Non-Invasive Imaging of Reactor Cores Using Cosmic Ray Muons

SMU Physics Department seminar

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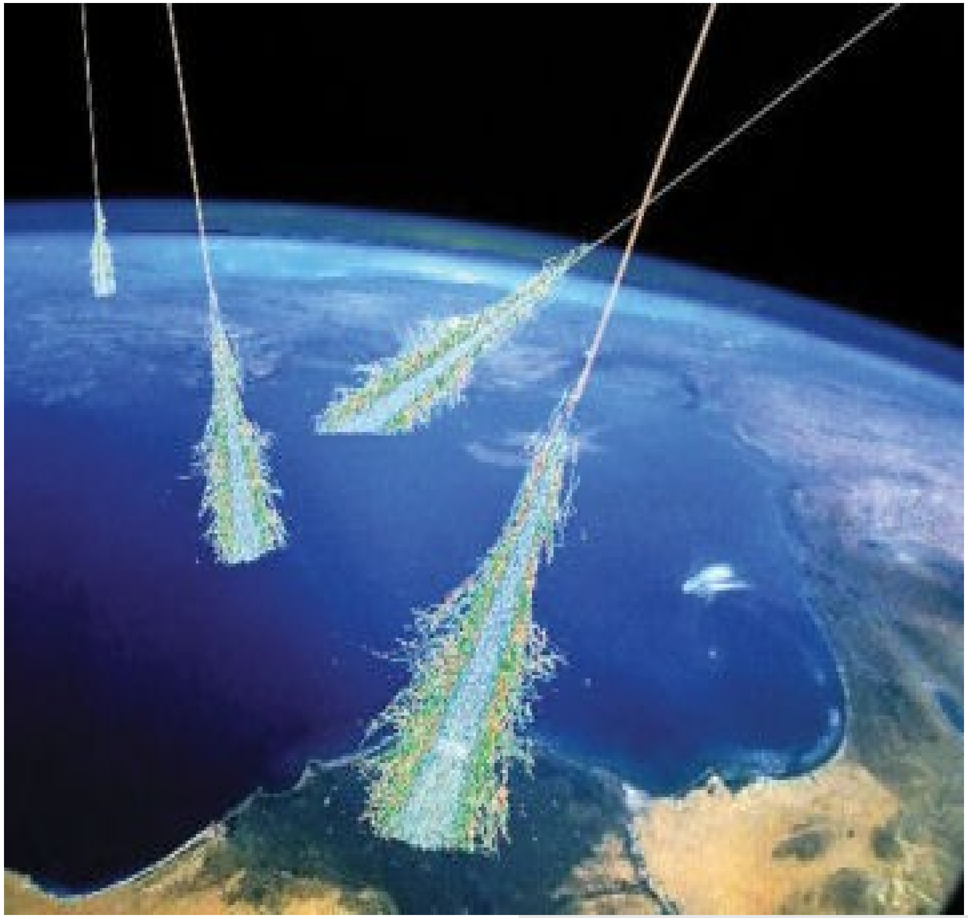
High energy cosmic rays interacting in the atmosphere generate extensive showers of secondary particles.



Source: Simon Swordy, U. Chicago

- Flux at sea level

  ~ 10,000 /m^2 /minute

  ~ 1 /60 cm^2 /s

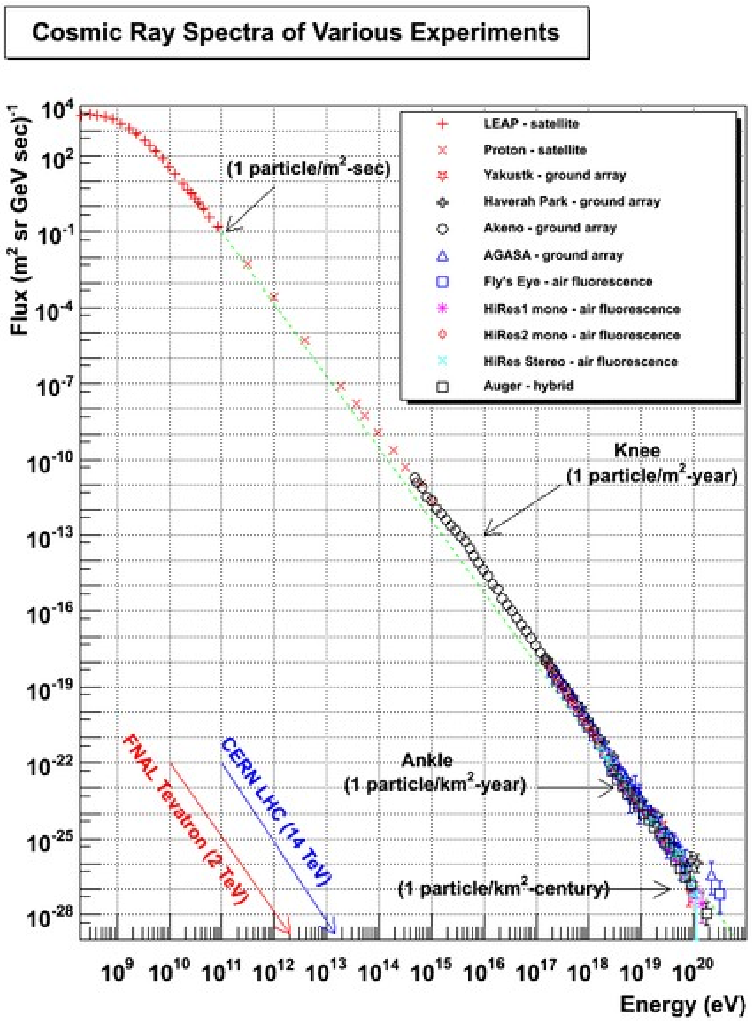
  ~ 1 / "hand" /s)

- p + N_2 → hadronic showers:

  $E^2 = \underline{m}^2c^4 + p^2c^2$

- Primary "sources" somewhat obscure
- Arrive isotropically
- Some primaries have **<u>very high</u>** energy
- High energy component of secondary flux is very useful

The primary cosmic ray energy spectrum is well known.

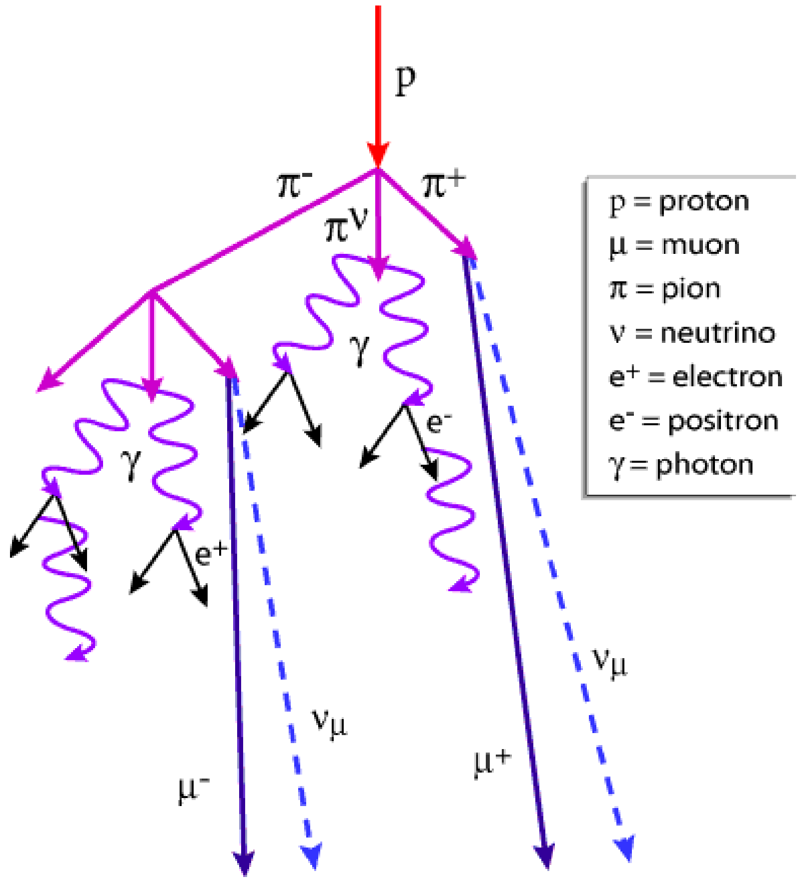


Ref: W.F. Hanlon, Ph.D. Dissertation, U. Utah, 2008.

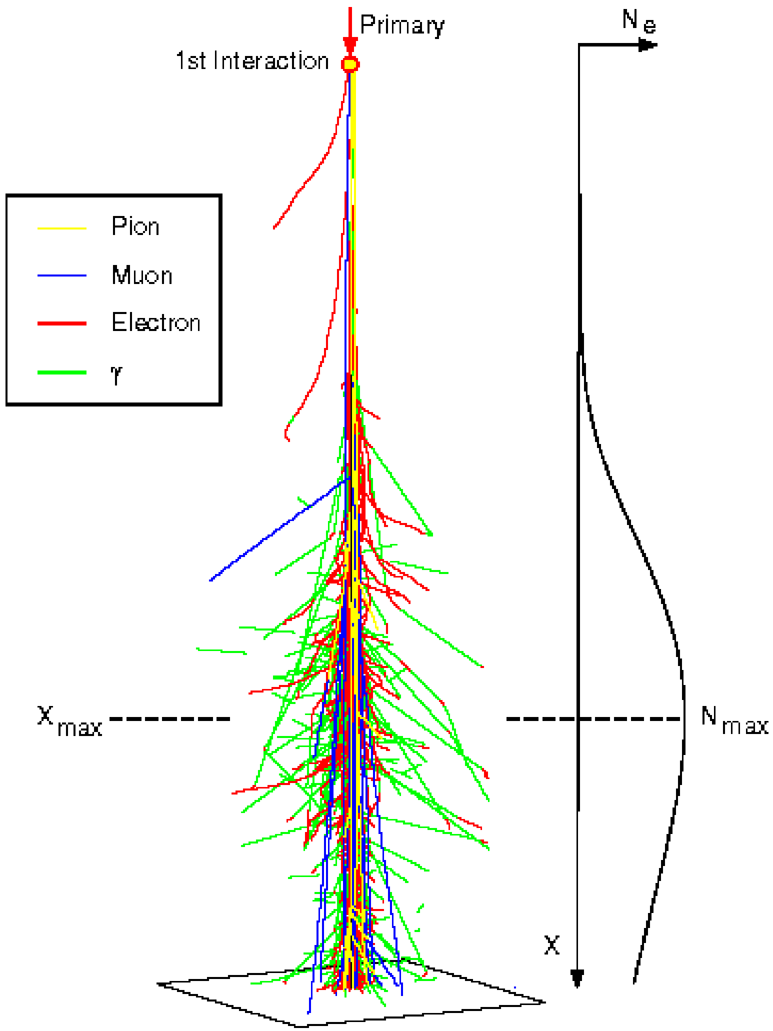
- Useful flux in the GeV to TeV range
- Flux scales as ~ E^{-2}

The secondary cosmic ray particle showers are primarily hadronic, with significant decay muon content.

- High production of π^o, π^+, π^-, K, etc.
- Muons (μ) produced in $\pi^{+/-}$, K, etc. decay
- Muon component of shower is penetrating and long lived
    - τ ~ 2.2 µs in μ rest frame of reference, but much longer in our frame of reference



Muons are penetrating, making radiography of thick objects possible.



- Highly penetrating
  - Muons interact only through the Coulomb and weak force
  - Mass ~200x e^- mass, so e^- deflection is very small
- 3 GeV muons have a range of ~17 m in concrete

Cosmic ray muons have been used to probe the interior of mountains, pyramids and shipping containers.

- **Measurement of mine overburden (under a mountain!)**
  - E.P. George, Commonwealth Engineer, 455 (July 1, **1955**).
- **Search for structure in the Second Pyramid (Kephren) at Giza**
  - L. W. Alvarez, J. A. Anderson, F. Elbedwe, J. Burkhard, et al., Science (USA) 167 (3919), 832 (**1970**).
- **Location of lava inside volcano**
  - K. Nagamine, M. Iwasaki, K. Shimomura, K. Ishida, NIM Phys. Res. A 356, 585-595 (**1995**).
- **Imaging interior of buildings on UT campus**
  - C. Hui, MA Thesis, The University of Texas at Austin, (**2007**).
- **Detection of dense metal objects in shipping containers**
  - C. Morris, C. Alexander, J. Bacon, K. Borozdin, et al., Science & Global Security 16 (1), 37-53 (**2008**).

Volcano interior densities have been measured using cosmic ray muons.

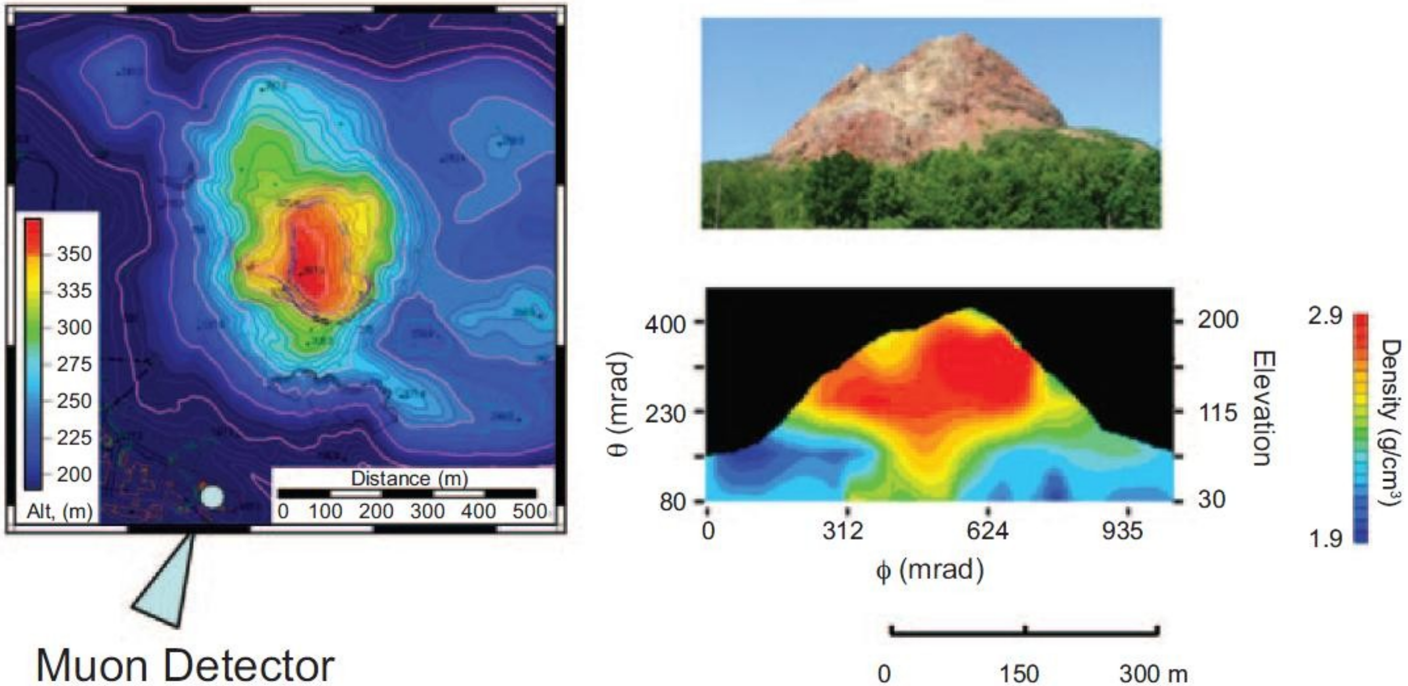


Fig. 5. Radiographic image of the conduit beneath 1944 Usu lava dome. (left) a map of the lava dome showing the location of the cosmic-ray muon detector (arrow). (right) the exterior shape of the lava dome and the average density distribution. The average density distribution is projected on the cross sectional plane that is parallel to the detector plane and includes the dome peak. The coordinate at the right side indicates elevation in m.

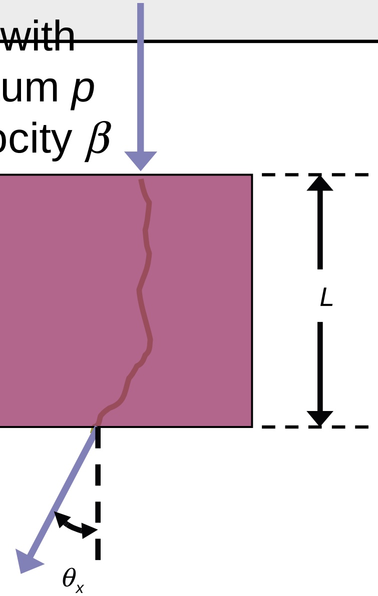
Ref: "**Radiographic Imaging Below a Volcanic Crater Floor with Cosmic-Ray Muons**", H.K.M. Tanaka, *et al.*, American Journal of Science, v. 308, Sept. 2008, pg. 843-850.

There are two techniques for imaging the interior of large objects with cosmic ray muons.

- **Muon transmission imaging**
  - Measure muons transmitted through object.
  - More muons successfully pass through paths in which they encounter less material (integrated density and length), compared to higher density paths.
  - Muon intensity data from a variety of directions and detector positions is used to reconstruct a 3-dimensional image of the relative density of material.
- **Muon scattering tomography imaging**
  - Angular deflection of muons passing through the reactors is measured by detectors placed on two opposing sides of an object.
  - Muons are deflected more strongly by heavy nuclei like uranium, than by relatively lighter nuclei like the iron in steel or the elements in concrete.
  - A three-dimensional map showing the regions of large deflections will identify the location of uranium.

The multiple scattering distribution is wider for high-Z objects; muon scattering is sensitive to material composition.

Particle with momentum p and velocity β



$$\frac{dN}{d\theta_x} = \frac{1}{\sqrt{2\pi}\,\theta_0} e^{-\frac{\theta_x^2}{2\theta_0^2}}$$

- **Scattering distribution is approximately Gaussian**

$$\theta_0 = \frac{13.6}{p\beta}\sqrt{\frac{L}{\lambda}}$$

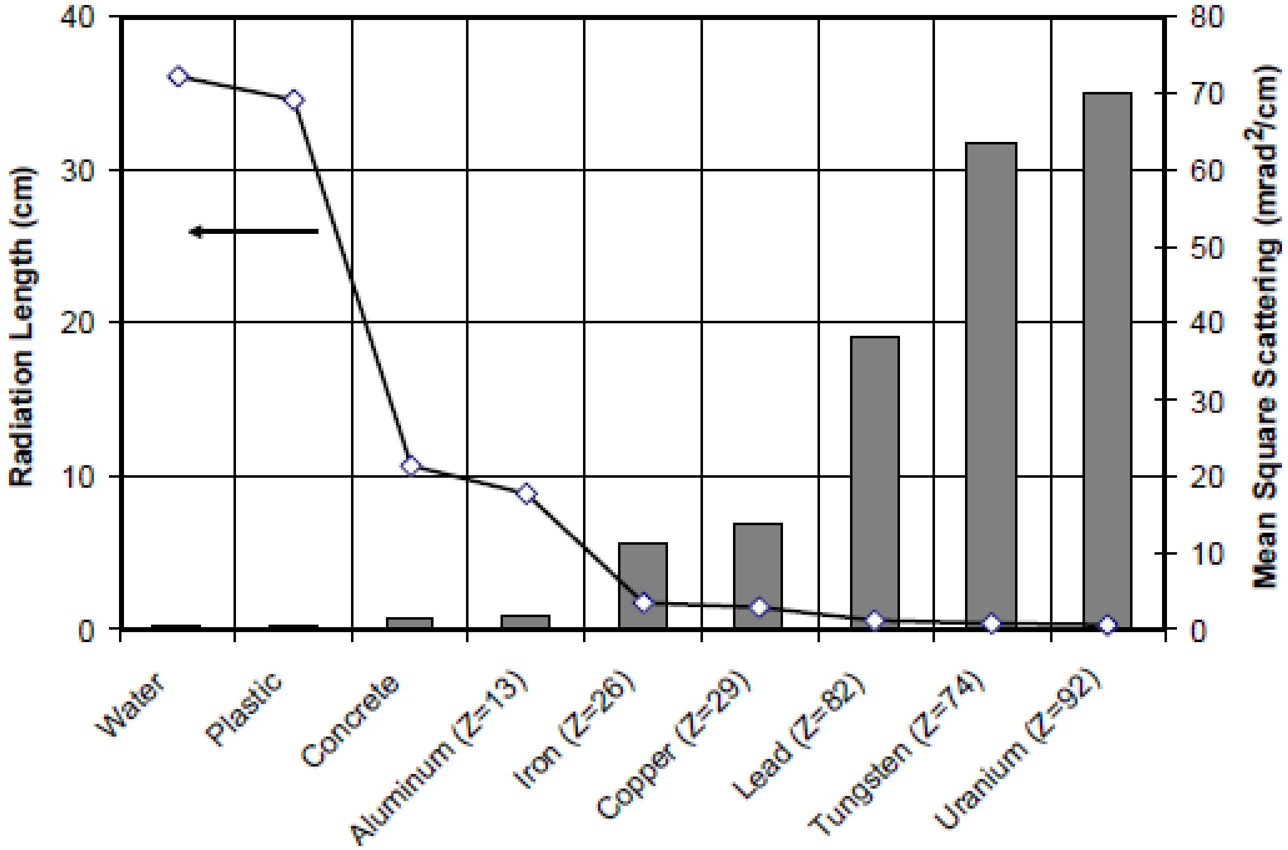
- **Distribution width is related to the material (λ is radiation length).**
- **λ ~ proportional to $1/Z^2$**
- **θ_o ~ proportional to Z**

Scattered particles carry information, and material may be identified.

Material	λ (cm)	θ_o (mrad)
Water	36.10	2.4
Fe	1.76	10.8
Pb	0.56	19.2
U	0.32	25.3

(10 cm material, p = 3 GeV)

The high mean-scattering angle for high-Z materials makes possible high image contrast.



Radiation length and mean square scattering per unit depth of 3-GeV muons.

L.Z. Schultz, K.N. Borozdin, C.L. Morris *et al.*, NIM A519 (2004) 687.

In comparison, muon transmission rely on measuring density – and result in less image contrast.

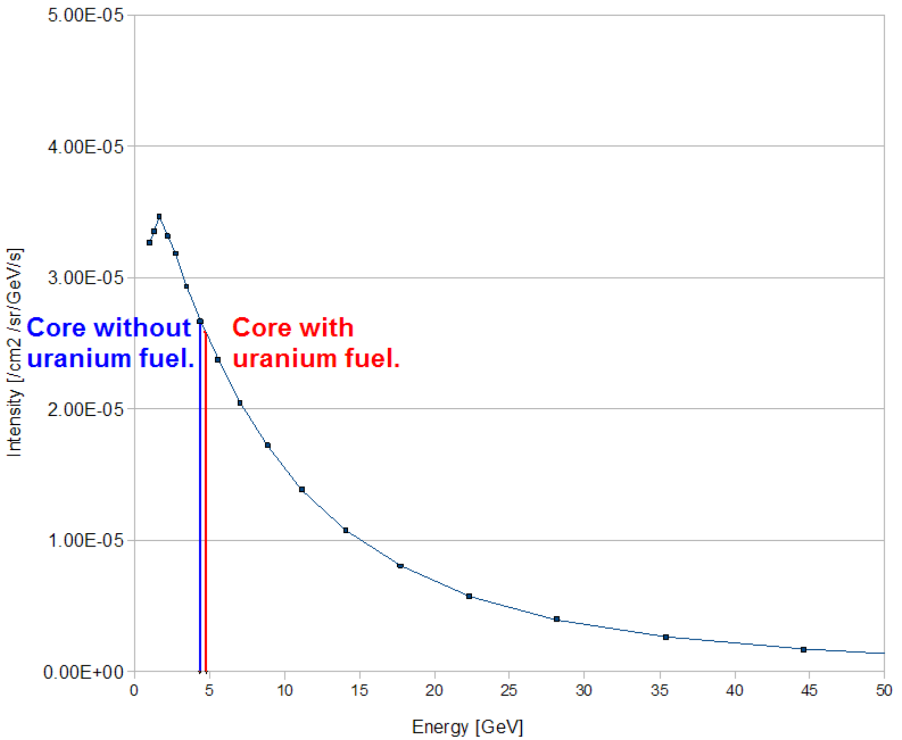
<u>Contrast between fuel and water</u>

E Loss [MeV] = $-dE/dx \times \rho \times L$

dE/dx: UO_2 (2.3), H_2O (1.6) [$MeV \cdot g^{-1} \cdot cm^2$].
ρ : UO_2 (2.6), H_2O (1.0) [g/cm^3].
L (fuel) 280 [cm] (Reactor #1)

Difference in the E loss between water and fuel in the core is **430 MeV**.

Transmitted muon intensities differ by ~1.5%.



Difference in muon absorption in reactors **with** and **without** uranium fuel.

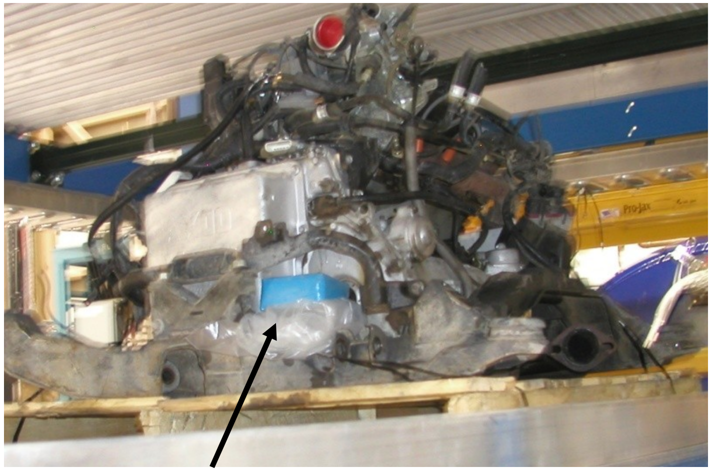
At LANL, we have used cosmic ray muon scattering for detecting concealed high-Z material (uranium, etc.)

- **Measure deflection of cosmic muons**
  - tracking before and after passing through object
  - Generate muon “scattering density” image
    - » “High-z” materials (like uranium) deflect muons strongly

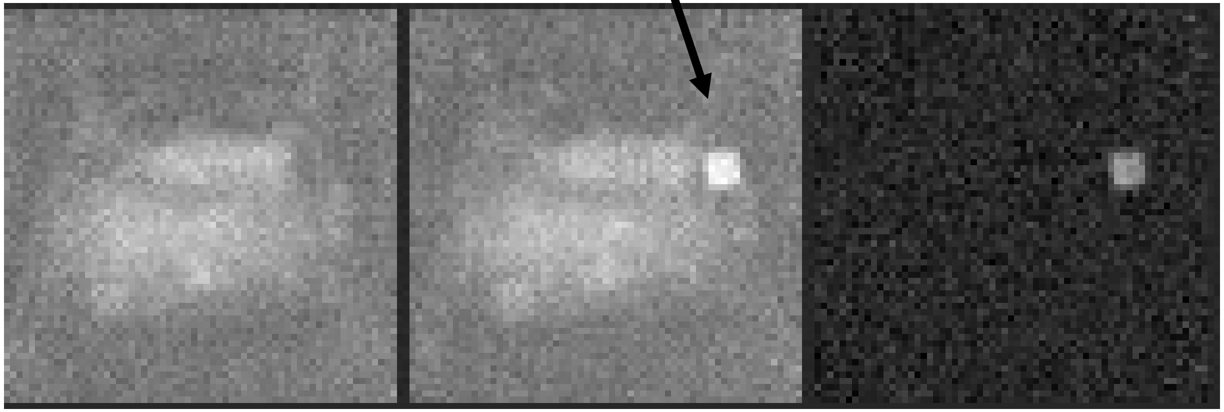
- **Advantages over other methods:**
  - No artificial radiation
  - Simple technology
  - Inexpensive
  - Can penetrate thick cargoes
  - Automatic Identification

Source: Decision Sciences Corporaton (licensee)

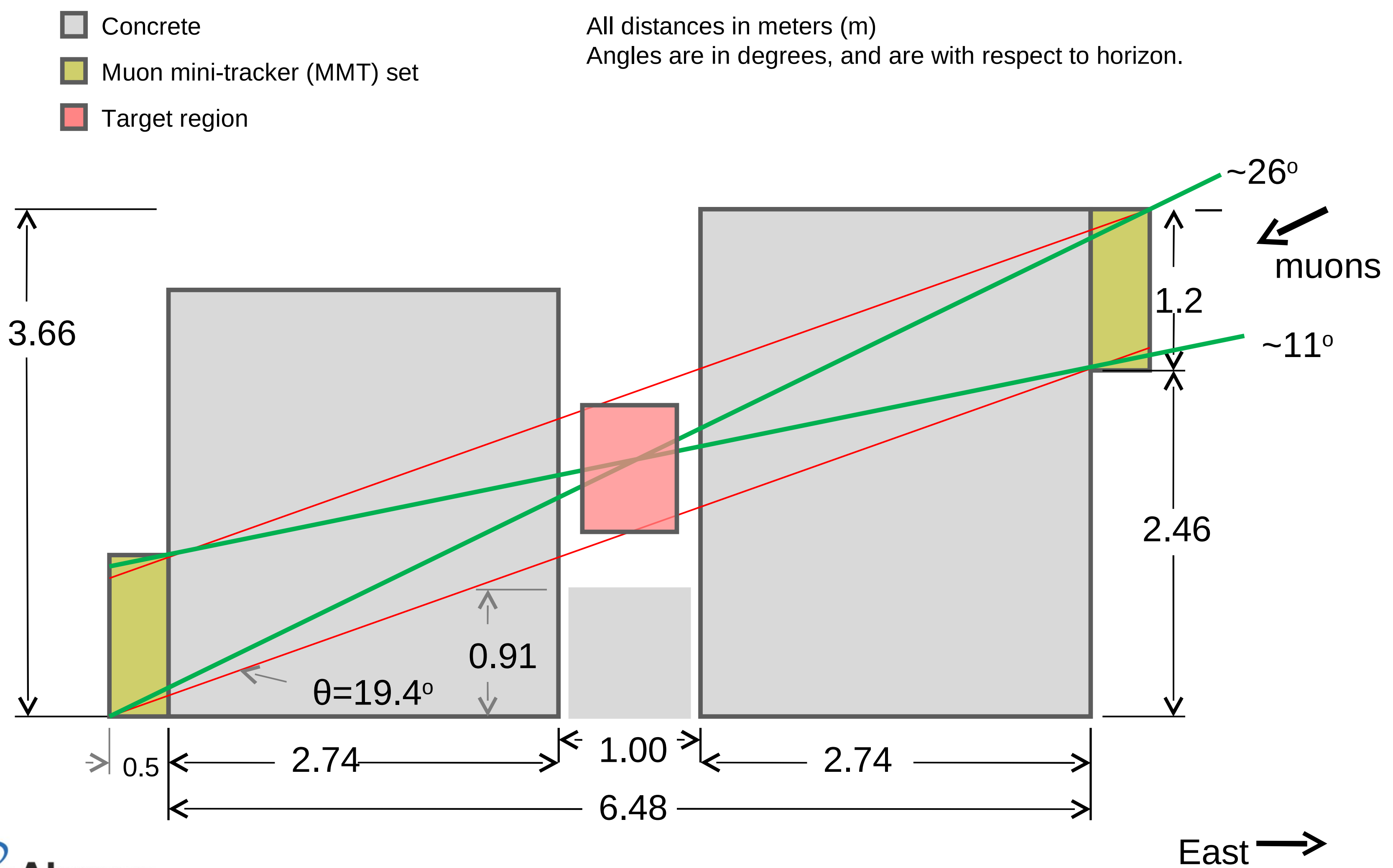
It really works!



Lead Brick

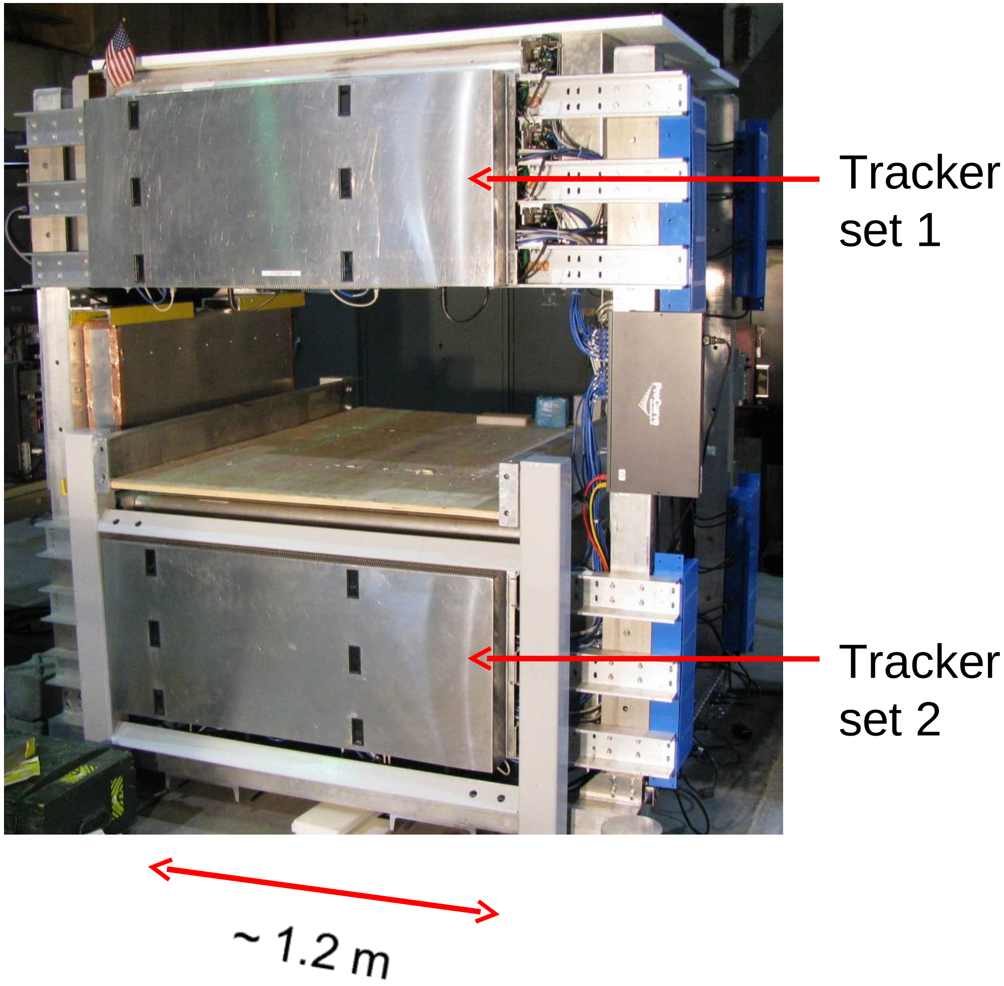


We have extended Muon Tomography to the task of imaging thick objects in very thick shielding.



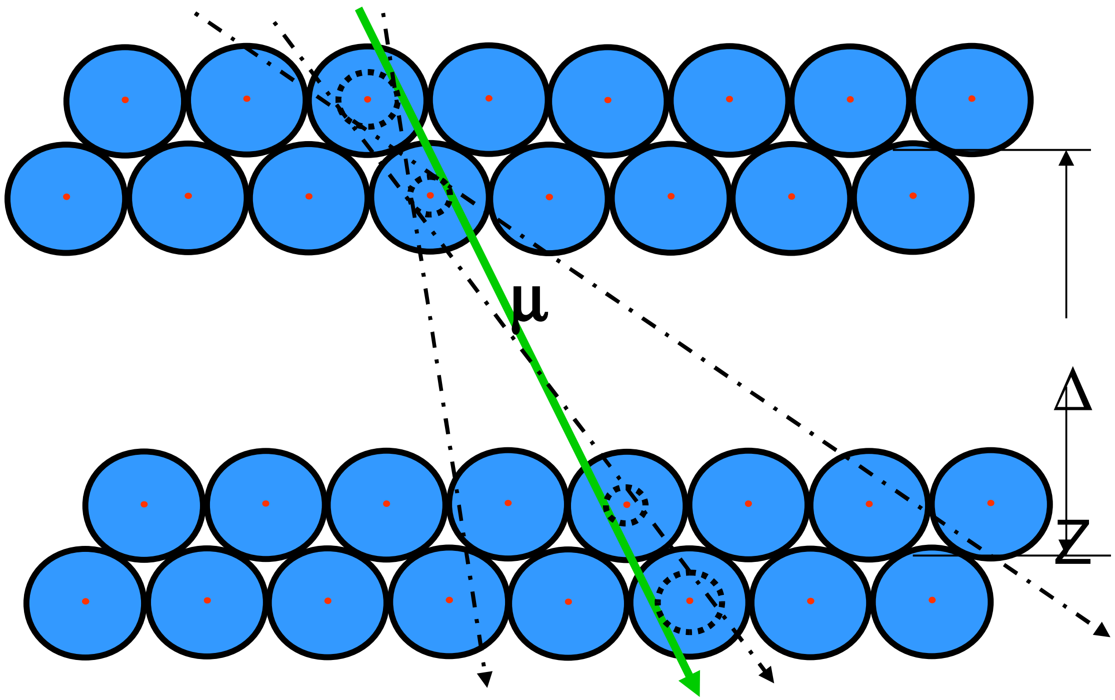
The experiment used previously constructed equipment.

- **Two sets of trackers (MMT – Muon Mini-Tracker)**
- **Each tracker set has 3 x-y pairs planes, for a 6-fold tracking coincidence, in and out.**
- **Tracker sets moved to “mock reactor”.**
- **One set placed high onshielding, to track incoming muons.**
- **Other set placed low on the “exit” side of the shielding.**

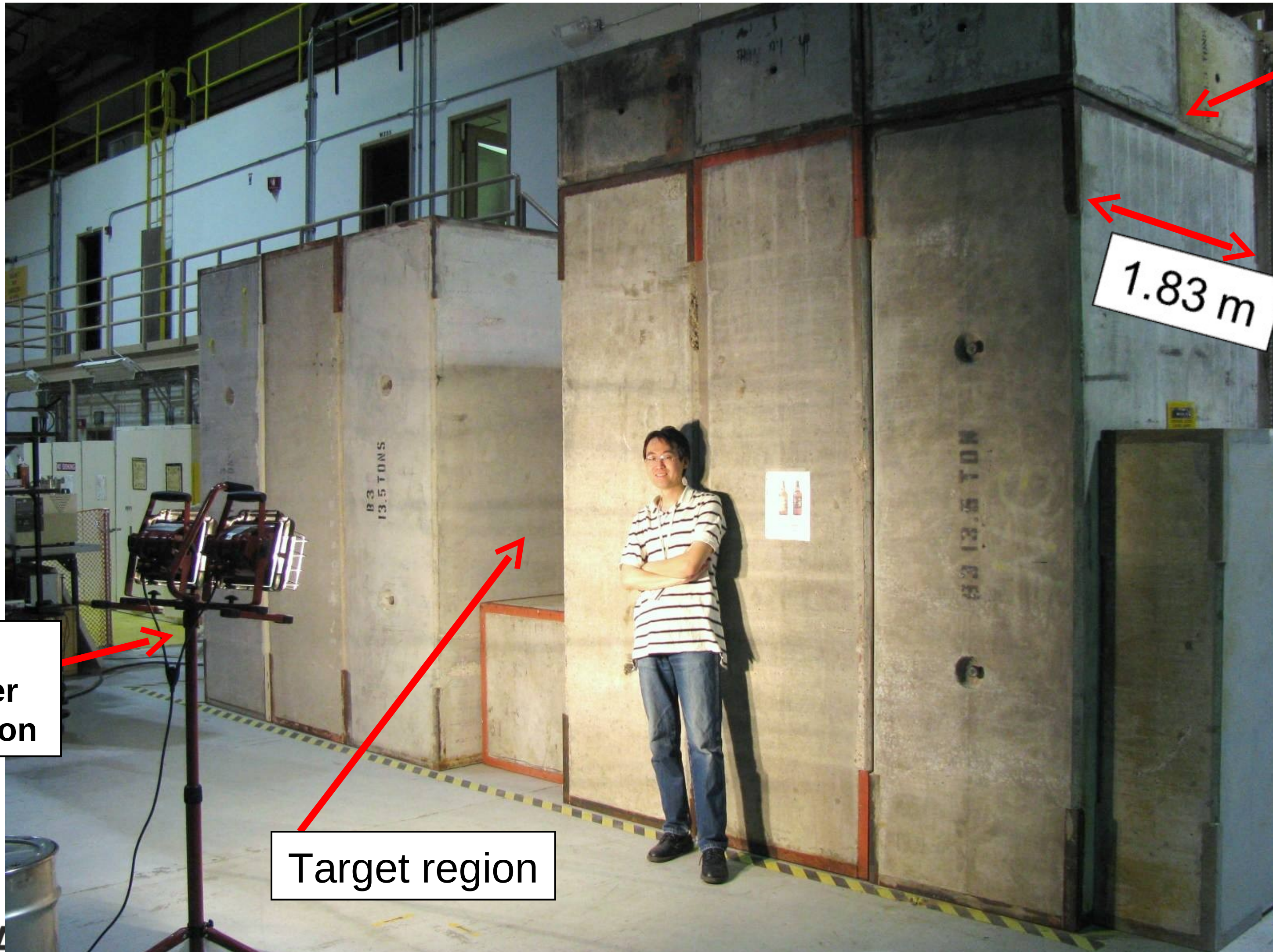


Cylindrical drift tubes measure radial distance from wires of passing charged particles.

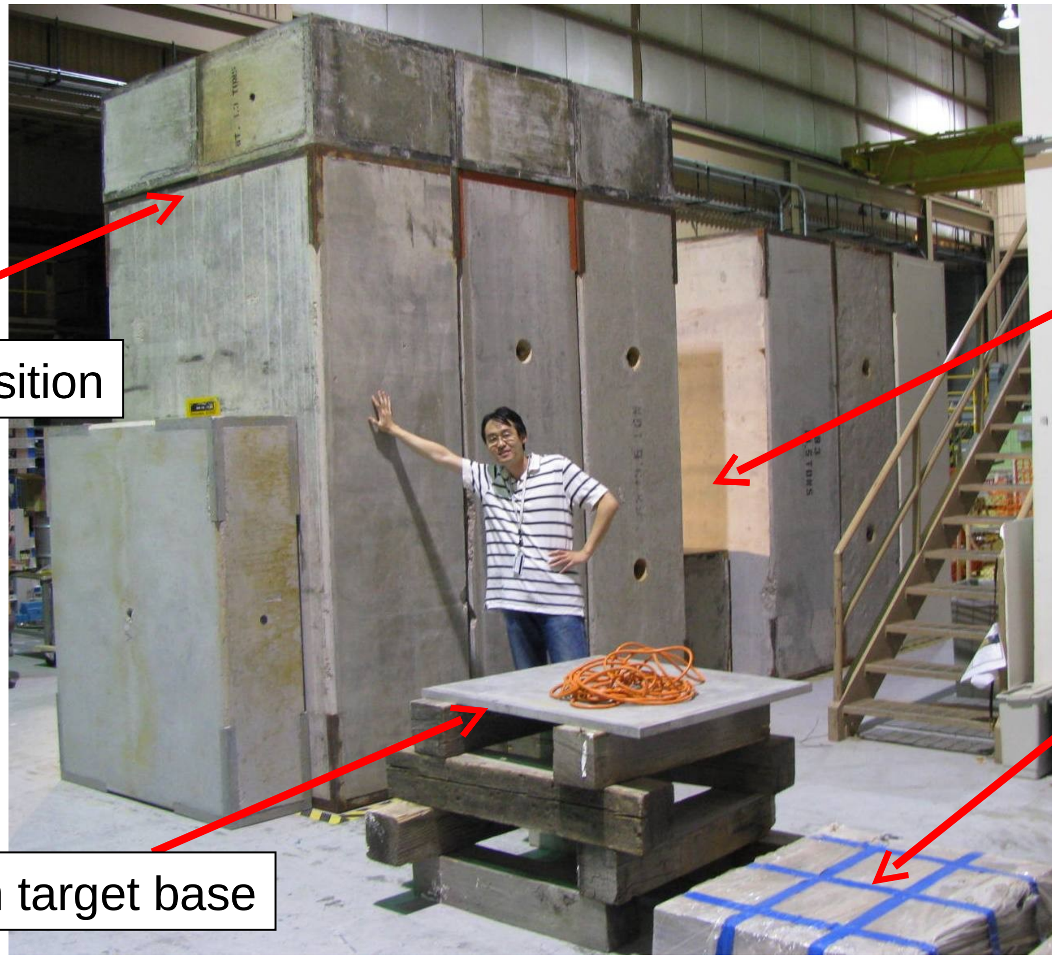
- Analyze for intercept and angle in two dimensions by interleaving tubes in x- and y- directions
- Sets of tubes located above and below object to measure scattering angle (average scattering density)



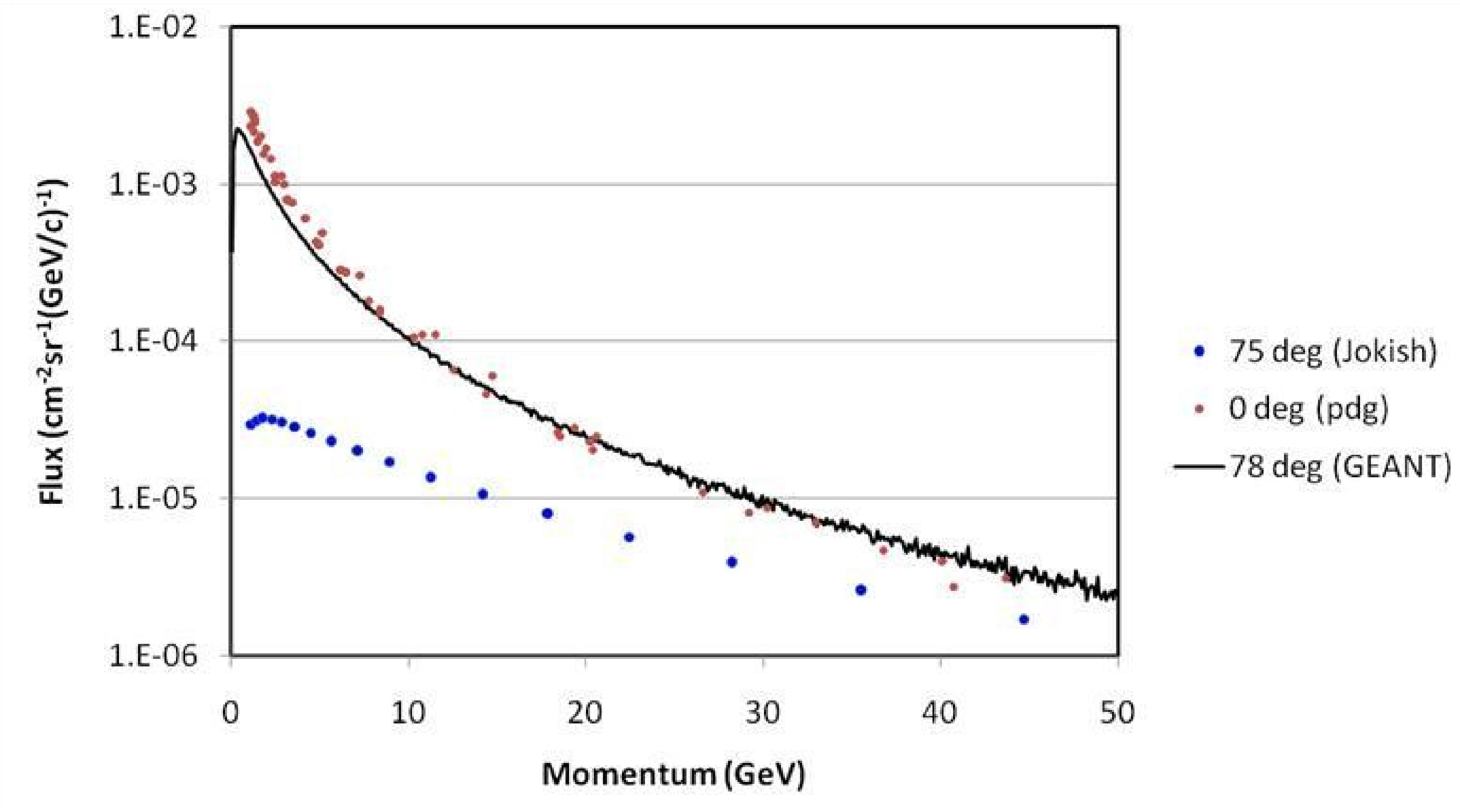
Concrete shielding was 18 feet – similar to a reactor shield.



Lead-brick target material ready for stacking.



The near-horizontal muon spectrum differs significantly from the vertical spectrum.



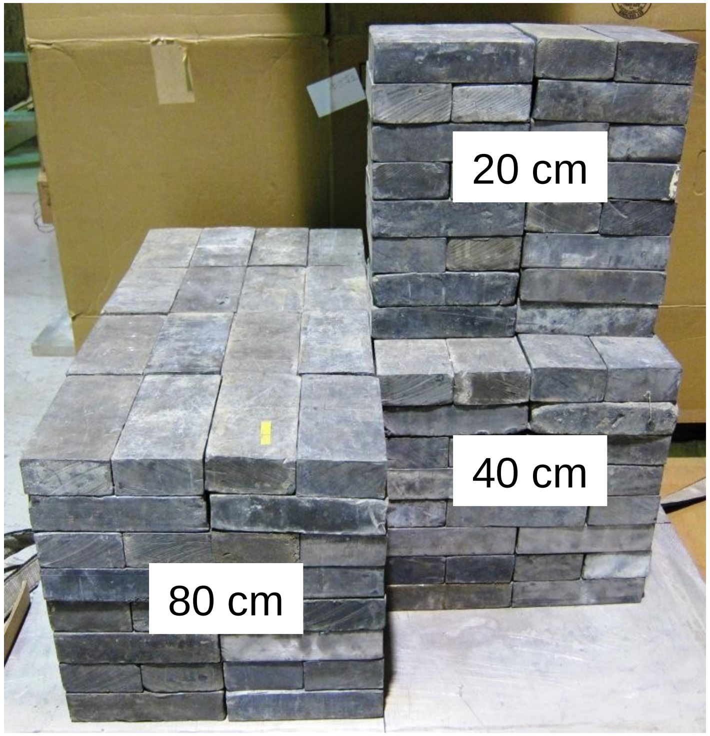
Ref: H. Jokisch, K. Carstensen, W. Dau, H. Meyer, O. Allkofer, *et al.*, Cosmic Ray Muon Spectrum Up to 1-TeV at 75-Degrees Zenith Angle, PHYSICAL REVIEW D (**1979**) Vol.19, iss.5, p.1368-1372F

Data analysis resulted in images of high-Z material.

- **Deflection angle squared at target mid-plane**
  - Accept tracks passing within 10-cm of each other at mid-plane
  - Deflection = (angle-out – angle-in)^2
  - Plot average deflection for each x-y pixel (10 cm x 10-cm) at mid-plane
- **Compare to simulation Monte Carlo**
  - GEANT4 model of experiment
  - Use near-horizontal spectrum (rather than standard vertical spectrum)
- **Calculate mass of target**
  - Model input spectrum
  - Estimate mass based on scattering

A target of 80-, 40-, and 20-cm of lead (Pb) was imaged.

- 210 hours of data



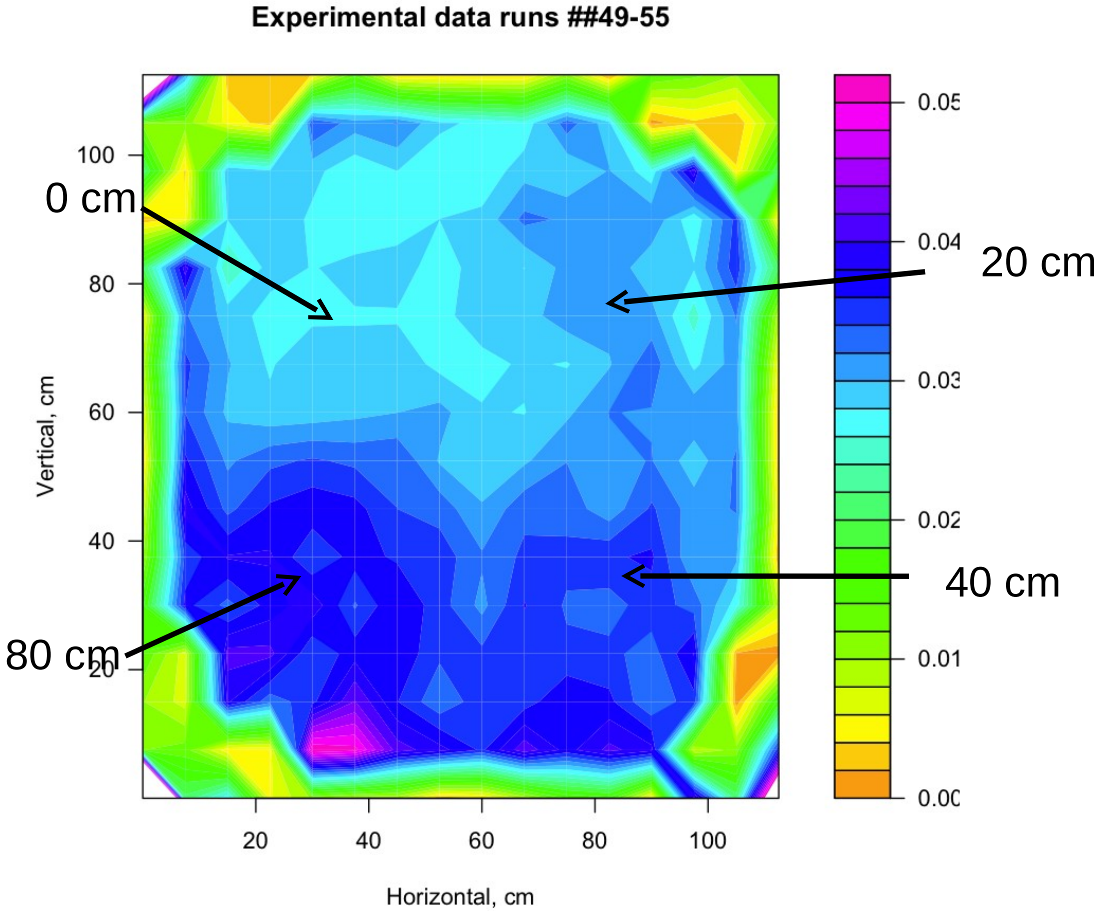
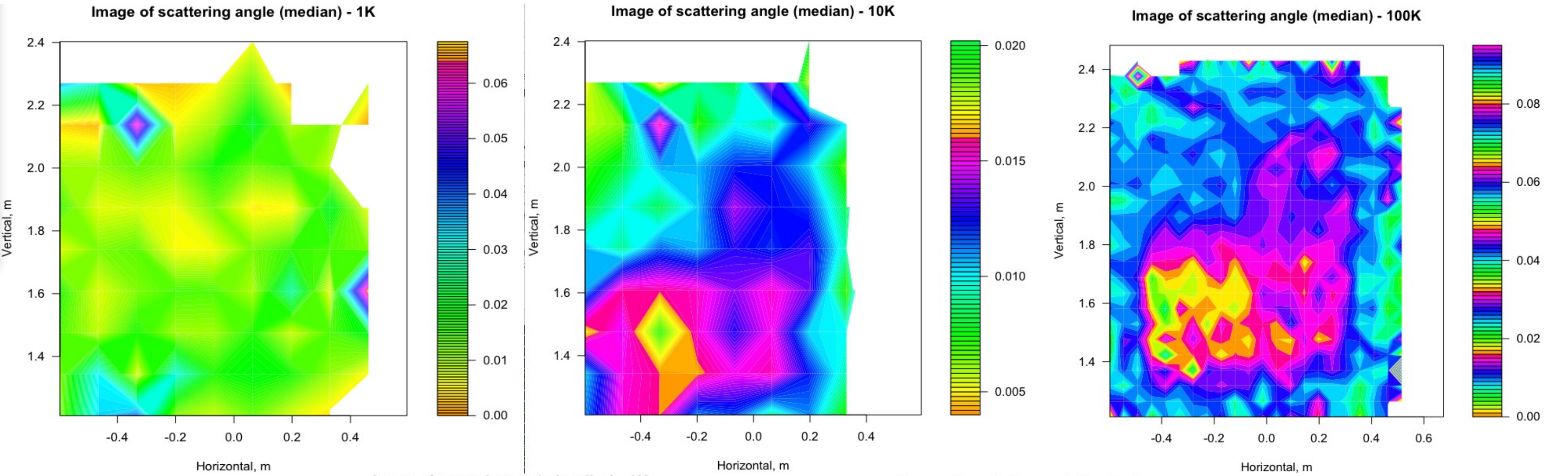
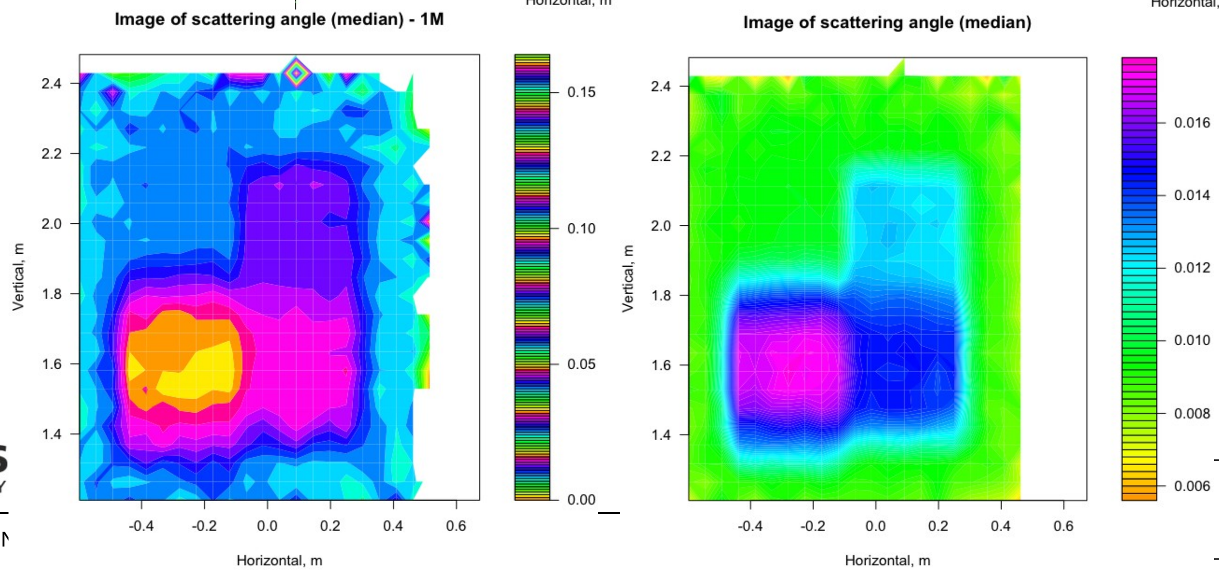


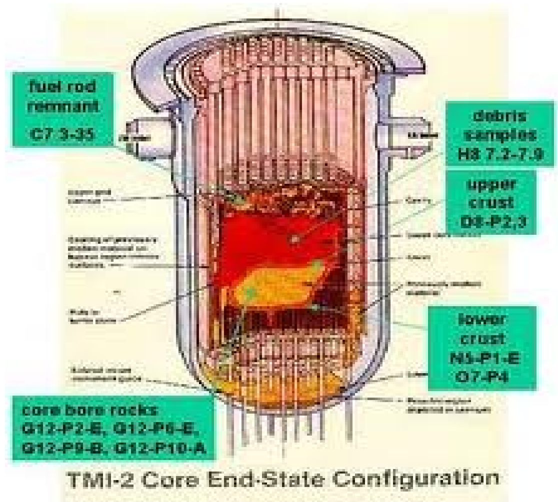
Image quality is determined by statistics, as shown in Monte Carlo simulations varying the number of tracks.

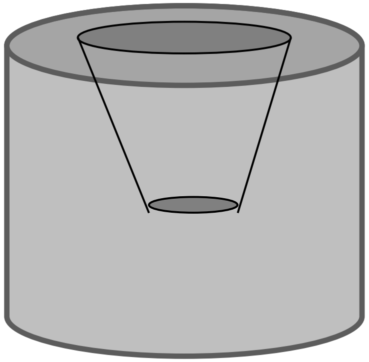


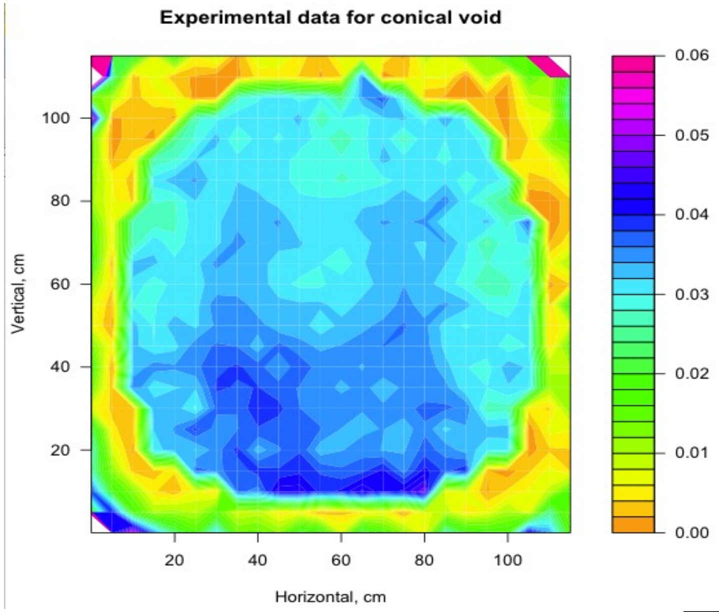


An 80-cm-thick Pb target, with "conical void" was imaged – an attempt to approximate TMI core.

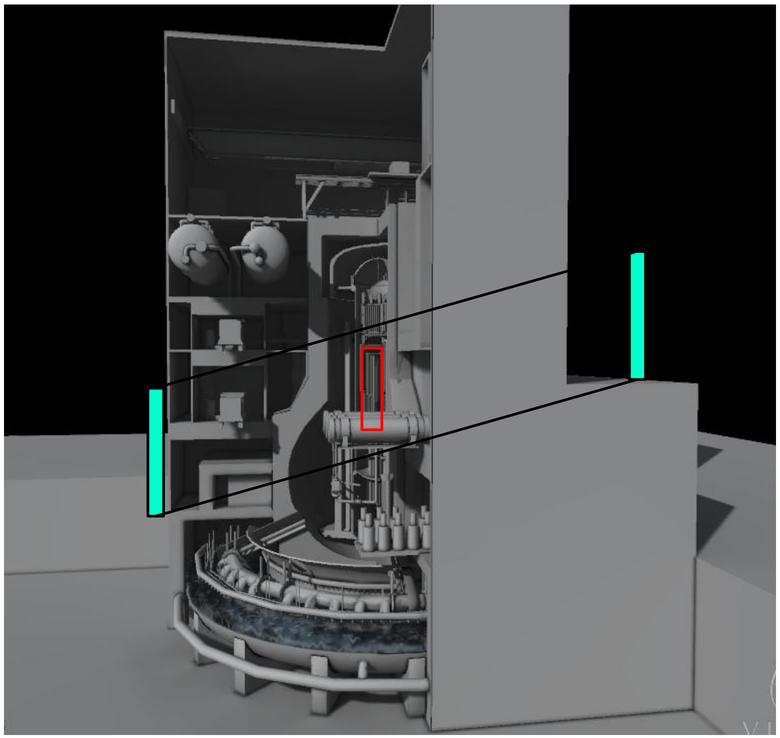
- 4.5 tons of Pb
- 500 hours data (20 days)

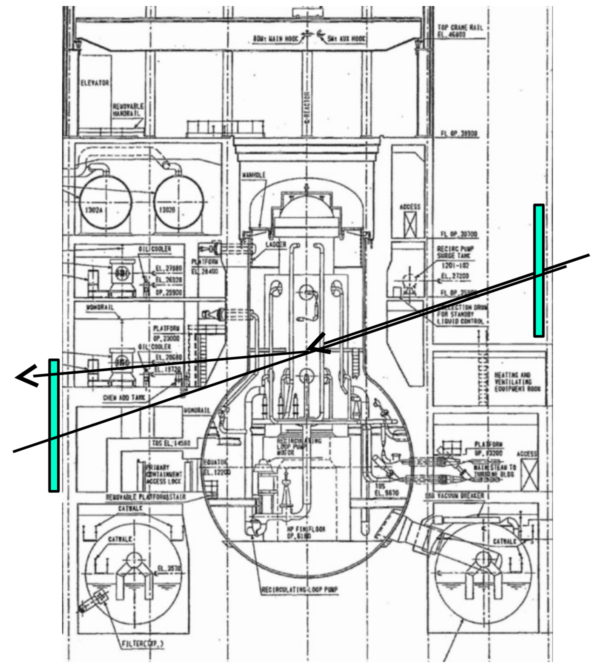




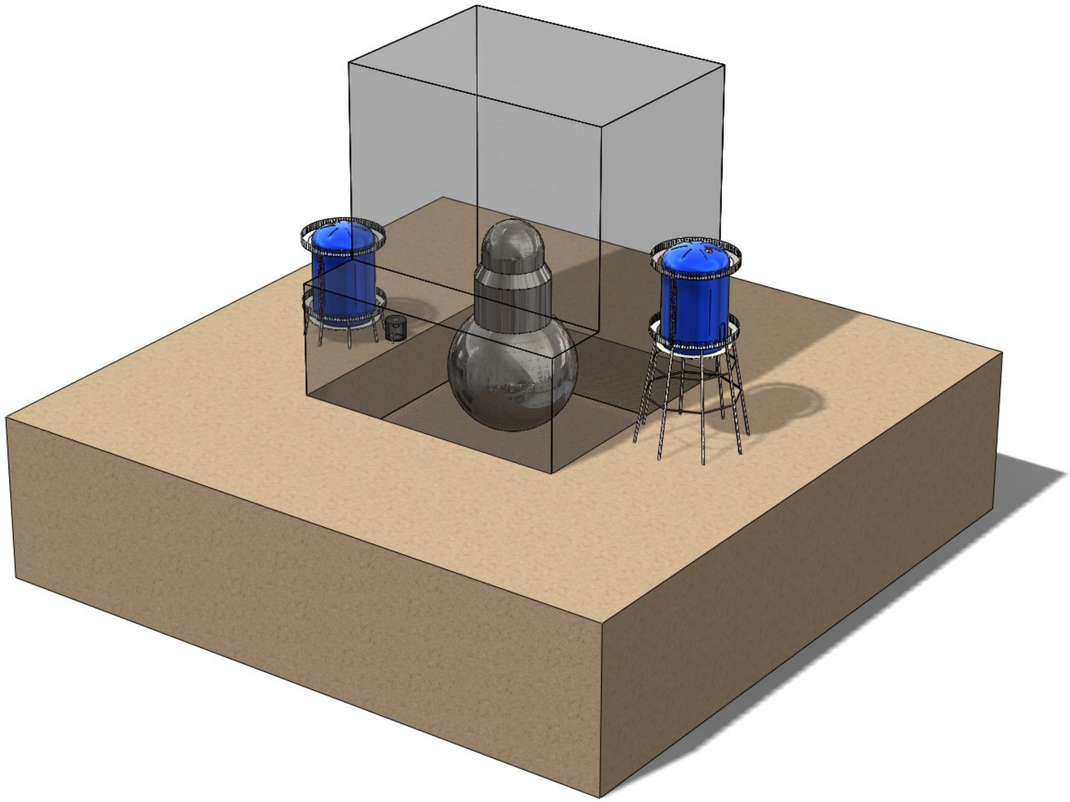


Our demonstration measurement could be scaled-up, to image the fuel in the Fukushima Daiichi reactors.





The placement of water tanks (containing trackers) near the reactor, could provide radiation shielding.



- Radiation shielding:
  - ~0.5 m concrete or
  - ~1.0 m water
- Drift tube rate ~1 kHz

A Japan-US collaboration has been formed to image the Fukushima Daiichi reactors with cosmic ray muons.

- **Japan-US workshop held, Washington, DC, 15-16 February, 2012**
  - Institutions: KEK, U. Texas, Sandia Nat. Lab, Los Alamos National Laboratory (LANL)
  - Co-spokespersons: H. Takasaki (KEK), R. Schwitters (UT), C. Milner (LANL)
- **Our proposals for 2012 and beyond:**
  - Creation of Monte Carlo platform in GEANT4:
    - Flexible definition of muon spectrum
    - Reactor geometry and materials
    - muon ray-files at various detector positions – input for analysis programs
  - Demonstrate LANL “small” system (0.6-m x 0.6-m) at Fukushima reactor
    - Remote operation
    - Study tracking efficiency as a function of shielding thickness
  - Engineering studies of shielding, support, installation, operations, etc.
  - Image cores of Fukushima reactors

We have established Muon Tomography as a technique for non-invasively imaging large objects.

- **Thick targets imaged inside very thick concrete shield**
  - 3 m of concrete – similar to Boiling Water Reactor (BWR)
  - 80-cm of Pb – similar to areal-density thickness of reactor fuel
  - ~ weeks to image each target
- **Scale-up to reactor**
  - Detectors would be on building exterior, ~50 m apart
  - Maintain same solid angle with detectors 5 m x 5 m (commercially available)
  - Measure image of location of fuel ~ weeks to make each image
  - Measure amount of fuel remaining in the reactor pressure vessel (RPV)
    - Consistent with known quantity? **Remove intact RPV for disposal**
    - Less than known fuel quantity? **Melt down. Complicated remediation.**