COSMIC RAY TOMGRAPHY

A Feasibility Study

Duncan Carlsmith

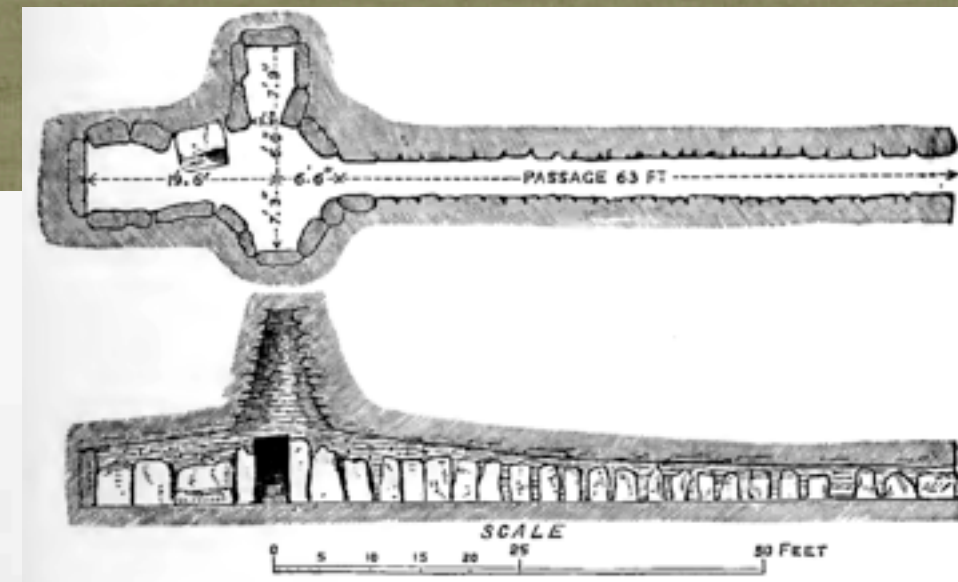
THE TROY PROJECT

- With 4,500 years of settlement history, Troy is one of the most fascinating archeological sites in the world, and as the fabled setting of Homer’s Iliad, of profound cultural significance.
- In 2013, the University of Wisconsin–Madison will take on a greater role in the expedition to Troy with new excavations and research directed by Professor William Aylward in collaboration with Çanakkale Onsekiz Mart University.
- What remote sensing technologies might be used?

http://www.news.wisc.edu/21160

http://troy.wisc.edu/

PROBLEM



Plan and Section of Chamber in Newgrange Tumulus.

Newgrange Neolithic Burial Mound, Bru na Boinne: One of the most common ancient megalithic structures was the passage grave, which included a center chamber, slabbed roof and long passageway, all covered by a mound of earth. Europe's largest collection of these is at Bru na Boinne, Ireland, which has been dated to as early as 3500 B.C. *(Photo Credit: Getty Images)*

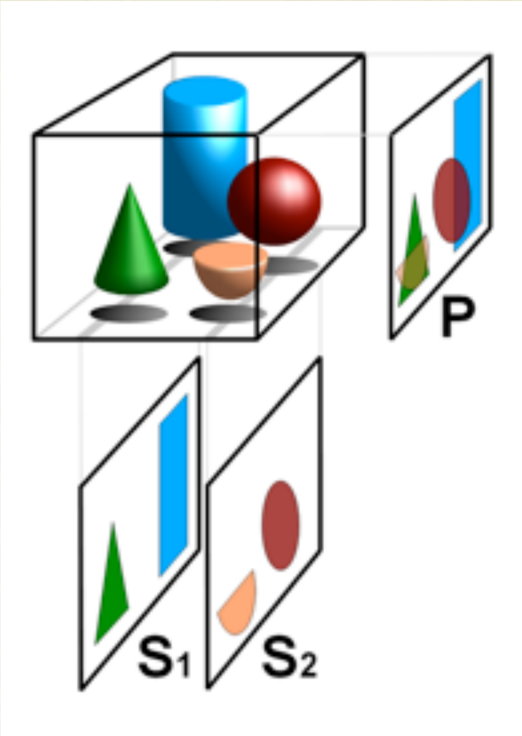
- How do we see inside a large structure like a burial mound or a nuclear reactor without going inside?

TOMOGRAPHY

- Radiography is the use of X-rays to view a non-uniformly composed material such as the human body. Tomography refers to imaging by sections or sectioning, through the use of any kind of penetrating wave. A device used in tomography is called a tomograph, while the image produced is a tomogram.

- "Non-invasive" tomography is used routinely in medical imaging.

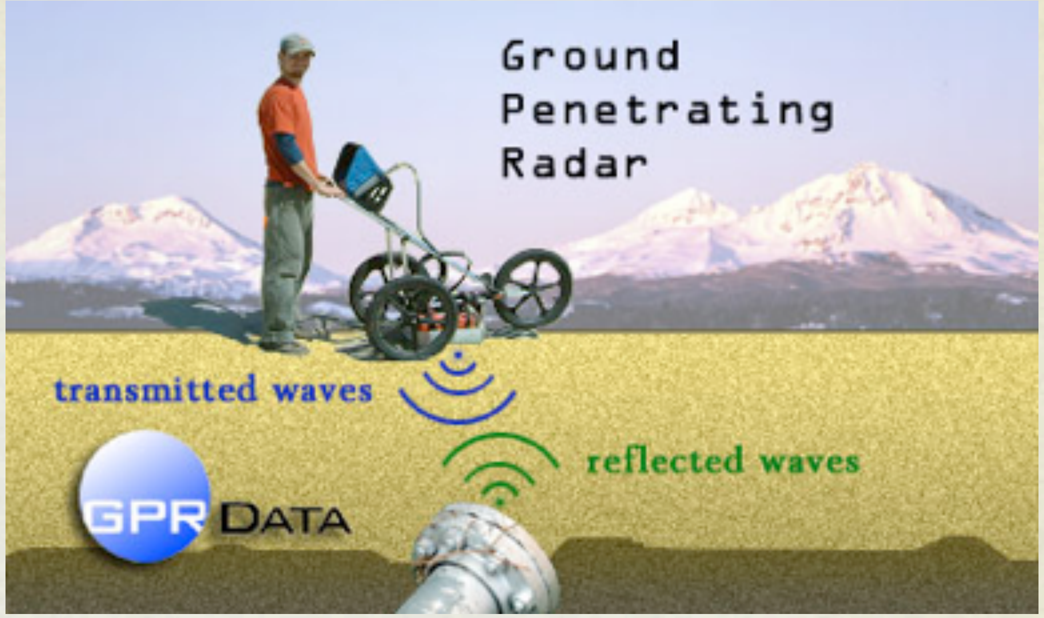
- X-rays and gamma rays are attenuated over cm length scales and not useful in archaeology.

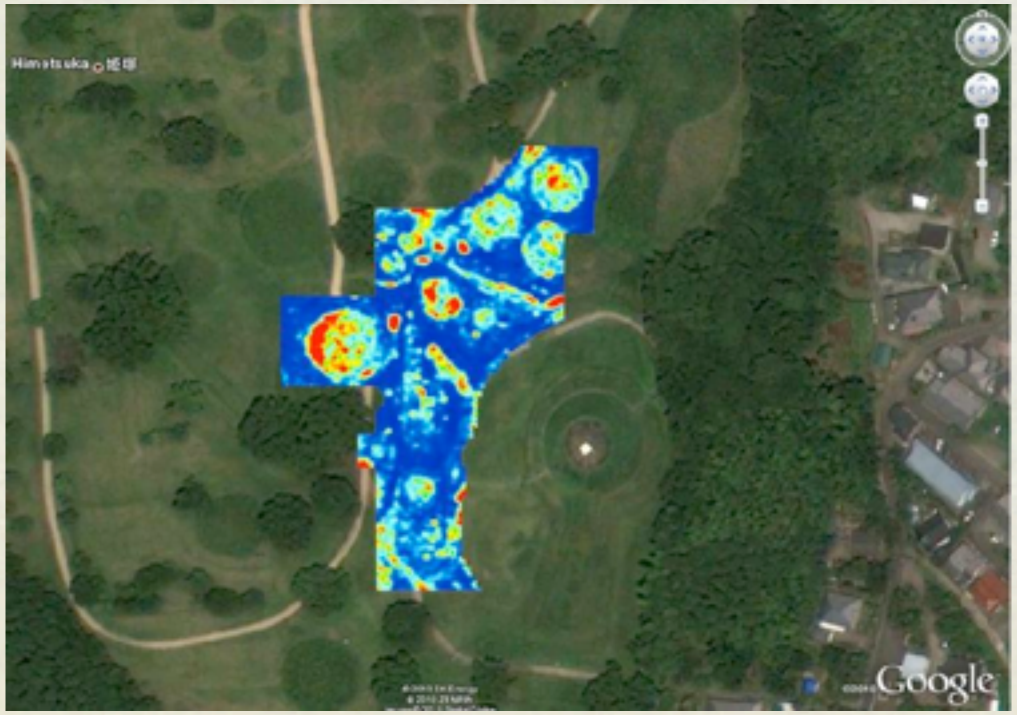


Physical phenomenon	Type of tomogram
X-rays	CT
gamma rays	SPECT
radio-frequency waves	MRI
electron-positron annihilation	PET
electrons	Electron tomography or 3D TEM
ions	atom probe
magnetic particles	magnetic particle imaging

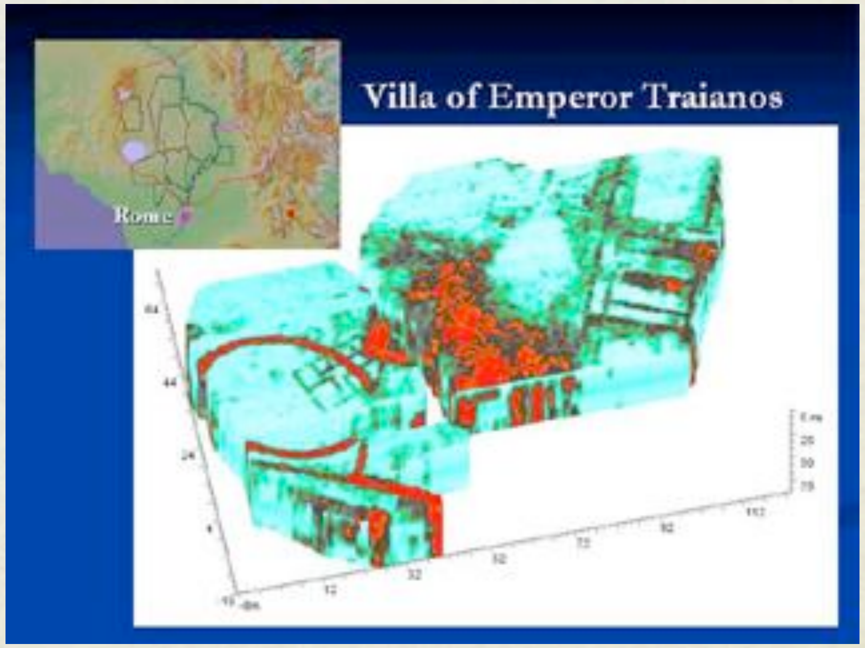
GROUND PENETRATING RADAR

- Radio waves can penetrate the ground to a degree and are reflected wherever there is a change in material refractive index.
- Ground penetrating radar has been used to map sites of archaeological significance. Radar penetration depth depends upon soil conditions and may be limited to a few meters.



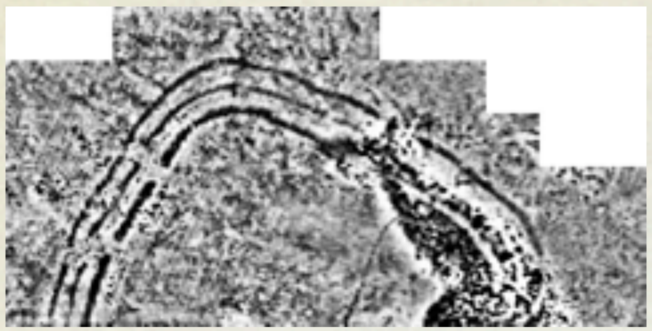


http://www.gpr-survey.com/

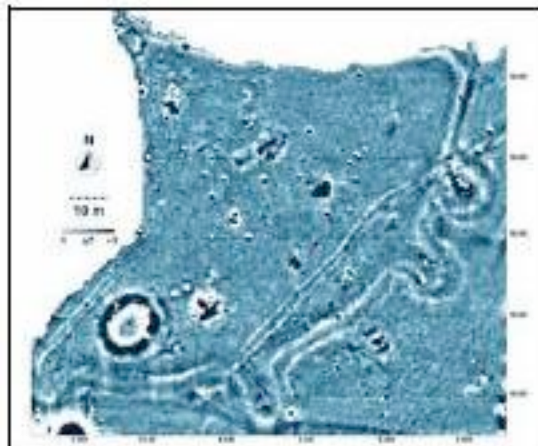


http://www.pastperfect.org.uk/archaeology/gpr.html#

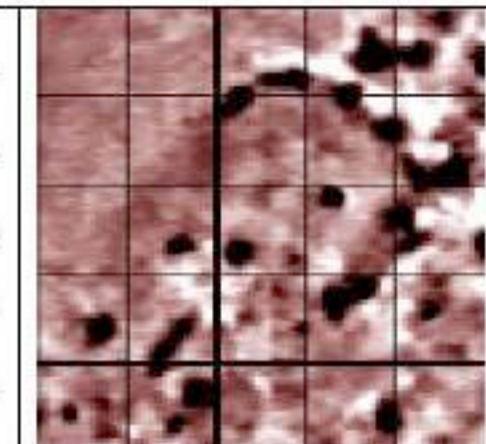
MAGNETOMETRY



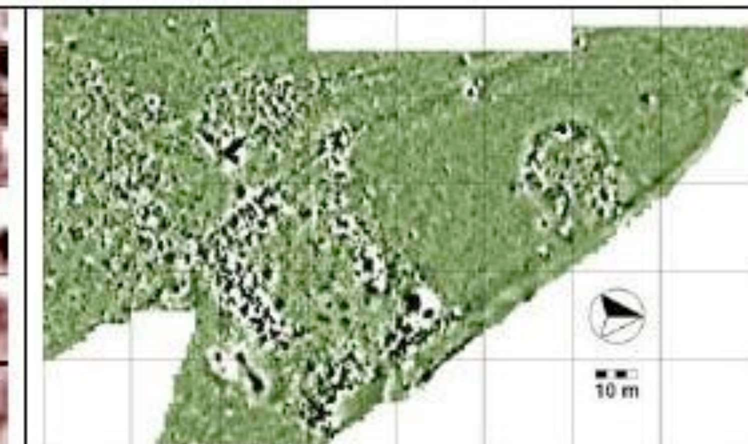
http://www.pastperfect.org.uk/archaeology/magneto.html#



Magnetometry image, 13th century Menoken Village, ND.



Magnetometry image, internal features of 15th century house, Huff Village, ND.



Magnetometry image, Fort Clark Trading Post, Garreau's Lodge & Compound, 1832-1860, ND.

- Magnetometry refers to detailed measurements of the magnetic field on a surface, sensitive to ferrous objects submerged to depths of order 1 m.
- Active magnetometry injects a magnetic field to measure the magnetic susceptibility of submerged objects and also has limited depth, of order a meter.

GRAVITOMETRY

- A survey of gravity can be used to locate subsurface cavities at a few meter depth.

Contributions to Geophysics and Geodesy Vol. 39/3, 2009 (237–254)

Fig. 3. Vertical gravity gradient measurement; the CG-5 gravimeter is placed on a tripod in the upper position (1 m elevation difference).

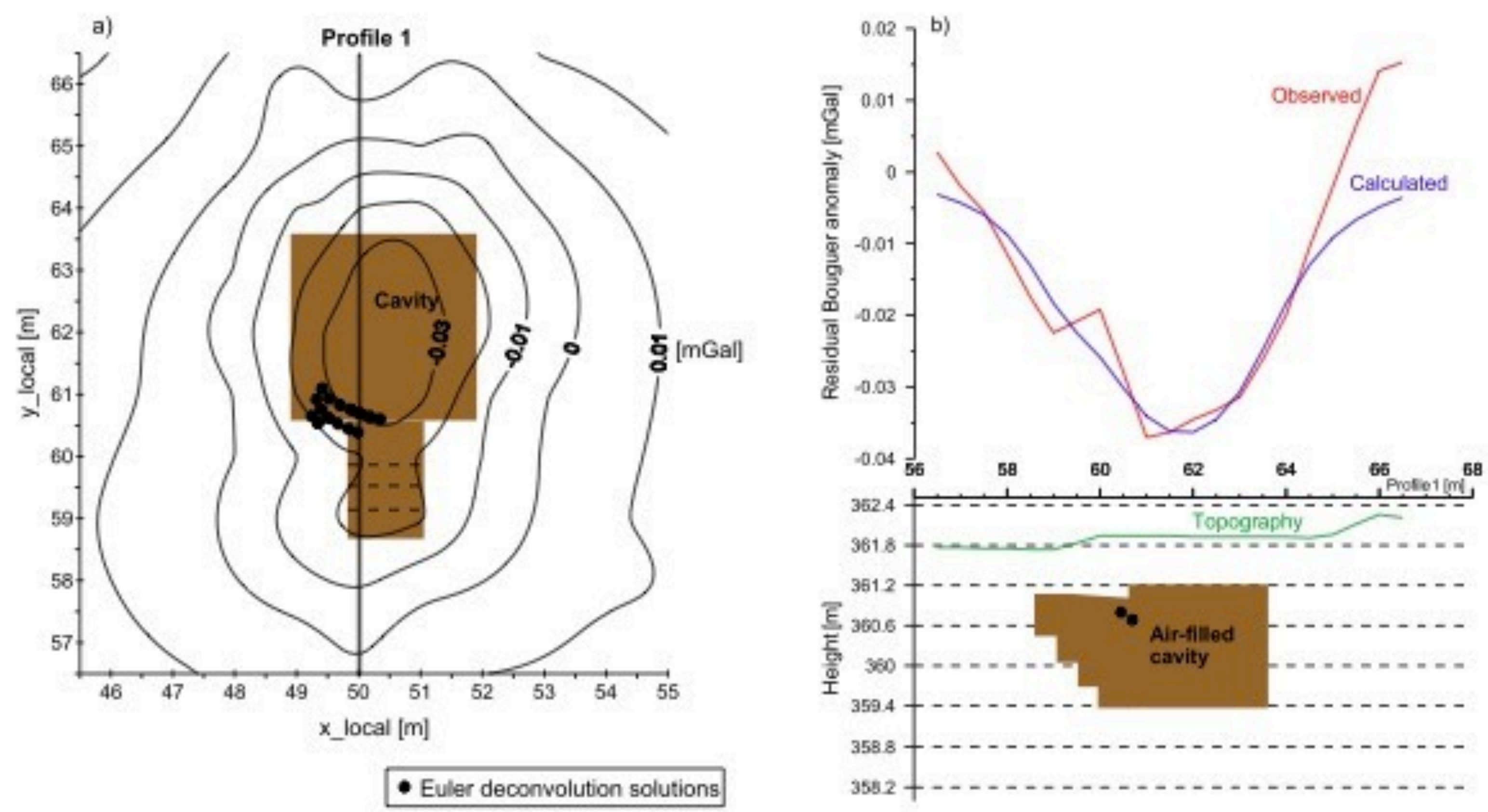
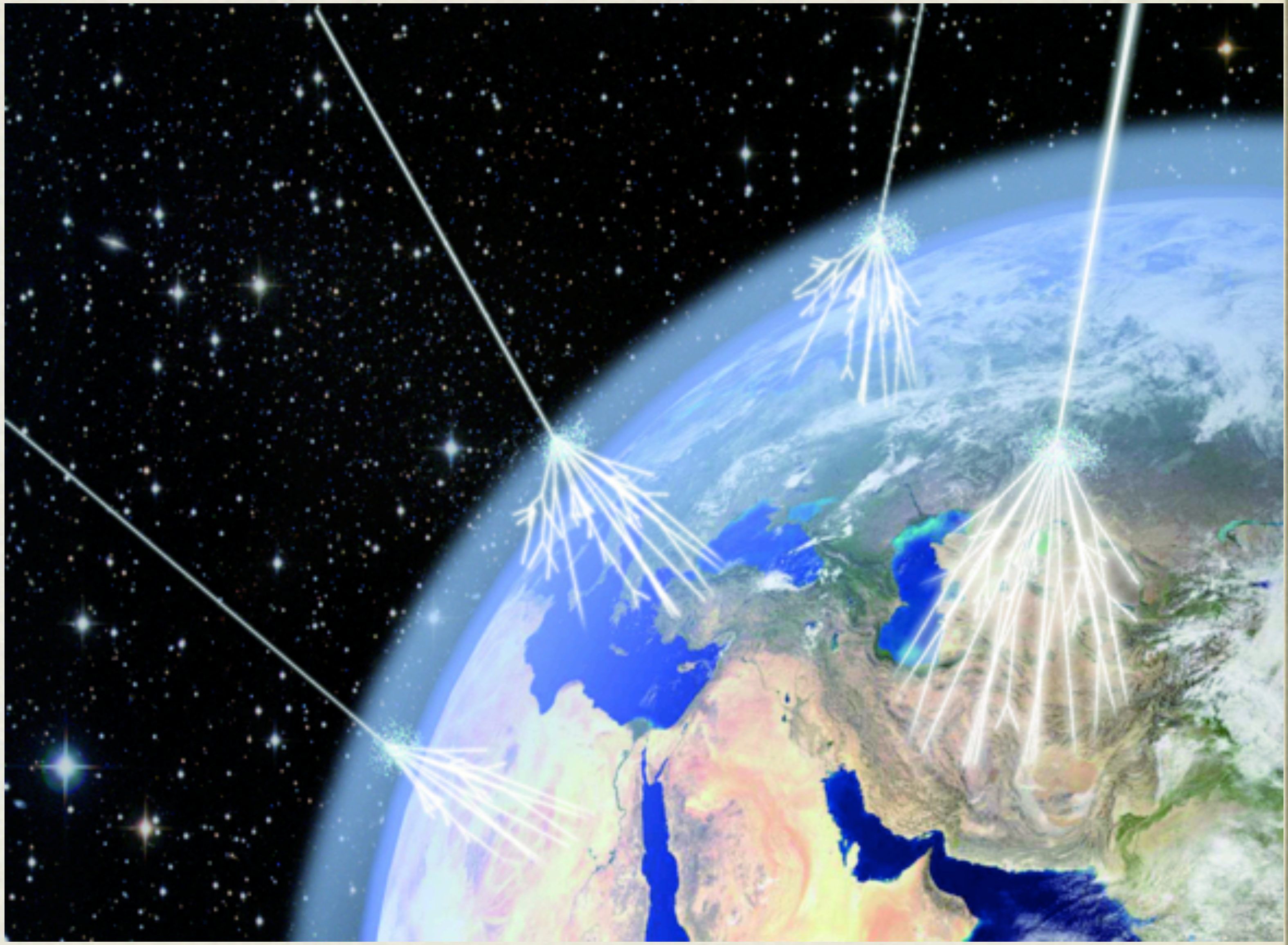


Fig. 9. Three-dimensional model of sub-surface interpretation: a) upper view of modelled air-filled cavity and observed field; b) a view of the possible location and shape of the crypt – results along E-W Profile 1: observed field (red line), calculated field (blue line). Filled circles denote positions of the 3D Euler deconvolution depth estimates.

COSMIC RAYS

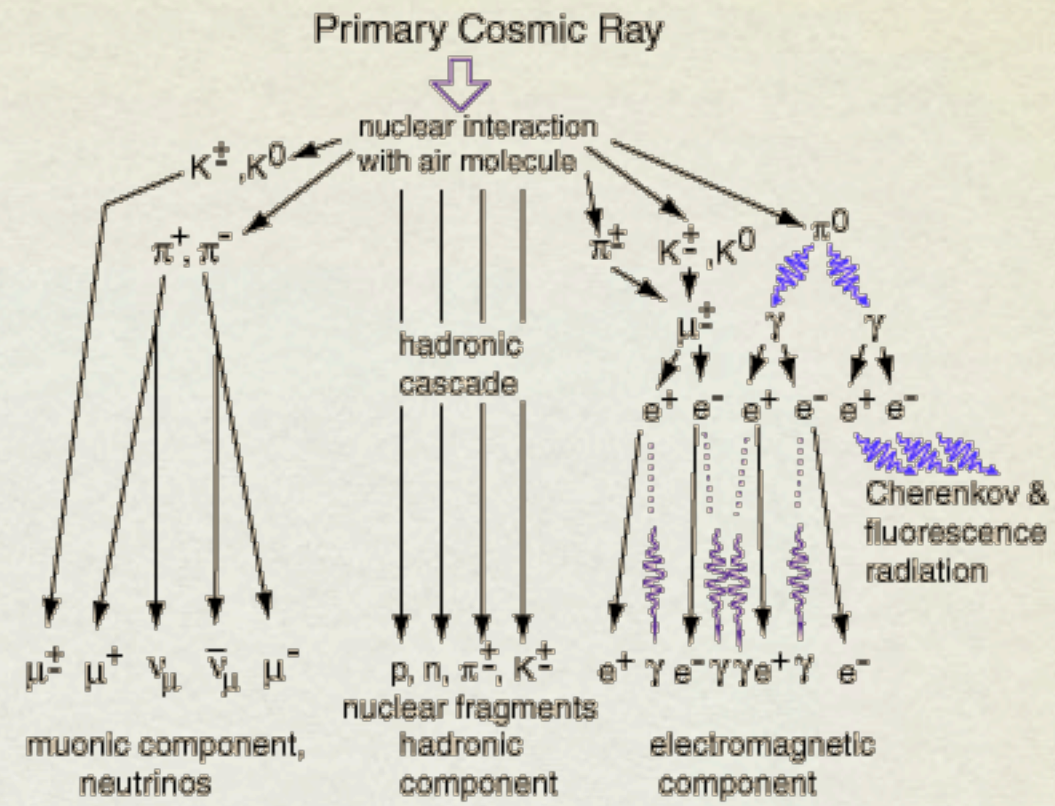
- Cosmic rays are high energy protons impacting the Earth atmosphere resulting in showers of particles at sea level.

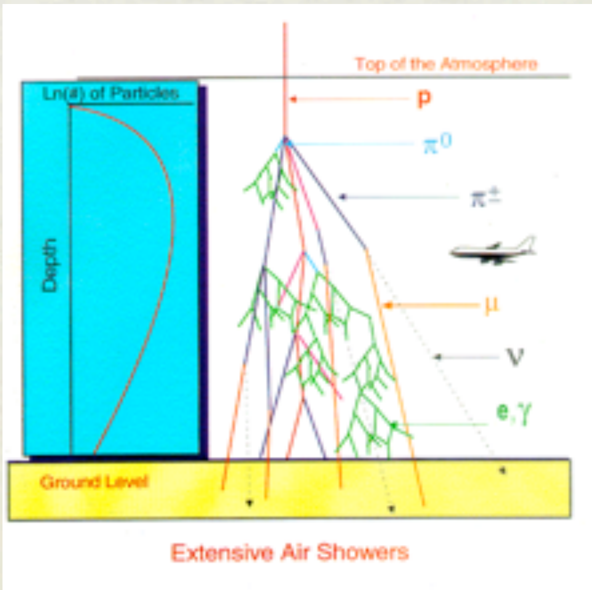
- The particles in showers may be used to probe surface structures.



ANATOMY OF COSMIC RAY SHOWERS

- Numerous hadrons (p, n, K) and leptons (e, mu, nu) are produced in showers.
- All but neutrinos and muons are generally absorbed in the atmosphere. Neutrinos pass through the entire Earth without interaction usually.
- Muons are penetrating charged particles capable of passing through a large mound of Earth.
- The deflection and absorption of muons provides a means to observe something inside.



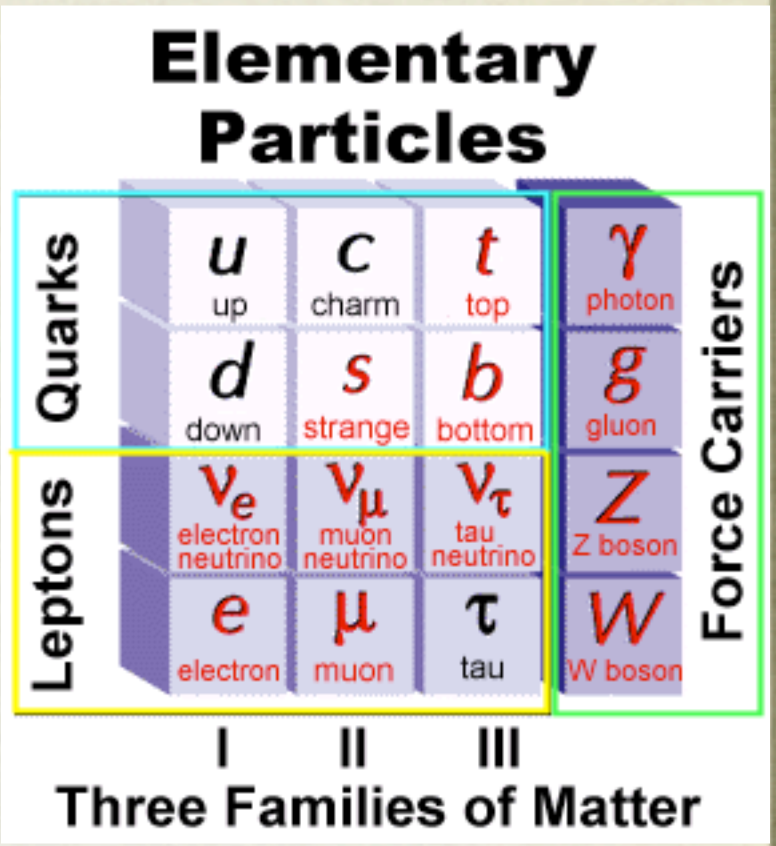


MUONS

- A muon is a heavy electron. Its mass 105 MeV/c^2 is some 200 times that of the electron mass 0.511 MeV/ c^2. A muon does not not suffer strong interactions, only electromagnetic and weak interactions.

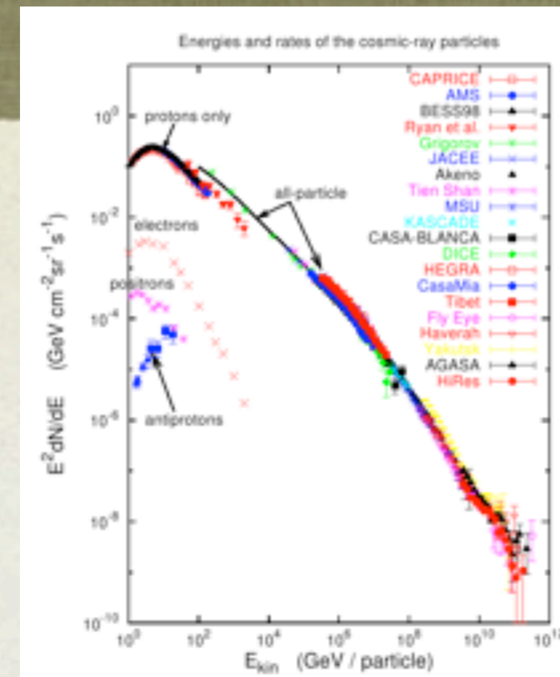
- In cosmic ray showers, muons (mu^+ and mu^-) are produced through the weak interaction fusion of quark+antiquark in pions and kaons to produce a W-boson which then materializes as a muon plus a neutral neutrino.

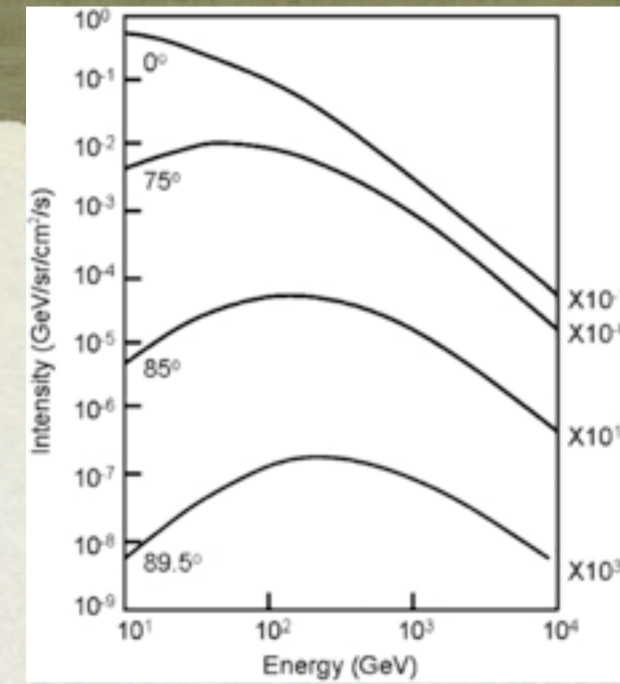
- The muons which make it to the Earth's surface are relativistic particles with energies of order ten times their rest energy.



ENERGY SPECTRUM OF MUONS

- The energy spectrum of primary cosmic rays extends to 10^{21} eV = 10^{12} GeV.
- At sea level, the mean muon energy is 4 GeV. The vertical flux for energies above 1 GeV is 70 m^{-2} s^{-1} sr^{-1} and the intensity is proportional to the square of the cos of the angle from the vertical so peaked straight down. The total is about 1 per square cm per min of horizontal detector.





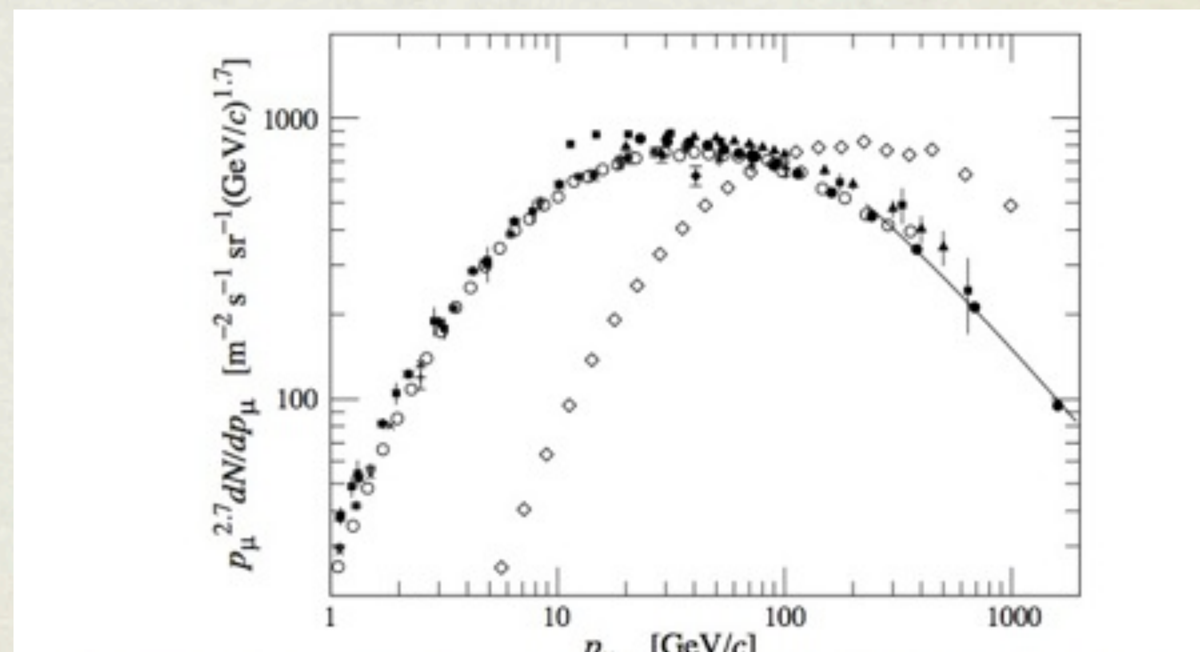


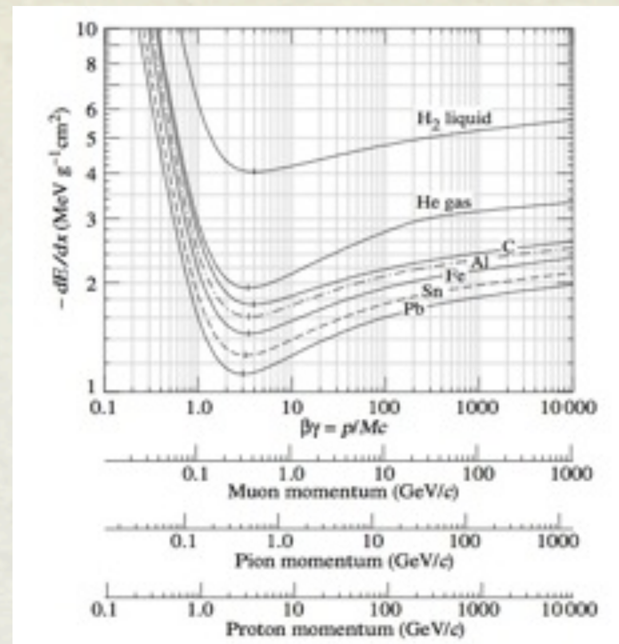
Figure 26.4: Spectrum of muons at $\theta = 0°$ (♦ [41], ■ [46], ▾ [47], ▲ [48], ×, + [43], ○ [44], and • [45] and $\theta = 75°$ ◊ [49]) . The line plots the result from Eq. (26.4) for vertical showers.

INTERACTIONS OF MUONS WITH MATTER

- The most important interactions are electromagnetic interactions with electrons and with nuclei.
- Like a lead ball encountering a sea of pingpong balls, a muon plows straight through the electron sea constituting normal matter knocked electrons left and right. This results in a trail of ionization and an energy loss of a few MeV per cm of material in proportion to the electron density and hence in proportion to the matter density.
- Matter also contains point-like nuclei with masses much larger than the muon mass which behave like fixed pins in pinball. A muon suffers elastic (energy conserving) scattering from nuclei.

ENERGY LOSS

- Energy loss dE in traversing a length dx is proportional to density and usually quoted as about 2 MeV per g-cm^{-2} for a relativistic muon.
- For rock of density 2.5 gm cm-3 translates to dE/dx~5 MeV/cm. A 4 GeV muon will traverse 4000 MeV/5 MeV/cm=8 m of rock before ranging out.



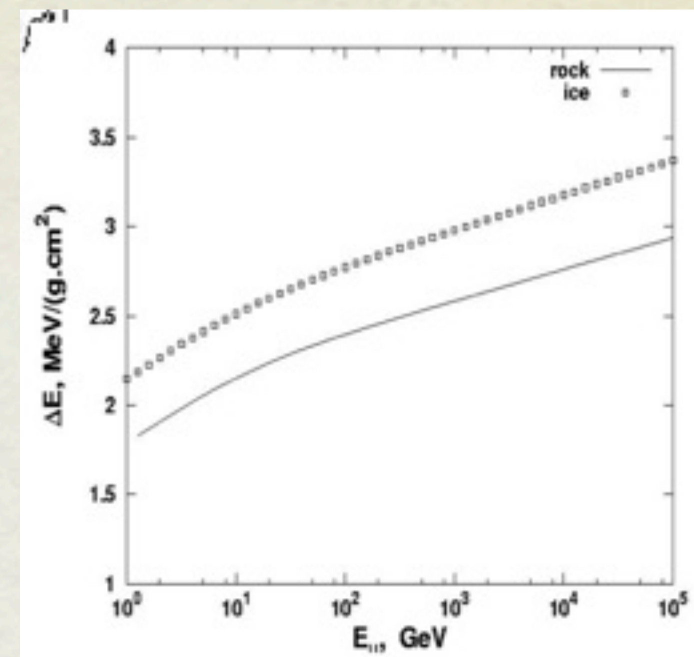
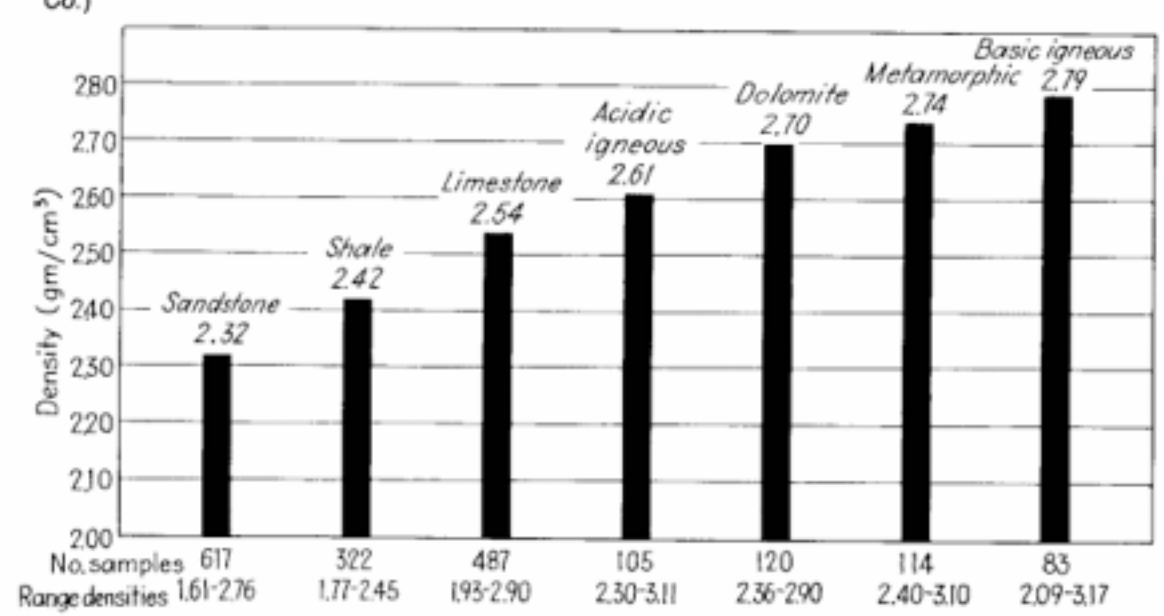


FIGURE 14-6 Average densities of surface samples and cores based on laboratory measurements. (*Mobil Oil Co.*)



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Thursday, November 15, 12

SCATTERING

- Random successive scattering from nuclei leads to a random walk and gaussian distribution of net scattering angles with a significant tail.
- The standard deviation of the scattering angle is inversely proportional to momentum and, for a uniform medium, to the square root of the length traversed divided by the radiation length, a material dependent quantity.

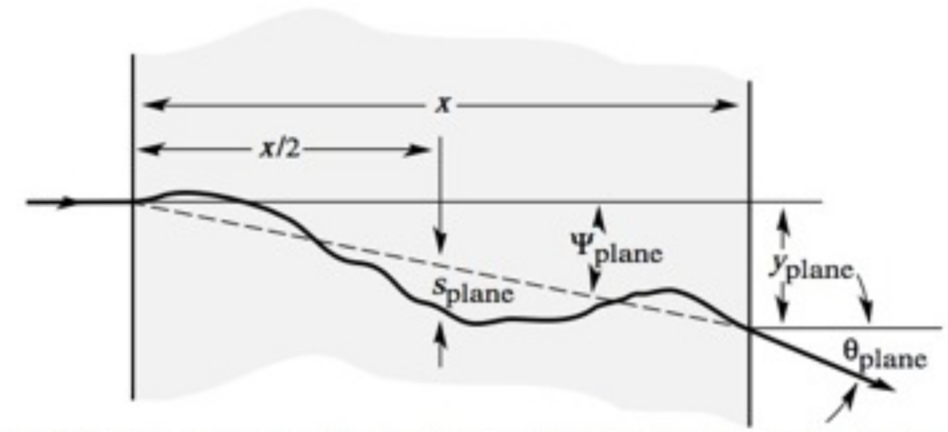


Figure 27.8: Quantities used to describe multiple Coulomb scattering. The particle is incident in the plane of the figure.

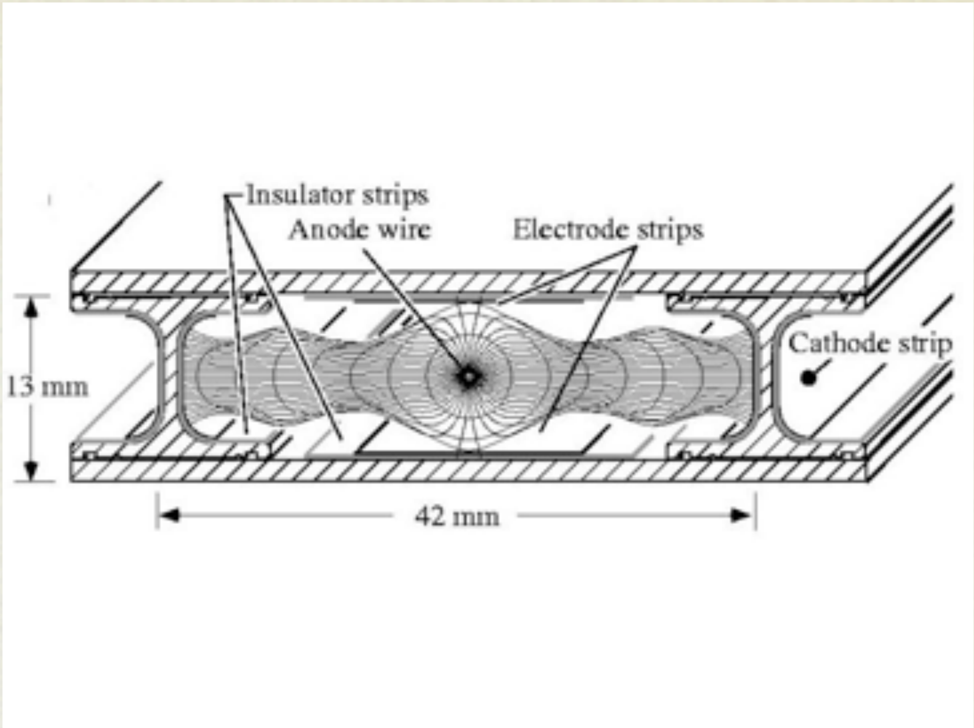
$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\Big[1 + 0.038 \ln(x/X_0)\Big]$$

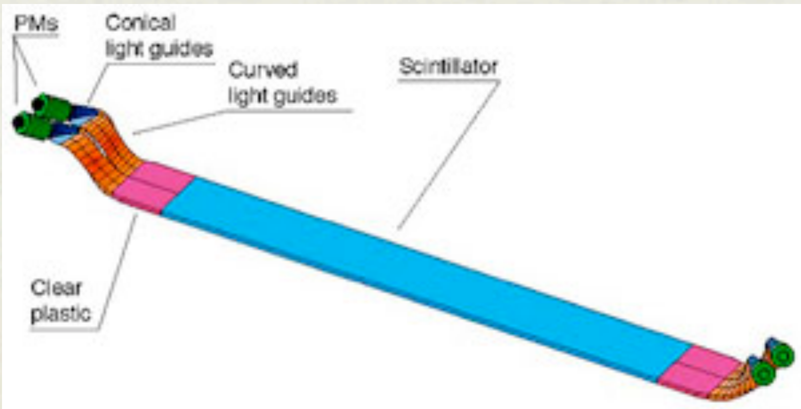
MUON DETECTION

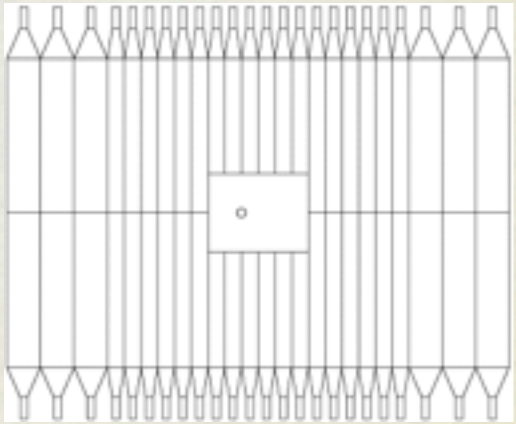
- Muons are detected through the energy they lose.

- Ionization can be amplified and detected in gaseous and solid and liquid state devices. A typical detector is an array of so-called drift tubes. Each tube is a gas-filled volume surrounding a fine wire which collects and amplifies free electrons in the gas.

- De-excitation of atoms excited by the passage of a muon produces light which may be detected. A typical detector is an array of scintillating plastic bars viewed with photomultiplication sensors.

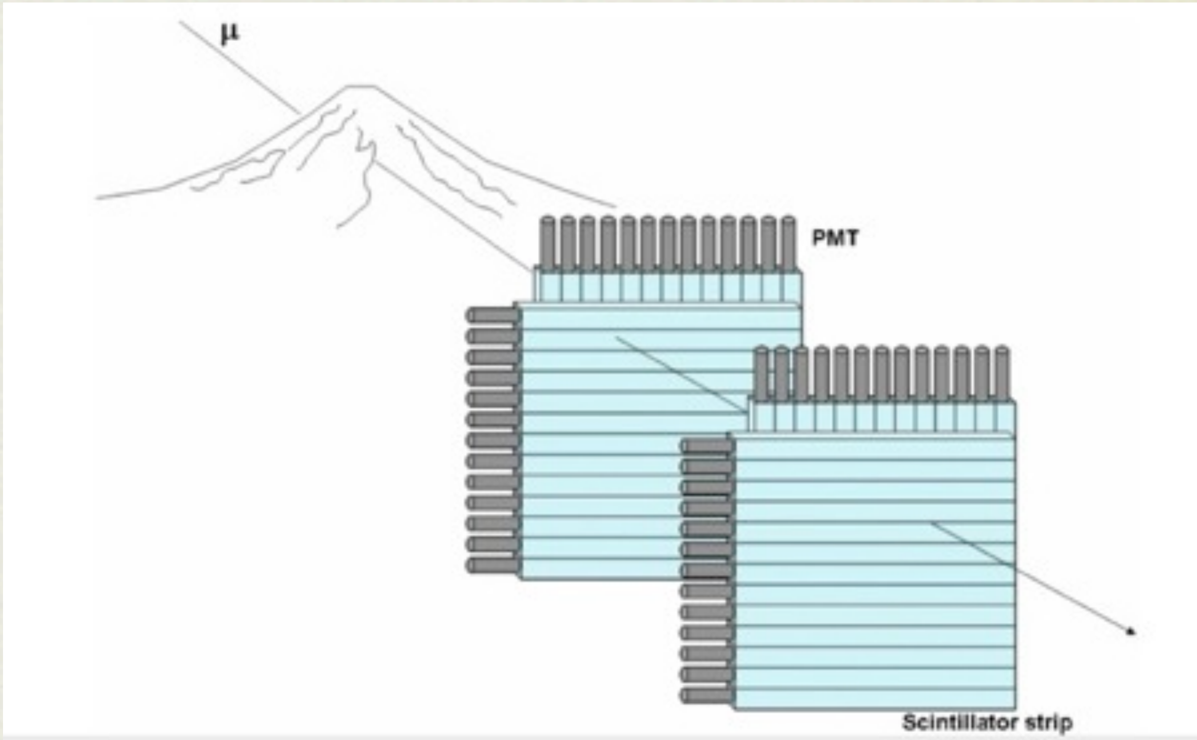






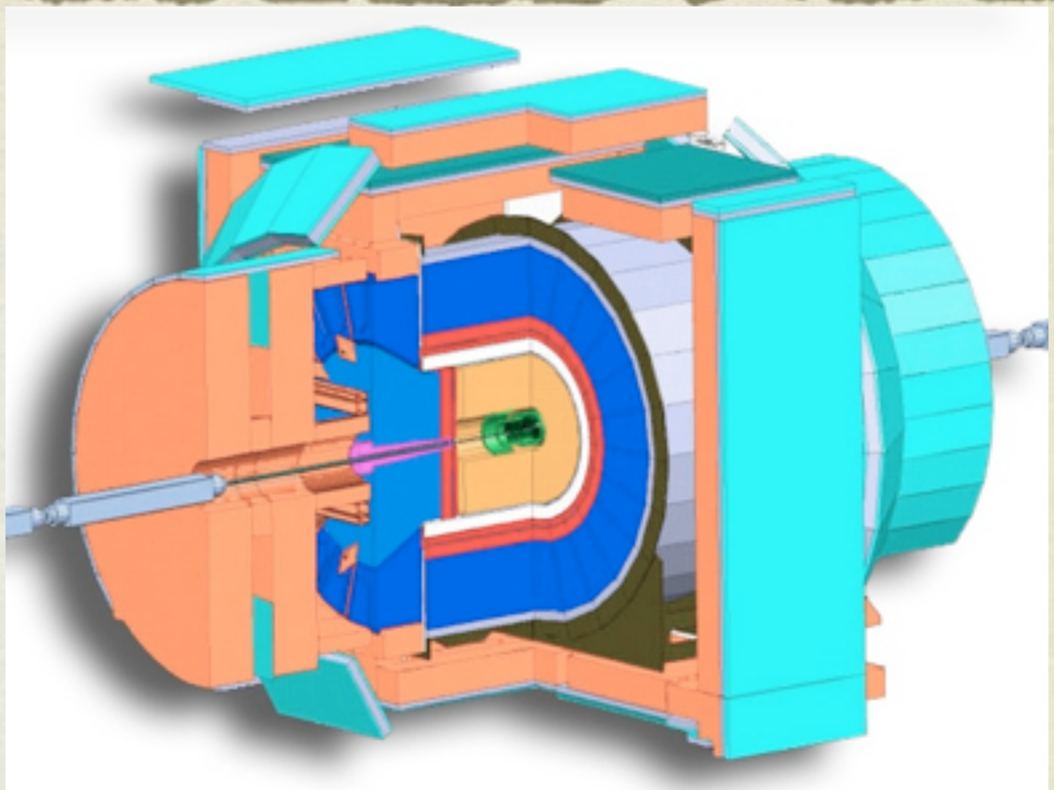
DETECTABLE EFFECTS

- An increase in density in a part of region probed leads to an increase in absorption and an increase in the scattering angle and displacement of muons which pass through it.



SOME AVAILABLE DETECTORS

- The Collider Detector at Fermilab (CDF) operated for 25 years until 2011. Muon detectors (blue) comprising drift tubes and scintillator paddles could be used to create cosmic muon telescopes.
- The endcap barrel muon drift tubes and scintillator paddles (black)were built and maintained by the University of Wisconsin CDF group.



ABSORPTION / TRANSMISSION MUGRAPHY

- The first use of cosmic ray muons is credited to L. Alvarez who searched the Pyramids for hidden chambers

Search for Hidden Chambers in the Pyramids
Luis W. Alvarez, Jared A. Anderson, F. El Bedwei, James Burkhard, Ahmed Fakhry, Adib Girgis, Amr Goneid, Fikhry Hassan, Dennis Iverson, Gerald Lynch, Zenab Miligy, Ali Hilmy Moussa, Mohammed-Sharkawi, Lauren Yazolino
Science, New Series, Vol. 167, No. 3919 (Feb. 6, 1970), pp. 832-839

- More recently, "muography" has been used to study volcanos.

- Mugraphy has been based on absorption. One measure the intensity from a given direction for several detector locations.

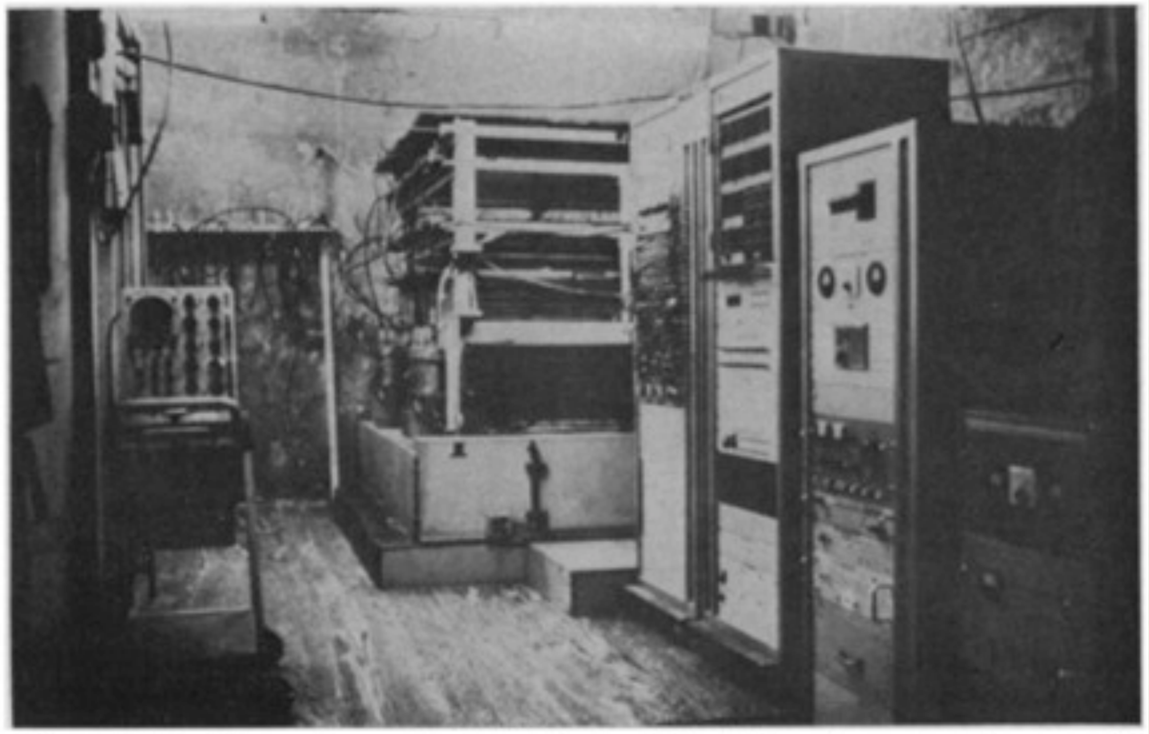


Fig. 6 (left). The equipment in place in the Belzoni Chamber under the pyramid.

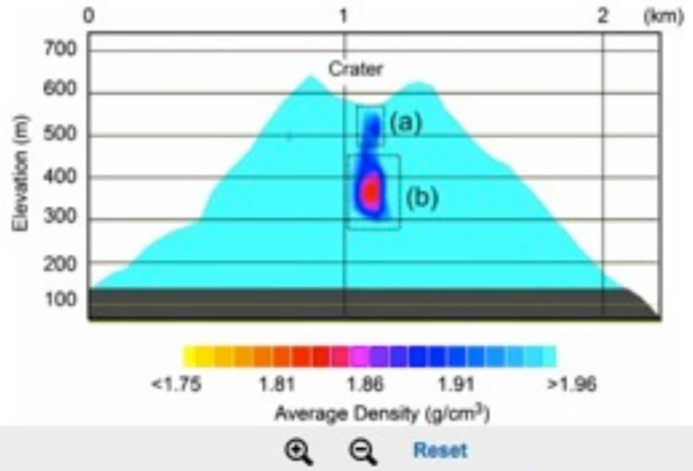


Figure 8. Average density distribution obtained with the PAC system at Mt Iwodake [43]. Density anomalies larger than 1.96 g cm^{-3} are not mapped for the sake of simplicity.

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SCATTERING MUOGRAPHY

PRL **109,** 152501 (2012) PHYSICAL REVIEW LETTERS week ending 12 OCTOBER 2012

Cosmic Ray Radiography of the Damaged Cores of the Fukushima Reactors

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The passage of muons through matter is dominated by the Coulomb interaction with electrons and nuclei. The interaction with the electrons leads to continuous energy loss and stopping of the muons. The interaction with nuclei leads to angle "diffusion." Two muon-imaging methods that use flux attenuation and multiple Coulomb scattering of cosmic-ray muons are being studied as tools for diagnosing the damaged cores of the Fukushima reactors. Here, we compare these two methods. We conclude that the scattering method can provide detailed information about the core. Attenuation has low contrast and little sensitivity to the core.

- While mugraphy has been based on absorption (measuring the intensity from a given direction), recent studies indicate that measurement of scattering angles with two detectors provides higher resolution images. This can not be done with x-rays, only with charged particle "rays."

COMPARISON

- This simulation of muon tomography applied to a nuclear reactor core shows the higher resolution and contrast obtained by measuring scattering angle in comparison to the "traditional" transmission/ attenuation method.

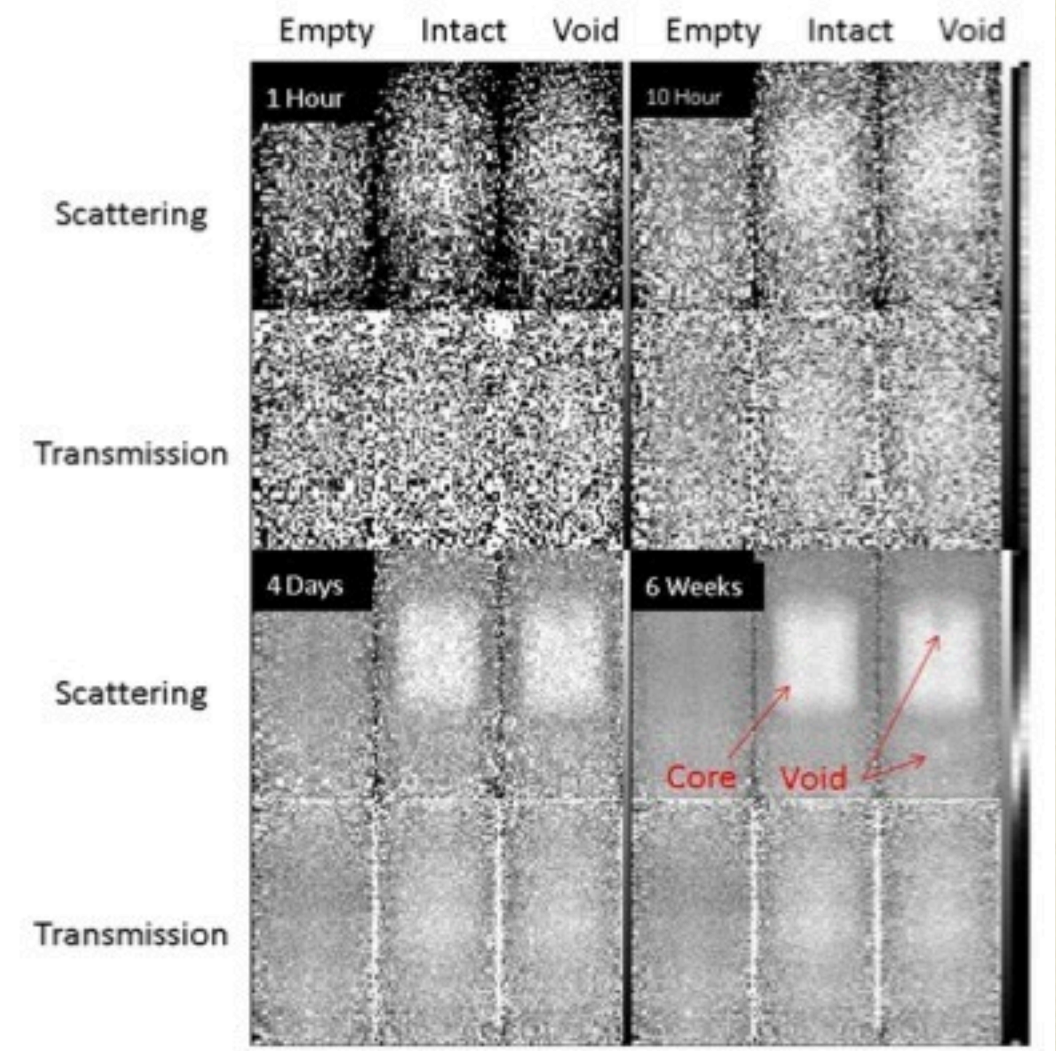

FIG. 3 (color online). Reactor reconstructions at different exposure times. In scattering radiography, the reactor core can be detected after about 10 hours of exposure. After four days, a 1 m diameter (1%) void can be detected when compared to an intact core. After 6 weeks, the void is clear and the missing material can be observed. With the attenuation method, the core can be observed when compared to an empty scene in four days. The void is undetectable even after 6 weeks of exposure.

GOALS OF FEASIBILITY STUDY

- Review literature and capabilities of groups working in muography.
- Review other remote sensing technologies - the physics, the available systems, the commercial and archaeological applications
- Simulate applications of scattering angle based muography to archaeological sites.
- If warranted, design and cost a muography telescope.

GEANT SIMULATION TOOLKIT

- Sophisticated tools exist for simulating the passage of muons through matter and their detection.
- GEANT is installed on WI HEP cluster machines and may be used.

STUDY GROUP RESPONSIBILITIES AND COMMITMENTS

- We are a fairly large group of novices who need to learn library research tools and how to organize and how to share information.
- I suggest we divide up tasks and define a biweekly meeting schedule with specific action items.

REFERENCES

Just a couple of references. See references in these for further information.

Nuclear Waste Imaging and Spent Fuel Verification by Muon Tomography
G. Jonkmans, V. N. P. Anghel, C. Jewett, M. Thompson, http://arxiv.org/abs/1210.1858

Imaging the density profile of a volcano interior with cosmic-ray muon radiography combined with classical gravimetry, S Okubo and H K M Tanaka 2012 Meas. Sci. Technol. 23 042001
doi:10.1088/0957-0233/23/4/042001, http://iopscience.iop.org/0957-0233/23/4/042001/article