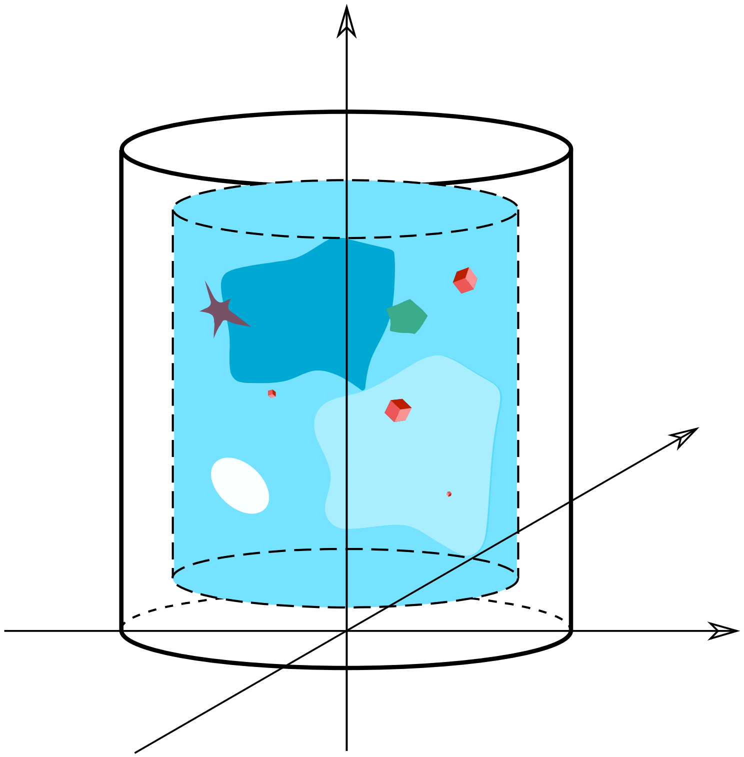
Results on muon absorption tomography for nuclear storage facility at Sellafield

Nicola Mori

21/7/2014

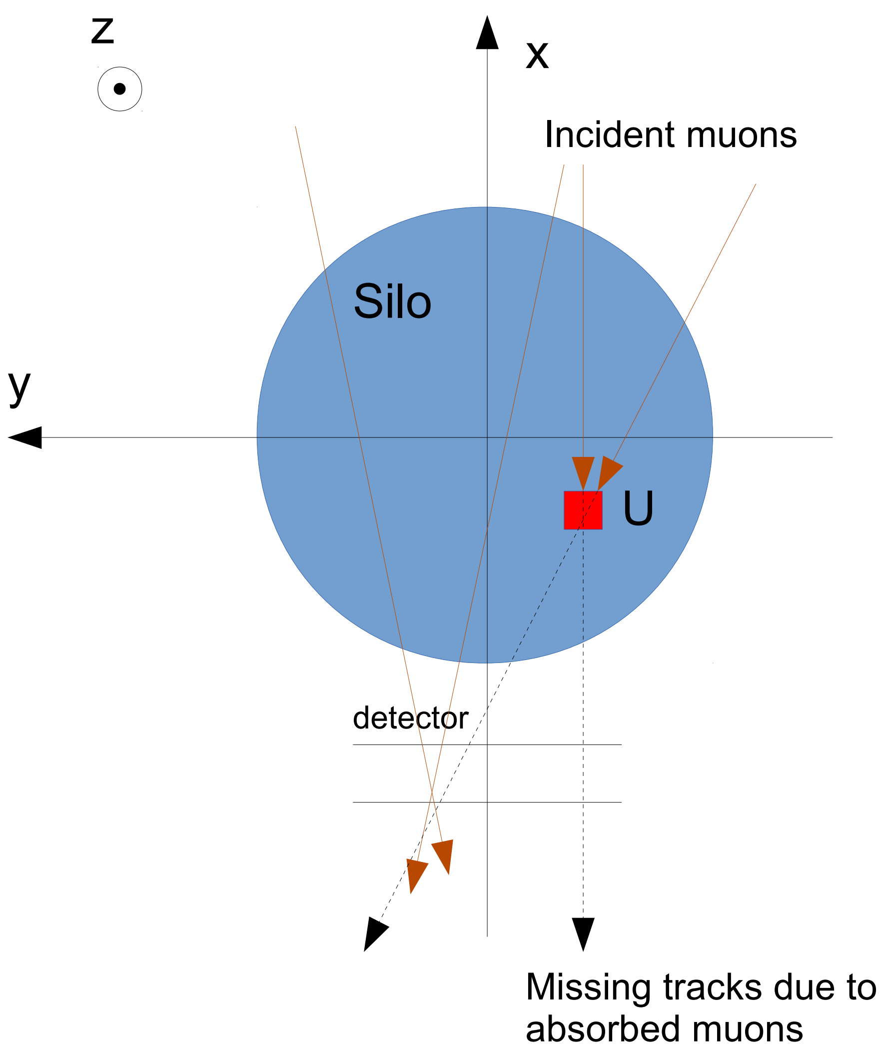
The study case



- **Sellafield scenario #2:**
  - Cylindrical storage silo
  - Concrete + reinforced concrete
  - Dimensions ~ some m
- **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
  - ???

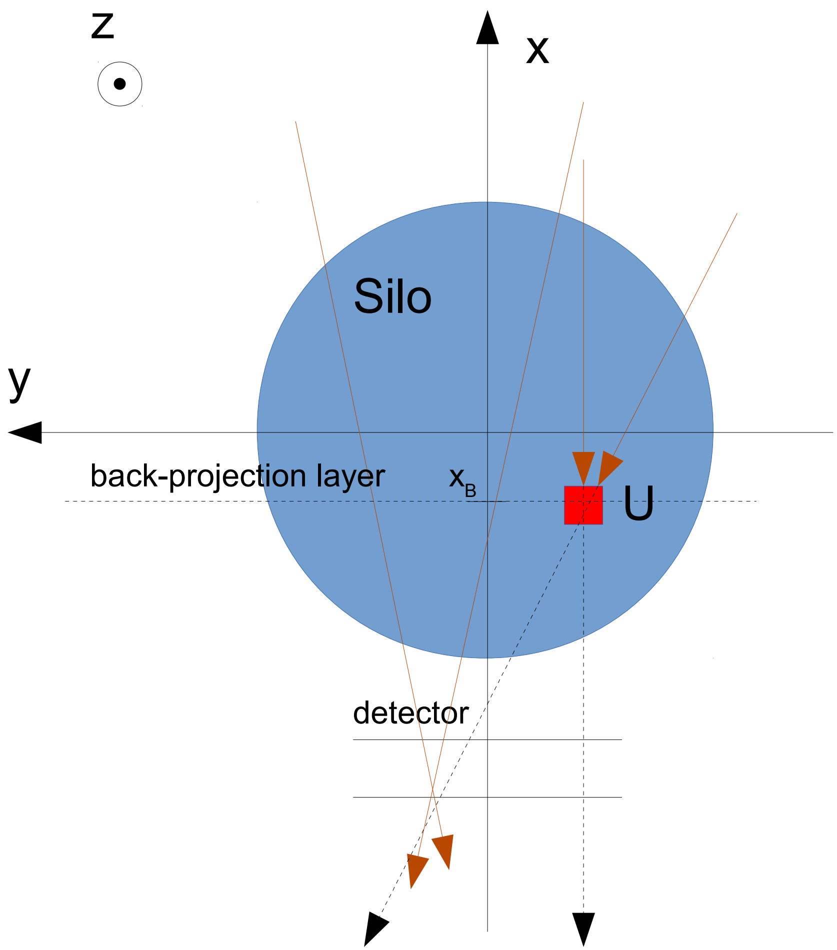
<u>Target</u>: assess the uranium detection capability as a function of data acquisition time and the effect of noise materials

Muon absorption tomography

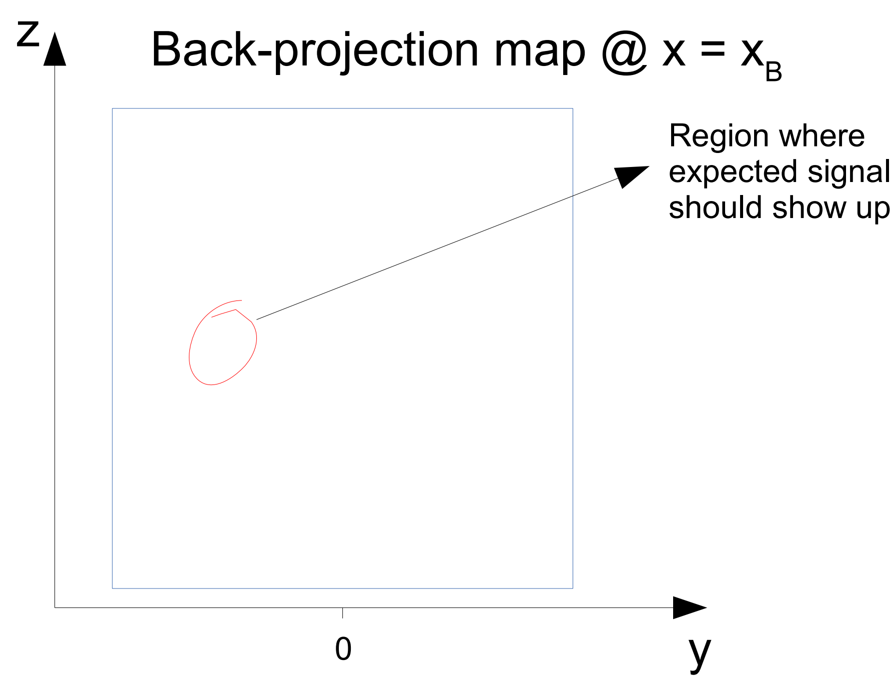


- Detector size ~ distance from target
- Target (U) size << detector size
- Stereoscopic view
- 3D position reconstruction with only one detector
- Need to estimate the expected event count when no U is present ("background")

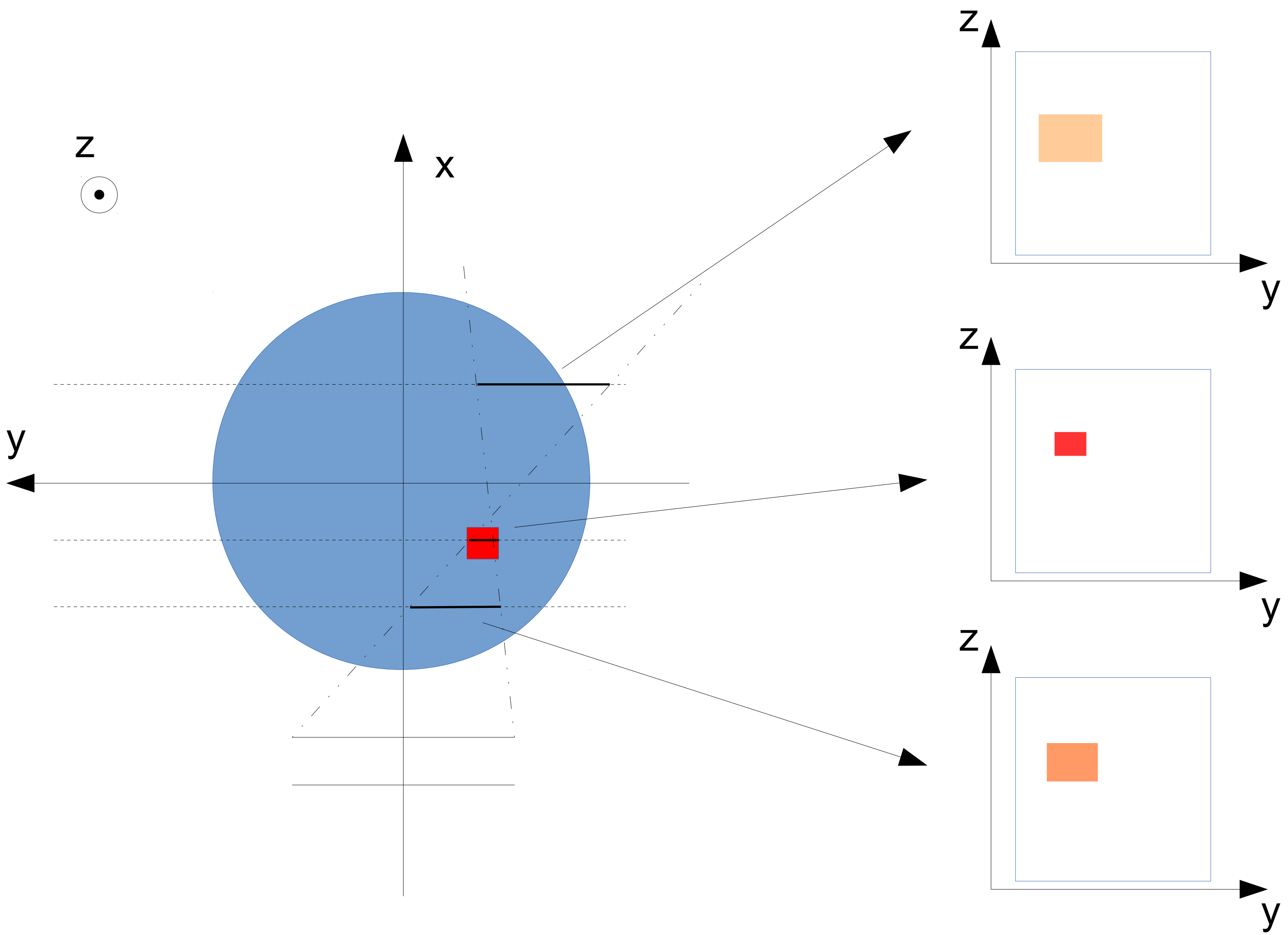
Back-projection technique



- Back-extrapolate reconstructed tracks on layers intersecting the target
- Build track density maps
- Expected event count deficit w.r.t. the case with no U target
  - Background subtraction to extract signal



Focusing effect

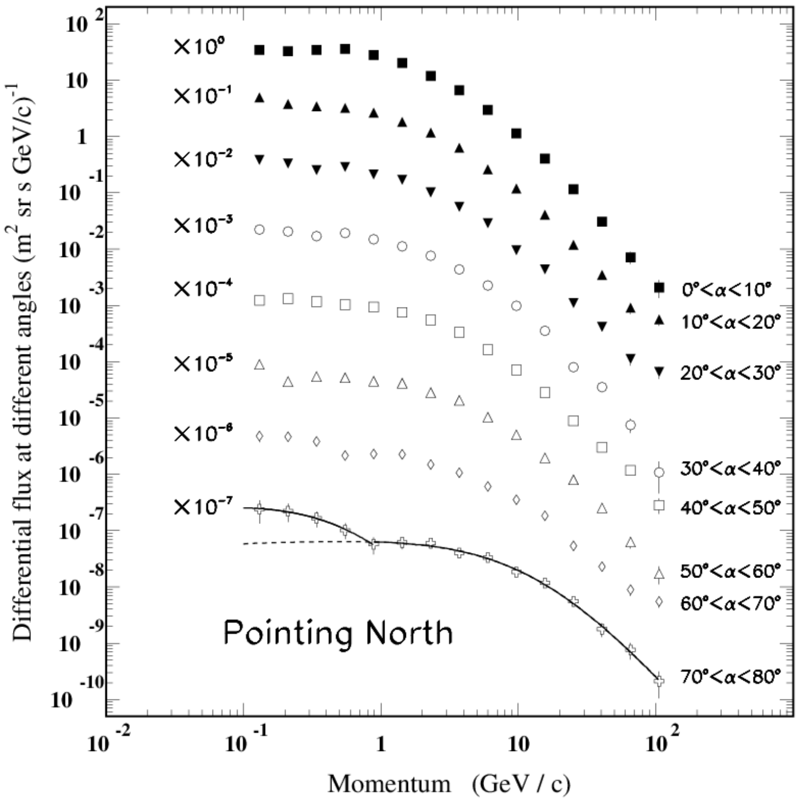


Expected max. S/N & min. size when the backprojection layer intersects the U sample

Monte Carlo simulation

- Checklist:
  - Simulation code
    - Generic 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

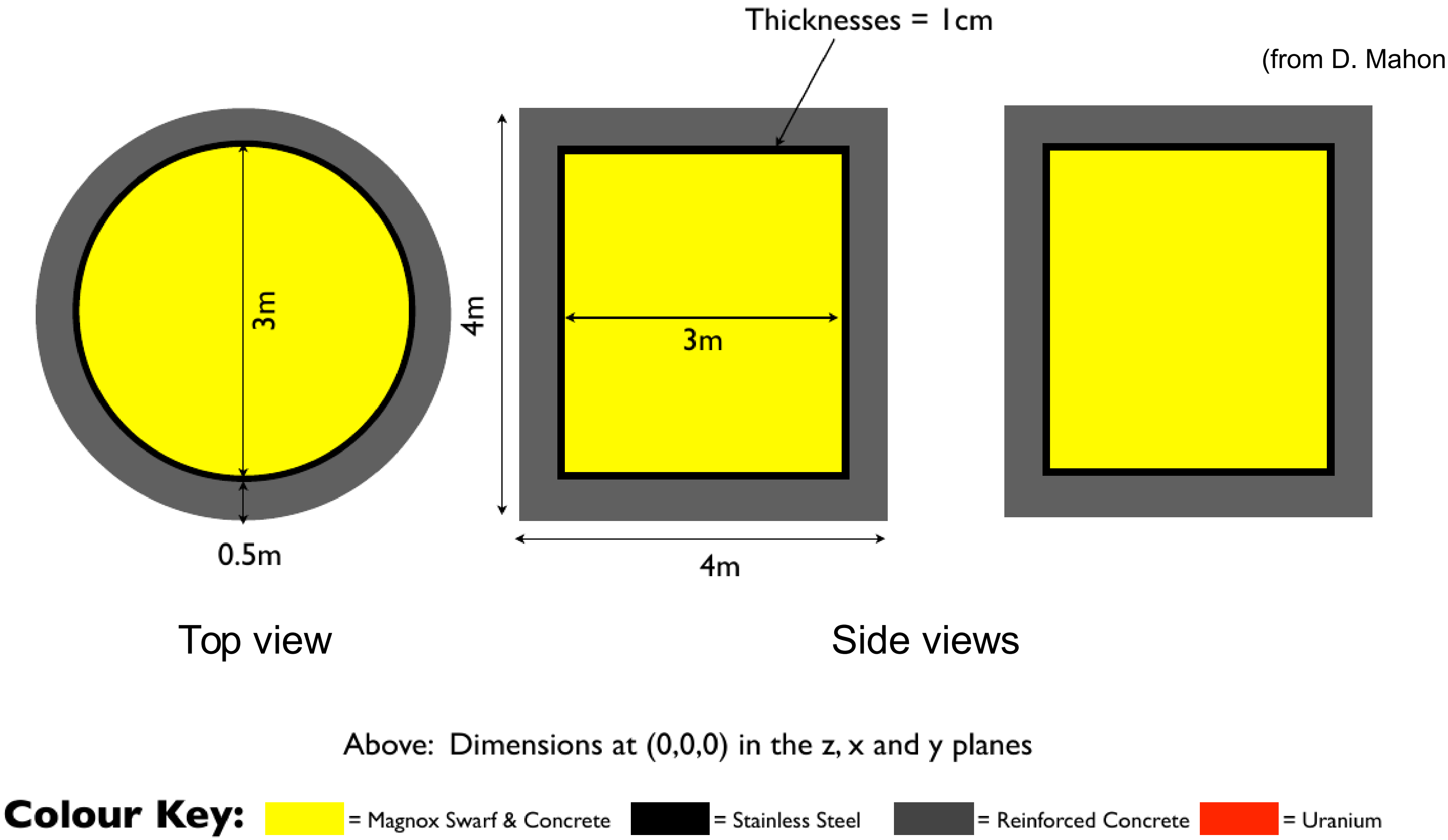
Muon generator



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

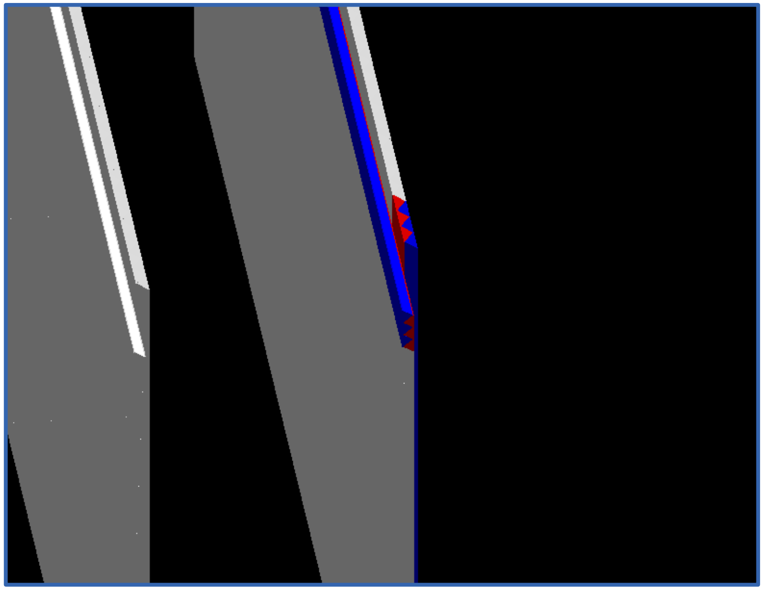
- Based on ground measurements with a magnetic spectrometer
- 0.1 GeV/c < p < 130 GeV/c
- 0 deg < θ < 80 deg
- Smoothing + discretization
- Hit&Miss sampling of (E_k, θ)
- Random generation point on a horizontal surface

Silo geometry



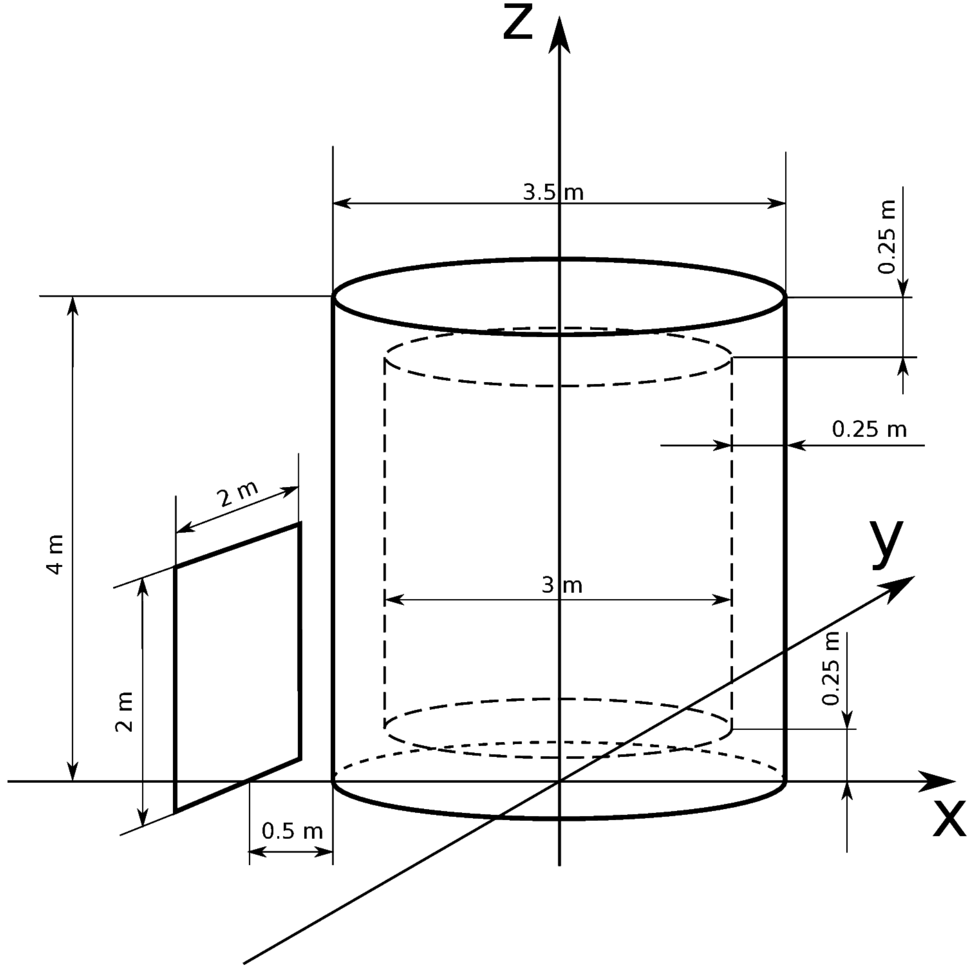
- Homogeneous materials
- Densities (g/cm^3): reinforced concrete 5, stainless steel 8.03, concrete 2.3, uranium 18.95
- Arbitrary number of U and air cubes with arbitrary position and size

Detector implementation



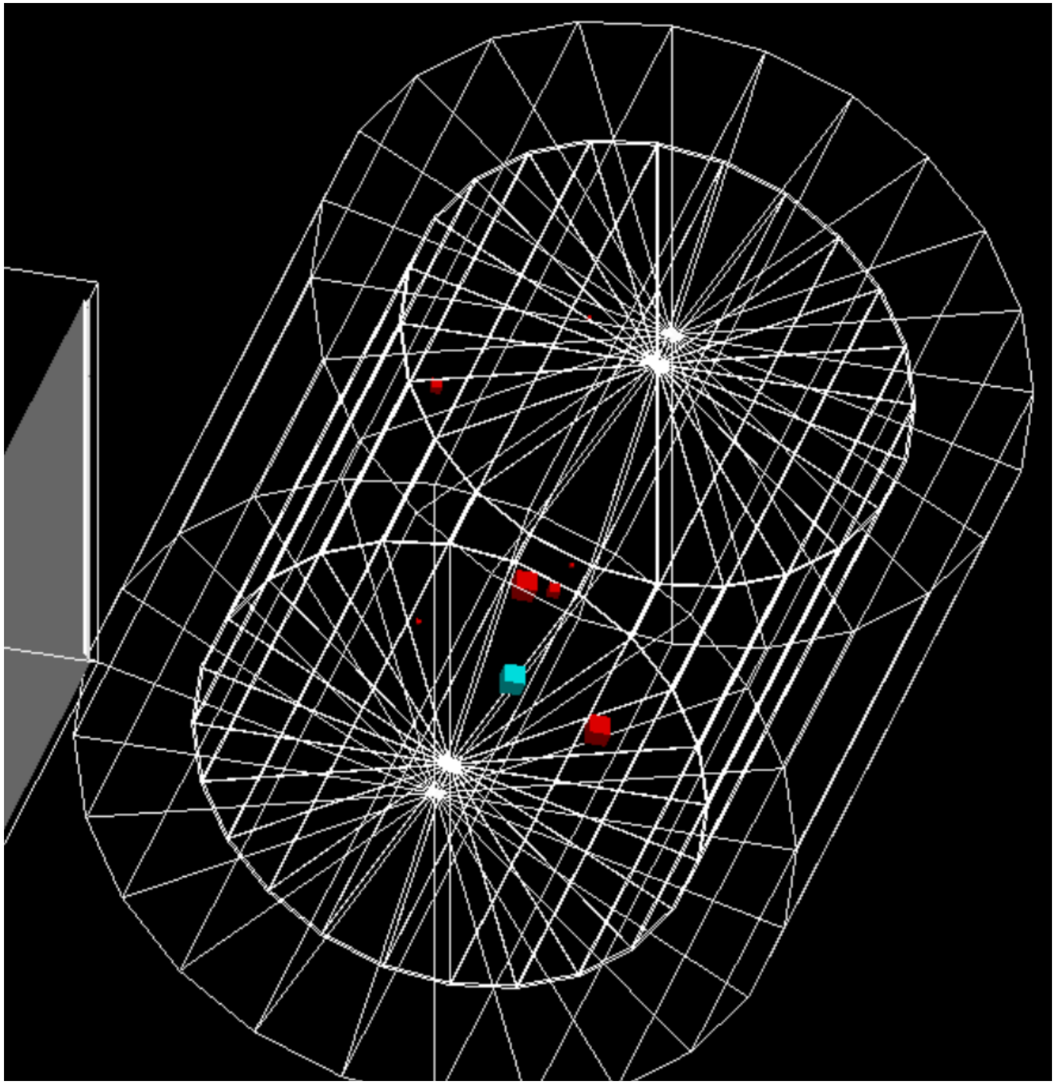
- 1st approach: MURAY-like detector
  - 2 XY layers made of triangular scintillating bars
  - Plane spacing 50 cm
  - Based on G4GenericTrap solid
- Too many rotations:
  - Degraded accuracy of net rotation
  - Low-energy electrons occasionally got stuck between two bars
    - Can't determine the current volume
  - Simulation job didn't end
- Maybe other reasons
  - Voxelized geometry?
- Some tentative solutions:
  - Kill low-energy, stuck tracks
  - Play with geometrical optimizations (voxels)
  - None of them worked
- Fallback solution: single, homogeneous, 2m x 2m detector layer.
  - Use MC truth for impact point
  - Position resolution: 0.3 cm

Simulation scenario



- 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
  - ~ 10^{12} generated
  - 1.2 x 10^9 simulated
- Computation:
  - CPU time: ~ (1.5 days * 300 cores)
  - Size of output: ~ 330 GB

U and air samples



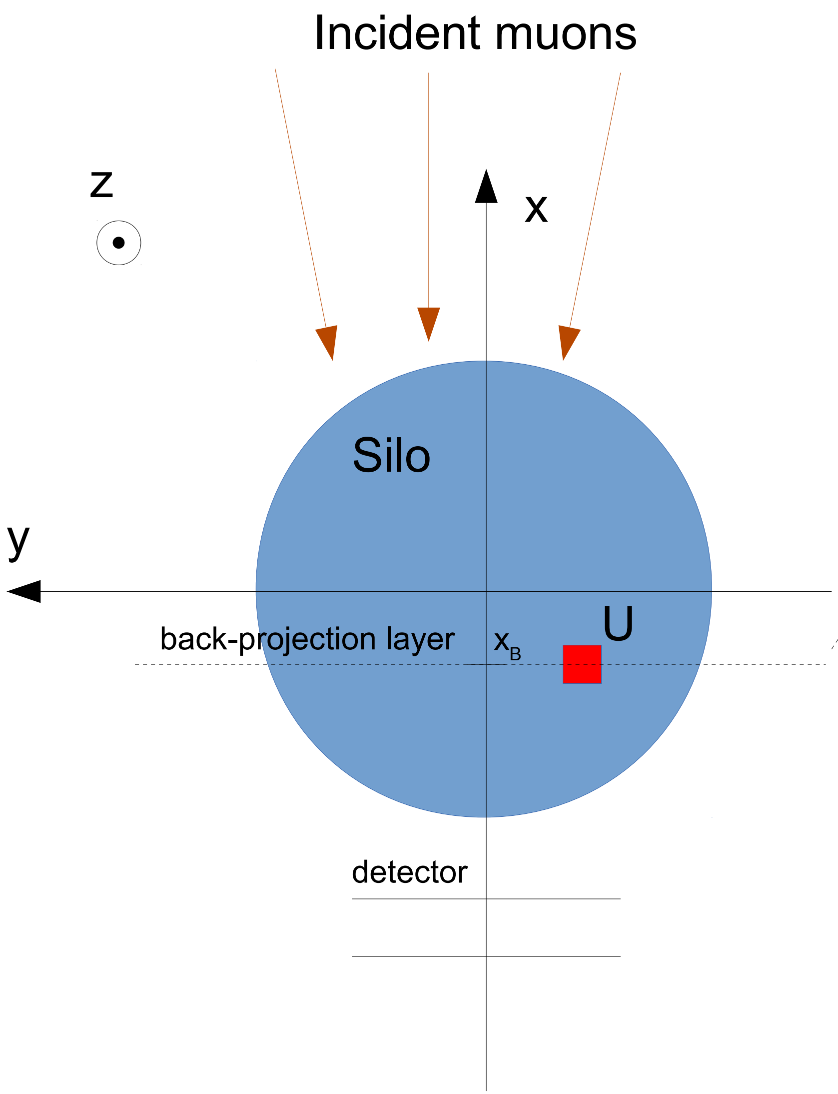
- $(10\ cm)^3$ U:
  (0, 0.2, 1.5) m (center)
  (0.5, -0.2, 1) m (bottom-far)
- $(5\ cm)^3$ U:
  (0, -0.15, 2) m (center)
  (-1, -0.15, 3.5) m (top-near)
- $(2\ cm)^3$ U:
  (0, 1, 2.6) m (lateral)
  (0, -0.2, 2.3) m (center)
  (-0.8, -0.8, 2.5) (lateral-near)
- $(10\ cm)^3$ air:
  (0, -0.2, 1.3) m (center-bottom)

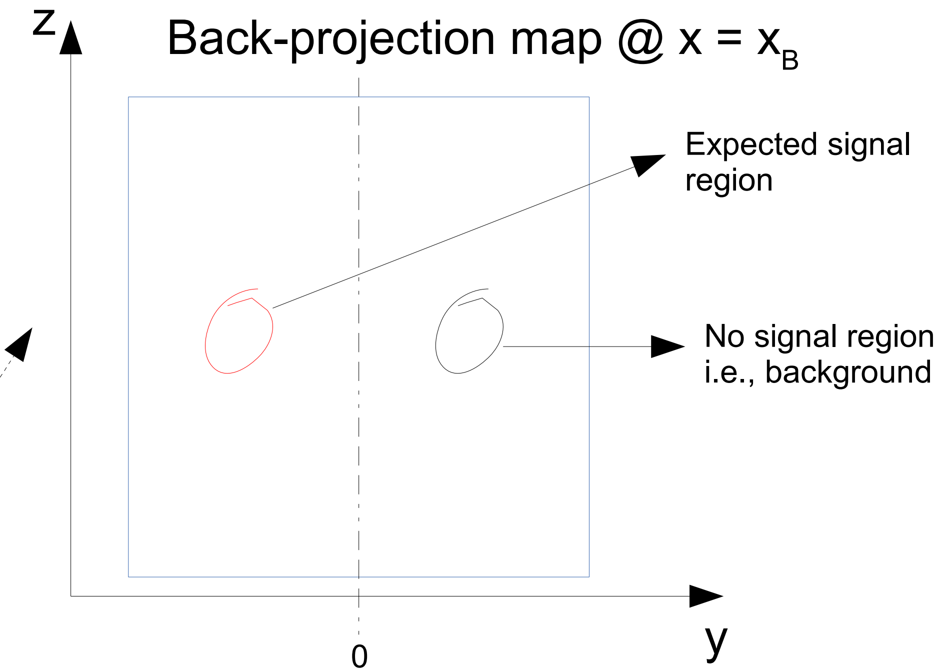
The autobackground method

- Signal is computed as the difference of two back-projected maps:

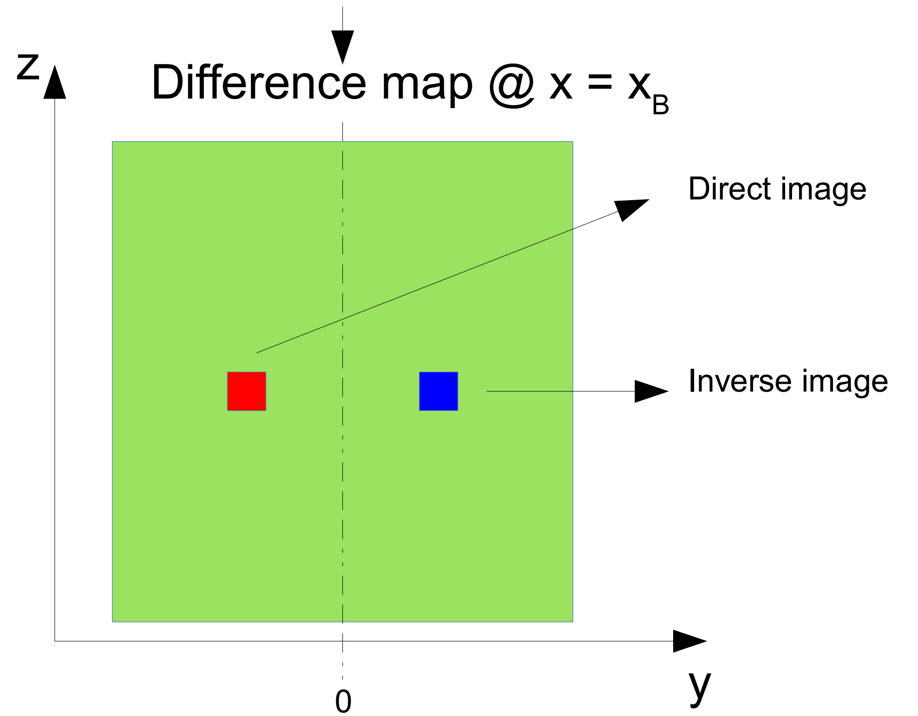
  S = (map without U)-(map with U)

- In real-life there is no “reference silo” without U to be used to measure the background map (i.e. without U)
- But much of the silo volume does not contain U (assumption)
- Idea: use the “silo with U” itself to estimate the background, exploiting the cylindrical symmetry of scenario #2





Recipe: mirror the map about the y=0 axis and use it as background map



- Works only for symmetric geometries and off-axis samples
- “Mirrored” samples will be invisible
- Inverse images from low-density regions may be misinterpreted as direct images from high-density regions
- **No need to simulate an empty silo, i.e. background**

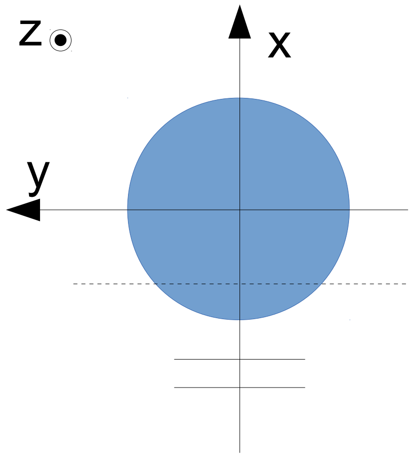
Data analysis

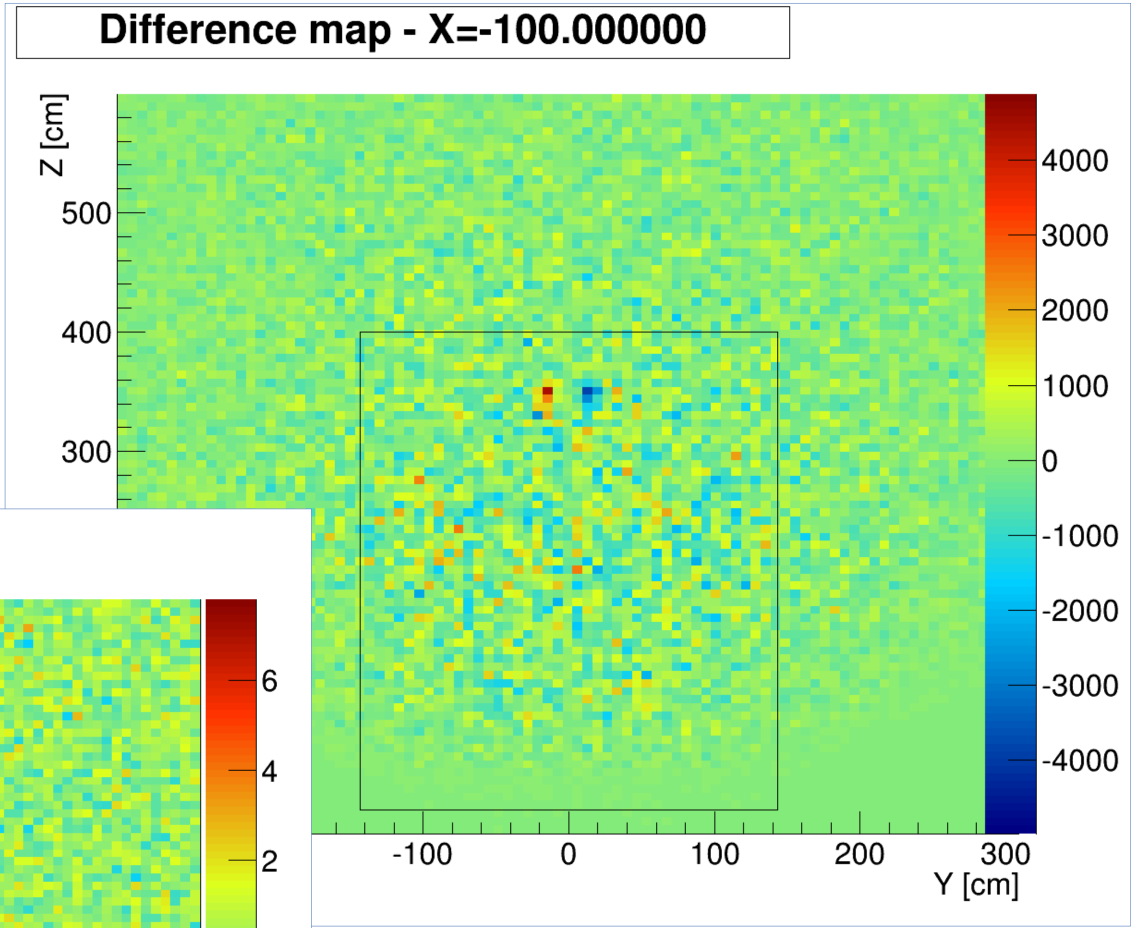
- Impact point and direction:
  - Retrieve true impact points on front layer and on an eventual back layer 50 cm apart (MC truth)
  - Apply a gaussian smearing with $\sigma = 0.3$ cm
  - Reconstruct the smeared impact direction
- Build back-projection maps
  - Bin size: (7x7) cm^2
- Compute signal and S/N maps (see next slide)
- Estimate DAQ time
  - Integrate the flux over E_k, θ, φ and divide by the area of the generation surface to obtain (<u>generated</u> particles)/sec
- No data quality cut
  - Efficiency = 1

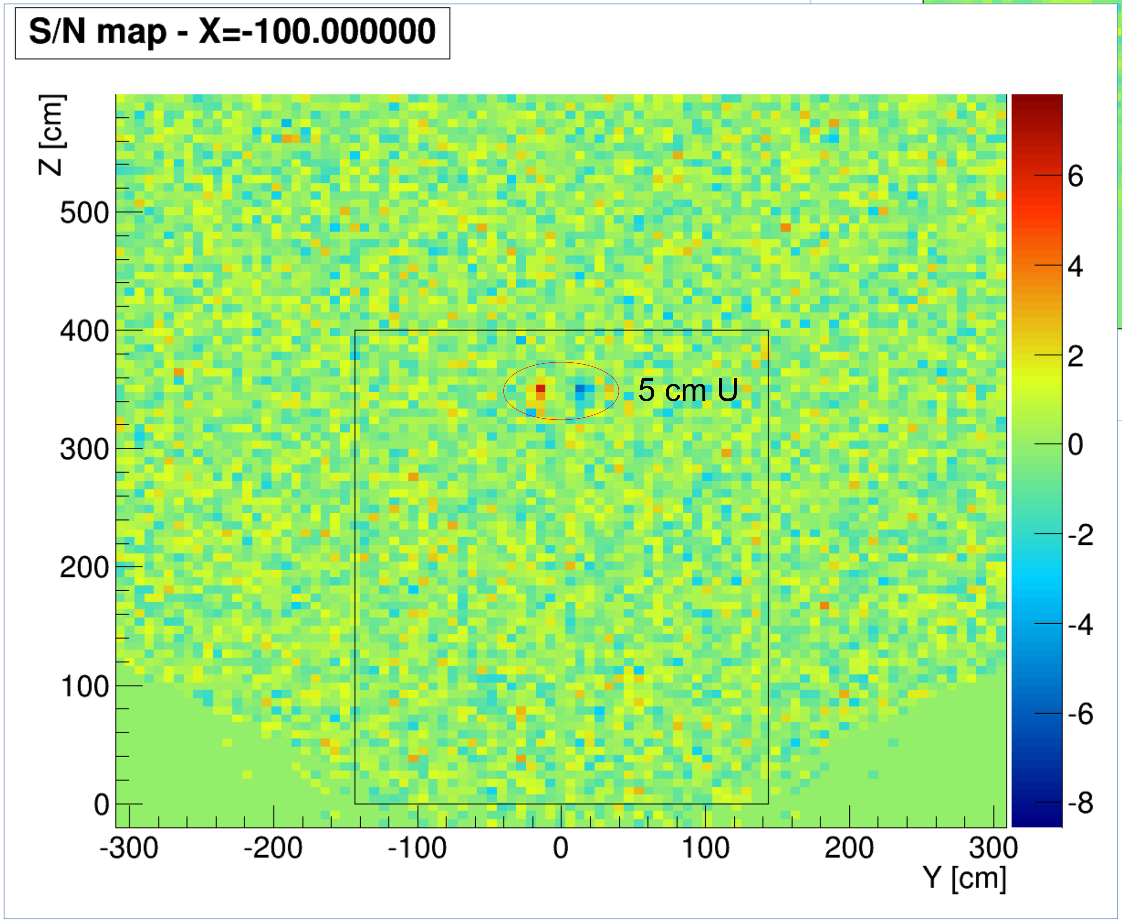
S/N estimation

- In difference maps, signal is computed as the difference between two independent Poisson variables → Skellam distribution
- $\sigma^2 = \mu_1 + \mu_2$
- $S/N = (N_1 - N_2)/\mathrm{sqrt}(\mu_1 + \mu_2)$
- $S/N \approx (N_1 - N_2)/\mathrm{sqrt}(N_1 + N_2)$

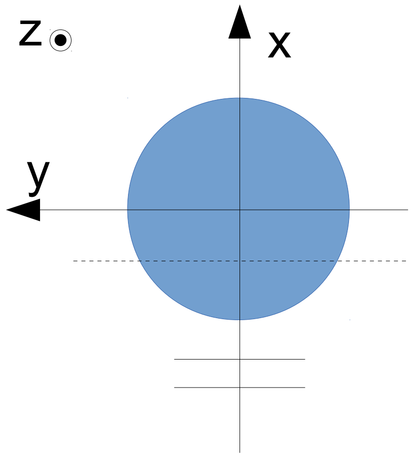
Simulation results

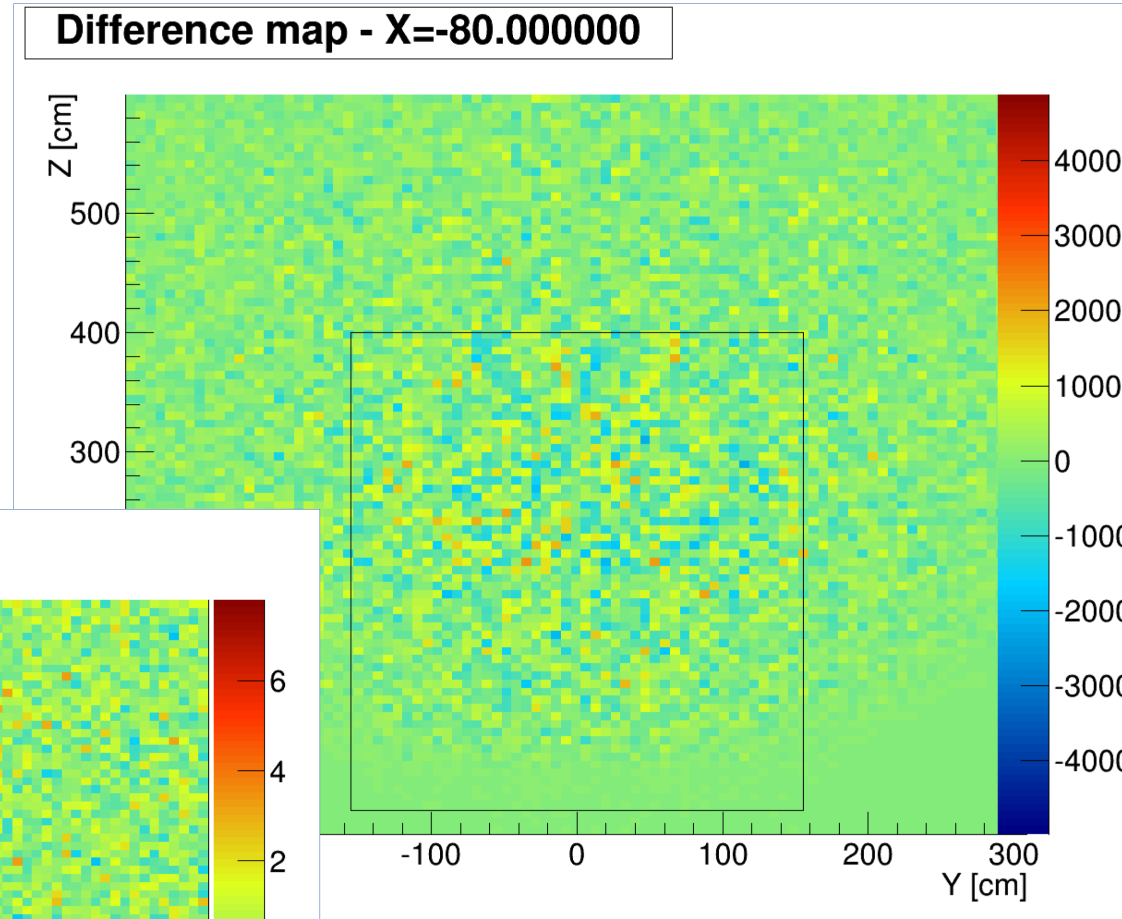


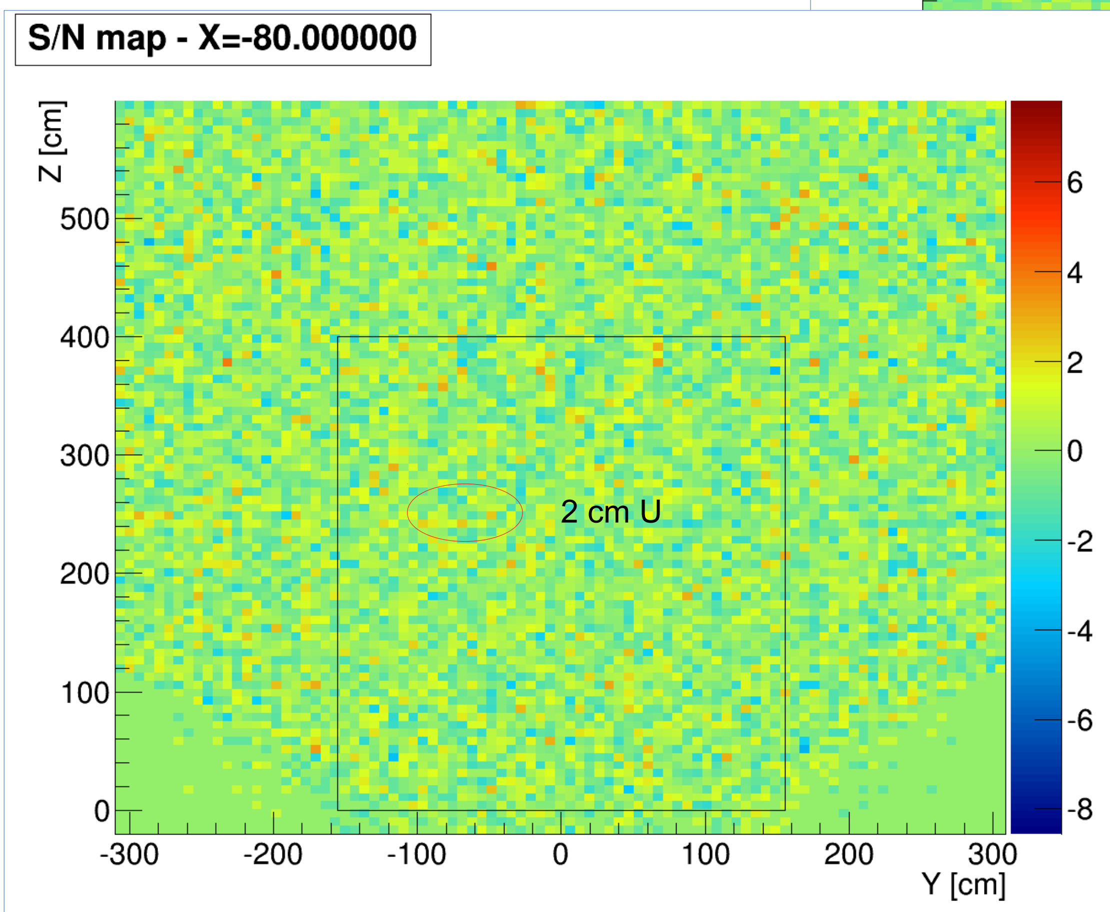




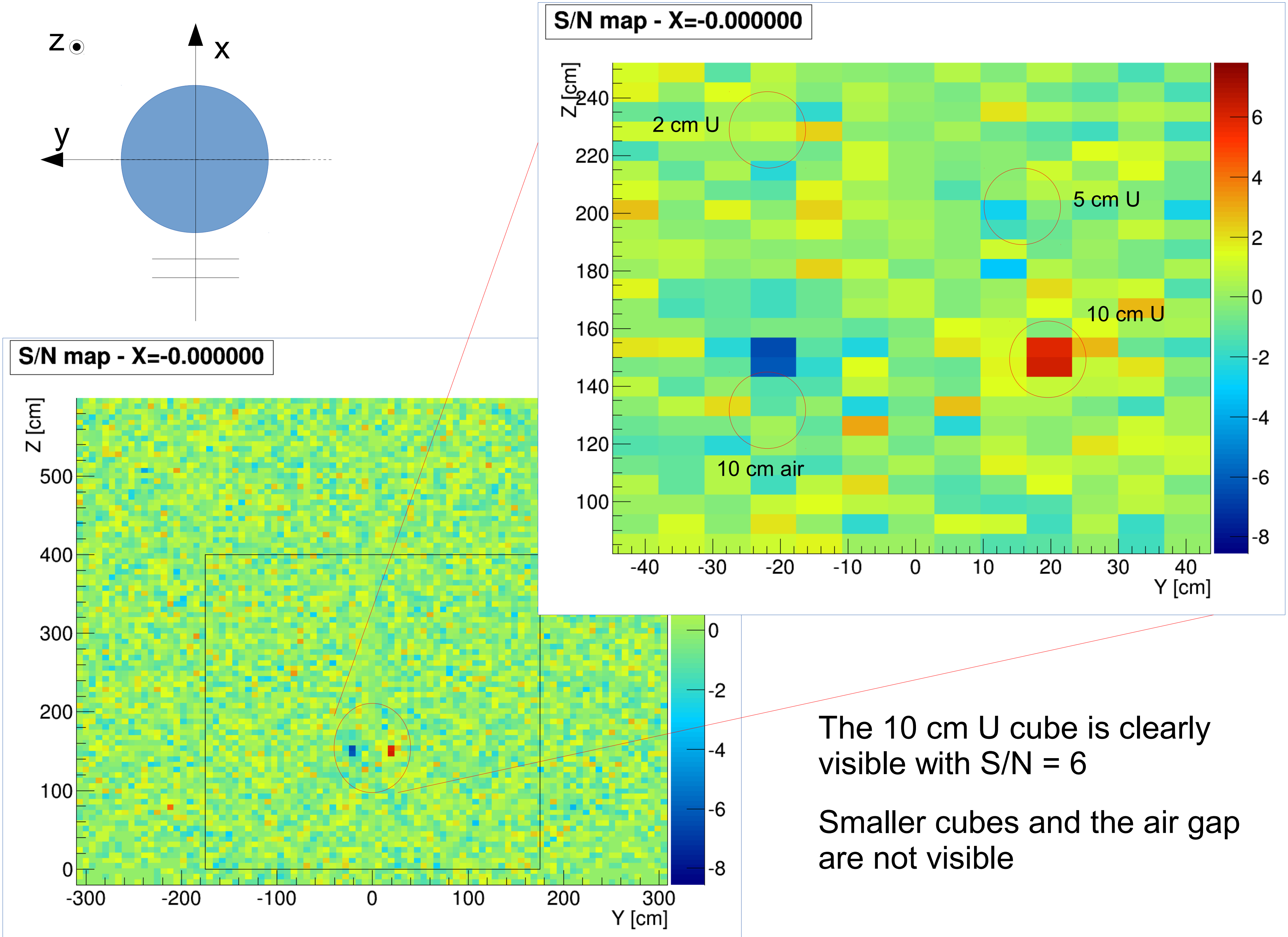
The 5 cm U cube is clearly visible with S/N = 6





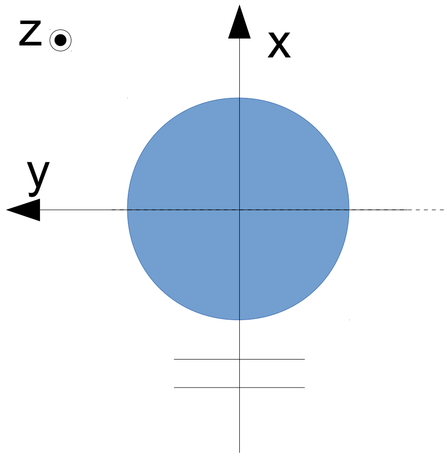


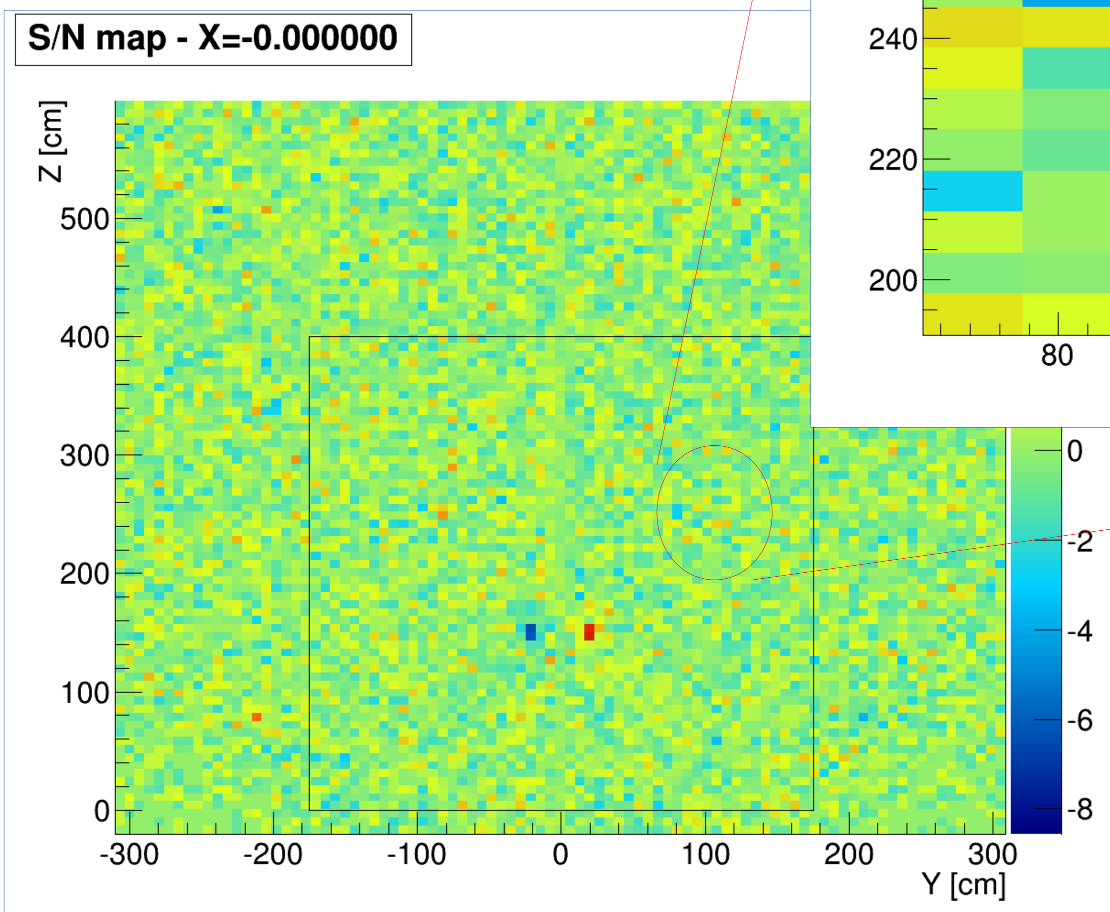
The 2 cm U cube is not visible

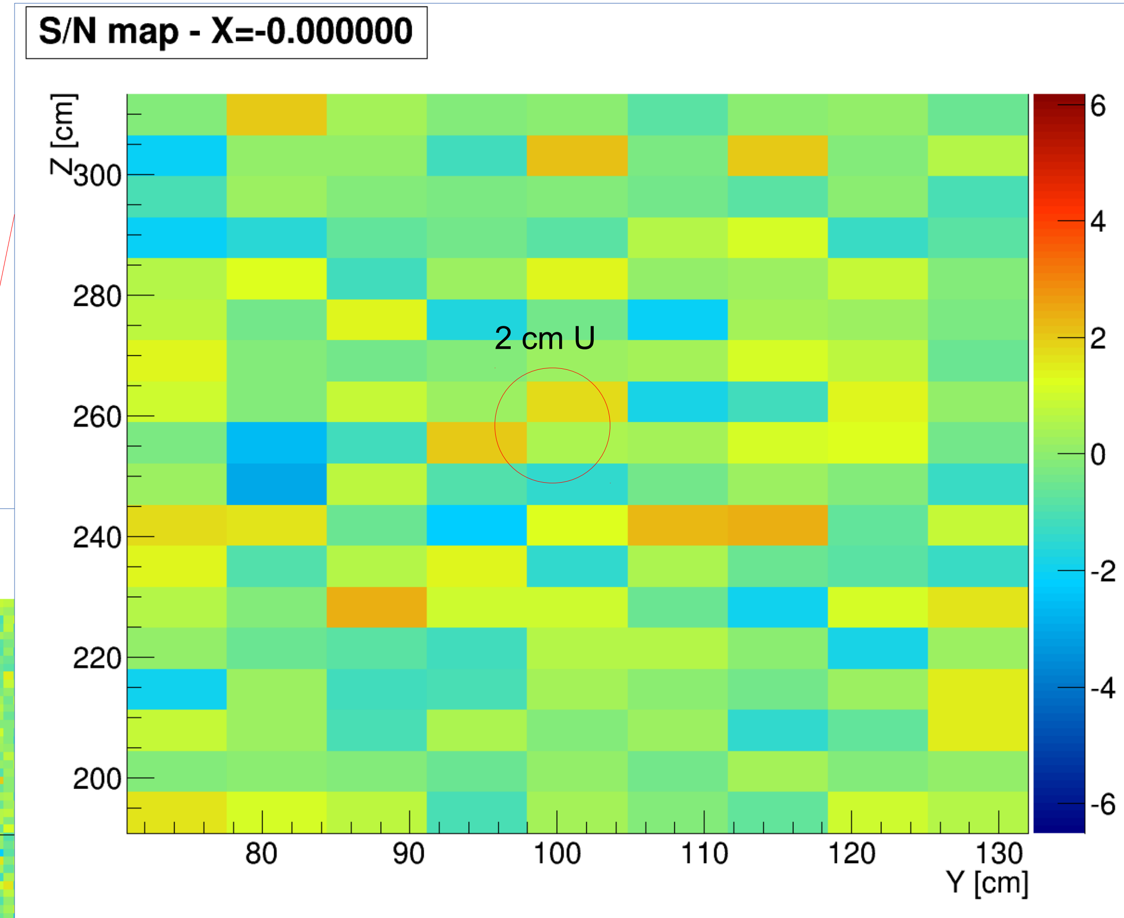


The 10 cm U cube is clearly visible with S/N = 6

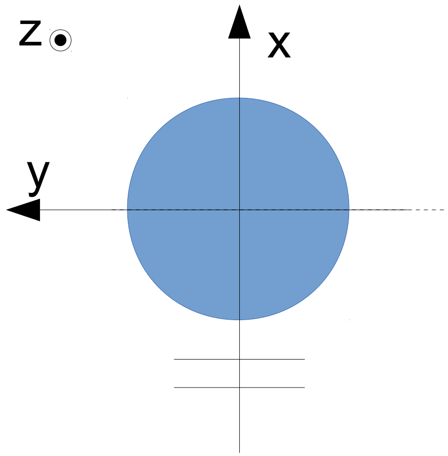
Smaller cubes and the air gap are not visible

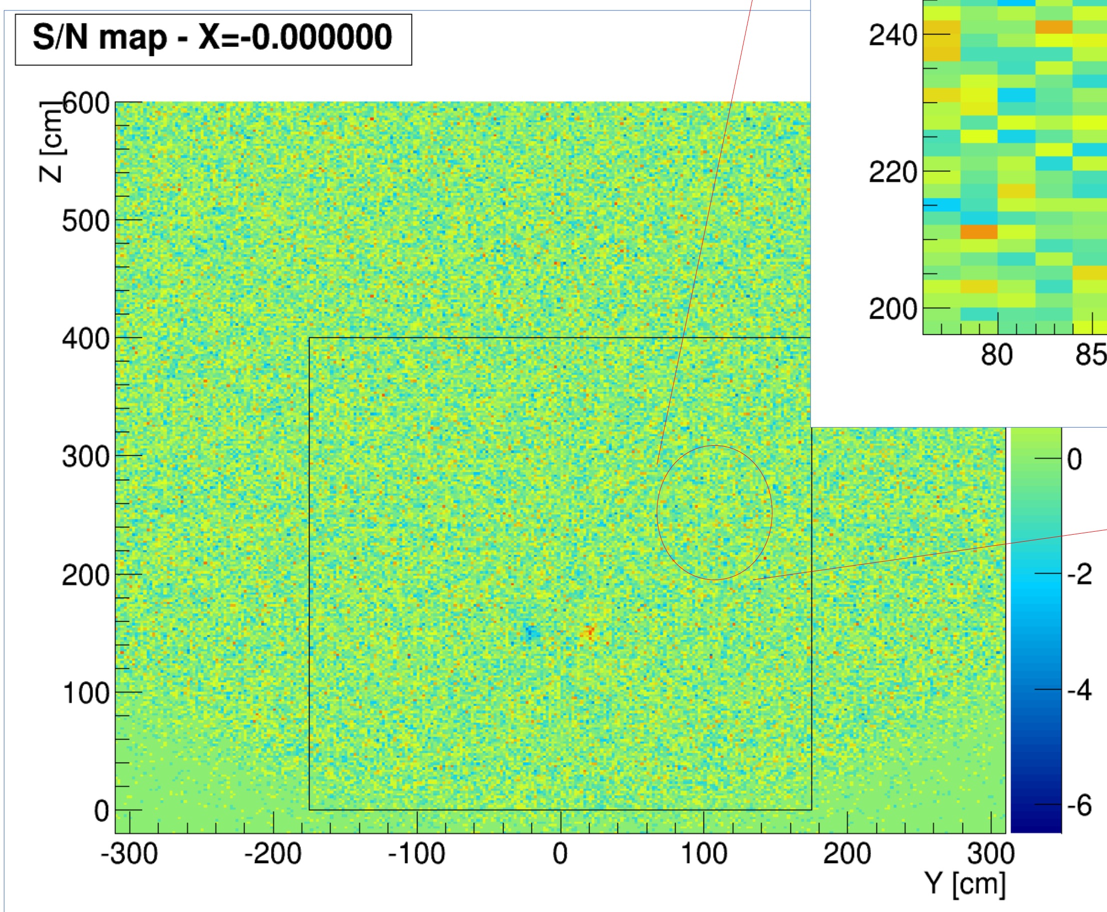


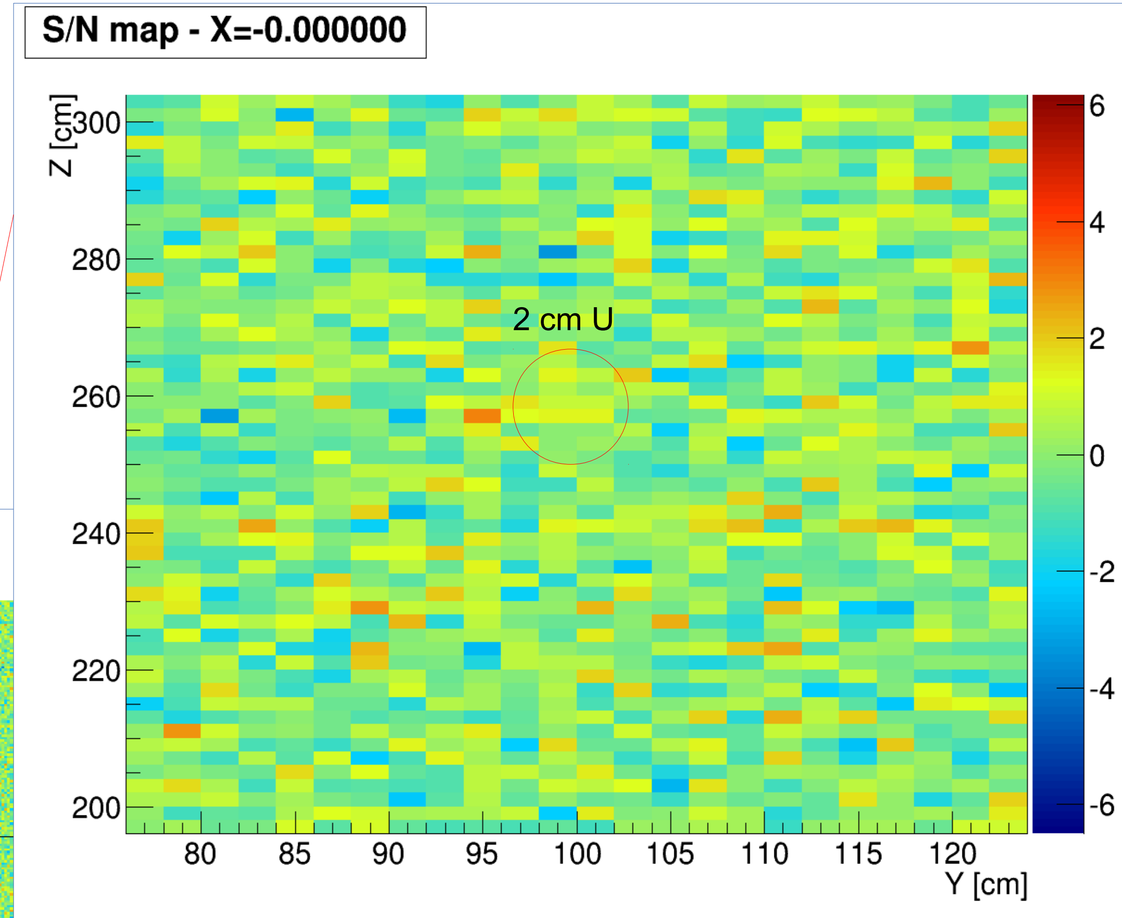




The 2 cm U cube placed off-axis is not visible...

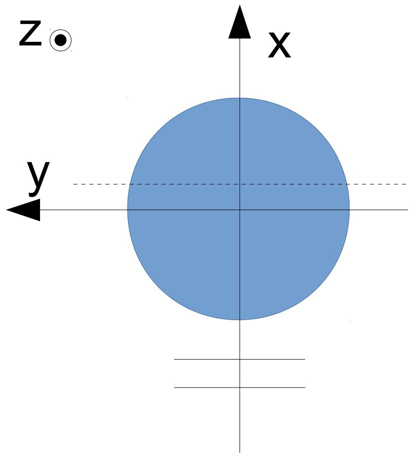


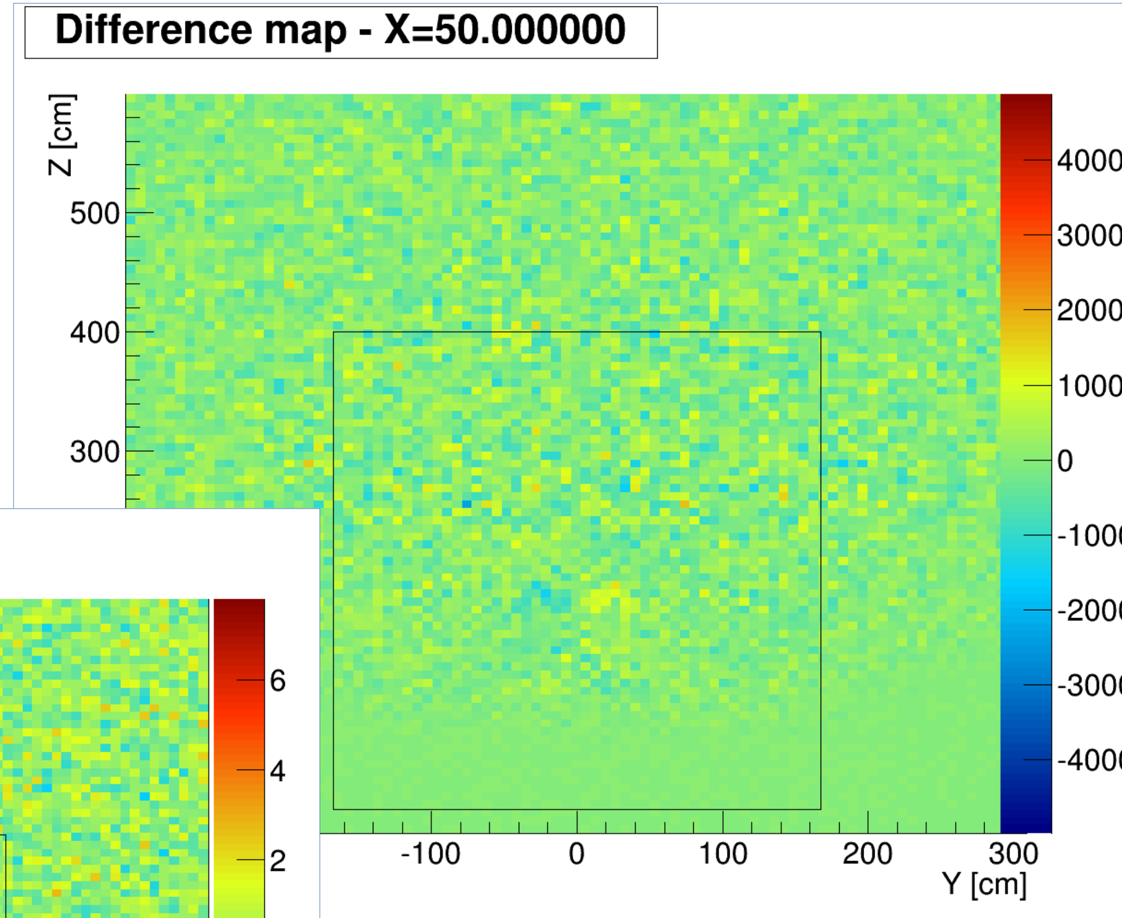


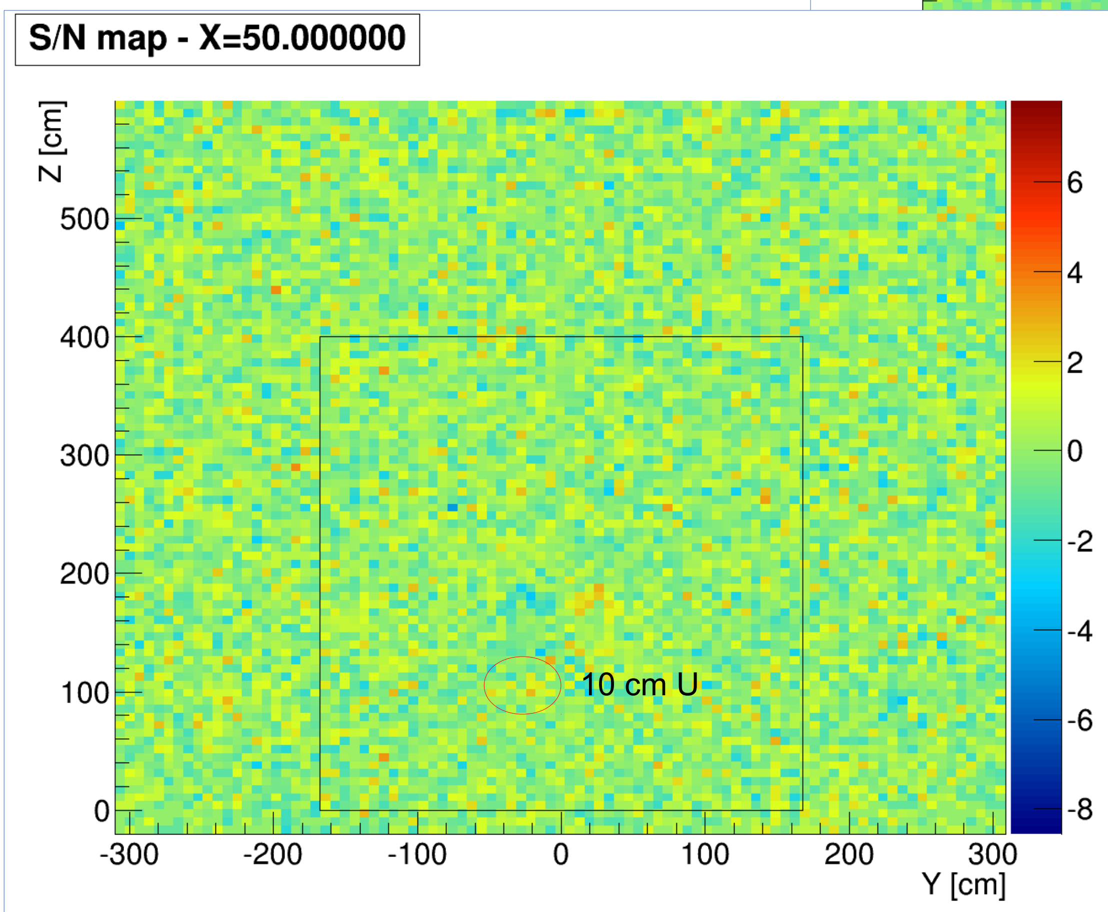


...even with optimized bin size (2x2 cm^2)

The big sample is still clearly visible but clustering would be needed to clearly identify it (max S/N of single bin ~ 4)



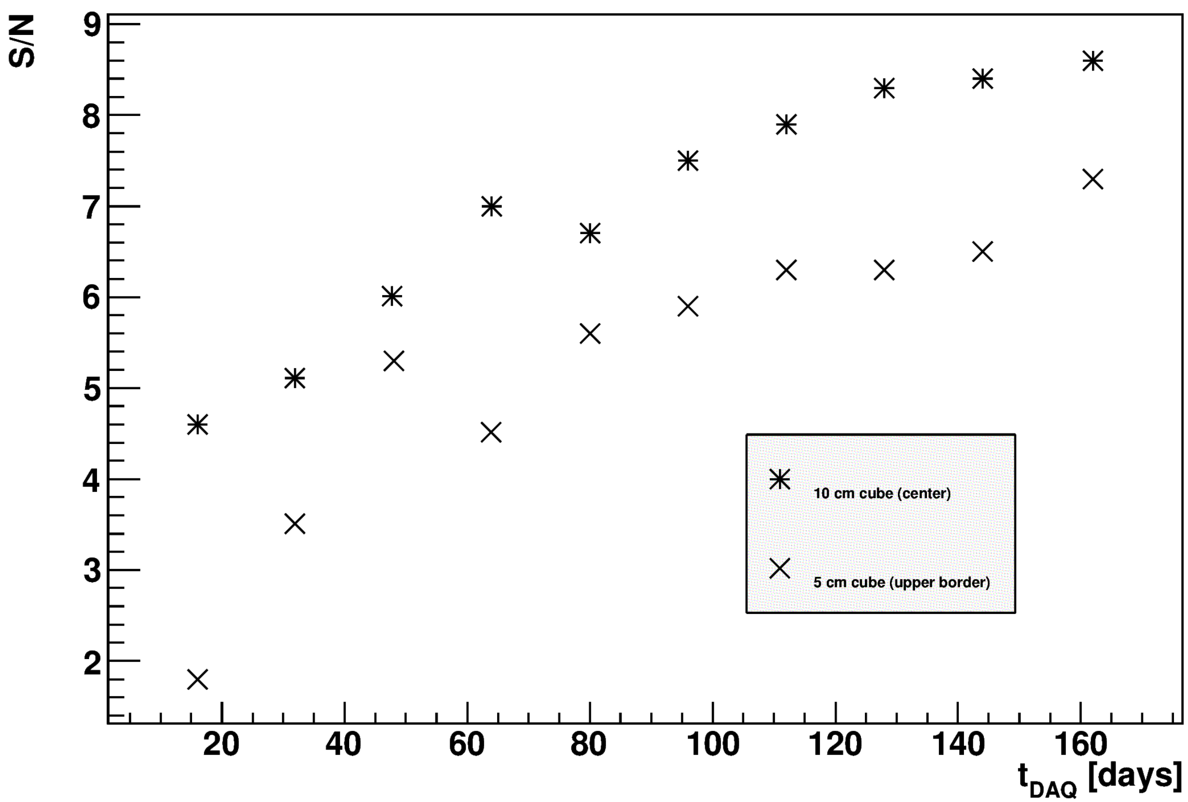




The 10 cm U cube is not visible

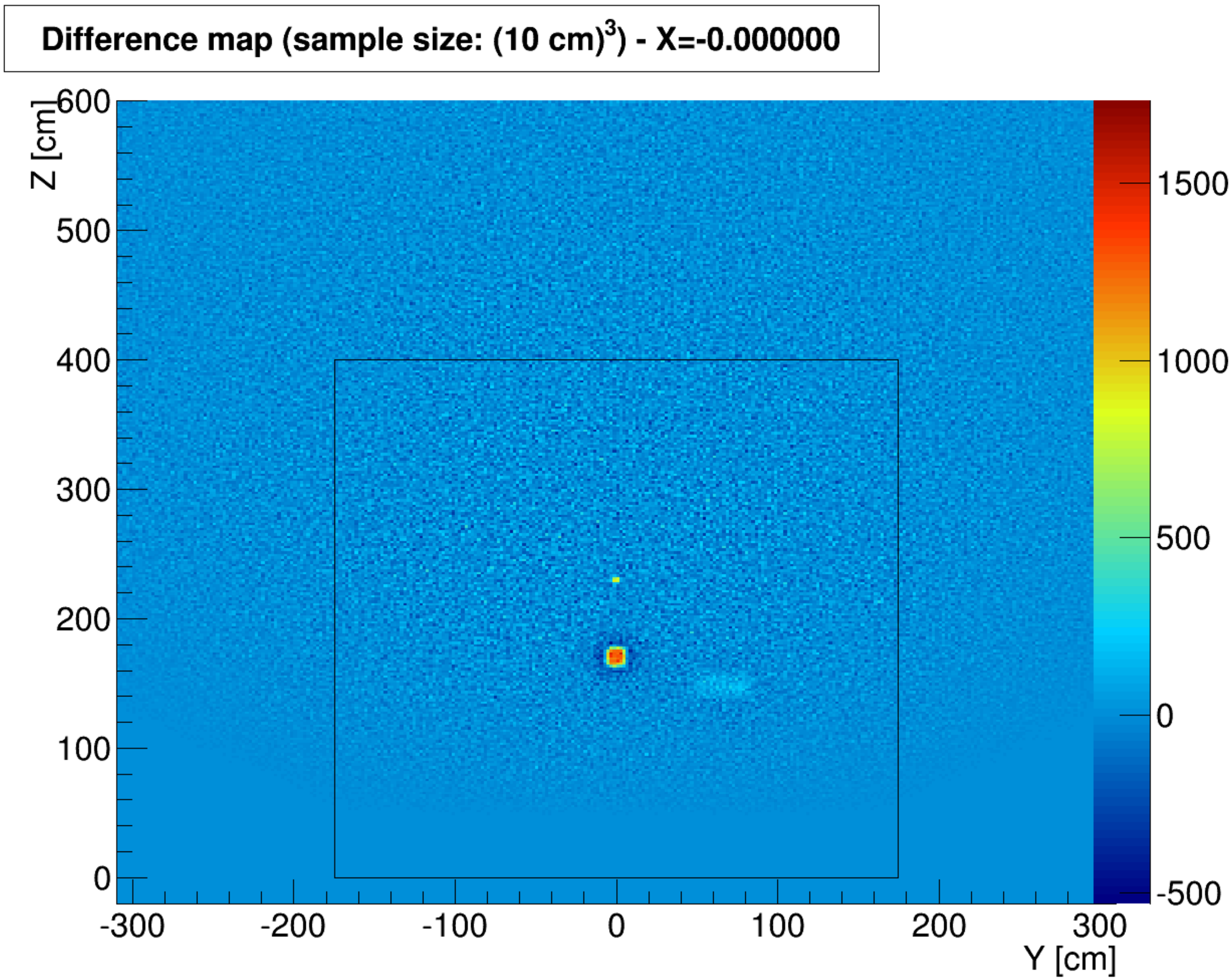
The position of the two blurs at Z ~ 1.75 m is consistent with the predicted position on the X=50 layer of the shadow of the 10 cm U sample at X=0

S/N vs acquisition time



- For the 10 cm U sample @ X=0 and 5 cm U @ silo border
- Manual clustering
  - Signal is divided many bins
- For 10 cm U case: the probability of obtaining no fluctuation at Nσ level or more over ~ 1430 bins (3.5m x 4m with (7x14) cm^2 pitch) is:
  - N=3: 2%
  - N=3.5: 52%
  - N=4: 91%
  - N=5: 99.92%
  - N=6: 99.9997%
  - Computed in the large μ approx. of Skellam distribution, where $\mu = \mu_1 = \mu_2$

Analysis of Multiple Scattering



- Turn off MSc in concrete
  - But not in U
- (2 cm)^3 and (10 cm)^3 samples @ center of silo
- (10 cm)^3, off-axis sample @ X=80 cm
- ~ 4x10^{11} generated events
- Very clear signal
  - MSc seems the limiting factor

Summary

- Feasibility study for U detection with muon absorption tomography technique
- Monte Carlo simulation: geometry, muon flux, detector
- Data analysis: backprojection, autobackgrond, S/N, DAQ time
- Detection capability strongly depends on the position of the sample
  - Nevertheless the 2 cm sample seems out of reach (MSc)
- Air bubbles seem to be not a problem (at this stage)
  - Results may vary when enlarging or changing the position
  - Density fluctuations may not be an issue (to be further investigated)
- S/N vs. time estimate
  - Need ~ 1 month to reliably detect a 10 cm U sample at center of silo
  - May (Will) vary with varying size and position

Outlook

- Towards a more realistic MC scenario:
  - Non-uniform concrete density
  - Macroscopic debris (steel rods, clothes etc.)
  - Neighbouring buildings
  - Realistic detector
- Analysis:
  - Event reconstruction
  - Automated scanning (X tomography, bin size)
  - Clustering algorithm
    - Improved S/N computation
    - Signal finding
- Checks:
  - Dependence on assumed flux
    - Acquisition time estimation
    - S/N
  - S/N vs. time for most probable high-density debris