Muography applied to nuclear waste storage sites

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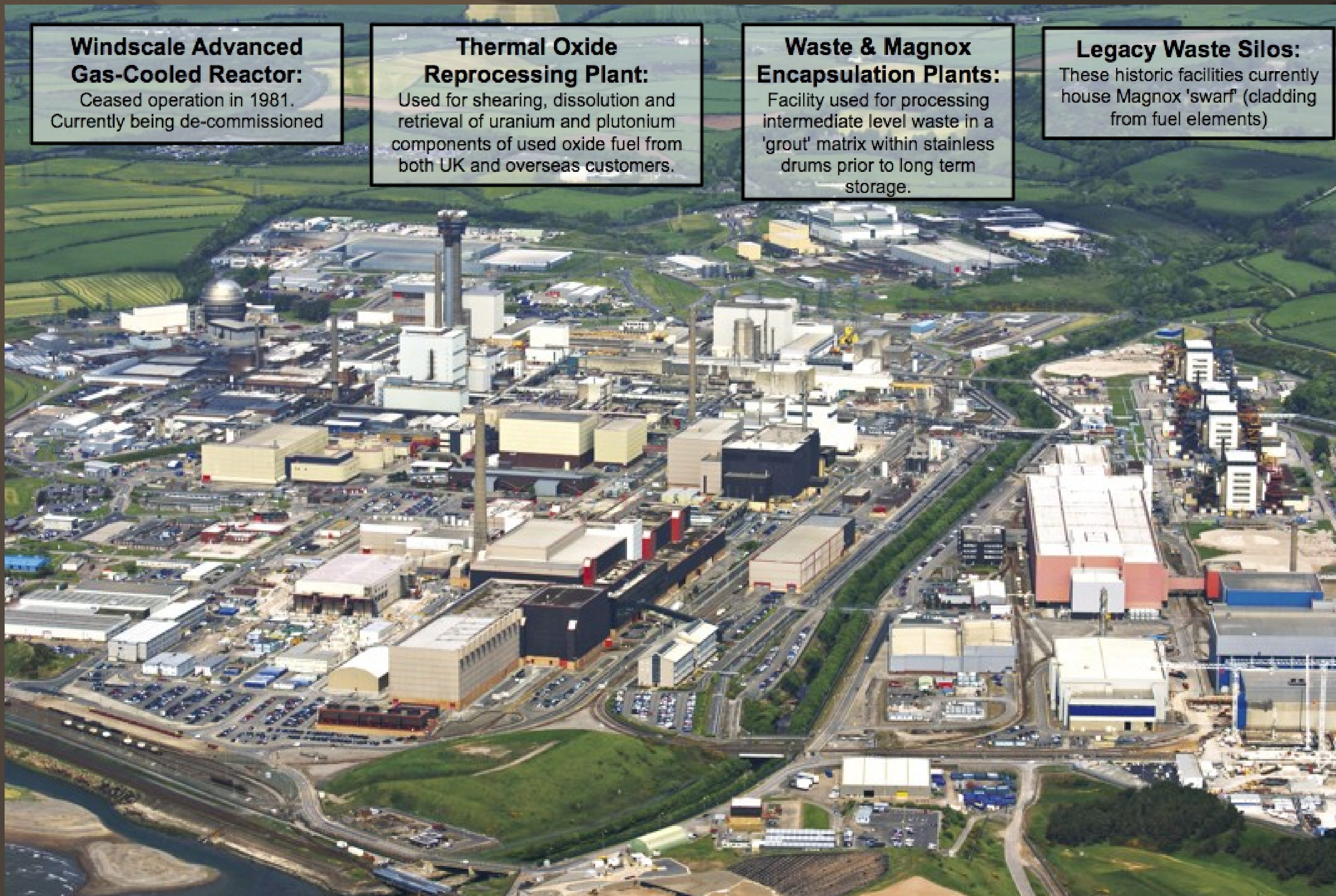
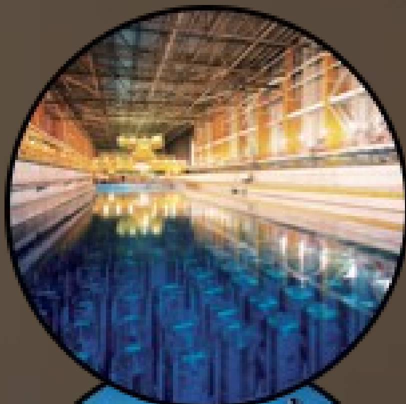
For the material in these slides I would like to thank:
David Mahon from Glasgow University
and especially
Nicola Mori from the University of Florence

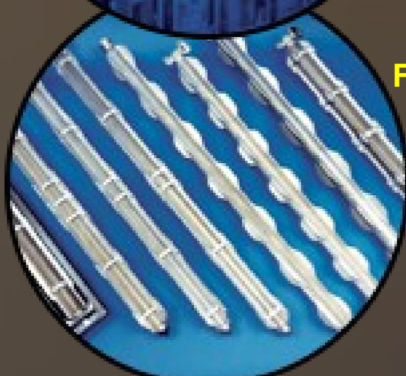
Nuclear waste management, i.e. Sellafield



- Images courtesy of Sellafield Ltd. (www.sellafieldsites.com)

Storage



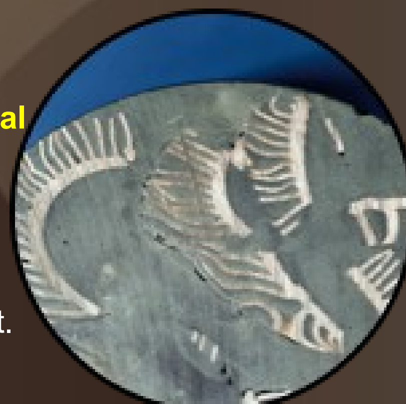


Fuel Element Swarf Removal

The swarf is stripped from the fuel element in the Fuel Handling Plant. The fuel is then transported to the Magnox Reprocessing Plant.

Magnox Fuel Elements

Uranium fuel surrounded by a magnesium alloy 'swarf' cladding. Before reprocessing, irradiated Magnox fuel must be stored for at least 180 days in ponds to allow short lived fission products to decay.

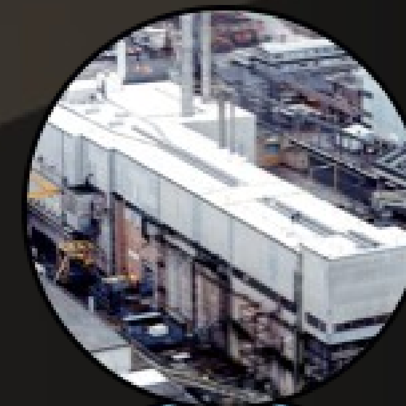


Encapsulated Swarf

The swarf stripped from the fuel elements is Intermediate Level Waste (ILW). Shown is a cross section view of ILW which has been grouted in cement for long term storage.

Long-term Storage of ILW

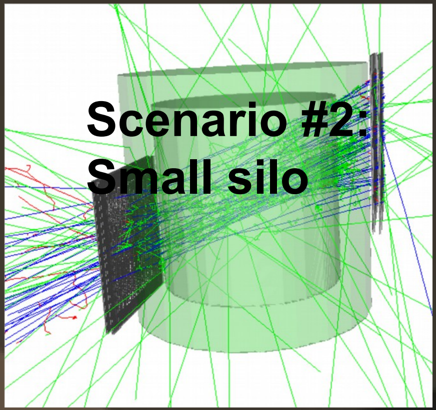
The ILW is stored in 500-litre stainless-steel waste containers (shown here for a test drum with outer section removed) or in $3m^3$ boxes.



Magnox Swarf Storage Silos

Prior to the encapsulation of dry waste, 'wet storage' of Magnox swarf was undertaken within silo facilities. Retrieval and treatment operations are in development.

Scenarios



Scenario #1:

With ideal detector placement (i.e. above and below) can a 10cm cube of uranium in Scenario #1 be imaged by absorption muography ? This is usually the realm of multiple scattering measurements. And what about smaller cubes ?

Scenario #2:

In principle, it is possible to obtain an image from this silo though the size, timescales and image resolution are yet to be fully established. This is the Scenario for which I will show some preliminary feasibility studies.

Scenario #3

If Scenario 2 → OK, then imaging of a full scale silo will be investigated. Determine which of the compartments (if any) can be imaged successfully using the Muography approach.

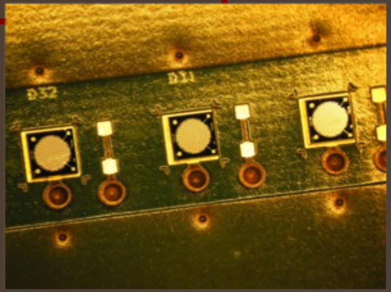
The Muray detector

- TRIANGULAR SCINTILLATOR BARS WITH WLS FIBERS
- SILICON PHOTOMULTIPLIERS
- CUSTOM FRONT END ELECTRONIC BASED ON EASIROC ASIC
    - ❖ LOW POWER CONSUMPTION
    - ❖ SELF TRIGGERING
    - ❖ TIME MEASUREMENT
    - ❖ CHARGE MEASUREMENT
    - ❖ LOW COST
- CUSTOM STANDALONE DAQ

The full detector: 3 X-Y planes , 384 ch

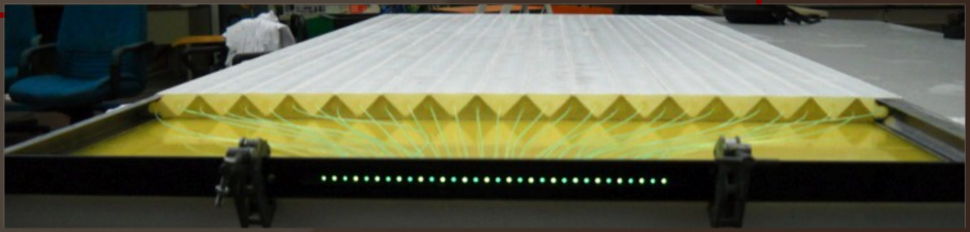
DETECTOR PERFORMANCES:

SPATIAL RESOLUTION: some mm
TIME RESOLUTION : < 1ns
PLANE EFFICIENCY : > 95%
TOTAL POWER CONSUM.: < 50 W
COST: O(100) k€ / 1 m^2 detector



Particular of SiPMs bonded on the PCB carrier

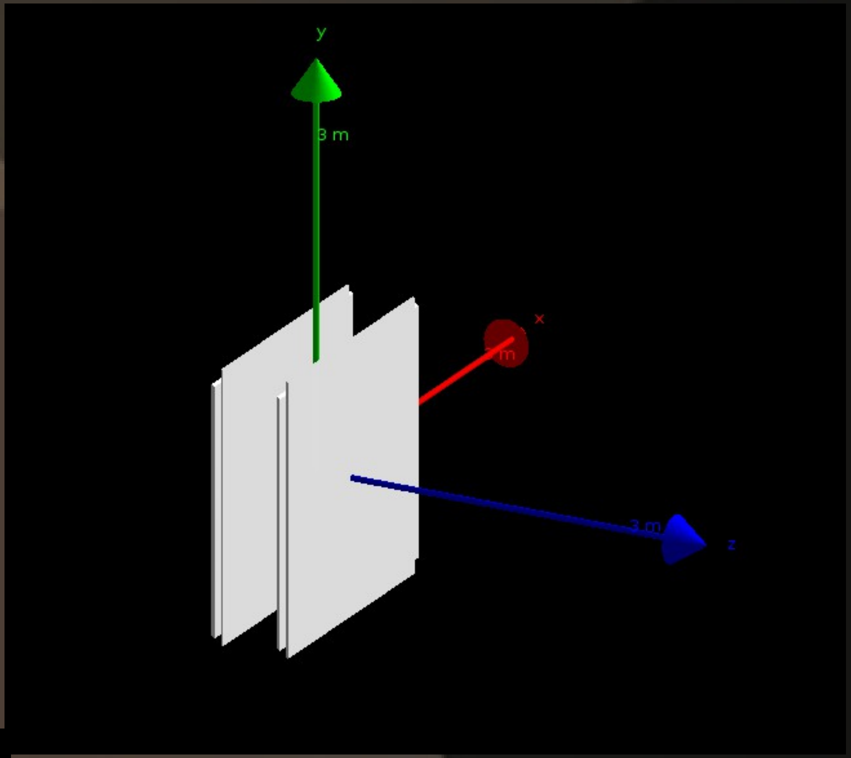
One FEE board (32 channels)

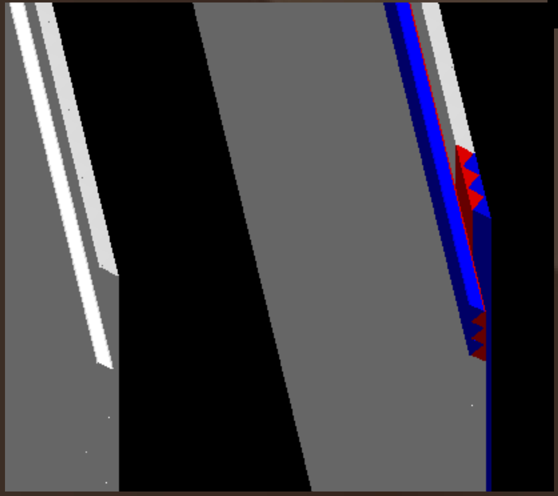


One module: 32 bars with WLS fibers

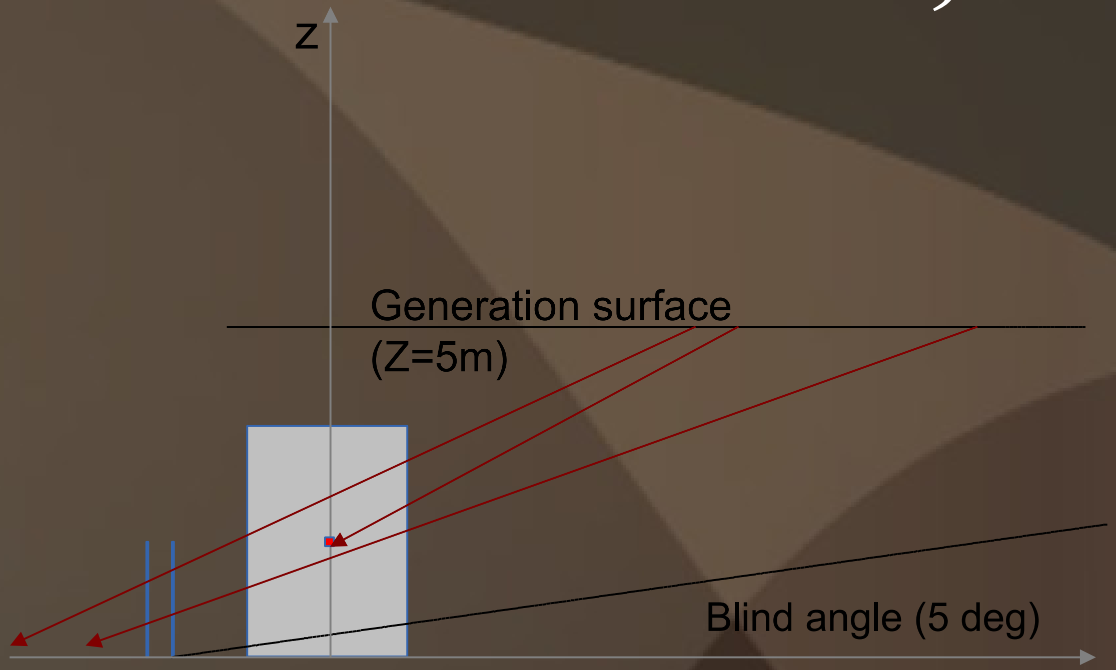
Simulations with Geant4

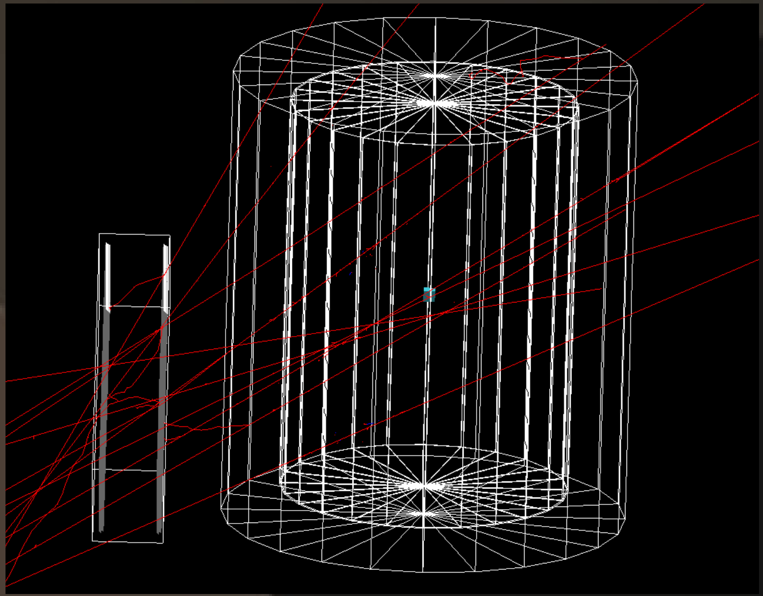
- 2 XY layers made of plastic scintillating bars
- Triangular bar section
- 2m x 2m detector surface
- Can be placed in any position and orientation
- Can be deployed multiple times inside simulation scenario (eventually)

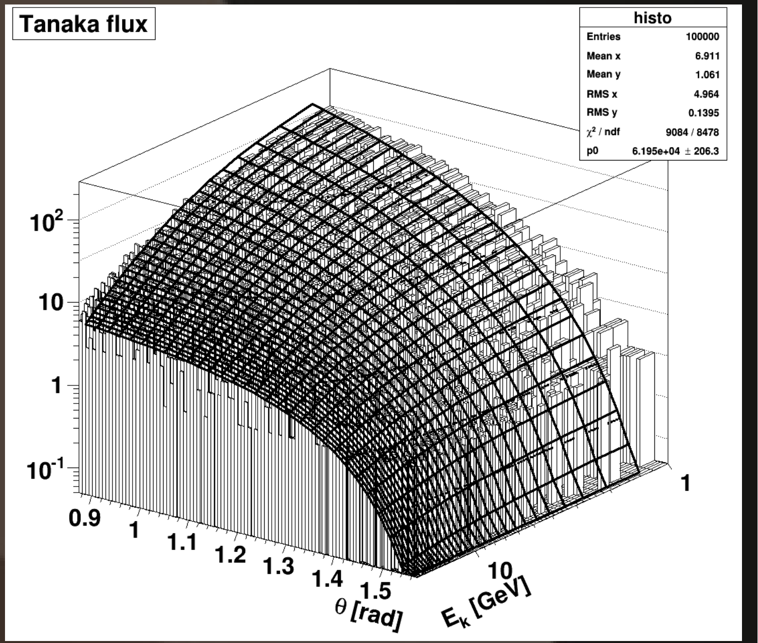




Geant 4 simulation, Scenario 2



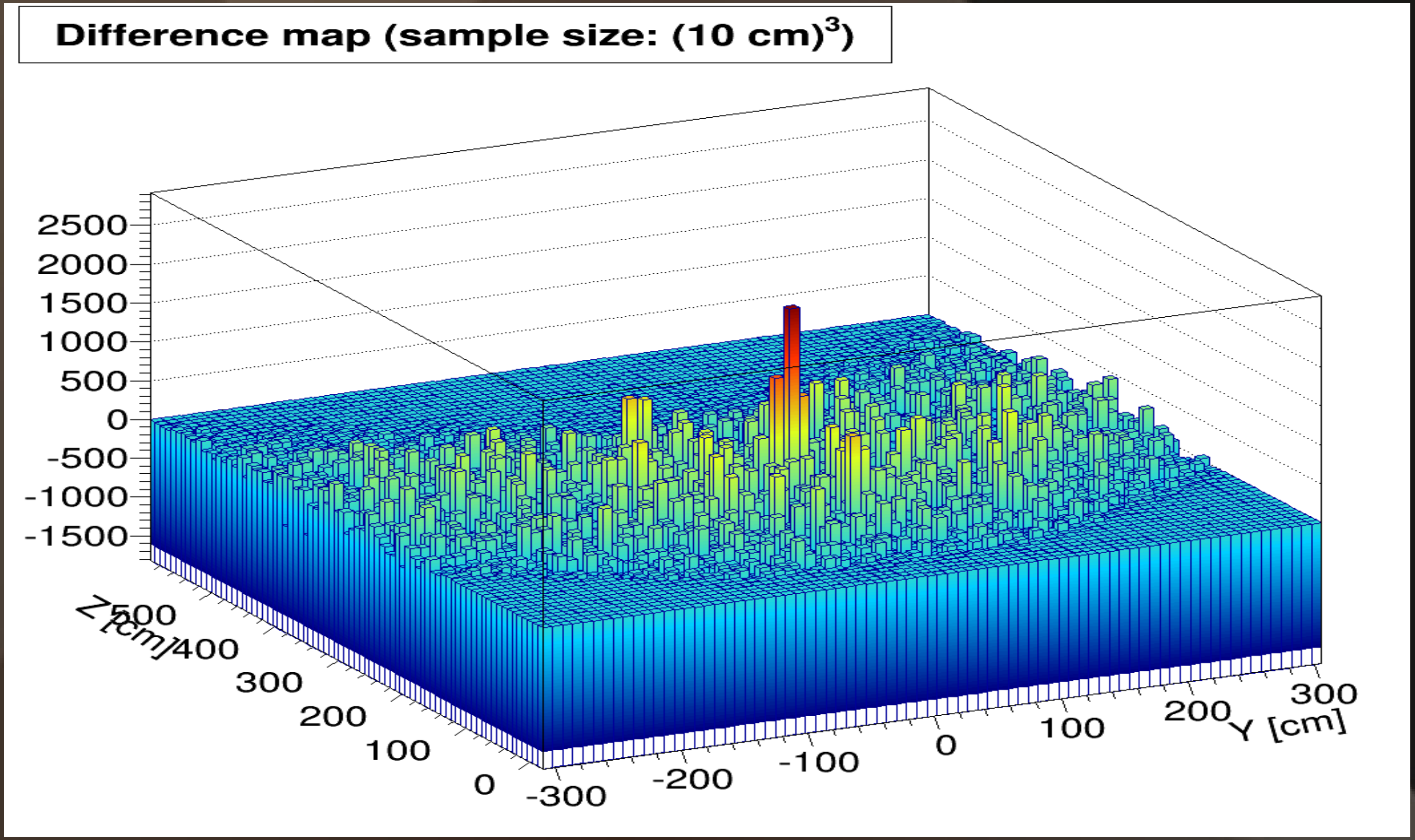




- Sellafield scenario #2 (small silo): (10 cm^3) U sample @ (0, 0, 2) m (center of silo)
- Background simulation without U
- Realistic input spectrum: Tanaka et al., Hyperf. Int. 138 (2001) 521-526

Muon absorption map

- $5x10^{10}$ generated events → ~ 80 days
- ~ $2x10^{8}$ events inside acceptance
- Difference map @ X=0 (i.e. YZ layer containing the U sample)

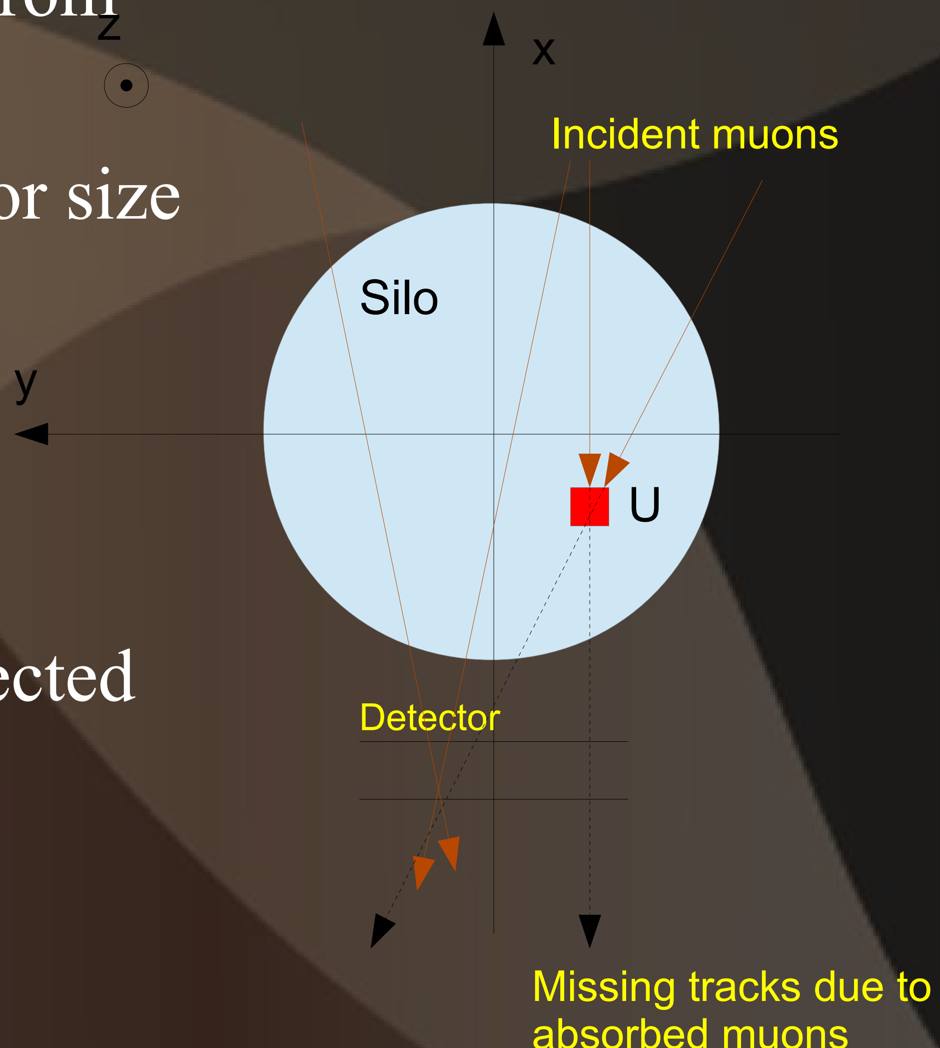


Complicate the picture

- Sellafield scenario #2:
  - Cylindrical storage silo,
  - Concrete + reinforced concrete
- Uranium debris:
  - Unknown number/position,
  - Expected size ~ some cm
- Unknown “noise” content:
  - Variable concrete density,
  - High/low density debris,
  - Clothes, bricks, steel rods,
  - Air bubbles ….

Parameters

- Detector size ~ distance from target
- Target (U) size << detector size



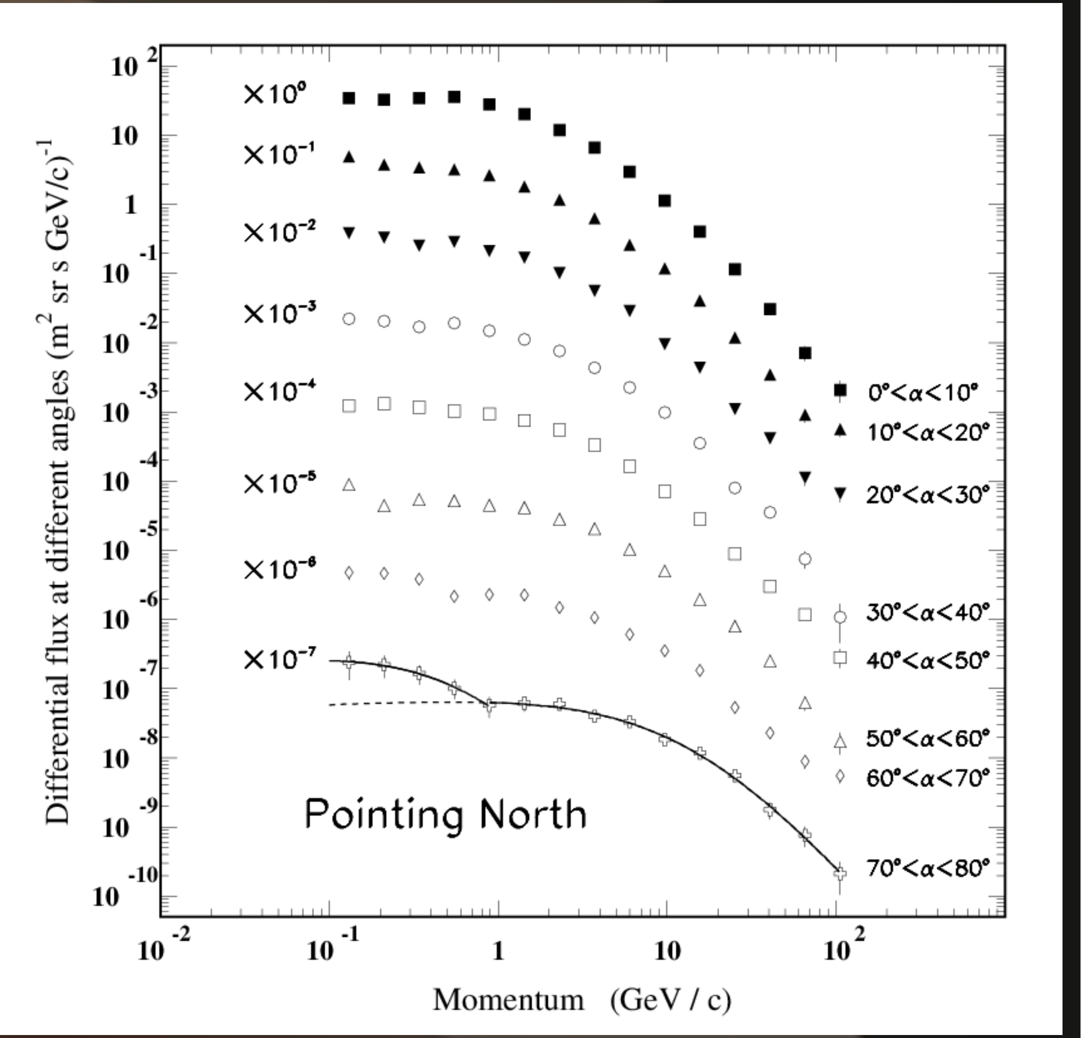
- Need to estimate the expected event count when no U is present ("background")

Checklist

- Simulation code:
  - General simulation code developed in Florence, based on Geant4
- Realistic muon generator:
  - Shape, normalization
- Scenario #2 geometry implementation:
  - Realistic detector implementation
  - Reconstruction and analysis routines
- # of simulated events → acquisition time

Muon Generator

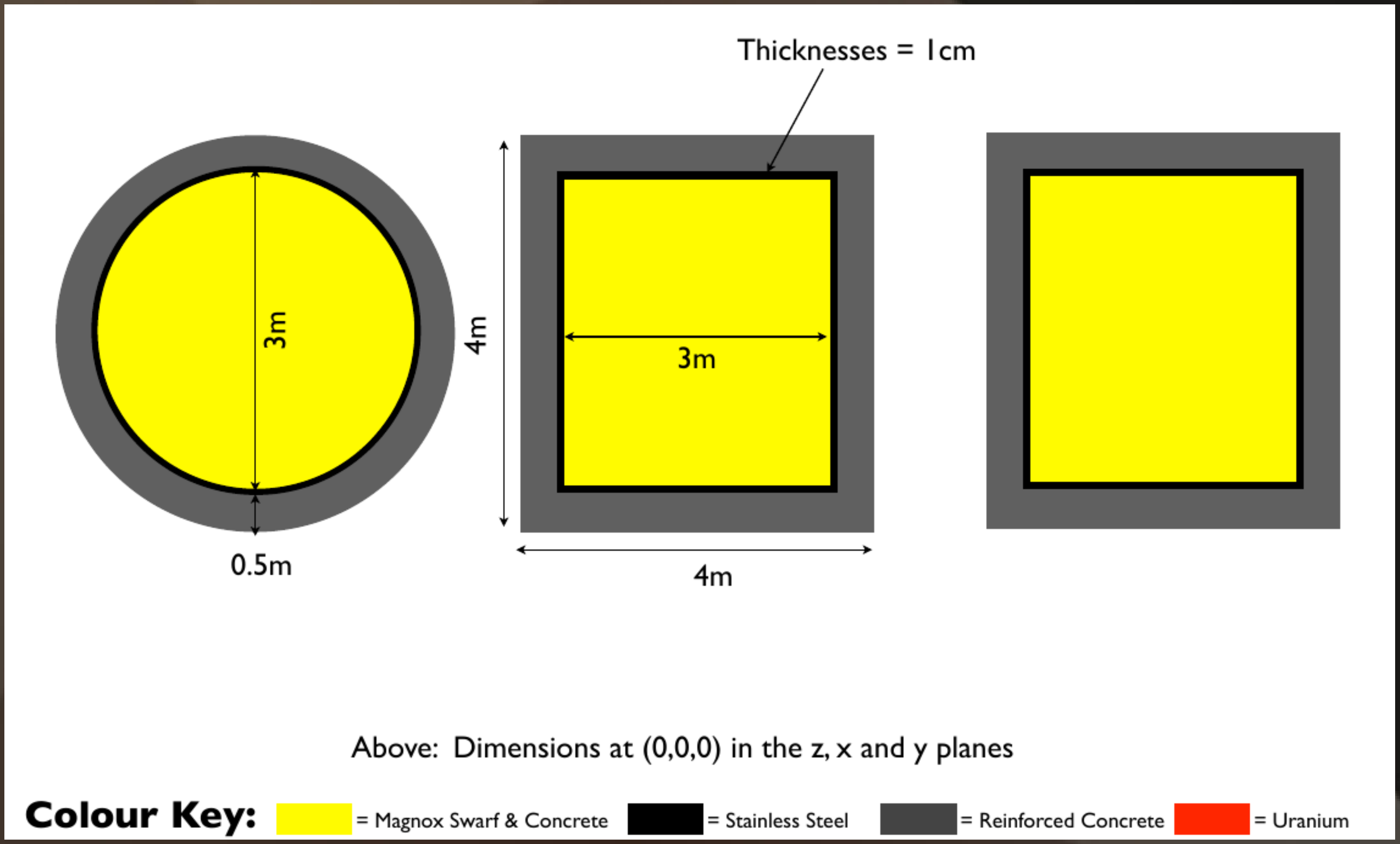
- Based on ground measurements with a magnetic spectrometer:
  - 0.1 GeV/c < p < 130 GeV/c
  - 0 deg < θ < 80 deg
- Smoothing + discretization
- Hit&Miss sampling of (Ek, θ)
- Random generation point on a horizontal surface



Bonechi, L., et al., Intl. Cosmic Ray Conf. Proc. (2005), 283

Silos Geometry

- Homogeneous materials
- Densities (g/cm3): reinforced concrete 5, stainless steel 8.03, concrete 2.3, uranium 18.95
- Arbitrary number of U and air cubes with arbitrary position and size

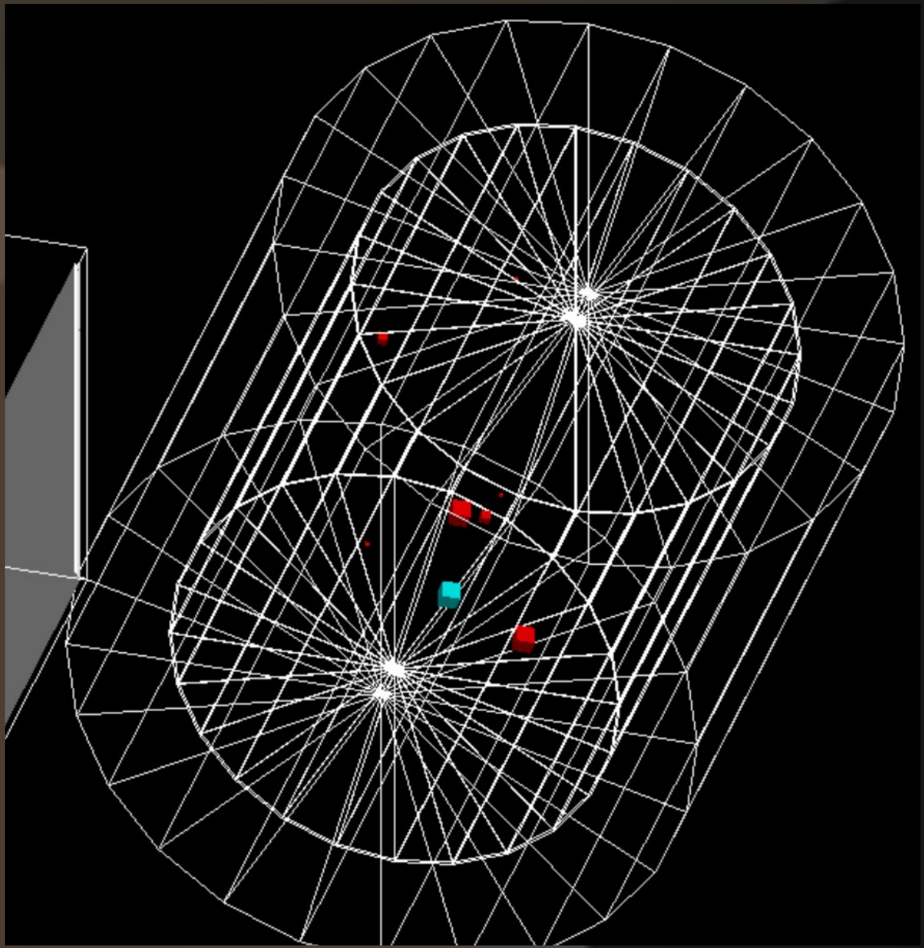


Simulation (continued)

- Full detector simulation (triangular bars, etc.) time consuming.
- Approximated to a $2x2m^2$ plane with 3mm impact point resolution.
- Flux parameters:
  - $E_k \in [0.7, 130]$ GeV
  - $\theta \in [0, 80]$ deg, $\varphi \in [-90, 90]$ deg
- Generation surface:
  - $z = 5$ m, $x \in [-3, 65]$ m, $y \in [-10, 10]$ m
  - Area: 1360 m^2, Full coverage of the detector-silo acceptance
- Acceptance check:
  - $\sim 10^{12}$ generated, 1.2×10^9 simulated
- Computation:
  - CPU time: ~ (1.5 days * 300 cores)
  - Size of output: ~ 330 GB

U and air samples

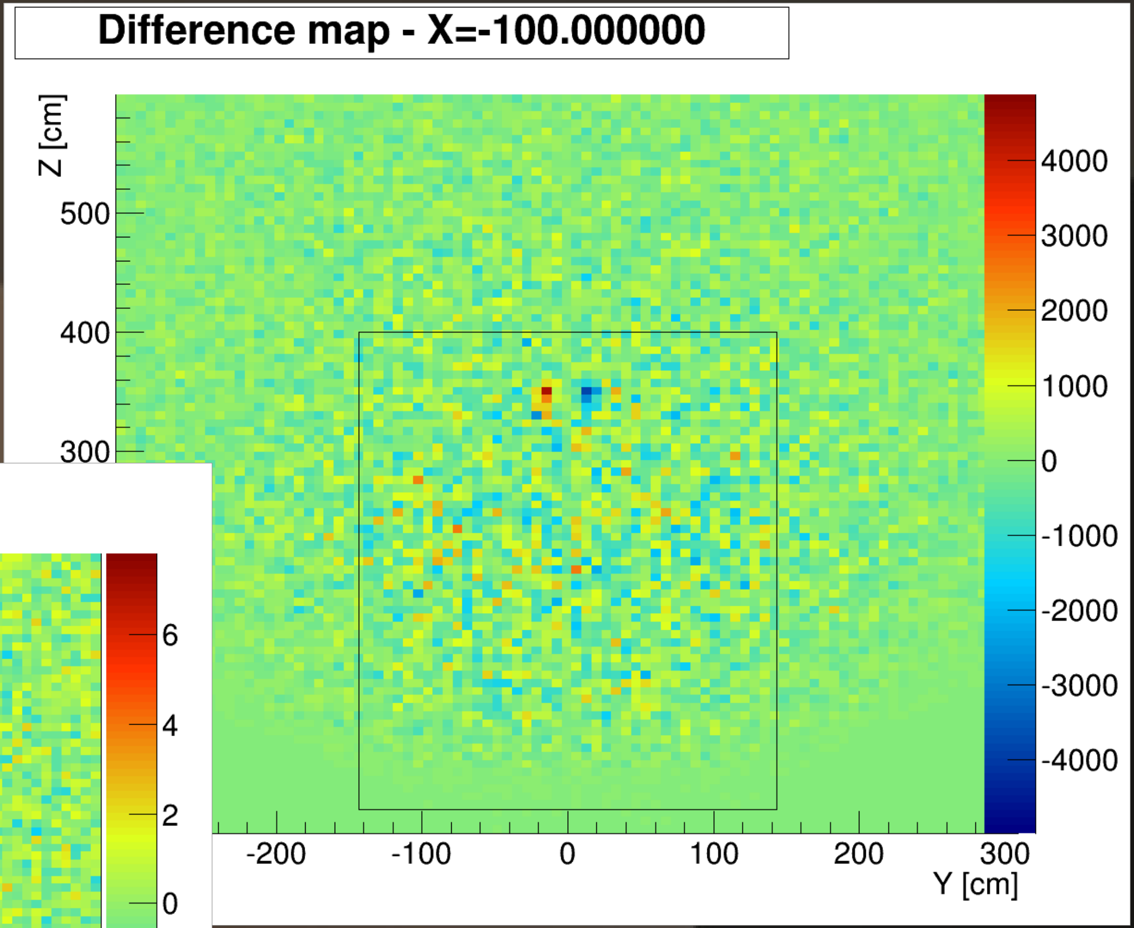
- (10 cm)3 U:
  - (0, 0.2, 1.5) m (center)
  - (0.5, -0.2, 1) m (bottom-far)
- (5 cm)3 U:
  - (0, -0.15, 2) m (center)
  - (-1, -0.15, 3.5) m (top-near)
- (2 cm)3 U:
  - (0, 1, 2.6) m (lateral)
  - (0, -0.2, 2.3) m (center)
  - (-0.8, -0.8, 2.5) (lateral-near)
- (10 cm)3 air:
  - (0, -0.2, 1.3) m (center-bottom)

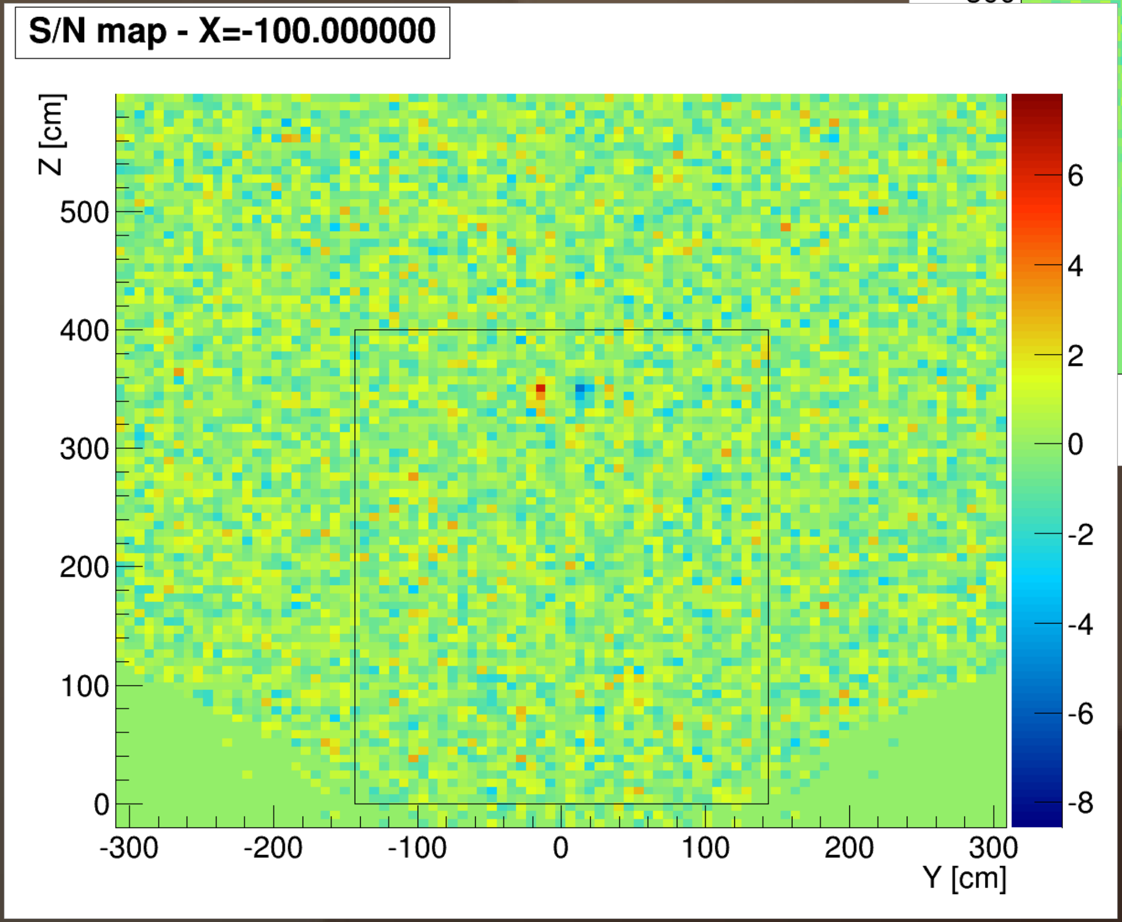


S/N estimation

- Results are obtained by subtracting two maps :
  - one with a “signal” and the other “background only” from a reference silo
- In difference maps, signal is computed as the difference between two independent Poisson variables → Skellam distribution
- $\sigma^2 = \mu 1 + \mu 2$
- $S/N = (N1 - N2)/\mathrm{sqrt}(\mu 1 + \mu 2)$
- $S/N \approx (N1 - N2)/\mathrm{sqrt}(N1 + N2)$

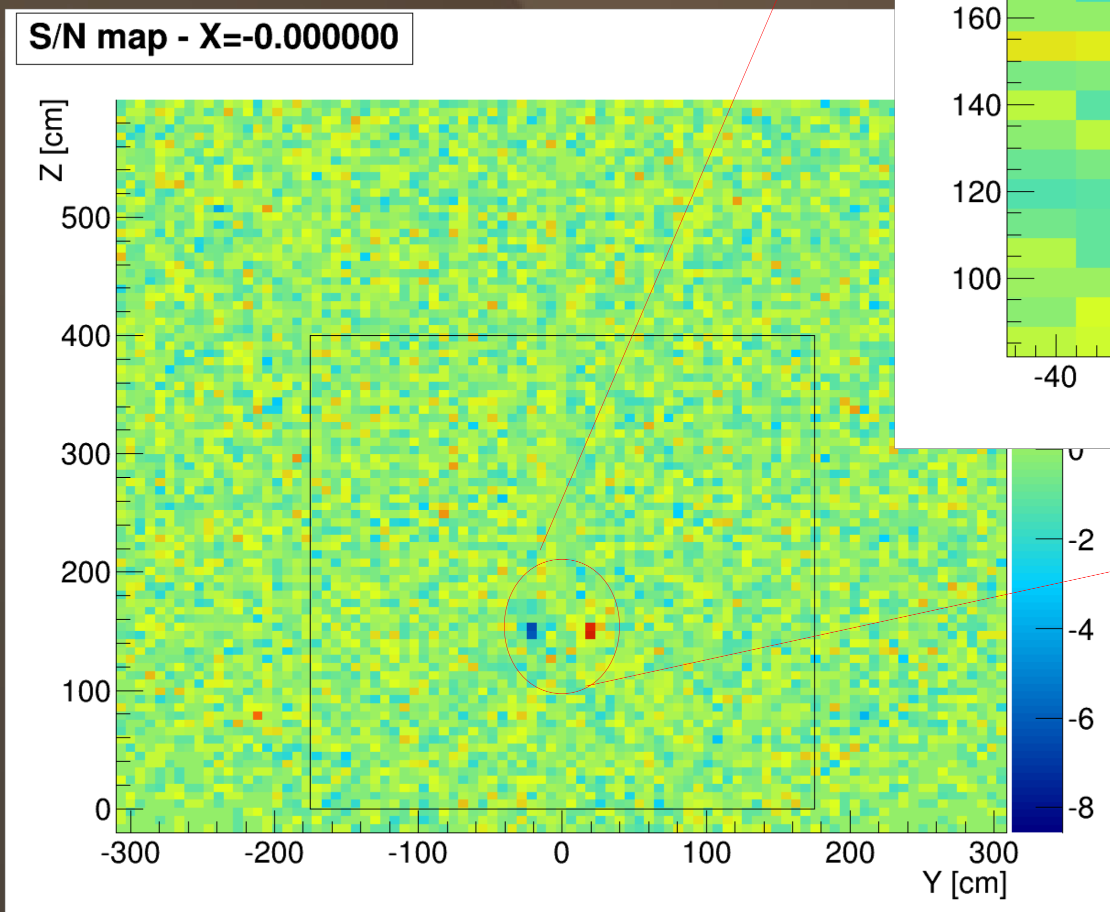
Some Preliminary Results

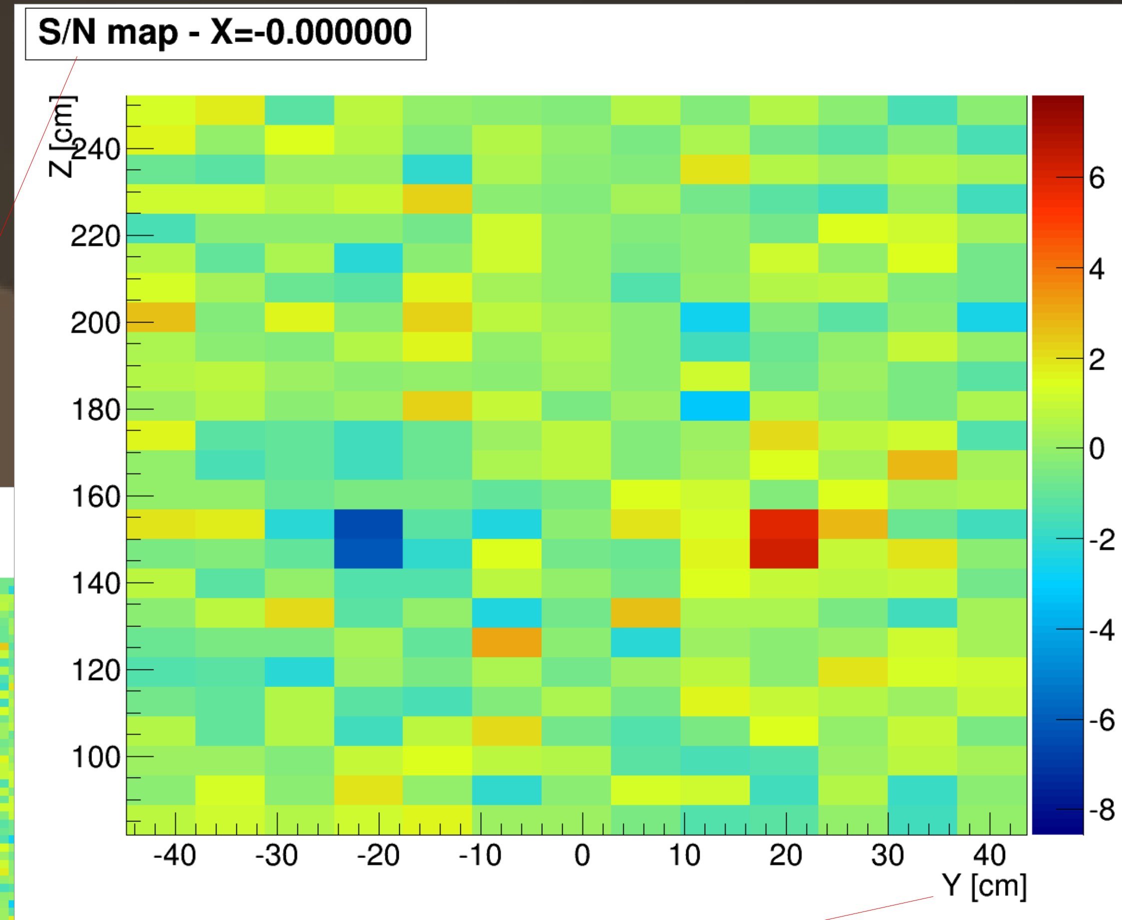




- The 5 cm U cube is clearly visible with S/N = 6

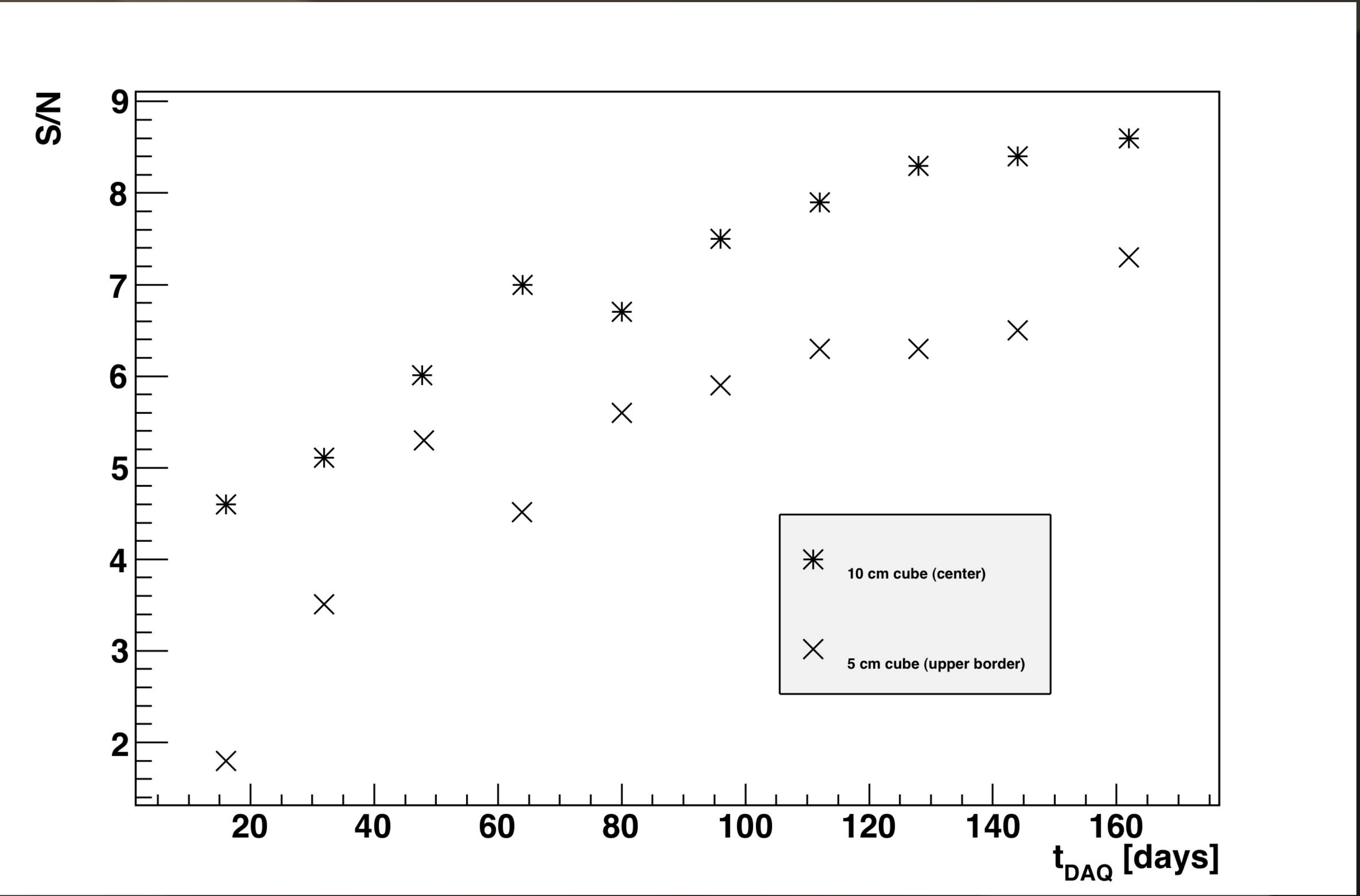
Other sizes ….





- The 10 cm U cube is clearly visible with S/N = 6
- Smaller cubes and the air gap are not visible

S/N vs Acquisition Time



Conclusions and acknowledgments

- The simulation that has been shortly described in these slides has been set up thanks to the collaboration between two Italian groups (belonging to INFN and Physics Departments of Naples and Firenze), NNL and the group from Glasgow headed by Dr. Craig Shearer and Dr. David Mahon.
- Details of the silos geometries were collected by Dr. Mahon (Glasgow) and discussed with the Italian teams during several meetings.
- In this framework Nicola Mori has implemented a simulation framework based on Geant4
- Lorenzo Bonechi provided precious data on which we calibrated our muon generator.

- A paper has been submitted to Applied Physics Letters, http://arxiv.org/abs/1411.2382

Acknowledgements

- I wish to express my gratitude to all the organizers of the MNR2014 Workshop and in particular
  - Prof. H. Tanaka of E.R.I.
  - Prof. P. Strolin of University of Naples “Federico II”, representative of INFN
- I wish to thank also Dr. Domenico Giorgi, the Italian Ambassador, and the staff at the Italian Embassy for the splendid venue and organisation.