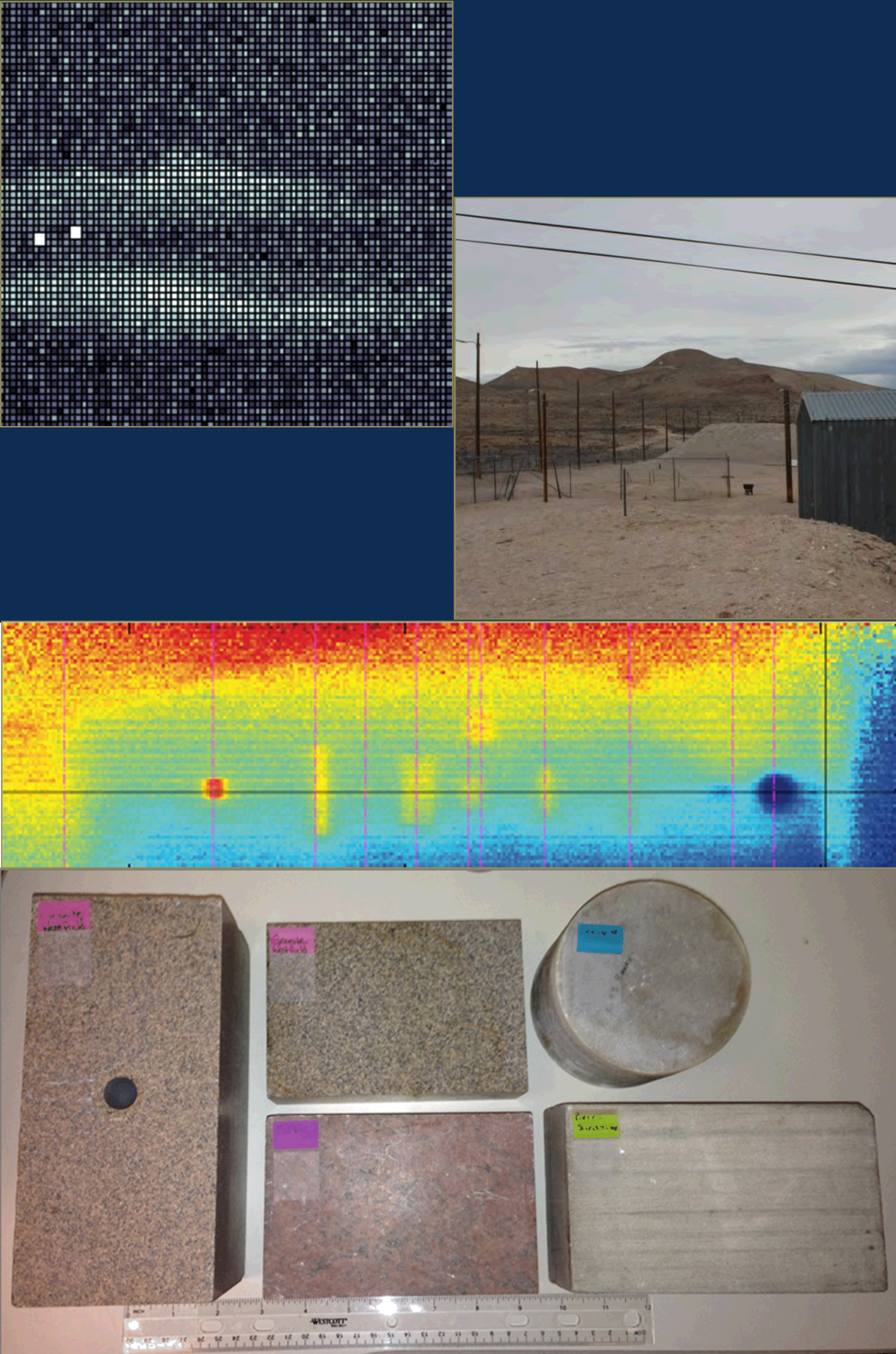


# Underground Imaging with Muons

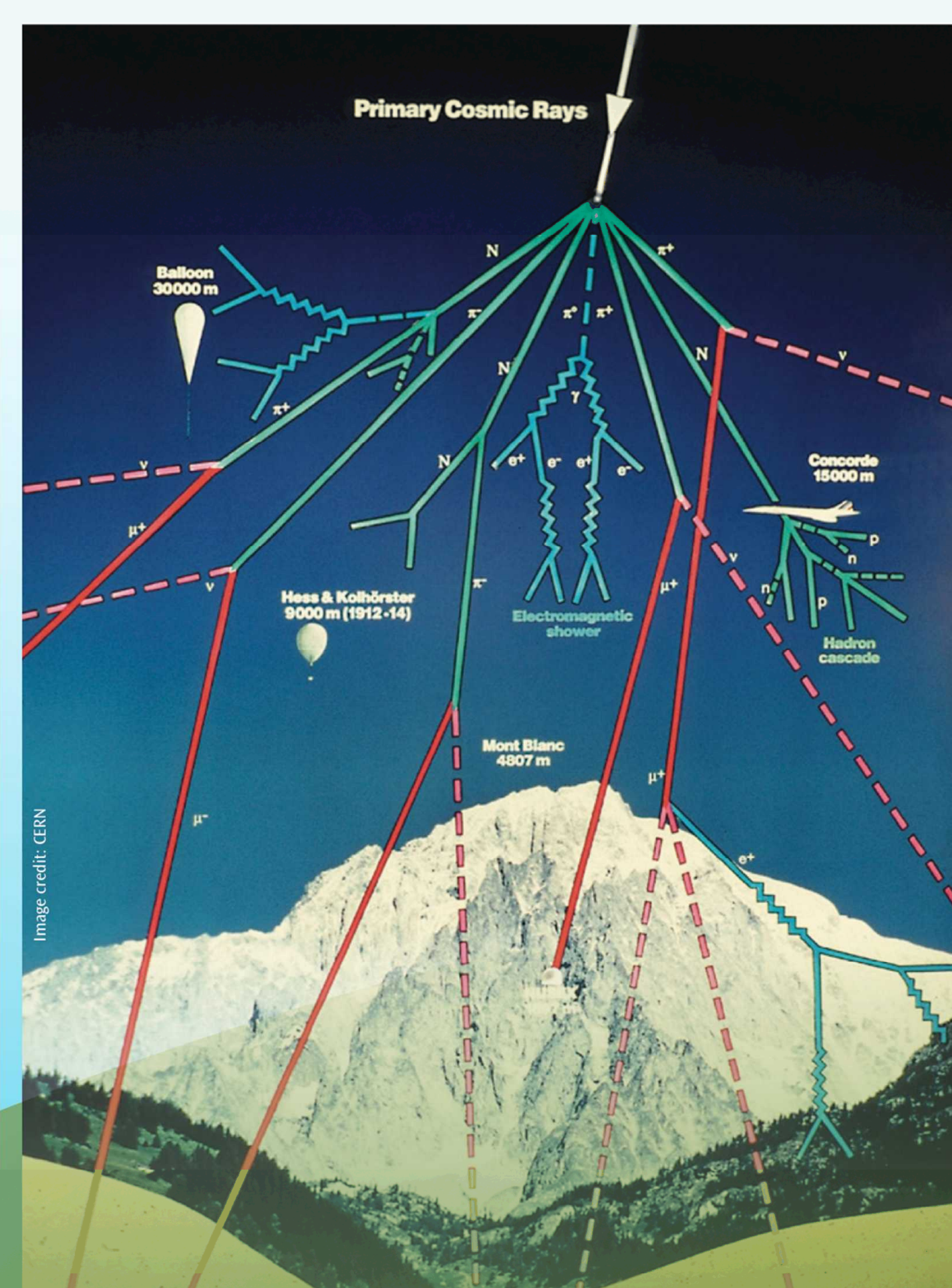
Nedra D. Bonal, Leiph A. Preston, Daniel J. Dorsey *Sandia National Laboratories*

David Schwellenbach, Wendi Dreesen, and J. Andrew Green *National Security Technologies*

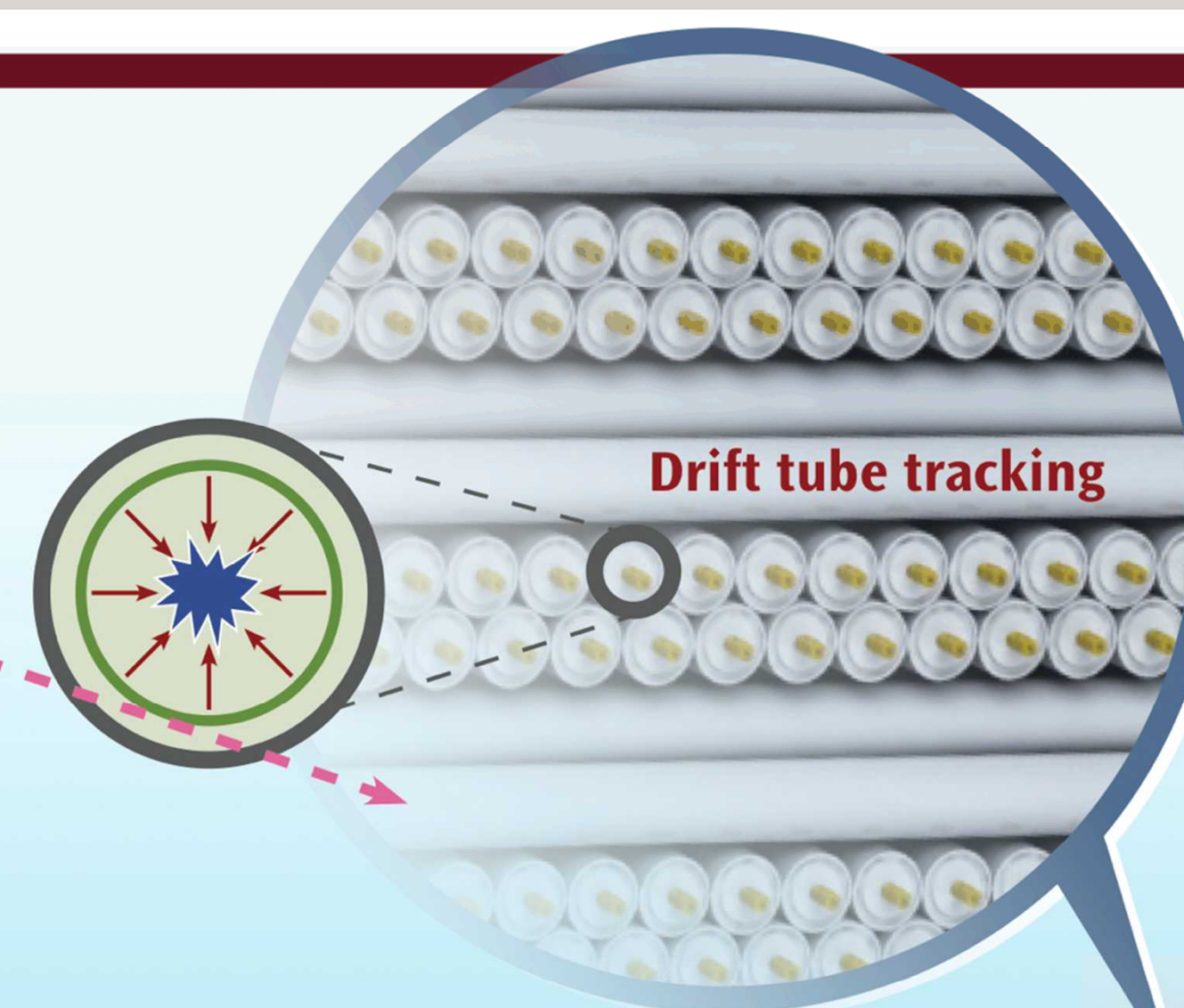


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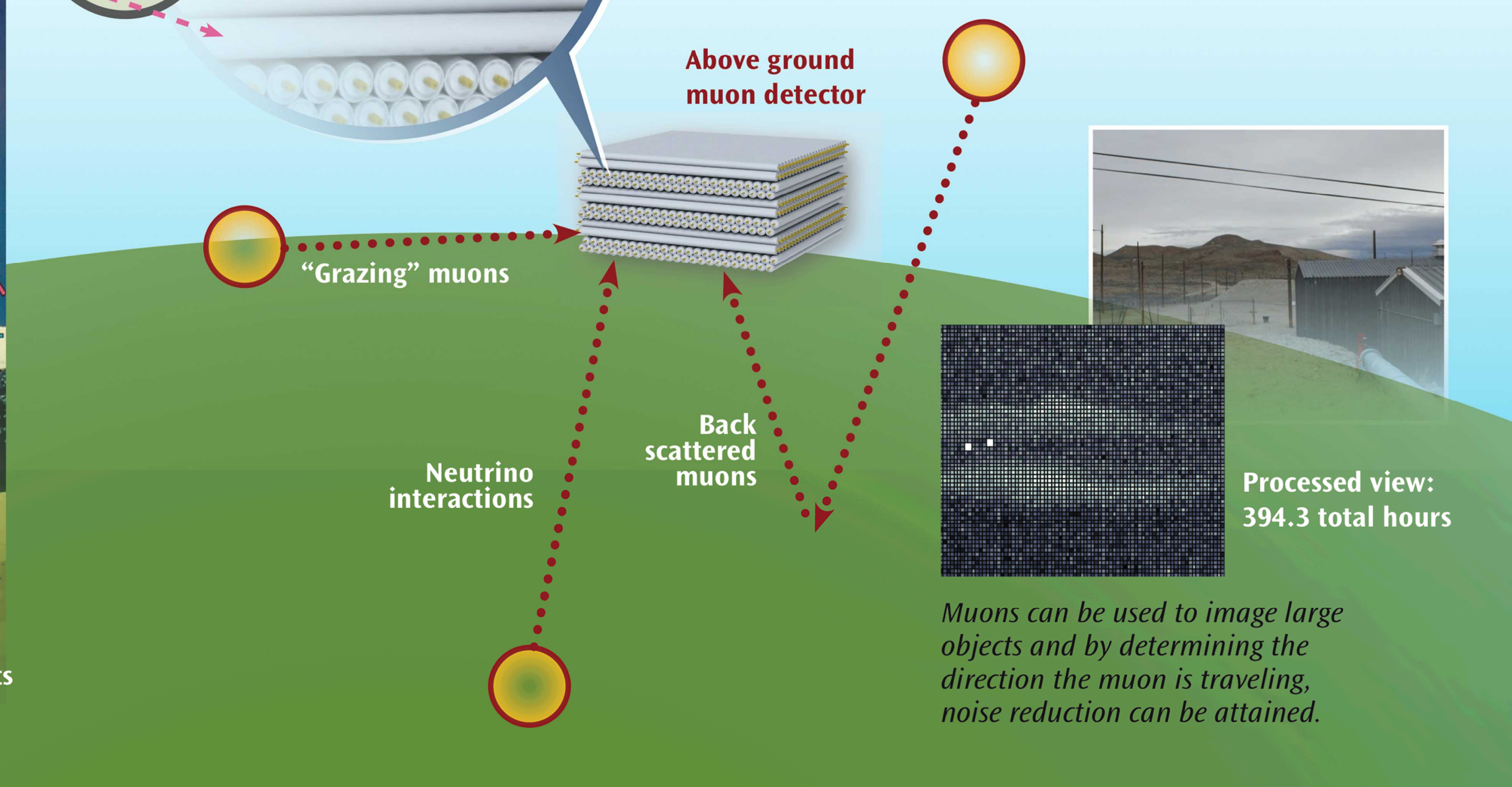


- Muons are naturally occurring subatomic particles from cosmic ray interactions in the upper atmosphere
- Highly penetrating to image thick/deep targets
- Rate of 10K/min/m<sup>2</sup>
- Density dependent



## Upgoing muons

Upgoing muon tracking may help in locating and characterizing underground engineered structures such as tunnels and caverns that are important to areas of energy surety, nonproliferation, and border and facility security.



### VISION:

Utilize upward traveling muons to image objects underground using a detector on the surface.

### PATH:

- Track the direction a muon is traveling to reject the more prolific downgoing muons.
- Obtain statistically significant measurements of the upward muon flux.

### OBJECTIVES:

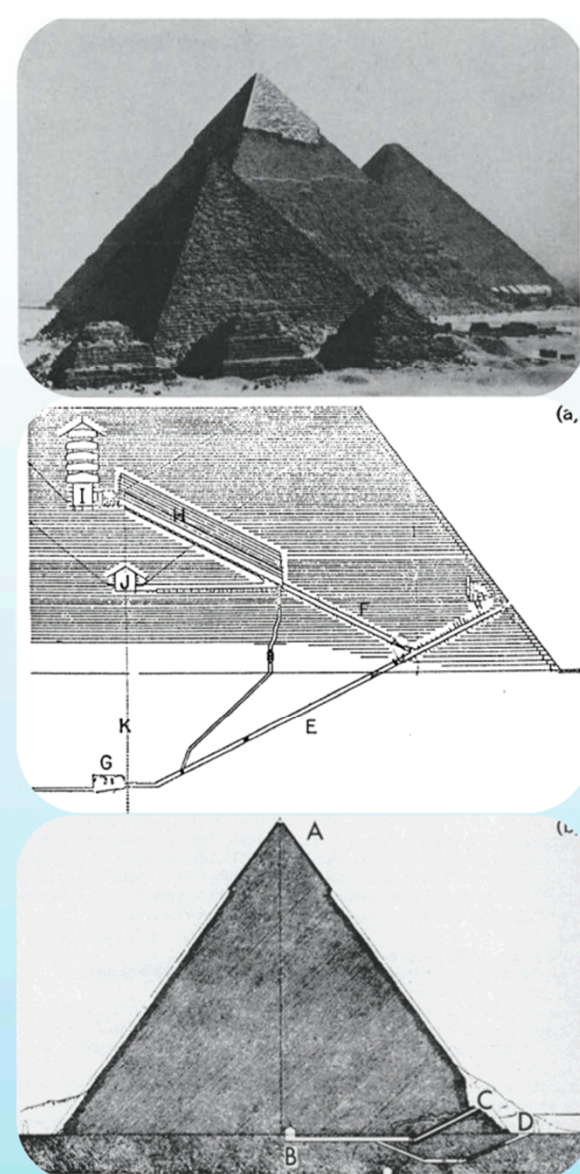
- Determine the feasibility of utilizing upgoing muons for subsurface target characterization.
- Address trade-offs between acquisition time, density contrast, and target size.

### BENEFITS:

- Saves costs and increases application space.
- No prior knowledge of target is needed.

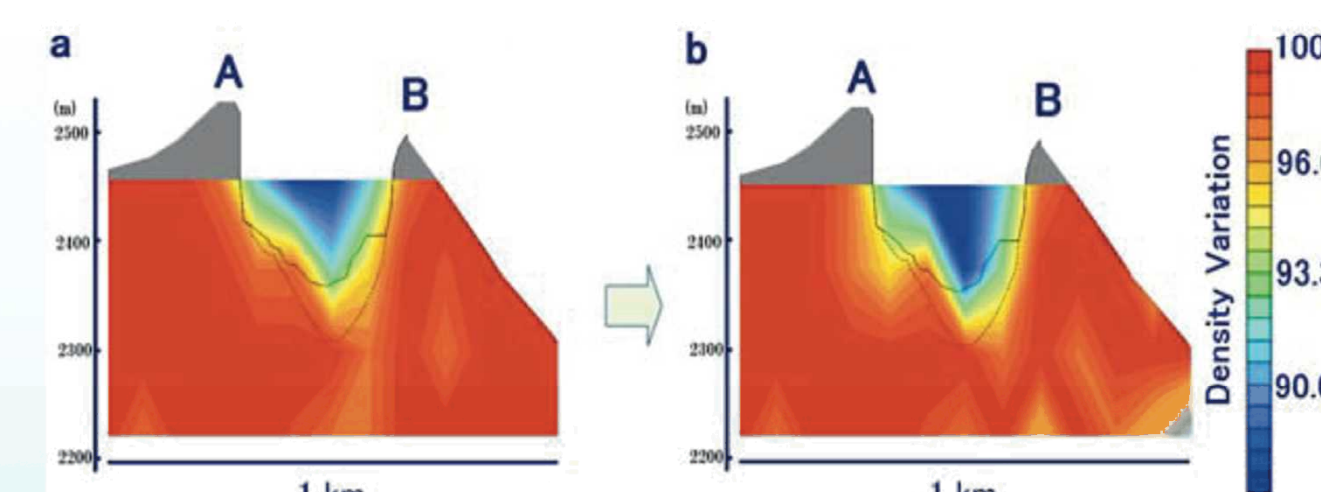
## HISTORY OF MUON IMAGING

### Chephren Pyramid



Alvarez, Luis W., et al., 1970, Search for Hidden Chambers in the Pyramids, Science 167, 832-839.

### Volcano Imaging



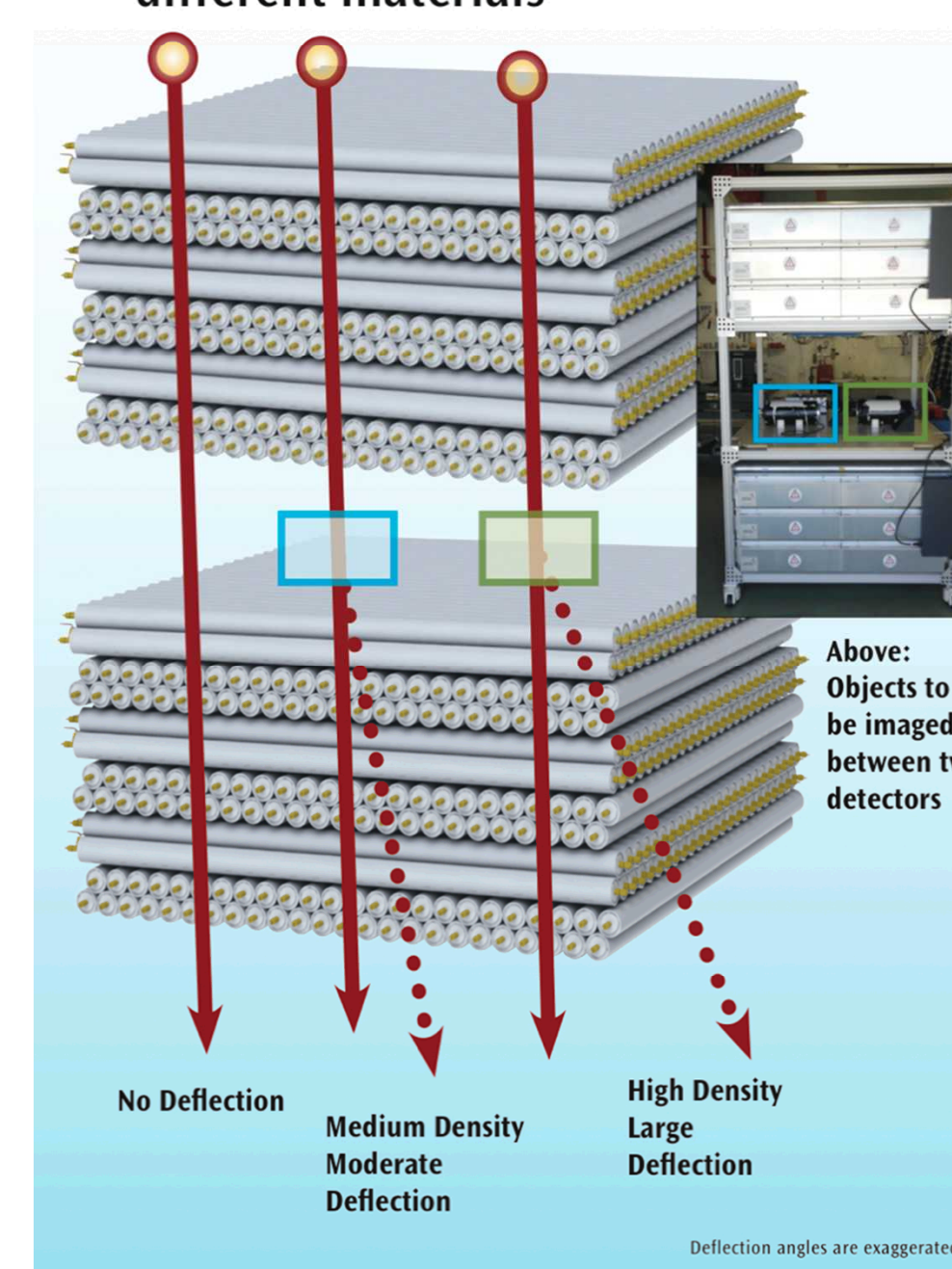
Tanaka, et al., 2009, Detecting a mass change inside a volcano by cosmic-ray muon radiography (muography): First results from measurements at Asama volcano, Japan, Geophysical Research Letters, v. 36, L17302.



## TOMOGRAPHIC & TELESCOPIC MODES

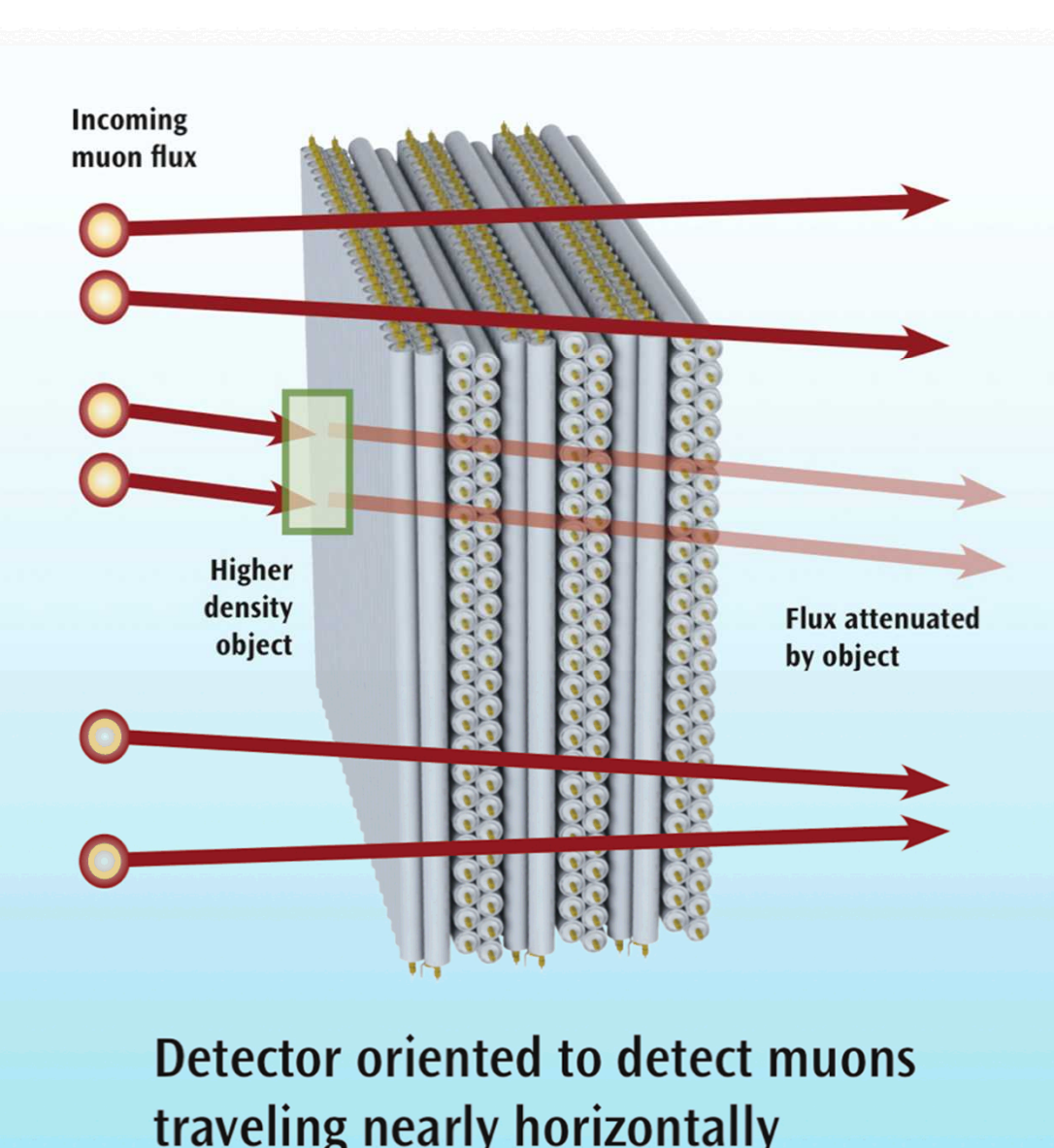
### Tomographic mode

Scattering of the muon through different materials

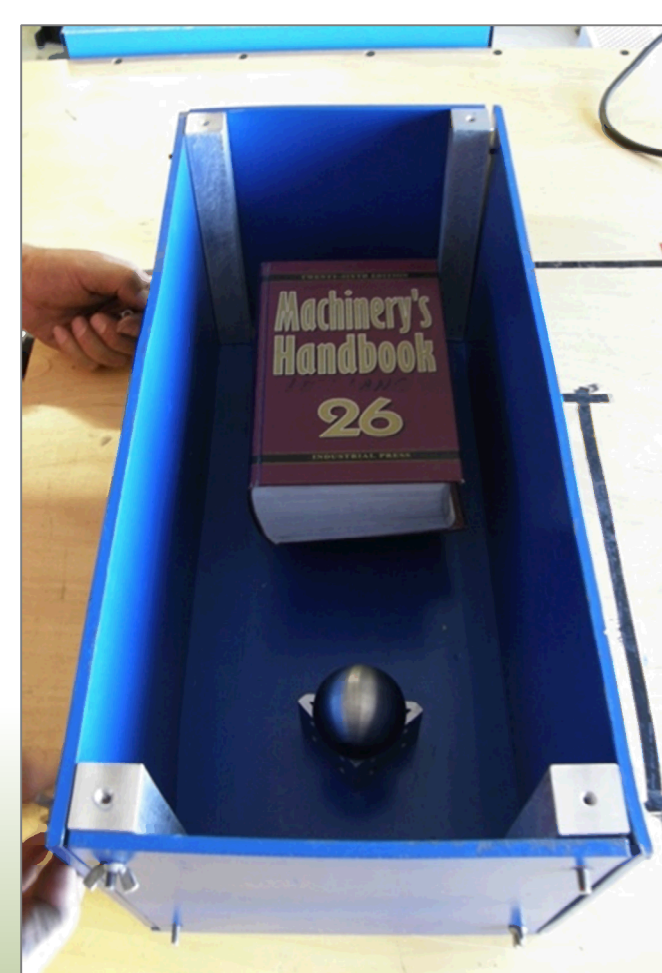


### Telescopic mode

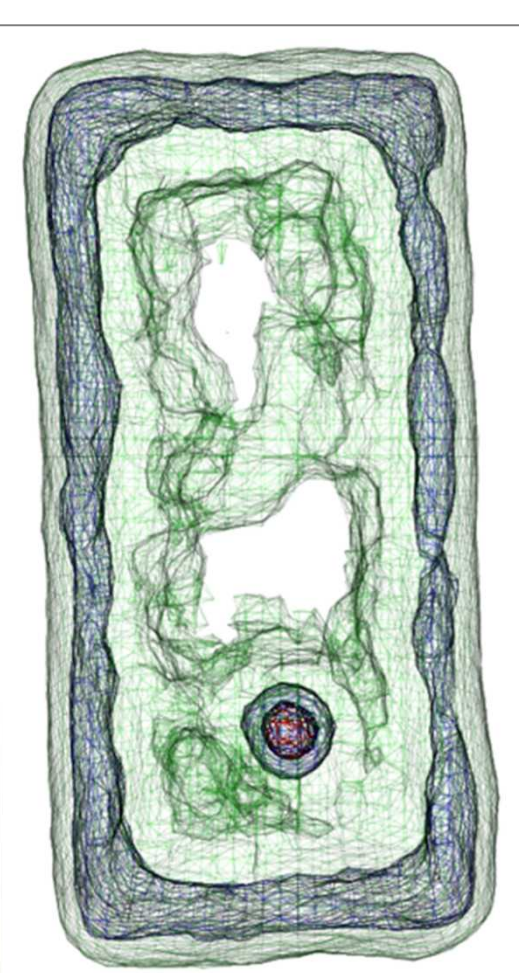
Muon flux attenuation through different materials



## DETECTING CONCEALED OBJECTS

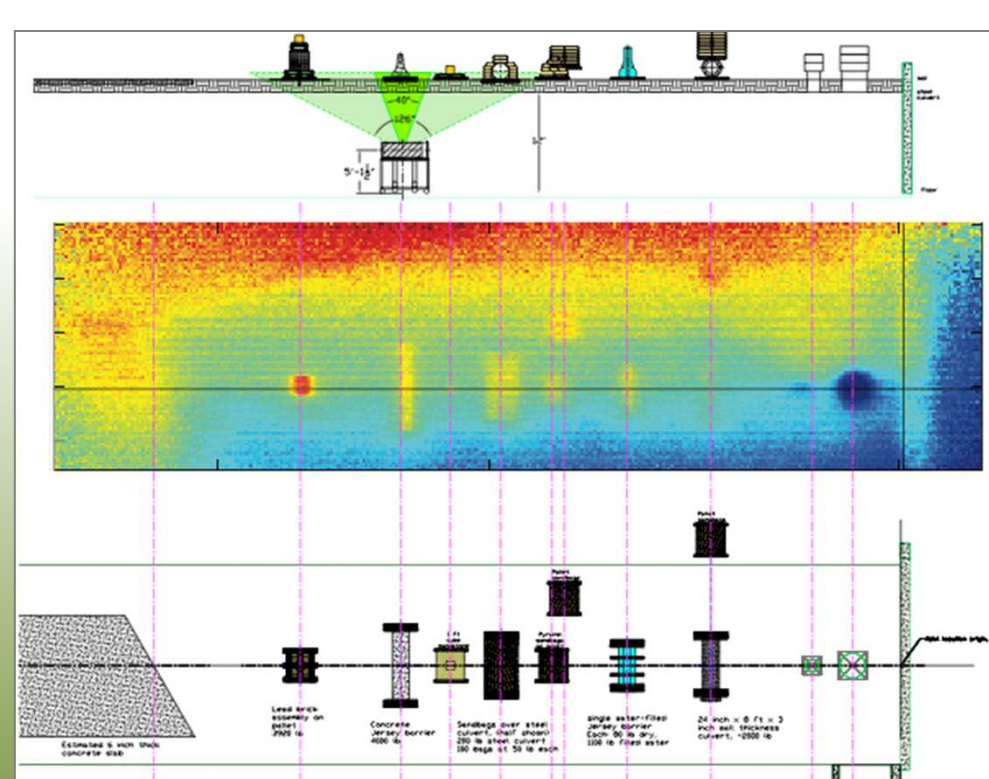


Picture of setup



Processed image

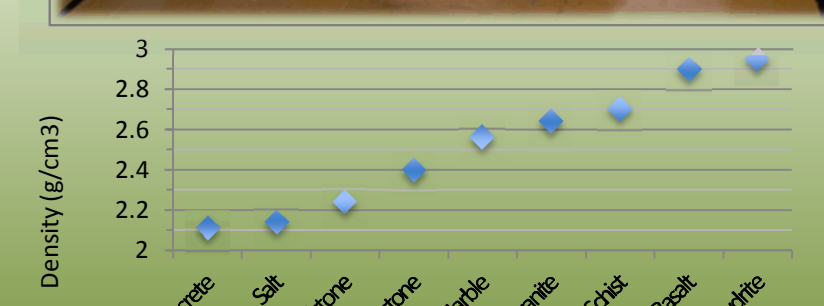
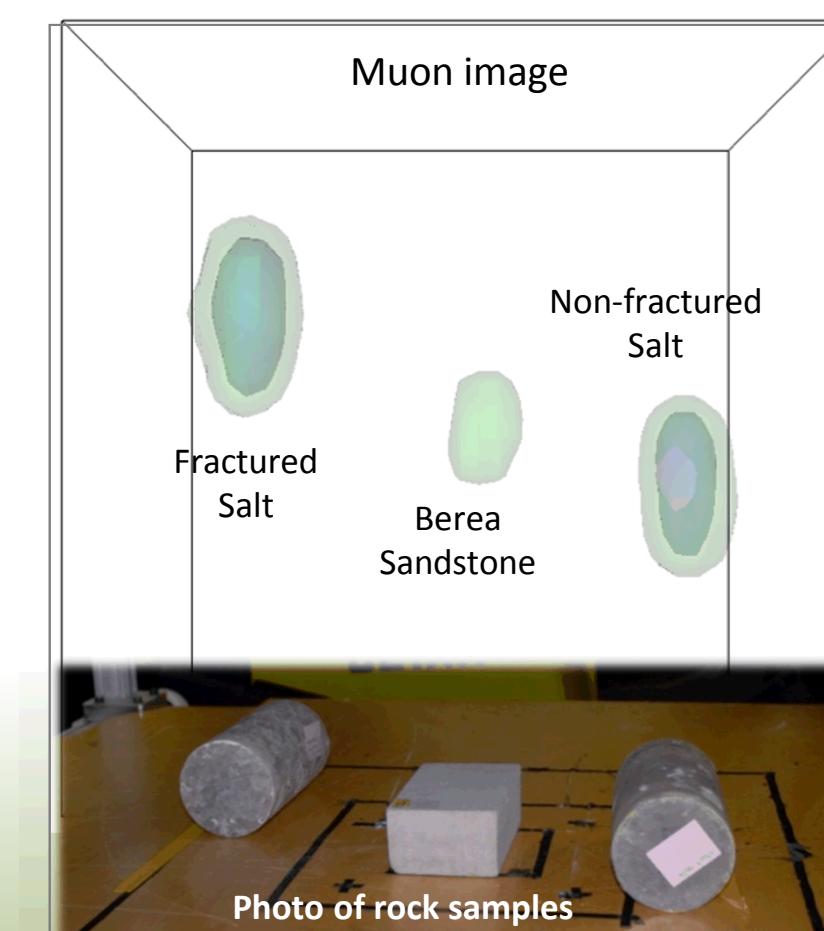
Below: Muons can not only accurately map the size and locations of objects, but also the variability in density of objects.



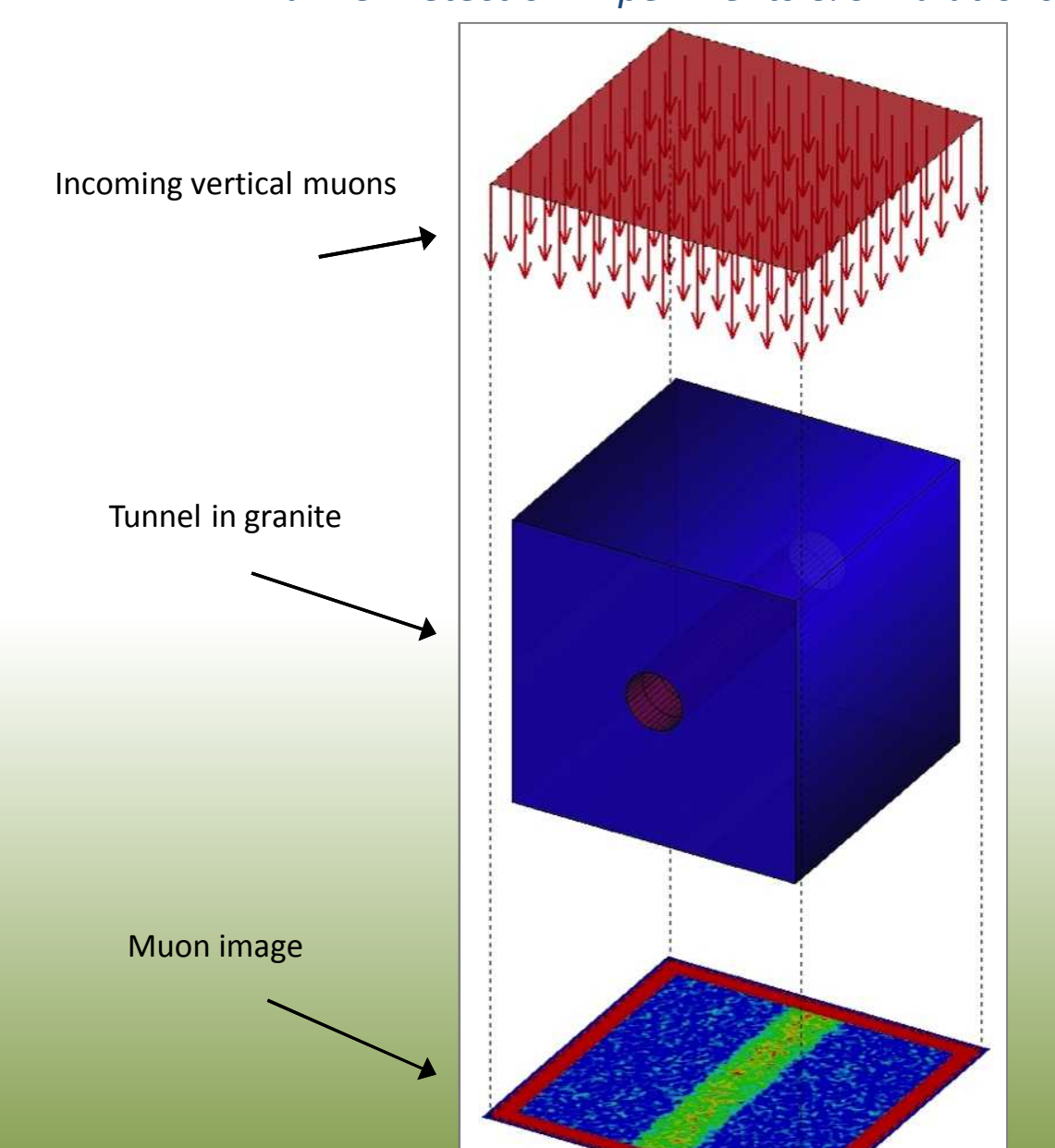
Above: Muons can be used to image objects concealed in lead (blue box shown without top cover), which is a benefit over x-rays. Also, muons can image low density (book) and high density (tungsten sphere) objects.

## CURRENT WORK

### Rock Density Estimation & Simulation



### Tunnel Detection Experiments & Simulations



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