Predicting the ambient neutron flux at SNOLAB

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Low Background Team at SNOLAB:

- ❖ Backgrounds for rare-event detectors:
  - → Intrinsic backgrounds from samples
  - → Ambient backgrounds(due to environment)
- ❖ Robust low background detection systems to measure backgrounds:
  - → HPGe detectors, Radon emanation boards, ICP-MS, XIA
- ❖ What about ambient neutrons?

My experience at SNOLAB:

- **My experience as a Low Background Student this year**:

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

  →**Fall 2025**: Neutron detection

- This summer and fall, spent **>70% time** on ambient neutron detectors!

Active Neutron detectors

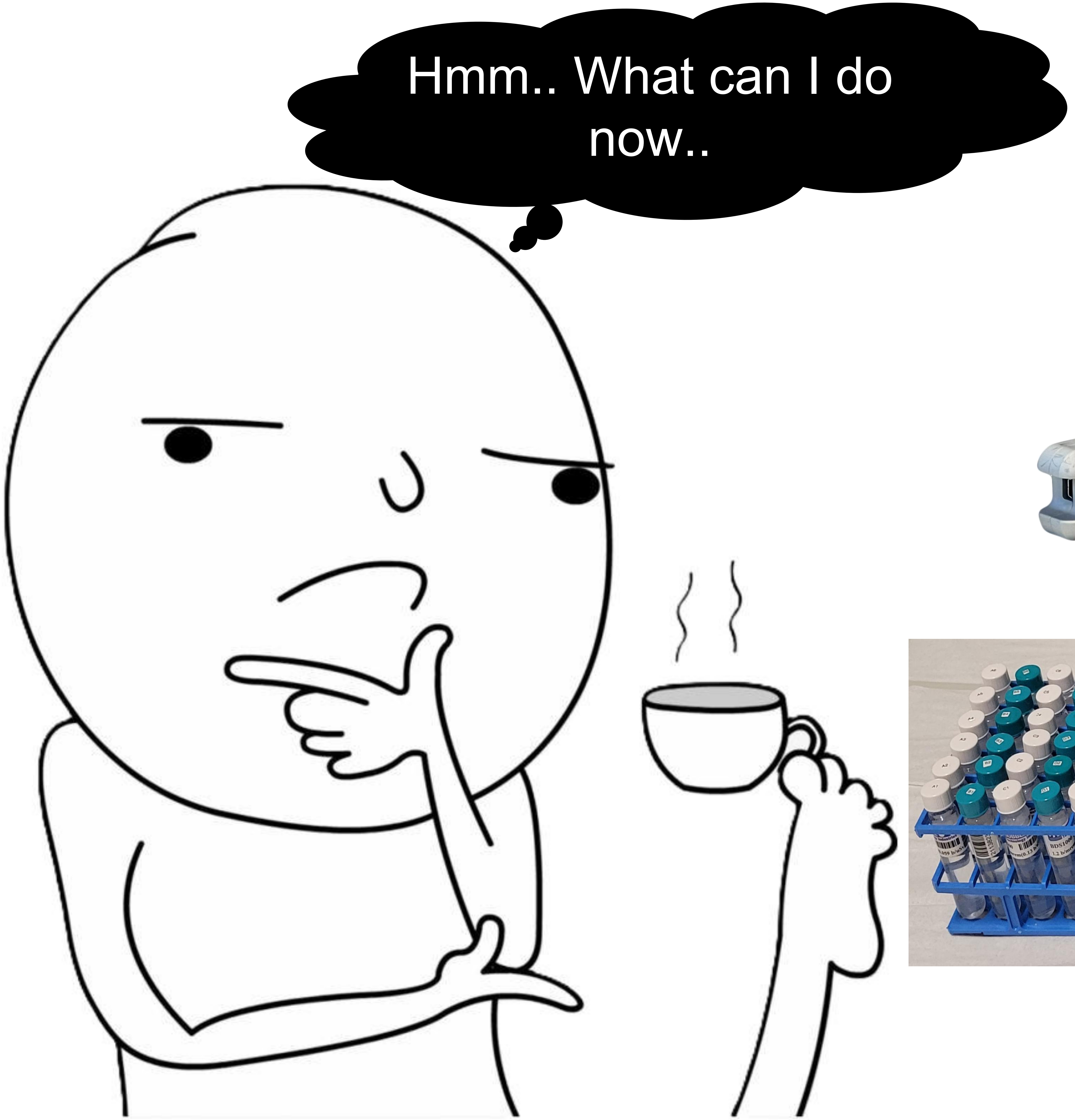
Thermal Neutrons

Epithermal + Fast neutrons

$10^{(-10)}$ MeV — $10^{(-6)}$ MeV — 0.1 MeV — 11 MeV

Thermal neutrons | Epithermal neutrons | Fast neutrons

Time: Early May 2025



Part 1:
Ambient thermal neutrons

Time: Mid May 2025

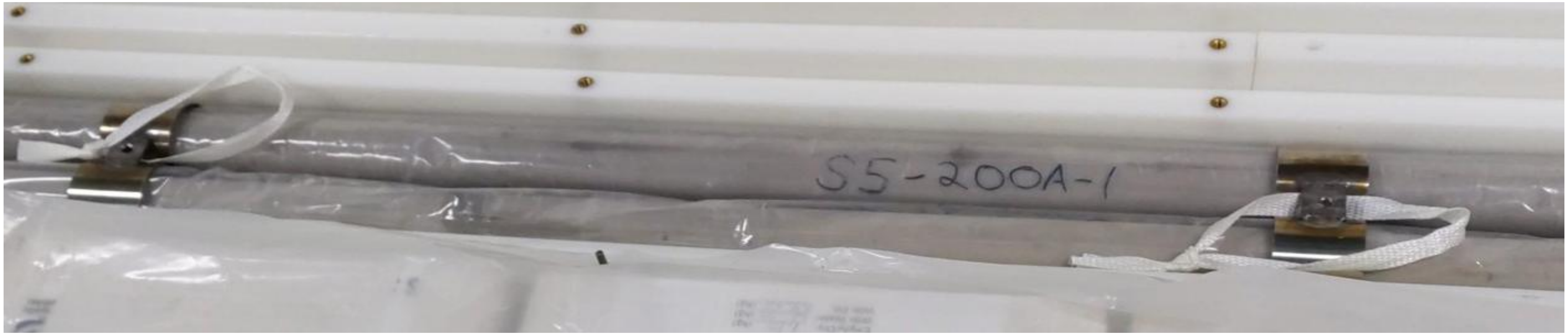
Kishan, you can
use NCDs for
thermal neutrons

Time: Mid May 2025

Kishan, you can use NCDs for thermal neutrons

Neutral Current Detectors(NCDs):

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	$2.50\ \pm 0.01$ atm
Detection principle	Proportional counters: ^{3}He neutron capture



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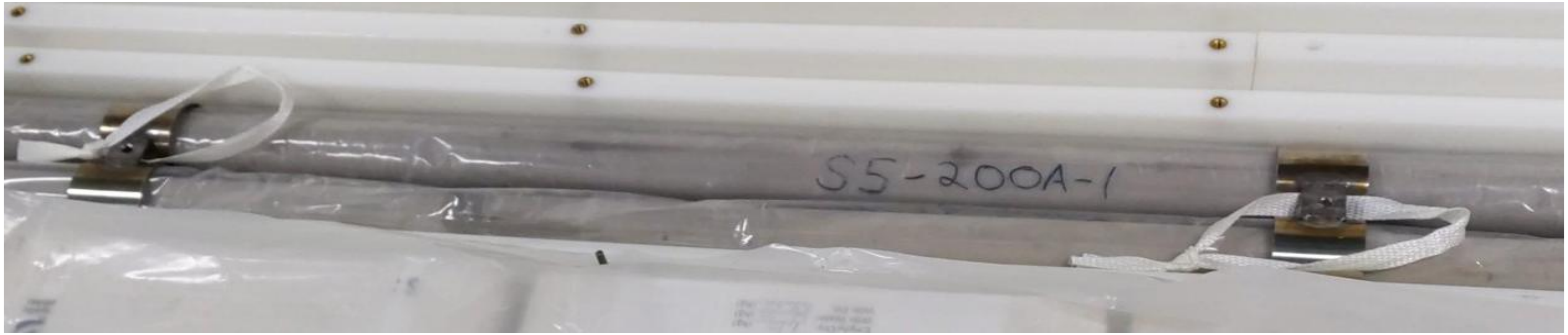
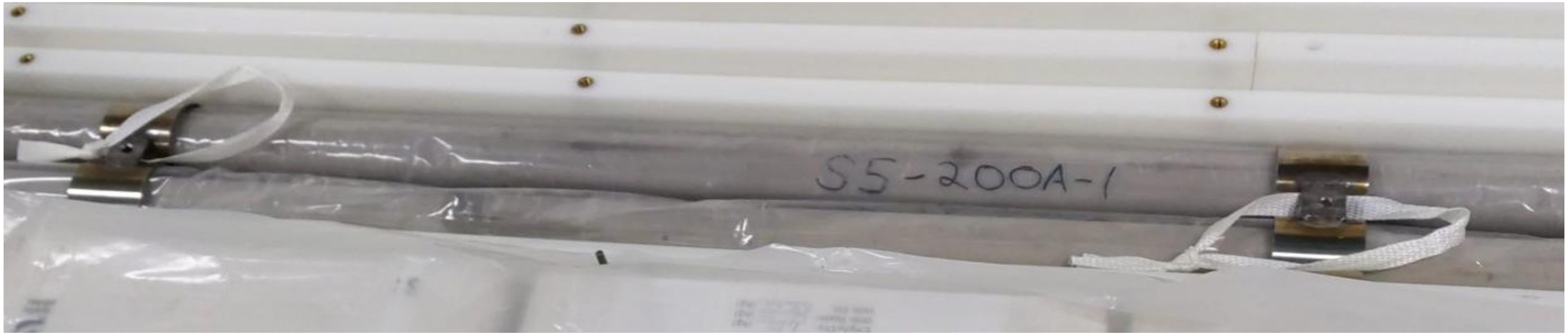


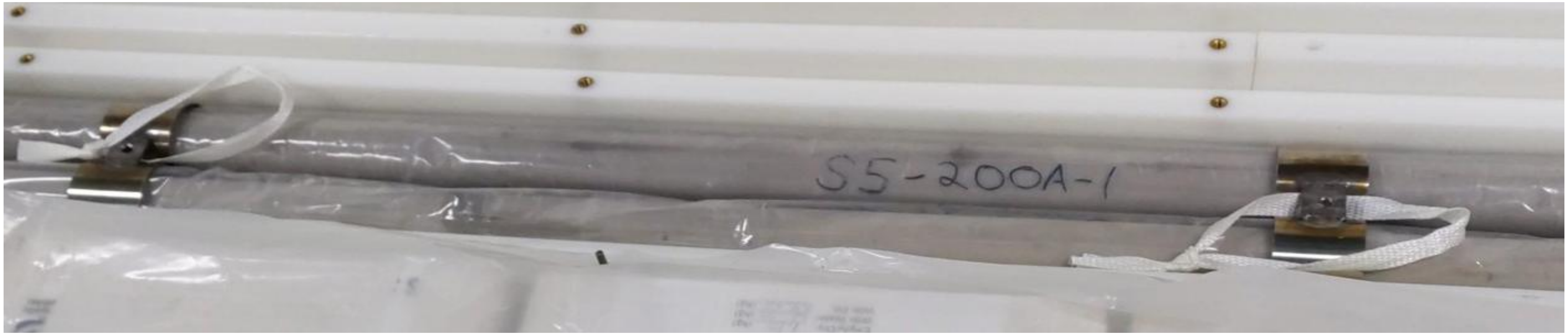
So, I can just use NCDs instead, that easy?

Time: Mid May 2025



You would have to prepare the methodology

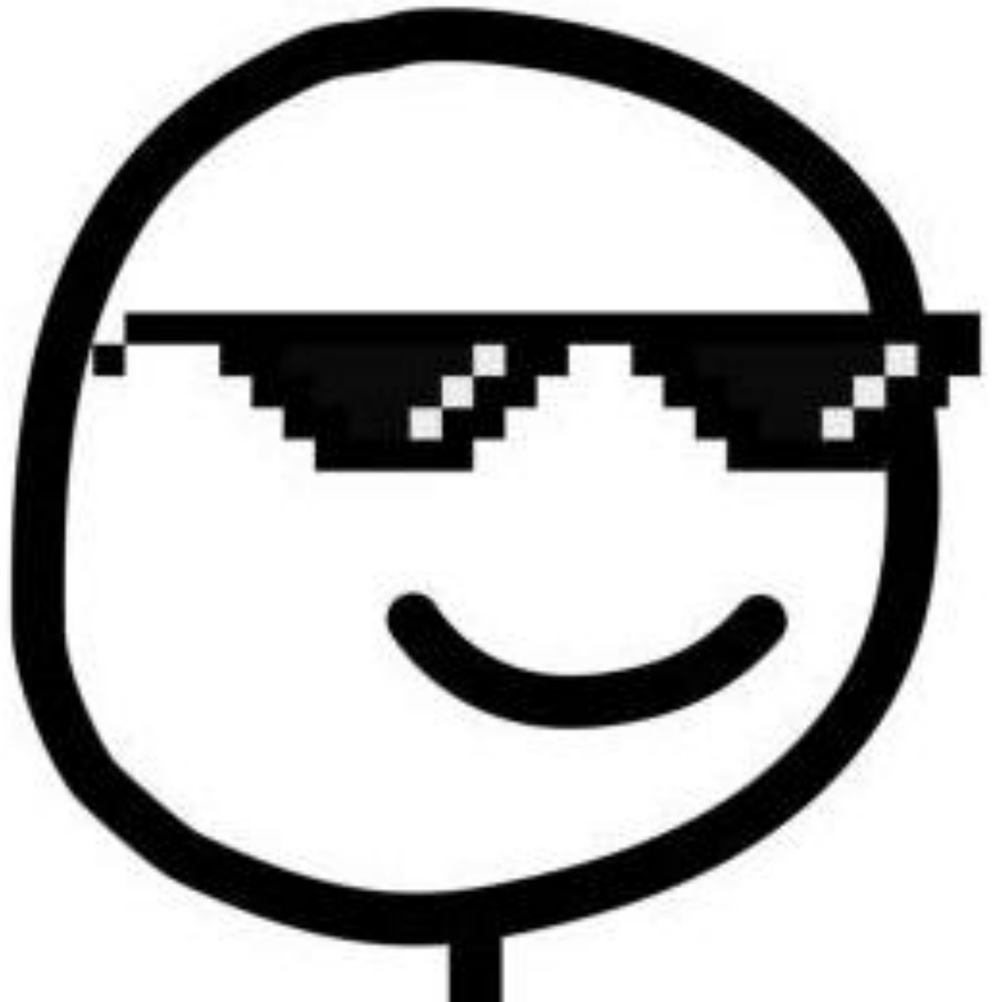
Time: Mid May 2025



Yes, that would be good progress
for neutron measurements

Prepared NCDs neutron detection methodology:

Timeline	Progress
June	Setup three NCDs, made GEANT4 simulation



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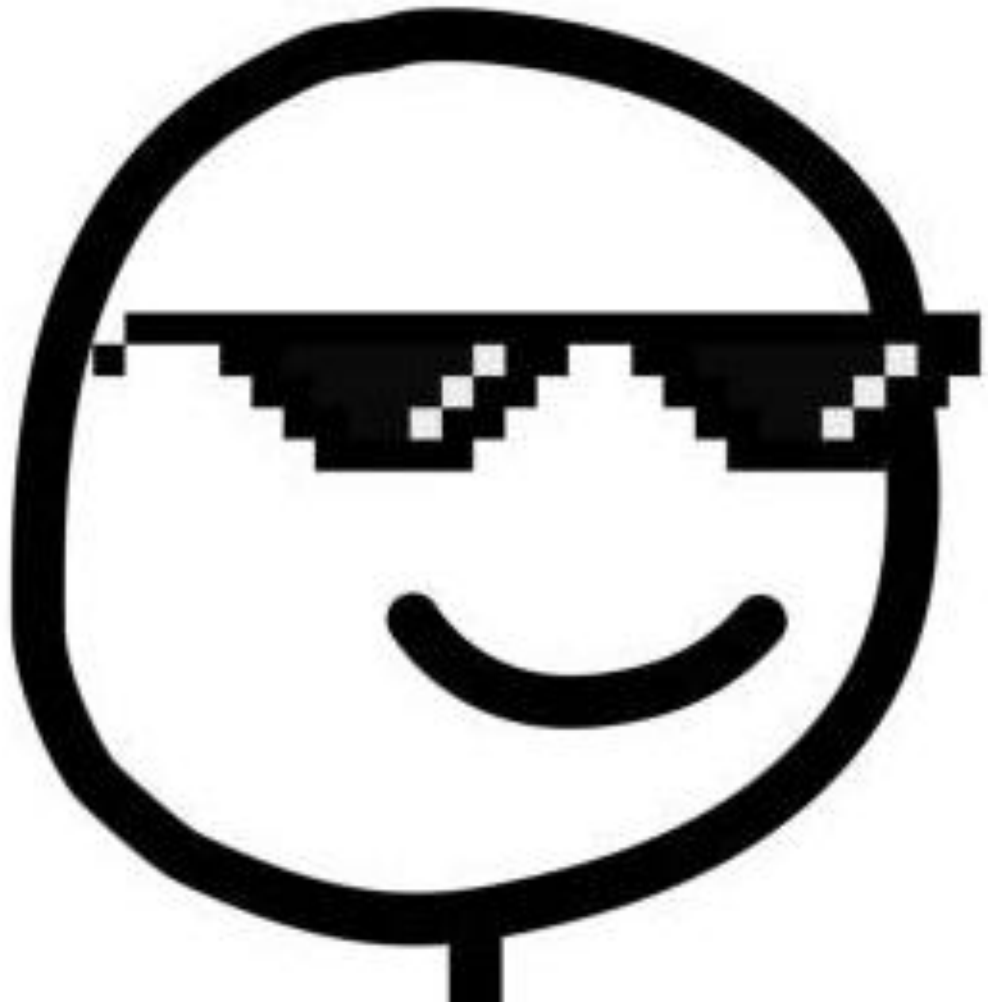

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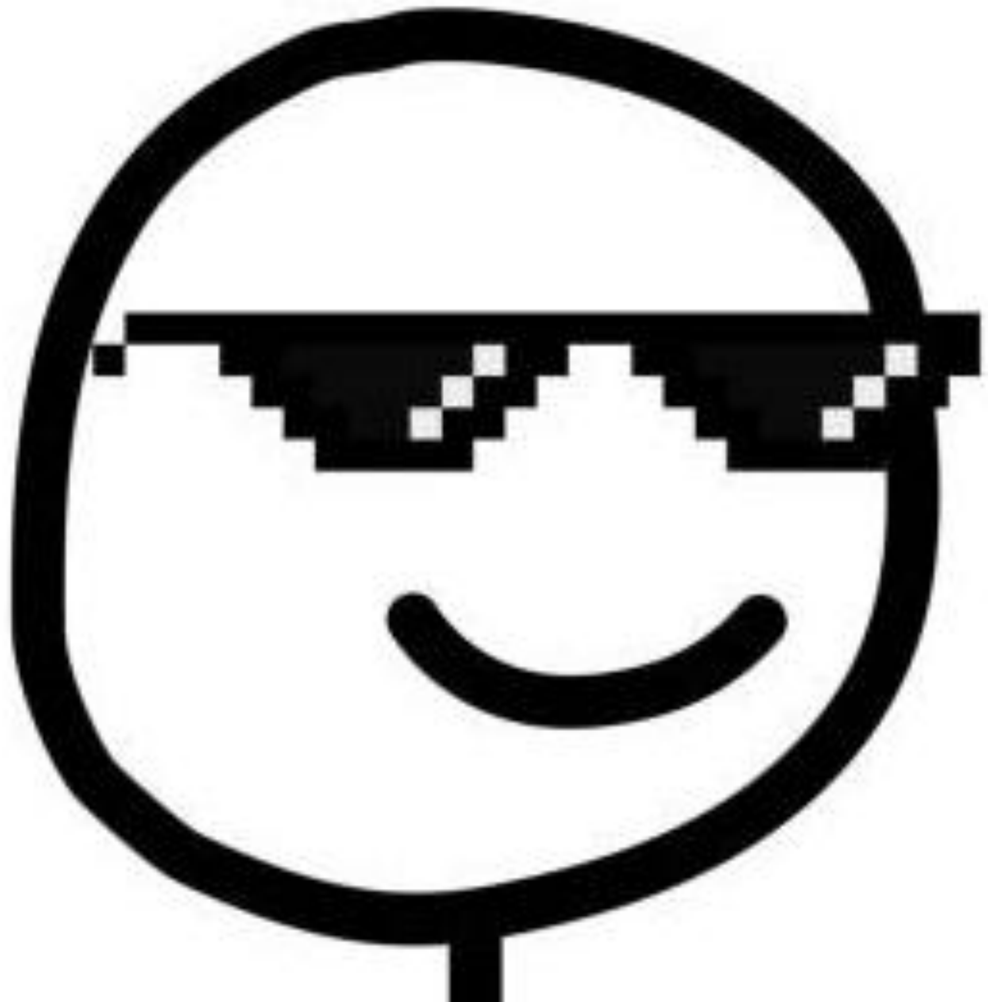

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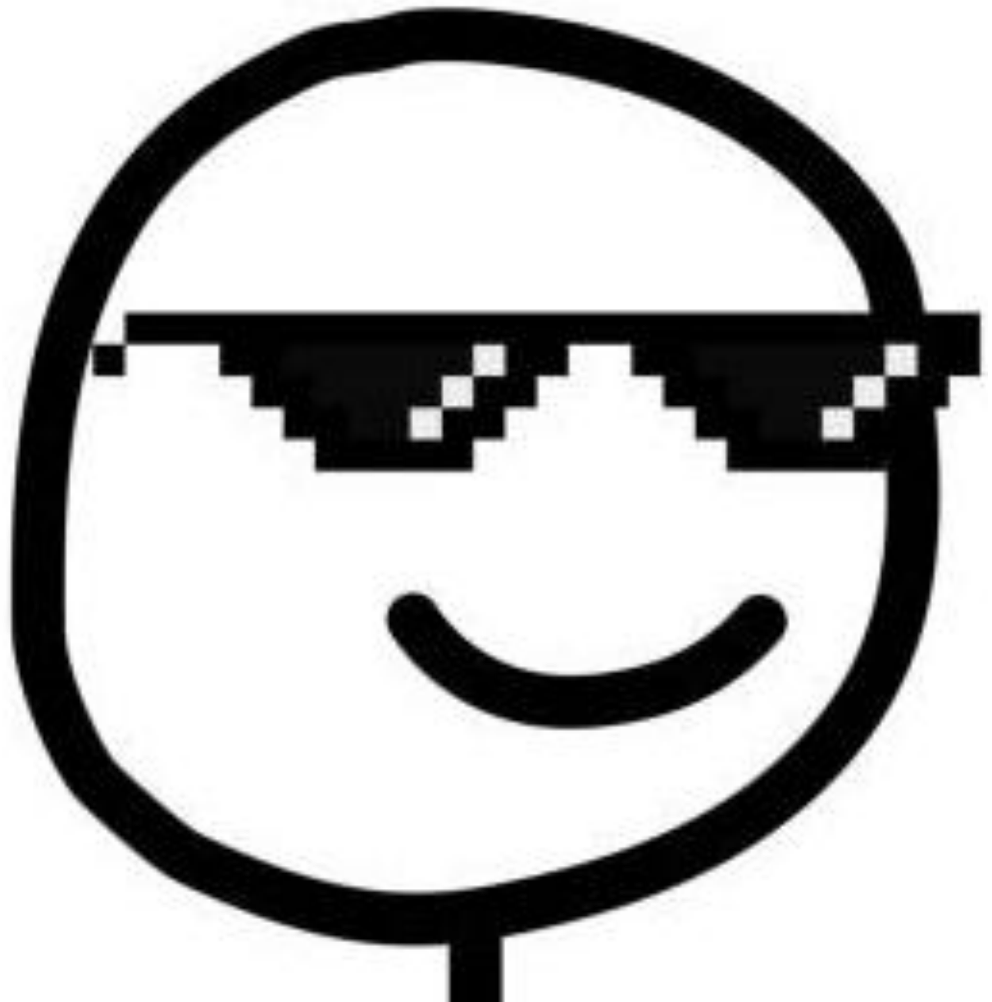

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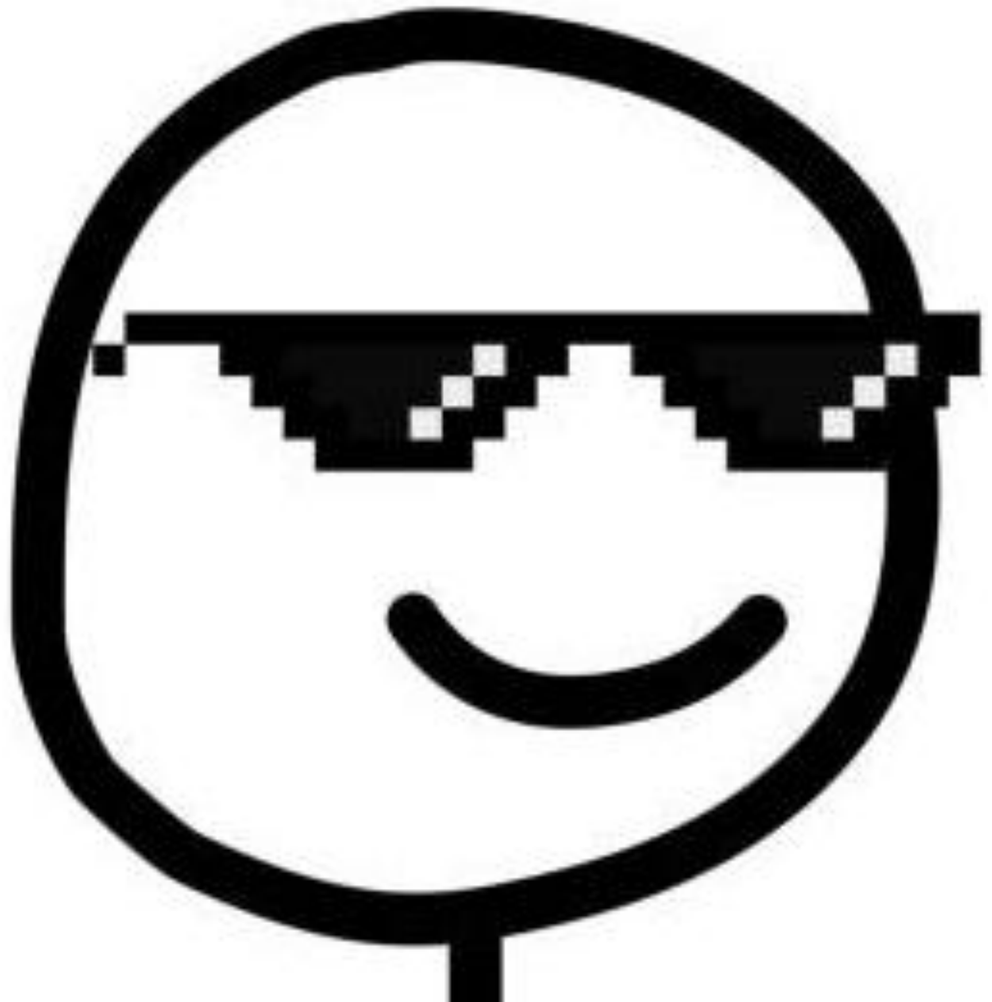

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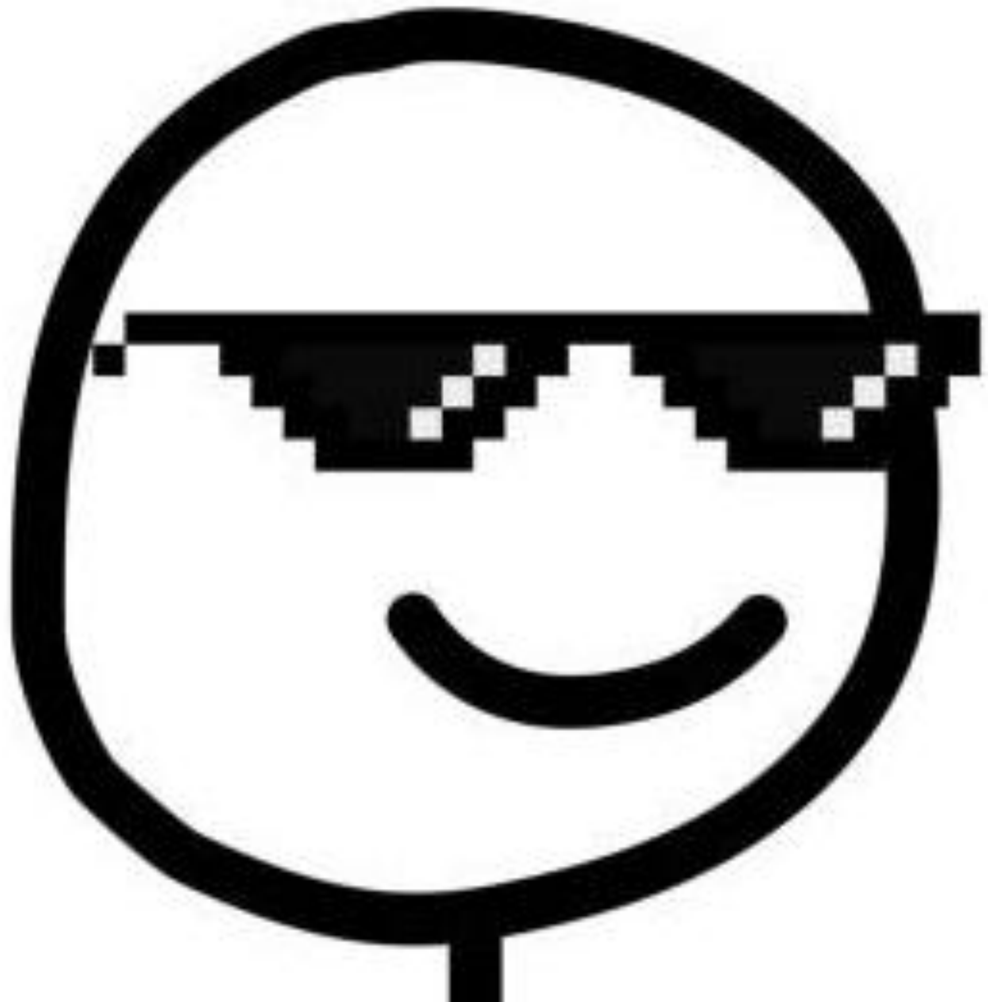
6th December	Calculated thermal flux in J-drift(efficiency was Maxwell-Boltzmann weighted)



Thermal flux across underground labs:

SNOLAB's area(time)	Depth (m.w.e)	Ambient neutron thermal flux $(\mathbf{10^{-6}}\ \boldsymbol{neutrons\ cm^{-2}\ s^{-1}})$	Detector used
SNO area(1999)	6000	$4.80\ \pm 0.06(\text{stat})\ \pm 0.12(\text{sys})$	^{3}He PC
J-drift(present)	6000	$4.37\ \pm 0.04(\text{stat})\ \pm 0.11(\text{sys})$	^{3}He PC

This new measurement is based on ~17 days of data with the three NCD setup

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Excellent, just make sure to document the method!

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Underground lab	Depth (m.w.e)	Ambient neutron thermal flux $(10^{(-6)}\ neutrons\ cm^{(-2)}\ s^{(-1)})$	Detector used
YangYangA6	2000	$24.2\ \pm 1.8$	^3He PC
Canfranc	2450	$1.28\ \pm 0.04$	^3He PC
Kamioka	2700	7.88	^3He PC
LNGS Hall C	3800	$0.24\ \pm 0.17$	^3He PC
Modane	4800	$3.57\ \pm 0.05\ \pm 0.27$	^3He PC
CJPL-1	6720	$7.03\ \pm 1.81$	^3He PC

Table: Neutron flux for UG labs

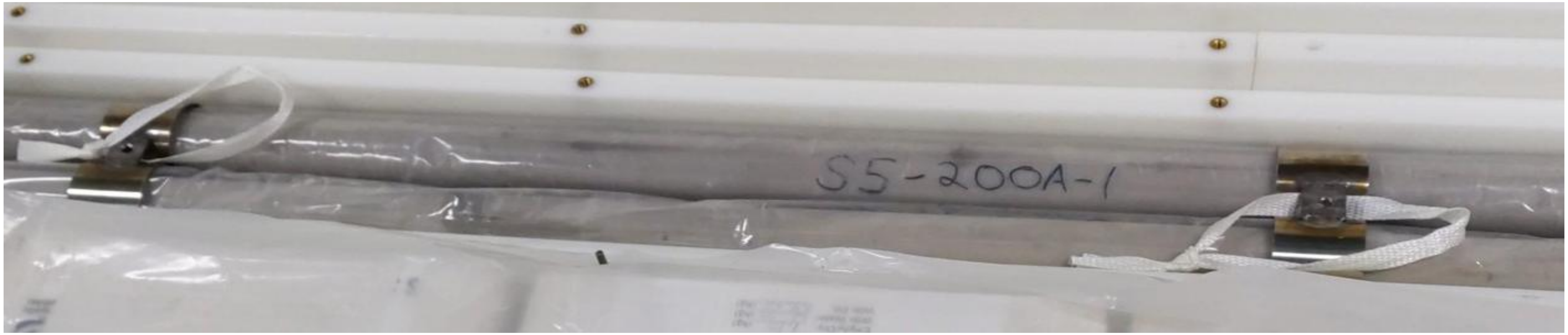
(Yoon et al., Astroparticle Physics, 126, 2021)

Active Neutron detectors

Thermal Neutrons

Epithermal + Fast neutrons

Thermal Neutrons



Questions for part A?

SPOILER ALERT

Part 1 took only ~**20% of my time**

Part 2:
Neutron flux prediction attempt

Time: Mid May 2025

Do we have another fast neutron detector too?

Time: Mid May 2025

No

Time: Mid May 2025

Moderated NCDs…

But it’s difficult

Idea: Moderators

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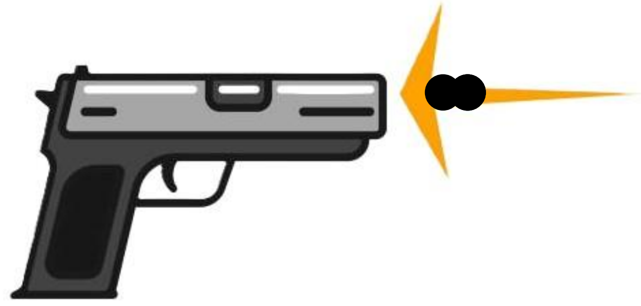
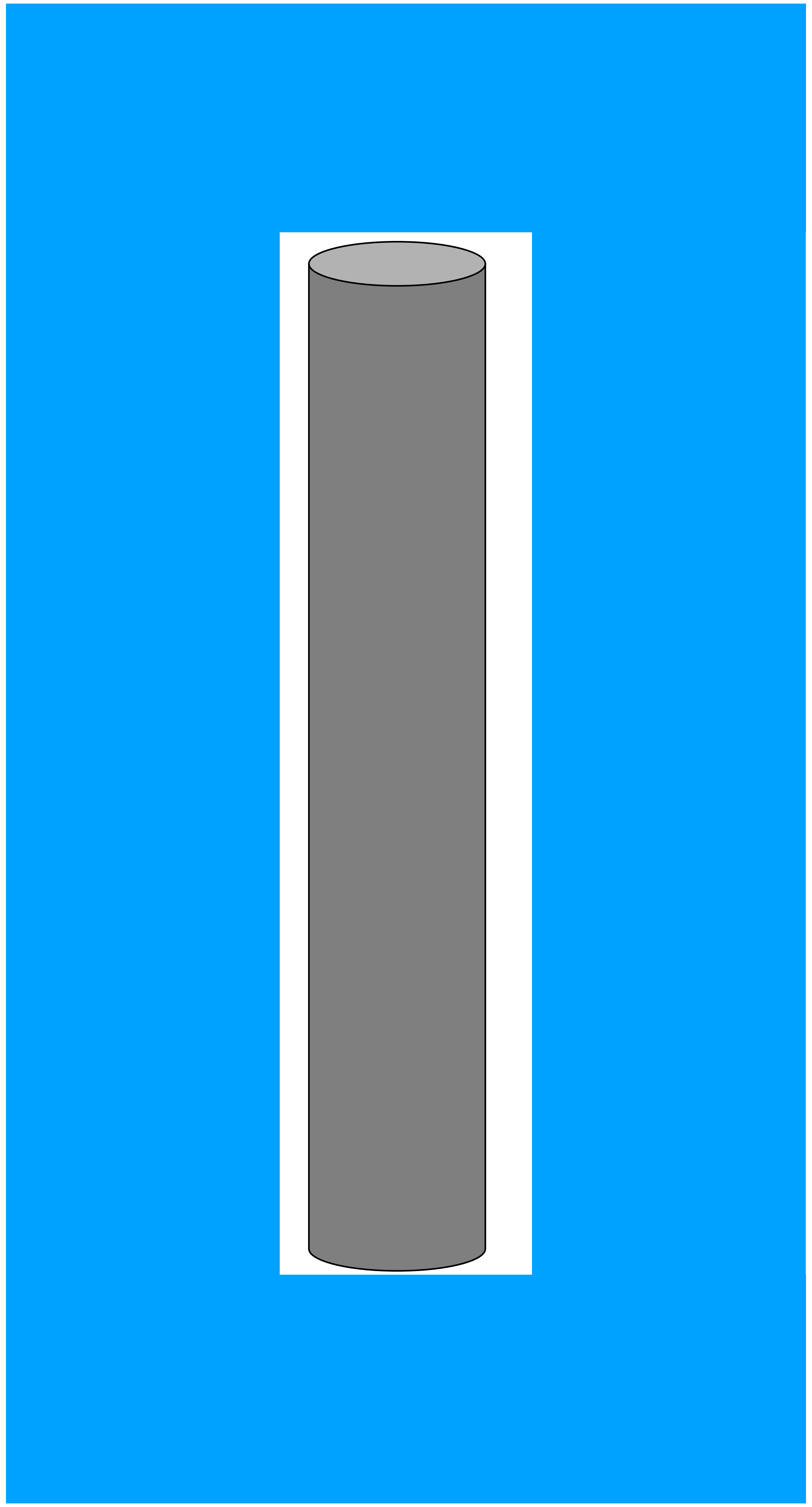




Time: Early June 2025

We already have three
moderators:
1”,2” and 3” polyethylene

Time: Mid May 2025

The nature of scattering is very… random.. how do experts find the “initial neutrons” from “neutrons detected”

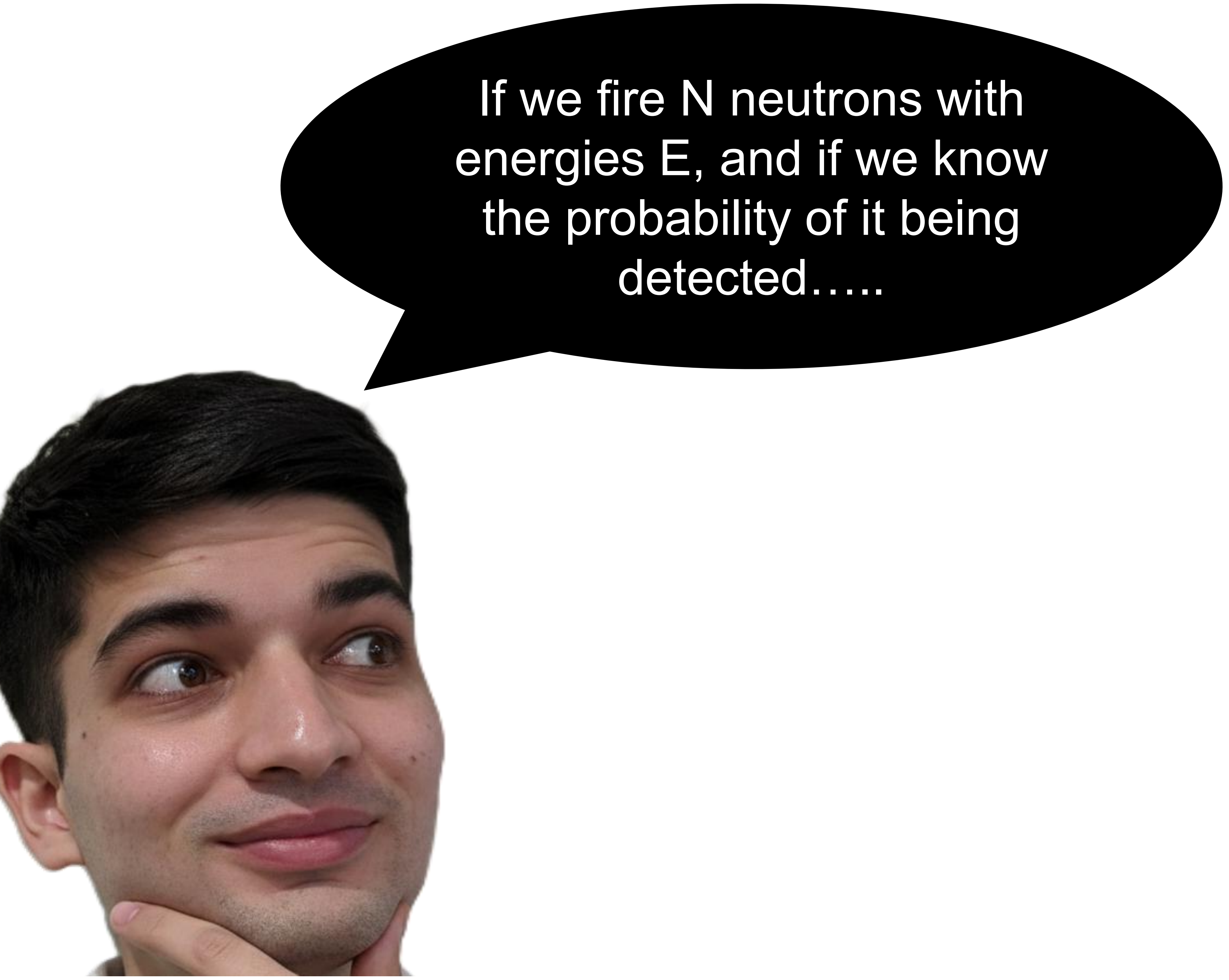
Time: Mid May 2025

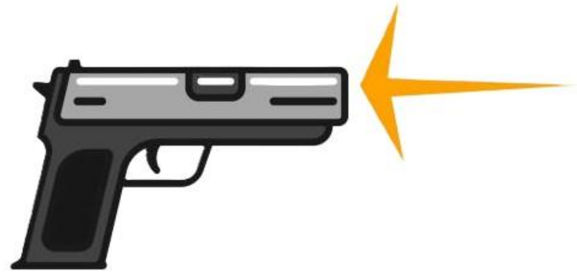
Time: Late July 2025

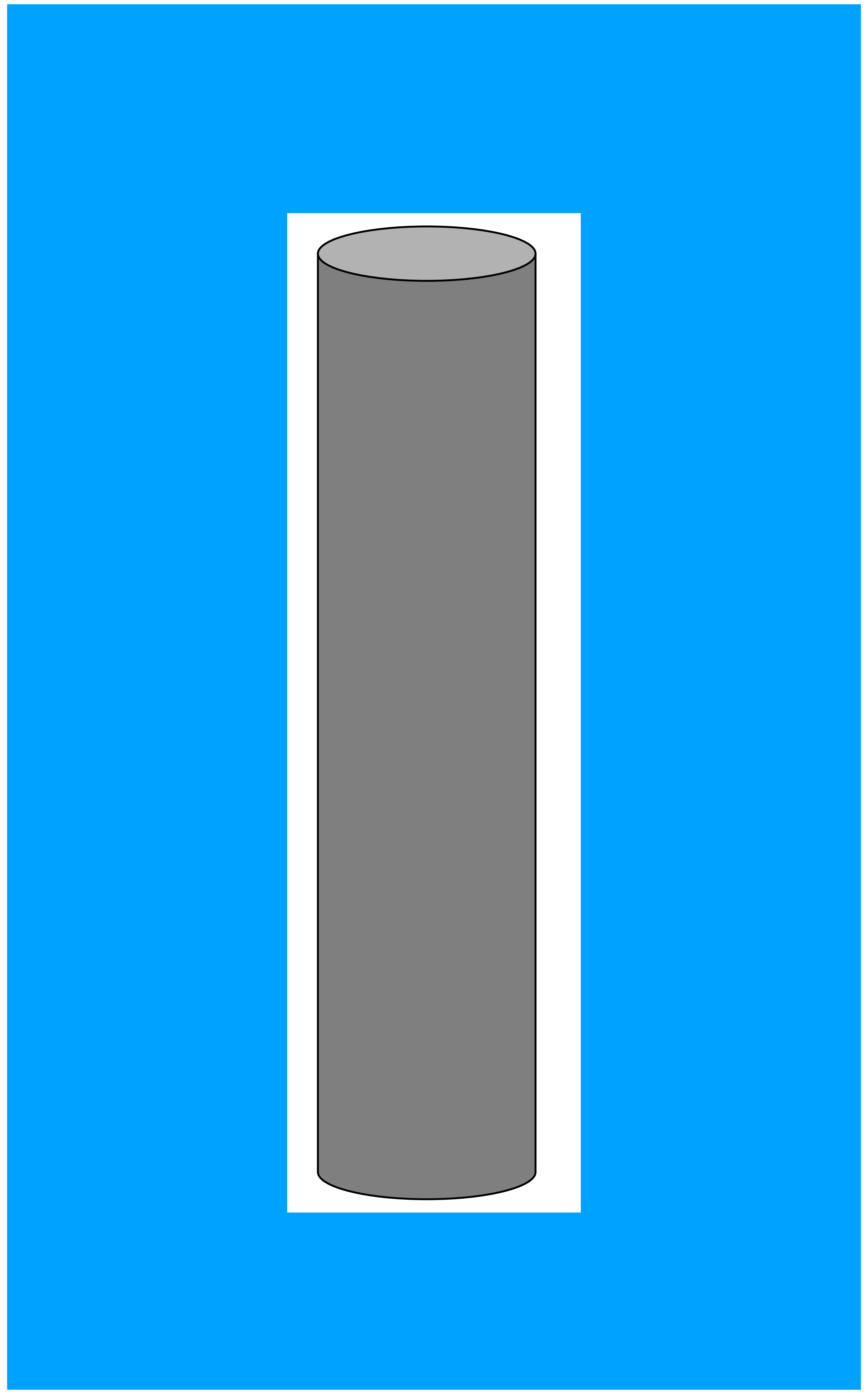
Inference:

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

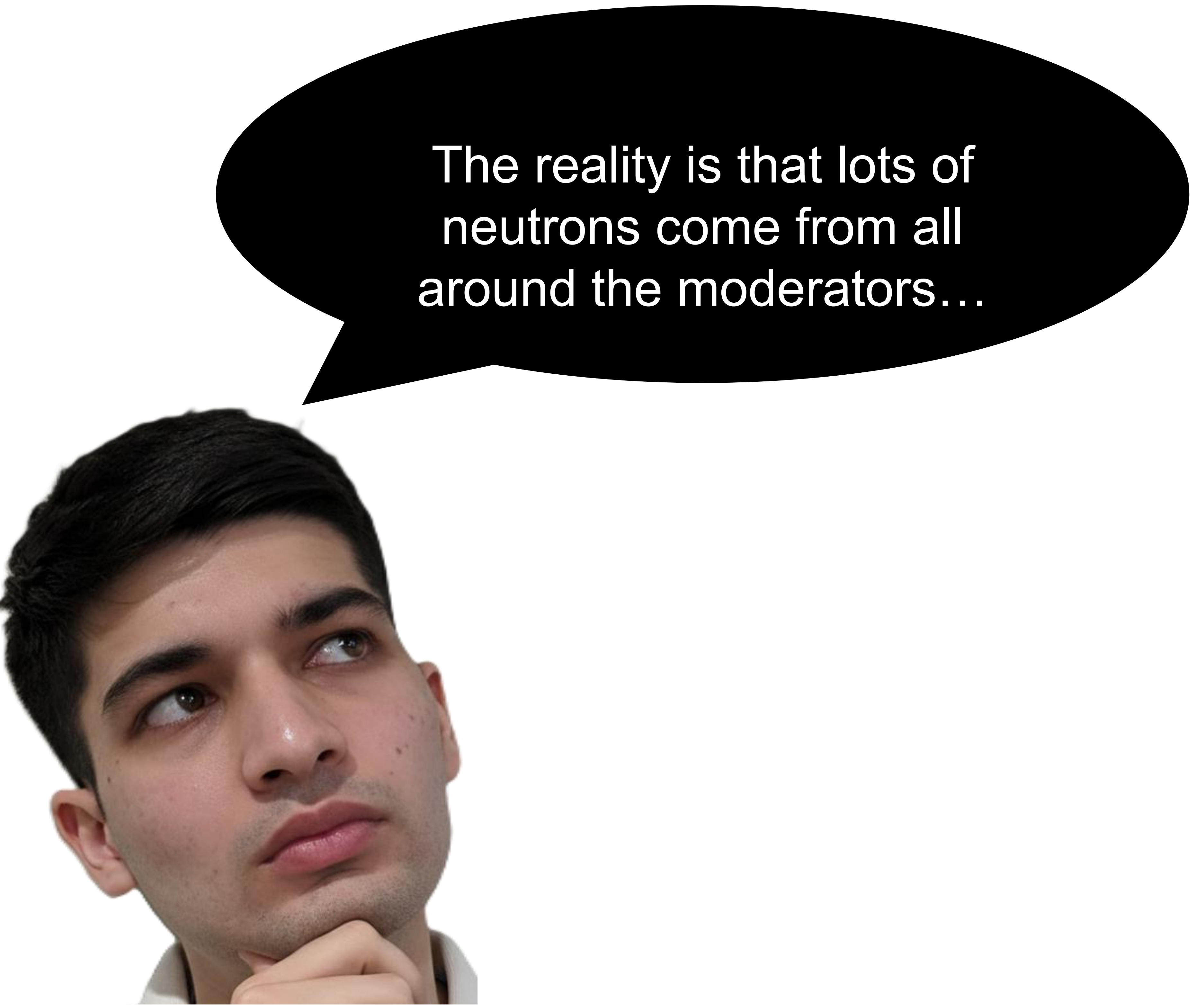
$$C = R(E) \times \phi(E)$$

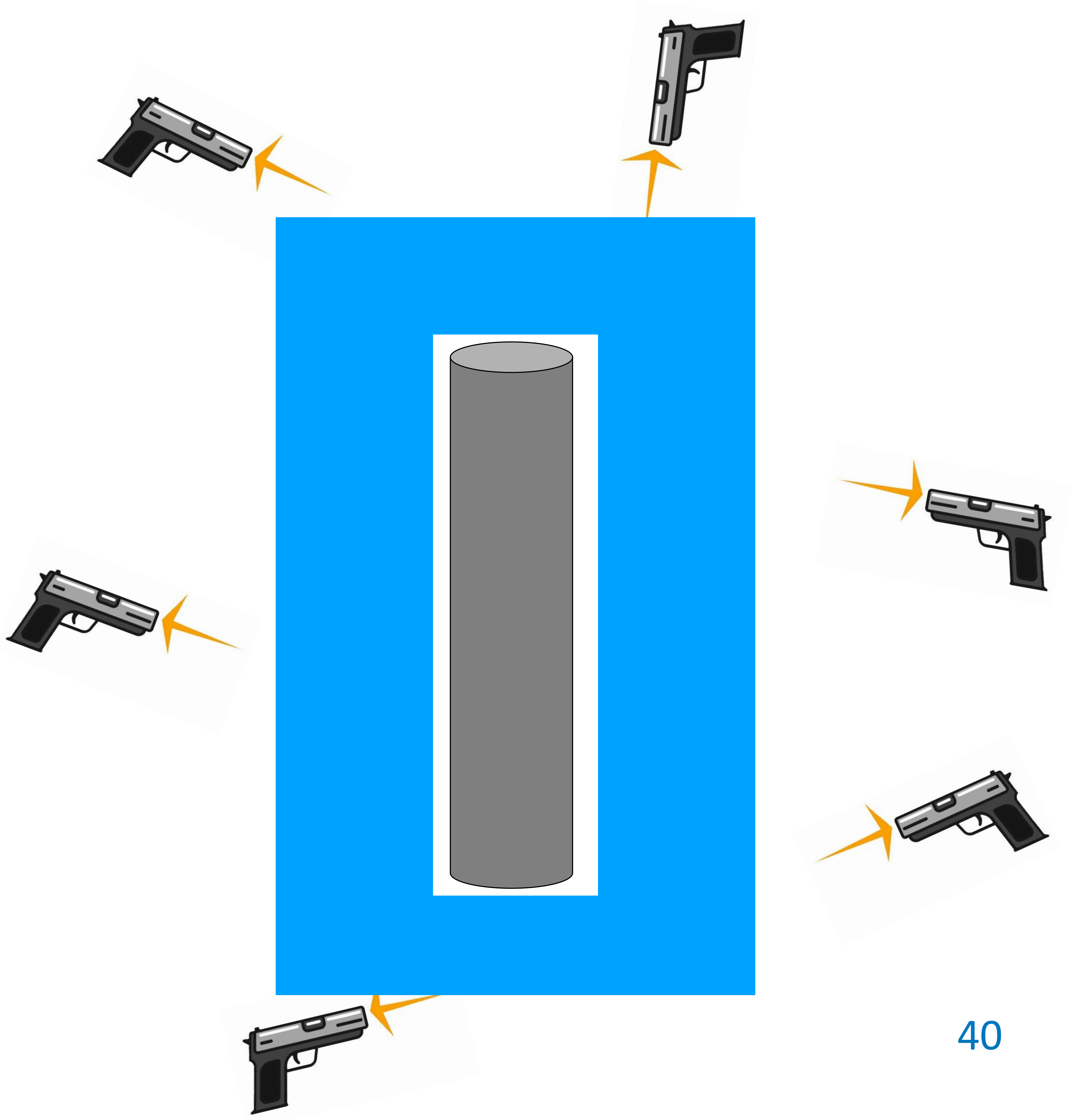




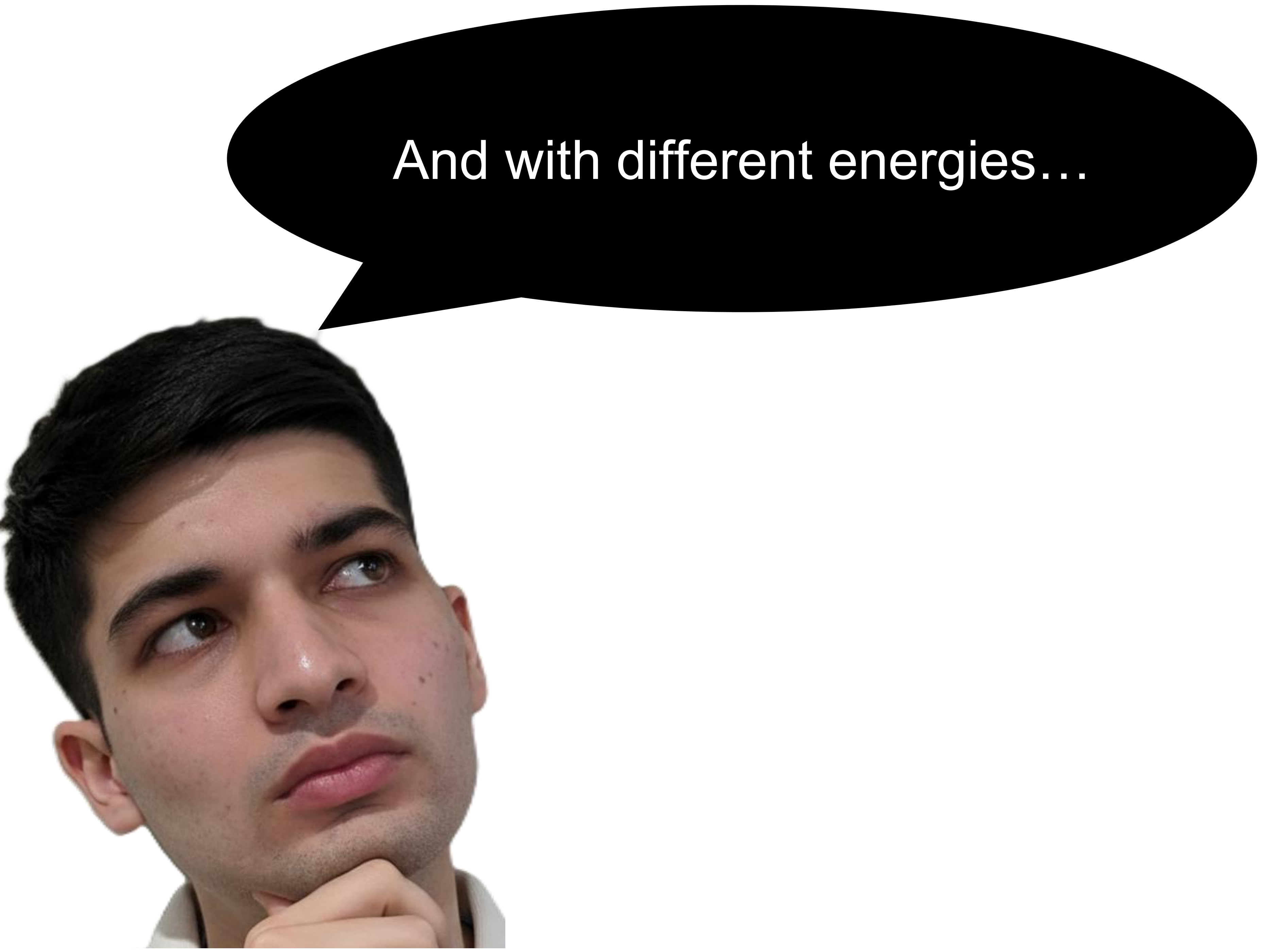


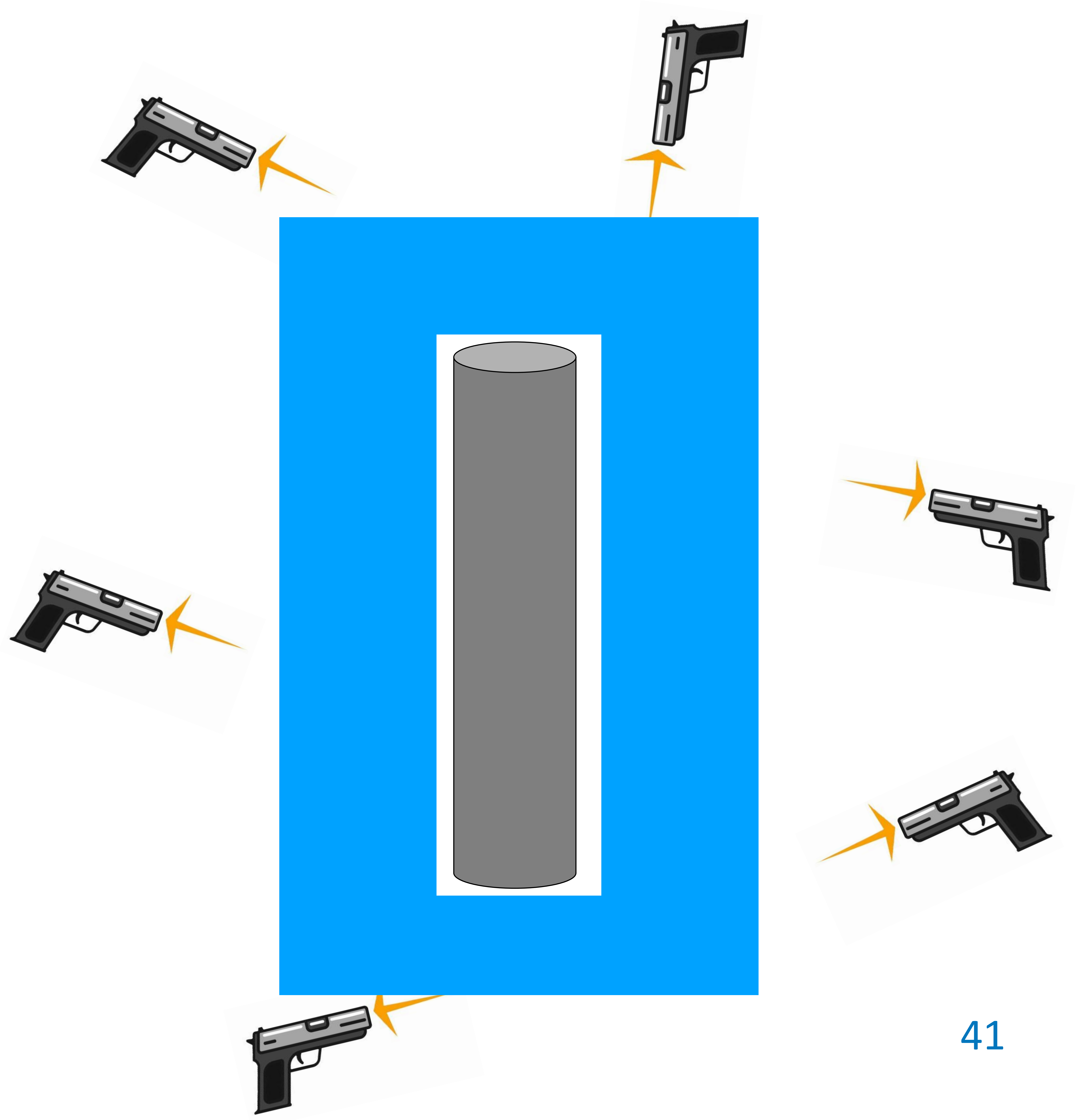
Inference:


The reality is that lots of neutrons come from all around the moderators…

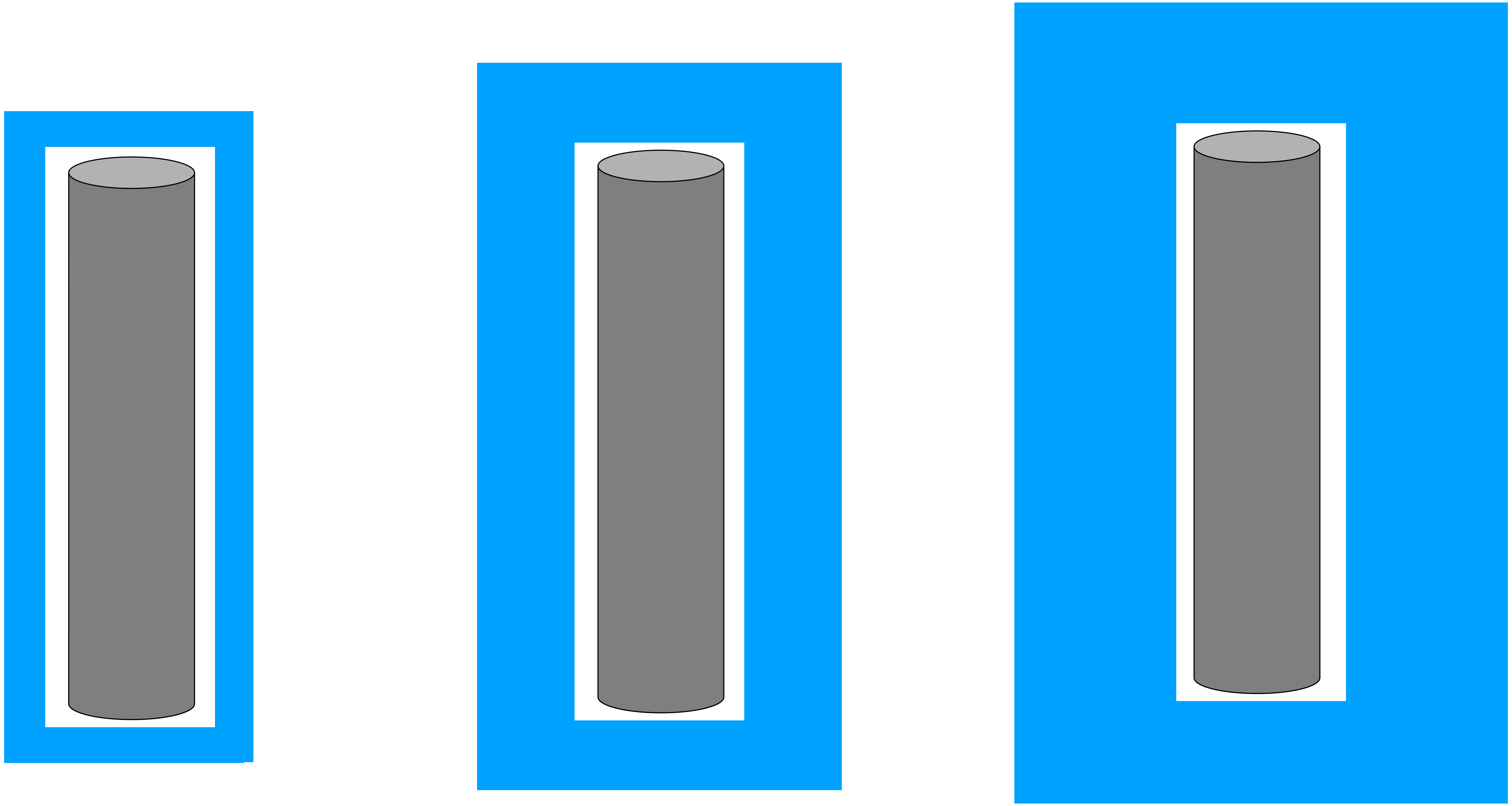


Inference:





Simplified de-convolution:



Simplified de-convolution:

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

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

Simplified de-convolution:

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

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

“4” linear equations with “j” unknown variables:

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

$$\vdots$$

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

Simplified de-convolution:

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

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

Matrix form:

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

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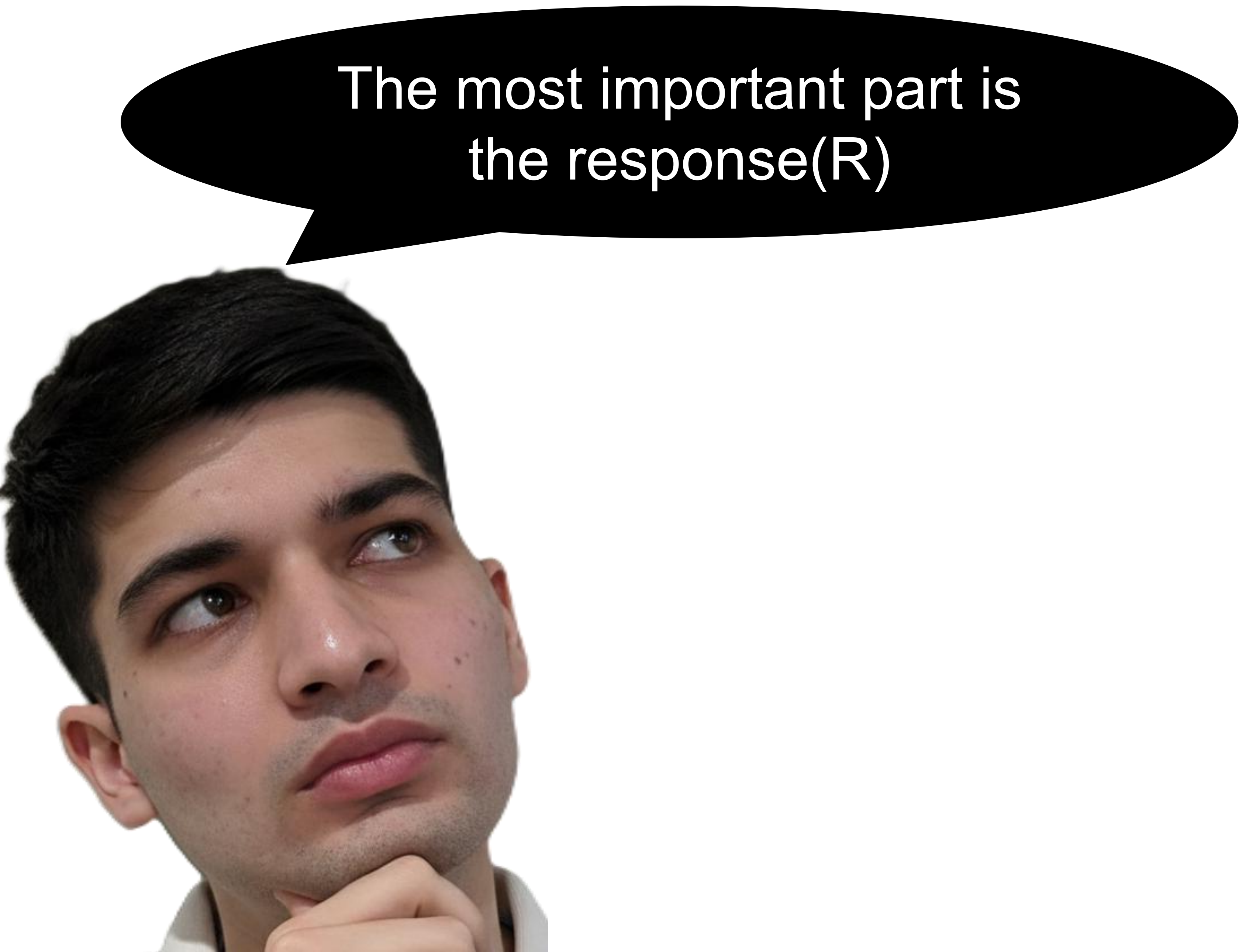


Time: September 2025

Hello Tom, I need your help…

Time: September 2025

Need advice to determine
response for neutron
deconvolution

Time: September 2025

Alright

Evaluated Response using GEANT4 on HPC cluster:

Fig: 1” NCD

Fig: 2” NCD

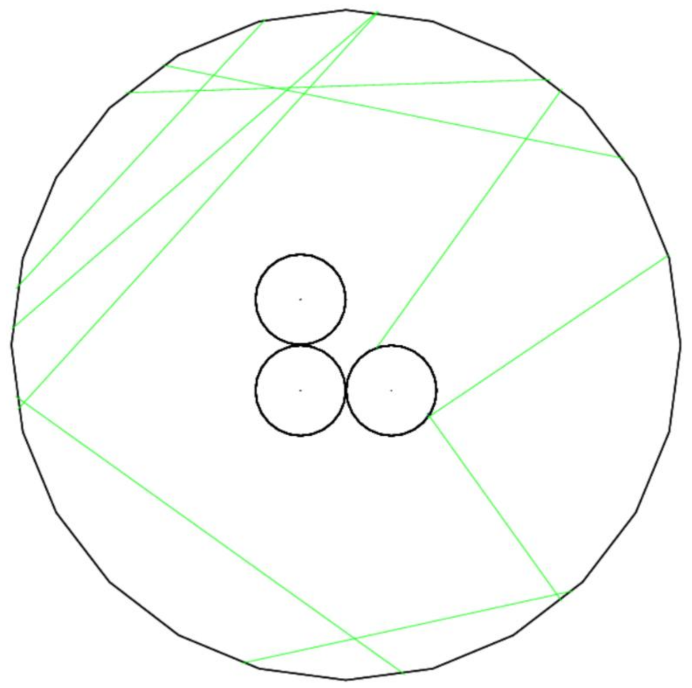
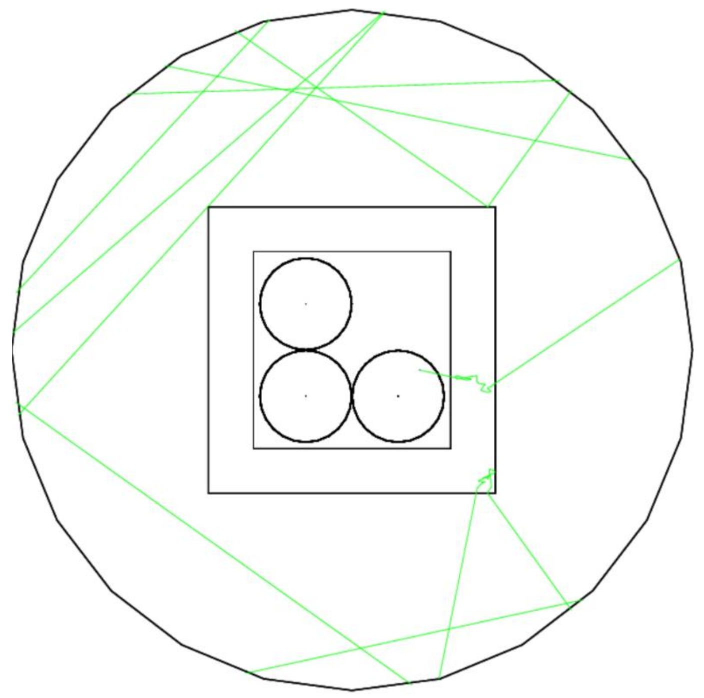
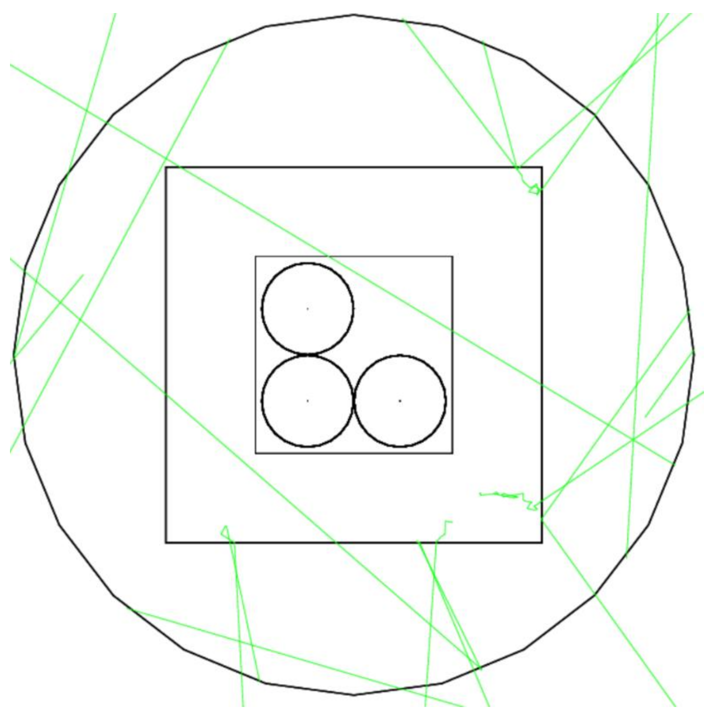


Fig: Bare NCD





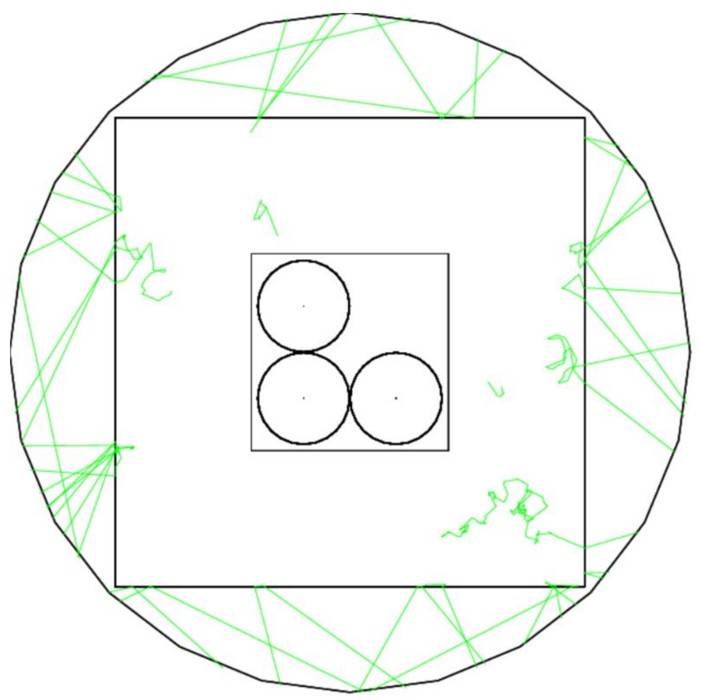
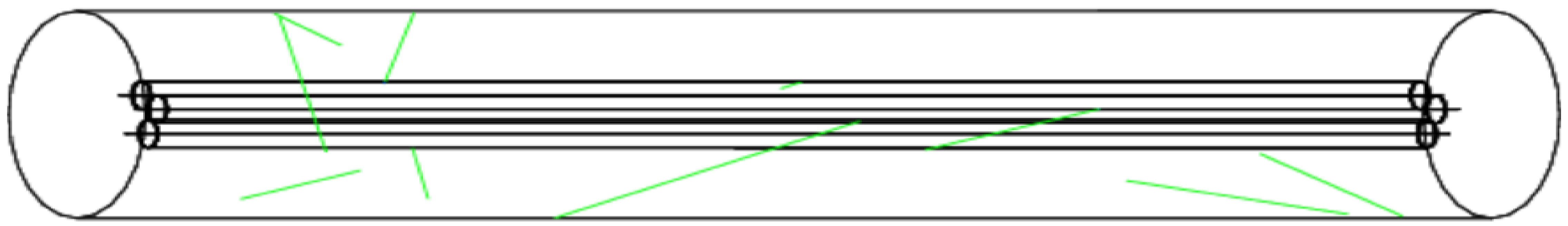
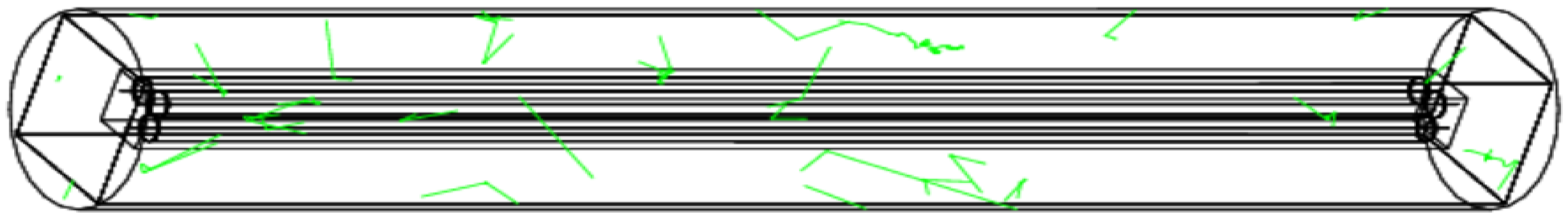
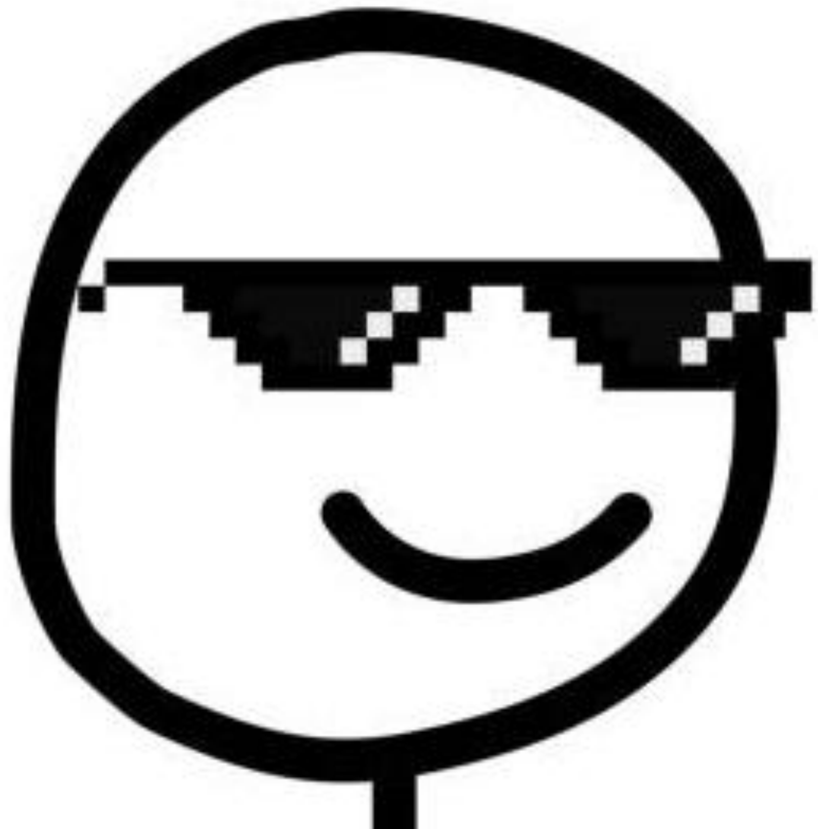


Fig: 3” NCD







→Response(probabilities in terms of effective area) of three NCD setup for four moderations

→Events optimized to limit Poisson fluctuations around 1% relative uncertainty

Response plot across energies for four moderators:

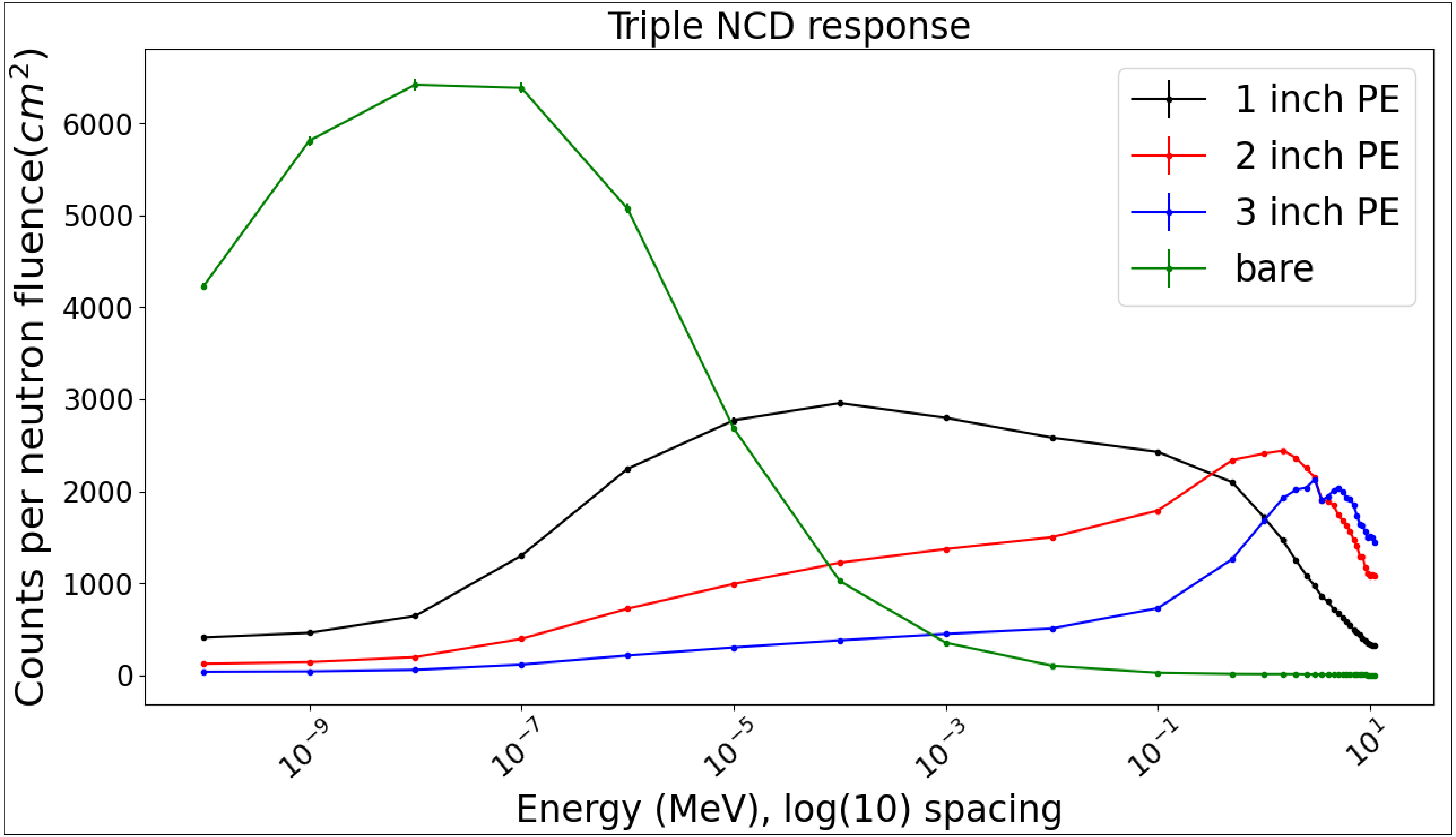
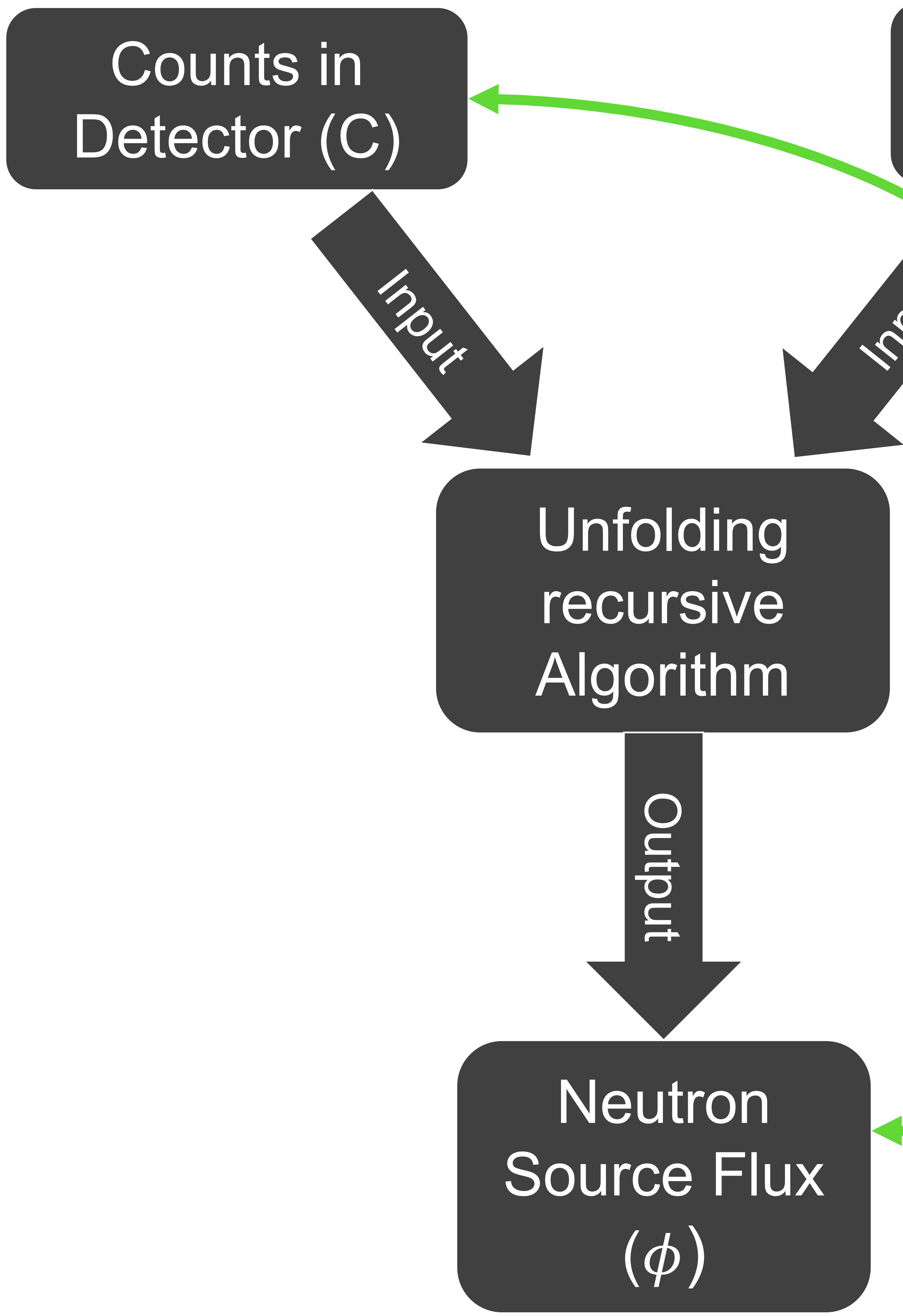


Fig: Triple NCD response

Unfolding(De-convolution) intuition:

- One way to de-convolute such linear equations is through unfolding algorithms



$$\begin{bmatrix} \mathbf{C}_1 \\ \mathbf{C}_2 \\ \vdots \\ \mathbf{C}_i \end{bmatrix} = \begin{bmatrix} \mathbf{R}_{1,1} & \cdots & \mathbf{R}_{1,j} \\ \vdots & \ddots & \vdots \\ \mathbf{R}_{i,1} & \cdots & \mathbf{R}_{i,j} \end{bmatrix} \begin{bmatrix} \boldsymbol{\phi}_1 \\ \boldsymbol{\phi}_2 \\ \vdots \\ \boldsymbol{\phi}_j \end{bmatrix}$$

Time: Late November 2025

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Alan Turing's LU decomposition method:

Image: Alan Turing(Wikipedia)

"Father of Computer Science"

→Goal: Solve for $\boldsymbol{\phi}$ in **C=R** $\boldsymbol{\phi}$ (determined system, ill-conditioned R)

1) Decompose: **R= LU**, so **C=L(U$\boldsymbol{\phi}$)**

$$\overset{\boldsymbol{R}}{\begin{bmatrix} R_{1,1} & R_{1,2} & R_{1,3} & R_{1,4} \\ R_{2,1} & R_{2,2} & R_{2,3} & R_{2,4} \\ R_{3,1} & R_{3,2} & R_{3,3} & R_{3,4} \\ R_{4,1} & R_{4,2} & R_{4,3} & R_{4,4} \end{bmatrix}} = \overset{\boldsymbol{L}}{\begin{bmatrix} 1 & 0 & 0 & 0 \\ L_{2,1} & 1 & 0 & 0 \\ L_{3,1} & L_{3,2} & 1 & 0 \\ L_{4,1} & L_{4,2} & L_{4,3} & 1 \end{bmatrix}} \cdot \overset{\boldsymbol{U}}{\begin{bmatrix} U_{1,1} & U_{1,2} & U_{1,3} & U_{1,4} \\ 0 & U_{2,2} & U_{2,3} & U_{2,4} \\ 0 & 0 & U_{3,3} & U_{3,4} \\ 0 & 0 & 0 & U_{4,4} \end{bmatrix}}$$

Alan Turing's LU decomposition method:

Image: Alan Turing(Wikipedia)
"Father of Computer Science"

→Goal: Solve for ϕ in **C=R** $\boldsymbol{\phi}$ (determined system, ill-conditioned R)

1) Decompose: **R= LU**, so **C=L(U**$\boldsymbol{\phi}$**)**

2) Solve for Y in: **C= LY**, where **Y=U**$\boldsymbol{\phi}$

3)Solve for ϕ in: **Y=U**$\boldsymbol{\phi}$

Prediction results:

Time: 4th December 2025

Method	0 to 11 MeV flux $(10^{(-6)} cm^{-2} s^{-1})$	Thermal flux $(10^{(-6)} cm^{-2} s^{-1})$	Epithermal flux $(10^{(-6)} cm^{-2} s^{-1})$	Fast flux $(10^{(-6)} cm^{-2} s^{-1})$
LU	13.12 ± 1.14	4.13 ± 0.13(MC)	6.14 ± 0.45 (MC)	2.85 ± 0.56(MC)
MLEM	13.14 ± 1.16	4.14 ± 0.14(MC)	6.11 ± 0.45 (MC)	2.89 ± 0.57(MC)
GRAVEL	13.14 ± 1.15	4.14 ± 0.14(MC)	6.11 ± 0.45 (MC)	2.89 ± 0.56(MC)

→Agreement between LU and unfolding algorithms(relatively stable R matrix)

→Note: (Personally) suspect the epithermal and fast neutron flux binning

→Room for improvement!

Questions for part B?

DATE	PROGRESS
May 2025	Began studies with Bubble detectors
June 2025	Terminated Bubble detector studies and shifted focus to NCD experimental setup
July 2025	Found GRAVEL & MLEM unfolding packages (thanks to Tyler Dolezal)
Aug 2025	**Started thermal flux studies**; did simulative test for unfolding
Sep 2025	Collaboration meeting with HENSA, experimental data taking for thermal flux measurements
Oct 2025	Simulations moved to Nibi; validated correction factor from SNO thesis
Nov 2025	Evaluated response using Nibi cluster, prepared Monte Carlo sampling
Dec 2025	Executed prediction method using unfolding and LU

Part 3:
De-convolution is cool

Convolution:

- Generic Convolution integral:

$$A(x) = \int K(x)\, B(x)\, dx \qquad \text{;where K is called kernel}$$

- A very special case: linear algebra approximation:

$$A = K\, B$$

- Lots of real-world application in science

- Example: C=RS(Neutron deconvolution), image reconstruction, solving deterministic simulations etc.

Convoluted image

Convoluted image

De-convoluted image

Original image:



Convoluted image



De-convoluted image



Convoluted image

Convoluted image

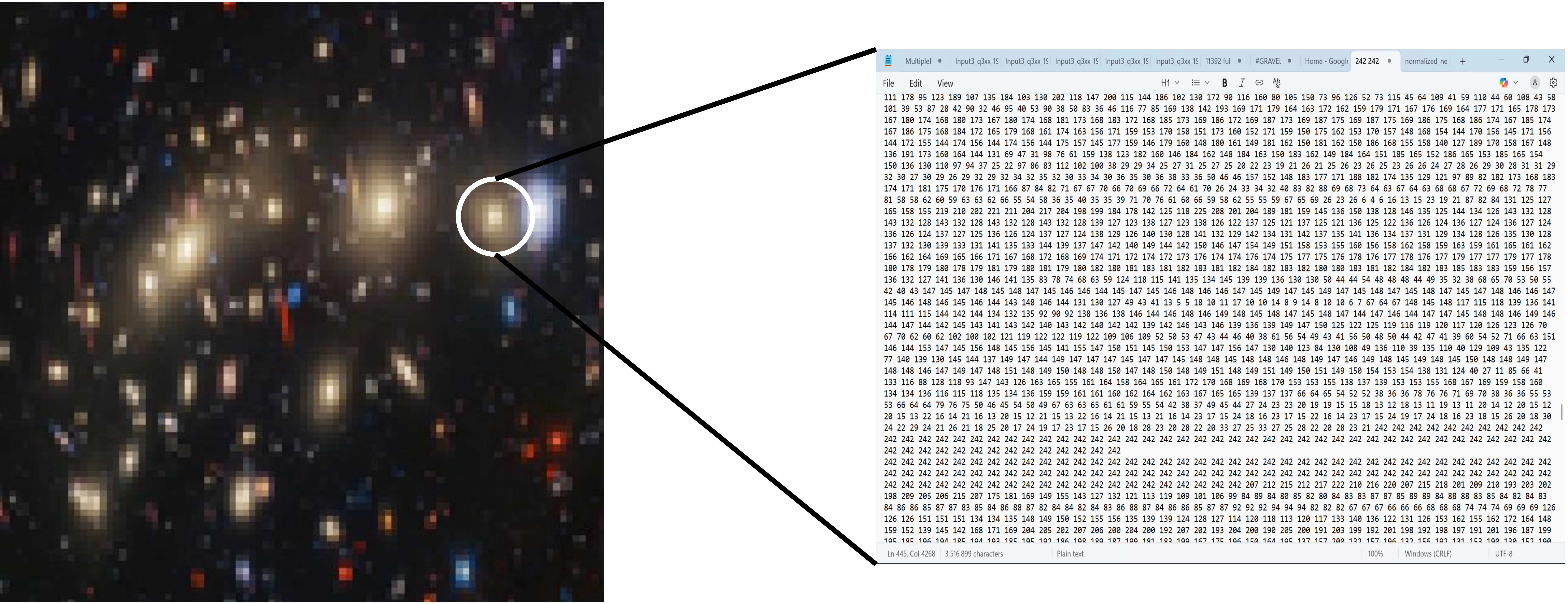
De-convoluted image

Original image

Convoluted image

De-convoluted image

$$\text{New image} = \text{Point spread kernel} \times \text{Original image}$$



Thank you for listening!

Special Thanks to:

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

Questions?

Check simulations validity

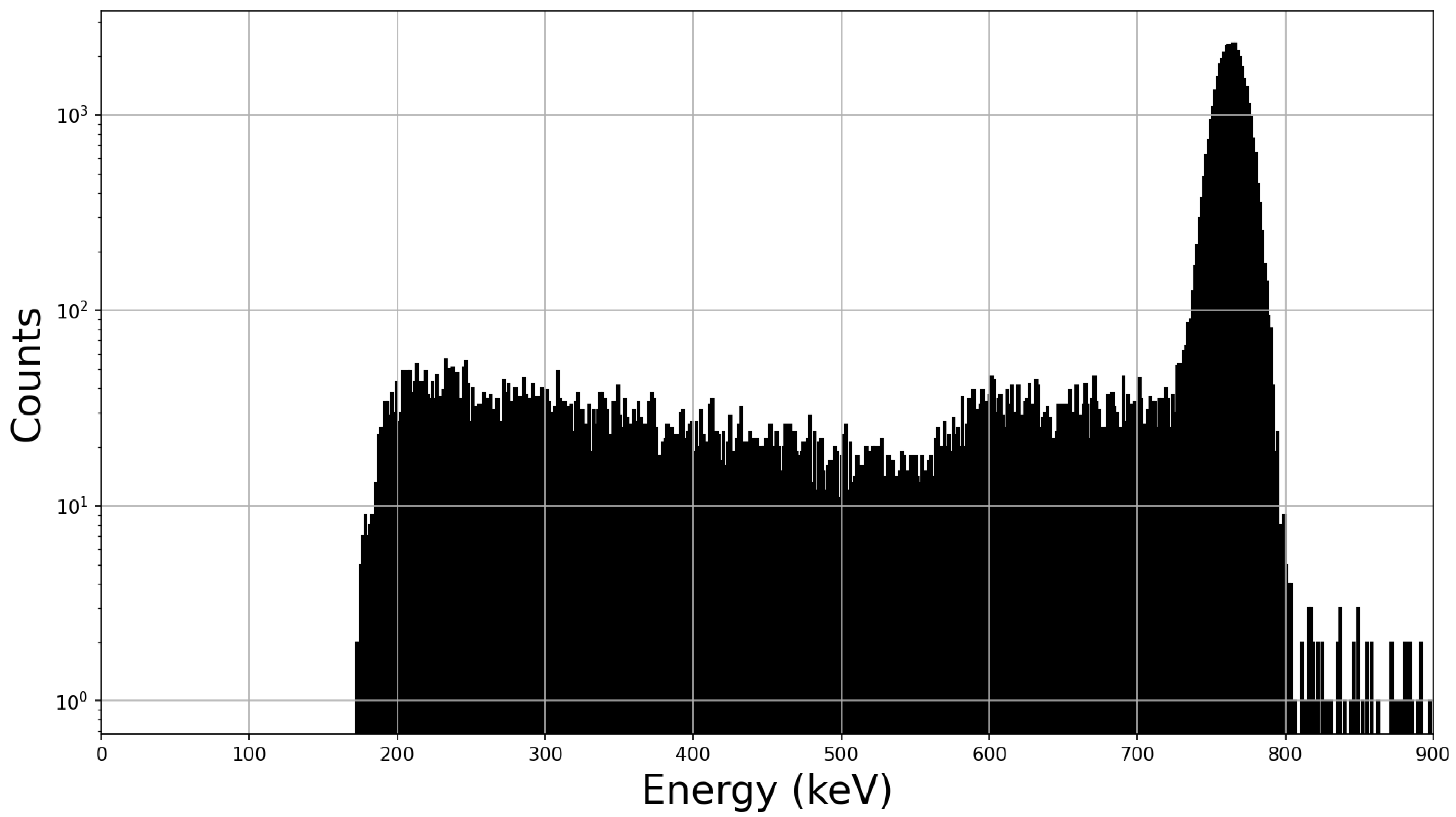


Fig: GEANT4's neutron capture energy deposition with 10 keV gaussian noise

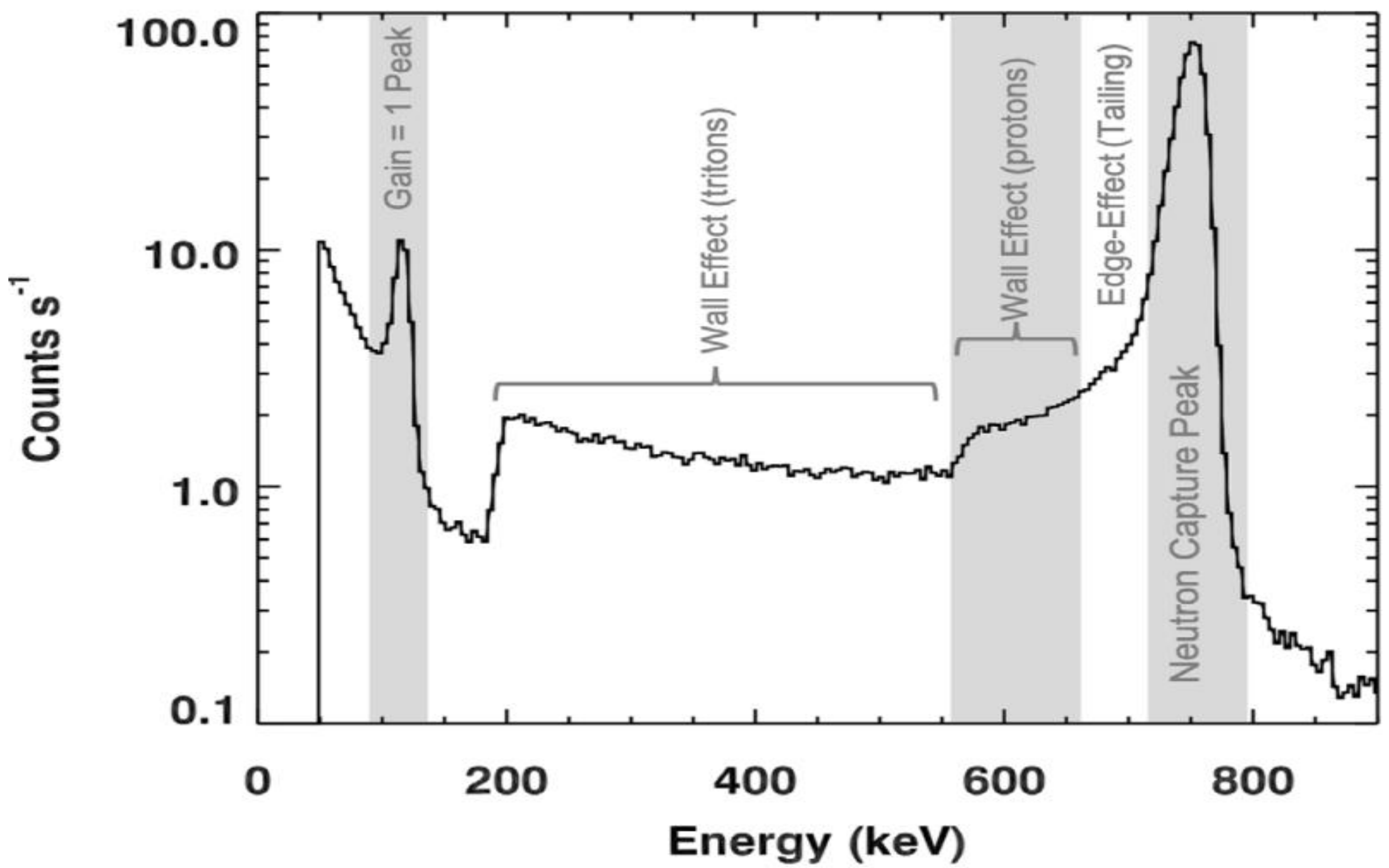


Fig: Experimental energy deposition data (Peplowski et al., NIM A, 982, 164574, 2020)

Check simulations validity → Calculate “R” (using GEANT4) → Measure “C” for AmBe (using GEANT4) → Unfolding: Predicted AmBe counts “S" → Check results!

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%!

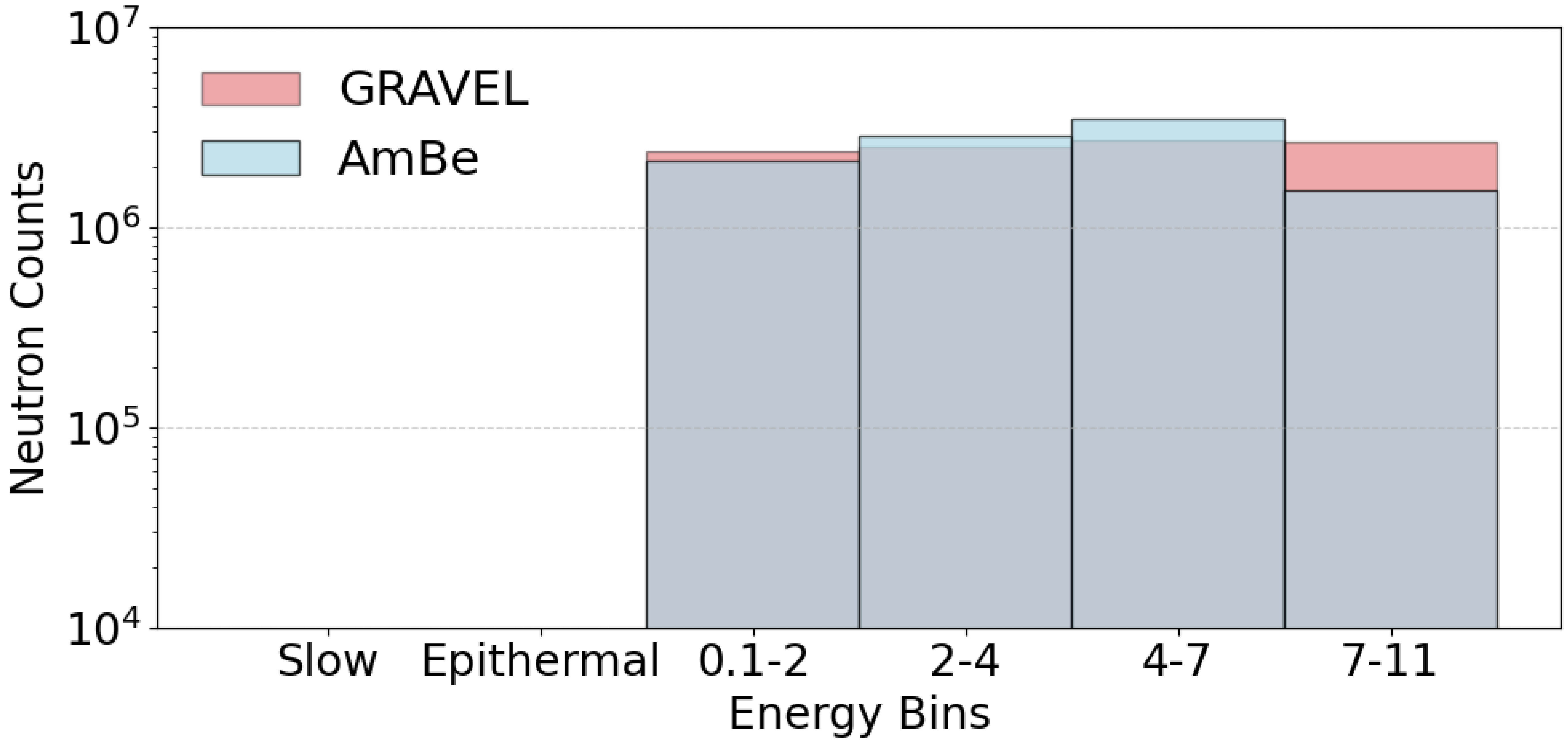
→<u>Takeaway</u>: The Helium-3 counter successfully counts for fast neutrons!

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

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