Le détecteur nFacet : un spectromètre directionnel pour la caractérisation de rayonnements ionisants neutrons et gammas

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42ème Séminaire des PCR et acteurs de la radioprotection du Réseau Grand Ouest

RÉGION NORMANDIE

cnrs

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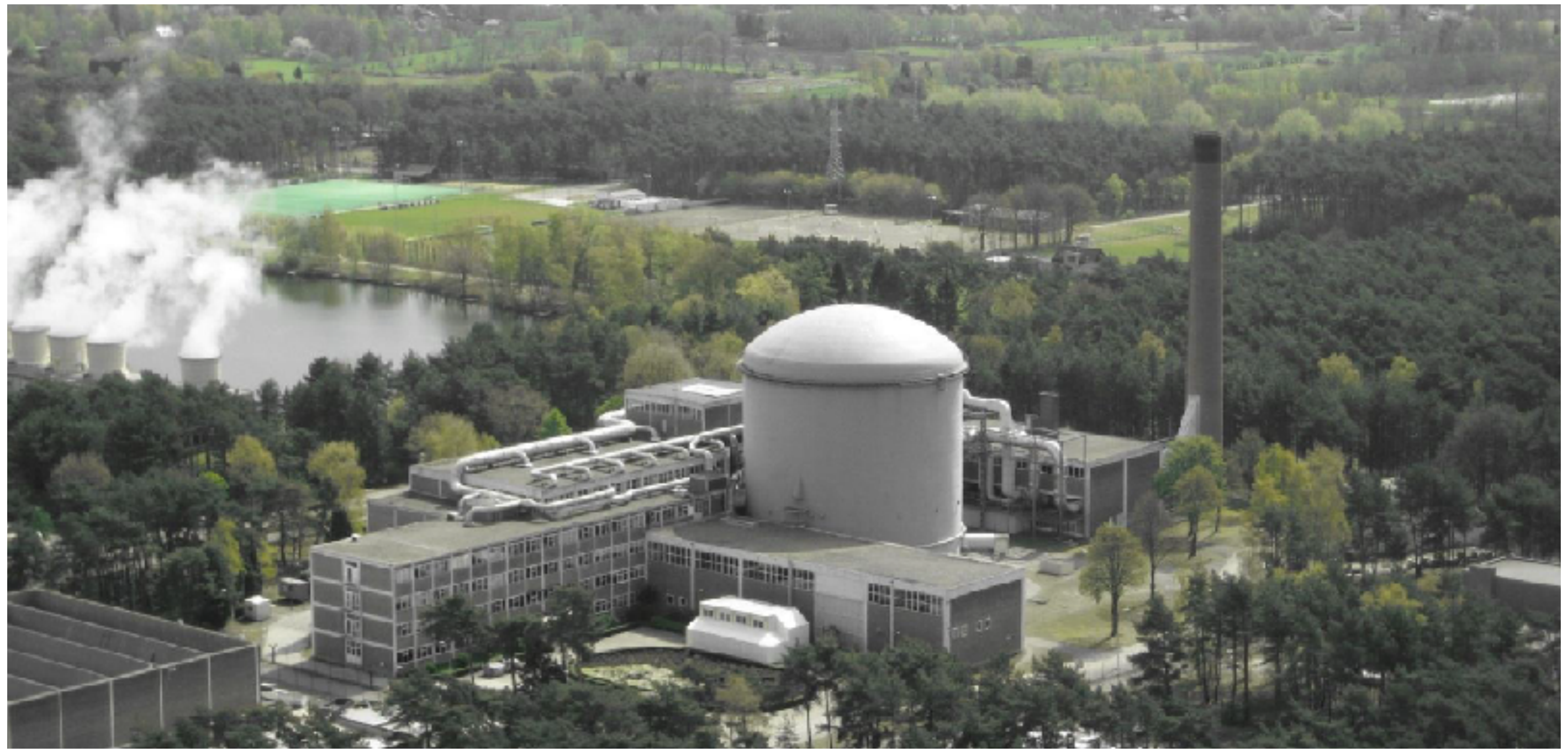
ENSI CAEN

Normandie Université

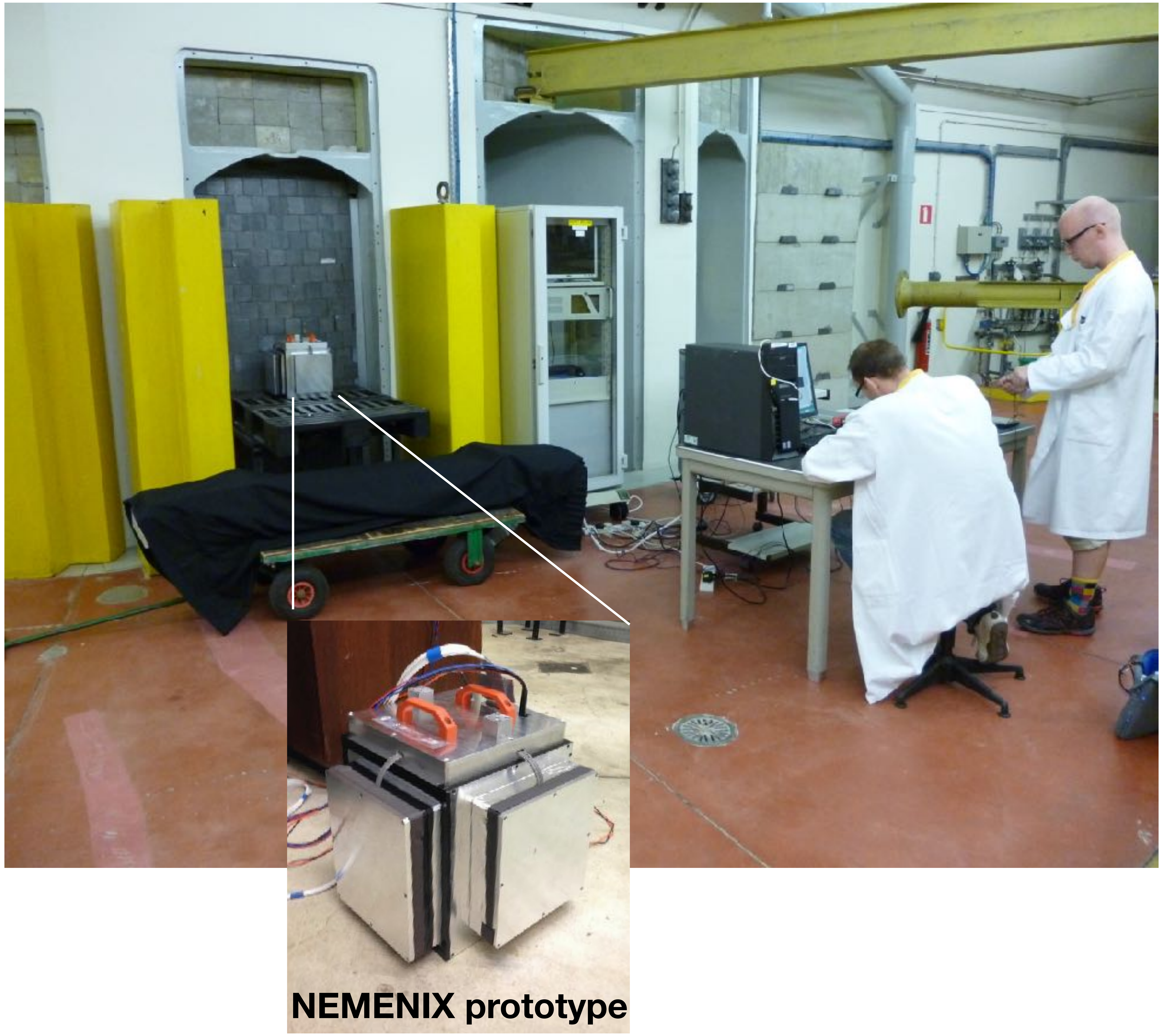
A spin out from Fundamental Science

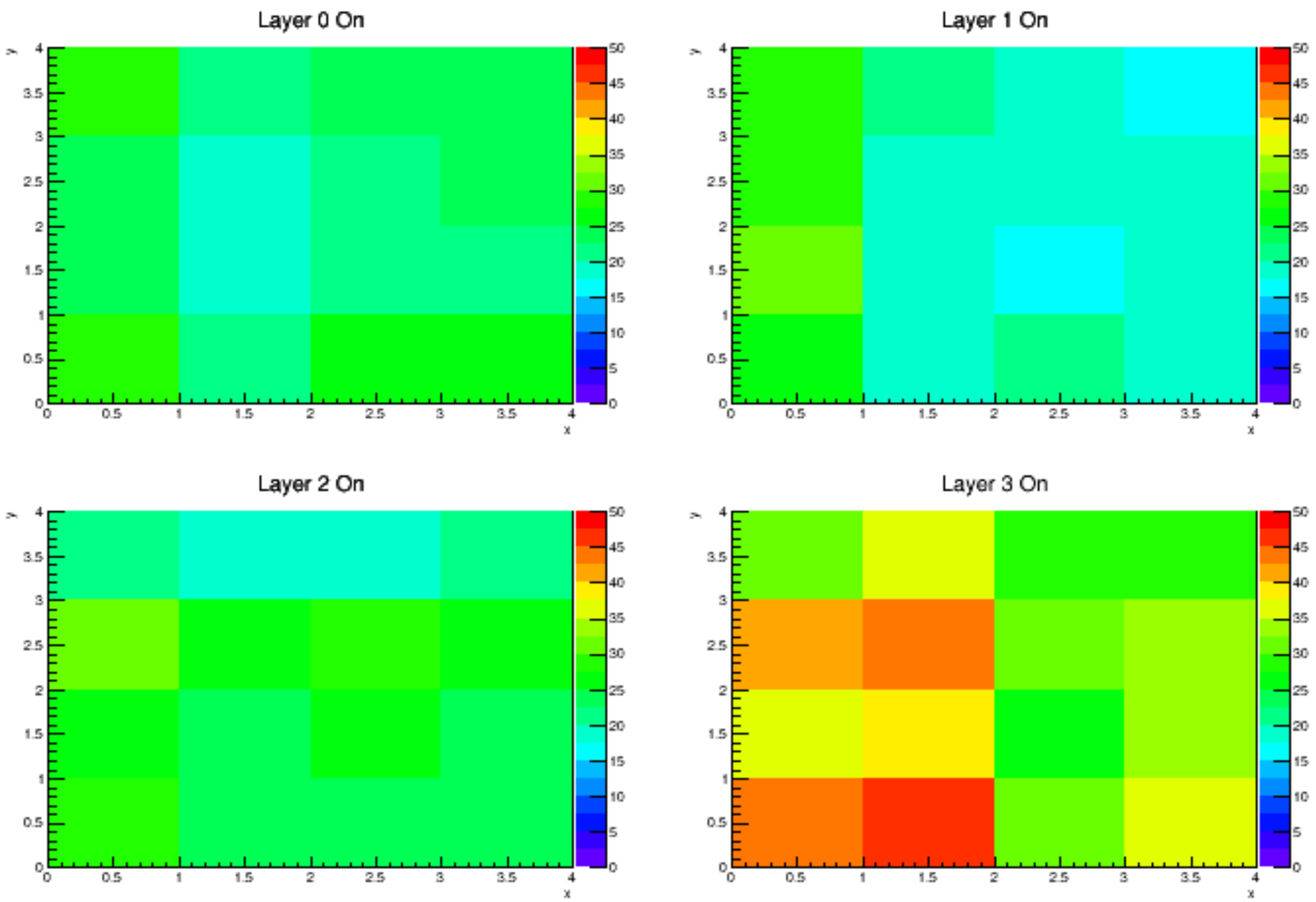


Summer 2013 : trip to SCK-CEN for the “No Equipment MonEy NeutrIno eXperiment (NEMENIX)”

- a new technology to detect antineutrinos produced at the BR2 reactor

2013: NEMENIX measurements at SCK-CEN

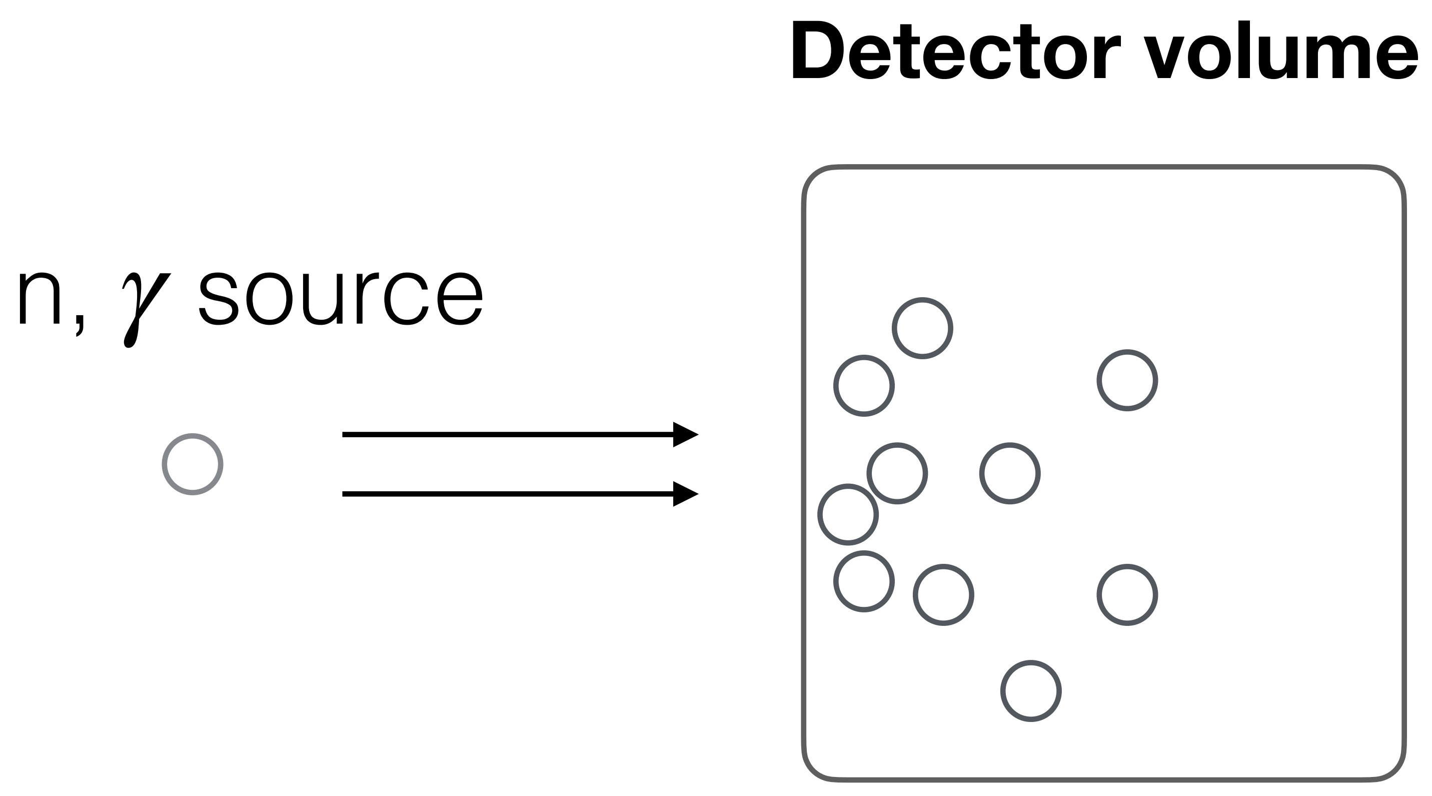




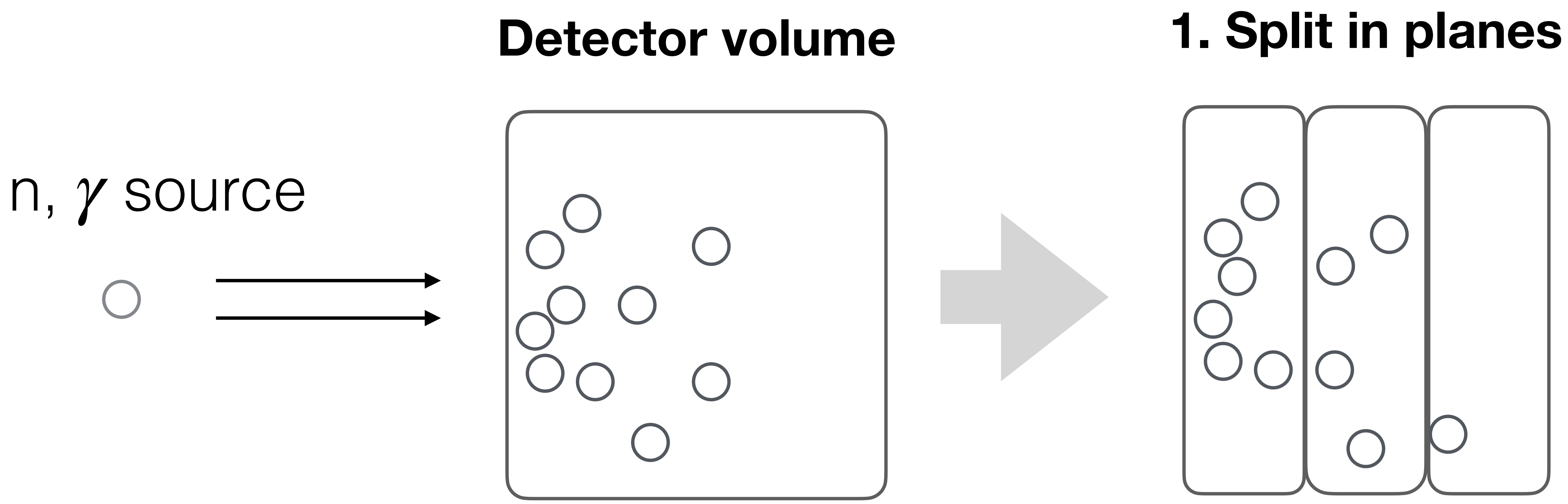
PoC of the technology successful but no neutrinos measured (system too small)

We detected a leak of thermal neutrons from the beam port … the nFacet concept was born !

The nFacet concept



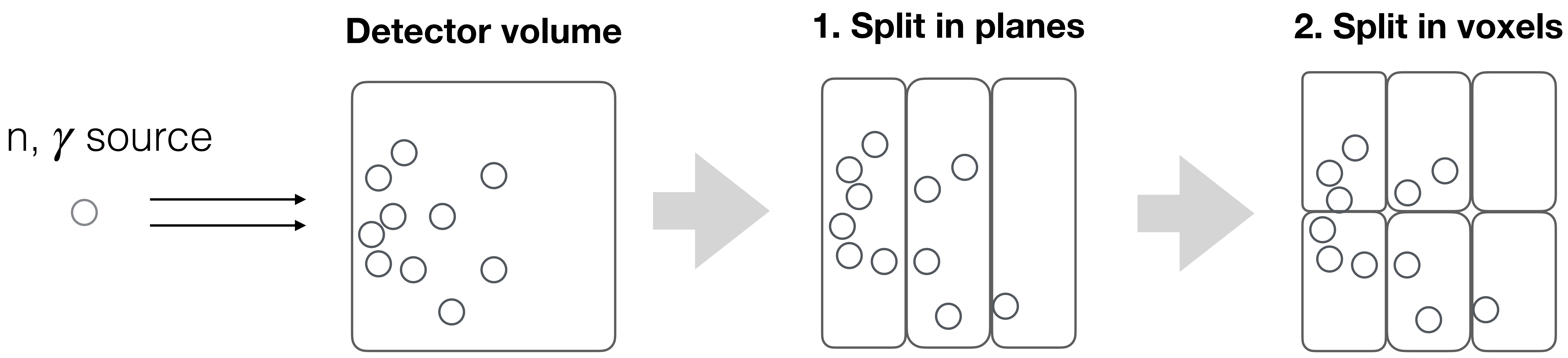
The nFacet concept



Segmentation in different dimensions provides :

1. Stopping power : Energy sensitivity

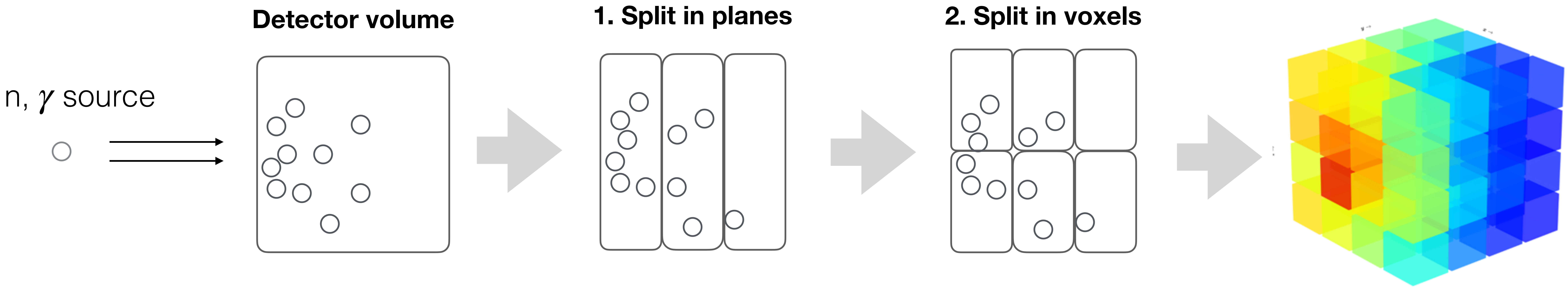
The nFacet concept



Segmentation in different dimensions provides :

1. Stopping power : Energy sensitivity
2. X, Y, Z localisation : Directional information

The nFacet concept



Segmentation in different dimensions provides :

1. Stopping power : Energy sensitivity
2. X,Y,Z localisation : Directional information

3D segmentation enables **directional spectrometry in 4pi** !

Directional information is key

Most measurements are limited by :

High background rate &/or low counting statistics usually due to large separation distances & short accumulation time.

Directional capability provides :

Superior information about source in shorter time AND statistics AND with reduced background counts.

Requires also good spatial resolution if multiple sources are present

Very helpful for radiation dose measurements of non-standard fields

Detection principle

- Technique based on dual scintillator voxel
  - Organic scintillator : PVT cube 5 x 5 x 5 cm (ELJEN 200)
  - Inorganic scintillator : LiF:ZnS(Ag) 250 um phosphor screen (Scintacor ND)
  - Tyvec reflector

Detection principle

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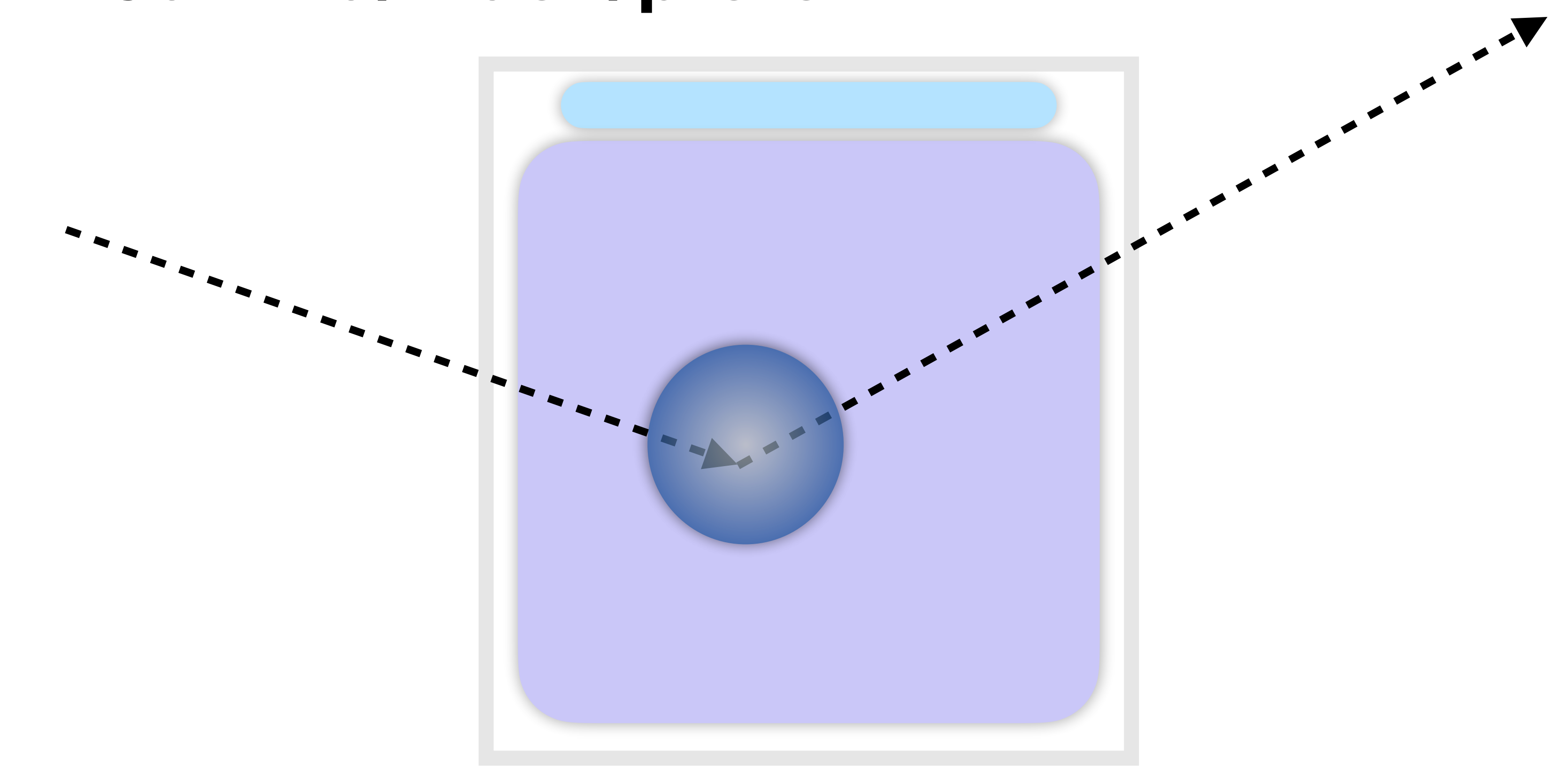
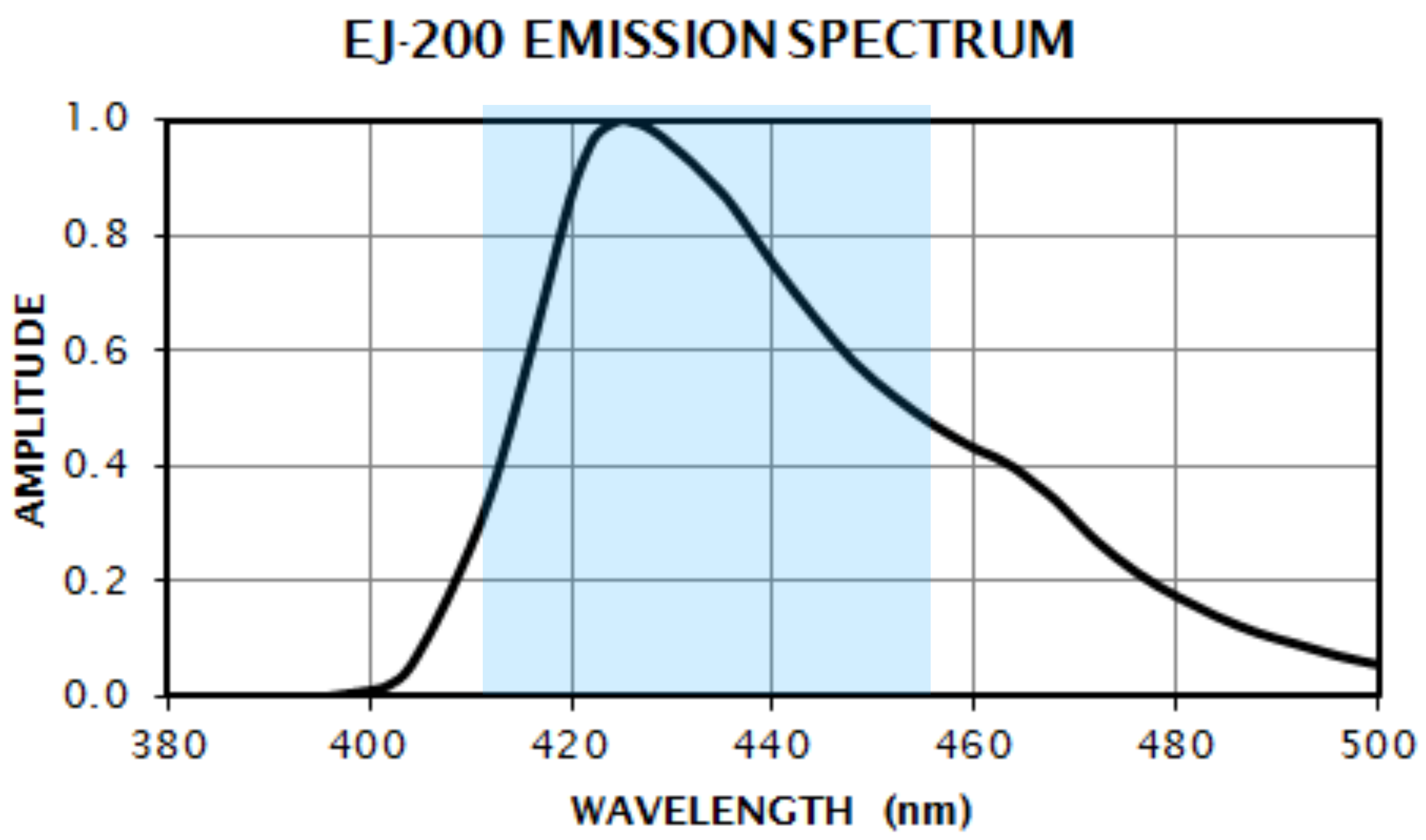
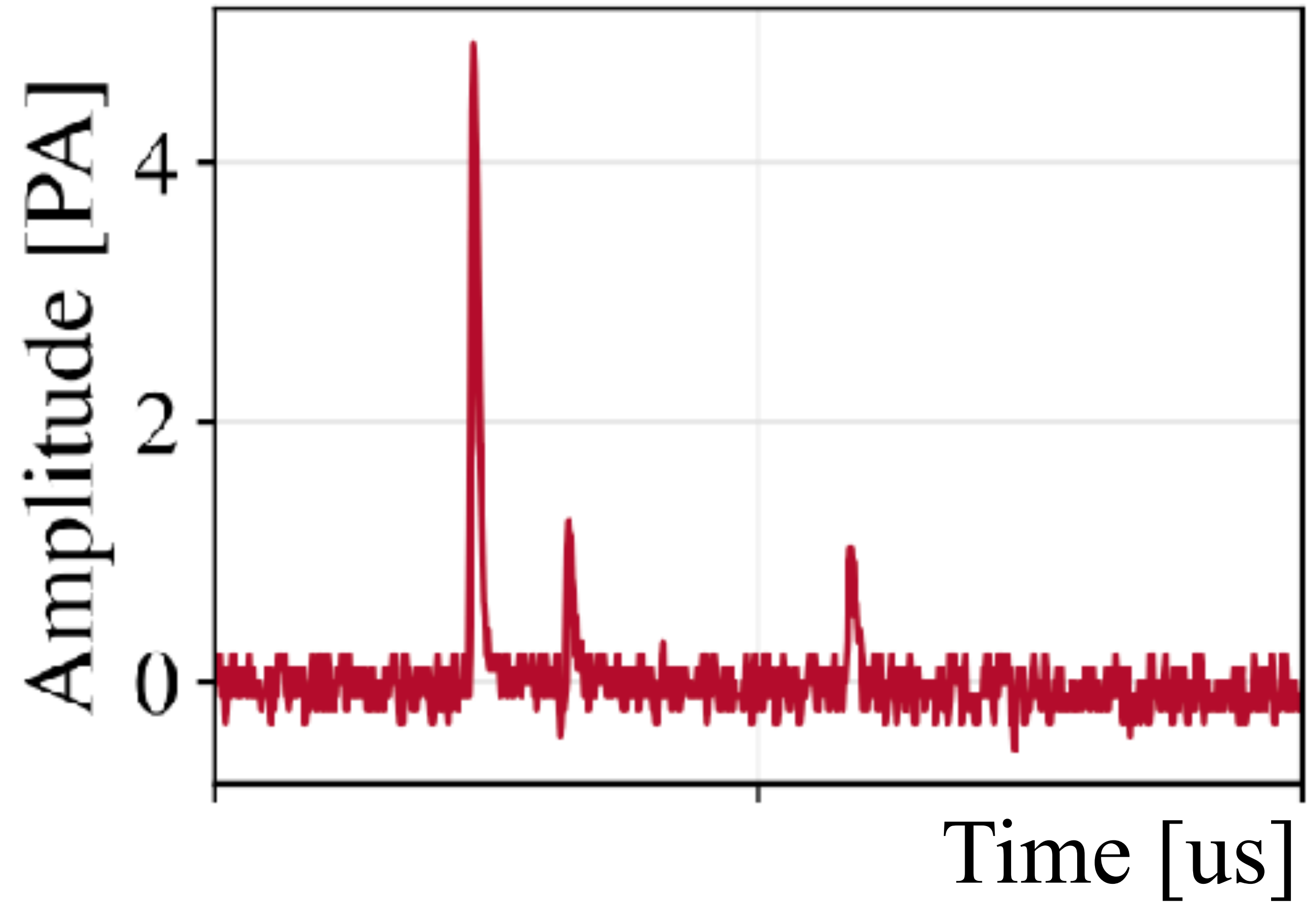
  - Inorganic scintillator : LiF:ZnS(Ag) 250 um phosphor screen (Scintacor ND)
  - Tyvec reflector
  - Construct 2D planes of cubes

Detection principle

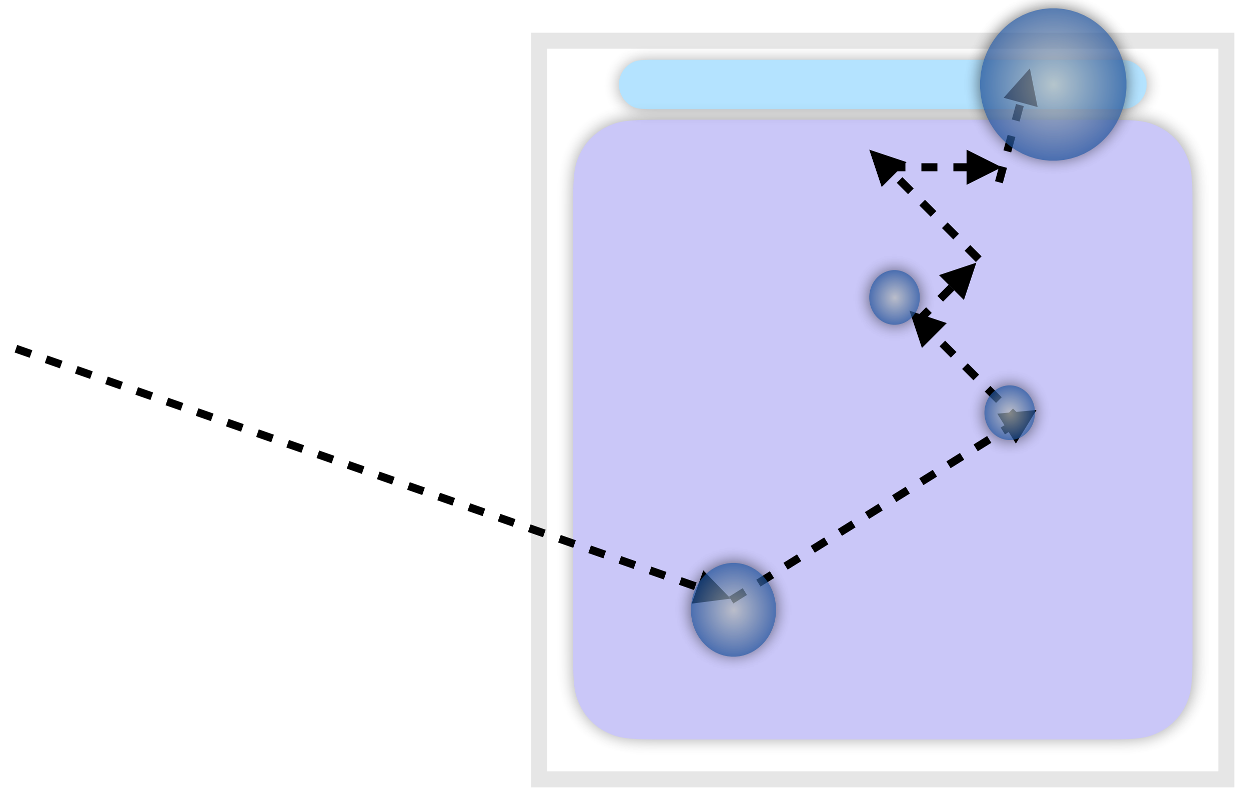
1. Gamma/muon/proton

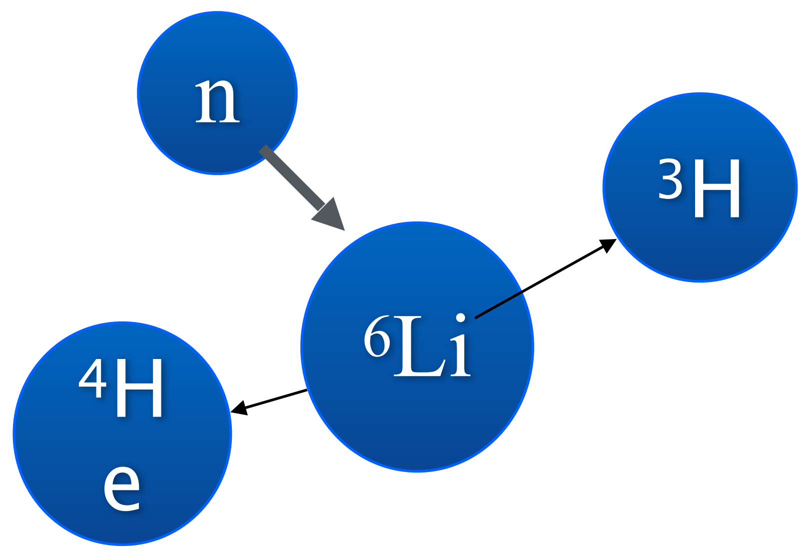




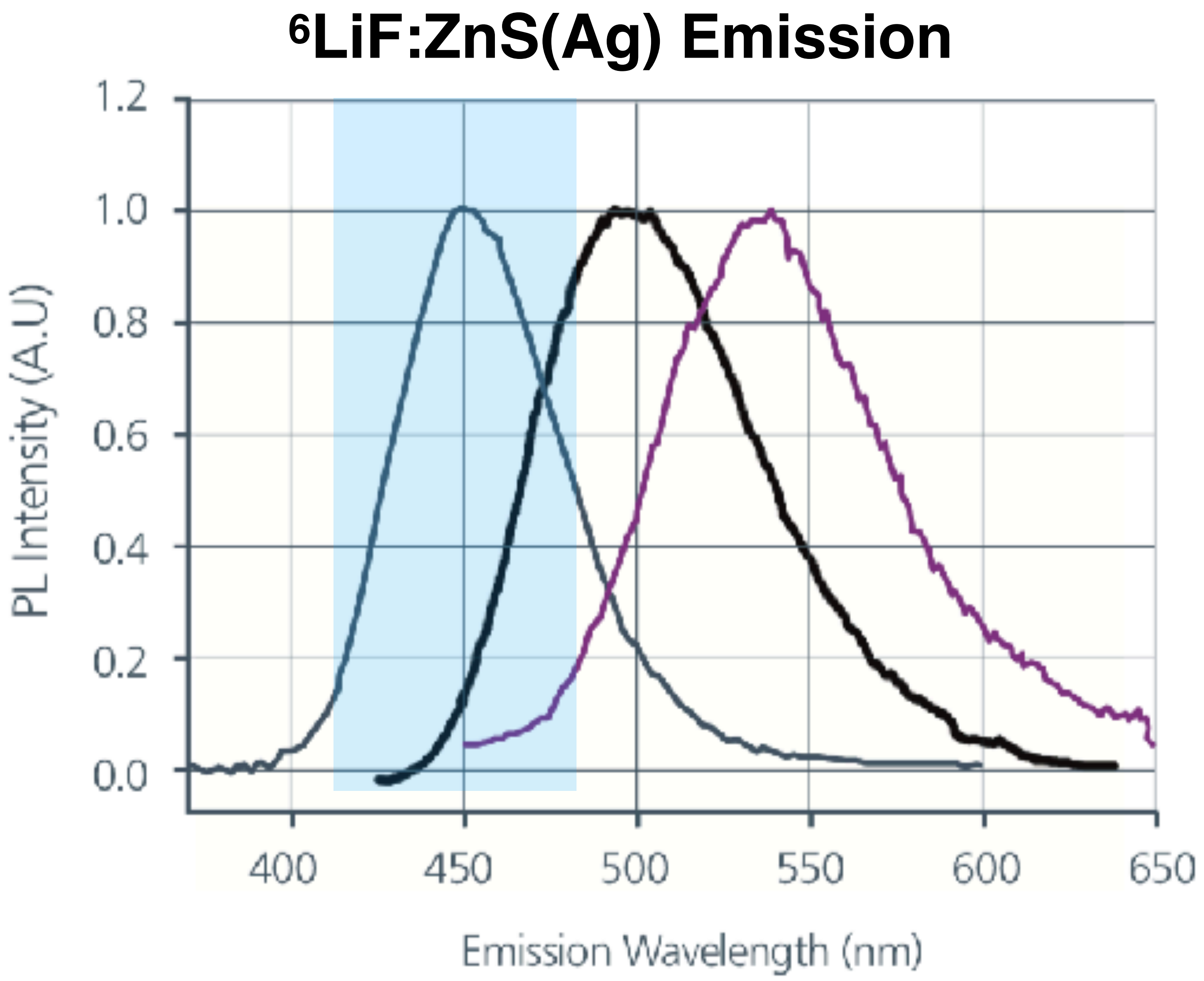


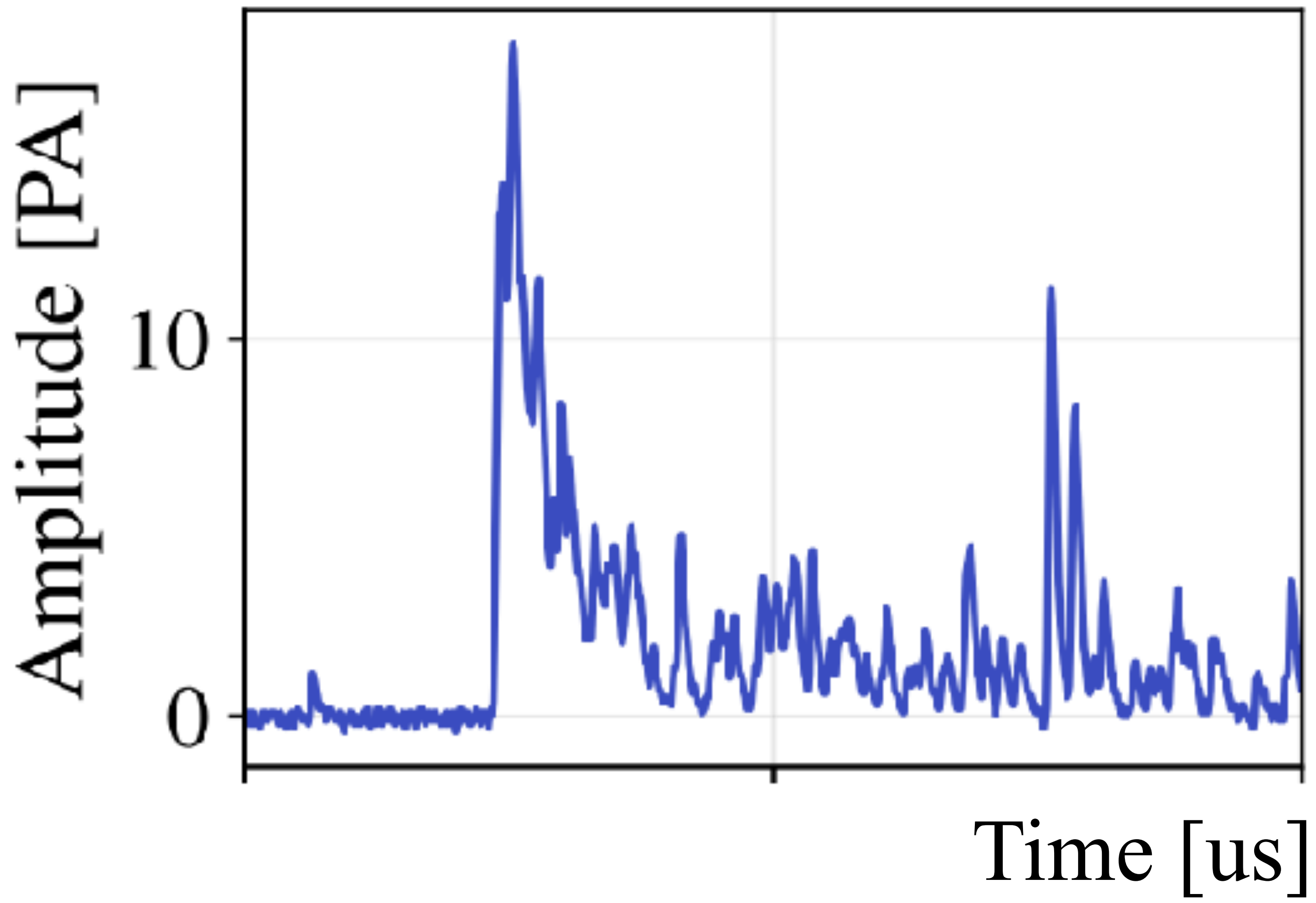
2. Neutron



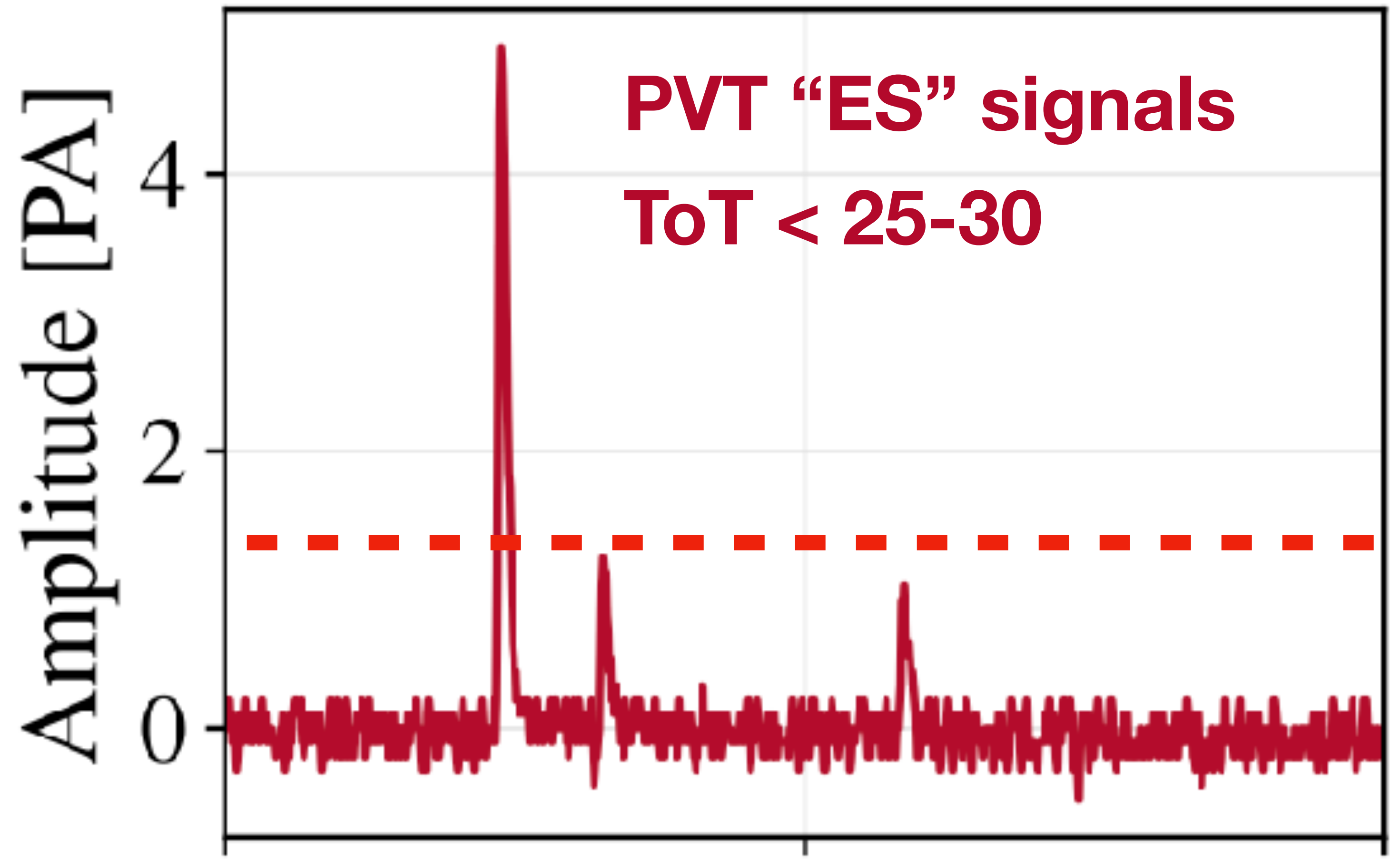


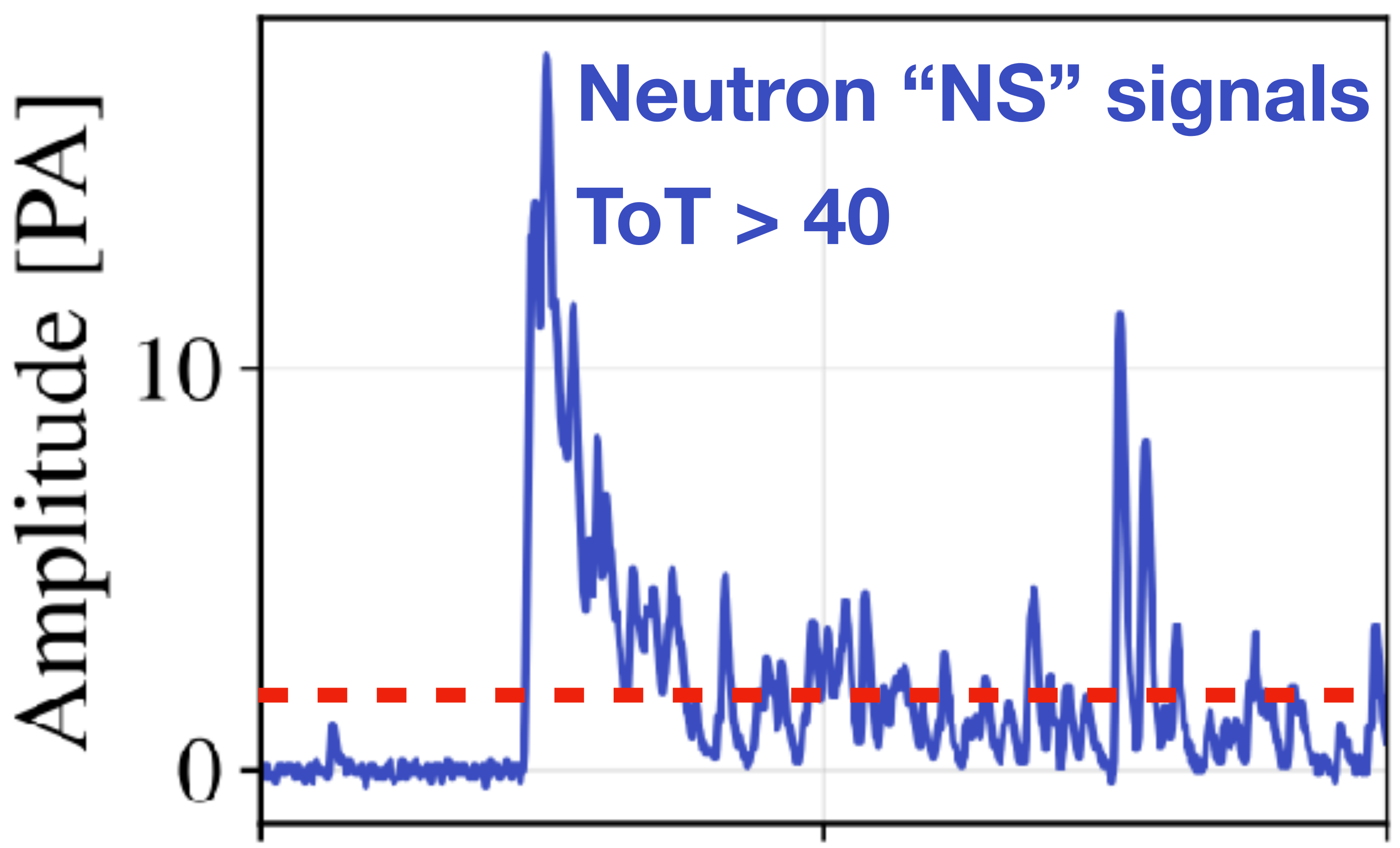
E_{tot} = 4.78 MeV

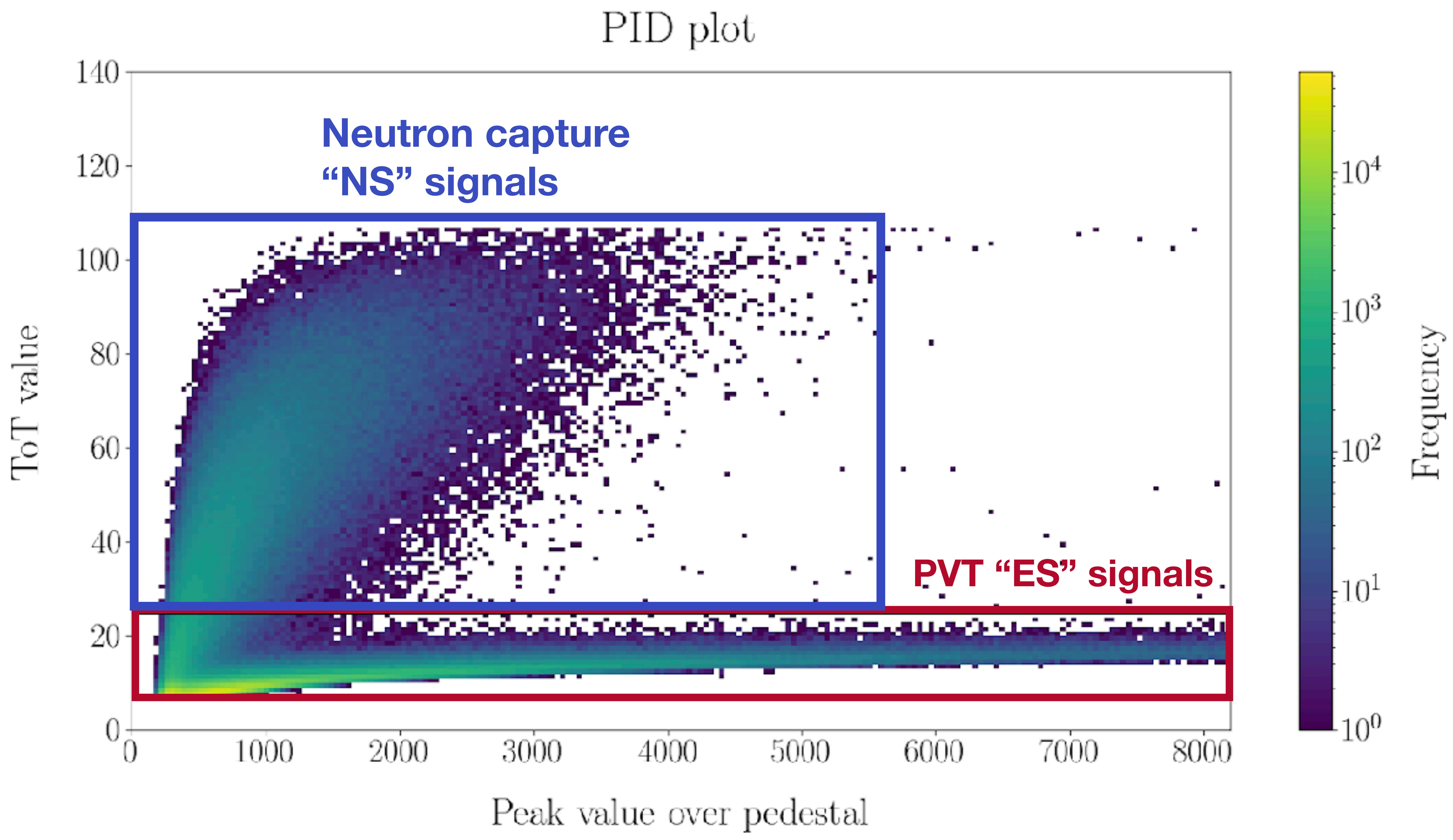




Pulse Shape Discrimination







- PID technique based on pulse width

nFacet M1 : a demonstrator system

Imperial College London

J. Borg, S. Hayashida, S. Ihantola, O. Jeremy, N. Reed, D. Smith, A. Vacheret

NPL National Physical Laboratory

G. Taylor

2017: M1 Demonstrator

M1 Demonstrator Specs

System dimensions	25 x 25 x 27 cm^3
System weight	16 kg (8kg active matrix)
Number of cube elements	64
Neutron energy range	Capture eV - 20 MeV Elastic 450 keV – 50 MeV
Field of view	4 Pi
Neutron sensitive detector / moderator	LiF:ZnS(Ag) / PVT
Gamma-ray energy range (CS)	60 keV – 4 MeV
Gamma-ray energy resolution	~ 20% at 1 MeV
Gamma-ray sensitive detector	PVT
Waveform Digitisation	33 MS/S
Interface	ETH / Python DAQ
Power	5V Power cable or battery pack

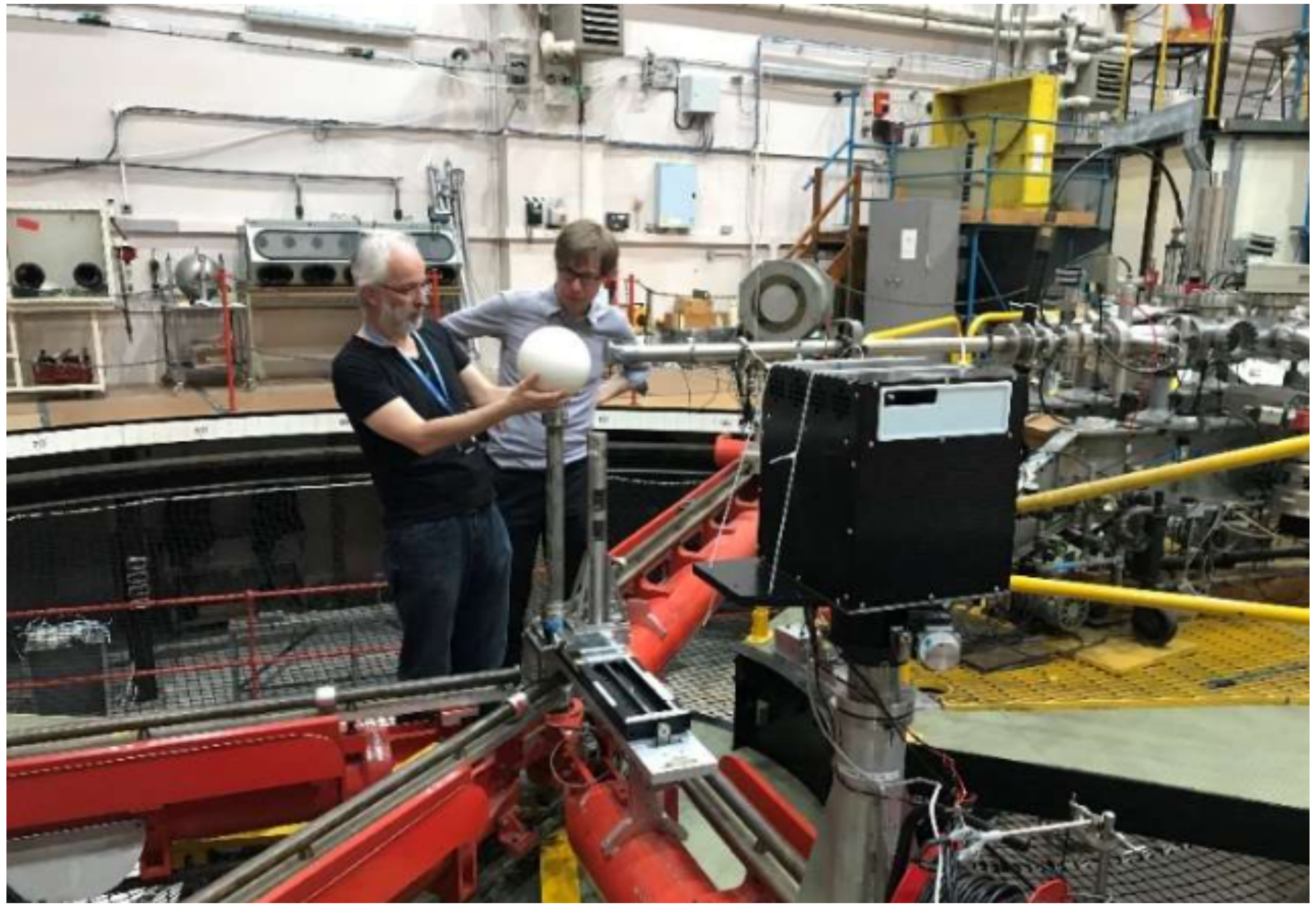
2017: First NPL characterisation campaign

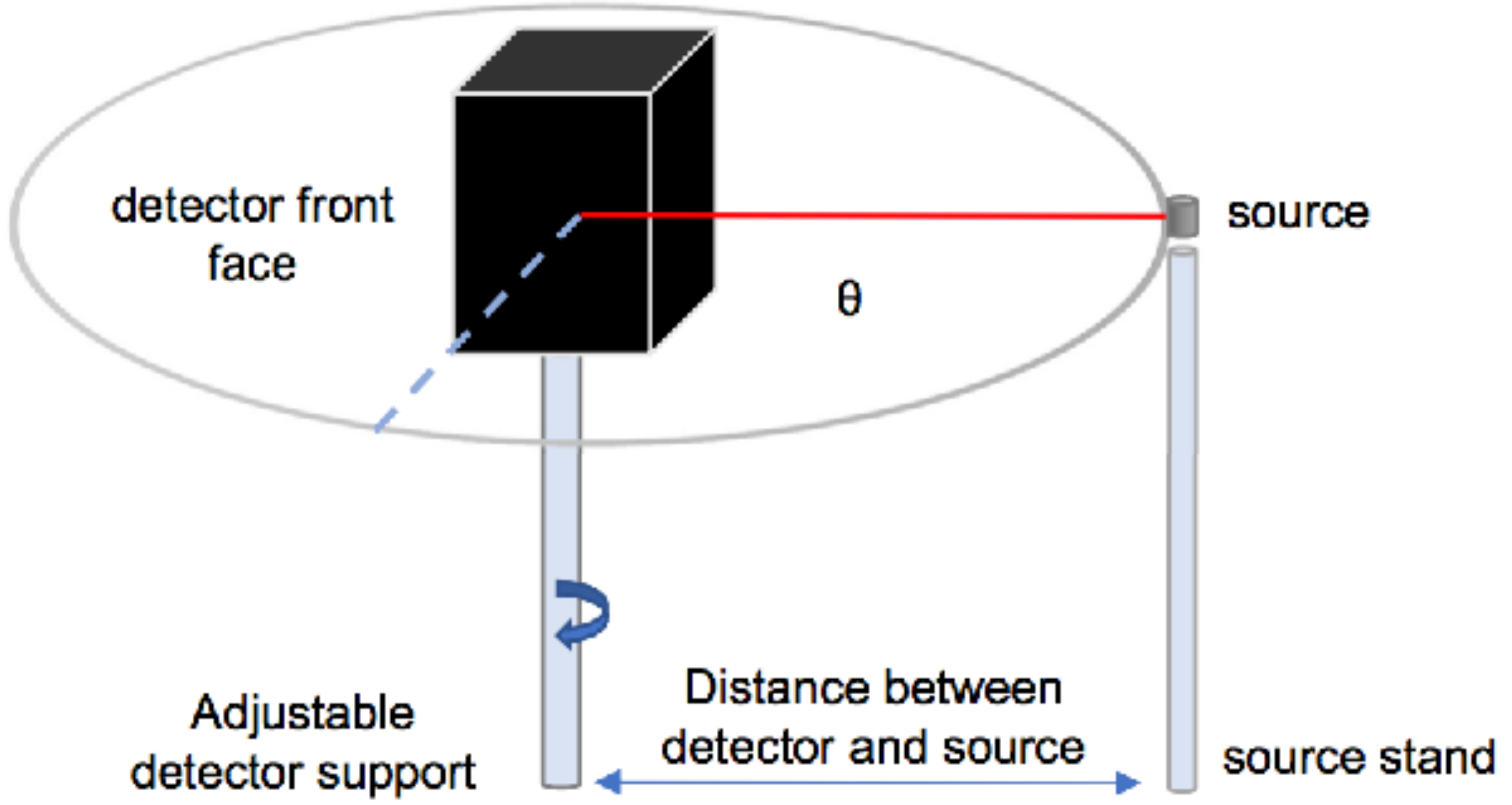
Source datasets with high signal purity (3% background)

Background data corresponding to typical surface background

Most data taken at 1.5 m from source to collect large statistical samples

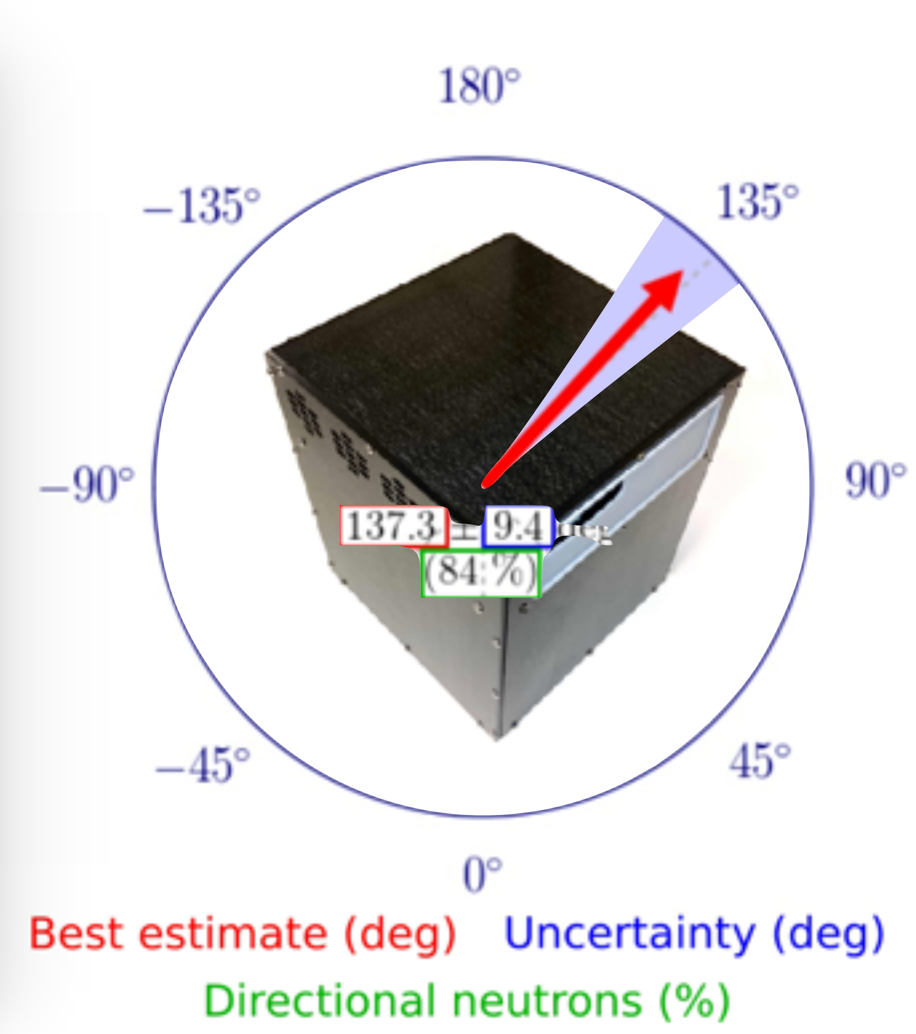
- ~300 Hz neutron rate gives roughly 1000 events for a few seconds exposure

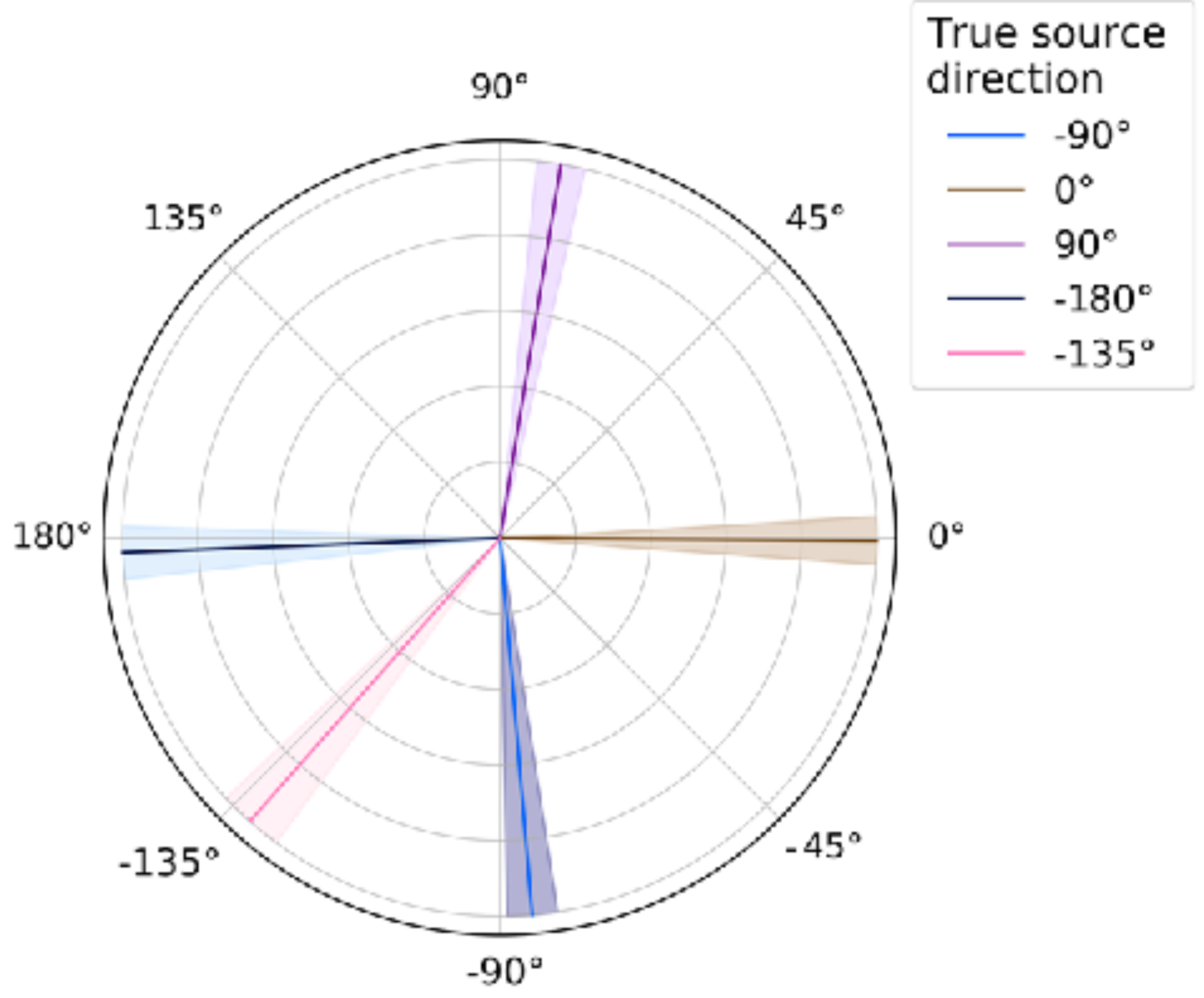




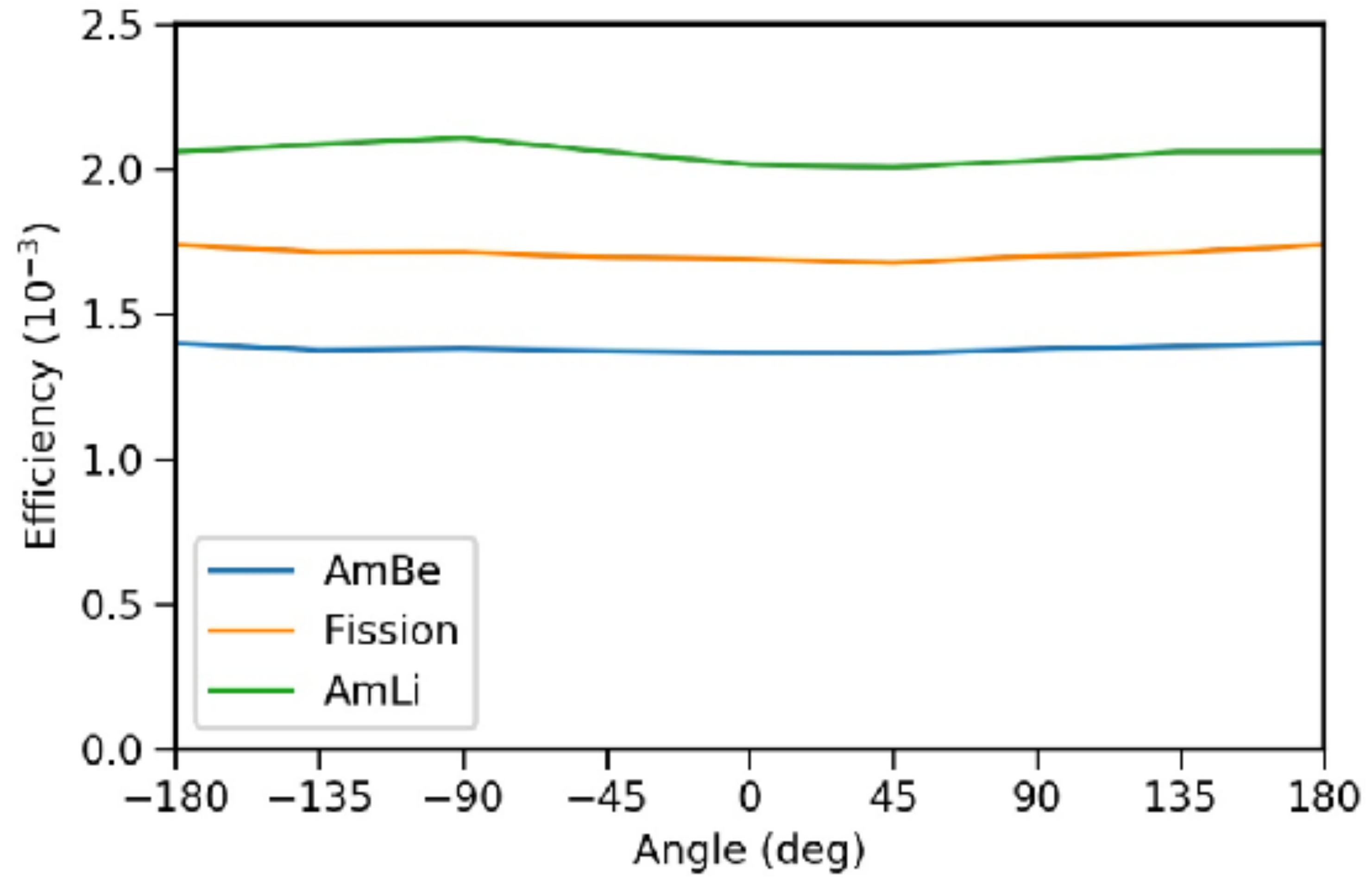
Analysis type	Category	Label
Source detection	Background only	0
	Source present	1
Source characterisation	AmBe	0
	Cf	1
	AmLi	2
	Background only	0
	Moderated source	1
	Naked source	2
Source localisation	0°	0
	45°	45
	90°	90
	135°	135
	180°	180
	-135°	-135
	-90°	-90
	-45°	-45
	-30°	-30
	-15°	-15

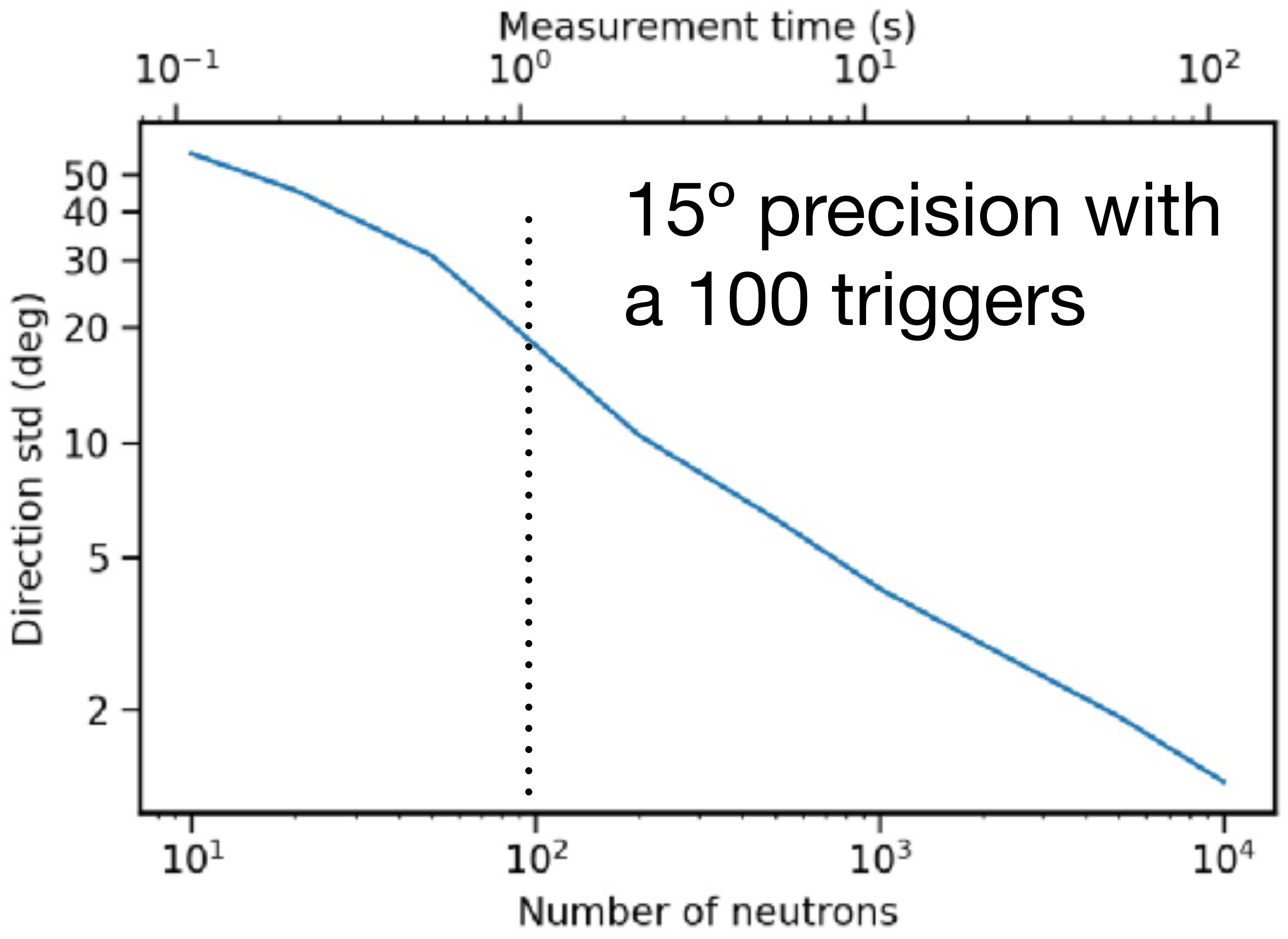
First results on directionality





360° flat efficiency





Fulfils neutron detection requirements for pedestrian monitor (ANSI N42.382006, singlesided)

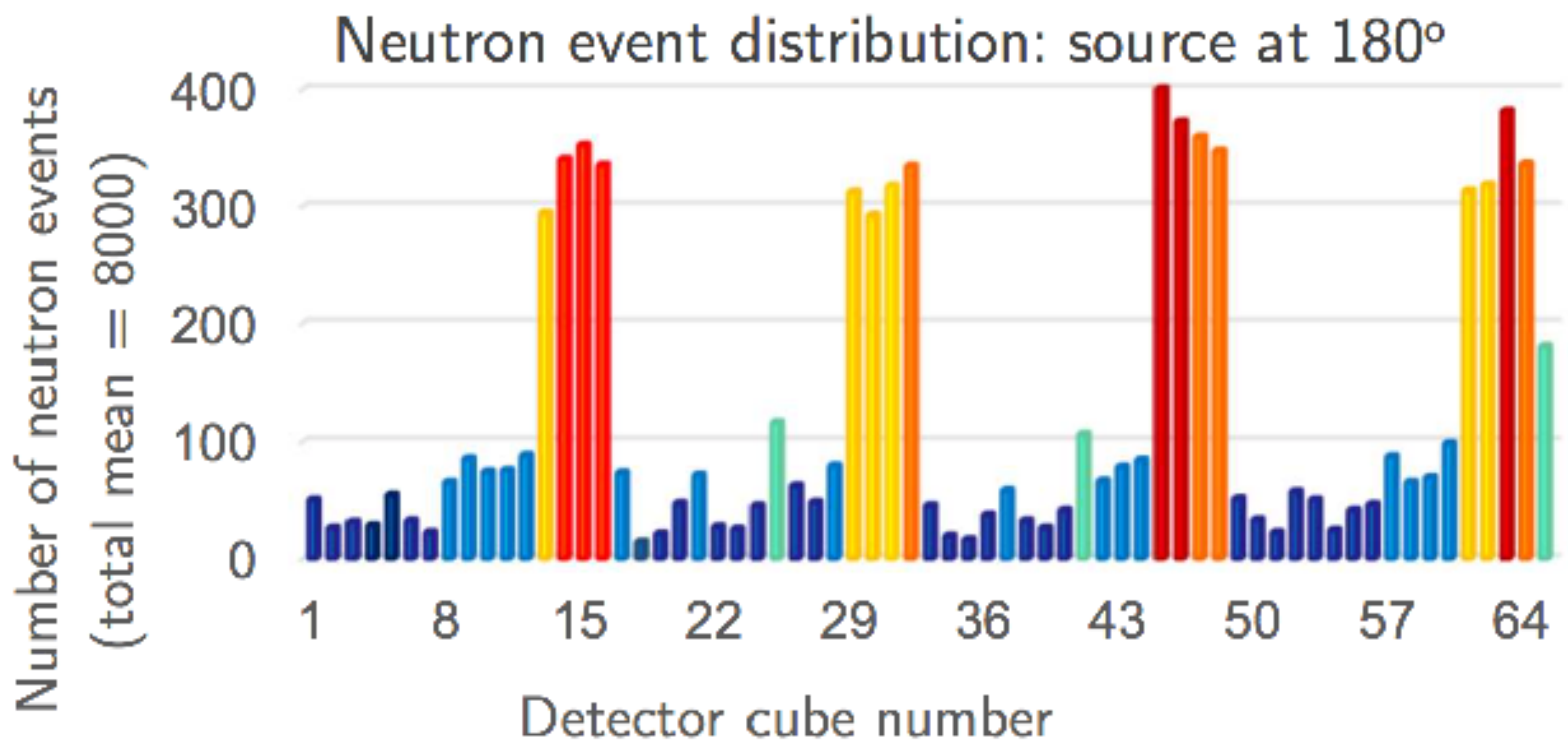
Fulfils neutron detection requirements for vehicle monitor (ANSI N42.382006, double-sided)

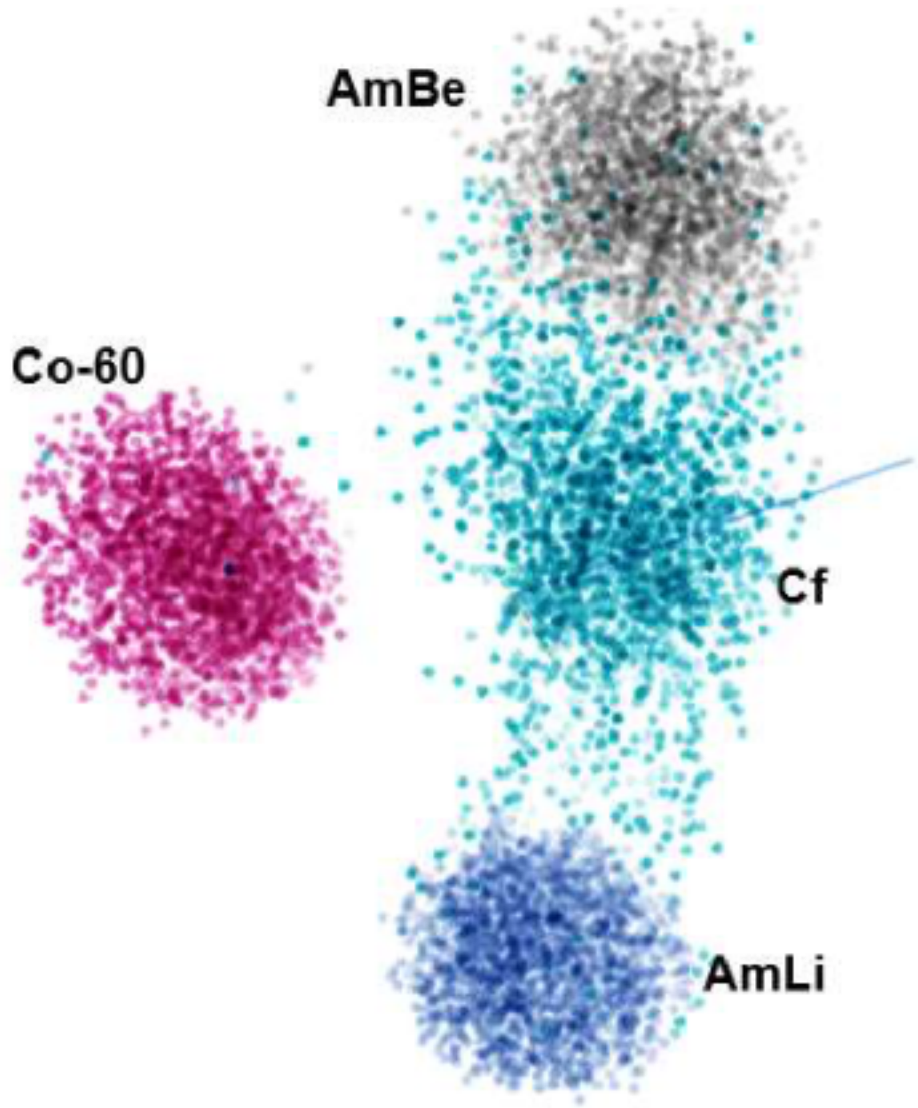
Sensitivity to the type of source and energy

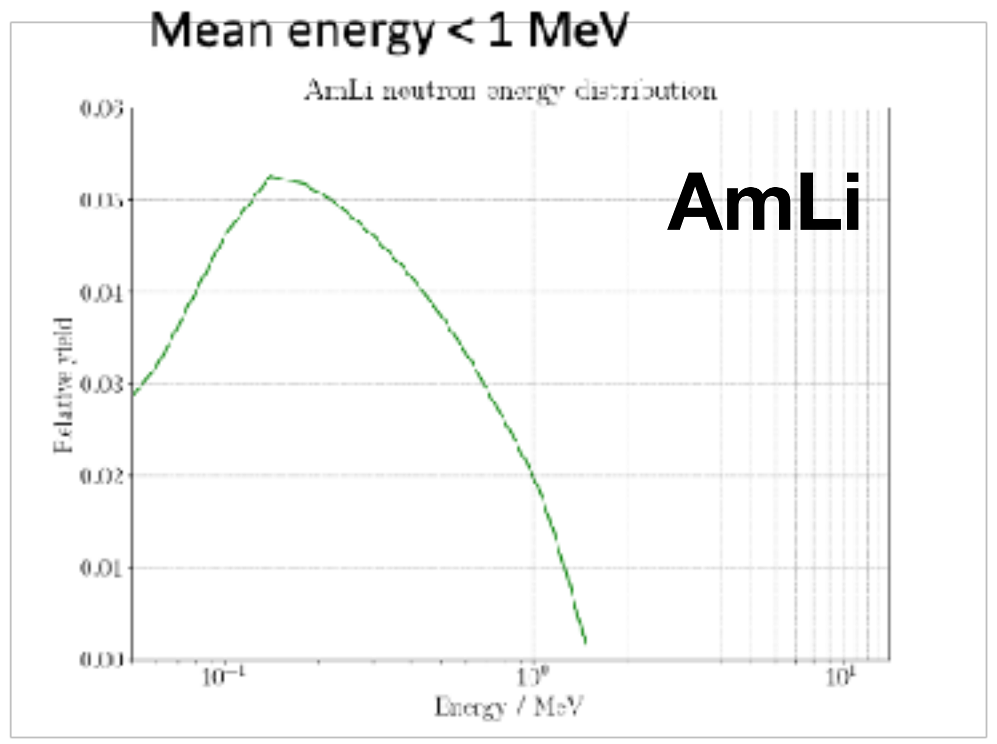
Stopping power of AmBe, Cf-252 and AmLi sources

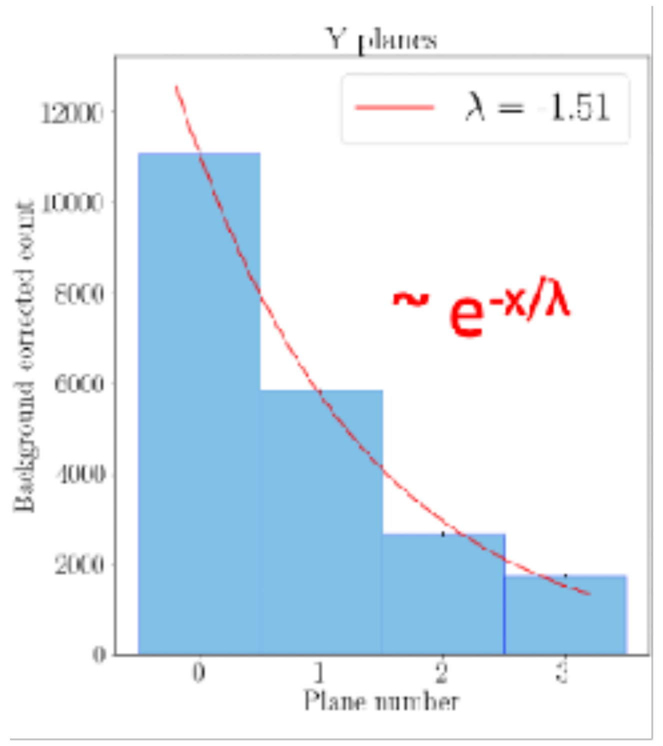
Validated the sensitivity and calibration data

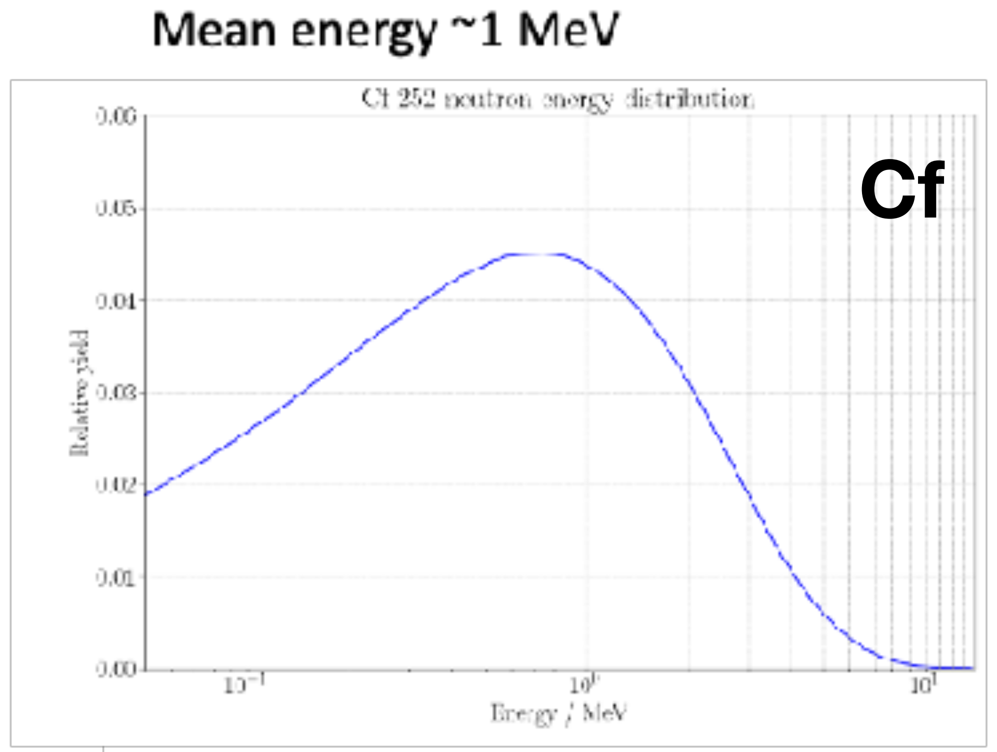
First work on Machine learning technique (ANN, CNNs) for direction reconstruction, source ID etc…

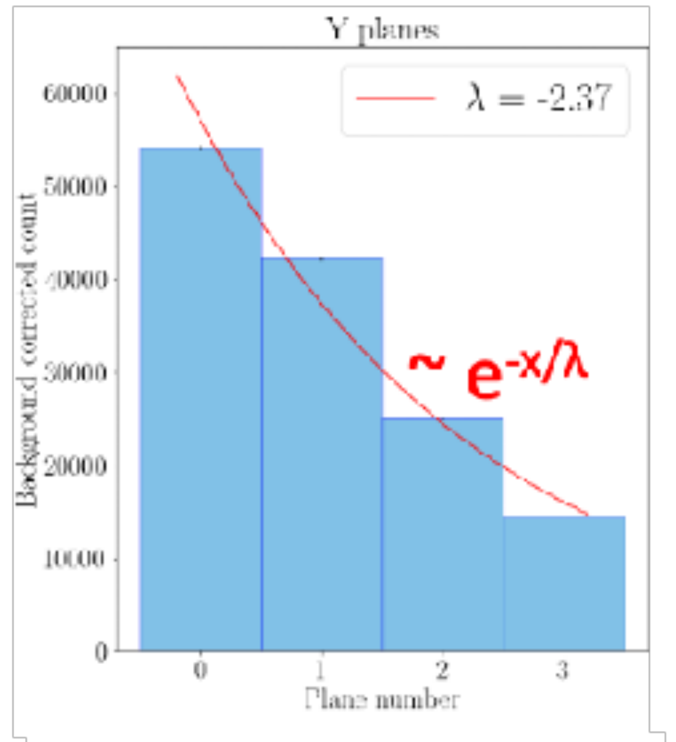


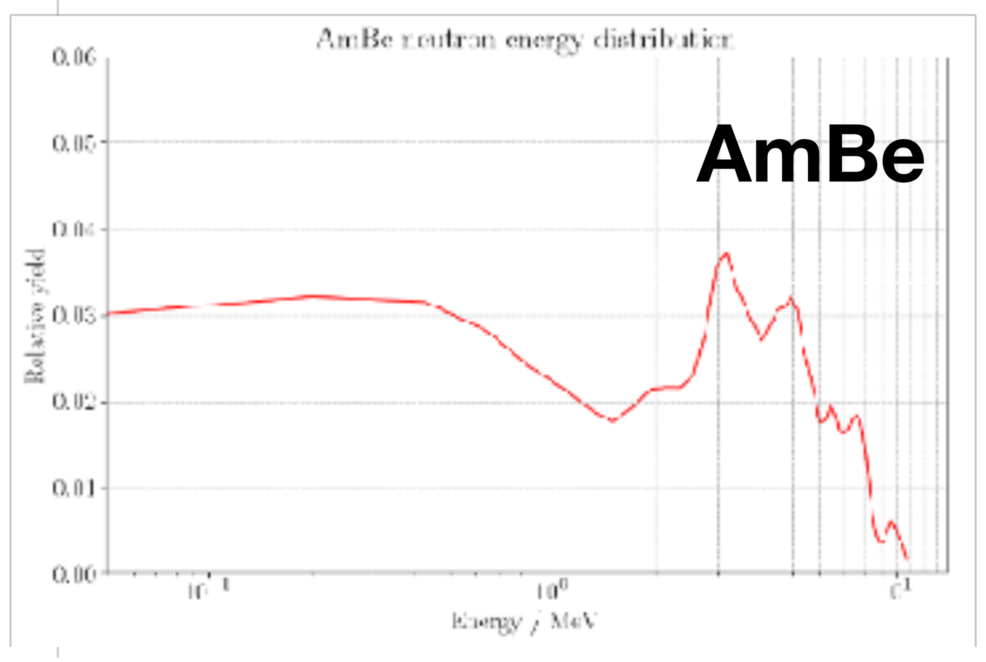


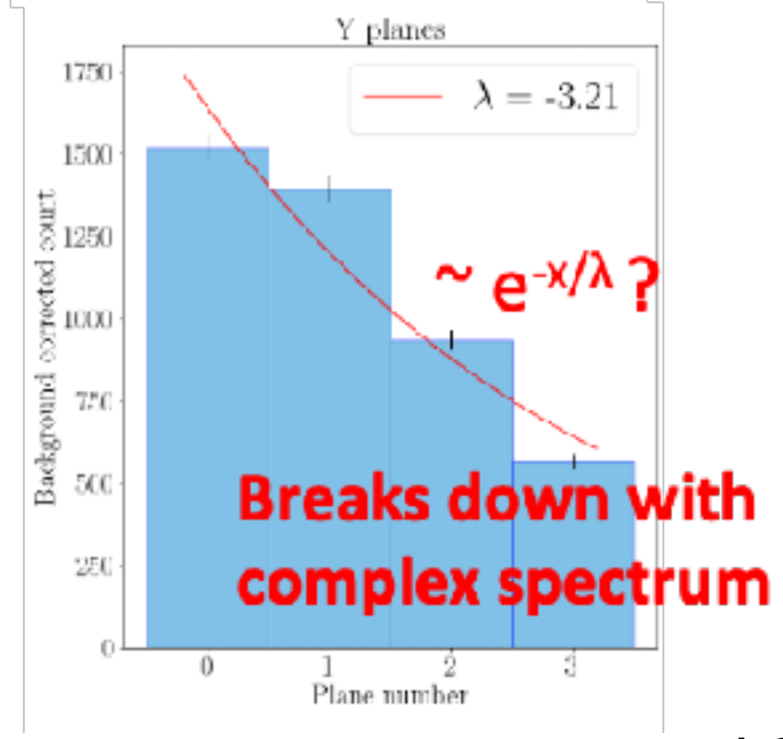












2019: Technical demonstration at SCK-CEN BR1 with IPNDV

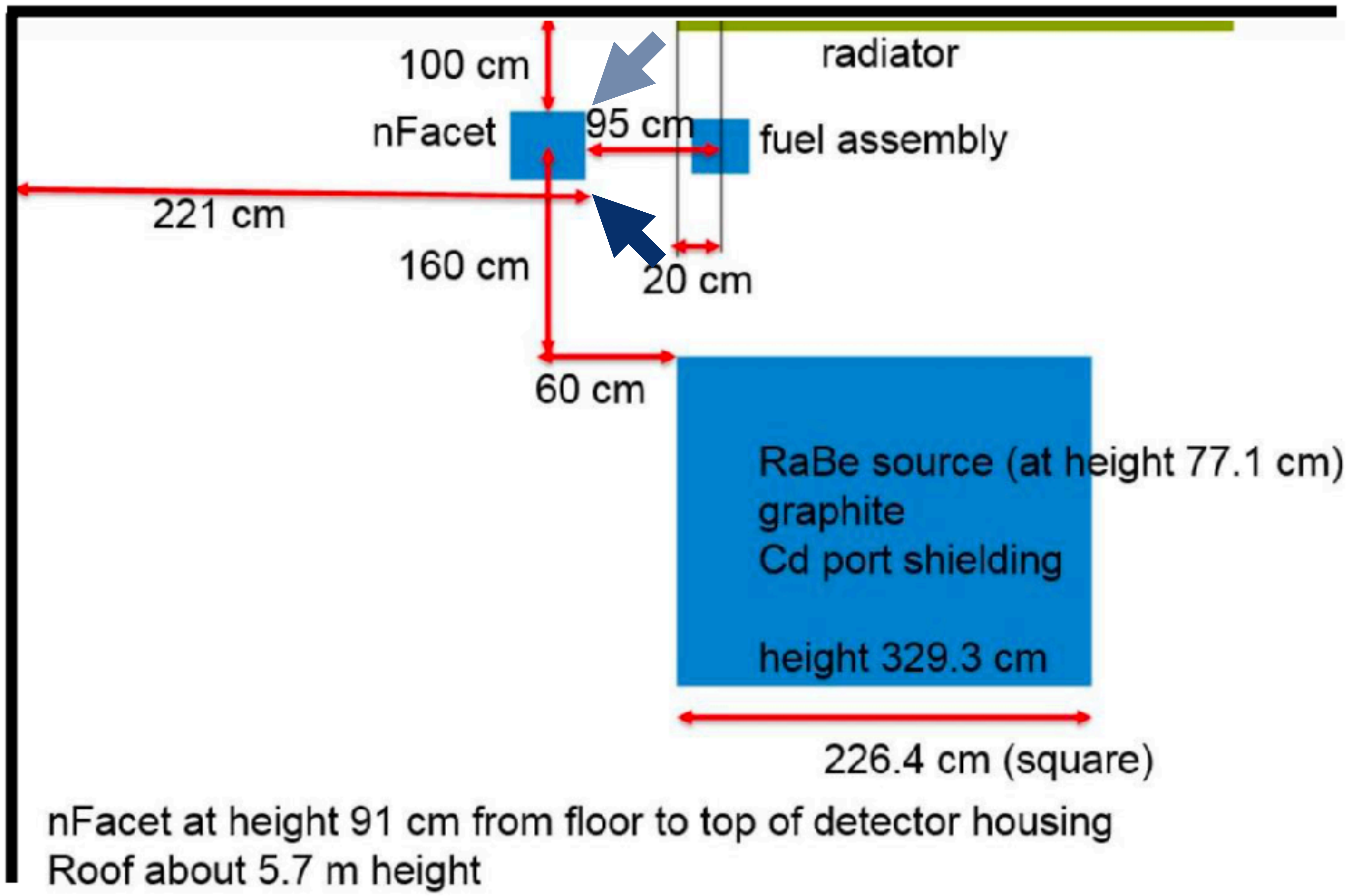
Realistic deployment in challenging non-standard field with Finnish-Swedish team(A. Axelsson - FOI, K. Peräjärvi - STUK)

Measured mixed-oxide (MOX) fuel assemblies with different Pu-239 enrichment

5 International teams with various systems (HPGe, Gamma camera, He-3 counters, Scintillator slabs)

Challenging environment with high neutron background

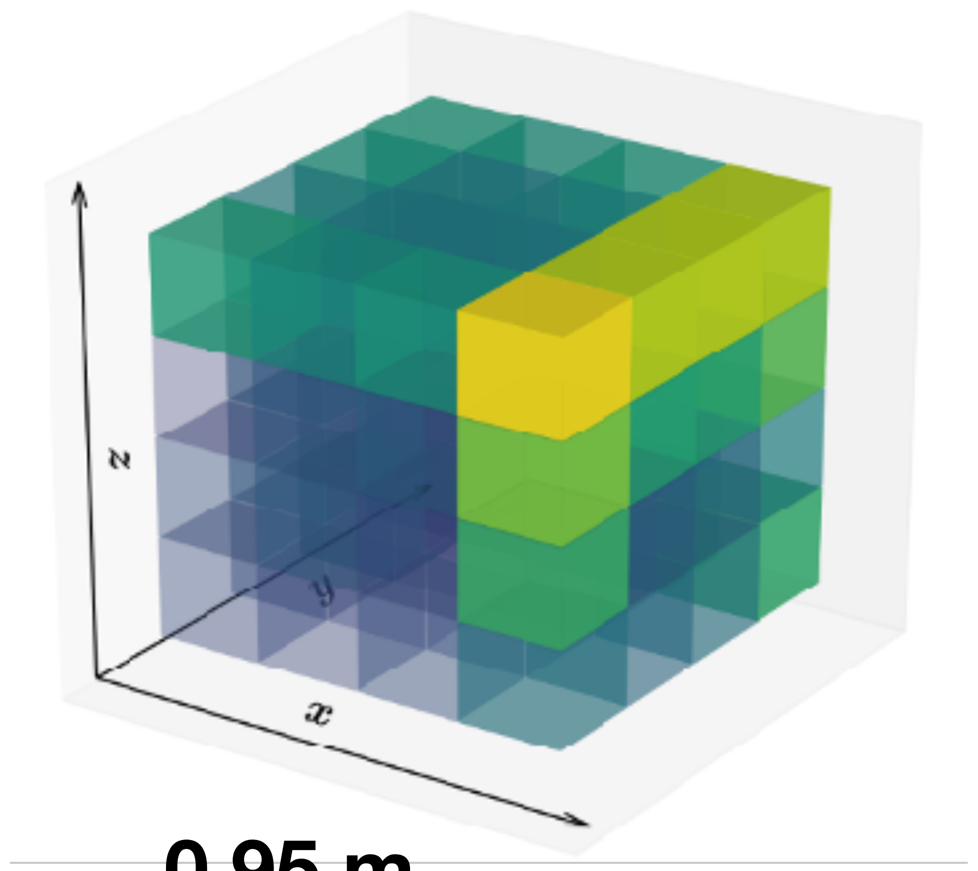
Experimental setup and neutron background

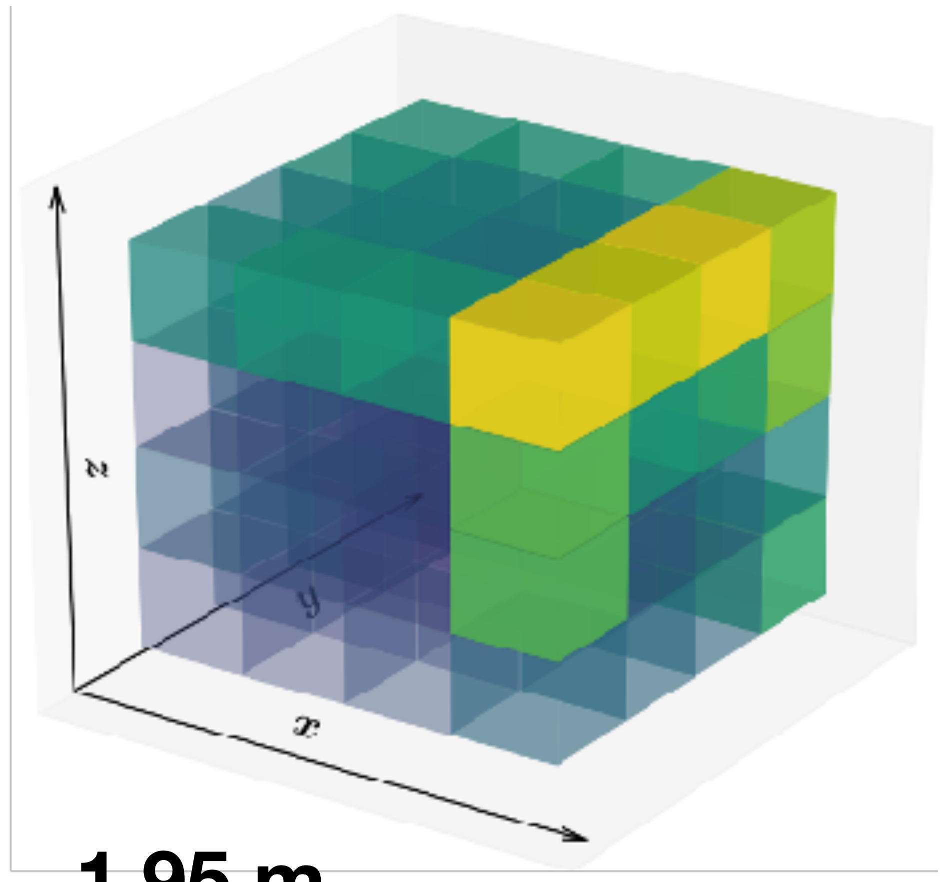


High background environment:

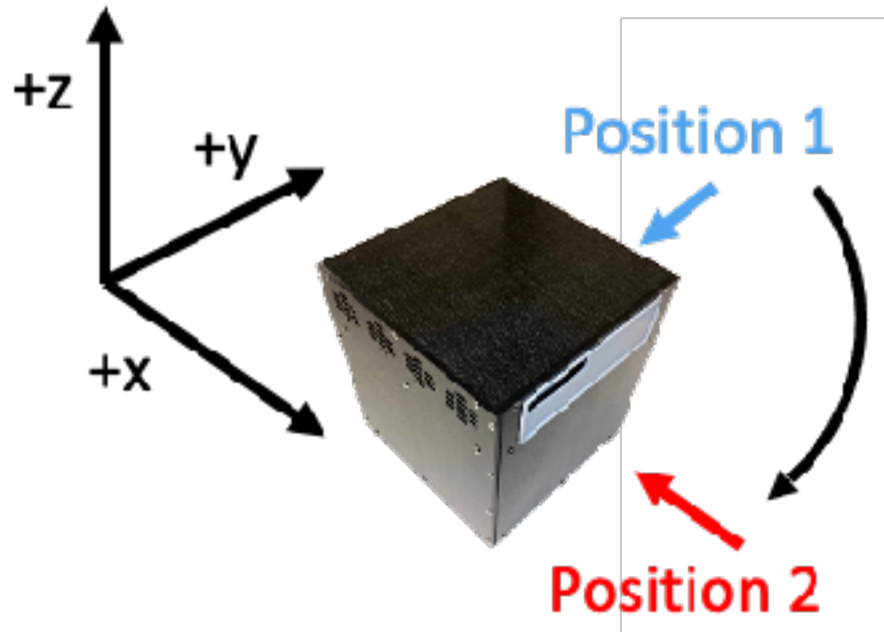
- Proximity of RaBe pile and assemblies in room next door

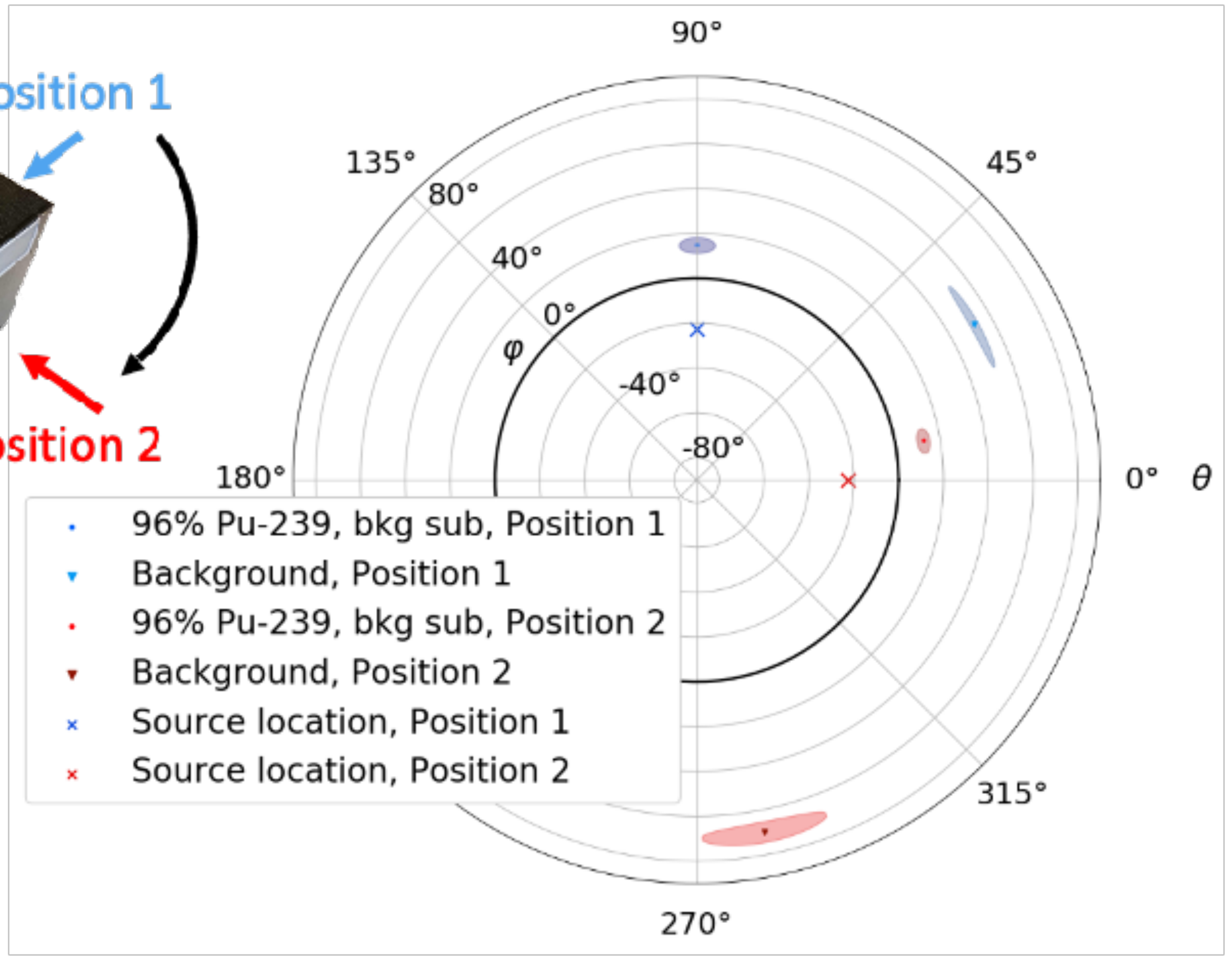
- Background well characterised and subtracted to extract MOX neutron fluence





IPNDV main results

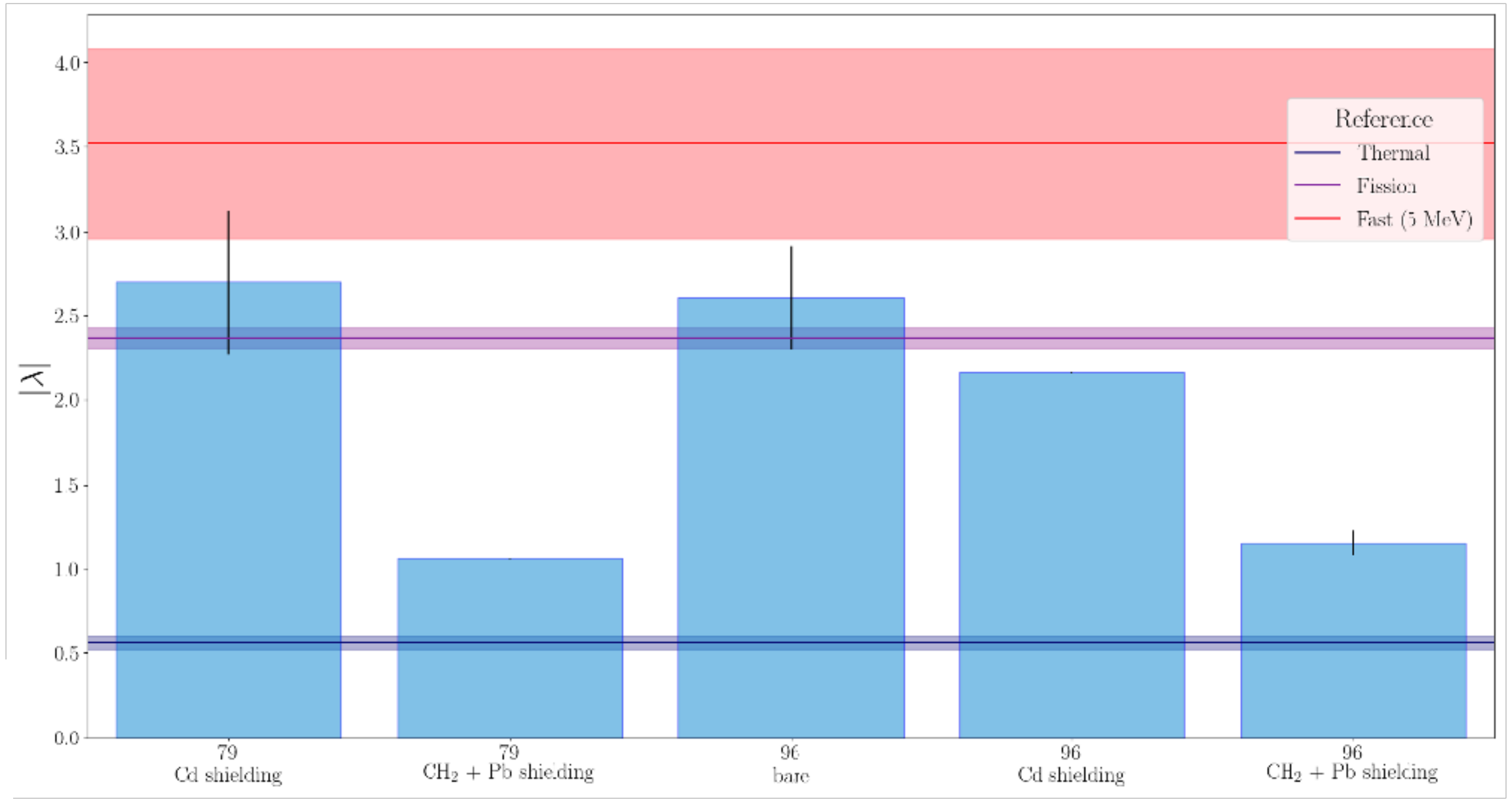




- Direction reconstruction at degree level accuracy
- Slight φ bias due to vertical acceptance

IPNDV report available here

- Source identification via source profiles metric – can discriminate between fission/thermal/fast sources

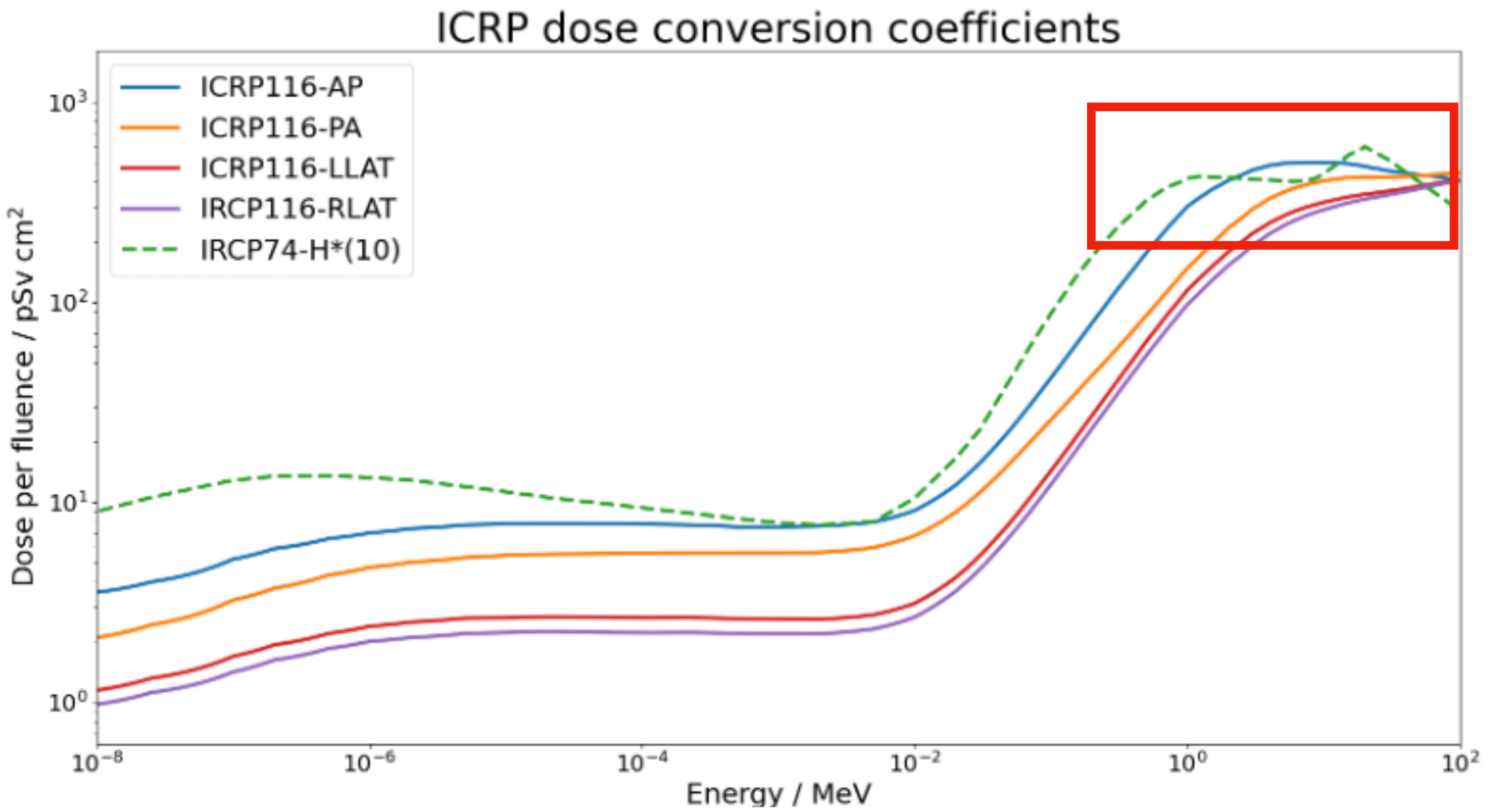


2019-2023 : Developping the neutron fluence and dose rate measurements

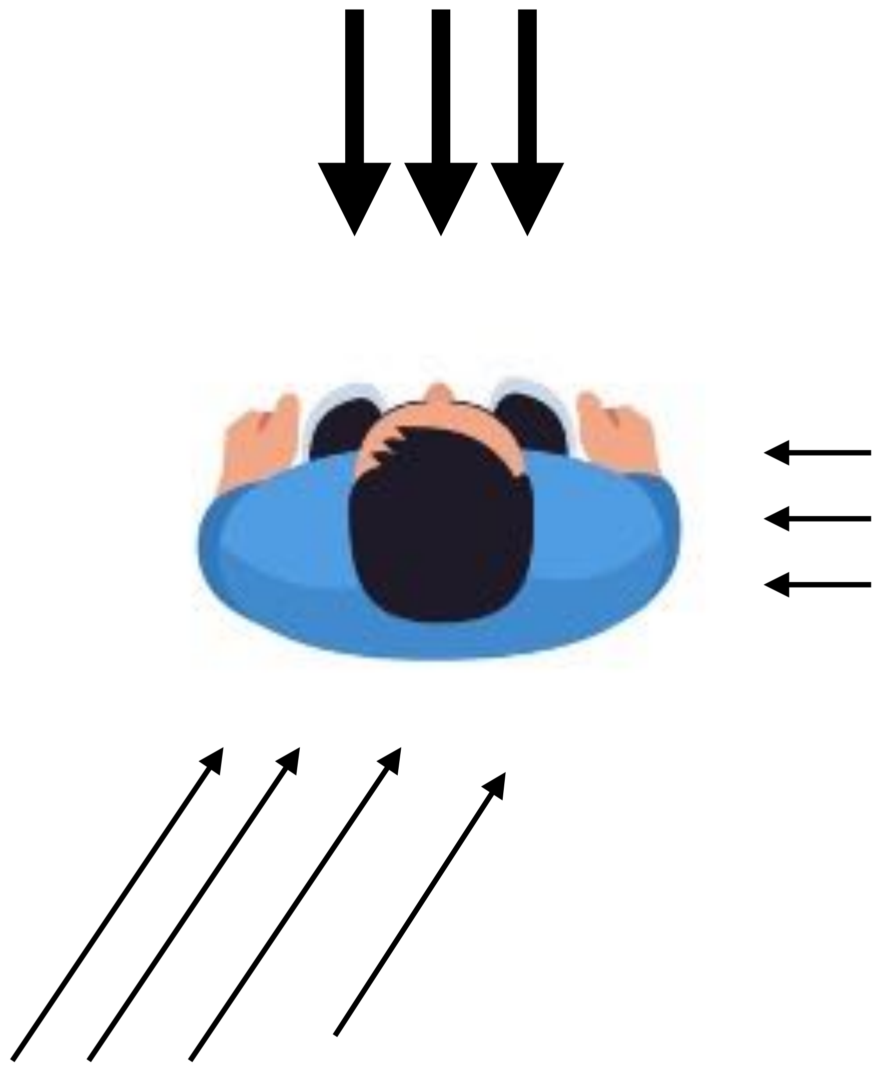
Characterisation of the sensitivity of the detector over the range of neutron energies accessible and the dose rate H*(10) estimation.

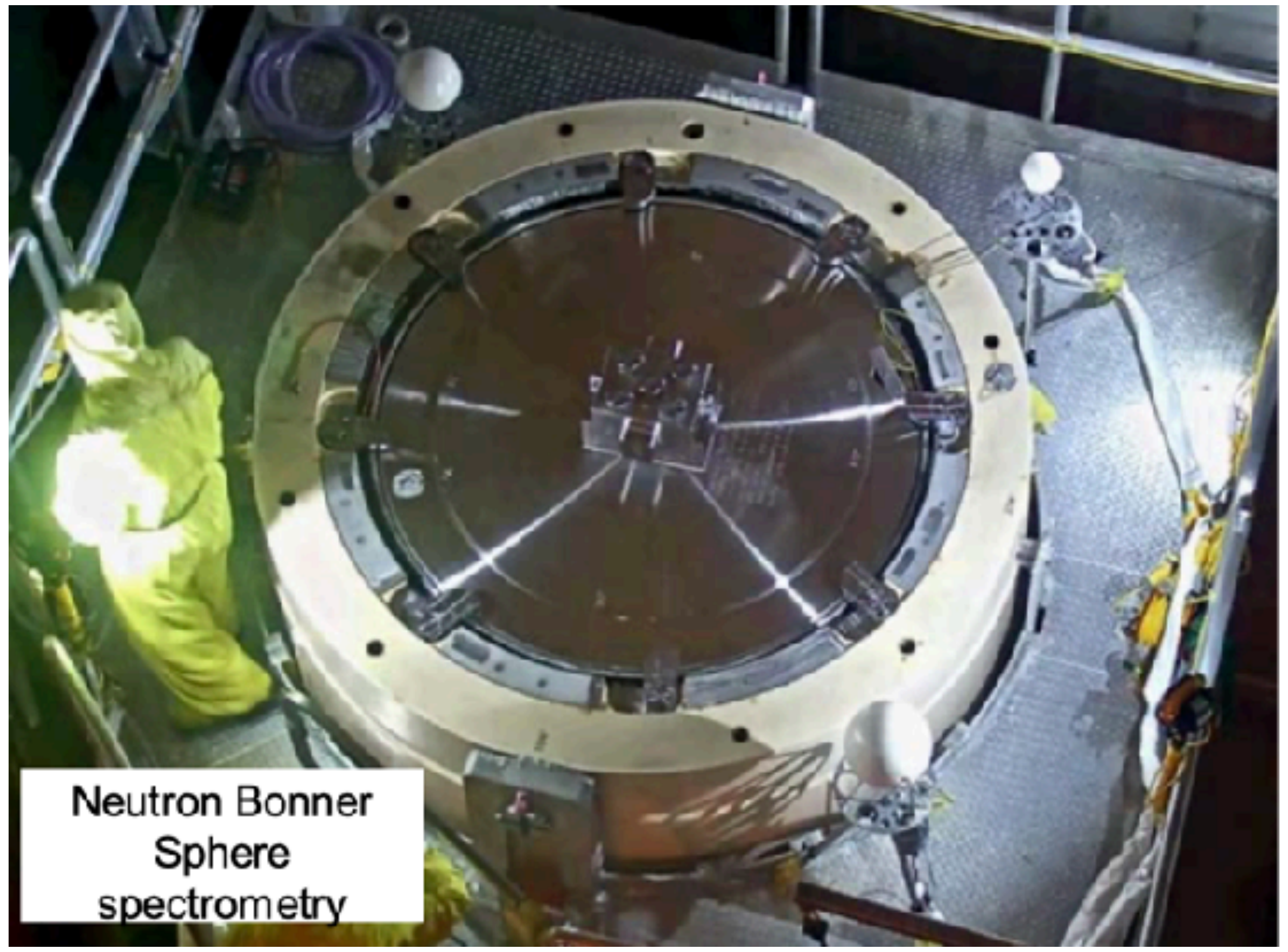
Explore the possibility to measure H*(10) and estimate the effective dose

System well suited for ML techniques which can be used to infer the **neutron fluence** and the **dose rate in real time**

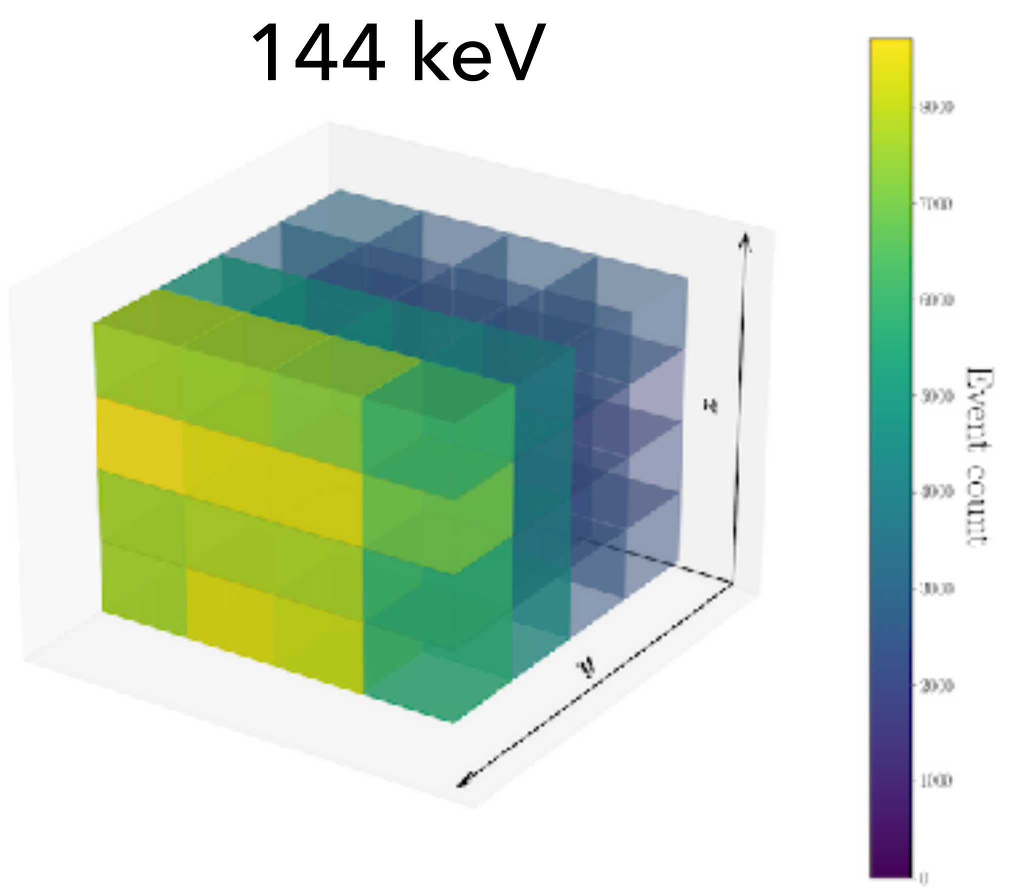


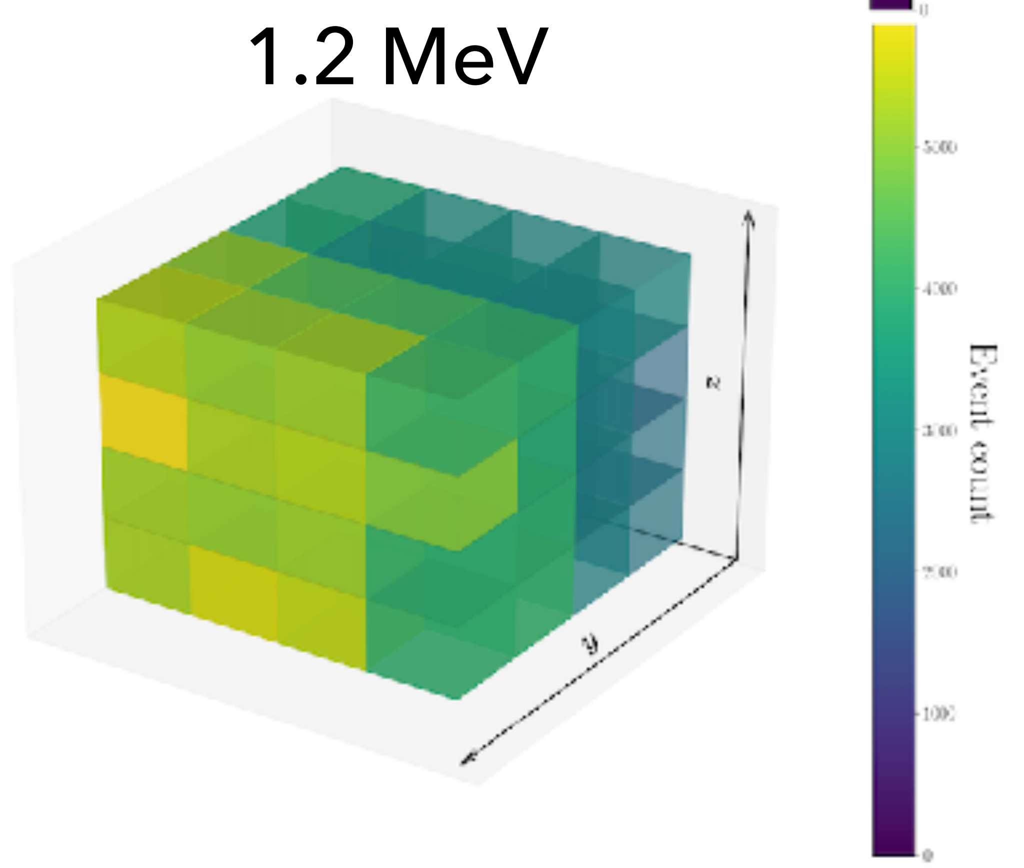
Balmer MJ, Gamage KA, Taylor GC. A novel approach to neutron dosimetry. Med Phys. 2016 Nov;43(11):5981. doi: 10.1118/1.4964456. PMID: 27806600.

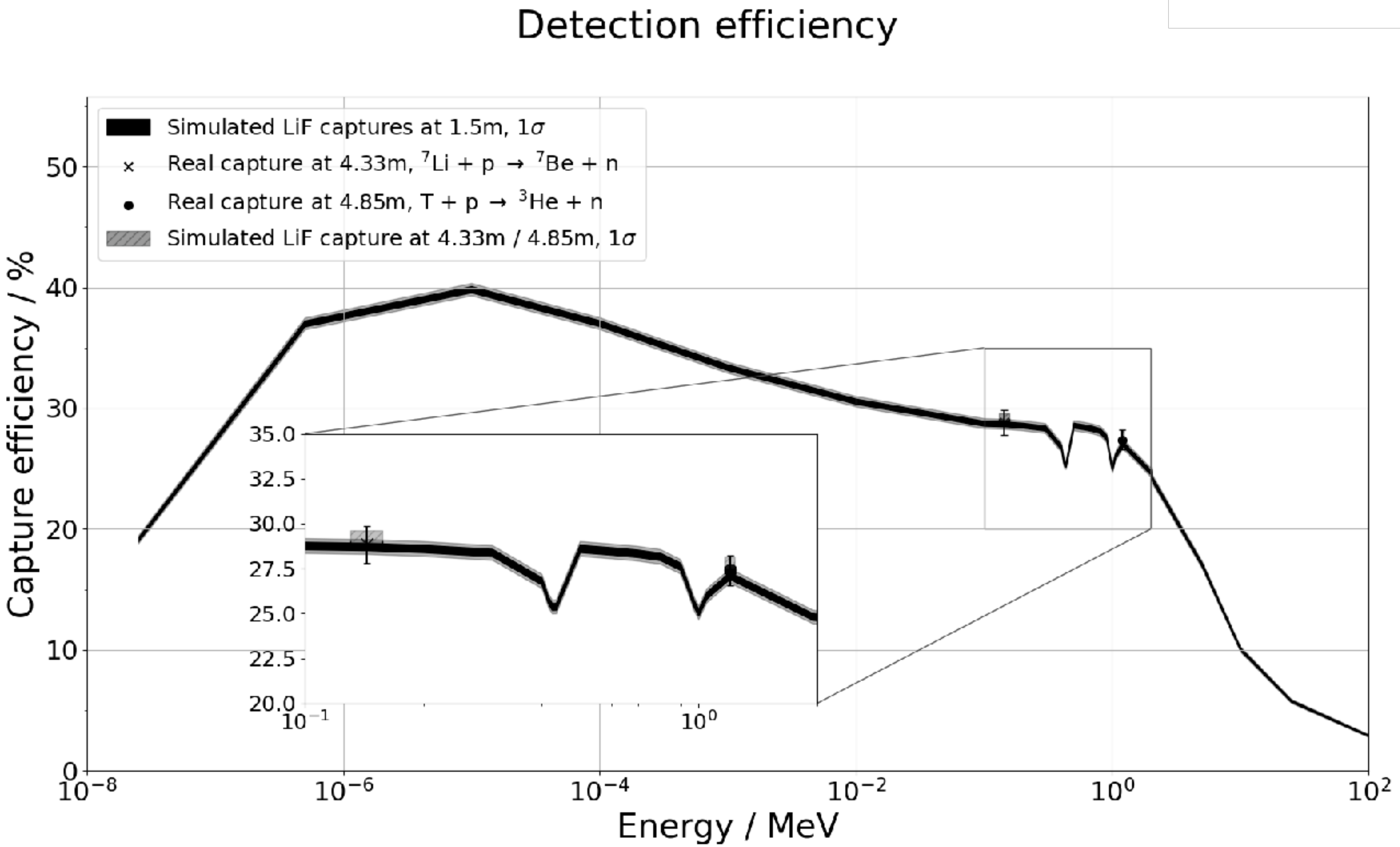




Li-6 neutron efficiency





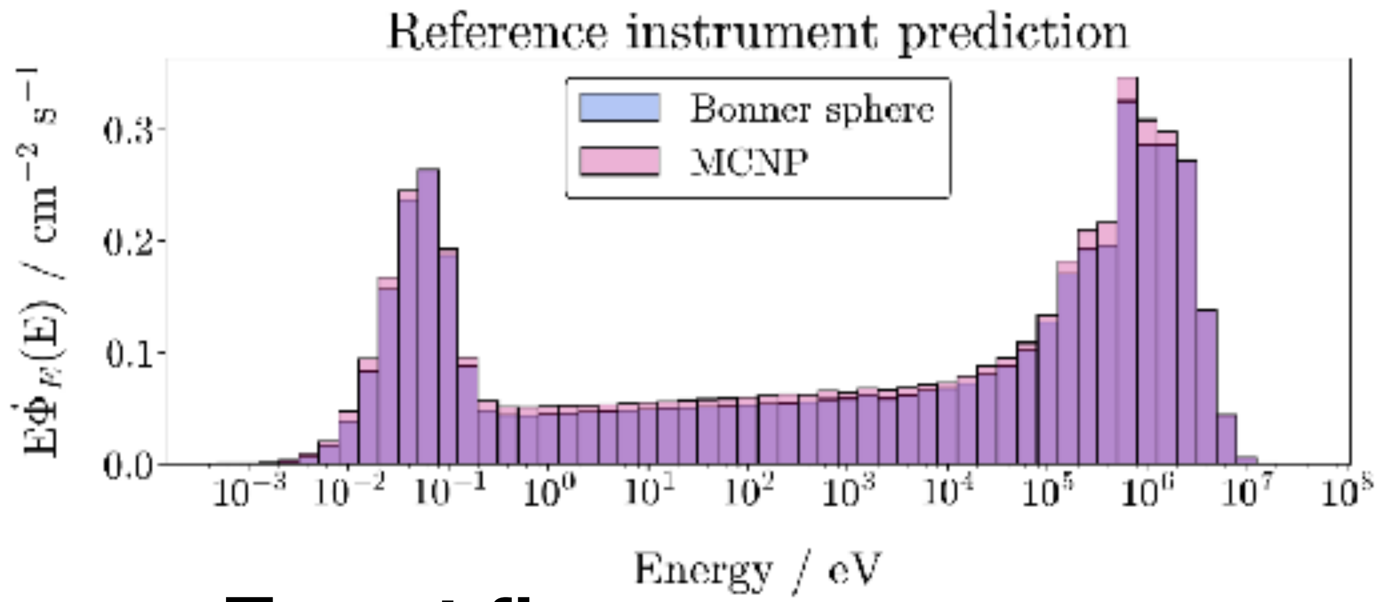


- Mono-energetic neutrons used to anchor the efficiency vs energy

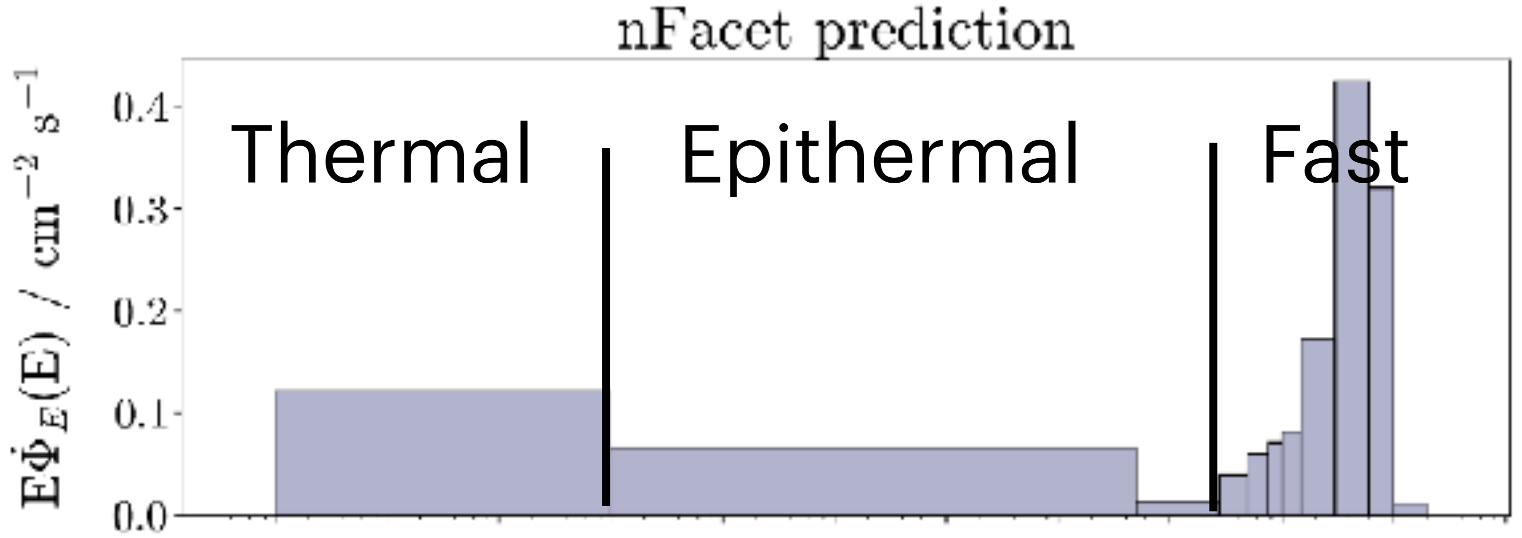
Fluence & dose ML reconstruction

- nFacet 3D encodes the energy and direction of neutrons which can be unfolded using deep learning methods
  - Better than traditional inversion as it doesn't require any assumption only availability of training data
  - All energies captured in 1 measurement (unlike Bonner sphere) and inference possible in real time
  - Can use any coefficients for dose measurements (ICRP 74 or 95 or …)

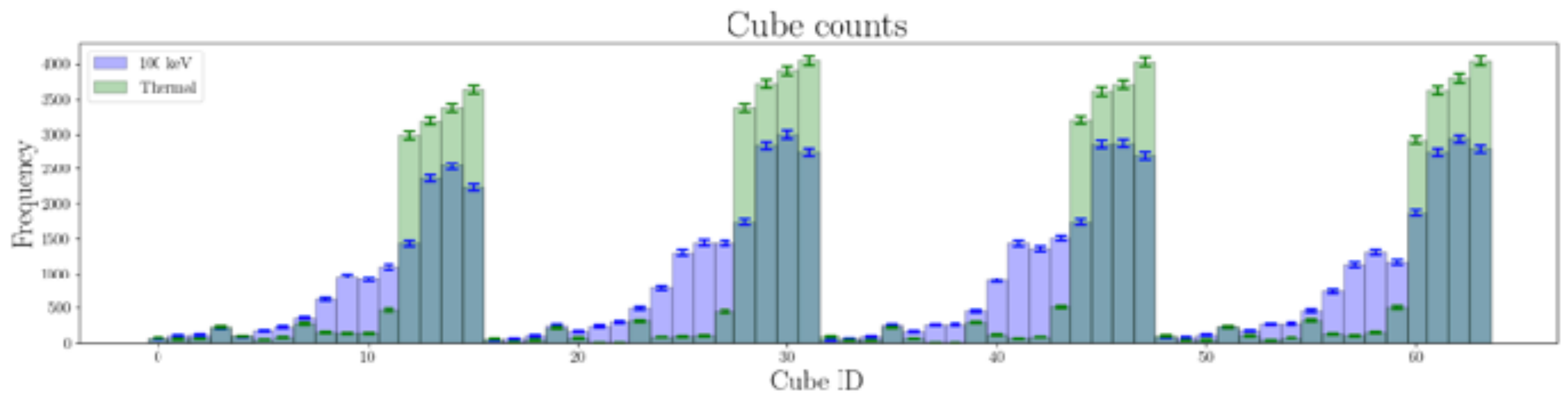
Simulate nfacet 3D response to neutron spectrum



Target fluence vs energy



NN inference returns neutron fluence

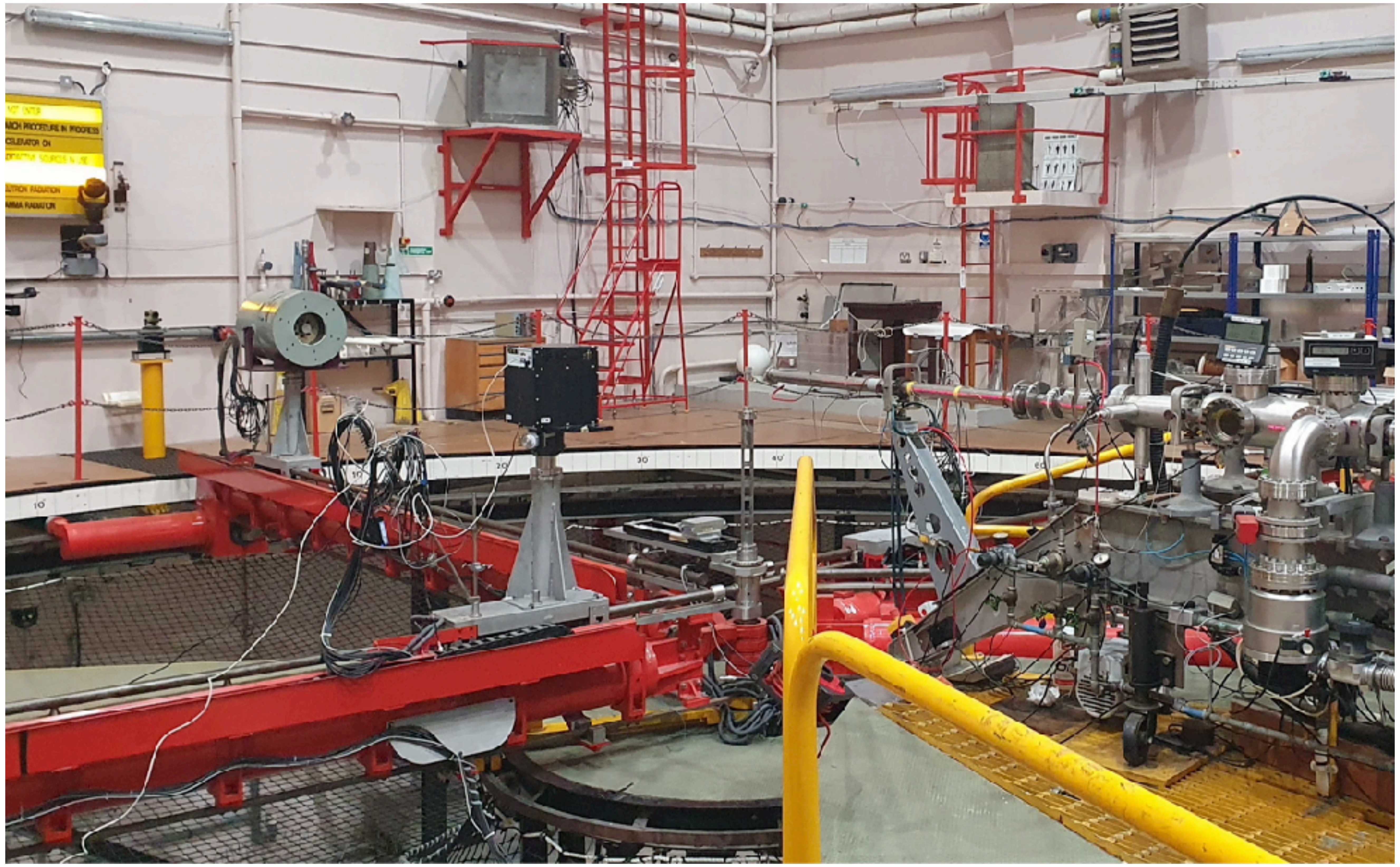


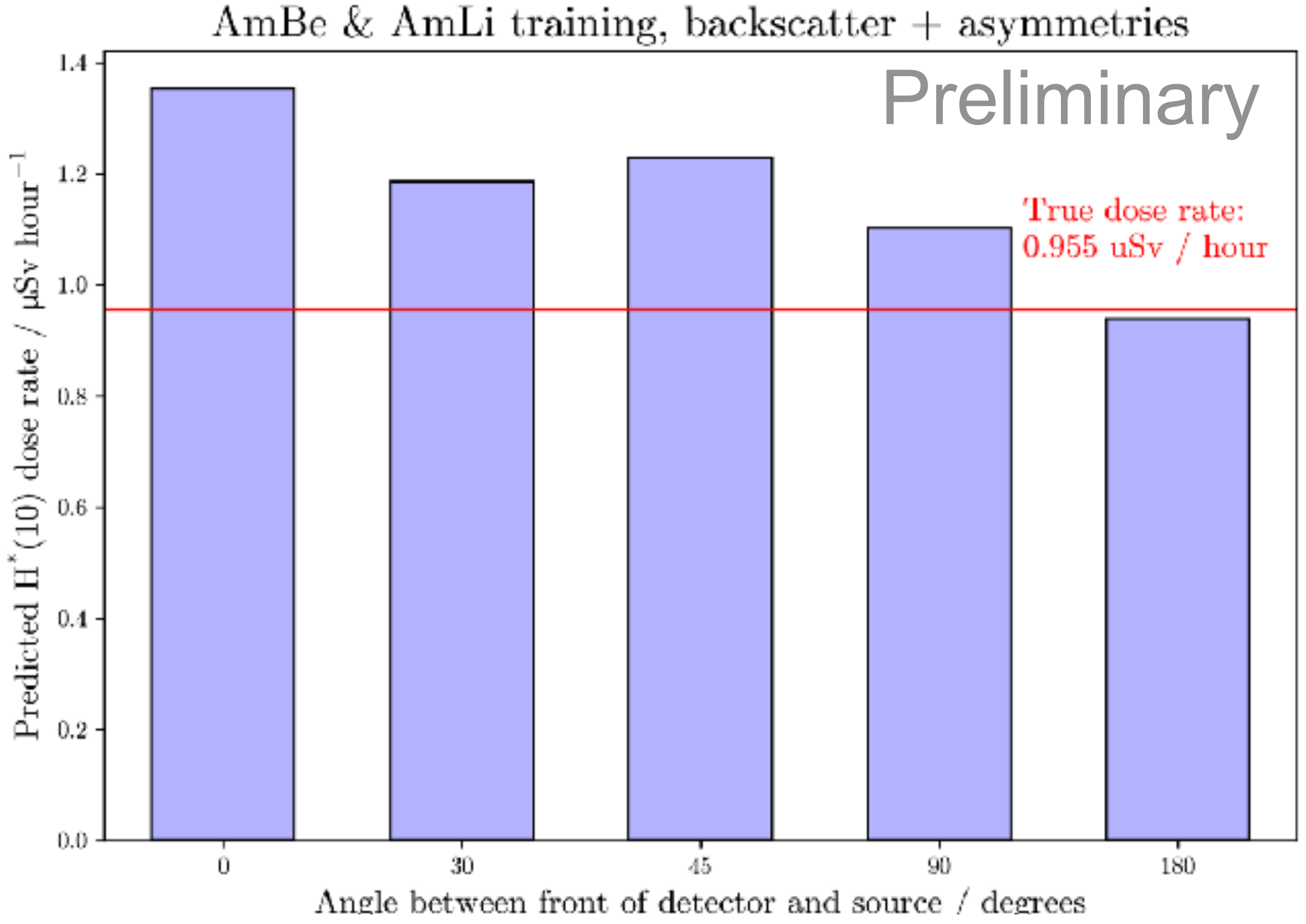
Cube rate distribution dataset

Testing the ANN with low scattering data

AmBe source at various angles (0-180°)

Testing the ANN response to source and mono-energetic neutrons





Test dataset	Predicted dose rate D_p / μSv hour^{-1}	Reference dose rate D_r / μSv hour^{-1}	Fractional deviation / %
AmBe at 0.805 m	1.352 ± 0.001	1.349	0.26 ± 0.10
^{252}Cf at 1.5 m	1.470 ± 0.068	1.264	16.34 ± 5.39
144 keV at 4.337 m, shadowcone subtracted	0.906 ± 0.032	0.638	41.95 ± 5.01
1.2 MeV at 4.853 m, shadowcone subtracted	2.597 ± 0.250	2.546	2.00 ± 9.82

Summer 2022 Workplace dose measurement @ NPL National Physical Laboratory

nFacet 3D M1

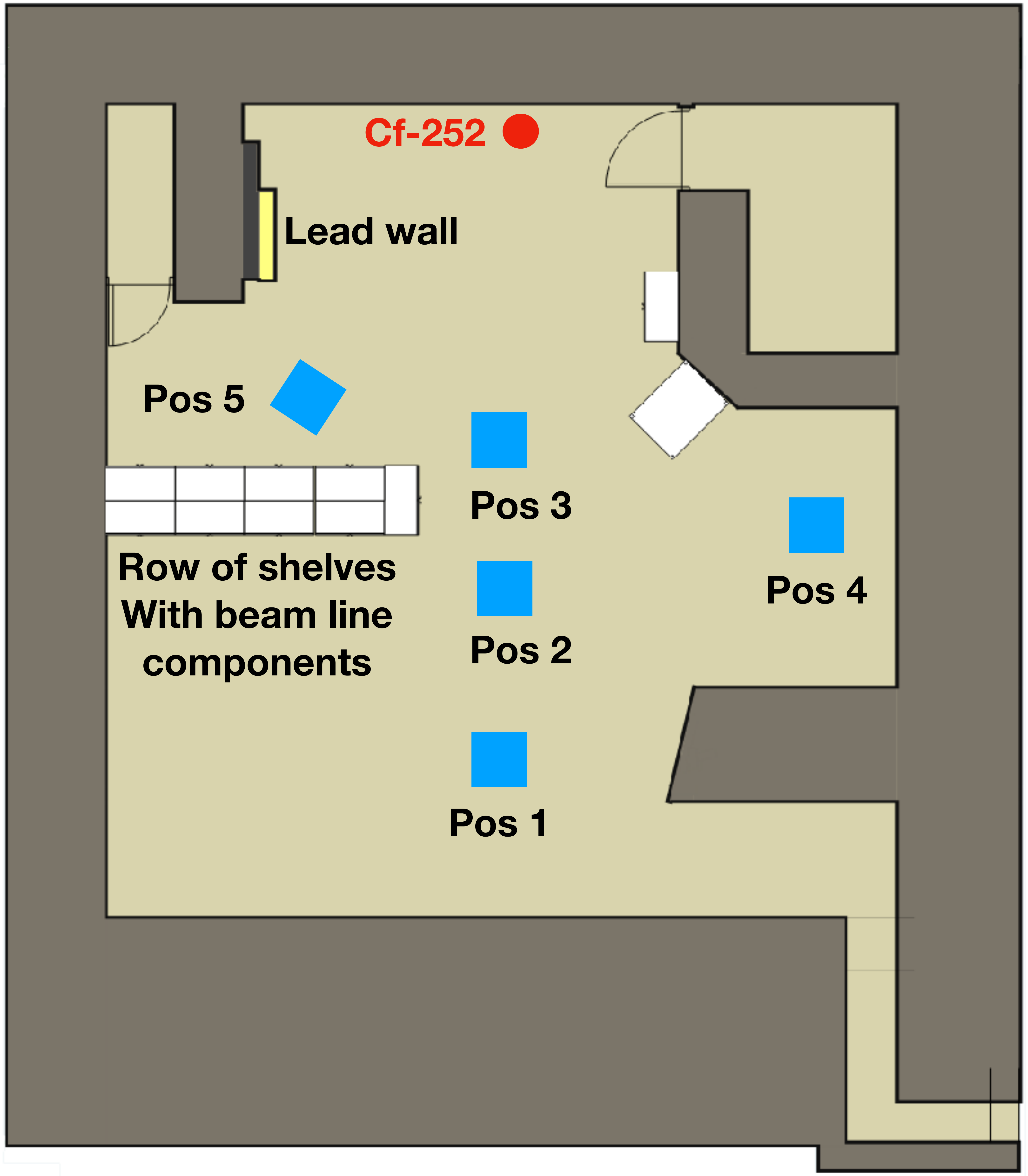
EPDN2-n

Bonner spheres

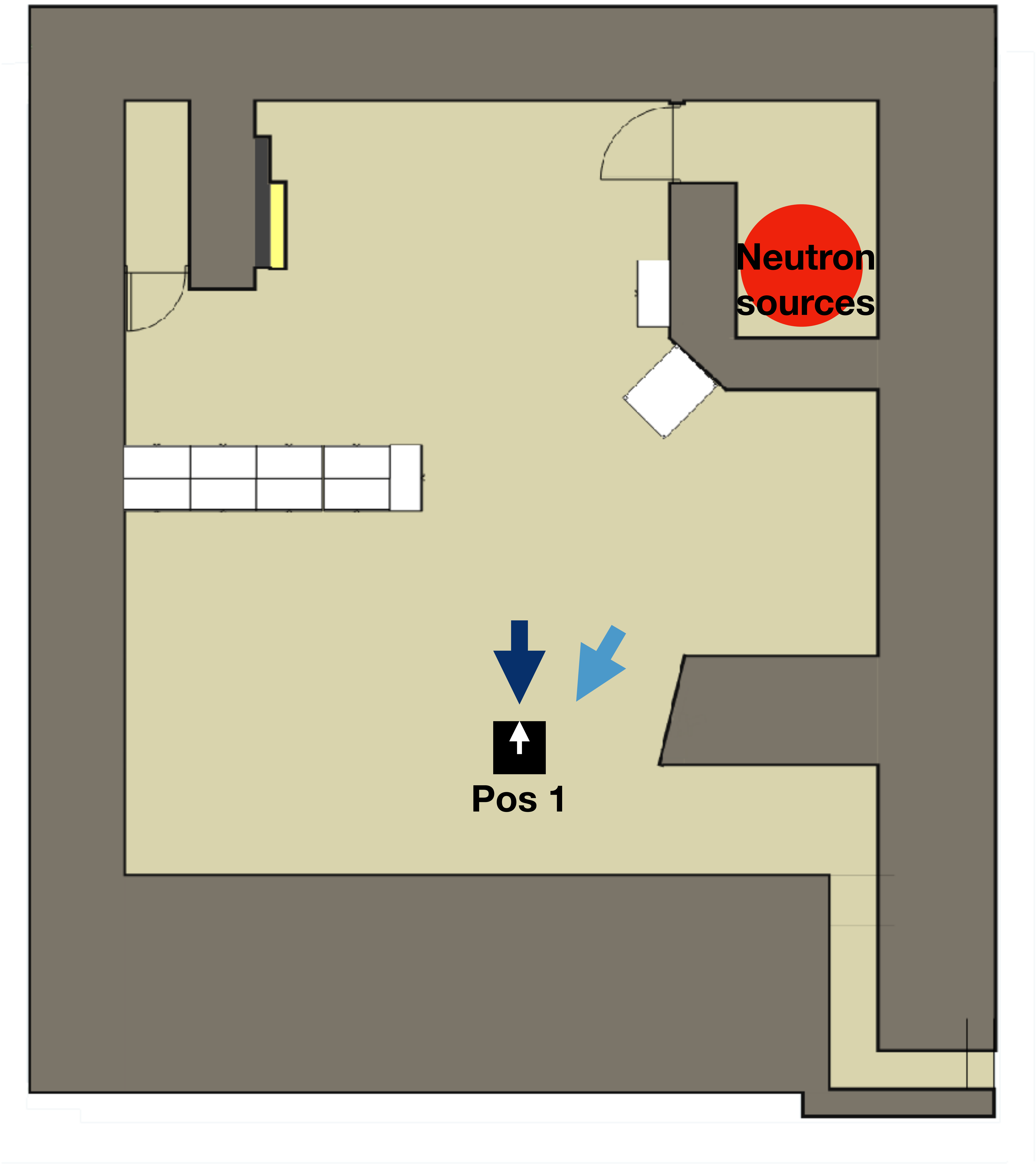
Berthold LB 6411

Measurement in the basement to reproduce non-standard field conditions

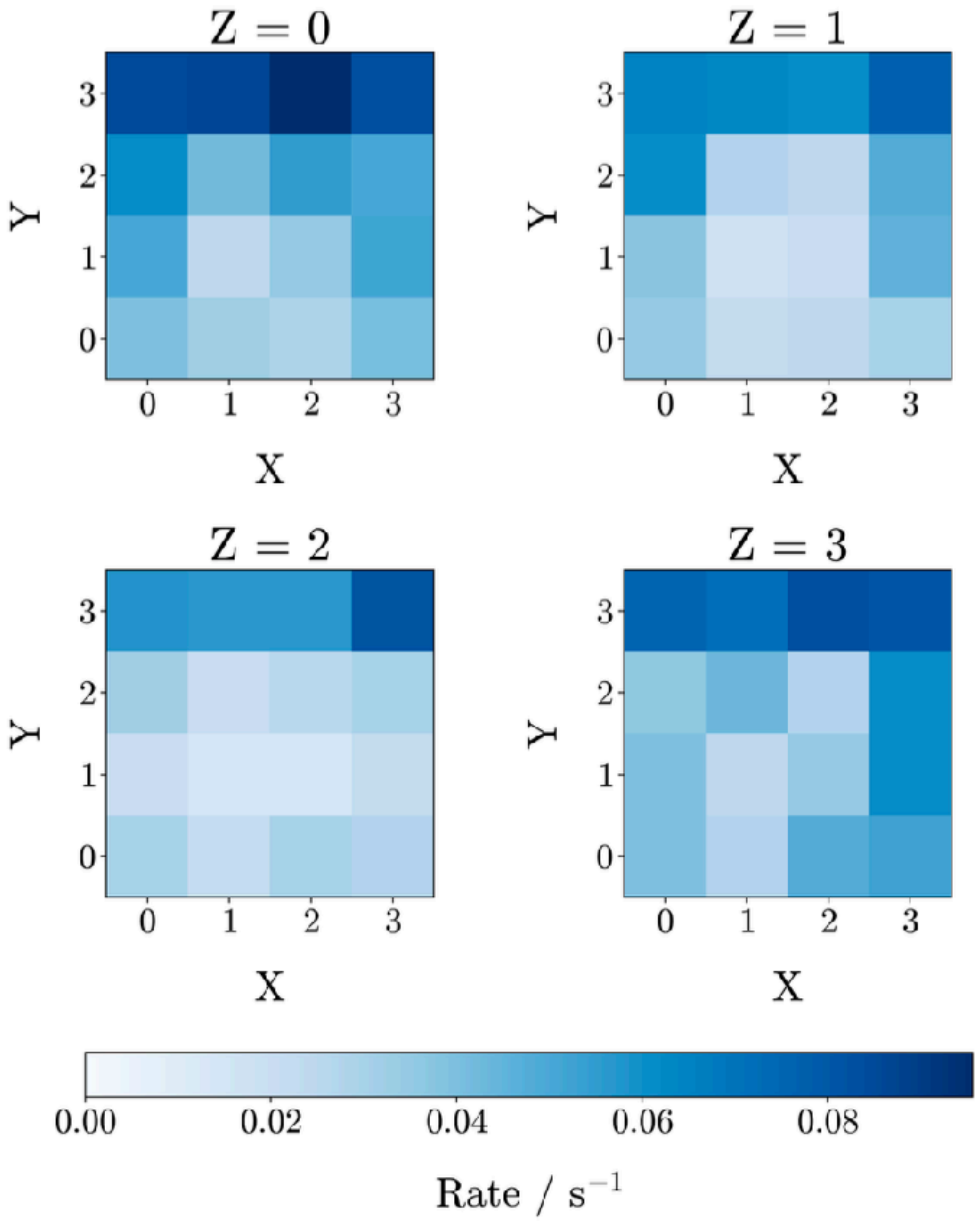
Comparison with state-of-the-art survey meter, Bonner sphere and personal dosimeters

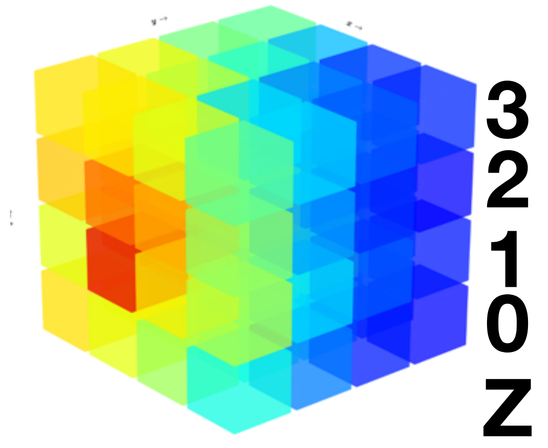


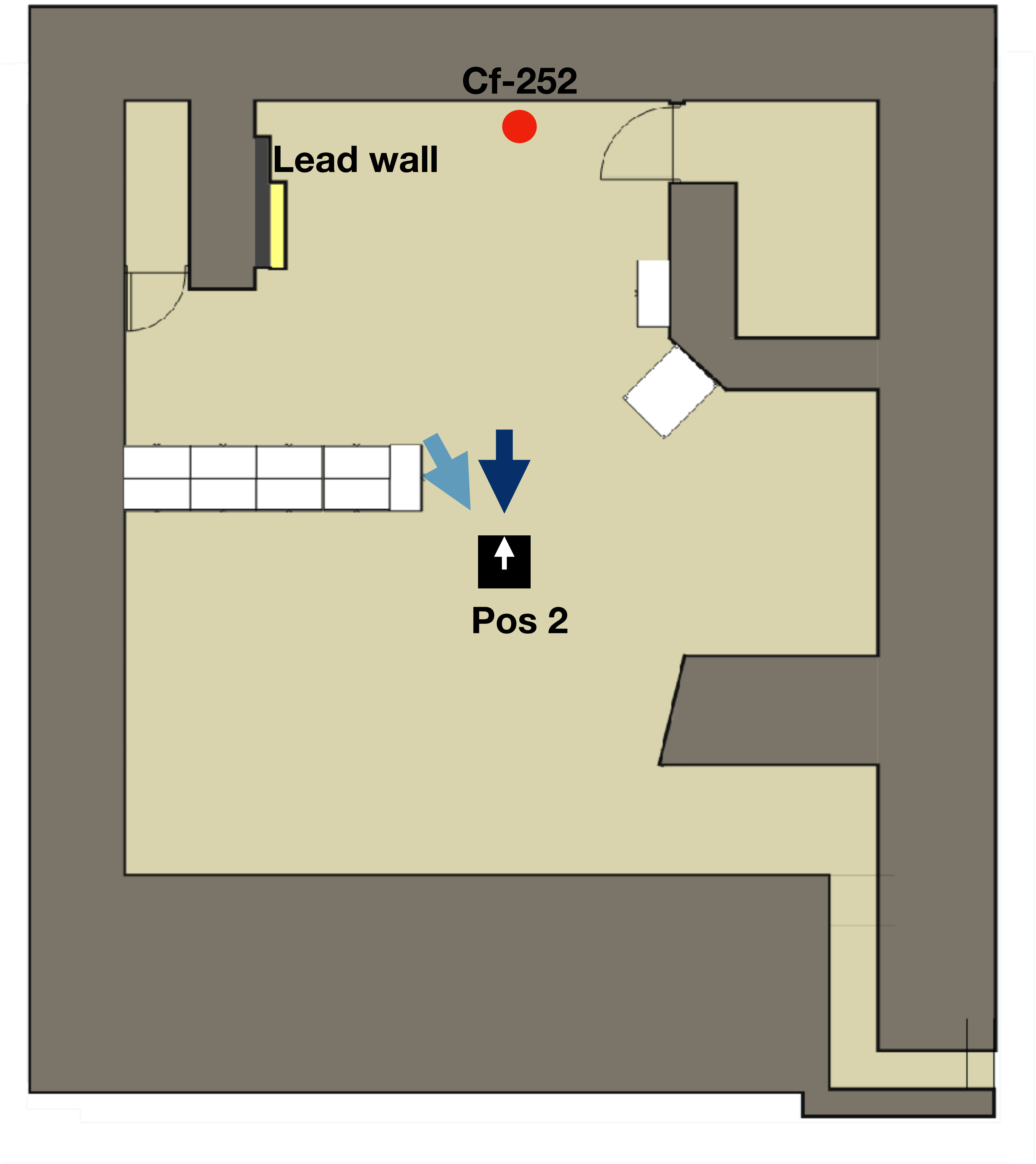
- Basement area was simulated in MCNP
- Concrete and main geometry of the area taken into account
  - There is a lot more stuff lying around that will never make it to the simulation…
- Detector positions were chosen to vary significantly the neutron field measured

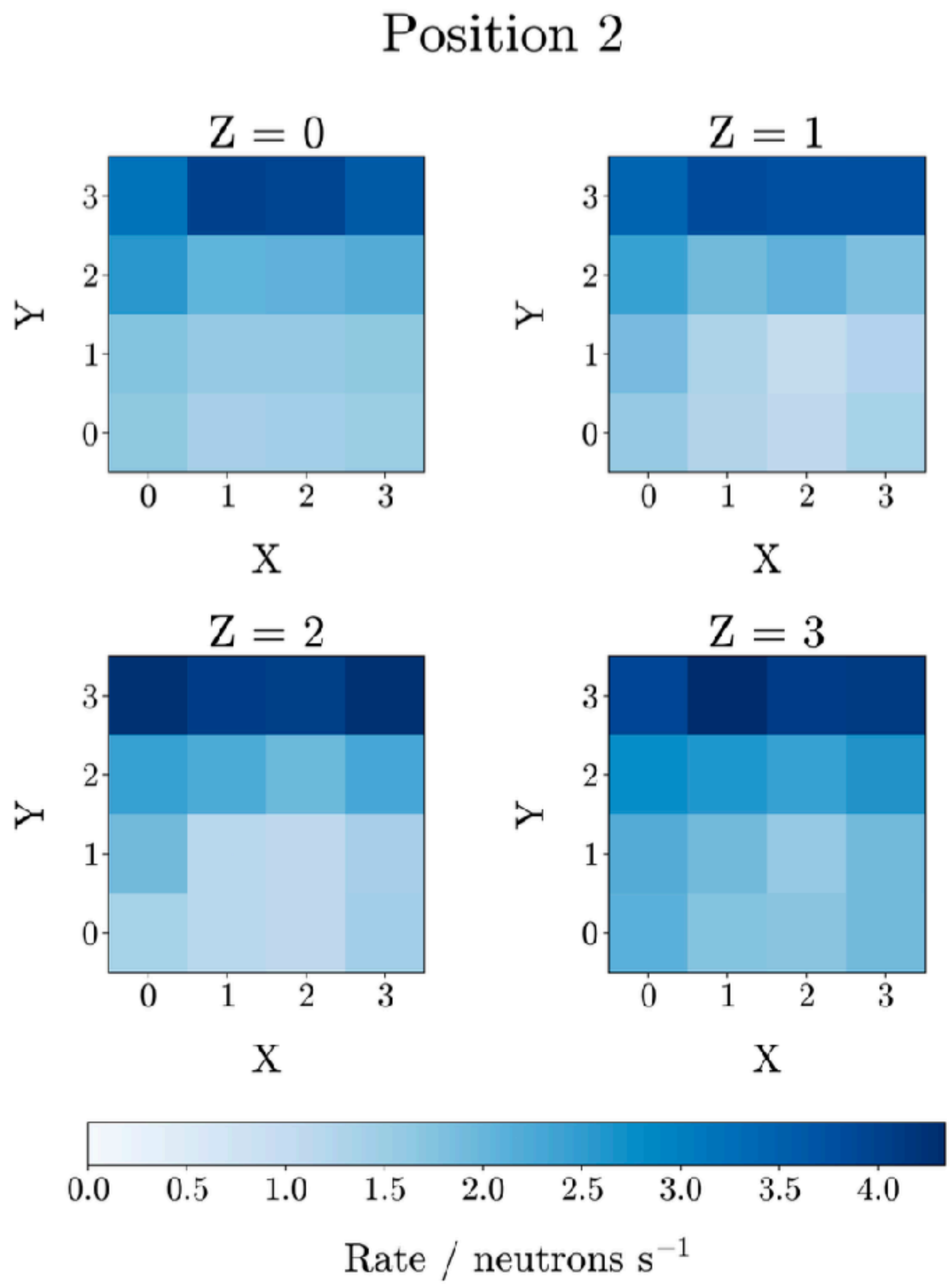


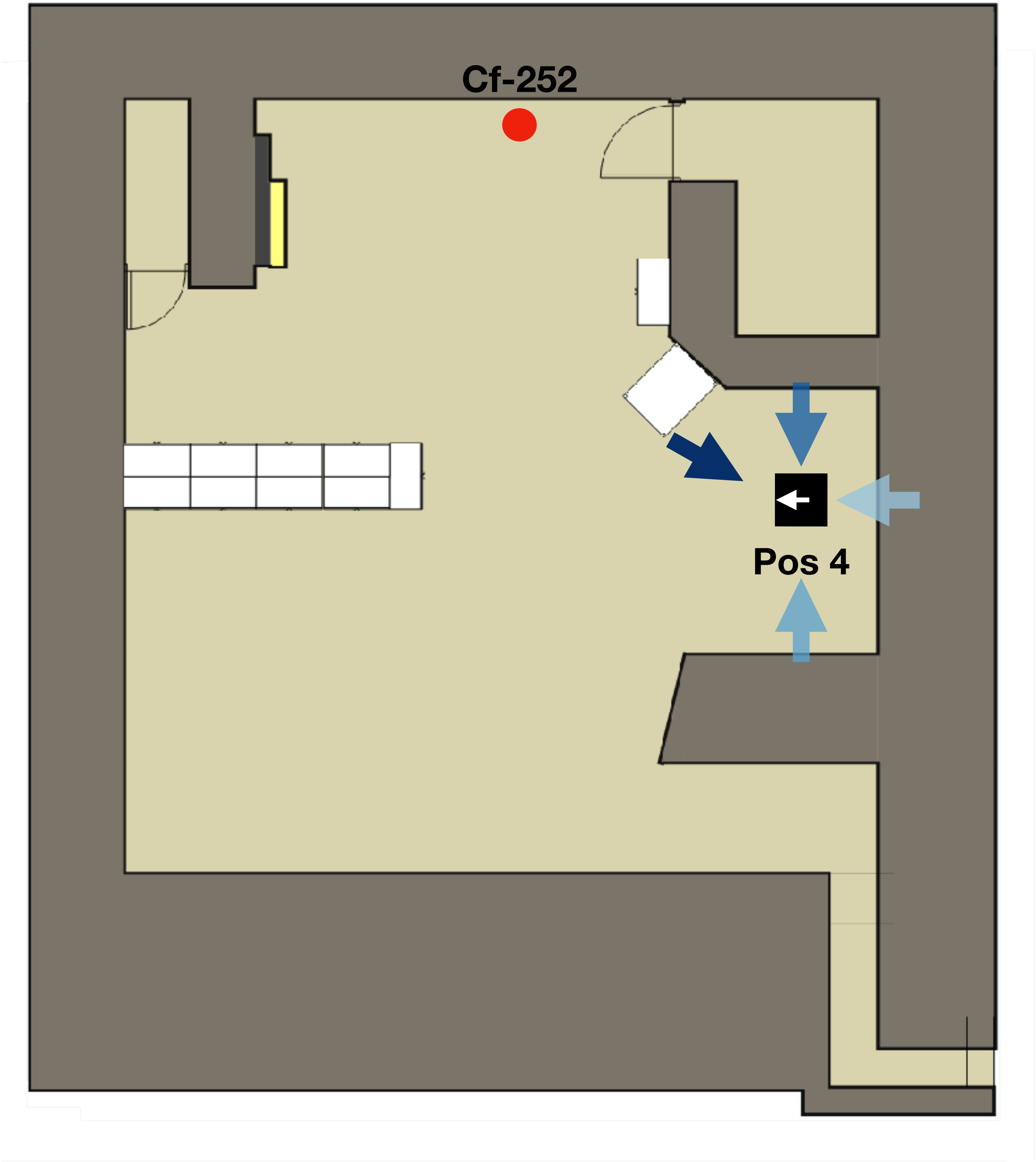
Position 1 background

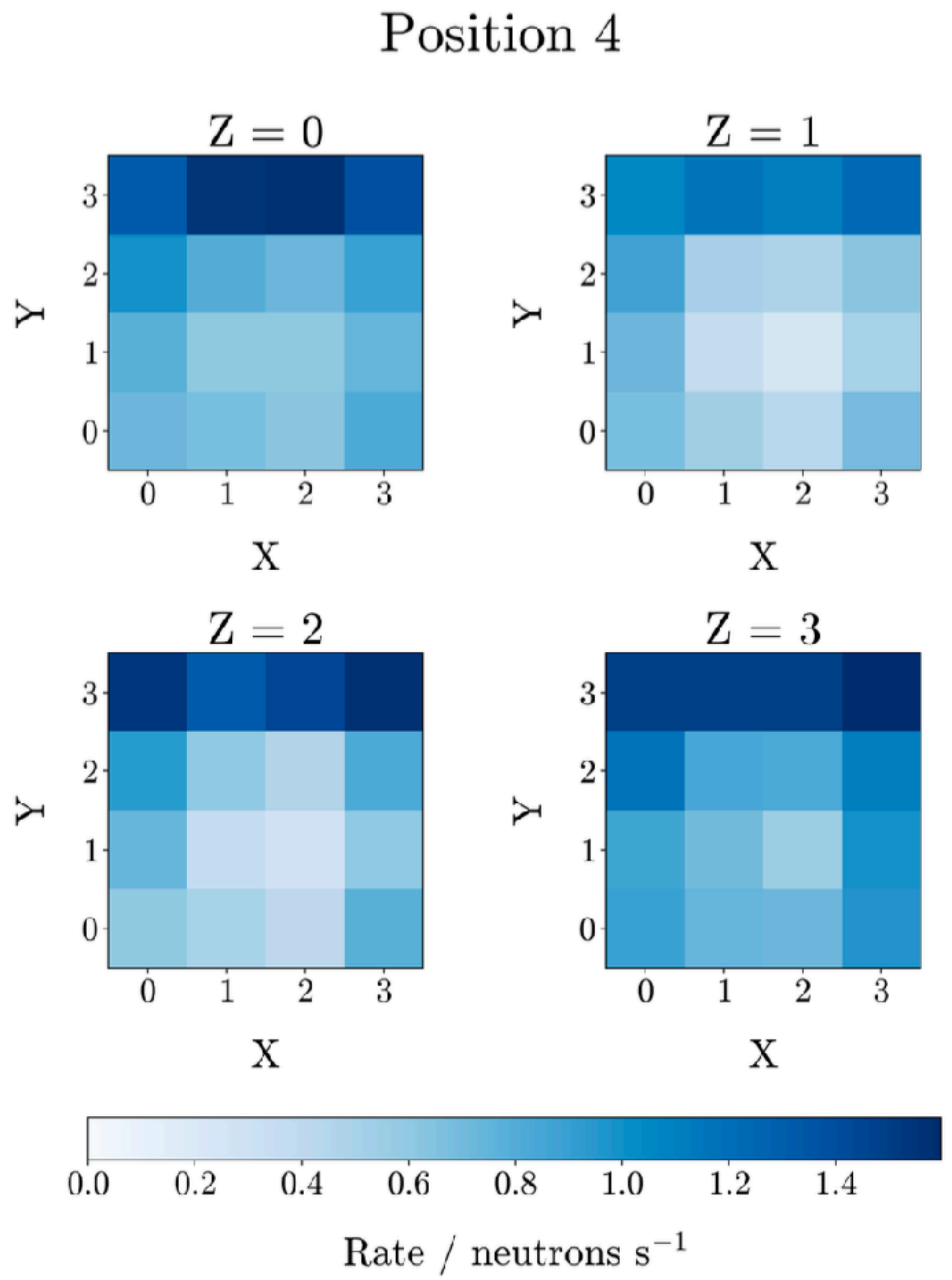


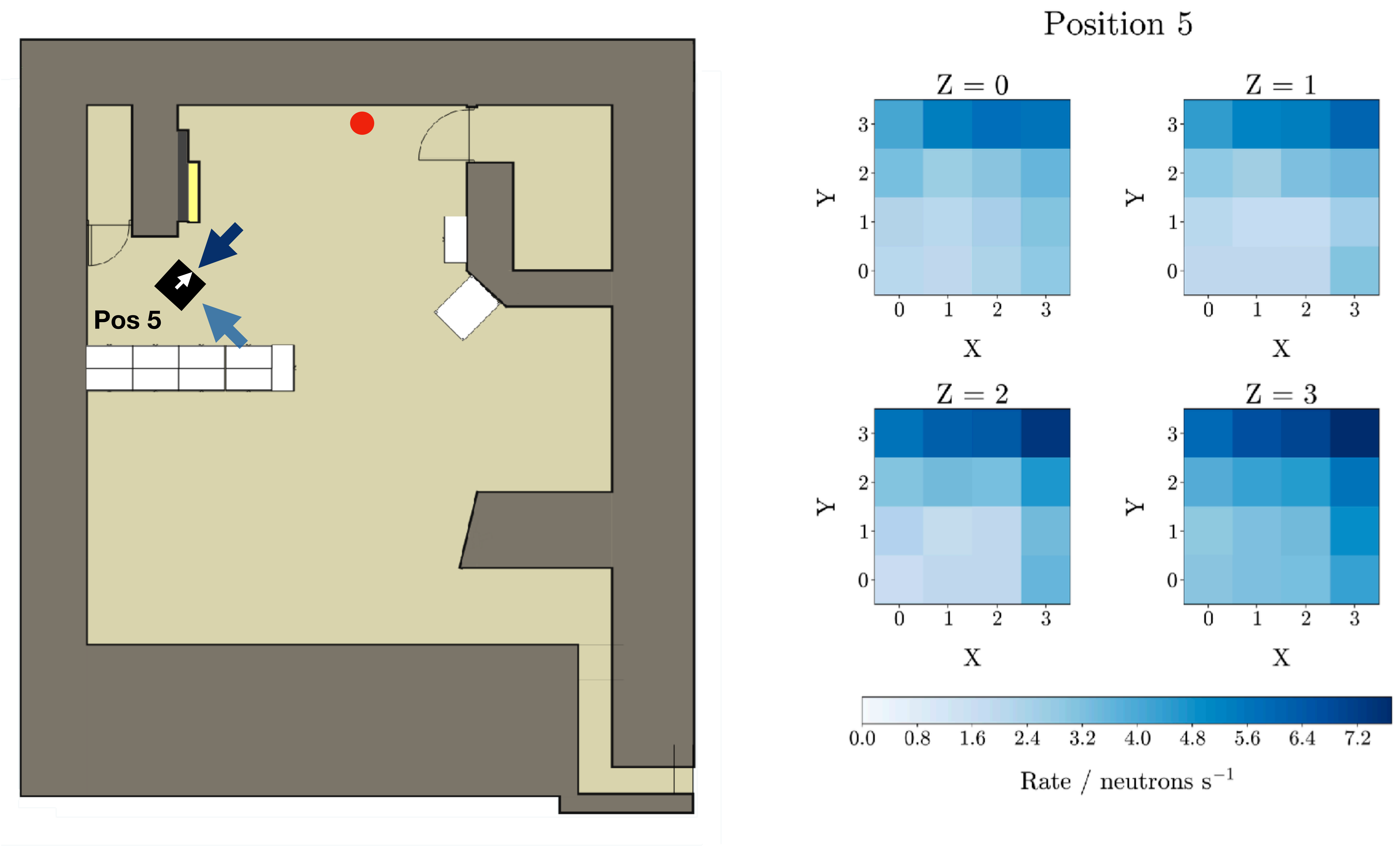



Cf-252
Lead wall
Pos 2


Position 2
Z = 0
Z = 1
Z = 2
Z = 3
Y
X
0
1
2
3
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Rate / neutrons s^{-1}

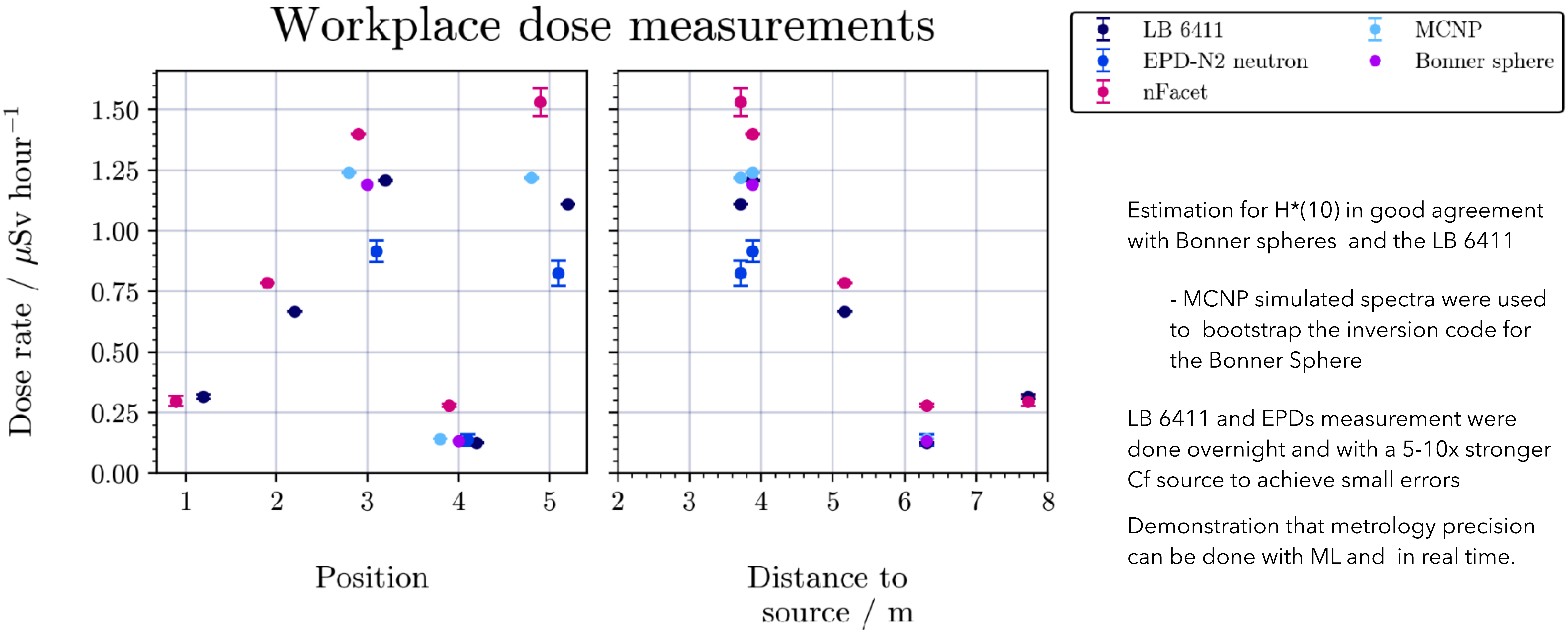

Cf-252
Pos 4


Position 4
Z = 0
Z = 1
Z = 2
Z = 3
X
Y
0
1
2
3
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Rate / neutrons s^{-1}



Pos 5
Position 5
Z = 0
Z = 1
Z = 2
Z = 3
X
Y
0
1
2
3
0.0
0.8
1.6
2.4
3.2
4.0
4.8
5.6
6.4
7.2
Rate / neutrons s^{-1}

Dose rate comparison with SOTA



Estimation for H*(10) in good agreement with Bonner spheres and the LB 6411

- MCNP simulated spectra were used to bootstrap the inversion code for the Bonner Sphere

LB 6411 and EPDs measurement were done overnight and with a 5-10x stronger Cf source to achieve small errors

Demonstration that metrology precision can be done with ML and in real time.

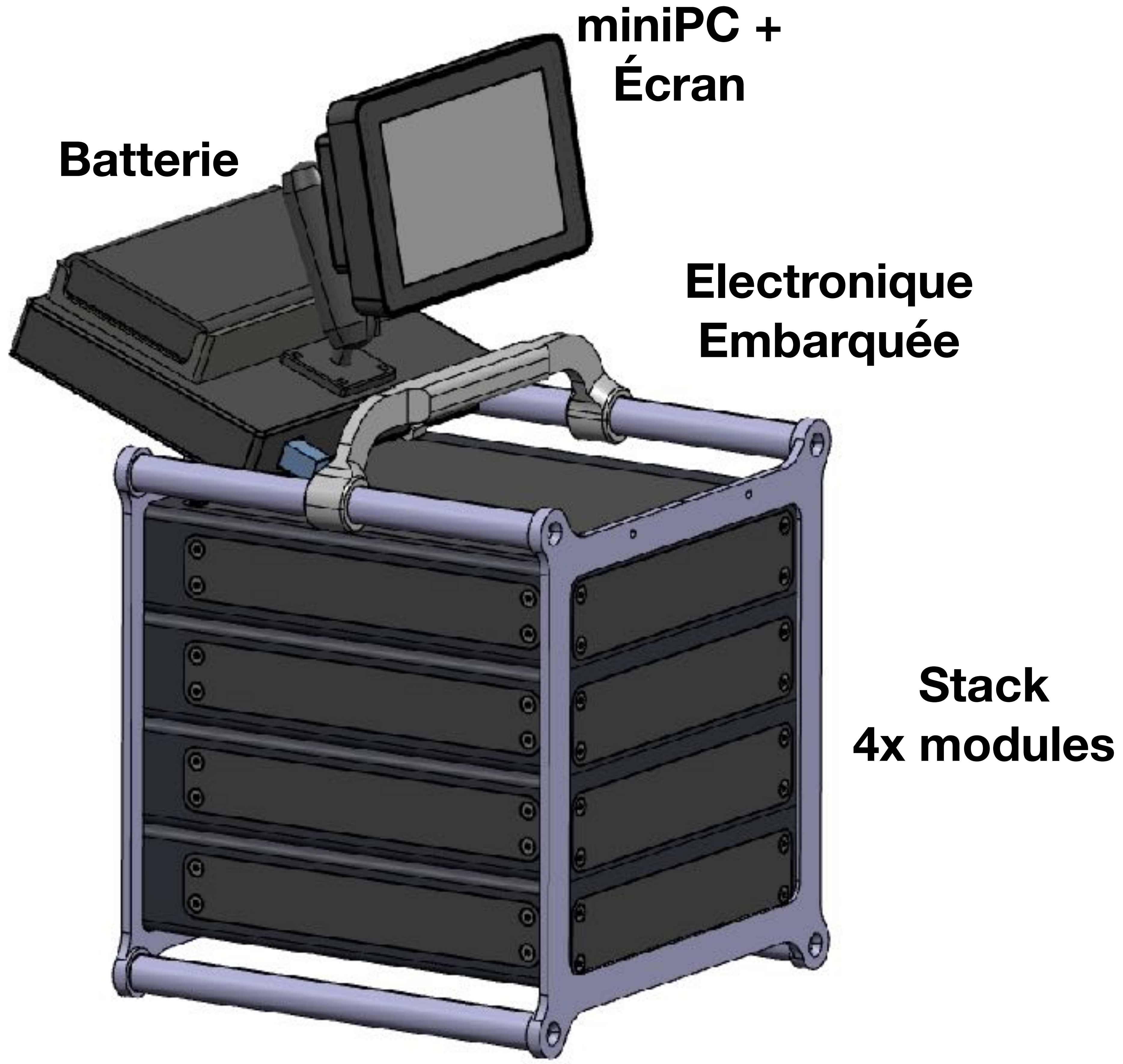
Dose rate comparison with SOTA

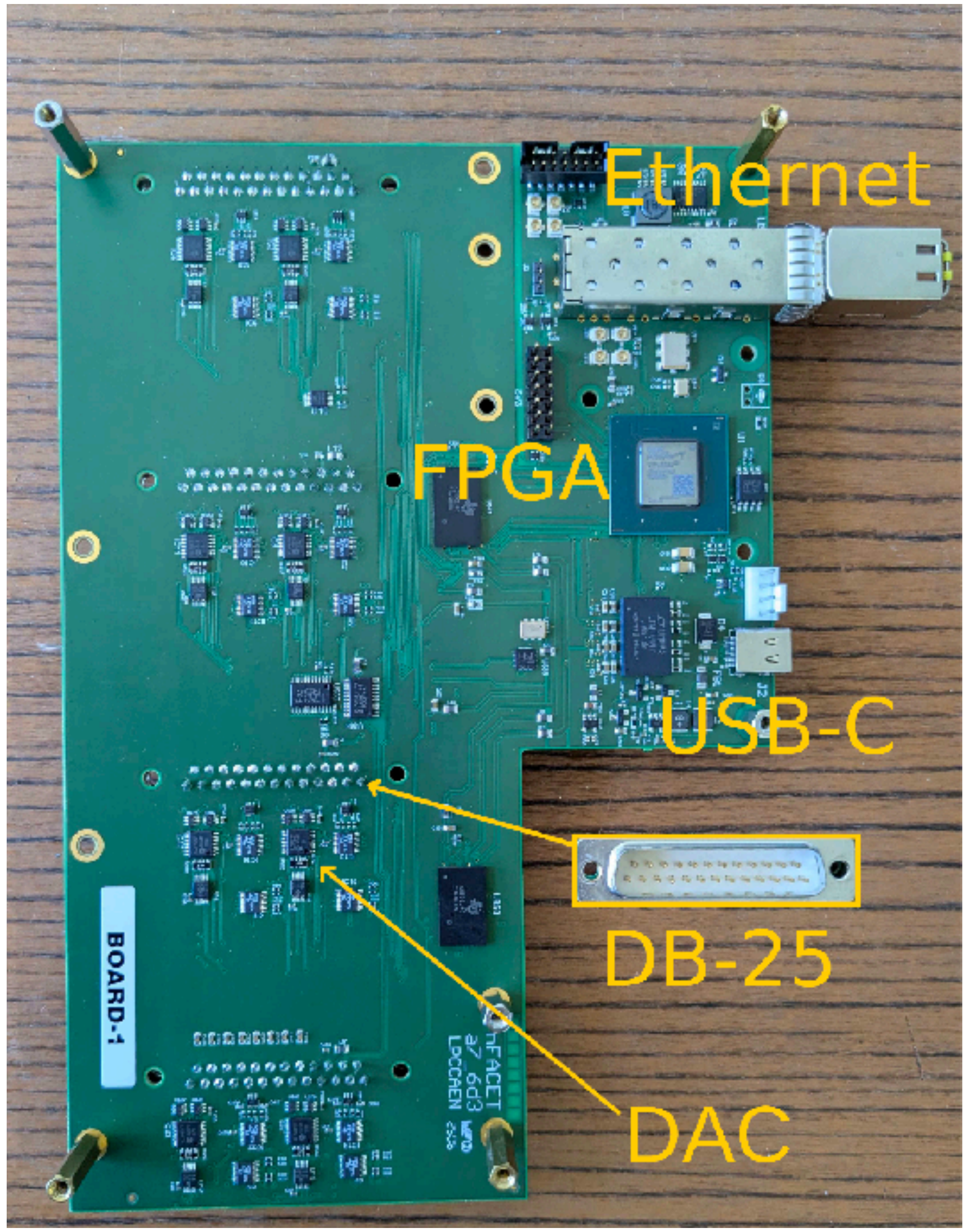
Position	Component	Bonner sphere fluence rate / $cm^{-2}s^{-1}$	MCNP fluence rate / $cm^{-2}s^{-1}$	nFacet fluence rate / $cm^{-2}s^{-1}$
Position 3	Thermal	0.561	0.598	0.817
	Epithermal	0.632	0.706	0.542
	Fast	0.988	1.041	0.907
	Total	2.180	2.345	2.267
Position 4	Thermal	0.176	0.224	0.184
	Epithermal	0.155	0.177	0.114
	Fast	0.120	0.126	0.180
	Total	0.450	0.528	0.474
Position 5	Thermal	N/A	0.588	0.606
	Epithermal	N/A	0.681	0.460
	Fast	N/A	1.016	1.010
	Total	N/A	2.285	2.076

nFacet M2 : a portable system for neutron and gamma radiation fields

K. Béraud, G. Lehaut, A. Vacheret,
Y. Merrer, L. Leterrier, F. Ingouf

nFacet M2 : “Le Cube”

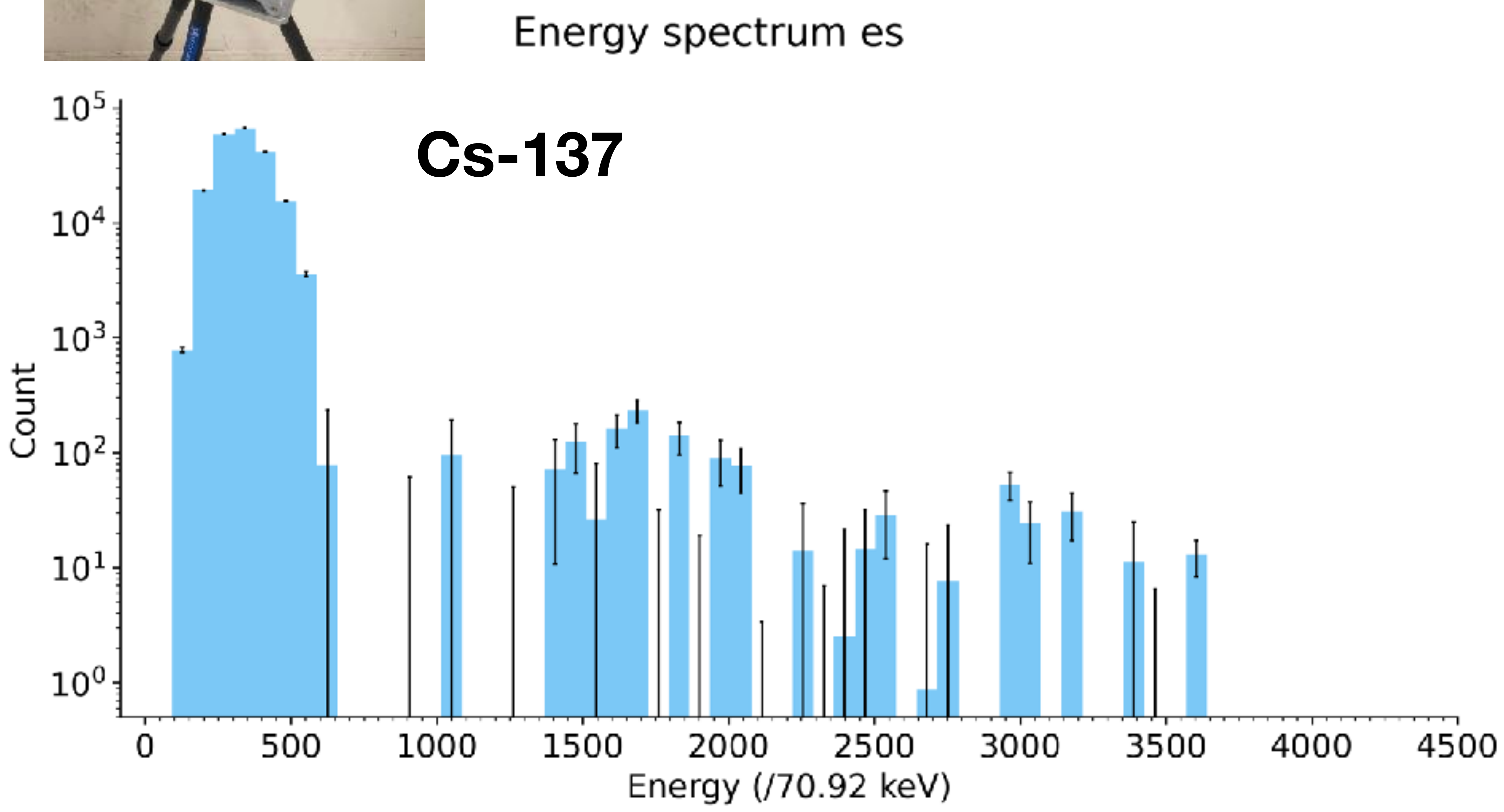


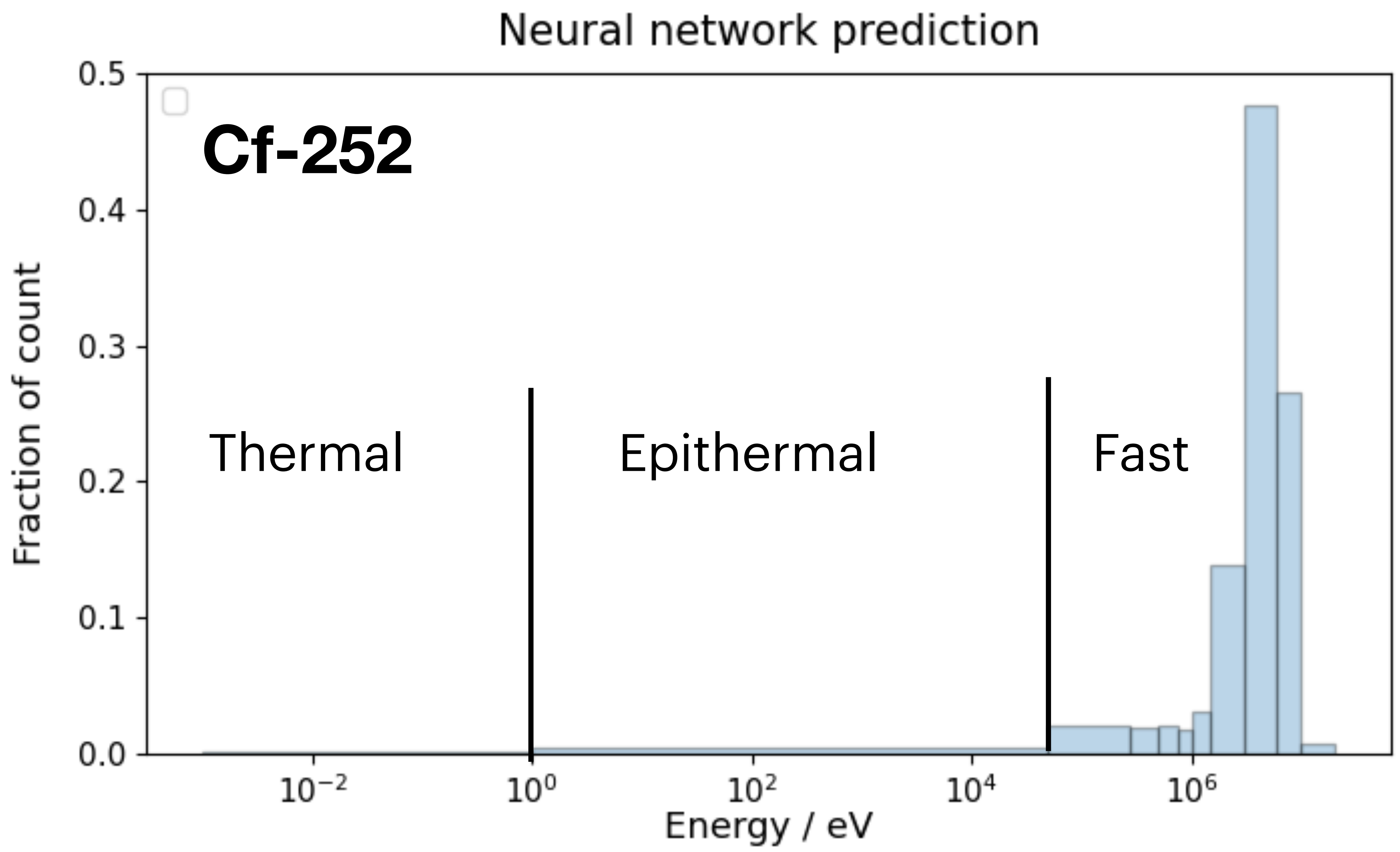


nFacet 3D	Specifications
Digitization rates	65 MHz
Acquisition mode	Waveform, Integration
Trigger	Amplitude, Time over threshold, Coincidence, Periodic
Saturation rates	10 kHz
Power draw	7 W
Connection	Ethernet
UI	Touchscreen

nFacet real time measurements

- The system provides higher level measurements in real time :
  - Gamma-rays compton edge spectra
  - Binned neutron fluence vs energy





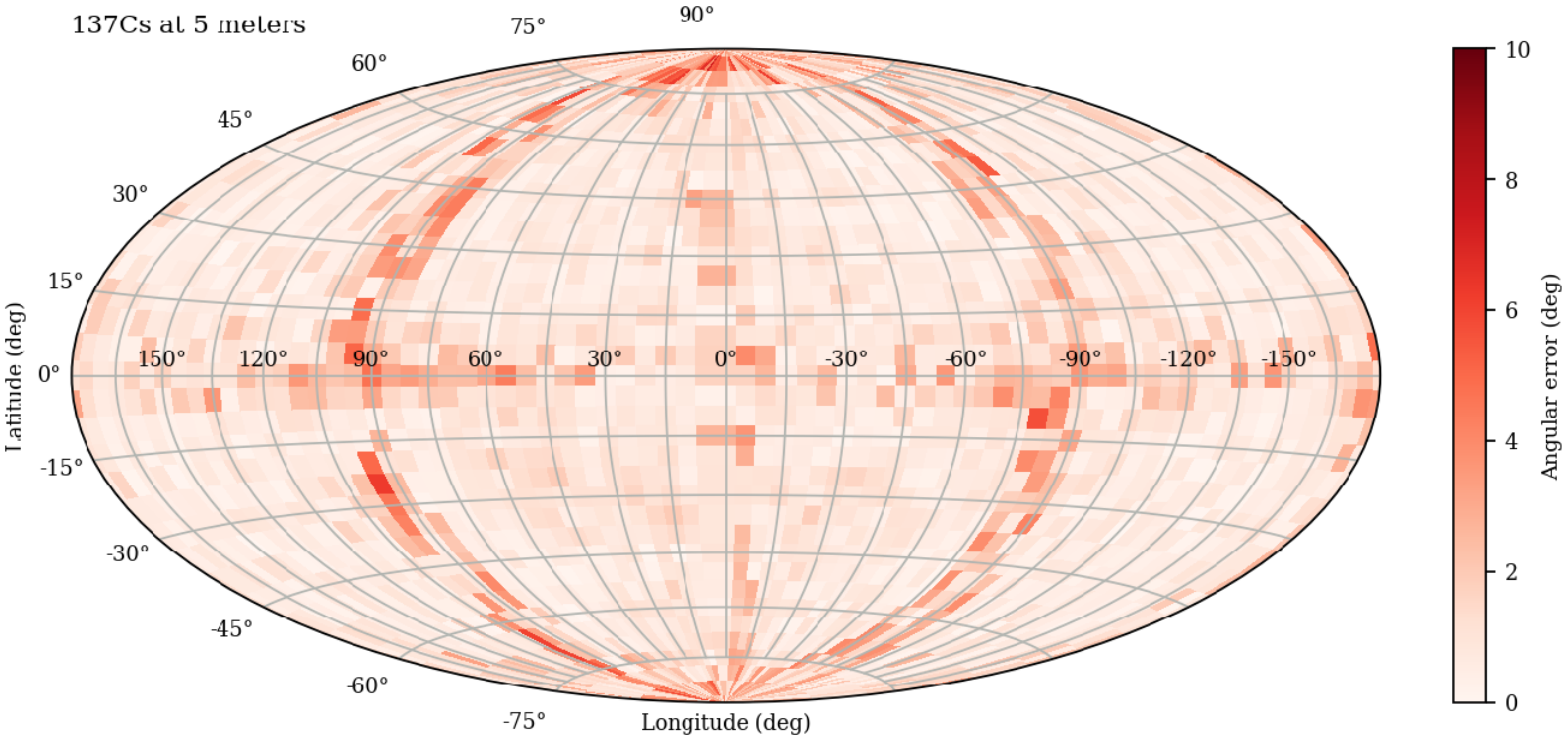
Direction inference using ANN

Directional prediction using ANN

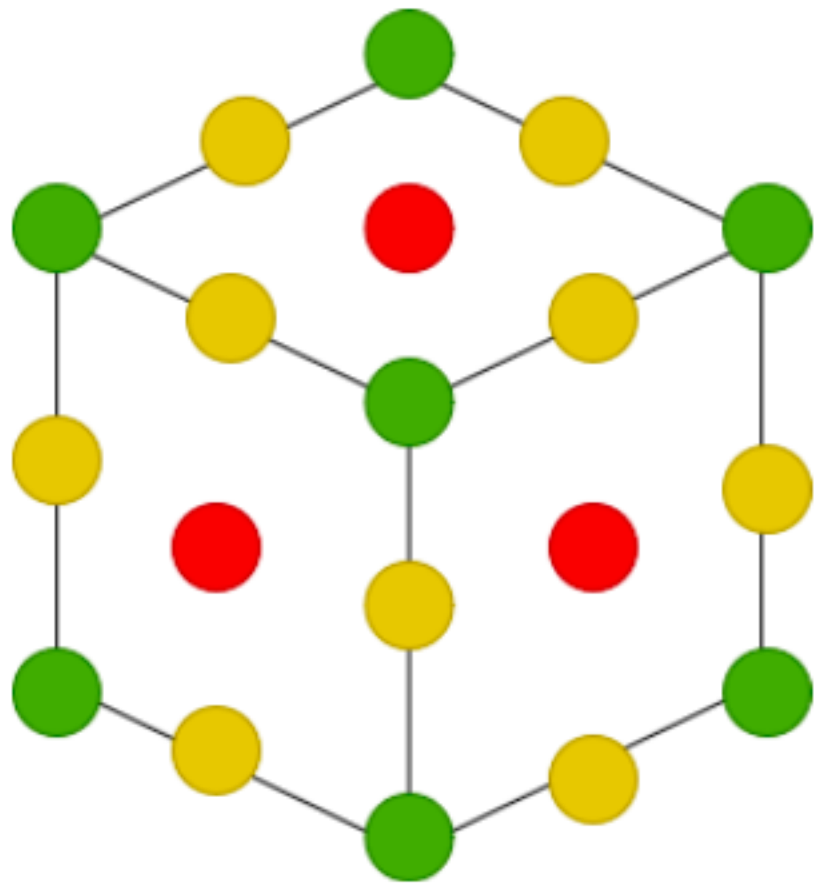
Pre-Training on large datasets
Fine-tuning on real data to account for detector effects

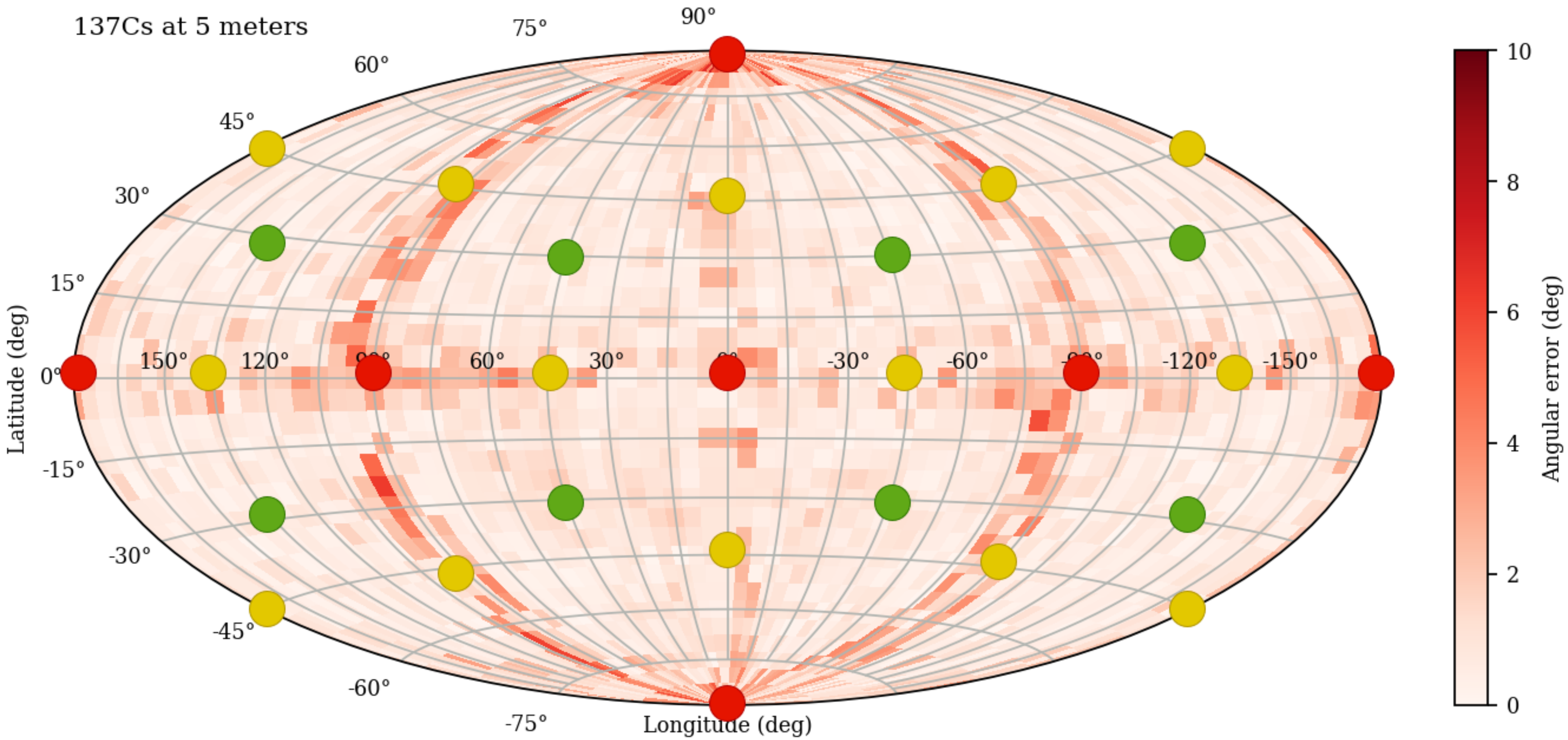
Angular resolution below 5 degrees at 5 m almost in all directions

Large database of Gamma and neutron emitters for training

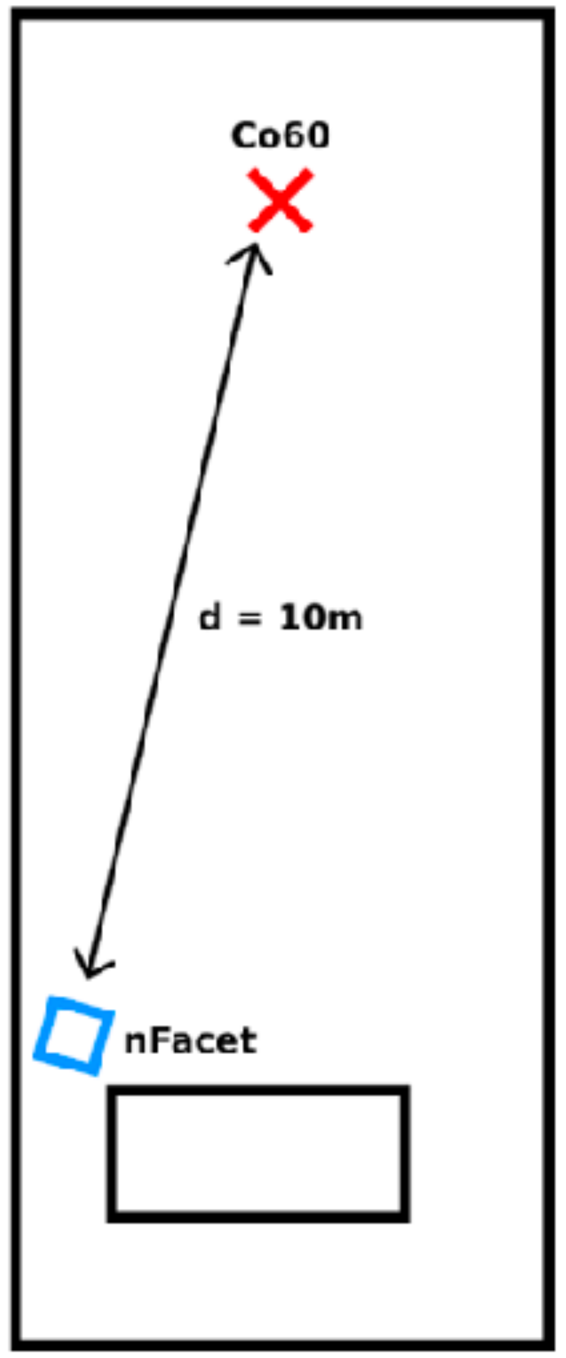


Direction inference using ANN



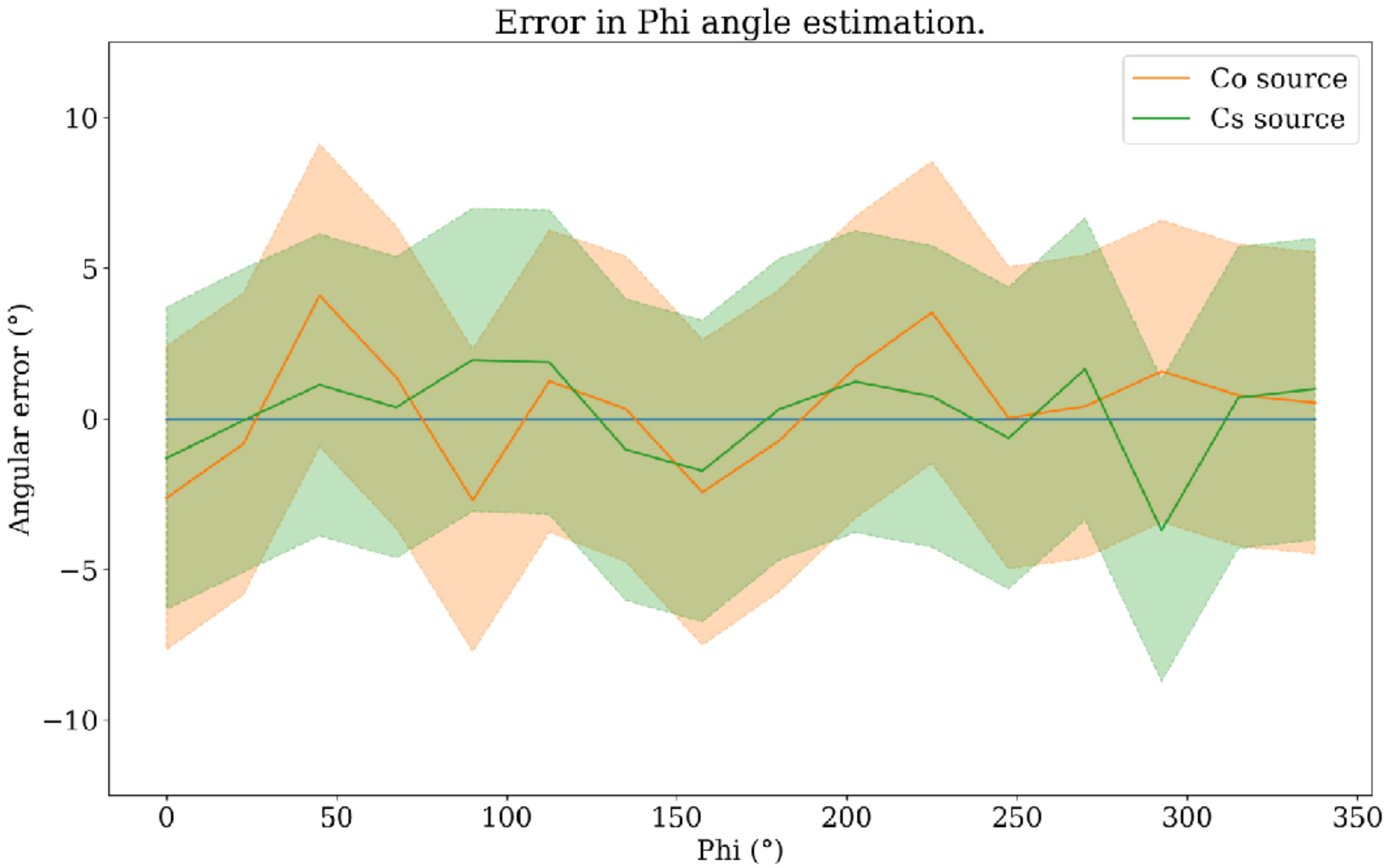


Direction inference using ANN

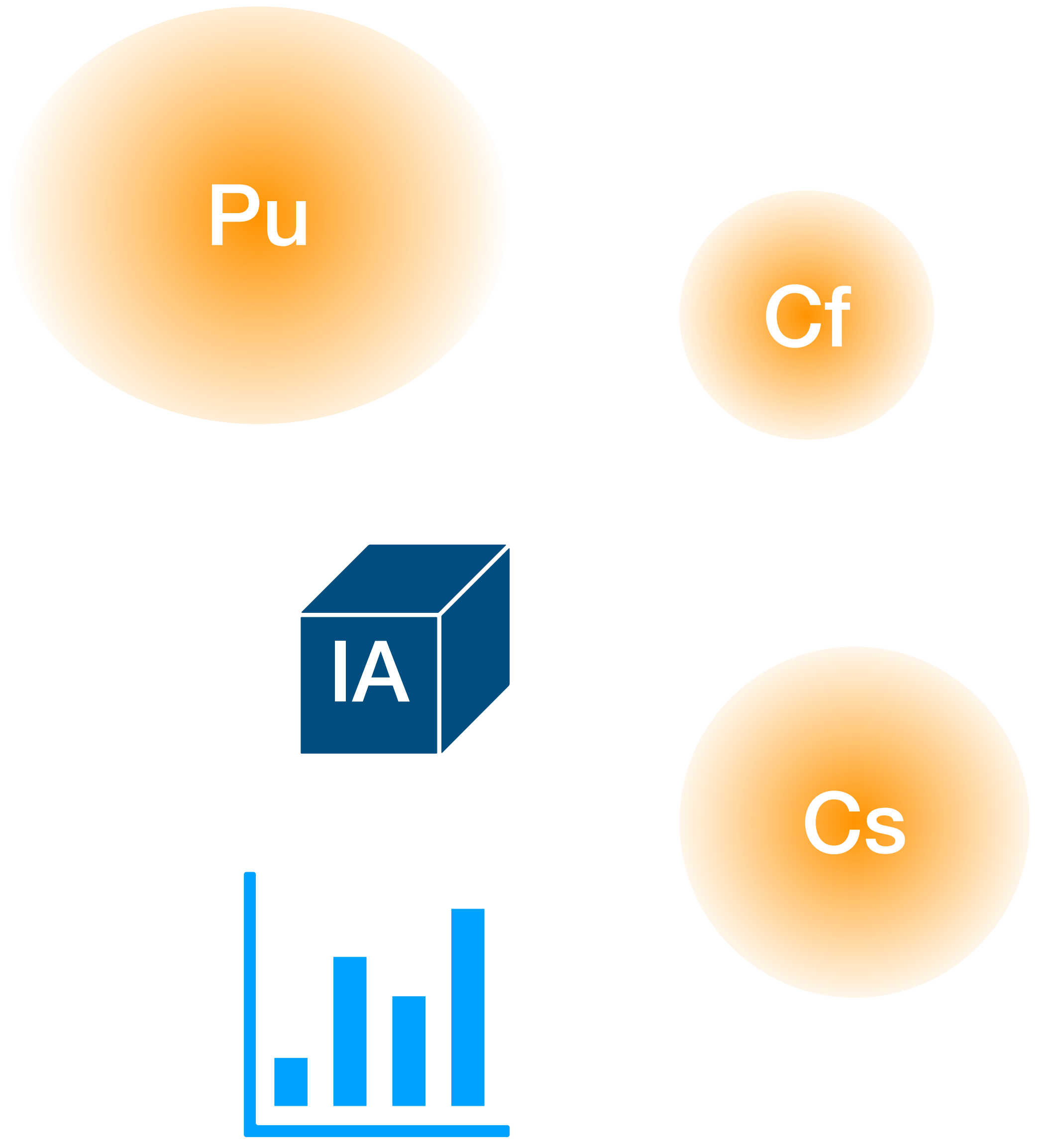


Calibration data indoors using Cs-137 and Co-60 sources at 5 and 10 m

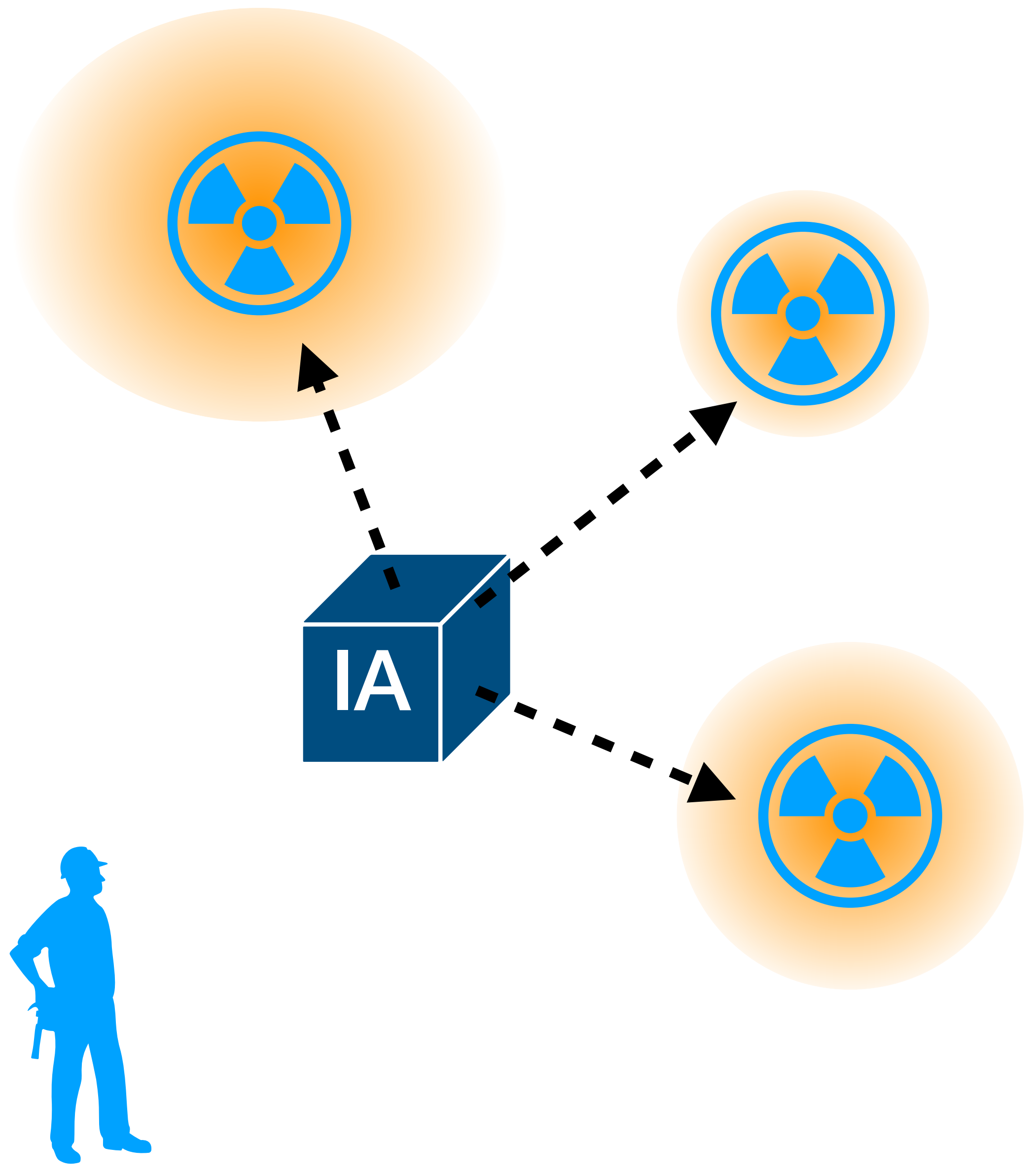
Angular resolution below 5 degrees at 5 m



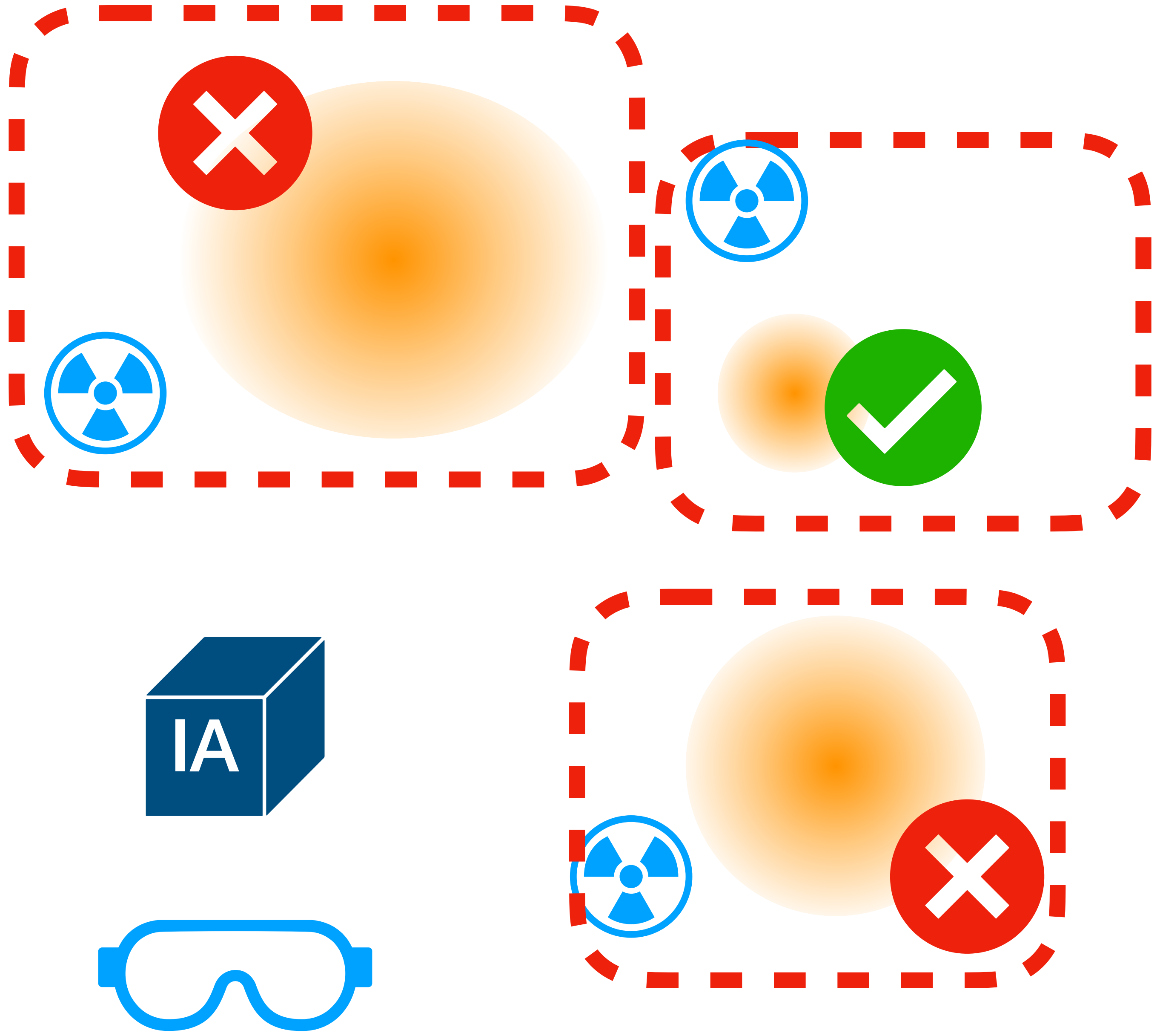
Technological opportunity : Le Cube + AI



Identification de radio-émetteur



Cartographie



Protection des travailleurs

Summary and Outlook

- The nFacet 3D is a detector that integrates multiple measurements in one system providing directional and spectral information
- A M1 system was built in 2017 to explore the capability of the system for security application. The system demonstrated high sensitivity in the direction and energy of the incident radiations.
- The system was brought to TRL 6 during a successful technical demonstration at the IPNDV measurement campaign at SCK-CEN in 2019.
- It demonstrated in 2022 competitive results with SOTA for neutron fluence and dose rate measurements using a ML approach.
- A M2 system was designed and built for dual mode measurements
- The aim is to provide a system “le Cube” for rapid survey, identification and radioprotection using state-of-the-art machine learning techniques


Thank You for listening !