Muographic Detection of Voids within Khufu’s Pyramid

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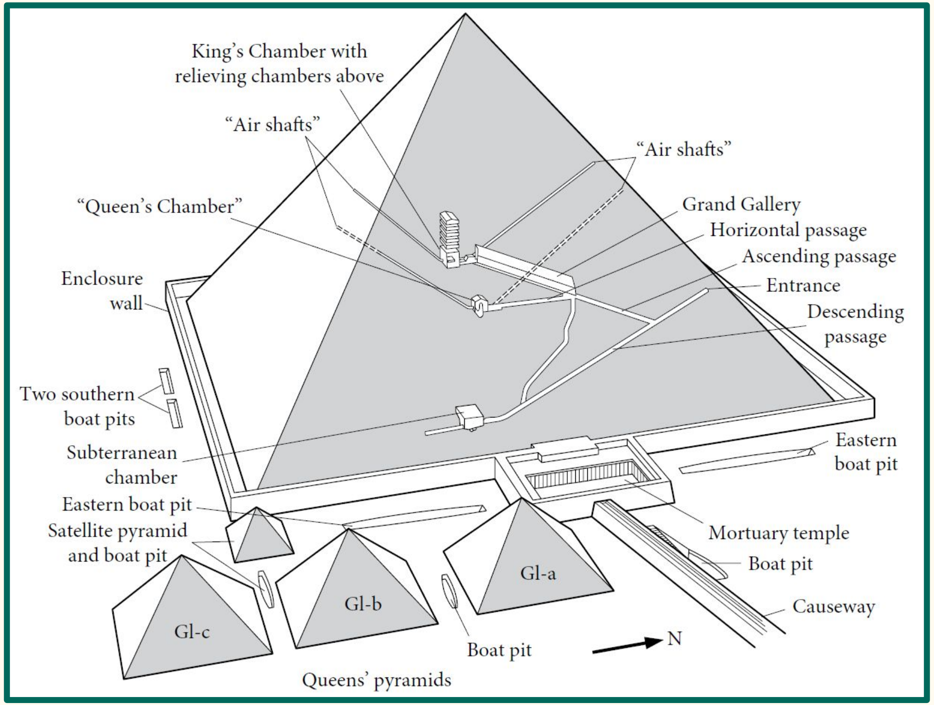
Khufu’s Pyramid

- Khufu, son of Sneferu (OK 4th Dynasty)
- Part of the first pyramid complex at Giza
- Impressive size and precise construction
    - ~2.3 million blocks of limestone laid in horizontal courses with gypsum mortar
    - Sides of length 230.3 m
        - 0.044 m deviation
    - Aligned to the cardinal points
        - ~0.05°deviation
- Known internal structure
    - Subterranean chamber
    - Descending passage
    - Tunnel of Caliph al-Ma’mun
    - Ascending passage
    - Horizontal passage
    - “Queen’s Chamber”: new subterranean tomb(?)
    - Grand Gallery
    - King’s Chamber
    - Five stress-relieving chambers
    - “Air shafts”: symbolic route for king’s spirit(?)



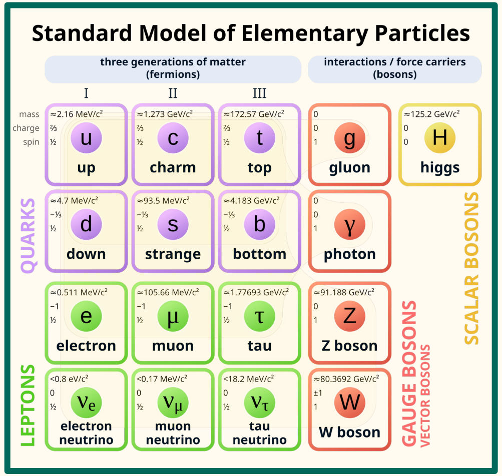
Khufu’s Pyramid Complex at Giza.
From Lehner, Mark. "The Complete Pyramids." drawn by Philip Winton, p. 108. London and New York: Thames & Hudson, 1997.

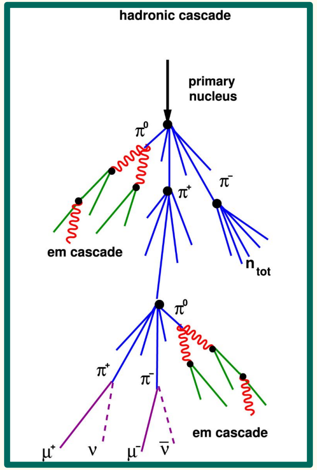
Historical Sources

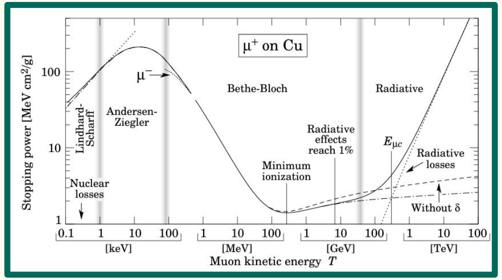
- *P. Jarf*
  - 2013 discovery at Wadi el-Jarf, a Red Sea harbor used to access Sinai copper/turquoise mines
  - Accounts of delivered commodities and logbooks
    - Recorded by *sḥḏ* "inspector (lit. one makes white = illuminator)" Merer
    - Important evidence for the transport of fine limestone from Tura used for casing
- Herodotus' *Histories*
  - "Herodotus Machine": machine or series of machines for raising stones up successive steps
- Unknown corridor running parallel to the horizontal corridor (?)
  - 1986 microgravimetry survey: unsuccessful and found sand
  - 1988 ground-penetrating radar survey: no further conclusions

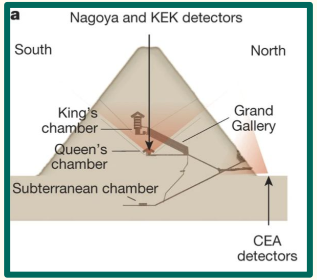
Physical Background: Cosmic Ray Muons

- **Muon (μ):** type of elementary particle in the Standard Model
  - Similar to an electron but more massive
- **Cosmic Ray:** primary cosmic ray (relativistic nuclei > electrons ≫ antimatter) triggers secondary particle shower
- Appreciable muon flux reaching Earth: $\sim 10{,}000 \frac{\text{muon}}{\text{m}^2 \cdot \text{min}}$
  - Decay mediated by only the weak interaction- not the strong or electromagnetic interactions- so relatively long rest-frame half-life
  - Plus, significant relativistic effects (relative velocity time dilation)
- **Stopping power:** loss of energy with penetration distance
  - Nuclear, electronic, and radiative stopping powers
    - Most important factor depends on energy regime
  - Less dense regions have lower magnitude stopping powers
  - ~1% of incident muons still can get to the Queen's Chamber
    - *Bremsstrahlung* radiative power loss $\propto$ m^{-6}
- Idea: non-invasive **muon tomography = "muongraphy"**
  - Detectors measure muon flux to see how many muons get through, and if there are more than would be expected with the limestone in the way, there must have been a cavity









Sources: see references at the end of presentation.

Cosmic-Ray Muon Imaging Techniques

Three independent techniques were used to confirm the detection of the large void above the Grand Gallery:

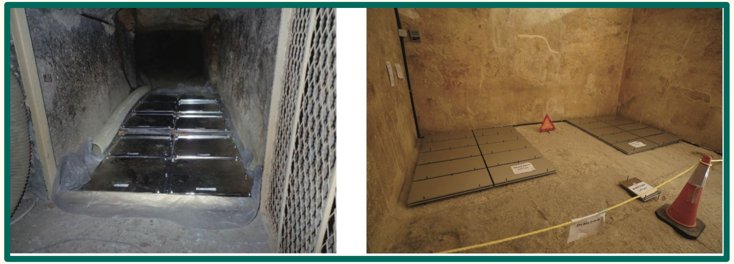
- Nuclear Emulsion Films
- Scintillator Hodoscopes
- Micropattern Gaseous Detectors

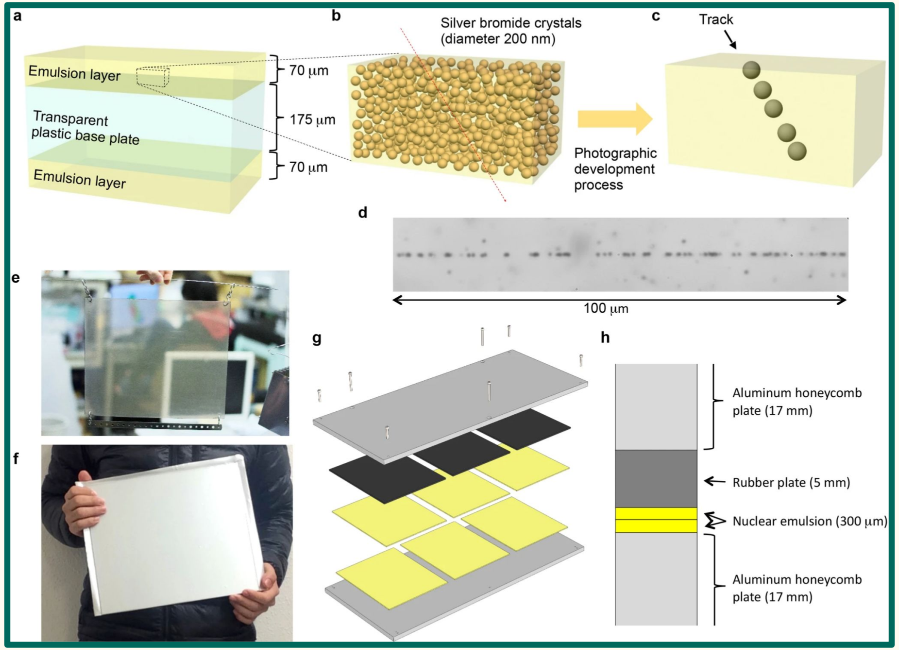
	Nuclear emulsion *Nagoya University*	**Hodoscopes** *KEK*	**Gas detectors** *CEA*
Angular Resolution	2-14mrad	7-10 mrad	0.8 - 4 mrad
Angular Acceptance	45 degrees	34 - 45 degrees	45 degrees
Active area (for this analysis)	30 cm x 25 cm / unit: 0.75 m x 0.6 m (NE1) 0.9 m x 0.5 m (NE2)	1.2 m x 1.2 m	50 cm x 50 cm
Position Resolution	1 μm	10 mm	400 μm
Height	0.2 mm	1-1.5 m	60 cm
Power requirement	No	Yes (300W)	Yes (35W)
Data taking	Need development	Real time	Real time

Extended Data Table 1: Comparison of the three muon detection technologies.
From Morishima, Kunihiro, Mitsuaki Kuno, Akira Nishio, Nobuko Kitagawa, Yuta Manabe, Masaki Moto, Fumihiko Takasaki, et al. "Discovery of a Big Void in Khufu's Pyramid by Observation of Cosmic-Ray Muons." Nature 552, no. 7685 (2017/12/01 2017): 386-90. https://doi.org/10.1038/nature24647. https://doi.org/10.1038/nature24647.

Nuclear Emulsion Films

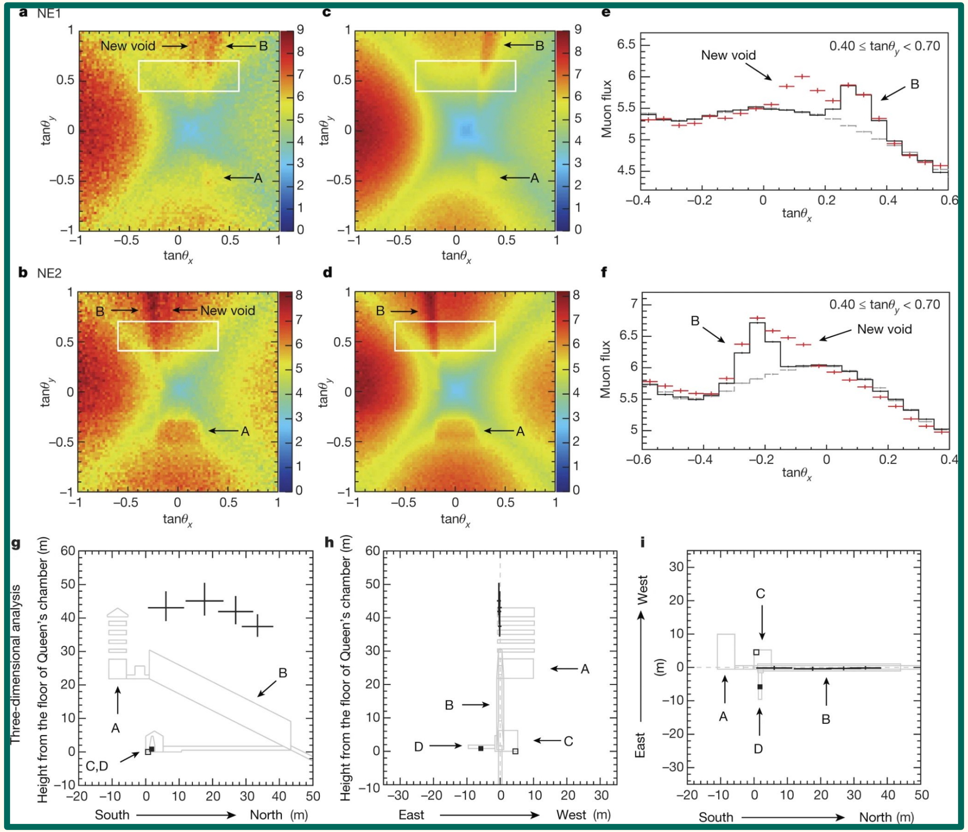
- Polystyrene plastic base coated on both sides with an emulsion layer, a suspension of crystalline AgBr grains in gelatin
- Capable of revealing 3D trajectory of muons with micrometer precision
  - Frenkel defects and electron traps lead to reduction of Ag^+
- Placed in the Queen's Chamber (NE1 = the "Niche", NE2) (right/left, below)





Extended Data Figure 1: Overview of the nuclear emulsion films (Nagoya University).
From "Discovery of a Big Void in Khufu's Pyramid by Observation of Cosmic-Ray Muons."

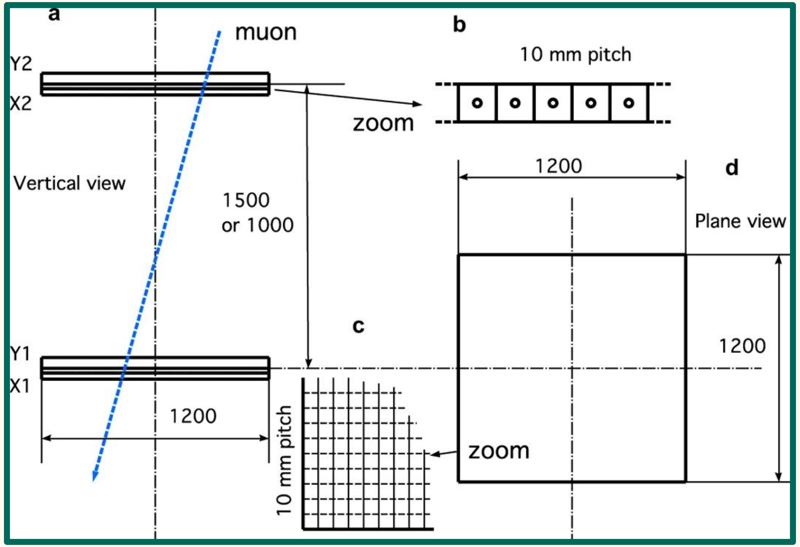
Nuclear Emulsion Films Results



- Accurately detects known internal structures
  - A: King's Chamber
  - B: Grand Gallery
- But also suggests that there is an unknown void above the Grand Gallery of a comparable size

Figure 2: Results of the analysis of the nuclear emulsion films.
From "Discovery of a Big Void in Khufu's Pyramid by Observation of Cosmic-Ray Muons."

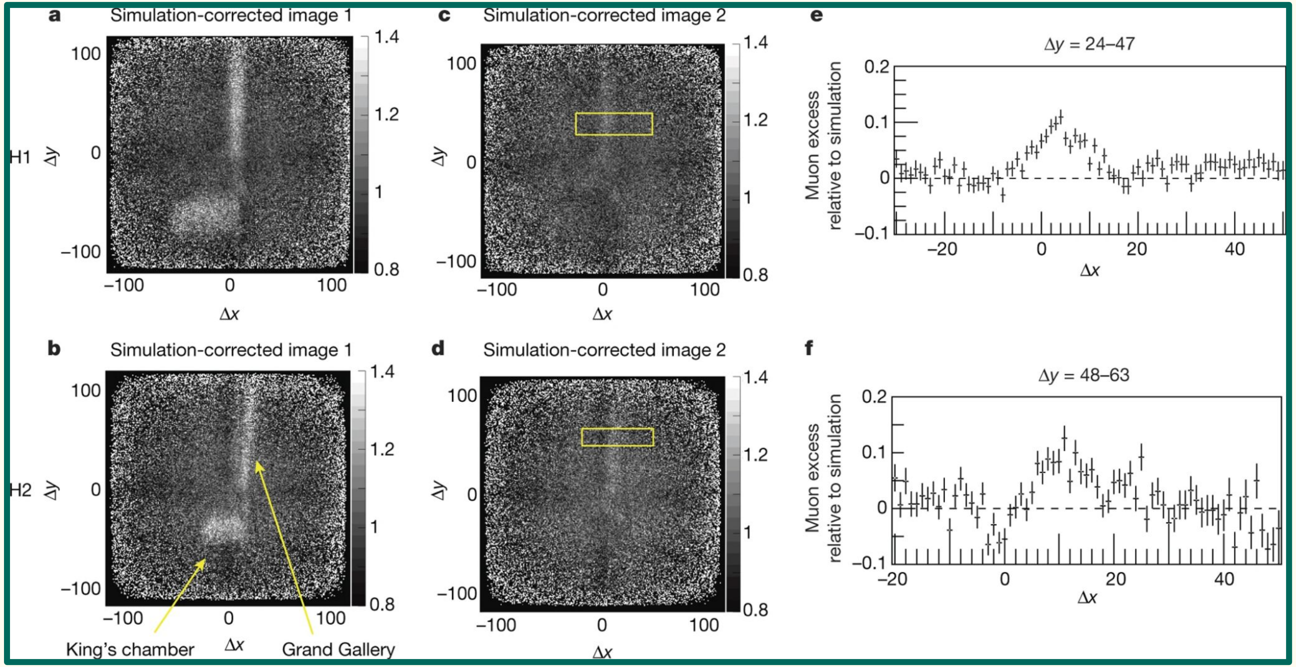
Scintillator Hodoscopes



Extended Data Figure 3: Overview of the scintillator hodoscopes (KEK).
From "Discovery of a Big Void in Khufu's Pyramid by Observation of Cosmic-Ray Muons."

- Scintillator: material that luminescences with ionizing radiation
  - Scintillator light can then be turned into an electric signal via the photoelectric effect
  - Amplification of signal with photomultiplier within the photon counter sensor

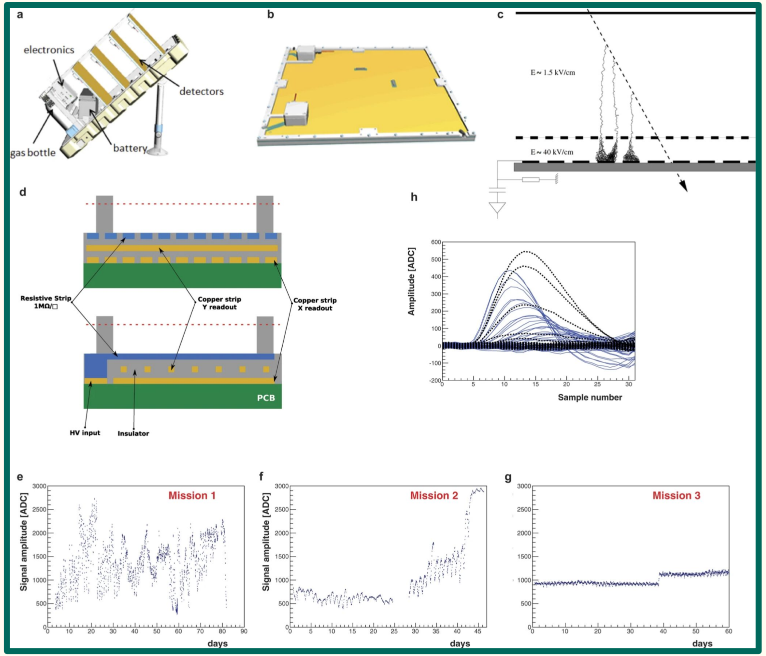
Scintillator Hodoscopes Results



- Corroborates the results of nuclear emulsion experiment
  - Simulations with and without known internal structure as in NE

Figure 3: Results of the analysis of the scintillation hodoscopes.
From "Discovery of a Big Void in Khufu's Pyramid by Observation of Cosmic-Ray Muons."

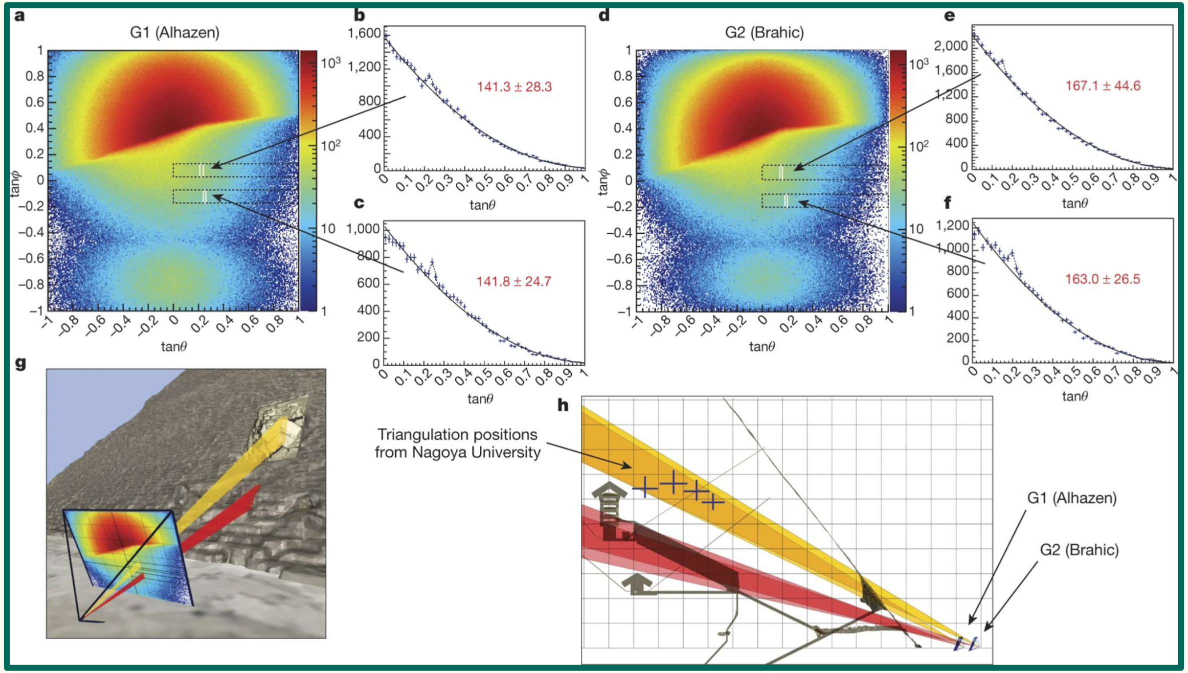
Micropattern Gaseous Detectors



- Micropattern Gaseous Detector: chamber filled with $Ar–iC_4H_{10}–CF_4$, non-flammable gas mixture (95-2–3)
- Ionization due to relativistic muons and application of an external electric field leads to an **avalanche process** and a strong electronic signal

Figure 5: Overview of the gas detectors (CEA).
From "Discovery of a Big Void in Khufu's Pyramid by Observation of Cosmic-Ray Muons."

Micropattern Gaseous Detectors Results



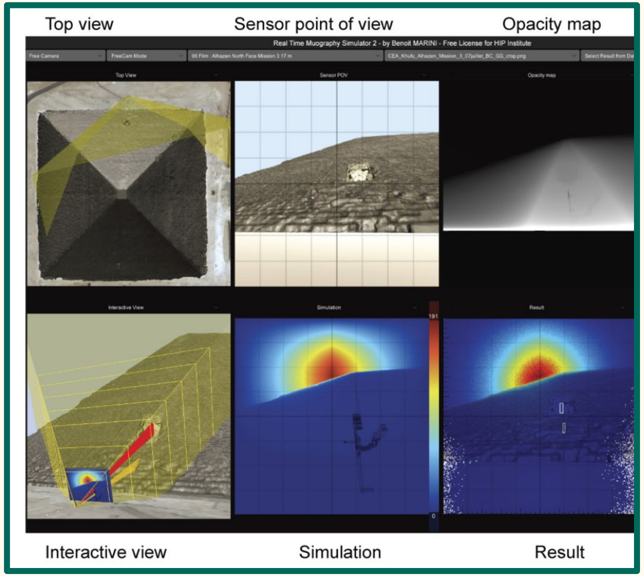
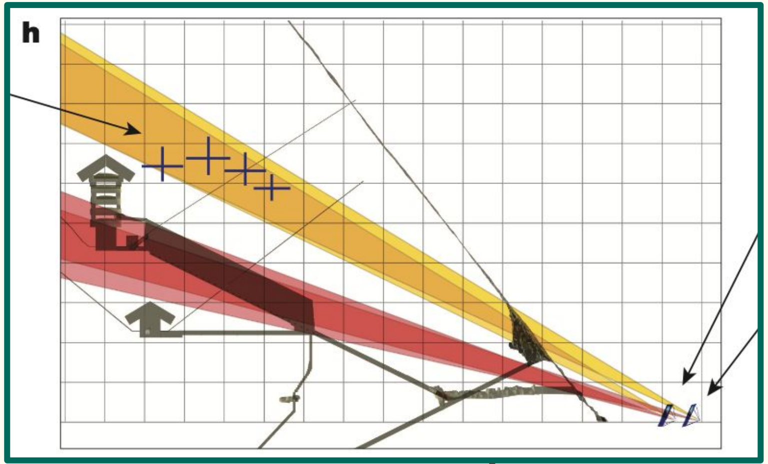


Figure 4: Results of the analysis of the gas detectors
Extended Data Figure 7: RTMS and 3D models
From "Discovery of a Big Void in Khufu's Pyramid by Observation of Cosmic-Ray Muons."

Conclusion

- Three techniques of cosmic-ray muon imaging were applied to investigate the inner structure of the pyramid.
- The known voids (the King’s chamber and the Grand Gallery) were observed, as well as an unexpected big void
- Still many architectural hypotheses to consider; big void could consist of one or several adjacent voids, and it could be inclined or horizontal



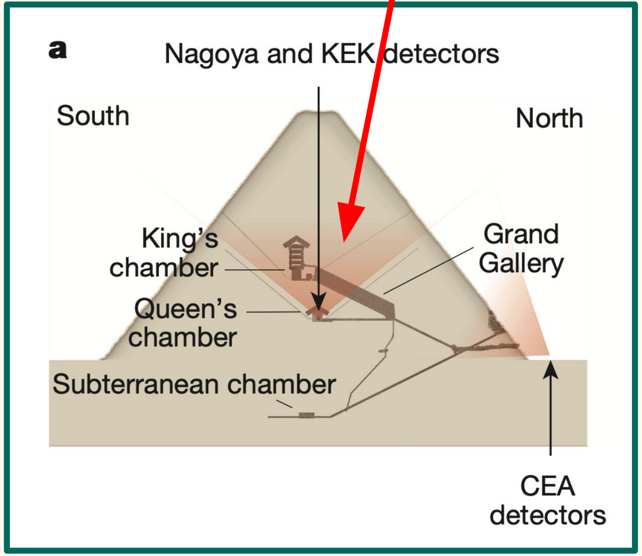
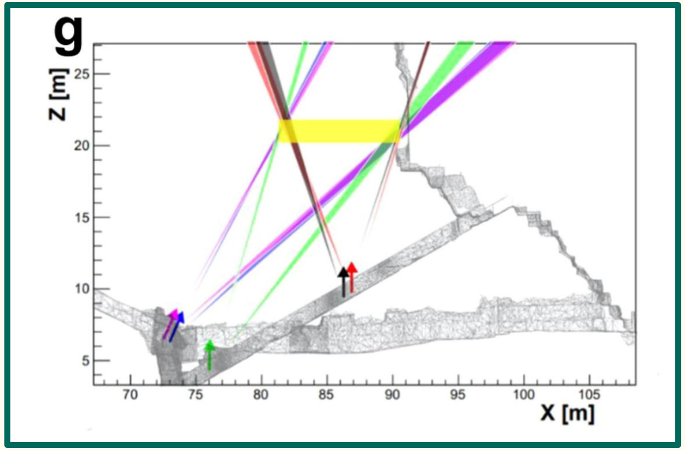
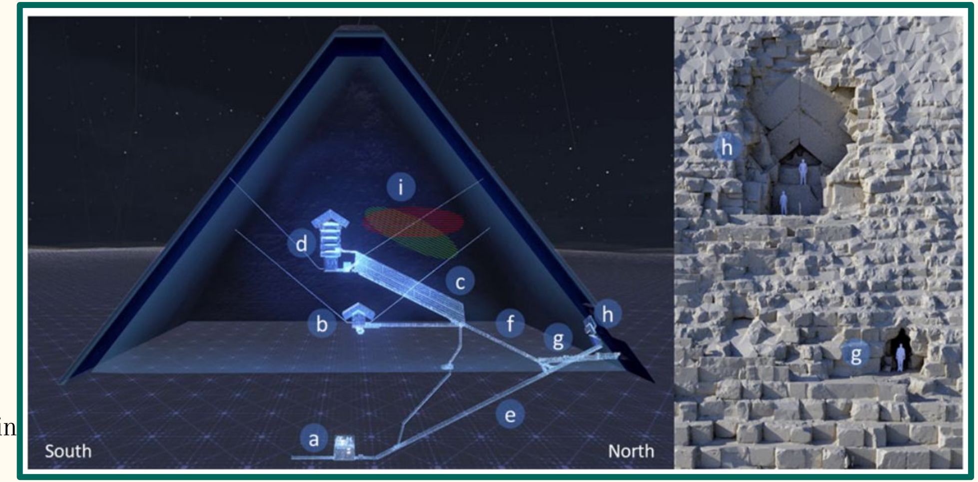


Figure 4: Results of the analysis of the gas detector
Figure 1: Muon detectors installed for Khufu’s Pyramid
From "Discovery of a Big Void in Khufu’s Pyramid by Observation of Cosmic-Ray Muons."

Second Article

- Published 2023
- Utilized nuclear emulsion films and gaseous detectors
- Exact shape and size of NFC (ScanPyramids North Face Corridor) determined
- Structure of about 9 m length with a transverse section of about 2.0 m by 2.0 m (more complex shapes than a simple parallelepiped are possible, but with the same mean height and width)
- Void has larger cross-section than the other pyramid corridors; may aid in determining the role of the Northern Chevron





From "Precise characterization of a corridor-shaped structure in Khufu's Pyramid by observation of cosmic-ray muons."

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" sḥḏ " (Lemma ID 856130) <https://thesaurus-linguae-aegyptiae.de/lemma/856130> , edited by Altägyptisches Wörterbuch , with the collaboration of Andrea Sinclair , in: Thesaurus Linguae Aegyptiae , Corpus Edition 18, Web App Version 2.1.5, July 26, 2024, edited by Tonio Sebastian Richter & Daniel A. Werning on behalf of the Berlin-Brandenburg Academy of Sciences and Humanities and Hans-Werner Fischer-Elfert & Peter Dils on behalf of the Saxon Academy of Sciences in Leipzig (accessed on: September 17, 2024)