Measurement of the electrical properties of a thundercloud through muon imaging by the GRAPES-3 experiment

B. Hariharan, GRAPES-3

PoS(ICRC2019)185

(GRAPES-3 Collaboration)

Outline

- Importance
- GRAPES-3 Muon Telescope
- Event on 1st December 2014
- Monte Carlo Simulations
- Electrical Properties
- Summary
- Future Prospects

Importance

Known for more than two centuries

- 1750s – B. Franklin
- 1920s – C.T.R. Wilson
- Studies by many cosmic ray experiments

Annual global cause of

- ~6000 deaths (more than tornadoes and hurricanes)
- Damage to property (~0.5 billion USD)
- Forest fires (tens of thousands)

Backbone

DATA

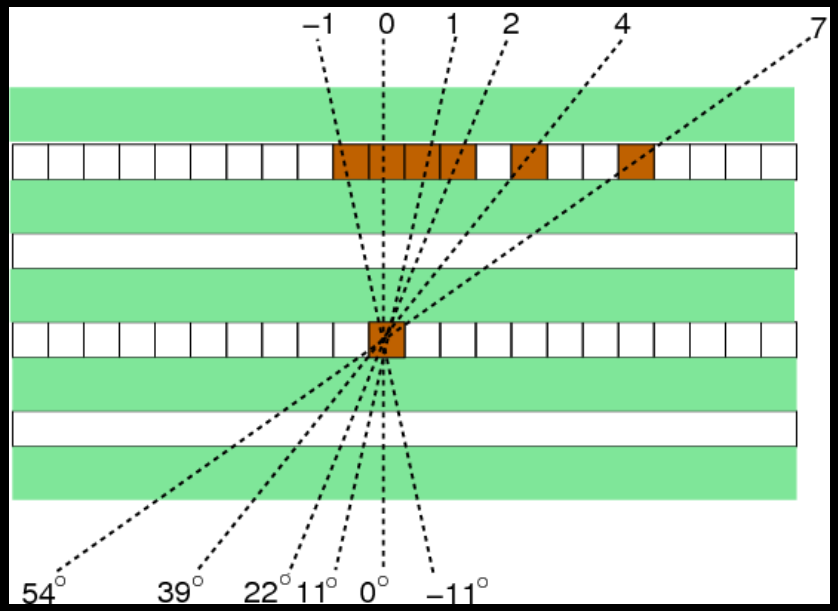
Muon Telescope

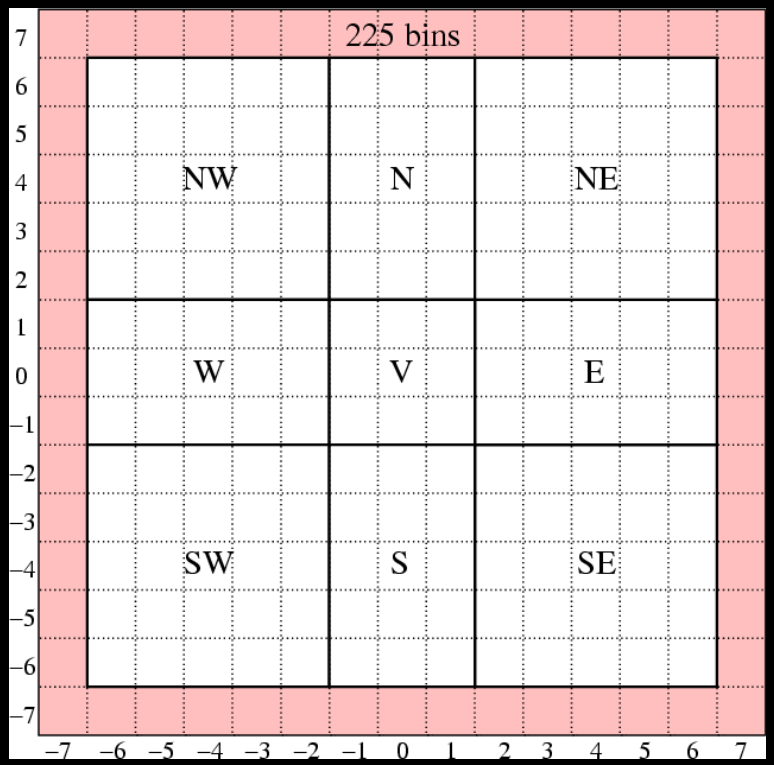
- 3712 PRCs
- 16 Modules
- Area 560 m^2
- 169 Directions
- Sec(θ) GeV

MC

- Rigidity
- CORSIKA
- Detector

Muon Direction Reconstruction



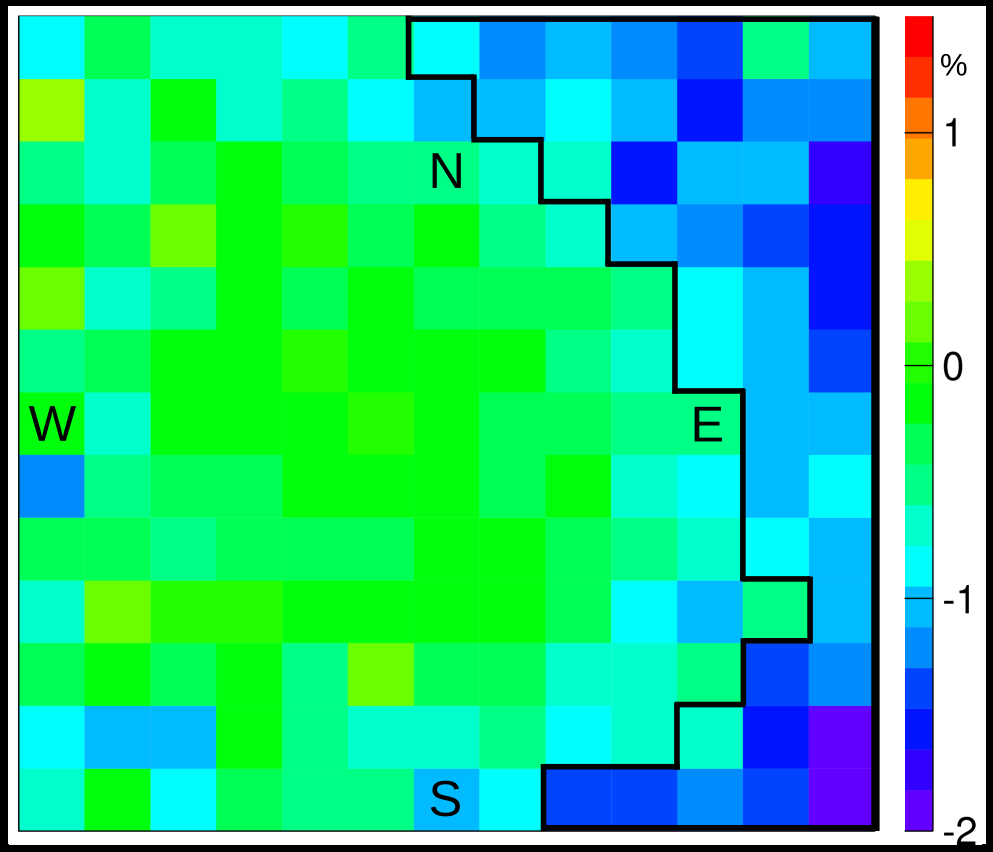


Thunderstorm Event Statistics

- Electric Field Monitors (EFMs) since April 2011
- Events during April 2011 - December 2014
  - 184 events
  - 7 large events ($\Delta I_\mu > 0.4\%$)
  - 1 simple structure !!!
  - 1st December 2014

High Exposure Muon Image

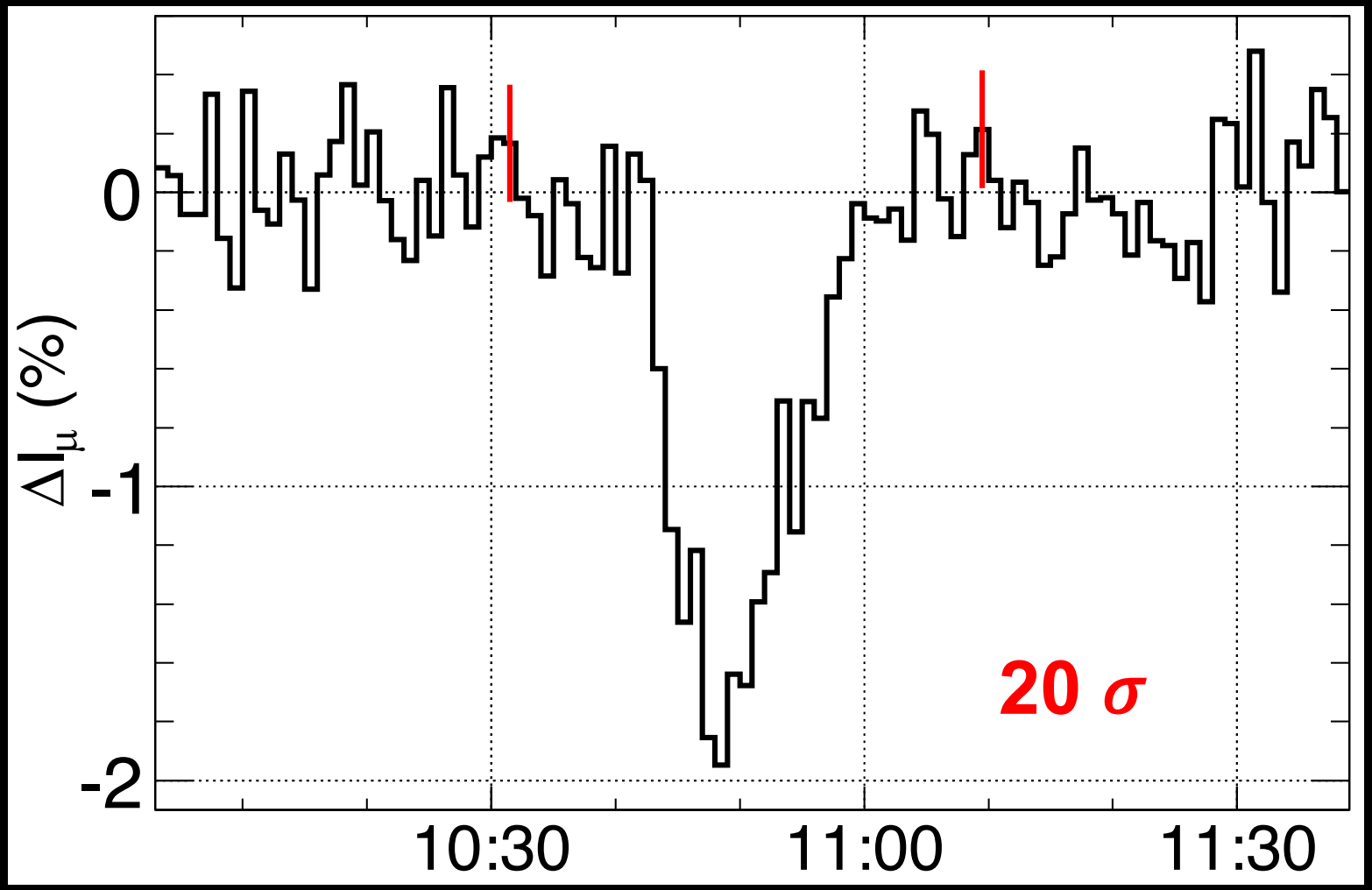
1st December 2014



18 Minutes

45 Directions

Muon Intensity Variation



Time (UT)

Monte Carlo Simulation

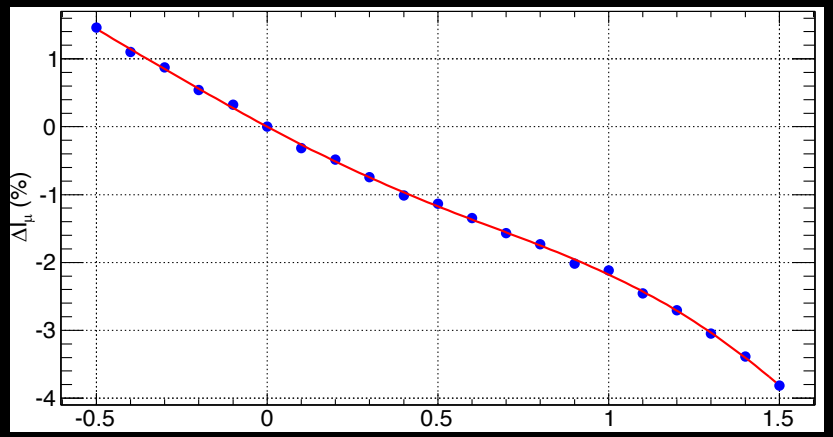
CORSIKA v74001
(FLUKA – SIBYLL)

Electric Potential
(Steps of 0.1 GV)

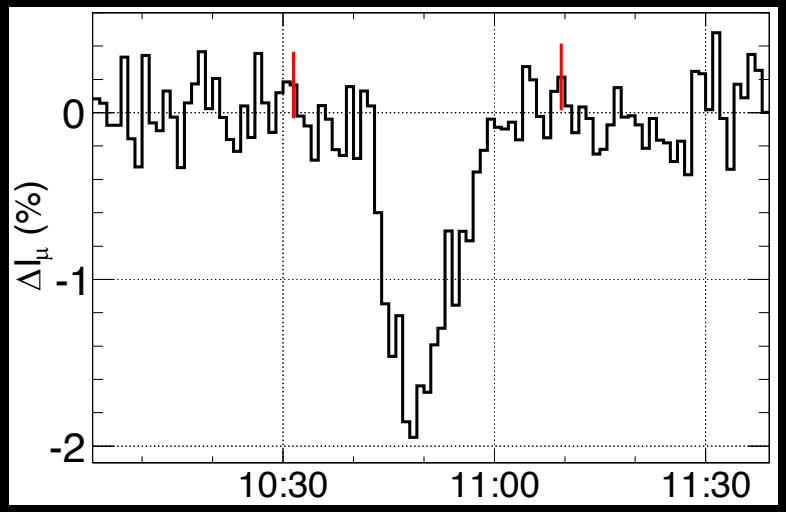
Detector Simulation
(ΔI_μ for 169 dir)

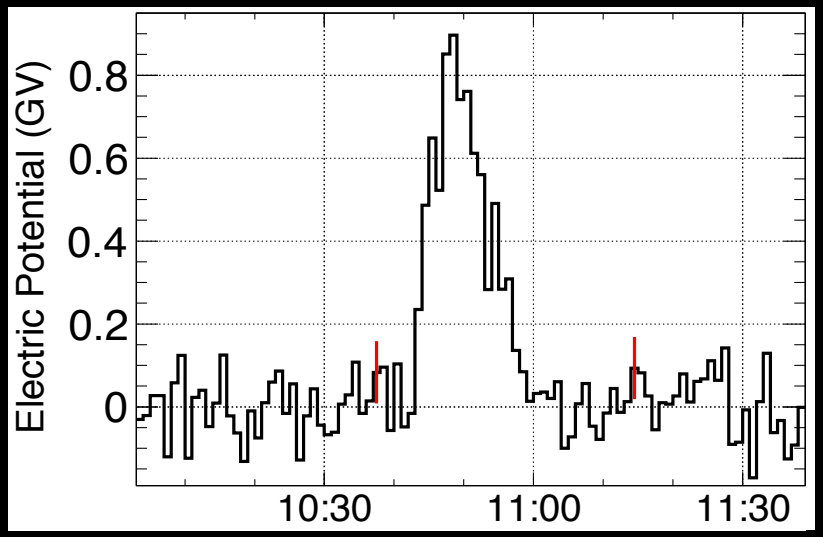
- Proton (10 GeV – 10 TeV)
- Error (Simulation << Data)

Monte Carlo Simulation



Electric Potential (GV)



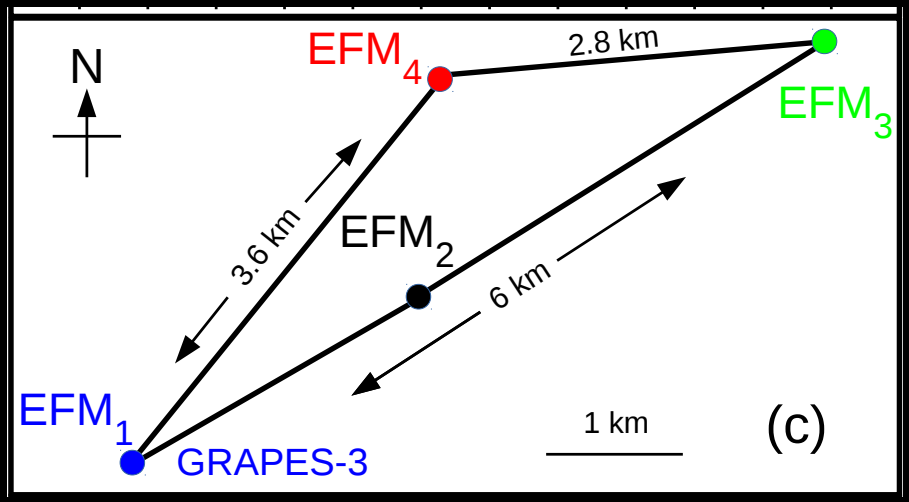


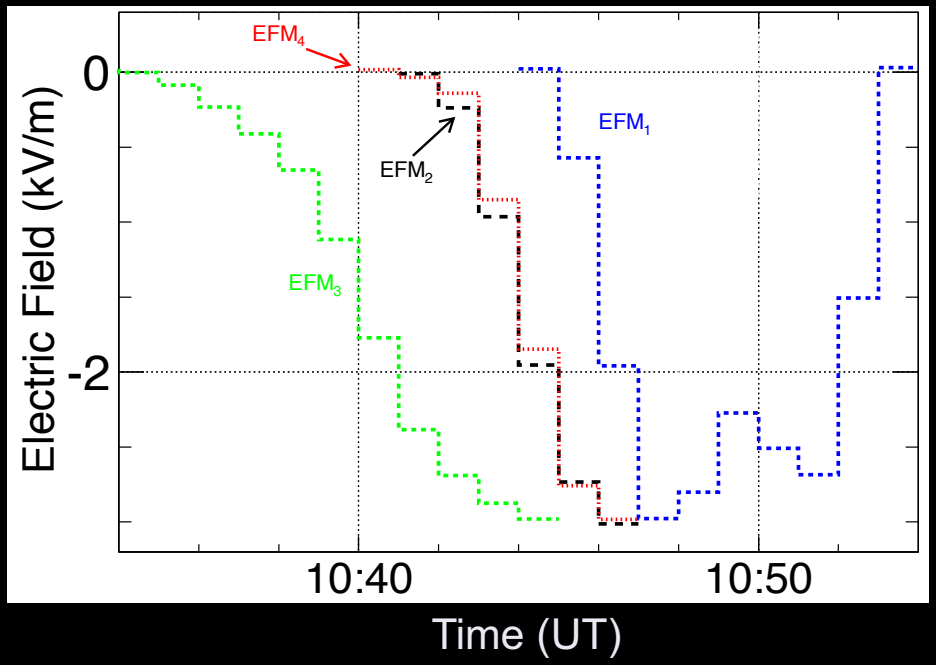
Time (UT)

- $\Delta I_{\mu(Peak)}$ = (-2 ± 0.2) %
- V_{Peak} = (0.90 ± 0.08) GV

EFMs

- 4 Monitors
- Maximum distance of 6 km





- Velocity = 60 km hr^{-1}

Cloud Movement

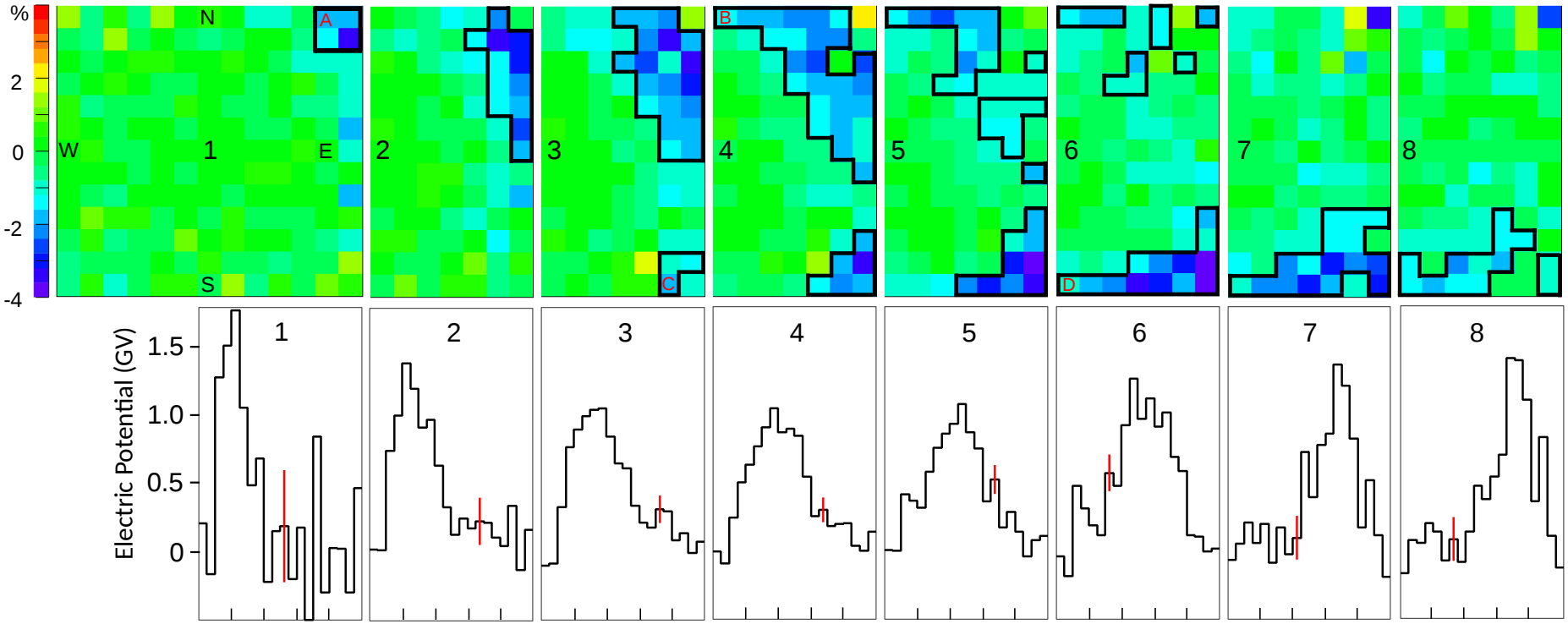


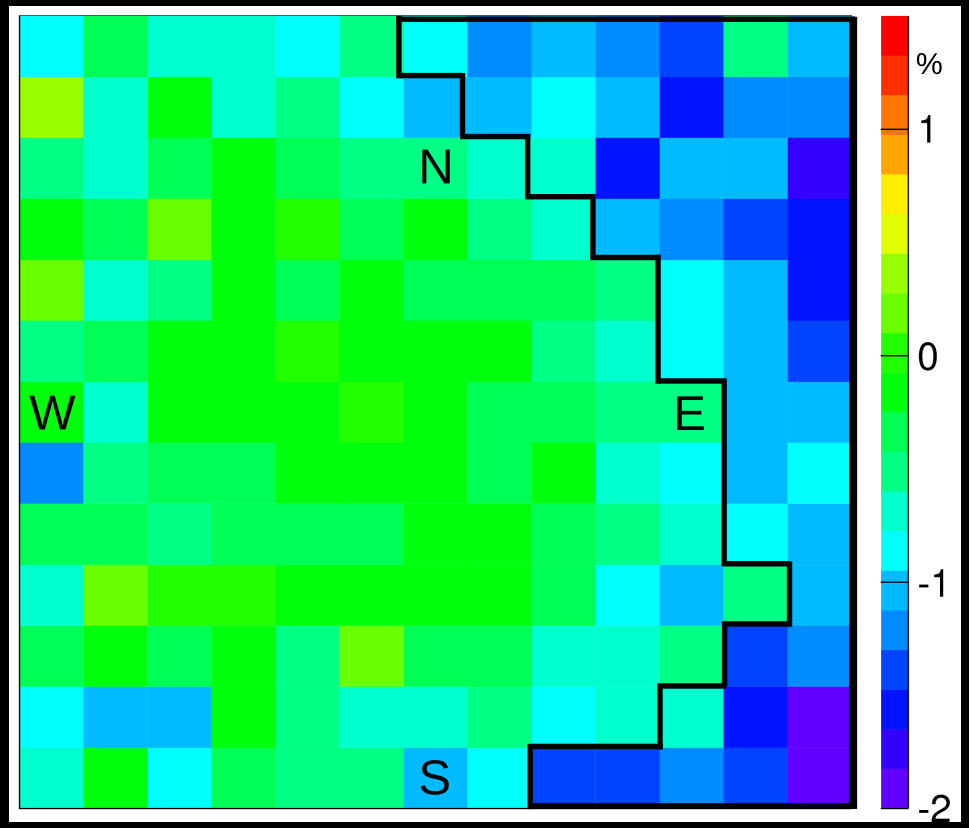
Image	Dir	V (GV)
1	4	1.8
2	12	1.4
3	23	1.0
4	32	1.0

Image	Dir	V (GV)
5	28	1.1
6	23	1.2
7	16	1.3
8	13	1.4

- Mean V = 1.3 GV
- Angular Velocity = 6.2° min^{-1}

Electrical Properties

- Mean V = 1.3 GV
- Lin. Vel. = 60 km hr^{-1}
- Ang. Vel. = 6.2° min^{-1}
- Height = 11.4 km amsl
- Radius ≥ 11 km
- Area ≥ 380 km^2
- C ≥ 0.85 μF
- Q ≥ 1100 C
- E ≥ 720 GJ
- P ≥ 2 GW



- Comparable to biggest nuclear reactor / hydroelectric / thermal power plants
- Enough to power a big town

Physical Review Letters 122, 105101 (2019)
(Focus article & Editors' suggestion)

Attraction

TH Ooty's muon detection facility

SCIENCE

Ooty's muon detecti
potential of thunder

nature

PHYSICS · 22 MA

Supercha
1.3 billion

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Researchers used a cosmic ray detector to clock one storm in at a shocking 1.3 billion volts

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BREITBART

'RAT INFESTED' BALTIMORE AL SHARPTON GILROY SHOOTING

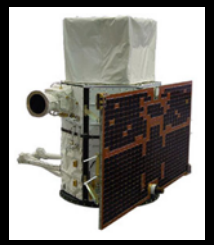
ERSTORM HAD ELECTRIC
POTENTIAL OF 1.3B VOLTS

Summary

B. Franklin Charging mechanism

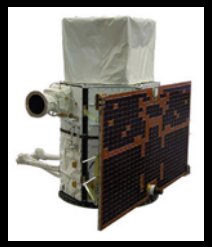
1750s

Discovery of TGFs



1994

Detection of 100 MeV γ-ray in TGFs

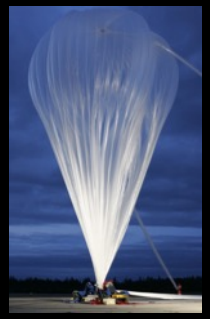


2011

1920s

C.T.R. Wilson's prediction of 1GV 90Y ago

2001



Measurement of 0.13 GV

2019

Measurement of 1.3 GV

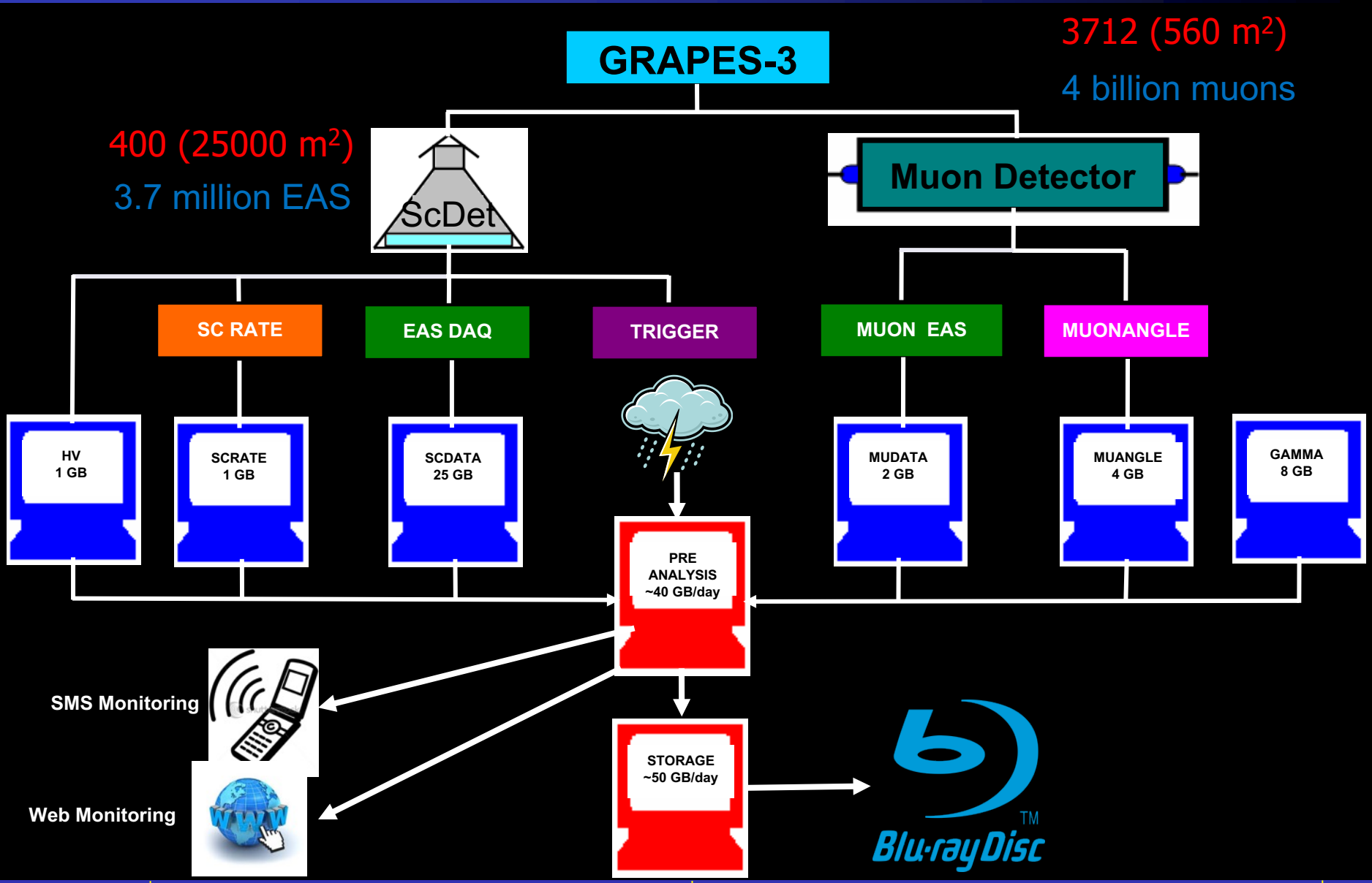
Future prospects

- More data → More events
- Is there an "incredible hulk" ?
- Any upper limit?
- Angular distribution?
- Short-term acceleration?
- Correlation with TGFs?
- γ-rays at ground?

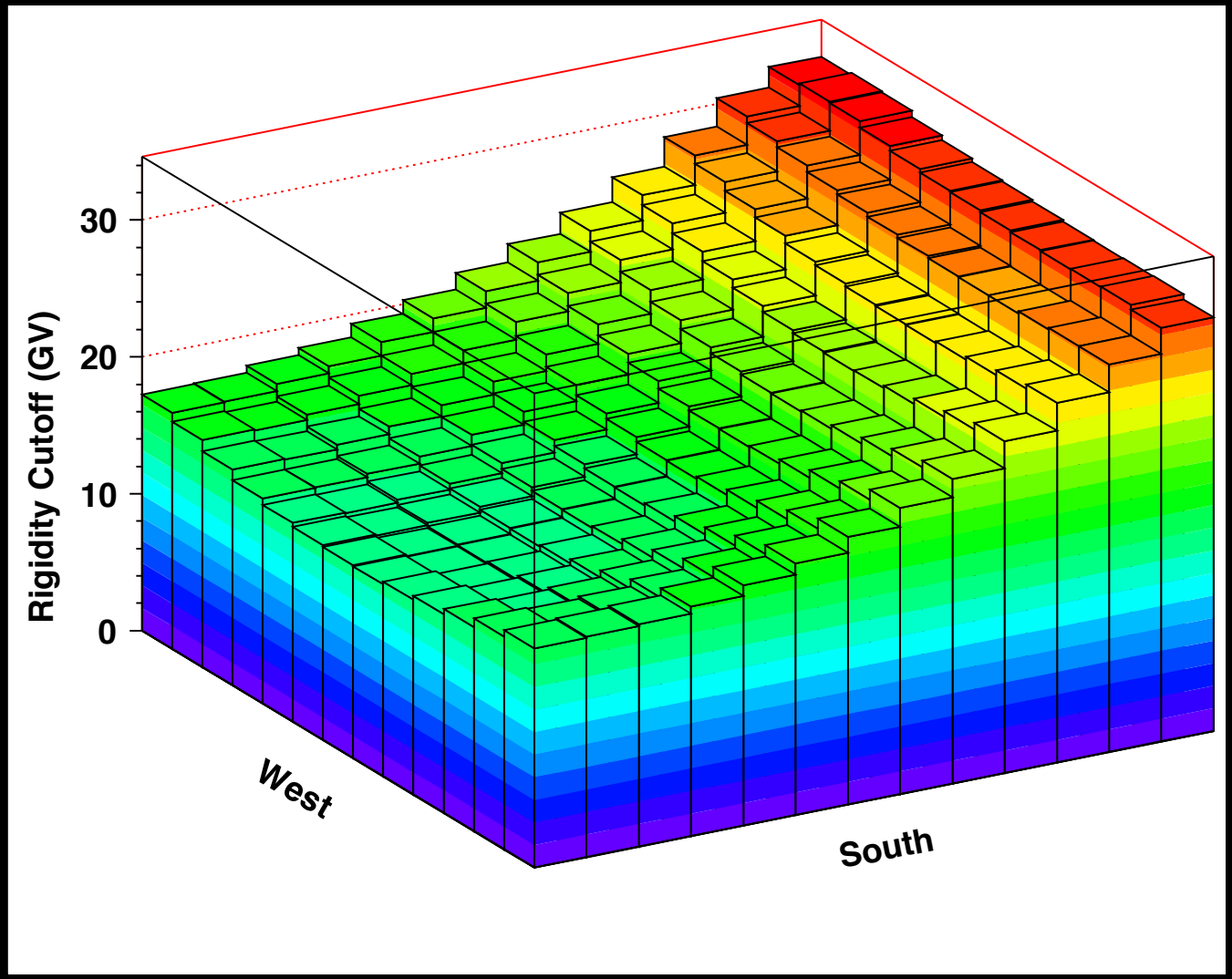
Thank You All

Backup Slides

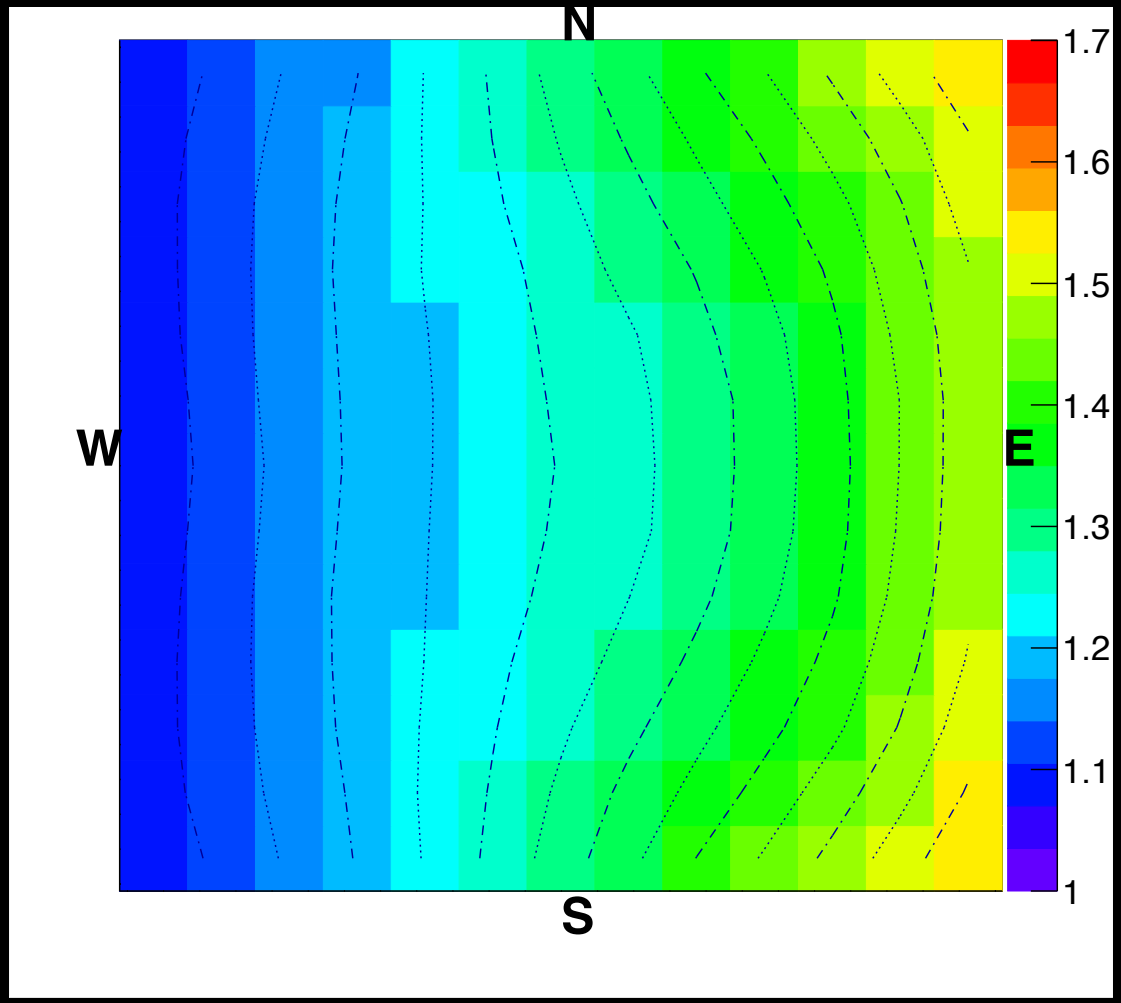
GRAPES-3 DAQ


GRAPES-3
3712 (560 m²)
4 billion muons
400 (25000 m²)
3.7 million EAS
ScDet
Muon Detector
SC RATE
EAS DAQ
TRIGGER
MUON EAS
MUONANGLE
HV
1 GB
SCRATE
1 GB
SCDATA
25 GB
MUDATA
2 GB
MUANGLE
4 GB
GAMMA
8 GB
PRE
ANALYSIS
~40 GB/day
SMS Monitoring
Web Monitoring
STORAGE
~50 GB/day
Blu-ray Disc

Cutoff Rigidity



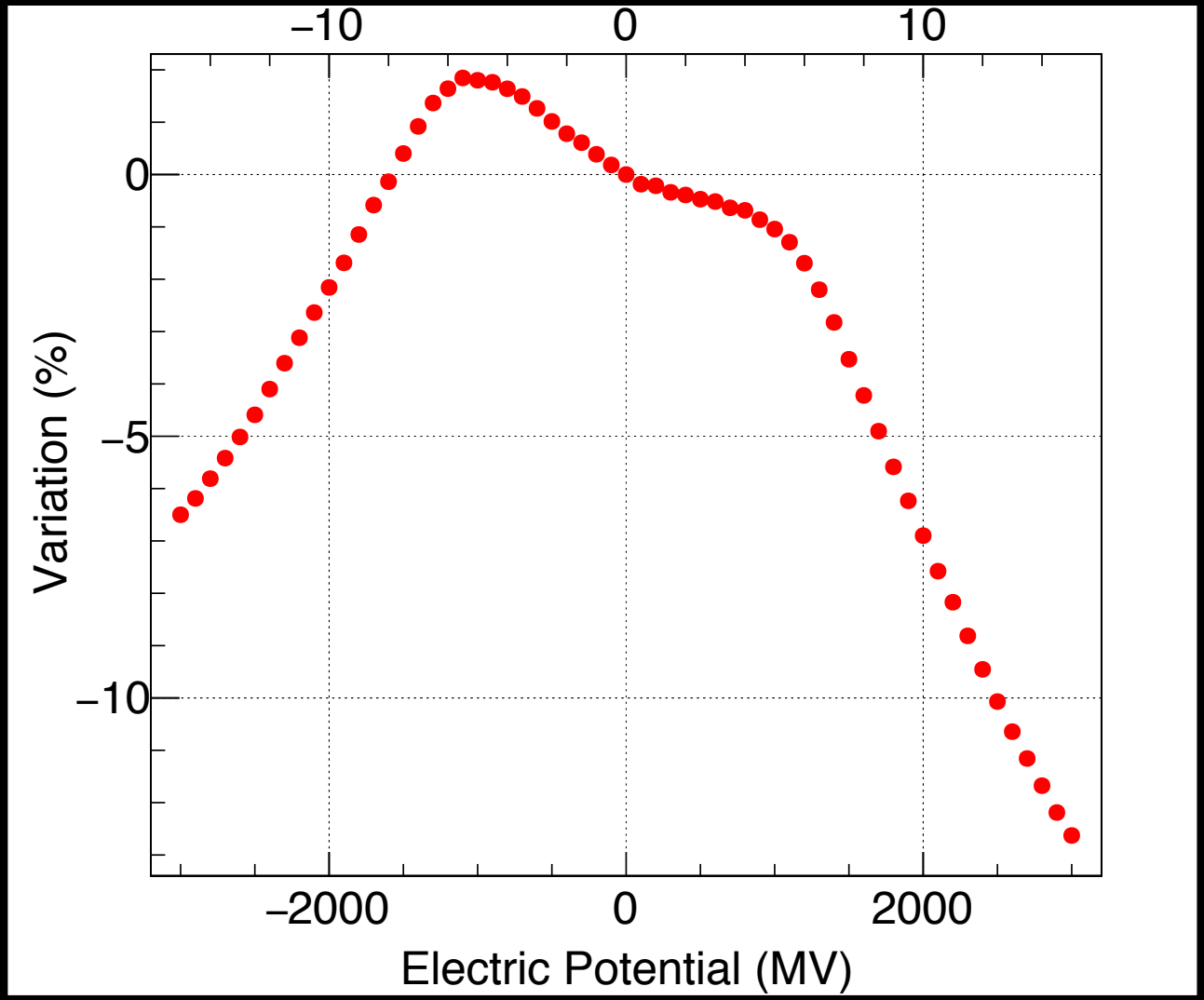
Muon Charge Ratio



Monte Carlo Simulation

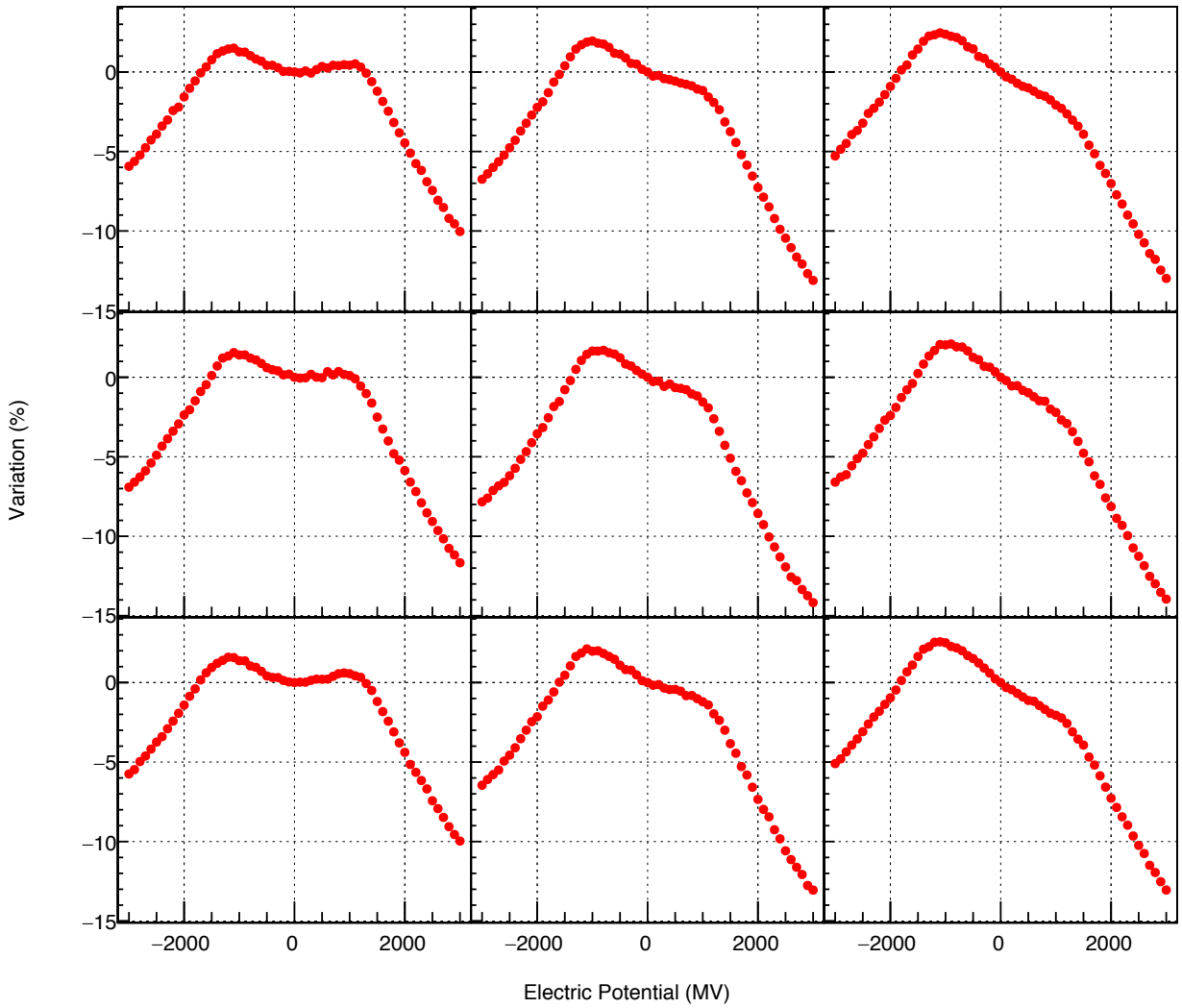
- CORSIKA v74001
  - ✓ SIBYLL-FLUKA
- Cloud region with simple dipole
  a) 8-10 km asl
  b) 2.2-10 km asl
  c) 10-20 km asl
- -3 to +3 GV (0.1 GV steps)
- 10^6 muons in each of 169 directions, 10^7 for BG
- ~10^{10} proton EAS (10 GeV – 10 TeV)
- Geomagnetic cutoff rigidity validation
- Detector simulation
- 1 month of simulation time

Monte Carlo Simulation

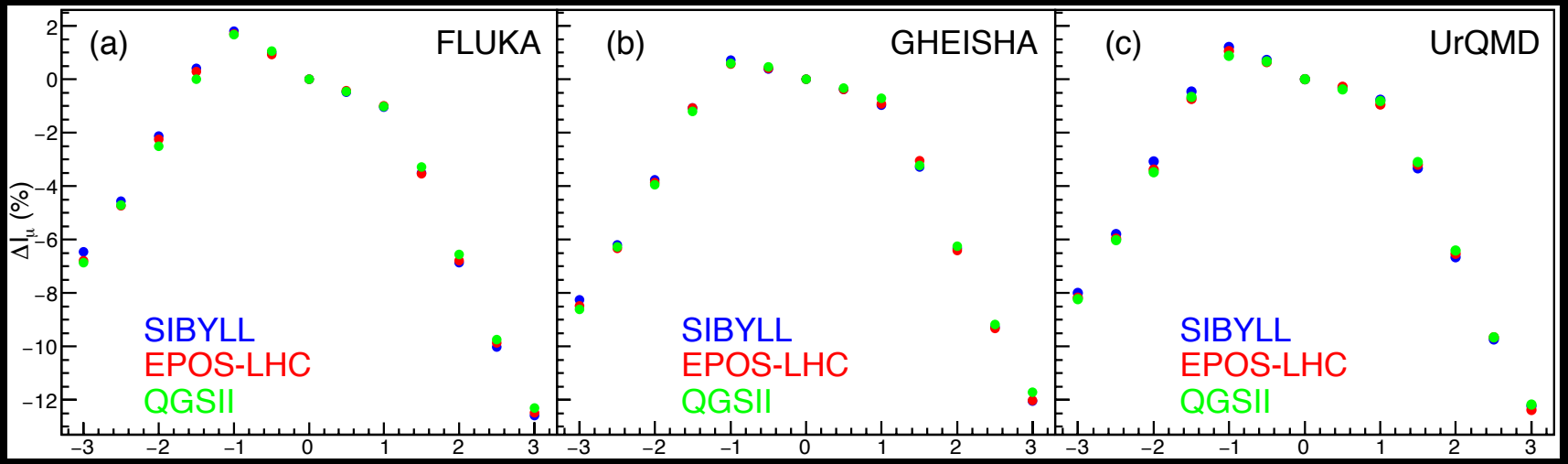


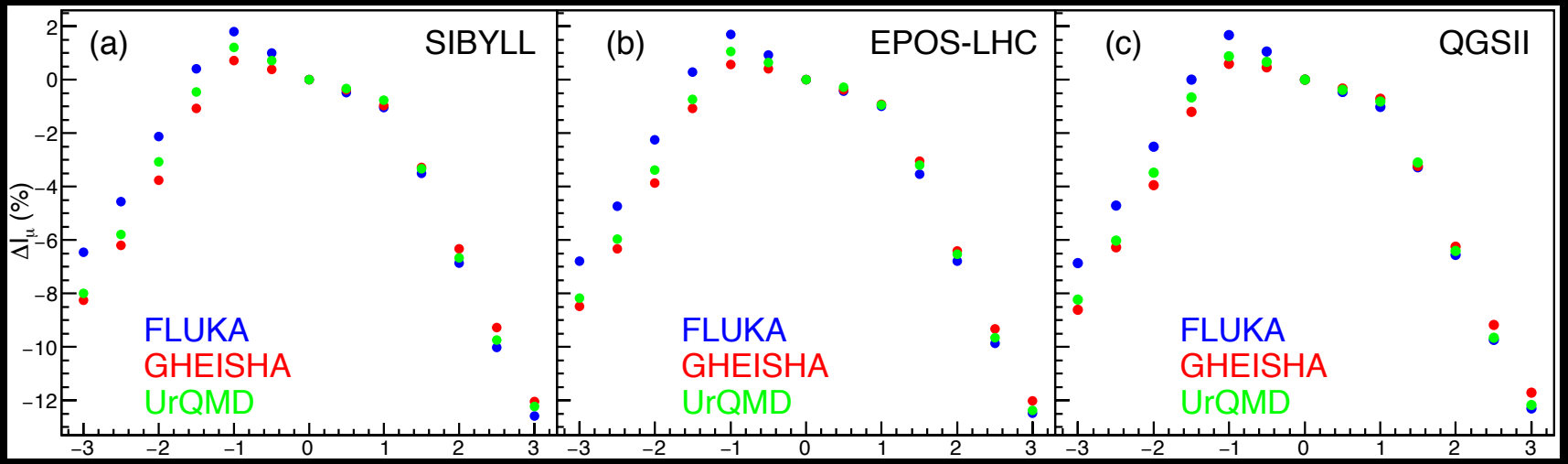
$\mu^+/\mu^- > 1$

9 Direction Simulation



Hadronic Model Dependence





Hadronic Model Dependence

	FLUKA	GHEISHA	UrQMD
SIBYLL	0.89 ---	1.07 (20%)	1.00 (12%)
EPOS-LHC	0.93 (4%)	1.07 (20%)	0.97 (9%)
QGSJETII	0.96 (8%)	1.12 (26%)	1.03 (16%)

Electric Potential is in Giga-Volts
(% difference wrt SIBYLL-FLUKA)

Conservative Estimate of Potential

- Hadronic model
  - Gheisha - +15%
  - UrQMD - +6%
- Cloud height
  - 2.2-10 km - 0%
  - 10-20 km - +15%

Area Covered by 169 Directions (at 11.4 km)

2.3	2.3	2.3	2.5	2.8	3.1	3.3	3.1	2.8	2.5	2.3	2.2	2.3
2.3	1.9	1.9	2.1	2.3	2.6	2.8	2.7	2.4	2.1	2.0	1.9	2.3
2.3	1.9	1.9	2.1	2.3	2.6	2.7	2.6	2.3	2.1	1.9	1.9	2.3
2.5	2.1	2.1	2.3	2.6	2.8	3.0	2.8	2.5	2.3	2.1	2.1	2.7
2.8	2.3	2.3	2.5	2.8	3.2	3.4	3.2	2.8	2.5	2.3	2.3	3.1
3.3	2.6	2.6	2.9	3.1	3.6	3.7	3.5	3.2	2.9	2.6	2.6	3.5
3.5	2.8	2.8	3.0	3.4	3.8	4.0	3.8	3.4	3.0	2.7	2.7	3.6
3.5	2.6	2.6	2.8	3.2	3.6	3.8	3.5	3.2	2.8	2.6	2.6	3.2
3.0	2.3	2.3	2.5	2.8	3.1	3.4	3.2	2.8	2.6	2.3	2.3	2.8
2.6	2.1	2.1	2.3	2.5	2.8	3.0	2.8	2.5	2.3	2.1	2.1	2.5
2.3	1.9	1.9	2.1	2.3	2.6	2.8	2.6	2.3	2.1	1.9	1.9	2.3
2.3	1.9	1.9	2.1	2.4	2.6	2.8	2.6	2.4	2.1	1.9	1.9	2.3
2.3	2.2	2.3	2.6	2.8	3.2	3.4	3.2	2.8	2.5	2.3	2.3	2.3

Calculation of parameters

- Cloud Height
  - 1 km min^{-1} / (6.2° km min^{-1}) + 2.2 km = 11.4 km
- Radius
  - R = Sin(74.6)*11.4 km = 11.0 km
- Area
  - A = 3.14159 * 11^2 km^2 = 380 km^2
- Capacitance
  - C = 8.8 x 10^{-12} x 380 km^2 / 2 km = 1.7 x 10^{-6} F
  - C = 50% of above = 0.85 x 10^{-6} F

Calculation of parameters

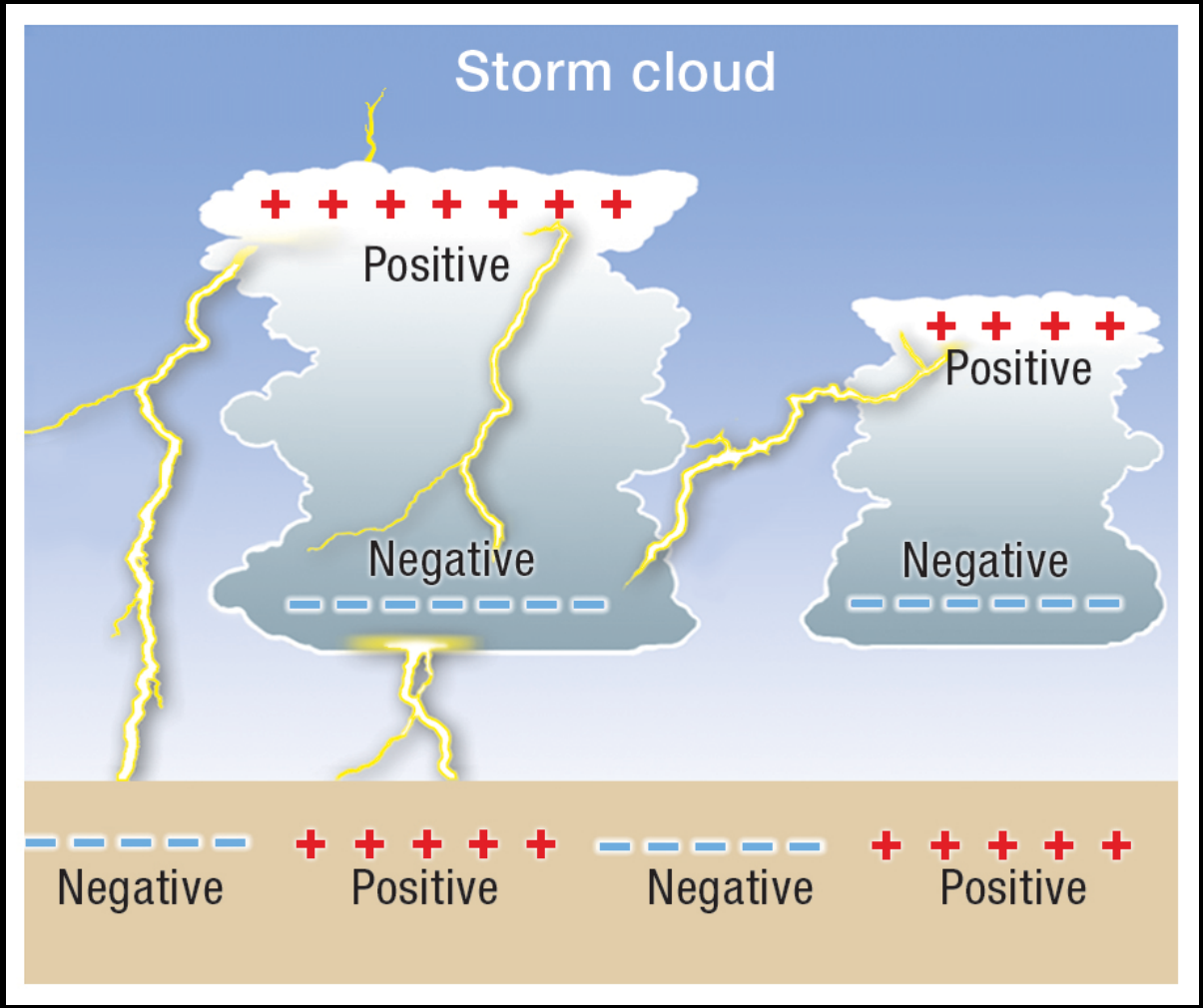
- Charge
  - $Q = 0.85 \times 10^{-6}$ F $\times 1.3 \times 10^{9}$ V = 1105 C
- Energy
  - $E = 1100$ C $\times 1.3 \times 10^{9}$ V / 2 = 720×10^{9} J
- Power
  - $P = 720 \times 10^{9}$ / (6 min x 60 sec) = 2×10^{9} W

Electric Energy Consumption

- World
  - 20900 TWh
- India
  - 940 TWh

- 1 Wh = 3600 J
- For 720×10^9 J = 2×10^8 Wh

Power Generation

- World biggest nuclear reactor
  - 1100 MW
- Hydro
  - 700 MW
- Thermal
  - 800 MW

Cumulonimbus Cloud