Imaging the Invisible:
The Evolution of Germanium Detector Technology and Application

Prof Andy Boston

University of Liverpool

ajboston@liverpool.ac.uk

UNIVERSITY OF LIVERPOOL

Overview of presentation

- **Motivation: Blue sky science**
  - Nuclear Physics – Gamma spectroscopy
  - Neutrino Physics – Double beta decay
- **Imaging Applications**
- **Future technology and direction**

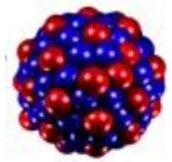
Blue sky science: Nuclear Physics

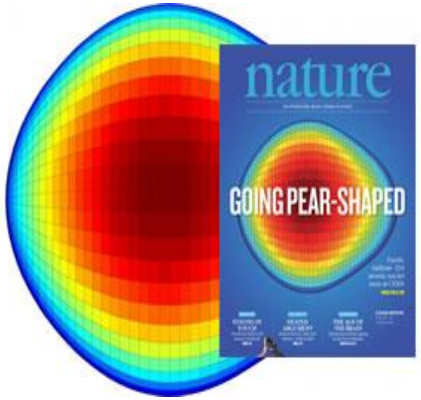
Gamma spectroscopy

Precision spectroscopy of nuclear states

- Gamma-ray (hence level) energies
- Complex level schemes (γ^n coincidences)

(high resolution essential – i.e. Ge)

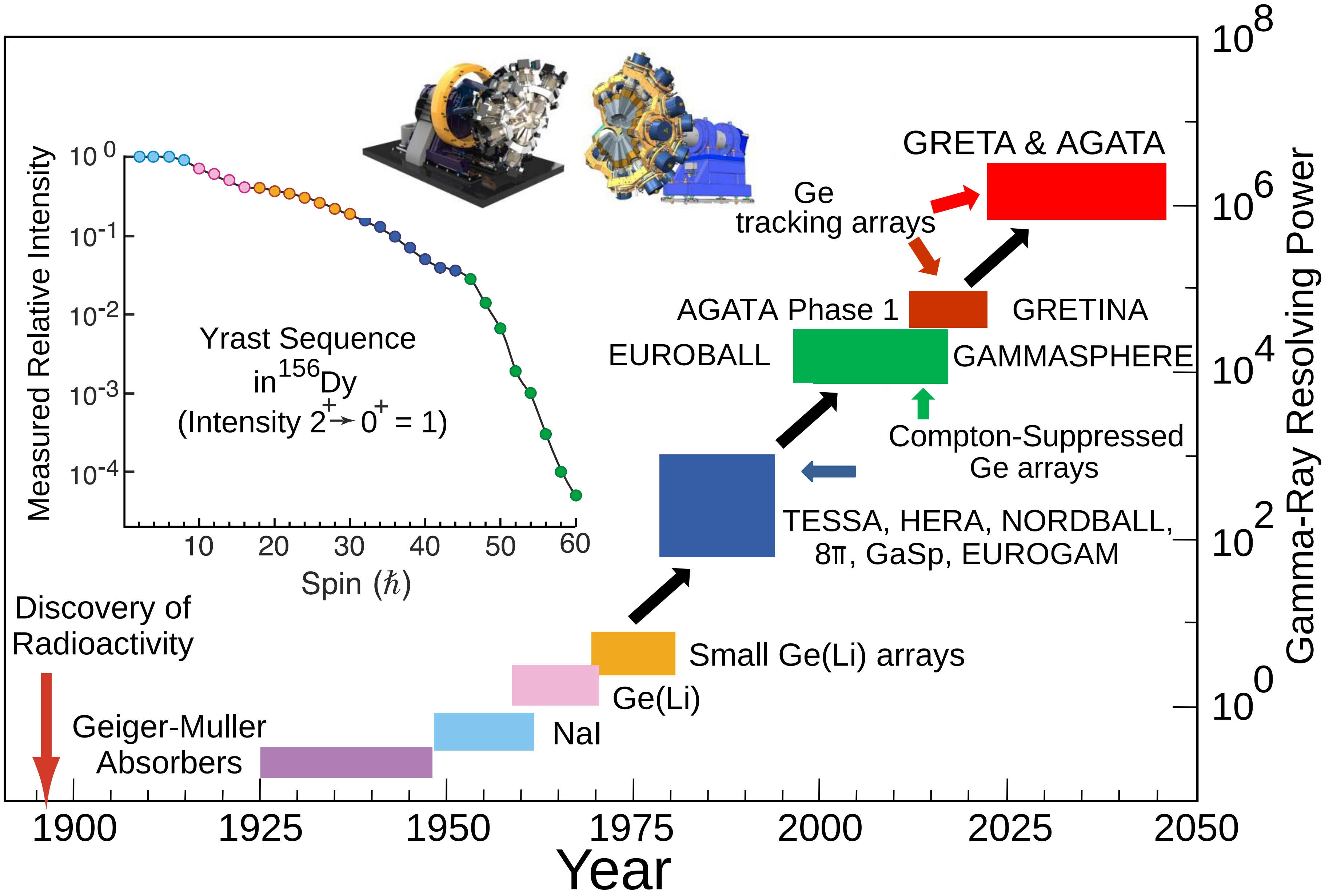




Precision probes of the nuclear wave function:

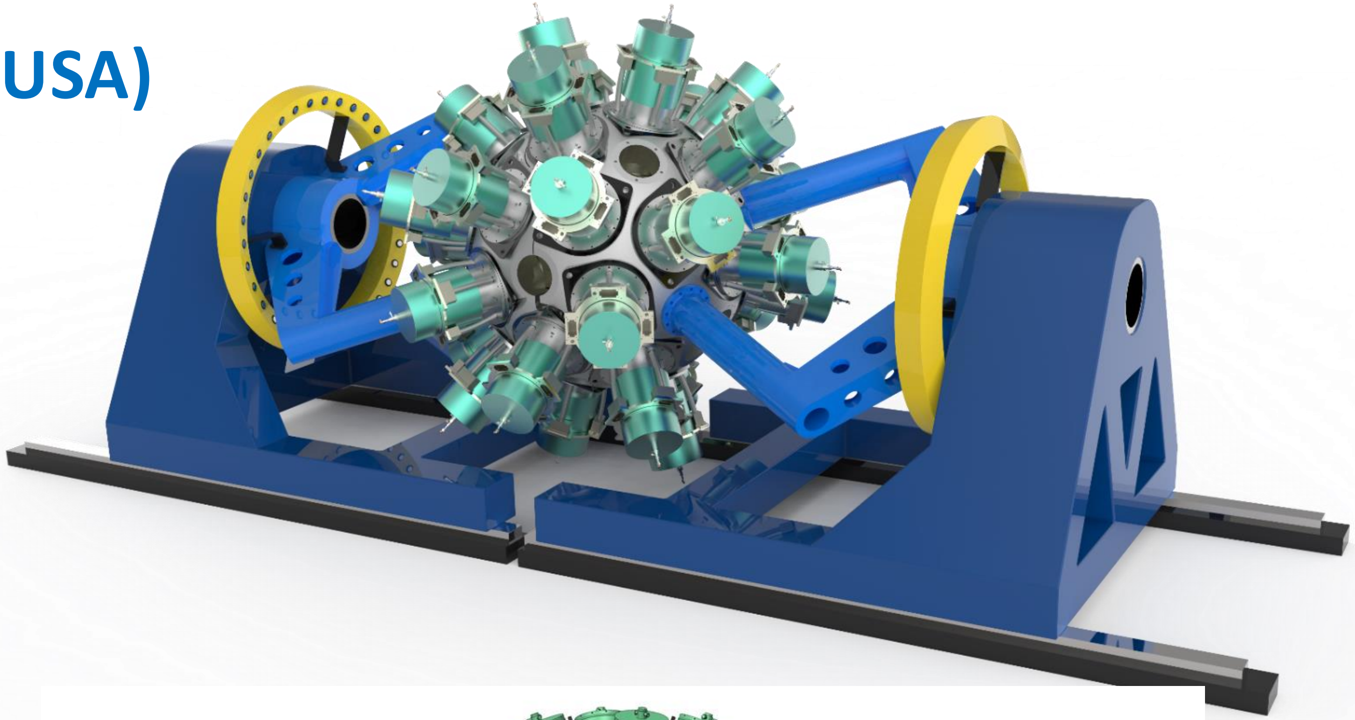
- Lifetimes (transition matrix elements)
- Electromagnetic moments
- Cross-sections for direct reactions

How technology enables the science programme



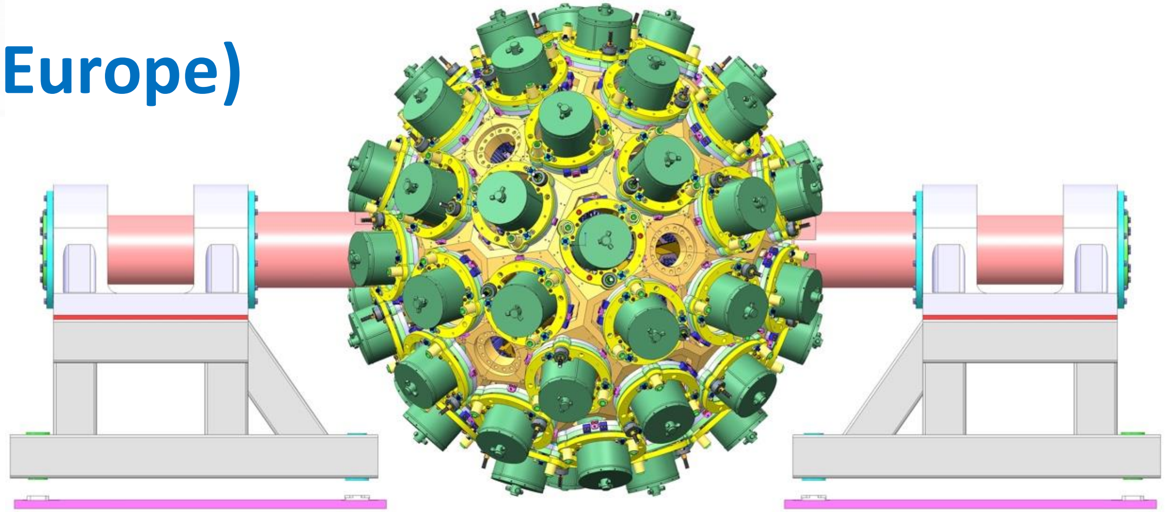
Gamma-Ray Energy Tracking Arrays Worldwide

GRETA (USA)



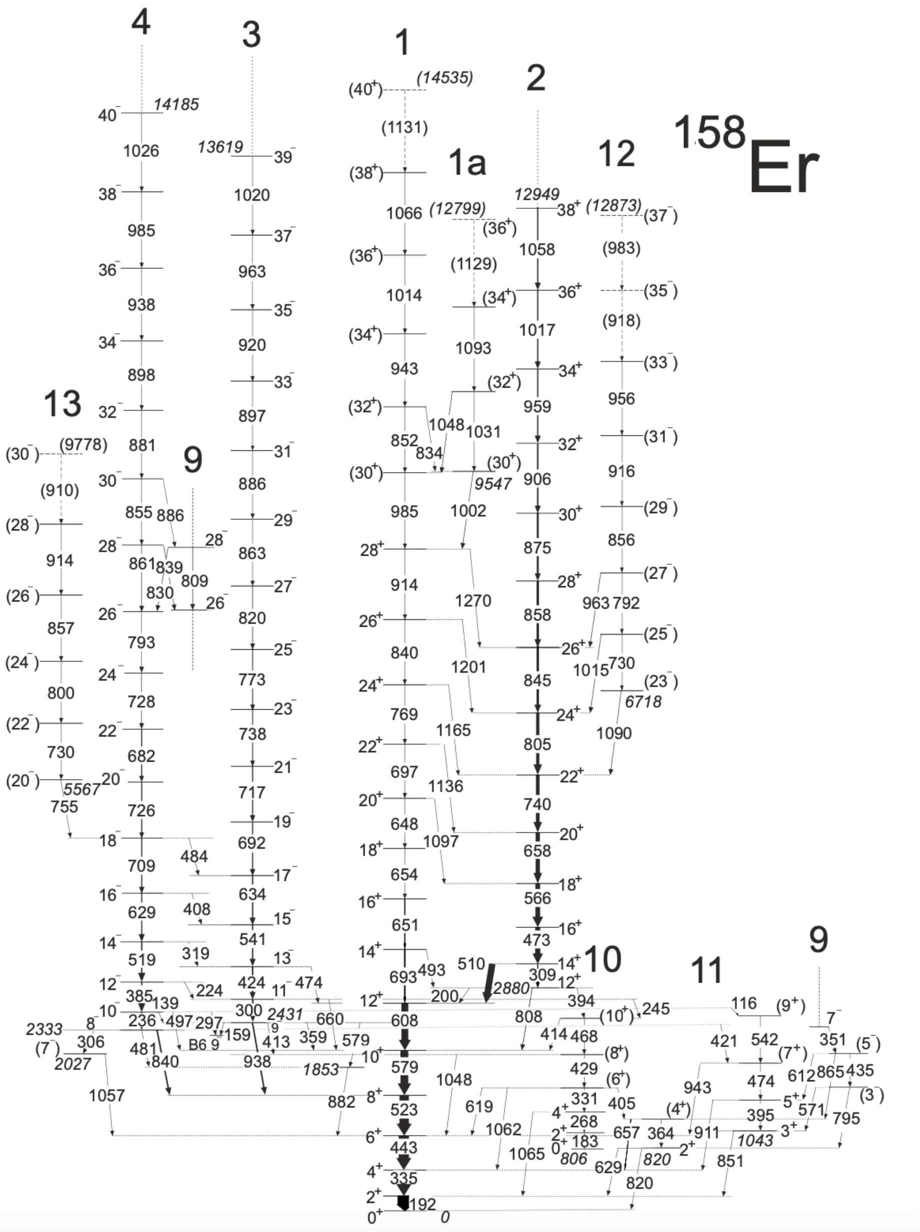
- 120 Ge crystals
- 30 Quad "modules"
- ~17 cm internal diameter

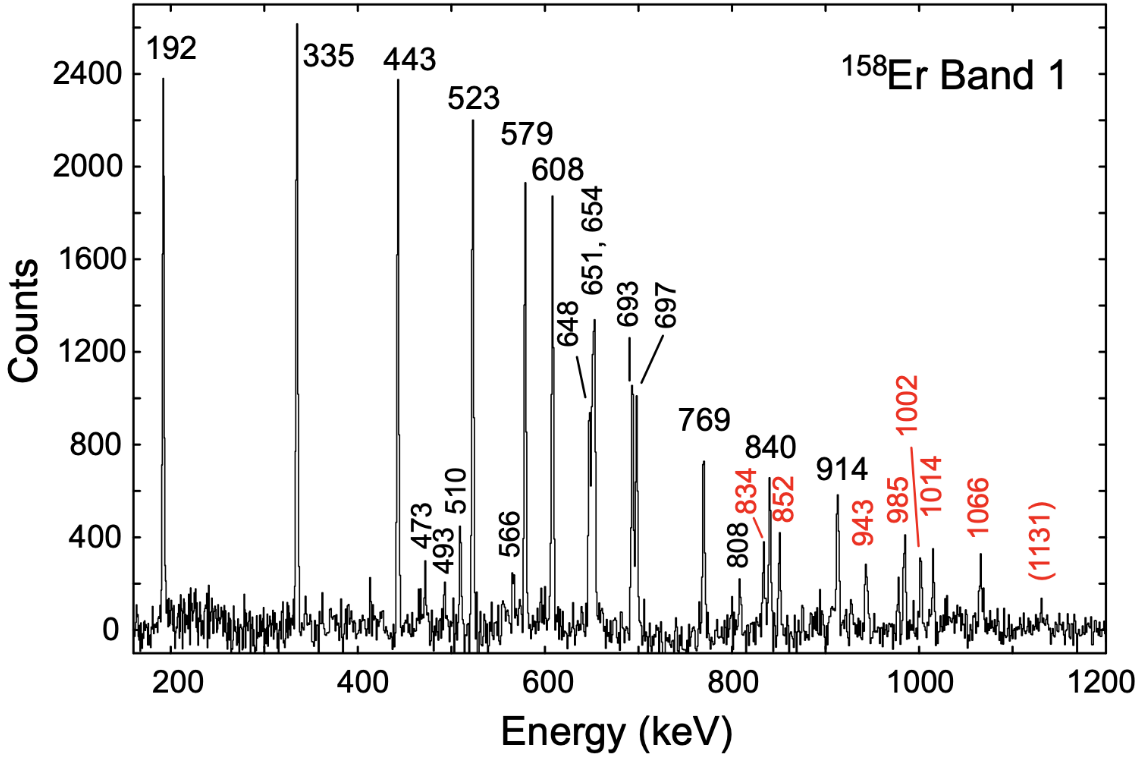
AGATA (Europe)



- 180 Ge crystals
- 60 Triple "clusters"
- ~23 cm internal diameter

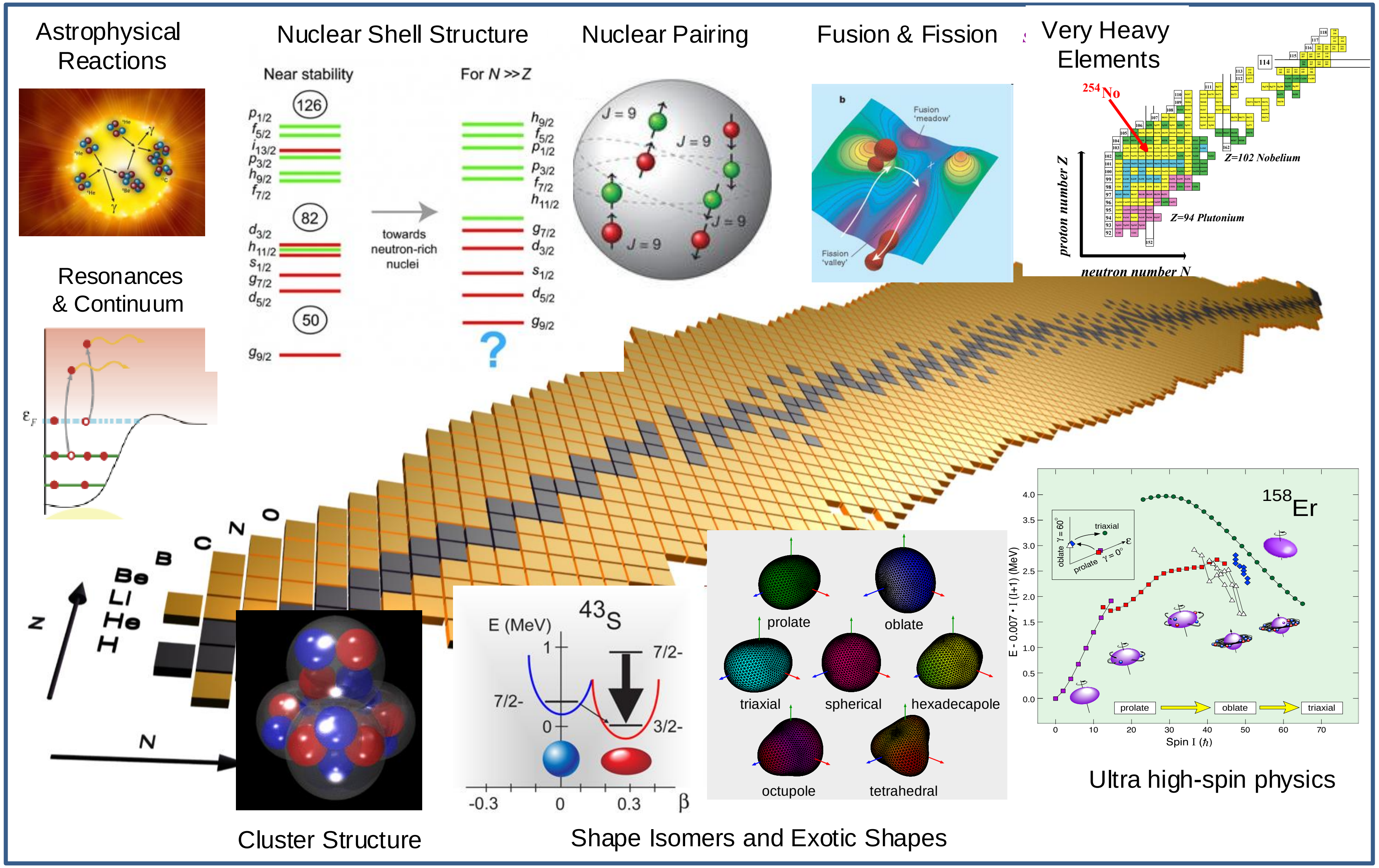
Gamma spectroscopy



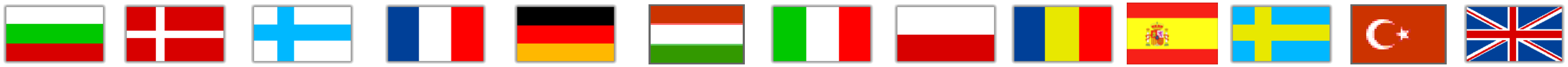


Simpson, Riley *et.al.* PHYSICAL REVIEW C **107**, 054305 (2023)

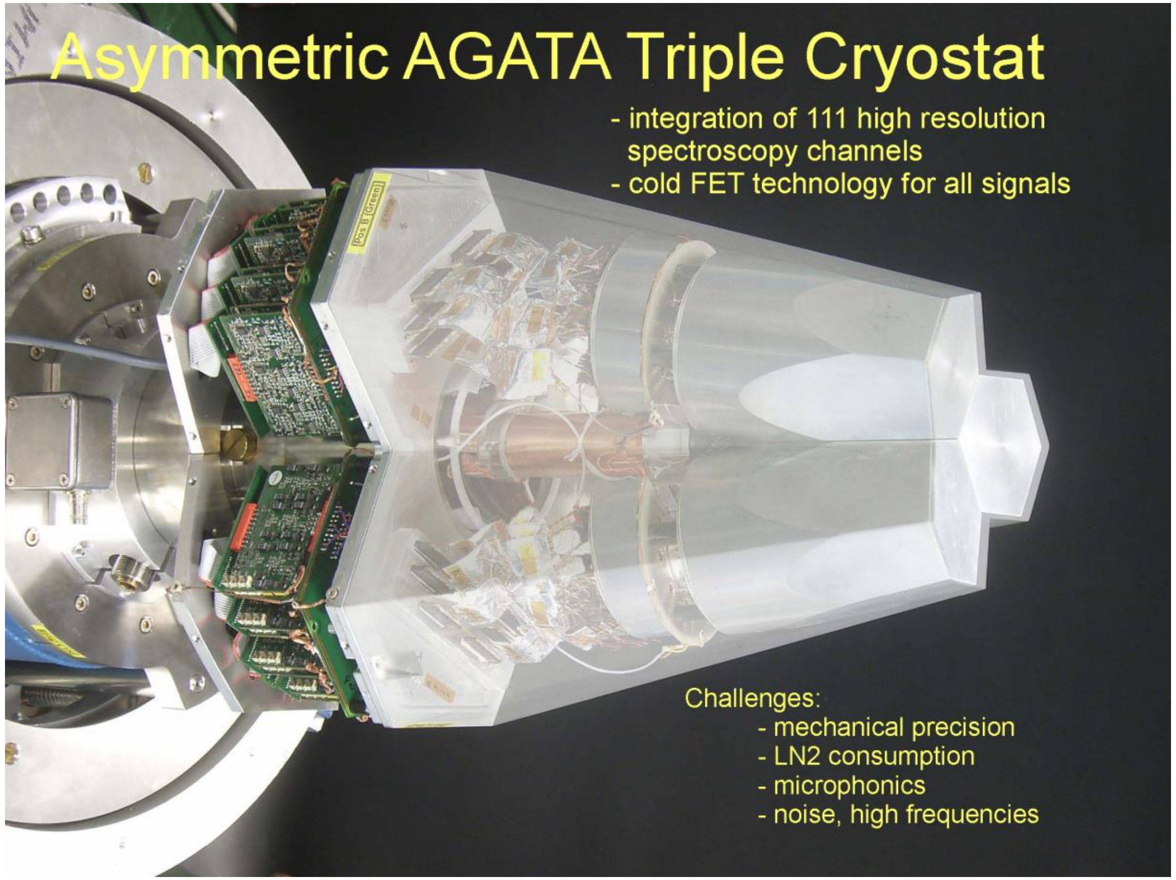
The AGATA science case



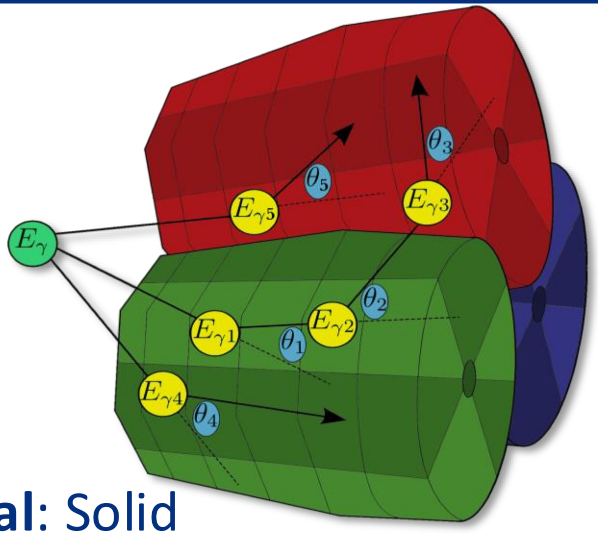
What is AGATA?



13 Countries, >40 Institutions



AGATA Definition: NIM A 668 (2012) 26



- Solid **Sphere of Ge material**: Solid angle coverage ~ 82 %
- 36-fold **segmentation** of crystal
- **Track** each gamma interaction through the crystal
- **Reconstruct** and **disentangle** gammas

180 hexagonal crystals:	3 shapes
3 fold clusters (cold FET):	60 all equal
Inner radius (Ge):	23.5 cm
Amount of germanium:	362 kg
36-fold segmentation	6480 segments

The need for AGATA

The challenge of the new generation of radioactive beam facilities

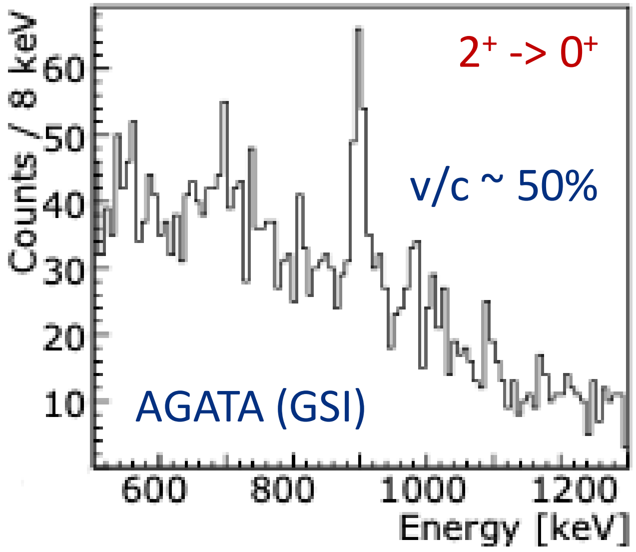
FAIR (Germany)
SPIRAL (France)
SPES (Italy)
HIE-ISOLDE (CERN)

- Low intensity
- High background
- Large Doppler broadening
- High counting rates
- High gamma-ray multiplicities

The ideal γ-ray spectrometer

- High efficiency
- Distinguish gammas from b/g
- Highly position sensitive
- High data throughput
- Can distinguish multiple gammas

Radioactive beam of ^{46}Cr

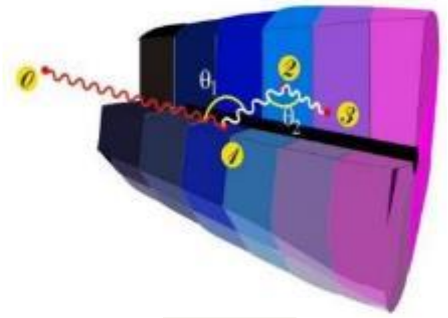


The concept of γ-ray tracking

1

Highly segmented HPGe detectors

γ



2

Digital electronics to record and process signals

3

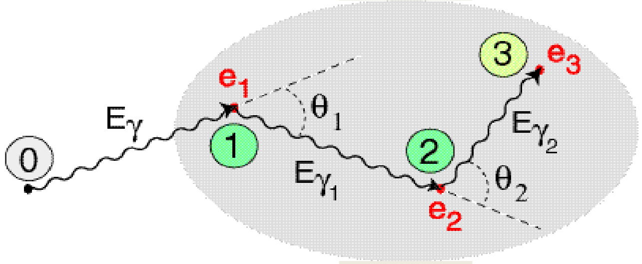
Pulse Shape Analysis to decompose recorded waves

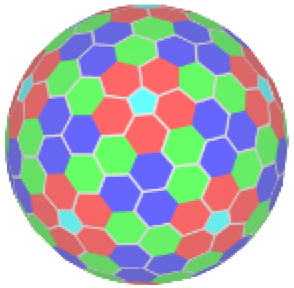
Identified interaction points

$(x,y,z,E,t)_i$

4

Evaluation of permutations of interaction points



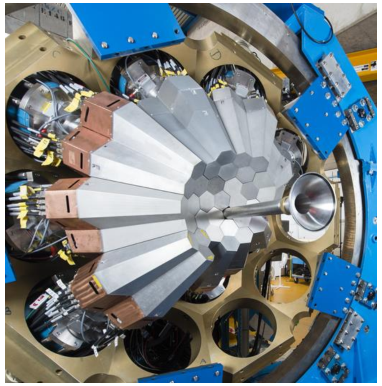


Reconstructed γ rays

AGATA ADVANCED GAMMA TRACKING ARRAY

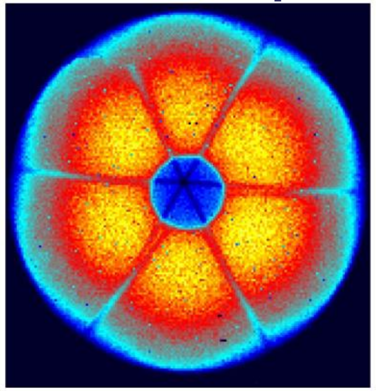
UK AGATA Project (STFC): 2020-24

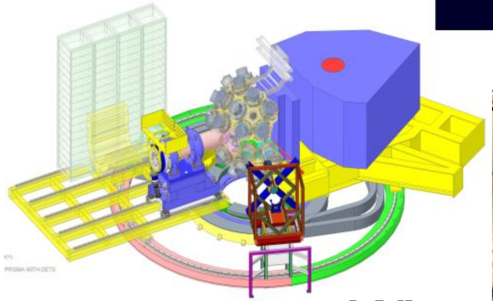
- Next phases of AGATA (SPES and FAIR)
- AGATA triple-cluster modules
- **Detector prototyping and characterisation**
- **Mechanical support structure**
- Electronics and Firmware
- **Pulse-Shape Analysis**
- Simulation

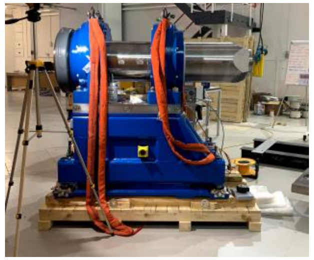


GANIL

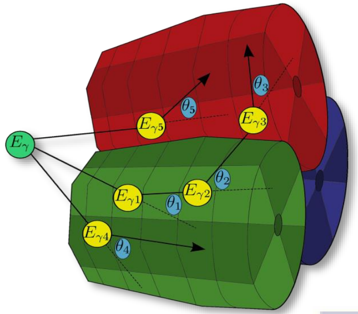
γ-interaction heat map







Support structure at LNL



UNIVERSITY of York

UNIVERSITY OF THE WEST of SCOTLAND UWS

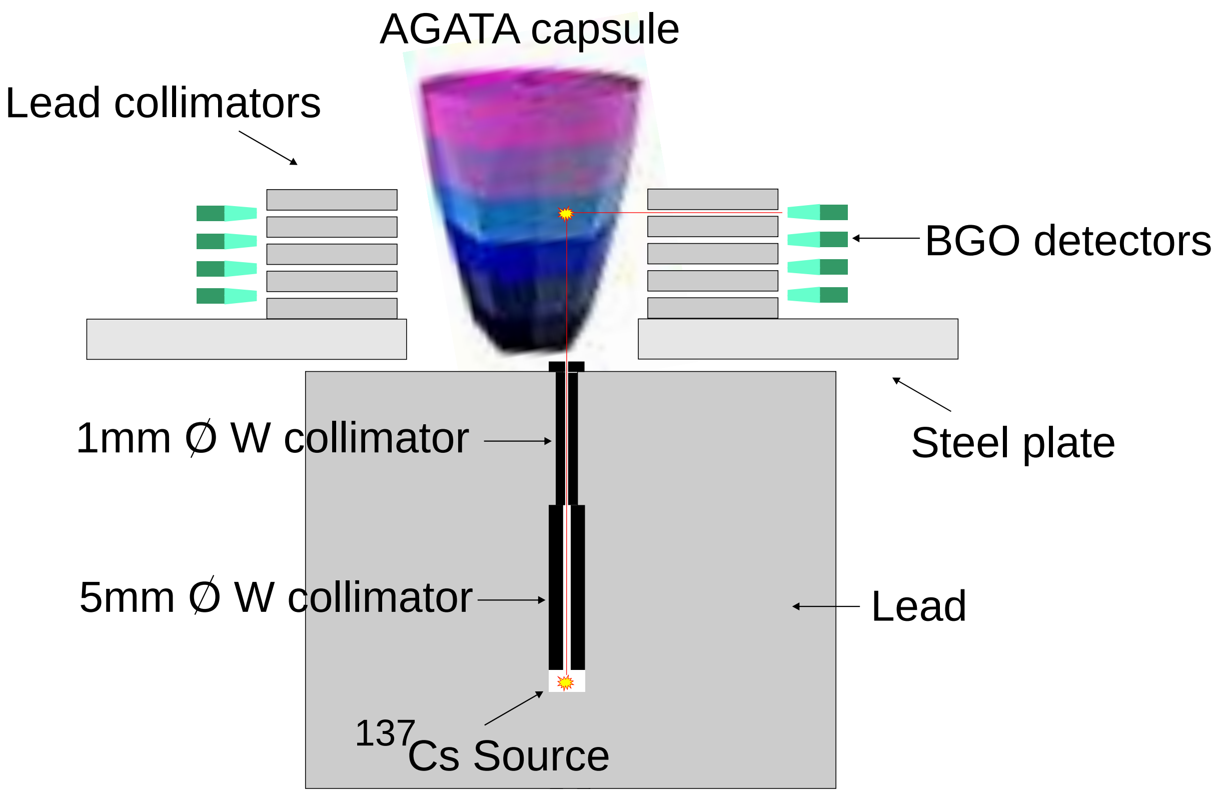
UNIVERSITY OF LIVERPOOL

UKRI Science and Technology Facilities Council

AGATA ADVANCED GAMMA TRACKING ARRAY

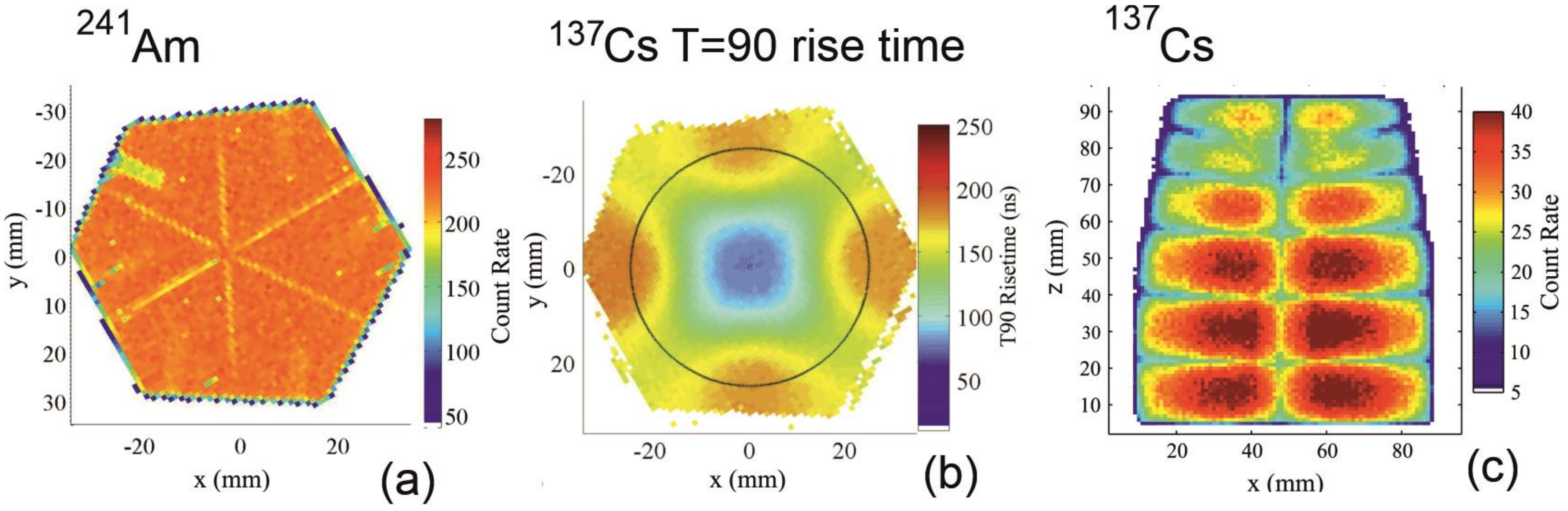
Characterisation Objectives

- **How does the position performance of each AGATA detector vary with:**
  - Crystal shape / effective segmentation
  - Impurity gradient
  - HV
  - Axis orientation
  - Differential cross talk

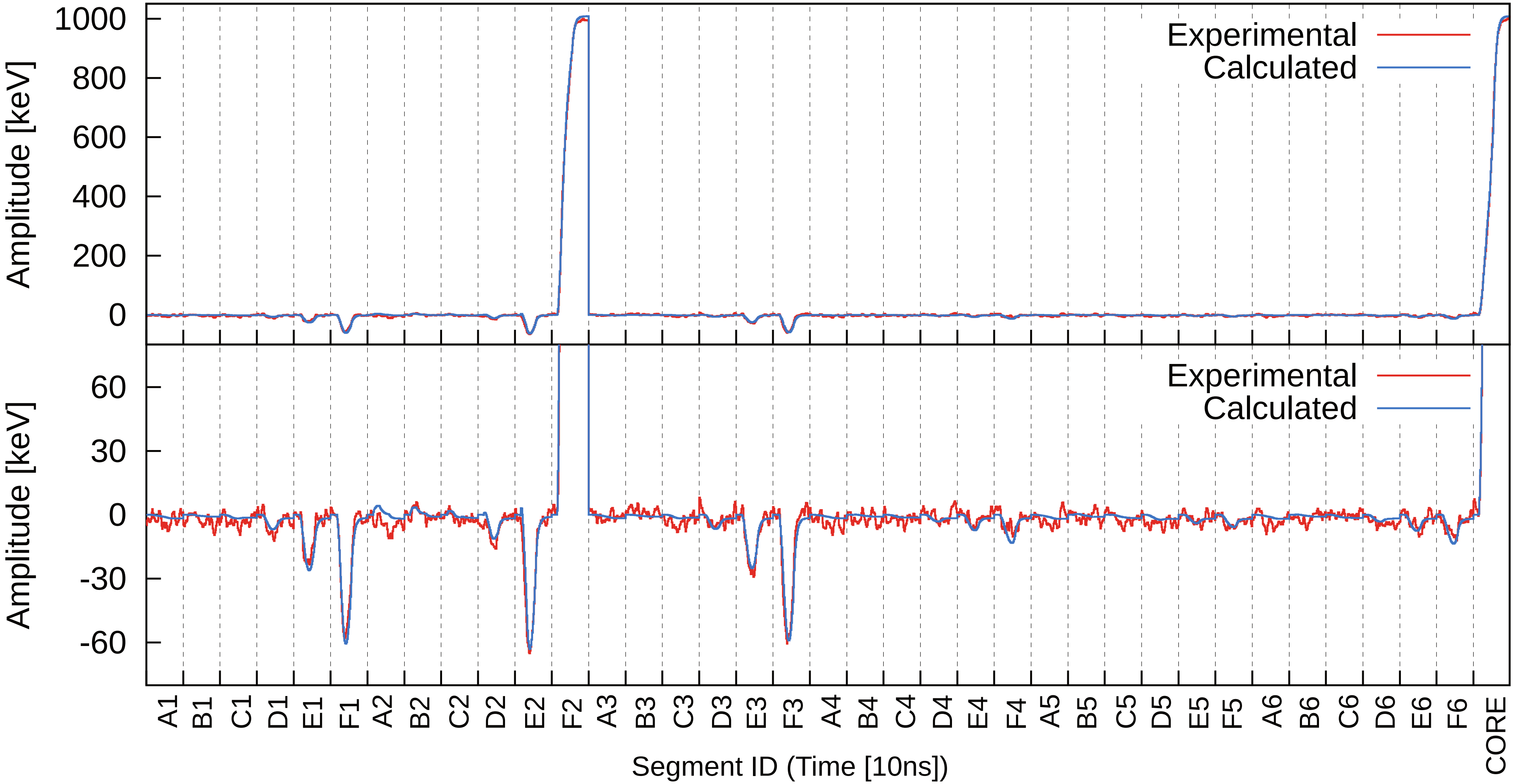


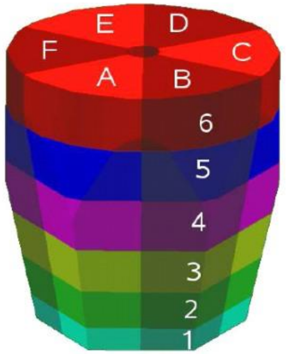
Characterisation Objectives

- **How does the position performance of each AGATA detector vary?**



Challenges in pulse-shape analysis

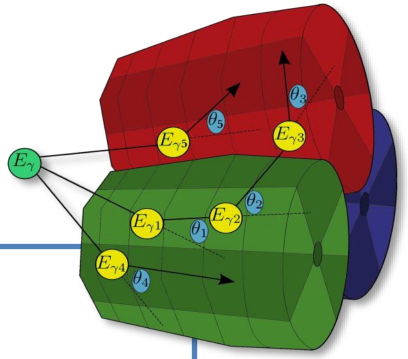




AGATA
ADVANCED GAMMA TRACKING ARRAY

Challenges in pulse-shape analysis

signal basis generation



Experimental (scanning)

- long acquisition times
- experimental conditions change

Analytical (calculated)

- Physics model, Complex Electric fields
- Impurity/n-damage
- electronics response
- temperature etc

Signal matching (grid search)

Grid Search

- Require positions at resolution $\leq$ 5mm
- Dataset is ~ 50,000 points (37x121)
- PSA-grid search needs to be very fast (~ ms)

University of Liverpool:

- Experimental validation of Simulation.
- **Machine Learning** for Advanced Signal Inference
- High resolution simulations of new detectors.
- Novel PSA techniques for **accelerated Grid Search**

AGATA ADVANCED GAMMA TRACKING ARRAY

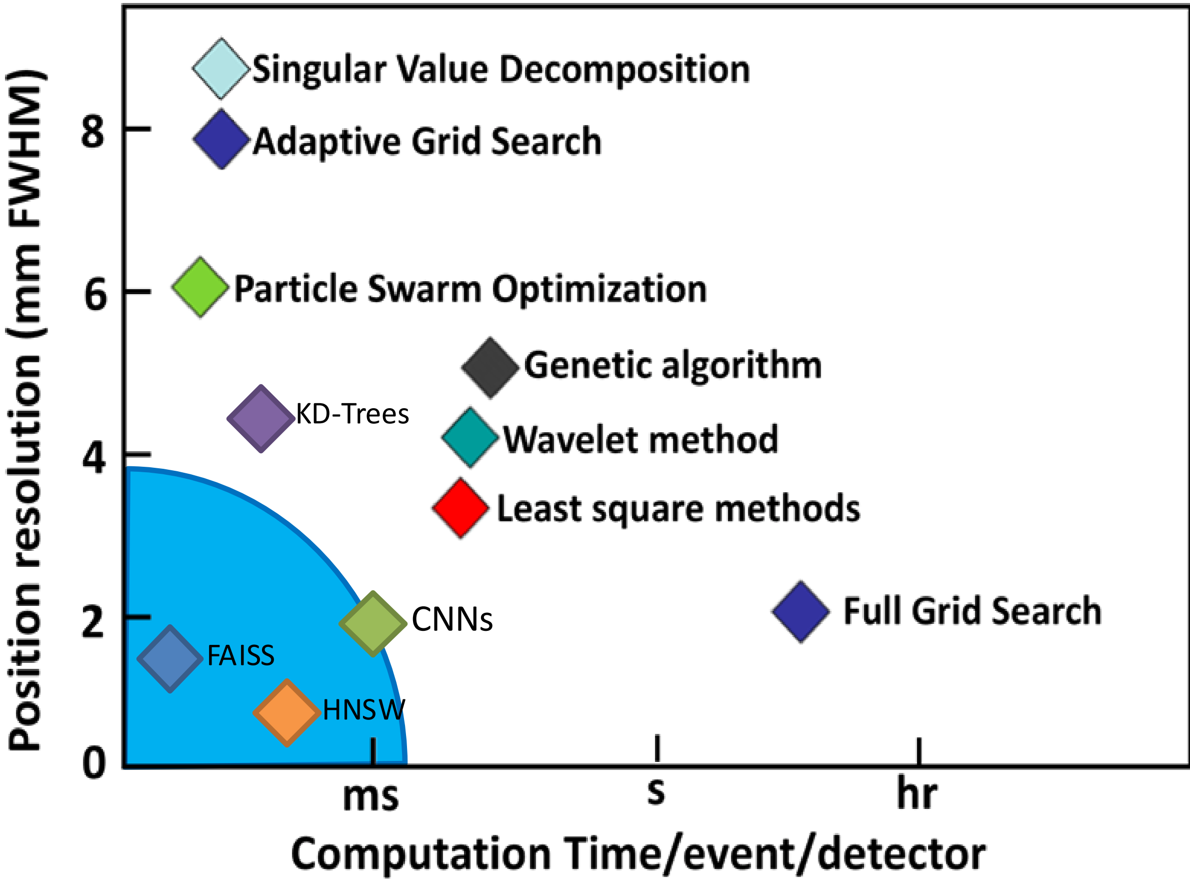
Novel Algorithm Development for PSA

Graph-accelerated techniques try to organize data and form efficient searches

- Search spaces can be Non-Euclidean, Embedded spaces.
- Searching n points can be $\mathcal{O}\log(n)$.
- Processing rates in region (12-400) kHz.

Machine Learning uses a simulated basis to learn trends via inference e.g. Position Regression, Autoencoding & Fold tagging

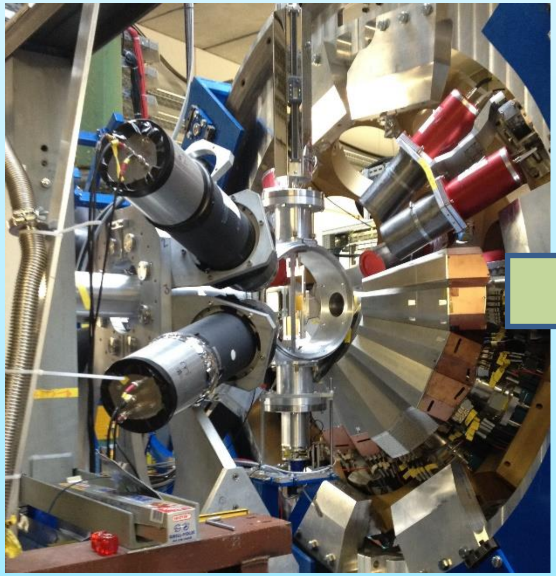
- No searching is performed whatsoever.
- Simulated basis only needed for training.
- Needs an appropriate model & good data.
- Can be used for hyper-efficient signal compression.
- Useful for determining Fold accurately.



Courtesy of **Fraser Holloway**, University of Liverpool
F.Holloway@liverpool.ac.uk

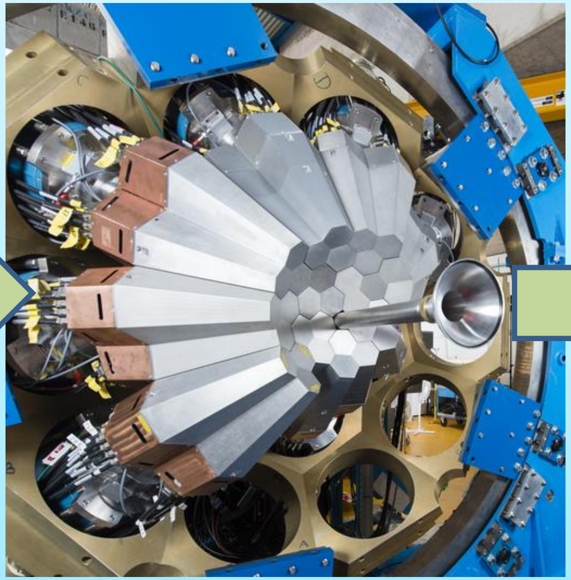
The AGATA journey…

2012-2014
GSI, Germany
~25 detectors



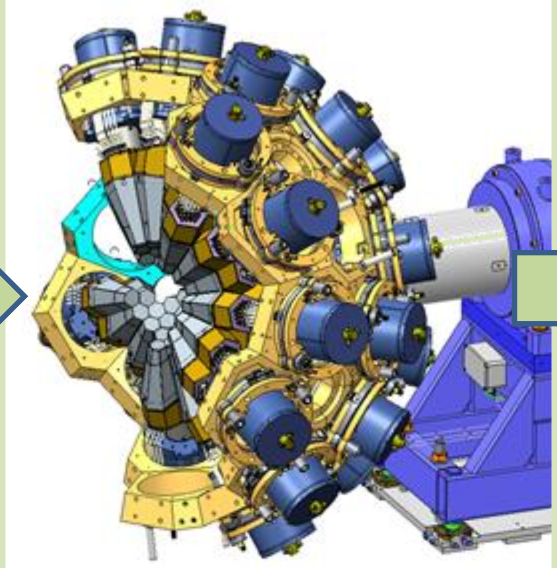
AGATA at GSI

2014-2021
GANIL, France
45 -> detectors



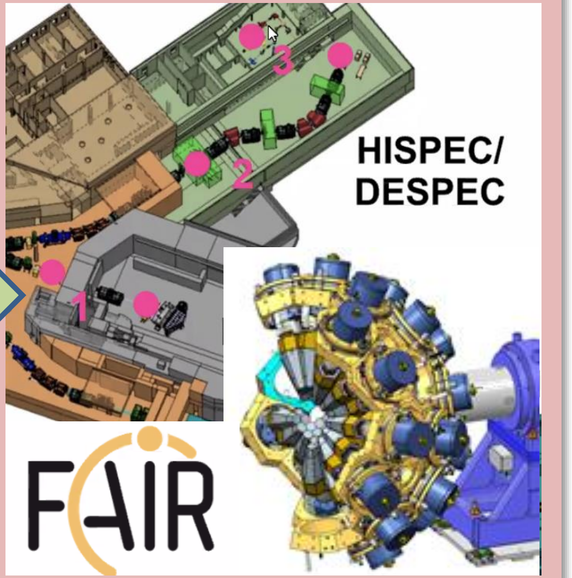
AGATA at GANIL

2021-2026
Legnaro, Italy
60 -> detectors



AGATA at LNL

2027 ->
FAIR, Germany
80-90 detectors



AGATA at NUSTAR

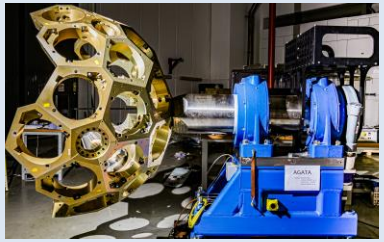
Reaccelerated RIBs:
- Coulomb Excitation, Direct Reactions, MNT, Deep Inelastic, Fusion
- **Direct and inverse kinematics $\beta \sim 10\%$**

In-flight RIBs:
- Relativistic Coulomb Excitation, Knockout, Fragmentation.
- **$\beta \sim 50\%$**

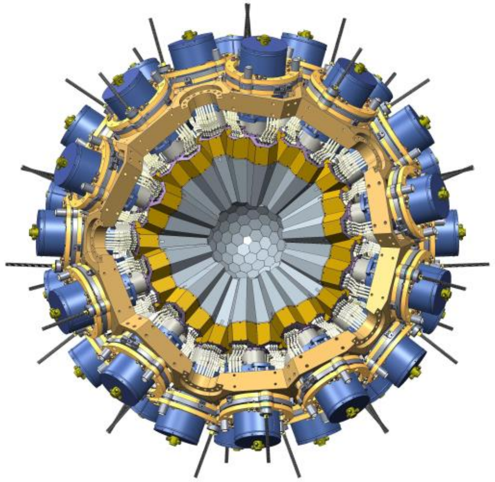
New MoU signed and in operation
Evolution of AGATA to 4π

From 2021

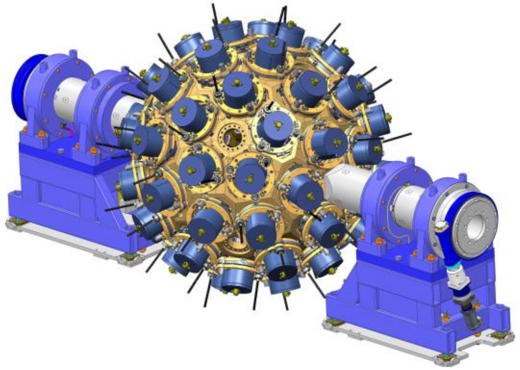
2021--
LNL, Italy
Stable beams
SPES radioactive beams



AGATA at LNL
The first campaign in the new MoU
60 > detectors



3π in 10 years



4π

Signed by 11 countries (14 Parties)

Blue sky science: Neutrino Physics

The LEGEND Experiment

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

Introduction to LEGEND

- The LEGEND collaboration proposes a 0νββ decay search experiment, using a 1 tonne of ^{76}Ge enriched detectors
- The programme follows a staged approach:
  - **LEGEND-200**: a 200 kg mass experiment, installed in the GERDA LAr cryostat at LNGS, Gran Sasso
  - It is an approved experiment at LNGS, with data taking in progress
  - **LEGEND-1000**: a 1T experiment will require a new underground infrastructure and additional R&D to further reduce backgrounds
  - LEGEND-1000 to start running later this decade

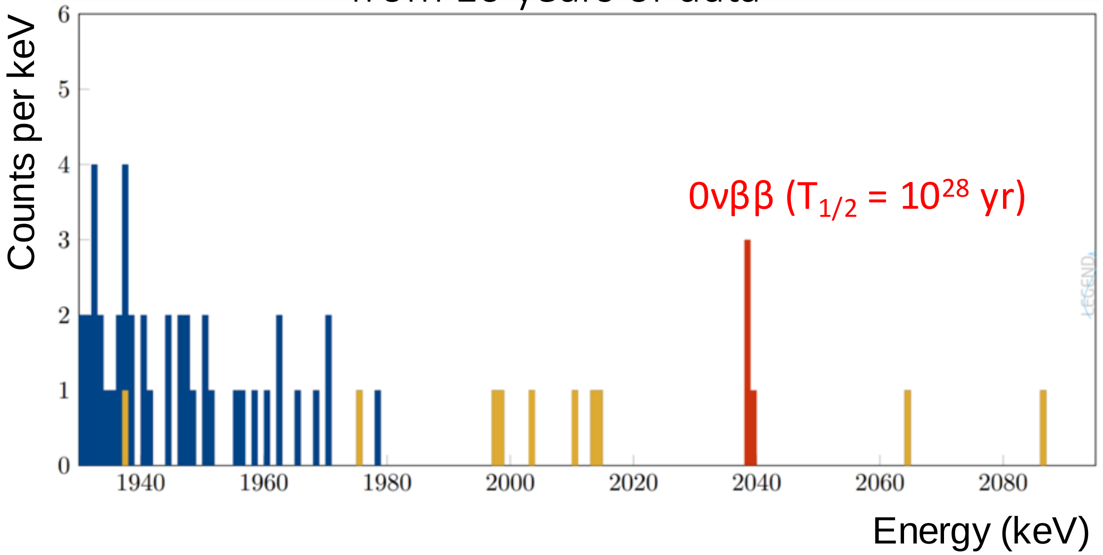
LEGEND Large Enriched Germanium Experiment for Neutrinoless ββ Decay

The LEGEND-1000 Discovery Sensitivity

"The collaboration aims to develop a phased, ^{76}Ge-based double-beta decay experimental program with <u>discovery potential</u> at a half-life beyond 10^{28} years..."

- What is required for a discovery of 0νββ decay at a half-life of 10^{28} years?
- This is less than one decay per year per ton of material
  - Need 10 ton-years of data to get a few counts
  - Need a good signal-to-background ratio to get statistical significance
    - A very low **background event rate**
    - The best possible **energy resolution**

Simulated example spectrum, after cuts, from 10 years of data



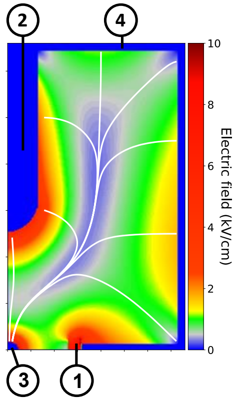
LEGEND 200 Overview

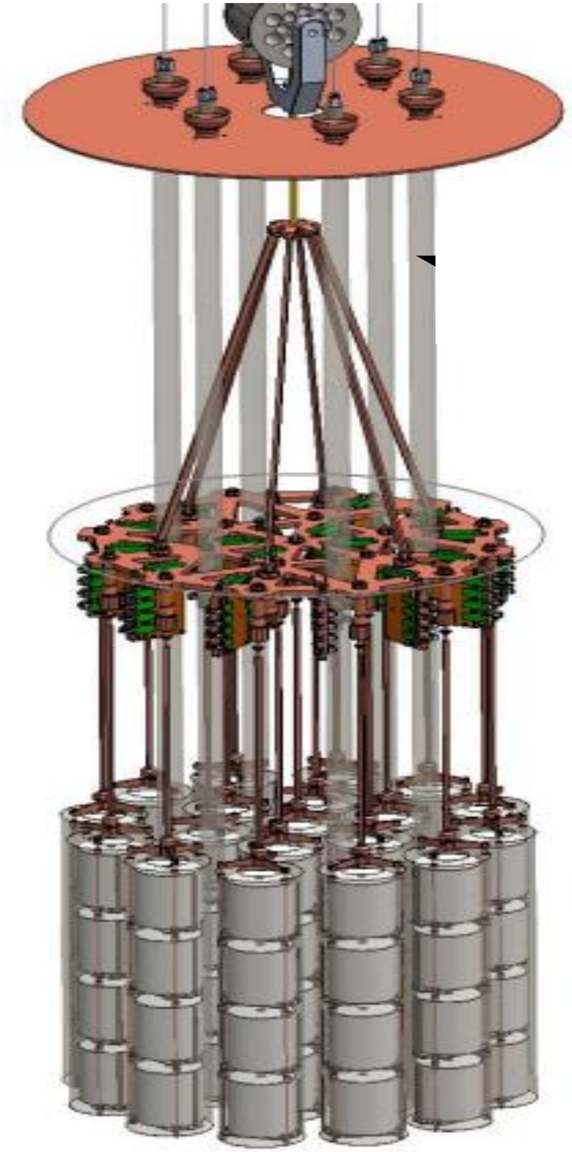
- A merger of the GERDA and MJD demonstrators @LNGS
- Re-use GERDA LAr cryostat: optimise geometry
- Low-background MJD front-end electronics, further from detectors
- Refinements to:
    - Veto system
    - Calibration systems
    - DAQ
- Trial PEN
- Physics data taking in progress
- STFC Experiment support for M&O

New detectors for LEGEND:

P-type Inverted-Coaxial Point Contact

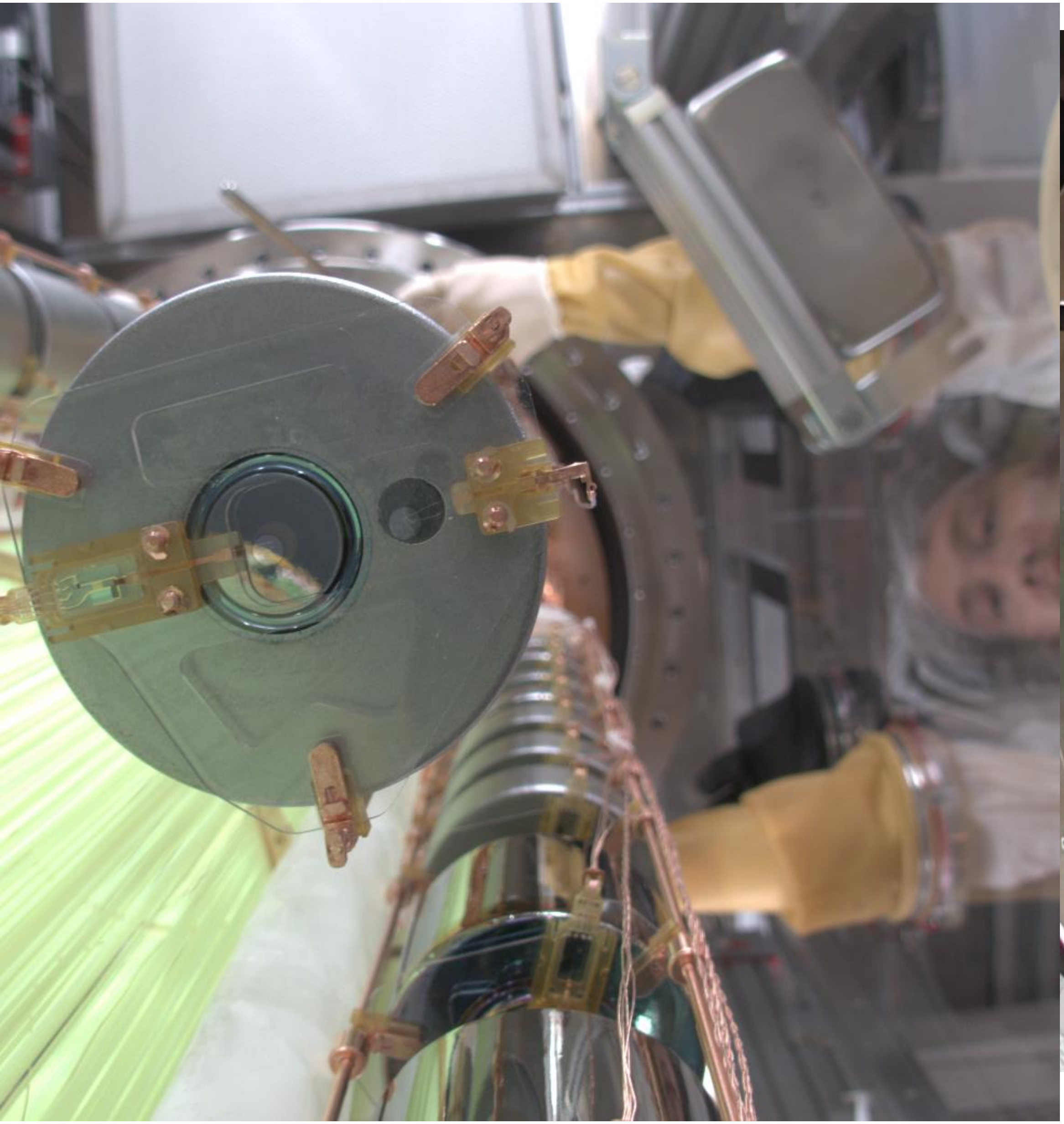
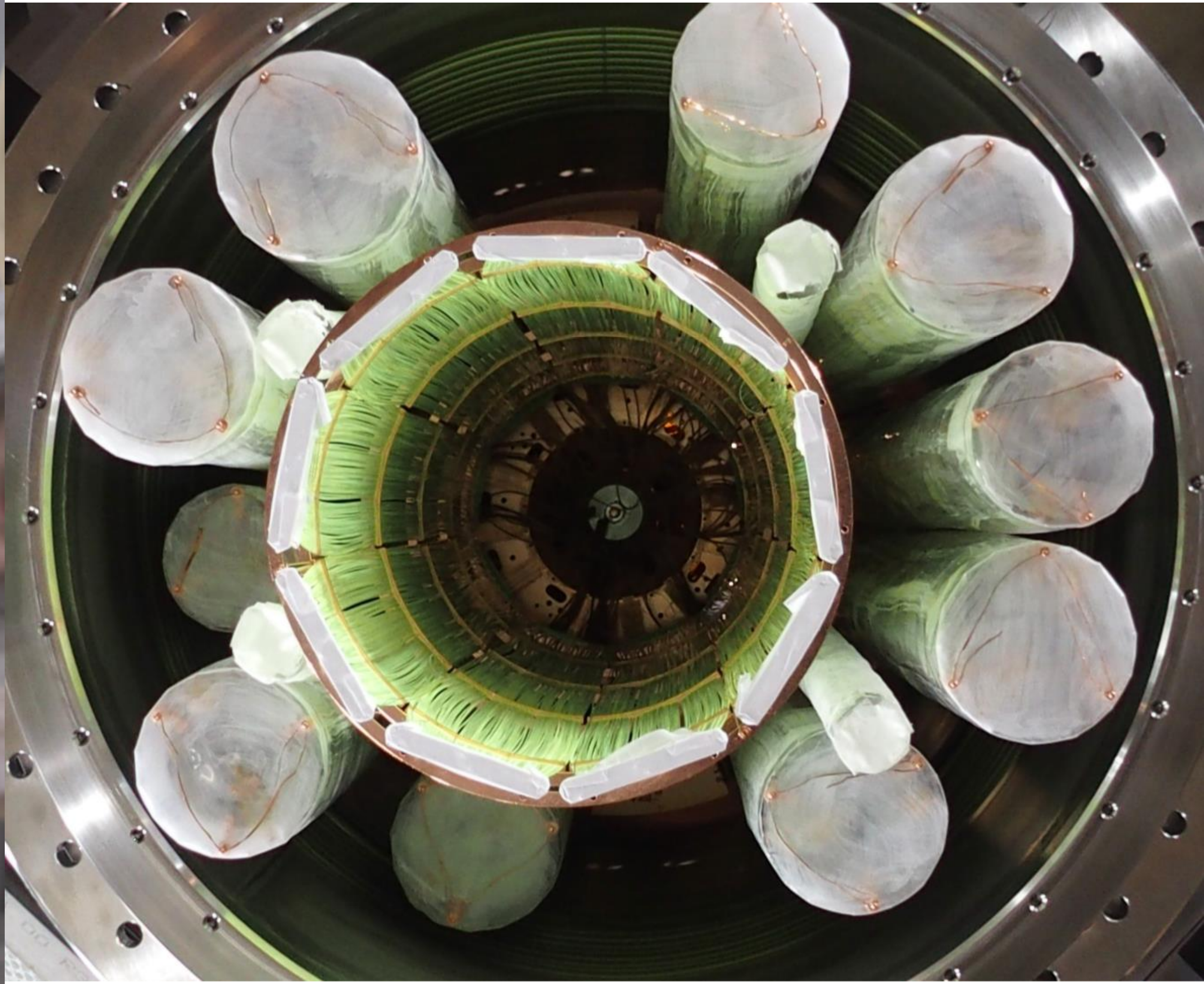
Larger mass : > 2 kg/detector





LEGEND

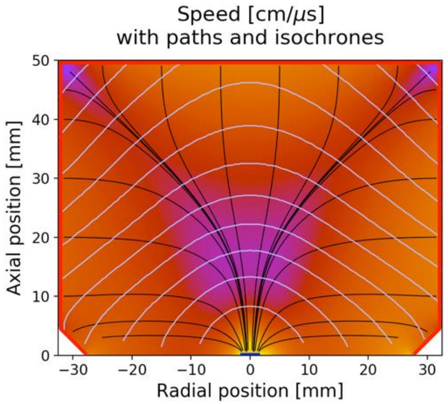
Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

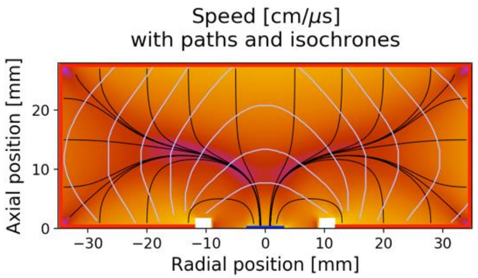
Innovation toward LEGEND-1000: ^{enr}Ge Detectors

- Superb energy resolution: $\sigma / Q_{\beta\beta} = 0.05\ \%$
- P-type detectors: Insensitive to alphas on n^+ outer contact
- Pulse-shape discrimination against background events
- Large-mass ICPC detectors: About 4 times lower backgrounds compared to BEGes / PPCs
- Proven long-term stable operation in LAr

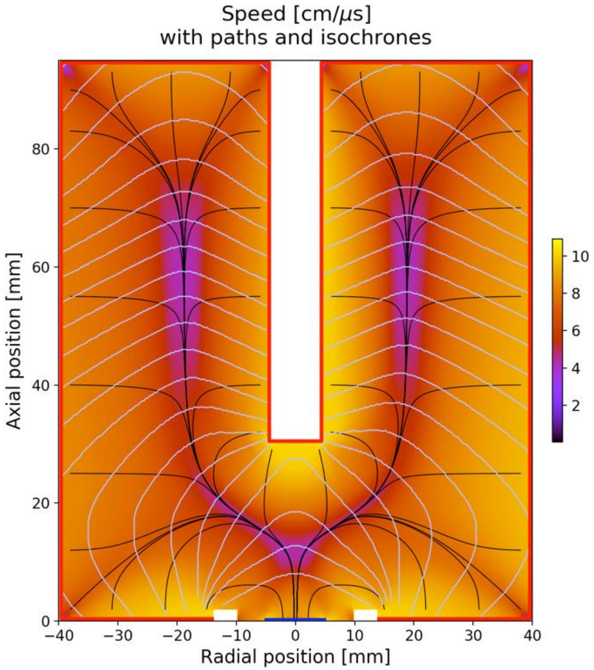
MAJORANA (PPC)

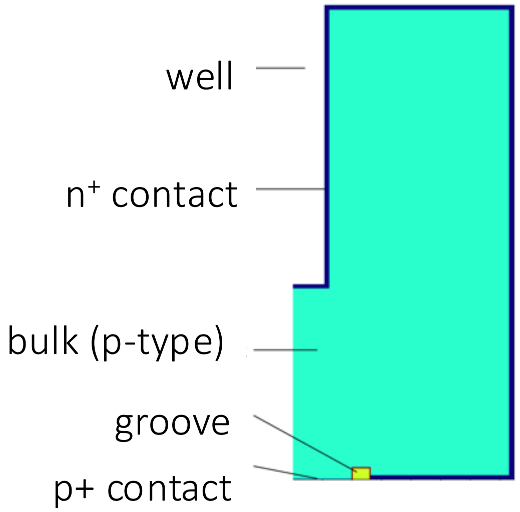


GERDA (BEGe)



LEGEND (ICPC)





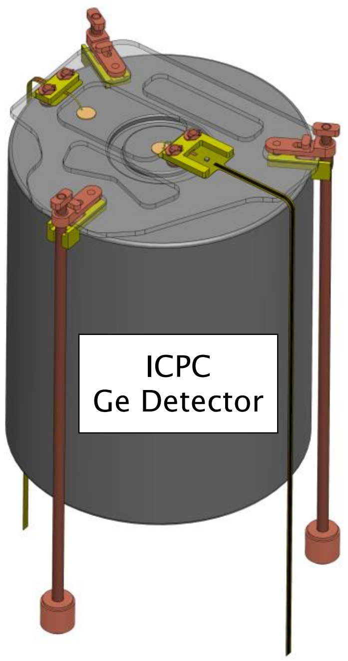
The LEGEND-1000 Experiment: Overview

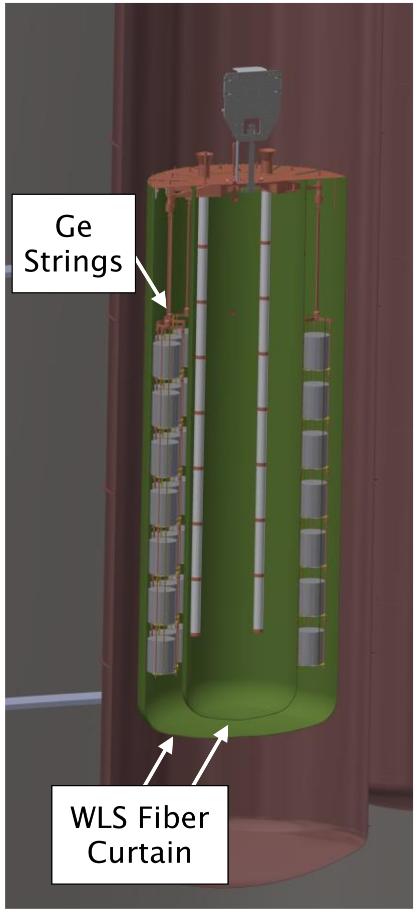
1000 kg of enriched Ge detectors (92% ^{76}Ge)

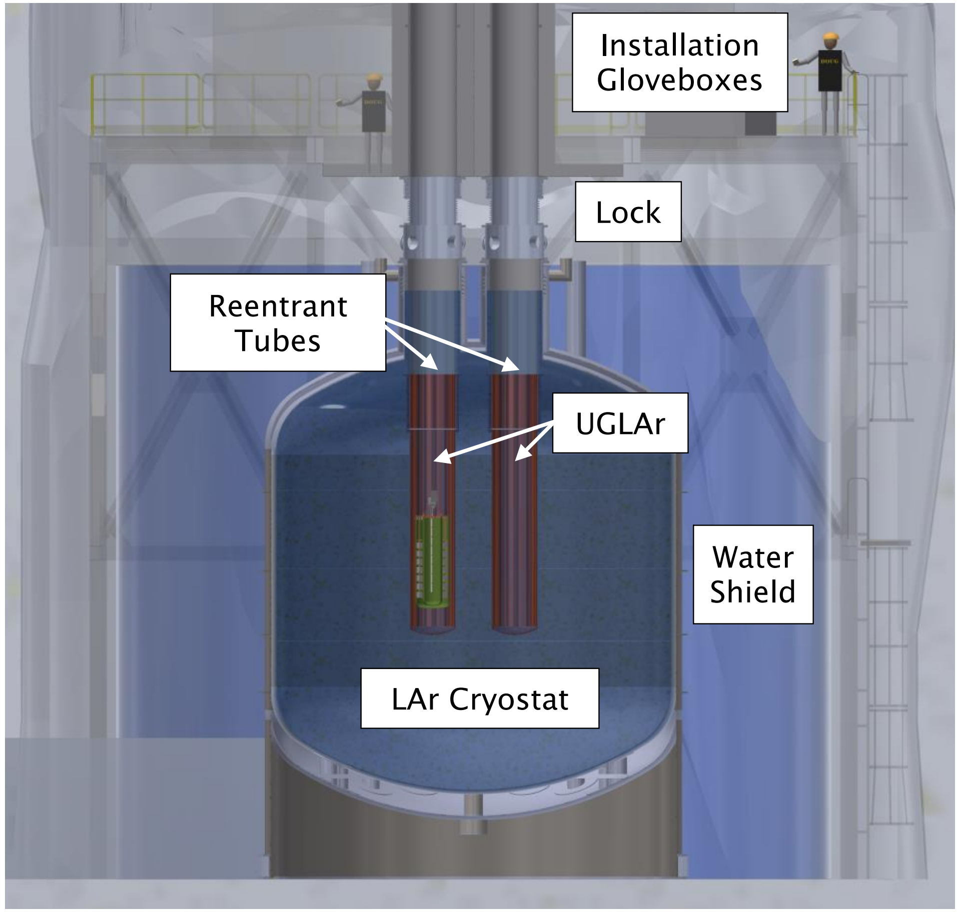
- 2.6 kg average mass
- Mounted in “strings” using components made from electro-formed Cu and scintillating plastic, PEN

- Arranged in 4 modules
- ~100 detectors per module

- Underground-sourced LAr active shield
- Dual fiber-curtain LAr instrumentation
- EFCu Reentrant tubes

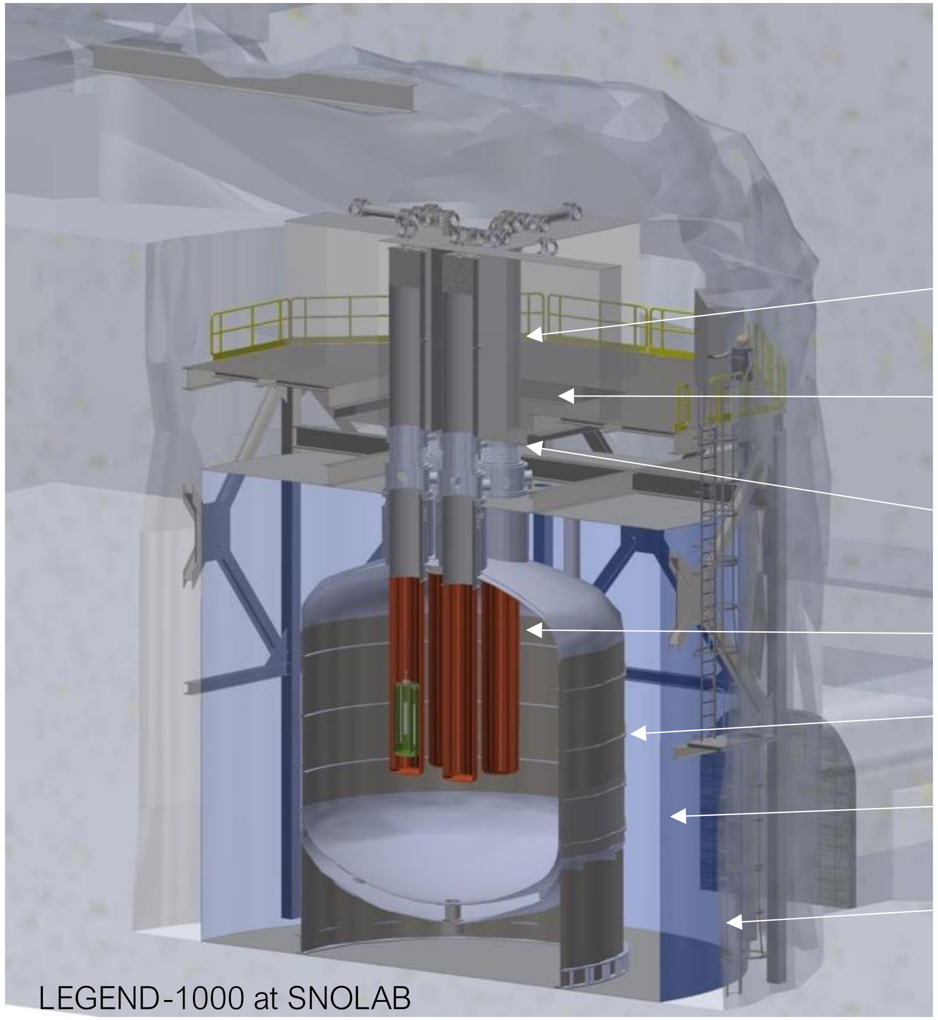




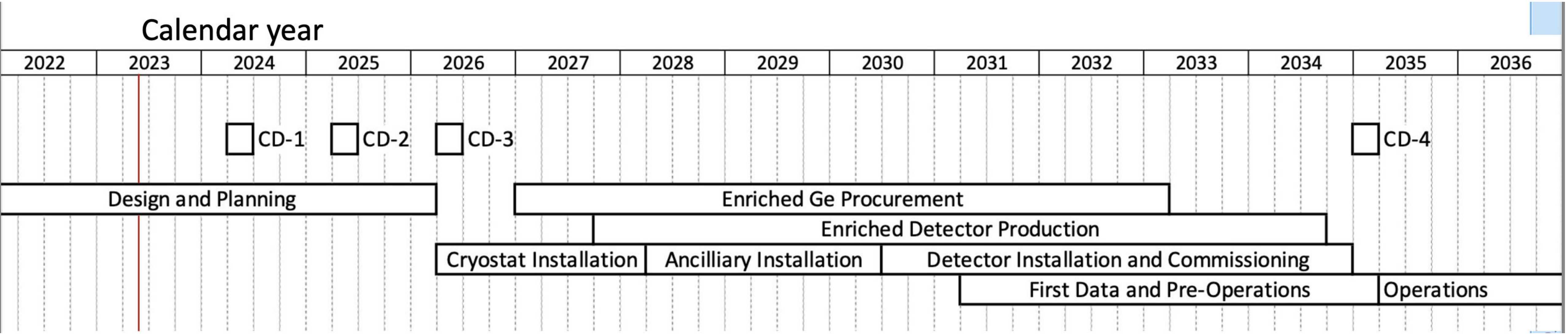


LEGEND-1000 Baseline Design: Underground Site

- A deep-underground site is needed to shield the experiment from backgrounds generated by cosmic rays
- Baseline site: The SNOLAB "Cryopit"
  - 2 km underground (6000m water equivalent)
  - In an active nickel mine in Sudbury, Ontario
  - Vertical access through mine shaft
- Alternative site: LNGS (Italy)
  - 3500m water equivalent depth
  - Lower overburden somewhat increases background
  - Horizontal access reduces cost/schedule risk
- Staff at both sites are actively involved in planning



Technically Driven Schedule: LEGEND 1000



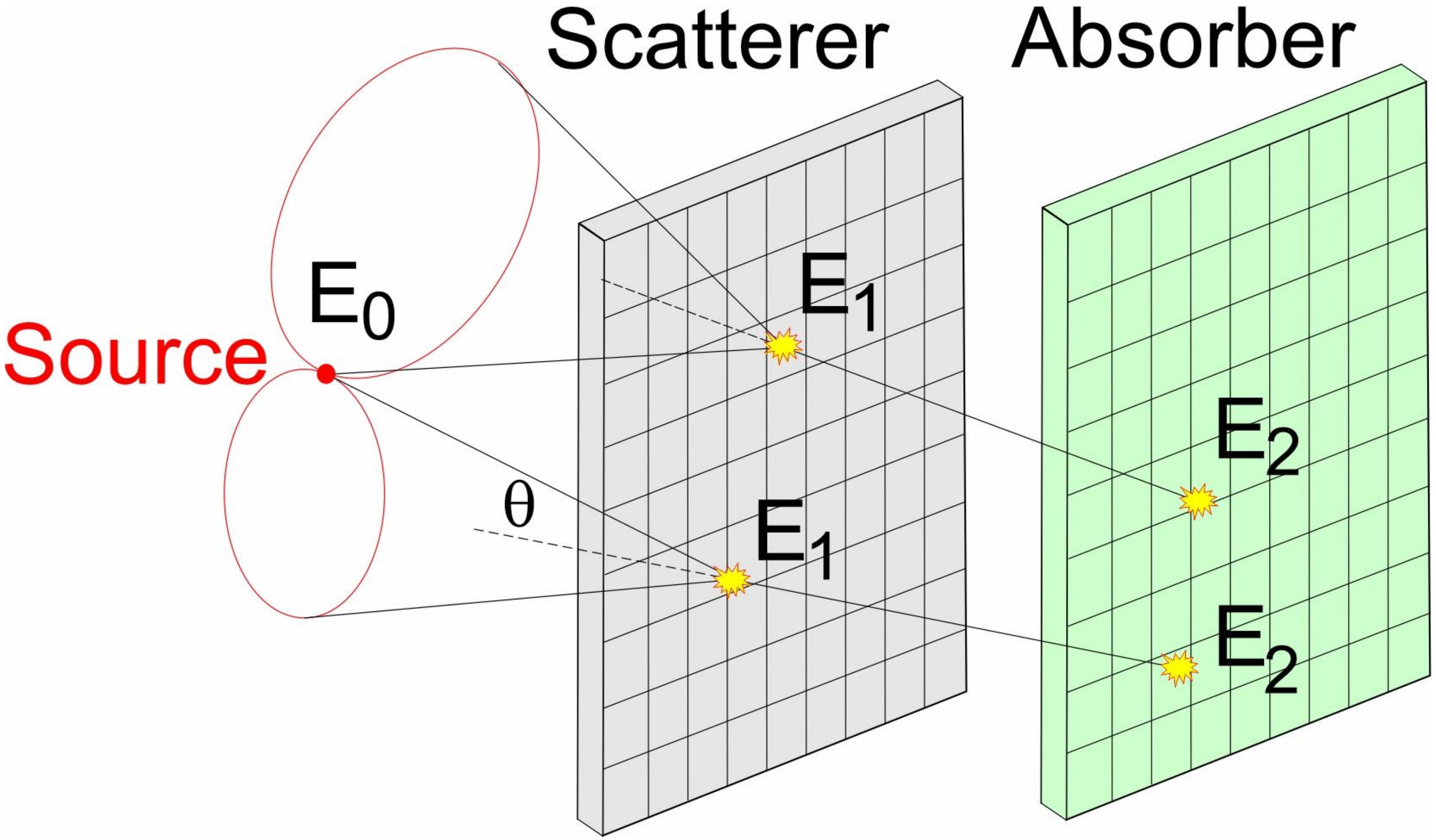
- Assumes technically driven funding profile
- Key Dates:
  - CD-1 review — Q4 2024
  - First 250 kg Commissioning Complete (start of physics data) — Q2 2031 – Q3 2032
  - Early Finish: Commissioning Complete: — Q1 2035
  - Late Finish (36 months of float): — Q1 2038

Imaging applications: Nuclear

What constitutes a gamma imager?

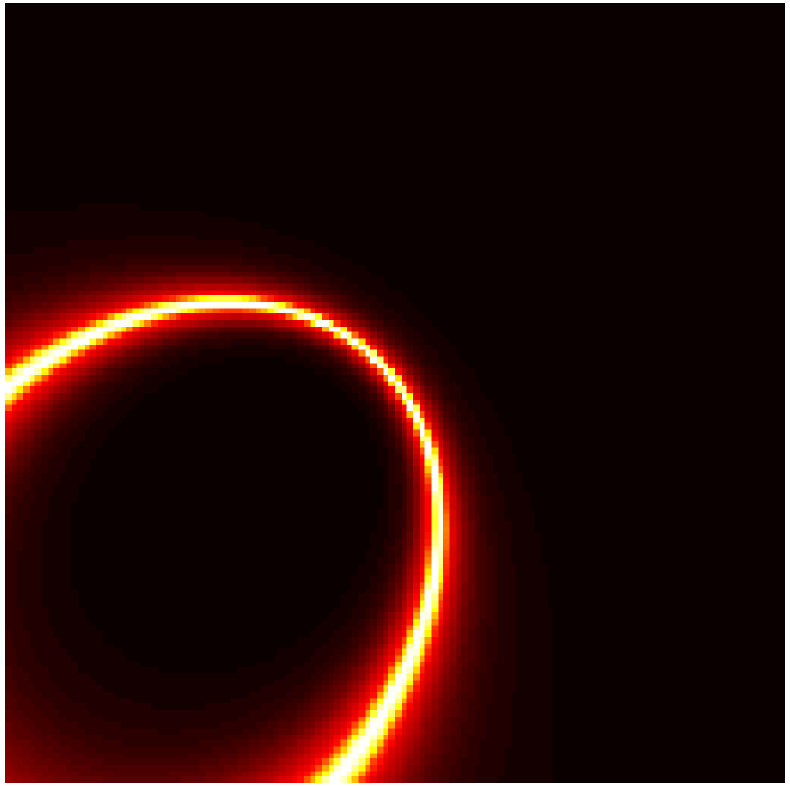
- A detector, or detectors, sensitive to gamma radiation
- A means of measuring the direction of each detected gamma ray
- A means of displaying the data as an image showing the spatial distribution and intensity of gamma radiation.
- This ‘gamma image’ is usually superimposed onto an image from a conventional optical camera so that the physical location of the sources can be readily identified.

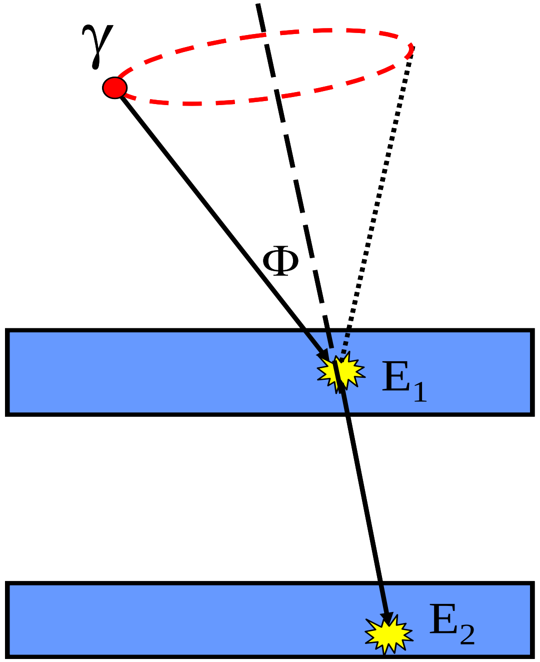
What constitutes a Compton Imager?



Research : Compton Imaging

- Compton *Cones of Response* projected into image space

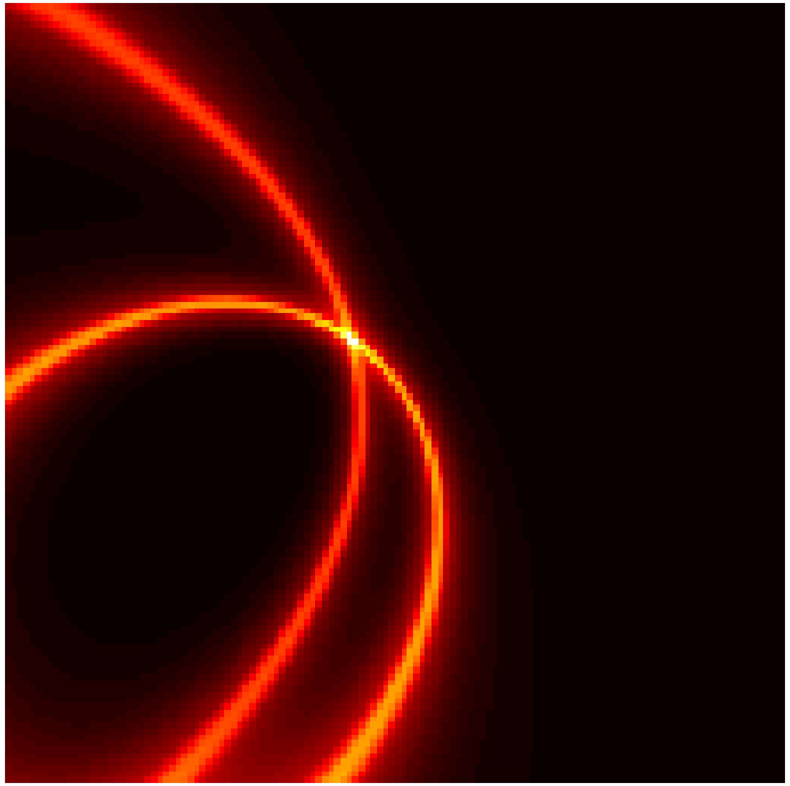


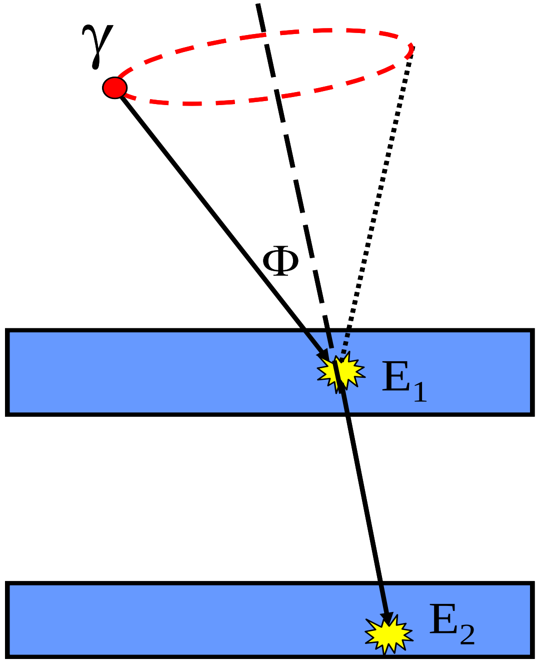


$$\cos\phi = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1 + E_2} \right)$$

Research : Compton Imaging

- Compton *Cones of Response* projected into image space

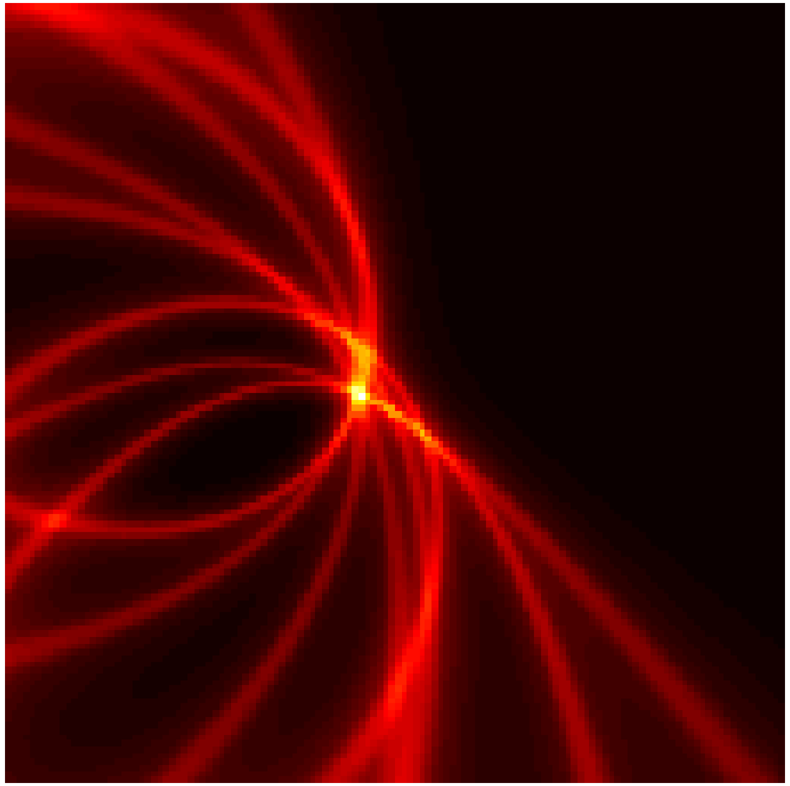


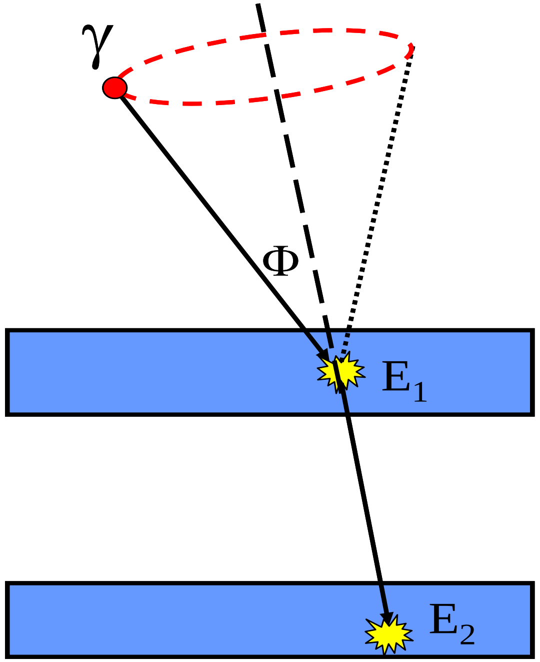


$$\cos\phi = 1 - m_e c^2\left(\frac{1}{E_2} - \frac{1}{E_1 + E_2}\right)$$

Research : Compton Imaging

- Compton *Cones of Response* projected into image space

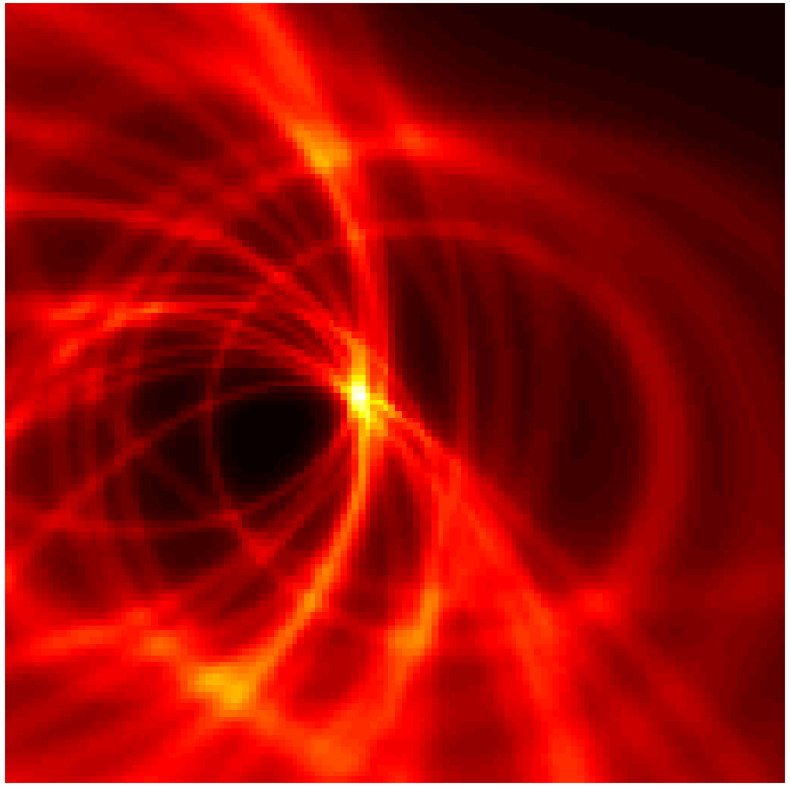


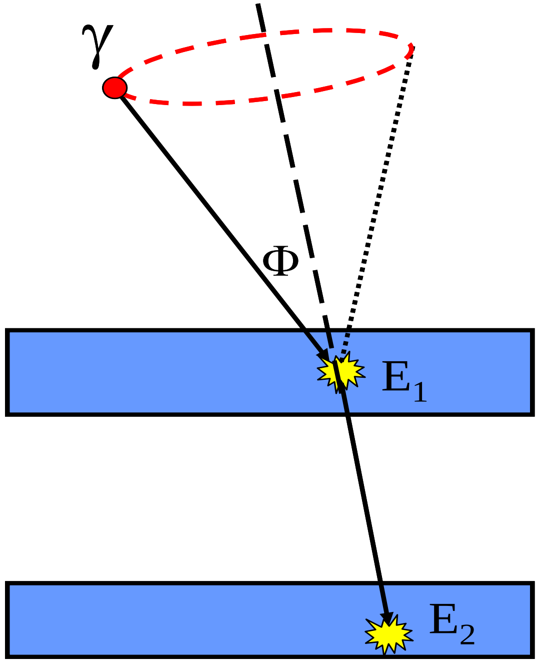


$$\cos\phi = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1 + E_2} \right)$$

Research : Compton Imaging

- Compton *Cones of Response* projected into image space

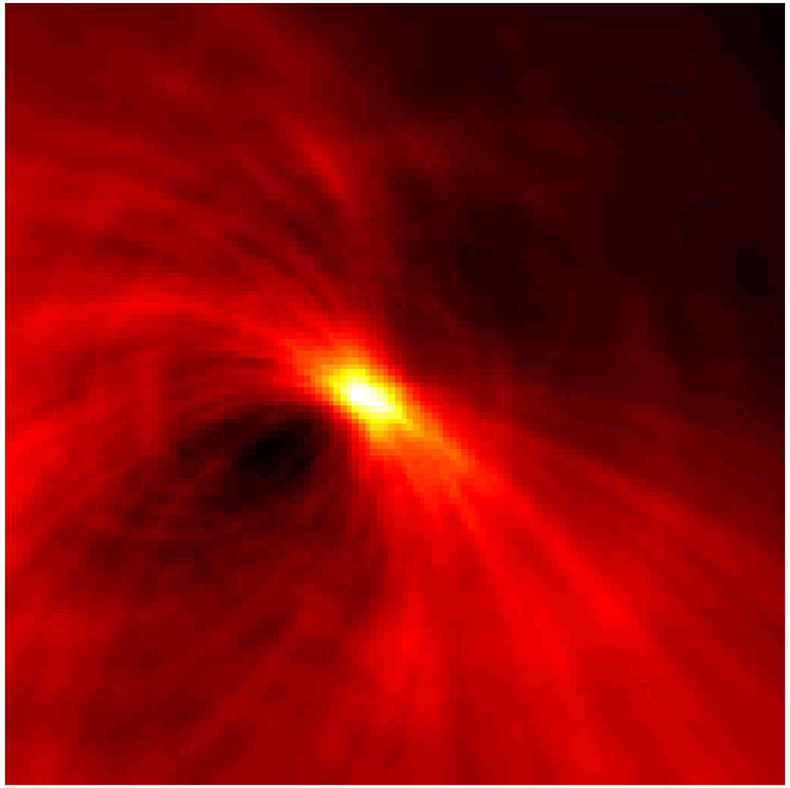


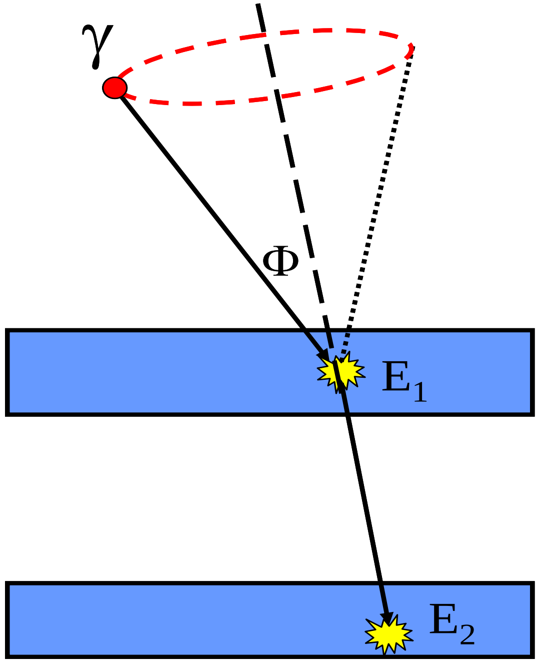


$$\cos\phi = 1 - m_e c^2\left(\frac{1}{E_2} - \frac{1}{E_1+E_2}\right)$$

Research : Compton Imaging

- Compton *Cones of Response* projected into image space





$$\cos\phi = 1 - m_e c^2\left(\frac{1}{E_2} - \frac{1}{E_1 + E_2}\right)$$

GRI+ Compton Camera Imaging Trials

Mirion Technologies - Birchwood

GRI+ System

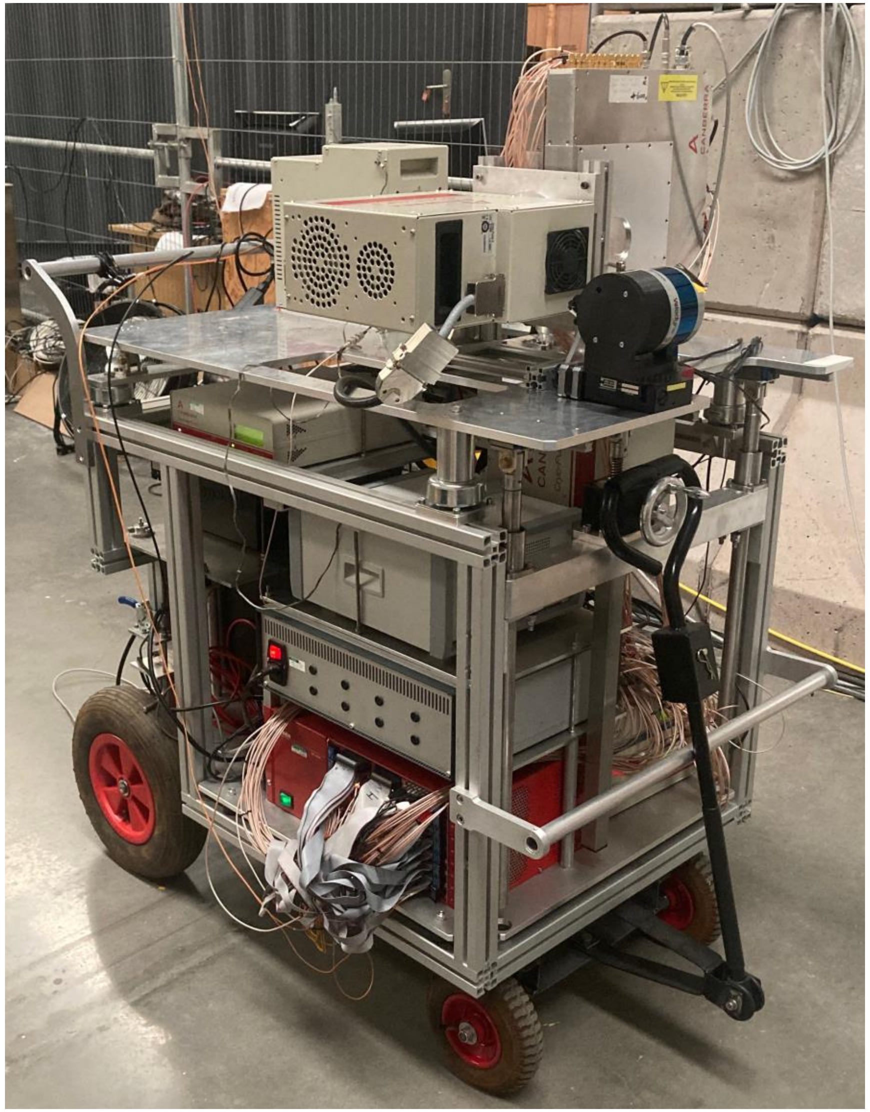
Transportable Compton Imaging system

Three-tiered Compton Camera System

- Planar Strip Si(Li) Detector
- Planar Strip HPGe Detector
- Coaxial HPGe Detector

Full HV/LV and digital system

LIDAR system



Double sided germanium strip detector

Detector systems fully characterized

ADL simulations performed

Grid search algorithm

MIRION TECHNOLOGIES

Gri+: System status

- Si(Li) and Ge
- Double Sided strip detectors
- Excellent Performance
- V1724 Caen digitisers, V1495 trigger control
- System characterisated
- Laboratory tests : Complete
- **Active demonstrator facility tests**

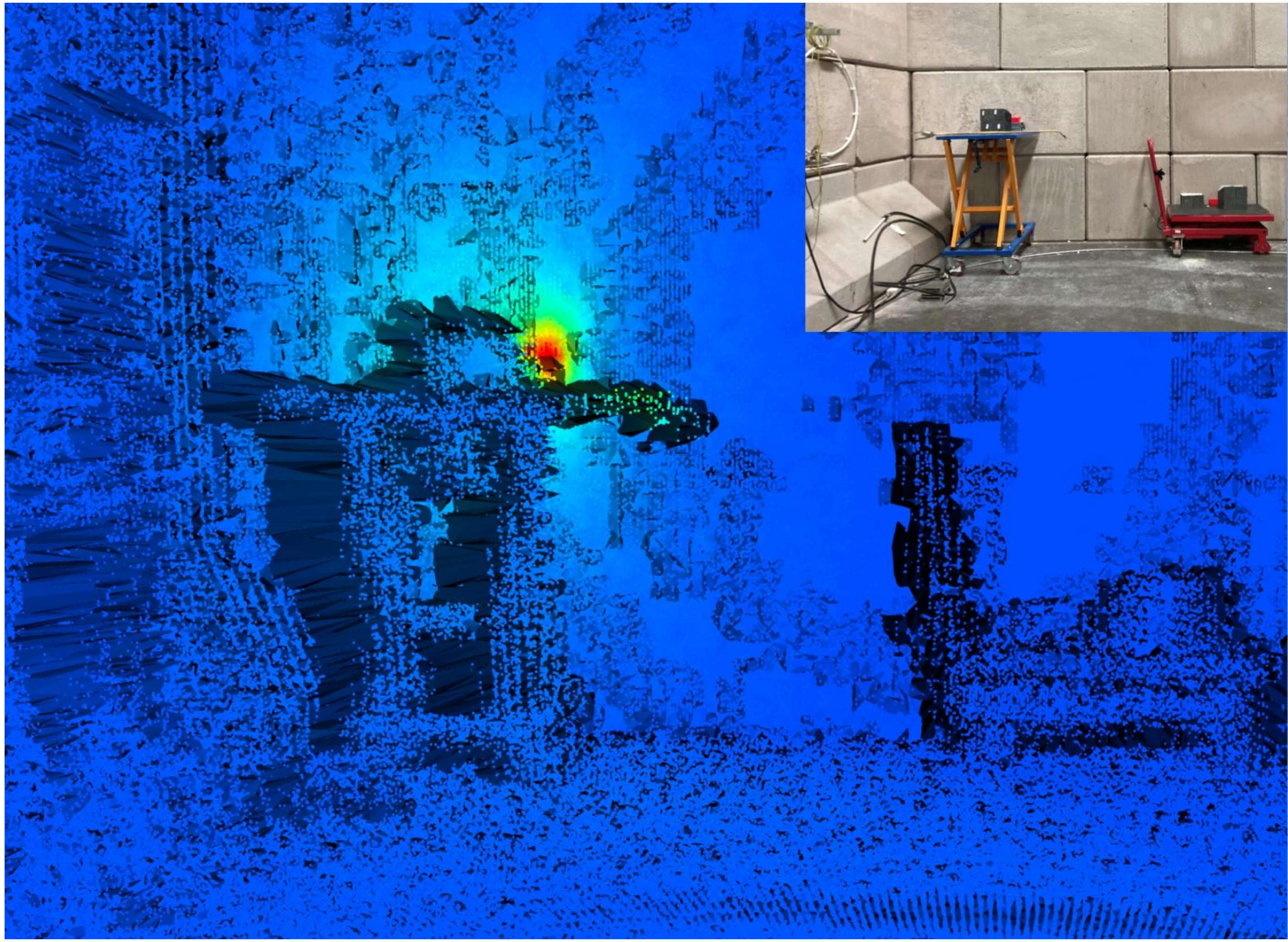
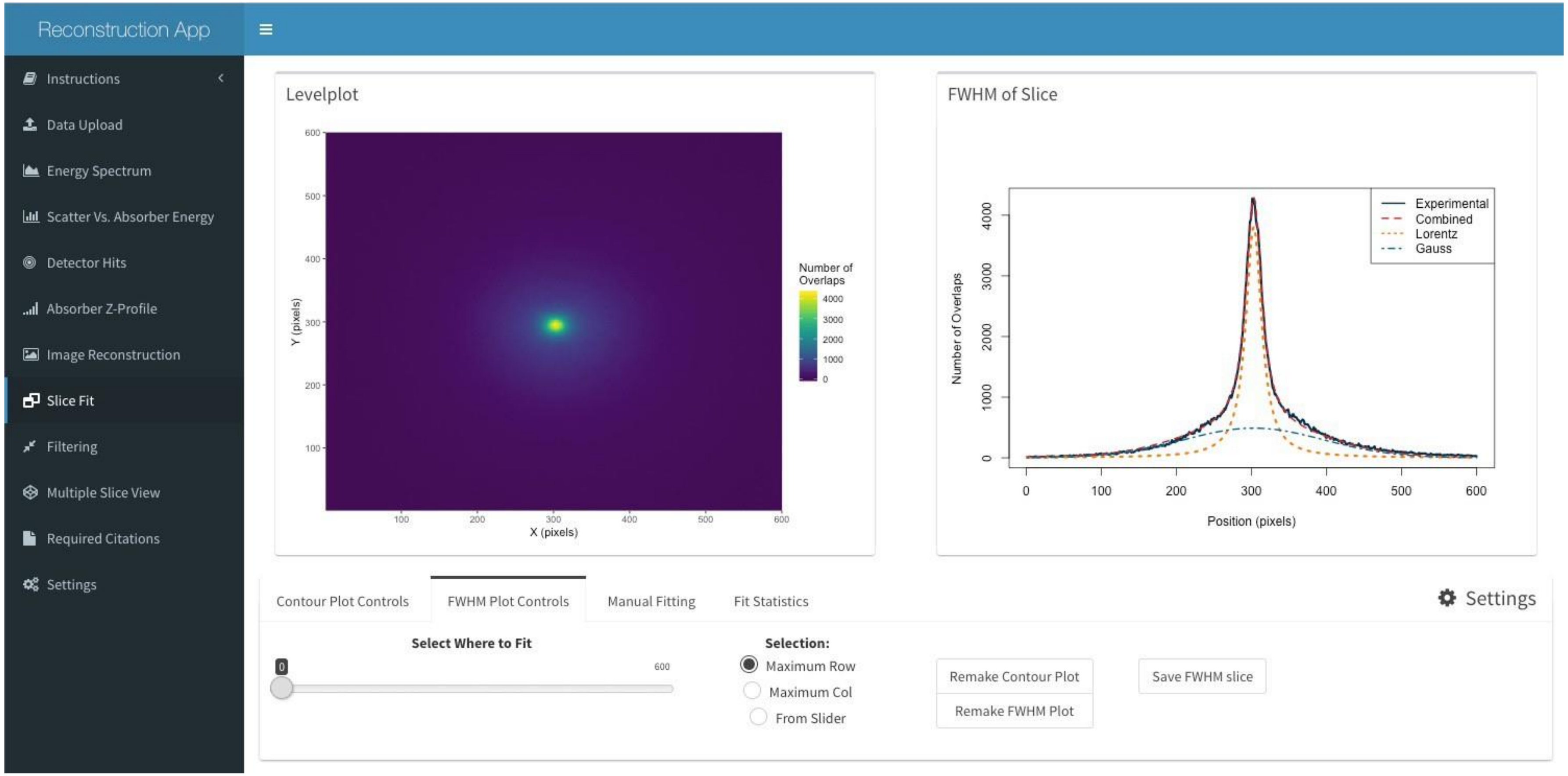


Image Reconstruction GUI

- Performed using a reconstruction application
- Easy to use – analytical and iterative reconstruction techniques available
- Inbuilt image filtering options
- Simple quantification of image quality



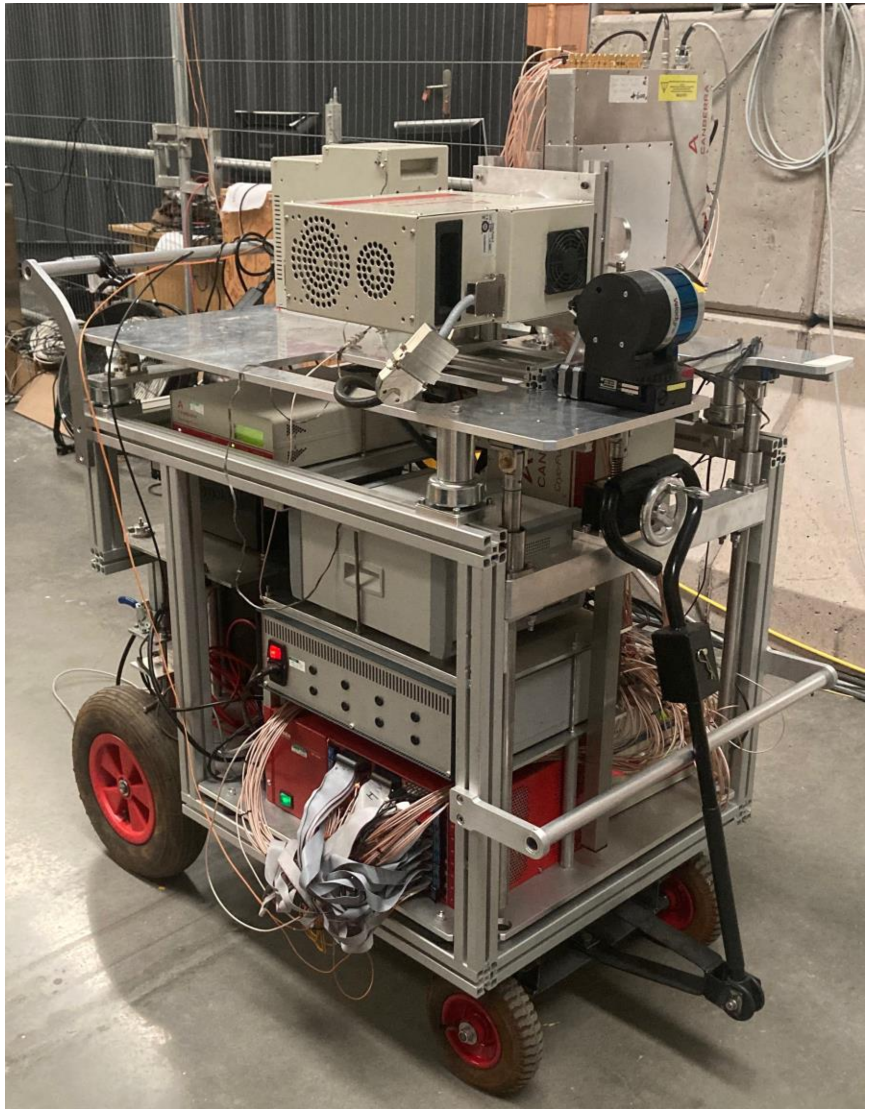
Mirion Measurements

System taken to Mirion Technologies at Birchwood Warrington to

Perform measurements not possible at the University of Liverpool

- Large stand-off (4-5 m)
- High-activity sources (>10 MBq)
- Distributed sources (Rod sources)

Trials supported by Chris McPeake and Cory Binnersley at Birchwood



Measurements

Initial measurement tests undertaken during summer 2022

- High-activity source measurements not possible at the time (safety reasons)

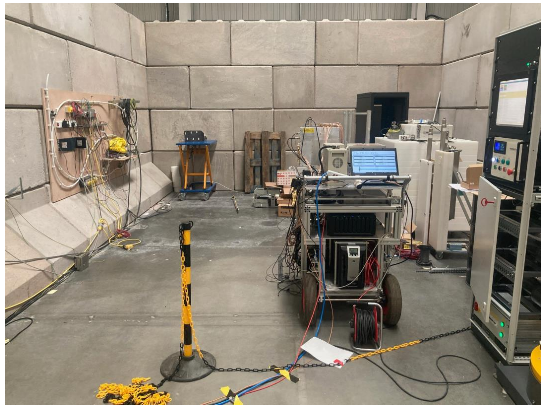
High activity measurements taken summer 2023

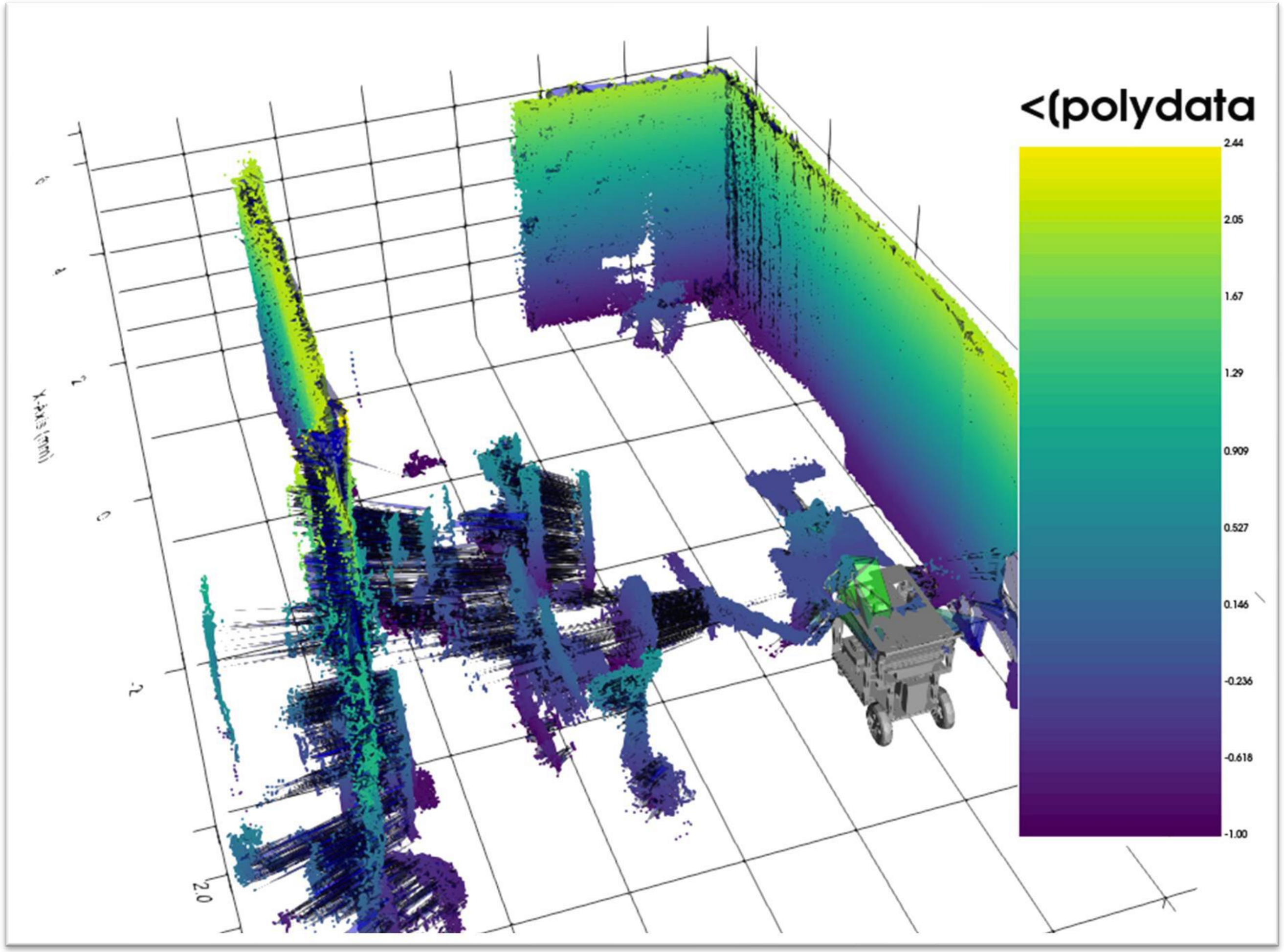
- Analysis being finalised – production of images
- Brief summary/highlights presented here

LIDAR System

Quantify distance of surfaces from camera

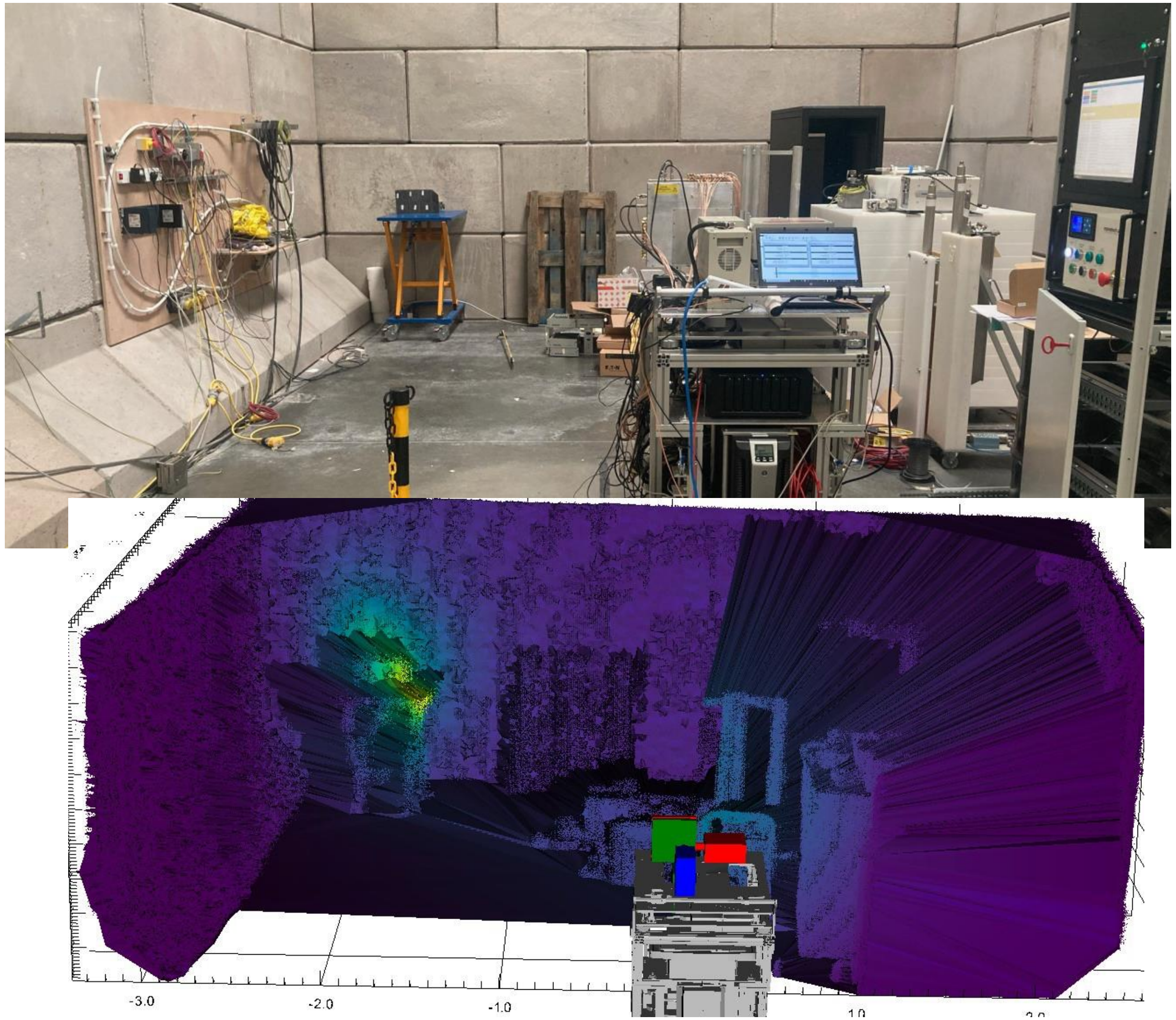
- ▶ LIDAR provides 4π point cloud
- ▶ Construct surfaces on point cloud
- ▶ Project Compton reconstruction image onto LIDAR surfaces
- ▶ Fused gamma-point cloud image





Single-position LIDAR scan – Birchwood

Point Cloud Imaging



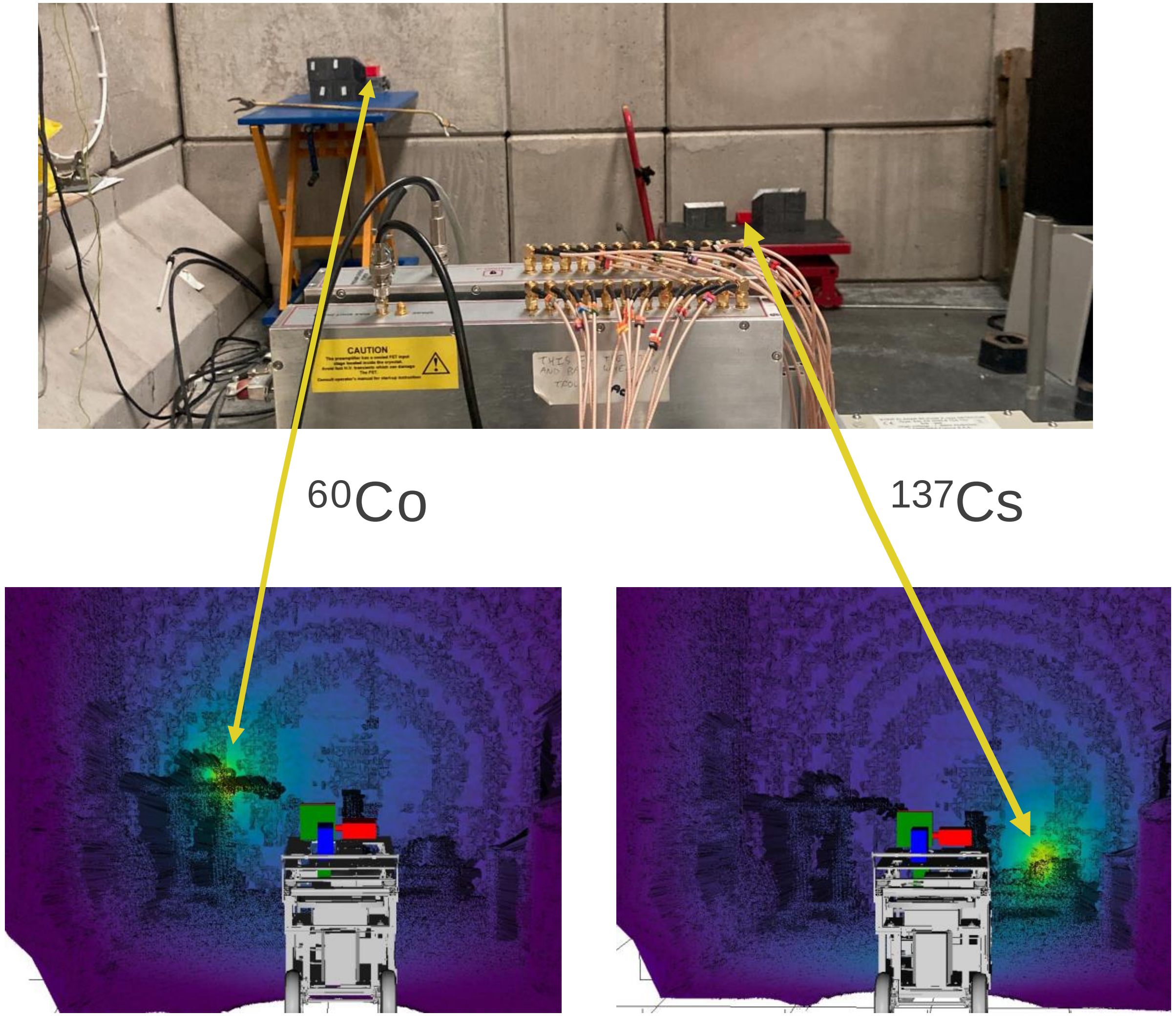
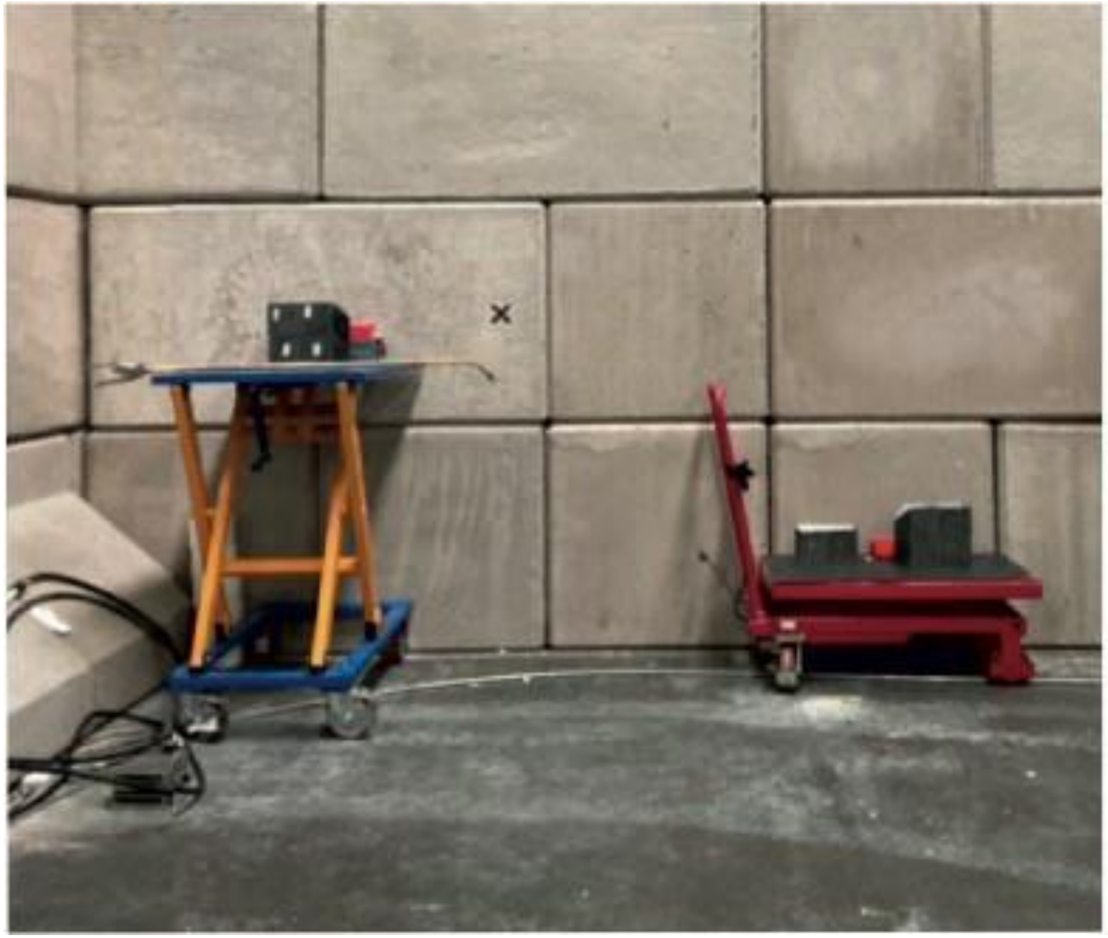
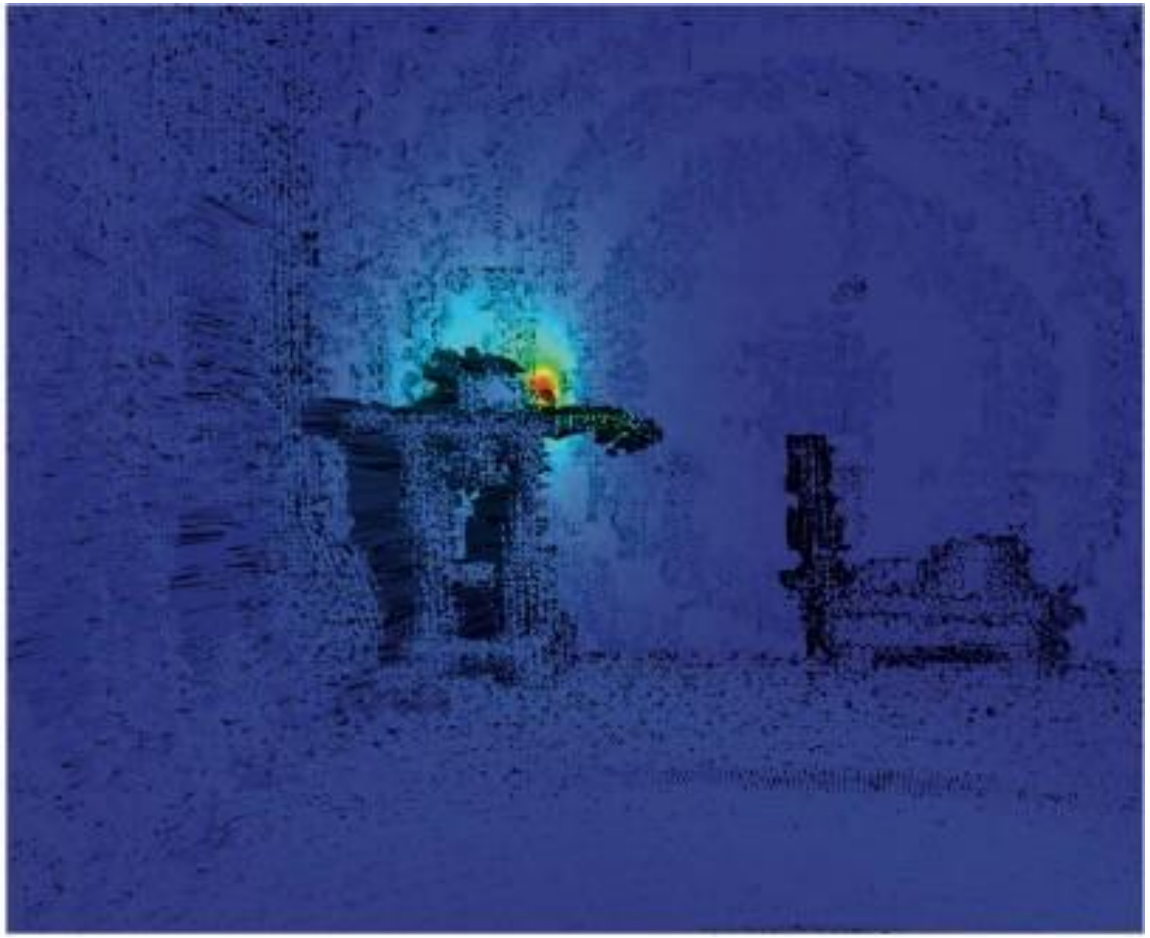


Image Fusion

Raw projection and fusion – no post-processing





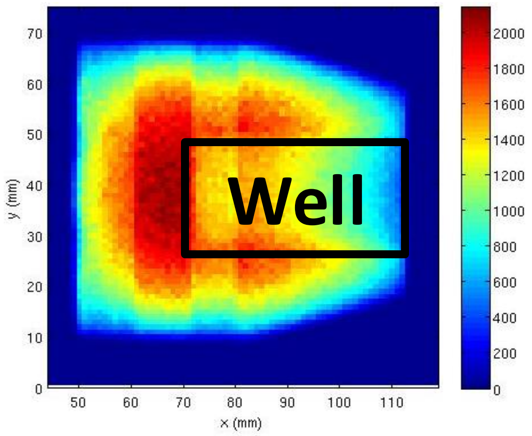
Future technology and direction

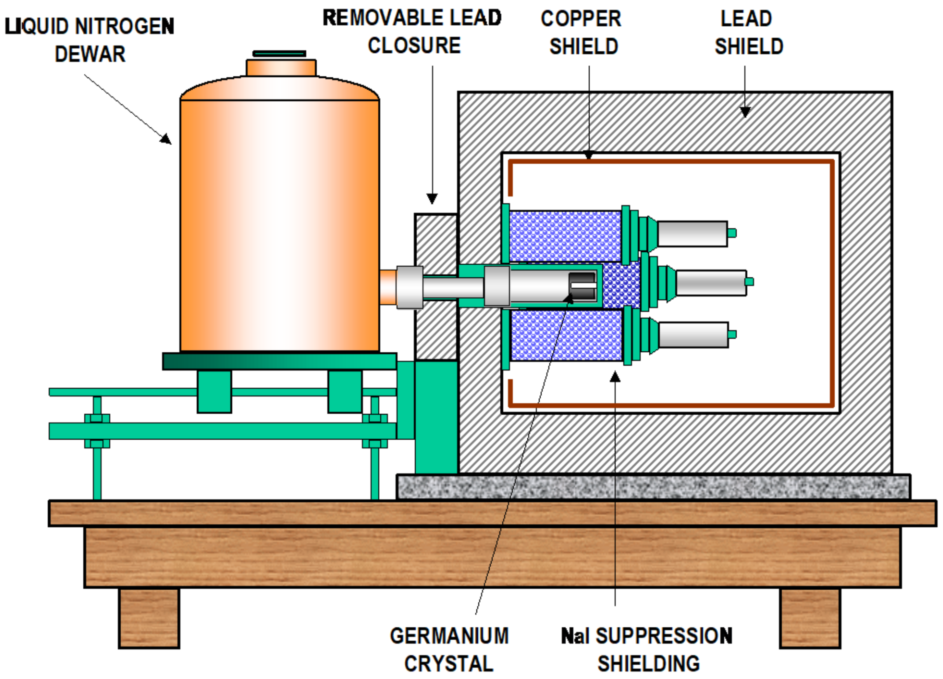
Point ”like” contact detectors

Future technology and direction

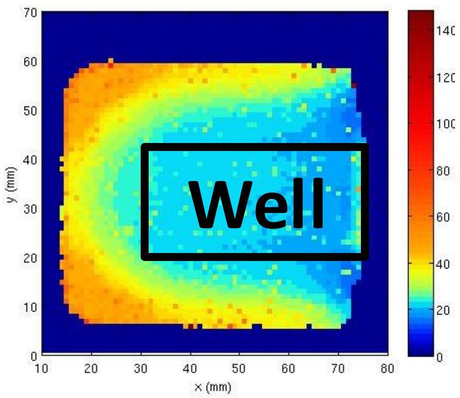
- **How can we improve performance further?**
  - Energy resolution
  - Peak to Total
  - Maintain or increase efficiency
  - Improve long term reliability for segmented detectors
- **Consider small contact detectors**

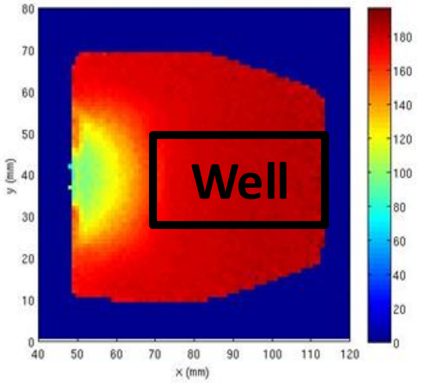
Example SAGe Well & Ortec Well Scans



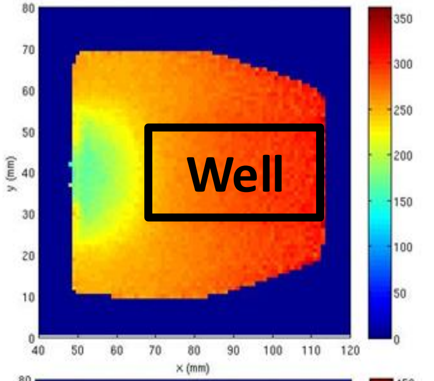


T30

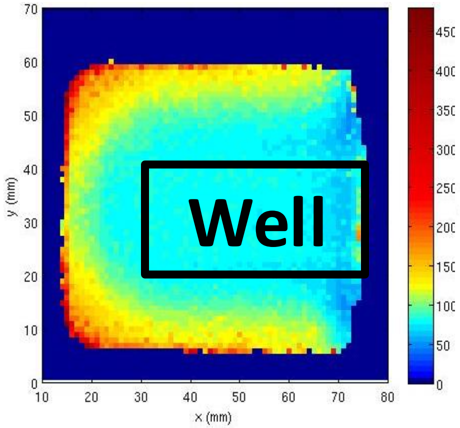


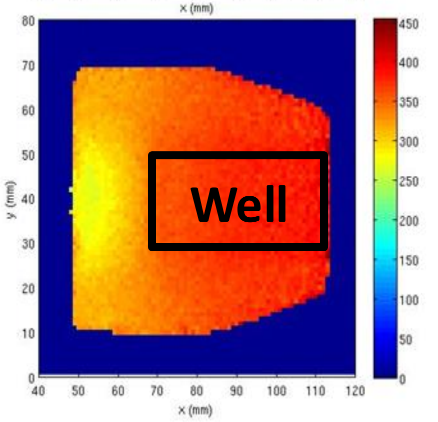


T60



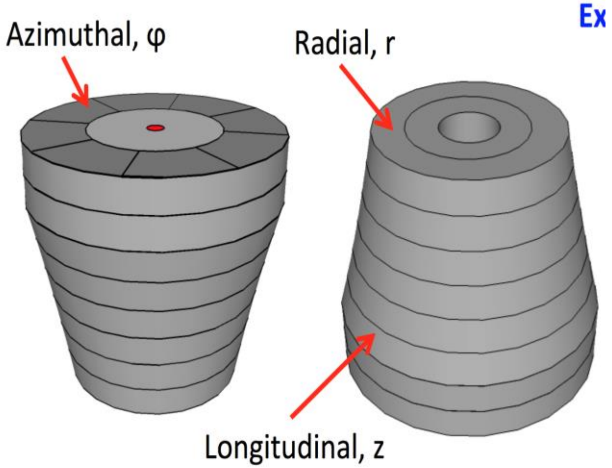
T90

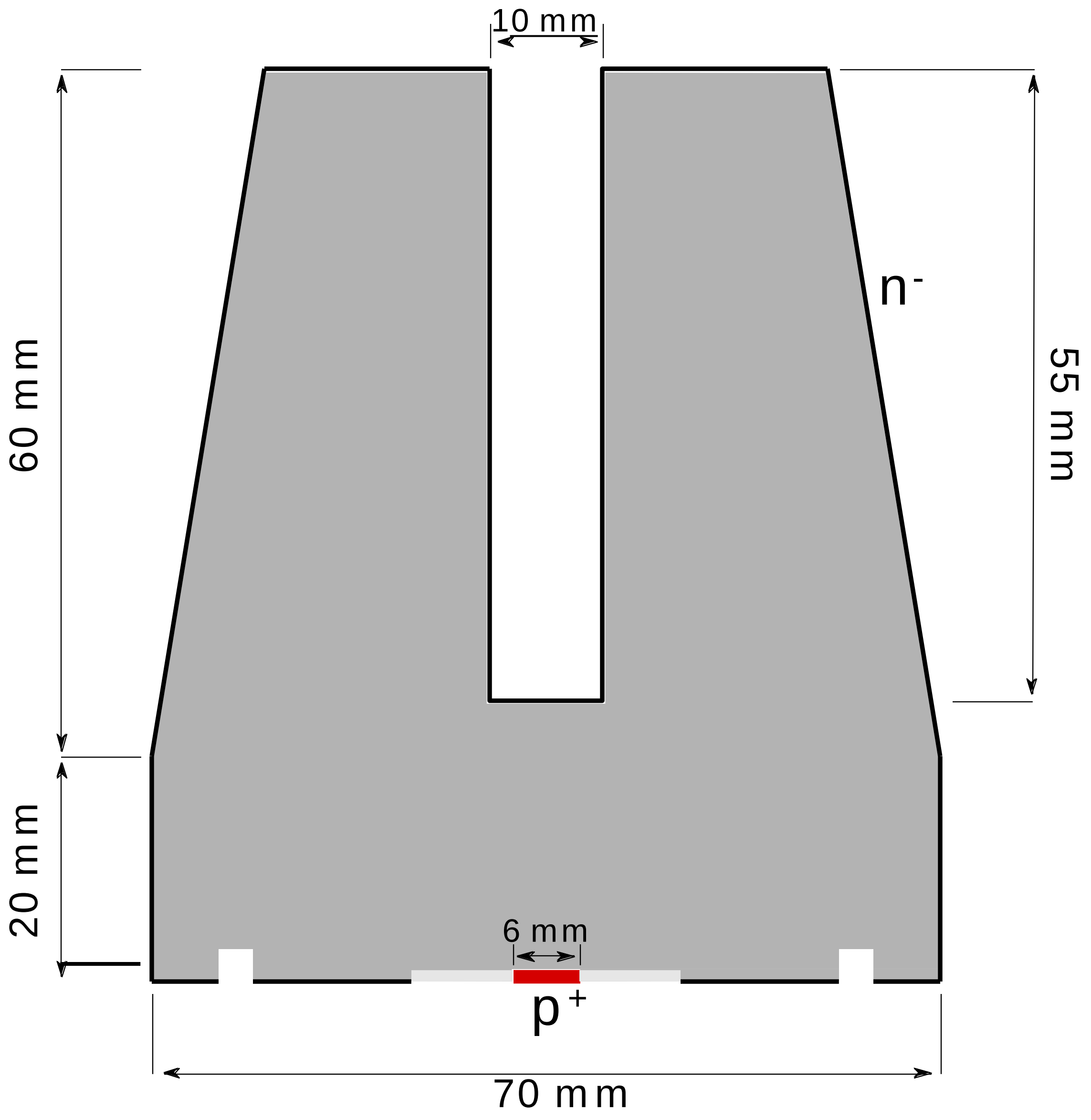




SIGMA: detector status

- Spectroscopic gamma-ray imaging with a Segmented, Inverted-coaxial GerMAnium detector
- Potential single detector γ-ray imaging system for energy, security, healthcare & environment
- P-type material for improved charge collection
  - 8 wedges
  - 8 circular segments
  - 1 front and bore

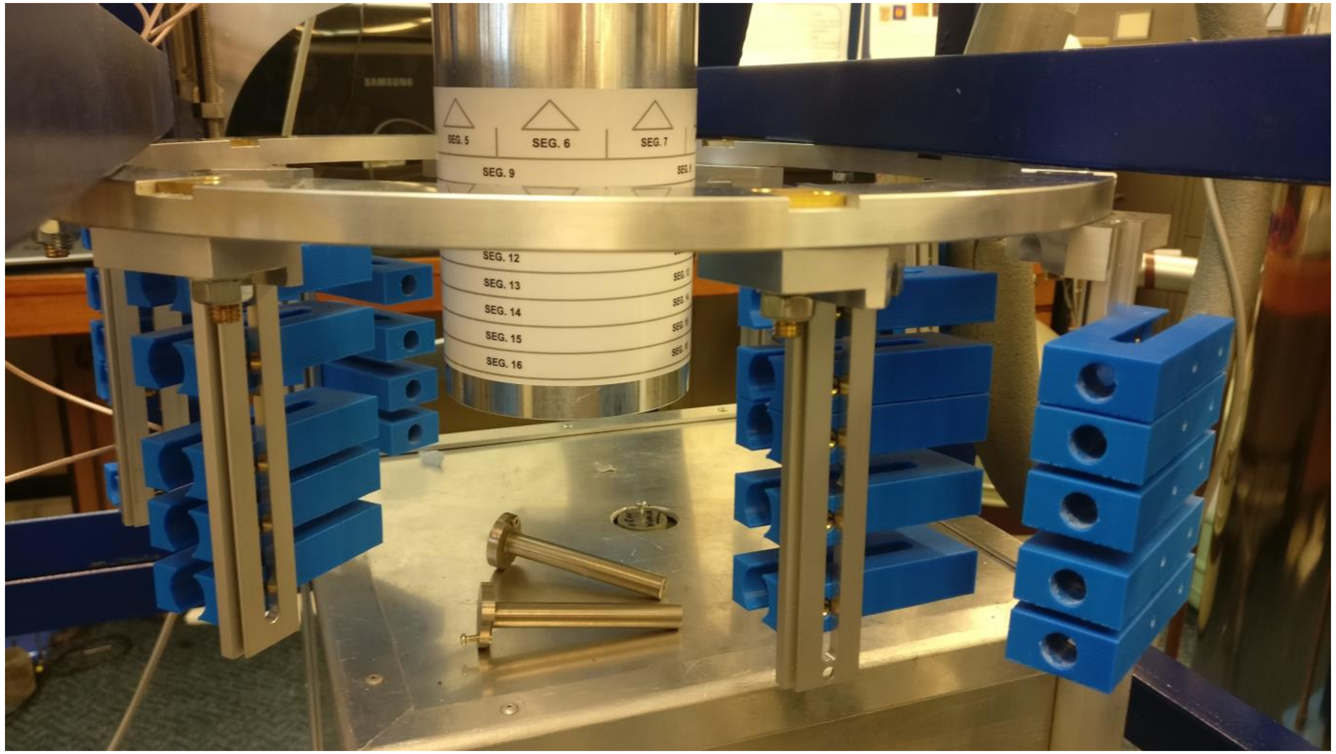




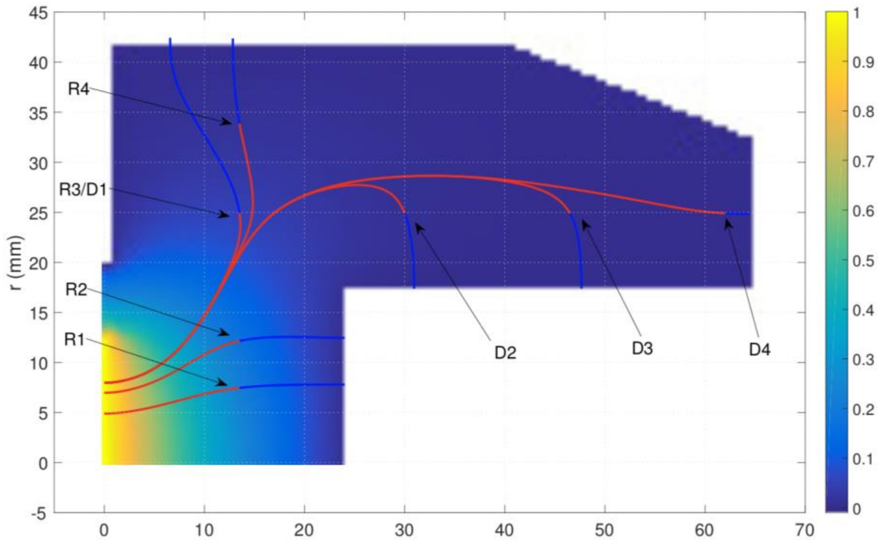
J. Wright et al. NIM, A 892 (2018) 84–92
M. Salathe et. al, NIM. A 868 (2017) 19-26

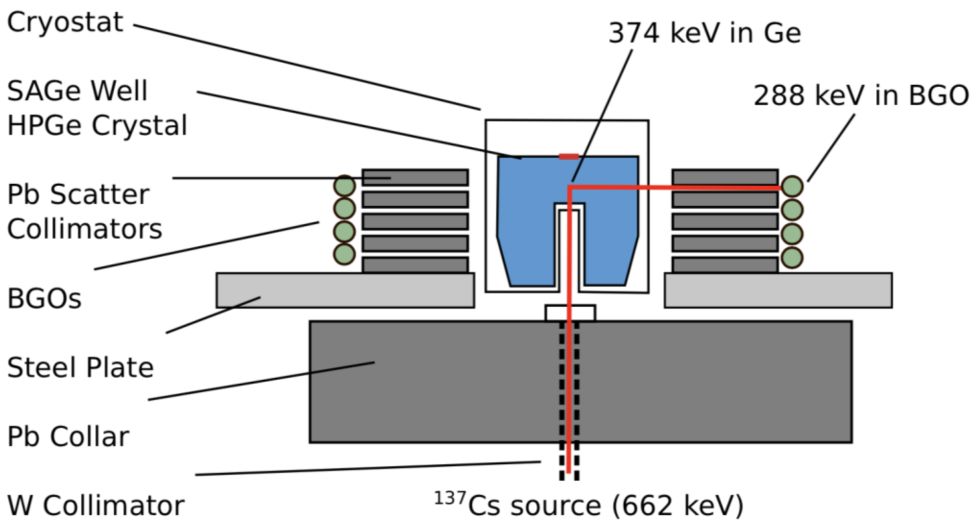
SIGMA: characterisation

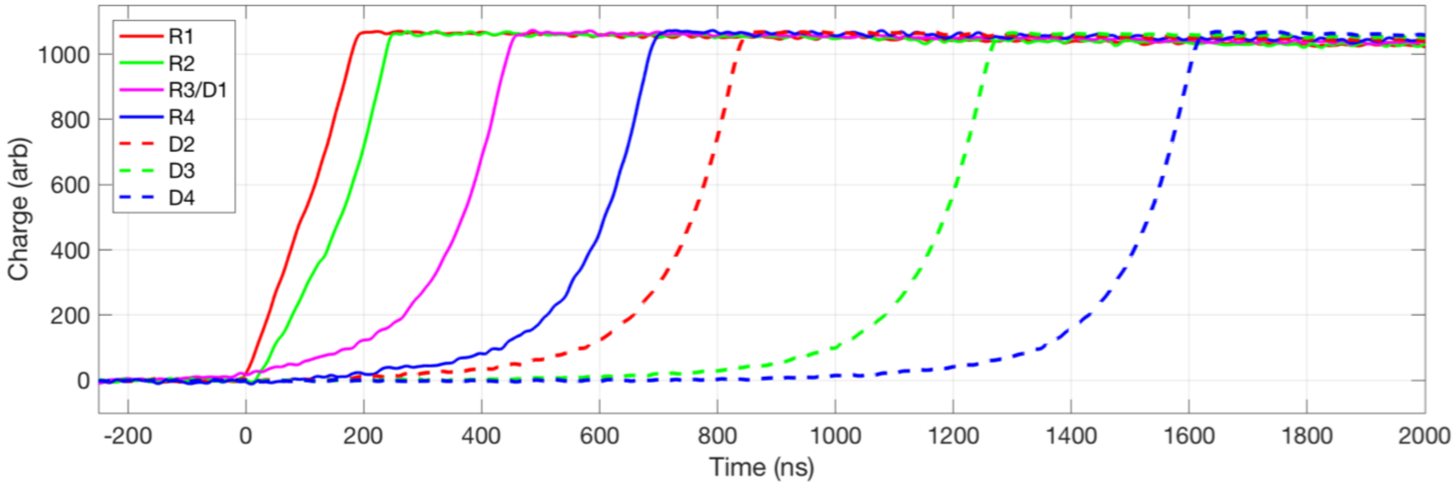
- Scans of charge collections profile
- SSE cuts applied

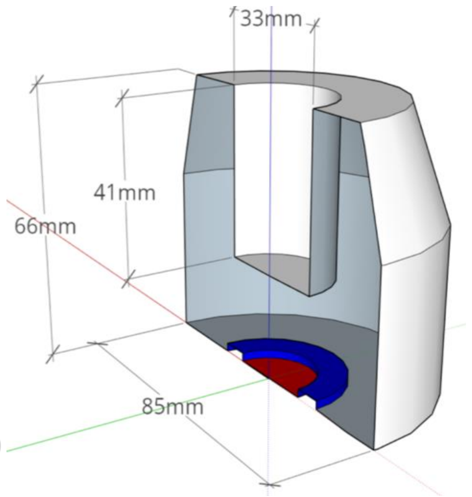


Advanced germanium detector characterisation





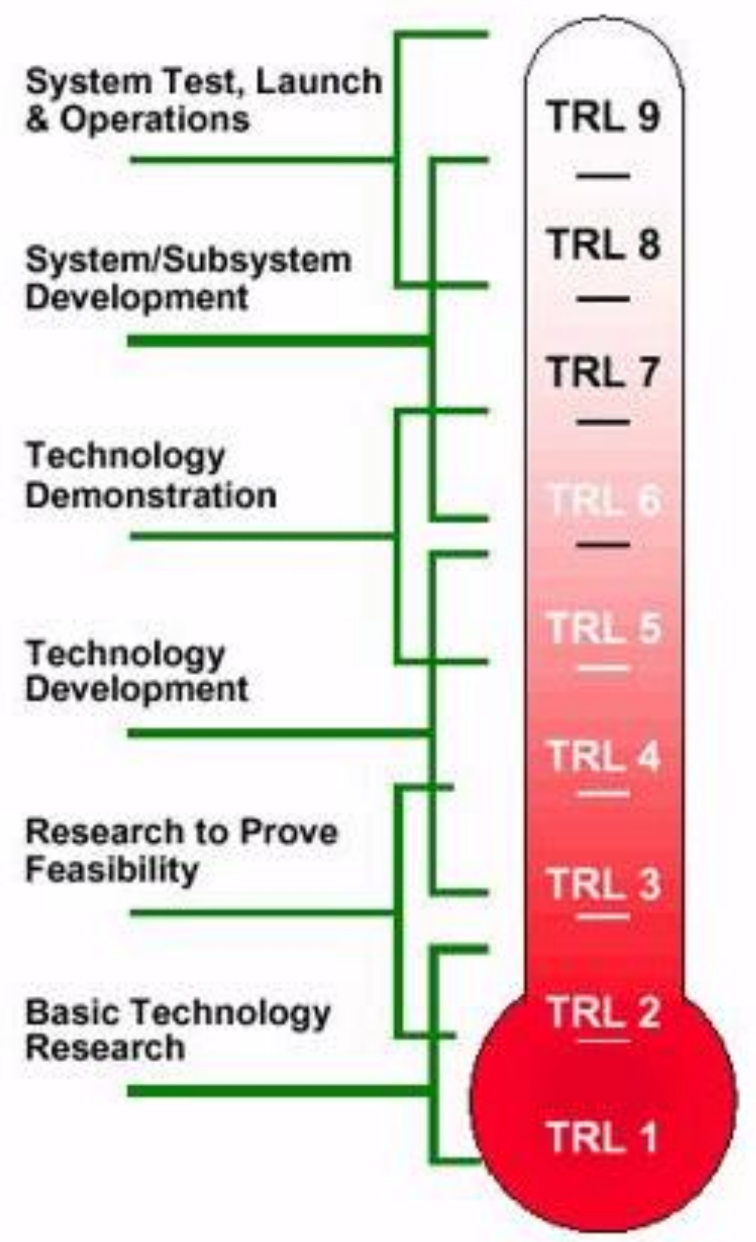




Unsworth *et al.*, NIMA 927 (2019)

Radiation Mapping

- Overview of select commercial technologies
- Performance in decommissioning scenarios
- Next generation imaging
  - Single element
  - Multi element
  - Advanced Scene Data Fusion
- SIGMA detector



Overview of presentation

- **Motivation: Blue sky science**
  - Nuclear Physics – Gamma spectroscopy
  - Neutrino Physics – Double beta decay
- **Imaging Applications**
- **Future technology and direction**

Thanks to.....

MIRION TECHNOLOGIES

NATIONAL NUCLEAR LABORATORY

AWE

NERC SCIENCE OF THE ENVIRONMENT

UKRI Science and Technology Facilities Council

EPSRC Engineering and Physical Sciences Research Council

Imaging the Invisible:
The Evolution of Germanium Detector Technology and Application

Prof Andy Boston

University of Liverpool

ajboston@liverpool.ac.uk

UNIVERSITY OF LIVERPOOL