Muon Radiography In Japan
-ScanPyramids-

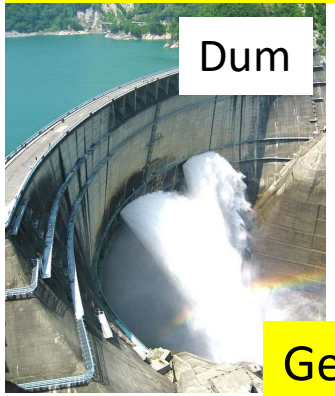
K. Morishima, N.Kitagawa, A.Nishio, M.Kuno, Y.Manabe

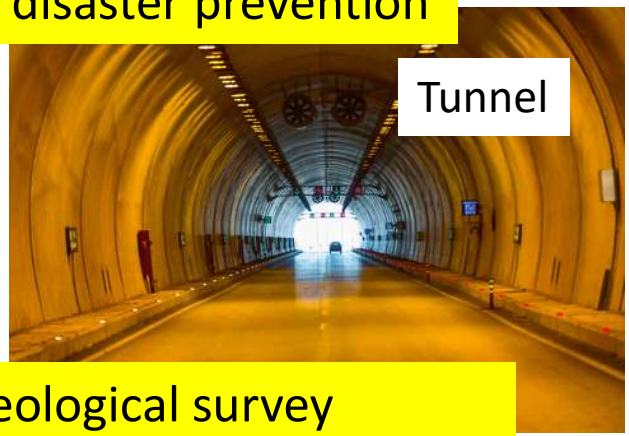
Cosmic-ray Radiography Group

F-lab., Nagoya University

Cosmic-ray Muon Radiography

Earth Science, disaster prevention





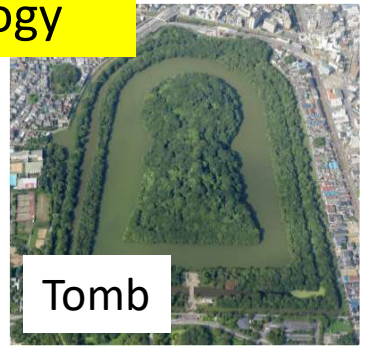
Geological survey
Infrastructure Inspection

Nuclear Power Plant

Blast Furnace

Industrial plants

Cultural Assets
Archaeology



Scan Pyramids (2015-)

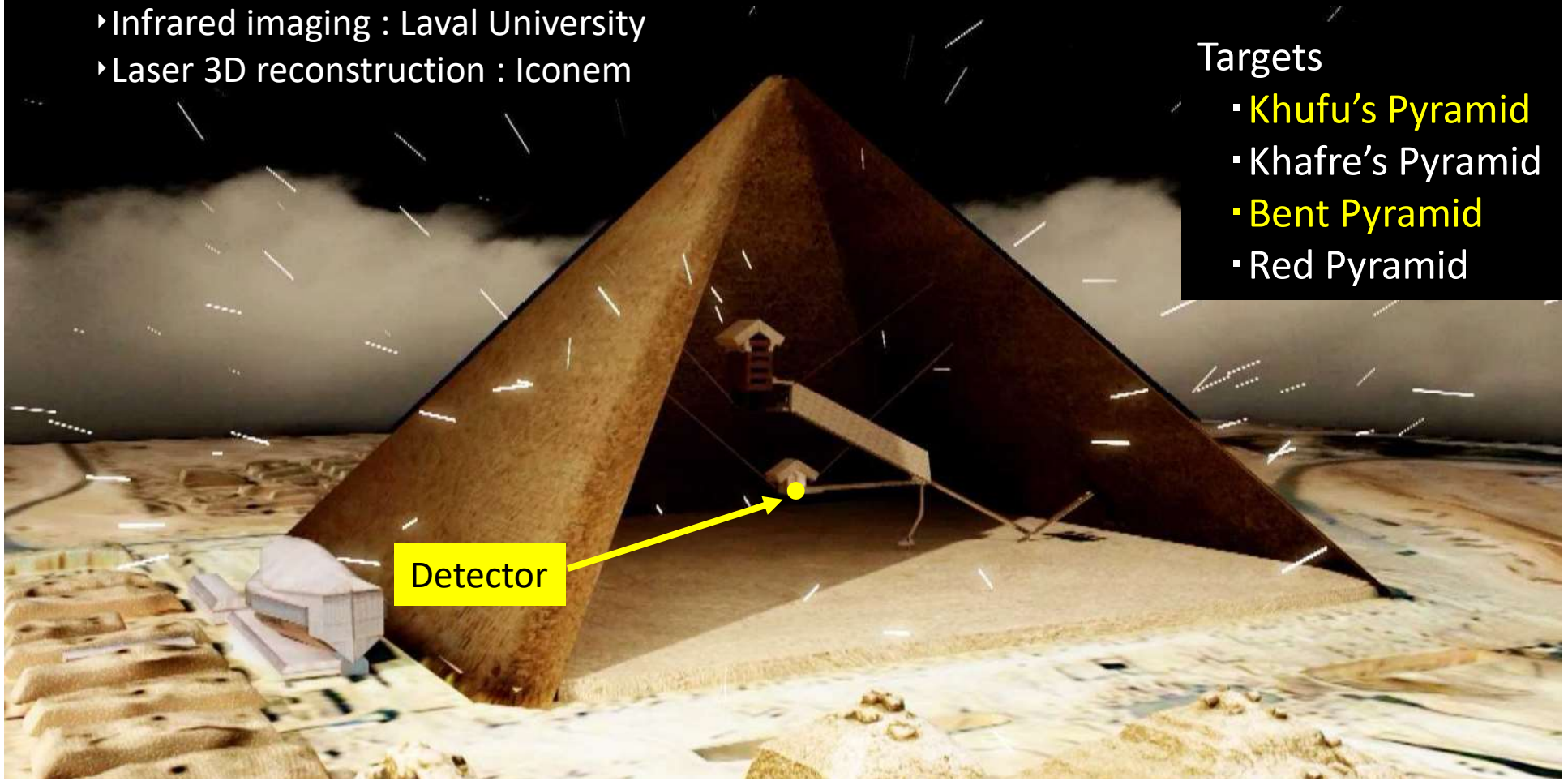
Organization : Egyptian Ministry of Antiquities, Cairo University and HIP institute
Participating countries : Egypt, France, Canada and Japan

Non-destructive Imaging Technologies

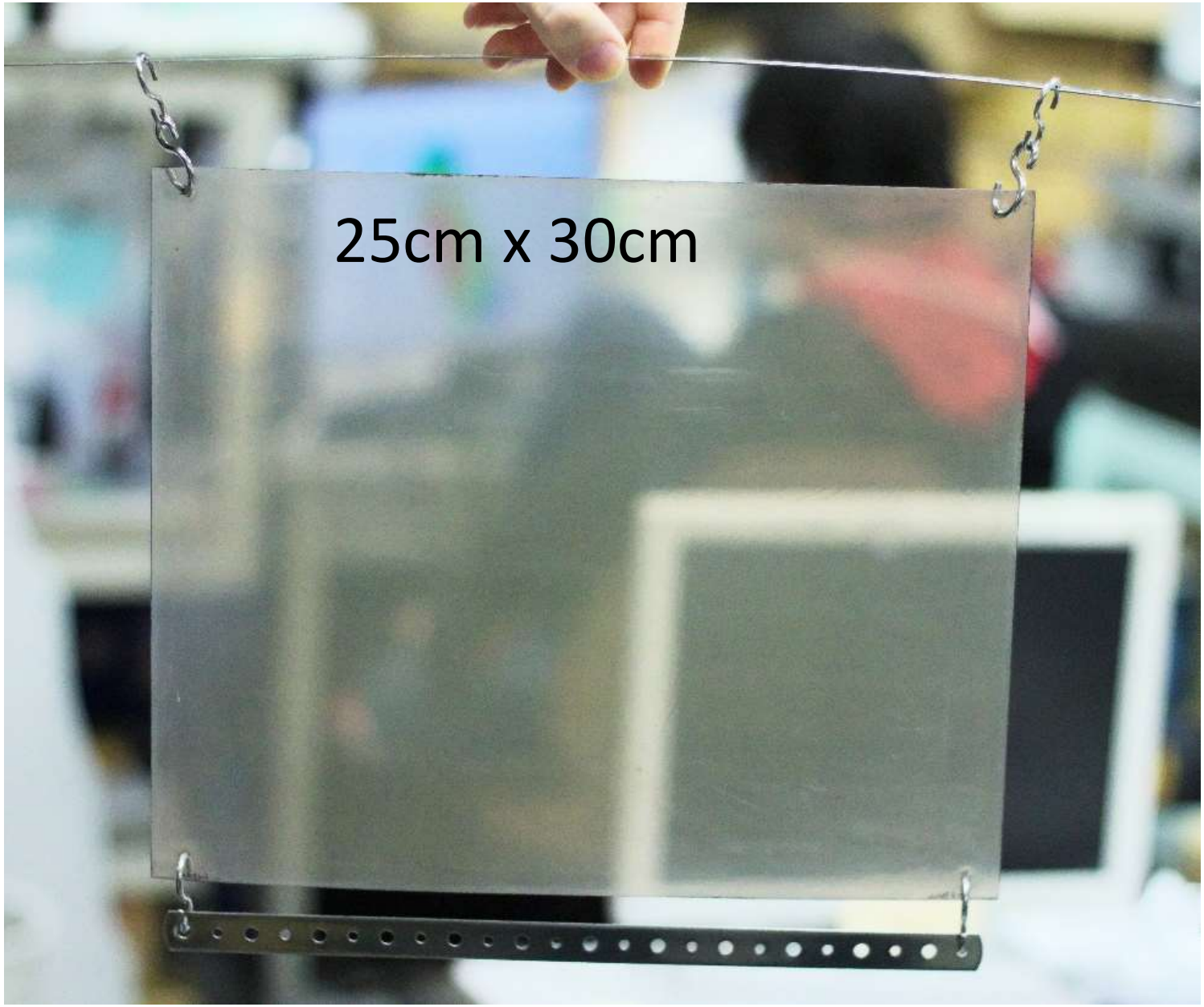
- Cosmic-ray Muon Radiography : Nagoya University, KEK, CEA
- Infrared imaging : Laval University
- Laser 3D reconstruction : Iconem

Targets

- Khufu's Pyramid
- Khafre's Pyramid
- Bent Pyramid
- Red Pyramid



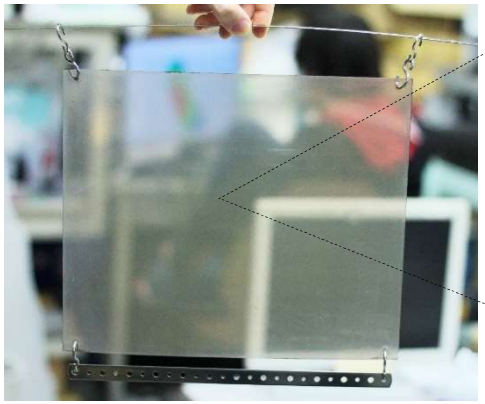
Nuclear emulsion



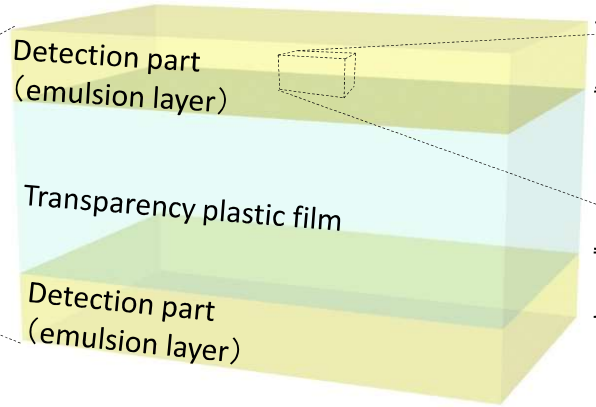
Nuclear Emulsion Film

Three dimensional Tracking Detector for charged particles

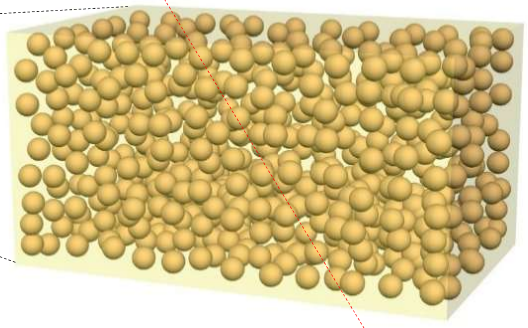
Nuclear Emulsion
after chemical development



Cross section in three dimension

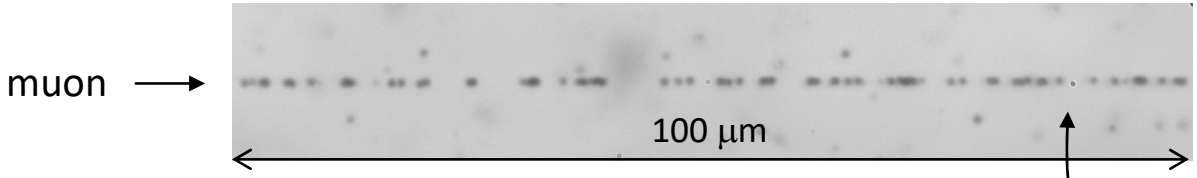


Silver bromide crystal
(diameter 200 nm)

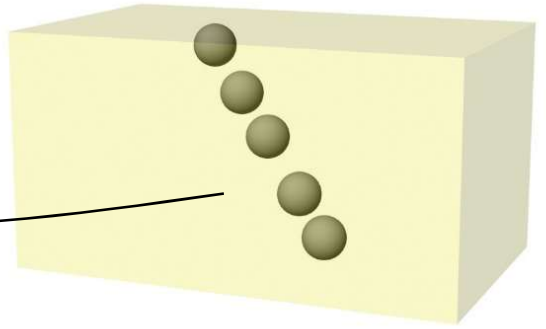


Photographic
development

Optical microscope image of recorded muon track



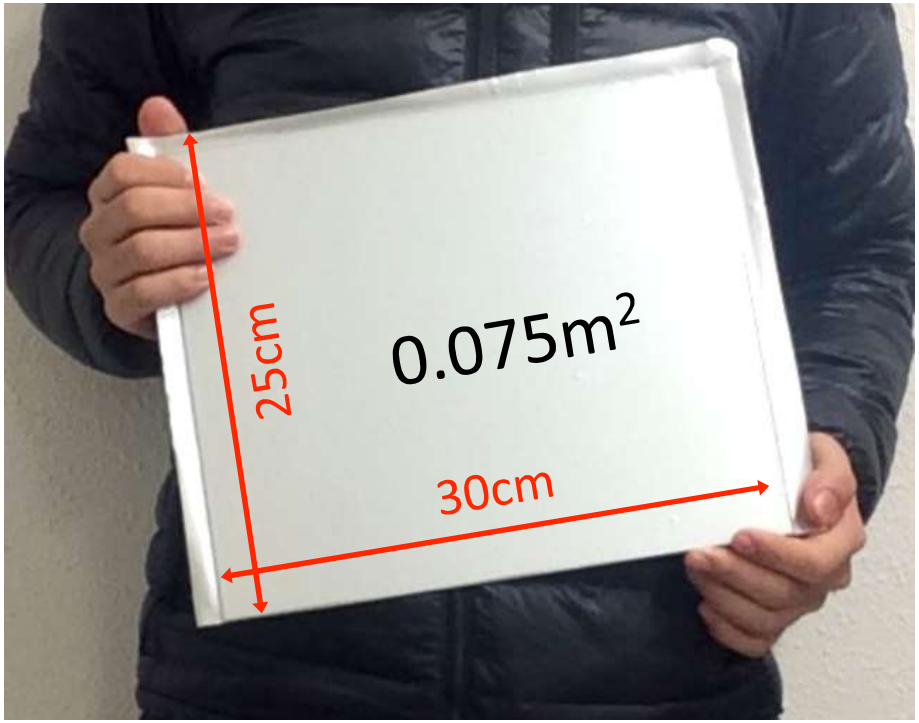
Muon



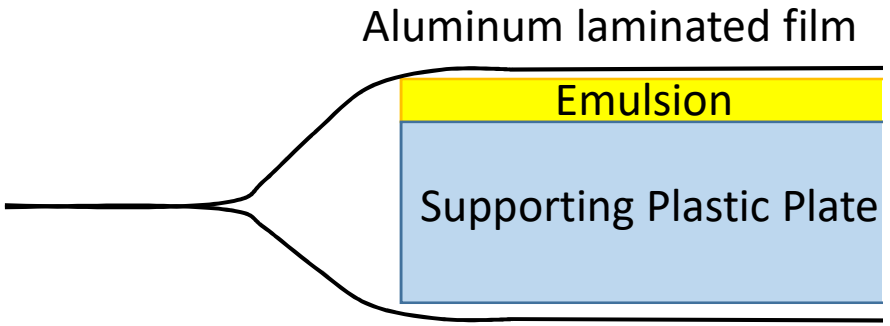
Technical advantages

- Sub-micrometric spatial Resolution in three dimension, detection in 4π steradian
- No electric power, light weight, thin, Water proof -> No limitation to installation place
- Mass production : Large area detector, multi target, multi position in parallel

Nuclear emulsion detector

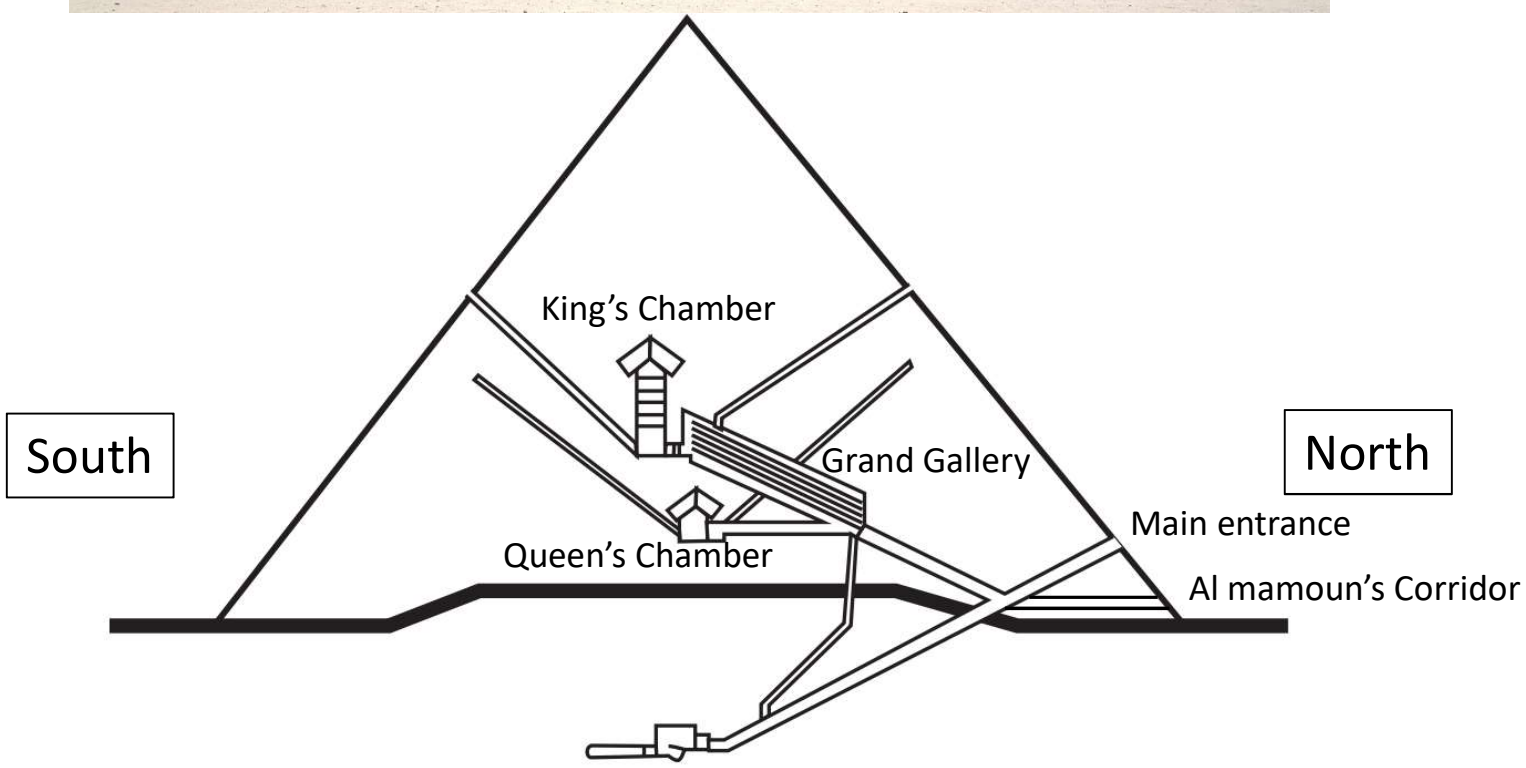


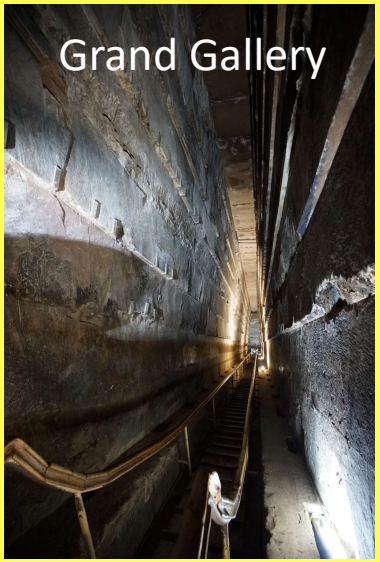
Cross section

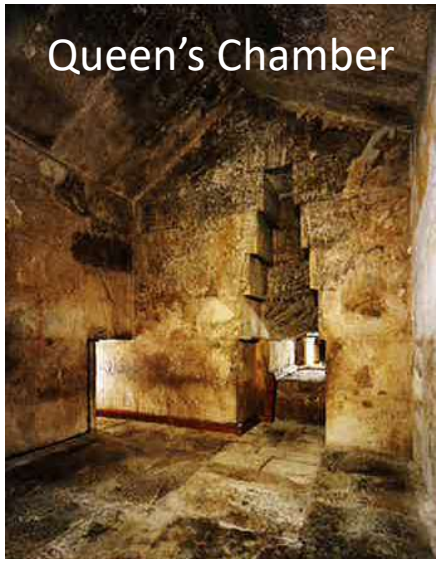


Khufu’s Pyramid

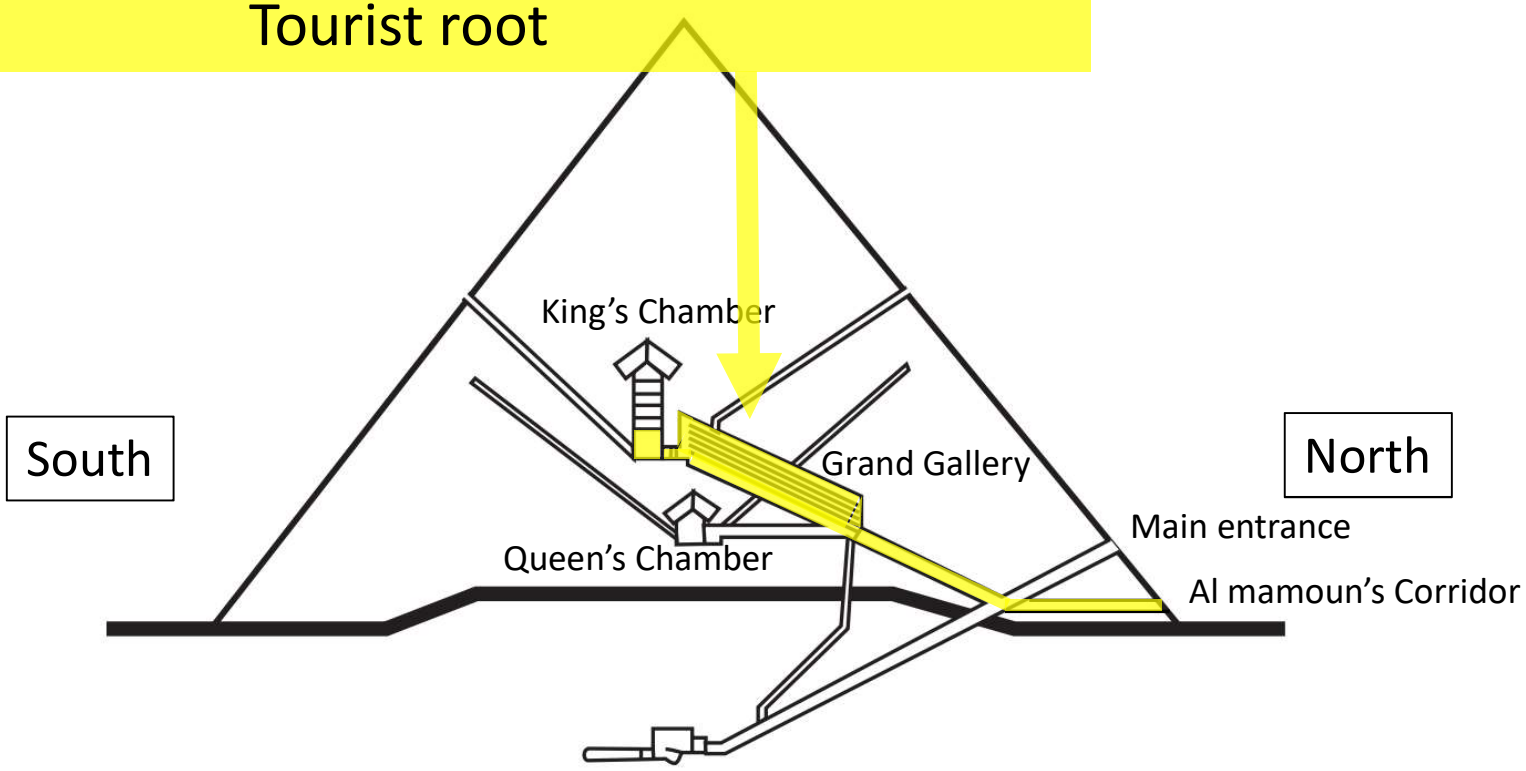
Height: 147m
Width: 230m

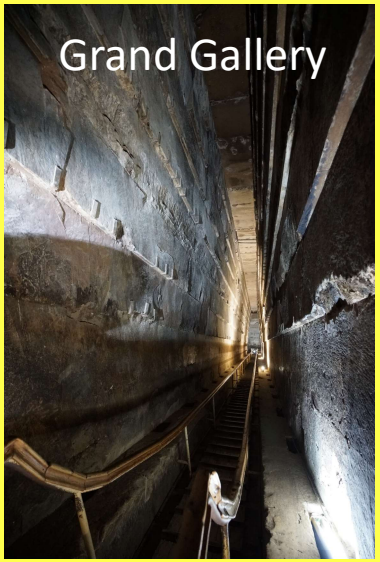


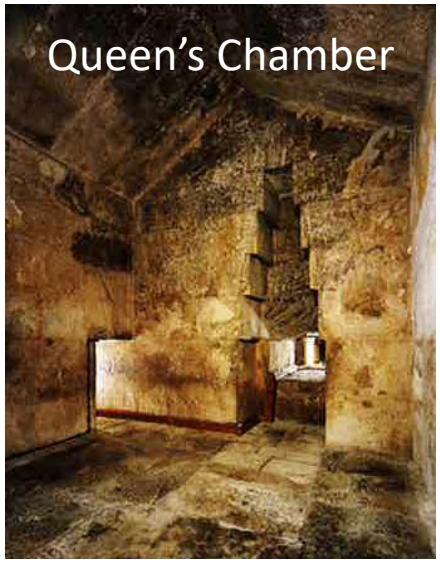




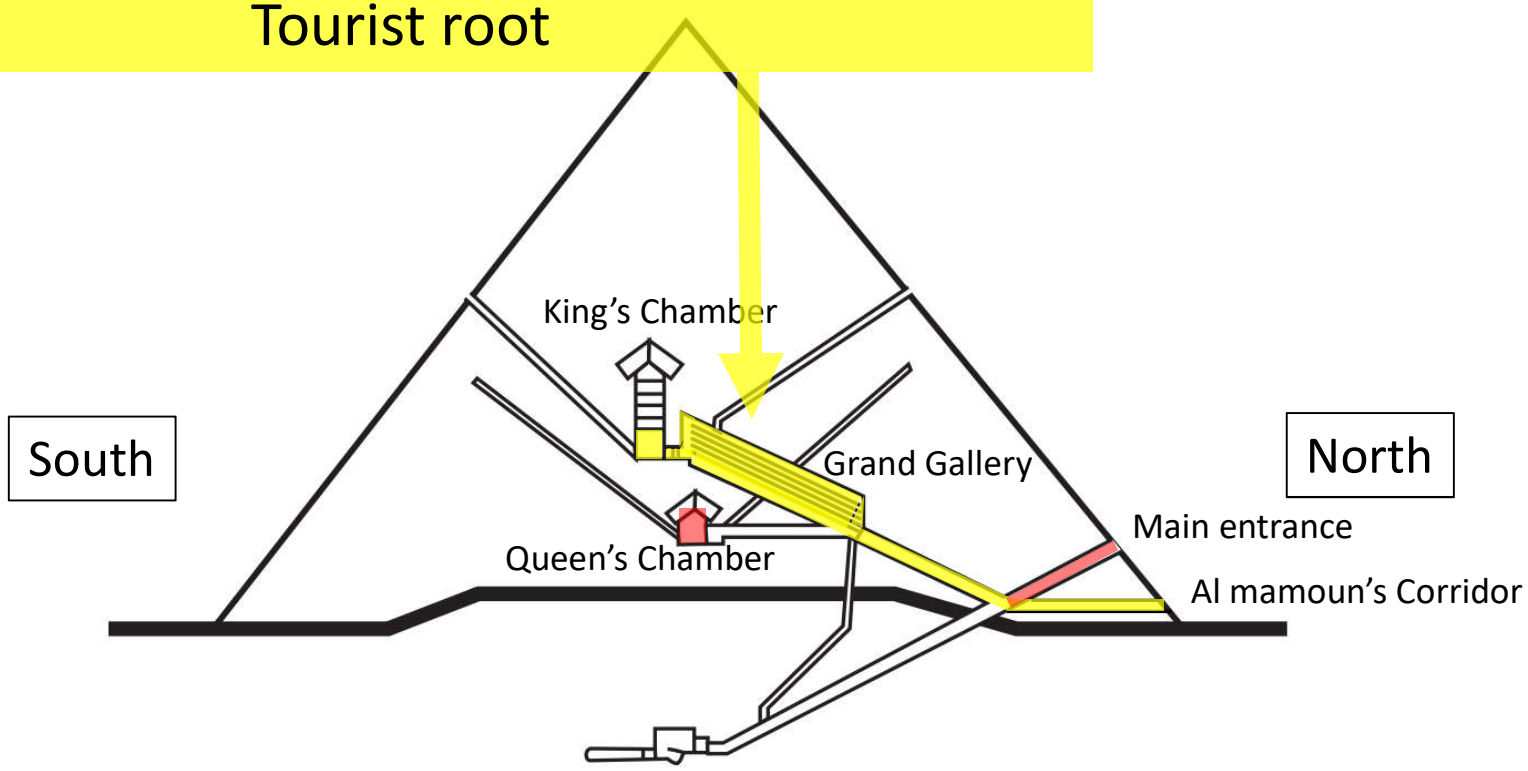
Tourist root

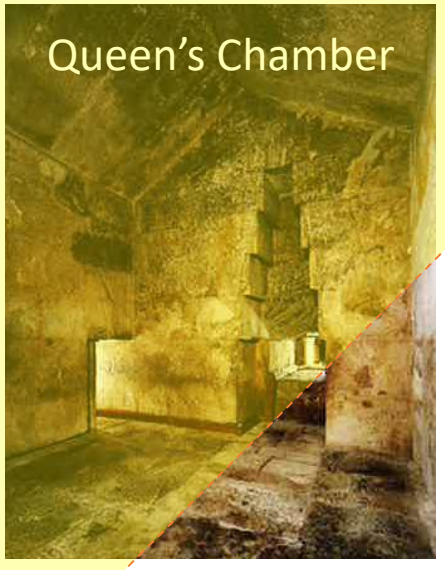




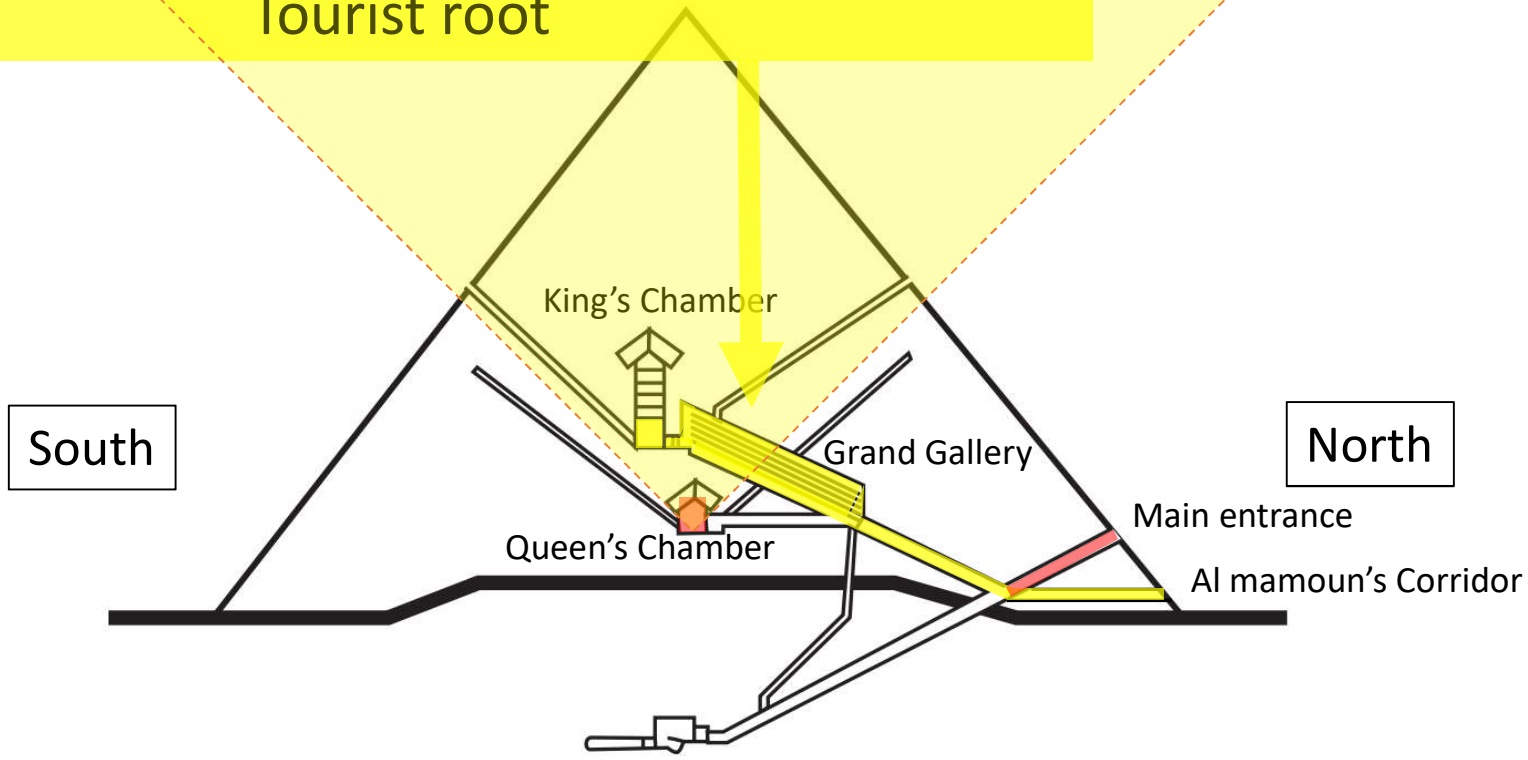


Tourist root

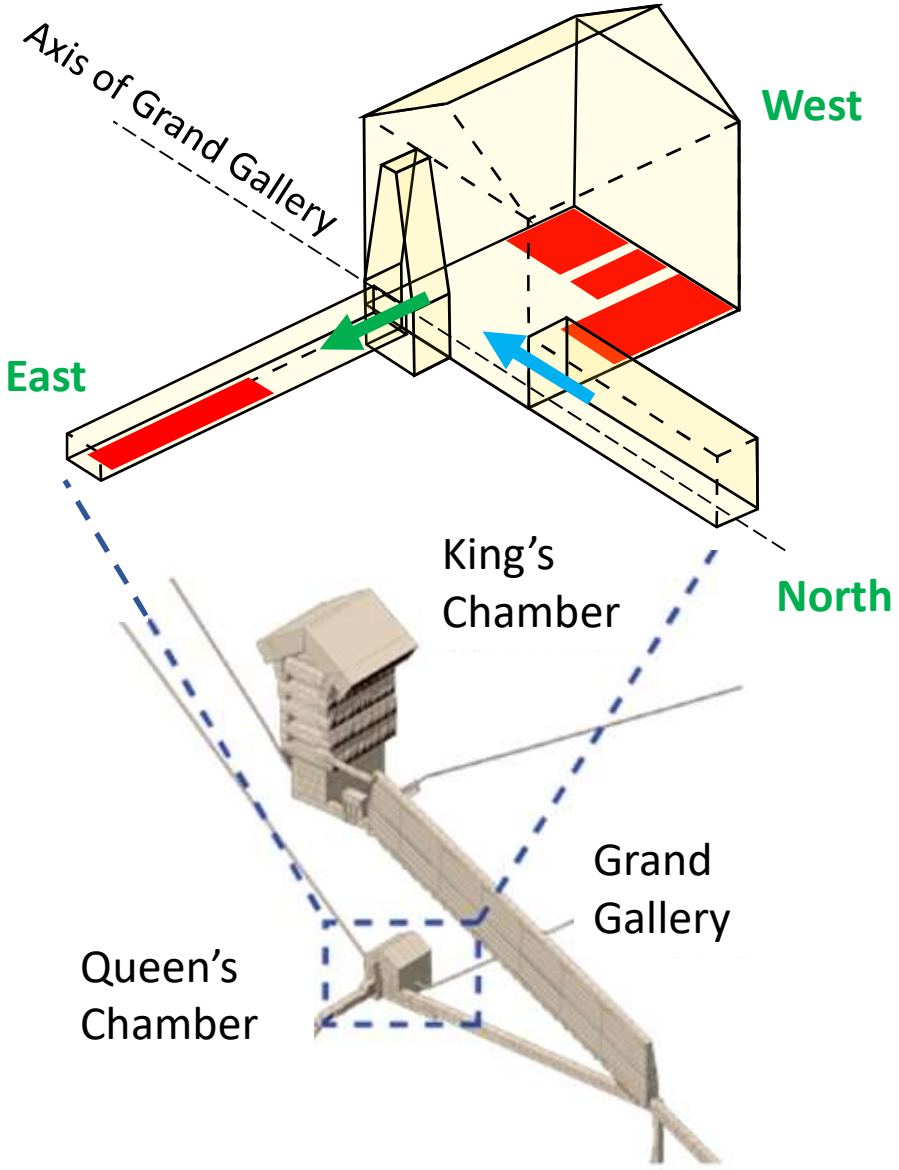




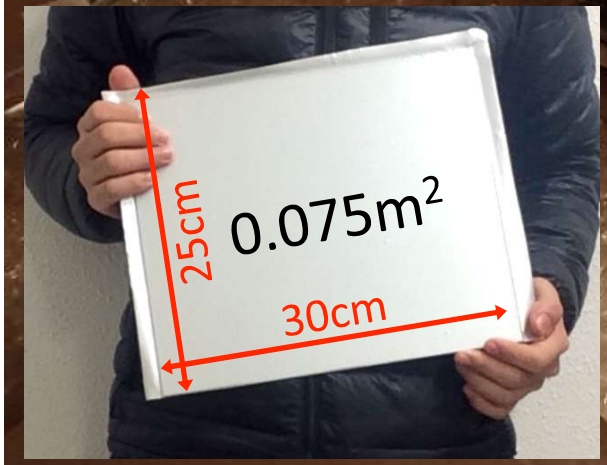
Tourist root



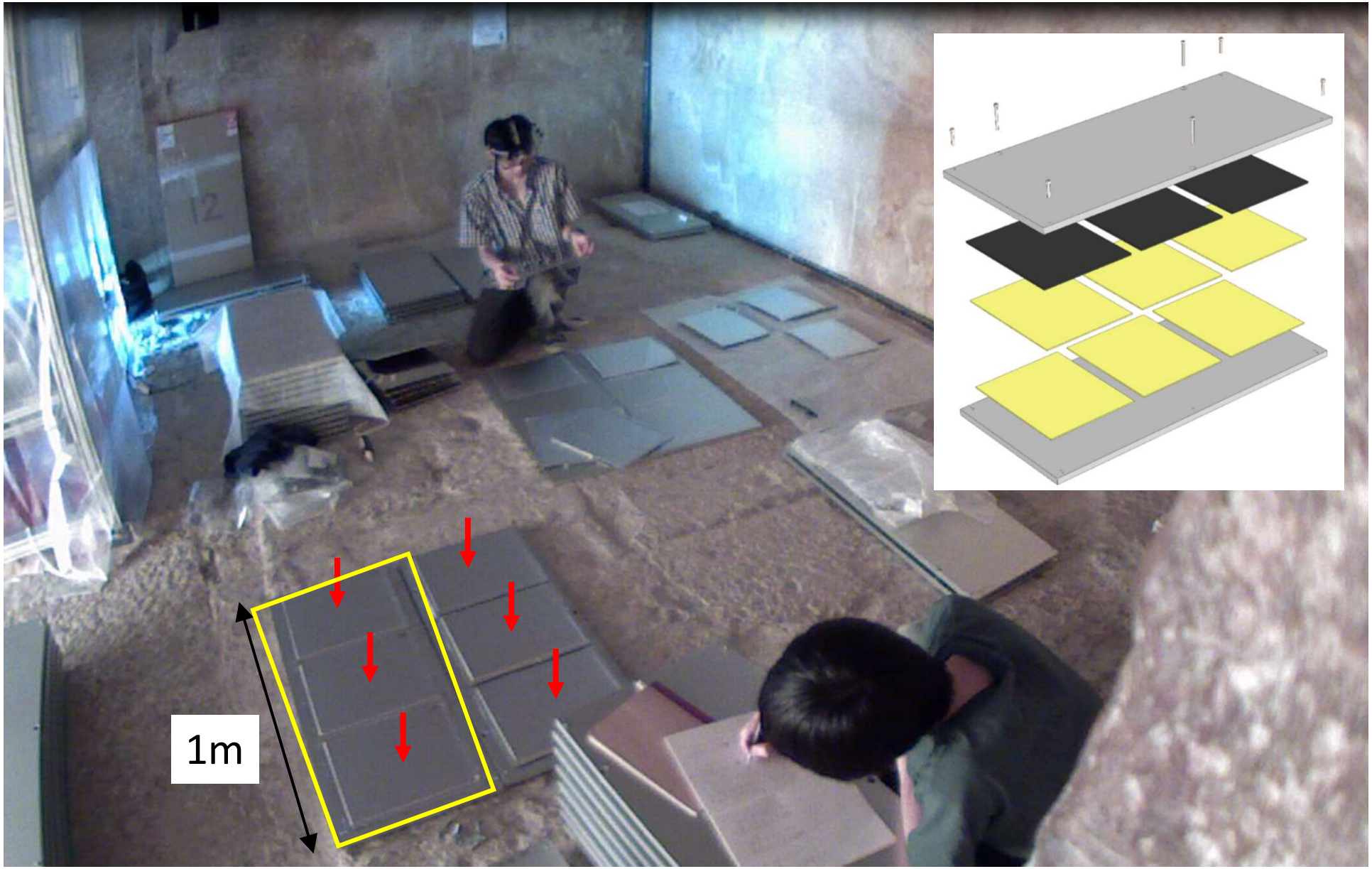
Observation from the Queen's Chamber



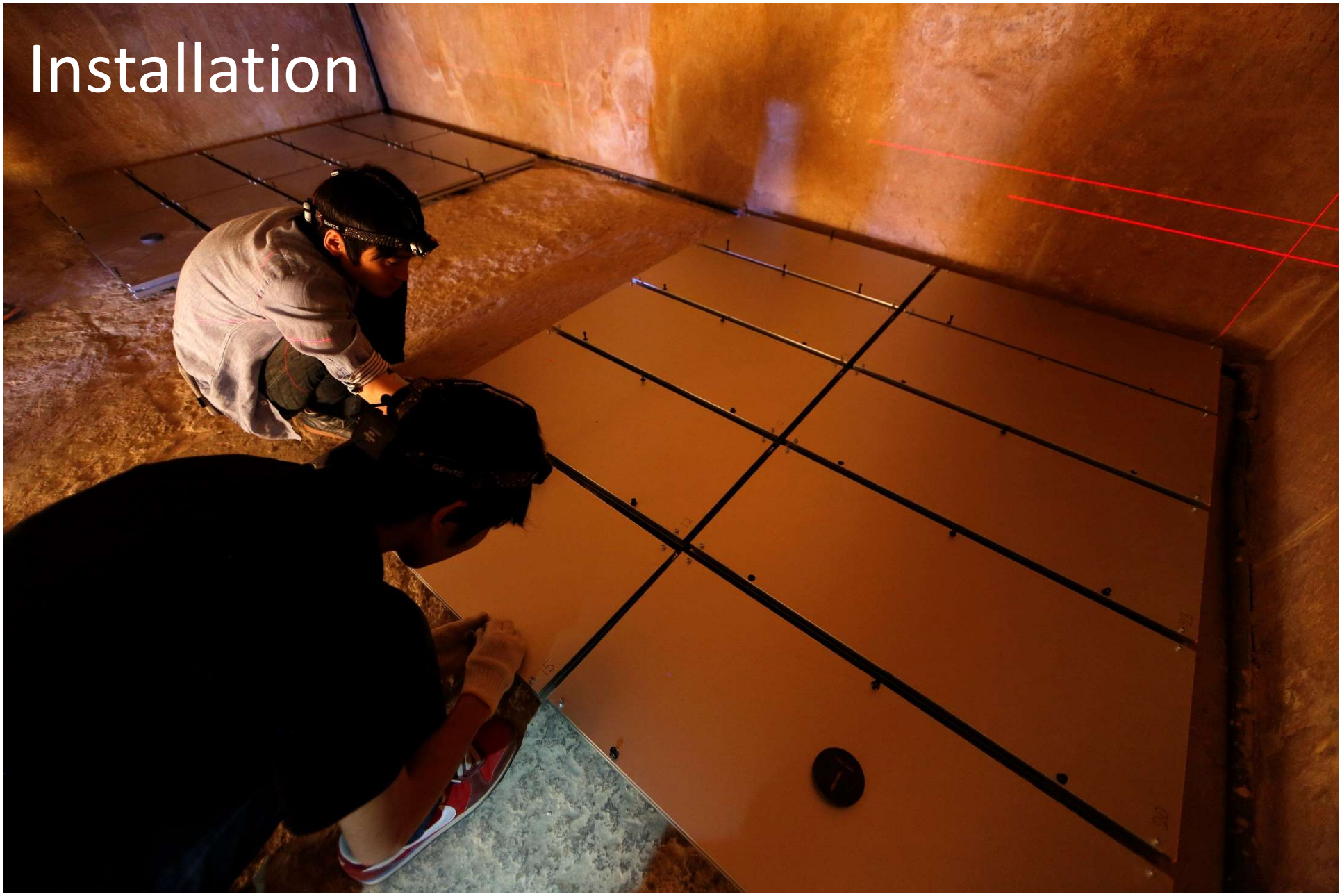
Nuclear Emulsion Detectors



Installation in the Queen's Chamber



Installation



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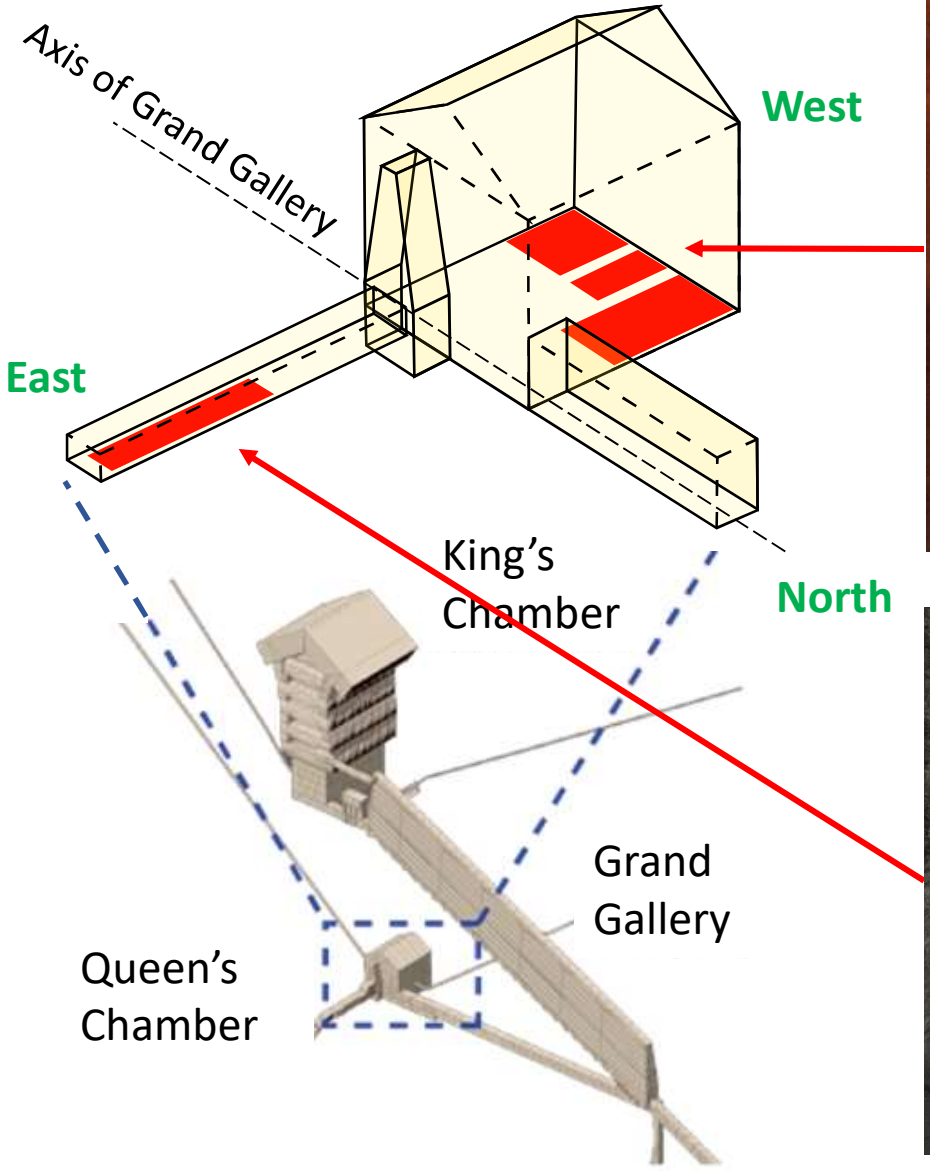
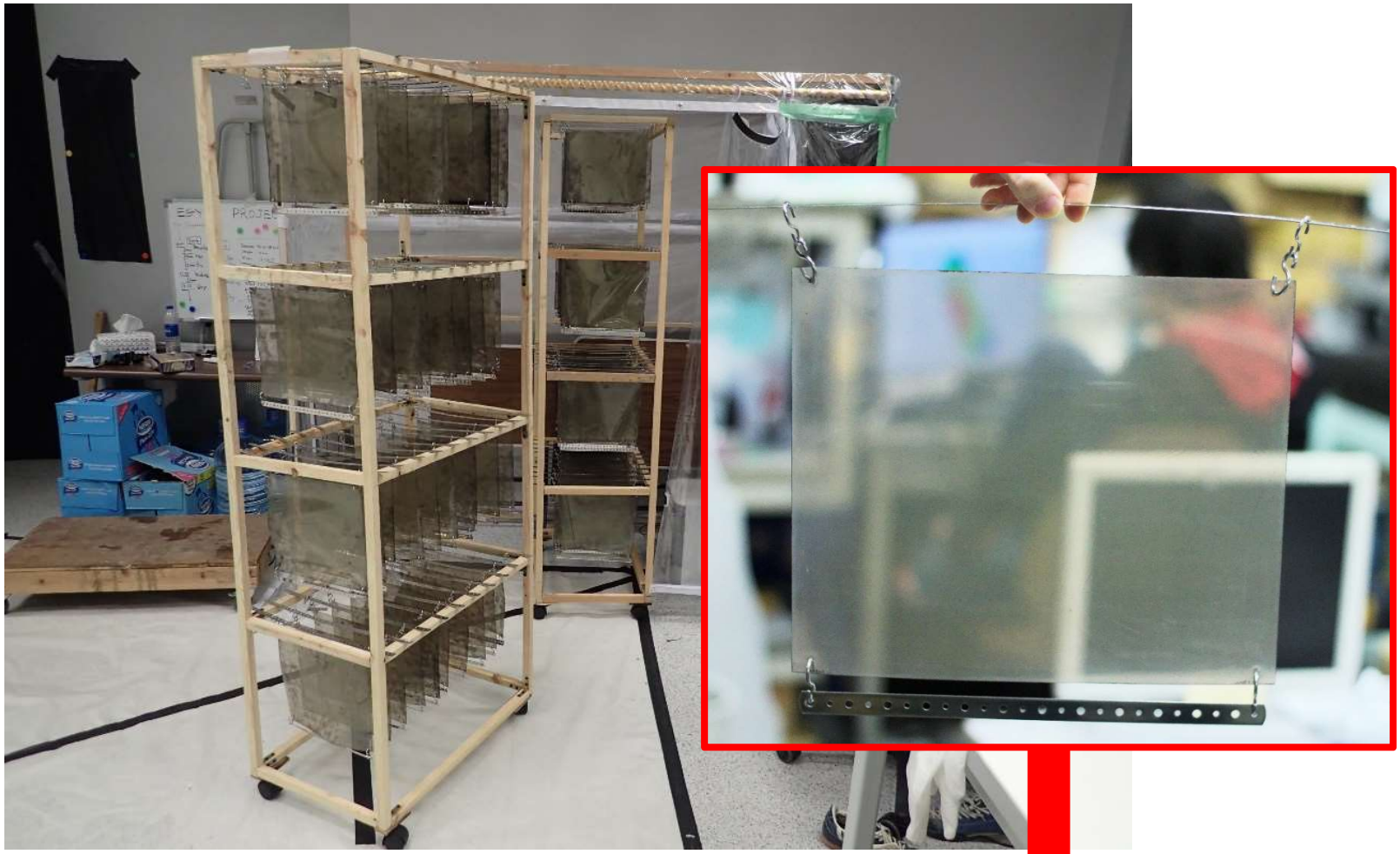


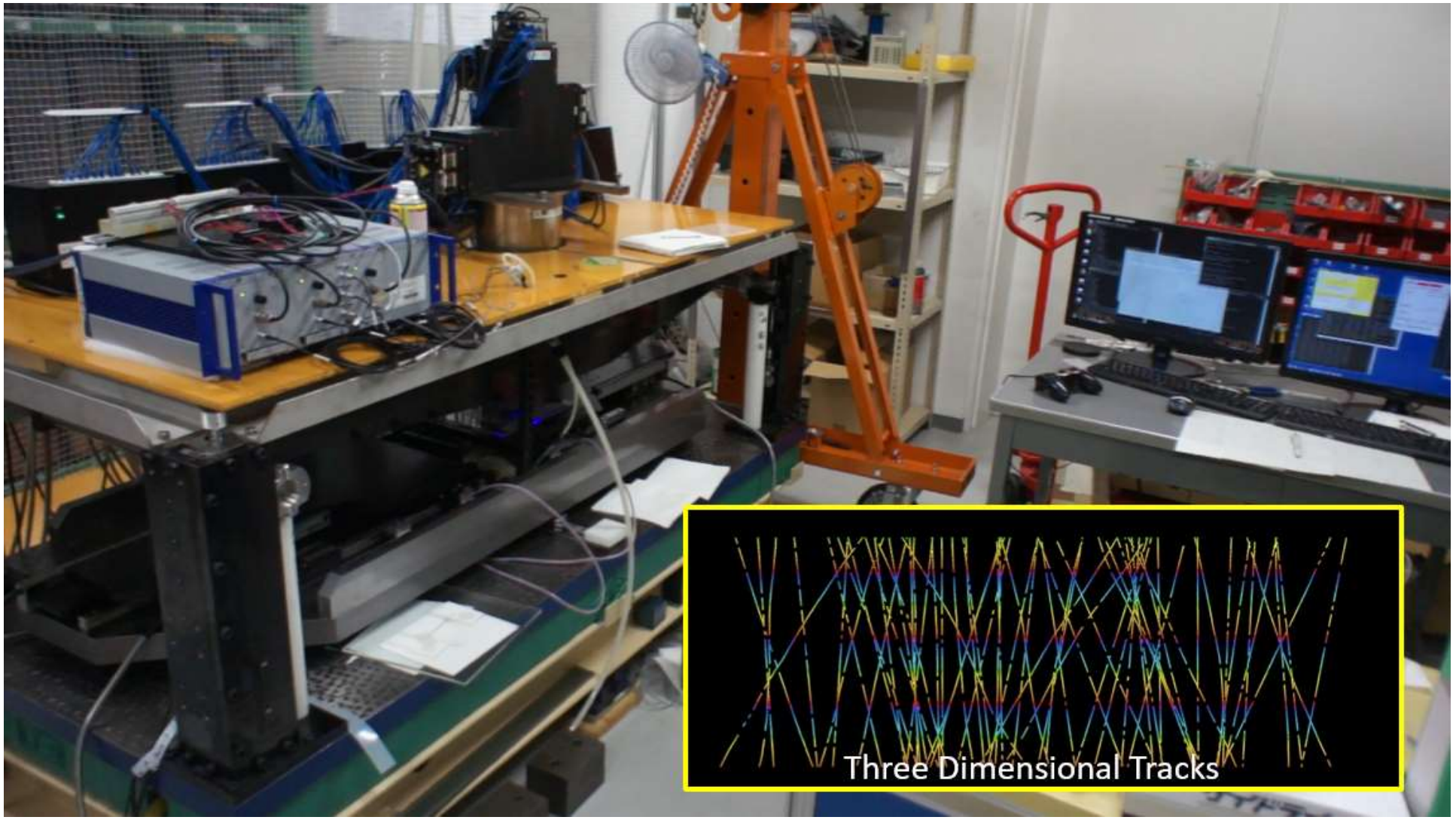
Development facility at Cairo（GEM-CC）

Development facility built at Cairo（GEM-CC）

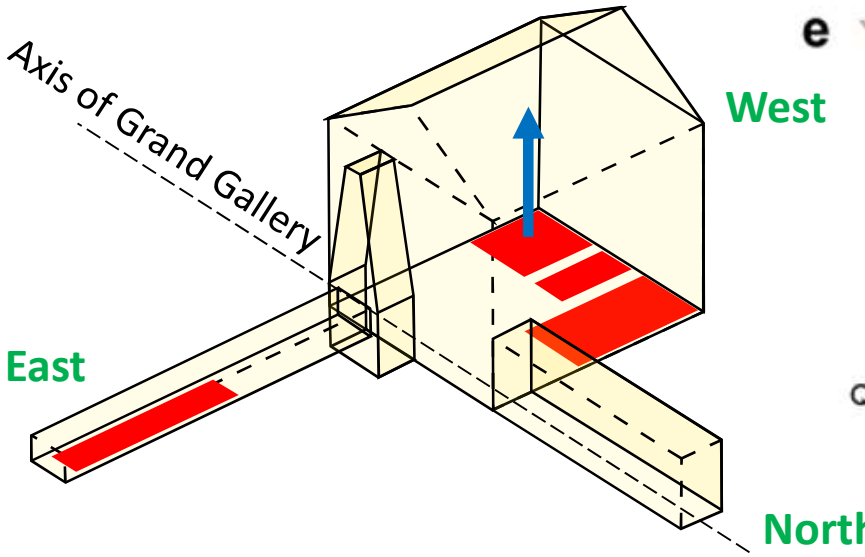


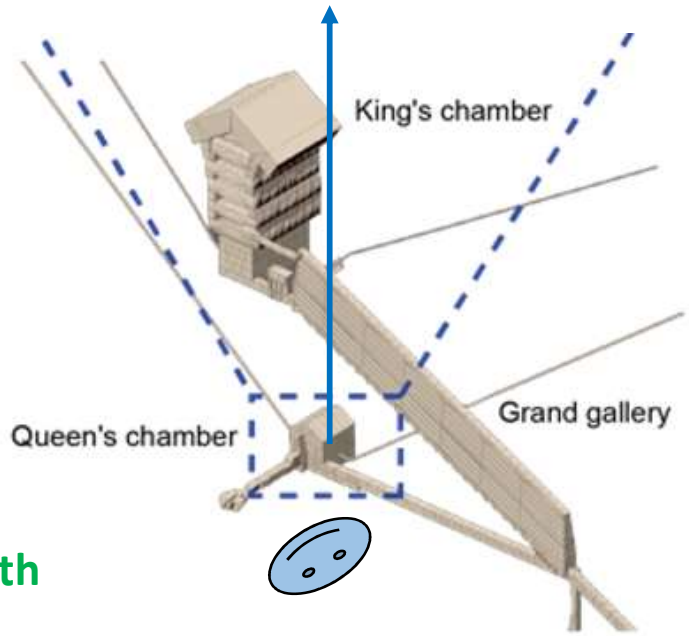
Take them back to Nagoya University for analysis

Automated Scanning System at Nagoya University
HTS（Hyper Track Selector）

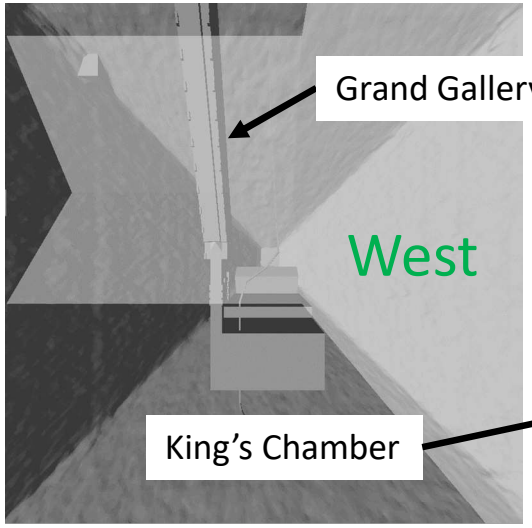


Simulation of expected muon angular distribution

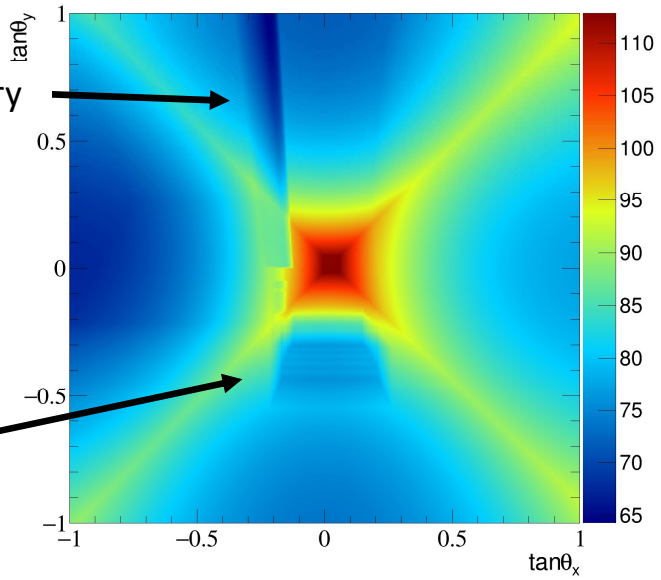




3D model of the pyramid



Thickness distribution in angle



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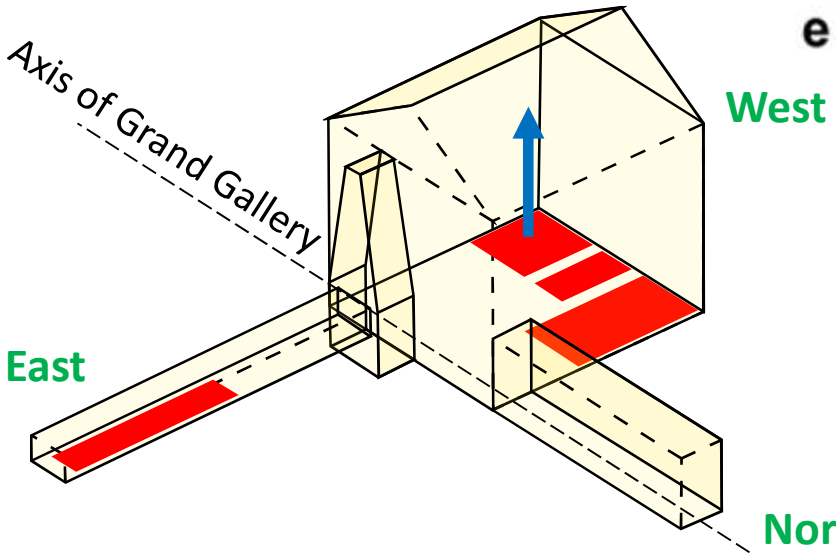

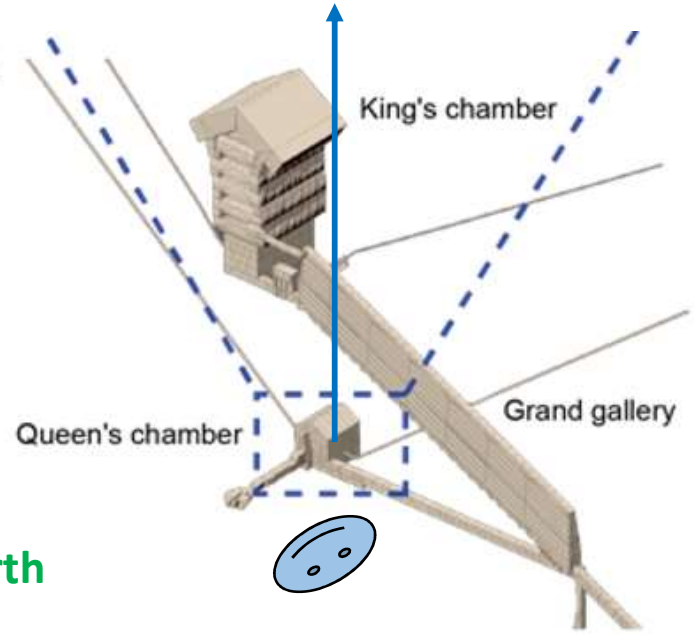

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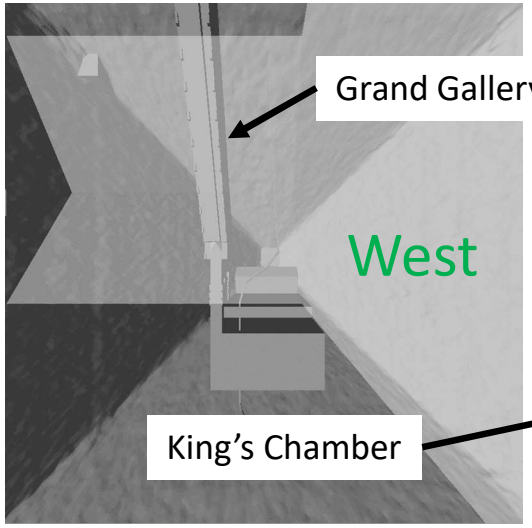
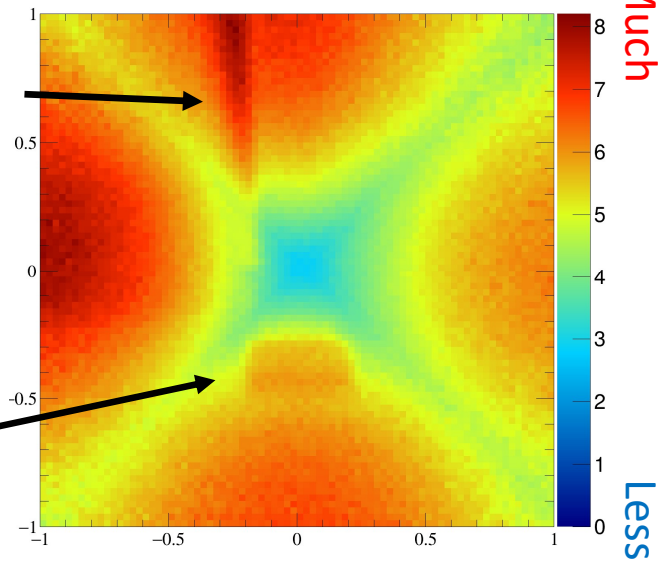
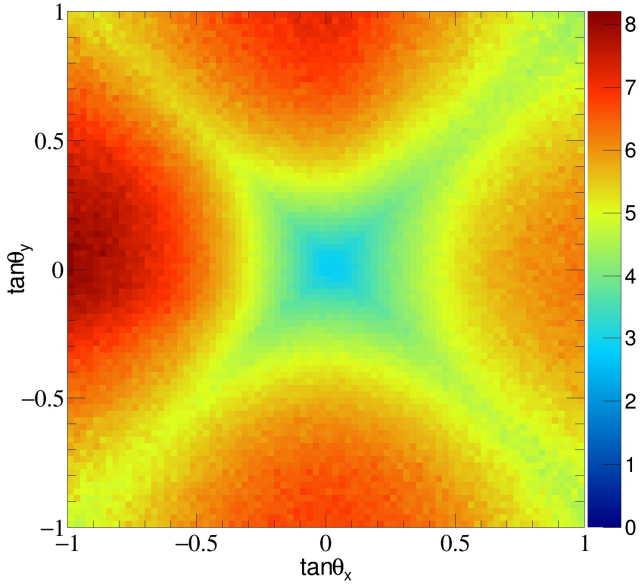


Muon flux distribution in angle



Without inner structures



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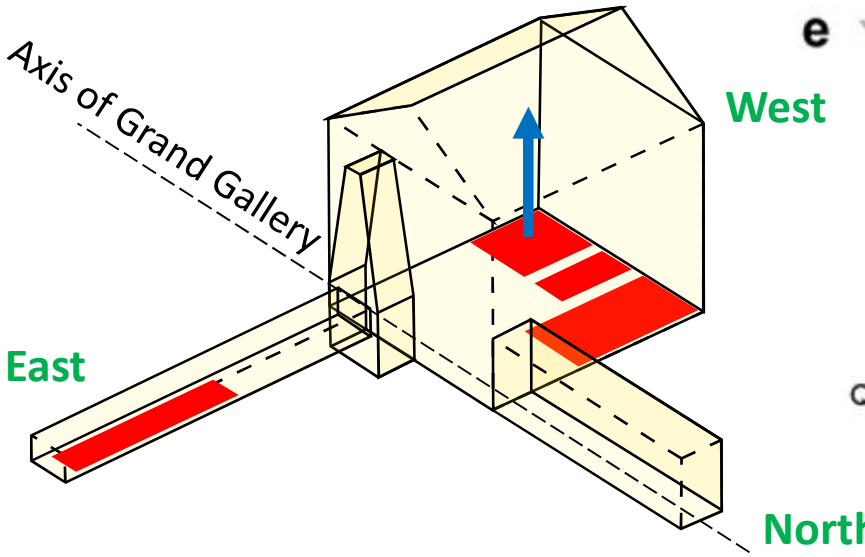

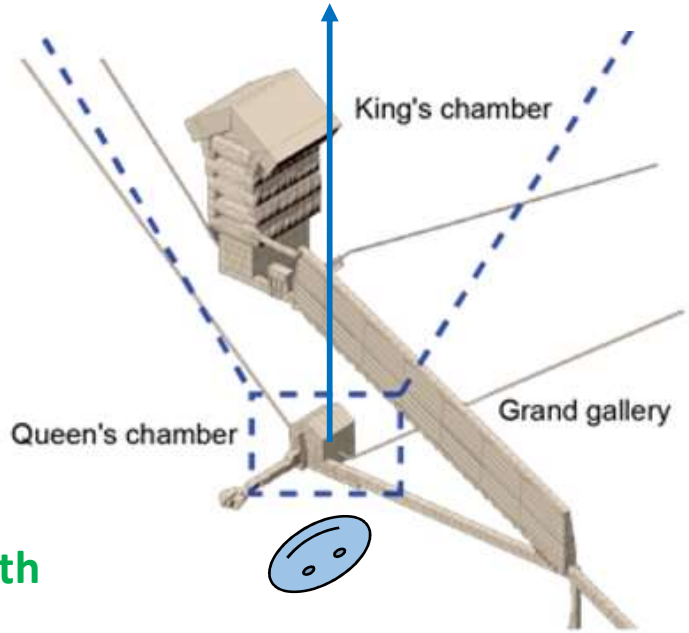

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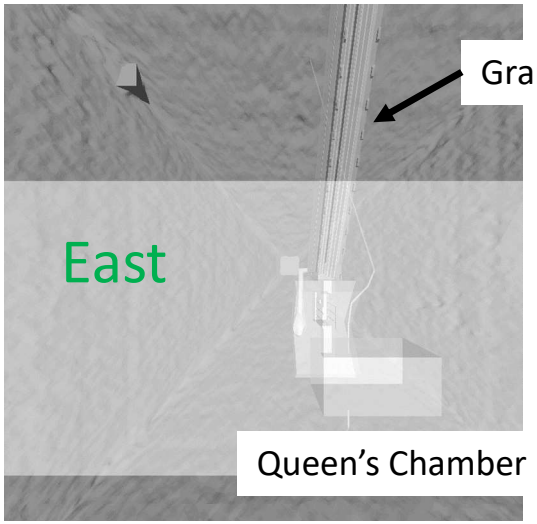
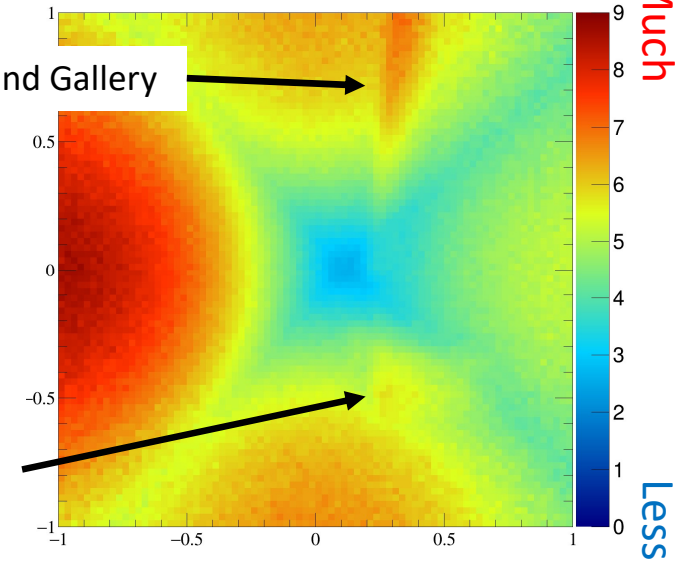
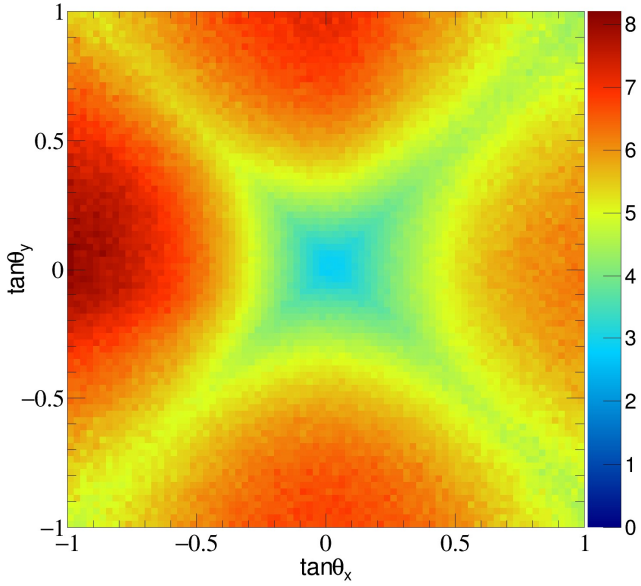


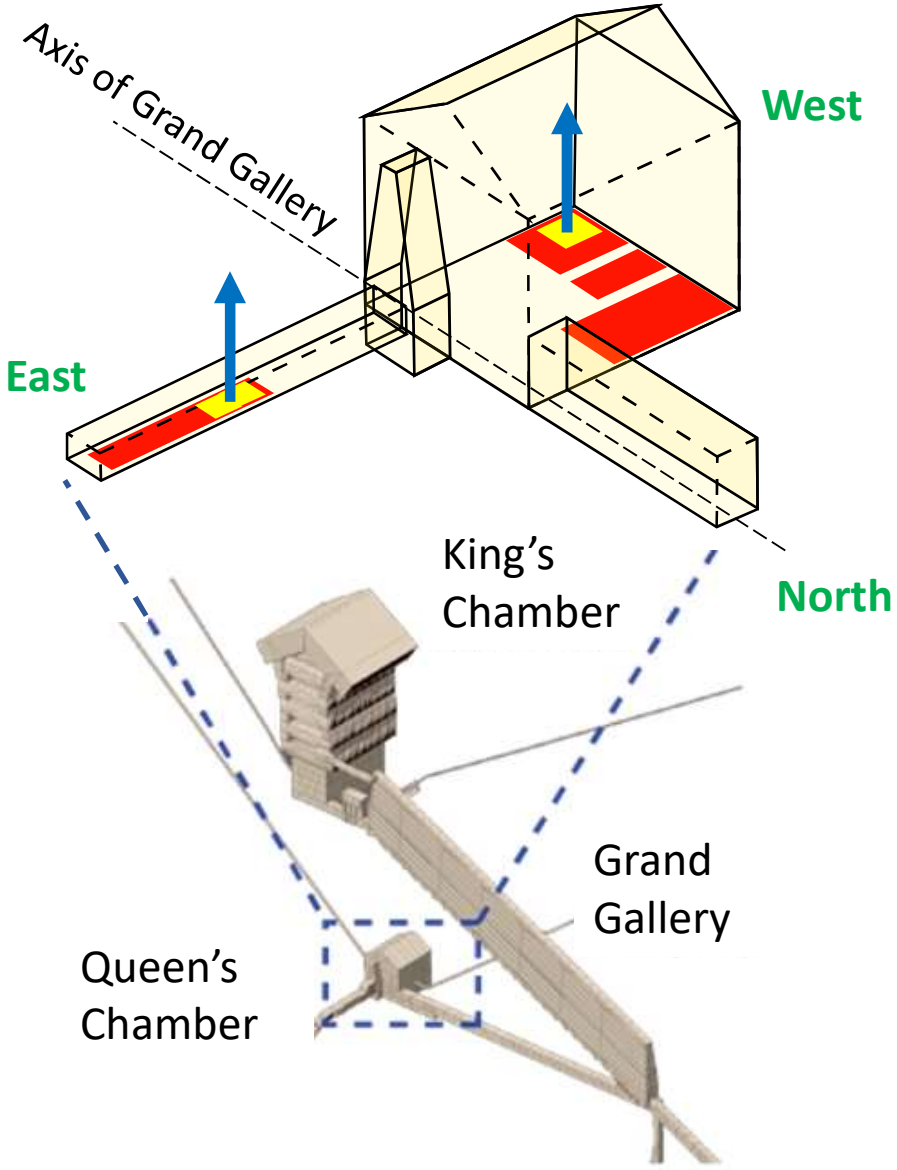
Muon flux distribution in angle

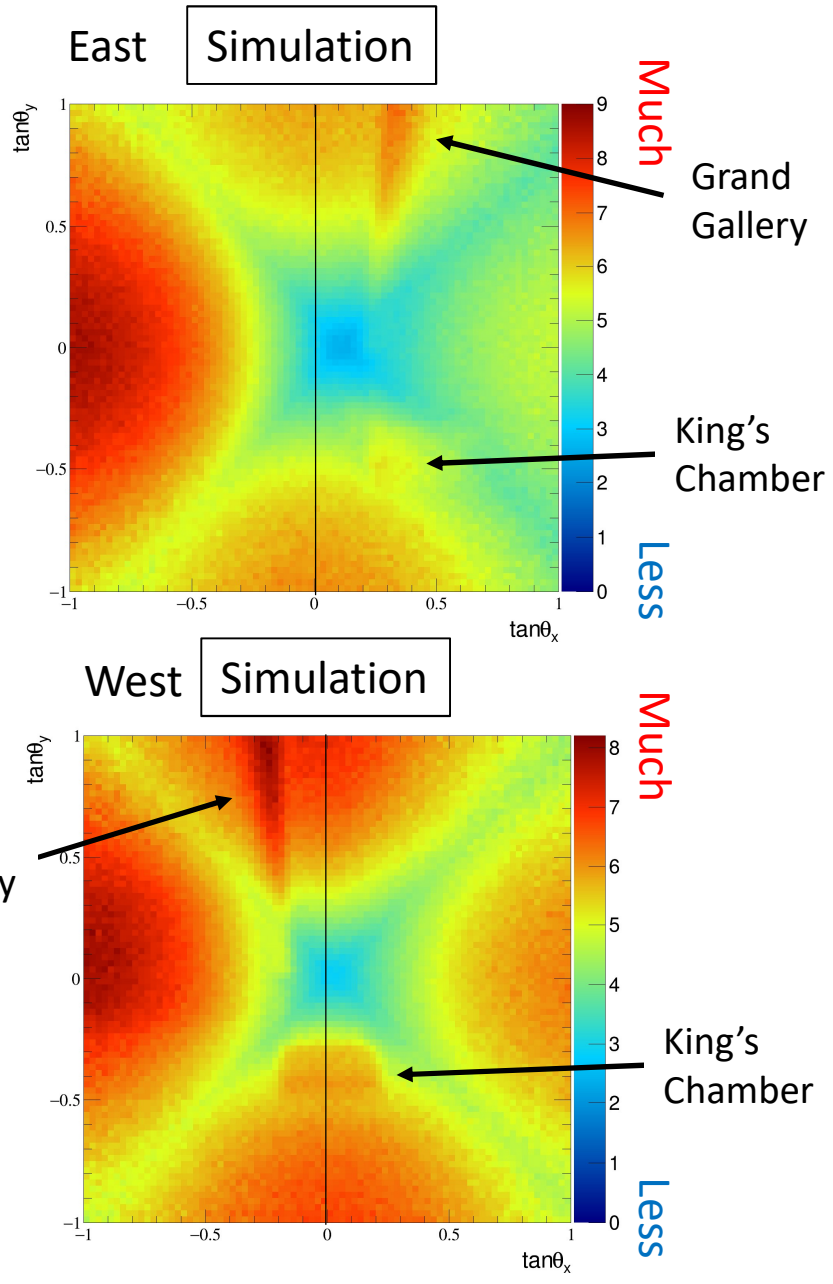


Without inner structures



Analysis of cosmic-ray muon flux in Queen's Chamber





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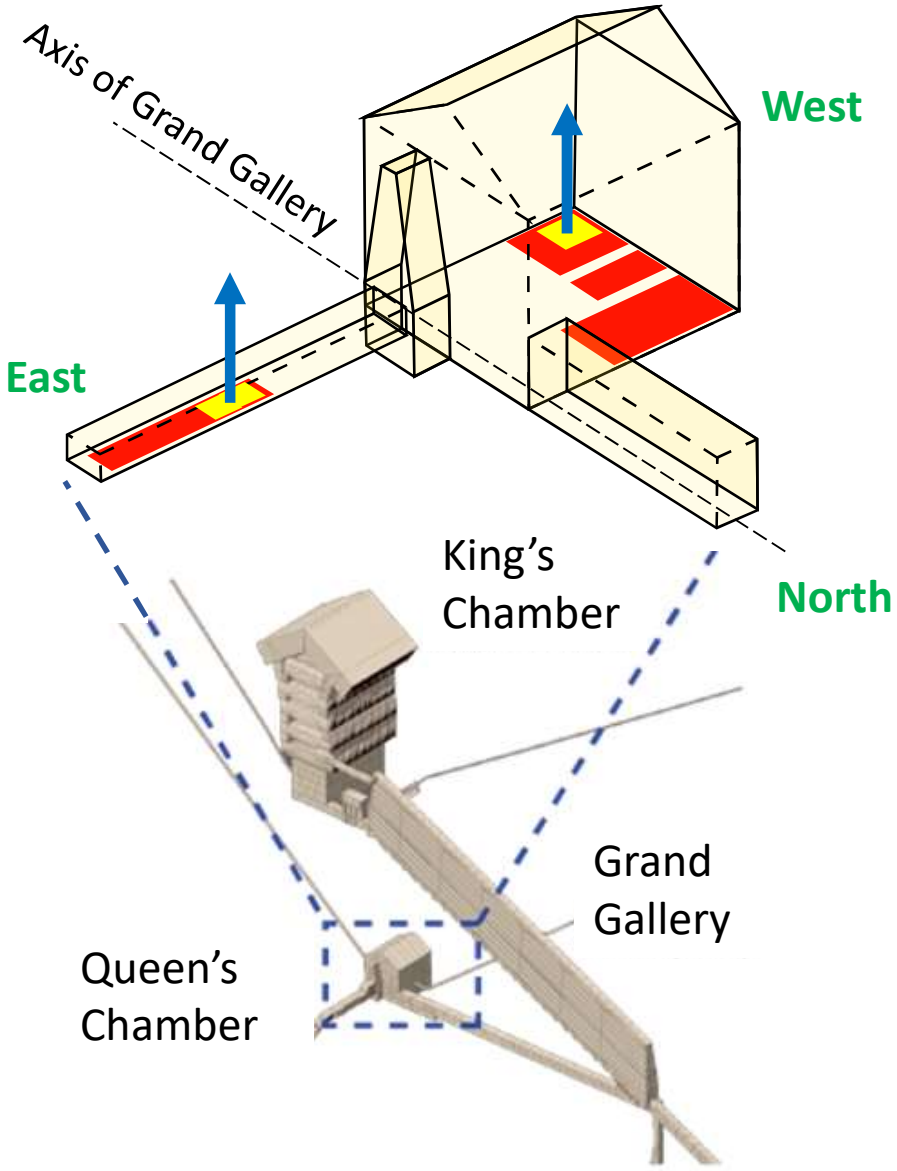

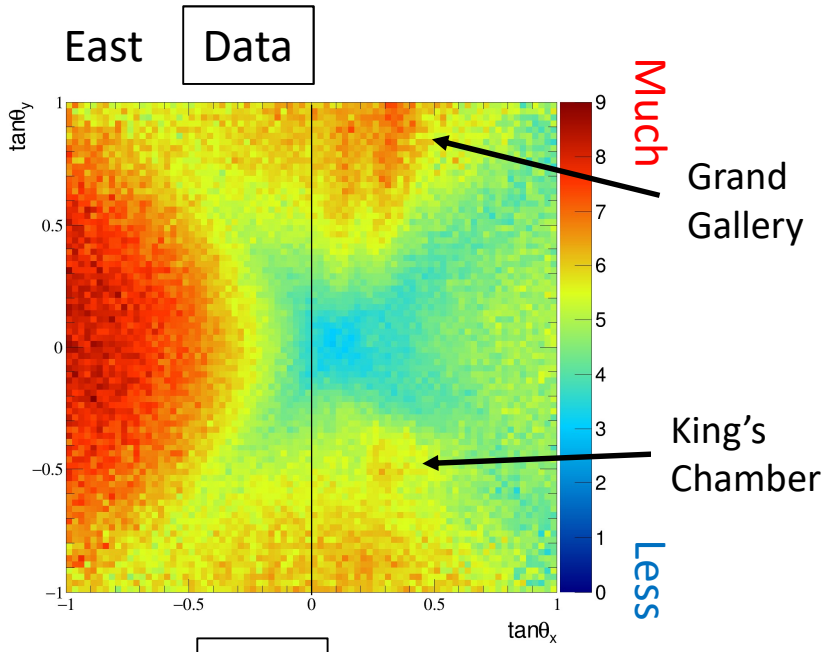

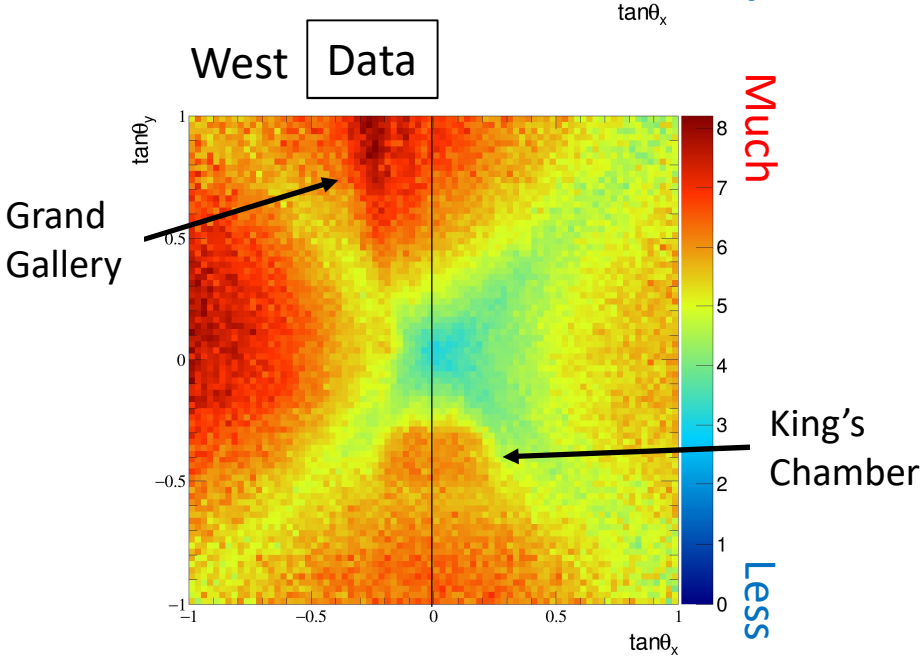

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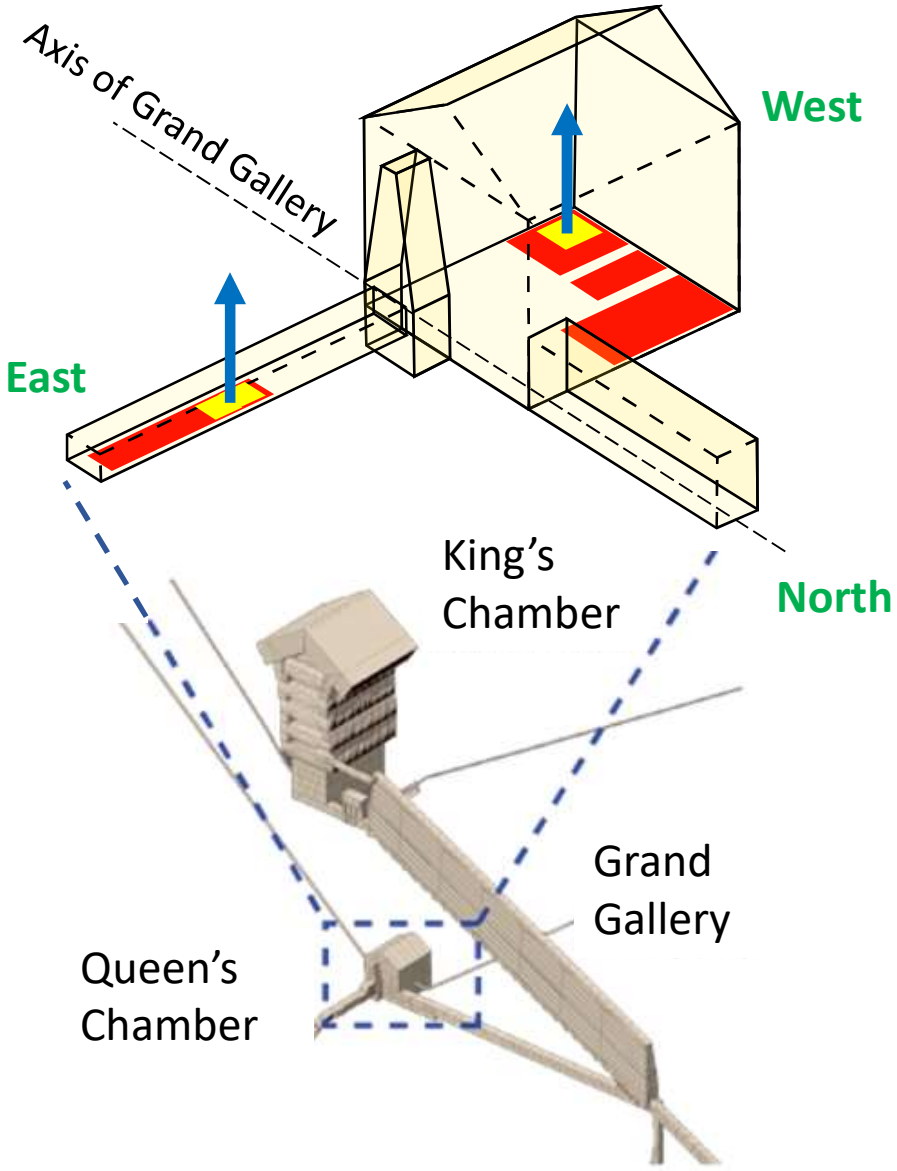
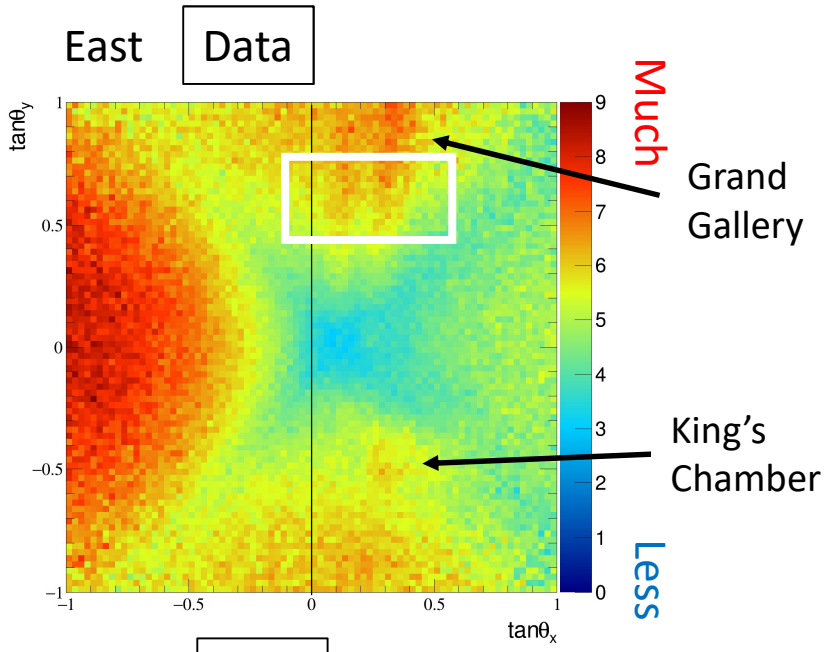
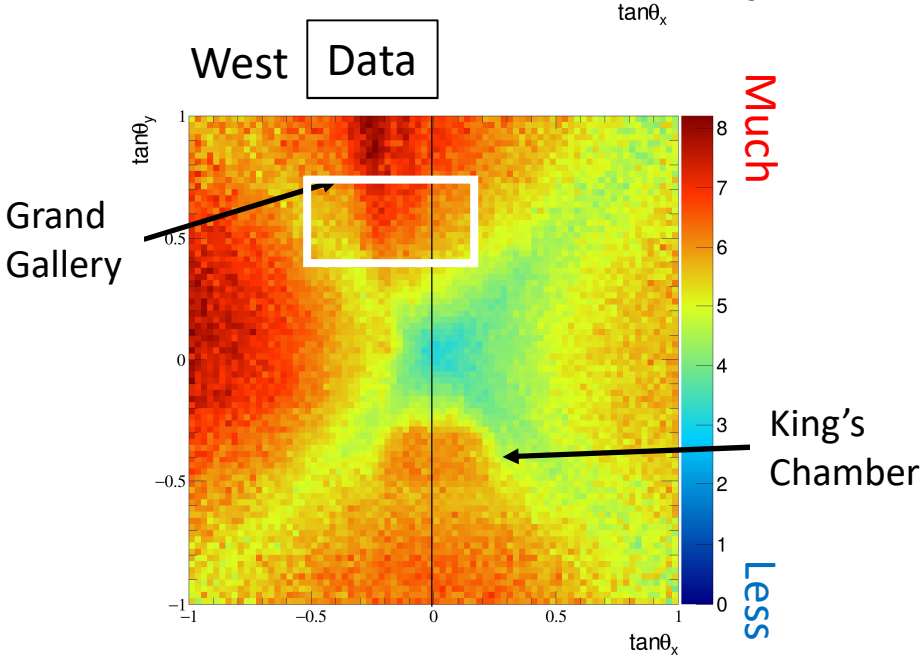


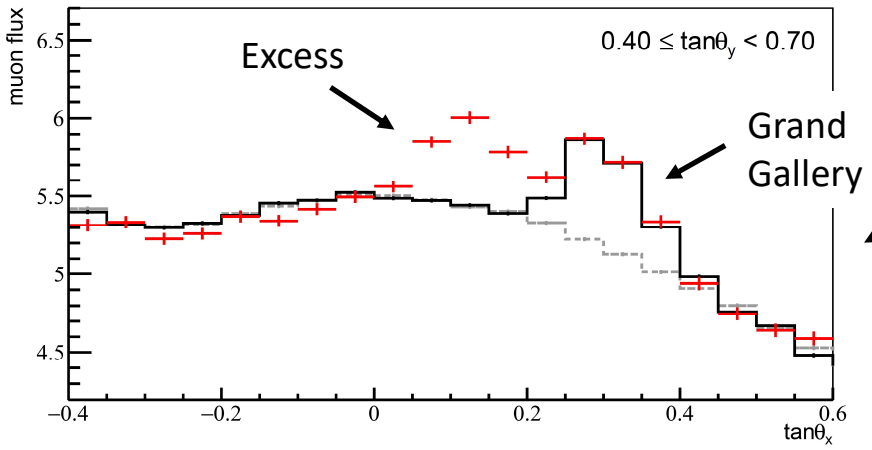




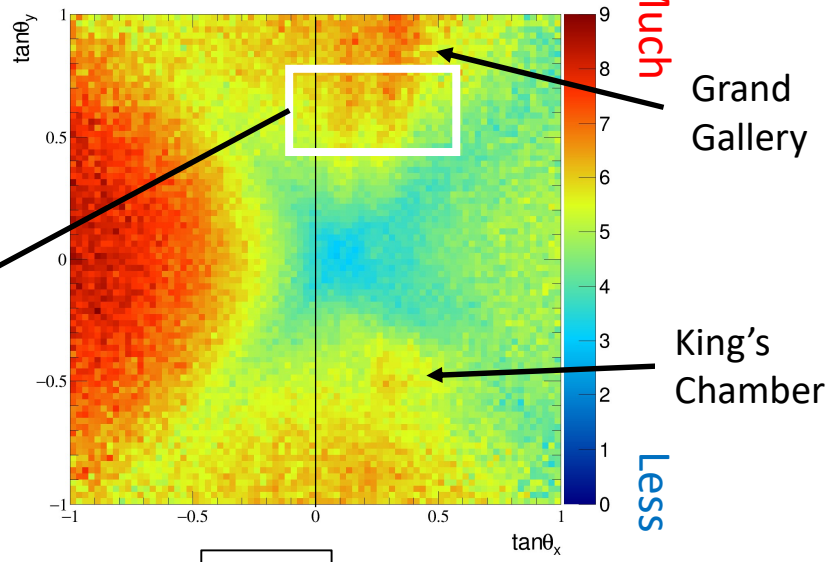
Analysis of cosmic-ray muon flux in Queen's Chamber

Histgram

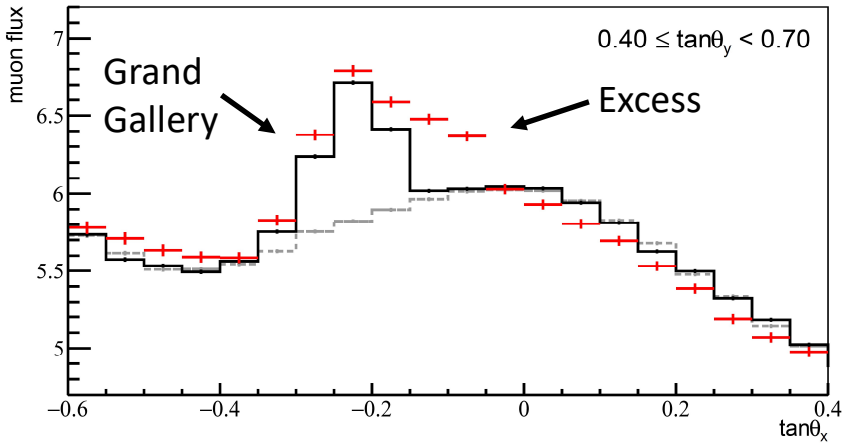
Data (+) and **Simulation (-)**



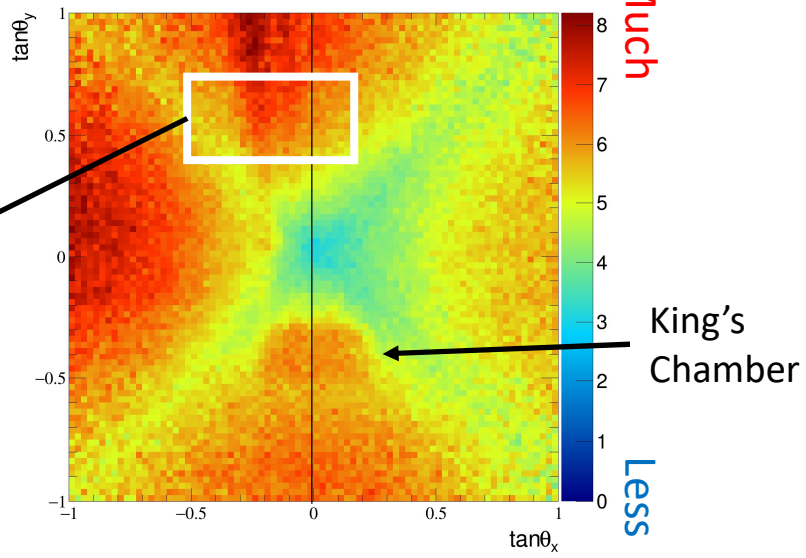
East Data



Data (+) and **Simulation (-)**



West Data



Analysis of cosmic-ray muon flux in Queen's Chamber

Histgram

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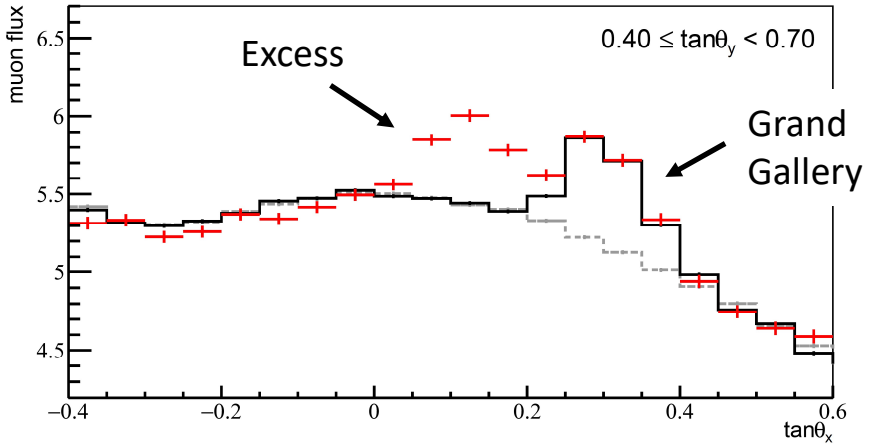

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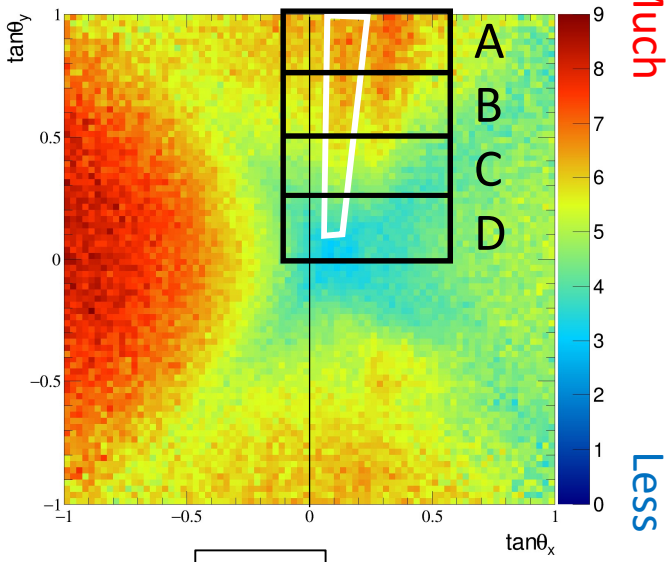

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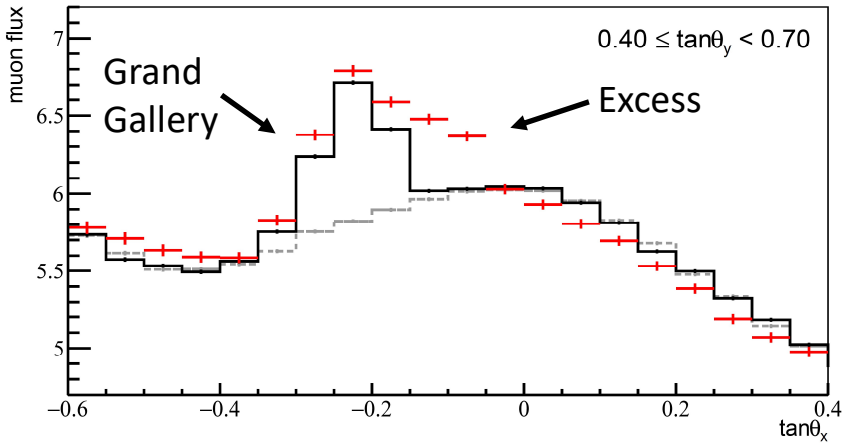
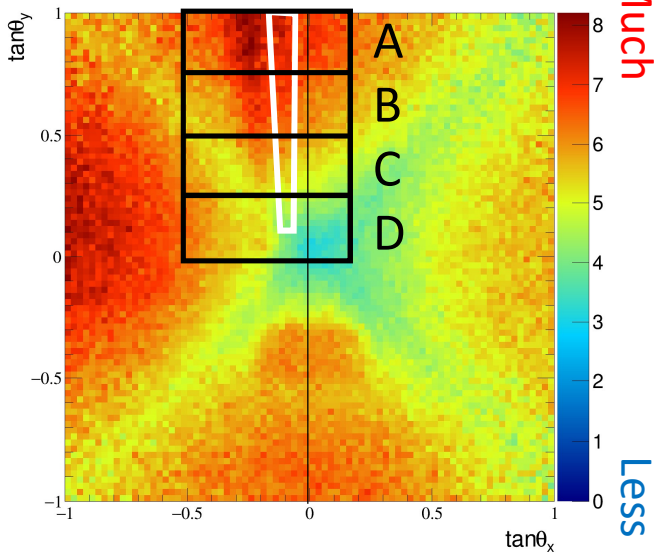
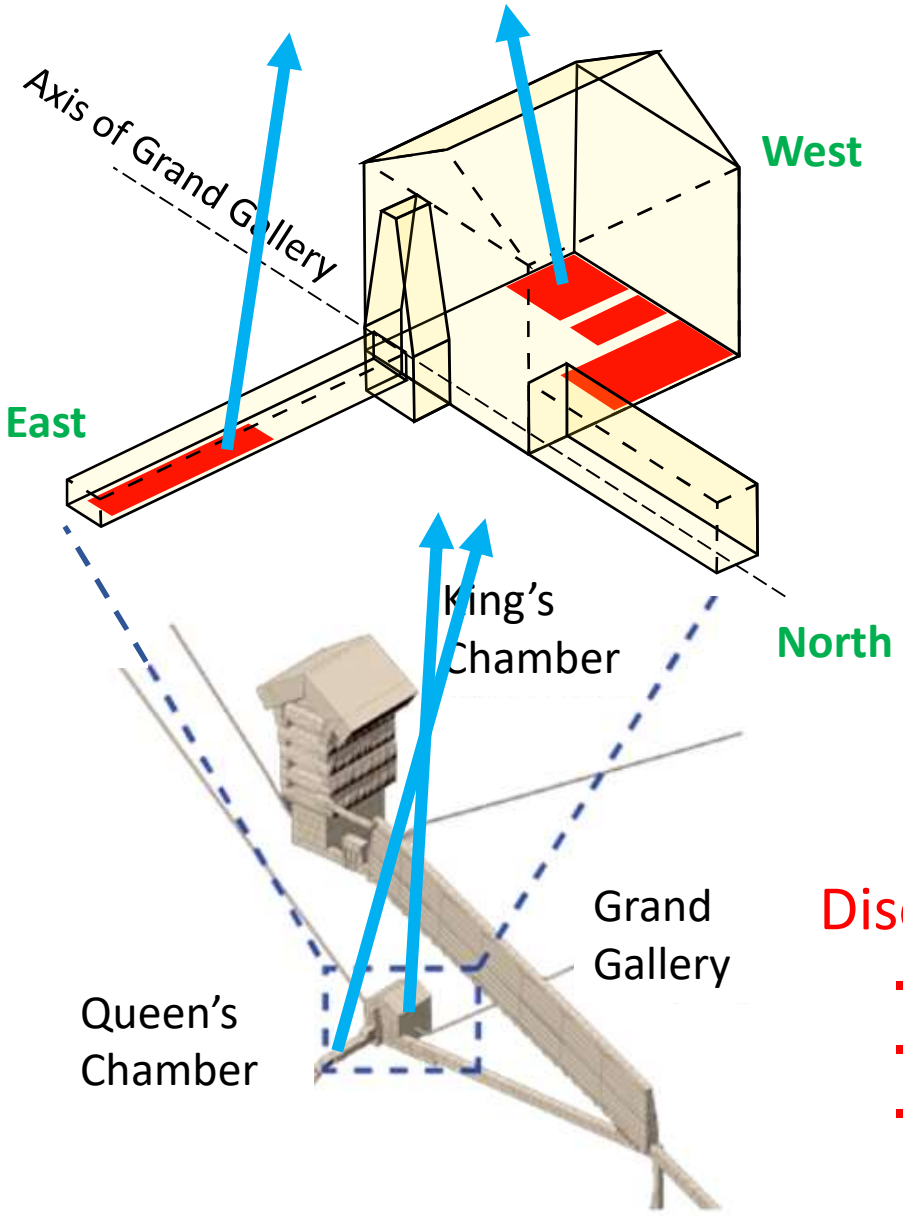
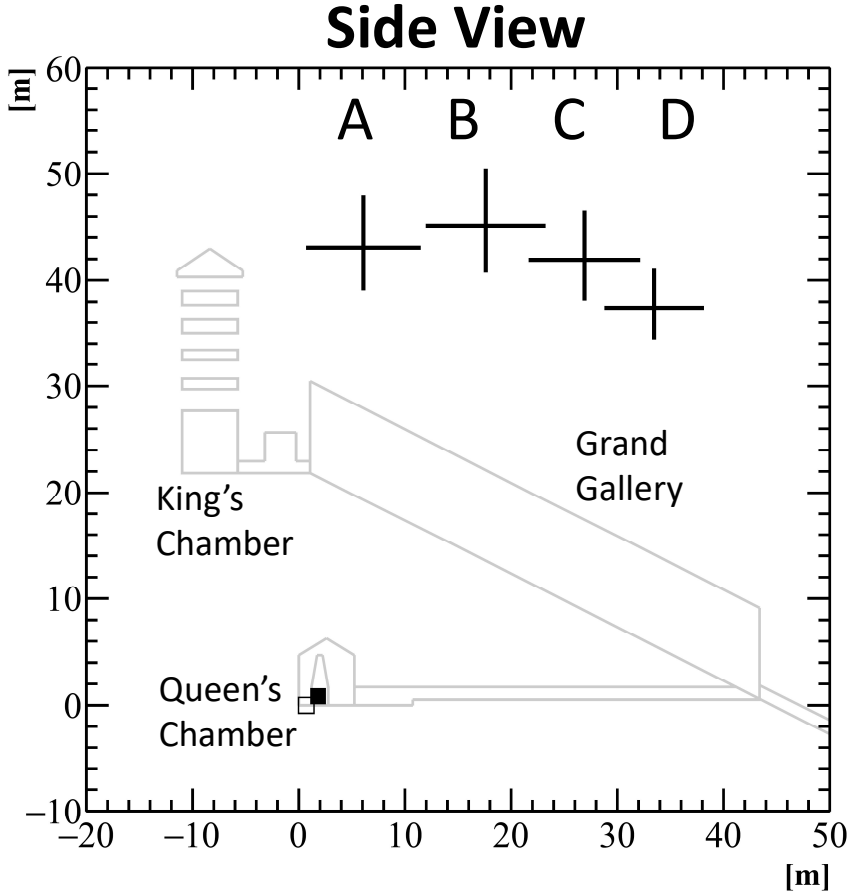


West Data



Position distribution of void above the Grand Gallery

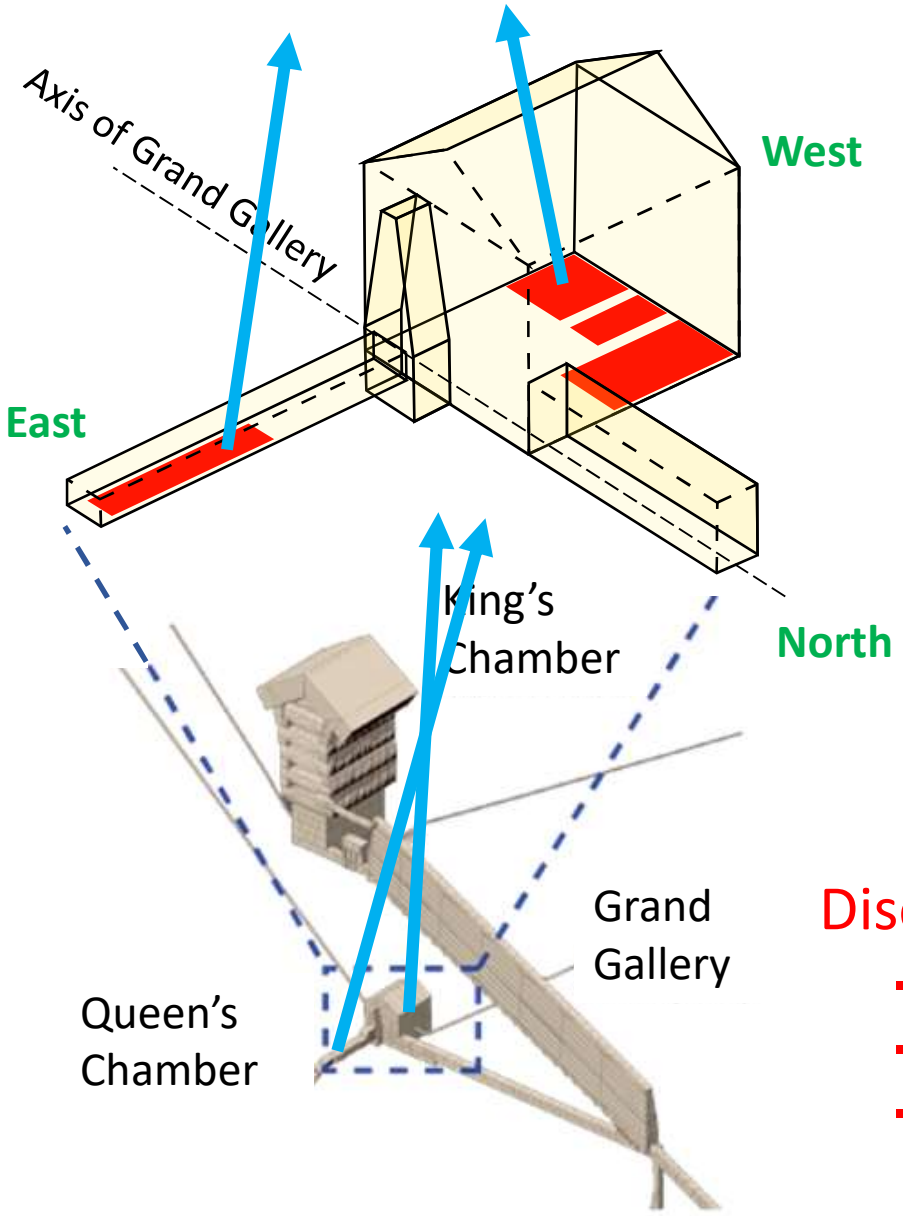


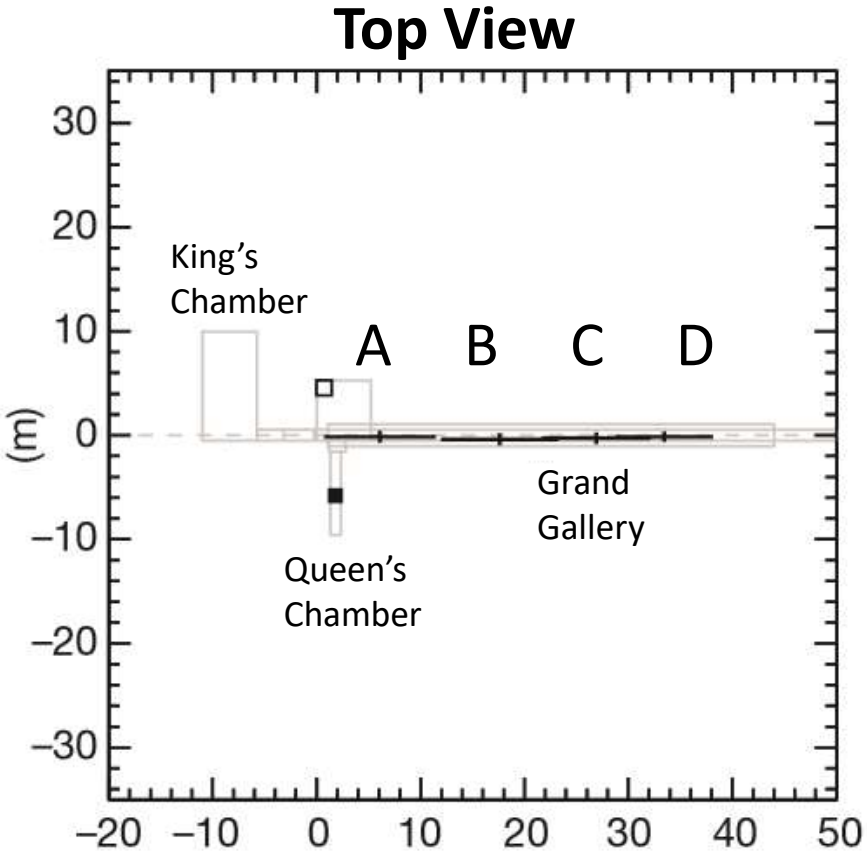


Discovery of new large void

- Cross section is similar to the Grand Gallery
- Length is more than 30m
- Location is just above the Grand Gallery
  (40-50m away from detector position)

Position distribution of void above the Grand Gallery





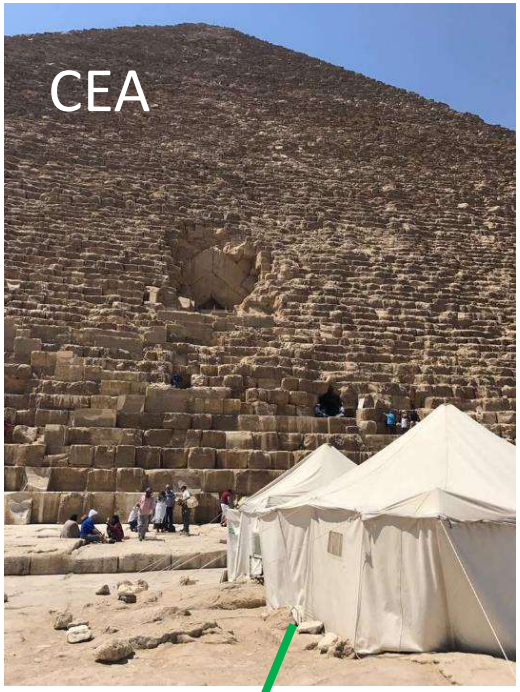
Discovery of new large void

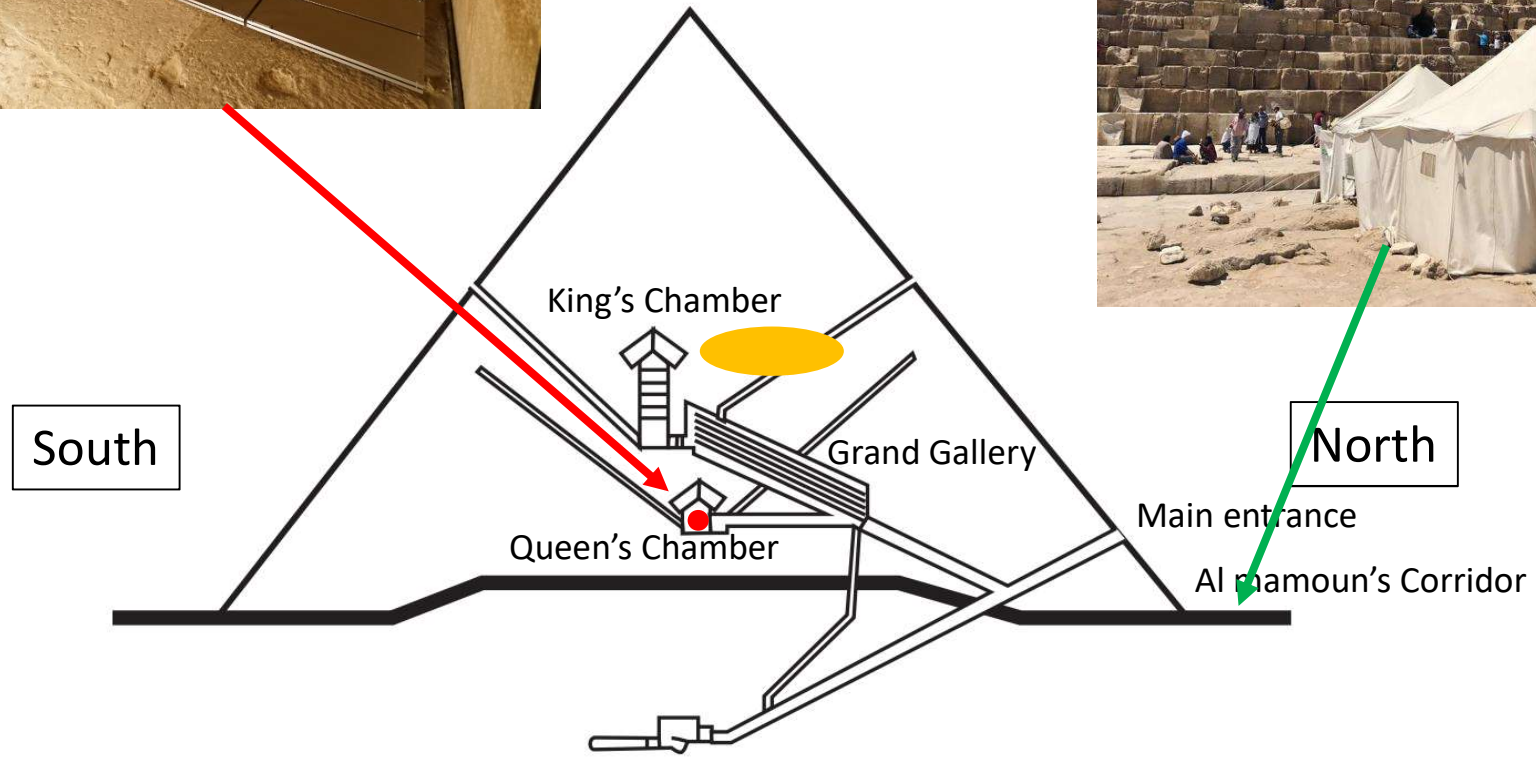
- Cross section is similar to the Grand Gallery
- Length is more than 30m
- Location is just above the Grand Gallery
  (40-50m away from detector position)

Confirmation by two independent measurement

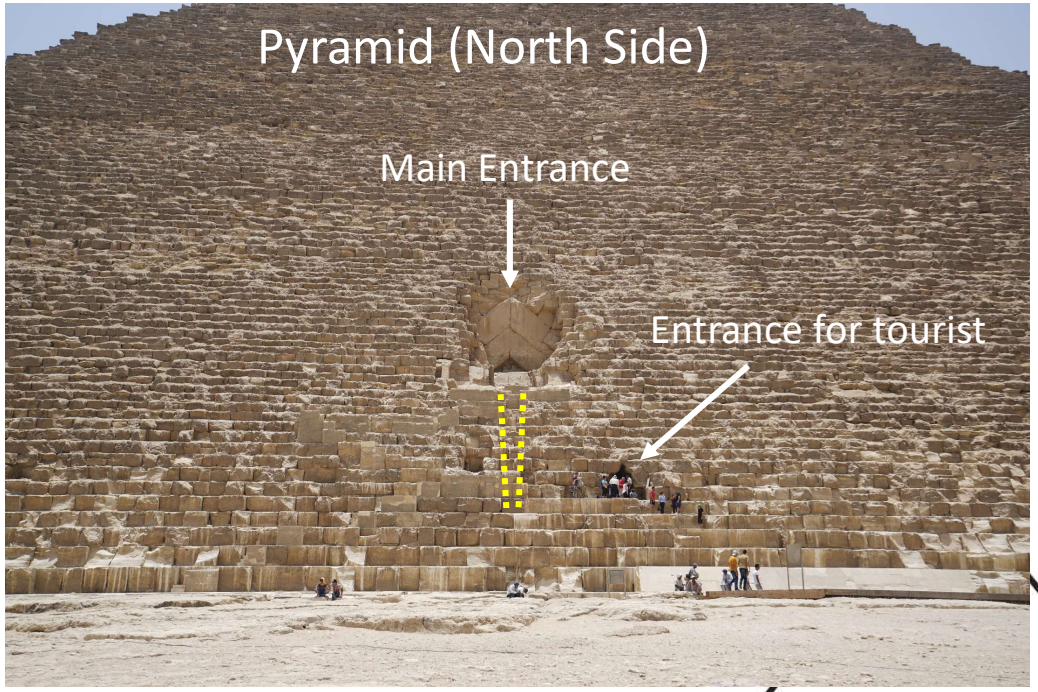
In the Queen's Chamber

In front of north dace (outside)





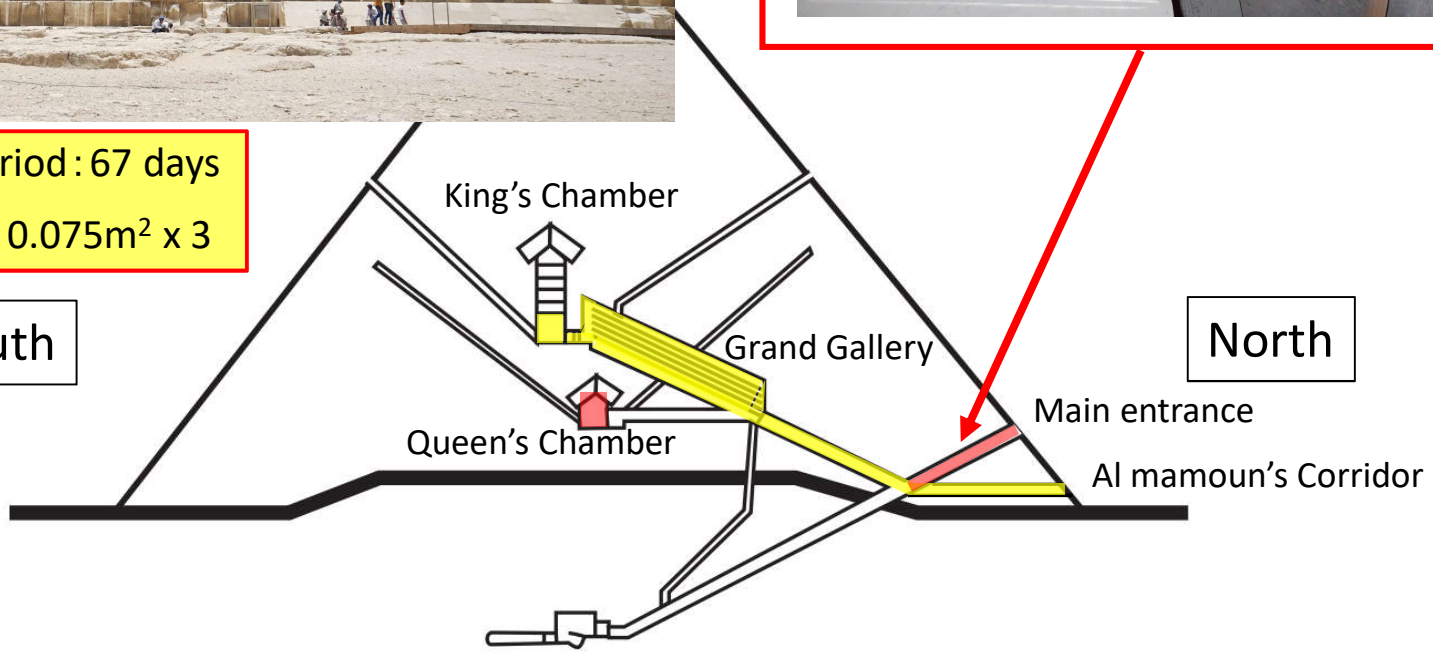
Observation from the Descending Corridor



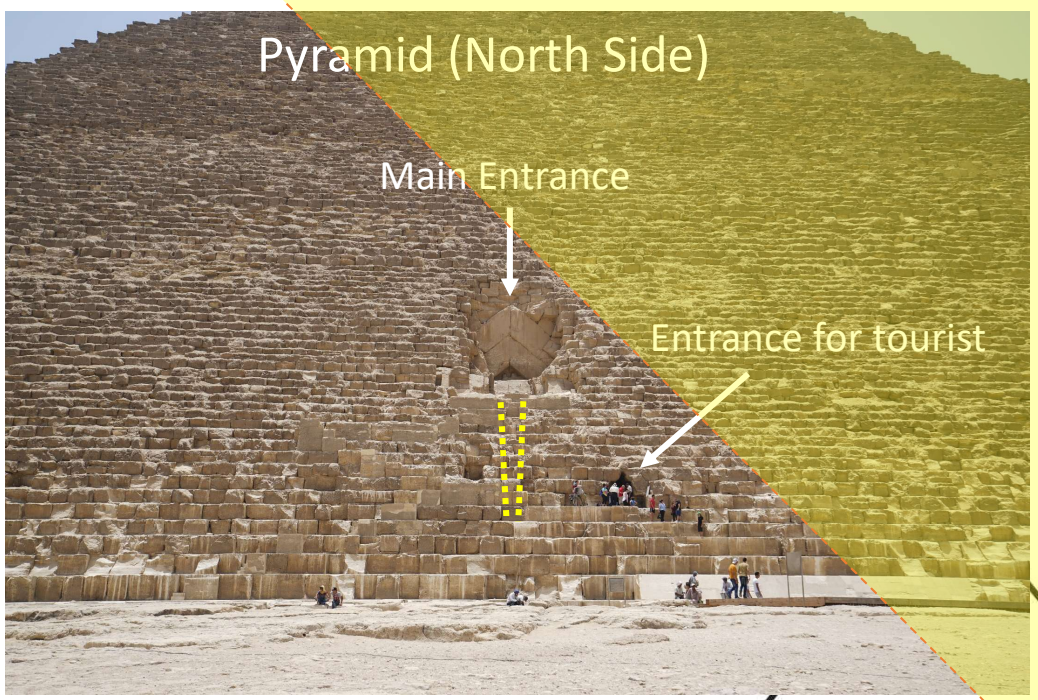
Descending Corridor

Observation period : 67 days

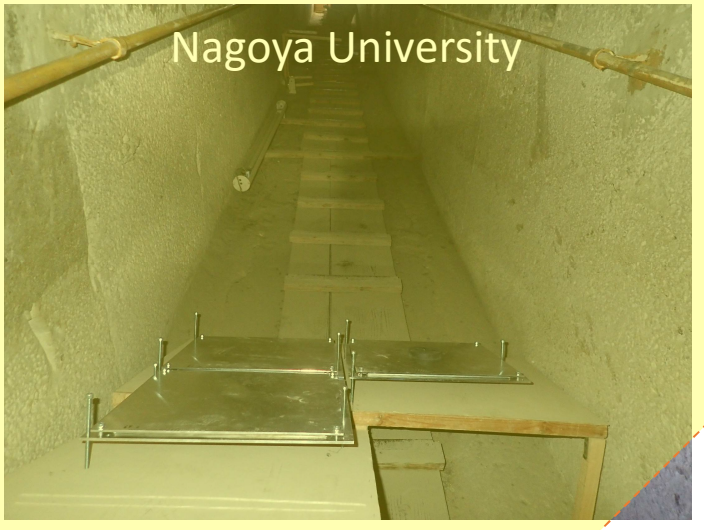
Detector Area : 0.075m^2 x 3



Observation from the Descending Corridor

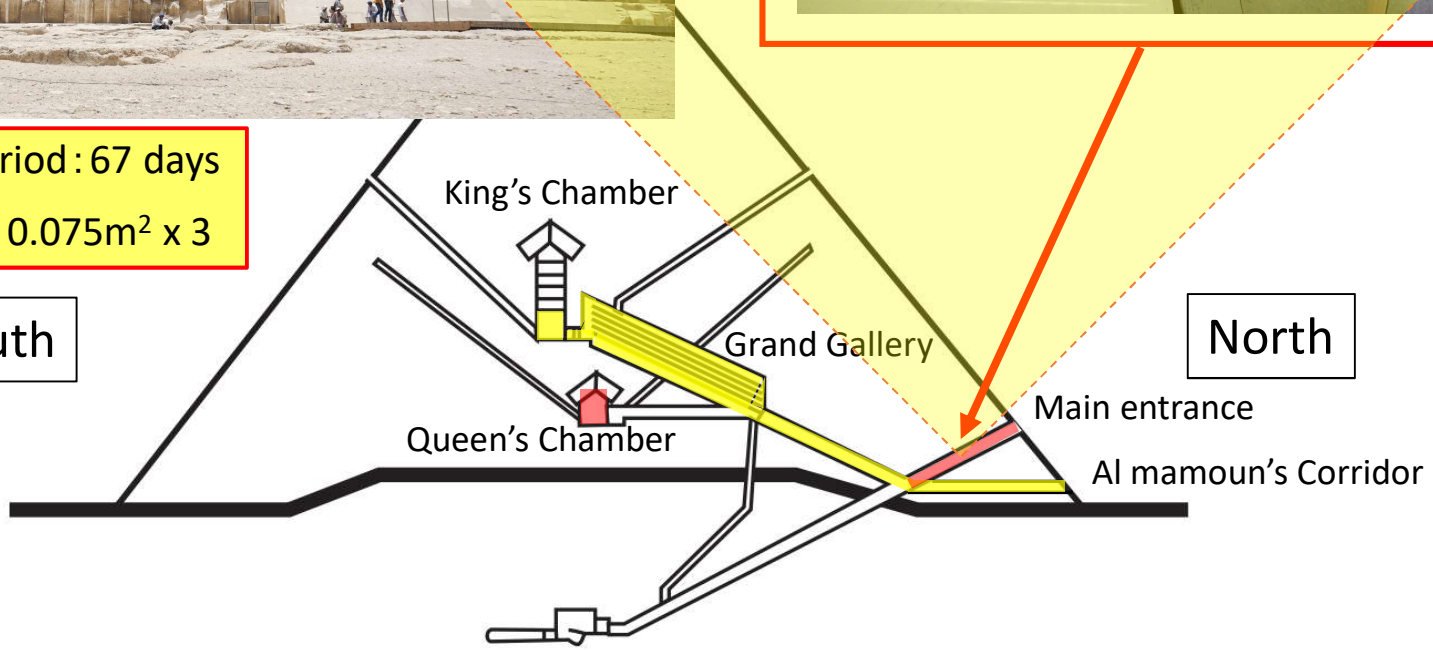


Descending Corridor



Observation period : 67 days

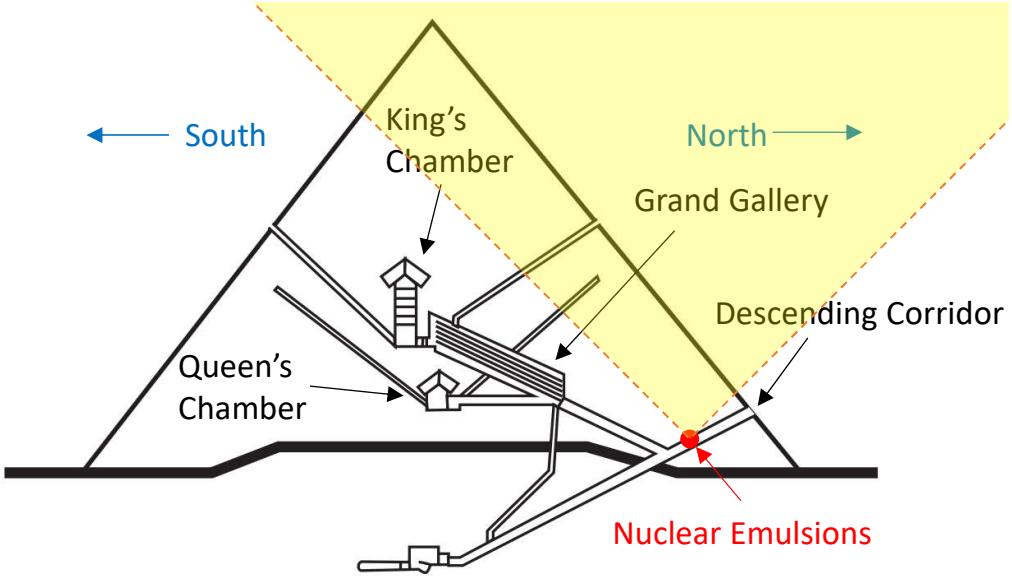
Detector Area : 0.075m^2 x 3

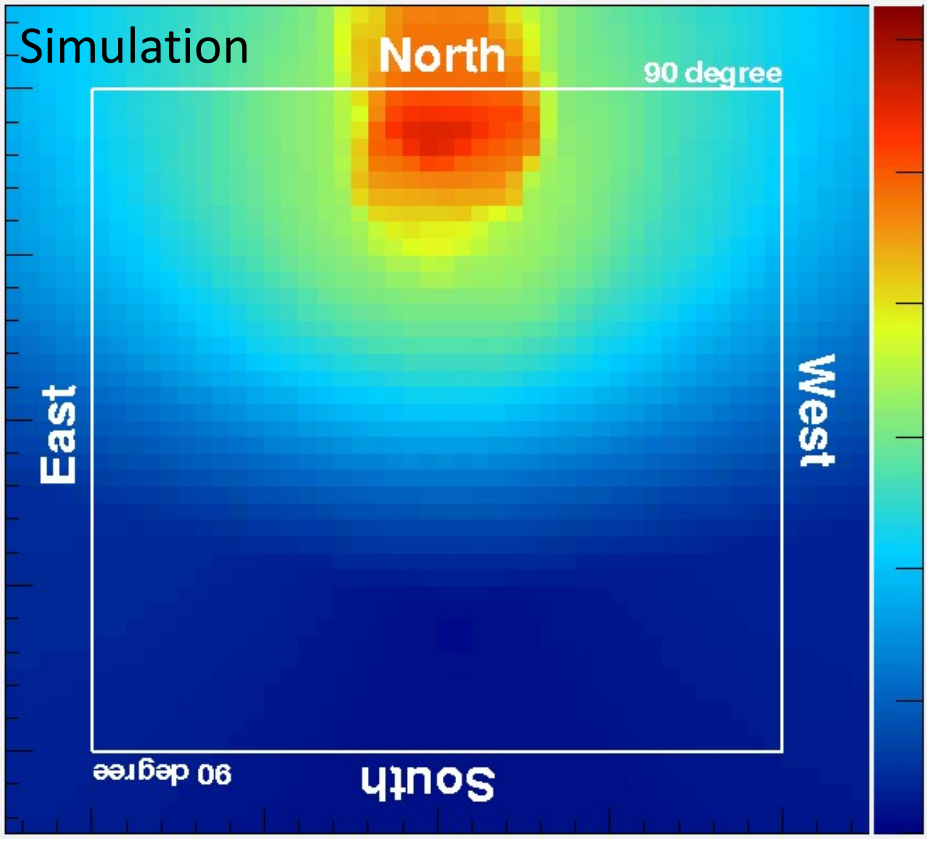


South

North

Observation from the Descending Corridor





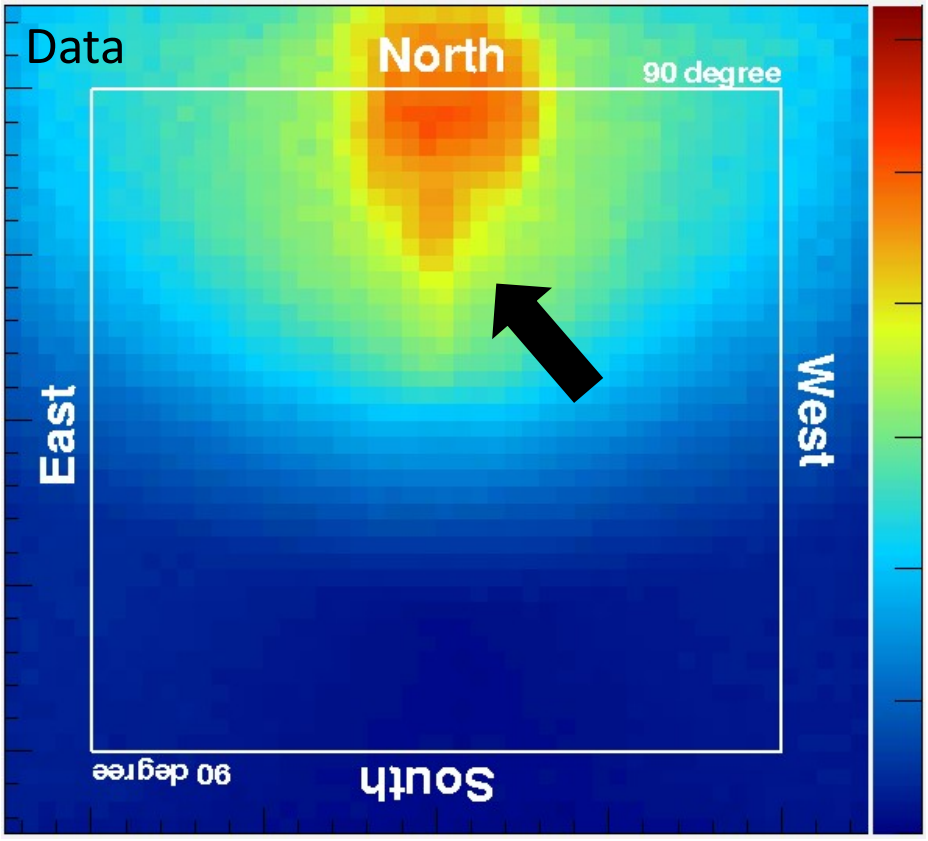
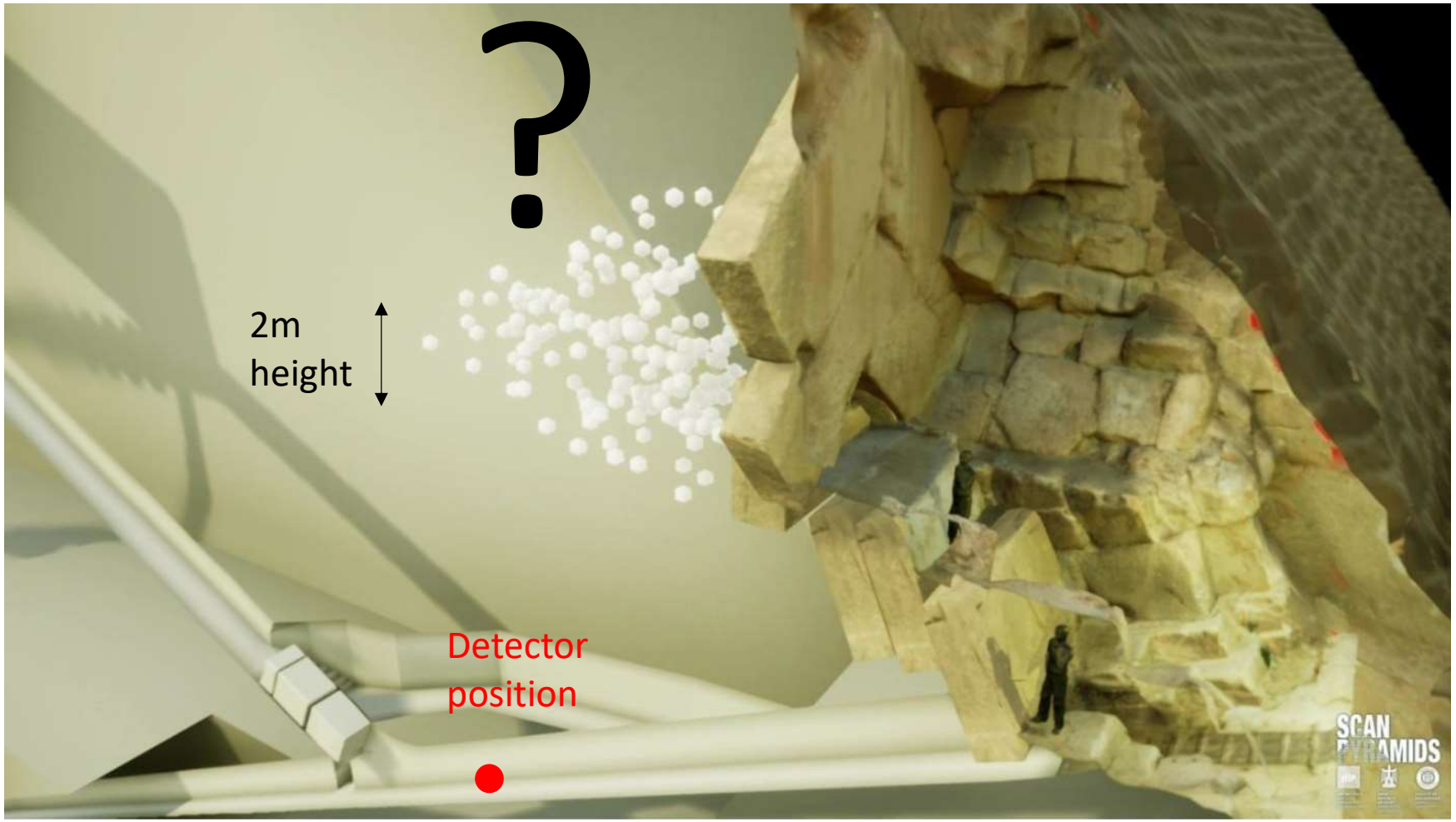


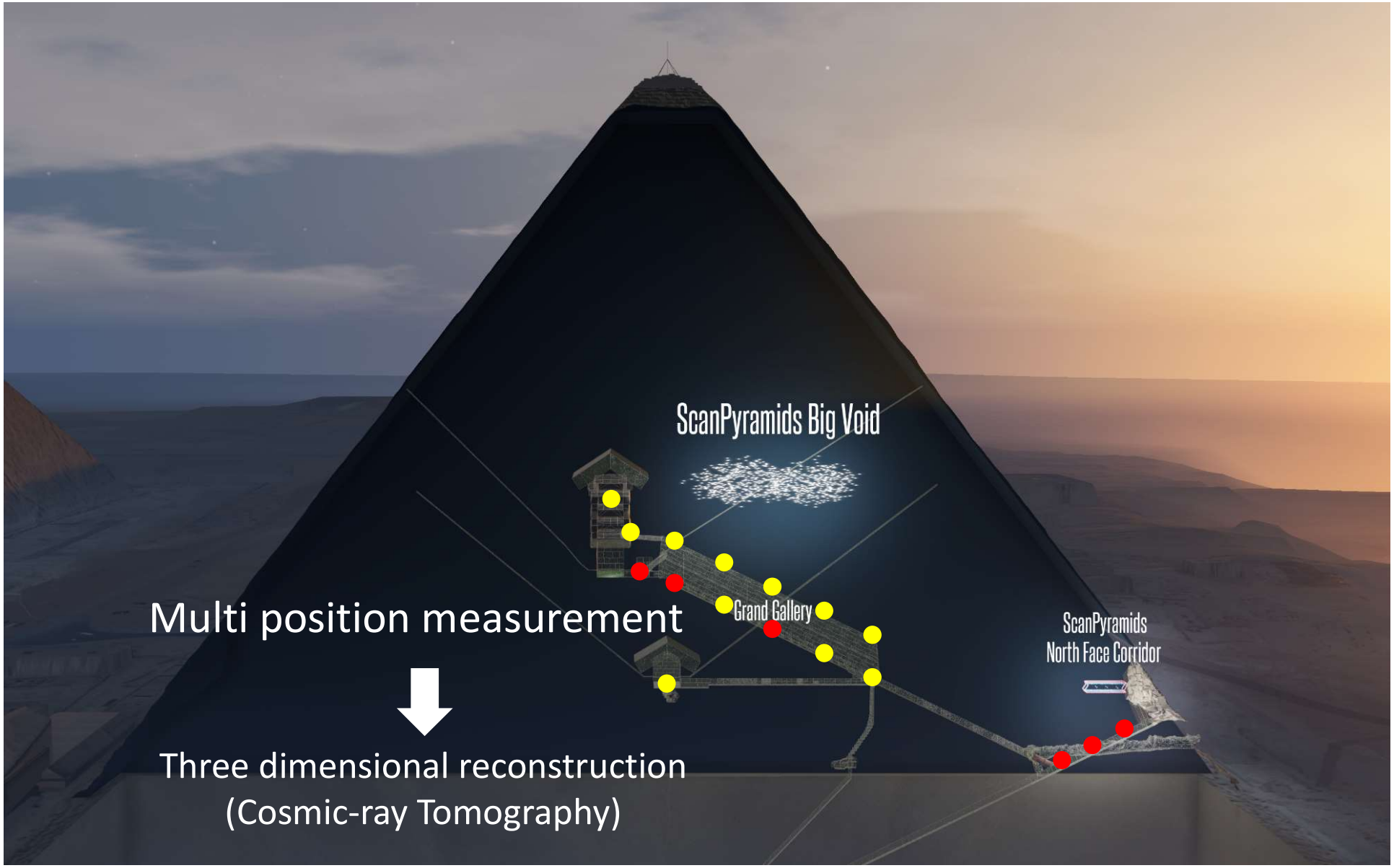
Image of discovered space behind the north face



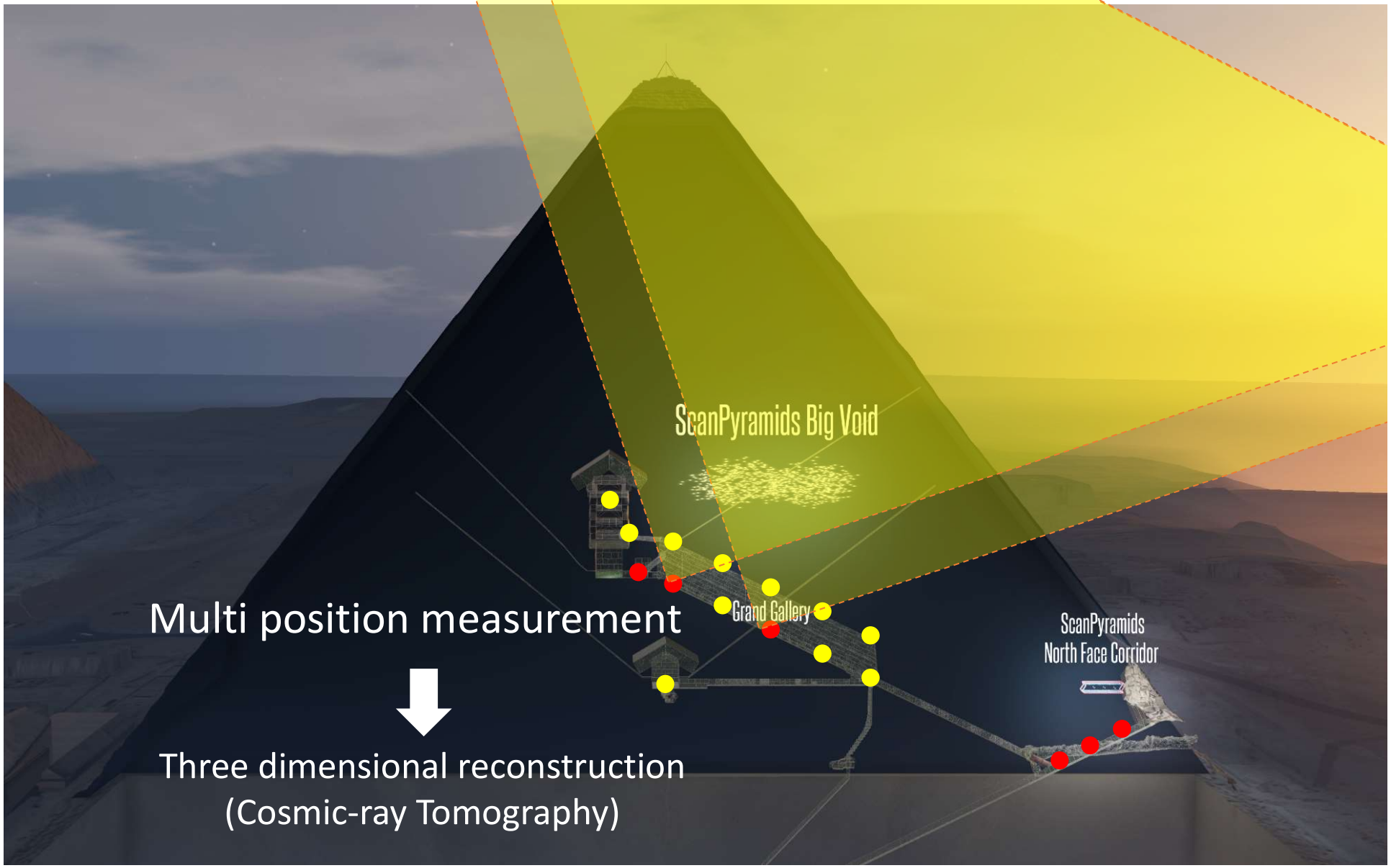
The precise size, shape and exact position of this space is now under future investigation

Future prospect of Khufu’s Pyramid

Future prospect of Khufu's Pyramid



Future prospect of Khufu's Pyramid



Conclusions

- Scan Pyramids experiment
  - Cosmic-ray muon radiography to search for hidden structures
  - Khufu's Pyramid, Khafre Pyramid, Bent Pyramid, Red Pyramid

- Muon radiography of pyramids was successfully conducted by using nuclear emulsion in the Queen's Chamber and the Descending Corridor
  - Validation at Queen's chamber : King's Chamber, Grand Gallery were clearly imaged
  - Large void was found just above the Grand Gallery with high statistical significance (more than 10 sigma at highest different direction) at the Queen's Chamber
  - Void was found just behind the north face called "Shevron" at the Descending Corridor.

- Future plan of ScanPyramids
  - Additional measurement for tomography analysis to reconstruct prescise reconstruction

- Future plan of our team
  - Application to archaeology (collaboration with Napoli group).
  - Application to civil engineering
  - Application to Mt.Fuji