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Virtual archaeology: Tomographic Imaging of the Great Pyramid of Giza on the OSG

Alan Bross
Open Science Grid All-Hands Meeting
31 August 2020

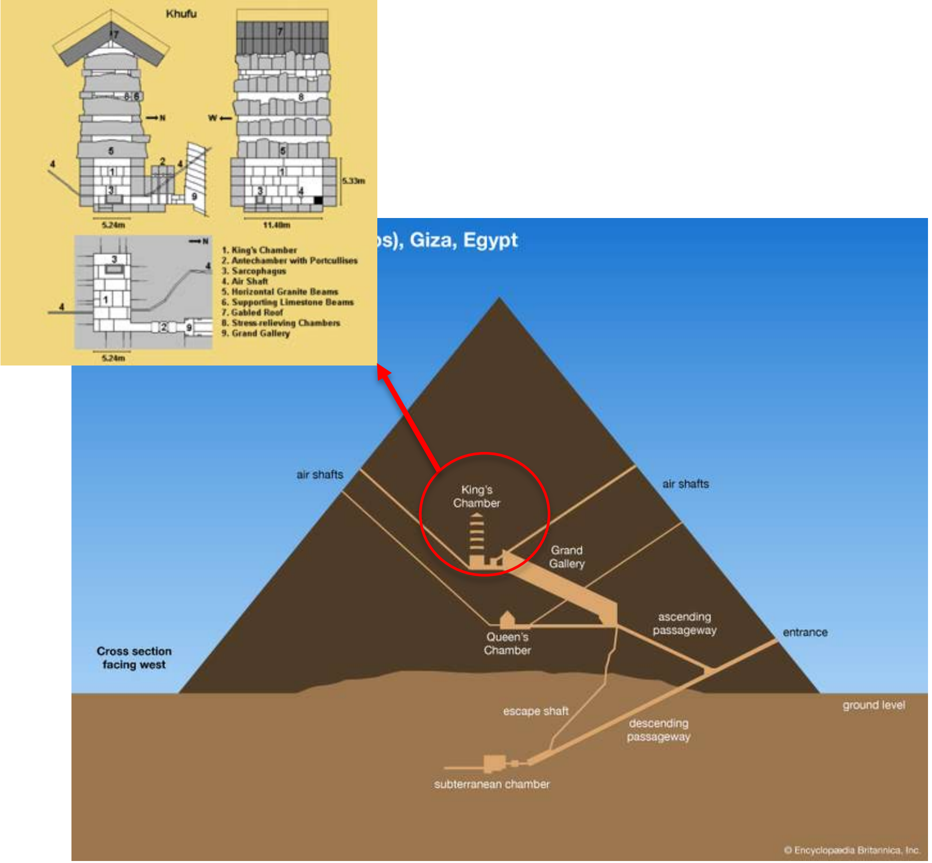
Cairo University Faculty of Science Geophysics Department 1981 | The University of Chicago | The Oriental Institute | University of Virginia | Yale

Imaging Khufu: Historical Background

The Great Pyramid of Khufu

- Cosmic-Ray Muon Radiography
  - **Feb. 1970:** Alvarez et al. publish study of Khafre's Pyramid using cosmic rays
    - First application of the technique
  - **Nov. 2017:** ScanPyramids Collaboration publishes Nature article announcing discovery of new void above Grand Gallery in the Great Pyramid of Khufu
    - **Unexpected within Archaeological community**
- After 200 years of study, archaeologists still have an incomplete understanding of how the Great Pyramid at Giza was built.
  - Much of the internal structure is unknown and debate rages on regarding specifics of the construction techniques
  - There are still discoveries to be made

The Great Pyramid (Khufu) of Giza: *By the Numbers*



- Completed ~ 2500 BCE
- Height ~ 140m
- Base ~ 230m on a side
- Total Mass: ~ 6.5M tons
- Number of Blocks: ~ 2,500,000
  - Blocks varied in size, most ~ 1m^3 (3t), some up to 40t
- Note: Largest man-made structure for ~ 3800 years
  - Beaten by Lincoln Cathedral in UK
- Angle of Slope: 51° 50' 40'
- Time to build ~ 20 years
- Work force ~ 20k
  - Paid government workers
- TPC: ??
  - DOE accounting ~$100B (FY2020 $s)

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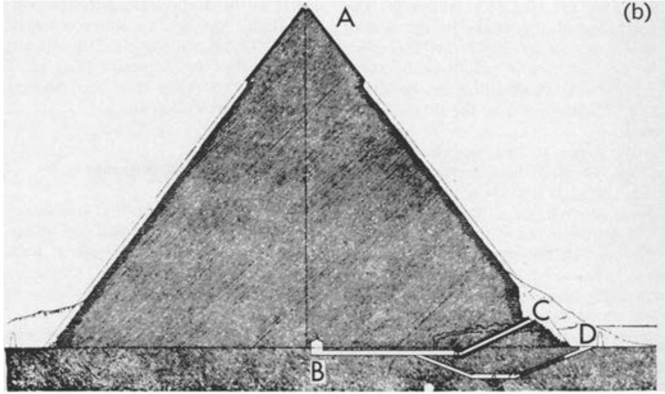
Alvarez et. al

Science, Vol. 167, Feb. 1970

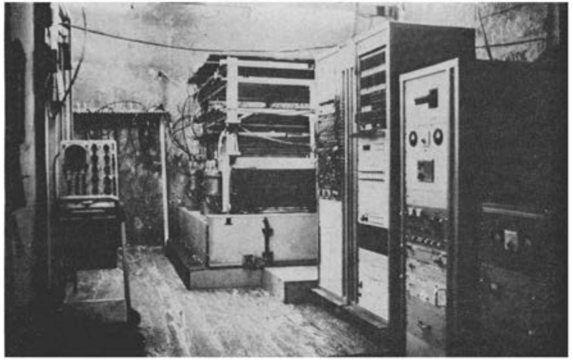
Search for Hidden Chambers in the Pyramids

The structure of the Second Pyramid of Giza is determined by cosmic-ray absorption.

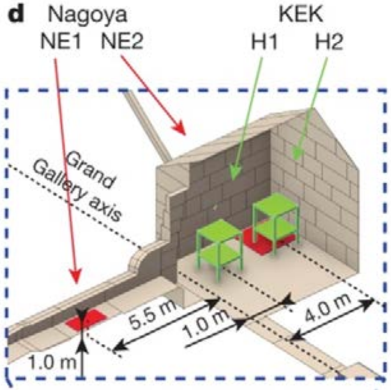
Luis W. Alvarez, Jared A. Anderson, F. El Bedwei, James Burkhard, Ahmed Fakhry, Adib Girgis, Amr Goneid, Fikhry Hassan, Dennis Iverson, Gerald Lynch, Zenab Miligy, Ali Hilmy Moussa, Mohammed-Sharkawi, Lauren Yazolino



- Question:
  - *Why the sudden decrease in internal complexity from the Great Pyramid (Khufu) to the Second Pyramid (Khafre)?*
    - Did Archaeologists miss something?
- Radiograph Khafre with cosmic-ray muons
  - Detector: Spark Chambers (~3m^2)
- No evidence found



Scan Pyramids (~2015-2017+)



- Again cosmic-ray muon radiography is used to detect any unknown voids in the Great Pyramid.
- Nature, Vol. 552 (2017)
  - They reported the discovery of a large void (with a cross-section similar to that of the Grand Gallery (10m tall & 3 m wide) and a minimum length of 30 meters) situated above the Grand Gallery – 30m (L) X 10m (H) X 3m (W).
    - **The first major inner structure found in the Great Pyramid since the 19th century!**
    - Stress relieving structure?
- Technology
  - Emulsions, plastic scintillator (inside) and micromegas trackers (outside facing Grand Gallery), all ~ few m^2
    - BTW – Scintillator was produced at Fermilab

The Exploring the Great Pyramid (EGP) Mission

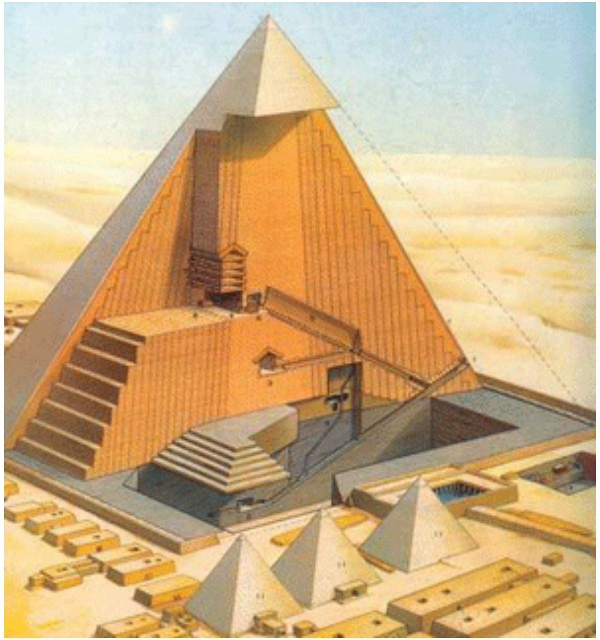
- The Scan Pyramids team discovery caused quite a stir in the Egyptology community and in Egypt
- However
  - The size of their detectors was small – a few m^2 in area.
  - This limited the number of muons that they could detect.
  - Imaging was possible, but the image resolution was limited, and interpretation of the results is difficult.
  - It was again a 2D, radiographic image to a large degree
- The Egyptian Ministry of Antiquities requested proposals for a follow-up study
- We applied and were approved (2018) – EGP Mission born

Mission Team

- Cairo University: Mohamed Gobashy
- Fermilab: AB, Adam Para, Anna Pla, Leah Welty-Rieger, Paul Rubinov
- Oriental Institute of the University of Chicago: Nadine Moeller‡, Gregory Marouard‡, Chris Woods
  - ‡Now at Yale University
- University of Chicago: Henry Frisch (PD), Patrick LaRiviere (RD), Mira Liu (RD), Omar Shohoud, Christian Sodano, Tabitha Welch
  - Physics Department (PD), Department of Radiology (RD)
- University of Virginia: Craig Dukes, Ralf Ehrlich†
  - † OSG driver
- Virginia Tech: Sophie Dukes¶
  - ¶Also Fermilab

CAIRO UNIVERSITY

EGP Scientific Goals



Is this what the inside of Khufu really looks like?

- What can be learned from a **high-resolution muon tomographic** image of the Great Pyramid?
  - Detailed analysis of the entire internal structure
  - Not just differentiate between stone and air, but measure small (30%) variations in density
    - Note: Stone:air = 2000:1
  - Answer questions regarding construction techniques by being able to see small structural discontinuities
    - **Non-Invasive!**
- High-resolution imaging offers a much better opportunity to reveal (& understand) any “Unknowns-unknowns” within the structure.

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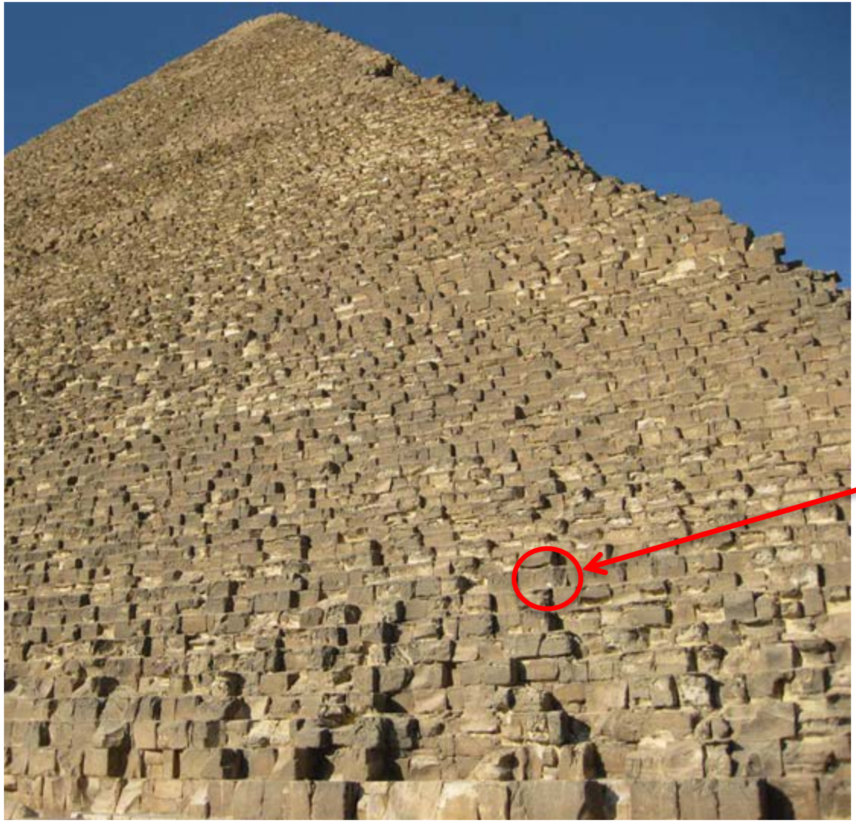
EGP Scientific Goals II



- Move to a true tomographic approach
- 100X the detector area of ScanPyramids
- Image voids as small as a single pyramid block (1 m^3) visualized (reconstructed) in 3D
  - Spoiler: not there yet

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Muon radiography/tomography: Basic measurable

- For a given line of sight through an unknown opacity ϱ, we will measure an integrated flux of all the muons whose initial energy exceeds $E\_min\ (\varrho)$.

$$I(\varrho) = \int_{E_{min}(\varrho)}^{\infty} \Phi(E_0) dE_0$$

Measured intensity

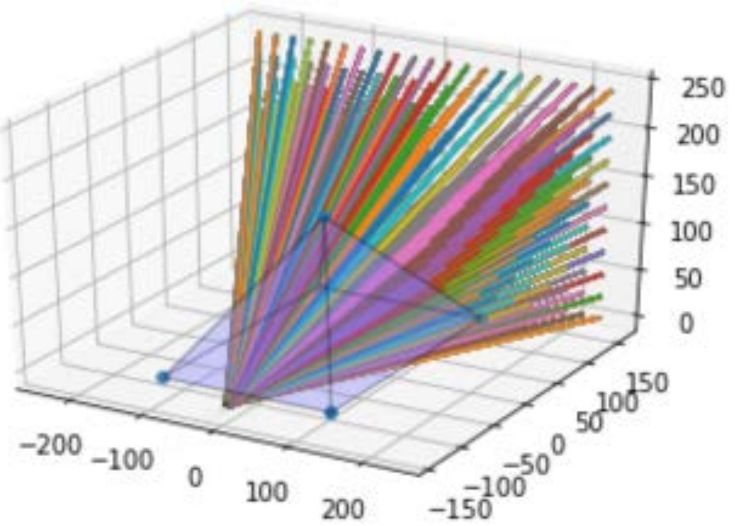
Unknown E_{min}, but mapping $E_{min}(\varrho)$ is known/ calibrated

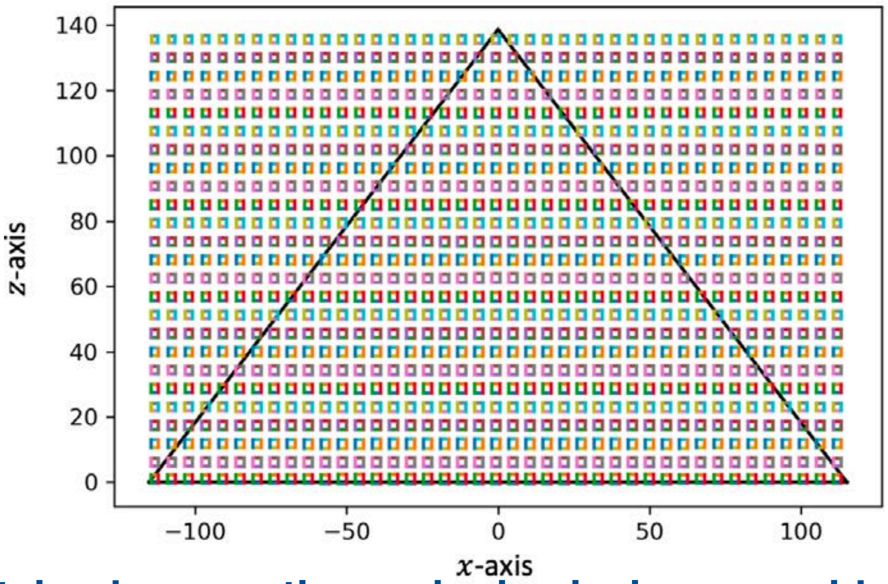
Incident differential flux of muons. Known/calibrated but could be wrong.

- So, to isolate line integrals (opacity values) we need to find the lower limit of this integral such that it integrates to the measured intensity and then invert $E\_min\ (\varrho)$.

Radiographic Sampling

Mira Liu





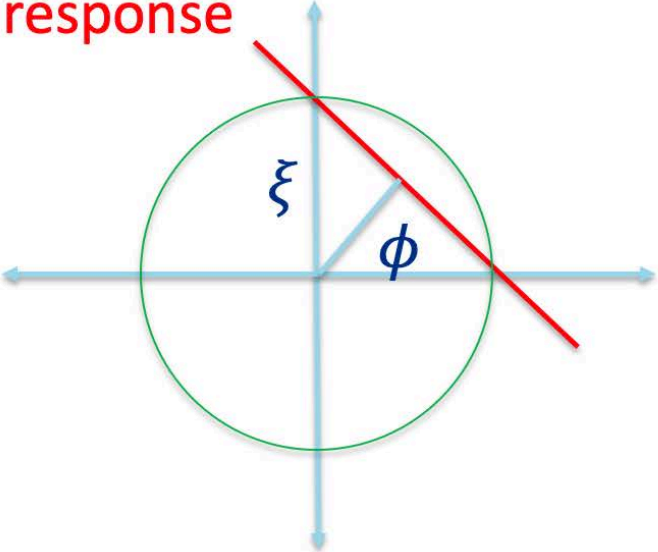
These figures show the Lines of Response obtained connecting a single pixel on one side of detector to all pixels on other (radiograph)

Need to move along pyramid, producing views over many angles & ONLY then can we reconstruct using tomographic techniques

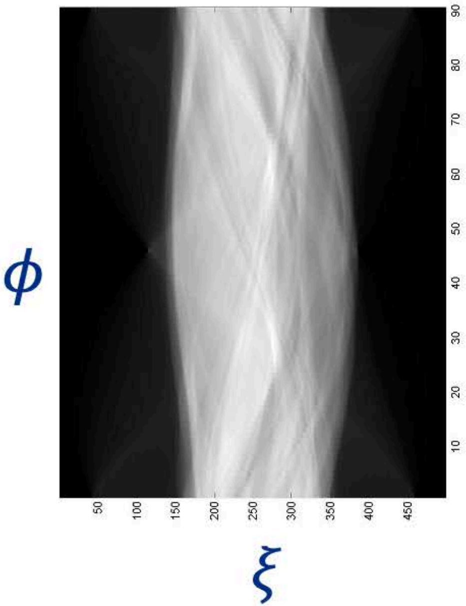
"Cone beam" source complicates tomographic reco. *Work in progress*

Tomographic Sampling

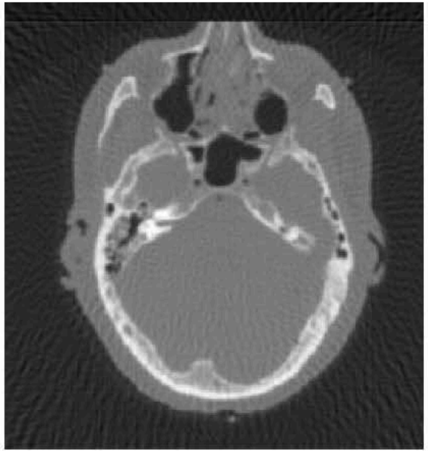
Line of response



Complete sinogram.
Phi spans 180 deg
Xi the FOV



Reconstructed image



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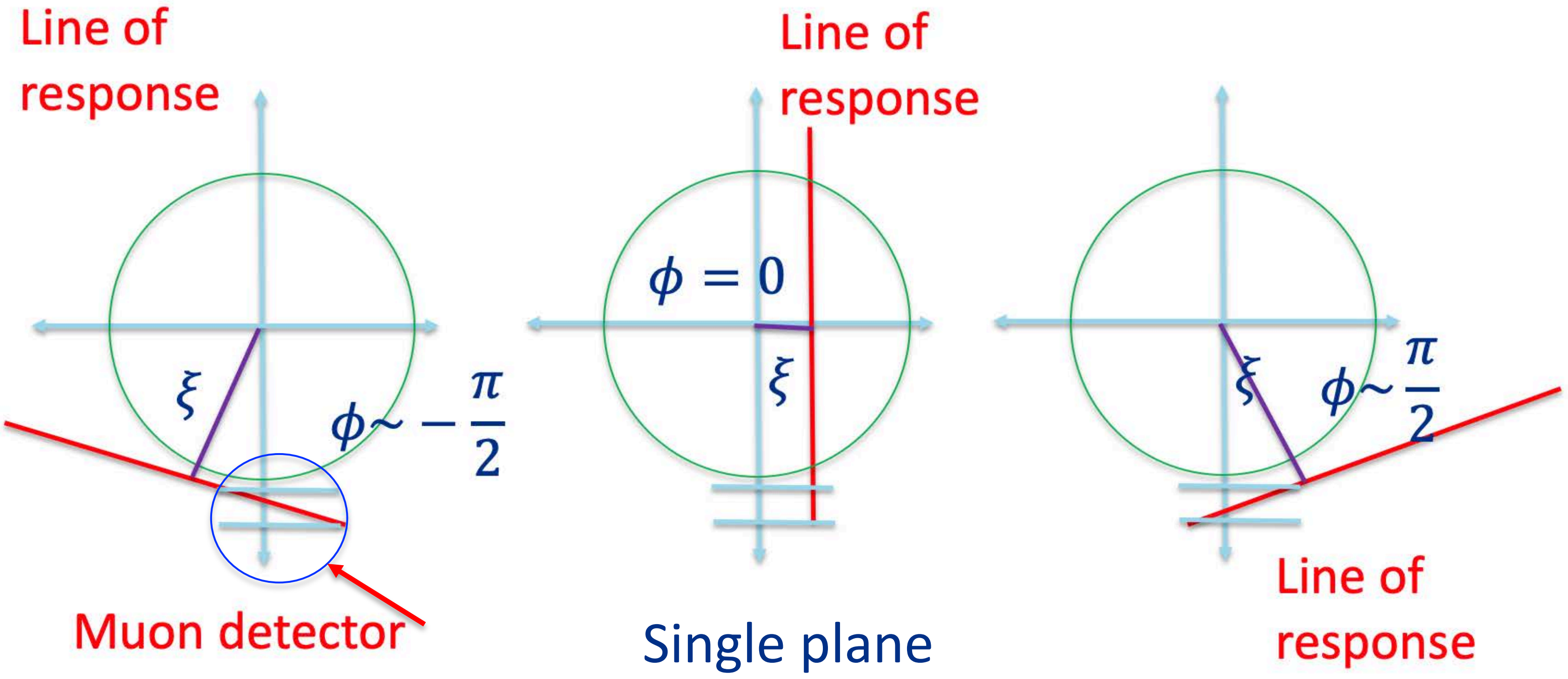
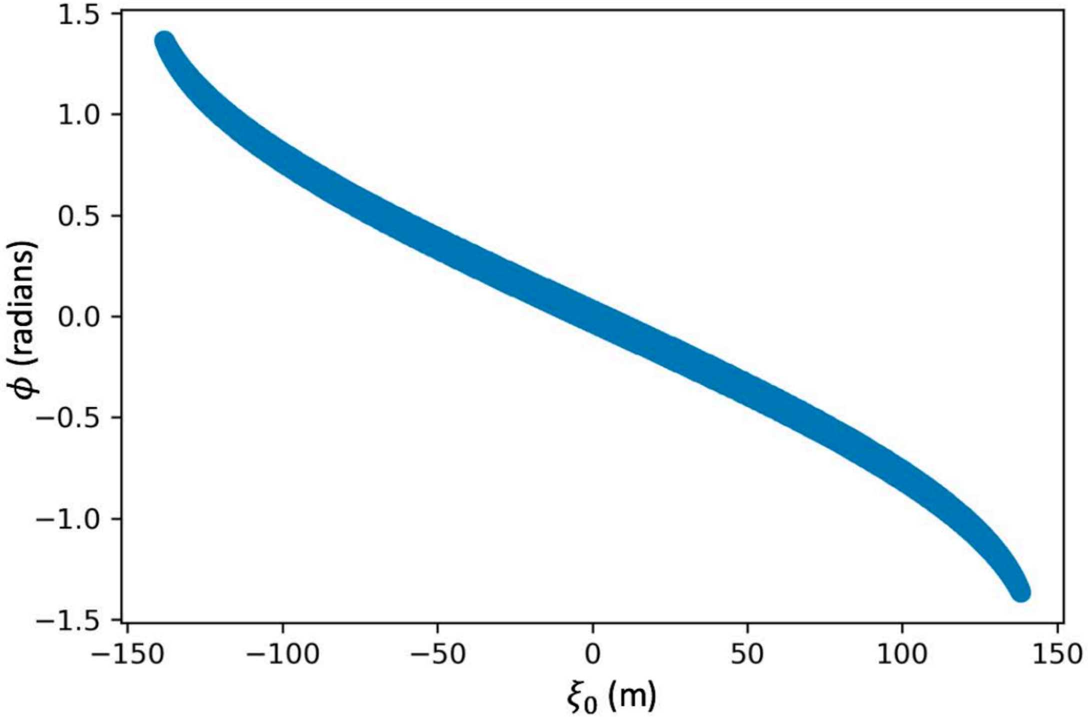
Tomographic Sampling II: Extrapolation to muons



Tomographic Sampling III

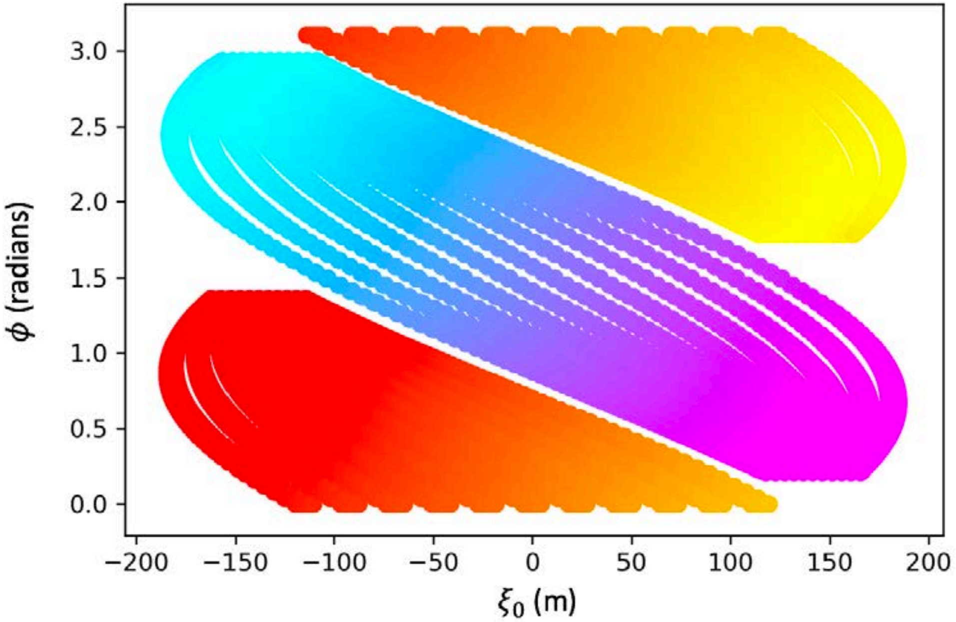
Single detector position



With a limited detector size, we only sample a small part of the sinogram space.

Even with a very large detector

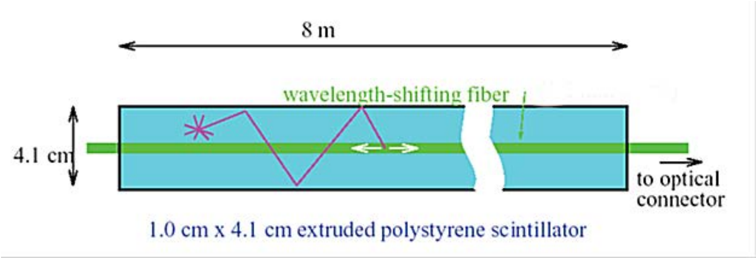
Tomographic Sampling IV



- However, by moving detectors along the base of the pyramid, we can cover a large fraction of the sinogram space.
- What is shown here is the result of of moving detectors along the full length of two sides of Khufu
- Details, details
  - Detector response, resolution
  - Effects due to multiple-coulomb scattering
  - Cone beam (cosmic-ray muons)

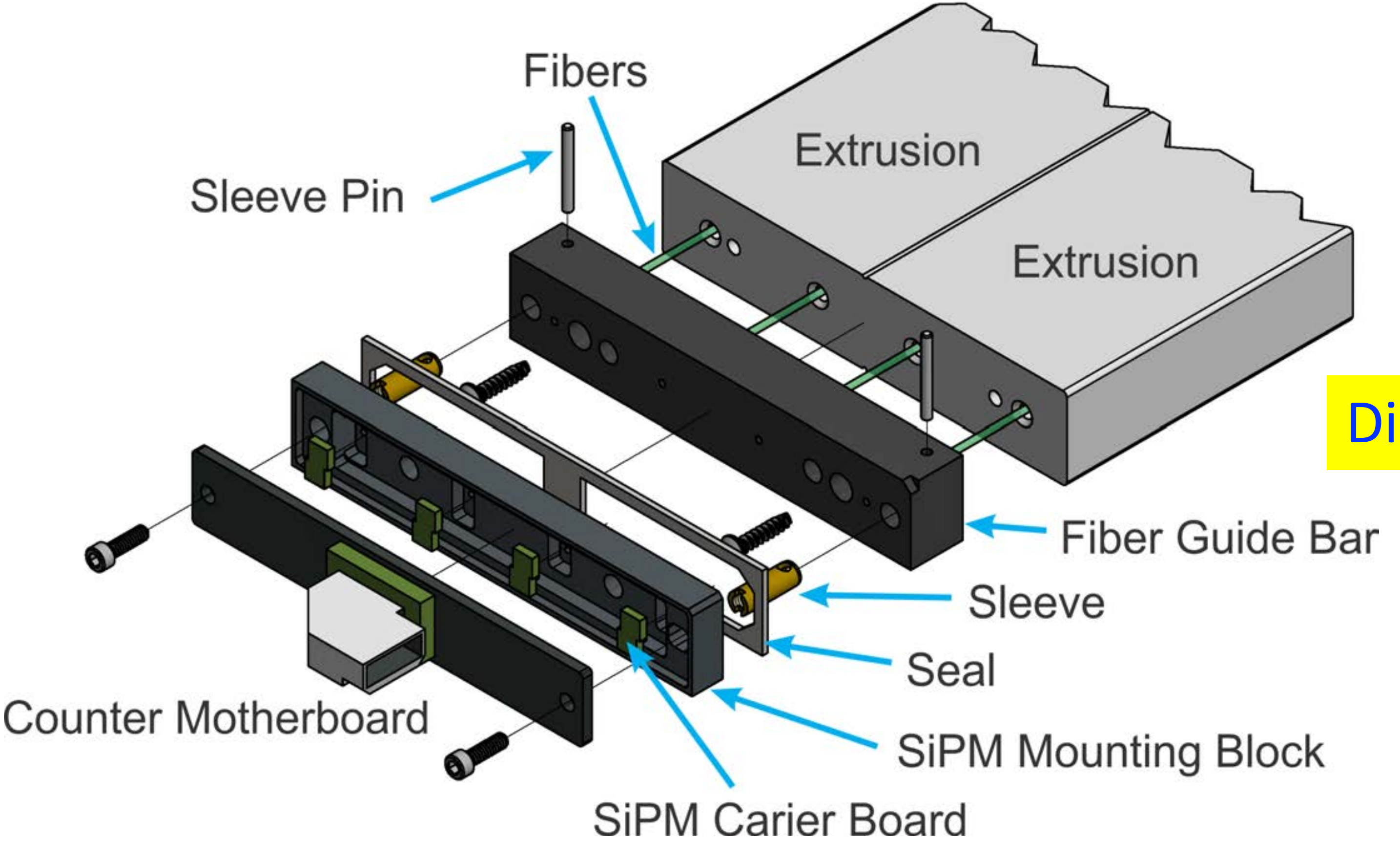
EGP Technical Approach

Basic detector configuration



- EGP detector telescopes will use ~ 1000 m^2 of active detector.
  - Using a scintillator strip design following that of the Mu2e experiment
  - Readout with SiPMs
  - The system is very modular in nature
  - Package detectors in temperature-controlled cargo containers
    - Very easy to reconfigure and deploy around the perimeter of the Great Pyramid or move to another site for future studies.
  - EGP telescopes are a mobile “Observatory”

Detector Detail (from Mu2e)



Di-counter

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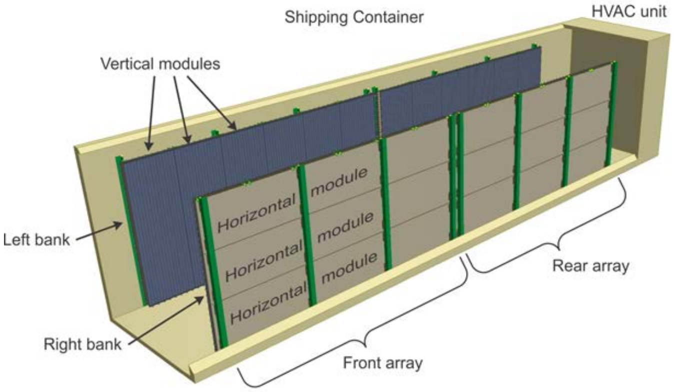
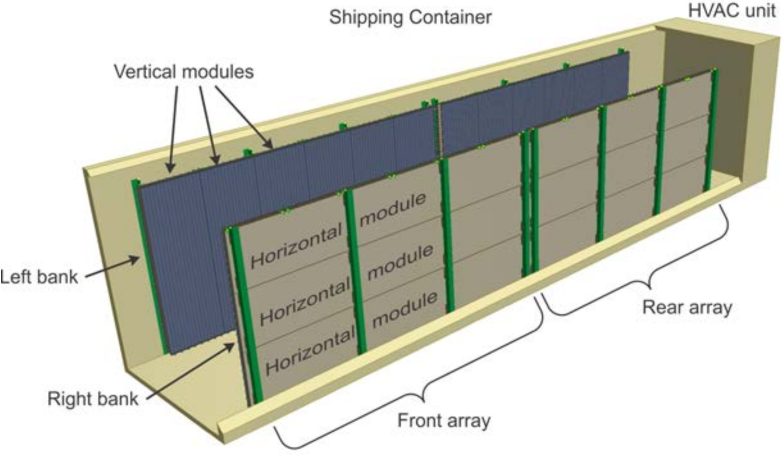
Modular muon telescope



- Assemble detector arrays in temperature-controlled cargo containers to form modules.
  - Reconfigurable, robust, secure,
  - Outfit 8 modules.
- Can be configured in several ways, one 4X2 array or two, 2 X 2 arrays, for example.
  - Need 2 high to "reach" top of Khufu
  - Can be unstacked moved and restacked along the pyramid perimeter.
- Ultimately sample entire perimeter of Khufu
- For muons of interest (energy) collect approximately 500 muons/sec for the full array.
  - **~ 2 X 10^{10} muons per year of viewing**
  - **>100X the sample obtained in Scan Pyramids**

Module Model Detail



- 12 vertical modules per bank (2 banks)
  - 40 counters per module
  - Counter dimensions:
    2.5 m (L) x 2 cm (W) x 1 cm (T)
- 6 (3 high X 2 long) horizontal modules per bank
  - 40 counters per module
  - Counter dimensions:
    4.8 m (L) x 2 cm (W) x 1 cm (T)
- Distance between detector banks is ~2m
- Each muon telescope will be a 2 X 2 array of these container systems
- Build two telescopes
  - ~23k channels total

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Container detail

40-ft REFRIGERATED CONTAINER

Standard Features

- 40-ft (2,360 cu ft) Size
- -10°F to 70°F Range
- Adjustable Thermostat
- Automatic Defrost
- Full Opening Swing Cargo Doors
- Aluminum T-grade Floors
- Stainless Steel Interior
- 3 Phase /230V or 460V/60Amps or 30Amps
- Lockable Doors
- On-site Delivery

Our spacious 40-ft refrigerated units (reefers) hold twice as much as our 20-ft reefers and are available for purchase and lease, in both new and used conditions. Rigid, high quality construction, and double swing doors allow you to load and unload product with the aid of forklifts and pallet jacks.

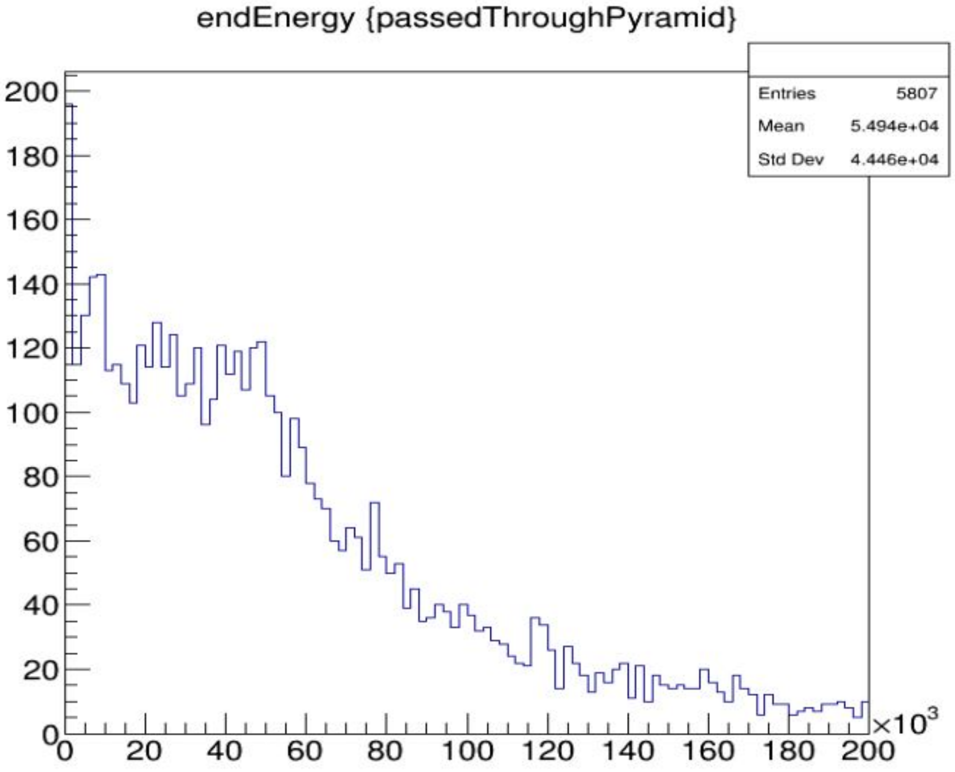
Note: We decided on refrigerated containers because of the SiPM's large temperature dependence

Unit	Length		Height		Width		Door Opening	
	Exterior	Interior	Exterior	Interior	Exterior	Interior	Height	Width
US	40' 0"	38' 0 3/4"	9' 6"	8' 3 5/8"	8' 0"	7' 5 5/8"	8' 6 1/2"	7' 5 5/8"
Metric (mm)	12,192	11,602	2,896	2,531	2,438	2,276	2,603	2,276

Detector Optimization

Independent non-OSG toy MC studies

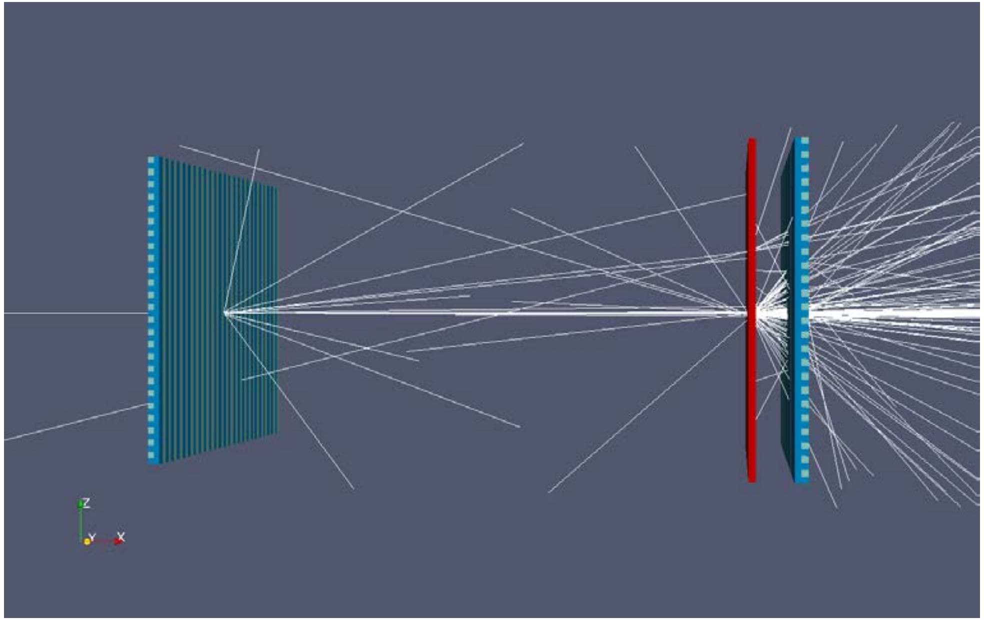
Detector Optimization



- To the right is a plot of the # “good” muons vs E_{μ} from simulation on OSG
- We have speculated if removing low (excess scatter) or high energy (too little/no absorption/scatter) would improve image quality.
- Look at dE/dx and hit multiplicity in each view
- Conclusion: Very Difficult. dE/dx not viable, multiplicity…
  - More work to be done

Muon Hit-Multiplicity study

Tabitha Welch



- In this study a layer of lead was added just upstream of bank two to increase the muon hit-multiplicity.
- Although there is a measurable effect that can distinguish E_{μ} = 10 GeV from E_{μ} = 100 GeV, the tagging efficiency is too small to be useful

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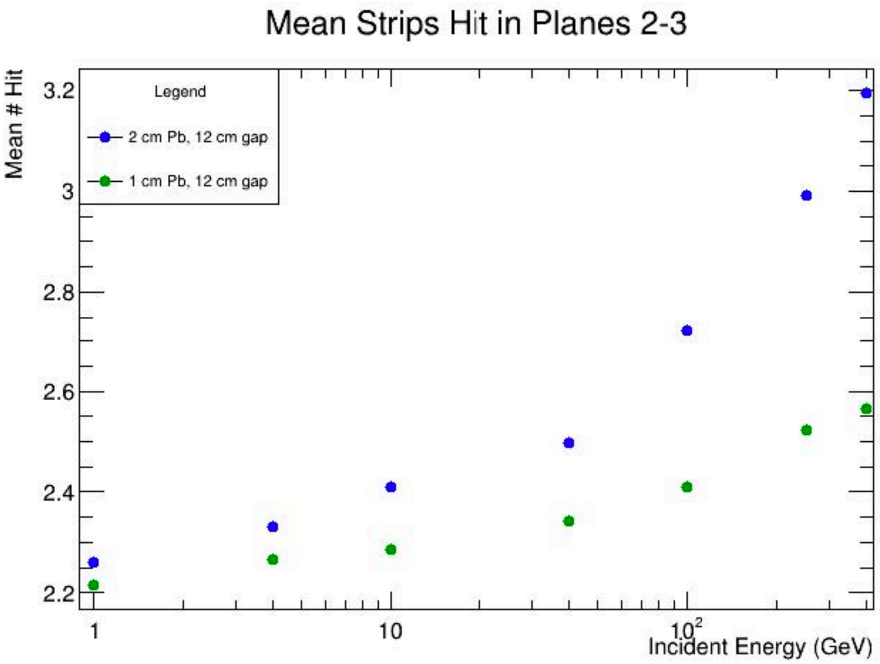
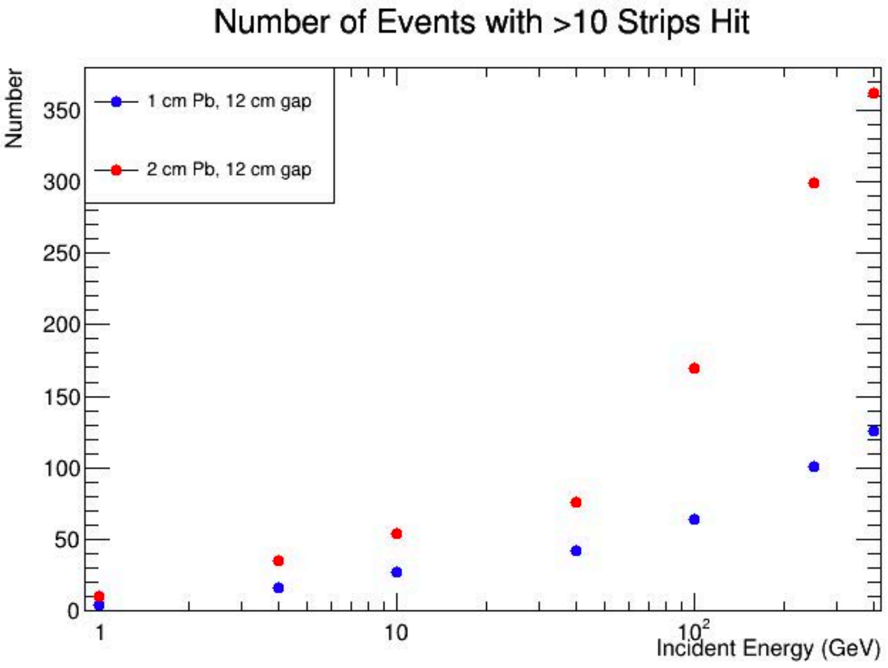
MC: Pb Layer – Energy Results

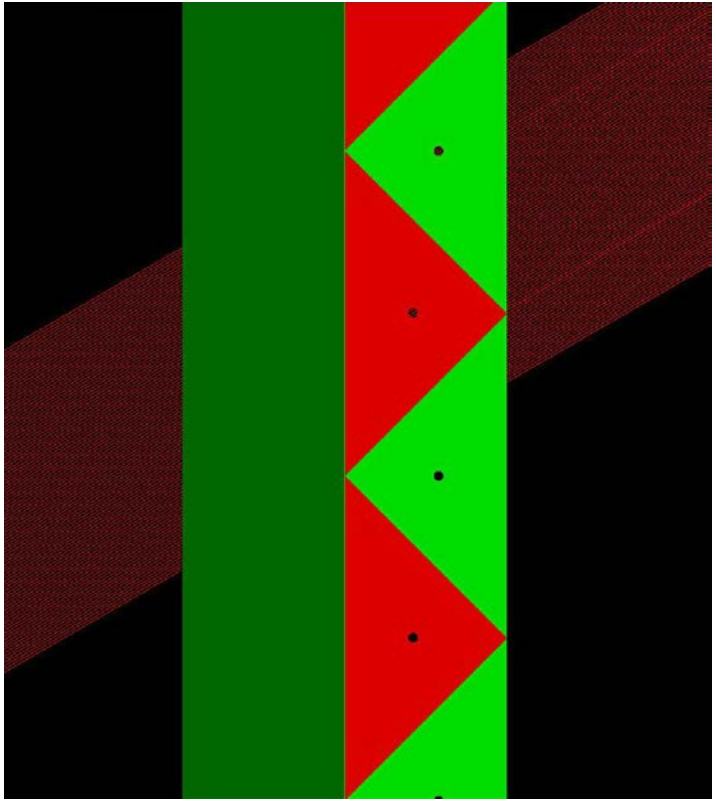
10,000 evts





Detector cell optimization

Omar Shohoud



- The scintillator strip geometry that has been used in the simulations on the OSG have used a 2cm wide strip
  - Point resolution ~ $20/\sqrt{12} \approx 3$ mm
- We can get better resolution ($\lesssim$ 1mm) using a triangle (similar to Minerνa)
  - 4 cm base, 2 cm height. Same channel count as with 2 cm wide rectangular strip

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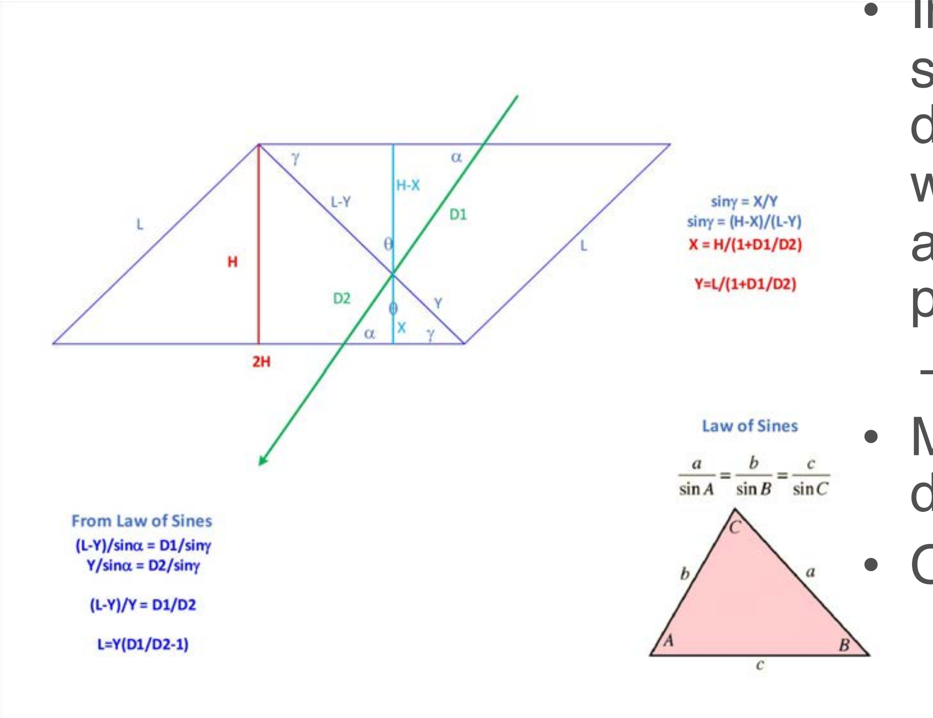
Triangular scintillator extrusion



- Interestingly, even though these triangular strips have been used for many years, we discovered that the use of a simple weighted mean of detected light (Minerνa algorithm) produced a small artifact in pointing resolution
  - Only have two space points
- Making the correction indicated in the diagram on the left improves the pointing
- Overall ~ 1mrad pointing resolution

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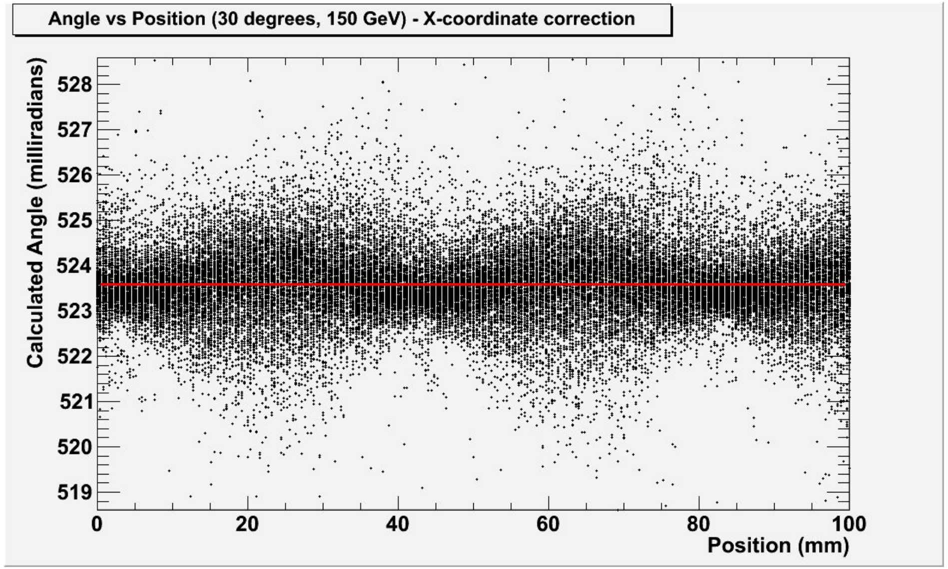
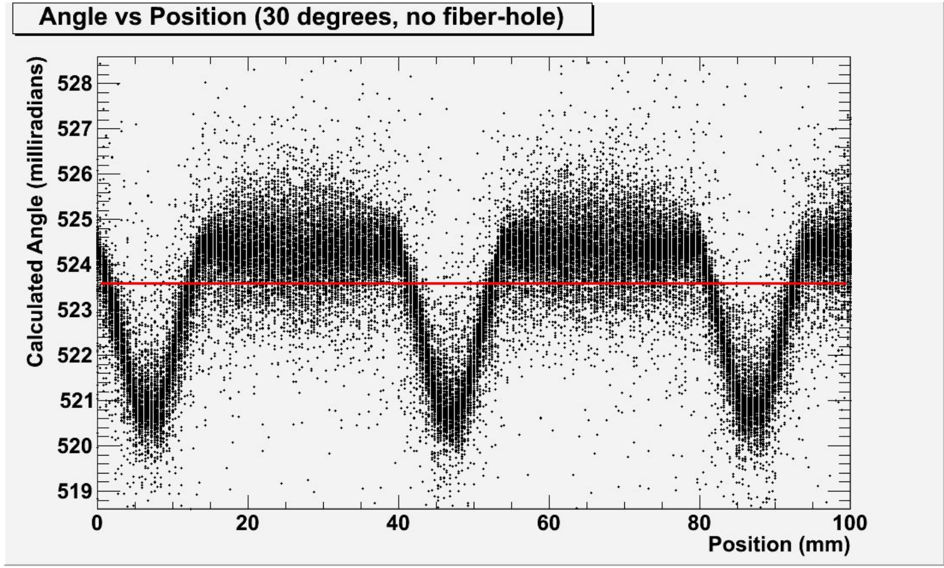
Pointing resolution -- Triangle





With correction

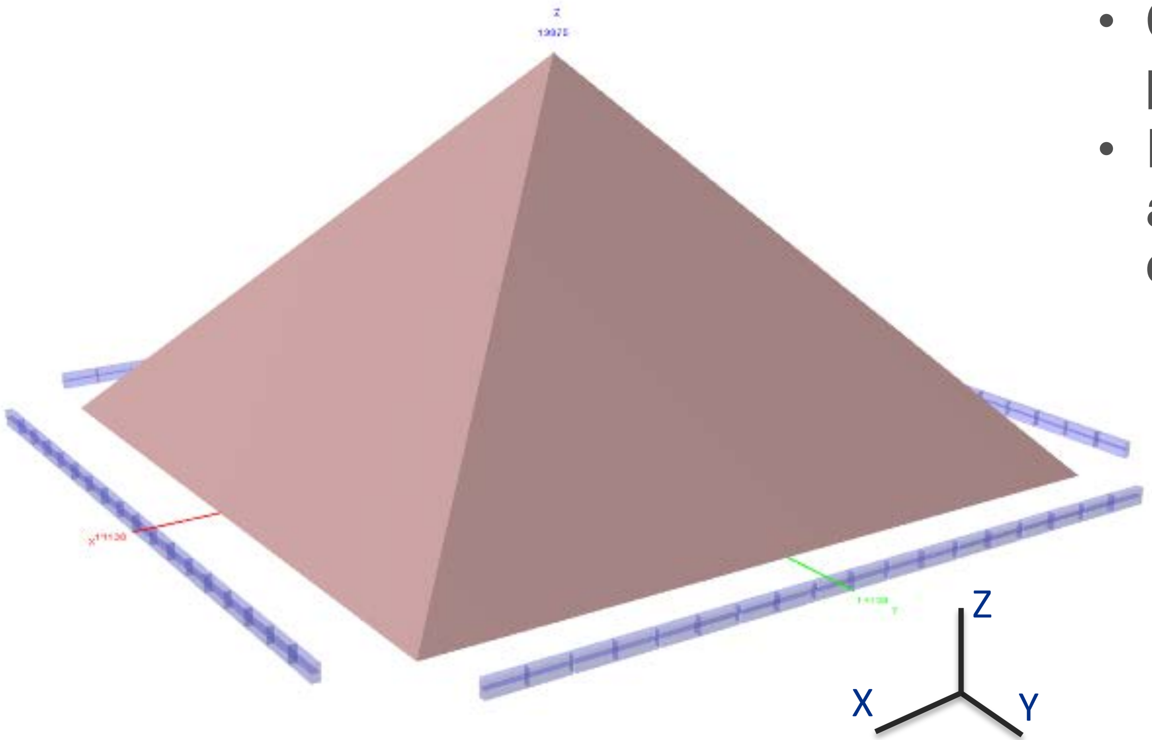
Without correction

On the Grid

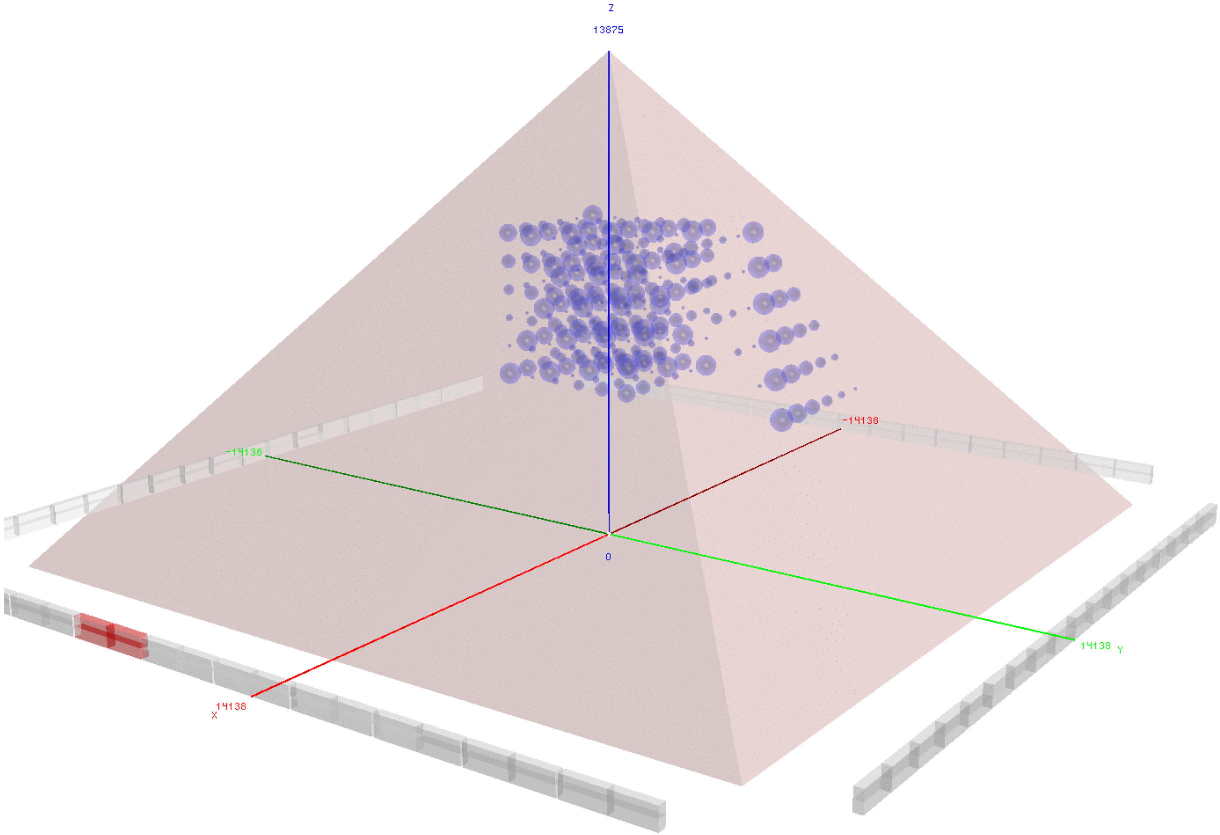
This is all Ralf Ehrlich's work

BTW, not his day job

Basic GEANT model



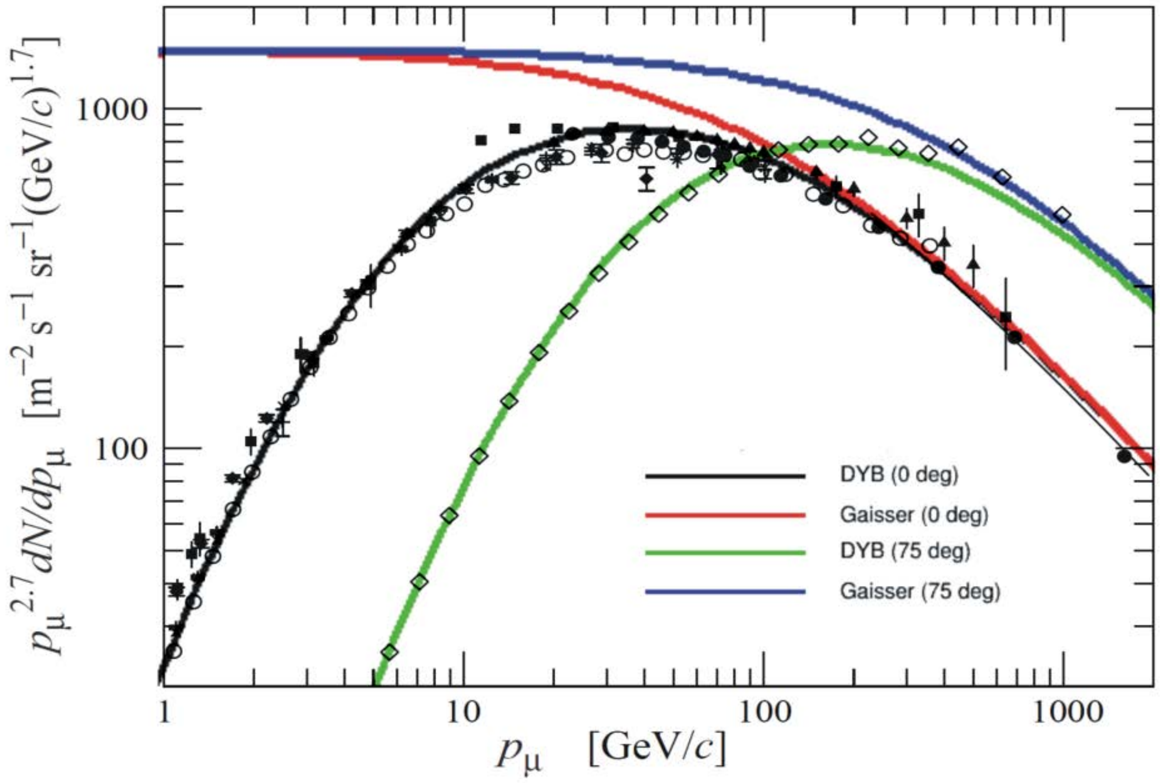
- Concrete (GEANT material) pyramid with voids (phantoms)
- For the simulation, 2 X 2 arrays are placed fully along each side of the pyramid
  - Note: Only build Two of these and move
  - What has been simulated is the equivalent of ~ 2 years of viewing
  - More efficient use of CPU


Z
13875
-14138
-14138
0
14138 Y
14138
X

Basic OSG run

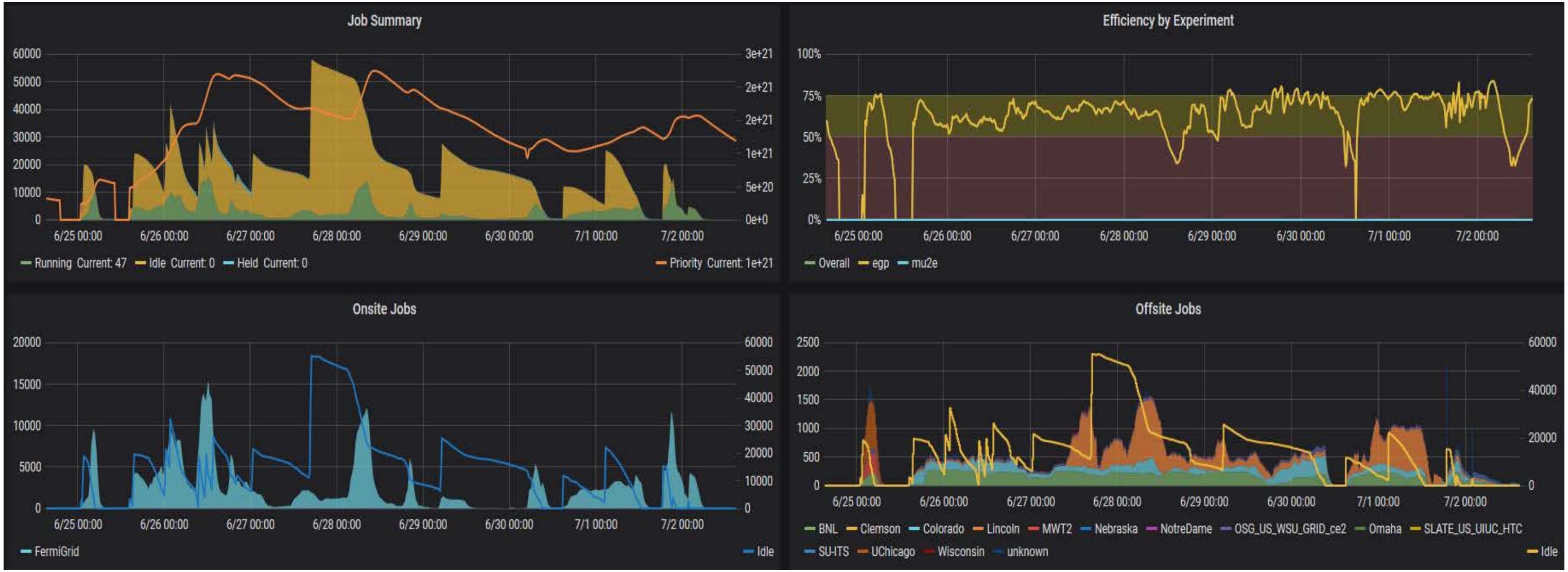
- Data run" setup
  - Generate cosmic ray muons using Daya Bay cosmic ray muon distribution for an energy interval between 50 GeV and 1 TeV, and polar angles between 40 and 90° .
    - The full azimuth angle range from -90° to +90° w.r.t. to the detector was used. The next simulation should use a smaller range.
    - The detector arrays of all locations are simultaneously present so that all locations can be handled in one simulation.
    - Cosmic rate 4.89 kHz for all four production planes combined.
  - Starting point of the events are projected to the surfaces of the world volume, so that GEANT can simulate the muon trajectories through the pyramid.
  - Simulated 2.61×10^{10} events, which corresponds to ~62 days with 36 container arrays present.
    - 3 year effective exposure (2 arrays of 4 containers each)
- "Baseline run"
  - Repeat the simulation for a pyramid without voids.
  - Simulated similar number of events (2.71×10^{10} events).

Cosmic-ray flux model



- Experiments have shown that the Gaisser model has disagreements with the data at lower energies. The Daya Bay group modified this formula to have a better agreement with the latest data and it is this cosmic-ray flux model that is used in this work.

Open Science Grid Jobs



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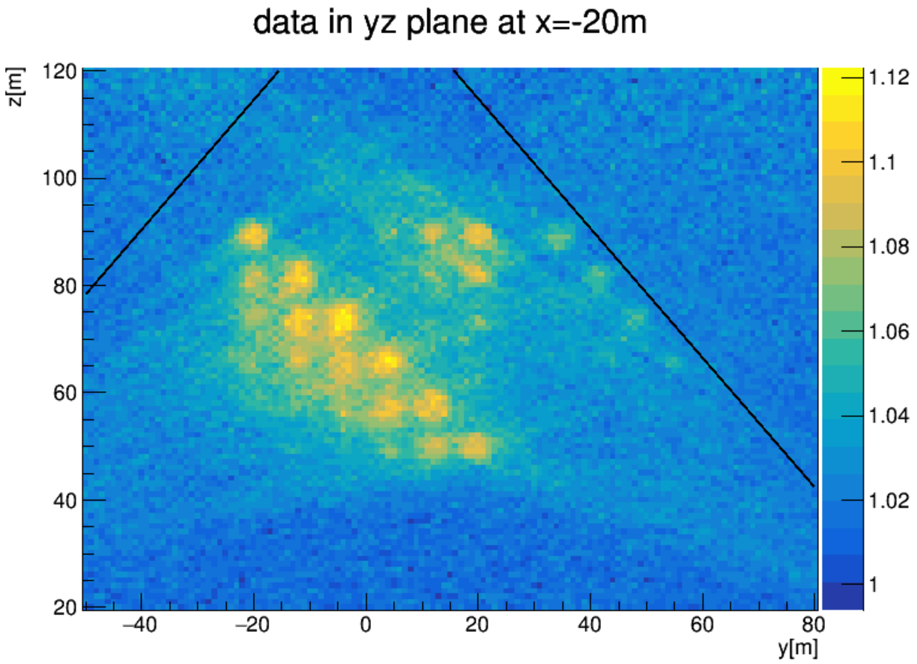
Reconstruction

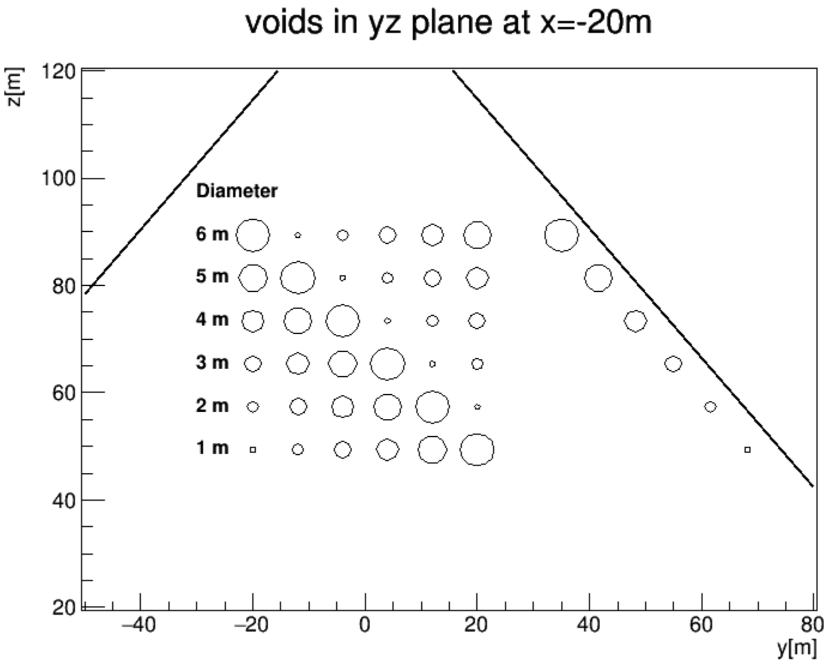
- Event selection
  - Use only events where either only one counter or two neighboring counters per layer has hits.
  - If two neighboring counters were hit, the average counter position (weighted by the deposited energies) was used.
  - Efficiency only 30%. Much room for improvement. Known issues.
- Basic Reconstruction
  - Calculate direction and location of track at center between both detector banks based on the positions of the counters which were hit.
  - Projected the tracks back to the pyramid and fill a 3D histogram representing voxels of the interior of the pyramid where the track went through.
    - Voxel dimension: 1 m x 1 m x 1 m.
    - The 3D histogram only covers the volume of the phantoms (plus a bit)

Reconstruction II

- Merging
  - Merge all 3D histograms from all runs and from all four sides.
  - Repeat for the baseline simulation (i.e. a pyramid without voids).
  - Divide the results of the baseline simulation from the main simulation.
  - Voids should be revealed by voxels which have more entries.

Results in yz planes





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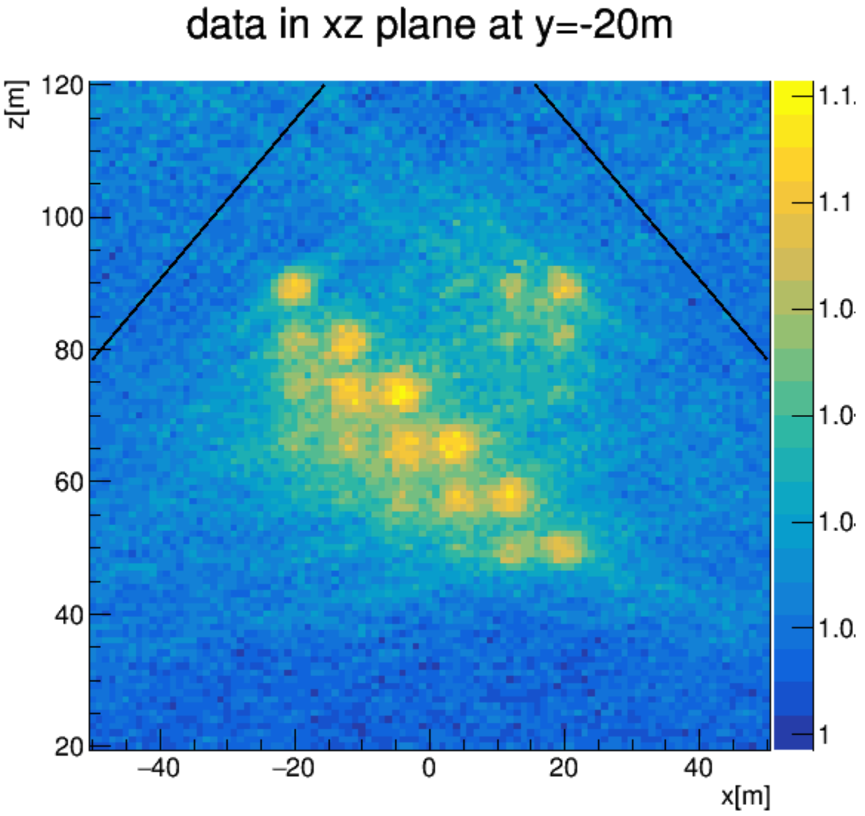
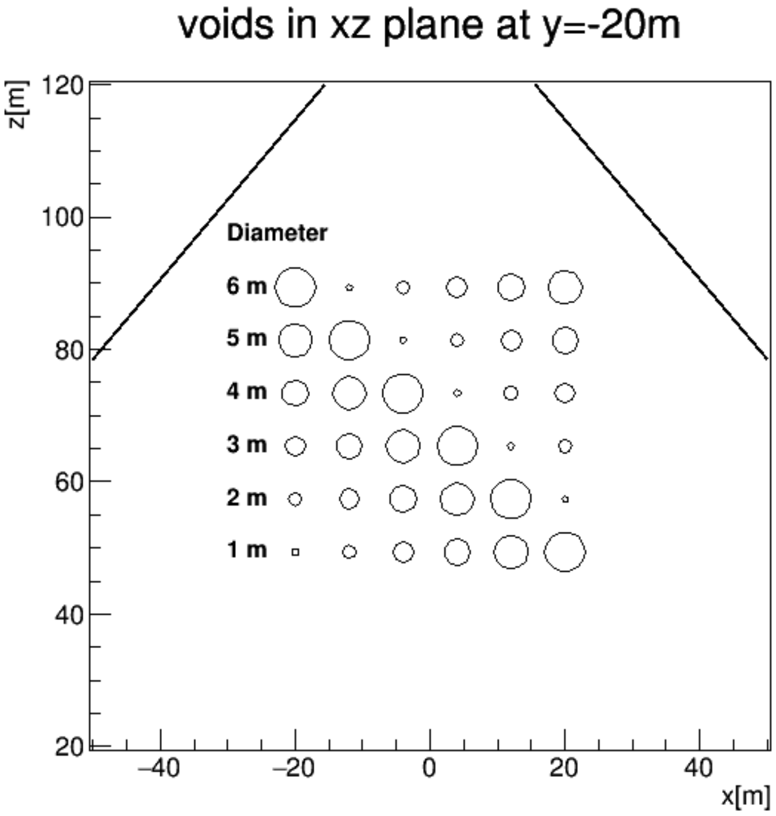
Results at xz planes





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Note on the model of Khufu

- The model of the pyramid currently in the simulation is for development and debugging.
- However, as I have shown the imaging does use a baseline division step. In MC this is easy. In real life not
- We need a solid model of the known structure of Khufu
  - Existing models are mostly wire-frame
  - Need typical densities of the limestone and granite

Khufu CAD model

Sophie Dukes

- The current state of the solid model is shown on the left
- We are performing an extensive literature search regarding know structure
  - Some of the best data from the early 20th century
  - Still need rock densities+
- More work to be done, but good start

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OSG run details

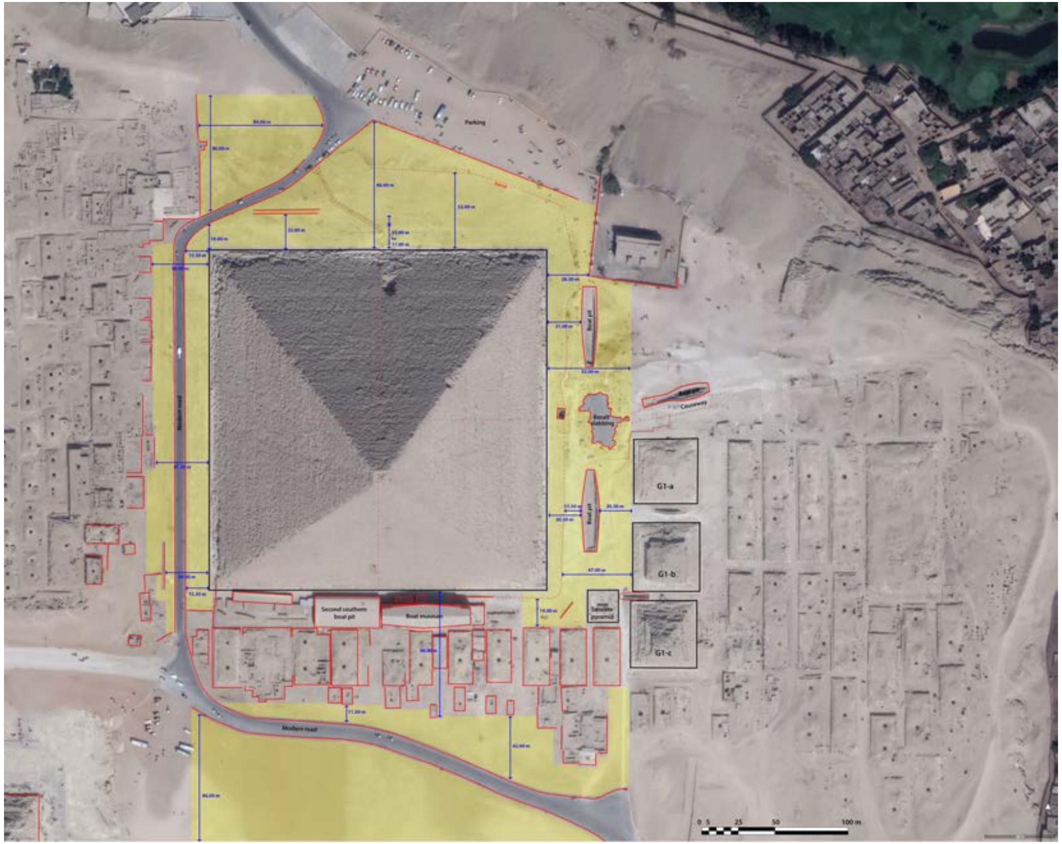
- The simulation is split into 2 stages
  - Stage 1: Simulates the cosmic-ray muons (and secondaries) up to the point where they reach the detector.
  - Stage 2: Continues the simulation where stage 1 stopped. Track filtering and reconstruction is also performed at this stage but may eventually be moved to a new stage 3.
  - Having the detector simulation separated in its own stage, allows us to simulate different detector designs without re-running the time-consuming stage 1.
- All OSG jobs are submitted with
  - The maximum of 10,000 processes in stage 1,
  - 2,000 processes in stage 2 (where 5 output files from stage 1 are used per process).
- Each stage 1 (2) process simulates 100,000 (500,000) events.
- Requested memory for each process: 1000MB.
- Run as OPPORTUNISTIC, DEDICATED, OFFSITE.
- All code is in C++ using the GEANT4 and ROOT libraries. The output files are in ROOT format.

OSG usage

Date	Number of data events (pyramid with voids)	Number of baseline events (pyramid without voids)	CPU hours
August 2020	2.6e10	2.7e10	1.3e6
June 2020	1.2e10	1.2e10	0.4e6
February 2020	1.0e10	1.0e10	0.5e6
September 2019	1.0e10	1.0e10	0.8e6 (?)
April 2019	0.4e10	0.4e10	?
February 2019	0.5e10	no baseline	?

Expect to need 4-5 additional runs similar to 8/20 run in CPU hrs.
Optimization of code continues.

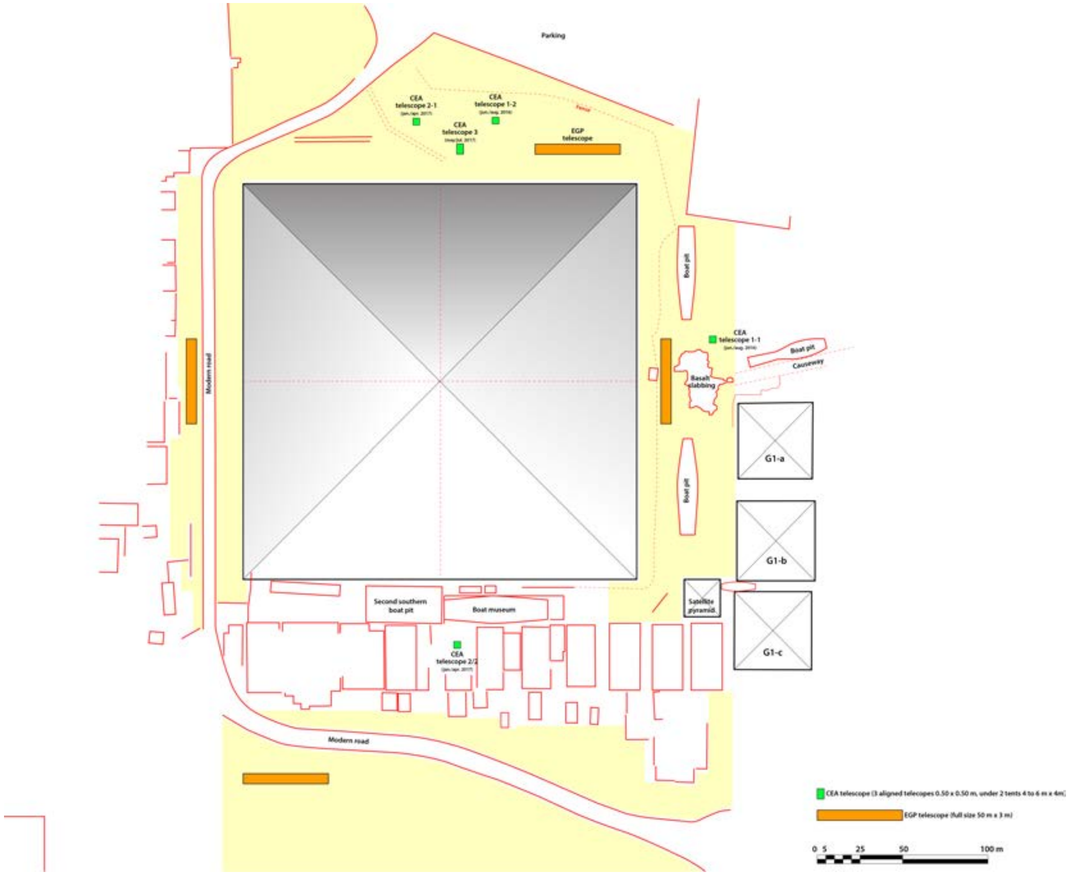
On the Giza Plateau



A busy place

On the Giza Plateau: Logistics

Gregory Marouard



Note: These are potential locations.

The actual siting plan will have to be approved by the Egyptian Ministry of Antiquities

Seed Funding

- The EGP mission was awarded a grant from the University of Chicago’s Big Ideas Generator
  - http://big.uchicago.edu/projects
- Fermilab/DOE has supplied matching funds
- And, of course, we have been given OSG resources

Fermilab

Moving Forward

- Continue optimization of the simulation on the OSG
  - Muon propagation
  - Detector
  - Architecture
- Develop tomographic reco algorithms
  - Need some extensions of medical techniques
  - Also requires data (root) manipulations
- Complete solid model of Khufu & develop models with hypothetical new unknowns
- Continue to explore private funding for full project

Conclusions

- *The pyramids of the Giza plateau have fascinated visitors since ancient times and are the last of the Seven Wonders of the ancient world still standing*
- Debate continues among researchers as to their origins, purpose and how they were built
- The very large size of the EGP's telescope system will provide 100X more data than was accumulated in previous measurements of this kind
  - By moving the telescopes around the pyramid, we will collect data that has potential for detailed 3D image reconstruction (Need many more μs)
- The telescopes are very modular in nature. This makes it very easy to reconfigure and deploy at another site for future studies
- We are very encouraged by the initial simulation results

Thank you & Be Safe Out There

Questions?