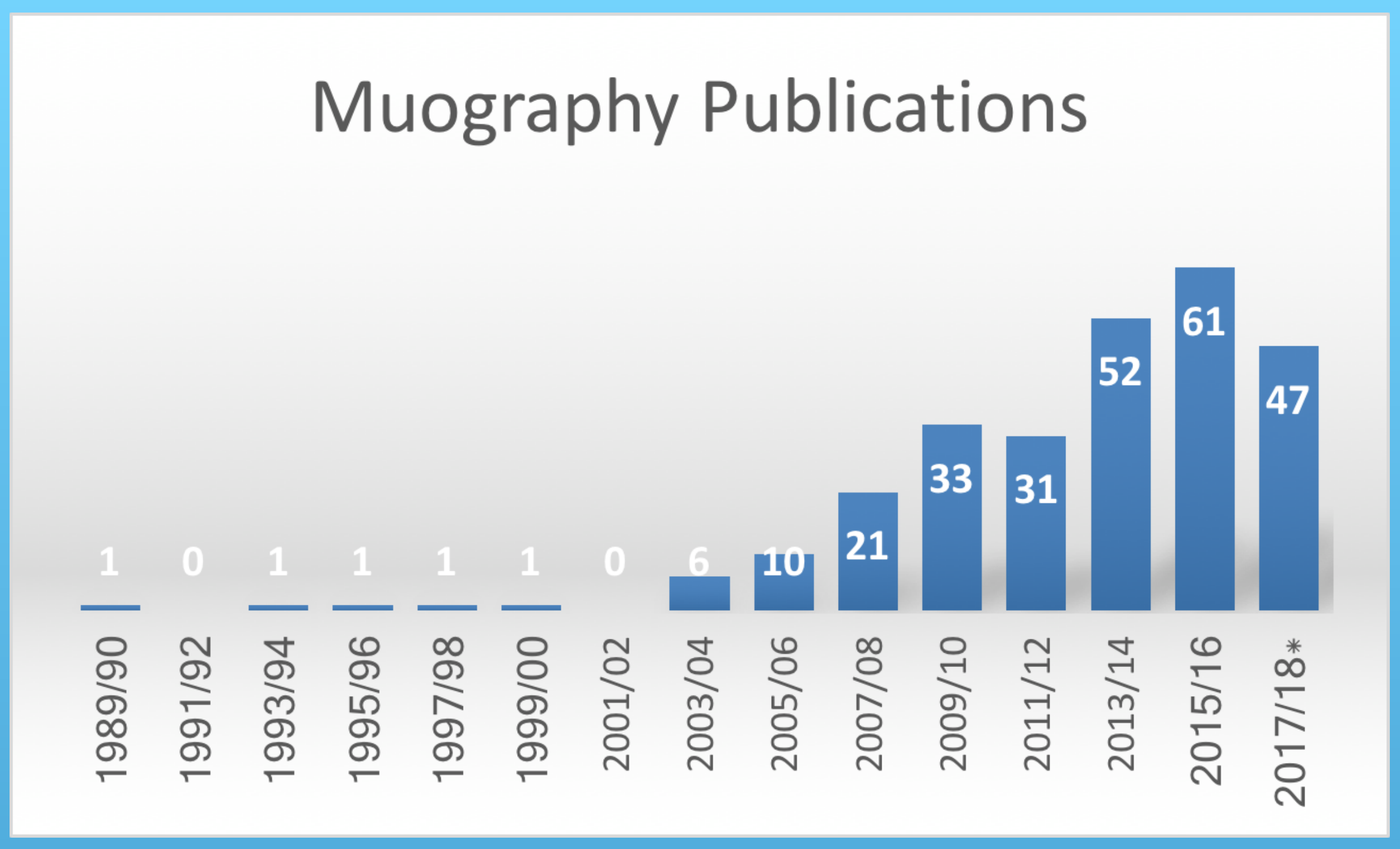
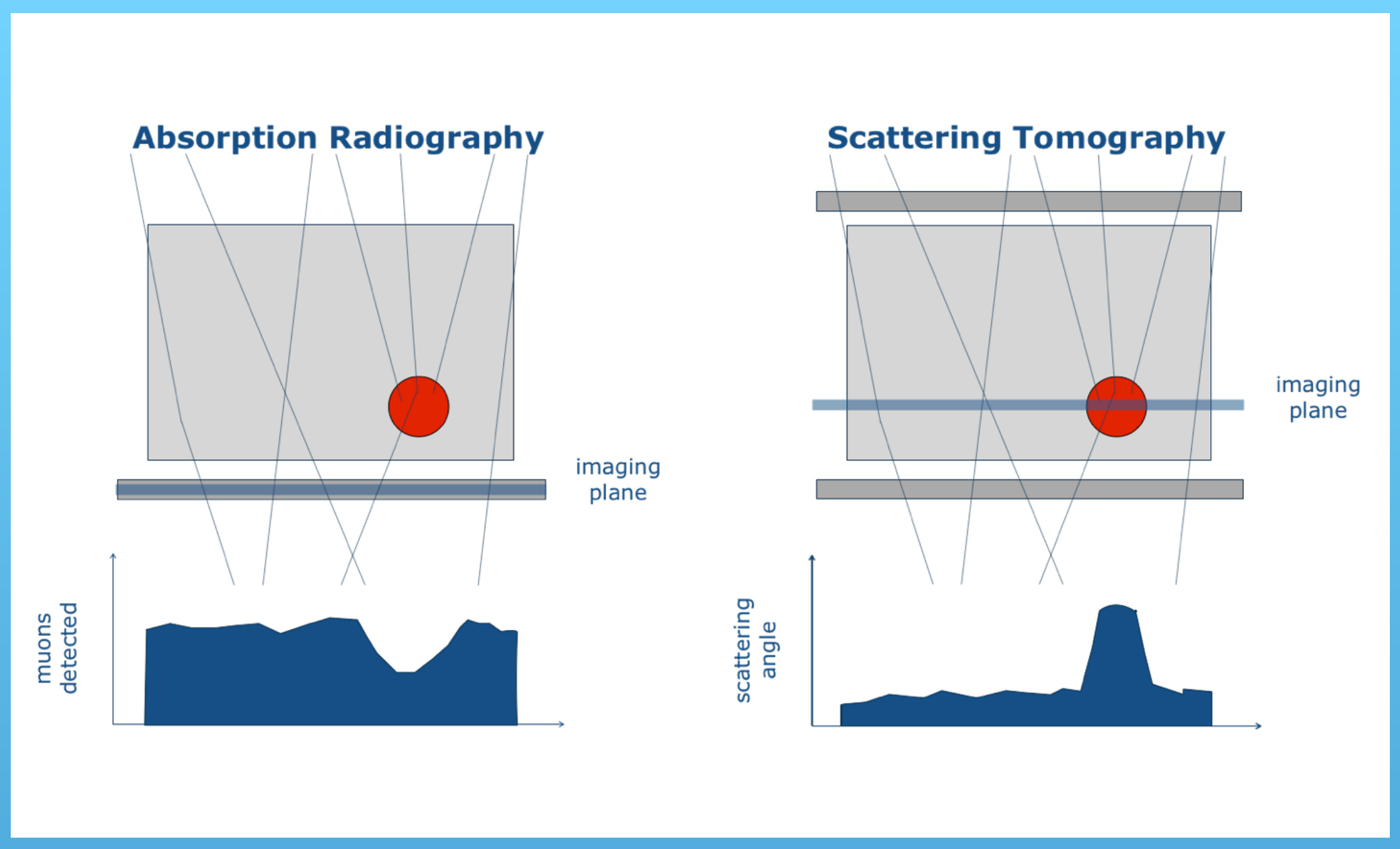
COSMIC-RAY MUOGRAPHY



Cosmic rays, respectively the secondary particles from the atmospheric showers that they cause, were discovered more than 100 years ago, in 1912, by Austrian physicist Victor Hess in high-altitude balloon flights. Muons were discovered in 1936 at Caltech, when Carl Anderson and Seth Neddermeyer investigated cosmic rays in detail. By the 1960s cosmic-ray muons were no longer only a research subject, but they were well enough understood to be used as a research tool by Luis Alvarez in his search for hidden chambers in the Chephren pyramid in Egypt.

Over time, it became routine in particle physics experiments to use them for the commissioning of new particle detectors. Their high average energy of 3 GeV leads to straight tracks in the Earth’s magnetic field and their low flux of about 100 Hz per square-metre at sea level is not challenging for any data acquisition system, but enough to take some useful data. At several underground experiments, the cosmic-ray muon shadow of the moon has been used to verify the position resolution of the detector.

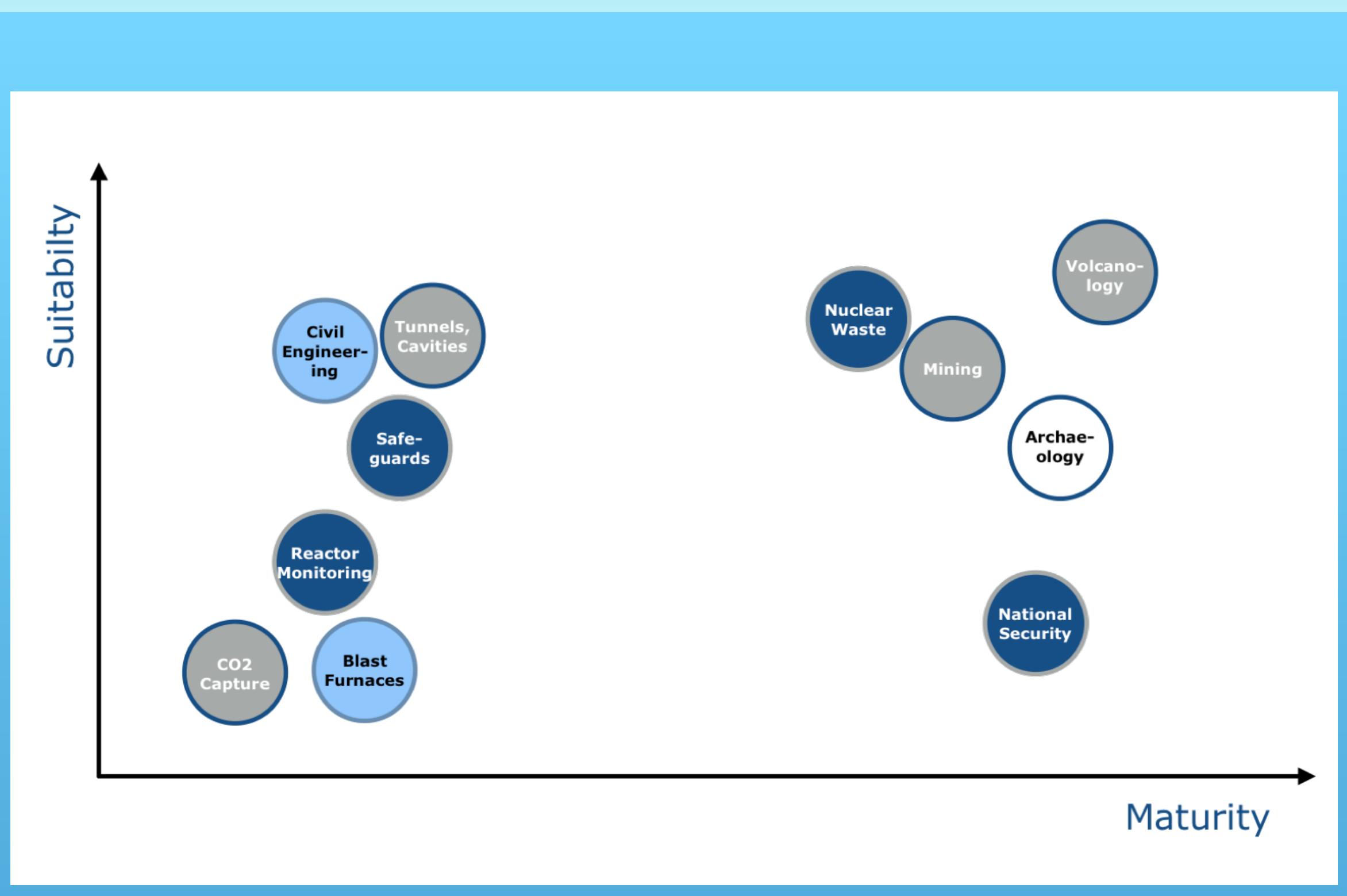
In 2003 researchers at Los Alamos National Laboratory published a seminal paper on imaging with cosmic-ray muons that showed for the first time how the Coulomb scattering of muons in matter could be used for imaging applications. Previously, only information from the absorption of muons in matter had been used. This paper is the kick-off point for a rapid increase of publications on muography. In the developmental chain from research subject to research tool to technology, this marks the transition from research tool to technology, i.e. a tool with applications outside of research.



Muon radiography requires at least two detector planes that allow to define the tracks of the detected cosmic muons to produce a 2D absorption image. Muon radiography results are not necessarily limited to 2D images; the information from several detectors imaging the same volume can be combined to form a 3D image, as was done e.g. by the ScanPyramids project. The applications, e.g. in volcanology, usually require a mobile detector system. The typical size of a muon radiography detector plane is about 1 m2, not least because this is about the limit for mobility. Typical examples are the muon telescopes used by the MURAY experiment in Italy and by ToMuVol in France, as well as the systems used by CRM GeoTomography in Canada.

Muon tomography requires at least two detector planes above and two below the object that is to be imaged. The upper detectors can be seen as defining the radiation source, similar to the X-ray source in a CT system, while the lower detectors detect the presence, absence and scattering of the muons that were defined by the upper detectors. This is in fact very similar to a CT system, but due to the angular distribution of cosmic muons and due to the geometric limits imposed by the detector system only a narrow angular range around the vertical is covered. This necessarily means that the resolution of such a muon tomography system in the horizontal plane will be much better than the vertical resolution.

The existing muon tomography systems are static systems, i.e. they require that the object or sample is place inside their active volume. This active volume is most typically of the order of m3; the largest one has an active volume of tens of m3. Typical examples for static muon tomography systems are shown below.



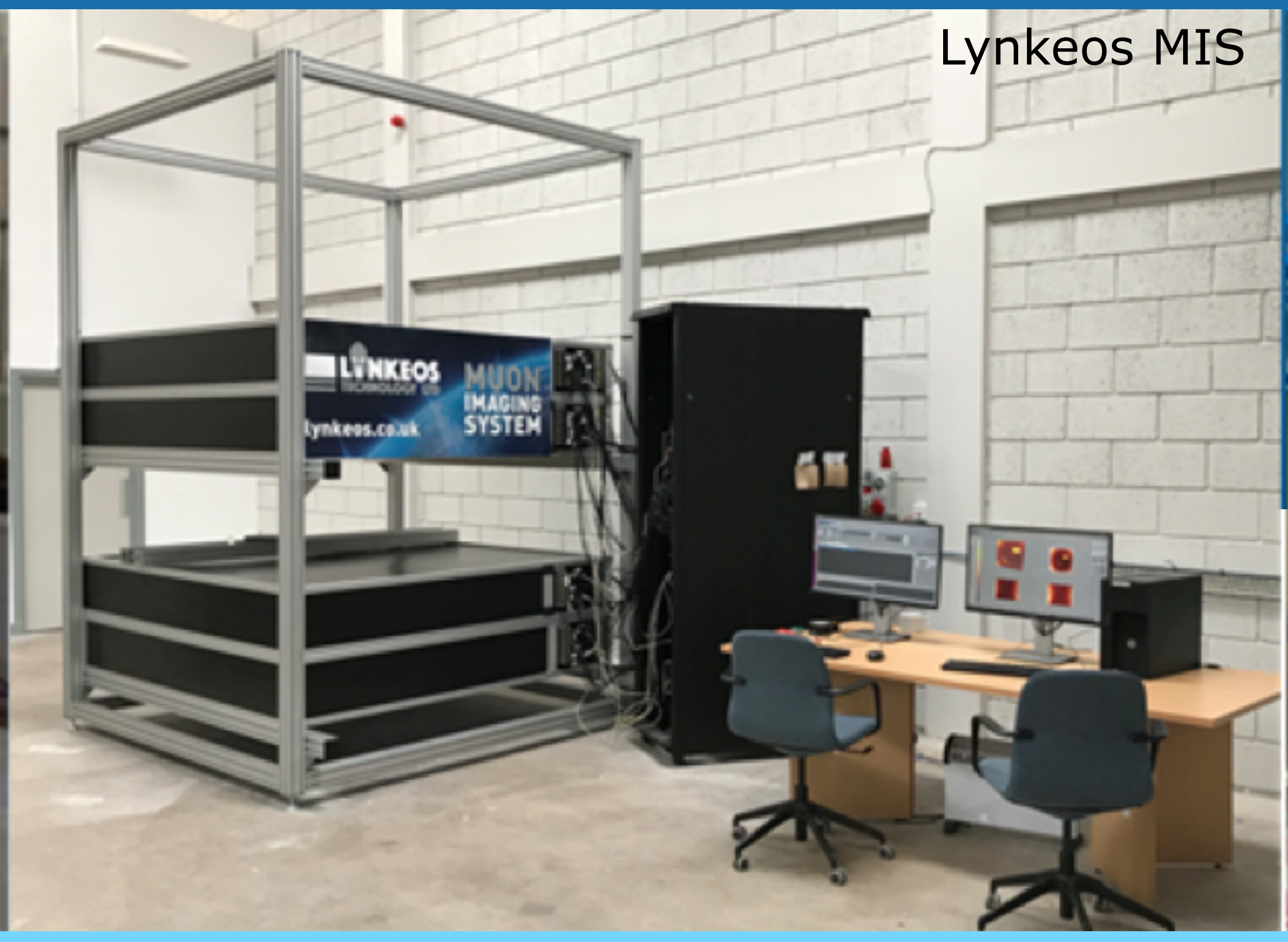
The muography applications that have been realised and commercialised up to now are not necessarily going to be the main applications in the future. They just happened to be those that offered a good combination of available funding and technical suitability. To get an impression of which future directions can be expected in muography, it is instructive to consider the suitability of muography and the technical maturity of the application.

Applications that can be expected to play an important role in the future are those which score high in suitability and those that at the same time are not yet very mature are those that are likely going to be developed in the future. These applications are civil engineering (e.g. monitoring bridges), tunnels and cavities and nuclear safeguards (e.g. monitoring of dry storage casks).

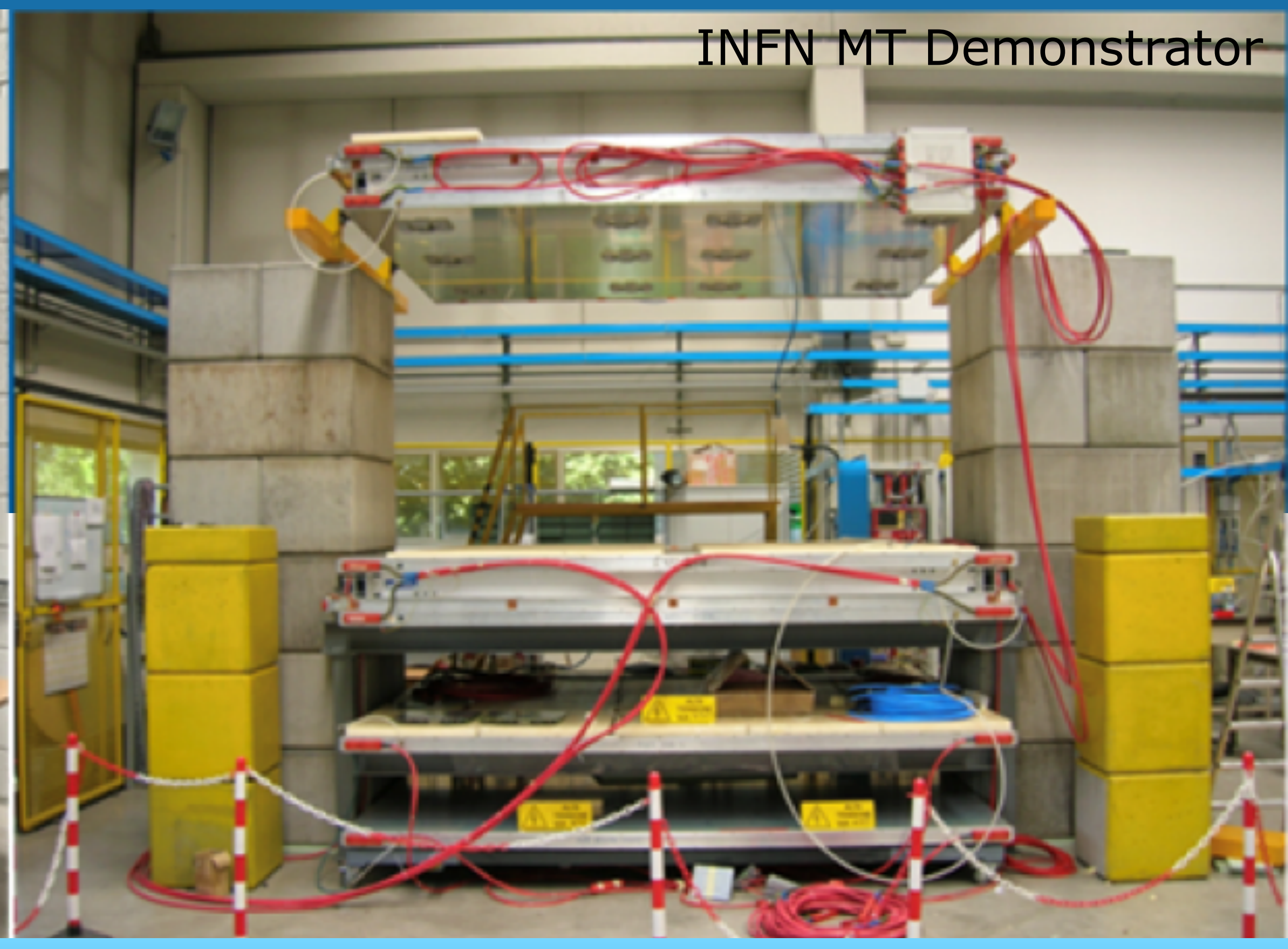
If this is combined with the detector types that are currently being used for which applications, it seems logical that mobile detector systems for radiography, but also for tomography, are going to be more typical in the future. At the same time, detector systems will have to become commercial products and be designed with the application in mind, rather than being based on available detectors from particle or nuclear physics experiments. Ultimately this may lead to the commodification of large-scale tracking detectors, in a way that has already taken place for detector technologies with medical applications.

I expect muography to become a technology that finds its place between other imaging technologies and that is used when it simply is the best technology for the purpose.

LANL MMT



Lynkeos MIS



INFN MT Demonstrator

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