV) 0
Momentum cut (keV) 0
Mass cut (keV) 0
Range cut (mm) 0
Edep cut (keV) 0

Bin Setting
Scaling Mode
● Kinetic E
○ Momentum
○ Mass
○ Range
NBins 10
Min (keV or mm) 1
Max (keV or mm) 1000
☐ Set bin log scale

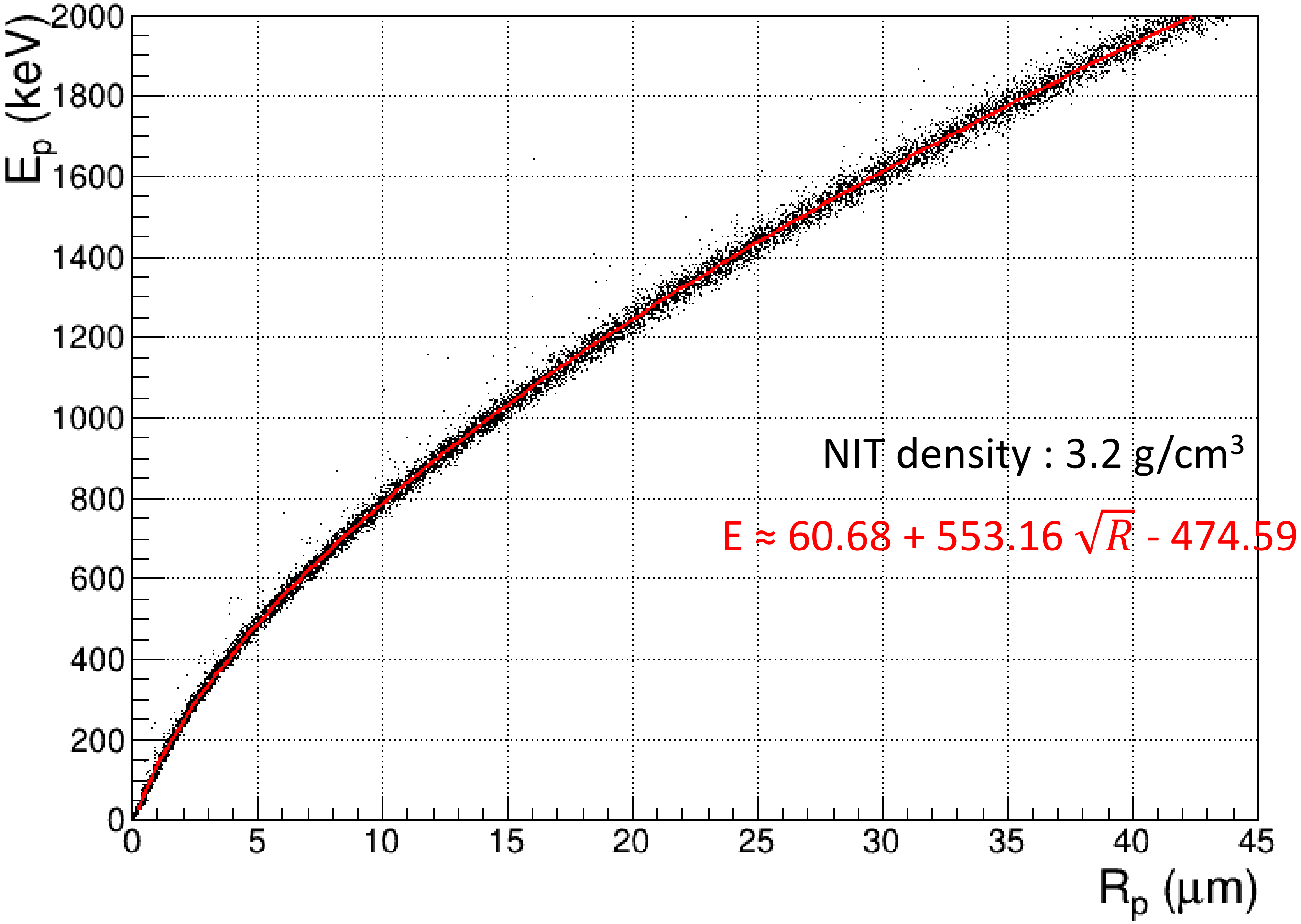


AIST 2019 Neutron Fluence



2023/12/14

Correlation of Proton Energy and Range in NIT (GEANT4)

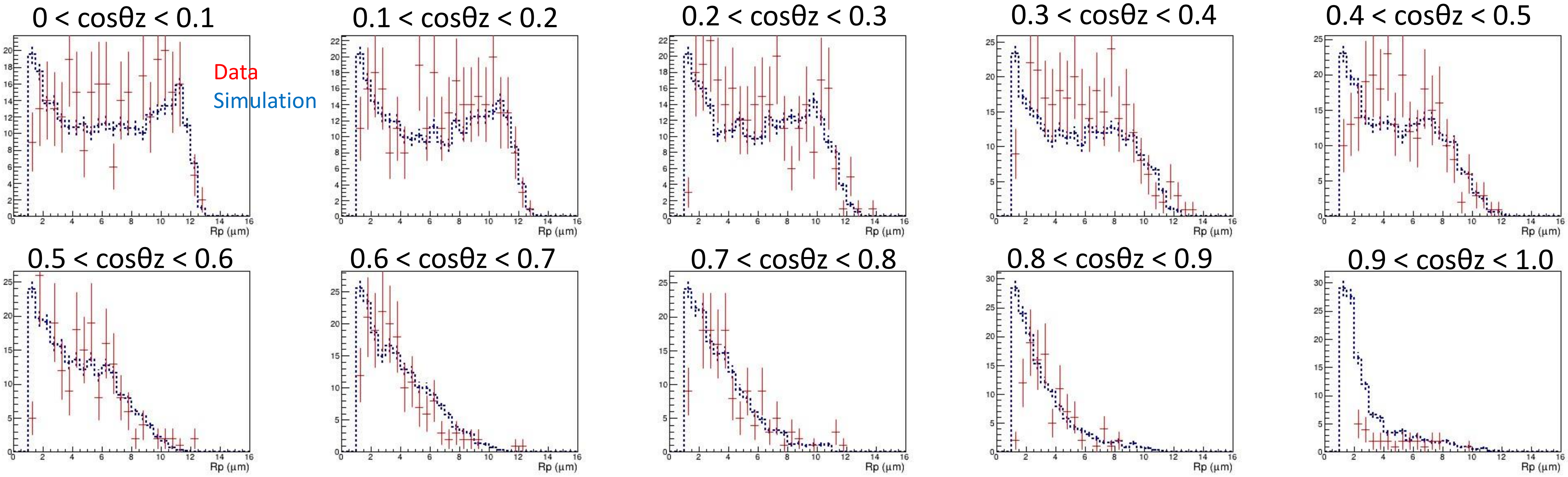


NIT density : 3.2 g/cm^3

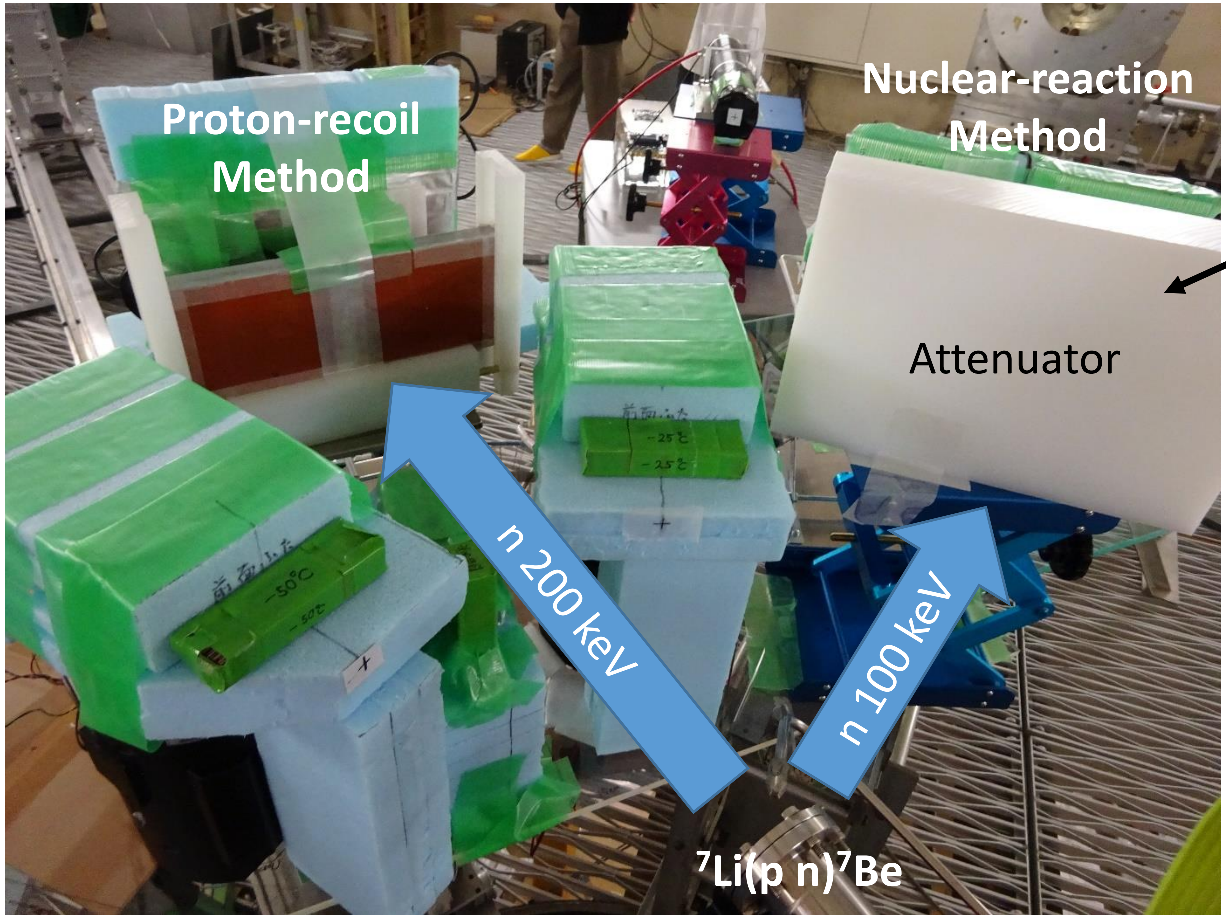
$E \approx 60.68 + 553.16\,\sqrt{R} - 474.59\,\sqrt[3]{R}$ (keV)

Angular dependency

AIST 2019 : 880keV neutron sample



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



Behind the attenuator

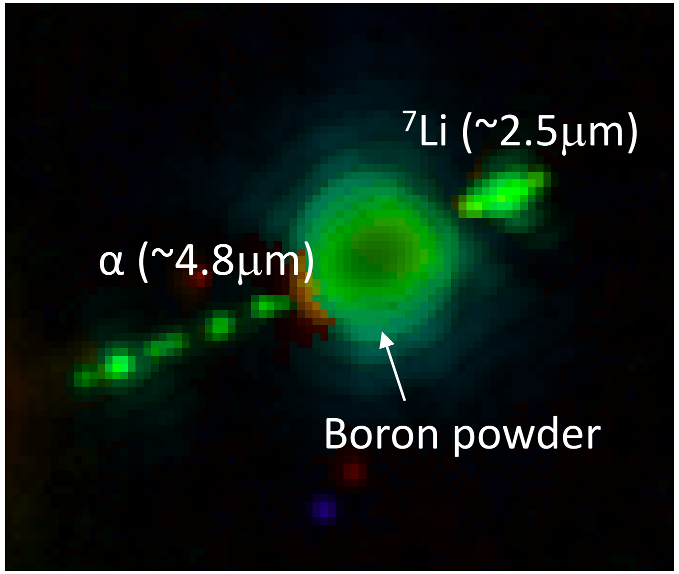
Following nuclear reactions occurred after attenuation

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

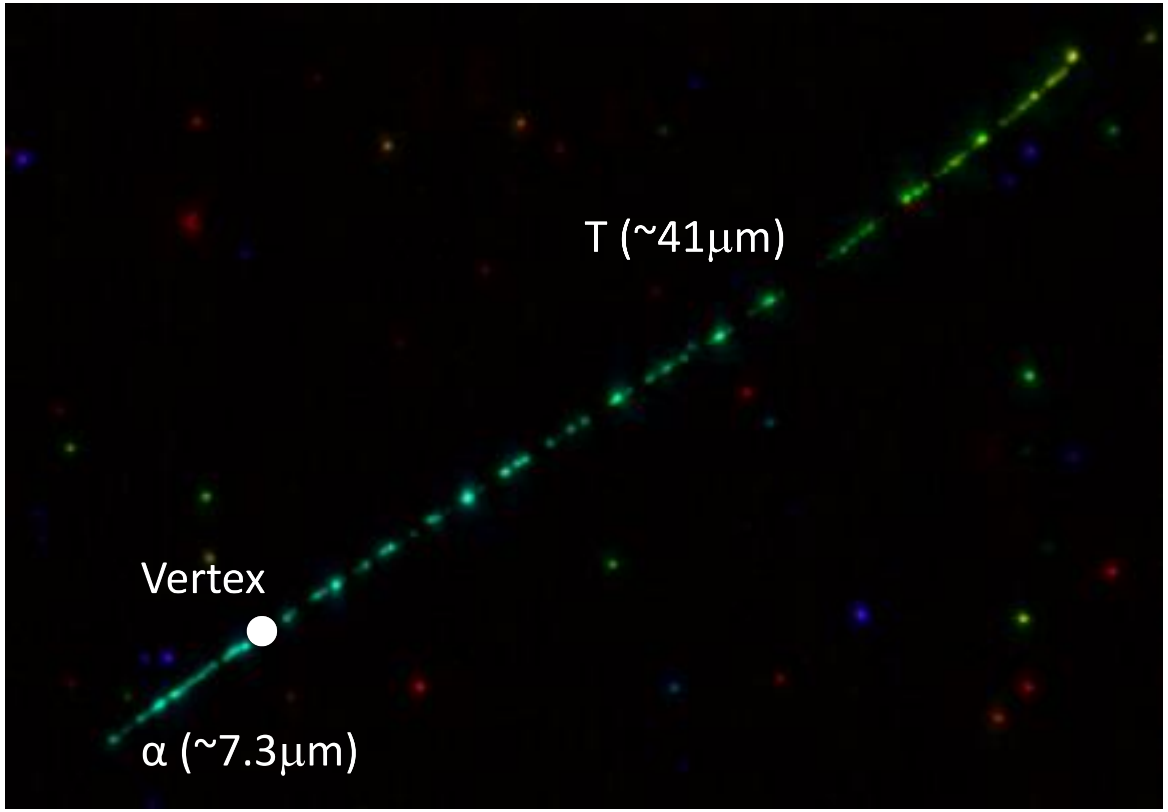
② $n + {}^6Li \rightarrow \alpha + T + 4.78MeV$

Detected event in Boron or Lithium contained sample

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

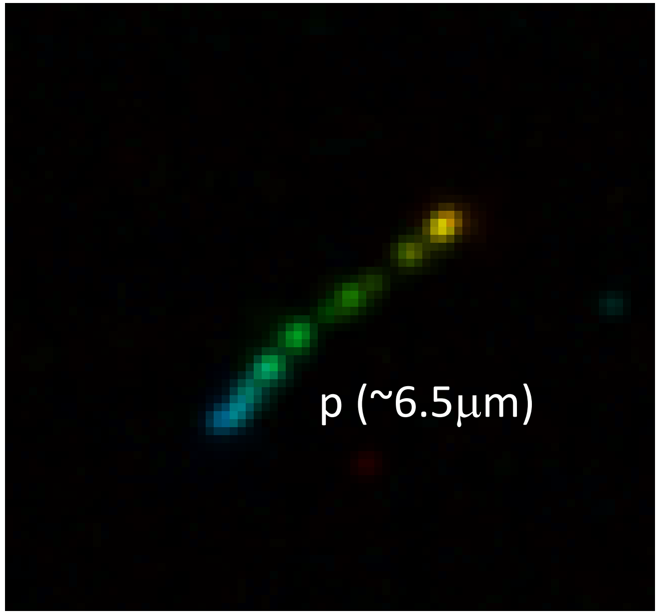


② n + $^{6}Li \rightarrow \alpha + T$ + 4.78MeV



Detected event in Boron or Lithium contained sample

③ n + $^{14}N \rightarrow p + {}^{14}C$ + 0.62MeV

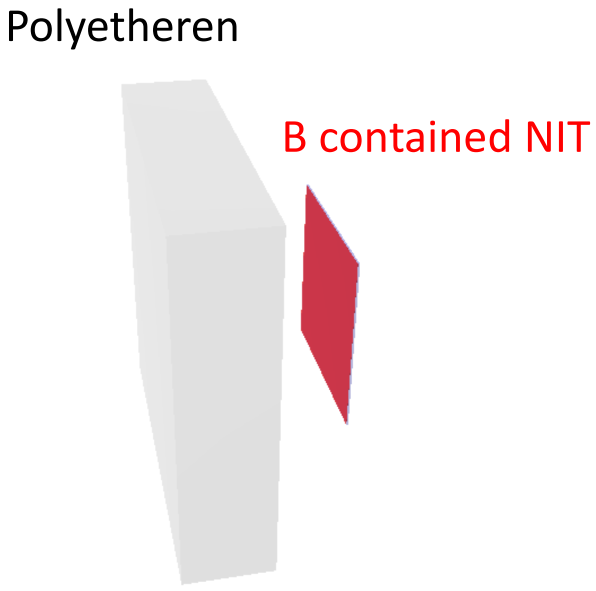


There are too many events around 6.5 μm…

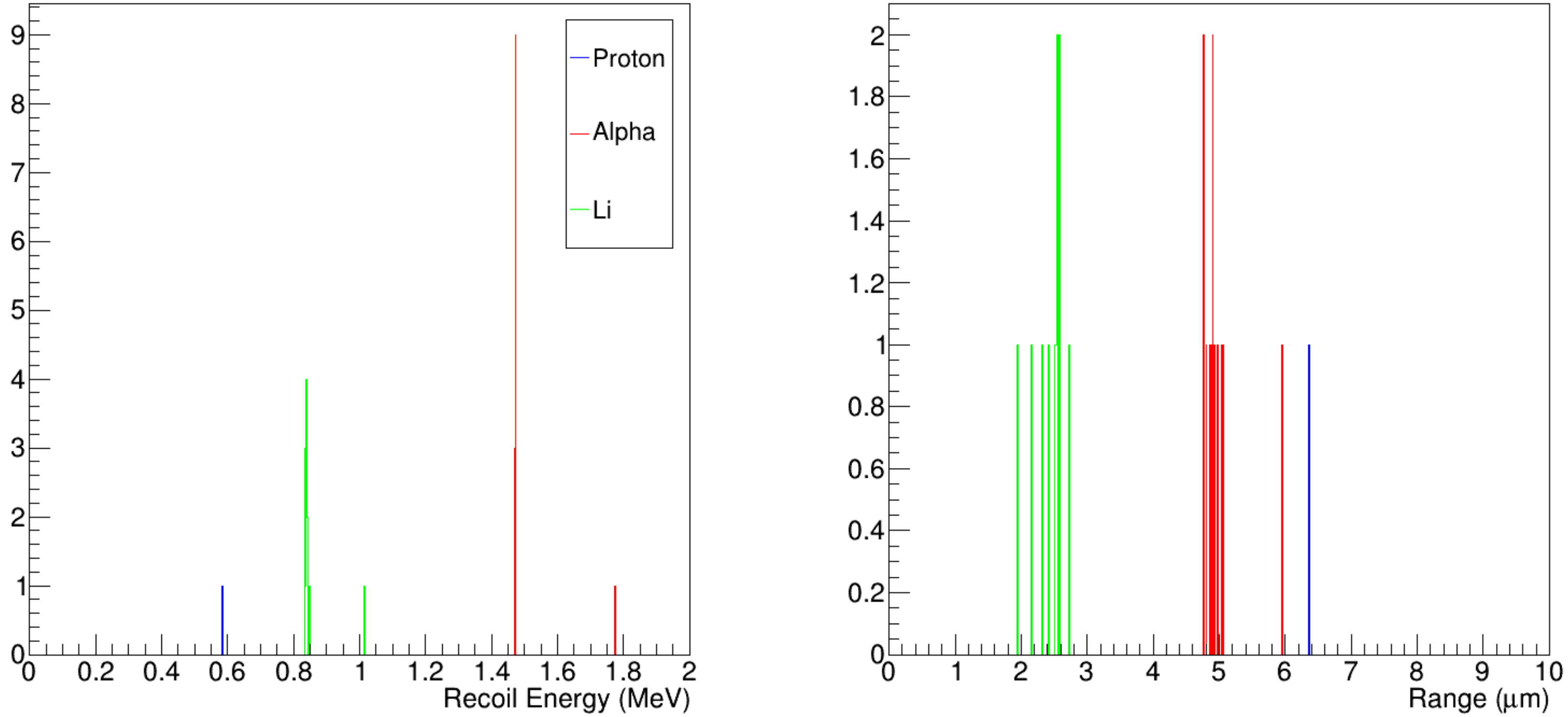
Atom	Mass fraction	Mol / Ag mol		σ @ 1eV
N	3.74%	0.694	^{14}N 99.6%	0.3 barn
B	0.042%	0.01	^{10}B 20%	620 barn

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

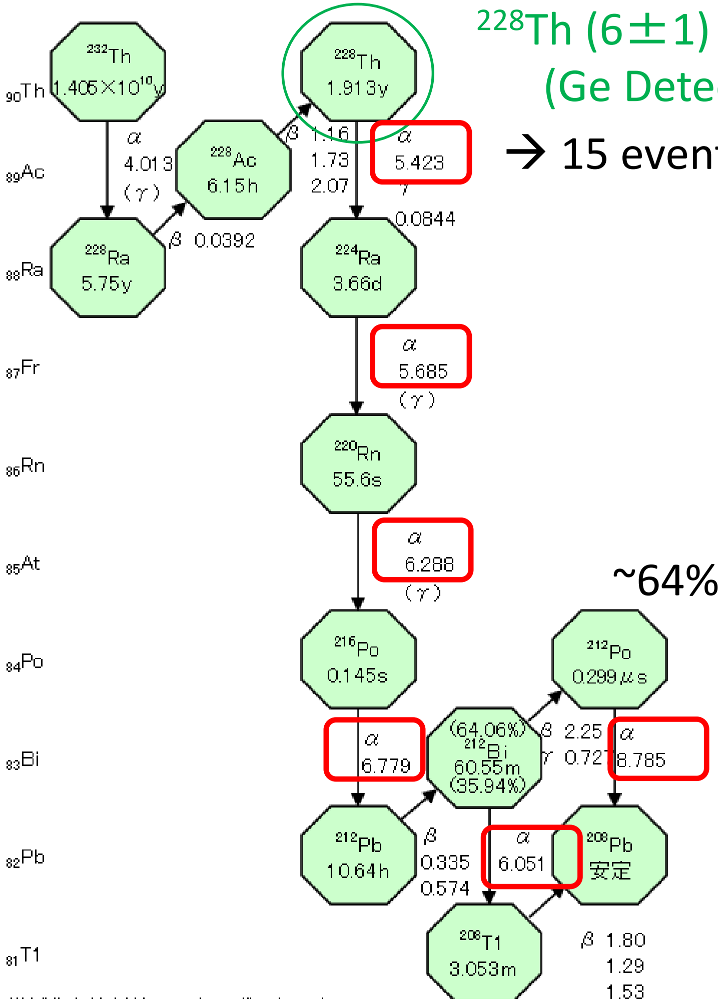
Radon Daughter Contamination

Sample	Condition	Analyzed mass (g)	# of internal event (/g)	# of top α (/cm^2)
Run16 ID1 Aside	Dry in Rn free room (shielded)	0.24	4 +- 4	0.9 +- 0.2
Run16 ID1 Bside		0.47	4.3 +- 3.0	1.1 +- 0.2
Run16 ID2 Aside	Dry in Rn free room (no-shielded)	0.50	8.0 +- 4.0	0.3 +- 0.1
Run16 ID2 Bside				
Run15 ID3 Aside	Dry in Rn free room + Hall F (35min)	0.27	4 +- 4	0.48 +- 0.14
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 (Almost thin tracks)	0.40 +- 0.09
Run13 ID11	N2 purged dry	0.16	< 14 (90% C.L.)	0.1 +- 0.1
Run13 ID8	Normal dry	0.08	650 +- 90	50 +- 3
Run7	Normal dry in Shield	0.44	220 +- 20	11.0 +- 0.5
n-Run1	Dry outside chamber	0.65	2200 +- 60	280 +- 6

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)

~64%

~36%

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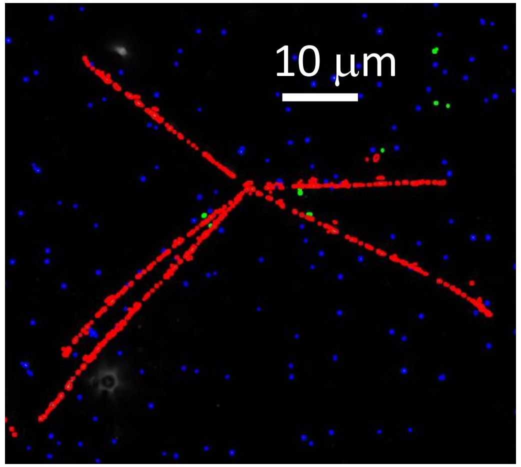
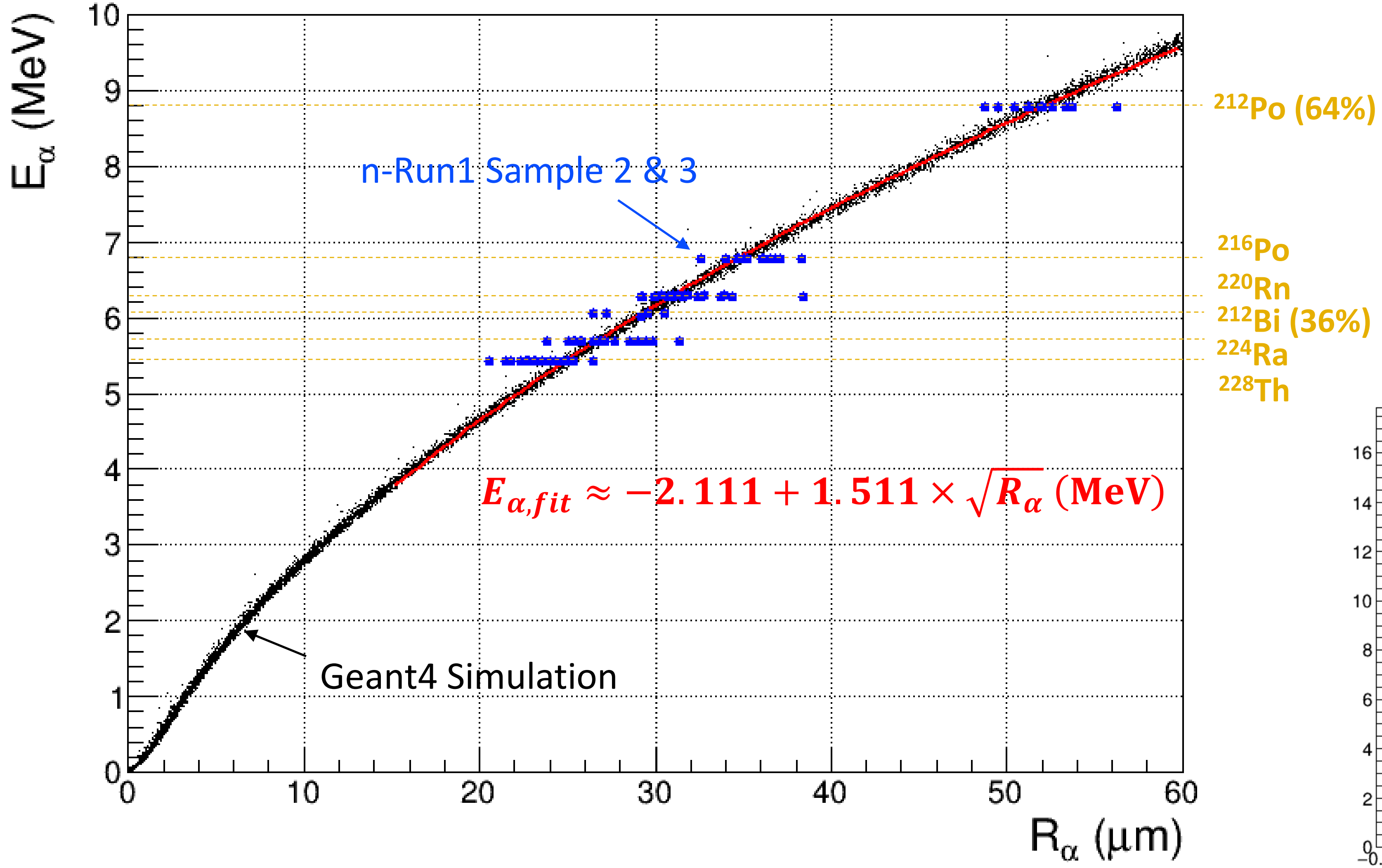
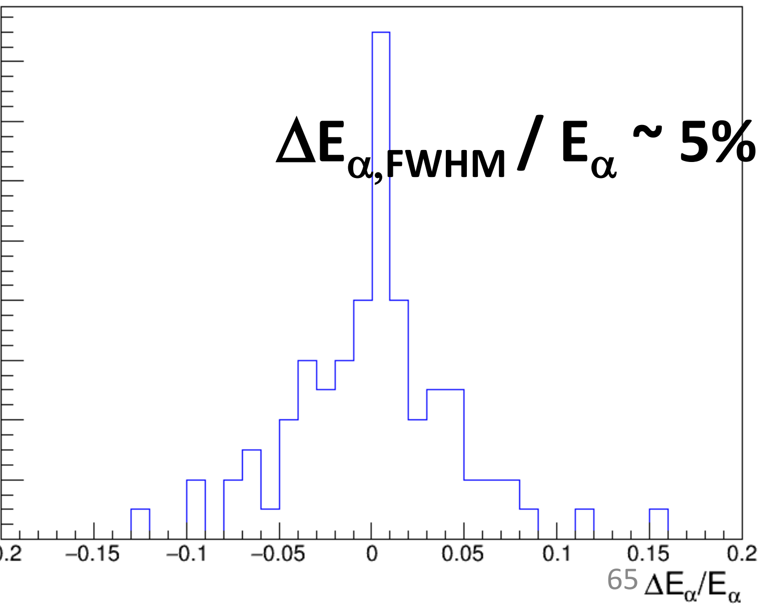
- ➢ Th star event is useful for calibration of run condition, such as brightness or E-R relation
- ➢ It should be accumulated during run, and 5 prong event can be identified as ^{228}Th to ^{208}Pb
    - ➢ 5.423, 5.685, 6.288, 6.779, [8.785 or 6.051] MeV



α-energy calibration with Th star



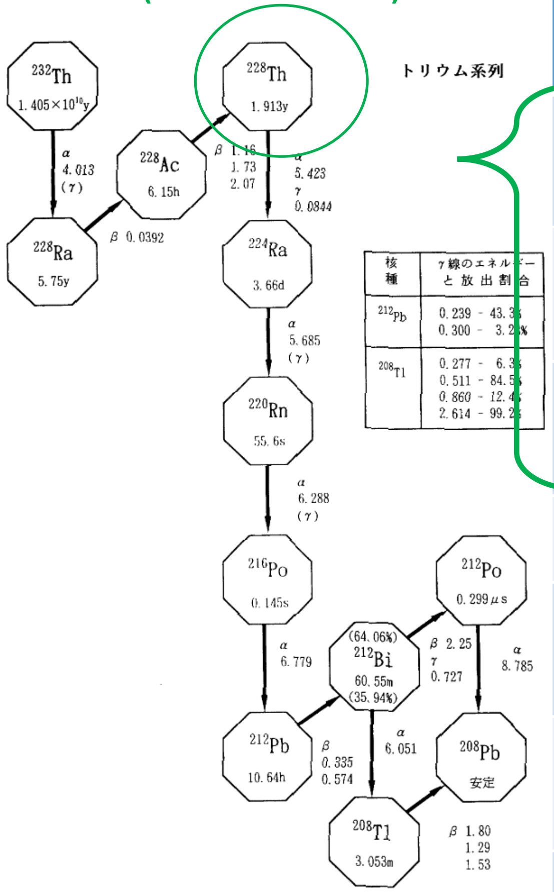
$$E_{\alpha,fit} \approx -2.111 + 1.511 \times \sqrt{R_\alpha}\ (\mathrm{MeV})$$



$\Delta E_{\alpha,\mathrm{FWHM}} / E_\alpha$ ~ 5%

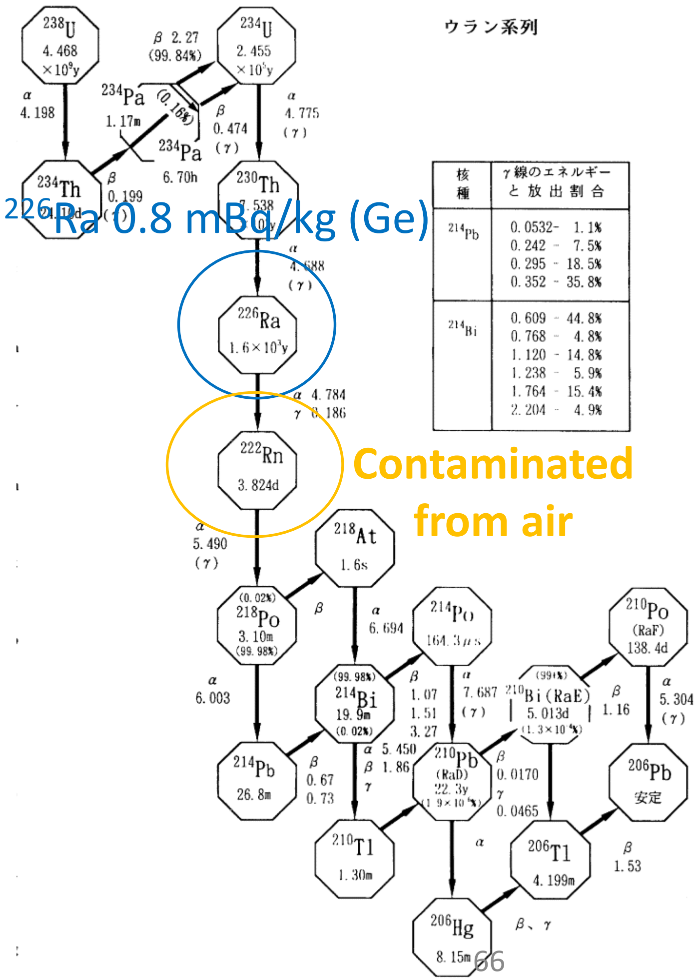
Concerning the excess in MeV region
- Understanding for ^{210}Po contamination -

^{228}Th (6±1) mBq/kg
(Ge Detector)



核種	γ線のエネルギーと放出割合
^{212}Pb	0.239 - 43.3 0.300 - 3.2%
^{208}Tl	0.277 - 6.3 0.511 - 84.5 0.860 - 12.4 2.614 - 99.2

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?

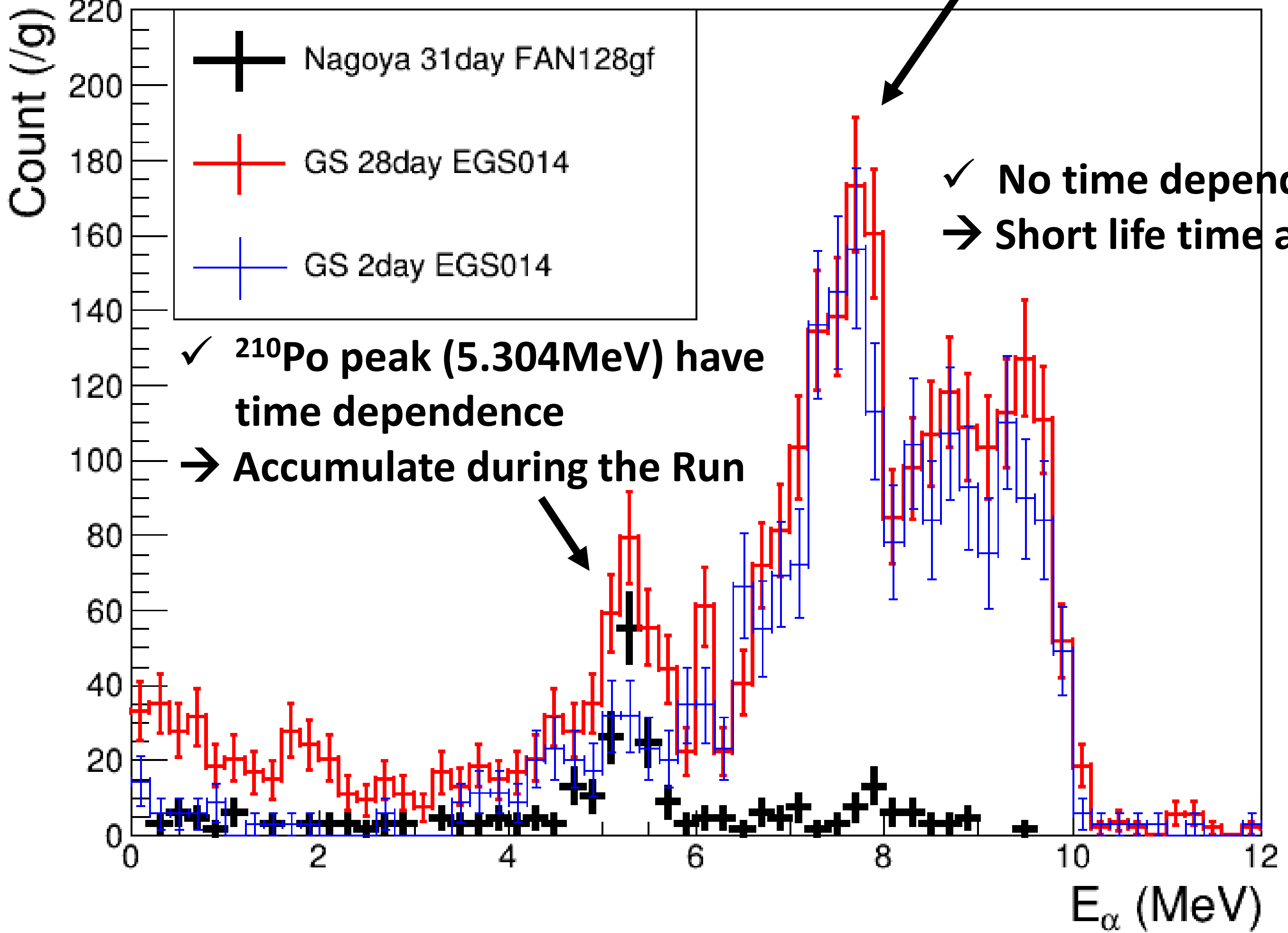


核種	γ線のエネルギーと放出割合
^{214}Pb	0.0532 - 1.1% 0.242 - 7.5% 0.295 - 18.5% 0.352 - 35.8%
^{214}Bi	0.609 - 44.8% 0.768 - 4.8% 1.120 - 14.8% 1.238 - 5.9% 1.764 - 15.4% 2.204 - 4.9%

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

Contaminated from air

Eα Spectrum



^{214}Po peak (7.687MeV) ???

→ ^{214}Po should be 3prong!

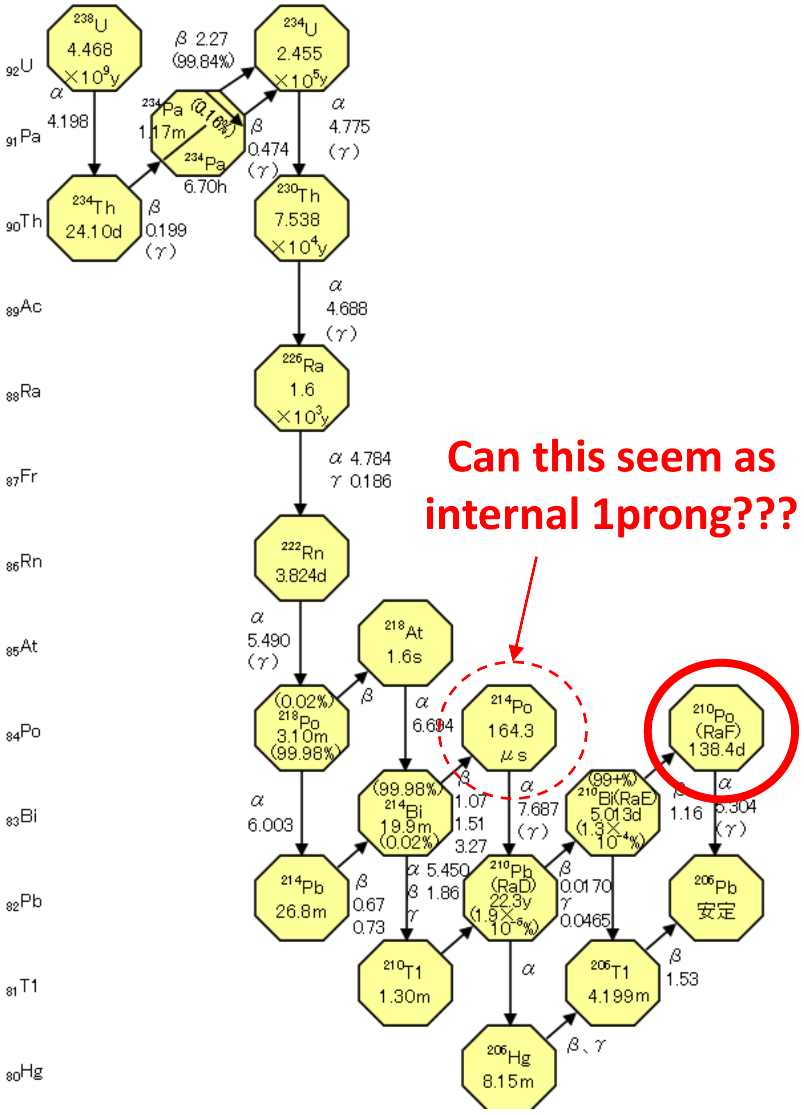
✓ No time dependence excess

→ Short life time alpha decay?

✓ ^{210}Po peak (5.304MeV) have time dependence

→ Accumulate during the Run

U decay chain



Can this seem as internal 1prong???

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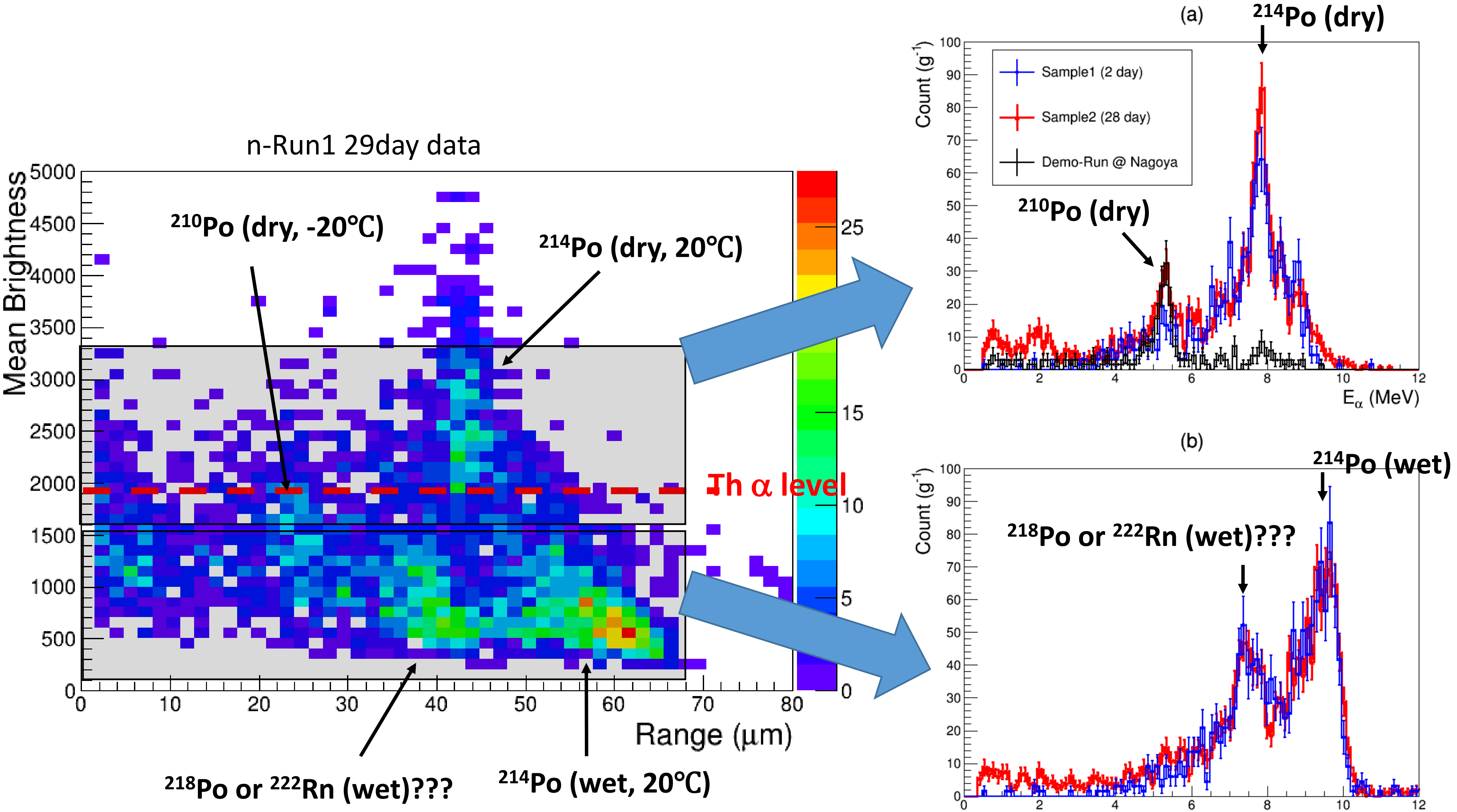


n-Run1 29day data

^{210}Po (dry, -20℃)

^{214}Po (dry, 20℃)

Th α level

^{218}Po or ^{222}Rn (wet)???

^{214}Po (wet, 20℃)

(a)

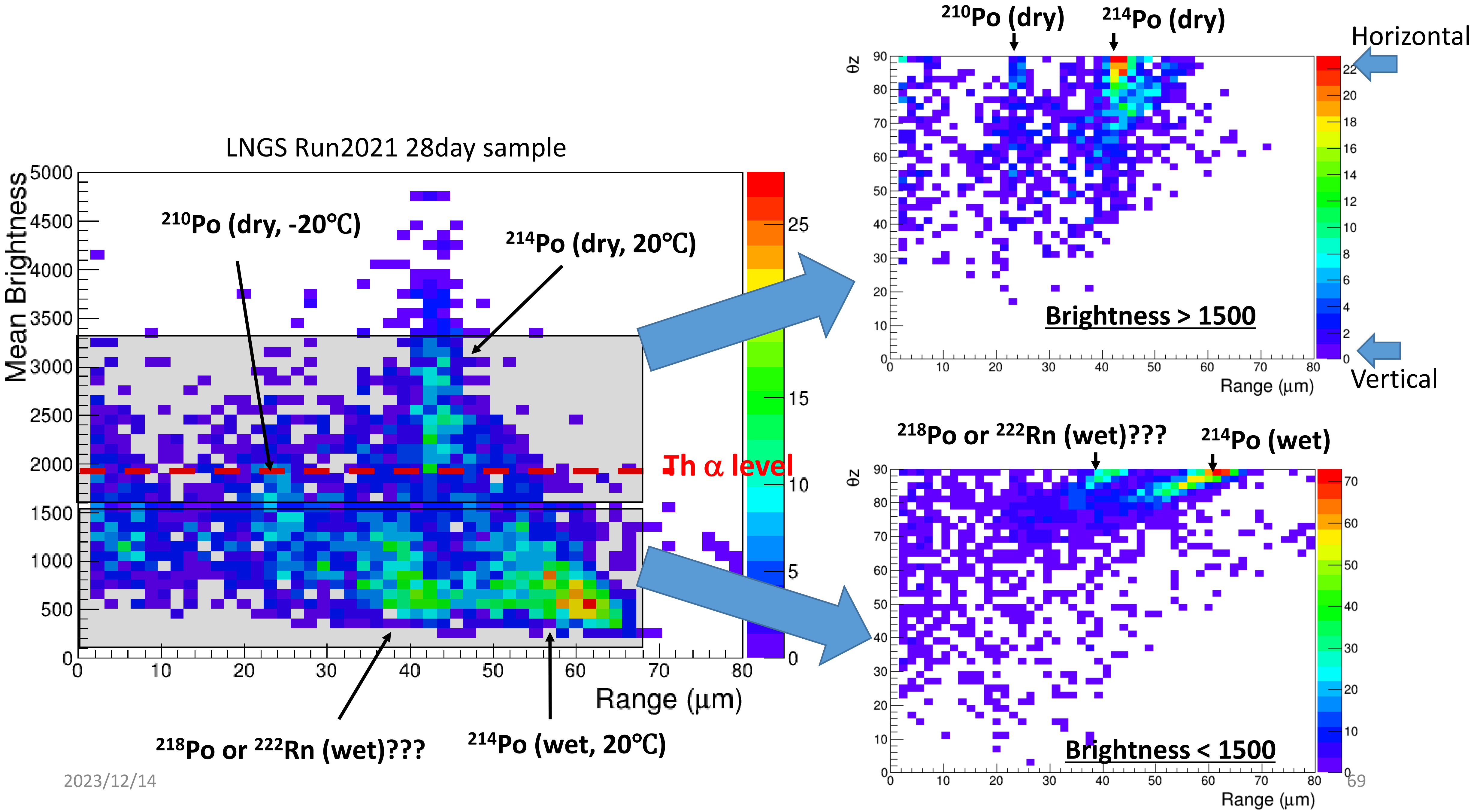
^{214}Po (dry)

^{210}Po (dry)

(b)

^{214}Po (wet)

^{218}Po or ^{222}Rn (wet)???

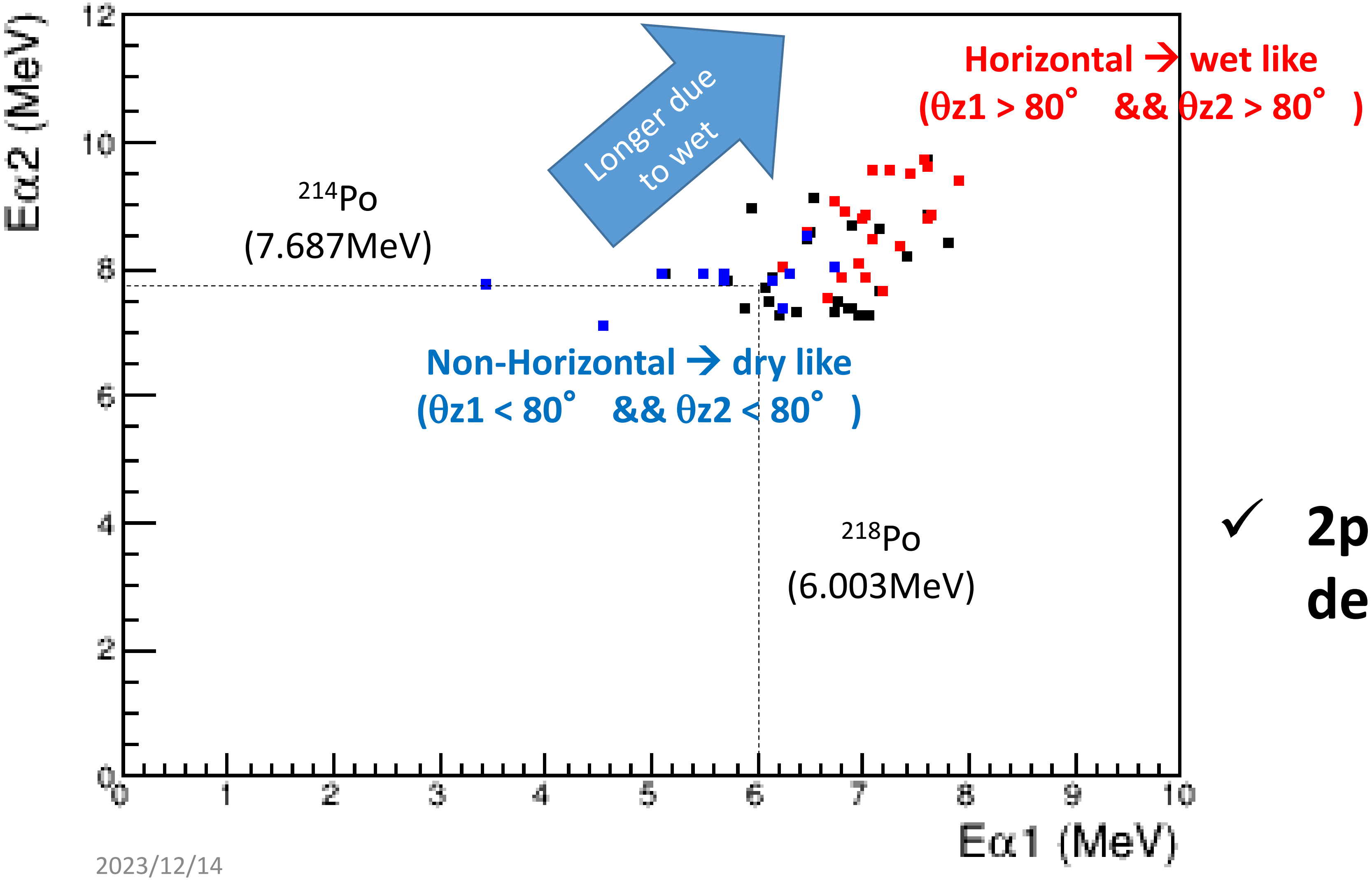

LNGS Run2021 28day sample
Mean Brightness
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
10
20
30
40
50
60
70
80
Range (μm)
25
15
10
5
0
^{210}Po (dry, -20℃)
^{214}Po (dry, 20℃)
Th α level
^{218}Po or ^{222}Rn (wet)???
^{214}Po (wet, 20℃)
^{210}Po (dry)
^{214}Po (dry)
Horizontal
Vertical
θz
90
80
70
60
50
40
30
20
10
0
Brightness > 1500
22
20
18
16
14
12
10
8
6
4
2
0
^{218}Po or ^{222}Rn (wet)???
^{214}Po (wet)
Brightness < 1500
70
60
50
40
30
20
10
0

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



Longer due to wet

Horizontal → wet like
(θz1 > 80° && θz2 > 80°)

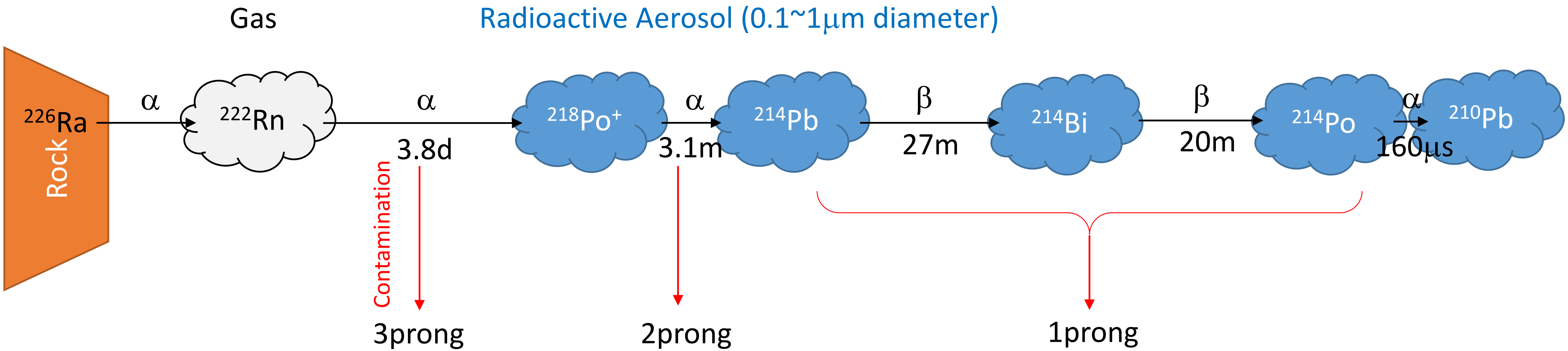
^{214}Po
(7.687MeV)

Non-Horizontal → dry like
(θz1 < 80° && θz2 < 80°)

^{218}Po
(6.003MeV)

- ✓ **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)

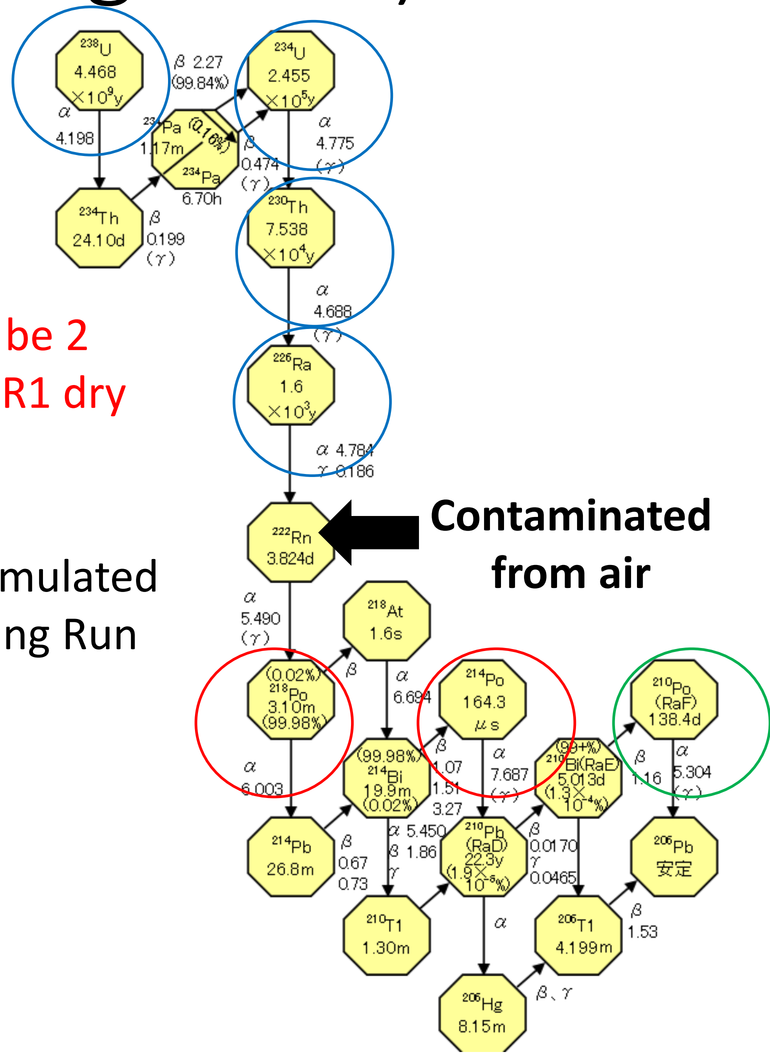
n-Run3 4 month sample

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



Contaminated from air

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

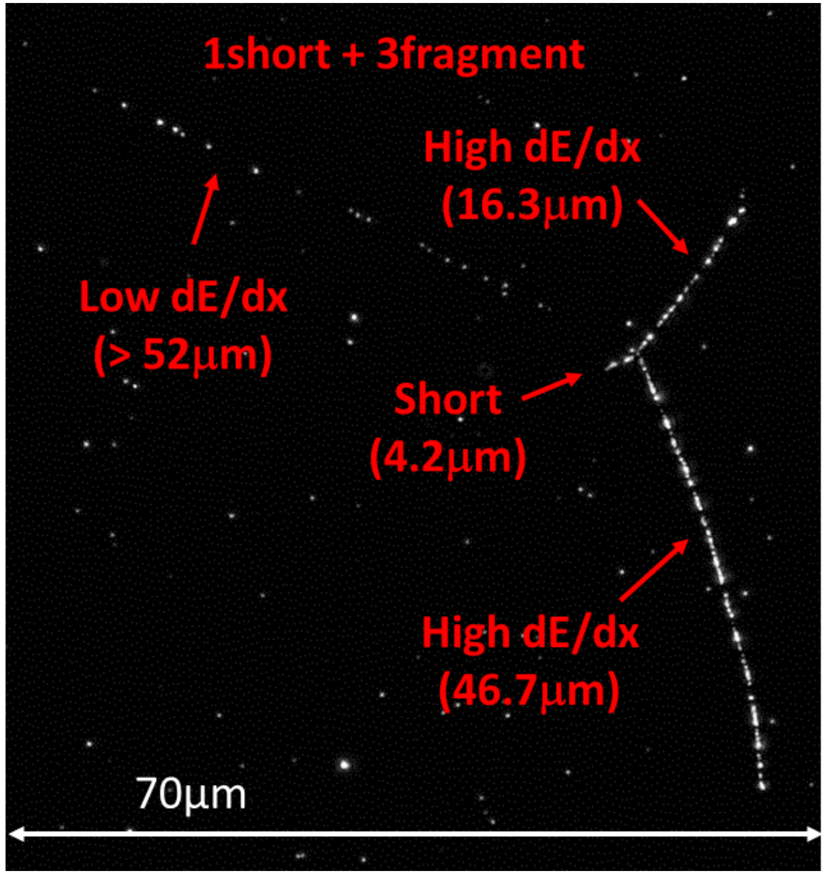
Multi-prong Neutron Inelastic Scattering

Multi-prong Analysis

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

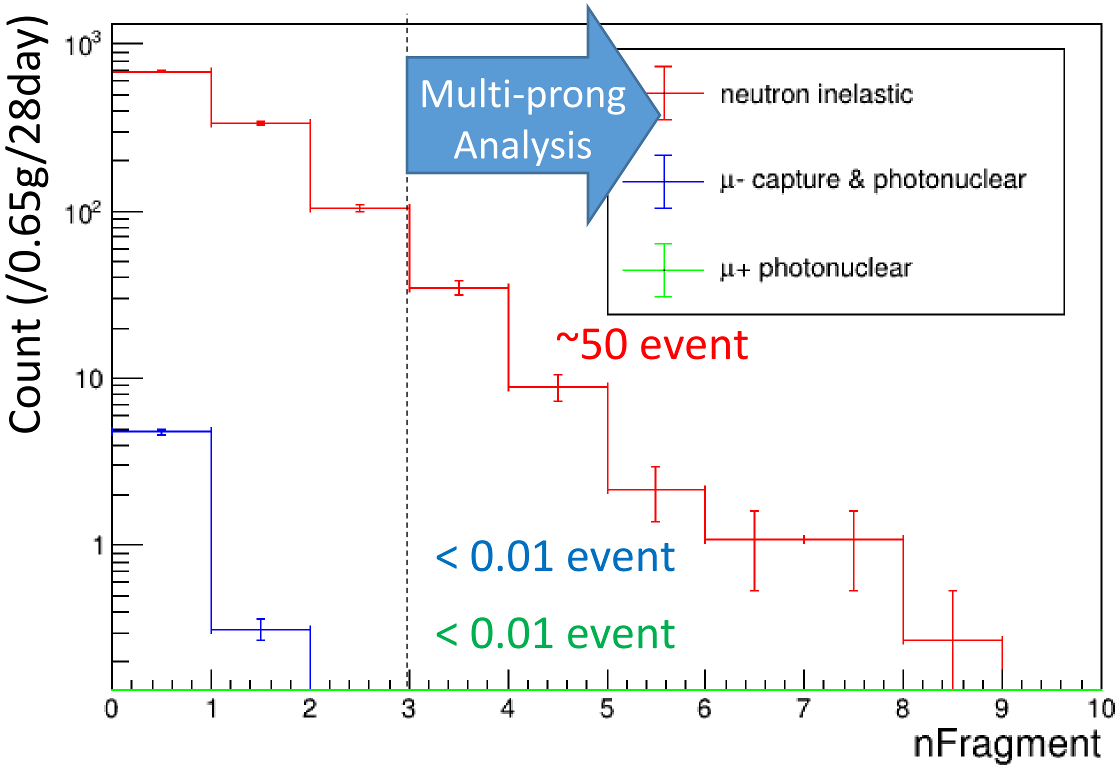
Candidates

- **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**



*Projection Image

Rough estimation of the number of fragments by Geant4

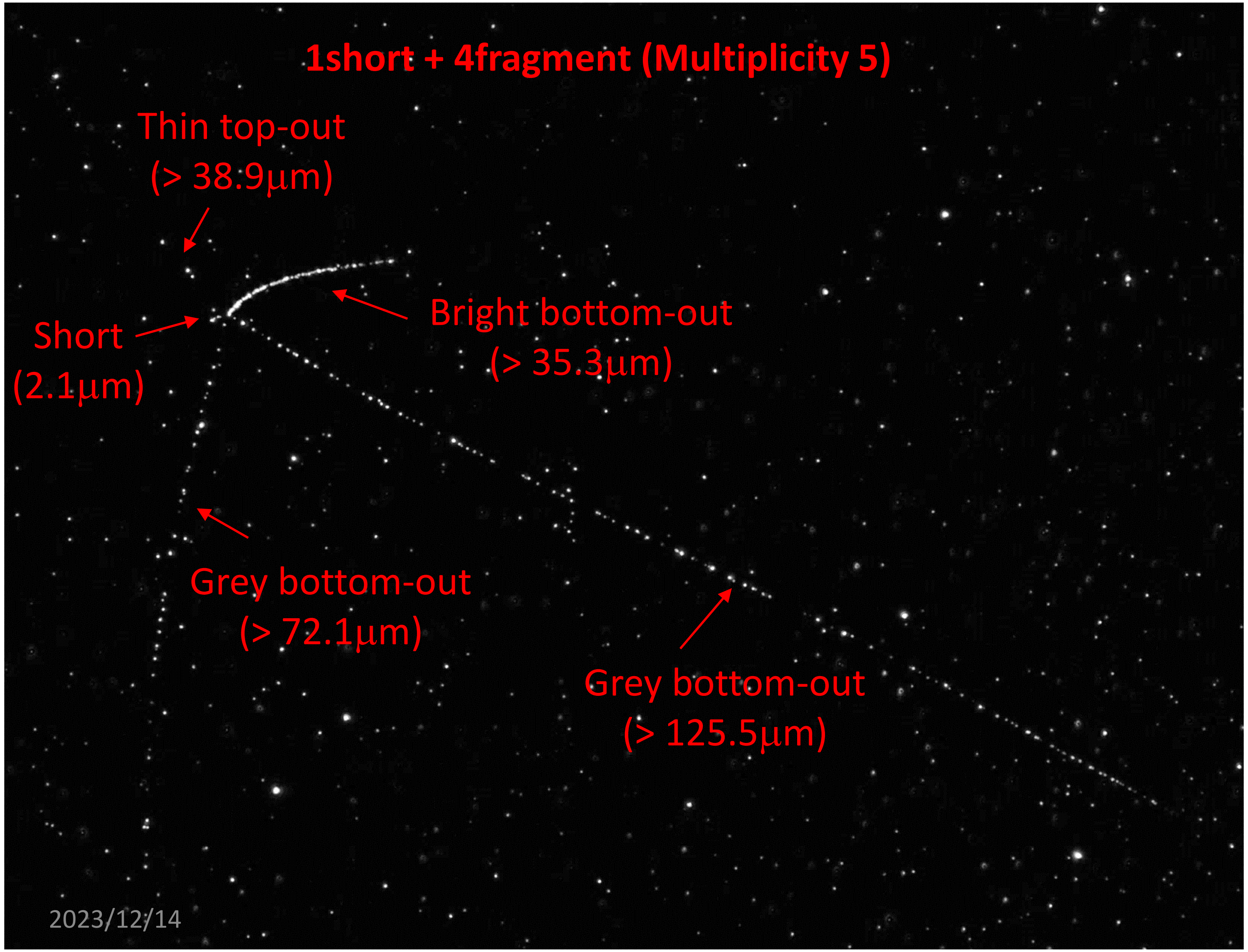


More likely neutron inelastic scattering!

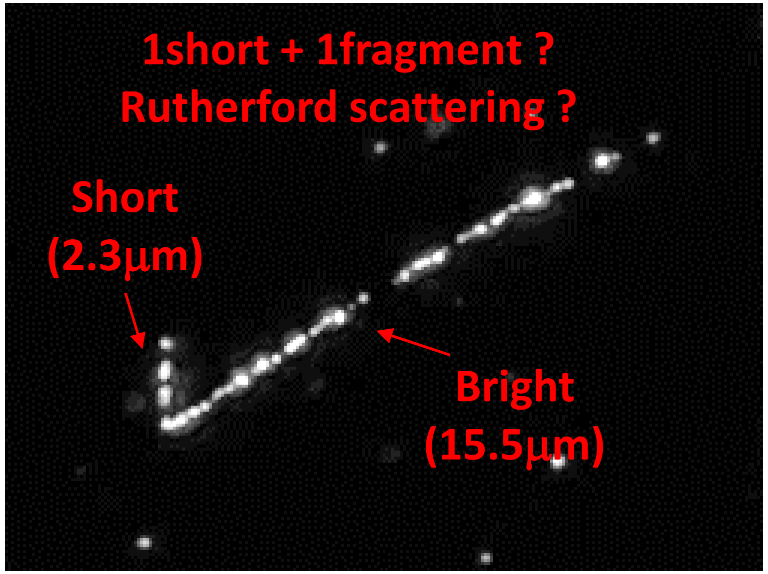
Interesting Multi-prong Event from 28day sample

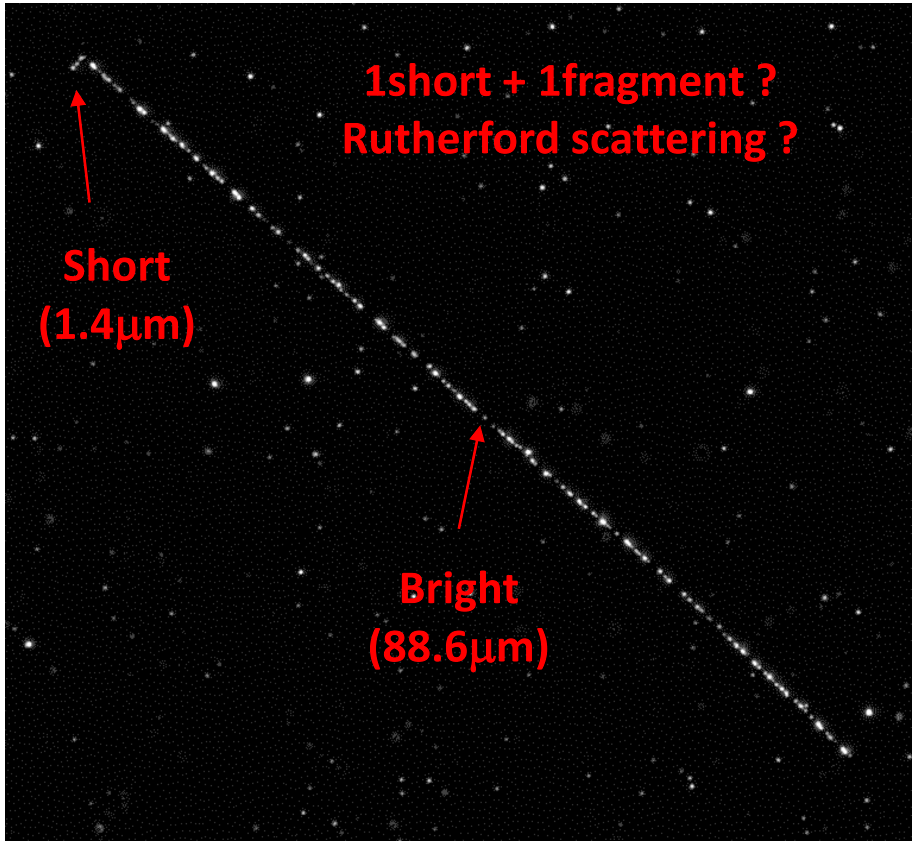
What is this ???

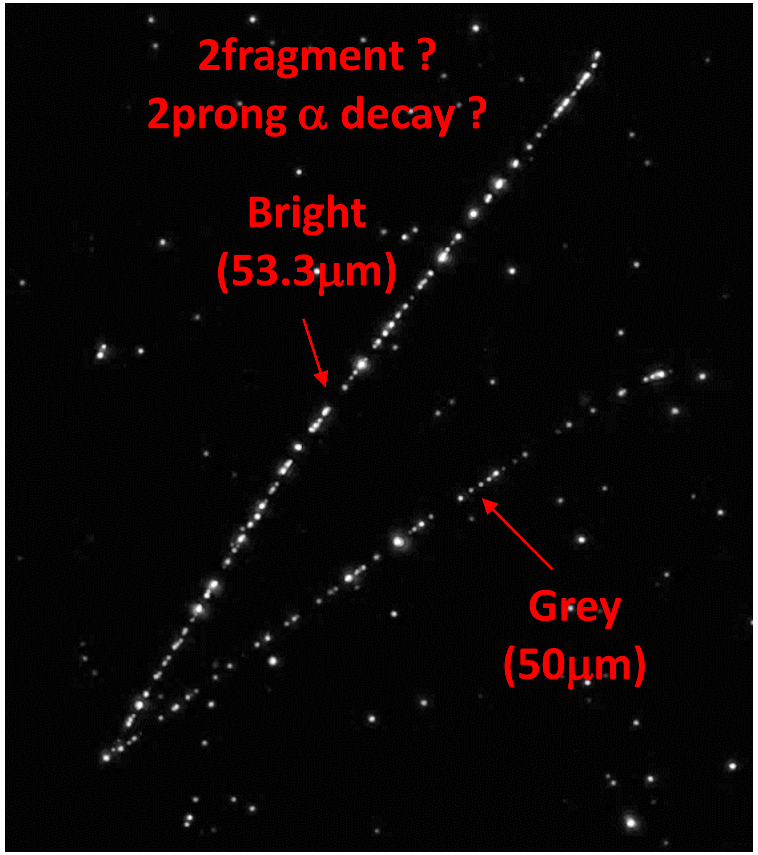
Projected Image



Kink and 2prong Events are Excluded in Current Analysis



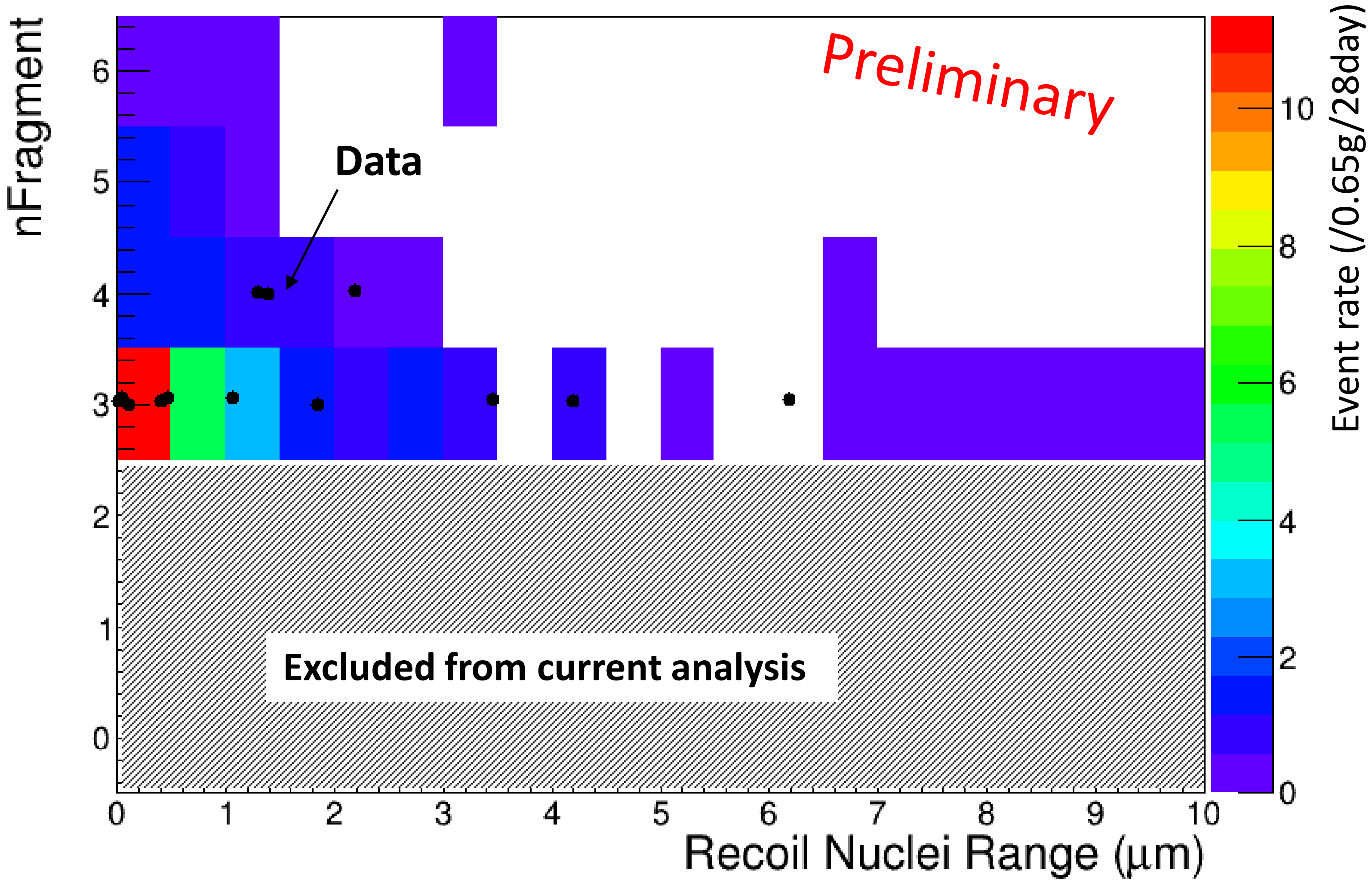




- ➢ Although I feel there are many kink and 2prong events, they are rejected in current analysis because they might be Rutherford scattering or 2prong of α-ray
- ➢ They might be included after reduction of MeV excess

Topological Analysis of Neutron Inelastic Scattering

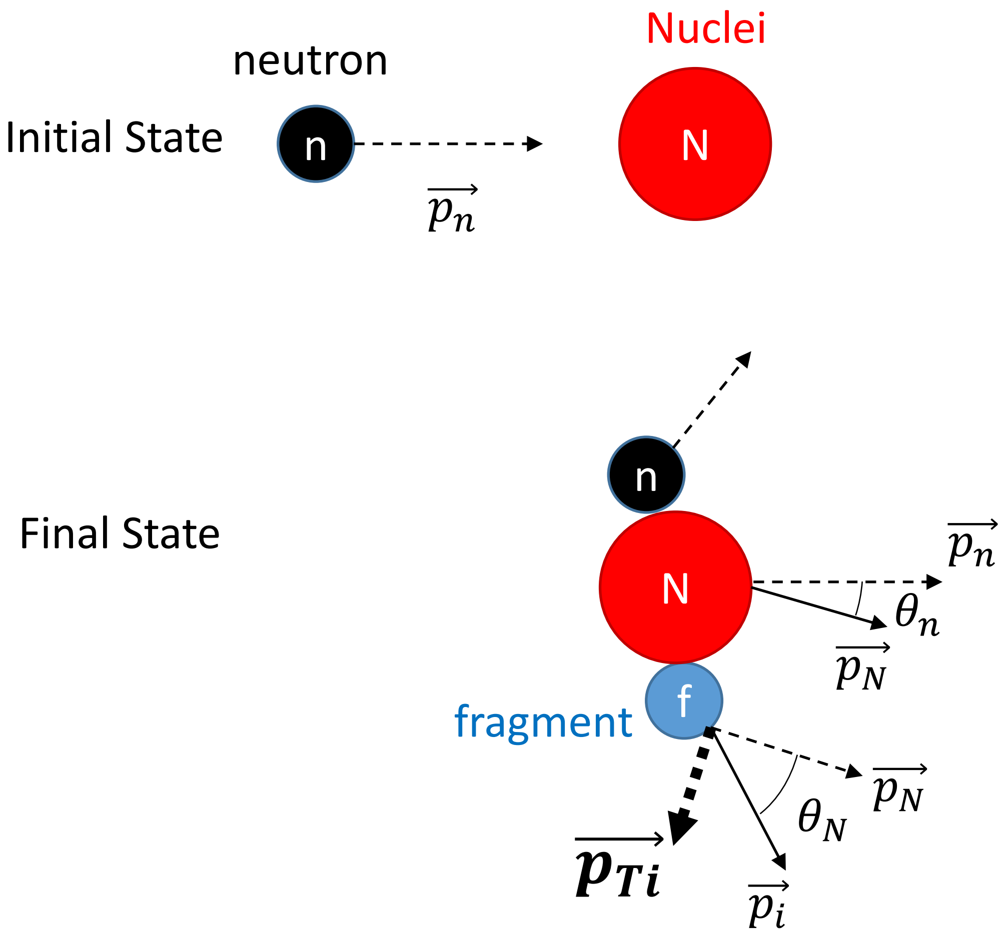
Comparison of Simulation and Data



- ✓ **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

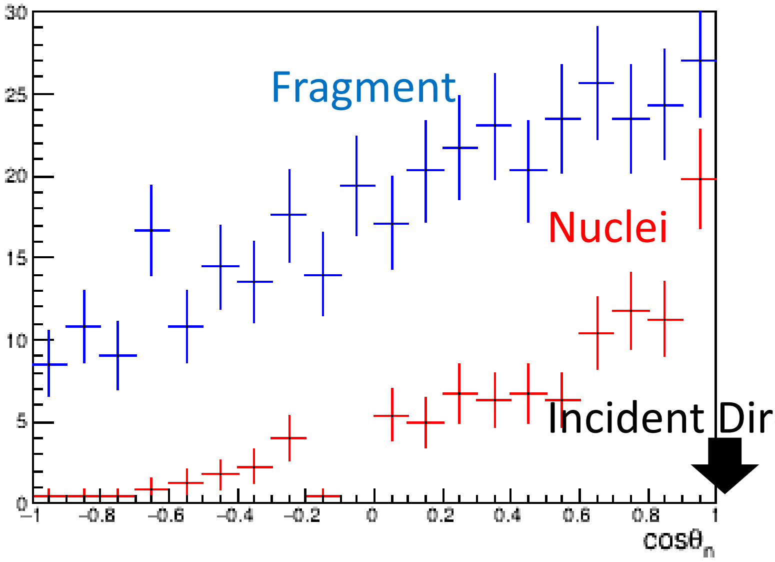
Transverse momentum (p_T) should be a good kinematical parameter because it is Lorenz invariant!

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

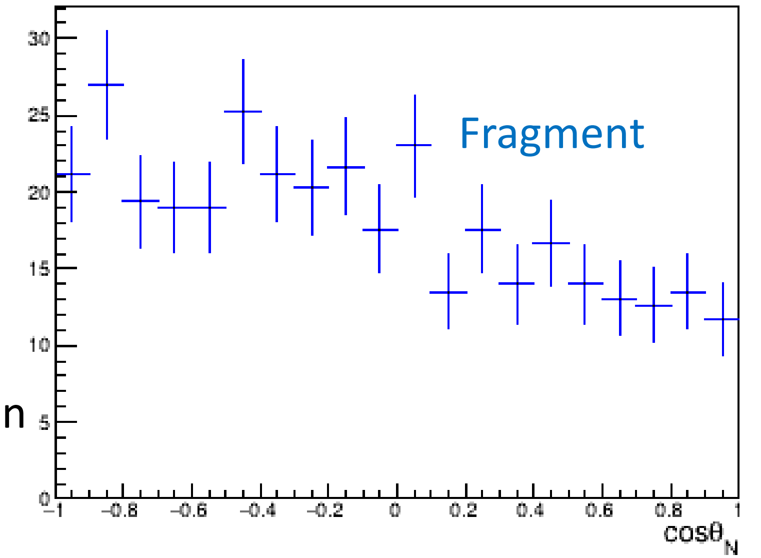
- Trying to calculate kinematical parameter on the MC-base…

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

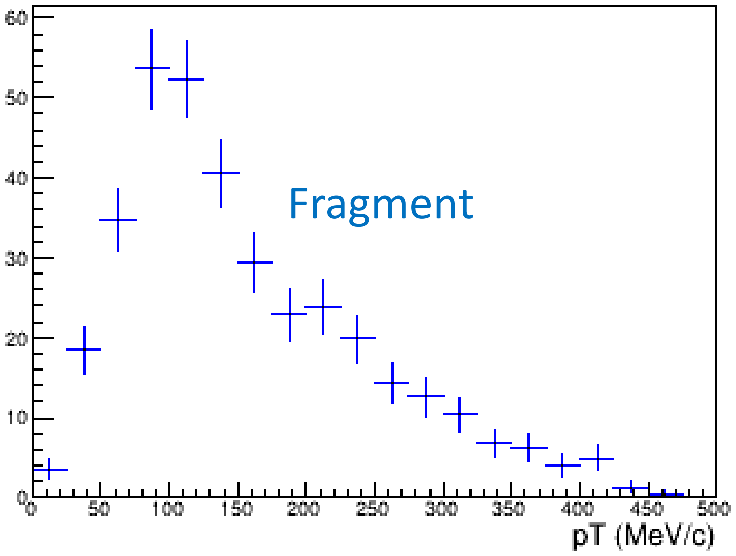
Relative angle to incident neutron



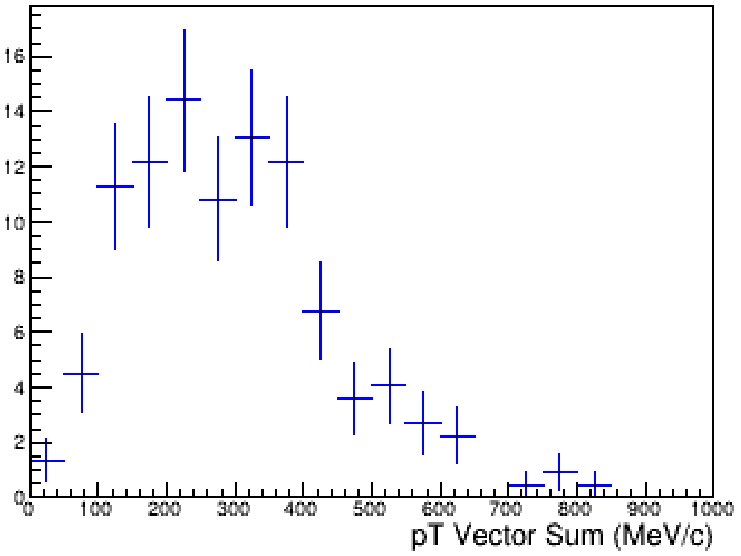
Relative angle to recoil nuclei

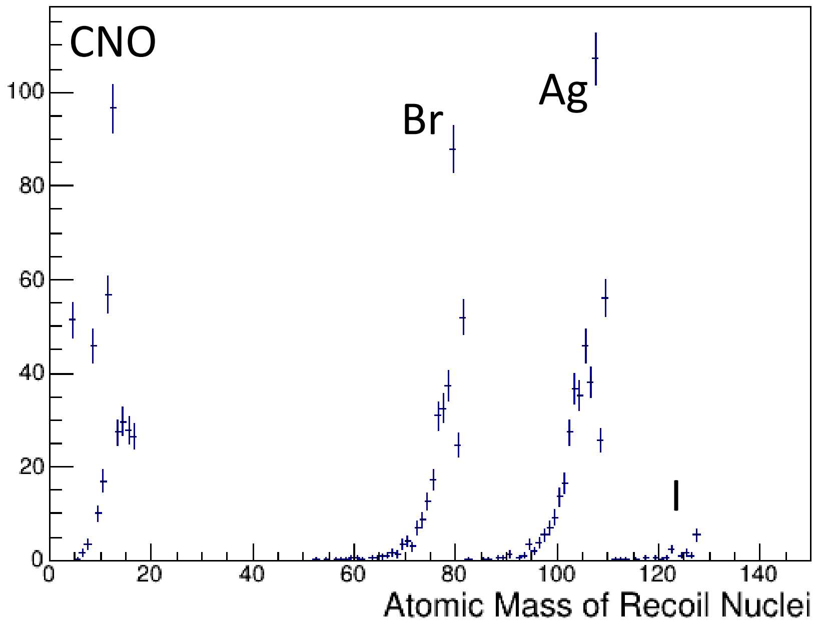


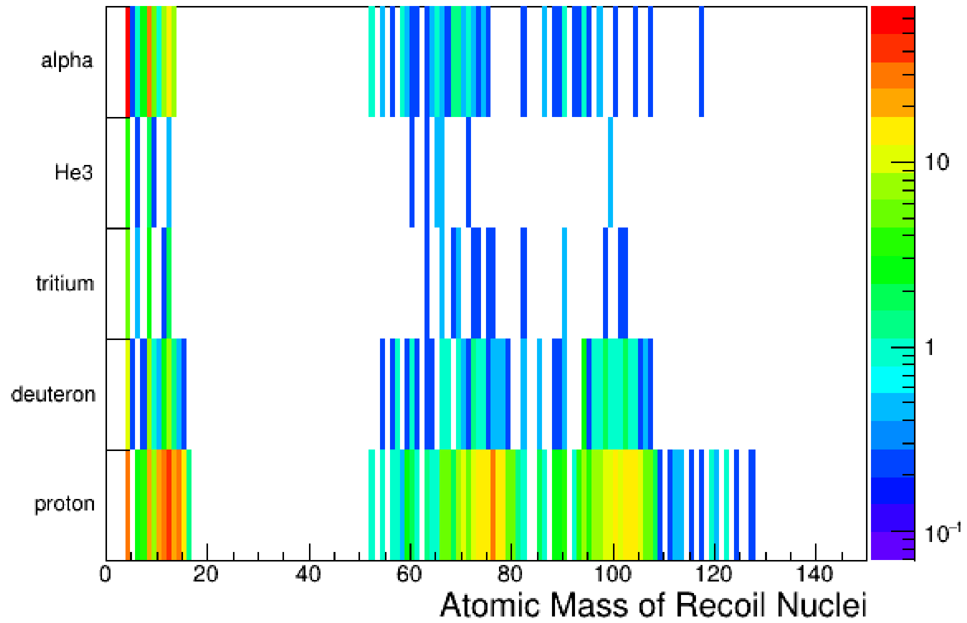
Relative p_T to recoil nuclei

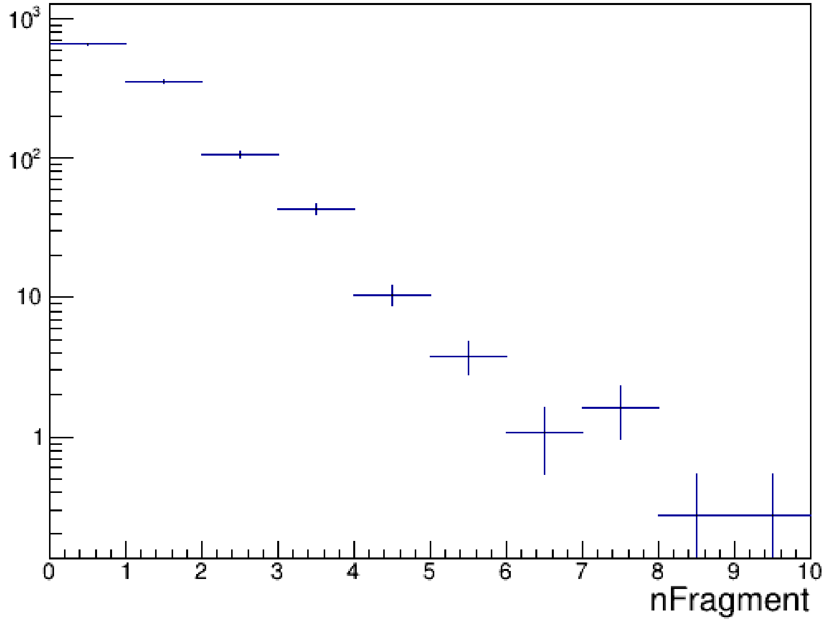


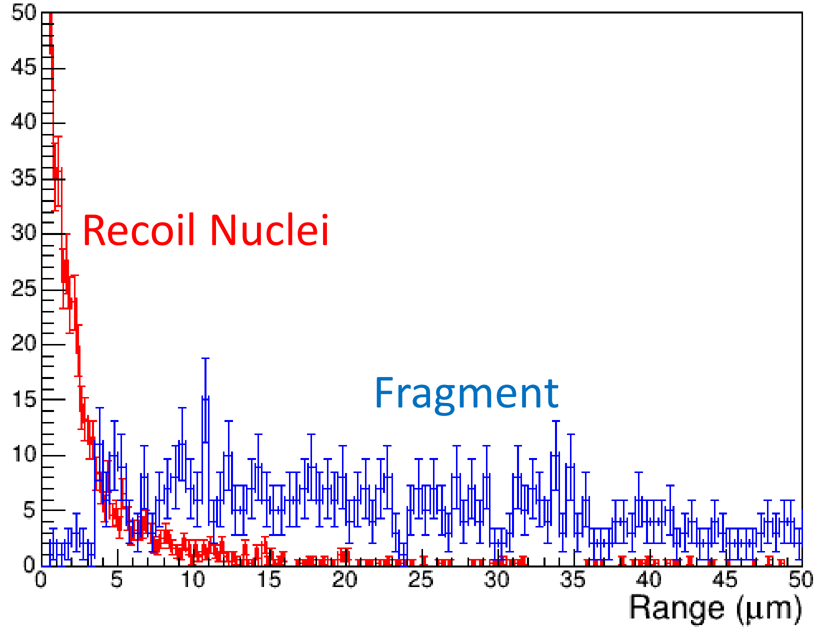
Vector sum of relative p_T to recoil nuclei




CNO
Br
Ag
I
0
20
40
60
80
100
120
140
Atomic Mass of Recoil Nuclei

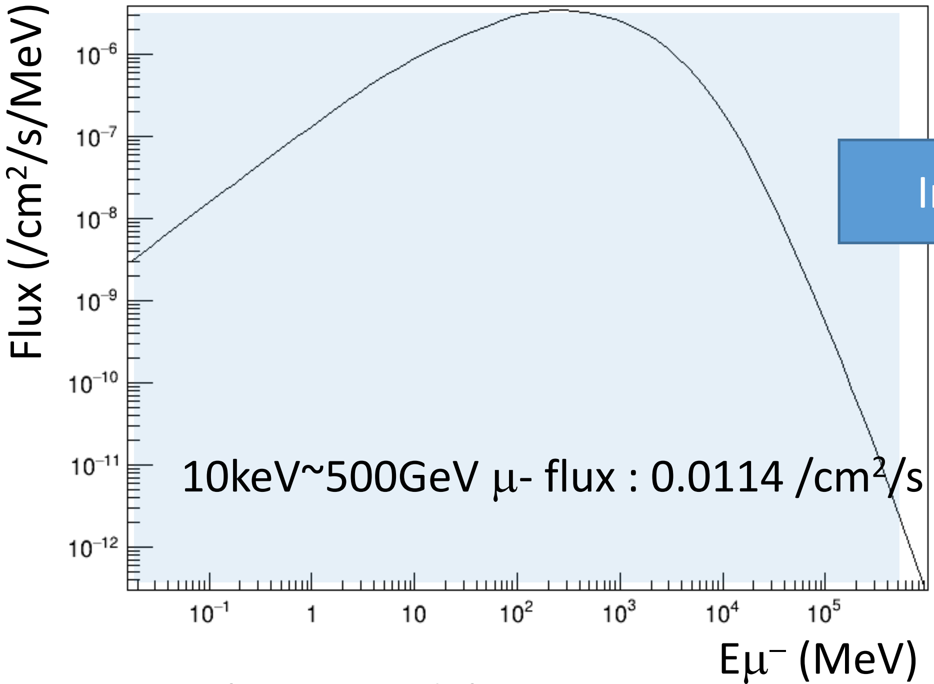

alpha
He3
tritium
deuteron
proton
0
20
40
60
80
100
120
140
Atomic Mass of Recoil Nuclei
10
1
10^{-1}


10^3
10^2
10
1
0
1
2
3
4
5
6
7
8
9
10
nFragment


50
45
40
35
30
25
20
15
10
5
0
Recoil Nuclei
Fragment
Range (μm)

Muon Simulation in NIT

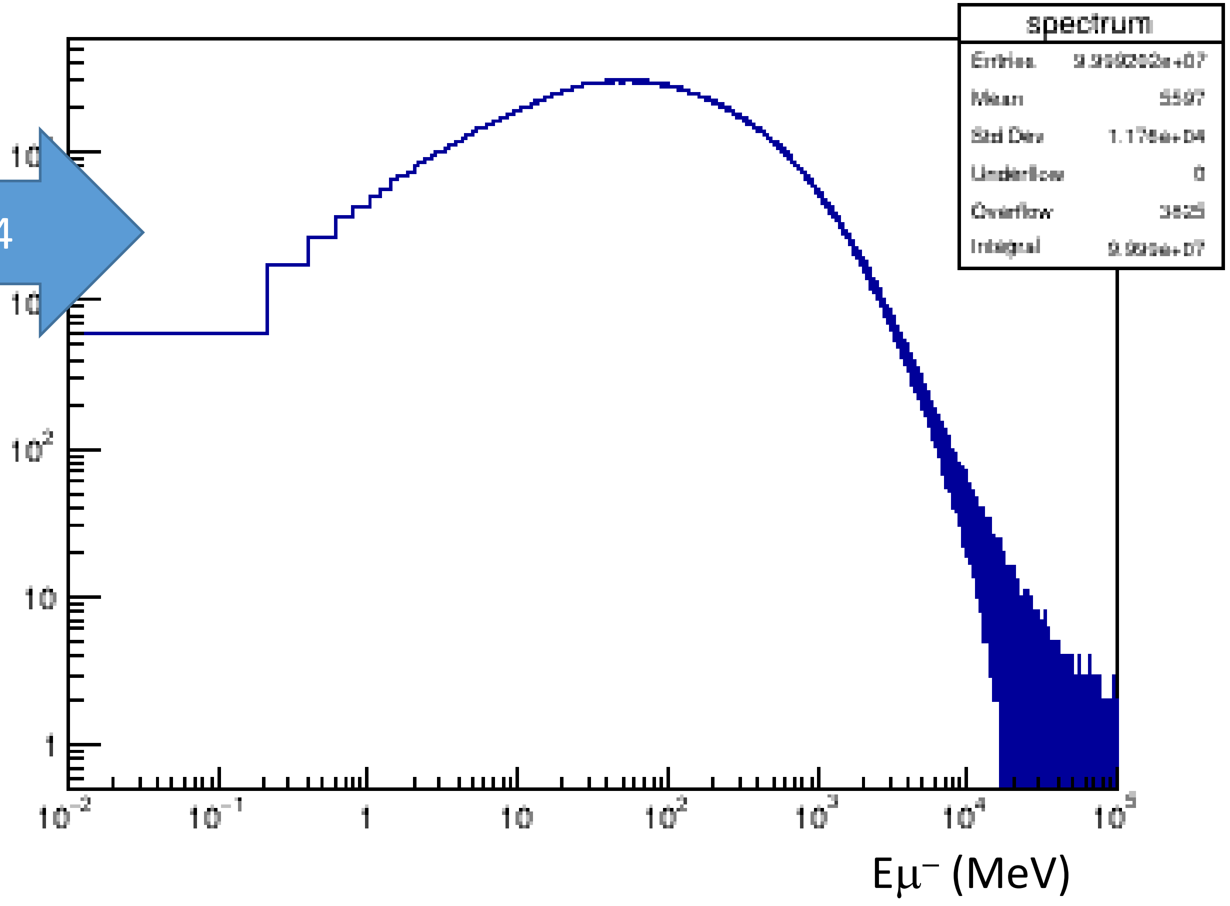
EXPACS (PARMA model) @ LNGS



10keV~500GeV μ- flux : 0.0114 /cm²/s

Input to Geant4

Simulation μ⁻ Spectrum



Physics Model

Muon Photo-Nuclear Interaction

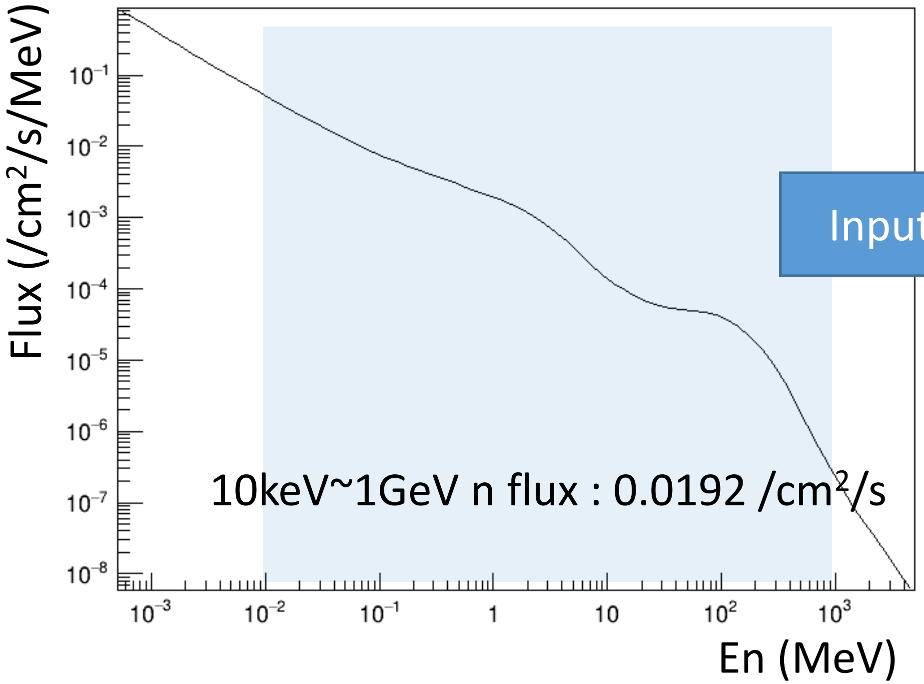
Muon Capture

Radioactive Decay

Livermore for EM

Neutron Simulation in NIT

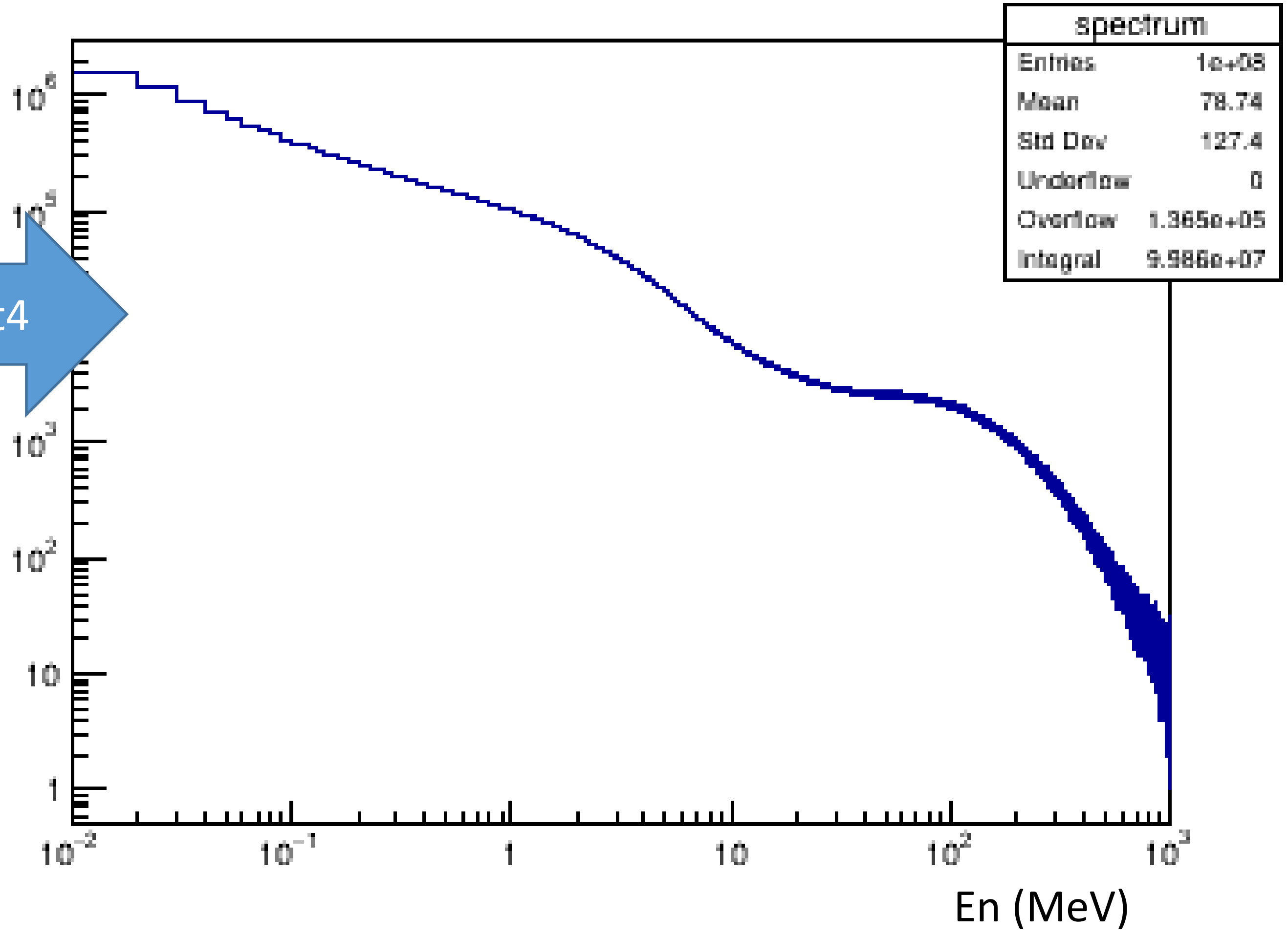
EXPACS (PARMA model) @ LNGS



10keV~1GeV n flux : 0.0192 /cm^2/s

Input to Geant4

Simulation Neutron Spectrum



<u>Neutron Physics Model</u>

Elastic : NeutronHPElastic

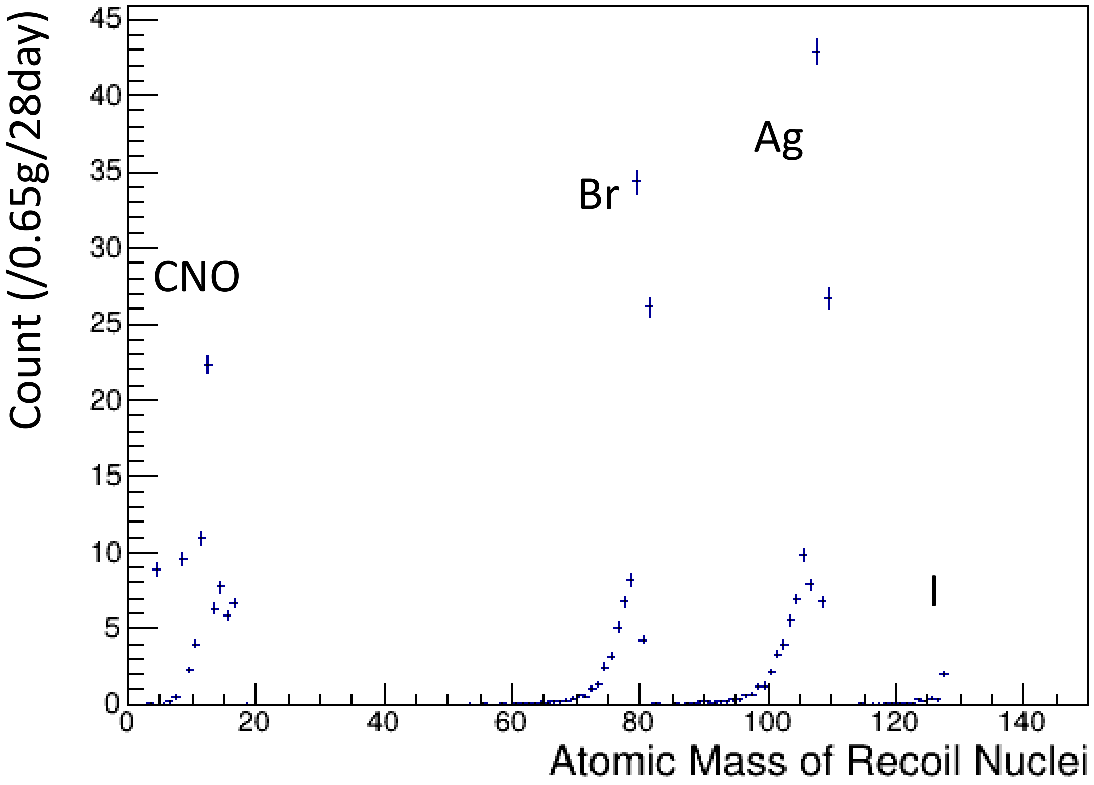
Inelastic : NeutronHPInelastic

EM : Livermore

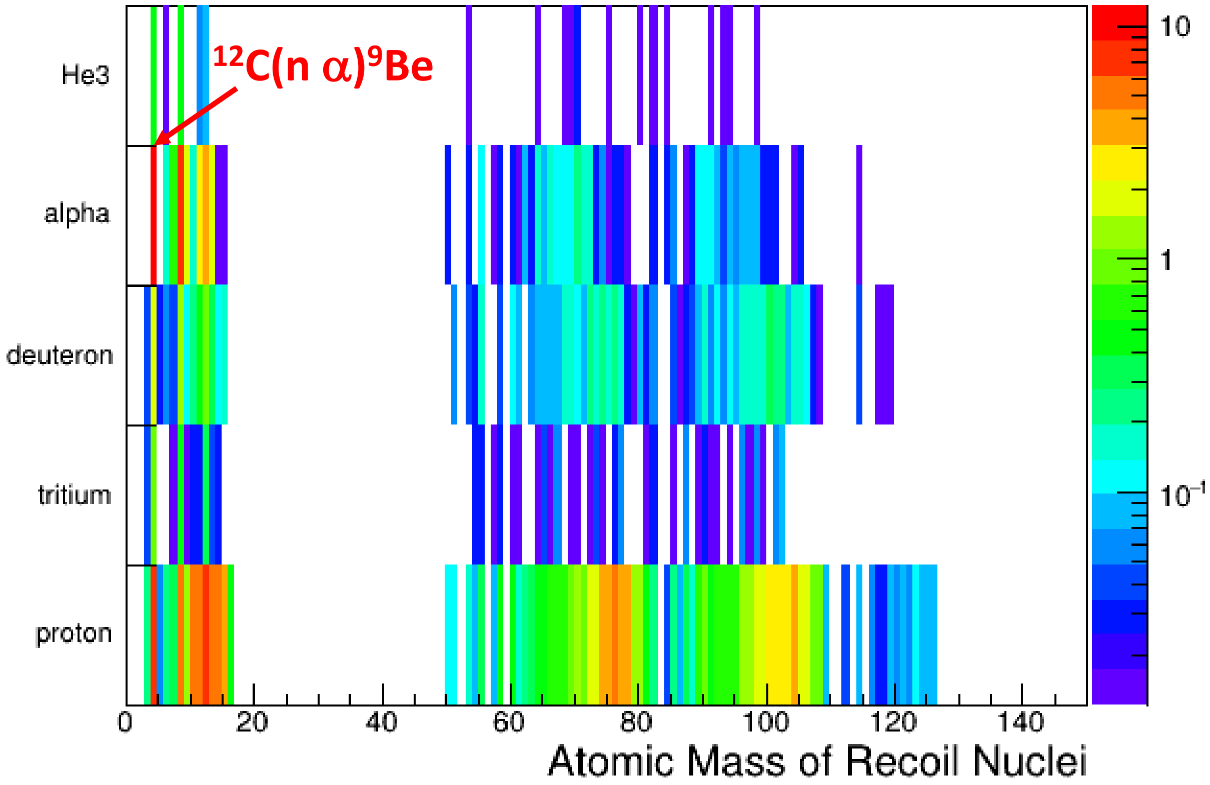
Neutron Inelastic Simulation in NIT

Extract only “Inelastic” of neutron physics process

Atomic Mass of Recoil Nuclei

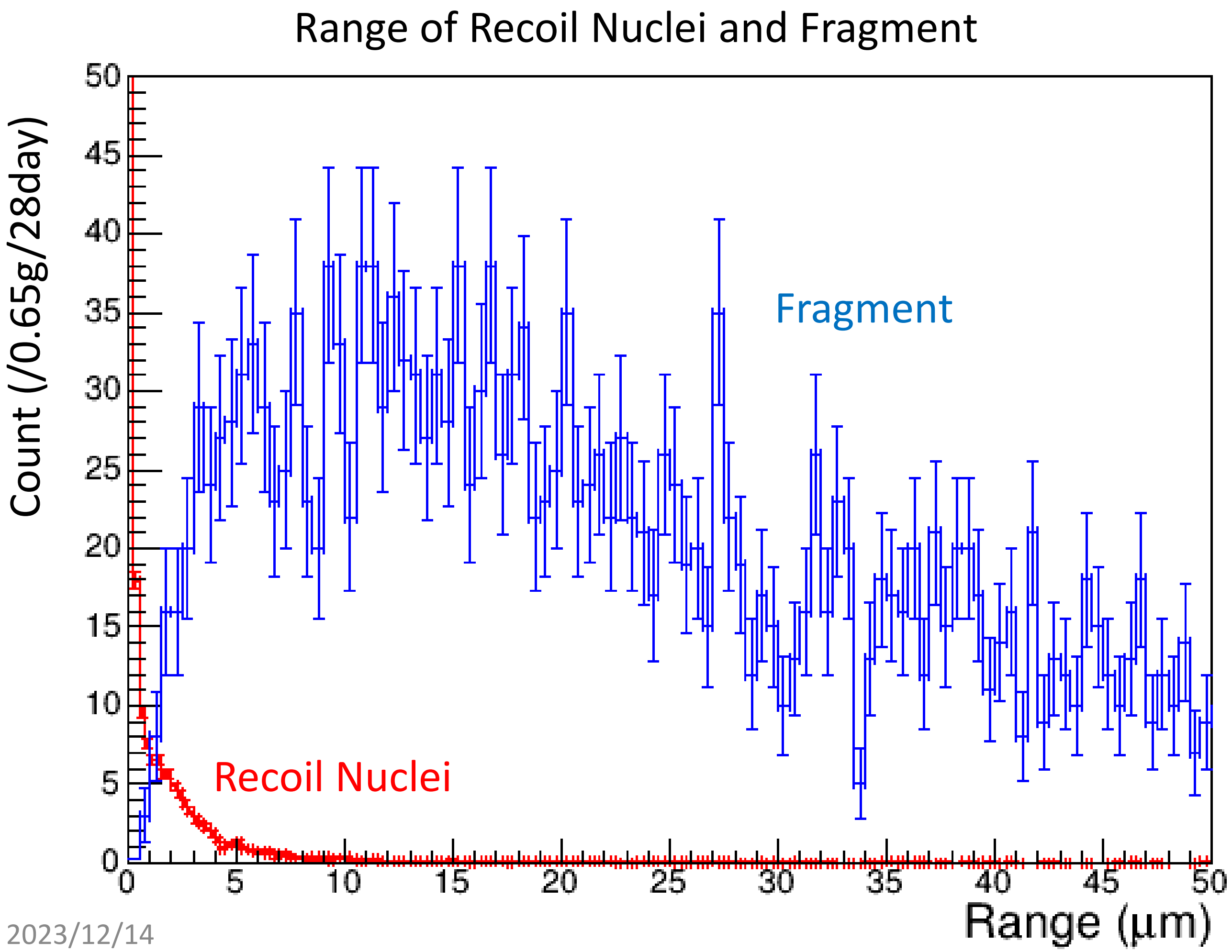


Atomic Mass of Recoil Nuclei vs Fragment particles



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