Monte Carlo Simulation
Optimisation in Imaging - HSST

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Science Area Leader Medical Radiation Physics

National Physical Laboratory, UK
The Christie NHS Foundation Trust, UK

March 2023

- What is Monte Carlo simulation?
- Why use it for medical imaging?
- Examples (demos)
- Validation of simulations
- Tools you can use
- Q & A

What is Monte Carlo simulation?

What is Monte Carlo simulation?

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Based on the Monte Carlo method

What is Monte Carlo simulation?

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What is Monte Carlo simulation?

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WolframAlpha computational knowledge engine.

what is the monte carlo method

Web Apps | Examples | Random

Input interpretation:

Monte Carlo method

Open code

Definition:

Any method which solves a problem by generating suitable random numbers and observing that fraction of the numbers obeying some property or properties. The method is useful for obtaining numerical solutions to problems which are too complicated to solve analytically. It was named by S. Ulam, who in 1946 became the first mathematician to dignify this approach with a name, in honor of a relative having a propensity to gamble. Nicolas Metropolis also made important contributions to the development of such methods.

The most common application of the Monte Carlo method is Monte Carlo integration.

More information »

Related topics:

Monte Carlo integration | quasi-Monte Carlo method | stochastic geometry | uniform distribution theory

What is Monte Carlo simulation?

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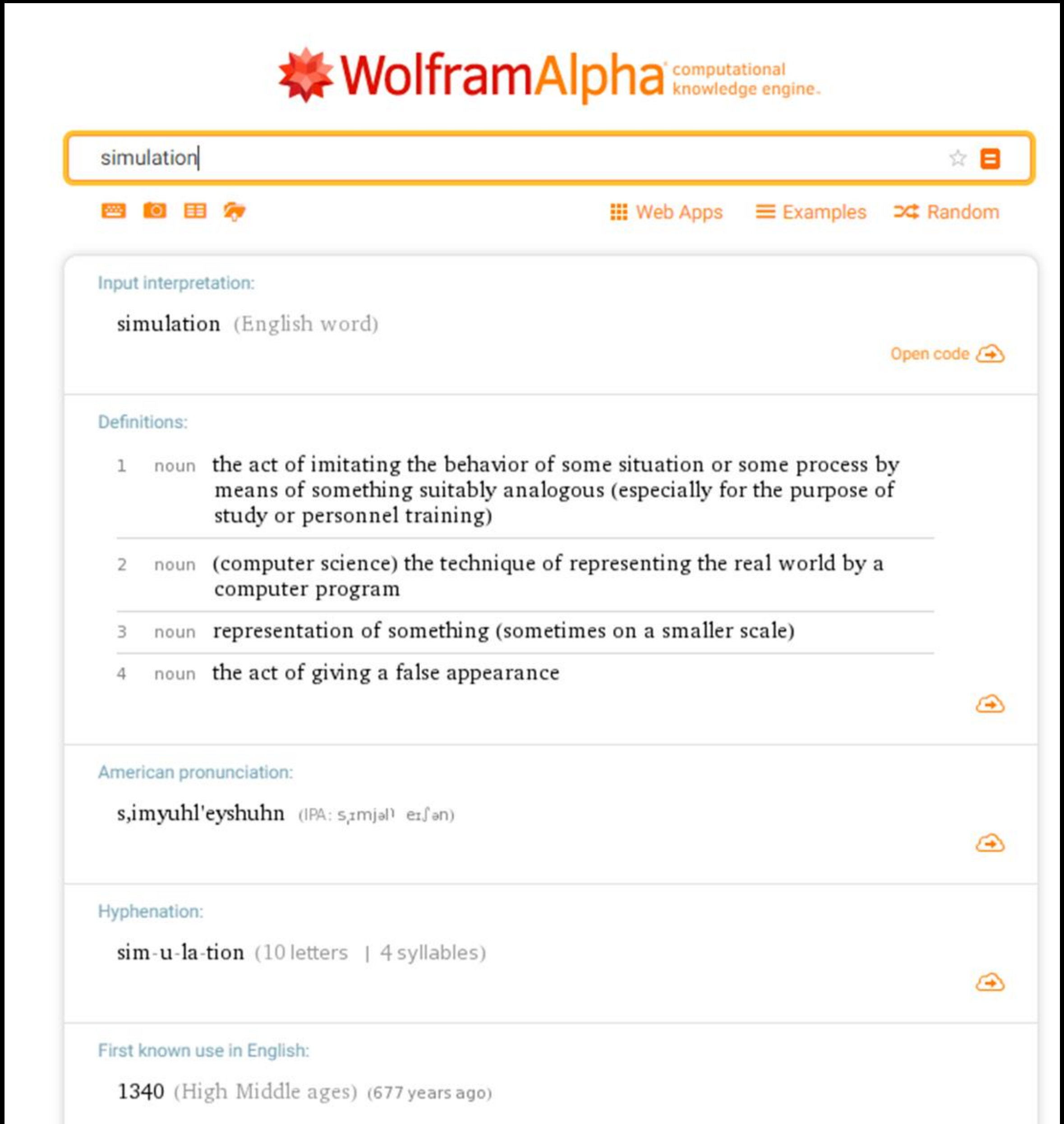
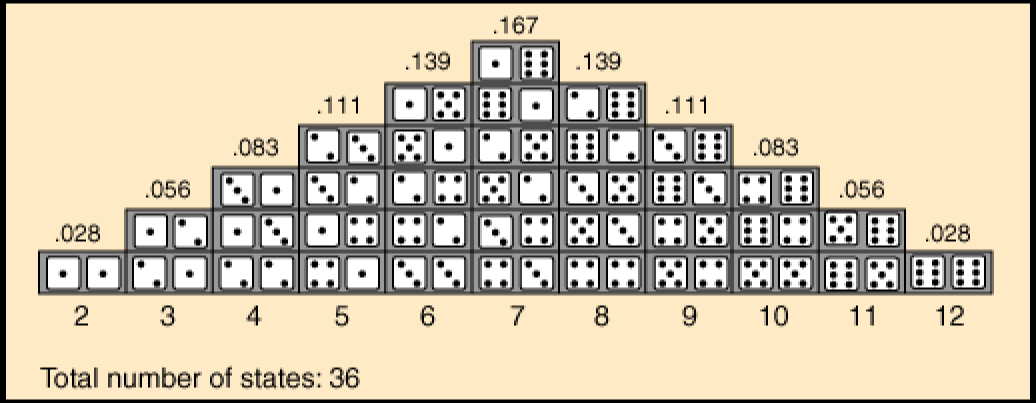


What is Monte Carlo simulation?

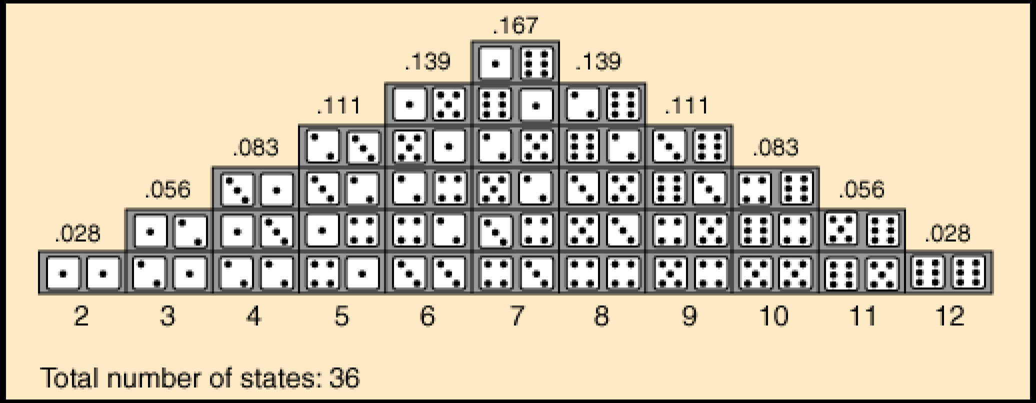
“A method which solves a problem by generating suitable random numbers and observing that fraction of the numbers obeying some property or properties. The method is useful for obtaining numerical solutions to problems which are **too complicated to solve analytically.”**

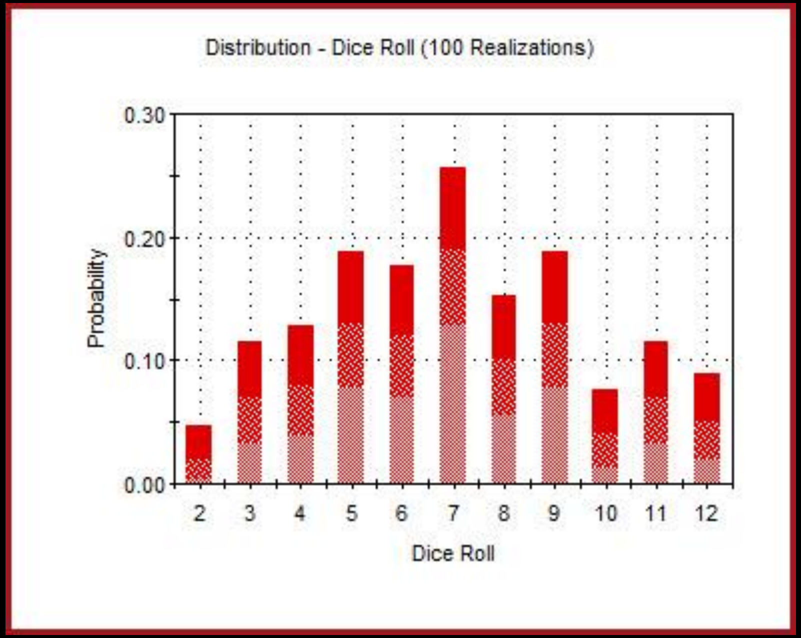
“A technique of **representing the real world by a computer program**.”

Simple Example



Simple Example





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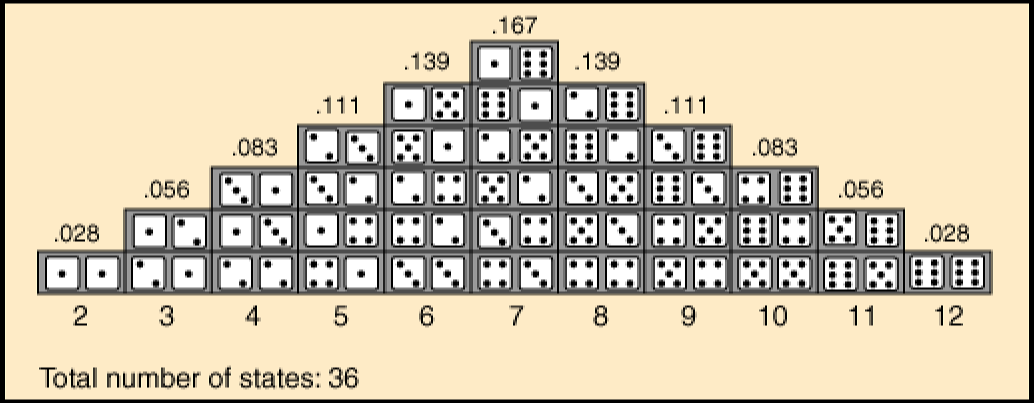
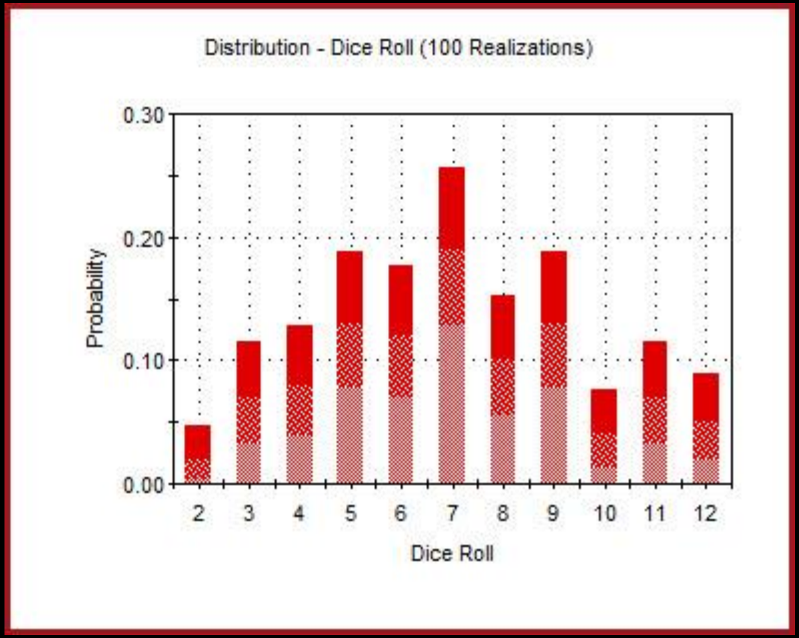
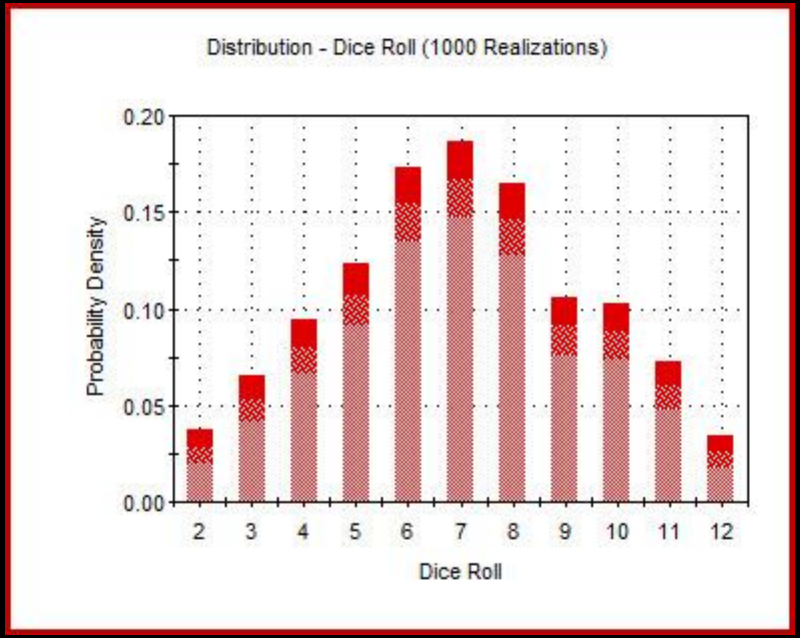
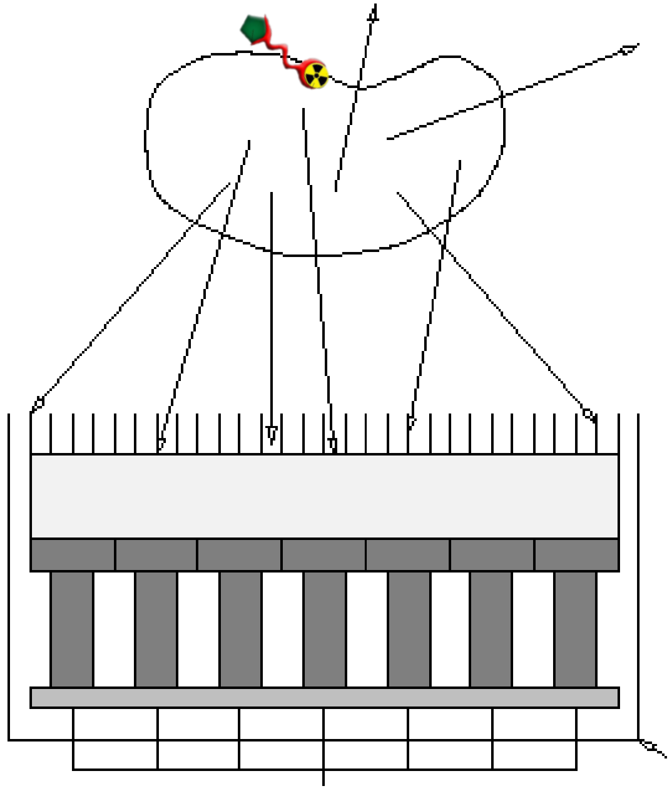


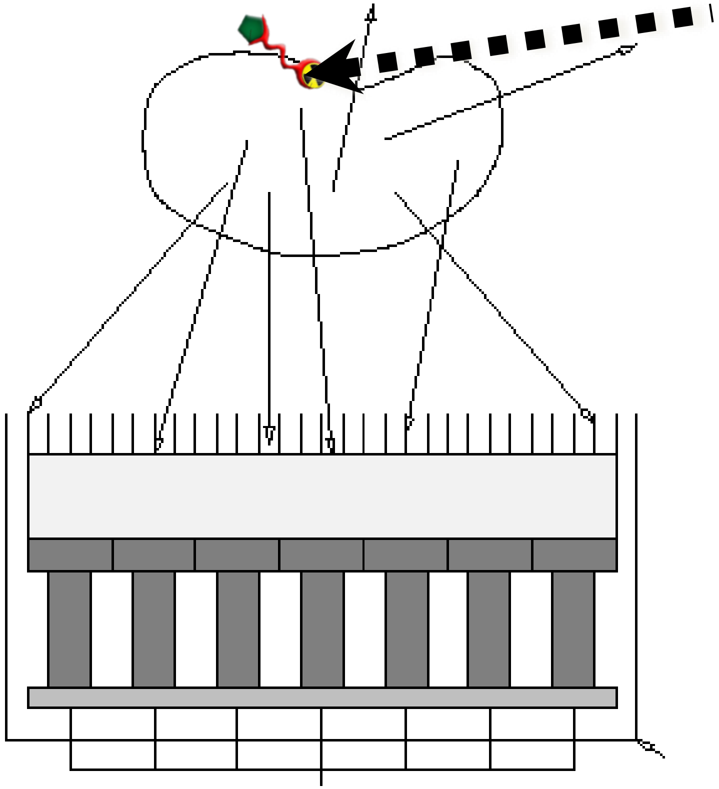




Physics and Probability

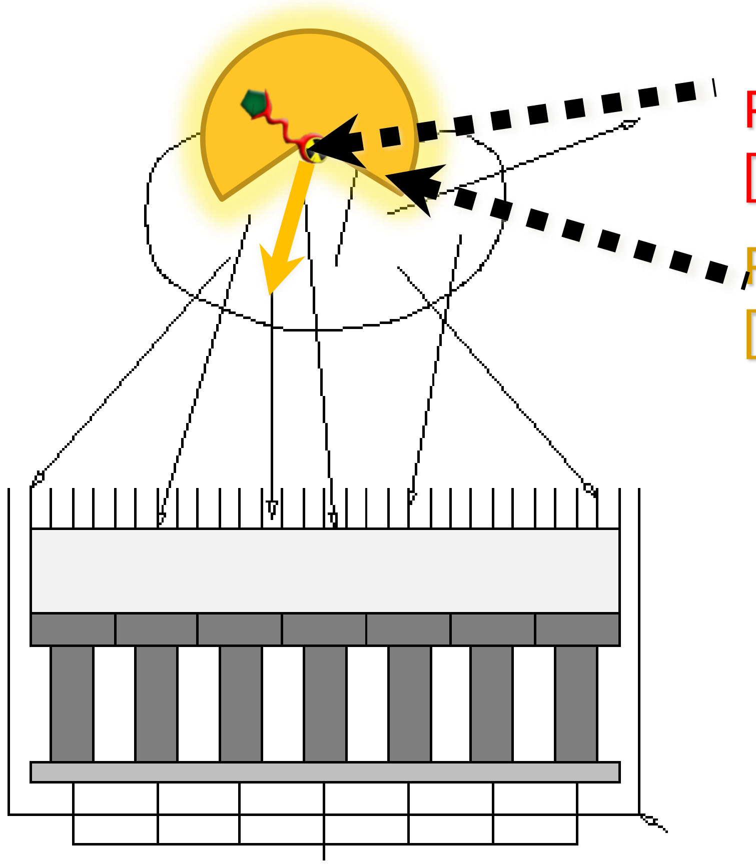


Physics and Probability



P1 = Probability of decay
[half-life]

Physics and Probability



P1 = Probability of decay
[half-life]

P2 = Probability of emission direction
[isotropic]

Physics and Probability

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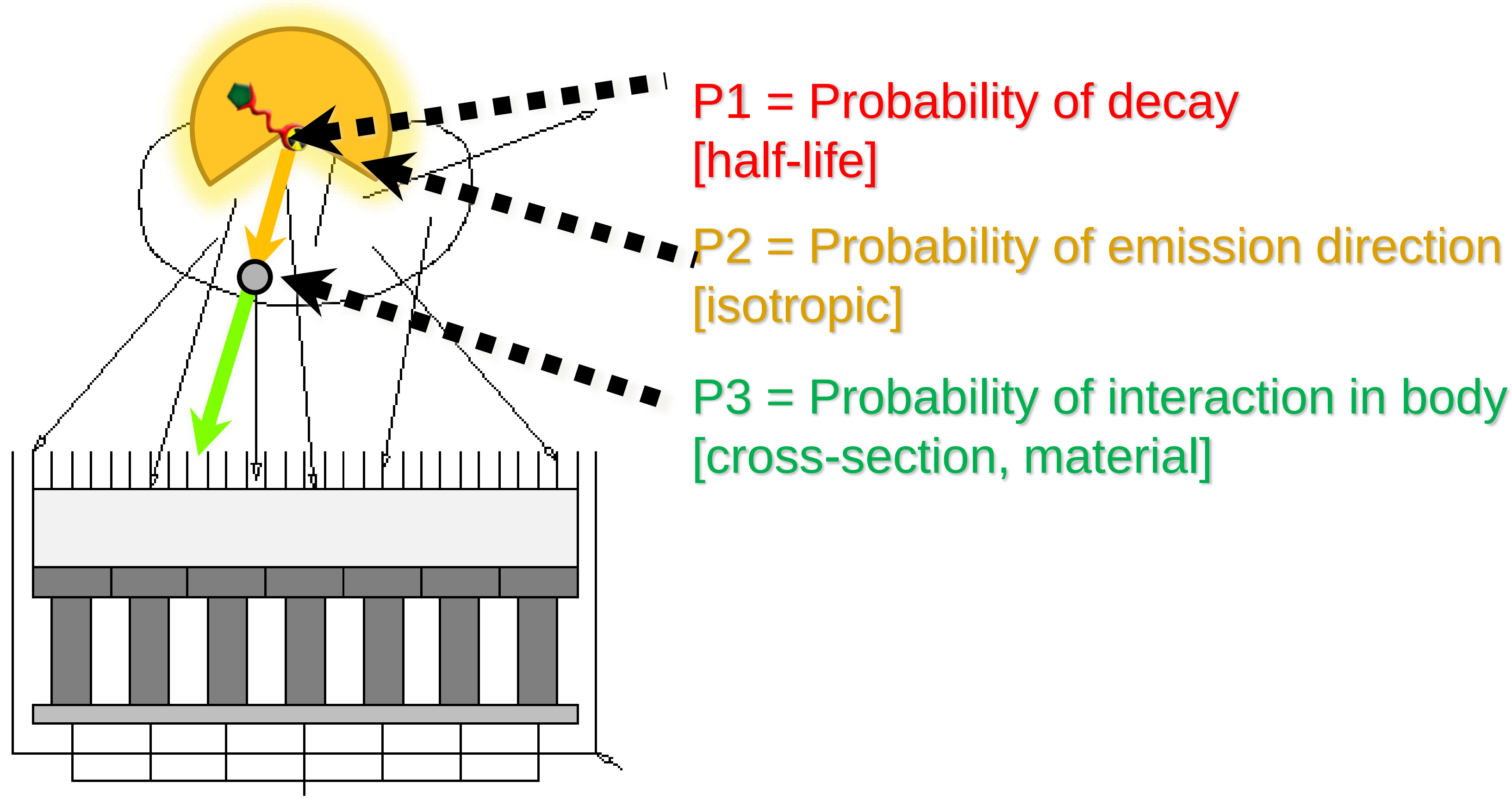

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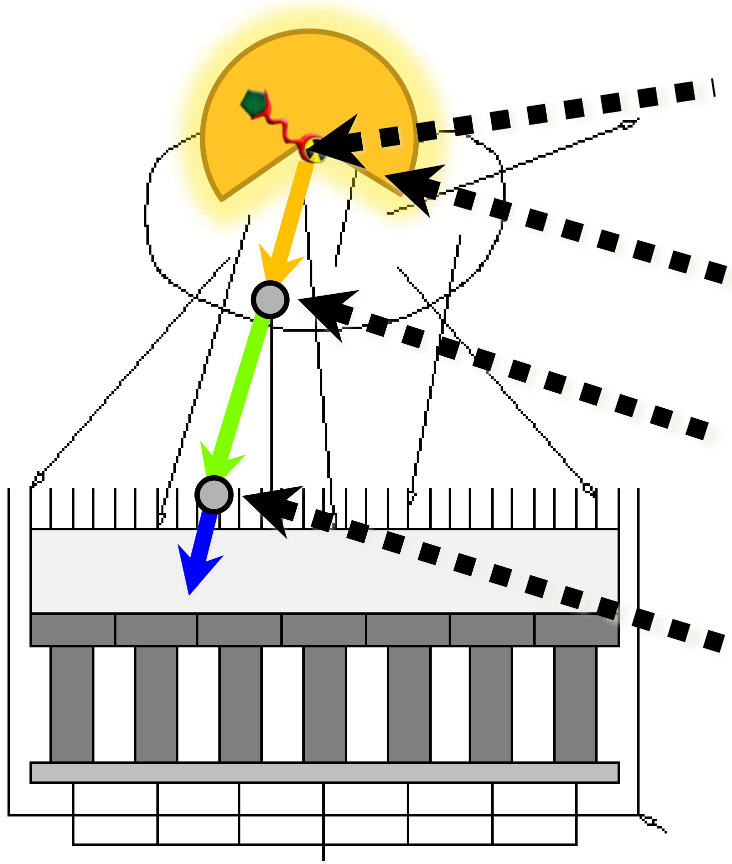

P1 = Probability of decay [half-life]

P2 = Probability of emission direction [isotropic]

P3 = Probability of interaction in body [cross-section, material]

P4 = Probability of interaction with collimator [cross-section, material]

Physics and Probability

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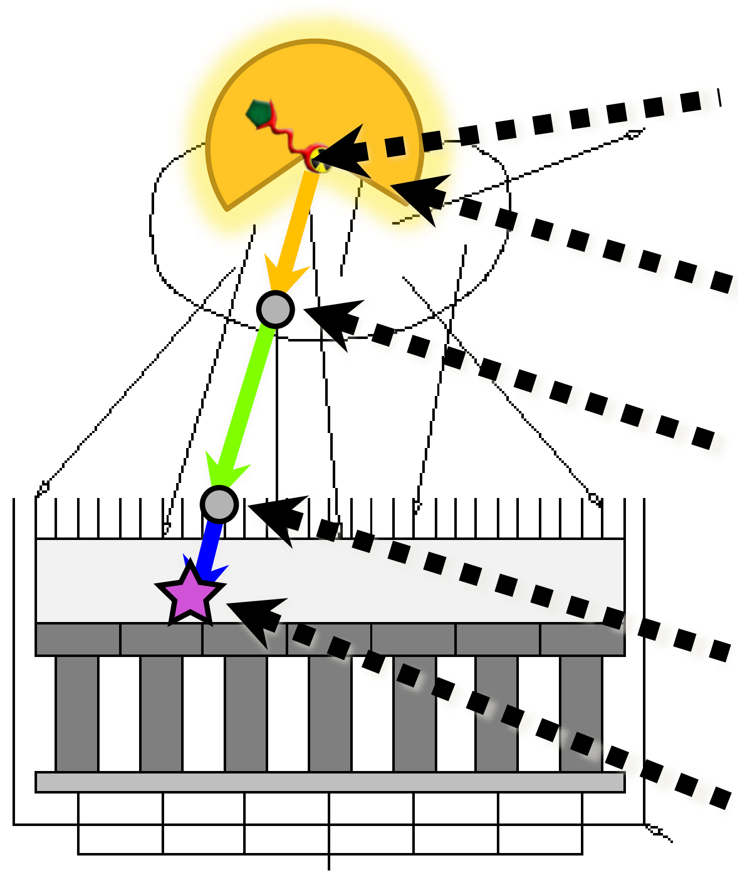

P1 = Probability of decay
[half-life]

P2 = Probability of emission direction
[isotropic]

P3 = Probability of interaction in body
[cross-section, material]

P4 = Probability of interaction with collimator
[cross-section, material]

P5 = Probability of absorption in crystal
[cross-section]

$$p(E\gamma) = p1 * p2 * p3 * p4 * p5$$

Physics and Probability

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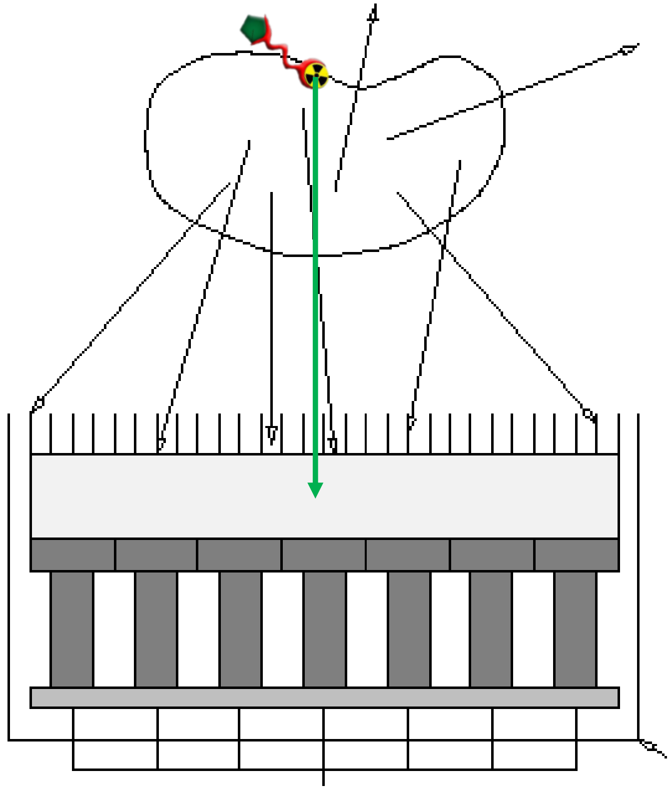
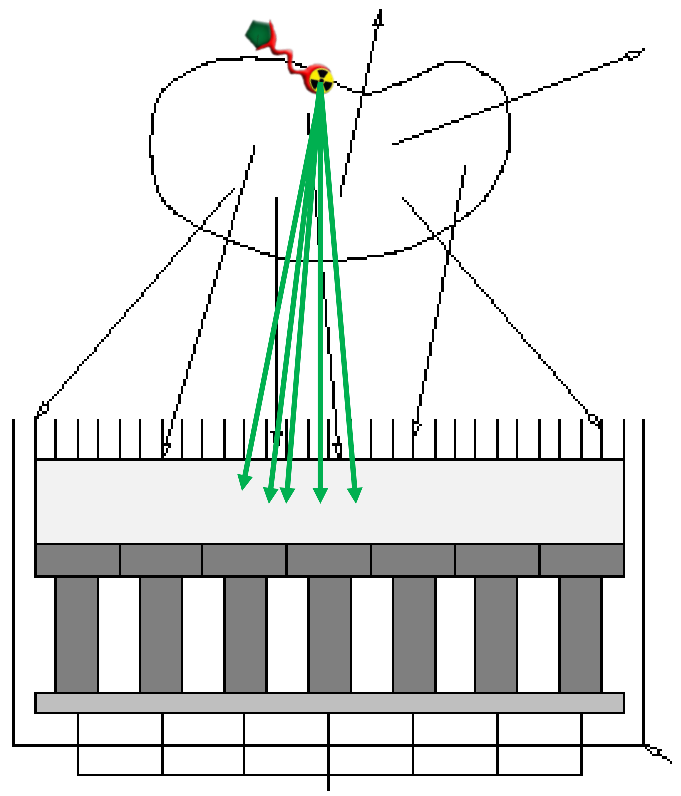


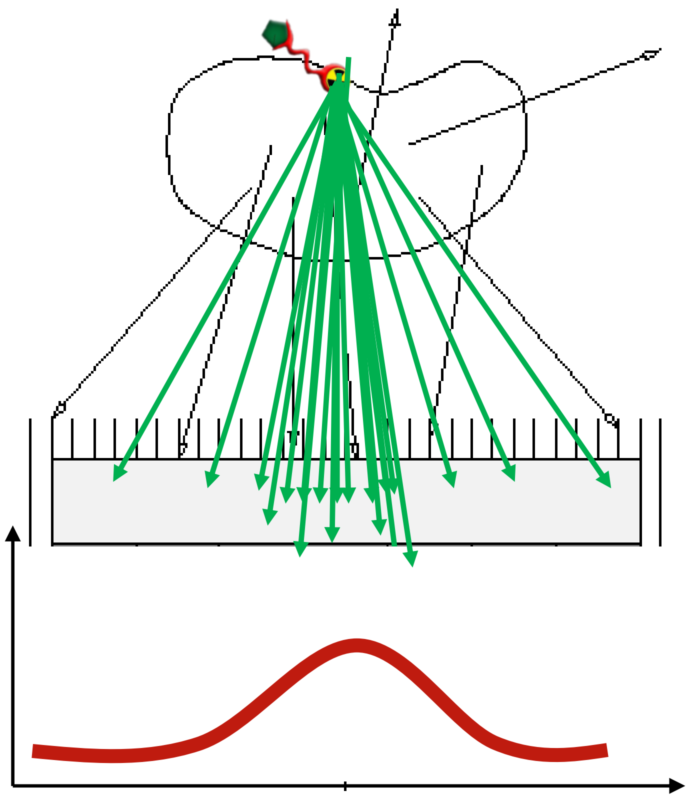
$p(E\gamma) = p1 * p2 * p3 * p4 * p5$

Physics and Probability



$p(E\gamma) = p1 * p2 * p3 * p4 * p5$

Physics and Probability



$p(E\gamma) = p1 * p2 * p3 * p4 * p5$

- What is Monte Carlo simulation?
- Why use it for medical imaging?
- Examples (demos)
- Validation of simulations
- Tools you can use
- Q & A

Why use it for medical imaging?

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Doesn't require patients

No camera time

Extra information (physically non-observable)

Easily modify the system

Can provide a "ground truth"

Infinitely repeatable

No radiation dose (patient or operator)

Optimise imaging protocols

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Blue	= Positive Charge
Green	= Neutral Charge
Red	= Negative Charge

Optimisation of imaging windows using Monte Carlo Simulation

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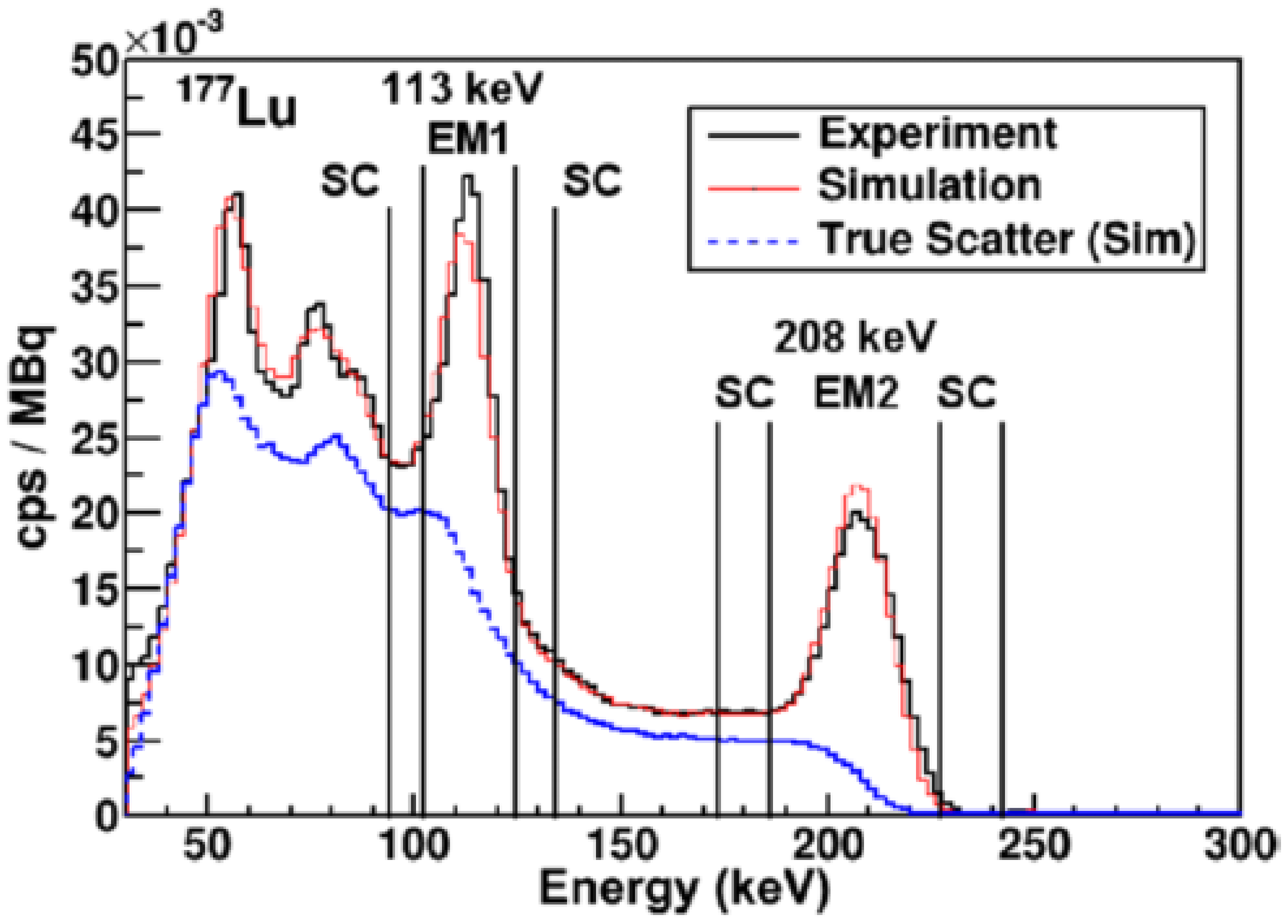

Figure 5. Emission spectrum for a water filled phantom measured

Example:
Optimisation of imaging windows

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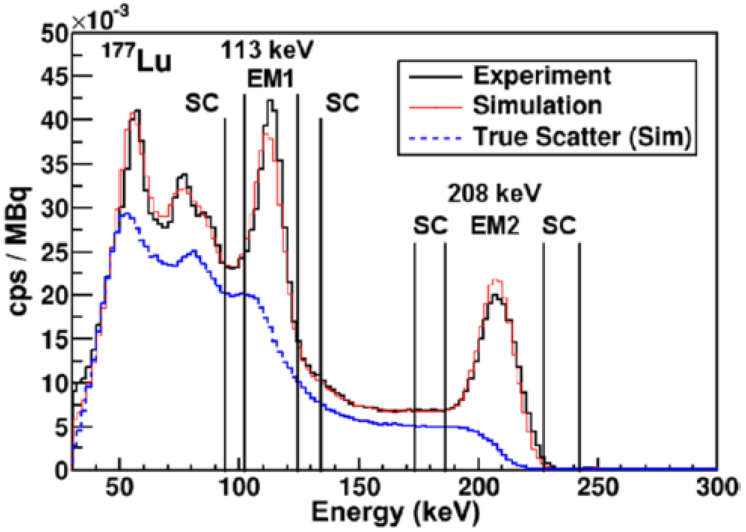
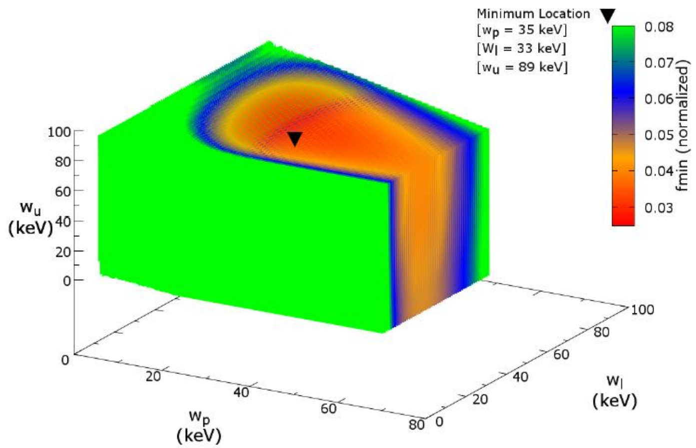


Figure 5. Emission spectrum for a water filled phantom measured



$$C_{TEW} = \left(\frac{C_l}{w_l} + \frac{C_u}{w_u}\right) \times \frac{w_p}{2}$$

$$f_{min} = \left|1 - \frac{C_{TEW}}{TS}\right| = \left|1 - \frac{\left(\frac{C_l}{w_l} + \frac{C_u}{w_u}\right) \times \frac{w_p}{2}}{TS}\right|$$

$$\{w_l \in \mathbb{N}^0\}\ \{w_u \in \mathbb{N}^0\}\ \{w_p \in \mathbb{N}^1\}$$

$$E_l + \frac{w_l}{2} > E_{min}$$
$$E_u + \frac{w_u}{2} < E_{max}.$$

Sensitive range Camera.

$$E_l + \frac{w_l}{2} \leq E_p - \frac{w_p}{2}$$
$$E_u - \frac{w_u}{2} \geq E_p + \frac{w_p}{2}.$$

Over-lapping windows.

Tb$_{65}$ (Theranostic Isotope Quartet)

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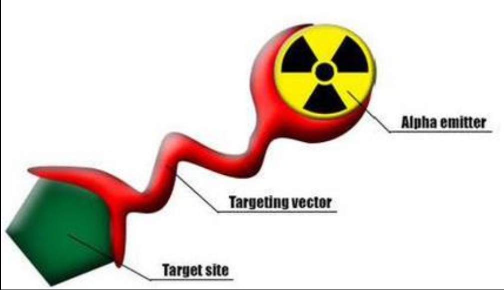
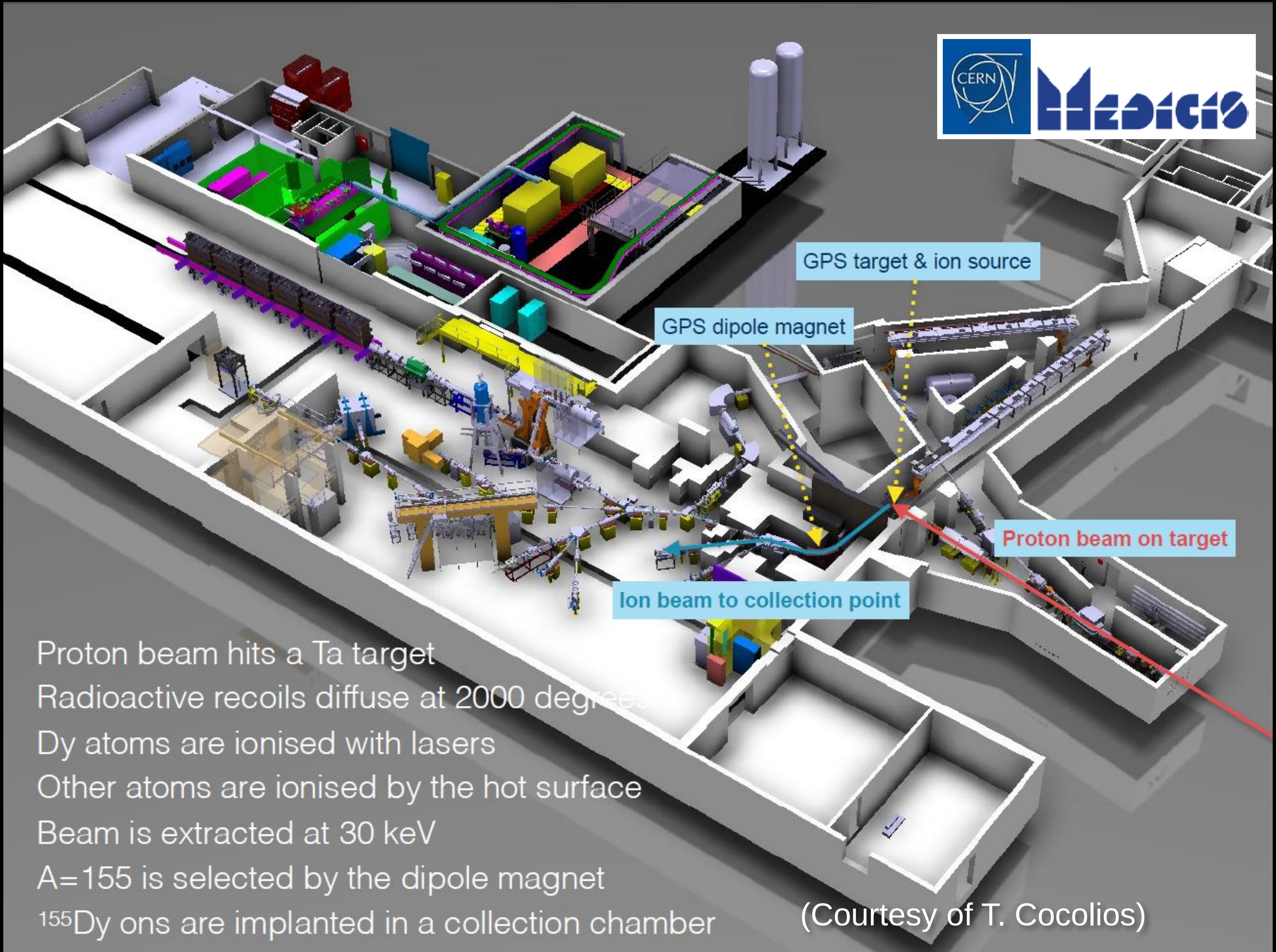


	Decay Mode	Half-life	MRT Application
^{149}Tb	α, $\beta+$ (17%, 7%)	4.12 hours	Therapy (α)
^{152}Tb	$\beta+$ (17%)	17.5 hours	PET Imaging
^{155}Tb	EC (100%)	5.32 days	SPECT Imaging
^{161}Tb	$\beta-$ (100%)	6.89 days	Therapy ($\beta-$)


CERN
MEDICIS
GPS target & ion source
GPS dipole magnet
Proton beam on target
Ion beam to collection point
Proton beam hits a Ta target
Radioactive recoils diffuse at 2000 degrees
Dy atoms are ionised with lasers
Other atoms are ionised by the hot surface
Beam is extracted at 30 keV
A=155 is selected by the dipole magnet
^{155}Dy ons are implanted in a collection chamber
(Courtesy of T. Cocolios)

Medical physics questions for ^{155}Tb

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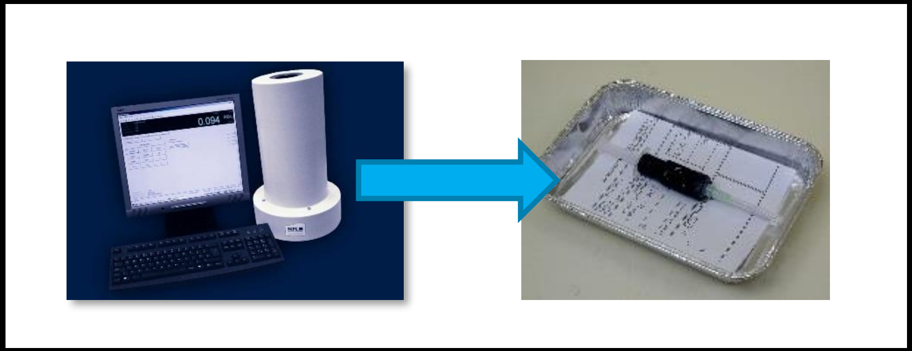
How to image it?

- Which gamma-rays to look at?
- What energy gate to set?
- Which collimators to use?

How to measure activity?

- Is there a primary standard?
- What dial factors to use on a hospital calibrator?



^{155}Tb (SPECT Imaging)

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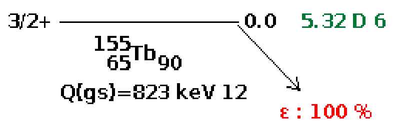
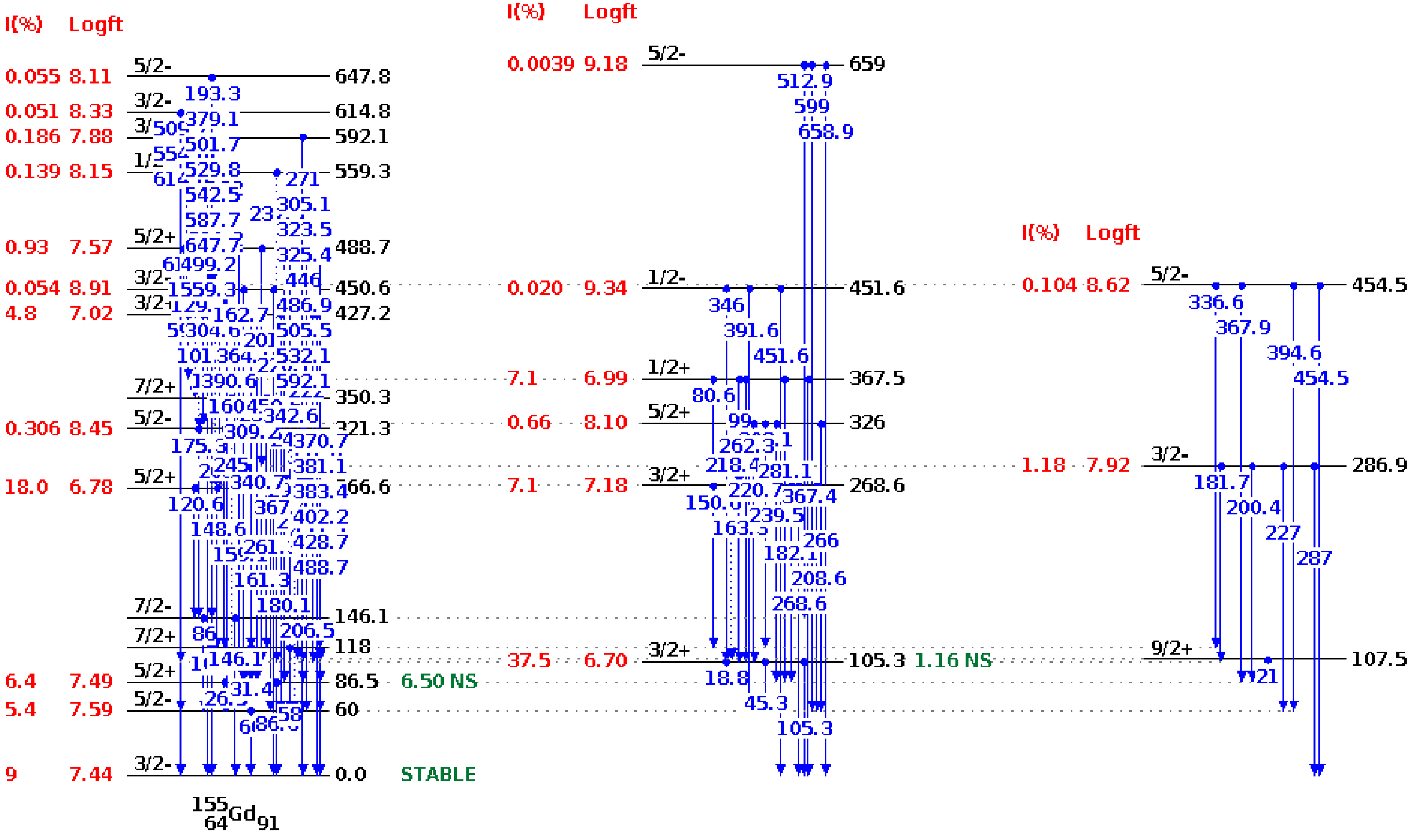


Eg (keV)	Ig (%)
86.545 3	32.0 6
105.305 3	25
180.103 1	7.45 15
262.322 2	5.29 5
163.311 1	4.44 5
161.334 1	2.76 3
148.650 1	2.648 23
45.2972 13	1.604 20
367.225 2	1.48 18
340.690 1	1.182 23
60.0086 10	1.11 4
160.589 2	0.781 15
367.638 2	0.78 13
268.625 2	0.71 5
220.778 2	0.508 5
181.694 1	0.422 5
26.533 6	0.394 13
286.999 4	0.317 6
281.087 2	0.302 4
208.089 2	0.231 13



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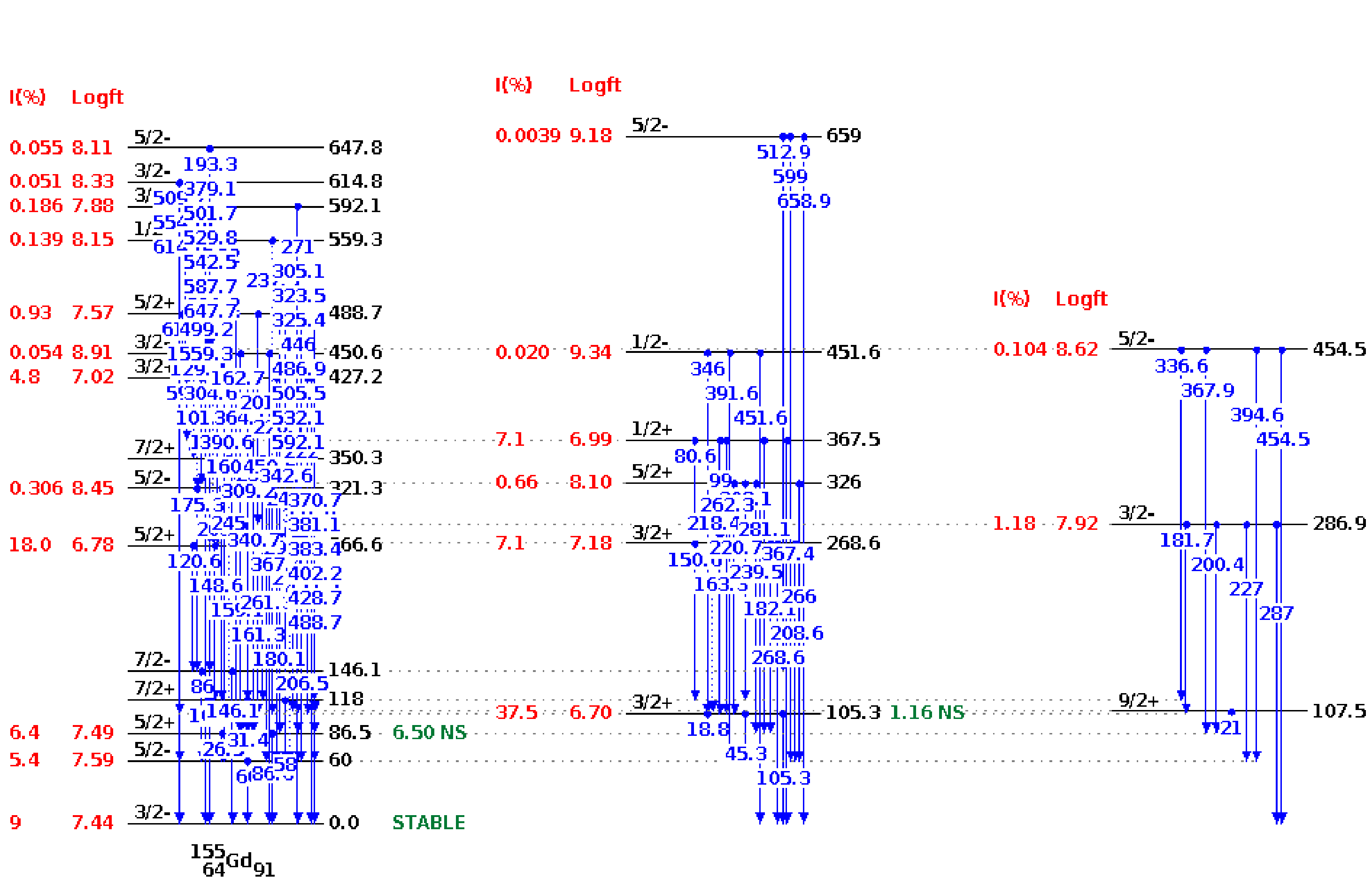

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Tb-155 SPECT

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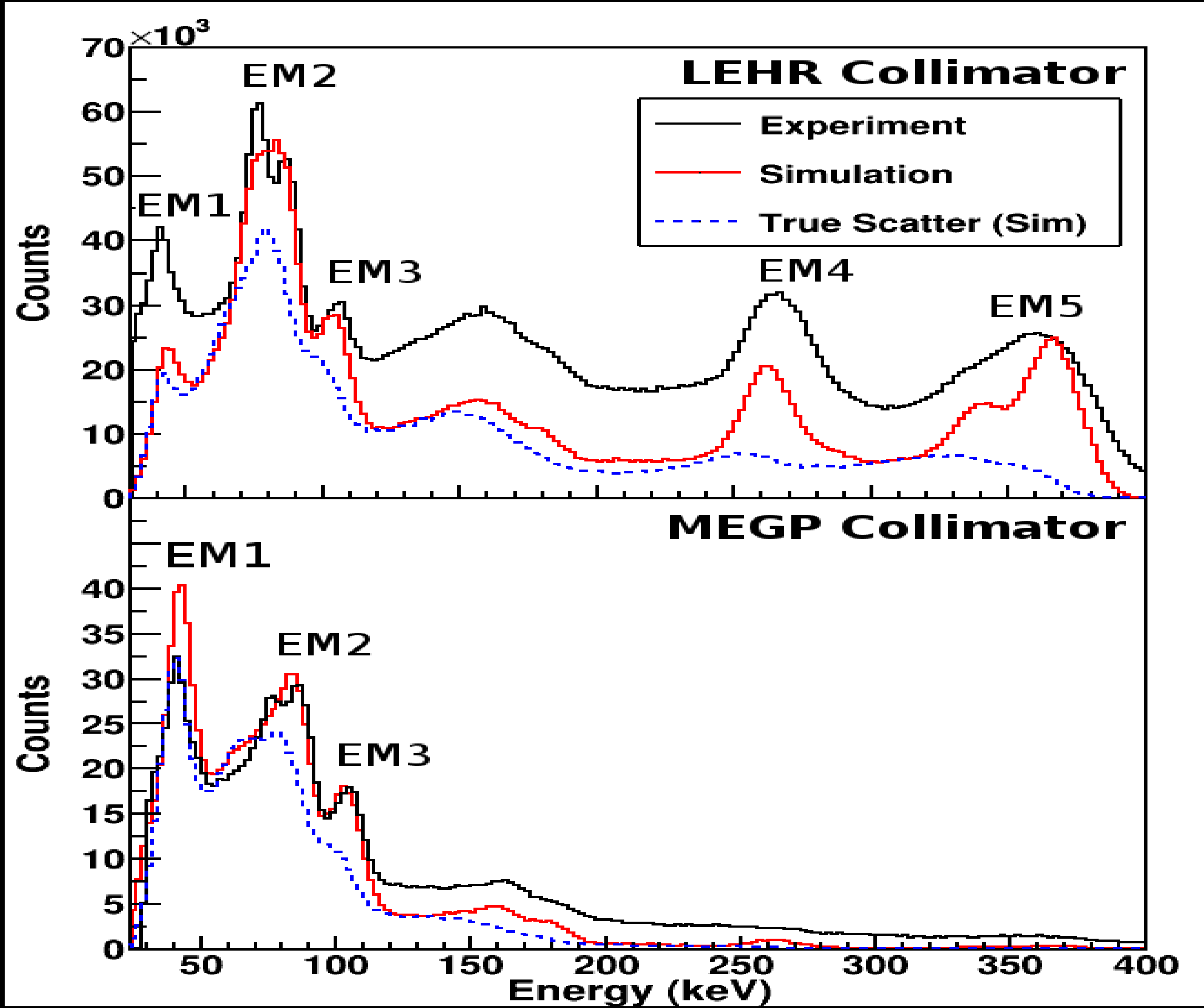

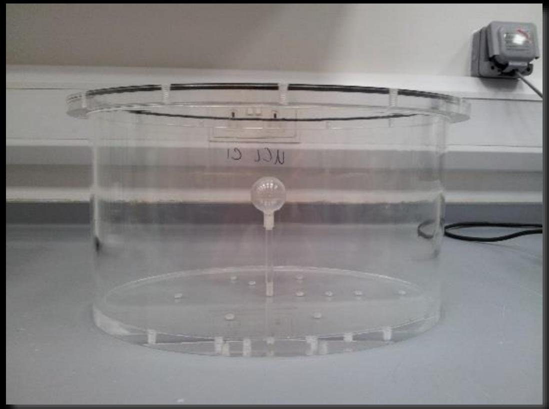

Tb-155 SPECT

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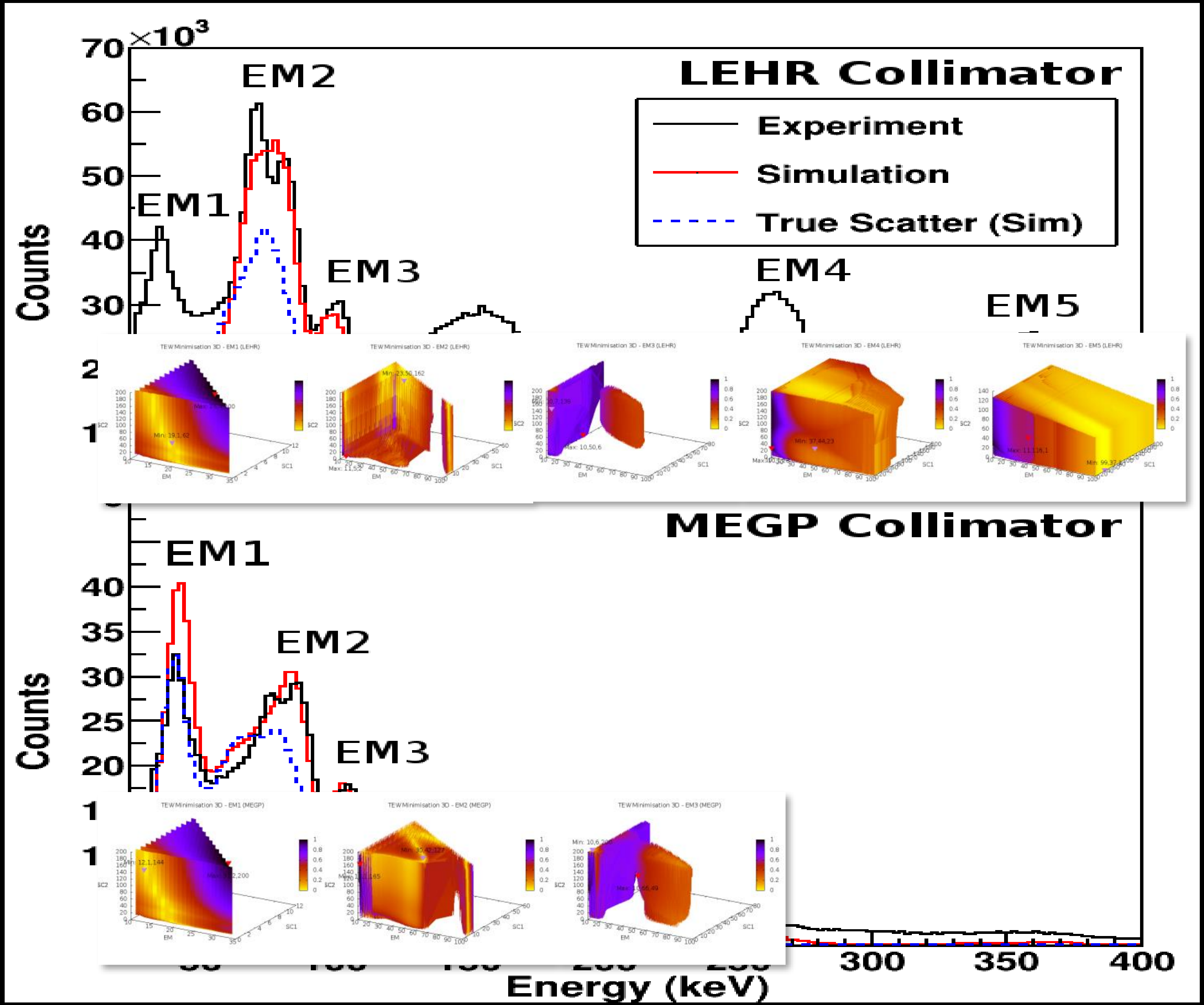
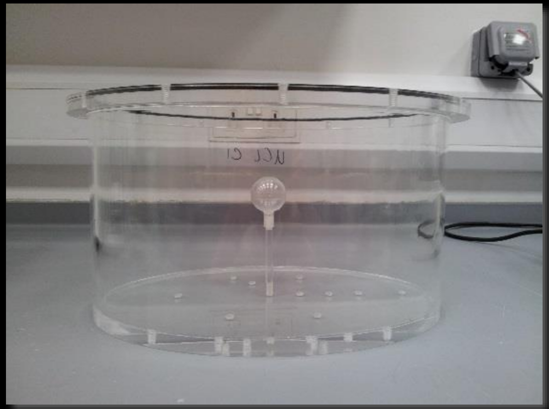
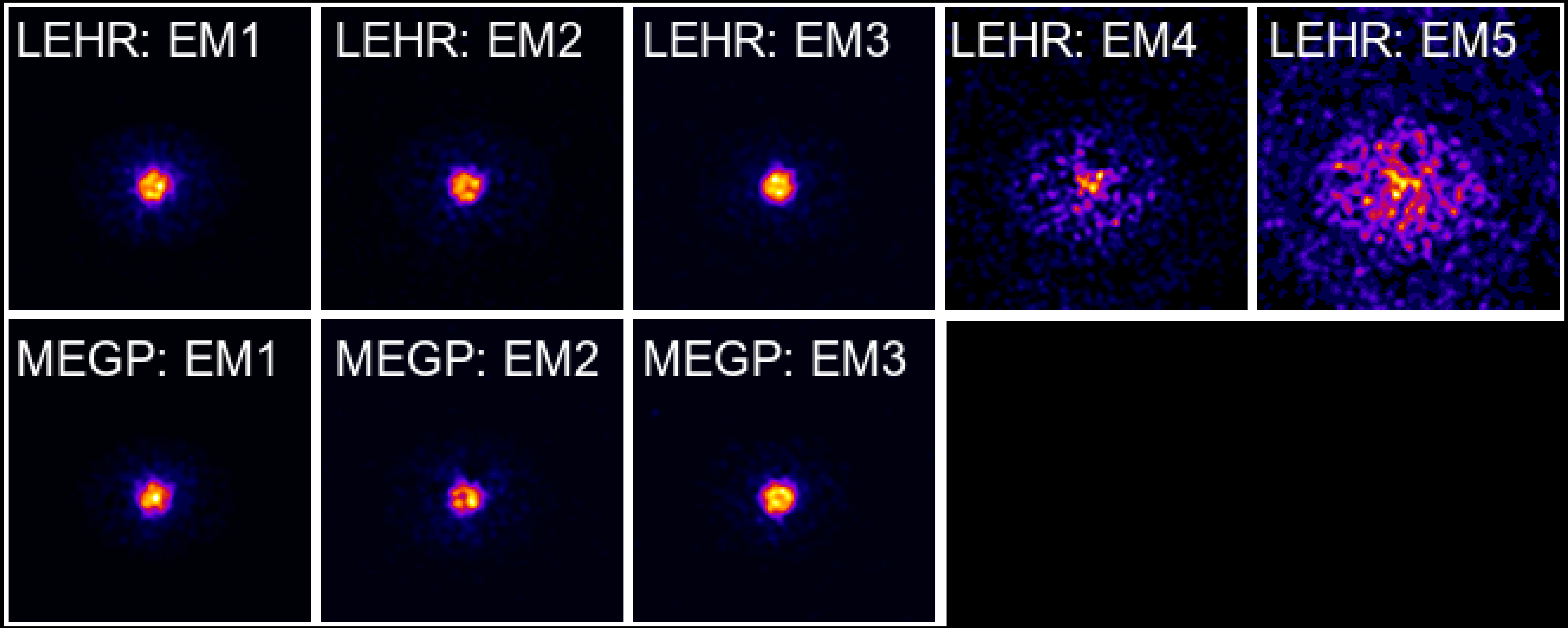




SPECT Imaging (List mode)



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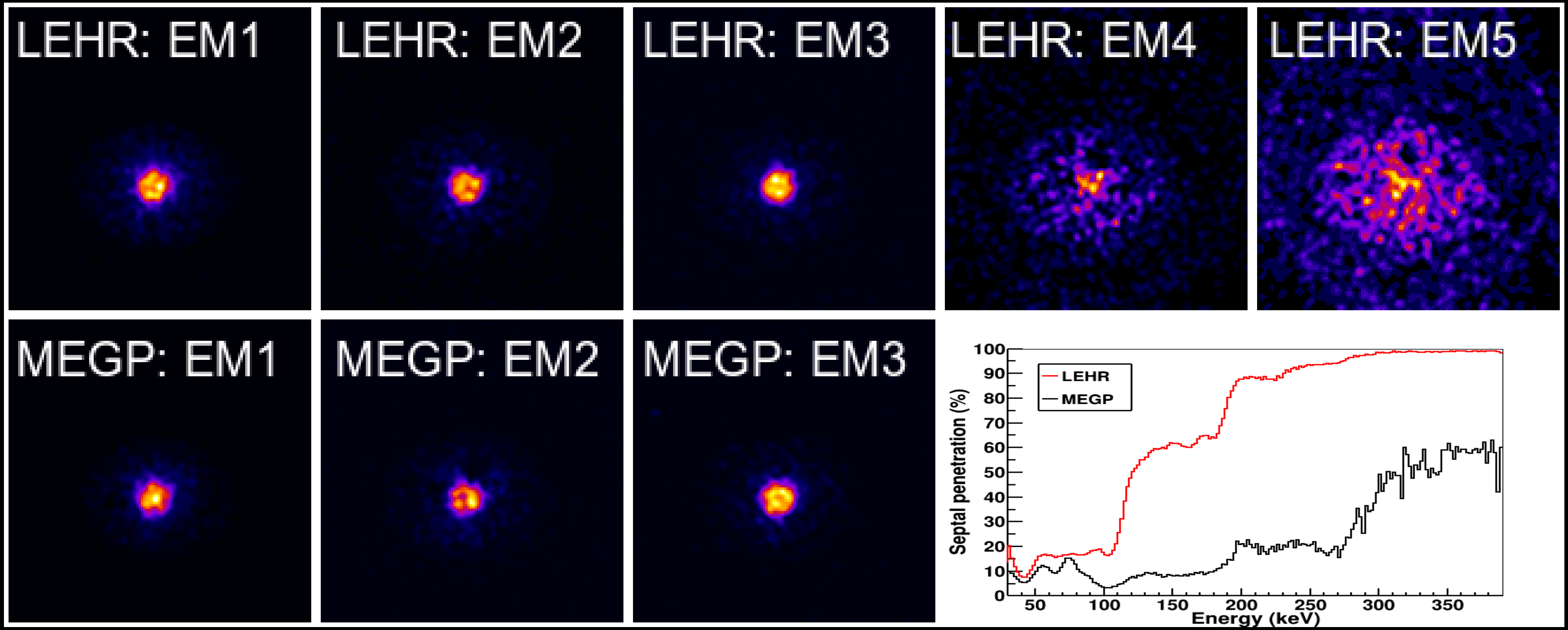

SPECT Imaging (List mode)

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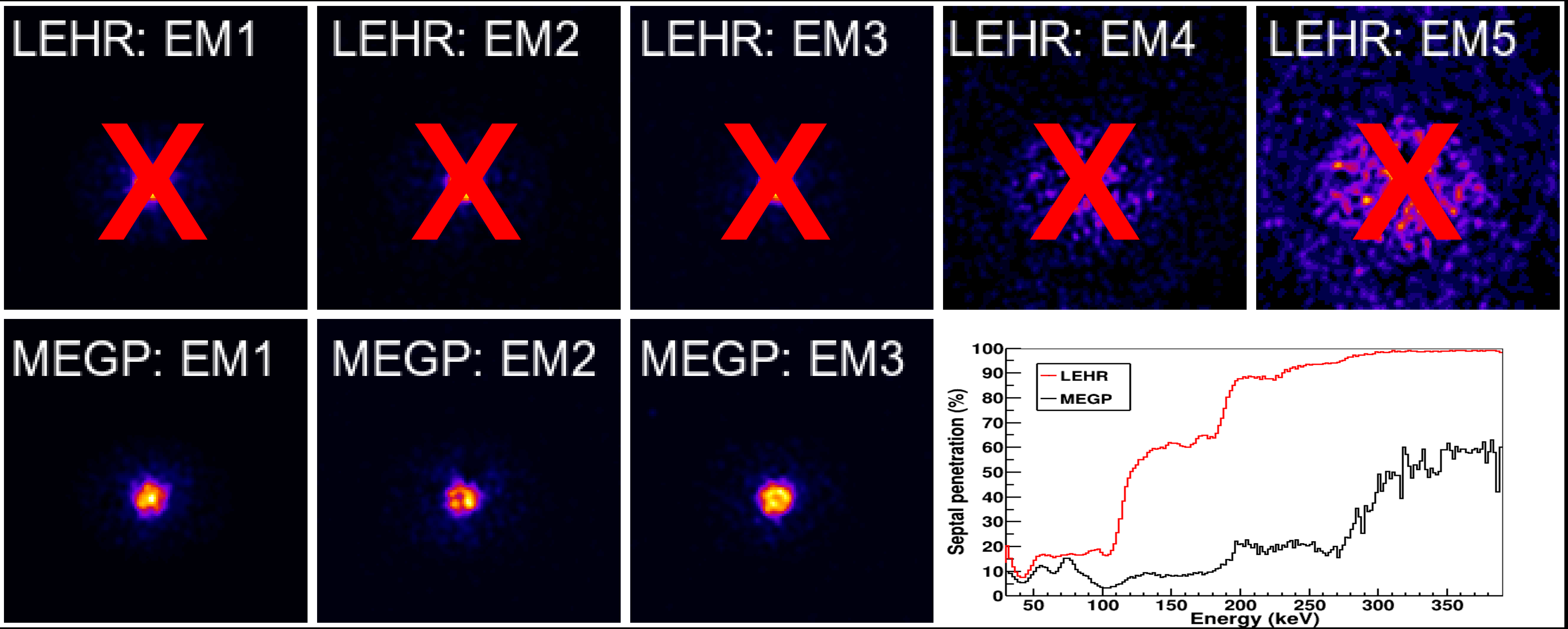

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Validation of simulations

- Can you trust the results from a simulation?

Validation of simulations

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- Can you trust the results from a simulation?

- Yes - **if the simulation has been validated**
  - ✓ Geometry
  - ✓ Detector modelling
  - ✓ Physics models (dependent on energy range)
  - ✓ (Nuclear) Data

Comparison with experimental data

Validation of simulations

- Can you trust the results from a simulation?

- Yes - **<u>if the simulation has been validated</u>**
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<u>Comparison with experimental data</u>

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Phys. Med. Biol. 61 (2016) 5107–5127
doi:10.1088/0031-9155/61/14/5107

The influence of triple energy window scatter correction on activity quantification for ^{177}Lu molecular radiotherapy

Andrew P Robinson[1], Jill Tipping[2], David M Cullen[1] and David Hamilton[2]

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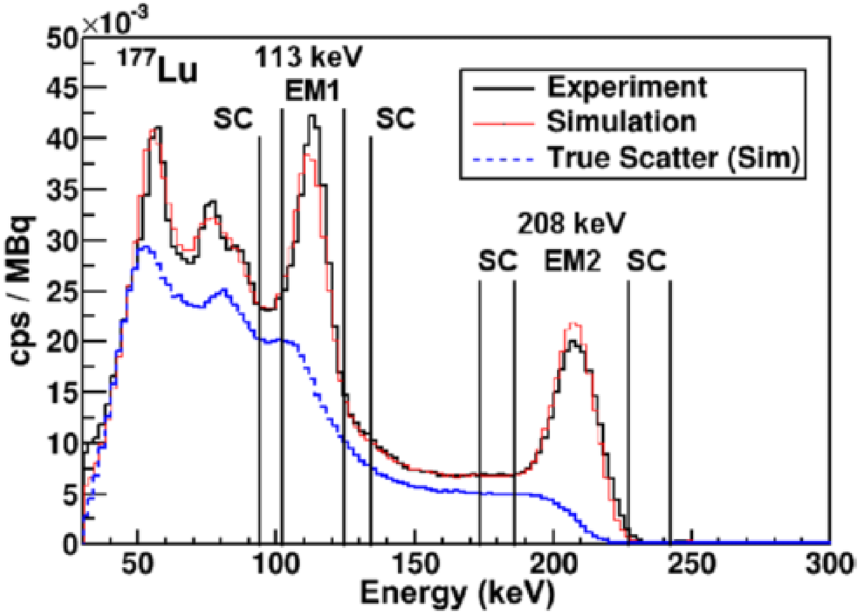

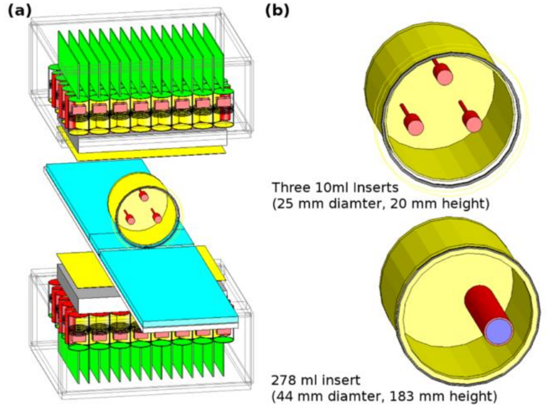

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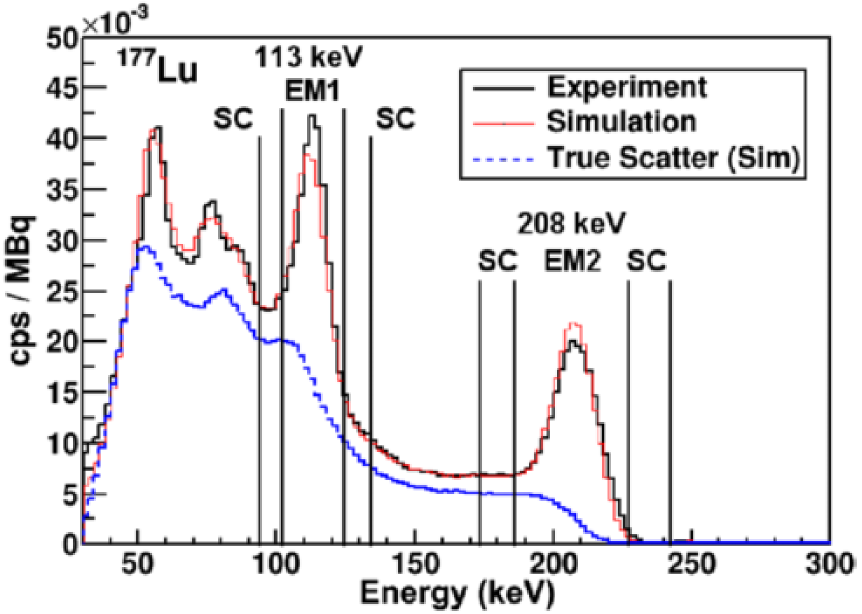

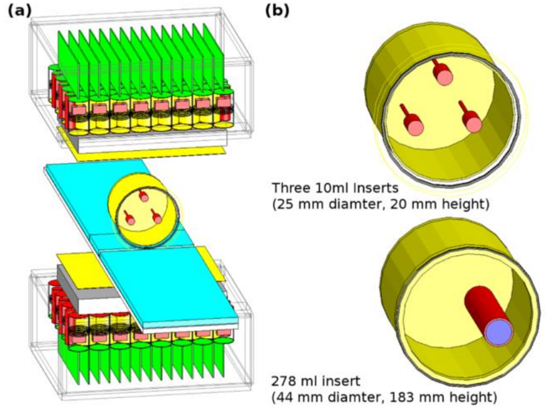

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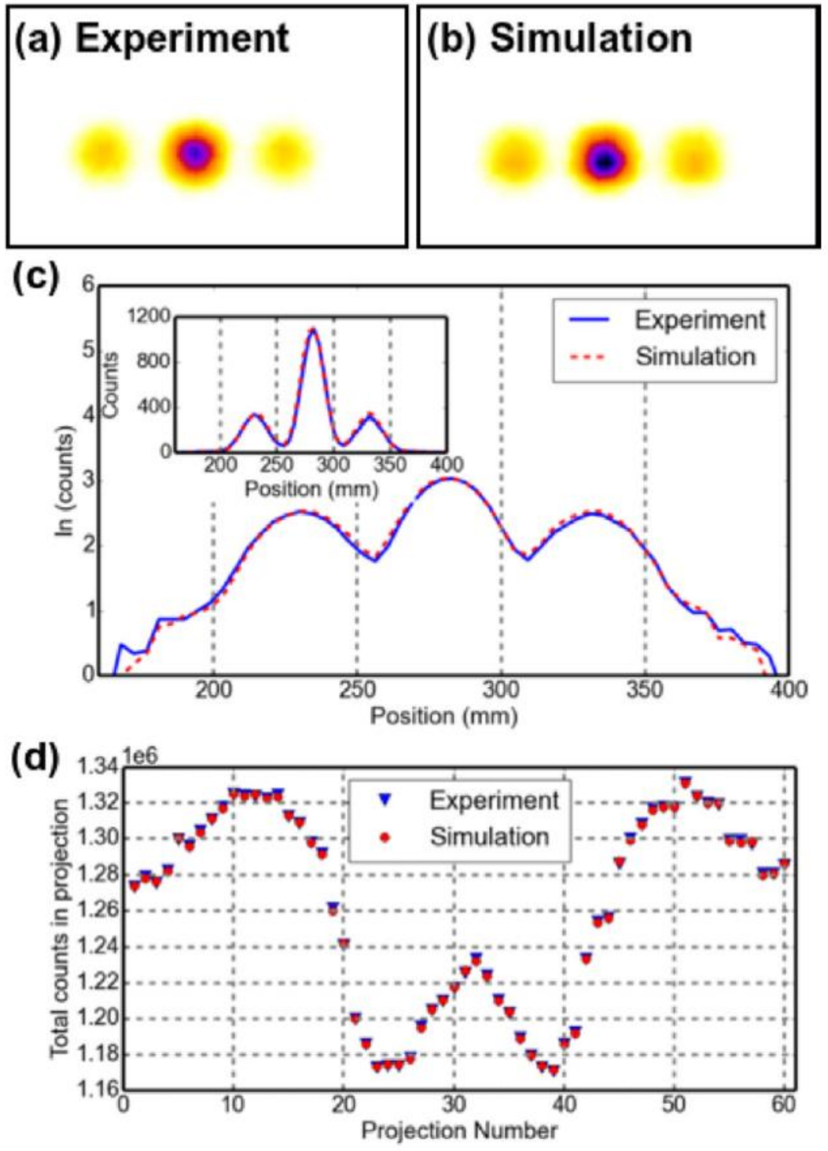

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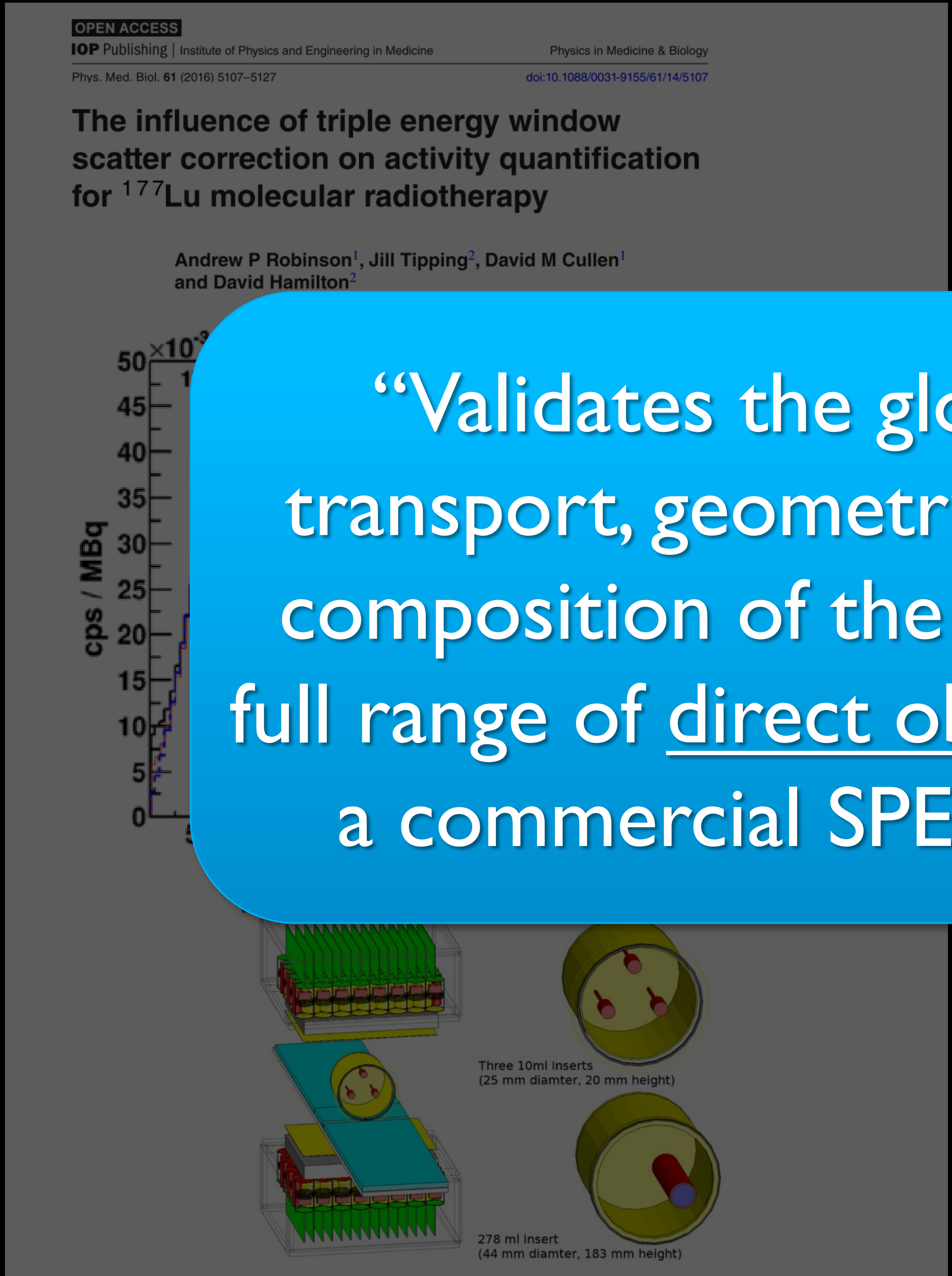
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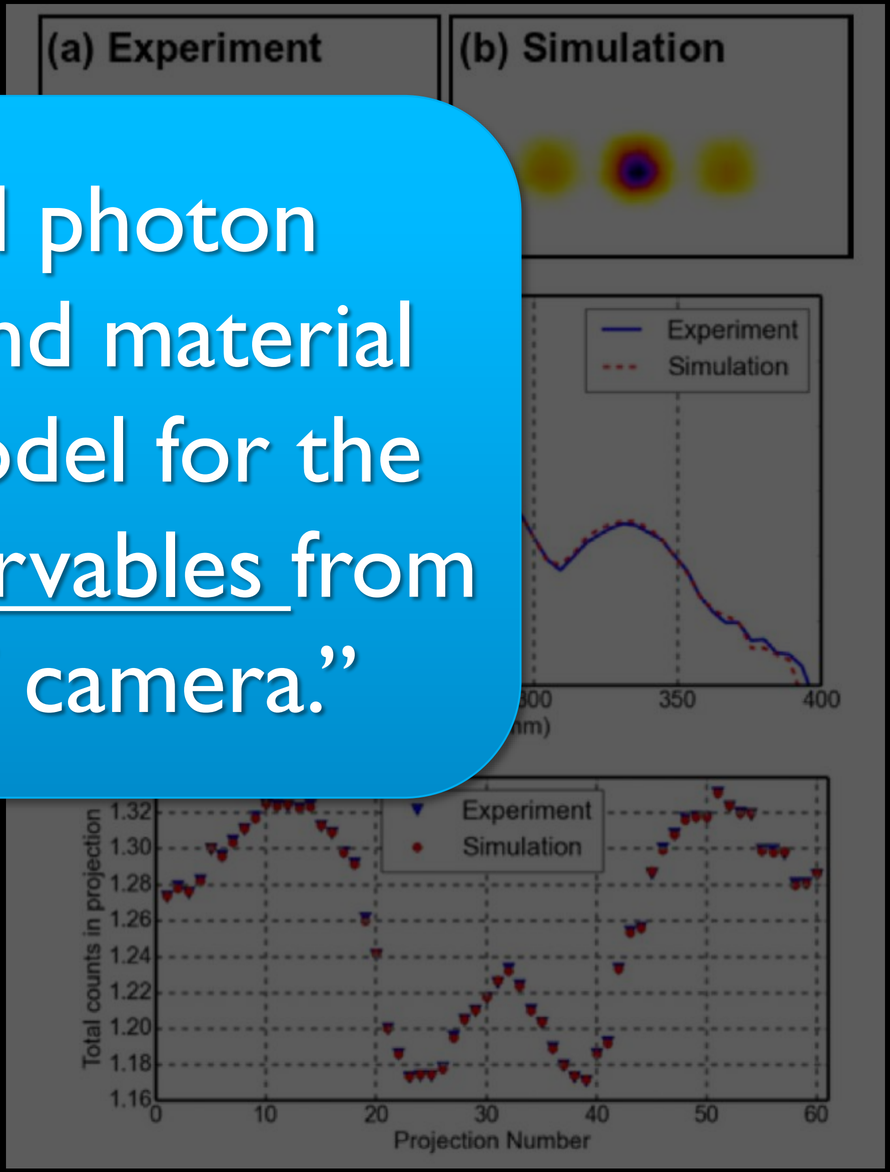
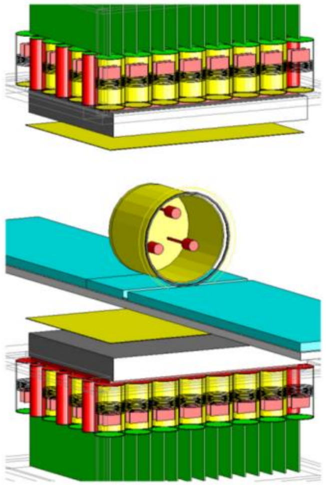
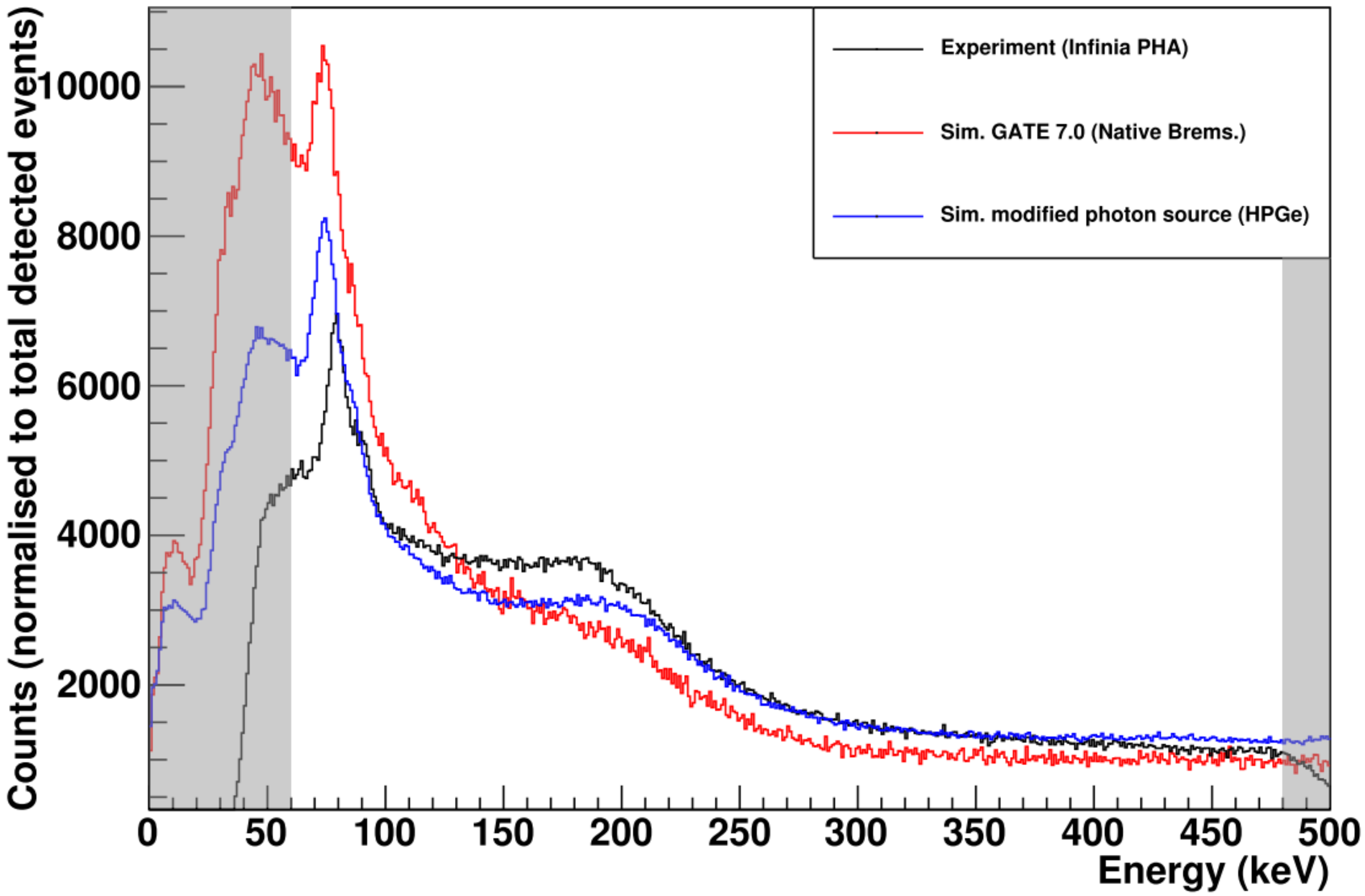
“Validates the global photon transport, geometry and material composition of the model for the full range of direct observables from a commercial SPECT camera.”



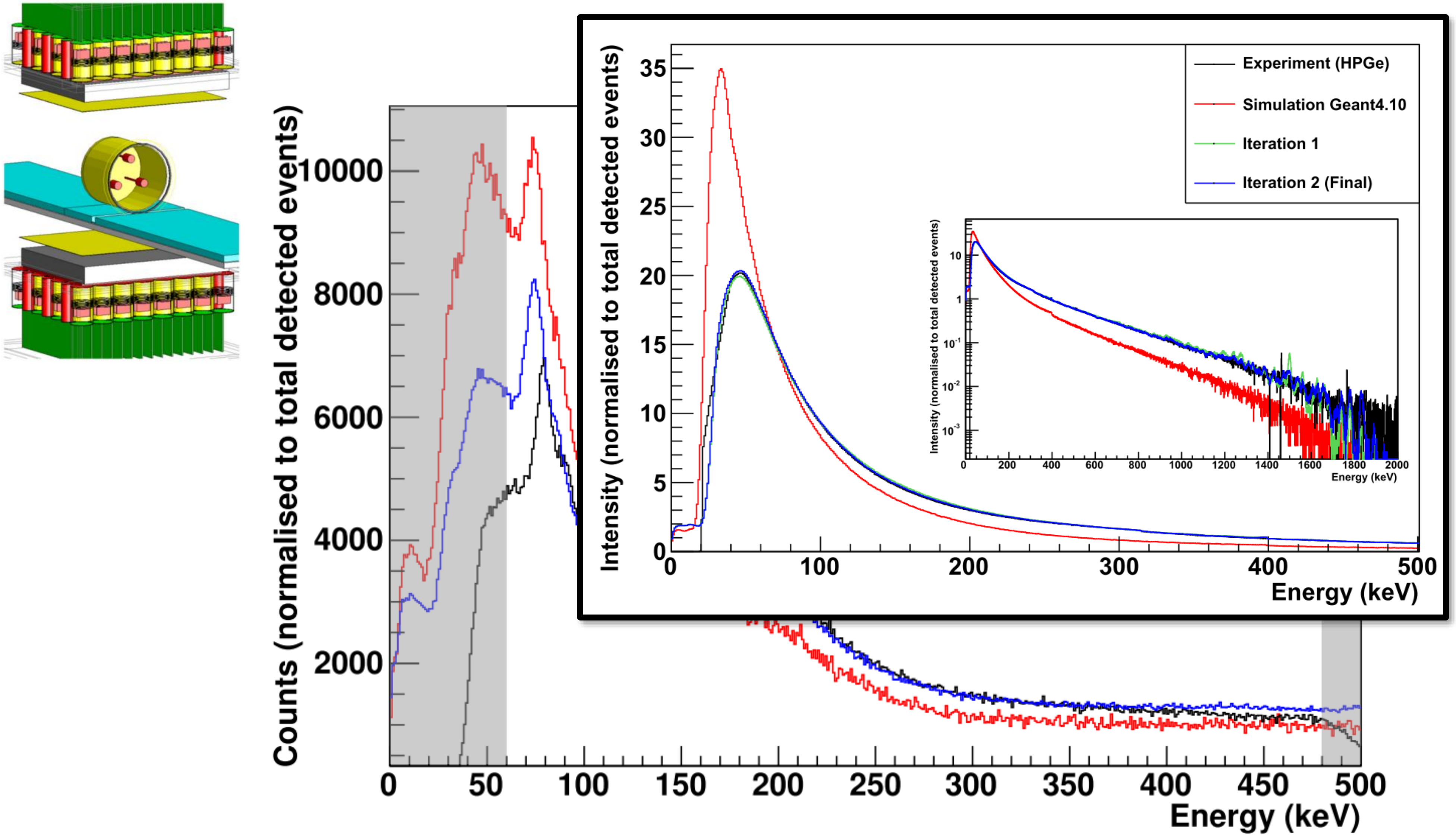
^{90}Y Bremsstrahlung Imaging





C. Oldfield, PhD Thesis, Uni. Of Manchester (2017)

^{90}Y Bremsstrahlung Imaging



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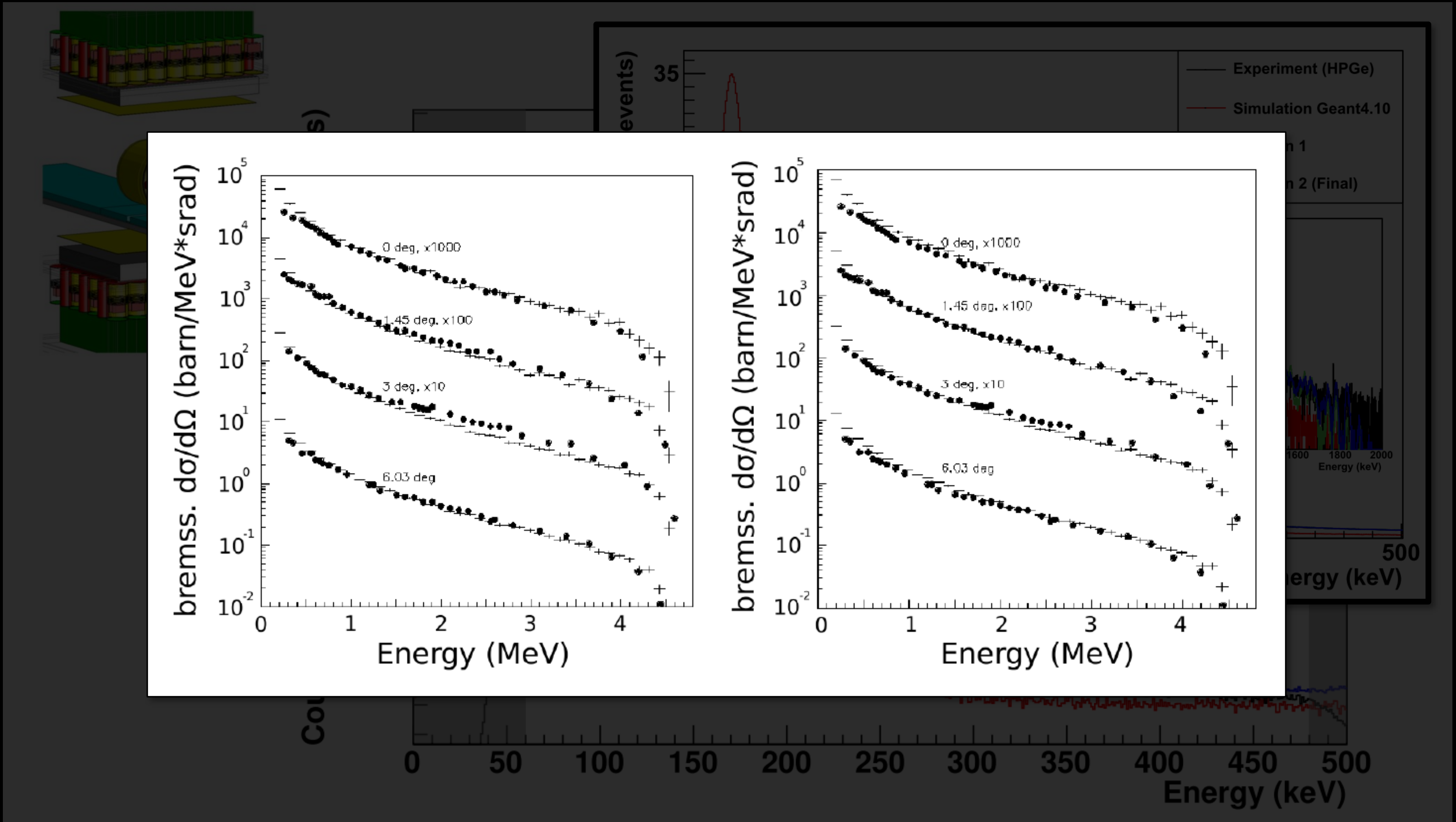

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^{90}Y Bremsstrahlung Imaging

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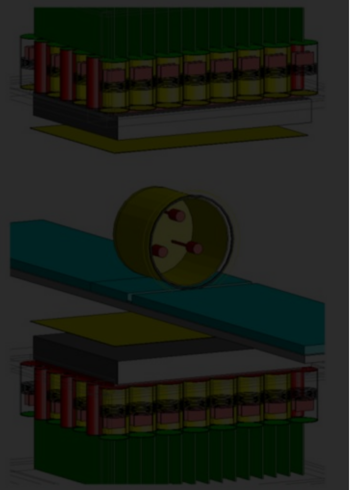
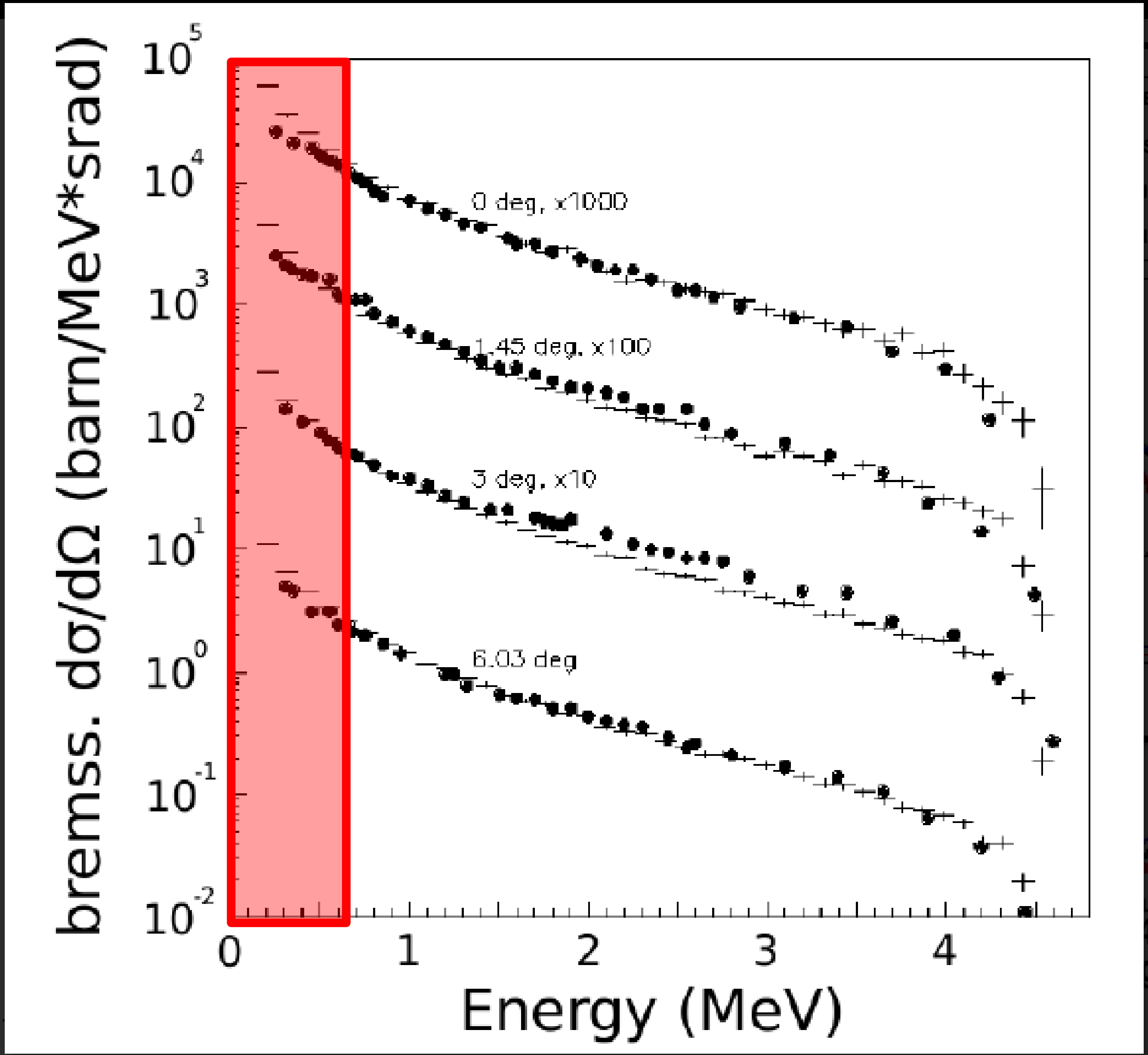
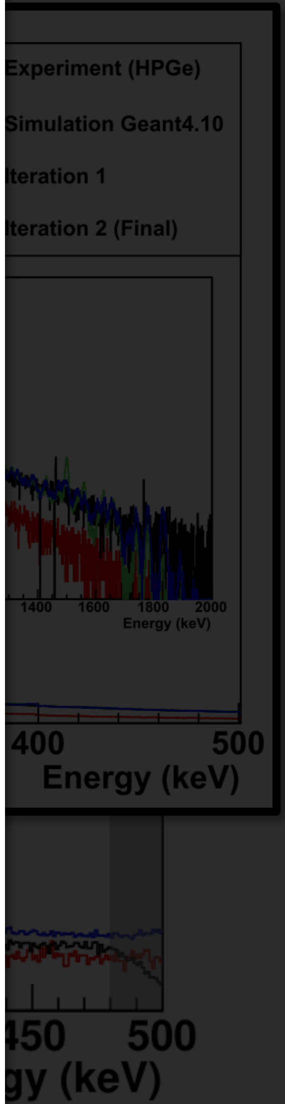






C. Oldfield, PhD

Uncertainties….

A quantitative validation methodology for Monte Carlo simulations for SPECT imaging studies

S. Pells, PhD Thesis (paper under review)

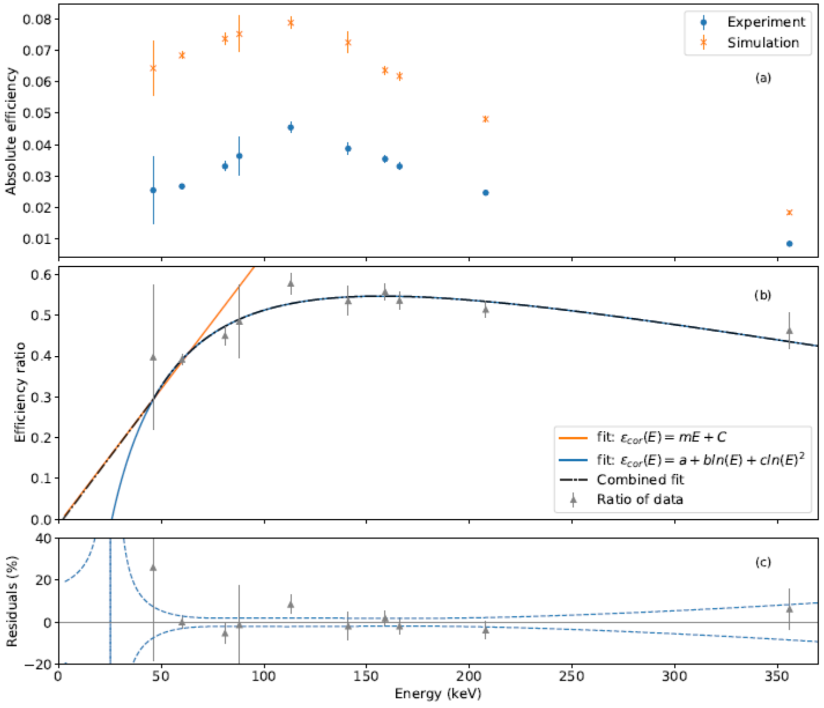


Figure 4: The data used to create the efficiency correction. (a): the absolute efficiency calculated from the experimental and simulated calibration sources. (b): the data points with the two fits as discussed in the text and the superposition of the two functions which was used for the efficiency correction. The points show the ratio of experimentally-measured and simulated efficiency for the calibration sources with their standard uncertainties. (c): the residuals of the fit to the data. The error bars on the residuals are the standard uncertainty of each data point and the dashed lines represent the uncertainty of the logarithmic fit.

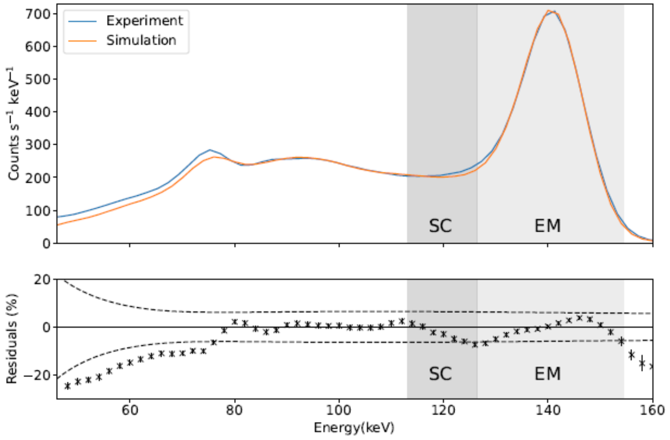
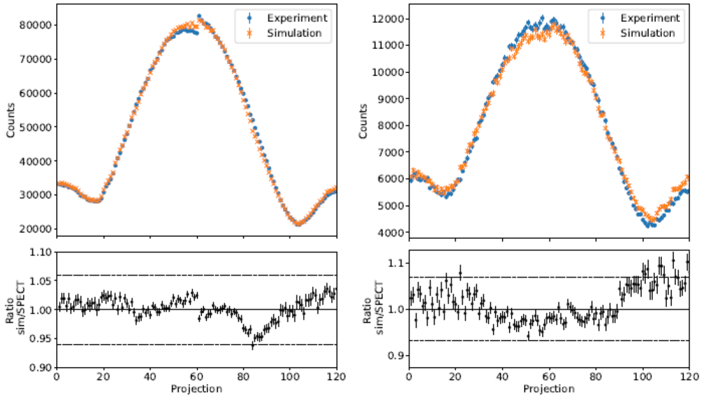


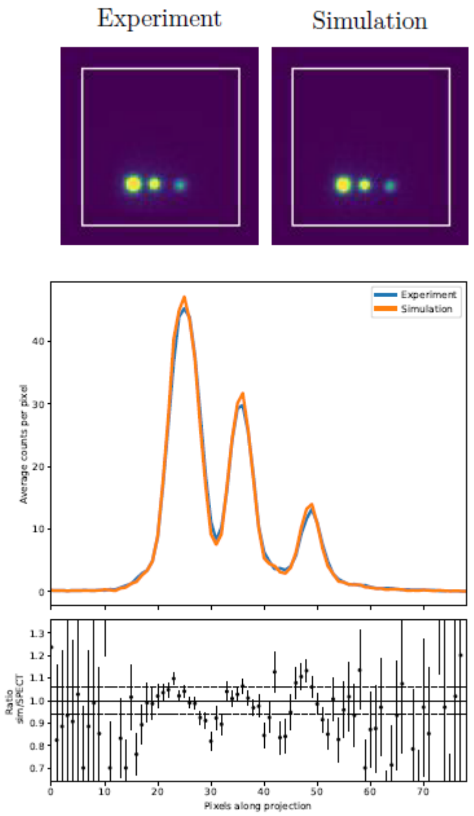
Figure 6: A comparison of the total simulated energy spectrum and the total spectrum extracted from the SPECT images for the cylindrical phantom of ^{99m}Tc, plotted with 2 keV bins. The bottom plot shows the percentage residuals with standard uncertainties and the 3σ bounds of the uncertainty on the efficiency correction shown as dashed lines. The emission (EM) and scatter (SC) windows are shaded.



(a) EM

(b) SC

Figure 7: The counts per projection in the emission (EM) and scatter (SC) window of the simulated and experimental images of the NEMA phantom of ^{99m}Tc. The simulation has been normalised using the sensitivity ratio given in Table 5. The bottom plots show the ratio of the simulated and SPECT counts for each projection and the dashed lines show the $\pm 3\sigma$ uncertainty of the sensitivity ratio.



(a) EM

Uncertainties….

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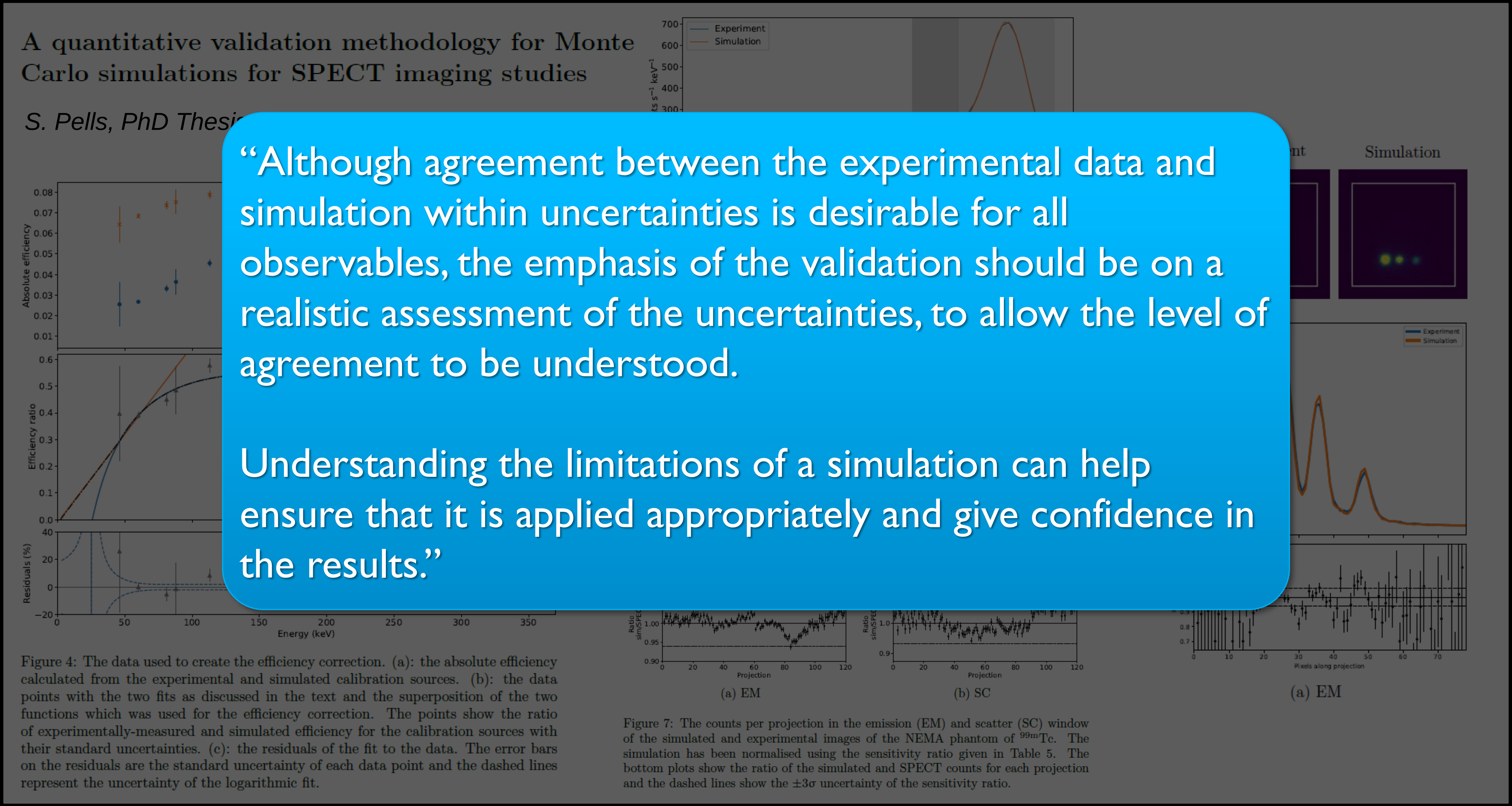

A quantitative validation methodology for Monte Carlo simulations for SPECT imaging studies

S. Pells, PhD Thesis

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(a) EM (b) SC

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(a) EM

"Although agreement between the experimental data and simulation within uncertainties is desirable for all observables, the emphasis of the validation should be on a realistic assessment of the uncertainties, to allow the level of agreement to be understood.

Understanding the limitations of a simulation can help ensure that it is applied appropriately and give confidence in the results."

OpenDose: a collaborative effort to produce reference dosimetric data with Monte Carlo simulations

Aims to provide a free and public resource of robust reference data to enable dosimetry calculations in nuclear medicine, using a variety of Monte Carlo codes through an international collaboration

OpenDose

Challenges

- 2 ICRP 110 reference adult phantoms
  (male and female)
- 140 organs (19600 target/source combinations!)
- ICRP 107: ~1200 radionuclides
- MIRD RADTABS source of decay data: ~300 radionuclides

Too big for a single institution!!!

Proposal

- Collaborative work, everyone is welcome!
- Create a free database
- Create an easily accessible website
- Make data available with associated uncertainties

Courtesy of Dr A. Denis-Bacelar

OpenDose

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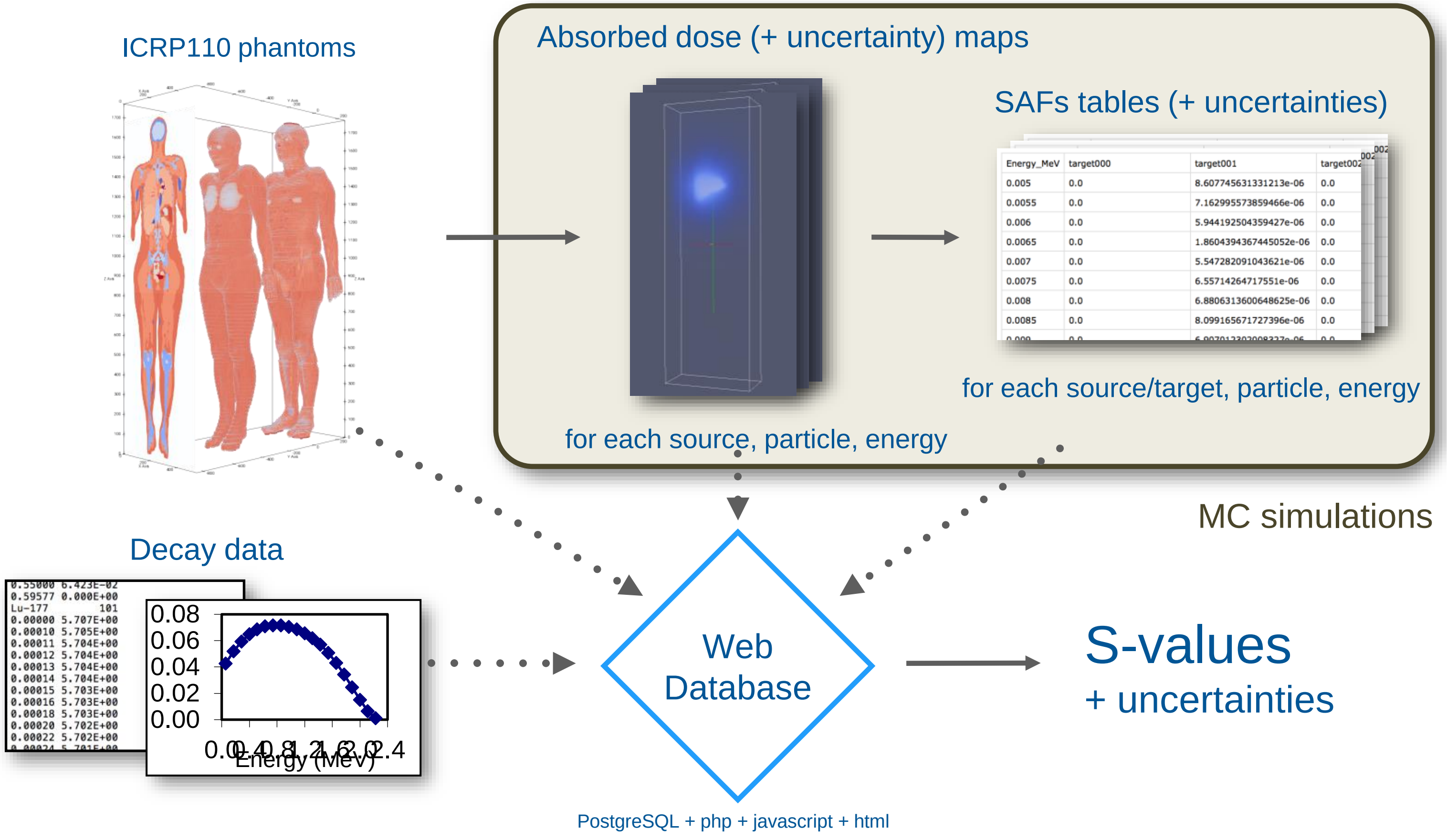
14 research teams (18 institutes)

5 Monte Carlo codes:

Geant4/GATE - FLUKA - PENELOPE - MCNP/MCNPX - EGSnrc/EGS++

Courtesy of Dr A. Denis-Bacelar

OpenDose



Courtesy of Dr A. Denis-Bacelar

OpenDose

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OpenDose: Open-Access Resource for Nuclear Medicine Dosimetry

Maxime Chauvin[1], Damian Borys[2], Francesca Botta[3], Pawel Bzowski[2], Jérémie Dabin[4], Ana M. Denis-Bacelar[5], Aurélie Desbrée[6], Nadia Falzone[7,8], Boon Quan Lee[7,8], Andrea Mairani[9,10], Alessandra Malaroda[11,12], Gilles Mathieu[13], Erin McKay[14], Erick Mora-Ramirez[1,15], Andrew P. Robinson[5,16,17], David Sarrut, Lara Struelens[4], Alex Vergara Gil[1], and Manuel Bardiès[1]

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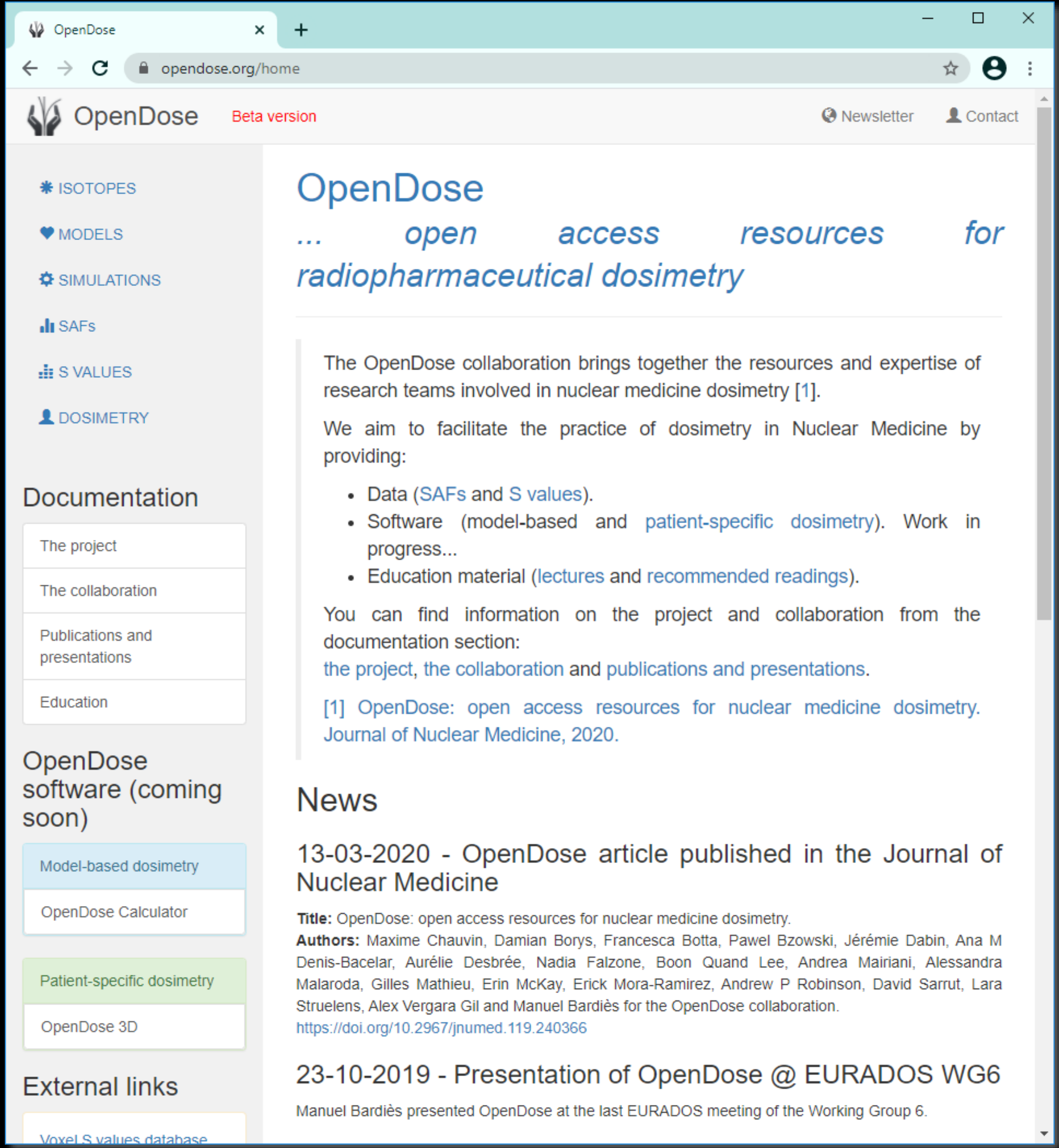

SAF results: Pancreas ← Liver (electrons)

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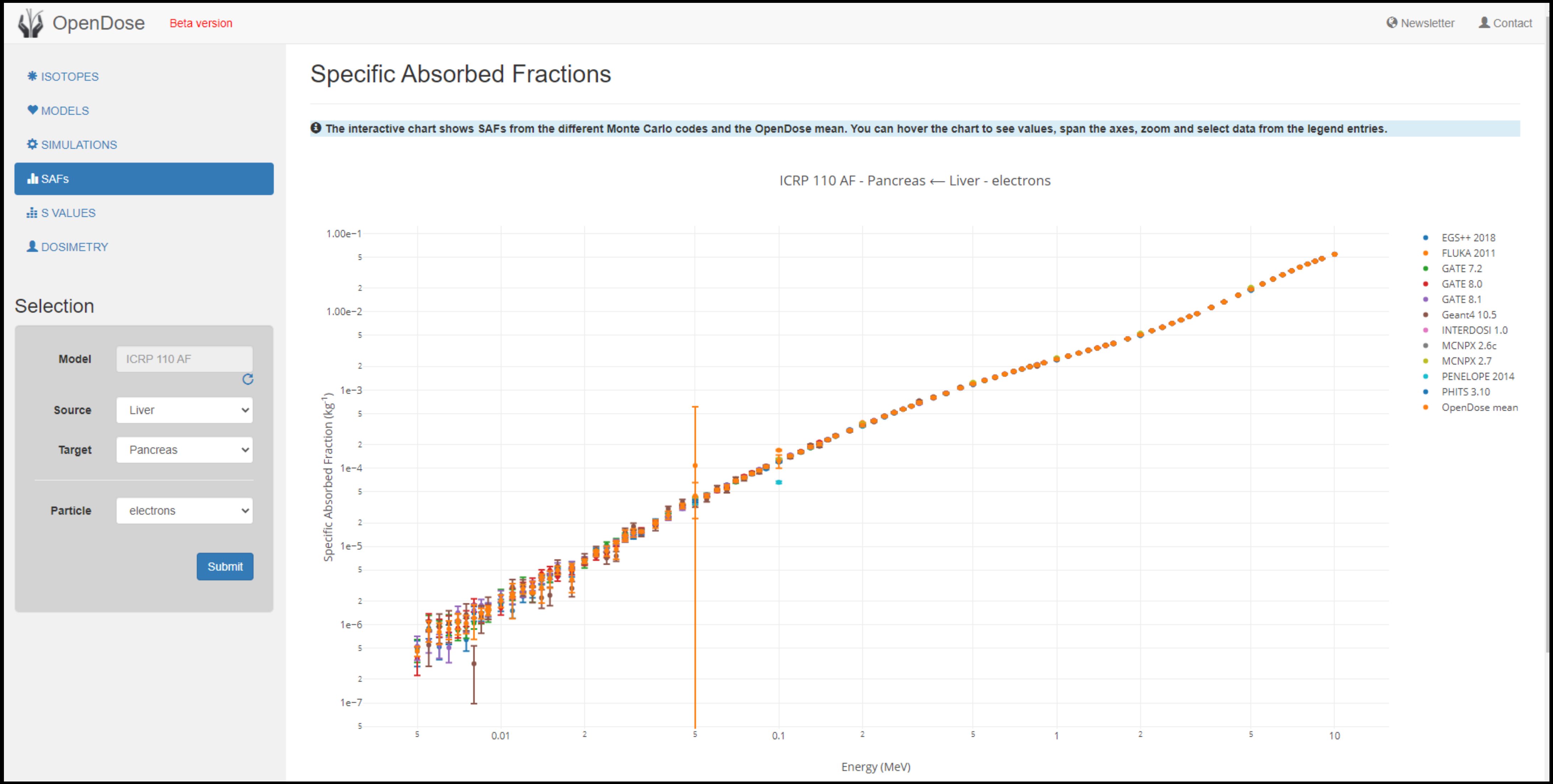

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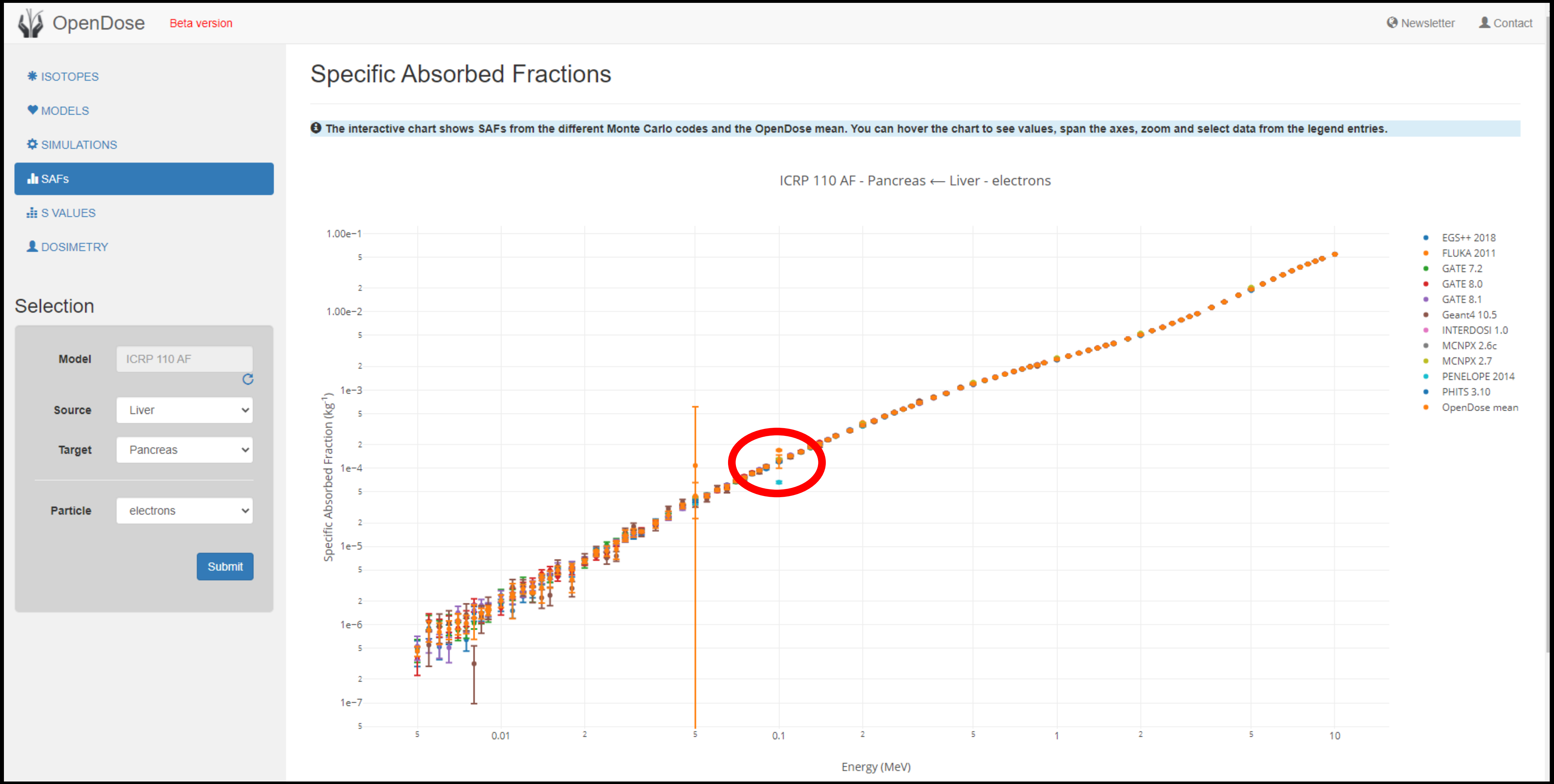
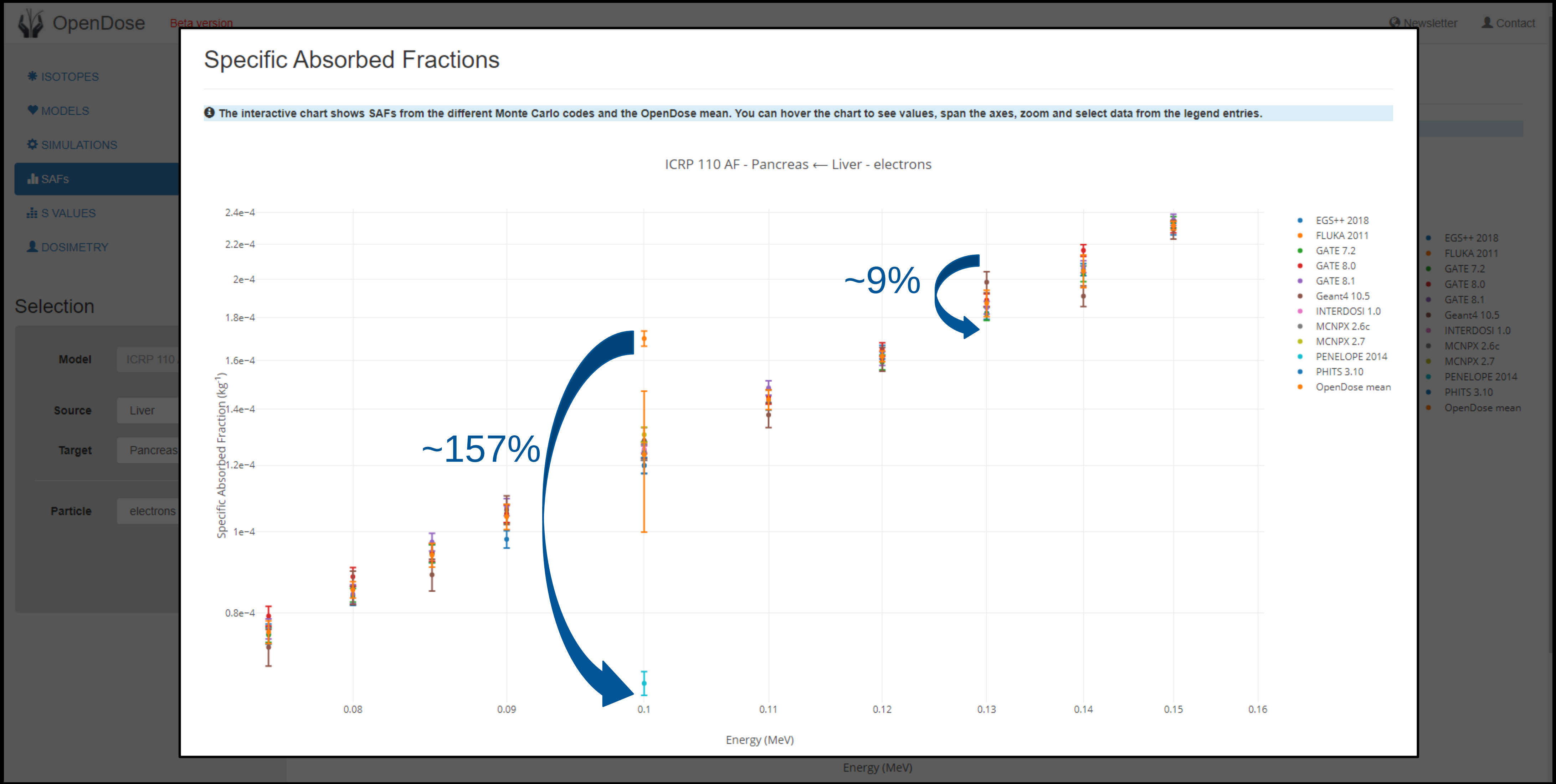
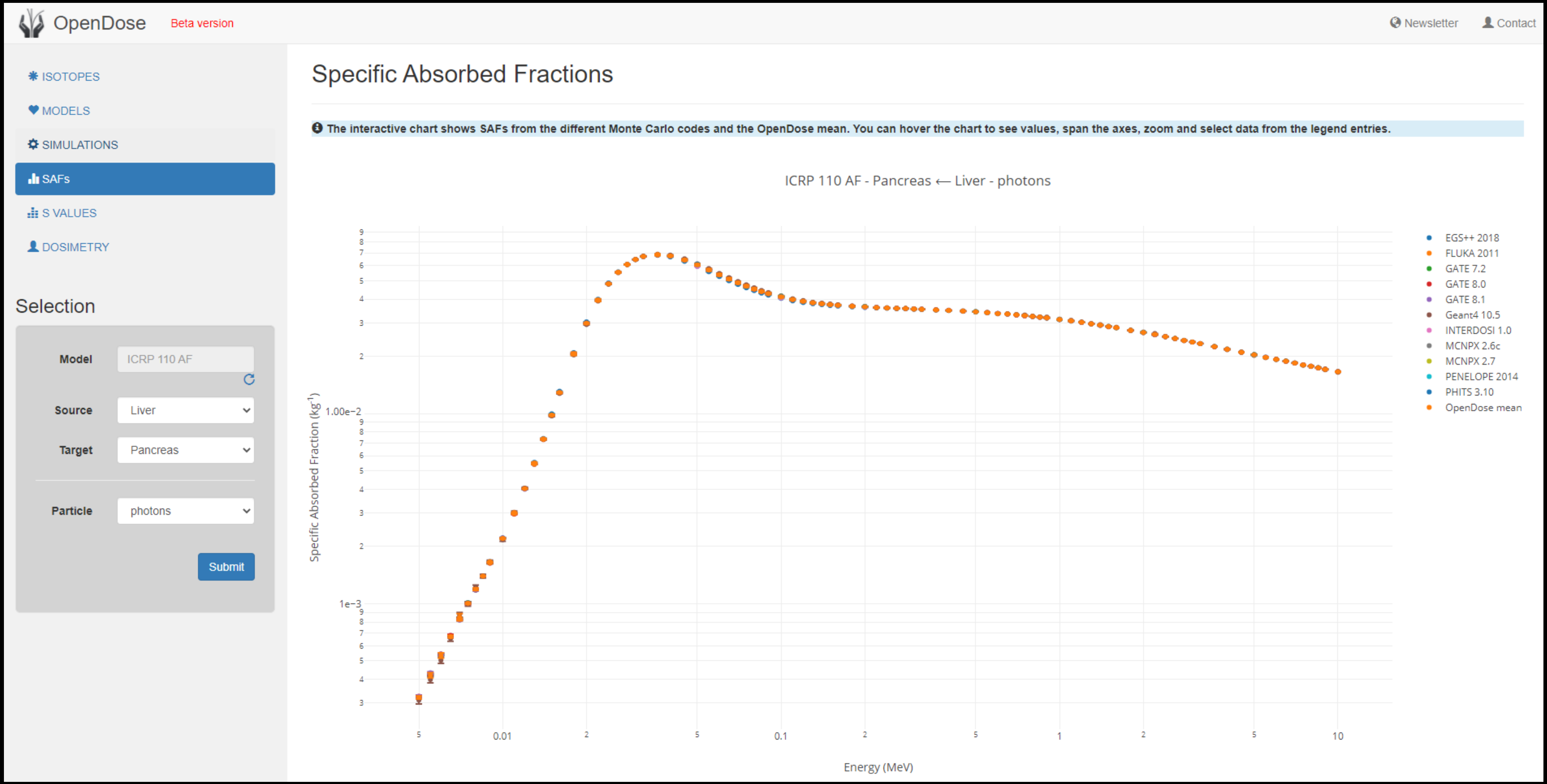


SAF results: Pancreas ← Liver (electrons)



SAF results: Pancreas ← Liver (photons)



SAF results: Pancreas ← Liver (photons)

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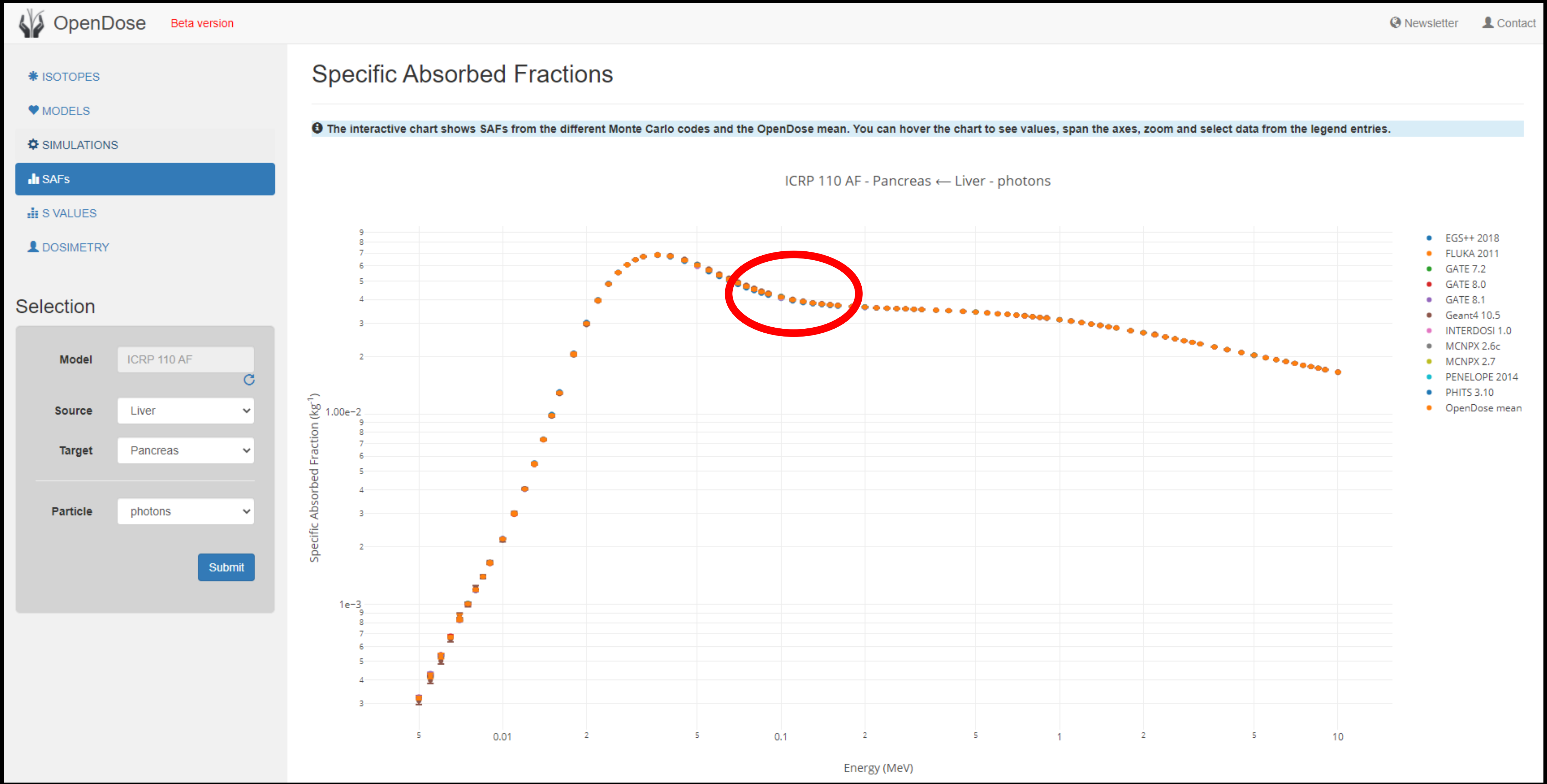
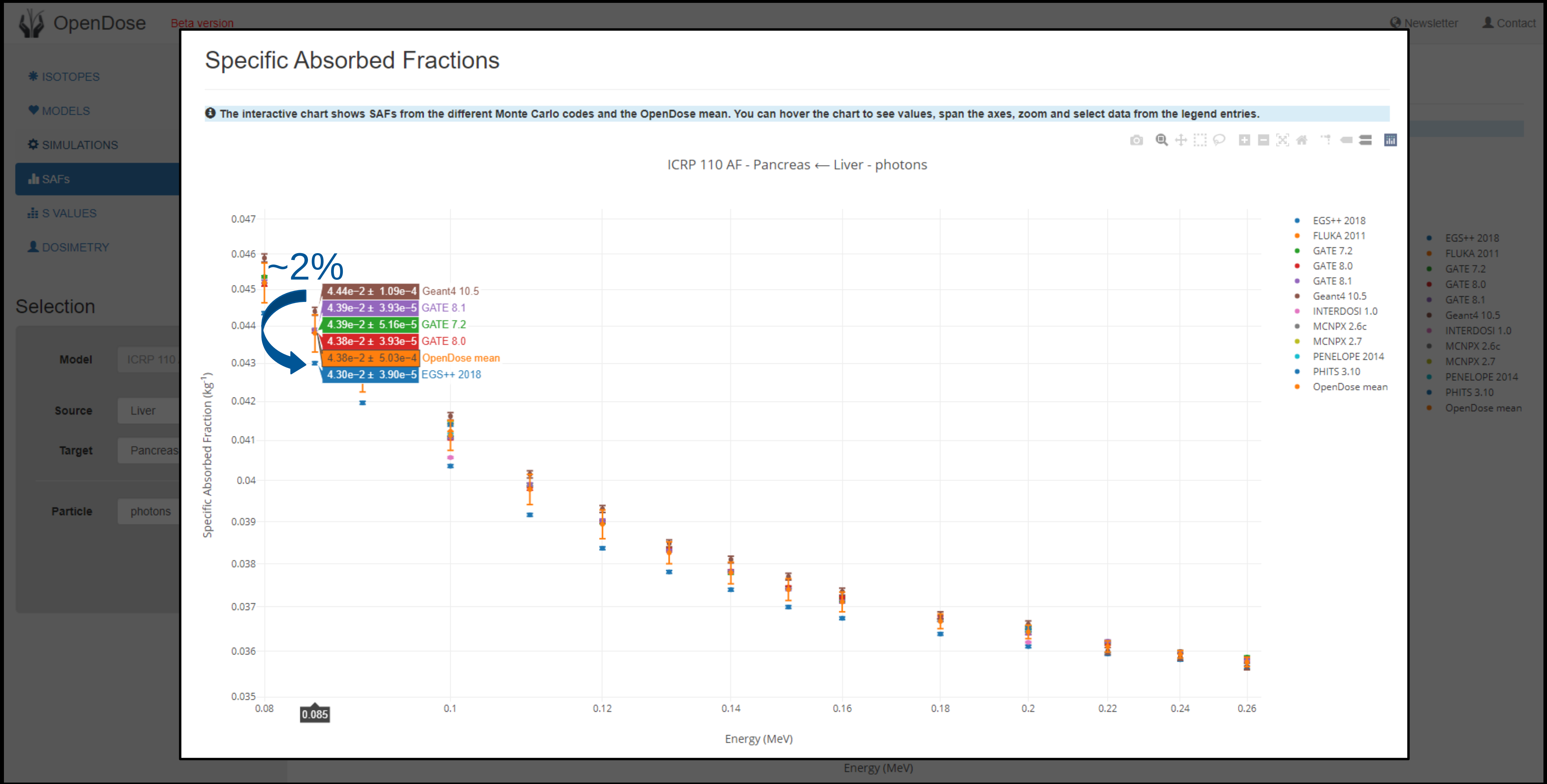


SAF results: Pancreas ← Liver (photons)



Validation of simulations

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- Can you trust the results from a simulation?

- Yes - **if the simulation has been validated**
  - ✓ Geometry
  - ✓ Detector modelling
  - ✓ Physics models (dependent on energy range)
  - ✓ (Nuclear) Data

Comparison with experimental data

- What is Monte Carlo simulation?
- Why use it for medical imaging?
- Examples (demos)
- Validation of simulations
- Tools you can use
- Q & A

Tools you can use

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EGSnrc (https://nrc-cnrc.github.io/EGSnrc/)

What is EGSnrc? | EGSnrc

nrc-cnrc.github.io/EGSnrc/

View on GitHub

EGSnrc

Toolkit for Monte Carlo simulation of ionizing radiation transport

tar.gz .zip

What is EGSnrc?

EGSnrc is a software toolkit to perform Monte Carlo simulation of ionizing radiation transport through matter. It models the propagation of photons, electrons and positrons with kinetic energies between 1 keV and 10 GeV, in homogeneous materials. EGSnrc was originally released in 2000, as a complete overhaul of the Electron Gamma Shower (EGS) software package originally developed at the Stanford Linear Accelerator Center (SLAC) in the 1970s. Most notably, EGSnrc incorporates crucial refinements in charged particle transport, better low energy cross sections, and the egs++ class library to model elaborate geometries and particle sources.

DOI: 10.4224/40001303

Documentation

- **Getting Started** with guided tutorials
- **EGSnrc** core manual (PIRS-701)
- **BEAMnrc** accelerators (PIRS-509a)
- **DOSXYZnrc** voxel dose (PIRS-794)
- **egs++** geometries, sources and applications (PIRS-898)
- **g** application reference manual (PIRS-3100)
- **RZ and SPH apps** user manual (PIRS-702)
- **RZ GUI** egs_inprz (PIRS-801)
- **BEAMDP basic** manual (PIRS-509e)
- **BEAMDP advanced** manual (PIRS-509c)
- **STATDOSE** 3D dose processor (PIRS-509f)

Tools you can use

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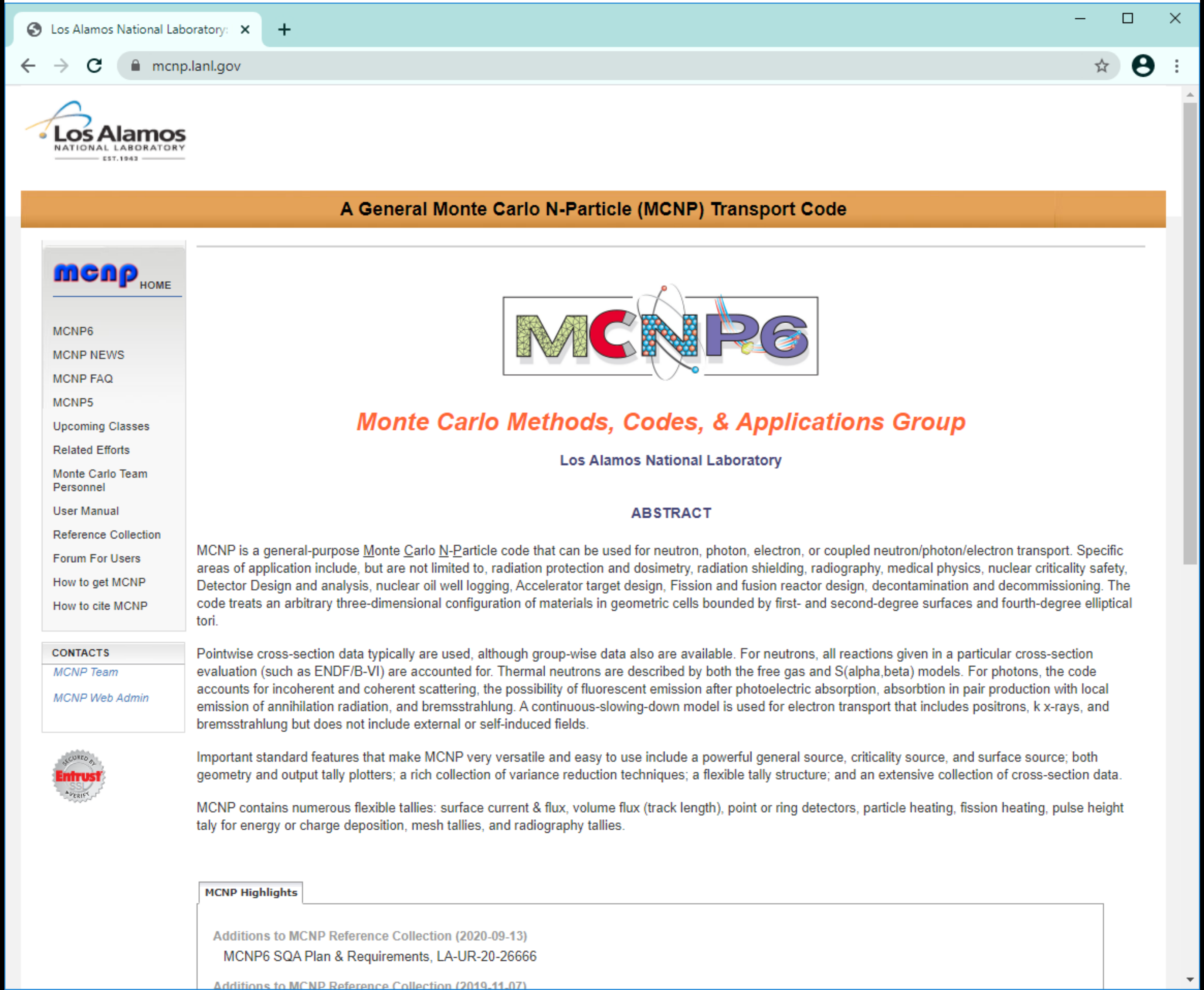
MCNP (https://mcnp.lanl.gov/)



Los Alamos National Laboratory

mcnp.lanl.gov

Los Alamos NATIONAL LABORATORY EST. 1943

A General Monte Carlo N-Particle (MCNP) Transport Code

mcnp HOME

- MCNP6
- MCNP NEWS
- MCNP FAQ
- MCNP5
- Upcoming Classes
- Related Efforts
- Monte Carlo Team Personnel
- User Manual
- Reference Collection
- Forum For Users
- How to get MCNP
- How to cite MCNP

CONTACTS

MCNP Team

MCNP Web Admin

MCNP6

Monte Carlo Methods, Codes, & Applications Group

Los Alamos National Laboratory

ABSTRACT

MCNP is a general-purpose Monte Carlo N-Particle code that can be used for neutron, photon, electron, or coupled neutron/photon/electron transport. Specific areas of application include, but are not limited to, radiation protection and dosimetry, radiation shielding, radiography, medical physics, nuclear criticality safety, Detector Design and analysis, nuclear oil well logging, Accelerator target design, Fission and fusion reactor design, decontamination and decommissioning. The code treats an arbitrary three-dimensional configuration of materials in geometric cells bounded by first- and second-degree surfaces and fourth-degree elliptical tori.

Pointwise cross-section data typically are used, although group-wise data also are available. For neutrons, all reactions given in a particular cross-section evaluation (such as ENDF/B-VI) are accounted for. Thermal neutrons are described by both the free gas and S(alpha,beta) models. For photons, the code accounts for incoherent and coherent scattering, the possibility of fluorescent emission after photoelectric absorption, absorbtion in pair production with local emission of annihilation radiation, and bremsstrahlung. A continuous-slowing-down model is used for electron transport that includes positrons, k x-rays, and bremsstrahlung but does not include external or self-induced fields.

Important standard features that make MCNP very versatile and easy to use include a powerful general source, criticality source, and surface source; both geometry and output tally plotters; a rich collection of variance reduction techniques; a flexible tally structure; and an extensive collection of cross-section data.

MCNP contains numerous flexible tallies: surface current & flux, volume flux (track length), point or ring detectors, particle heating, fission heating, pulse height taly for energy or charge deposition, mesh tallies, and radiography tallies.

MCNP Highlights

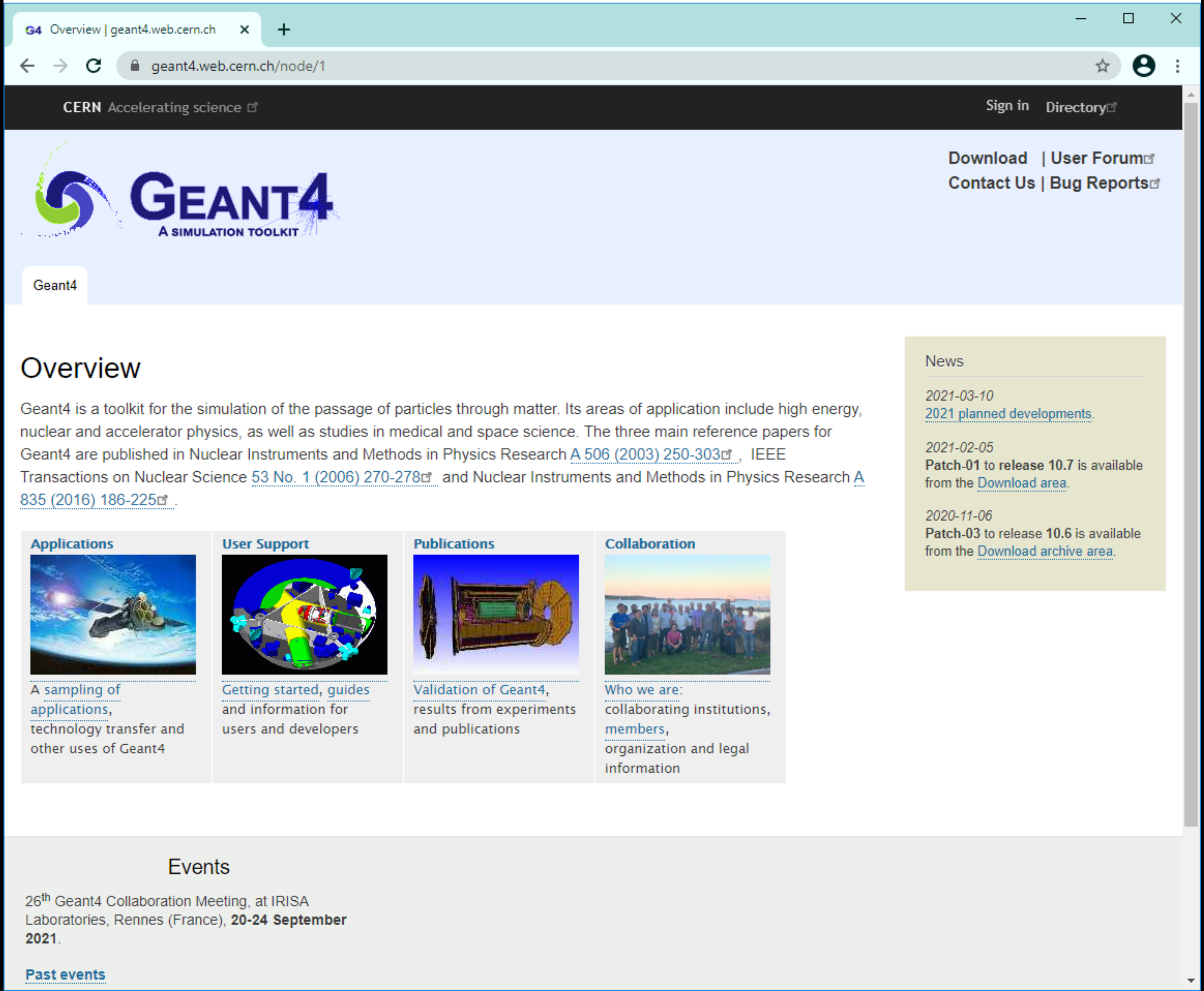
Additions to MCNP Reference Collection (2020-09-13)

MCNP6 SQA Plan & Requirements, LA-UR-20-26666

Additions to MCNP Reference Collection (2019-11-07)

Tools you can use

Geant4 (https://geant4.web.cern.ch/)



Tools you can use

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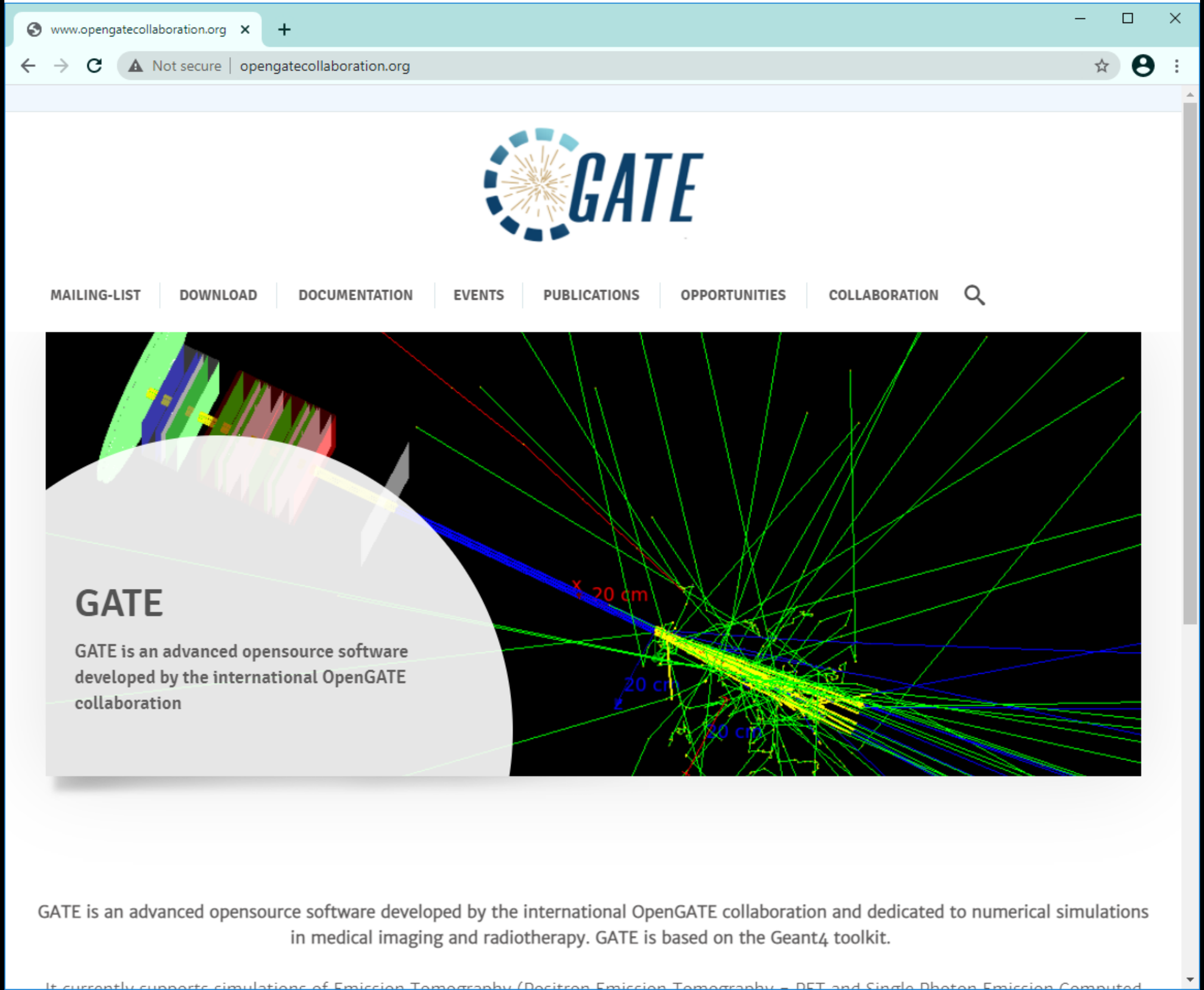
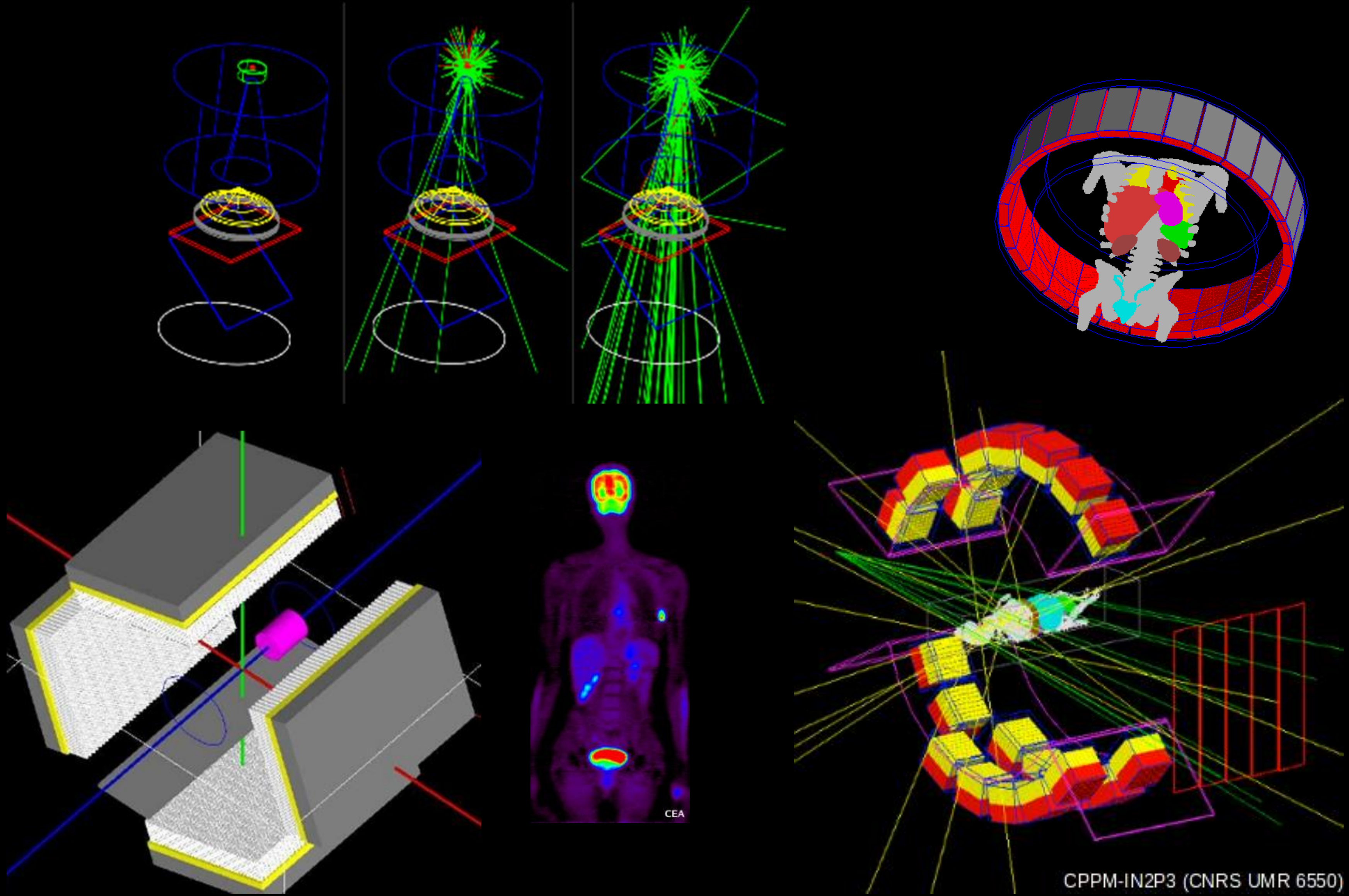
GATE (http://www.opengatecollaboration.org/)



GATE

http://www.opengatecollaboration.org/



GATE

http://www.opengatecollaboration.org/

```
.
├── AddExternalData.sh
├── CMakeLists.txt
├── example_ARF
├── example_CT
├── example_DNA
├── example_doseactor
├── example_dosimetry/
│   ├── brachytherapy
│   ├── electron_radiotherapy
│   ├── external-beam-therapy-photon
│   ├── molecular-therapy-I131
│   └── protontherapy
├── example_fluorescence
├── example_OPTICAL
├── example_PET
├── example_PHANTOM_SOURCE
├── example_PhysicsLists
├── example_Radiotherapy
├── example_ROOT_Analyse
├── example_SPECT
├── example_SPECT_GPU
├── example_TimeActivityCurve
├── example_TrackerDetector
├── example_UserFluenceSource
├── example_UserSpectrum
├── example_vpgtle
└── gpumacros
```

- ✓ Wide variety of examples
- ✓ Multiple modalities
- ✓ Doesn’t require C++
- ✓ Large user base
- ✓ Actively developed
- ✓ Increasingly well referenced

- χ Still requires validation
- χ User developed data analysis tools

Monte Carlo Training

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http://www.opengatecollaboration.org/

TRAININGS

The OpenGATE collaboration in partnership with CNRS Formation Entreprises are proposing two annual trainings organized in France: one dedicated to beginner users and one dedicated to Python data analysis. Those trainings are provided in english, they are open to 20 users maximum with 3 teachers.

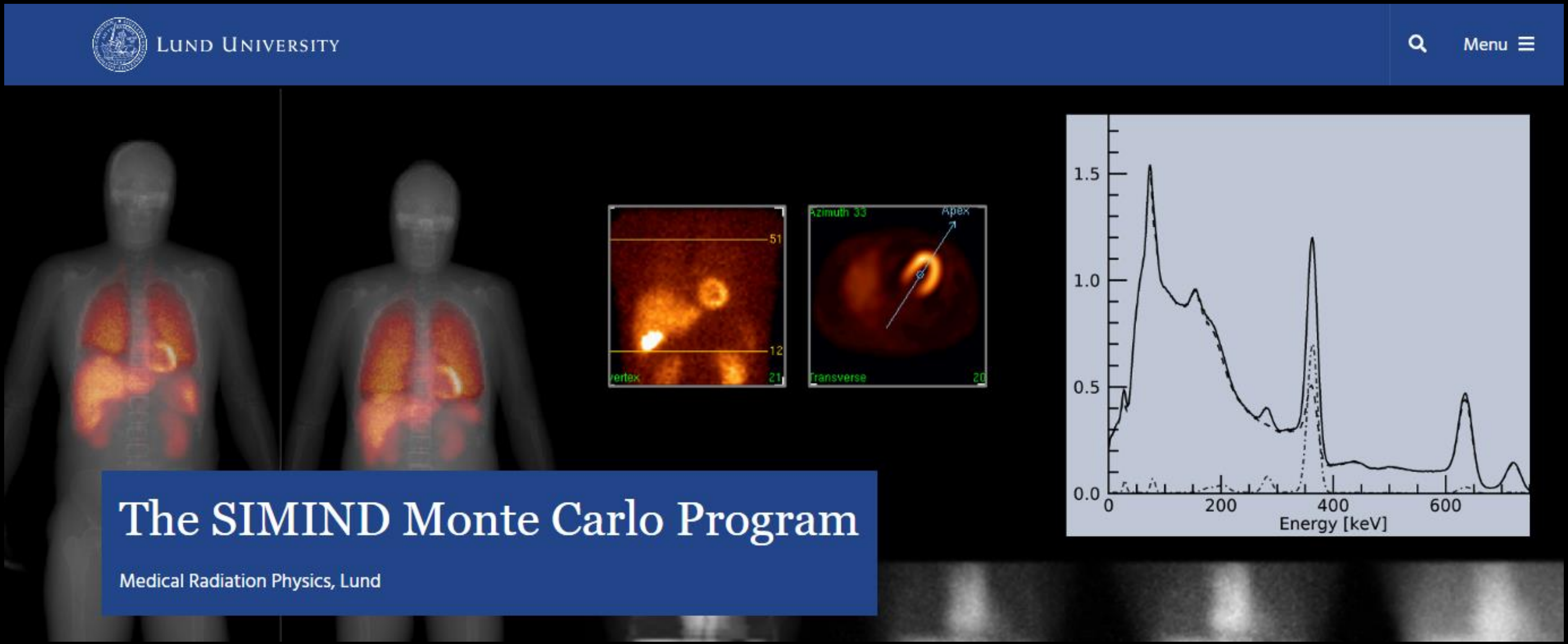
Further, the collaboration can propose special trainings for companies (on site) wishing to use GATE, don't hesitate to contact us for more information.

2022:

- 8-10 March: Python data analysis for GATE simulations, Registration open

SIMIND (SPECT)

https://simind.blogg.lu.se/



MRI?

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http://camino.cs.ucl.ac.uk/

UCL MICROSTRUCTURE IMAGING GROUP

UCL

UCL Camino Diffusion MRI Toolkit

Camino is an open-source software toolkit for diffusion MRI processing. The toolkit implements standard techniques, such as diffusion tensor fitting, mapping fractional anisotropy and mean diffusivity, deterministic and probabilistic tractography. It also contains more specialized and cutting-edge techniques, such as Monte-Carlo diffusion simulation, multi-fibre and HARDI reconstruction techniques, multi-fibre PICo, compartment models, and axon density and diameter estimation.

Camino has a modular design to enable construction of processing pipelines that include modules from other software packages. The toolkit is primarily designed for unix platforms and structured to enable simple scripting of processing pipelines for batch processing. Most users use linux, MacOS or a unix emulator like cygwin running under windows. However, the core code is written in Java and thus is simple to call from other platforms and programming environments, such as matlab running under unix or windows.

The microstructure imaging group at UCL lead development and maintenance of the toolkit. The PICSL group at the University of Pennsylvania also contribute heavily, as have Geoff Parker and colleagues at the University of Manchester. Many of the specialist modules arise from the research of the MIG and collaborating groups. However, the toolkit also includes implementations of many other techniques in the literature that we have found useful.

We hope you find Camino useful. We welcome any feedback, contributions or suggestions for additions to the toolkit.

Camino is distributed under the Artistic License 2.0. The full text of the license is here.

If you use Camino in your research, please include the appropriate citations from the citations page.

MRI?

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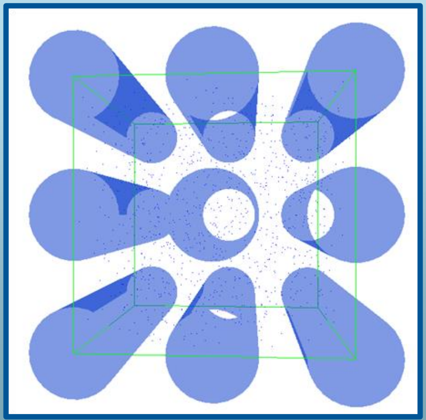
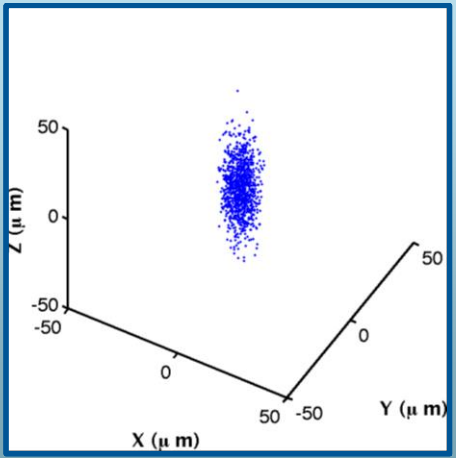
Simulation Pipeline

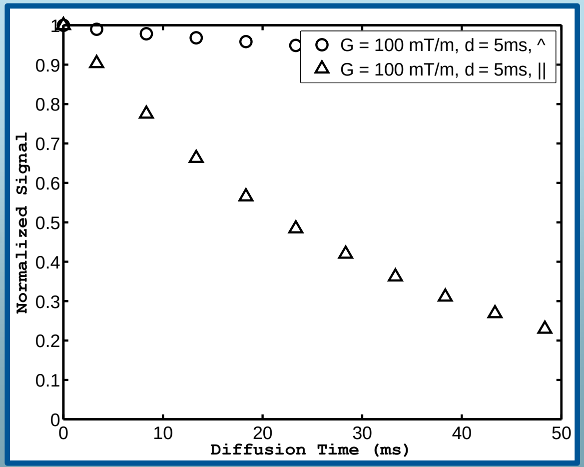
Diffusion Substrate



Displacement PDF



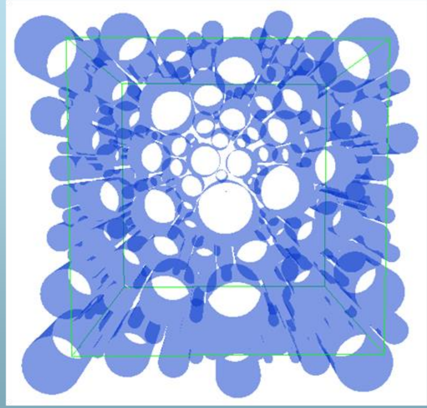
Diffusion MR Signal



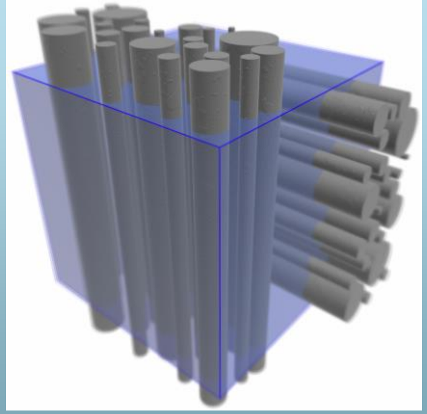
Camino
Simulation and analysis for
Diffusion MRI

Hall and Alexander
IEEE TMI 2009

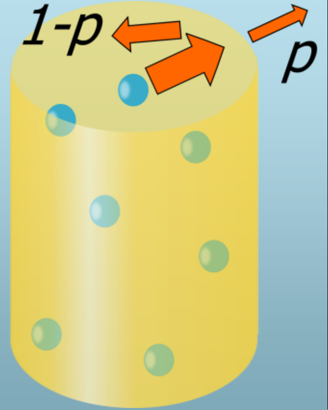
Available Substrates



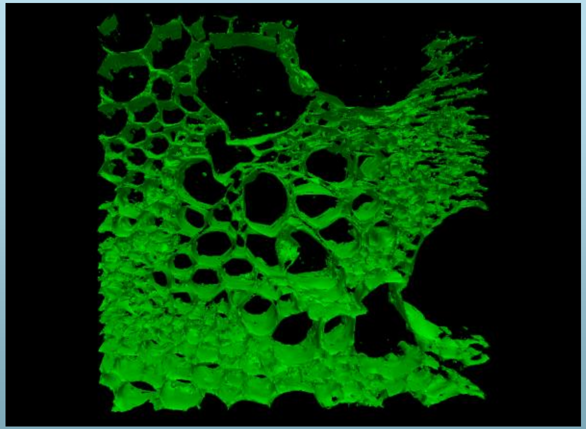
Gamma-Distributed Radii



Crossing Cylinders



Permeable Cylinders



Mesh-based substrates

Summary

- Monte Carlo simulation can be a powerful tool for modelling imaging systems.
- There are a number of benefits to using MC:
  - Extra non-observable information
  - “Ground truth”
  - Optimisation of protocols
- Importance of validation – comparison to experimental data
- A number of packages available
  (GATE is a good starting point for many modalities).

Validation of simulations

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- Can you trust the results from a simulation?

- Yes - **<u>if the simulation has been validated</u>**
  - ✓ Geometry
  - ✓ Detector modelling
  - ✓ Physics models (dependent on energy range)
  - ✓ (Nuclear) Data

<u>Comparison with experimental data</u>

- What is Monte Carlo simulation?
- Why use it for medical imaging?
- Examples (demos)
- Validation of simulations
- Tools you can use
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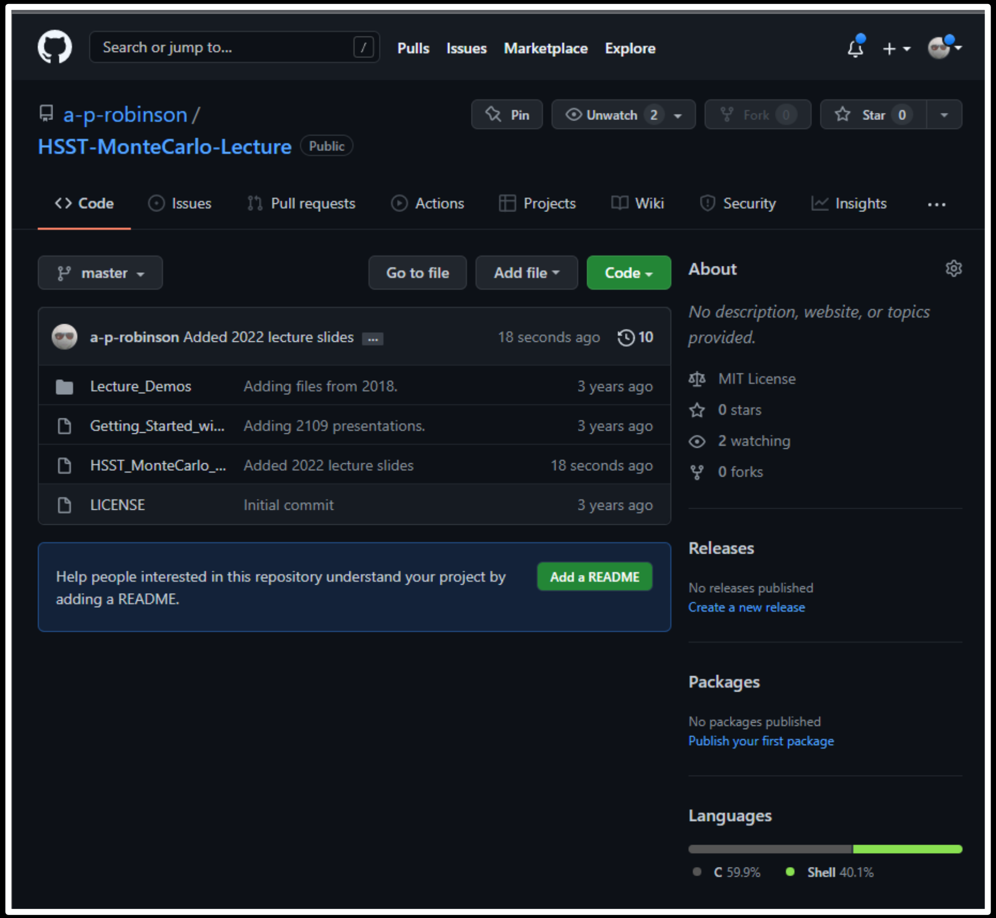
Getting Started with GATE



https://github.com/a-p-robinson/HSST-MonteCarlo-Lecture/

http://www.opengatecollaboration.org/

https://opengate.readthedocs.io/en/latest/

https://gate.uca.fr/download/vgate

https://www.virtualbox.org/

Getting Started with GATE

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Welcome to GATE's documentation!

Navigation

Quick search

Go