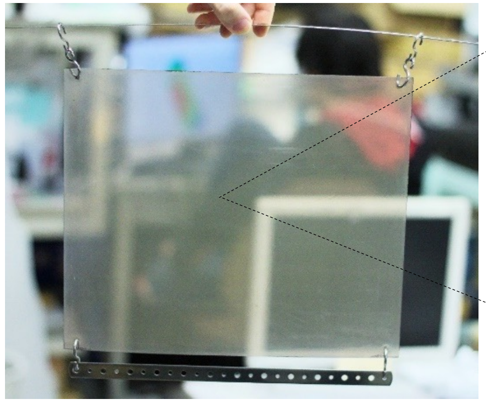
Cosmic-Ray Muon Imaging with Nucler Emulsions

Kunihiro Morishima
Nagoya University

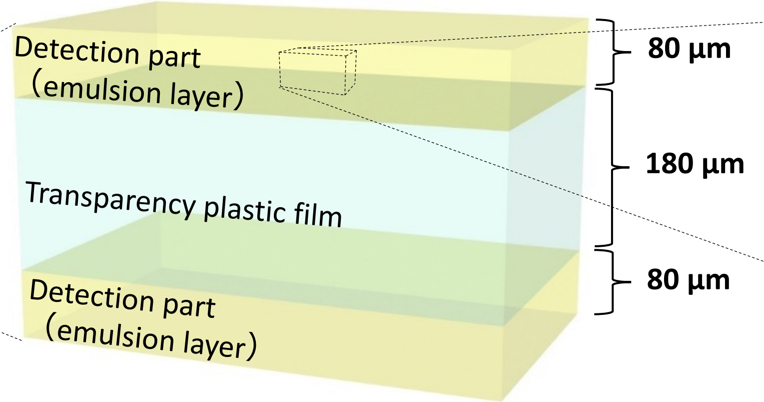
Nuclear Emulsions

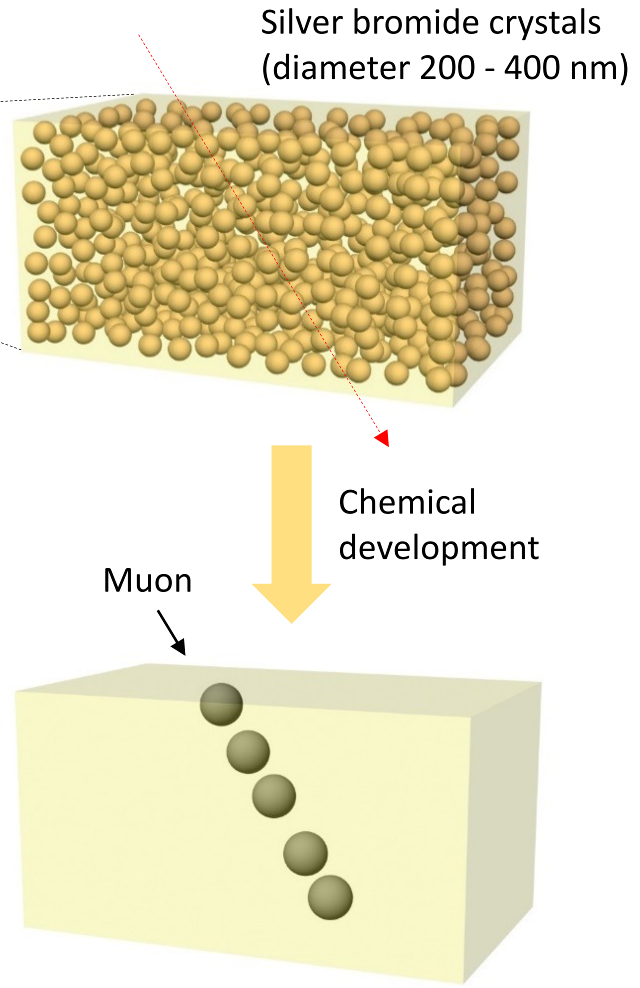
Three dimensional Tracking Detector for charged particles

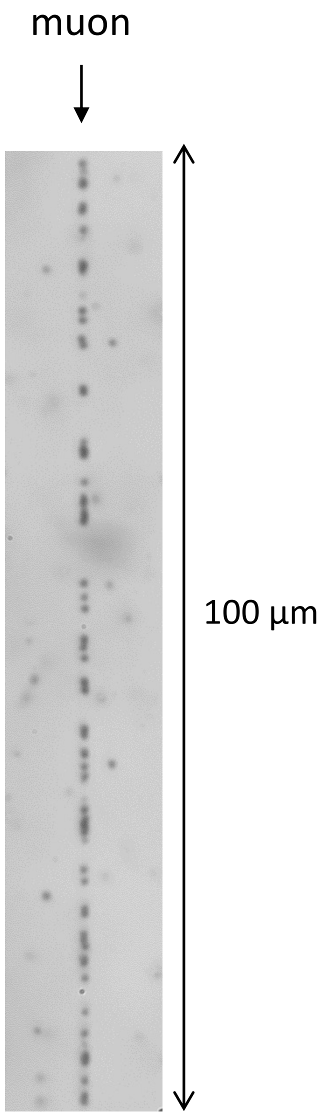
Nuclear Emulsion
after chemical development



Cross section in three dimension







Optical microscope
image of muon trajectory

Important Features

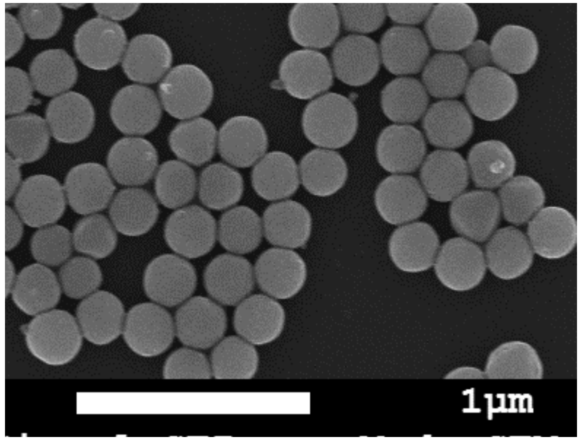
1. The angular measurement accuracy of mrad obtained from sub-micron position accuracy in three dimensions.
2. In principle, it is possible to measure in all directions.
3. No power supply is required, light weight, thin and compact, and the package is highly waterproof and dustproof. These features make it easy to carry and install in any location.
4. It is easy to manufacture in large quantities, which makes it possible to realize large-area detectors and to set up detectors at the same time to observe a single object from multiple directions.

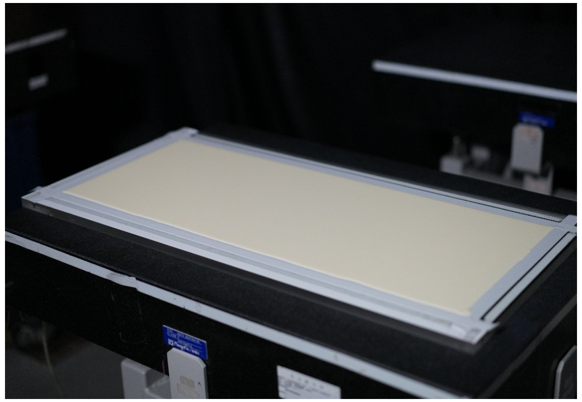
Development and Production of Nuclear Emulsion at Nagoya University

Nuclear emulsion films are produced at Nagoya University using dedicated production equipment.

The emulsion is produced and coated onto the film base in-house

Coating is now also being mechanized





Development of Nuclear Emulsion

The disappearance of latent images of tracks before development, caused by aging, is a major issue
This is especially significant in outdoor environments where the temperature exceeds 30°C

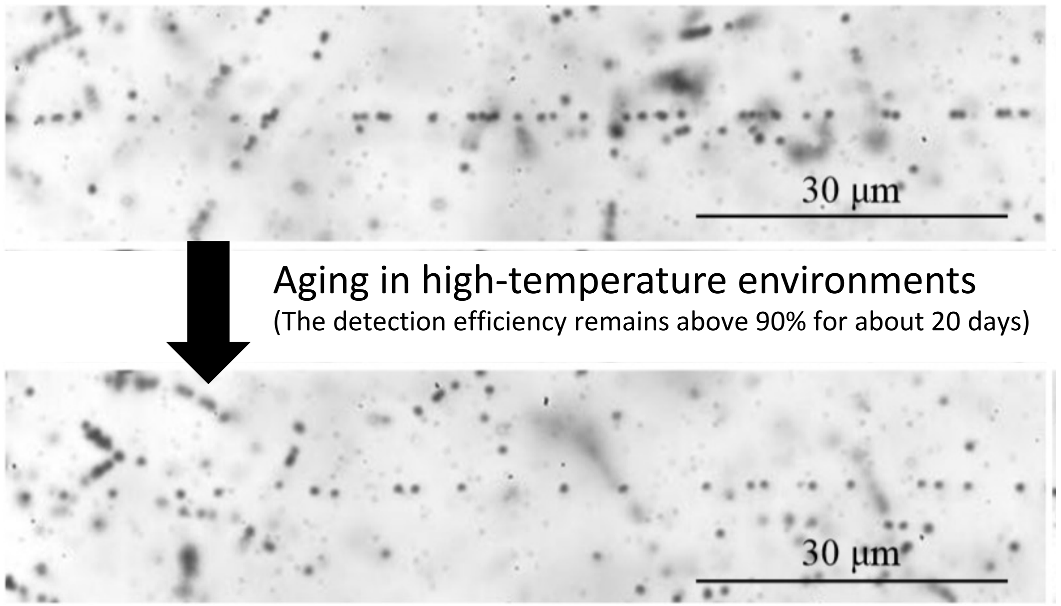
Two Approaches

1. Improvement of sensitivity(latent-image formation probability)

If the sensitivity is higher, the tracks can remain detectable for a longer time, even after latent image fading occurs.

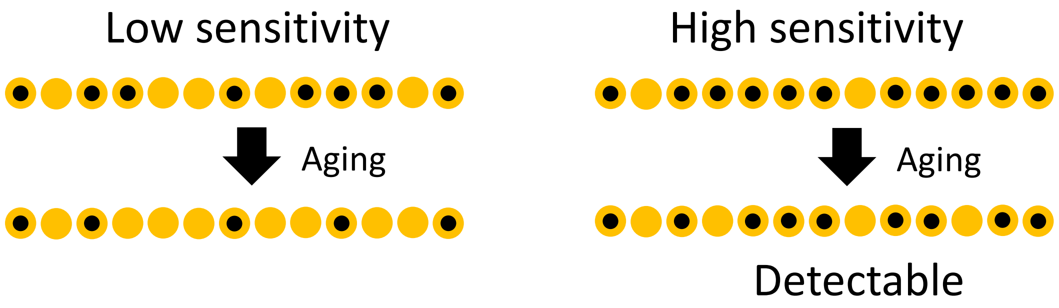
2. Improvement of latent image stability

- Main factors causing latent image fading:
  - Oxidation of silver nuclei by oxygen
  - Oxidation of latent image centers by holes generated by charged particles
- Stabilization of latent images by suppressing oxidation through control of chemical reactions



Development Topics

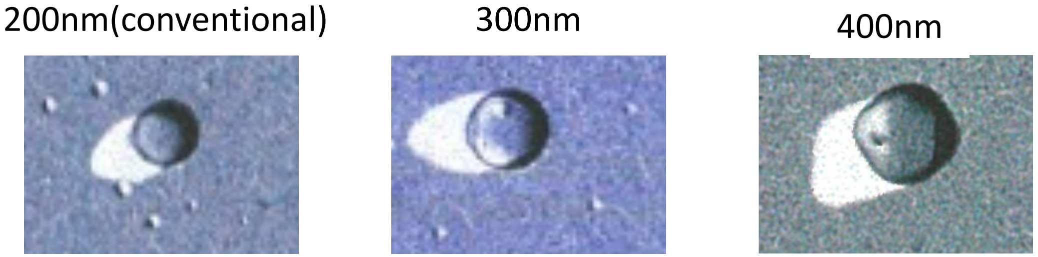
- Enlargement of emulsion grain size (Next slide)
- Improvement of gelatin that holds silver grains (Yoshihara's Talk, the final talk today)
- Search for effective chemical compounds (ongoing)

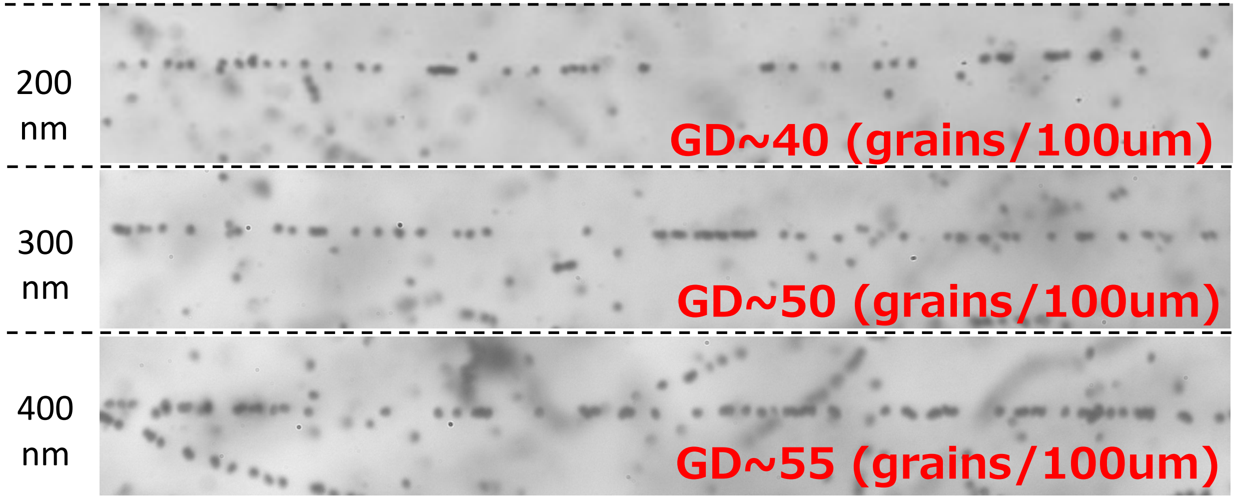


Large-Grain Nuclear Emulsion

- Designed and evaluated a process for enlarging silver bromide crystals
- Improved sensitivity and latent-image fading characteristics by increasing the crystal size
- Achieved up to a 1.4-fold improvement in sensitivity compared with the conventional type (about 200 nm diameter) . This corresponds to a fivefold extension of the observation period.
- Successfully improved sensitivity while suppressing an increase in noise
- Future work will focus on clarifying the mechanism of sensitivity improvement and further enhancing performance by increasing the grain size beyond 400 nm

Electron Microscopic Images of AgBr grains

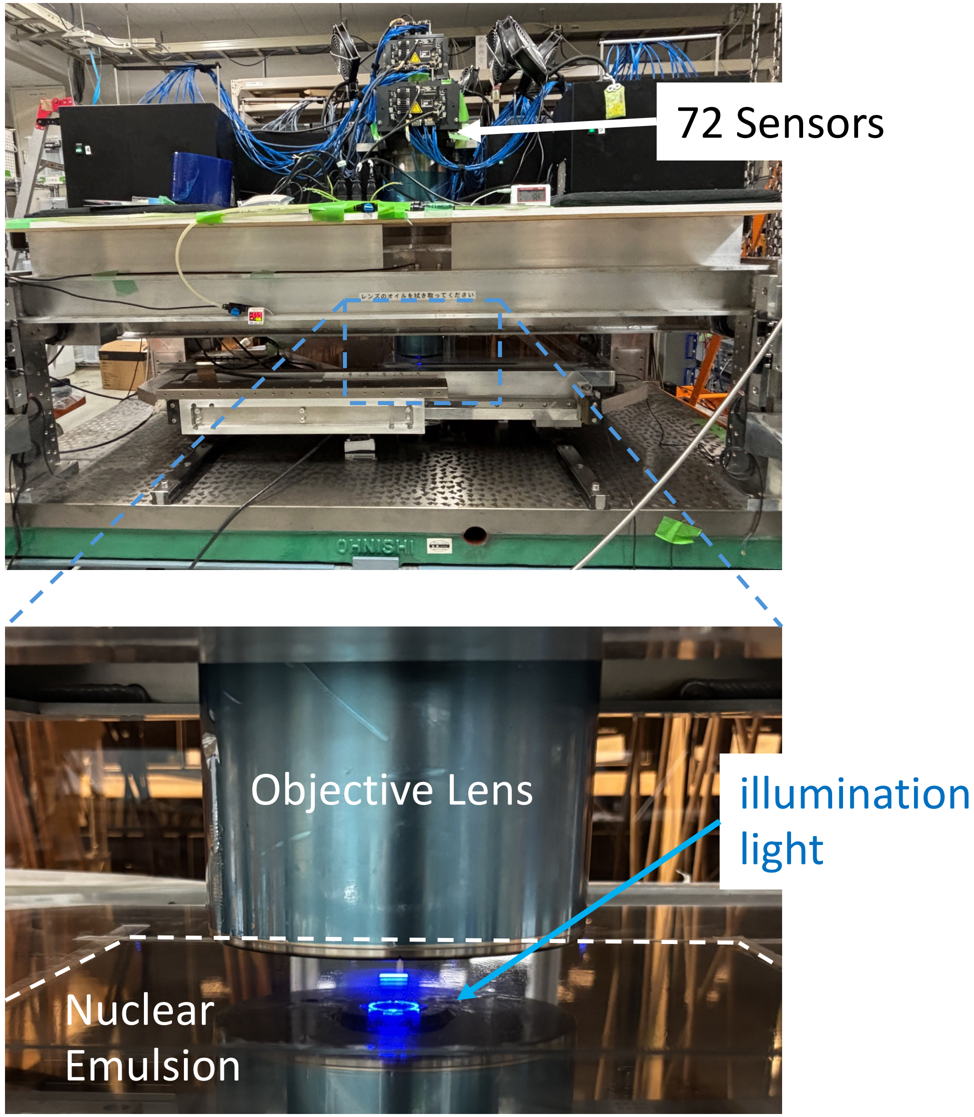




* 400 nm: preliminary result

Hyper Track Selector (HTS)

- The scanning speed of the conventional system, HTS1, is 0.45 m^2/h
- The new system, HTS2, entered full-scale operation for muon imaging applications one year ago
- HTS2 achieves a speed of up to 0.9m^2/h, by using lower magnification and a wider field of view than HTS1
- The scanning speed of HTS2 is two times faster than that of HTS1
- Development of the next-generation system, HTS3, has begun
- HTS3 aims to achieve up to a fourfold speed increase over HTS2, with half-scale operation planned in two years
  - While HTS1 and HTS2 are single-lens systems, HTS3 adopts a distributed optical system with multiple lenses.
  - HTS3 achieves higher speed by maintaining the same magnification as HTS2 while expanding the single field of view through the use of higher-resolution sensors
  - Detailed design is in progress, including the stage and lens arrangement.



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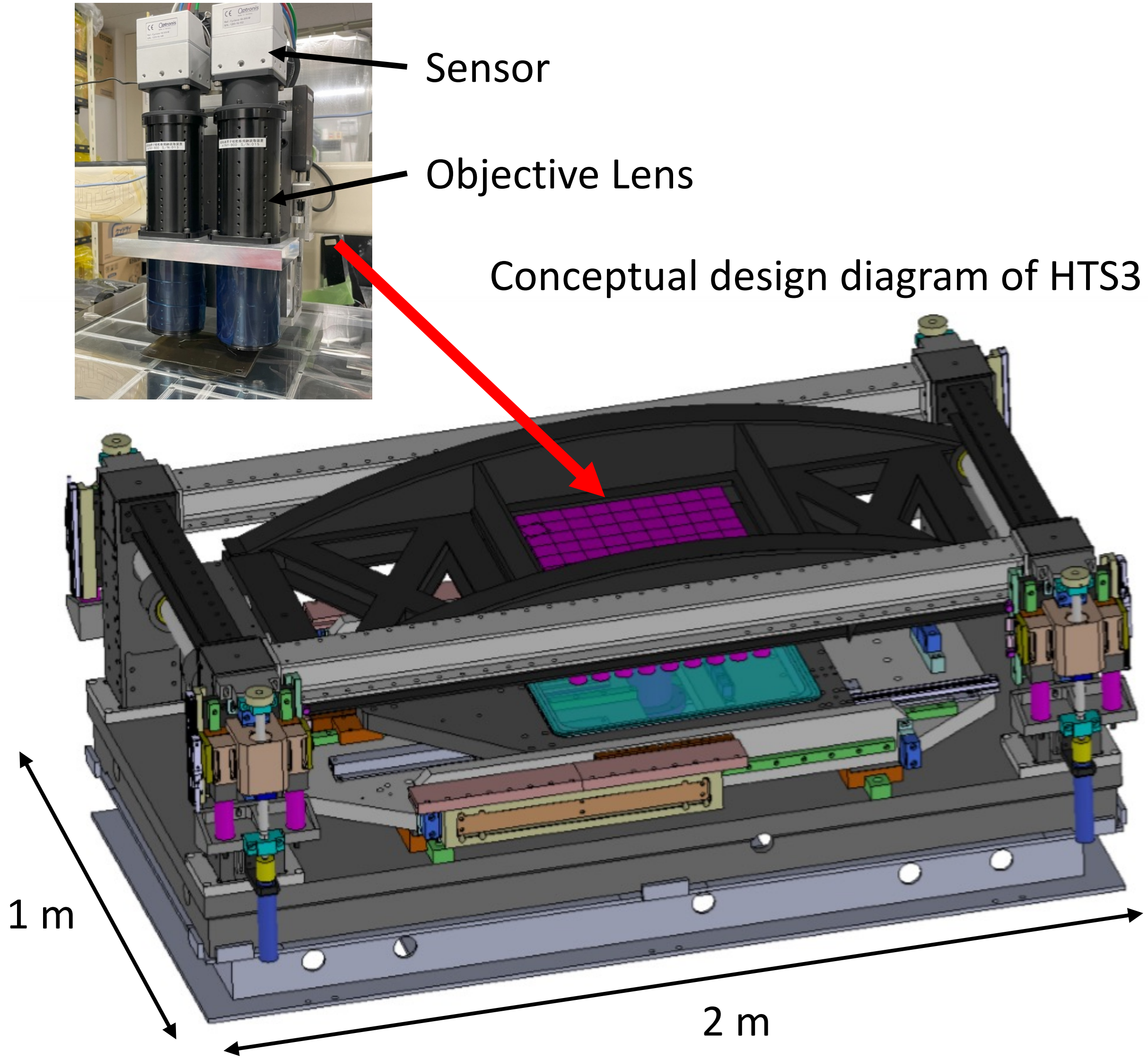


Conceptual design diagram of HTS3

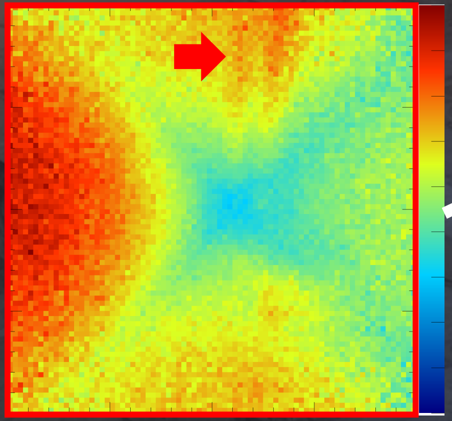
ScanPyramids

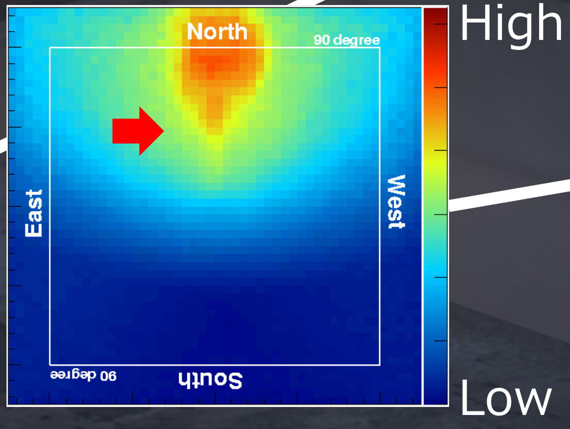
- Authorized by the Egyptian Ministry of Tourism and Antiquities
- An international collaborative project involving Egypt, Japan, France, Germany, and Canada
- Continuous surveys of the pyramids at Giza and Dahshur have been conducted since 2015

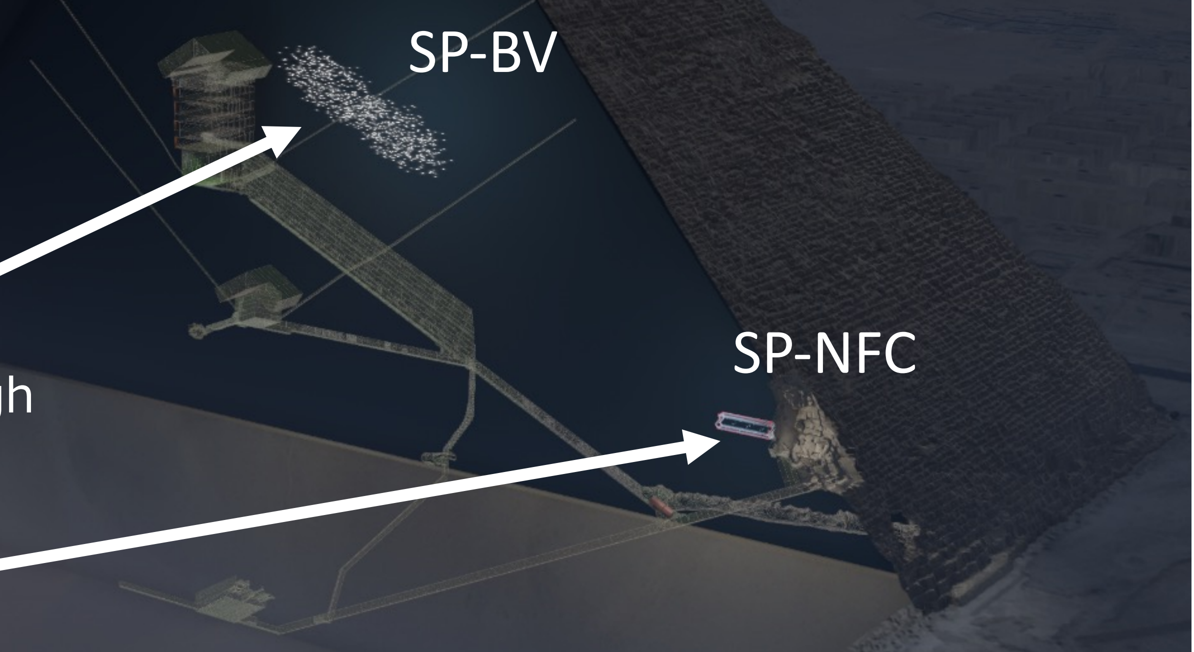
Target Pyramids

- Bent Pyramid (2015)
- Pyramid of Khufu (2015–)
- Pyramid of Khafre (2022–)
- Pyramid of Menkaure (2023–)

Cosmic-Ray Muograph







K. Morishima et. al., Nature 552, 386 (2017)

Recent progress on SP-NFC

- Nuclear emulsion detectors were installed at multiple locations from which the area behind the north face of the pyramid could be observed (the Descending Corridor and Al-Mamun's Corridor)
- In Al-Mamun's Corridor, measurements were carried out without obstructing tourist traffic
- Successful measurements were performed in an environment where other detectors would have difficulty operating
- The position and size of the discovered space were estimated with 10 cm accuracy by a chi-square test, assuming a cuboid structure, using measurements from six directions.
- Based on the muon imaging results, the existence of the space was confirmed using a fiberscope (March 2023)
- The internal structure was three-dimensionally reconstructed by photogrammetry using fiberscope images and LiDAR survey results
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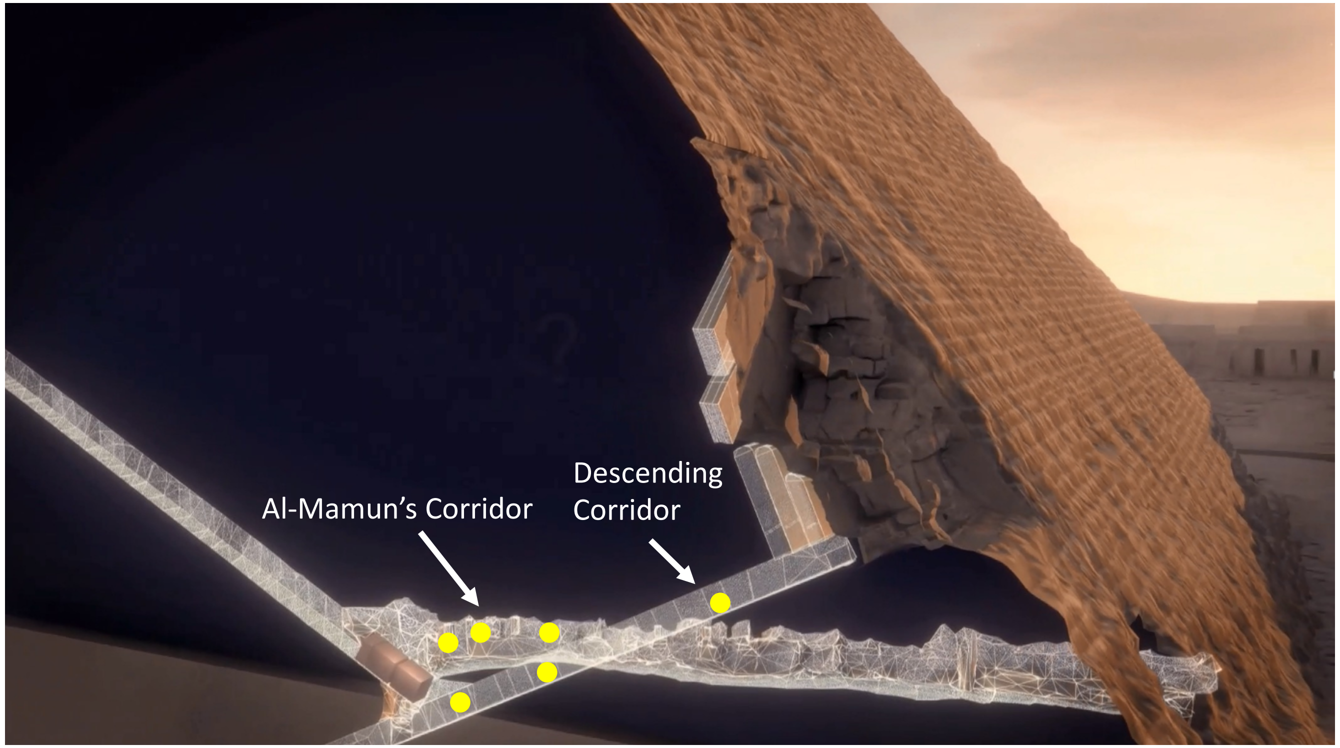

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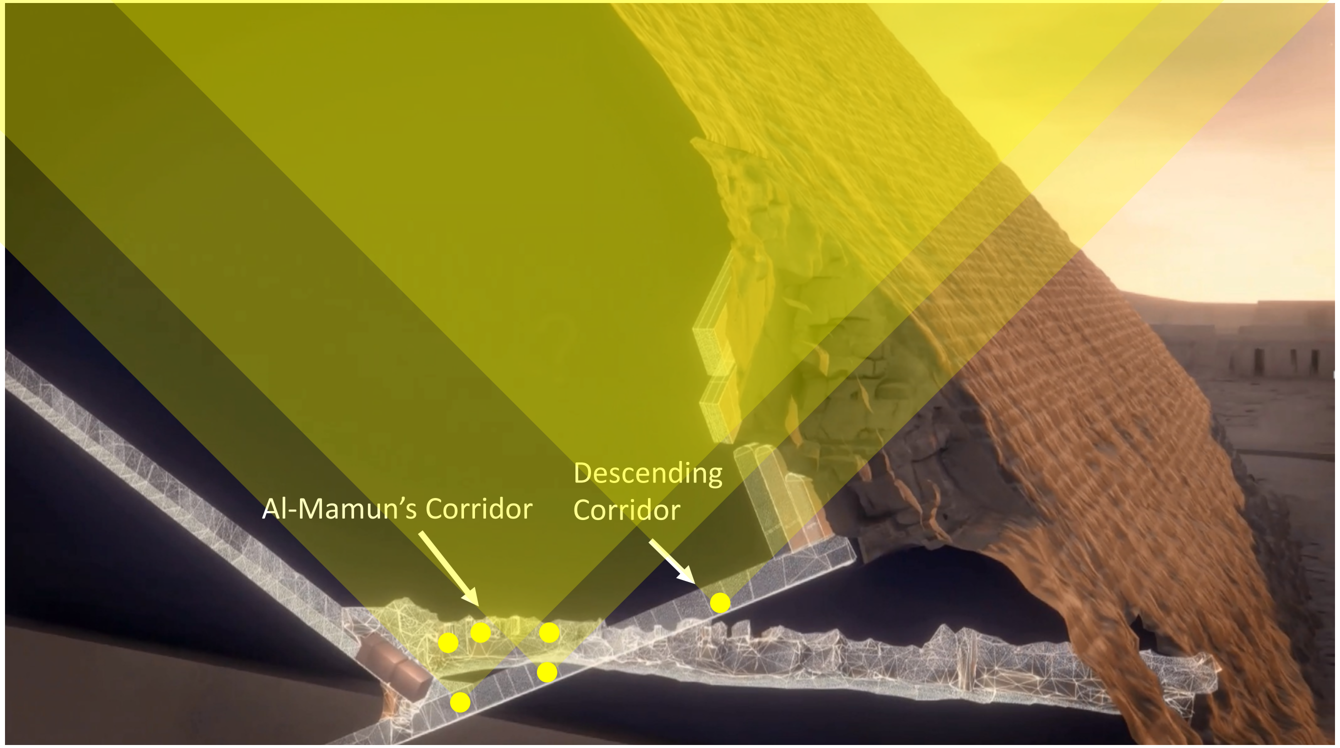

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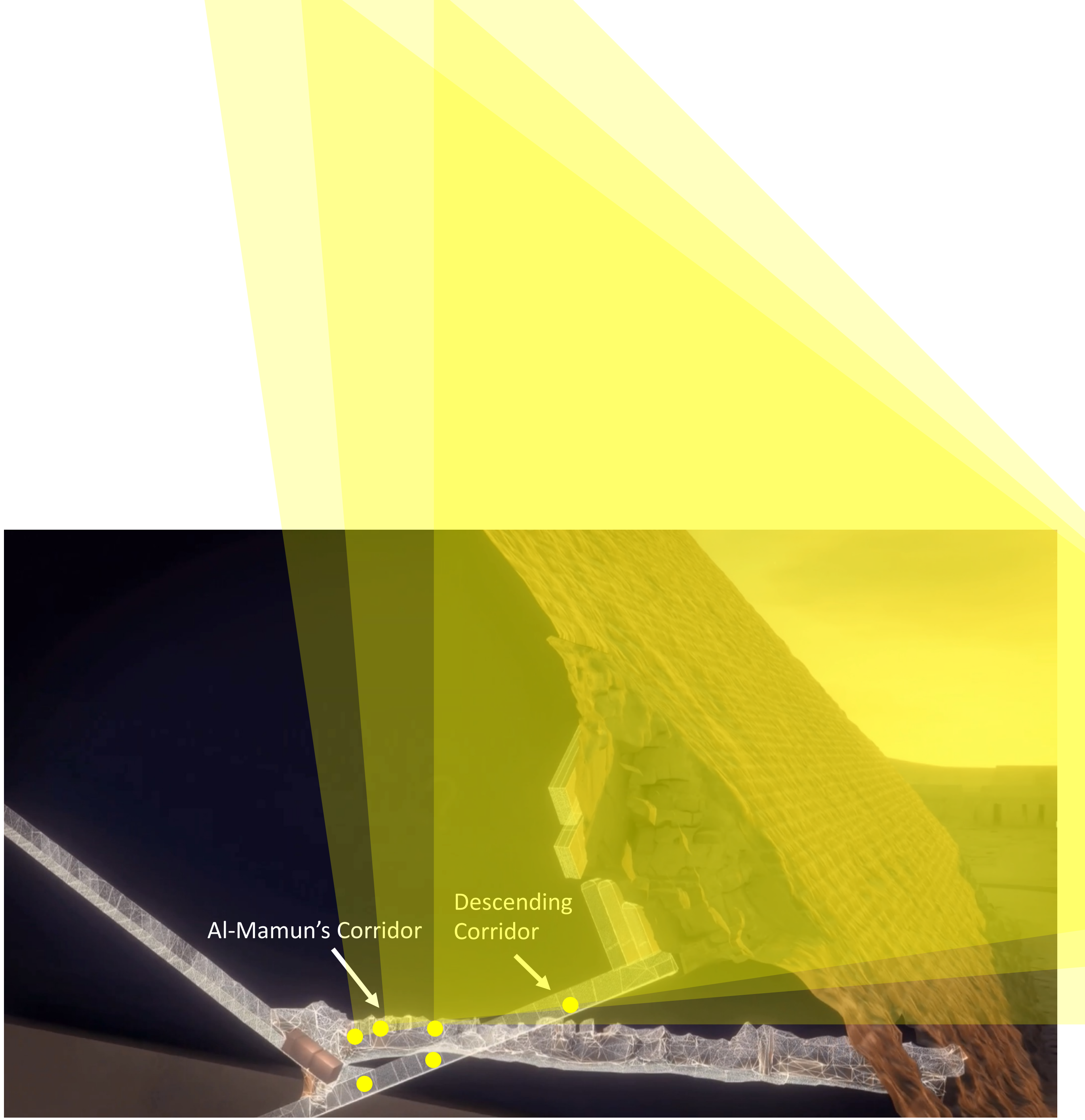

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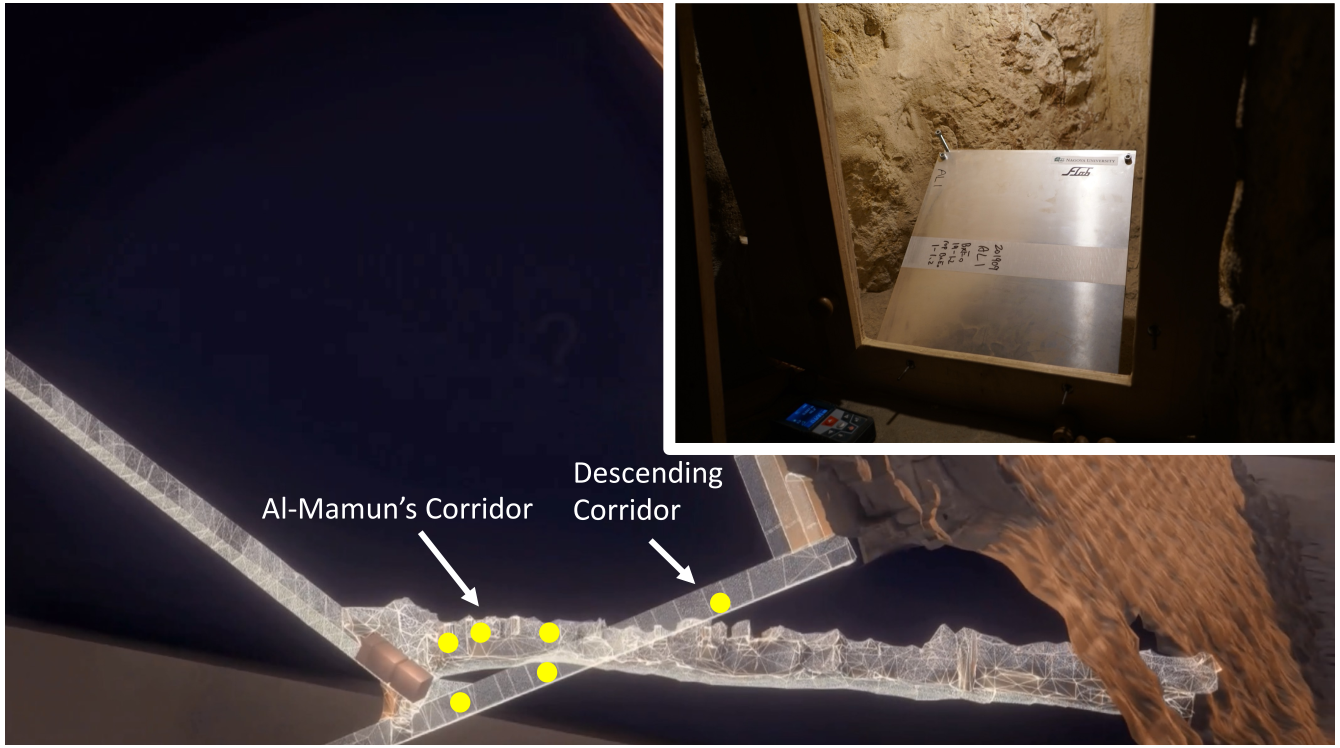

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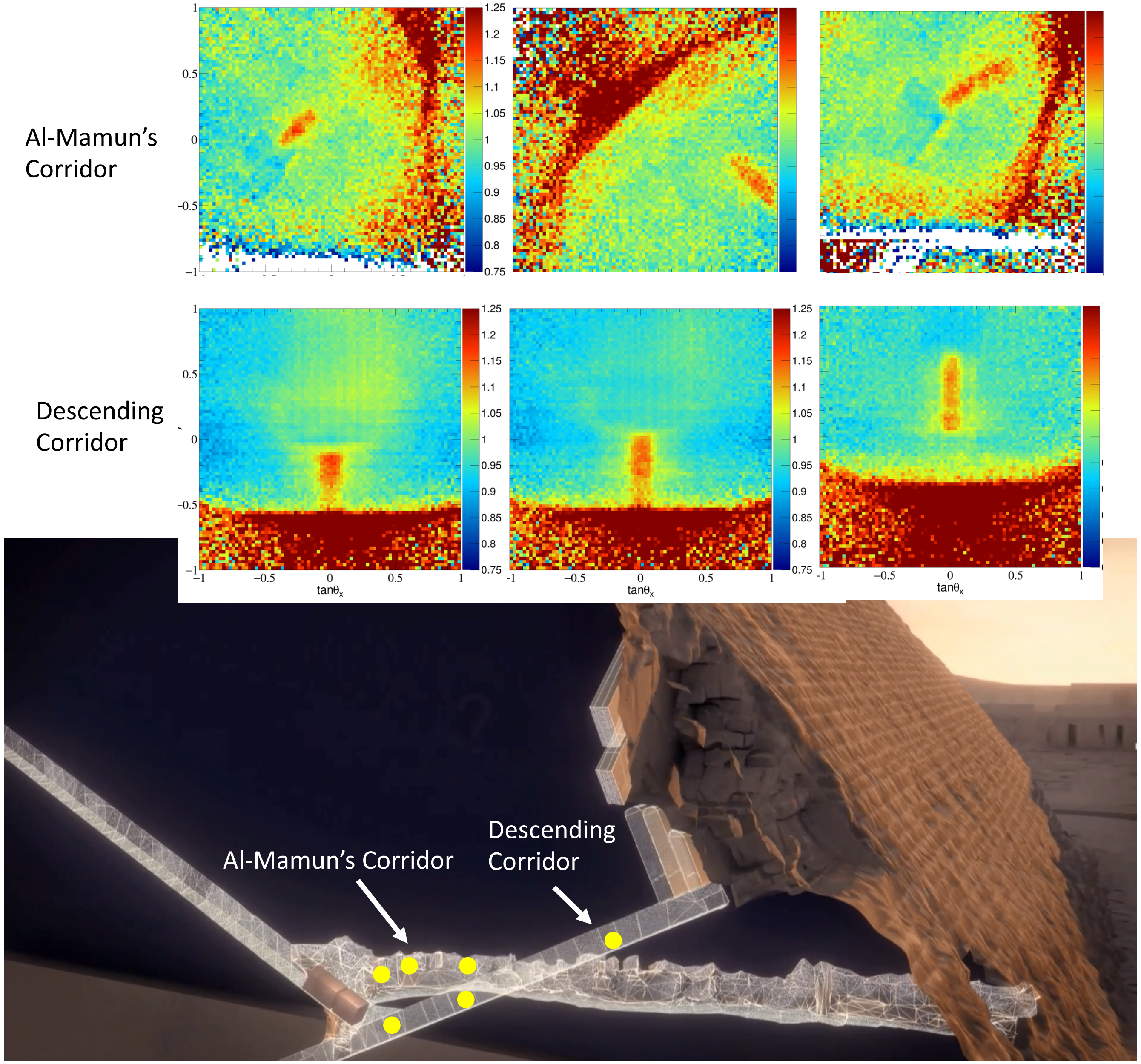
Observation from 6 positions



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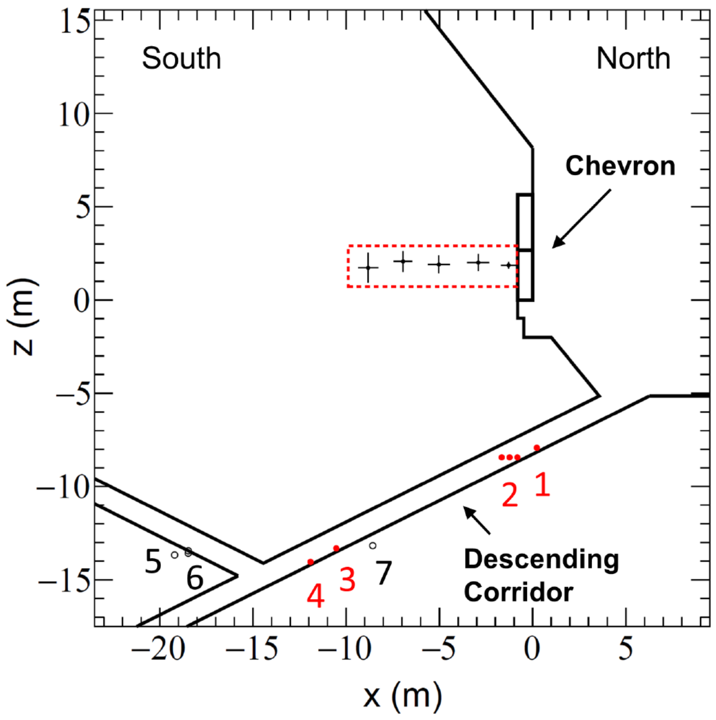
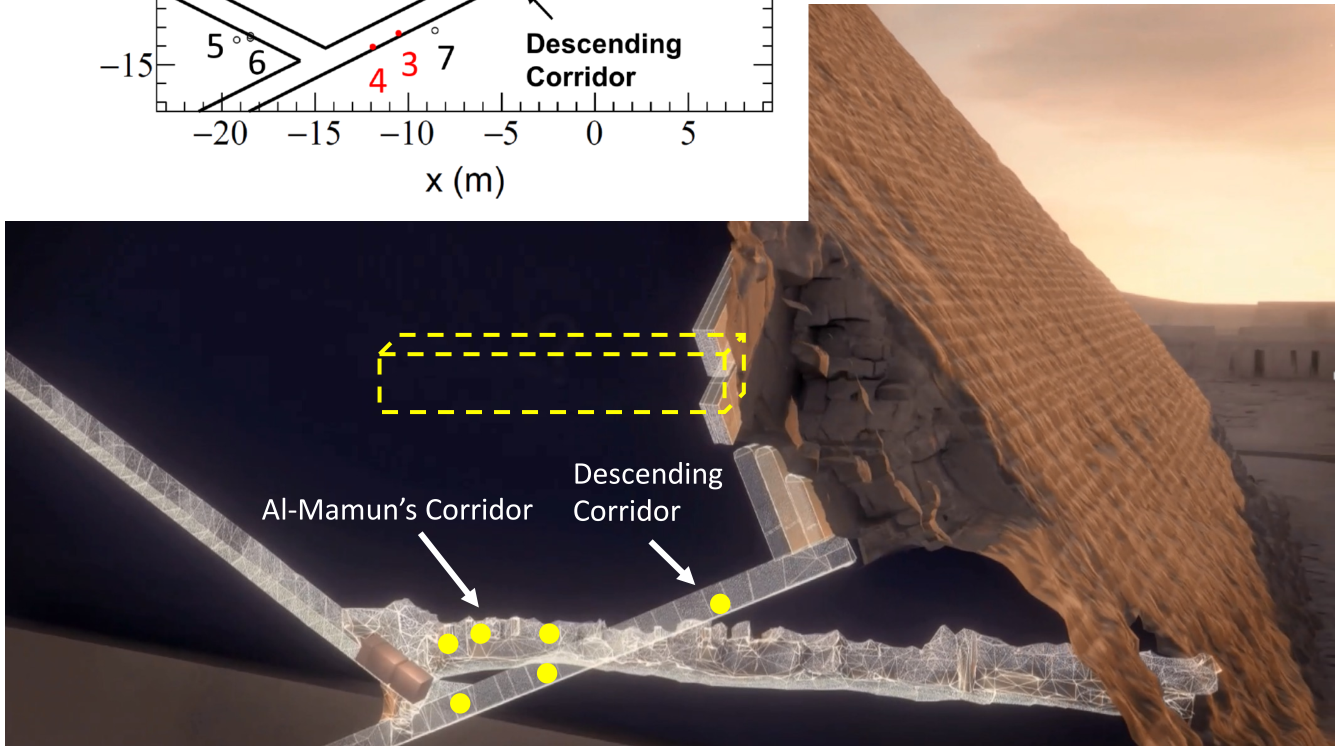


Structures	Muography
Width	2.02 m
Height	2.18 m
Length	9.06 m



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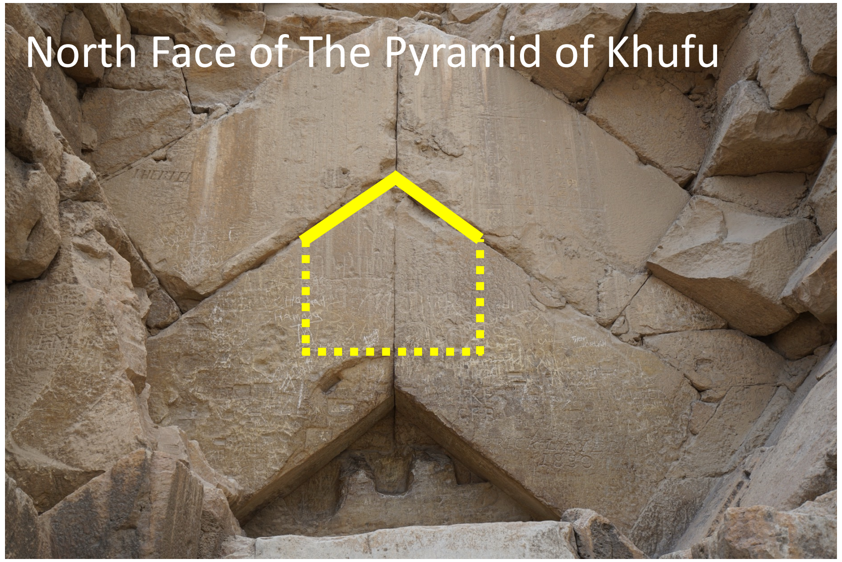

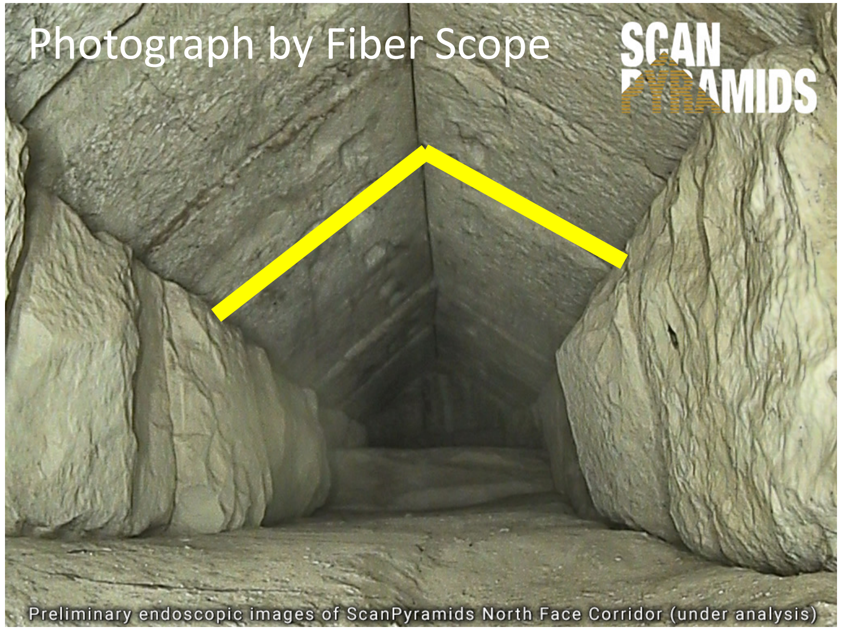

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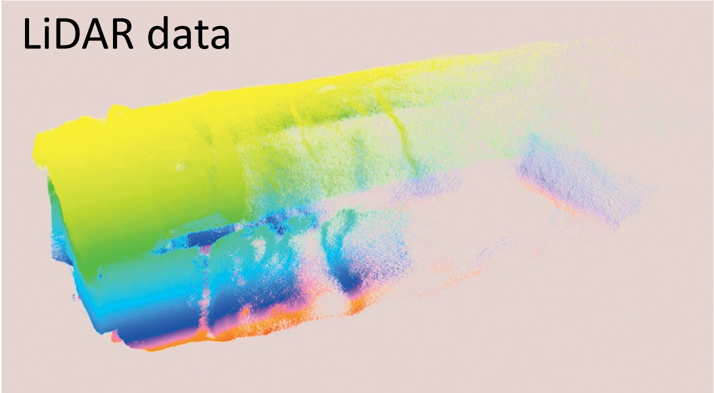
Photogrammetry (more than 2000 pictures)



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3D model of SP-NFC

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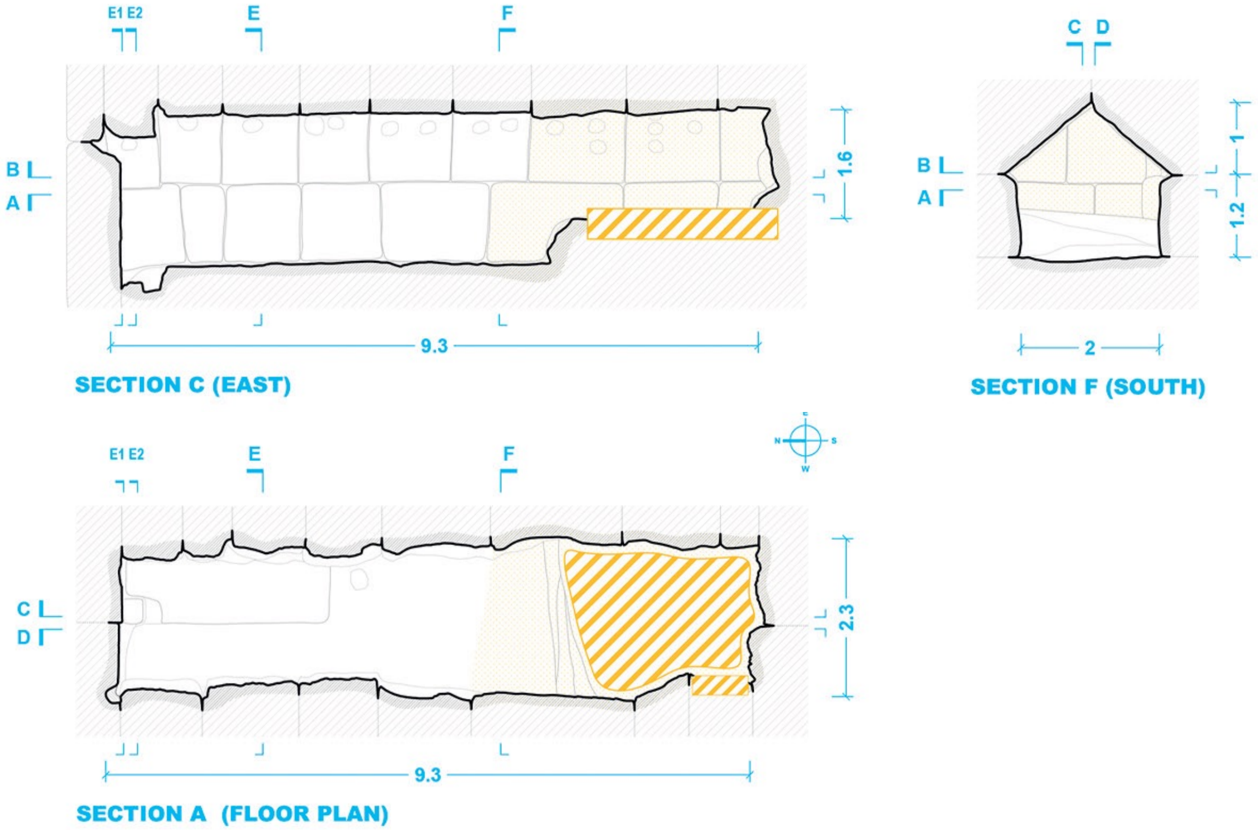
Three-view drawing of SP-NFC



Structures	Muography	Photogrammetry
Width	2.02 m	2.0 m
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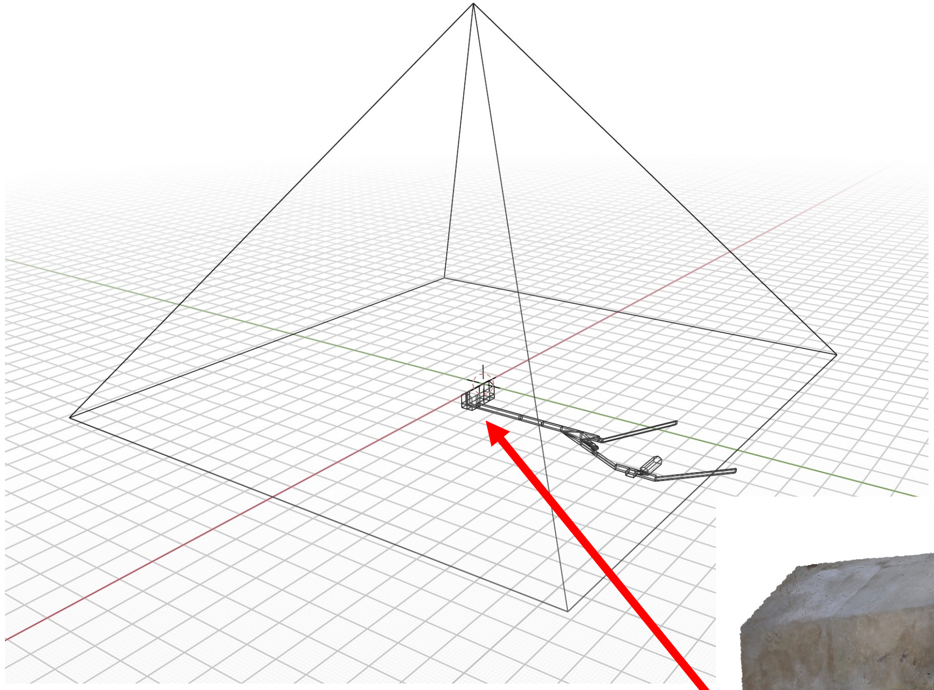
Length	9.06 m	9.3 m

The three major pyramids of Giza

Observation of the Pyramid of Khafre

- Nuclear emulsion detectors were installed at the same location in the Belzoni Chamber as those used by Alvarez et al. An observation with a detector area of 2.25 m^2 was conducted for a total of about 300 days, and 70 million muon tracks were recorded (currently under analysis).
- Additional nuclear emulsion detectors were installed at other locations in the Belzoni Chamber. Large-area detectors and inclined detectors have been deployed simultaneously at multiple sites, and observations are ongoing.
- Measurements are also being carried out beyond the observation region covered by Alvarez et al. to search for previously unknown internal structures.



Installed in the same location as Alvarez's detector.

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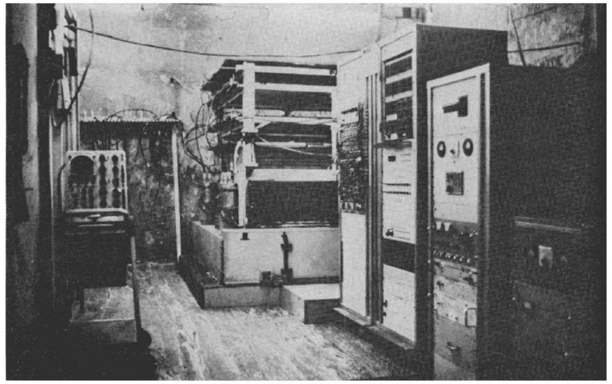
Spark Chamber by Alvarez.et al.,



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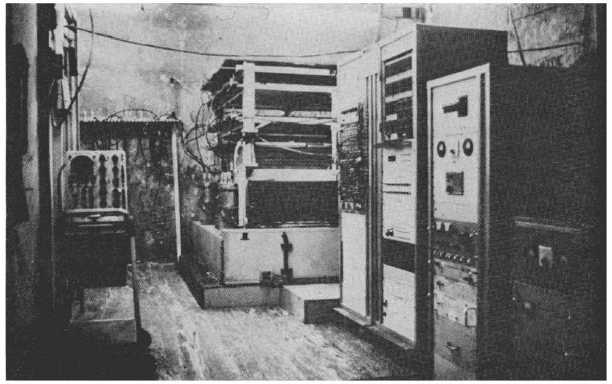
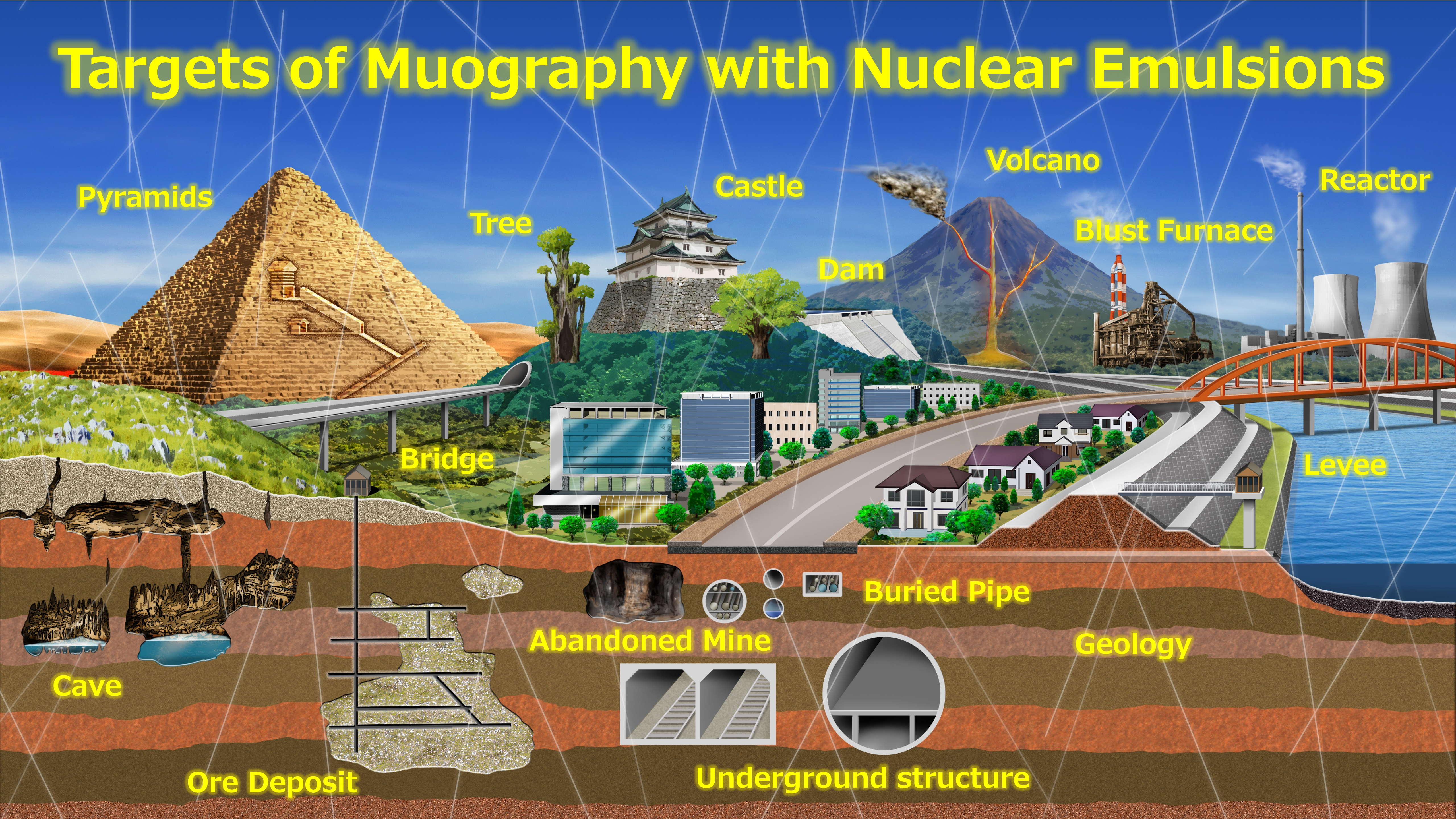
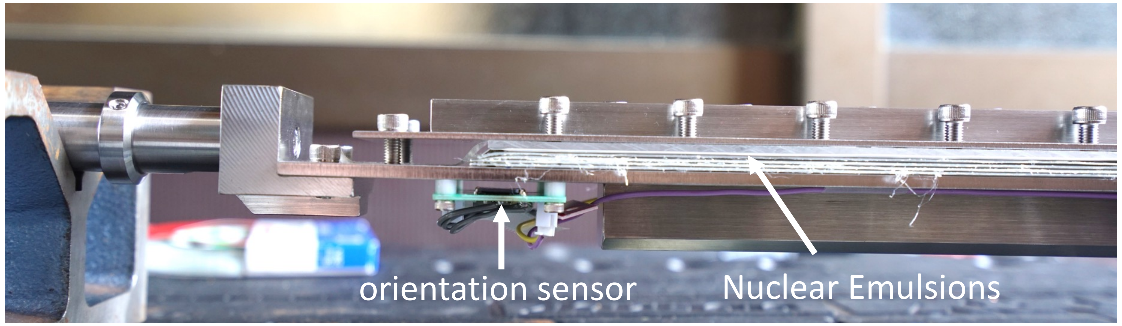



Targets of Muography with Nuclear Emulsions
Pyramids
Tree
Castle
Volcano
Reactor
Blust Furnace
Dam
Bridge
Levee
Buried Pipe
Abandoned Mine
Geology
Cave
Ore Deposit
Underground structure

Borehole Detector with Nuclear Emulsions

- Developed a borehole detector that can be inserted into boreholes with a diameter of 10 cm or less
- Nuclear emulsion films with a width of 4–5 cm and a length of 30–40 cm are fixed inside a stainless-steel pipe with a diameter of 7.3 cm
- The total detector length is 1 m or 2 m, and the weight is 15 kg
- Nuclear emulsion can be made compact without losing its high accuracy. Even at this size, it provides an angular resolution of several milliradians. This gives the borehole detector the world's highest resolution.
- A demonstration test was conducted at a site in Japan
- The direction in which a high muon flux was observed was checked by borehole investigation, and the results showed good agreement
- Future challenges include improving waterproof performance and ensuring the flatness of the nuclear emulsion films
- An improved new detector is currently under development
- A demonstration test at a new site is planned within this year



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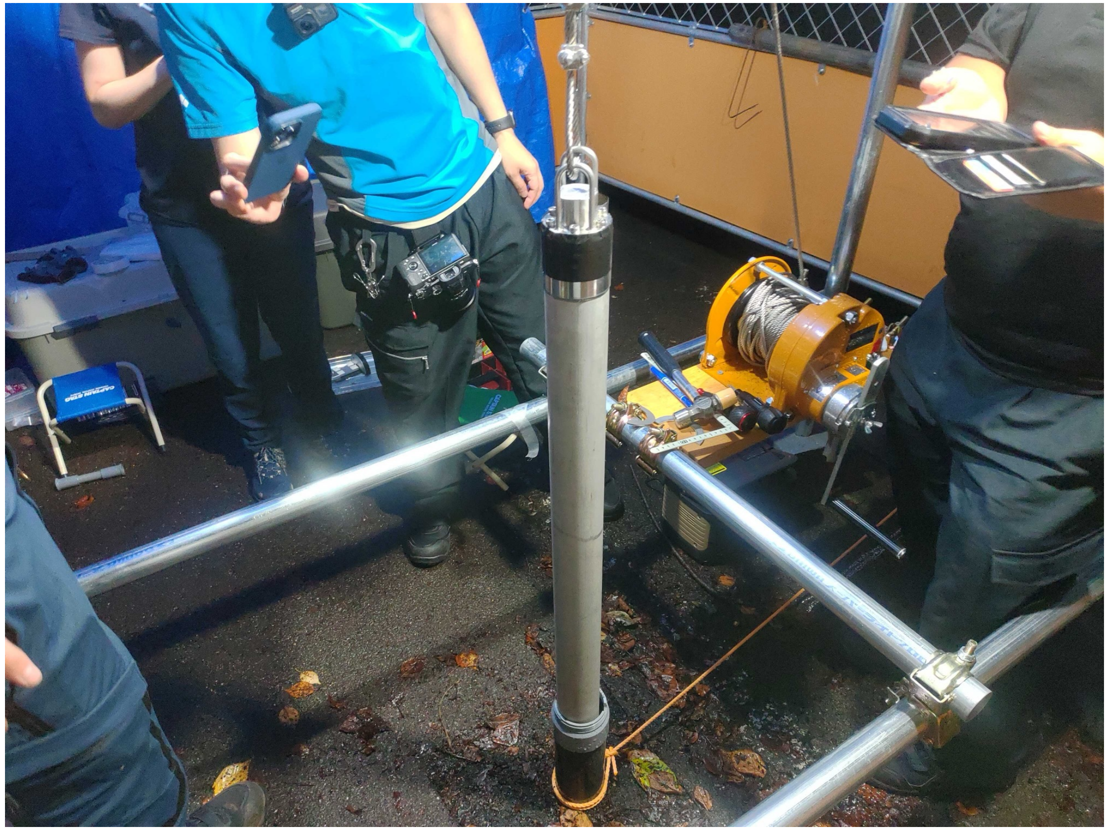
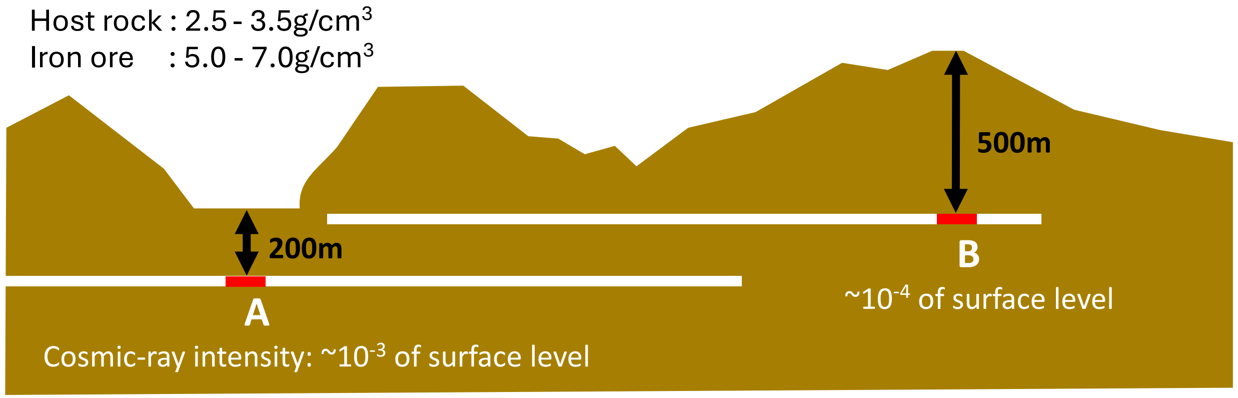
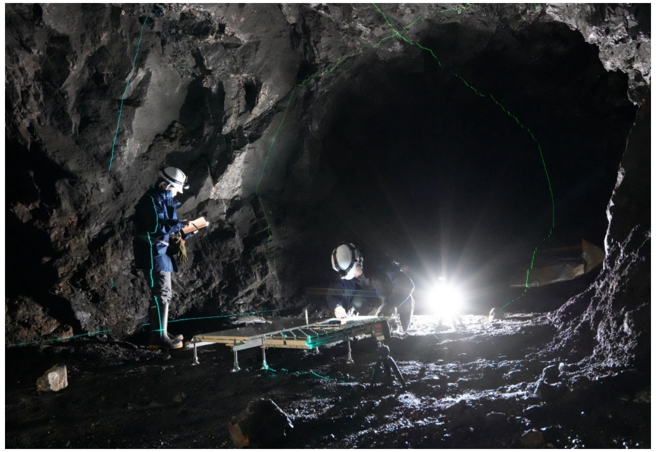


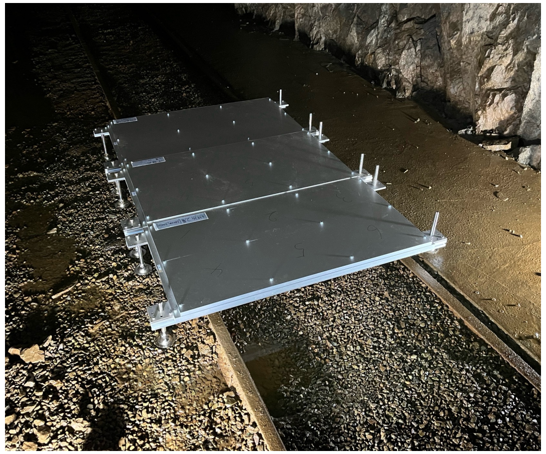
Underground mineral deposit exploration

- Measurements are currently being conducted at the Kamaishi Mine
  - It is a skarn-type iron ore deposit, and large-scale mining has already ended
  - The site is currently operated mainly for water-related business and underground space utilization
- Detectors were installed at depths of 200 m and 500 m for observation
- Large-area detectors are essential for this measurement
  - A up to 2.25 m^2 detector, comparable in scale to that used in the pyramid observation, was employed
  - Four months of stable, continuous observation were carried out in a low-temperature environment
- A key challenge is that radiation from geological materials becomes analysis noise in nuclear emulsion
  - In this measurement, detectors were installed at locations with low radiation dose
  - Improvements in the detector structure or analysis method are required.
- The analysis is currently ongoing
  - Tunnels and mined-out cavities above the detector are gradually being visualized



Cross-sectional view of the mine and detector installation locations





Conclusions

- Nuclear emulsion is a lightweight, power-free, and high-precision three-dimensional tracking detector, and Nagoya University is advancing in-lab production and coating, as well as mass production.
- To address latent image fading in high-temperature environments, developments to improve sensitivity and latent image stability are underway, and performance improvements through larger grain sizes have been confirmed.
- The HTS scanning system was upgraded to HTS2 for faster readout, and further speed improvements are being pursued with HTS3.
- In the ScanPyramids project, an internal voids in the Pyramid of Khufu was confirmed, and observations are now being extended to the Pyramids of Khafre and Menkaure.
- The applications of nuclear emulsion are expanding to underground structure exploration, including borehole detectors and mineral deposit exploration at the Kamaishi Mine.