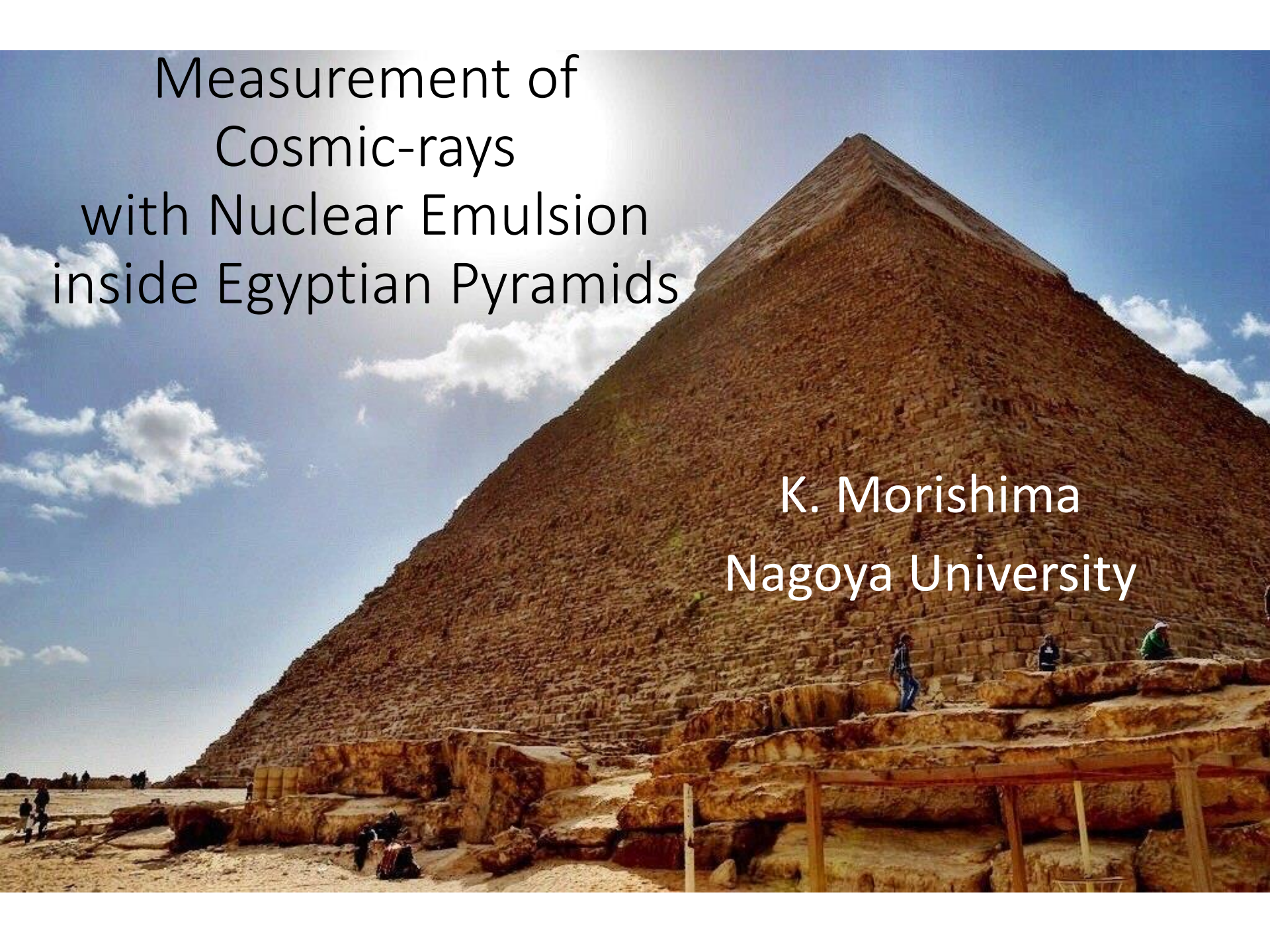


# Measurement of Cosmic-rays with Nuclear Emulsion inside Egyptian Pyramids

K. Morishima  
Nagoya University



# ScanPyramids

international scientific collaborations

Organization : Egyptian Ministry of Antiquities, Cairo University and HIP institute

Participating countries : Egypt, France, Canada and Japan

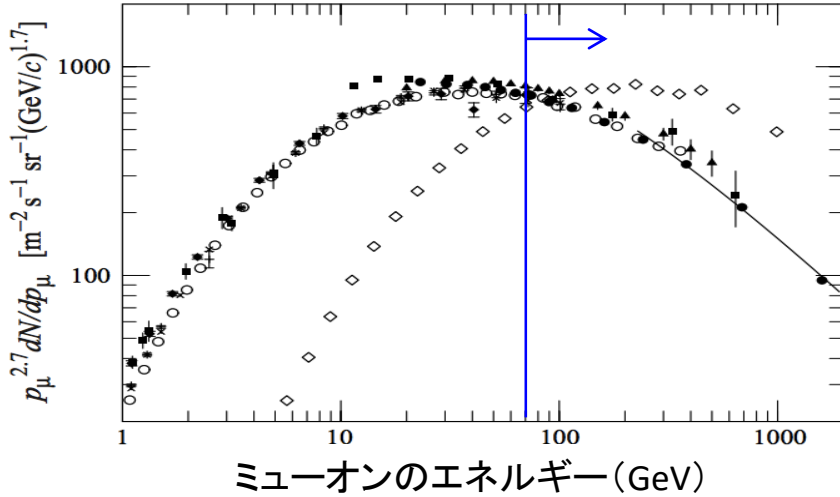
Non-destructive Imaging Technologies

- Muography : Nagoya University, KEK, CEA
- Infrared imaging : Laval University
- Laser 3D reconstruction : Iconem

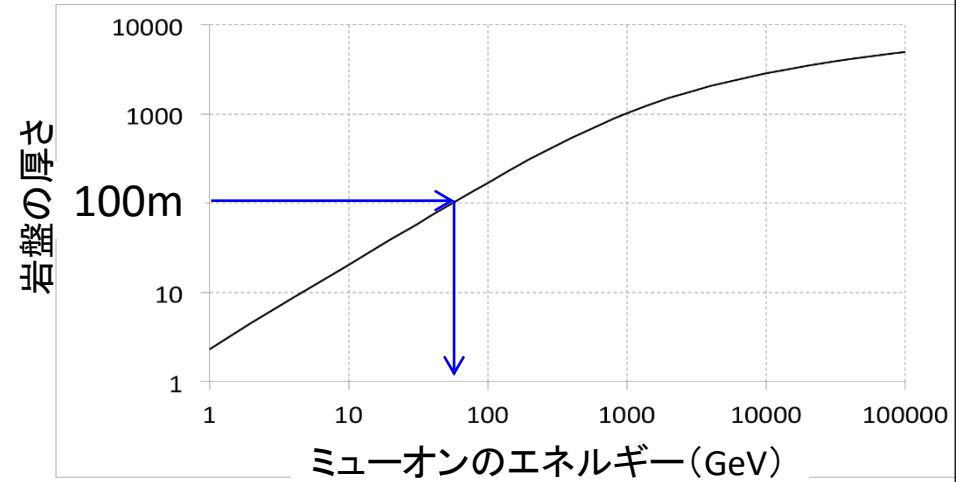


# 宇宙線ラジオグラフィの原理(火山を例に)

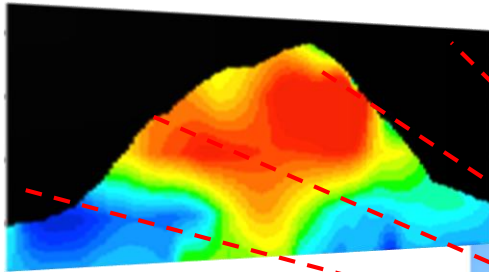
宇宙線ミュオンのエネルギースペクトル



ミュオンの物質に対する透過特性



宇宙線イメージ



物質量 (g/cm<sup>2</sup>)

$$E = dE/dl \times L \text{ (g/cm}^2\text{)}$$

昭和山

透過ミュオンの  
エネルギー下限値

入射ミュオン数:  $N_0$

検出ミュオン数:  $N$

ミュオンの飛来方向を  
検出する測定器



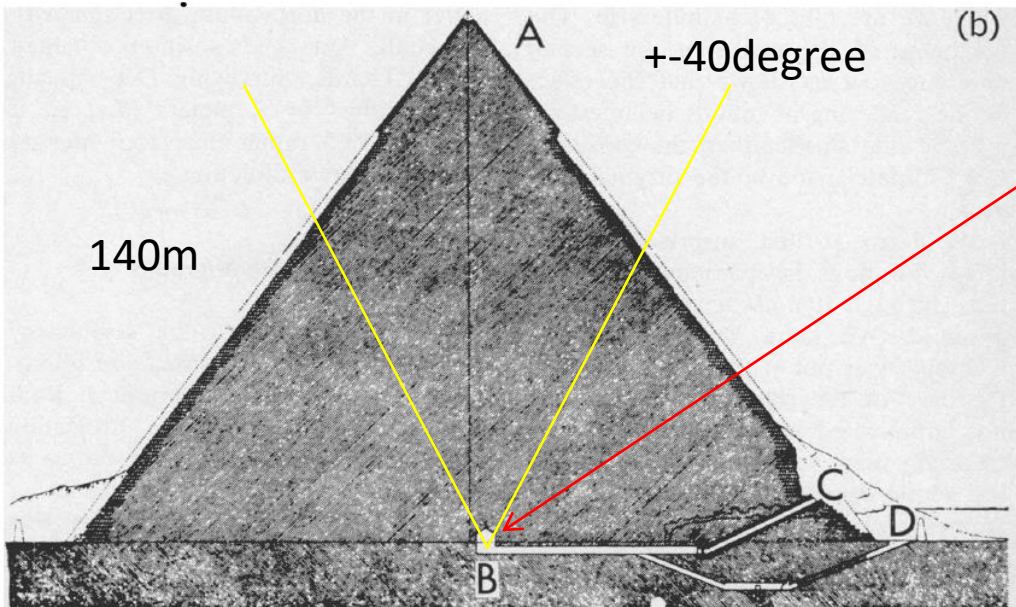
# First Experiment by Alvarez

- Chephren pyramid

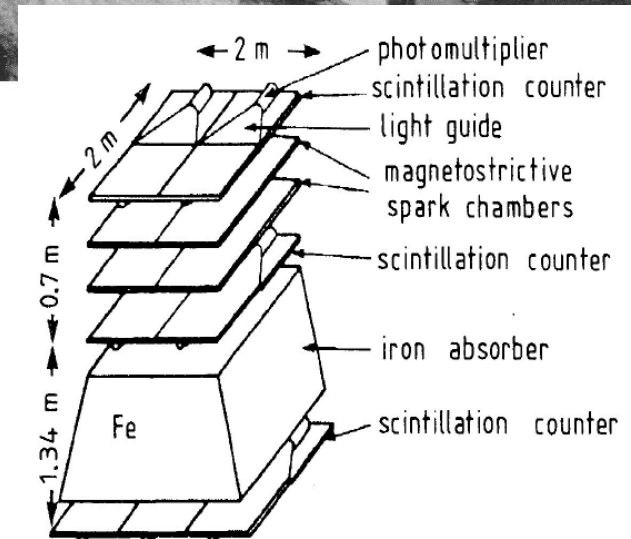
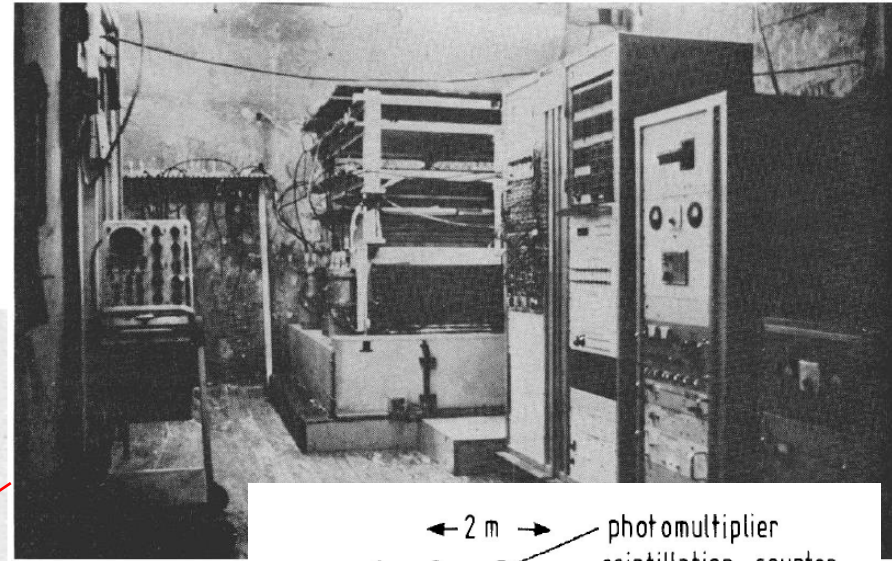
- L.W.Alvarez,A. J.Anderson, F. El Bedwei et al., "Search for hidden chambers in the pyramids," Science, vol. 167, no. 3919, pp.832–839, 1970.

- Detector : spark chamber

- 1967, Alvarez



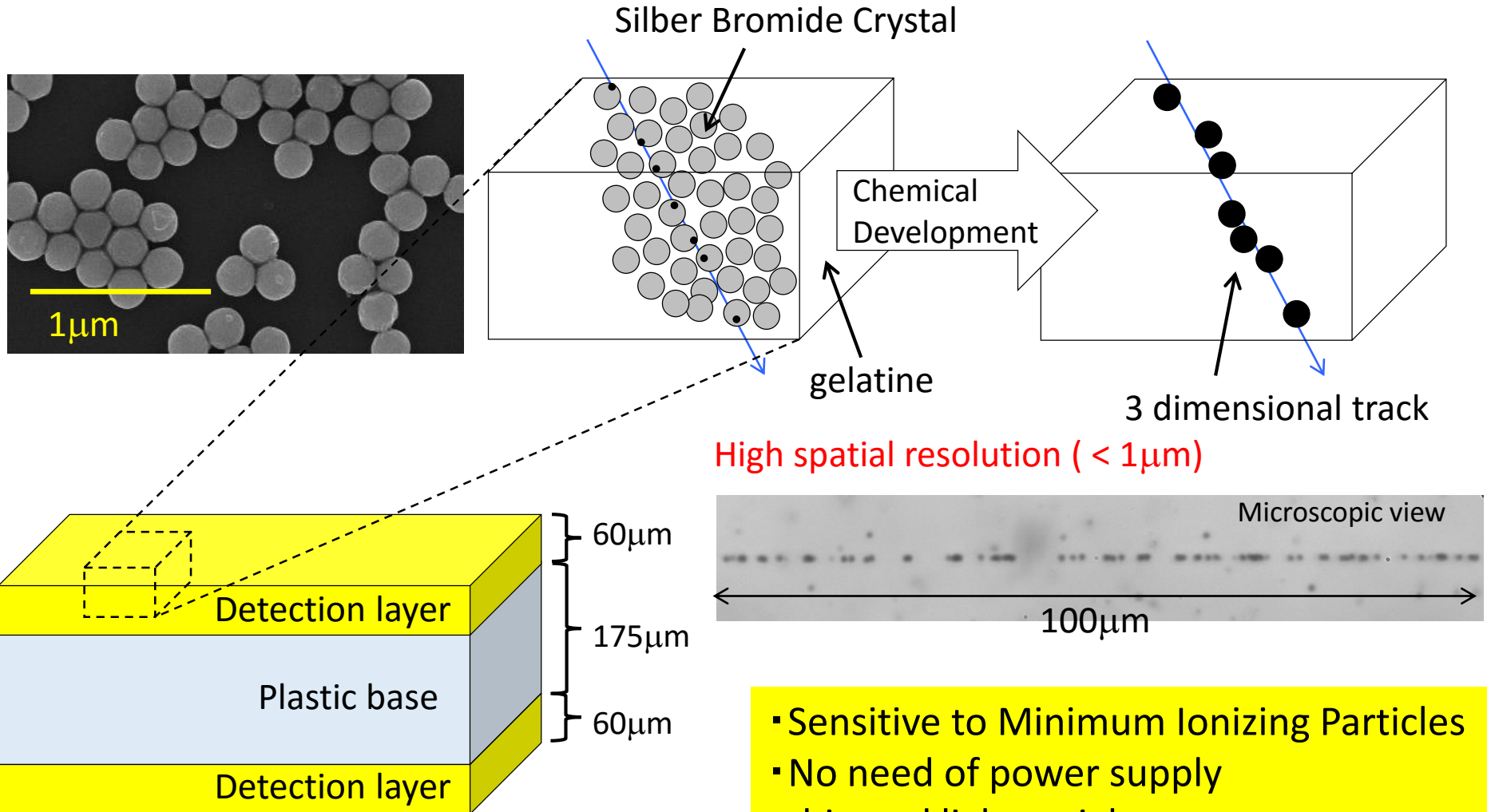
4m<sup>2</sup> x several months





# Nuclear emulsion

Visualization of trajectories of charged particles in three dimension



High spatial resolution ( $< 1\mu\text{m}$ )

- Sensitive to Minimum Ionizing Particles
- No need of power supply
- thin and light weight
- high resolution and Large field of view

# Candidates of the Pyramids in ScanPyramids

Cheops Pyramids

Jan. 2016 –

Nagoya University  
KEK  
CEA



Map of Egypt



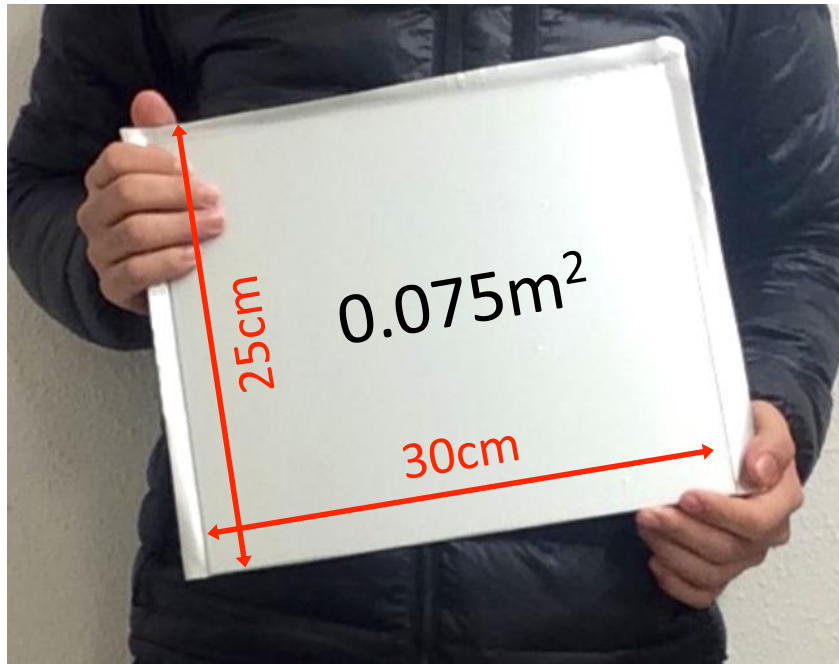
Bent Pyramid

Dec. 2015 – Jan. 2016

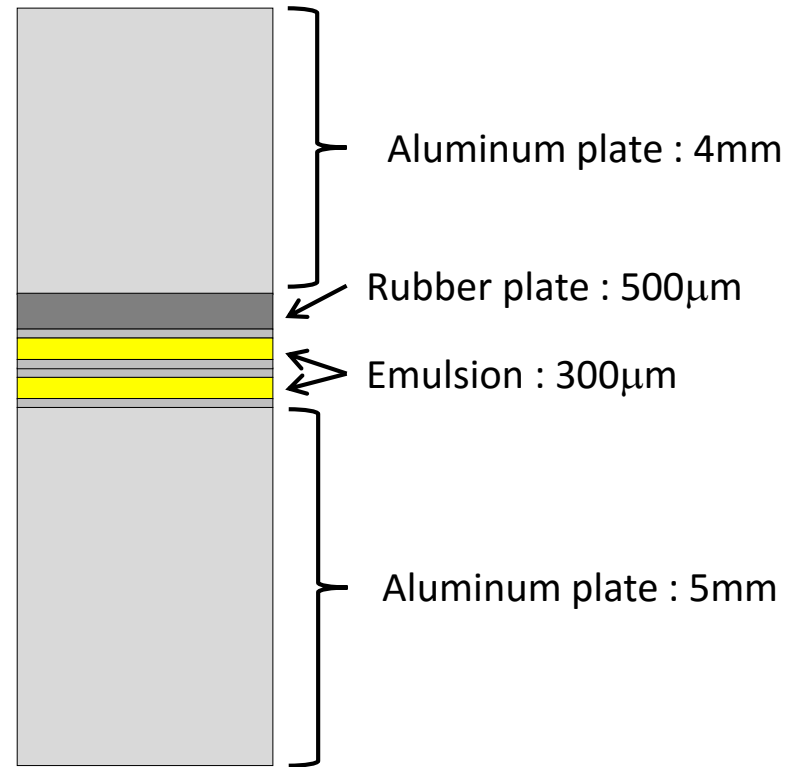
Nagoya University



# Nuclear emulsion Detector : Unit and structure



Example of detector structure

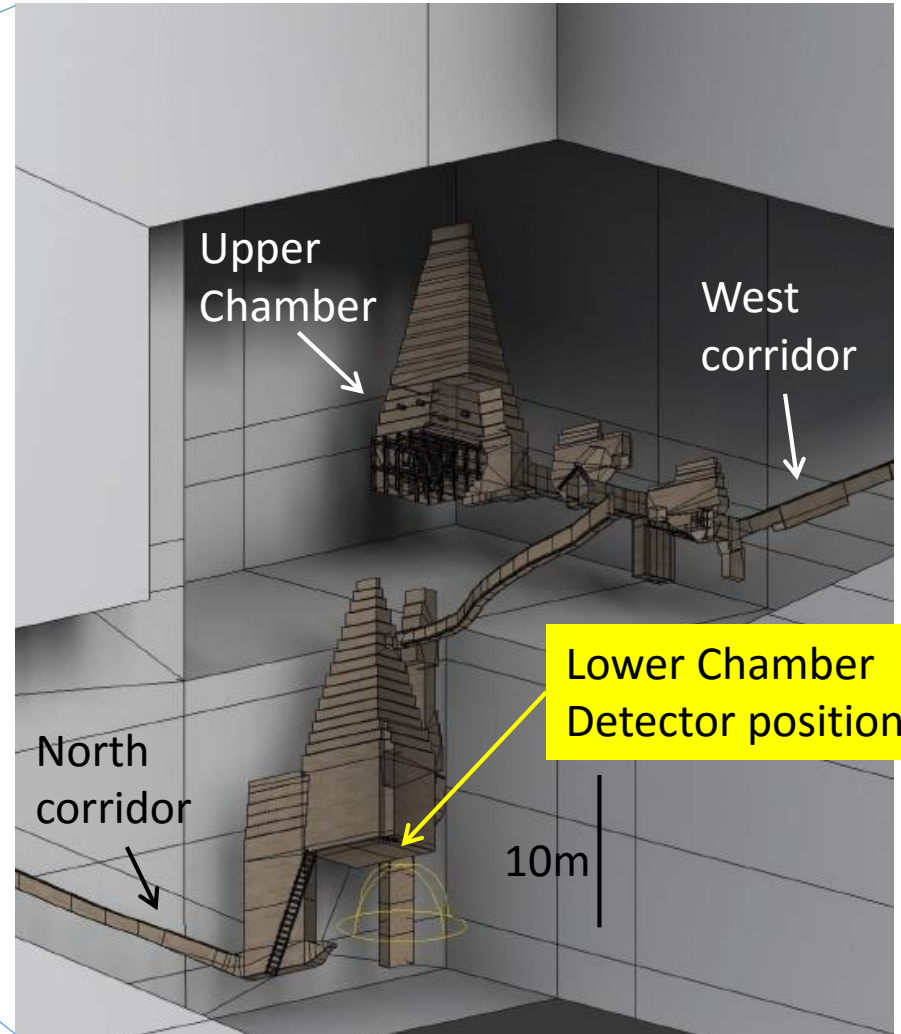
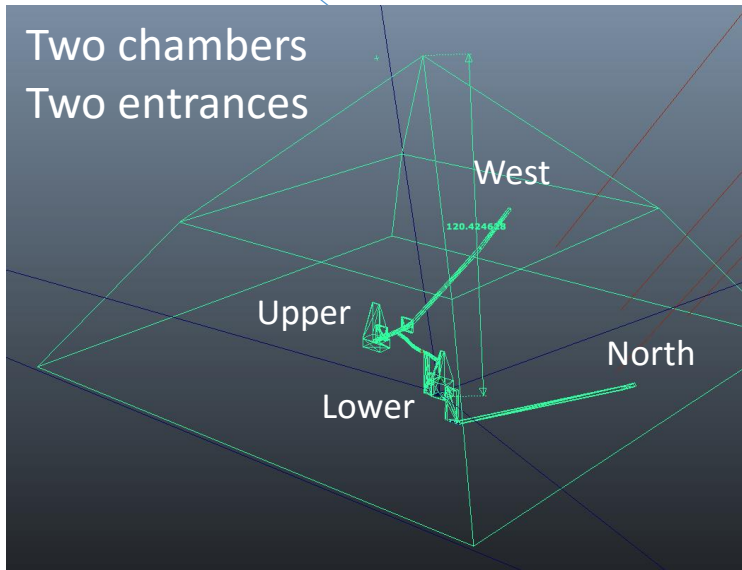
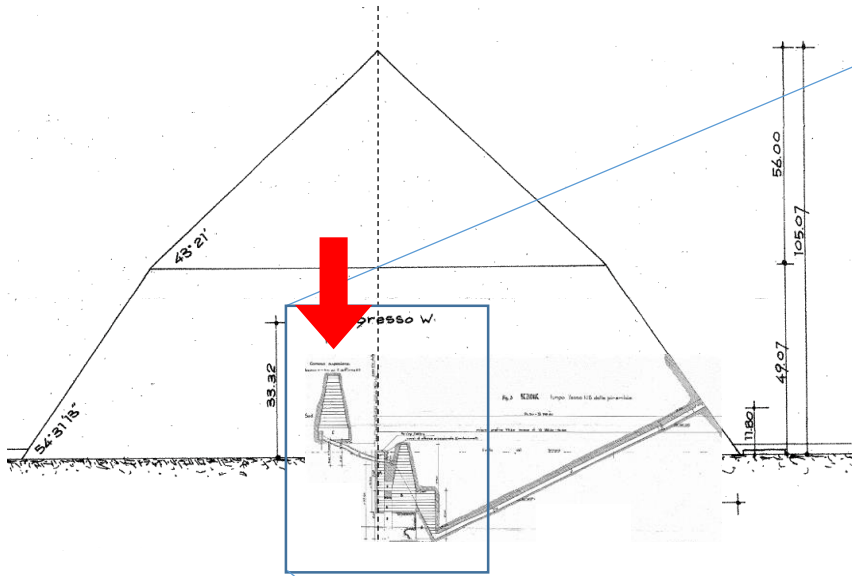




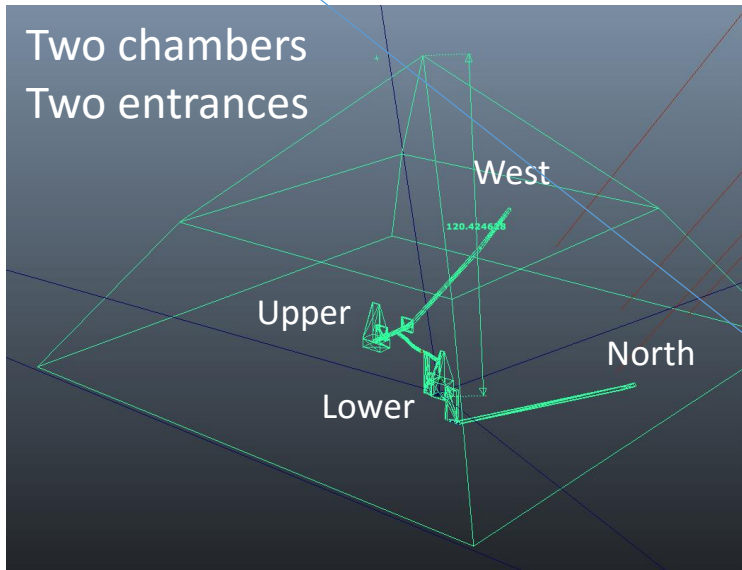
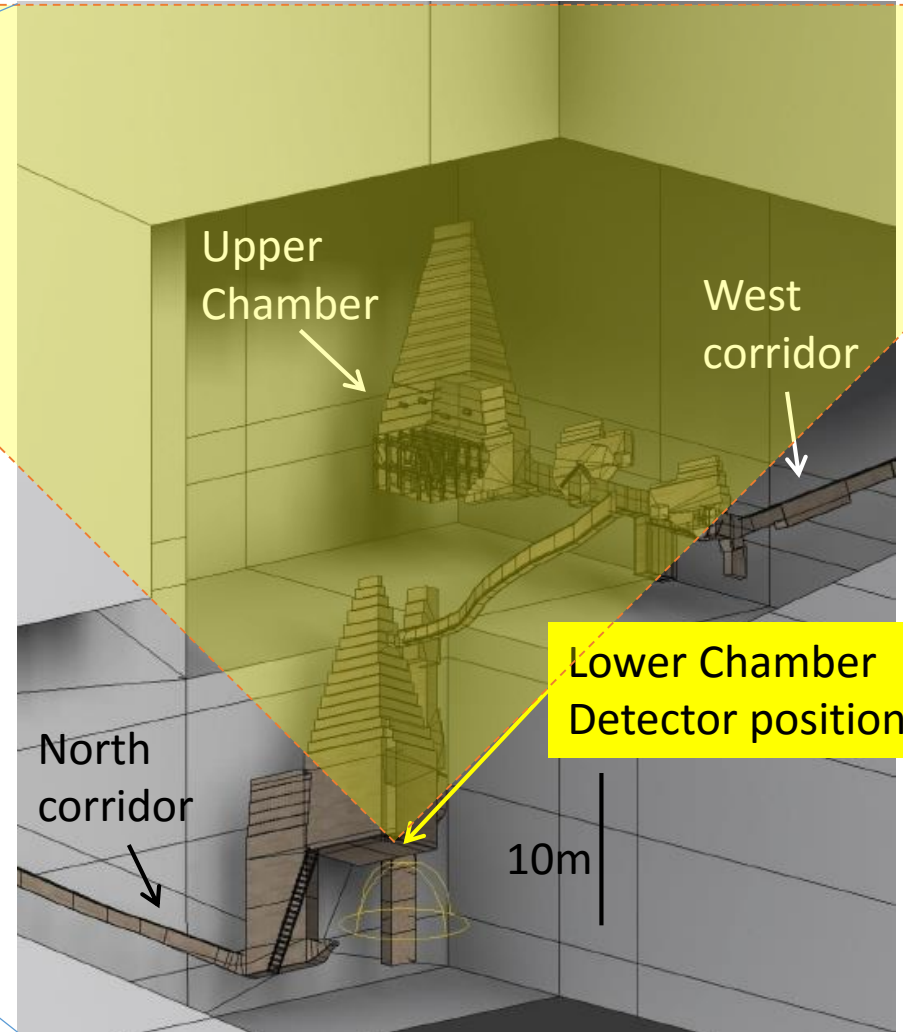
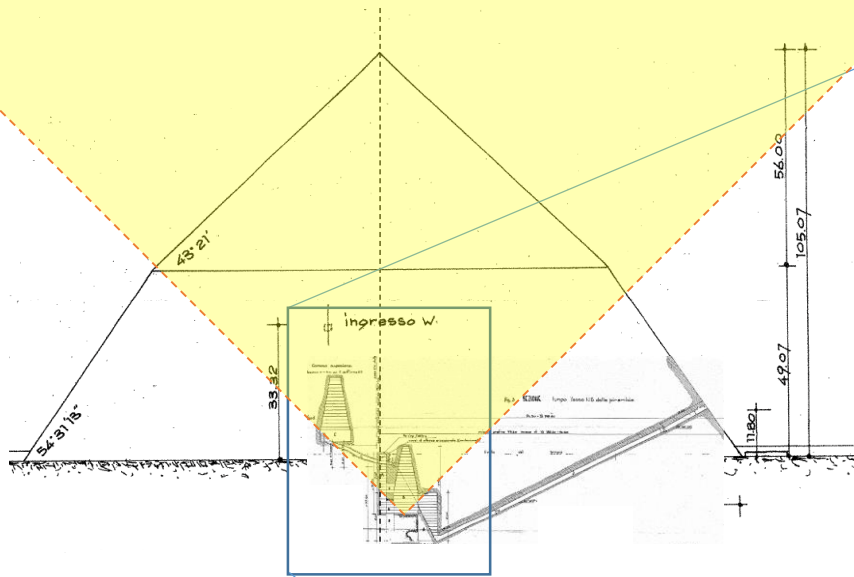
# Muography of Bent Pyramid



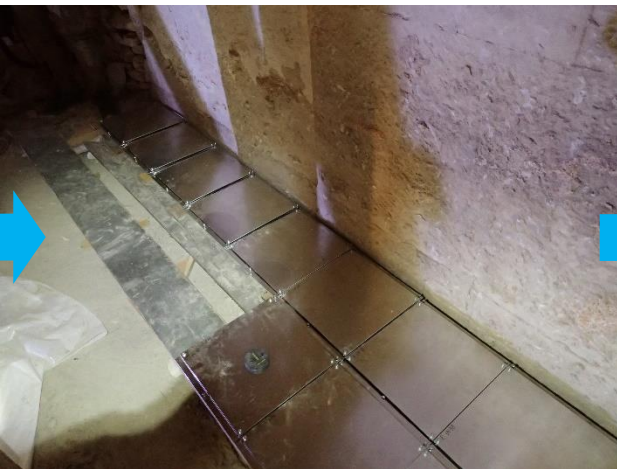
# Muography of Bent Pyramid

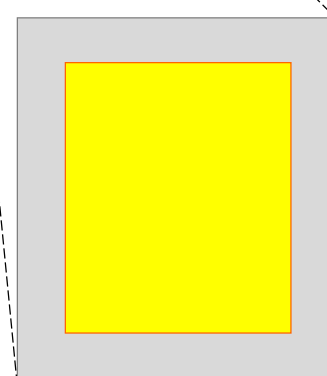
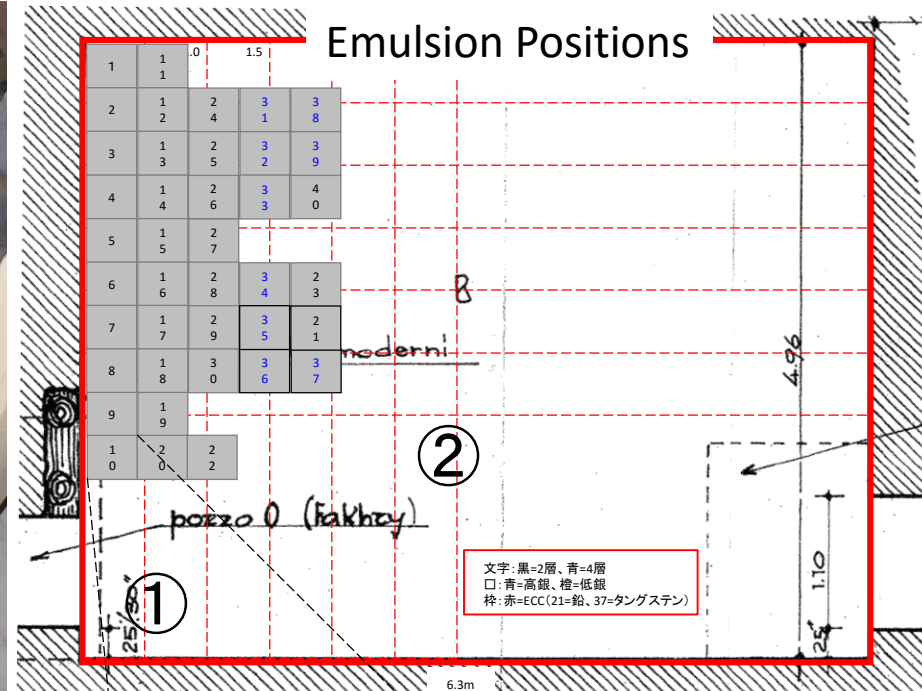


# Muography of Bent Pyramid



# Installation in Bent Pyramid

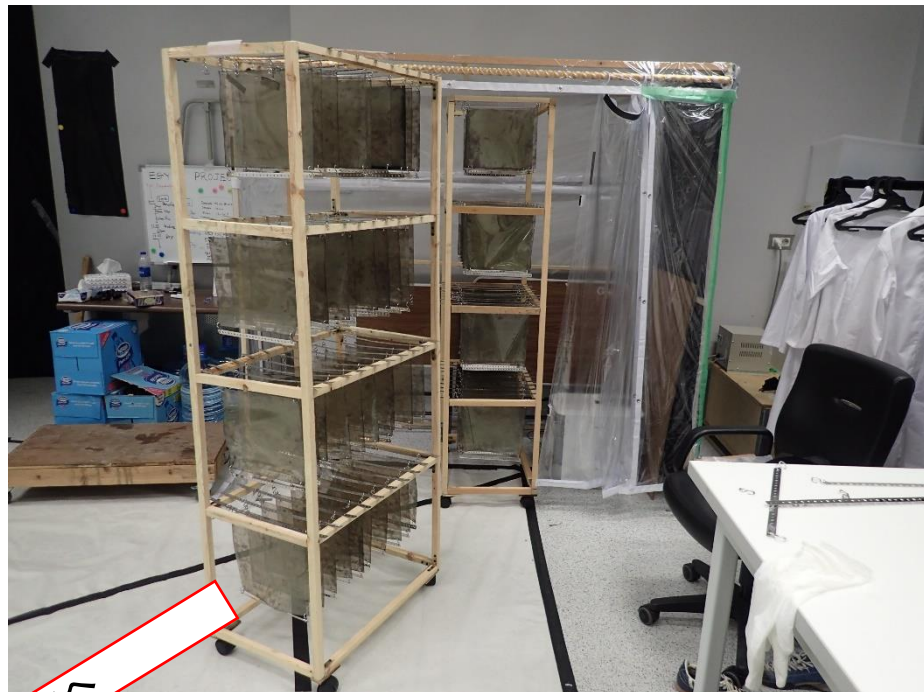




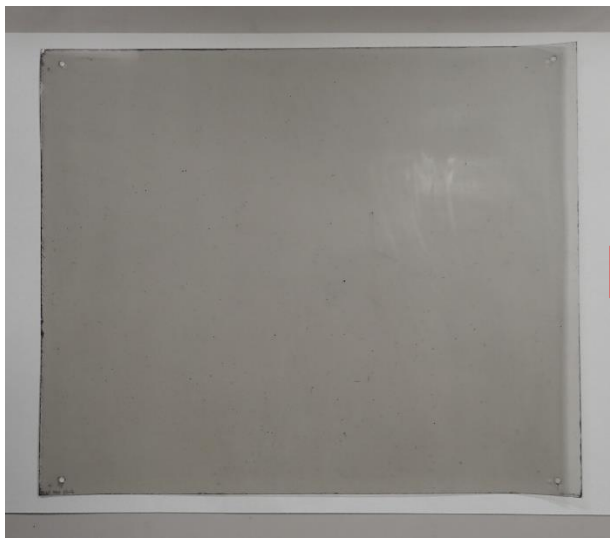
- 40 plates were installed and collected
- Muon detection area : 3m<sup>2</sup>
- Observation period : 40days

# Development at Cairo and scanning at Nagoya

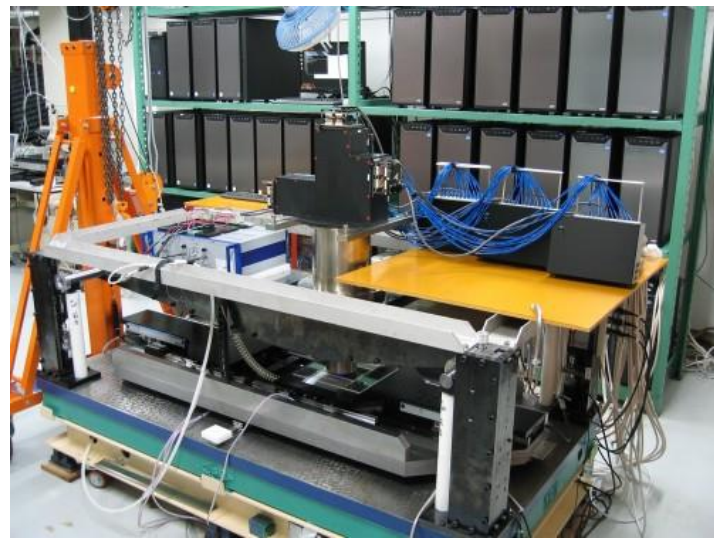
Great Egyptian Museum at Cairo



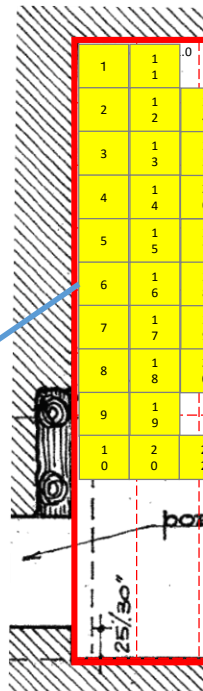
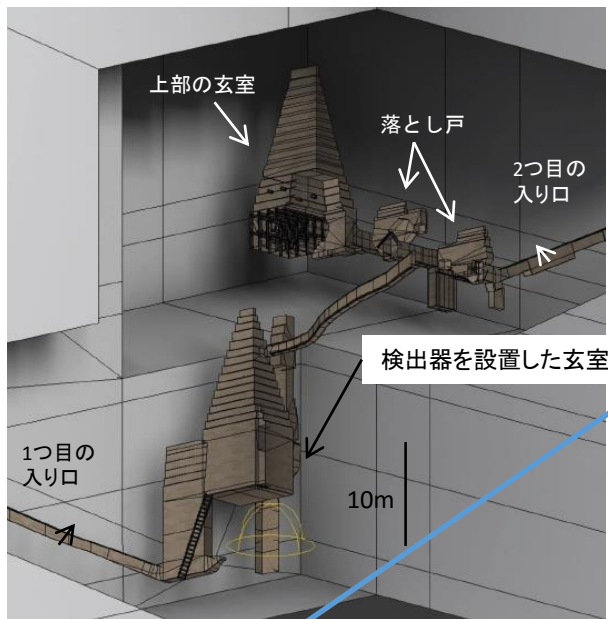
日本へ



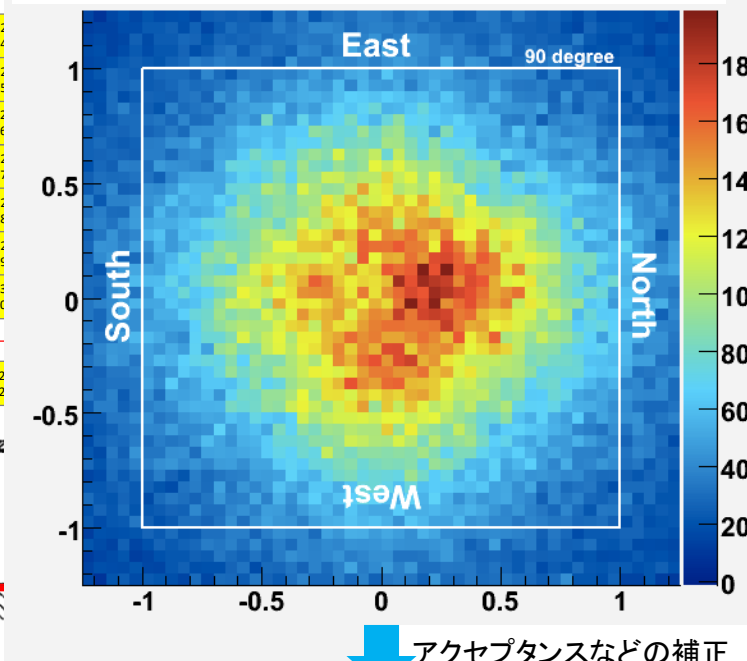
飛跡読み取り



# 観測結果との比較(1枚相当)

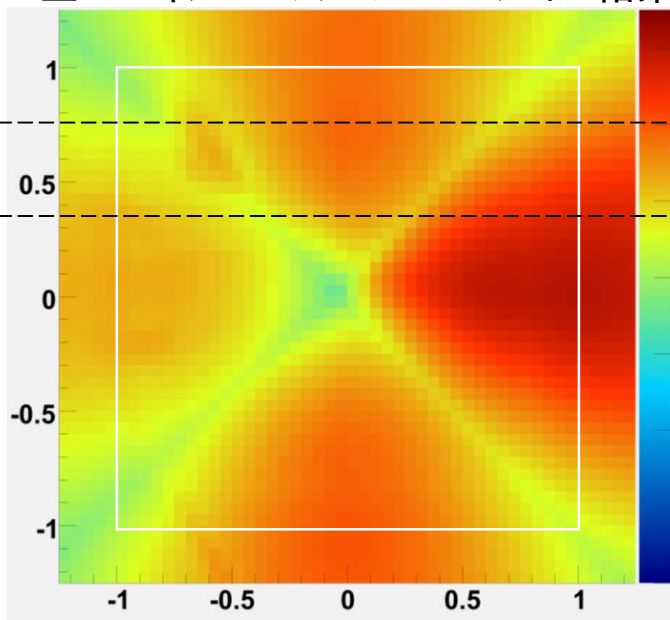


## 1枚から得られた宇宙線数

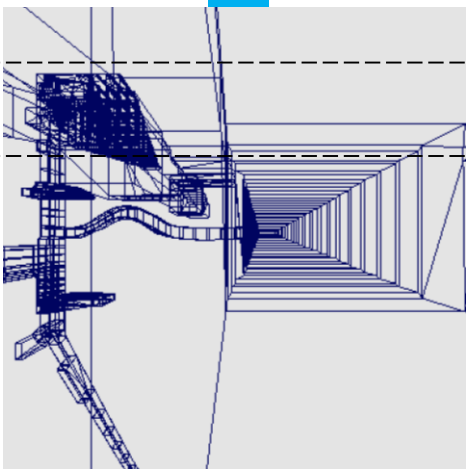
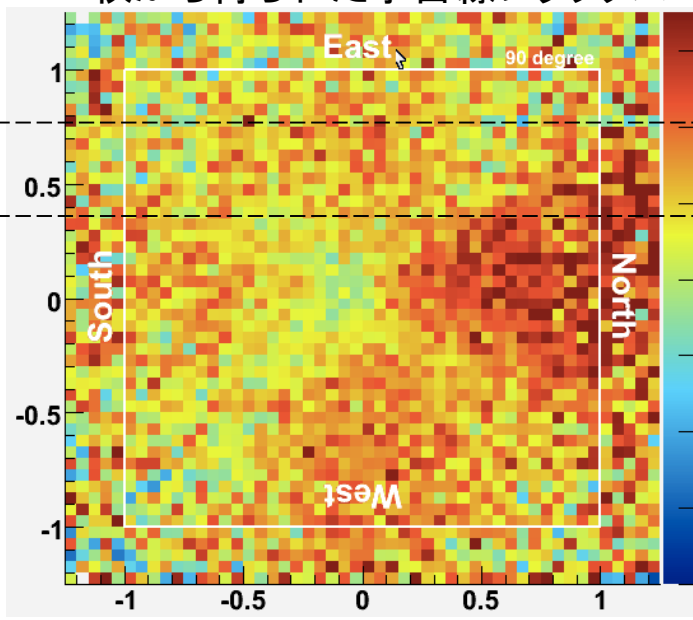


6

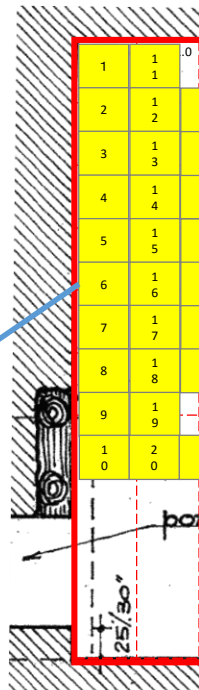
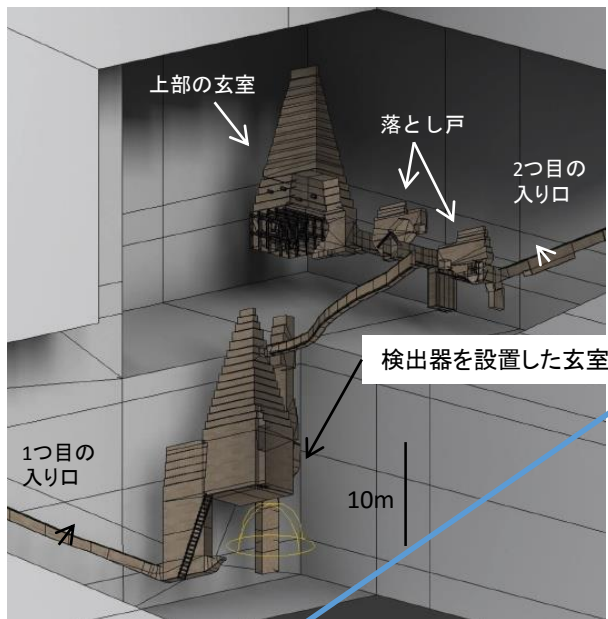
## 全40フィルムのシミュレーション結果



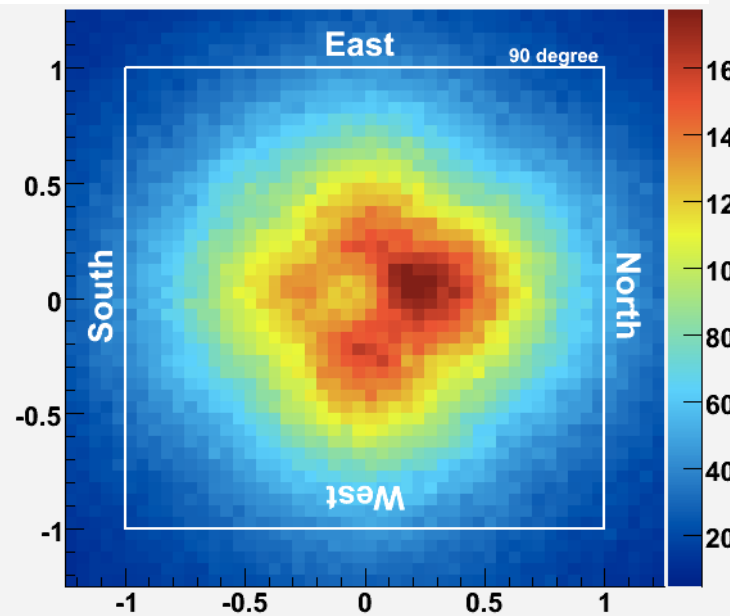
## 1枚から得られた宇宙線フラックス



# 観測結果との比較(4枚相当)

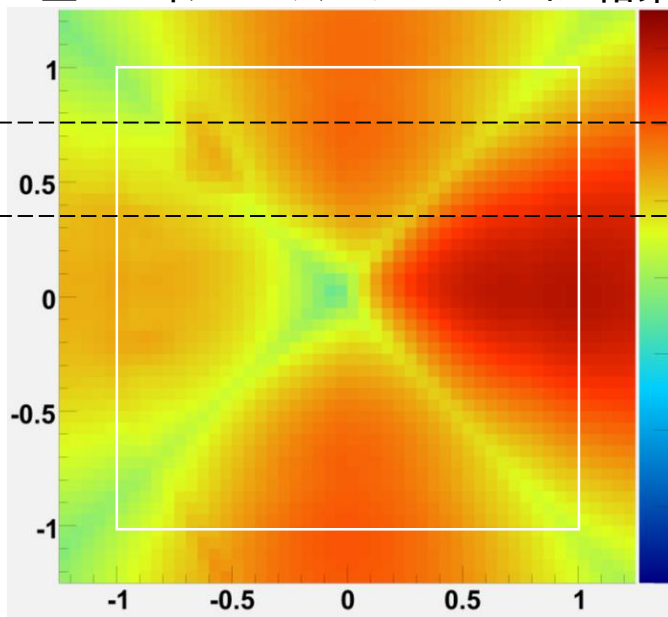


1枚から得られた宇宙線数

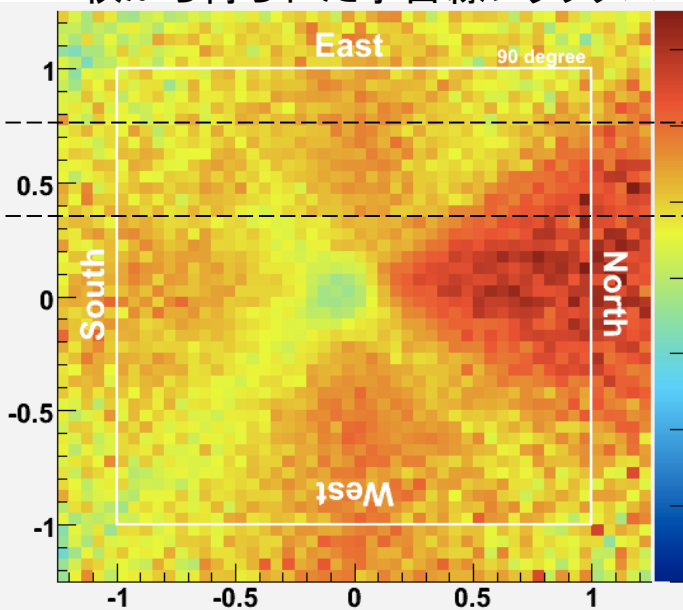


↓ アクセプタンスなどの補正

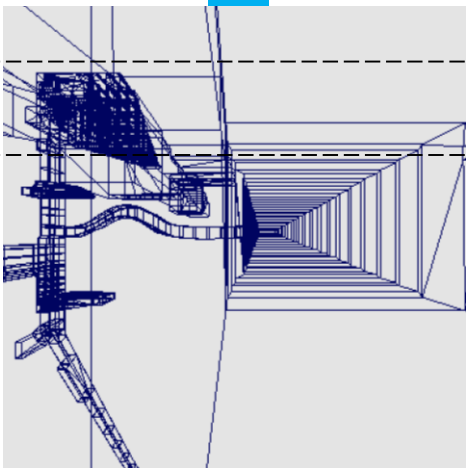
全40フィルムのシミュレーション結果



4枚から得られた宇宙線フラックス

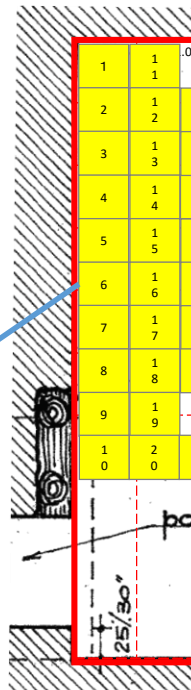
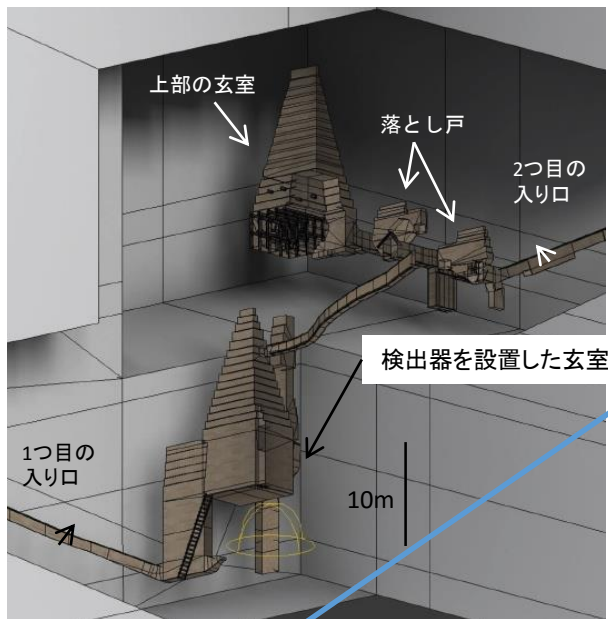


6

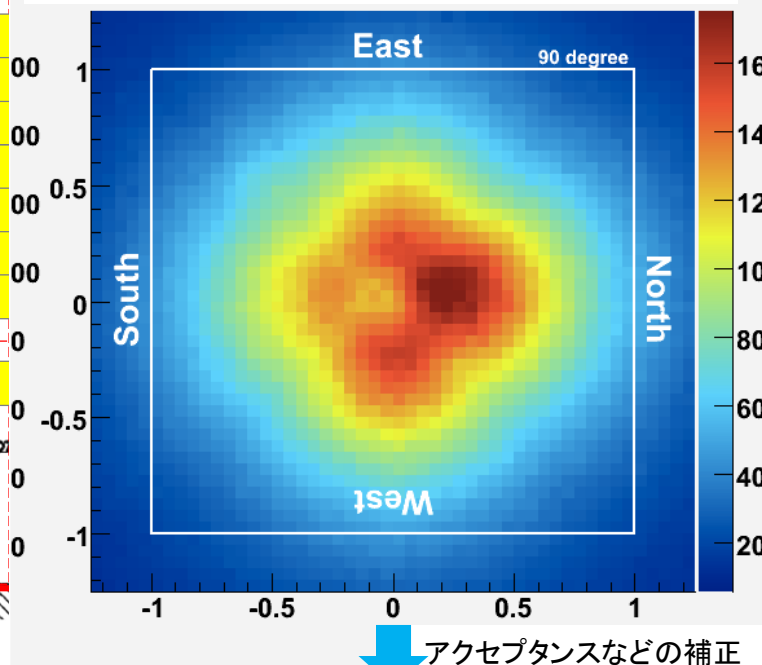




# 観測結果との比較(40枚)



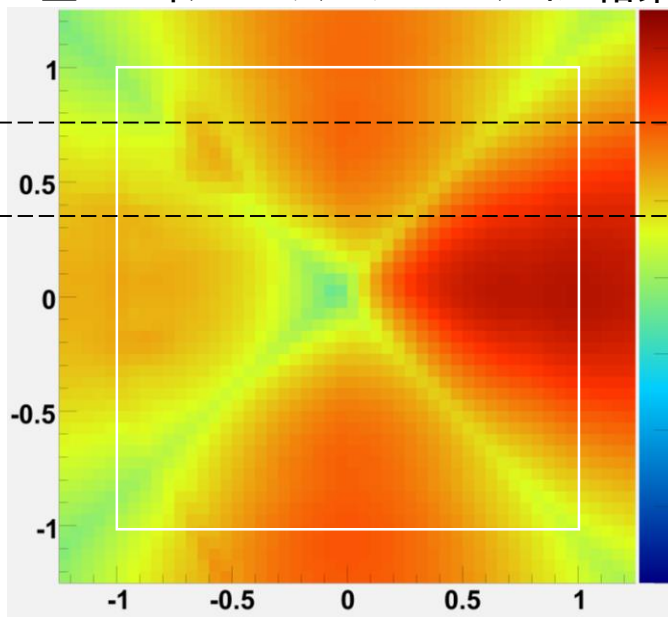
1枚から得られた宇宙線数



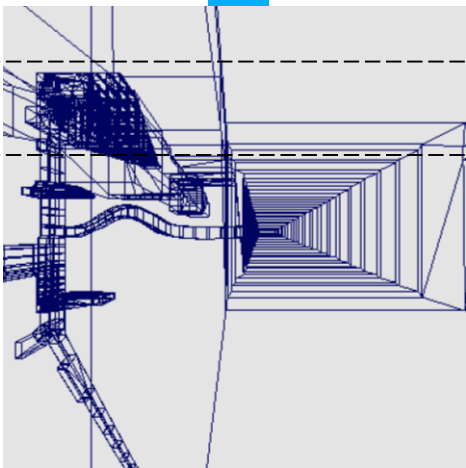
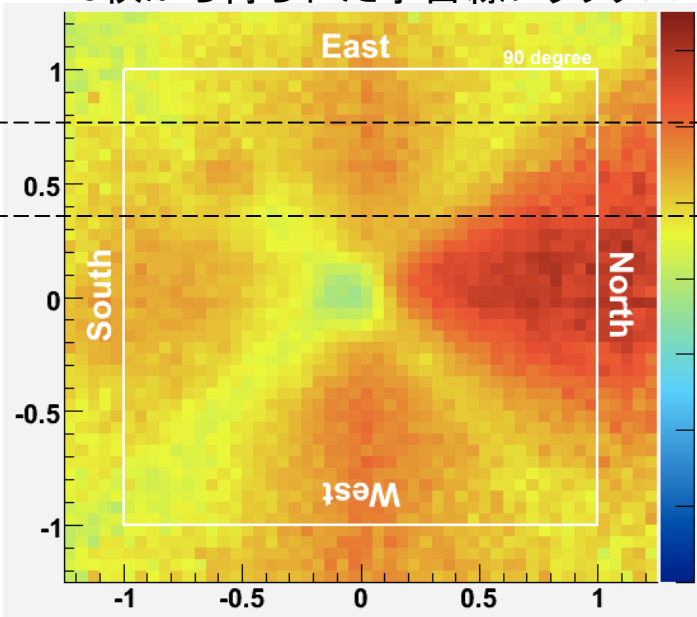
アクセプタンスなどの補正

6

全40フィルムのシミュレーション結果

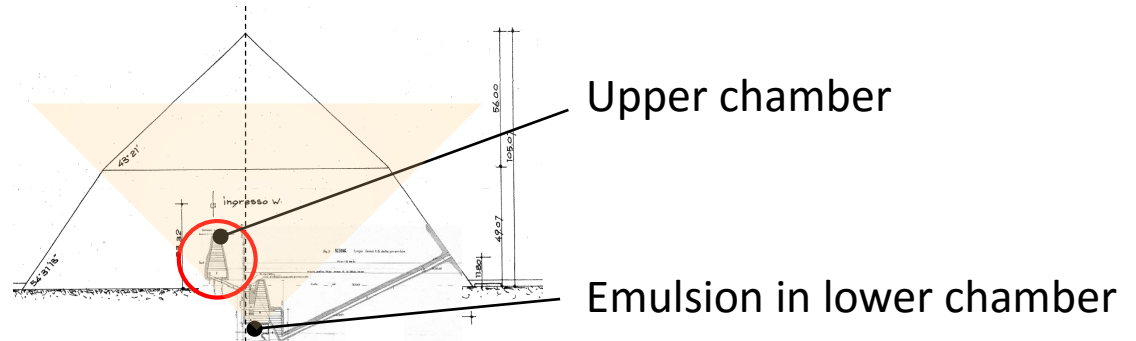


40枚から得られた宇宙線フラックス

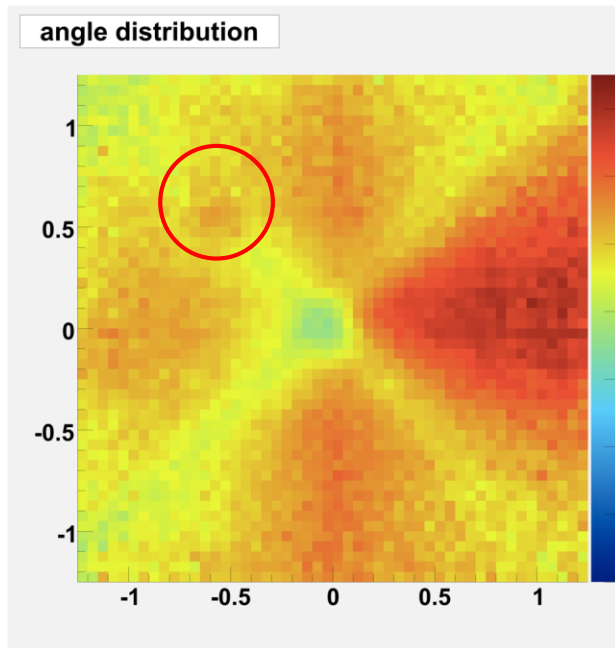


# Validation of Emulsion Technology for Muography

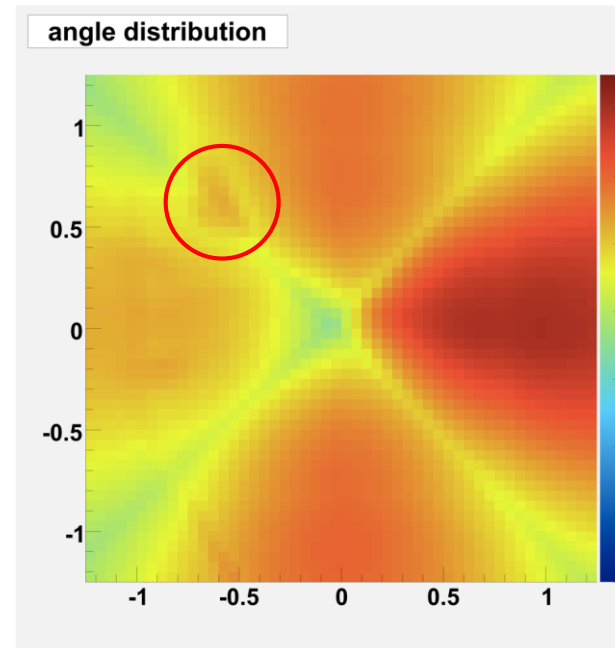
Bent pyramid



Data



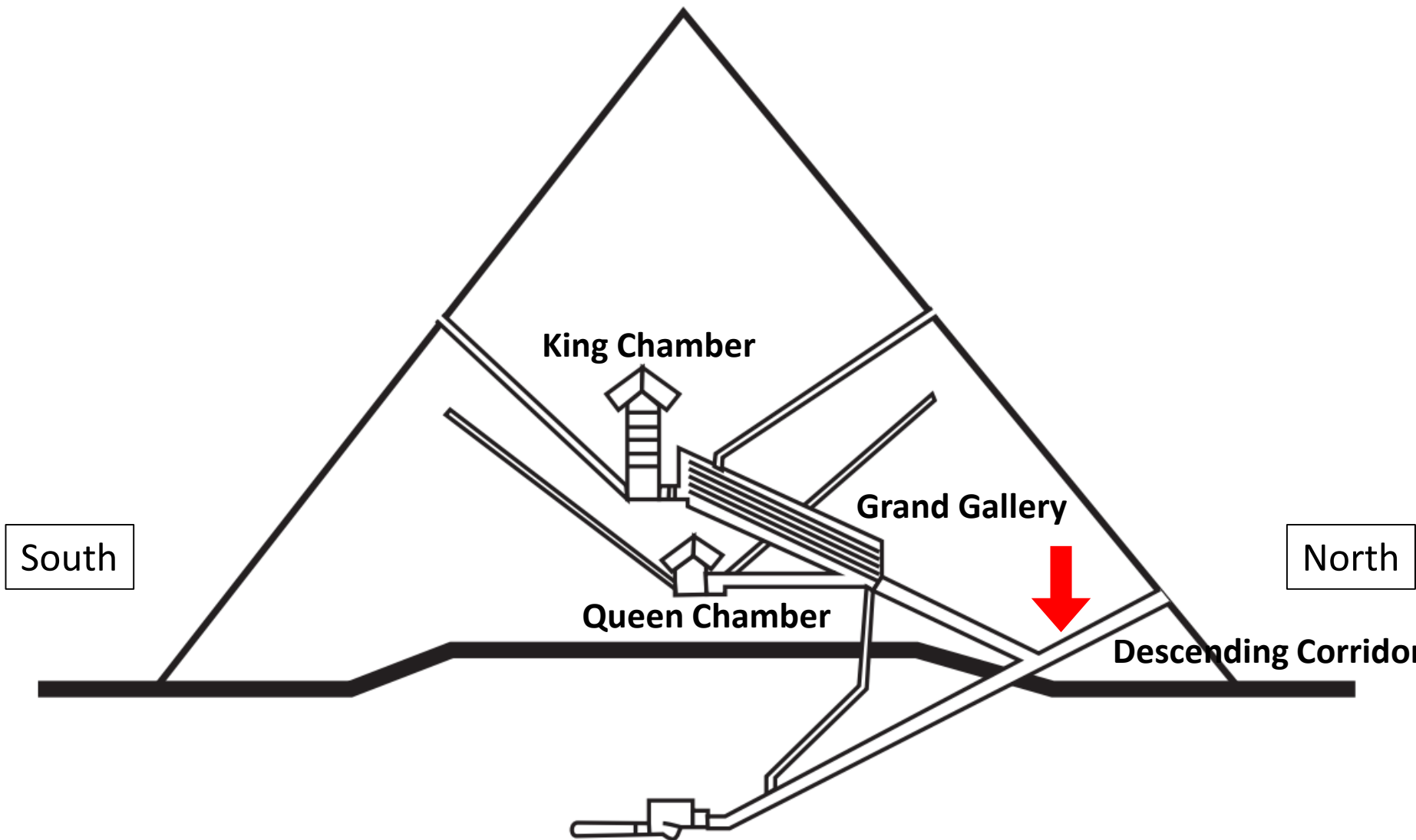
Simulation



This is first validation of muography of the chamber inside the pyramid !!

# Khufu's Pyramid





South

North

King Chamber

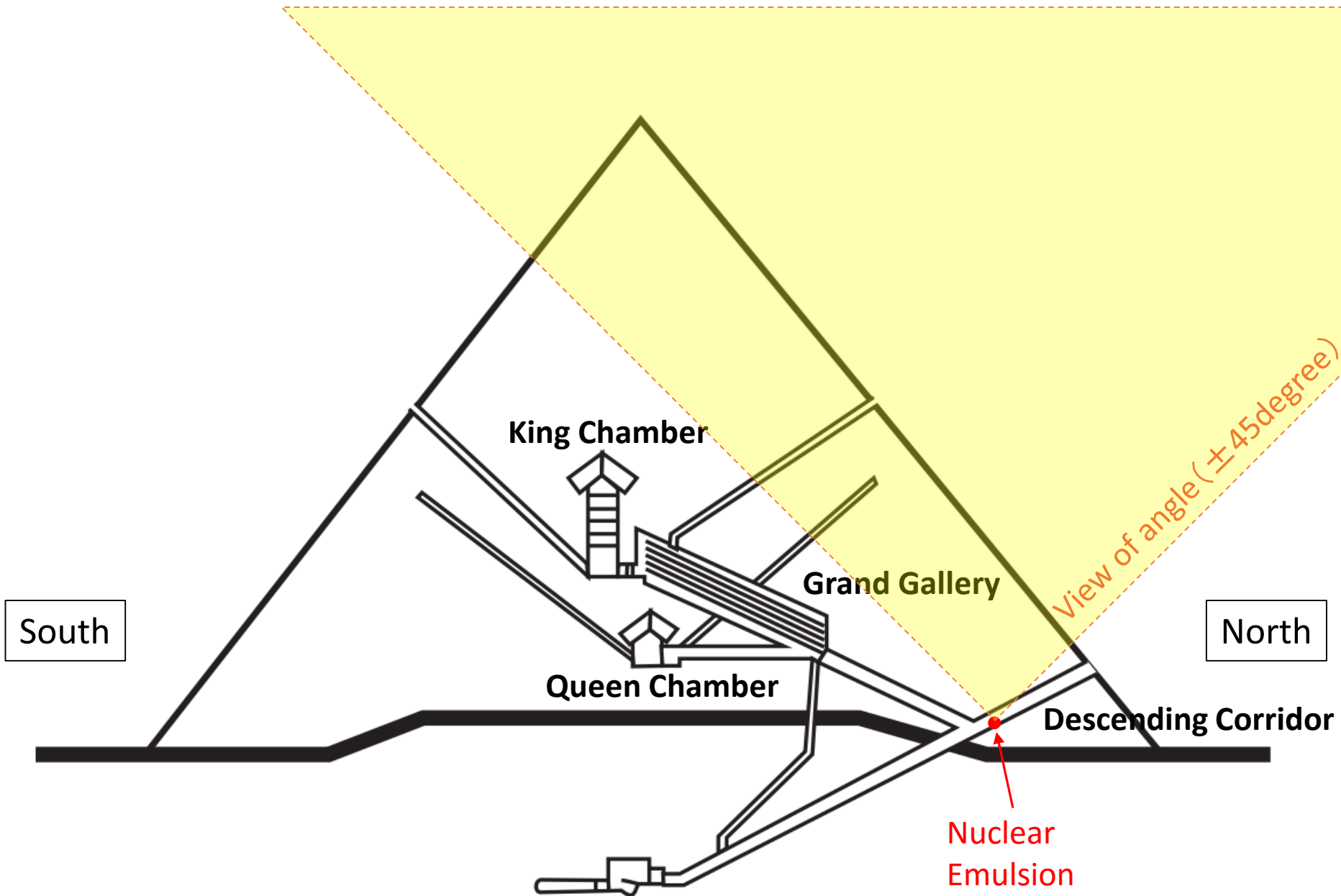
Grand Gallery

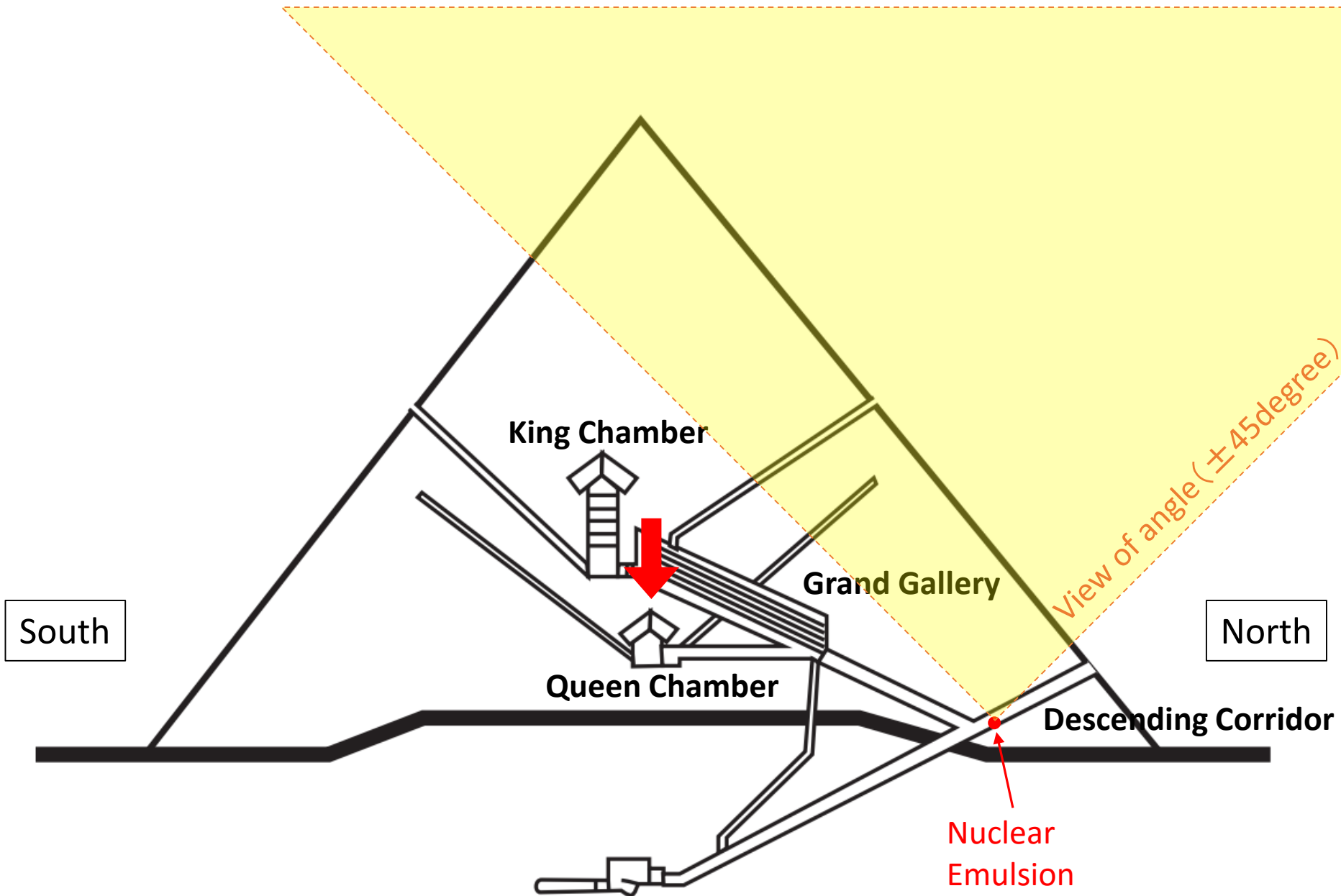
Queen Chamber

Descending Corridor

# Descending Corridor



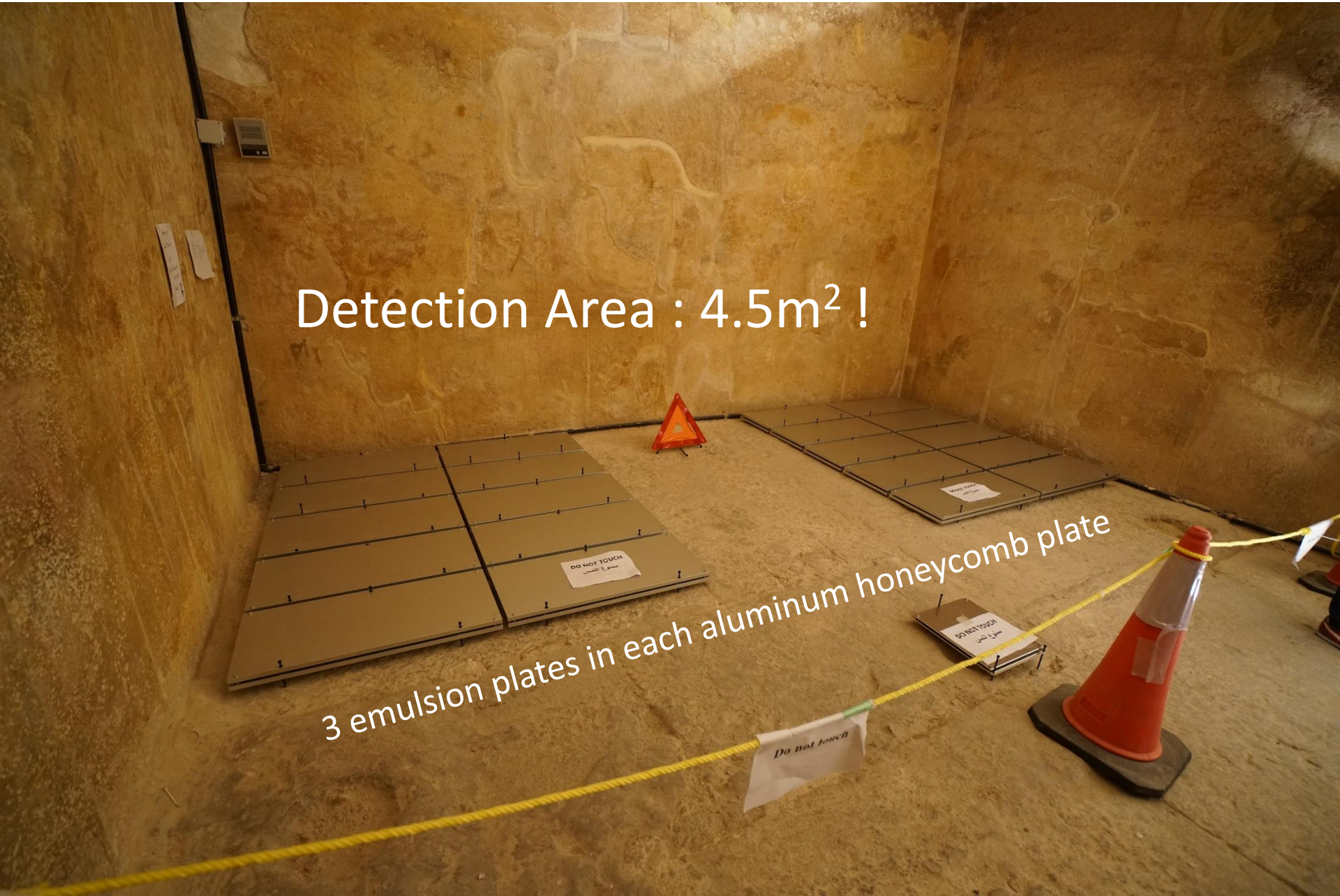




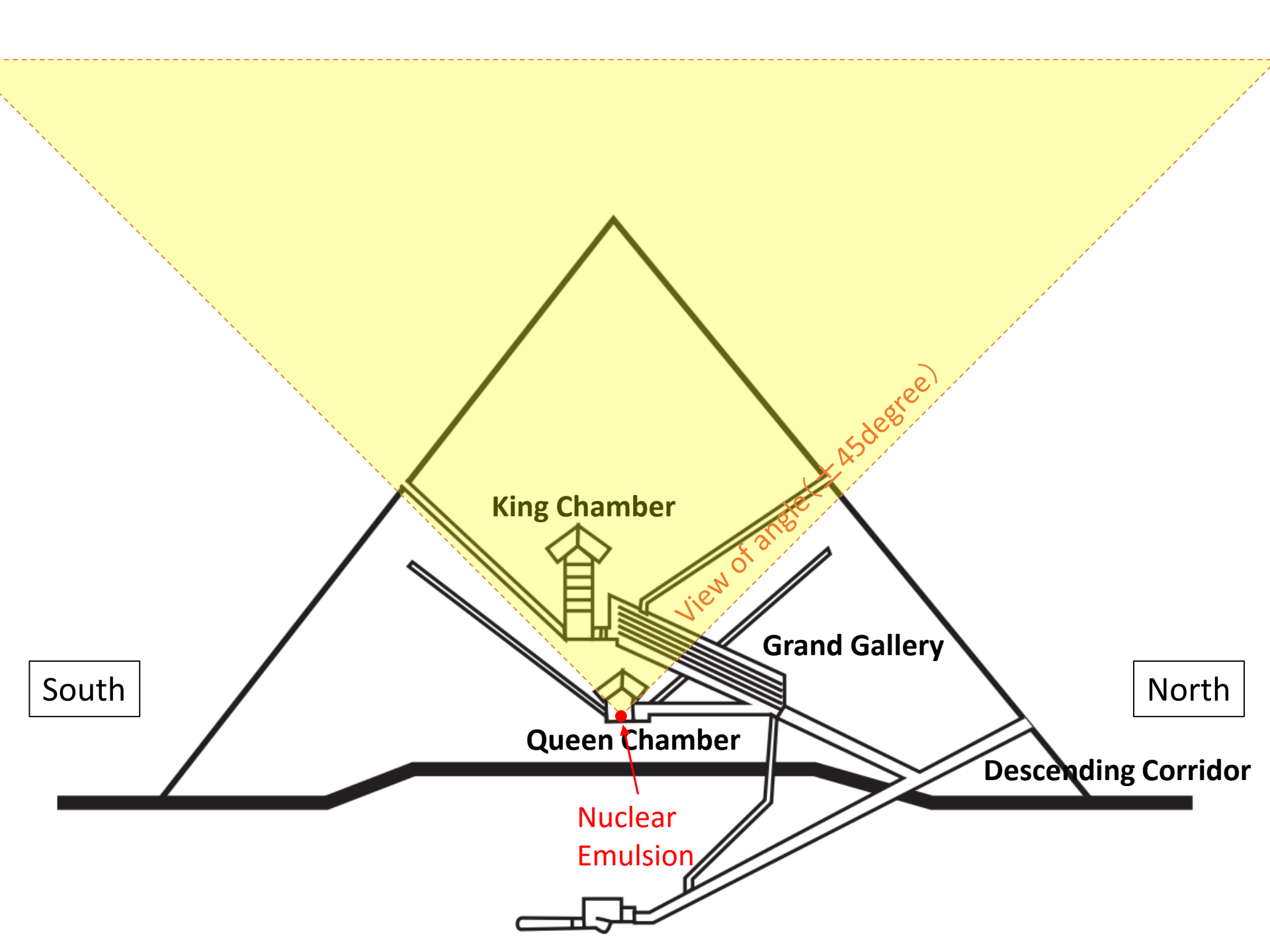
# Queen Chamber

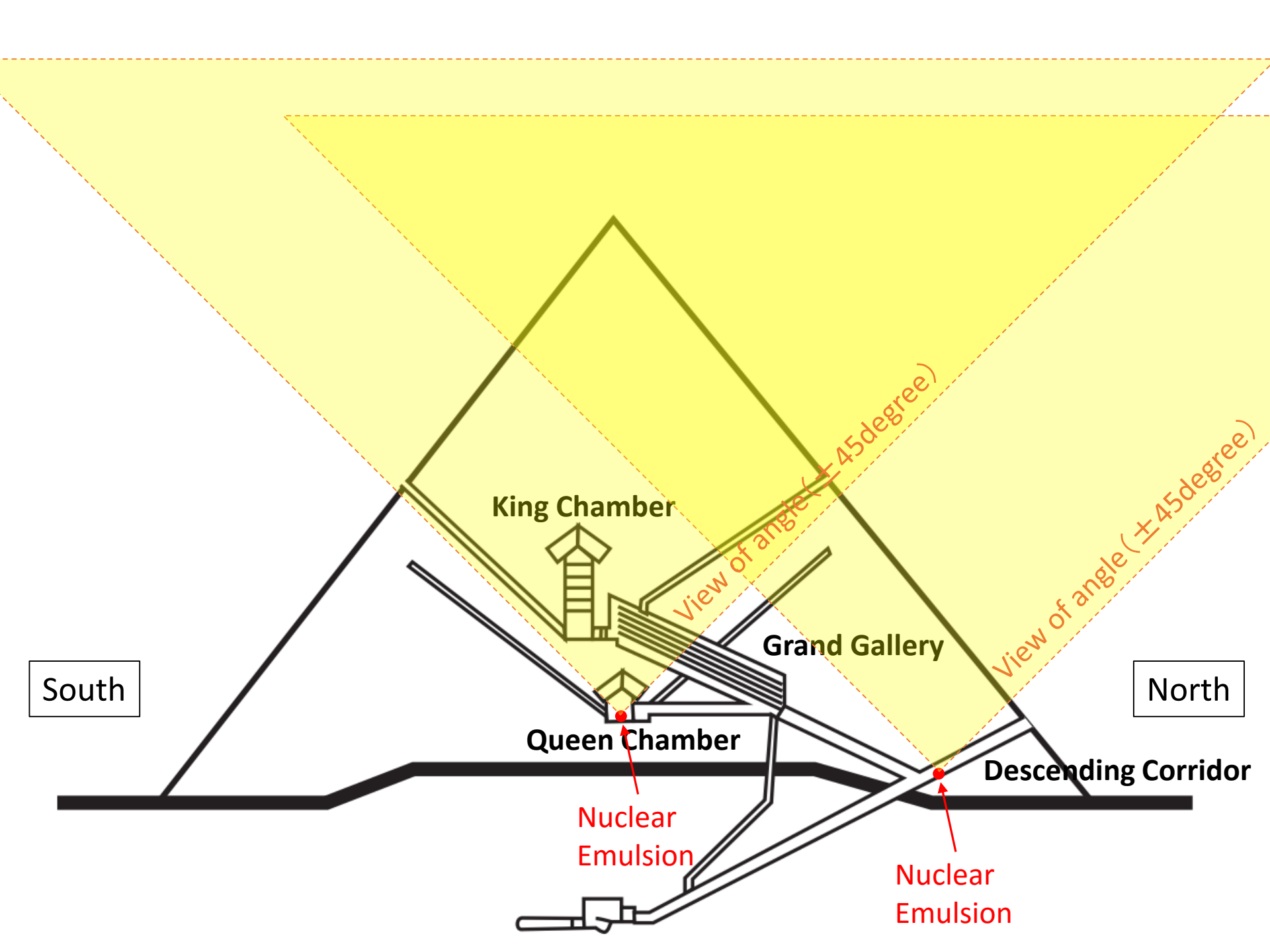
Detection Area : 4.5m<sup>2</sup> !

3 emulsion plates in each aluminum honeycomb plate



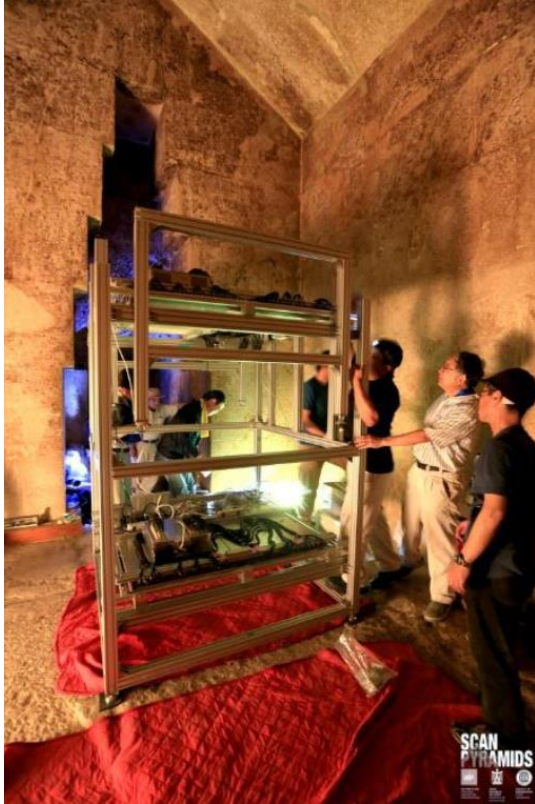




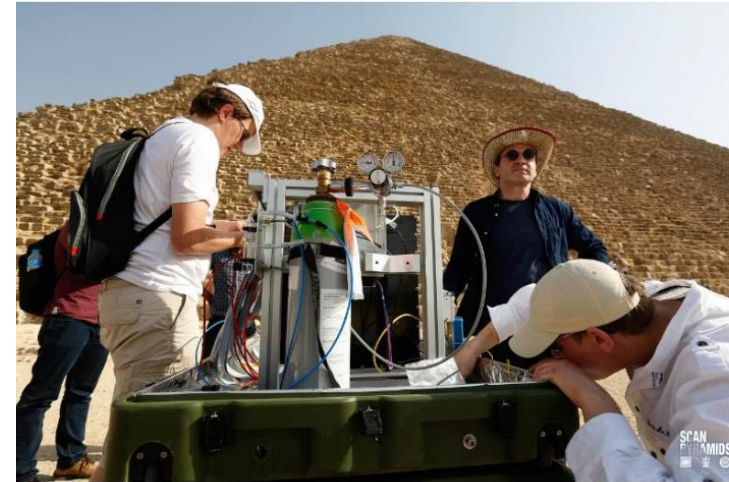


# Current Status of other groups

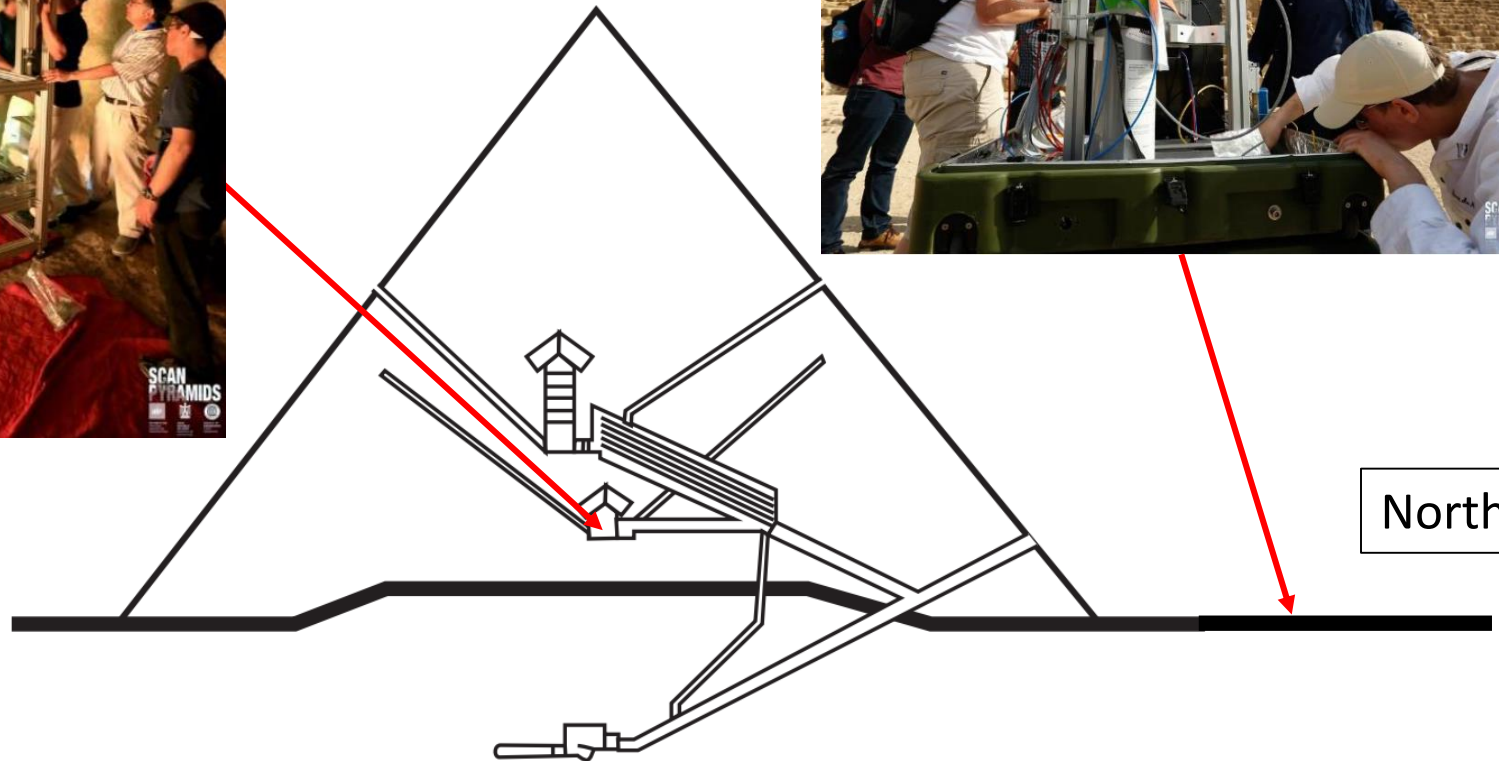
KEK in Queen Chamber



CEA outside of Khufu's Pyramid



South



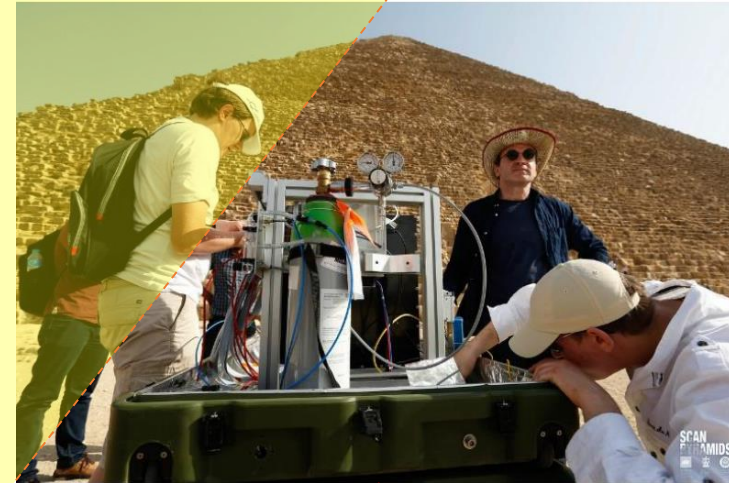
North

# Current Status of other group

KEK in Queen Chamber

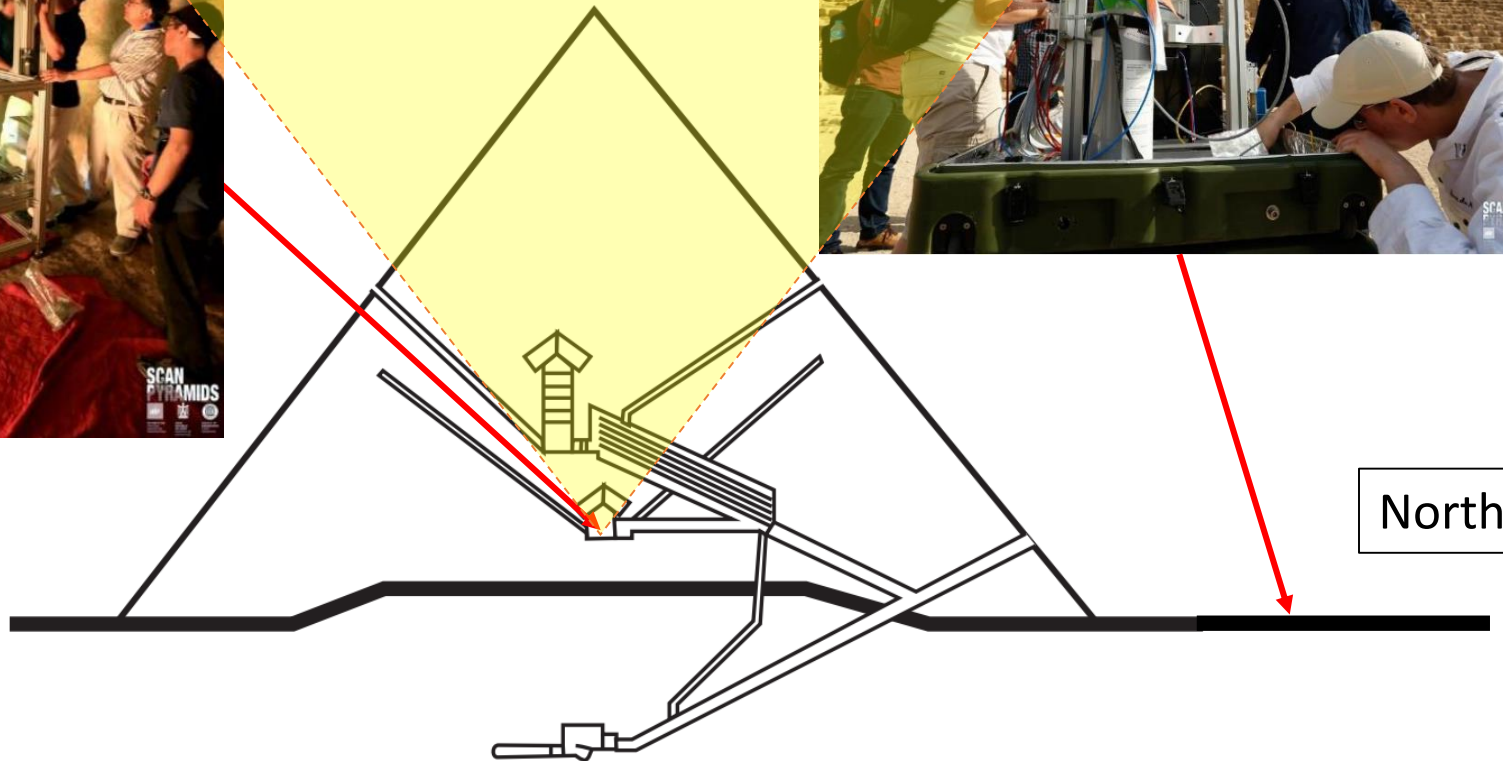


CEA outside of Khufu's Pyramid



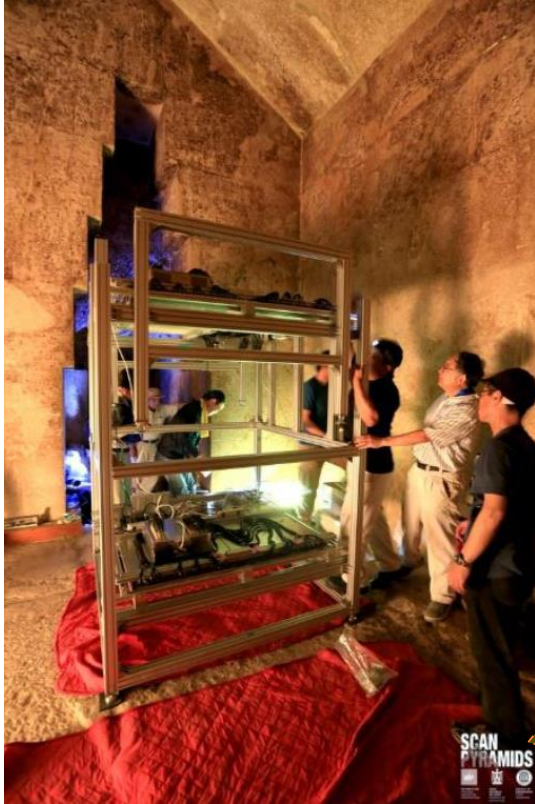
South

North



# Current Status of other group

KEK in Queen Chamber



South

CEA outside of Khufu's Pyramid

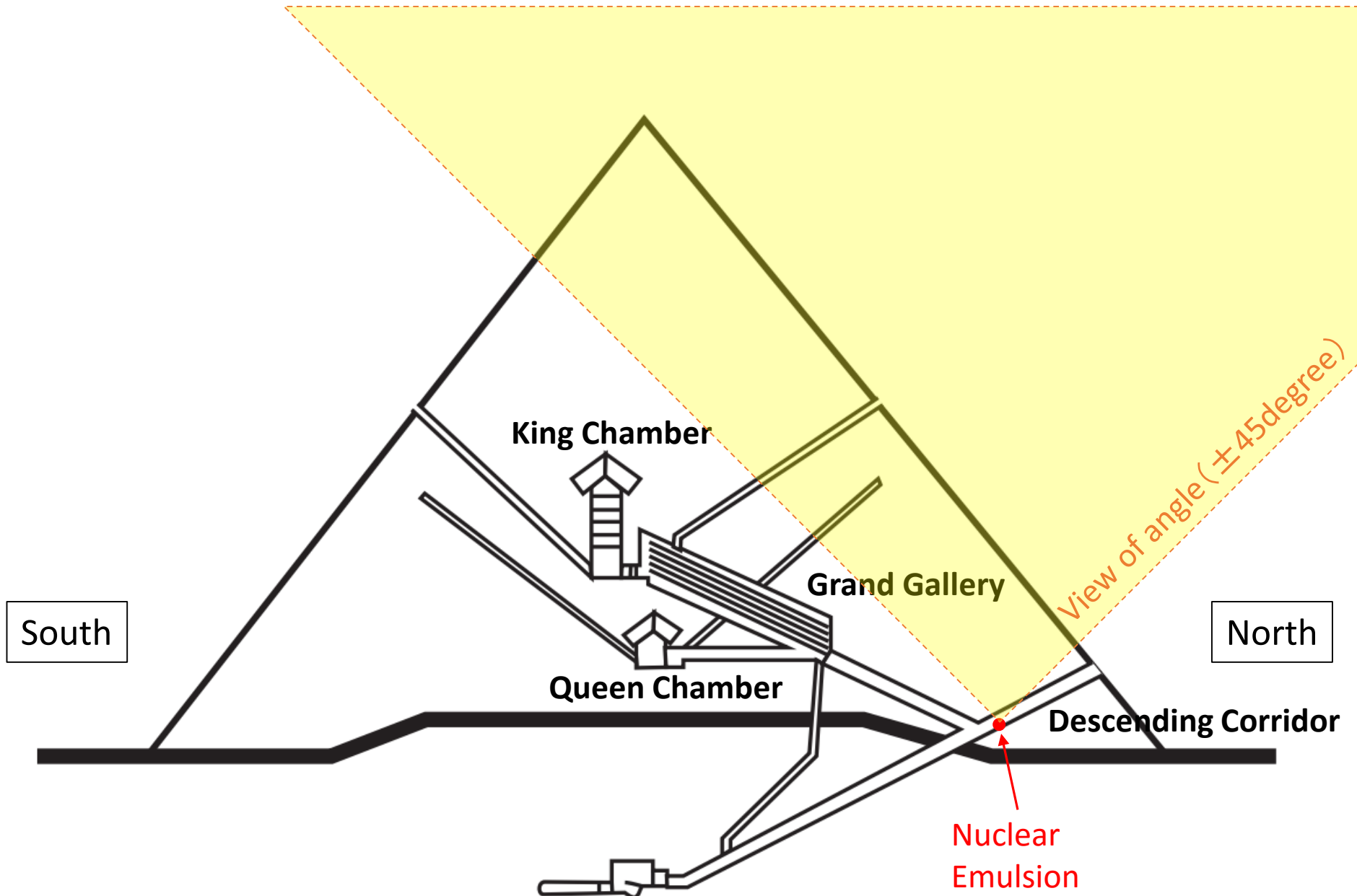


North



Fermilab will join soon ...

# Latest result of muography of descending corridor



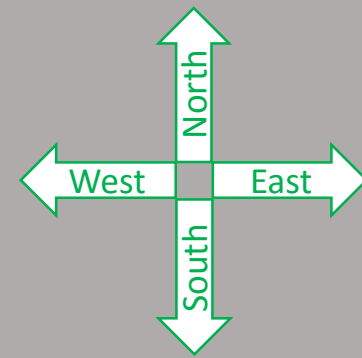
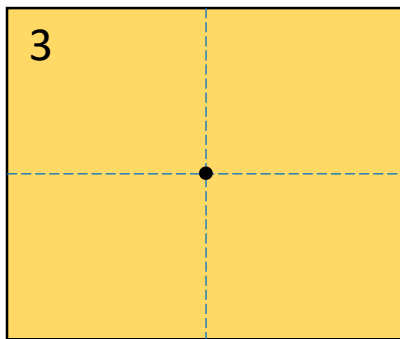
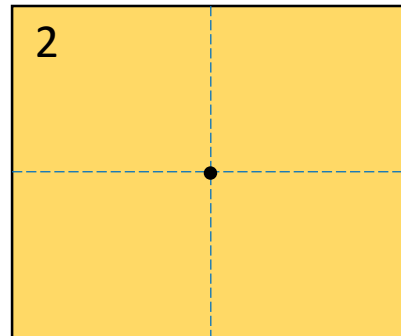
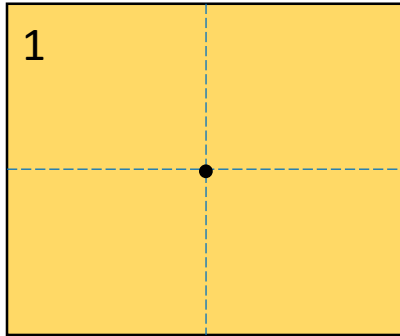
# Descending Corridor

A photograph of a descending corridor. The walls are made of rough, grey concrete. A wooden staircase with several steps leads down the center of the corridor. At the bottom of the frame, there are two large, rectangular metal plates mounted on a wooden frame. The plates are supported by several vertical metal rods. The lighting is dim, with a bright spot on the wall to the left.

- Installation : 1, Jun, 2016
- Collection : 7, Aug, 2016
- Observation period : 67 days
- Detection Area :  $0.075\text{m}^2/\text{plate}$

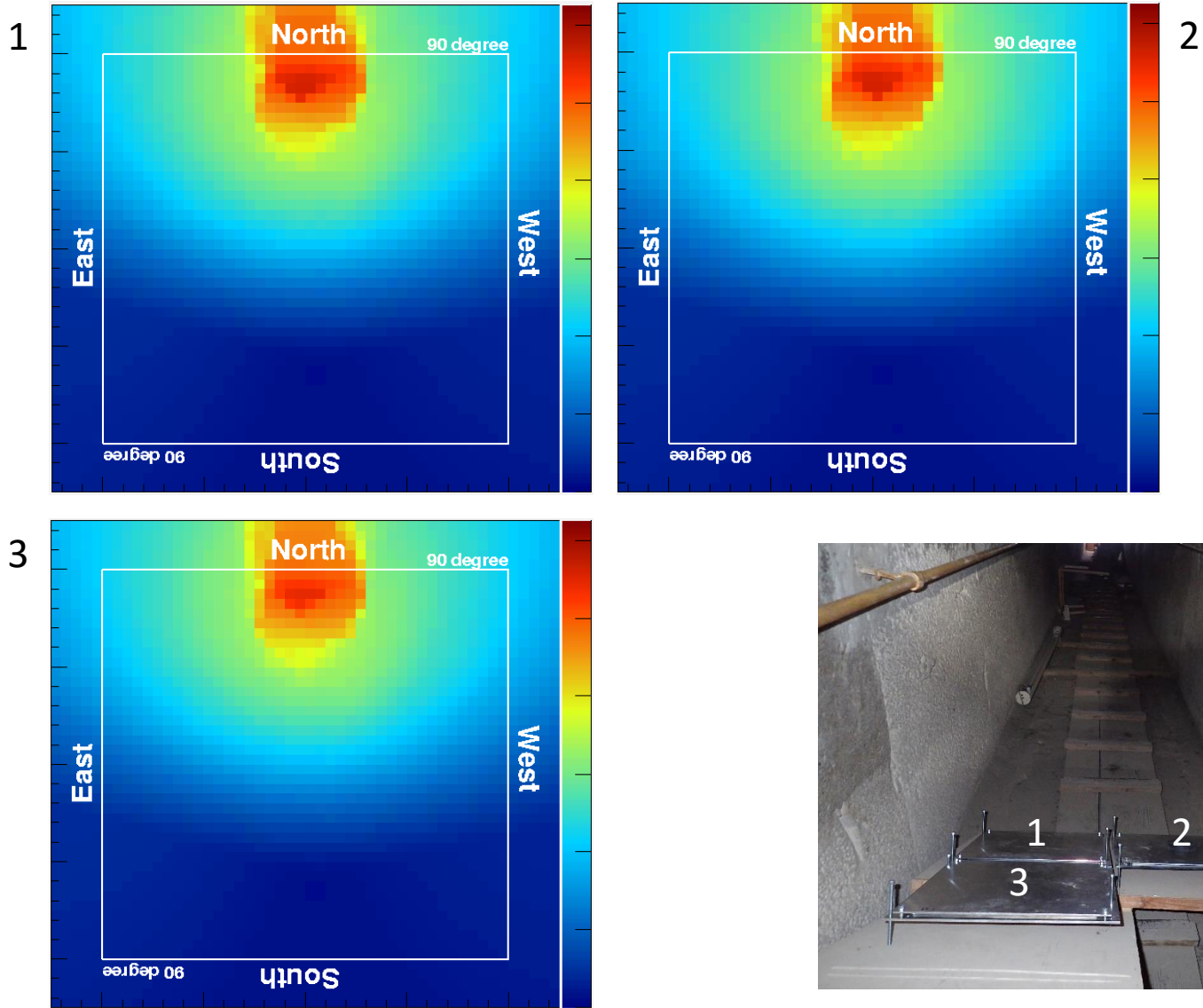
Width  $\sim 1\text{m}$   
Height  $\sim 1\text{m}$

# Detector Position

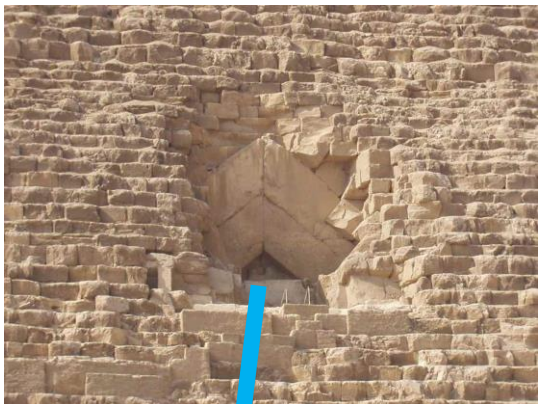




# Simulation results



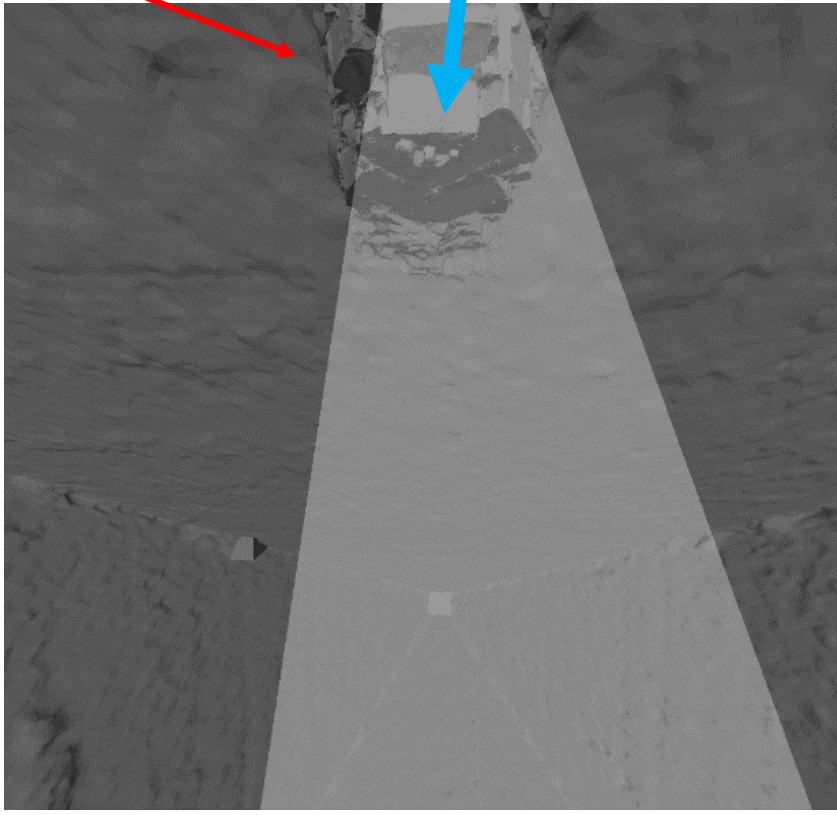
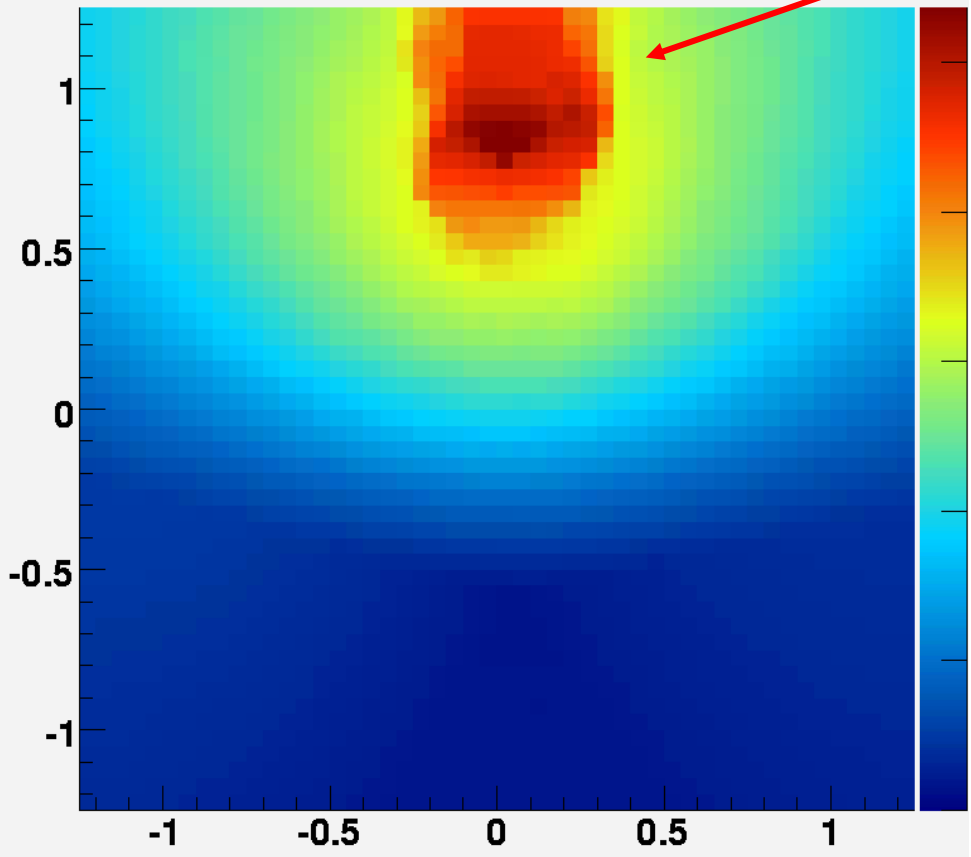
# Comparison between Simulation and 3D structure (CG)



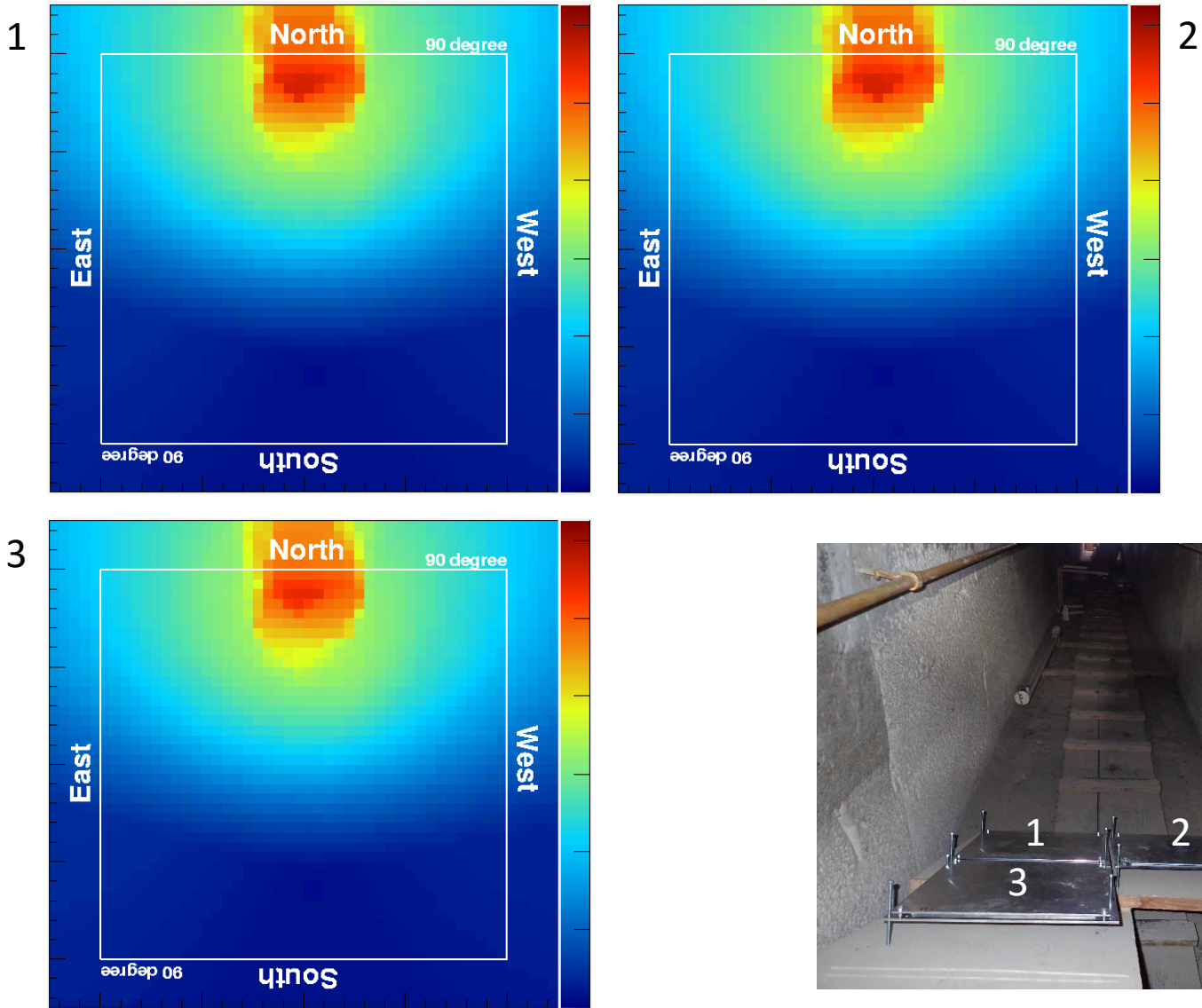
simulation

North entrance

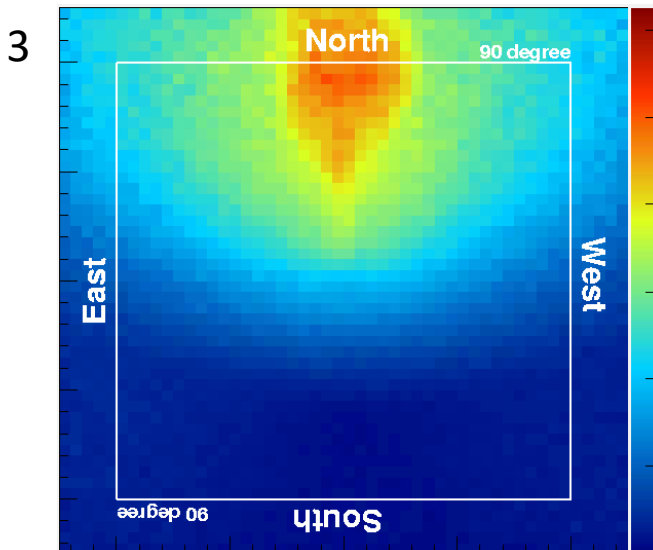
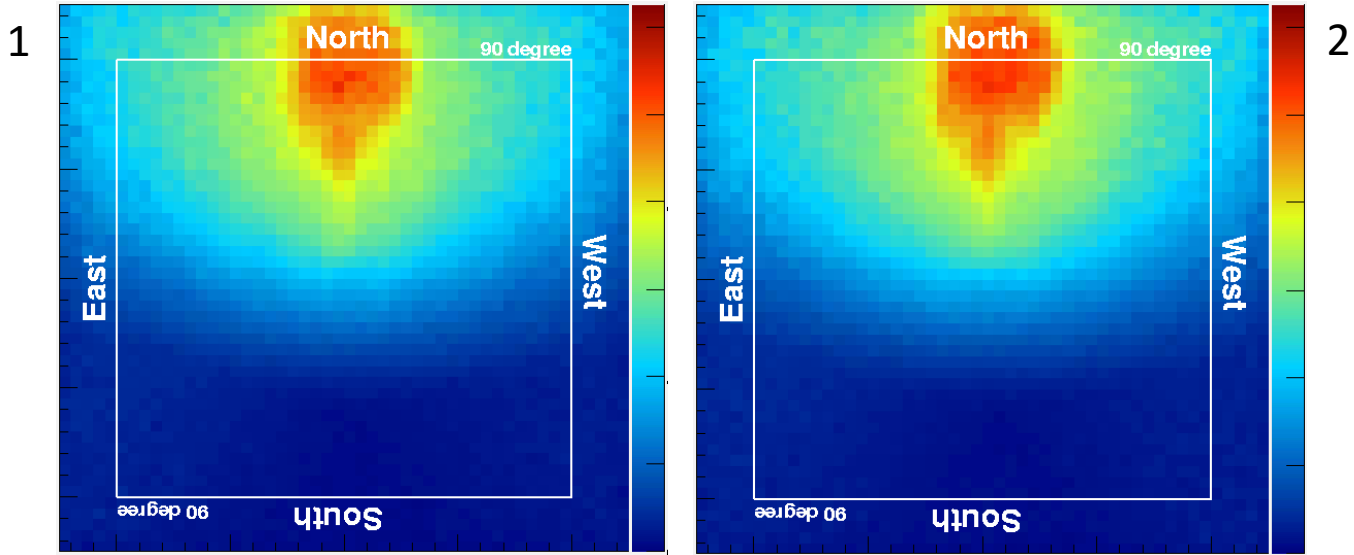
3D structure



# Simulation results



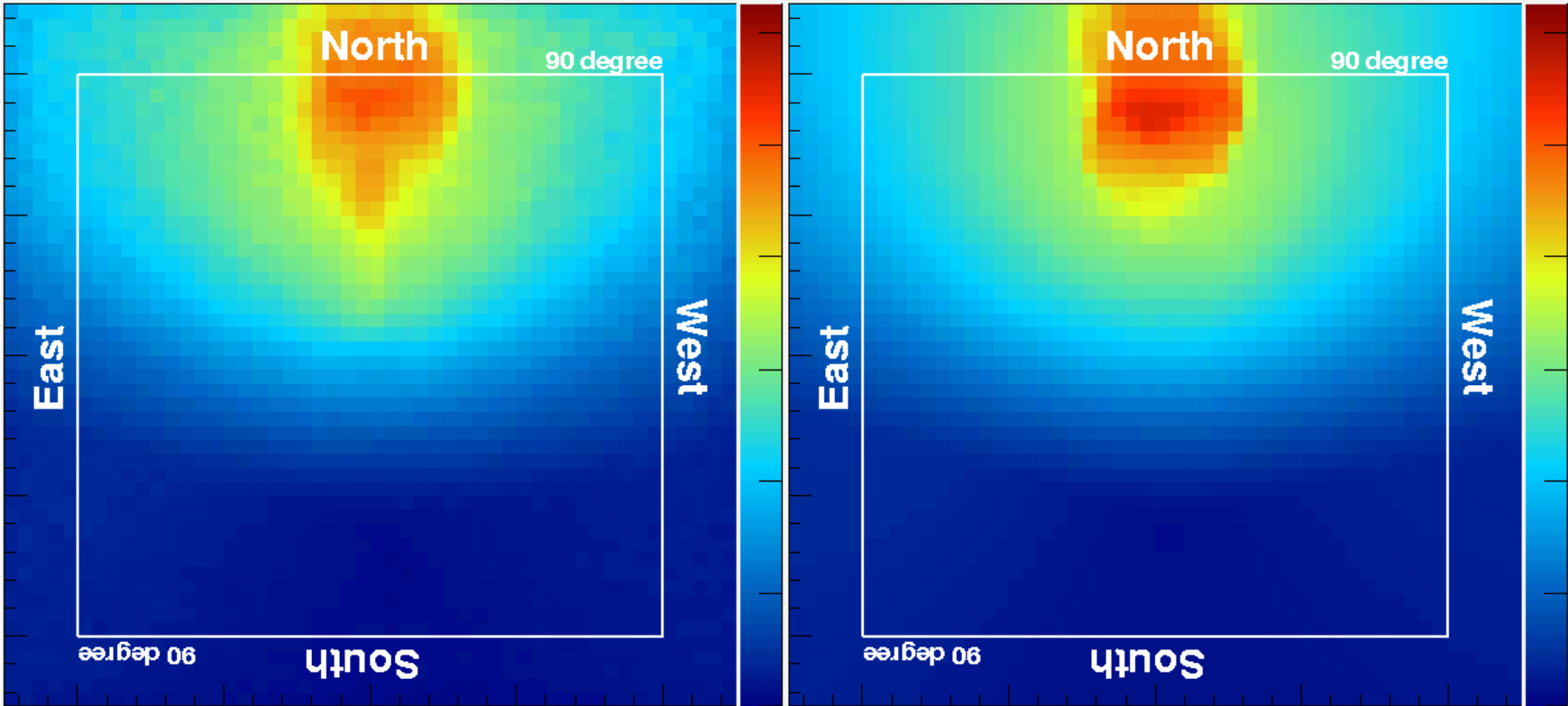
# Muography results



# Superimposed image by using 3 positions

Muography result

Simulation



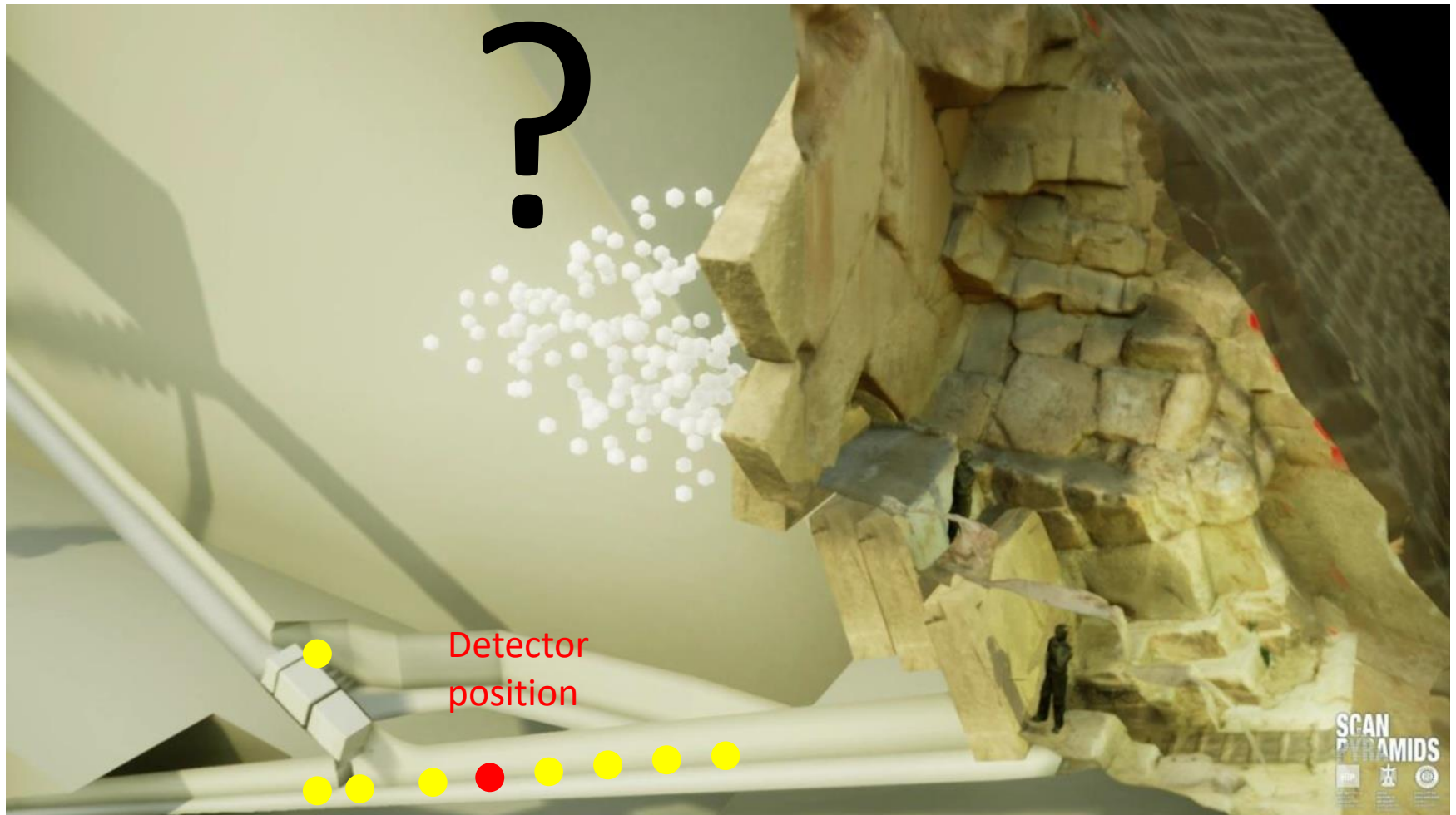
We found anomaly behind north face of Khufu's Pyramid

# Image of voids behind north face from ScanPyramids Press Release



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

# Image of voids behind north face from ScanPyramids Press Release



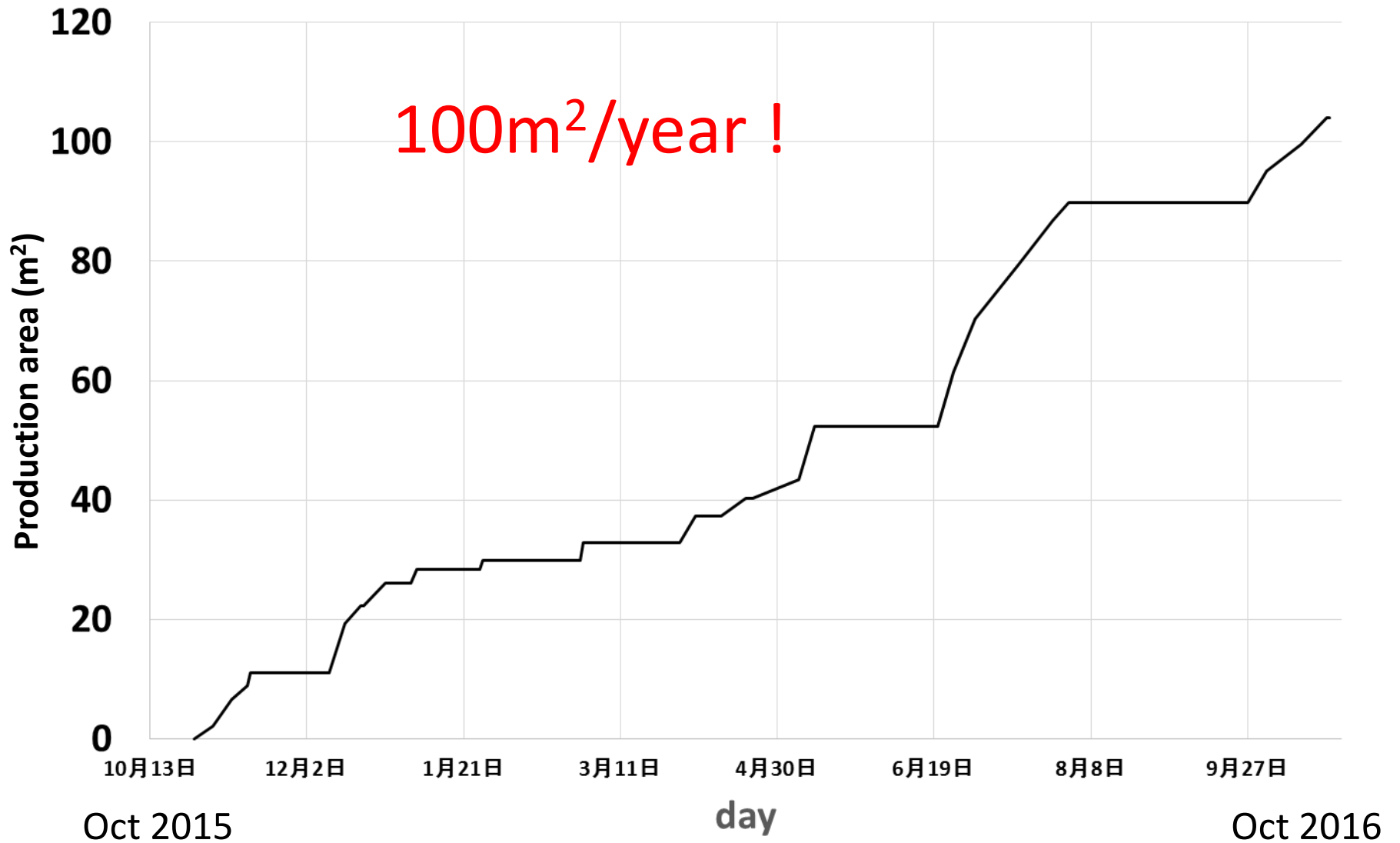
The precise size, shape and exact position of this space is now under future investigation



Additional measurement in Descending Corridor

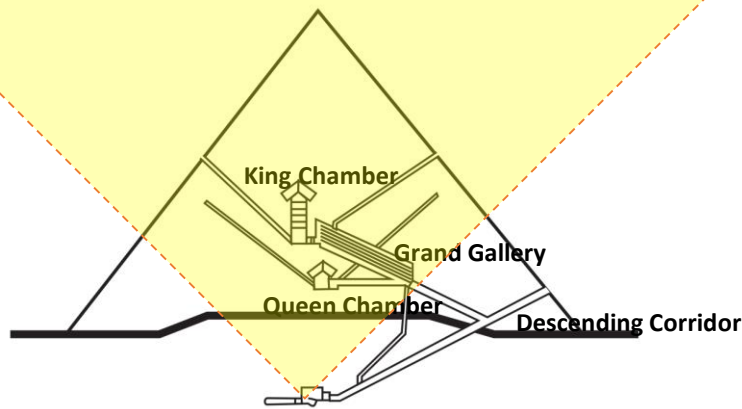


# Performance of Emulsion Production



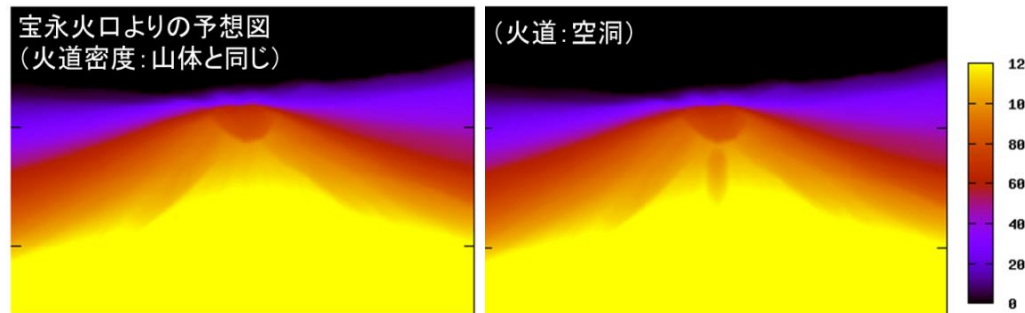
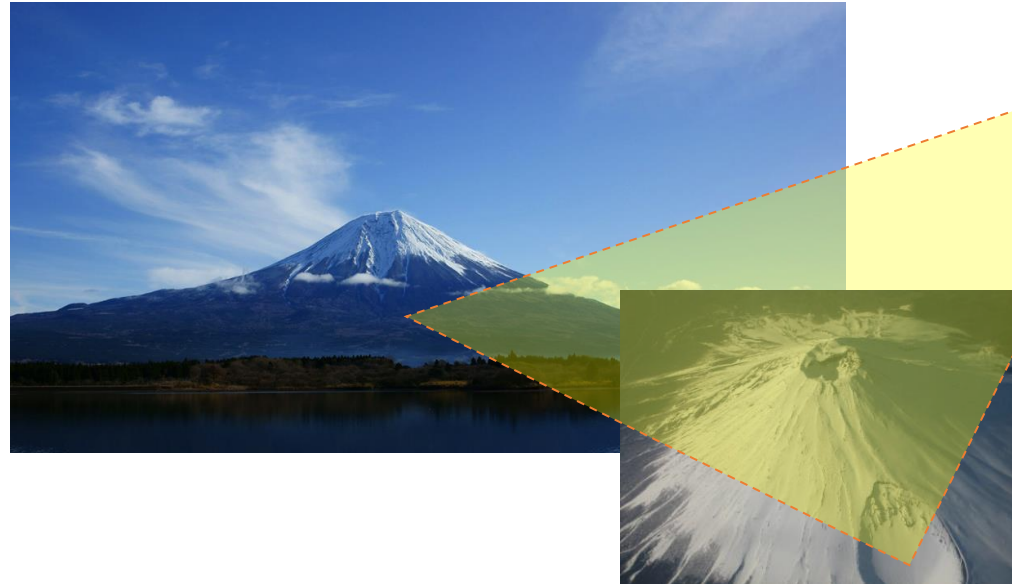
# Next step ...

## ScanPyramids



100 - 1000m<sup>2</sup>

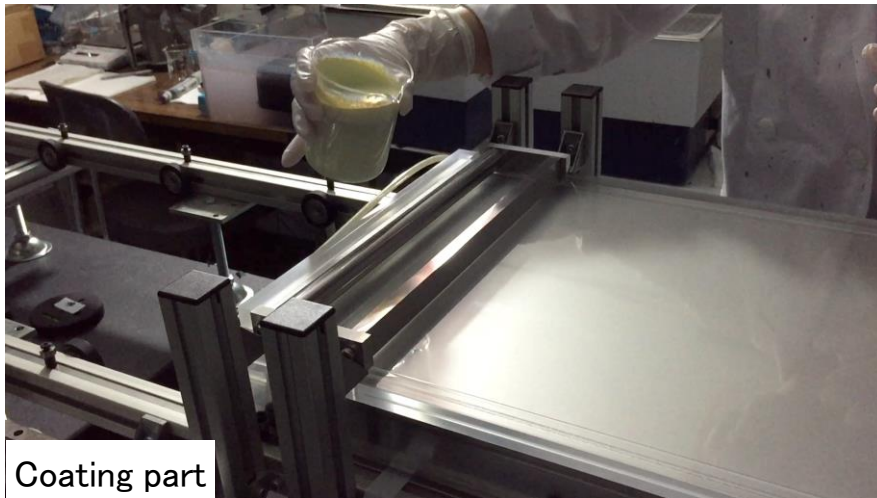
## Volcanoes : Mt. Fuji



1000 - m<sup>2</sup>

# Development of automated emulsion production system

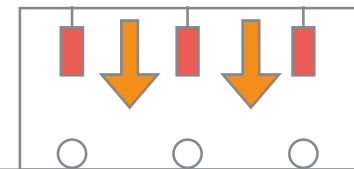
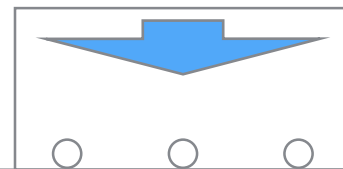
Under development



Coating part (1min)

Setting part (2min)

Drying part (7min)



20m<sup>2</sup>/week ~ 1000m<sup>2</sup>/year

Thickness uniformity <math>\pm 5 \mu\text{m}</math>

# Conclusions

- Scan Pyramids are international scientific collaborations
  - Egypt, France, Canada and Japan
  - Muography plays an important role in the project
- Muography of bent pyramid was successfully conducted by using nuclear emulsion
  - Upper chamber was clearly imaged
  - New unknown big chamber was not found
- Muography of Khufu pyramid is ongoing.
  - Anomaly was found behind north face
  - Additional measurement of north face is ongoing
  - Large area emulsion detector and KEK scintillator detector in Queen Chamber are on going
- Development of automated emulsion coating system
- Analysis of Cosmic-ray events