

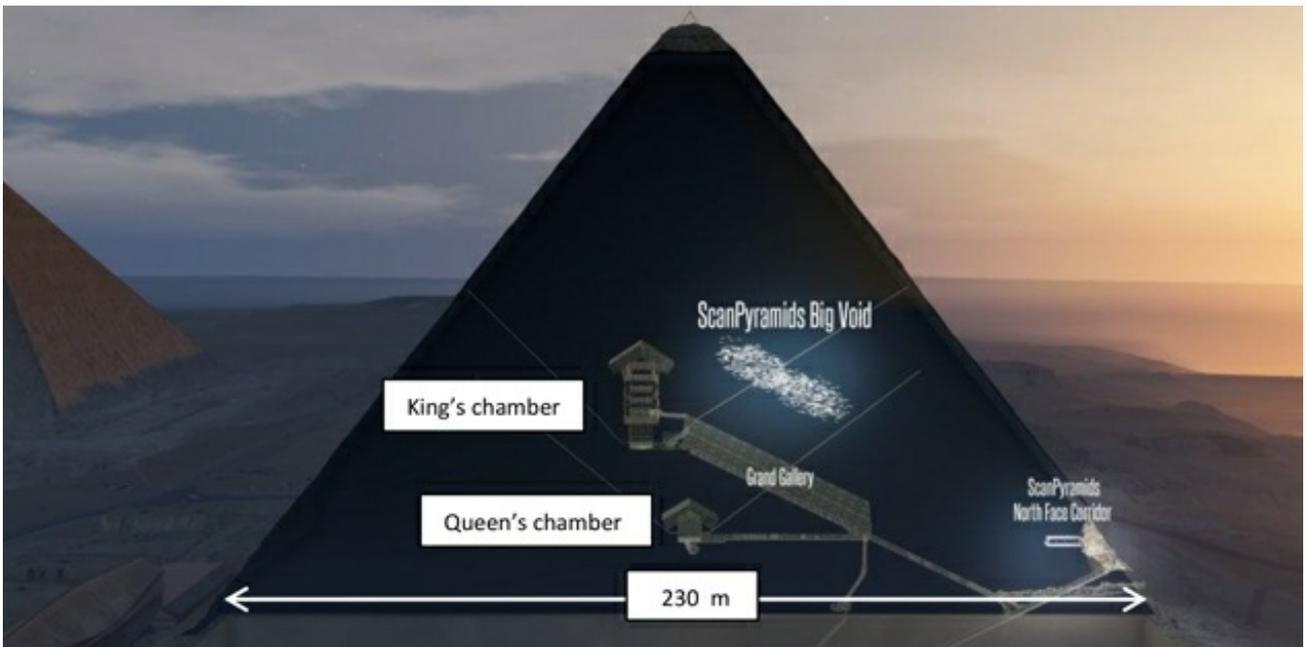
# Muons unveil the secrets of a pyramid

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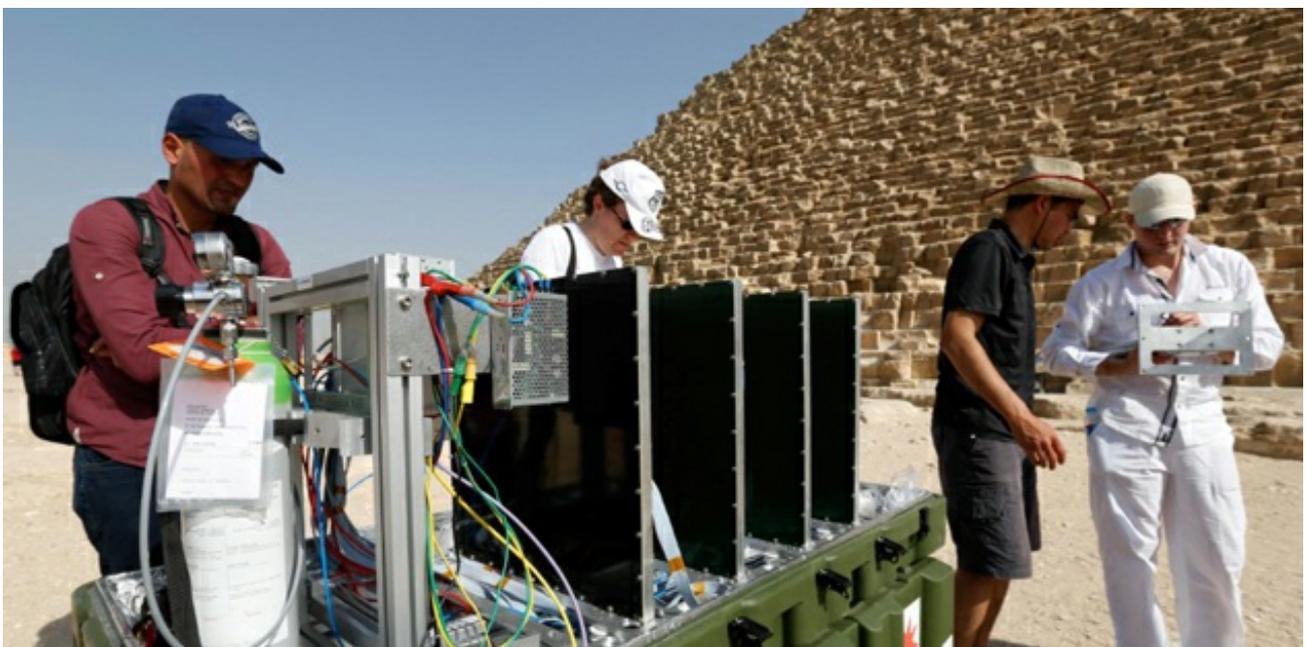
There is currently no answer to I.I. Rabi's famous question "Who ordered that?", yet muons have made numerous and notable contributions to research. The latest was published online in Nature on November 2nd, 2017. An Egyptian-French-Japanese (Nagoya-KEK-CEA-Cairo-Dassault-Systèmes) collaboration observed a "Big Void" hidden in Khufu's pyramid using various types of cosmic-ray muon detectors.

The pyramids at Giza are 4500 years old and many of their secrets are yet to be discovered, starting with how they were built. Given the volume of Khufu's pyramid, about 2.5 million m<sup>3</sup>, and the time span over which it was built, presumably 20 years during Khufu's reign, in the XXVI century BC, the builders had to place roughly 900 tons of stone on average per day: bringing the stones up as it became taller must have been extremely challenging. Recently, fragments of papyrus have enabled us to uncover the complex logistics set up, during the early bronze age, to carry to the construction site stone blocks not quarried locally (limestone for the bulk), from tens of kilometres away (limestone for the outside casing) and in some cases from hundreds of kilometres away (granite for the inner chambers). The construction method remains, as yet, unknown, even though theories, implying different kinds of ramps, are abundant. What remains unknown, for instance, is whether, in addition to galleries and rooms already known, there were other galleries used to slip the stone blocks in place or other hidden rooms. A first search for cavities hidden in Khafre's pyramid was performed with a muon detector by Louis Alvarez and his co-workers at the end of the 1960s and had a negative outcome. The ScanPyramids project began in 2015 as collaboration between Egyptians and researchers from an international team: French physicists from the Heritage Innovation and Preservation Institute led by Mehdi Tanjoub and Japanese elementary particle physicists led by Konihiro Morishima. The project involves using different non-invasive techniques (drone surveys, IR thermography, muon absorption) to investigate the internal structure of the pyramid. Thermal anomalies were reported more than a year ago, suggesting the existence of voids close to the surface of the pyramid, and one year ago the first evidence for a big void was reported by the teams using muon absorption. Now the existence of a large void has been independently validated with three different types of muon detectors: nuclear emulsions, plastic scintillator hodoscopes, gas detectors of the micromegas type, which all have different acceptances, resolutions and systematic uncertainties.



Section of Khufu's pyramid showing access corridors, Grand Gallery, King's and Queen's chambers, and four air shafts, with the approximate location of the big void detected by the ScanPyramids team superimposed. The pyramid base is 230 m wide, and its present height is 139 m. (Credits: ScanPyramids).

The void has a length of at least 30 m, comparable in size to the Grand Gallery, and is located roughly 40-50 m away from the nuclear emulsions and scintillator hodoscopes positioned in the Queen's chamber. Stereo views have been obtained by having detectors in various positions. The micromegas detectors were instead positioned outside the pyramid (this is the first time in a pyramid scan), and confirmed the findings of the inside detectors.



CEA detector comprising four planes of micromegas during installation in front of the north face of Khufu's pyramid, about 20 m from the base. One detector was pointing in the direction of the Grand Gallery, another in the approximate direction of the new void, as estimated from data collected with nuclear emulsions. This arrangement permits evidence for the new void based on raw data only to be obtained, independent of detailed modelling of the pyramid internal and external structure. (Credits: ScanPyramids).

Like other findings in research, the newly discovered void just pushes the frontier of our ignorance

a bit further, and opens up plenty of new questions. This success follows a long series of surveys of small and large structures, some performed by Italian teams of the Ministry of Education, University and Research (MIUR), of the National Institute for Nuclear Physics (INFN) and the National Institute of Geophysics and Volcanology (INGV), from volcanoes (pioneered by Kanetada Nagamine) to reactor cores, from other pyramids and heritage buildings to containers, which were accomplished during the last twenty years using diffusion and absorption of cosmic-ray muons.

Homepage: The pyramids at Giza with, at the front, the small pyramids of Queens: left (west), Menkaure, the smallest of the large ones; centre, Khafre, showing remaining parts of limestone casing at the top; right (east), Khufu, the Great Pyramid, the oldest and the largest. (Courtesy of Janice Navarria).