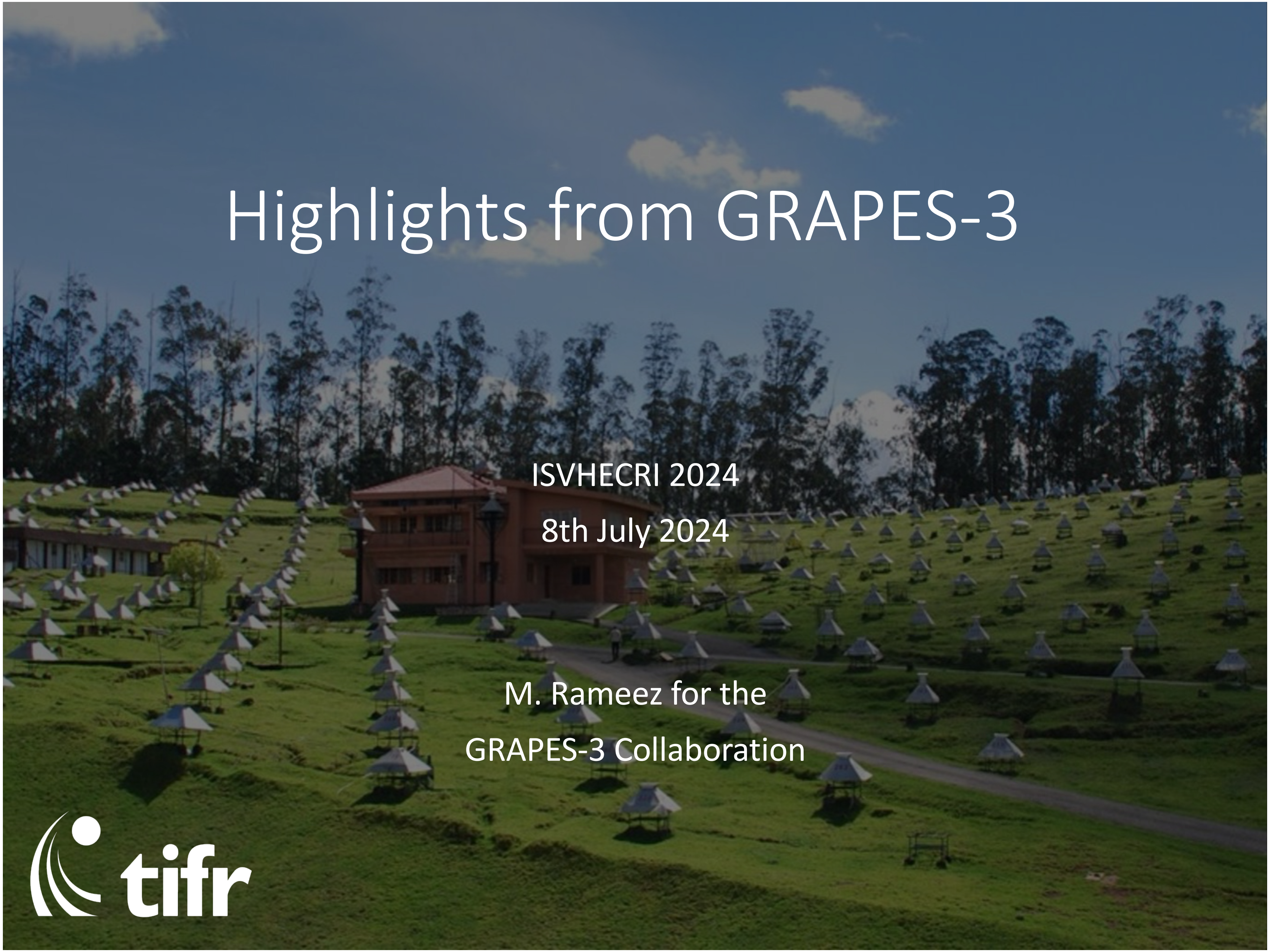


Highlights from GRAPES-3

ISVHECRI 2024

8th July 2024

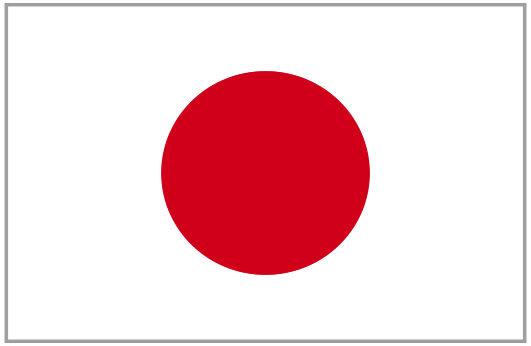
M. Rameez for the

GRAPES-3 Collaboration

tifr

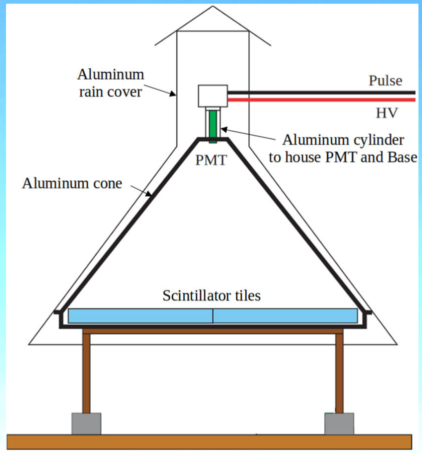
GRAPES-3 Collaboration

1. Tata Institute of Fundamental Research, Mumbai
2. J.C. Bose Institute, Kolkata
3. Indian Institute of Science & Edu. Res., Pune
4. Aligarh Muslim University, Aligarh
5. Indian Institute of Technology, Kanpur
6. North Bengal University, Silguri
7. Vishwakarma Inst. Of Information Tech., Pune
8. Utkal University, Bhubaneswar
9. Dibrugarh University, Dibrugarh
10. Tezpur University, Tezpur
11. Indian Institute of Technology, Jodhpur
12. Indian Institute of Technology, Indore
13. Amity University, Noida
14. Institute of Physics, Bhubaneswar



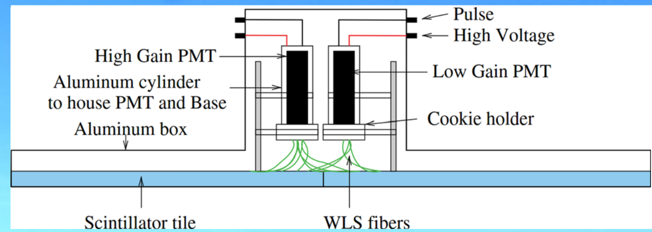
1. Osaka City University, Osaka
2. Aichi Institute of Technology, Aichi
3. Chubu University, Kasugai, Aichi
4. Hiroshima City Univeristy, Hiroshima
5. Kochi University, Kochi
6. Nagoya University, Nagoya
7. ICRR, Tokyo University

Gamma Ray Astronomy at PeV EnergieS - 3



Cone type

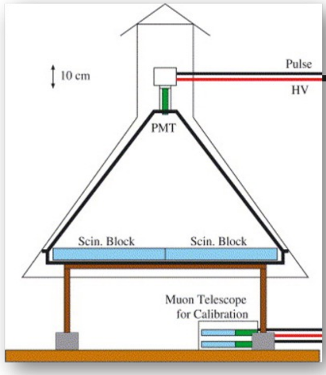
- 400 Plastic scintillators (1m^2 area)
- 8 m inter-detector separation
- 25000 m^2 area
- 3 million EAS / day (1 TeV – 10 PeV)



Fiber type

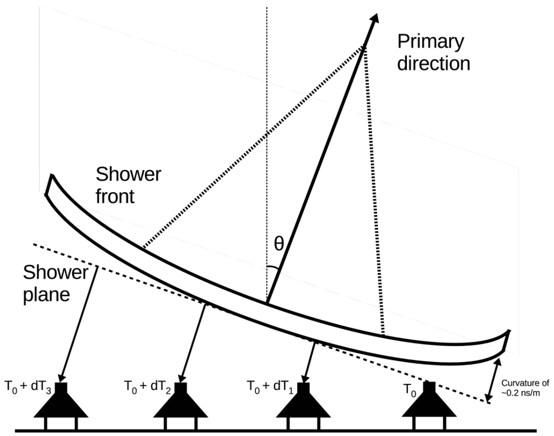
EAS Array

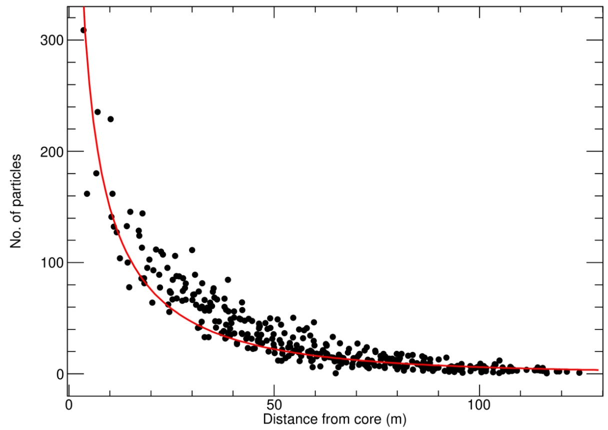
Observables

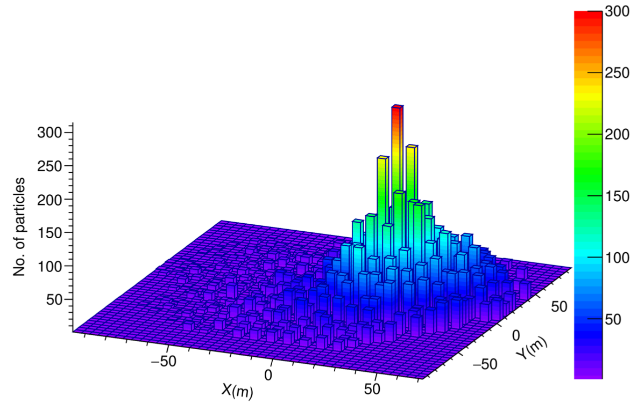


ADC → Pedestal → Calibration → Det. Gain → No. Of Particles

TDC → TDC Offset (Random walk) → Time of Flight





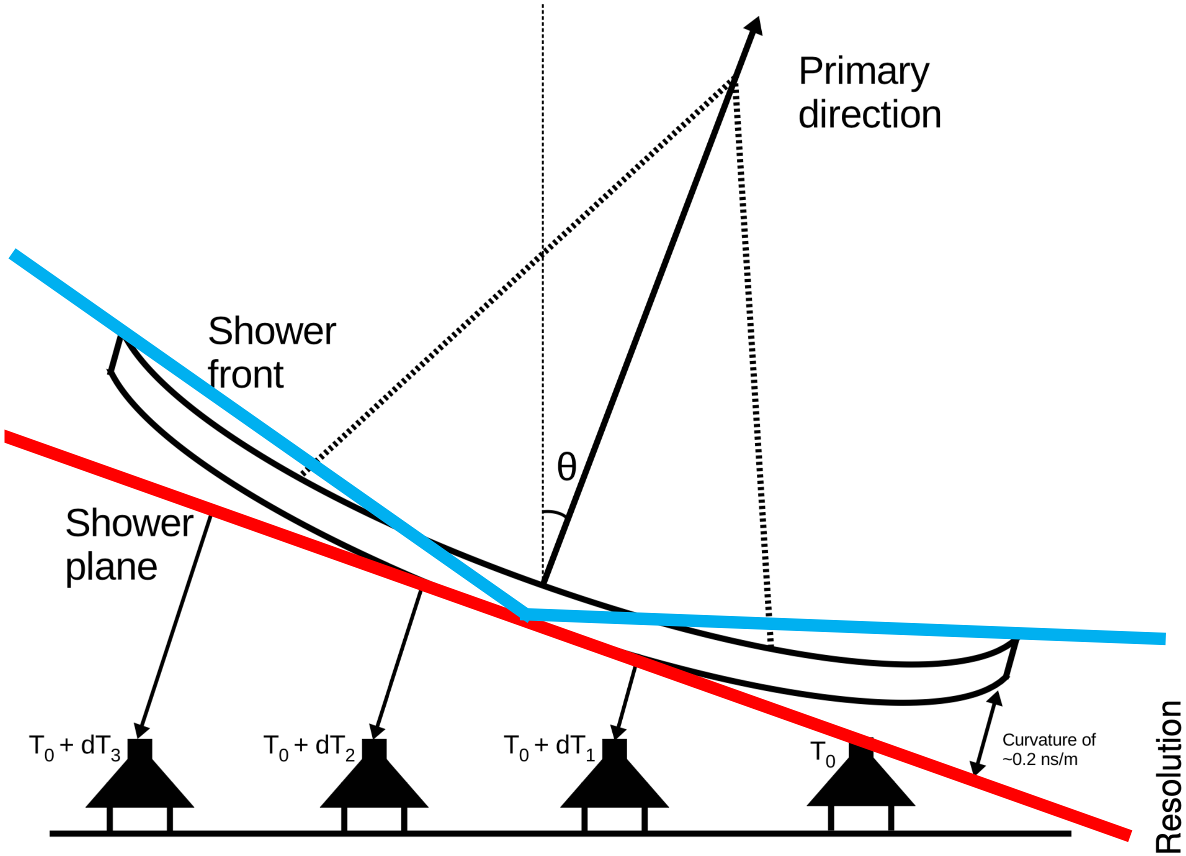


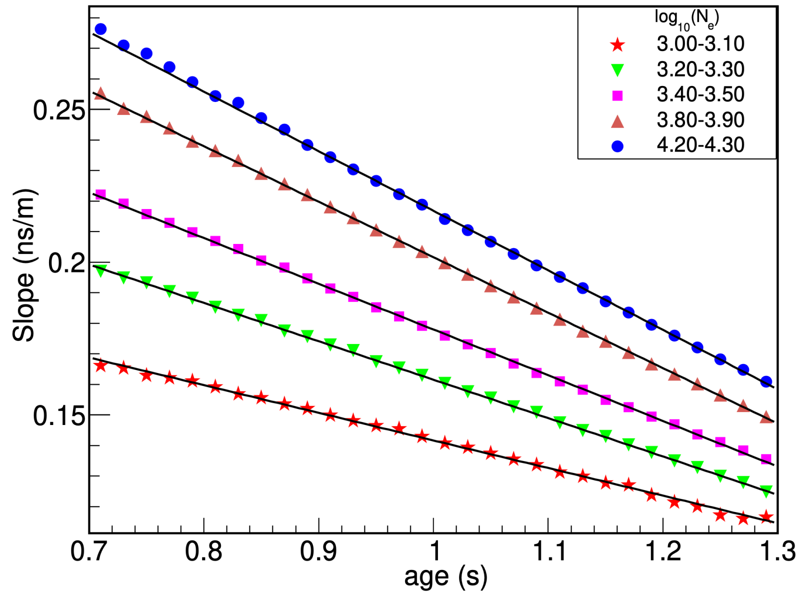
Direction (θ, ϕ)

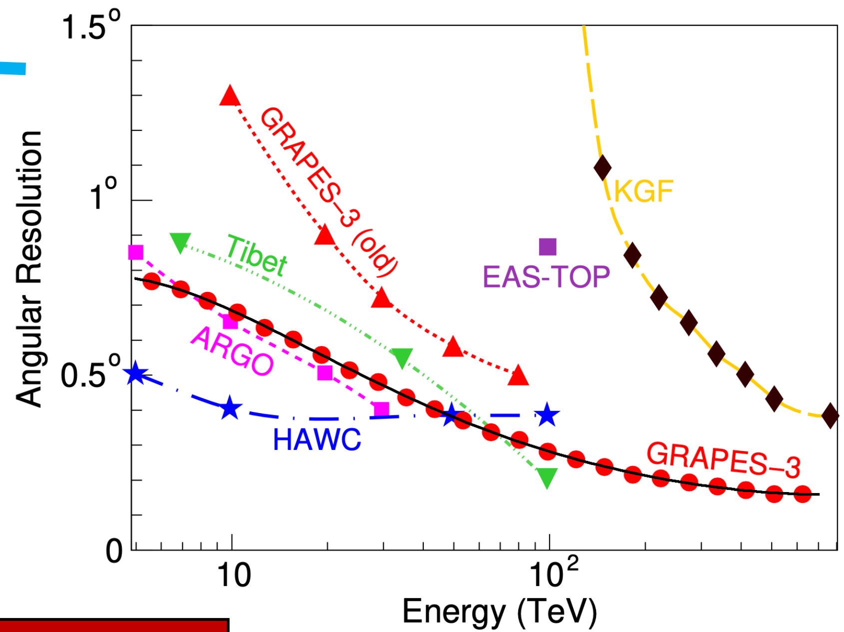
Age (s), Size (N_e), Energy ?

Core (X_C, Y_C)

Shower Front Correction







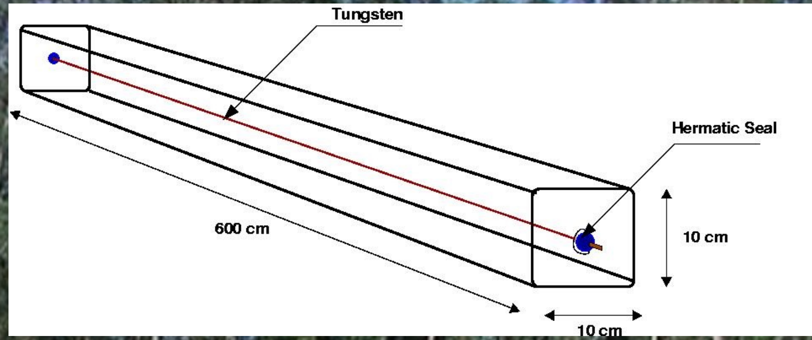
Traditional (Plane fit)

Improved (Cone fit)

Curvature correction with shower age and size

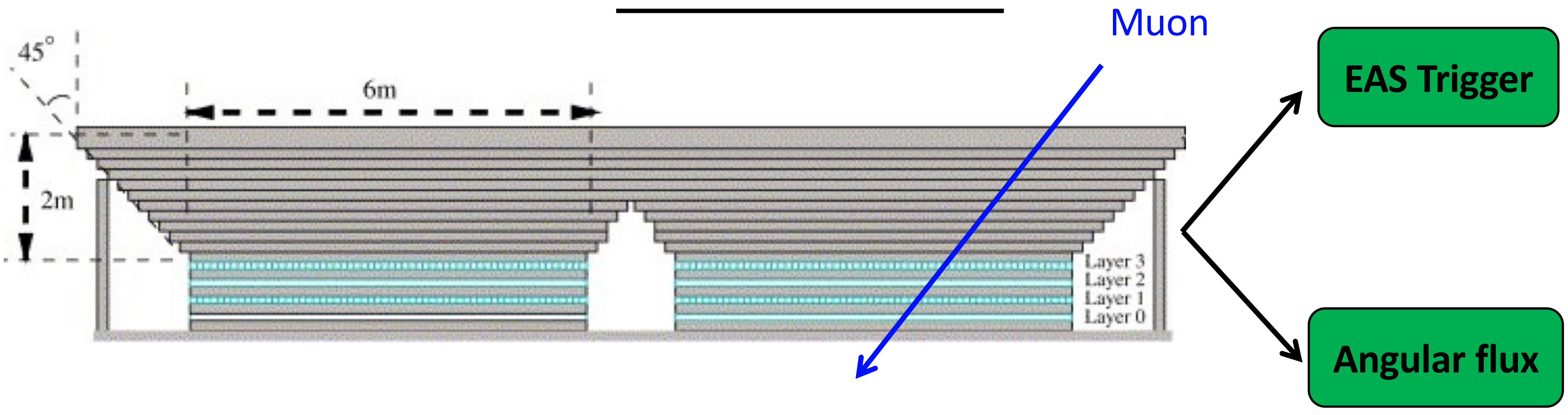
V.B. Jhansi et al., JCAP07(2020)024

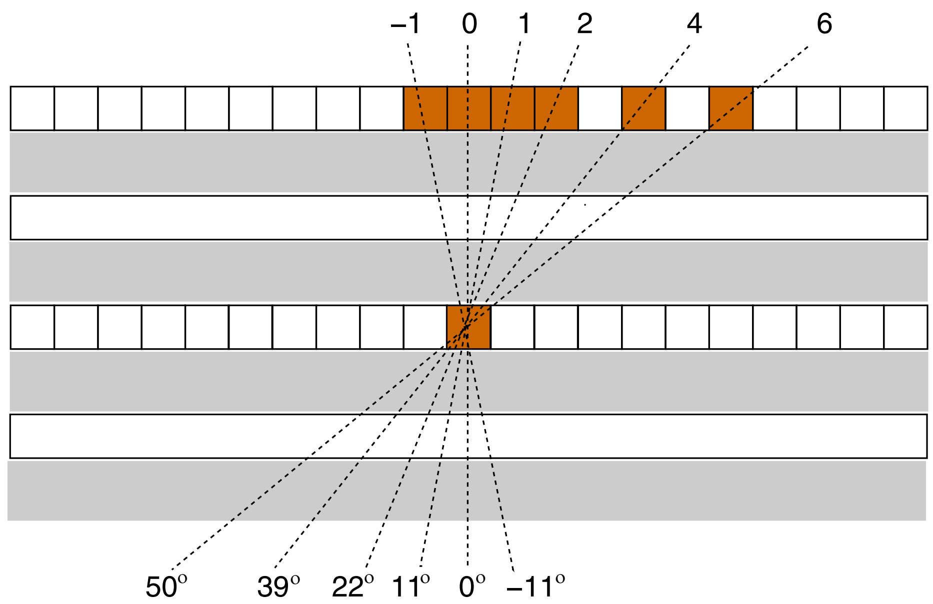
Muon Telescope

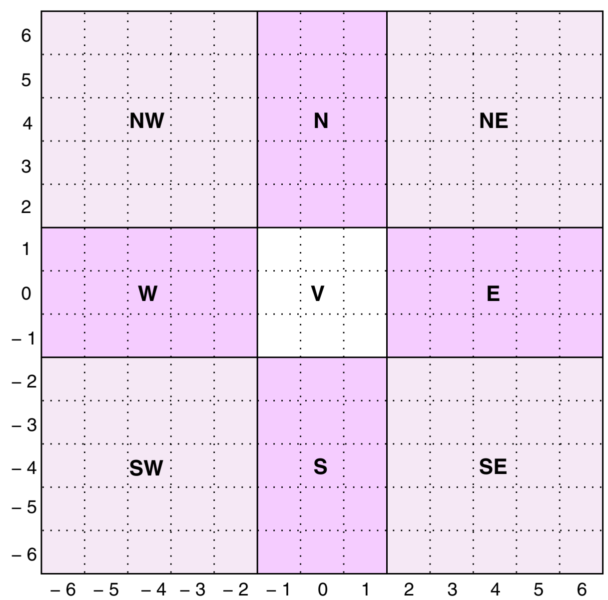


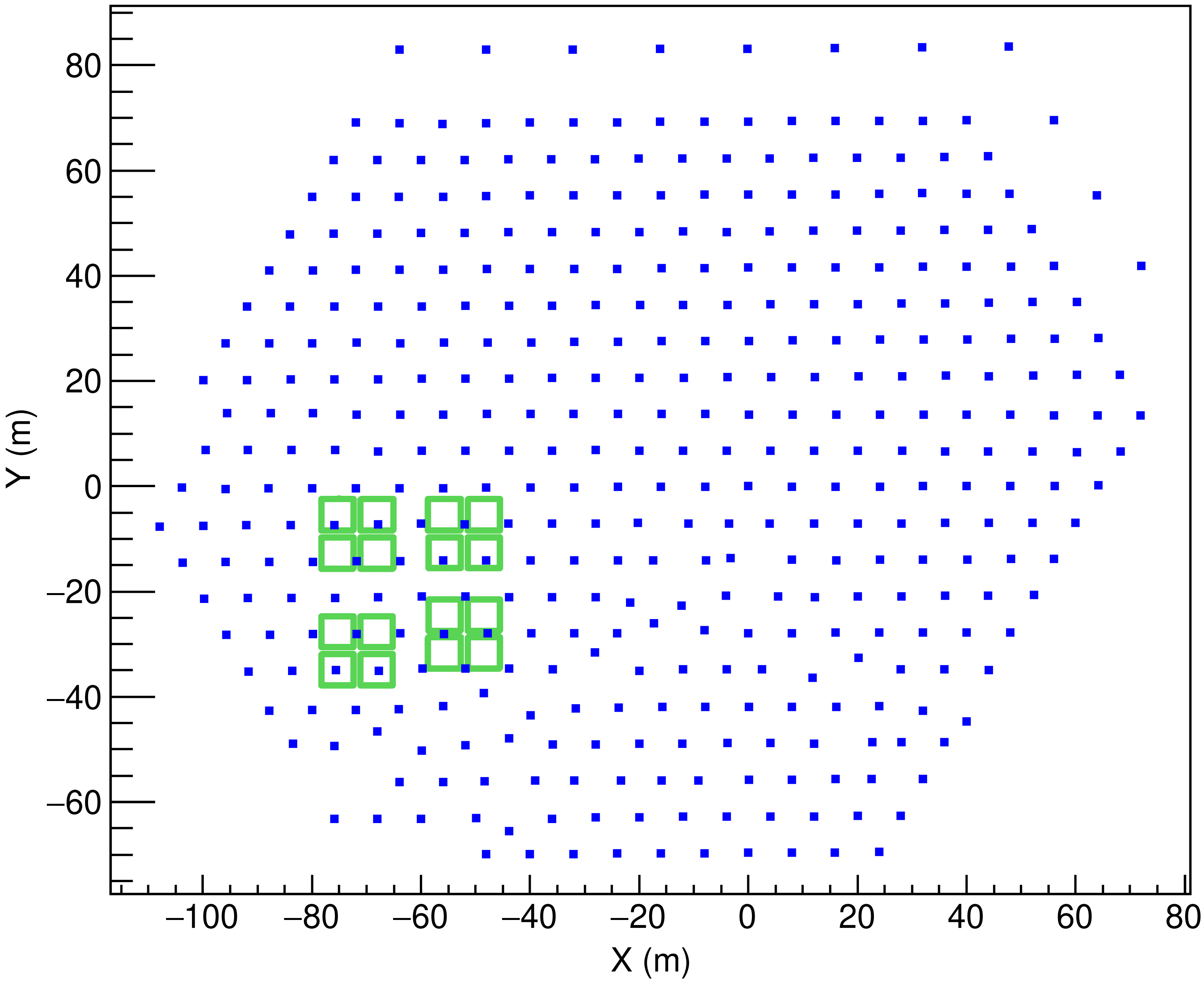
- 16 muon modules
- 3712 PRCs
- Area: 560 m^2
- Energy threshold: sec(θ) GeV
- 169 directions covering 2.3 sr
- 4° angular resolution
- 4 billion muons / day

Observables

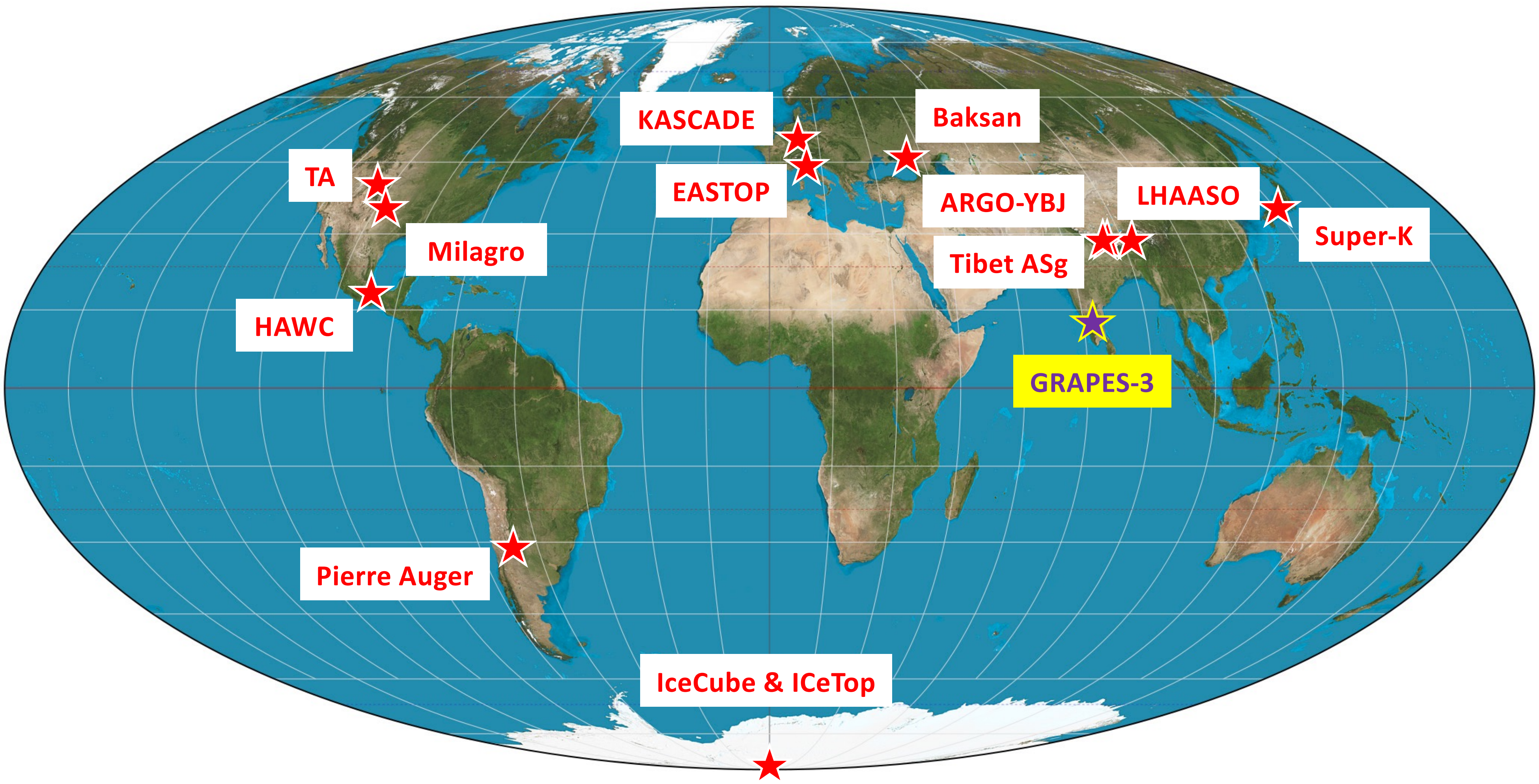






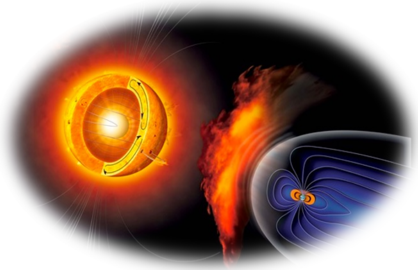


Y (m)
80
60
40
20
0
−20
−40
−60
−100
−80
−60
−40
−20
0
20
40
60
80
X (m)



11.4° N, 76.7° E, 2200 m amsl

Physics Analyses

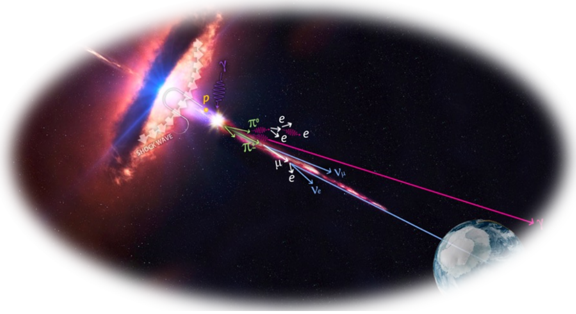


Solar & Heliospheric

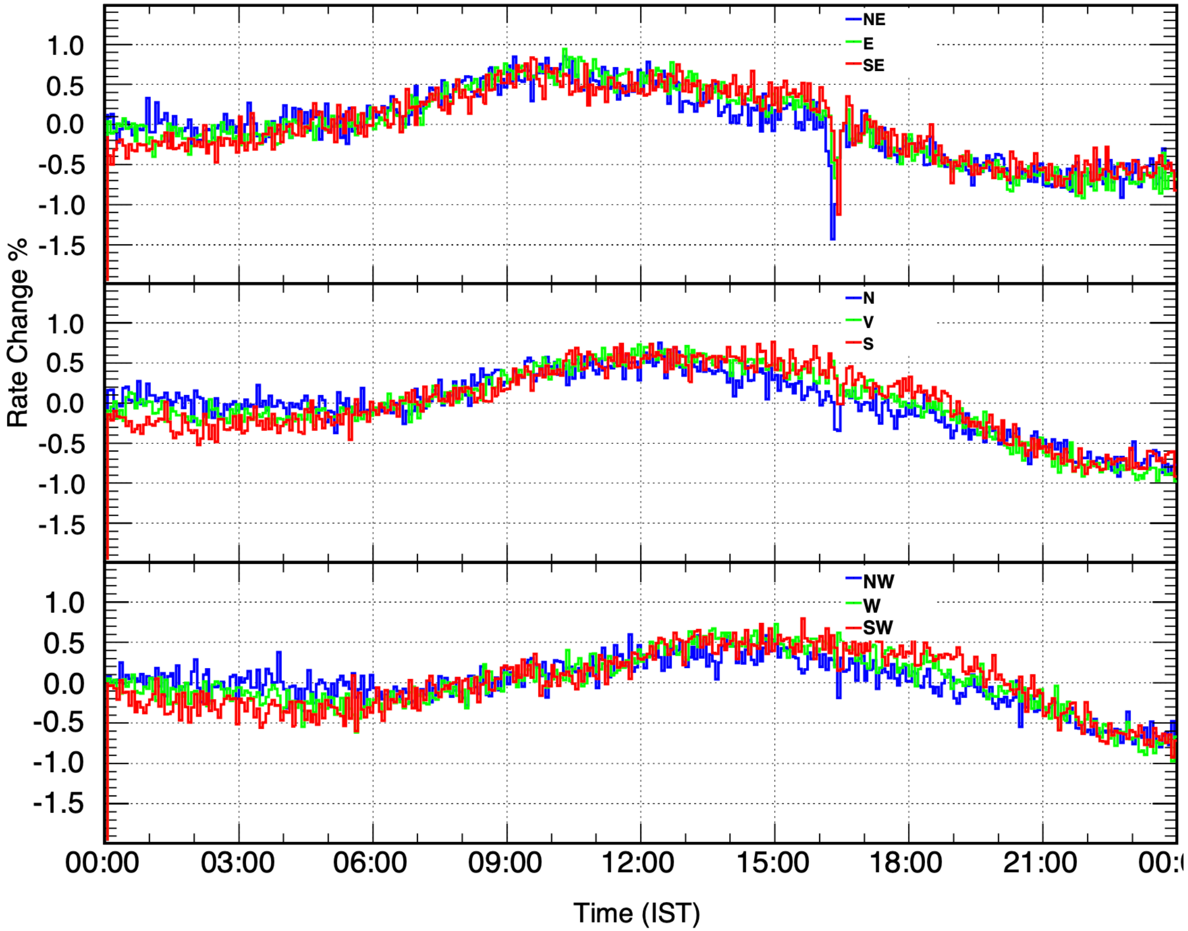
10^{9} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} (eV)

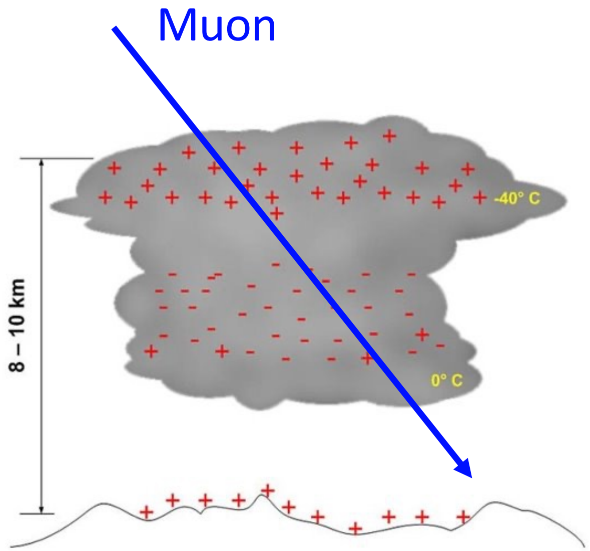
Atmospheric

Cosmic rays

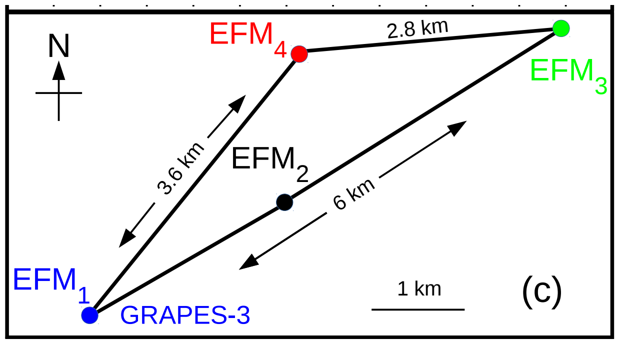


Atmospheric Acceleration



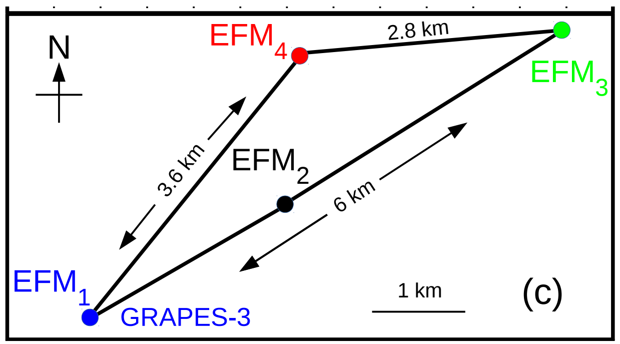


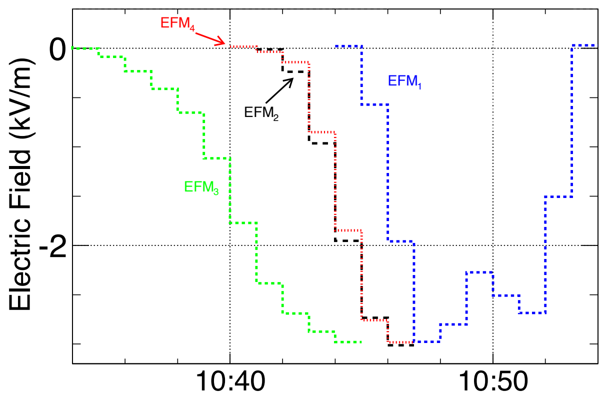
~50 events / year

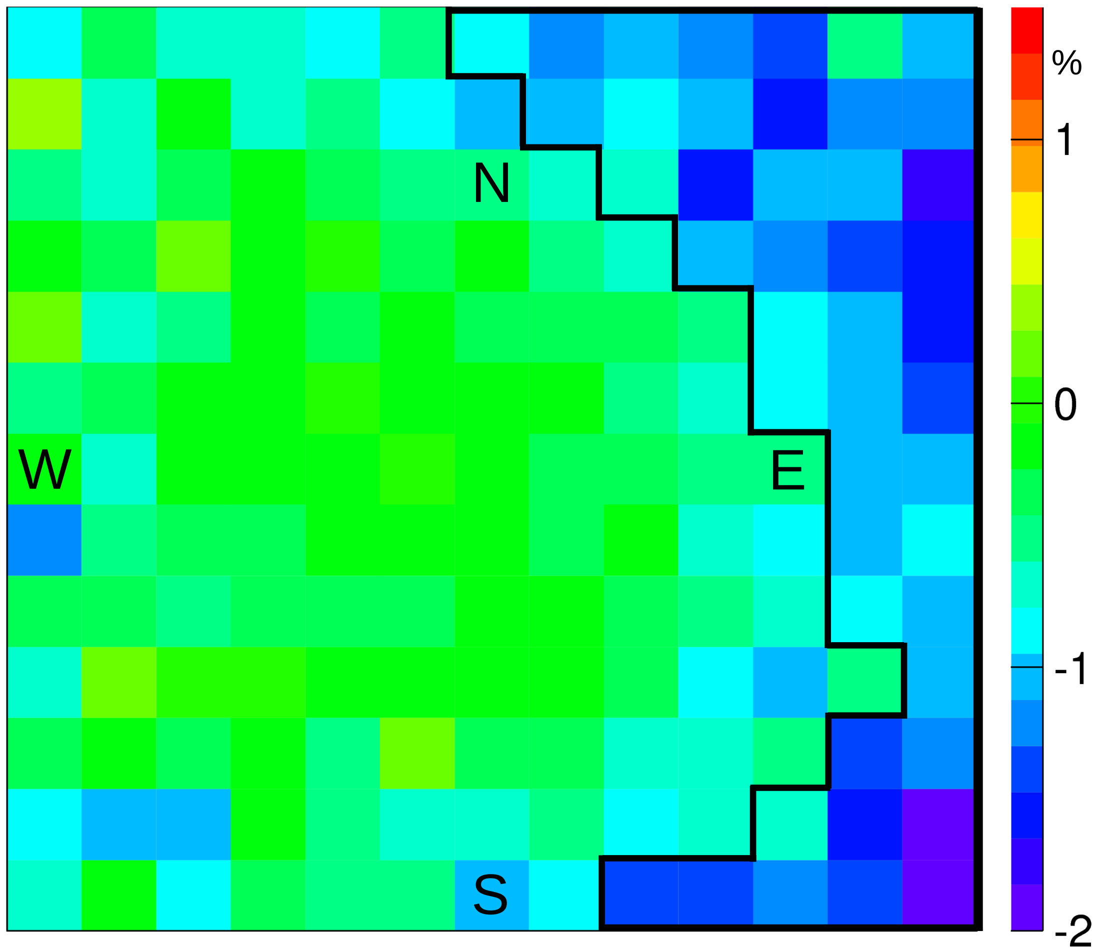


1 Dec 2014 – 18 minutes long

Muon Image of 1 Dec 2014







18 minutes

45 directions

Cloud Movement

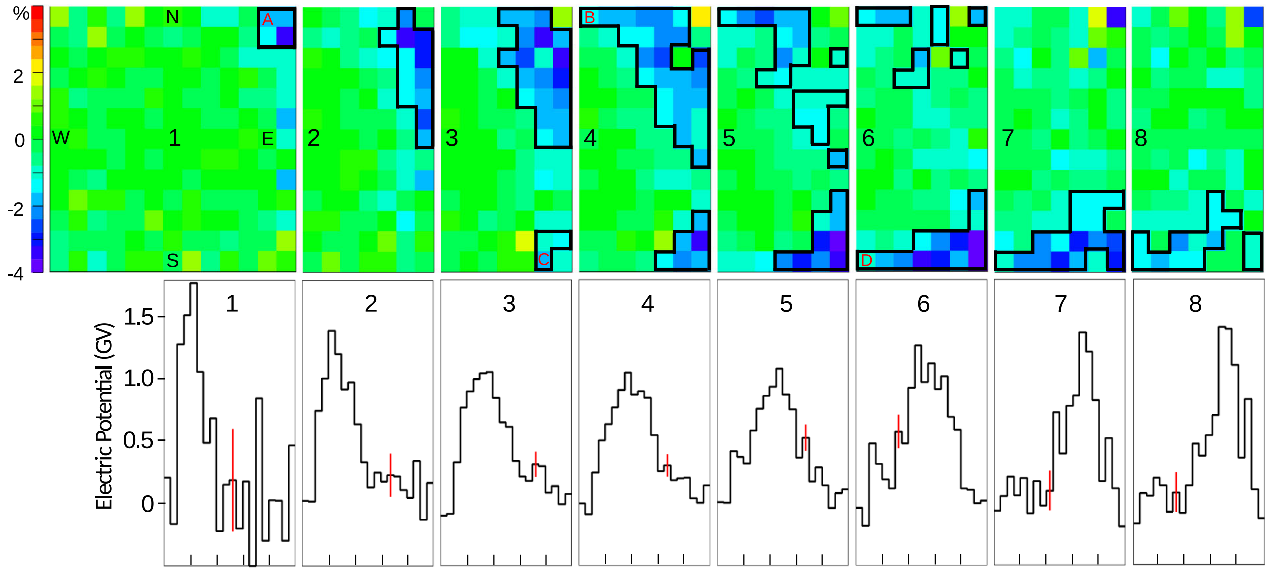


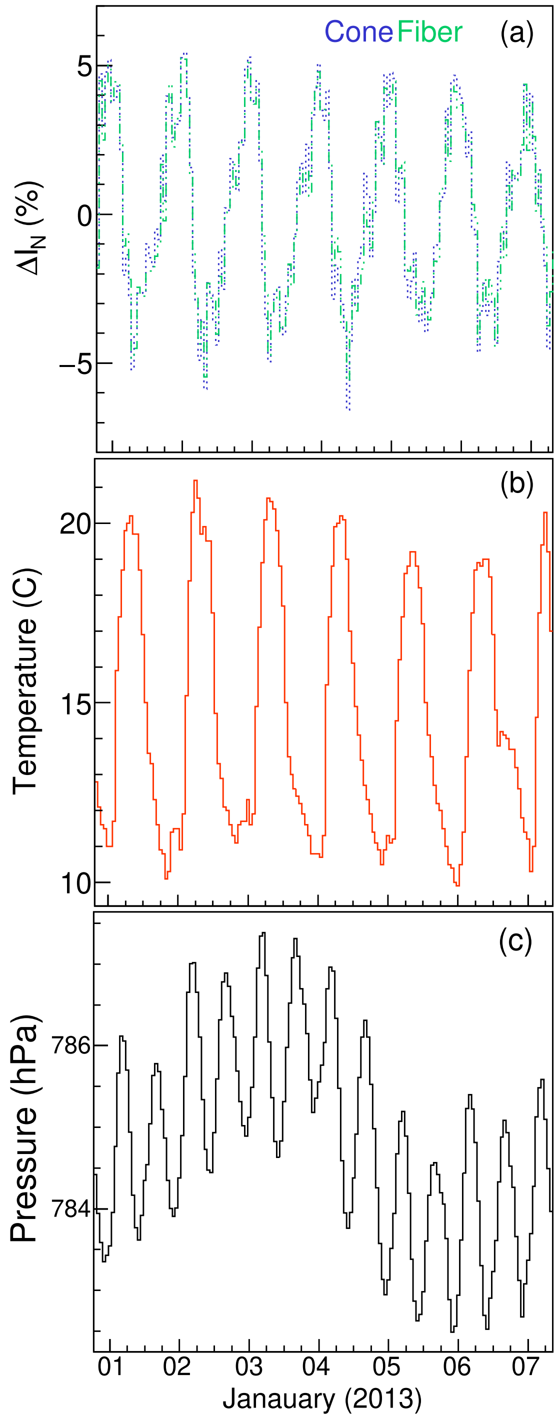
FIG. 7. Top eight panels show affected directions for successive 2 min exposures starting December 1, 2014 at 10:42 UT. Bottom eight panels show estimated potentials needed to reproduce ΔI_{μ} shown in the corresponding panel above for a 20 min duration (10:41–11:00 UT). Maximum potentials of 1.8, 1.4, 1, 1, 1.1, 1.2, 1.3, and 1.4 GV (mean = 1.3 GV) observed for panels labeled 1 through 8. Angular velocity of 6.2° min^{-1} inferred for directions (i) **A** to **B**, and (ii) **C** to **D** in northern and southern FOVs, respectively, are shown in Fig. 1(d). Vertical bar in each bottom panel corresponds to $\pm 1\sigma$ error.

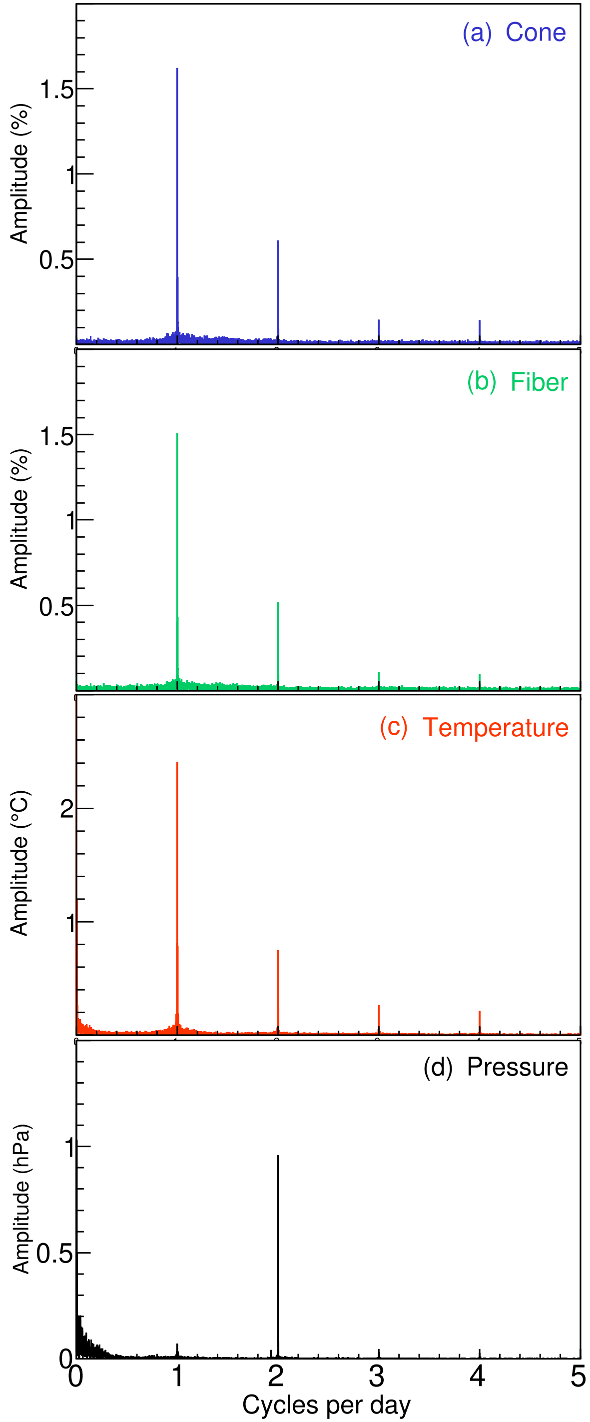
C.T.R. Wilson's prediction of 1 GV 90Y ago

Measurement of 0.13 GV

Mean V = 1.3 GV

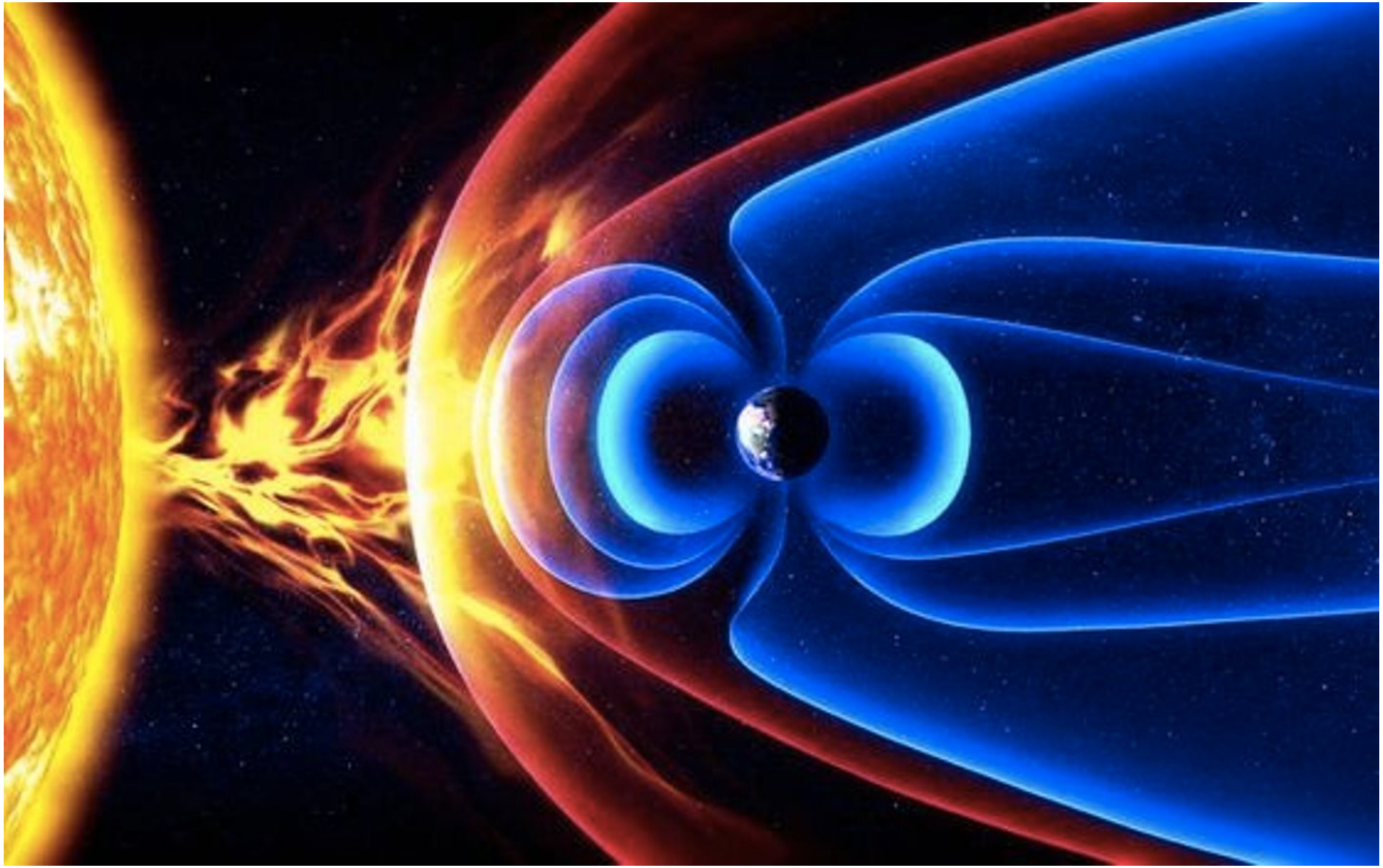
B. Hariharan et al., PRL 122, 105101 (2019)
(Focus article & Editors' suggestion)



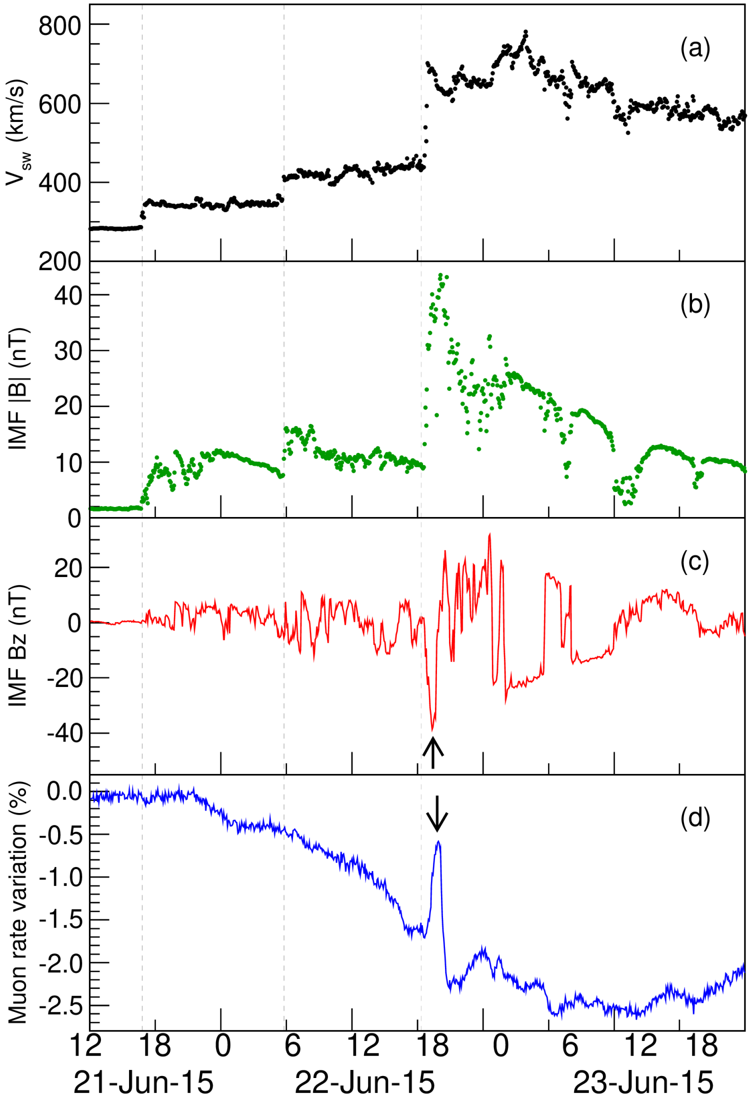


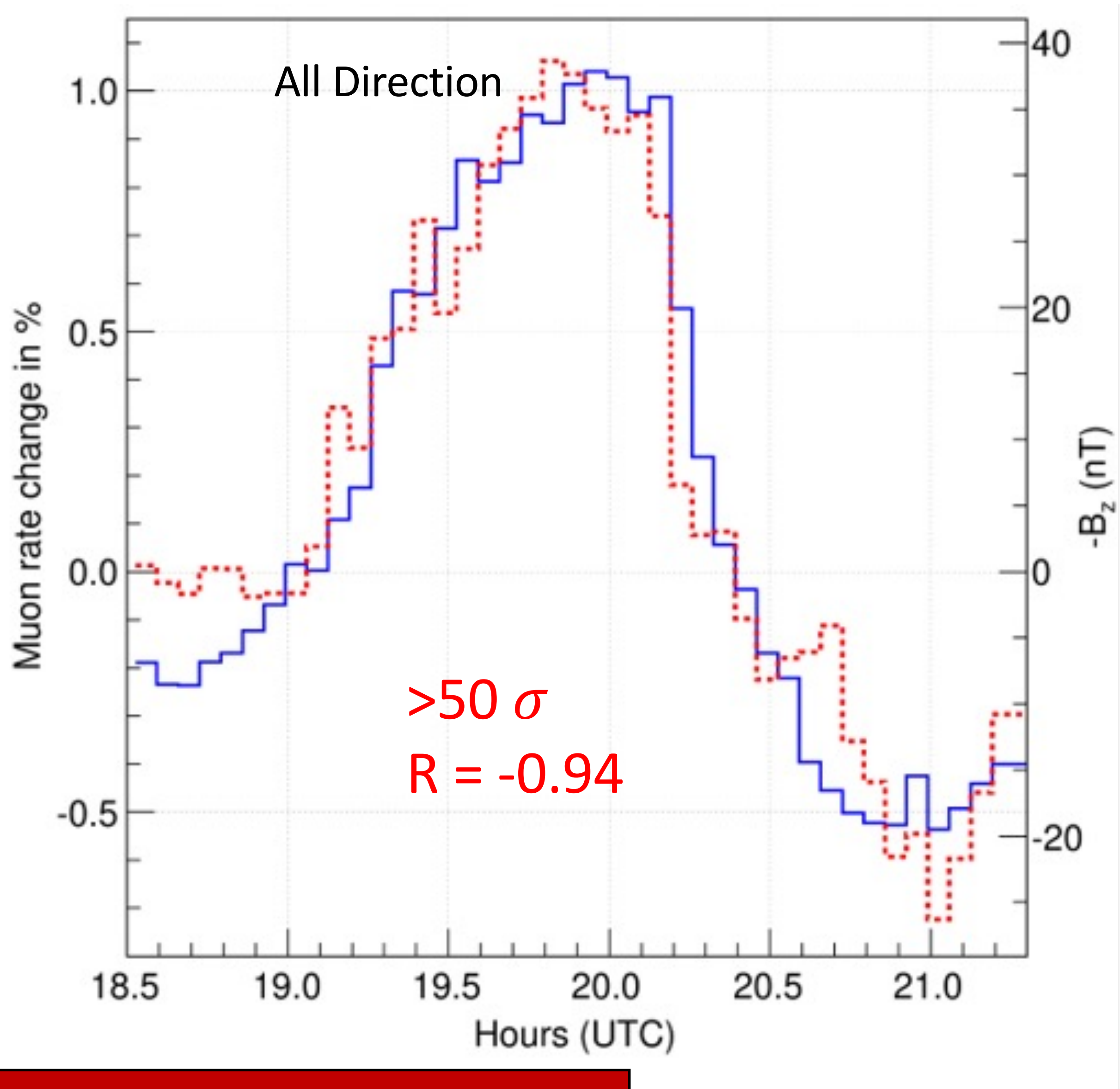
M. Zuberi et al *Eur.Phys.J.C* 84 (2024) 3, 255

Solar & Heliospheric physics



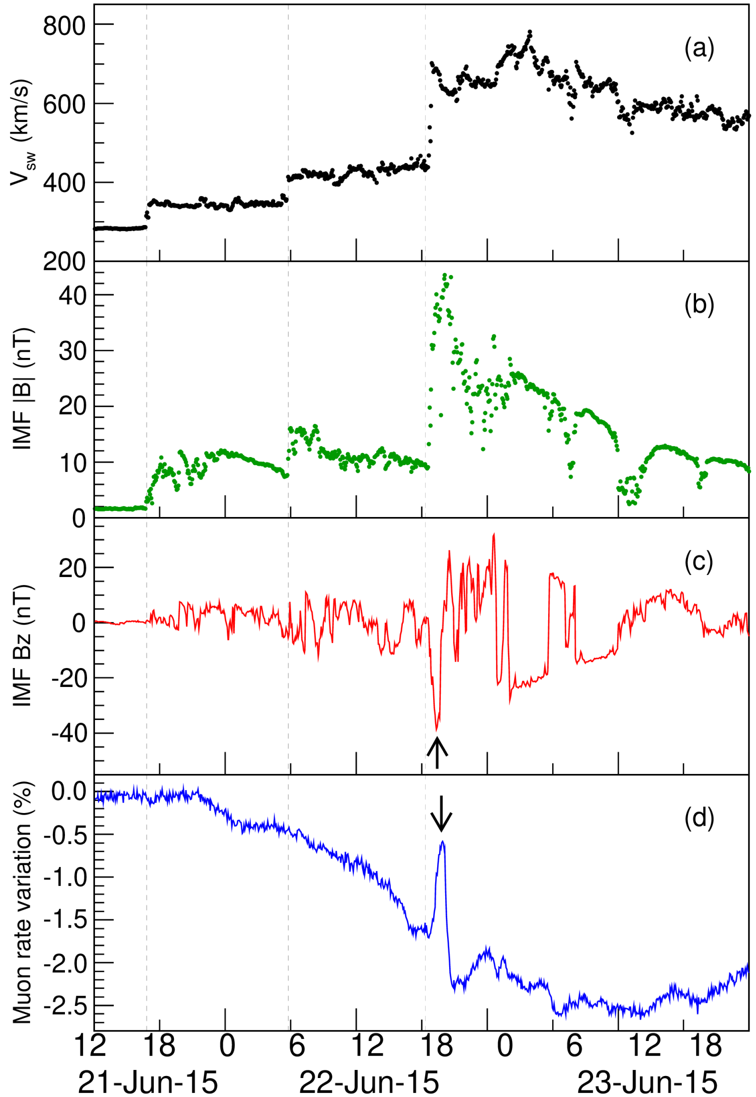
Transient Weakening of GMF

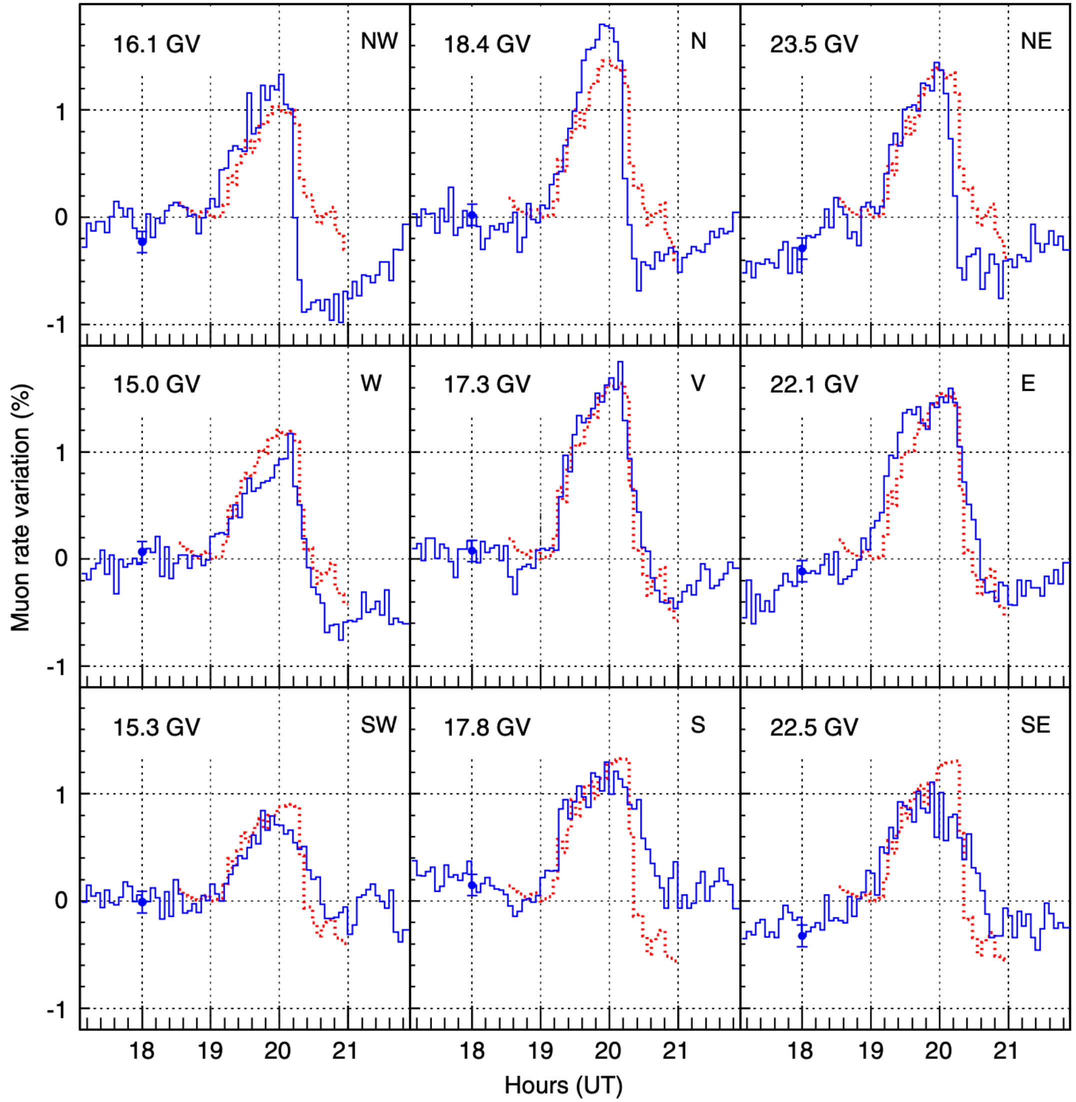




P.K. Mohanty et al., PRL 117, 171101 (2016)
P.K. Mohanty et al., PRD 97, 082001 (2018)

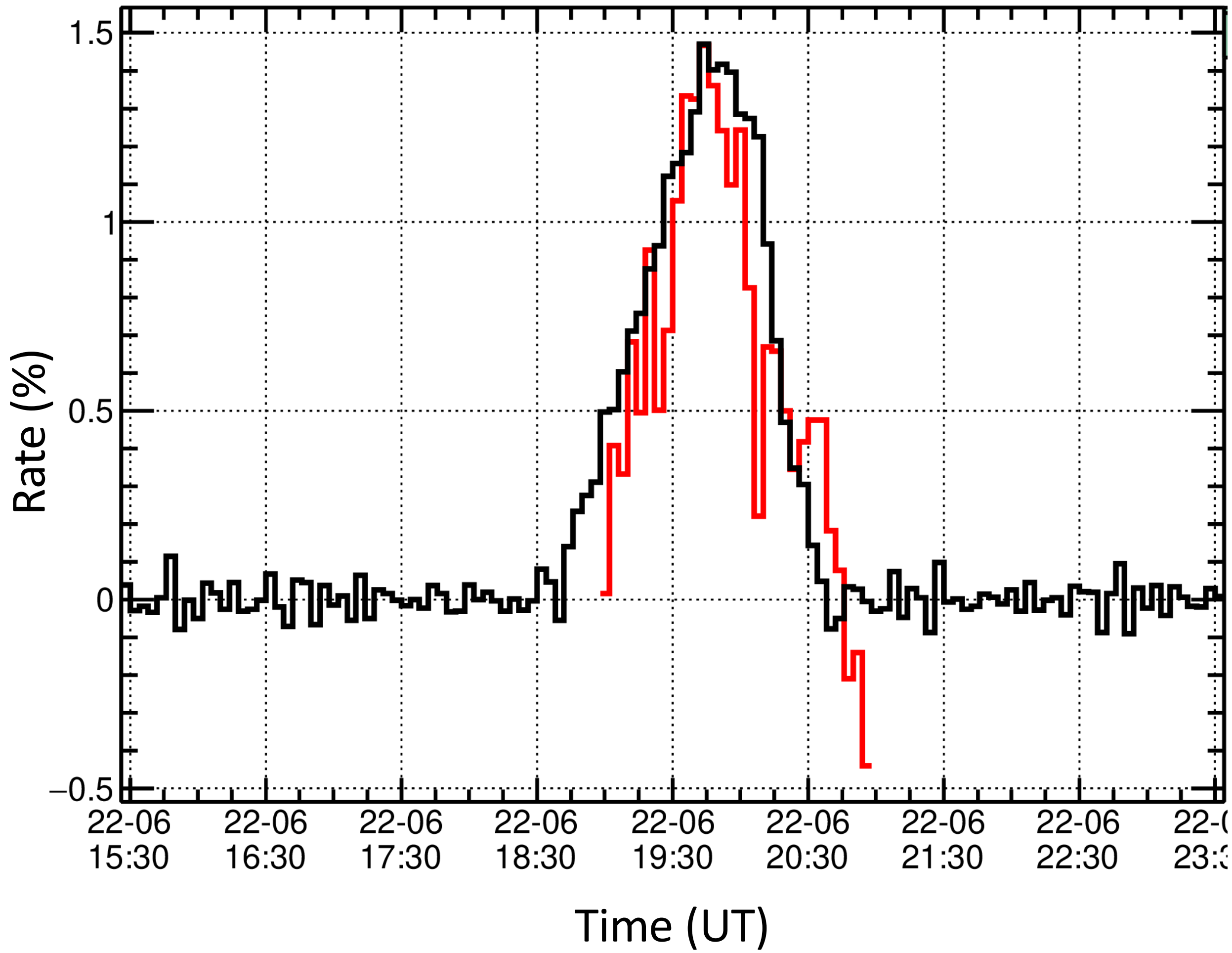
Transient Weakening of GMF





P.K. Mohanty et al., PRL 117, 171101 (2016)
P.K. Mohanty et al., PRD 97, 082001 (2018)

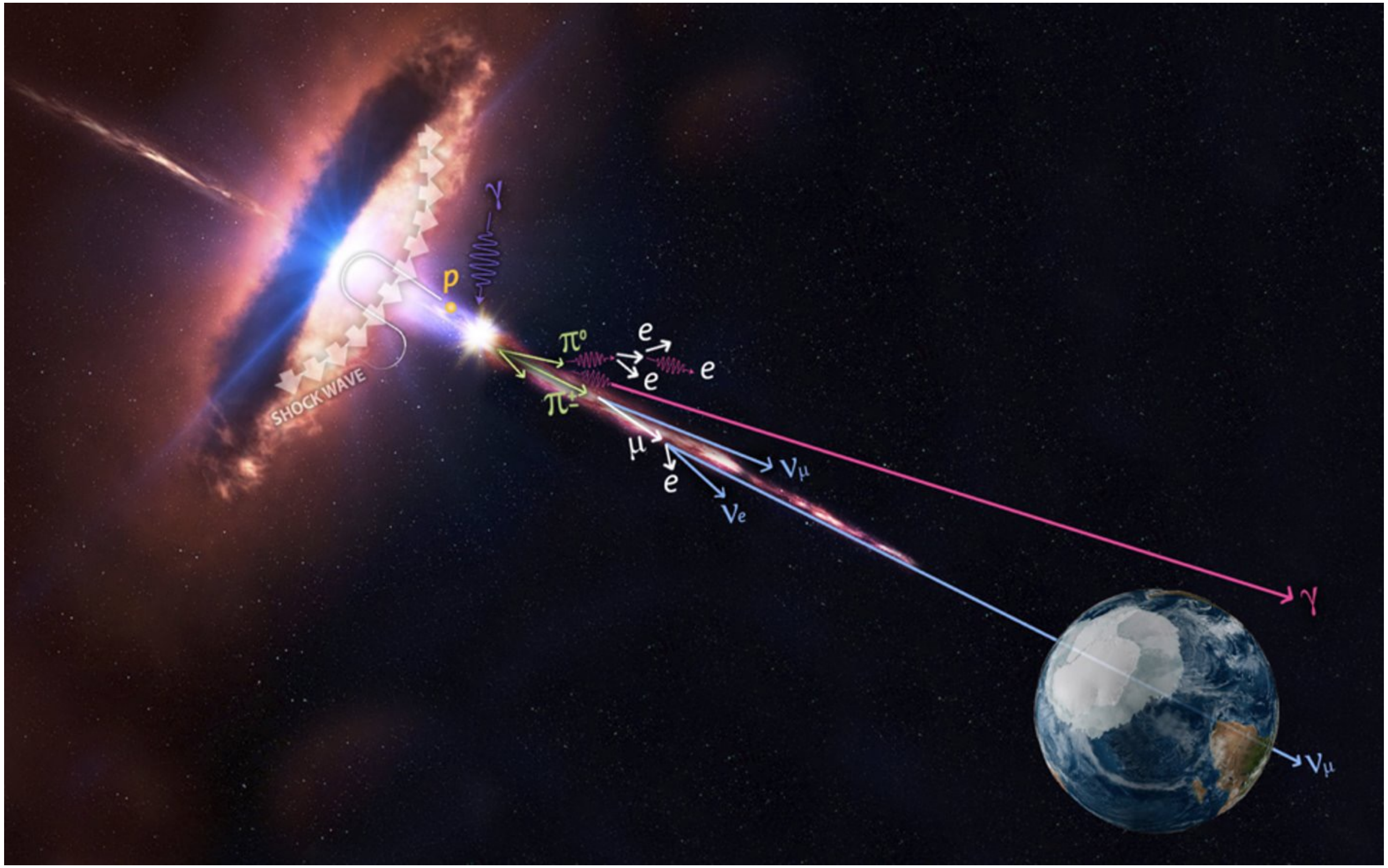
Detection also by Scintillator Detector



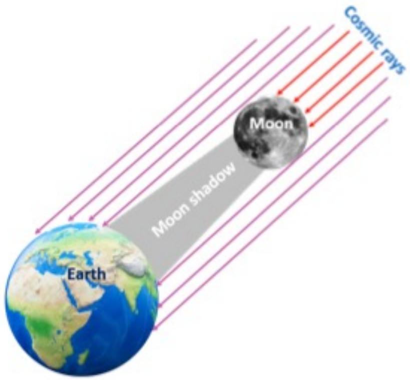
B. Hariharan et al., JASTP 243 (2023) 106005

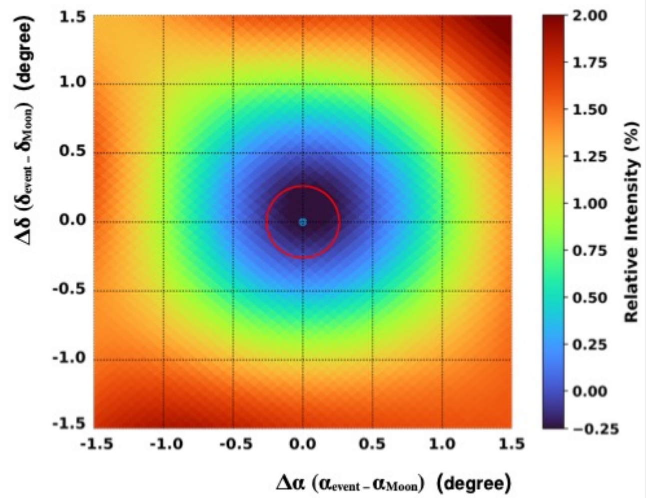
Cosmic Rays

E = 1 TeV – 10 PeV

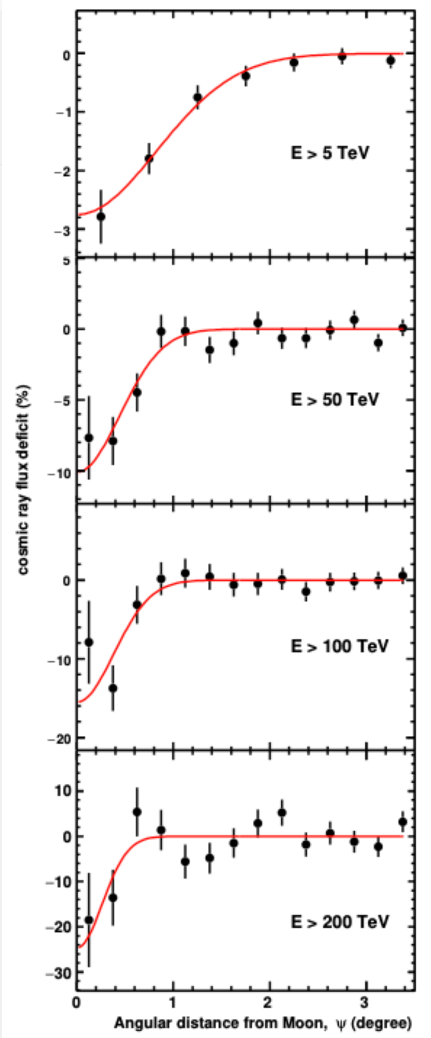


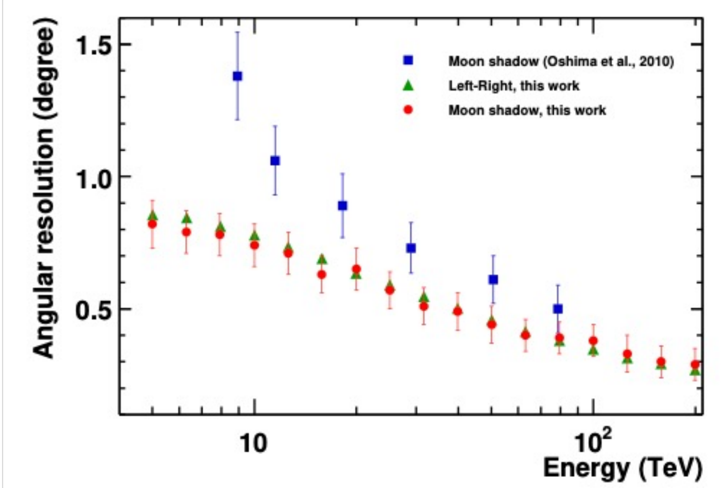
The Moon Shadow

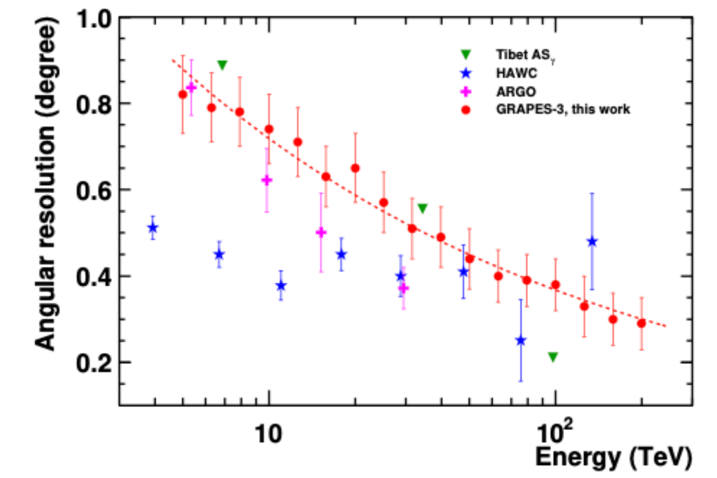




$\alpha = (0.032 \pm 0.004)°$
$\delta = (0.090 \pm 0.003)°$

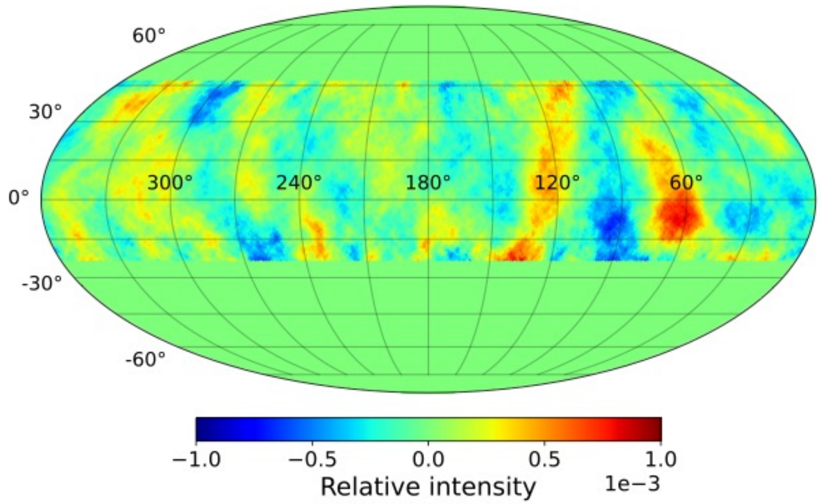






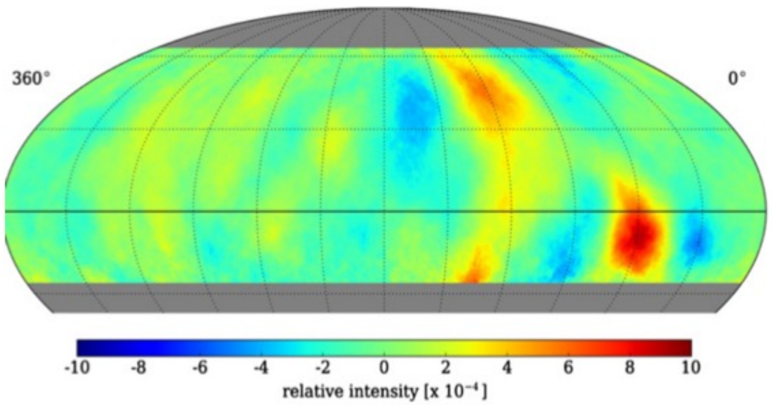
D. Pattanaik et al., PRD 106, 022009 (2022)

Cosmic Ray Anisotropy

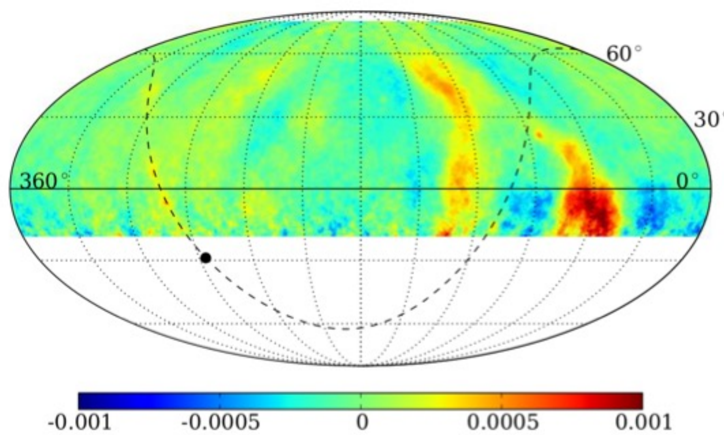


GRAPES-3

HAWC



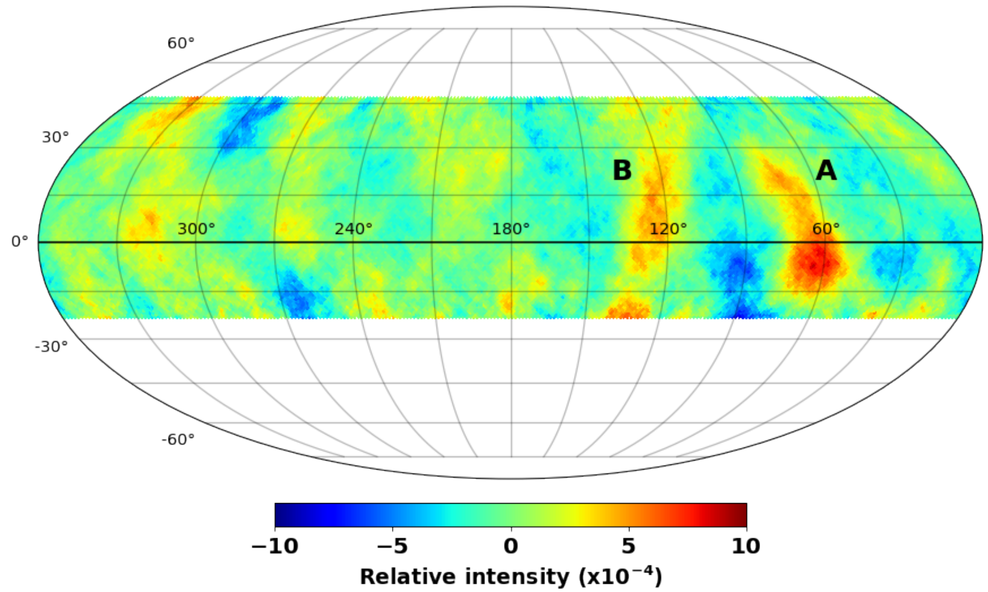
ARGO-YBJ



M. Chakraborty et al., *Astrophys.J.* 961 (2024) 1, 87

3.7×10^9 EAS events from 1st January 2013 to 31st December 2016 (1273.1 days)

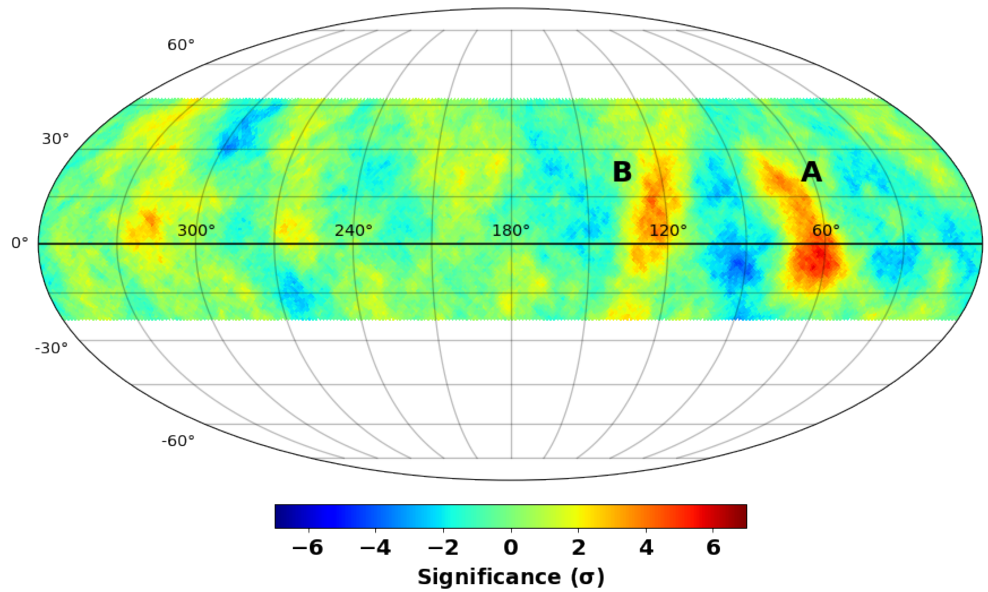
Median Energy 16 TeV

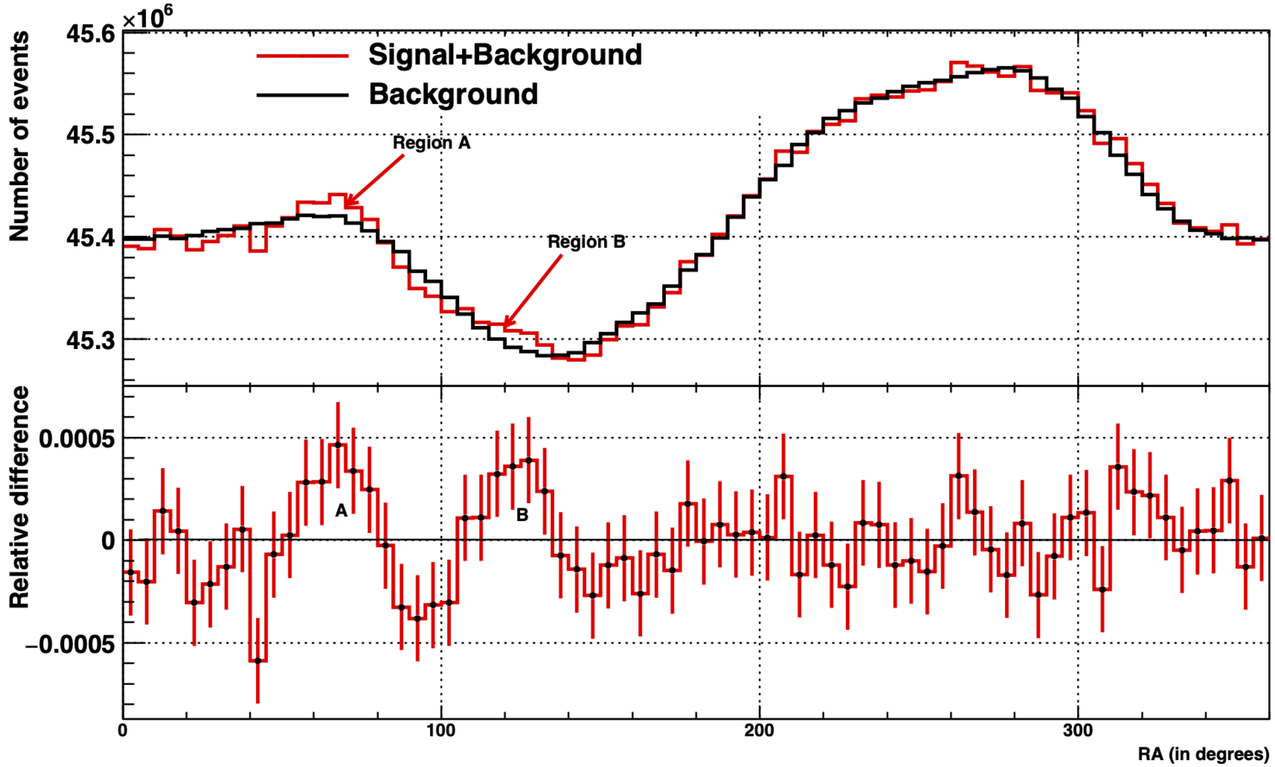


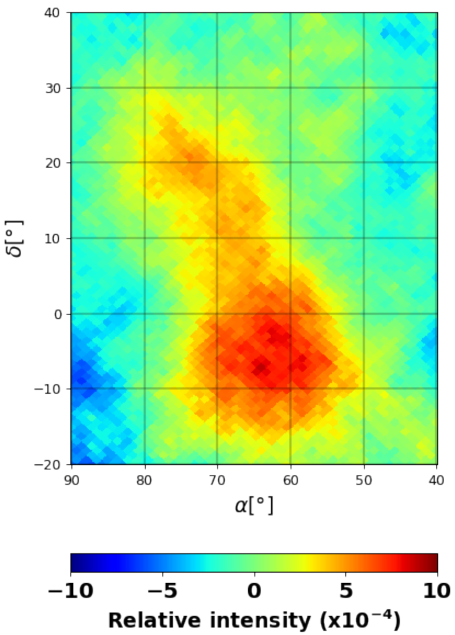
Region A – 6.8 σ

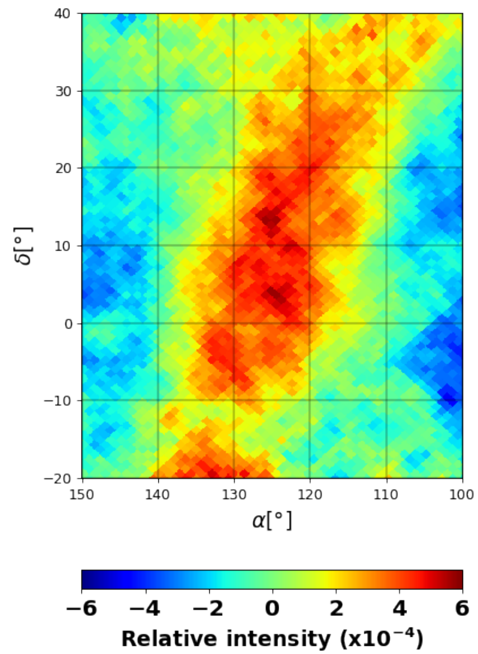
Region B – 4.7 σ

Li & Ma



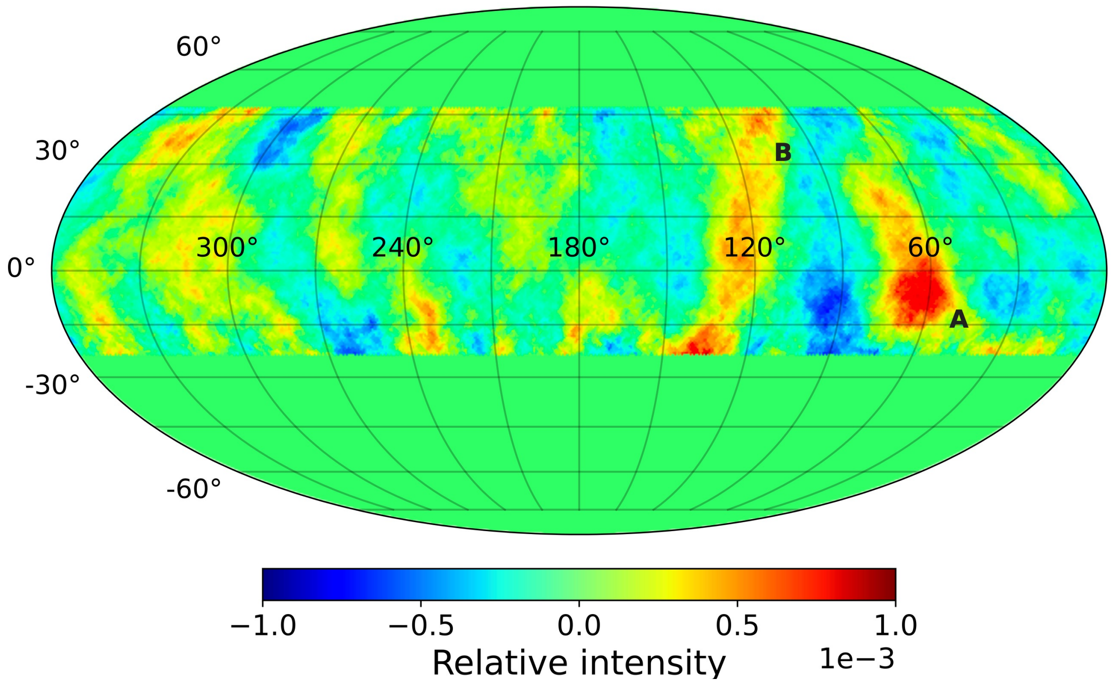

×10^6
45.6
45.5
45.4
45.3
Number of events
Signal+Background
Background
Region A
Region B
Relative difference
0.0005
0
−0.0005
A
B
0
100
200
300
RA (in degrees)


40
30
20
10
0
−10
−20
δ[°]
90
80
70
60
50
40
α[°]
−10
−5
0
5
10
Relative intensity (x10^−4)

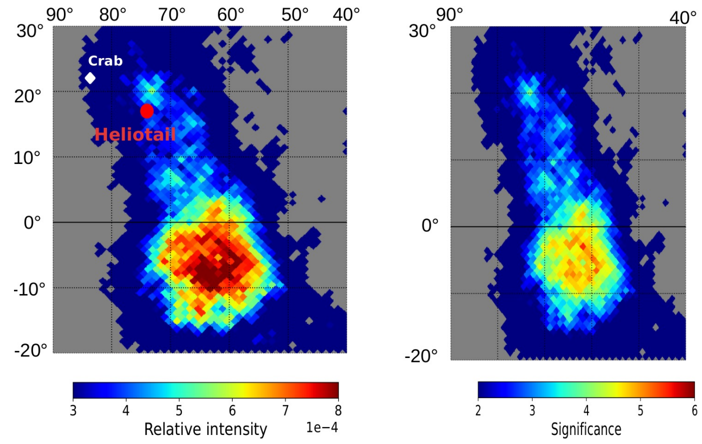

40
30
20
10
0
−10
−20
δ[°]
150
140
130
120
110
100
α[°]
−6
−4
−2
0
2
4
6
Relative intensity (x10^−4)

Cosmic Ray Anisotropy

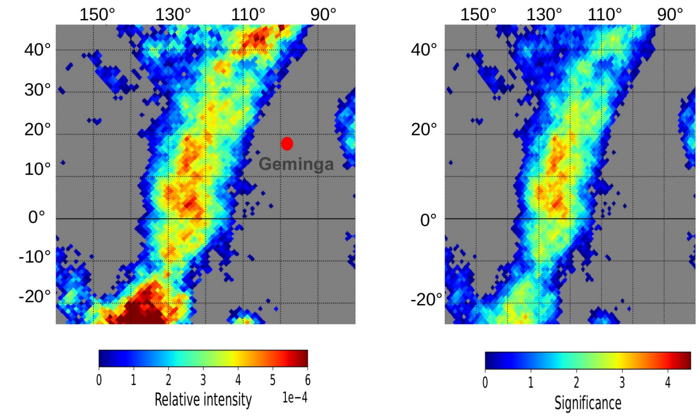
	Region A ($\times 10^{-4}$)	Region B ($\times 10^{-4}$)
ARGO-YBJ	10.0	5.0
HAWC	$(8.5 \pm 0.6 \pm 0.8)$	$(5.2 \pm 0.6 \pm 0.7)$
GRAPES-3	$(8.9 \pm 2.1 \pm 0.3)$	$(5.6 \pm 1.8 \pm 0.1)$



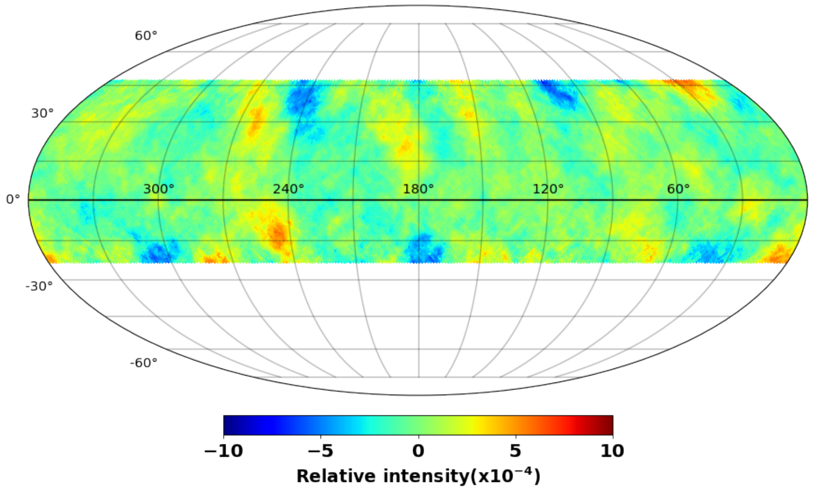
Region A

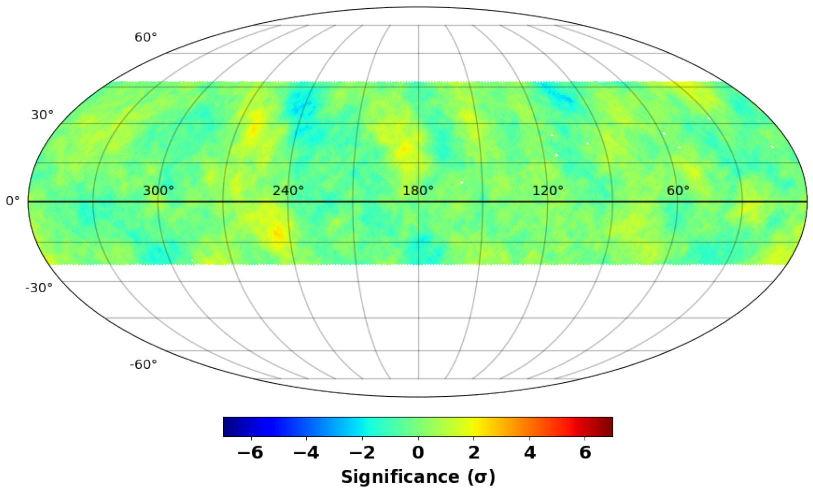


Region B



M. Chakraborty et al., *Astrophys.J.* 961 (2024) 1, 87





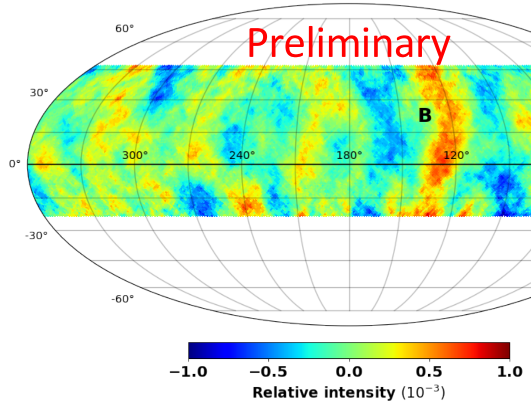
Not a spurious sidereal effect

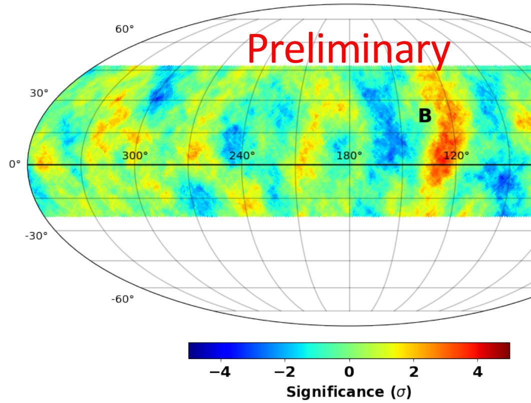
Analysis using anti sidereal time

Results with Muon cut

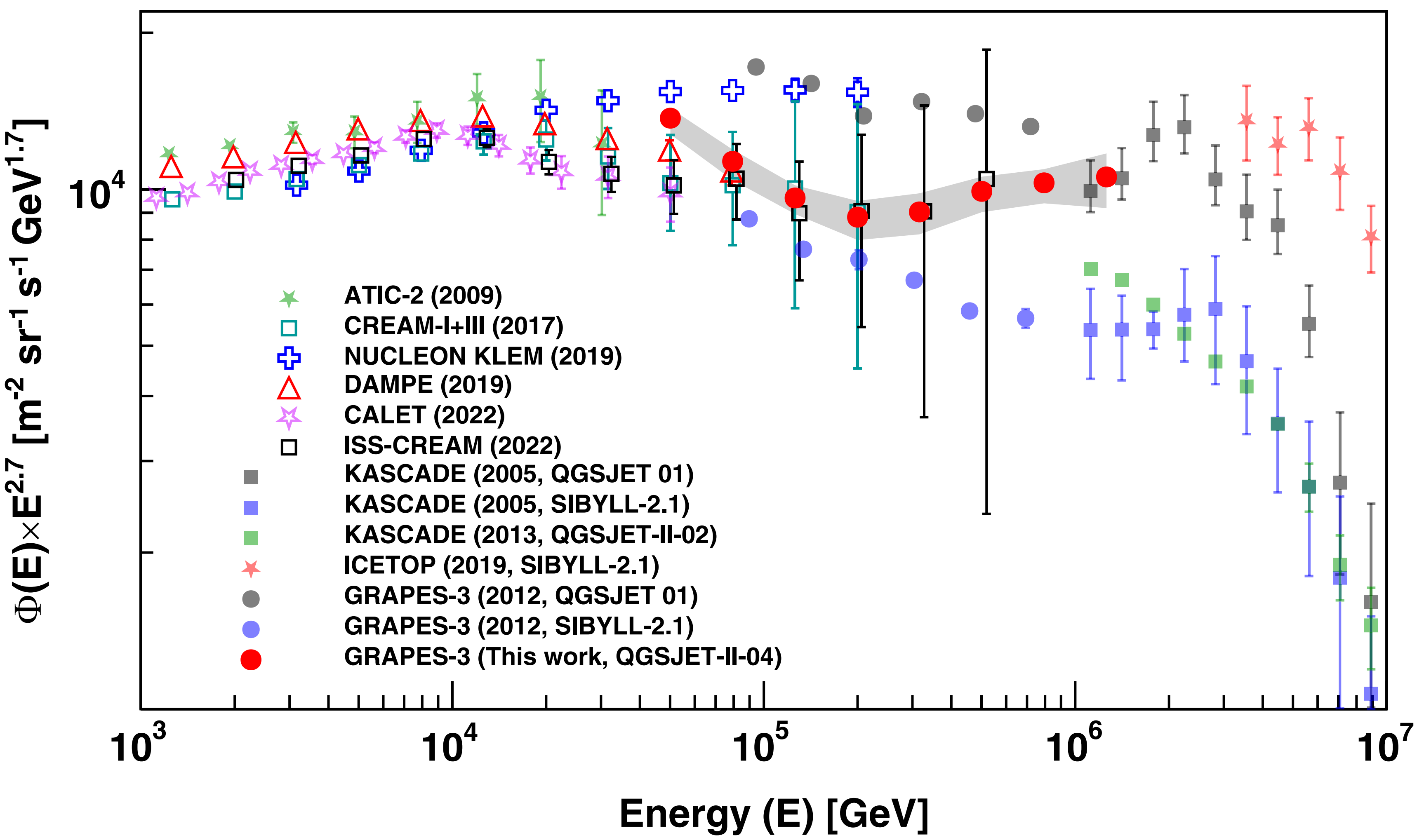
- Showers producing at least 2 tracks in the muon detector
- No of events: 1.9×10^9
- Change in strength of Region A : $(6.5 \pm 1.3) \times 10^{-4}$ to $(5.7 \pm 1.8) \times 10^{-4}$
- Change in strength of Region B : $(4.9 \pm 1.4) \times 10^{-4}$ to $(6.5 \pm 2.0) \times 10^{-4}$
- Change is within 1σ
- Hence, primary contribution to these structures is hadronic.

98% γ rejection

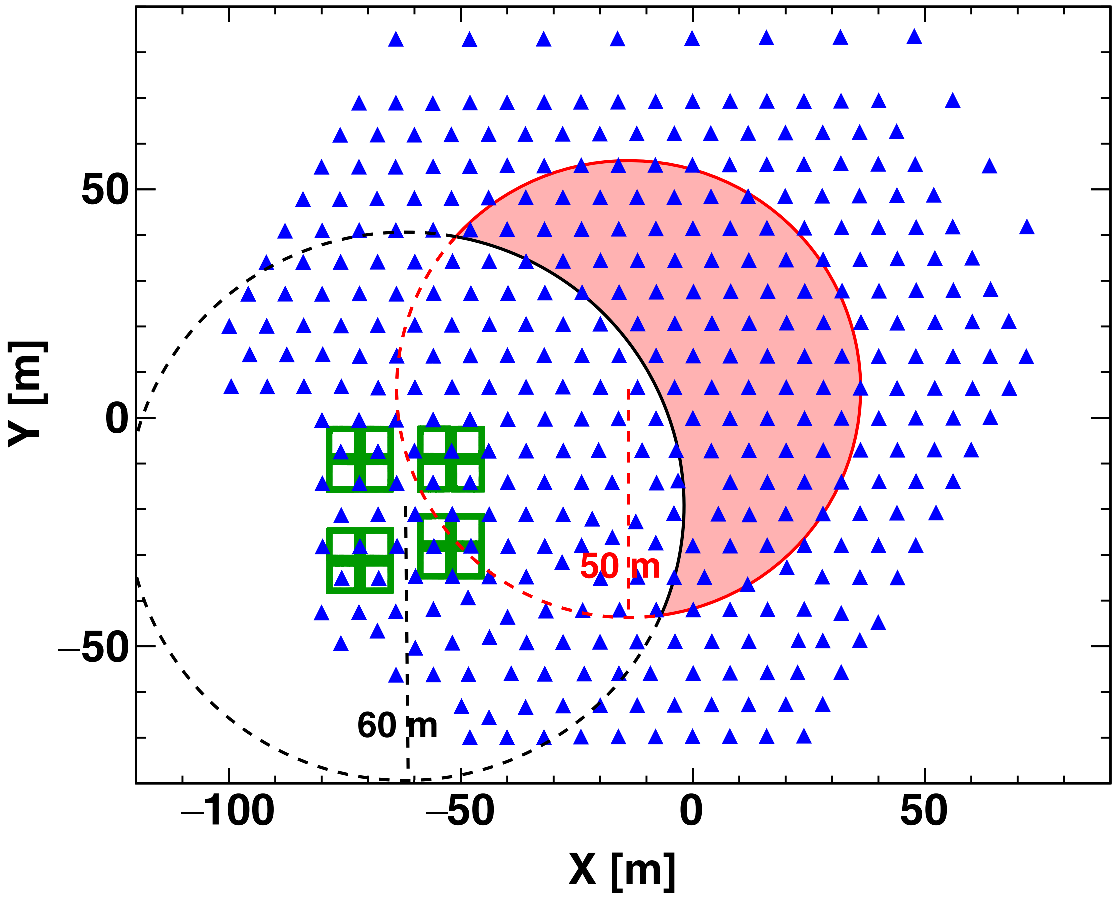




Proton spectrum measurements



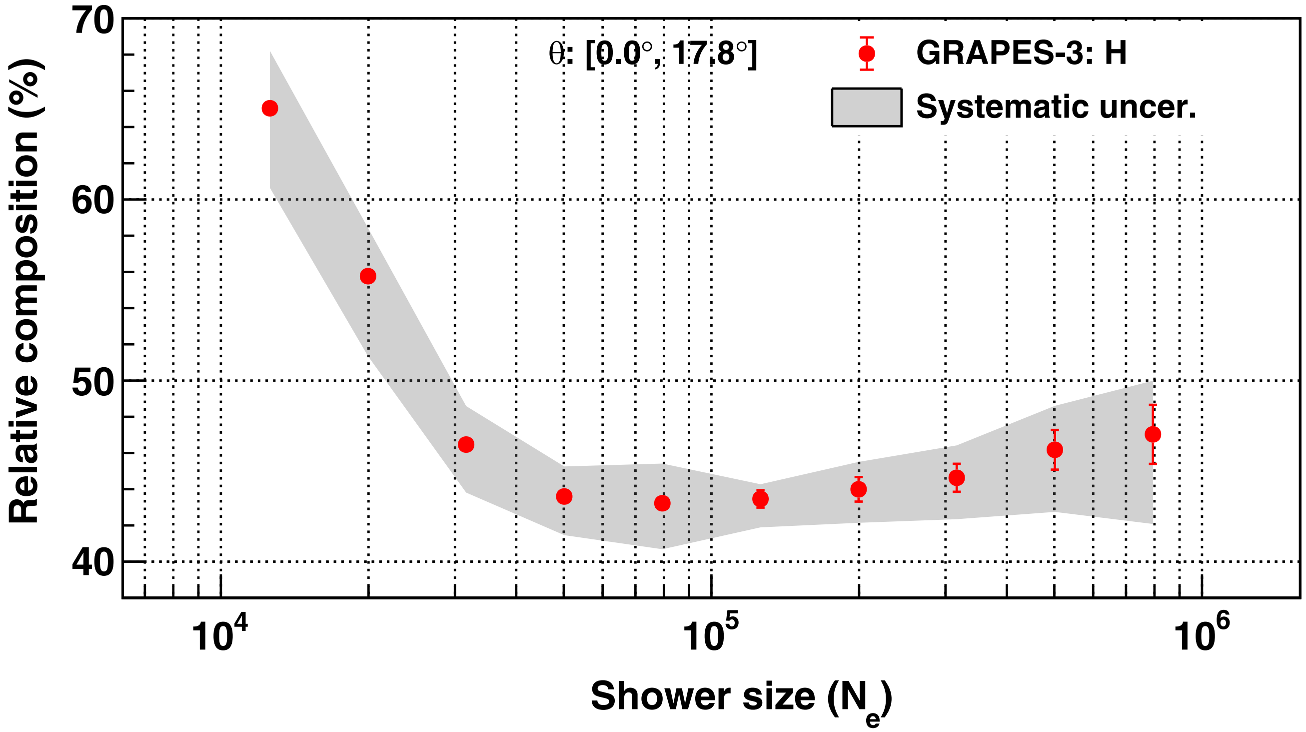
F. Varsi et al., *Phys.Rev.Lett.* 132 (2024) 5, 051002



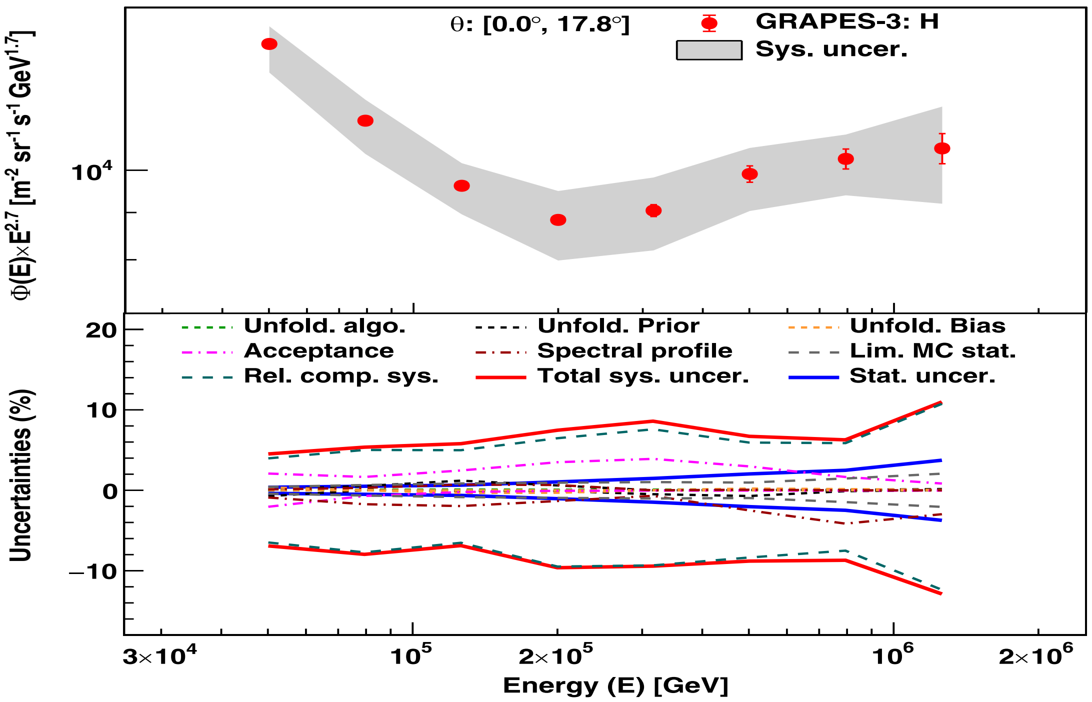
Fiducial Area

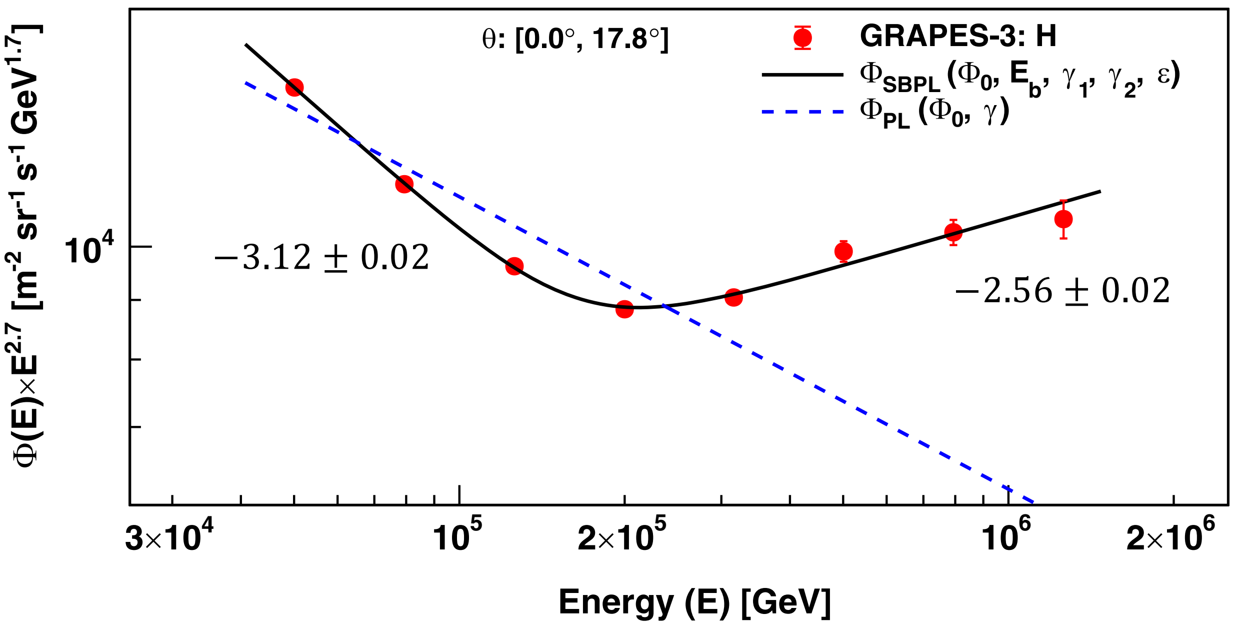
Starting with 1.75×10^9 EAS triggered events between 1st January 2014 and 26th October 2015

Core within Fiducial area
$\theta < 17.8°$
$N_e > 10^4$ (90% trigger efficiency)
$0.02 \le s \le 1.98$
7.81×10^6 EAS over 460 day livetime



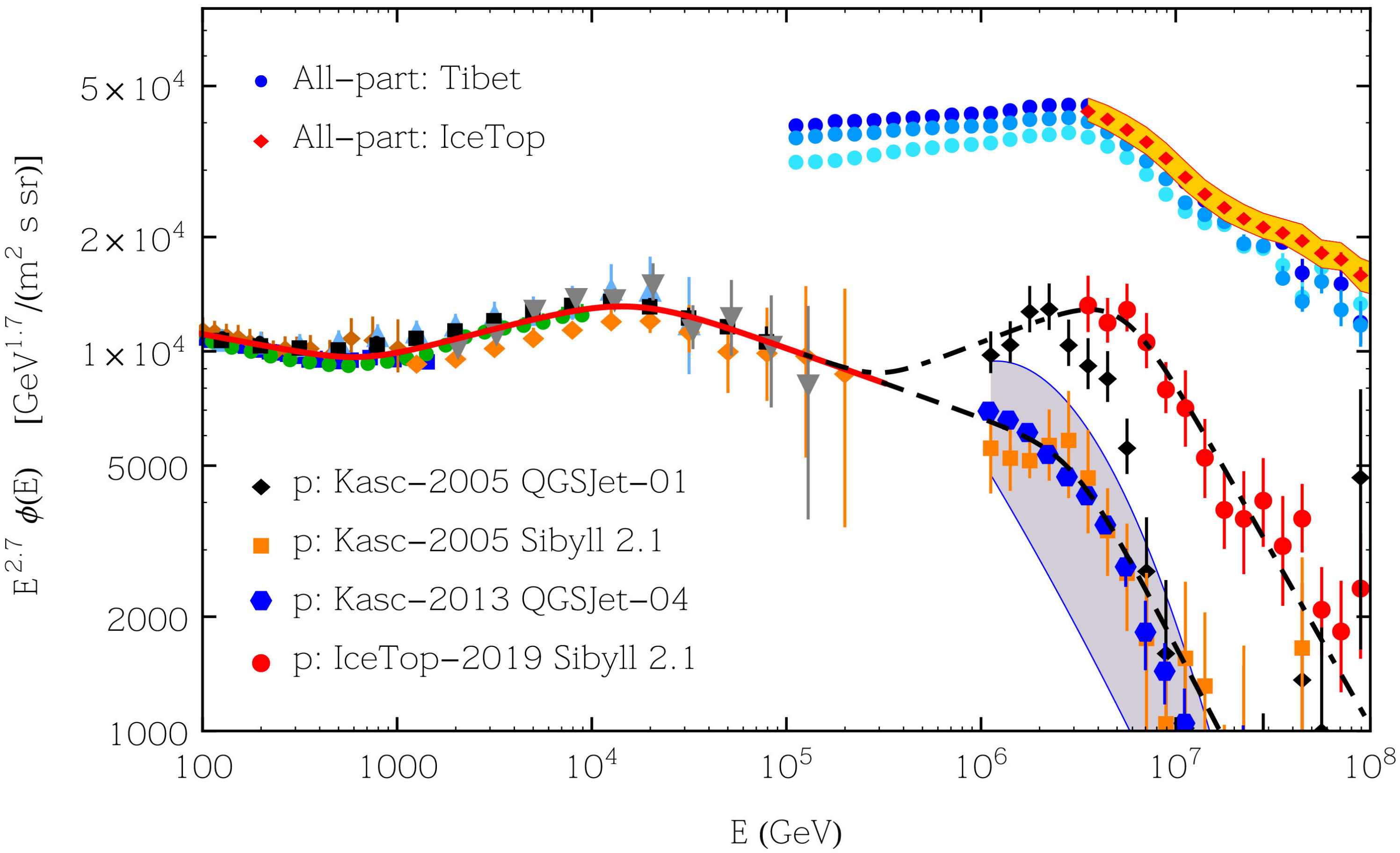
Relative composition of proton primaries obtained using Gold's unfolding on the muon multiplicity distributions





Broken power law favoured over unbroken power law at > 3.2 σ

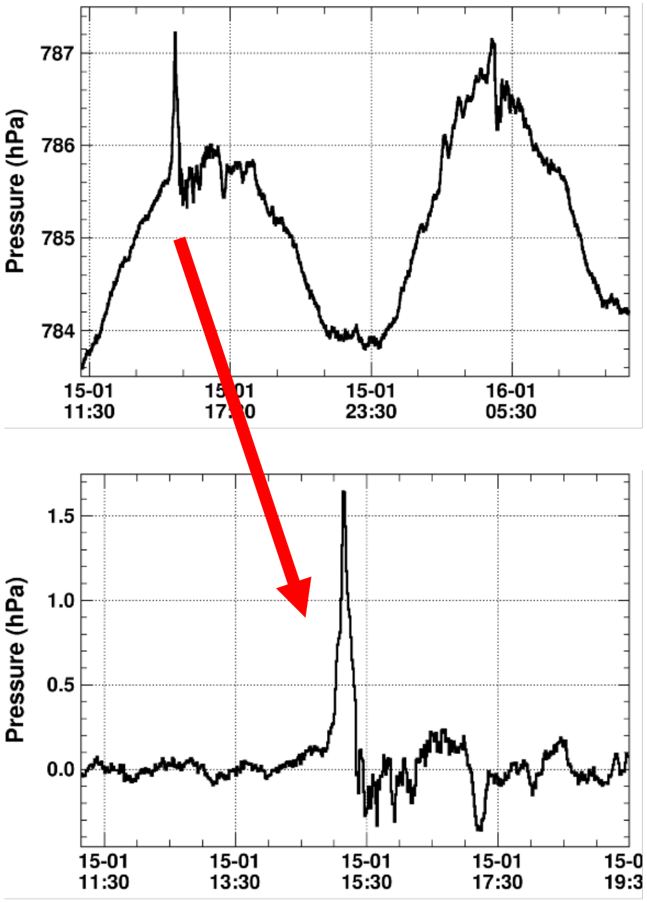
P. Lipari and S. Vernetto, APP 120 (2020) 102441



Similar hardening seen by DAMPE at ~150 TeV

Alemanno et al *Phys.Rev.D* 109 (2024)

Bonus: Tonga Volcano Eruption



Time (UT)

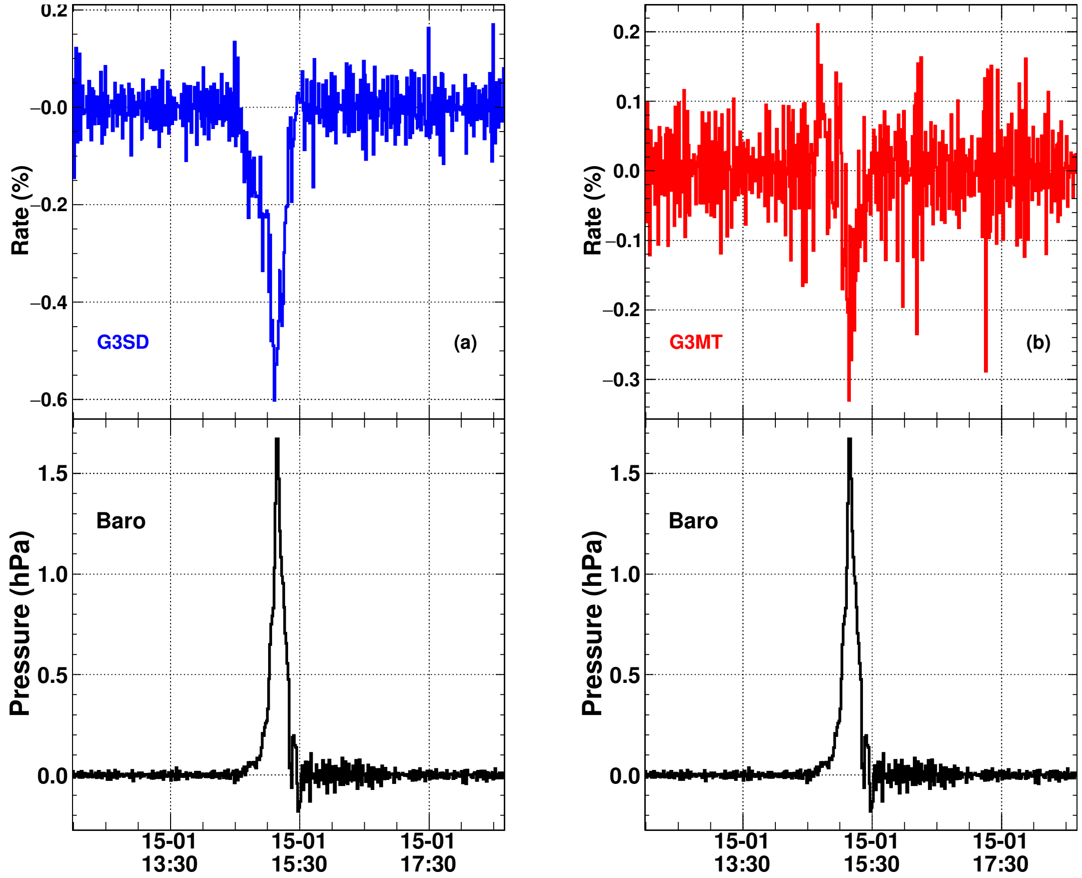


Figure 3: Percentage rate variation of (a) G3SD and (b) G3MT.

15 January 2022

B. Hariharan et al., PoS(ICRC2023)530

Future - New Muon Telescope under construction

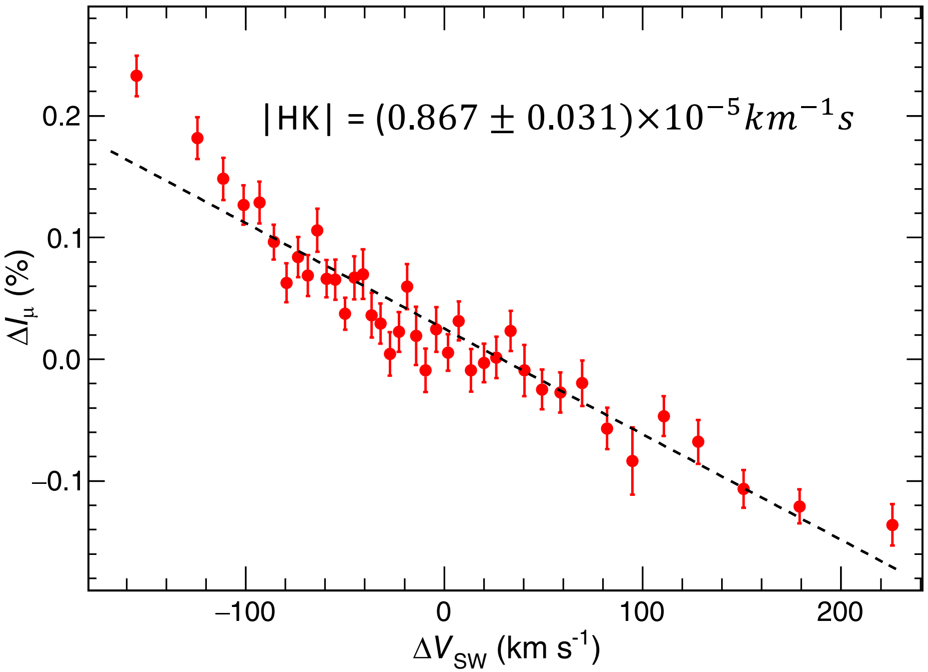
Summary

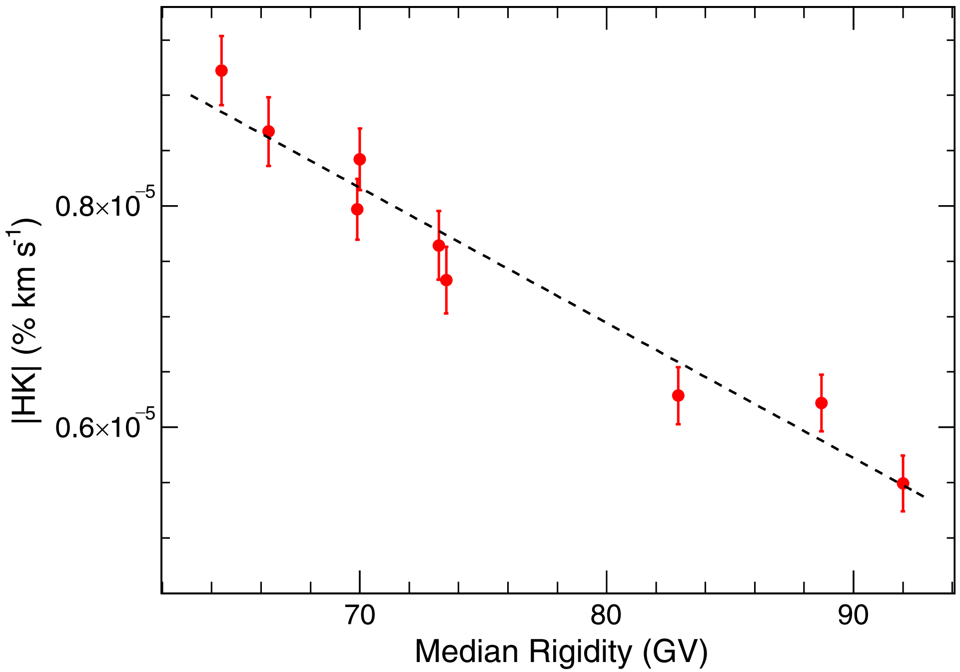
- Gigavolt potential in thundercloud
- Detected a short muon burst triggered by transient weakening of geomagnetic field
- Dependence of CR parallel mean free path on rigidity & solar activity
- Shower front curvature correction
- Moon shadow
- Cosmic ray anisotropy at TeV energies
- Hardening in the proton spectrum at ~ 166 TeV
- Moving towards blinded analyses and Machine learning based reconstructions
- More in the pipeline
  - Spectrum and composition of heavier elements
  - Crab
  - Gamma ray transients
  - Joint CR anisotropy analyses with IceCube and HAWC

- New muon telescope + extended scintillator array ~ 10% Crab in 1 year

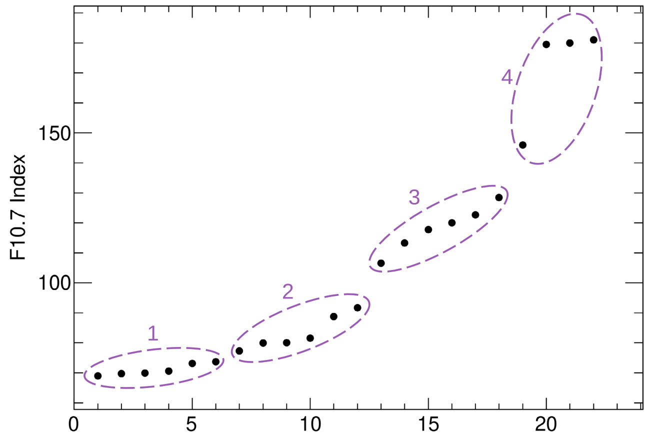
Backup

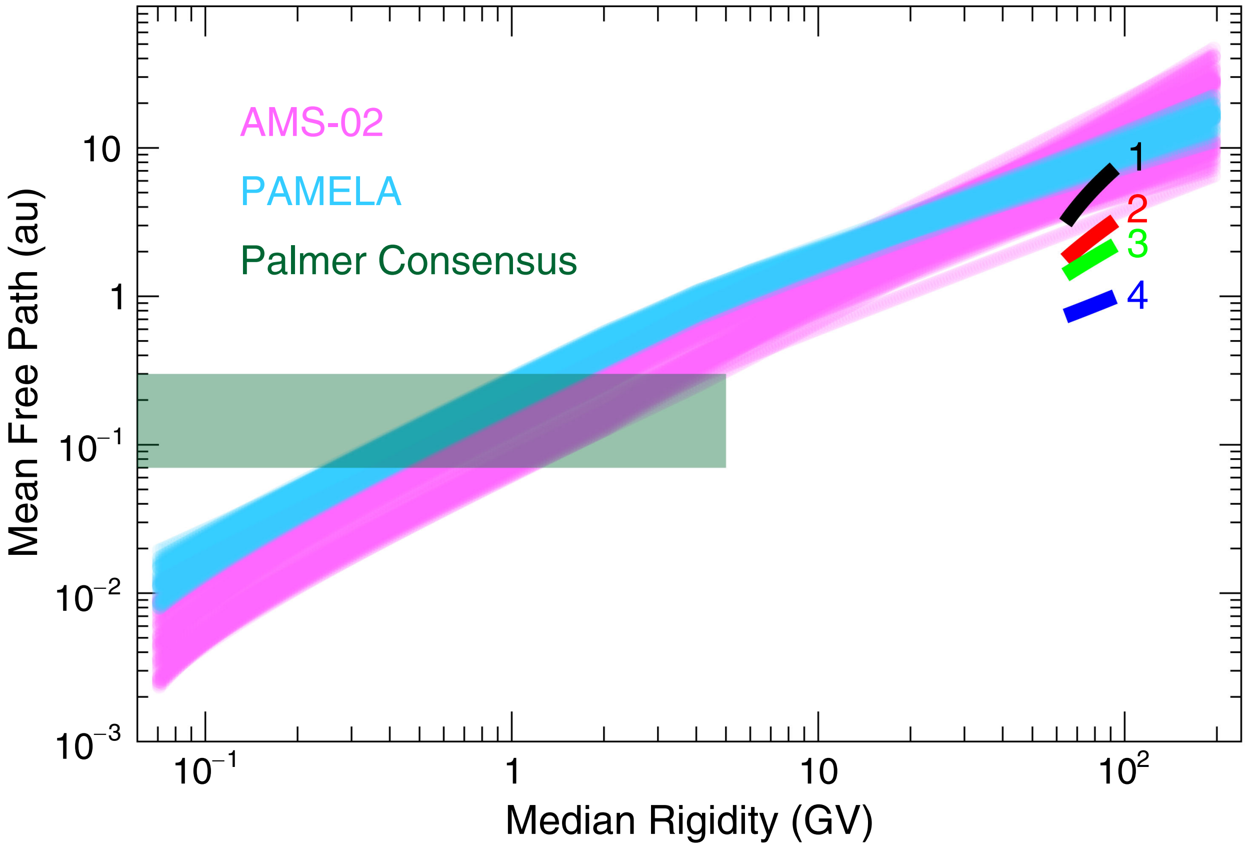
C.R. Parallel mean free path dependence on rigidity and solar activity





Kojima et. al. Phys.Rev.D 109 (2024) 6, 063011

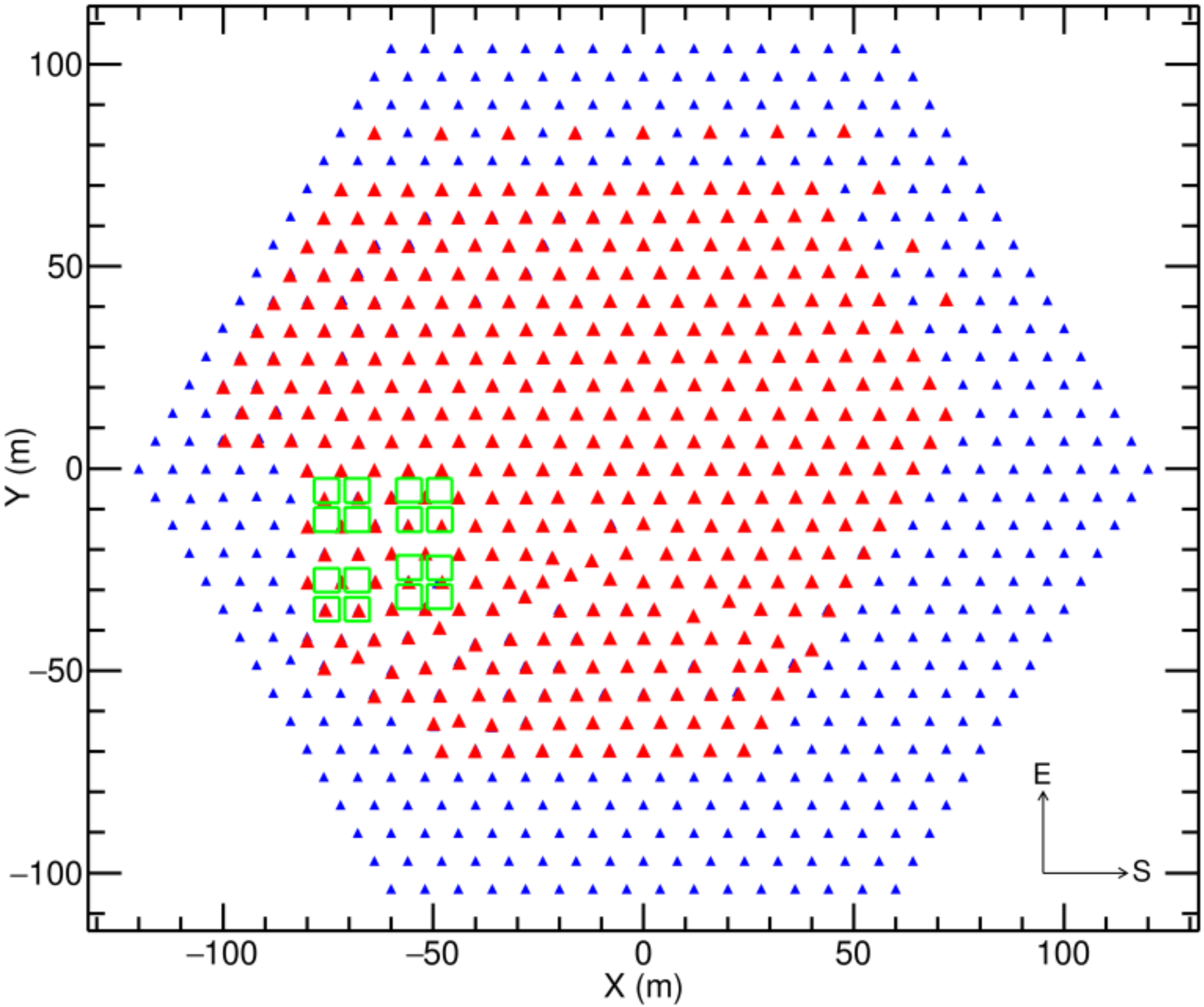




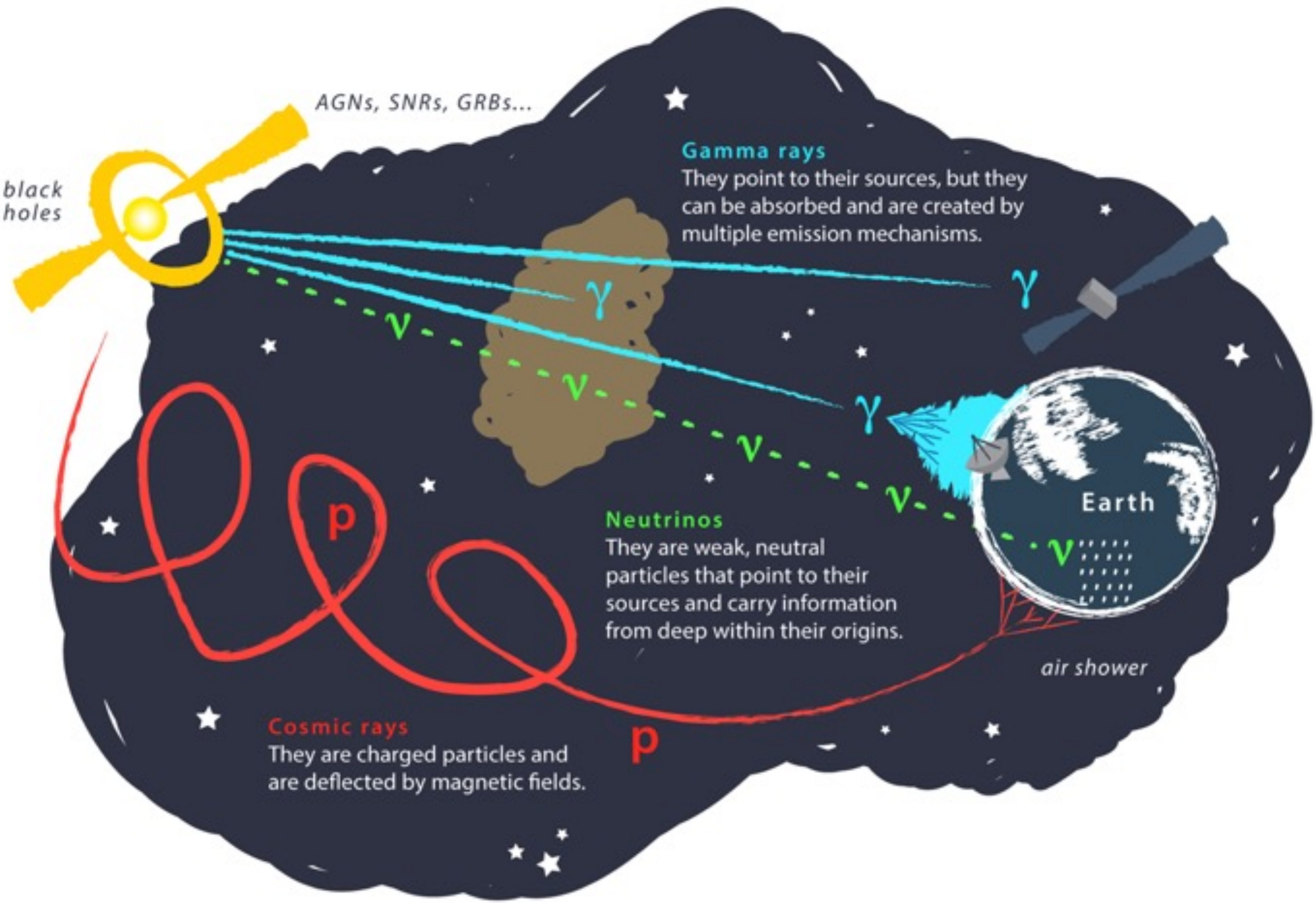
Kojima et. al. Phys.Rev.D 109 (2024) 6, 063011

Bonus: Tonga Volcano Eruption

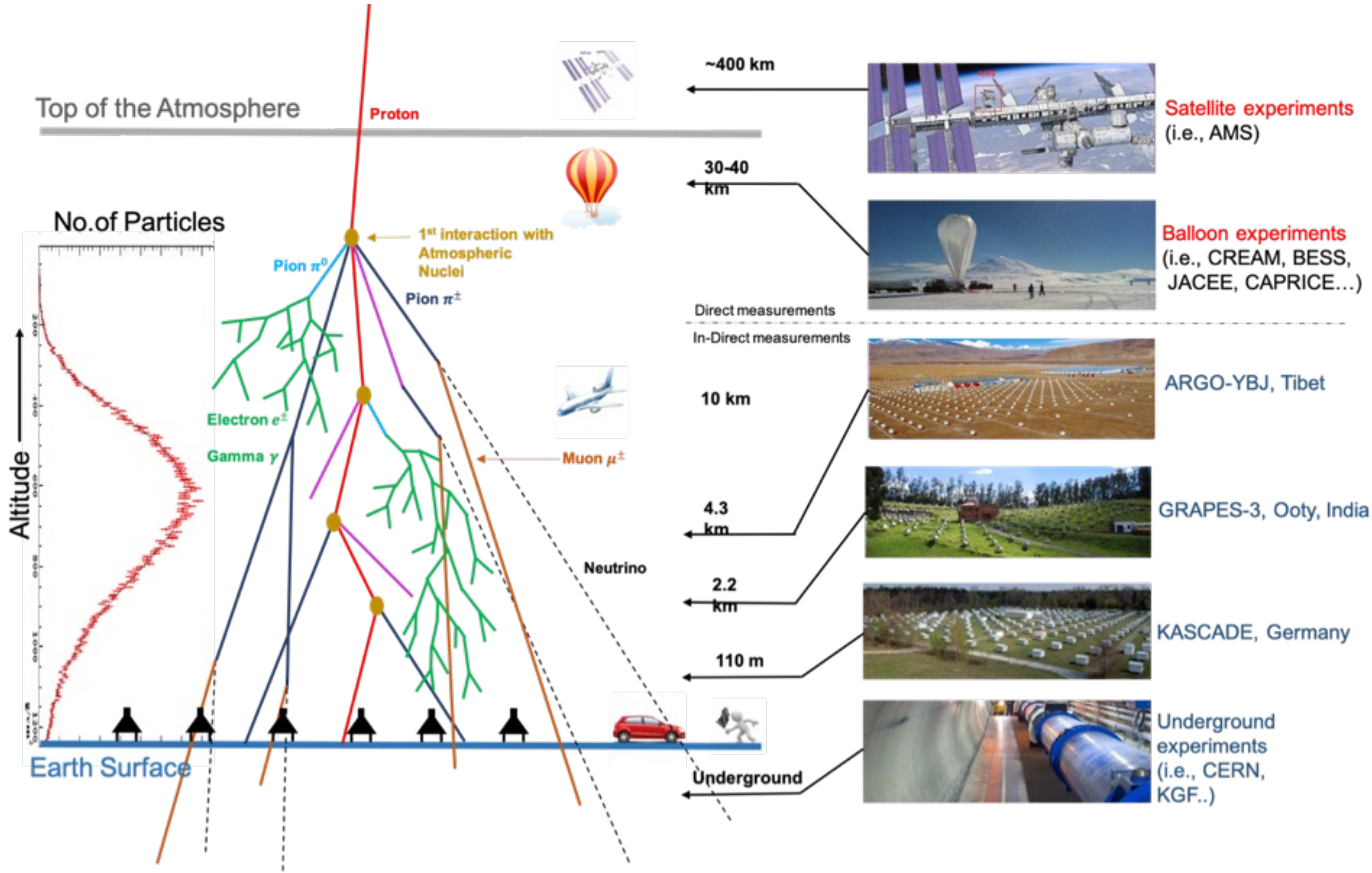
- Biggest after eruption of Krakatoa, Indonesia (1883)
- 5-200 megatons of TNT (~200 megatons of TNT)
- ~150 billion litres of water into stratosphere (~10%)
- Expelled ~10 km^3 rock & ash (~4000 pyramids)
- Record height of >55 km
- Raise in global temperature
- May dissipate in decade
- Record-breaking shock wave (pressure wave)



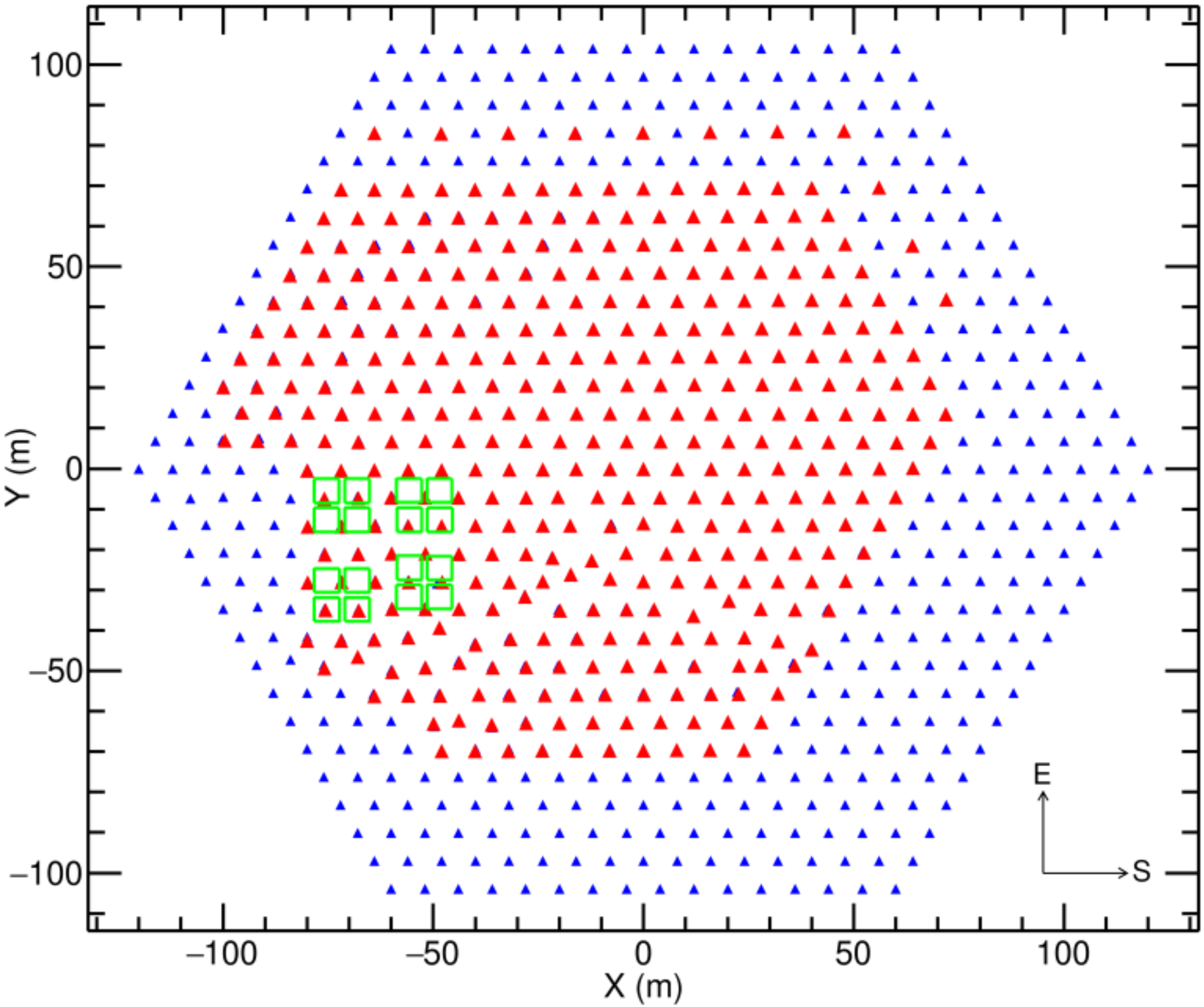
100
50
0
–50
–100
Y (m)
–100
–50
0
50
100
X (m)
E
S



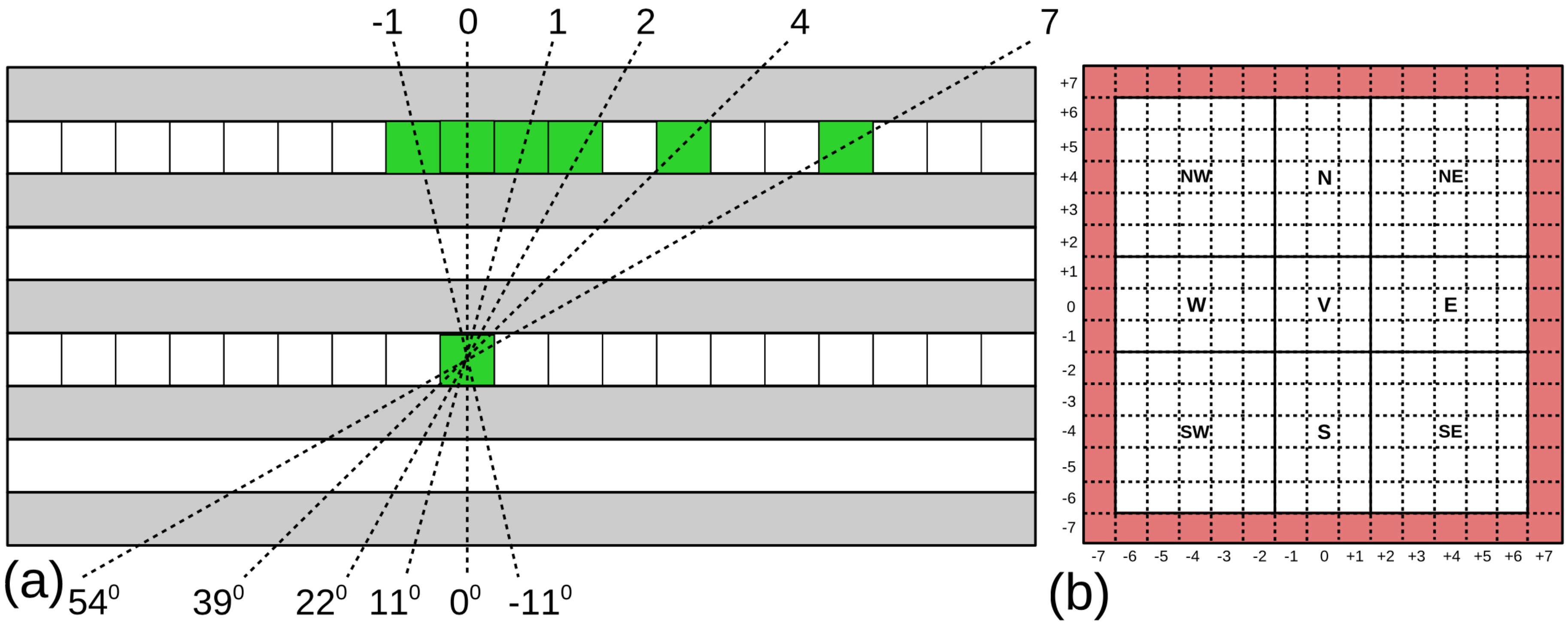
AGNs, SNRs, GRBs...
black holes
Gamma rays
They point to their sources, but they can be absorbed and are created by multiple emission mechanisms.
γ
γ
γ
ν
ν
ν
ν
ν
p
p
Earth
Neutrinos
They are weak, neutral particles that point to their sources and carry information from deep within their origins.
air shower
Cosmic rays
They are charged particles and are deflected by magnetic fields.



Top of the Atmosphere
Proton
~400 km
Satellite experiments
(i.e., AMS)
30-40 km
Balloon experiments
(i.e., CREAM, BESS, JACEE, CAPRICE…)
No.of Particles
1st interaction with Atmospheric Nuclei
Pion π^0
Pion $\pi^\pm$
Direct measurements
In-Direct measurements
10 km
ARGO-YBJ, Tibet
Altitude
Electron $e^\pm$
Gamma γ
Muon $\mu^\pm$
4.3 km
GRAPES-3, Ooty, India
Neutrino
2.2 km
KASCADE, Germany
110 m
Earth Surface
Underground
Underground experiments (i.e., CERN, KGF..)

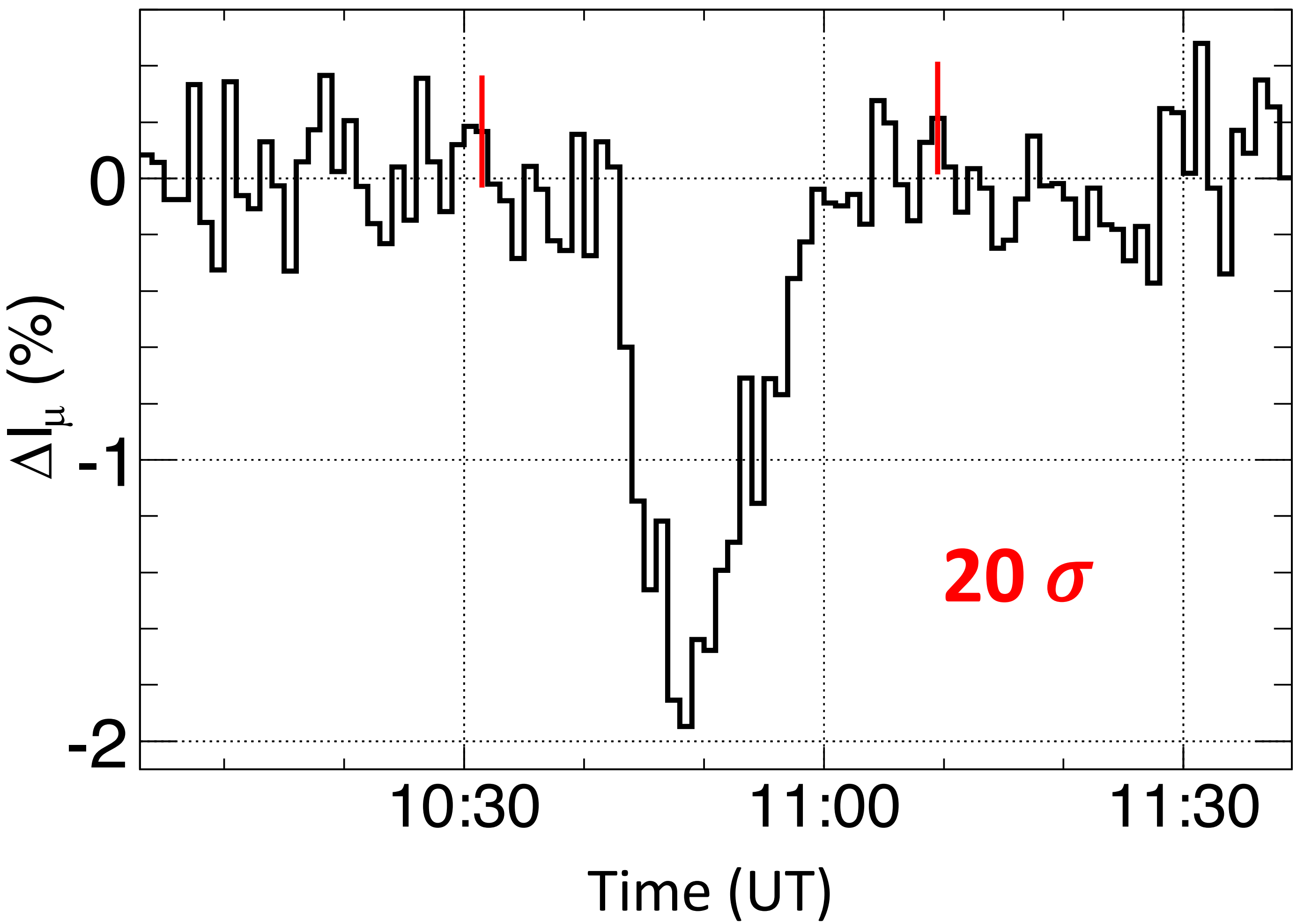


Y (m)
X (m)
100
50
0
–50
–100
–100
–50
0
50
100
E
S



-1
0
1
2
4
7
(a)
54⁰
39⁰
22⁰
11⁰
0⁰
-11⁰
+7
+6
+5
+4
+3
+2
+1
0
-1
-2
-3
-4
-5
-6
-7
NW
N
NE
W
V
E
SW
S
SE
-7 -6 -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5 +6 +7
(b)

Muon Intensity Variation



Timeline

1750s

1920s

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

Detection of 100 MeV γ-ray in TGFs

1990s

2000s

Measurement of 0.13 GV

Measurement of 1.3 GV

2019

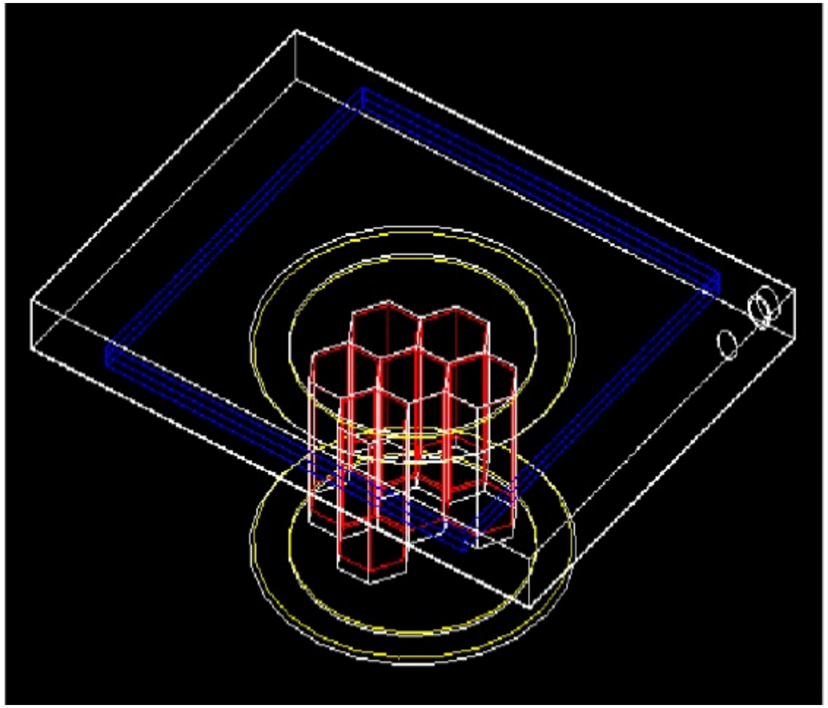
Properties of the Cloud

- 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

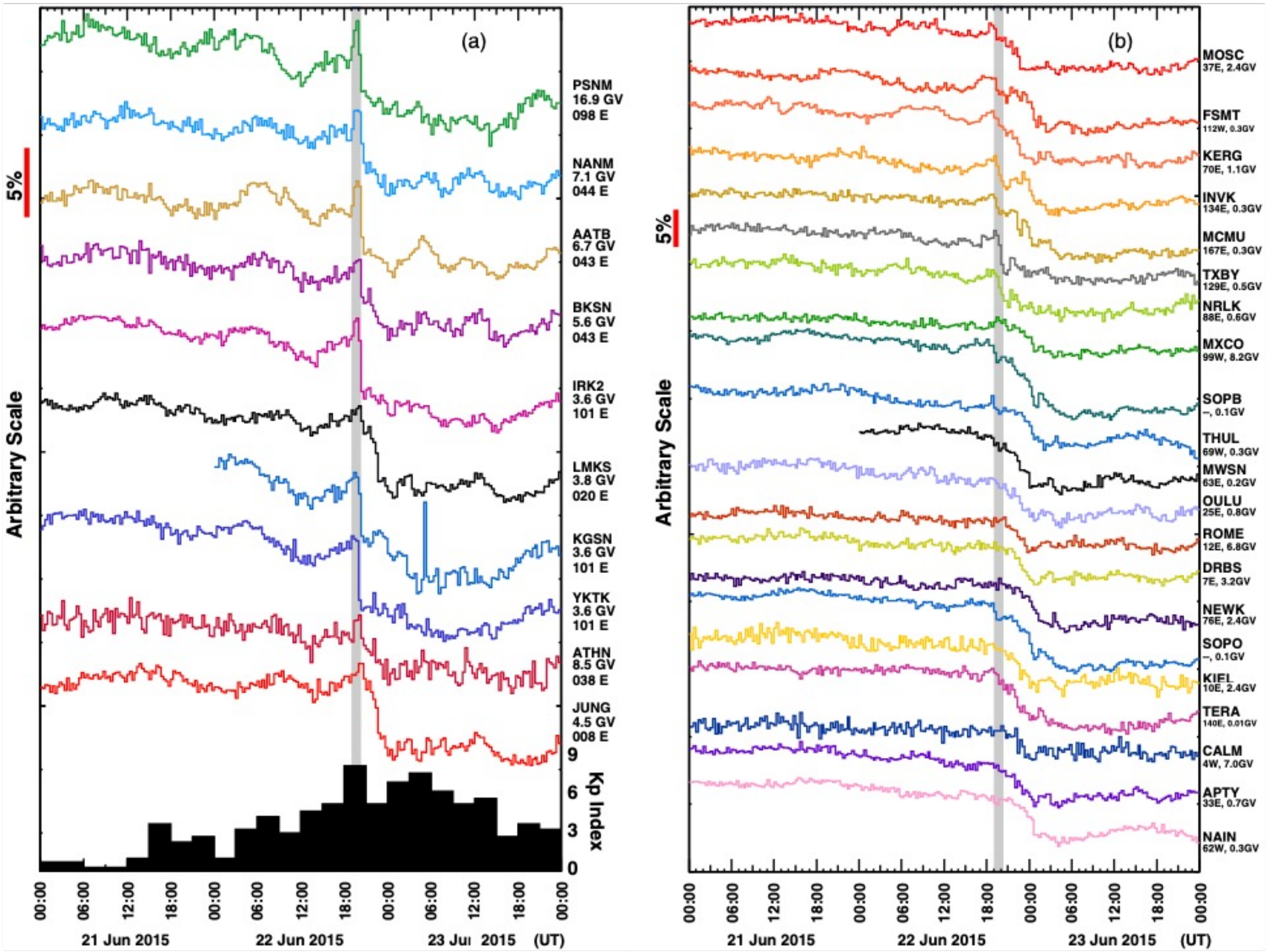
- Comparable to biggest nuclear reactor / hydroelectric / thermal power plants
- Enough to power a big town

B. Hariharan et al., PRL 122, 105101 (2019)
(Focus article & Editors' suggestion)

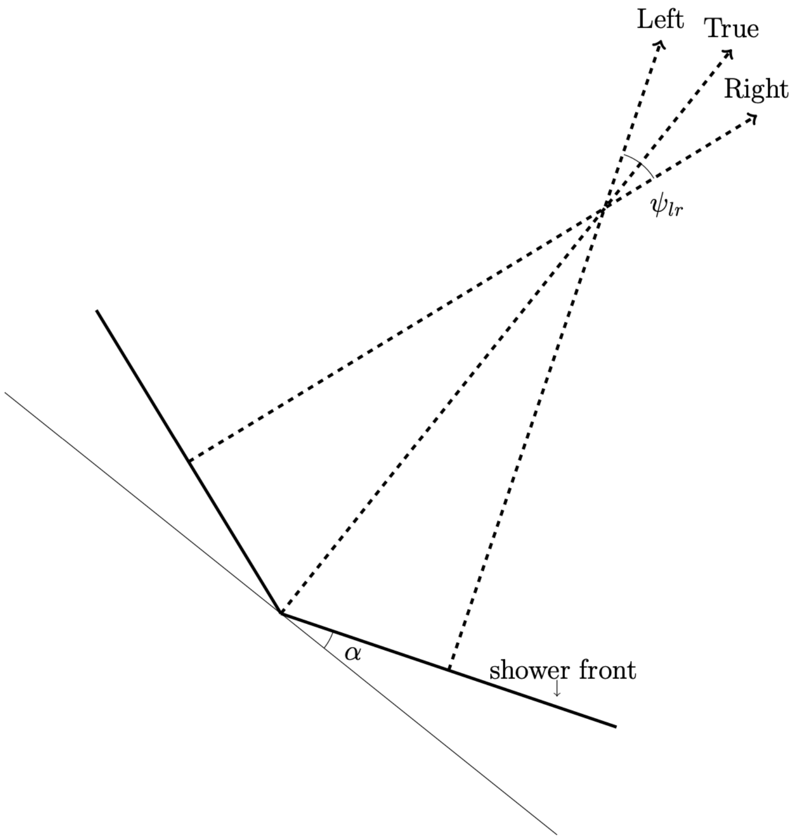
Gamma Ray Detection

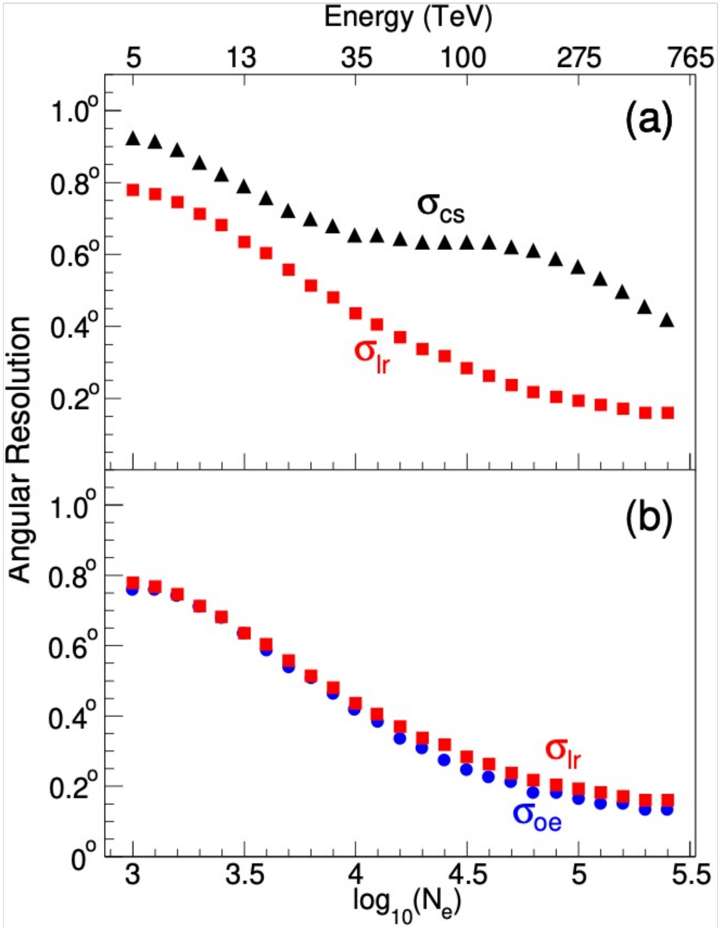


Neutron Monitor Data



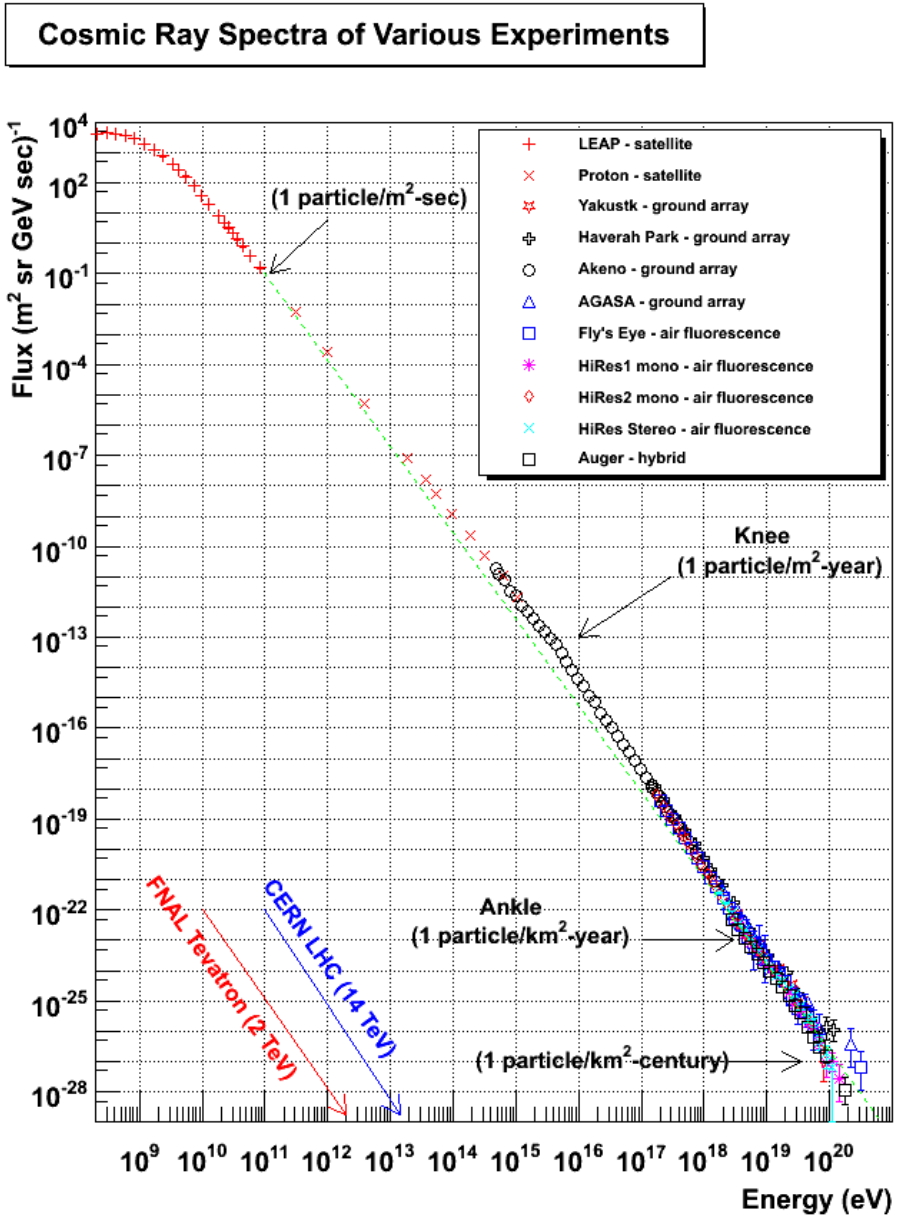
Shower Front Correction





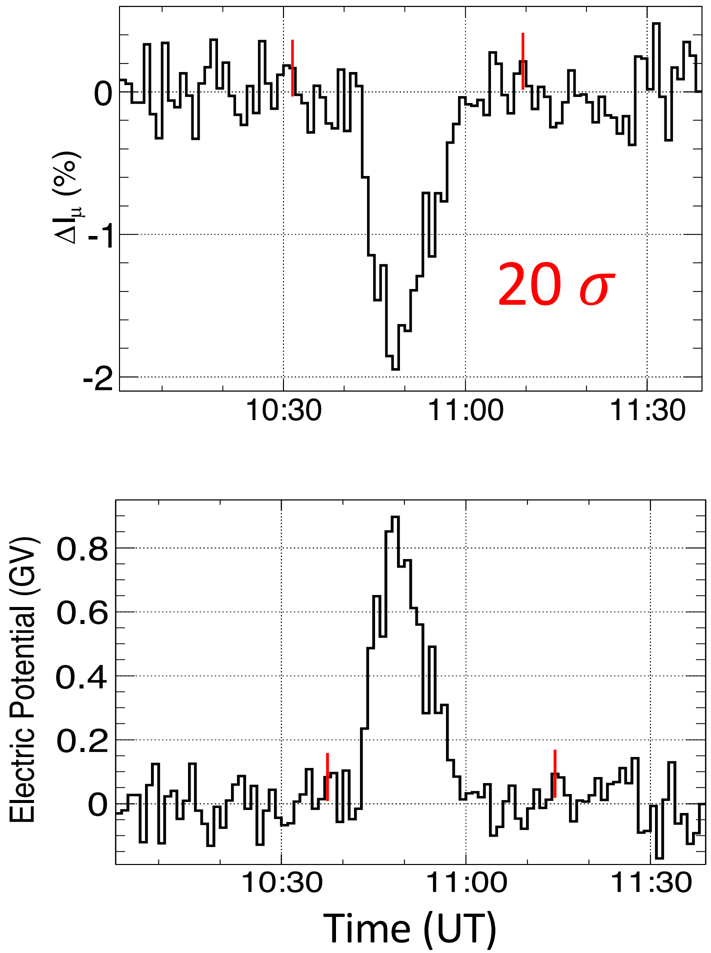
V.B. Jhansi et al., JCAP07(2020)024

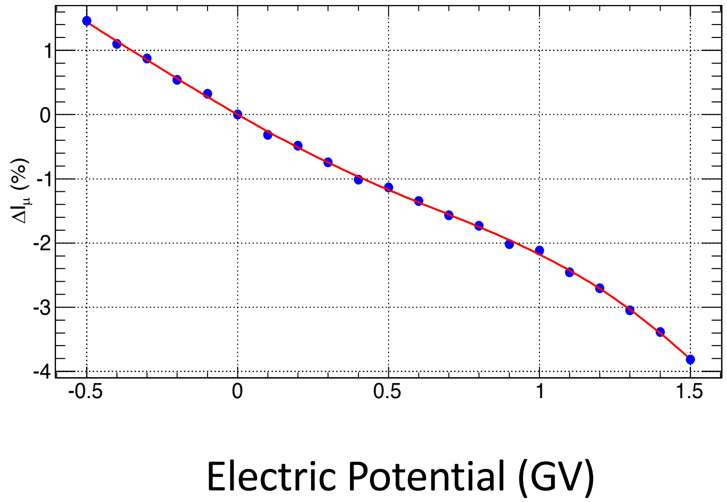
Advantages



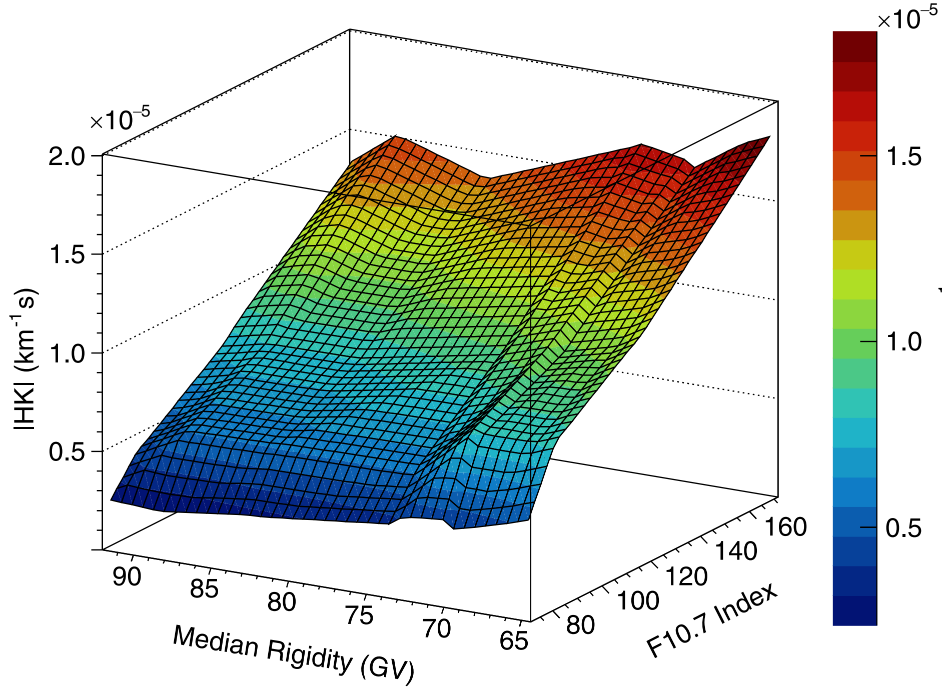
Cosmic Ray Spectra of Various Experiments
Flux (m² sr GeV sec)⁻¹
10⁴
10²
10⁻¹
10⁻⁴
10⁻⁷
10⁻¹⁰
10⁻¹³
10⁻¹⁶
10⁻¹⁹
10⁻²²
10⁻²⁵
10⁻²⁸
LEAP - satellite
Proton - satellite
Yakustk - ground array
Haverah Park - ground array
Akeno - ground array
AGASA - ground array
Fly's Eye - air fluorescence
HiRes1 mono - air fluorescence
HiRes2 mono - air fluorescence
HiRes Stereo - air fluorescence
Auger - hybrid
(1 particle/m²-sec)
Knee
(1 particle/m²-year)
Ankle
(1 particle/km²-year)
(1 particle/km²-century)
FNAL Tevatron (2 TeV)
CERN LHC (14 TeV)
10⁹ 10¹⁰ 10¹¹ 10¹² 10¹³ 10¹⁴ 10¹⁵ 10¹⁶ 10¹⁷ 10¹⁸ 10¹⁹ 10²⁰
Energy (eV)

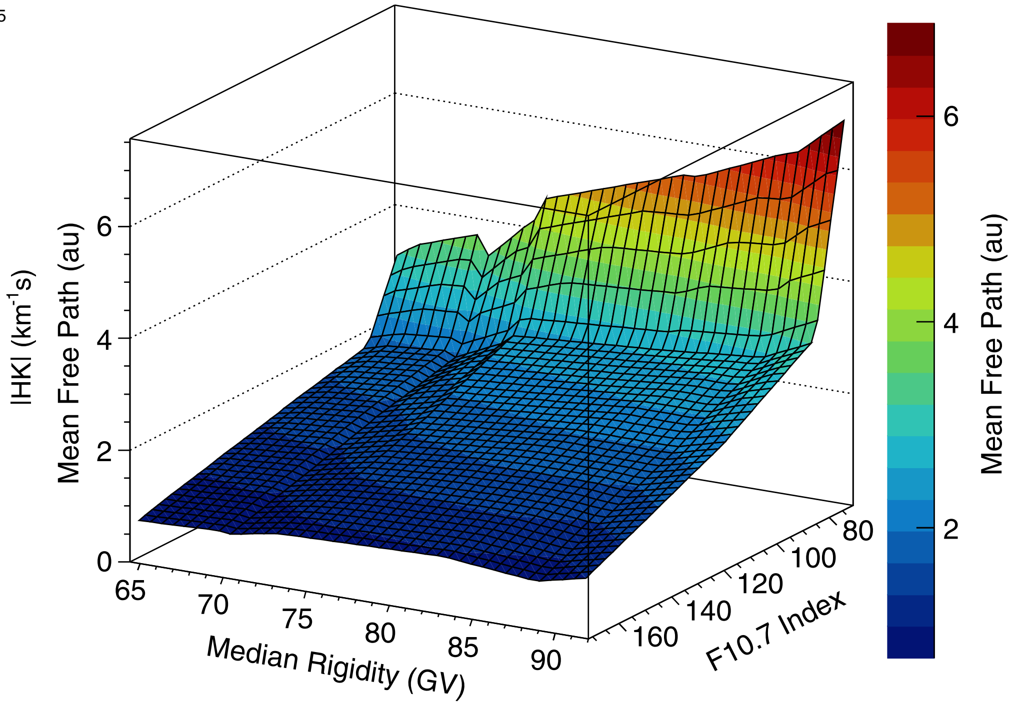
Monte Carlo Simulation





- $\Delta I_{\mu(Peak)}$ = (-2.0 ± 0.2) %
- V_{Peak} = (0.90 ± 0.08) GV





Kojima et. al. Phys.Rev.D 109 (2024) 6, 063011