地下環境sub-MeV中性子測定へ向けた原子核乾板検出器の開発

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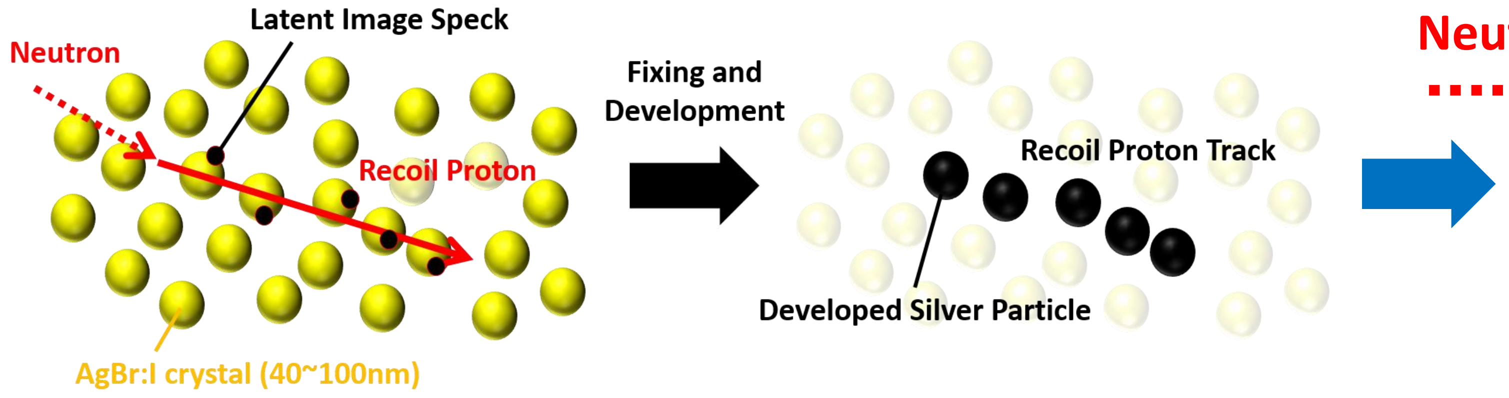
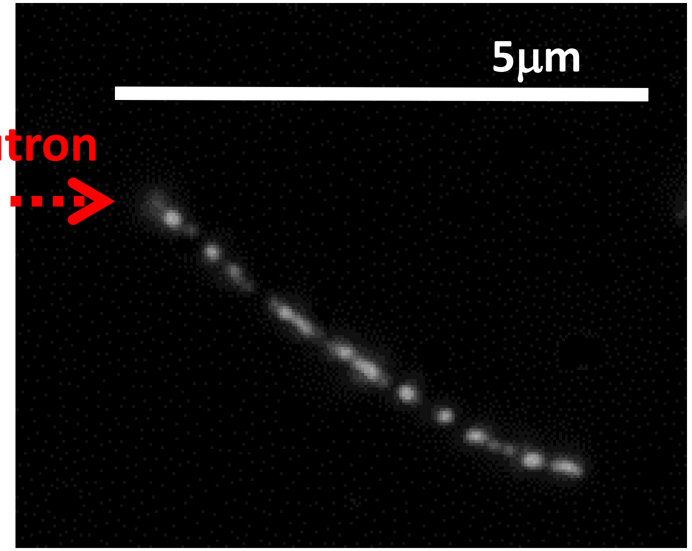
Nano Imaging Tracker (NIT) as a Sub-MeV Neutron Detector

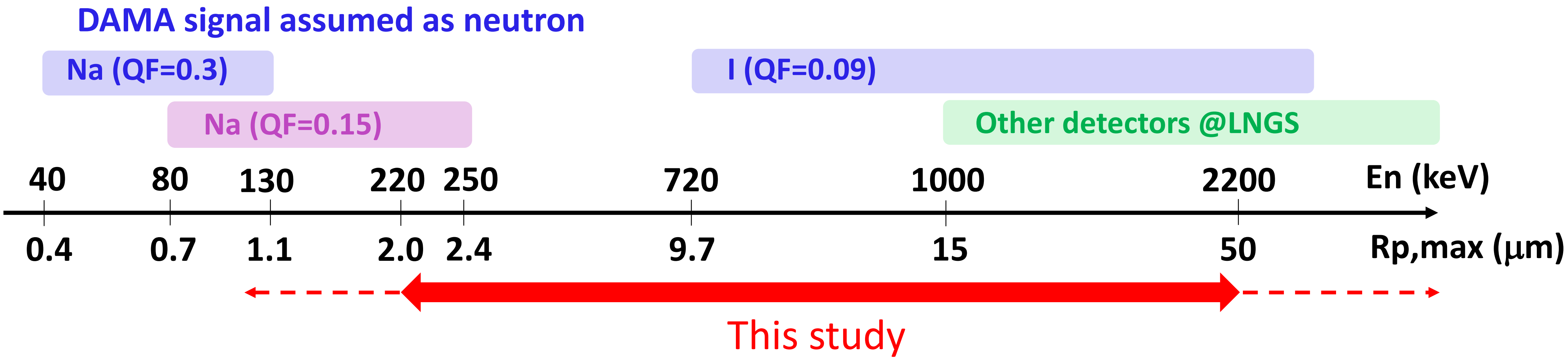
- NIT is a nuclear emulsion tracking detector with achieving submicro-metric accuracy
- It developed for Directional Dark Matter Search, also has high potential as a sub-MeV neutron detector
- The principle is to detect elastic collision with hydrogen contained 1.7% in NIT





Motivation

- Background study for WIMP or $0\nu2\beta$ search
  - If assumed DAMA signal (Eee=2~6keV) as neutron, it's energy region is sub-MeV
  - It should be well understood



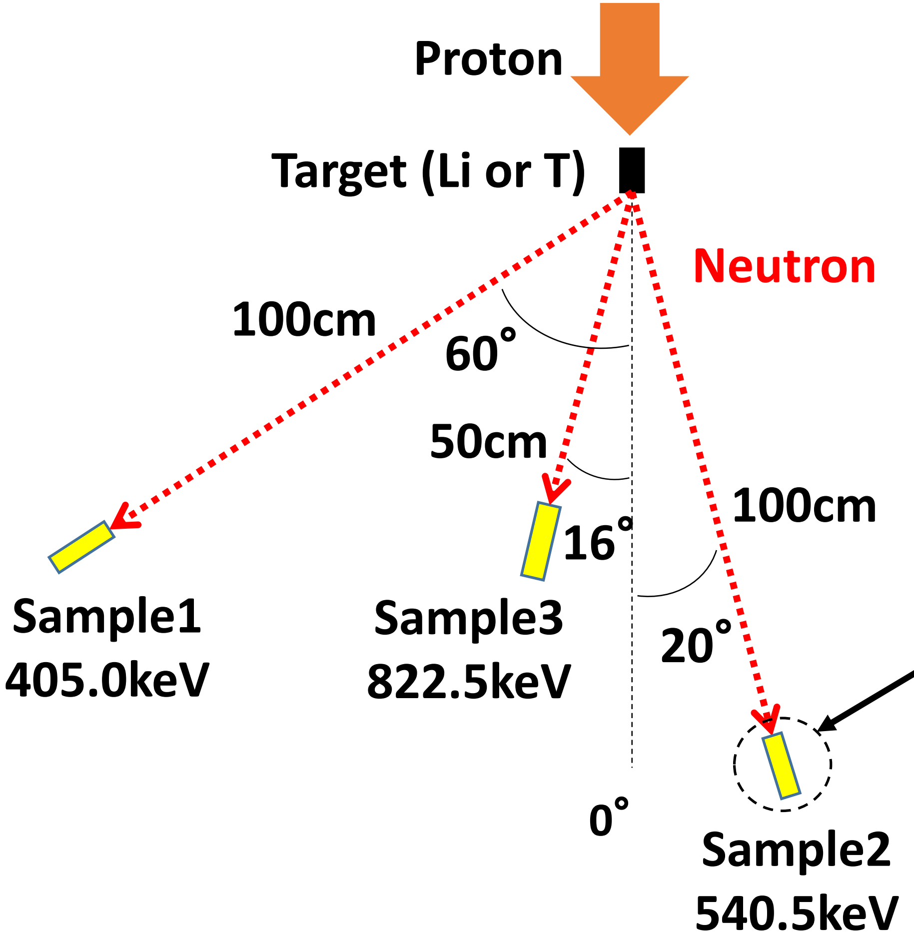
No spectrum and directional data in sub-MeV environmental neutron at LNGS

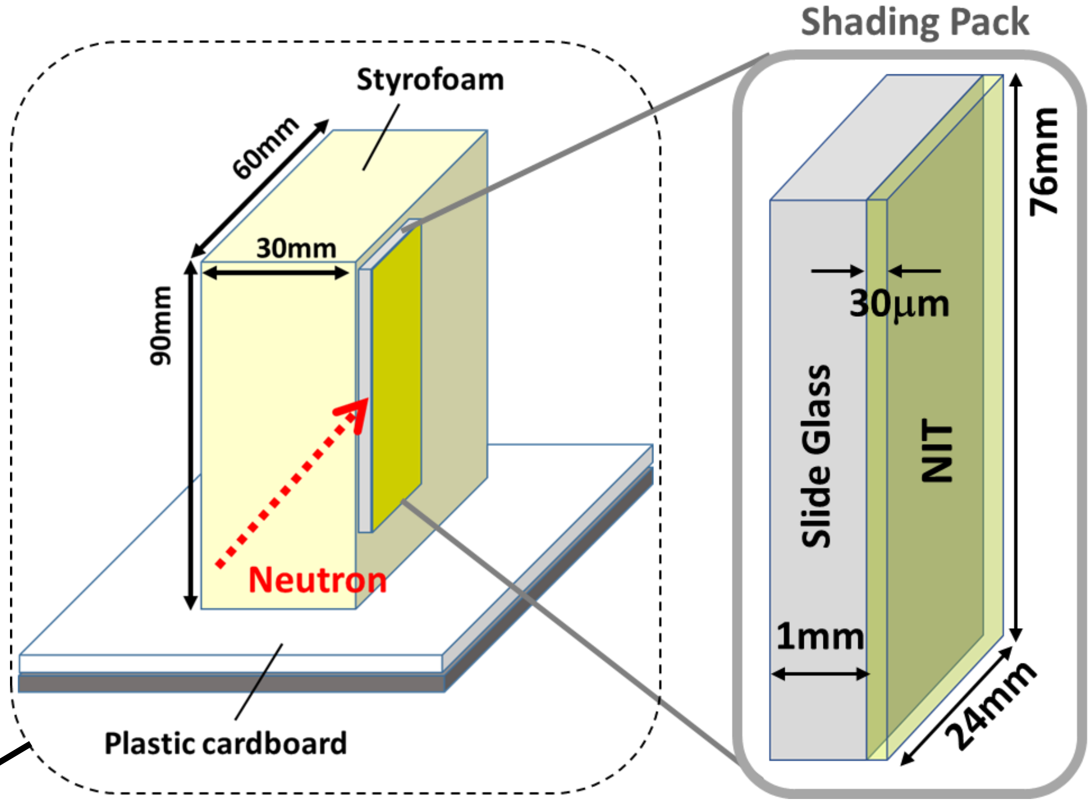
- Reactor Neutron Imaging …

Monochromatic Neutron Exposure at AIST

$$^{7}Li + p + 2.3MeV \longrightarrow {}^{7}Be + n + 565keV,$$

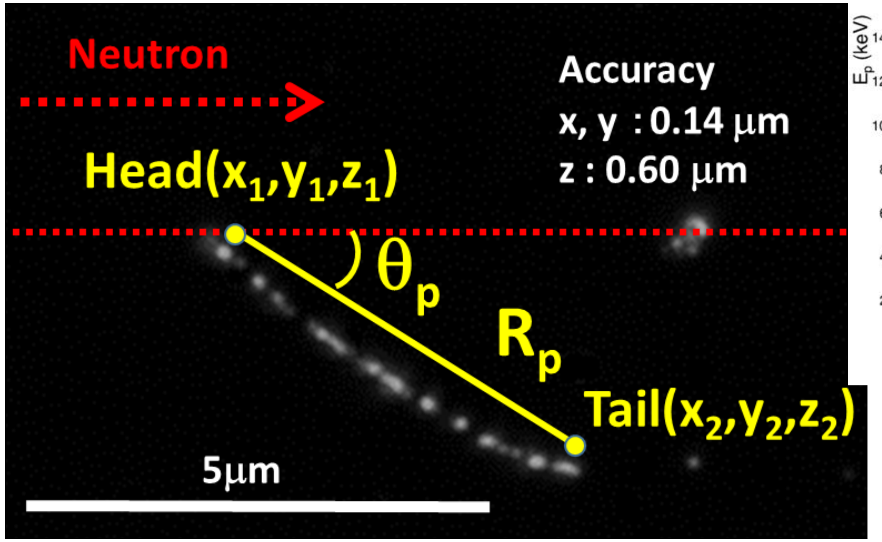
$$^{3}T + p + 1.7MeV \longrightarrow {}^{4}He + n + 880keV.$$



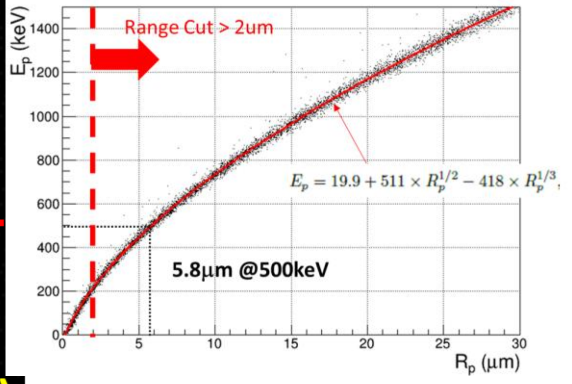


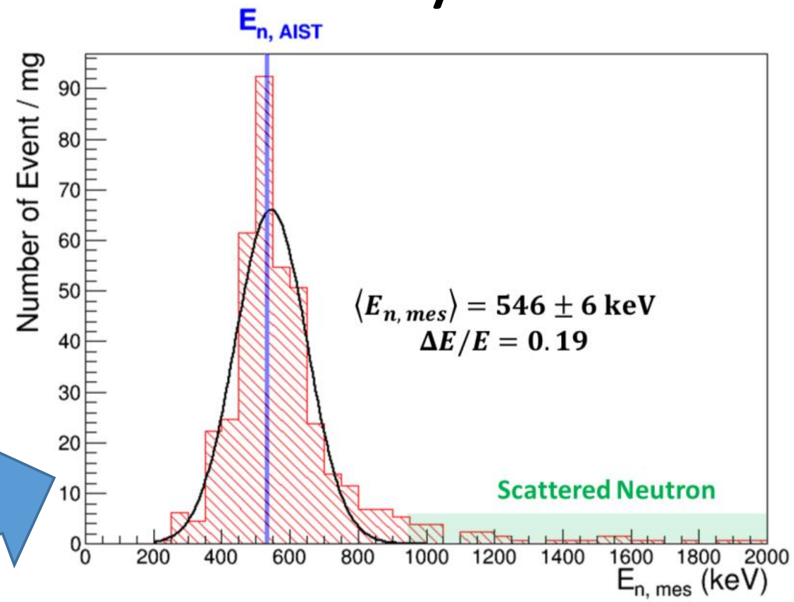
	Nuetron Source	Distance (cm)	Angle	$E_{n,AIST}$ (keV)	Flux (n cm^{-2} s^{-1})	Exposure Time (hour)
Sample1	Li(p,n)Be	100	60°	405.0 ± 9.3	361 ± 12	5.68
Sample2	Li(p,n)Be	100	20°	540.5 ± 12.7	791 ± 26	5.68
Sample3	T(p,n)He	50	16°	822.5 ± 16.7	908 ± 30	6.92
Reference Sample	-	-	-	-	0	0

Energy Reconstruction by Manual Analysis

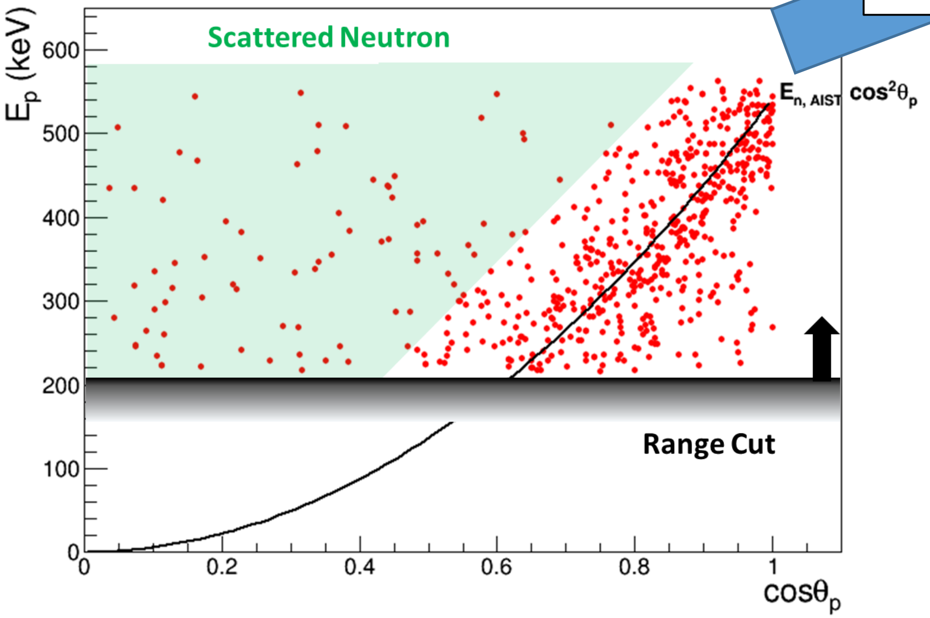


Rp vs Ep in NIT

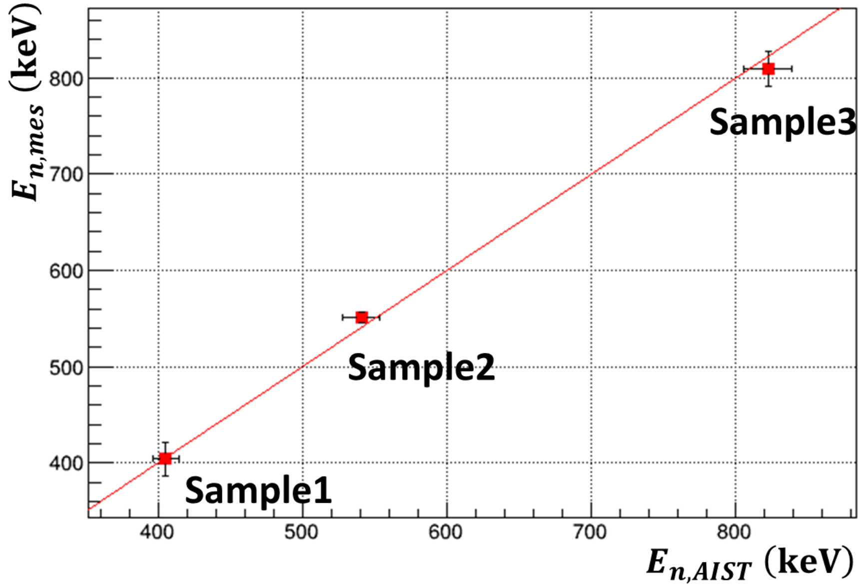




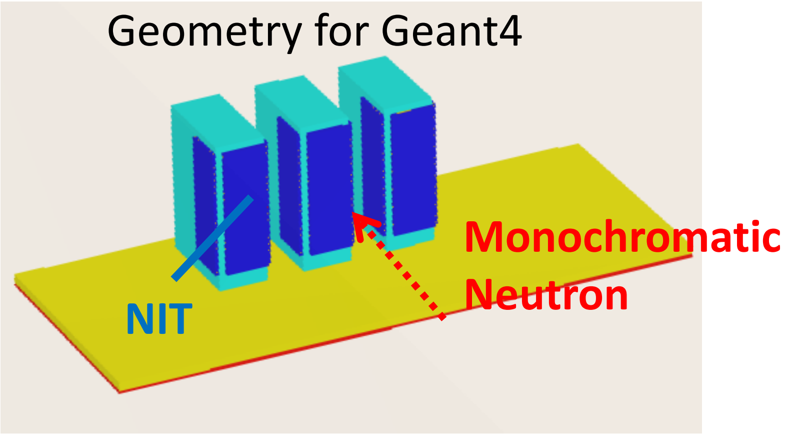
$$E_n = \frac{E_p}{\cos^2 \theta_p}$$



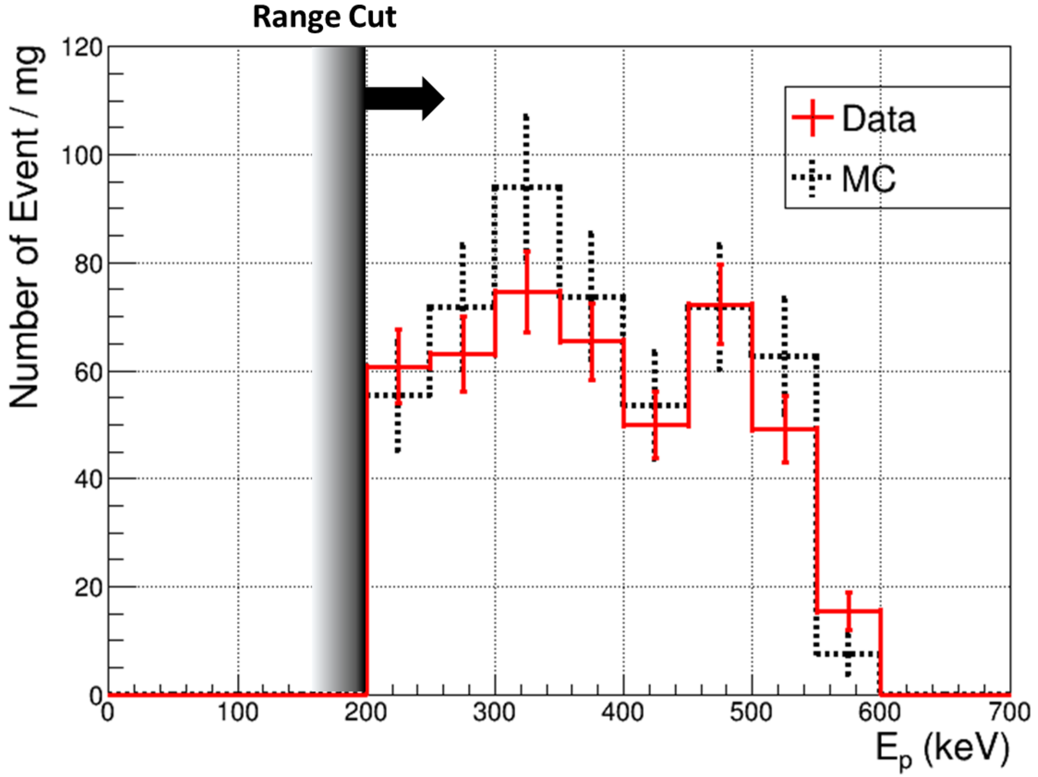
Reconstructed Energy vs AIST Energy

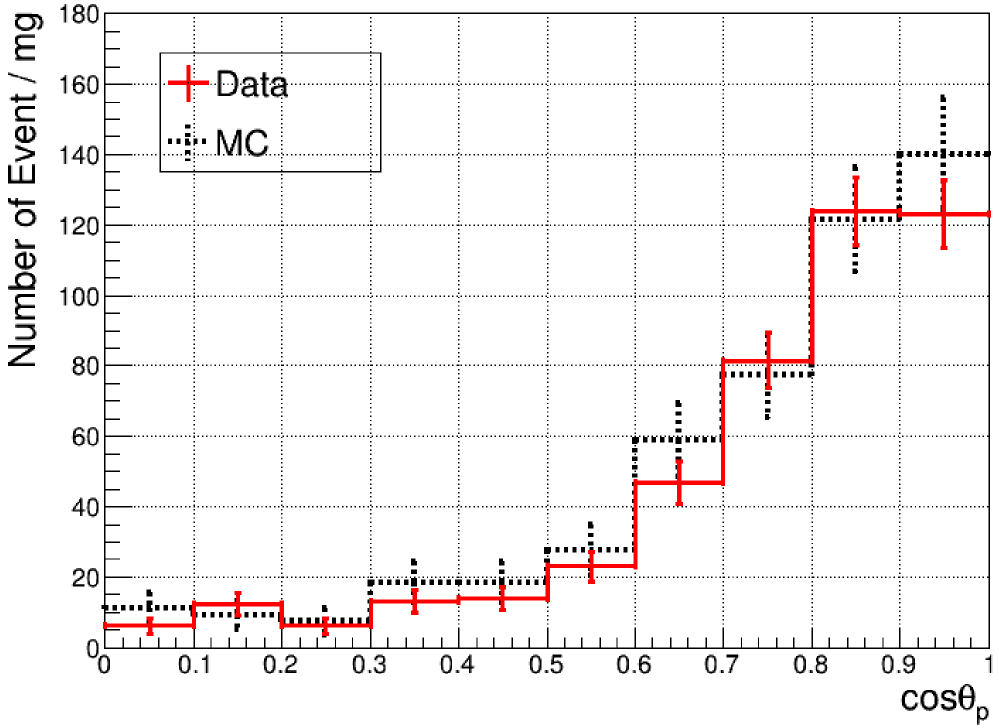


Comparison with Geant4 Simulation



✓ Head and Tail points of the simulation are smeared with optical resolution



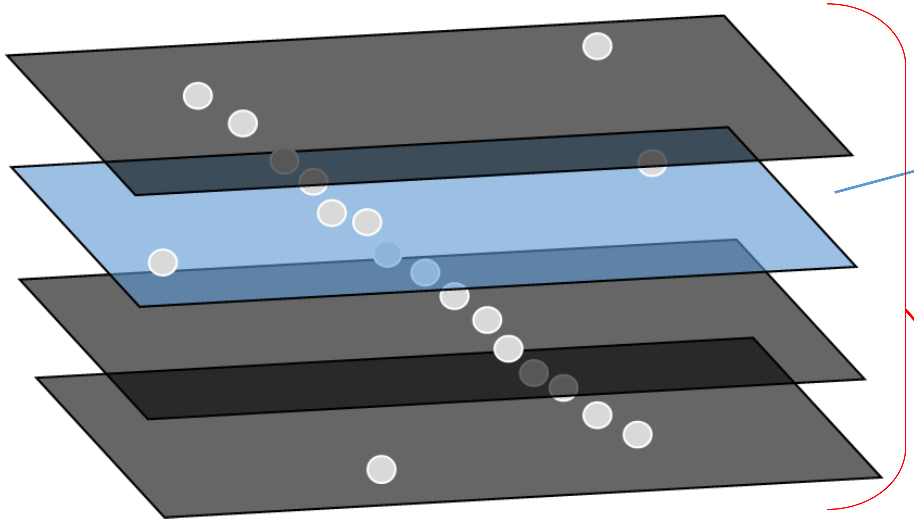


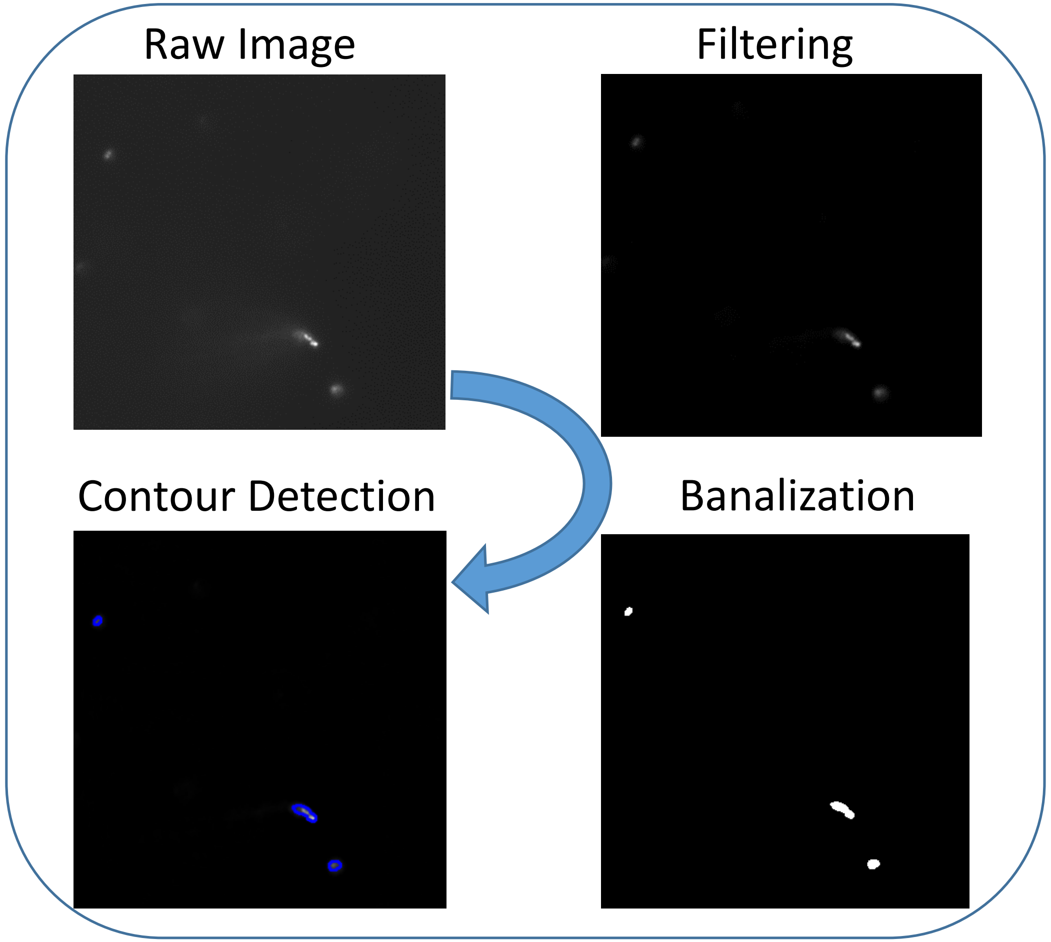
✓ Data(Sample2): 451 ± 39 events, Simulation: 489 ± 30 events

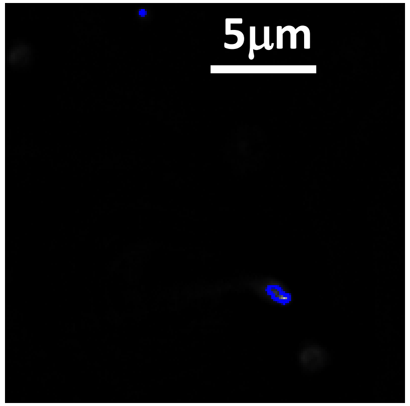
✓ **Manual Analysis Data is good agreement with Monte Carlo Simulation**

Automatic Analysis

116 layer images taken by PTS3







Detect contours in all layers
→ Best focus selection by Clustering

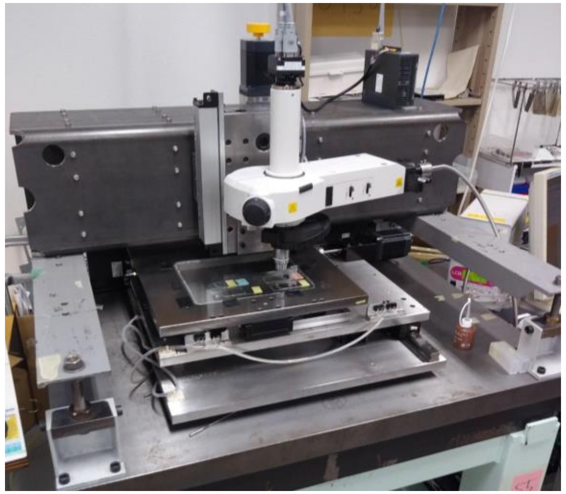
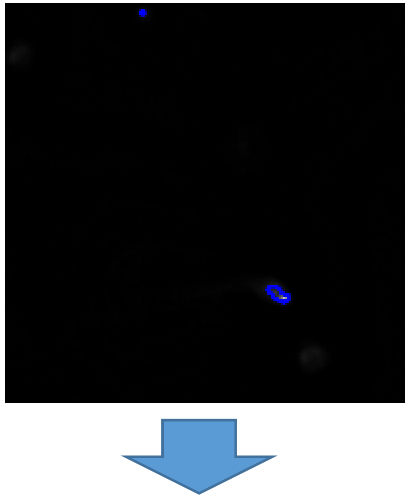


Table 2: Specification of current PTS system.

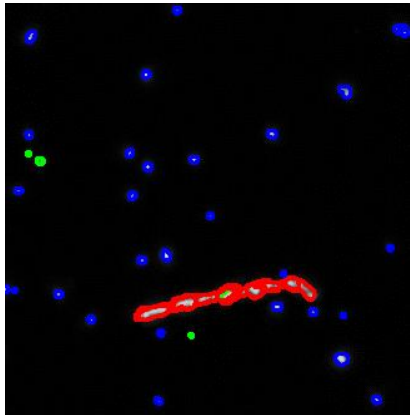
Objective lens Light source	N.A. 1.45, 100x 455 ± 27 nm, 17W, LED
Camera pixel pitch Number of pixels F.O.V.	0.055μm 2048 × 1088 $112\mu m \times 60\mu m$
Layer pitch Number of layers	0.33μm 116
Data Taking Speed	0.73s/view 43g/year

Automatic Analysis

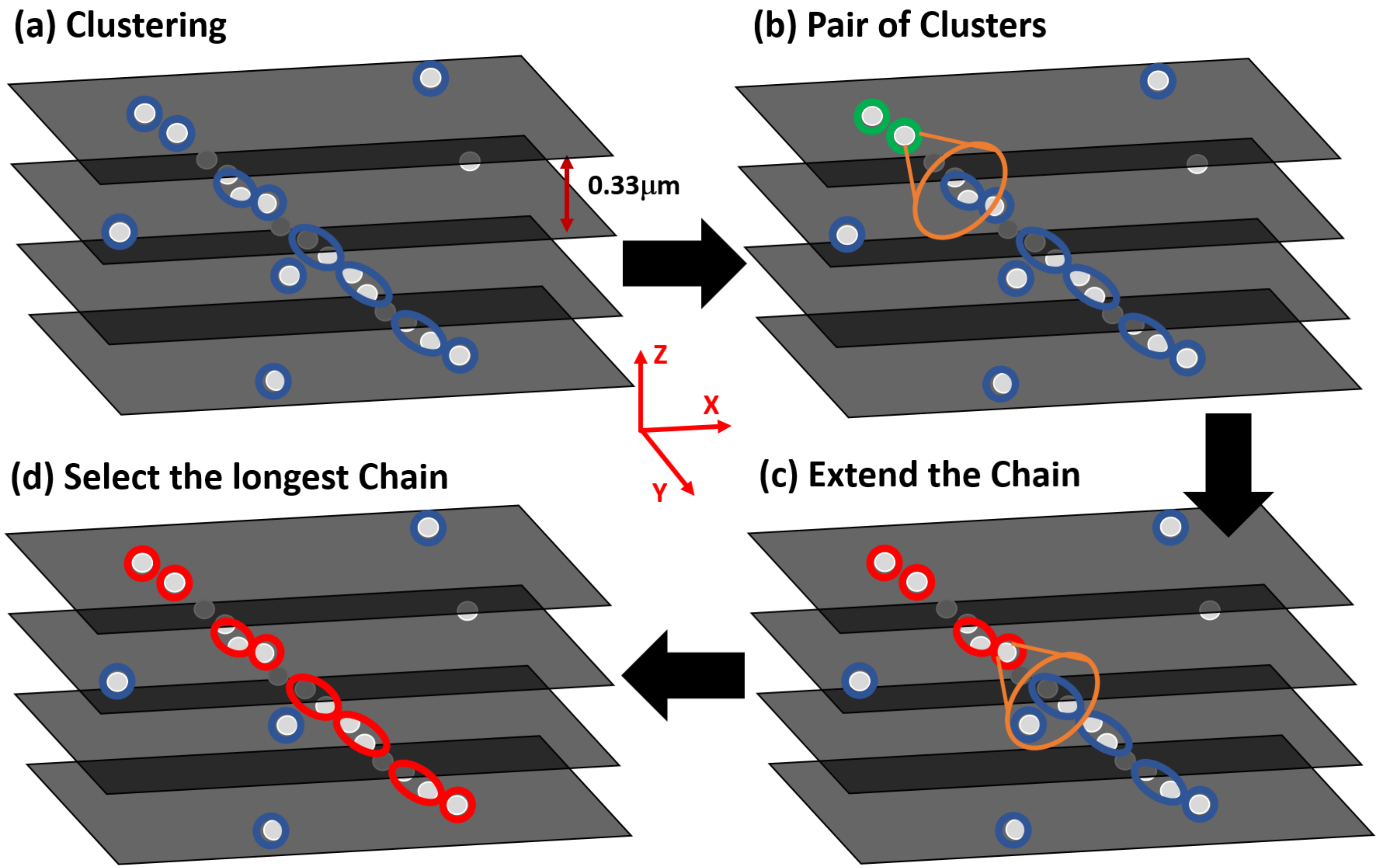
Clustering



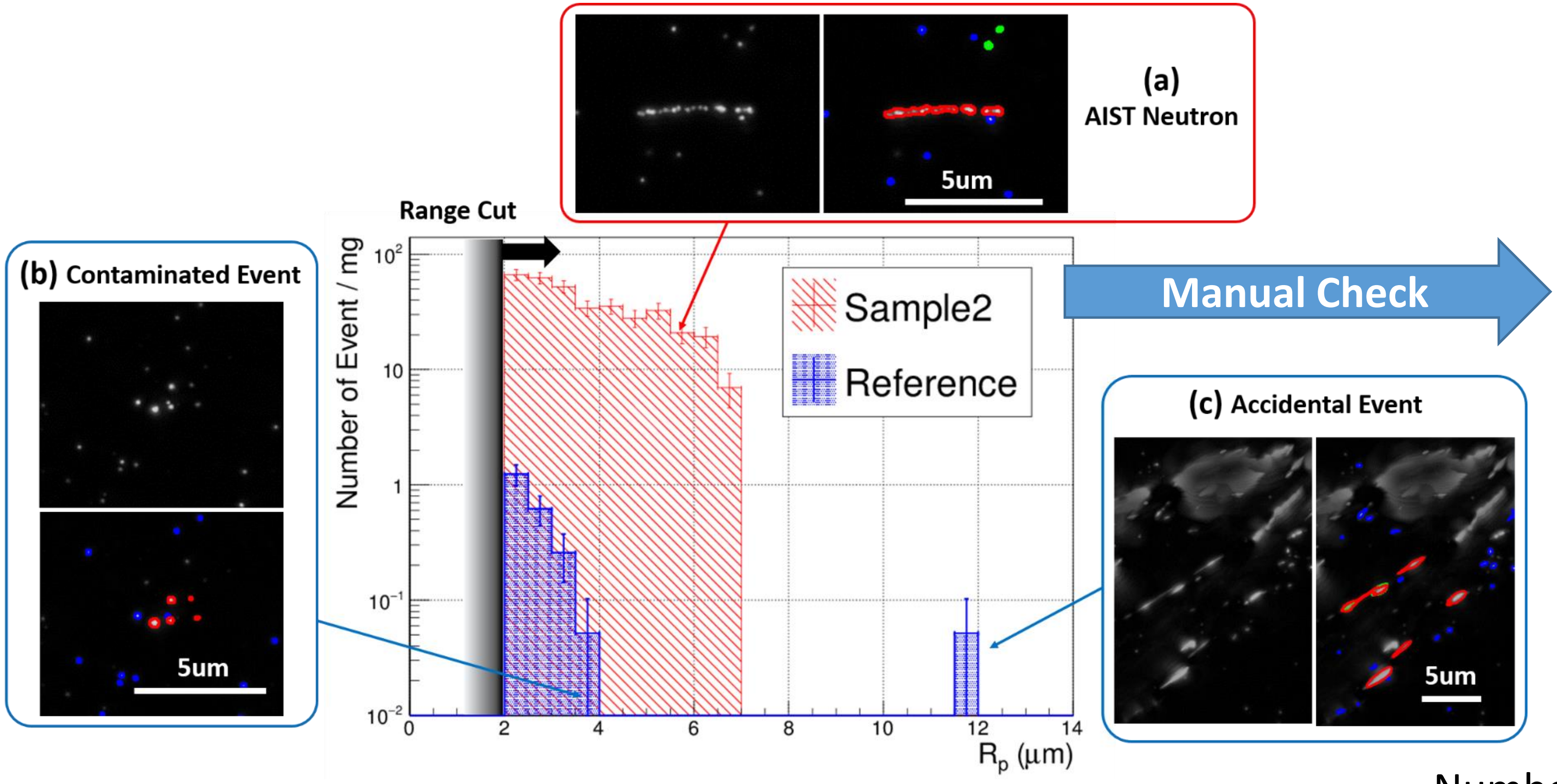
Chain Tracking



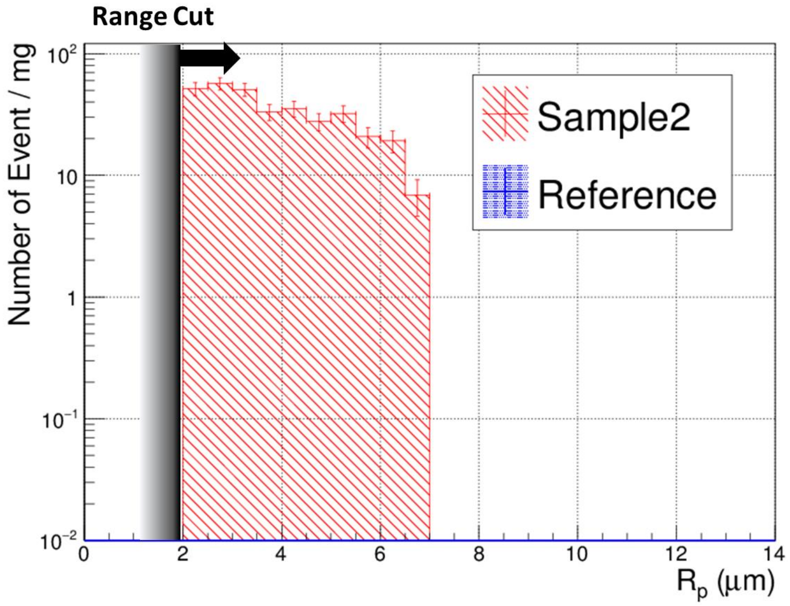
3 Dimensional Chain Tracking Algorithm



Automatic Analysis



After manual check for triggered events by Automatic Analysis

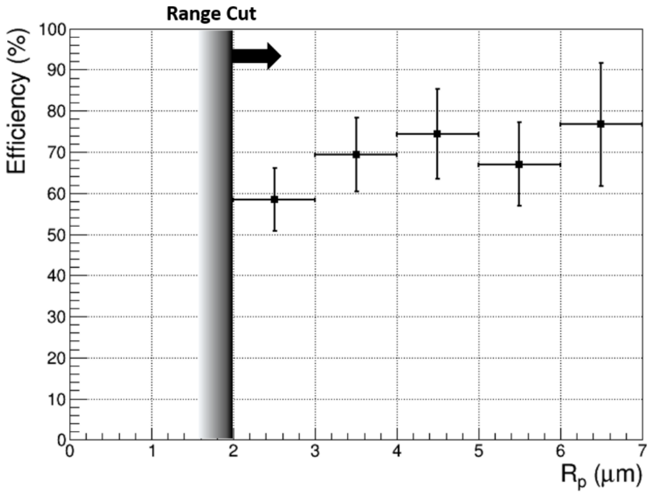


Number of Events in these analysis

Range Cut	Sample	Triggered Events by Chain Analysis (/mg)	After Manual Analysis (/mg)
$2\mu m$ (E_p >220keV)	Sample2	357 ± 17	335 ± 16
	Reference	2.22 ± 0.34	< 0.12 (90% C.L.)
$4\mu m$ (E_p >380keV)	Sample2	142 ± 10	142 ± 10
	Reference	0.05 ± 0.05	< 0.12 (90% C.L.)

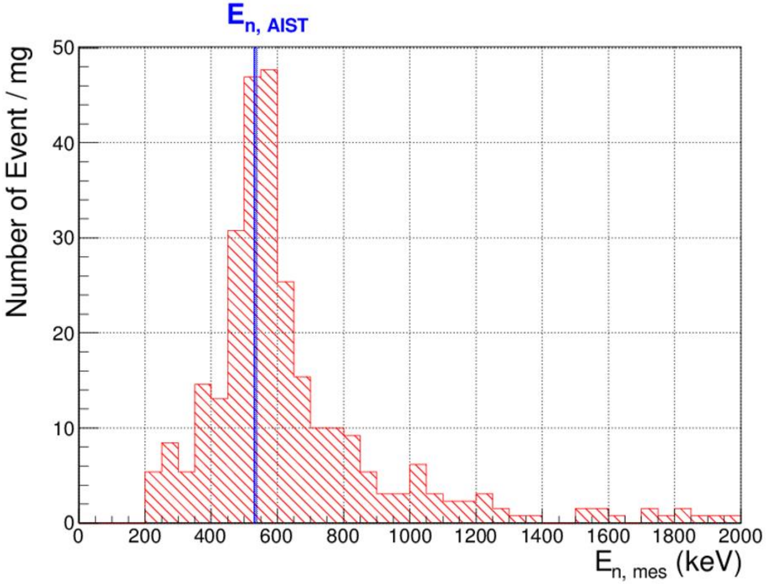
Chain analysis is good trigger for proton recoil tracks!

Performance of Automatic Analysis

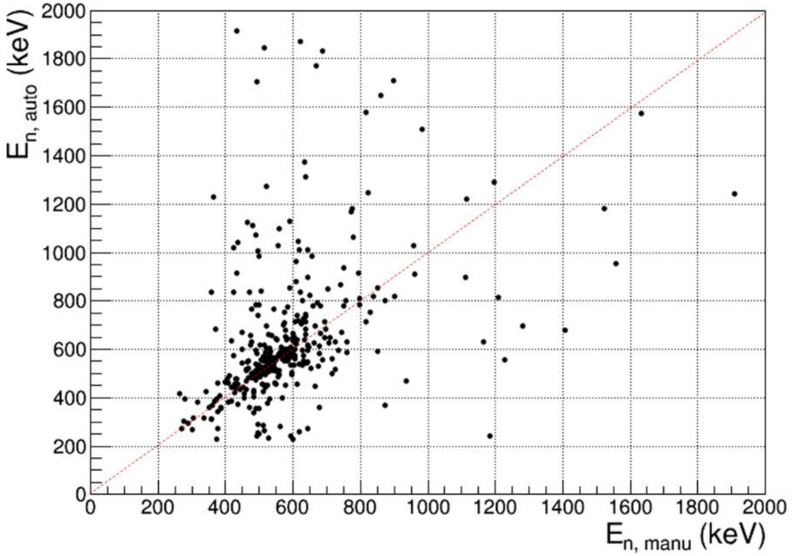


$$Recognition\ Efficiency \equiv \frac{(Automatic\ Analysis)}{(Manual\ Analysis)}$$

✓ **Recognition efficiency for recoil-proton is ~70%**



Comparison with Manual and Automatic analysis



✓ **Energy reconstruction accuracy is comparable with Manual Analysis**

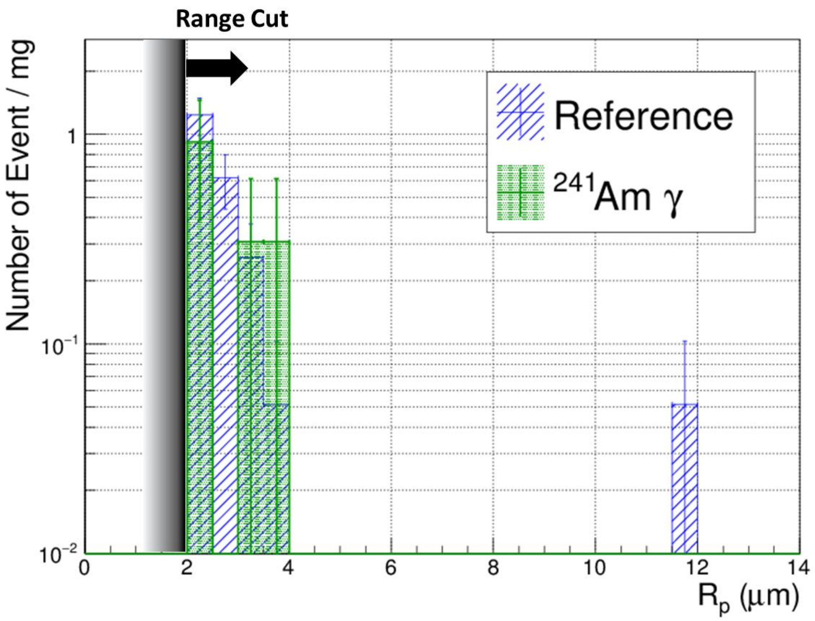
γ-rays Rejection Power

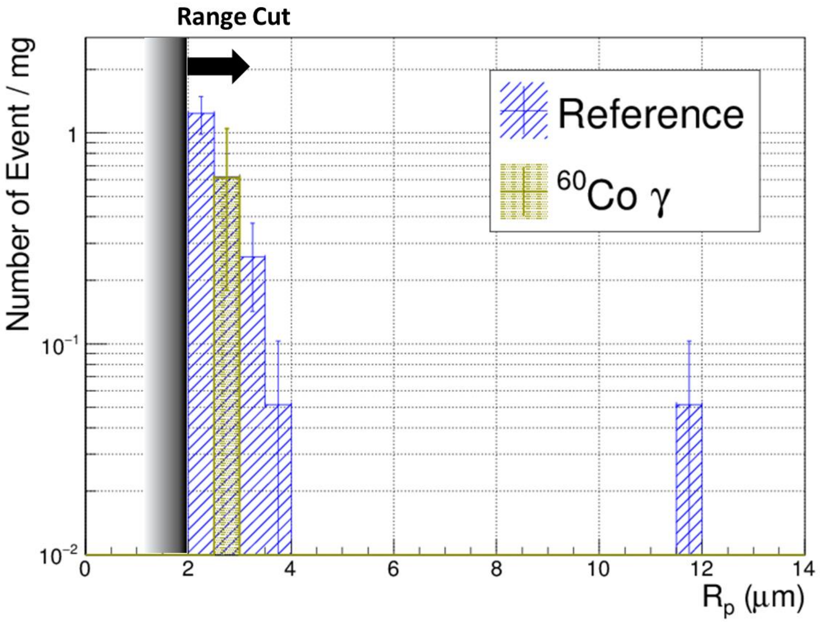
This is comparable to the 10 years exposure in LNGS environment

We prepared 2 type of γ-ray exposed samples

γ-ray source	Energy (keV)	Exposed Flux (/cm^2)	Reacted Flux in NIT (/cm^2)	Reacted Flux in NIT (/cm^3)
^{241}Am	10 - 60	10^7	2×10^6	6×10^3
^{60}Co	1170, 1330	10^7	5×10^3	15

Automatic Scanning Results

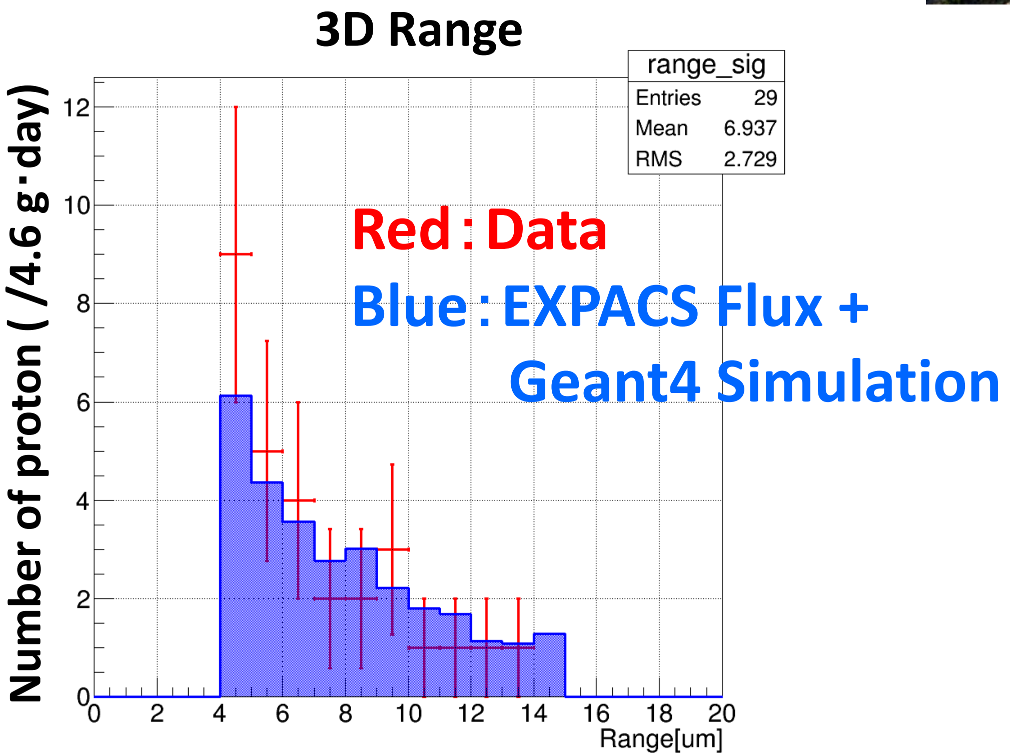


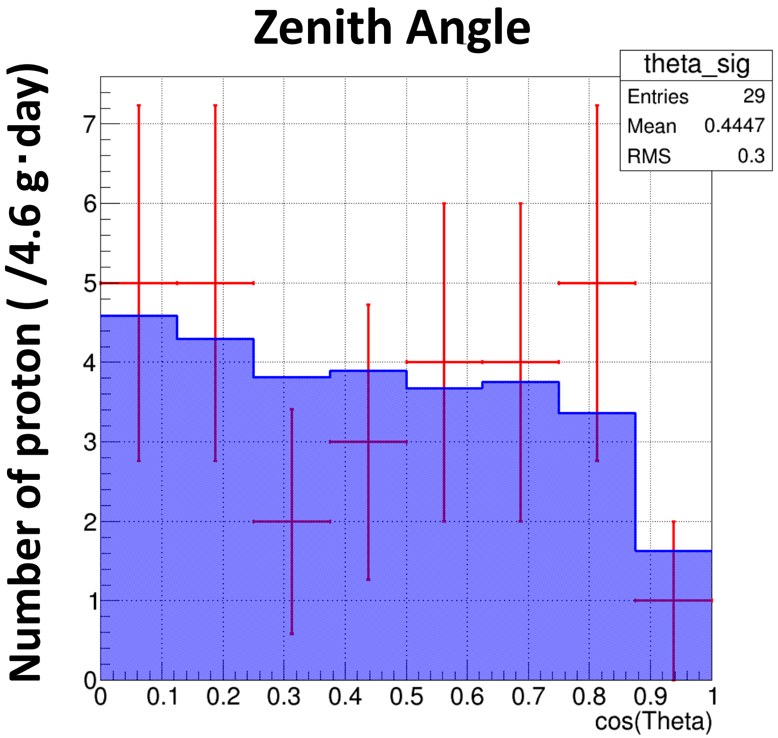


- ✓ **No significant γ-ray excess both of 2 samples**
- ✓ **NIT has quite high γ-rays rejection power!**

Surface Run @ LNGS

- ✓ **NIT was installed outside the building**
- ✓ **Analyzed Amount: 4.6 g･day**





Data @ 4um~15um (400keV~2.5MeV)

$(6.9 \pm 1.7) \times 10^{-3}$ [neutron/cm^2/s]

Simulation using EXPACS and Geant4

7.7×10^{-3} [neutron/cm^2/s]

For Underground Run

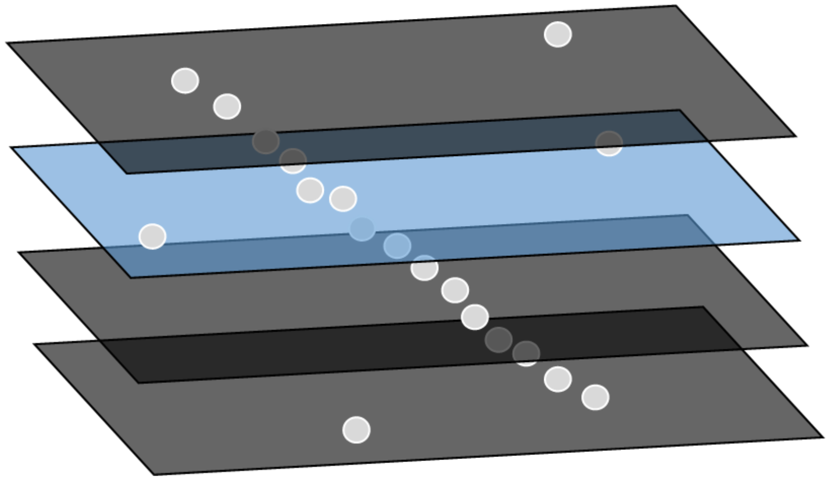
Table 5: Analysis mass scale of NIT and sub-MeV Neutron Physics Target.

Analysis Mass Scale (g)	Sub-MeV Neutron Measurement
0.001	Flux, spectrum, direction, and imaging from Reactor or Radio Isotope
1	Flux, spectrum and direction in Gran-Sasso Surface (1 month Run)
100	Flux, spectrum and direction in Gran-Sasso Underground (1 month Run)
1000	Annual modulation in Gran-Sasso Underground (1 month Run)

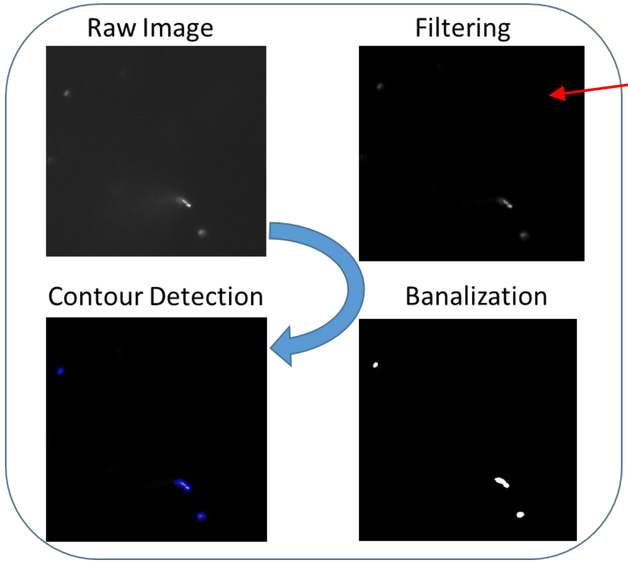
Current Analysis Speed
= 2.4 s/view
= **12 g/year**

Surface Run is available!

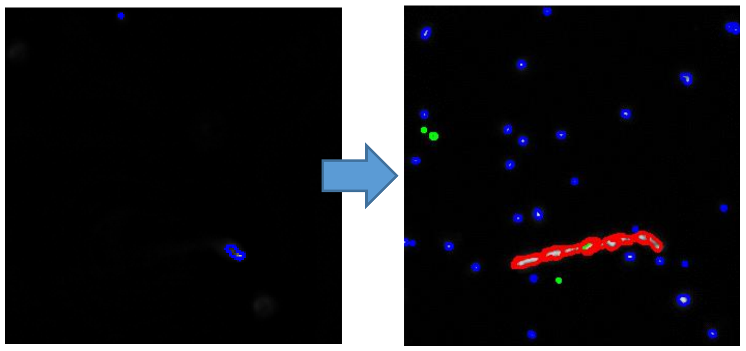
Image Data Taking
(~ 0.8 s/view)



Chain Analysis
(Filtering: 1.4 s/view, Other: 0.2 s/view)



This should be faster by using GPU



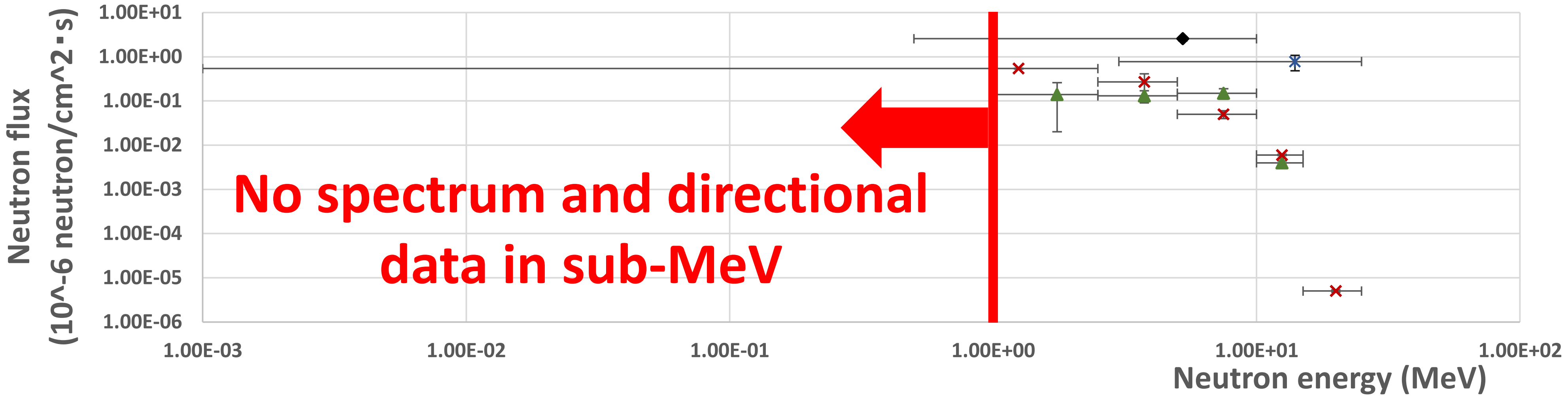
Summary

- NIT also has high potential as sub-MeV neutron detector
    - High detection efficiency, energy resolution, directionality and quite high γ-rays rejection power
- We developed the Automatic Analysis as the proton recoil trigger for large scale analysis
    - Still developing (should be optimized)
        - Contaminated dust in NIT can be 1 order decrease by through 0.22um filter
        - There are some parameters (e.g. brightness, shape, linearity, …), almost of them are not used yet
    - Analysis speed must be 10 times faster for Underground Run
        - It has been already shown to be faster with GPU processing

Backup

Environmental Neutron Measurement @LNGS Underground

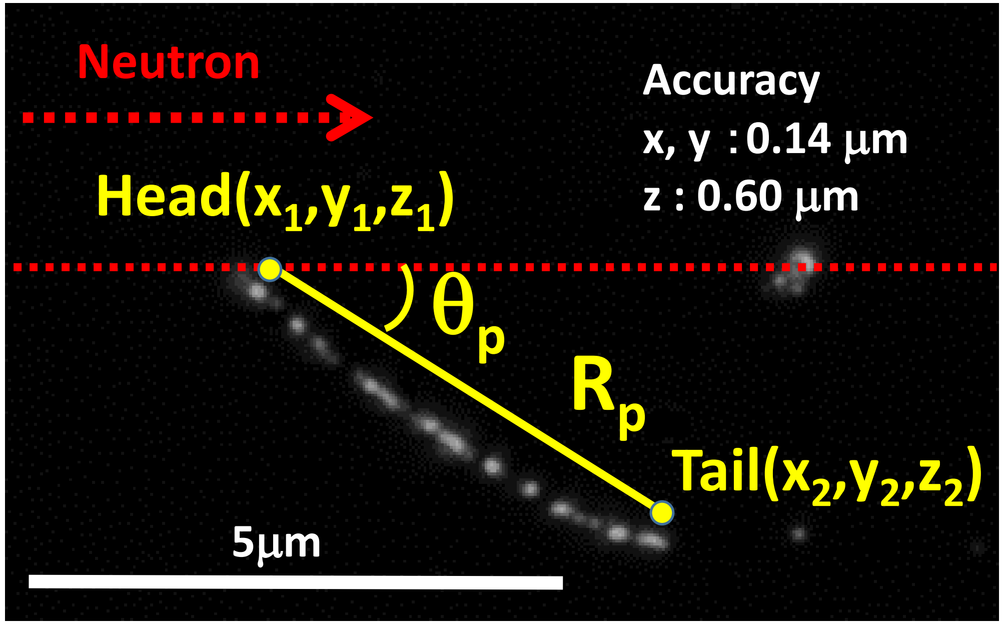
H. Wulandari, et al., Astropart. Phys. **22** (2004) 313.
A. Rindi, et al., Nucl. Inst. Meth. A, **272** (1988) 871.



^{6}Li liquid scintillator (Hall A)	Plastic Scintillator (Hall C)	BF_3 Counter (Hall A)	^{3}He Counter (Tunnel)

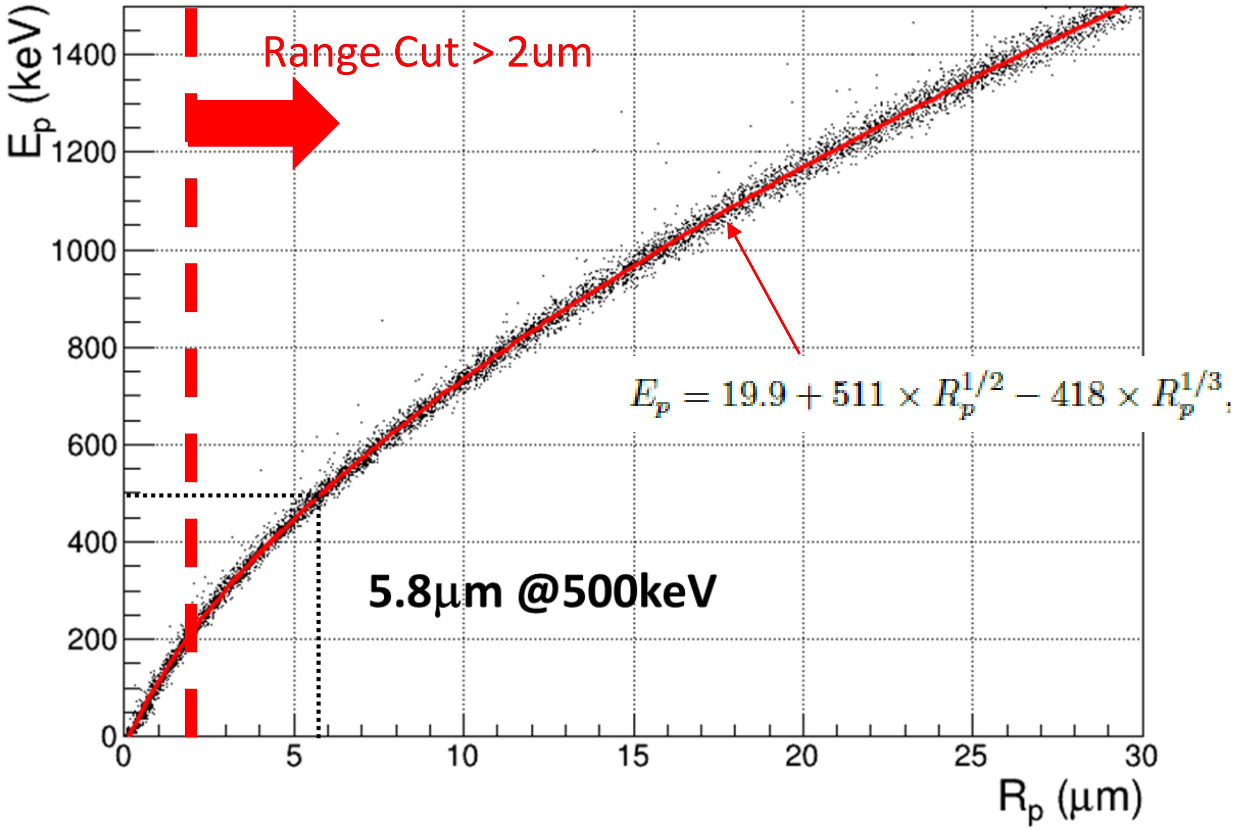
Neutron Detector	Energy Range	γ-ray rejection power	Detection Efficiency	Energy Spectrum	Directionality
Organic Scintillator	1MeV~100MeV	Bad	Good	Good	Bad
BF_3 ,^{3}He Counter	thermal~20MeV	Good	Good	Bad	Bad
Proton-recoil Proportional Counter	10keV~2MeV	Bad	Bad	Good	Bad
NIT	Sub-MeV~	Good	Good	Good	Good

Manual Analysis



$$E_n = E_p \cos^2 \theta_p$$

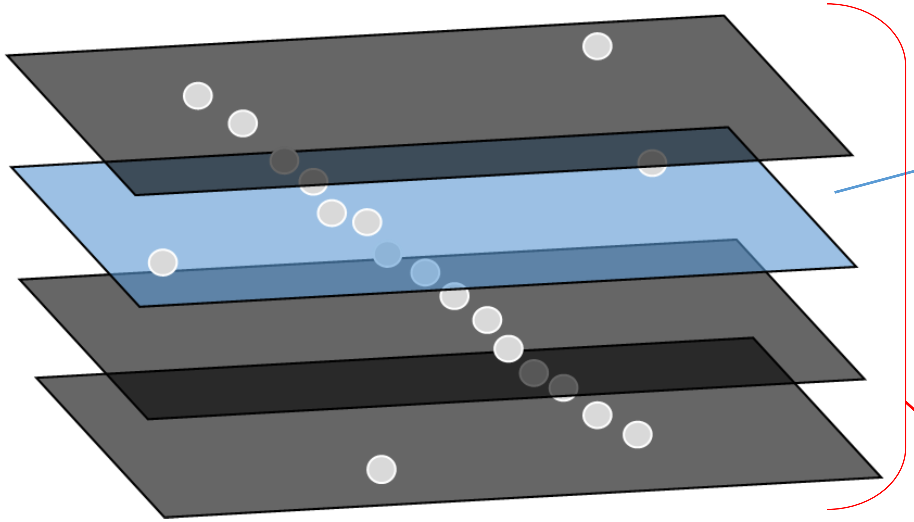
Proton Range vs Energy in NIT
(Geant4 simulation)

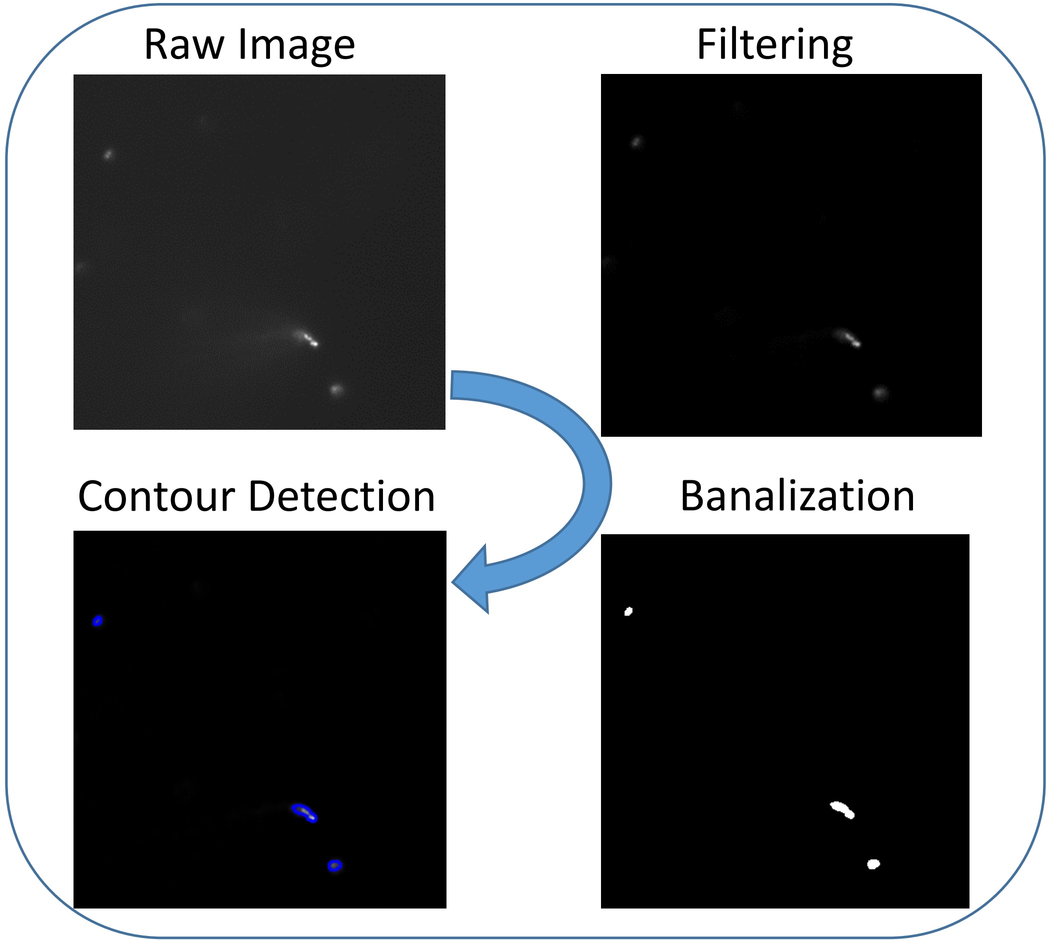


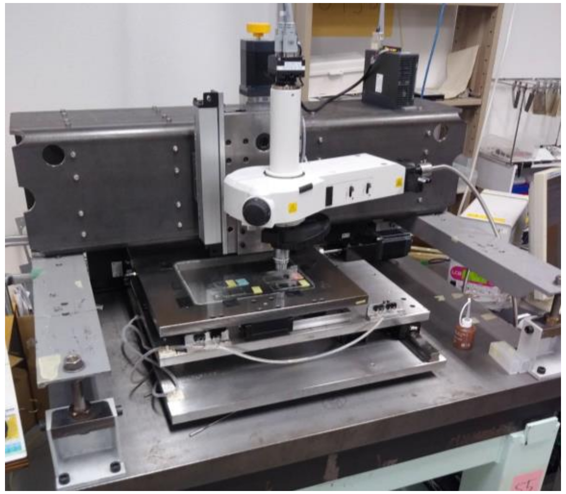
✓ 451 events are found in Sample2 by Manual Analysis

Automatic Analysis

116 layer images taken by PTS3







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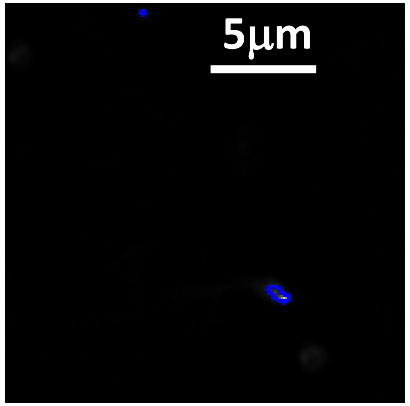
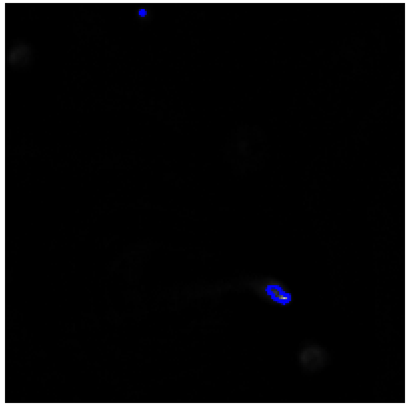
Layer pitch Number of layers	$0.33\mu m$ 116
Data Taking Speed	0.73s/view 43g/year



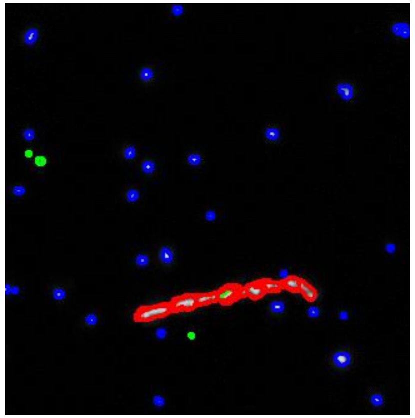
Detect contours in all layers
→ Best focus selection by Clustering

Automatic Analysis

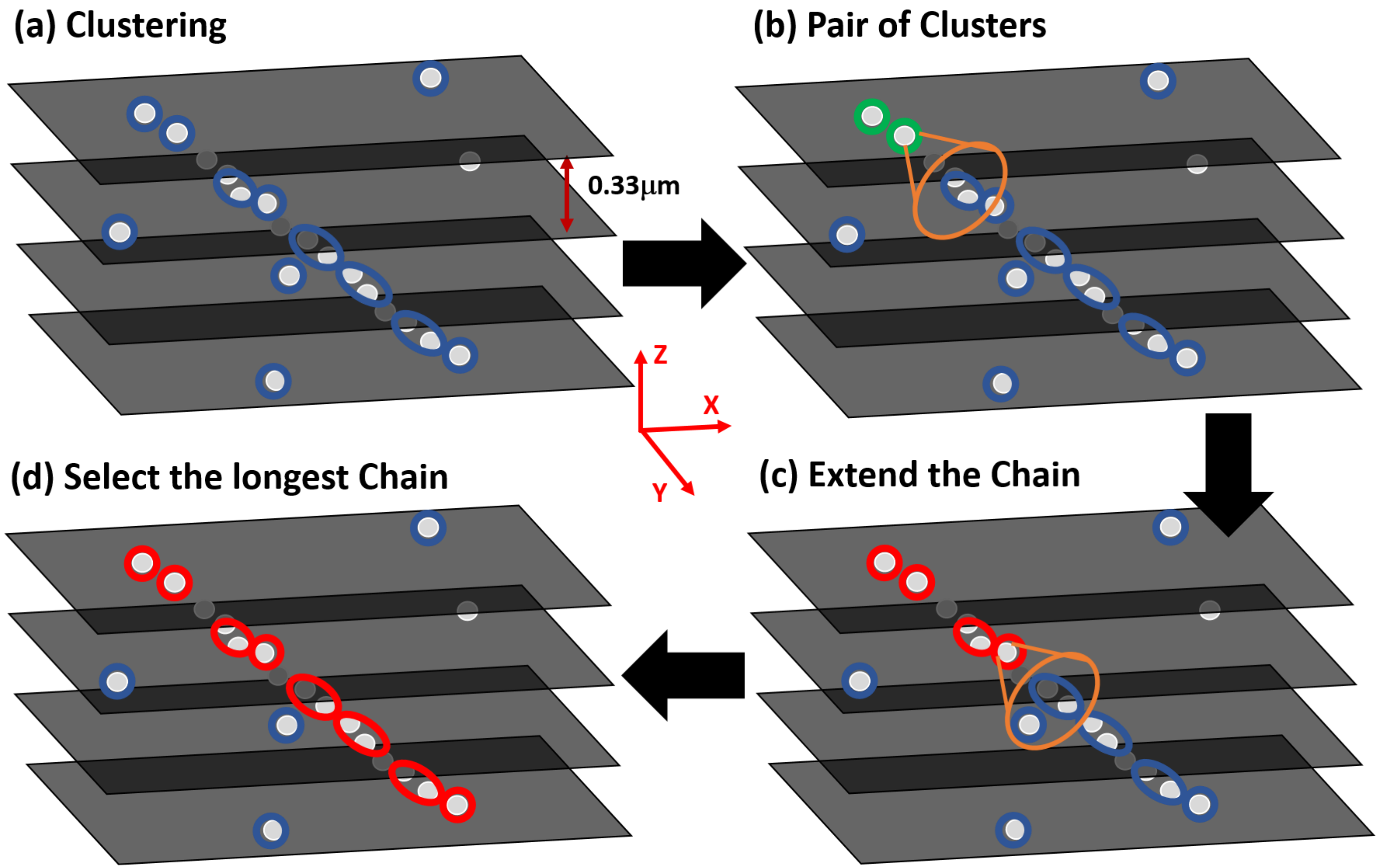
Clustering



Chain Tracking

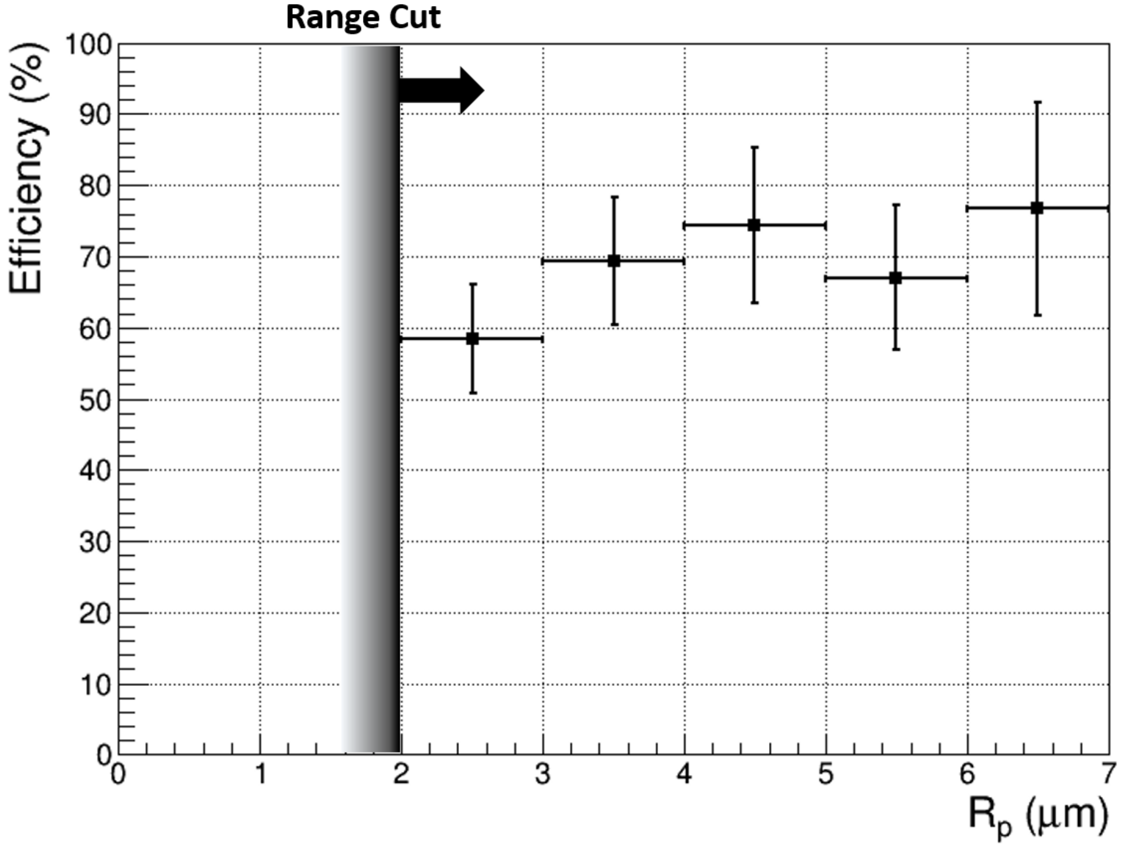


3 Dimensional Chain Tracking Algorithm



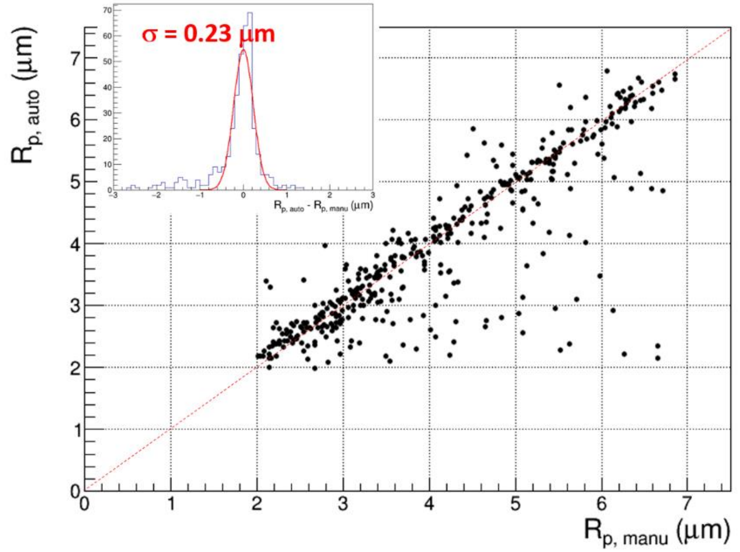
Recognition Accuracy by Automatic Analysis

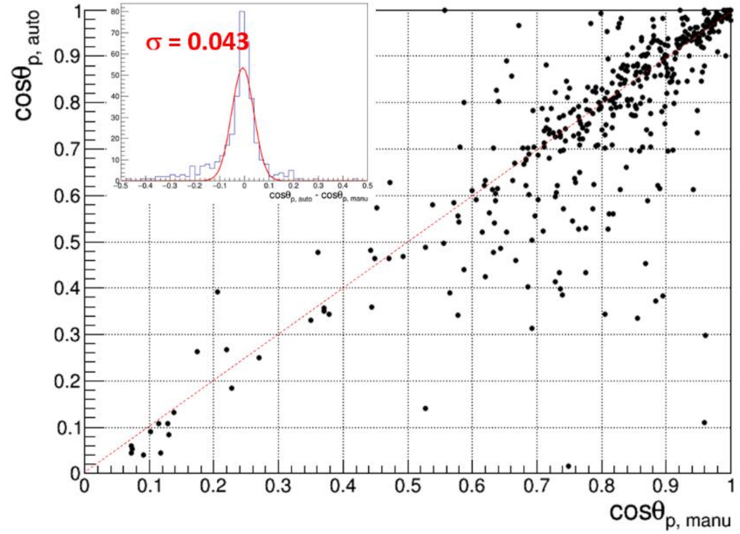
$$Recognition\ Efficiency \equiv \frac{(Automatic\ Analysis)}{(Manual\ Analysis)}$$



✓ **Recognition efficiency for recoil-proton is ~70%**

Comparison with Manual and Automatic analysis





PTEP

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Development of sub-MeV Neutron Detector for Environmental Neutron Measurement

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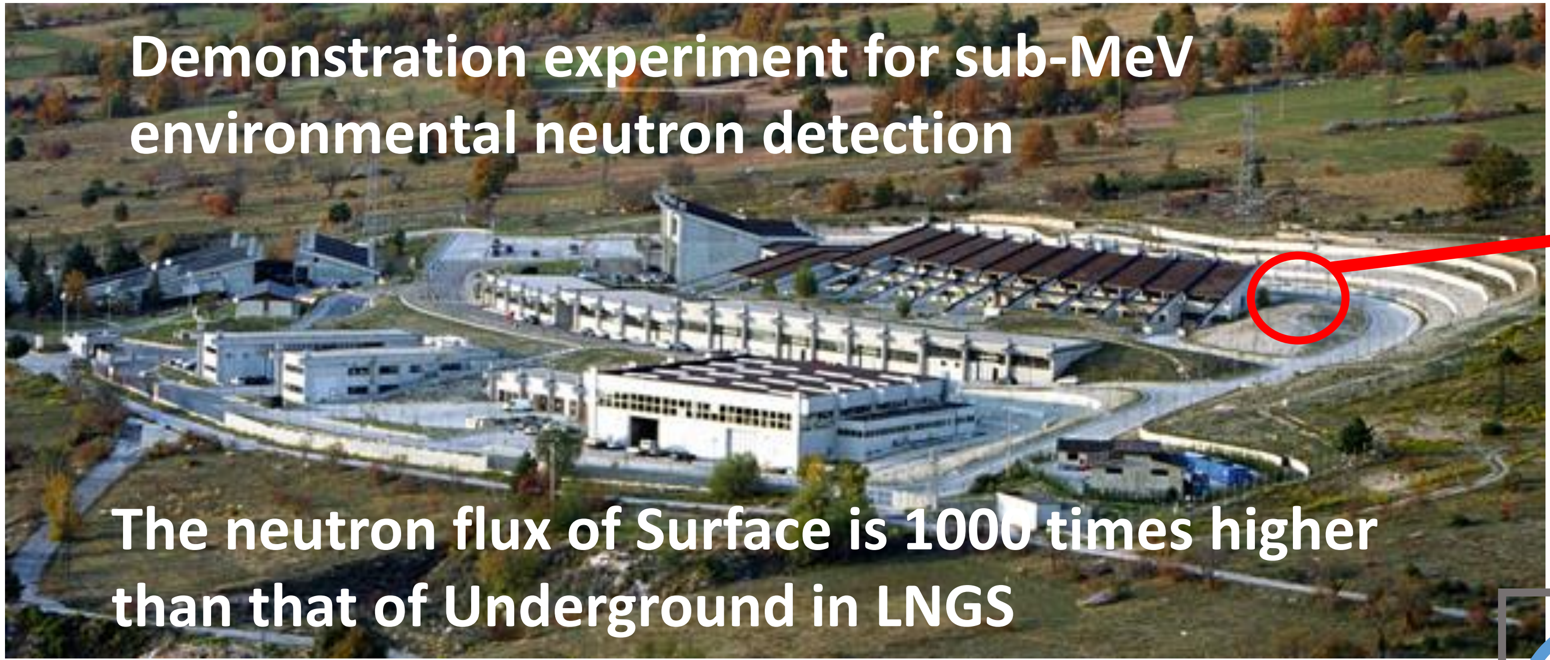
[2] *Department of Physics, Toho University, Chiba 274-8510, Japan*
[*] *E-mail: takuya.shiraishi@sci.toho-u.ac.jp*
[3] *???, Nagoya University, Aichi 464-8602, Japan*

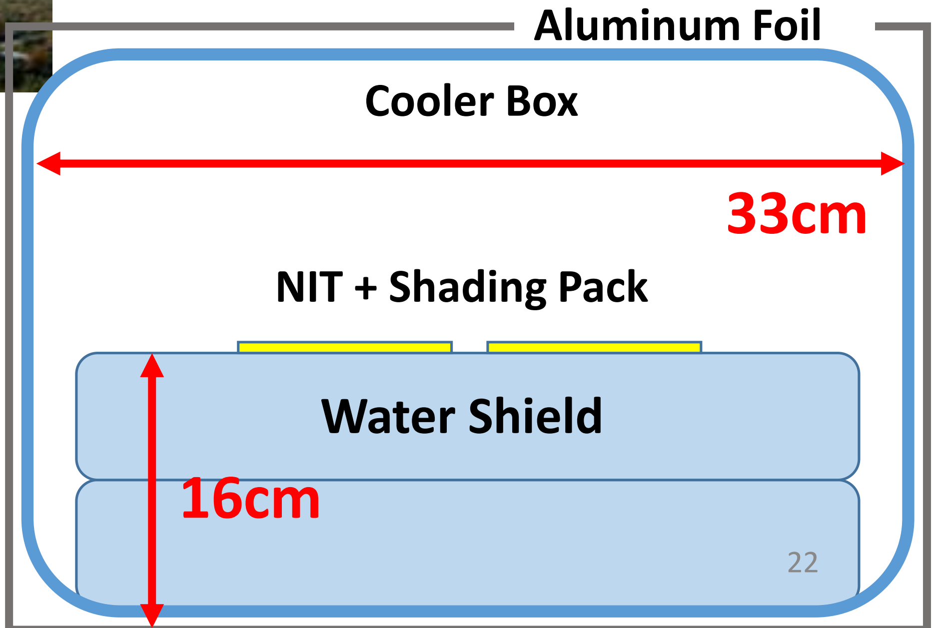
In this paper, we have developed a sub-MeV neutron detector which has high energy resolution, high background rejection power, and directional sensitivity. The detector is based on a 3-dimensional tracking detector called the Nano Imaging Tracker (NIT) with sub-micrometric accuracy. In order to improve the detection efficiency for recoil proton tracks by the elastic collision with hydrogen in the NIT, a new type of NIT with AgBr:I crystals of (98 ± 10)nm size dispersed in the gelatin was used. At first, as a verification experiment, NITs are exposed to monochromatic neutrons, it was shown that the detection efficiency for recoil proton tracks was (92.2 ± 9.8)% by manual analysis, and the resolution of reconstructed neutron energy was 20% at 540keV. Furthermore, for large scale analysis for sub-MeV neutron measurements under the low flux such as environmental neutrons, a system that can automatically discriminate proton tracks was developed and its performance was evaluated. It achieves the recognition efficiency of (68 ± 3)% at the analysis speed of 12g/year. The rejection power for γ-rays in this analysis is ...

Subject Index

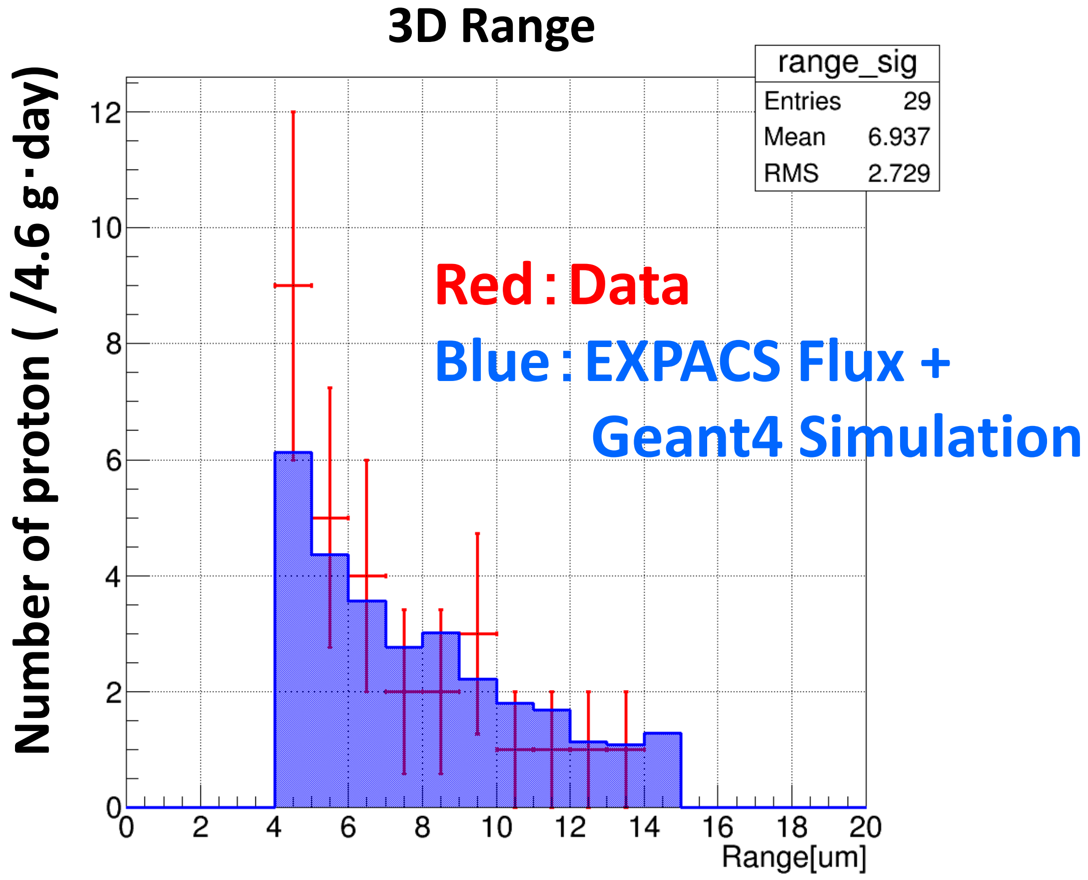
Surface Run @ LNGS

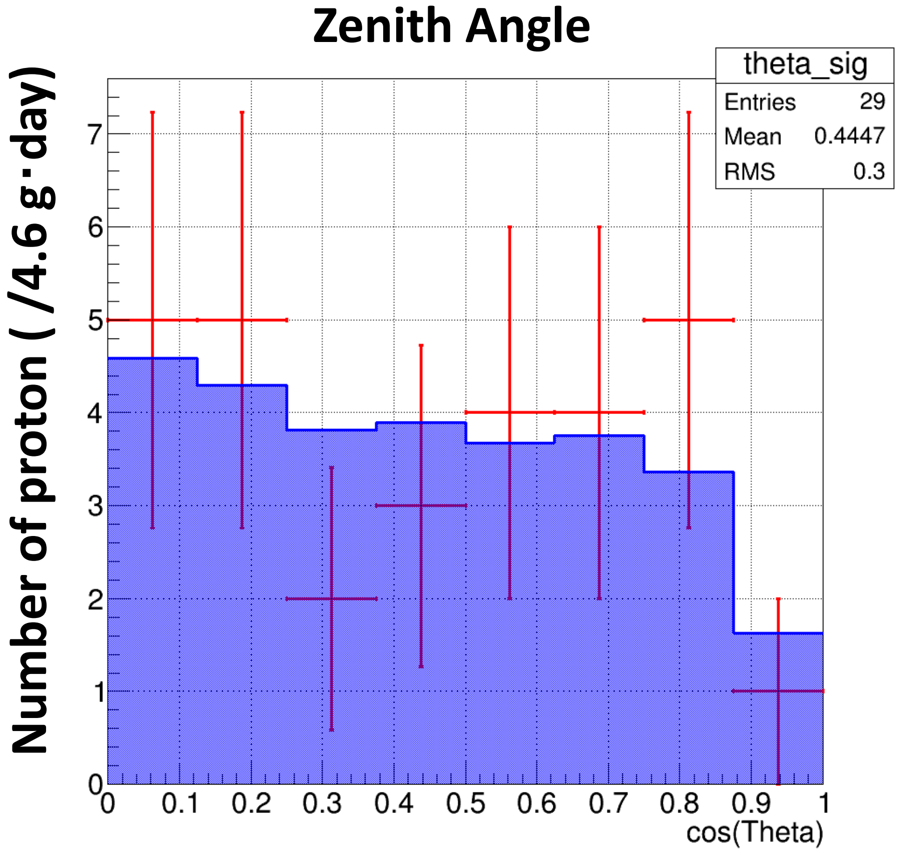


- ✓ NIT was installed outside the building
- ✓ Exposure Time: 140 hours
- ✓ Analyzed Mass Scale: 780 mg
- ✓ Analyzed Amount: 4.6 g·day



Surface Run @ LNGS



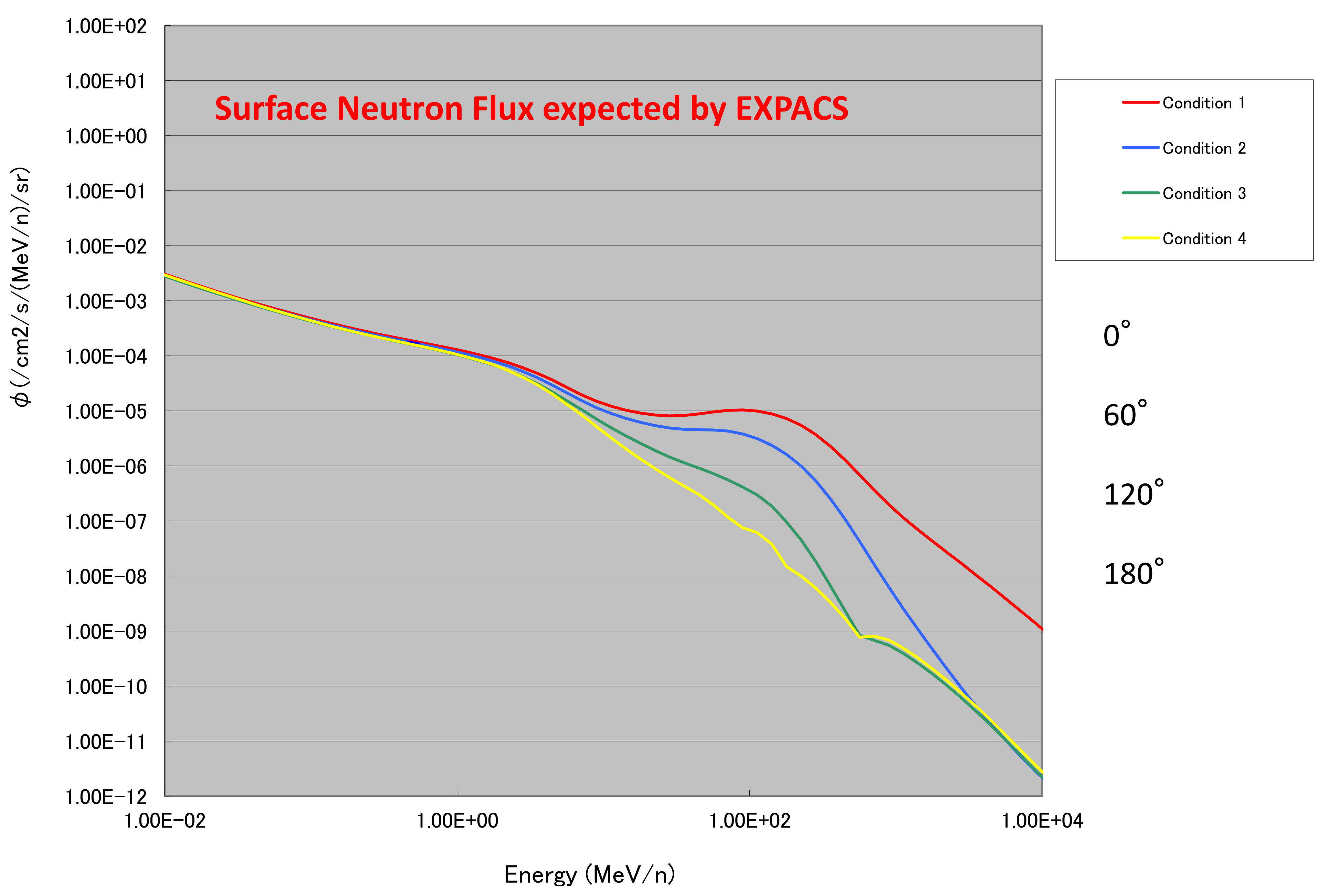


Data @ 4um~15um (400keV~2.5MeV)

$(6.9 \pm 1.7) \times 10^{-3}$ [neutron/cm²/s]

Simulation using EXPACS and Geant4

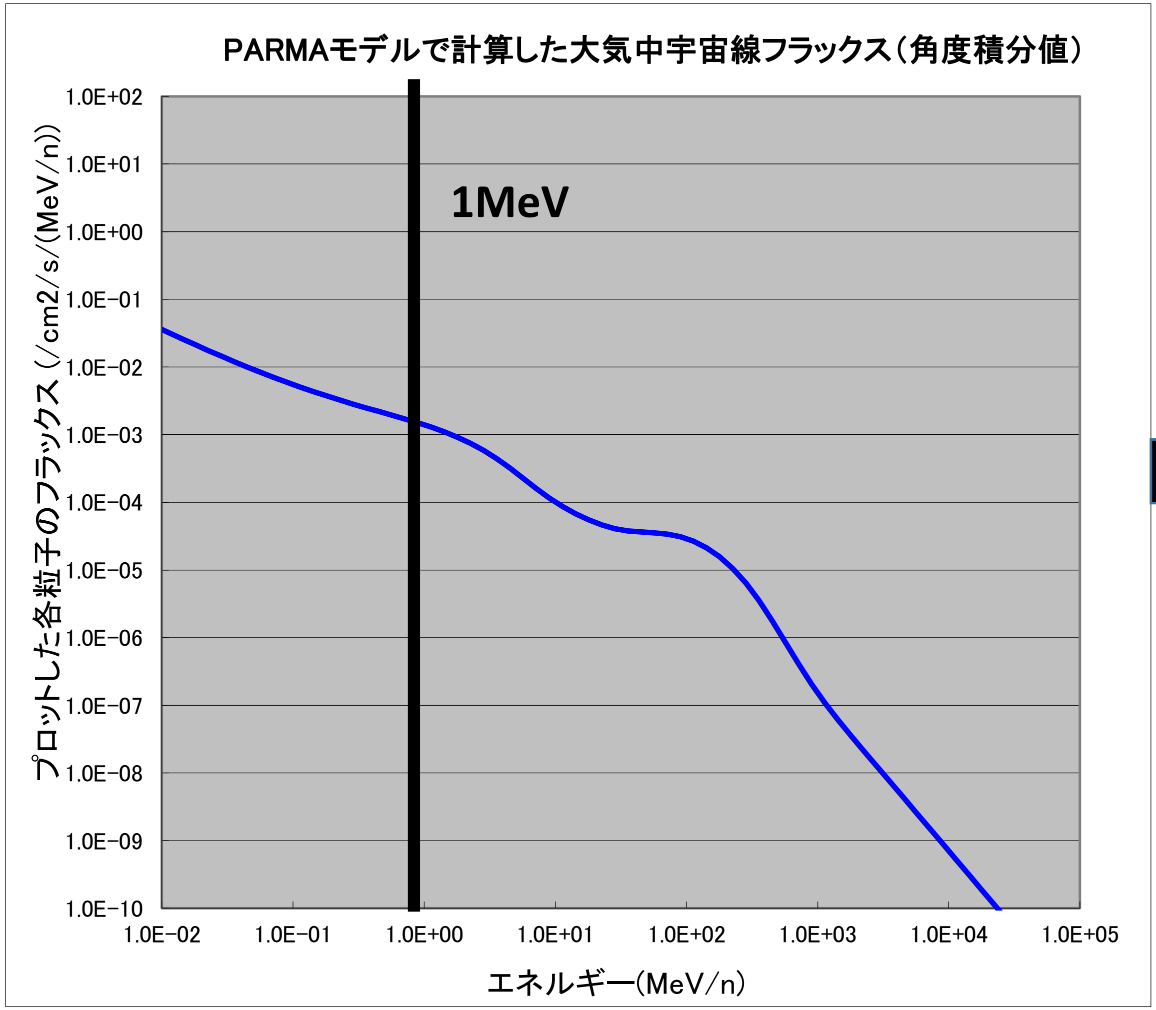
7.7×10^{-3} [neutron/cm²/s]



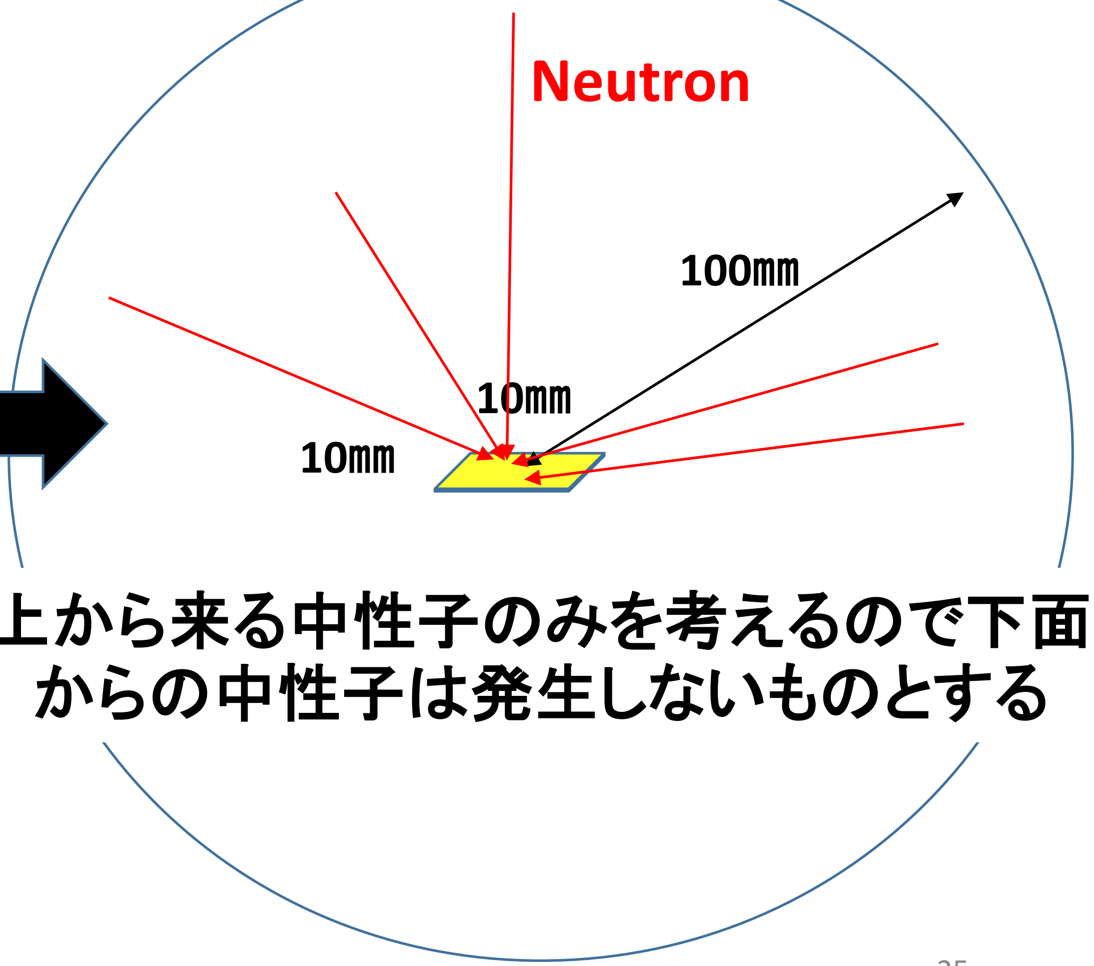
Surface Neutron Flux expected by EXPACS
φ(/cm2/s/(MeV/n)/sr)
1.00E+02
1.00E+01
1.00E+00
1.00E−01
1.00E−02
1.00E−03
1.00E−04
1.00E−05
1.00E−06
1.00E−07
1.00E−08
1.00E−09
1.00E−10
1.00E−11
1.00E−12
1.00E−02
1.00E+00
1.00E+02
1.00E+04
Energy (MeV/n)
Condition 1
Condition 2
Condition 3
Condition 4
0°
60°
120°
180°

Geant4 Simulation @ LNGS Surface

EXPACSによって地上の中性子fluxを設定しそれをGeant4で照射地上の条件
グランサッソ→北緯：42.5　東経：13.6　高度：1.0㎞



球面から等方的に中性子を照射



上から来る中性子のみを考えるので下面からの中性子は発生しないものとする