High-resolution Computed Muon Tomography

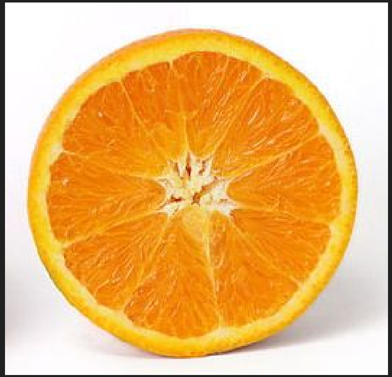
2017-12-15

Laboratori Nazionali del Gran Sasso
B. Suerfu

Outline

1. What is computed tomography?
2. Why muon tomography
3. Advantage of using muon beams
4. Potential applications

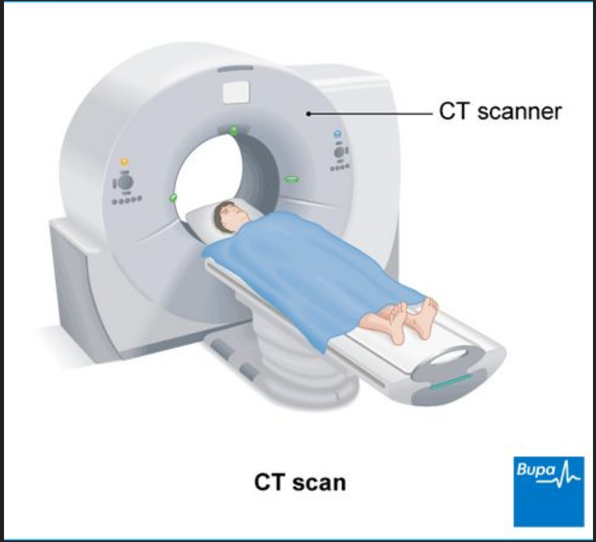
What is Computed Tomography



Tomography : image by section

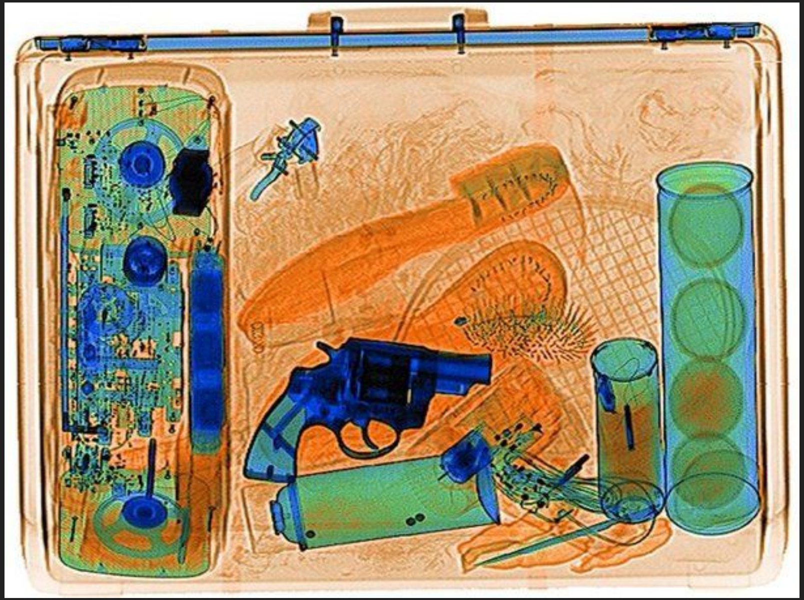
Computed Tomography : application of computer in obtaining a cross section image.

CT-scan : using X-ray for medical imaging and diagnostics

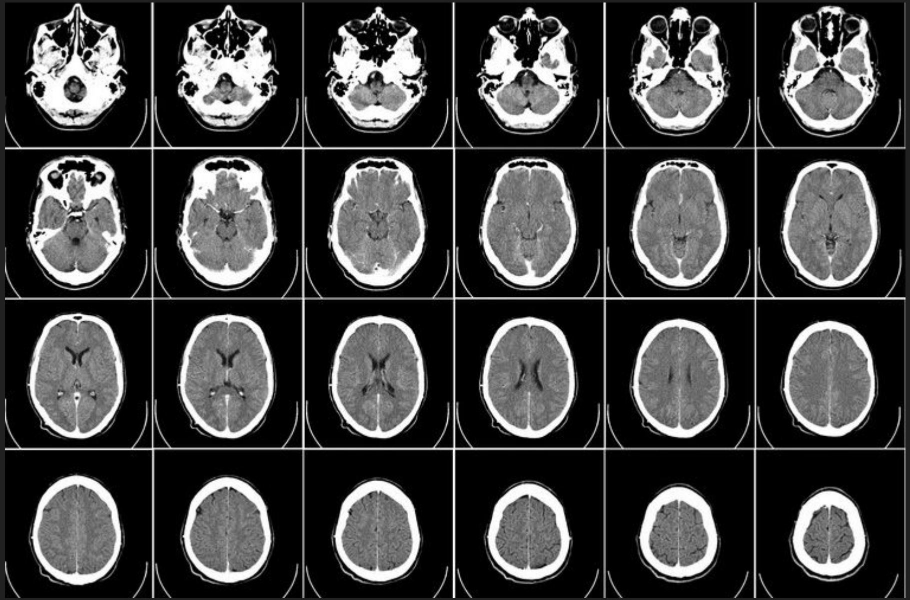


What is Computed Tomography

X-ray scan: only projection



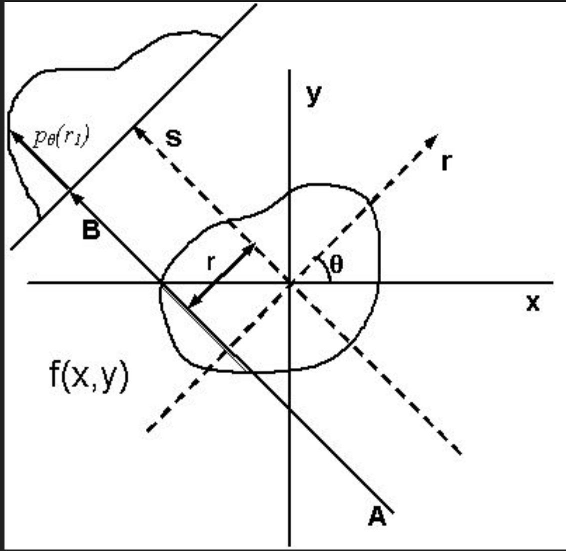
CT: 3D reconstruction



Tomographic Reconstruction

Mathematically: given a 2D scalar function (e.g. density), if it's integral projection (e.g. intensity loss in X-ray) is known at every direction, is it possible to find out the original scalar function.

Plainly: if you scan a suitcase in every orientation, can you find out the shape of the object.



Tomographic Reconstruction

Answer is yes (obviously)

First introduced in 1917 by Johann Radon, known as Radon transform.

Later filtered back projection, iterative algorithm and many more proprietary algorithms

- Better algorithm means better precision at lower dosage

e.g. Filtered Backprojection

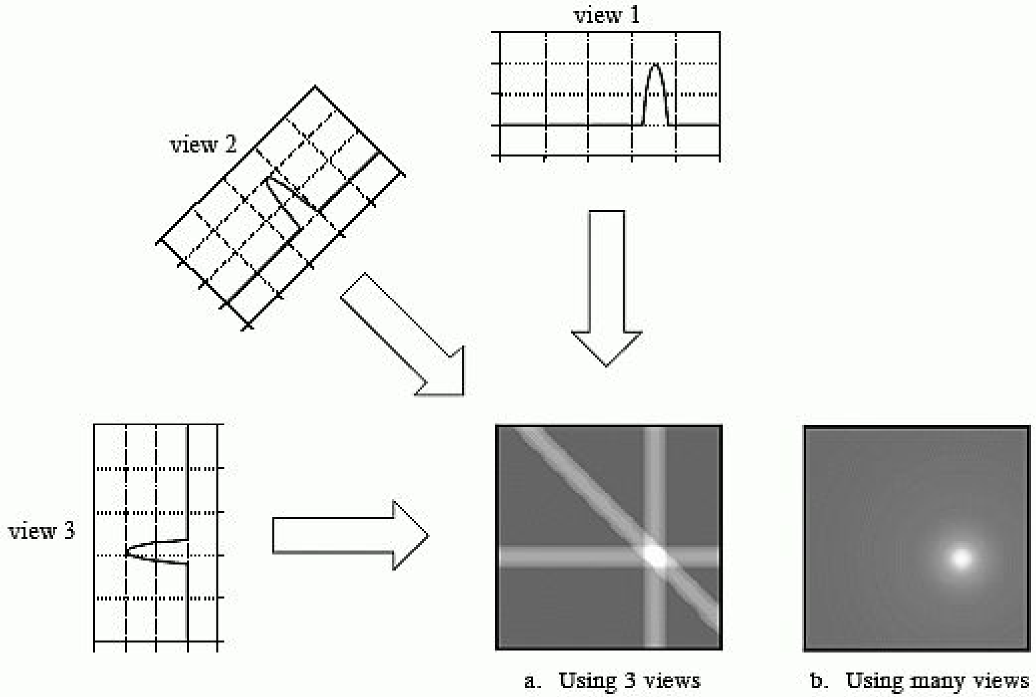
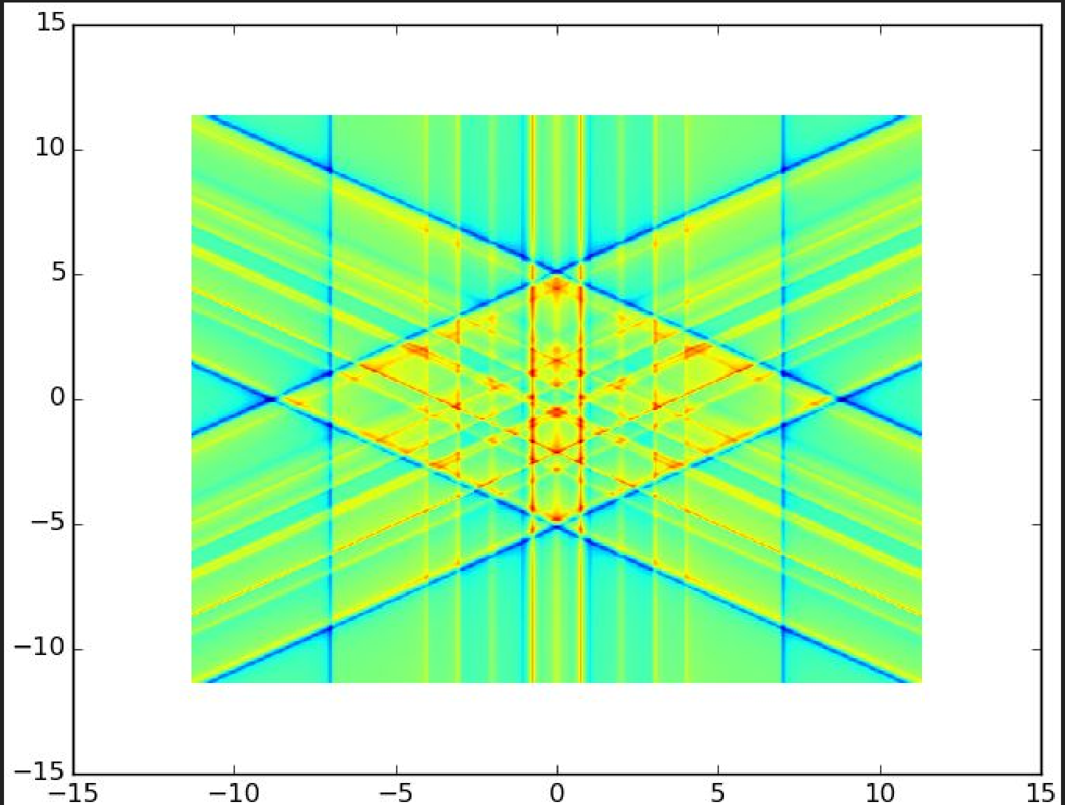
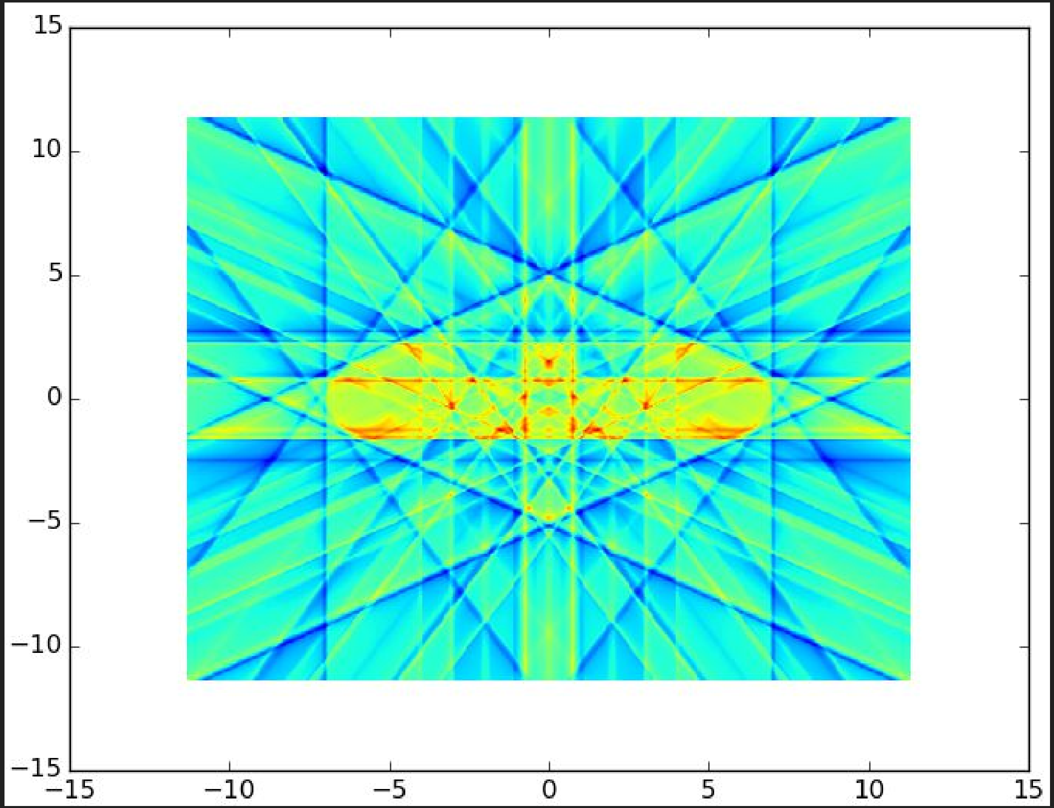


FIGURE 25-16
Backprojection. Backprojection reconstructs an image by taking each view and *smearing* it along the path it was originally acquired. The resulting image is a blurry version of the correct image.

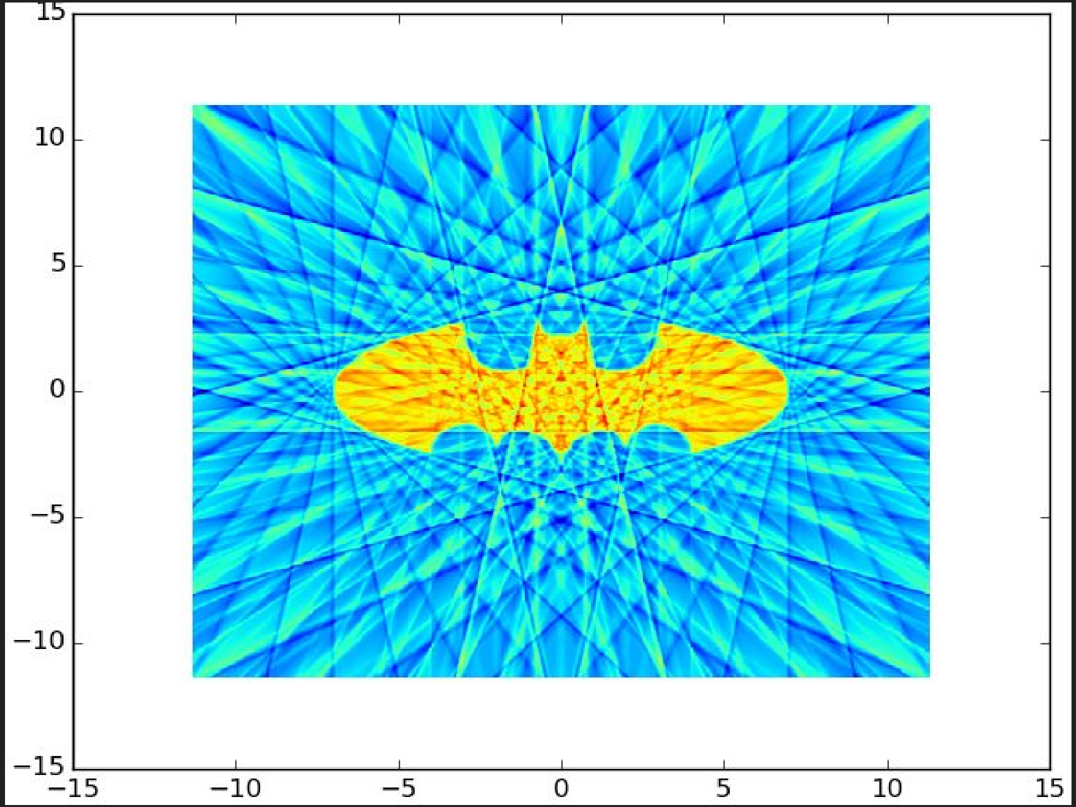
FBP in action - 3 back projections



FBP in action - 6 back projections



FBP in action - 18 back projections



Initial Motivation for Muon Tomography

100 keV X-ray: attenuation coefficient ~ 3.5 /cm

- After 2 cm of Cu, intensity is 0.1%

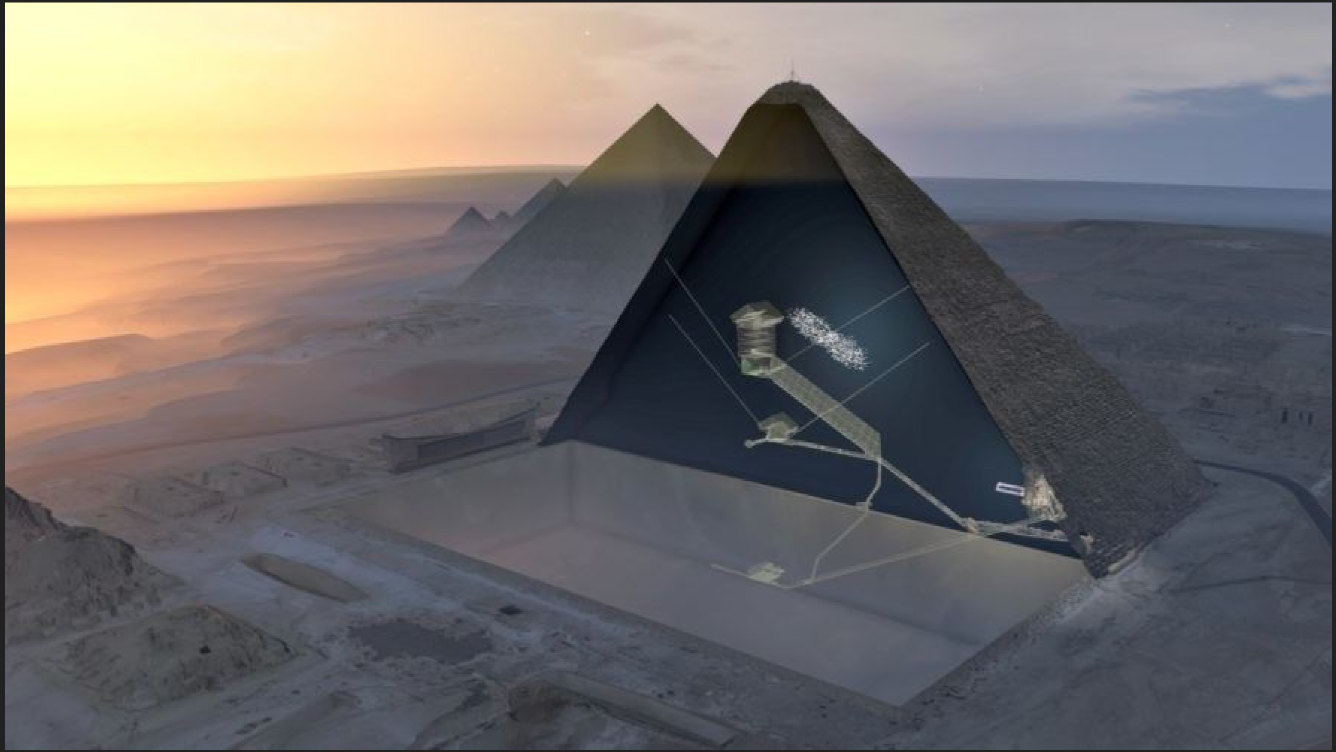
Why Muon Tomography

Muon is more penetrating than photons:

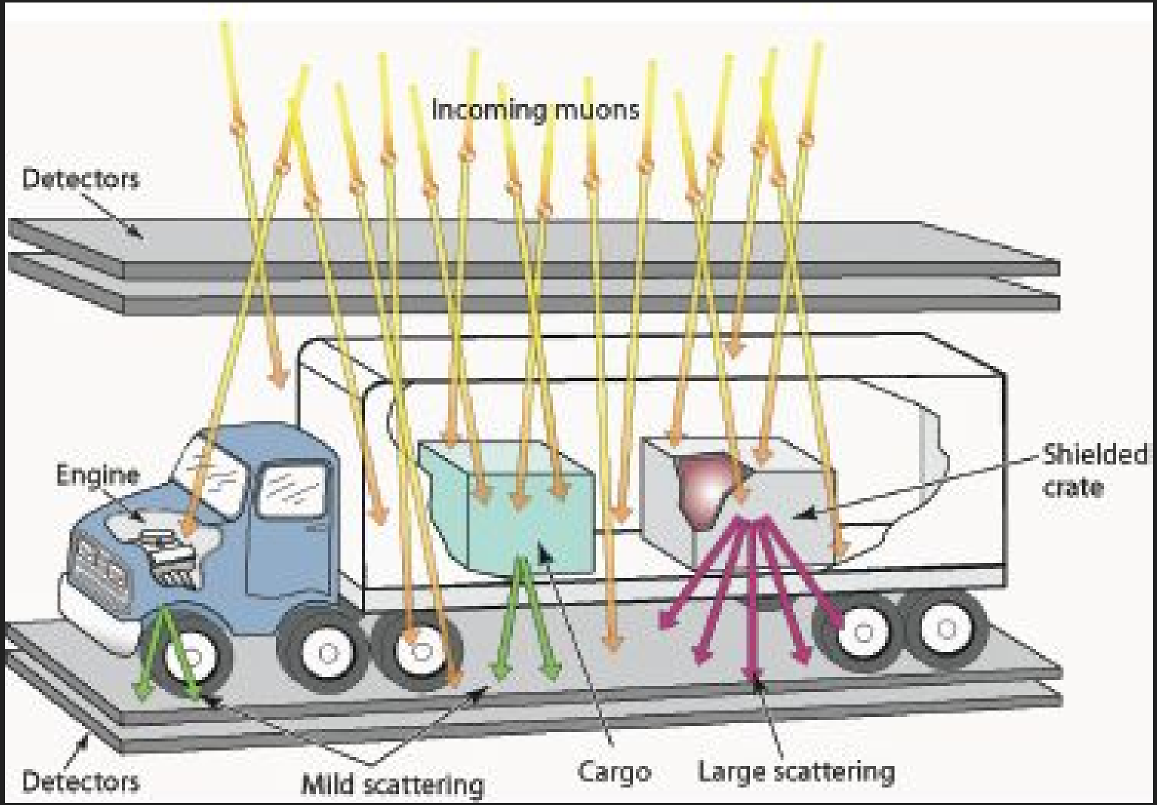
- Muons lose roughly 2 MeV per cm of water,
- 100 keV X-ray: attenuation coefficient ~ 3.5 /cm
  - After 2 cm of Cu, intensity is 0.1%

Cosmic muon has been used to image Pyramids, volcanoes, nuclear reactors and cargos.

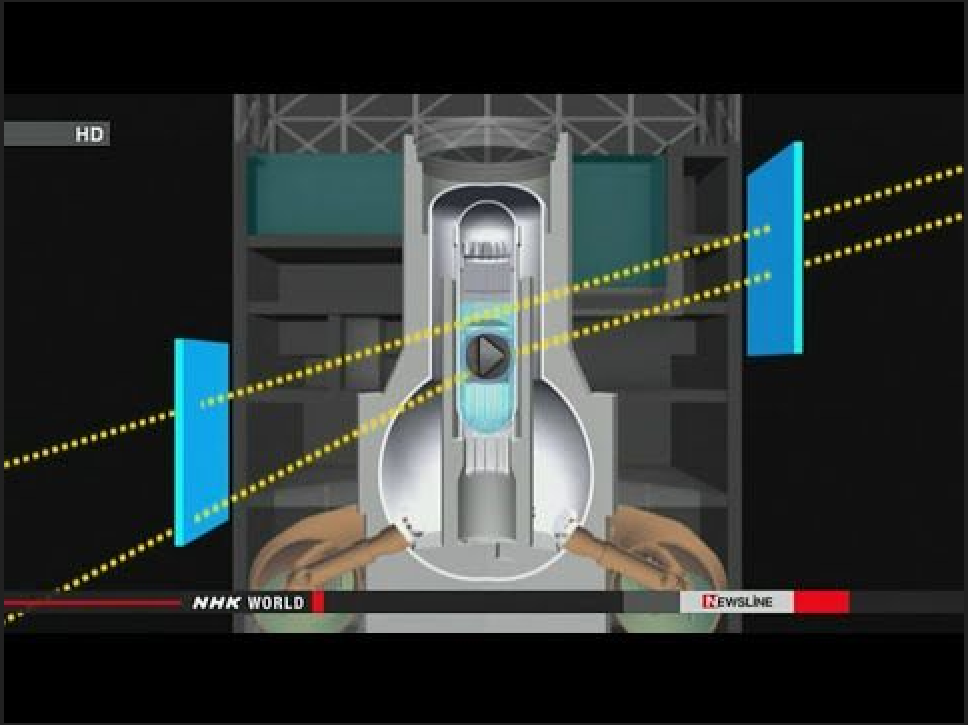
Cosmic muon helps find hidden chamber



Cosmic muon helps find nuclear material



Cosmic muon can help see the core of Fukushima



Limitation of using cosmic muons

On the surface, roughly 1 muon per cm2 per second

Can wait for months before hidden chamber is found

Better not wait for too long to scan a cargo, or to find out what is happening to a reactor.

Using muons from accelerator beams

Control over energy and flux; faster imaging.

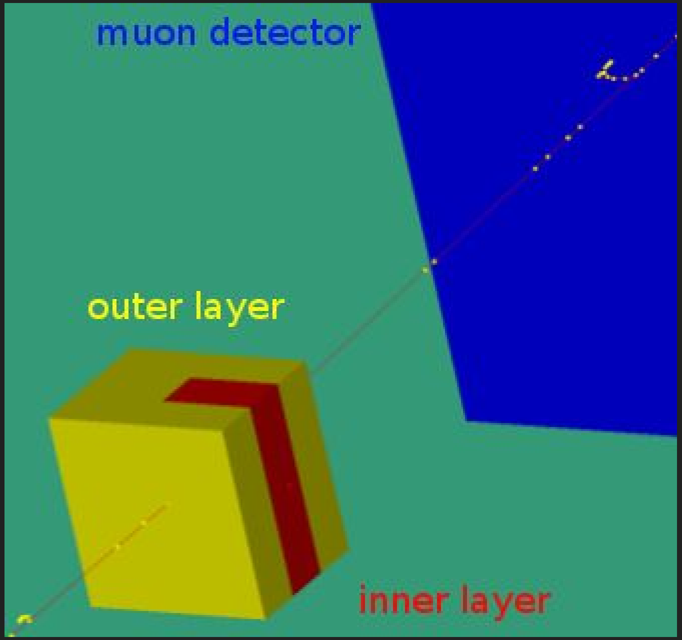
More expensive, not available everywhere, special facility needed.

Simulation Setup

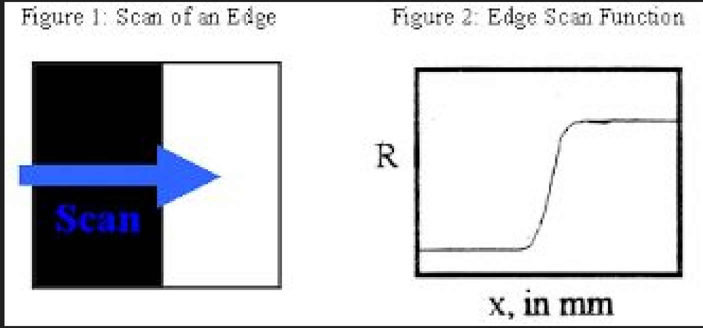
“Sandwiched geometry”

A different material is sandwiched inside one material.

Monoenergetic muon beam and a Muon detector is used to measure energy loss as function of XY



Modulation transfer coefficient



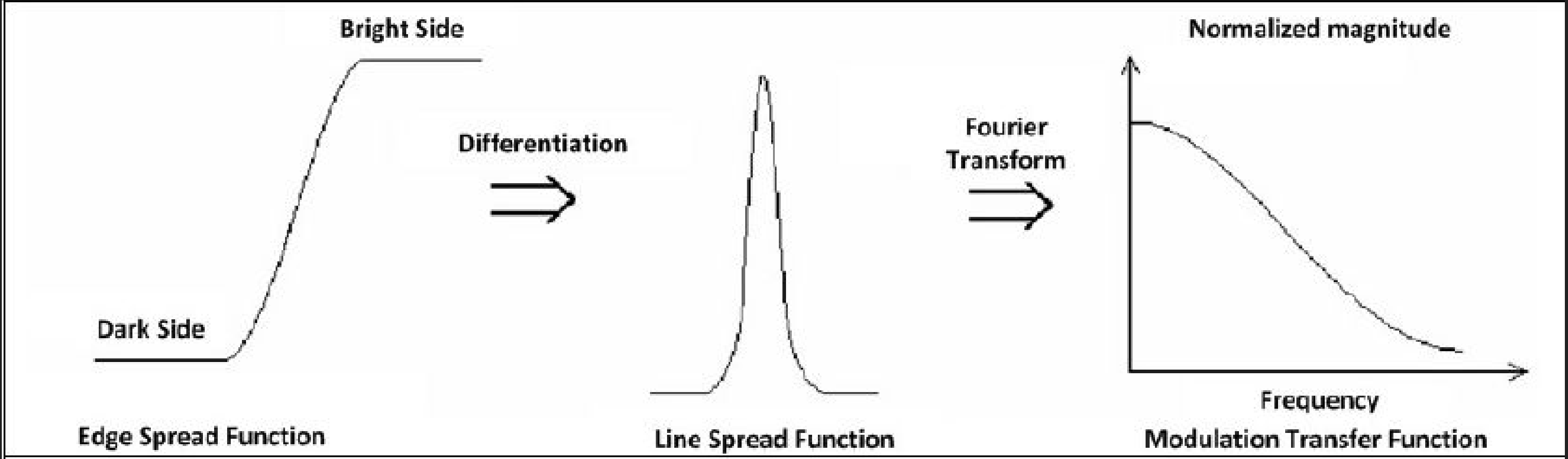
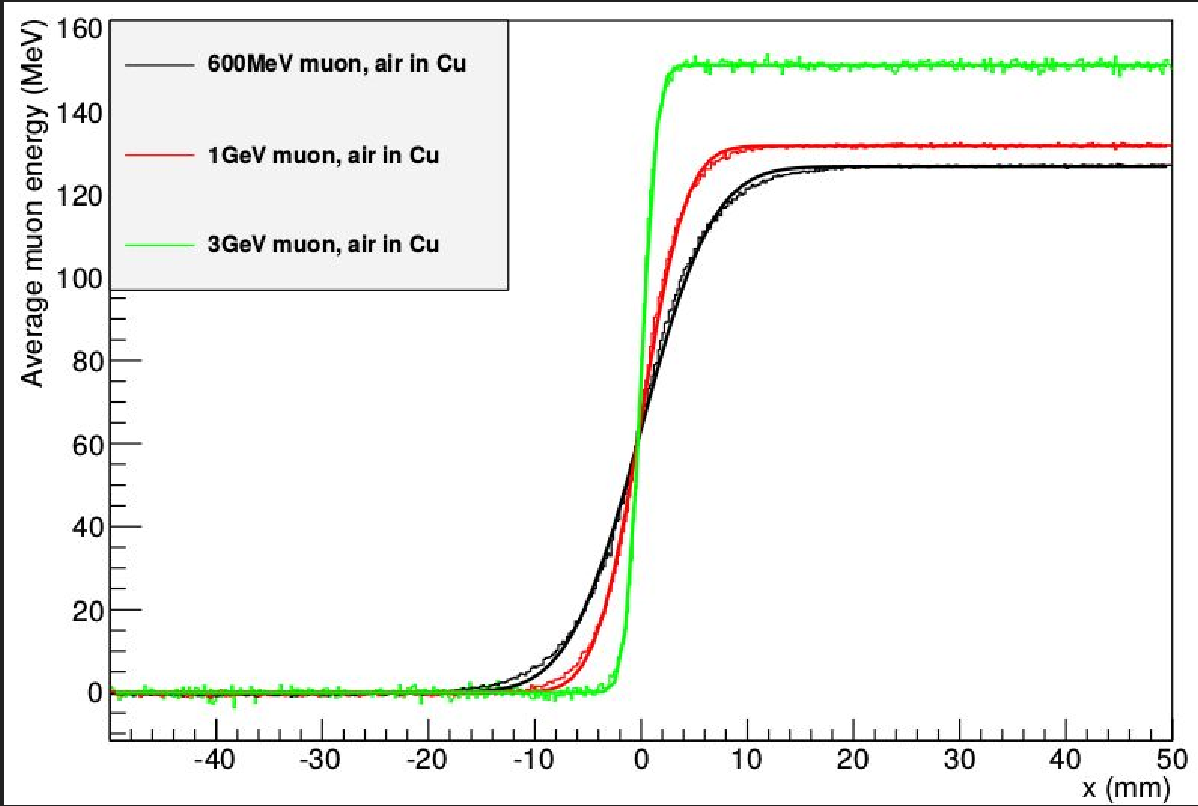
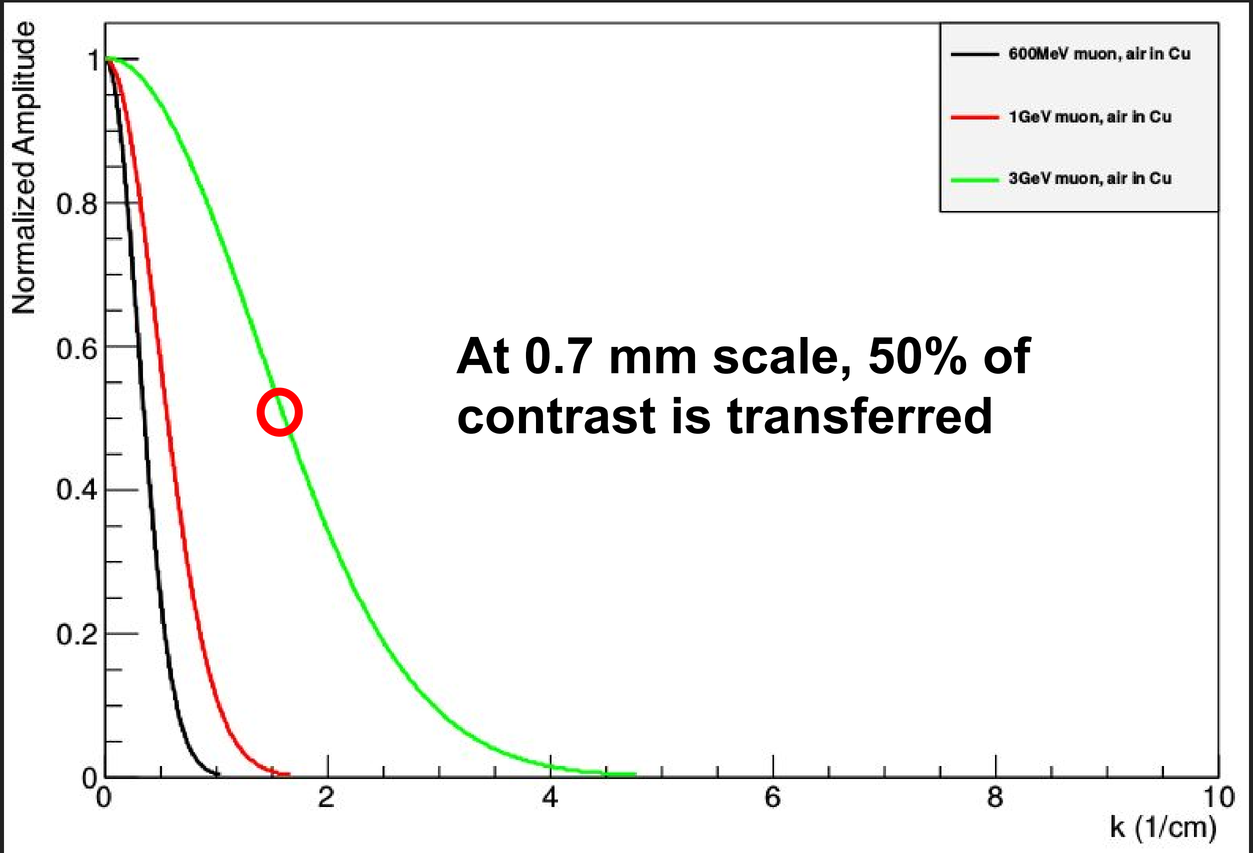


Figure 3. Computation of the Modulation Transfer Function using the knife-edge target.

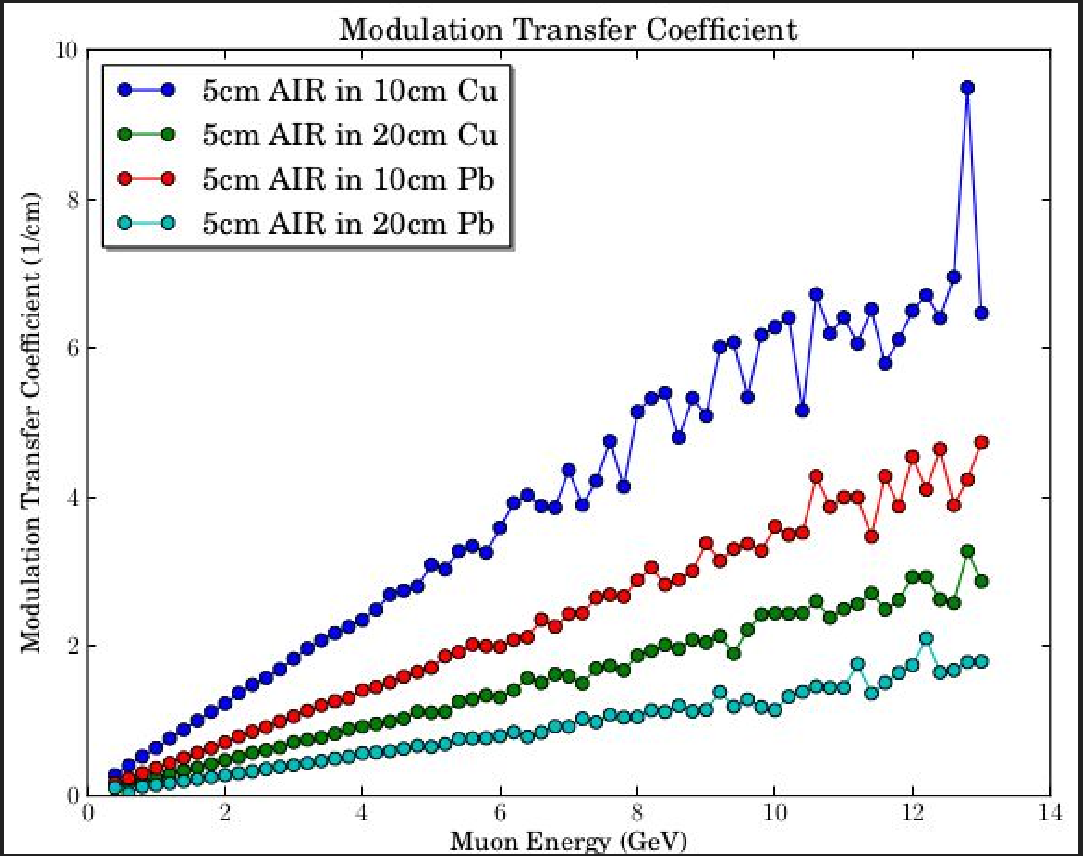
Edge-spread function



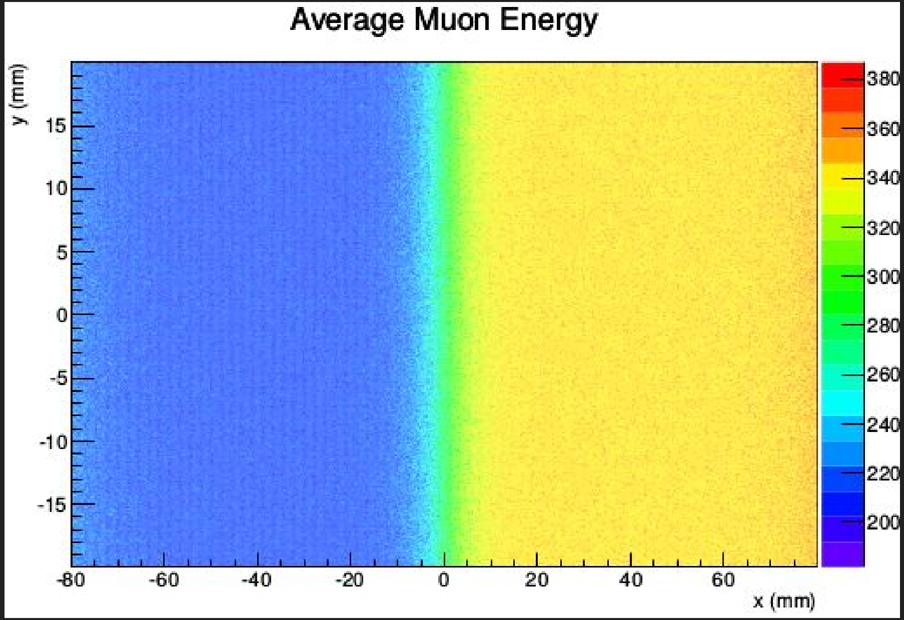
Modulation-transfer function



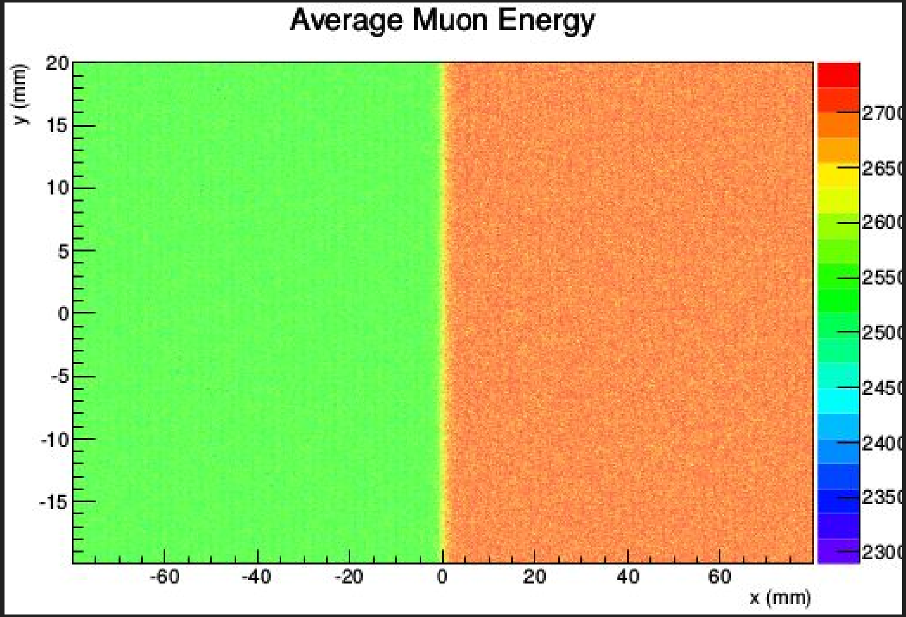
Modulation transfer for different material and geometry



The cost of increased resolution

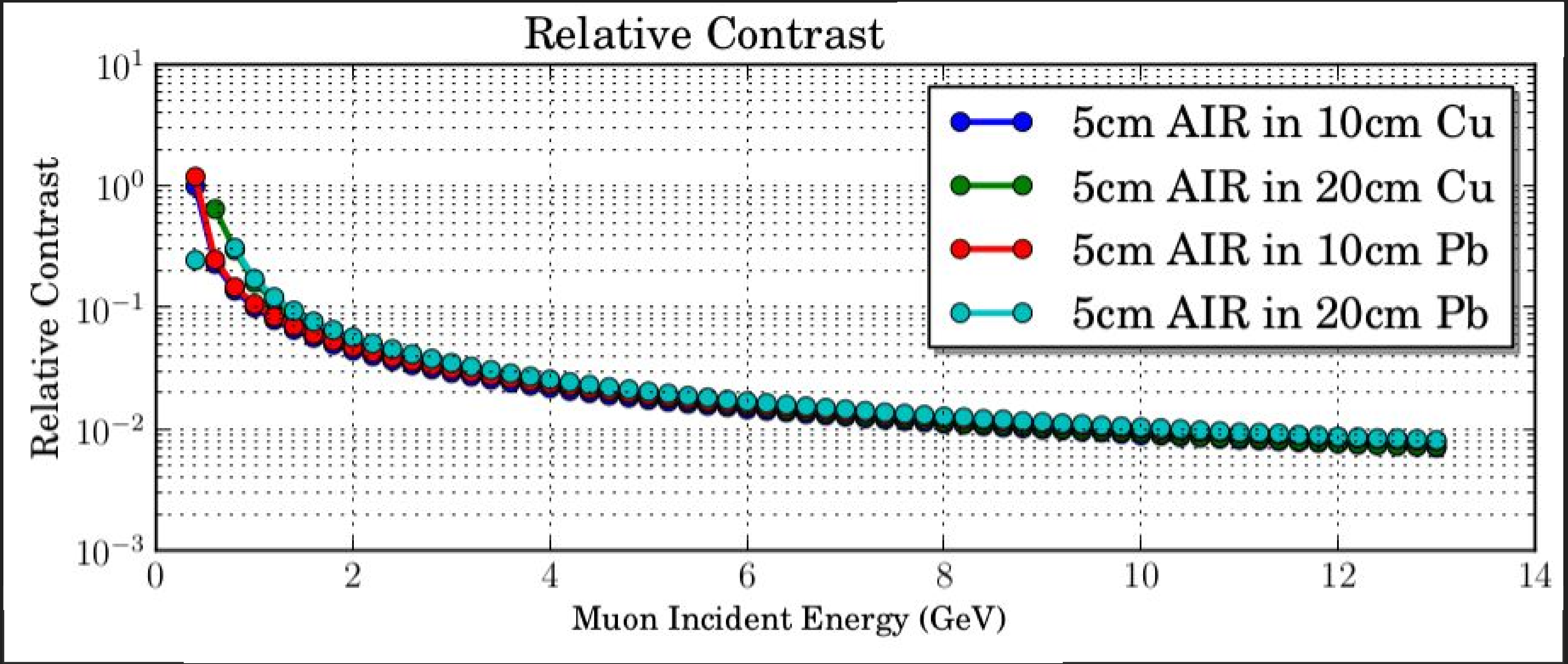


600 MeV



3 GeV

The cost of increased resolution



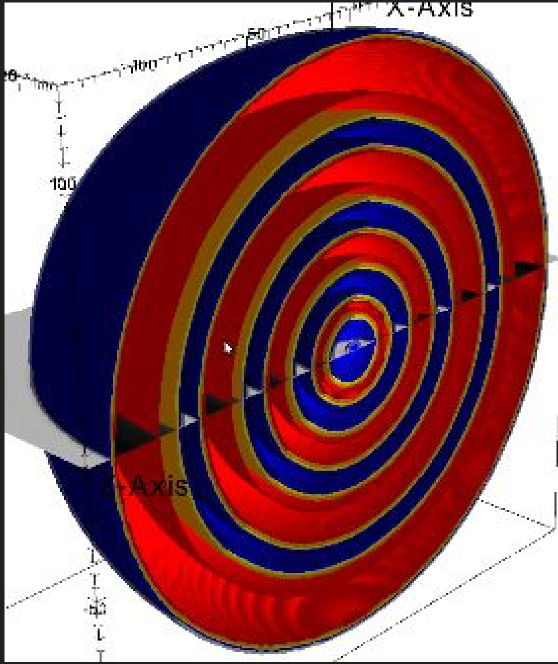
A few comments:

1. Muon tomography will have more information than mean energy loss, e.g. scattering, calculation by Bethe-Bloch.
2. Multispectrum muon beam
    a. Low energy for rough scan,
    b. High energy for precision.

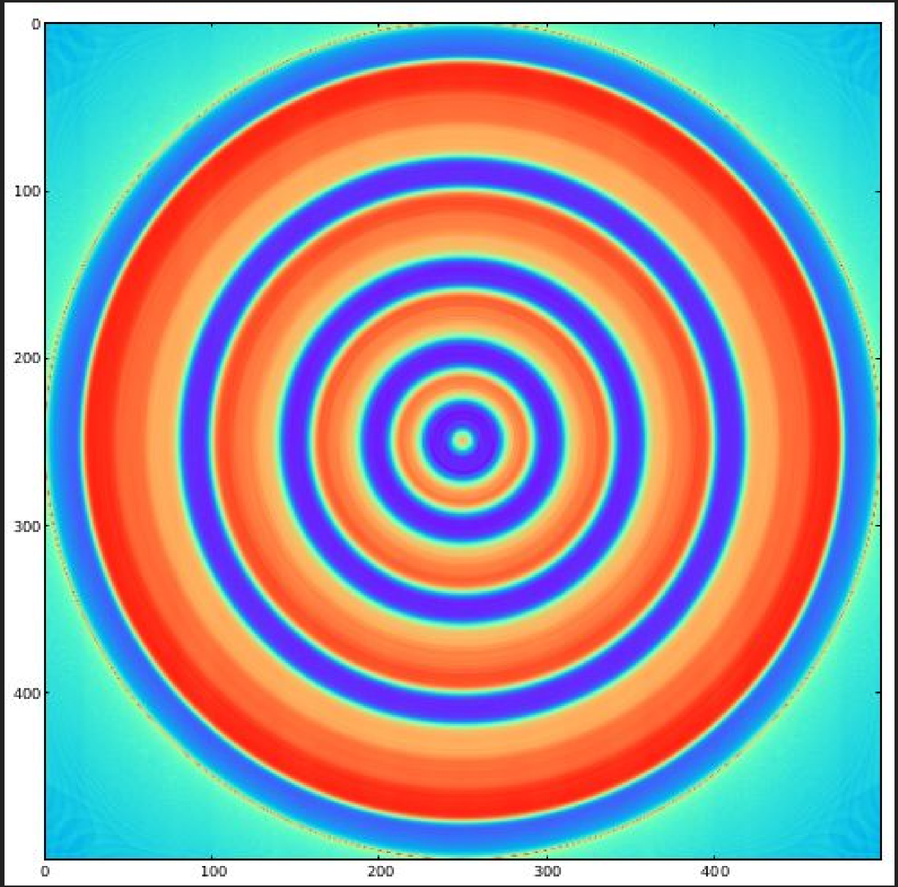
Performance in tomographic reconstruction

Test object:

- 5 layers of concentric spheres, thickness 3, 9, 15, 21, 30 mm
- Between each concentric sphere is 1 cm of water
- Each metallic layer is equal amount of copper, iron and lead



Performance in tomographic reconstruction



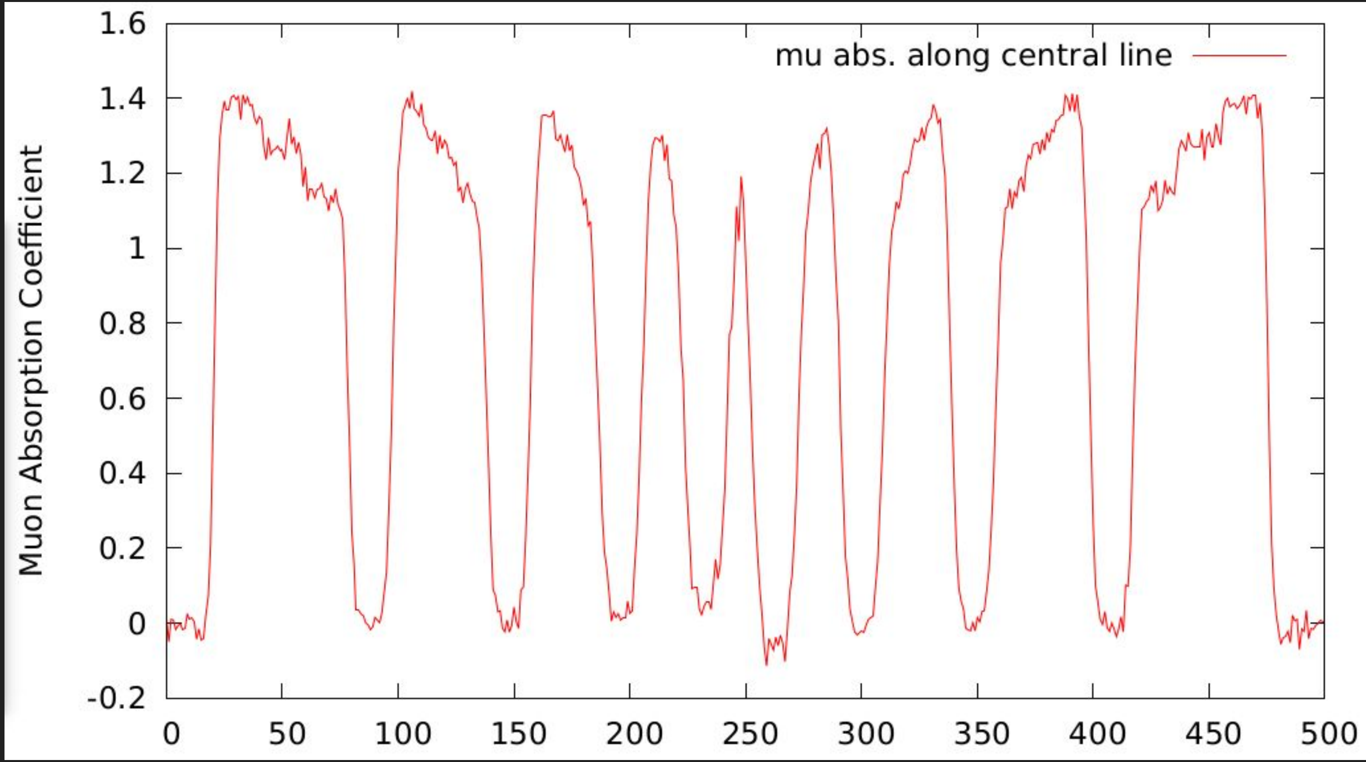
Density distribution reconstructed with FBP

Blue - water

In some of outer layers, different material density is clearly visible

Performance in tomographic reconstruction

In outer layers, material density clearly visible



Practical consideration:

1. Special muon beam would be ideal, but expensive too.
2. Muon neutrinos are produced by pion decay, with all muon dumped away
   a.
   $$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2E_\pi - 2p_\pi \cos\theta}$$
   $$\approx \frac{(1 - m_\mu^2/m_\pi^2)}{1+\gamma^2\theta^2} E_\pi. \text{ (small angle)}$$
   b. For NuMI beam in FermiLab, neutrino - 1~3 GeV, muon is 3 ~ 10 GeV.
   c. 10^7 / cm2 over 1 m^2 per spill over ~ 2 us, need highly pixelated trackers operating at hundreds of MHz

Future prospects:

1. A better reconstruction algorithm
2. Challenge is instrumental: required instruments exist
3. Interest in muon physics and neutrino physics
    a. g-2, NOvA, future muon collider
4. Interest in archaeology, industry and border protection
    a. Potential support from archaeologists in NY and DoE

references

[1] B. Suerfu and C. G. Tully, High resolution muon computed tomography at neutrino beam facilities, JINST 11 P02015, 2016
[2] M. Slaney, et al., Principles of Computerized Tomographic Imaging.
[3] M. Rossi, et al., Nuclear Science, IEEE Transactions on 46, 897 (1999).
[4] L. W. Alvarez, et al., Science 167, 832 (1970),
[5] H. K. Tanaka, et al., Earth and Planetary Science Letters 263, 104 (2007),
[6] A. Anastasio, et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment.
[7] J. Chistiansen and M. Garcia-Sciveres, Tech. Rep., CERN-LHCC-2013-008.