The link between experimental capabilities and scientific discoveries

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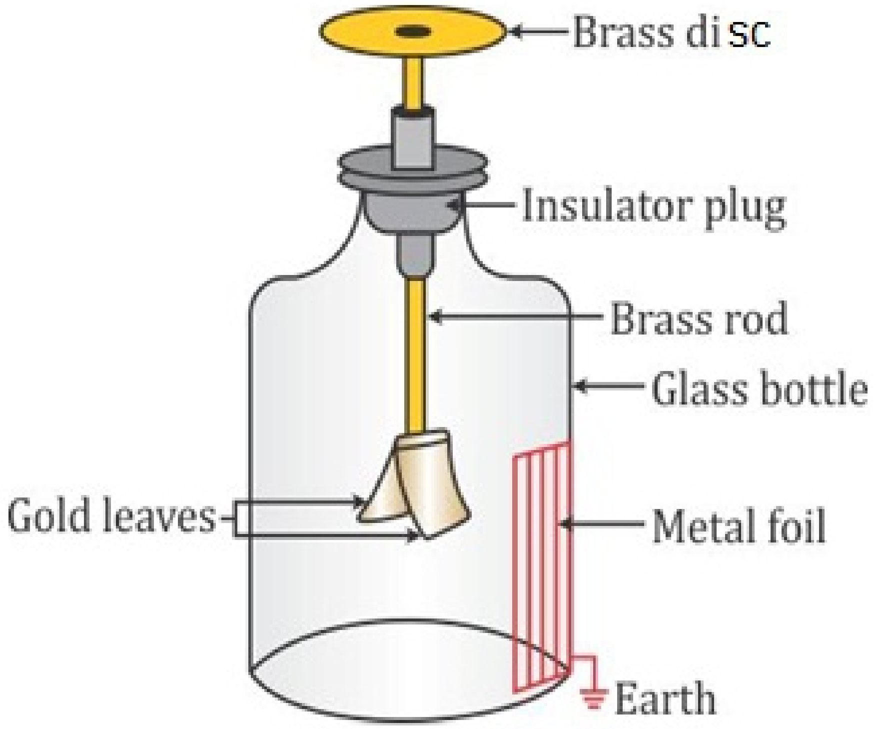
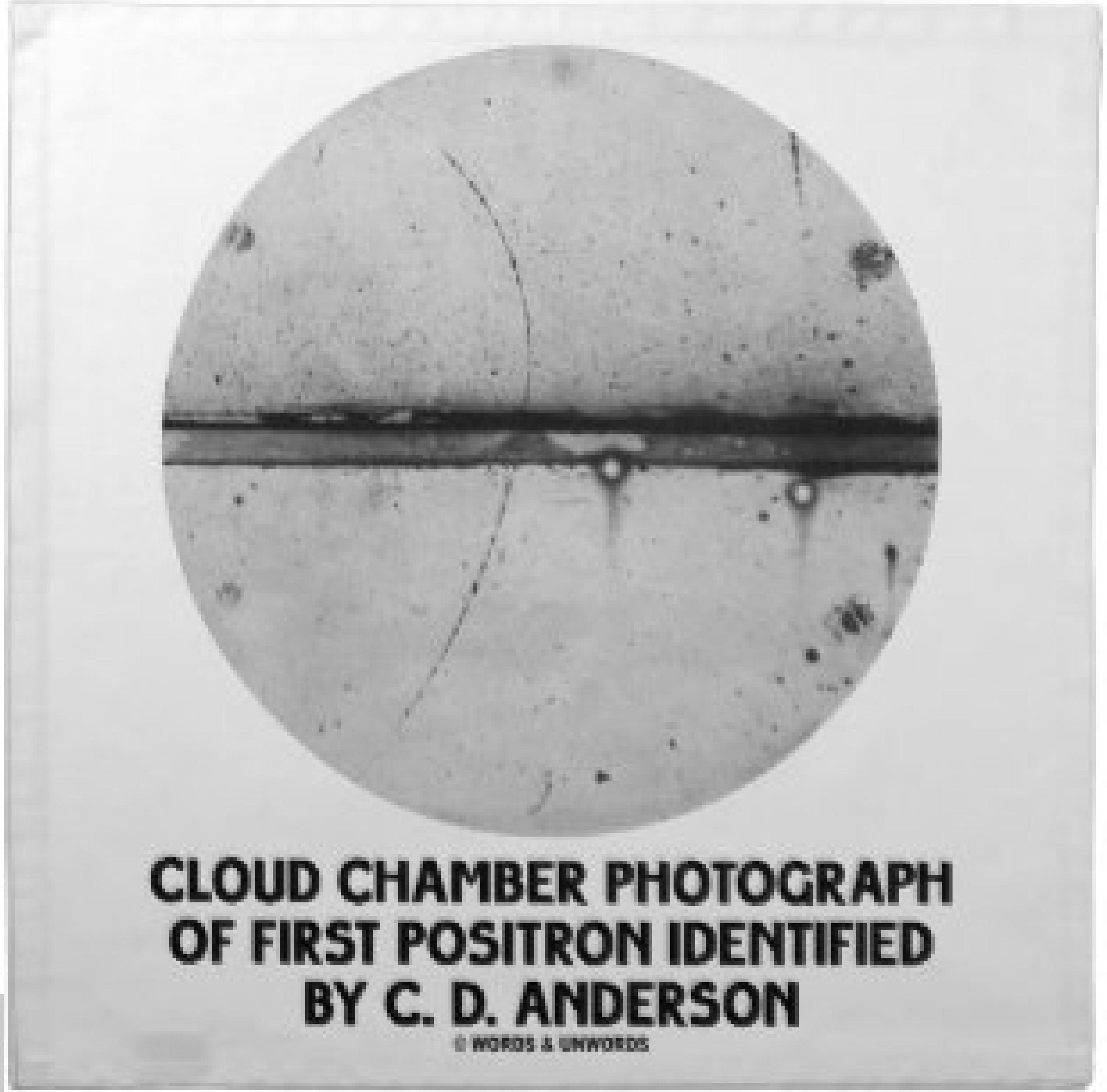
- New capabilities and discoveries
- Experimental innovation for GRAPES-3
- GRAPES-3 work on Solar storms
- Summary

Hot air balloon was invented in 1783 and gold leaf electroscope in 1786. But more than a century would lapse before Hess combined these instruments and flew above 5000m to discover cosmic rays on 12 August 1912.



Anderson operated a cloud chamber in magnetic field and discovered positron in 1932



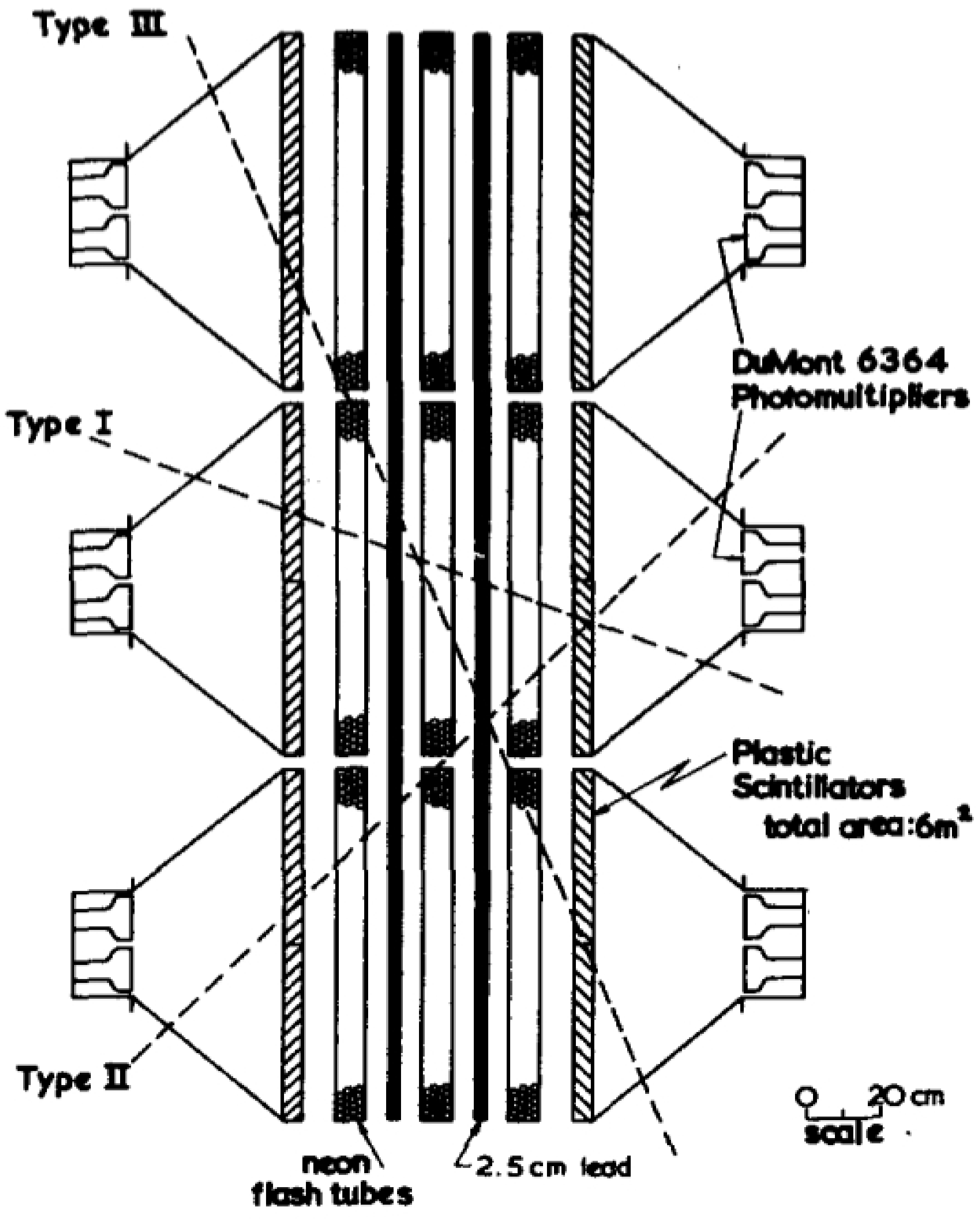
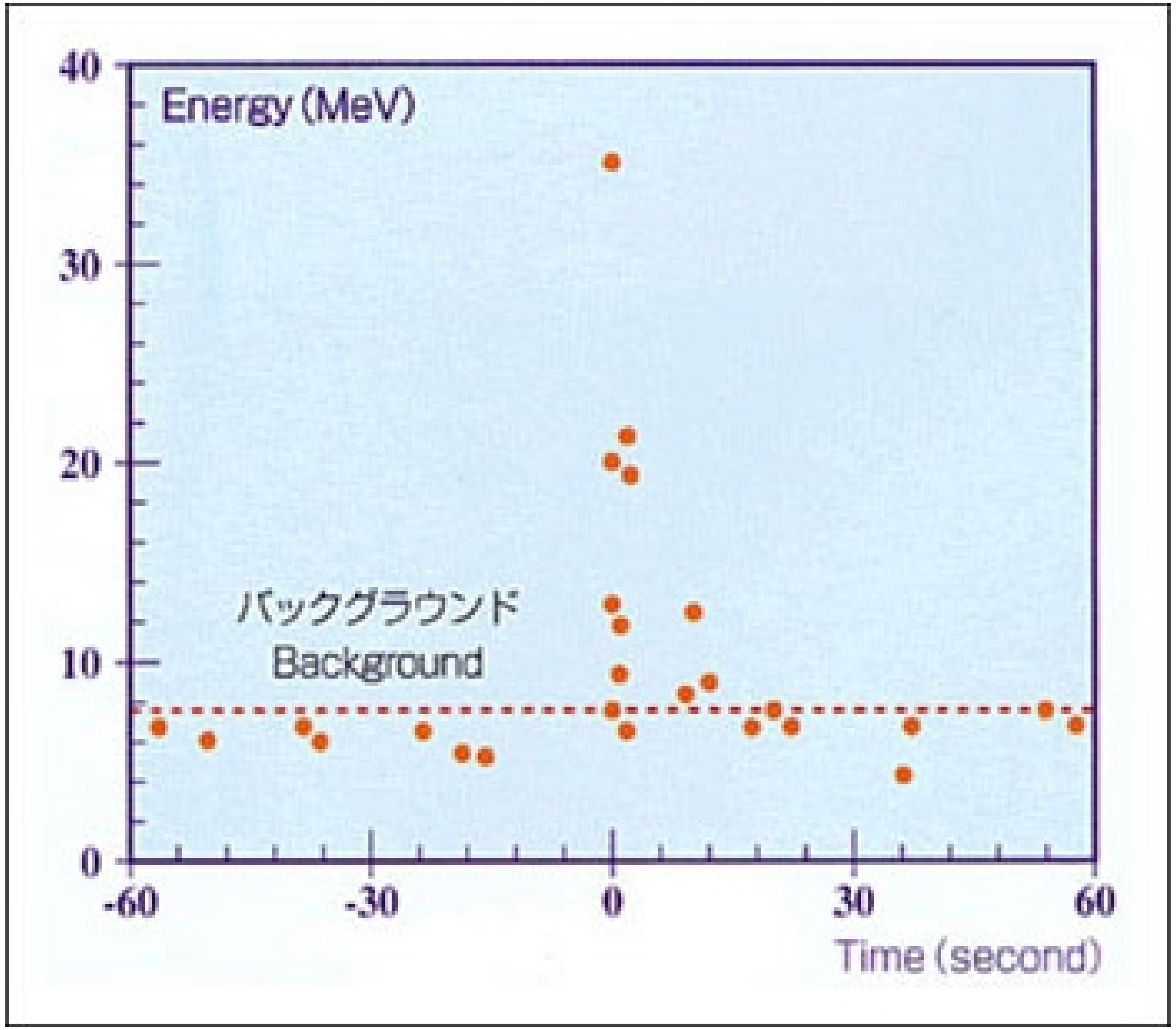


Fig. 1. Neutrino telescope.

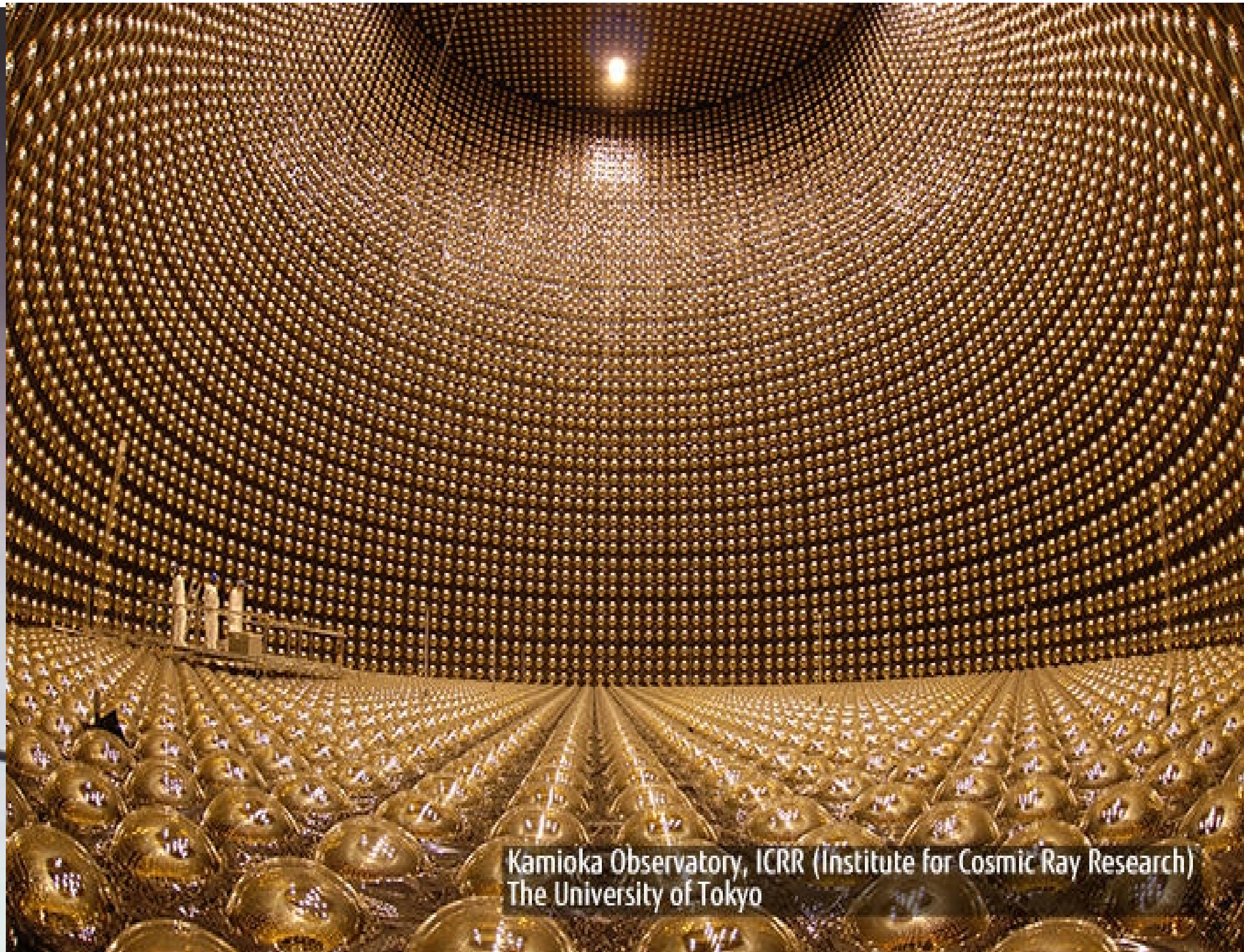
Underground mines in KGF >2000m deep allowed discovery of atmospheric neutrinos in 1965

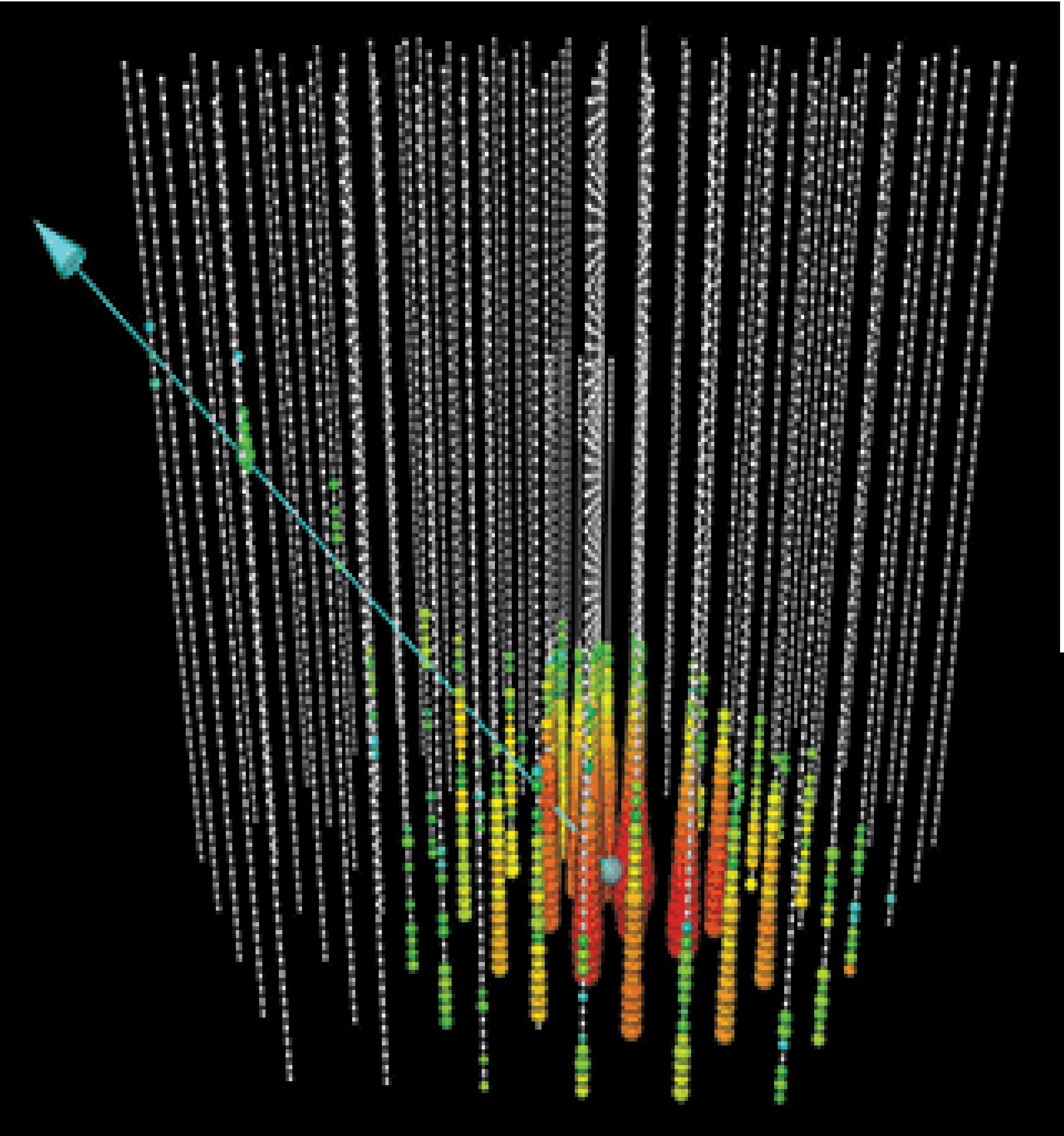
Reference: C.V. Achar et al. Phys. Lett. 18 196 (1965)

Discovery by the KAMIOKANDE experiment of neutrinos from supernova 1987A on 23 February 1987 was possible only due to invention of 20'' diameter photomultiplier tubes (20%). Birth of neutrino astronomy and Nobel prize for M. Koshiba in 2002



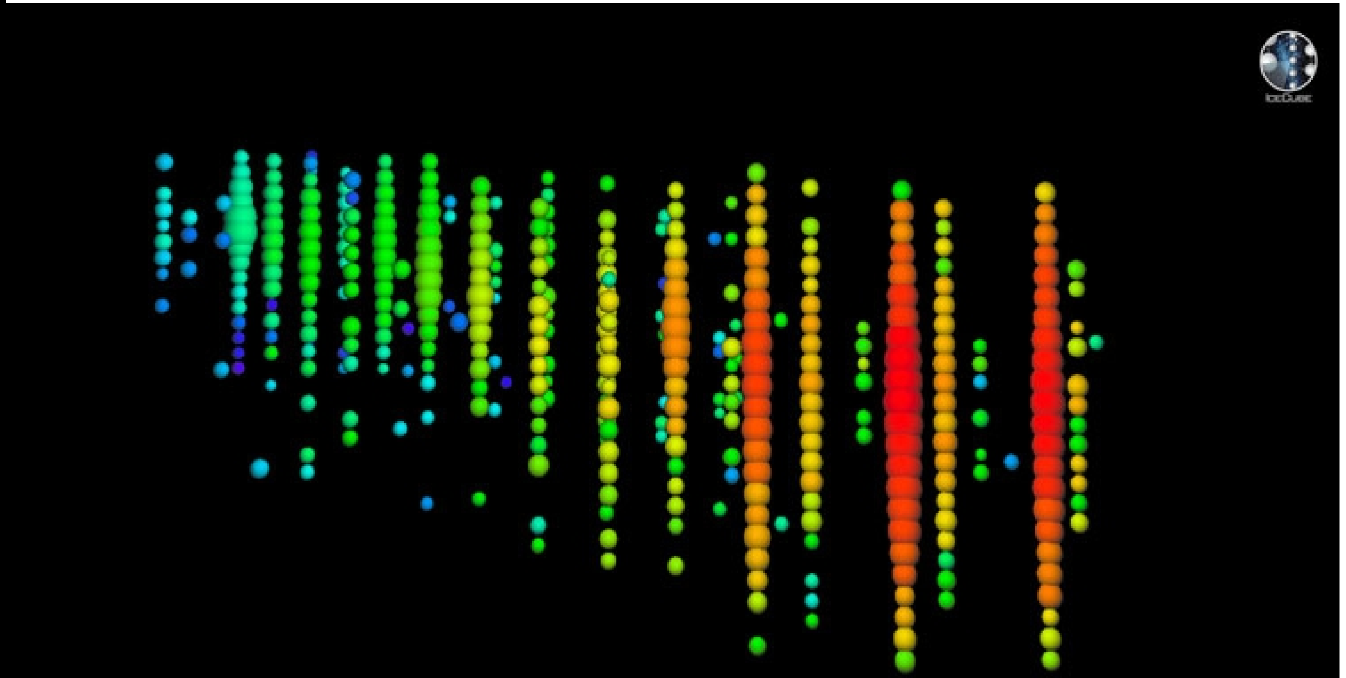
Upgrade to Super-K experiment by increasing the volume and photomultipliers by >10 times, neutrinos oscillations discovered in 1998. Nearly 40% wall-to-wall coverage by photomultipliers permitted this discovery, establishing finite neutrino mass and Nobel prize for T. Kajita in 2015



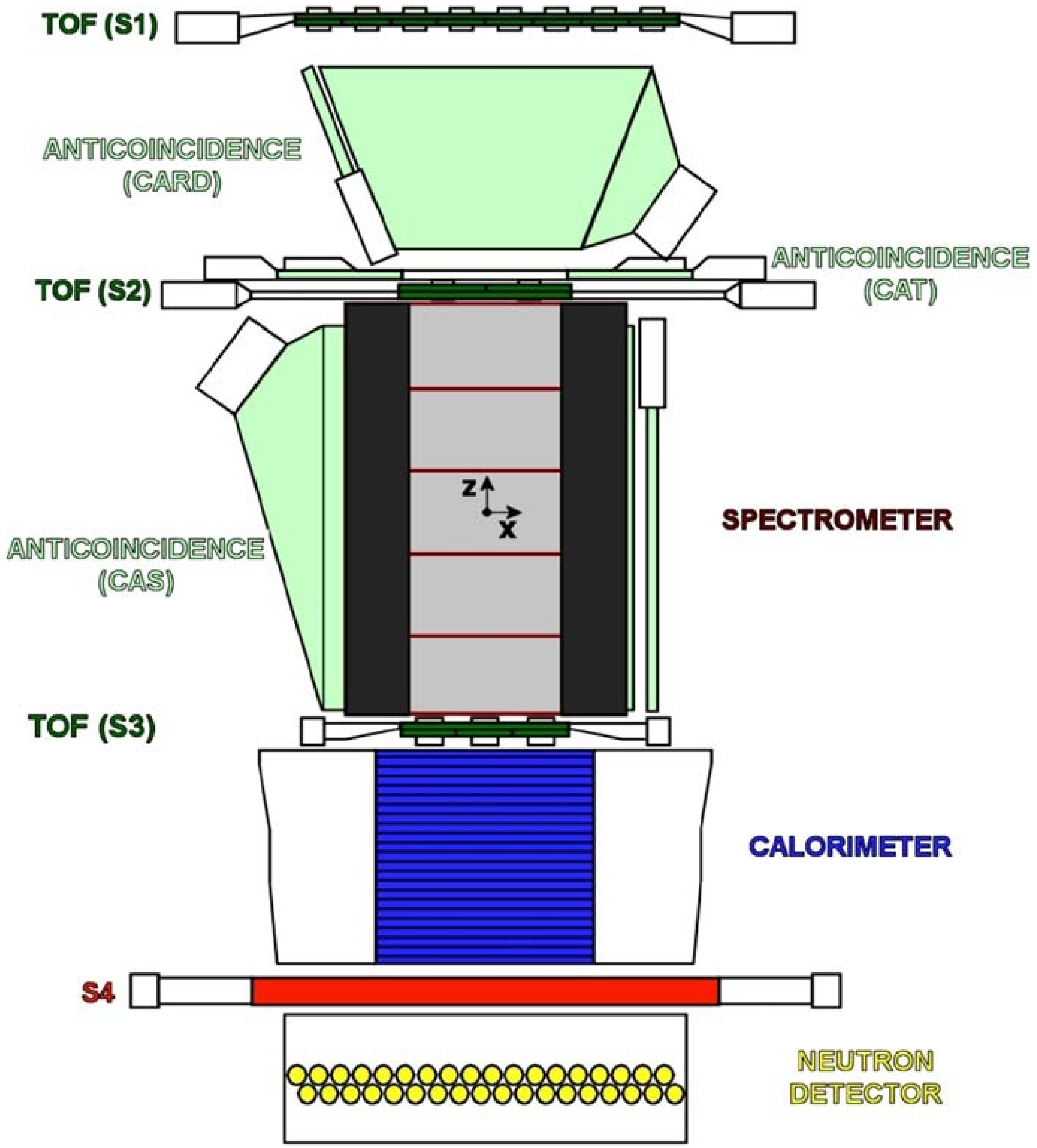


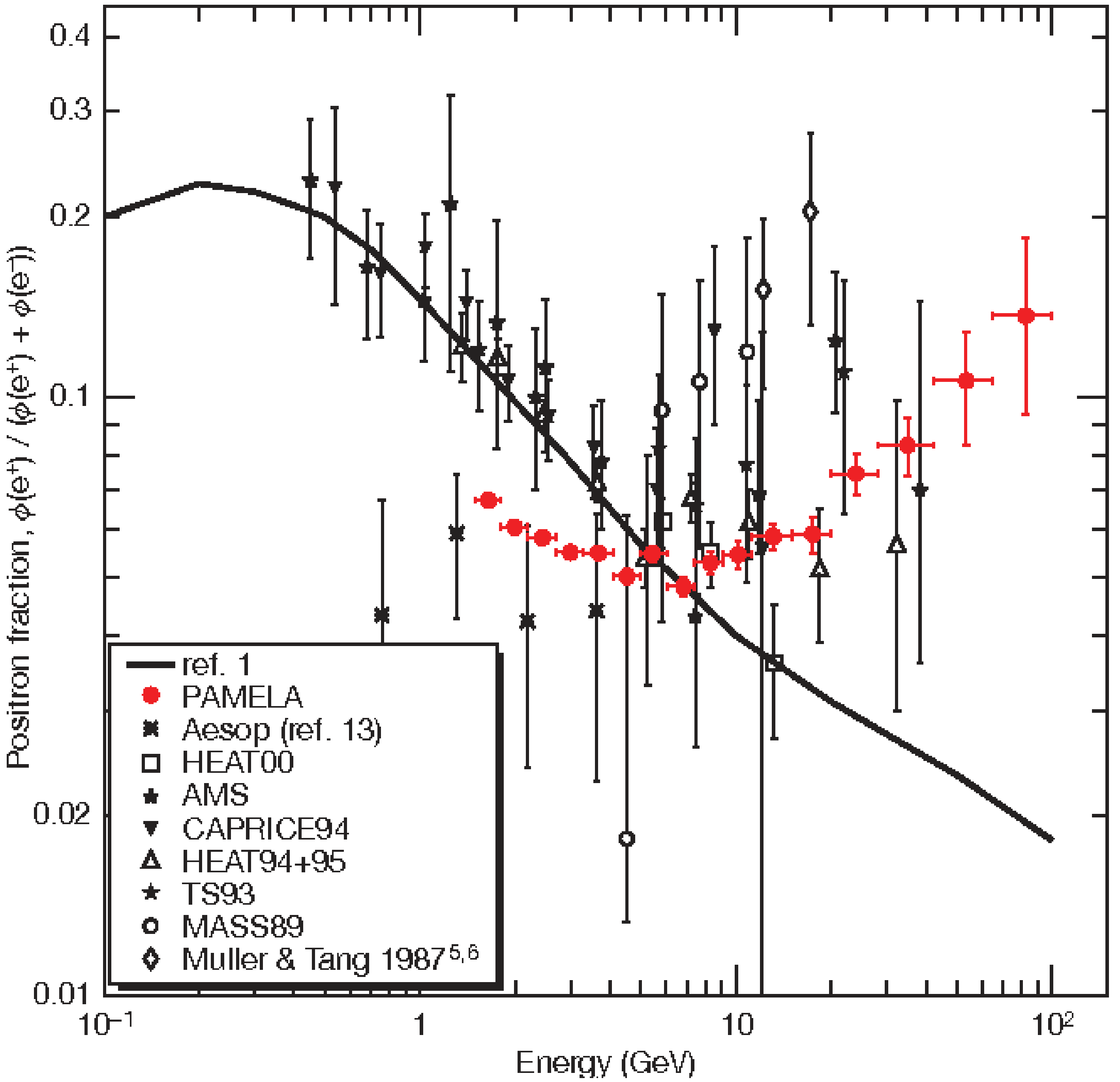
IceCube detected PeV ν (left)

Neutrino in association with gamma rays by Fermi from TXS 056+056 (below) may be a source of cosmic rays

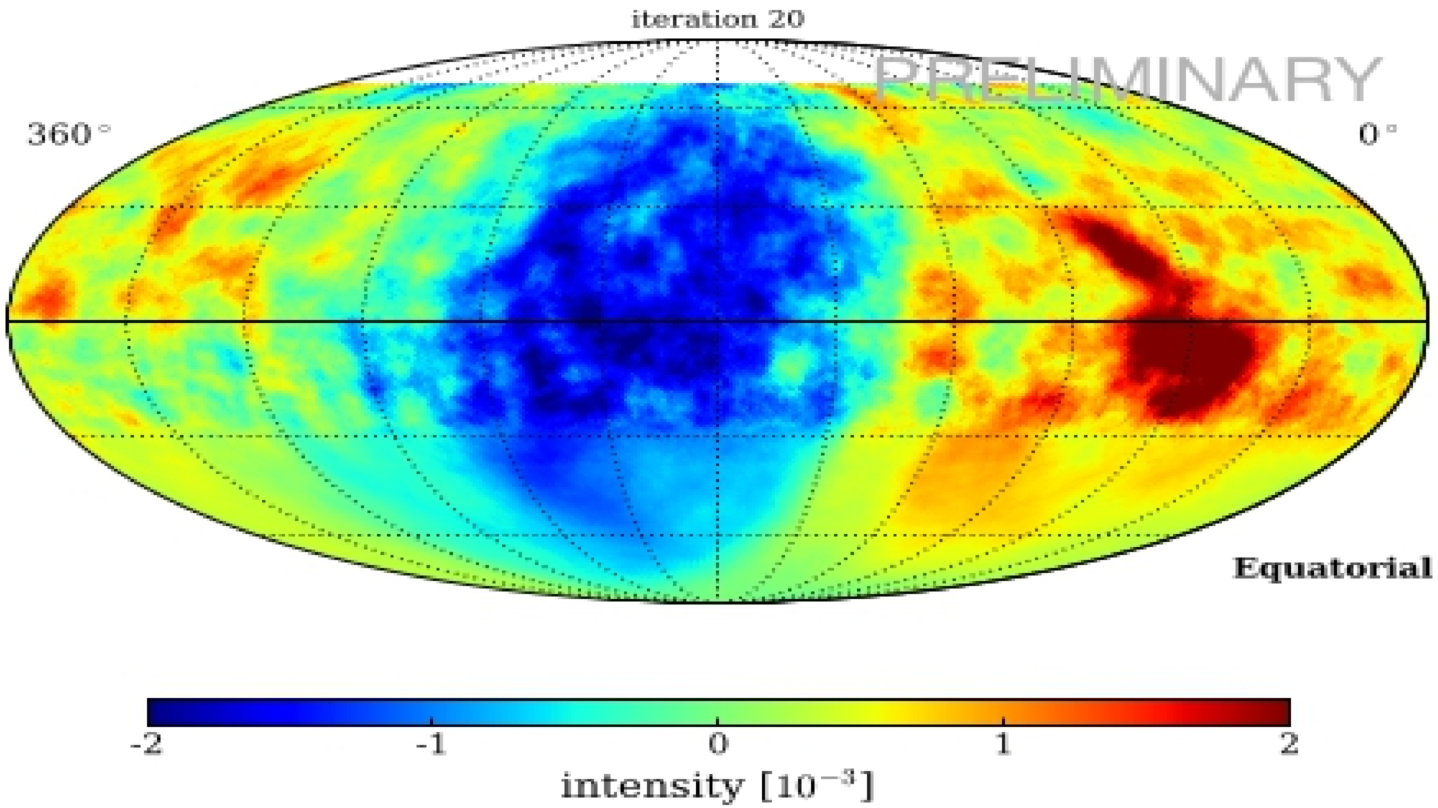


PAMELA is the first large Magnetized Spectrometer in space





Anisotropy of cosmic rays from HAWC and IceCube data



Cosmic Rays

- Cosmic rays are the highest energy particles produced by nature
- Cosmic rays have been observed over an extraordinary range of energies

10^{8} - 10^{20} eV 12 order of magnitude

$E_{C.R} < 10^{12}$ eV space based detectors $E_{C.R} > 10^{12}$ eV ground based detectors

- cosmic rays are mostly charged particles of various nuclei

P ~ 90%

He ~ 7-8%

C, N, O,..... Si, S,...... Fe,....... etc ~ 2-3%

e^{-}, γ 1%

- CRs are energetic charged particles with a good representation from entire periodic table
- *Since physics is basically an experimental science any progress in understanding of cosmic rays would require instruments to precisely measure their properties.*
- *Due to huge energy range of cosmic rays, a variety of experimental techniques are used for their detection and measurement.*

Top

100 $g cm^{-2}$

200

300

400

500

600

700

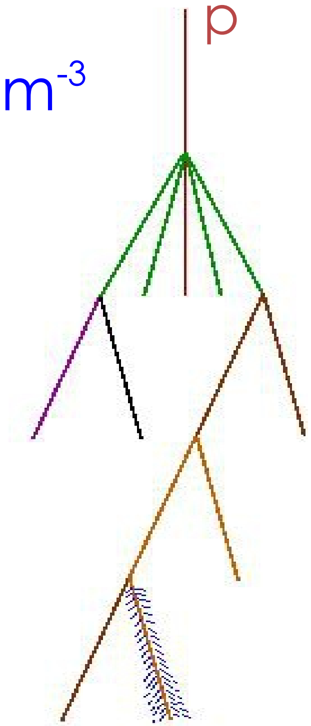
Ooty 800

900

Mumbai 1000

Extensive Air Shower

$76 cm \times 13.6\ g\ cm^{-3}$
$\simeq 1030\ g\ cm^{-2}$



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

$\pi^+ \longrightarrow \mu^+ + \nu_\mu$ 2×10^{-8} s

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

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

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

Particles multiply and at lower altitudes one gets:

1. Electrons, Positrons, gamma rays: E-M component (90 %)
2. Muon (μ^+, μ^2): Muon or Penetrating Component (8 – 10 %)
3. Pions, Kaons etc called Hadronic Component (1 %)
4. Neutrinos largely pass through the Earth undetected

For proton of energy E, Number of particles $N \propto E$

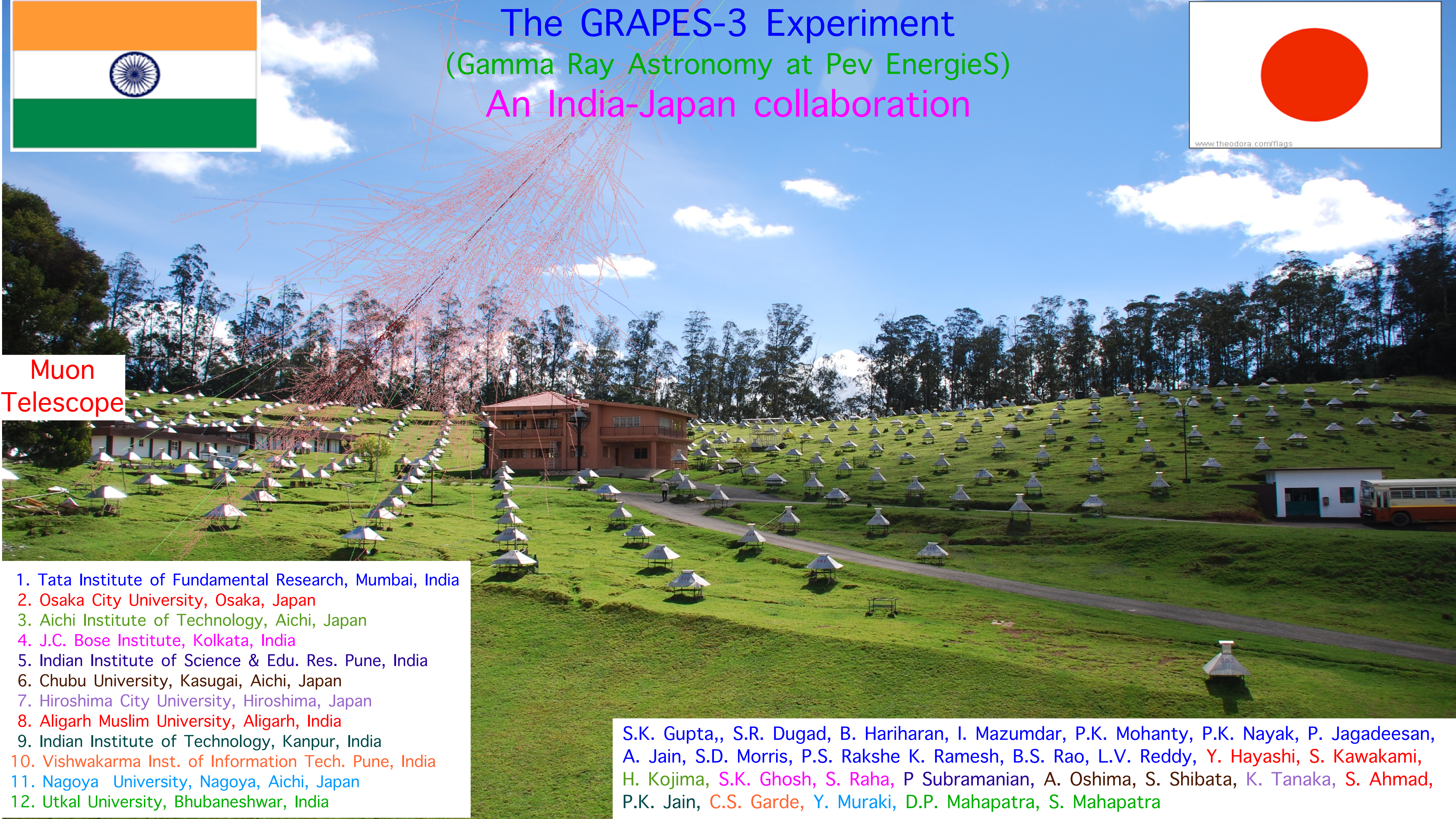
At Ooty for $E = 10^{14}$ eV, $N \simeq 20000$ particles spread over 1000 m^2

1. E-M density and time (ns) provides energy and direction of primary particle
2. Muon density provides primary composition, discrimination among γ and p
3. Muons sensitive to solar and atmospheric phenomena

The GRAPES-3 Experiment

(Gamma Ray Astronomy at Pev EnergieS)

An India-Japan collaboration



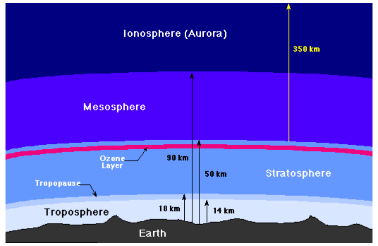
1. Tata Institute of Fundamental Research, Mumbai, India
2. Osaka City University, Osaka, Japan
3. Aichi Institute of Technology, Aichi, Japan
4. J.C. Bose Institute, Kolkata, India
5. Indian Institute of Science & Edu. Res. Pune, India
6. Chubu University, Kasugai, Aichi, Japan
7. Hiroshima City University,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

S.K. Gupta,, S.R. Dugad, B. Hariharan, I. Mazumdar, 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, C.S. Garde, Y. Muraki, D.P. Mahapatra, S. Mahapatra

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 storms**, Coronal Mass Ejections: Energy ~10 GeV Scale ~10^{11}-10^{13} cm

3. Galactic Cosmic Rays at “ knee ”: Energy ~10^{6} GeV Scale ~10^{21}-10^{23} cm

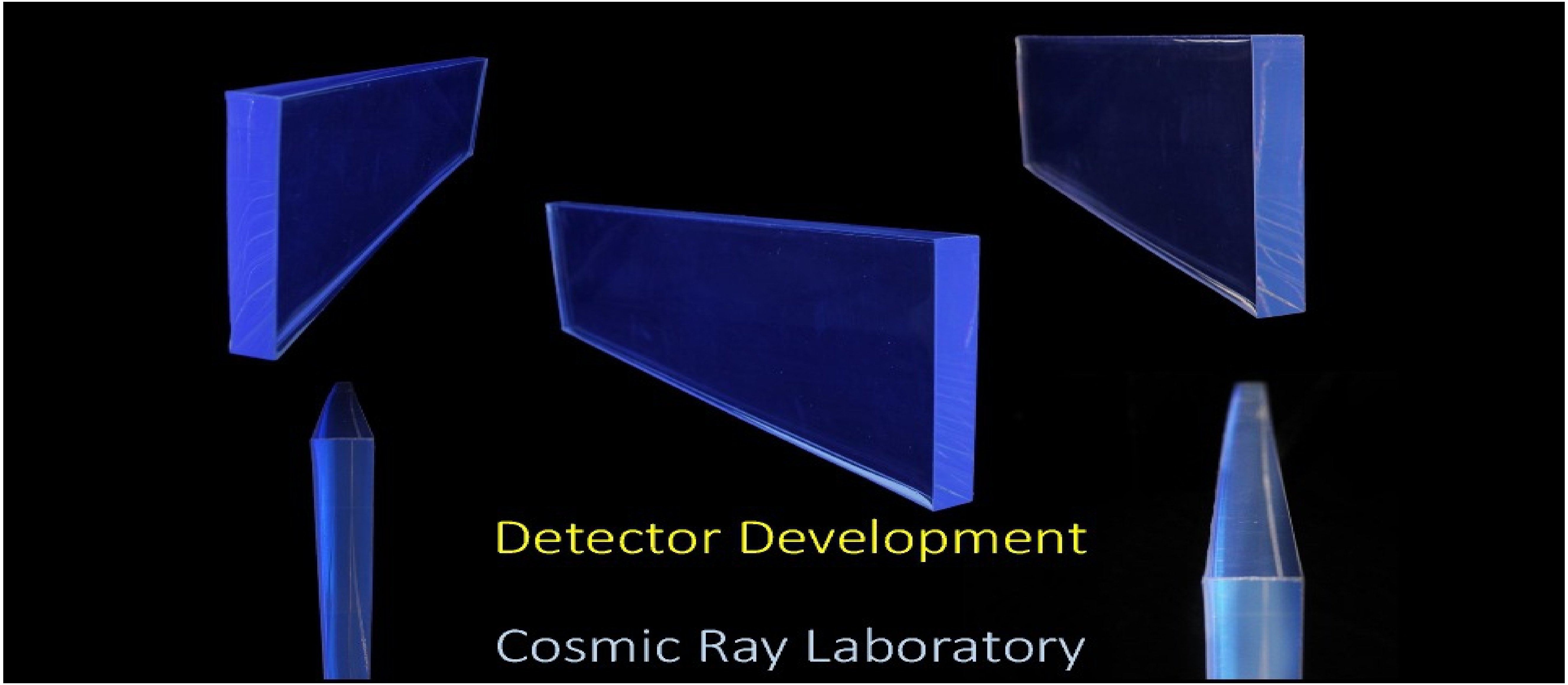
4. Diffuse multi-TeV gamma-rays: Energy ~10^{11} GeV Scale ~10^{24}-10^{26} cm

400 Plastic Scintillator detectors (1 m^2 area)

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

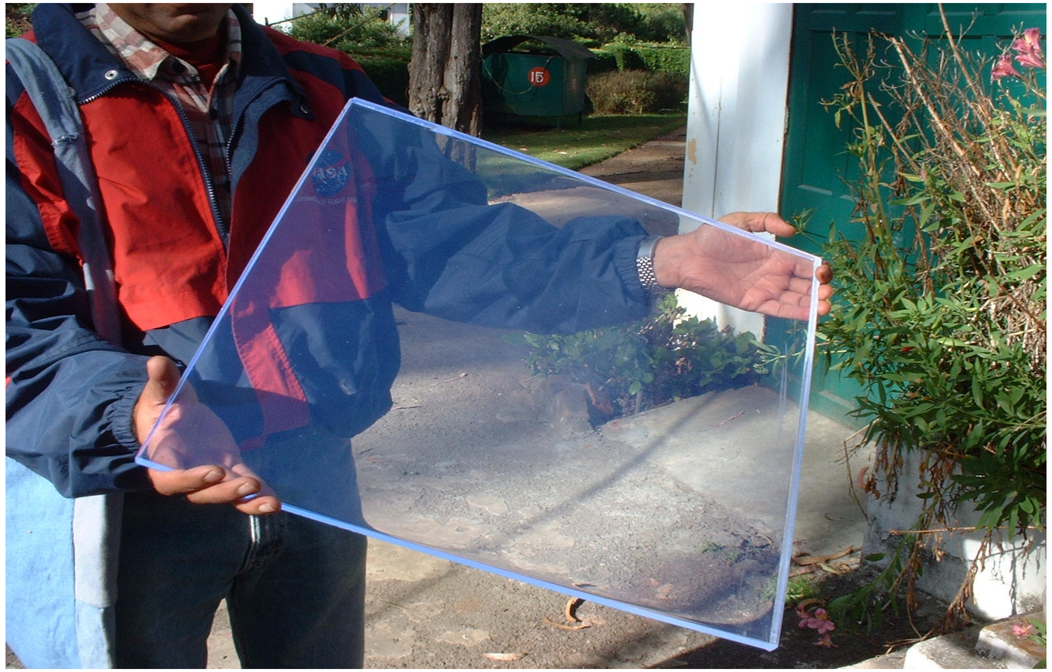
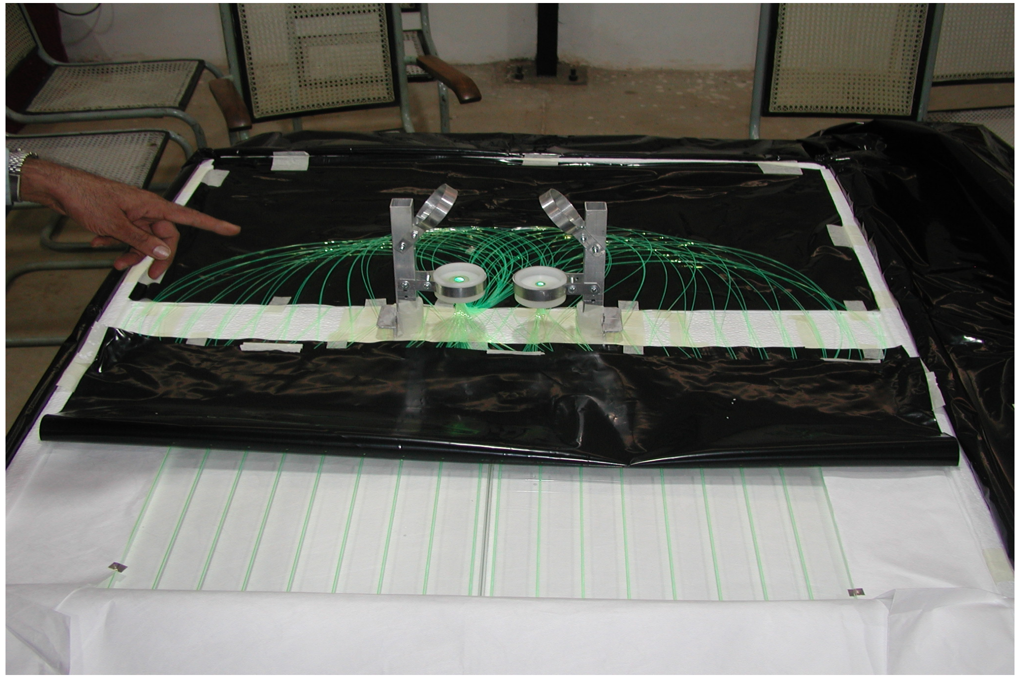
S.K. Gupta et al. Nucl. Instr. and Meth. **A 540** 311-323 (2005)
S.K. Gupta et al. Pramana **65** 273-283 (2005)
Y. Hayashi et al. Nucl. Instr. and Meth. **A 545** 643-657 (2005)

Innovation & Technology Development

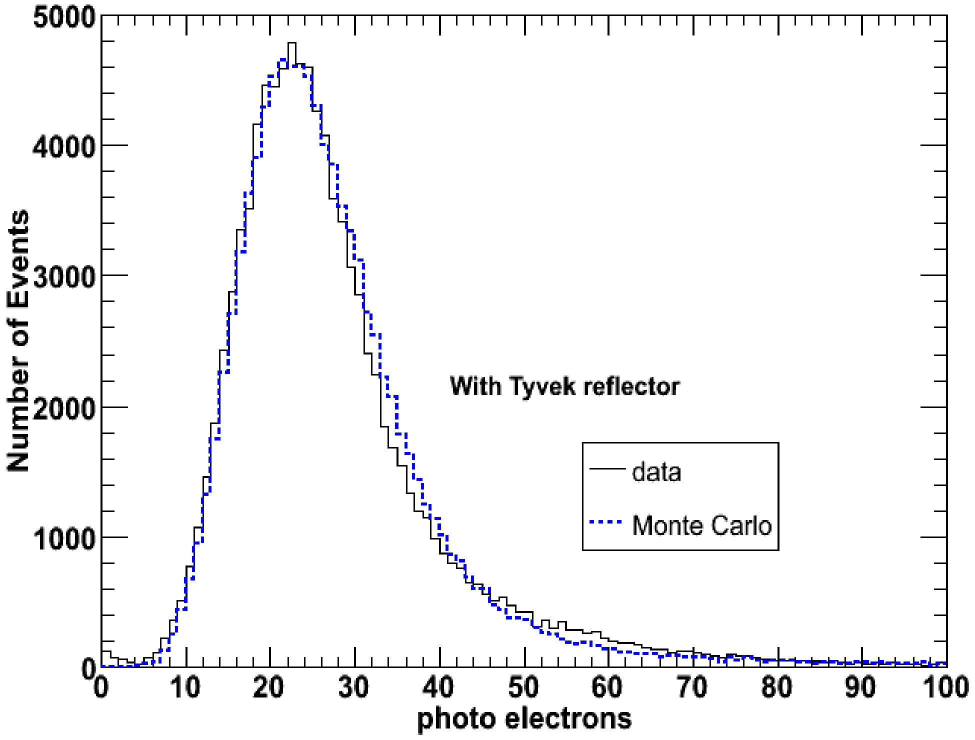


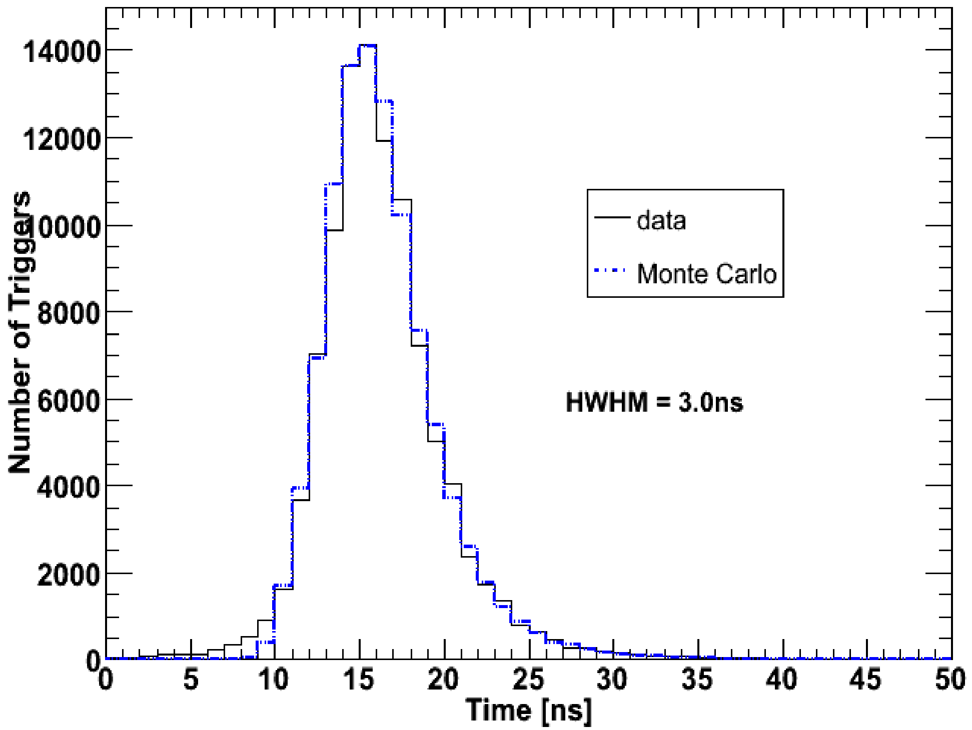
Plastic Scintillator development:

Decay Time= 1.6 ns, Light Output = 85% Bicron (54% anthracene), Timing 25% faster, Atten Length **λ**= 100cm, Cost ~30% of import, Maximum Size 100cmX100cm Total > 2500 Used by more than dozen collaborating institutes

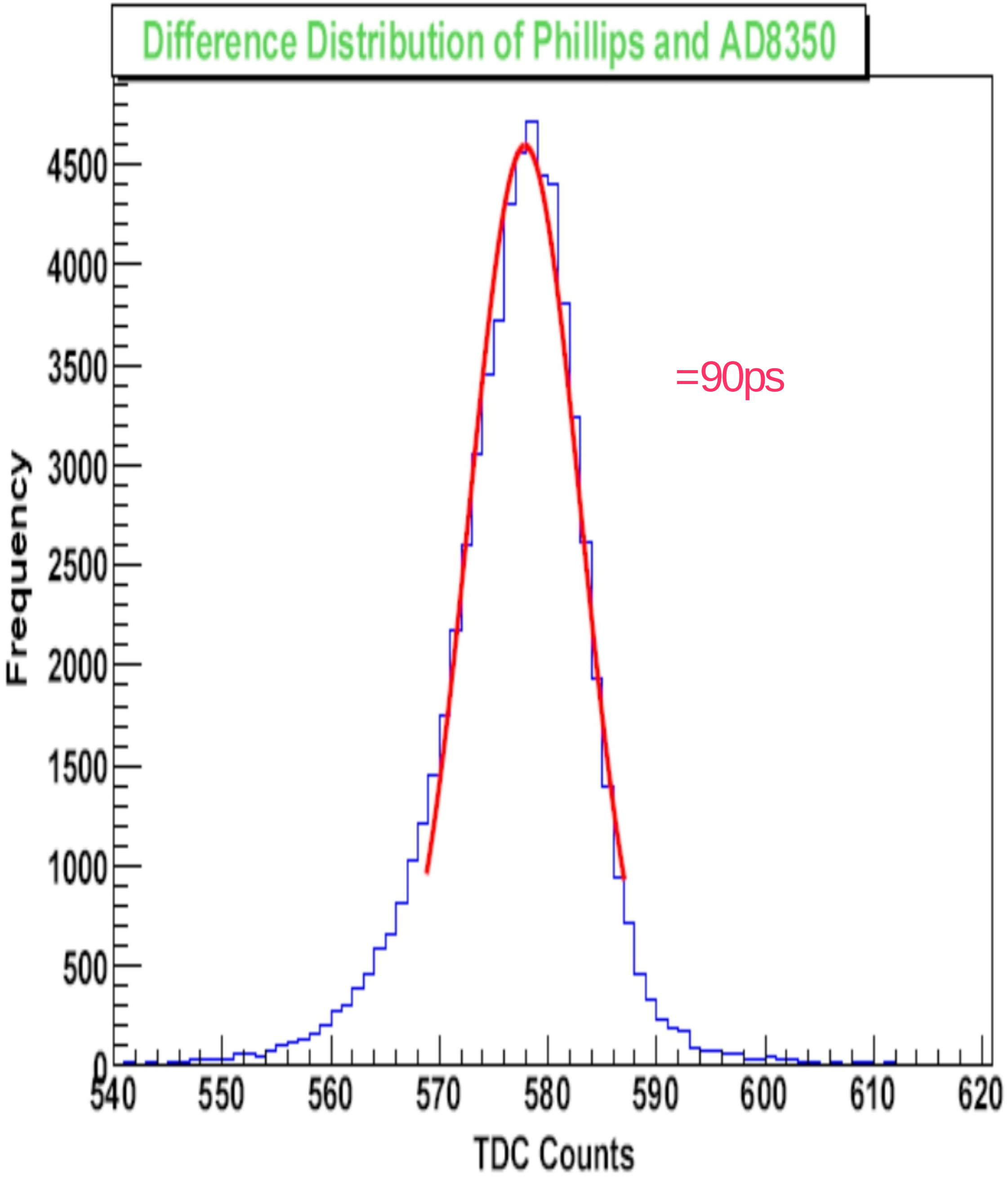



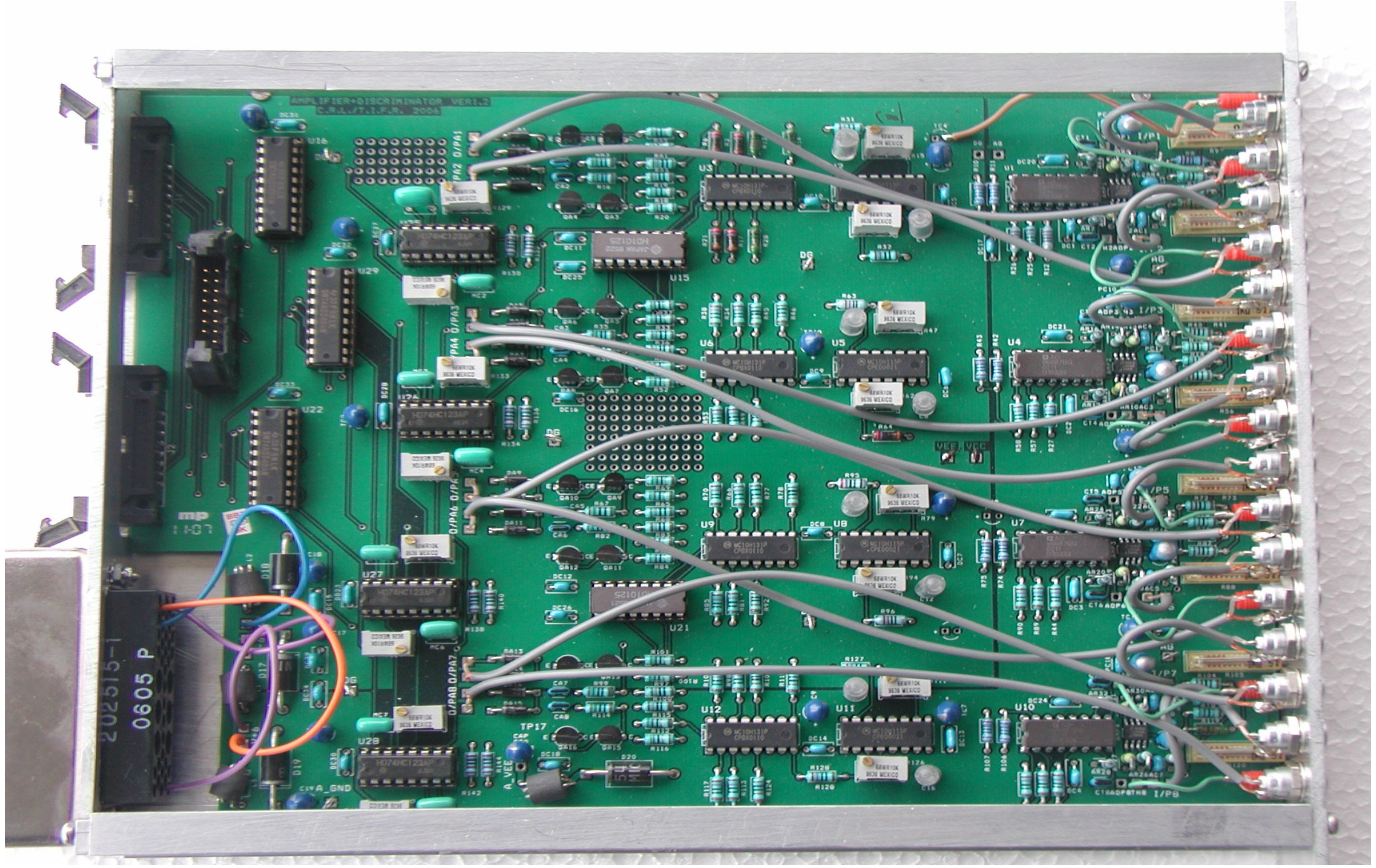
P.K. Mohanty et al. Rev. Sci. Instr. **83** 043301 (2012)





Amplifier-Discriminator response to muons





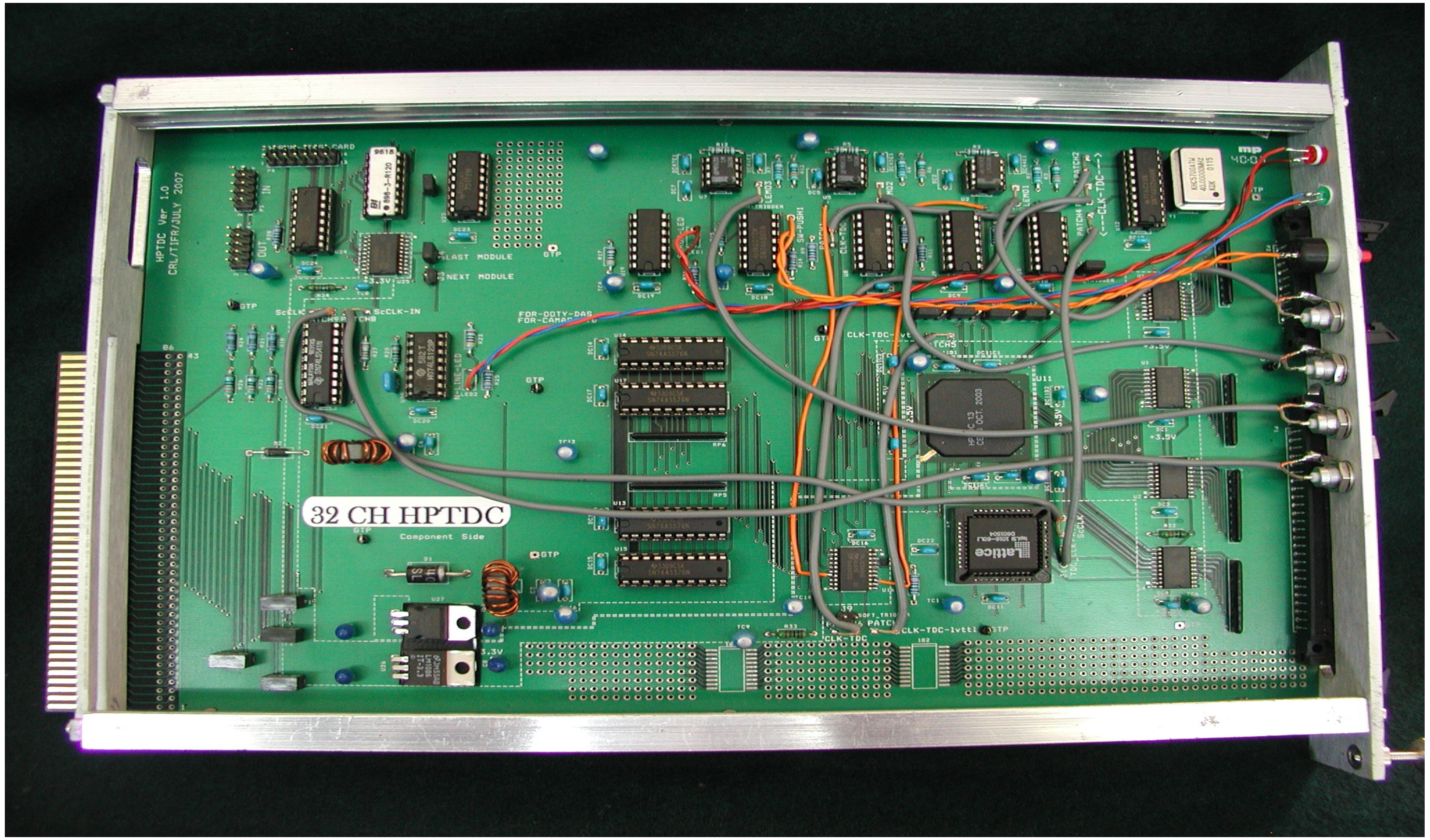
HPTDC (Stop Watch)

32-channels τ=100 ps Range: 50 μs

Multi-hit capability Trigger mode (no delay cables needed)

Novel method measuring TDC-Zero

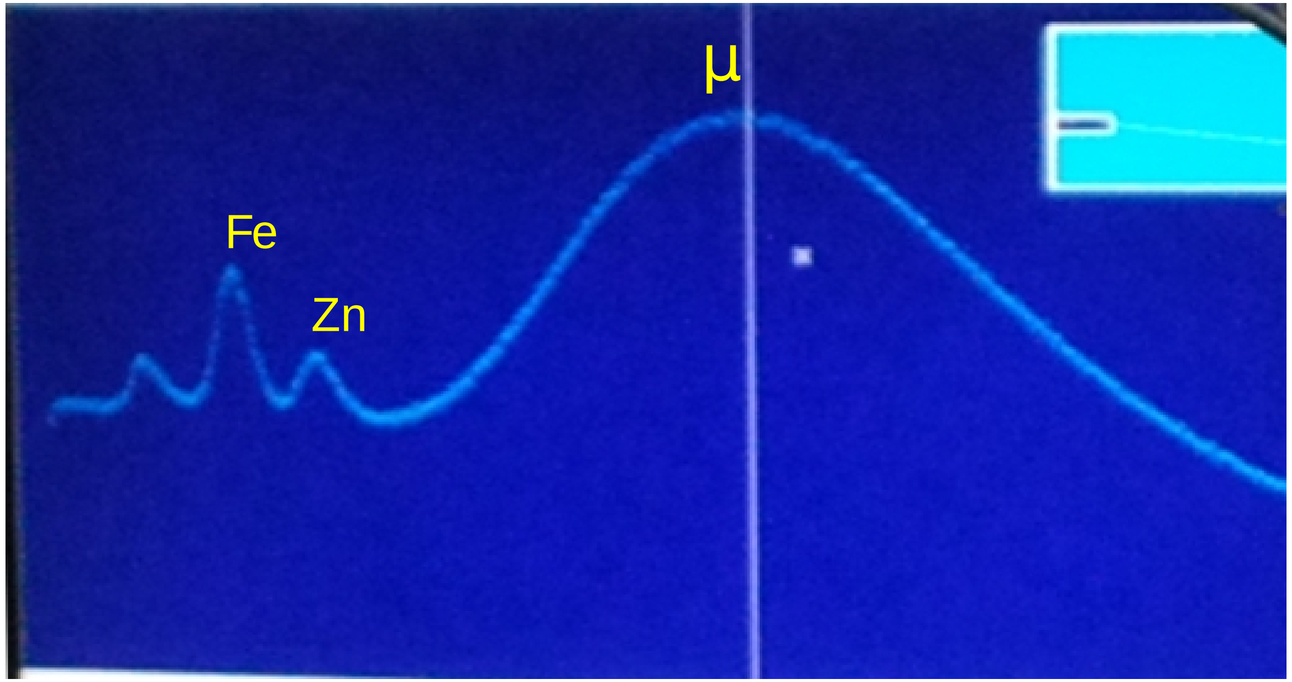
S.K. Gupta et al. Experimental Astronomy DOI: 10.1007/s10686-012-9320-3(2012)



World's most sensitive muon telescope

Large (600cmX10cmX10cm) Proportional Counter (PRC) Fabrication

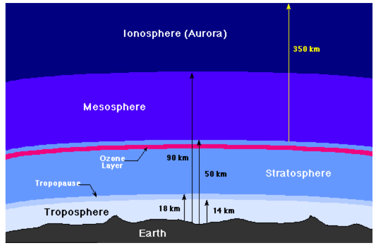
PRCs fabricated=3800 PRCs Required=3780




November 2018
80% completed

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 storms, Coronal Mass Ejections: Energy ~10 GeV Scale ~10^{11}-10^{13} cm

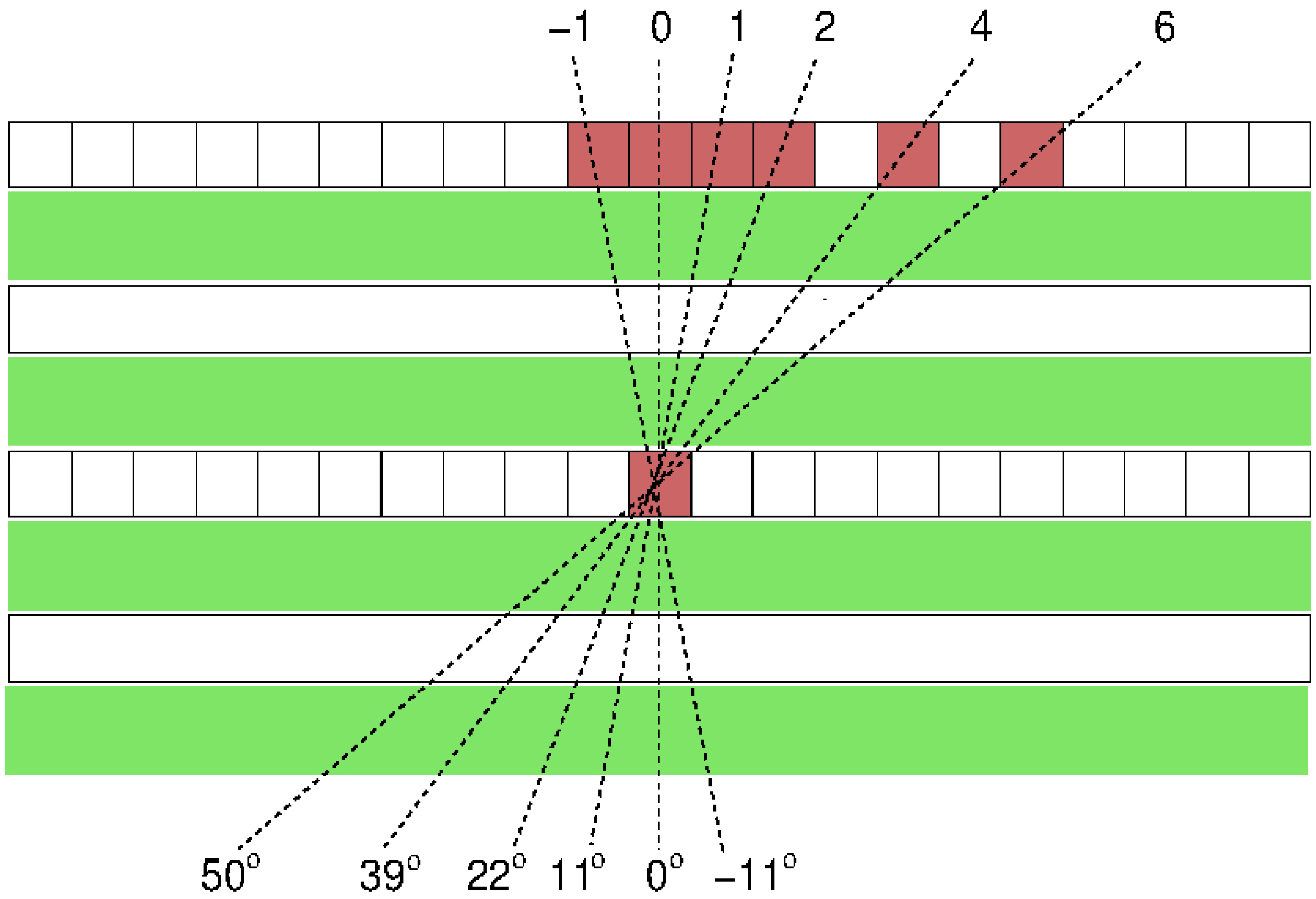
3. Galactic Cosmic Rays at “ knee ”: Energy ~10^{6} GeV Scale ~10^{21}-10^{23} cm

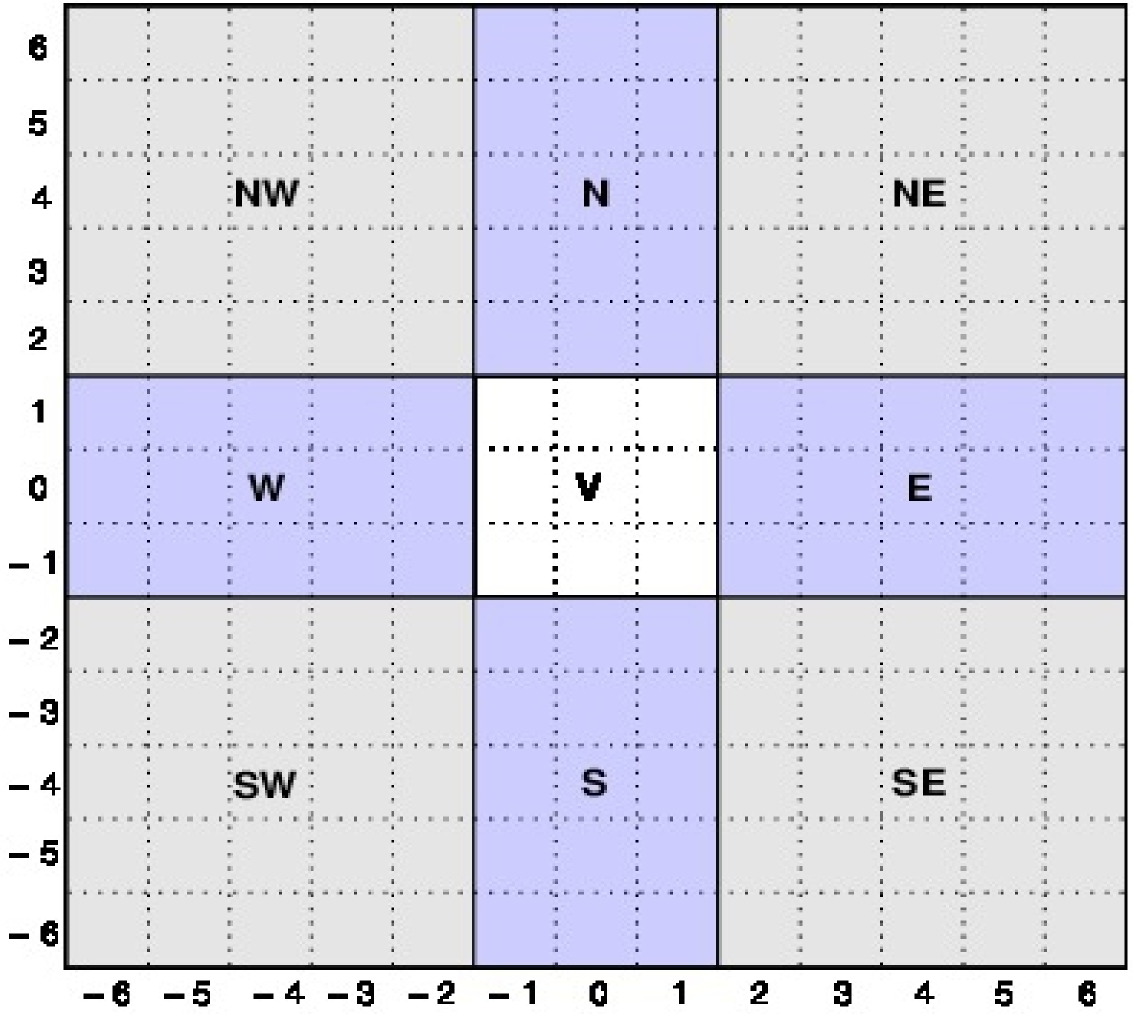
4. Diffuse multi-TeV gamma-rays: Energy ~10^{9} GeV Scale ~10^{24}-10^{26} cm


World's most sensitive muon telescope
Total area = 560 m²


Inside view of
muon telescope

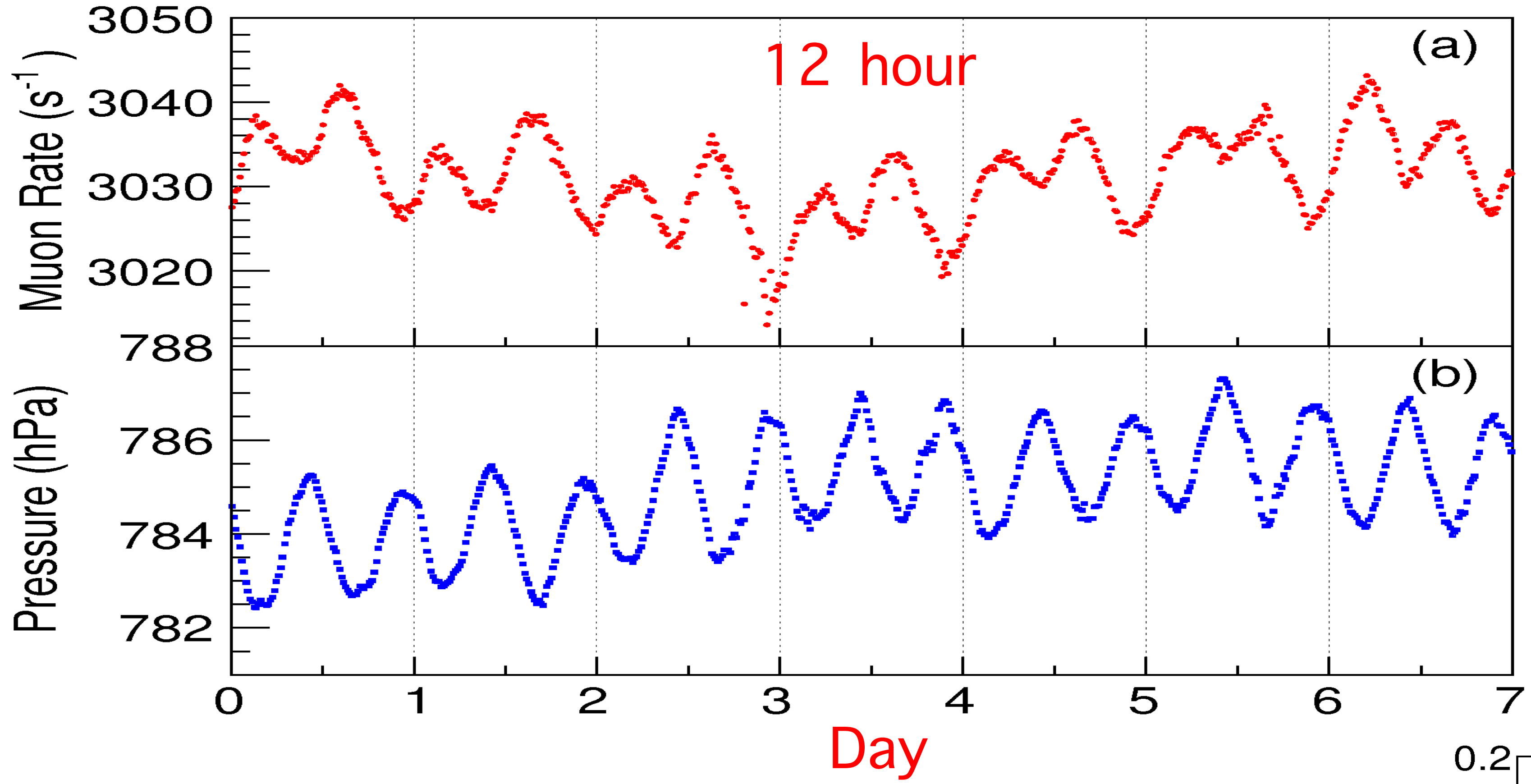
The muon telescope works by using the pattern of hits in PRCs



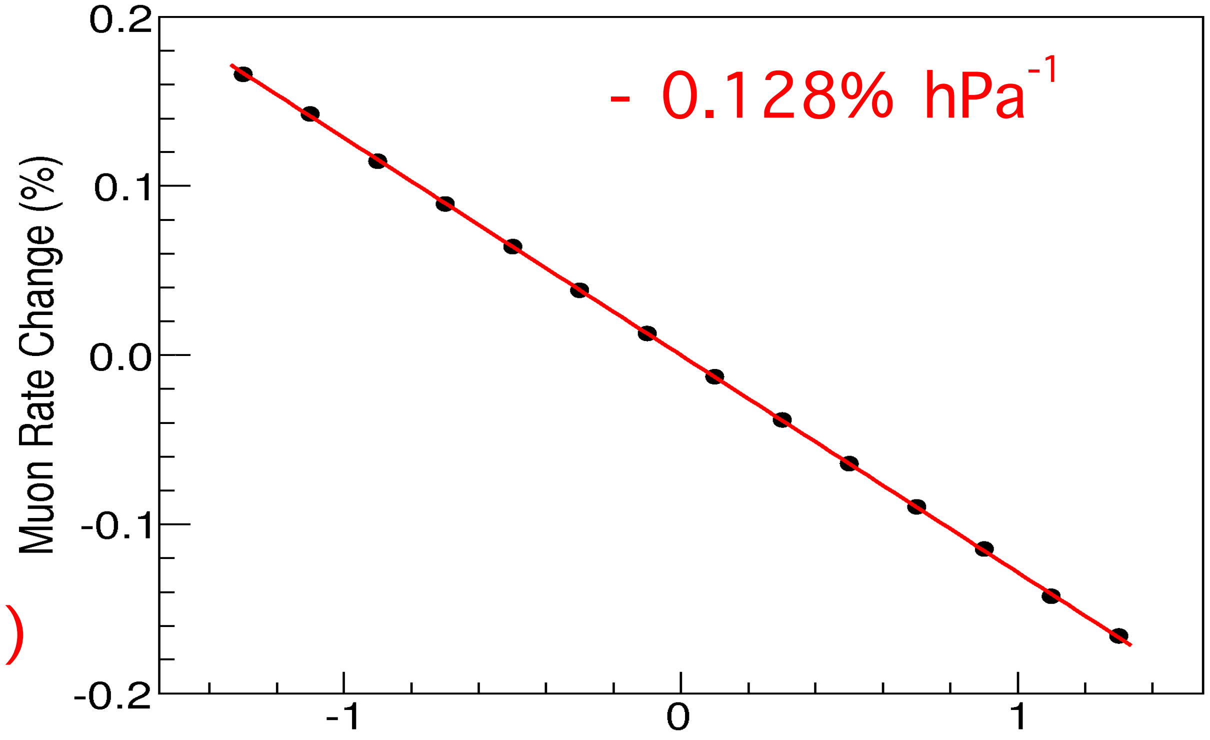


H. Kojima et al. Phys. Rev. D **98** 022004 (2018)

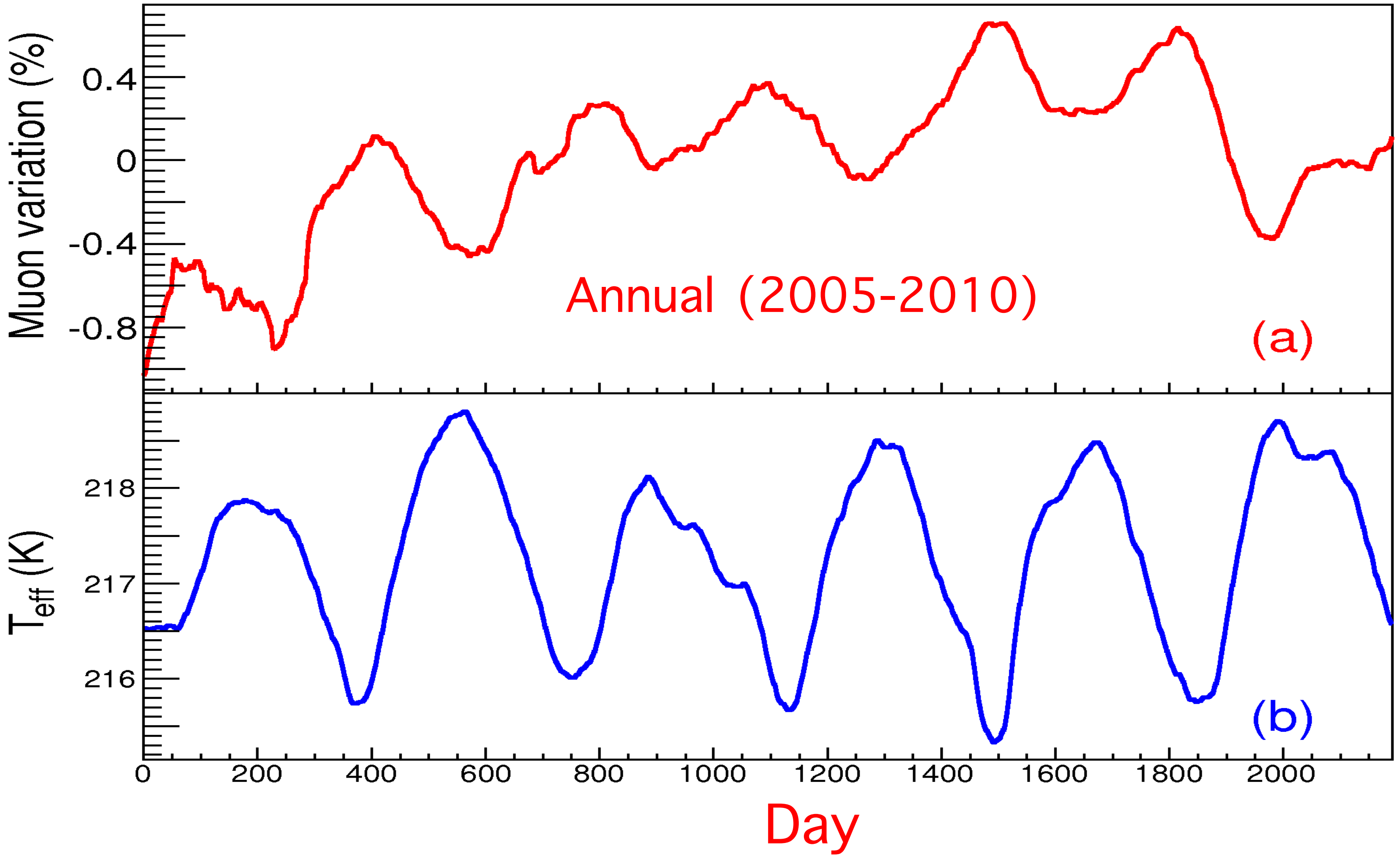
Performance



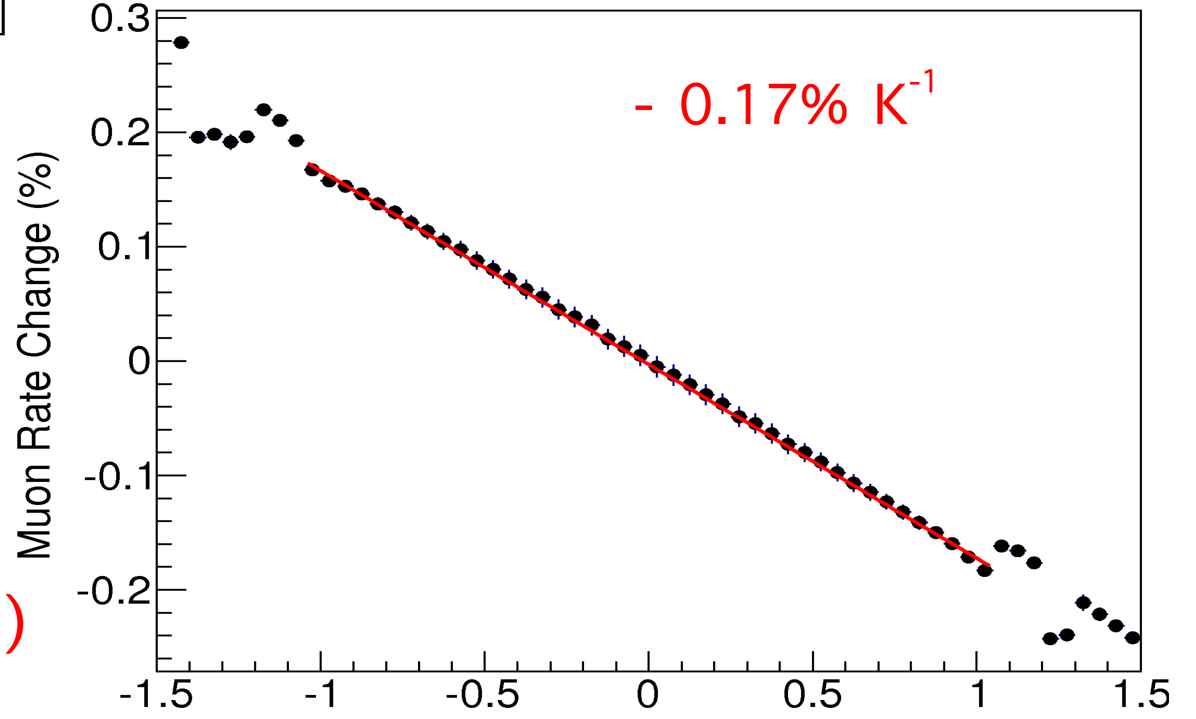
1 m air column = 5σ



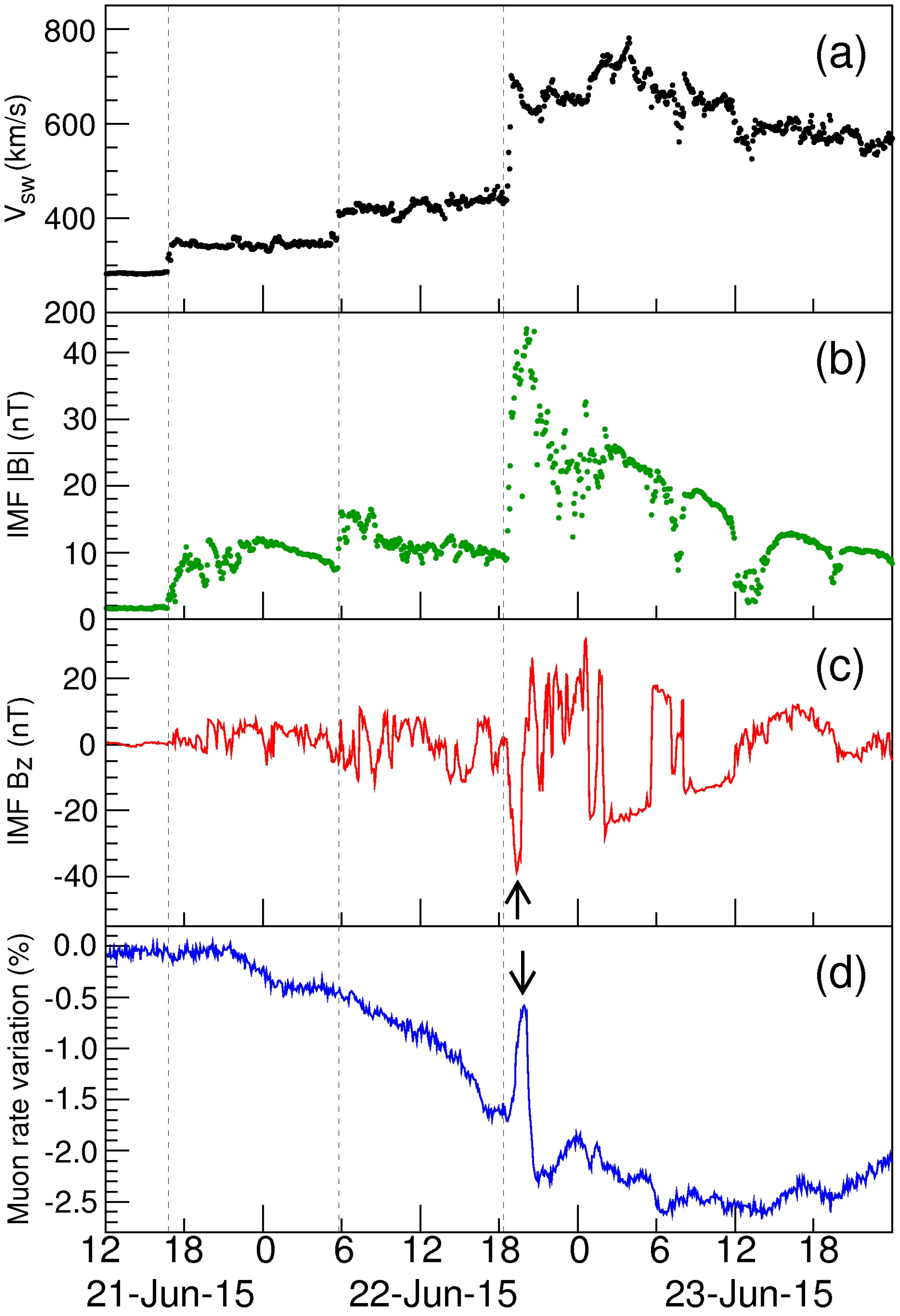
P.K. Mohanty et al. Astropart. Phys. **79** 23 (2016)



0.3 K = 5□



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



On 22 June 2015 a massive solar storm occurred (Coronal Mass Ejection)

Mass=10^{10} tonne

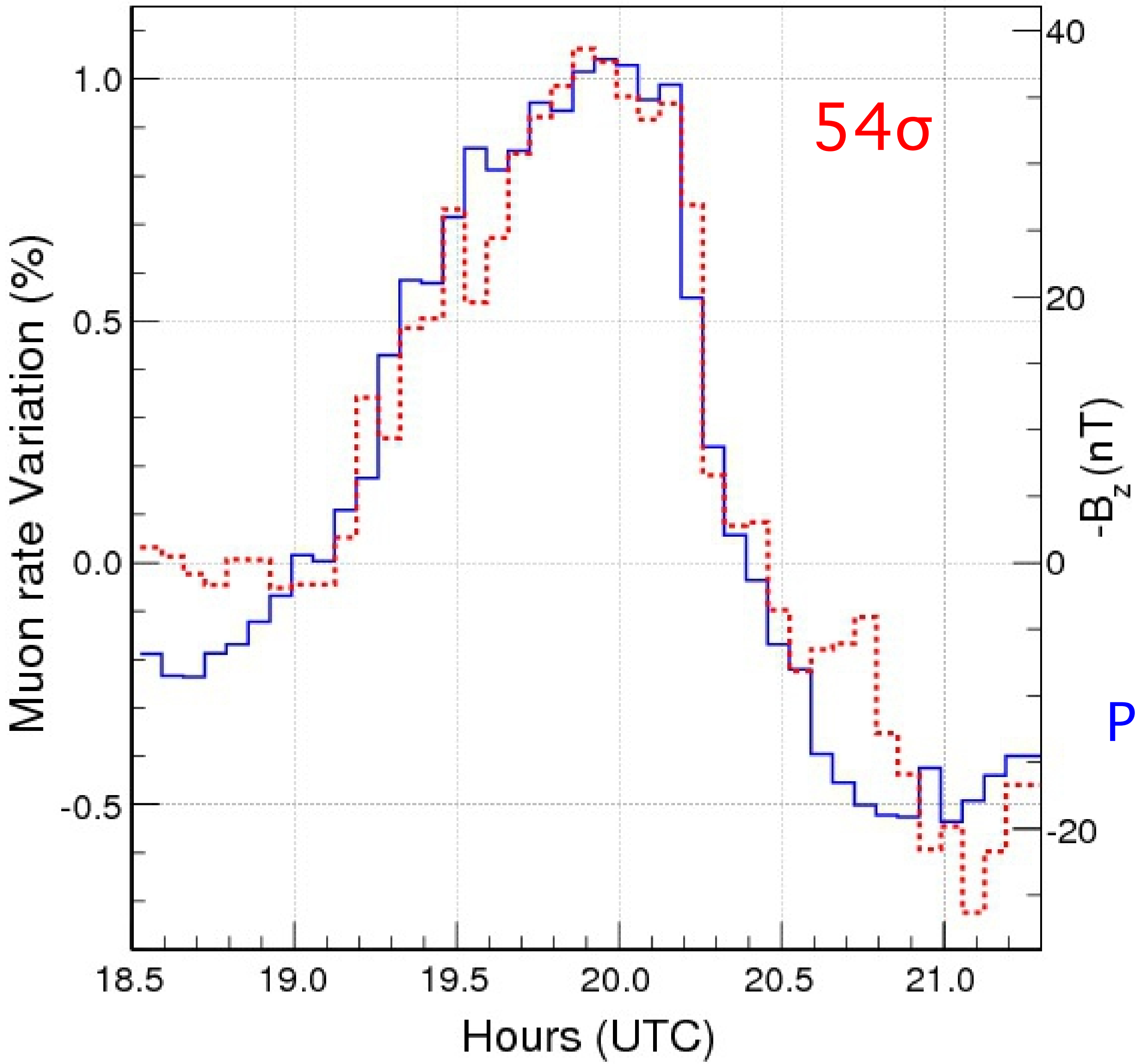
Energy=10^{33} erg (10^{5} Y)

Solar power= $4\text{x}10^{33}$ erg/s

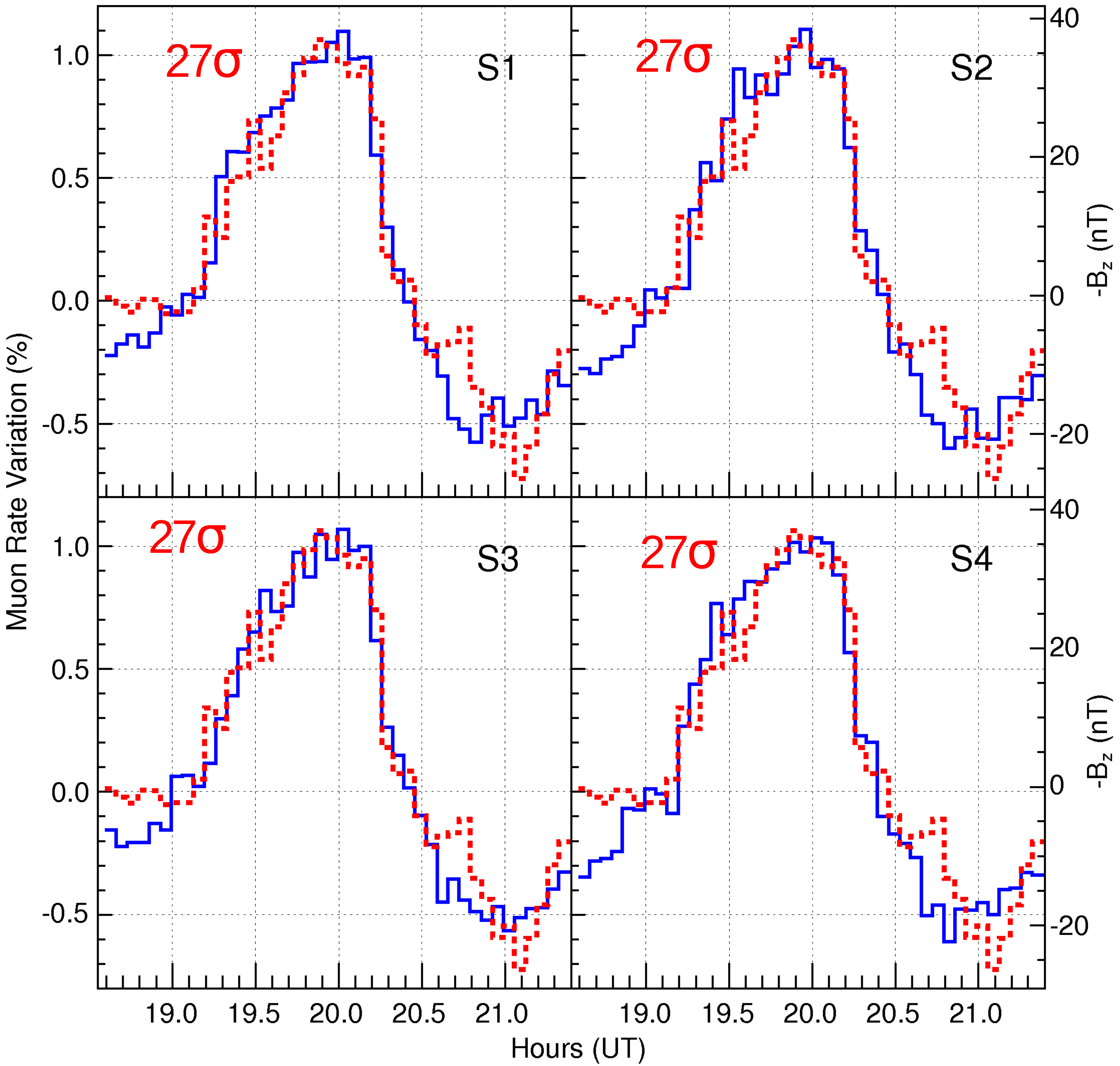
Initial Speed= 1400 km/s

Speed at L1=700 km/s

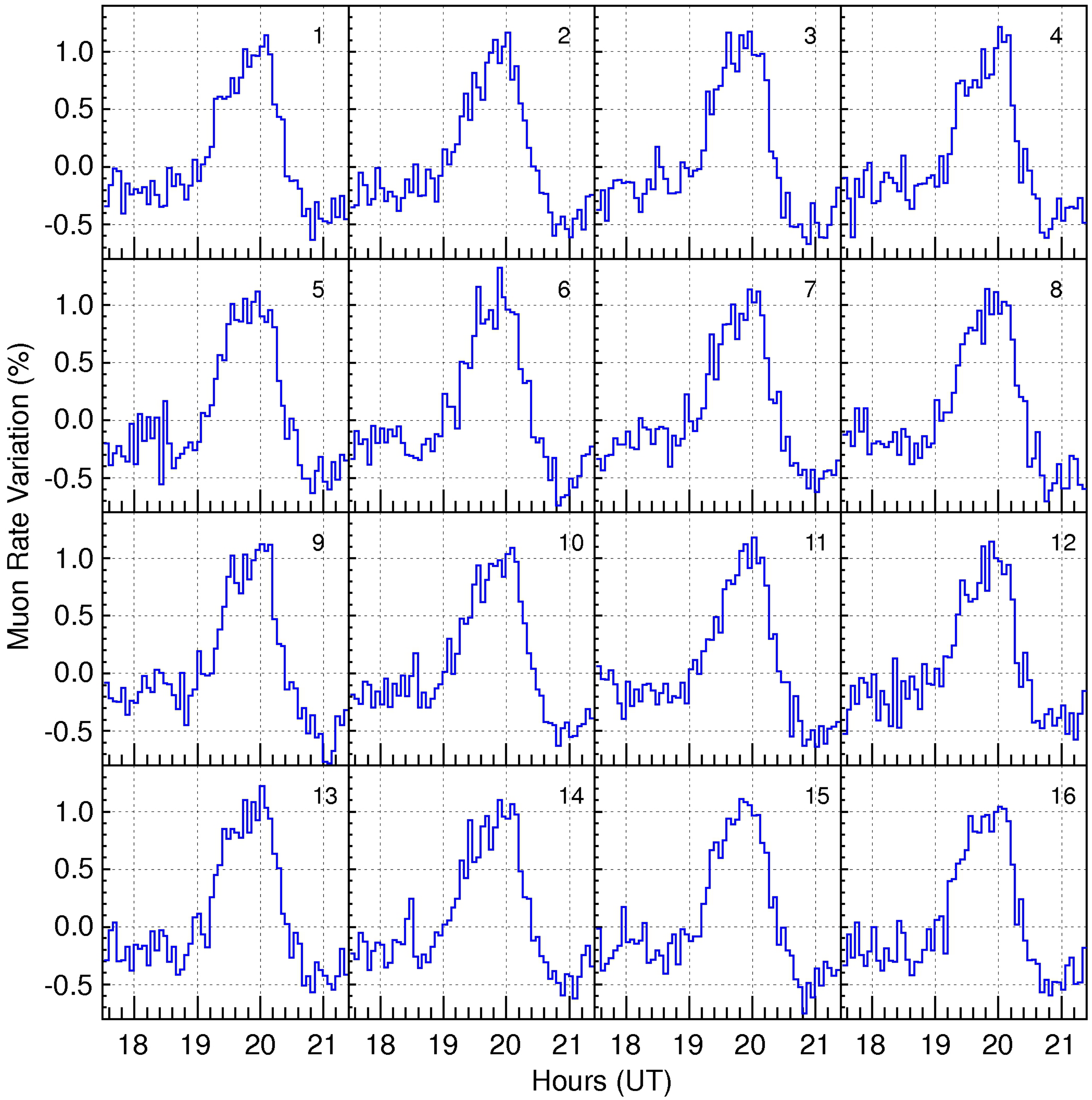
22 June 2015 Ooty, midnight



P.K. Mohanty et al.
Phys. Rev. Lett. **117** 171101 (2016)

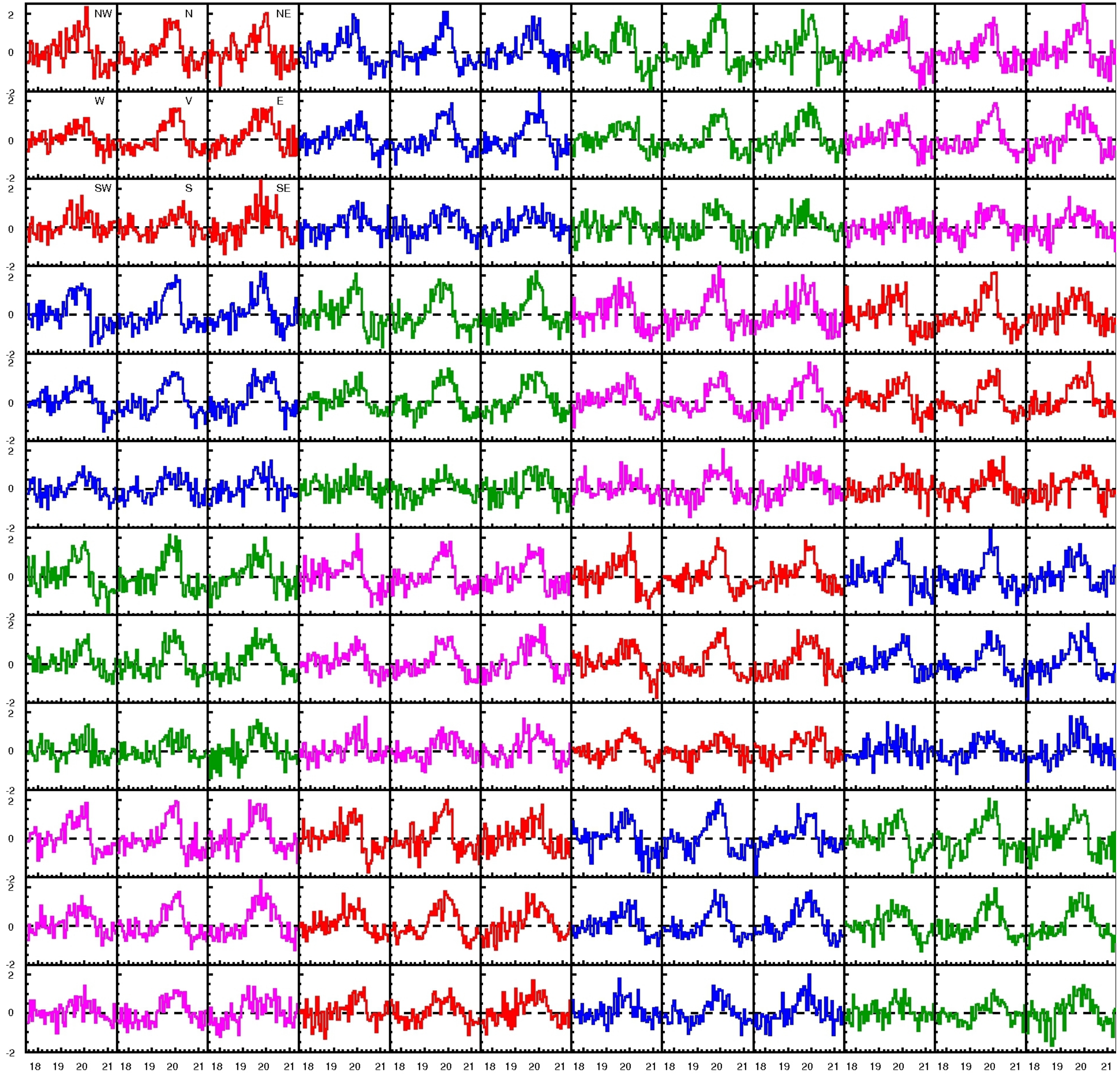


27σ
S1
27σ
S2
27σ
S3
27σ
S4
Muon Rate Variation (%)
-B_z (nT)
-B_z (nT)
1.0
0.5
0.0
-0.5
40
20
0
-20
19.0
19.5
20.0
20.5
21.0
Hours (UT)



Muon Rate Variation (%)
Hours (UT)
1.0
0.5
0.0
-0.5
18
19
20
21
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16

13σ



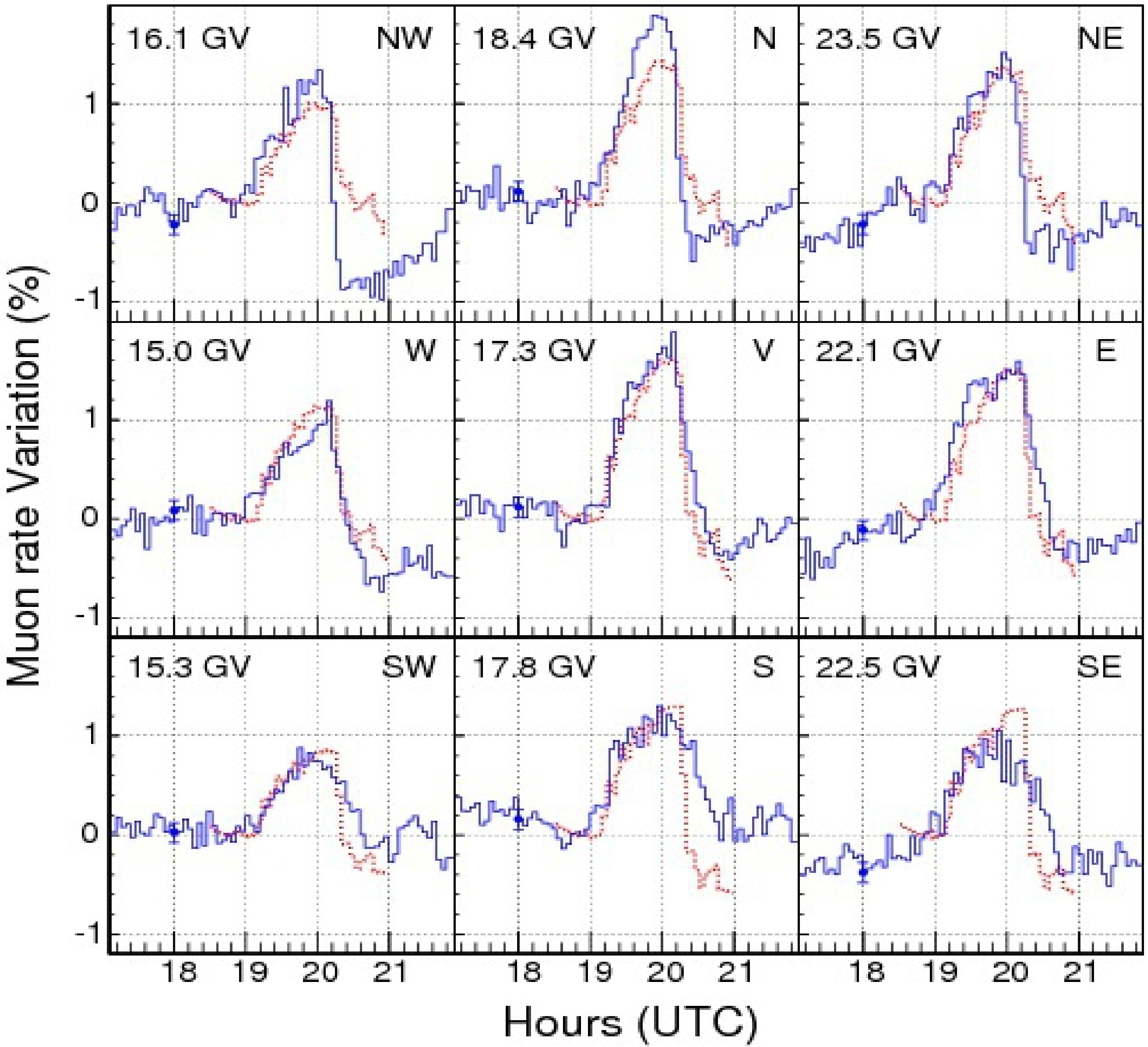
>5σ 42

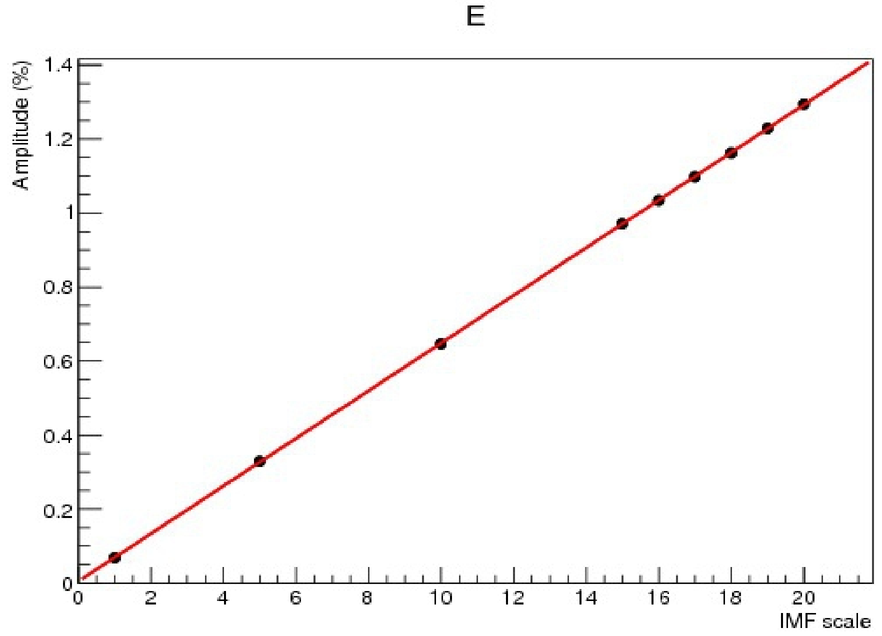
4-5σ 37

3-4σ 40

<3σ 25

-Bz=680 nT

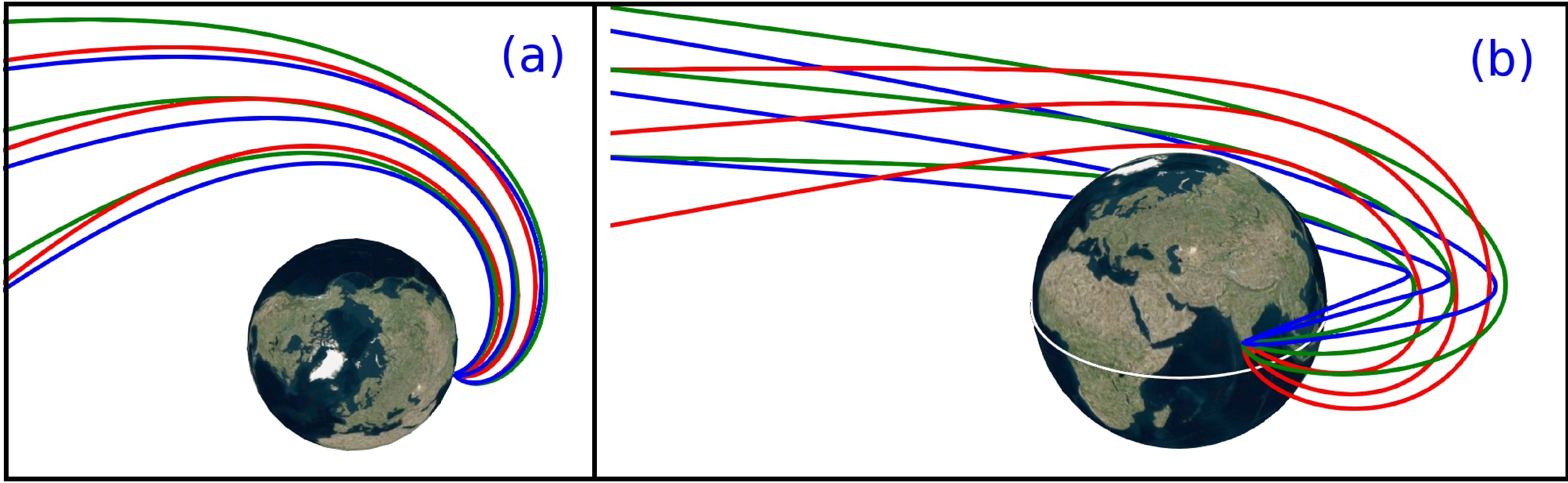




0.7 GV

0.6 GV

0.5 GV



NW N NE W V E SW S SE

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

08/07/2016

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

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.

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,*
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(Received 16 June 2016; published 20 October 2016)

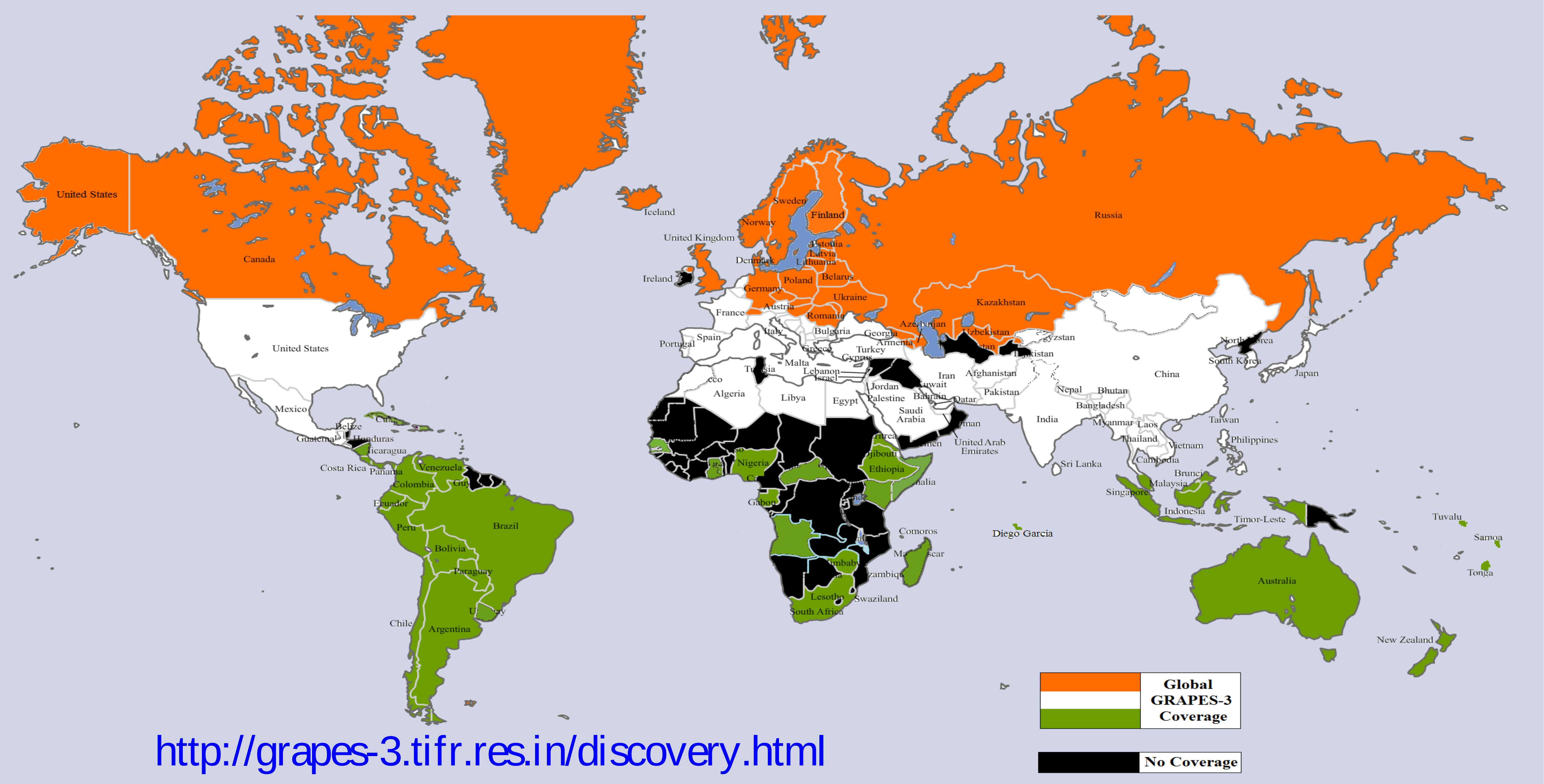
The GRAPES-3 tracking muon telescope in Ooty, India measures muon intensity at high cutoff rigidities (15–24 GV) along nine independent directions covering 2.3 sr. The arrival of a coronal mass ejection on 22 June 2015 18:40 UT had triggered a severe G4-class geomagnetic storm (storm). Starting 19:00 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

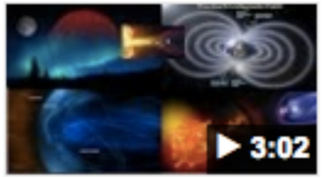


24 YouTube Videos

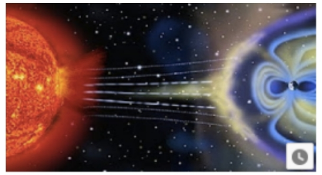
http://grapes-3.tifr.res.in/discovery.html

1. The Earth's Magnetic Shield Cracked, Are We Doomed?
   https://www.youtube.com/watch?v=lYFt40J12go
   500K

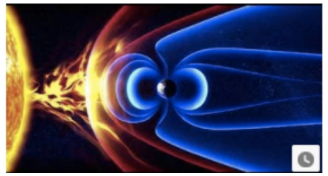
2. ALERT: Crack in Earth's Magnetic Shield Just Detected, 'A Flip is Overdue' Experts say
   https://www.youtube.com/watch?v=kFdxA8MRNmo
   8K



3. Powerful geomagnetic storm cracks Earth's magnetosphere
   https://www.youtube.com/watch?v=82X0V7yQmoE
   7K

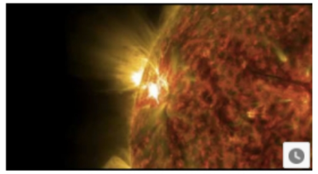


4. TERRIFYING! Earth's Magnetic Shield Has CRACKED And We Could FRY At Any Moment!
   https://www.youtube.com/watch?v=hVERCMe9k0o
   5K



5. Earth's Magnetosphere Has Cracked ★★★
   https://www.youtube.com/watch?v=WWQnyQhQ7Xc
   5K

6. Solar flare radiation burst cracked Earth's magnetic field caused radio blackouts
   https://www.youtube.com/watch?v=2F8Ud-gDDnU
   1.5K



7. The crack indicates that Earth's magnetic shield is weakening
   https://www.youtube.com/watch?v=XAjk_pI88yY
   1K

8. Study: Solar Flare Caused A 'Crack' In Protective Field Around Earth
   https://www.youtube.com/watch?v=SDoi5HTyv8I
   1K

Present Status

GRAPES-3 studies solar storms with highest sensitivity at present. But data is analyzed post-facto after the event.

(1) Analysis of existing 19 years of data indicates about 40 solar storms, 10 of which are fairly prominent events.

(2) 22 June 2015 showed a delay of 28 minutes relative to satellite prediction. All 10 events also show delays ranging from 16 to 64 minutes. The GRAPES-3 data indicates that Earth's magnetic field acts as a brake and slows down the solar storm after reaching the magnetosphere. It thus provides a more accurate estimate of the onset of a solar storm (1 minute = 1000 Crores).

(3) Suitable software tools are being developed to estimate delay based on storm parameters such as IMF, shock speed, compression of magnetosphere from a subset of data with the aim to improve the precision of storm onset time by cross checking with remaining events.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