NAUM (Non-invasive Archaeometry Using Muons)

Exploration of El Castillo pyramid using atmospheric muons.

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Sten Hansen, Edit Peronja (Fermilab)

Eduardo Pérez de Heredia (Proyecto PARME, Centro INAH Yucatán)

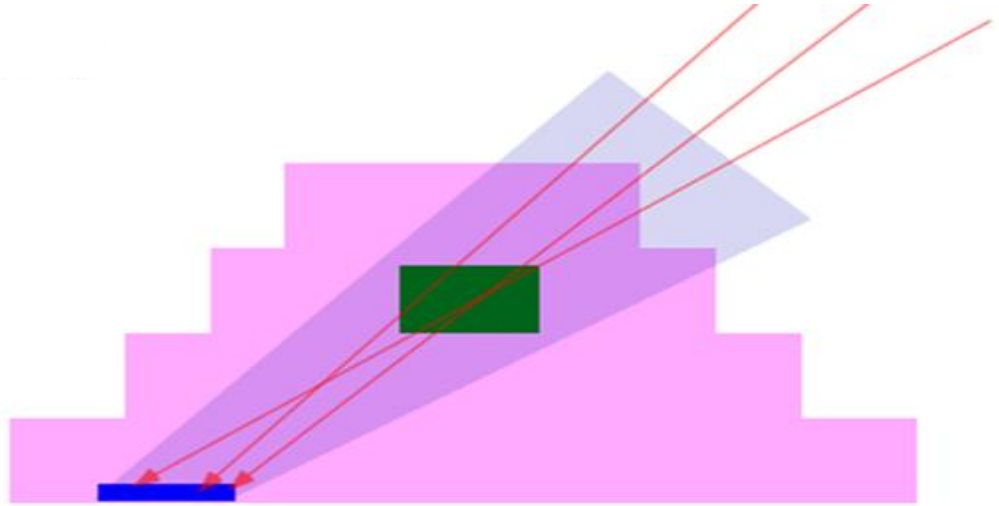
Jose Francisco Javier Osorio Leon (Instituto Nacional de Arqueologia e Historia - INAH)

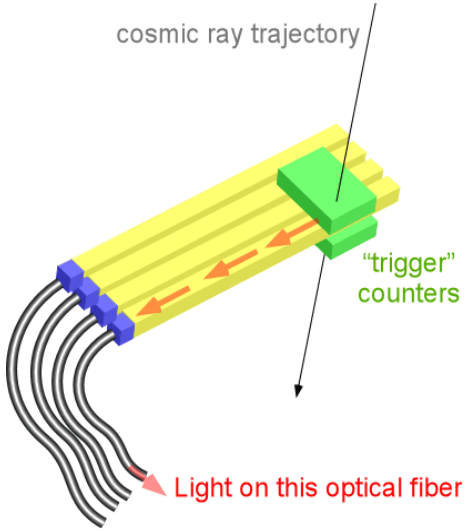
Arturo Menchaca Rocha, Hesiquio Vargas (Universidad Nacional Autnoma de Mexico - UNAM)

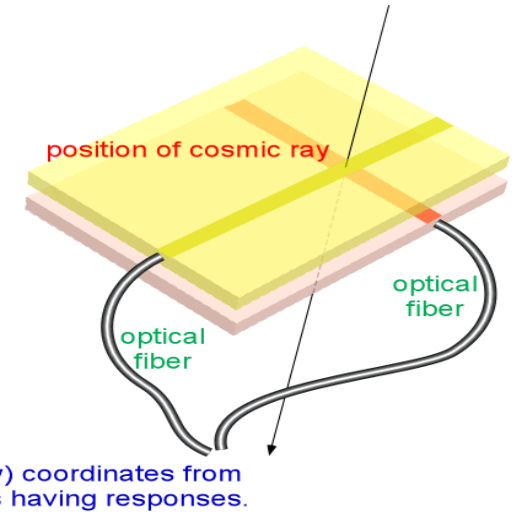
E. Craig Dukes (University of Virginia)

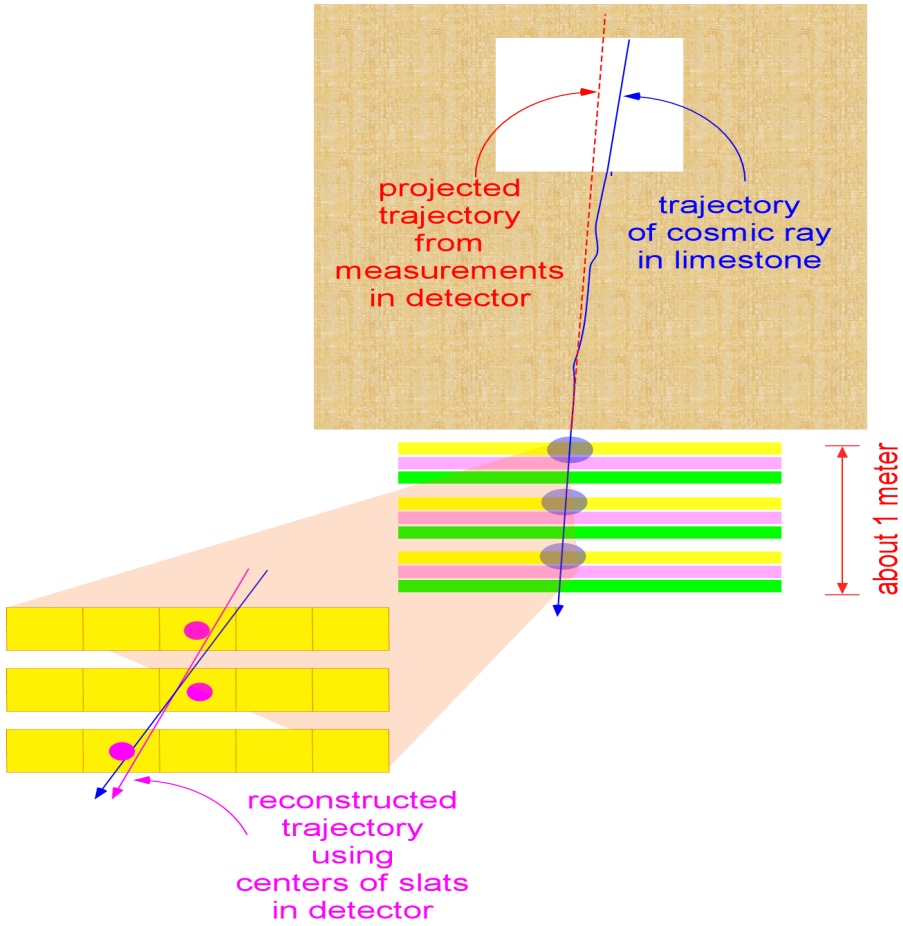
This project is supported by the National Science Foundation under awards PHY-2011339 and PHY-2011442

ATHA (A Tracker Hodoscope for Archaeometry)





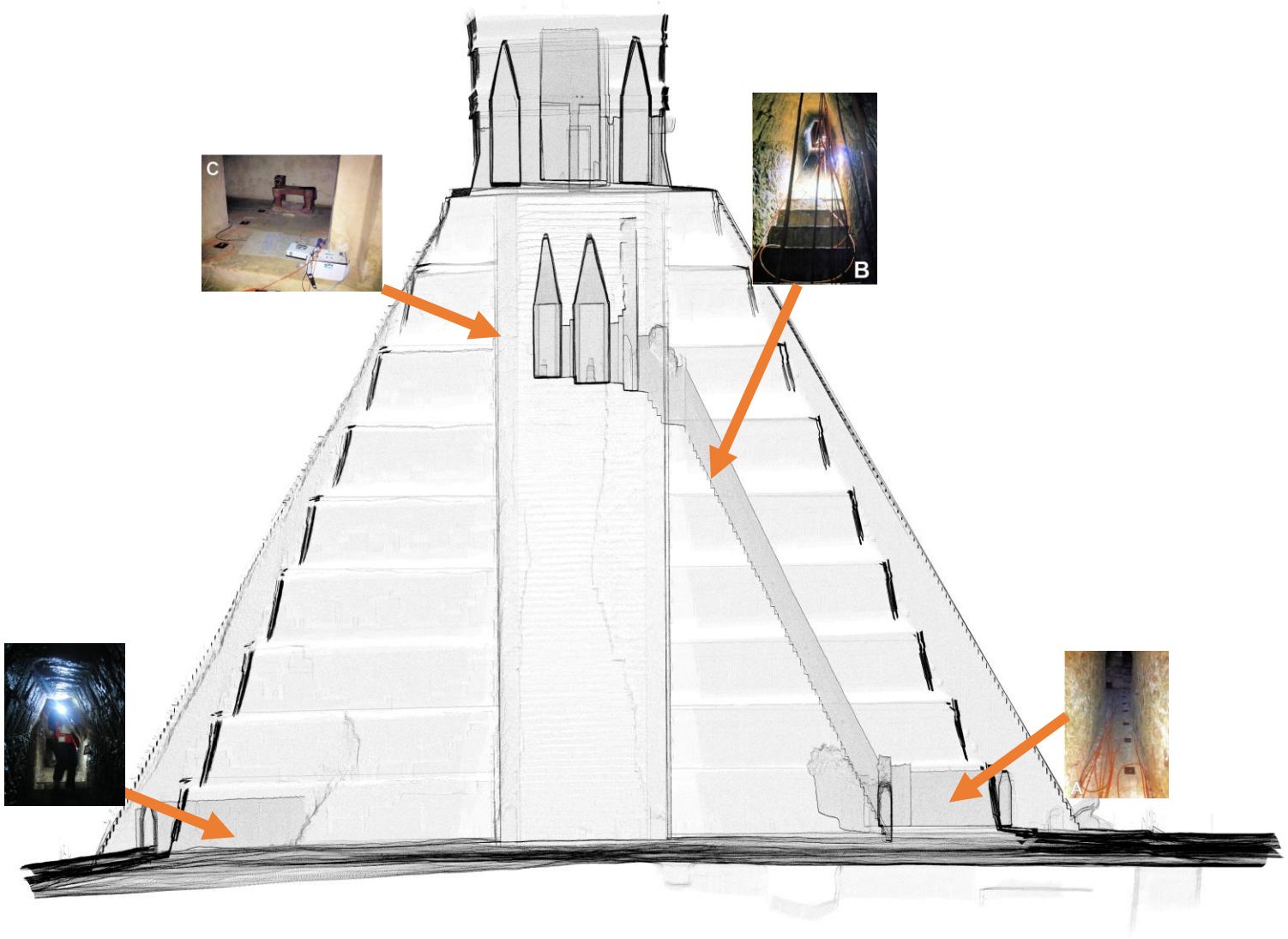


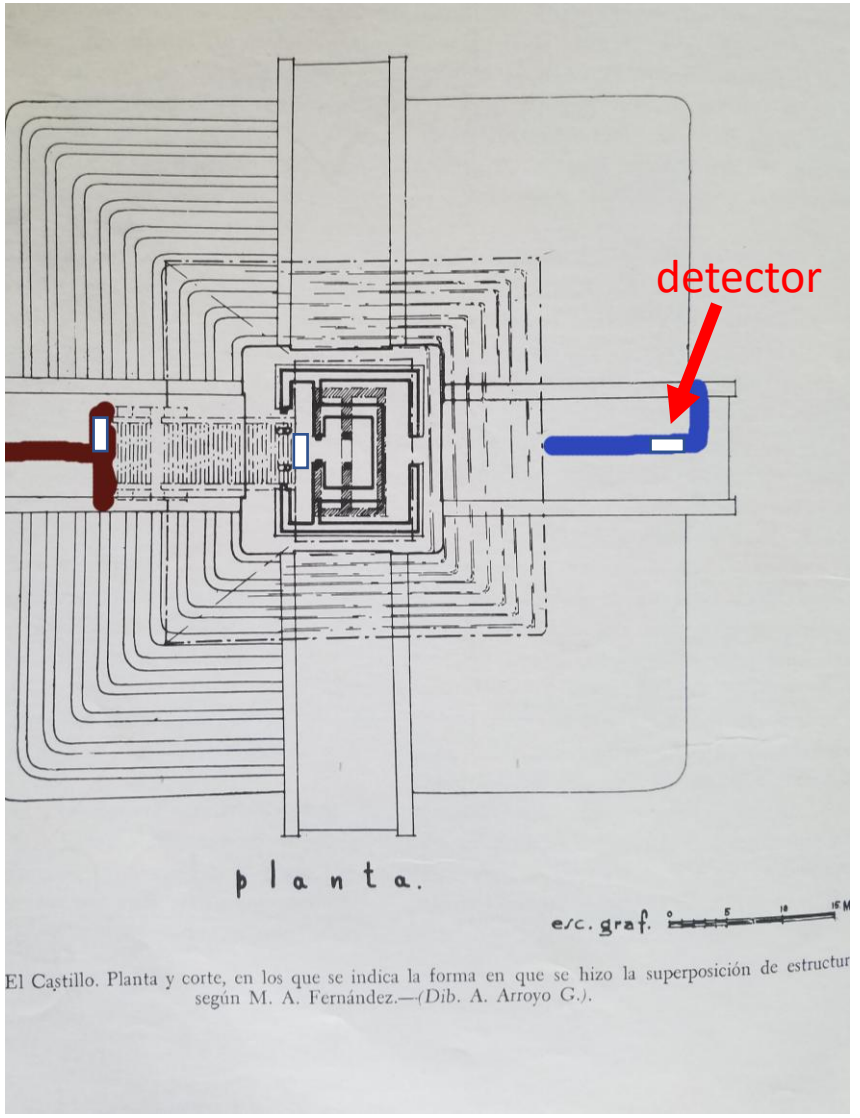


El Castillo (Kukulcan's Pyramid)

Why El Castillo pyramid?

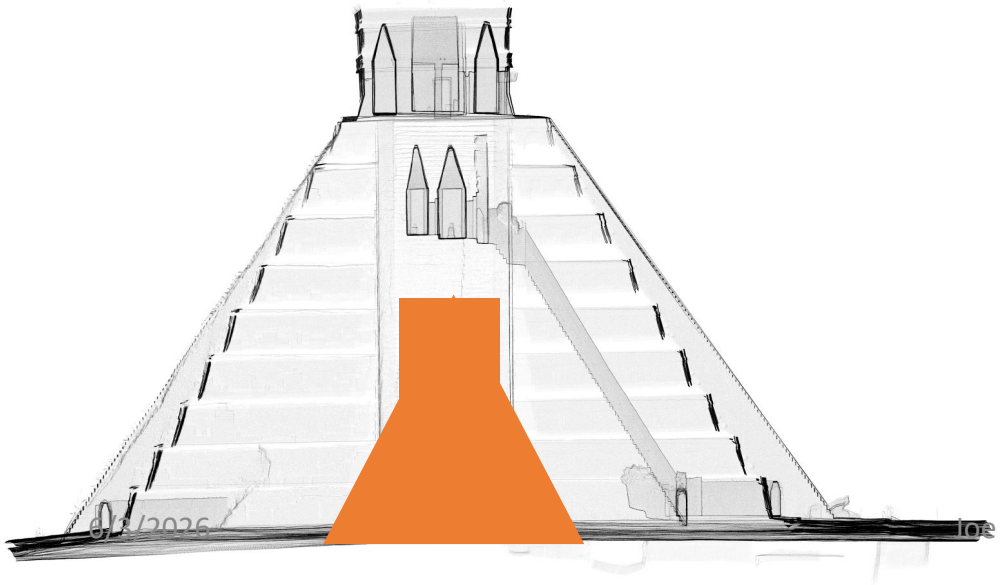
1) Known Target Substructure





2) Available tunnels where to put the detectors

3) Complimentary Studies



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'Illuminating' the interior of Kukulkan's Pyramid, Chichén Itzá, Mexico, by means of a non-conventional ERT geophysical survey

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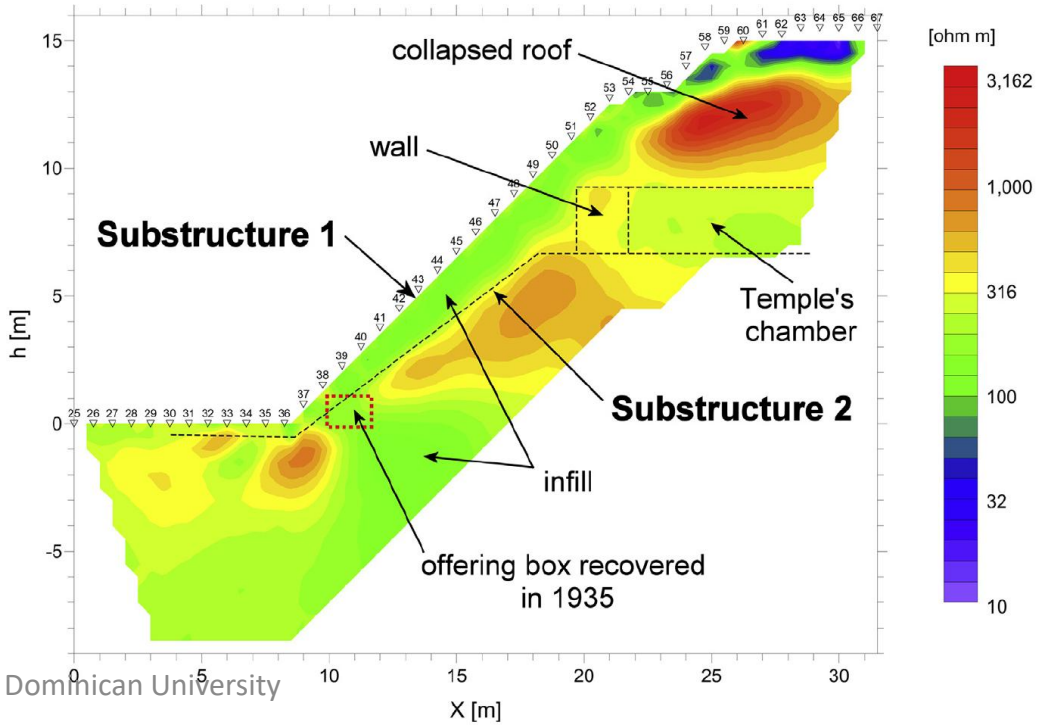
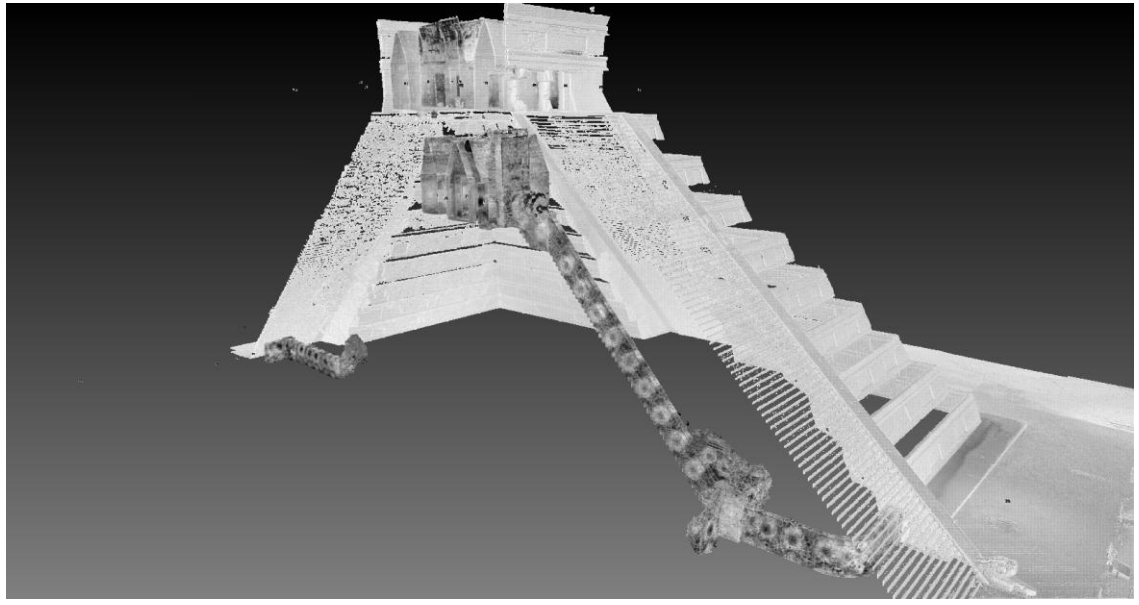
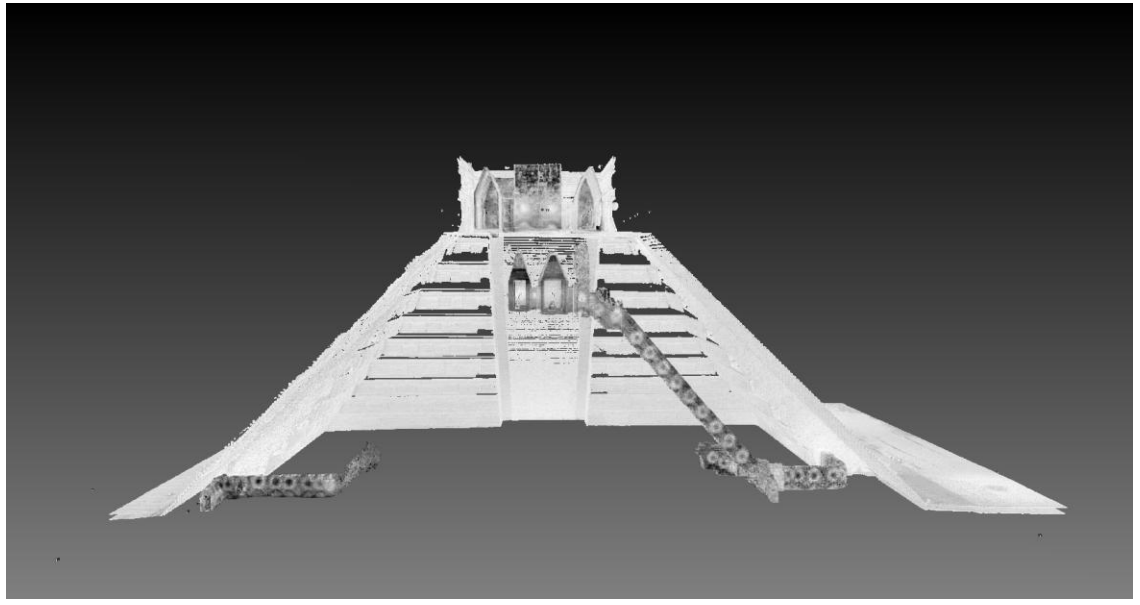


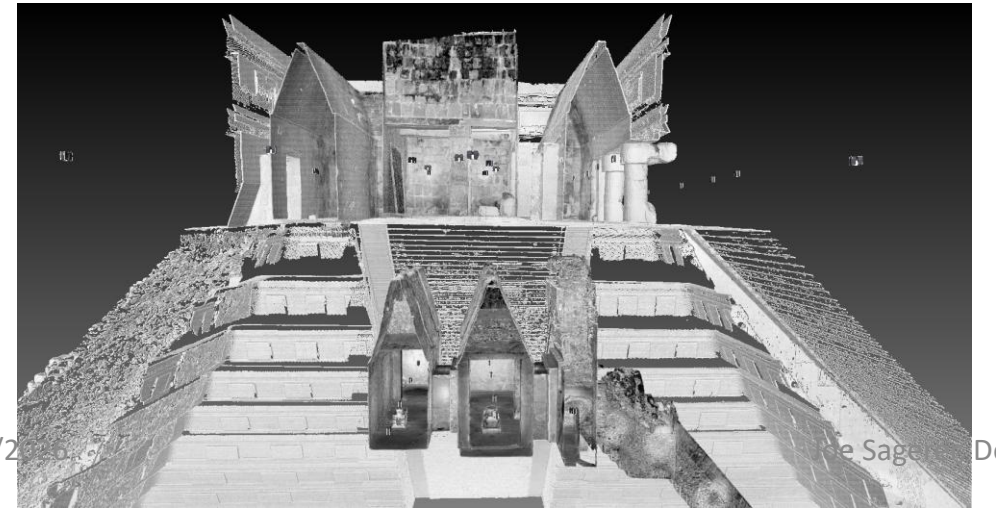
Pre detector construction field work

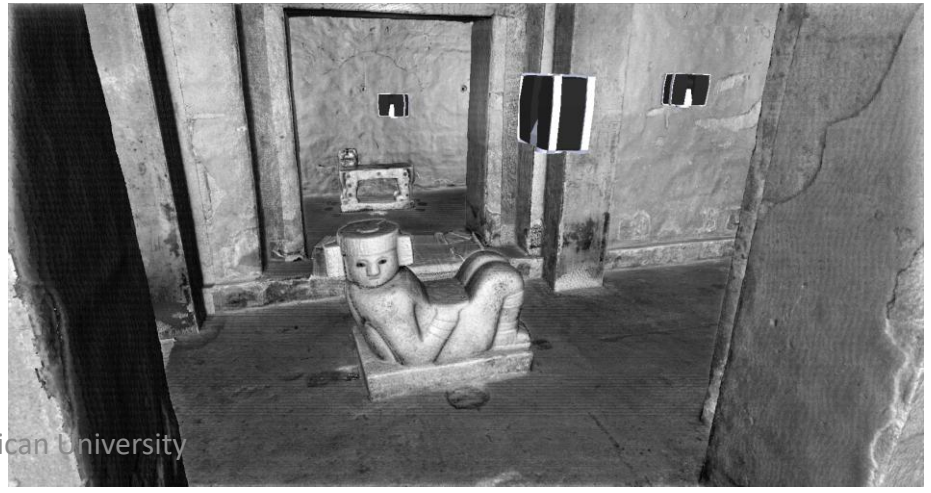
Lidar Scan

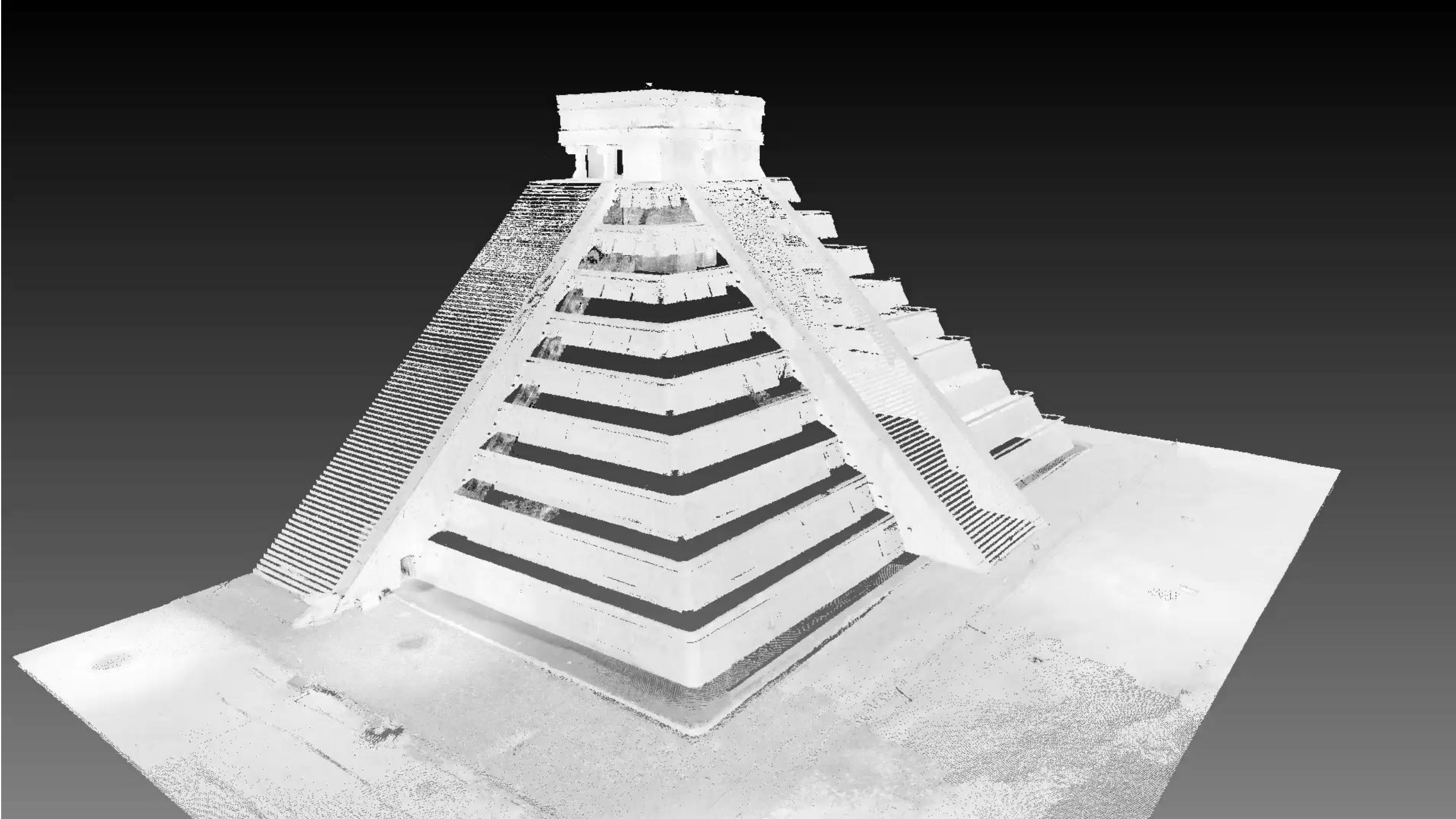
https://vimeo.com/688147844/0be25b017d



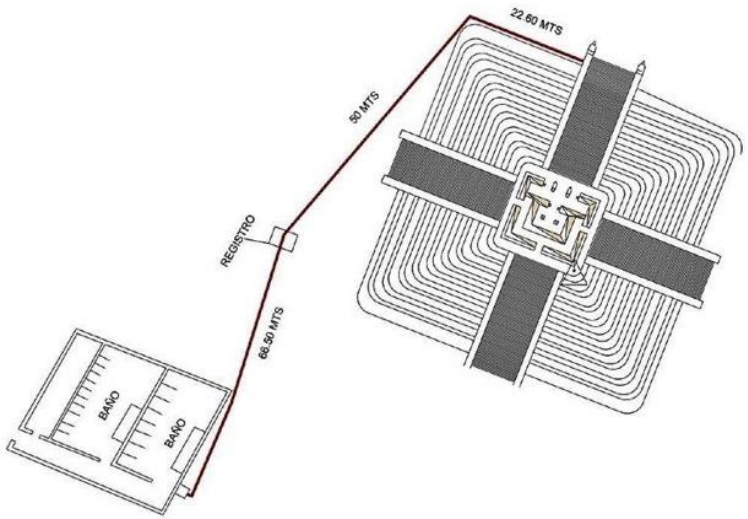


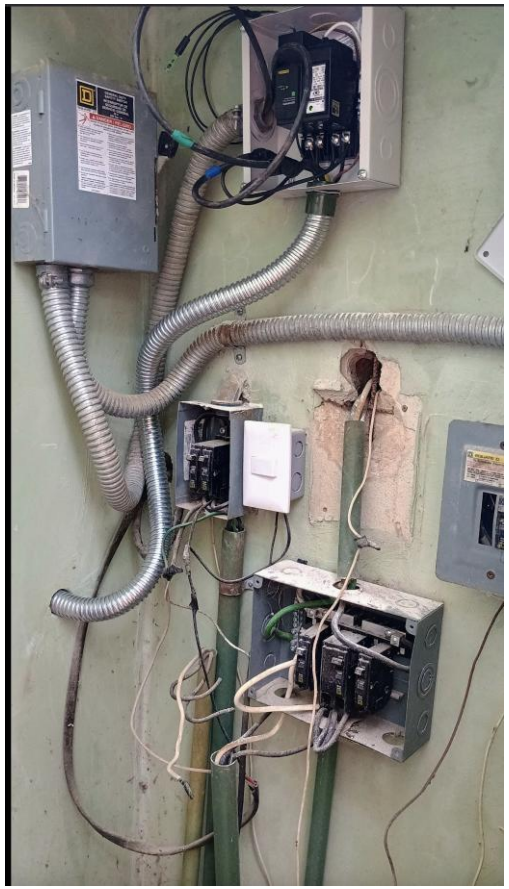






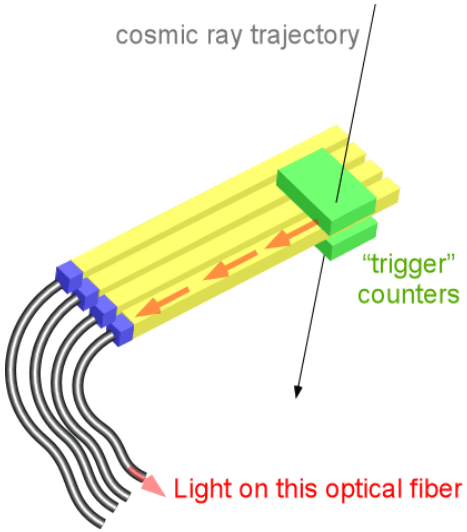
Repairing of the of electricity flow

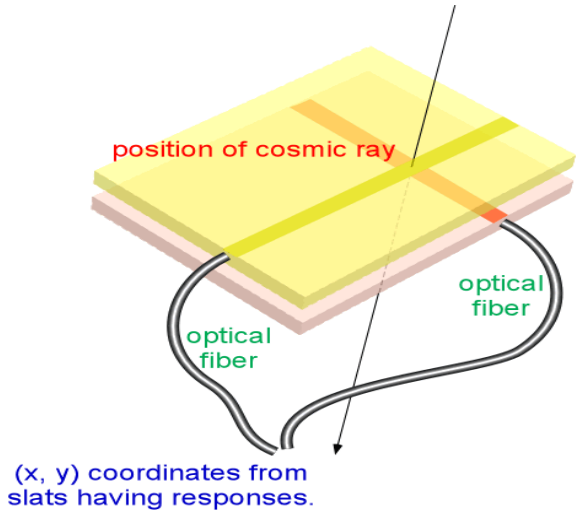




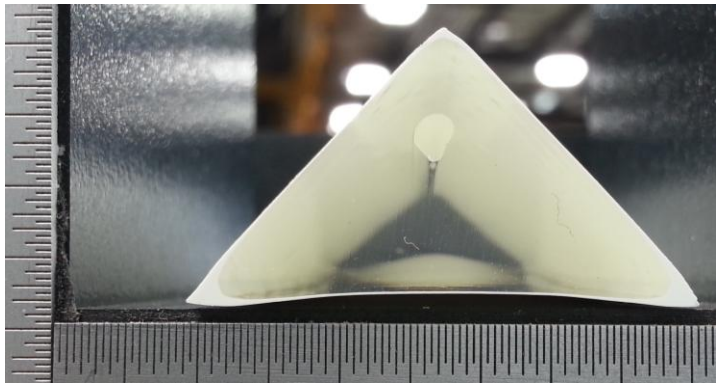
The Detector

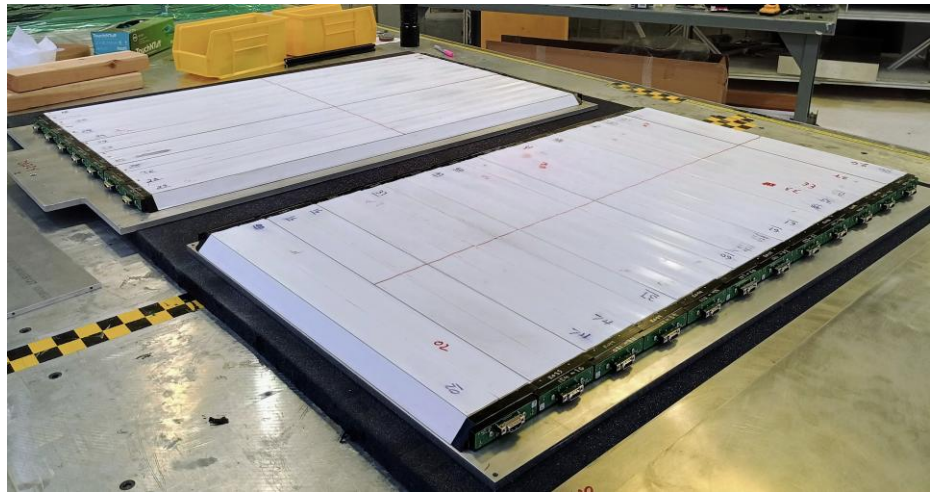
- Scintillators from (FermiLab's Lab 6)
- Fibers: BCF92, Single-Clad Round 2mm, Rough-Cut (Kuraray)
- SiPMs (Silicon Photo Multipliers – Hamamatsu)
- Readout electronics: partially based on Mu2e's CRV (Cosmic Ray Veto) detector,
  E. Craig Dukes, U of Virginia:
  - Counter Mother Board (CMBs)
- CAEN Front end Boards (FEBs)
- UNAM mechanical structures and supporting facilities (electricity)



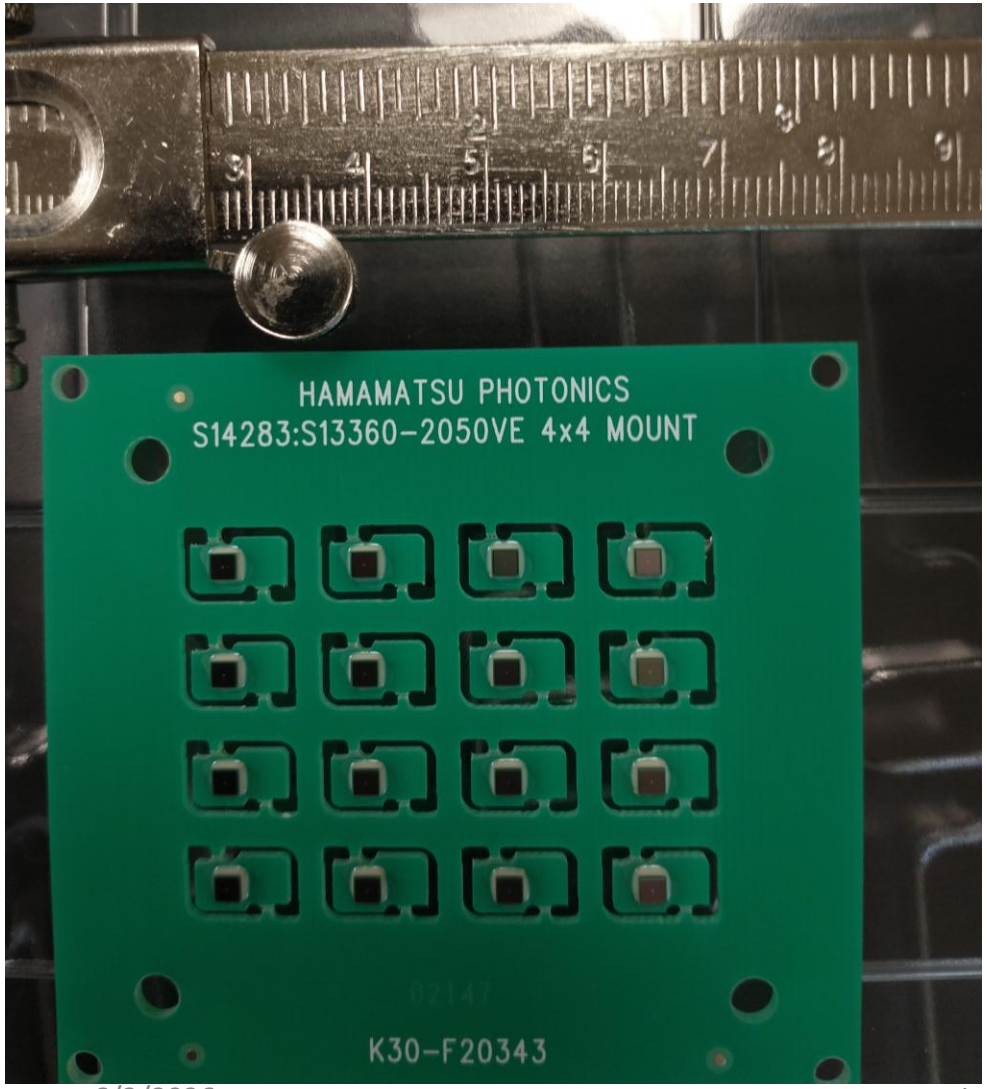


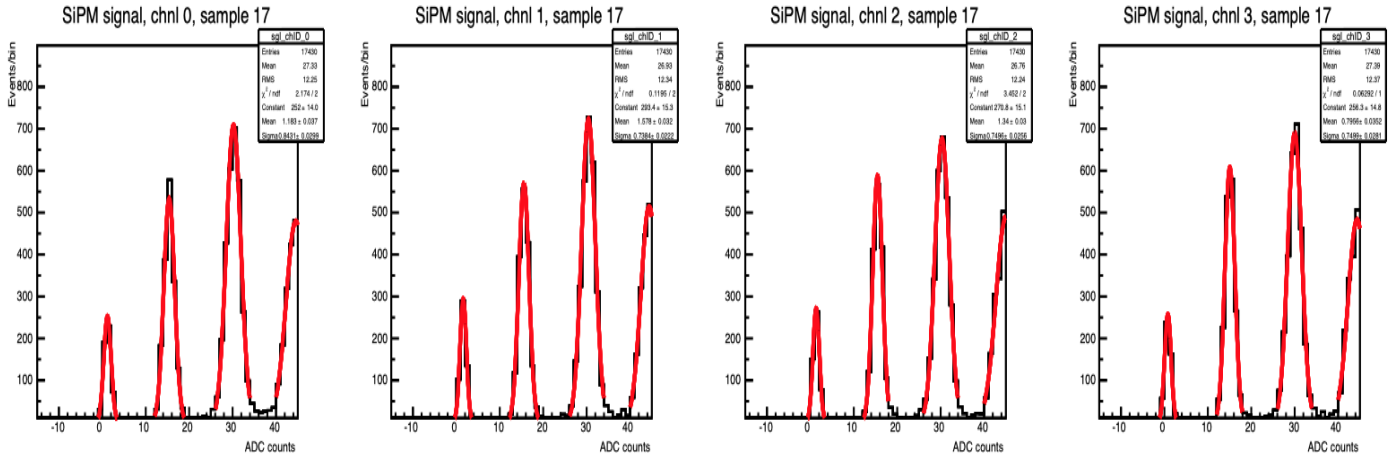
Scintillators & Fibers





SiPMs (Silicon Photo Multipliers)



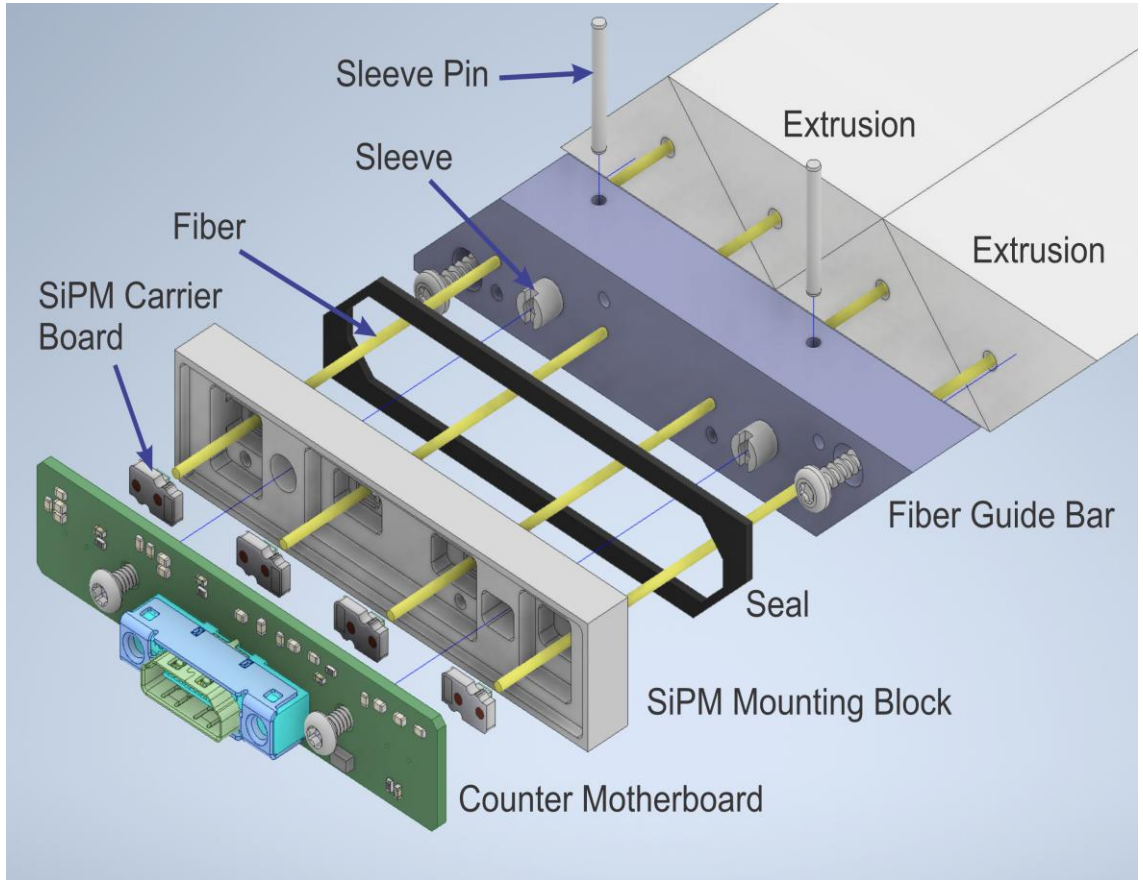


Hamamatsu MPPC S13360-2050VE

All values at 25° C at overvoltage of 2.5V:
1) 2mm x 2mm, 50 µm pixel
2) Surface-mount, TSV packaging
3) PDE > 35% (530 nm)
4) Gain ≥ 1.0×10^6
5) Pulse rise time < 5 nsec
6) Dark rate < 250 kHz @ 0.5 PE threshold
7) X-talk (inter-pixel) < 2%
8) Bias spread: ±0.5V (within batch); ±1.5V (all)
9) Temperature dependence ≤ 50 mV/°C

Tested at NIU! with help from Prof. Zutshi and Dr. Francis

CMBs (Counting Mother Boards)

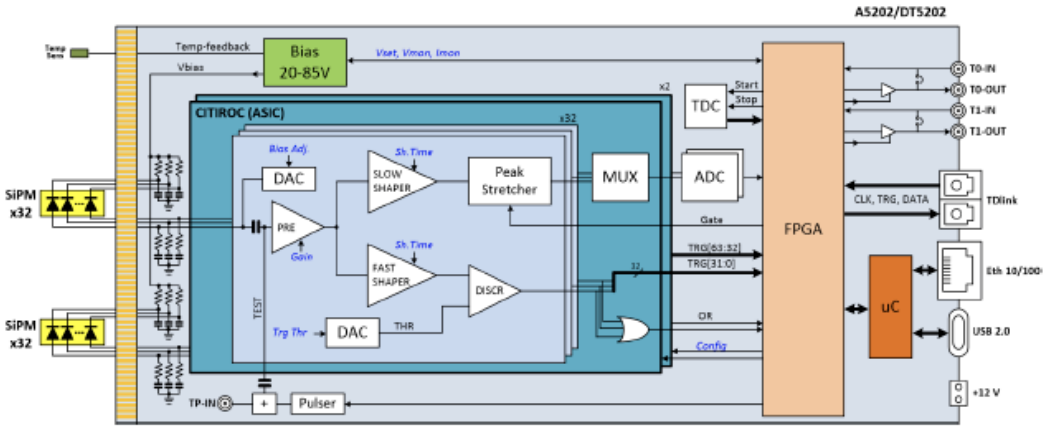


CMBs include a temperature sensor.

Front end Boards (FEB)

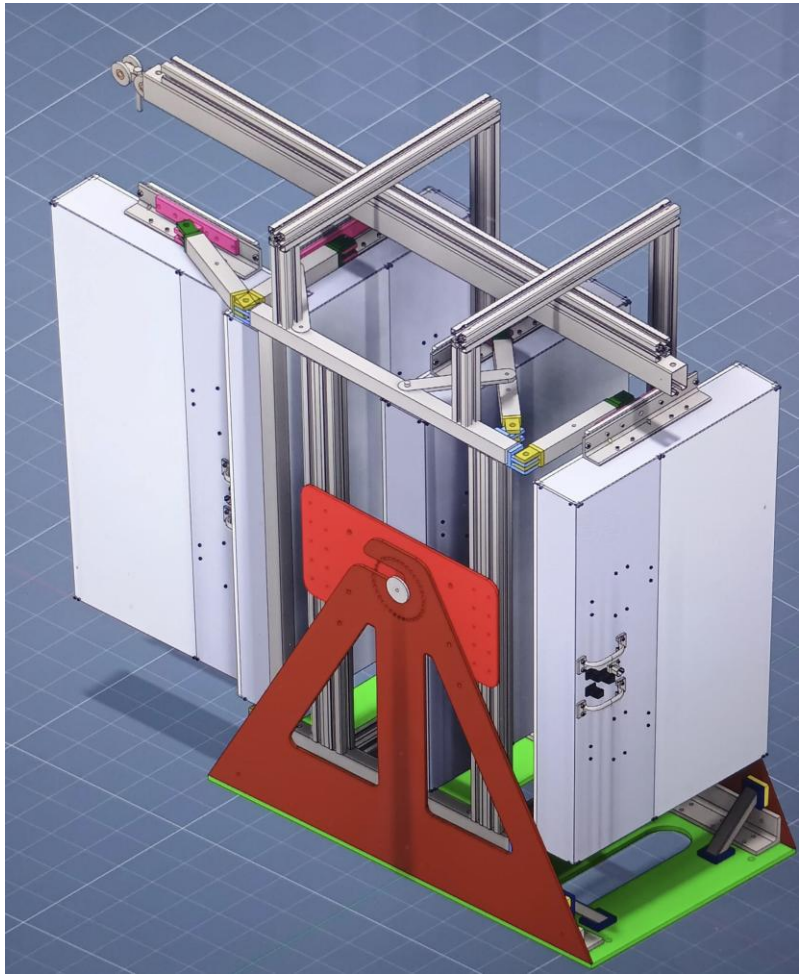
- Takes SiPM signals from 16 CMBs over HDMI cables
- Individual bias for all 28 (X) or 48 (Y) SiPMs
- Amplifies, shapes, digitizes in amplitude and time, zero suppresses, and buffers signals
- Lives (along with scintillator and SiPMs) inside of sealed aluminum boxes that act as heat sinks.
- Connected via switch to mini-computer for readout. Mini-computer lives in tunnel (100% humidity, 30° C) – considered consumable.
- Router in tunnel connects to cellular modem near entrance (right) DAQ buffers data when connection is lost…

FEB

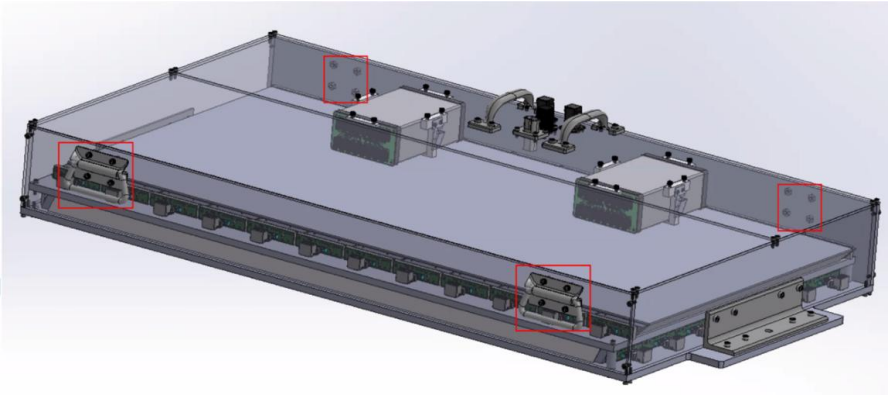


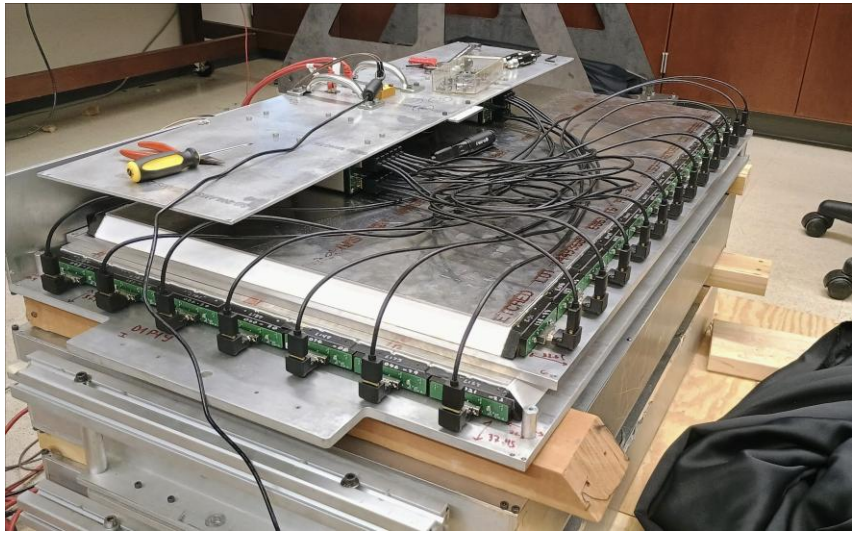
Mechanical Structures

- Allows passage through the tunnel
- Rotates around horizontal axis
- Can be setup from one side of the tunnel
- Can be assembled inside the tunnel
- Resistant to environmental conditions



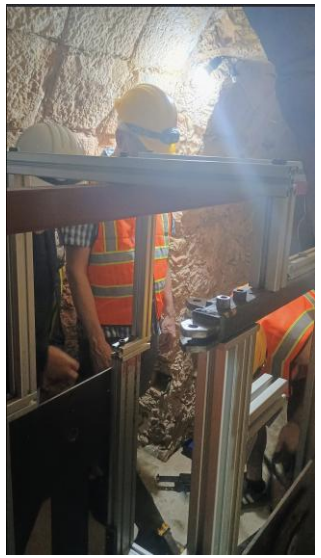
The Detector





Transporting the Detector (CSU, Chicago to UNAM, Mexico City to Chichen Itza)

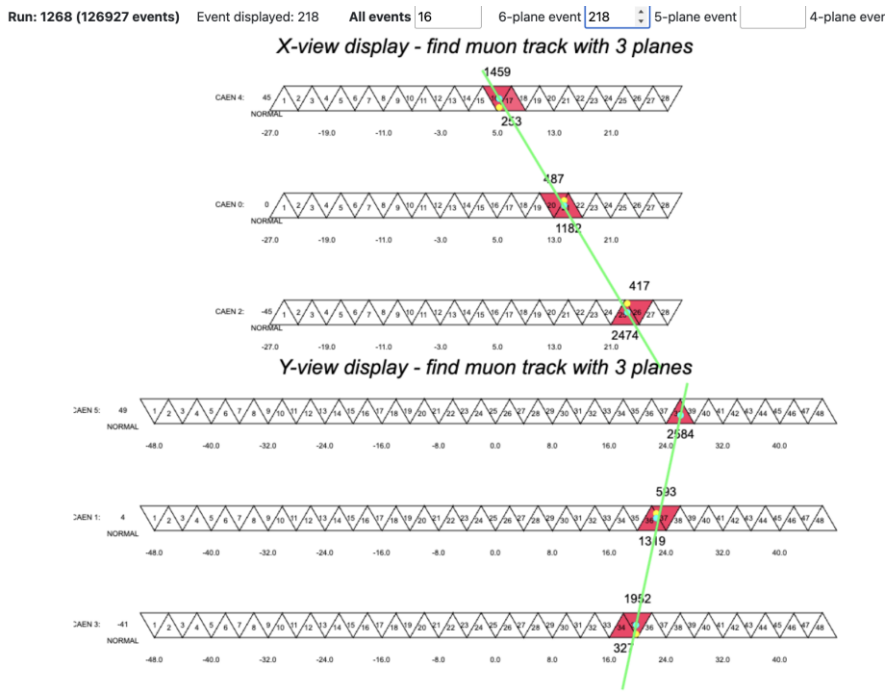
Installation of the Detector

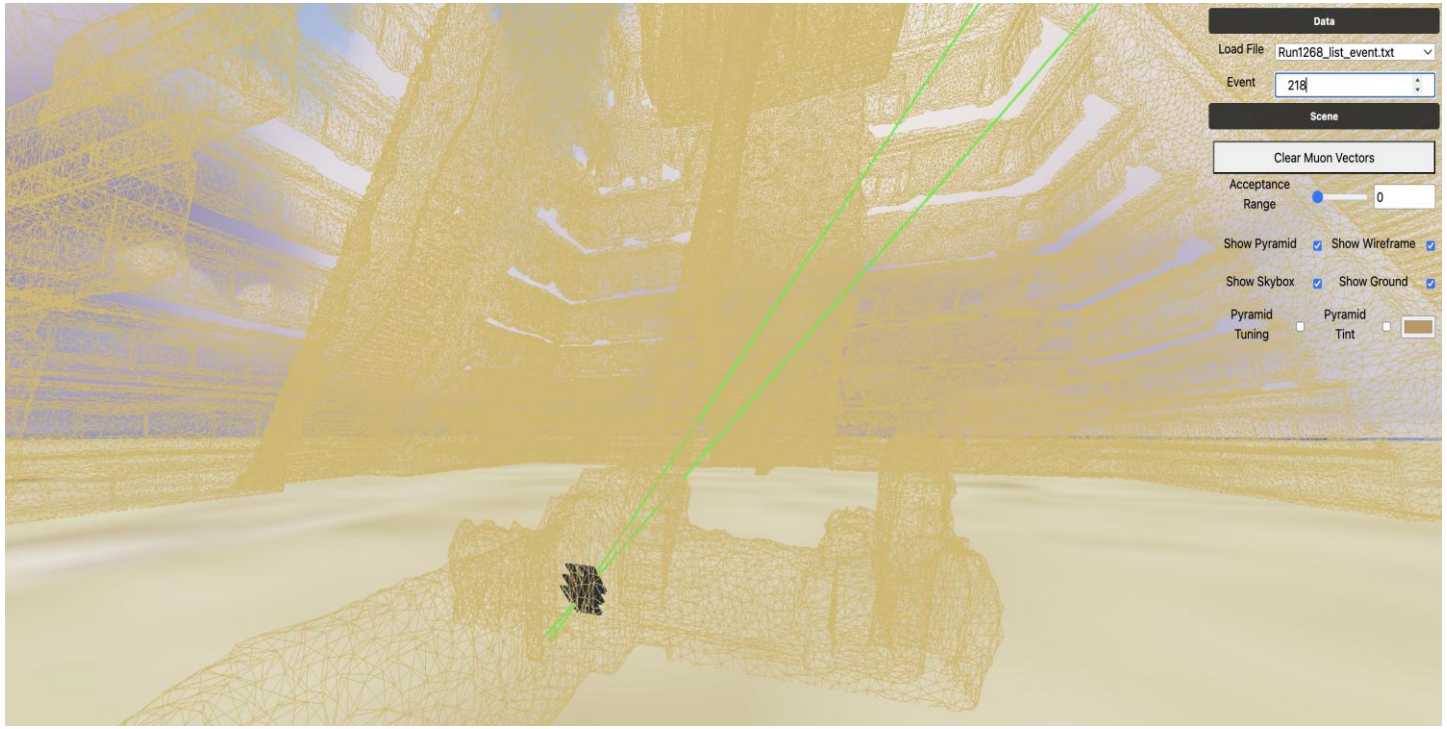


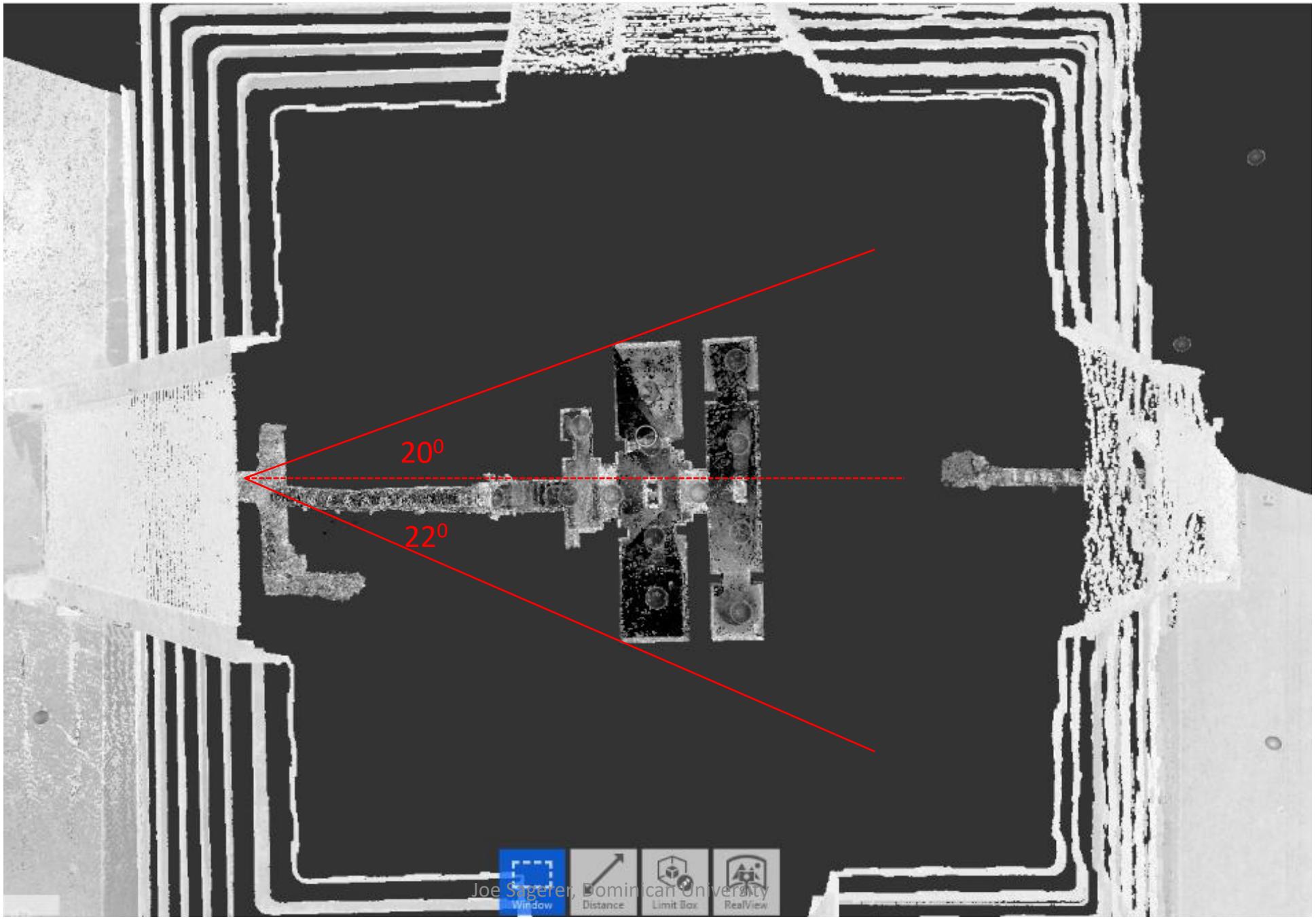
Current Status

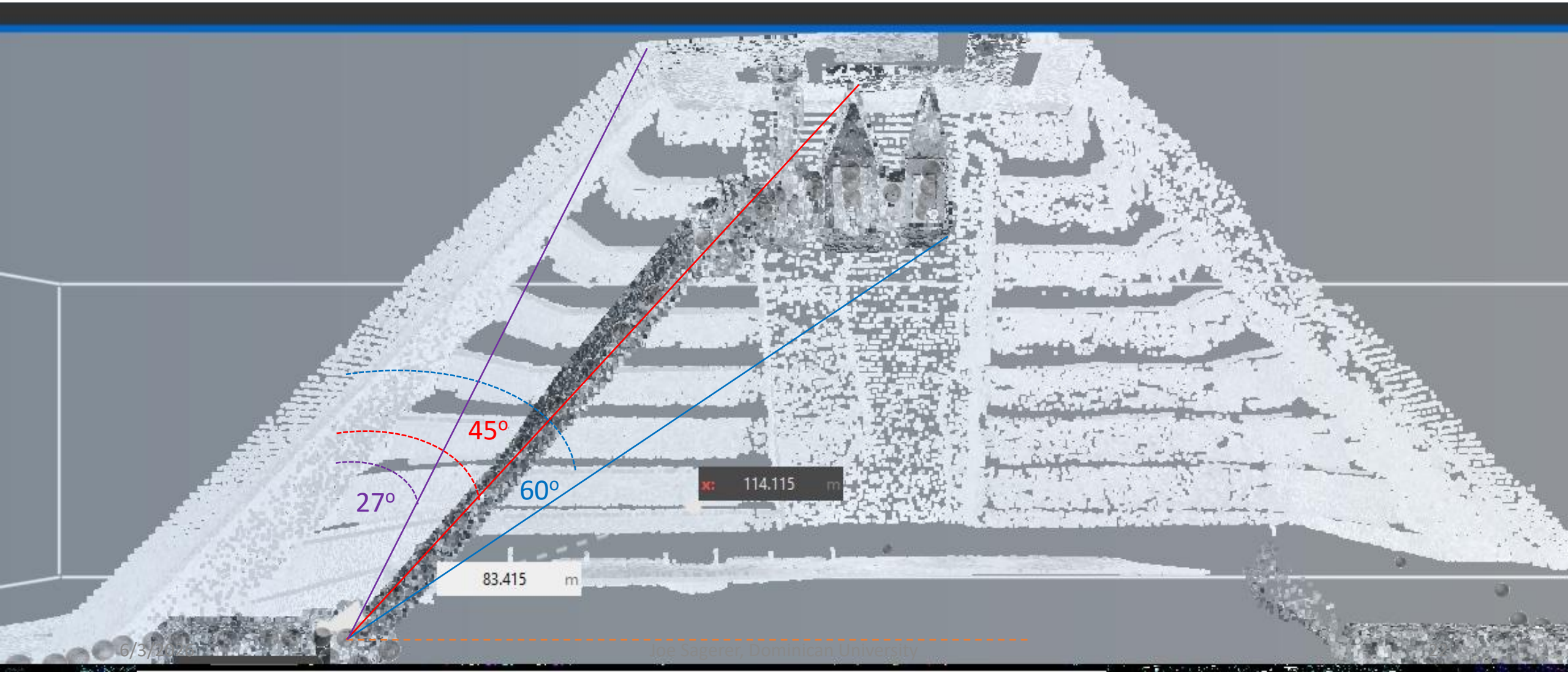
- We have been taking data (remotely) since February 1, 2026.
- So far, we have taken around 5 million events, in four angular positions
- Goal is another 2.5 months at current angle, then rotate the detector in azimuthal angle to repeat.

NAUMProject.com (https://www.i2u2.org/elab/cosmic/pyramid-display/pyramid.html)



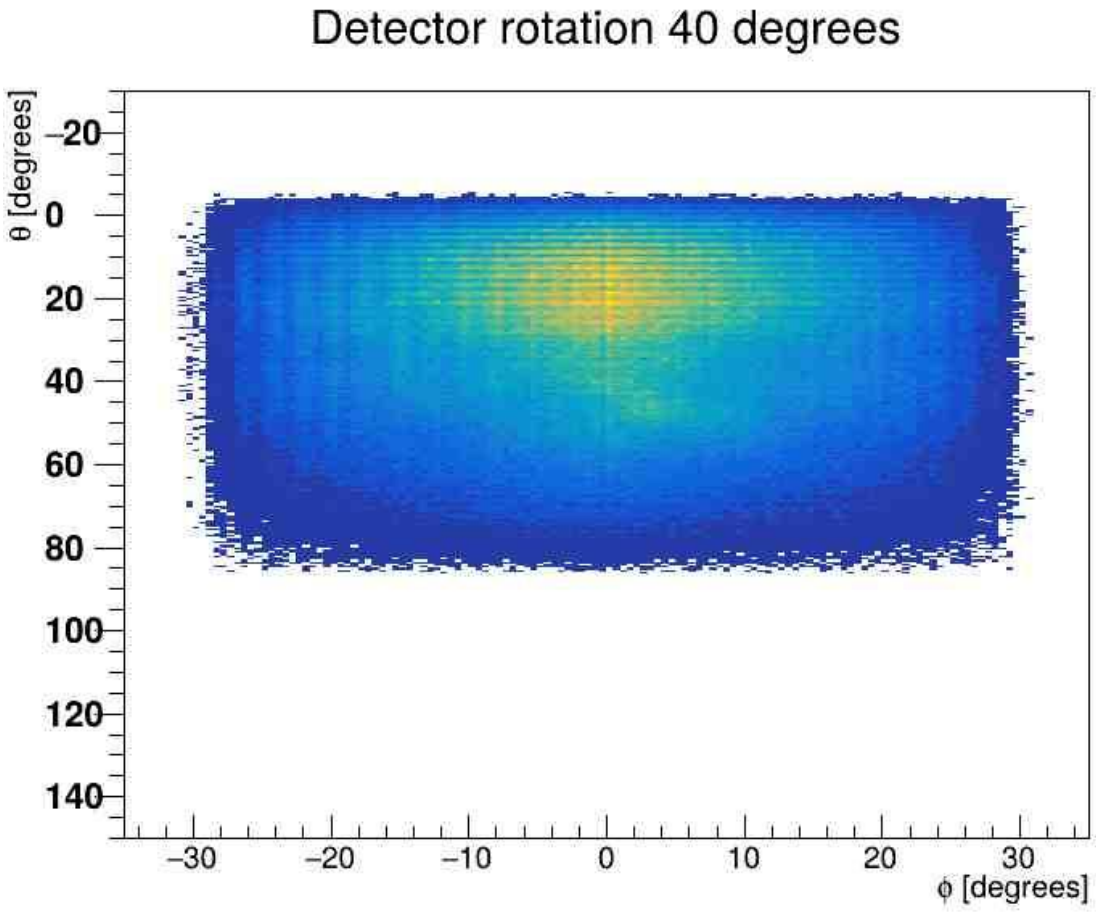



20⁰
22⁰
Window
Distance
Limit Box
RealView


45°
27°
60°
x: 114.115 m
83.415 m

(Very) Preliminary Data

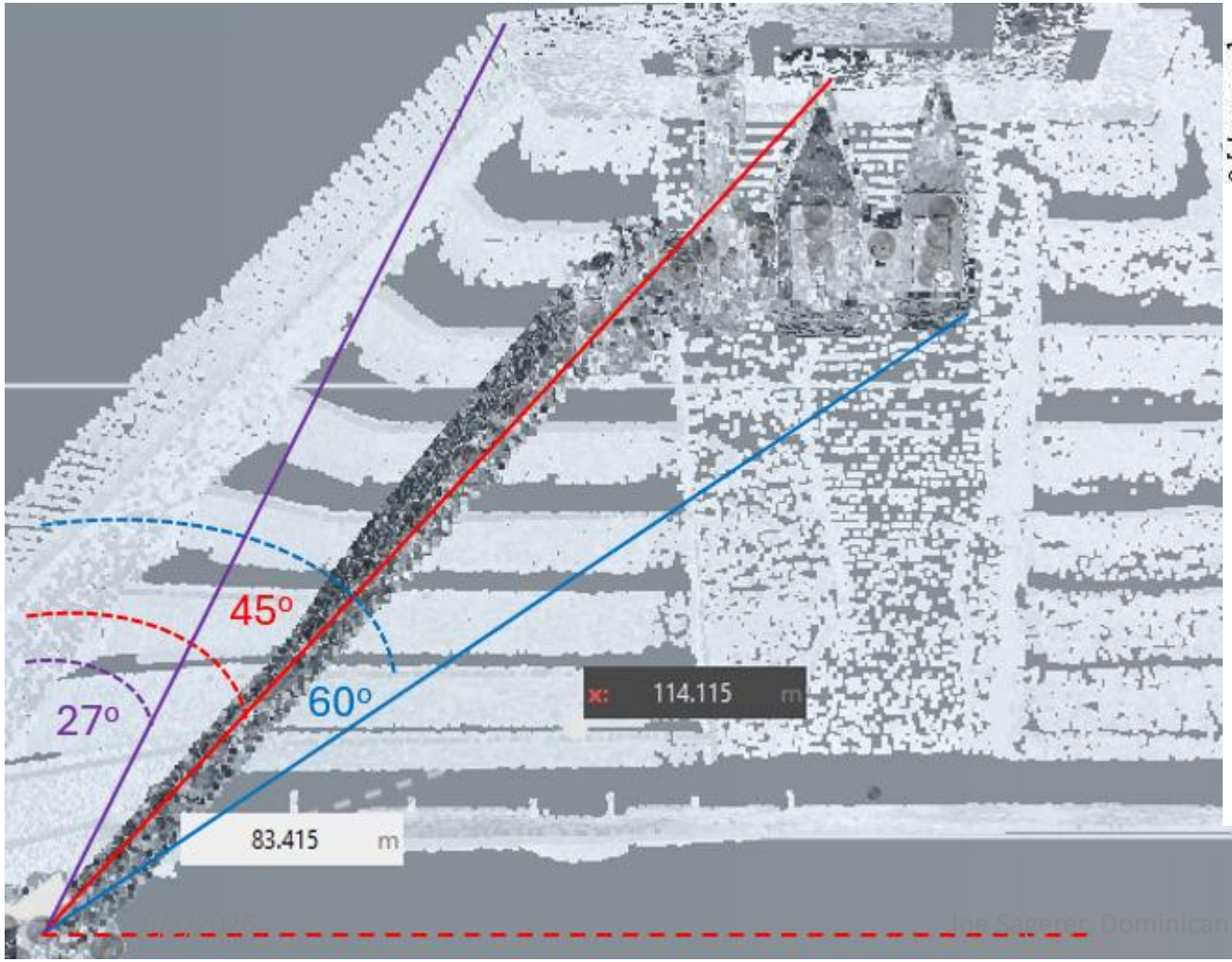
Uncorrected for Detector Acceptance and Zenith Rate Dependance

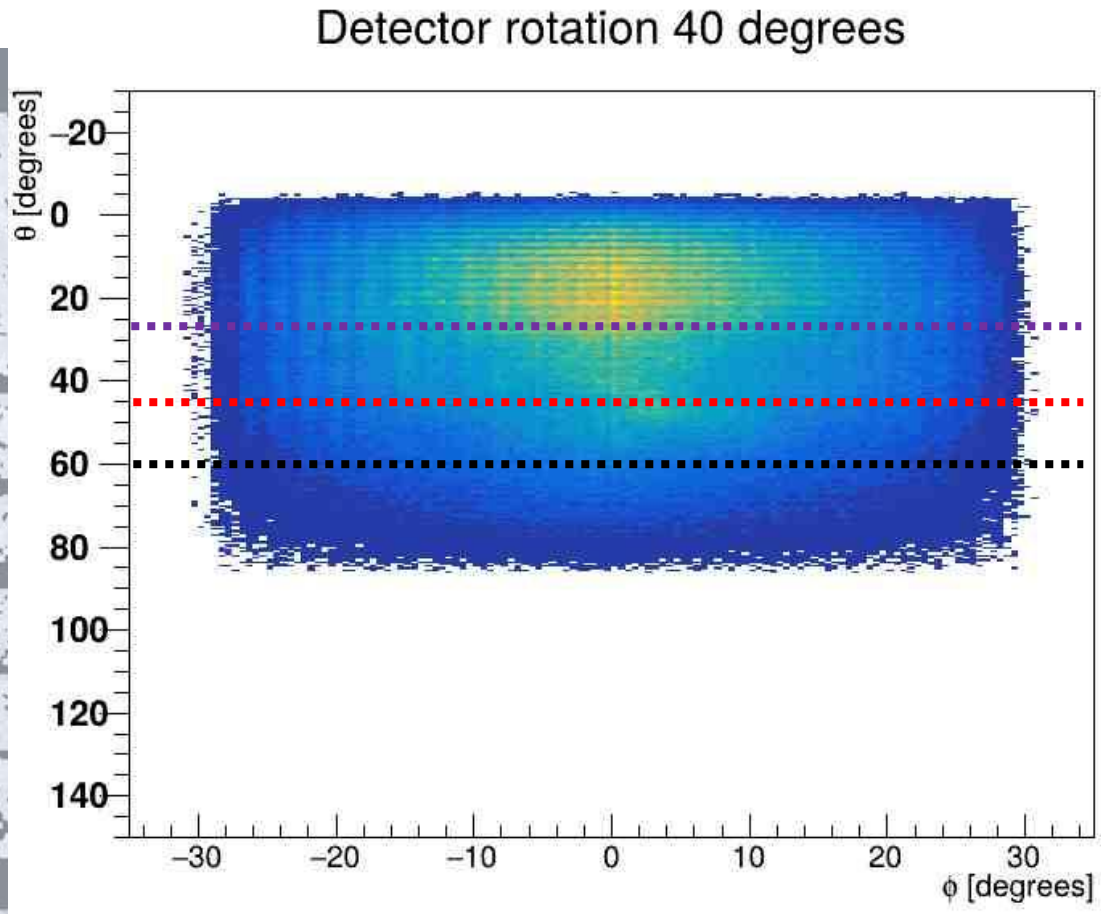


1.88M Events, ~26 days

(Very) Preliminary Data

Uncorrected for Detector Acceptance and Zenith Rate Dependance





(Very) Preliminary Data

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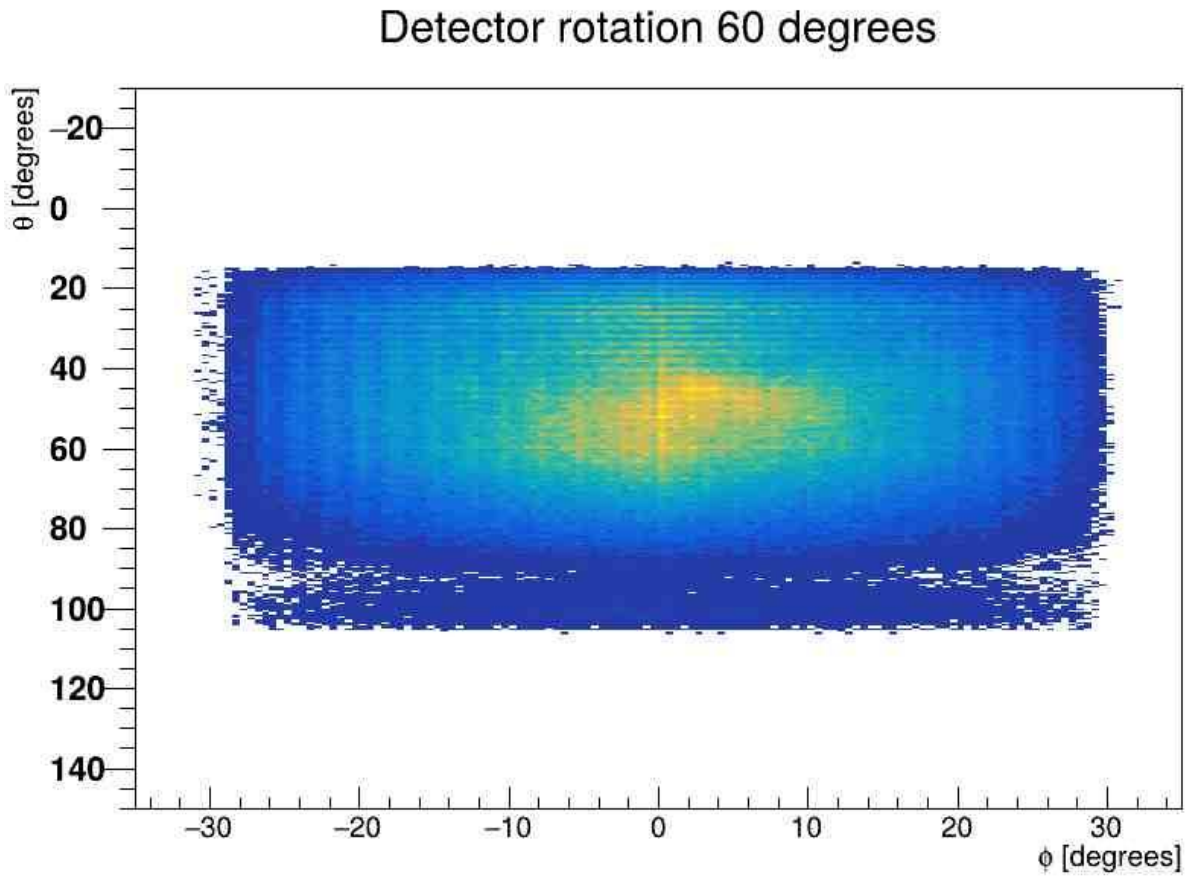
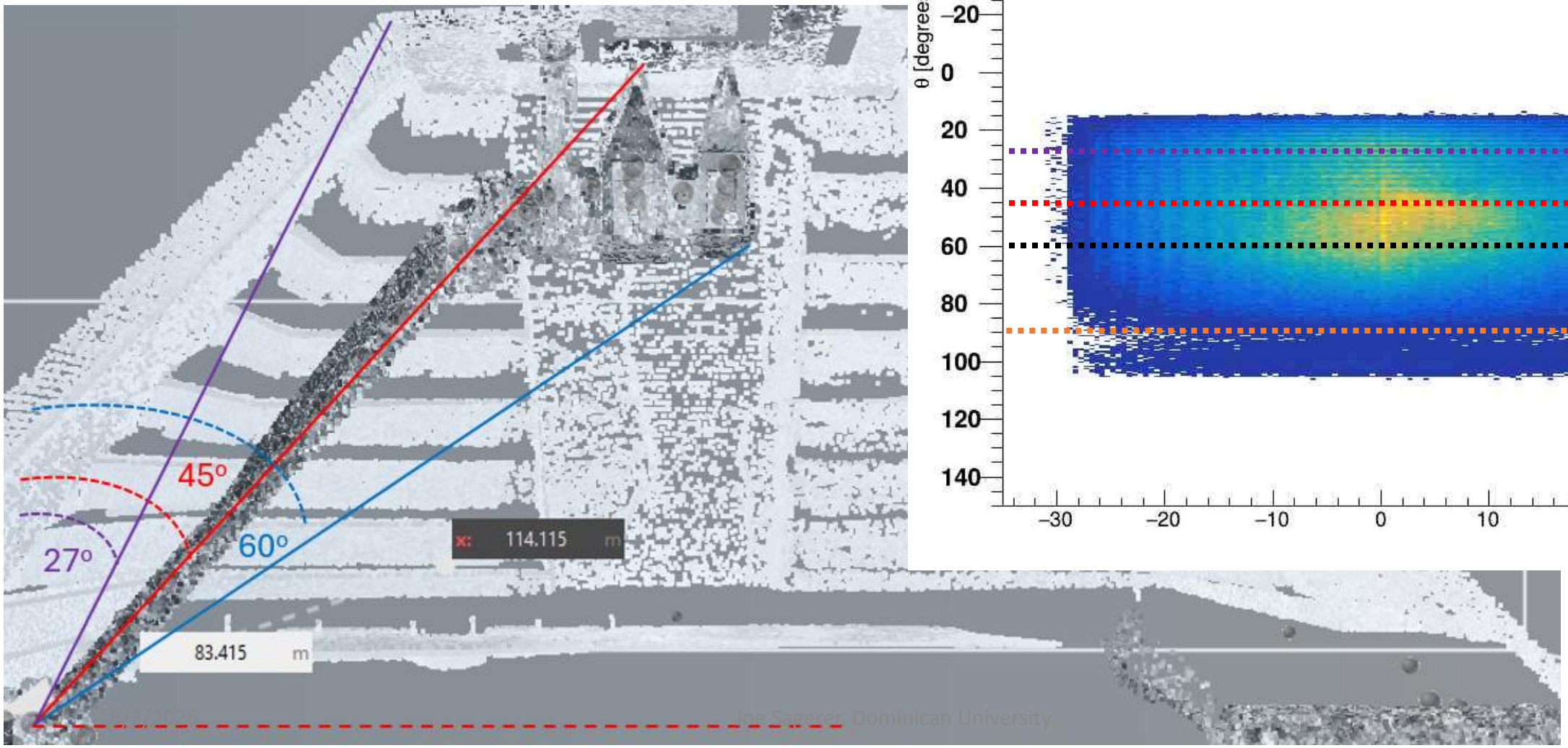
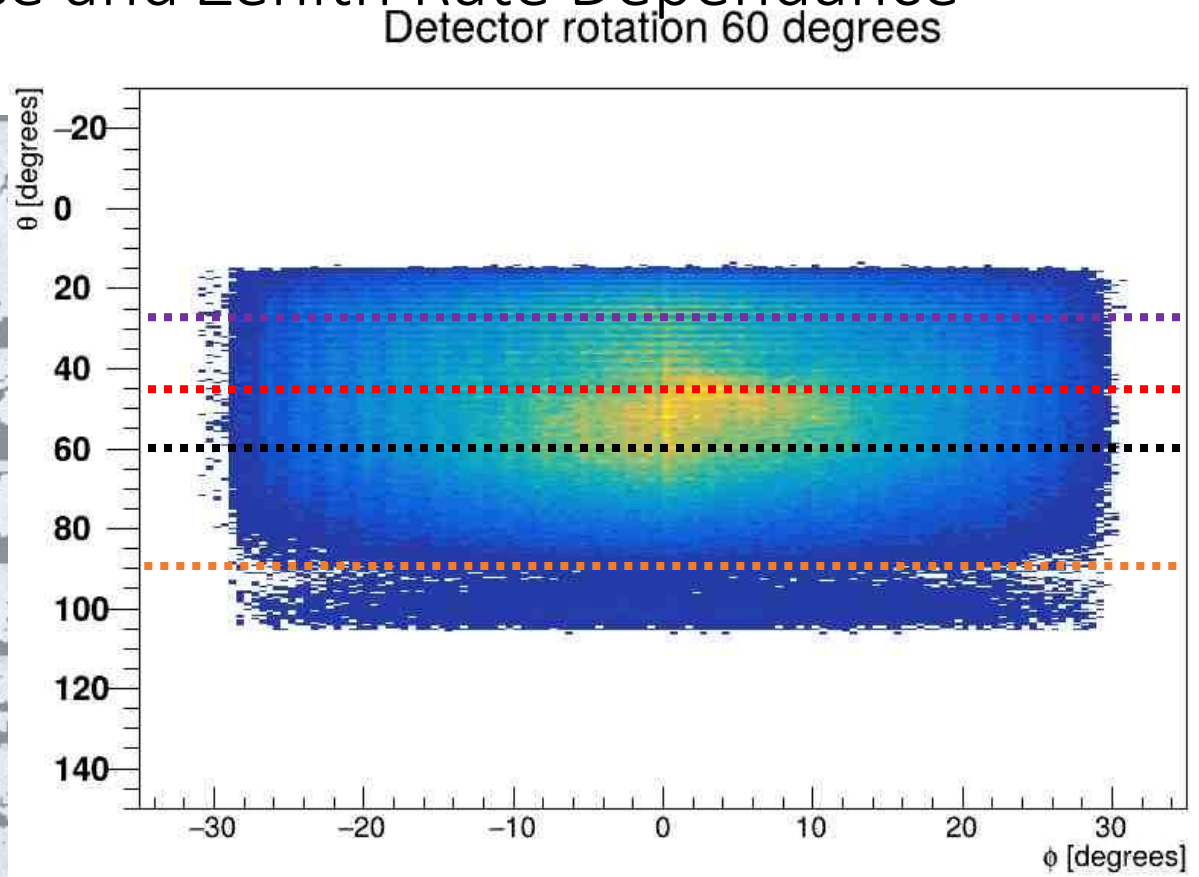


1.58M Events, ~46 days

(Very) Preliminary Data

Uncorrected for Detector Acceptance and Zenith Rate Dependance





Status and Next Steps

- 1.88M events at 40° from vertical
- 1.58M events at 60° from vertical
- 1.02M events at 50° from vertical
- 575k events at 70° from vertical, continued running until mid-August

- Detector is working and taking data in a challenging environment!

- Will Rotate detector and repeat interesting angles

Analysis Next Steps

- Improved Tracking using actual geometry of each plane
- Corrections for detector acceptance and zenith rate effect
  - Sister detector at Dominican University can run same angles without pyramid
- Simulations from point cloud with and without interesting features
- Compare simulations to open sky and pyramid data

NAUM

This project is supported by the National Science Foundation under awards PHY-2011339 and PHY-2011442