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Supplement of

The use of muon radiography in safeguarding geological repositories

Lee Thompson et al.

Correspondence to: Lee Thompson (l.thompson@sheffield.ac.uk)

Interdisciplinary research symposium on the safety of nuclear disposal practices

The use of Muon Radiography in Safeguarding Geological Repositories

Lee Thompson, University of Sheffield

on behalf of

Katharina Aymanns, Irmgard Niemeyer, Christiane Vieh, Michael Weekes

12th November 2021

Muons and Muon Tomography

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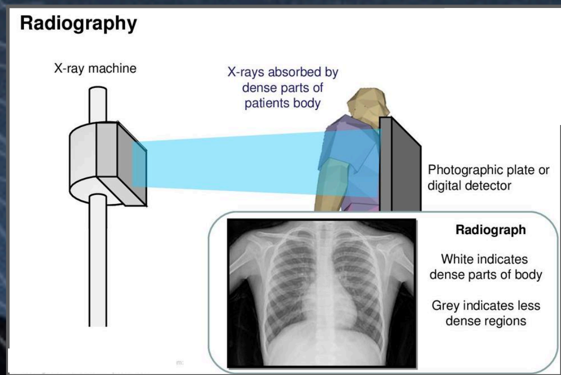
What is a muon?

- Muons are omnipresent fundamental particles that we are constantly bathed in
- They are created in the upper atmosphere
- From an imaging perspective they are both plentiful (1 per cm^2 per minute) and free
- Importantly they are highly penetrating and pass through many tens of metres of rock
- Permits **non-invasive, non-destructive imaging**

What is muon tomography?

- Works in exactly the same way as medical x-ray imaging
- A beam of x-rays (muons) passes through the object of interest
- A “detector” (film or digital system) is placed on the other side of the object of interest
- Density differences in the object are evident in the “image”



- However there are differences: muons are free and more penetrating than X-rays

Muon Tomography Track Record

- This is not a new technique, it was first used to measure tunnel overburdens in 1955 and has been famously used to image pyramids and the magma chambers of volcanoes
- Currently undergoing a huge renaissance with many applications


Commonwealth Engineer, July 1, 1955

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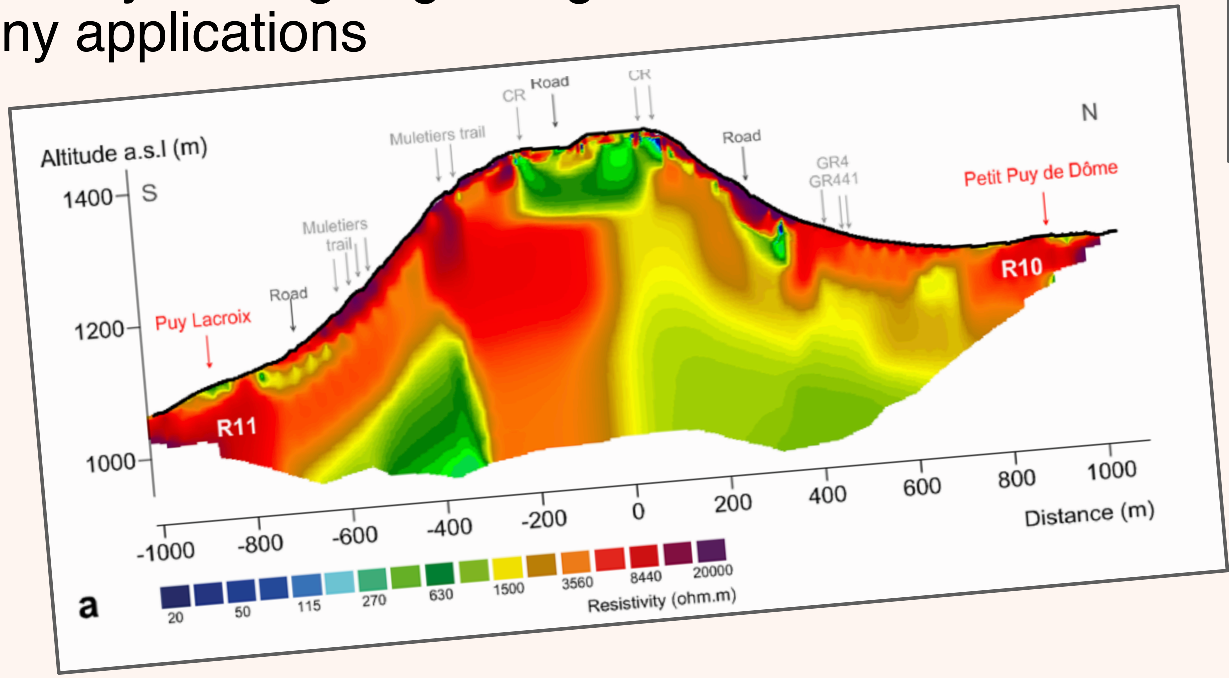
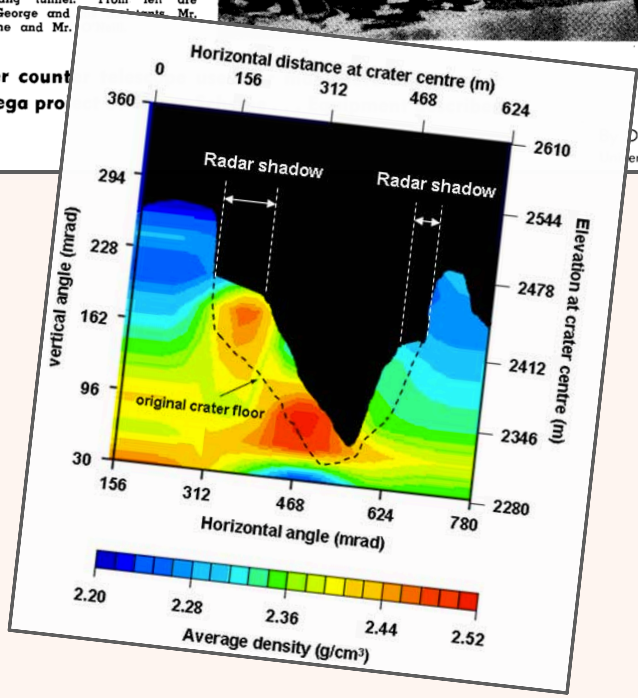
Cosmic Rays Measure Overburden of Tunnel

● Fig. 1—Geiger counter "telescope" in operation in the Guthega-Munyang tunnel. From left are Dr. George and ... Mr. Lehane and Mr.

Geiger count...
Guthega pro...

...r. E. P. George
...ersity of Sydney, N.S.W.





Applications of Muon Tomography

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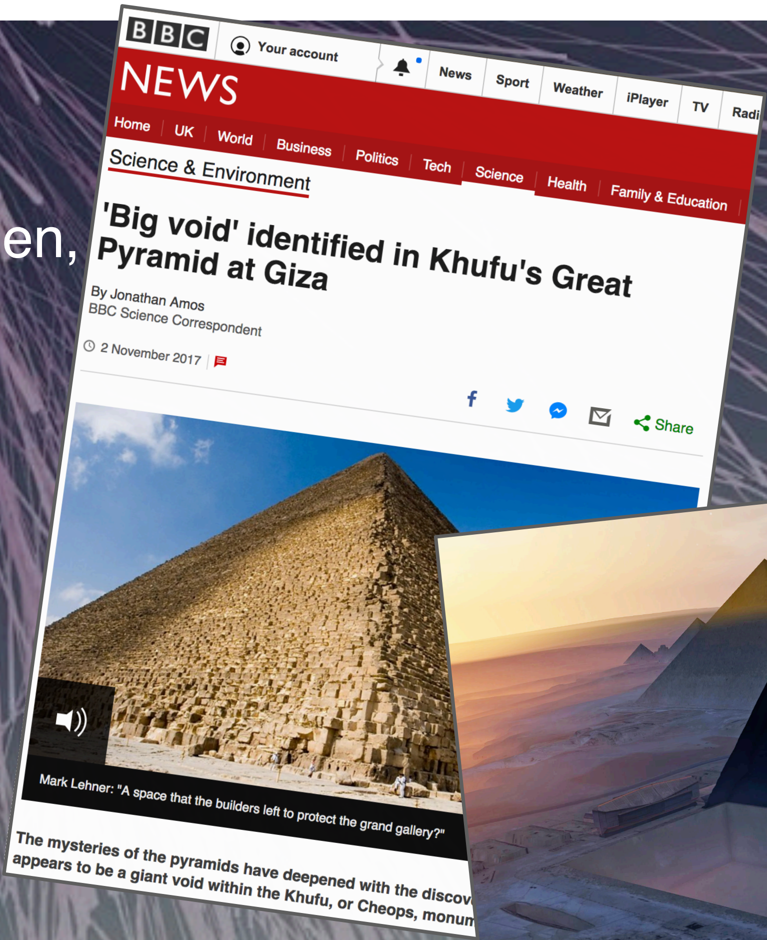
- Civil infrastructure:
  - Tunnels
  - Viaducts
  - Bridges

  } unknown voids, water in overburden, etc.
- Blast furnace imaging
- Glaciers - ice thickness measurements
- Volcanoes - magma chambers
- Mining - ore body imaging
- Stored CO_2 (carbon capture and storage)
- Pyramids / Archaeology
- **Imaging during nuclear waste storage and/or disposal**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Science & Environment

'Big void' identified in Khufu's Great Pyramid at Giza

By Jonathan Amos
BBC Science Correspondent

2 November 2017

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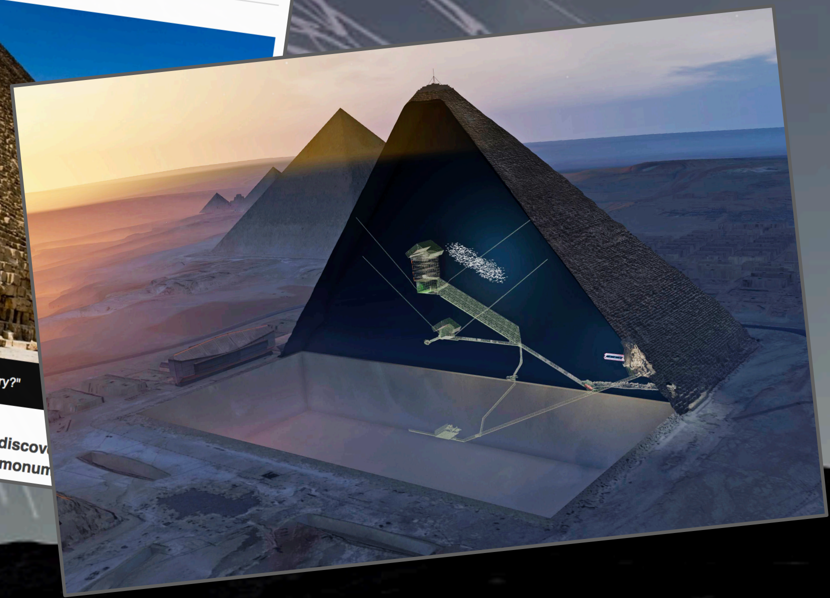
Mark Lehner: "A space that the builders left to protect the grand gallery?"

The mysteries of the pyramids have deepened with the discov
appears to be a giant void within the Khufu, or Cheops, monum



Muon Tomography and Geological Repositories (GRs)

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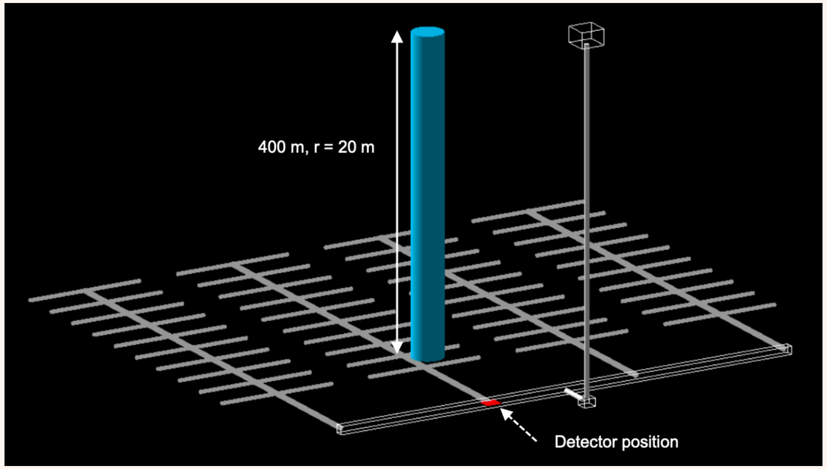
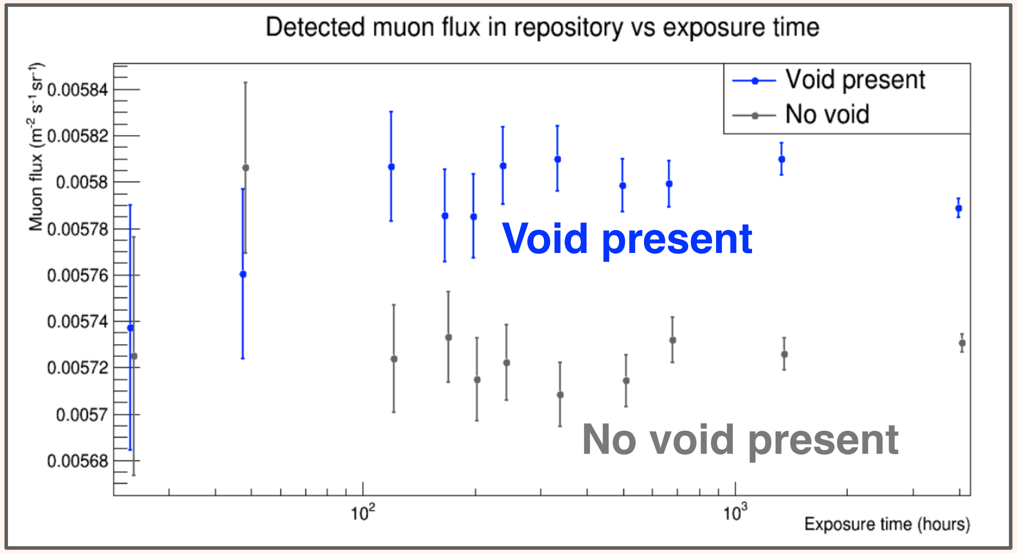
- Civil infrastructure imaging and imaging of ore bodies in mines with muons is already underway
- For example: in the UK the technique is being used to search for hidden shafts in railway tunnels
- Elsewhere in the world nickel and uranium ore bodies are being located without the need for drilling boreholes





- In general muon tomography is a powerful tool for locating irregularities in overburdens
- Initial proof of principle studies have simulated the ability to detect a large unknown shaft in a GR with a single detector
- CAVEAT: going deeper requires large area detectors and/or long measurement times

Muon Tomography and Geological Repositories (GRs)

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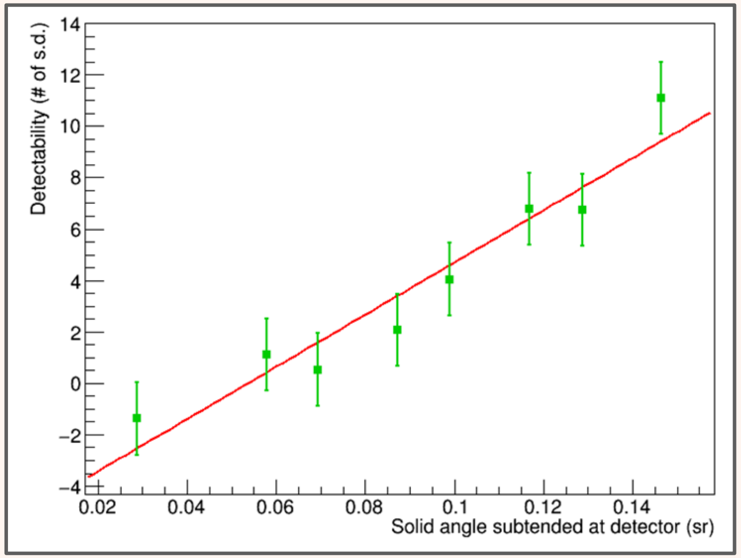
- Other studies have looked at the detectability of an unknown feature in the GR as a function of the solid angle that the feature presents at the detector
- Note: multiple detectors plus imaging techniques such as SART and/or use of machine learning methods should considerably reduce the time needed to detect a feature



<u>Possible application to GRs:</u>

- design information verification
- continuous geological overburden monitoring for overburden change detection
- understanding the condition of the host geology
- searching for undocumented voiding
- checks of backfill integrity in the vaults
- tunnel lining system checks/monitoring
- sensitivity to water ingress and movement in the overburden
- long-term monitoring of the GR post-closure

<u>REMINDER:</u> muon tomography is non-invasive and non-destructive

<u>COMMENT:</u> data fusion from seismic and muon radiography studies will be beneficial in some of these applications (resolves all material properties)

Muon Tomography - Other Methods

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Muon Radiography ("Muography")

- Works in exactly the same way as medical x-ray imaging
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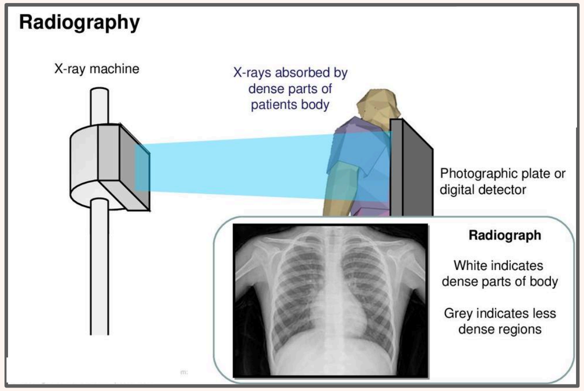
- Density differences in the object are evident in the "image"
- However there are differences: muons are free and more penetrating than X-rays

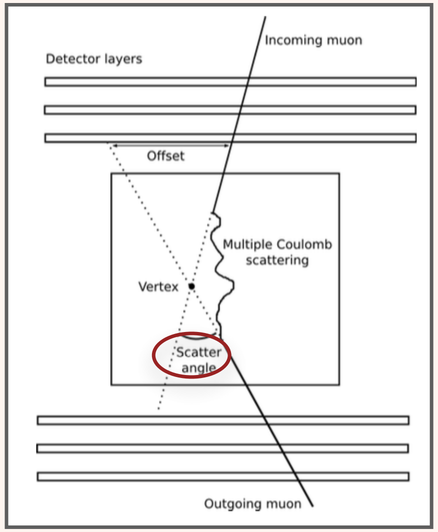


Muon scattering tomography ("MST")

- By placing muon detectors both above and below (or either side) of the object of interest <u>additional information </u>(about the nuclear composition) of the object being imaged can be determined
- Larger scattering angles correspond to materials with high atomic number Z

$$\sigma = \frac{13.6\,\text{MeV}}{pc\beta} z \sqrt{X/X_0}\left(1 + 0.038 \ln(X/X_0)\right)$$

$$X_0 = \frac{A \cdot 716.4\,\text{g/cm}^2}{Z(Z+1)\ln(287/\sqrt{Z})}$$



Bubble ID in Heterogenous Waste Drums

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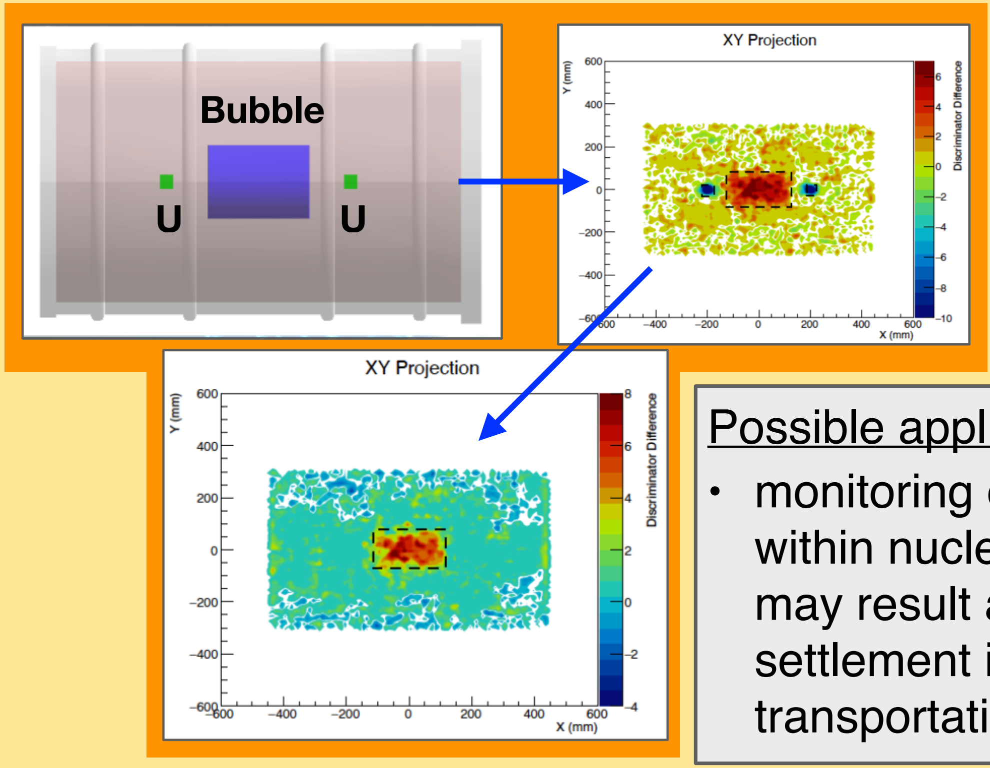
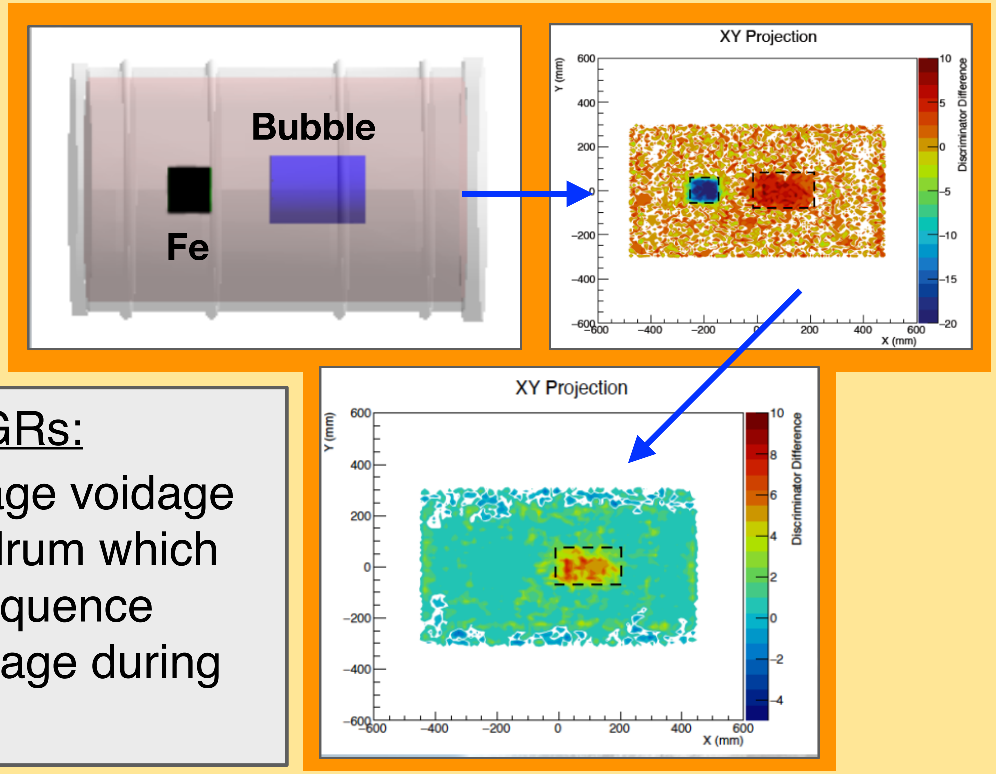
- Gas bubbles can form within the matrix of a waste drum and are a concern. Using muon scattering tomography bubbles can be identified and their volume accurately determined





Possible application to GRs:

- monitoring of in-package voidage within nuclear waste drum which may result as a consequence settlement in the package during transportation

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 755371.

Material ID in Heterogenous Waste Drums

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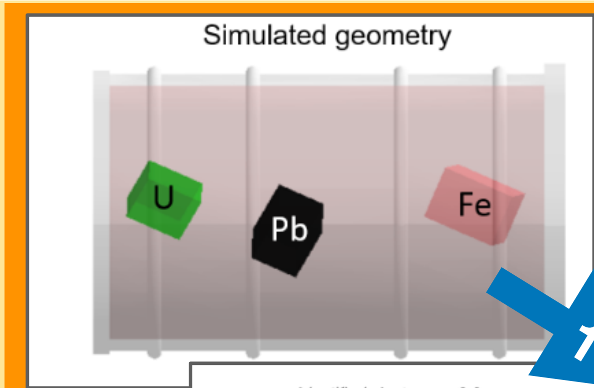
A method has been developed to perform material identification using **machine learning techniques**

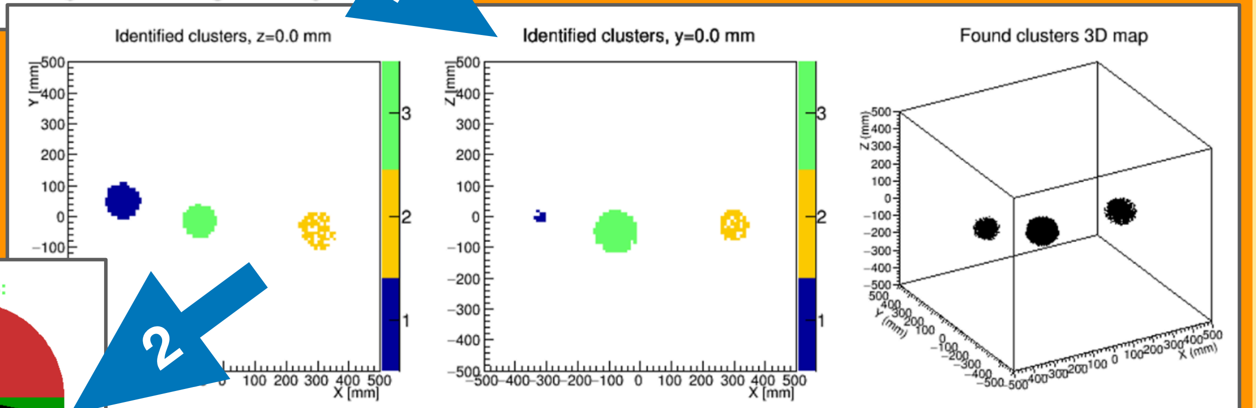
STEP 1: identification of material boundaries in the waste drum which has a concrete matrix

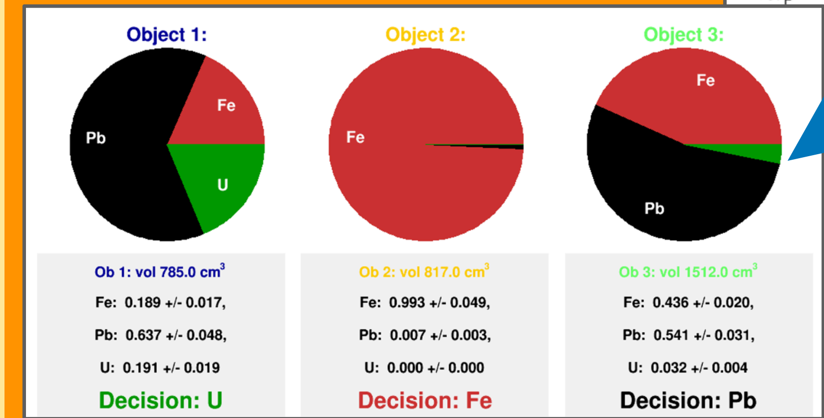
STEP 2: uses machine learning MVA algorithms to assign a probability for each identified object being a particular material. See https://arxiv.org/abs/2012.01554



Possible applications to GRs:

- safeguarding any outgoing potentially-empty package (e.g. MST would be able to confirm, quickly, any presence of high-Z material in the outgoing package that shouldn't be there)





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Safeguards Applications

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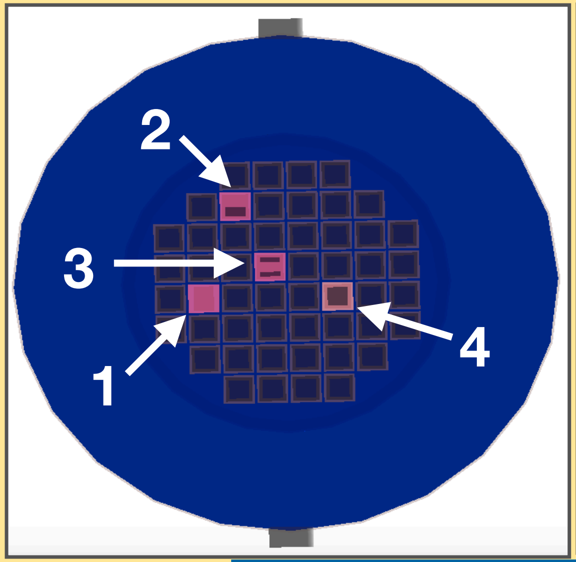
Looking at the potential for muon scattering tomography to identify possible changes to a CASTOR drum

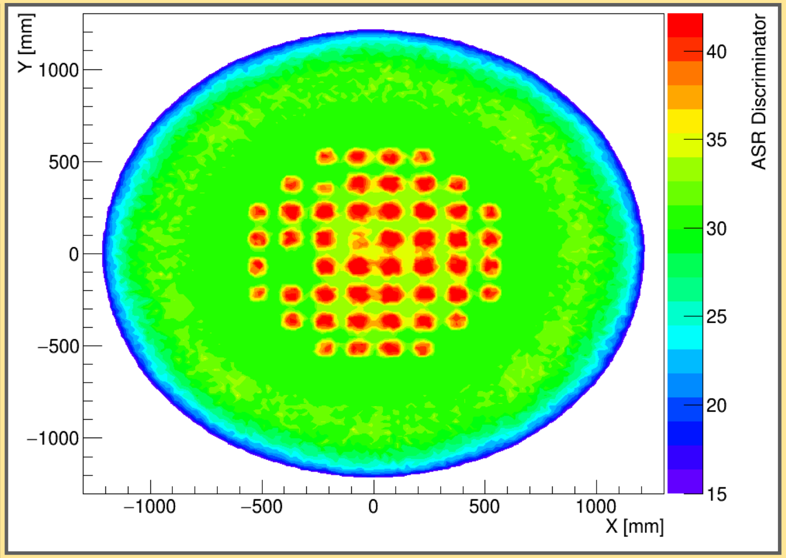
Possible applications to GRs:

- confirming that a full complement of in-package components is present (no unauthorised diversion of materials)
- confirmation that out-going packages are truly empty

Diversion Scenarios considered:

1. Empty basket
2. Half-loaded basket (Unloaded side fuel assemblies)
3. Half-loaded basket (Unloaded centre fuel assemblies)
4. Pb pellets basket (UO_2 pellets replaced by Pb pellets)





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Conclusions

- Muon tomography is a powerful tool that exploits naturally occurring radiation to form images of objects in a non-invasive and non-destructive way
- It has been famously used to search for hidden chambers in pyramids and to image the magma chambers in volcanoes
- The technique is currently applied globally to a huge range of applications including imaging of civil infrastructure, mines, nuclear safeguards and material control, homeland security
- Within the management of nuclear waste there are a number of areas where muon radiography is a promising technology to address specific problems such as geological repository design information verification, integrity assurance and long-term monitoring
- Similarly, muon scattering tomography offers the possibility to identify issues such as material diversion, package voiding and material identification.