Muography Status Report

National Central University

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Introduction to *NCUμ*

National Central University Muography Research

Motivation

- **Monitoring Volcanic Activity**

  Muography can image subsurface magma chambers in active systems like the Tatun Volcano Group, aiding eruption risk assessments.

- **Landslide and Subsurface Stability Studies**

  Frequent typhoons and rainfall make Taiwan prone to landslides. Muography helps detect subsurface voids and assess slope stability.

- **Gold Mine Exploration**

  Taiwan’s historic gold mines, such as those in Jiufen and Jinguashi, could benefit from muography to map ore deposits and investigate the internal structure of mining sites, improving resource extraction and safety.

Daxi Test Site

Daxi, Taoyuan, Taiwan

Purpose: Preliminary Muography Experiment Site

- Extensively studied by Earth science collaborators
- Identification of key issues and challenges
- Equipped with second-generation prototype detector

Activity: Preliminary Muon Tomography

- Imaging techniques development
- Identify Technical Challenges

NCU Test Site

Chien-Shiung Building, National Central University, Taoyuan, Taiwan

Purpose: On-campus R&D Site

- Facilitates quick testing and prototyping
- Addresses challenges identified at Daxi
- Refines designs based on field data insights

Activity: R&D, Stress Test, Benchmark and Calibration

- Zenith angle dependency of muon flux measurement
- Timing performance stress test and benchmark
- Detector efficiency measurement

Detector Construction

Detector Overview

Detector Pixel

- Plastic Scintillator

  (49.5 mm x 49.5 mm x 12.0 mm)

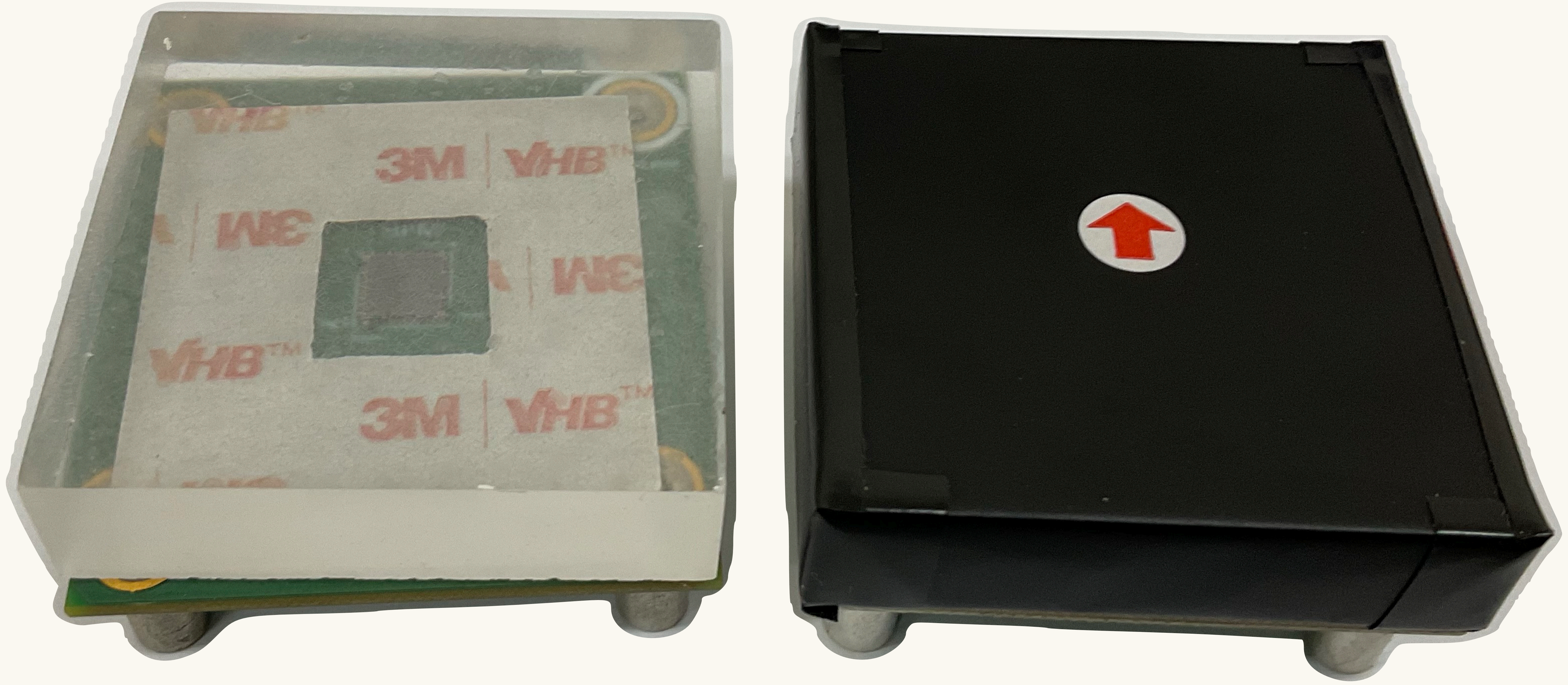
- SiPM

  onsemi MICROFC-60035-SMT-TR

  (6 mm x 6 mm)

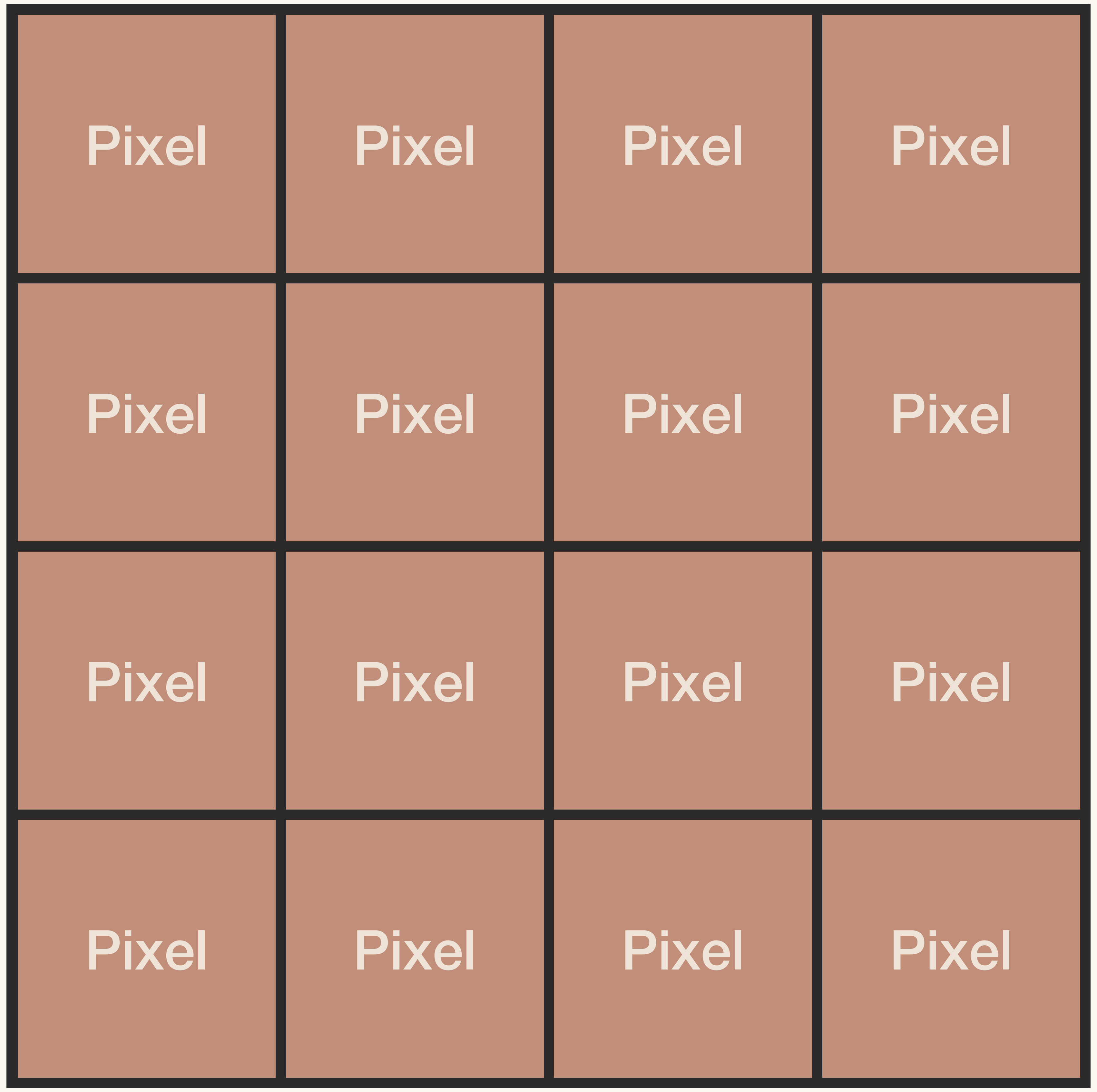
- Pixel Efficiency

  98.2% ± 0.7%



Muon Tracker Board

- 4x4 Pixel Array
- FPGA
  - Data Processing
  - Inter-board Communication
- Packing Density
  - 97.0% ± 1.0%



Second Generation Prototype Detector

- 4 Layers of 2x2 MTBs
- Layer Seperation

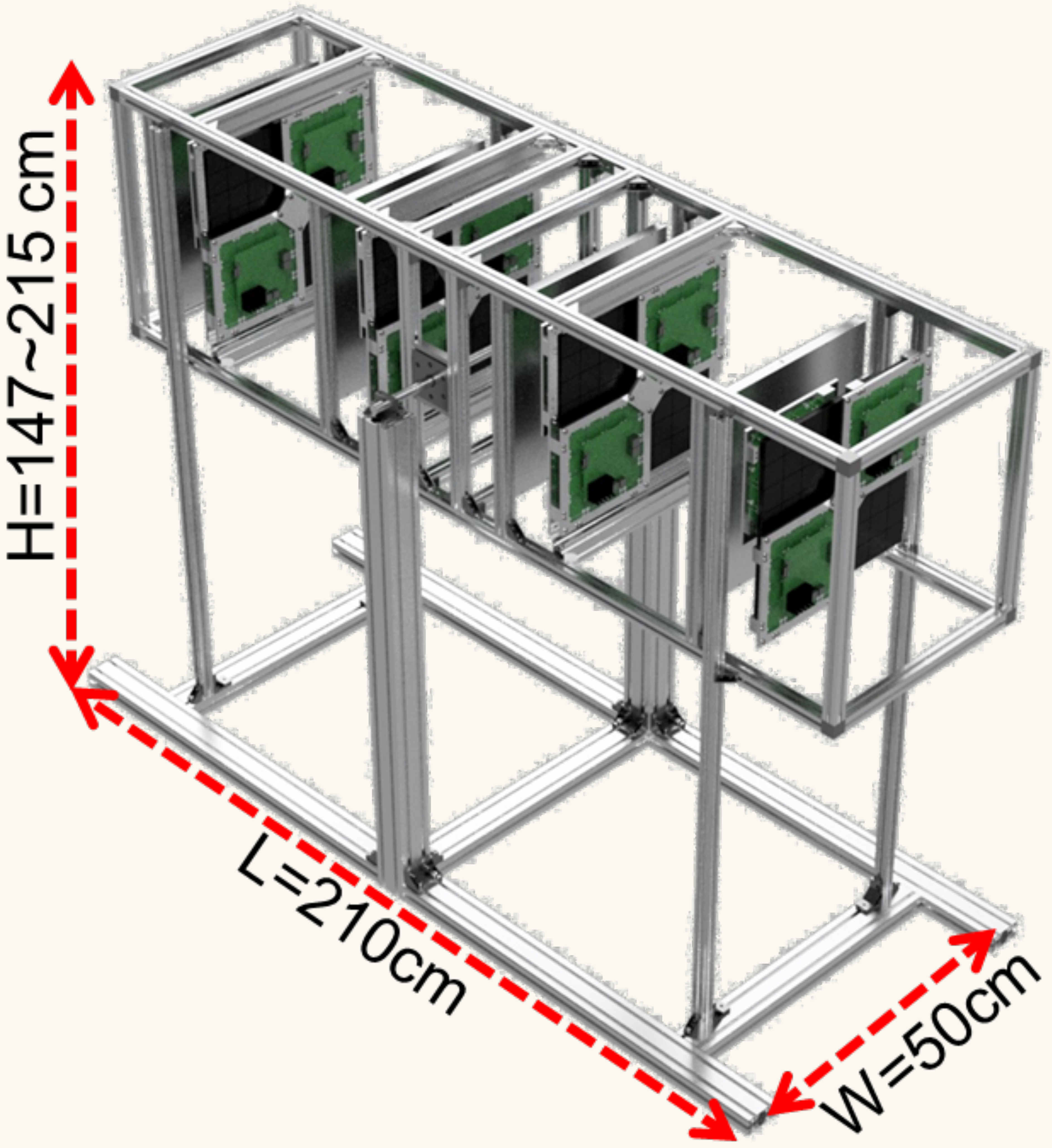
  0.5 m

- Opening Angle

  $\approx 30^{\circ}$

- Geometric Factor

  $\approx 0.011\ \mathrm{m^2\,sr}$



Latest R&D Detector

- 2 Inner Layers of 2x2 MTBs
- 2 Outer Layers of 3x3 MTBs
- Layer Seperation

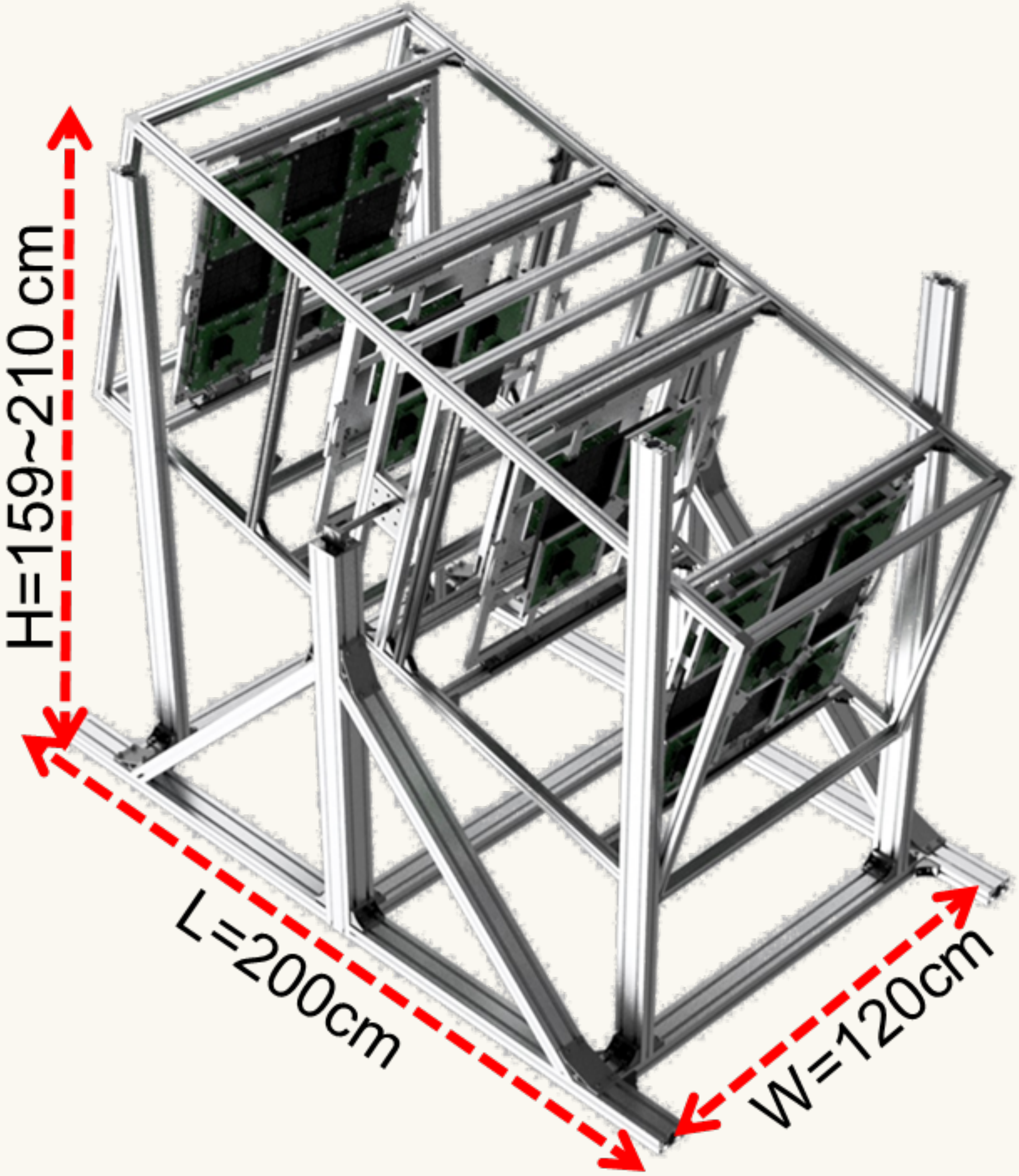
  $0.5\,\mathrm{m}$

- Opening Angle

  $\approx 42^\circ$

- Geometric Factor

  $\approx 0.037\,\mathrm{m}^2\,\mathrm{sr}$

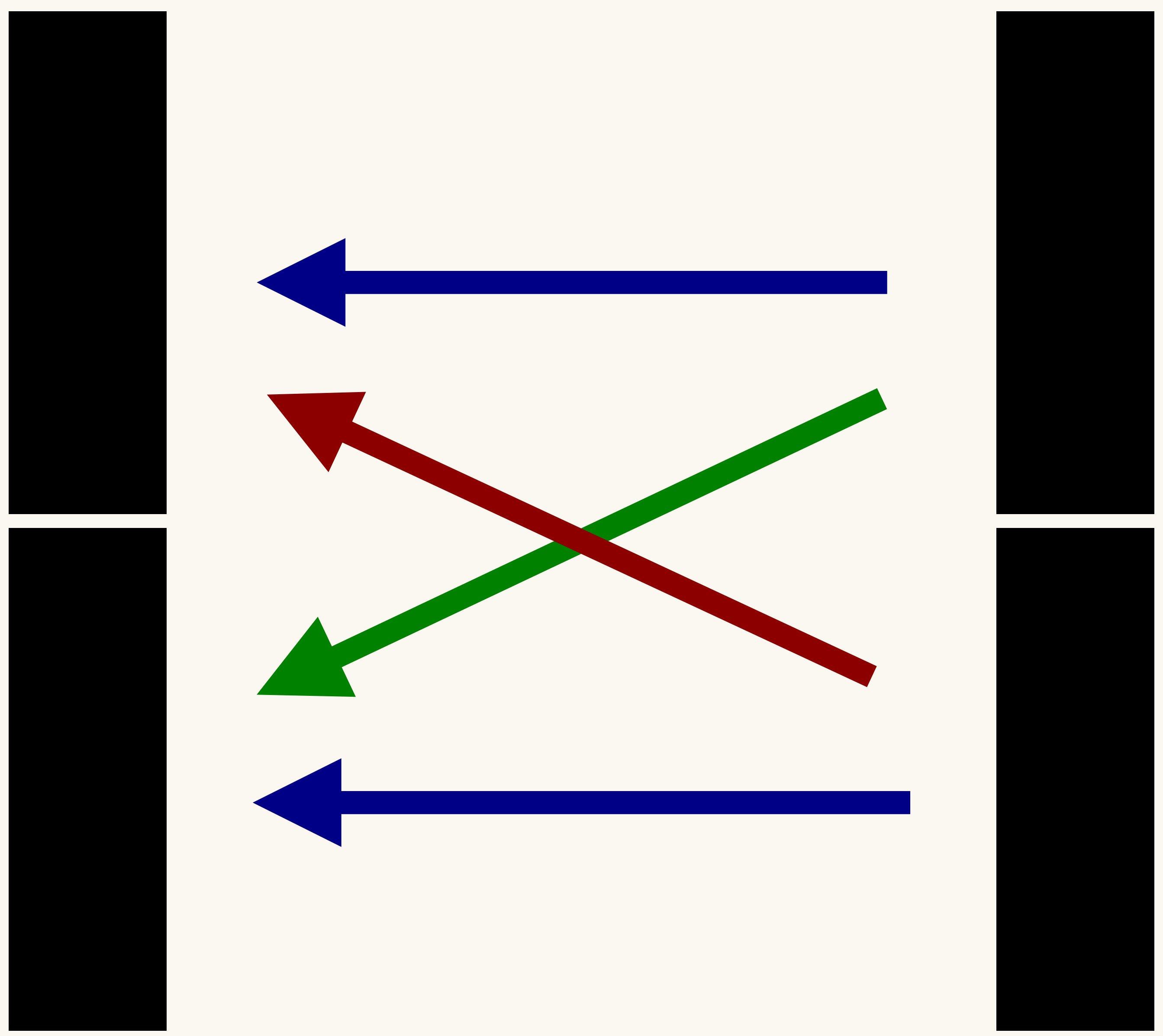


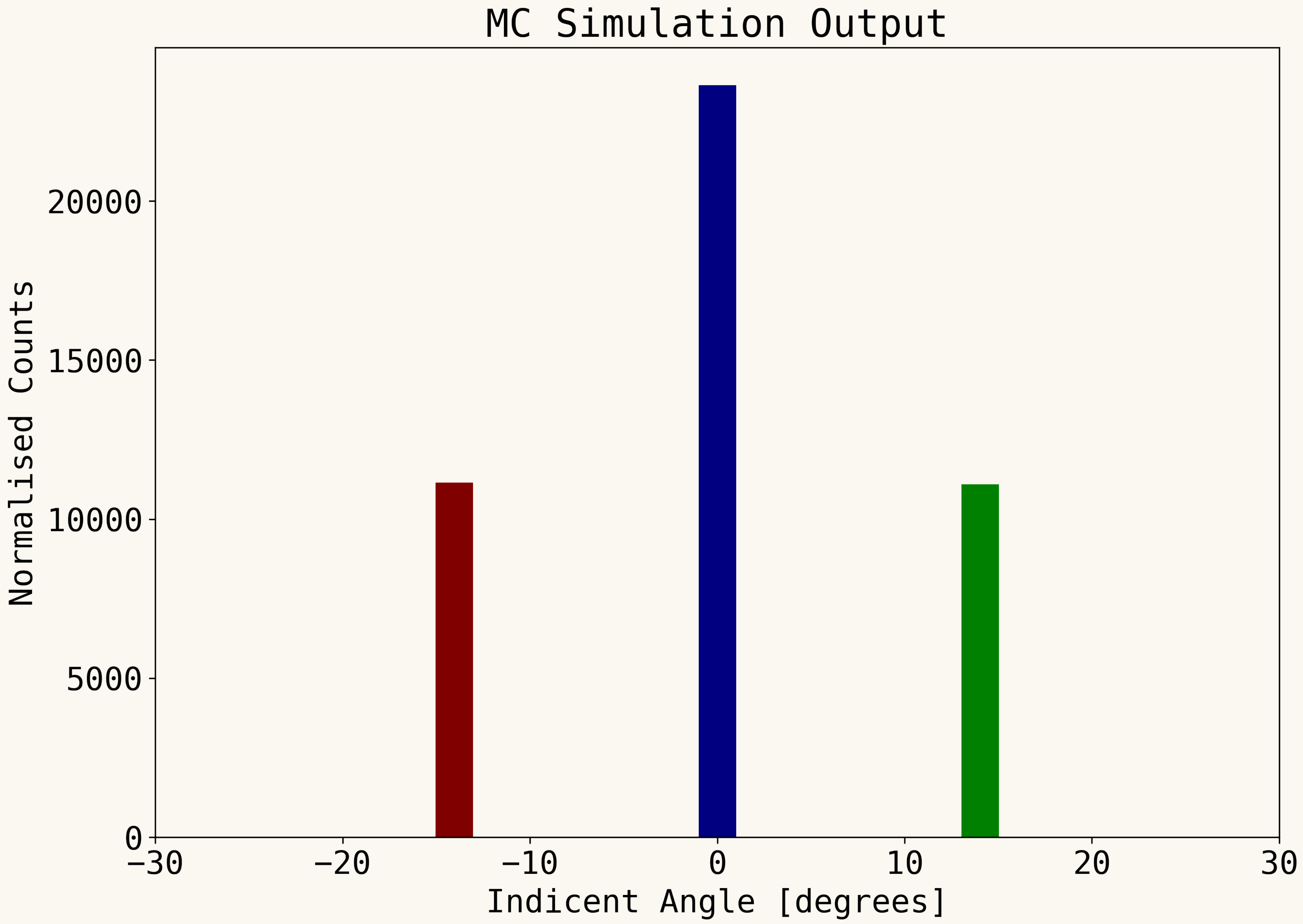
Flux Reconstruction Techniques Progress

Advancements in Flux Reconstruction Techniques

Detection Concepts in a Nutshell

1D Example





$$Detector : \theta_{incident,\, continuous} \rightarrow \theta_{ouput,\, discrete}$$

Monte Carlo-Assisted Kernel Density Estimation

1D Example

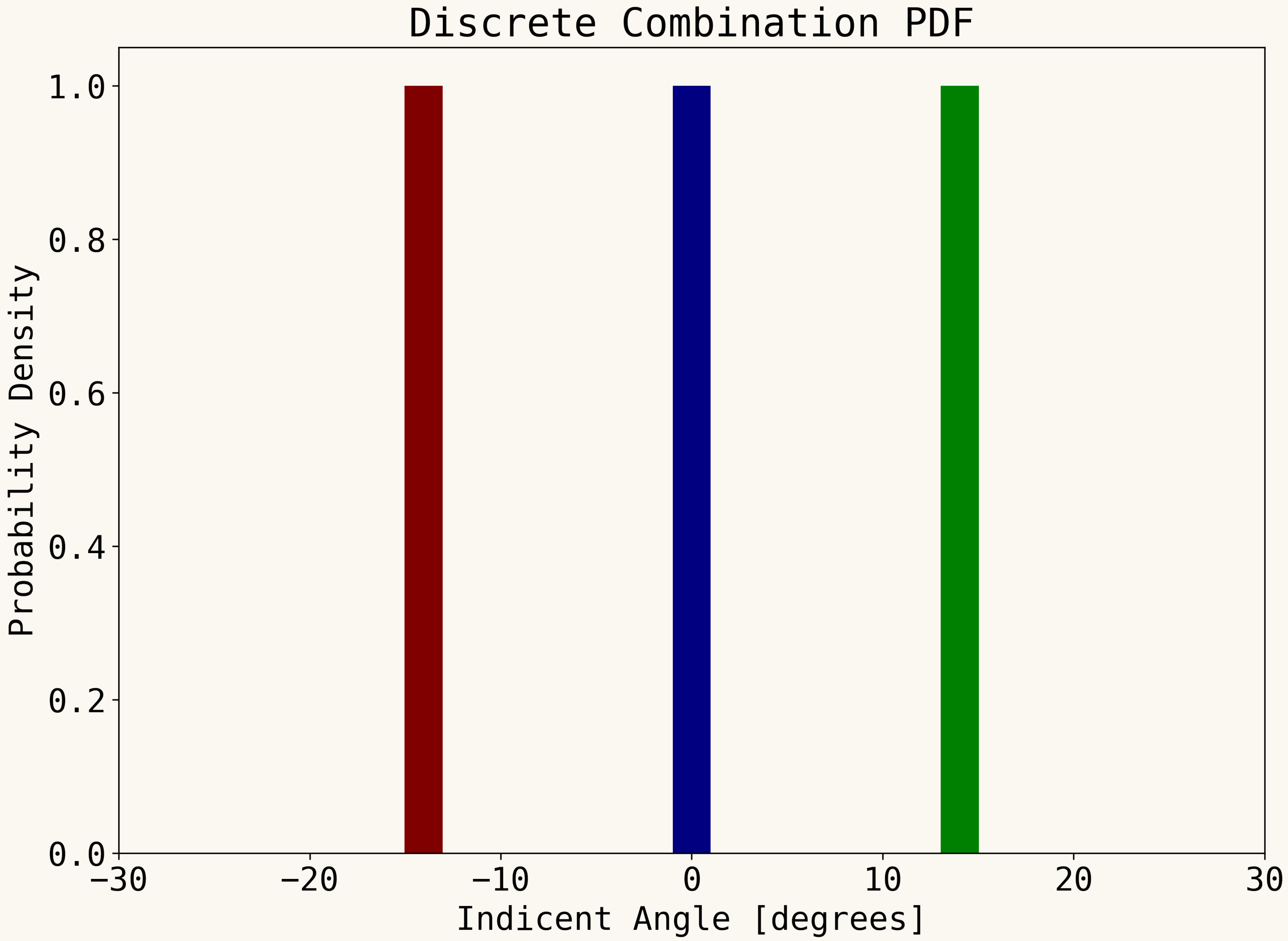
$$Detector : \theta_{incident,\, continuous} \rightarrow \theta_{ouput,\, discrete}$$

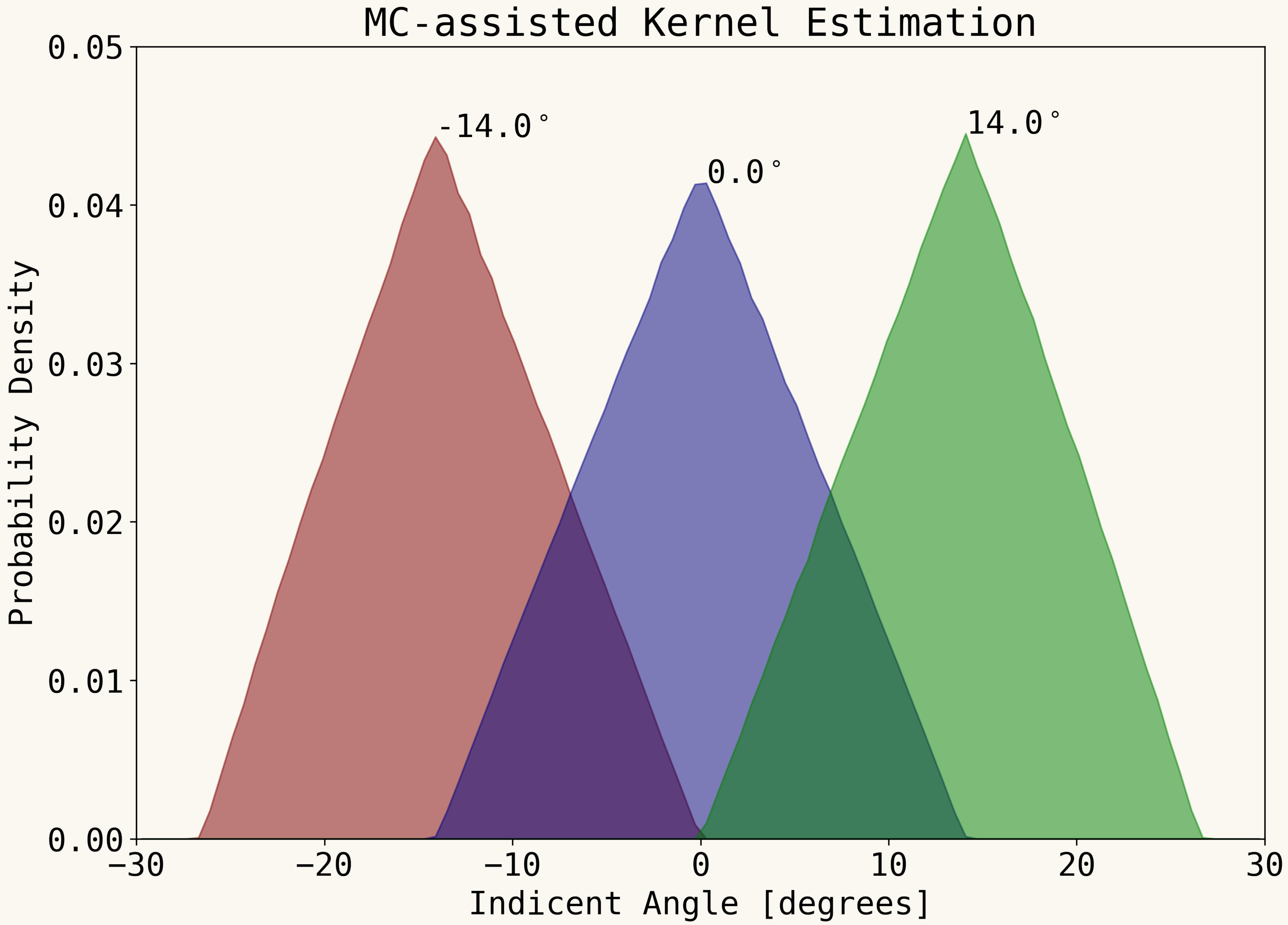
$$MC : \theta_{incident,\, continuous} \rightarrow \theta_{ouput,\, discrete}$$

$$MC^{-1} : \theta_{ouput,\, discrete} \rightarrow \theta_{incident,\, continuous}$$

Monte Carlo-Assisted Kernel Density Estimation

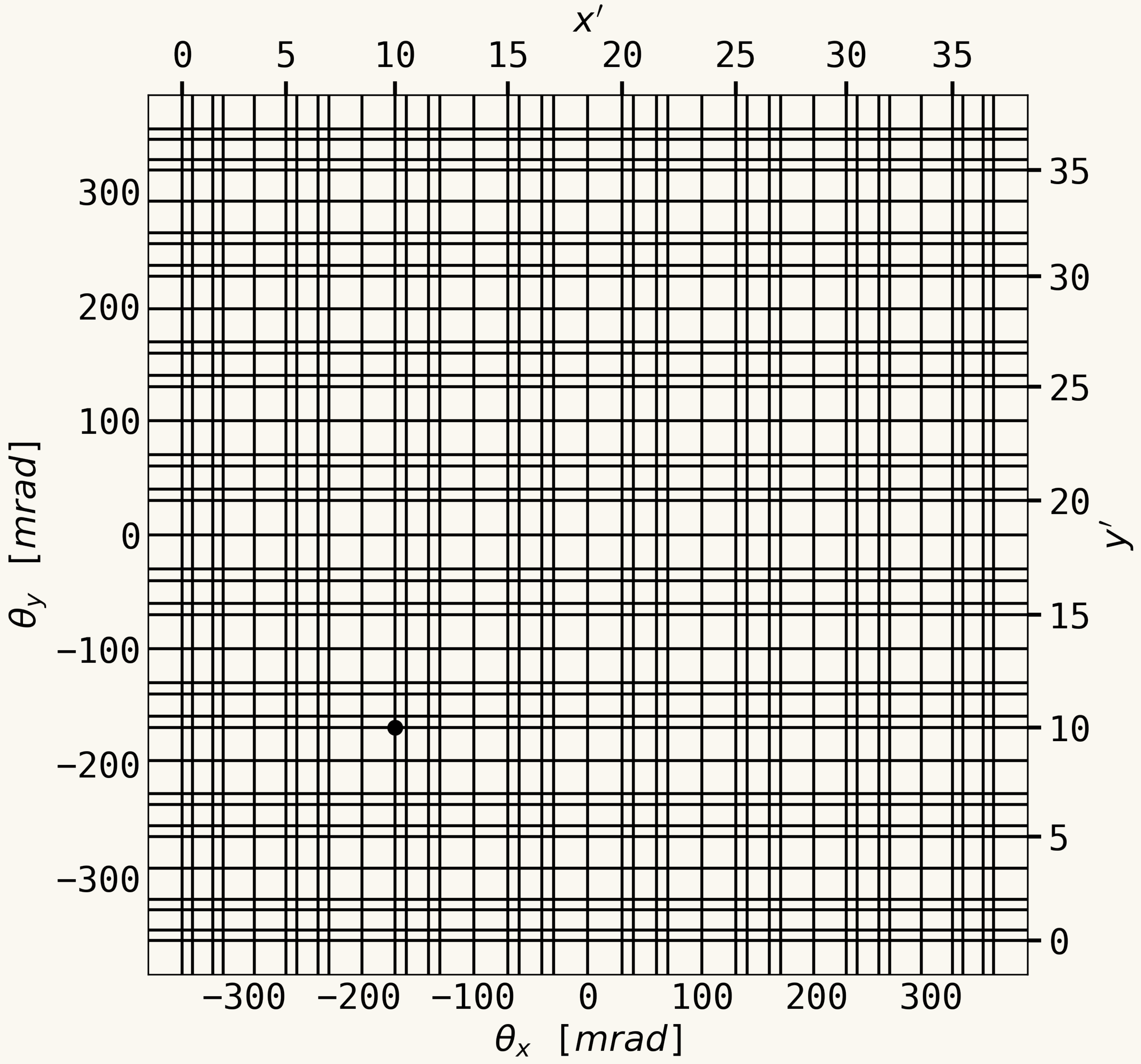
1D Example

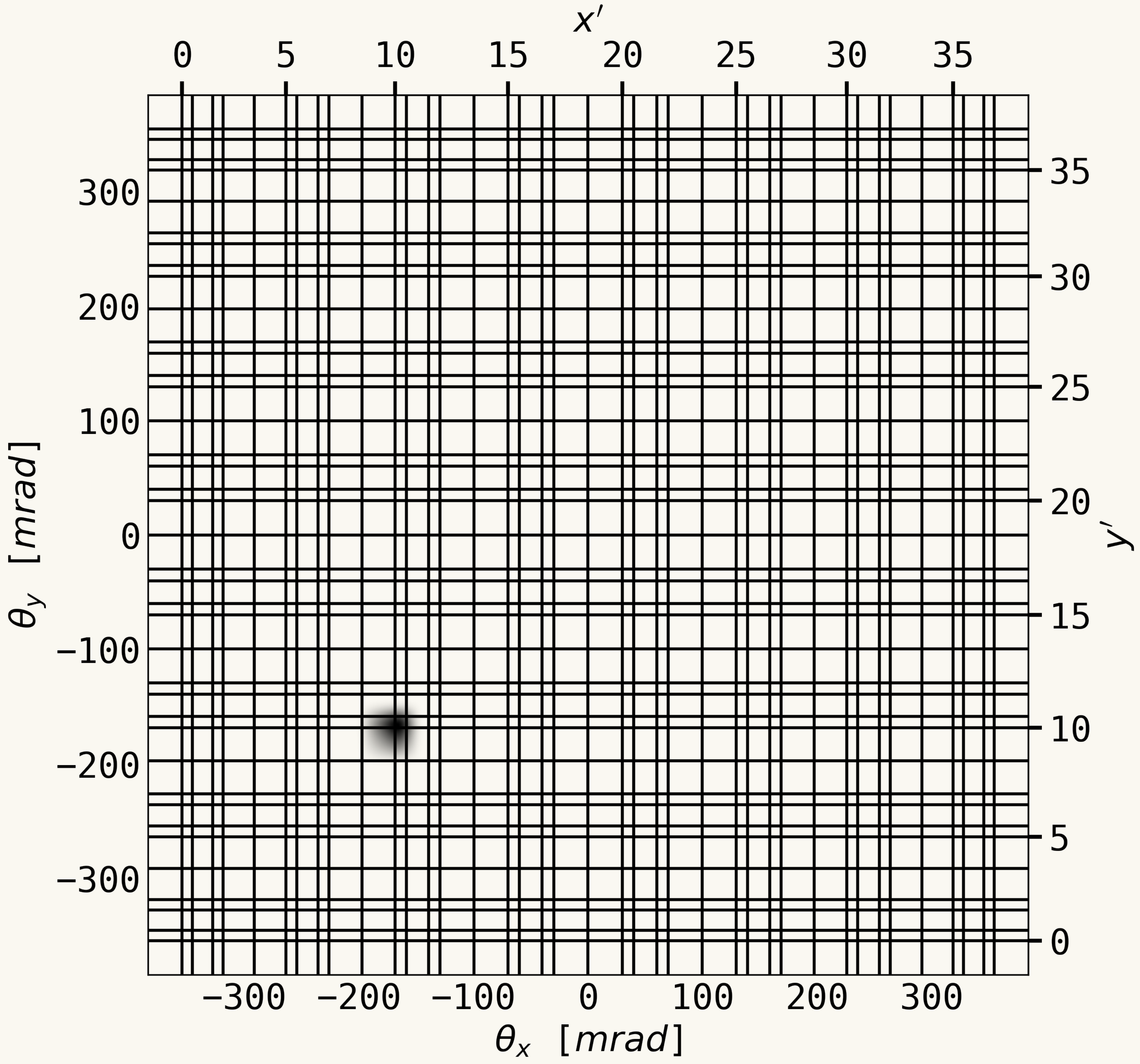




Monte Carlo-Assisted Kernel Density Estimation

2D Reconstructed Example of the Latest Detector





*R&D Detector

Muon Flux Calculation

2D Reconstructed Example of the Latest Detector

Φ : Muon Flux

$\langle N \rangle$: Reconstructed Counts

A : Effective Area of the Detector

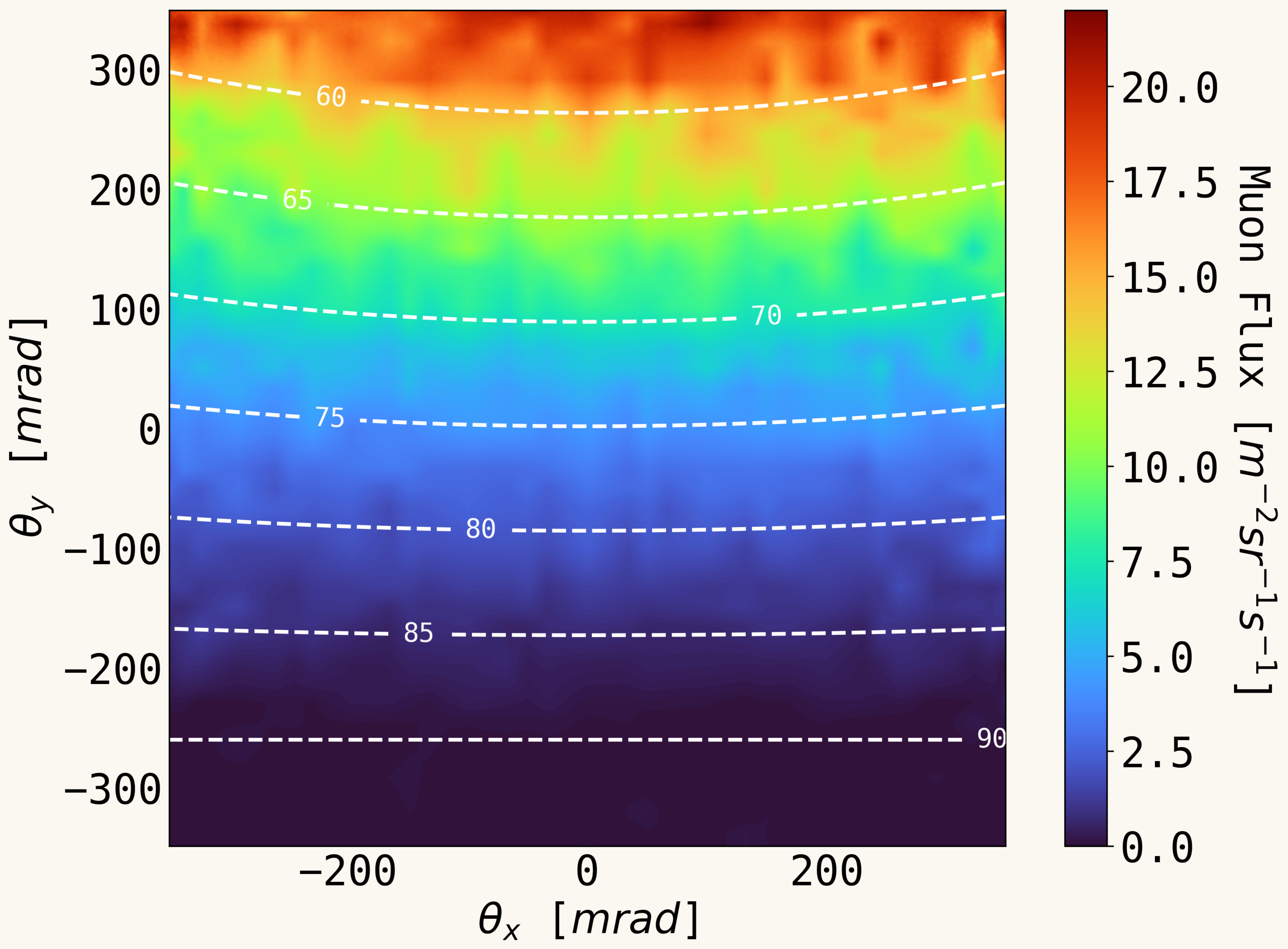
Ω : Solid Angle of Respective Bin

$$\Phi(\theta_x, \theta_y) = \frac{\langle N \rangle}{A(\theta_x, \theta_y)\Omega(\theta_x, \theta_y)T}$$

Reconstructed Data

NCU Zenith Angle Experiment

- Detector orientated at 75.1° zenith angle
- Data acquisition period of one week
- TOF Activated



*R&D Detector

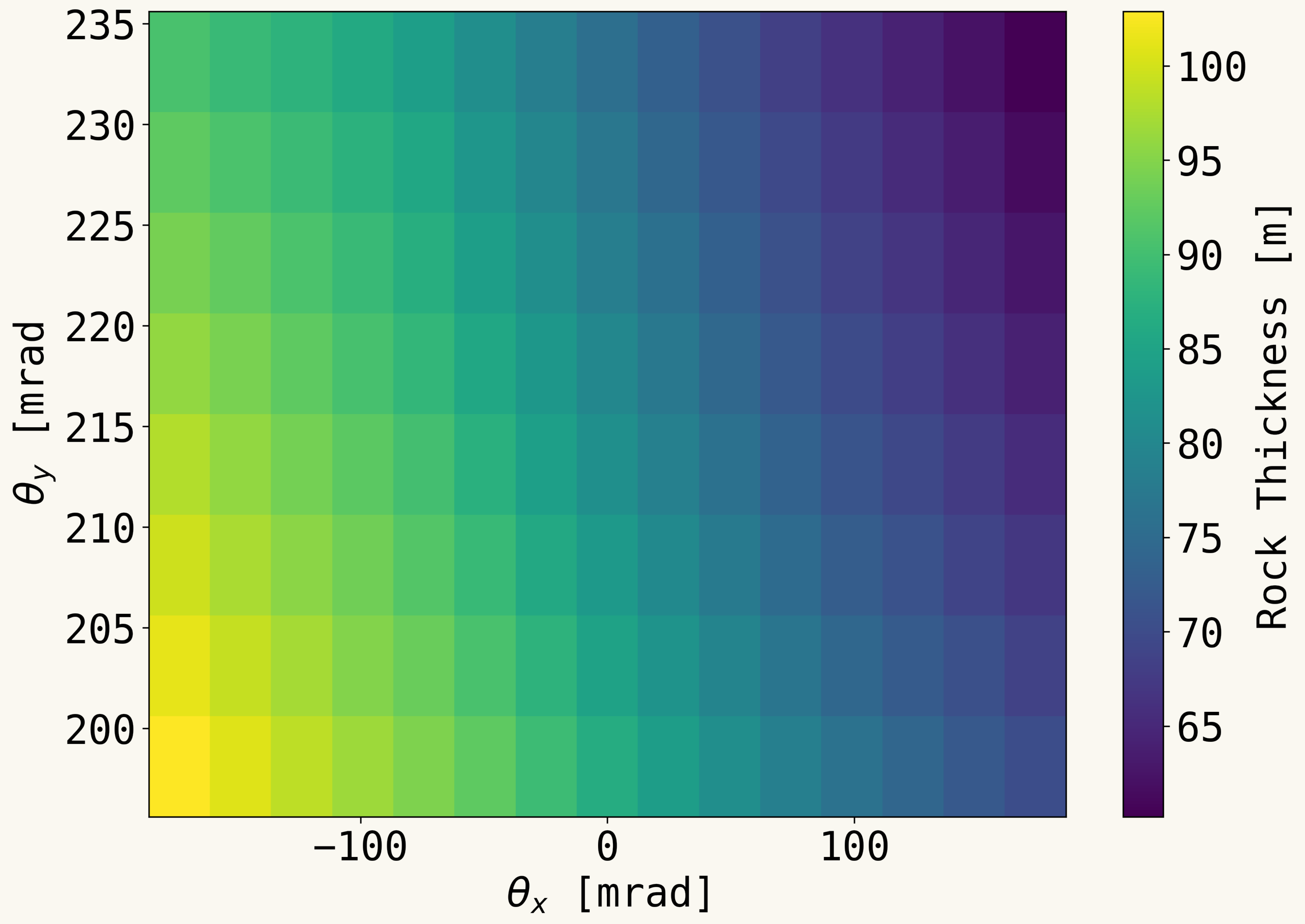
Preliminary Muon Tomography Progress

Measuring Density Length and Deducing Density

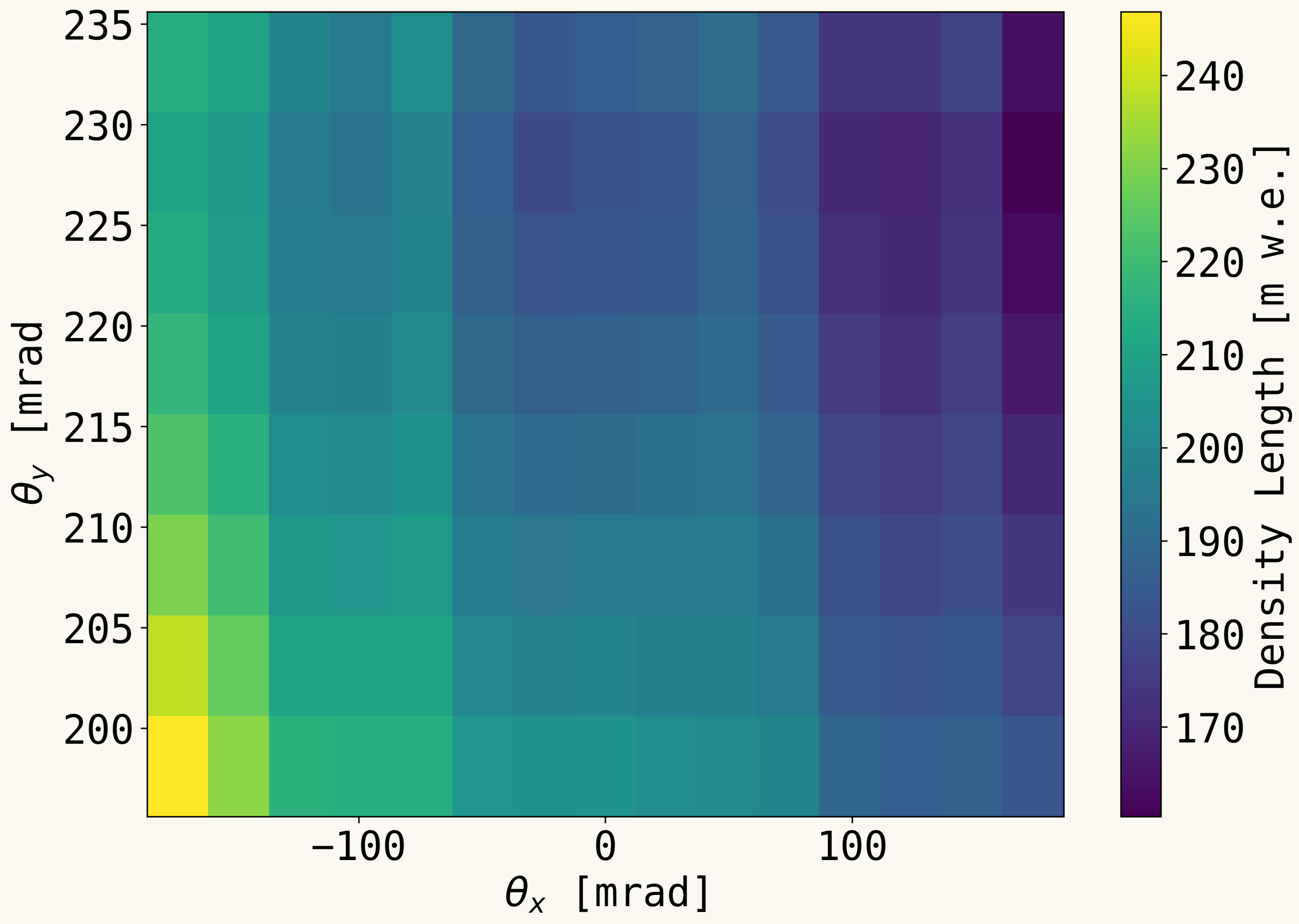
Preliminary Muon Tomography at Daxi

Measuring Density Length

Geography (Rock Length)



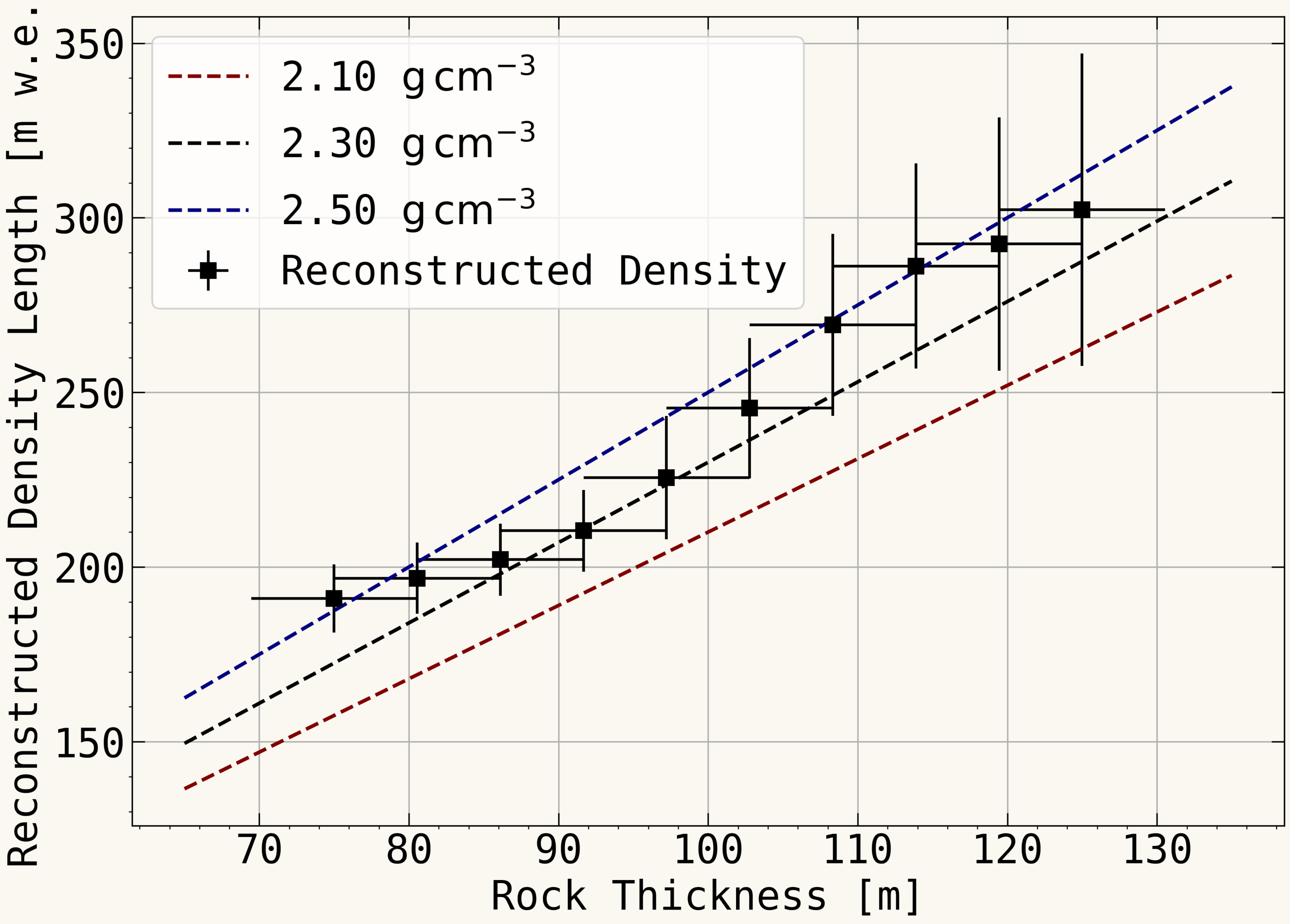
Muography (Density Length)



*Prototype Detector

Measuring Density

- Previous geological studies reported a density of around $2.3\ g\ cm^{-3}$ at the detection site.
- Our preliminary results indicate a similar density.



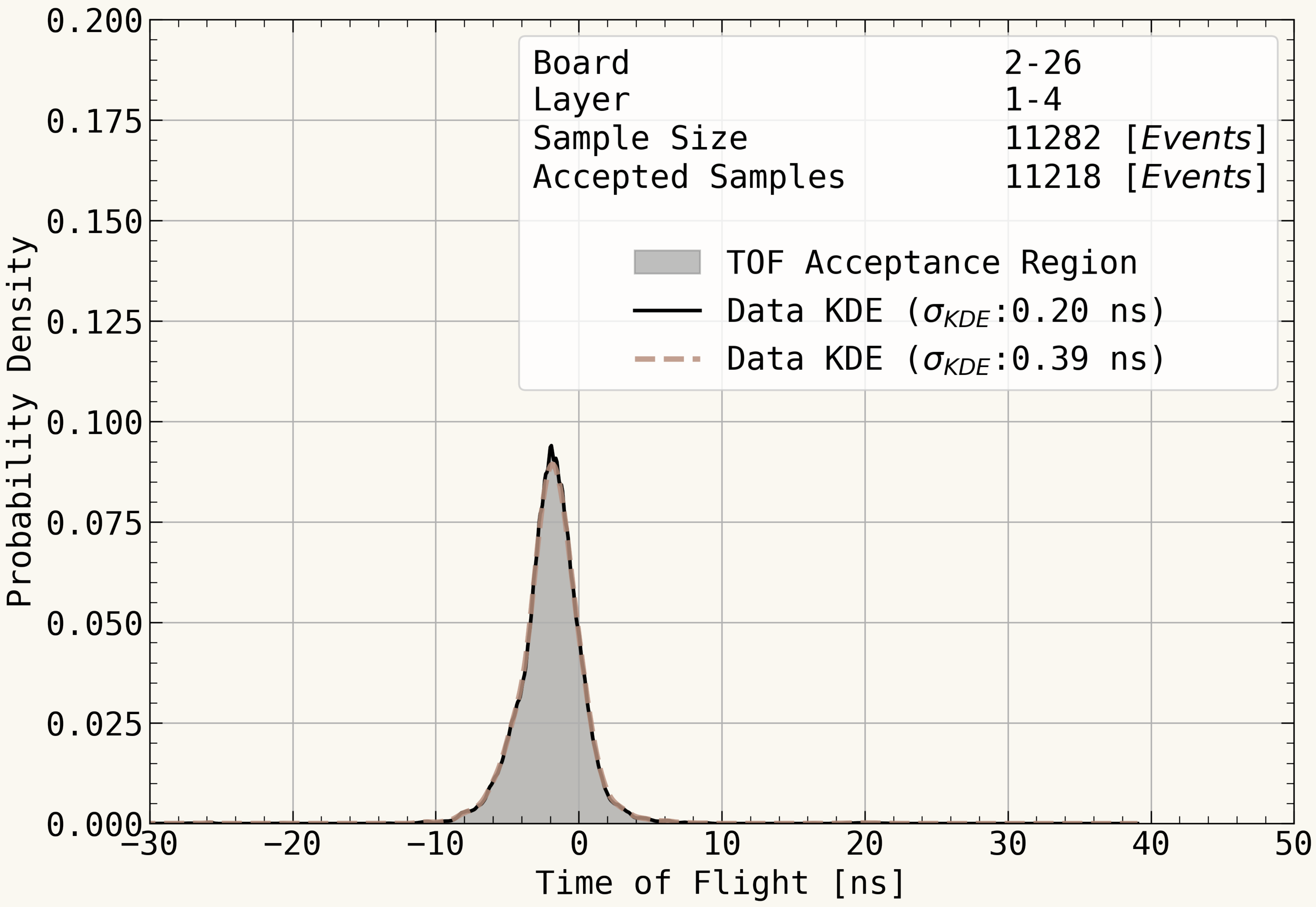
*Prototype Detector

Research and Development Progress

Enhanced Time-of-Flight Optimazation

Latest TOF Performance

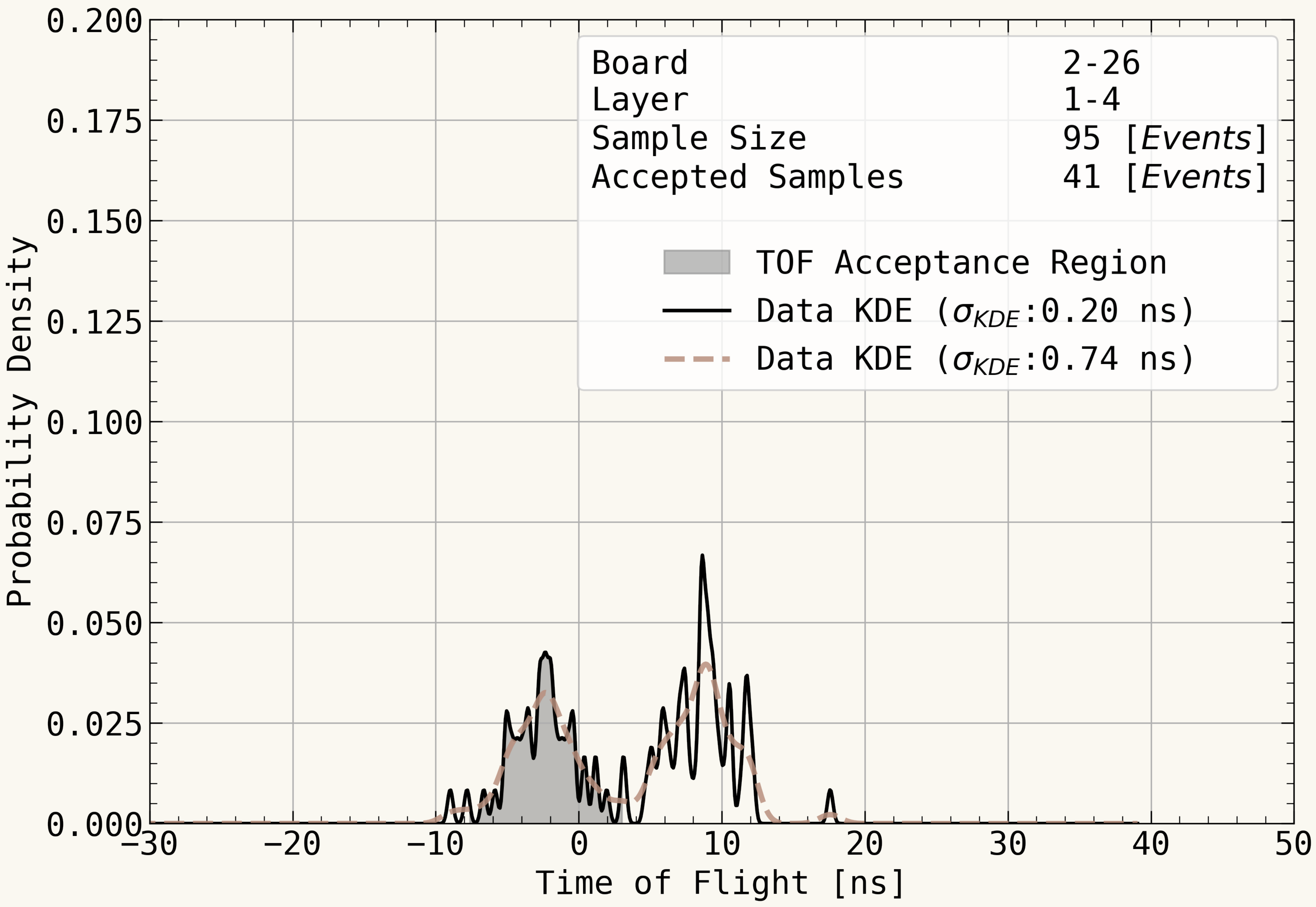
- A clean single-peak signal with contributions from opposite-direction particles negligible by several orders of magnitude.



*R&D Detector

Latest TOF Performance

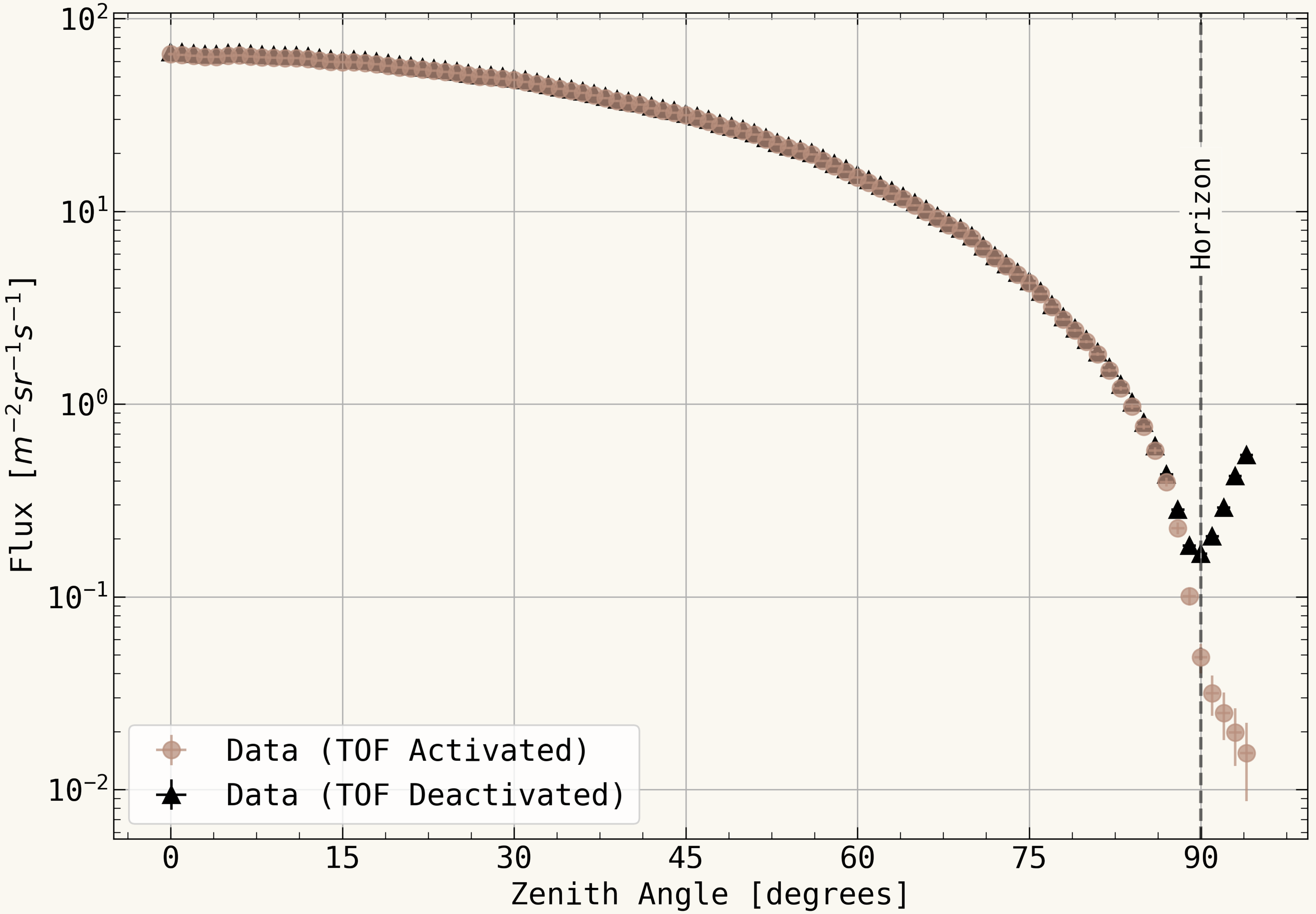
- Adequate separation between the distributions of particles from opposite directions.
- Additional improvements, as a further icing on the cake, are scheduled.



*R&D Detector

Latest TOF Performance

- A significant difference is observed in the measured flux at large zenith angles when the TOF system is activated.
- A low false negative rate, approximately $2.5\% \pm 0.4\ \%$



*R&D Detector

Research and Development Progress

Muon Flux Zenith Dependency Measurement

Efficiencies

Source	Efficiency
Pixel	98.2% ± 0.7%
TOF Algorithm	97.5% ± 0.4%
Ideal Packing Density (MC)	98.0% ± 0.5%
Overall	**88.9% ± 2.6%**

*R&D Detector

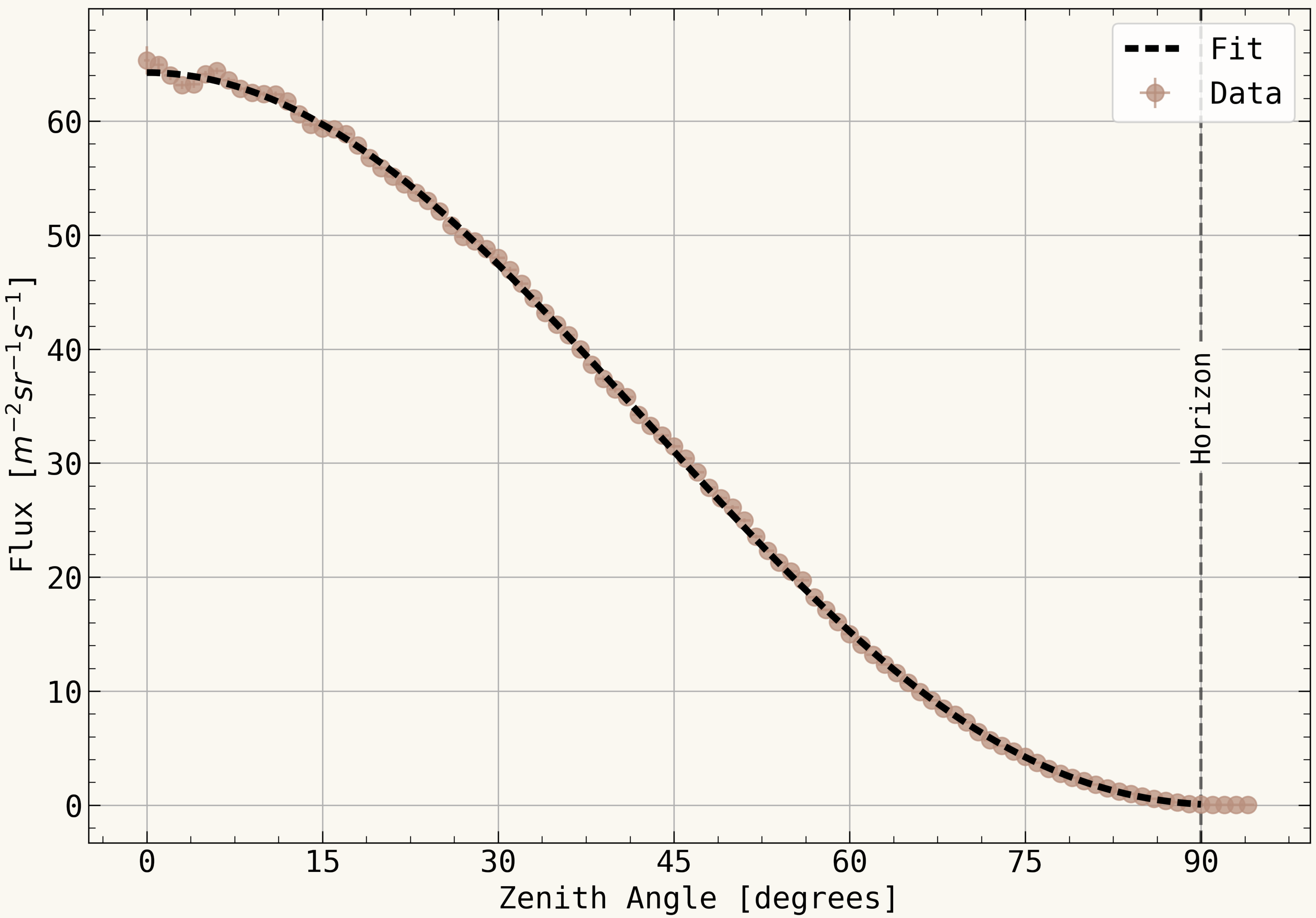
Zenith Dependency of Muon Flux

$$\Phi = \Phi_0 \left(\frac{\cos\theta + c}{1 + c} \right)^n$$

Φ_0 : Verticle Muon Flux

c : Large Angle Muon Flux Correction

n : Exponent



*R&D Detector

Zenith Dependency of Muon Flux

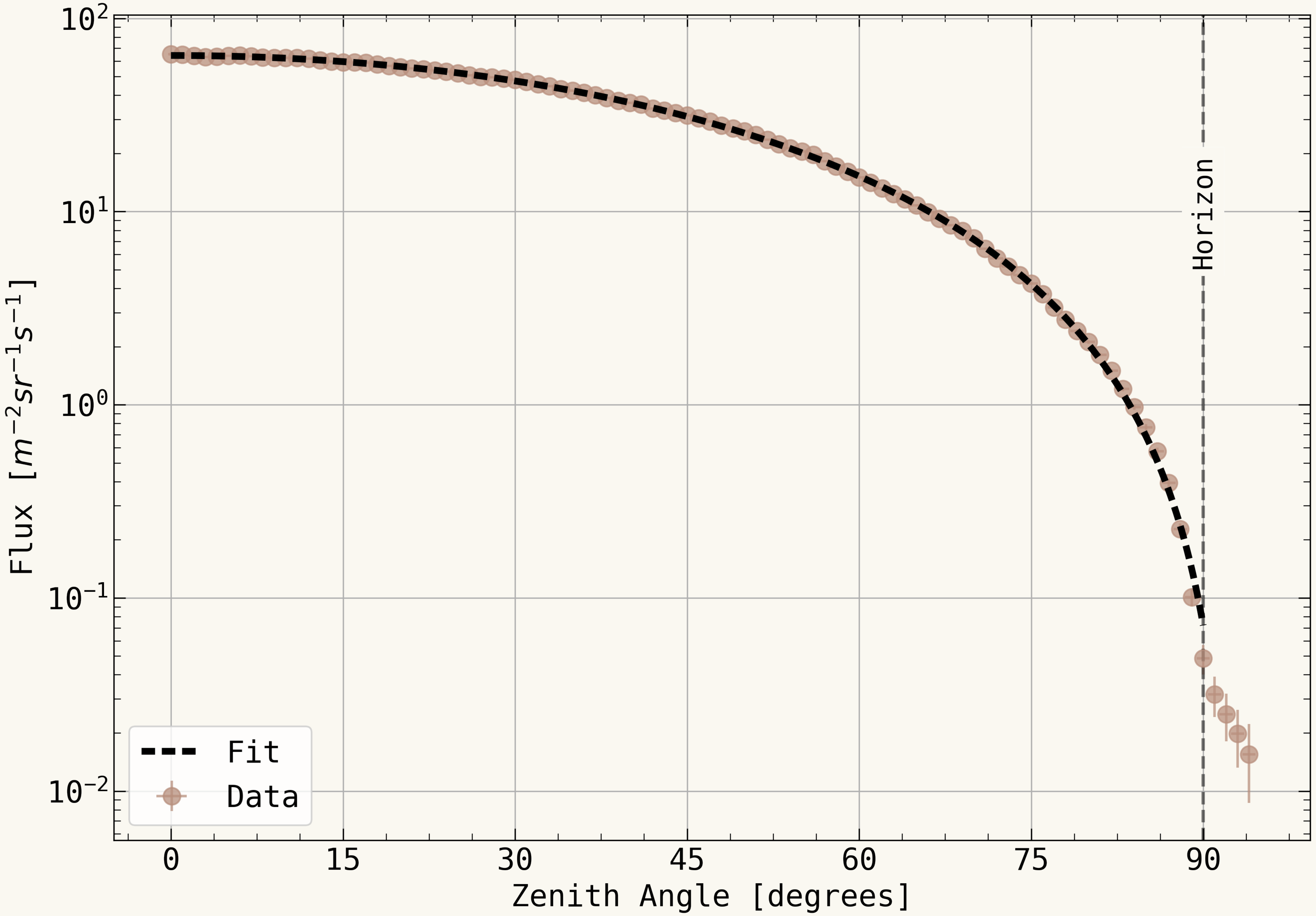
$$\Phi = \Phi_0 \left(\frac{\cos\theta + c}{1 + c} \right)^n$$

$\Phi_0 : 64.2 \pm 1.7\ \mathrm{m^{-2}\,sr^{-1}\,s^{-1}}$

$c : 0.050 \pm 0.001$

$n : 2.22 \pm 0.01$

$\chi^2_\nu : 2.978$



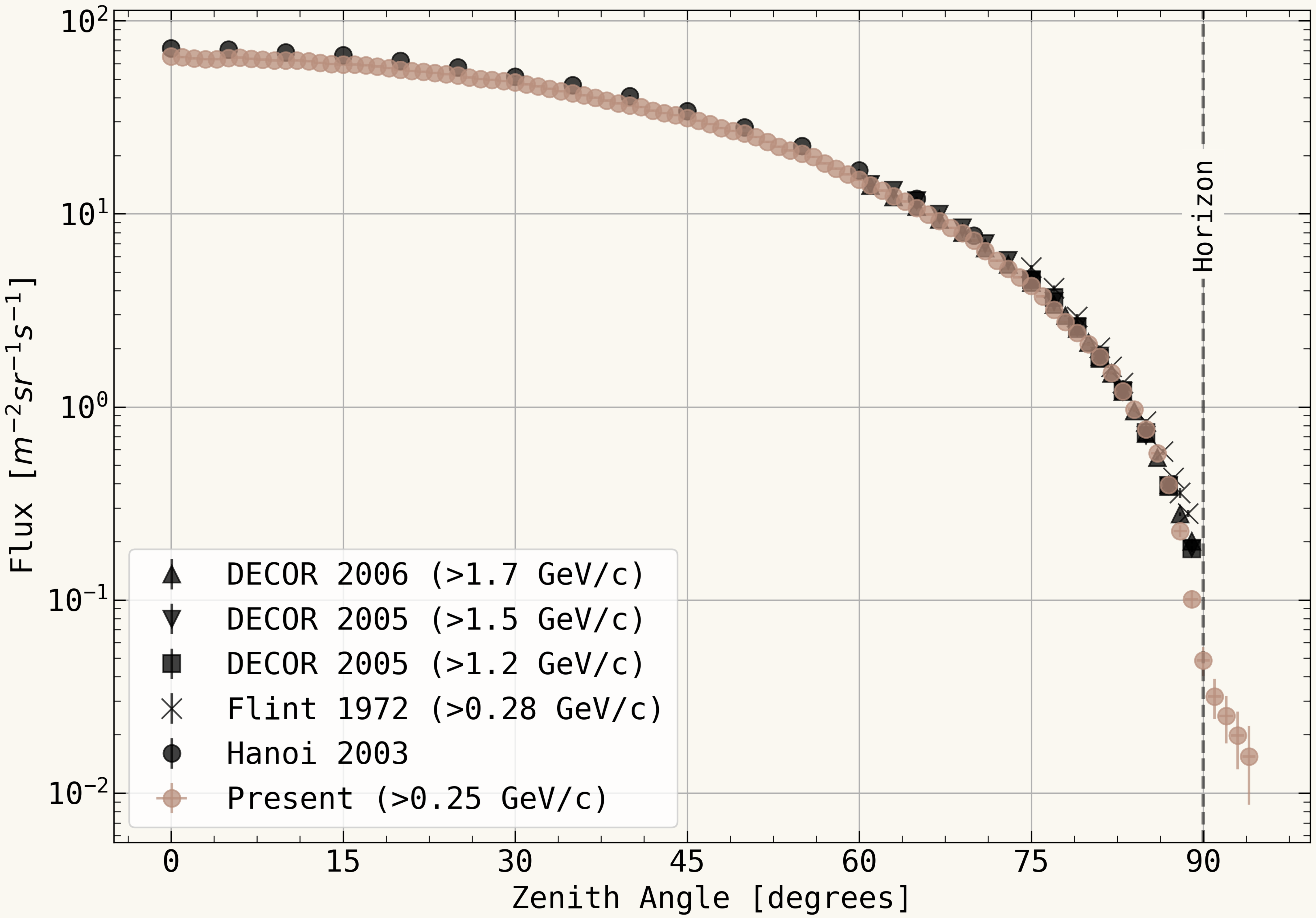
*R&D Detector

Zenith Dependency of Muon Flux

- The observed flux is consistent with values previously reported in the literature.

- Vertical Flux

$$\Phi_0 : 64.2 \pm 1.7 \ \mathrm{m^{-2}\,sr^{-1}\,s^{-1}}$$



*R&D Detector

Zenith Dependency of Muon Flux

References	Latitude (°N)	Altitude (m)	Momentum Cutoff (GeV/c)	Flux ($m^{-2}sr^{-1}s^{-1}$)
Hayman et al.	58	S.L.	≥0.32	76 ± 0.6
Greisen	54	259	≥0.30	82 ± 1
Crookes and Rastin	53	40	≥0.35	91.3 ± 0.2
Barbouti and Rastin	52	40	≥0.44	88.7 ± 1.2
Fukui et al.	**24**	**S.L.**	**≥0.34**	***73.5 ± 2***
Gokhale	**19**	**124**	**≥0.27**	***75.5 ± 1***
Pal et al.	**19**	**S.L.**	**≥0.28**	***62.2 ± 0.1***
Sorgawal et al.	**19**	**S.L.**	**≥0.26**	***66.7 ± 1.9***
Karmakar et al.	16	122	≥0.35	89.9 ± 0.5
Sinha and Basu	12	30	≥0.27	73 ± 2
Pethuraj et al.	10	160	≥0.11	70.1 ± 5.3
Allkofer et al.	9	S.L.	≥0.32	72.5 ± 1
Present	**25**	**170**	**≥0.25**	**64.2 ± 1.7**

*R&D Detector

Summary

Data Reconstruction

- Advancements in Flux Reconstruction Techniques

Preliminary Muon Tomography

- Preliminary Measurement of Density Length and Density

Research and Development

- Enhanced Time-of-Flight Optimazation
- Muon Flux Zenith Dependency Measurement

References

Bugaev, E. V., et al. (1998). *Atmospheric muon flux at sea level, underground, and underwater*. Physical Review D, 58(5), 054001. https://doi.org/10.1103/PhysRevD.58.054001

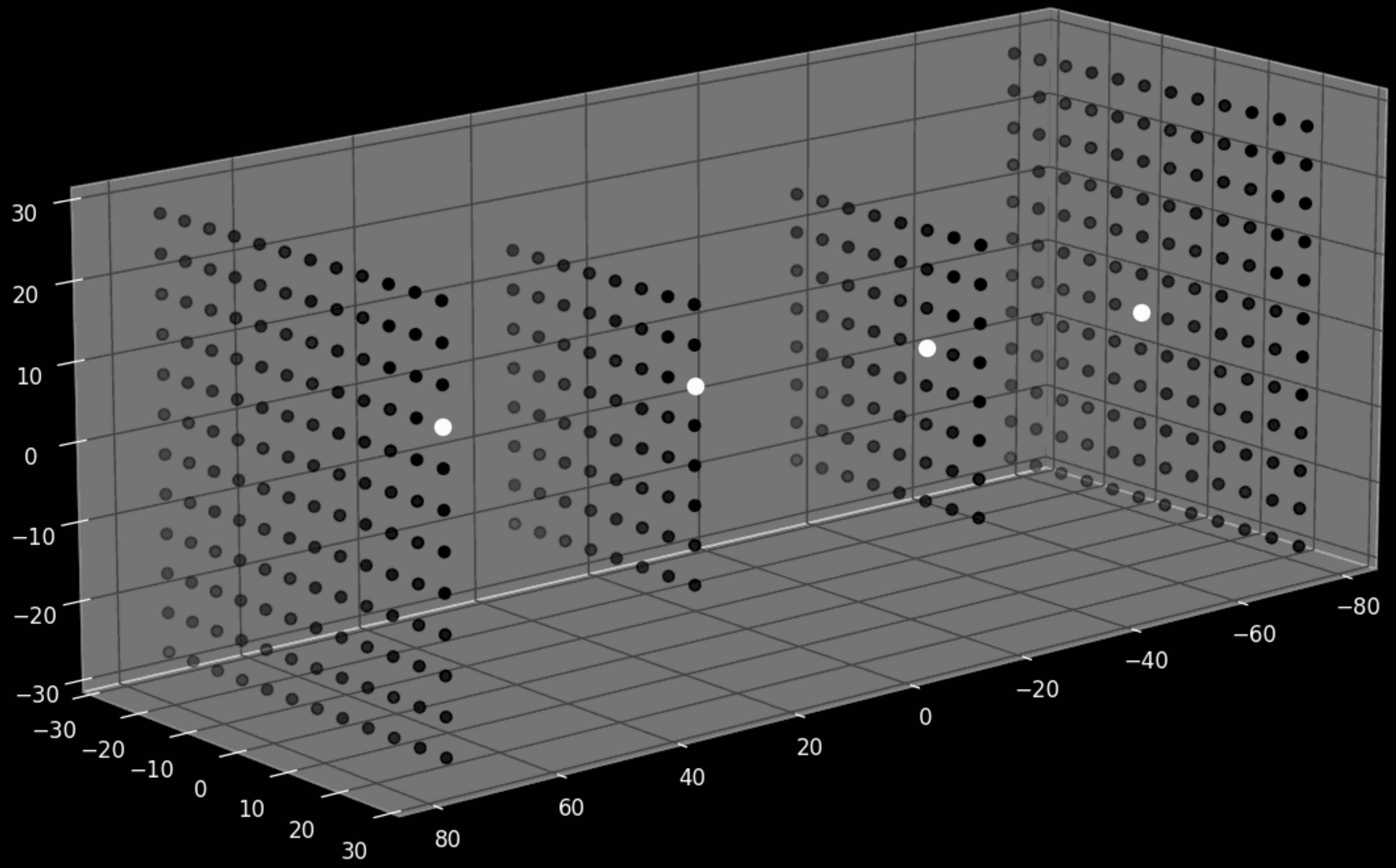
Dinh, P. N., et al. (2003). *Measurement of the zenith angle distribution of the cosmic muon flux in Hanoi*. Nuclear Physics B, 661(1–2), 3–16. https://doi.org/10.1016/s0550-3213(03)00337-7

Dmitrieva, A. N., et al. (2005). Measurements of Integrated Muon Intensity at Large Zenith Angles. *Moscow Engineering Physics Institute (State University)*. *Physics of Atomic Nuclei*, 68(5), 878–883. DOI: 10.1134/S1063778806050097.

Flint, R. W., Hicks, R. B., & Standil, S. (1972). Variation with Zenith Angle of the Integral Intensity of Muons near Sea Level. Canadian Journal of Physics, 50(8), 843–848. doi:10.1139/p72-118

Sogarwal, H., & Shukla, P. (2022). Measurement of atmospheric muon angular distribution using a portable setup of liquid scintillator bars. *Journal of Cosmology and Astroparticle Physics*, *2022*(7), 011. DOI: 10.1088/1475-7516/2022/07/011.

Back Up Slides



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−80

Selection Criteria

Single Event Criteria

Time window between first and last trigger

- 25 ns

Muon Event Criteria

Maximum hits of front facing layer

- 2

Maximum hits of other layers

- 4

Maximum total hits per event

- 8

Zenith Dependency of Muon Flux

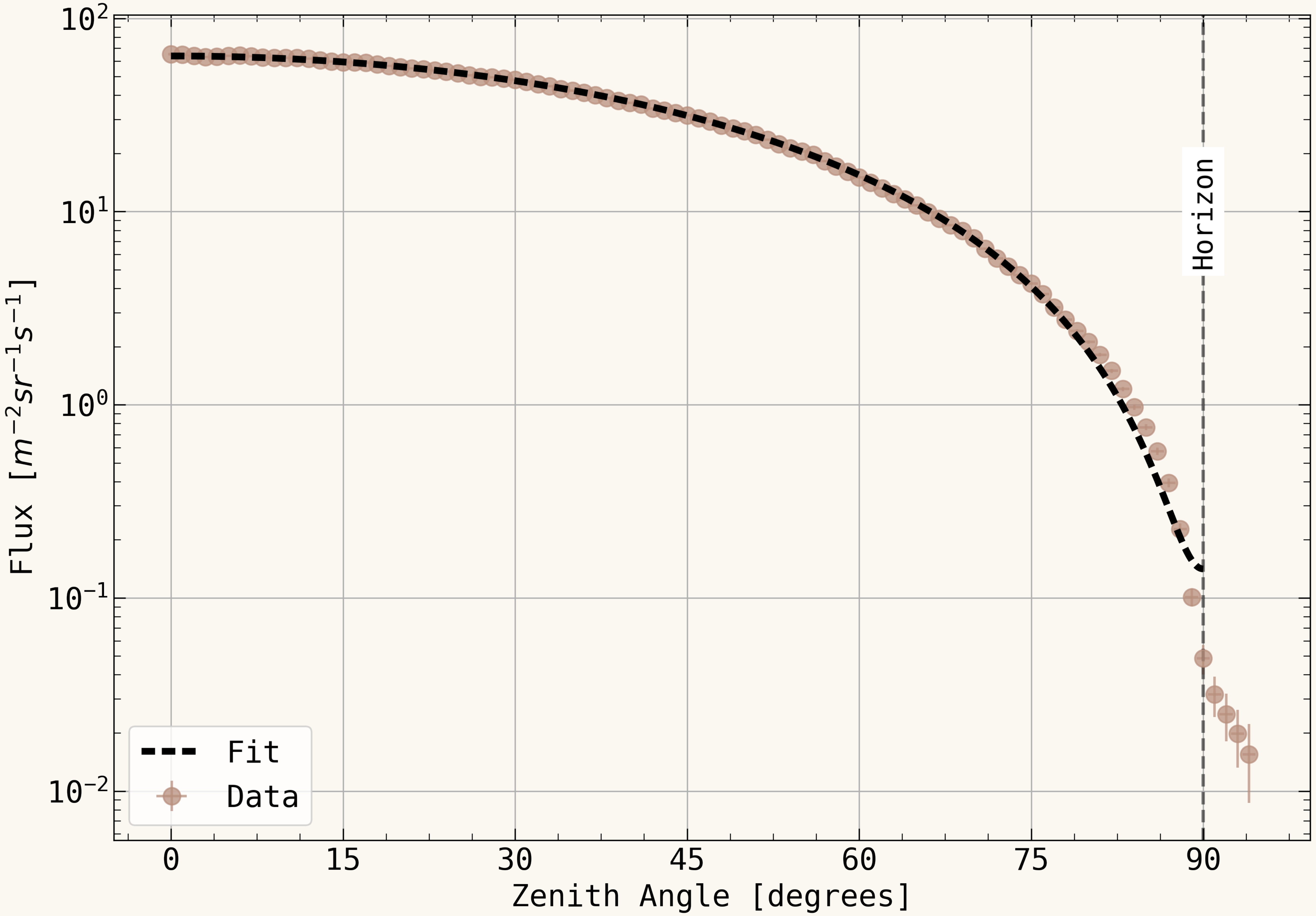
$$\Phi = \Phi_0 \left(\frac{\cos^n \theta + c^n}{1 + c^n} \right)$$

$\Phi_0 : 63.9 \pm 1.7 \ \mathrm{m}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}$

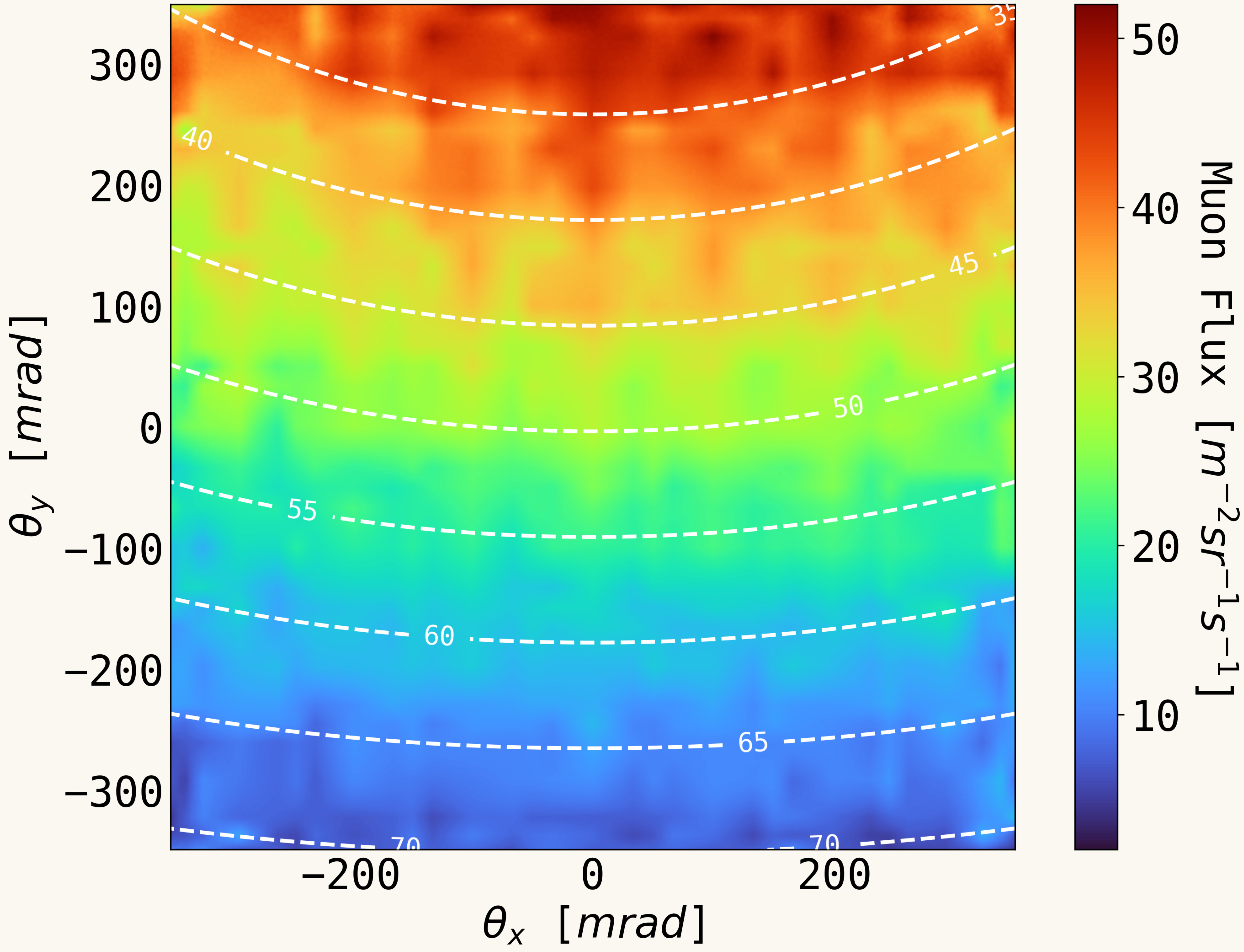
$c : 0.050 \pm 0.001$

$n : 2.06 \pm 0.002$

$\chi^2_\nu : 8.805$



*R&D Detector



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θ_y [mrad]
θ_x [mrad]
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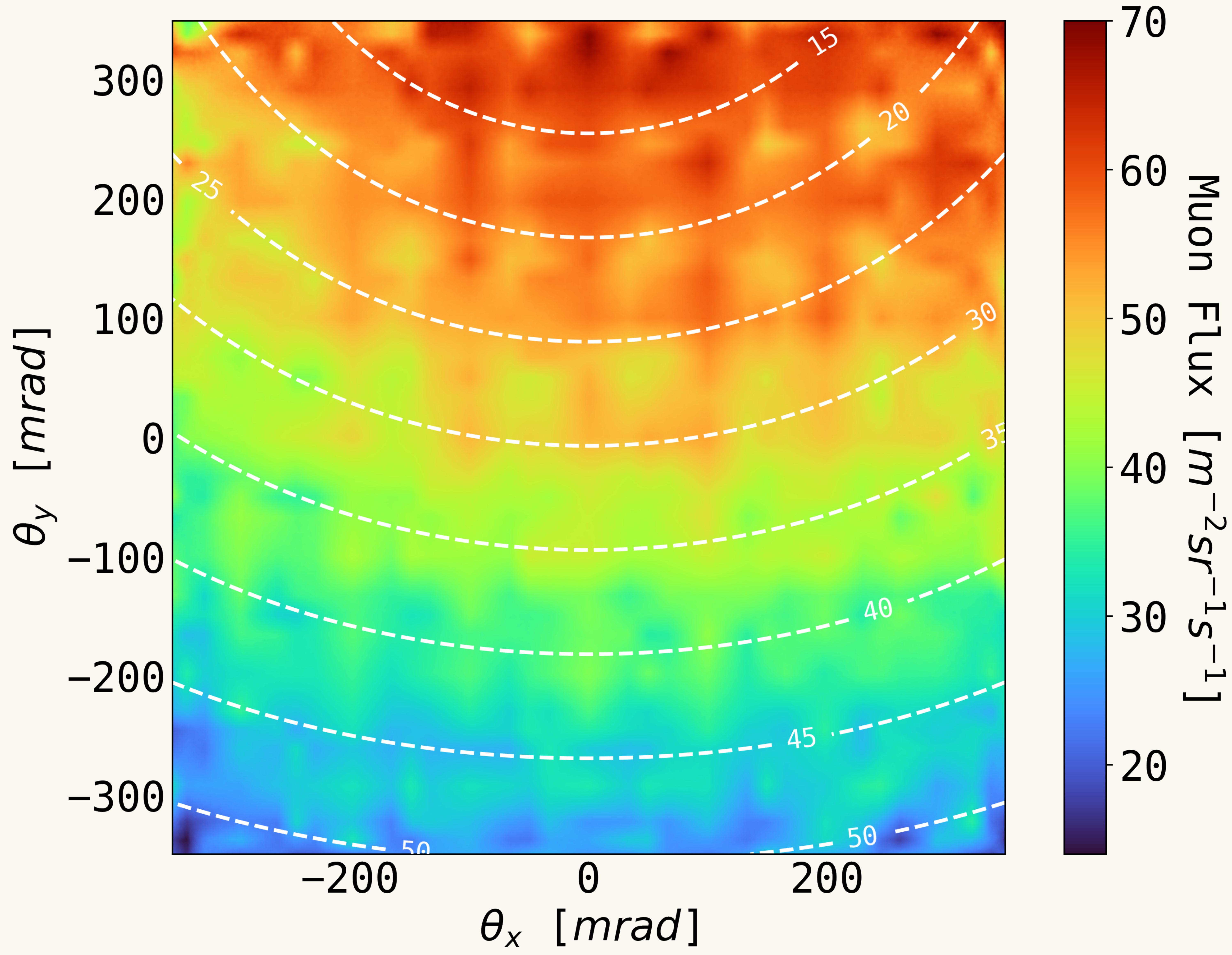
10
Muon Flux [$m^{-2}sr^{-1}s^{-1}$]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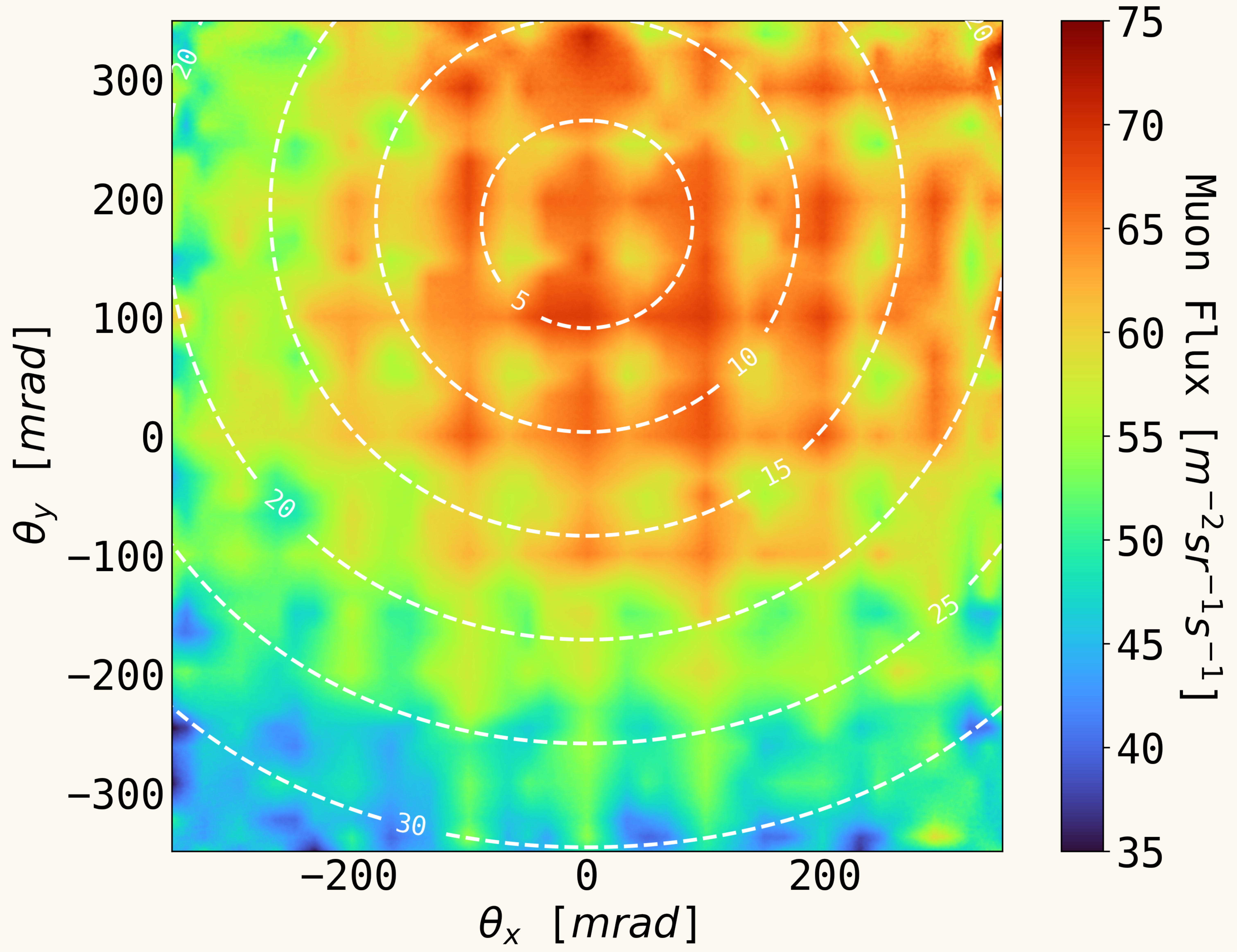
Muon Flux [$m^{-2}sr^{-1}s^{-1}$]



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θ_y [mrad]
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35
Muon Flux [$m^{-2}sr^{-1}s^{-1}$]