COSMIC RAY TOMOGRAPHY

with applications to archaeology

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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 2014-, 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/

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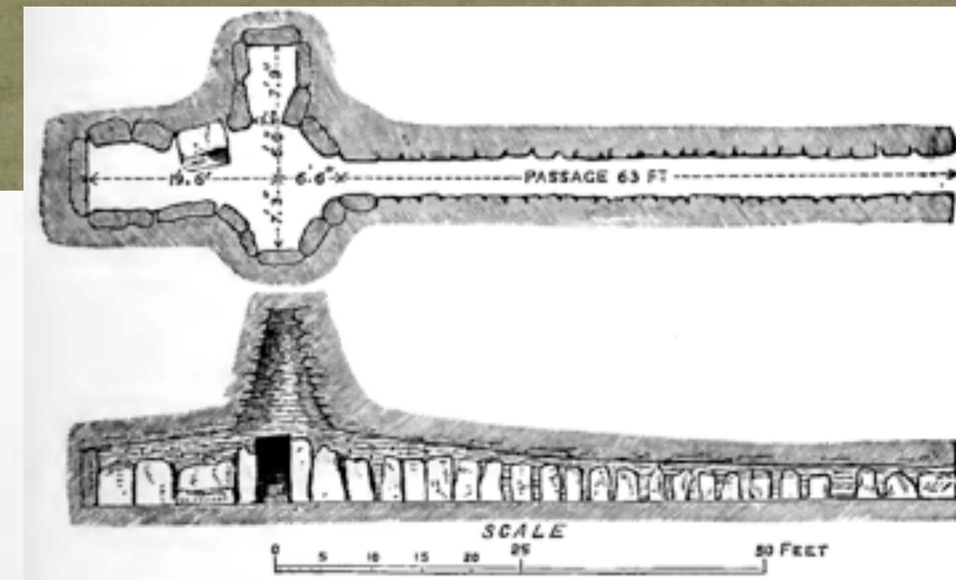
PROBLEM



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)*

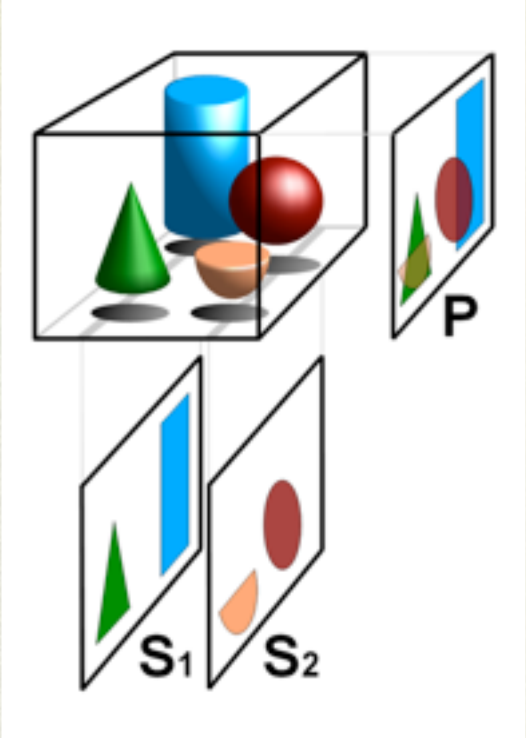
- How do we see inside a large structure like a burial mound or the Troy citadel (or a nuclear reactor) without going inside?

TOMOGRAPHY

- Radiography is the use of X-rays to view a non-uniform material such as the human body. Tomography refers to imaging by sections (sectioning), through the use of any kind of penetrating wave or particle. 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.

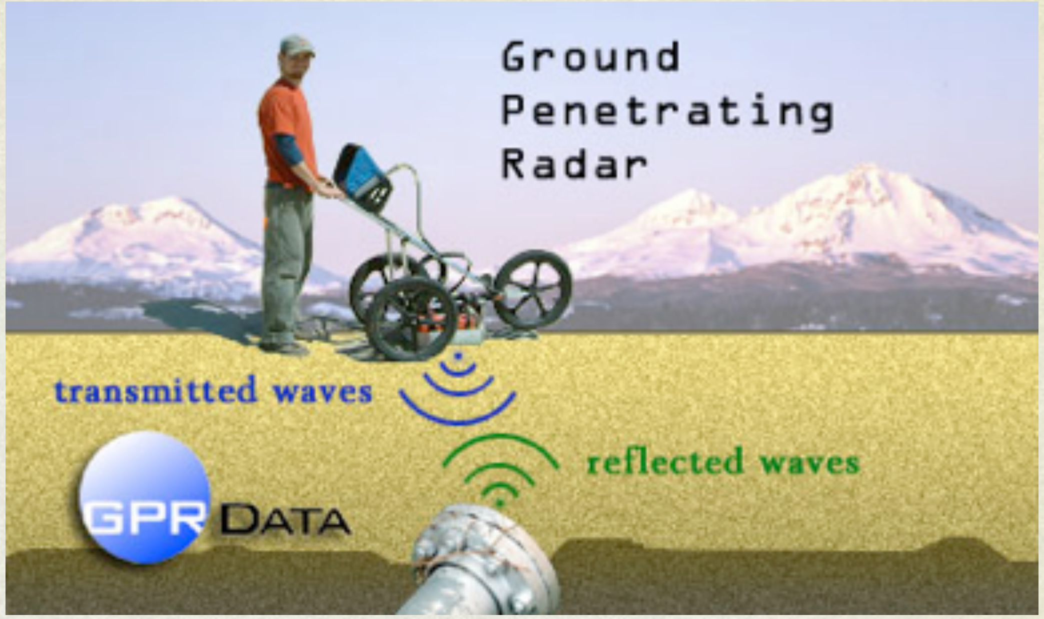
- X-rays and gamma rays are attenuated in normal solid or liquid matter over centimeter length scales and not useful in multiple meter scale archaeology.

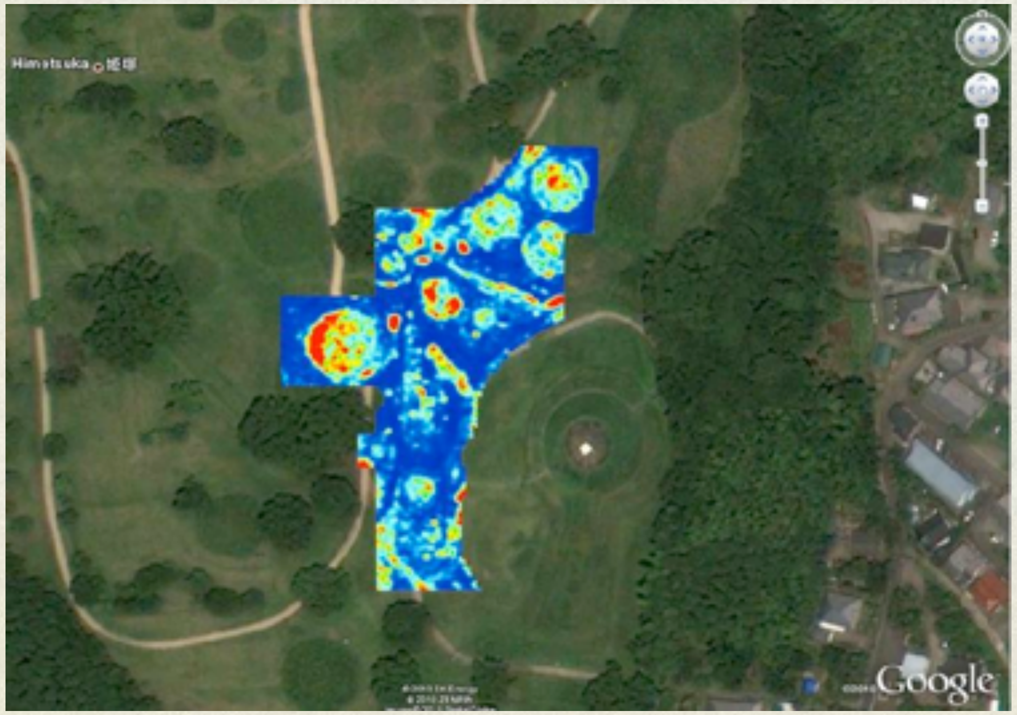


Physical phenomenon	Type of tomogram
X-rays	CT
gamma rays	SPECT
radio-frequency waves	MRI
electron-positron annihilation	PET
electrons	Electron tomography or 3D TEM
ions	atom probe
magnetic particles	magnetic particle imaging

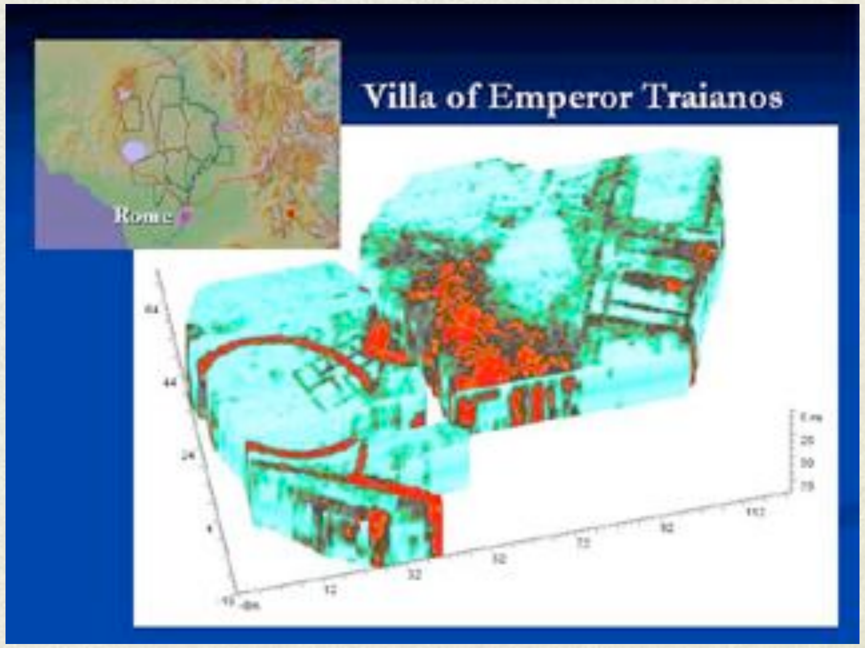
GROUND PENETRATING RADAR

- 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.



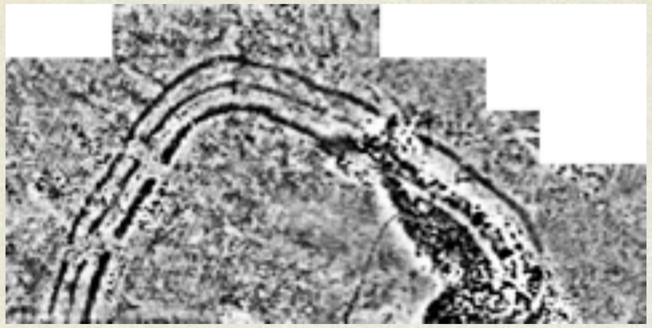


http://www.gpr-survey.com/

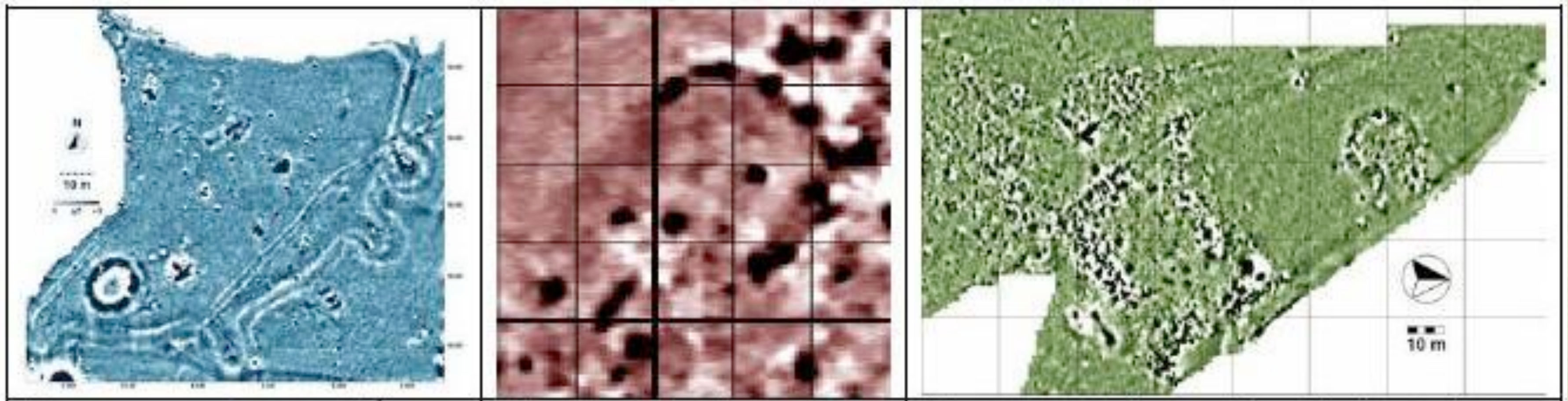


http://www.pastperfect.org.uk/archaeology/gpr.html#

MAGNETOMETRY



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

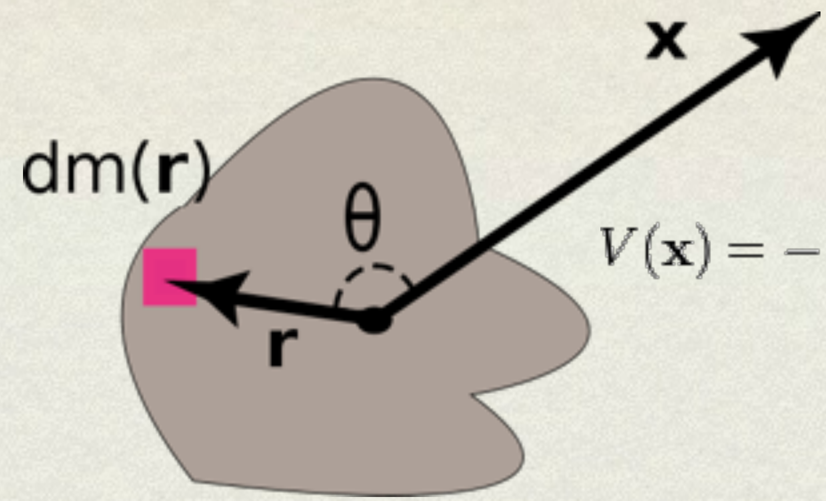


Magnetometry image, 13th century Menoken Village, ND.	Magnetometry image, internal features of 15th century house, Huff Village, ND.	Magnetometry image, Fort Clark Trading Post, Garreau's Lodge & Compound, 1832-1860, ND.

- Passive magnetometry refers to detailed measurements of the magnetic field on a surface, and is 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.

LIMITS OF PASSIVE SENSING

- The static gravitational/magnetic field of an object decreases with distance and approximates that of a monopole (point)/dipole at large distance. The details of the geometrical structure disappear at distances x large compared to its size.



$$V(\mathbf{x}) = -\int_{\mathbb{R}^3} \frac{G}{|\mathbf{x}-\mathbf{r}|}\, dm(\mathbf{r}).$$

$$V(\mathbf{x}) = -\frac{GM}{|\mathbf{x}|} - \frac{G}{|\mathbf{x}|}\int \left(\frac{r}{|\mathbf{x}|}\right)^2 \frac{3\cos^2\theta - 1}{2} dm(\mathbf{r}) + \cdots$$

Leading point particle term in gravitational potential

Structure effects proportional to $(r/x)^2$

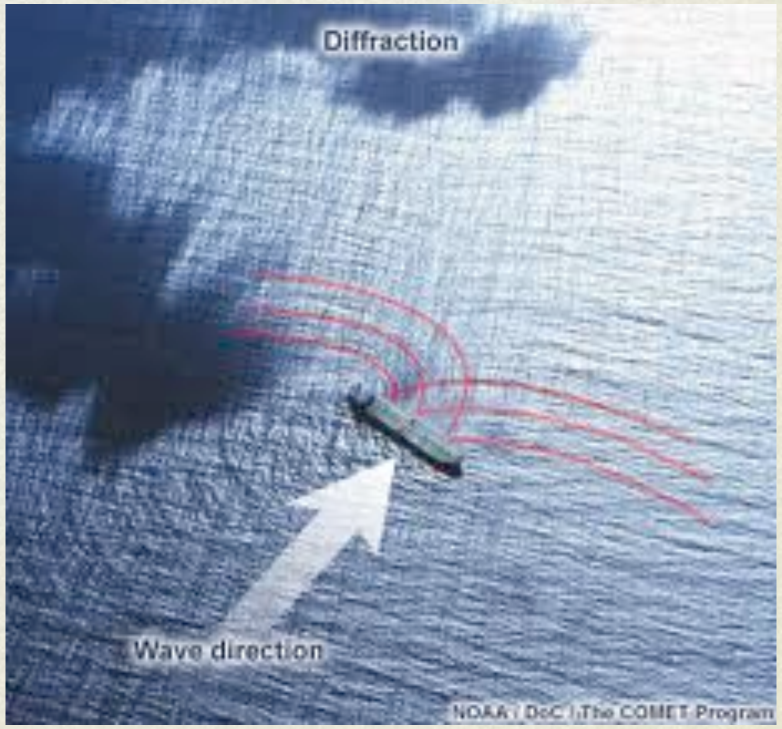
- A surface field survey can locate subsurface meter-scale features (e.g. cavities) only at meter-scale depth.

LIMITS OF ACTIVE SENSING

- Actively sensing refers to sending a wave energy probe to interact with an object and studying the returned waves. (e.g. sonar, optical, and radar.)

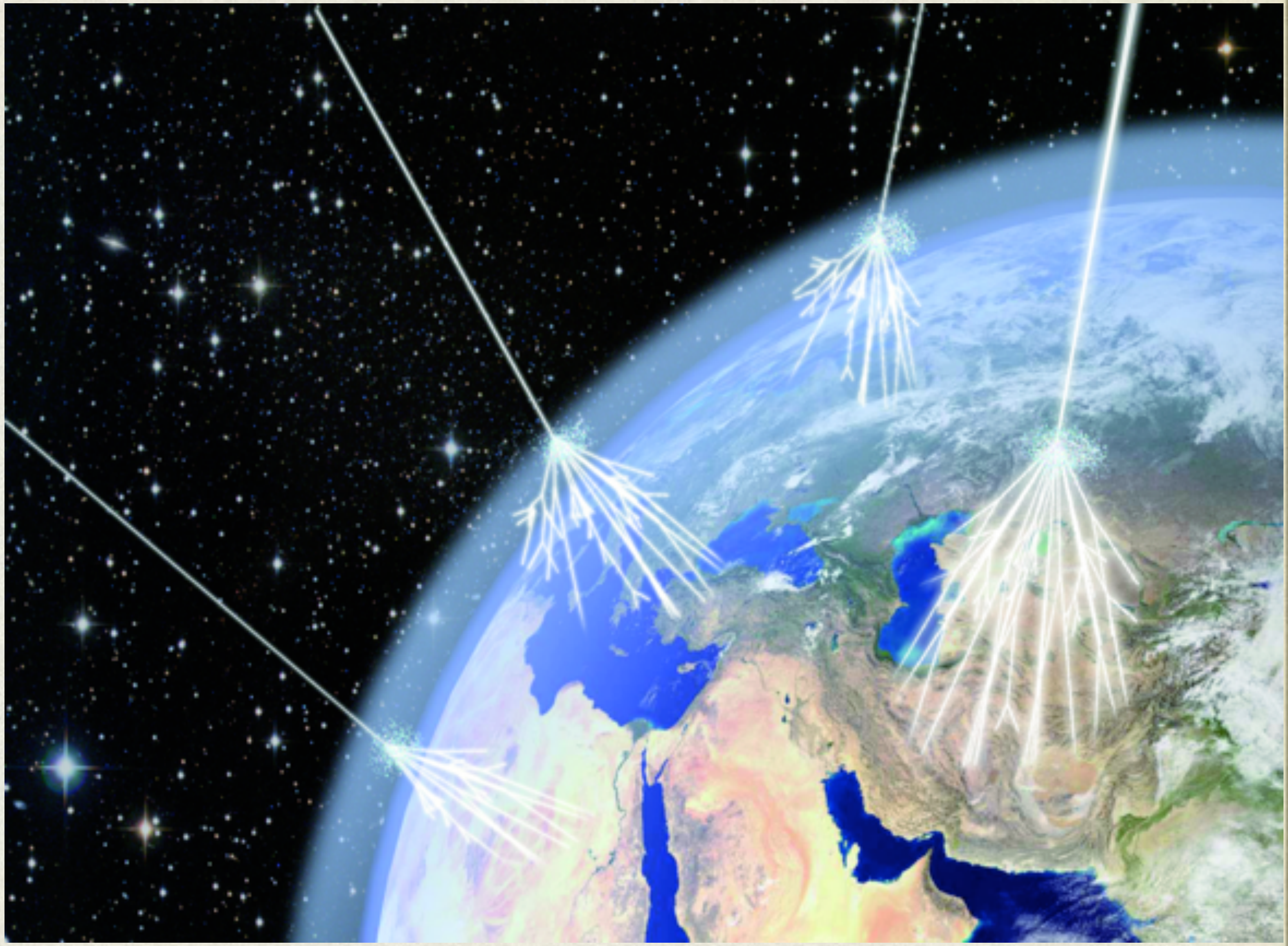
- Waves must not be attenuated or scattered severely by intermediate material.

- Wavelength must be short compared to feature size.



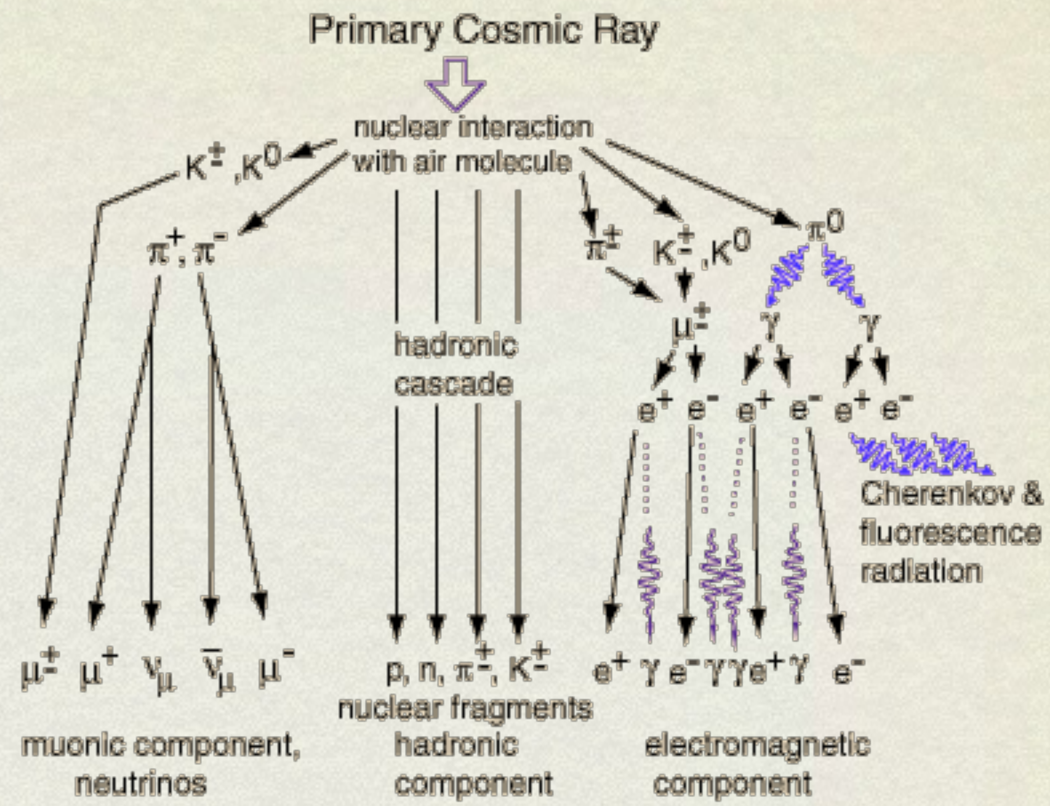
COSMIC RAY ORIGINS

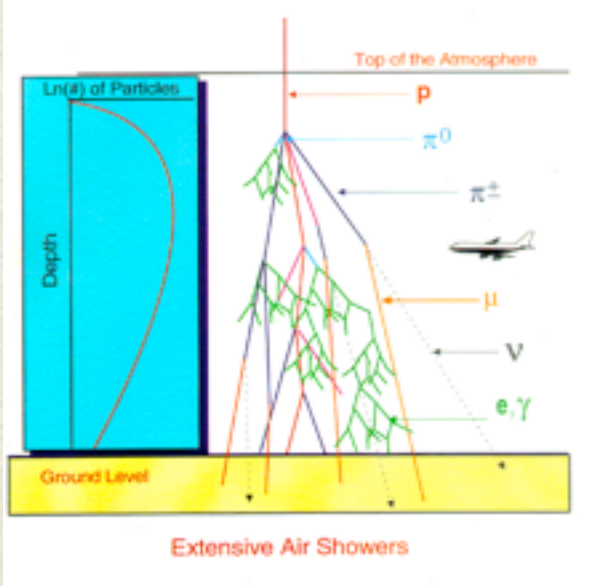
- Cosmic rays originate as high energy protons impacting the Earth atmosphere resulting in showers of particles at sea level.
- The particles in showers may be used to probe surface structures.



COSMIC RAY SHOWERS

- Numerous stringy interacting nuclear-like hadrons (p, n, K) and weakly interacting 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 short wavelength charged particles capable of passing through yet interacting with a large mound of Earth.
- The deflection and absorption of muons provides a means to observe something inside that mound with high resolution.



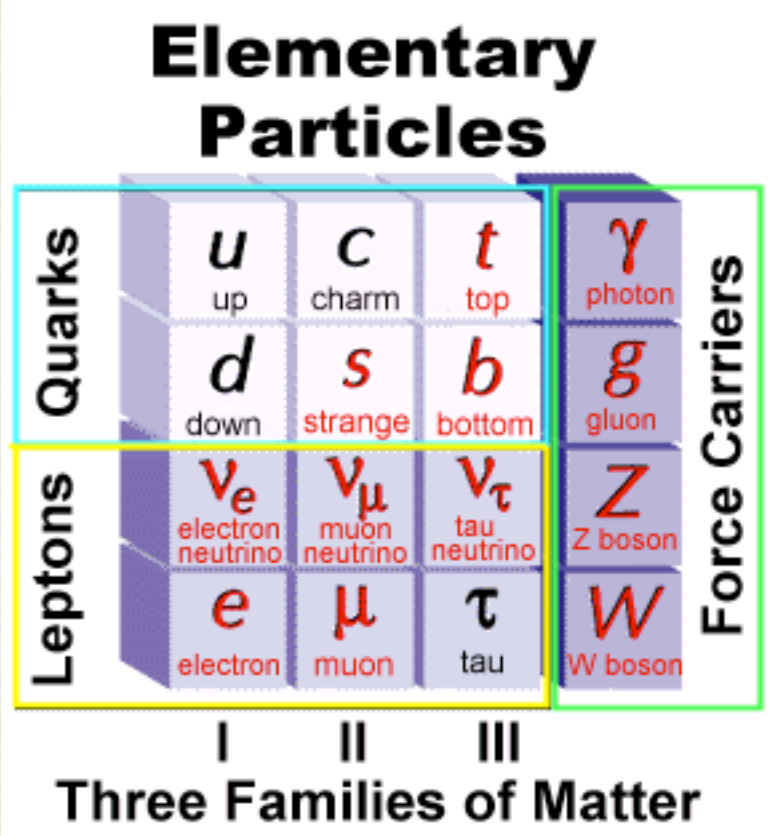


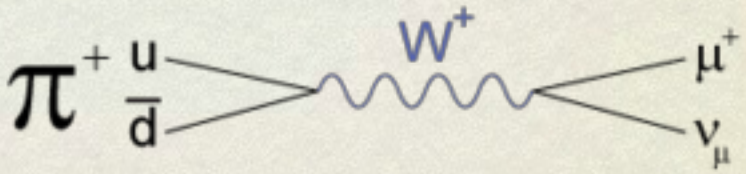
WHAT IS A MUON?

- 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.

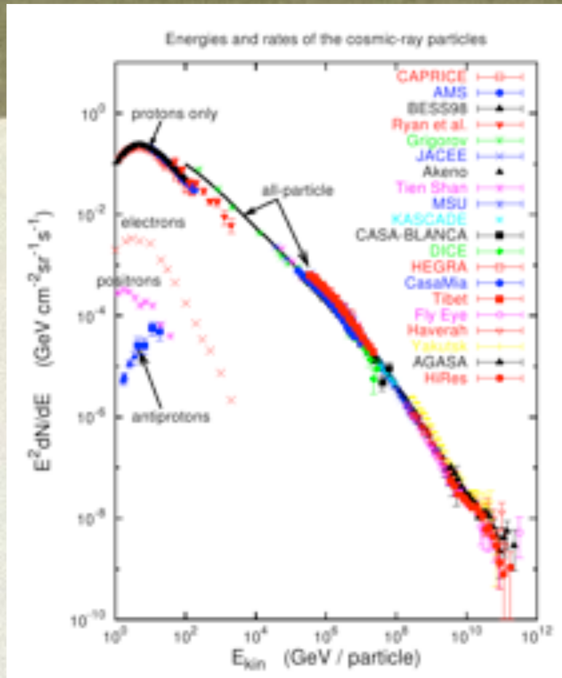
- The muons which make it to the Earth's surface are relativistic particles with energies of order ten times their rest energy.

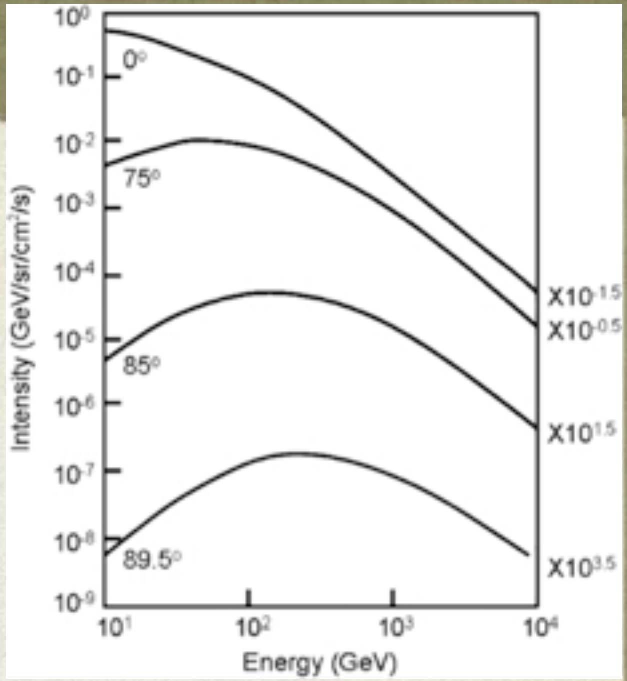




MUON ENERGY SPECTRUM

- 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. Horizontal muons are fewer but more penetrating.





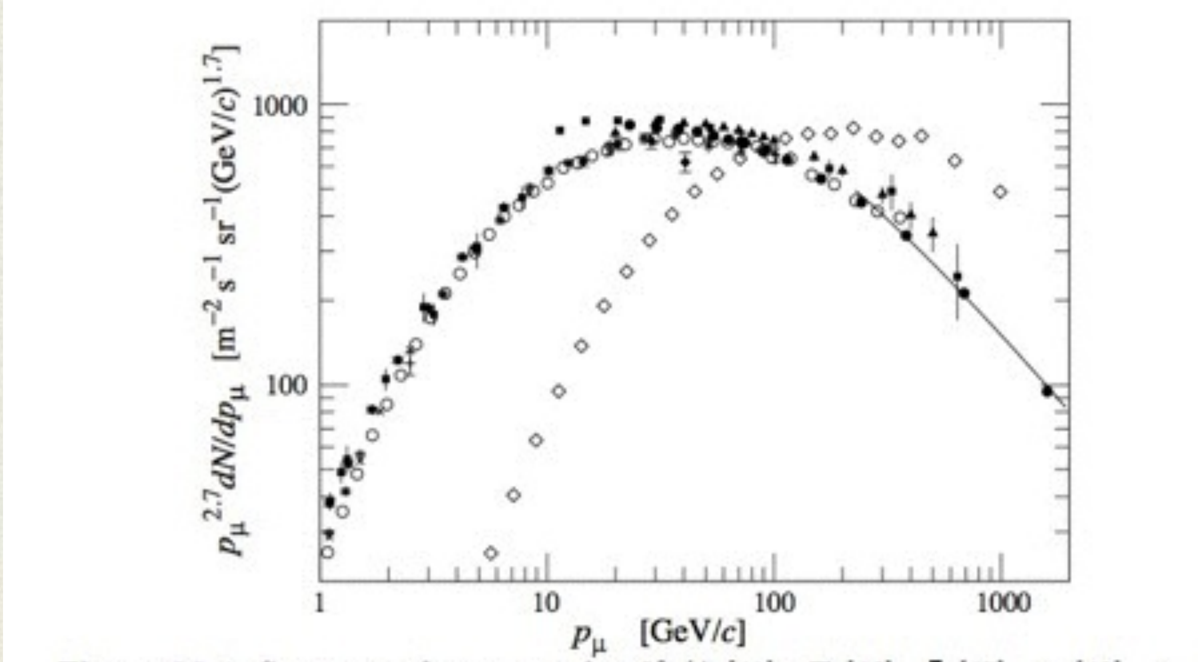


Figure 26.4: Spectrum of muons at $\theta = 0°$ (♦ [41], ■ [46], ▾ [47], ▲ [48], ×, + [43], ∘ [44], and • [45] and $\theta = 75°$ ◊ [49]) . The line plots the result from Eq. (26.4) for vertical showers.

MUON INTERACTIONS WITH MATTER

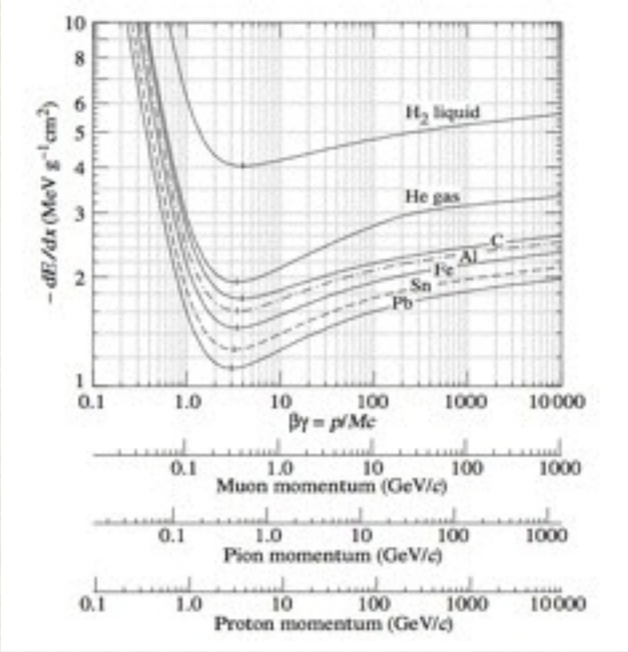
- The most important interactions are electromagnetic interactions with electrons and with nuclei.

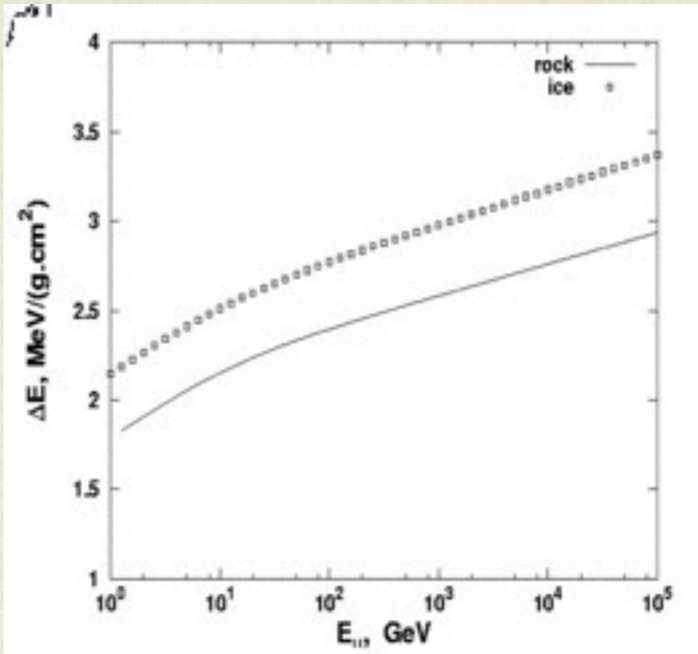
- Like a lead ball encountering a sea of pingpong balls, a muon plows straight through the electron sea constituting normal matter knocking electrons left and right. This results in a trail of ionization and an energy loss of a few MeV per cm of material in proportion to the electron density and hence 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.

MUON ENERGY LOSS AND RANGE

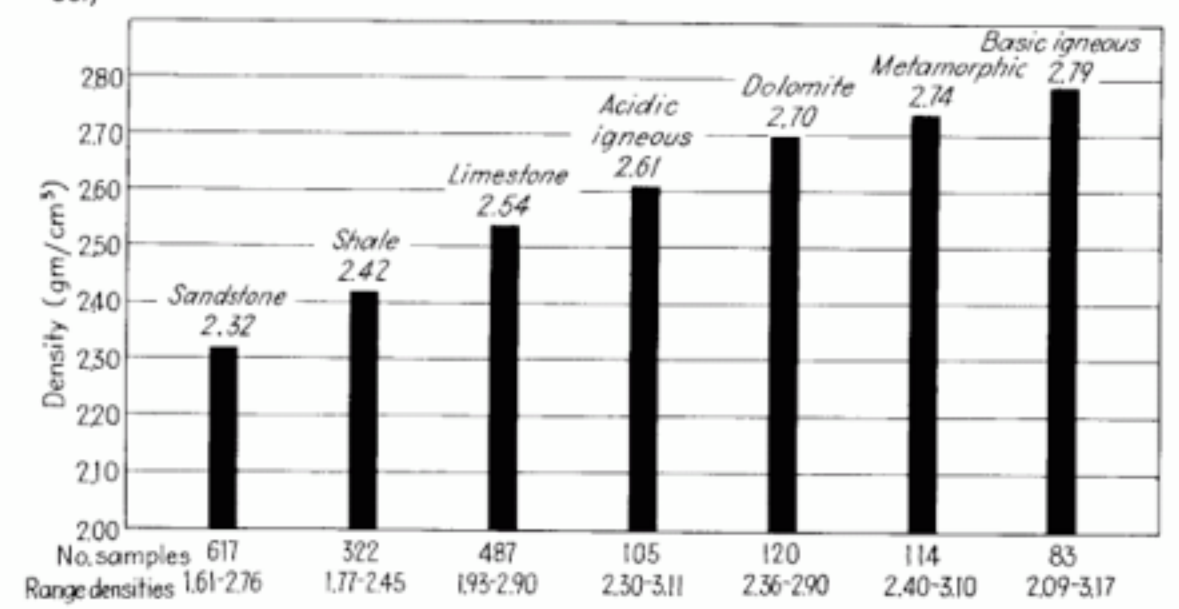
- Energy loss dE in traversing a length dx is proportional to density and usually quoted as about 2 MeV per g-cm^{-2} for a relativistic muon.





- 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.)*



MUON 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.

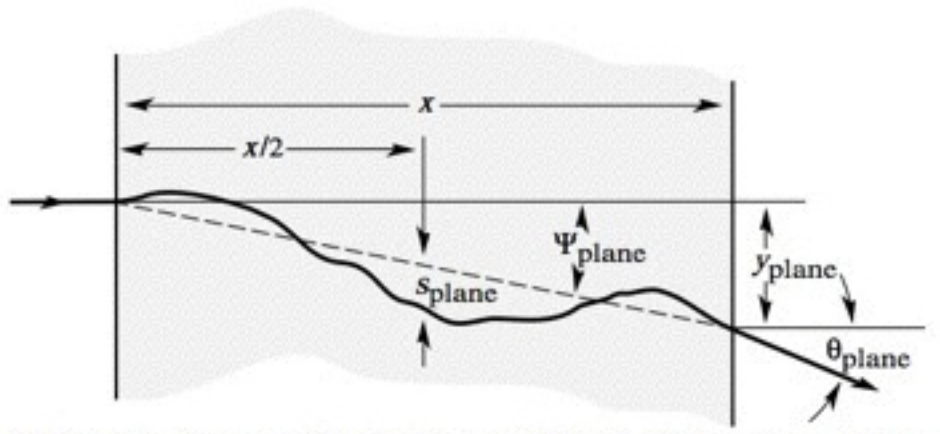


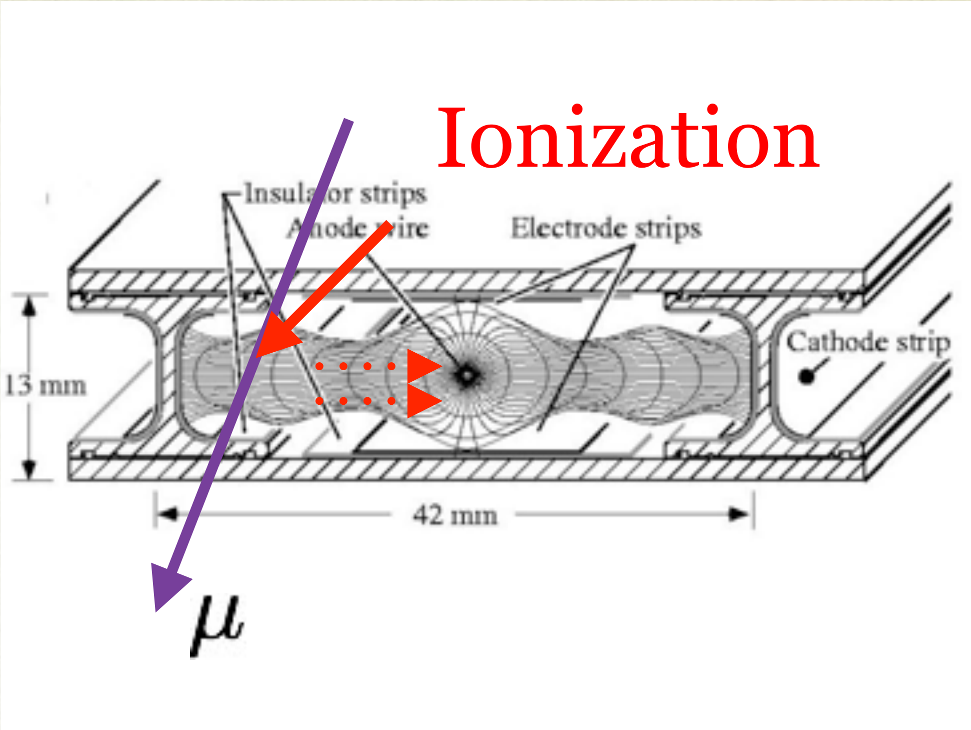
Figure 27.8: Quantities used to describe multiple Coulomb scattering. The particle is incident in the plane of the figure.

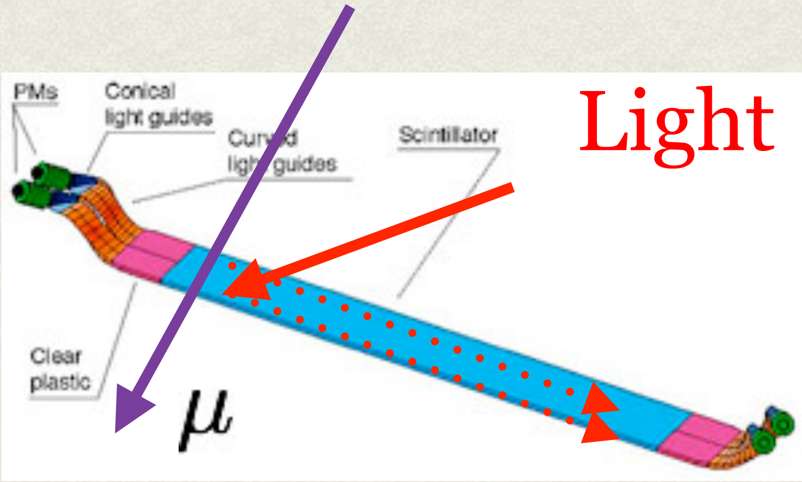
$$\theta_0 = \frac{13.6 \text{ MeV}}{\beta c p} \, z \, \sqrt{x/X_0} \Big[1 + 0.038 \ln(x/X_0) \Big]$$

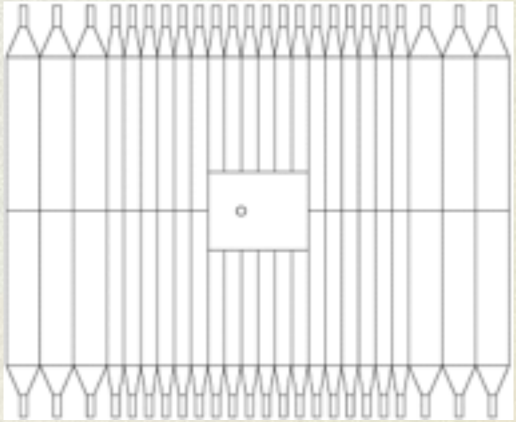
More energetic muons penetrate farther and scatter less but appear with lower intensity

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.

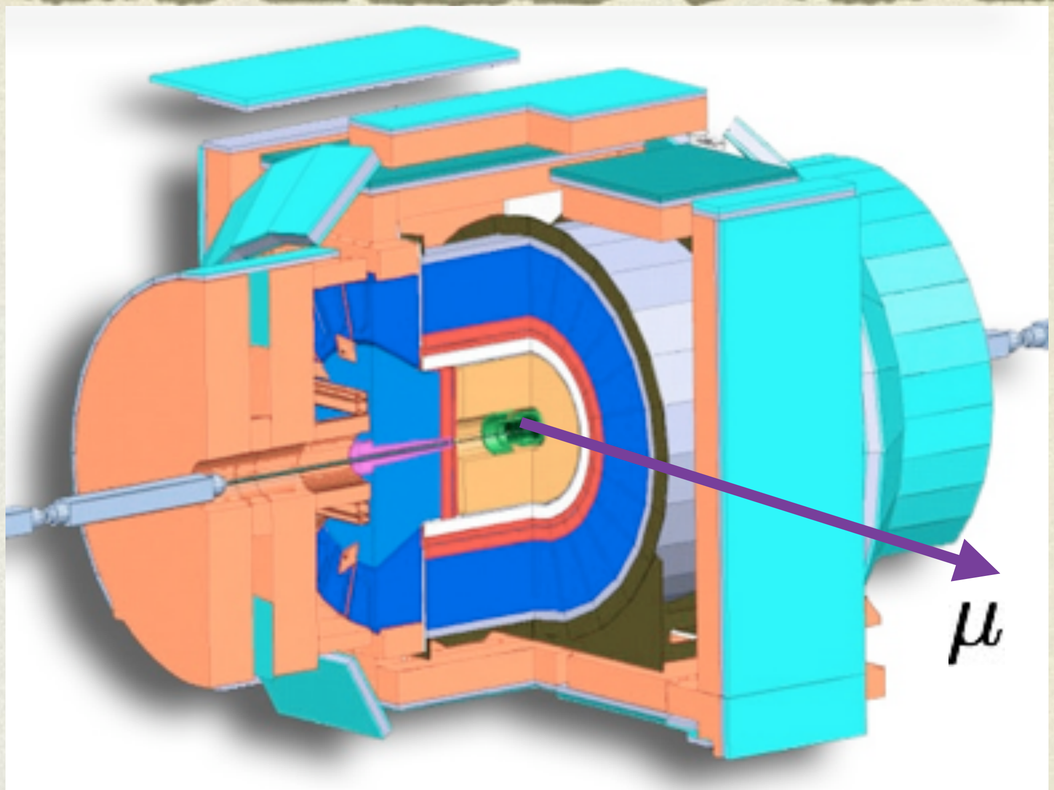




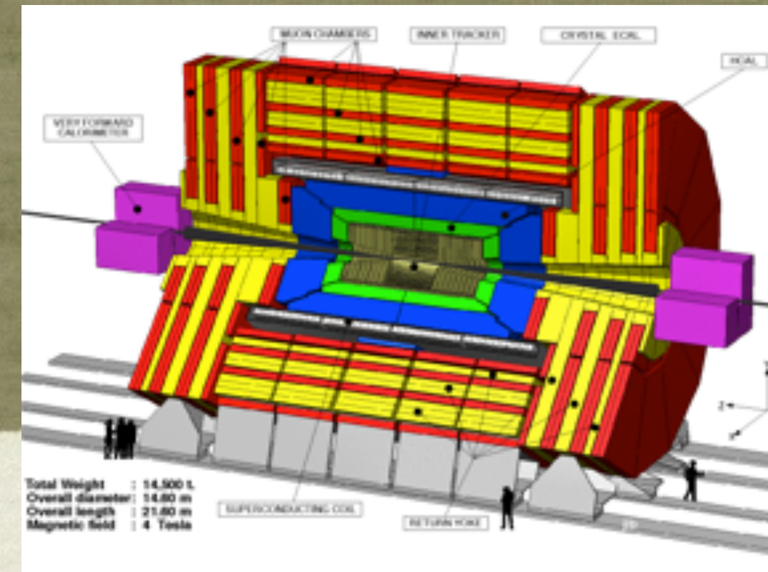


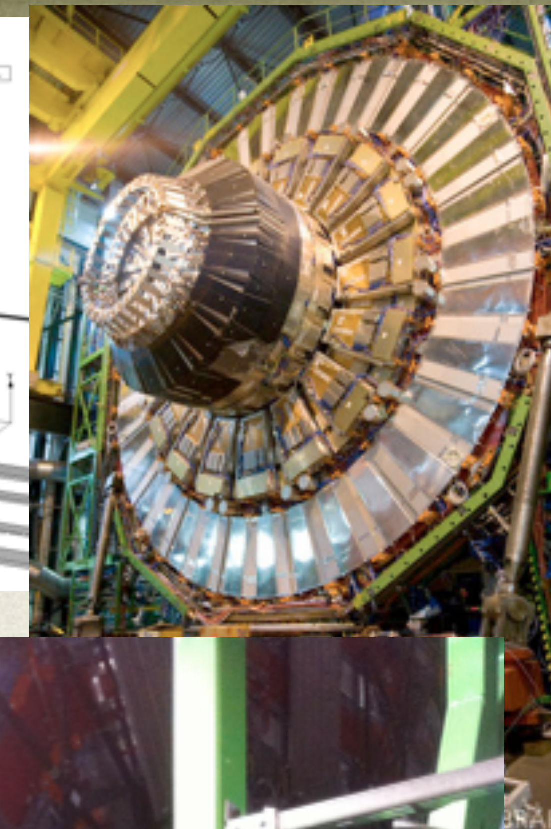
COLLIDER DETECTOR

- The Collider Detector at Fermilab (CDF) discovered the top-quark while studying proton-antiproton collisions. 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 Carlsmith's University of Wisconsin CDF group.



CMS@CERN





- This diagram shows the Compact Muon Solenoid (CMS) detector at the Large Hadron Collider used to discovery the Higgs boson in 2012.
- The red material is iron and yellow bands show interleaved drift tube and cathode strip chamber (CSC) muon detectors. The end caps are a UW-Madison responsibility.

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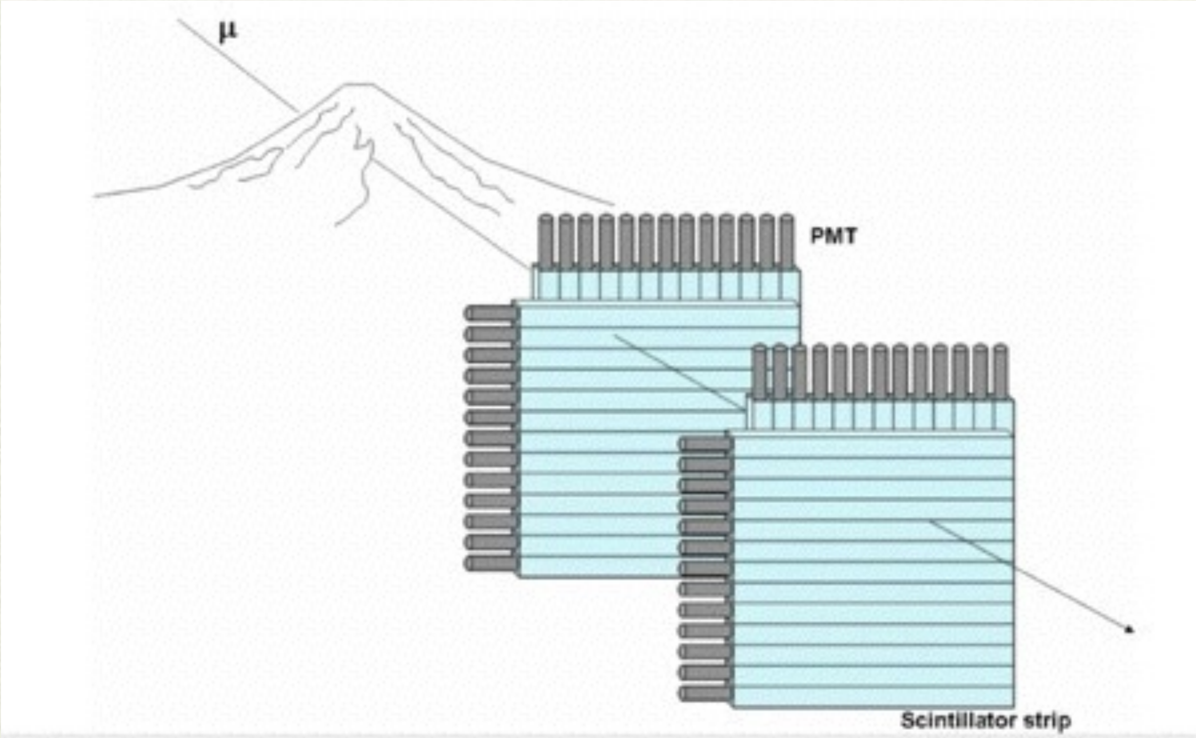
ABSORPTION TOMOGRAPHY

- 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.
- The simplest muon tomography schemes make use only of absorption, ignoring scattering and muon energy.



Scintillator paddle array "hodoscope"

MUOGRAPHY HISTORY

- 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

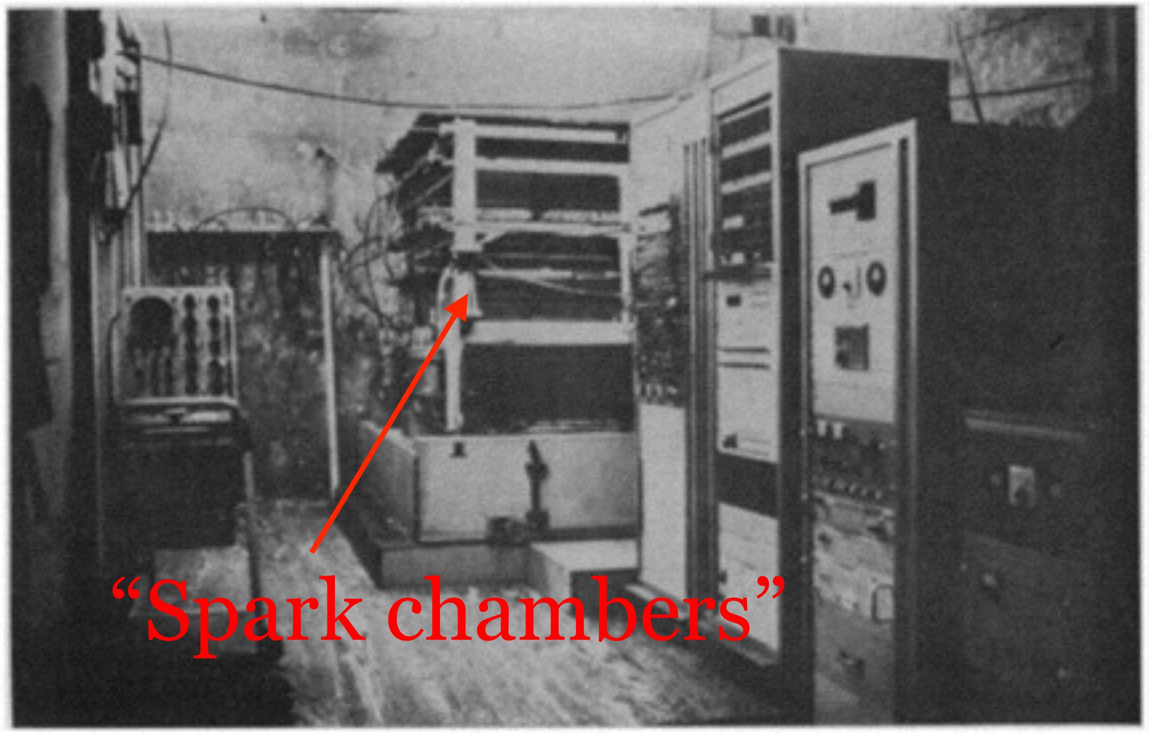


Fig. 6 (left). The equipment in place in the Belzoni Chamber under the pyramid.

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

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

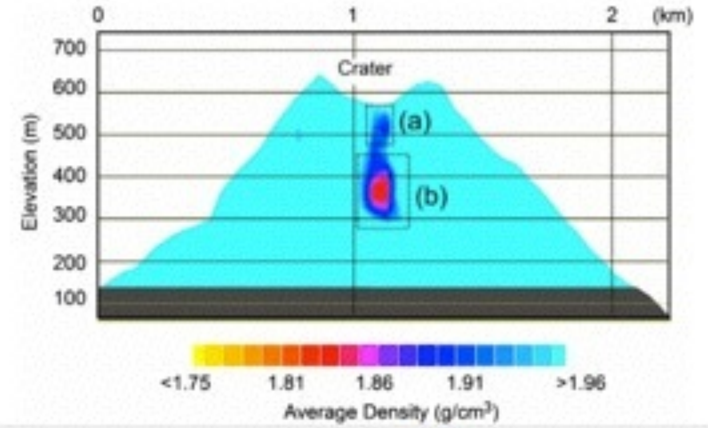


Figure 8. Average density distribution obtained with the PAC system at Mt Iwodake [43]. Density anomalies larger than 1.96 g cm^{-3} are not mapped for the sake of simplicity.

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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(Received 9 August 2012; published 11 October 2012)

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 muography 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. Entrance and exit measurements 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.

- Now in progress by LANL.

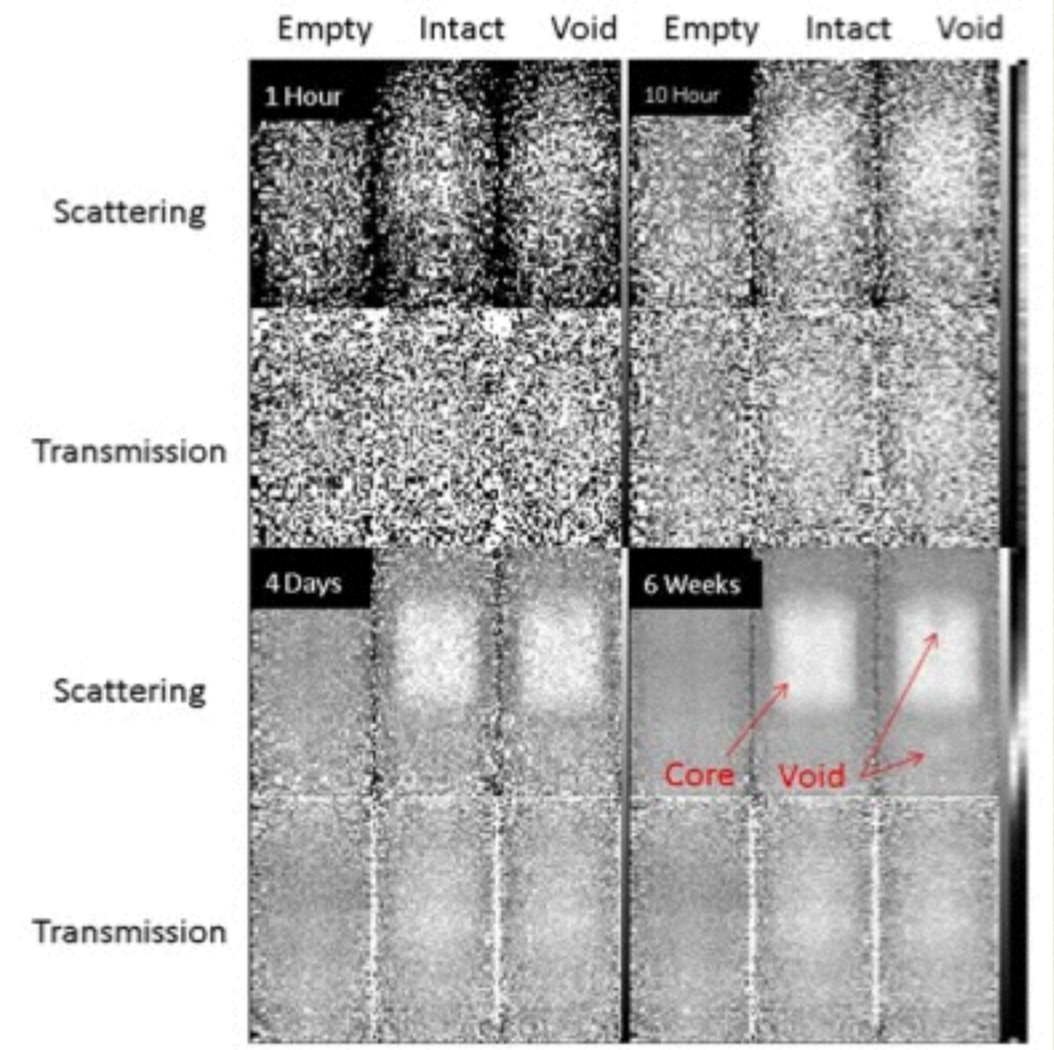


FIG. 3 (color online). Reactor reconstructions at different exposure times. In scattering radiography, the reactor core can be detected after about 10 hours of exposure. After four days, a 1 m diameter (1%) void can be detected when compared to an intact core. After 6 weeks, the void is clear and the 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.

UW MUOGRAPHY GROUP

wiki.physics.wisc.edu//garage

- UW-Madison muography activity started in 2013 by Carlsmith with undergraduates Anna Christenson and Bia (Sean)Wang with support from Garage Physics and a Wisconsin Space Grant. The activity has evolved to include collaboration with the UT-Austin Mayan Muography group.

- Goals:evaluate muon tomography feasibility through simulation and analysis of UT-Austin data and participate in applications in Belize and at Troy.

GARAGE PHYSICS

- Launched in 2013, Garage Physics an open lab for interdisciplinary undergraduate research and entrepreneurship.
- Active projects include muography, an 20 lb-lift homegrown arduino-controlled quadcopter, 3d-food printing R&D, and a pilot maker-style class in sustainability.

Active projects

- EEG Mind control
- Quadcopter Flies and carries a payload
- Troy project Archaeology and muography
- Homemade GPS Receiver Improving on your smartphone
- Bubble Stability A novel kind of bubble
- 3D printing Resources and suggested projects
- Graphene Micro-Supercapacitors Towards a cheap battery replacement
- Laser pointer safety Be wary of those pointers
- Drones, drones, and more drones Resources and project ideas
- Hammocks! Outdoor learning spaces for the 21st century
- Xbox Kinect for Instructional Labs So many markets for this...
- Website We need more than this wiki, eh?
- Sustainability Resources and suggested projects
- 3D Printer Recycling A personal recycler prototype
- Personal Greenhouse Living Pantry for the inner city, 3rd world, and 1st world
- Grey Water Toilet Use that shower/bath water, OK?
- Foucault Pendulum The Earth rotates. This demonstrates it.

UW MUOGRAPHY GOALS

- Review literature and capabilities of groups working in muography.
- Consider integration with other remote sensing and survey technologies - the physics, the available systems, the commercial and archaeological applications.
- Simulate applications of absorption and of additional 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 freely downloaded.

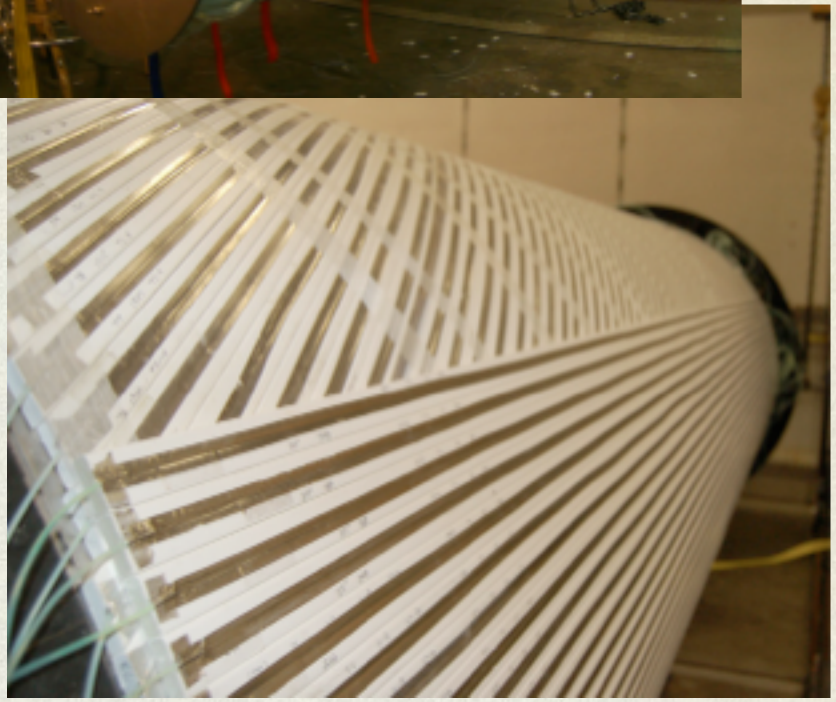
MAYAN MUOGRAPHY GROUP

- The Mayan muography group at UT-Austin is led by Professor Roy Schwitters and includes a graduate student and technical support.

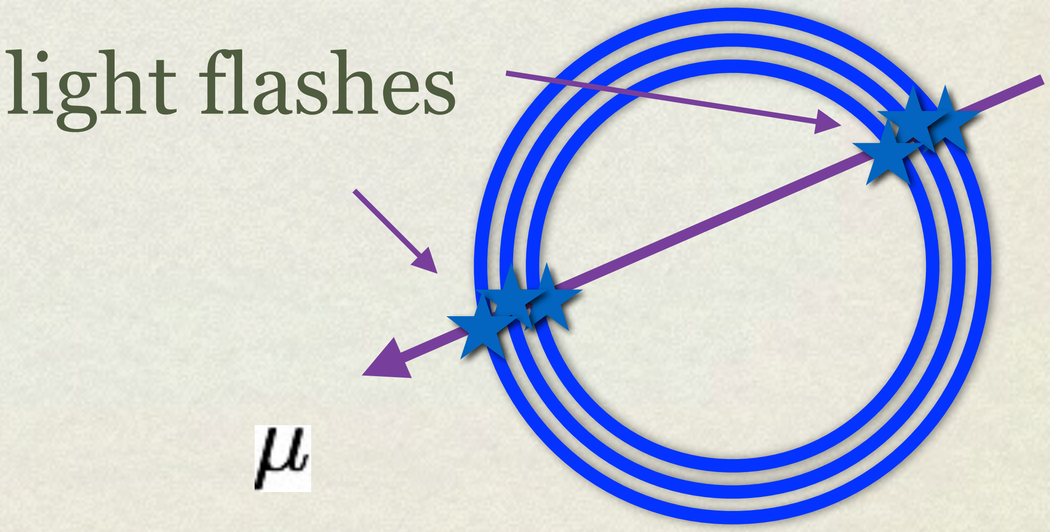
- This group has completed 6 scintillator barrel muon telescopes, developed reconstruction software, and in the summer of 2013 tested deployment in Belize.

http://www.hep.utexas.edu/mayamuon/

UT-AUSTIN DETECTORS



- The UT detectors are 3-layer barrels of scintillating plastic bars with wavelength-shifting optical fiber light collection and multi-anode photomultiplier readout.
- The angles between the staves of the barrel layers affords localization of muon light generation in three dimensions.



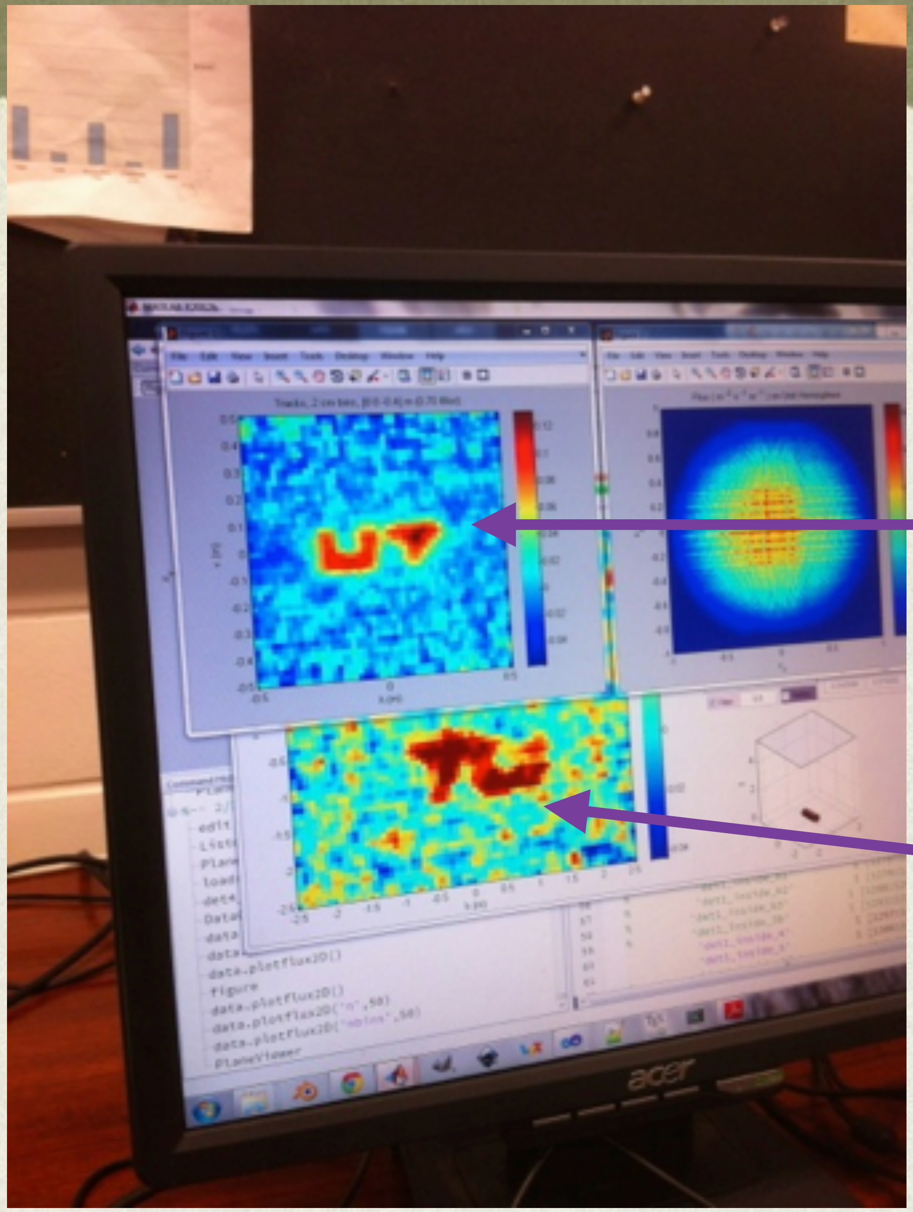
BENCH TEST

- This image shows a muography detector with a 70 watt power supply and USB port. Data is collected and stored in an internal memory.

- Notice the letters "UT" constructed of lead bricks just above the detector.

Image by Carlsmith, 2013

RECONSTRUCTION



“UT” above detector

“UT” atop building

- Reconstructed images of lead brick letters atop the detector and atop the UT lab building, Feb 2013.

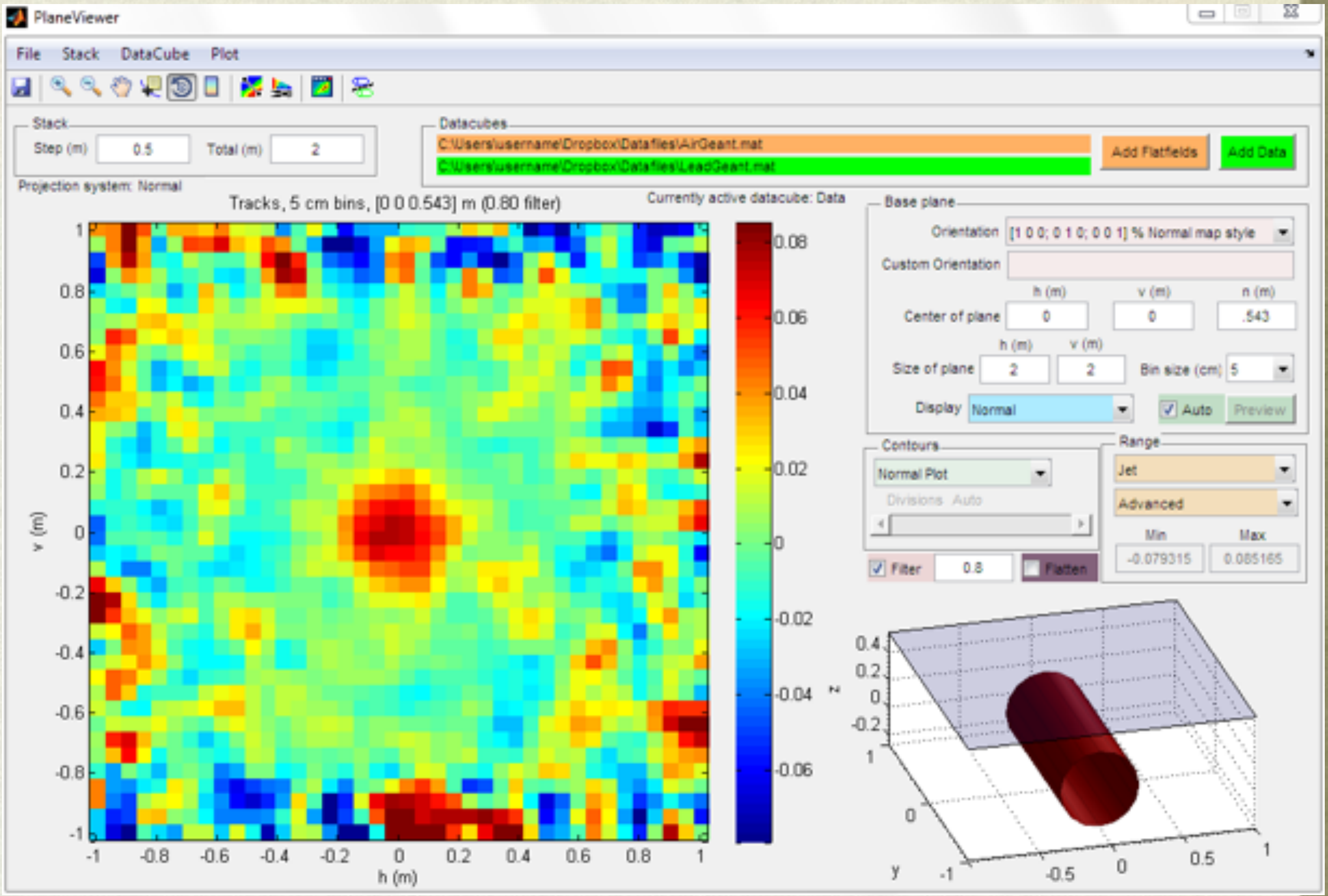
FIELD TEST

- These images from June 2013 show a field test in Belize.
- Maintaining power in a wet and remote environment limited data taking and the detector was removed after one month.
- Test observed outline of Mayan temple.

Images from Roy Schwitters

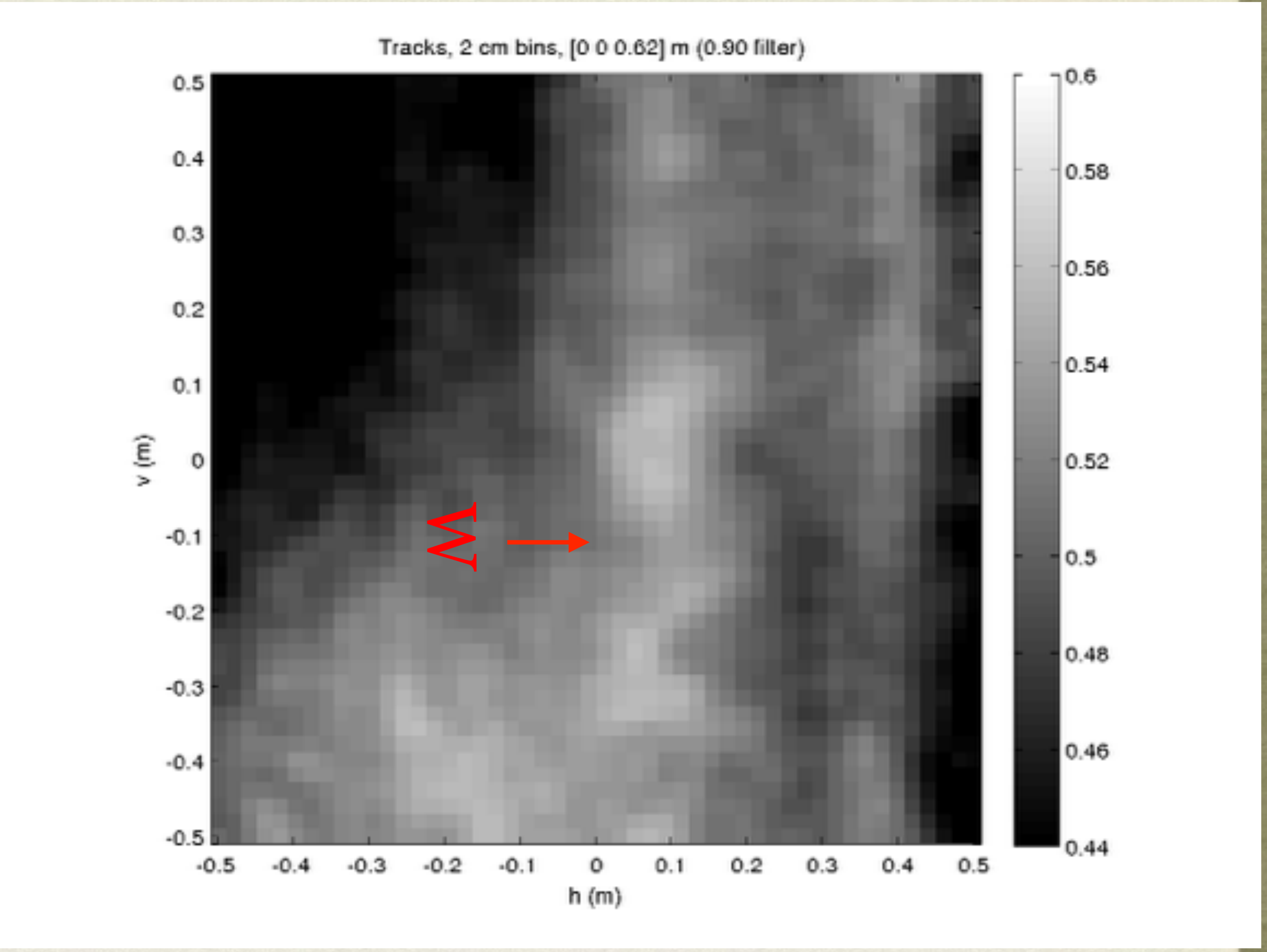
RECONSTRUCTION SOFTWARE

- UT reconstruction software has been installed in Madison. It presently uses a MATLAB interface.



“W” AS IN UW

- This image shows a “W” made of lead bricks atop the UT detector in Austin October 2013 observed for four days.



RECONSTRUCTION IMPROVEMENT

- The illustrated reconstruction is based on subtraction of background field so is to a degree unreal. The algorithm is rudimentary. It simply uses the raw intensity of muons which passed through each 3d volume element minus the background field ignoring correlation.

- A more compute intensive algorithm based on the integral absorption along all paths through the image field should be more effective!

ALTERNATE TECHNOLOGIES

- Field tests indicate some of the limitations of the scintillation bar design including weight, robustness, and tracking resolution (pointing accuracy).

- Micro-pattern gas (ionization) detectors may be a better choice.

RD51 Collaboration
Development of Micro-Pattern Gas Detectors Technologies

The proposed R&D collaboration, RD51, aims at facilitating the development of advanced gas-avalanche detector technologies and associated electronic-readout systems, for applications in basic and applied research. **The main objective of the R&D programme is to advance technological development and application of Micropattern Gas Detectors.**

STATUS AND PLANS

- Study improvement to the algorithm using full model of attenuation and actual data.
- Complete a GEANT simulation of the device with model realistic archaeological environments.
- Assist in development of field robust power and communication systems of UT detectors and study GEM and MicroMegas options.
- Reconnaissance and planning for Troy citadel imaging.

REFERENCES

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