nFacet 3D: a novel dosimeter for effective dose measurement

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Outline

Modern dosimetry

The nFacet 3D detector

Measurement campaigns

Development of an effective dose measurement

Summary

Modern dosimetry

Want to estimate **risk to health** → measures stochastic effect of radiation on tissue

External radiation

Physical quantities
- Fluence
- Absorbed dose

Detector measurements

Calculate via simulated human phantoms

Calculate from absorbed dose and simple phantom

Calibrate detector on known dose to relate measurement to dose

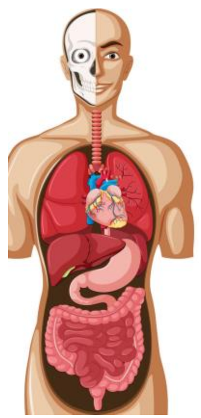
Protection Quantities
- **Effective Dose**
- Used to set limits on exposure

Not currently measurable – Human body is too complex!

Compare operational to protection

Operational Quantities
- E.g. Ambient dose equivalent H*(10)
- Used as practical measurement of dose

Measurable



VS

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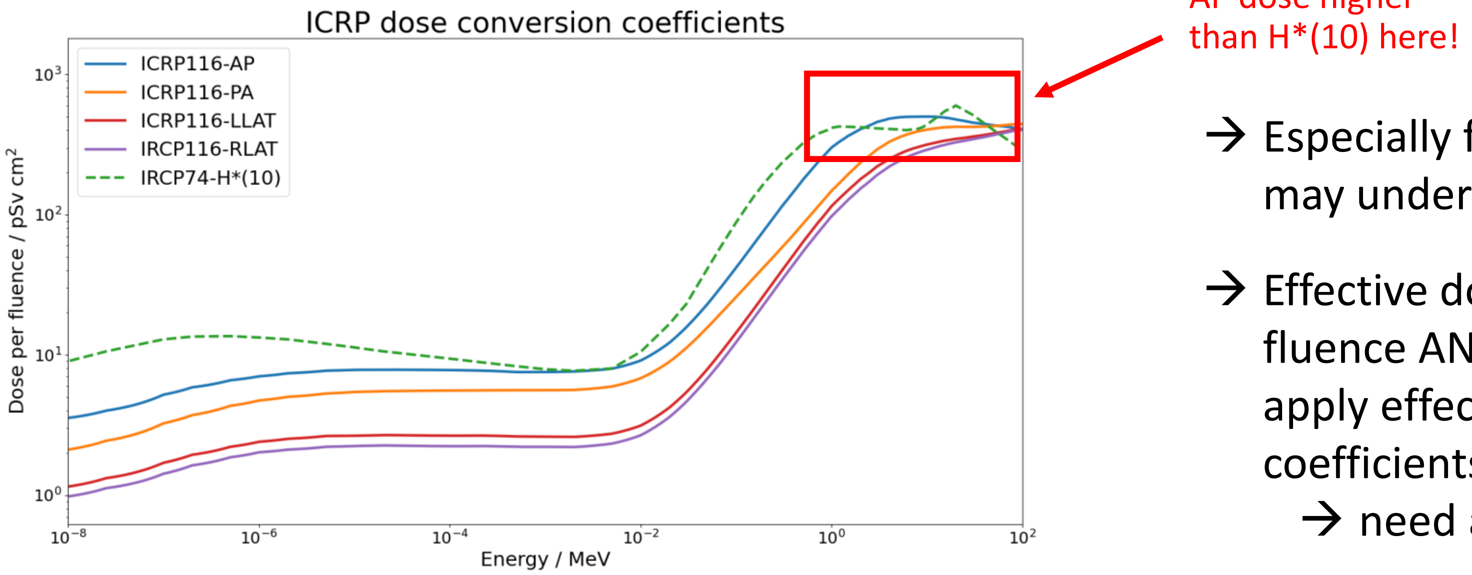
Modern dosimetry – operational vs protection

- To find operational quantities need to know the fluence as a function of energy → most modern dosimeters optimised for this
- Operational quantities like H*(10) want to be conservative estimates, but are they?



→ Especially for fast neutrons (E_n > 1 MeV), may underestimate dose!

→ Effective dose requires measurement of fluence AND direction of radiation field to apply effective dose conversion coefficients

→ need a detector that can do **both**

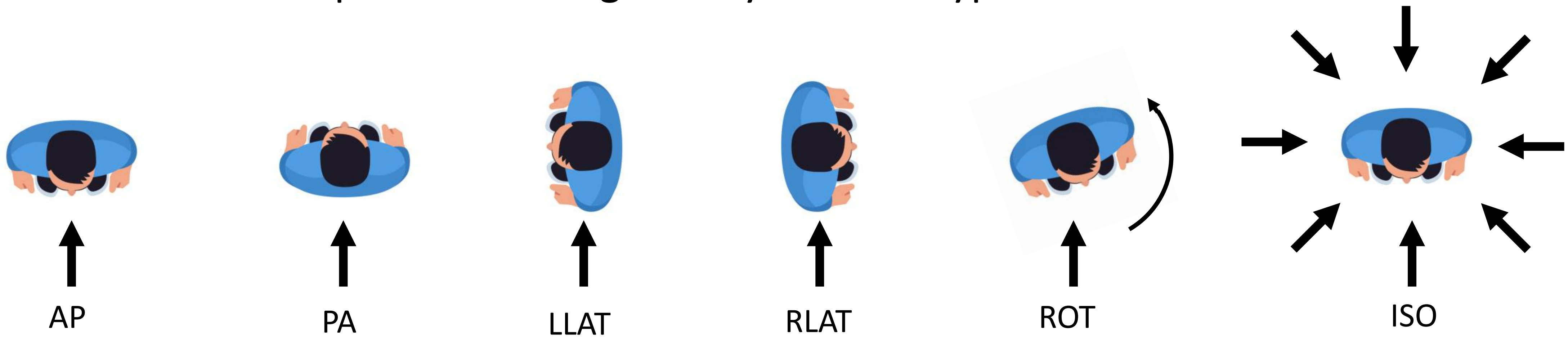
Modern dosimetry – Effective dose

Gold standard for protection – why?

→ weights dose to different tissues by risk for that tissue

→ weights dose based on **type** of radiation, e.g. γ, α, neutron

ICRP: Conversion coefficients per fluence for 6 geometries from simulated human phantoms weighted by tissue & type of radiation



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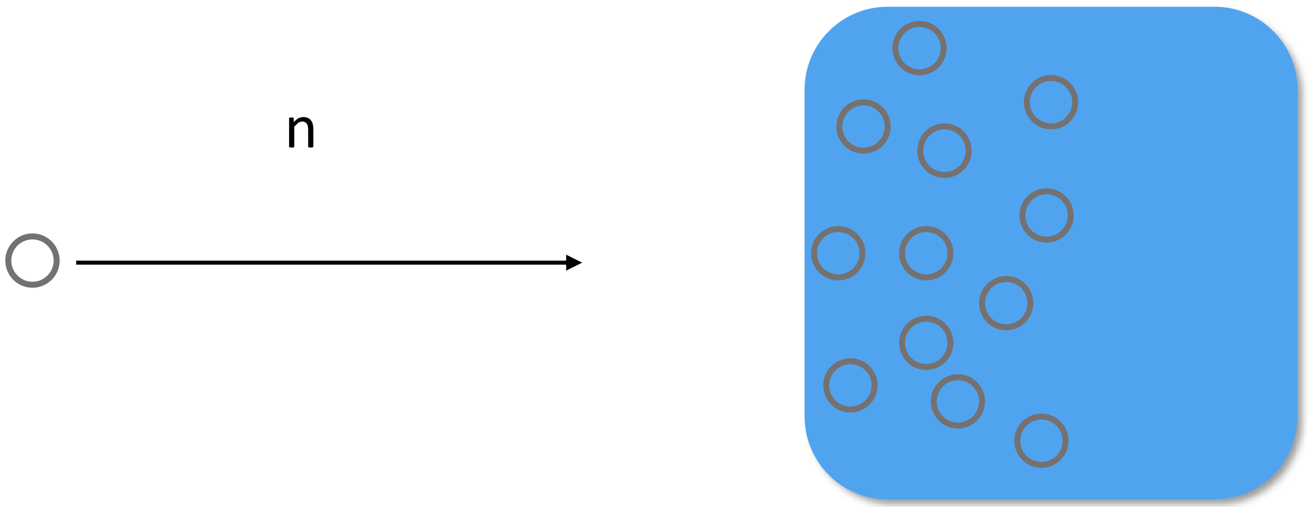
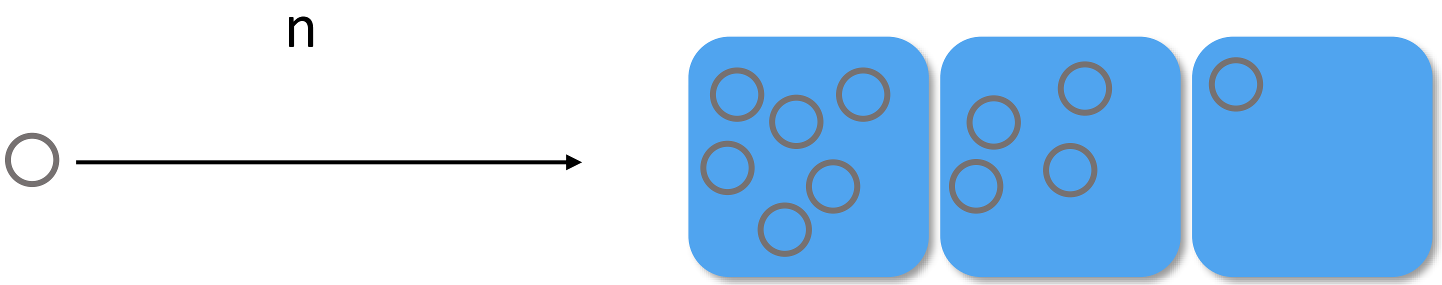
nFacet 3D detection principle

- Neutrons detected via capture after moderation



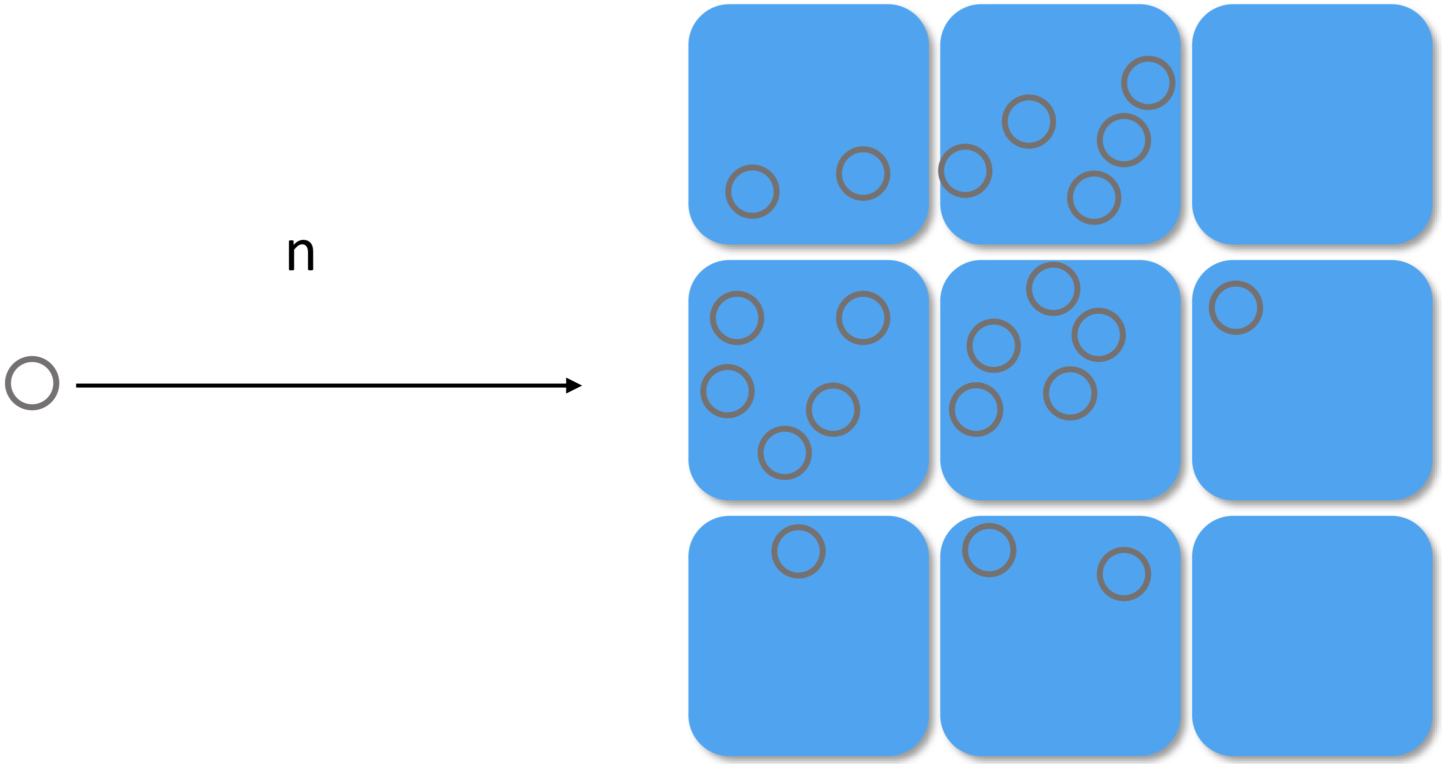
nFacet 3D detection principle

- Longitudinal segmentation allows for sampling of neutron energy, based on stopping power



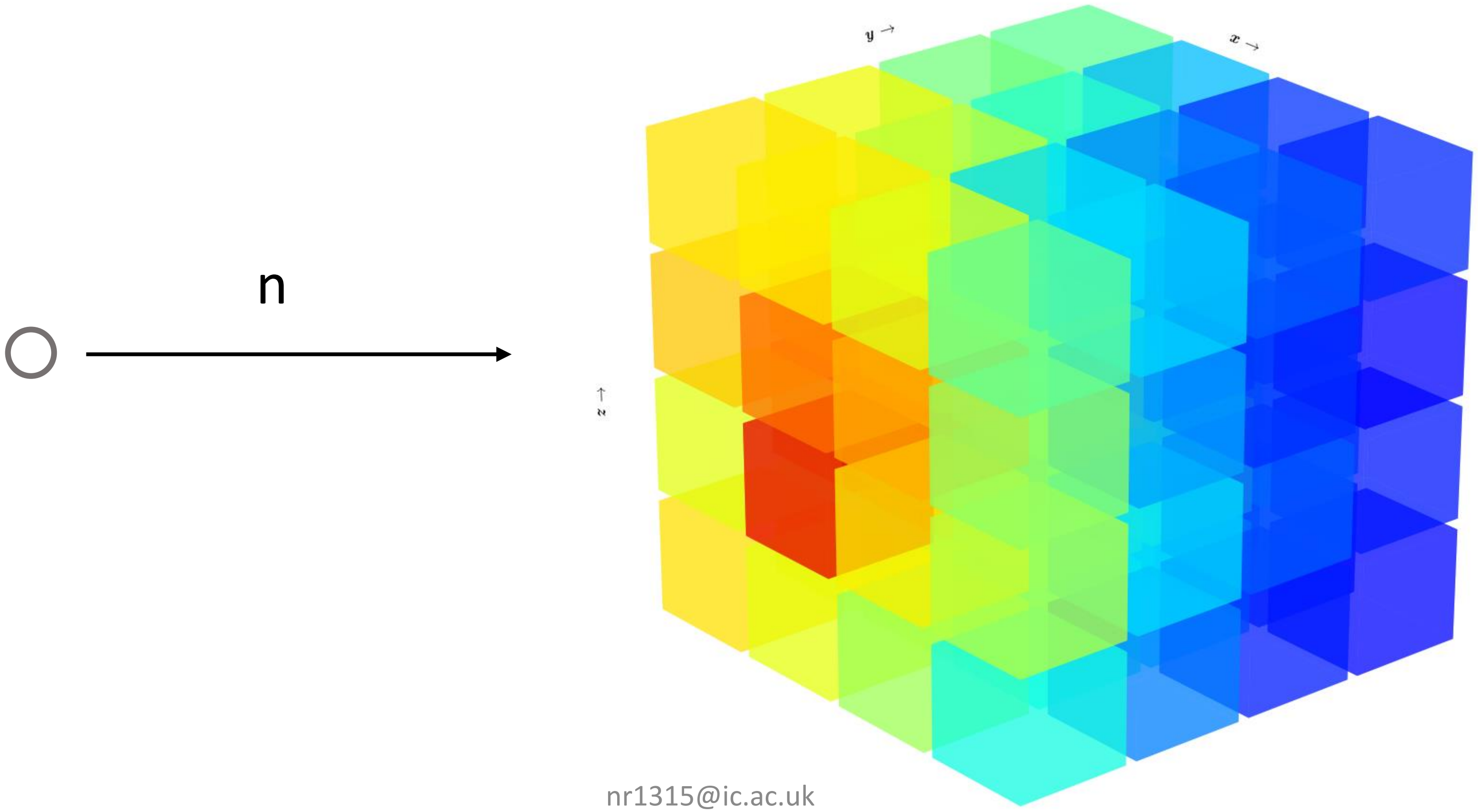
nFacet 3D detection principle

- Transverse segmentation provides directional information of the neutron field



nFacet 3D detection principle

- Full 3D segmentation allows for energy sampling & direction reconstruction in 3D



The nFacet 3D detector system

Multi-mode system (gamma, neutrons, muon) with directionality and source identification capabilities

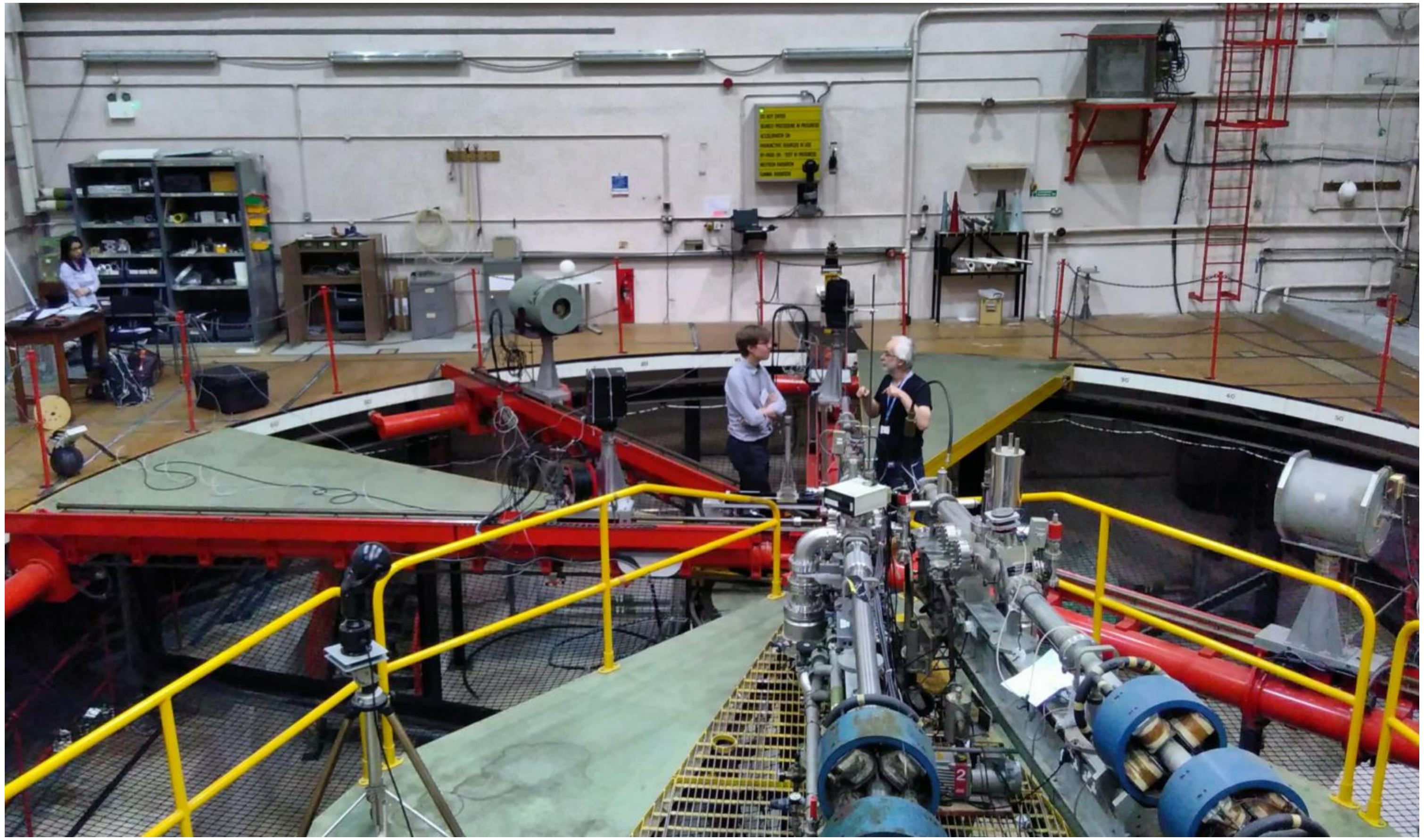
System dimensions	25 x 25 x 27 cm^3
System weight	16 kg
Number of cube elements	64
Neutron energy range	Capture eV - 20 MeV Elastic 450 keV – 50 MeV
Field of view	4 Pi
Neutron sensitive detector / moderator	LiF:ZnS(Ag) / PVT
Gamma-ray energy range (CS)	60 keV – 4 MeV
Gamma-ray energy resolution	~ 20%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

nFacet 3D - online monitoring quantities

Measurement campaigns NPL 2017

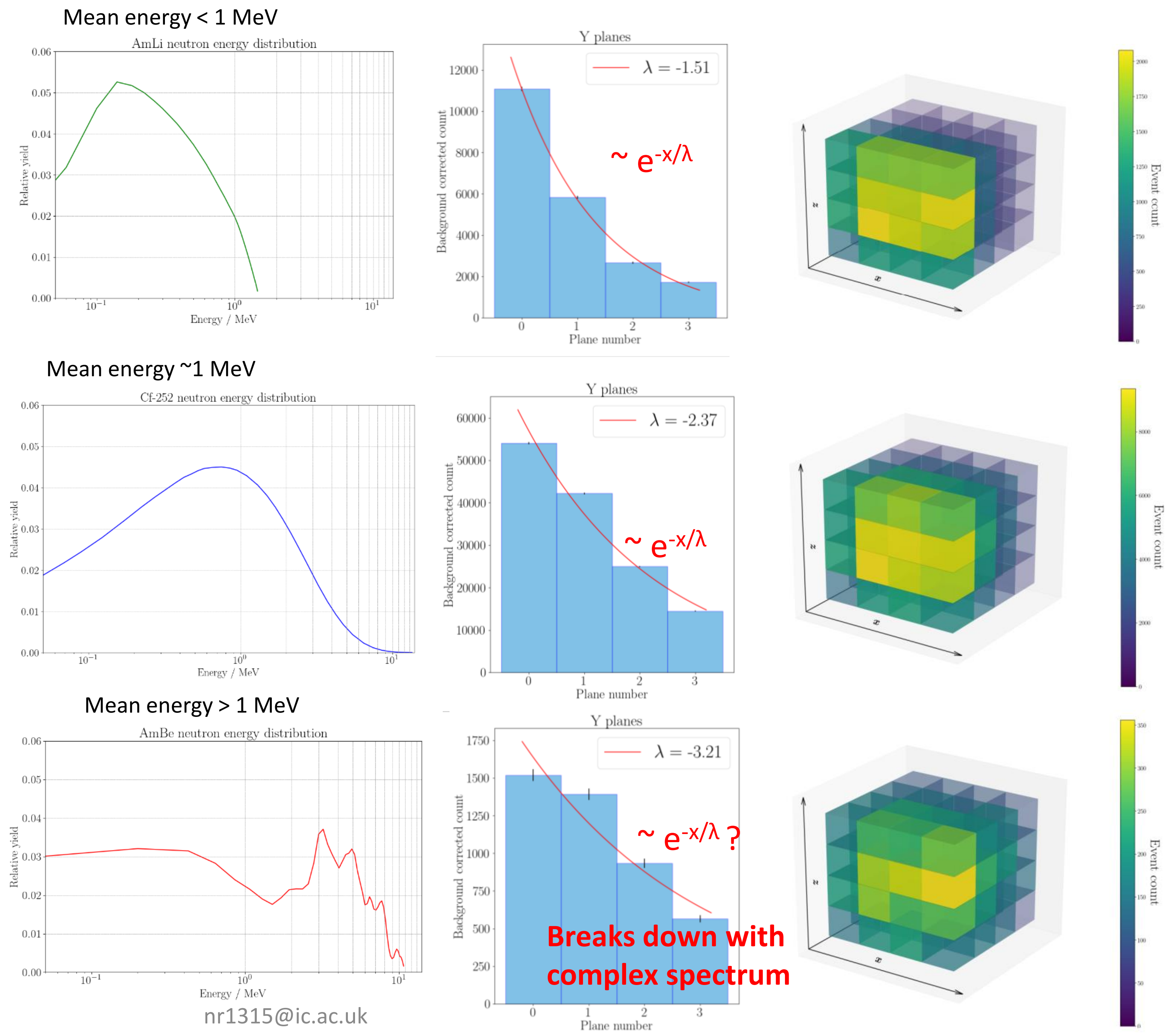
National Physical Laboratory

- Reference data in low scatter facility at NPL
- Measured ^{252}Cf, AmBe, AmLi
- Used for system validation & Monte Carlo development



NPL 2017 source profiles

- Sum count rates in planes to probe stopping power
- Use simple exponential dependence ~ $e^{-x/\lambda}$ to model detector penetration
- First validation of the concept



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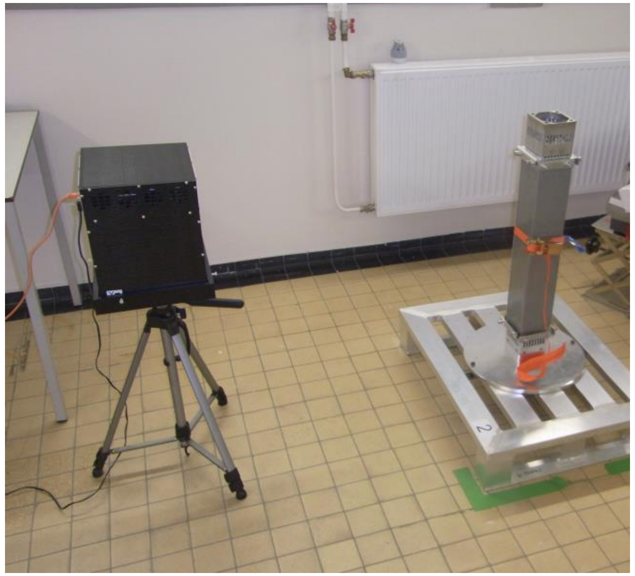
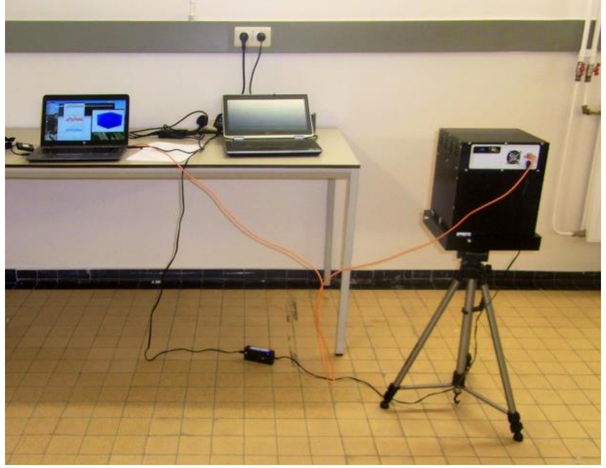
Measurement campaigns IPNDV 2019

- Exercise with International Partnership for Nuclear Disarmament Verification at SCK CEN
- Measured mixed-oxide (MOX) fuel assemblies with 79% ^{239}Pu and 96% ^{239}Pu respectively, with significant RaBe background
- Measurements in operational conditions → demonstration of system at TRL 7
- Results previously presented at INMM/ESARDA Joint Annual Meeting 2021





INTERNATIONAL PARTNERSHIP FOR
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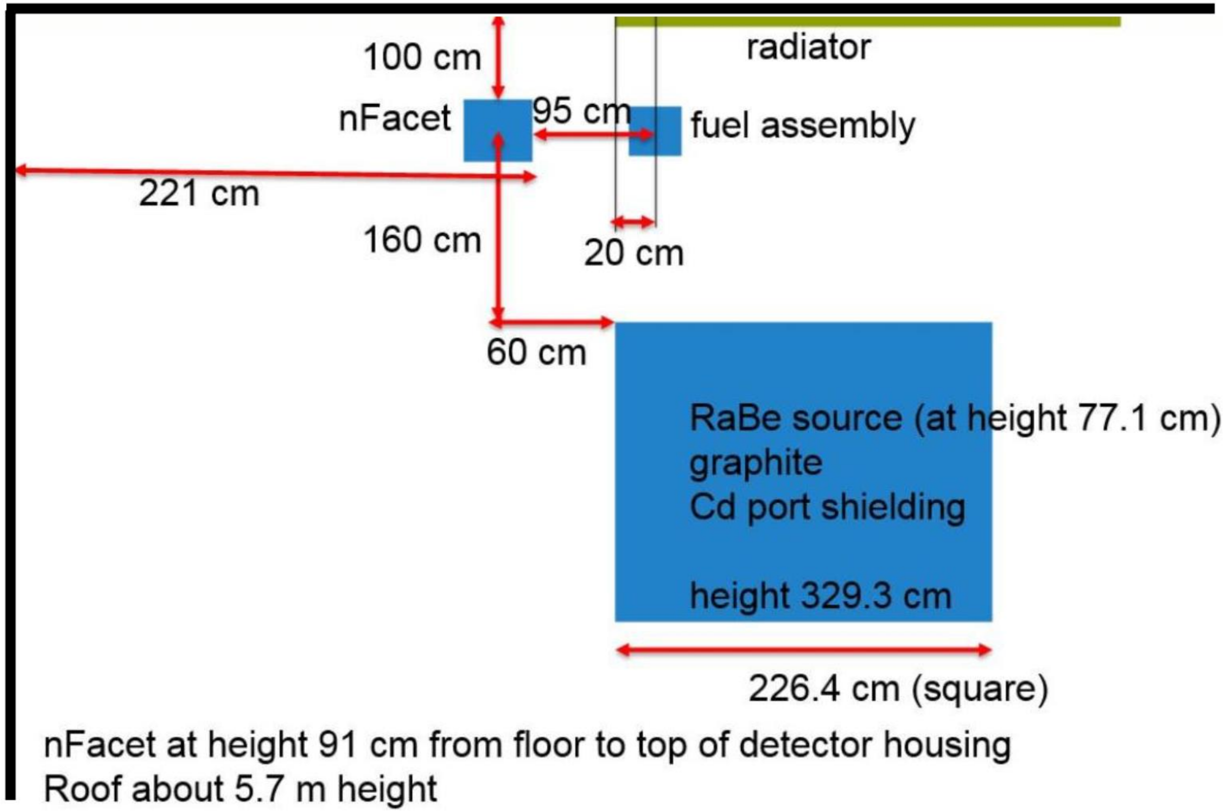
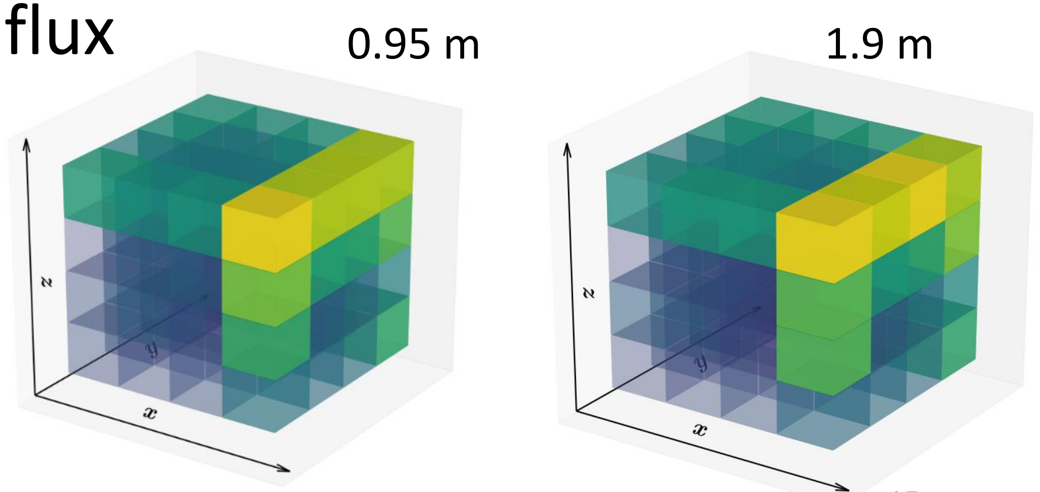
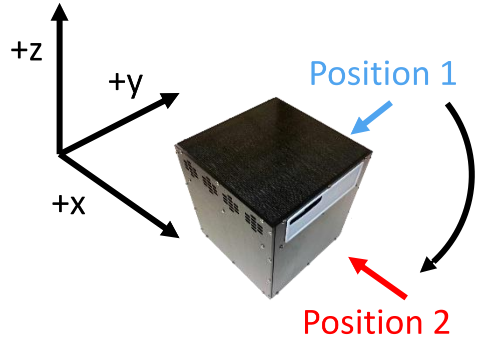
IPNDV 2019
Experimental setup & background

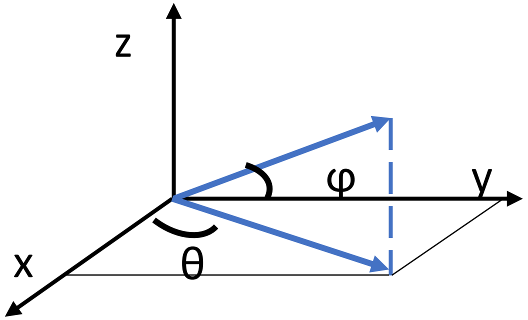


- Proximity of RaBe pile and assemblies in room next door generates large neutron background
- Background subtraction method used to extract MOX neutron flux

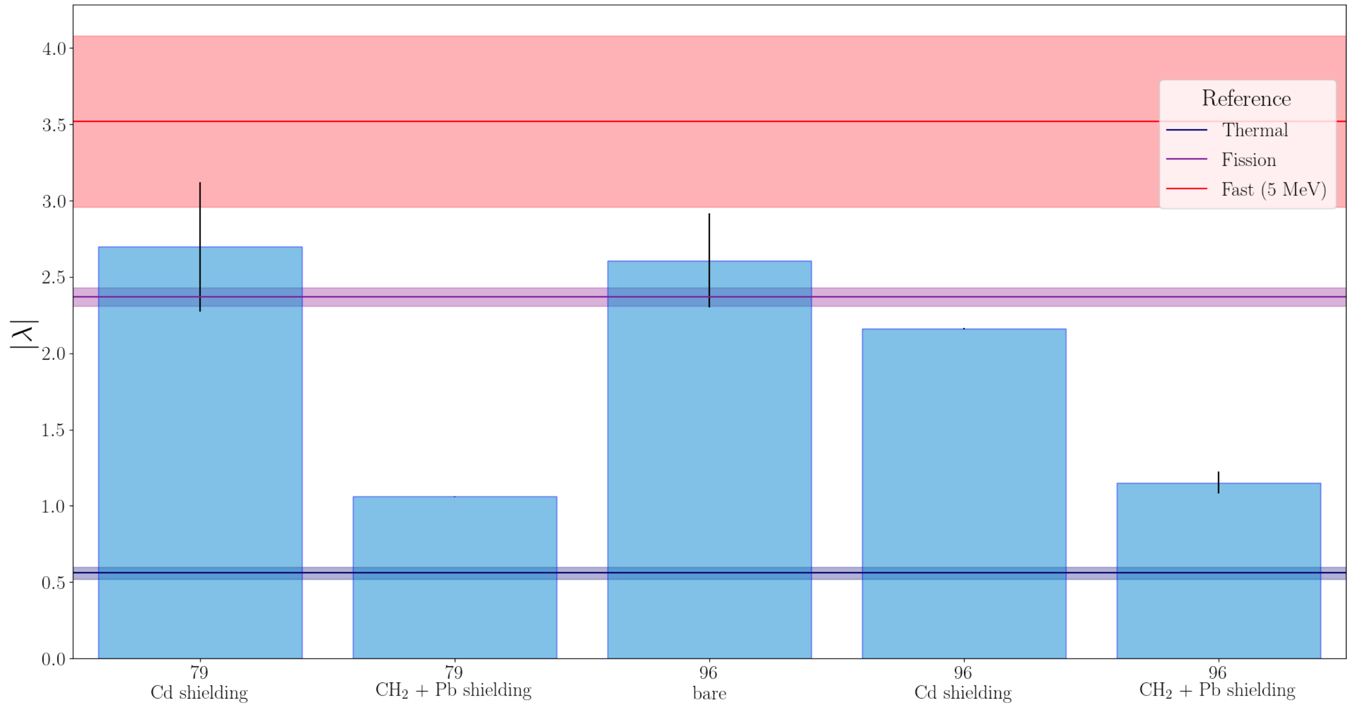


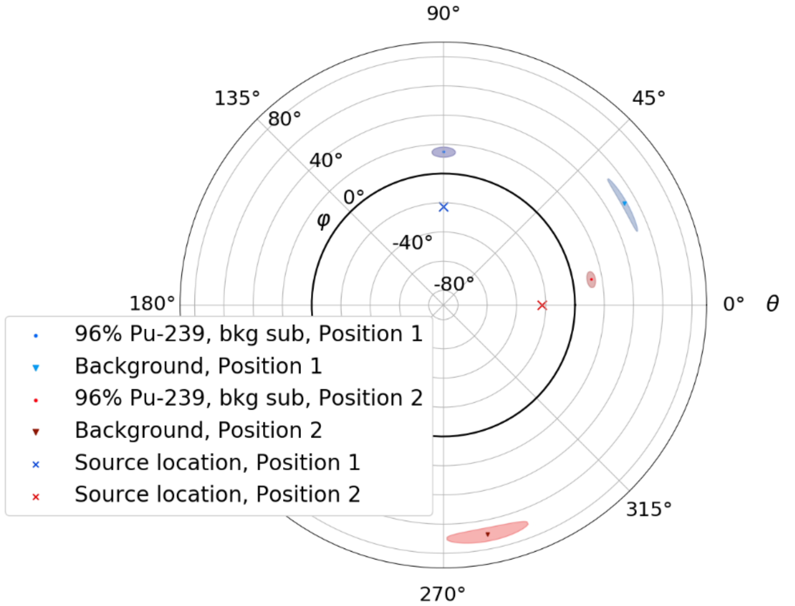
IPNDV 2019 Results





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





- Direction reconstruction at degree level accuracy
- Slight φ bias due to vertical acceptance
- Further detail available in the IPNDV report

Measurement campaigns NPL 2021

National Physical Laboratory

- Measured monoenergetic neutrons from proton accelerator incident on target

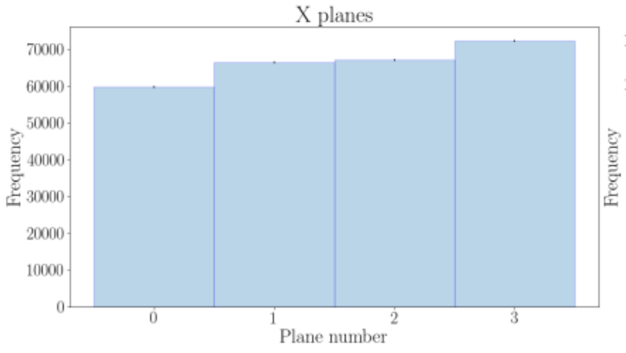
E_n	Reaction	Distance
144 keV	$^{7}Li + p \rightarrow {}^{7}Be + n$	433 cm
1.2 MeV	$T + p \rightarrow {}^{3}He + n$	485 cm

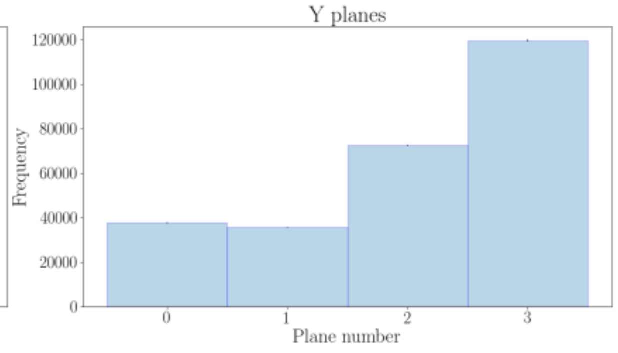
- Large distances needed due to rate causing detector saturation
- Also made γ measurements using Cs sources

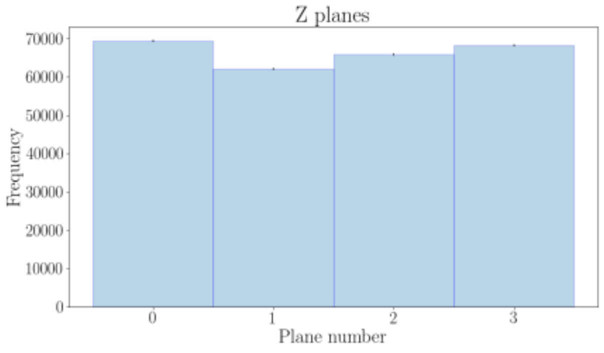
NPL 2021

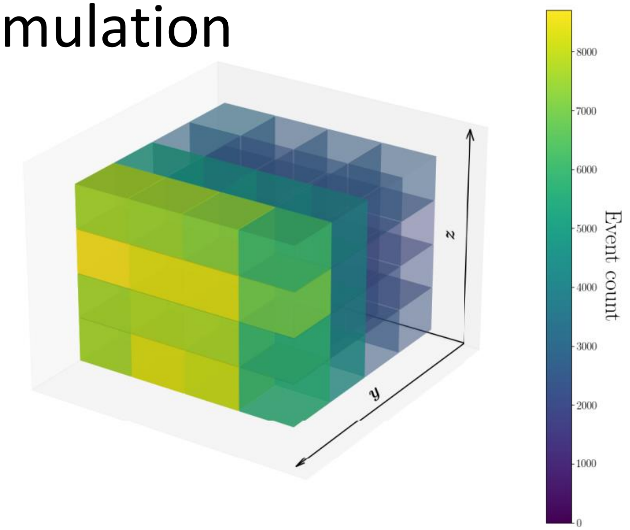
- Monoenergetic neutron data for further validation of simulation

144 keV

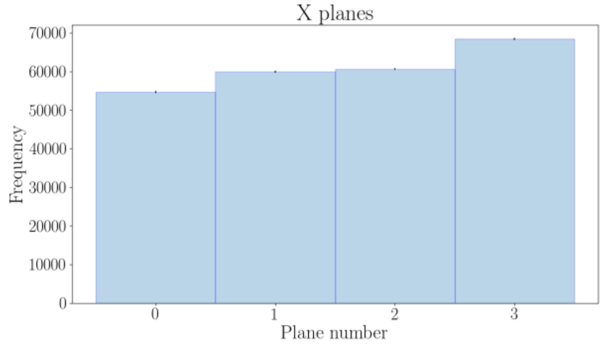


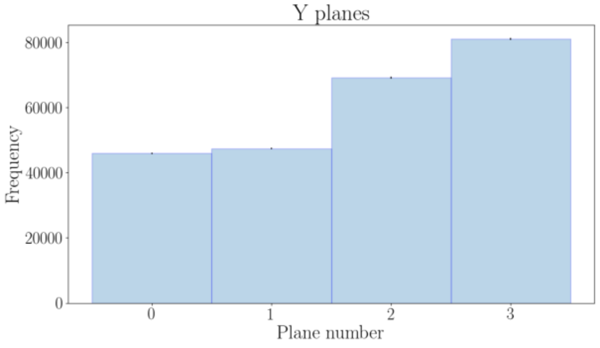


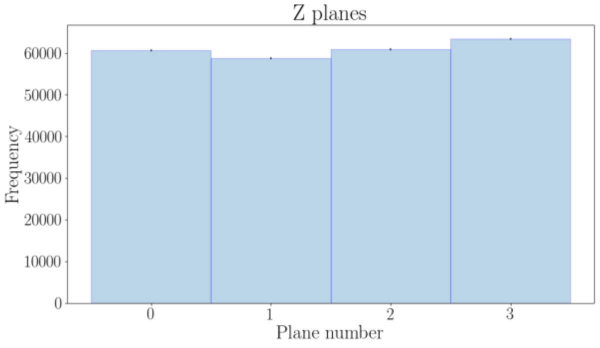


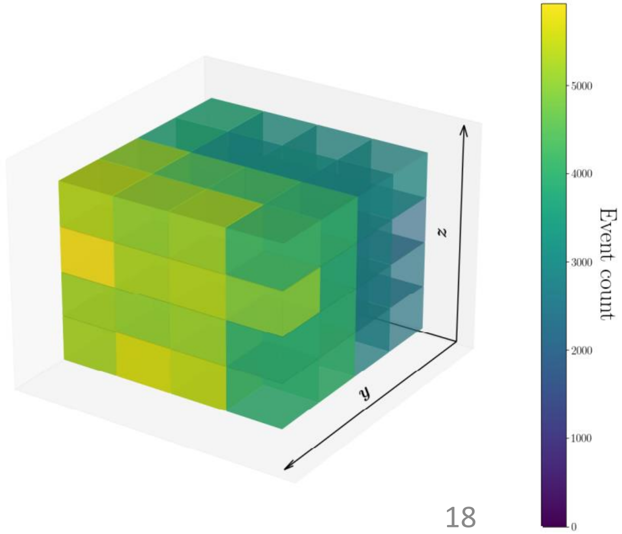


1.2 MeV





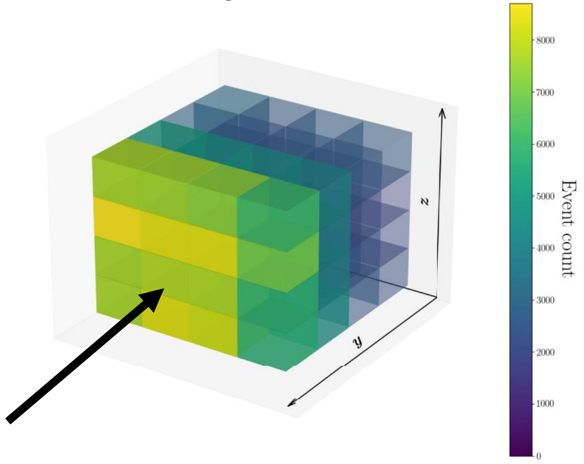




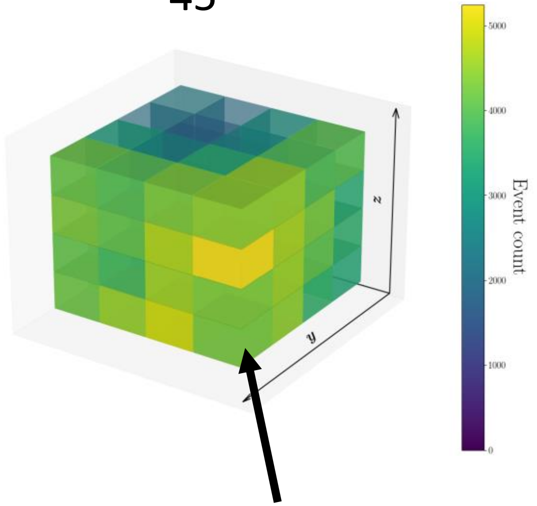
NPL 2021
Neutron field direction

144 keV neutrons

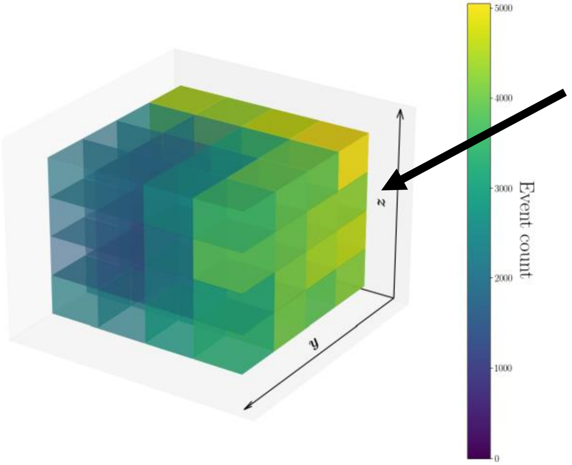
0°



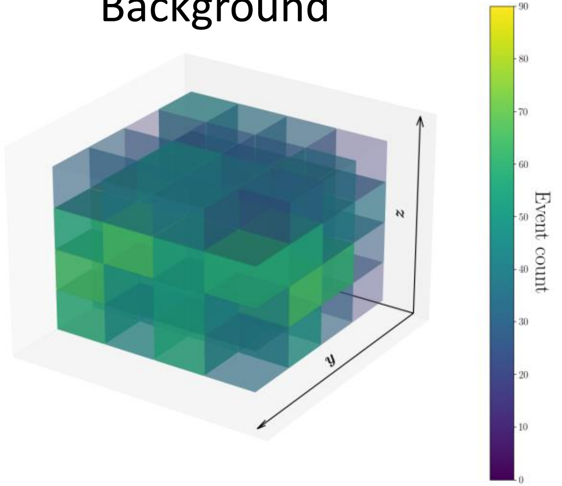
45°



135°



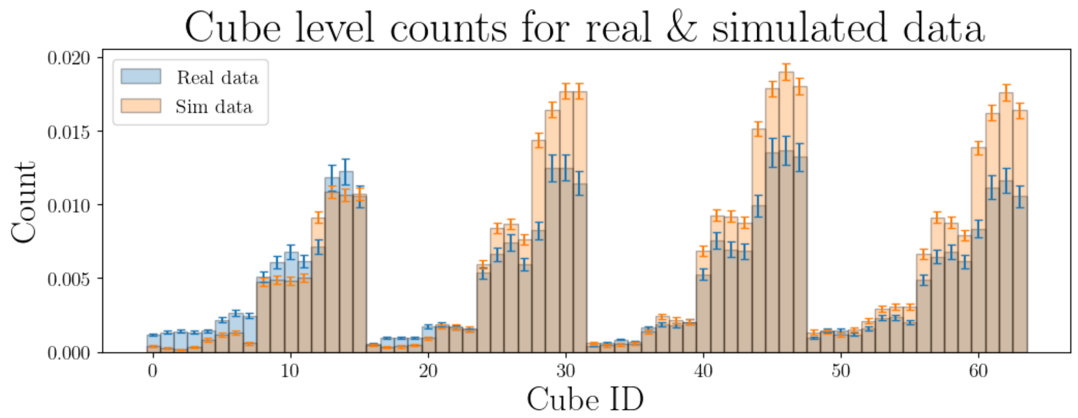
Background

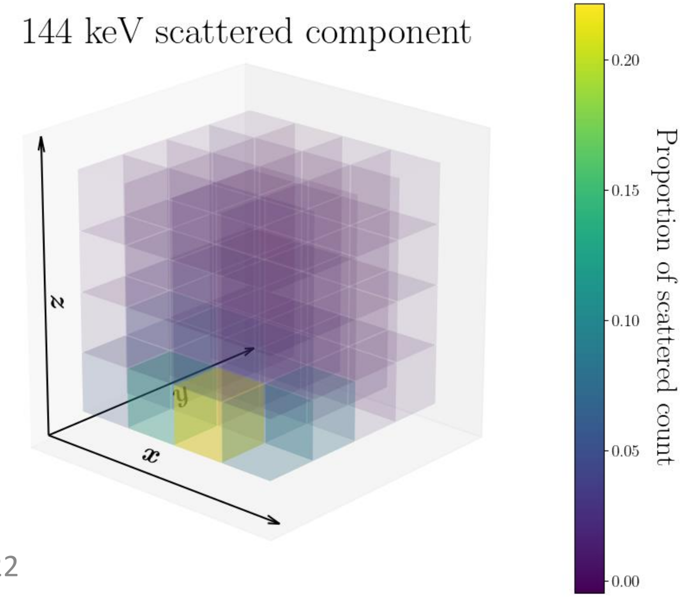


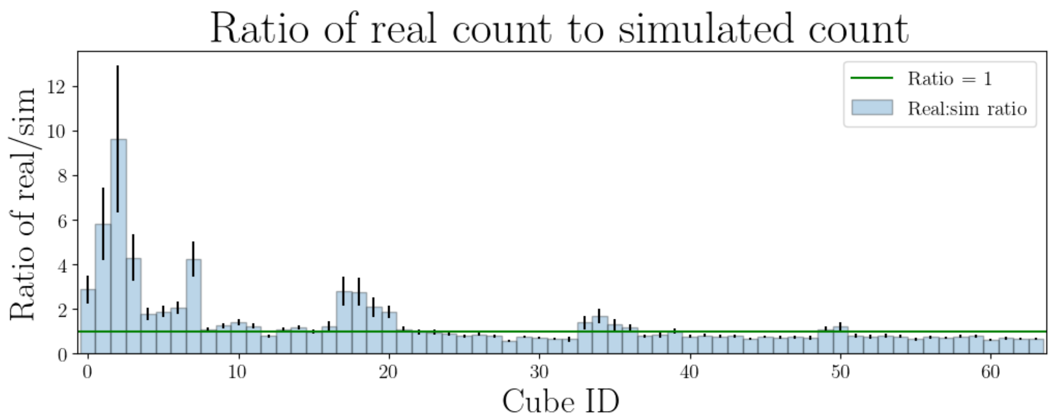
Clear difference in response in presence of source vs pure background measurement

NPL 2021
Direct and scattered component

- Can use cube rates & efficiency to extract scattering component via comparison with MC prediction
- Can clearly separate components from **different directions**







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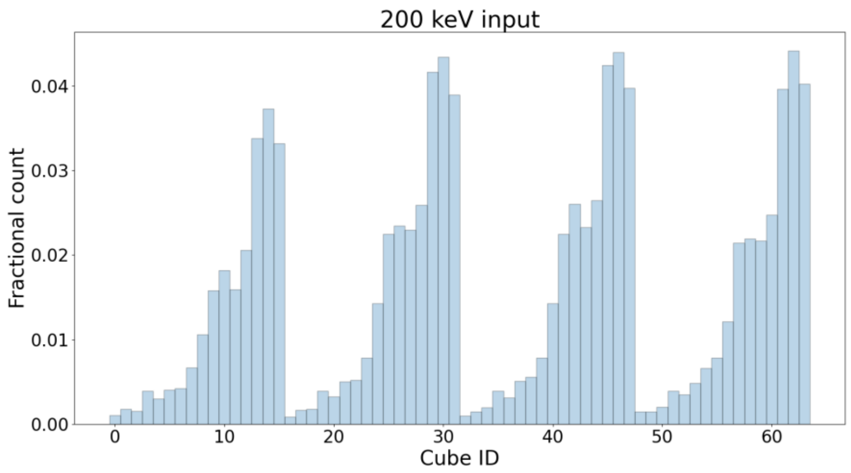
Development of an effective dose measurement

- nFacet 3D encodes energy & direction of radiation field in cube count distribution
- Now, aim to produce accurate results

  → Adopt a **neural network** approach

Input: 1D array of cube counts



Use source **fluence** as the target
→ Apply effective dose coefficients after prediction

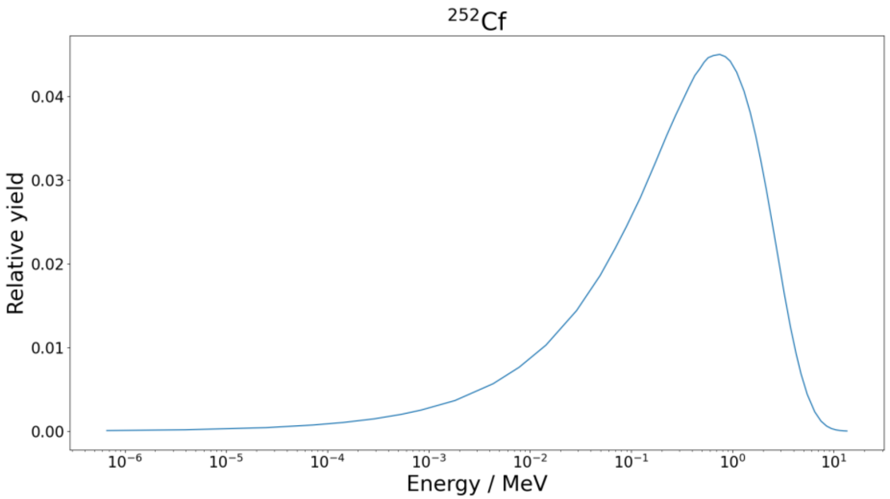
4 layers (neurons under optimisation) → 1 x 8 output

Aim for **< 20%** error on effective dose

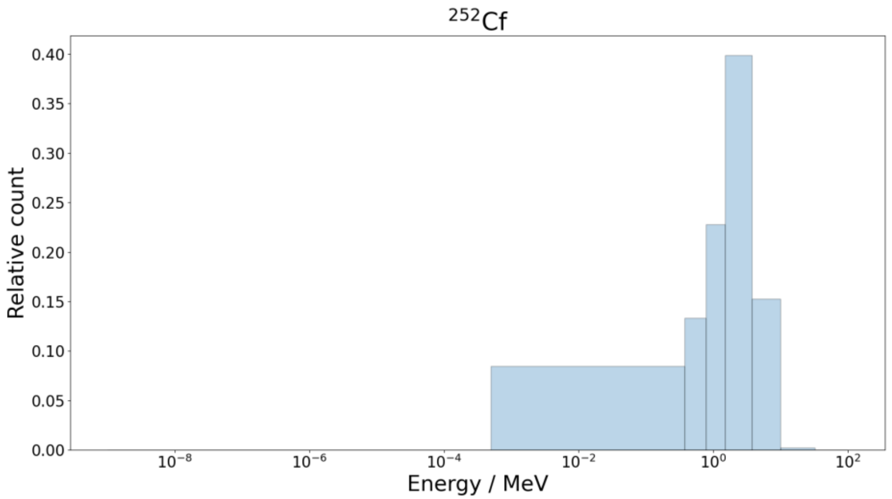
Development of an effective dose measurement
Targets

- Energy is encoded in stopping power
- Finite number of detector voxels limits resolution of stopping power and therefore energy resolution

→ Must **bin** fluence



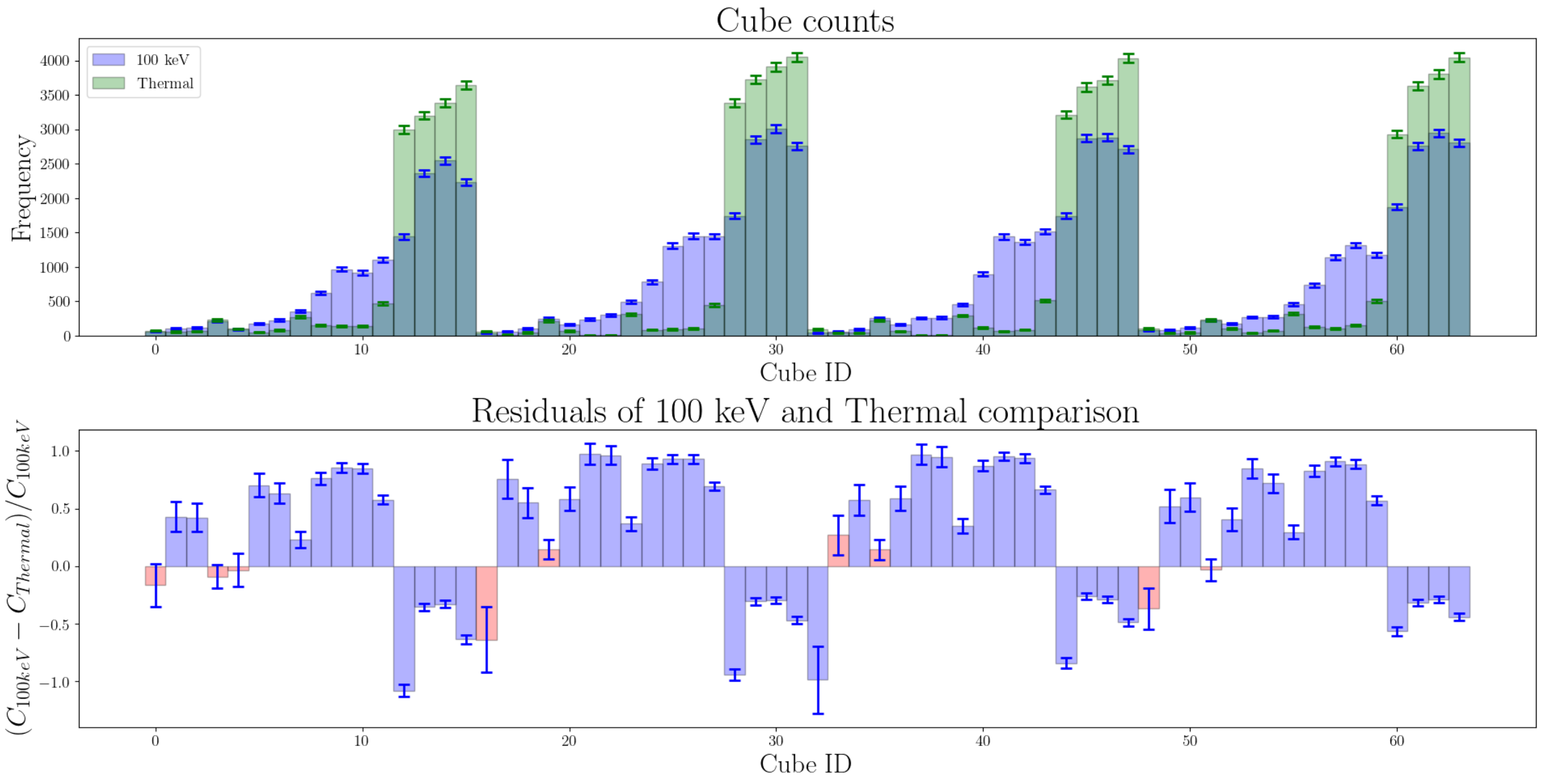
→



Development of an effective dose measurement
Fluence binning scheme

- Binning scheme is determined by energy resolution of the detector
- For NN, resolution determined by ability to distinguish inputs

→ Require at least 75% of cubes separated by at least 3σ in training inputs

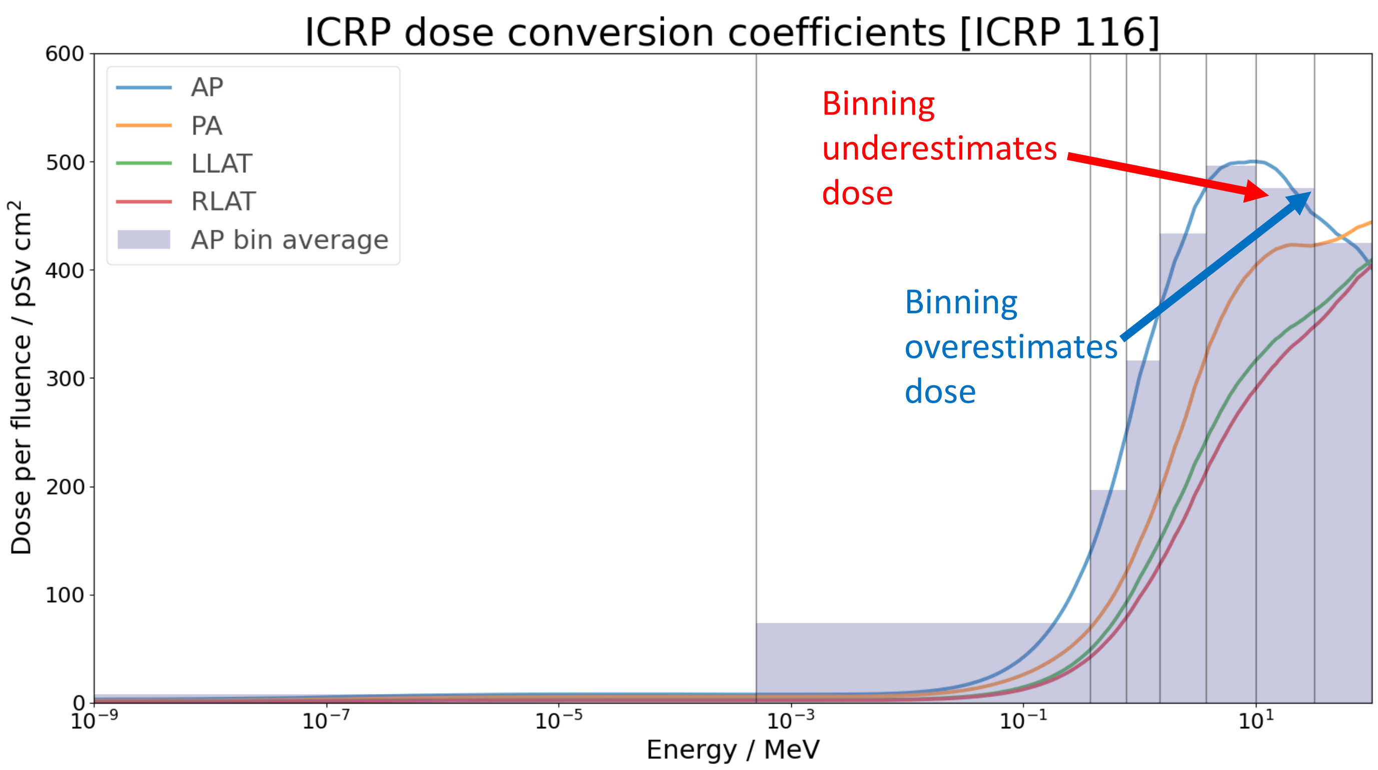


→ 8 distinct energy bins

Development of an effective dose measurement

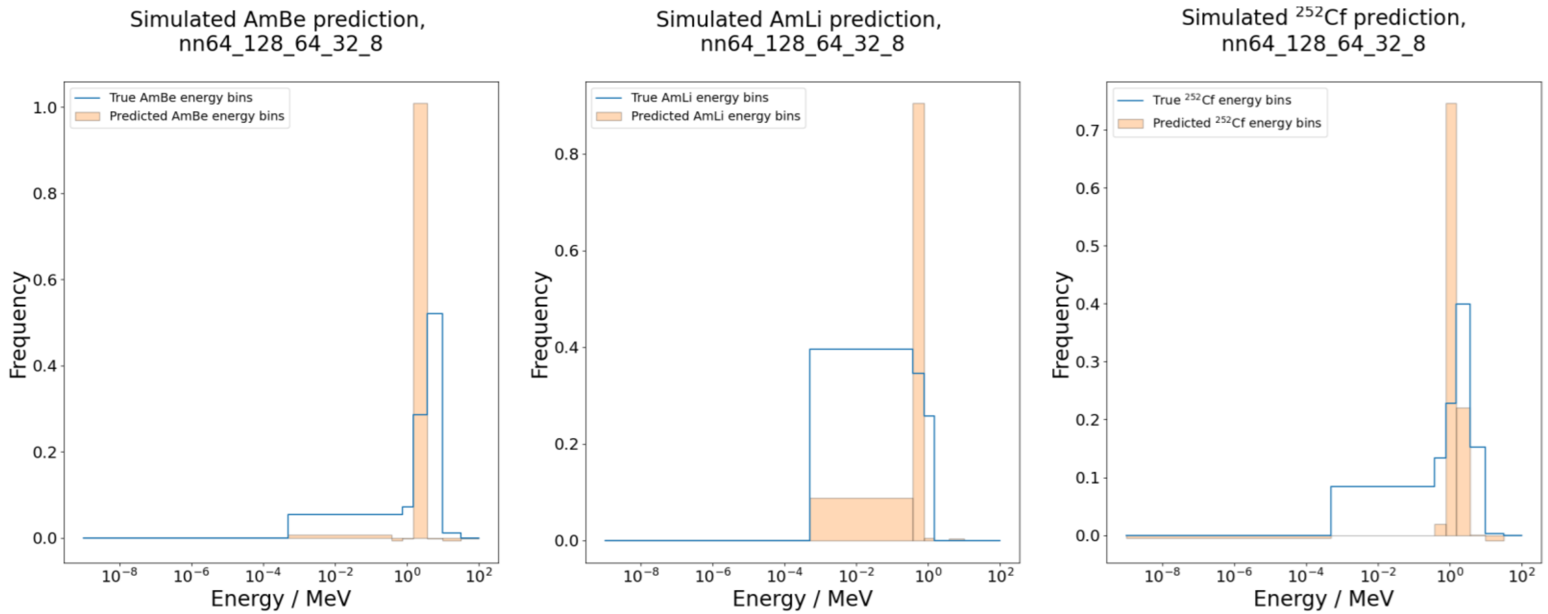
Training metric

- Key metric in training is the error on effective dose
- Binning introduces an error to dose
- Stop network training when dose error on validation data stops improving
- In this work focus on AP dose, aim to extend to more directions in future



Dose curves over the bins determined for the nFacet neural network. The scatter points indicate the average value of dose across the bin used to compute dose from a binned fluence.

Development of an effective dose measurement
Prediction on unseen data



Fluence reconstruction has significant errors

BUT

Effective dose error is < 20% in all 3 cases

Source	True AP dose / pSv cm^2	Binned AP dose / pSv cm^2	Predicted AP dose / pSv cm^2	Predicted vs true error
AmBe	427.0	425.7	431.2	1.0%
AmLi	175.4	178.7	186.4	6.2%
^{252}Cf	350.4	354.5	331.2	-5.4 %

→ **Proof of NN feasibility!**

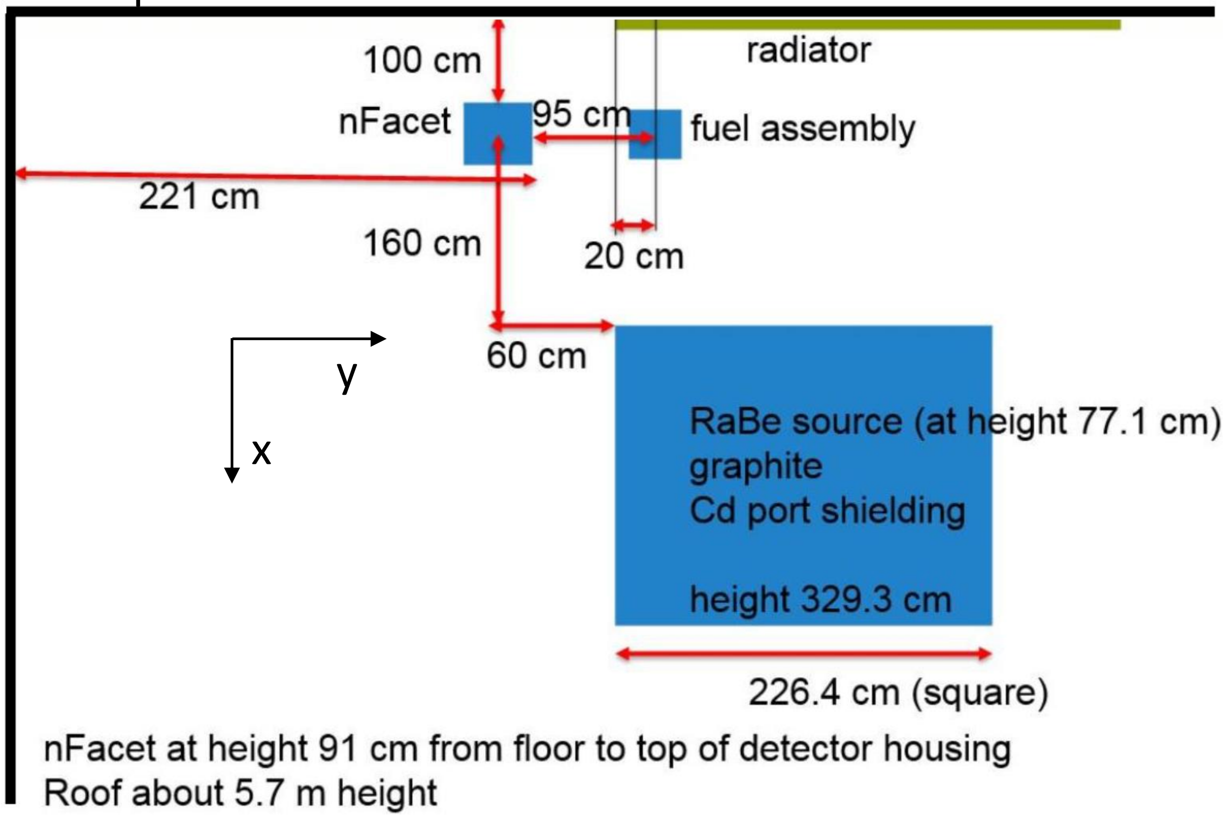
→ **Aim to extend to more directions**

Summary

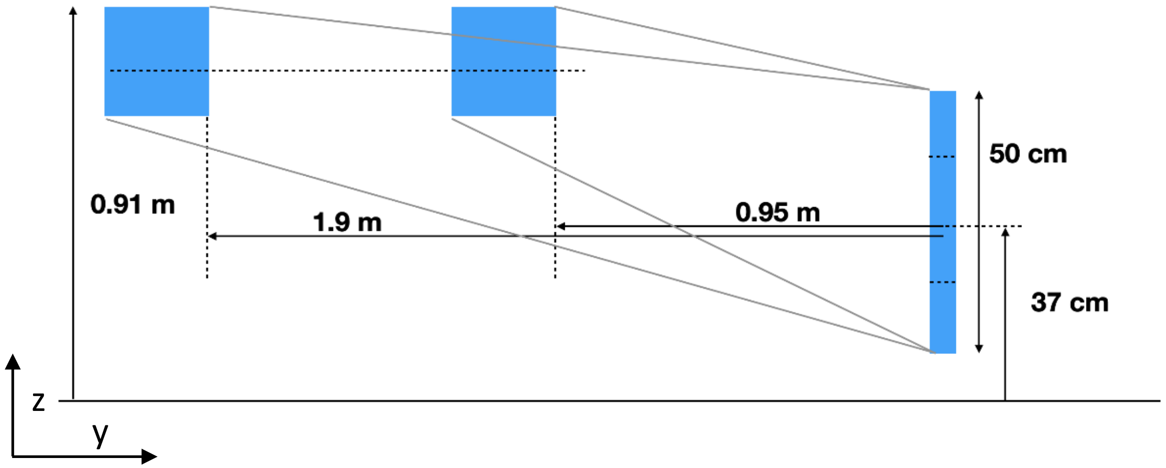
- Modern dosimetry requires measurement of energy & direction of radiation to meet the gold standard of protection
- nFacet 3D encodes energy in stopping power & direction in count distribution
- Capabilities have been demonstrated in an operational environment at SCK CEN → system at TRL 7
- Neural network approach validated with effective dose prediction < 20 % error
- Further analysis work focuses on refinement of NN work

IPNDV 2019
Experimental setup

Top view



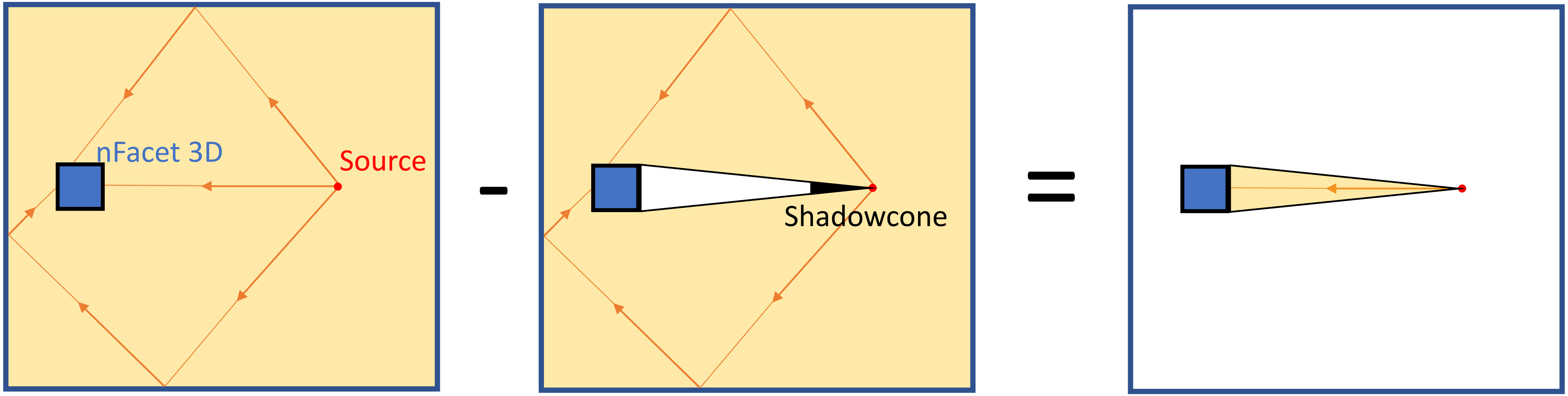
Side view



Measurements at 2 distances

Source	Shielding	Distance
79% ^{239}Pu	Bare, Cd, CH_2 + Pb	1.9 m
96% ^{239}Pu	Bare, CD, CH_2 + Pb	0.85 m

Measurement campaigns
NPL 2021 – shadowcone measurements



Full exposure

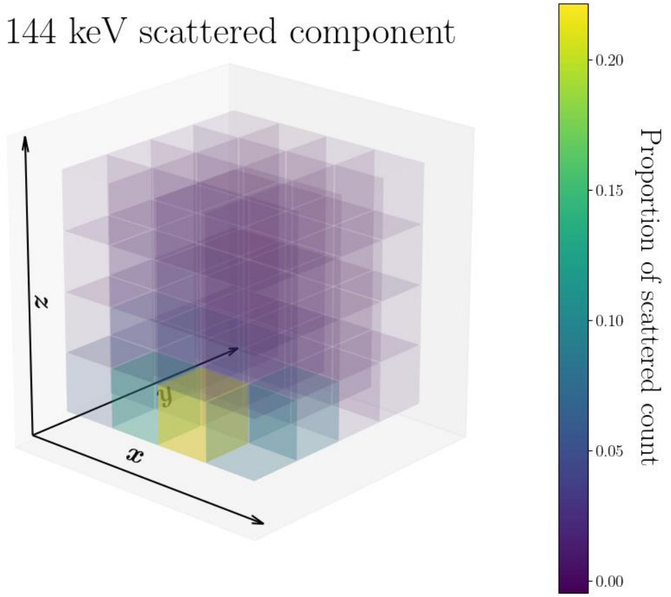
Shadowcone

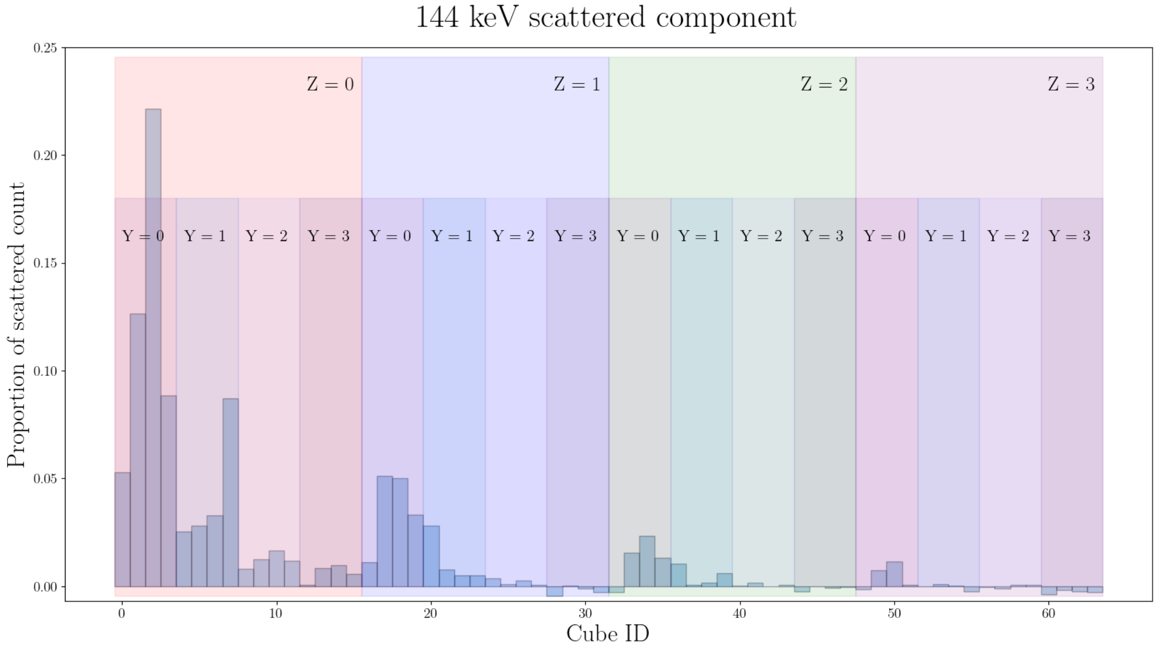
Direct component

→ Shadowcone measurements allow for extraction of direct component for calibration against a known source

NPL 2021
Direct and scattered component

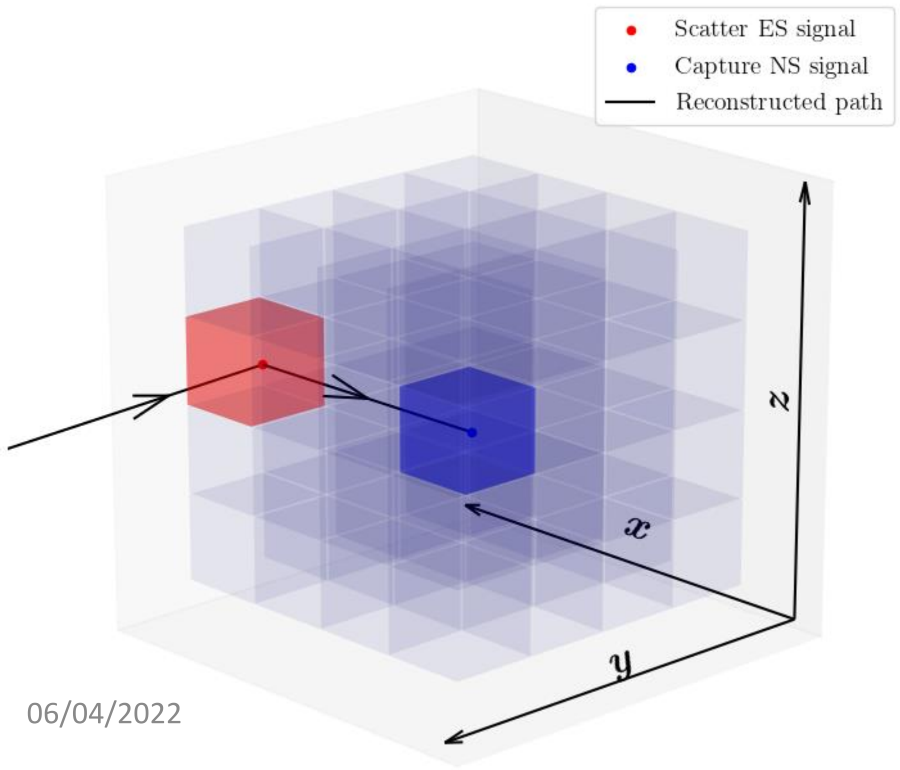
- Can use cube rates & efficiency to extract scattering component via comparison with MC prediction
- Enables more accurate dose determination in complex environments

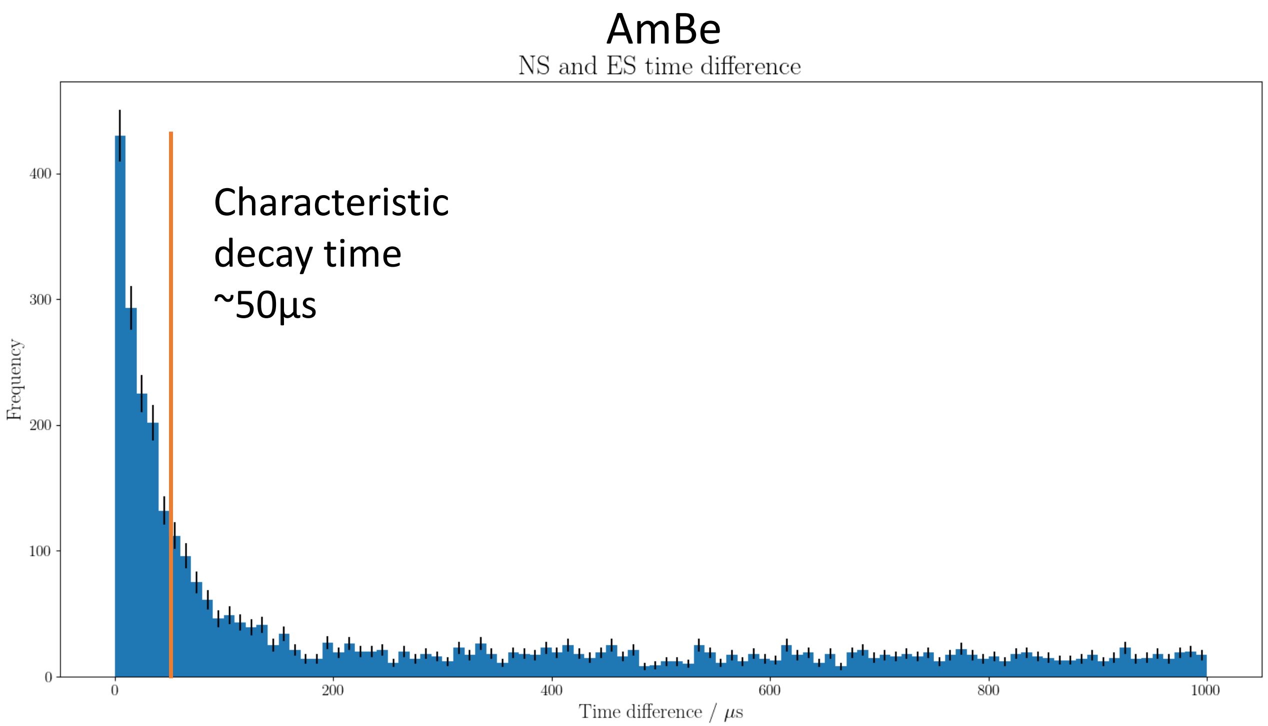




Future work
Neutron scatter analysis

- Can record both neutron scatter (ES) & capture on ^6Li (NS) in a gamma trigger mode

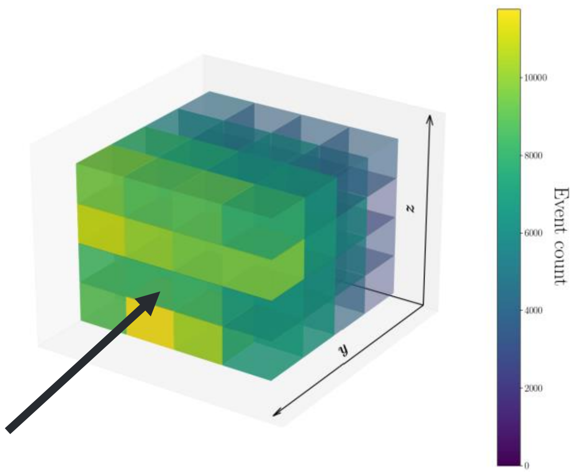




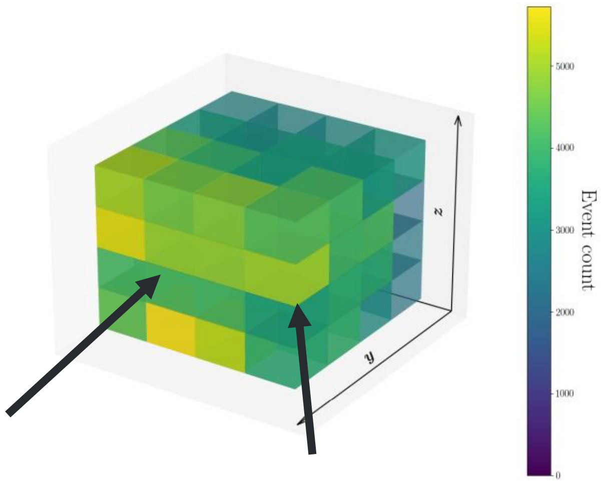
Time between coincident ES & NS signals for AmBe source

Future work
Gamma analysis

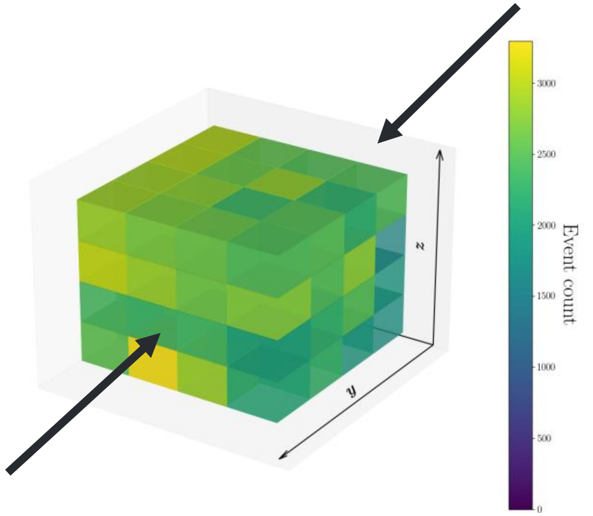
- nFacet capable of measuring γ → look at γ dosimetry
- Data taken in NPL 2021 campaign of Cs sources including data to analyse ability to separate multiple sources



1 source



Two sources, 45° separation



Two sources, 180° separation