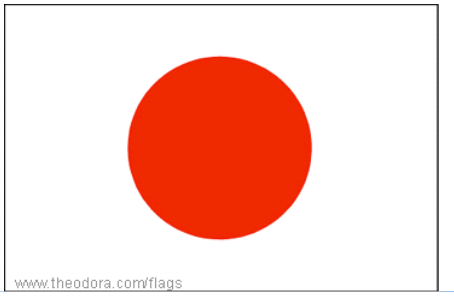
Probing the properties of thunderstorms by the GRAPES-3 muon telescope

Sunil K. Gupta

6 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

560 m^2 Muon telescope

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)

GRAPES-3 Experiment on Google Map

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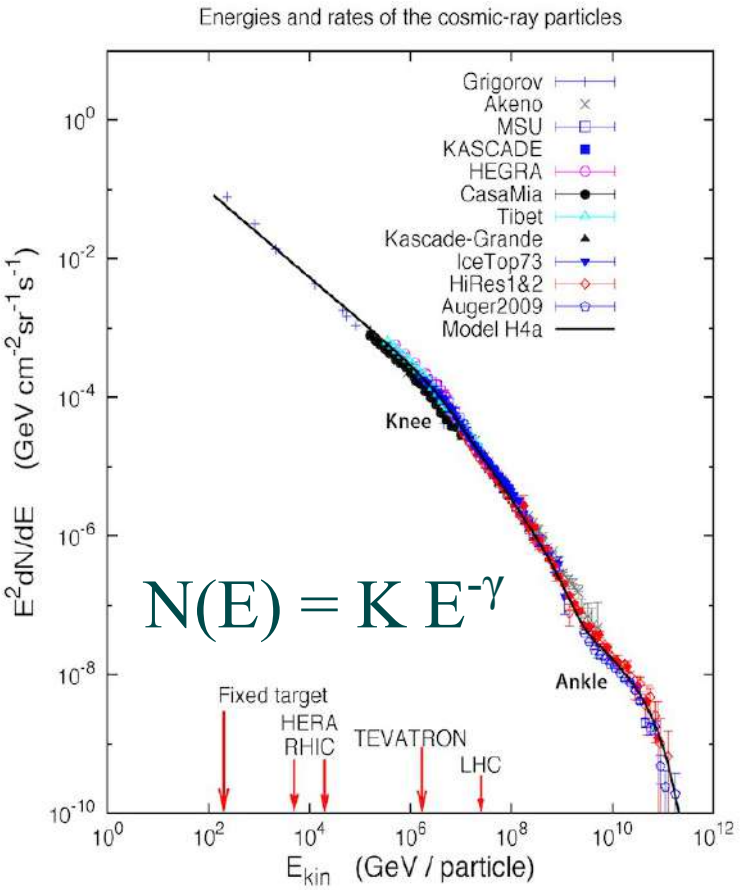
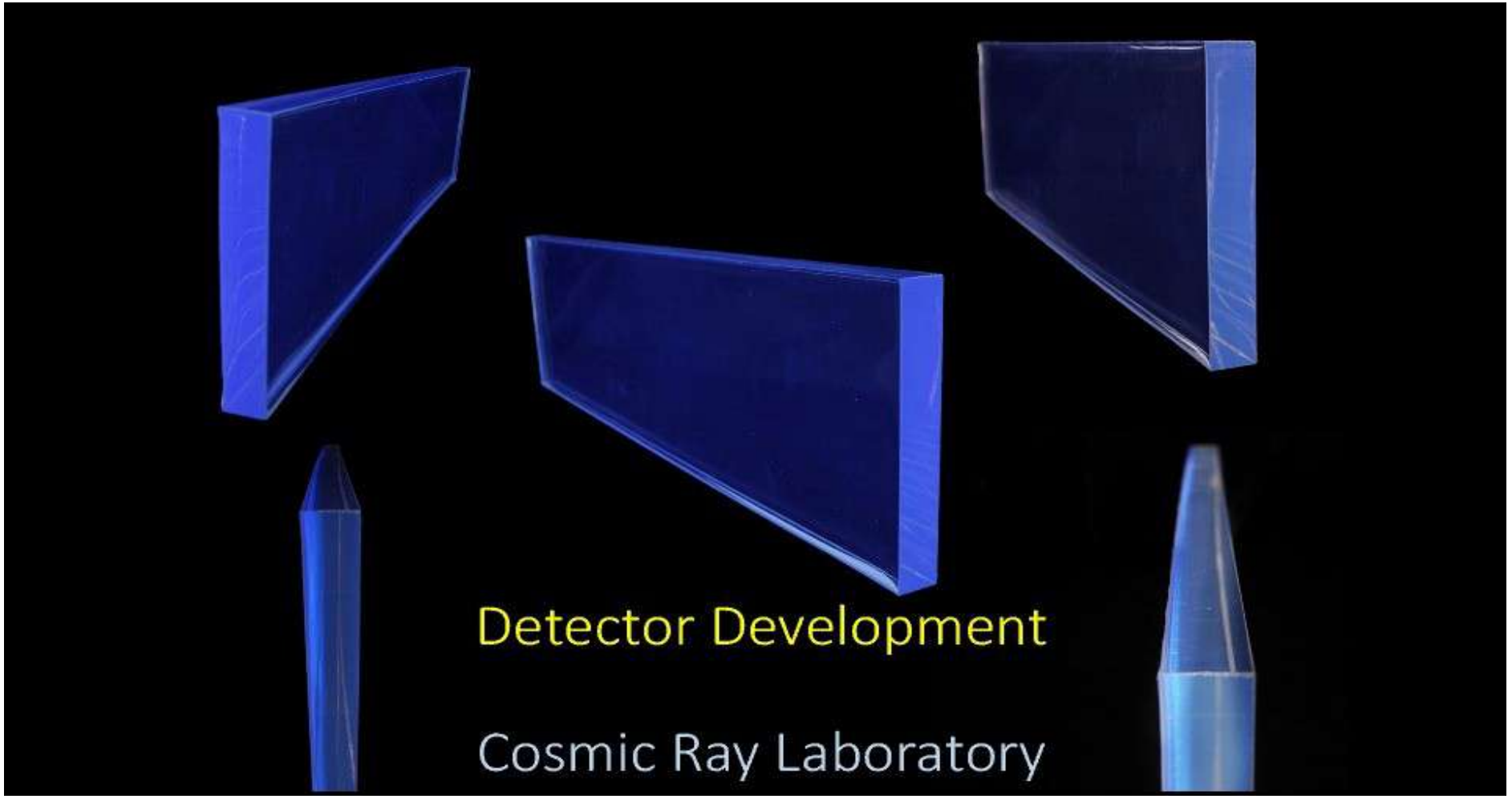
1. Cosmic Ray Composition
2. Thunderstorms



Fabrication of plastic scintillator detectors at Cosmic Ray Laboratory, Ooty



Plastic Scintillator development:

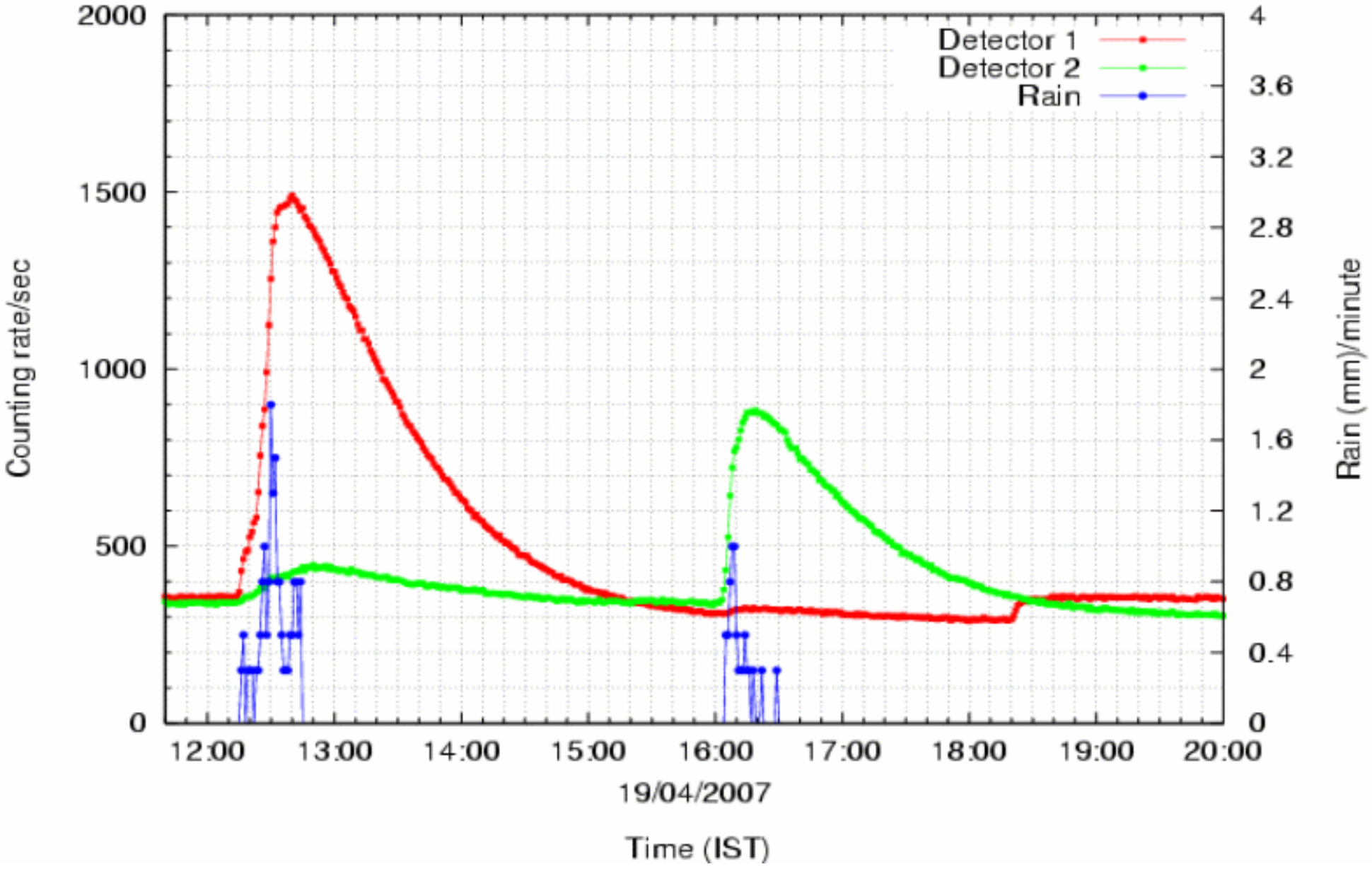
Decay Time= 1.6 ns Light Output = 85% Bicron (54% anthracene)

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, ...

Radioactivity in rain water, using scintillators.



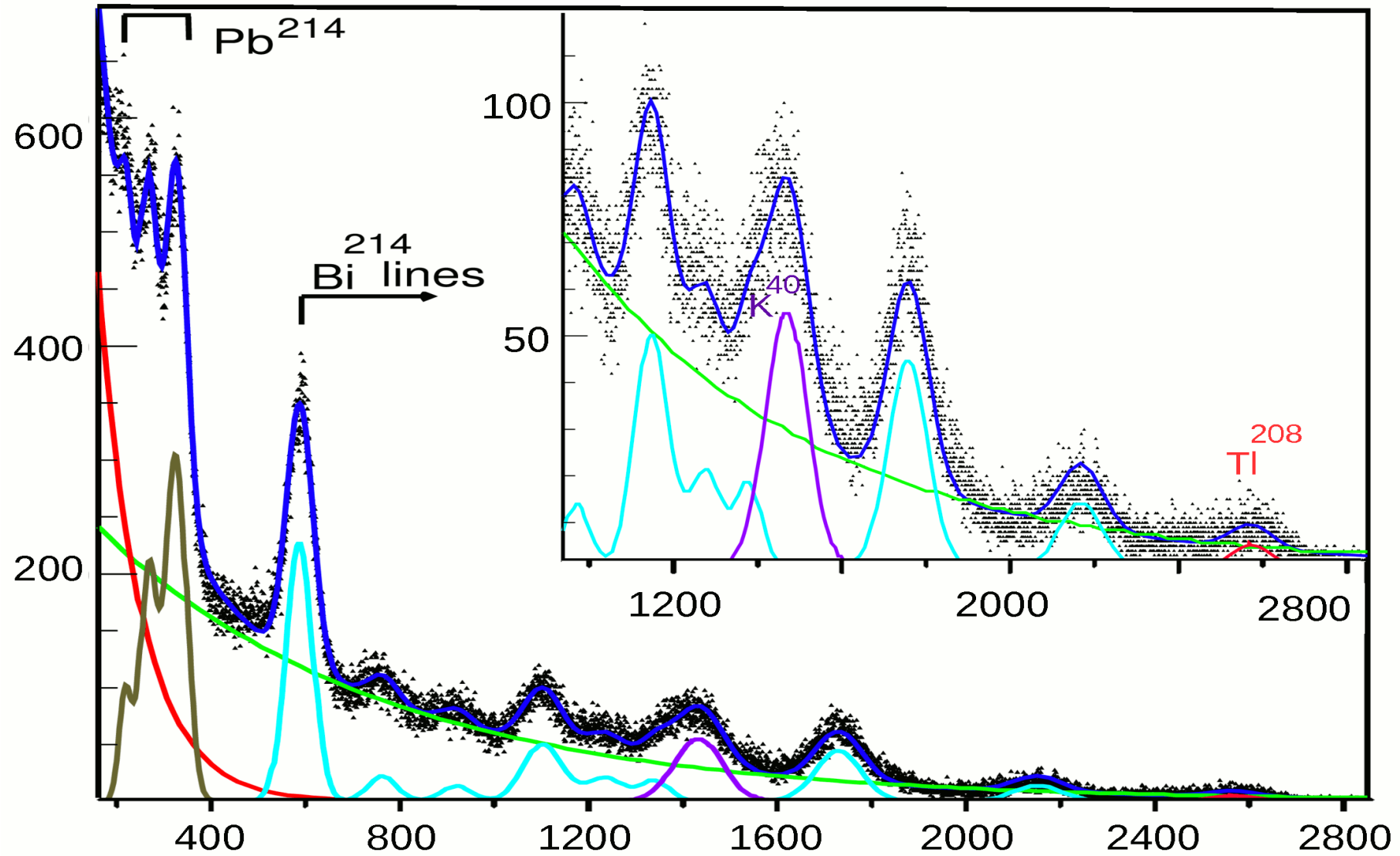
$_{92}U^{238}$ —α, 4.5x10⁹ Y→ $_{90}Th^{234}$ —β, 24.1 d→ $_{91}Pa^{234}$ —β, 70.2 s→ $_{92}U^{234}$ —α, 2.5x10⁵ Y→ $_{90}Th^{230}$ —α, 7.5x10⁴ Y→ $_{88}Ra^{226}$ —α, 1600 Y→ $_{86}Rn^{222}$

$T_{1/2}$

$_{86}Rn^{222}$ —α, 3.82 d→ $_{84}Po^{218}$ —α, 3.1 d→ $_{82}Pb^{214}$ —β,γ, 26.8 min→ $_{83}Bi^{214}$ —β,γ, 19.9 min→ $_{84}Po^{214}$

1 in 100,000,000,000,000,000,000

STORY OF THE EARTH



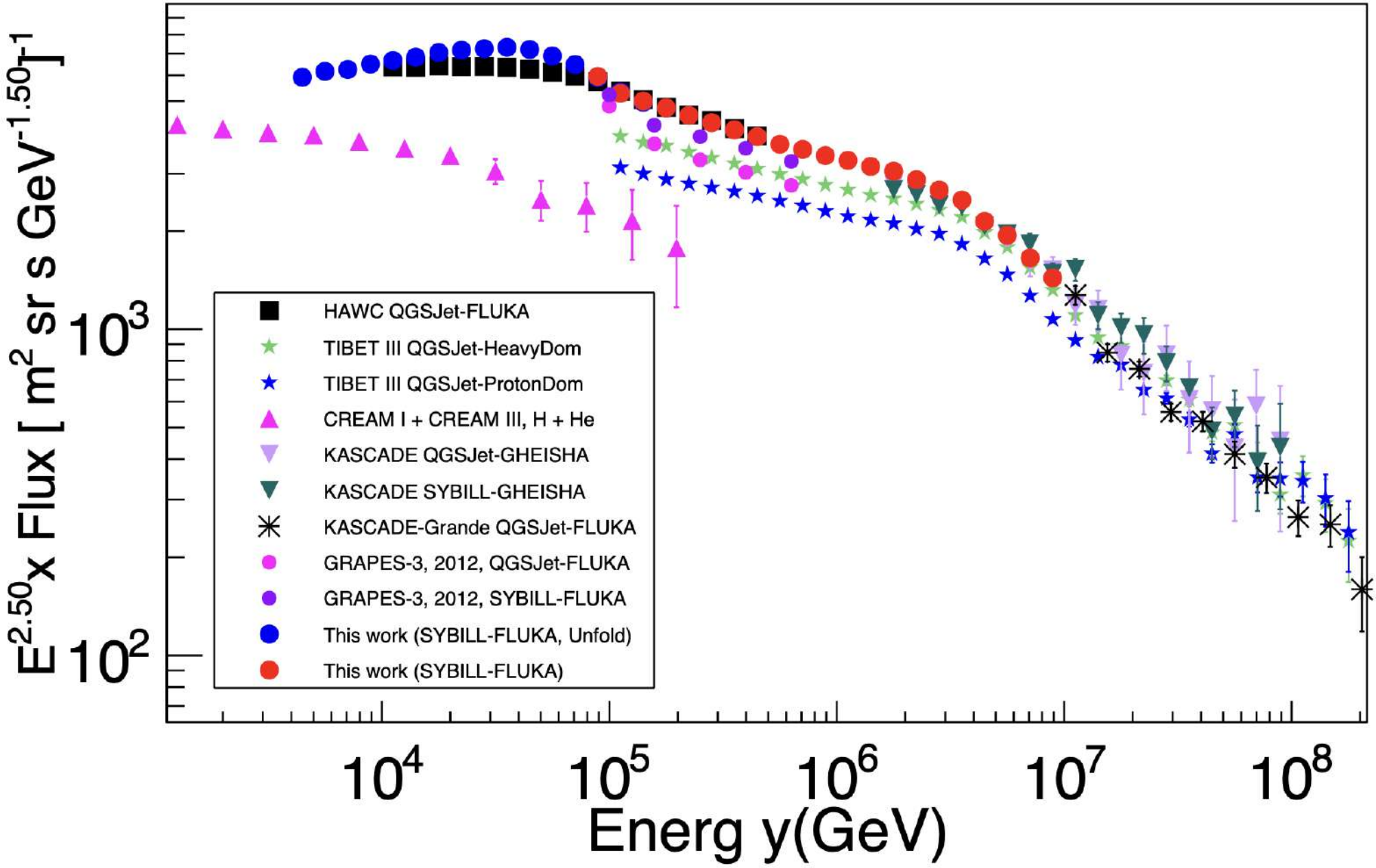
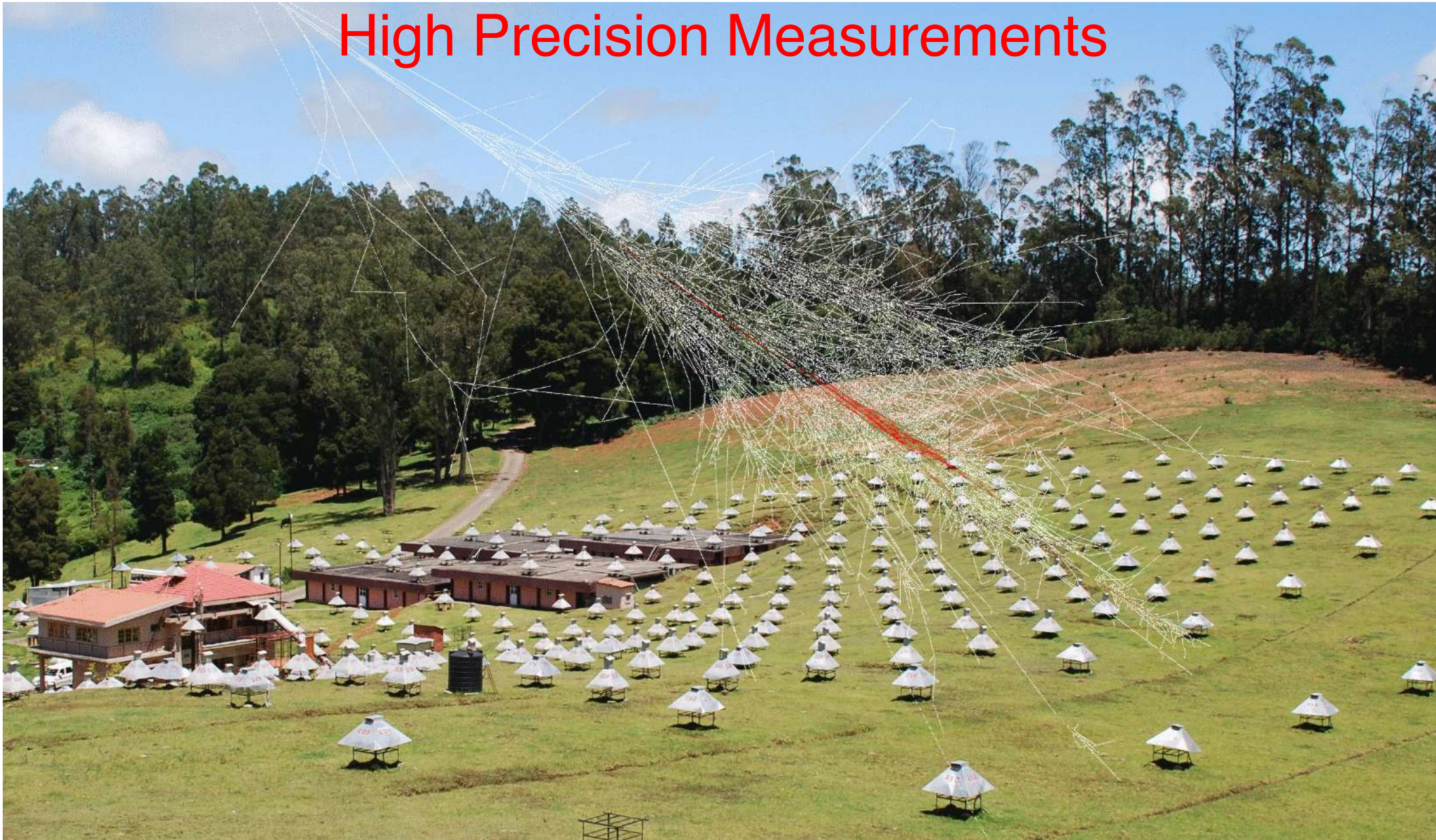


Figure 6: All particle energy spectrum scaled by $E^{2.5}$

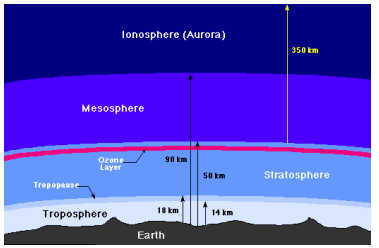
400 Plastic Scintillator detectors (1 m^2 area)
560 m^2 muon telescope (E_μ=1 GeV) (11.4N, 76.7E)
3712 Proportional Counters (6m x 0.1m x 0.1m)
E = 10^{14} eV ~20000 particles over ~1000 m^2



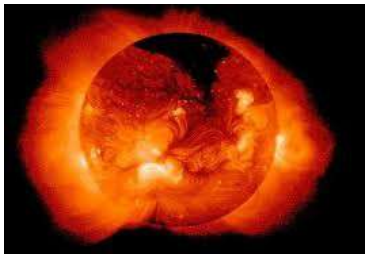
Objective: Universe at high energies

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

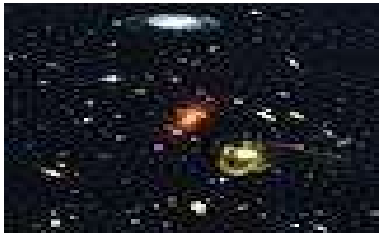


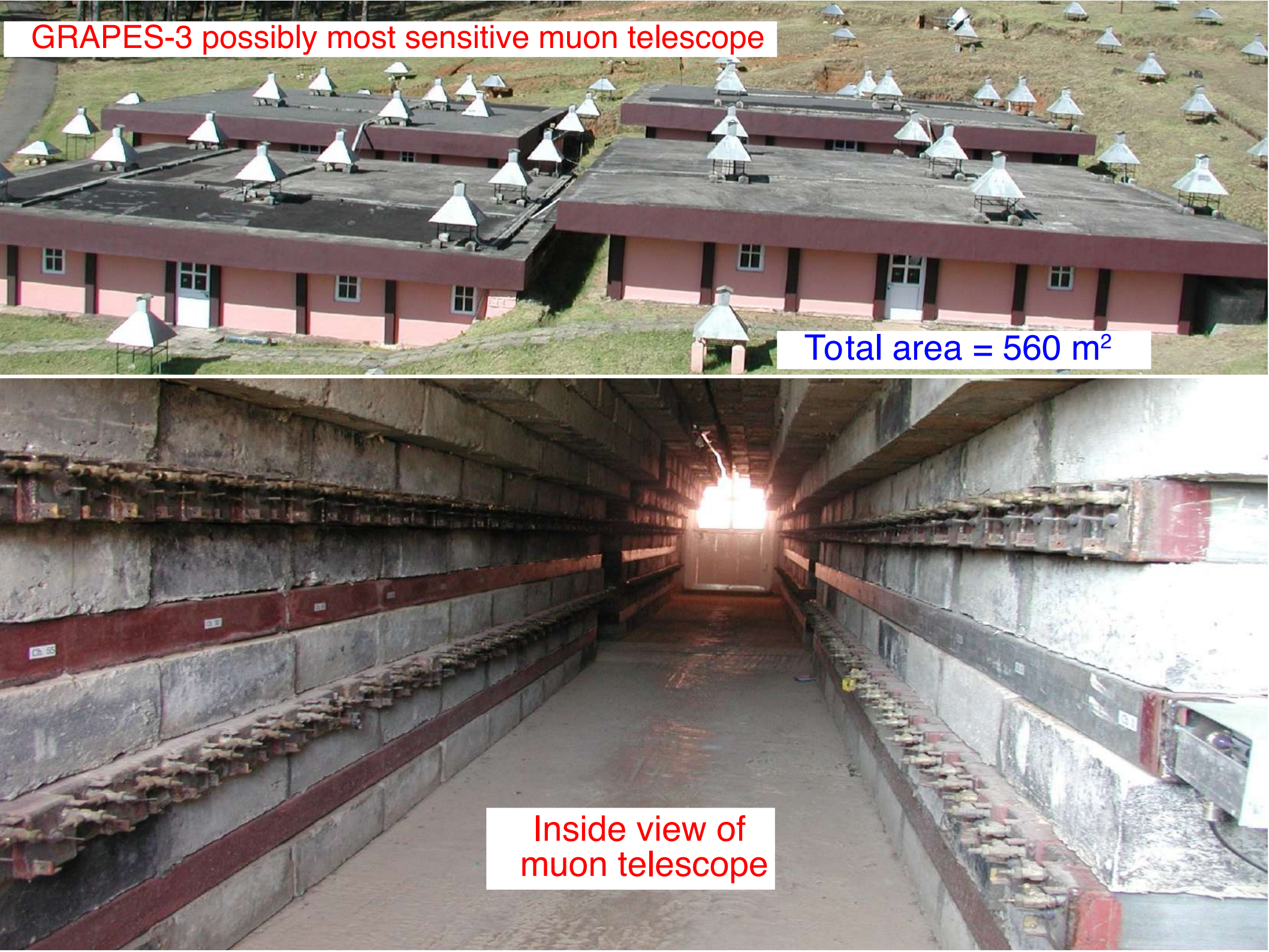
2. Solar flares, Coronal Mass Ejections
   Energy ~10 GeV Scale ~10^{11}-10^{13} cm

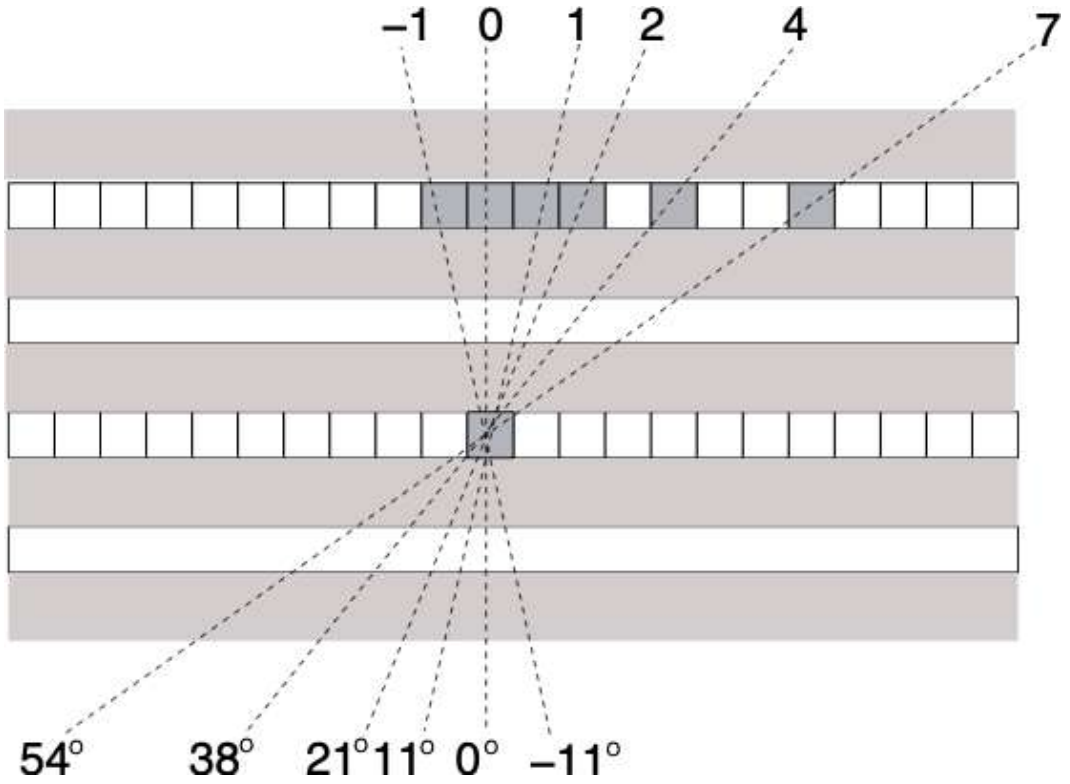


3. Galactic Cosmic Rays at "Knee"
   Energy ~1 PeV Scale ~10^{21}-10^{23} cm

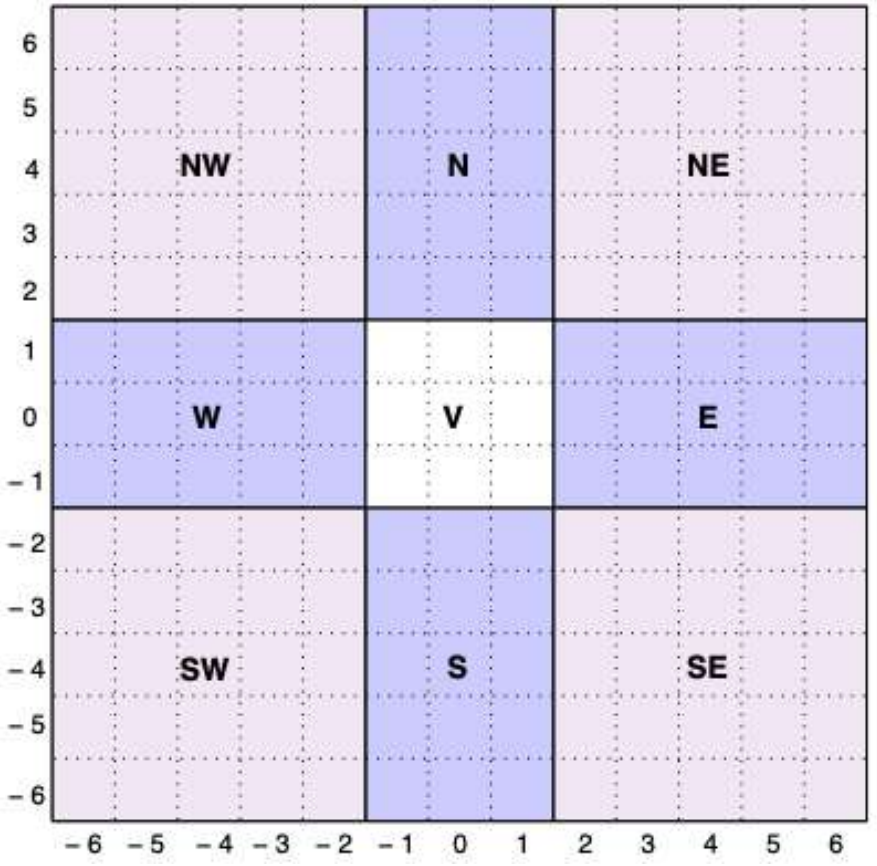
4. Diffuse multi-TeV **γ**-rays
   Energy ~100 EeV Scale ~10^{24}-10^{26} cm

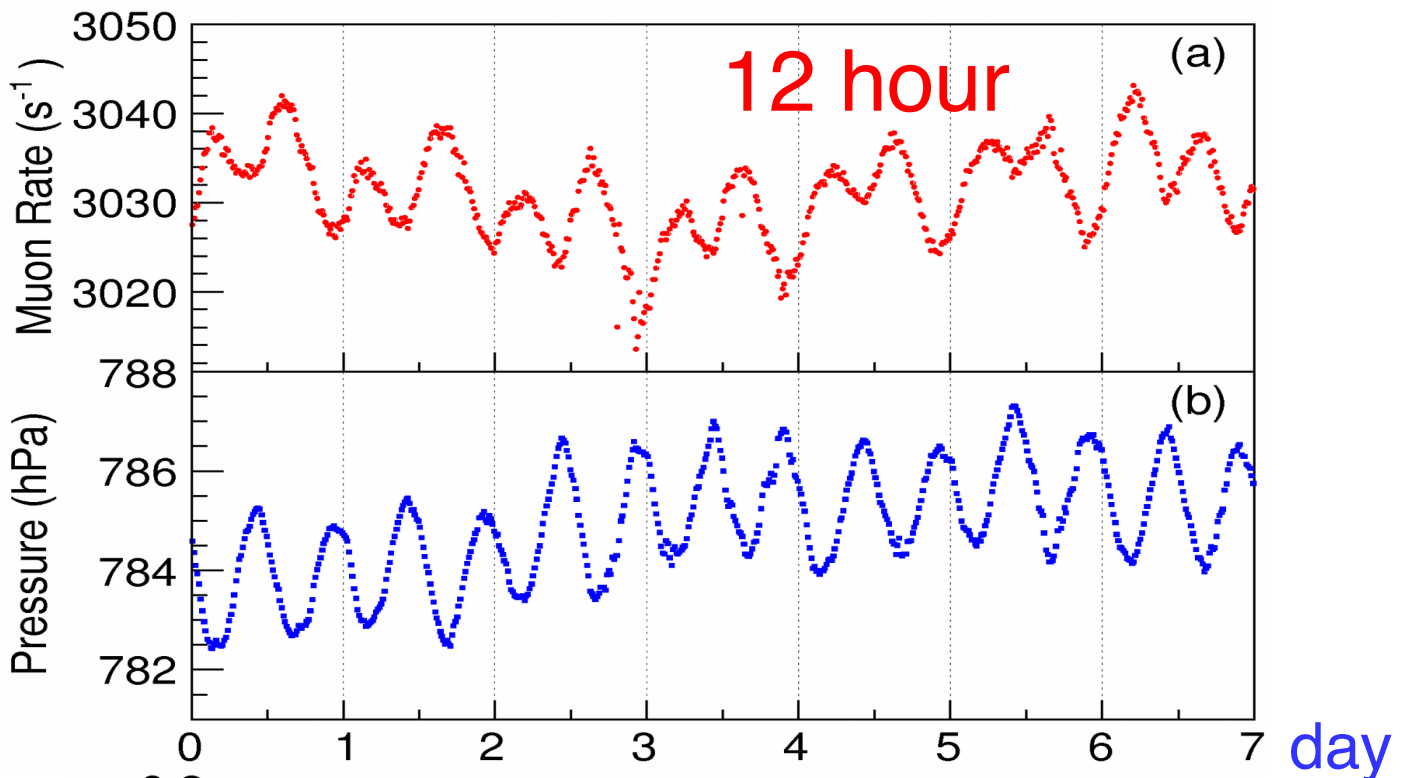


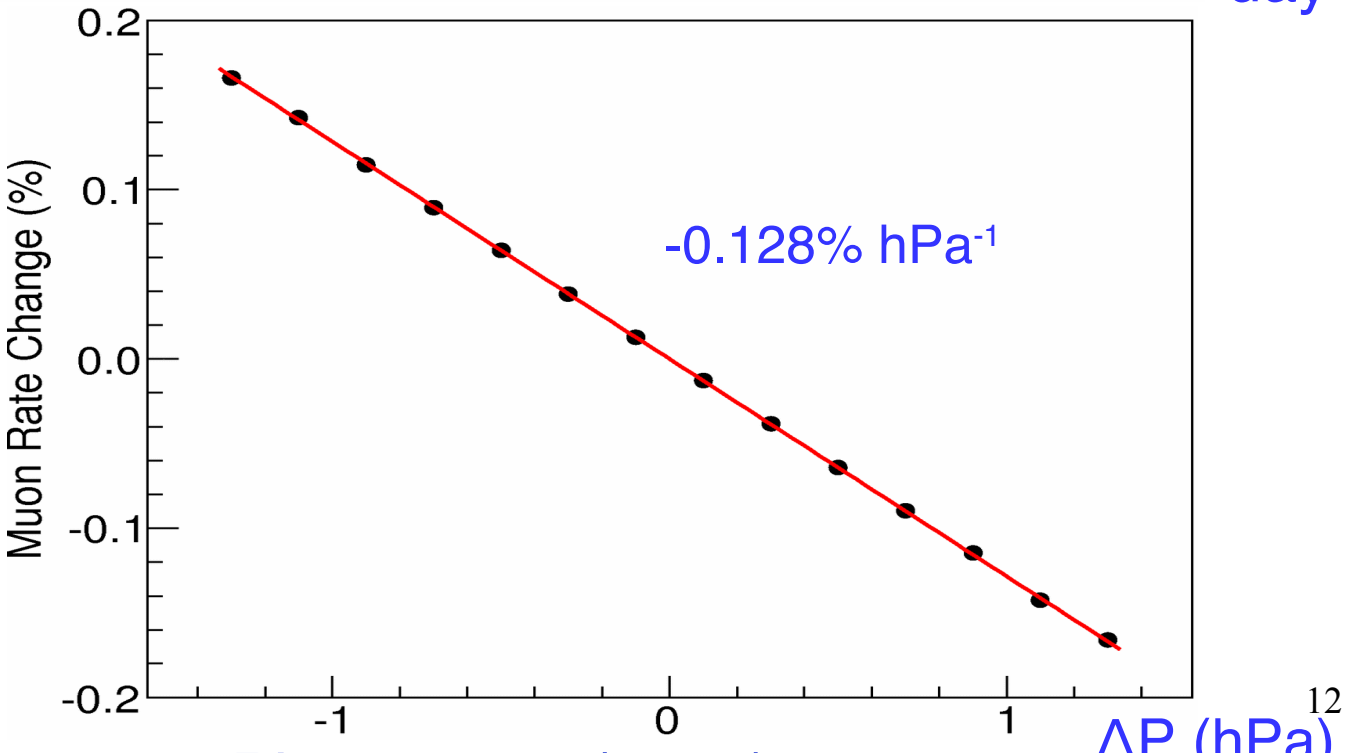

GRAPES-3 possibly most sensitive muon telescope
Total area = 560 m²
Inside view of
muon telescope



Muon Direction Reconstruction
Field of View = 2.3 sr

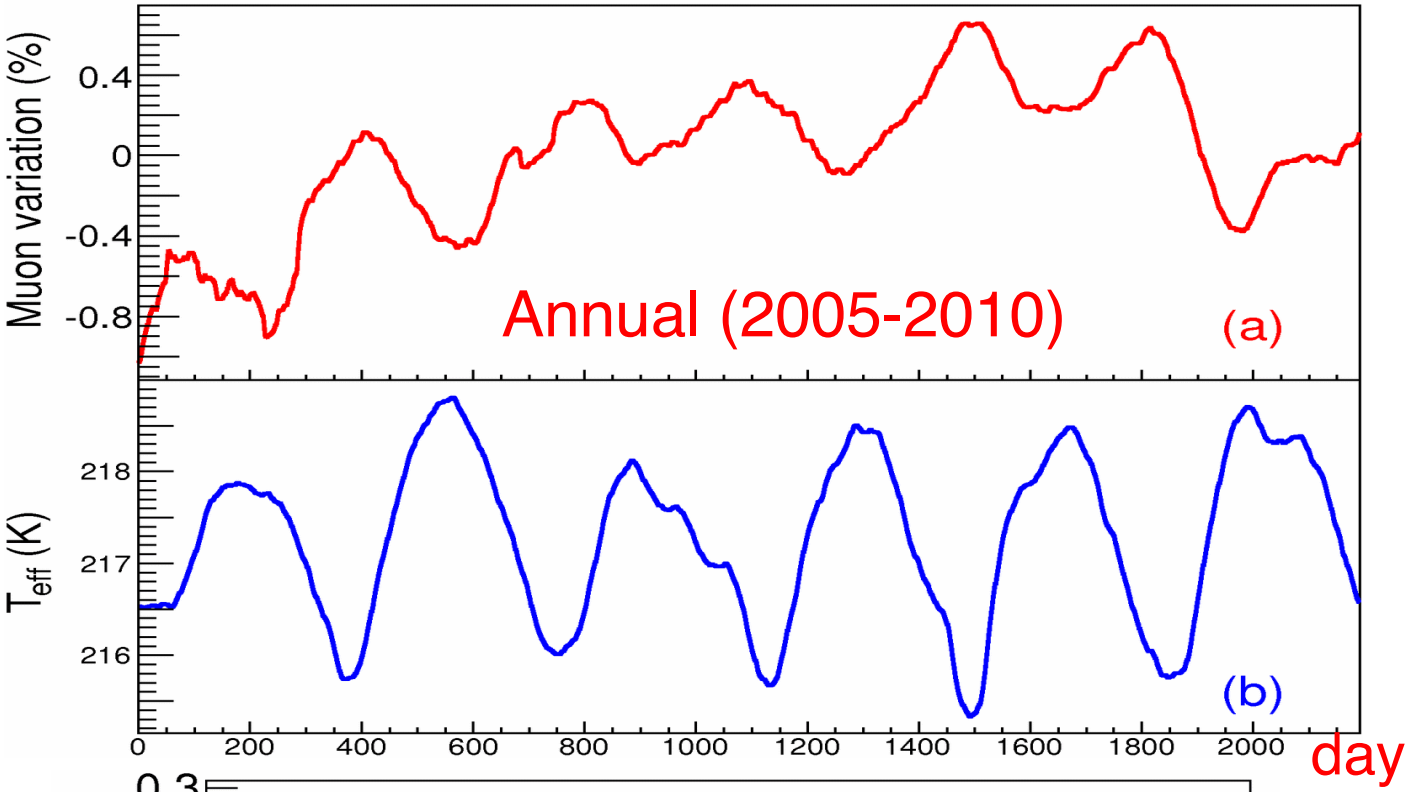


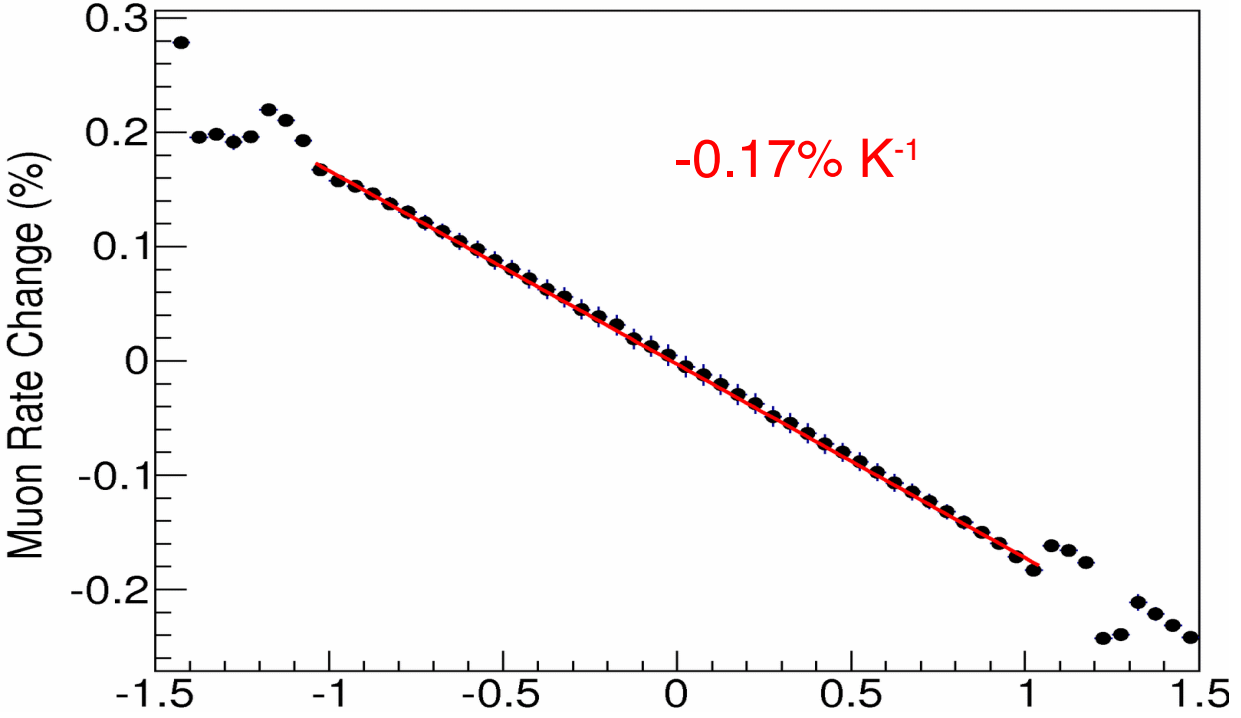




20 cm air column = 1σ

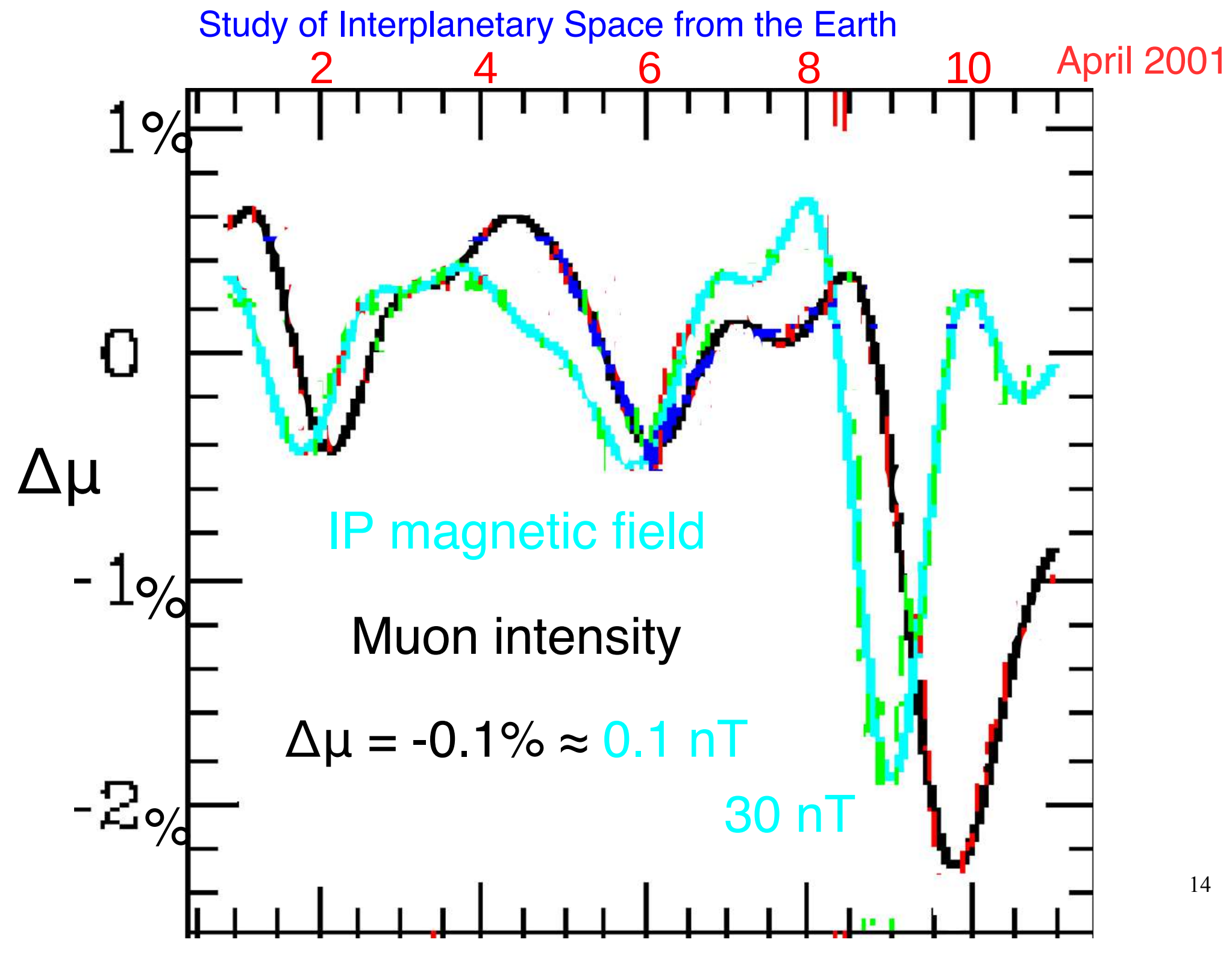
P.K. Mohanty et al. Astropart. Phys. **79** 23 (2016)





0.06 K = 1σ

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


Study of Interplanetary Space from the Earth
2
4
6
8
10
April 2001
1%
0
Δμ
-1%
-2%
IP magnetic field
Muon intensity
Δμ = -0.1% ≈ 0.1 nT
30 nT

GRAPES-3 is uniquely sensitive instrument;

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)

- There is good reason to study thunderstorms because they are the leading cause of death by a natural phenomenon across the globe;
- For example in India ~2000 people die every year due to lightning strikes and especially during thunderstorm season
- A disproportionate number of people killed are farmers working outdoors during Monsoon
- Worldwide several tens of thousands lives are lost due to thunderstorms
- Lightning is estimated to increase (12 ± 5)% for every degree celsius rise in global temperature

  D.M. Romp et al. Science, **346** (2014) 851

BBC

NEWS

Four people critically injured by lightning strike near White House

Four people have been critically injured after being struck by lightning near the White House.

The two men and two women were in Lafayette Park in Washington DC during a violent storm when they were struck down, fire officials said.

Because of the park's closeness to the seat of the US presidency, members of the secret service were among the first people to assist the victims.

The identities of those injured have not yet been confirmed.

The lightning struck the four people near a tree by the fence that surrounds the White House complex on Thursday evening.

"All four were suffering from critical, life-threatening injuries," **said DC Fire and EMS in a statement.** "We were able to quickly treat and transport all four patients and they were all taken to area hospitals."

The National Weather Service had issued a thunderstorm warning for the area on Thursday evening.

Lafayette Square is a seven-acre public park directly north of the White House. It is often crowded with visitors, especially during the summer.

Bihar: Lightning strikes kill 20 in Indian state

27 July

Hundreds die in India every year in lightning incidents during monsoon rains

Lightning strikes have killed 20 people across eight districts of the eastern Indian state of Bihar in just 24 hours.

More thunderstorm with lightning has been forecast in northern parts of the state for Wednesday and Thursday.

Benjamin Franklin's 1749 electrical experiments

EXPERIMENTS

AND

OBSERVATIONS

ON

ELECTRICITY,

MADE AT

Philadelphia in *America*,

BY

Mr. BENJAMIN FRANKLIN,

AND

Communicated in feveral Letters to Mr. P. COLLINSON, of *London*, F. R. S.

LONDON:

Printed and fold by E. CAVE, at *St. John's Gate.* 1751.

(Price 2s. 6d.)

ADDITIONAL PAPERS.

TO

Mr. PETER COLLINSON, F.R.S. *London.*

SIR, PHILADELPHIA, *July* 29, 1750

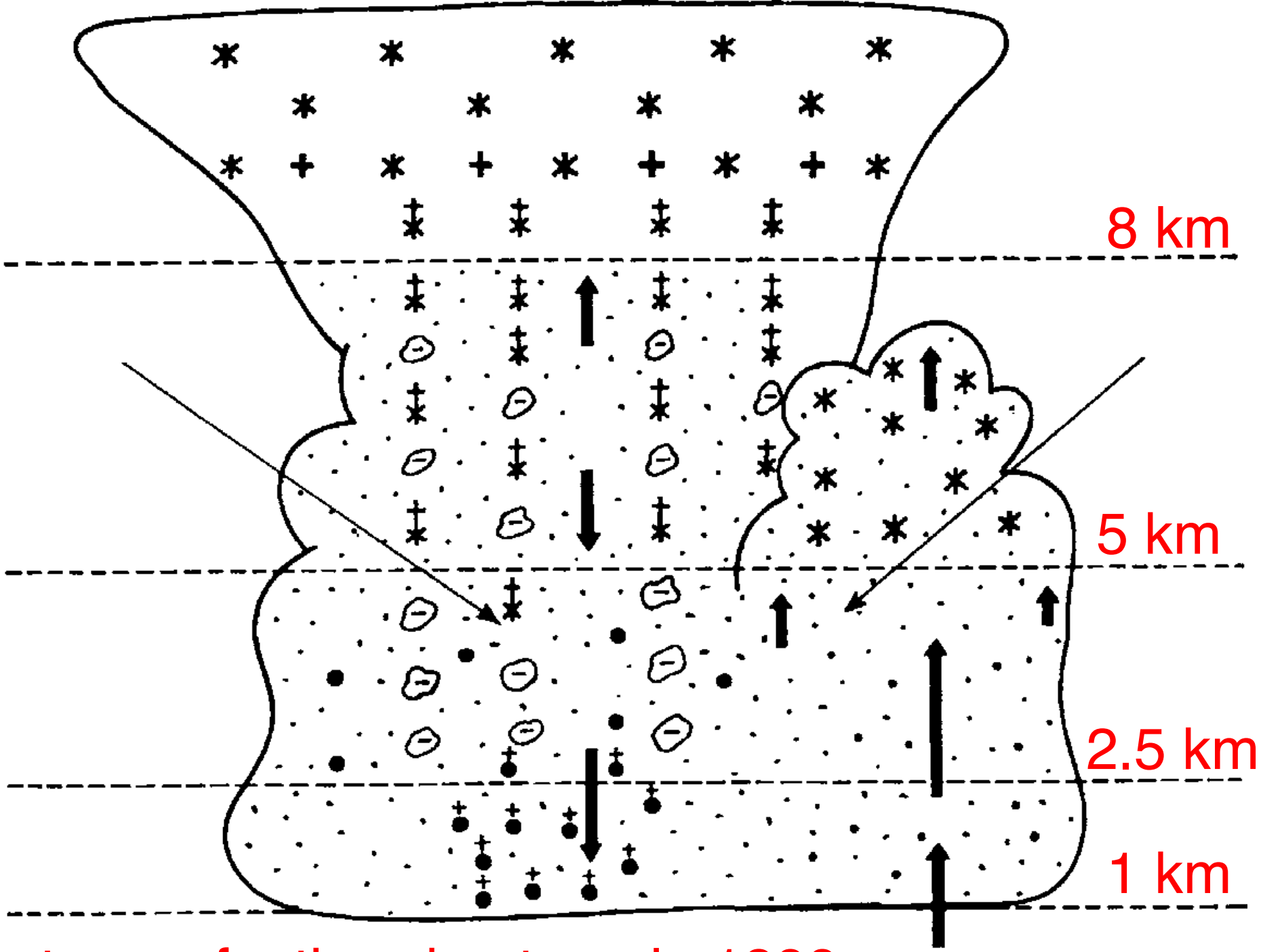
AS you firſt put us on electrical experiments, by ſending to our library company a tube, with directions how to uſe it; and as our honourable proprietary enabled us to carry thoſe experiments to a greater height, by his generous preſent of a compleat electrical apparatus; 'tis fit that both ſhould know from time to time what progreſs we make. It was in this view I wrote and ſent you my former papers on this ſubject, deſiring, that as I had not the honour of a direct correſpondence with that bountiful benefactor to our library, they might be communicated to him through your hands. In the ſame view I write, and ſend you this additional paper. If it happens to bring you nothing new (which may well be, conſidering the number of ingenious men in *Europe*, continually engaged in the ſame reſearches) at leaſt it will ſhow, that the inſtruments, put into our hands, are not neglected; and, that if no valuable diſcoveries are made by us, whatever the cauſe may be, it is not want of induſtry and application.

I am, Sir,

Your much obliged

Humble Servant,

B. FRANKLIN.



Anatomy of a thunderstorm in 1899,
150 Y after Franklin, Elster & Geitel

Conventional wisdom of thunderstorm development

(i) Average duration of precipitation and electrical activity from a single thunderstorm cell is about 30 min.

(ii) Average electric moment destroyed in a lightning flash is ~110 C km, corresponding discharge of 20–30 C.

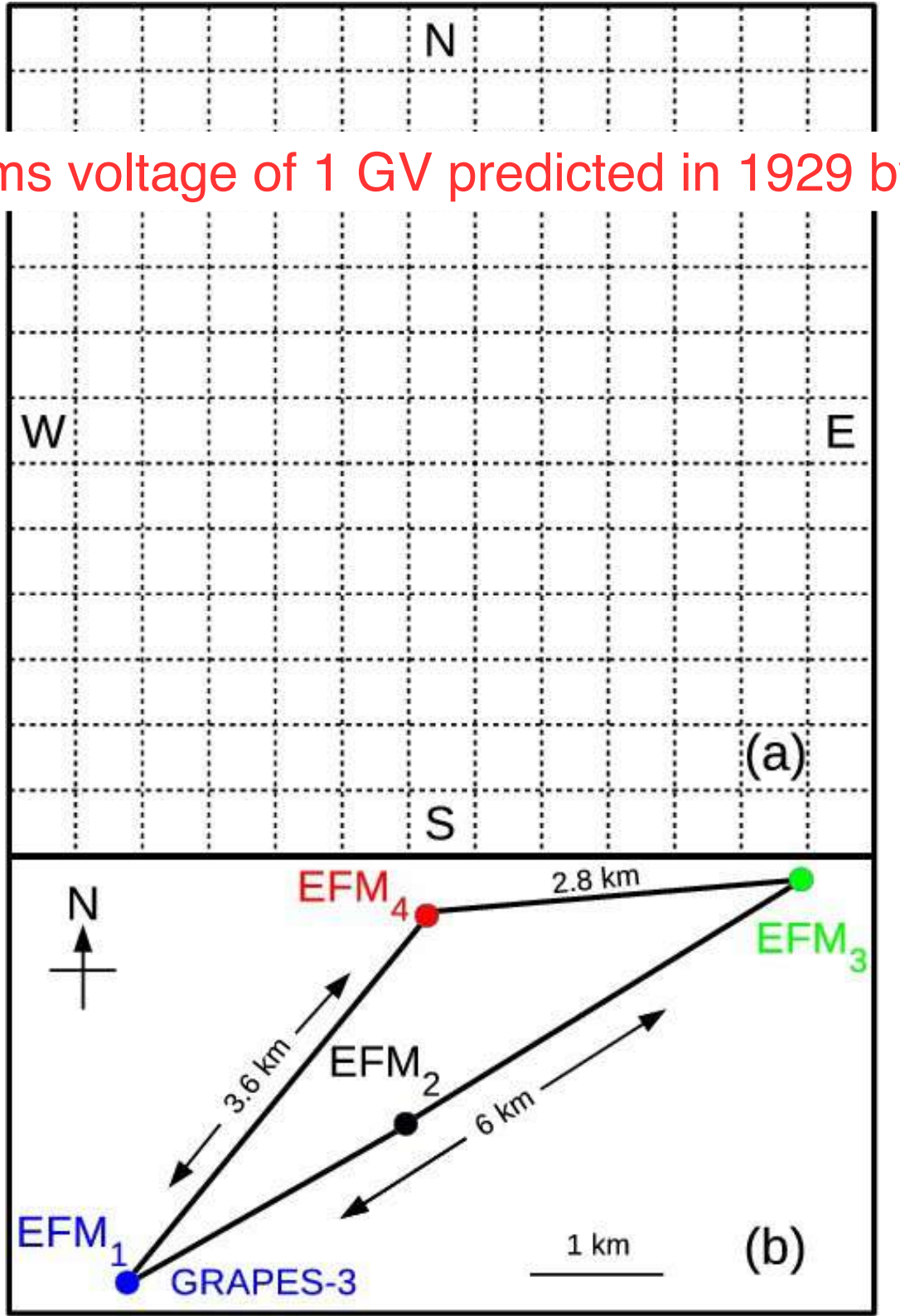
(iii) This charge is generated and separated in a volume bounded by the –5 and –40 celsius levels and having an average radius of ~2 km.

(iv) The separated negative charge is contained in a vertical column stretching from near the 0 level up to –40 celsius level 6 km higher up. Positive charge extends from about –30 celsius level well into the ice-crystal anvil. A subsidiary positive charge may exist near cloud base astride 0 celsius level.

(v) Charge generation and separation operates in supercooled part of cloud and is associated with development of precipitation, in form of soft hail pellets formed by aggregation and freezing of supercooled cloud droplets.

(vi) Sufficient charge must be generated and separated to supply a lightning flash within 10–20 min of precipitation particles of radar-detectable size, and to establish large-scale electric fields of at least a few kV/cm.

A thunderstorms voltage of 1 GV predicted in 1929 by C.T.R. Wilson



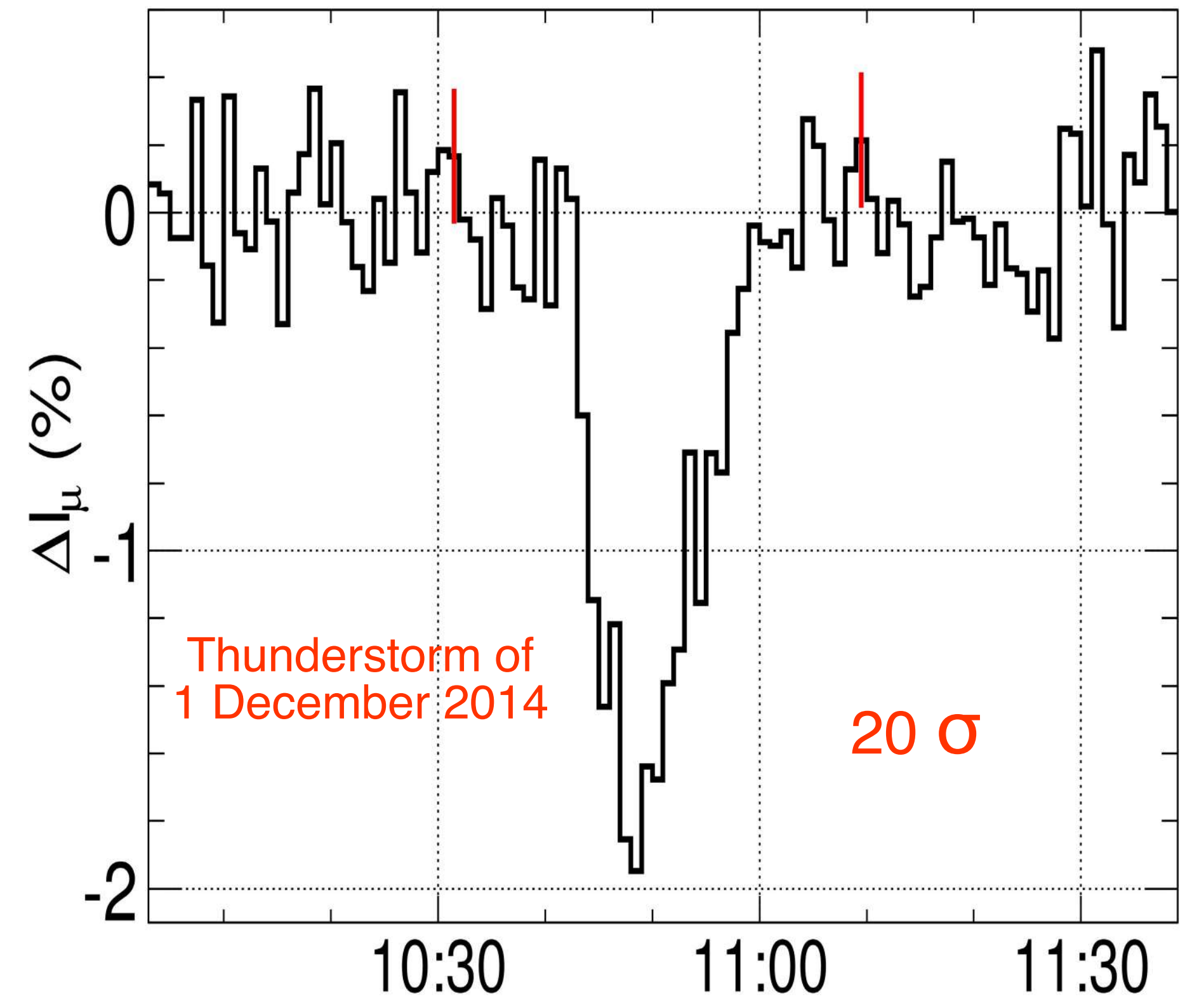
0.13 GV 2000

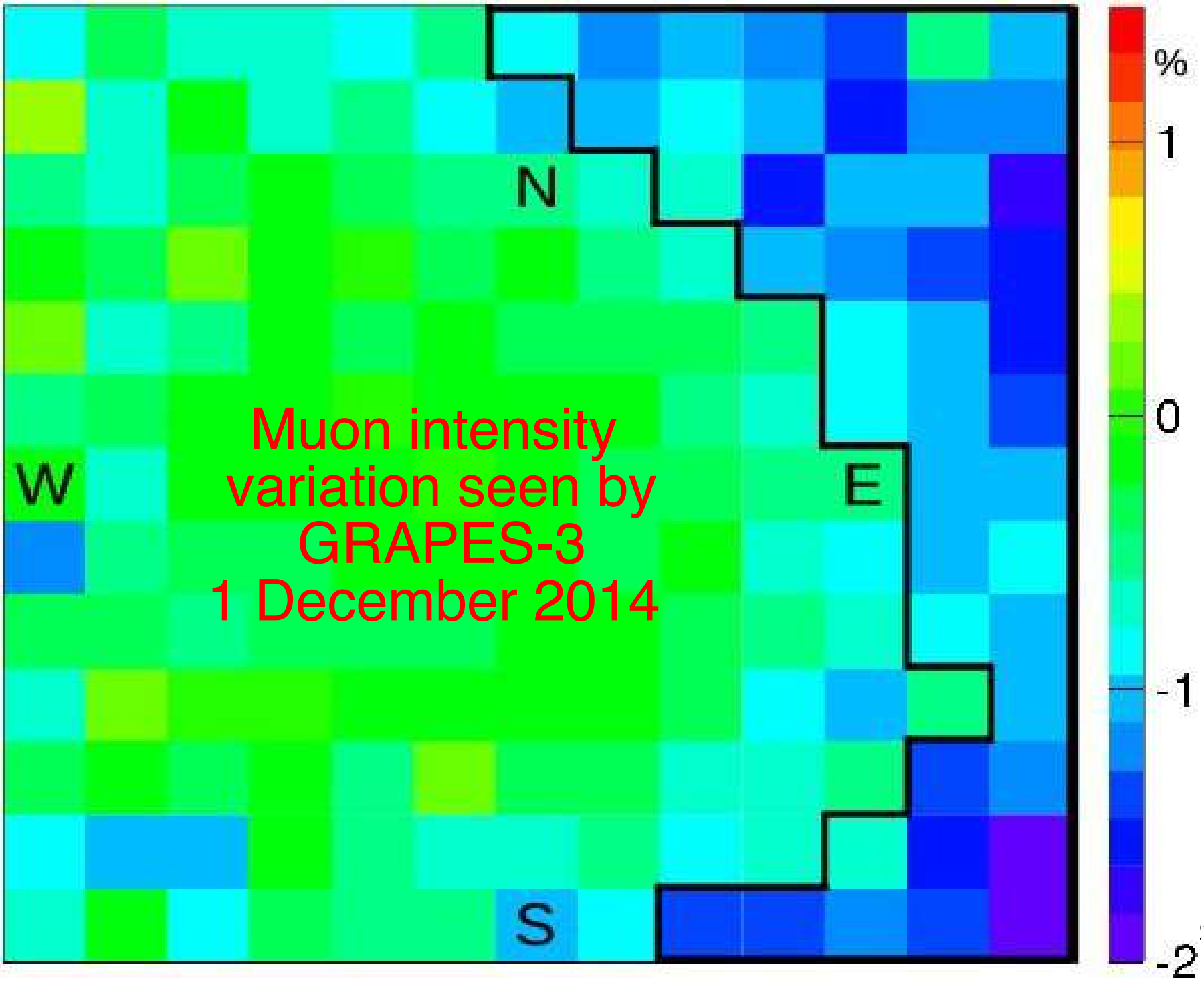
April 2011 – December 2014 184 thunderstorms

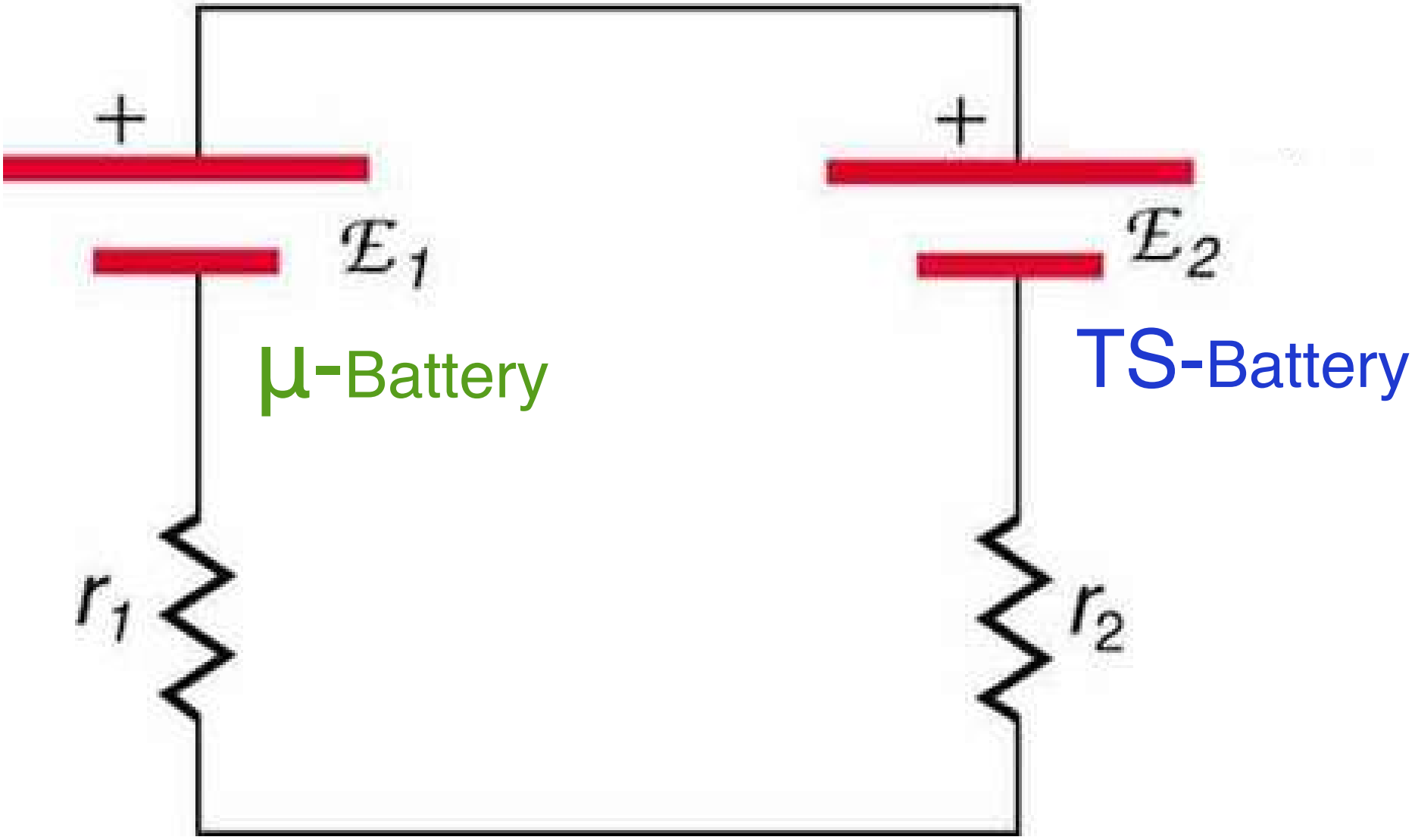
7 Largest events $\Delta I_{\mu} > 0.4\%$ selected

6 events had very complex electric field profiles.

Only the event on 1 December 2014 had a simple profile

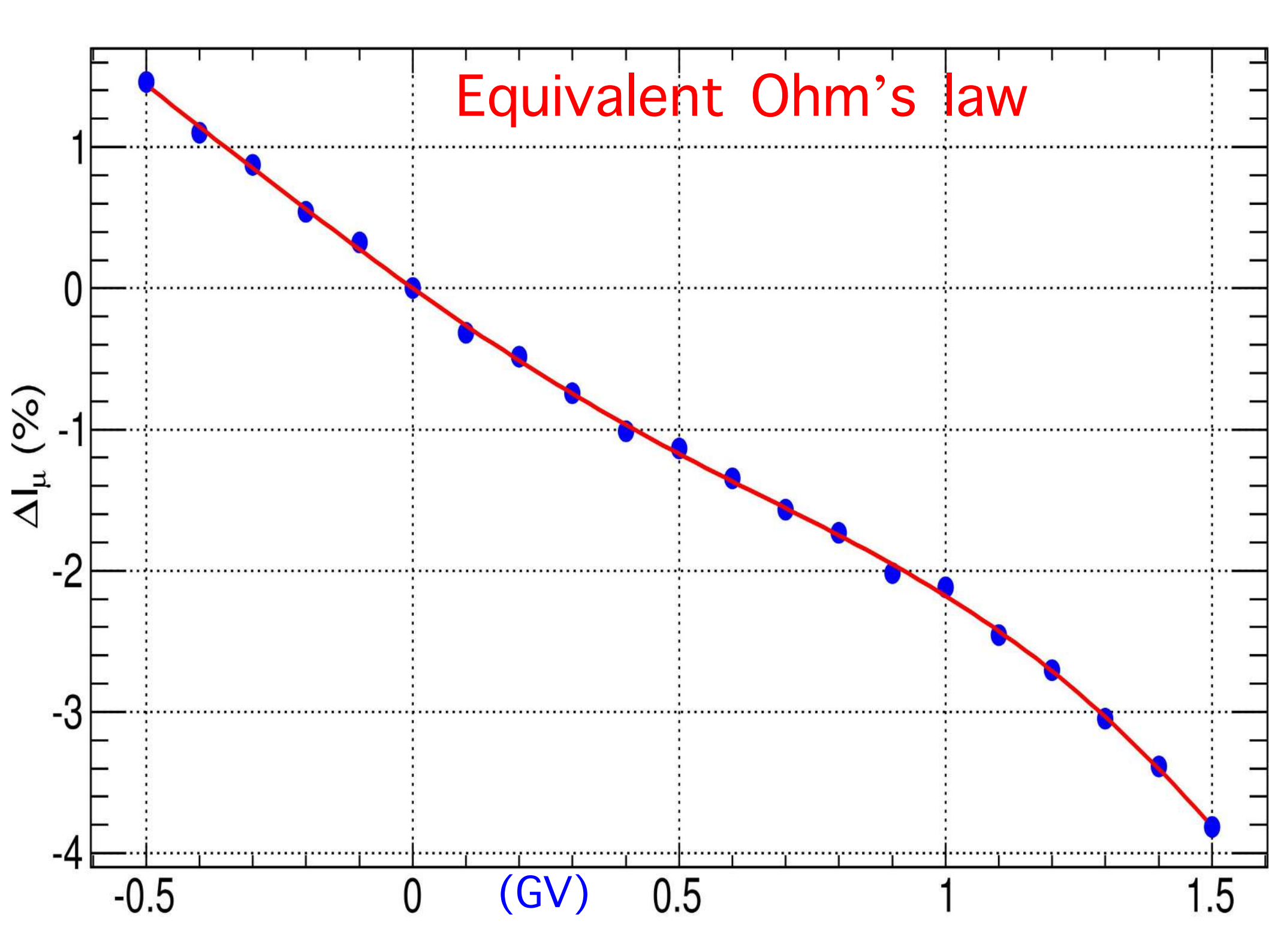

0
-1
-2
ΔI_μ (%)
Thunderstorm of
1 December 2014
20 σ
10:30
11:00
11:30


N
W
E
S
Muon intensity
variation seen by
GRAPES-3
1 December 2014
%
1
0
-1
-2

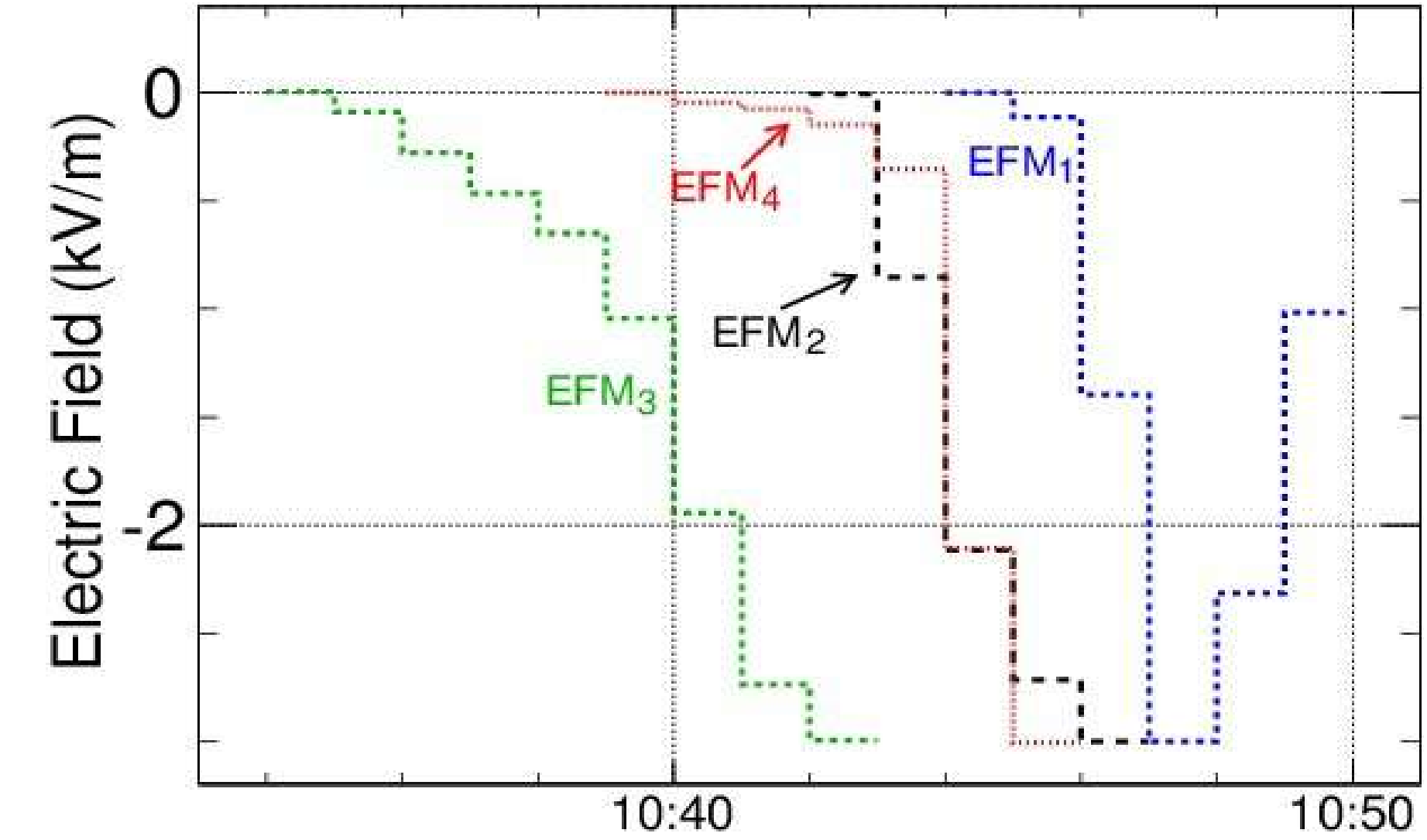


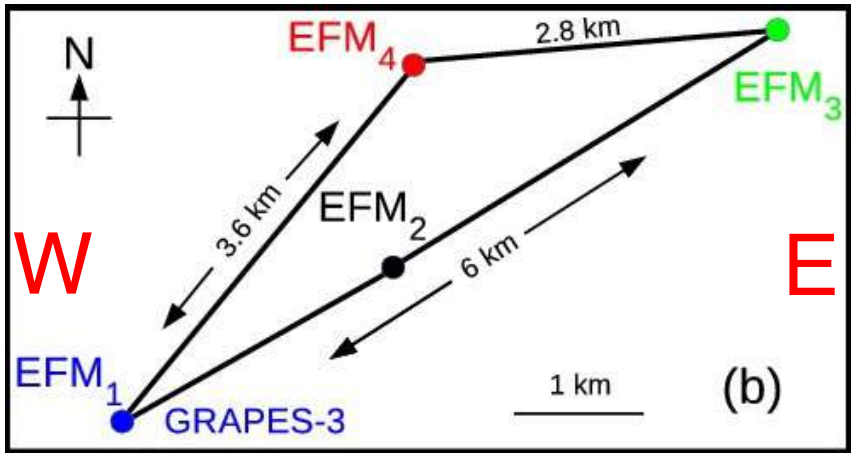
$$I_1 = E_1/(r_1+r_2) \quad ; \quad I_2 = (E_1-E_2)/(r_1+r_2)$$

$$\Delta I = E_2/(r_1+r_2)$$

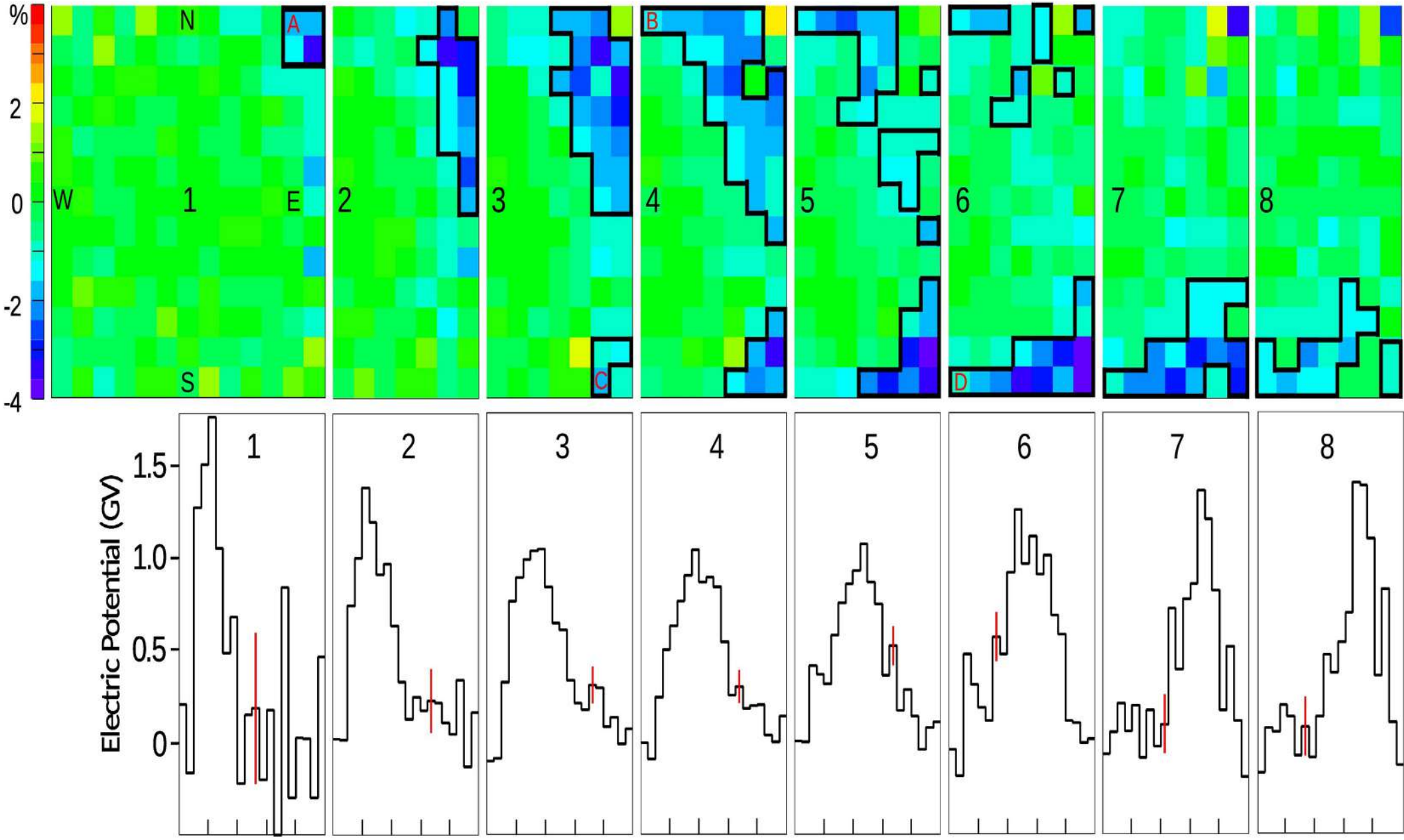

Equivalent Ohm's law
1
0
-1
-2
-3
-4
ΔI_μ (%)
-0.5
0
(GV)
0.5
1
1.5


0.9 GV
PRL, 122, 105101(2019)
Electric Potential (GV)
0.8
0.6
0.4
0.2
0
10:30
11:00
11:30





6 km travel in 6 min
speed = 60 km h^{-1}

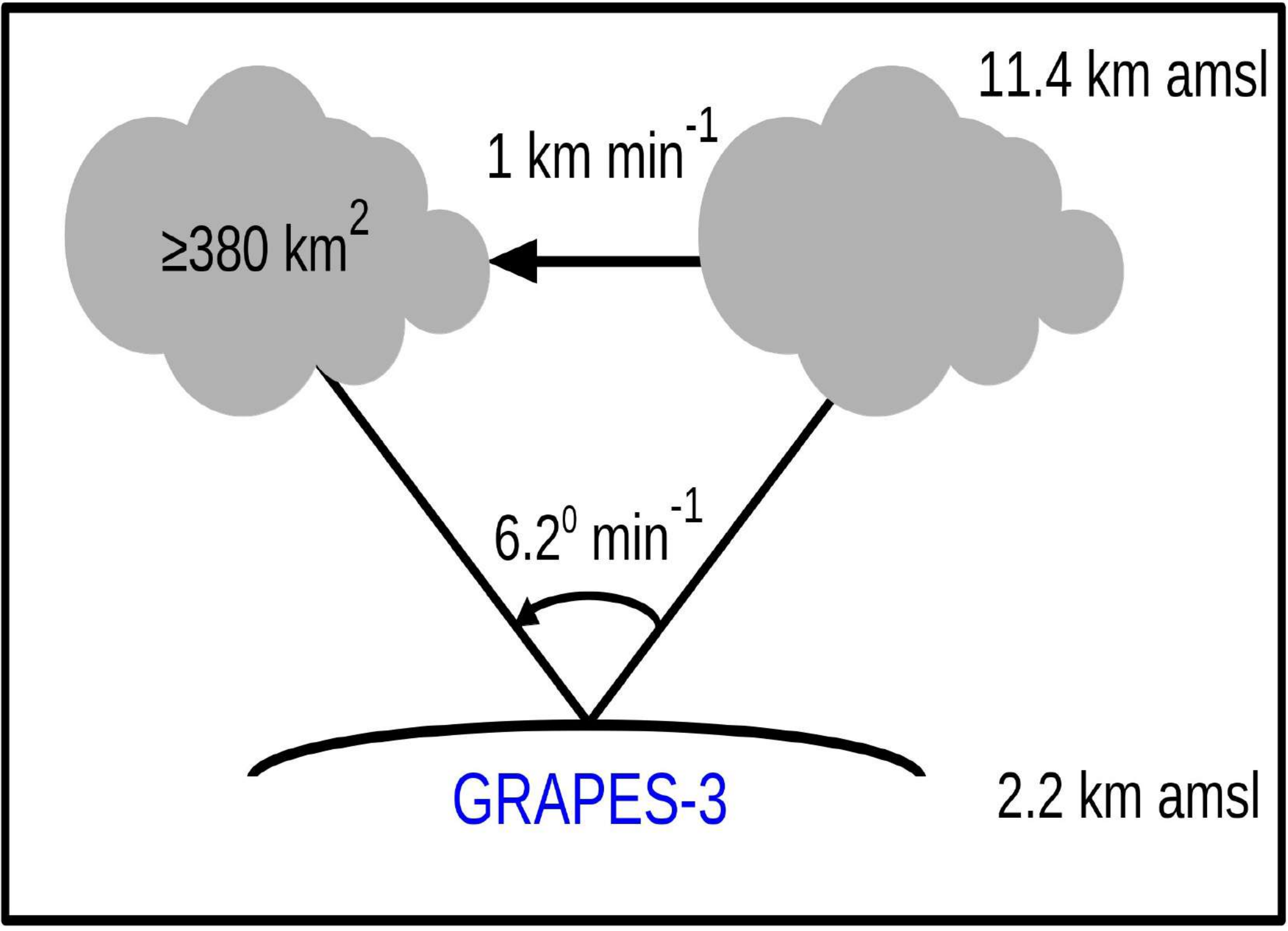


PRL, **122,** 105101(2019)

Mean = 1.3 GV

Charging Time = 6 min

Angular velocity = 6.2^{O} min^{-1}


11.4 km amsl
1 km min-1
≥380 km2
6.20 min-1
GRAPES-3
2.2 km amsl

1. Angular velocity- 6.2^{o}/min, linear velocity 1 km/min → height of cloud 11.4 km amsl consistent with velocity and height of subtropical jet stream in south India.

2. Angular size 75^{o} →cloud radius >11km Area > 380 km^{2}

3. A cloud is a thick (2 km) parallel plate capacitor with similar sepration; capacitance > 0.85 μF

4. V= 1.3 GV → Q > 1100 C, → Energy > 720 GJ
Charging time = 6 min → Power > 2 GW

Properties of 1 December 2014 Thunderstorm

(1) Electric potential of December 1, 2014 event = 1.3 GV
previously reported maximum = 0.13 GV.
Consistent with prediction of C.T.R. Wilson of 90 years ago.

(2) Gigavolt potentials can explain production of high-energy γ-rays in TGFs discovered by over 25 years back.

(3) Moving at a speed of 60 km h^{-1} near the top of the troposphere possibly carried by the westerly Jet stream.

(4) Area~400 $km^{2,}$ Charge stored ≥ 1100C Power ≥ 2 GW
Energy stored ~ 720 GJ → Mumbai for about hour
Biggest nuclear reactor/ hydroelectric/ thermal generator

Editors' Suggestion | Featured in Physics

Measurement of the Electrical Properties of a Thundercloud Through Muon Imaging by the GRAPES-3 Experiment

B. Hariharan,[1,2] A. Chandra,[1,2] S. R. Dugad,[1,2] S. K. Gupta,[1,2,*] P. Jagadeesan,[1,2] A. Jain,[1,2] P. K. Mohanty,[1,2] S. D. Morris,[1,2] P. K. Nayak,[1,2] P. S. Rakshe,[1,2] K. Ramesh,[1,2] B. S. Rao,[1,2] L. V. Reddy,[1,2] M. Zuberi,[1,2] Y. Hayashi,[2,3] S. Kawakami,[2,3] S. Ahmad,[2,4] H. Kojima,[2,5] A. Oshima,[2,5] S. Shibata,[2,5] Y. Muraki,[2,6] and K. Tanaka[2,7]

(GRAPES-3 Collaboration)

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[3]*Graduate School of Science, Osaka City University, Osaka 558-8585, Japan*
[4]*Aligarh Muslim University, Aligarh 202002, India*
[5]*College of Engineering, Chubu University, Kasugai, Aichi 487-8501, Japan*
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(Received 6 January 2019; revised manuscript received 21 January 2019; published 15 March 2019)

The GRAPES-3 muon telescope located in Ooty, India records rapid (~10 min) variations in the muon intensity during major thunderstorms. Out of a total of 184 thunderstorms recorded during the interval of April 2011–December 2014, the one on December 1, 2014 produced a massive potential of 1.3 GV. The electric field measured by four well-separated (up to 6 km) monitors on the ground was used to help estimate some of the properties of this thundercloud, including its altitude and area that were found to be 11.4 km above mean sea level and ≥ 380 km^2, respectively. A charging time of 6 min to reach 1.3 GV implied the delivery of a power of ≥ 2 GW by this thundercloud that was moving at a speed of ~60 km h^{-1}. This work possibly provides the first direct evidence for the generation of gigavolt potentials in thunderclouds that could also possibly explain the production of highest-energy (100 MeV) gamma rays in the terrestrial gamma-ray flashes.

DOI: 10.1103/PhysRevLett.122.105101

FOCUS

Muons Reveal Record-Breaking Thunderstorm Voltage

March 15, 2019 • *Physics* 12, 29

A thunderstorm probed with atmospheric muons had an electric potential exceeding one billion volts, much higher than values measured previously.

iStock.com/jerbarber

Quite a shock. Using a muon detector, researchers measured a record-breaking thunderstorm electric potential greater than 1 billion volts.

Researchers have documented a thunderstorm producing an electric potential of about 1.3 billion volts (GV), 10 times greater than the largest value ever reported. The team's new thunderstorm monitoring method makes use of the muons raining down on Earth, produced by cosmic rays hitting the atmosphere. A thundercloud's potential can reduce the energies of the charged particles and decrease the likelihood that they will be detected beneath the storm. The new measurement indicates that thunderstorms with several-billion-volt potentials are possible, voltages high enough to explain the mysterious flashes of high-energy gamma rays sometimes observed during thunderstorms.

Lighting bolts sizzle over Johannesburg, South Africa. Credit: Mitchell Krog/Getty

PHYSICS · 22 MARCH 2019

Supercharged thunderstorm reaches a record 1.3 billion volts

Measurements also help to explain mysterious flashes of radiation inside thunderclouds.

Thunderstorms can reach voltages ten times greater than those previously recorded, a new measurement suggests.

Sunil Gupta at the Tata Institute of Fundamental Research in Mumbai, India, and his colleagues used an instrument called a muon telescope to measure storms' electric potential — the voltage between the top and bottom of a thundercloud.

Massive voltages in thunderclouds can slow down subatomic particles

By Sid Perkins | Mar. 14, 2019 , 11:50 AM

The electric potentials that build up in thunderclouds can exceed 1.3 billion volts, **about 10 times the voltages previously measured**, *Science News* reports. Besides being the driving forces for lightning, electric potentials in thunderclouds also tend to decelerate negatively charged subatomic particles known as muons, which rain down from the upper atmosphere where they are created when cosmic rays collide with gas molecules. The new finding, based on analyses of a severe thunderstorm that occurred in southern India in December 2014 and reported in a forthcoming issue of *Physical Review Letters*, **may help explain how strong storms can be a source of brief flashes of gamma rays**, researchers say.

Most powerful thunderstorm ever measured produced 1.3 billion volts

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PHYSICS 20 March 2019

Thunderstorms can produce billions of volts
Enrique Díaz/7cero/Getty

By **Chelsea Whyte**

A thunderstorm in India produced an electric potential of 1.3 billion volts – 10 times the highest voltage previously recorded. The finding could help explain how high-energy gamma rays are produced during storms.

Lightning strikes in Casco Bay off the coast of Portland, Maine.
PHOTOGRAPH BY ROBBIE GEORGE

SCIENCE | NEWS

Most powerful electrical storm on record detected

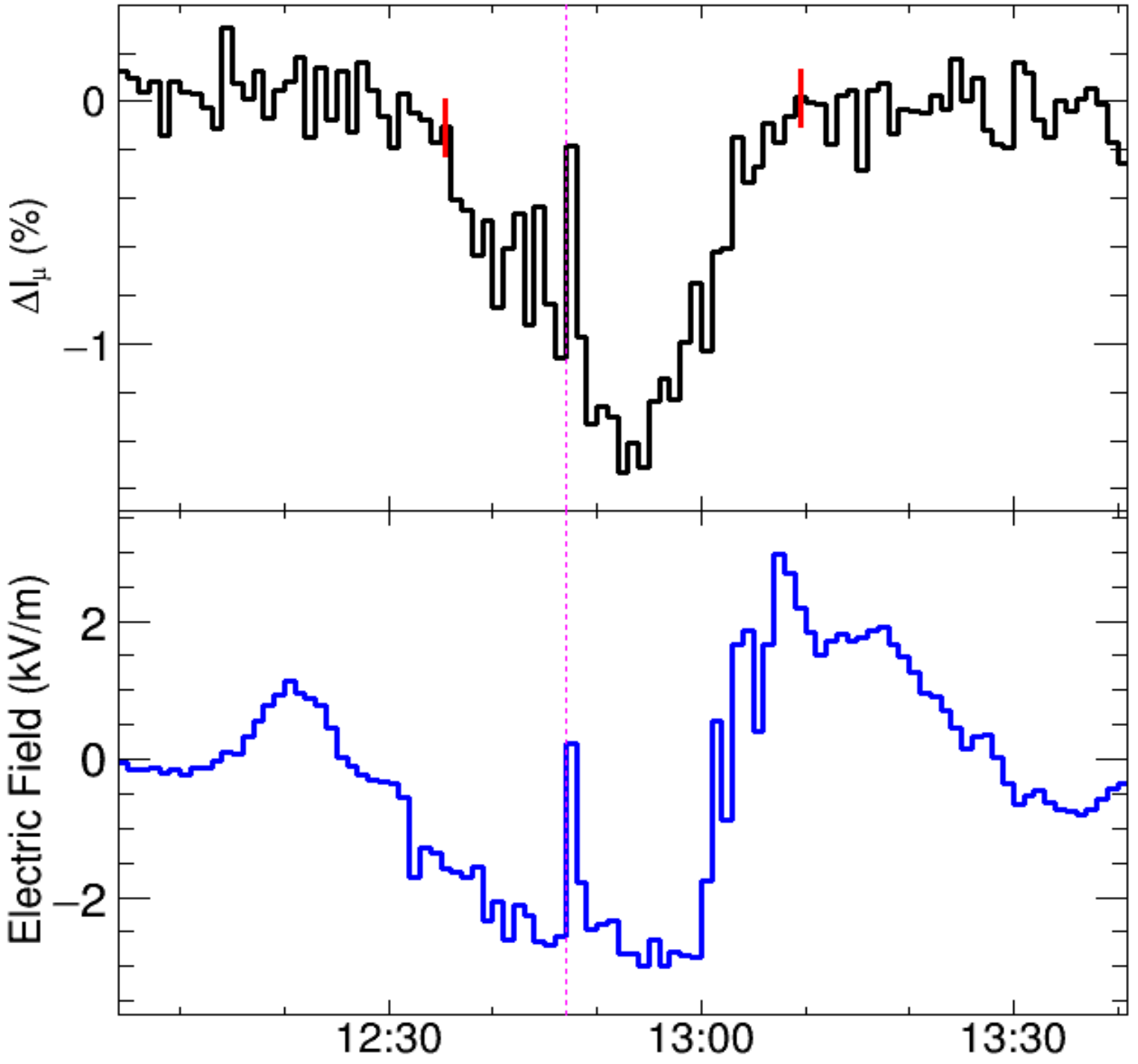
The total charge in a single thundercloud could have powered New York City for half an hour.

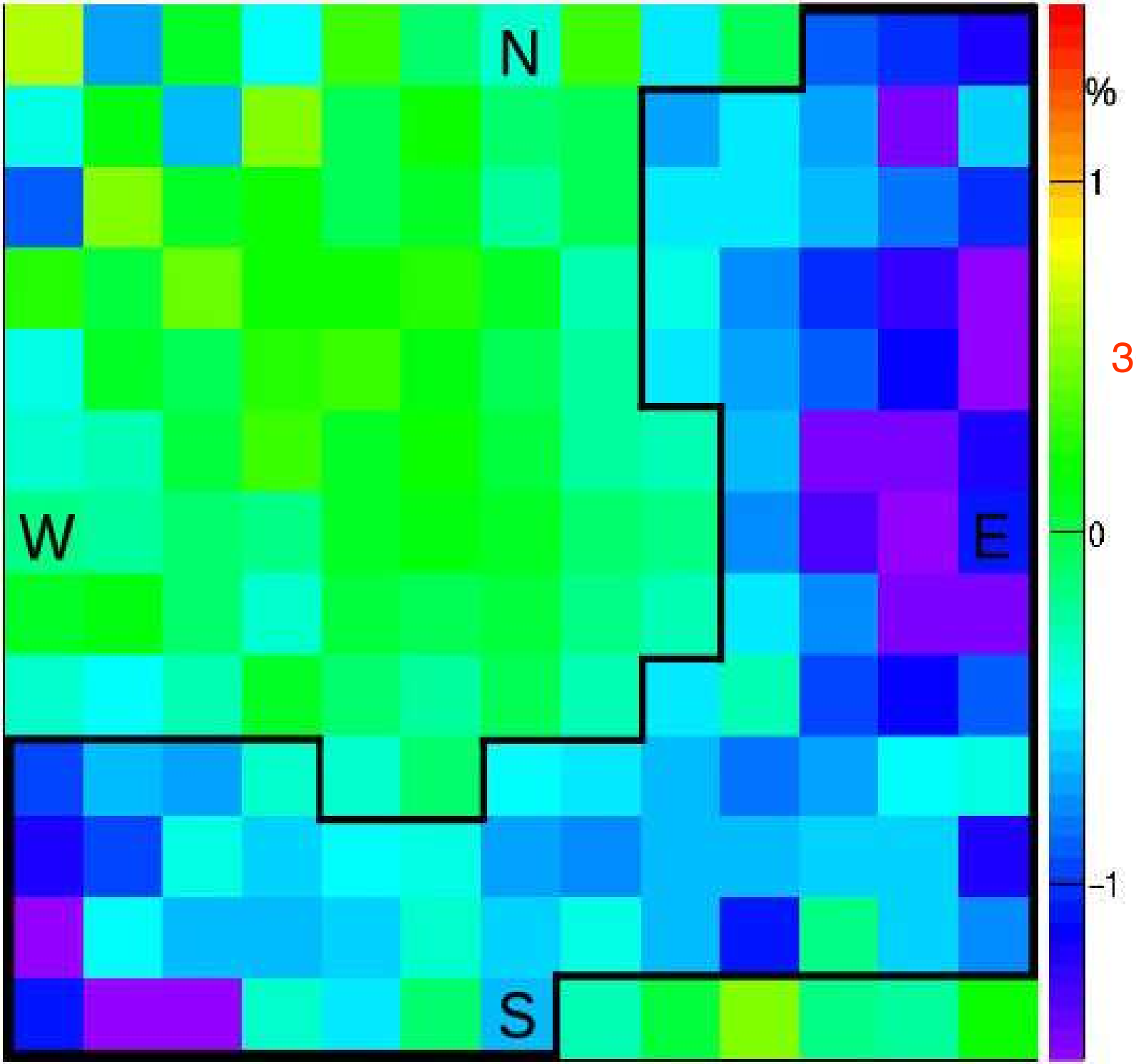
BY ADAM MANN

There are over 100 reports……

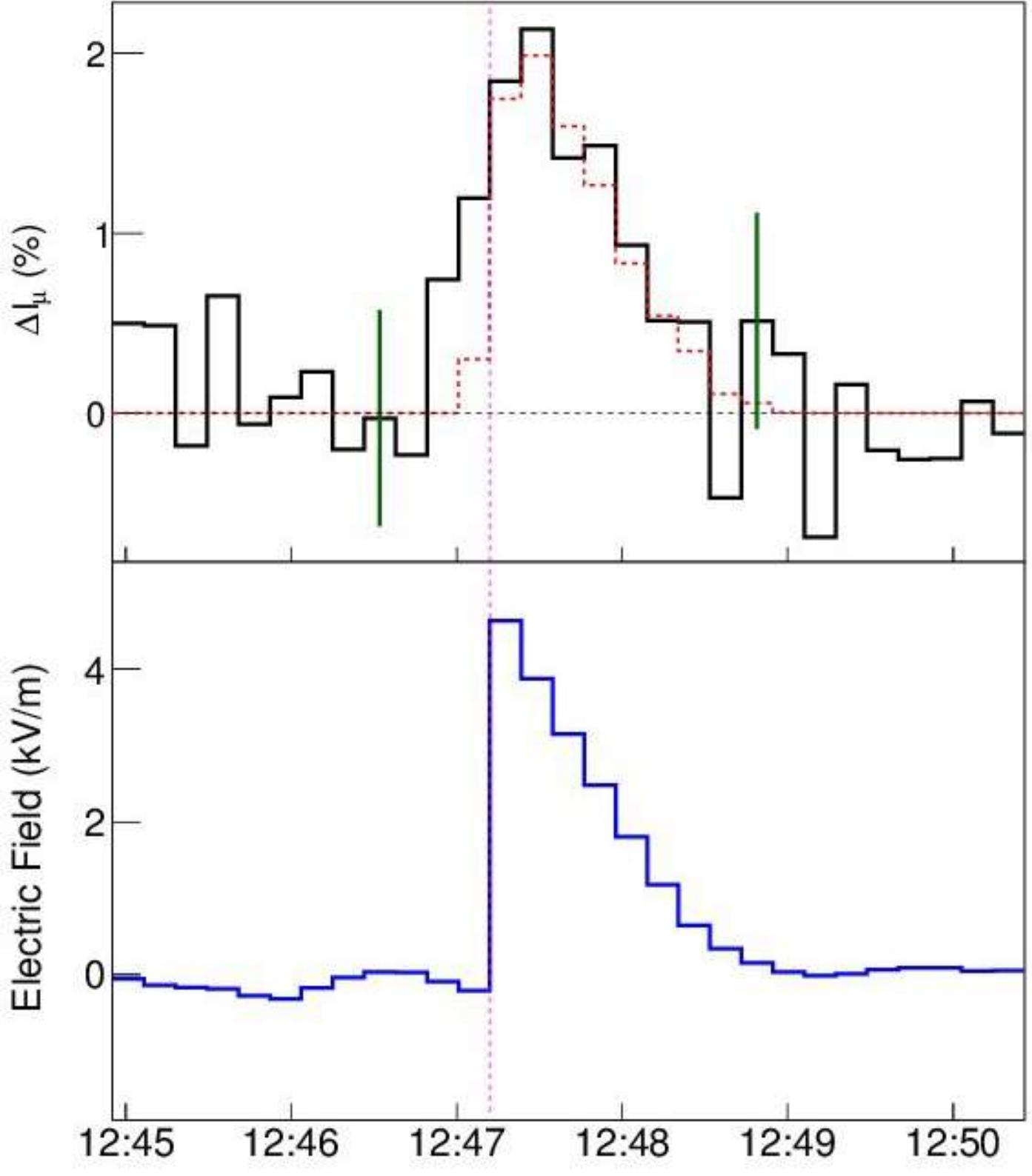
https://grapes-3.tifr.res.in/publications/misc/Thunderstorm_v3.pdf

30 September 2015 thunderstorm



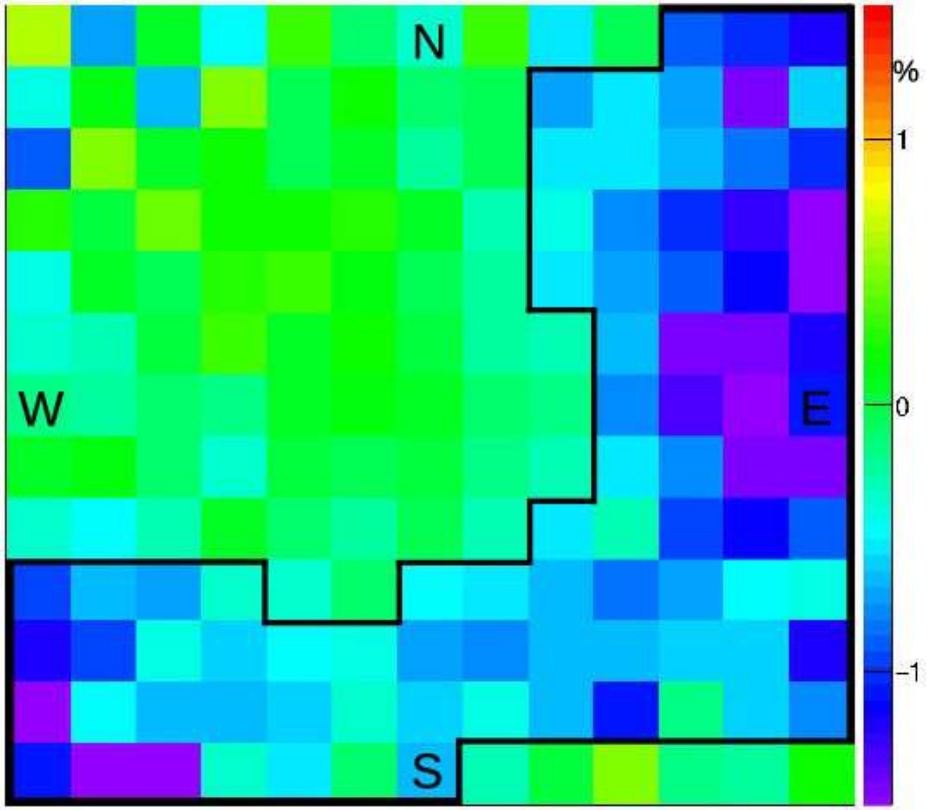


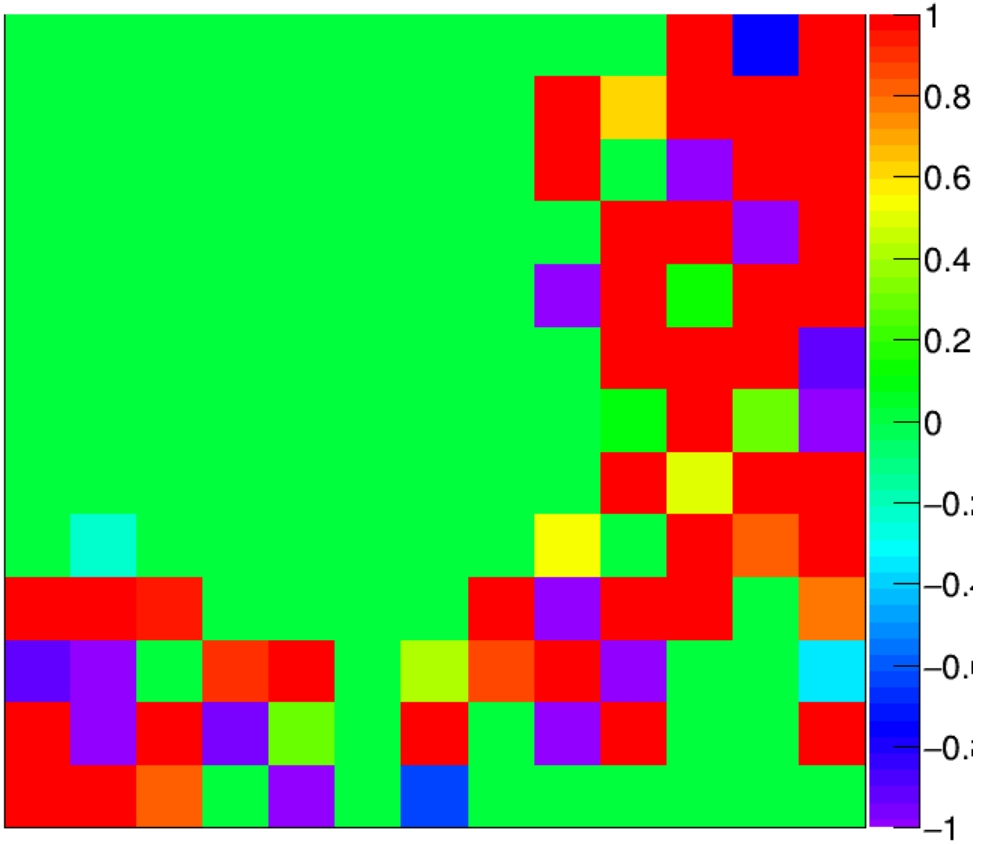
30 September 2015
Thunderstorm



Charging time = 60 s
Power > 10 GW

Discharging Pixels





Summary

1. Ooty with a long rainy season (8-9 months), ideal location for thunderstorm studies

2. GeV threshold is well-suited for GV

3. GeV muons serve as an excellent precision tool

4. Electric field measurements provided unique complementary information

The GRAPES-3 Team

THANKS