Muon radiography for carbon storage monitoring

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Carbon capture and storage (CCS)

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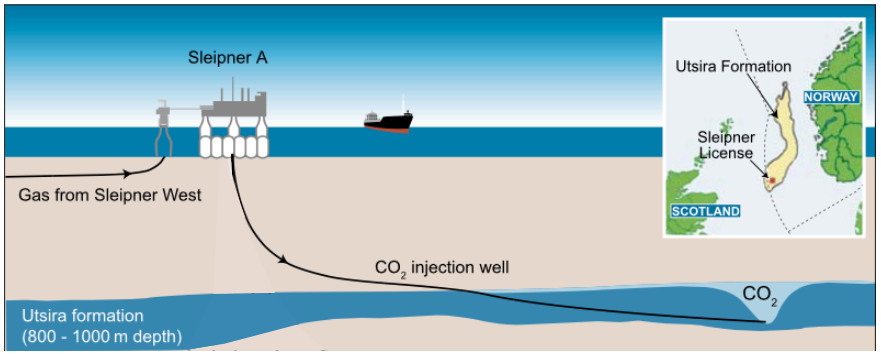
- Capture CO_2 --> Compress --> Transport --> Injection.

Sleipner Field, North Sea



Monitoring CO_2

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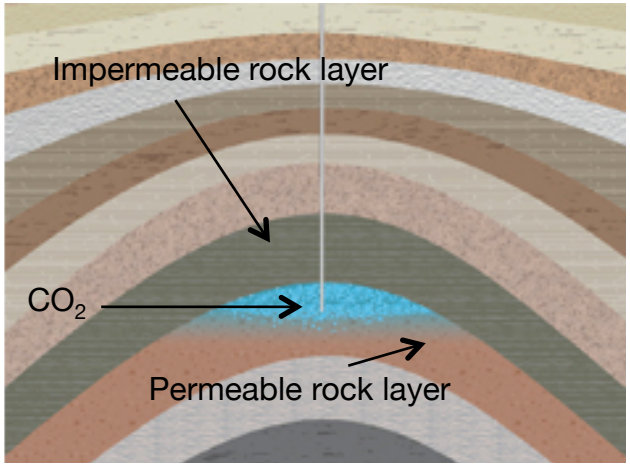
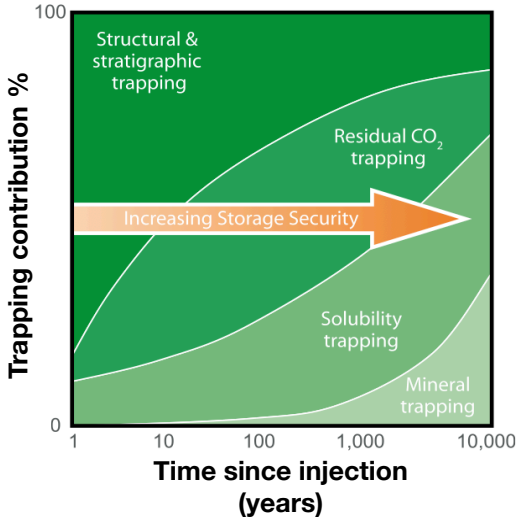
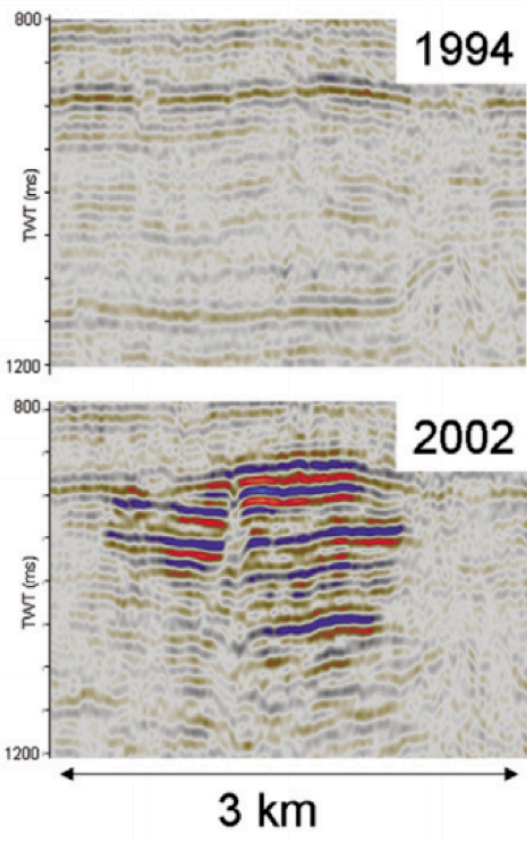
- Structural trapping dominates in the early stages after injection.
- Monitoring of the CO_2 plume is required to understand emplacement within the reservoir.
- After injection there is an overall **change in bulk density** of the rock.







Muon radiography

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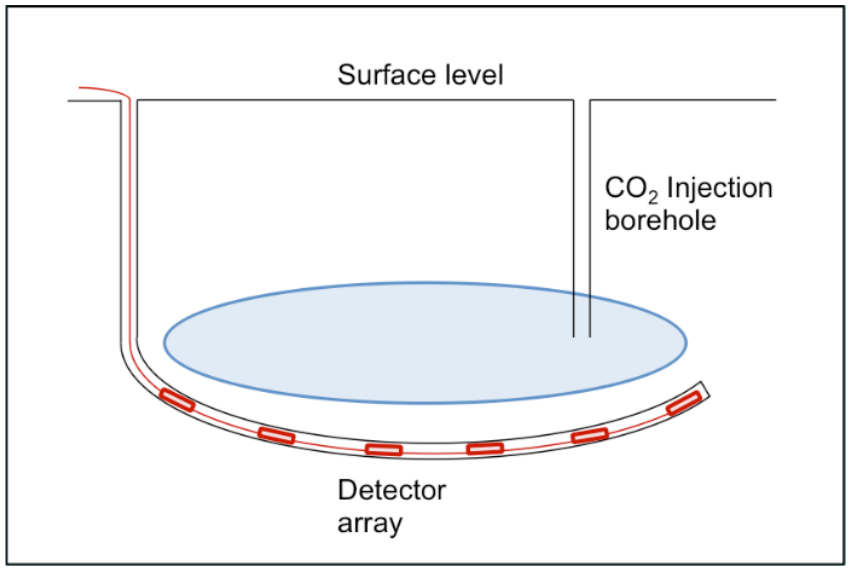
- Cosmic-ray muons are produced in the upper atmosphere, their spectrum on the Earth's surface and underground is well known.
- Survival probability and therefore intensity of muons is fundamentally associated with the density of material they propagate through.

Search for Hidden Chambers in the Pyramids [1]

The structure of the Second Pyramid of Giza is determined by cosmic-ray absorption.

Luis W. Alvarez, Jared A. Anderson, F. El Bedwei,



[1] **Alvarez et al. *Science*, 167 (1970).**

Muon detectors for CCS monitoring

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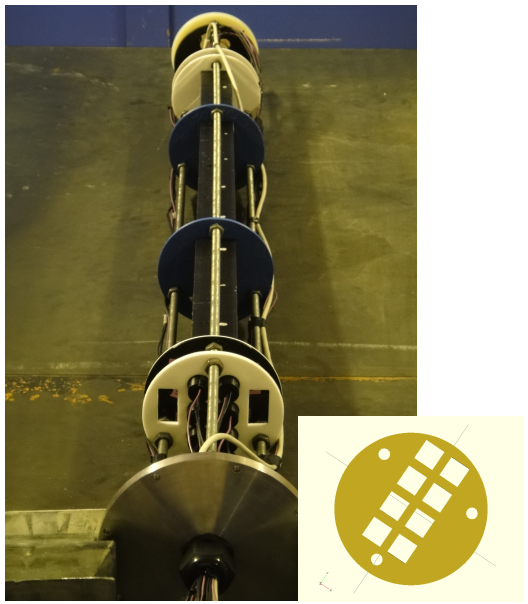
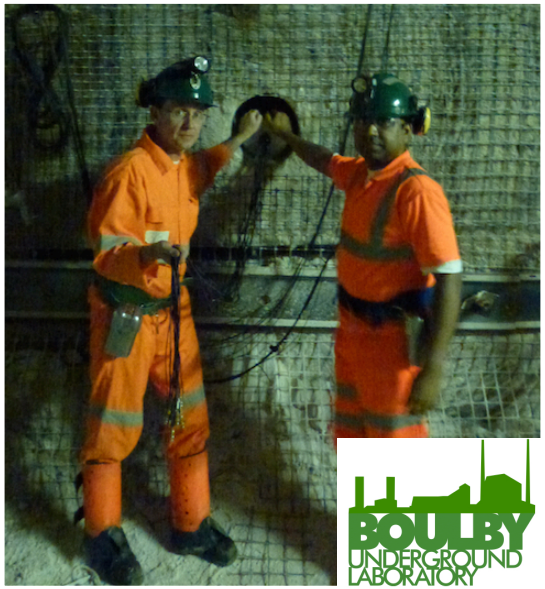
- Array of muon detectors to fit in existing boreholes or side tracks from a mother well – 5.5” cross-sectional area, high temperatures (> 50°C).
- Plastic scintillator rods arranged inside a cylindrical casing to determine muon trajectory.





Simulation software

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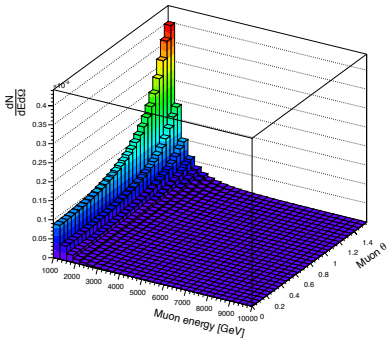
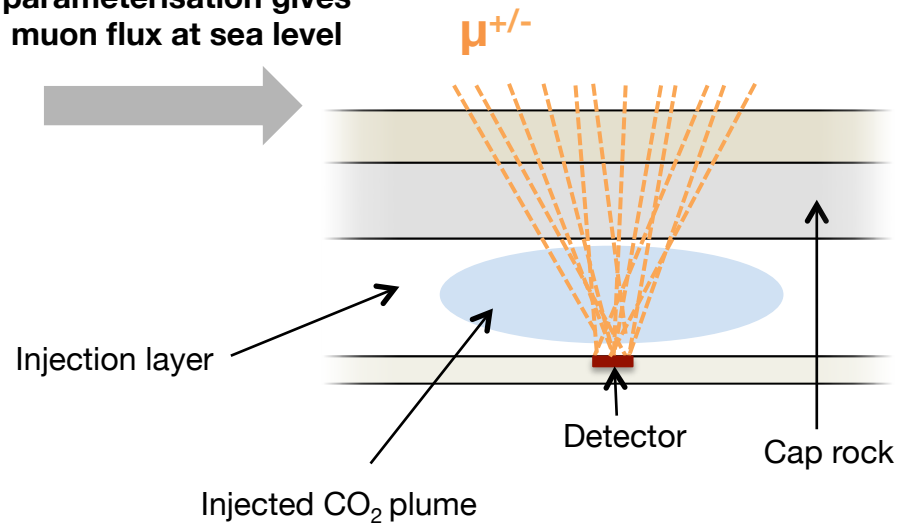
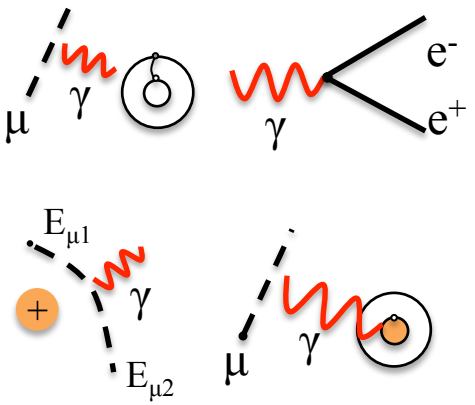
- Is there a significant change in muon intensity after CO_2 injection?
- Muon transport simulation using a) GEANT4 or b) tracing muons through the rock layers and considering total column density changes.



Gaisser's parameterisation gives muon flux at sea level





Geological modelling

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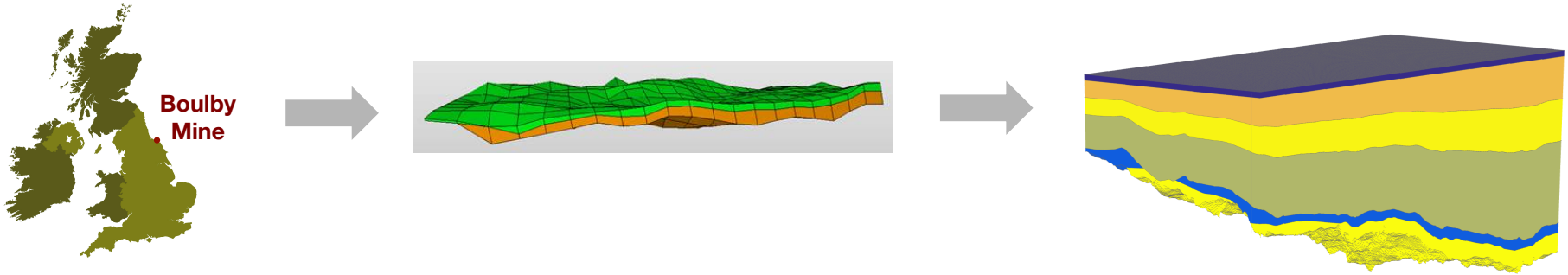
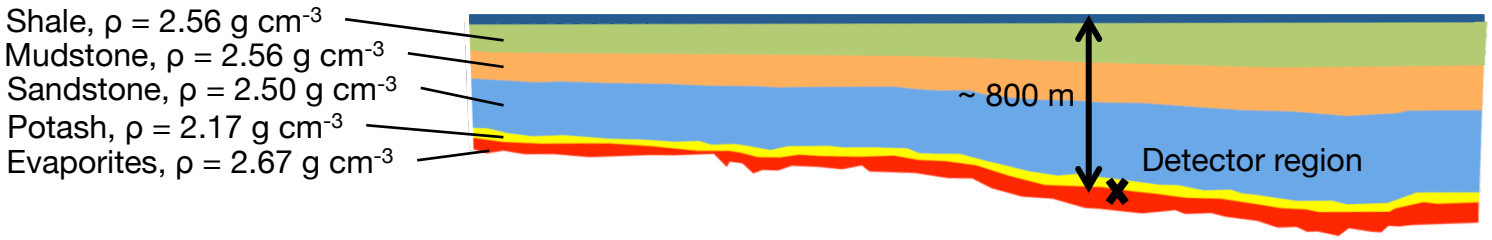
- Geocellular models of the geology of a storage reservoir can be produced. Typically they are exported in a standardised format as a corner-point grid geometry.
- Model these grids as a collection of triangular and quadrangular meshes to store in ROOT for construction in GEANT4.





CO_2 plume distributions

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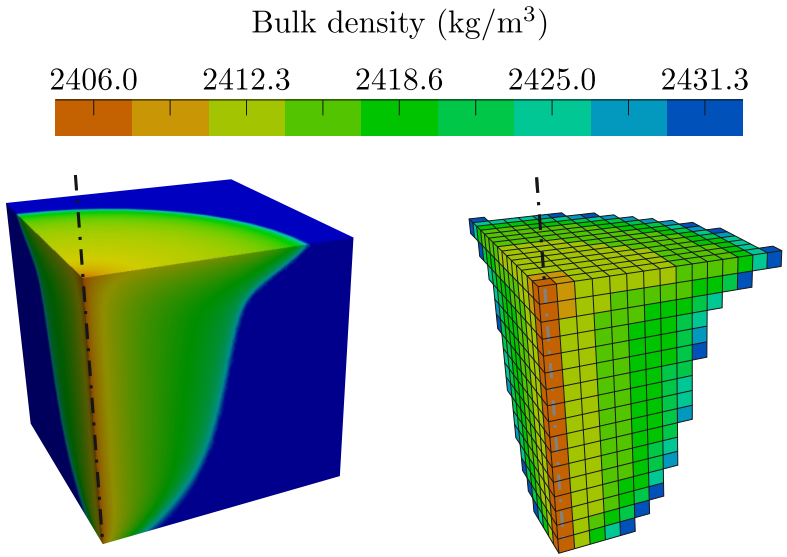
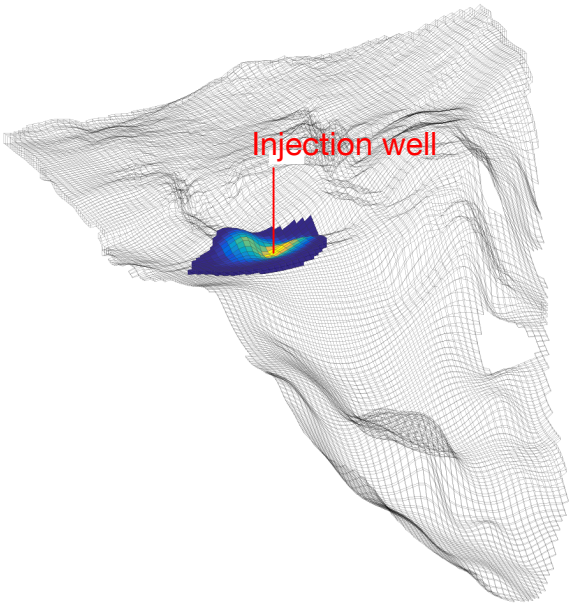
- A numerical model [2] is used to calculate the spatial and density distributions of CO_2 after injection starts.
- The distributions are either voxelised then superimposed onto the GEANT4 geometry or incorporated directly into the geocellular model.





[2] **D. Lincoln et al., Numerical Methods in Geotechnical Engineering, 989–994.**

Results – Boulby Mine

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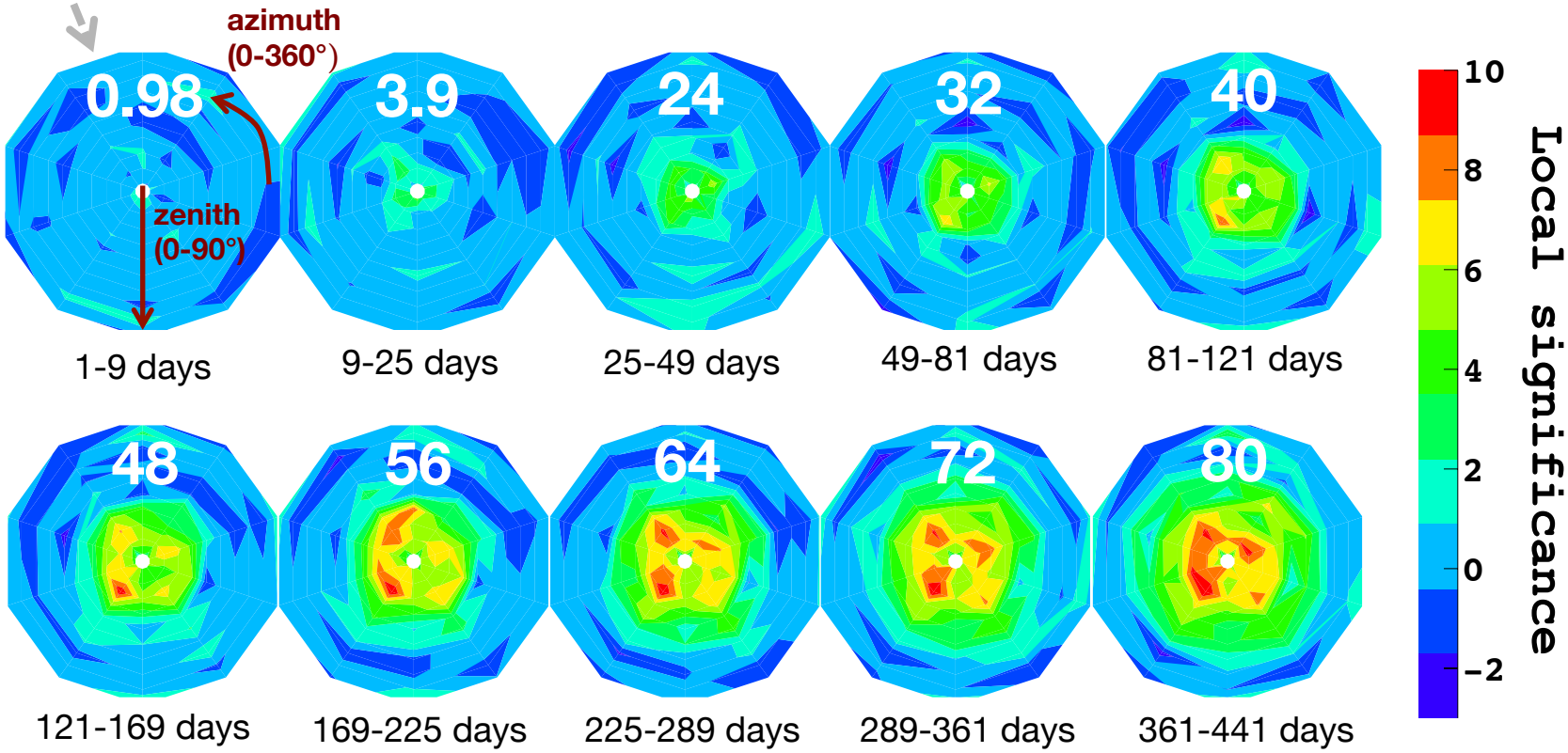
Global significance, $S = \frac{N_0 - N_1}{\sqrt{N_0 + N_1}}$



Results - Hewett Field

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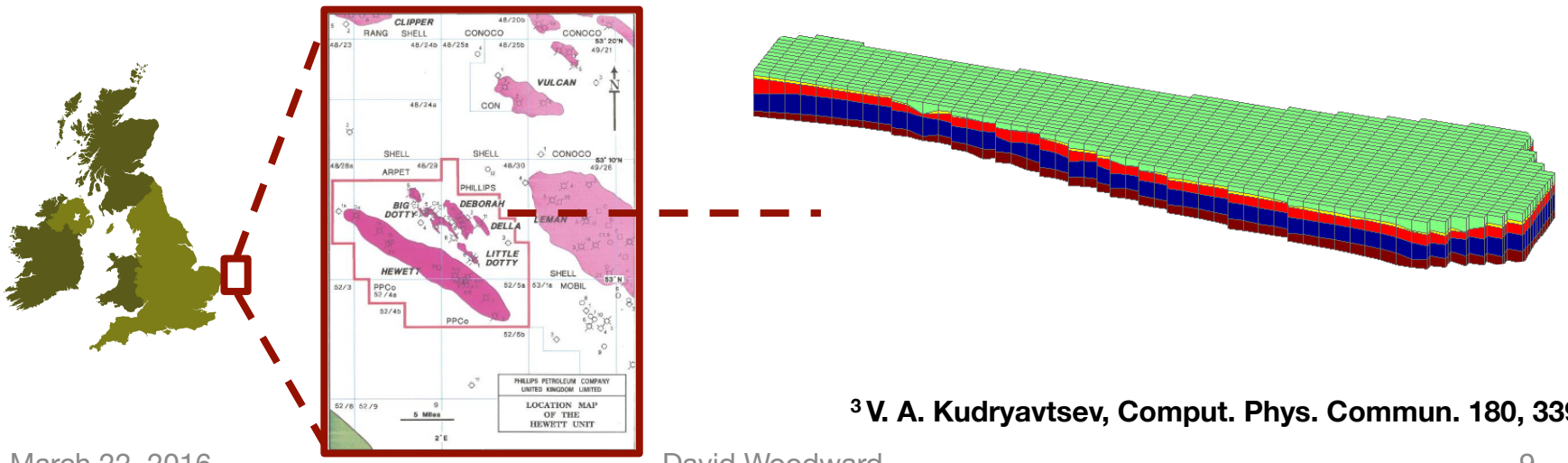
- Hewett is a depleted gas field that considers injection into a Sandstone layer above a detector depth ~ 1.3 km.
- Depleted gas field, at low pressure so the density changes after injection are small (<1%).
- Based on the total column density changes and muon transport using MUSIC code [3], significant deviation in the muon intensity after ~ 290 days.



[3] V. A. Kudryavtsev, Comput. Phys. Commun. 180, 339.

Outlook

- Muon simulations demonstrate the potential of muon radiography for monitoring CCS sites.
- A prototype detector has been developed and deployed underground.
- Further work will look more closely at backgrounds from rock radioactivity, trigger conditions and analysing data from the prototype detector.

For more see: Klinger, J., et al. International Journal of Greenhouse Gas Control 42: 644-654.

Backup slides

Efficiency studies

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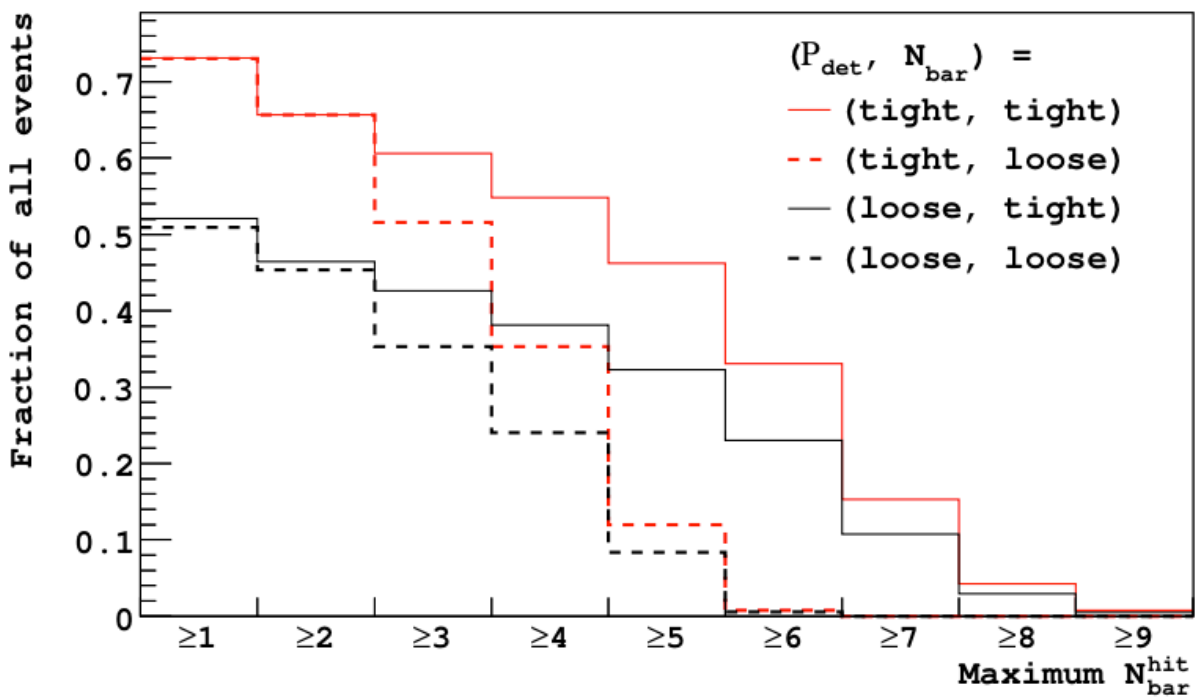
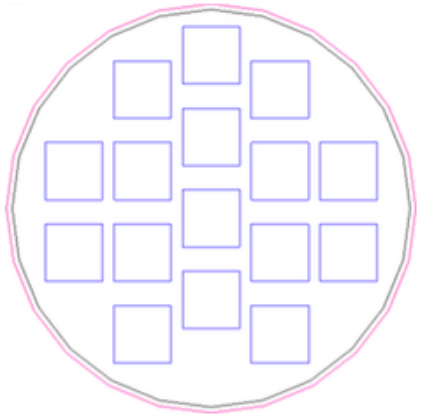
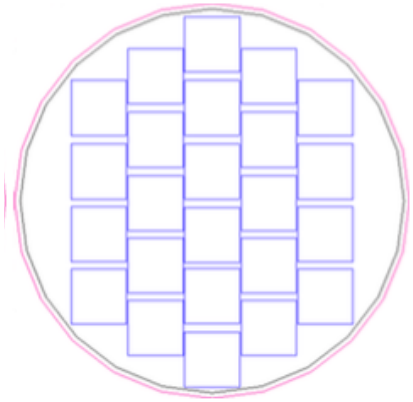




(a) Loose bar packing (16 bars)



(b) Tight bar packing (24 bars)

P_{det} is detector packing fraction; **tight = 75%, loose = 50%.**