Imaging Maya Pyramids with Cosmic Ray Muons

An Application of the Tools of High Energy Physics

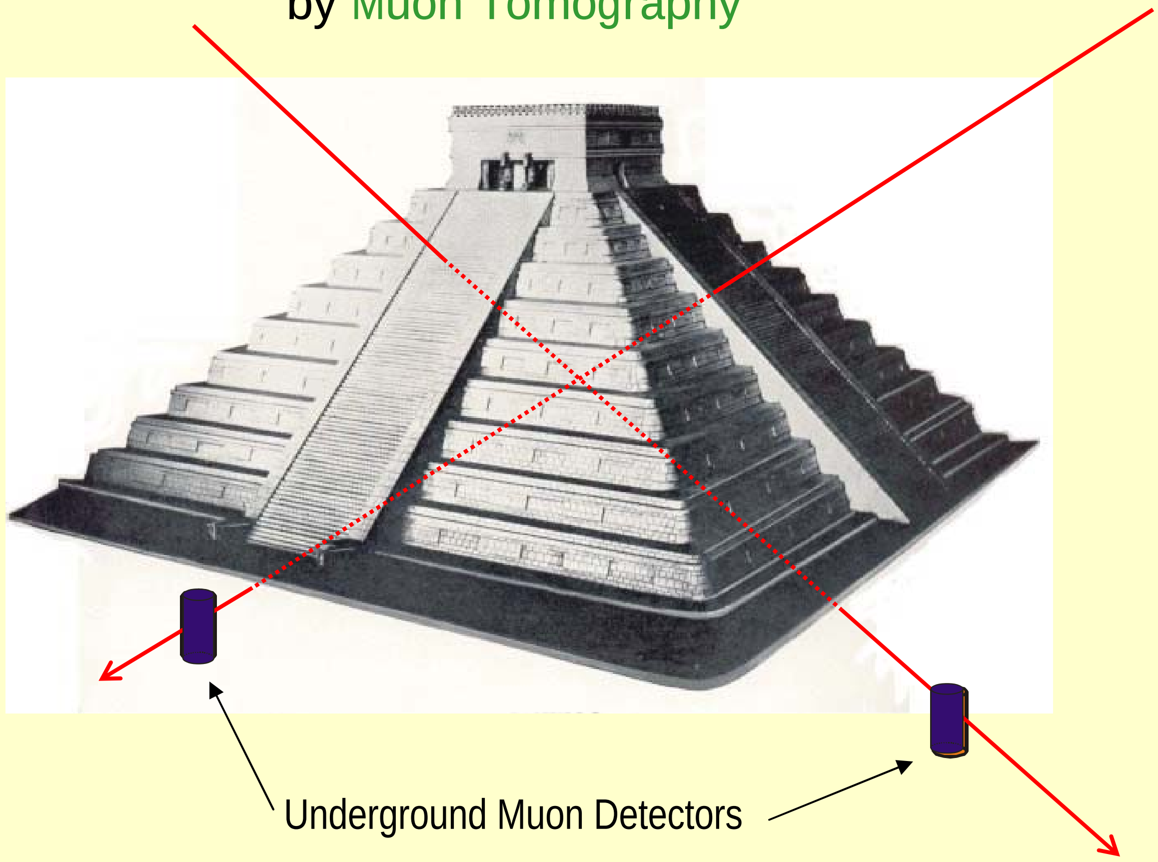
The Maya:
Extraordinary American Culture

Some Background

- 1839-*ff*: John Lloyd Stephens with Frederick Catherwood, artist
  - *Incidents of Travel in Central America, Chiapas, and Yucatan* (1841)
  - *Incidents of Travel in Yucatan* (1843)
- Linda Schele (1942 – 1998) UT Austin
  - *The Code of Kings* (1998) with Peter Mathews

What is the internal structure?

Measure Spatial Distribution of Material *Inside*
by Muon Tomography



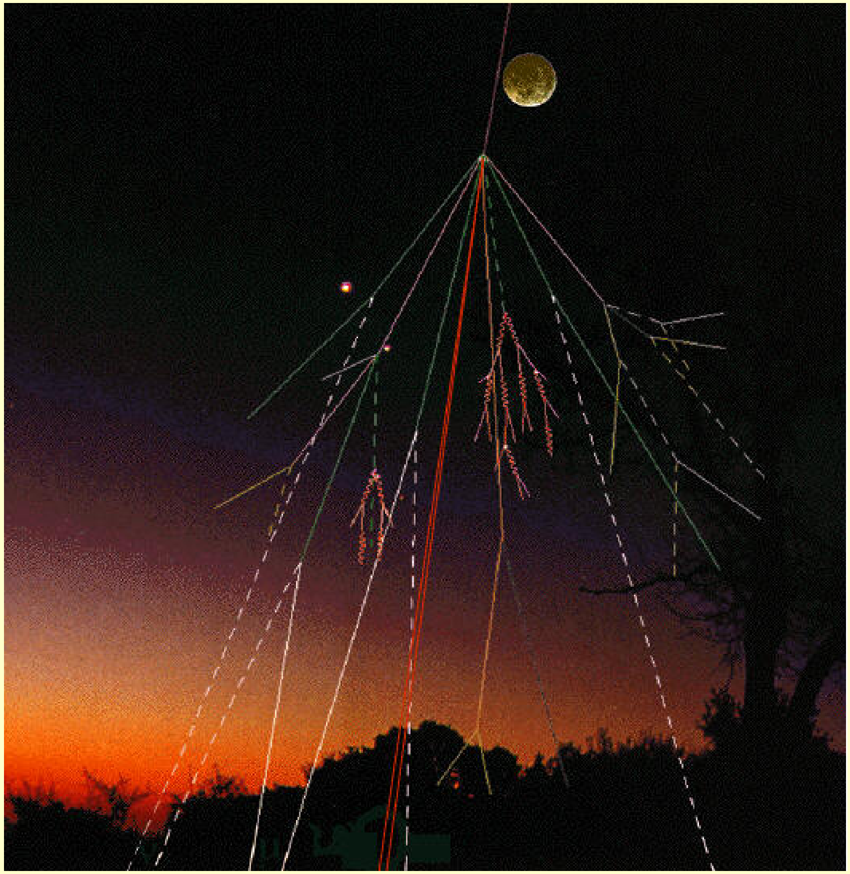
This is Proven Technology

- Luis Alvarez* invented muon tomography in 1960's to study the 2nd Pyramid of Chephren
- Spark chambers used to track muons from Belzoni Chamber
- System worked well—could see structures of caps
- Main discovery: *No* other chambers exist

* L.W. Alvarez, *et al*, *Search for Hidden Chambers in the Pyramids Using Cosmic Rays*, Science **167**, 832-839, 1970.

Cosmic Rays

- Very high energy “primary” cosmic rays – typically protons – interact in upper atmosphere
- Shower of unstable sub-nuclear particles created: typically pions, kaons
- Muons and neutrinos are decay products of pions and kaons



Muon Interactions in Matter

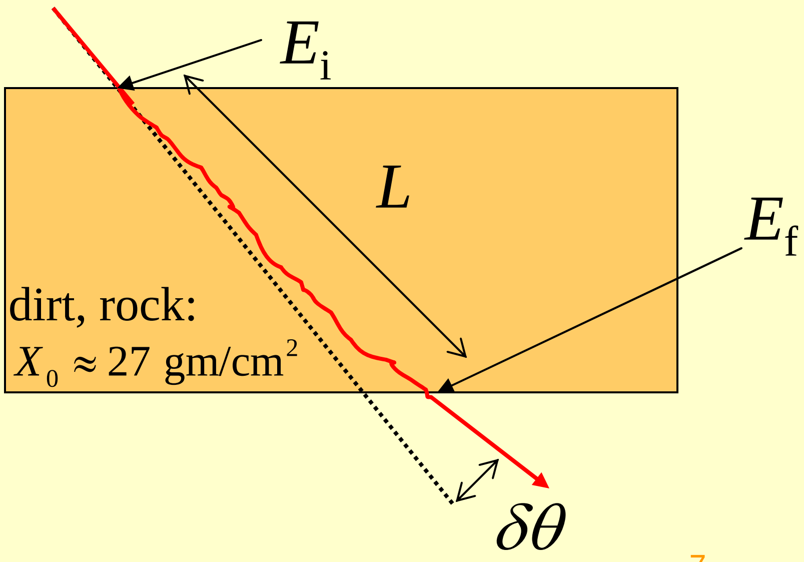
- Energy loss: predominately by ionization

$$\frac{dE}{dx} \approx 2.3\ \text{MeV/gm/cm}^2 \approx 0.6\ \text{GeV/m in rock}$$

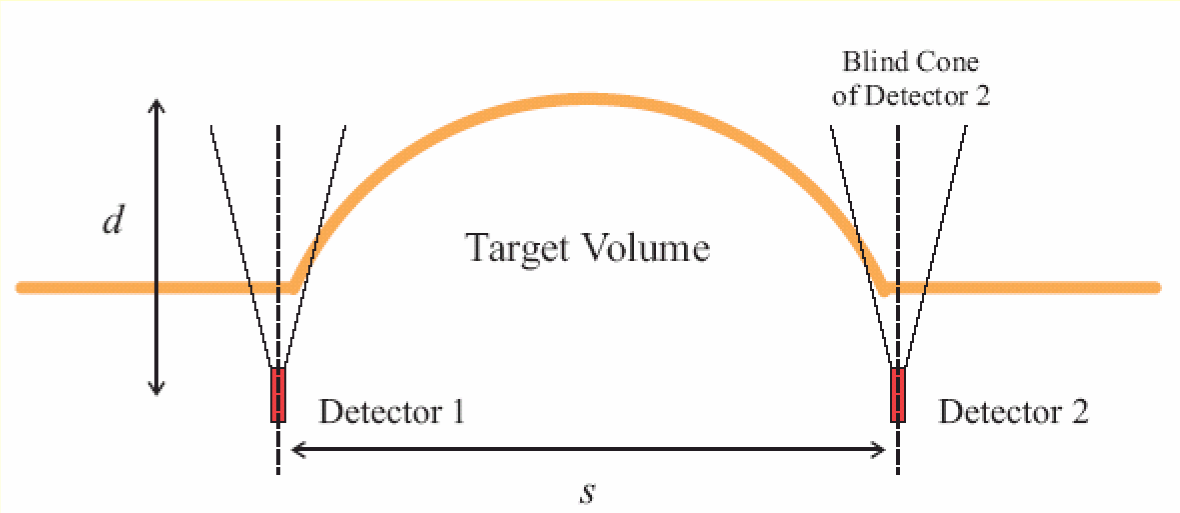
- Multiple-Coulomb Scattering

$$\delta\theta \approx \frac{13.6\ \text{MeV}}{\sqrt{E_\text{i} E_\text{f}}} \sqrt{\frac{L}{X_0}}$$

$$E_i - E_f \approx L\frac{dE}{dx}$$



Arrangement Involving Cylindrical Detectors



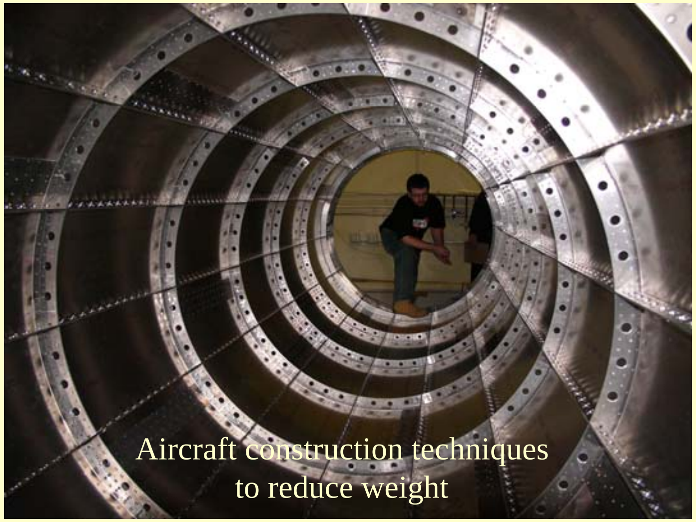
- Use 2 or more detectors
  - Compensates for "blind cone" inherent in cylindrical detectors
  - Improved stereo sampling of target volume
  - Symmetry of cylindrical detectors good for measuring "average" image
- Minimizes excavation

Detectors

- Cylindrical structure
  - 1.5 m diameter
  - 4.5 m long
- Muon tracking
  - 3 stereo layers
  - WLS-scintillator technology
  - PMT readout
- Threshold energy selection
  - Use inner volume as a Cherenkov radiator
  - PMT readout
- Other systems
  - Electronics
  - Mechanical
  - Power/communications

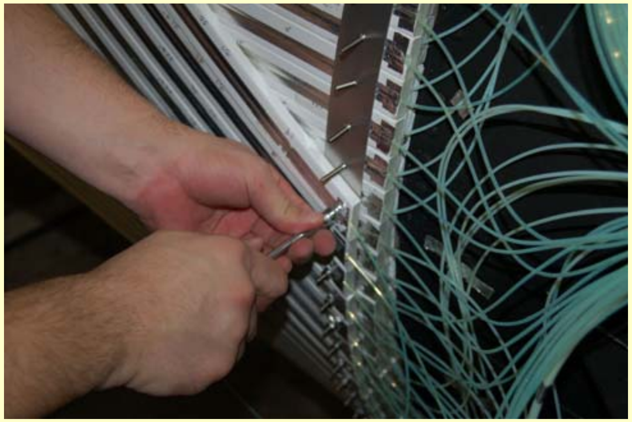
Frame


Completed frame during lay-up of scintillator strips


Aircraft construction techniques to reduce weight


PMTs and electronics will be mounted in end-rings

Tracking System Elements

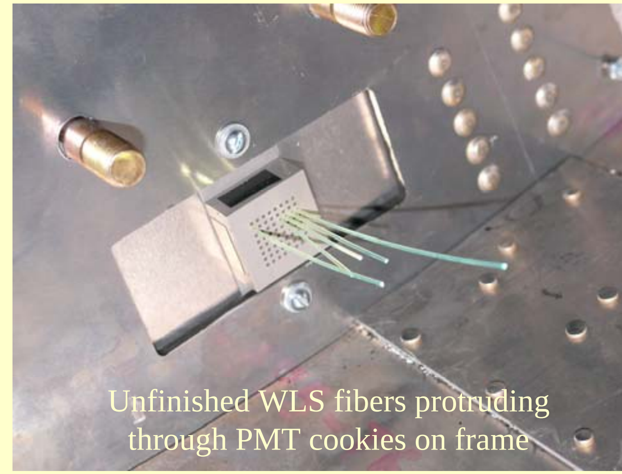


"MINOS" scintillator
- 30 mm wide
- 10 mm thick

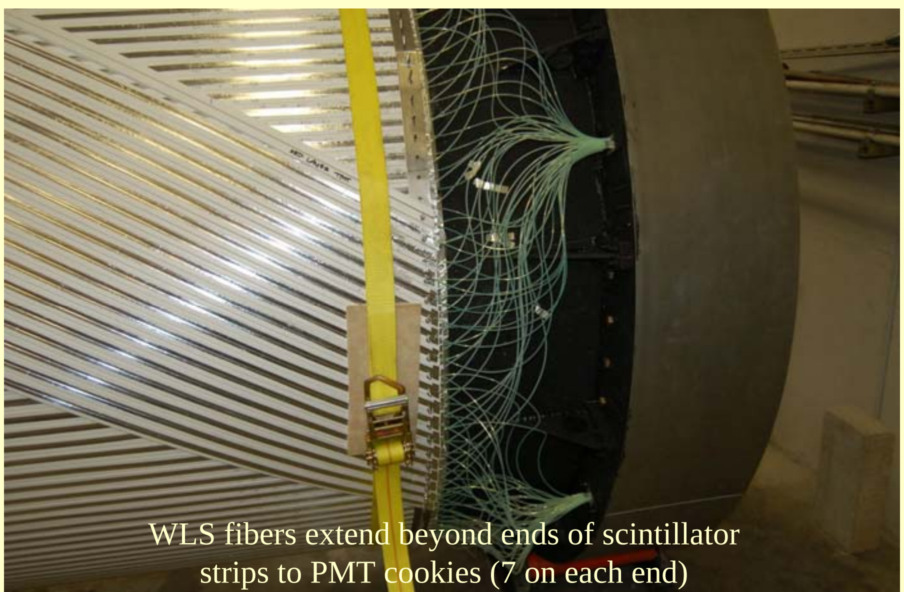
WLS fiber readout

2 helical layers
1 axial layer (center)

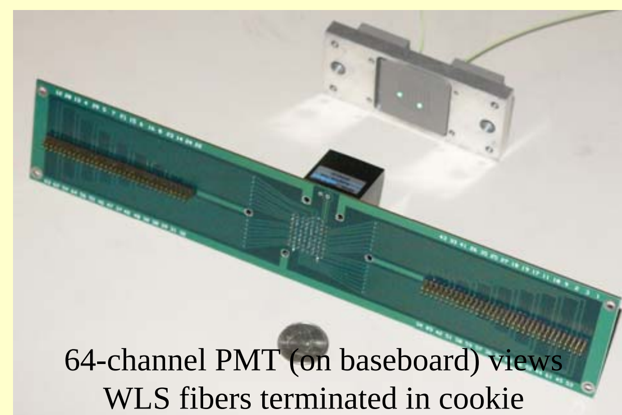
441 total strips



Unfinished WLS fibers protruding through PMT cookies on frame

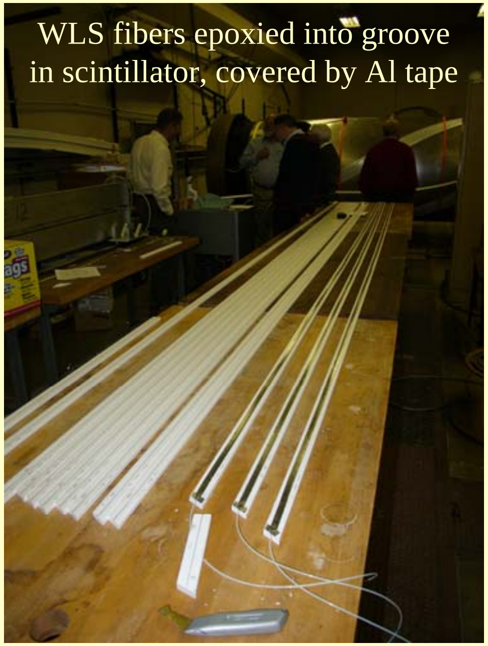


WLS fibers extend beyond ends of scintillator strips to PMT cookies (7 on each end)



64-channel PMT (on baseboard) views WLS fibers terminated in cookie

Scintillator Installation


WLS fibers epoxied into groove in scintillator, covered by Al tape


Helical wrap applied with twist; temporary straps tensioned


1^{st} end of strip secured with machine screw, temporary straps applied

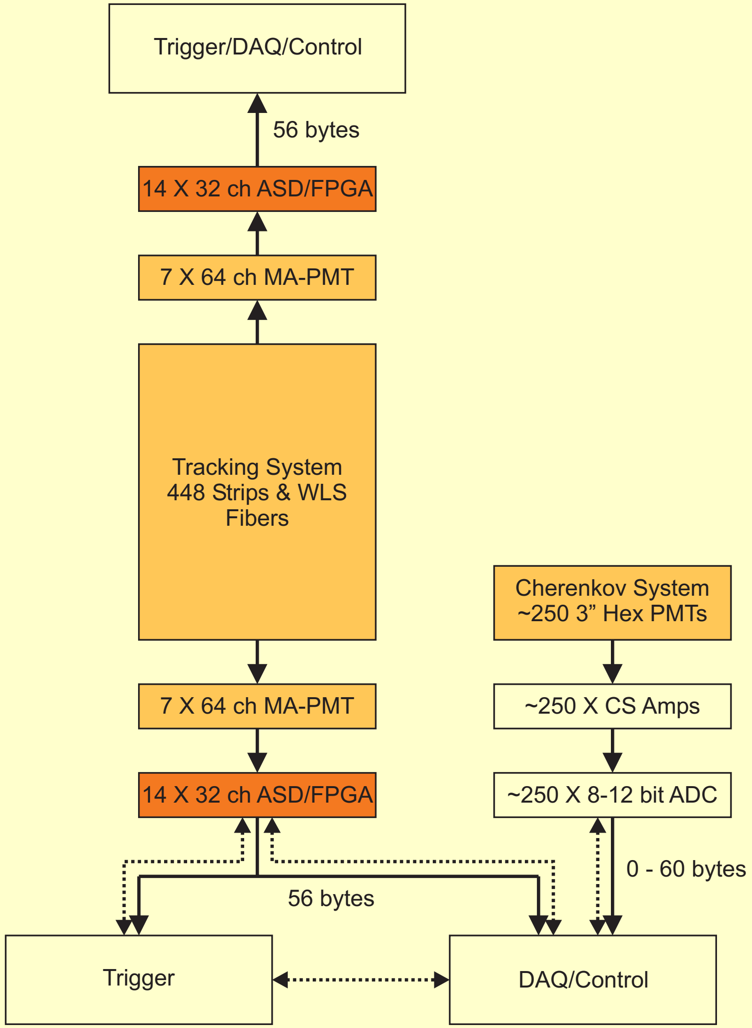

Strip attached along full length with double-sided adhesive tape


Secure 2^{nd} end of strip


Plug fiber into PMT cookie

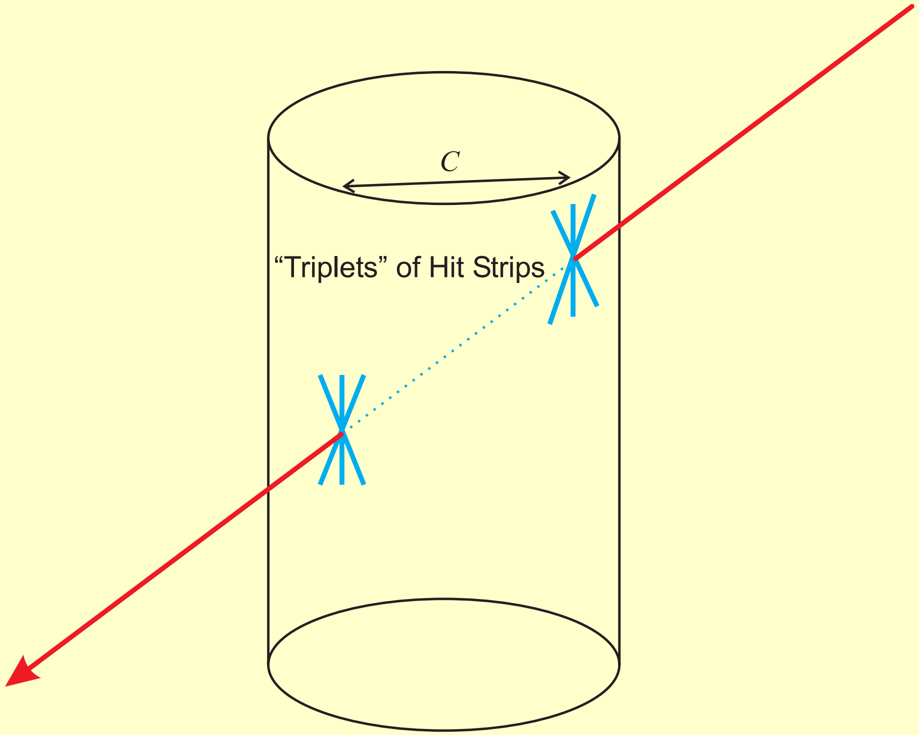
Detector Electronics Systems

- Data from detector
  - Tracking: 2X448 “hit” bits
  - Cherenkov: Analog out
- Trigger
  - Based on tracking information only
  - Programmable logic
- DAQ
  - All tracking bits
  - Cherenkov hits *above* pedestal
- Control
  - Trigger/DAQ control
  - Monitor all detector systems



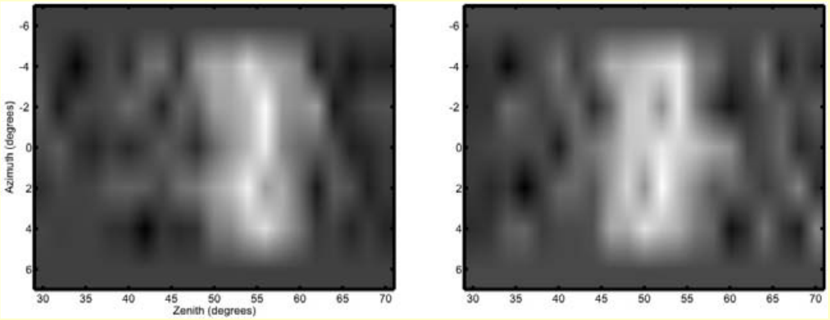
Trigger Requirements

- Use only tracking information
- Require:
  - >/= 2 Hit "Triplets"
  - Chord $c > c_{\min}$
  - Direction ?
- Flexible definition of Triplet
  - Coincidence gate: 25—50 ns
  - Number/pattern of hits to balance:
    - Noise – singles rates
    - Inefficiencies
- Typical rates:
  - True events ~ 100 Hz
  - CR singles:
    - ~ 4 KHz full detector
    - ~ 25 Hz per strip

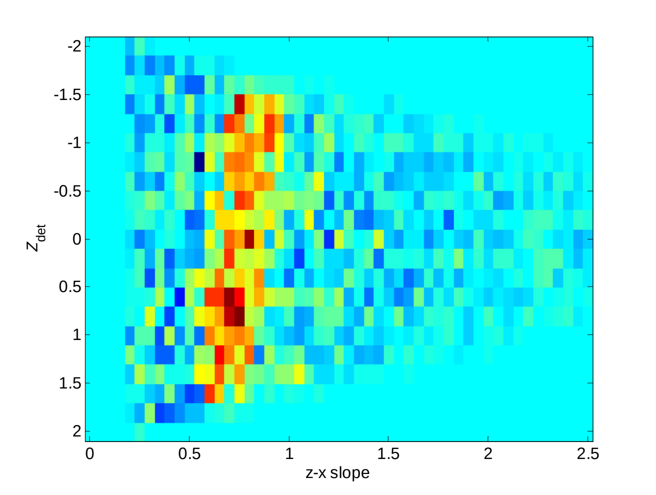


Imaging

- Have begun studies of imaging with a single detector
  - Stereo pairs of spherical projections
  - Radon transformations
- Collaboration expected with UT CS experts
- Extensive sets of tools available:
  - MATLAB
  - LabVIEW

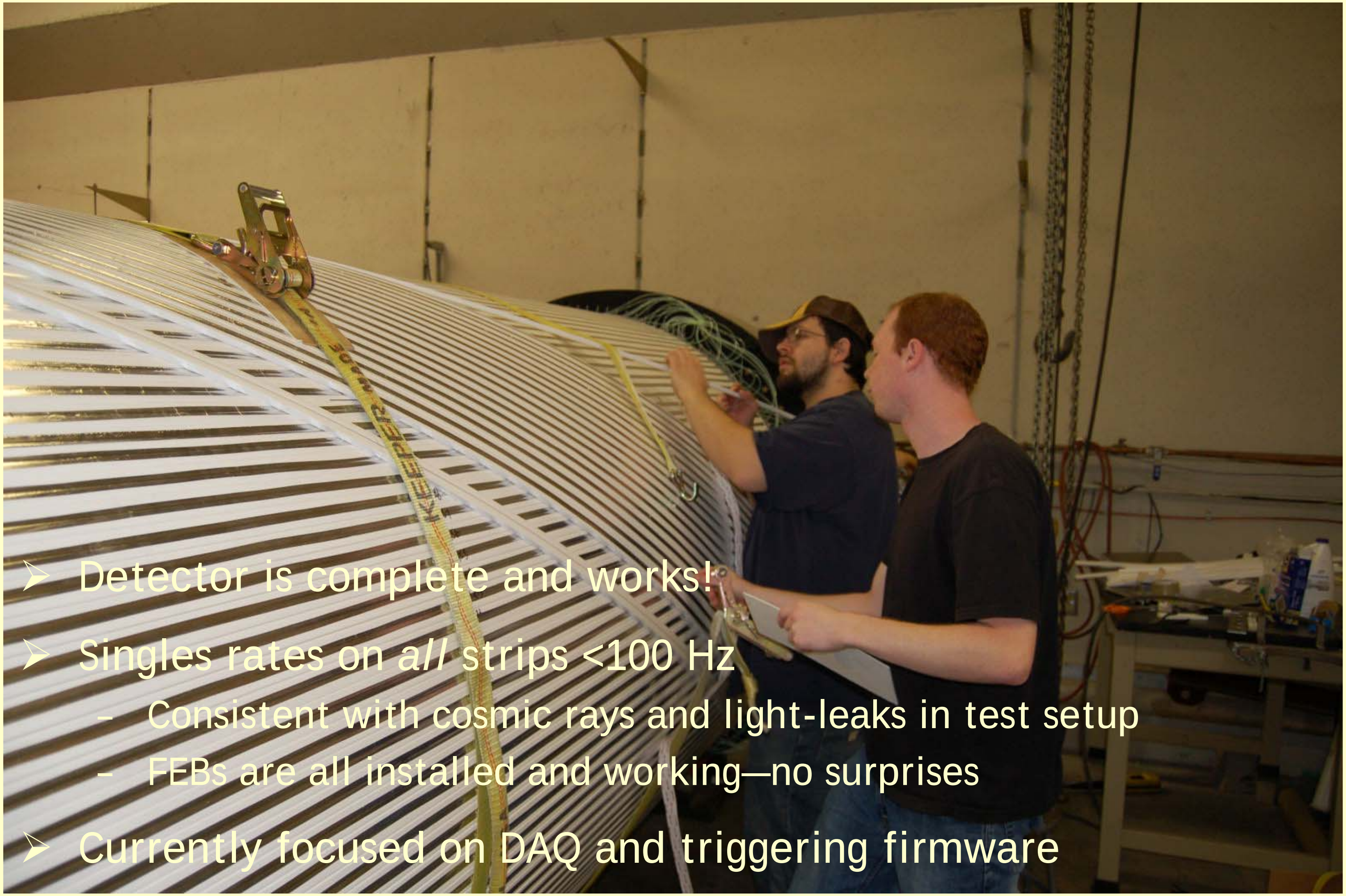


Simulated tunnel 20m distant in one week of running



$$z_{\det,i} = z_{\text{tunnel}} - x_{\text{tunnel}} \left(\frac{p_{z,\det}}{p_{x,\det}} \right)_i$$

This is Also Real

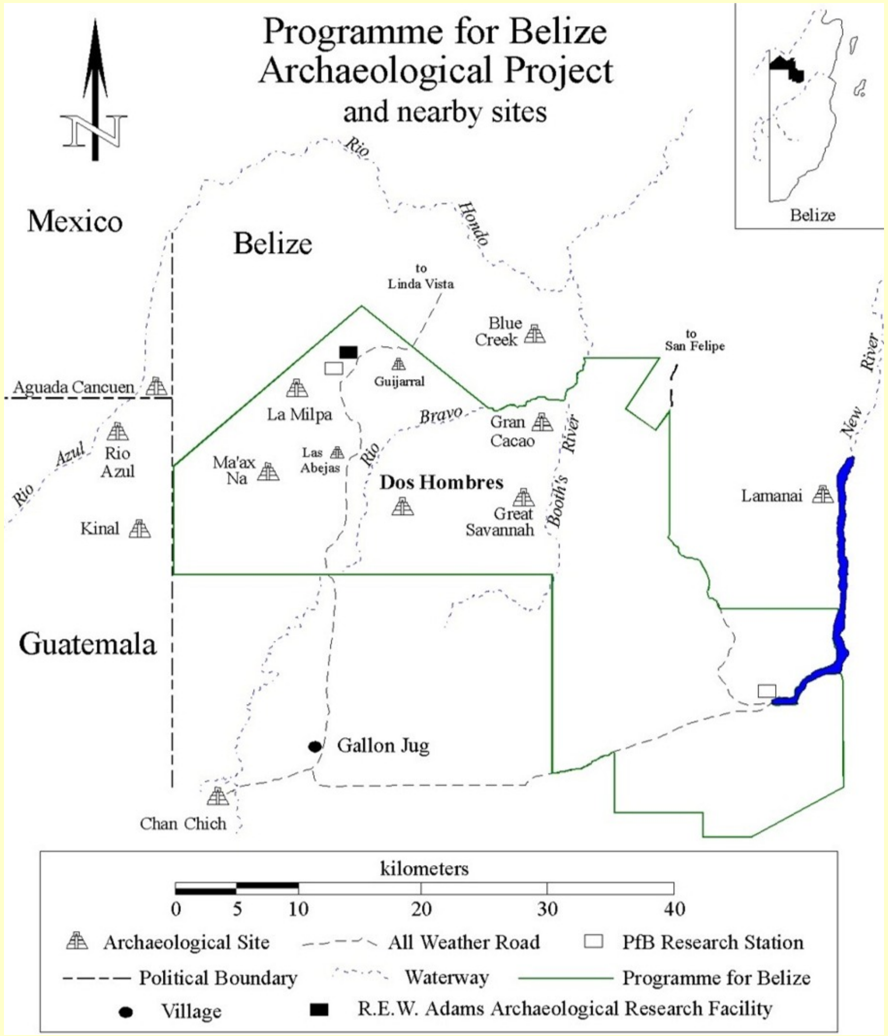


- Detector is complete and works!
- Singles rates on *all* strips <100 Hz
  - Consistent with cosmic rays and light-leaks in test setup
  - FEBs are all installed and working—no surprises
- Currently focused on DAQ and triggering firmware

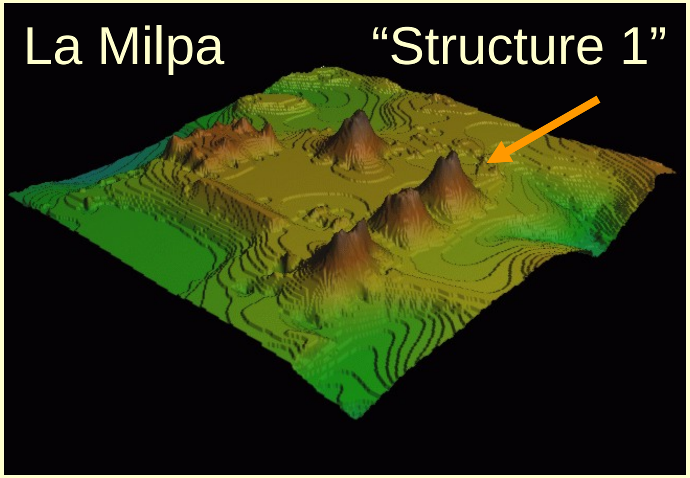
People & Things

- UT Physics
  - Jared Bennatt, Mark Cartwright
  - Brian Drell, JJ Hermes
  - Becket Hui, Jeremy Johnson
  - K. Krishnakumar, Nicholas Raspino
  - Cesar Rodriquez, Anandi Salinas
  - Mark Selover, Derrick Tucker
  - Brad Wray, Eric Wright
  - H. Adam Stevens
  - Austin Gleeson, RFS
- UT Electrical & Computer Eng.
  - Bill Bard, Lizy John
  - Carlos Villarreal
  - Elizabeth Van Ruitenbeek
  - Daniel Garcia, Nakul Narayan
- National Instruments
  - Hugo Andrade, Joe Peck
- Fermilab—Scintillator Production
  - Anna Pla-Dalmau
- Harvard HEPL—Front-end Electronics
  - John Oliver, Sarah Harder
- Other physicists who contributed in the early stages
  - Prof. Rich Muller, UC Berkeley
  - Dr. Dick Mischke, LANL
- UT Mesoamerican Archaeological Research Laboratory (MARL)
  - Prof. Fred Valdez, Director

UT Mesoamerican Archaeological Research Laboratory



Potential Target Structure



- La Milpa site has relatively good access/infrastructure
- Developing simulation tools to optimize detector design and placement
- Plan excavations for deployment

Other Potential Applications

- Muon Tomography is good for monitoring large underground volumes (~100 m)^3, provided:
  - You are interested in structures of scale 1 m – 10 m
  - You can afford to wait for weeks to months to acquire the data
  - The volume of interest is between your detector and the surface
- Geological studies of aquifers
  - Shapes of underground cavities
  - Time-dependence of water levels
- Monitoring of geology surrounding underground sites, e.g. underground nuclear waste storage

Summary

- Muon tomography is feasible
  - Proven in Alvarez experiment
  - New technologies enable simplified detector design
  - WLS/scintillator tracking well-developed/good match
  - Cherenkov threshold detector is indicated
    - New approach to problem of low-energy multiple-scattering
    - Well-understood physics/technology
    - Simplifies system design
- Excellent project for engaging students
- Other applications are possible
- Maybe we can help to learn more about the Maya!