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Imaging large object structure using cosmic muons

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WIV2023
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CONTENTS

/01

Induction

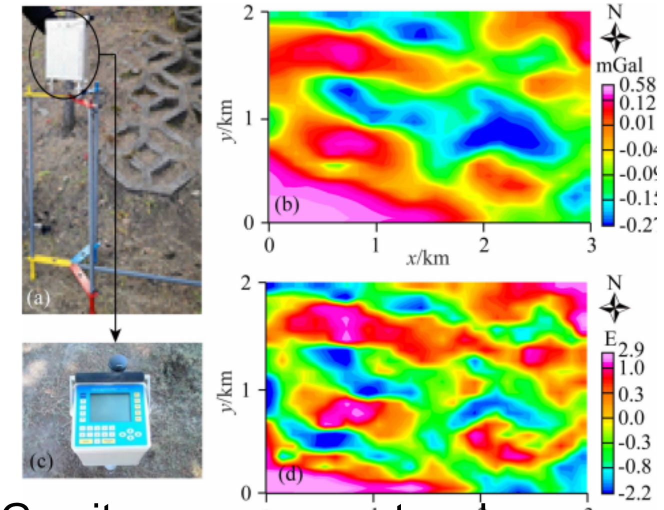
Imaging of density structure

Density Structures Imaging

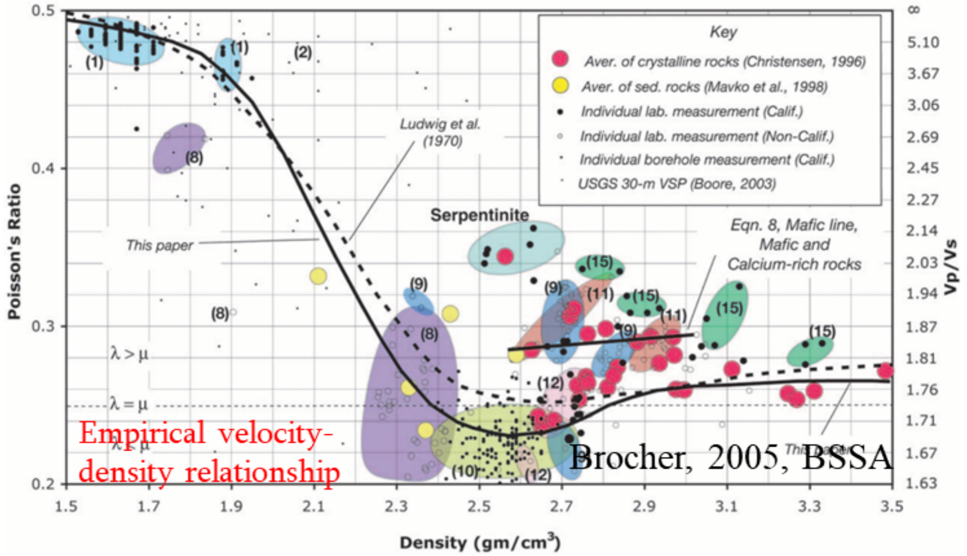
- Density is **a fundamental physical property** of matter that plays a crucial role in geophysical imaging,
- High-resolution and high-precision imaging of density structures has a **wide range of applications**, including mineral exploration, earthquake hazard assessment, and environmental monitoring.

Gravity and Seismic Imaging Method

- Gravity is an important method, but it suffers **from low resolution and strong non-uniqueness**
- Seismic imaging is also an important method, but it is **affected by errors in the relationship** between velocity and density.

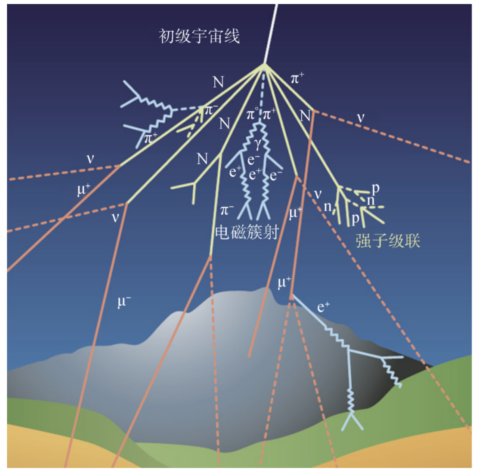


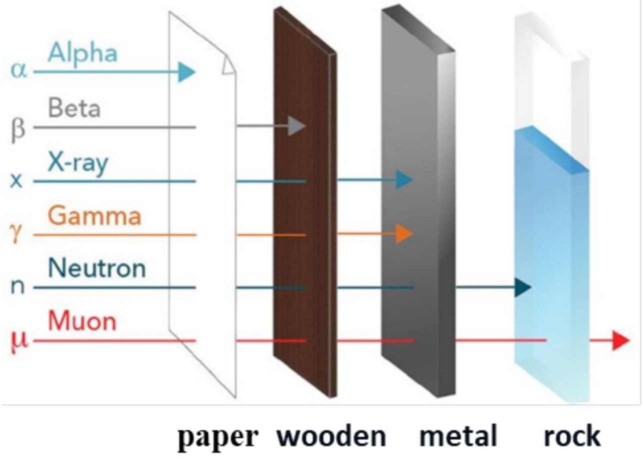
Gravity measurement and abnormal



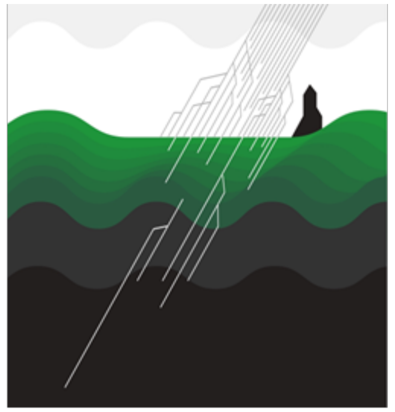
Cosmic Muon Imaging Method

- Provide **high-resolution and high-precision** density structure with a **spatial resolution** of up to a few meters., Not effected by surface topography or weather conditions,
- Non-destructive and Non-invasive
- Strong penetrating power and **direct related to density**





Comparison of penetrating power


Cosmic Muon can penetrate through hundreds of meters of rock

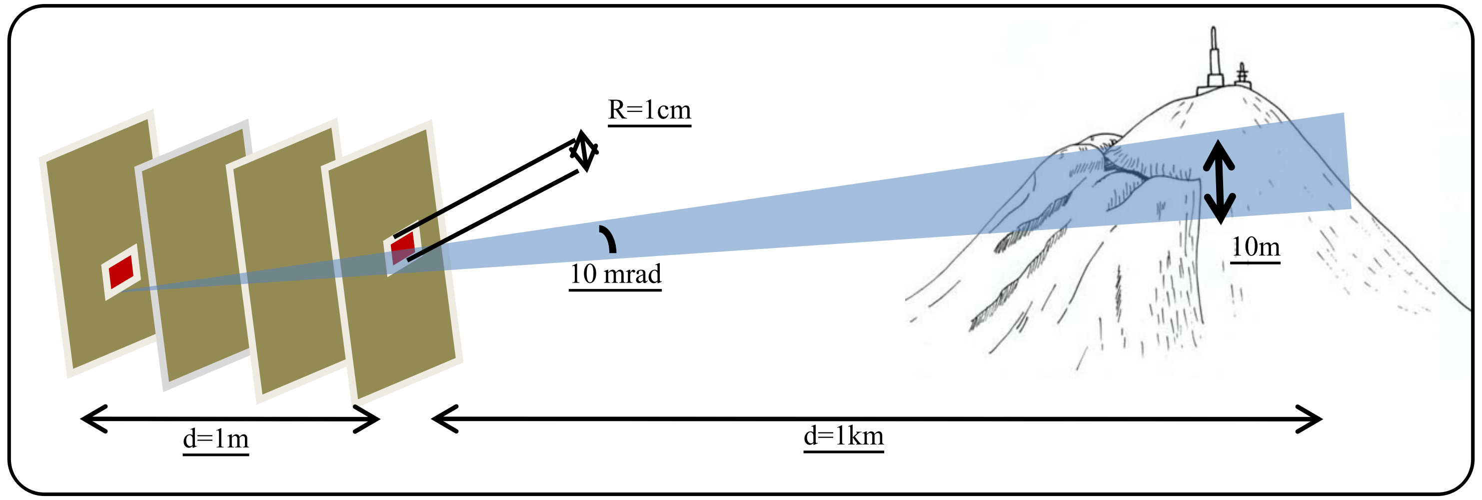
Cosmic muon imaging method is widely used

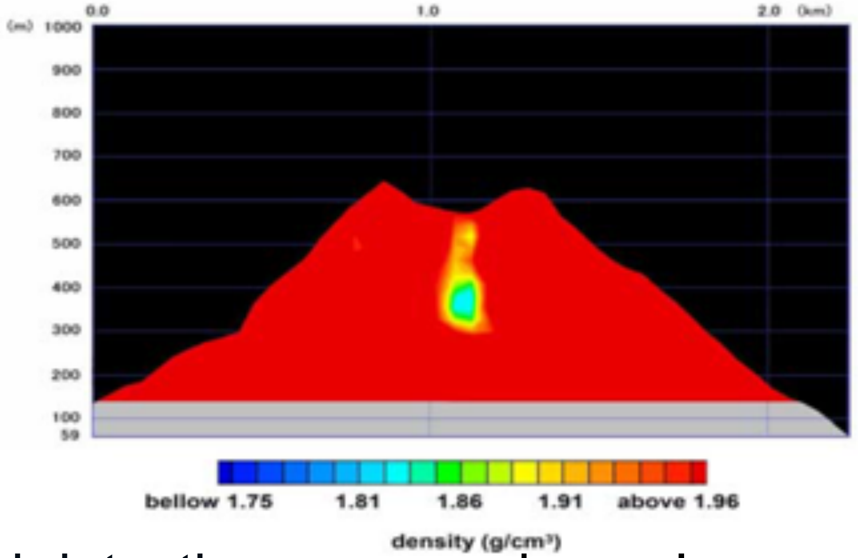
in geological exploration, archaeology, blast furnace, nuclear power plant, and nuclear waste inspection…

Summary of cosmic muon potential application

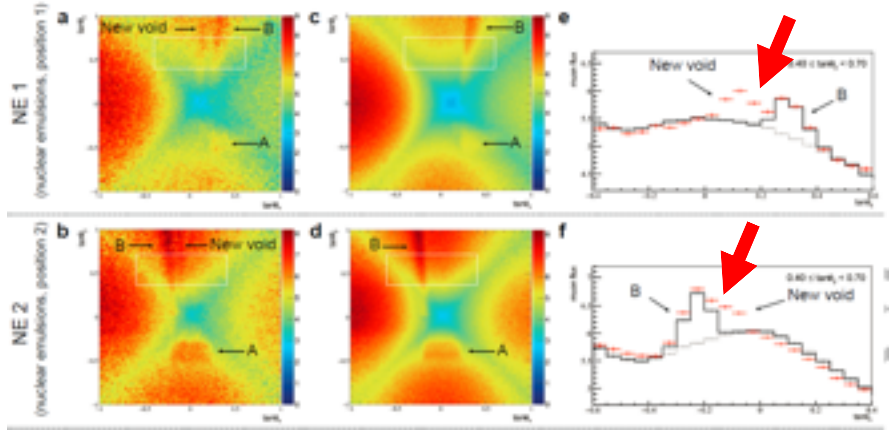
Typical applications of muon transmission imaging

widely applied to the detection and dynamic monitoring of density structures in large objects

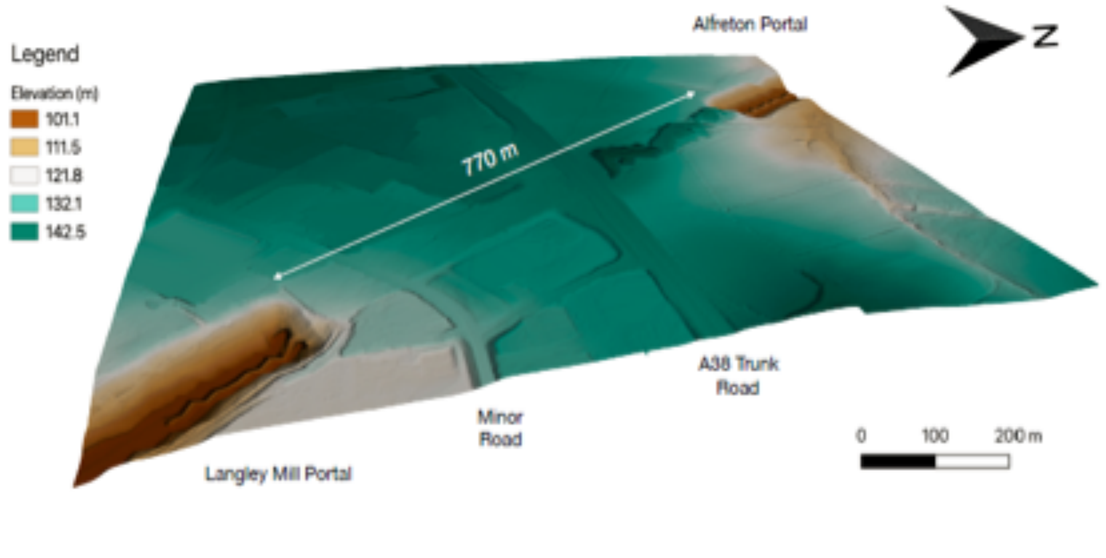




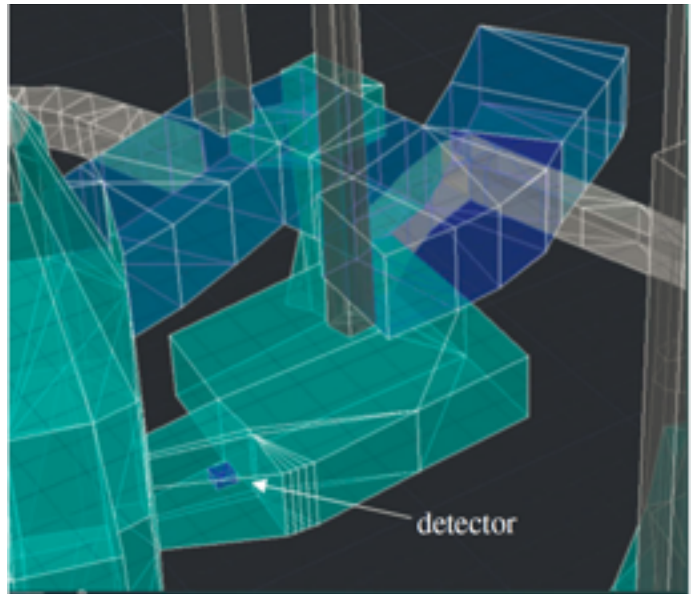
Monitoring internal density of volcanoes and detecting magma channels



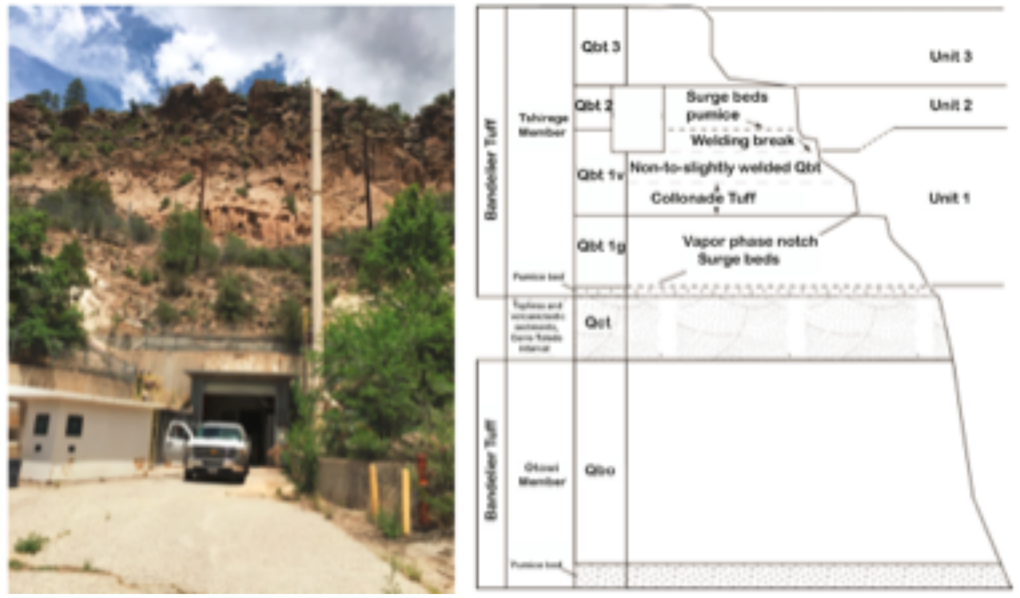
Hidden chambers in pyramids



Monitoring overburden structure of highways and railways tunnels

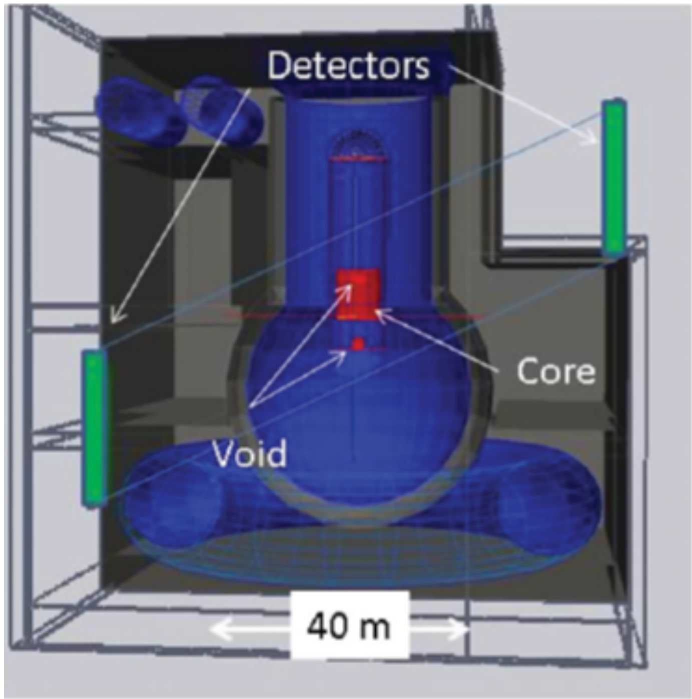


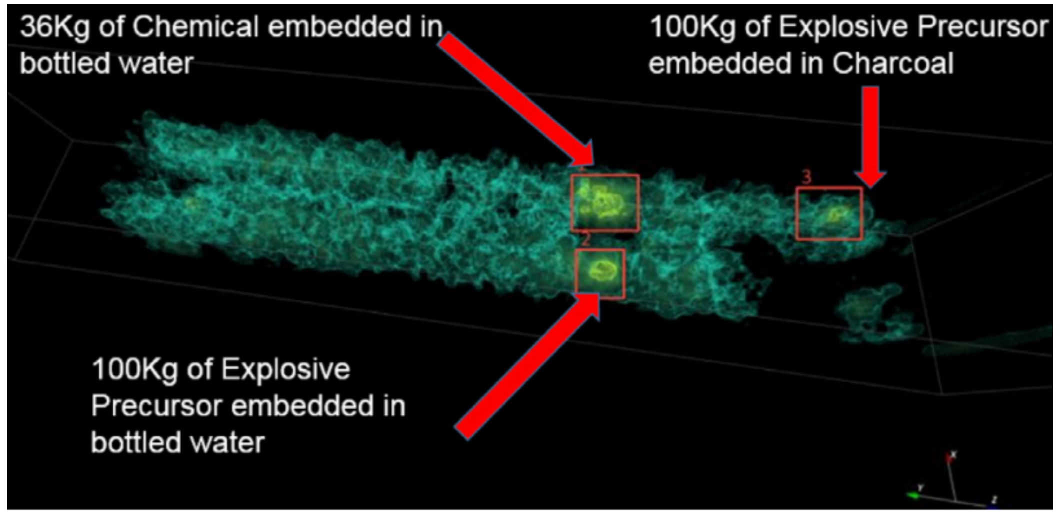
Detection of building structures



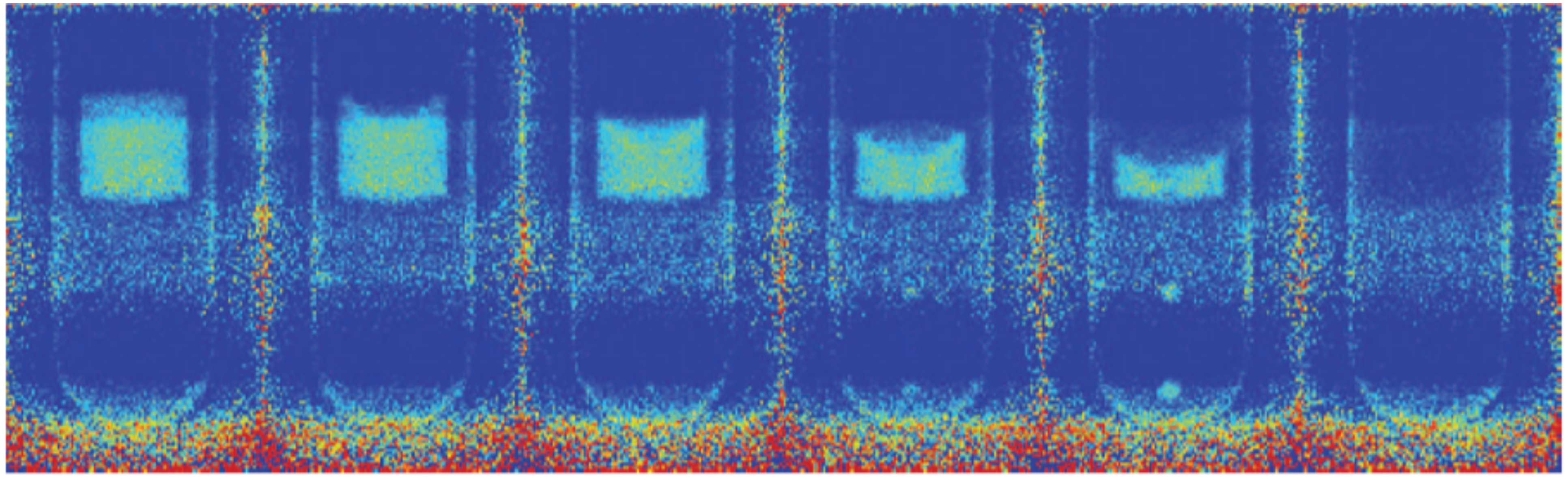
3D monitoring of overburden layers in tunnels

Typical applications of muon scattering imaging





Customs inspection of containers and vehicles



Monitoring nuclear power core, nuclear waste inspection…

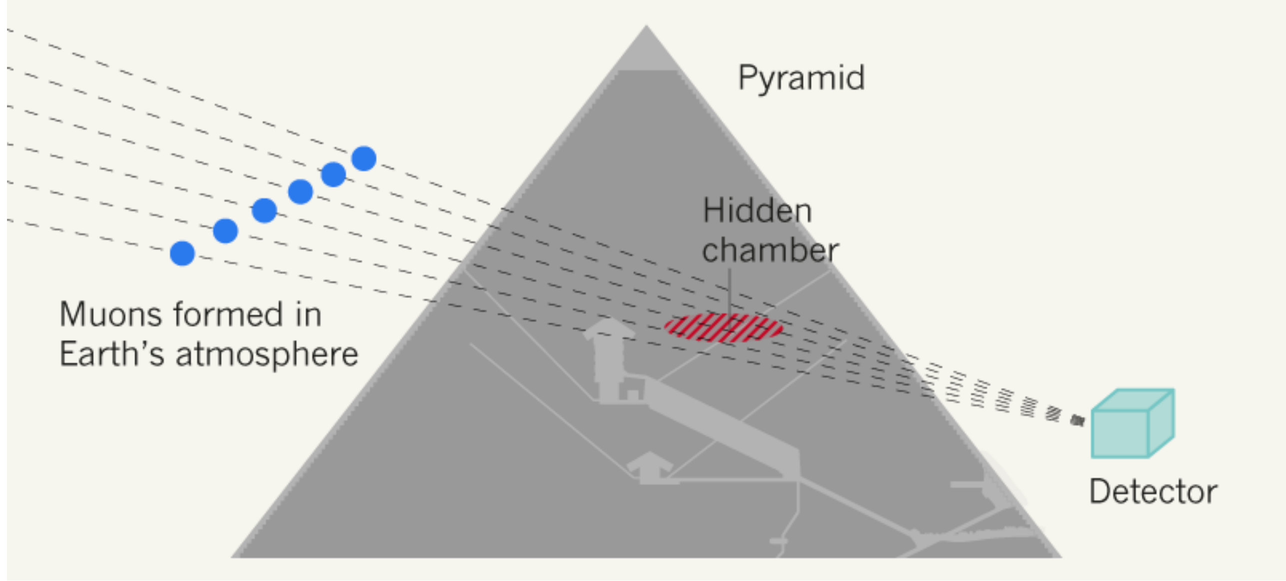
/02

Transmission Imaging Method

Theory， Simulation ability，Instrument

The principle of cosmic muon imaging

- By detecting the flux difference before and after muons penetrate an object, can achieve "CT-like" imaging of the internal density structure of the object;
- Spatial resolution: tens of centimeters ;
- non-contact, passive source, and two-dimensional/three-dimensional imaging



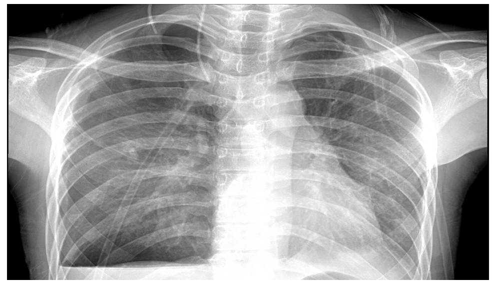
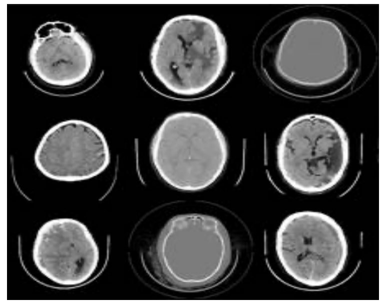
Cosmic muon can be used for imaging the internal density of large objects

$$-\frac{\mathrm{d}E}{\mathrm{d}x}=Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\left(\frac{2m_e c^2\beta^2\gamma^2 W_{\max}}{I^2}\right)-\beta^2-\frac{\delta}{2}\right]$$

$$-\frac{\mathrm{d}E}{\mathrm{d}\varrho}=a(E)+b(E)E$$

$$\varrho(L)\equiv\int_L\rho(\xi)\,\mathrm{d}\xi \quad\Longleftrightarrow\quad \tau=\int_L s(\xi)\,d\xi$$

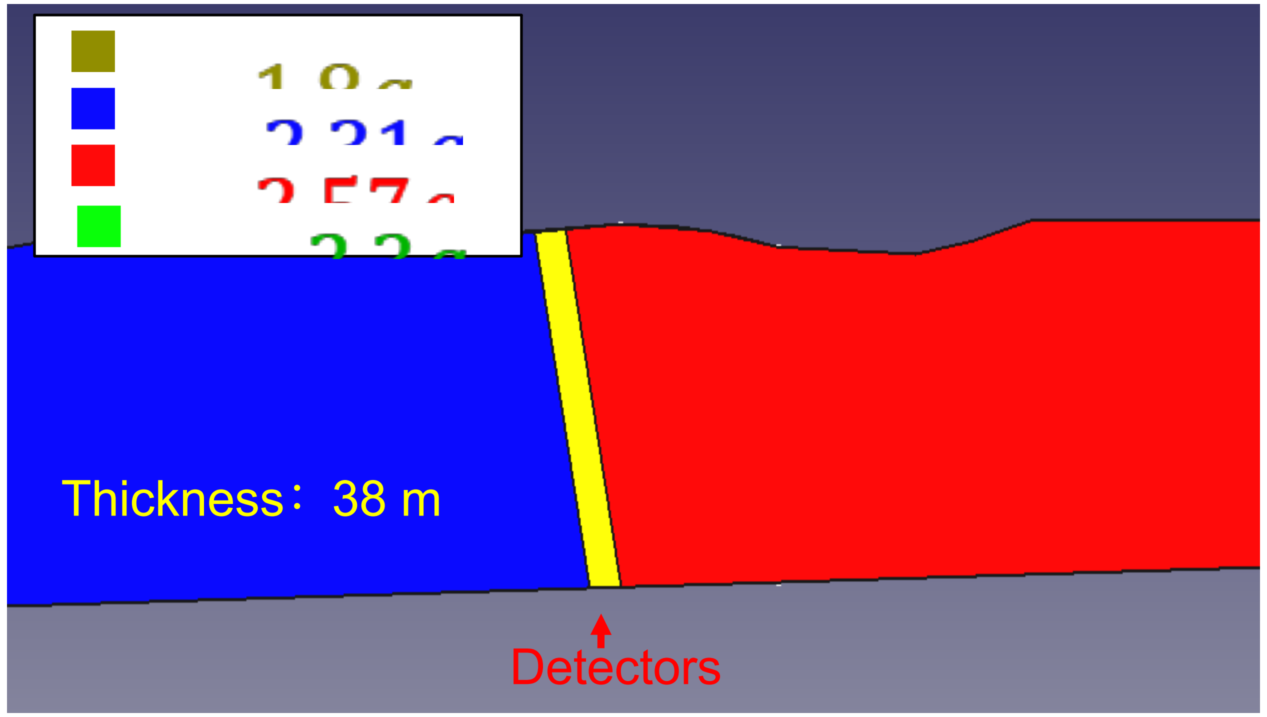


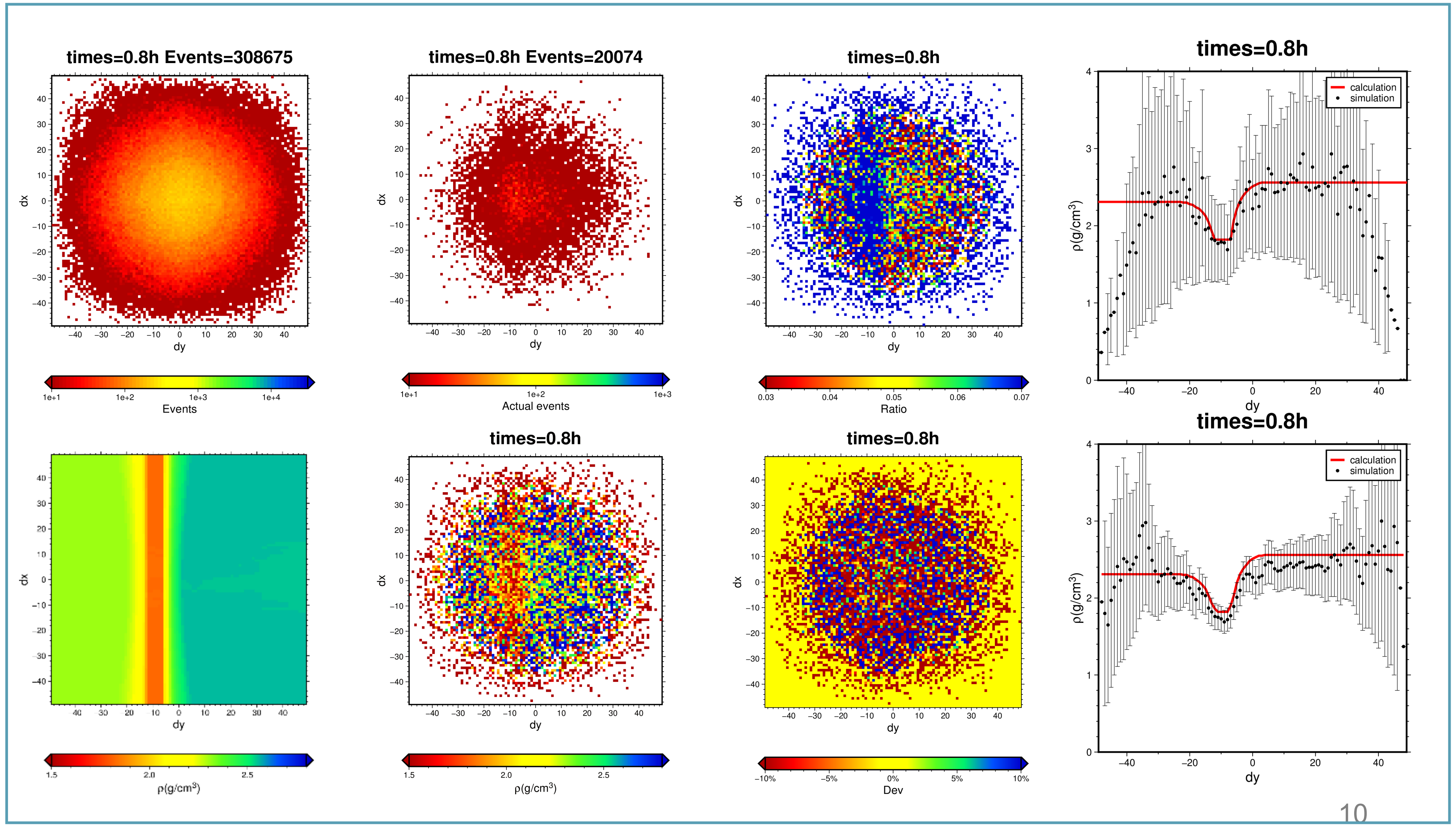



Single point **Radiography** Multiple points **Tomography**

MC Simulation — 2D imaging ability

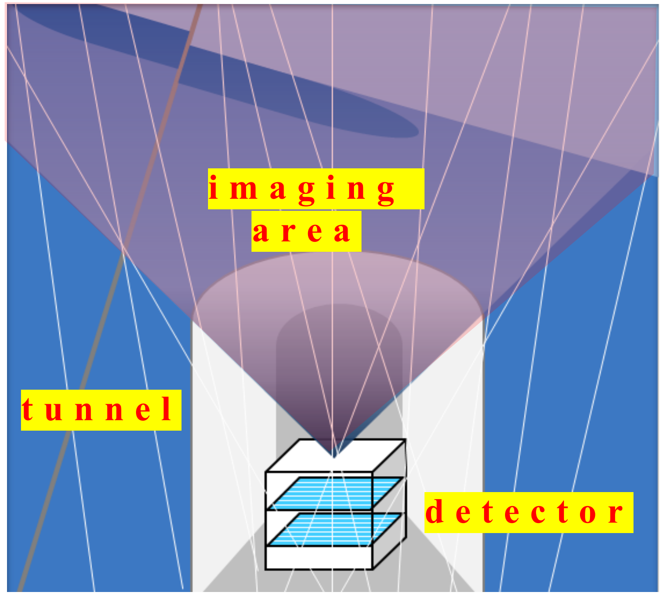
- For a 38-meter-thick overburden, it takes 2 hours to reconstruct the 20% low-density fault zone.
- The error decreases with the observation time (or muon flux increases) to ~1%.



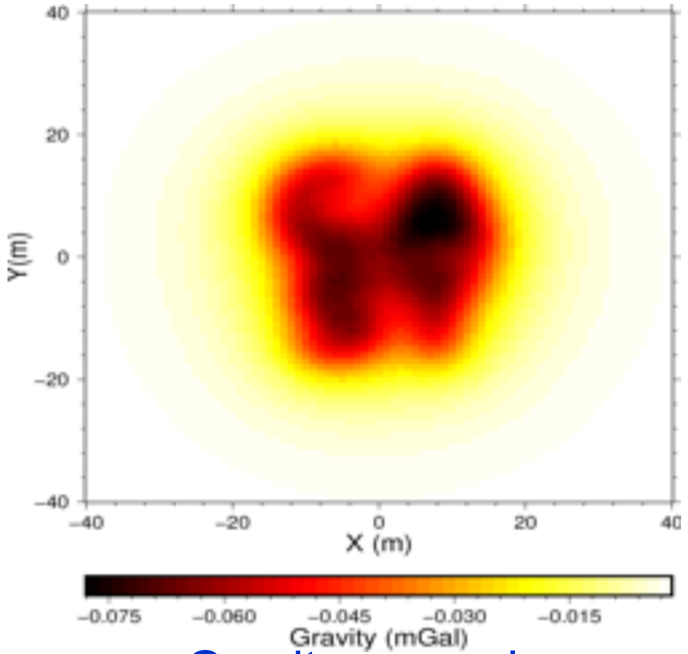


1m² detector, simulated imaging of a low-density fault zone in a 38-meter-thick overburden.

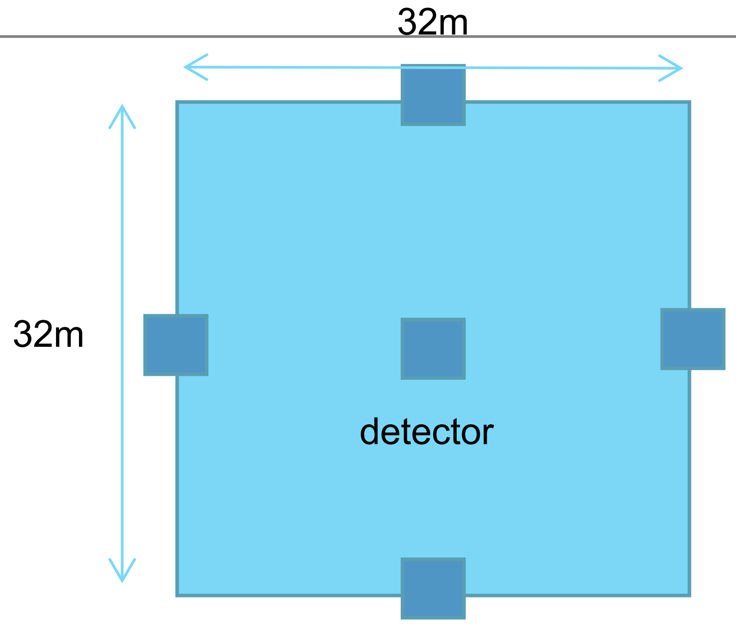
MC Simulation — 3D imaging ability



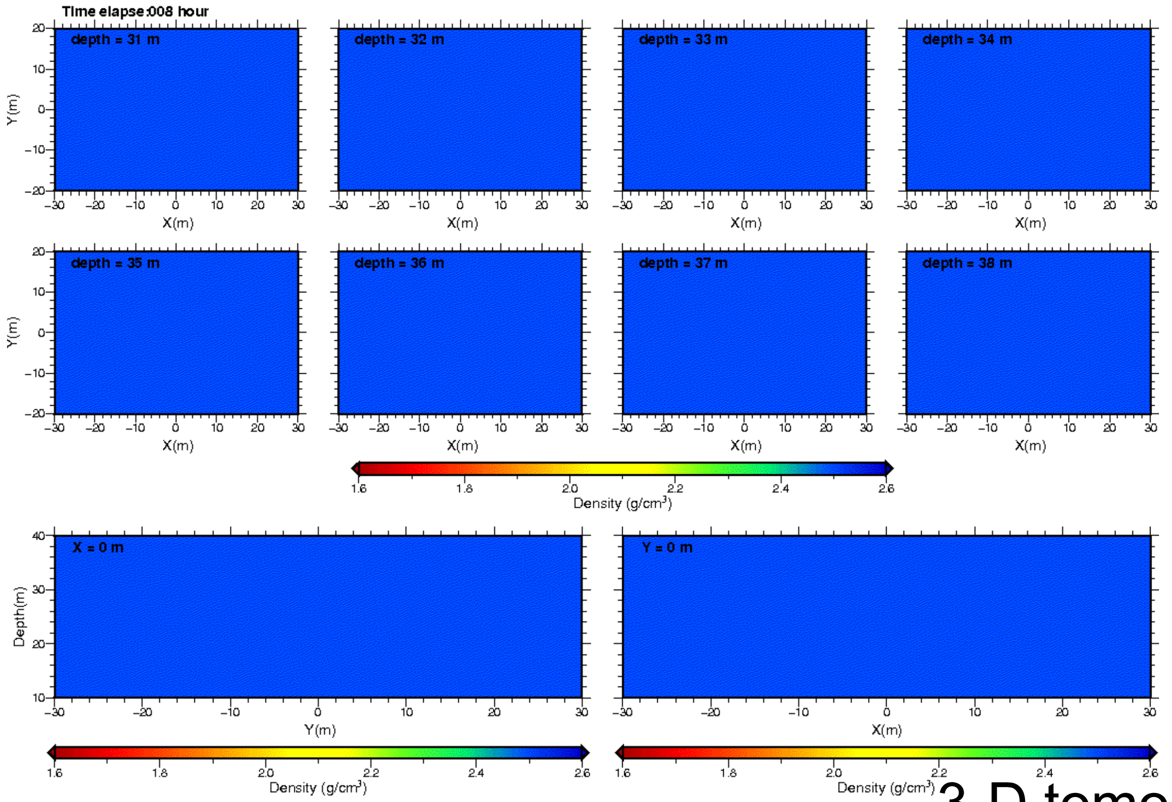
30 m thick overburden +
5 m thickness+40% low density abnormal

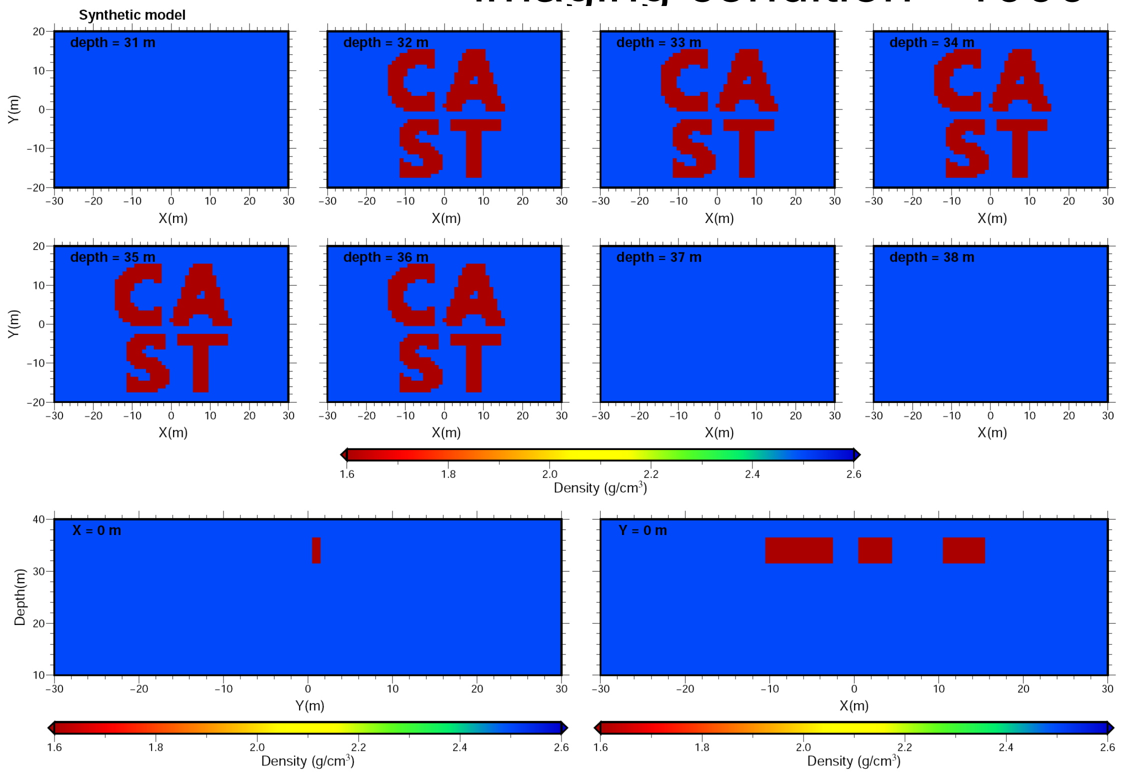


Gravity anomaly：
~50~70 uGal



5 detectors, 1m x 1m,
position resolution 5 cm；
imaging condition >1000





3-D tomogrphy with depth constraints

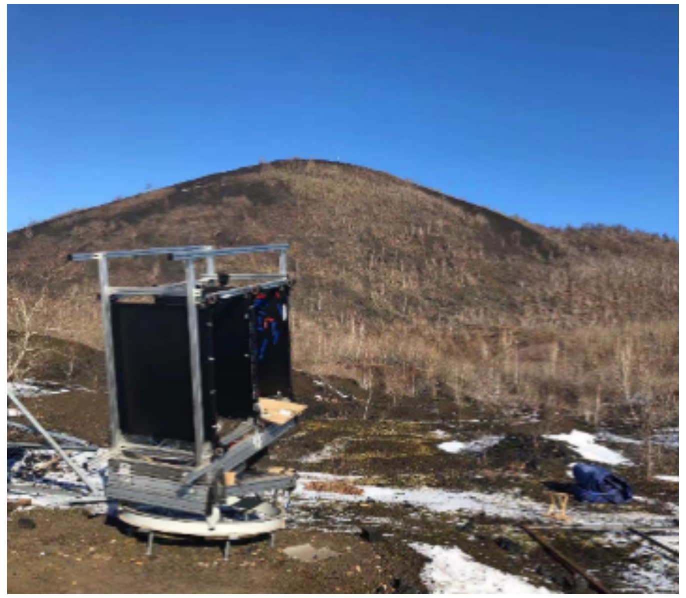
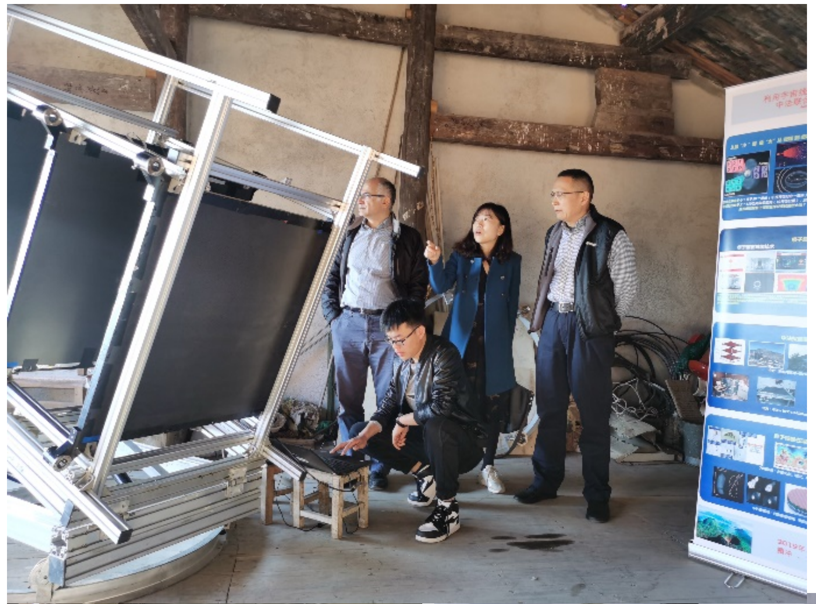
/03

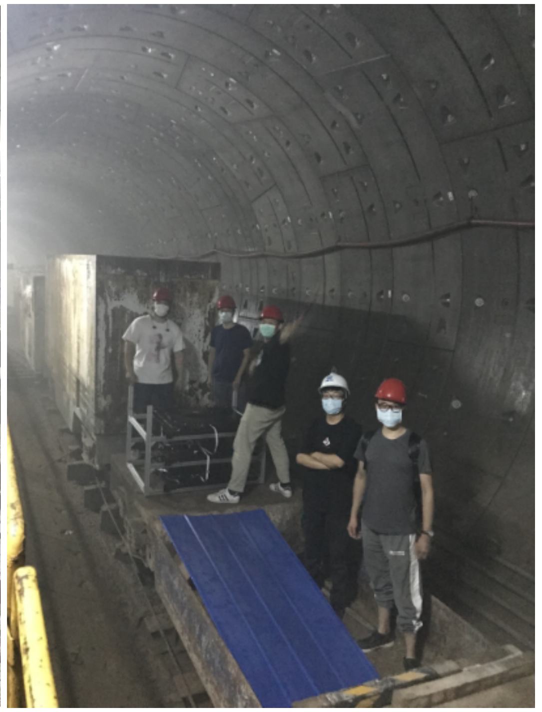
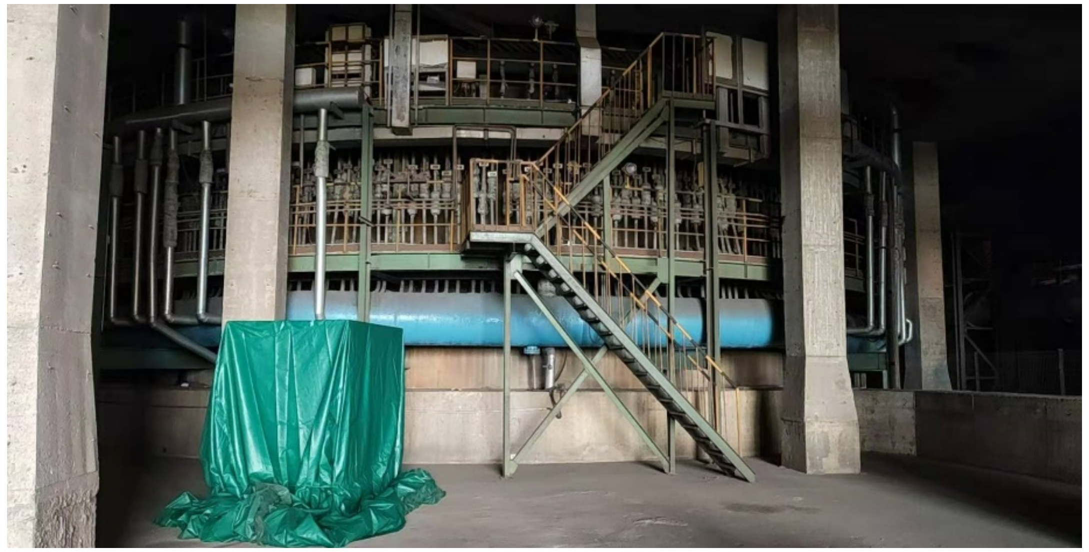
Experiment Observation

Tunnel，Volcano，Blast Furnace，Cultural Artifacts…

Muon imaging experiment activities



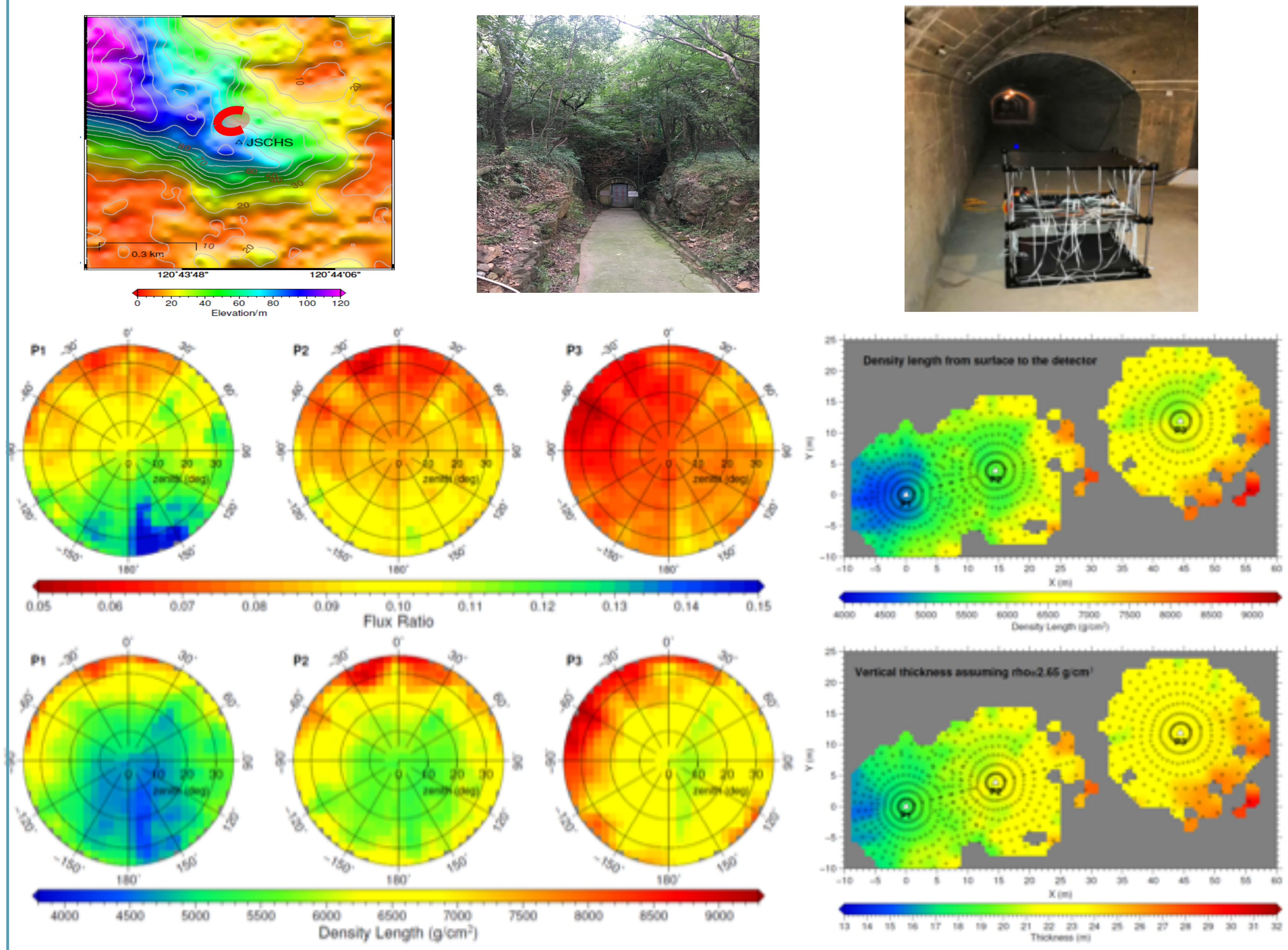









Tunnel -- Changshu seismic station



Jinst
Published by IOP Publishing for Sissa Medialab
Received: March 30, 2020
Revised: May 2, 2020
Accepted: May 11, 2020
Published: June 15, 2020

Cosmic muon flux measurement and tunnel overburden structure imaging

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Abstract: We present a cosmic ray muon radiography experiment for measuring the muon flux and imaging the tunnel overburden structures in Changshu, China. The device used in this study is a tracking detector based on the plastic scintillator with SiPM technology, which can be conveniently operated in field works. The compact system with sensitive area of $6400 cm^2$ can measure the angular distribution of cosmic muons. It's able to image the overburden density length from the surface of overburden to the detector along the muon tracks. The open sky muon flux measurement outside the tunnel has a good agreement with the modified Gassier Formula model. The distributional pattens of muon flux at three positions inside the tunnel are very similar to that of open sky. Assuming the average density of overburden compact sandstone is $2.65 g/cm^3$, the overburden thickness can be obtained from the density length derived from the difference of muon flux inside and outside the tunnel. Moreover, for known penetrated lengths (i.e., topography of overburden), the density anomalies of the overburden can also been obtained. This study suggests a potential application for imaging and detecting subsurface structures in civil engineering, tunnels or caverns with the cosmic ray muon telescope.

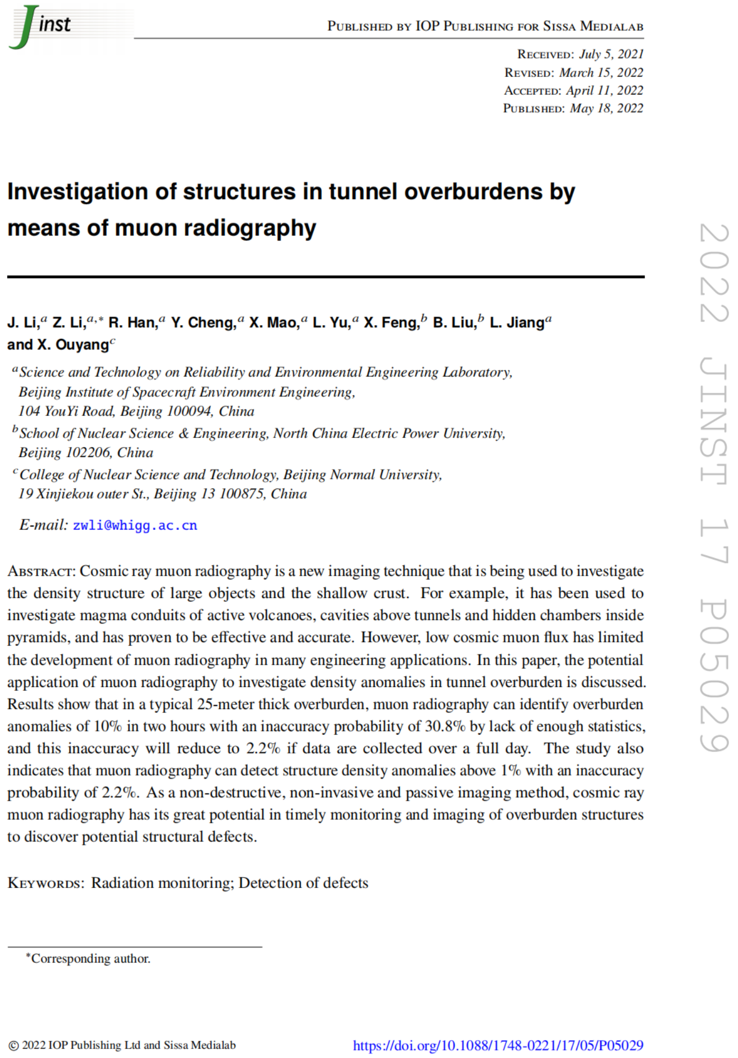
Keywords: Muon spectrometers; Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators)

ArXiv ePrint: 2003.12376

[1]Corresponding author.

https://doi.org/10.1088/1748-0221/15/06/P06019

2020 JINST 15 P06019



Jinst
Published by IOP Publishing for Sissa Medialab
Received: July 5, 2021
Revised: March 15, 2022
Accepted: April 11, 2022
Published: May 18, 2022

Investigation of structures in tunnel overburdens by means of muon radiography

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Abstract: Cosmic ray muon radiography is a new imaging technique that is being used to investigate the density structure of large objects and the shallow crust. For example, it has been used to investigate magma conduits of active volcanoes, cavities above tunnels and hidden chambers inside pyramids, and has proven to be effective and accurate. However, low cosmic muon flux has limited the development of muon radiography in many engineering applications. In this paper, the potential application of muon radiography to investigate density anomalies in tunnel overburden is discussed. Results show that in a typical 25-meter thick overburden, muon radiography can identify overburden anomalies of 10% in two hours with an inaccuracy probability of 30.8% by lack of enough statistics, and this inaccuracy will reduce to 2.2% if data are collected over a full day. The study also indicates that muon radiography can detect structure density anomalies above 1% with an inaccuracy probability of 2.2%. As a non-destructive, non-invasive and passive imaging method, cosmic ray muon radiography has its great potential in timely monitoring and imaging of overburden structures to discover potential structural defects.

Keywords: Radiation monitoring; Detection of defects

*Corresponding author.

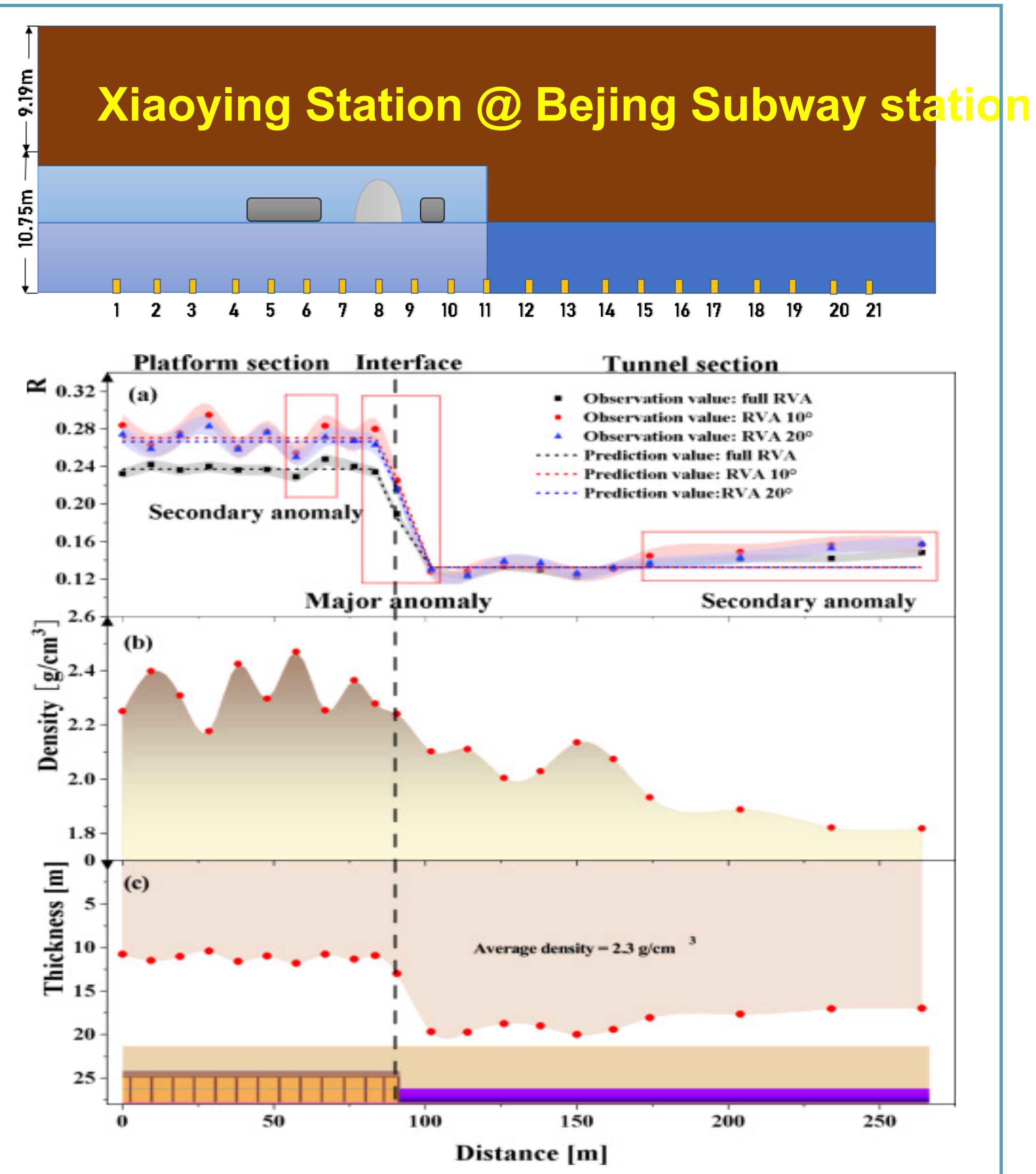
https://doi.org/10.1088/1748-0221/17/05/P05029

2022 JINST 17 P05029

Muon ratio and density structure from the perspective of a detector

Tunnel -- Xiaoying subway station

Continuous observation for 1 hour can yield the average density structure of the overburden in a subway



Muon radiography experiments on the subway overburden structure detection

Xin Mao[a,*], Zhiwei Li[a,*], Shuning Dong[b], Jingtai Li[a], Jianming Zhang[c], Jie Pang[c], Yaping Chen[a], Bin Liao[d], Xiaoping Ouyang[d], Ran Han[a,*]

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Abstract

Muon radiography is an innovative and non-destructive technique for internal density structure imaging, based on measuring the attenuation of cosmic-ray muons after they penetrate the target. Due to the strong penetration ability of muons, the detection range of muon radiography can reach the order of hundreds of meters or even kilometers. Using a portable muon detector composed of plastic scintillators and silicon photomultipliers, we performed a short-duration($1\,h$) flux scanning experiment of the overburden above the platform and tunnel of the Xiaoying West Road subway station under construction. With the observation direction facing up, the detector is placed on the north side of the track and moved eastward from the platform section inside the station to the tunnel section. The scanning length is $264\,m$ and a total of 21 locations are observed. By comparing the observed and predicted values of the muon survival ratio at different locations, the experiment accurately detects the jump in thickness at the interface of the platform section and tunnel section. Furthermore, unknown anomalies caused by random placed light brick piles and side passage mouth above the observation

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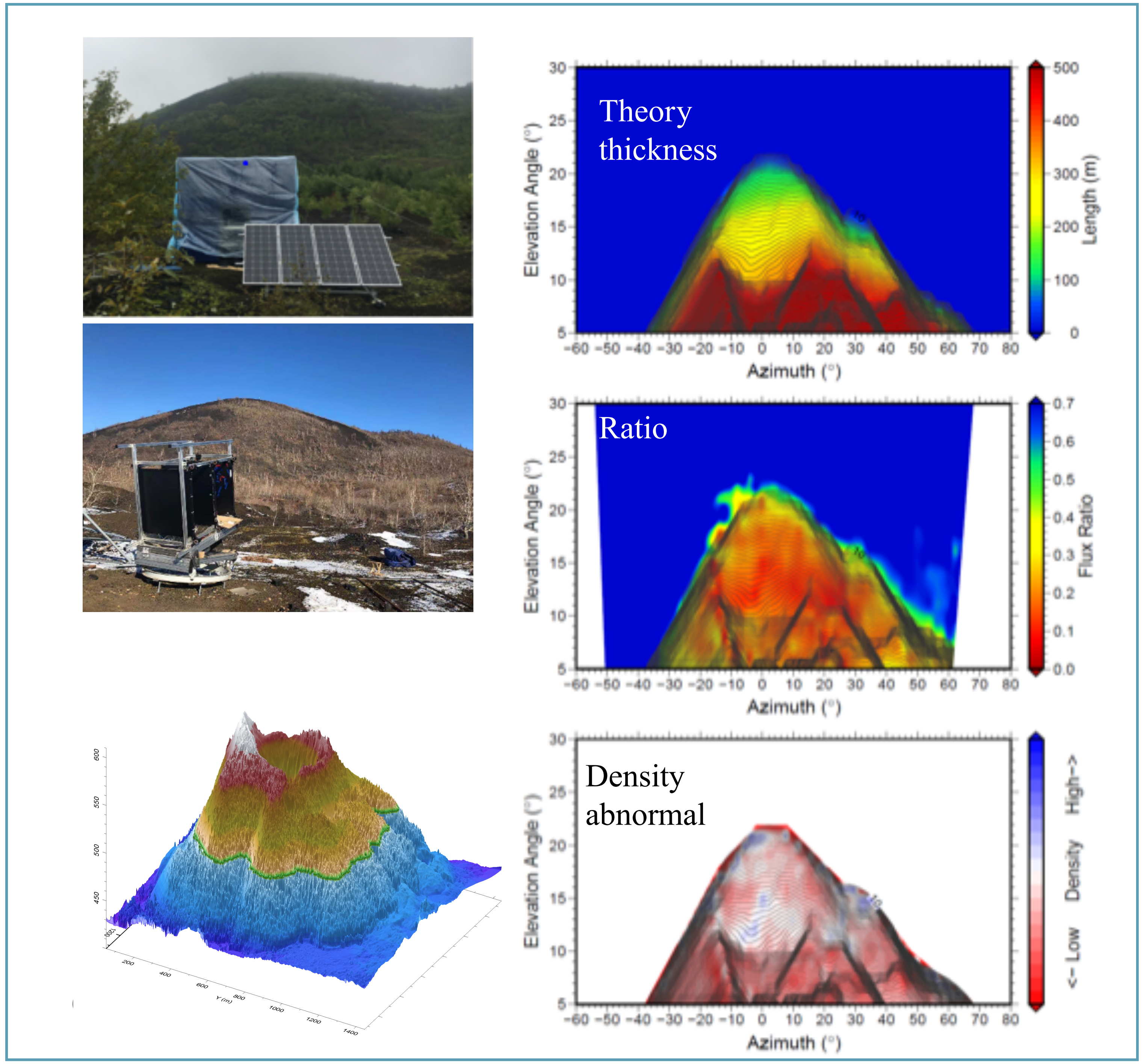
Preprint submitted to Nuclear Inst. and Methods in Physics Research, A March 9, 2023

Volcano



NUCL SCI TECH (2022)33:88
https://doi.org/10.1007/s41365-022-01072-4

Imaging internal density structure of the Laoheishan volcanic cone with cosmic ray muon radiography

Ya-Ping Cheng[1] · Ran Han[1] · Zhi-Wei Li[1] · Jing-Tai Li[1] · Xin Mao[1] · Wen-Qiang Dou[2] · Xin-Zhuo Feng[2] · Xiao-Ping Ou-Yang[2] · Bin Liao[3] · Fang Liu[2] · Lei Huang[4]

Received: 10 January 2022 / Revised: 22 May 2022 / Accepted: 22 May 2022

Abstract Muon radiography is a promising technique for imaging the internal density structures of targets such as tunnels, pyramids, and volcanoes up to a scale of a few hundred meters by measuring the flux attenuation of cosmic ray muons after they have traveled through these targets. In this study, we conducted experimental muon radiography of one of the volcanoes in the Wudalianchi area in Northeast China to image its internal density structure. The muon detector used in this study was composed of plastic scintillators and silicon photomultipliers. After approximately one and a half months of observing the crater and conduit of the Laoheishan volcano cone in Wudalianchi from September 23rd to November 10th 2019, more than 3 million muon tracks fulfilling the data selection criteria were collected. Based on the muon samples and high-resolution topography obtained through aerial photogrammetry using an unmanned aerial vehicle, a density image of the Laoheishan volcano cone was constructed. The results obtained in this experiment demonstrate the feasibility of using a radiography technique based on plastic scintillator detectors. To obtain the density distribution, we performed a detailed background analysis and found that low-energy charged particles dominated the background noise. Relatively higher densities were found near the surface of the volcanic cone, whereas relatively lower densities were found near the center of the volcanic cone. The experiment in this study is the first volcano muon tomography study performed in China. Our work provides an important reference for future research.

Keywords Muon radiography · Muon transmission imaging · Density

This work was supported by the National Natural Science Foundation of China (Nos. 41974064, 42174076 and U1865206) and Young Elite Scientists Sponsorship Program by CAST (No. 2019QNRC001).

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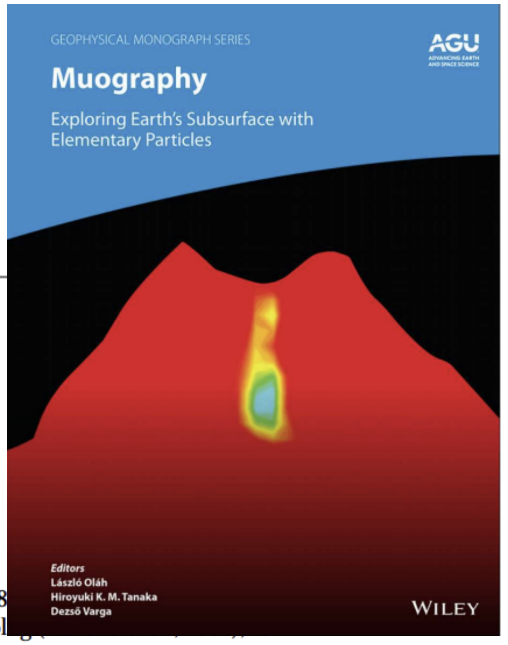
1 Introduction

Volcanic hazard assessment and risk management are important for both population safety and economic development. On January 15, 2022, a powerful explosive eruption from the underwater volcano Hunga Tonga-Hunga Ha′apai brought powerful tsunami waves and heavy ashfall to islands in Tonga, severely damaging coastal communities. Understanding the internal structures of volcanos is essential for forecasting such volcanic hazards.

Conventional geophysical methods have spatial resolutions that typically range from tens of meters to 1 km. Such low resolutions are insufficient for detecting small volumes of magma or magma conduits [1]. Gravimetry is a

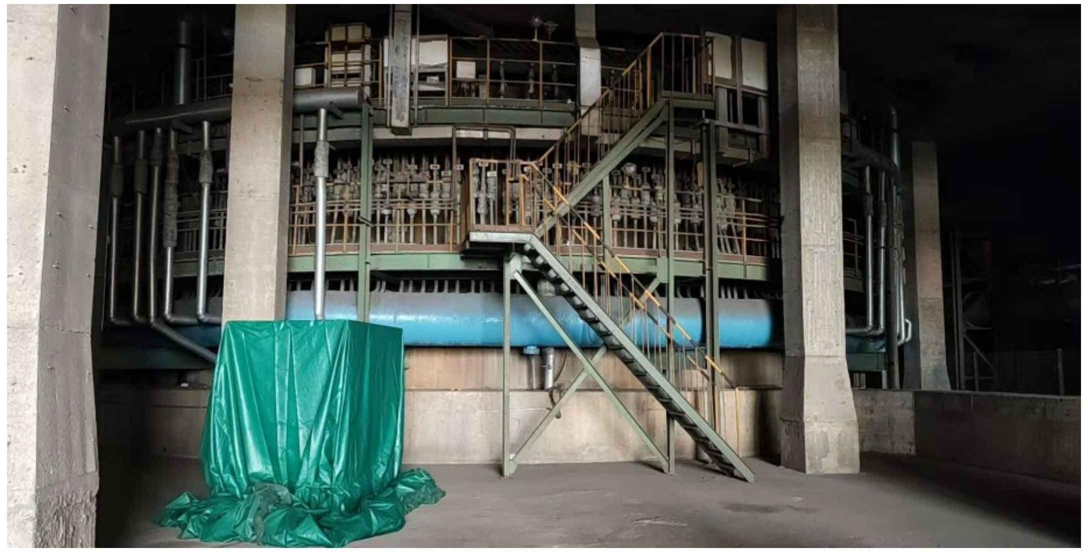
Published online: 16 July 2022
Springer

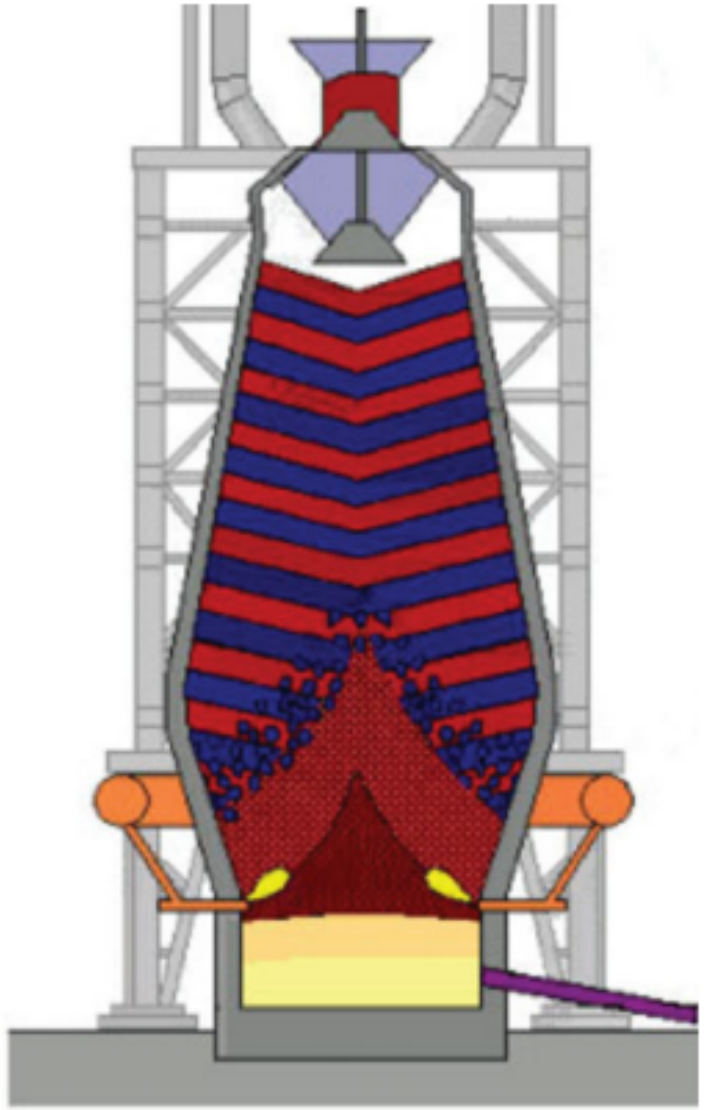


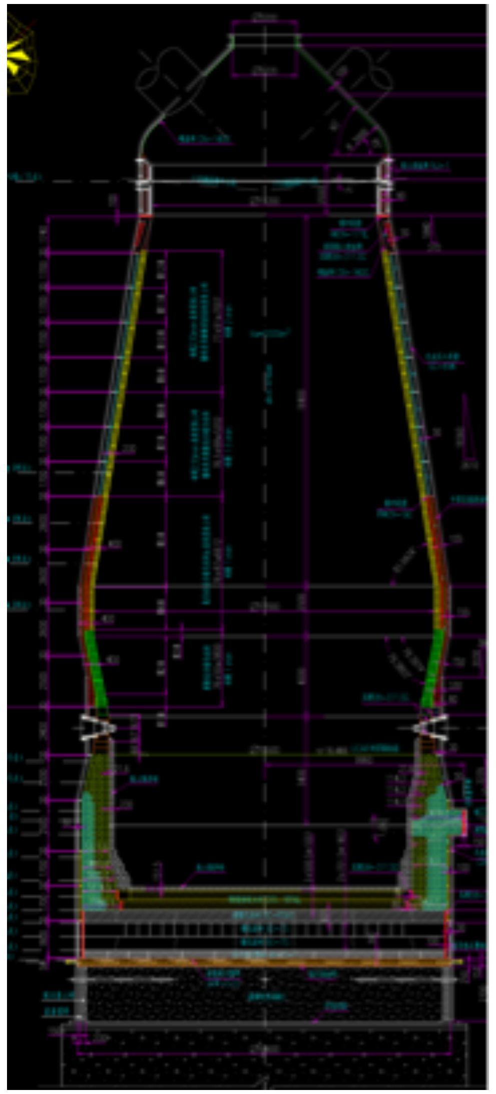
et al., 2017; Portal et al., Tanaka & Yokoyama, 2008 located beneath a volcanic pl mation of magmatic plug beneath deactivated crater (Oláh et al., 2019b); explosion of a volcanic plug (Tanaka et al., 2009b); tephra deposition (Tanaka, 2020b); tectonic evolution (Lo Presti et al., 2020; Tanaka, 2015); mechanical fracture within rock (Carbone et al., 2014); conduit size (Tanaka et al., 2007; Tioukov et al., 2019); magma ascent and descent during eruption sequence (Tanaka et al., 2014); degassing process (Shinohara & Tanaka, 2012; Tanaka et al., 2009a); and hydrothermal changes in lava dome (Jourde et al., 2016; Rosas-Carbajal et al., 2017). Muographic surveying of further volcanic edifices are in progress in Asia (Cheng et al., 2020; Nagahara & Miyamoto, 2018), Europe (Athanassas, 2020; Catalano et al., 2016; D'Alessandro et al., 2019; Macedonio et al., 2021), and South America (Peña-Rodríguez et al., 2020; Vesga-Ramírez et al., 2020).

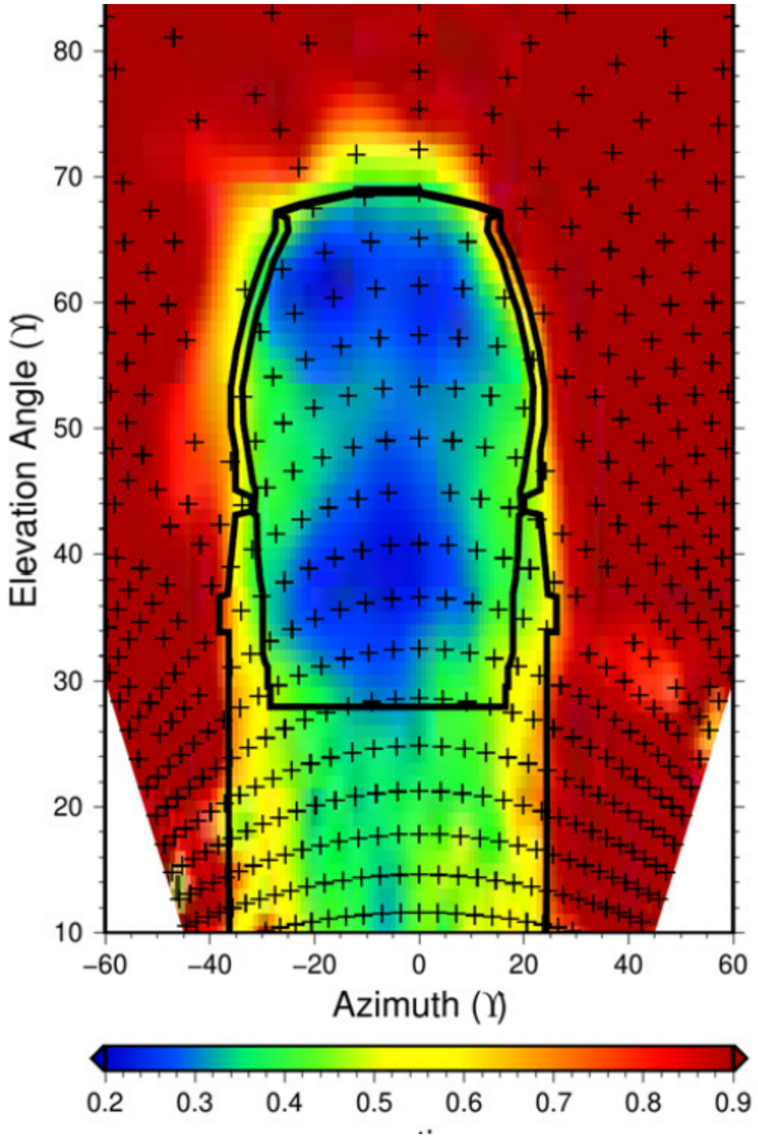
The muographic monitoring of subsurface magmatic bodies is motivated by its possible applicability for volcanology and hazard assessment, specifically for forecasting of location, size, duration, and time of impending volcano eruptions (Tanaka, 2019). The first muography campaigns were conducted at different active volcanoes in Japan for imaging of subsurface magma movements. After the 2004 eruption of Mt. Asama, Tanaka et al. (2007) imaged a dense region that corresponded to the position and shape of a lava mound created beneath the crater floor at a depth of a few hundred meters. A low-density region was also imaged beneath the crater floor, and it suggested that the magma pathway plugged by magma deposit. Ascending and descending convecting magma columns were monitored with muography consistently with the eruption sequences of the Satsuma-Iwojima volcano from 14 June to 10 July in 2013 (Tanaka et al., 2014). The average flow of low-density (1 g/cm^3) magma was quantified to approx. 30 meters per day based on the muographically observed

Blast furnace









Diameter 18 m, High 50 m,

Oct, 2019,

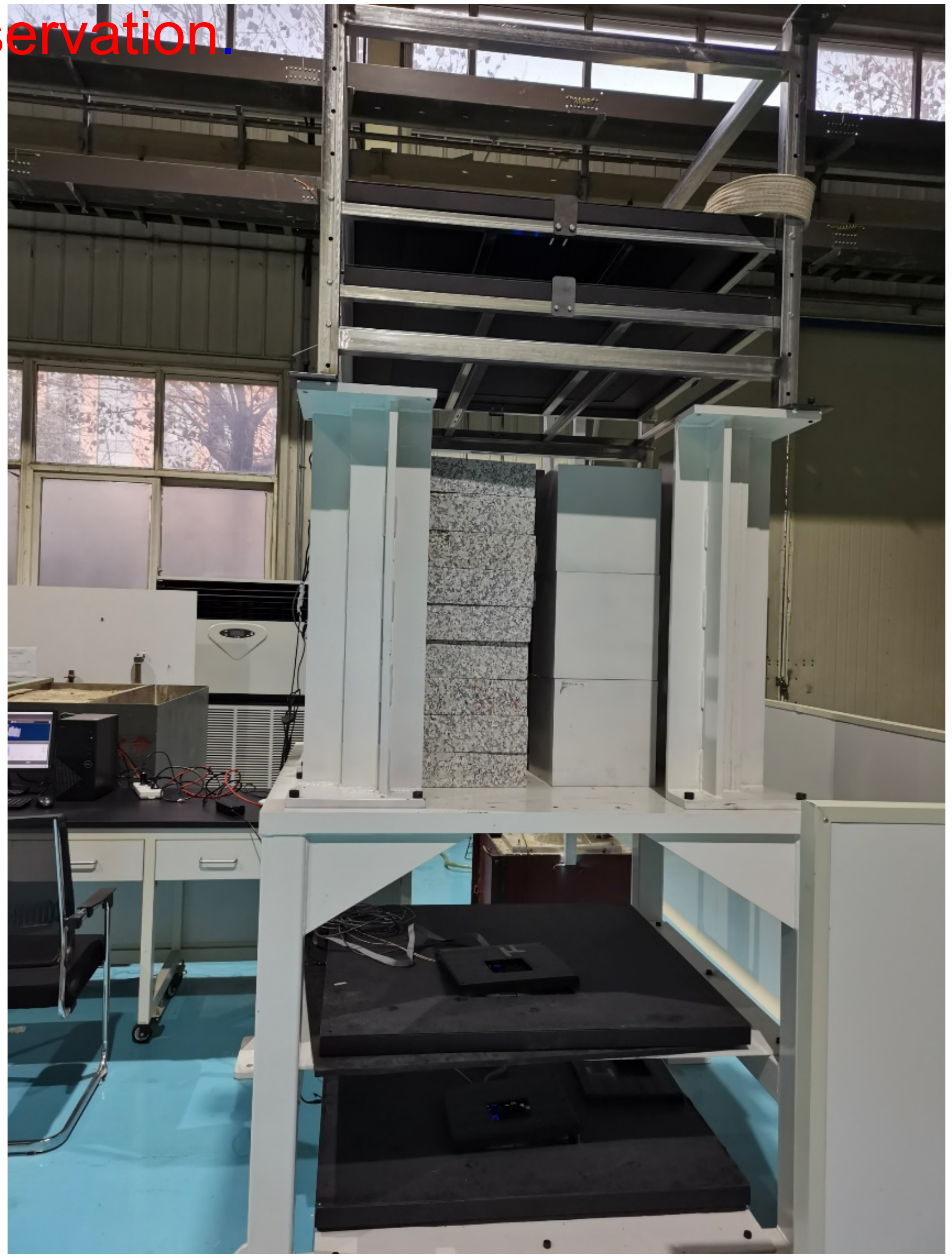
/04

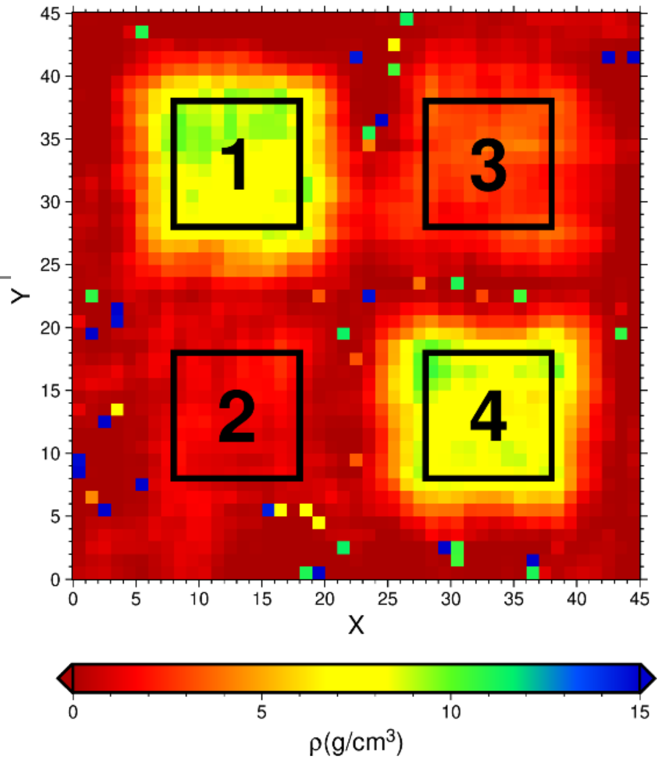
New Method Development

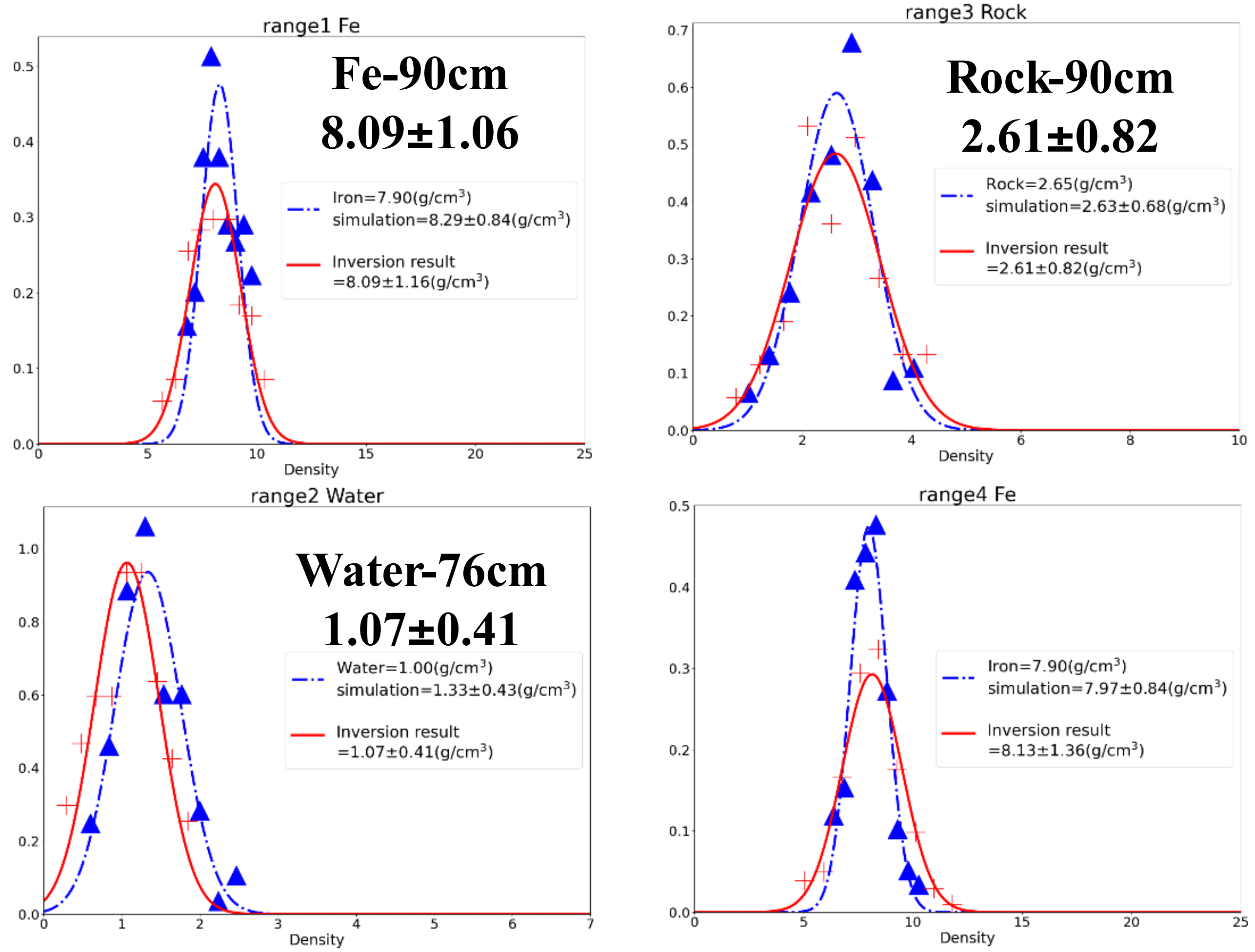
Absolute Density Inversion,   Joint Inversion , PoCA+ GRA

Absolute density inversion

Accurate 2D density measurement of samples with dimensions of several tens of centimeters can be achieved through 200 hours of observation.





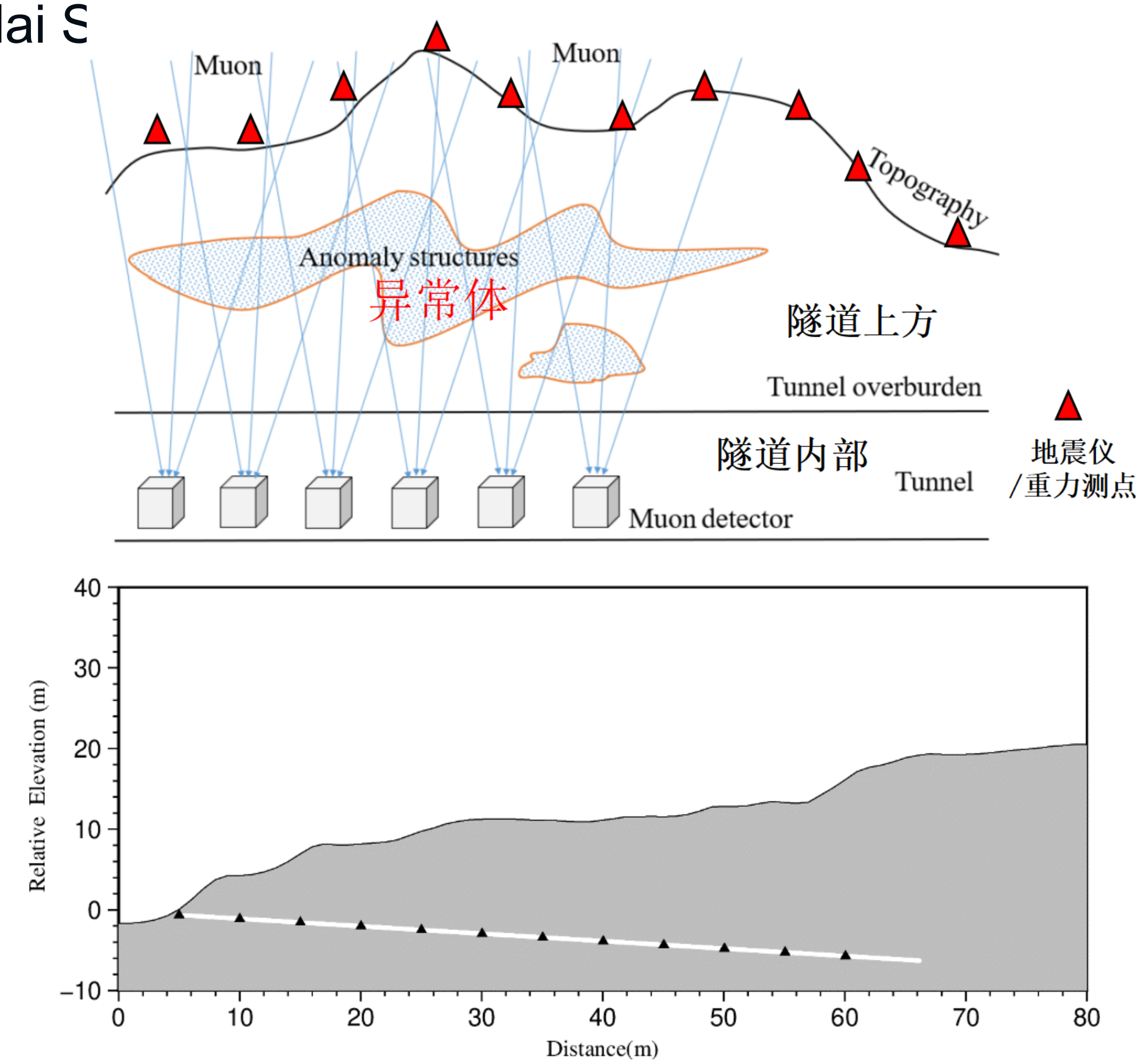


Density results from Data(red) and Simulation(blue)

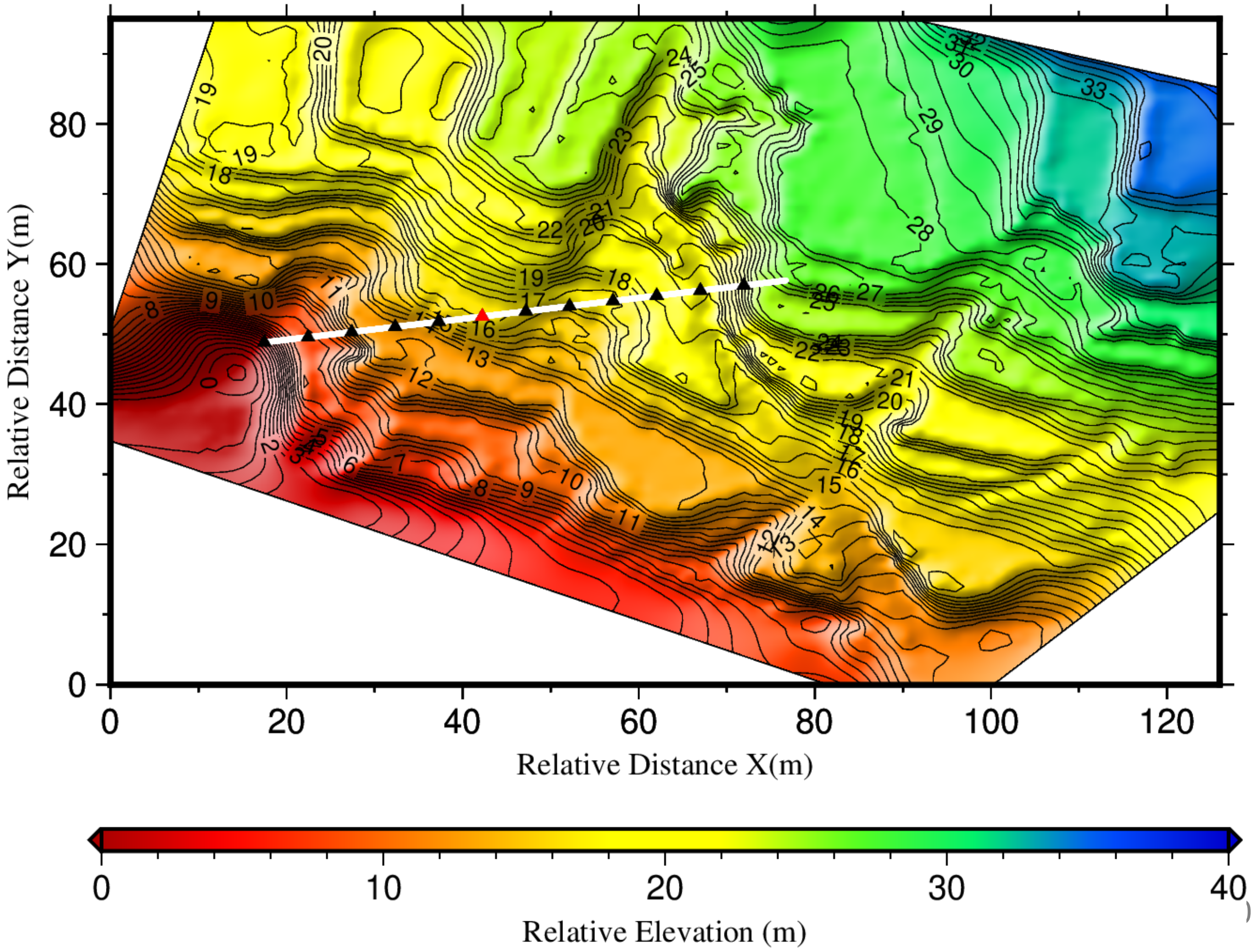
Cosmic Muon and Seismic joint inversion

- Joint can significantly improve the observation system and reduce non-uniqueness ；
- Sep.2022 to April. 2023, muon-seismic joint observation and imaging experiments were conducted in

Huailai S



Position of the muon imaging instrument

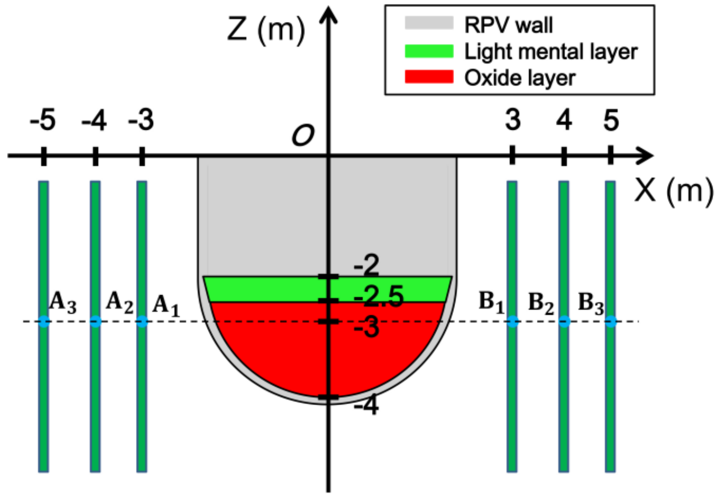


PoCA+GRA

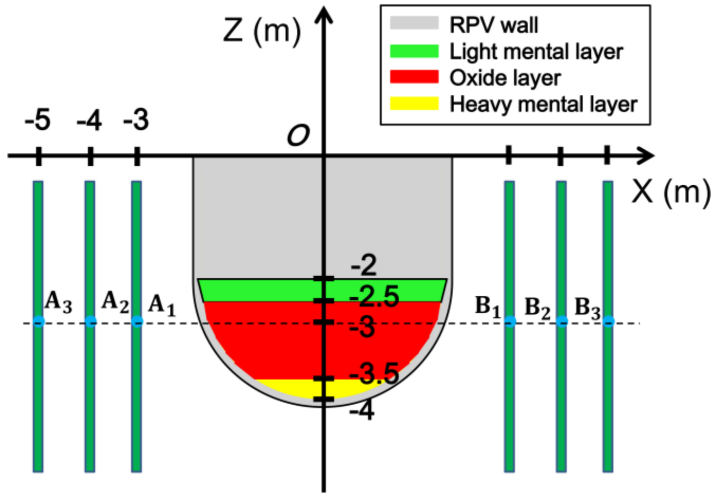
Chen et.al, Nuclear Energy 154 (2022) 104416

➤ **PoCA+Grey relational analysis method to simulate layered molten pool**

after the reactor core is damaged （the melt will enter the molten pool）



(a) The geometrical structure of two-layered molten pool.

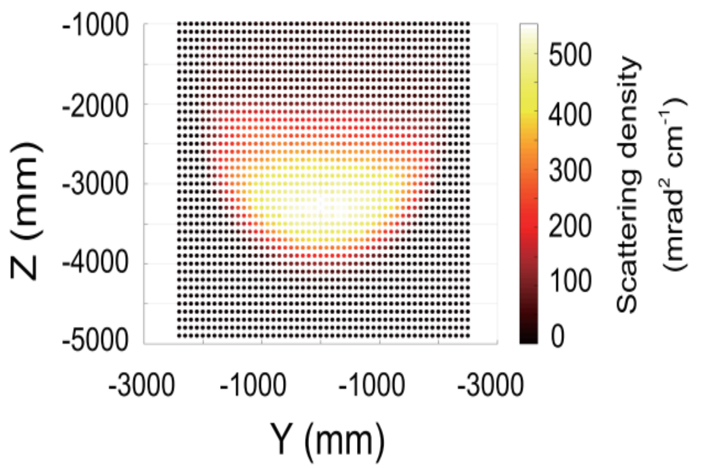


(b) The geometrical structure of three-layered molten pool.

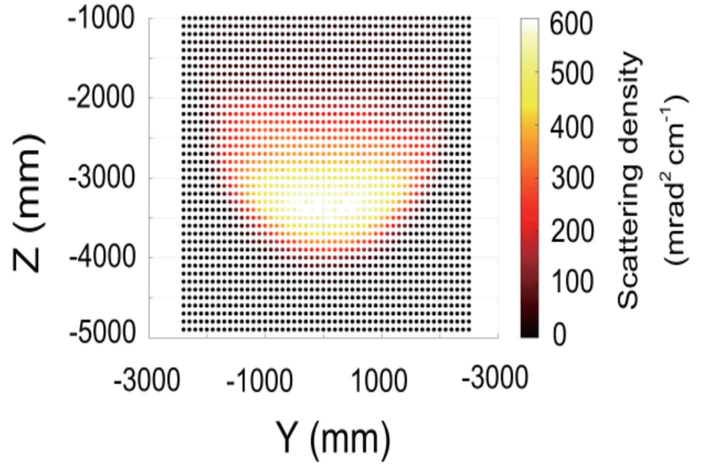
The structure of molten pool in simulation.

(a): two-layers model : light metal(green) + oxide layer (red) ,

(b): three-layers model: light metal(green) + oxide layer (red) + heavy metal mixture （yellow）

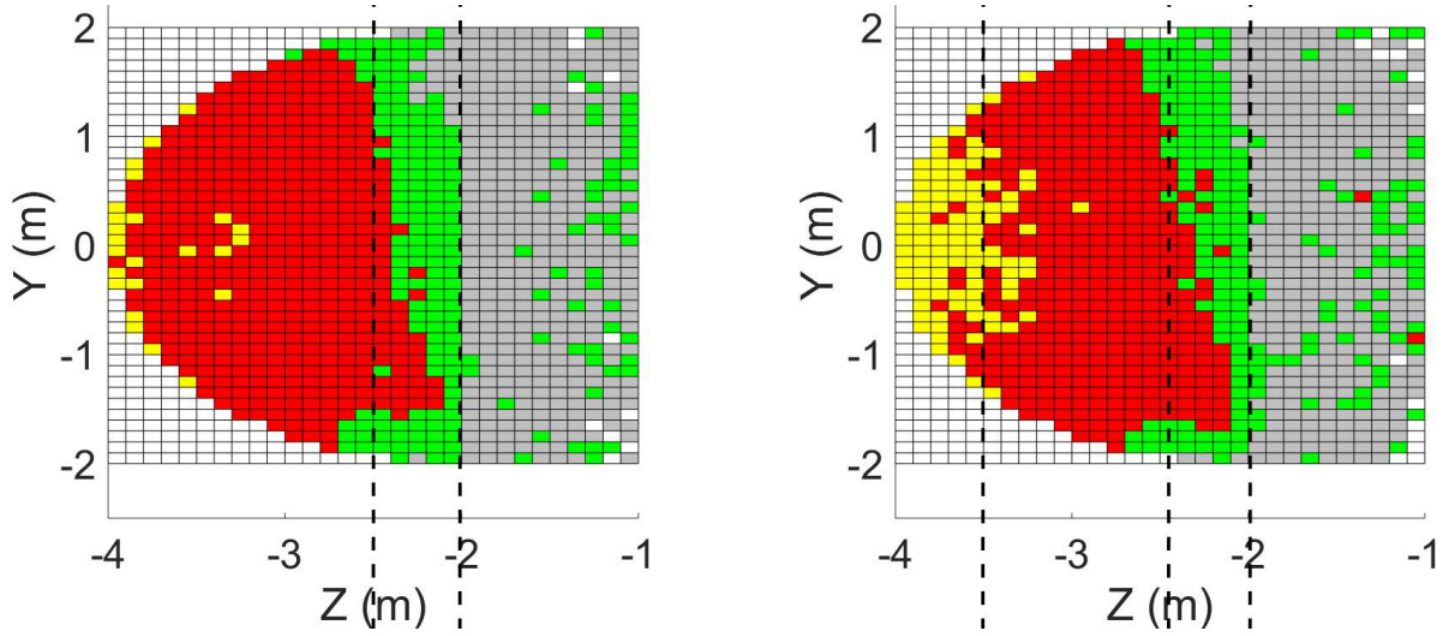


(a) The image reconstruction by PoCA of the two-layered molten pool model with measurement time spans of 54 days.



(b) The image reconstruction by PoCA of the three-layered molten pool model with measurement time spans of 58 days.

Results only by PoCA



Results by PoCA+GRA

/05

Summary

Summary

Cosmic Muon Imaging	
Features	Density-sensitive, non-contact, and bottom-up ……
Advantage	High-quality imaging results of large object
Disadvantage	Long time for 3D imaging
Application	Some important results in tunnel, volcano，mineral…
Future	Algorithm optimization, improvement of observation equipment, and exploration of new application……

THANKS