Predicting Ambient Neutron Flux Underground with He-3 Counters(NCDs)

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Low Background Team at SNOLAB:

Background Particle / Source	Primary Monitoring Instrument & Facility
Gamma (γ)	Shielded, Low-Background HPGe Spectroscopy
Radon (^{222}Rn)	High Efficiency Radon Trapping Emanation Systems
Alpha(α)	XIA & ICP-MS

- **What about ambient neutrons?**

My Co-op experience at SNOLAB:

❖ **My experience as a Low Background Student**:

→**Summer 2024**: Neutron detection, Health Canada Radon Monitoring, HPGe

→**Summer 2025**: Neutron detection, HPGe, Radon emanation

→**Fall 2025**: Neutron detection

→**Summer 2026**: Neutron detection

❖Spent **>80% time** on Neutron Detection Projects

Ambient Neutron Source at SNOLAB:

❖ (α, n) **Reactions:**

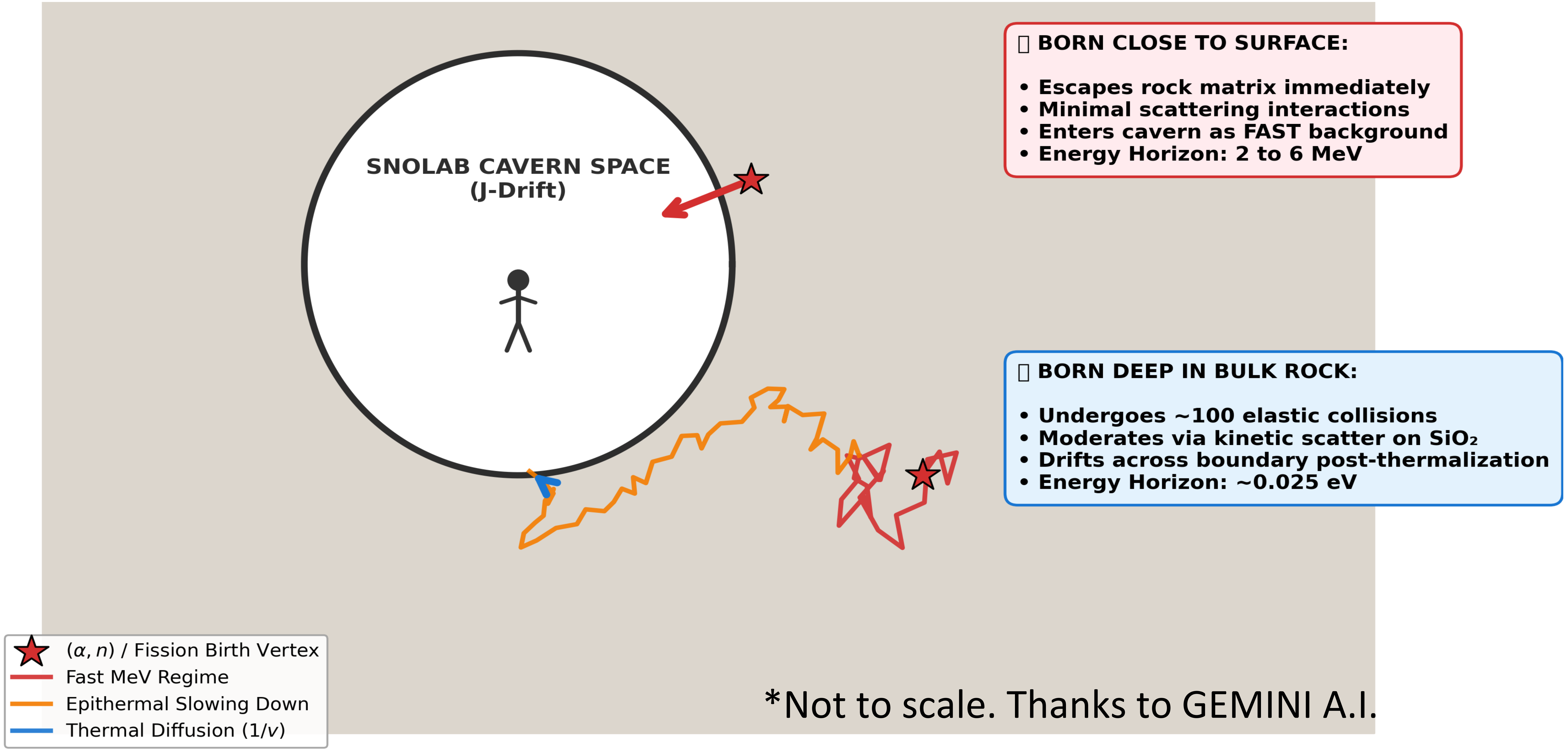
$$({}^{238}_{92}\mathrm{U} \text{ and } {}^{232}_{90}\mathrm{Th}) \text{ decay chain} \rightarrow {}^{4}_{2}\alpha$$

$${}^{4}_{2}\alpha + {}^{A}_{Z}\mathrm{X} \rightarrow {}^{A+3}_{Z+2}\mathrm{Y} + {}^{1}_{0}\mathrm{n}$$

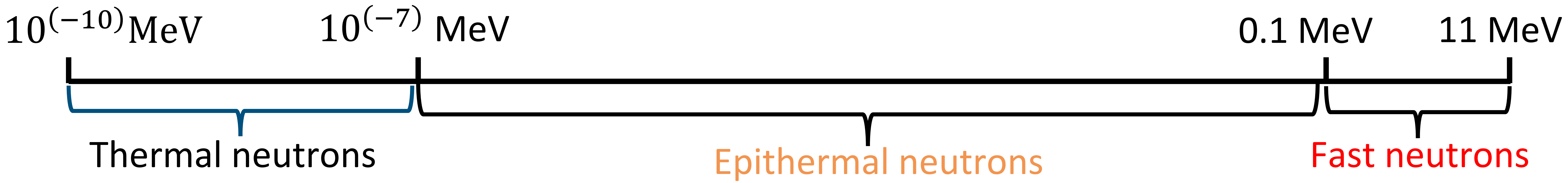
→Natural Source of Fast Neutrons(0.1 to 11 MeV)

→Reactions under Secular Equilibrium: Consistent Neutron Supply

Ambient Neutron Source at SNOLAB:

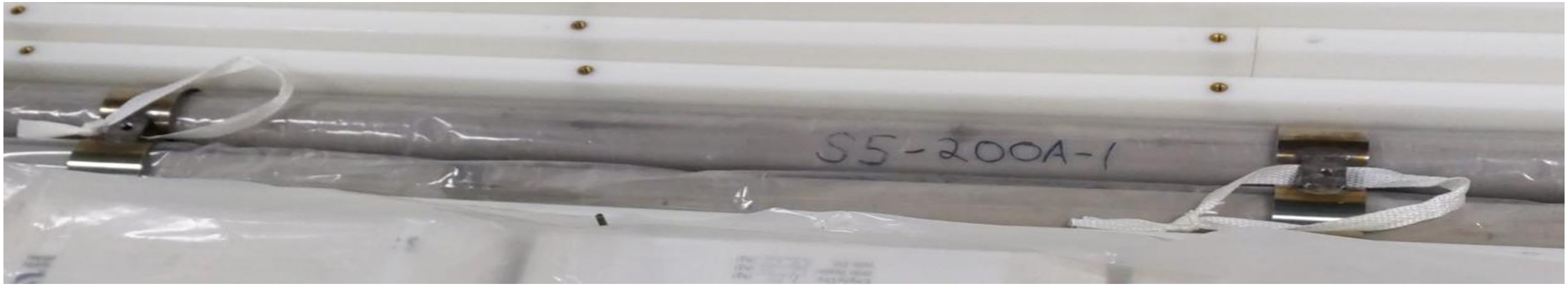


*Not to scale. Thanks to GEMINI A.I.



Neutral Current Detectors(NCDs): He-3 Counters

Geometry	Cylindrical(Thin nickel body, filled with gas)
Dimensions	205 cm long, 5.08 cm diameter
Weight	~1.0 kg
Gas mixture(by pressure)	$^{3}He(85\%): CF_4(15\%)$
Gas pressure	2.50 ± 0.01 atm
Detection principle	Proportional counters: ^{3}He neutron capture
Low Background	Robust Gas Purification, Chemical Vapour Deposition etc



Helium-3 counters: Detection principle

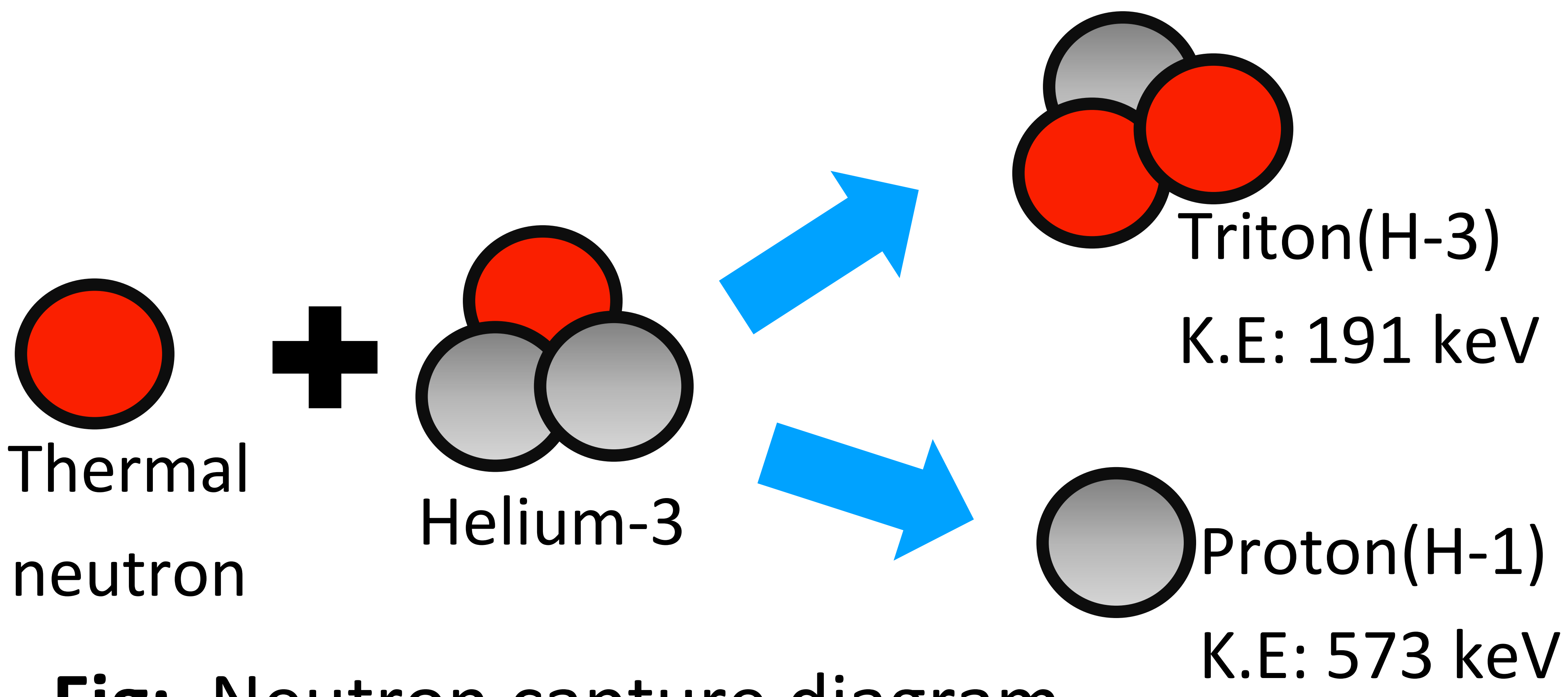


Fig: Neutron capture diagram

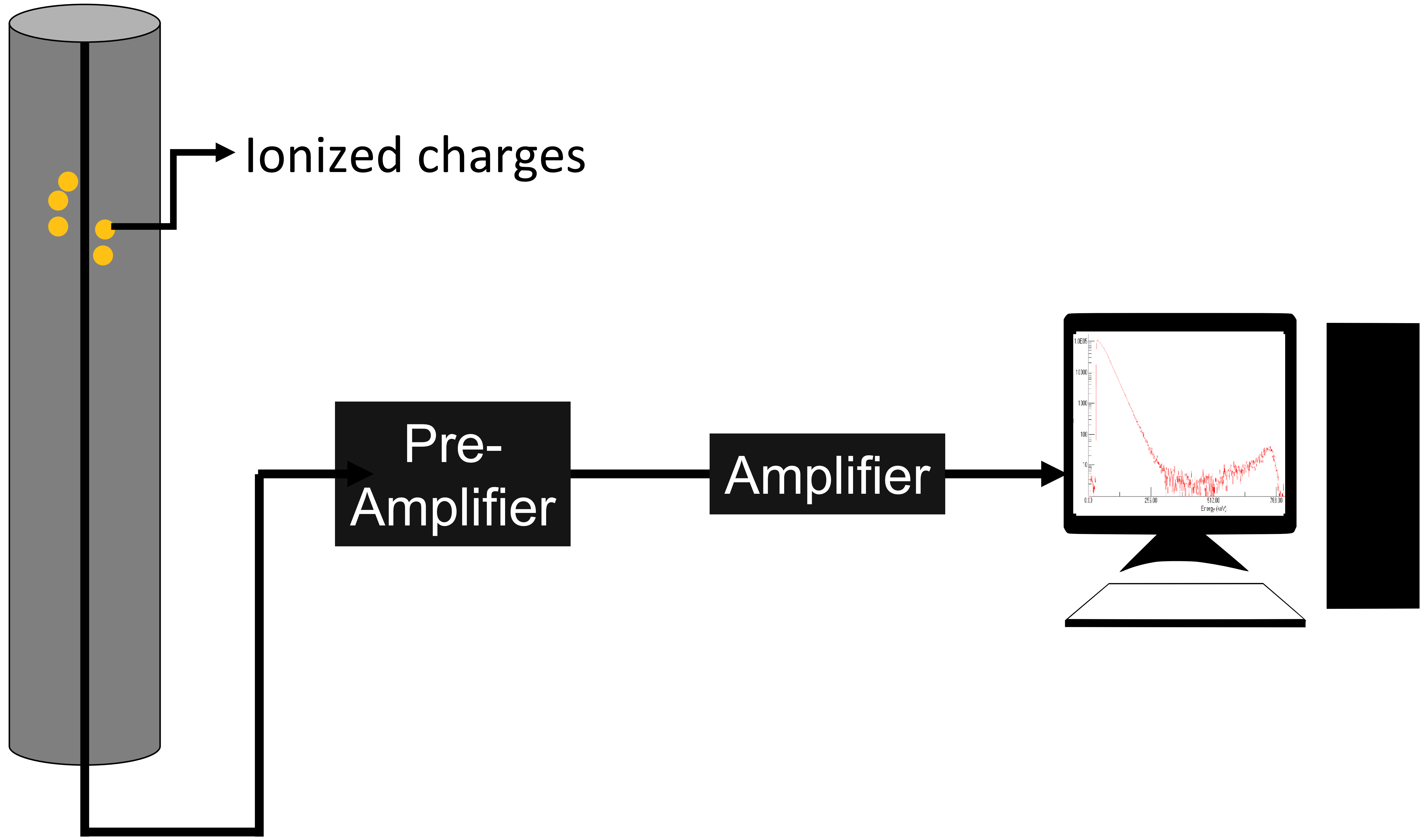


Fig: Simplified neutron counting flow diagram

Limitations of NCDs:

❖ Gamma-neutron overlap in ROI(~190 to 900 keV)

→Current solution: Energy Cuts and Count Correction Factor(Browne, 1999).

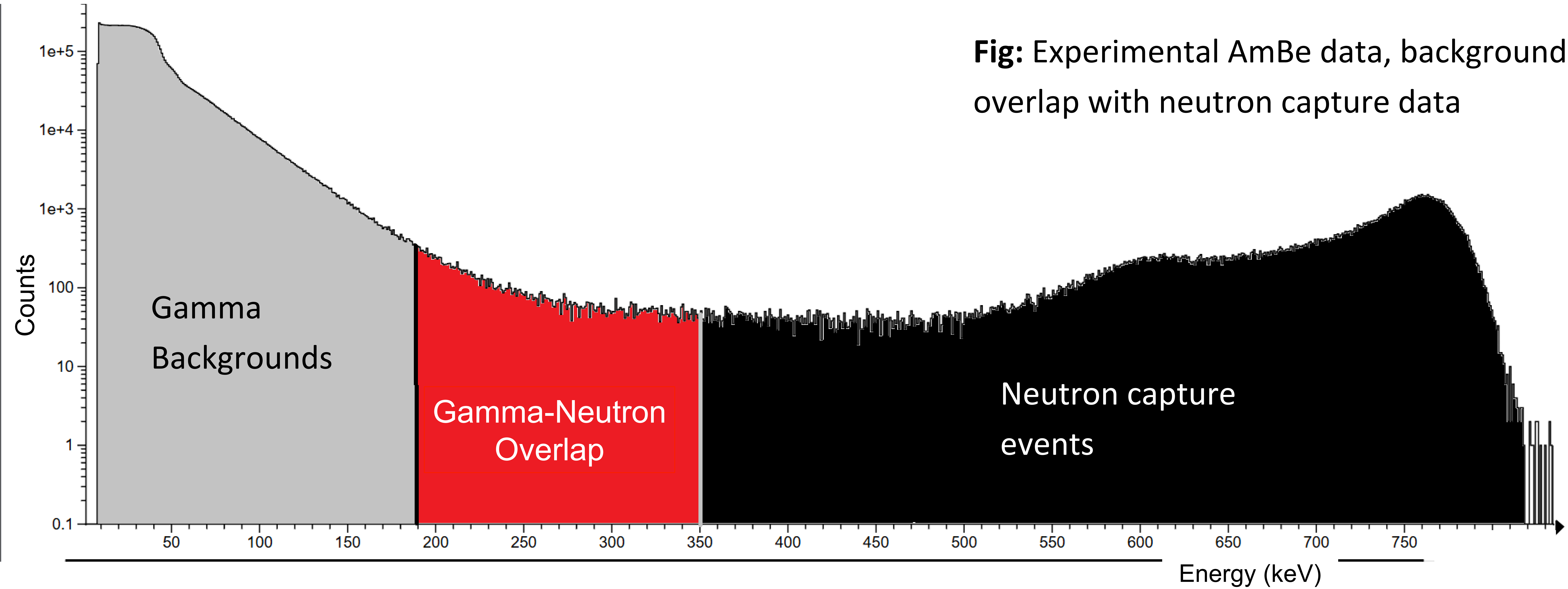
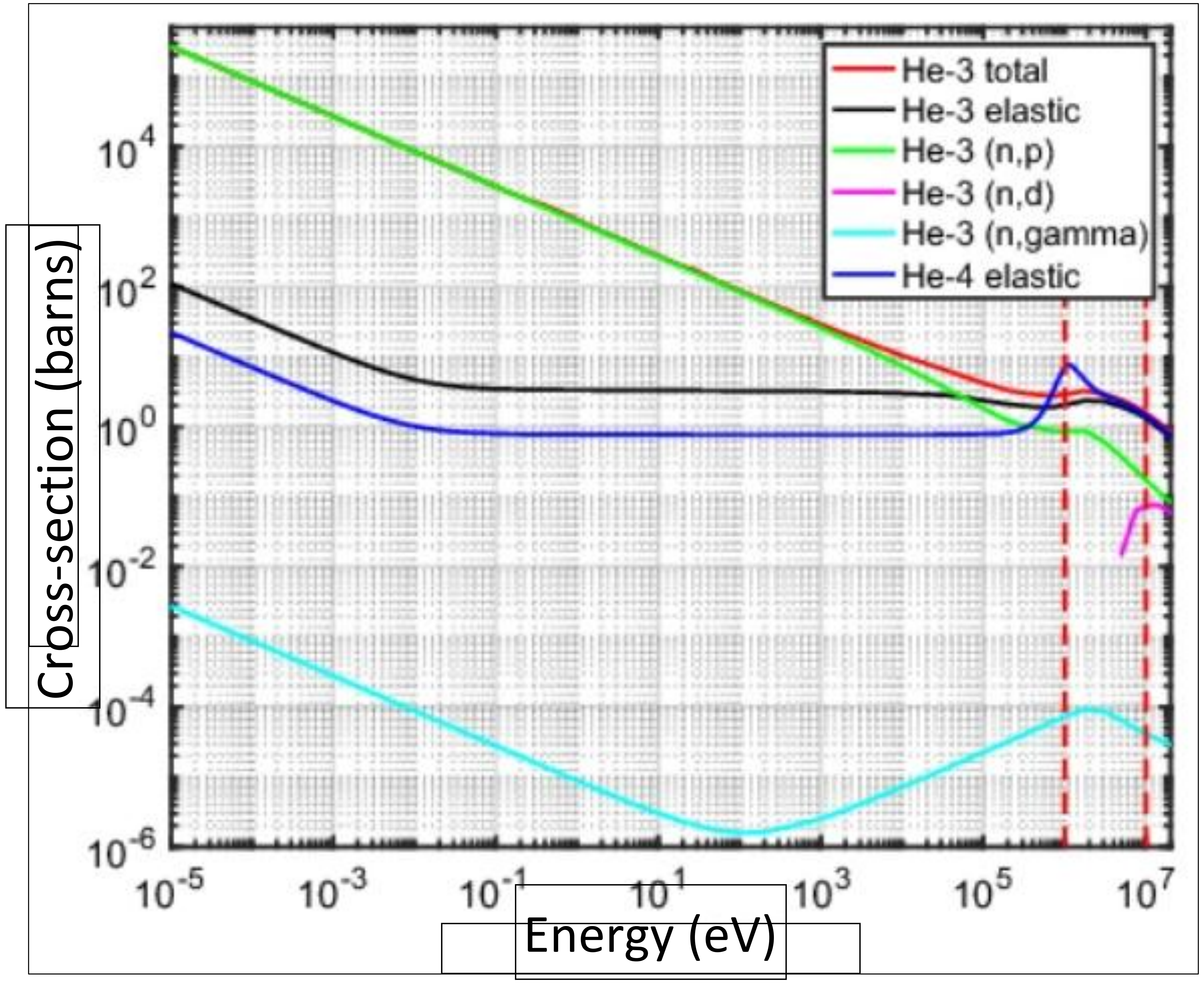


Fig: Experimental AmBe data, background overlap with neutron capture data

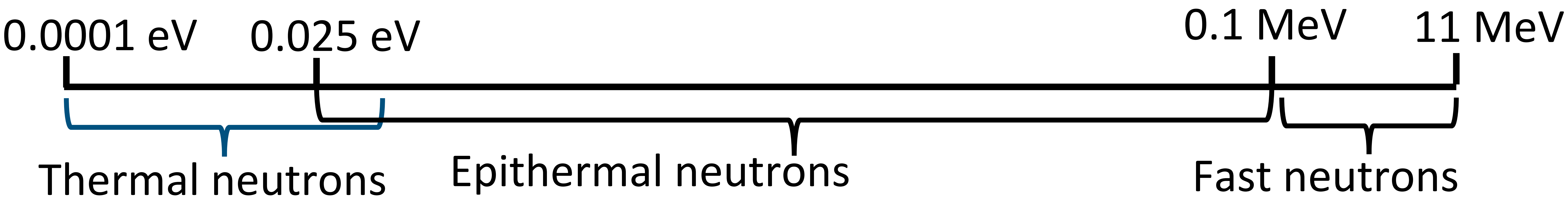
Neutron Capture Cross-section of Helium-3:



→Neutron capture drops rapidly over energy

→NCDs detect ambient thermal + some epithermal neutrons

Fig(left): Cross-Section plot for He-3 and He-4 interactions (Piscitelli et.al, *Eur. Phys. J. Plus* 135, 577, 2020)



Inverse problem: Moderated Response

❖ Discrete approximation of Fredholm's first kind integral using Response:

$$C_i = R_{\mathrm{ij}}\, \phi_j; \quad \text{where i} = \text{ moderation bin and } \text{ j} = \text{energy bin}$$

❖ In general, two "unfolding" philosophies/methods to solve the inverse problem:

High-Resolution Unfolding	This Work
Energy bins > detector responses	Energy bins = detector responses
Requires priors / regularization	Direct decomposition inversion
MAXED, GRAVEL, MLEM, Bayesian	LU, SVD
High apparent resolution	Stable conditioning analysis
Strong prior dependence	Physically constrained reconstruction

Evaluated Response using GEANT4 on Nibi cluster:

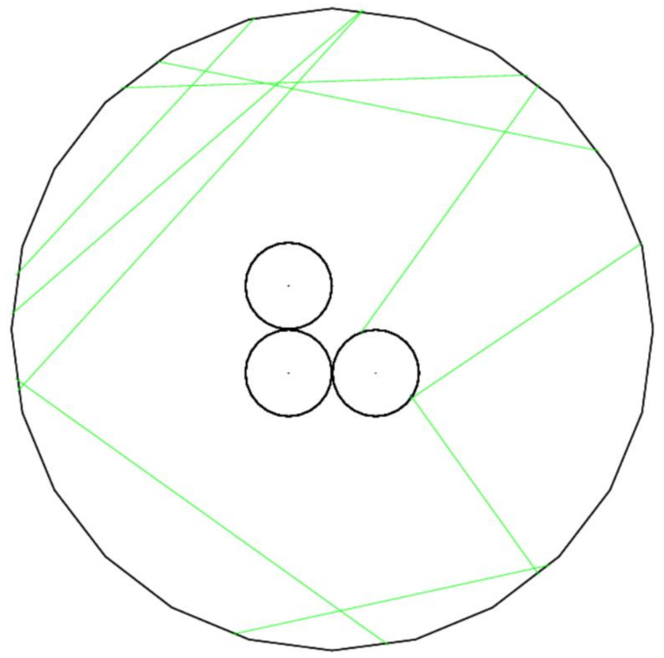


Fig: Bare NCD

Fig: 1” NCD

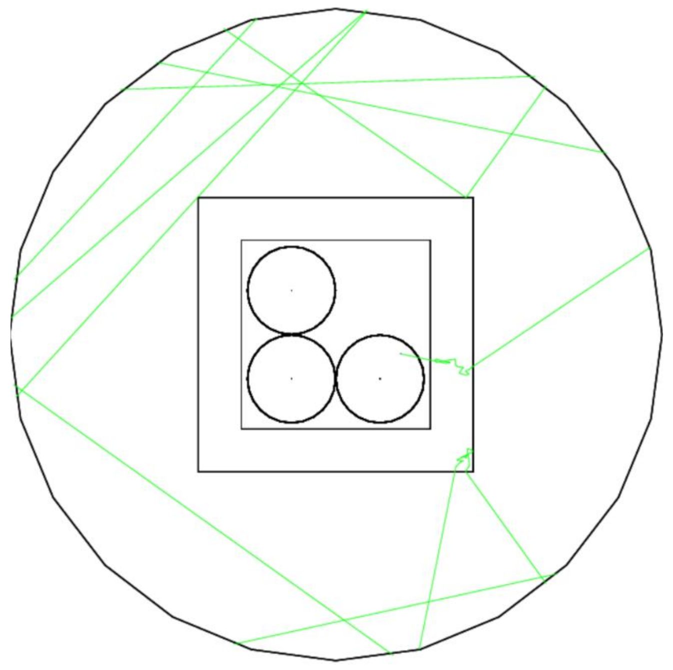
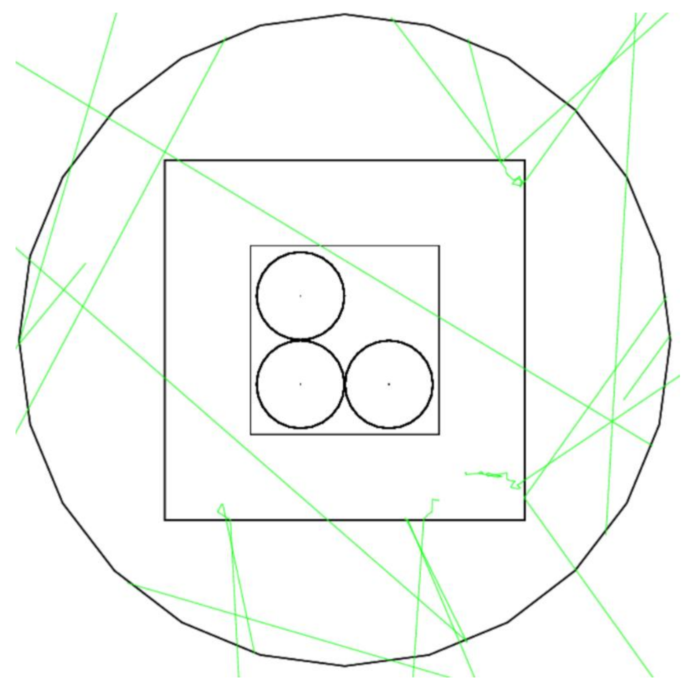


Fig: 2” NCD



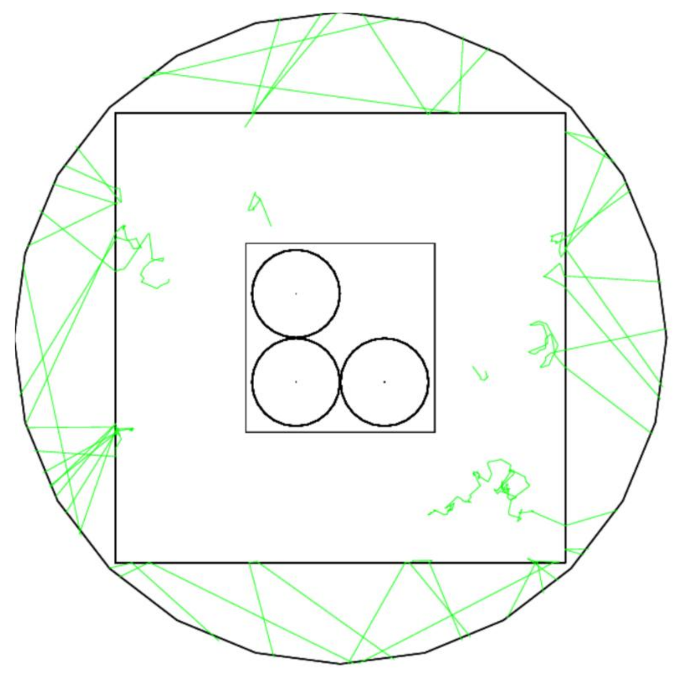
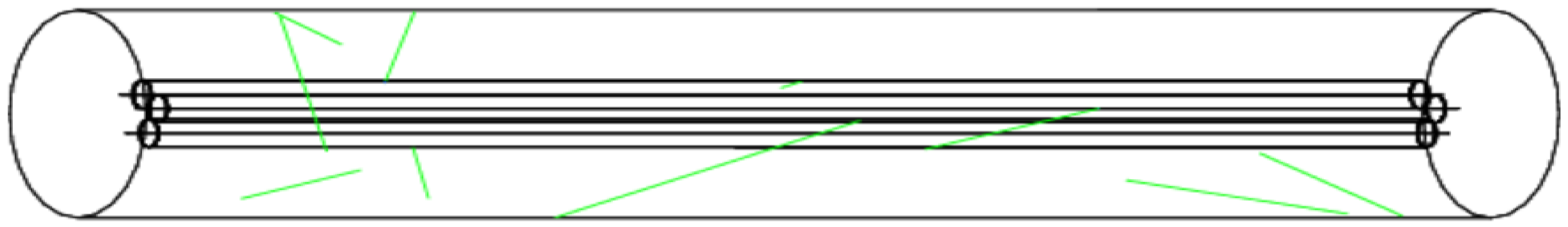
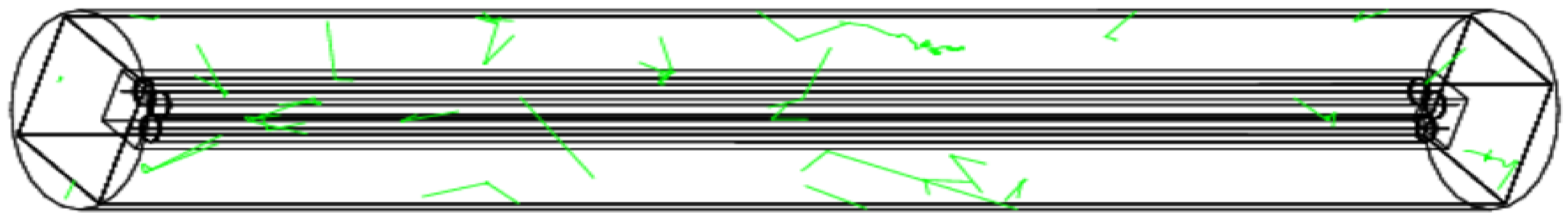


Fig: 3” NCD





$$\text{Response(E, Moderation)} = \frac{\text{Neutron Captures}}{\text{Events}} \times Source\ Surface\ Area$$

- ❖ **Response**: Cross-sections, Energy, Geometry, Angular Distribution, Moderation, Detector Efficiency
- ❖ **GEANT4(>11.0.0)**: HadronElasticPhysicsHP, G4HadronPhysicsQGSP_BIC_HP, G4IonPhysicsXS, G4StoppingPhysics, ElectromagneticPhysics, G4DecayPhysics, G4RadioactiveDecayPhysics

NCD Ambient Flux Inverse Summary(2025):

$$(\mathrm{C_i} + \delta \mathrm{C_i}) = (\mathrm{R_{i,j}} + \delta \mathrm{R_{i,j}})\ (\phi_\mathrm{j} + \delta \phi_j)$$

→ Typically $(\mathrm{R_{i,j}} \pm 1\%_{(\mathrm{stat})})$, $\left(C_i \pm 2.0\%_{(sys)} \pm\ \sim 1\%_{(\mathrm{stat})}\right)$

→ Utilized Monte Carlo Error Propagation(Brute Force) with solvers to evaluate $\phi + \boldsymbol{\delta}\phi$.

→ Tested MLEM/GRAVEL iterative unfolding against LU decomposition:

<u>Result: The inversion is "solvable" using decomposition techniques. Decomposition > Unfolding</u>

Brief Background from Applied Math:

❖ A fundamental Applied Math problem:

$$\boldsymbol{A_i} = \boldsymbol{B}_{\mathrm{i,j}}\boldsymbol{C_j}$$

❖ **Goal: Find C, from A and B under perturbations.**

→ The linear independence is a spectrum:

-- Conditioning determines inversion stability and sensitivity to uncertainties

--The condition number $\kappa(B)$ is a measure of the conditioning of the B matrix:

$$\kappa(B) \approx 1\text{(perfect)},\ \kappa(B) \gg 1\text{(ill-conditioned)},\ \kappa(B) \to \infty\text{(non solvable)}$$

--Wedin Perturbation Theorem: Error amplification scales with condition number.

$$\frac{||\delta C||}{||C||} \leq \frac{\kappa(B)}{1-\kappa(B)\left(\frac{\delta B}{B}\right)}\left(\frac{||\delta A||}{||A||}+\frac{||\delta B||}{||B||}\right);\ \text{if } \kappa(B)\left(\frac{\delta B}{B}\right) < 1$$

How does SVD help in our inversion:

❖ **Used PYTHON libraries to find $\kappa(R)$ for available HDPE configurations(flat distribution based):**

→ $\boldsymbol{\kappa}$ (R(1”, 2”, 3”, bare)) ≈ 32 ✖

→ $\boldsymbol{\kappa}$ (R(1”, 3”, bare)) ≈ 6 ✓

→ $\boldsymbol{\kappa}$ (R(1”, 2”, bare)) ≈ 8 ✓

❖ **Eg, for $\boldsymbol{\delta C \sim 2.2\%}$ and $\boldsymbol{\delta \mathrm{R} \sim 1\%}$:**

→ For $\boldsymbol{\kappa} \approx \mathbf{32}, \frac{||\delta S||}{||S||} \leq$ **137.1%**

→ For $\boldsymbol{\kappa} \approx \mathbf{8}, \frac{||\delta S||}{||S||} \leq$ **27.8%**

→ For $\boldsymbol{\kappa} \approx \mathbf{6}, \frac{||\delta S||}{||S||} \leq$ **20.4%**

→ **Note the theorem is for Max upper bound!**

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Method	Flux(10E-10 to 10E-6) $10^{-6} n\ cm^{-2} s^{-1}$	Flux(10E-6 to 0.1) $10^{-6} n\ cm^{-2} s^{-1}$	Flux(0.1 to 11) $10^{-6} n\ cm^{-2} s^{-1}$
LU	4.14 ± 0.14	5.98 ± 0.83	2.74 ± 3.45

❖Eg, for $\delta C \sim 2.2\%$ and $\delta R \sim 1\%$:

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LU	4.13 ± 0.14	6.14 ± 0.45	2.85 ± 0.56

→ **Note the theorem is for Max upper bound!**

Preliminary / Older Simulations Plots:

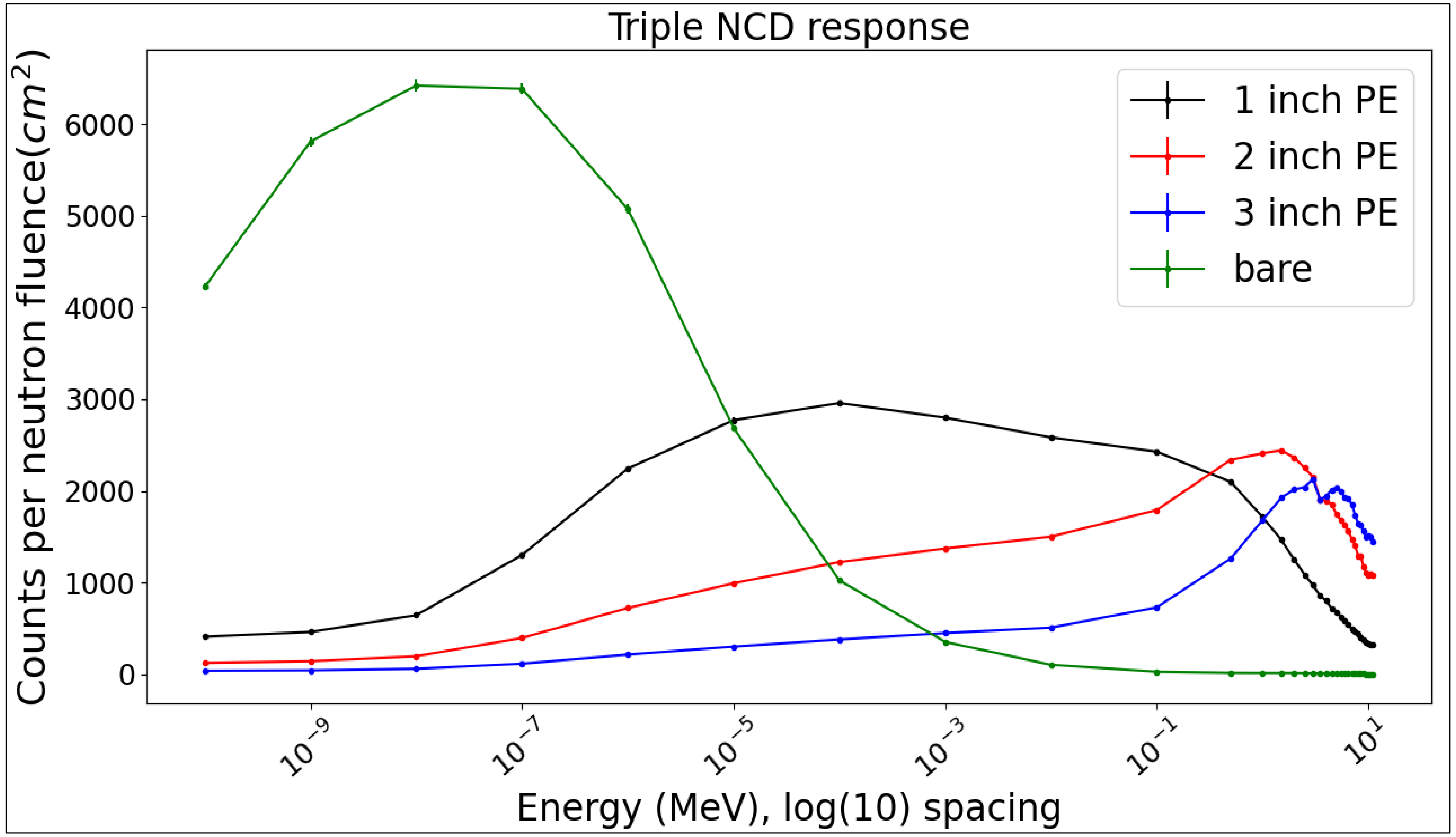


Fig: Triple NCD response

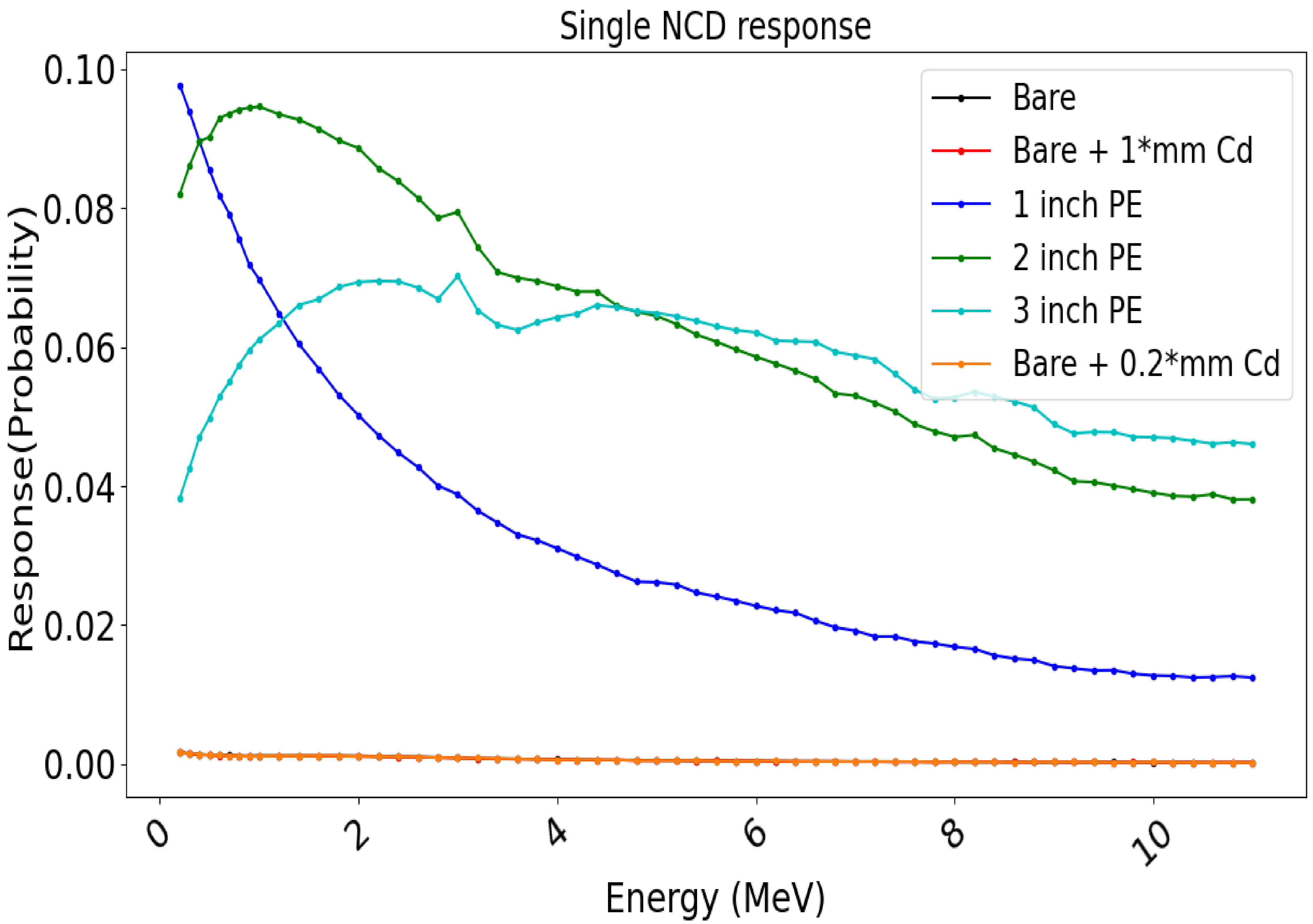


Fig: First fast neutron response value plot

→$\kappa(R)$ is measure of correlated system:

-- Two variables with same neutron sensitivity are not independent!

Comparison between two binning techniques:

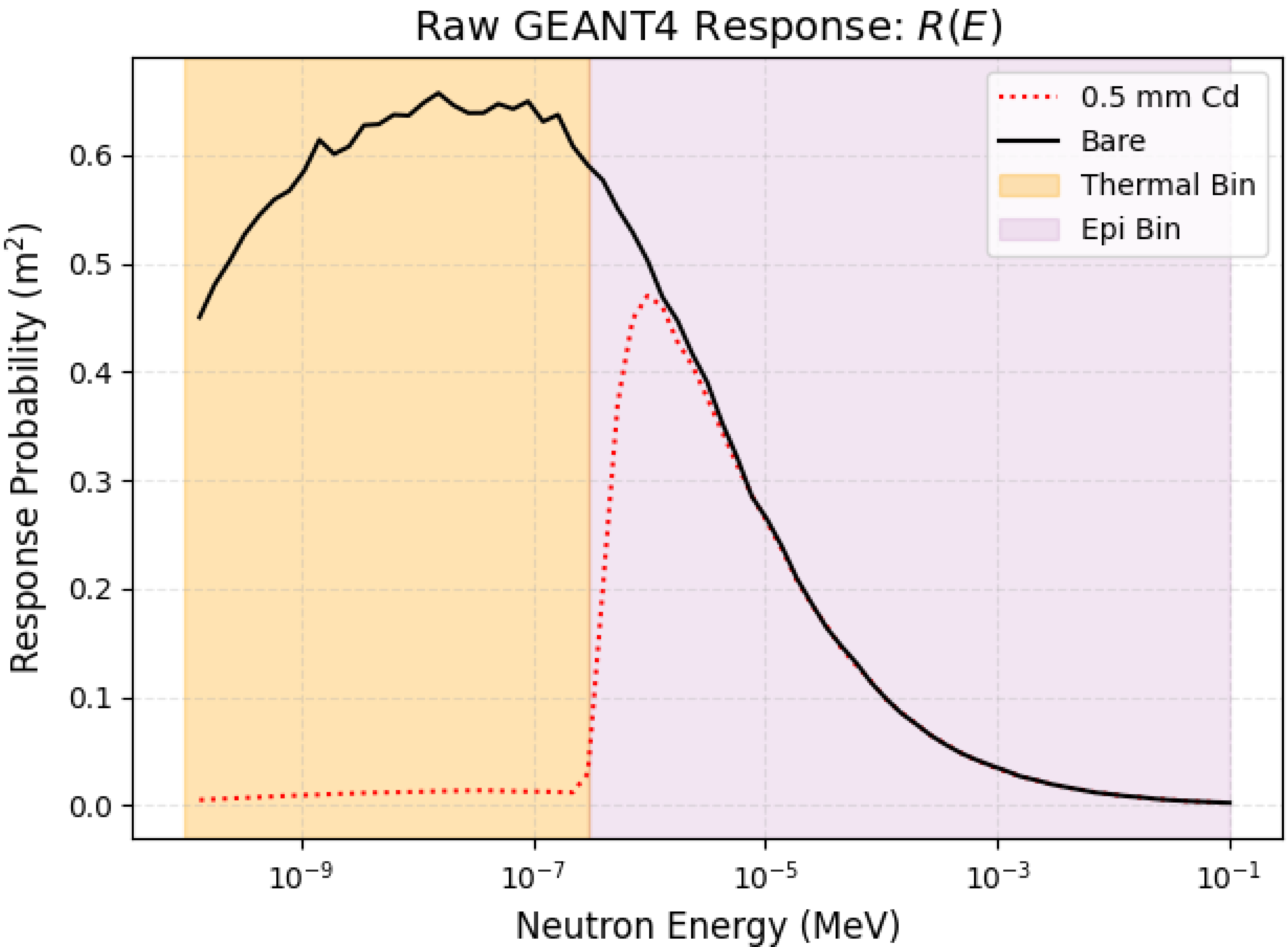
Table 1: Configuration R6 Analysis (1", 3", Bare | Prior Weight| κ: 5.65)

Method	Thermal (10E−10 to 10E-7 MeV) $10^{-6} n\ cm^{-2} s^{-1}$	Intermediate (10E-7 to 0.1 MeV) $10^{-6} n\ cm^{-2} s^{-1}$	Fast (0.1 to 11 MeV) $10^{-6} n\ cm^{-2} s^{-1}$	Total Flux (0–11 MeV) $10^{-6} n\ cm^{-2} s^{-1}$
Direct Inversion	2.551	5.896	3.124	**11.571**
LUD ± MC	2.550 ± 0.158	5.899 ± 0.313	3.121 ± 0.153	**11.570 ± 0.383**
SVD ± MC	2.553 ± 0.158	5.890 ± 0.309	3.126 ± 0.152	**11.569 ± 0.378**

Method	Thermal (10E−10 to 10E-7 MeV) $10^{-6} n\ cm^{-2} s^{-1}$	Intermediate (10E-7 to 0.1 MeV) $10^{-6} n\ cm^{-2} s^{-1}$	Fast (0.1 to 11 MeV) $10^{-6} n\ cm^{-2} s^{-1}$	Total Flux (0–11 MeV) $10^{-6} n\ cm^{-2} s^{-1}$
Direct Inversion	4.132	6.141	2.835	13.108
LUD ± MC	4.134 ± 0.118	6.141 ± 0.280	2.835 ± 0.162	13.110 ± 0.344
SVD ± MC	4.132 ± 0.118	6.142 ± 0.276	2.834 ± 0.163	13.109 ± 0.342

Table 3: Configuration R4 Analysis (1", 3", Bare |Flat Prior| κ: 4.66)

Bare setup has thermal + epithermal contributions



❖**Solution:**

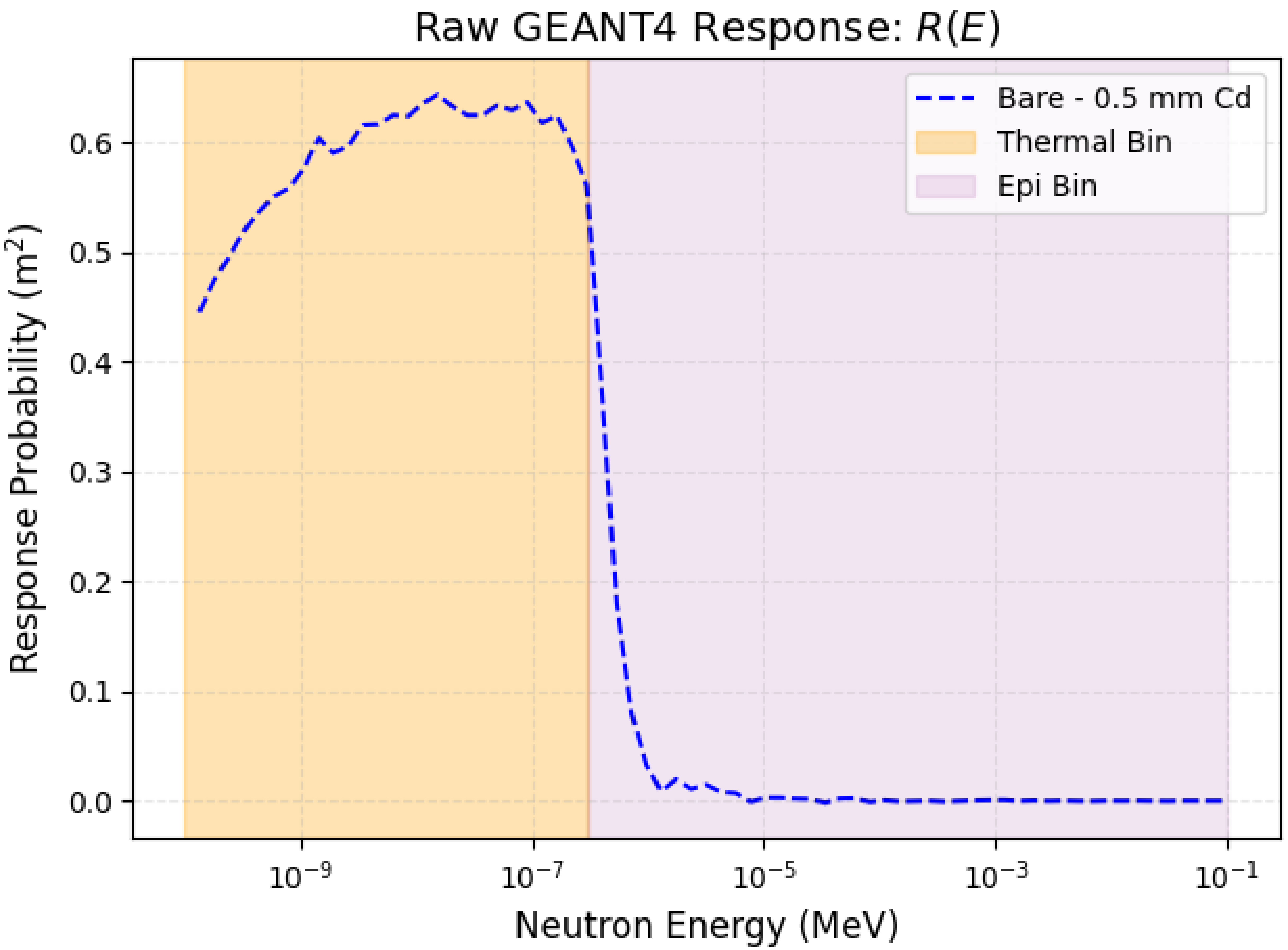
→ Cd Difference method

-- **Bare**: Thermal and some Epi

-- **0.5 mm Cd**: Some Epi

$$\rightarrow \boldsymbol{Thermal\ flux} = \frac{\boldsymbol{C_{(bare)} - C_{(Cd)}}}{\boldsymbol{R_{(thermal)}}}$$

Bare setup has thermal + epithermal contributions



❖**Solution:**

→ Cd Difference method

-- **Bare**: Thermal and some Epi

-- **0.5 mm Cd**: Some Epi

→ $\boldsymbol{Thermal\ flux} = \frac{C_{(bare)} - C_{(Cd)}}{R_{(thermal)}}$

❖**Rough** $\boldsymbol{Thermal\ flux}$ **:**

$\mathbf{2.73 \times (10^{-6} n\ cm^{-2} s^{-1})}$

❖**Inverse(Prior)** $\boldsymbol{Thermal\ flux}$**:**

$\mathbf{(2.553 \pm 0.158) \times (10^{-6} n\ cm^{-2} s^{-1})}$

Rough Flux Comparison:

SNOLAB's area(time)	Depth (m.w.e)	Thermal flux $(10^{(-6)}\ neutrons\ cm^{(-2)}\ s^{(-1)})$	Fast Flux $(10^{(-6)}\ neutrons\ cm^{(-2)}\ s^{(-1)})$	Detector used
SNO area(1999)	6000	$4.80\ \pm 0.06(\text{stat})\ \pm 0.12(\text{sys})$	--	^3He PC
J-drift(2025)	6000	2.55 ± 0.16	$3.13 \pm\ 0.15$	^3He PC

Underground lab	Depth (m.w.e)	Thermal flux $(10^{(-6)}\ neutrons\ cm^{(-2)}\ s^{(-1)})$	Fast Flux $(10^{(-6)}\ neutrons\ cm^{(-2)}\ s^{(-1)})$	Detector used
YangYangA6	2000	$24.2\ \pm 1.8$	$4.2 \pm\ 0.9$	^3He PC
Canfranc	2450	$1.28\ \pm 0.04$	$1.84 \pm\ 0.03$	^3He PC
Kamioka	2700	7.88	3.88	^3He PC
LNGS Hall C	3800	$0.24\ \pm 0.17$	$0.45 \pm\ 0.35$	^3He PC
Modane	4800	$3.57\ \pm 0.05\ \pm 0.27$	$1.06 \pm\ 0.1\ \pm\ 0.6$	^3He PC
CJPL-1	6720	$7.03\ \pm 1.81$	$3.63 \pm\ 2.77$	^3He PC

Table: Neutron flux for UG labs

(Yoon et al., Astroparticle Physics, 126, 2021)

Future Work(Summer 2026):

- **HDPE Moderation Optimization Strategy:**

$$\text{Minimize } \kappa\big(R(0", x_1, x_2, x_3)\big), \text{ subject to } 0.5" \leq x_i \leq 6.0" \text{ and } \left|x_i - x_j\right| \geq 0.5"$$

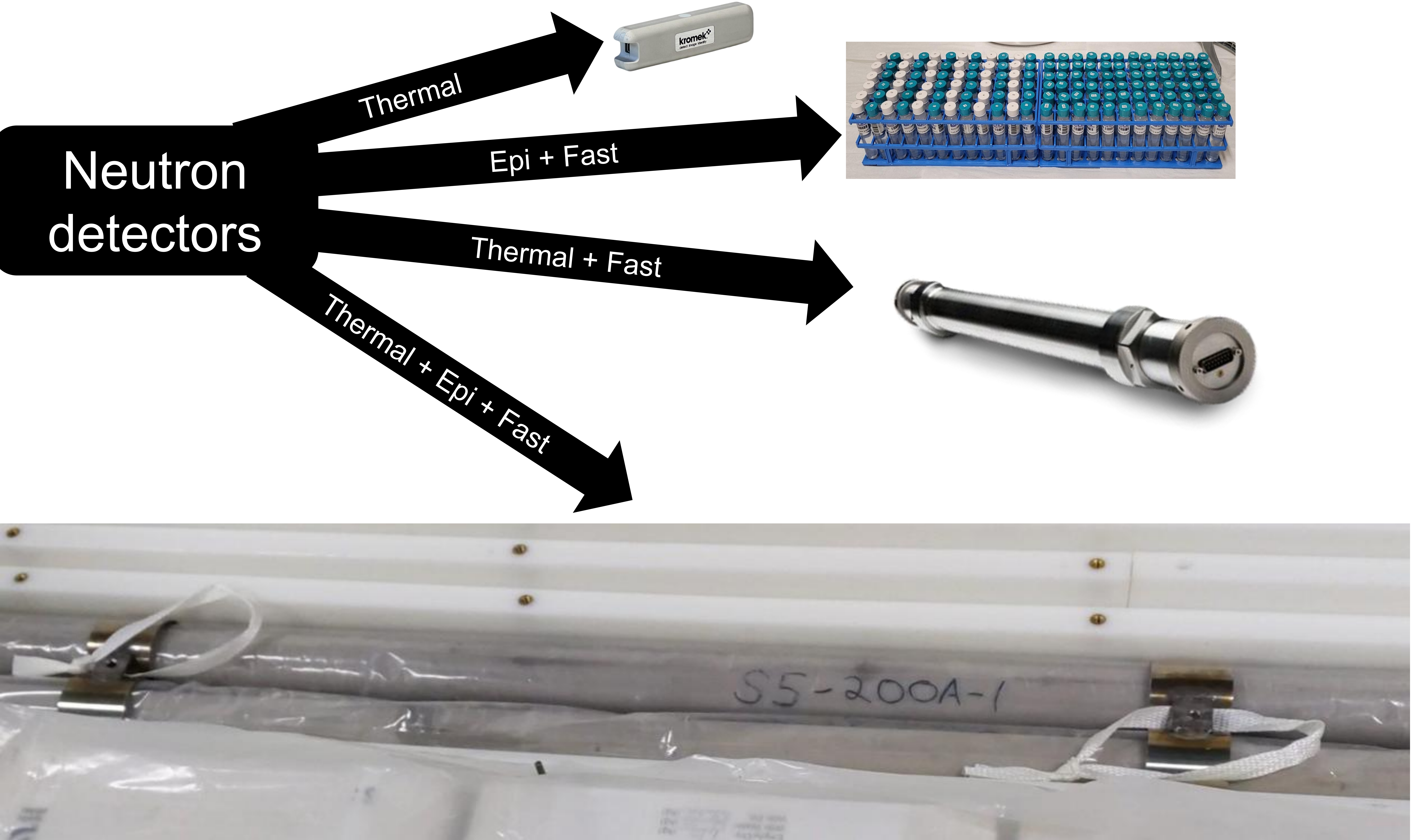
- **Cylindrical Moderators with one NCD only**
  - → Lower Epithermal contribution to bare, compliments NCD geometry
- **Intrinsic Background in ROI Test:**
  - → Response(0.5 mm Cd + 3” HDPE + 22” Water) for 11 MeV neutrons = 0.000434 m^2
- **Several different moderator setup and binning method**
  - → **Systematic study**: How does perturbations of binning and moderator affect flux values?
- **The methodology will be published in JINST**
- **Pulse Shape Discrimination Test and extending to Muon Spallation Neutrons?**

Thank you for listening!

Special Thanks to:

→ Thomas Sonley, Ian Lawson, Steffon Luoma, Chris Jillings, Dimpal Chauhan, Matt Stukel, Brianna Liz Binoy, HENSA

Questions?


Neutron detectors
Thermal
Epi + Fast
Thermal + Fast
Thermal + Epi + Fast
kromek
S5-200A-1

Check simulations validity

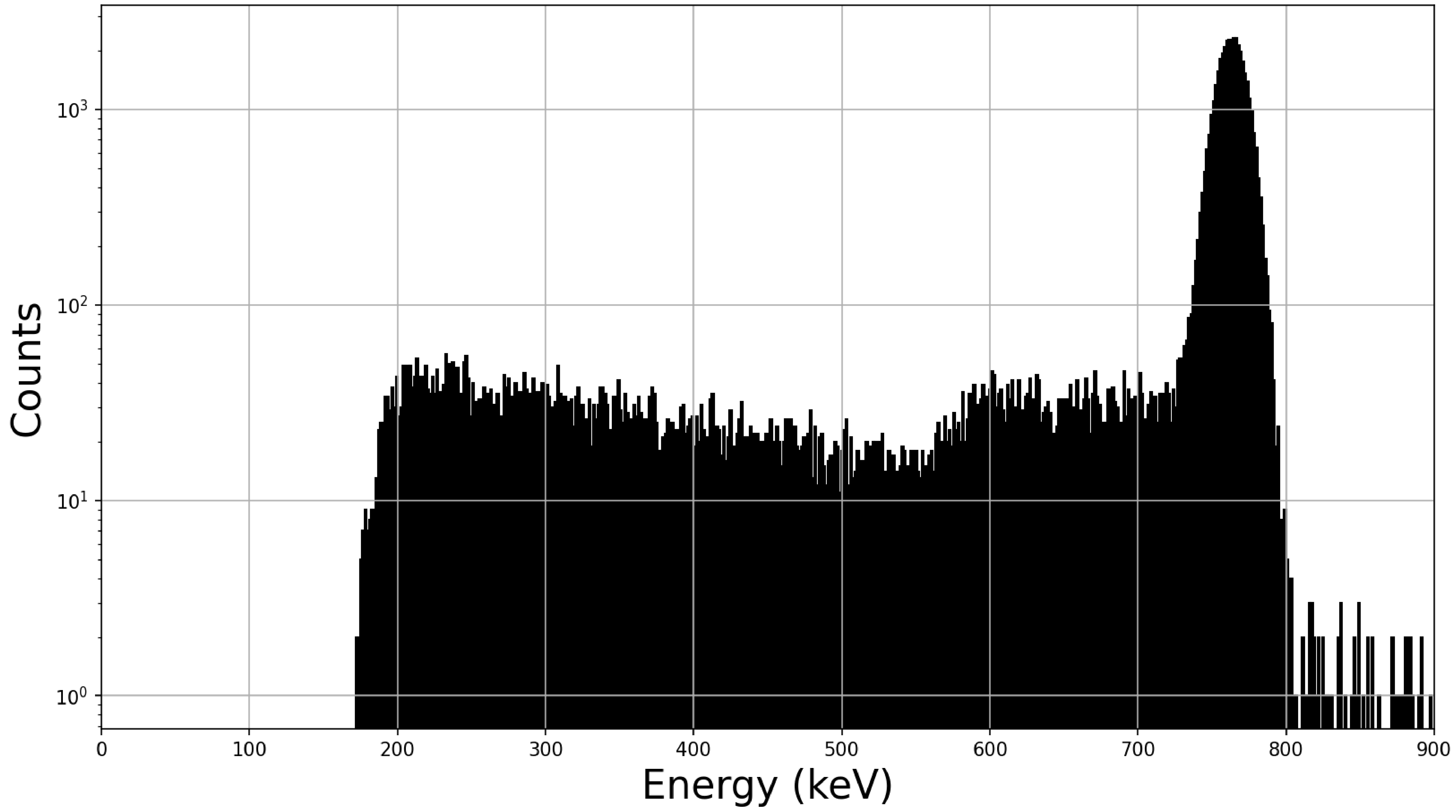


Fig: GEANT4's neutron capture energy deposition with 10 keV gaussian noise

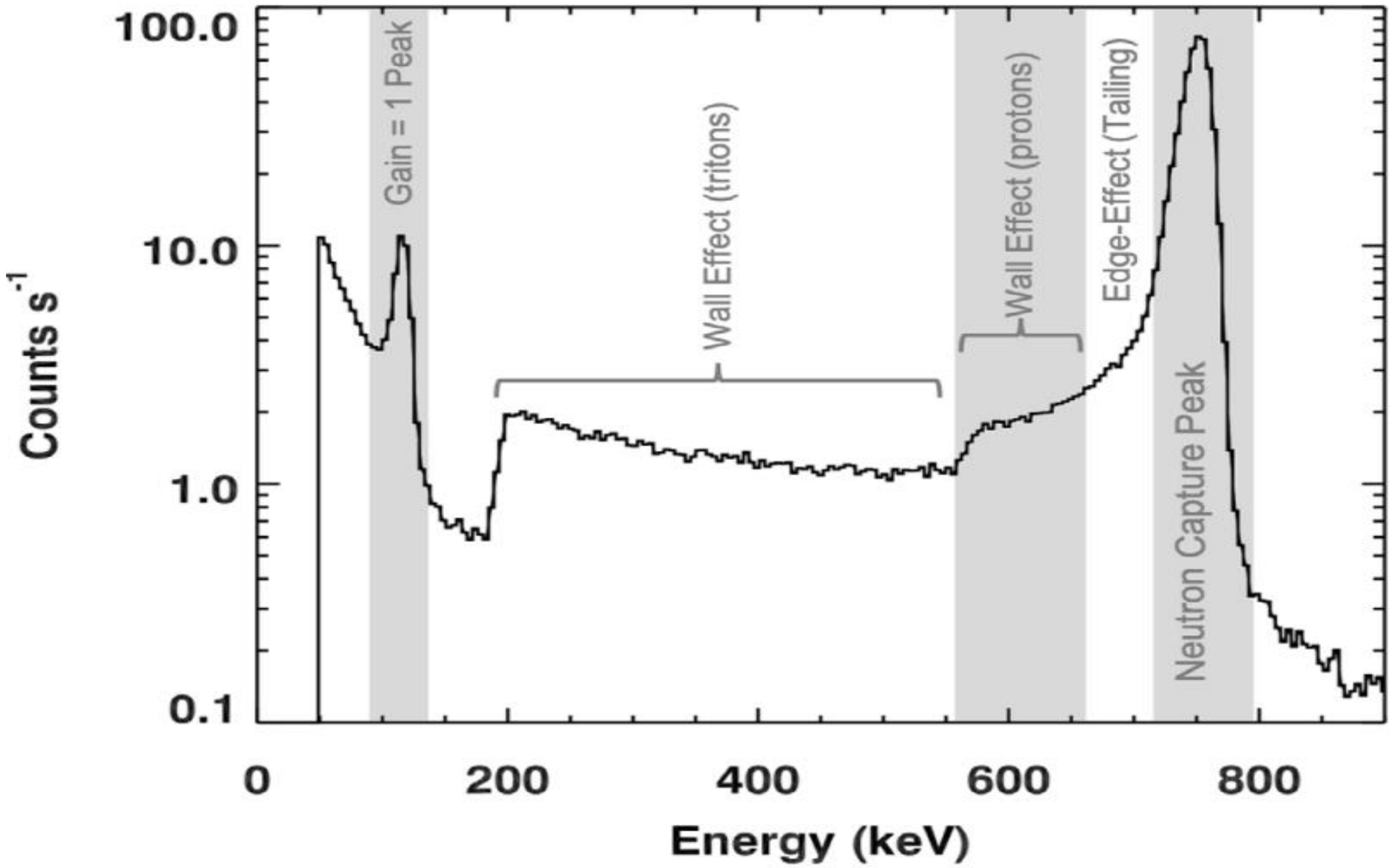
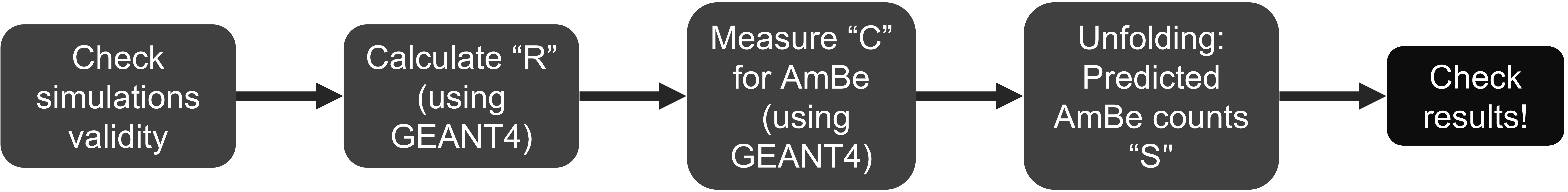


Fig: Experimental energy deposition data (Peplowski et al., NIM A, 982, 164574, 2020)



GRAVEL algorithm results:

During the test period:

The AmBe source emitted 10 000 000 fast neutrons

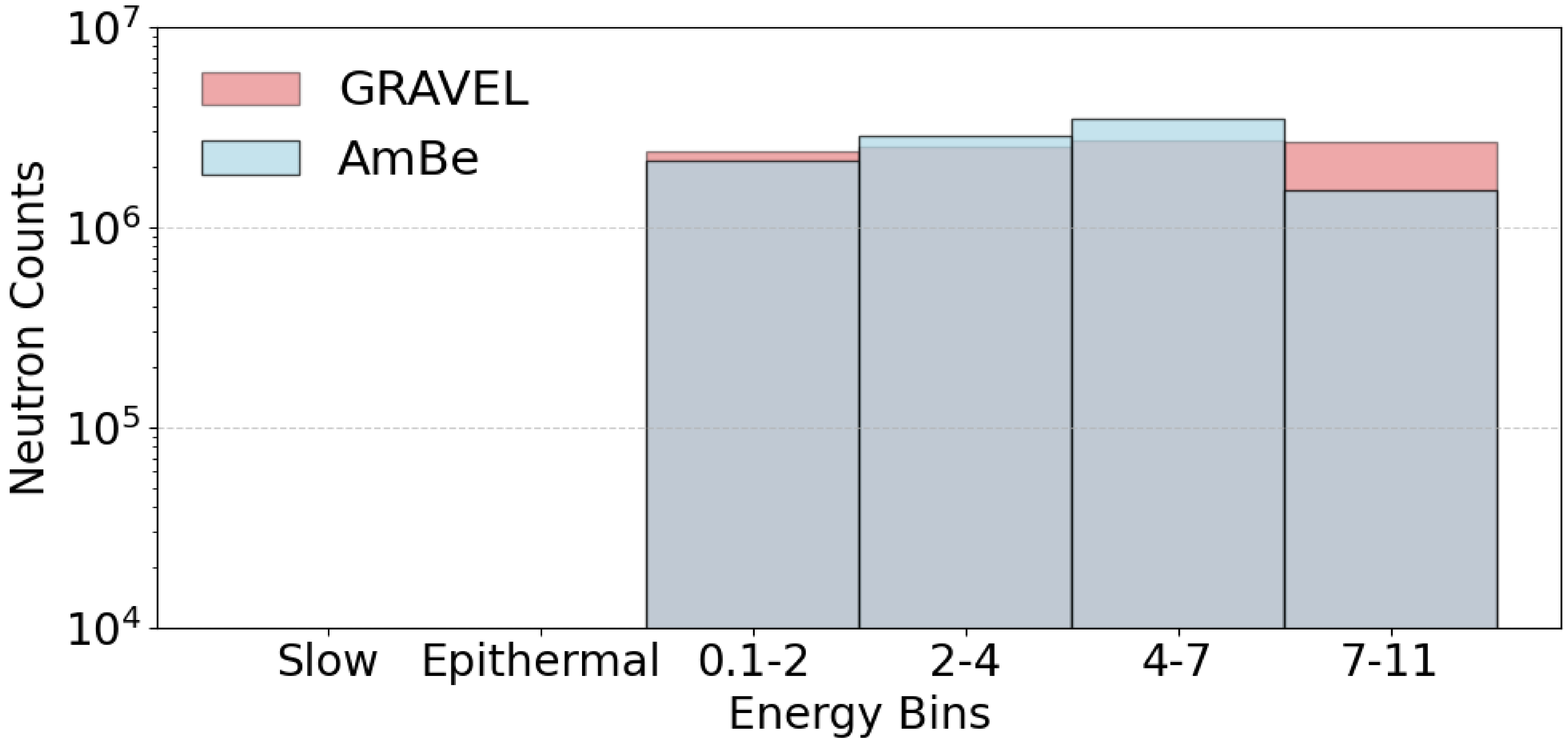
The algorithm predicted 9 893 254 fast neutrons, about 99%!

→<u>Takeaway</u>: The Helium-3 counter successfully counts for fast neutrons!

Attempt using simulation and GRAVEL:

- ❖**Used an AmBe neutron distribution and ran 10 million events**
- ❖*Unfolding for the source gave ~99% accuracy and reasonable initial energies.*

<u>Note: This prediction is for the total neutrons released from AmBe source!</u>



Prediction vs actual AmBe Spectra using GEANT4

Moderation Setup

Bare(No moderation)

1-inch Polyethylene

2-inch Polyethylene

3-inch Polyethylene

4-inch Polyethylene

5-inch Polyethylene

Idea: Moderators

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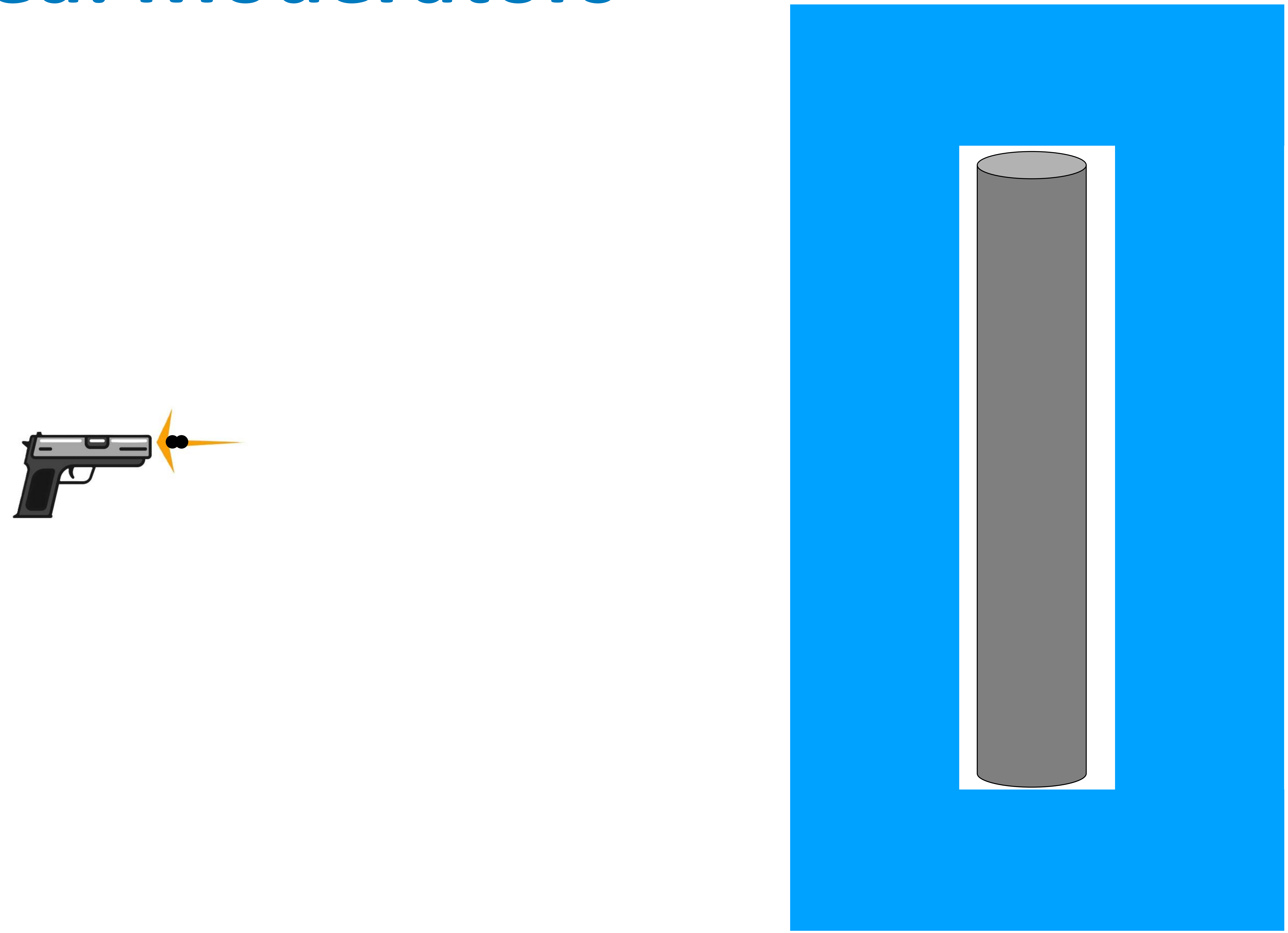
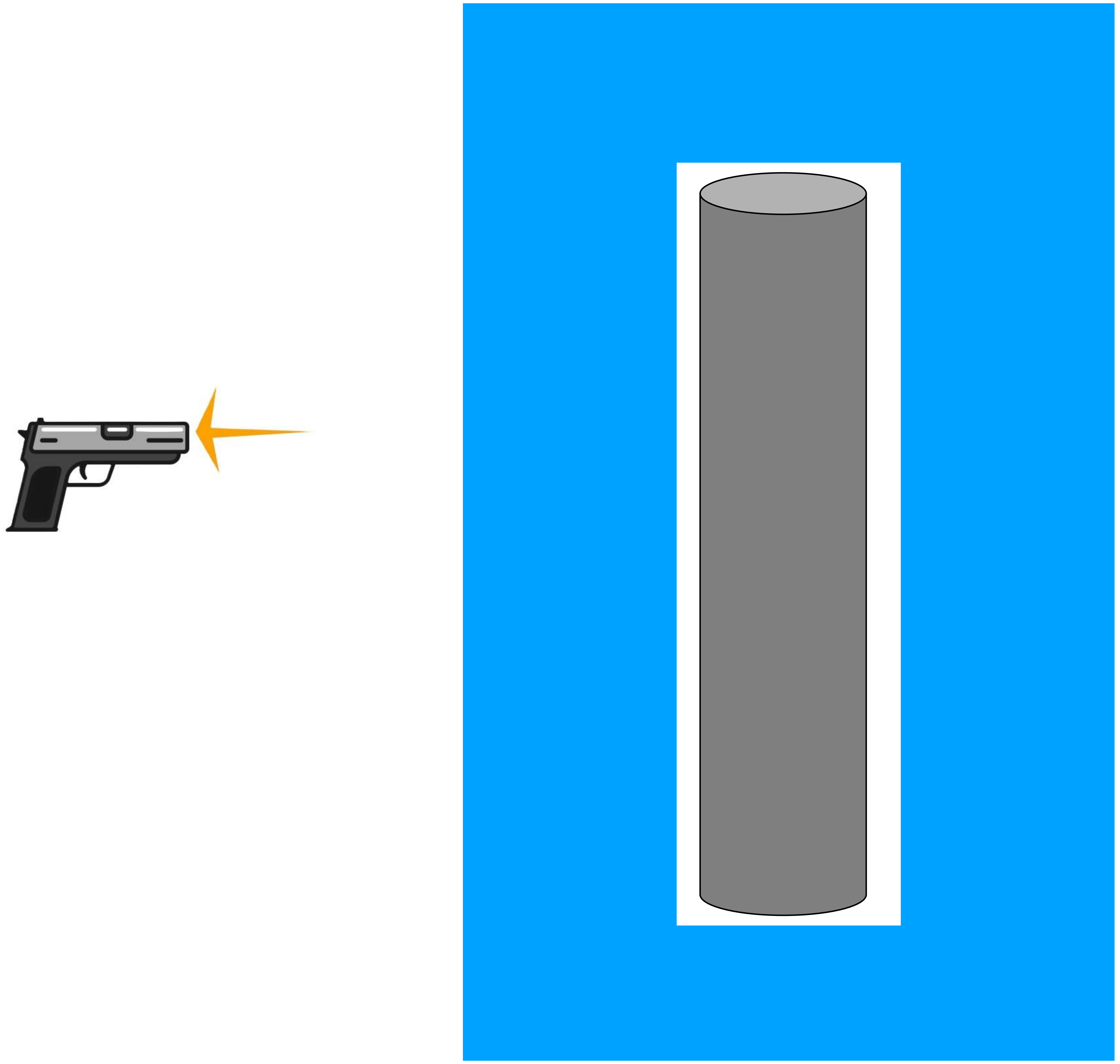


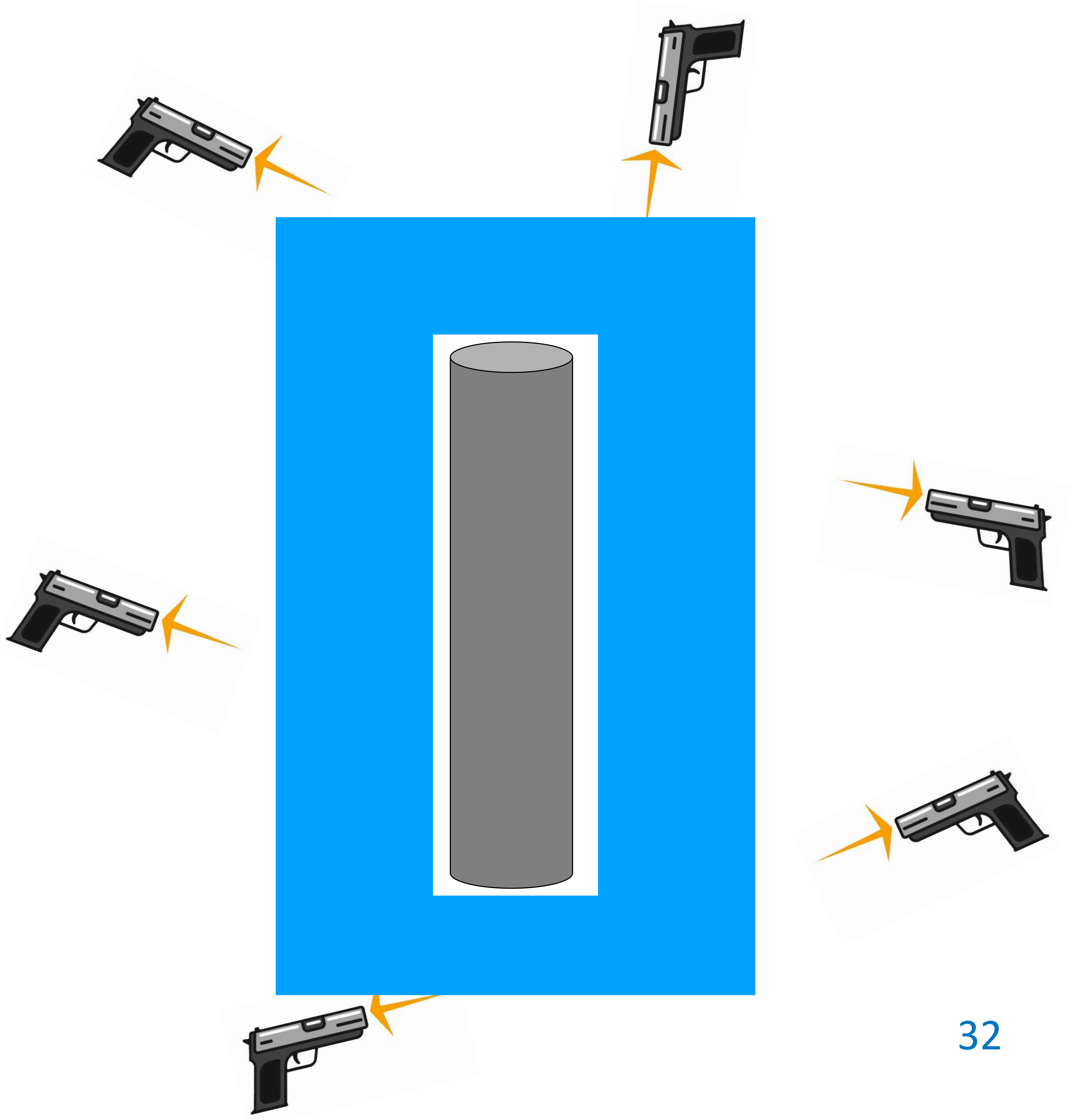
Inference:

For "ϕ" neutrons fired to some moderator "M" with energy "E" and probability of detection "R", we can get a prediction for detected neutrons:

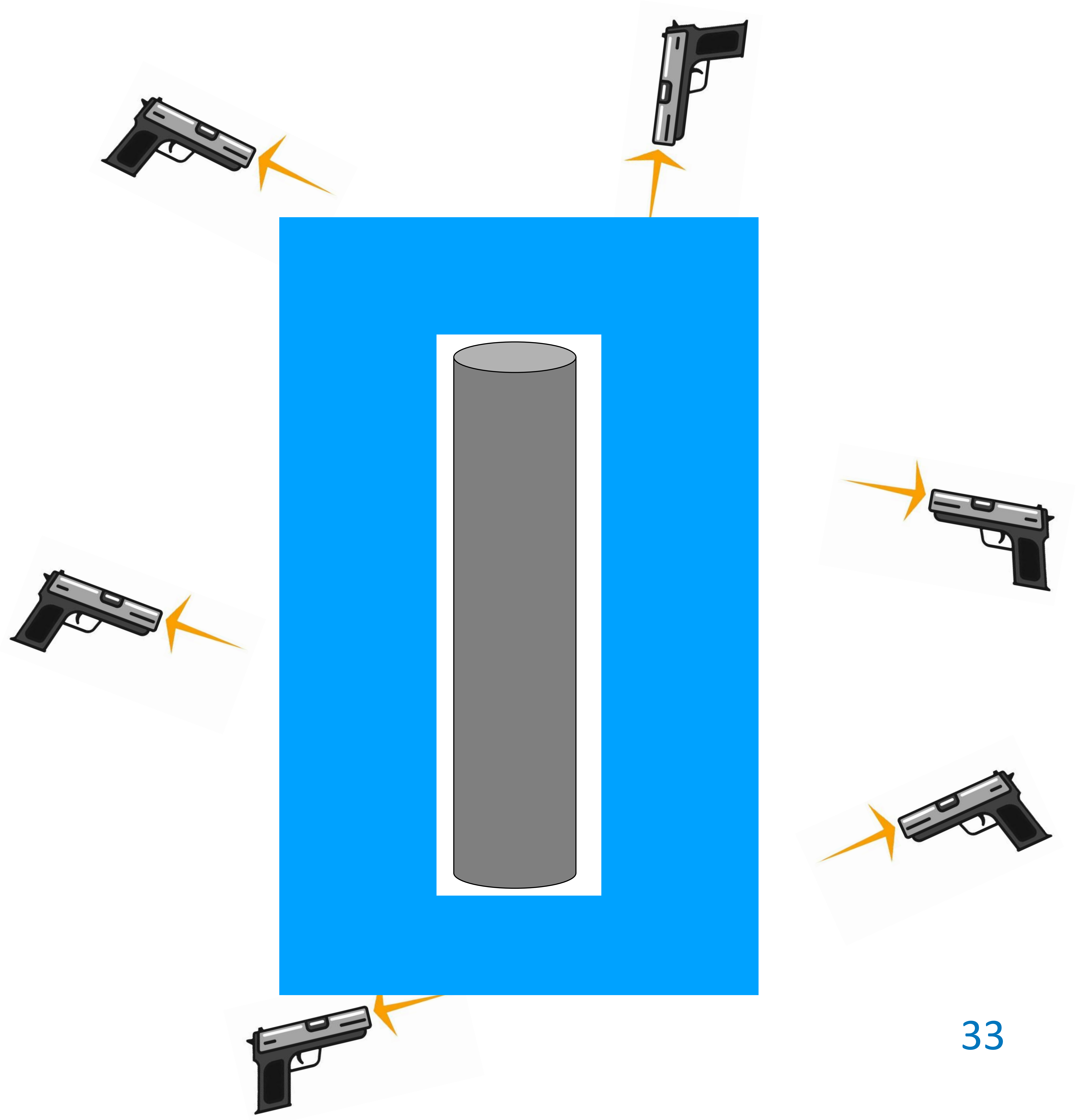
$$C = R(E) \times \phi(E)$$



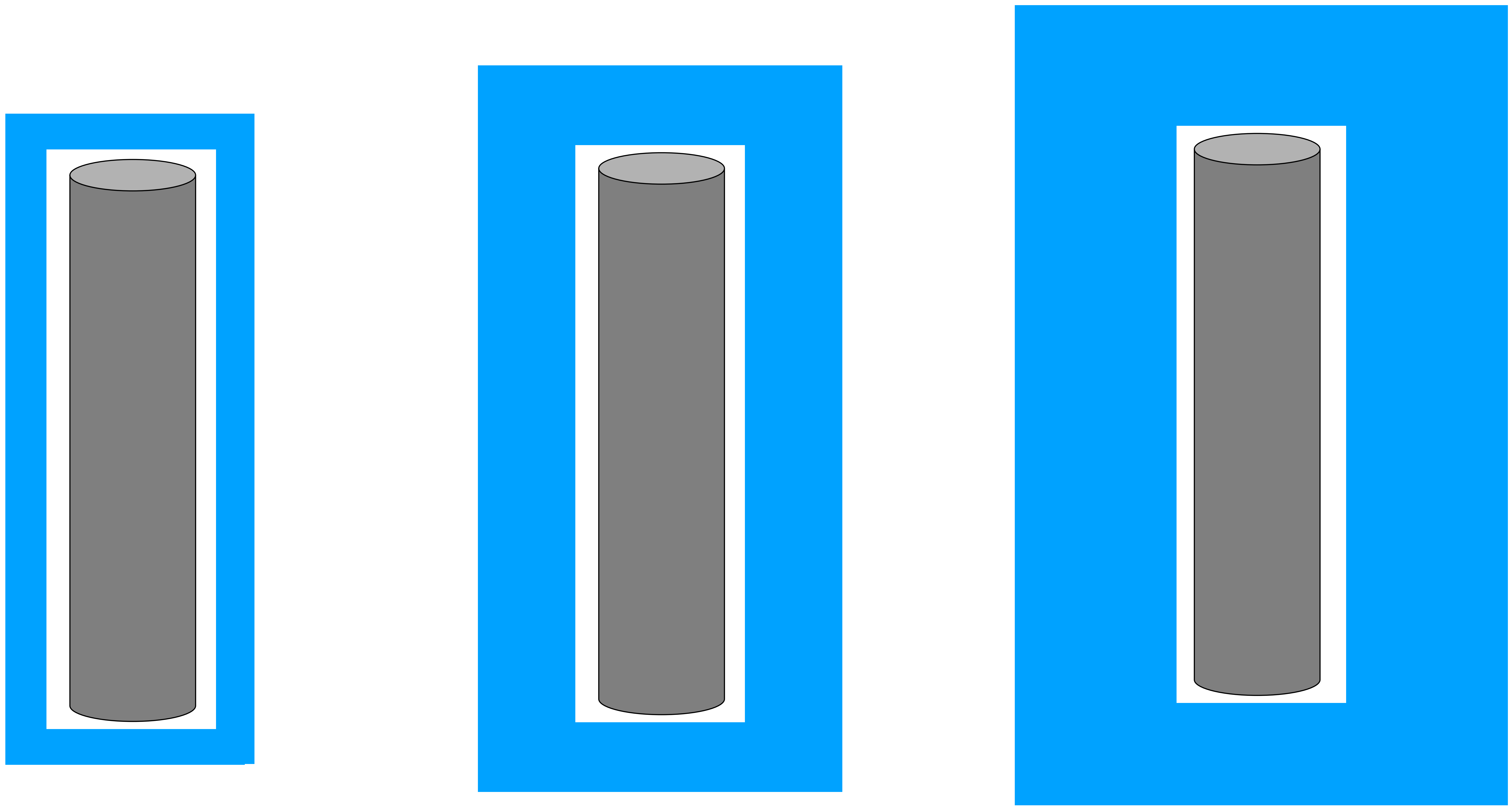
Inference:



Inference:



An Inverse Problem:



Inverse problem:

Assuming each neutron events are independent from one another, for some moderator setup:

$C_i = R_{\mathrm{ij}}\,\phi_j;\;$ where i = moderation bin and j = energy bin

"4" linear equations with "j" unknown variables:

$$\boldsymbol{C_1} = (\boldsymbol{R}_{11} \times \boldsymbol{\phi_1}) + (\boldsymbol{R}_{12} \times \boldsymbol{\phi_2}) + \cdots (\boldsymbol{R}_{1\boldsymbol{j}} \times \boldsymbol{\phi_j})$$

$$\vdots$$

$$\boldsymbol{C}_4 = (\boldsymbol{R}_{41} \times \boldsymbol{\phi_1}) + (\boldsymbol{R}_{42} \times \boldsymbol{\phi_2}) + \cdots (\boldsymbol{R}_{4\boldsymbol{j}} \times \boldsymbol{\phi_j})$$

Inverse problem:

Assuming each neutron events are independent from one another, for some moderator setup:

$$C_i = R_{\mathrm{ij}}\, \phi_j; \quad \text{where i} = \text{ moderation bin and } \text{j} = \text{energy bin}$$

Matrix form:

$$\begin{bmatrix} \mathbf{C}_1 \\ \mathbf{C}_2 \\ \boldsymbol{C}_3 \\ \boldsymbol{C}_4 \end{bmatrix} = \begin{bmatrix} \mathbf{R}_{1,1} & \cdots & \mathbf{R}_{1,\mathrm{j}} \\ \vdots & \ddots & \vdots \\ \mathbf{R}_{4,1} & \cdots & \mathbf{R}_{4,\mathrm{j}} \end{bmatrix} \begin{bmatrix} \boldsymbol{\phi}_1 \\ \boldsymbol{\phi}_2 \\ \vdots \\ \boldsymbol{\phi}_{\mathrm{j}} \end{bmatrix}$$

Response plot across energies for four moderators:

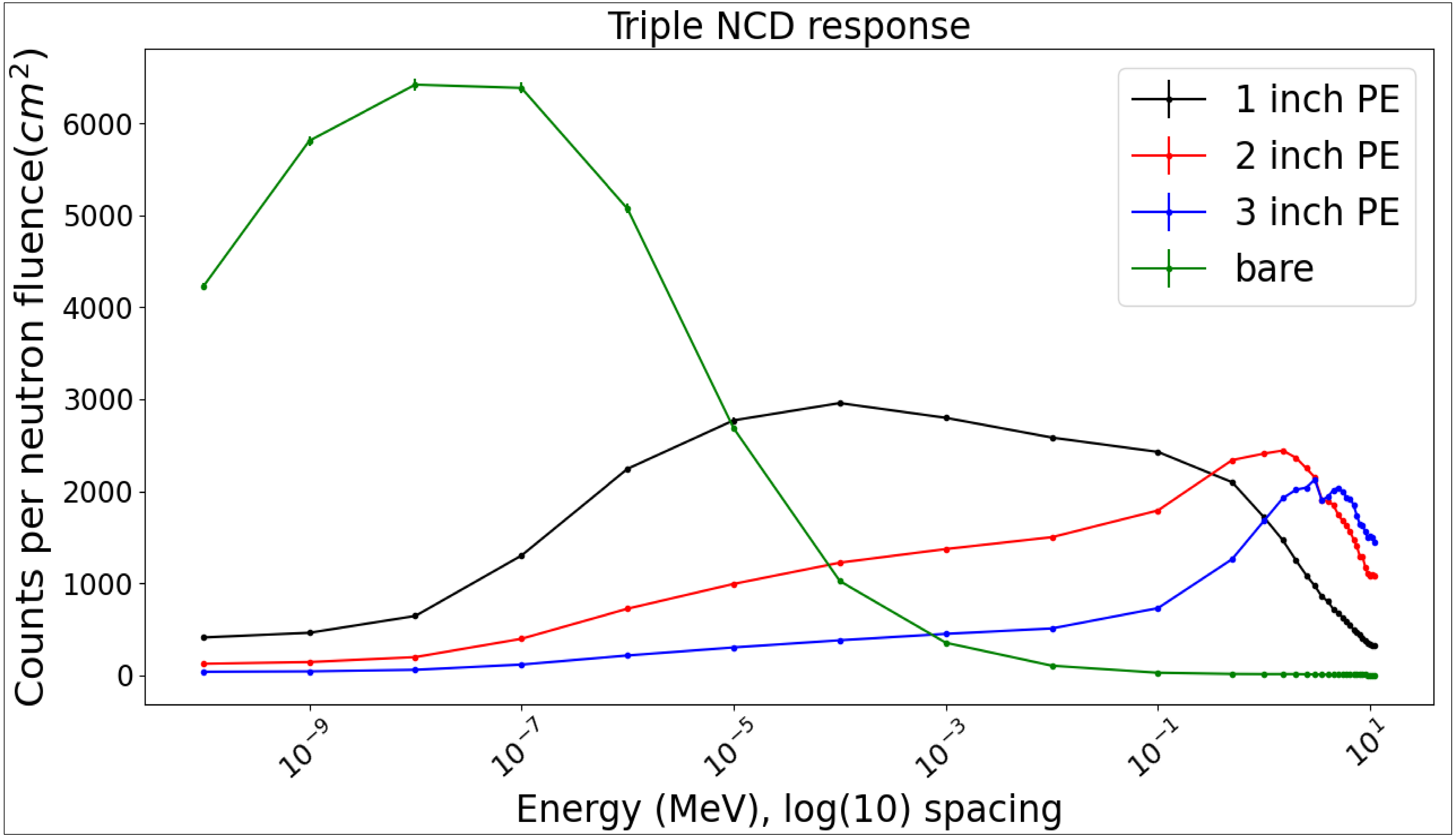


Fig: Triple NCD response

References:

[1] Piscitelli, F., Mauri, G., Laloni, A. *et al.* Verification of He-3 proportional counters' fast neutron sensitivity through a comparison with He-4 detectors. *Eur. Phys. J. Plus* **135**, 577 (2020). https://doi.org/10.1140/epjp/s13360-020-00600-8

[2] Peplowski, P. N., Yokley, Z. W., Liebel, M., Cheng, S., Elphic, R. C., Hoogerheide, S. F., Lawrence, D. J., & Nico, J. S. (2020). *Position-dependent neutron detection efficiency loss in 3He gas proportional counters*. Nuclear Instruments and Methods in Physics Research Section A, 982, 164574. https://doi.org/10.1016/j.nima.2020.164574

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