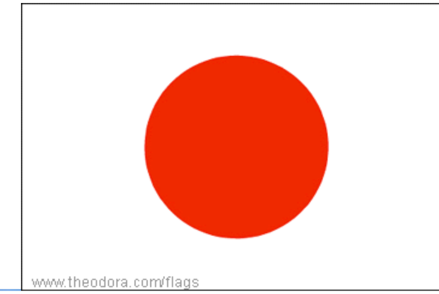
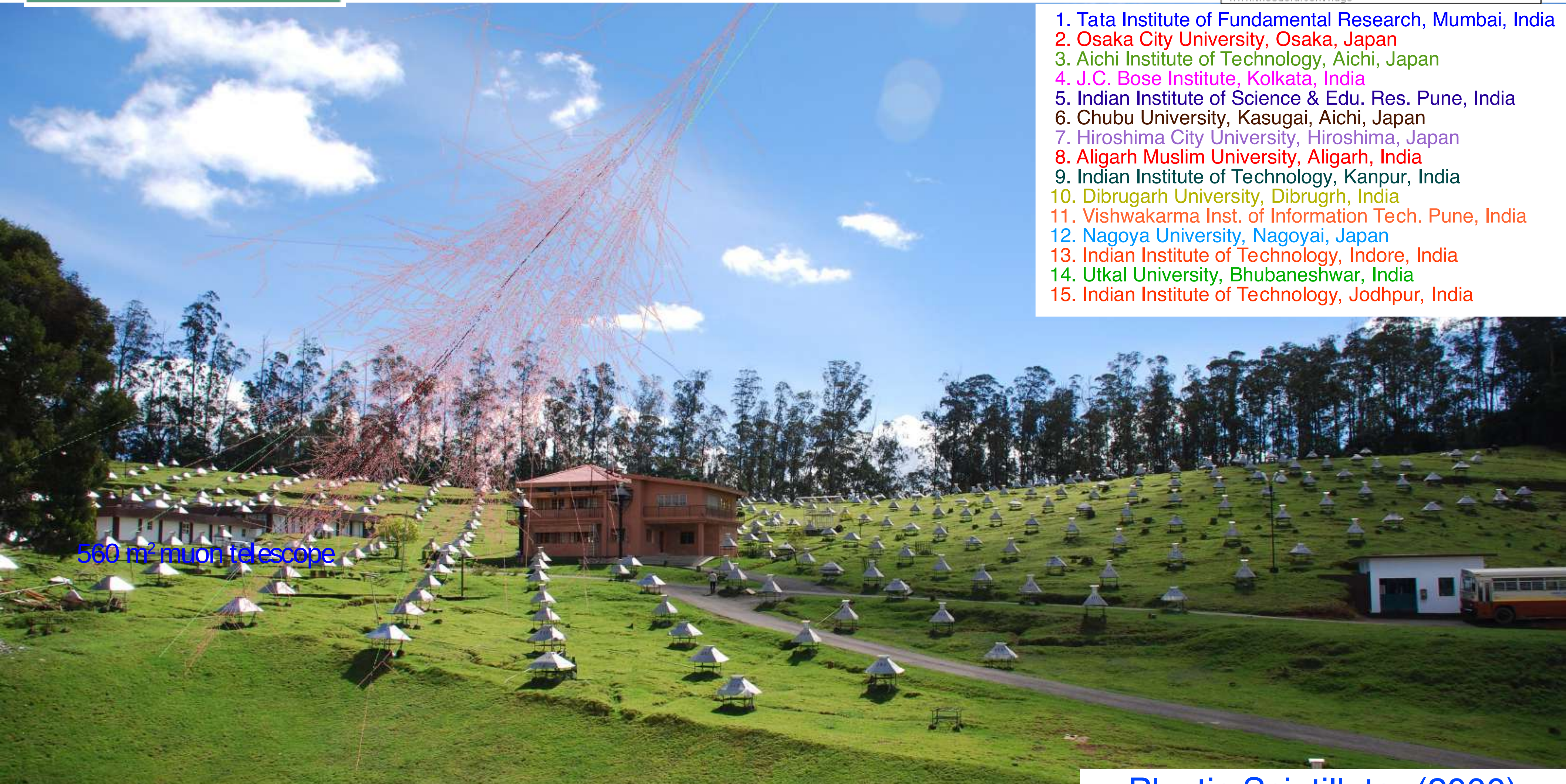
Solar storms & their impact on Earth studied through cosmic ray muons by the GRAPES-3



Sunil K. Gupta

5 August 2022 School on C.R. Astrophysics, Erice

1. Tata Institute of Fundamental Research, Mumbai, India
2. Osaka City University, Osaka, Japan
3. Aichi Institute of Technology, Aichi, Japan
4. J.C. Bose Institute, Kolkata, India
5. Indian Institute of Science & Edu. Res. Pune, India
6. Chubu University, Kasugai, Aichi, Japan
7. Hiroshima City University, Hiroshima, Japan
8. Aligarh Muslim University, Aligarh, India
9. Indian Institute of Technology, Kanpur, India
10. Dibrugarh University, Dibrugrh, India
11. Vishwakarma Inst. of Information Tech. Pune, India
12. Nagoya University, Nagoyai, Japan
13. Indian Institute of Technology, Indore, India
14. Utkal University, Bhubaneshwar, India
15. Indian Institute of Technology, Jodhpur, India



India-Japan scientific collaboration 30 Years (1992-)

S.K. Gupta, S.R. Dugad, B. Hariharan, P.K. Mohanty, P.K. Nayak, P. Jagadeesan, A. Jain, S.D. Morris, P.S. Rakshe K. Ramesh, B.S. Rao, L.V. Reddy, Y. Hayashi, S. Kawakami, H. Kojima, S.K. Ghosh, S. Raha, P Subramanian, A. Oshima, S. Shibata, K. Tanaka, S. Ahmad, P.K. Jain, U.D. Goswami, C.S. Garde, Y. Muraki, R. Sahoo, S. Mahapatra,, R. Moharana

Plastic Scintillator (2000)
Proportional Counters (8000)
Signal processing (8000)
DAQ systems > 20
Computer Clusters (1500)

«ETTORE MAJORANA» FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE
TO PAY A PERMANENT TRIBUTE TO ARCHIMEDES AND GALILEO GALILEI, FOUNDERS OF MODERN SCIENCE AND TO ENRICO FERMI, THE "ITALIAN NAVIGATOR", FATHER OF THE WEAK FORCES

INTERNATIONAL SCHOOL OF COSMIC RAY ASTROPHYSICS «MAURICE M. SHAPIRO»

22nd Course: *FROM COSMIC RAYS TO GRAVITATIONAL WAVES: NOW AND TO COME*

ERICE-SICILY: 30 JULY – 7 AUGUST 2022

Sponsored by the: • Italian Ministry of Education, University and Scientific Research • Sicilian Regional Government

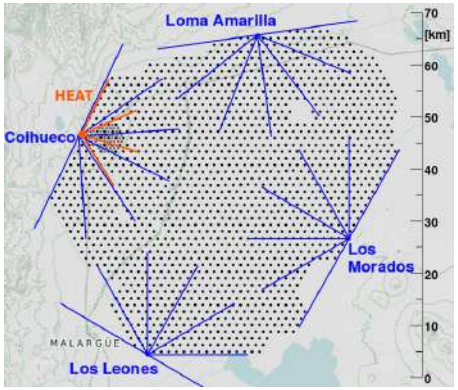
INTERNATIONAL SCHOOL OF COSMIC RAY ASTROPHYSICS

7th Course: Cosmic Rays, Supernovae and the Interstellar Medium
Erice-Sicily 26 July - 4 August 1990

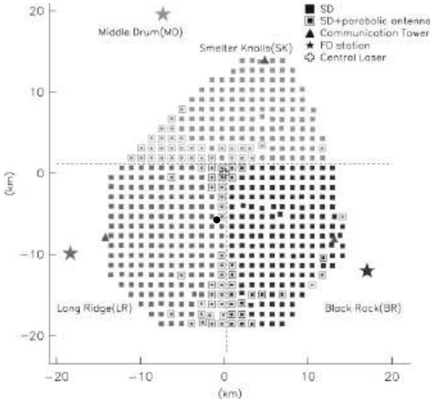
Directors: Maurice M. Shapiro and Rein Silberberg

CR experiments are at diverse & remote sites of earth and beyond

SURFACE



PAO EAS, ARGENTINA



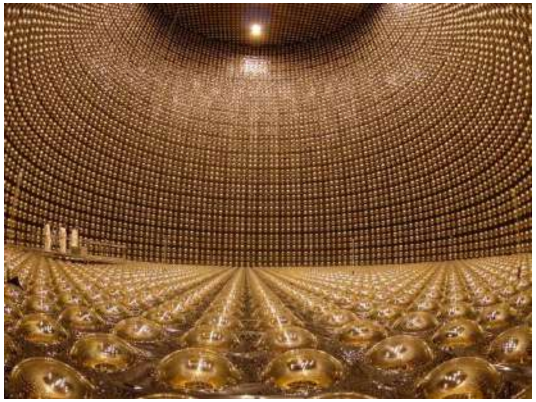
TA EAS, USA

MOUNTAINS

2.2 km GRAPES-3 India

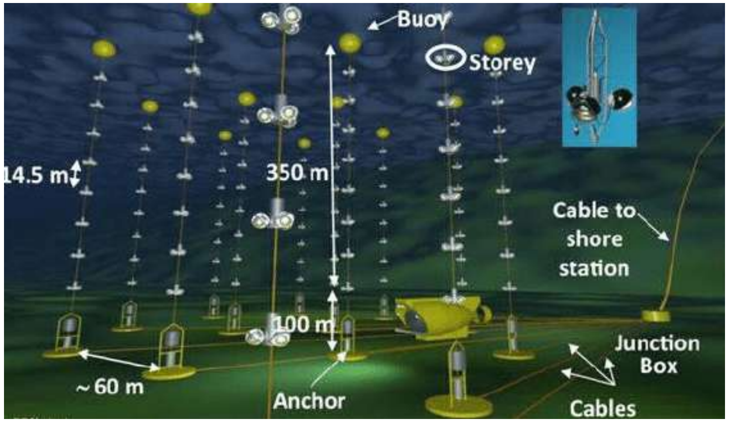
4.3 km HAWC MEXICO

UNDERGROUND



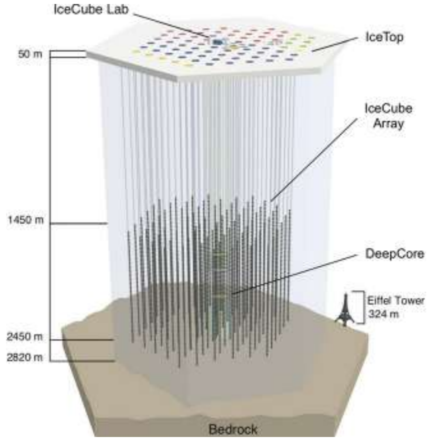
-1 km SUPER-K Japan

OCEAN



-1 km ANTARES Europe

POLAR ICECAP

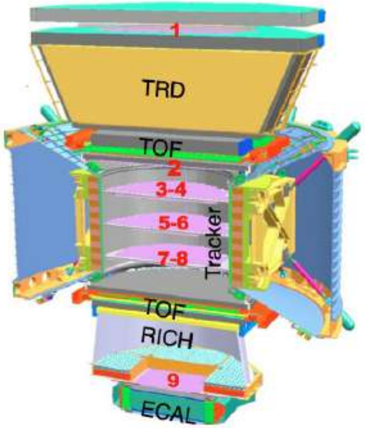


BALLOONS

-1.4 km ICE CUBE 1 km^3

40 km S-Tiger Antarctica

SPACE

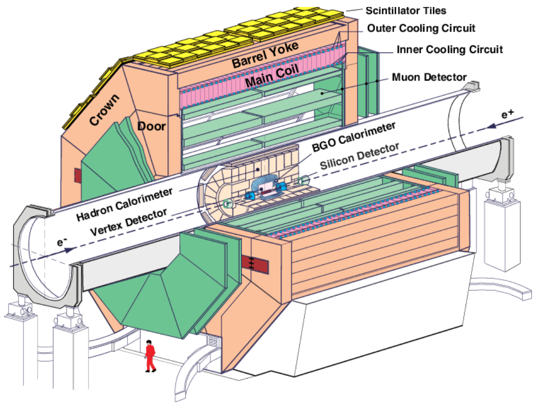


200 km AMS, ISS

10^6 km ACE L1

SPACE

ACCELERATOR

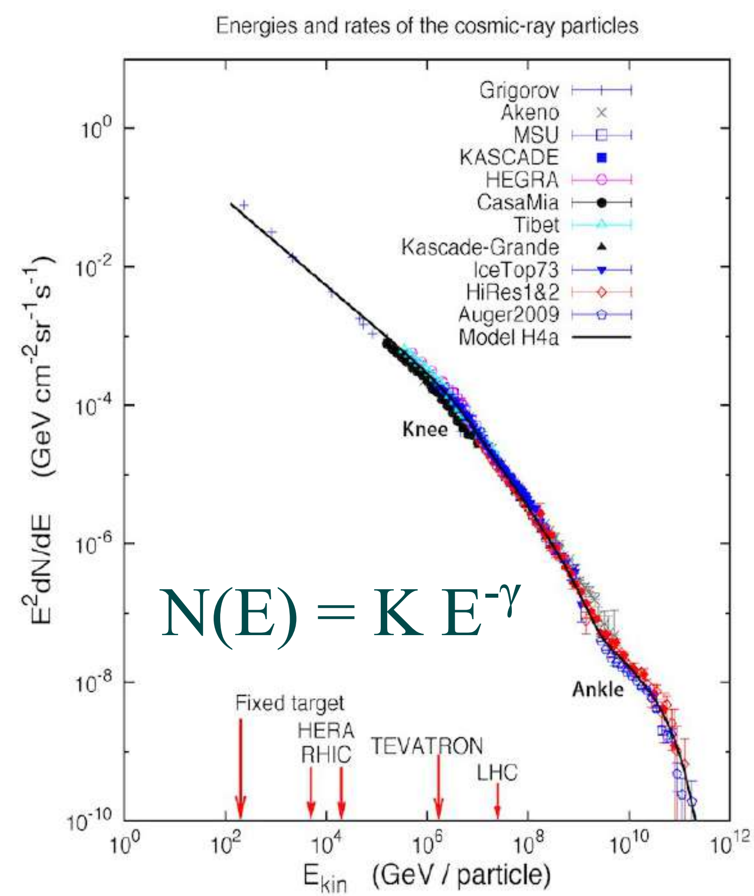


> 100 AU VOYAGER-1 & 2

L3 Experiment CERN

Sunil K. Gupta
gupta.crl@gmail.com

1. GRAPES-3 experiment
2. Benefits to society?
3. Solar storms



Context: COVID-19 pandemic started online talks

Greater dependence on internet than ever before

These tools allow for remote participation

Imagine living without internet and electricity?

That is what solar storm can do!

GRAPES-3 Experiment on Google Map

Top

100 $g.cm^{-2}$

200

300

400

500

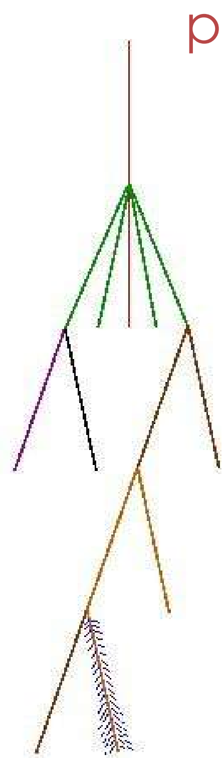
600

700

Ooty 800

900

Mumbai 1000



$$p + p \longrightarrow p + p + \pi^+ + \pi^- + \pi^0$$

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu \quad 20\text{x}10^{-9}\ \text{s}$$

$$\pi^0 \longrightarrow \gamma + \gamma \quad 10^{-16}\ \text{s}$$

$$\gamma \longrightarrow e^+ + e^-$$

$$e^- \longrightarrow e^- + \gamma$$

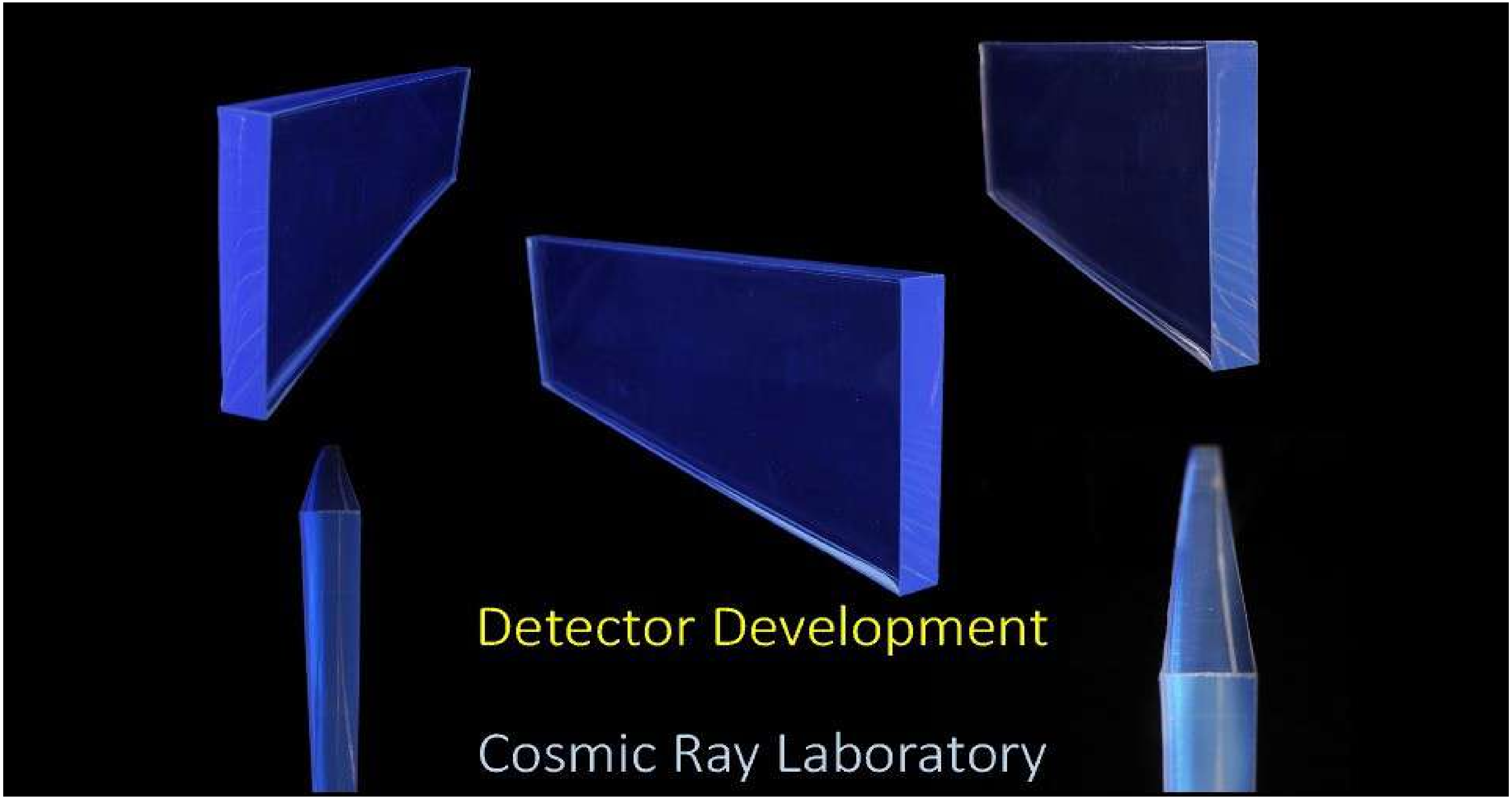
Cosmic Ray Shower:

1. Electrons, Positrons & Gamma rays
   (E-M component, 90 %)
2. Muon (μ^+, μ^-) Penetrating Component (8%)
3. Pions, Kaons, Hadron Component (1%)
4. Neutrinos usually go undetected

For E = 10^{14} eV at mountains (Ooty)
20000 particles spread over ~1000 m^2

https://www.nature.com/articles/nature24647

Fabrication of plastic scintillator detectors at Cosmic Ray Laboratory, Ooty



Plastic Scintillator development:

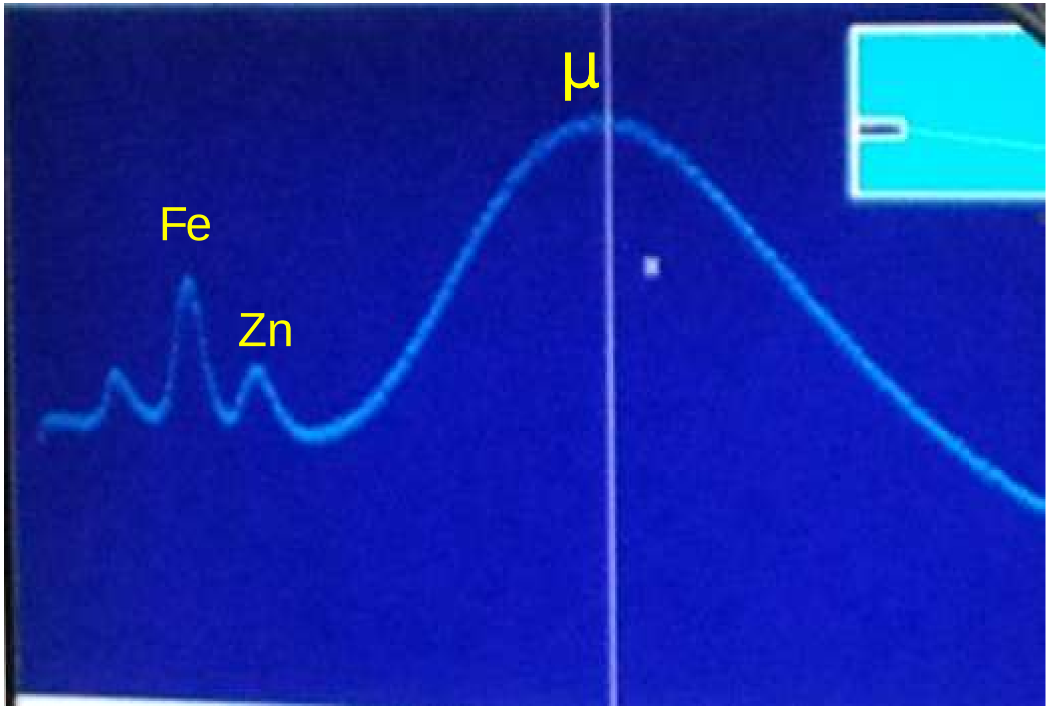
Decay Time= 1.6 ns Light Output = 85% Bicron (54% anthracene)
Timing 25% faster Atten. Length λ= 100cm Cost ~fraction of Bicron
Max Size 100cmX100cm Total > 2000
CERN, Osaka, IUAC Delhi, Bose, VECC, DEI Agra, BARC, ECIL, Utkal, BITS(H), IOP, ...

Proportional Counter (PRC) Fabrication

http://www.bbc.com/news/world-asia-india-39100109

3803 PRCs fabricated 101% of required 3776 PRCs in March 2018

http://www.bbc.com/news/world-asia-india-39100109



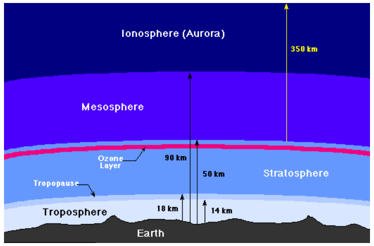
3 May 2018


14 October 2019

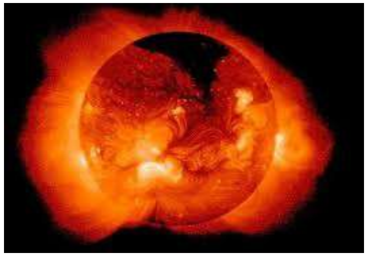
Objective: Universe at high energies

Acceleration, propagation of high energy particles,
Extreme conditions may require new physics ...

1. Acceleration in atmospheric electric field
   Energy ~1 GeV   Scale ~10^{6}-10^{7} cm

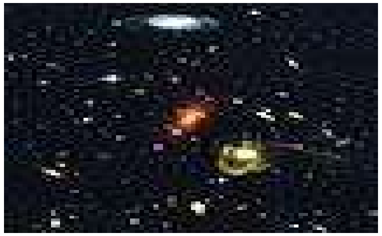


2. Solar flares, Coronal Mass Ejections
   Energy ~10 GeV   Scale ~10^{11}-10^{13} cm



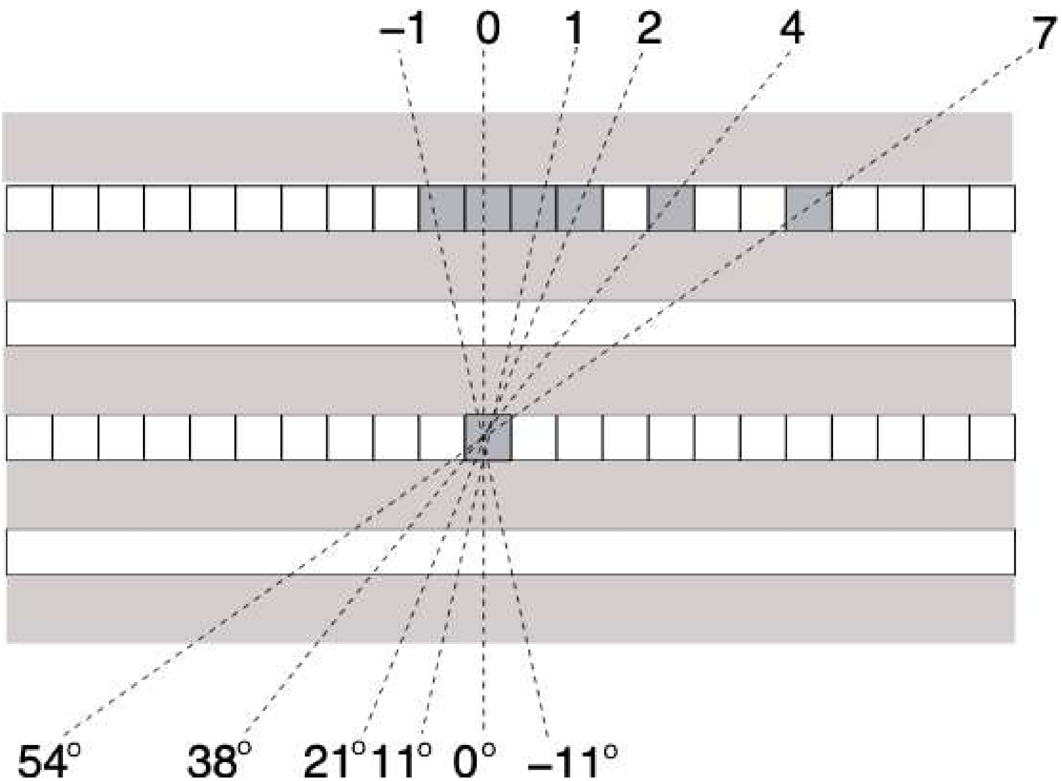
3. Galactic Cosmic Rays at "Knee"
   Energy ~1 PeV   Scale ~10^{21}-10^{23} cm

4. Diffuse multi-TeV **γ**-rays
   Energy ~100 EeV   Scale ~10^{24}-10^{26} cm

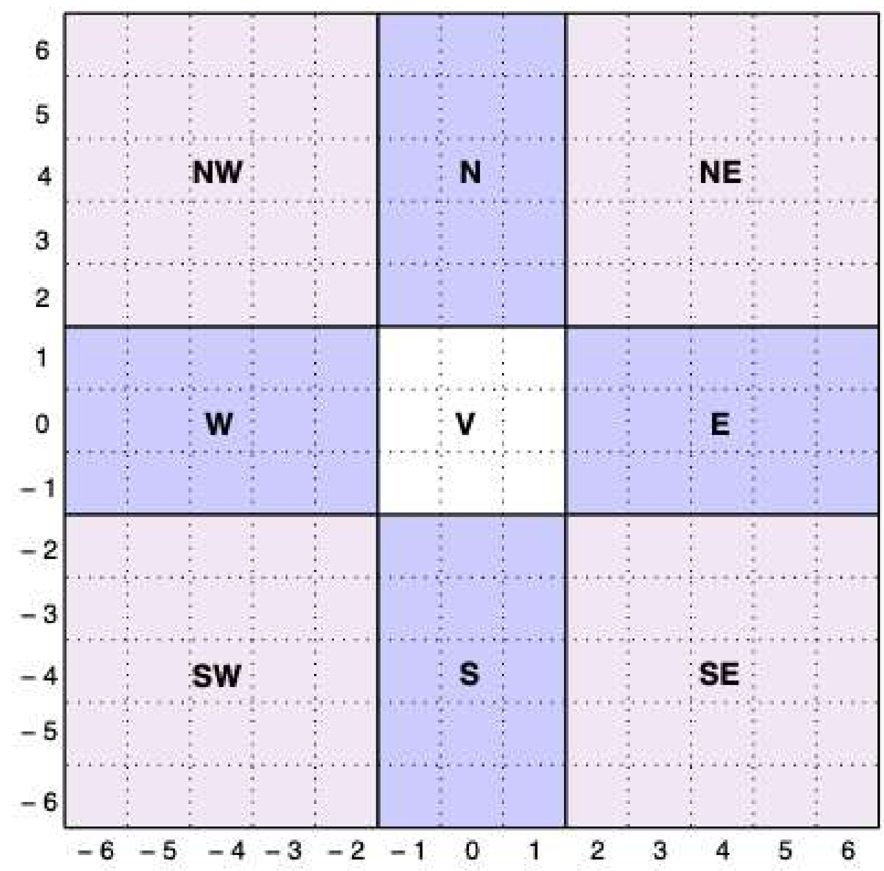



GRAPES-3 is a very sensitive muon telescope
Total area = 560 m²

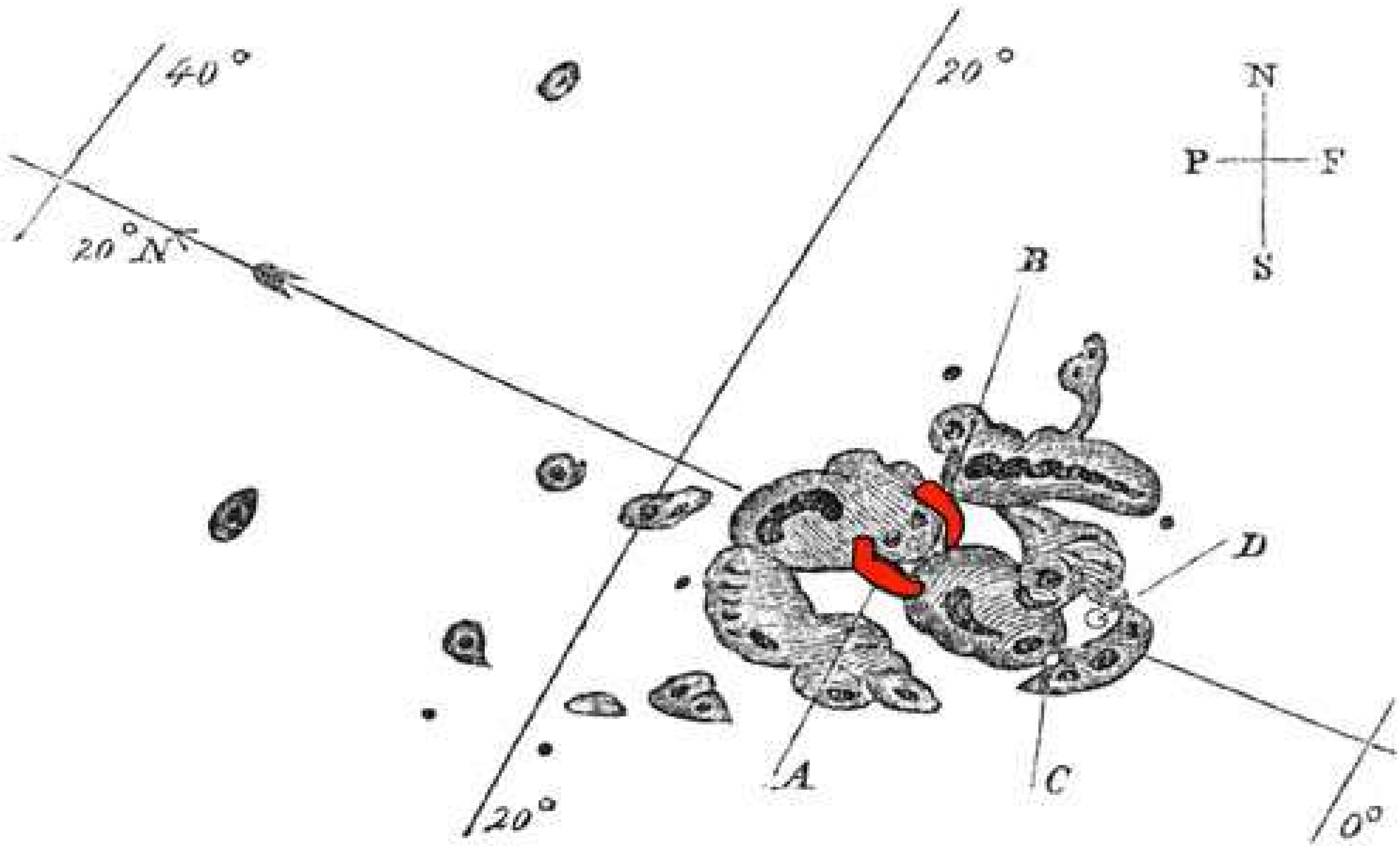

Inside view of
muon telescope



Muon Direction Reconstruction
Field of View = 2.3 sr



28 August 1859 two bright regions “A” and “B” in a sunspot seen by Carrington. On 1 September 1859 the biggest solar storm reached Earth at 2400 km/s, aurorae seen at low latitudes, DST=-1600 nT, disrupted telegraph lines in Europe and USA.



http://www.sciencemag.org/news/2016/07/here-s-how-world-could-end-and-what-we-can-do-about-it

Here's how the world could end—and what we can do about it

sciencemag.org/news/2016/07/here-s-how-world-could-end-and-what-we-can-do-about-it

By Julia Rosen Jul. 14, 2016 , 2:00 PM

08/07/2016

Threat one: Solar storms

CMEs don't harm human beings directly, and their effects can be spectacular. By funneling charged particles into Earth's magnetic field, they can trigger geomagnetic storms that ignite dazzling auroral displays. But those storms can also induce dangerous electrical currents in long-distance power lines. The currents last only a few minutes, but they can take out electrical grids by destroying high-voltage transformers—particularly at high latitudes, where Earth's magnetic field lines converge as they arc toward the surface.

Threat two: Cosmic collisions

For another menace from the sky—an impact by a large asteroid or comet—there is no way to limit the damage. The only way for humanity to protect itself, researchers say, is to prevent the collision altogether.

Threat three: Supervolcanoes

The most inexorable threat to our modern civilization, however, is homegrown—and it strikes much more often than big cosmic impacts do. Every 100,000 years or so, somewhere on Earth, a caldera up to 50 kilometers in diameter collapses and violently expels heaps of accumulated magma. The resulting supervolcano is both unstoppable and ferociously destructive. One such monster, the massive eruption of Mount Toba in Indonesia 74,000 years ago, may have wiped out most humans on Earth, causing a genetic bottleneck still apparent in our DNA—although the idea is controversial.

whitehouse.gov/the-press-office/2016/10/13/executive-order-coordinating-efforts-prepare-nation-space-weather-events

EXECUTIVE ORDER

COORDINATING EFFORTS TO PREPARE THE NATION FOR SPACE WEATHER EVENTS

By the authority vested in me as President by the Constitution and the laws of the United States of America, and to prepare the Nation for space weather events, it is hereby ordered as follows:

Section 1. Policy. Space weather events, in the form of solar flares, solar energetic particles, and geomagnetic disturbances, occur regularly, some with measurable effects on critical infrastructure systems and technologies, such as the Global Positioning System (GPS), satellite operations and communication, aviation, and the electrical power grid. Extreme space weather events -- those that could significantly degrade critical infrastructure -- could disable large portions of the electrical power grid, resulting in cascading failures that would affect key services such as water supply, healthcare, and transportation. Space weather has the potential to simultaneously affect and disrupt health and safety across entire continents. Successfully preparing for space weather events is an all-of-nation endeavor that requires partnerships across governments, emergency managers, academia, the media, the insurance industry, non-profits, and the private sector.

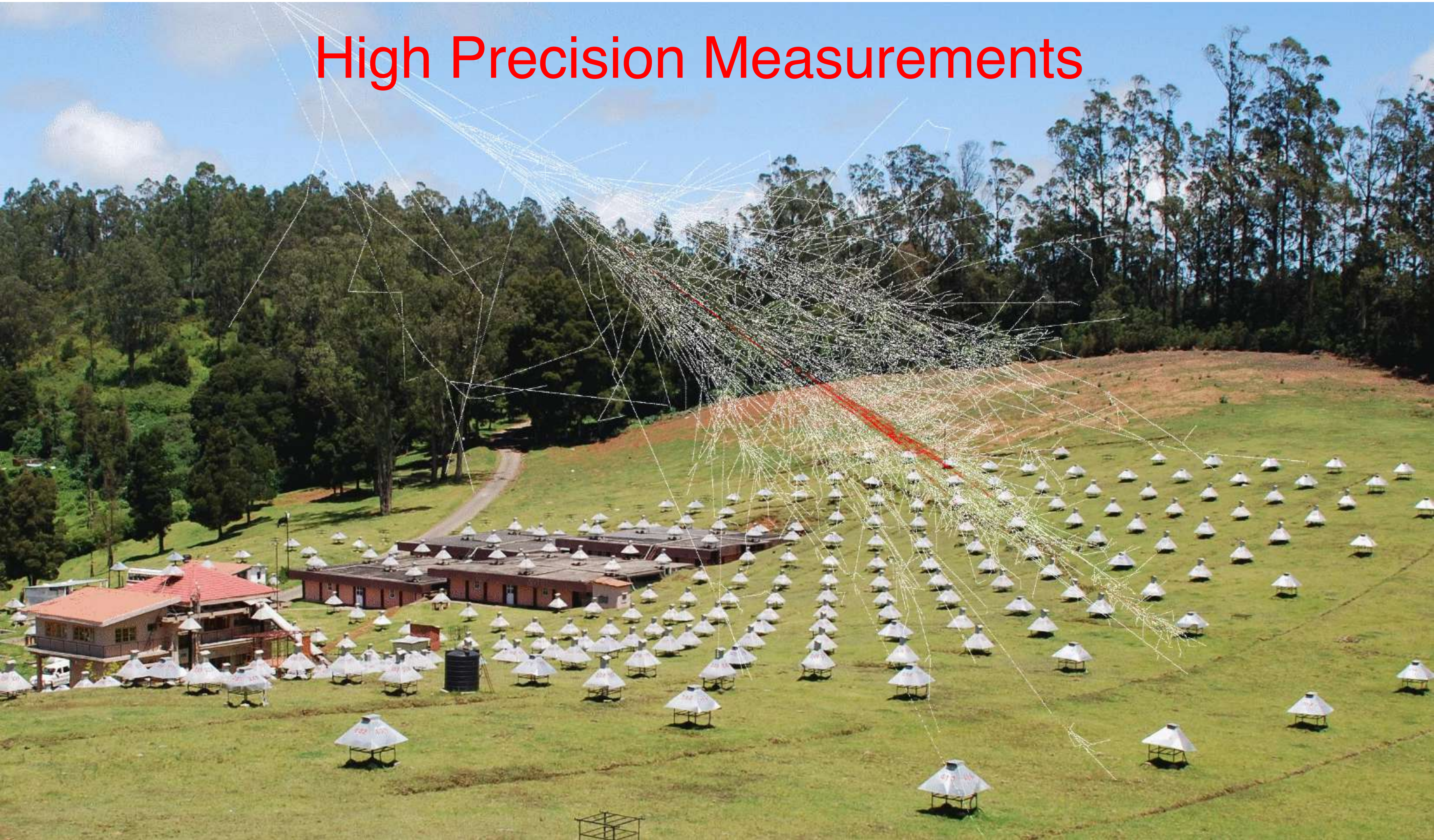
Terminology:
Solar flare → coronal mass ejection → solar storm → geomagnetic storm {Space weather}

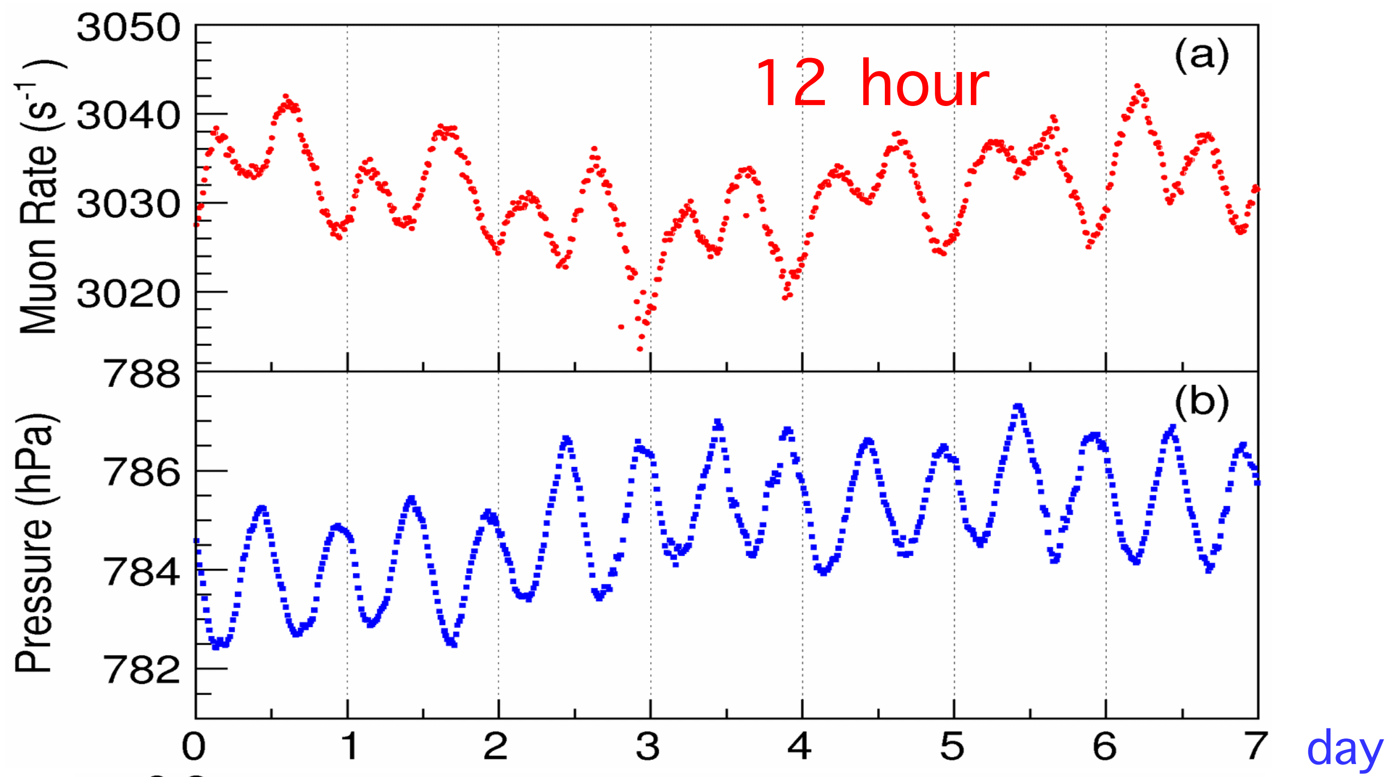
400 Plastic Scintillator detectors (1 m^2 area)

560 m^2 muon telescope (E_μ=1 GeV) (11.4N, 76.7E)

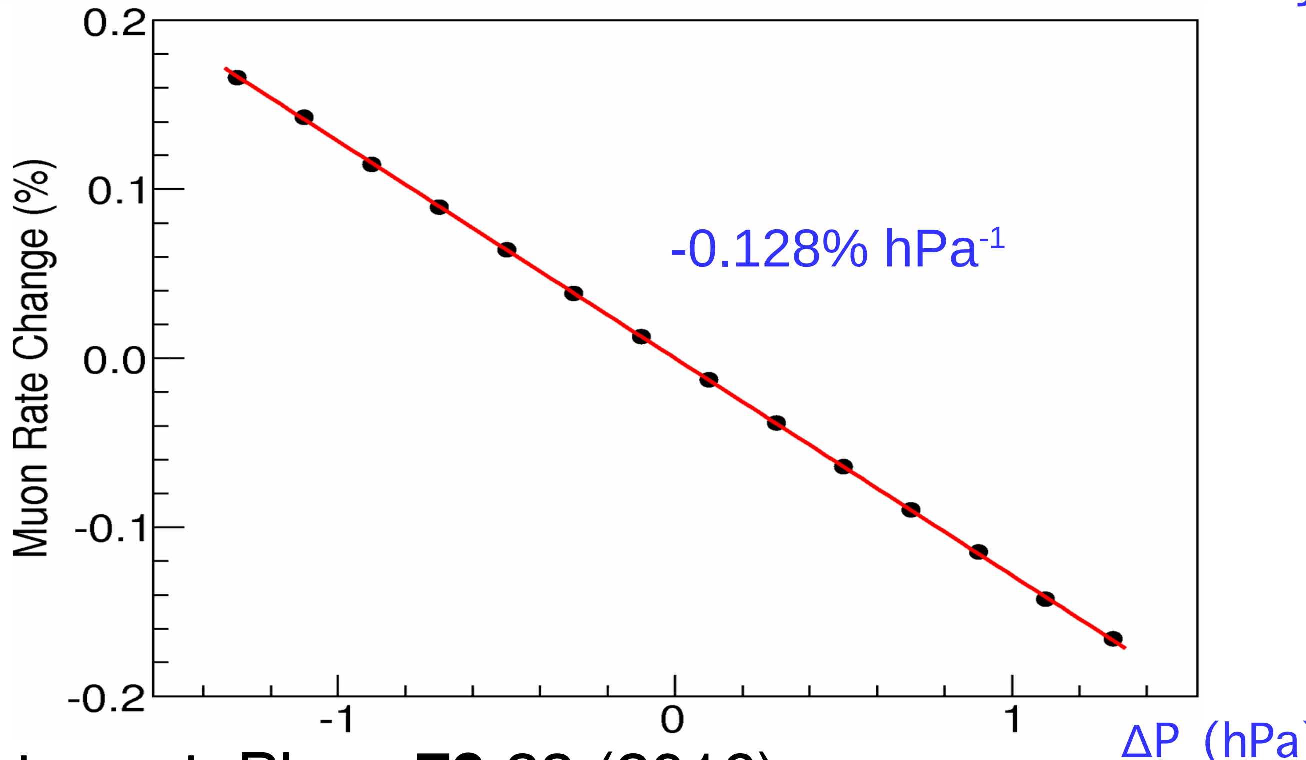
3712 Proportional Counters (6m x 0.1m x 0.1m)

$E = 10^{14}$ eV ~20000 particles over ~1000 m^2

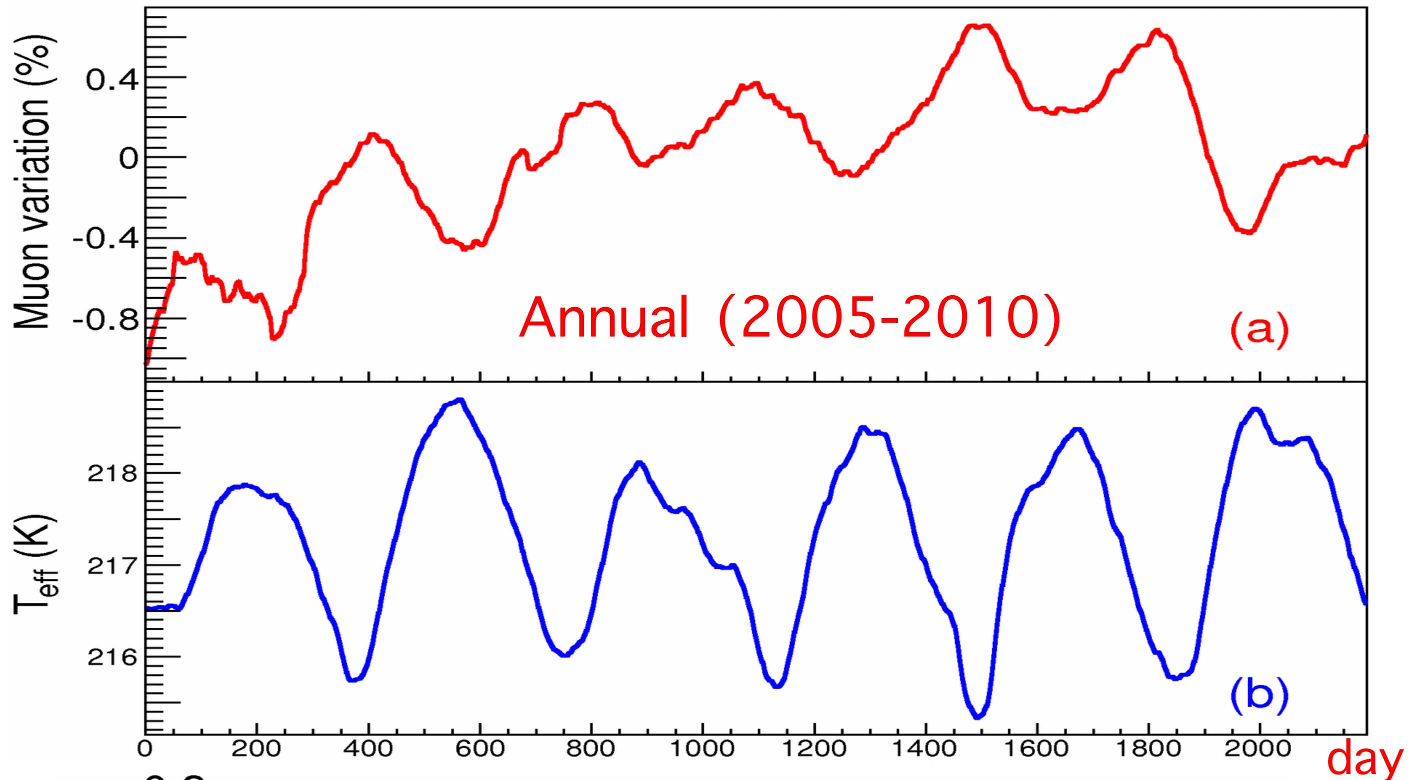


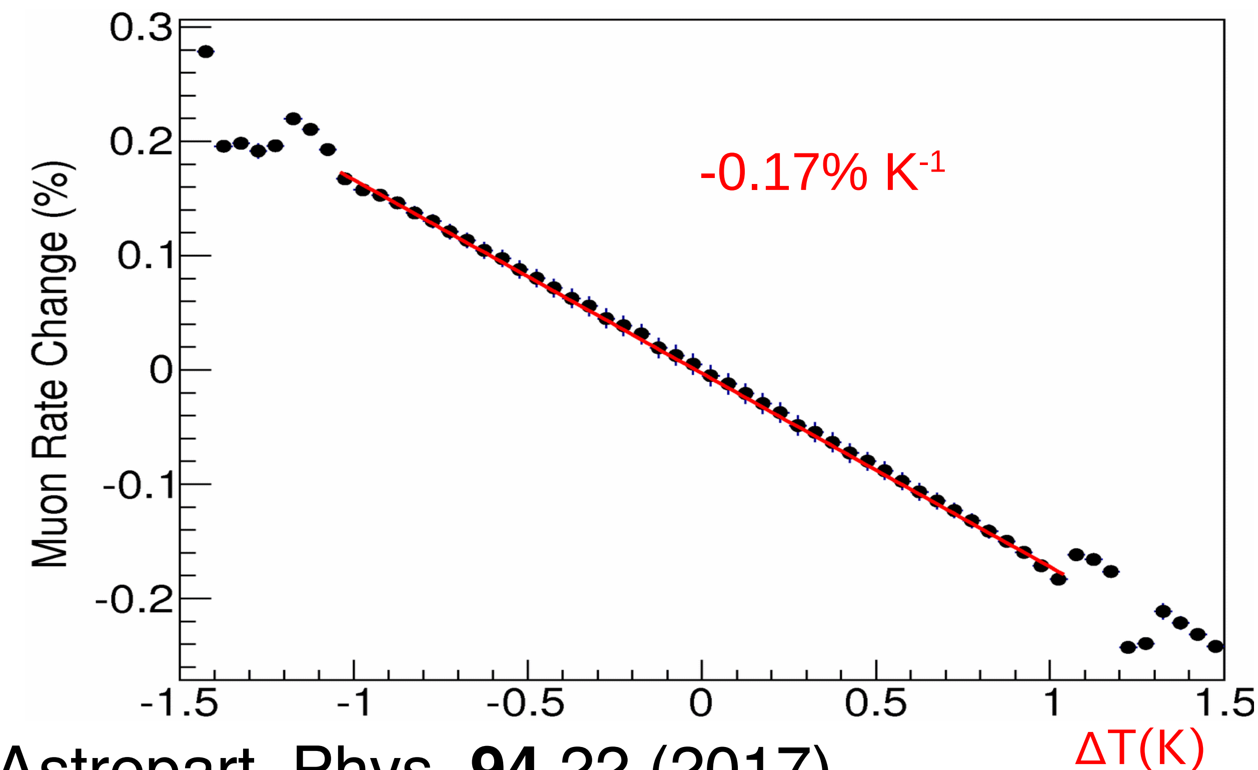


20 cm air column = 1σ



P.K. Mohanty et al. Astropart. Phys. **79** 23 (2016)

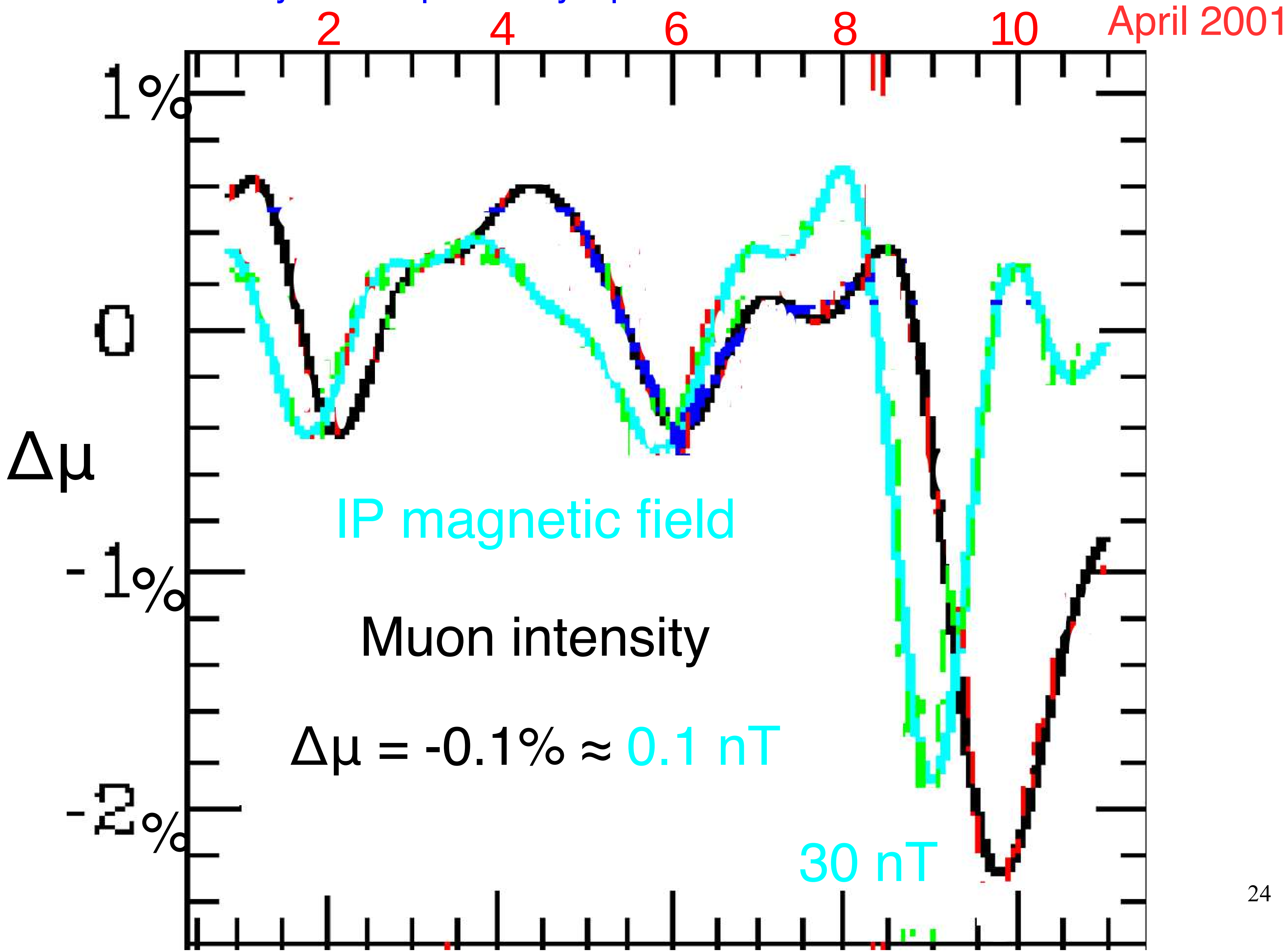




0.06 K = 1σ

K.P. Arunbabu et al. Astropart. Phys. **94** 22 (2017)

Study of Interplanetary Space from the Earth



GRAPES-3 is uniquely sensitive,

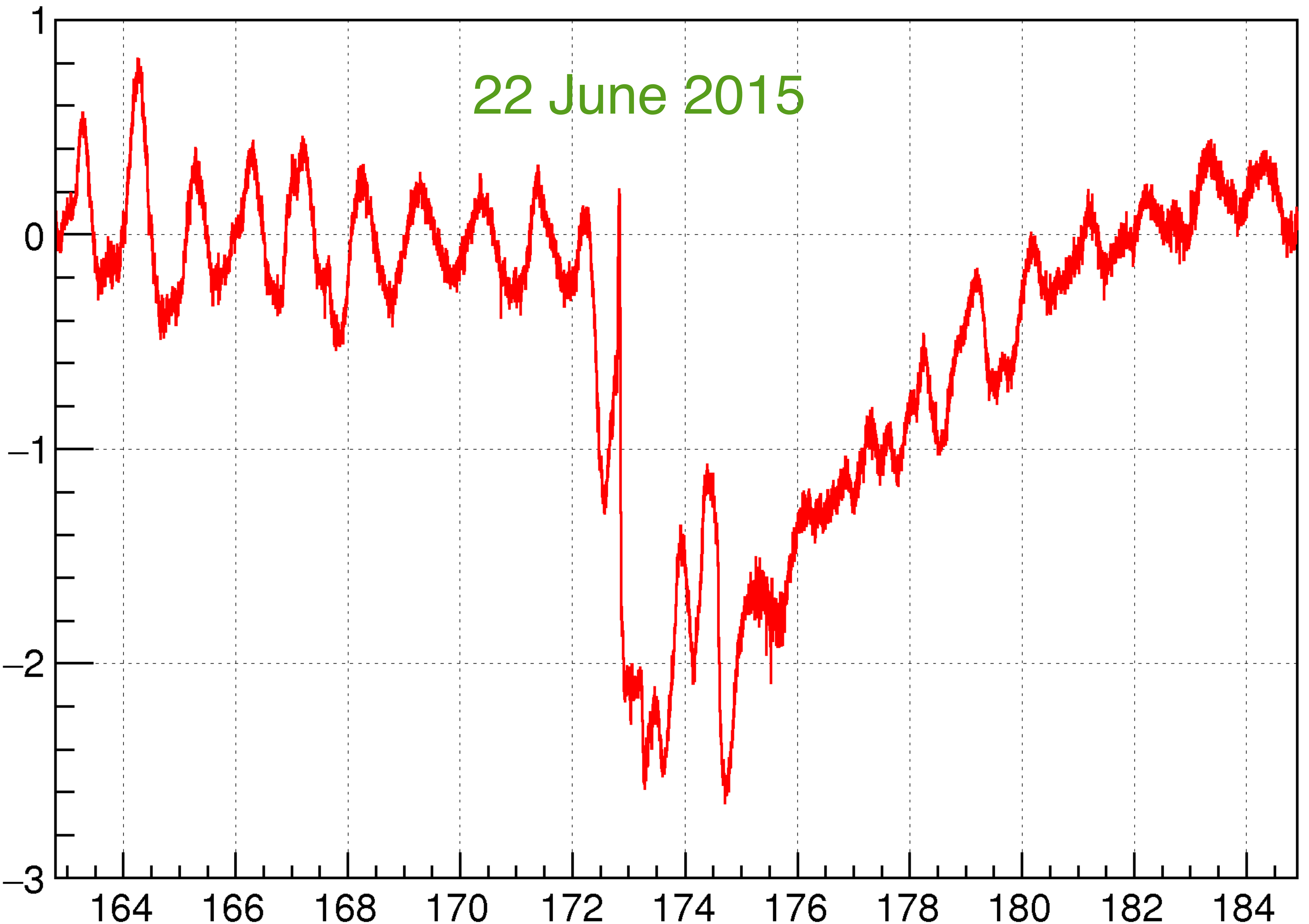
1. Barometer (20 cm air column or 1/2000 blood pressure change)

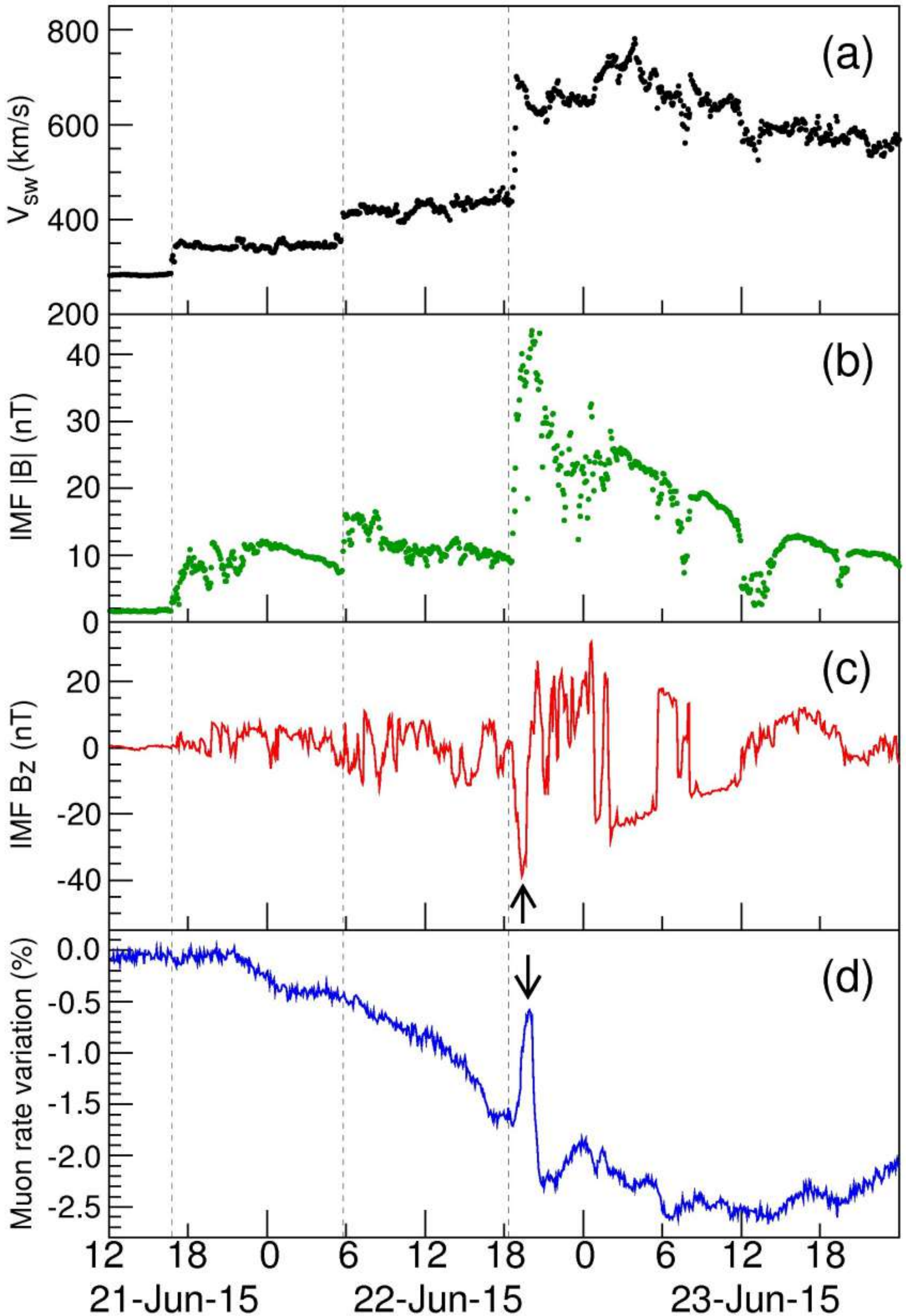
2. Thermometer (0.06 K)

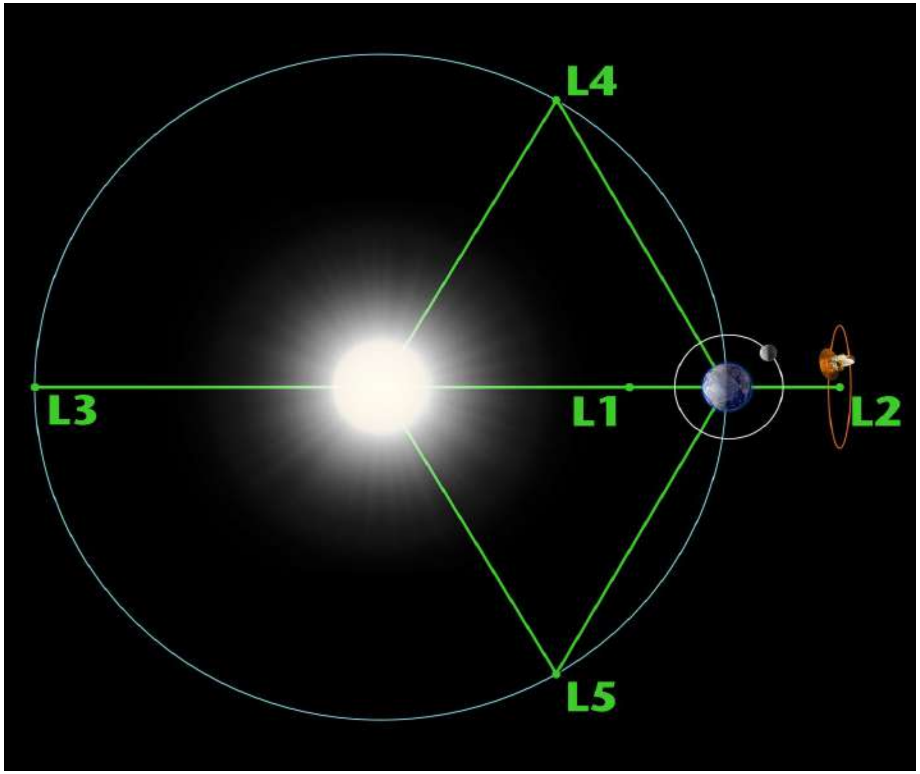
3. Interplanetary magnetometer (0.1 nT = 10^{-6} Geomagnetic field)

4. Atmospheric Voltmeter (GV electric potential)

5. Atmospheric ammeter (1 f A; precision=1 A A or 10^{-18} A)


22 June 2015
1
0
−1
−2
−3
164
166
168
170
172
174
176
178
180
182
184



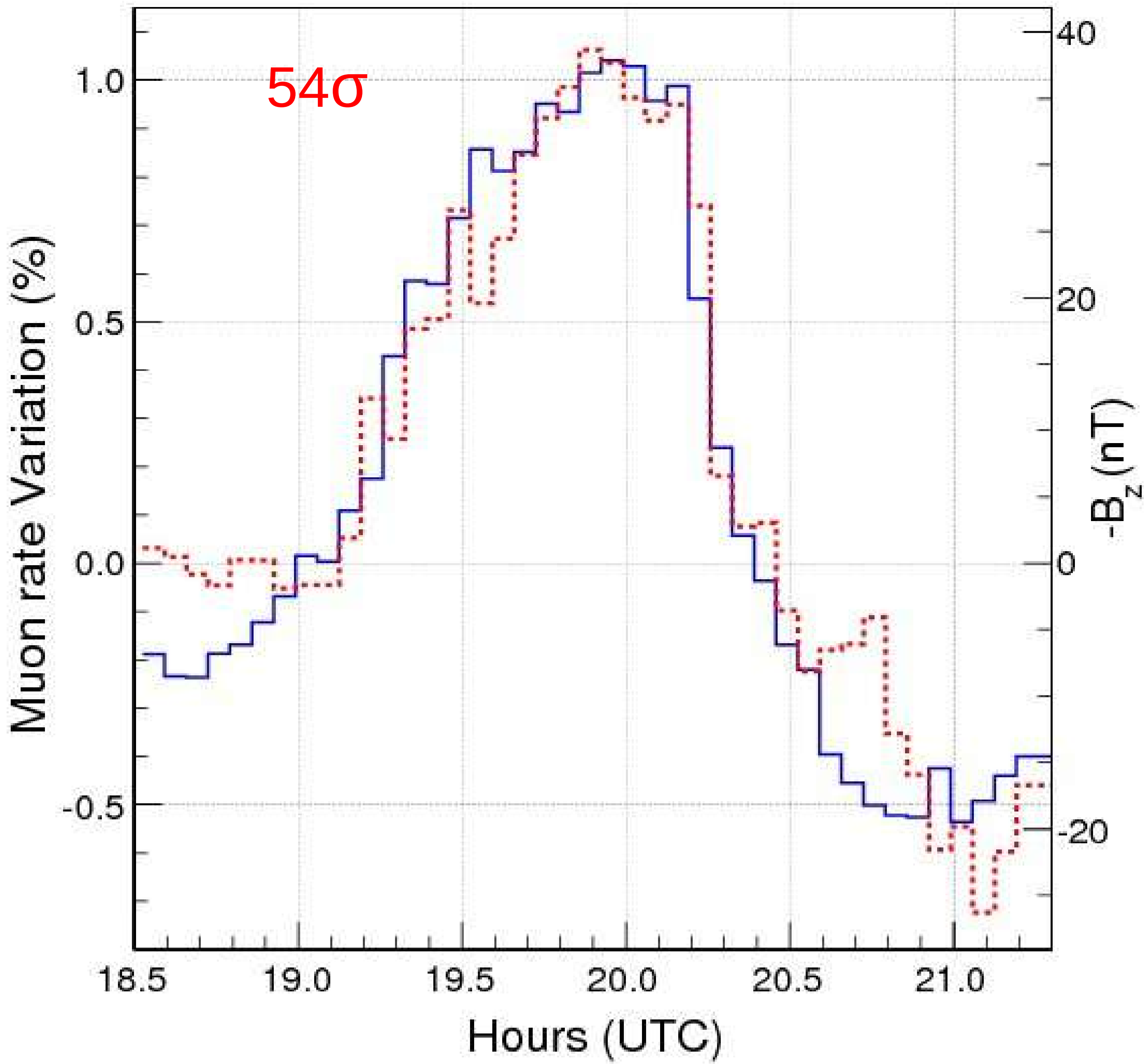


Massive Solar storm
of 22 June 2015

Mass=10^{10} tonne
Energy=10^{33} erg
Solar power= 4×10^{33} erg/s

Initial Speed= 1400 km/s
Speed at L1=700 km/s

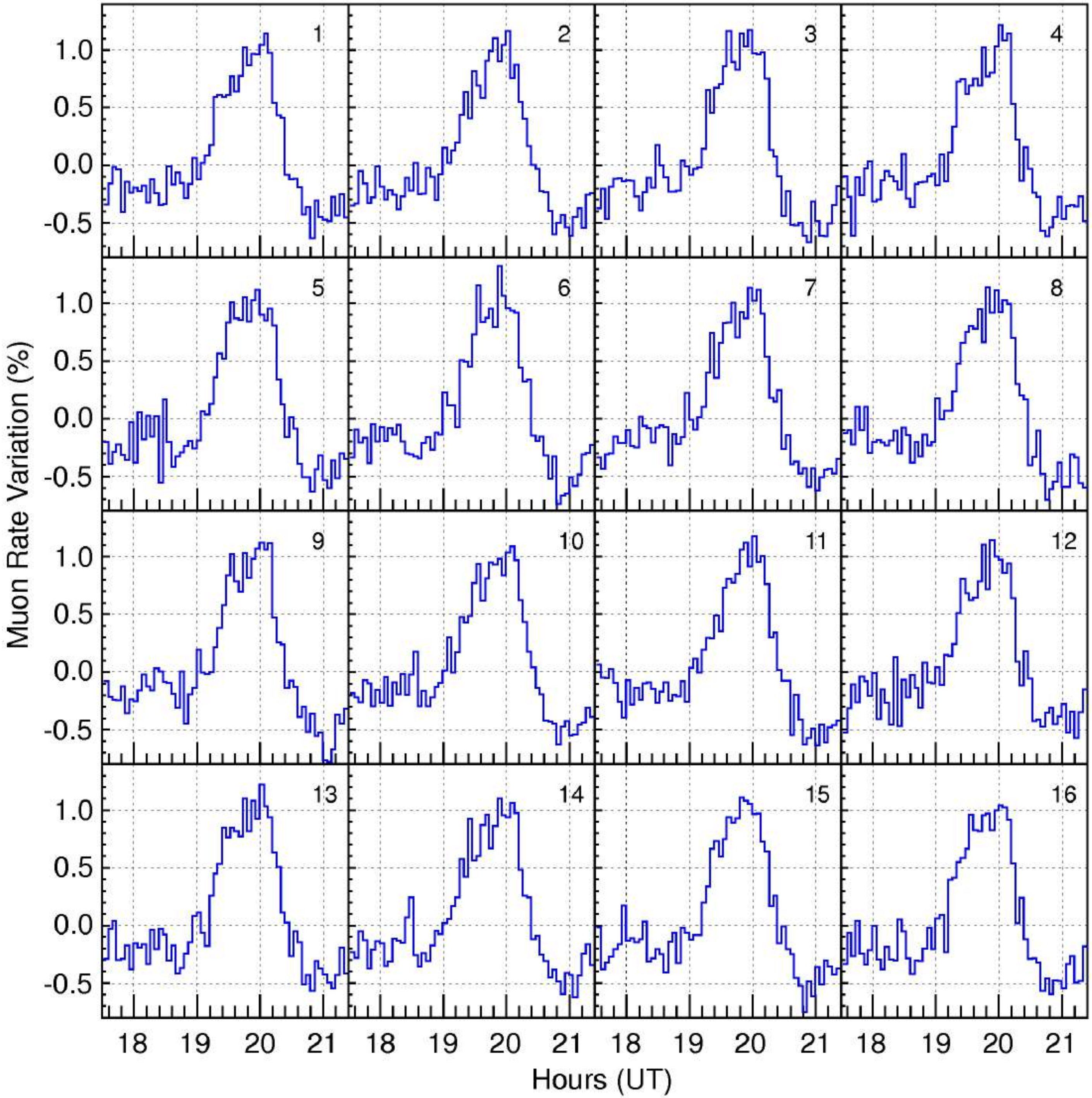
Solar Storm on 22 June 2015 Ooty, midnight



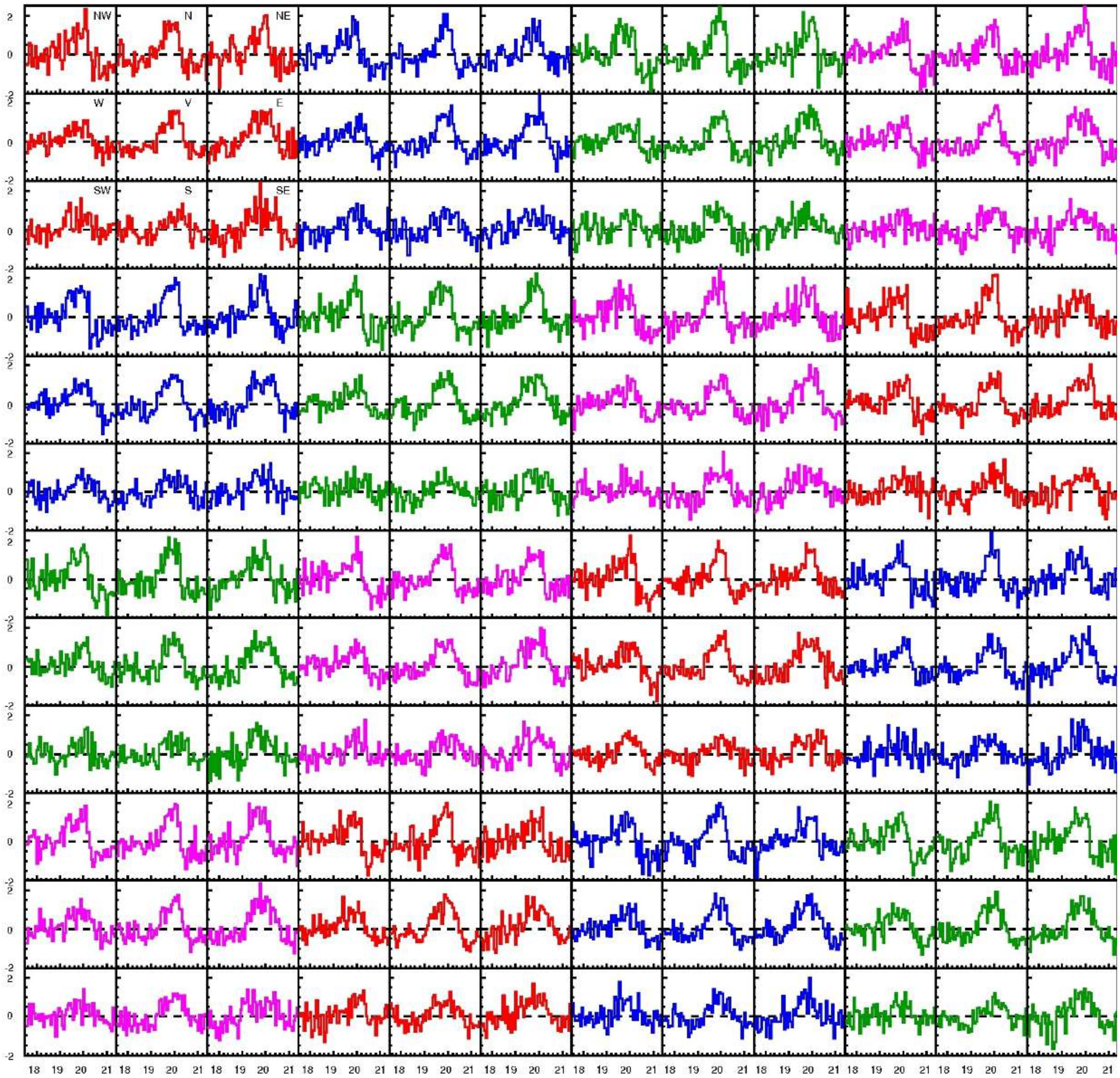
CME characteristics
for 22 June 2015 event

Mass=10^{10} tonne
Energy=10^{33} erg
Solar power= 4x10^{33} erg/s

Initial Speed= 1400 km/s
Speed at L1=700 km/s



13σ



$>5\sigma$ 42

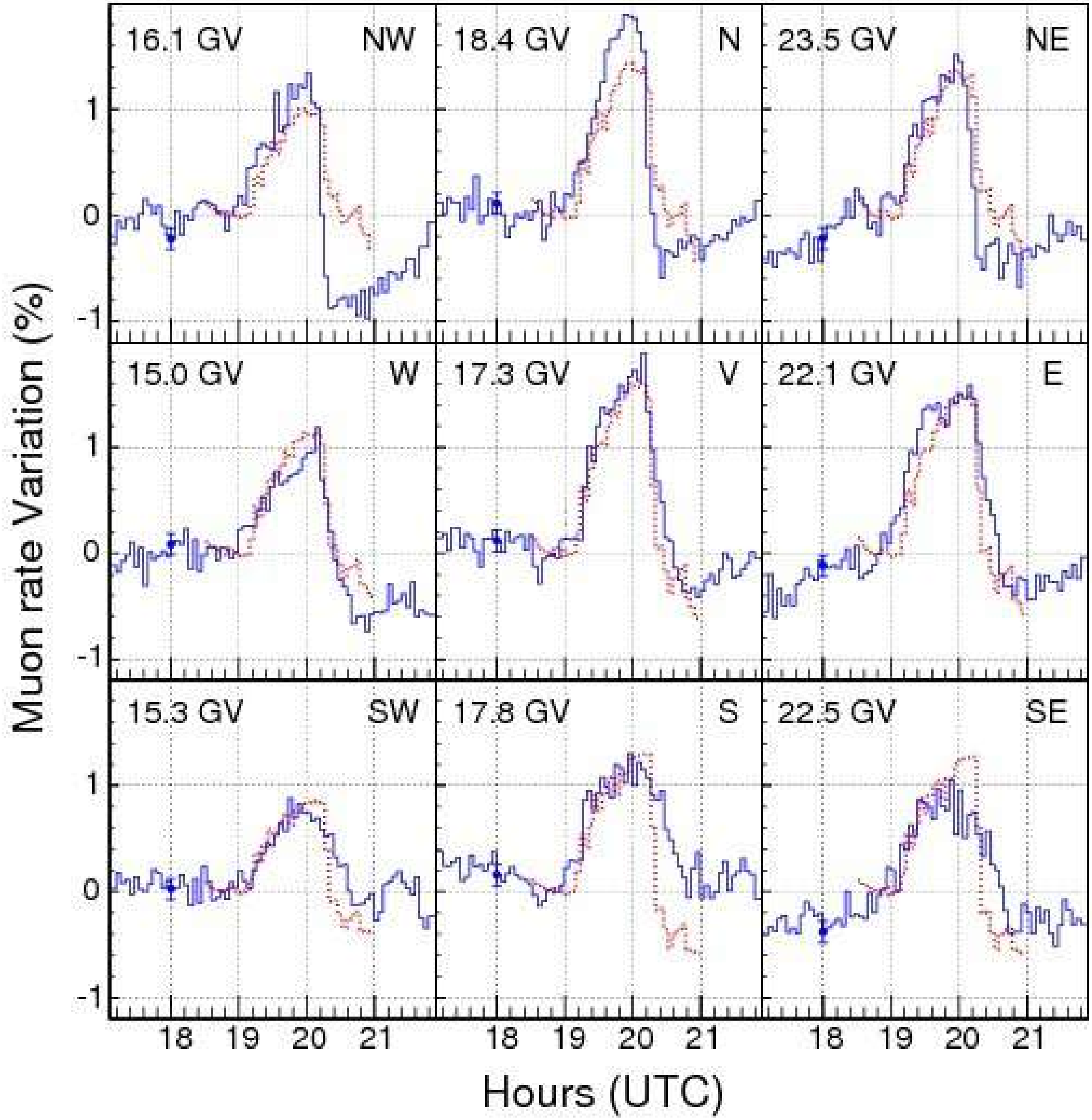
$4\text{-}5\sigma$ 37

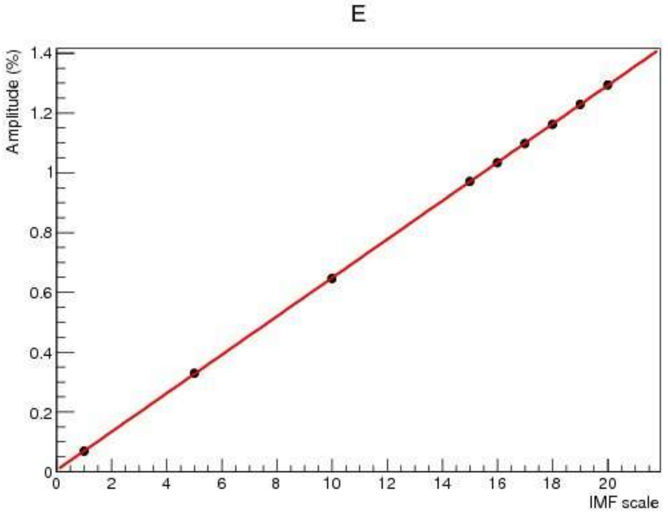
$3\text{-}4\sigma$ 40

$<3\sigma$ 25

-Bz=680 nT

28 minutes

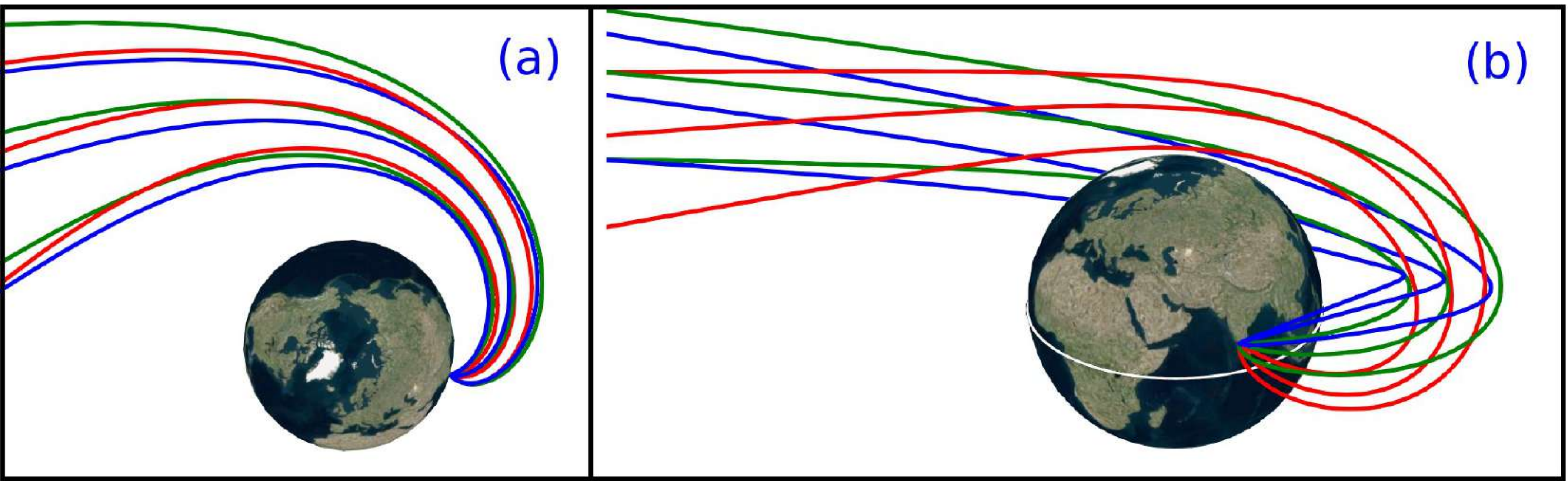




0.7 GV

0.6 GV

0.5 GV



NW N NE W V E SW S SE

Transient Weakening of Earth's Magnetic Shield Probed by a Cosmic Ray Burst

P. K. Mohanty, K. P. Arunbabu, T. Aziz, S. R. Dugad, S. K. Gupta,*
B. Hariharan, P. Jagadeesan, A. Jain, S. D. Morris, and B. S. Rao
Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005, India†

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P. Subramanian
Indian Institute of Science Education and Research, Pune 411021, India†

H. Kojima
Faculty of Engineering, Aichi Institute of Technology, Toyota City, Aichi 470-0392, Japan†
(Received 16 June 2016; published 20 October 2016)

The GRAPES-3 tracking muon telescope in Ooty, India measures muon intensity at high cutoff rigidities (15–24 GV) along nine independent directions covering 2.3 sr. The arrival of a coronal mass ejection on 22 June 2015 18:40 UT had triggered a severe G4-class geomagnetic storm (storm). Starting 19:00 UT, the GRAPES-3 muon telescope recorded a 2 h high-energy (~20 GeV) burst of galactic cosmic rays (GCRs) that was strongly correlated with a 40 nT surge in the interplanetary magnetic field (IMF). Simulations have shown that a large (17×) compression of the IMF to 680 nT, followed by reconnection with the geomagnetic field (GMF) leading to lower cutoff rigidities could generate this burst. Here, 680 nT represents a short-term change in GMF around Earth, averaged over 7 times its volume. The GCRs, due to lowering of cutoff rigidities, were deflected from Earth's day side by ~210° in longitude, offering a natural explanation of its night-time detection by the GRAPES-3. The simultaneous occurrence of the burst in all nine directions suggests its origin close to Earth. It also indicates a transient weakening of Earth's magnetic shield, and may hold clues for a better understanding of future superstorms that could cripple modern technological infrastructure on Earth, and endanger the lives of the astronauts in space.

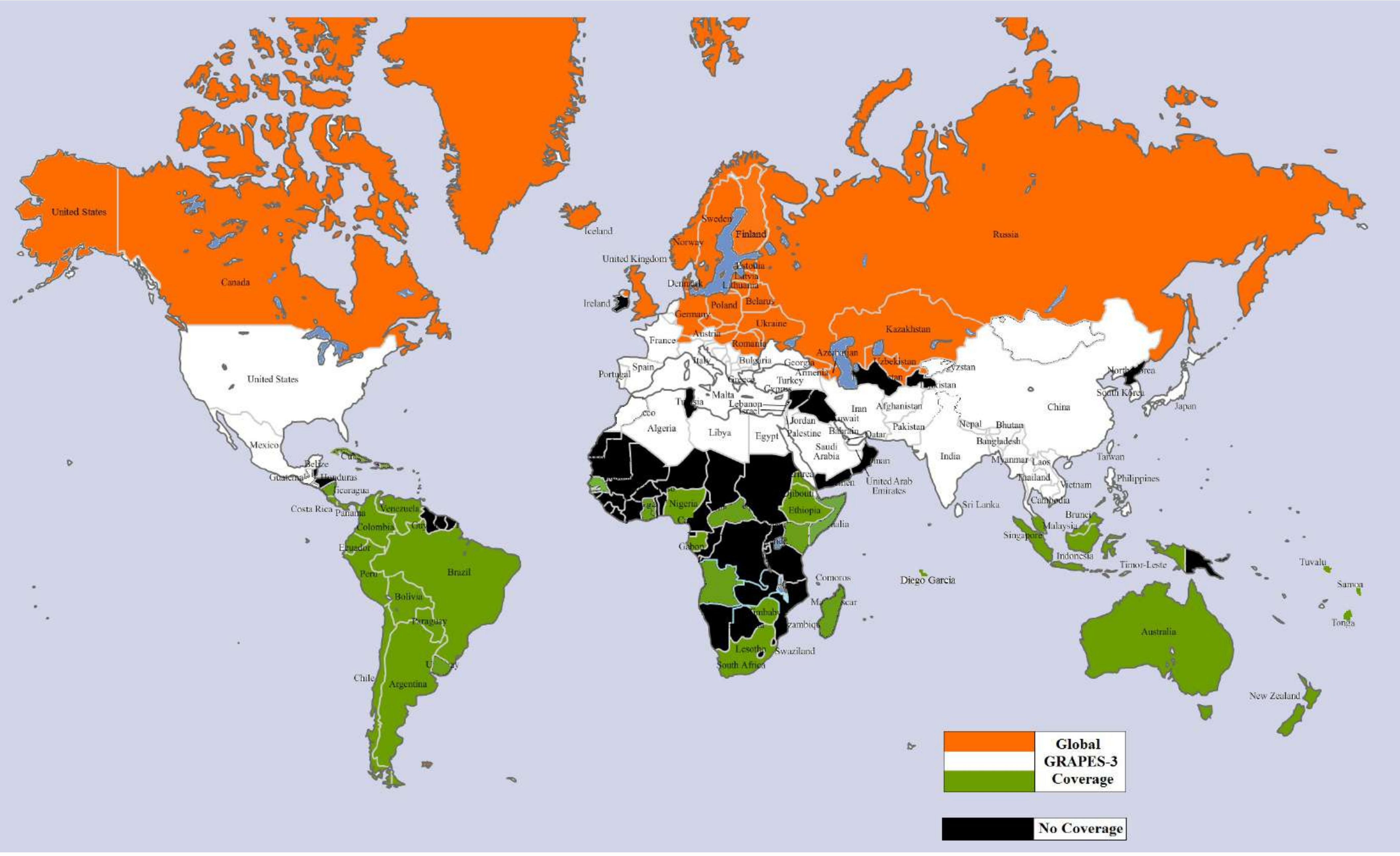
DOI: 10.1103/PhysRevLett.117.171101

Worldwide coverage in 119 Countries, 24 YouTube Videos

1093 Reports in 37 Languages

Seeker: > 510K views (English)
https://www.youtube.com/watch?v=IYFt40J12go&t=34s

BBC Click: > 2.97 million views (Hindi)
https://www.youtube.com/watch?v=azDU2SXBISM&t=290s

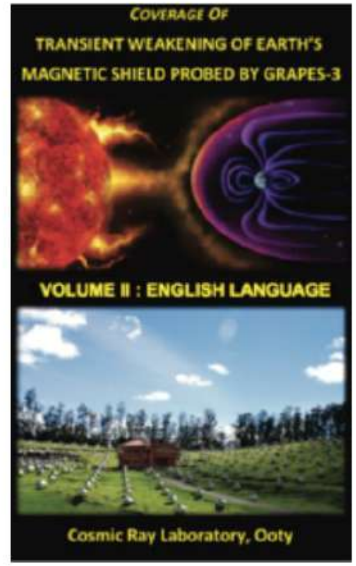


grapes-3.tifr.res.in/discovery.html

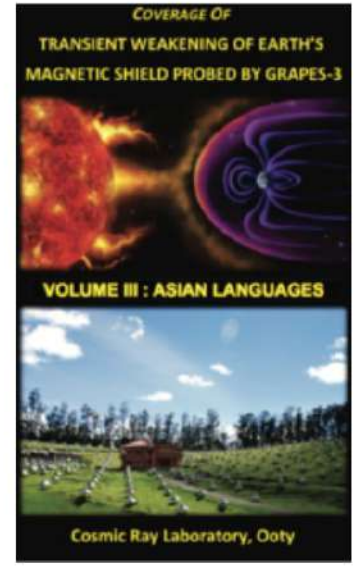
119 Countries, 1093 Reports, 37 Languages

Vol-1

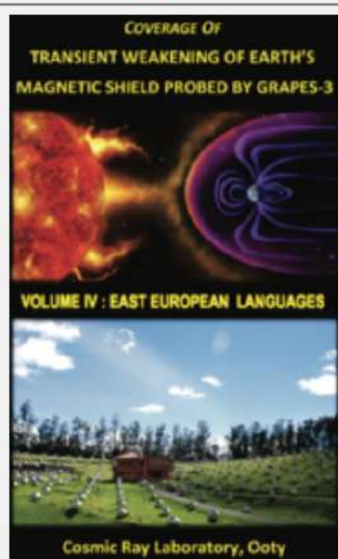
Vol-2



Vol-3



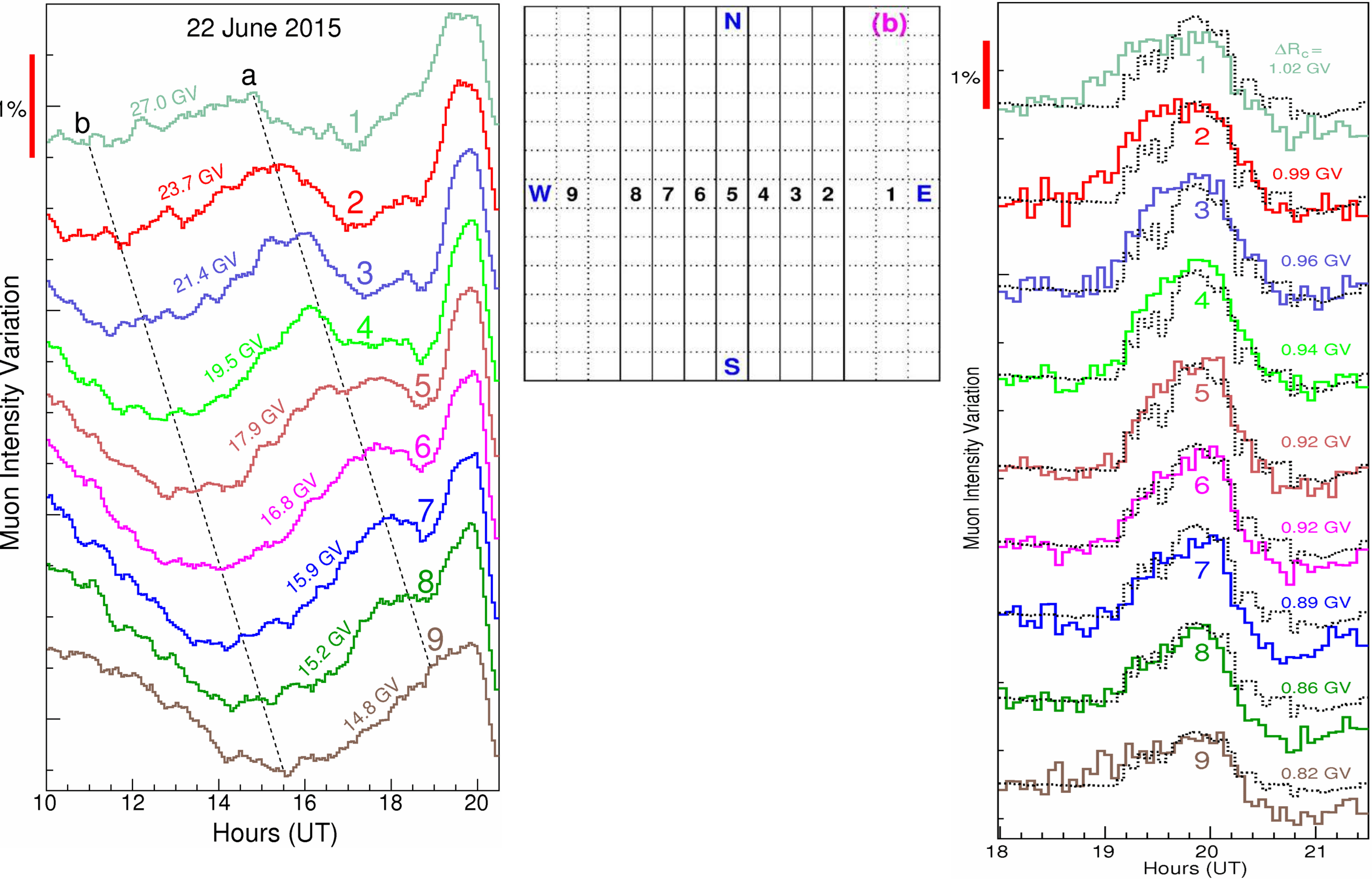
Vol-4



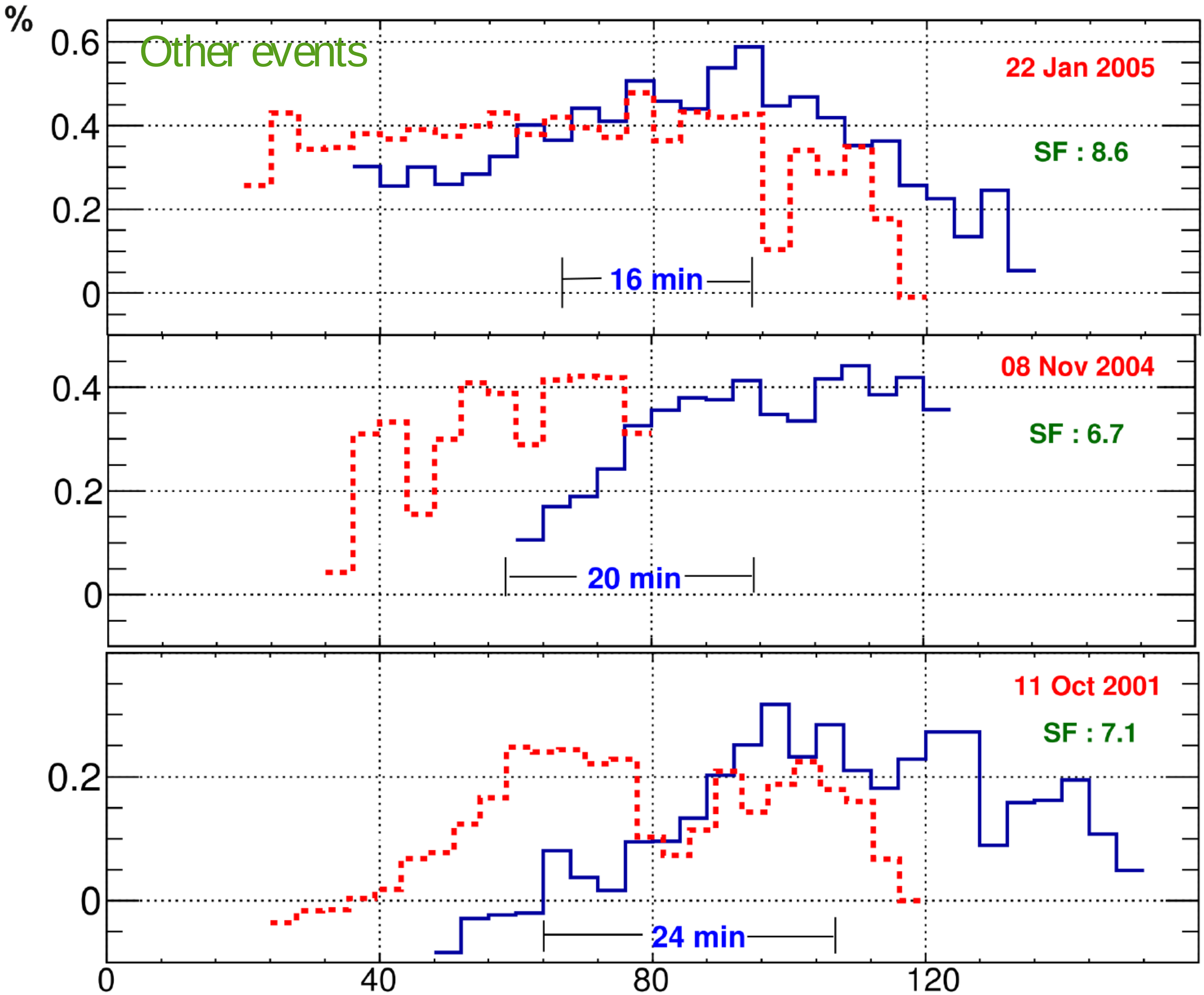
Vol-5

Vol-6

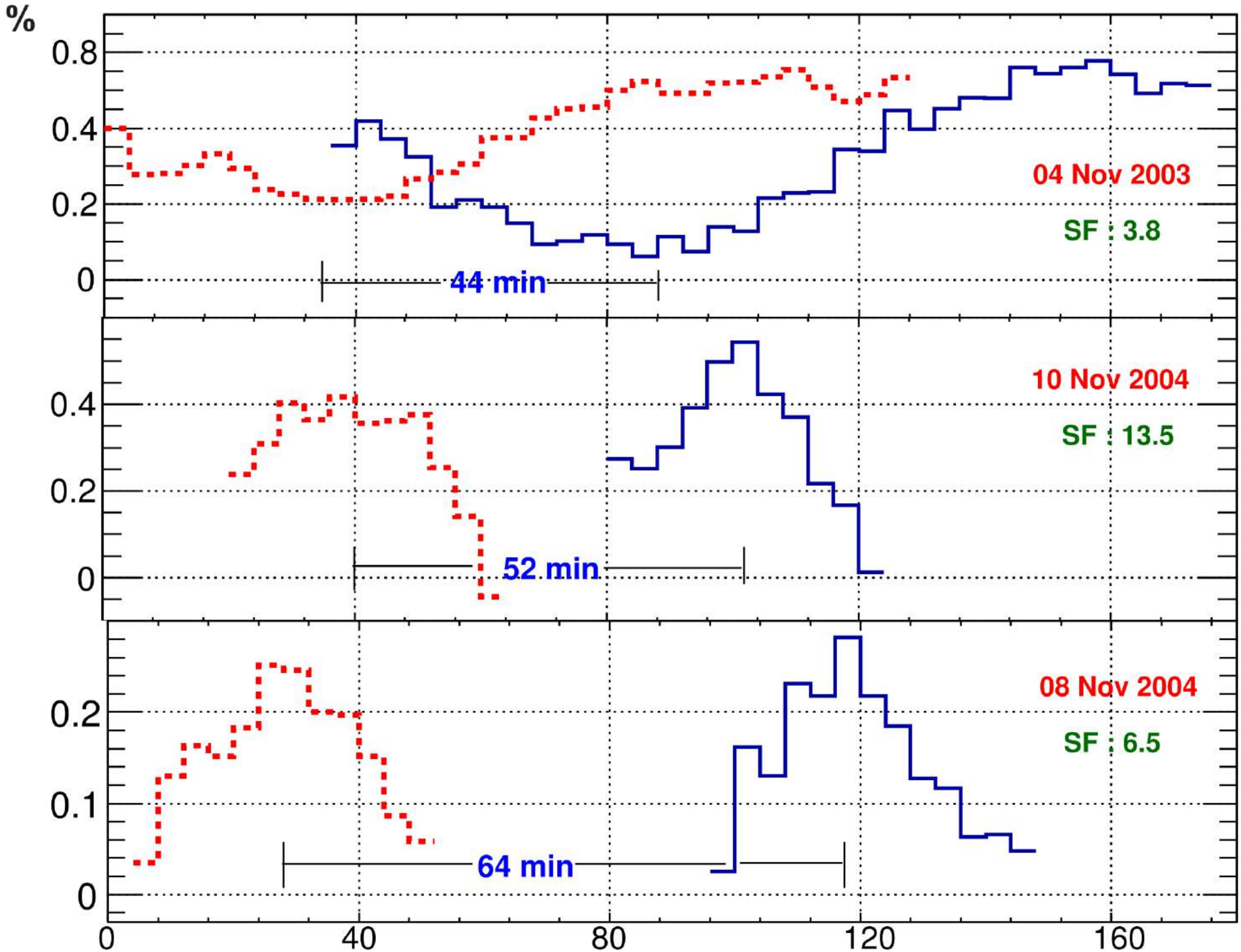
Screenshot



P.K. Mohanty et al. Phys. Rev. D **98** 022004 (2018)



%
Other events
22 Jan 2005
SF : 8.6
16 min
08 Nov 2004
SF : 6.7
20 min
11 Oct 2001
SF : 7.1
24 min
0.6
0.4
0.2
0
0
40
80
120



%
0.8
0.4
0.2
0
04 Nov 2003
SF : 3.8
44 min
0.4
0.2
0
10 Nov 2004
SF : 13.5
52 min
0.2
0.1
0
08 Nov 2004
SF : 6.5
64 min
0
40
80
120
160

Takeaways

1. High precision measurements vital for progress
2. Work where natural advantage exists
3. High energy particles are best messengers
4. Universe in the best laboratory

The GRAPES-3 Team

THANKS