Correlation of solar wind parameters with cosmic rays observed with ground station

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Petnica, May 11, 2019.

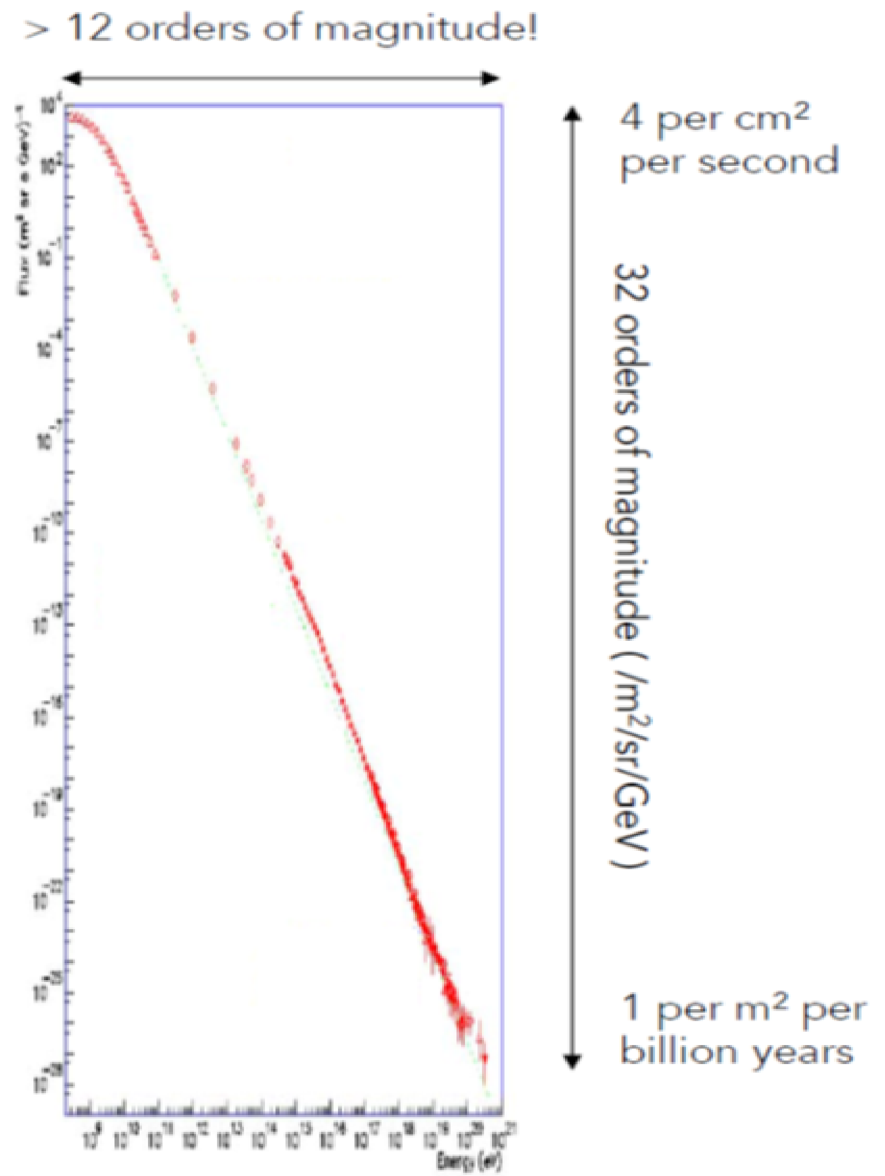
Overview

- Cosmic rays
- Transport through heliosphere
  - Solar activity and space weather
  - Parker equation
- Transport through geomagnetic field
- Interaction with atmosphere
- Detection of cosmic rays
  - Satellite
  - Airborne, ground detectors
  - Underground detectors
- Low level laboratory
- Measurement of solar activity
  - Comparison between ground detectors
  - Comparison with satellite
- Plans for future
- Conclusion

Cosmic rays

- Major phenomenon in our galaxy
  - Energy density ~ star light, thermal, B field
  - Regulate the equilibrium between the different phases of the interstellar medium
  - Control ionisation, heating
  - Regulate star formation
  - Control astrochemistry
  - Generate turbulent magnetic field
  - Produce Li, Be and B

  Major unknown
  - Sources are not well known (Galactic and Extragal.)
  - Acceleration processes are uncertain

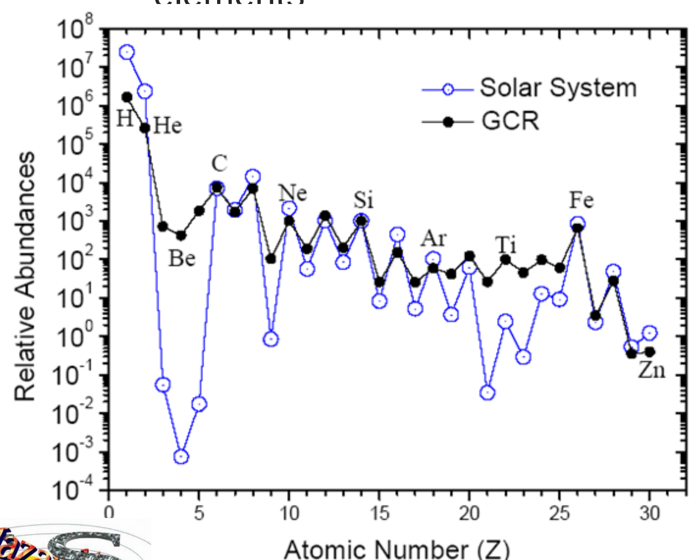


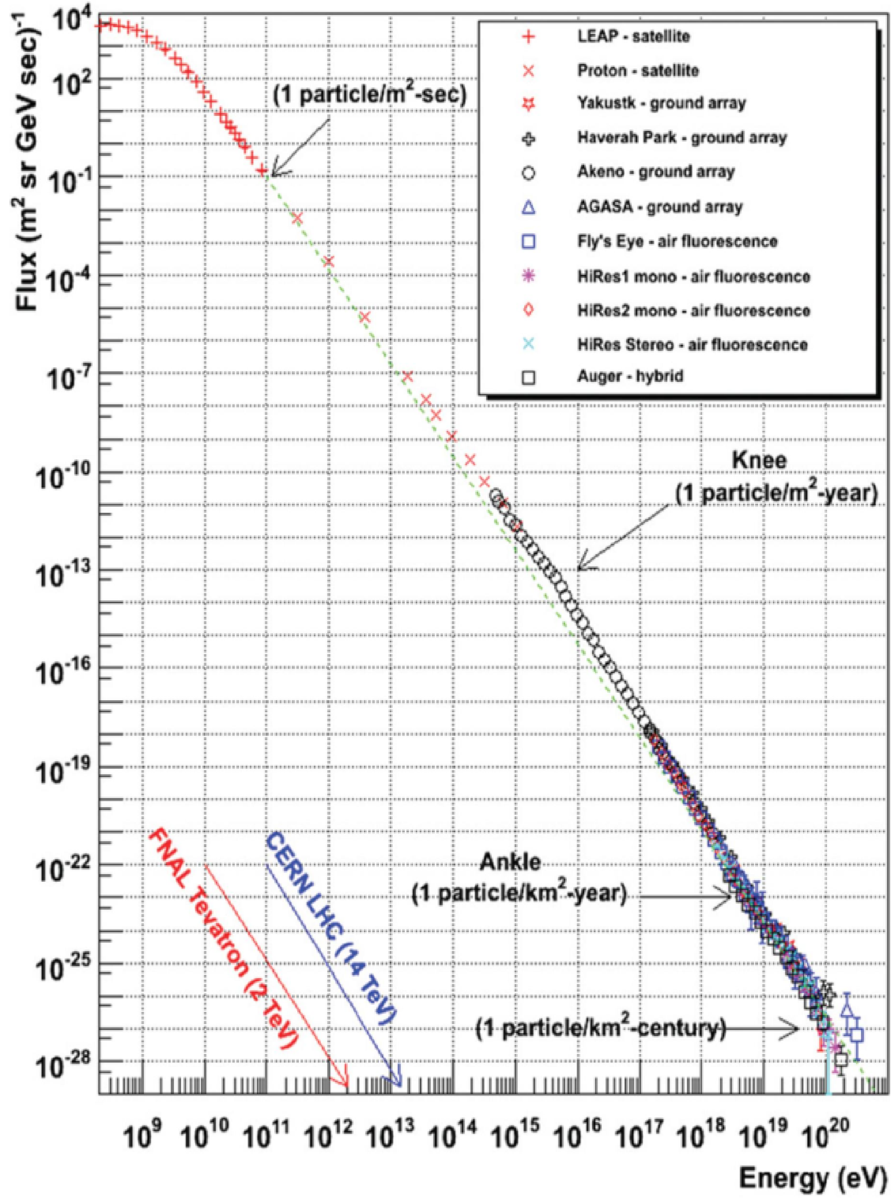
Cosmic rays

- Primary cosmic rays spectrum
  - Power law

$$j(E) = \frac{dN}{dE} \propto E^{-\gamma}$$

- γ ~ 2.7
- Cosmic rays composition
  - Depends on CR energy
  - ~80% protons, ~12% helium nuclei rest are electrons and nuclei of hevier elements

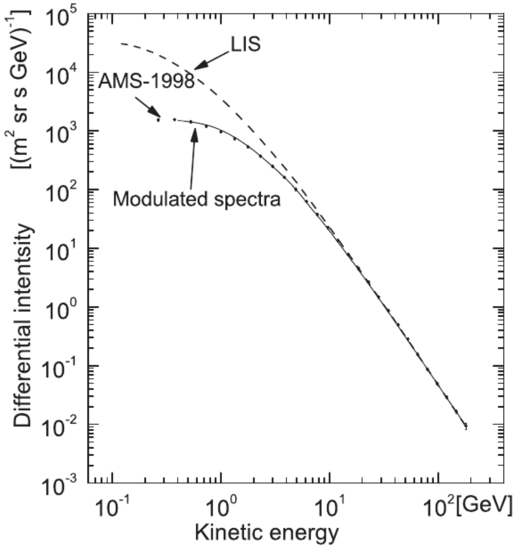


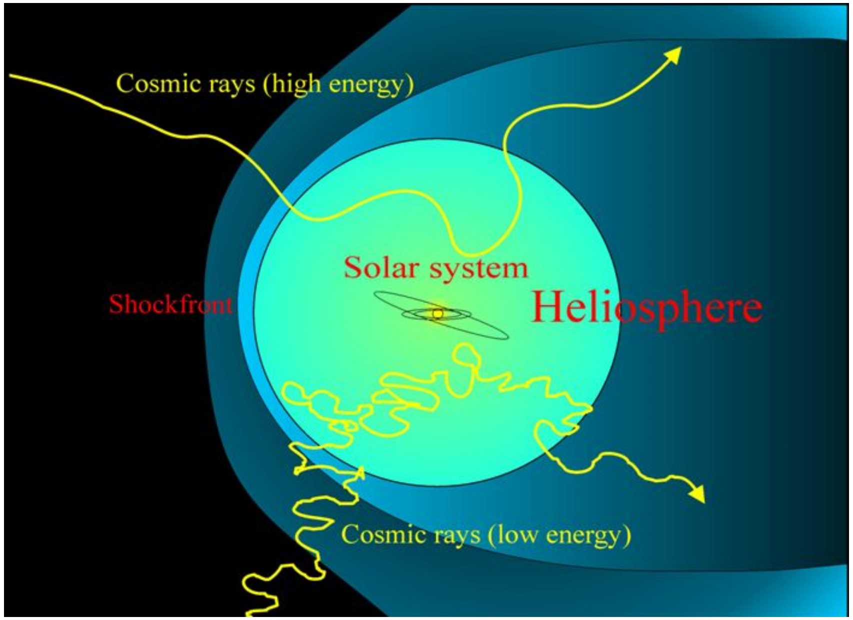


Transport through heliosphere

- **Solar wind**
  - stream of charged particles released from the upper atmosphere of the Sun
- CR interact with helioshere - **modulation of CR**
- Magnetic field and solar wind depend on activity of the Sun (**space weather**)
- 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**

$$R \equiv pc / Ze.$$





Transport through heliosphere

equation

- Propagation in the heliosphere was described by Parker (1965) equation

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x_i}\left[\kappa_{ij}^{(S)}\frac{\partial f}{\partial x_j}\right] - \mathbf{U}\cdot\nabla f - \mathbf{V}_{\mathrm{d}}\cdot\nabla f + \frac{1}{3}\nabla\cdot\mathbf{U}\left[\frac{\partial f}{\partial \ell n p}\right] + Q$$

Diffusion
Small scale magnetic field irregoularity

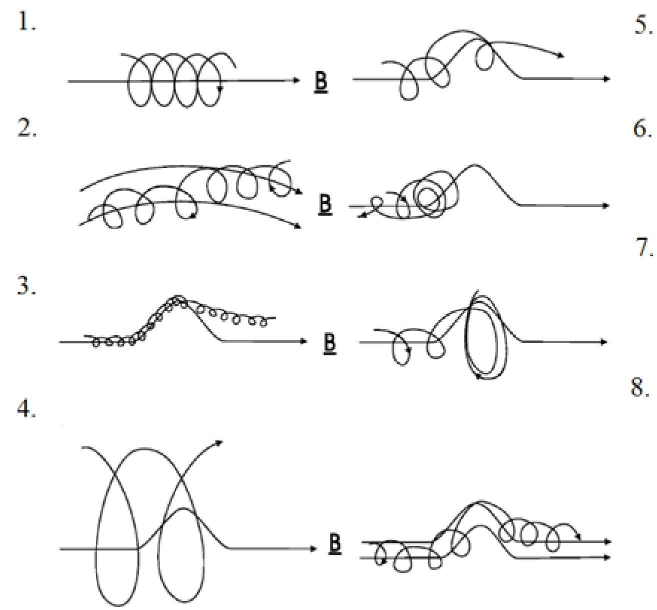
Convection
Presence of the solar wind moving outward from the Sun

Drift
Large scale structure of magnetic field (e.g. gradients, curvature)

Energy change
Due to adiabatic expansion of the solar wind

Source
within helioshere

- $f(R,t)$ – number of charged particles per unit volume of phase space
- Magnetic rigidity R
- Gyroradius $r_g = R/cB$.



Transport through heliosphere

Equation

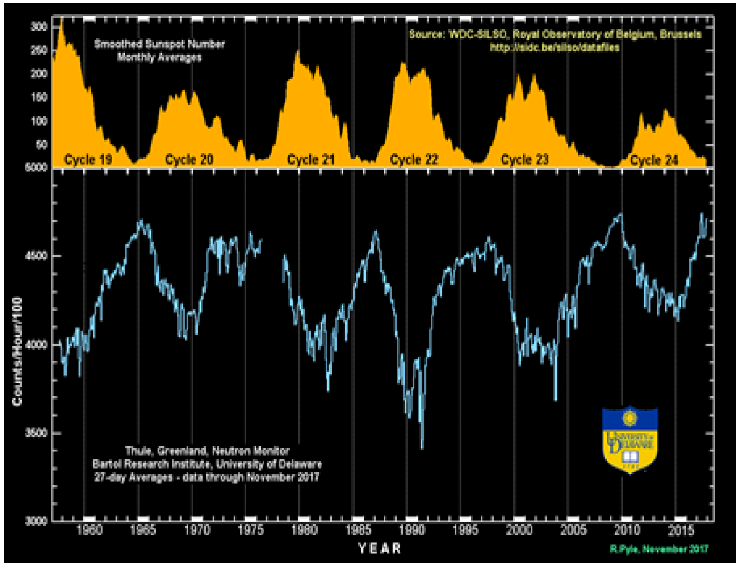
$$\frac{\partial f}{\partial t} + \nabla \cdot (Vf - K \cdot \nabla f) - \frac{1}{3}(\nabla \cdot V)\frac{\partial f}{\partial lnp} = q$$

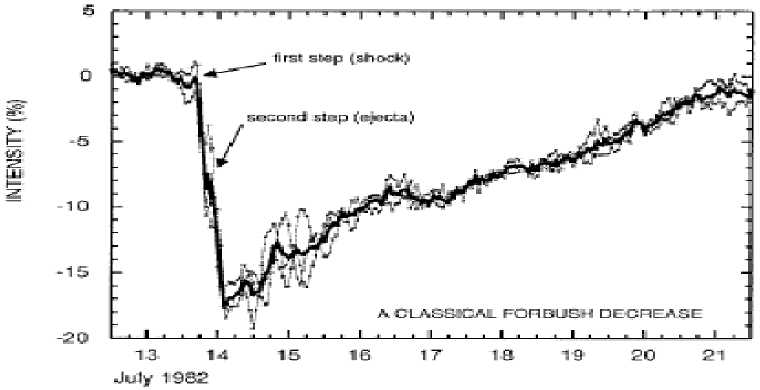
- Scattering of cosmic rays by turbulence is described by the cosmic-ray diffusion tensor
- the diagonal elements describe diffusion of particles parallel ($K_{||}$) and perpendicular ($K_{\perp}$) to the mean magnetic field,
- off-diagonal, antisymmetric terms (K_A) describe effects of gradient and curvature drift

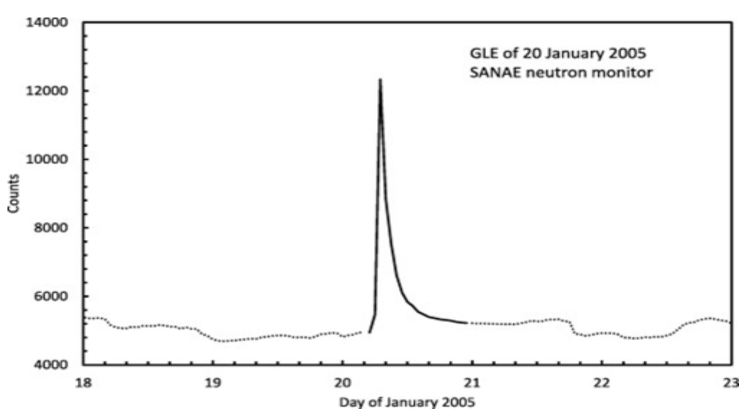
$$\mathbf{K} = \begin{pmatrix} K_{\perp} & K_A & 0 \\ -K_A & K_{\perp} & 0 \\ 0 & 0 & K_{||} \end{pmatrix}$$

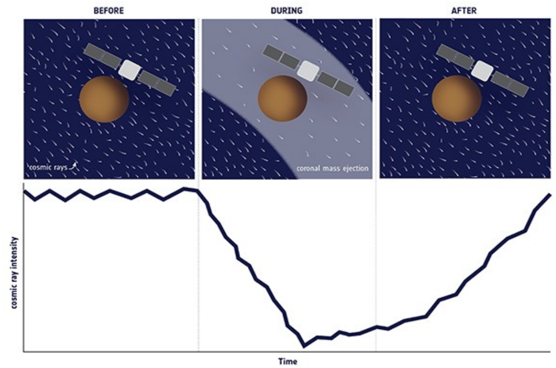
Solar activity

type	Amplitude	origin
Periodic variations		
11-years and 22-years	Up to 30%	Solar cycles (change of sunspot number)
27-days	< 2%	due to Sun’s rotation
daily	0,5 %	flux anisotropy due to Earth’s movement through heliosphere
Sporadic variation		
GLE	Up to 300%	additional flux of charged particles from CME
Forbush decrease	~10%	decrease due to reflection of low energy CR from the shockwave in heliosphere





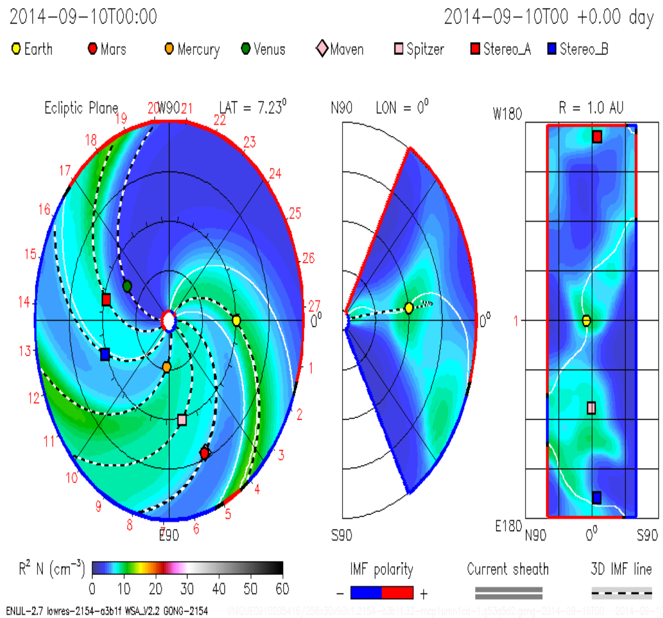


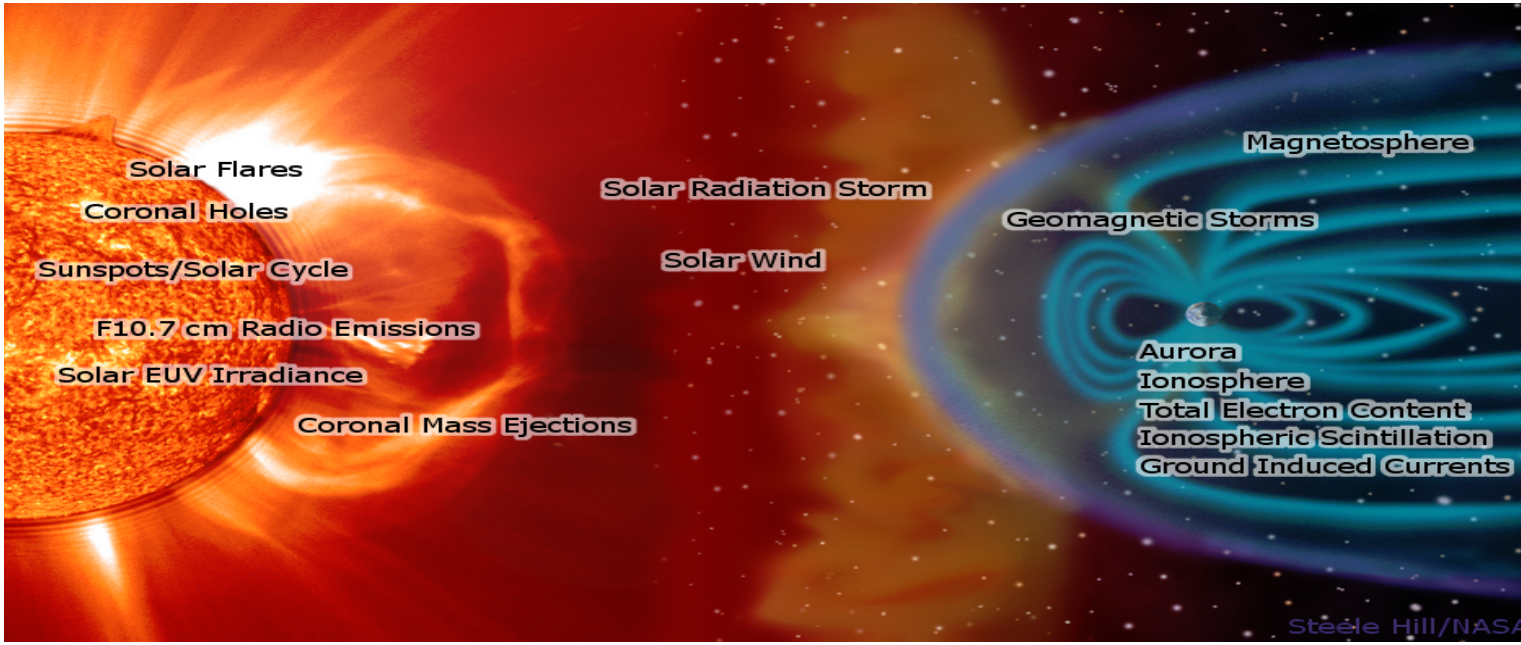


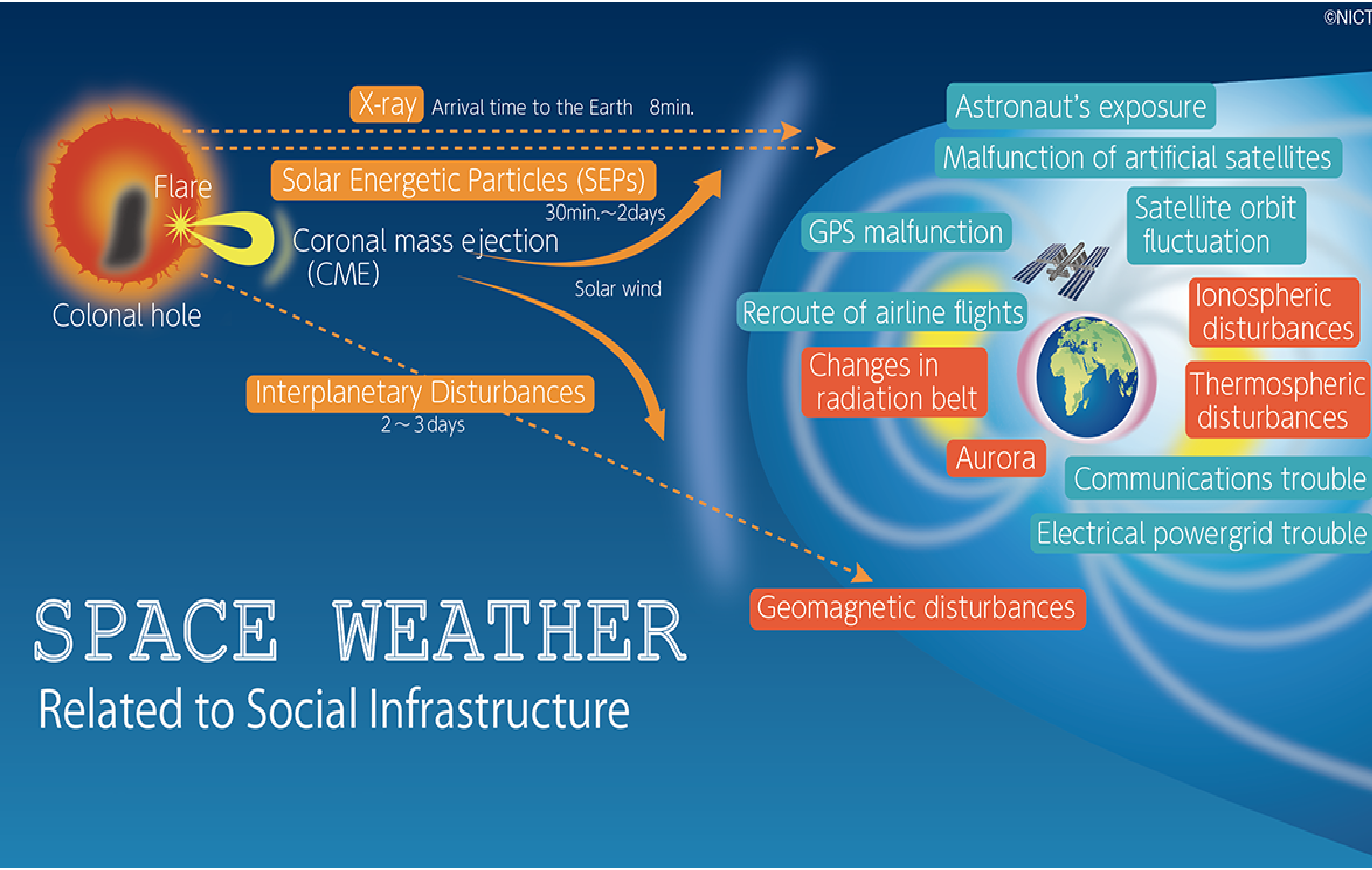
Solar activity

Sporadic events

- Violent processes at the Sun produces disturbance of the heliosphere.
- This disturbance interact with geomagnetic field.
- This interaction have disruptive potential on our civilization.



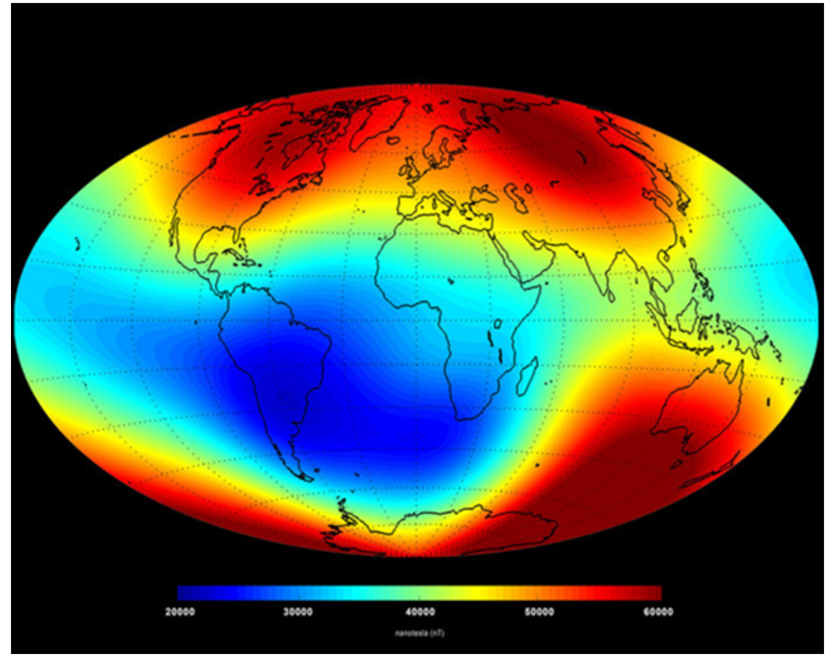


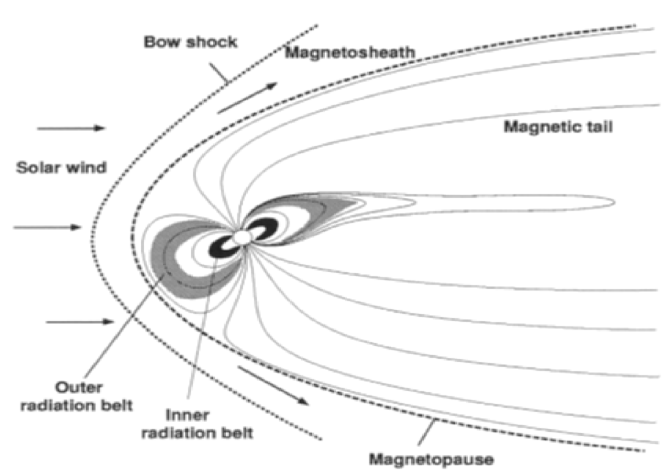

©NICT
X-ray
Arrival time to the Earth 8min.
Flare
Solar Energetic Particles (SEPs)
30min.~2days
Coronal mass ejection
(CME)
Solar wind
Colonal hole
Interplanetary Disturbances
2～3 days
Astronaut's exposure
Malfunction of artificial satellites
Satellite orbit
fluctuation
GPS malfunction
Reroute of airline flights
Ionospheric
disturbances
Changes in
radiation belt
Thermospheric
disturbances
Aurora
Communications trouble
Electrical powergrid trouble
Geomagnetic disturbances
SPACE WEATHER
Related to Social Infrastructure

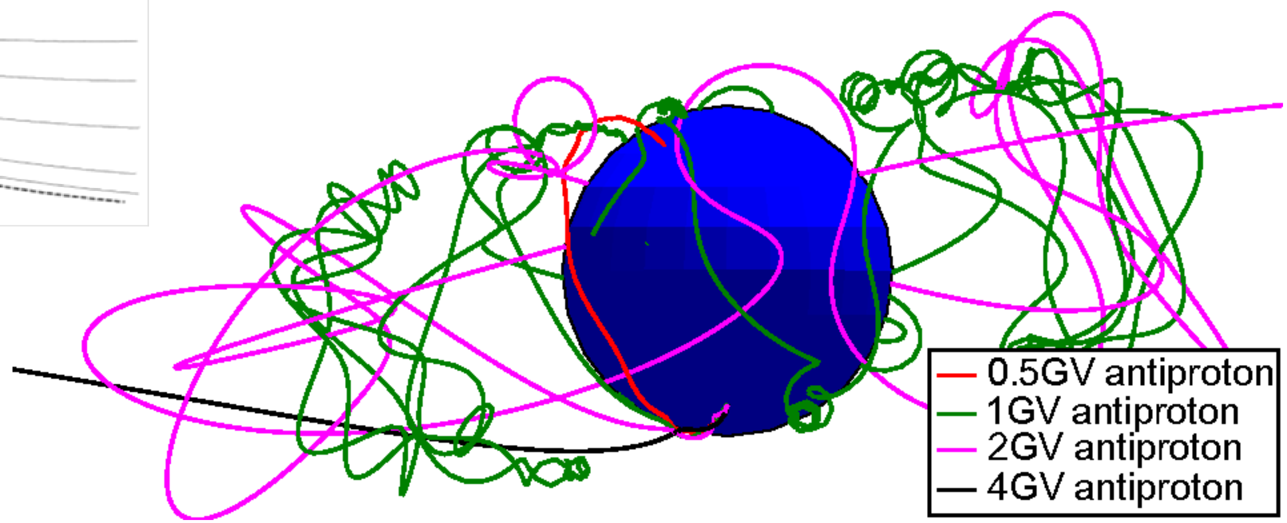
Transport through geomagnetic field

- Geomagnetic field also affect CR
- Dipole aproximation
- **R**$_s$ (geomagnetic cutoff rigidity)
  - Smallest rigidity for charged particle to reach surface

$$R_c = \frac{M \ \cos^4\lambda}{4\, r^2}$$





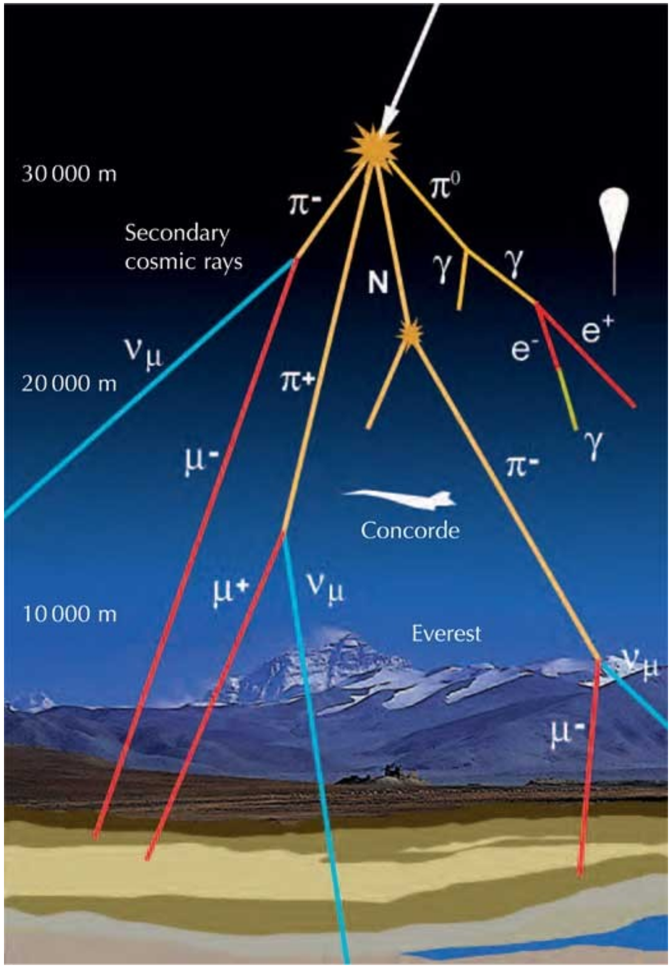


Interaction with atmosphere

Secondary CR

- Primary CR interact with nuclei from atmosphere
- ***Secondary CR shower***
  - Particles that are created from interaction

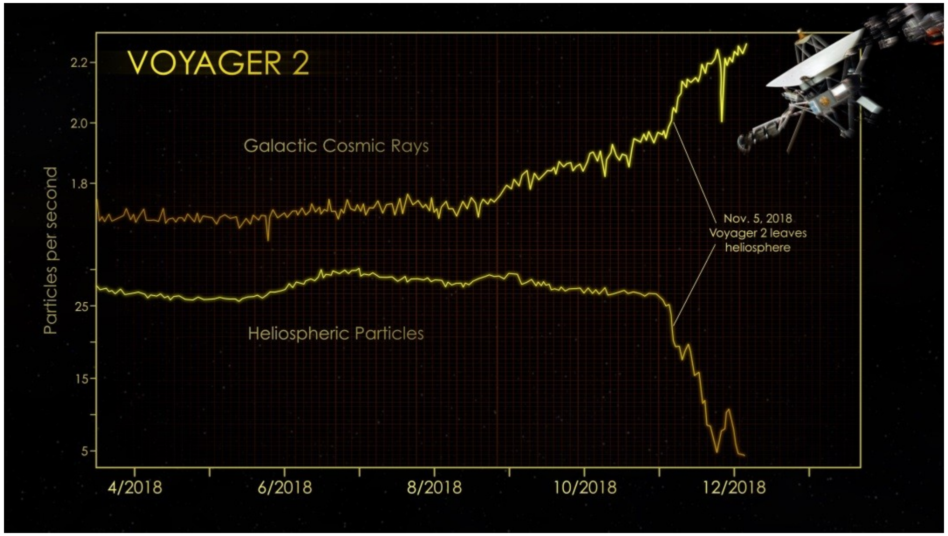
- Electromagnetic cascade
  - $\pi^0 \rightarrow 2\gamma$
  - $\gamma^* \rightarrow e^- + e^+$ pair production
  - $e \rightarrow e + \gamma$ *bremsstrahlung*
- Hadronic and mesonic cascade
  - $p + p \rightarrow p + \Delta^+ \rightarrow p + n + \pi^+$
  - $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - $\pi^- \rightarrow \mu^- + \nu_\mu$
- Shower spread with every new generation of particles
- Must be corrected with atmospheric parameters in mind

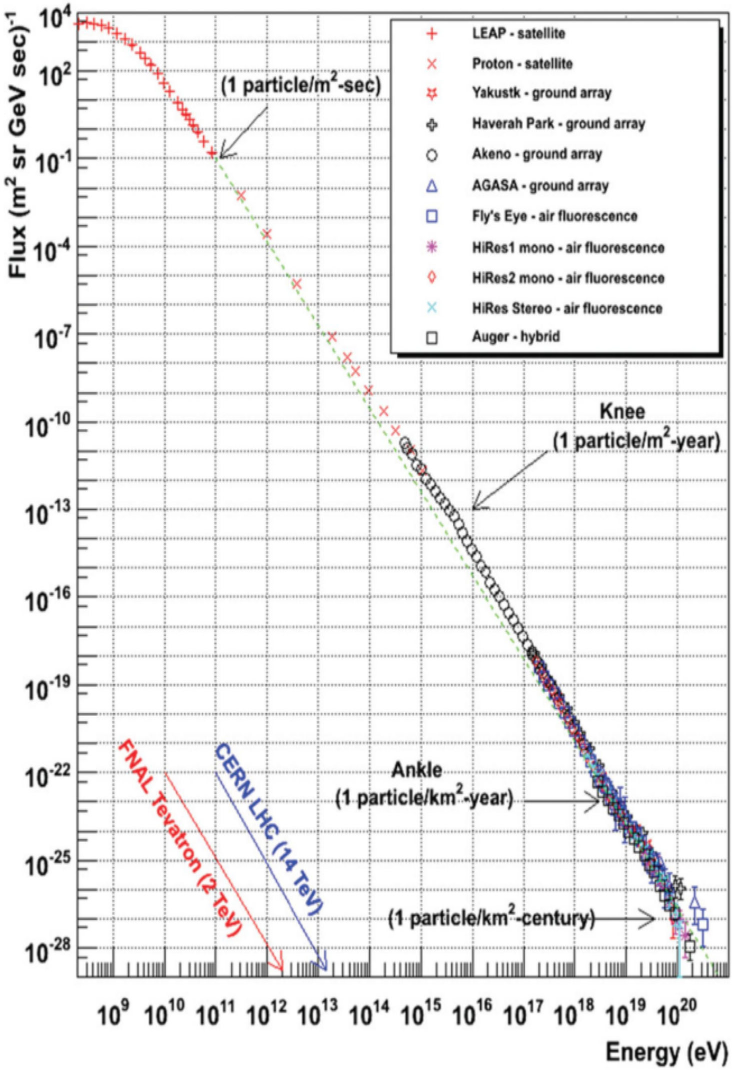


Detection of CR

Can be:

- Outside the heliosphere (Voyager)
- Above the atmosphere (various satellites)
- High in the atmosphere (high altitude balloons)
- On ground (secondary CR)
- Underground (secondary muons, neutrinos…)





Primary Space Weather Satellites for SEC

NASA STEREO (Ahead)

- Events are observed on and near the sun
- No measurements until the Particles or CMEs are 99% of the way to Earth
- This provides only 30 minutes lead time for CMEs and no lead time for other events

- **SOHO**
  - **Solar EUV Images**
  - **Solar Corona (CMEs)**

NASA SOHO

L1

NASA ACE

- **GOES**
  - **Energetic Particles**
  - **Magnetic Field**
  - **Solar X-ray Flux**
  - **Solar X-Ray Images**

NOAA GOES

- **ACE**
  - **Solar wind composition, speed, and direction**
  - **Magnetic field strength and direction**

NOAA POES

- **STEREO**
  - **CME Direction and Shape**
  - **Solar wind composition, speed, and direction**
  - **Magnetic field strength and direction**

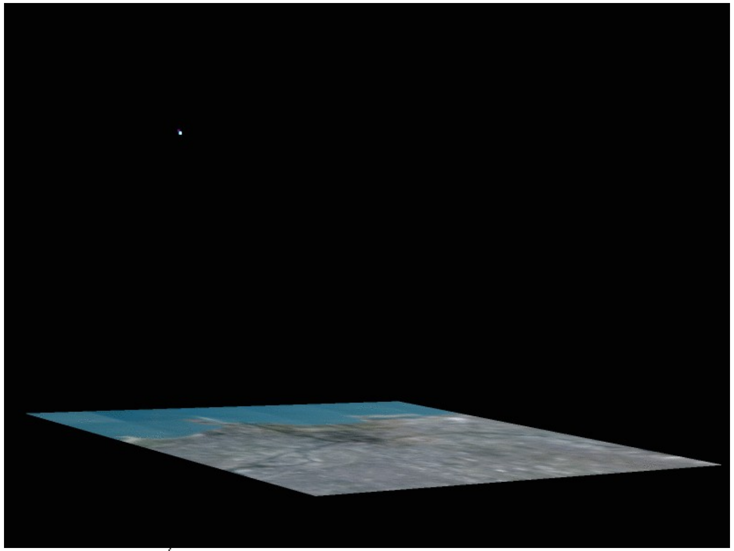
- **POES**
  - **High Energy Particles**
  - **Total Energy Deposition**
  - **Solar UV Flux**

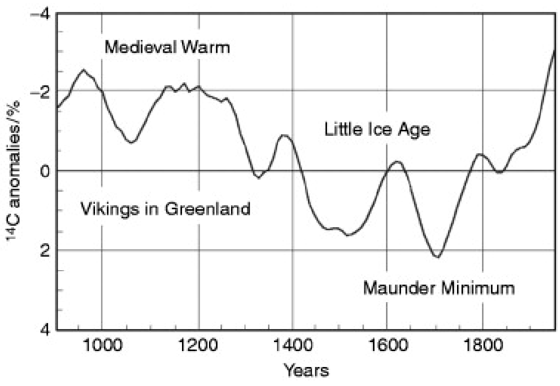
NASA STEREO (Behind)

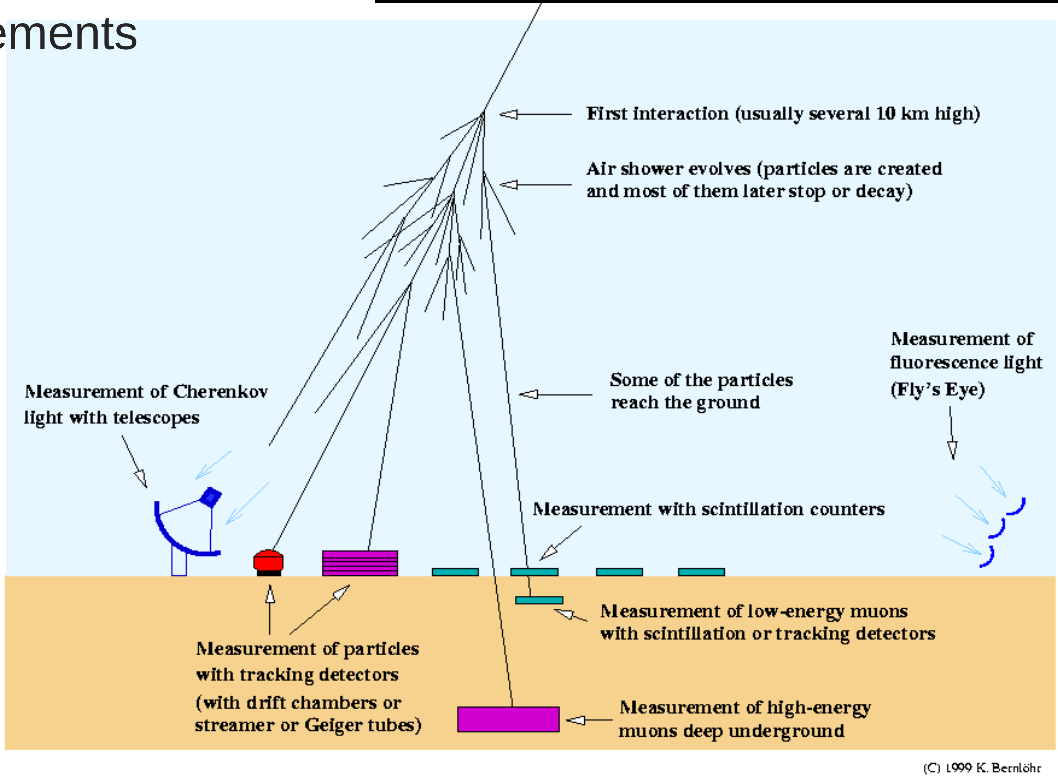
NASA.GOV

Ground systems

- Various methods are used to detect CR
- Some indirect methods includes measurement of concentration of cosmogenic radioisothopes ^{10}Be and ^{14}C in a sample
- Neutron monitors are standard detectors for ground measurements



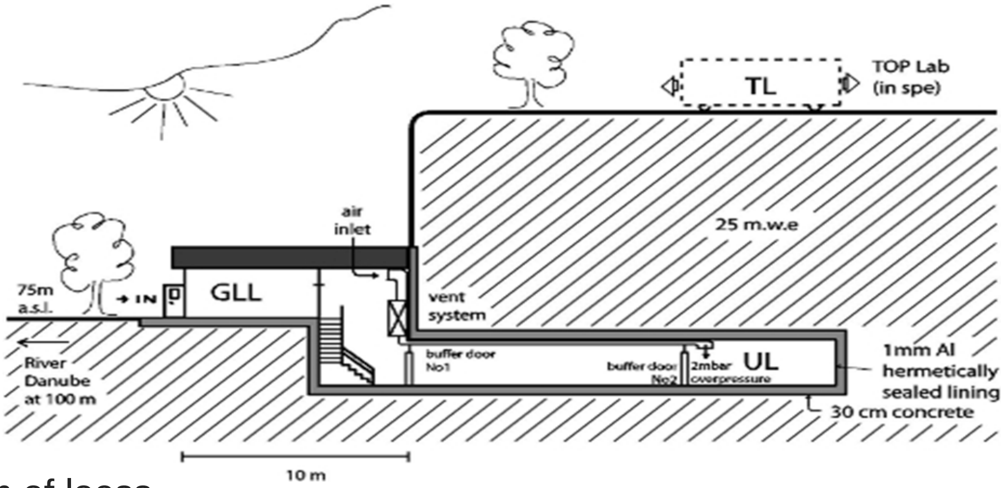




Low level laboratory for nuclear physics

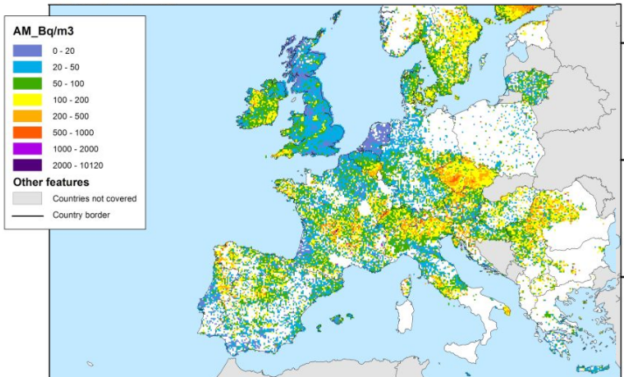
Institute of physics, Belgrade, Serbia

- 78 m a.s.l.,
  Geographic coordinates
  44^{o} 51' N, 20^{o} 23' E
- Minimal vertical rigidity 5.3 GV.



- Consist of two parts:
  - Ground level (GLL)
  - Underground (UL) level, dug in 12m of loess .

European Indoor Radon Map, March 2017



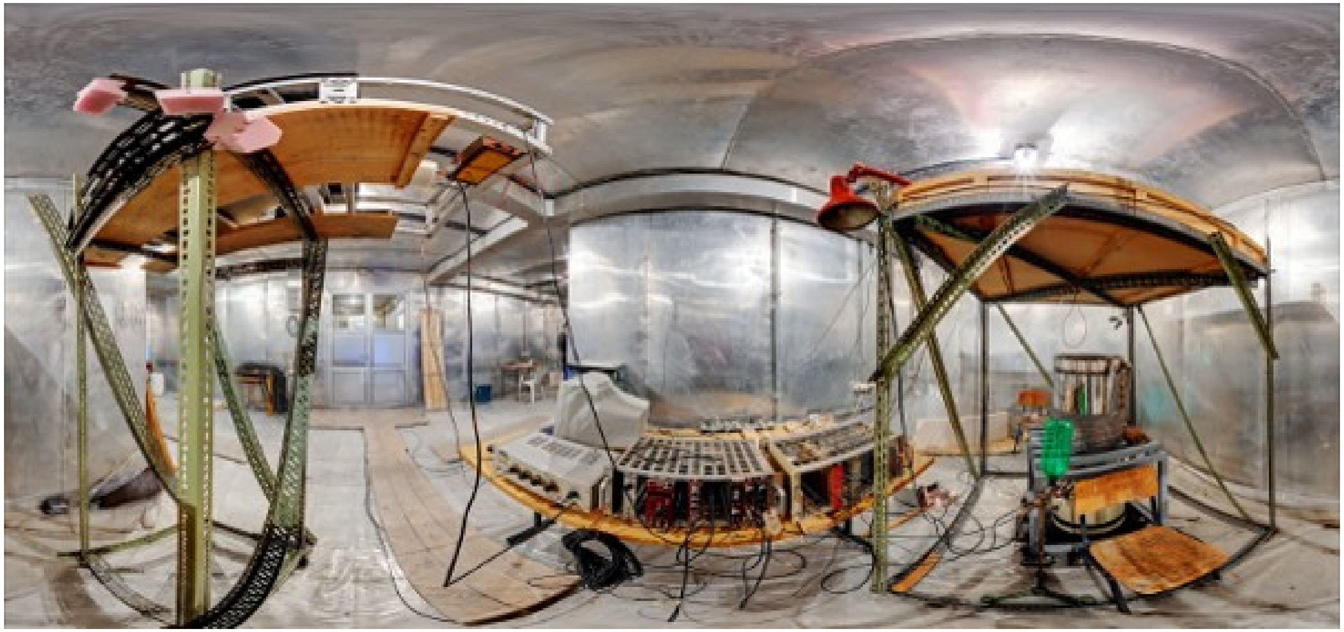
- Scientific research activities in the LBLNP are in the fields of nuclear and high energy physics. They are related in particular to cosmic-ray physics, nuclear spectroscopy, radon and environmental radiation measurements

- http://cosmic.ipb.ac.rs/

Low level laboratory for nuclear physics

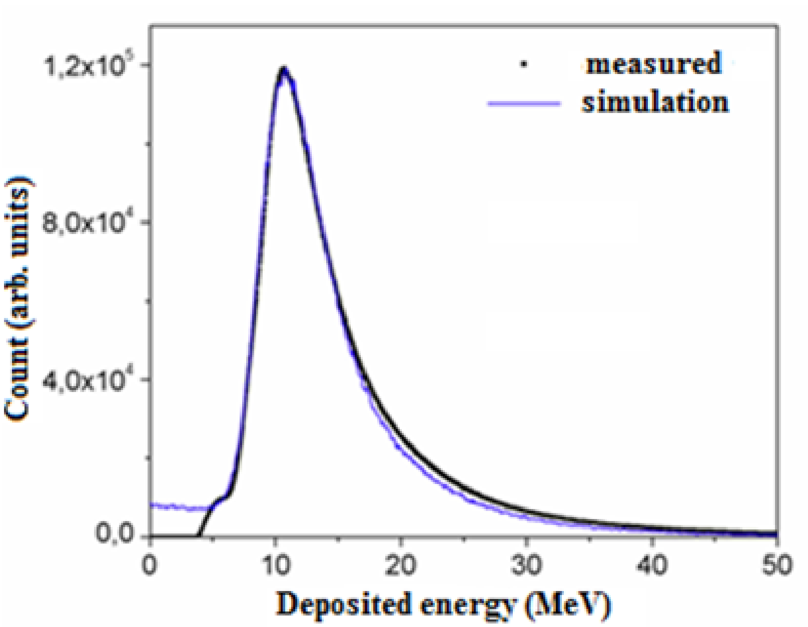
Cosmic rays physics

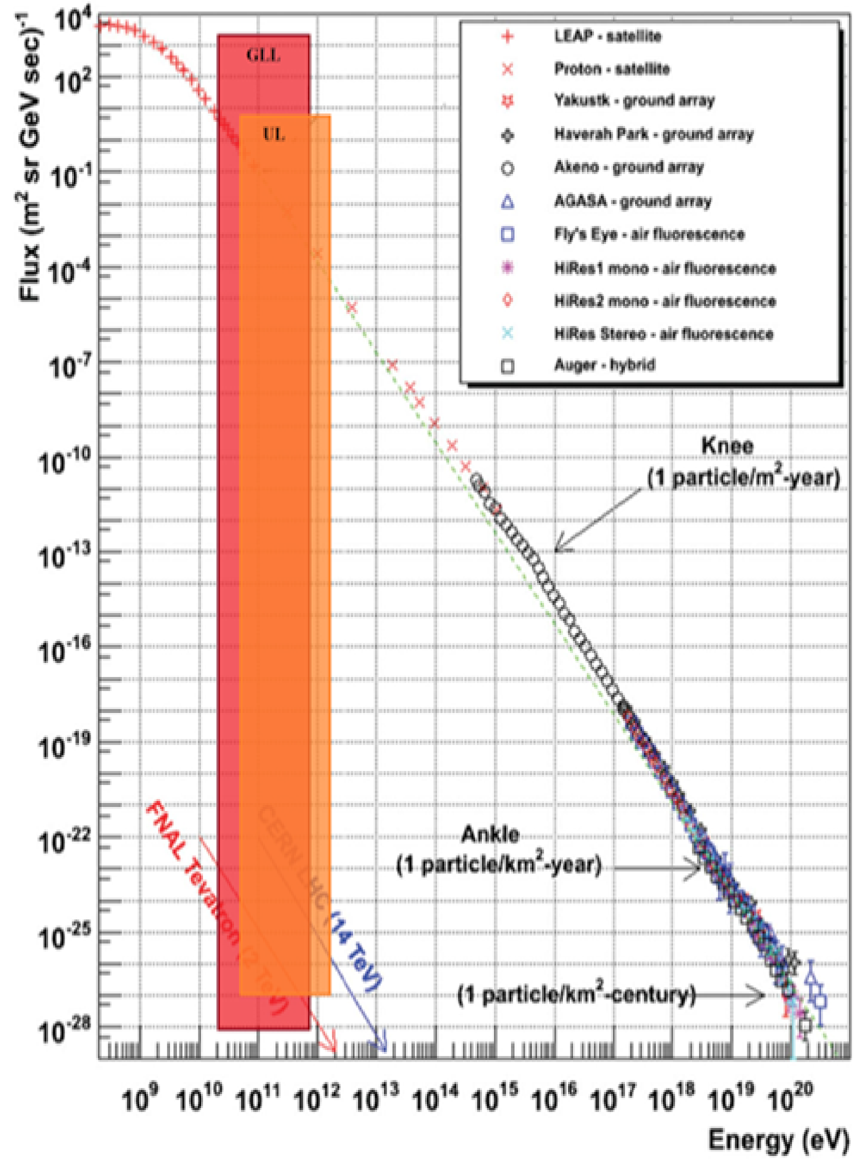
- Two scintilating detectors 100cm x 100cm x 5cm, with addition of two smaller 50cm x 23cm x 5cm.
- Aquisition of date use fADC (C.A.E.N. N1728B)
- Digital spectroscopy
- Time resolution of the events is 10 ns, stored in a list



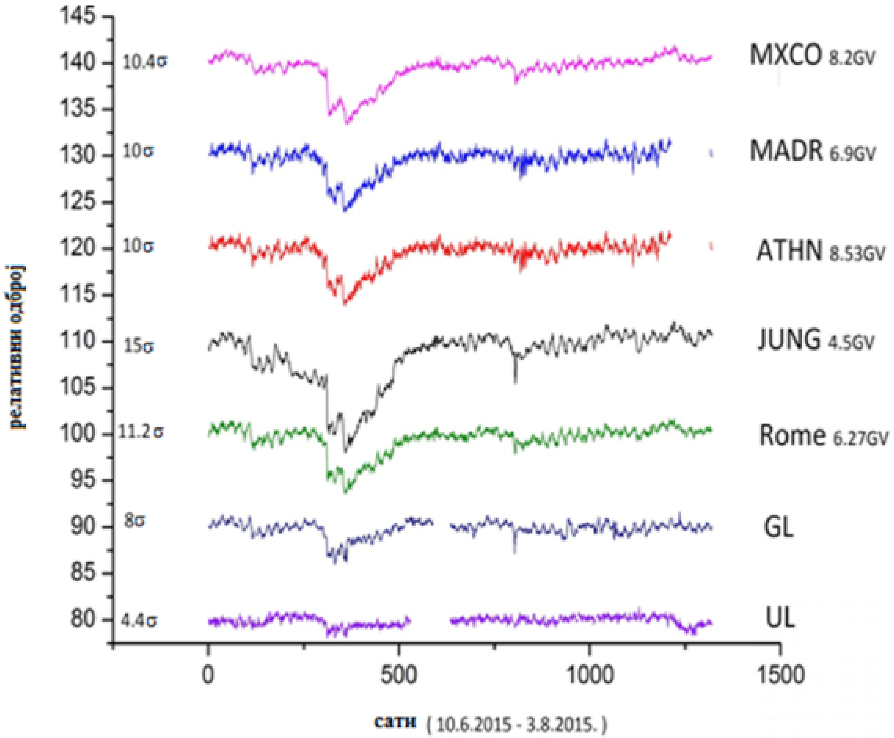
- Response of the detectors are calculated from simulation

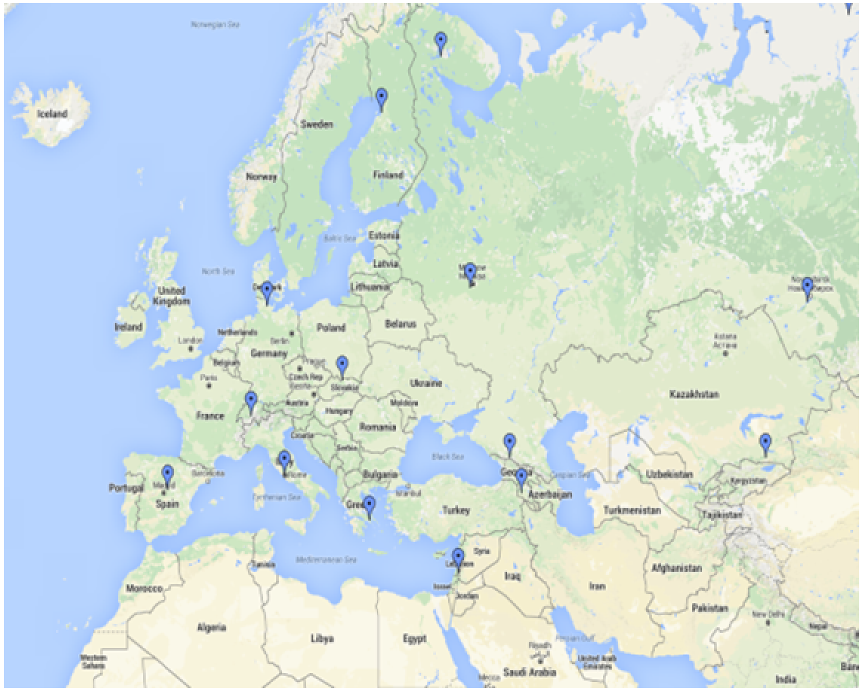
- Range of energy for the primary CR found





- Comparison with nearby NM
  - The amplitude of a Forbush decrease is one of its main characteristics.





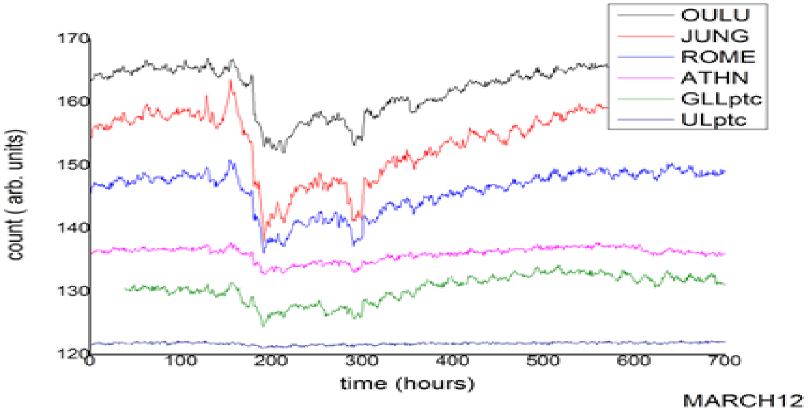
- **Dependence of FD amplitude on median rigidity (or energy) is expected to follow the power law:**

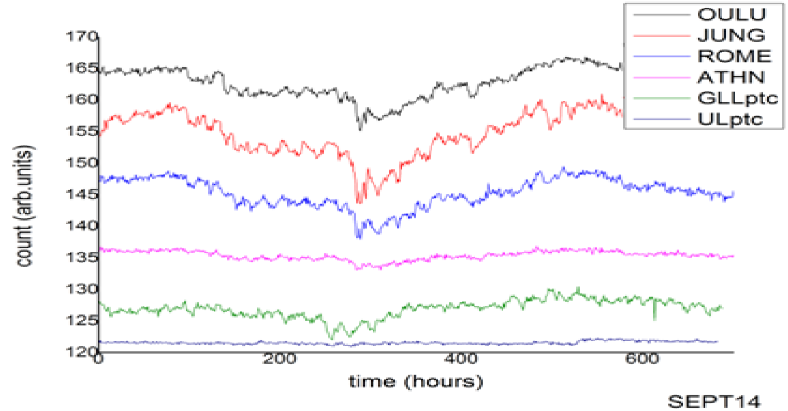
$$\frac{\Delta N}{N} \sim R_m^{-\gamma}$$

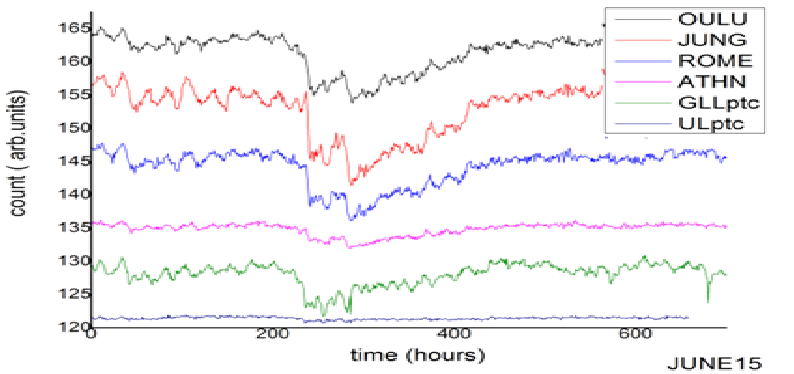
- γ should be ~(0,4-1,3)
- should be ~(0,4-1,3)

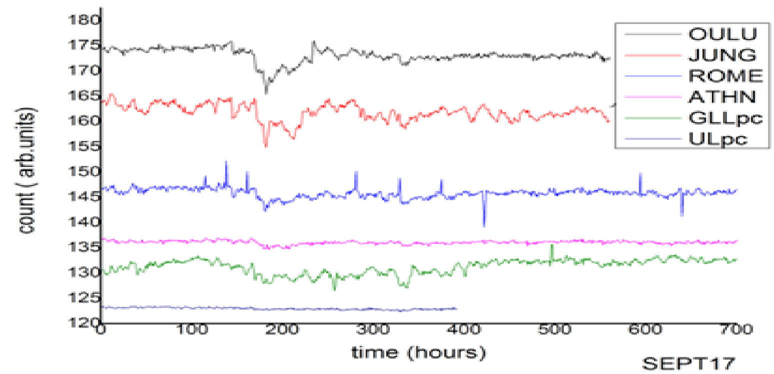
Solar activity

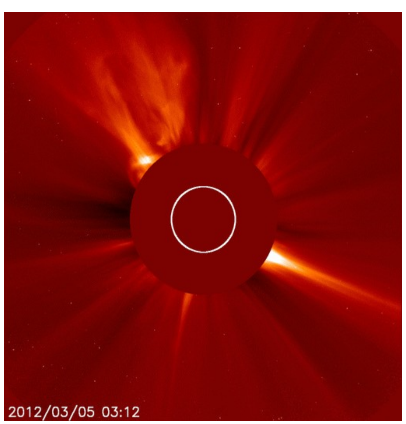
ground measurements Forbush decrease

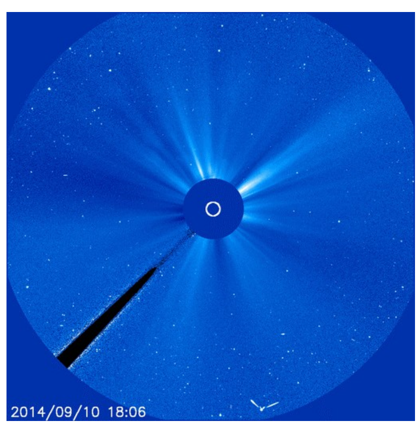


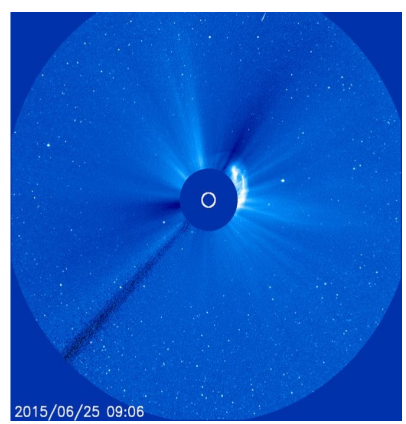


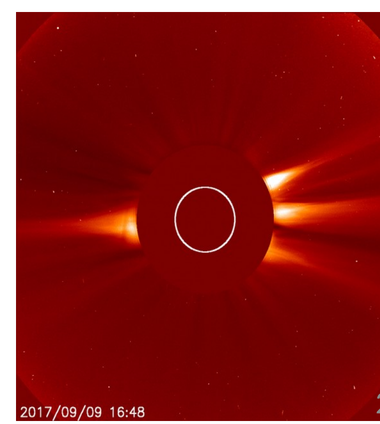








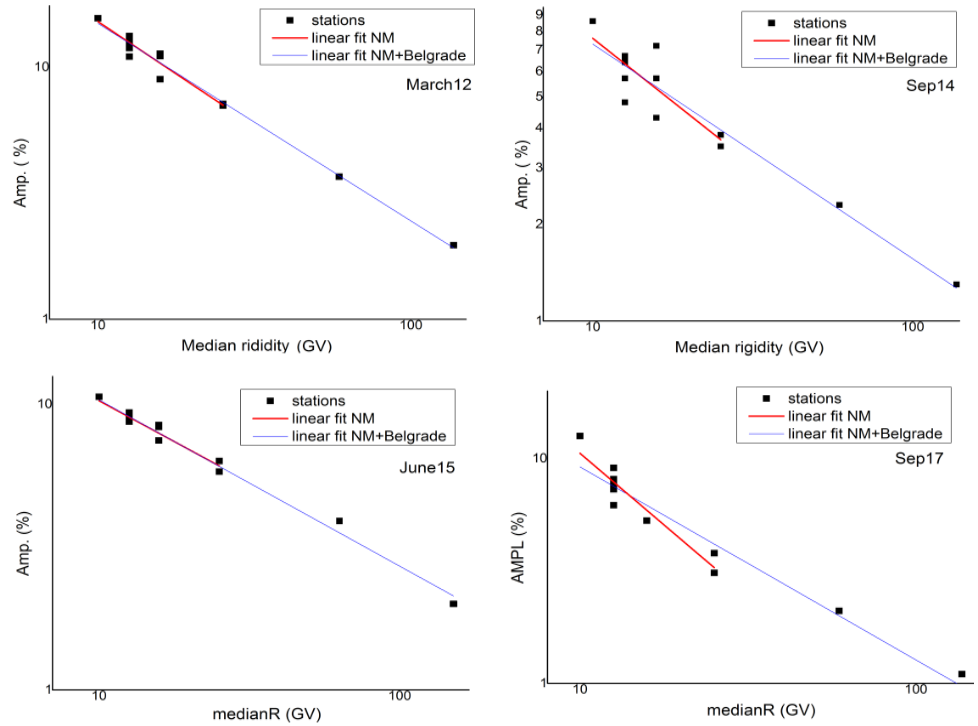




- Found dependence of FD amplitude on median rigidity o illustrates applicability of our setup for studies of consequences of CR solar modulation process in the energy region exceeding sensitivity of neutron monitors.

- Amplitude of Forbush decrease is inverse proportional to component of the diffusion tensor parallel to magnetic field which depends on CR rigidity

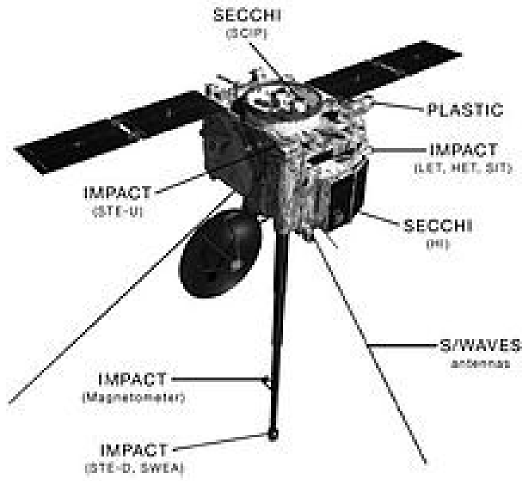
- Higher power indices can be due to more complex variation of GCR. This more complex variation is a result of series of CMEs during this event that leads to large compound ICME structure with multiple shocks and transient flow

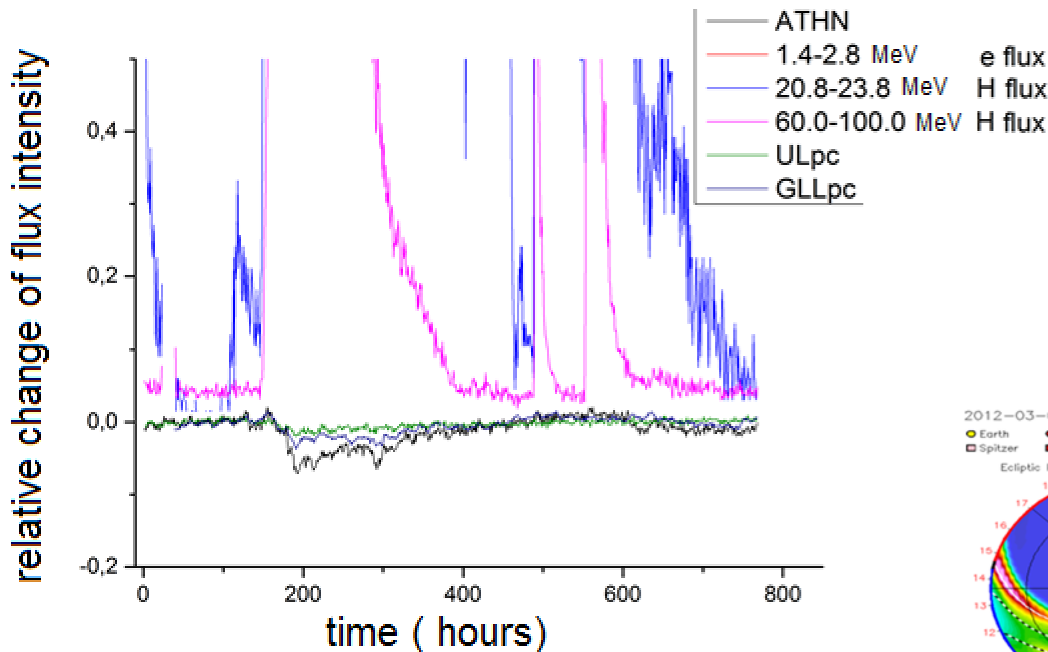


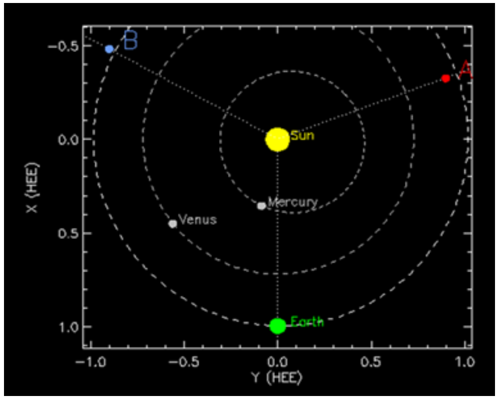
γ	NM	NM+Belgrade
March 2012.	0,82±0,08	0,78±0,03
Sept. 2014.	0,79±0,16	0,67±0,06
June 2015.	0,57±0,05	0,58±0,02
Sept. 2017.	1,27±0,16	0,86±0,07

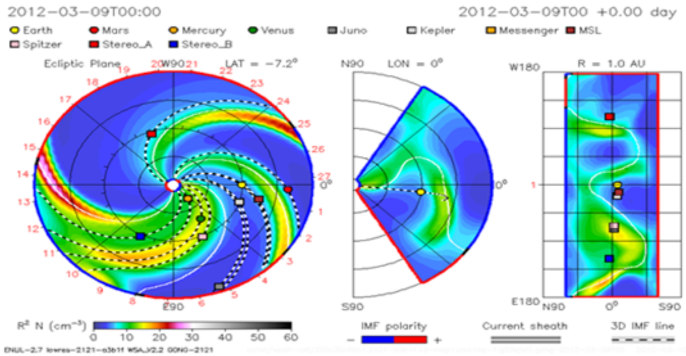
Comparison with satellite data

- **STEREO (Solar Terrestrial Relations Observatory)**
  - Two nearly identical spacecraft were launched in 2006 into orbits around the Sun
  - Communication with STEREO B stopped 2014.









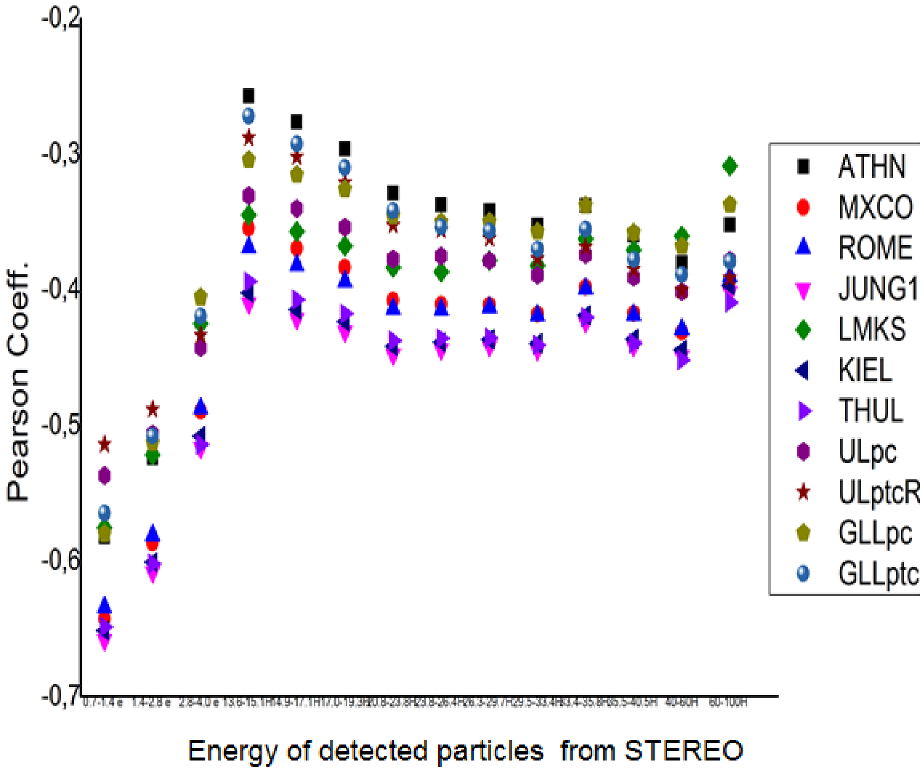
FD March 2012

Comparison with satellite data

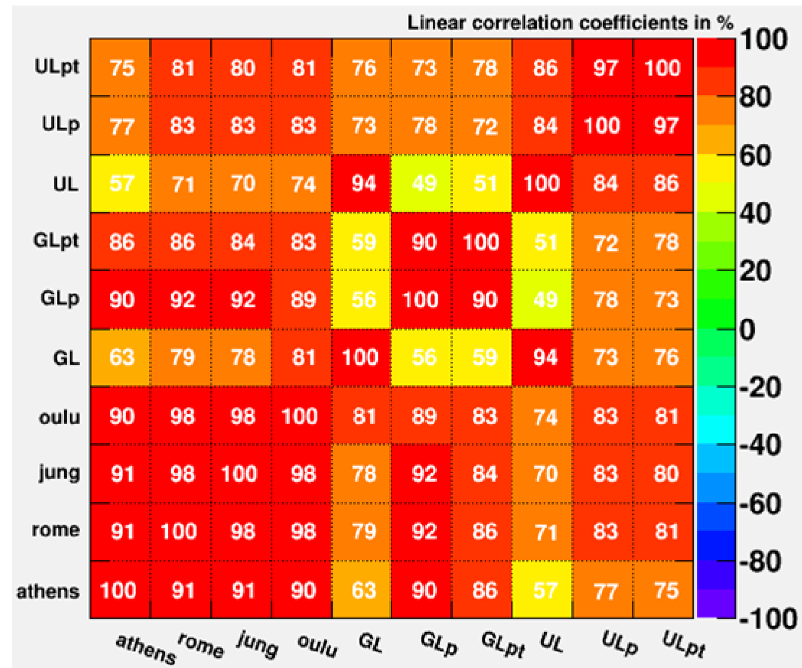
- Linear correlation with solar wind parameters (STEREO) during extreme solar event hourly MARCH12

Pearson Corr.	ATHN	MXCO	ROME	JUNG1	LMKS	KIEL	THUL	ULpc	ULptcR	GLLpc	GLLptc
ATHN	1	0,89938	0,90701	0,90218	0,81465	0,888	0,88237	0,72086	0,67525	0,88891	0,77835
MXCO	0,89938	1	0,96739	0,9608	0,90211	0,95985	0,95782	0,77569	0,74744	0,89333	0,84944
ROME	0,90701	0,96739	1	0,98264	0,92611	0,97964	0,95436	0,81064	0,77042	0,90403	0,83689
JUNG1	0,90218	0,9608	0,98264	1	0,89509	0,98492	0,97037	0,80202	0,7596	0,88574	0,80621
LMKS	0,81465	0,90211	0,92611	0,89509	1	0,91076	0,86013	0,761	0,73136	0,84775	0,80378
KIEL	0,888	0,95985	0,97964	0,98492	0,91076	1	0,97023	0,8066	0,765	0,8696	0,80671
THUL	0,88237	0,95782	0,95436	0,97037	0,86013	0,97023	1	0,77992	0,73156	0,84522	0,76112
0.7-1.4 e flux	-0,58228	-0,64269	-0,6341	-0,65826	-0,57558	-0,65141	-0,64866	-0,53708	-0,51431	-0,58012	-0,56474
1.4-2.8 e flux	-0,52385	-0,58666	-0,58112	-0,60831	-0,52183	-0,60102	-0,6021	-0,50646	-0,48822	-0,51288	-0,50805
2.8-4.0 e flux	-0,42281	-0,48951	-0,48754	-0,51667	-0,4249	-0,50815	-0,51419	-0,44263	-0,43361	-0,4055	-0,41936
13.6-15.1 H flux	-0,2573	-0,35436	-0,36857	-0,40984	-0,34493	-0,40239	-0,39397	-0,33062	-0,28817	-0,30439	-0,27192
14.9-17.1 H flux	-0,27618	-0,36952	-0,38179	-0,42128	-0,35699	-0,41451	-0,40732	-0,34003	-0,30206	-0,31516	-0,29229
17.0-19.3 H flux	-0,29621	-0,38353	-0,39378	-0,43075	-0,36779	-0,42355	-0,41765	-0,35381	-0,32104	-0,32595	-0,30998
20.8-23.8 H flux	-0,32848	-0,40774	-0,41419	-0,44778	-0,38342	-0,44162	-0,43737	-0,37725	-0,35234	-0,34555	-0,3416
23.8-26.4 H flux	-0,33741	-0,41084	-0,41454	-0,44406	-0,38681	-0,43875	-0,43577	-0,37501	-0,35614	-0,35024	-0,35357
26.3-29.7 H flux	-0,34183	-0,41127	-0,41288	-0,44152	-0,37854	-0,43649	-0,43533	-0,37854	-0,36217	-0,34986	-0,35643
29.5-33.4 H flux	-0,35216	-0,41808	-0,41868	-0,44443	-0,38209	-0,43939	-0,44069	-0,38926	-0,37713	-0,35704	-0,37009
33.4-35.8 H flux	-0,338	-0,39818	-0,39923	-0,42401	-0,3624	-0,41881	-0,42034	-0,37415	-0,36842	-0,33795	-0,35529
35.5-40.5 H flux	-0,35973	-0,41752	-0,41855	-0,44169	-0,37074	-0,43622	-0,43951	-0,39093	-0,38501	-0,35776	-0,37766
40.0-60.0 H flux	-0,38008	-0,43105	-0,4289	-0,44883	-0,36027	-0,44432	-0,45175	-0,40143	-0,40051	-0,36787	-0,38861
60.0-100.0 H flux	-0,35196	-0,39247	-0,39008	-0,40184	-0,30856	-0,39694	-0,40938	-0,37832	-0,39129	-0,33721	-0,37901
ULpc	0,72086	0,77569	0,81064	0,80202	0,761	0,8066	0,77992	1	0,95454	0,7403	0,69927
ULptcR	0,67525	0,74744	0,77042	0,7596	0,73136	0,765	0,73156	0,95454	1	0,69413	0,78014
GLLpc	0,88891	0,89333	0,90403	0,88574	0,84775	0,8696	0,84522	0,7403	0,69413	1	0,84765
GLLptc	0,77835	0,84944	0,83689	0,80621	0,80378	0,80671	0,76112	0,69927	0,78014	0,84765	1

Comparison of ground and satellite data



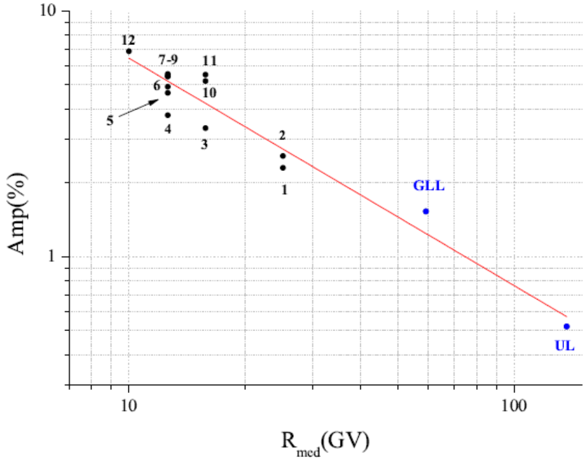
$$r = r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}}$$



Correlation matrix of linear correlation coefficient (in %) for Belgrade cosmic ray station with its temperature and pressure corrected underground and ground level detectors (UL_tpc, GL_tpc), only pressure corrected (UL_pc, GLL_pc),raw data (UL_raw, GLL_raw) and Rome, Oulu, Jungfraujoch (JUNG) and Athens NMs for March 2012.

Plans for future

- Enlarging the network of stations and collaboration with Georgia state university
  - Goal is to build a portable and low-cost cosmic ray muon telescope which could be easily duplicated and installed anywhere around the globe for studying the correlations between the cosmic ray muon flux variations and the dynamical patterns of the space and earth weather
- New method for temperature correction of cosmic rays' muon flux
  - Goal is to use this method to get clear data for studying space weather but also to use CR as thermometer for high altitude layers



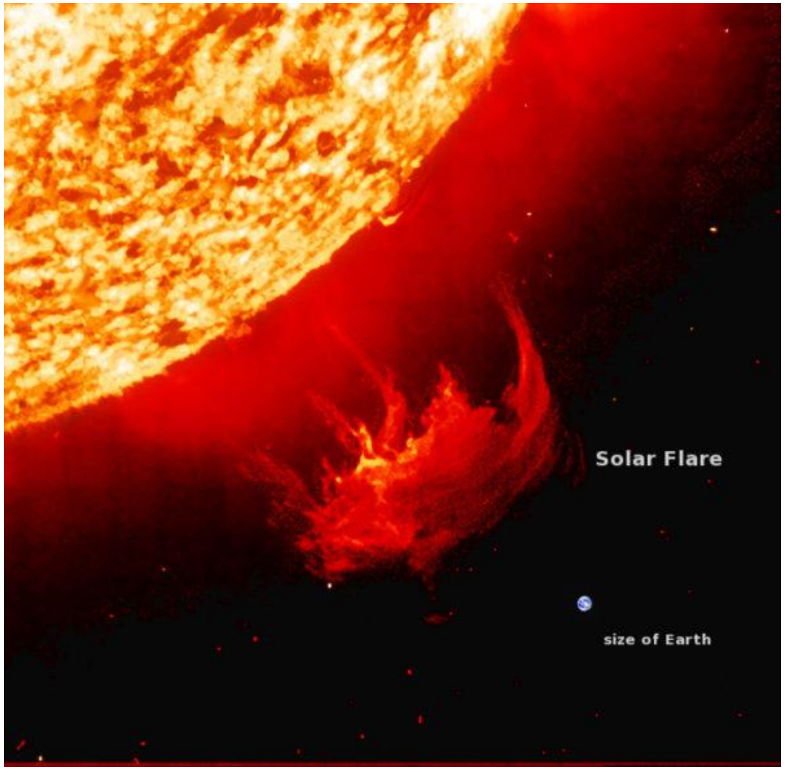
$$\left(\frac{\delta I}{I}\right)_T = \int_0^{h_0} \alpha(h) \cdot \delta T(h) \cdot dh$$

Conclusion

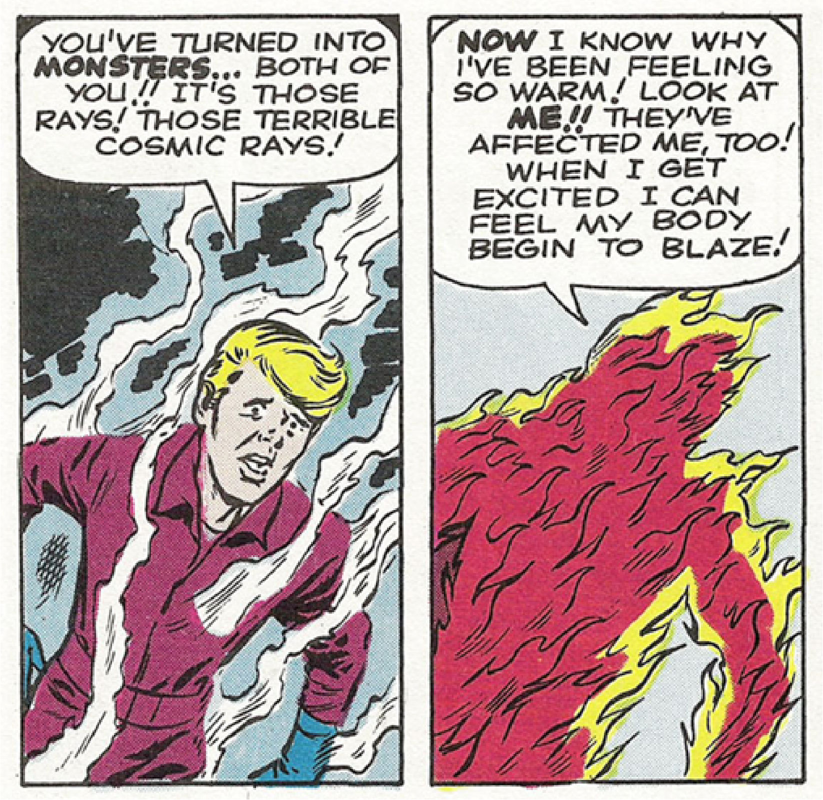
- Muon detectors at Low level laboratory are used to find rigidity dependence of Forbush decrease. These data for transient solar modulation of GCR are obtained over much higher range of rigidities than region sensitive to NM thus allowing more extensive studies of cosmic-ray solar modulation processes.

- Comparison of ground data with satellite data outside geomagnetic field shows different correlation depending on energy recorded particles thus allowing better understanding of correlation between Forbush decreases and CME that can lead to hazardous event on Earth.

- Dependence of FD amplitude on median rigidity can lead to better models of propagation of CR through heliosphere thus giving condition of the heliosphere.



Thank you for your attention!



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