Probing the Structures of Pyramids using Cosmic Ray Tomography

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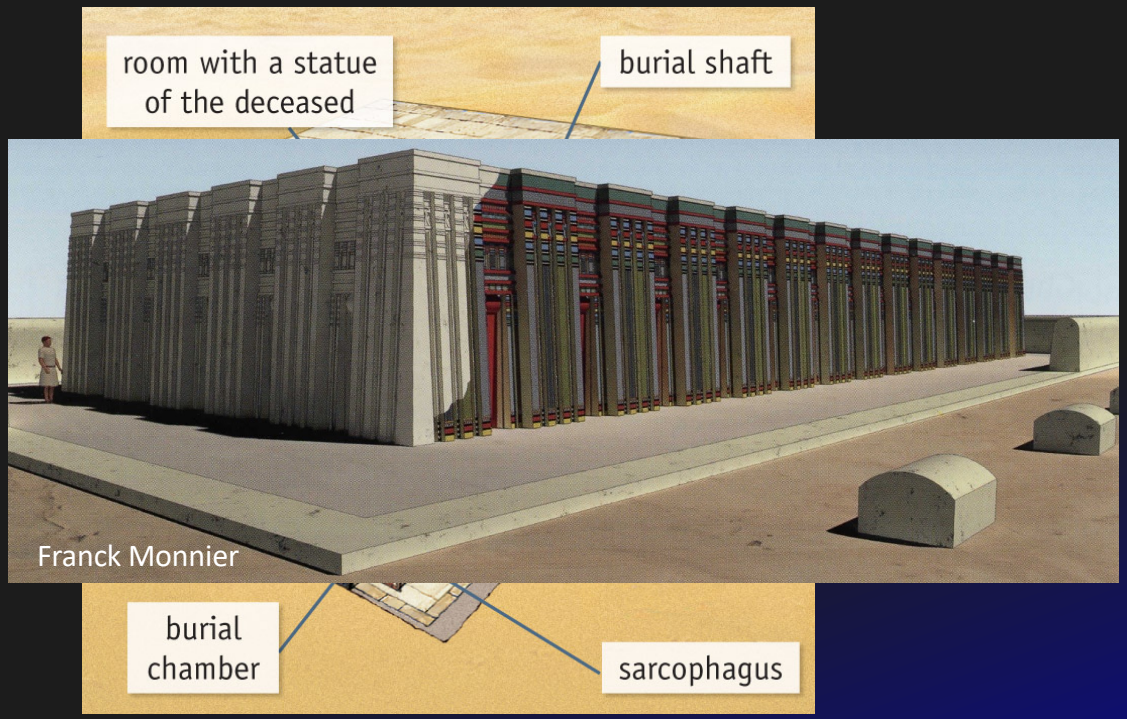
The Ancient Egyptian Pyramids

A Bit of History

The ancient Egyptians held the afterlife to be of supreme importance, and eternal life was only possible if the dead body was preserved from decay so the deceased could be reborn in the afterlife.

Burying the dead in earthen tombs would not preserve them from corruption from the elements, nor from tomb robbers, so structures called **mastabas** were developed that provided better protection.



Mastabat al-Fir'aun (2510–2503 BC)

The First Pyramid: Djoser

The Pyramid of Djoser (3rd Dynasty) at Saqqara is considered to be the first of its kind.

2670–2650 BCE

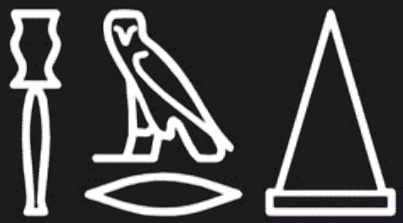
Started out as a Mastaba, and then more layers were added to it

First large Egyptian structure made from limestone, not mudbrick

Imhotep is attributed as the architect

Charles J. Sharp - Own work, from Sharp Photography, sharpphotography

myr



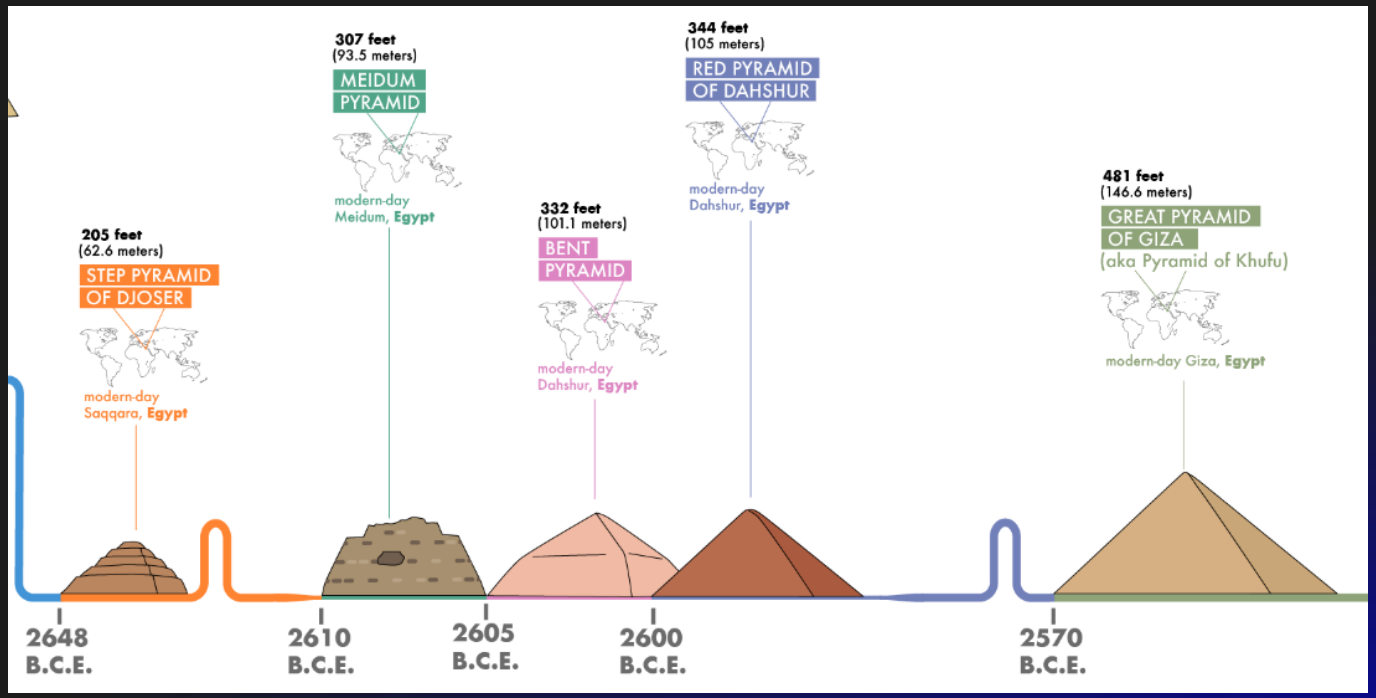
Who was Imhotep?

Advent of Pyramids Happened Very Quickly

First few pyramids: Step, Meidum and Bent Pyramids, were not quite successful

First successful pyramid, a prototype for those that followed, was the Red Pyramid of Dashur built in 2575–2551 BCE.

Largest pyramid is the Great Pyramid of Khufu, built immediately after the Red Pyramid and 80 years after the Step Pyramid of Djoser



Djoser Sneferu Khufu

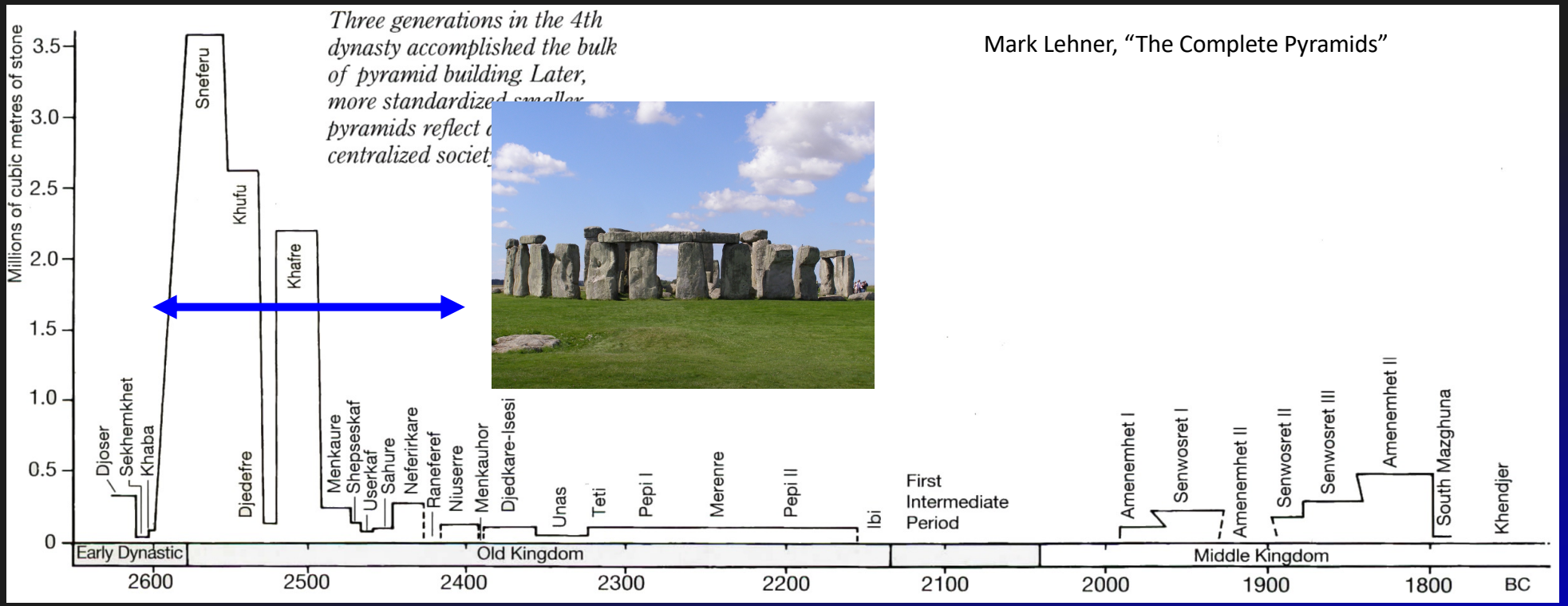
80 years

Great Era of Pyramid Building was Short Lived

Over 90 royal pyramids were built

Last pyramid built by Ahmose I 1560 BCE

Note: About 180 much smaller pyramids were built in Nubia, the first 800 years after the last in Egypt

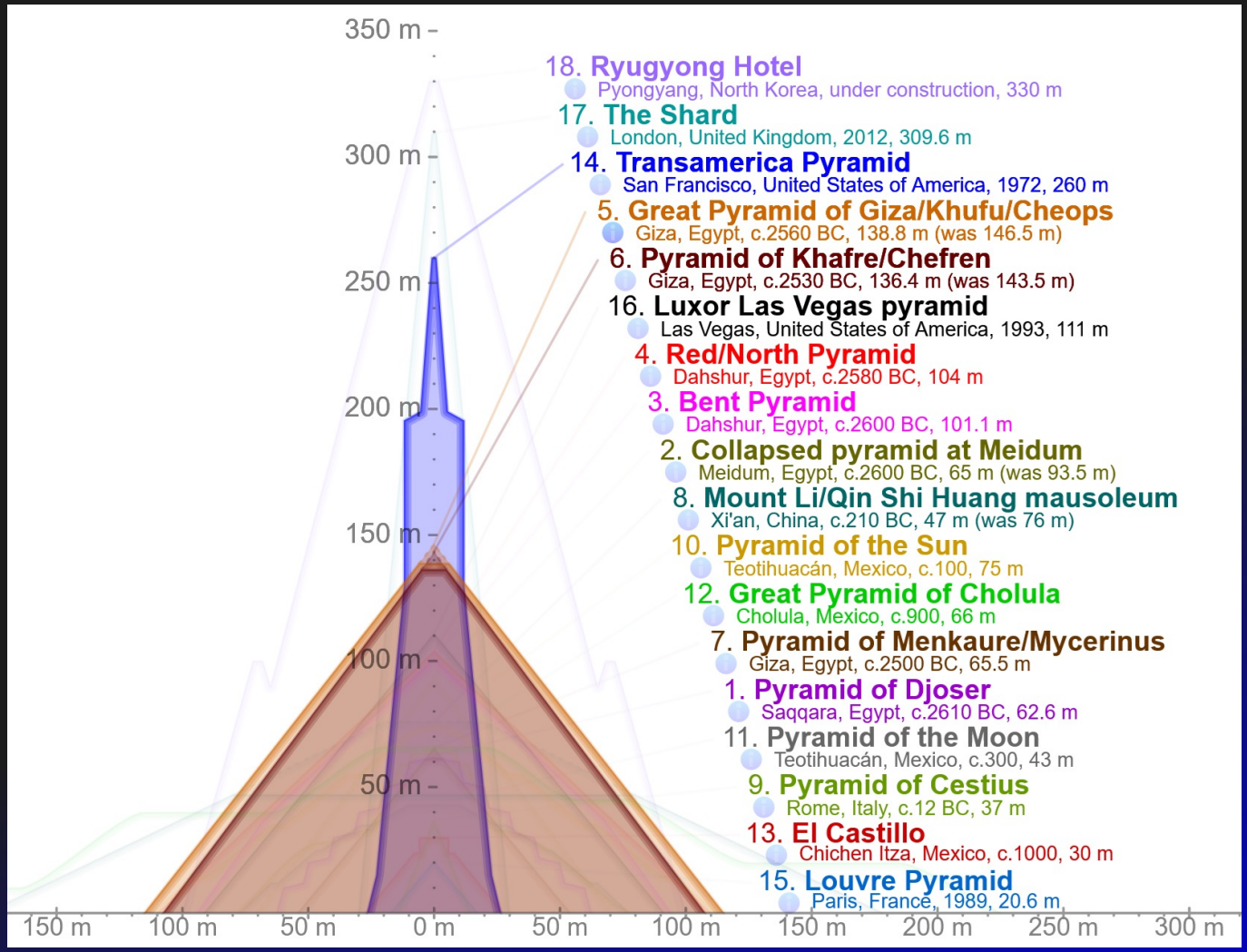


Relative Sizes of the First Pyramids

Pyramid Comparisons

Great Pyramid of Khufu remained the largest manmade structure for 3,880 years until surpassed by Lincoln Cathedral in 1311

The spire collapsed in 1549 giving the record back to Khufu's pyramid until the end of the 19th century



The Great Pyramid of Khufu

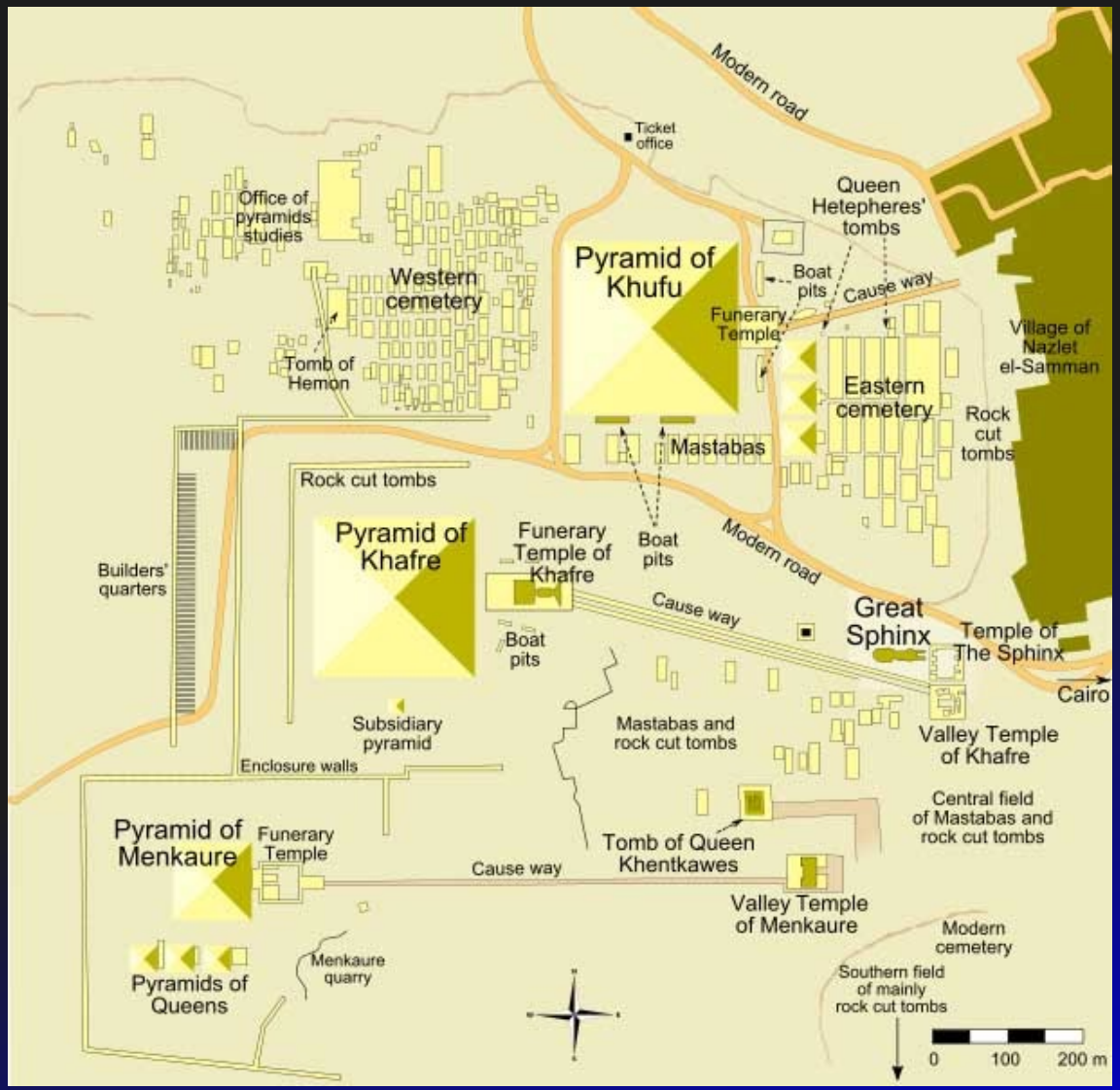
The Great Pyramid of Khufu is the last of the Seven Wonders of the ancient world still standing

Giza Pyramid Site

Khufu's immediate successor, his son Djedefre, build a large pyramid 8 km north of Giza, of which little remains.

Khafre, another son of Khufu, decided to build his pyramid next to his father's.

It is almost as tall: 136.4 m vs 146.6 m



Giza Pyramid Site as it Looked 4500 Years Ago

Giza Pyramid Site as it Looked 100 Years Ago

Before the Aswan dam halted the annual Nile flooding and before modern Giza

Giza Pyramid Site as it Looks Now

with modern Giza in the Distance

The Great Pyramid of Khufu

Built in 23 years by 20,000-30,000 paid workers

2,300,000 limestone blocks, each ~1 m^3

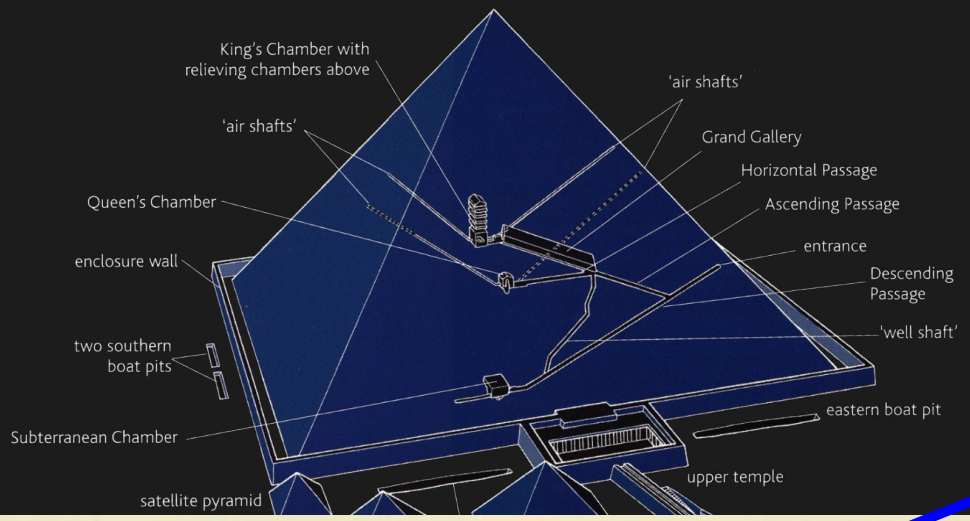
34 blocks laid per hour (8 hr day)!

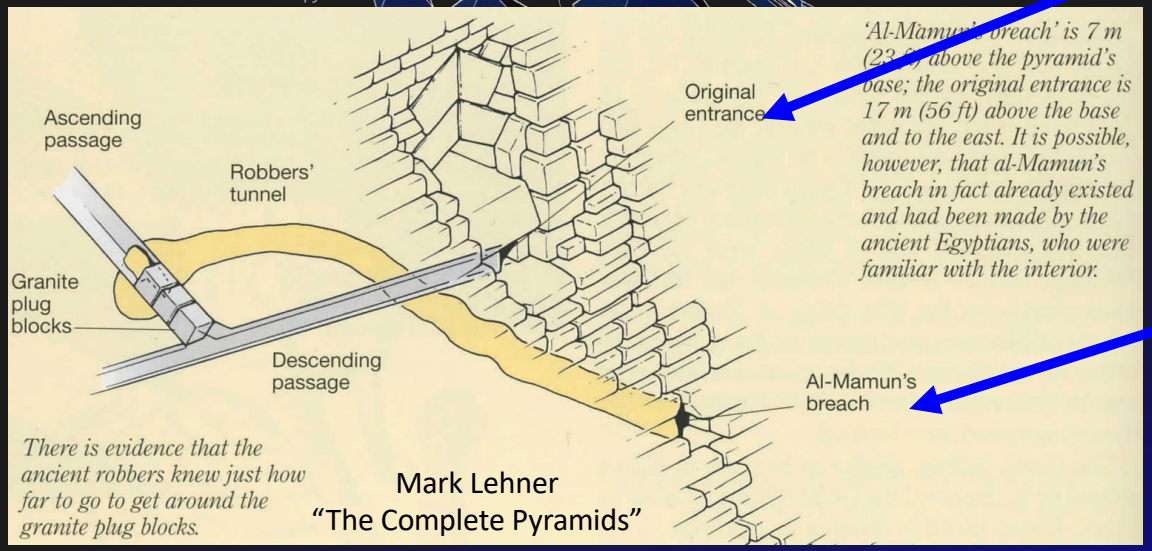
Stones as hard as granite and basalt had to be cut using Bronze Age tools

146.6 m (481 ft) high; 230.3 m (756 ft) wide

(Washington Monument: 169 m (555 ft) high)

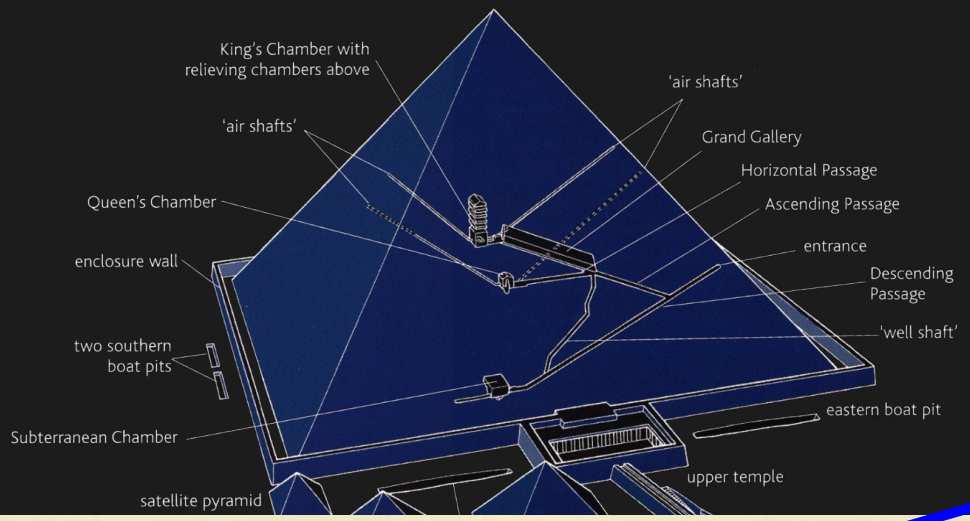
The Great Pyramid of Khufu

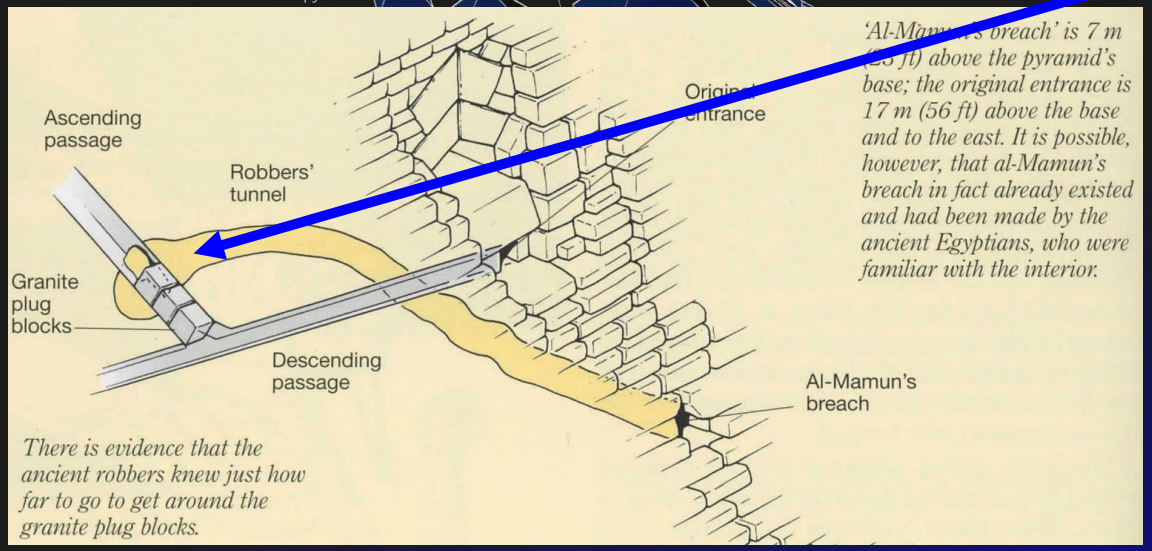




Mark Lehner
"The Complete Pyramids"

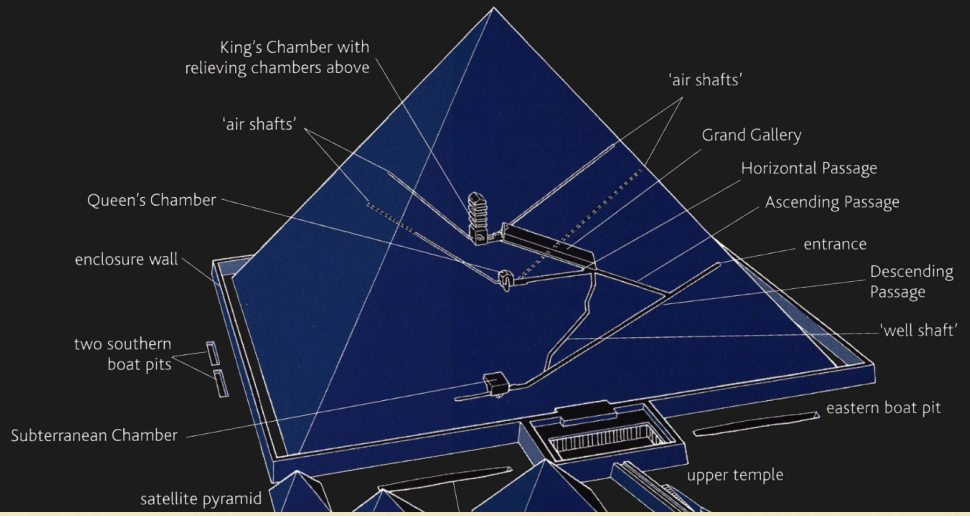
The Great Pyramid of Khufu

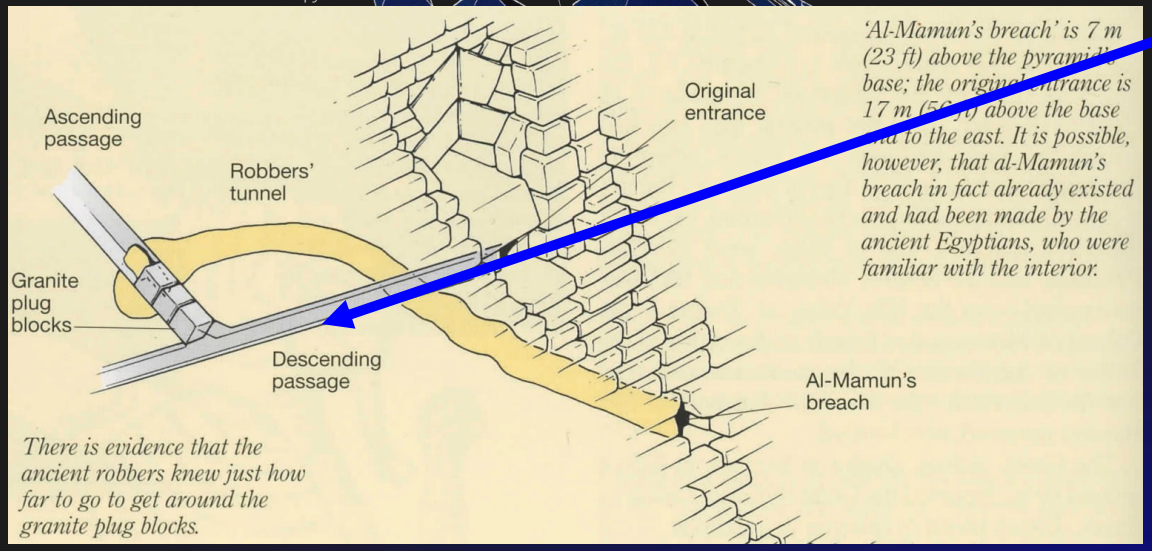




Robber's Tunnel

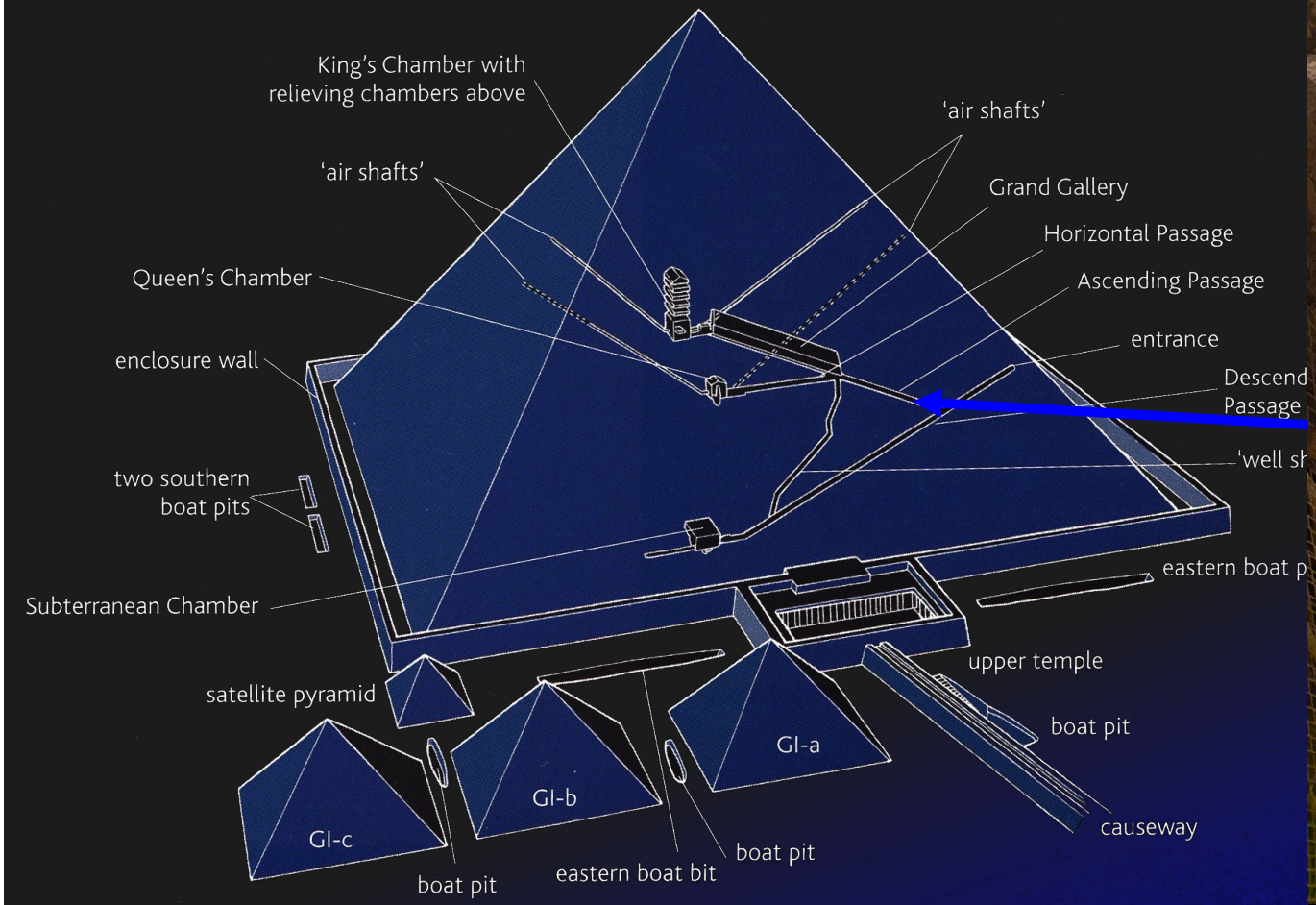
The Great Pyramid of Khufu





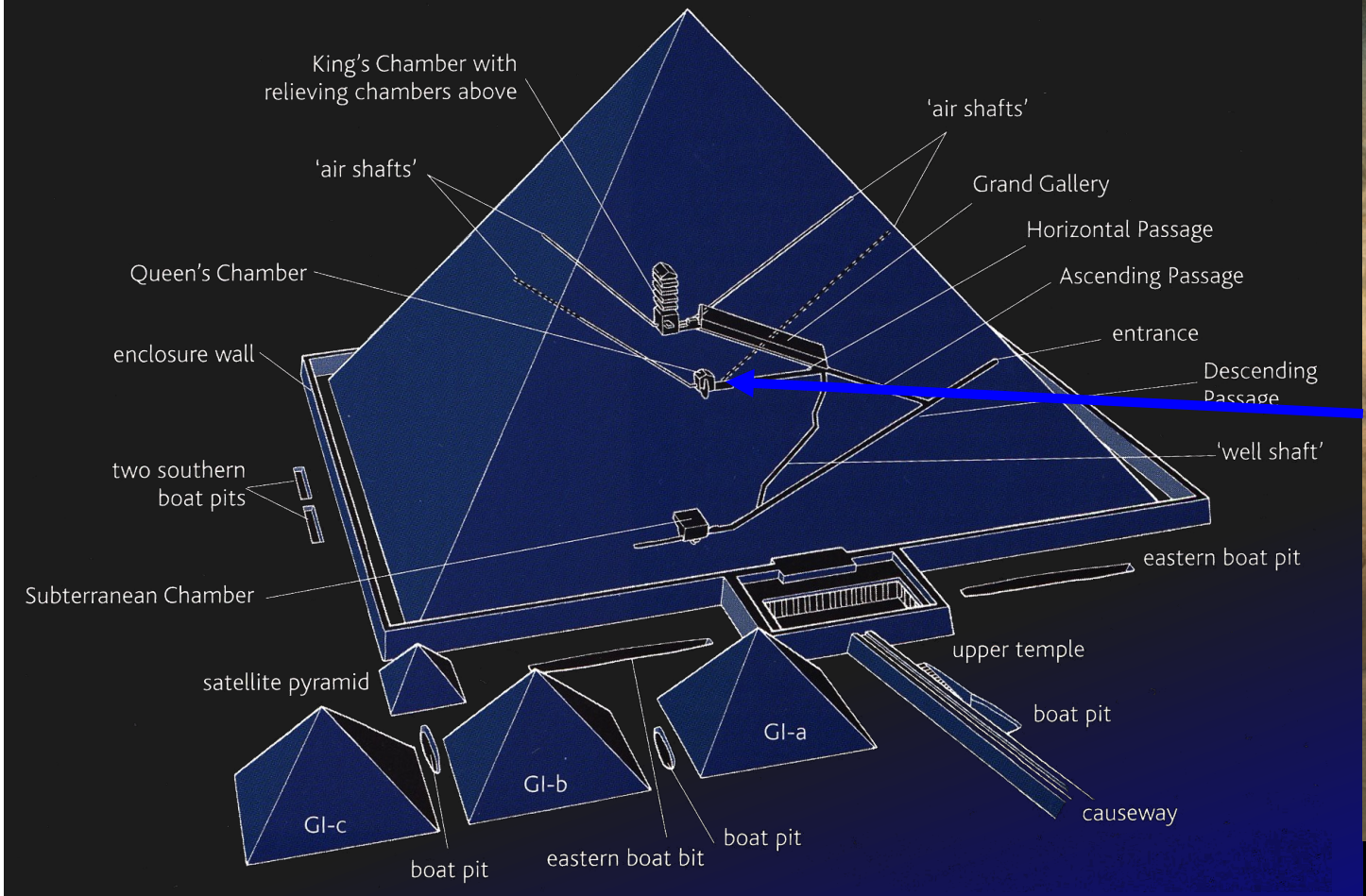
Descending Passage

The Great Pyramid of Khufu



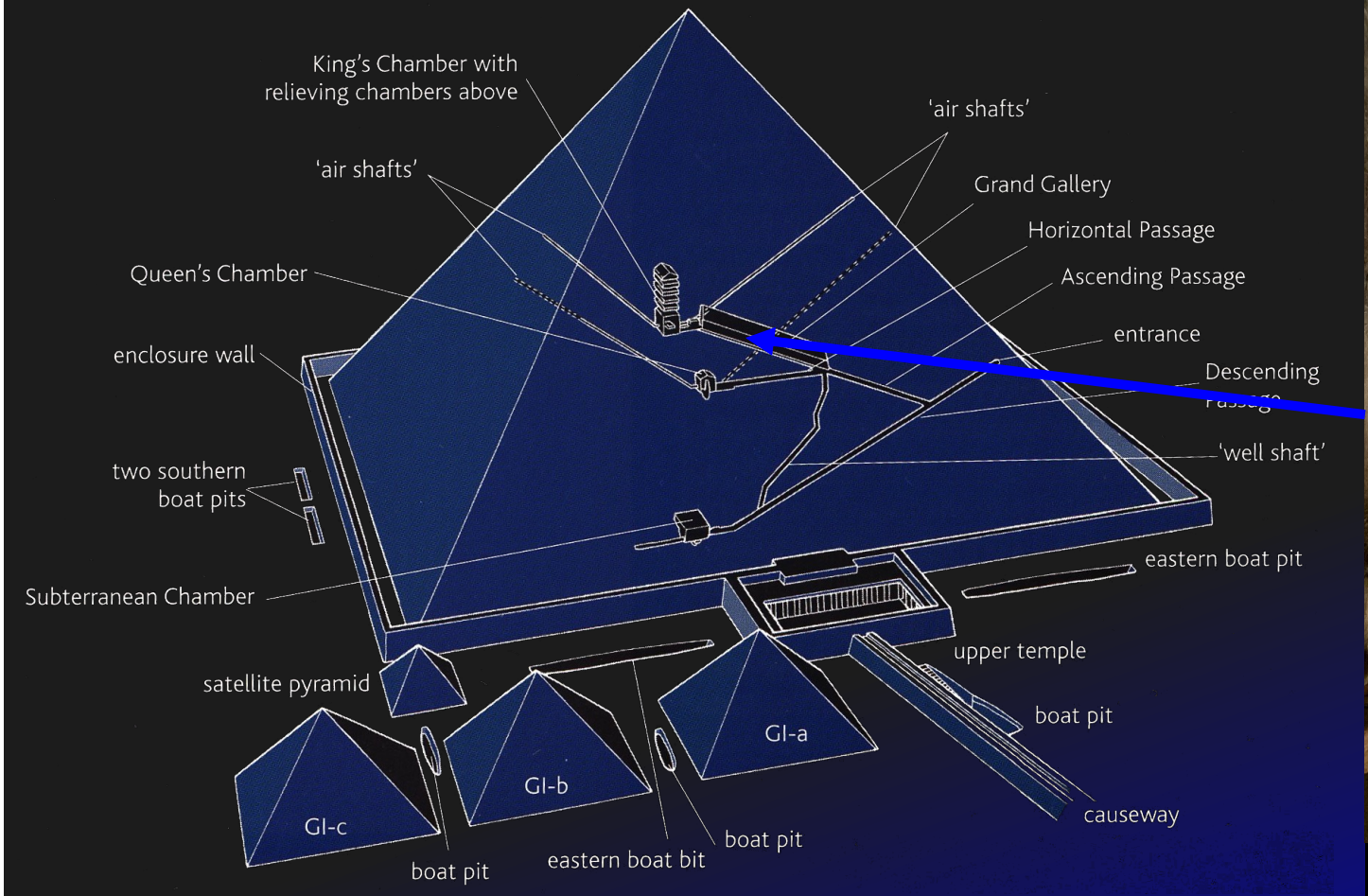
Ascending Passage

The Great Pyramid of Khufu



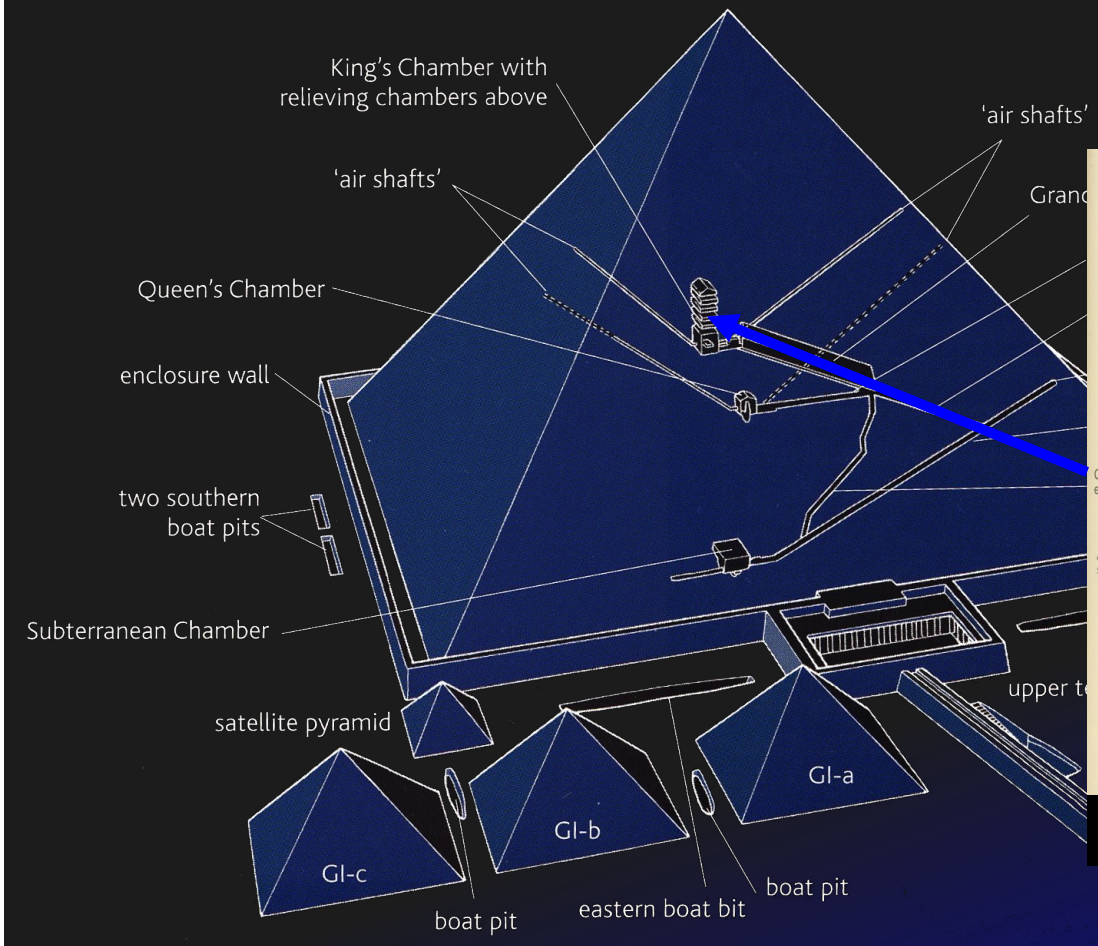
Queen's Chamber

The Great Pyramid of Khufu



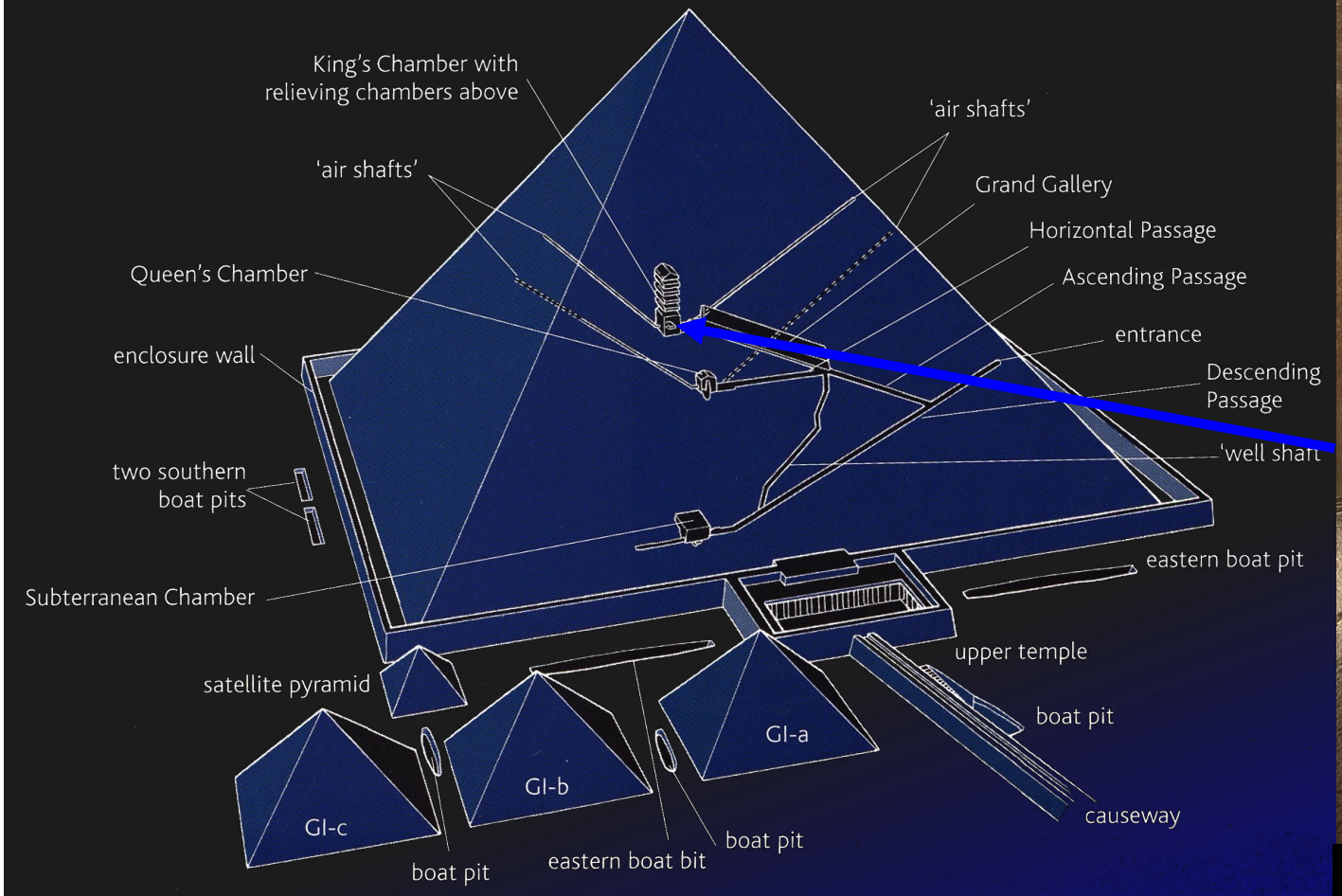
Grand Gallery

The Great Pyramid of Khufu



King's Chamber with Relieving Chambers

The Great Pyramid of Khufu



King's Chamber

Exploring the Pyramids

Exploring the Giza Pyramids

By the time of the Middle Kingdom (1980-1760 BCE) the pyramids were being plundered and stripped for stone

When in AD 820 Caliph al-Mamun broke into Khufu's pyramid, forcing a passage that is now the tourist entrance he found evidence that it had been entered much earlier

With the arrival of Napoleon's army in 1798, along with a host of scholars, an era of scientific exploration began, often aided by drilling and blasting new passages

No treasures or mummies were found in any of the pyramids; in the Great Pyramid of Khufu only an empty granite sarcophagus

The pyramids are now protected by the Egyptian Ministry of Antiquities so blasting any new passage is strictly forbidden

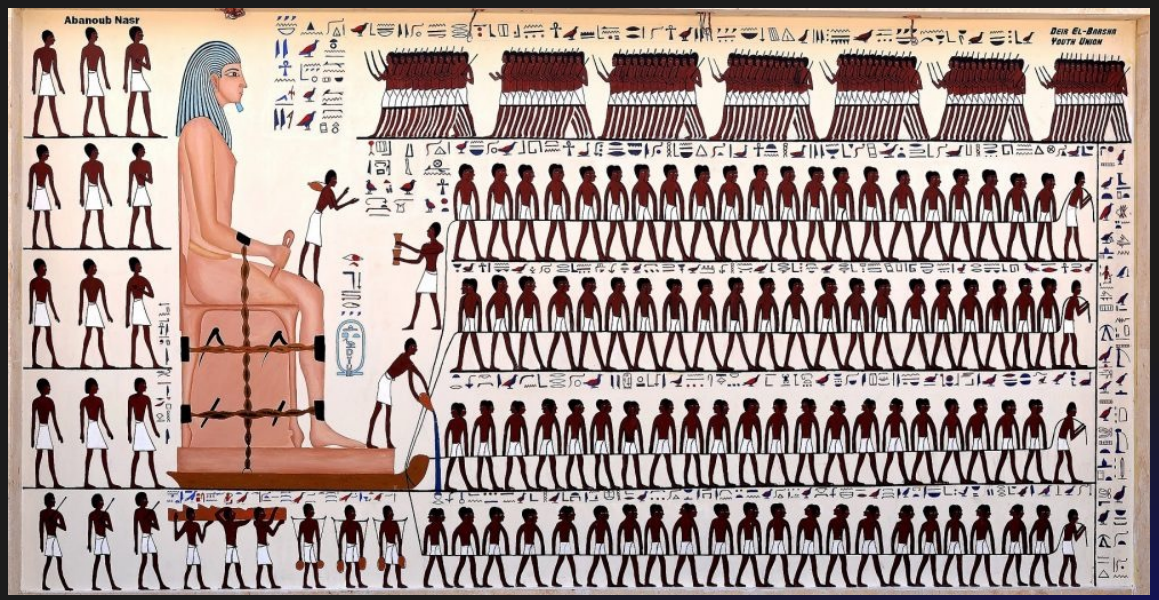
Modern Explorations

What captivates the public (and me) is the prospect that hidden chambers filled with treasure remain to be discovered in the pyramids of Egypt

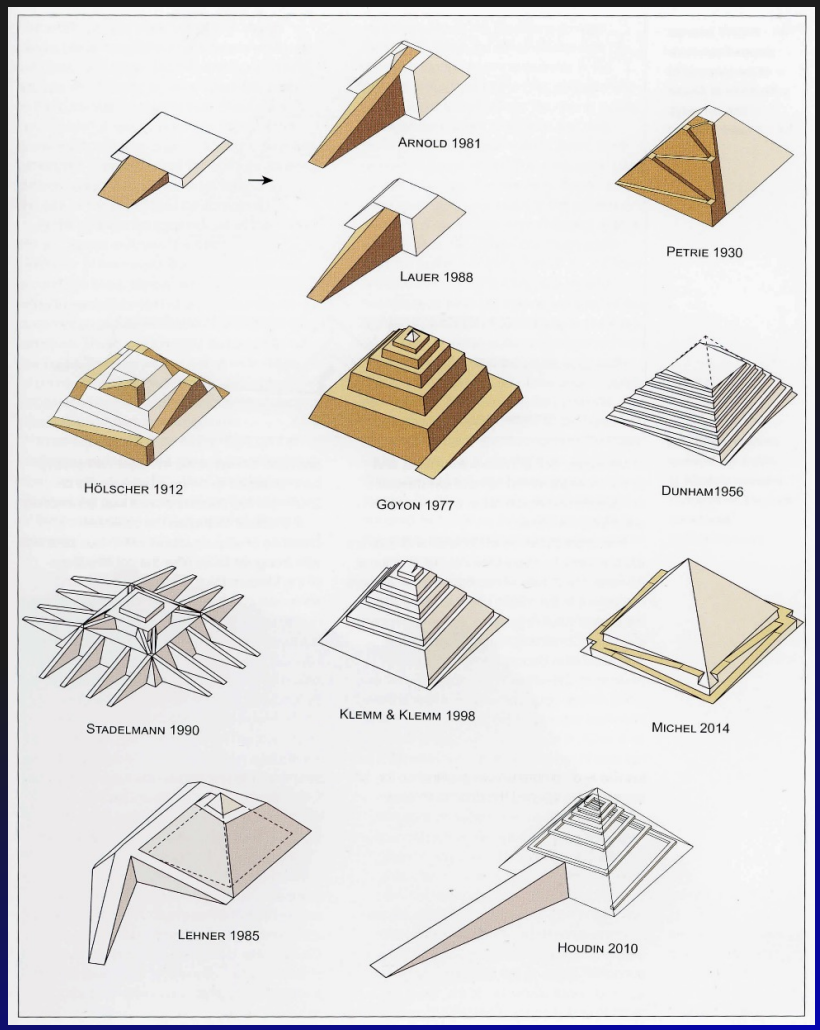
Modern Explorations

Egyptologists are more interested in: “how were the pyramids built?”

Ancient Egyptians left precious few records



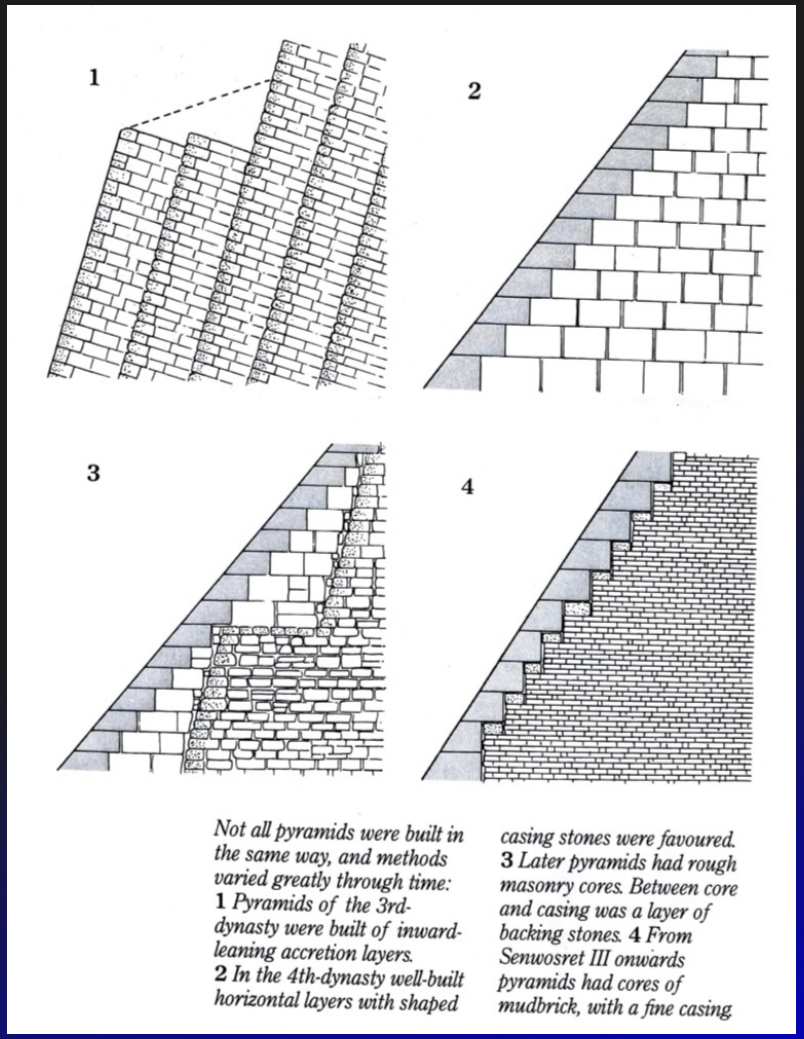
Relief from tomb of Djehutihotep at el-Bersheh showing 172 workers hauling his 58 tonne colossal statue



“The Great Pyramid”, F. Monnier and D. Lightbody

Modern Explorations

Egyptologists are more interested in the internal structure of the pyramids

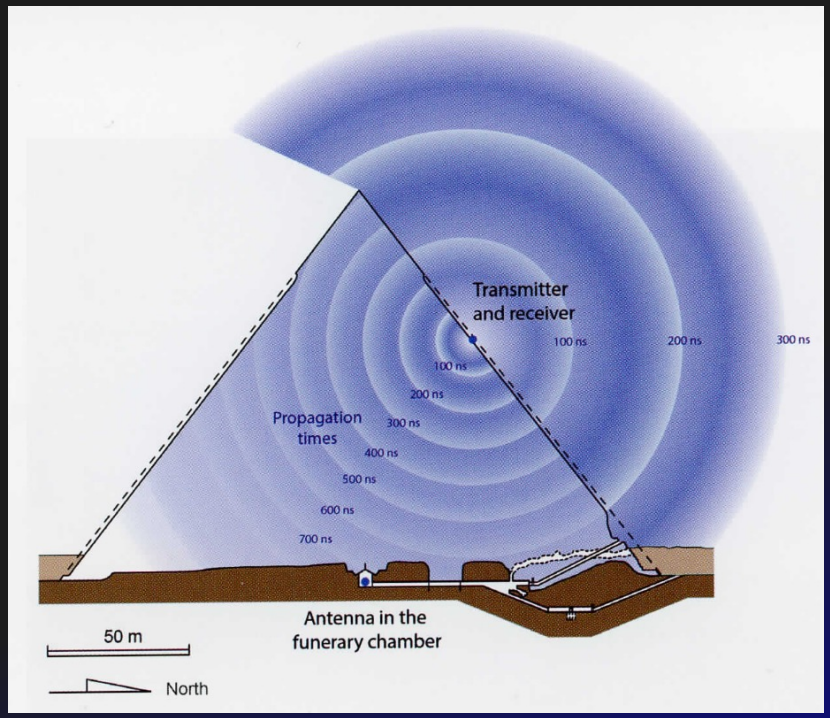


Mark Lehner, The Complete Pyramids, 1997

Non-Invasive Exploration: Radar

In 1974 a USA-Egyptian team used ground penetrating radar to probe the Khafre and Khufu pyramids

This did not produce any results as the technique failed



"The Great Pyramid", F. Monnier and D. Lightbody

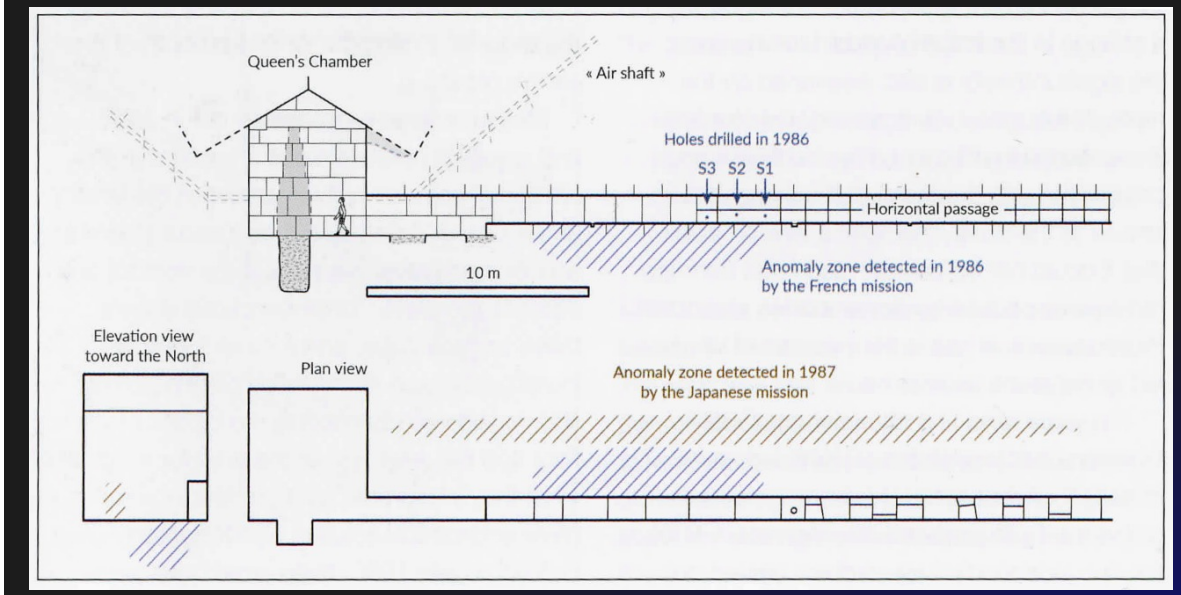
Non-Invasive Exploration: Microgravity

In the 1980s a French team made microgravity measurements of the Great Pyramid

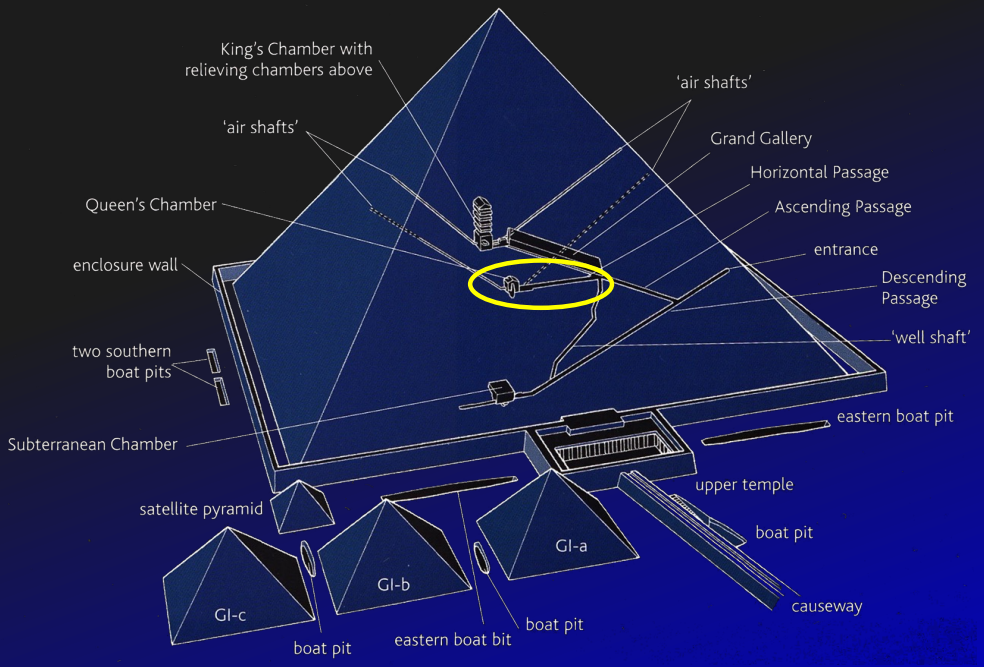
Gravimeter: can measure differences of one-billionth of Earth's gravity

In 1986 reported a "density defect" on the corridor to the Queen's Chamber

Received permission to dill holes for an endoscopy of the void: nothing was found but sand

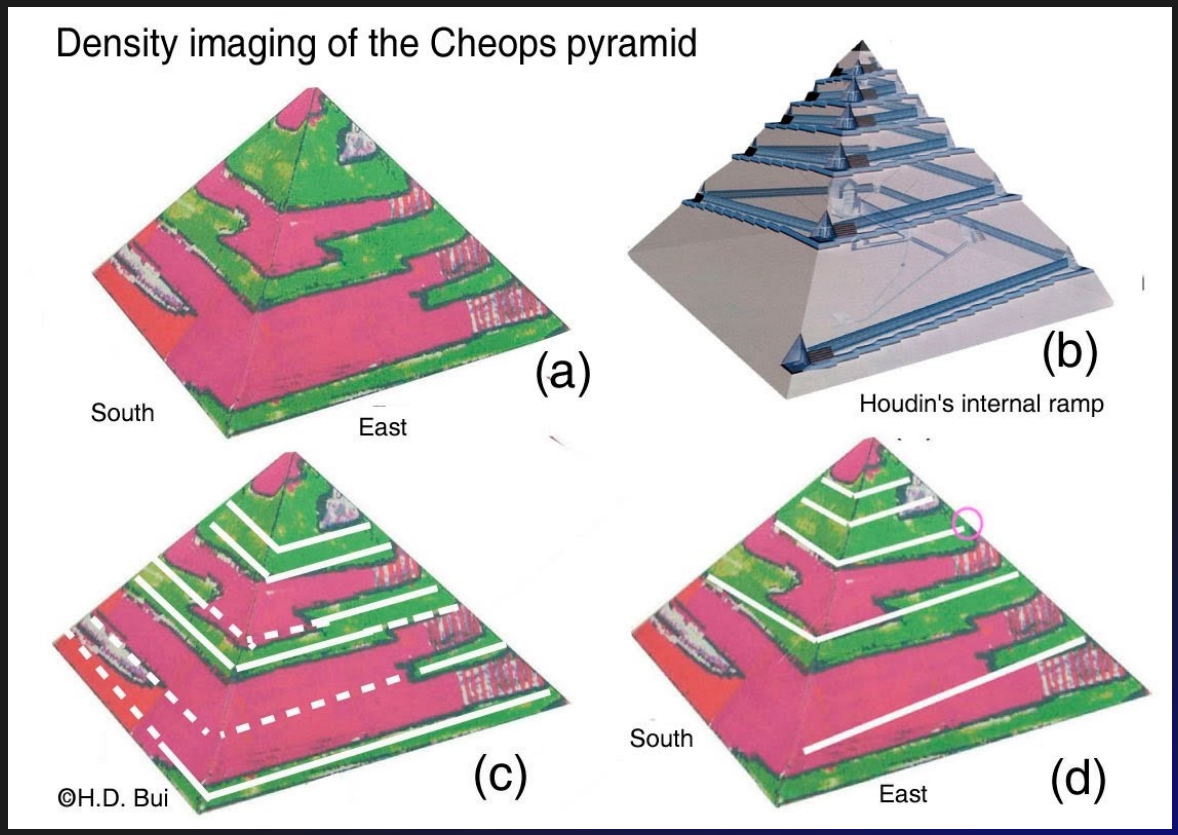


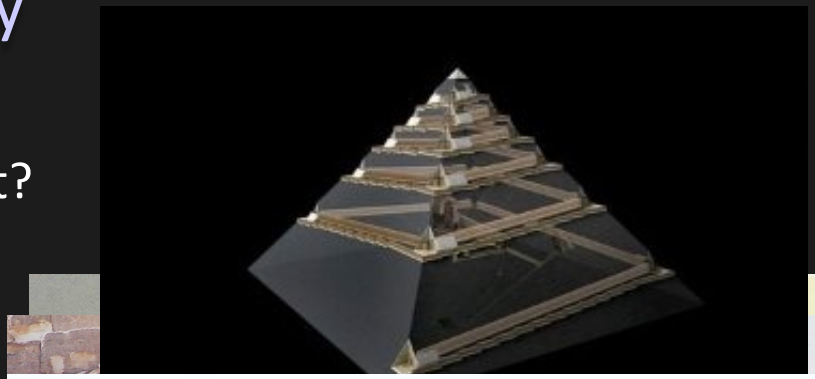
"The Great Pyramid", F. Monnier and D. Lightbody

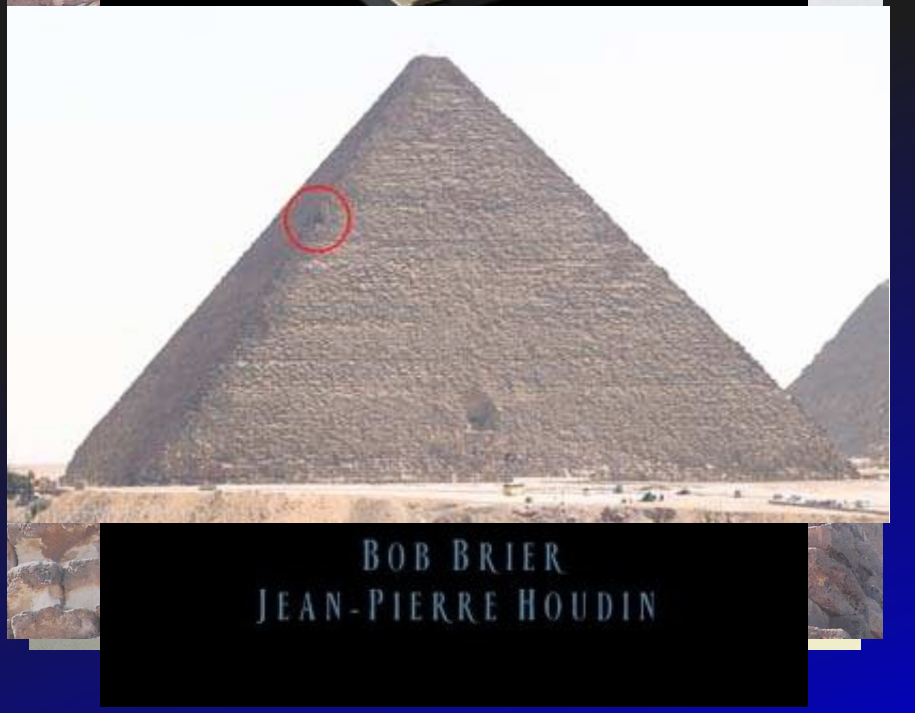


Non-Invasive Exploration: Microgravity

Do microgravity measurements suggest that Houdin's internal ramp theory of pyramid construction is correct?







Muography

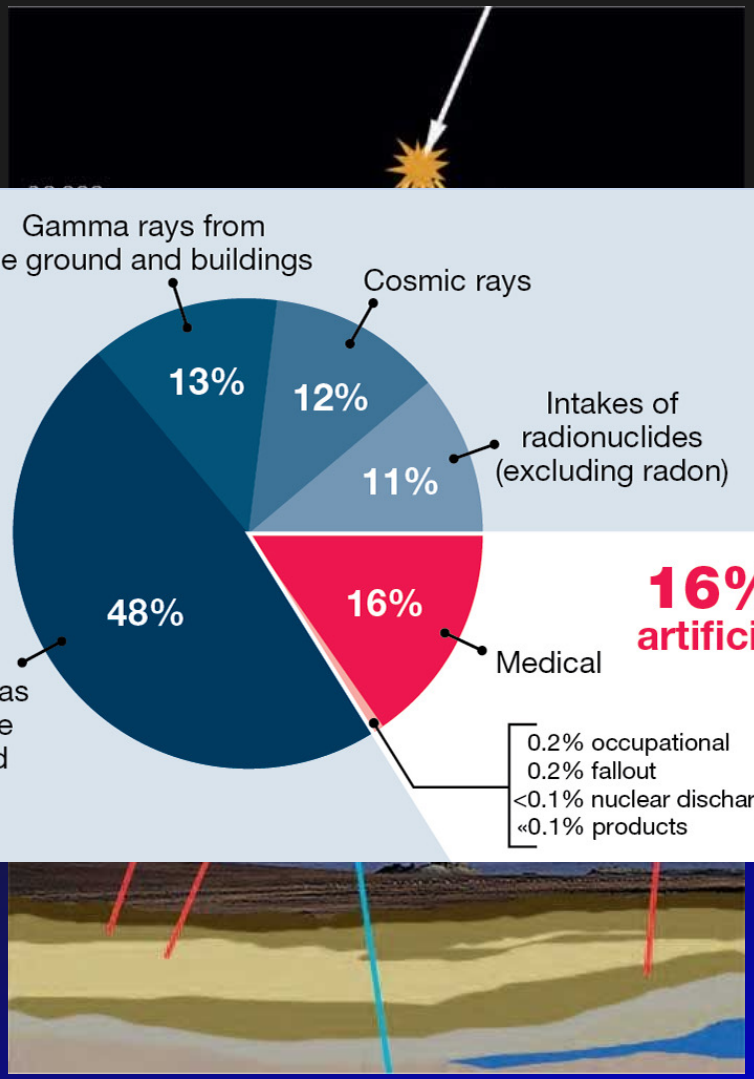
Non-Invasive Exploration: Muography

Similar to tomography but using cosmic-ray muons rather than X-rays

Cosmic-rays are created high in the atmosphere, mostly by high energy protons from beyond the solar system

In general, cosmic rays are a pain:

- For us living on Earth's surface, our atmosphere is a pretty good shield, and only a trickle of the cosmic-ray radiation reaches us.
- An astronaut on a year-and-a-half mission to Mars would receive a radiation dose over 1,000 times what you receive on Earth – 65 times the annual limit established by Fermilab. Your electronics would also take a pounding and must be specially designed to withstand the radiation dose.
- Cosmic rays for particle experiments can produce backgrounds to your signals, which can vary from being merely annoying to actually limiting your sensitivity.



Muography: How it Works

The cosmic rays we use are secondary particles called muons

The muon has a short lifetime: $\tau = 2.197\ \mu s$ ($\mu^- \rightarrow e^- + \nu_\mu + \nu$)

Going at speed of light:

$$d = vt = c\tau = 659\,\mathrm{m}$$

Forgot Einstein's relativistic time dilation!

$$d = vt = v(\gamma\tau) = \frac{(\gamma m_0 vc)}{m_0 c^2} c\tau = \frac{pc}{m_0 c^2} c\tau$$

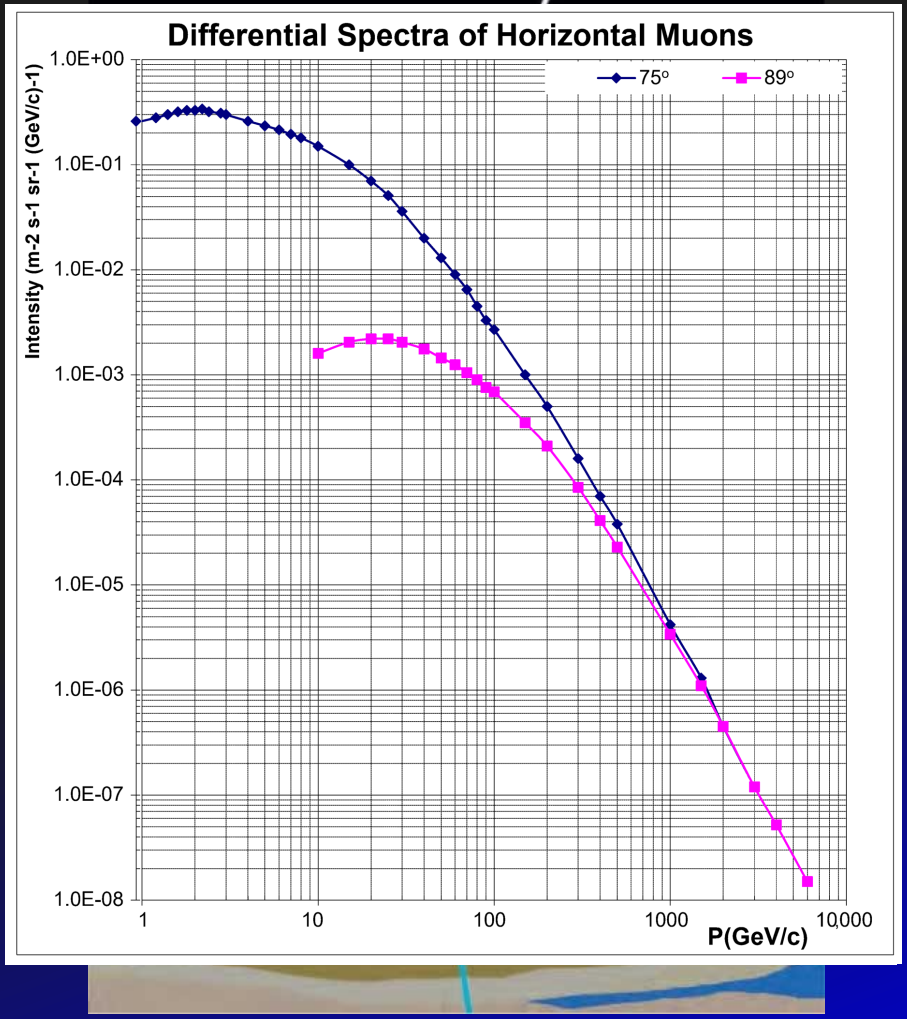
$$= 24.9\,\mathrm{km}$$

Many make it to the ground!

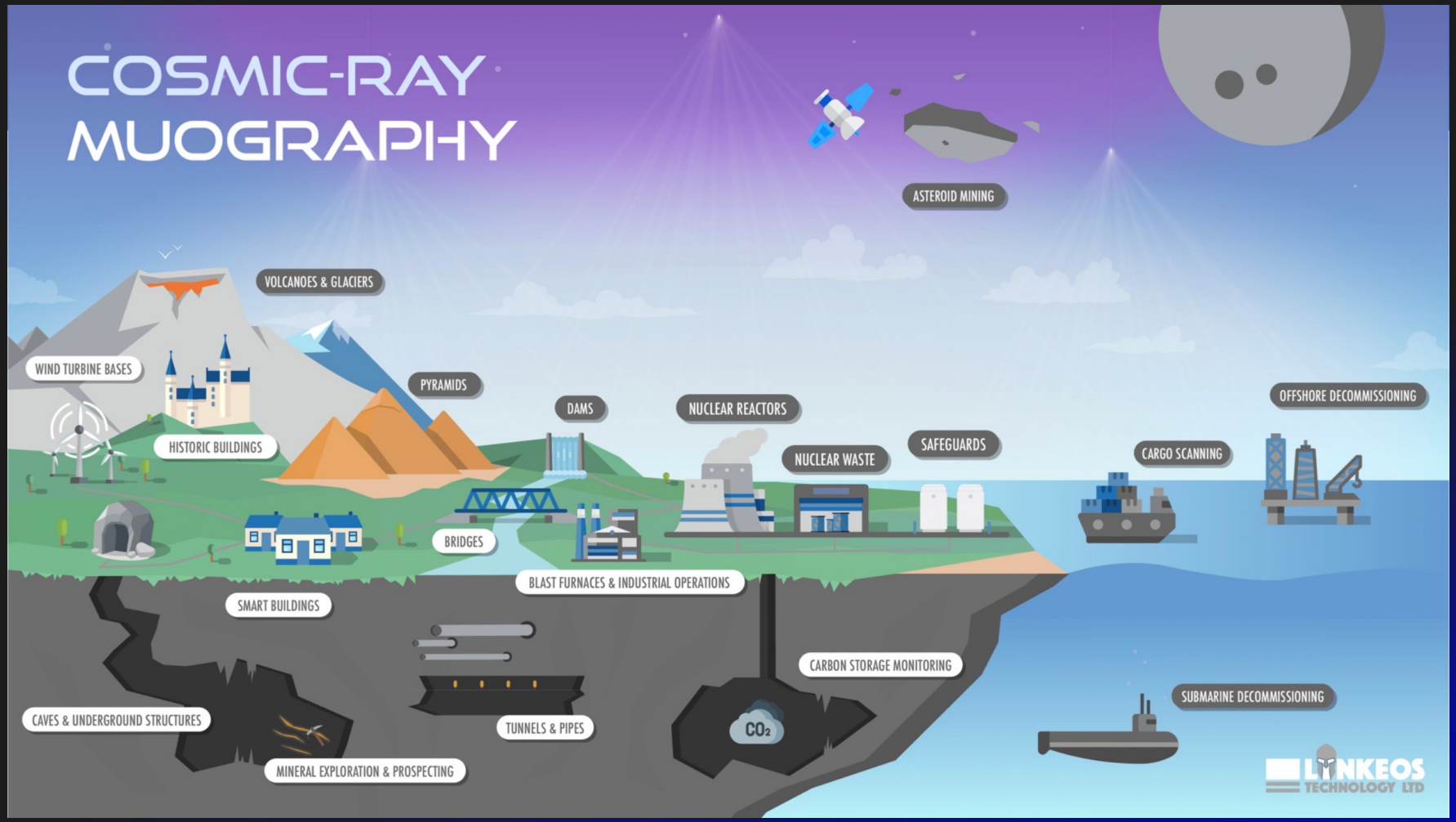
Relatively abundant: Cosmic ray muons arrive at sea level with a flux of about 1 per cm^2 per minute, or 170 $m^{-2}s^{-1}$

Penetrating: Their mean energy: 4 GeV (4 x 10^9 electron volts), which will penetrate ~10 m of "standard" rock

Non-invasive: Entrance by destruction is no longer possible since preserving these unique structures is paramount.



Muography: A New and Growing Field



Muography: A New and Growing Field

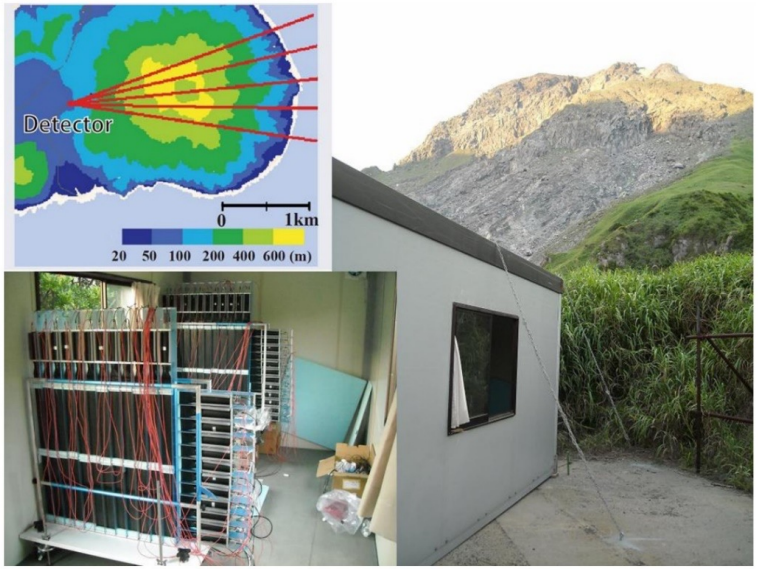
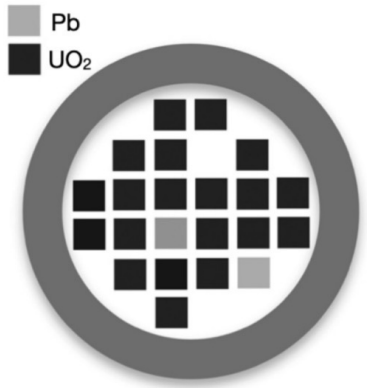
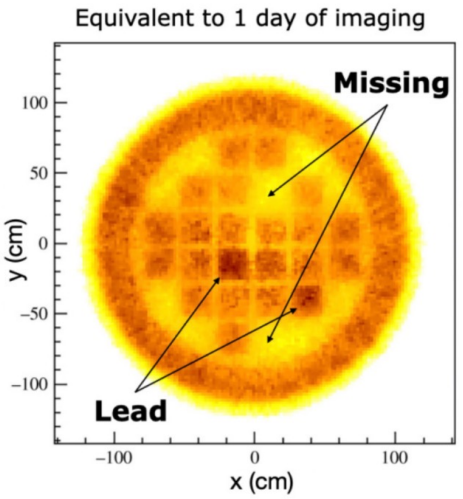


Fig. 18. The experimental set-up for the muon radiography of the Satsuma Iwo-jima volcano.

Spent fuel dry storage cask





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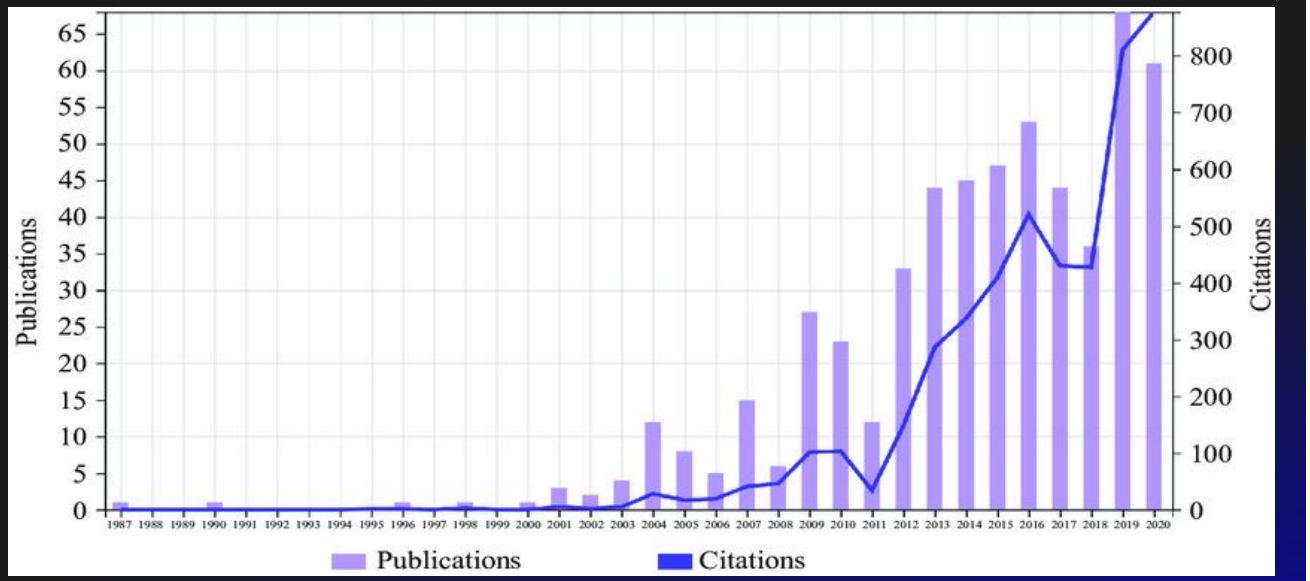
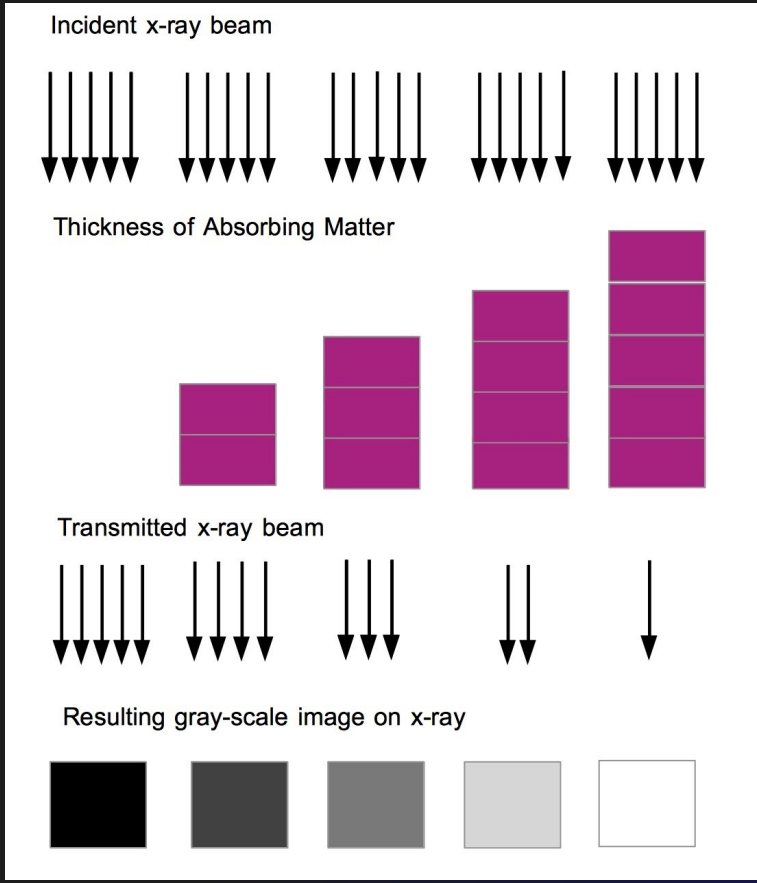
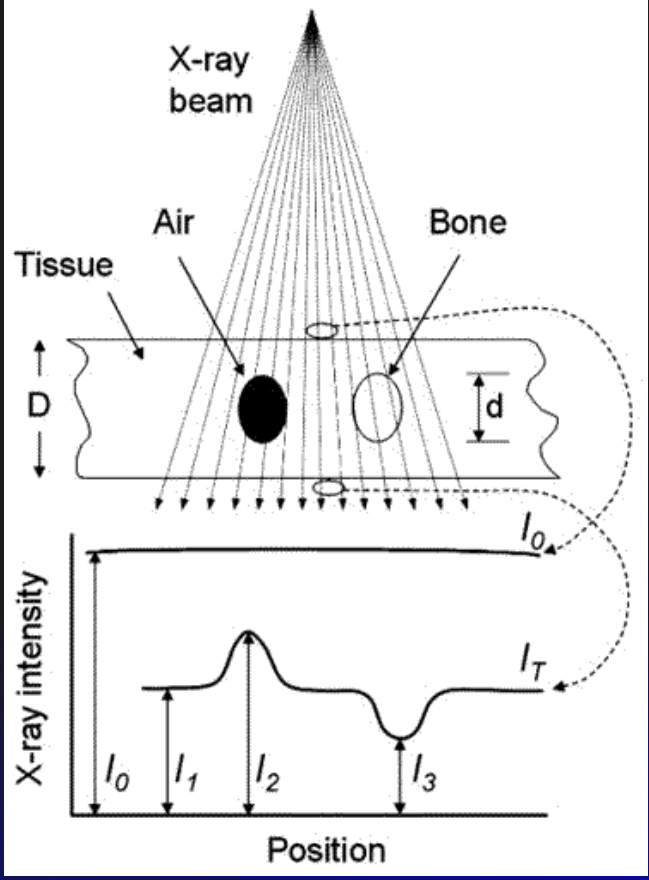


X-Ray Imaging





Computed Tomography: Taking "X-Rays" Along Different Axes

- Take "X-Rays" along different directions to allow a 3-D image to be constructed
- We do this by moving our detectors around the perimeter of the pyramid

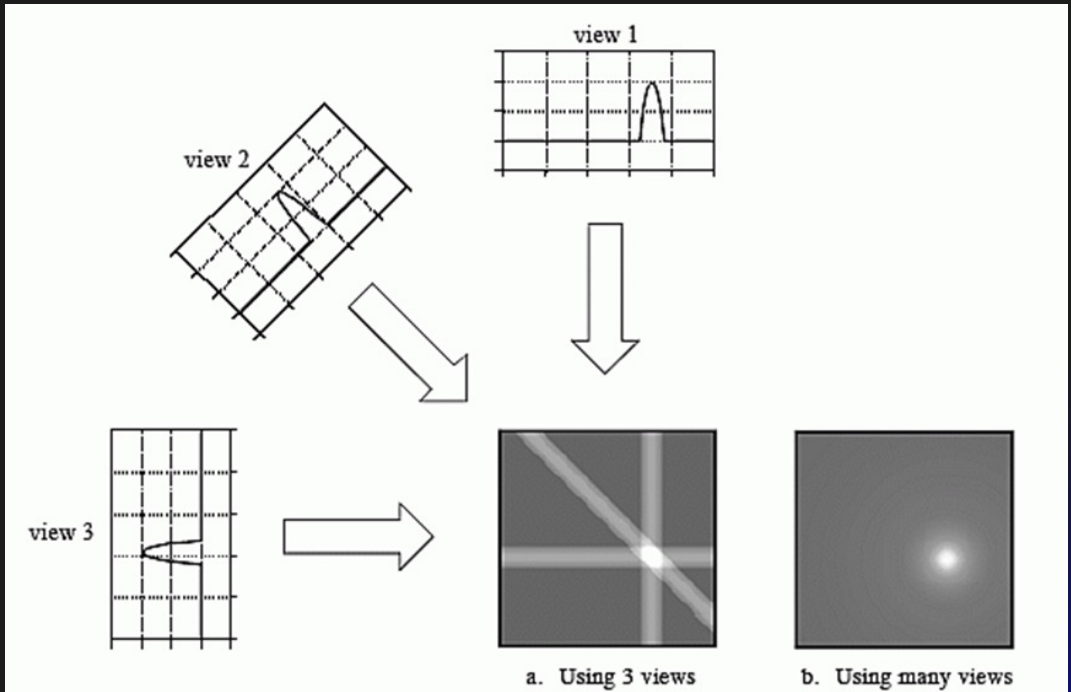
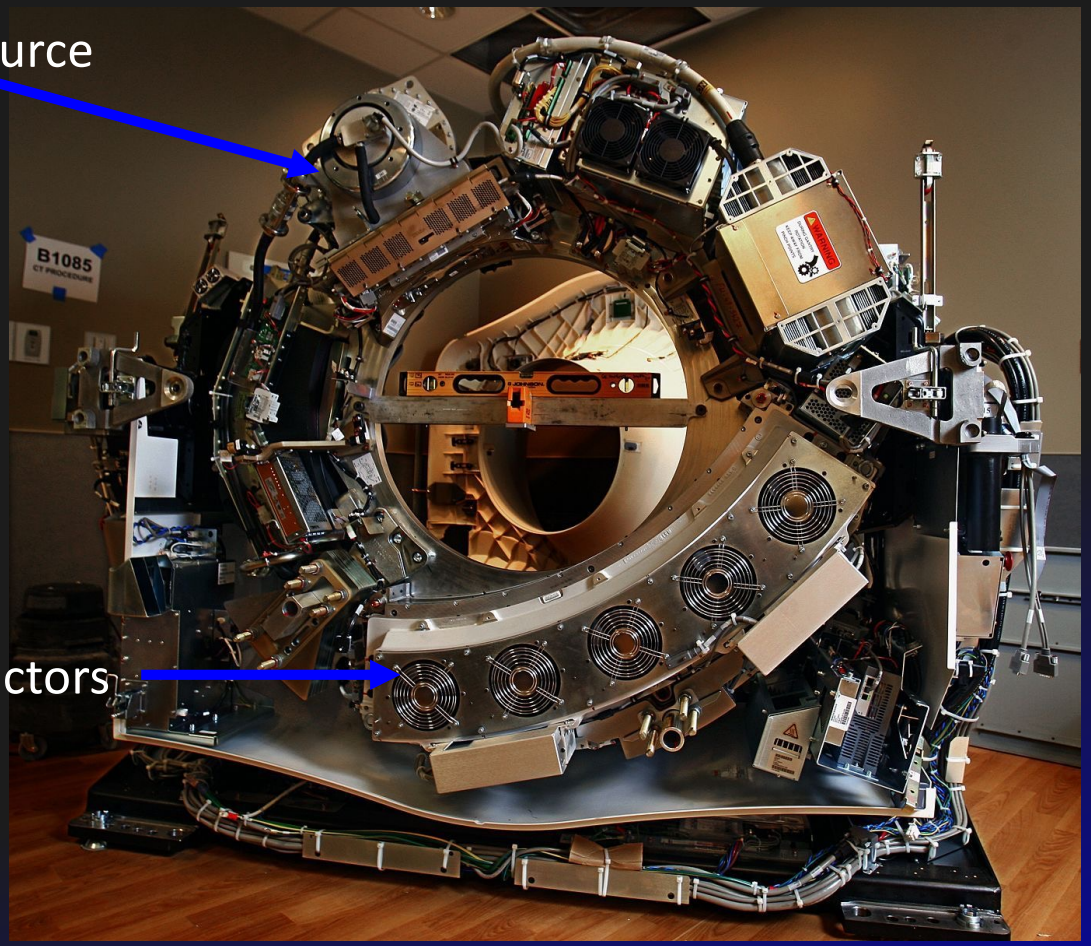


FIGURE 25-16
Backprojection. Backprojection reconstructs an image by taking each view and *smearing* it along the path it was originally acquired. The resulting image is a blurry version of the correct image.

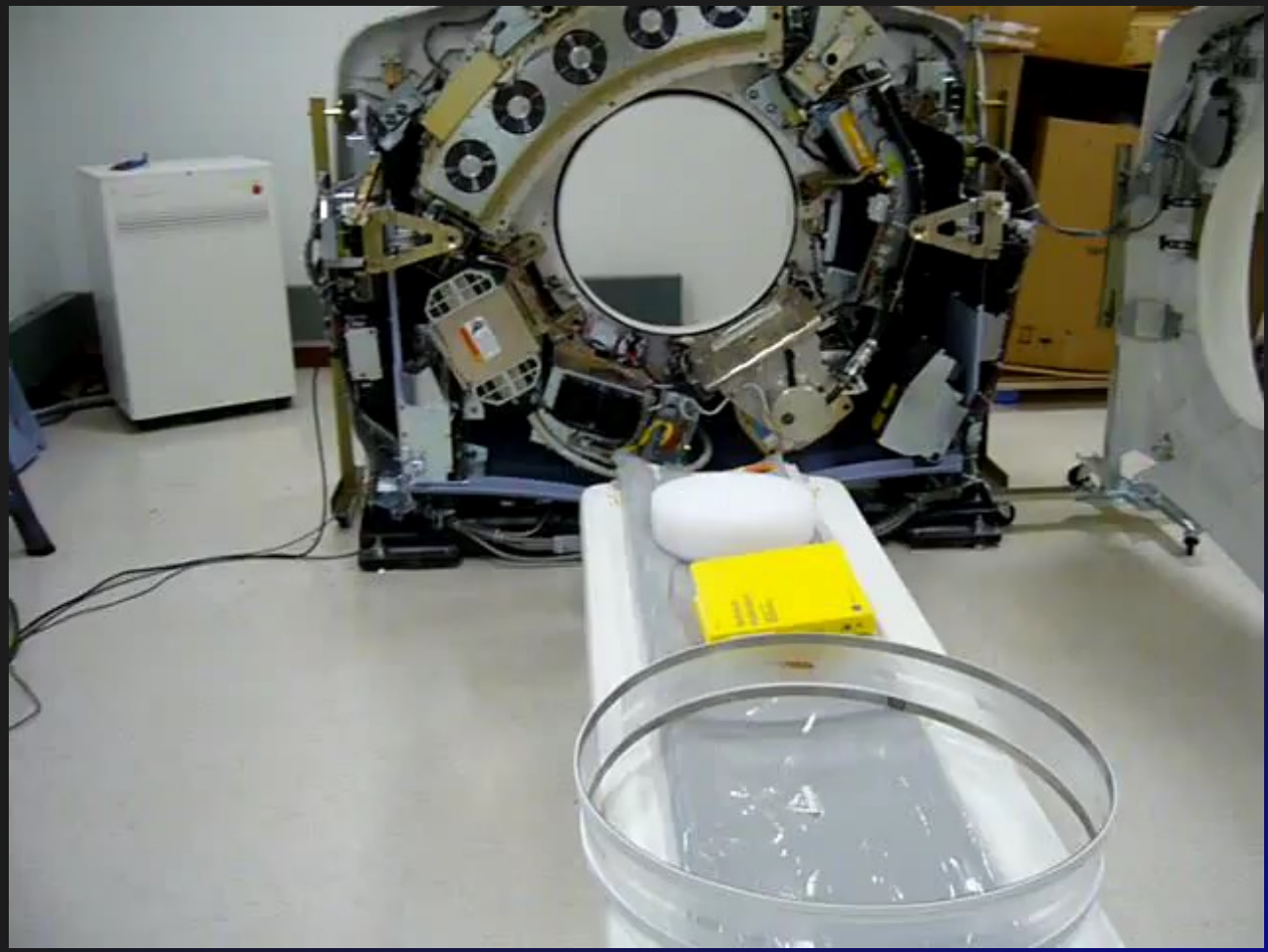
Computed Tomography: Taking “X-Rays” Along Different Axes

X-Ray source



X-Ray detectors

Computed Tomography: Taking “X-Rays” Along Different Axes



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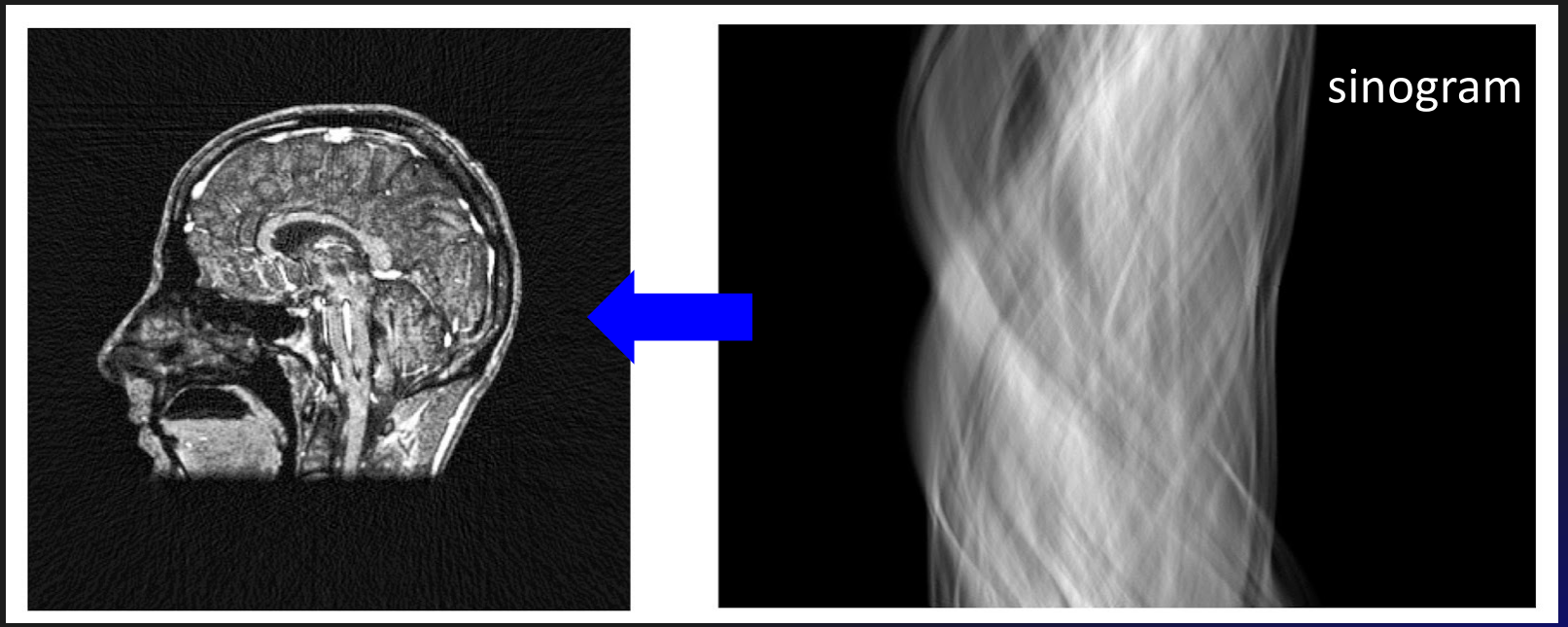
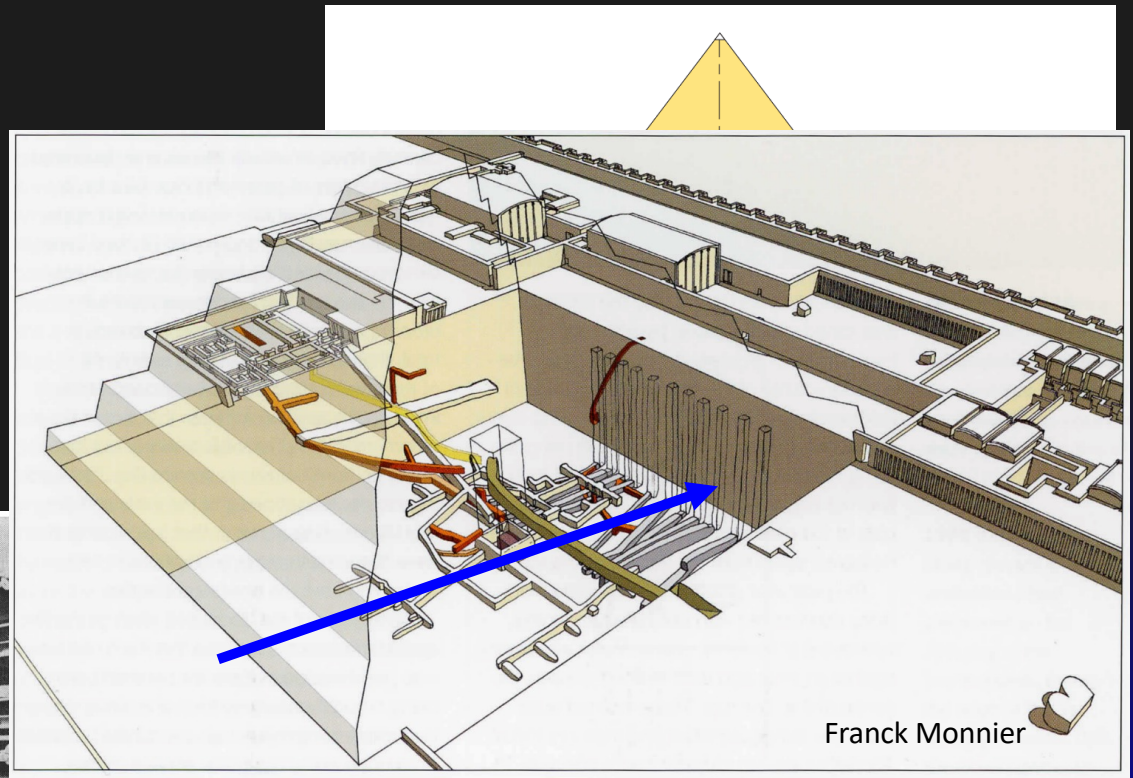


First Attempt at Muography: Alvarez et al in 1970

- Pyramid of Khafre: Nobel laureate Luis Alvarez placed spark chambers inside
- Why Khafre's pyramid? Internal structure appears much simpler than Khufu: is it really?
- Used spark chamber of 4 m^2 area.
- Finds nothing; however, "The explored volume is 19 percent of the pyramid's volume."



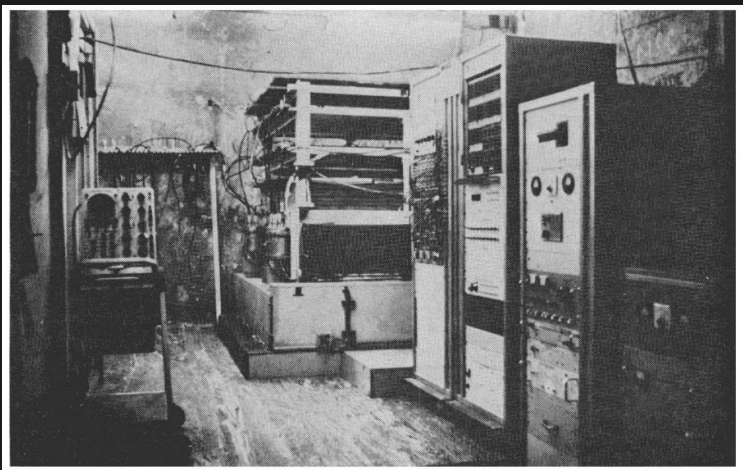
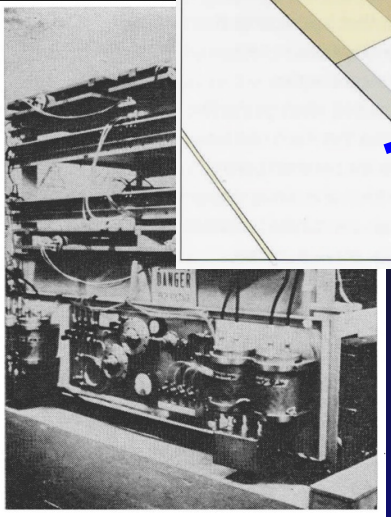


Fig. 6 (left). The equipment in place in the Belzoni Chamber under the pyramid.
Fig. 7 (right). The detection apparatus containing the spark chambers.



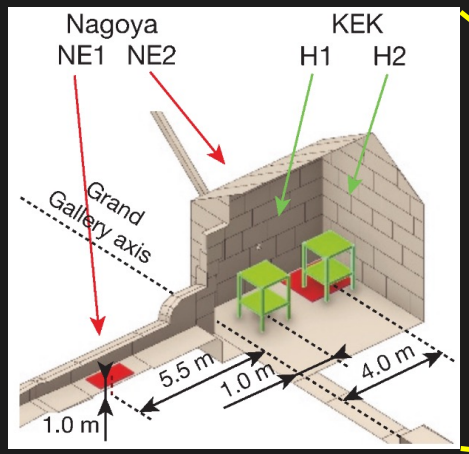
The structure of the Second Pyramid of Giza is determined by cosmic-ray absorption.

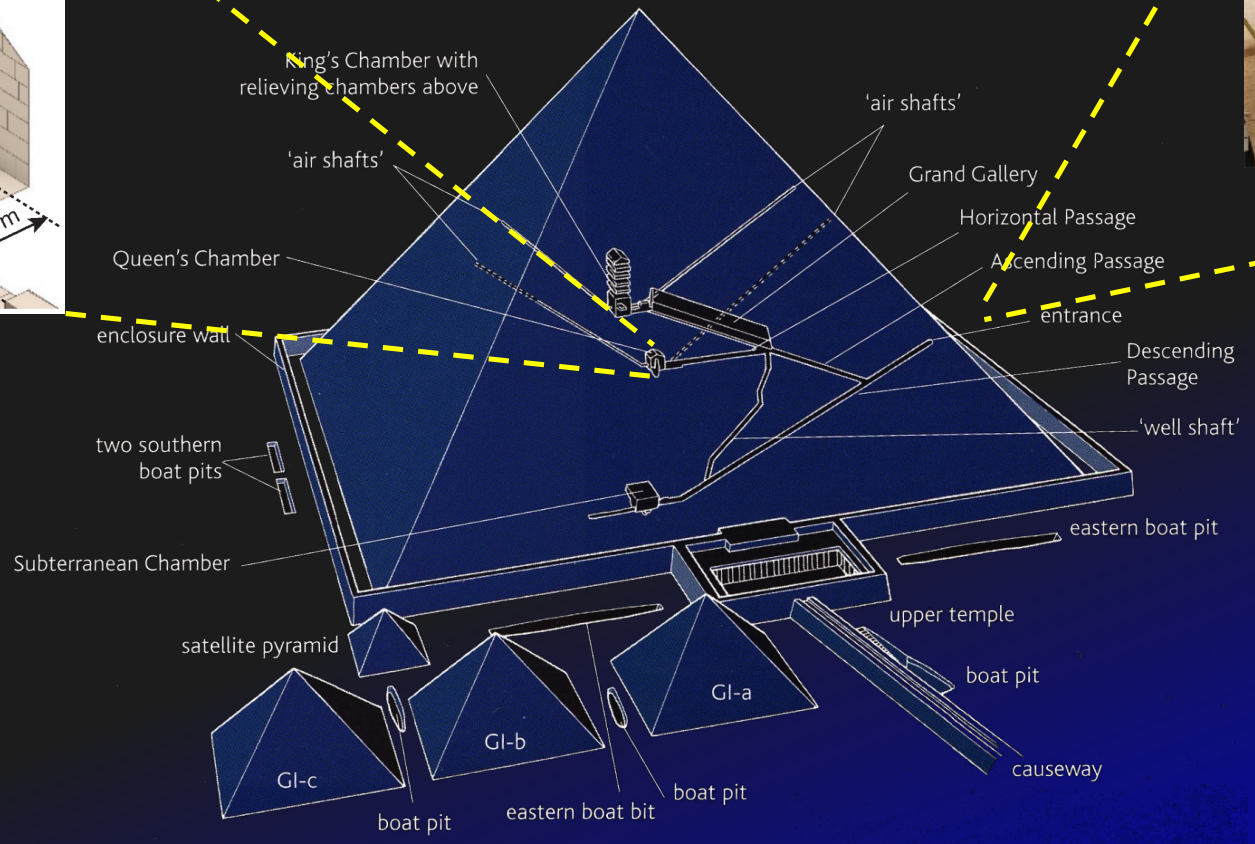
Luis W. Alvarez, Jared A. Anderson, F. El Bedwei, James Burkhard, Ahmed Fakhry, Adib Girgis, Amr Goneid, Fikhry Hassan, Dennis Iverson, Gerald Lynch, Zenab Miligy, Ali Hilmy Moussa, Mohammed-Sharkawi, Lauren Yazolino

Science, Vol. 167, p. 852 (1970)

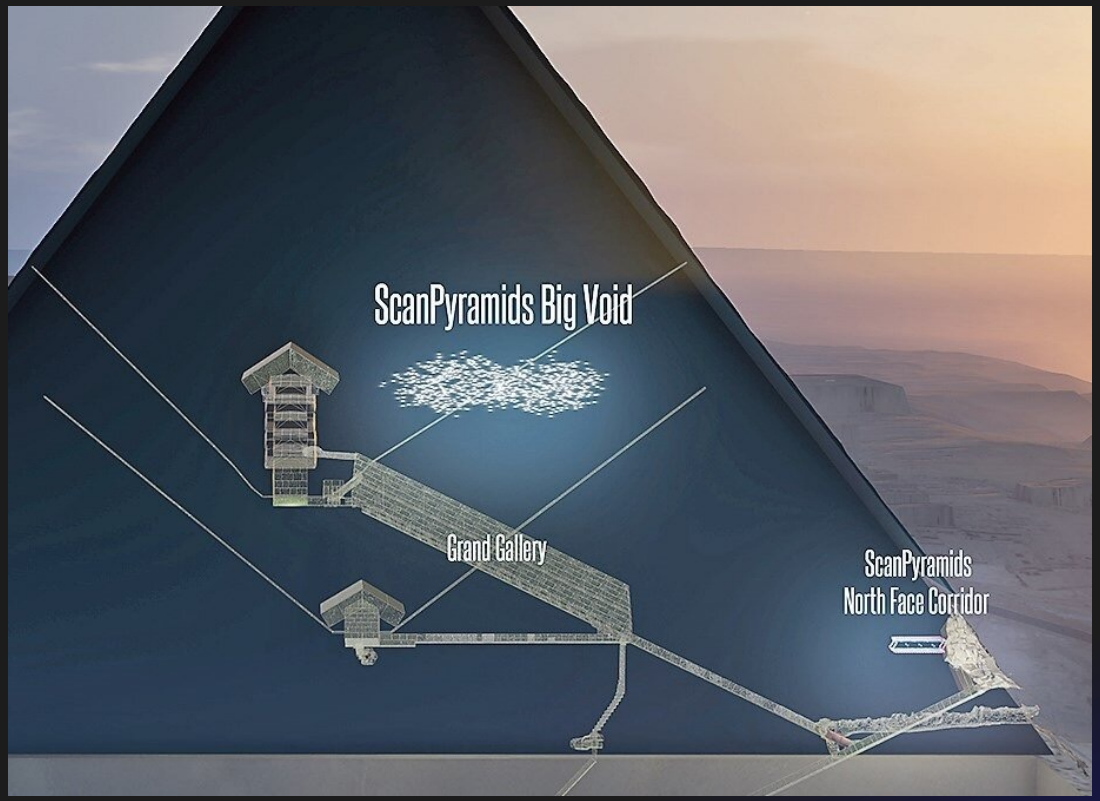
ScanPyramids: Cosmic Ray Muons Probe Great Pyramid of Khufu

French-Japanese team puts cosmic-ray muon detectors in two locations



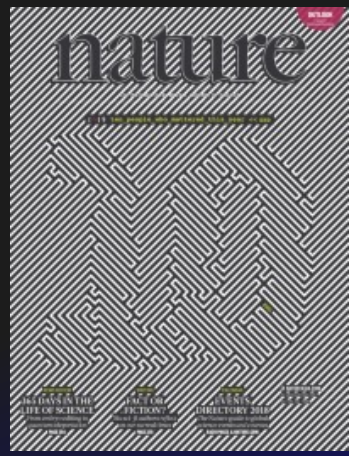


Scan Pyramids: Discovery of Void in Great Pyramid of Khufu



2017
"Scientists Discover a Void Inside Giza's Great Pyramid"

The New York Times



LETTER

doi:10.1038/nature24647

Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons

Kunihiro Morishima[1], Mitsuaki Kuno[1], Akira Nishio[1], Nobuko Kitagawa[1], Yuta Manabe[1], Masaki Moto[1], Fumihiko Takasaki[2], Hirofumi Fujii[2], Kotaro Satoh[2], Hideyo Kodama[2], Kohei Hayashi[2], Shigeru Odaka[2], Sébastien Procureur[3], David Attié[3], Simon Bouteille[3], Denis Calvet[3], Christopher Filosa[3], Patrick Magnier[3], Irakli Mandjavidze[3], Marc Riallot[3], Benoit Marini[4], Pierre Gable[5], Yoshikatsu Date[6], Makiko Sugiura[7], Yasser Elshayeb[8], Tamer Elnady[9], Mustapha Ezzy[8], Emmanuel Guerriero[5], Vincent Steiger[4], Nicolas Serikoff[4], Jean-Baptiste Mouret[10,11,12], Bernard Charlès[13], Hany Helal[4,8] & Mehdi Tayoubi[4,13]

First major discovery related to the Great Pyramid since the 19th century!

ScanPyramids Finds a Hidden Corridor Above Khufu Entrance

In March 2023 an endoscopic camera was inserted into a small hole above the entrance, revealing a hidden corridor

Inside of hidden corridor
ScanPyramids/Egyptian Ministry of Tourism and Antiquities

Responses From Archaeologists

On November 2, 2017, the Egyptologist Zahi Hawass told the New York Times: “They found nothing...This paper offers nothing to Egyptology. Zero.”

Mark Lehner of the Ancient Egypt Research Associates: “The Great Pyramid of Khufu is more Swiss cheese than cheddar”.

Yukinori Kawae of the Institute for Advanced Research at Nagoya University: “This is definitely the discovery of the century...There have been many hypotheses about the pyramid, but no one even imagined that such a big void is located above the Grand Gallery.”

The Egyptian Ministry of Antiquities requested proposals for a follow-up study to confirm the result, determine the exact nature of the “Big Void”, and see if other voids exist.

We applied and approved (2018) – The Exploring the Great Pyramid (EGP) Mission was born

Exploring the Great Pyramid (EGP) Collaboration

Fermilab:
Alan Bross, Anna Pla-Dalmau, Sten Hansen, Paul Rubinov

University of Virginia:
E. C. Dukes, Ralf Ehrlich, Eric Fernandez

Virginia Tech:
Sophie Dukes

Cairo University:
Mohamed Gobashy

University of Oxford:
Ishbel Jamieson

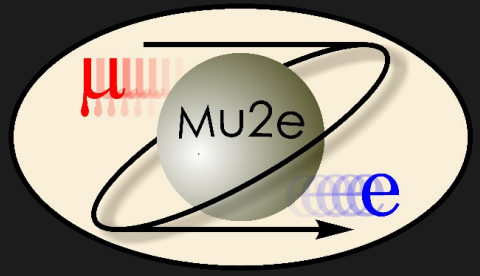
University of Chicago:
Joren Husic, George Iskander, Patrick LaRiviere, Mira Liu, Omar Shohoud, Phillip Vargas, Tabitha Welch

Yale University:
Gregory Marouard, Nadine Moeller

Mu2e: Using Muons to Probe Beyond the Standard Model

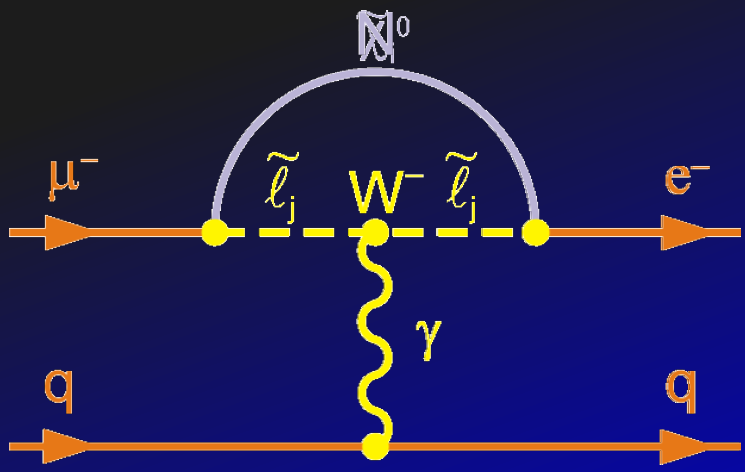
- The Mu2e experiment at Fermilab is using accelerator-produced muons to probe physics beyond the standard model through the conversion of (an accelerator produced) muon circling a nucleus into an electron

$$\mu^- N \rightarrow e^- N$$

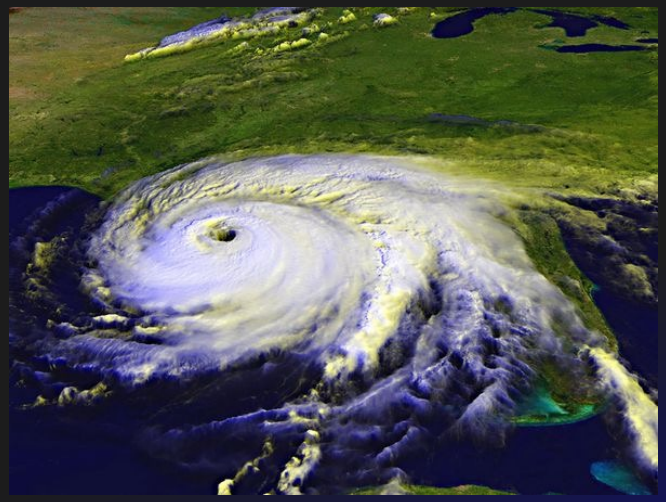


- This process is forbidden in the standard model, so any evidence would be unambiguous evidence of new physics
- Exquisite sensitivities can be obtained experimentally
  - ⇨We expect to produced sensitivities that allow favored beyond-the-standard-model theories to be tested

New heavy neutrino

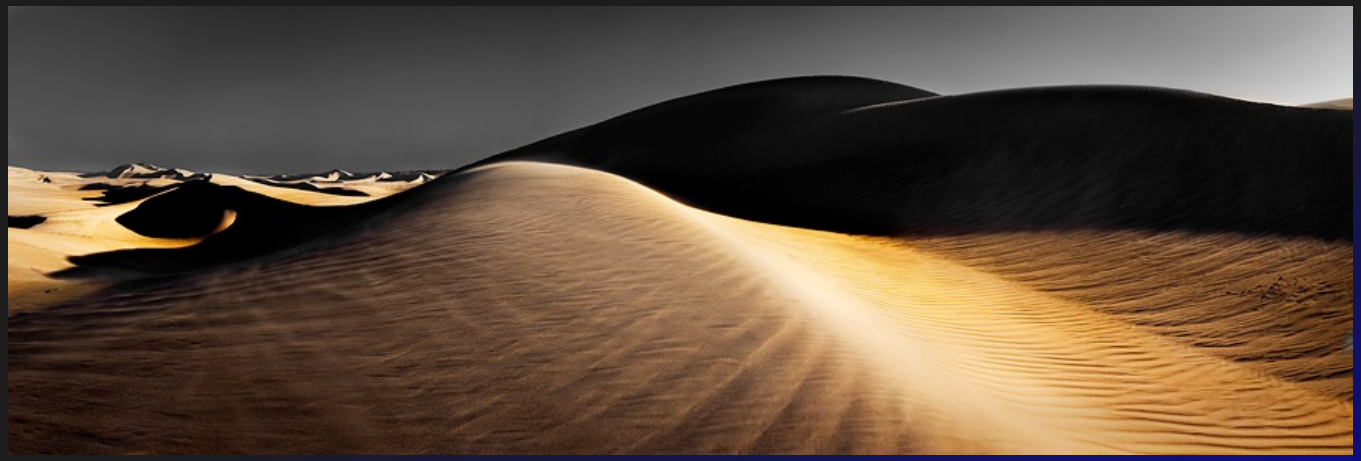


We’re All Fascinated by Rare Events



Perhaps One of the Rarest of them All!

Number of muons needed to achieve our desired sensitivity: ~10^{18}. Number of grains of sand on Earth: ~10^{19}

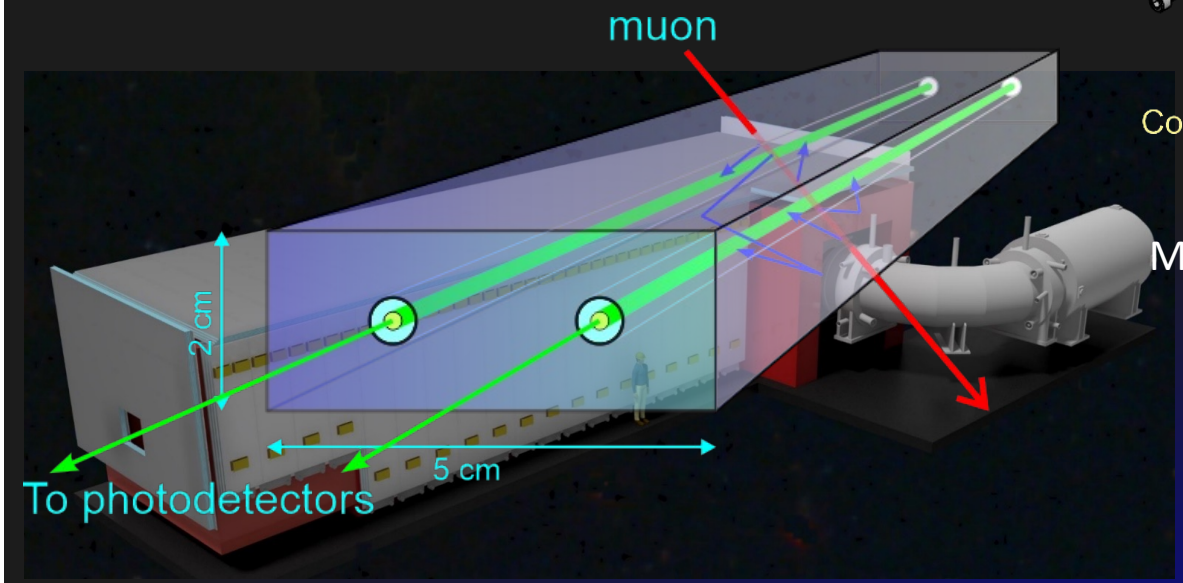


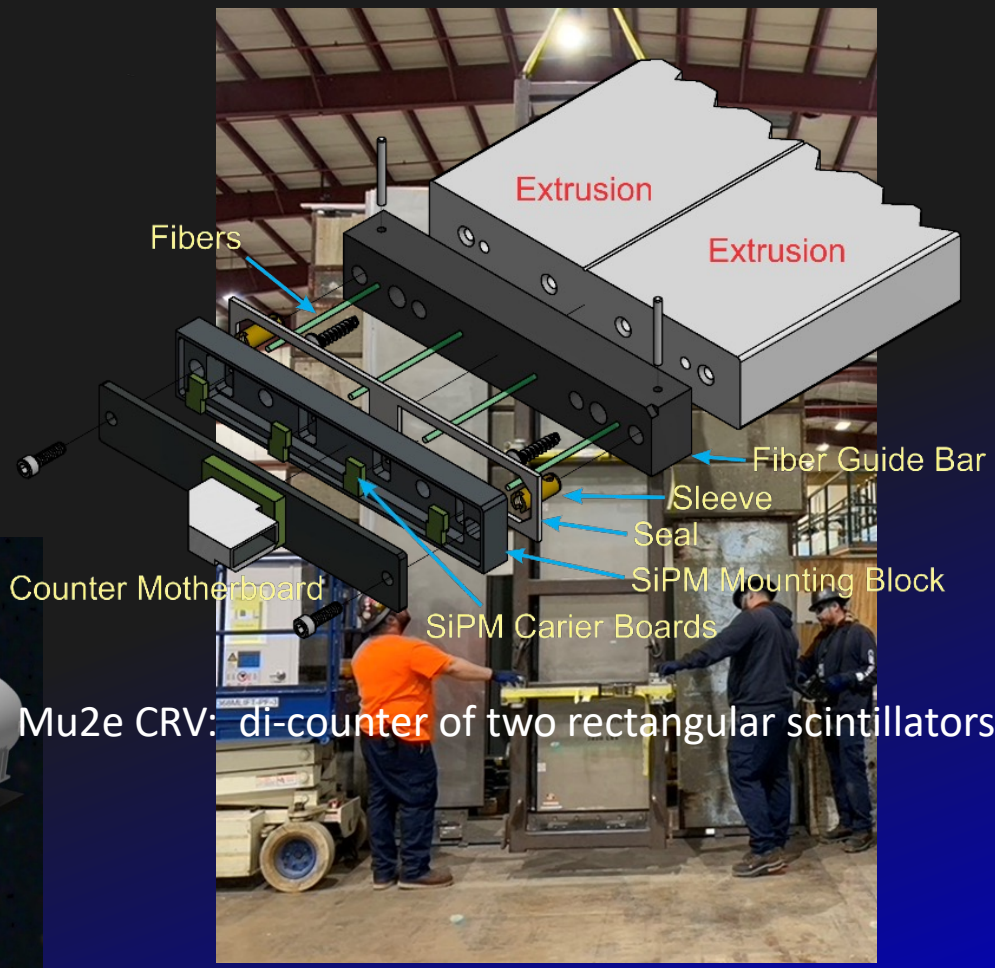
Problem: We get One Fake Event Per Day from Cosmic Ray Muons

Need to reduce that rate by 10,000X

Solution: Surround our detector by 4 layers of 5 x 2 cm^2 scintillator counters read out by waveshifting fibers, and silicon photomultipliers

The detector – Cosmic Ray Veto – has been fabricated at UVA and shipped out to Fermilab: now awaiting installation

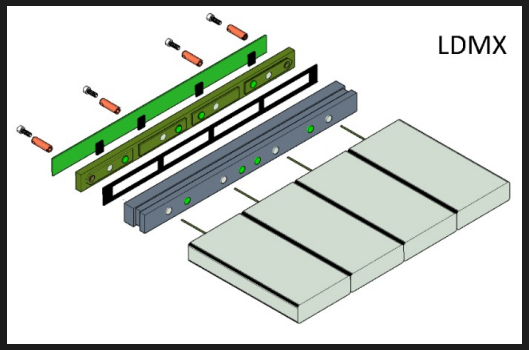




Mu2e CRV: di-counter of two rectangular scintillators

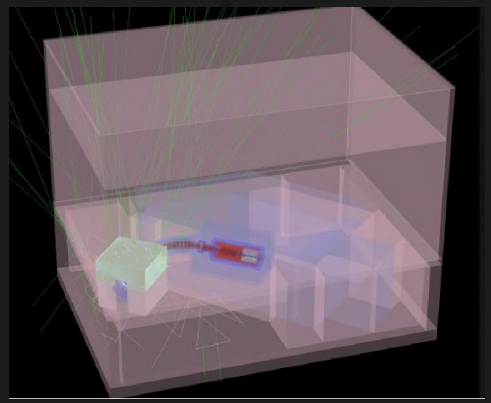
A module with 64 counters undergoing installation tests

Mu2e CRV Design Being Used by Several Different Experiments



Light Dark Matter eXperiment (LDMX) hadronic calorimeter

- quadcounter with 1 fiber/50-mm wide extrusion rather than di-counter



COMET

- Competitor to Mu2e

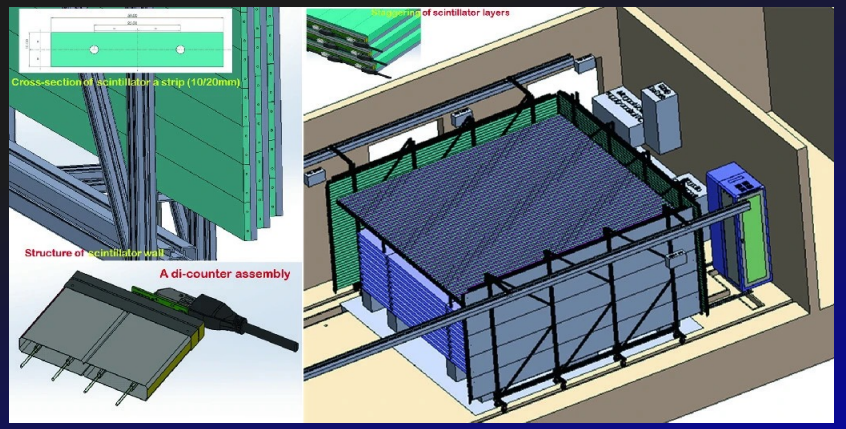
Advanced Radiation Detector Design for Applications in Food Safety and National Security

A. Bross[1] E.C. Dukes[2] S. Hansen[1] A. Pla-Dalmau[1] P. Rubinov[1]

[1]*Fermi National Accelerator Laboratory, Box 500, Batavia, IL USA*
[2]*Physics Department, University of Virginia, Charlottesville, VA, USA*

DUNE

- Exploring similar design for Near Detector



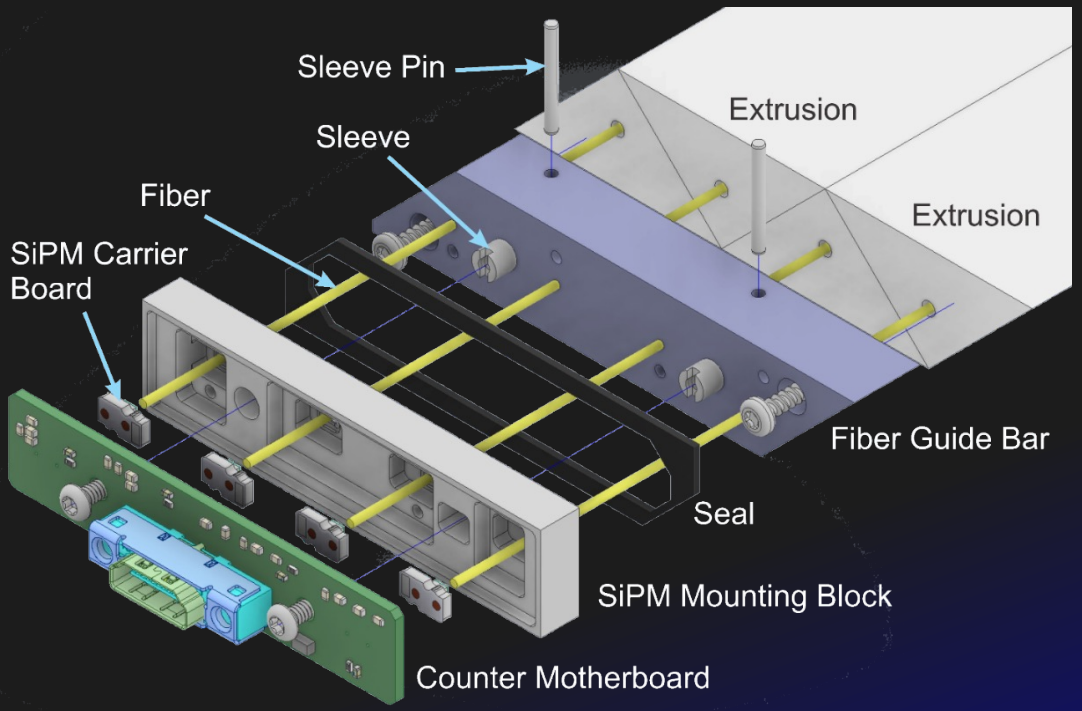
Mini-ICAL detector at IICHEP

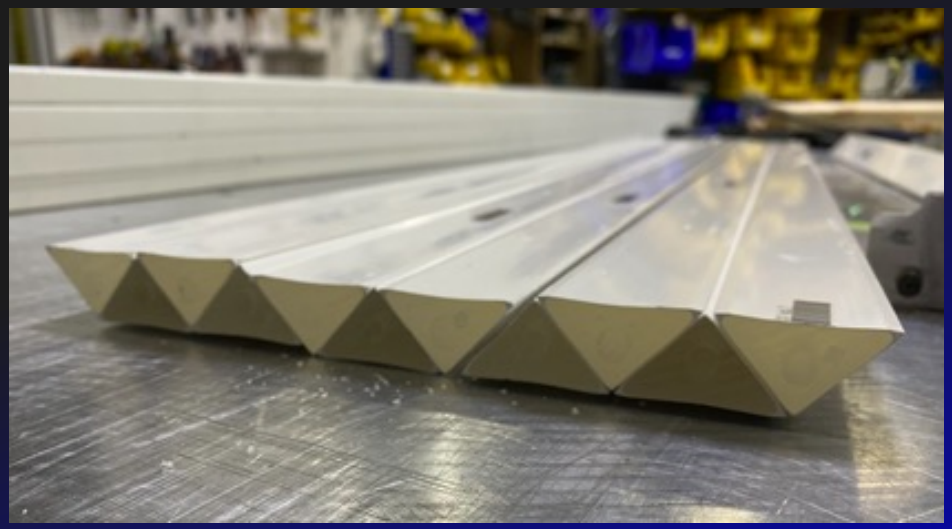
- Identical to the Mu2e CRV design

EGP: Modified Cosmic Ray Veto Counter Design

The Mu2e CRV design is ideal for Muography: simple, easy to fabricate, and inexpensive

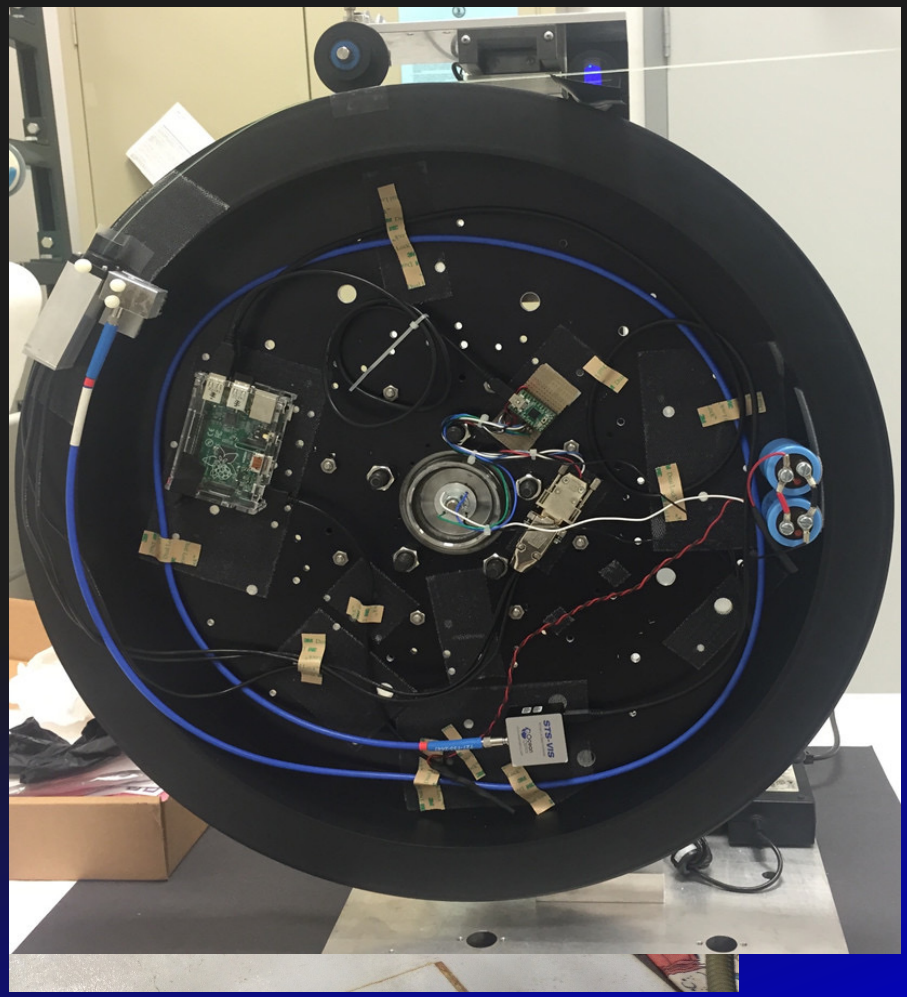
Design modified slightly for EGP: use triangular scintillator counters grouped into groups of 4 (quad-counters)





Prototype Quadcounters Fabricated at University of Virginia

- Extrusions fabricated at the Fermilab NICADD facility
- Fiber (1.4 mm dia.) from Kuraray and tested at UVA
- Four triangular extrusions glued together to form a quadcounter and vacuum bagged
- Fiber inserted
- Fiber guide bars glued to quadcounter ends
- Fiber ends polished with flycutter
- Readout manifold added to the ends



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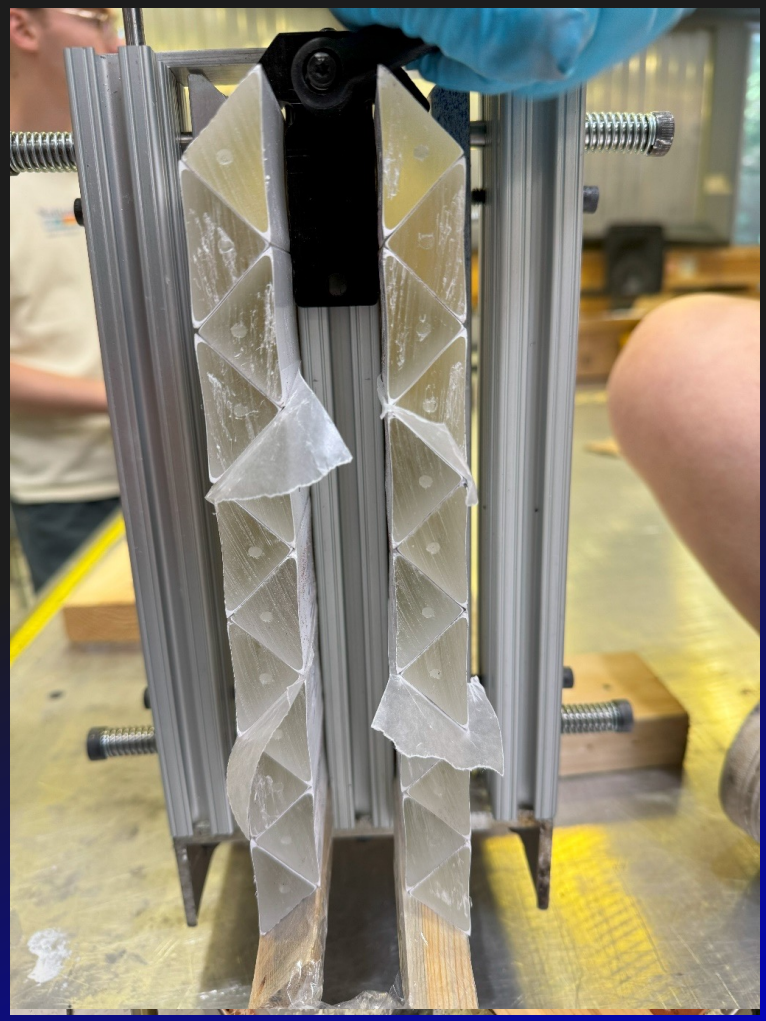
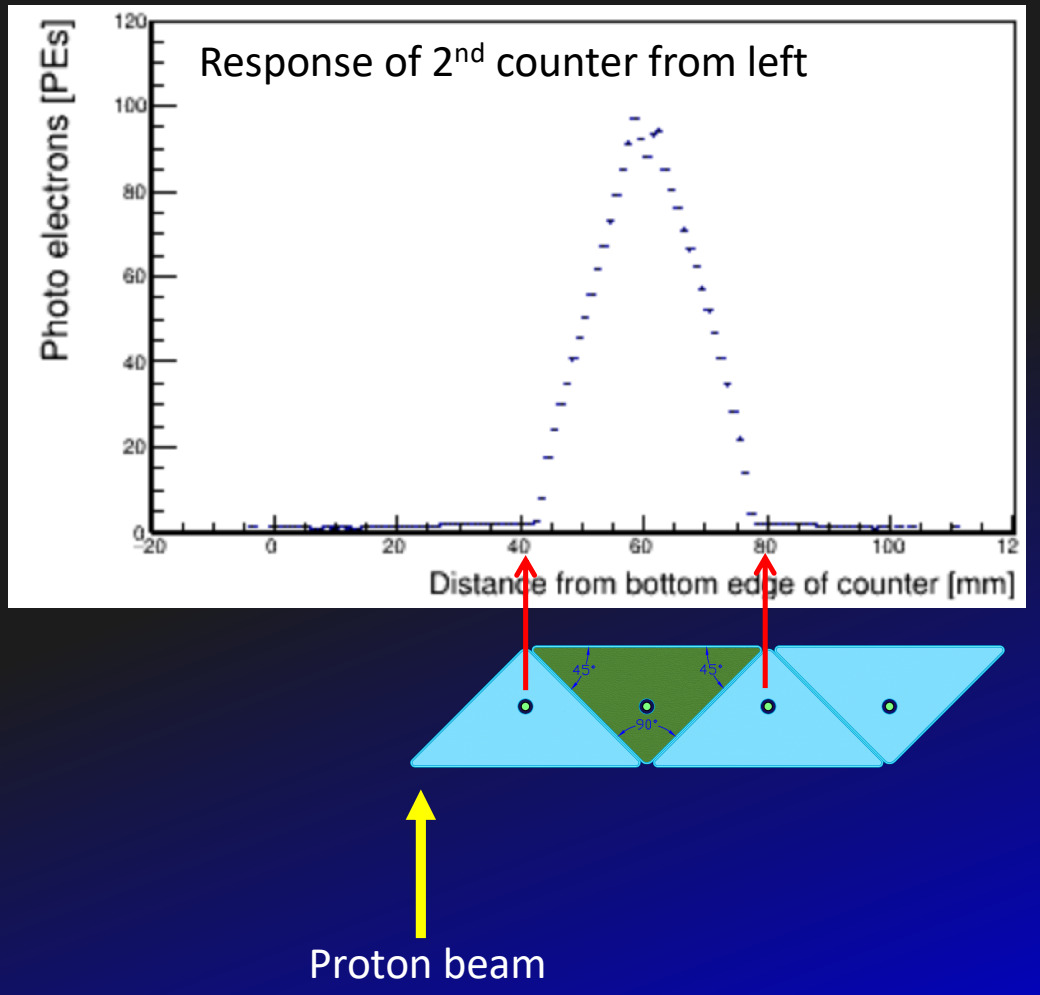


Photoelectron Yield vs Beam Impact Position

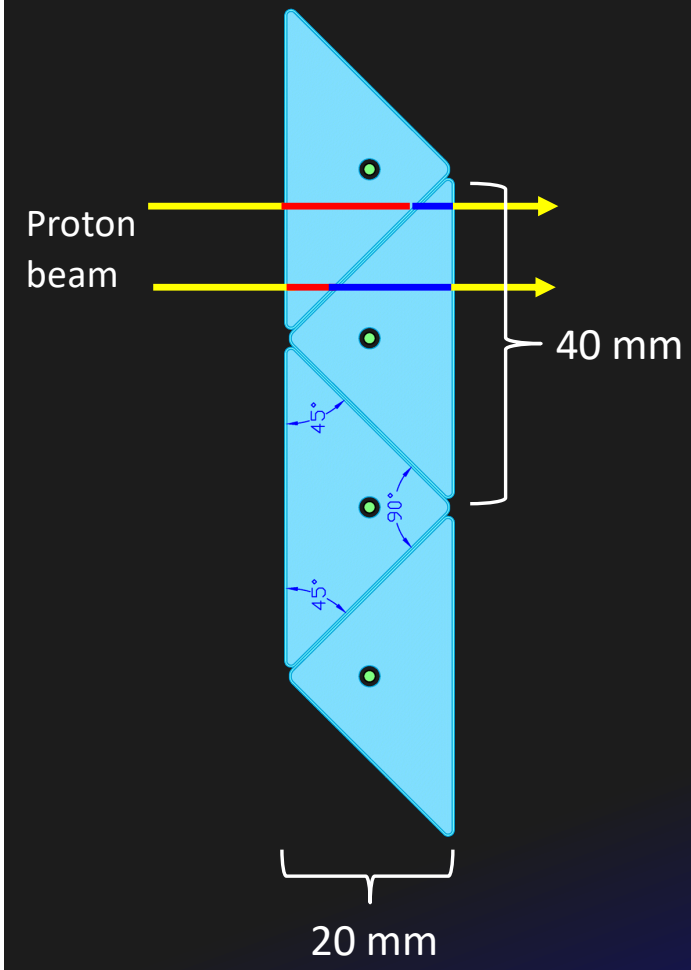
Several quadcounters tested at the Fermilab Test Beam Facility

- 120 GeV incident protons
- Mu2e CRV readout used

Beam scanned across the quadcounters to measure the photoelectron yield vs position

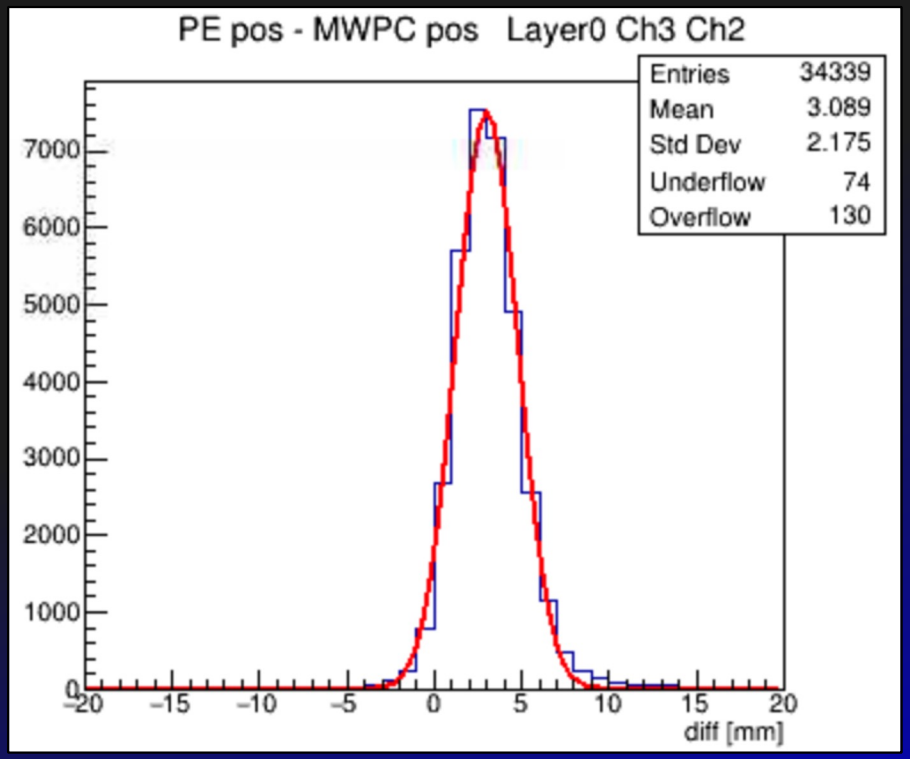


Using Light Sharing to Determine Beam Position



By measuring the relative light yield from the two counters we can determine the impact position of the proton beam

We find that at 0° incident angle we get σ ~ 2 mm

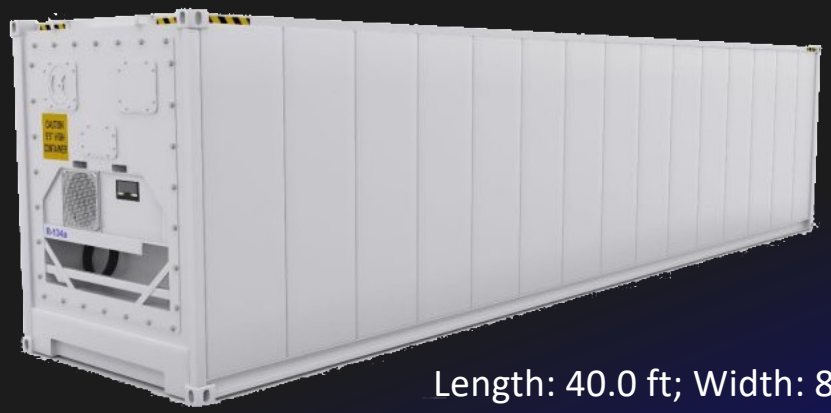


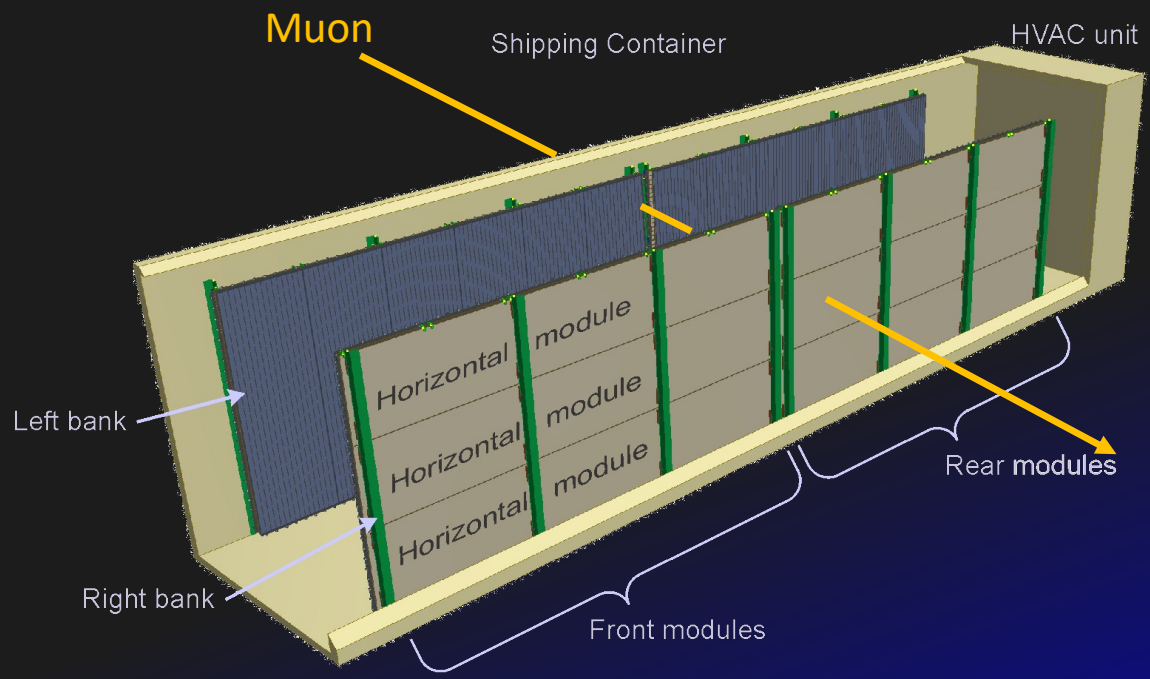
EGP: Muon Tomography with Large Exterior Detectors

Arrays of triangular counters will be placed in refrigerated shipping containers

Each container contains 2 detector banks with counters vertically and horizontally oriented to provide two space points from which the track can be back projected into the pyramid

Much larger area will allow us to take 100X more data to produce much better images than the French/Japanese group





6 vertical modules per bank: 240 counters
3 horizontal modules per bank: 120 counters

Length: 40.0 ft; Width: 8.0 ft, Height: 9.5 ft
12.2 m 2.4 m 2.9 m

Shipping Containers

Inexpensive: ~$8K-$10K

Can be made aesthetically pleasing, and perhaps used to enhance the tourist experience when visiting the site

Shipping rates are modest

Shipping rates from United States to Egypt

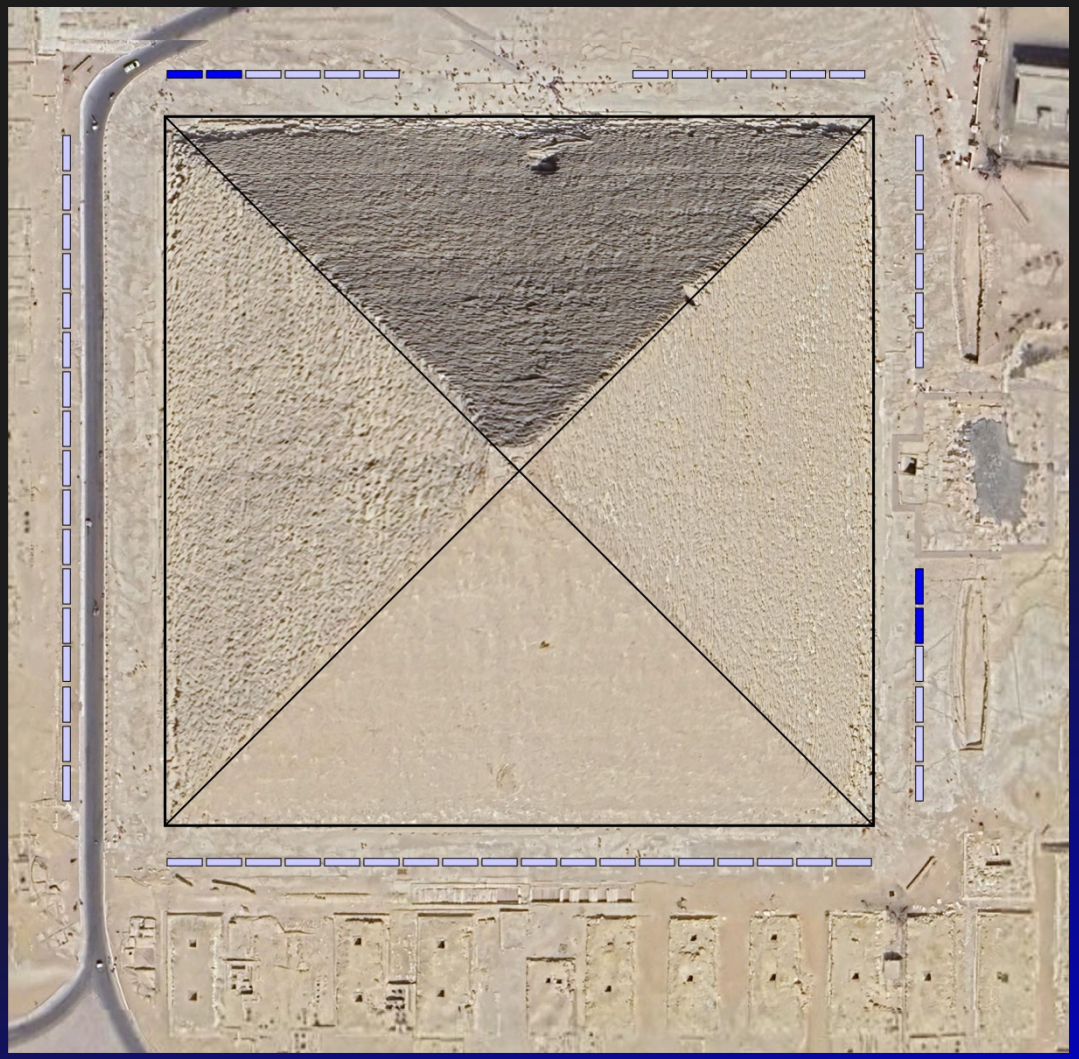
Savannah - Port Said	DV20 $734	DV40 $958	40HC $958
Charleston - Port Said	DV20 $734	DV40 $994	40HC $1,319
New York - Port Said	DV20 $759	DV40 $2,656	40HC $2,690
Charleston - Port Said	DV20 $789	DV40 $1,008	40HC $1,140
Savannah - Port Said	DV20 $789	DV40 $1,018	40HC $1,018

Where we Might Site the Containers

We plan to have 2 container groups, each 2 wide and 2 high: 8 containers in all.

They will be moved around to different locations near the base of the pyramid every several months.

Containers could be used to enhance the tourist experience: see the data being taken in real time!



Simulation Studies: How Well Can we Image Voids?

In one of the largest Monte Carlo simulations, UVA research scientist, Ralf Ehrlich, has validated the technique

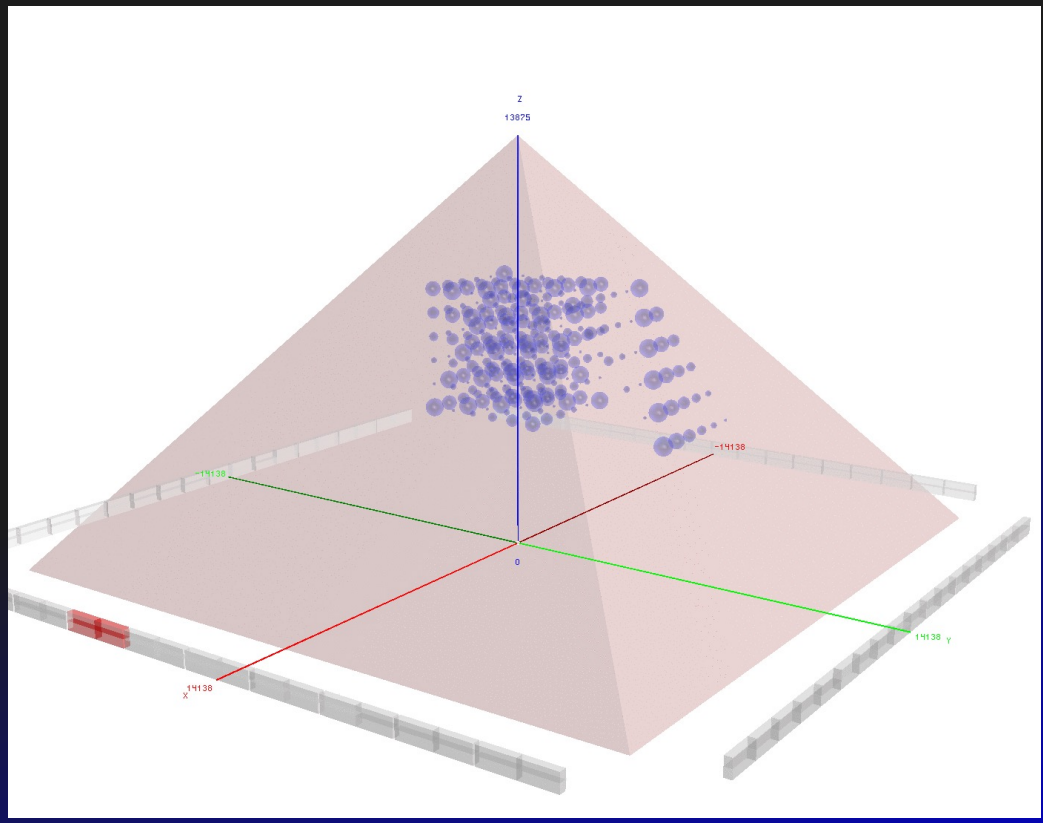
Two 2 x 2 container arrays placed a different positions around the pyramid

Phantom spherical voids of diameters from 1 m to 6 m put in model to validate the design

- An array at the pyramid center
- An array near one side of the pyramid

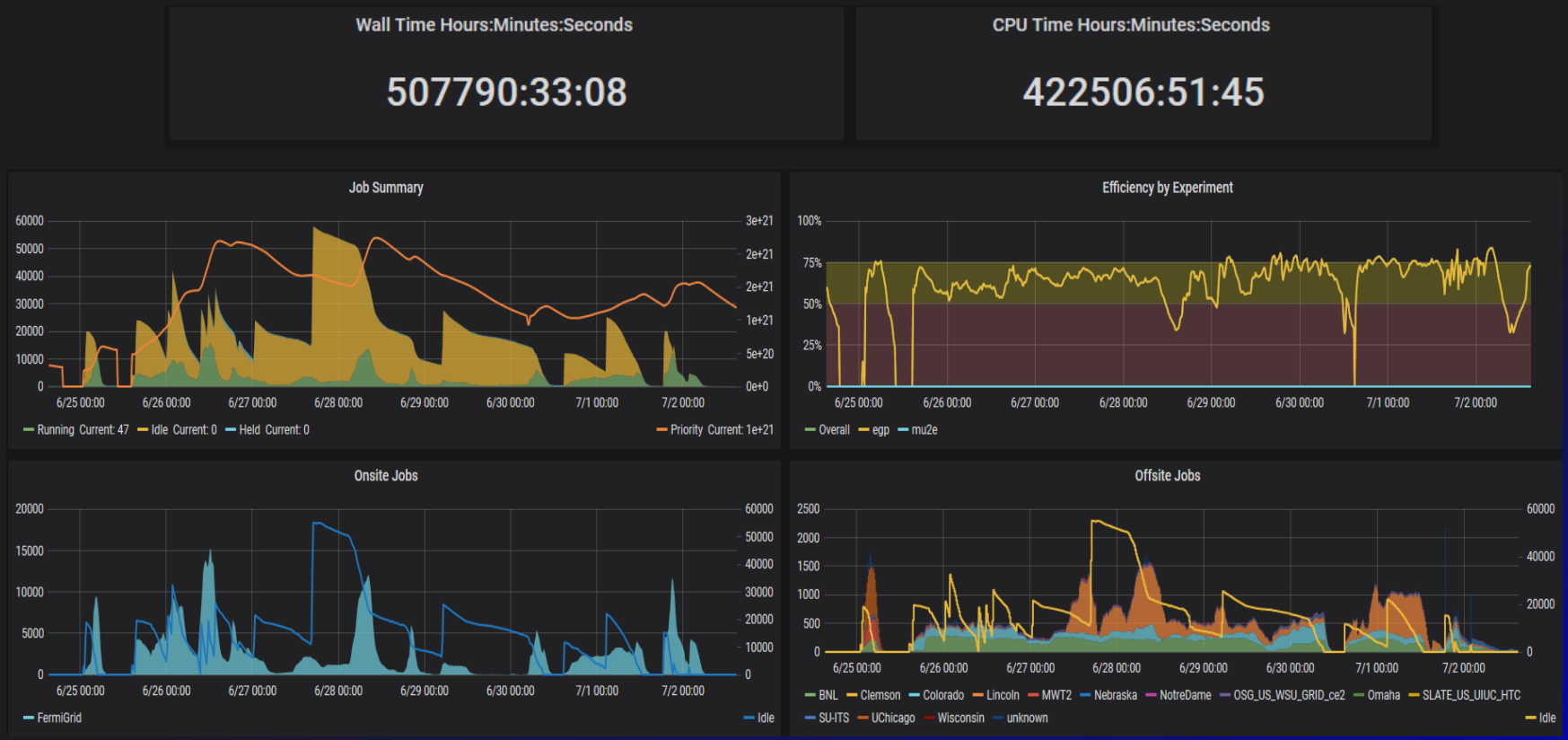
Two-year run: generated over 100 billion cosmic-ray muons

- 30 GeV – 1,000 GeV



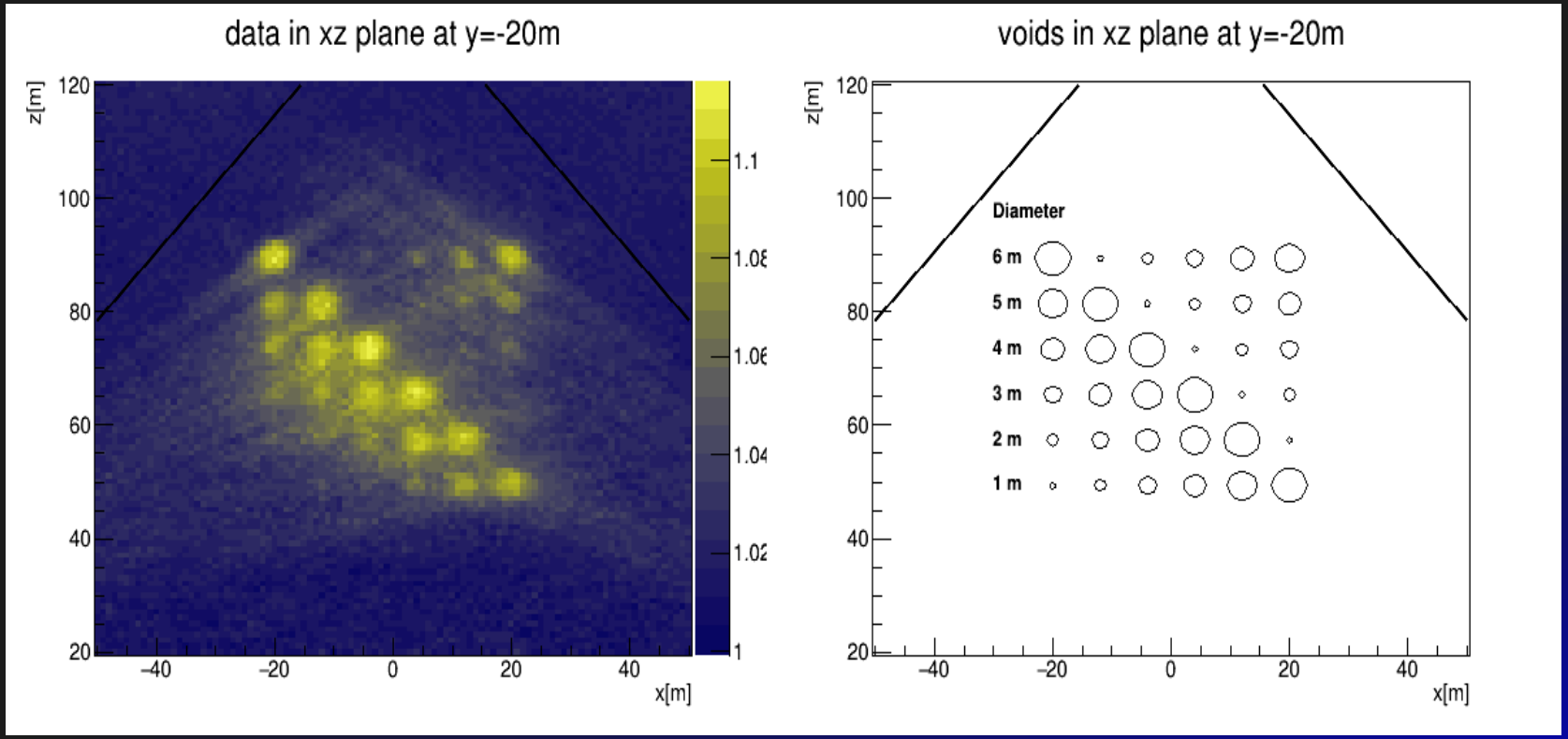
Simulation: Open Science Grid Jobs

420,000 CPU hours
48 CPU years



Simulation Results: Imaging Voids at Center of Pyramid

Back projection of simulated data to an array of voids at center of pyramid.
Voids with diameters as small as 3 m are visible.
Shown here: one slice through the 3D image (xz plane at y=-20 m).

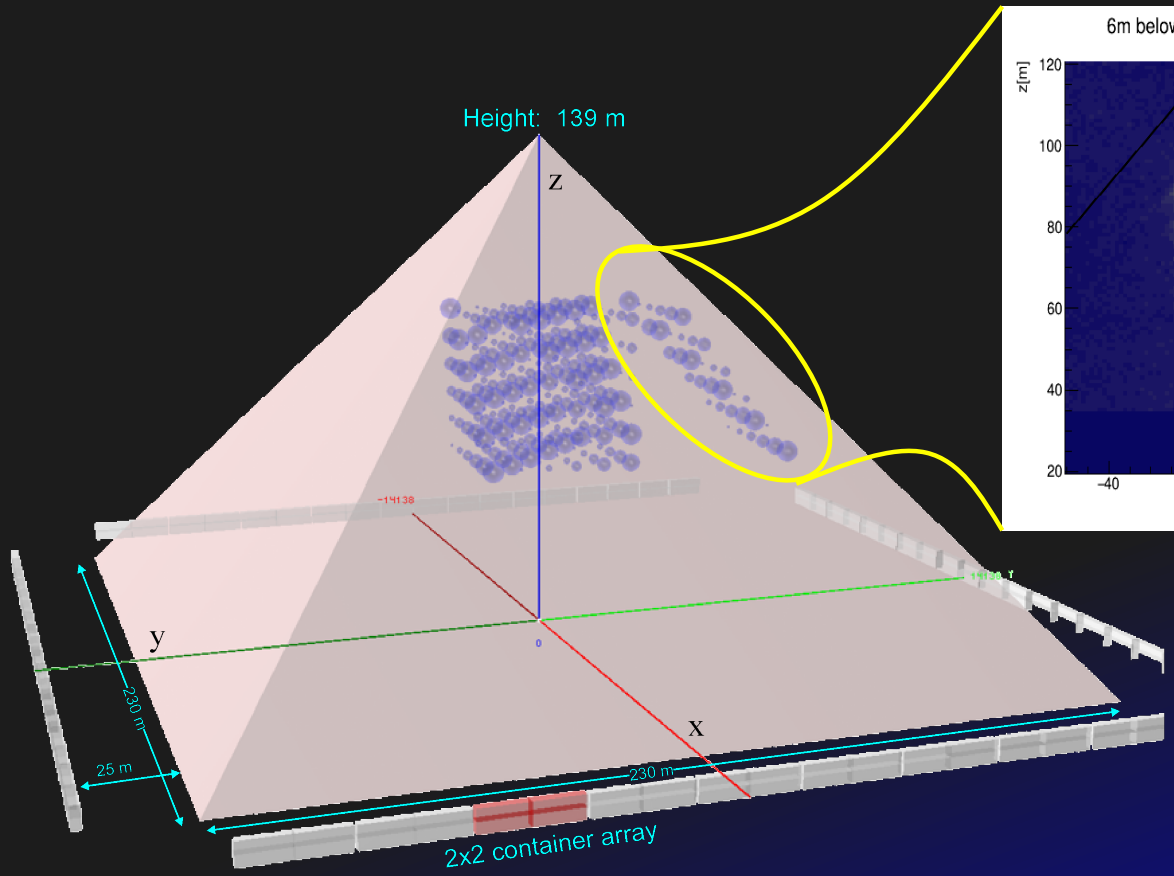


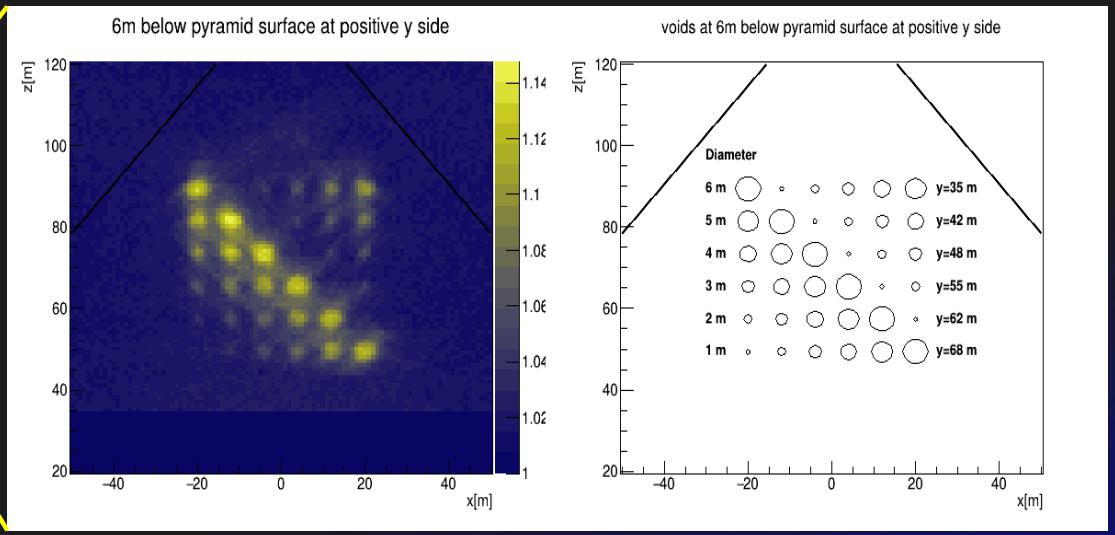
Reconstructed voids

Simulated voids

Simulation Results: Imaging Voids Near Pyramid Surface

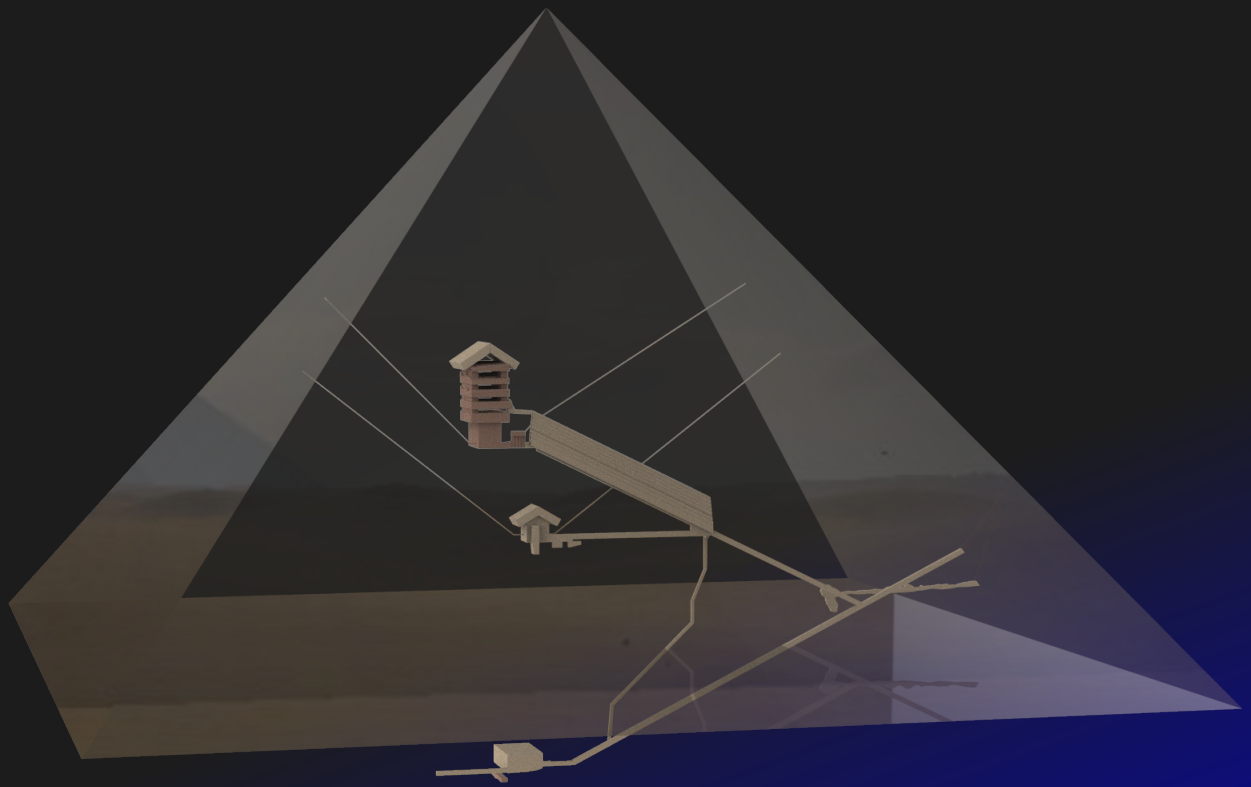
Voids with diameters as small as 2 m are visible.





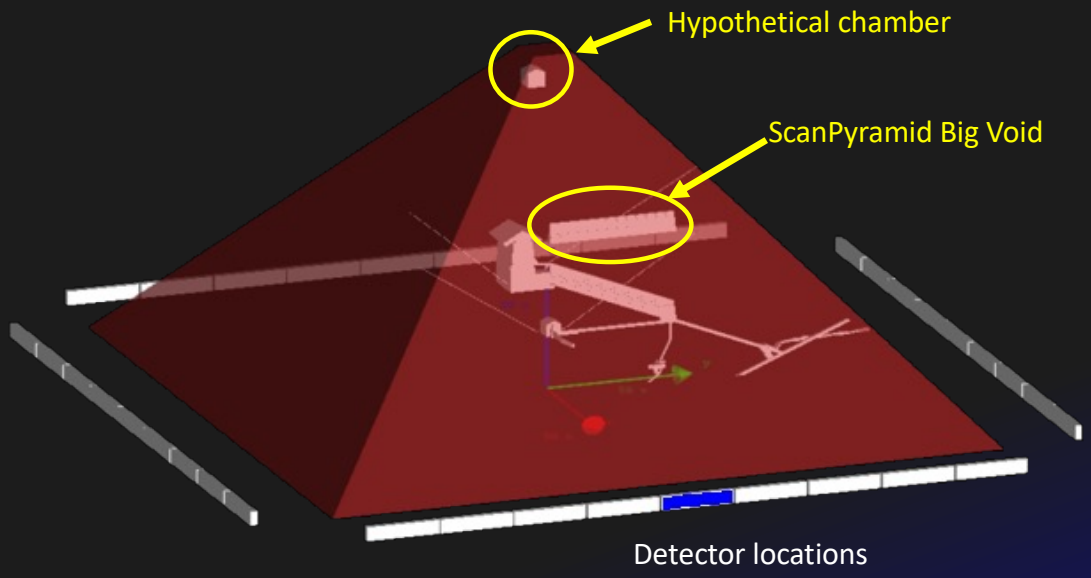
Simulation Studies: Building a Khufu CAD Model

Sophie Dukes, a design student at Virginia Tech, while at home during the 2020 pandemic lockdown, made a detailed CAD model of the Great Pyramid

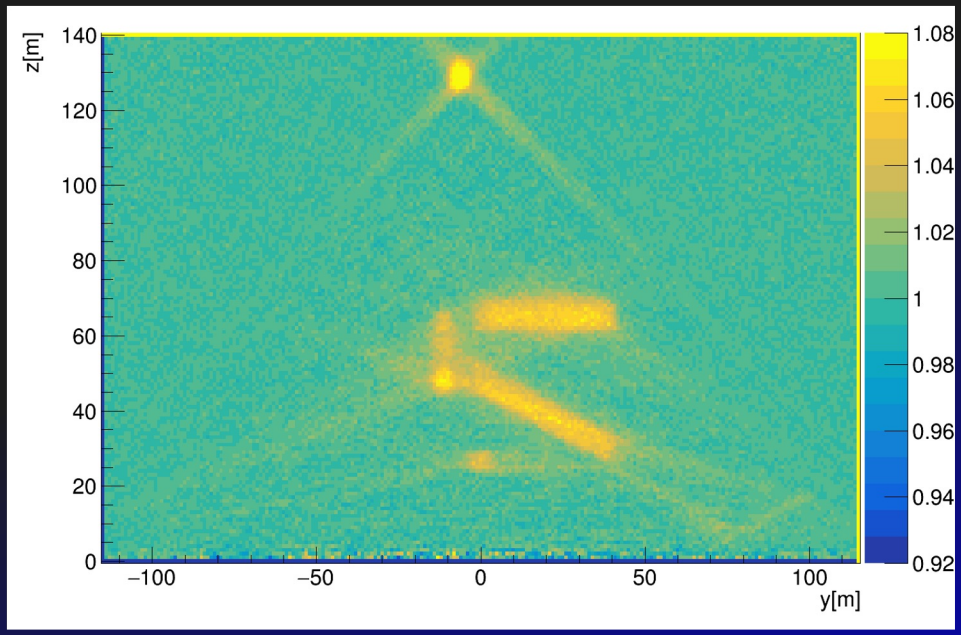


Simulating the Real Pyramid (with Additional Features)

Added two additional chambers to CAD model of Khufu's pyramid
Total exposure time about 2 years (of two 2x2 container arrays at different locations).
Back projection of simulated data.
Known and additional internal structures are visible.



CAD model of the pyramid with two additional chambers



North-south slice through King's chamber of the reconstructed 3D image of the simulated pyramid

Our Work has been Published

A. Bross et al., "Tomographic Muon Imaging of the Great Pyramid of Giza", Journal of Advanced Instrumentation in Science, 2022 (2022) 280.

Journal of Advanced Instrumentation in Science JAIS-280, 2022

Tomographic Muon Imaging of the Great Pyramid of Giza

Alan D. Bross,[1] E. C. Dukes,[2] Ralf Ehrlich,[2] Eric Fernandez,[2] Sophie Dukes,[3] Mohamed Gobashy,[4] Ishbel Jamieson,[5] Patrick J La Rivière,[6] Mira Liu,[6] Gregory Marouard,[7] Nadine Moeller,[7] Anna Pla-Dalmau,[1] Paul Rubinov,[1] Omar Shohoud,[8] Phillip Vargas,[6] and Tabitha Welch[8]

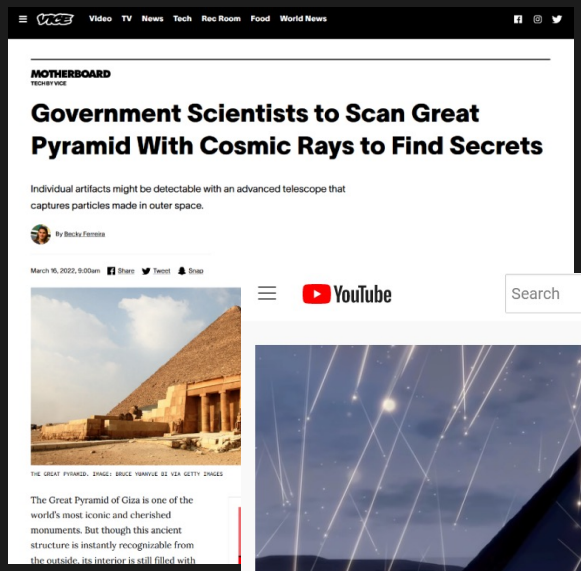
[1]*Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL, USA*
[2]*Physics Department, University of Virginia, Charlottesville, VA, USA*
[3]*Virginia Tech University, Blacksburg, WV, USA*
[4]*Geophysics Department, Faculty of Science, Cairo University, Cairo, Egypt*
[5]*Department of Physics, University of Oxford, Oxford, UK*
[6]*Department of Radiology, University of Chicago, Chicago, IL, USA*
[7]*Department of Near Eastern Languages & Civilizations Yale University, New Haven, CT, USA*
[8]*Department of Physics, University of Chicago, Chicago, IL, USA*

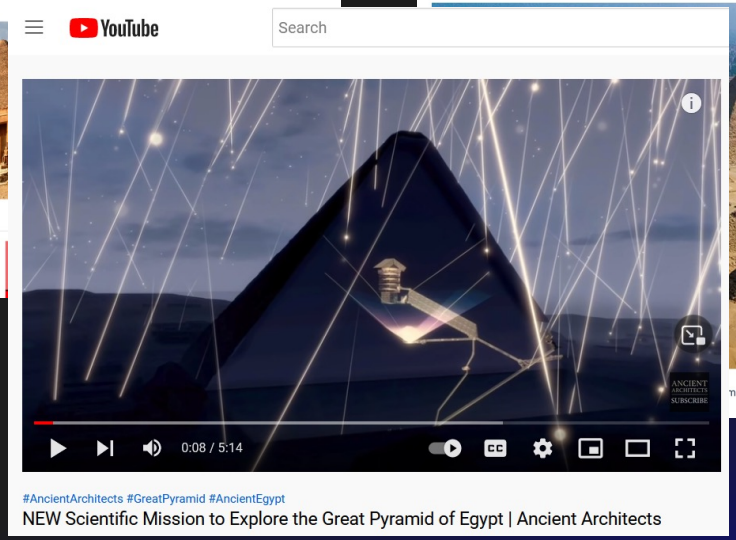
Abstract

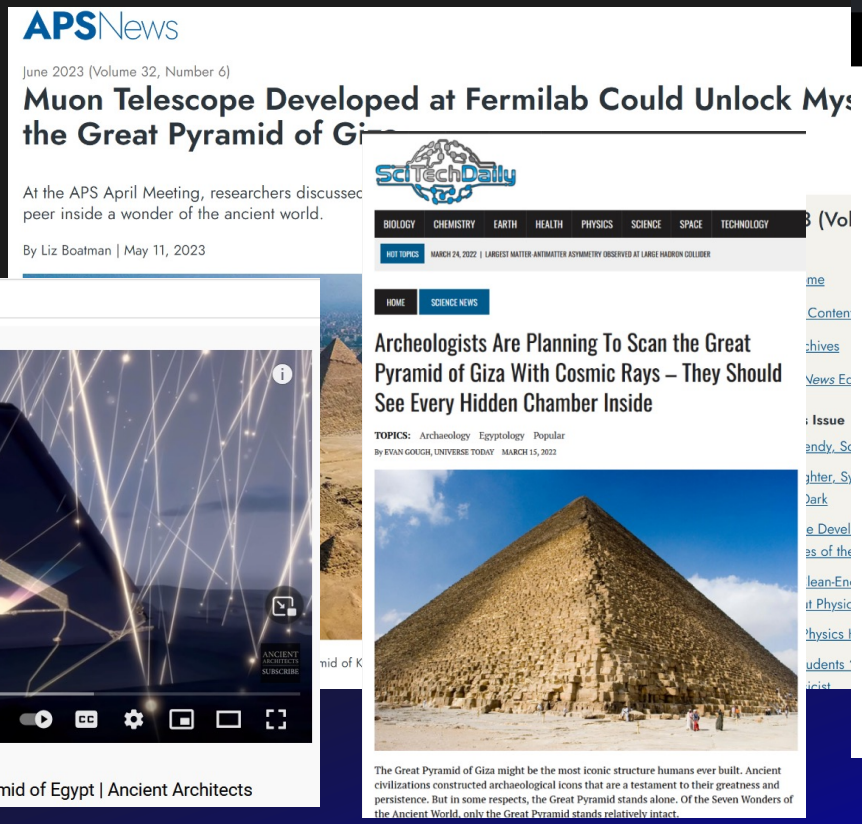
The pyramids of the Giza plateau have fascinated visitors since ancient times and are the last of the Seven Wonders of the ancient world still standing. It has been half a century since Luiz Alvarez and his team used cosmic-ray muon imaging to look for hidden chambers in Khafre's Pyramid. Advances in instrumentation for High-Energy Physics (HEP) allowed a new survey, ScanPyramids, to make important new discoveries at the Great Pyramid (Khufu) utilizing the same basic technique that the Alvarez team used, but now with modern instrumentation. Exploring the Great Pyramid Mission plans to field a very large muon telescope system that will be transformational with respect to the field of cosmic-ray muon imaging. We plan to field a telescope system that has upwards of 100 times the sensitivity of the equipment that has recently been used at the Great Pyramid, will image muons from nearly all angles, and will, for the first time, produce a true tomographic image of such a large structure.

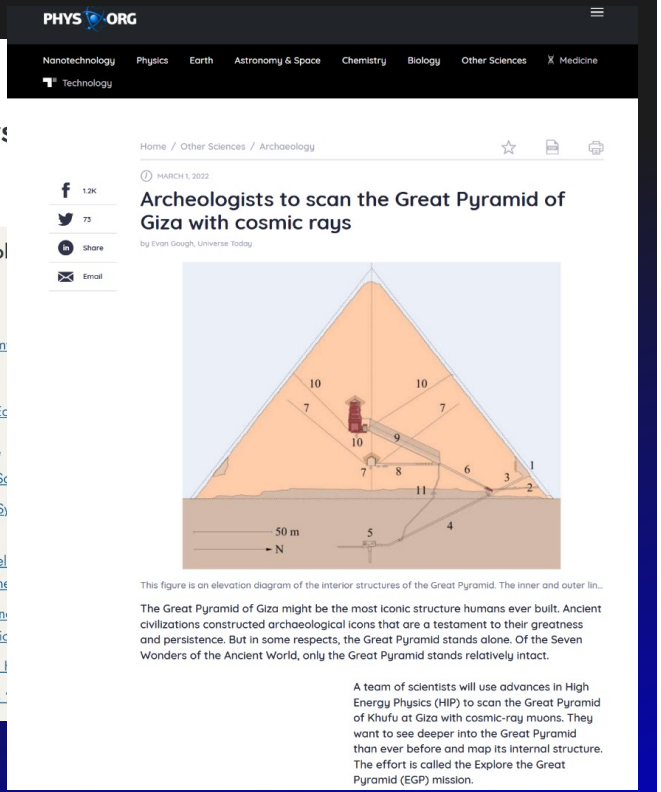
EGP in the News

The publication of our detector design has generated a large amount of interest in the field: we hope it will generate interest in funding this much larger detector





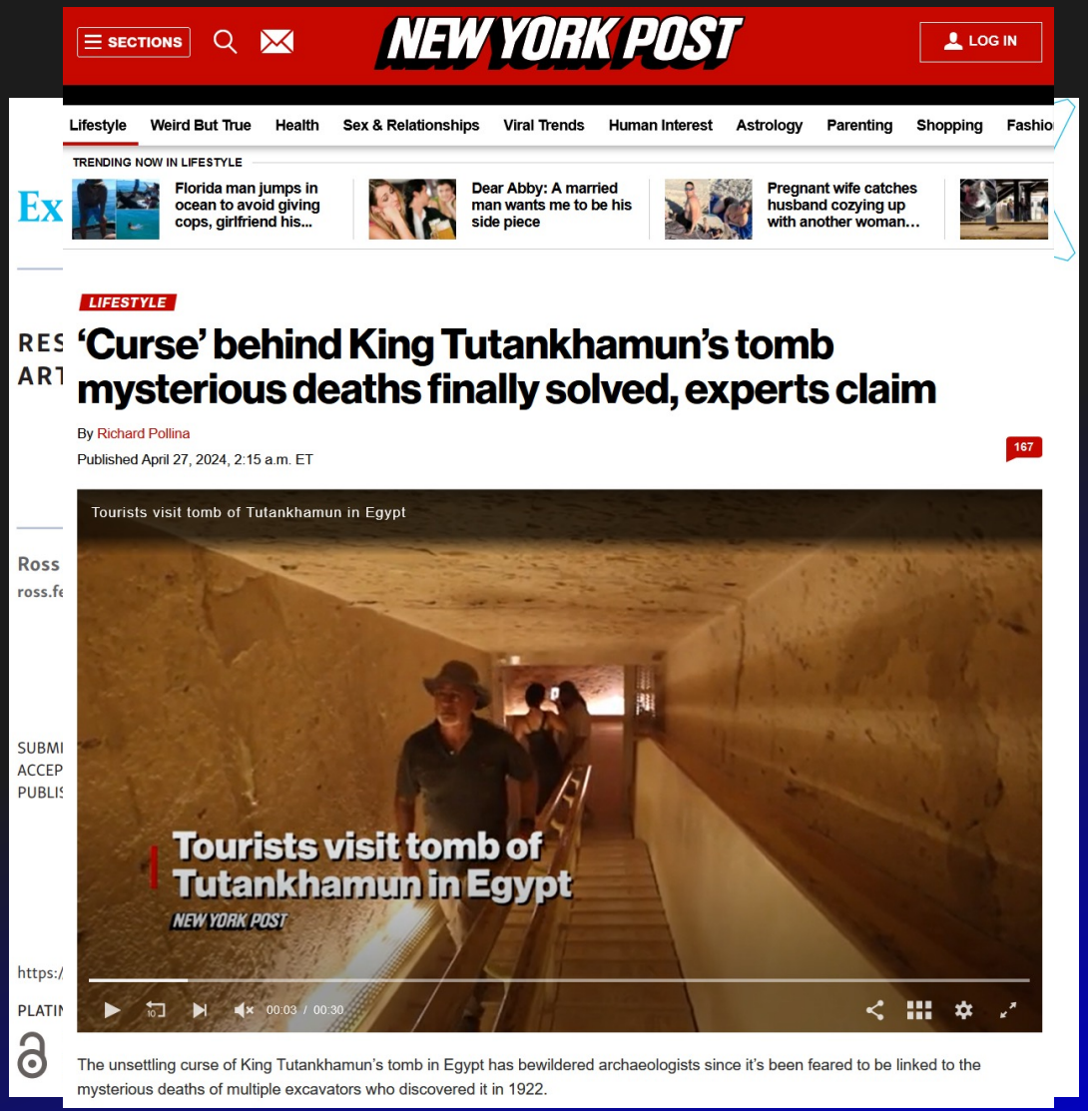




Pyramid Work is Dangerous

Figure 9. Fatal Gamma Waves Illustrated as the Venomous 'ka' Snake (Wikipedia Commons).

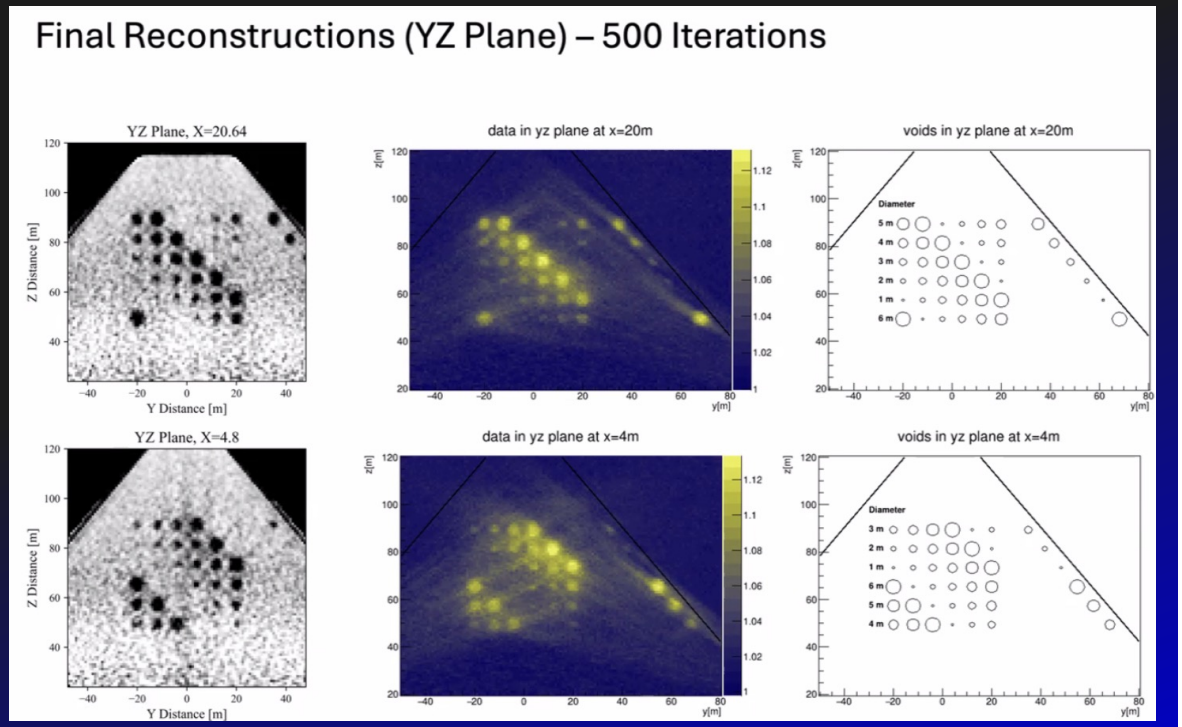
"Egyptian funerary literature (Pyramid Texts, Coffin Texts, Book of the Dead) is known from about 2300-2100 BCE onward but recognised as derivative from some earlier source. It is viewed as a largely unintelligible, mystical guide to the afterlife. Here, a re-examination of standard translations reveals frequent, plain language descriptions of nuclear technology. "



Status

- We received seed funding from University of Chicago's Big Ideas Generator with matching funding from Fermilab
- Simulation work is essentially complete, although we are still working on the tomography end
  - Need to replace the back projection with a real tomographic image as with a CT scan, where we expect to resolve voids as small as 1 m
- Detector design is complete
- A prototype detector was successfully tested at Fermilab
- Assembly jigs and fabrication procedures have been produced and tested
- **Need to find funding to build the complete detector**

Test tomographic image: vertical slice through a solid pyramid with spherical voids (400 iterations)



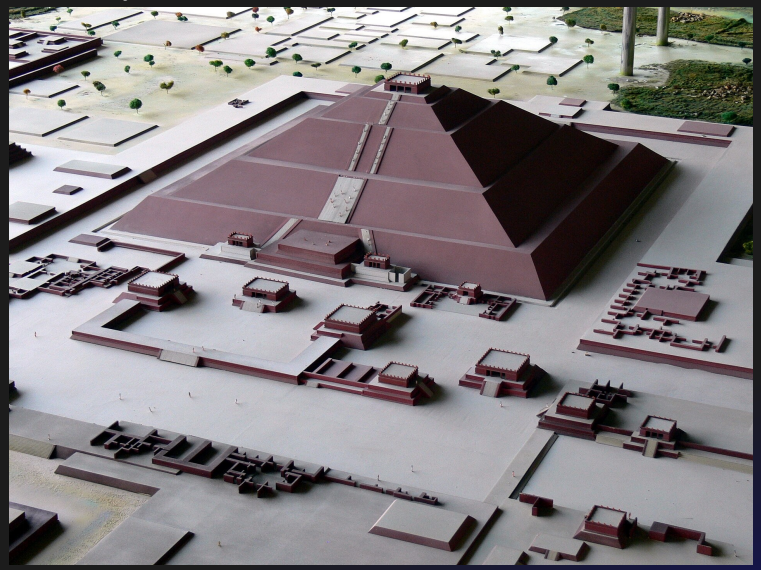
Chichén Itzá: Temple of Kukulkan (or El Castillo)

Mesoamerican Pyramids

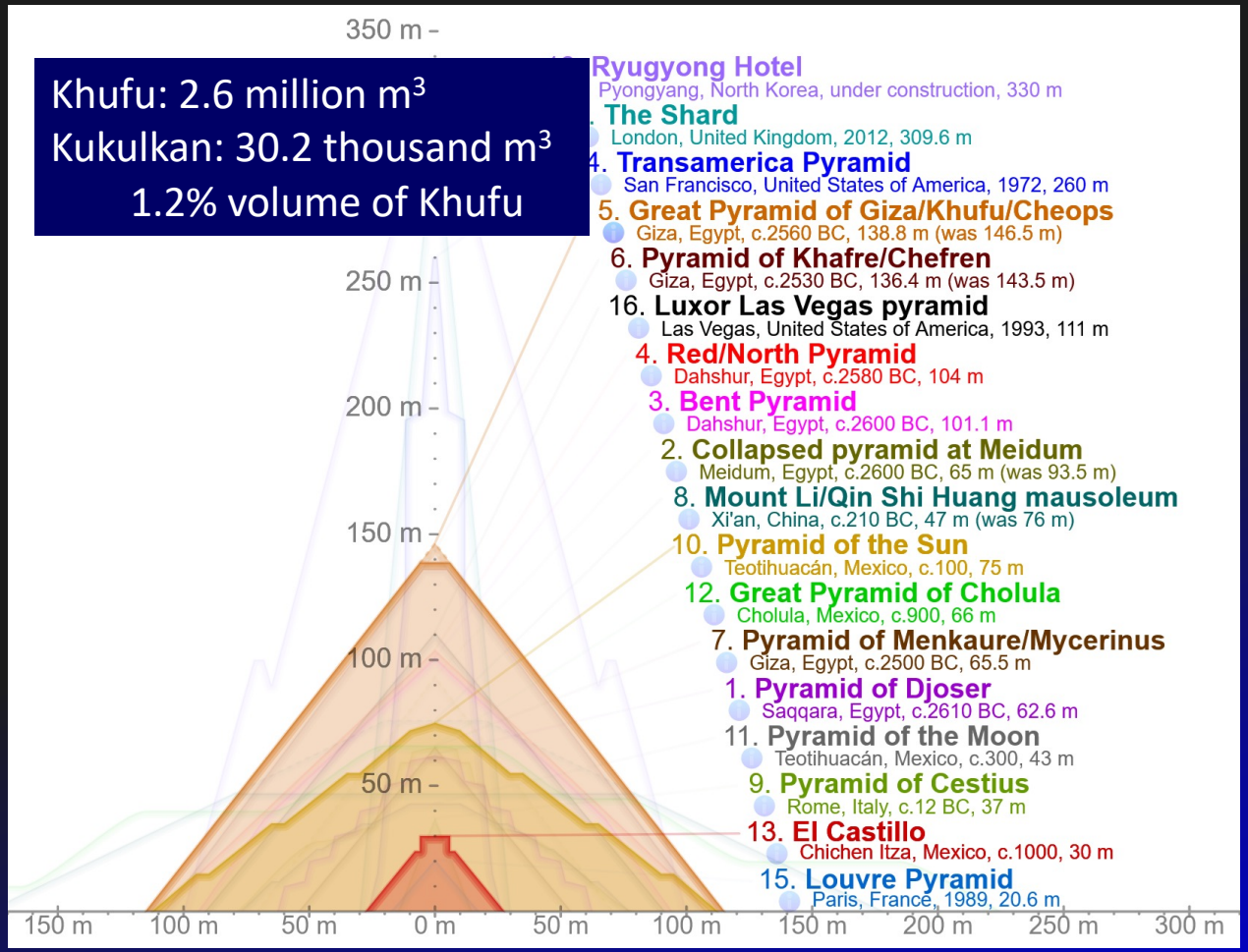
Both the Mayans and the Aztecs (and other Mesoamerican cultures) built large stone pyramids

Unlike the pyramids of Egypt, these were religious edifices; not burial sites

The Mesoamerican pyramids were built much later than those in Egyptian, and in general were much smaller, had flat tops and external stairs



Pyramid of the sun, Teotihuacan



Chichén Itzá

One of the largest pre-Columbian Mayan cities (AD 600-1200)

"Chichén Itzá " means "At the mouth of the well of the Itza.“

Site has a large sink hole, cenotes, called the “Cenote Sagrado”, Sacred Cenote

Largest structure is Temple of Kukulkán (El Castillo)

Temple of Kukulkán (or El Castillo) at Chichen Itza

Built by the Mayans between the 8th and 12th centuries AD.

Temple to the Kukulkán, a feathered serpent deity

Temple of Kukulkán (El Castillo)

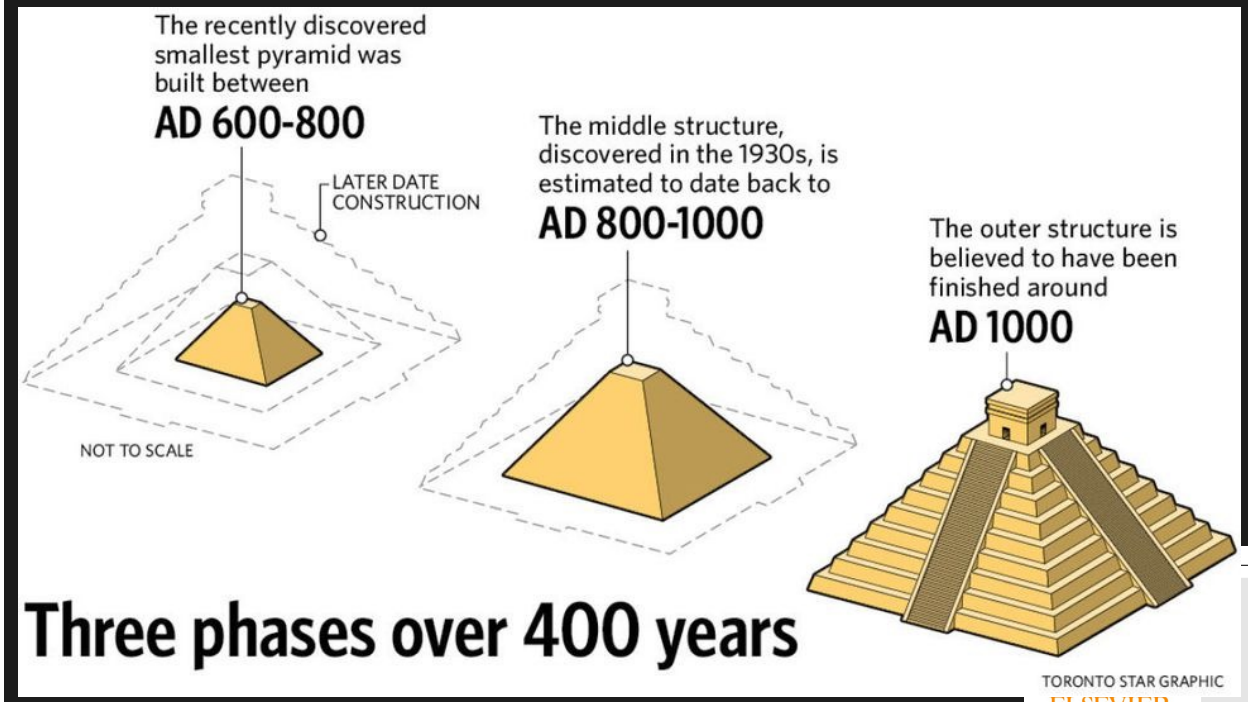
It was explored in the 1930s and found to have a substructure – an earlier pyramid with two chambers: one with a Chac Mool statue and jaguar throne inlaid with jade

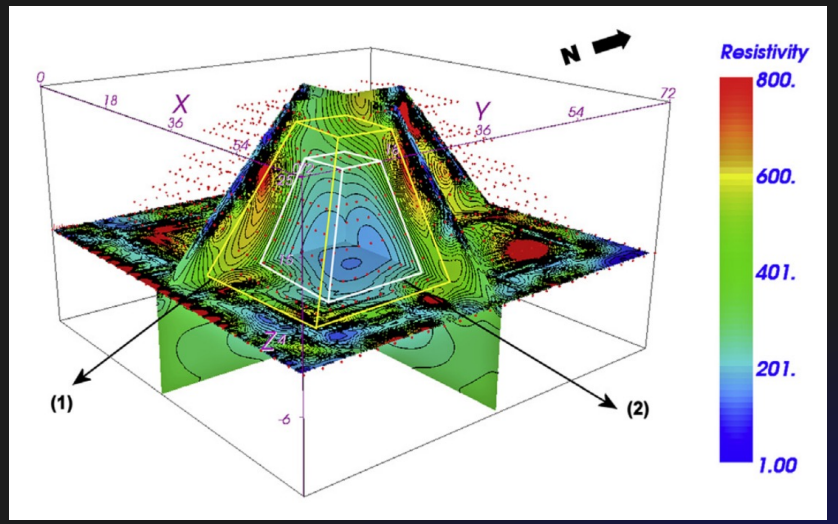
Interior of a second substructure, if it indeed exists, remains un-excavated

Anxo Miján Maroño & Andrés Armesto

Is this what the interior looks like?

Some Recent Evidence of Yet a Smaller Pyramid





Mexican scientists used a scanning technique known as tri-dimensional electrical resistivity tomography (2018).

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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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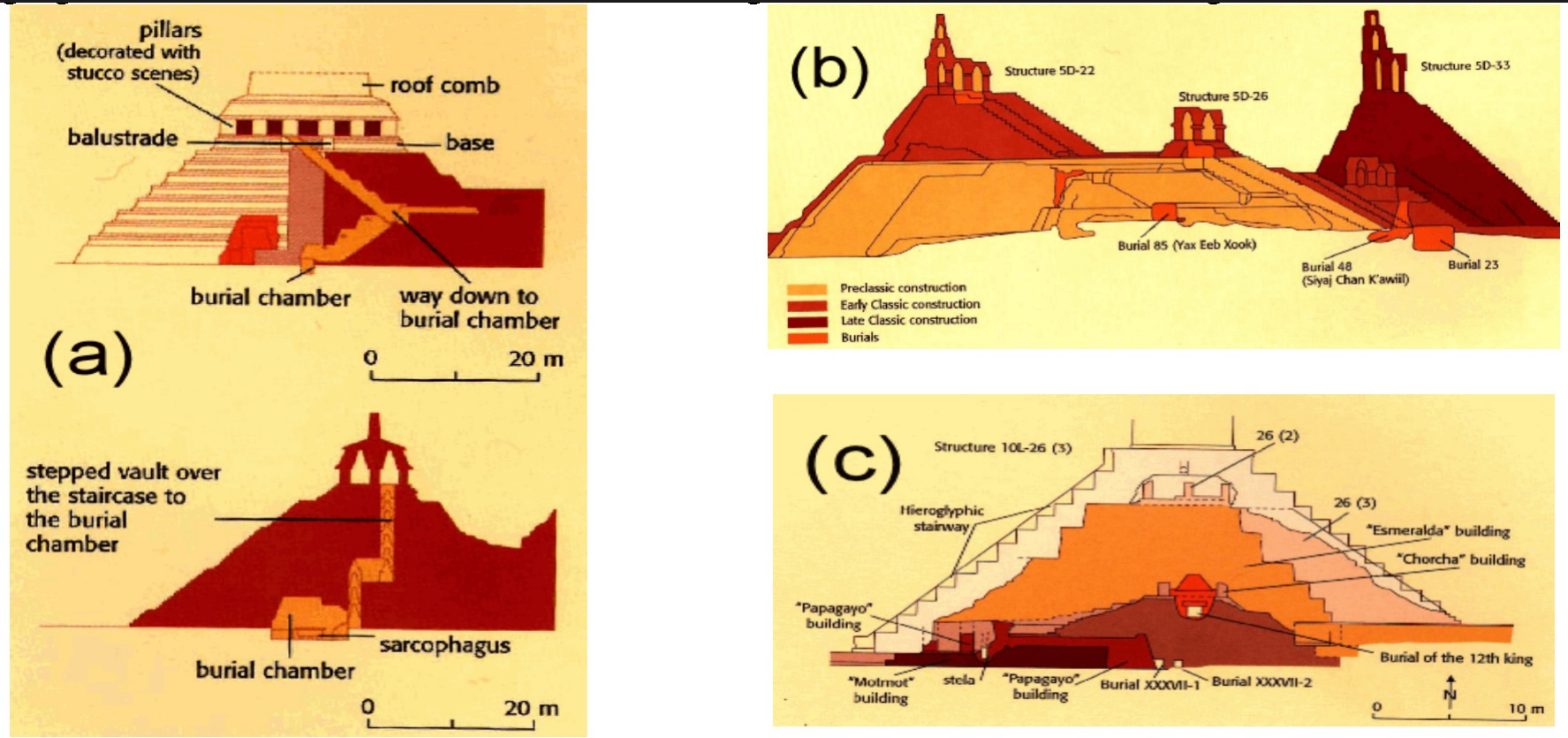
[b] Dirección de Estudios Arqueológicos, Instituto Nacional de Antropología e Historia, Lic. Primo Verdad 3, Col. Centro, Cuauhtémoc, C.P. 06060, Mexico City, Mexico
[c] Instituto de Geofísica, Universidad Nacional Autónoma de México, Circuito de Investigación, Ciudad Universitaria, Coyoacán, C.P. 04510, Mexico City, Mexico

Significant Substructures in Other Mesoamerican Pyramids



a) Palenque
b) Tikal
c) Copan

Non-Invasive Archaeology Using Muons (NAUM) Team

The team in front of Temple of Kukulkán

We have received funding from the National Science Foundation and the UVA Jefferson Trust to build the detectors and run the experiment

Edmundo Garcia-Solis, Austin Harton (Chicago State University)

Joseph Sagerer (Dominican University)

Mark Adams (UIC/Fermilab-QuarkNet)

Sten Hansen (Fermilab-Retired)

Eduardo Pérez de Heredia (Tecnologia Zero)

Jose Osorio, Marco Antonio Santos Ramirez (Instituto Nacional de Arqueologia e Historia - INAH)

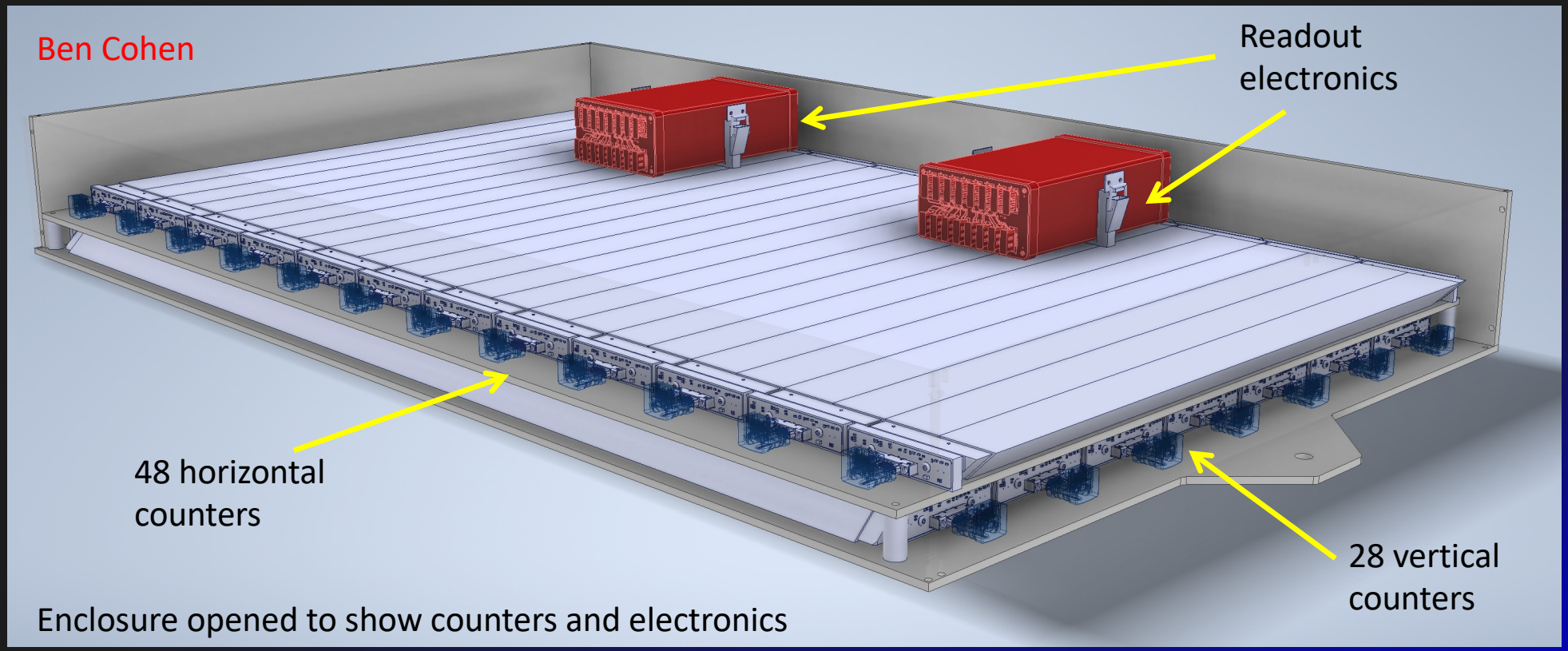
Arturo Menchaca Rocha, Azucena Cervantes, Hesiquio Vargas (Universidad Nacional Autonoma de Mexico - UNAM)

The Detector: Module Design

Design by my group at UVA.

Uses the same triangular counter design as with the Egyptian pyramid project.

Much smaller module size: 1 m x 0.6 m: 48 short horizontal and 28 long vertical counters

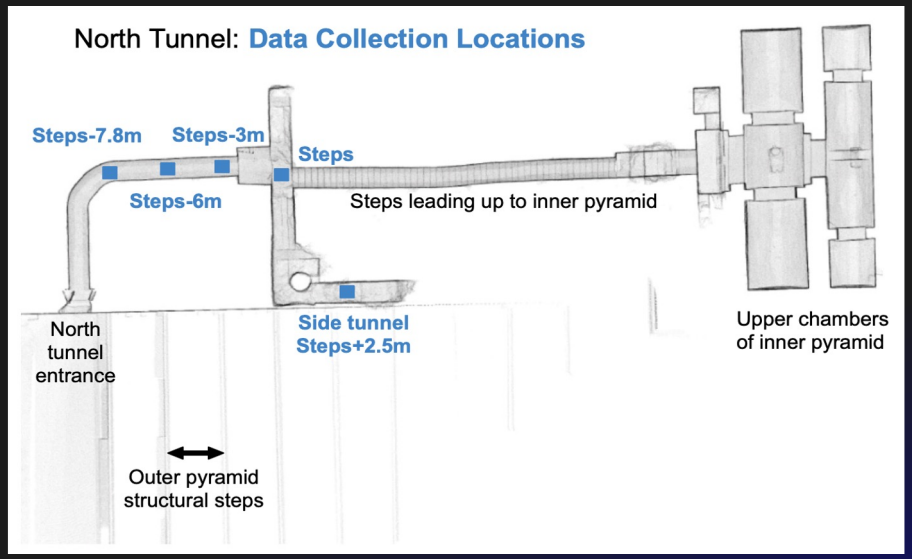


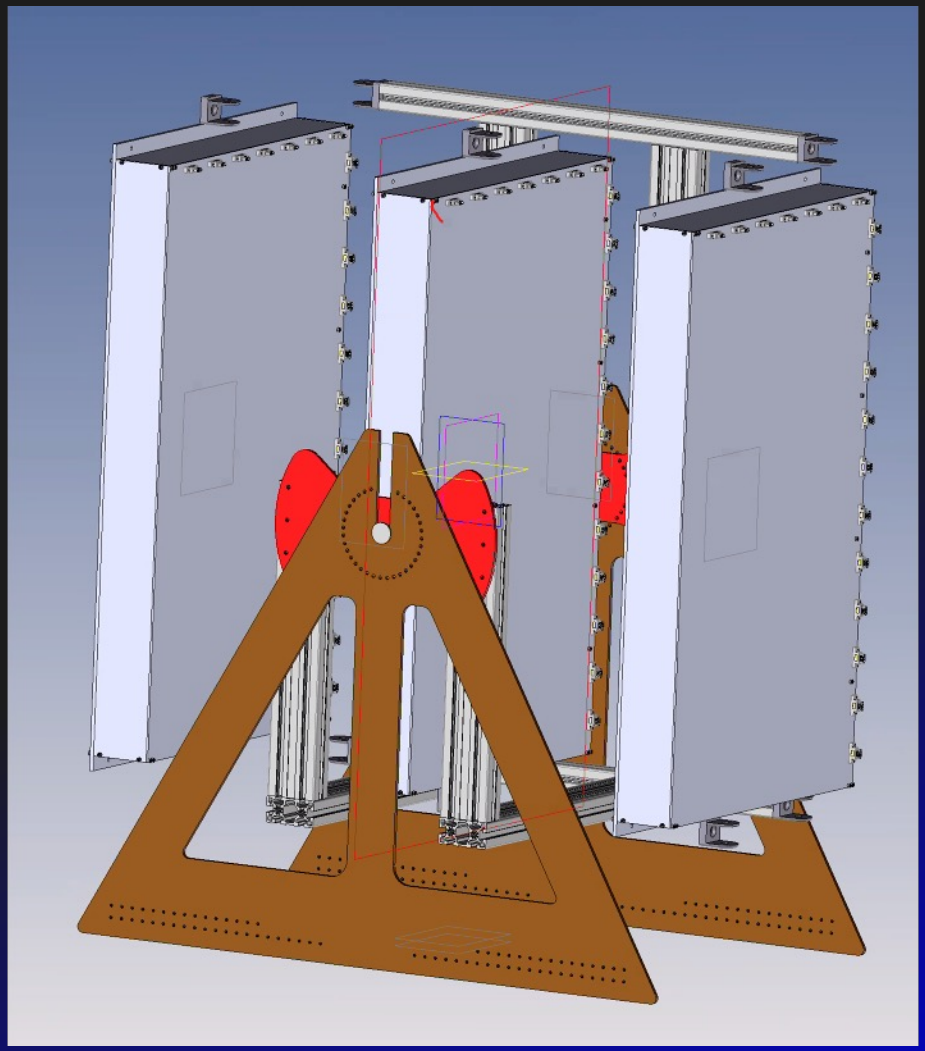
Enclosure opened to show counters and electronics

The Detector

Detector will be placed in small tunnel inside the pyramid

Detector consists of three modules mounted on a frame that allows them to be rotated and moved out of the way for access through the tunnel

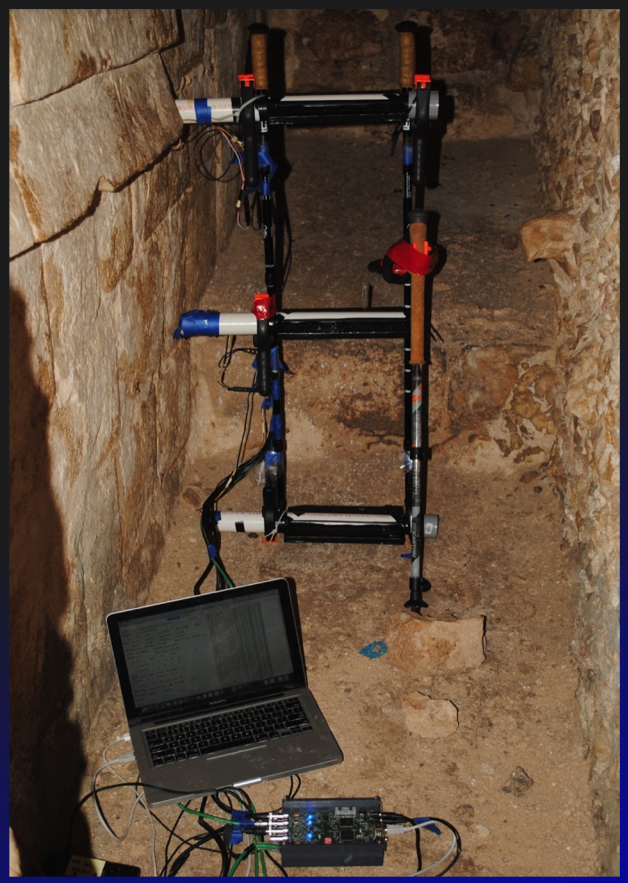




Preliminary Measurements

In the spring of 2022 Dukes and undergraduate student Sydney Roberts went to Chichen Itza to make various exploratory measurements with other members of the team

Preliminary Measurements: Cosmic Ray Flux



Undergraduate physics major, Sydney Roberts, at left preparing instruments to measure the cosmic-ray muon rate with other members of the NAUM team

Exploring Temple of Kukulkán

UVA undergraduate physics major, Sydney Roberts, and Chicago State student, Olesson Cesalien, making measurements El Castillo

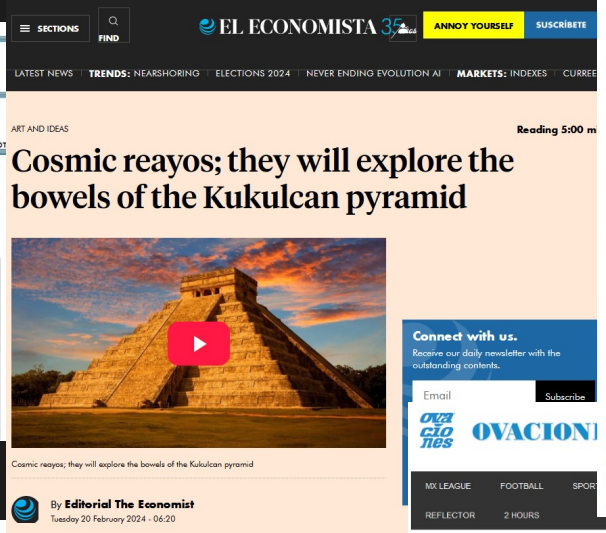
Current Inhabitants of the Temple of Kukulkán

Preliminary Measurements: Scan of Pyramid Interior

We brought along a laser scanner to make precision measurements of the interior (and exterior) of the pyramid

We also brought along a drone to take photos and video of the exterior of the pyramid

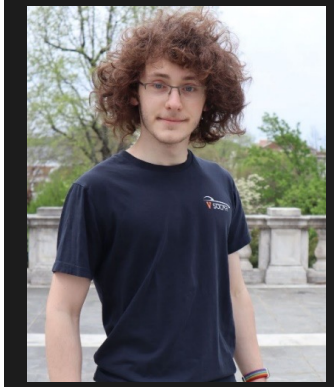
NAUM in the News



Status of the NAUM Project

- Successful visit to Chichén Itzá to scan pyramid interior and investigate services need to power the detector
- Detector design completed
- Detector protype successfully fabricated and tested in the Fermilab Test Beam Facility
- All parts have been ordered and have been received
- Readout electronics had to be redesigned due to the COVID supply-chain problems that have been plaguing all high energy physics experiments: this caused a two-year delay
- Detector being fabricated this summer at UVA with help from undergraduate students
- Detector to be installed in pyramid in early 2025

Many Thanks to My UVA, NAUM, & EGP Collaborators



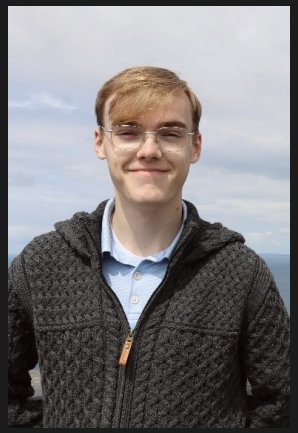
Benjamin Cohen

Anne Marie Branch

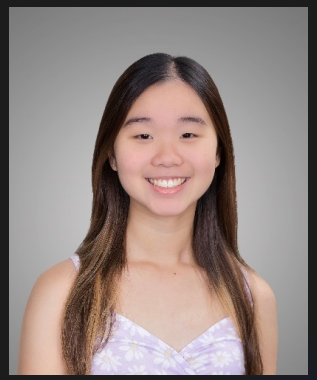
Sydney Roberts

The NAUM team at Chichen Itza

Wayne Farrell



Luke Watson



Jolie Ng

Eleanor Fetterer

Ralf Ehrlich

Eric Fernandez

New Non-Invasive Probes are Unlocking the Secrets of Pyramids

Many of these techniques are in their infancy: Stay tuned for more new, exciting results!