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THE ASTROPARTICLE PHYSICS CONFERENCE

Improvement of Cosmic-Ray Muography for Earth Sciences and Civil Engineering

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MEXT MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY-JAPAN

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REGARD RMKI ELTE Collaboration on Gaseous Detector Research and Development

WIGNER

Outline

I. Motivation: Muography

II. Sakurajima Muography Observatory

III. Portable Tracking Detectors for Civil Engineering

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V. NEWCUT: A Rotatable Muon Spectrometer

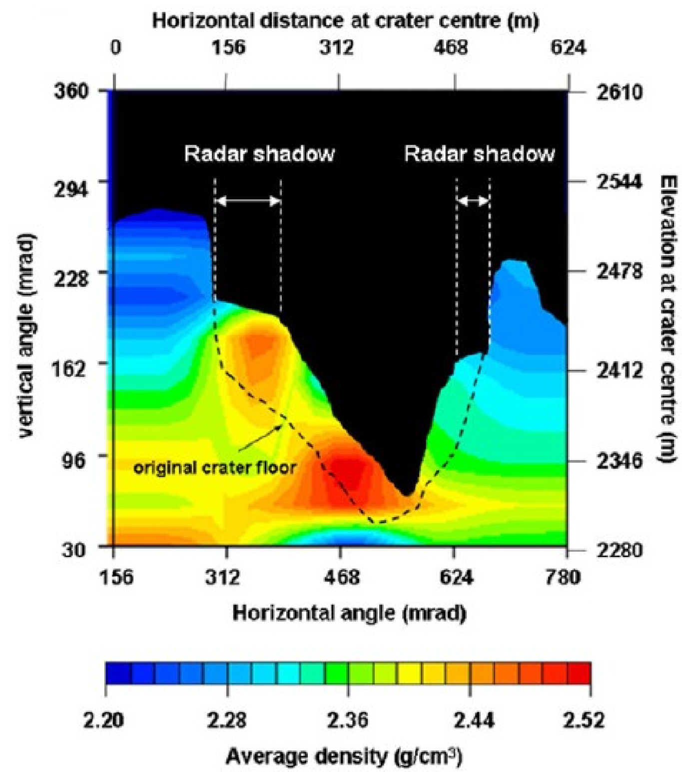
VI. Summary and Future Perspectives

I. Motivation: Muography

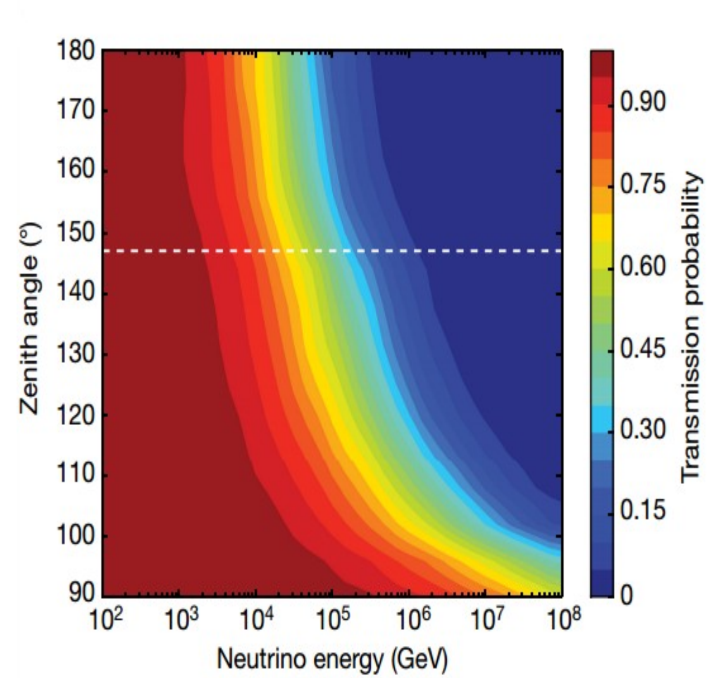
- **A non-invasive, remote sensing techinique that is based on the measurement of the absorption rate of cosmic-ray muons across the investigated body**
- It provides high-resolution (few mrad) images even about unacessible bodies from a safe distance
- Versatile applicability: volcanology, nuclear security, civil engineering, archeology, etc.
- **Motivation: application oriented development of instrumentation and imaging techniques** to make muography standard imaging tool for Earth sciences and civil engineering

X-ray radiography: – few m
W.C. Röntgen:
On a new kind of rays, 1895

Muography: few m – few km
H. Tanaka et al.: EPL 263 (2007) 104

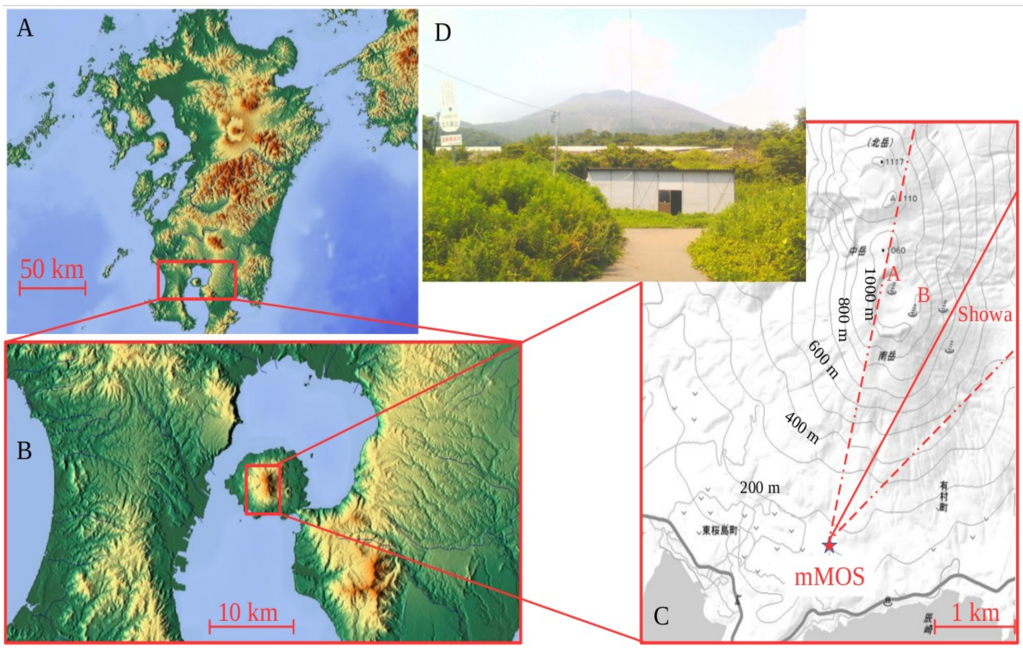


Neutrino radiography: ~ few 1000 km
ICECUBE: doi:10.1038/nature24459

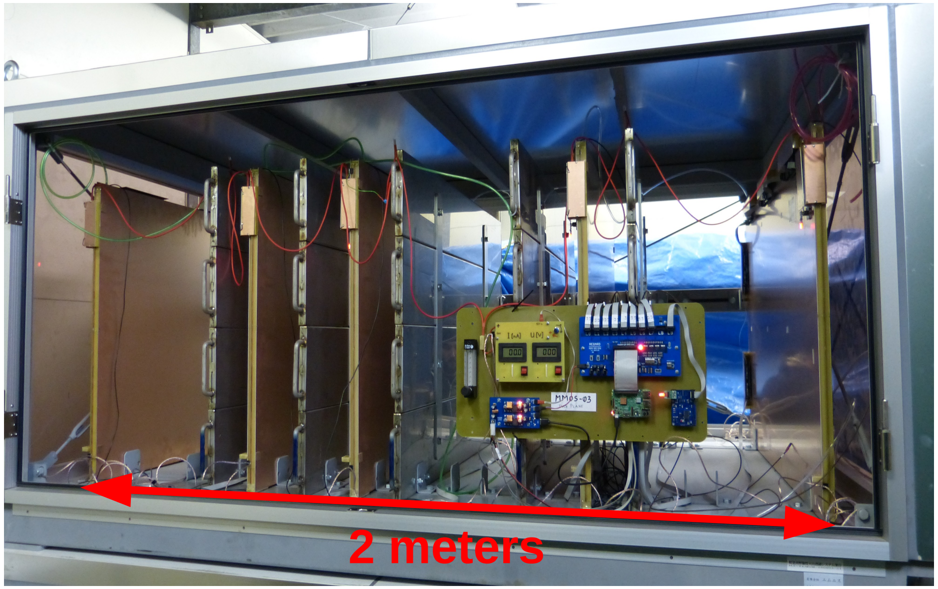


II. Sakurajima Muography Observatory

- Sakurajima is an active volcamo with a few hundreds of explosive eruptions per year
  → time-sequential muography and construction of database for understanding of volcanic activity
- Diameters of conduits range from 10 m to 100 m → angular resolution of few mrad
- 1-2 km-thick crater region results in a limited muon flux of $10^2 – 10^3$ $m^{-2}sr^{-1}day^{-1}$
  → large-sized observation system with optimized background rejection capabilities
- **SMO: a Multi-Wire-Proportional-Chamber (MWPC)-based, modular tracking system with a sensitive surface of 6 m² in July 2019** (20 m² by April 2021 to provide a time resolution of few days)



MWPC-based Muography Observation System



- **A 2-meter-length, 0.9 m² tracker consists of 5-8 MWPCs**
- **Low material budget MWPCs, with simplified design and exceptional operation stability at high (> 98 %) efficiency**
- Operated by Ar-CO_2 gas mixture with a flow of 1 Liter/hour
- High voltage of 1750 V provides a gas gain of few thousands
- 96×64 "pixels” with the size of 12 mm × 12 mm each: fair positional- (3.5 mm) and angular (3 mrad) resolutions
- **Micro-computer controlled system allows real-time DAQ**
- Trigger: triple coincidence of MWPCs
- Dead time of few hundreds of microseconds (< 2 %)
- Custom-designed electronics for data readout (few $/channel)
- **Total Power Consumption: ~ 6 W per MMOS**
- **Lead plates are applied for background suppression** (10 cm lead → 10 % transmission probability for 1 GeV)

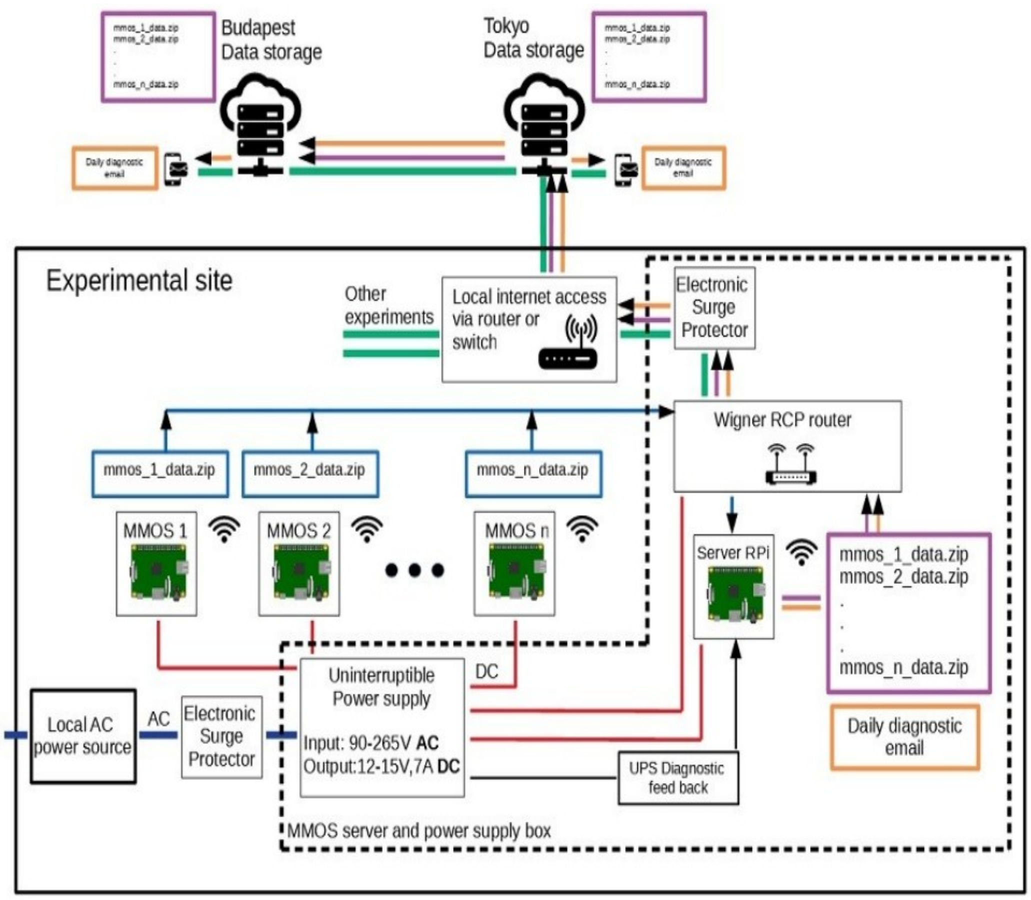
Advances in High Energy Physics 2016 (2016) 1962317

Scientific Reports, Vol. 8, 3207 (2018)
https://www.nature.com/articles/s41598-018-21423-9/

Muographic Observation Instrument (WO 2017/187308 A1)

Data Acquisition, Reconstruction and Monitoring

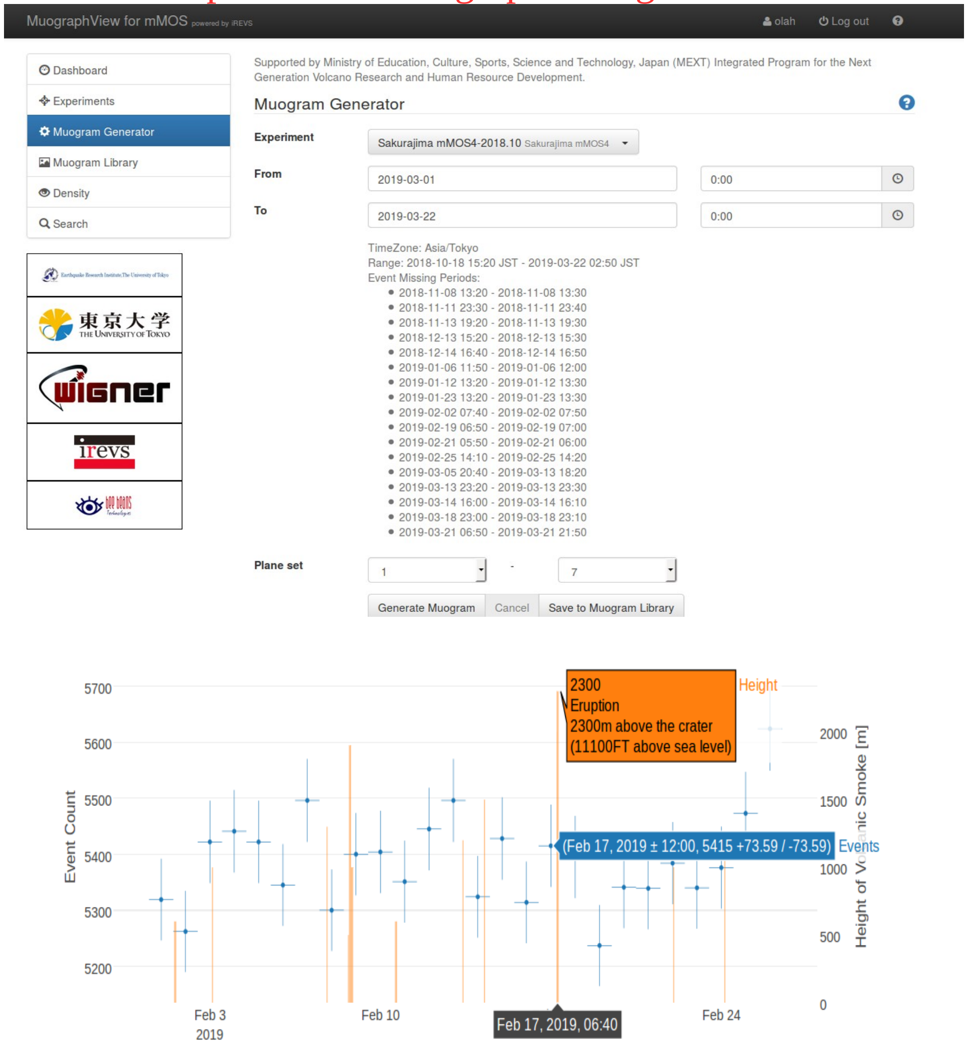
- **Local Server controls the data taking**
- **Data size of approx. 100 MB/day/MMOS**
- **Data are transfered to a remote server via VPN**



Source of this figure: Szabolcs József Balogh

- **Data reconstruction (combinatorial tracking), quality assurance and analysis are performed on remote server**
- **Data visualization via on-line user interface**

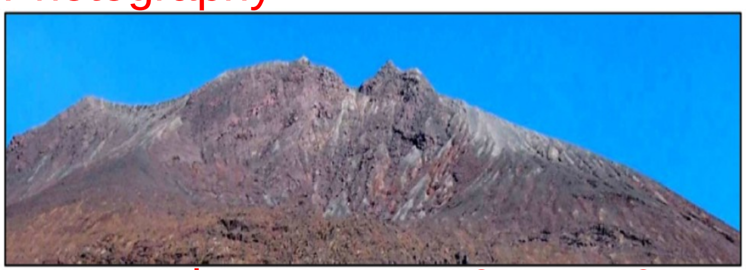
https://mmos.muographers.org



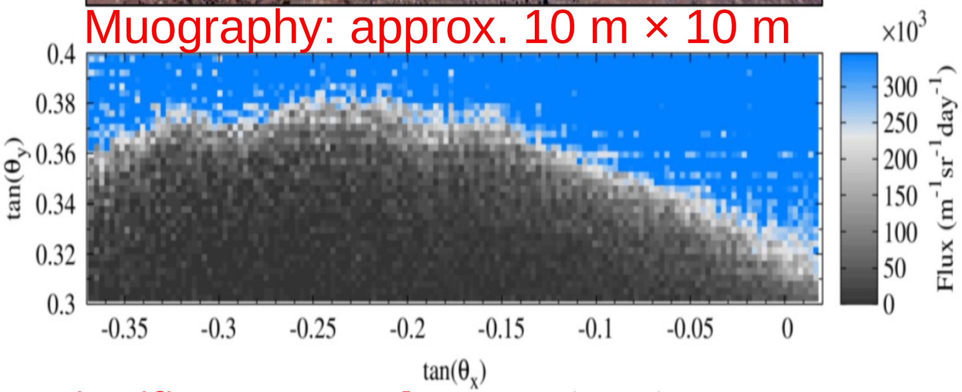
Operational Performance of the SMO

- **Angular resolution of 3 mrad (spatial resolution of ~ 10 m) was confirmed**
- Each MMOS is tracking the muons with an efficiency of above 95 % in varying environment
- **Track rates from the backward direction were found stable within ±5 %**
  → density variation of above 2 % can be measured by MMOS

Photography



Muography: approx. 10 m × 10 m



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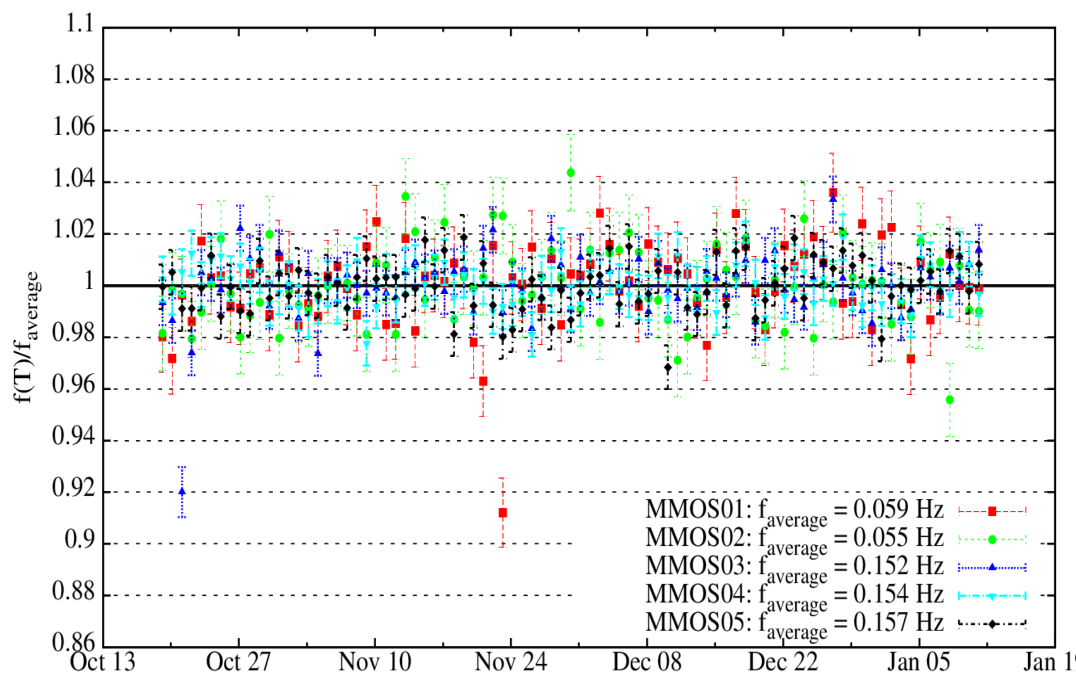
https://www.nature.com/articles/s41598-018-21423-9/

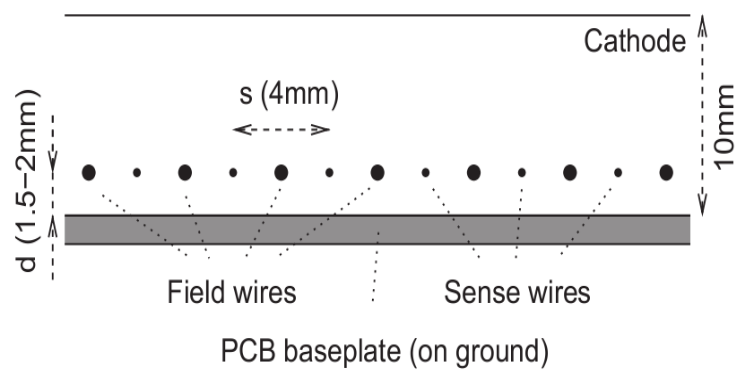


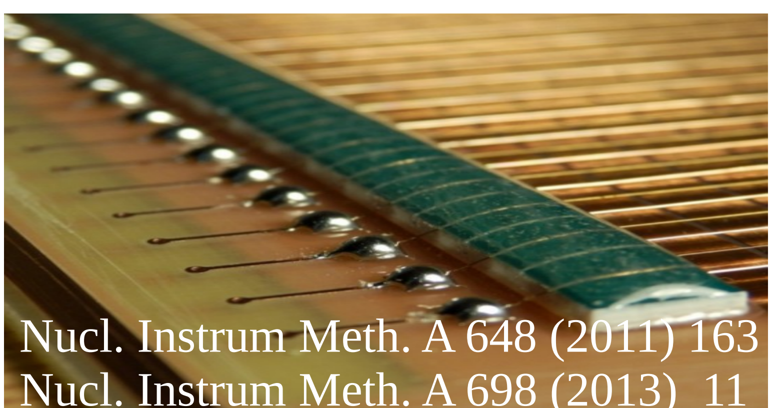
Journal of Disaster Research, Vol 14. No. 5, Dr14-5-966

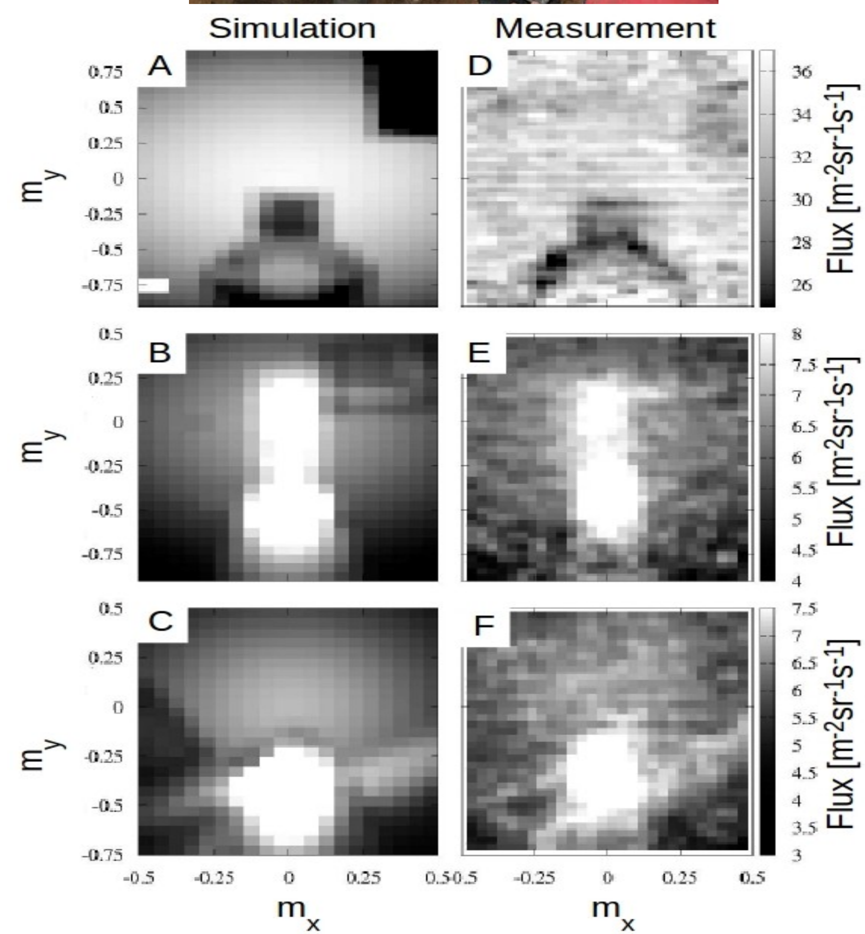
III. Portable Tracking Detectors for Civil Engineering

- **Compact, portable (< 10 kg), low-power (~ 5 W) trackers with high (> 95 %) efficiency and exceptional operational stability:**
  - Close Cathode Chambers (CCC): wire plane + perpendicular pad plane
  - Simplified construction up to one square meter
- **Applicability of this technology was demonstrated in natural caves and underground tunnels**

Geosci. Instrum. Method. Data Syst., 1, 229-234 (2012)
Advances in HEP Vol. 2013, 560192, (2013)



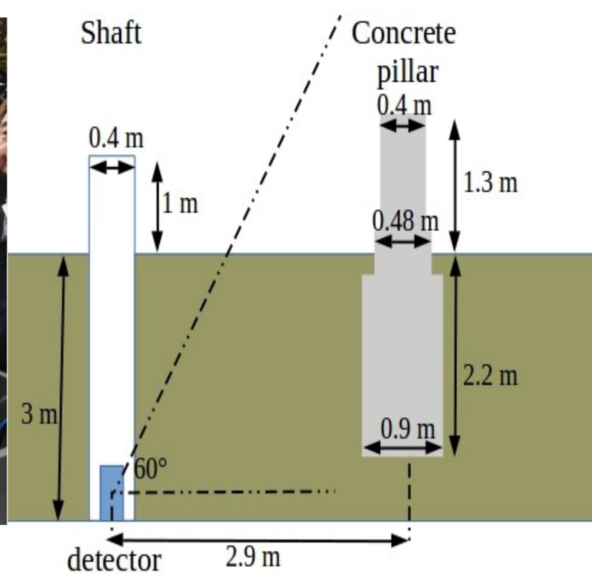


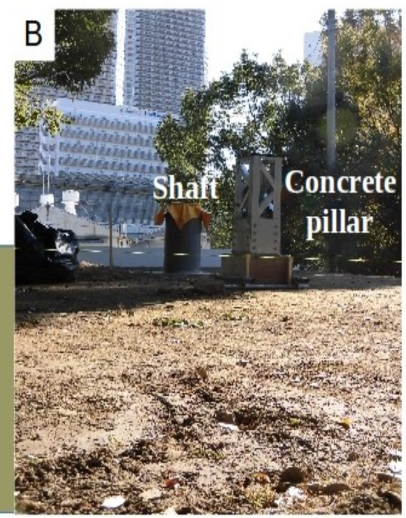


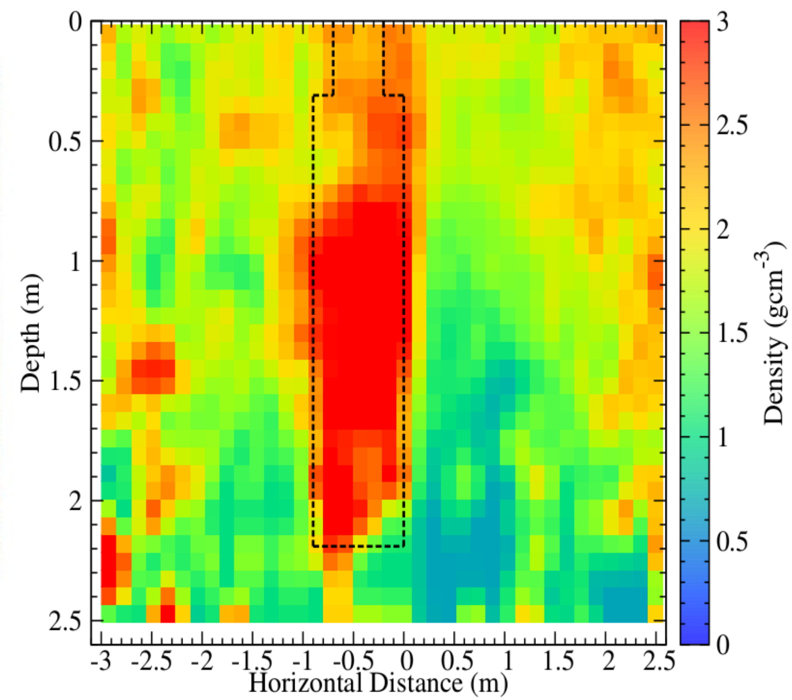
The first prototype of an MWPC-based Borehole Detector

- **Application: Inspection of the structure of standard railway pillars** in cooperation with NEC corporation and East Japan Railway Company
- **Aim of test experiment: measure the bottom of a buried concrete pillar with iron basement** from a 3 meter-depth shaft from a distance of 3 m with a portable MMOS
- **The bottom of the pillar was sucessfully observed at a depth of 220 cm** below the surface of the mound with a spatial resolution of approx. 10 cm

BUTSURI-TANSA(Geophysical Exploration) 71 161-168 (2018) DOI: 10.3124/segj.71.161





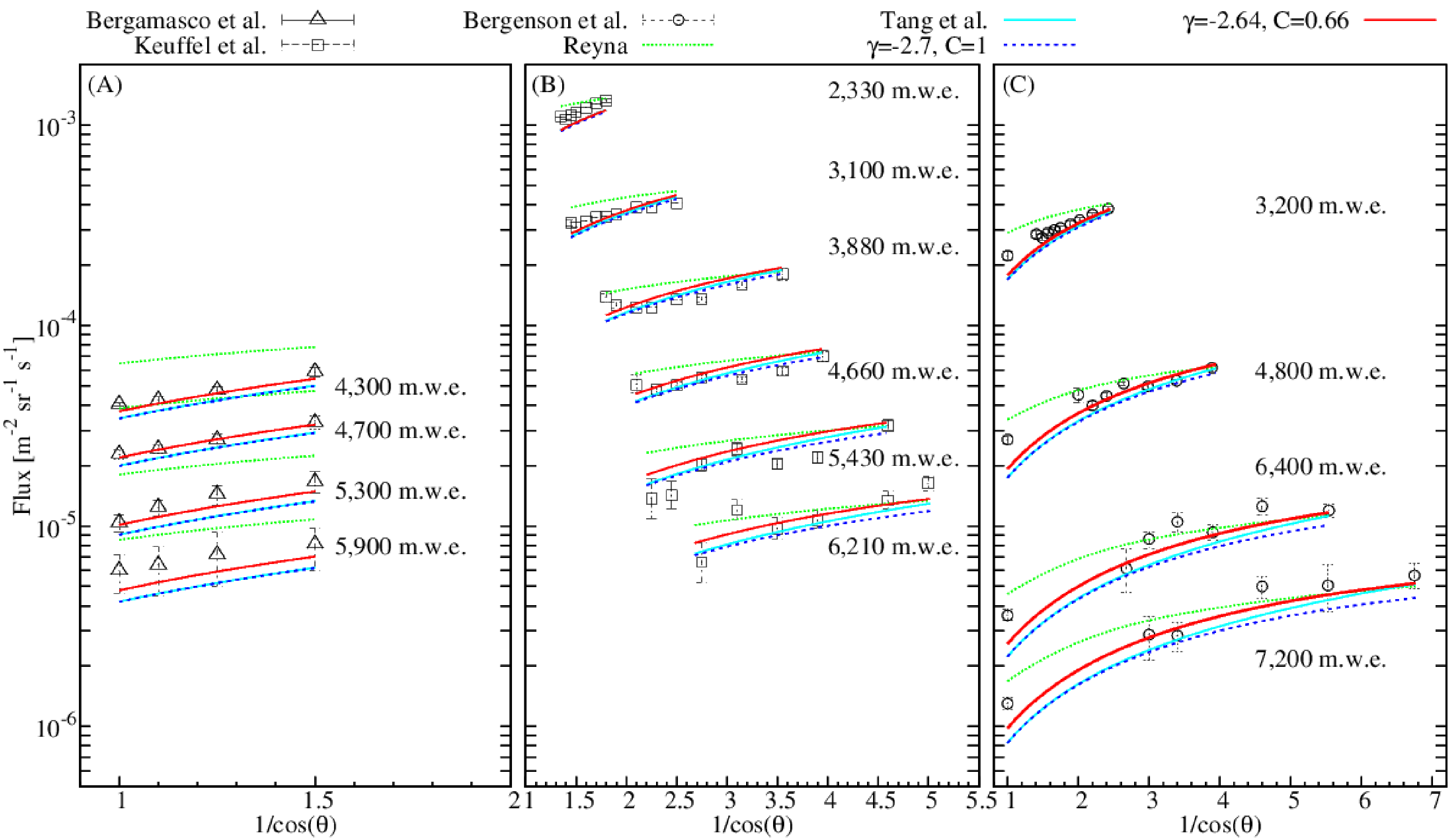


IV. Optimization of Muographic Imaging

- **Adjustment of Modified-Gaisser model for more accurate imaging of gigantic objects with near-horizontal muons:**
- Original parameters: C = 1 & γ = -2.7
  → $(F_{meas}-F_{model})/F_{meas}$ = 10.4 %
- **Suggested parameters: C = 0.66 & γ = -2.64**
  → $(F_{meas}-F_{model})/F_{meas}$ = 1.6 %

Scale Parameter **Energy Exponent**

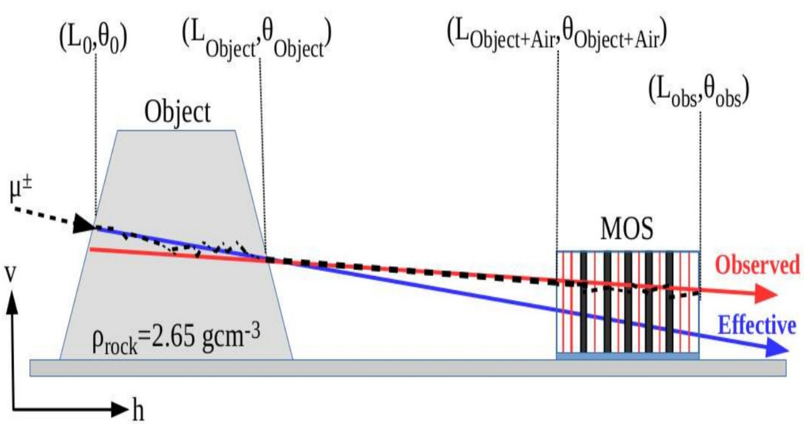
$$\frac{\mathrm{d}N}{\mathrm{d}E\,\mathrm{d}\Omega} \simeq \frac{0.14}{\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}\,\mathrm{GeV}^{-1}} \cdot C \cdot \left(\frac{E}{\mathrm{GeV}} + \frac{3.64}{\cos(\theta^*)^{1.29}}\right)^{-\gamma} \cdot \left(\frac{1}{1+1.1E\cos(\theta^*)/115\,\mathrm{GeV}} + \frac{0.054}{1+1.1E\cos(\theta^*)/850\,\mathrm{GeV}}\right)$$



Phil. Trans. R. Soc. A 377 https://royalsocietypublishing.org/doi/10.1098/rsta.2018.0135

The Multiple Scattering of Muons

- **GEANT4 simulation**: Muon beams injected across rock with "realistic spectra” + standard EM interactions → position- and momentum direction coordinates were recorded at different distances
- MS is determined at each distance by the RMS of the middle 98% of the scattering angle distributions
- **Decrease of the steepness of spectra cause the decrease of MS with the increase of thickness**
- **MS falls down after the object due to the increase of the observed zenith angle**
- **MS accross the air become dominant with the incrase of distance**

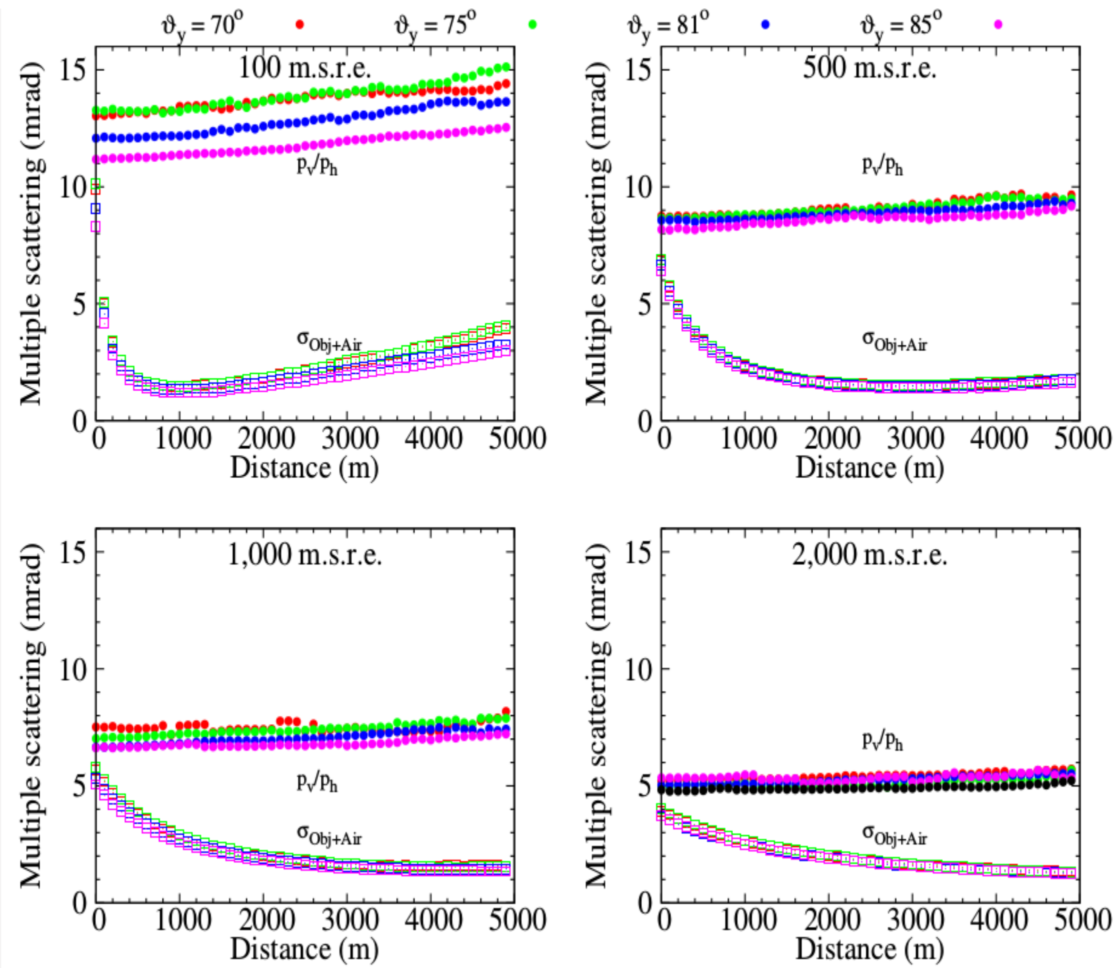


MS | Expected | Observed

$$\Delta\theta_{\mathrm{Object+Air}}(L_{\mathrm{Object+Air}}) = \frac{p_v(L_{\mathrm{Object+Air}})}{p_h(L_{\mathrm{Object+Air}})} - \frac{x_v(L_{\mathrm{Object+Air}}) - x_v(L_0)}{x_h(L_{\mathrm{Object+Air}}) - x_h(L_0)},$$

$$\Delta\theta_{\mathrm{Air}}(L_{\mathrm{Object+Air}}) = \frac{p_v(L_{\mathrm{Object+Air}})}{p_h(L_{\mathrm{Object+Air}})} - \frac{x_v(L_{\mathrm{Object+Air}}) - x_v(L_{\mathrm{Object}})}{x_h(L_{\mathrm{Object+Air}}) - x_h(L_{\mathrm{Object}})},$$

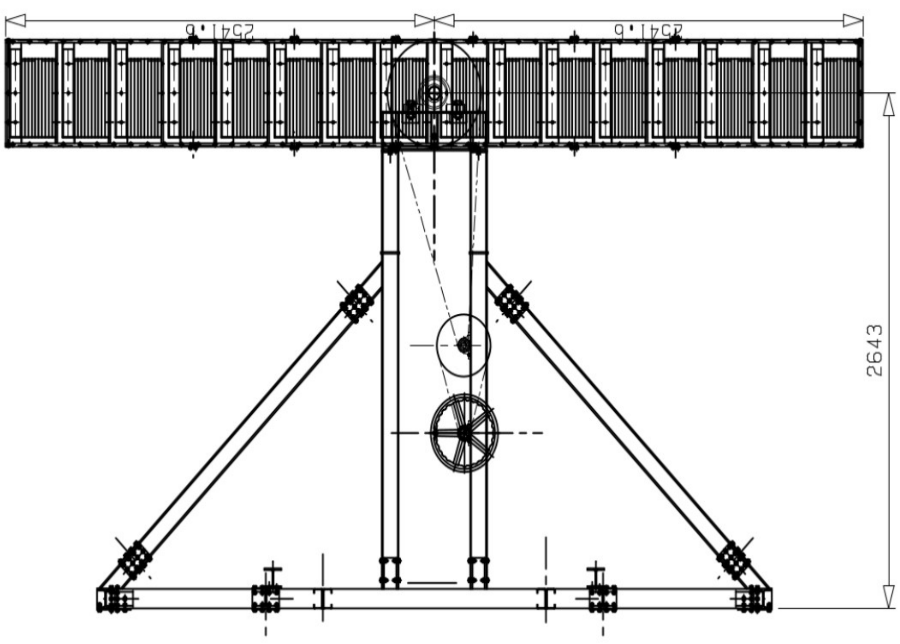
$$\Delta\theta_{\mathrm{MOS}}(L_{\mathrm{Obs}}) = \frac{p_v(L_{\mathrm{Obs}})}{p_h(L_{\mathrm{Obs}})} - \frac{x_v(L_{\mathrm{Obs}}) - x_v(L_{\mathrm{Object+Air}})}{x_h(L_{\mathrm{Obs}}) - x_h(L_{\mathrm{Object+Air}})},$$

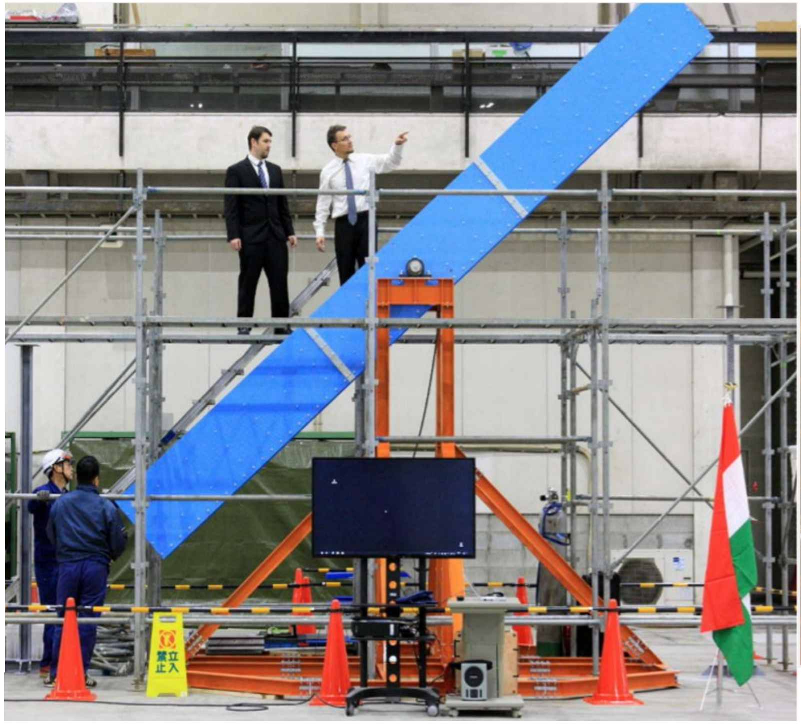


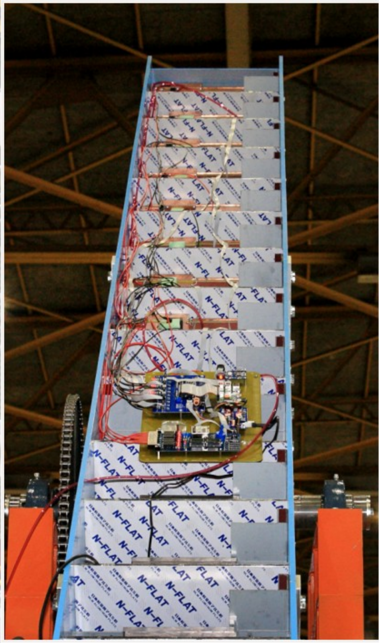
Phil. Trans. R. Soc. A 377 https://royalsocietypublishing.org/doi/10.1098/rsta.2018.0135

V. NEWCUT: A Rotatable Muon Spectrometer

- The improvement of small-scale muography requires the extension of muon spectra data sets
- **A rotatable, 5 meter-length spectrometer consists of 19 MWPCs and lead plates** is under development in NEWCUT (NEC-Wigner RCP-CRIEPI-University of Tokyo) laboratory, in Chiba, Japan to provide reference data from the horizon to vertical direction
- 3.2 t lead plates (~ 15 meter-standard-rock-equivalent) can be placed into the spectrometer
- Detector control and DAQ system is the same as used in MMOS
- Construction work has started in December 2018 with the installation of 9 MWPCs and actually the spectrometer is operating with 13 MWPCs

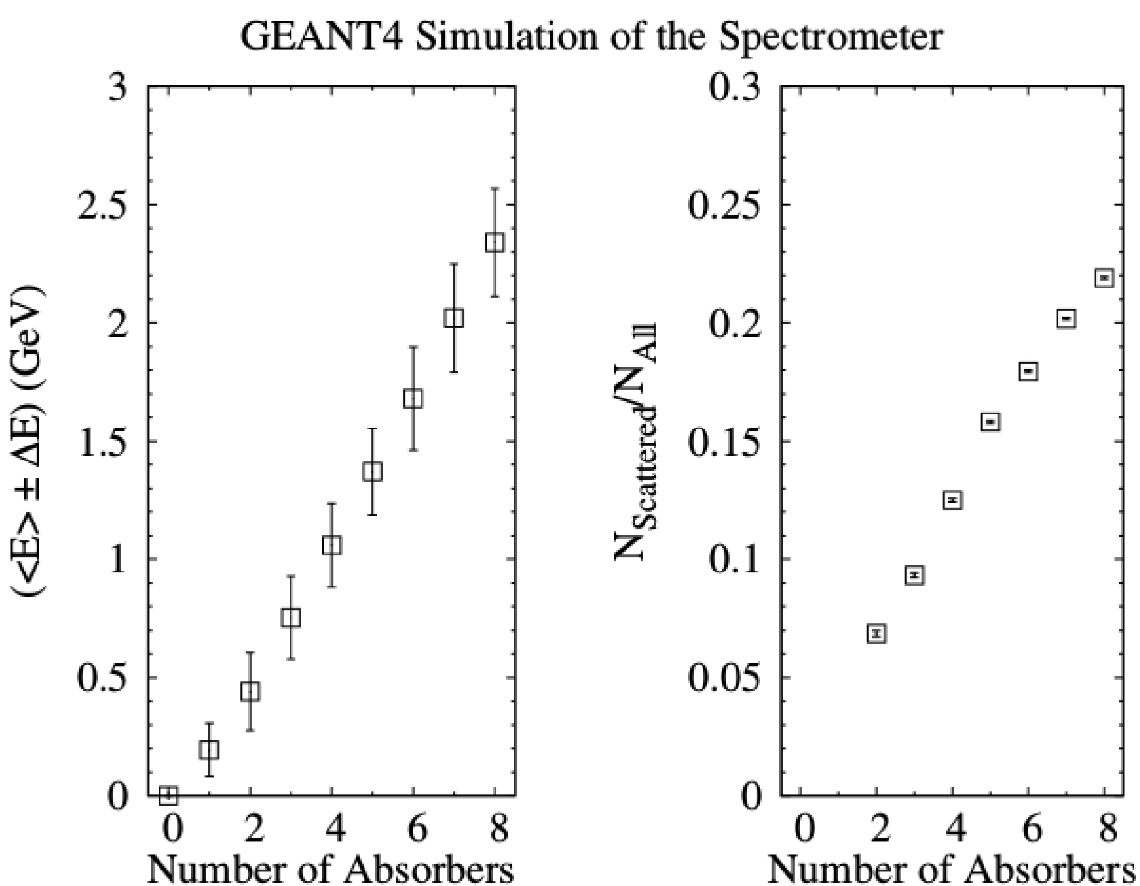


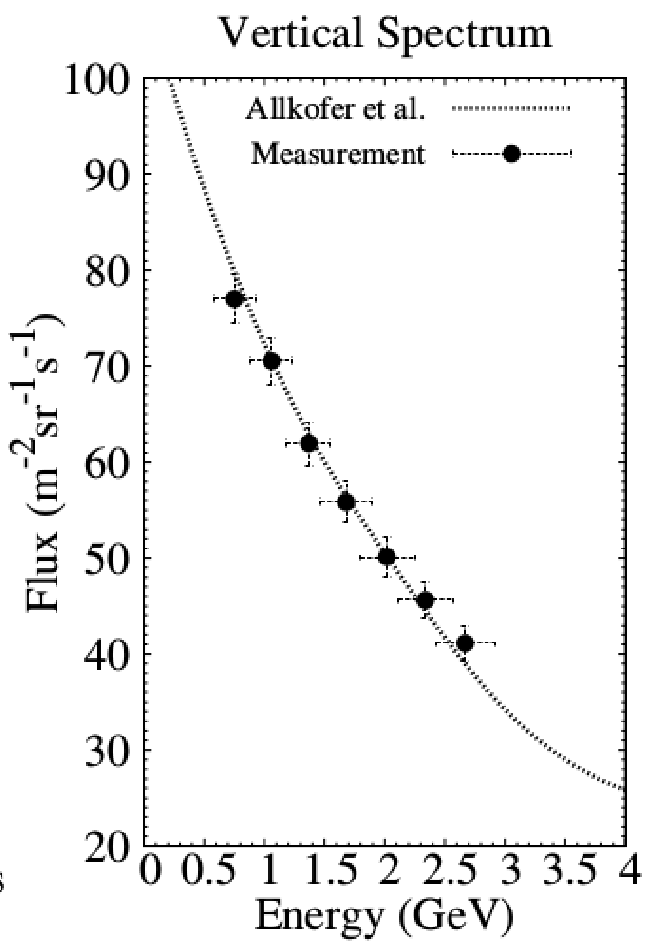




Preliminary Results

- GEANT4 simulation of the spectrometer was peformed to determine the average muon energies and their ranges after each absorber and the scattering effects
- **Preliminary vertical spectrum was found to be consistent with the earlier data (Allkofer et al., 1971) in the range of 0.5 GeV - 2.5 GeV**
- The construction of the spectrometer is expected to be completed in August 2019
- First reference spectra are expected from early 2020...

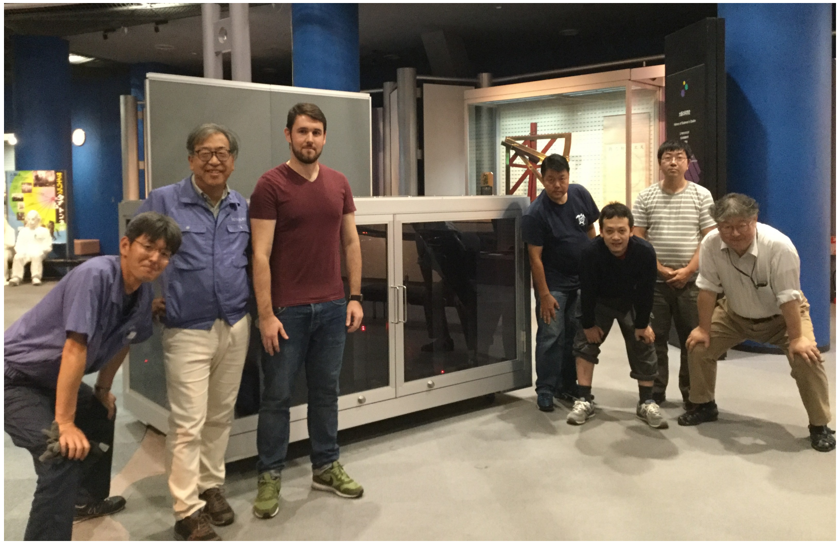




V. Summary and Future Perspectives

- Muography is a non-invasive, remote sensing technique for imaging of large-sized objects
- Sakurajima Muography Observatory is operating reliably with a sensitive surface of 6 m^2 and its extension is ongoing up to 20 m^2 (04/2021) to provide density images in every few days
- Portable, compact and low-power detectors were developed and successfully applied for measurement of underground tunnels and inspection of pillar structure
- A rotatable spectrometer is under development to provide reference spectra up to few GeV for small-scale muography
- **Future plans:**
  - Joint Sakurajima-Etna Muography Observatory
  - A common data analysis framework for various detectors → Global Muography Network
  - **Multi-Aspect Geo-Muography Array (MAGMA) Experiment for volcano eruption prediction and geophysical exploration of underground soil structure with 5,000 and 5,000 modules, respectively**

Thank You For Your Attention!



Further contributors: Gábor Nyitrai, Ádám László Gera, Szabolcs J. Balogh, Gábor Galgóczi (Wigner RCP), Takao Ohminato (ERI UT), Bee Beans Technology, Technoland Corporation, NEC Corporation.

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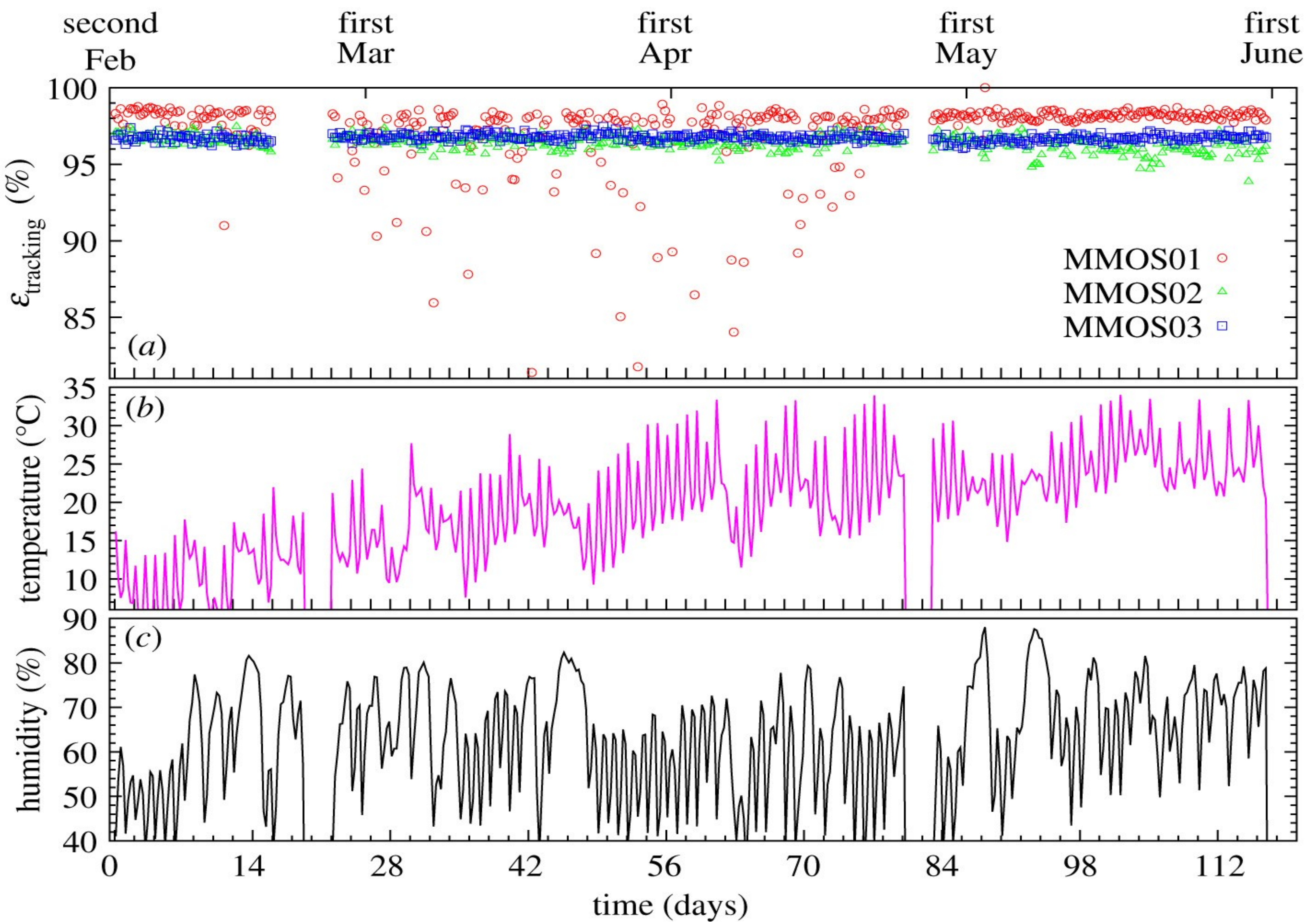
Backup slides

Operational Stability Versus Variation of Environmental Parameters



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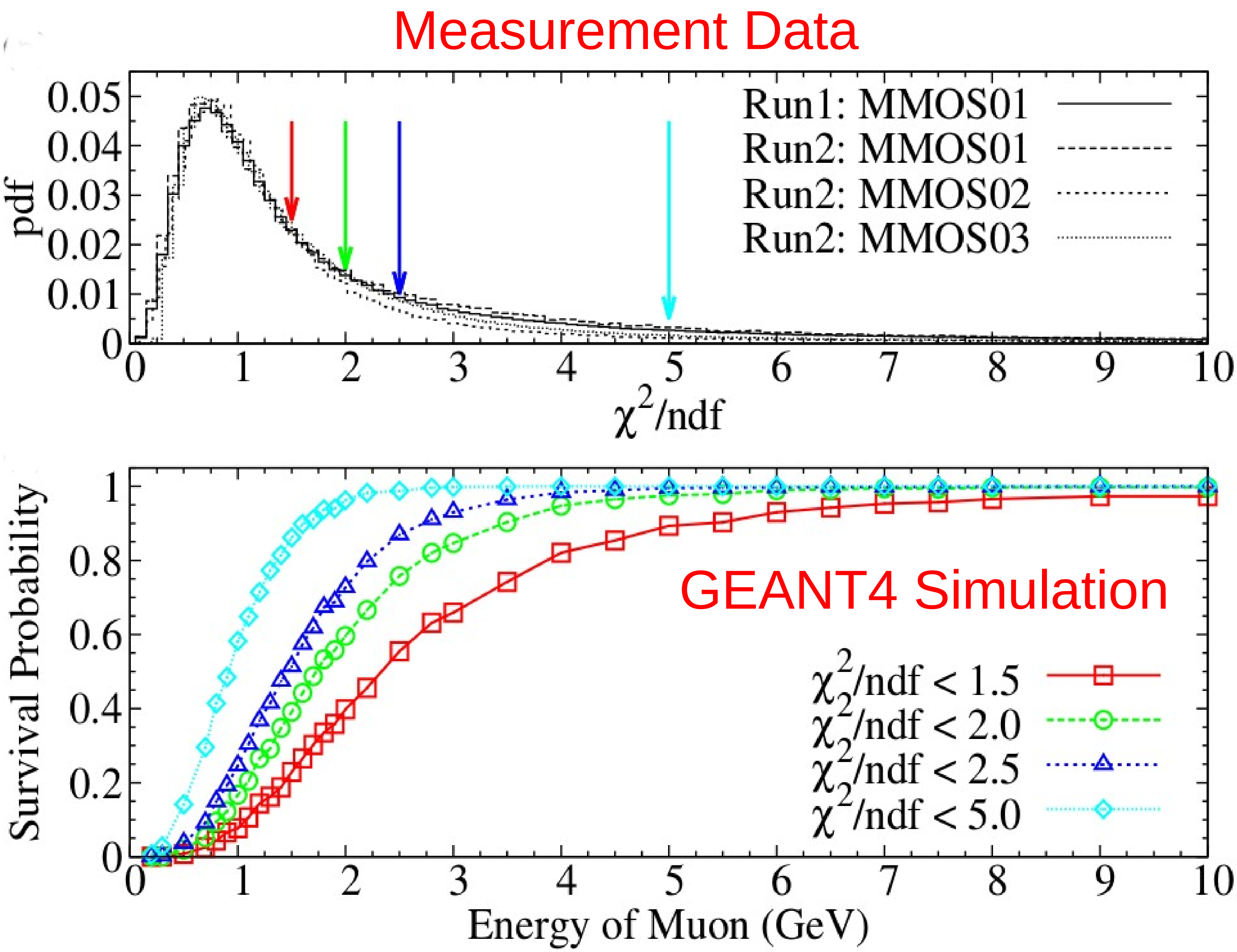
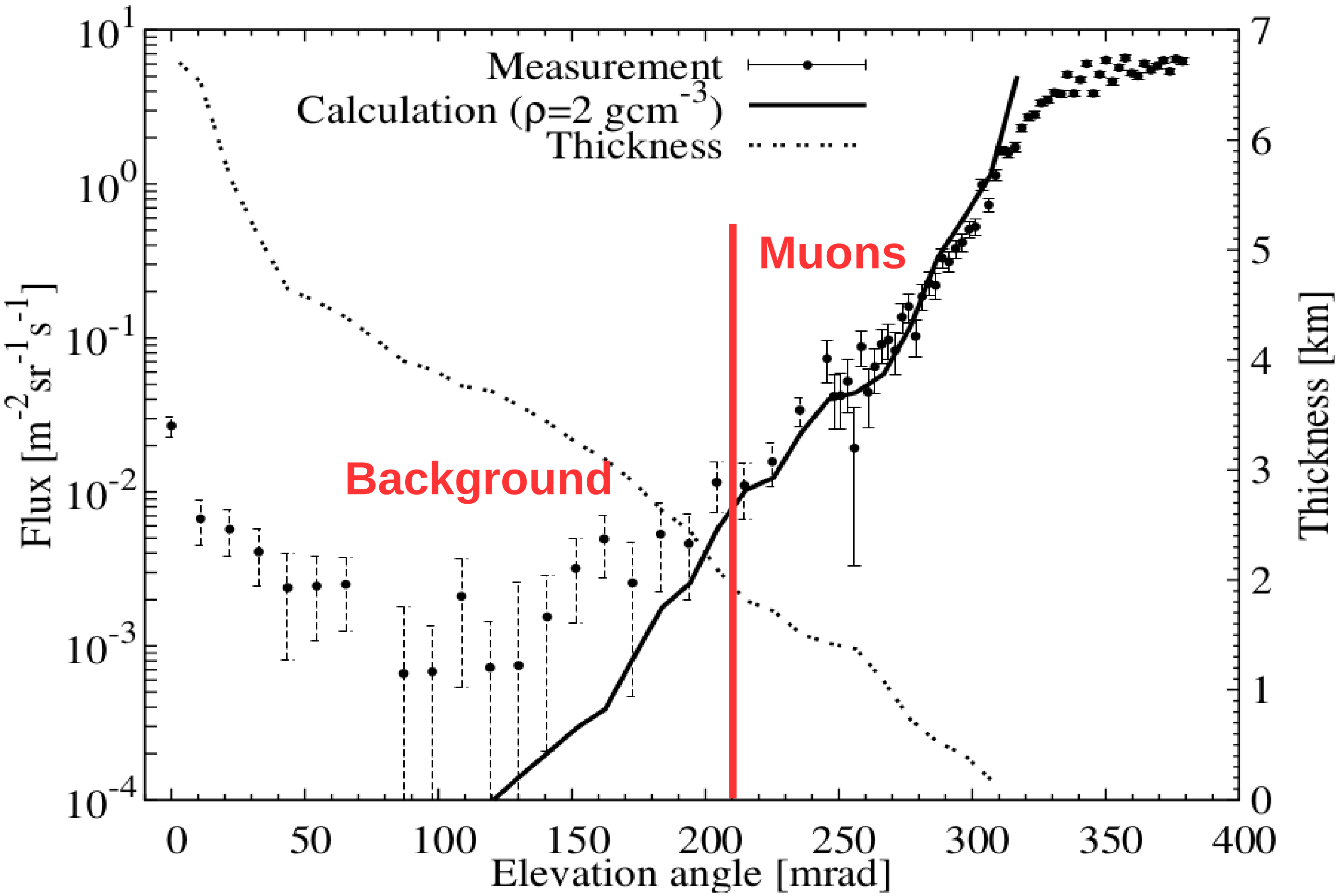
Background Suppression of MMOS (5-7 MWPCs + 5 x 2-cm-thick Pb)



Muons Versus Background



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