Heliospheric and atmospheric parameters affecting cosmic rays flux measured at Belgrade muon station

Nikola Veselinović

On behalf of **Low-background Laboratory for Nuclear Physics, Institute of Physics, University of Belgrade, Serbia**

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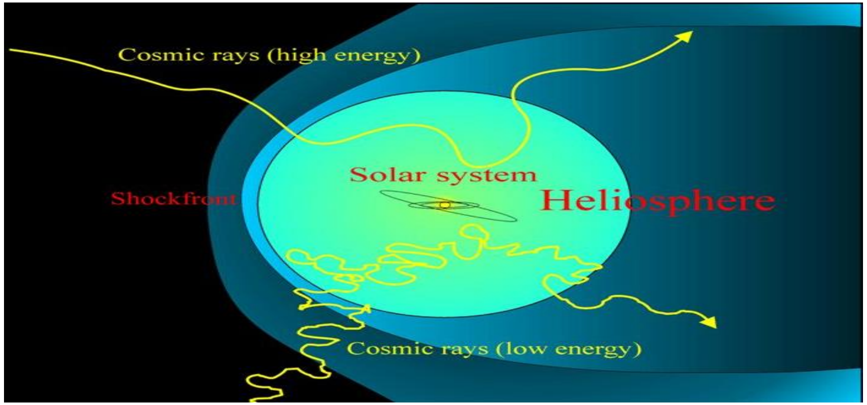
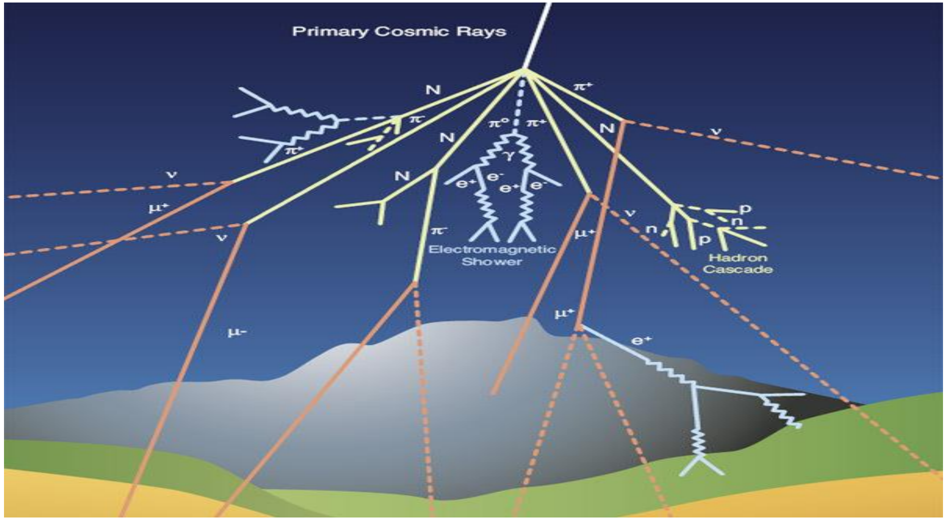
Cosmic rays

Primary cosmic rays - charged particles from outer space with energy obeying power law. Composition of cosmic rays (CR) depends on energy but mostly protons and helium nuclei (~92%).
Galactic cosmic rays are modulated in the heliosphere by Sun's activity through magnetic properties of Solar wind (SW). **CR modulation** will increase when solar activity is higher and decrease when activity is lower.
Solar modulation depends on energy of the CR
Magnetic rigidity $R \equiv pc / Ze$.





Secondary CR shower *–made of* particles that are created from Interaction of primary CR with atmospheric molecules, speading with every new generation of particles. Each shower has two components: **electromagnetic** cascade (pair production, bremsstrahlung) and **hadronic** and mesonic cascade (hadrons, muons ,neutrinos at the ground).
Atmospheric correction needed for flux detected at the ground level.

Belgrade muon station

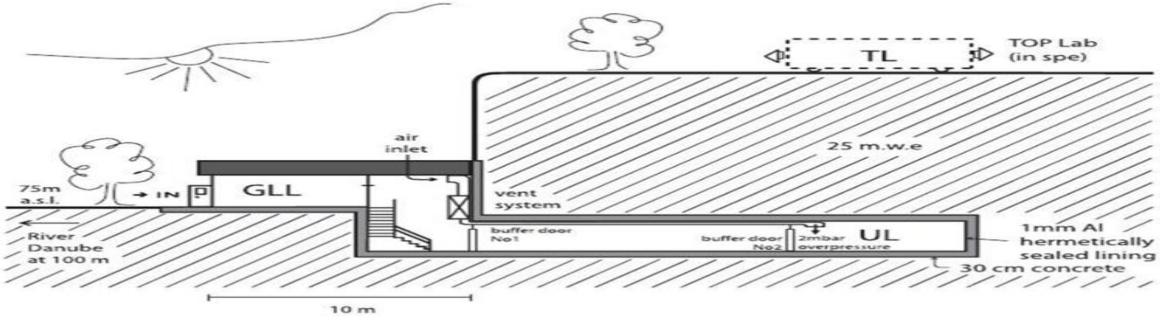
Belgrade muon station is a part of Low level laboratory for nuclear physics at the Institute of Physics, Belgrade, Serbia

It is divided into two parts: **Ground level** (GLL) and **Underground** (UL) level, dug in 12m of loess (25 m.w.e.).

The experimental setup consists of **two identical sets** of detectors and read out electronics which enables correlation of the events, both prompt and arbitrarily delayed with the time resolution of 10 ns.

The flexible software encompassing all above said off-line analyses is user-friendly and entirely homemade.

78 m a.s.l.
44º 51’ N, 20º 23’ E
Min. mag. rigidity 5.3 GV

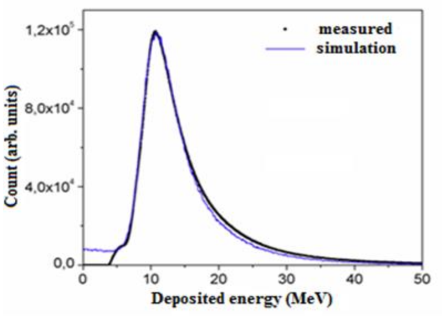


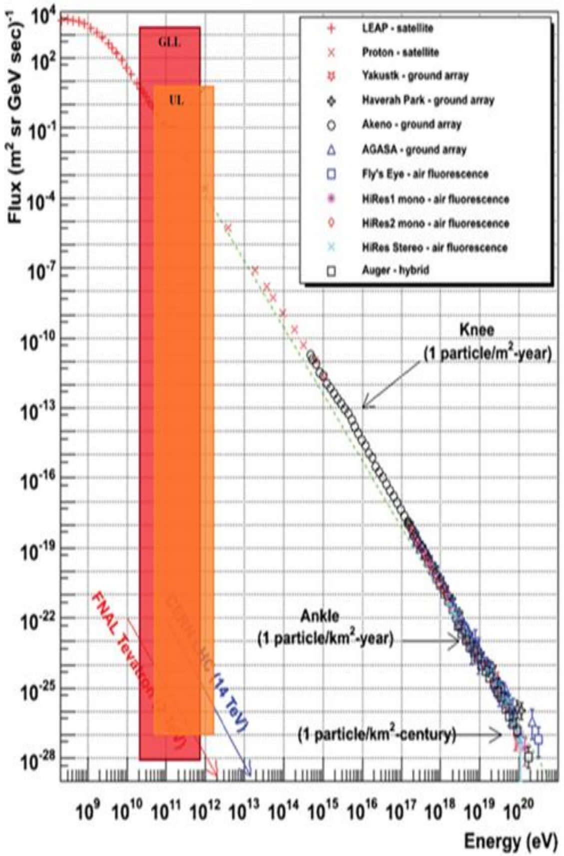
Simulation

Cosmic rays propagation and CR showers can be **simulated from primary cosmic rays** flux at the top of the atmosphere using Monte Carlo simulation. We used software packages to simulate this propagation through atmosphere (CORSIKA) and interaction of secondary CR with soil and detector systems (Geant4).

Response of the detectors are calculated from simulation but also **range** of energy for the primary CR found. This allow understanding of on-site productions of cosmogenic radionuclides useful for **space climate studies**

	E_{th} (GeV)	$E_{0.05}$ (GeV)	E_{med} (GeV)	$E_{0.95}$ (GeV)
GLL	5	11	59	915
UL	12	31	137	915





Corrections of meteorological effects

Correction on pressure

β barometric coefficient

Correction on temperature- Muons are more affected

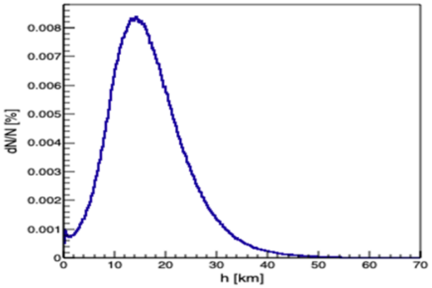
Negative temp. effect

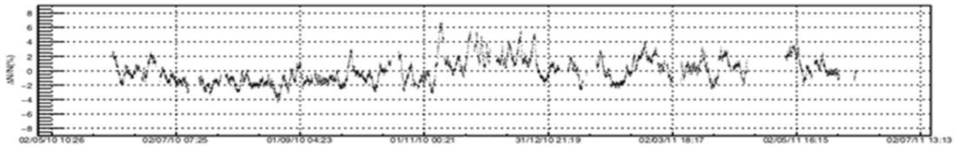
Positive temp. effect

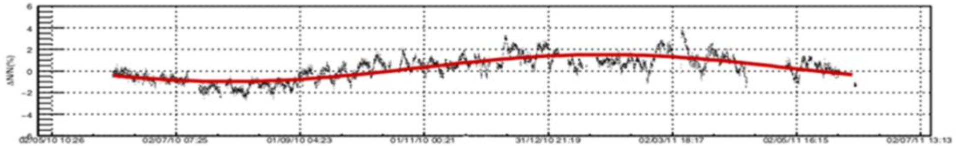
Apart from usual methodology of correcting cosmic ray flux, we developed a **new method** for modelling of meteorological effects which utilize **multivariate analysis techniques** like PCA and machine learning using fact that muons are produced throughout the atmosphere and that different levels have different conditions.

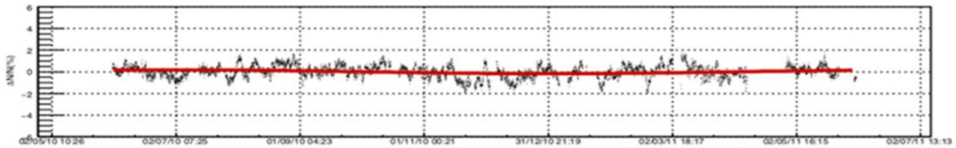
Goal is to use this new methods to get clear data for **studying space weather** but also to use cosmic rays (CR) as **thermometer** for high altitude layers of atmosphere.

$$\frac{\Delta I}{I} = \beta \Delta p + \int \alpha(h)\Delta T(h)dh$$









Forbush decrease

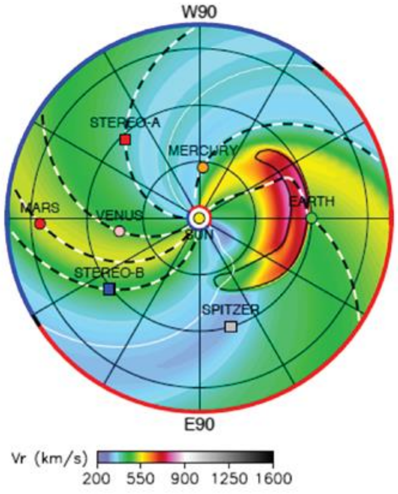
The **sudden decrease** of galactic CR, followed by a **gradual recovery** to the previous intensity (lasting for hours or days) is called **Forbush decrease** (FD).

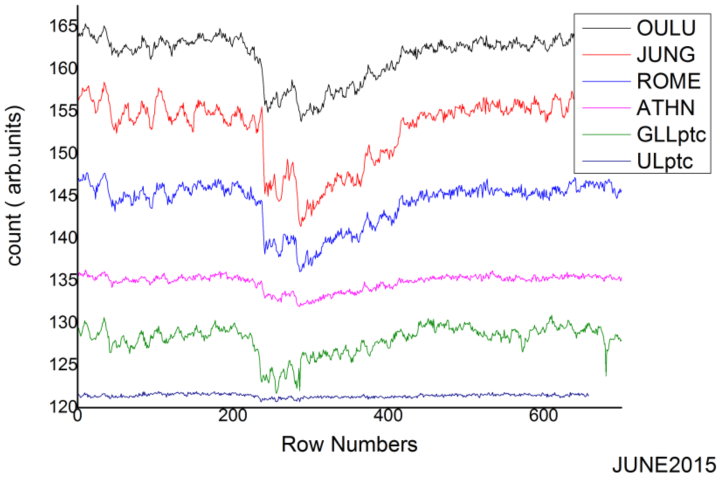
Transient event usually **caused by heliospheric magnetic shock**, following the coronal mass ejection (CME) from the Sun.

FD can be seen as a **drop in count** in ground based instruments (neutron monitors and muon stations).

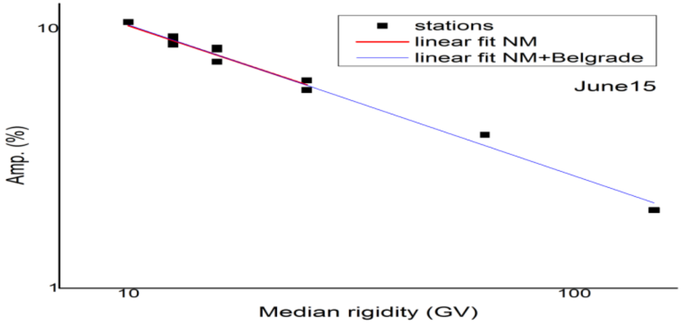
By registering flux originated from primary cosmic rays with higher energy muon monitors complement other ground detector.

Connection between different FD and SW parameters has been investigated and some non-negligible correlation has been found.





$$\frac{\Delta N}{N} \sim {R_m}^{-\gamma}$$

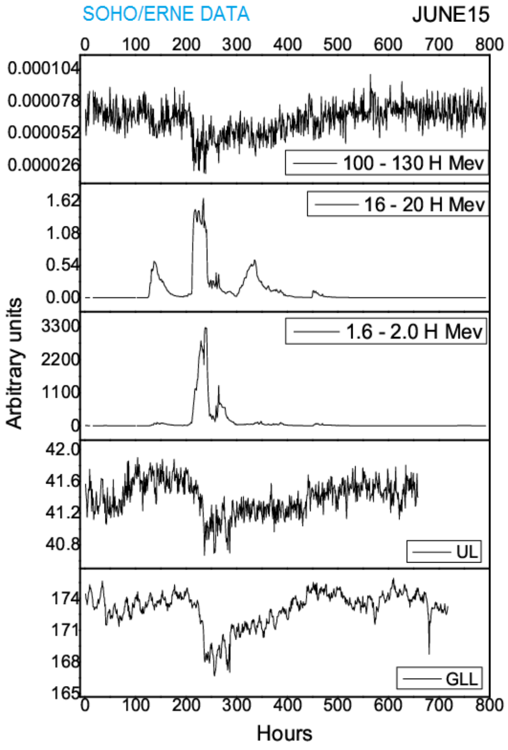


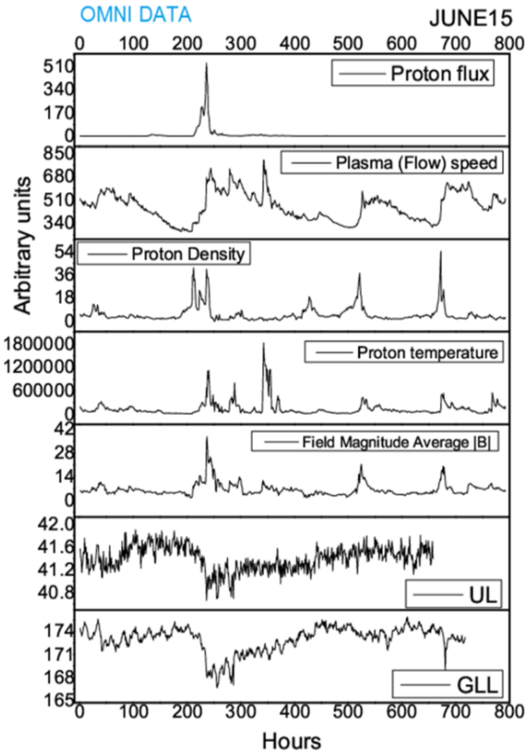
Dependence of FD amplitude on median rigidity

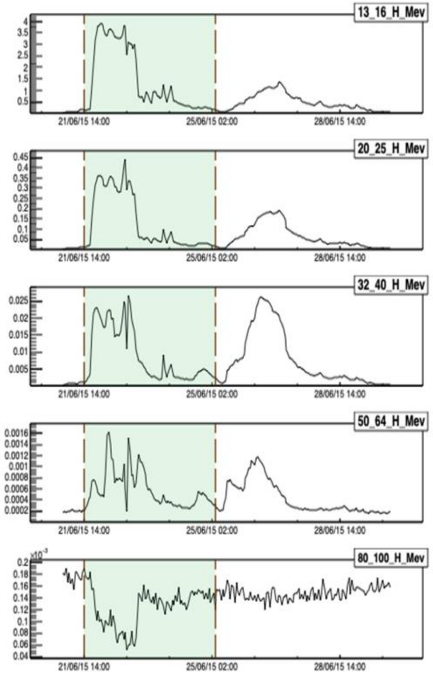
Connection between proton fluence spectra and FD

Connection between proton fluence spectra and selected space weather parameters was investigated by the means of correlative analysis.

Proton flux data (measured outside Earth's magnetosphere) done by ERNE device on board the NASA's SOHO spacecraft at L1, since 1996. Other SW parameters we used can be found on comprehensive NASA/OMNI database.







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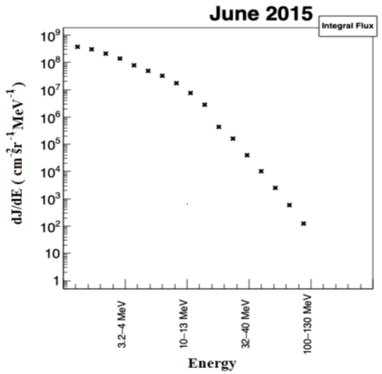
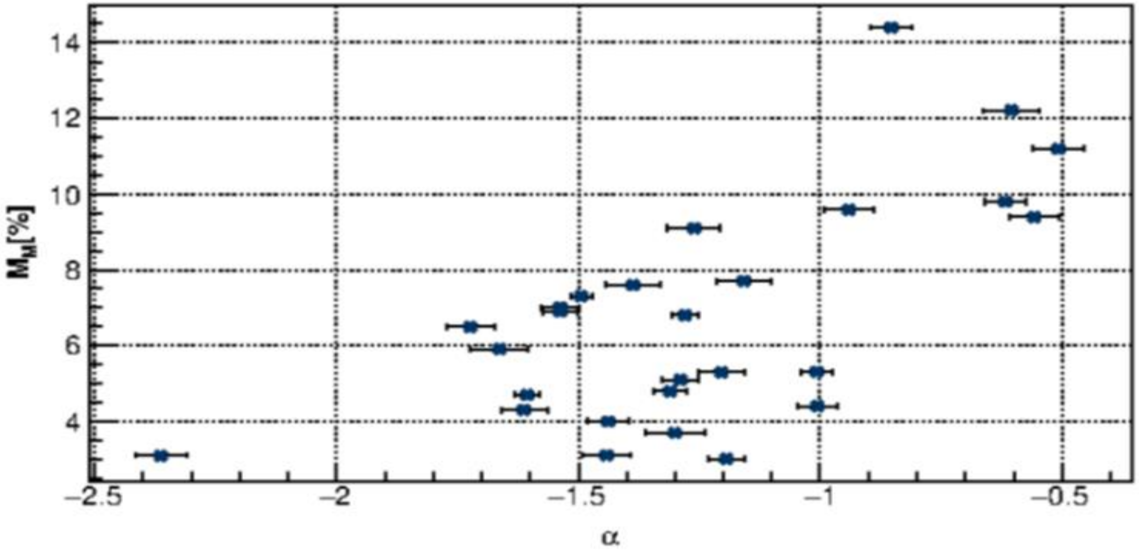
Connection between proton fluence spectra and FD

We fitted measured proton fluence spectra with double power law.
Power exponents were **correlated** with selected CME and SW parameters, as well as selected FD parameters and various parameters of geomagnetic activity.
For selection of FD events and their parameters **IZMIRAN** Space Weather Prediction Center database was used.





$$\frac{dJ}{dE}=\begin{cases} E^{-\alpha}\exp\left(-\frac{E}{E_b}\right), & E\le(\beta-\alpha)E_b \\ E^{-\beta}\left[(\beta-\alpha)E_b\right]^{\beta-\alpha}\exp(\alpha-\beta), & E>(\beta-\alpha)E_b \end{cases}$$

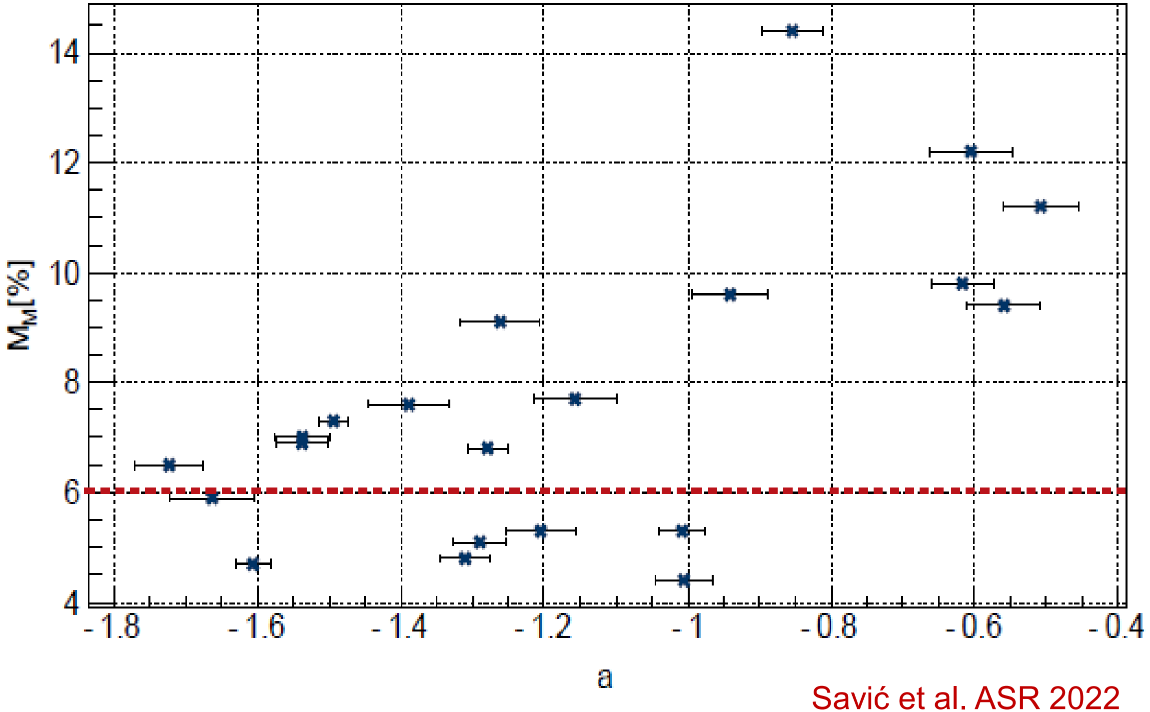
(***E*** – energy, $\boldsymbol{E_b}$ – knee energy)

Connection between proton fluence spectra and FD

We observed largest correlation between power exponents and CME velocities (V_{mean}).

Power exponents seem to be **better predictor** variables of FD magnitude (M) than CME velocities and even better for FD magnitude corrected for magnetospheric effects (M_M)

	α	**β**	**V_{mean}**
M_M	0.64	0.67	0.57
M	0.67	0.67	0.79
M_M >6%	0.77	0.76	0.49
M >6%	0.82	0.76	0.82

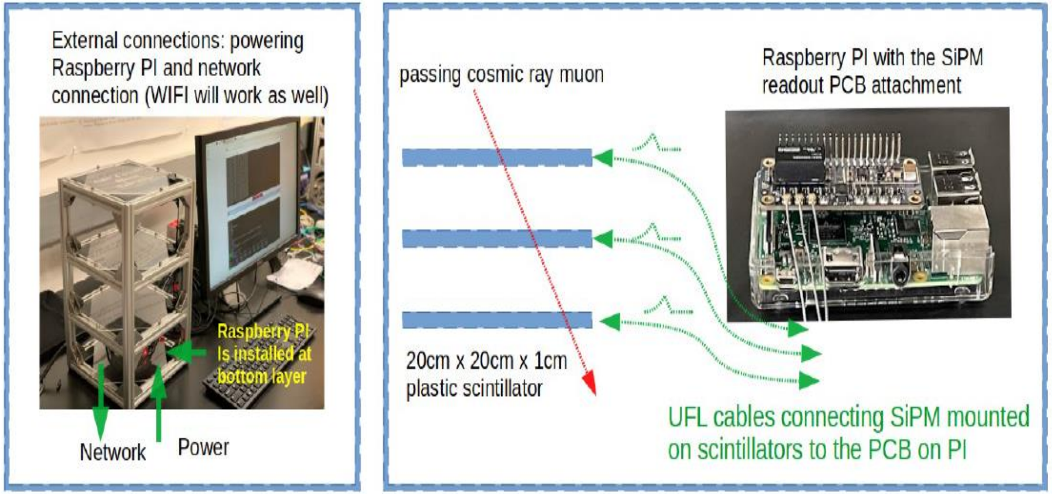


Savić et al. ASR 2022

Future plans- portable muon detector

We are part of **collaboration** led by Georgia state university, Atlanta, USA The goal is **building a worldwide network** of cosmic ray detectors for Monitoring Space & Terrestrial Weather in real-time at global scale. Small portable muon detectors suitable also for outreach activities.

A growing list of participating institutions from USA, China, India, Sri Lanka, Finland, Montenegro, Bulgaria, Serbia (as of October of 2022).



Low-cost detector readout.
Portable, standardized and extendable.
A **minimum site requirement** is a small desk, power and network connection.

We are looking for many more institutions to join this effort!

Contact: Xiaochun He (xhe@gsu.edu), Nikola Veselinovic (veselinovic@ipb.ac.rs)

Summary

Belgrade muon station has been monitoring CR flux during whole 24th cycle and into the 25th.

Conditions of measurements and detector systems are better understood using MC simulations which can be used for on-site cosmogenic radionuclides studies

New method for atmospheric correction of measured muon flux proposed in order to encompass position of muon creation in atmosphere. This correction allows not just to minimize Earth based variation but also to study atmospheric conditions by means of detected muon flux.

Belgrade muon station is sensitive to energy of primary CR exciding energies measured by standard ground detectors but is also sensitive to heliospheric modulation of these primary CR.

In order to understand connection between this modulation and heliospheric parameters we investigate relation between proton flux measured at L1 and Forbush decrease events. Differential proton fluence spectra was fitted with double power law (characterized by two exponents). We found non-negligible correlation between power law exponents and FD magnitudes (particularly FD magnitude corrected for magnetospheric effect).

Belgrade muon station is part collaboration with goal of creating world wide network of portable muon detectors useful for space weather and atmospheric parameters.

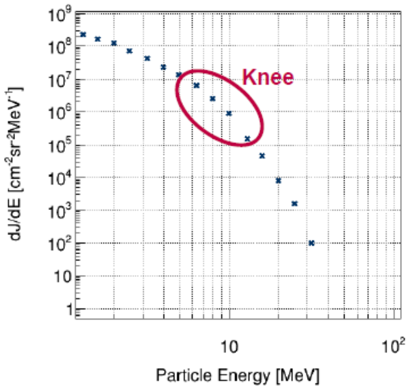
Aditional slides

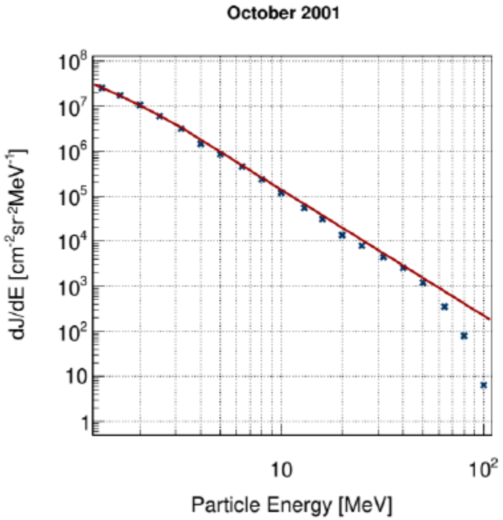
Good and not so good fits...

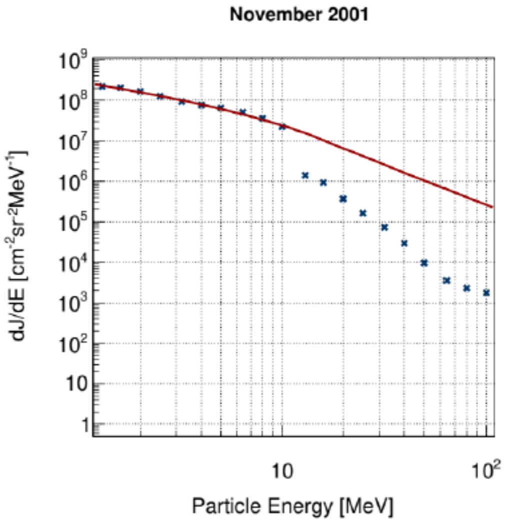
Double power law (Zhao at al. ApJ 2016)

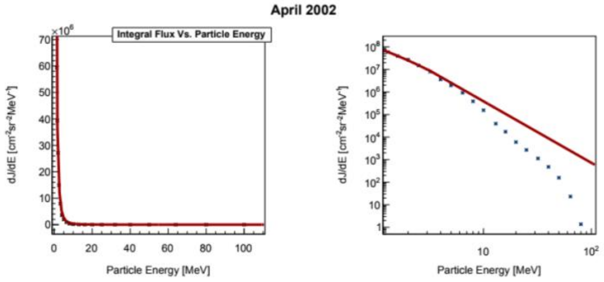
$$\frac{dJ}{dE}=\begin{cases} E^{-\alpha}\exp\left(-\frac{E}{E_b}\right), & E\le(\beta-\alpha)E_b \\ E^{-\beta}[(\beta-\alpha)E_b]^{\beta-\alpha}\exp(\alpha-\beta), & E>(\beta-\alpha)E_b \end{cases}$$

(***E*** – energy, ***E**$_b$* – knee energy)







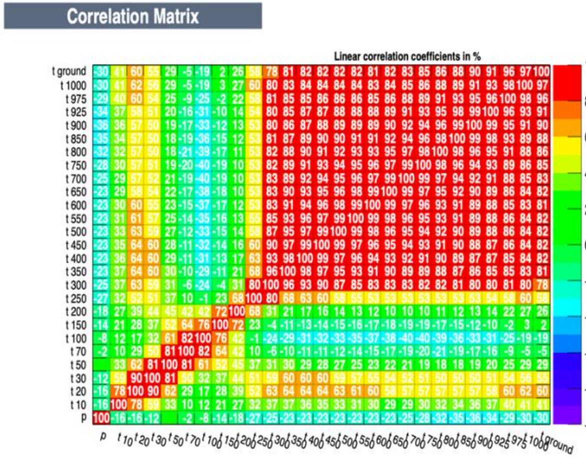


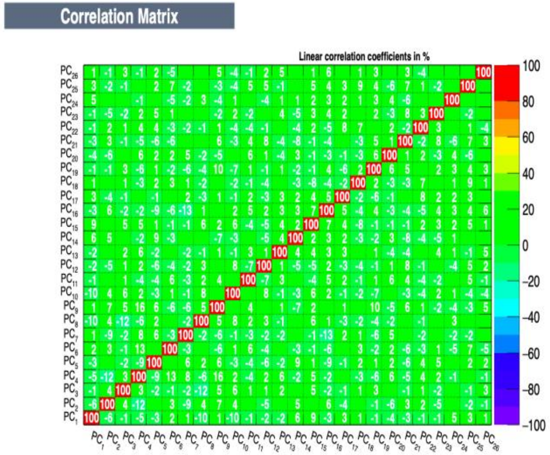
Aditional slides

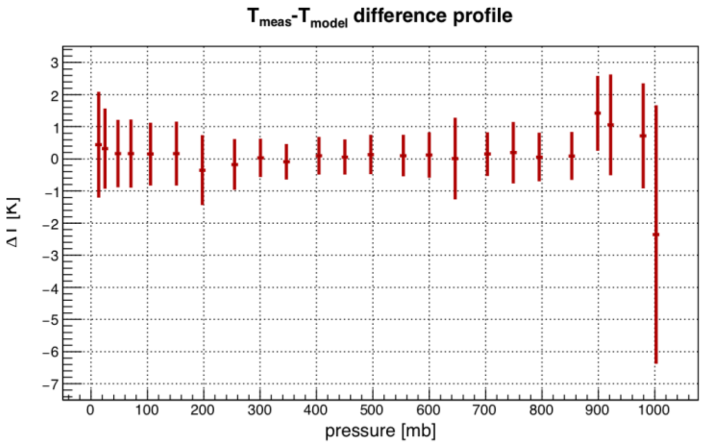
GFS (Global Forecast System)/NOAA

Input parameters: ground pressure, temperature of atmosphere on 25 different layers and ground temperature.

Savić M. et al.
Space Weather, 2021, 19(8)
Astroparticle Physics, 2019, 109, pp. 1–11

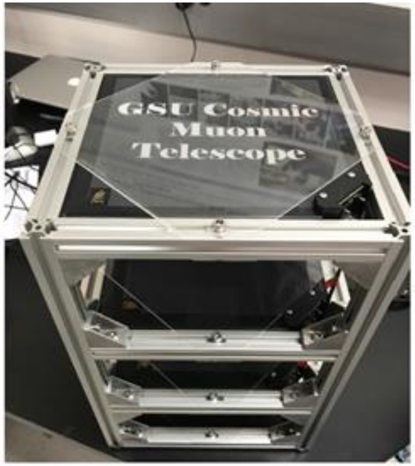






Aditional slides

- Portable
  - It is light and small relative to other detectors.
- Low-cost
  - Each fully assembled detector costs ~600 USD
  - Continuing to decrease the price
    - Cheaper electronics
- Standardized
  - Every detector will have the same hardware and same software



Georgia State University (led by Prof. Xiaochun He and Prof. Ashwin Ashok), Atlanta, USA

University of Belgrade (led by Dr. Nikola Veselinovic), Serbia

University of Oulu (led by Prof. Ilya Usoskin), Finland

Institute of Astronomy and National Astronomical Observatory (led by Prof. Nikola Evanov Petrov), Bulgarian

University of Montenegro (led by Prof. Gordana Jovanovic), Montenegro

Georgia Institute of Technology (led by Prof. Jingfeng Wang), Atlanta, USA

Northwestern Polytechnical University (Led by Prof. Ting-Cun Wei), Xian, China

Tsinghua University (led by Prof. Zhihong Ye), Beijing, China

Uva Wellasa University (led by Prof. H.M.J.C. Pitawata), Badulla, Sri Lanka

Muthoot Institute of Technology (led by Prof. Neelakantan), Kerala, India

- Not complicated
  - Few parts with potential to break or wear down with age
  - General concept is easy to grasp so can be used for STEM outreach in high/middle schools
  - Maintenance should be low-cost
- Expandable
  - We can continue to expand the telescopes with more tiles, etc. if we want
- Networked
  - Accessible worldwide

https://pos.sissa.it/358/078/pdf