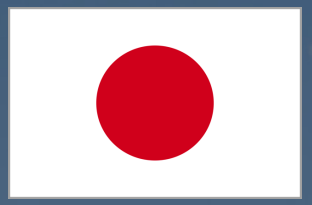
Recent results from the GRAPES-3 experiment



ISCRA 2025

25 June 2025

B. Hari Haran

The GRAPES-3 Experiment

Cosmic Ray Laboratory – TIFR

Ooty, India

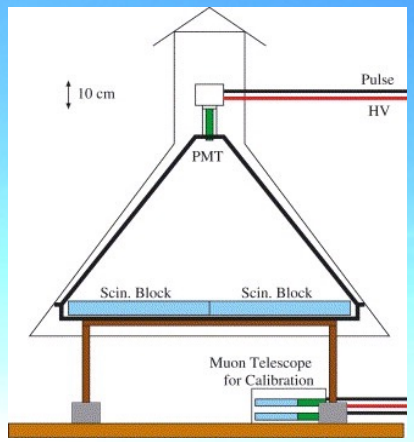
tifr

ISCRA-2025

Gamma Ray Astronomy at PeV EnergieS - 3

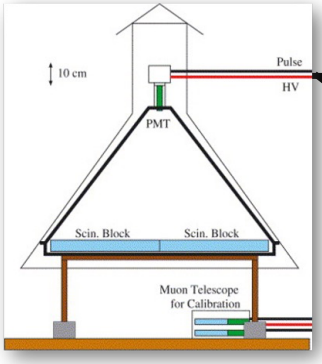
Ooty, India

EAS Array



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

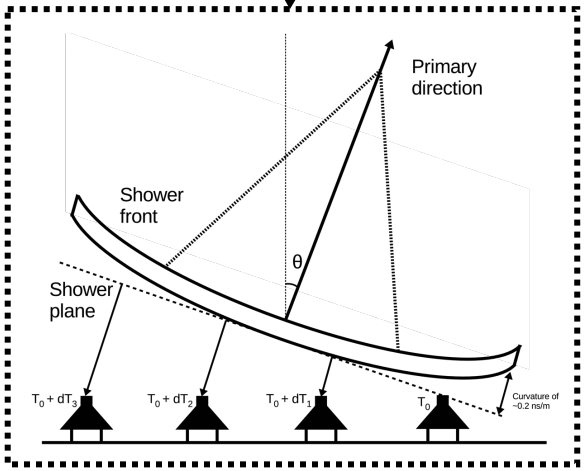
Observables

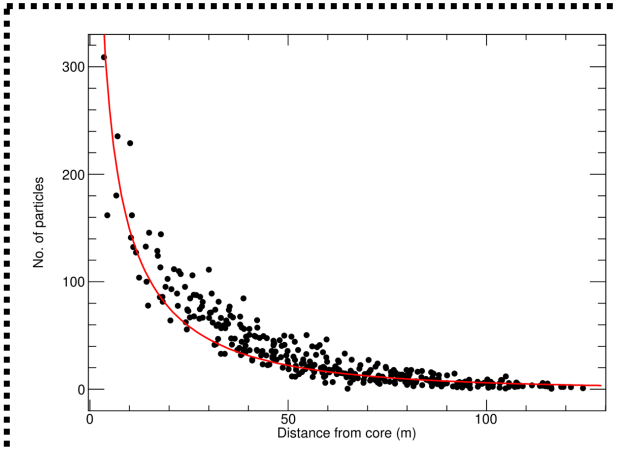


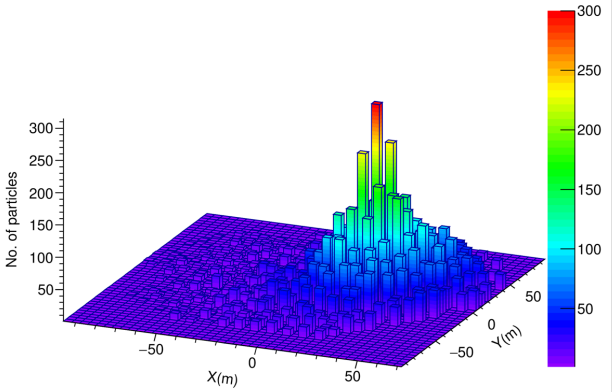
ADC → **Pedestal** → **Calibration** → **Det. Gain**

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

No. Of Particles







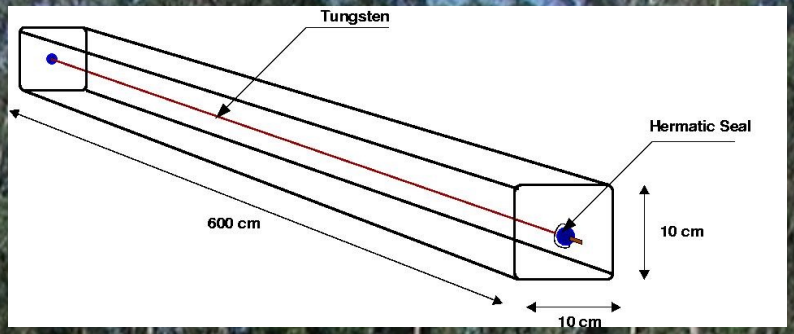
Direction (θ, ϕ)

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

Core (X_C, Y_C)

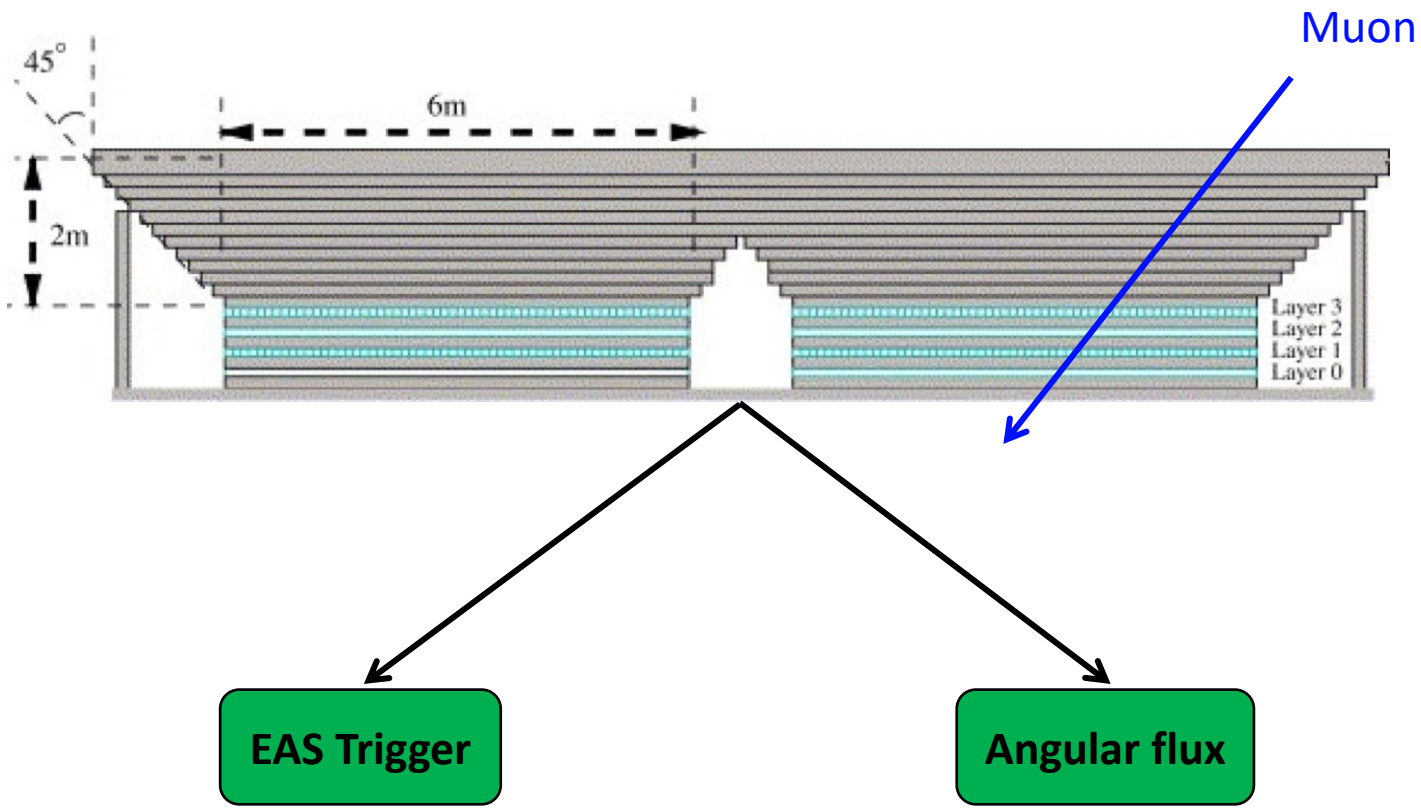
Muon Telescope

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

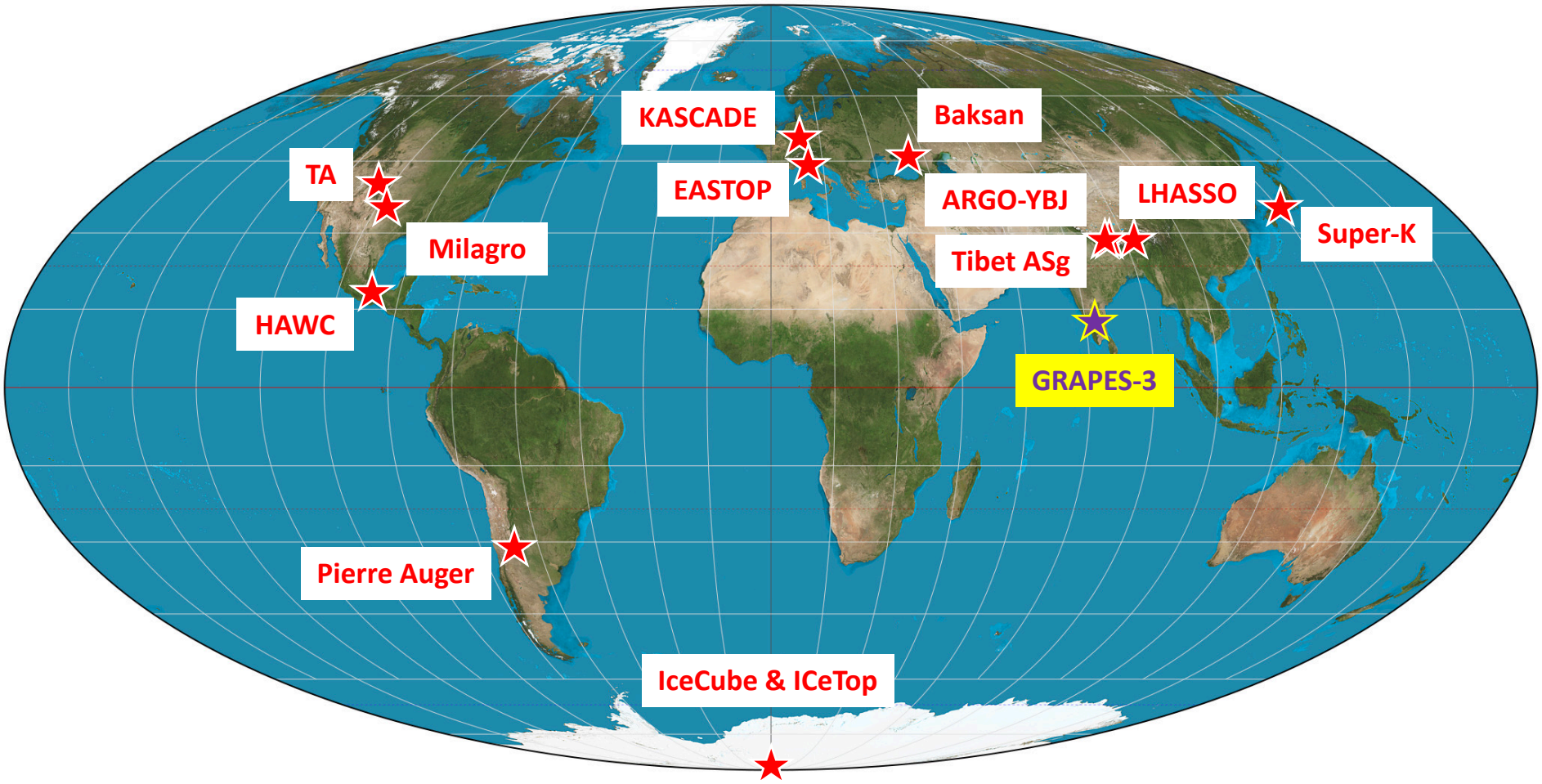


New Muon Telescope

Observables

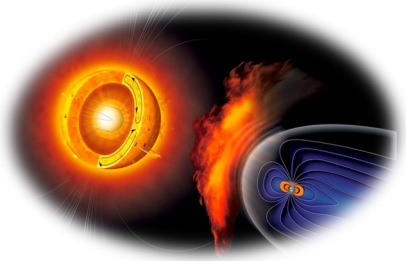


Advantages



11.4° N, 76.7° E, 2200 m amsl

Physics Studies

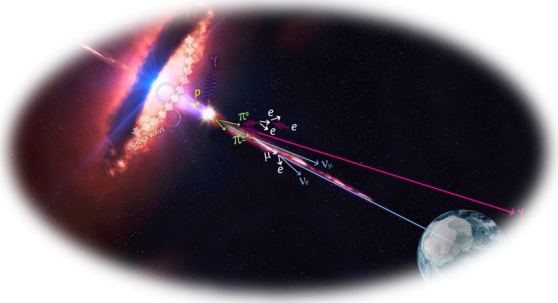


Part II: Solar studies

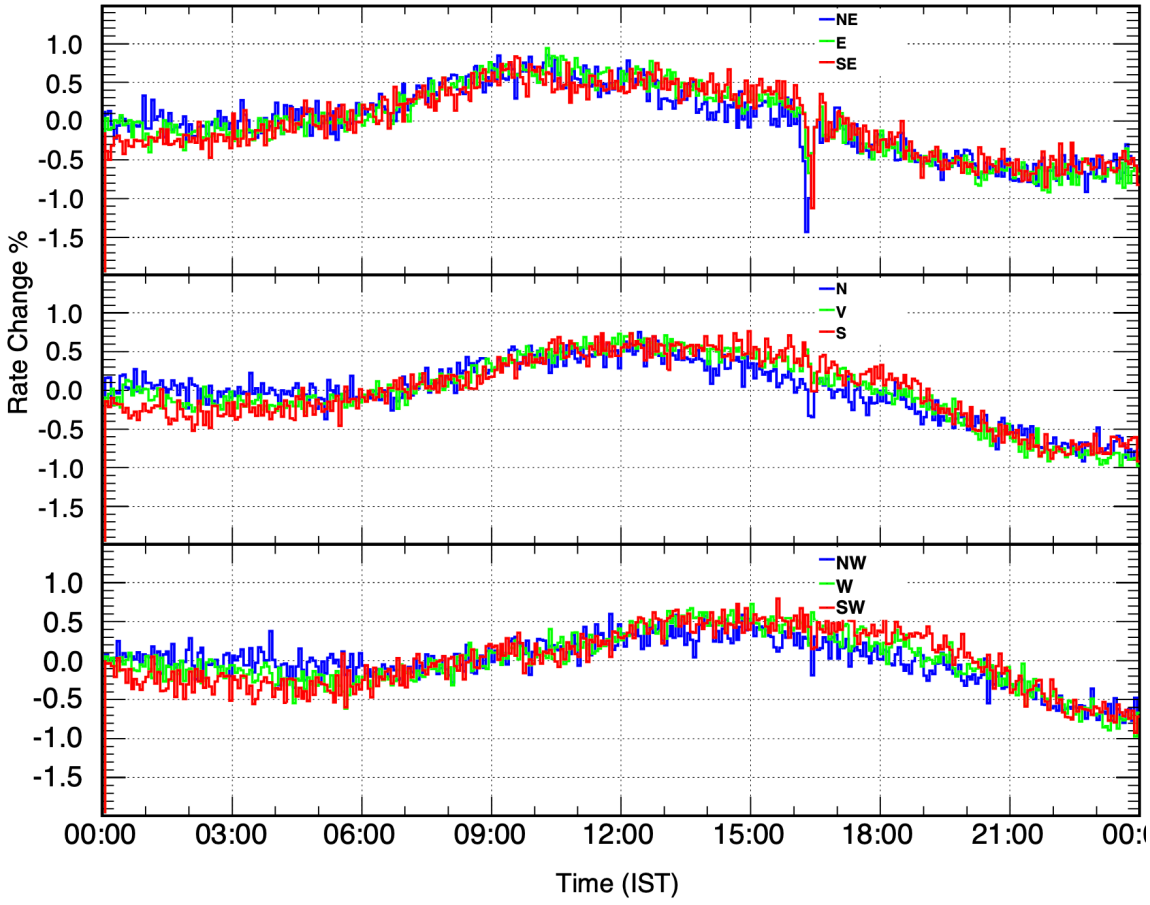
10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} (eV)

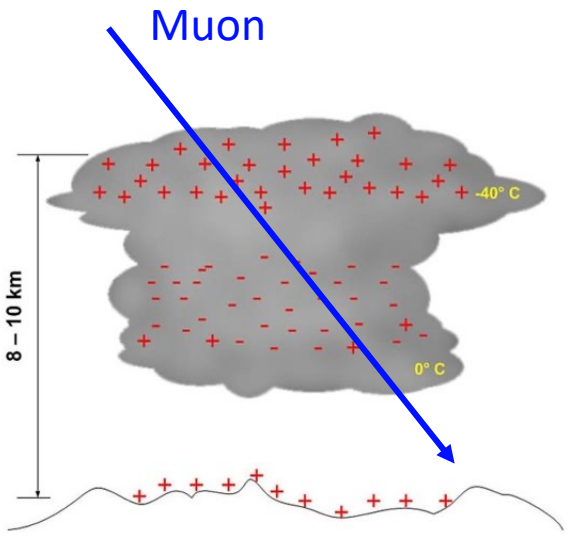
Part I: Atmospheric acceleration

Part III: Cosmic rays

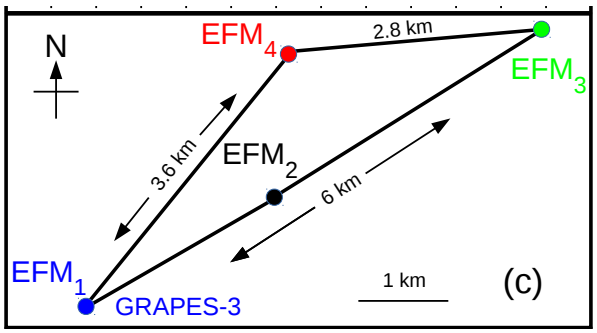


Part I: Atmospheric Acceleration

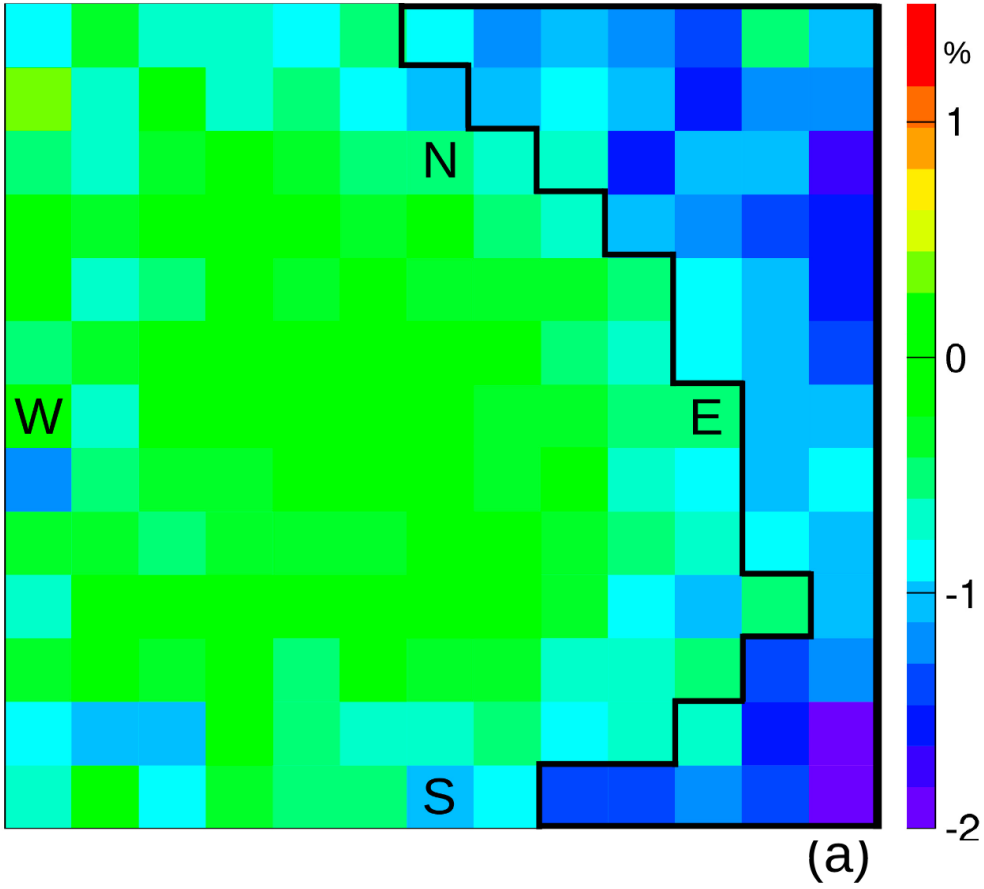


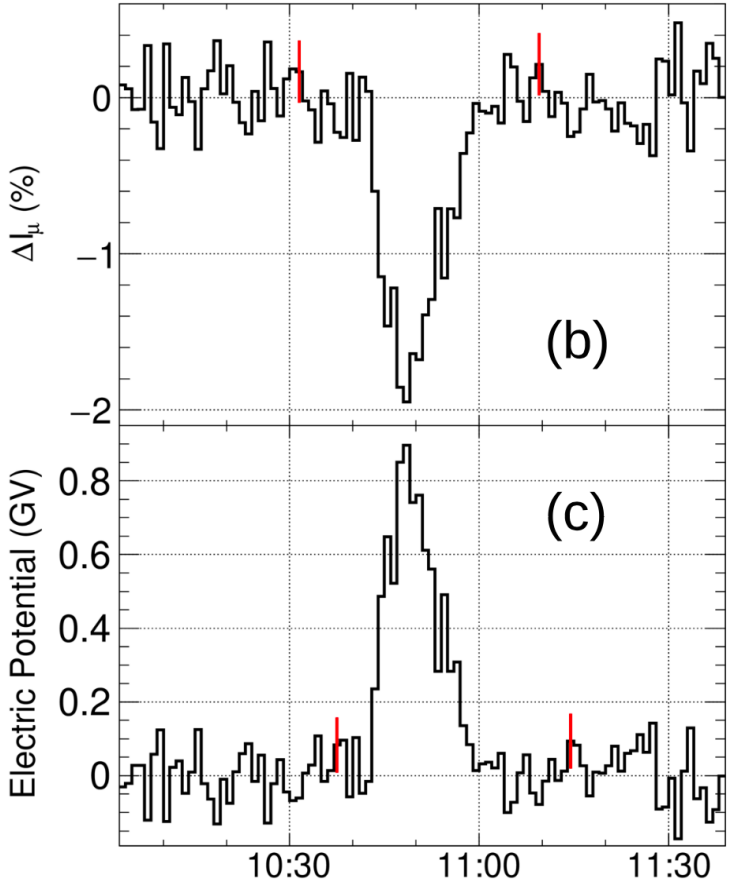


~50 events / year



Thunderstorm event on 1 Dec 2014

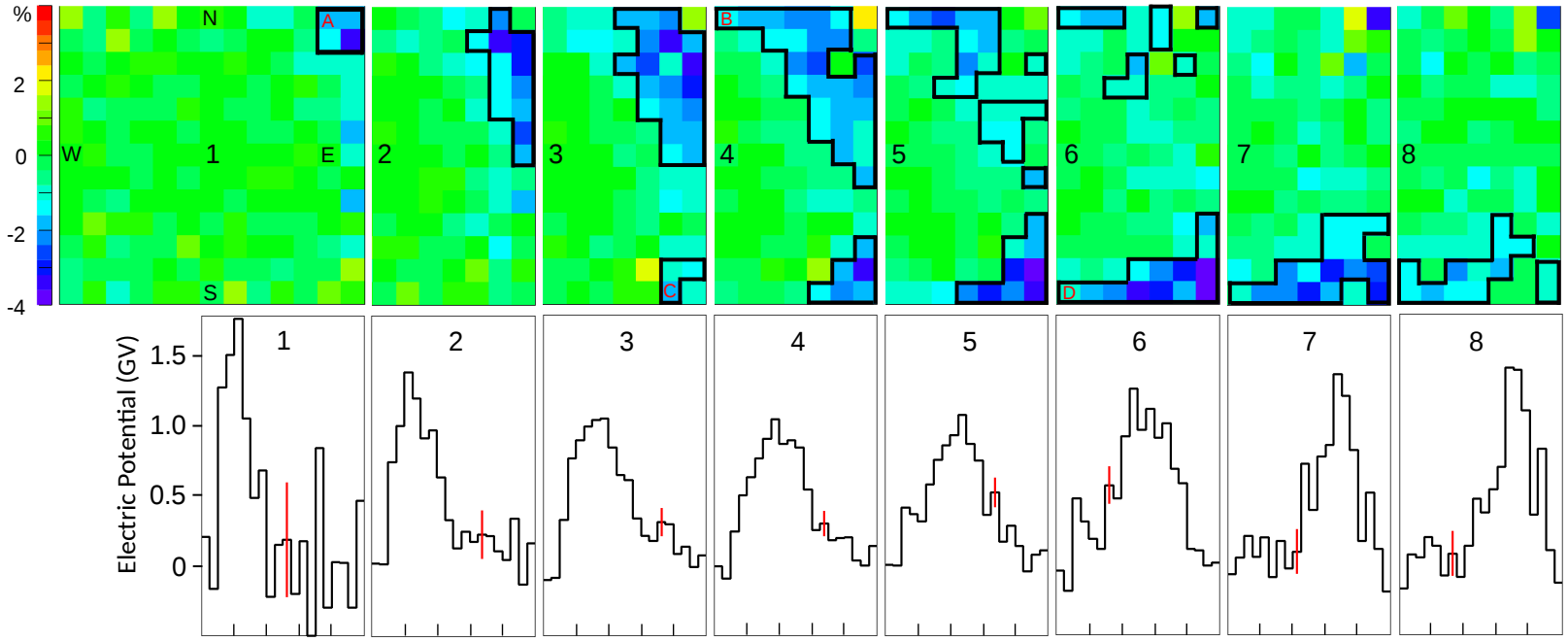




18 minutes

45 directions

Cloud Movement



Mean V = 1.3 GV

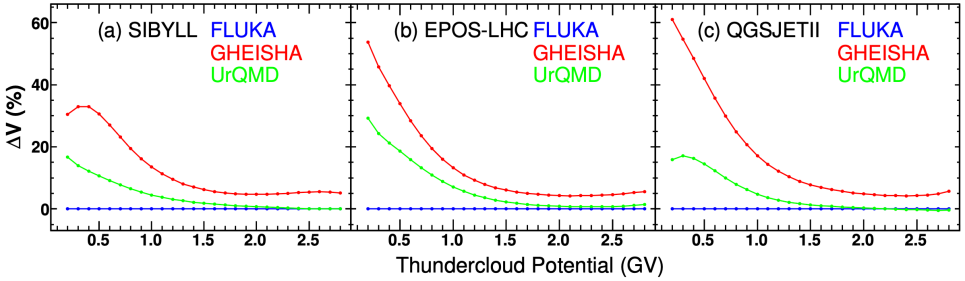
C.T.R. Wilson's prediction of 1 GV 90Y ago

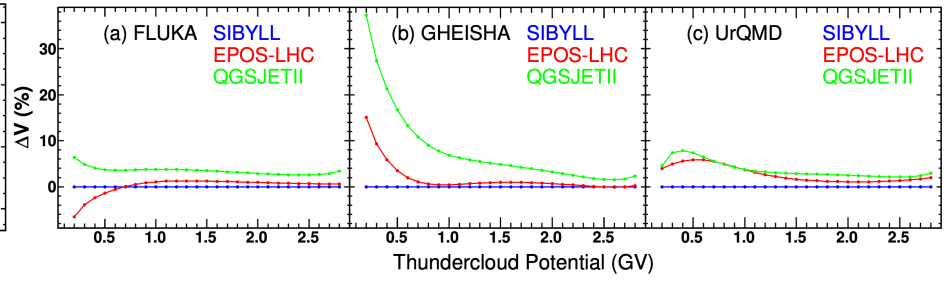
Measurement of 0.13 GV

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

Giga-volt Electric Potential

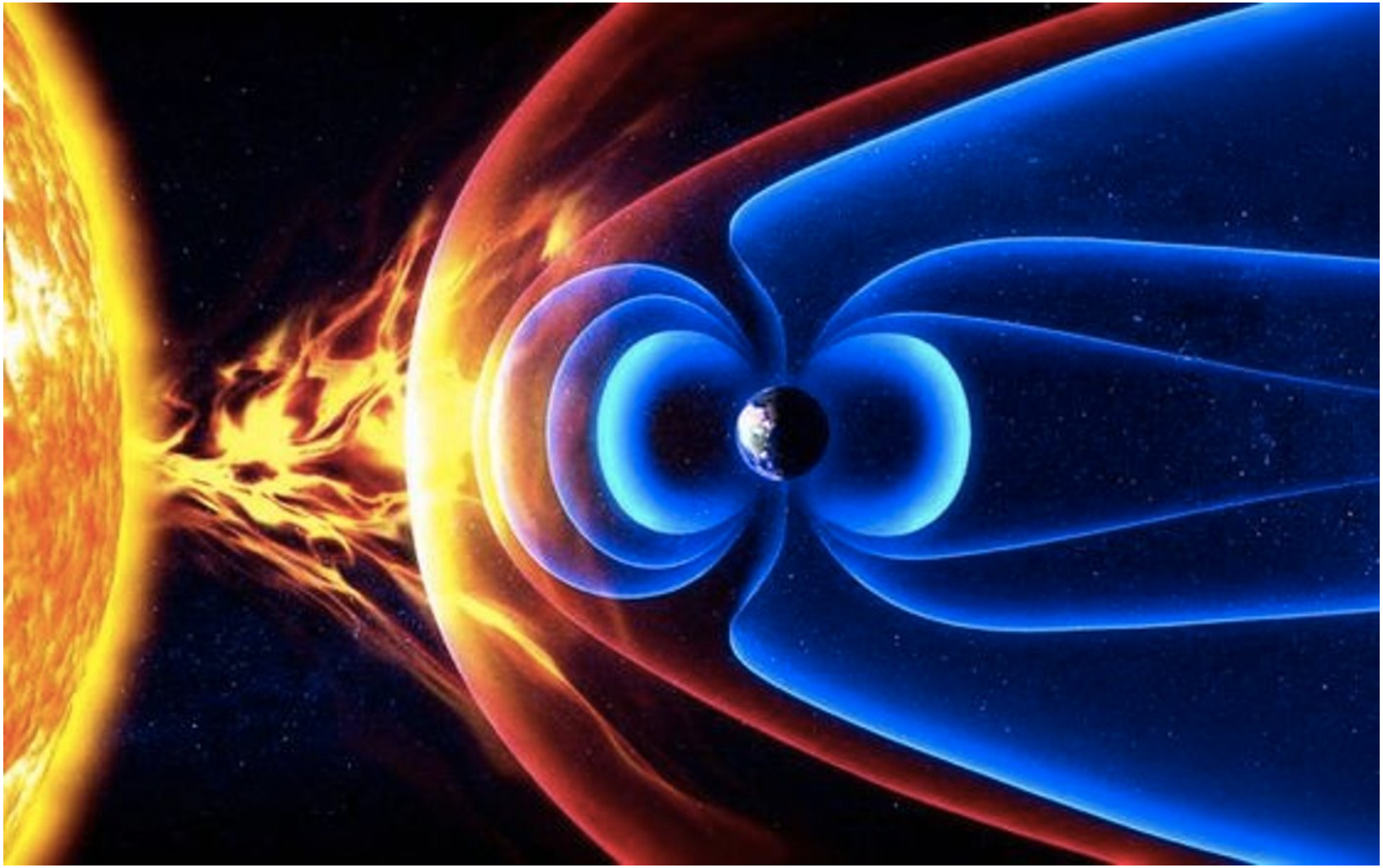
Thunderstorm event details				Thundercloud potential (GV) (Percent change with respect to SIBYLL-FLUKA)								
Date	No. of directions	ΔI_μ(%)	Duration (min.)	SIBYLL			EPOS-LHC			QGSJETII		
				FLUKA	GHEISHA	UrQMD	FLUKA	GHEISHA	UrQMD	FLUKA	GHEISHA	UrQMD
13-10-2012	28	−1.77	52	0.92 —	1.09 (18%)	0.98 (6%)	1.01 (9%)	1.13 (22%)	1.00 (8%)	1.01 (10%)	1.11 (20%)	1.04 (13%)
11-04-2014	27	−1.71	43	0.76 —	0.95 (25%)	0.83 (9%)	0.90 (18%)	0.93 (22%)	0.90 (18%)	0.89 (17%)	0.95 (25%)	0.88 (16%)
23-09-2014	20	−2.91	28	1.17 —	1.29 (11%)	1.23 (5%)	1.19 (1%)	1.33 (14%)	1.23 (6%)	1.26 (8%)	1.36 (16%)	1.28 (9%)
28-09-2014	39	−2.03	19	1.12 —	1.21 (8%)	1.18 (5%)	1.17 (5%)	1.22 (9%)	1.17 (4%)	1.20 (7%)	1.19 (6%)	1.20 (7%)
01-12-2014	45	−1.95	18	0.90 —	1.06 (18%)	0.96 (7%)	0.93 (3%)	1.08 (20%)	1.00 (11%)	0.95 (5%)	1.13 (26%)	1.00 (11%)
06-04-2017	12	−3.04	22	1.39 —	1.46 (5%)	1.42 (2%)	1.35 (−3%)	1.44 (4%)	1.42 (2%)	1.45 (4%)	1.55 (11%)	1.47 (6%)
06-02-2018	40	−2.00	47	1.04 —	1.13 (8%)	1.07 (2%)	1.13 (8%)	1.15 (10%)	1.11 (6%)	1.04 (0%)	1.18 (13%)	1.11 (6%)
22-04-2018	29	−1.64	35	0.86 —	0.99 (16%)	0.88 (3%)	0.94 (9%)	0.97 (13%)	0.95 (12%)	0.97 (13%)	1.03 (21%)	0.95 (11%)



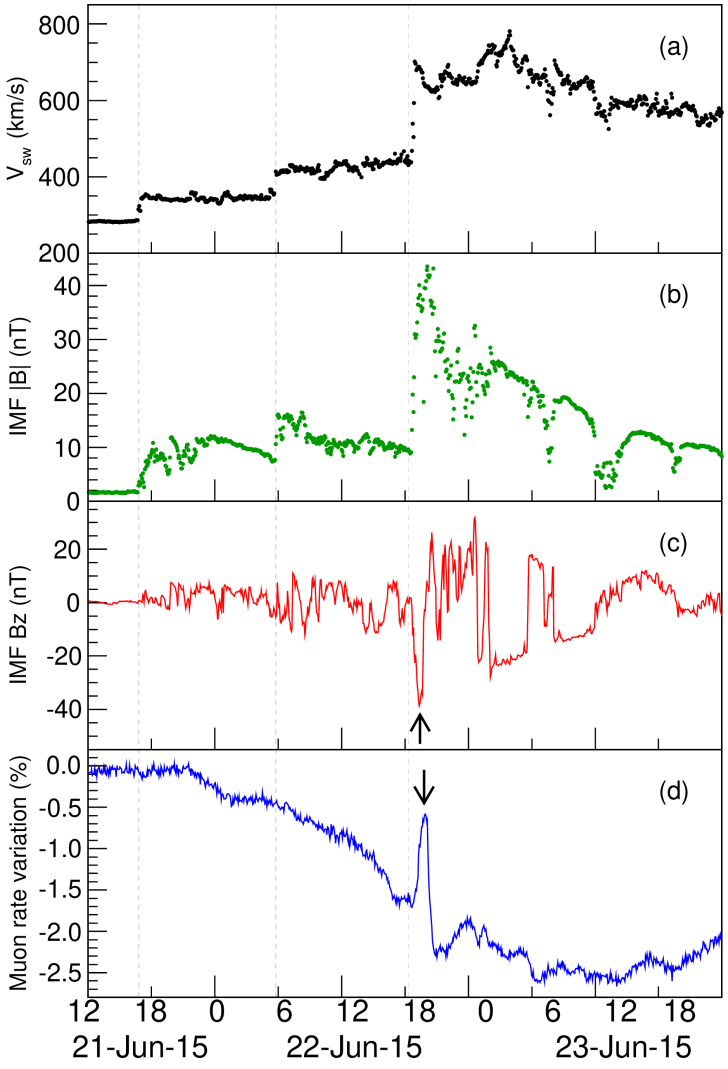


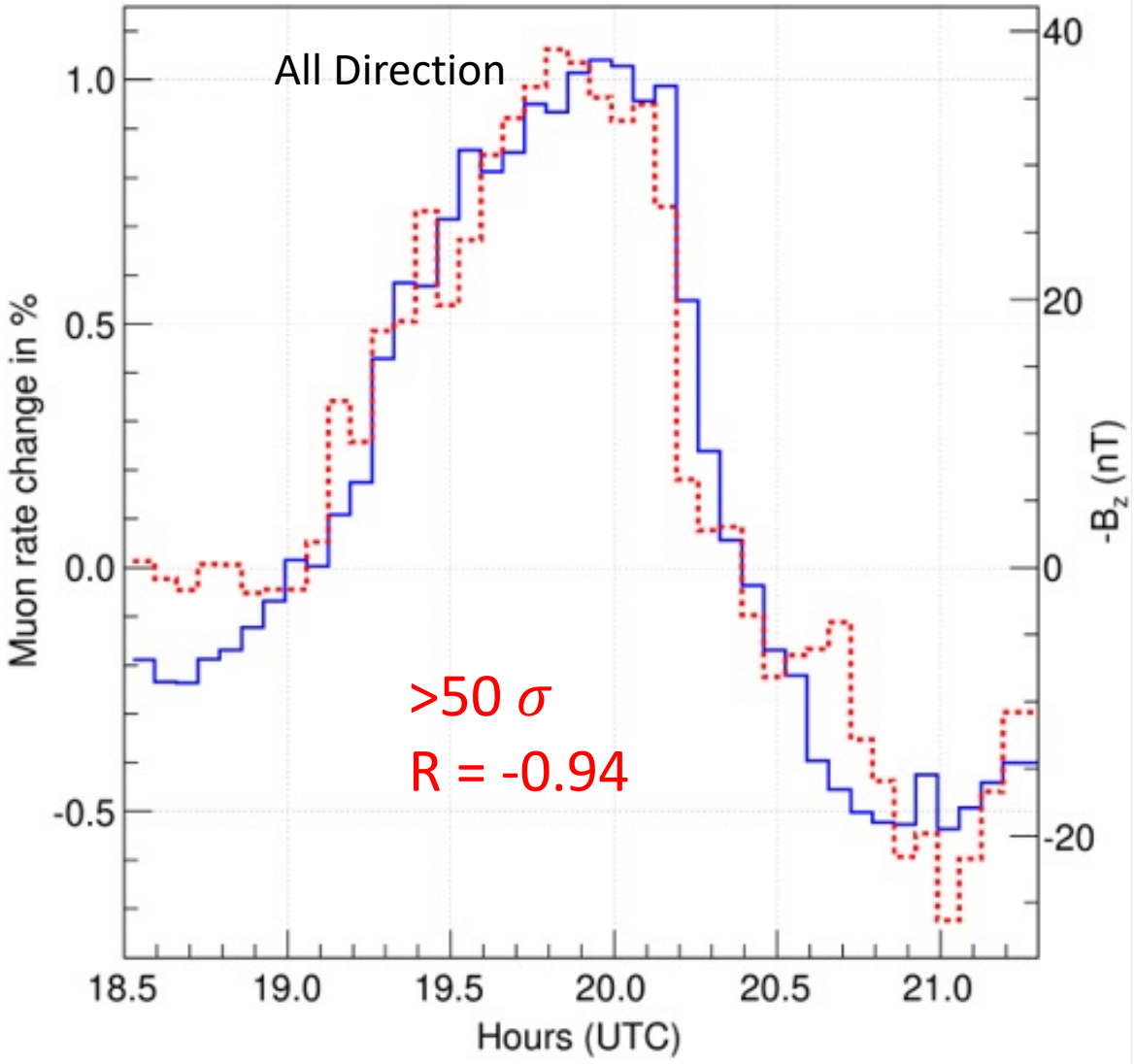
B. Hariharan et al., JCAP06(2025)012

Part II: Solar Studies



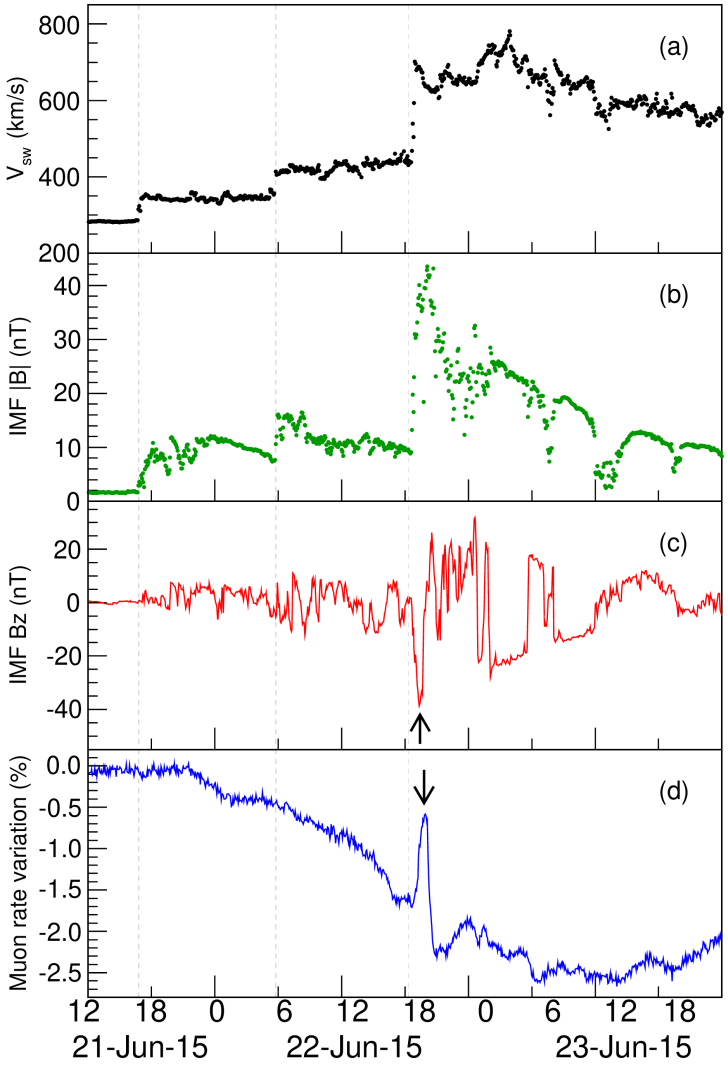
Transient Weakening of GMF

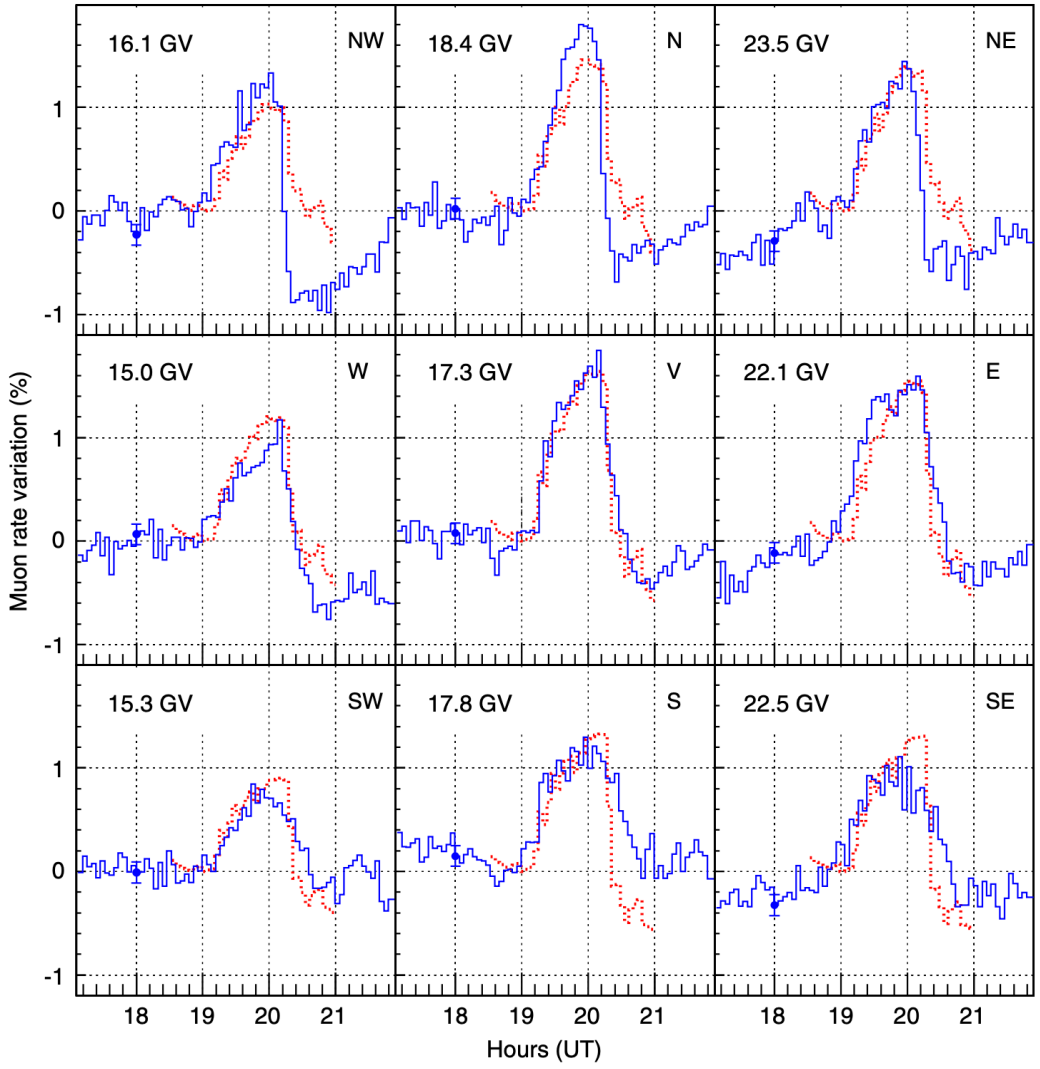




P.K. Mohanty et al., PRL 117, 171101 (2016)
P.K. Mohanty et al., PRD 97, 082001 (2018)

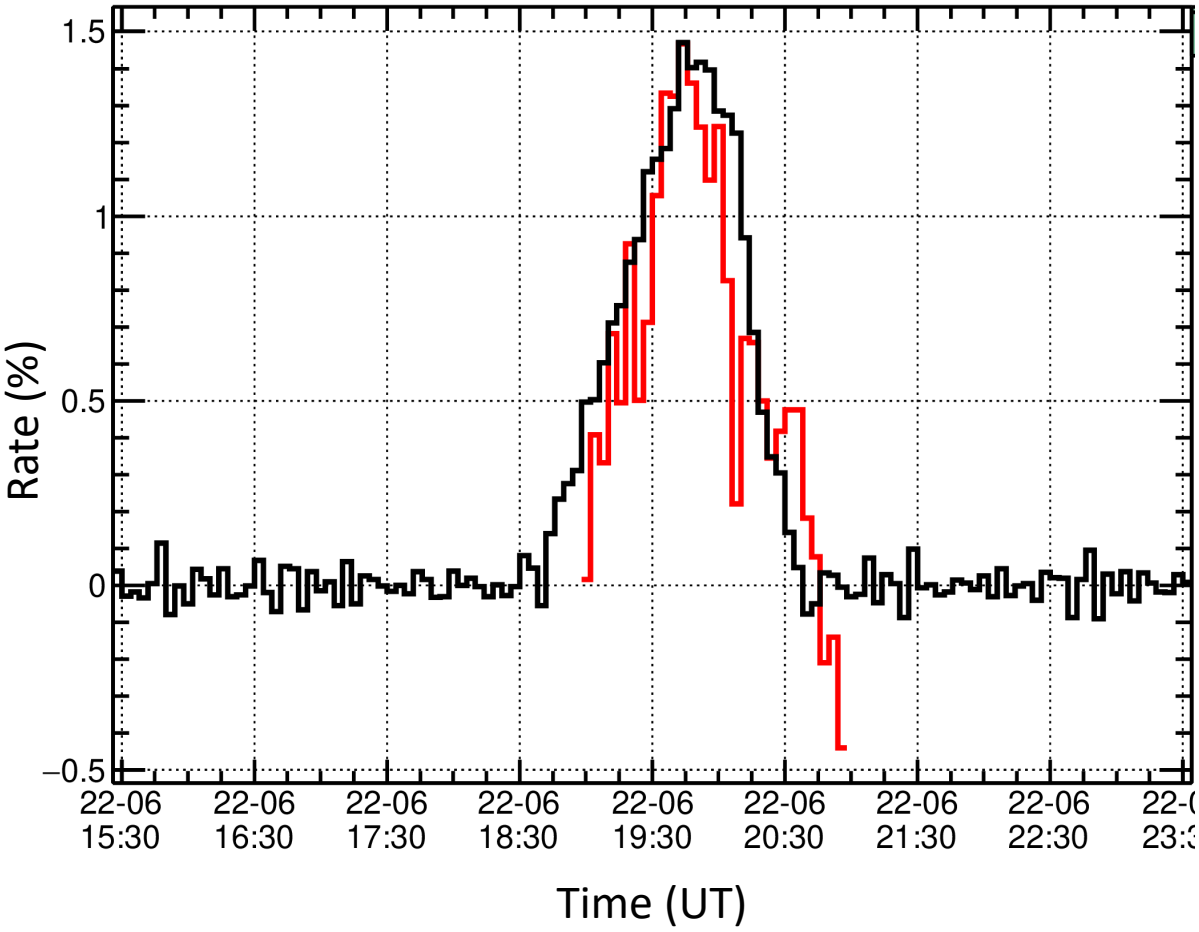
Transient Weakening of GMF





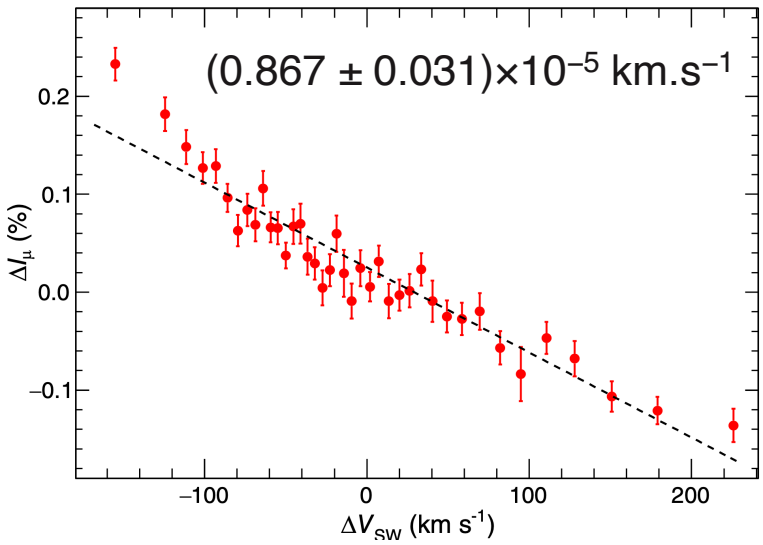
P.K. Mohanty et al., PRL 117, 171101 (2016)
P.K. Mohanty et al., PRD 97, 082001 (2018)

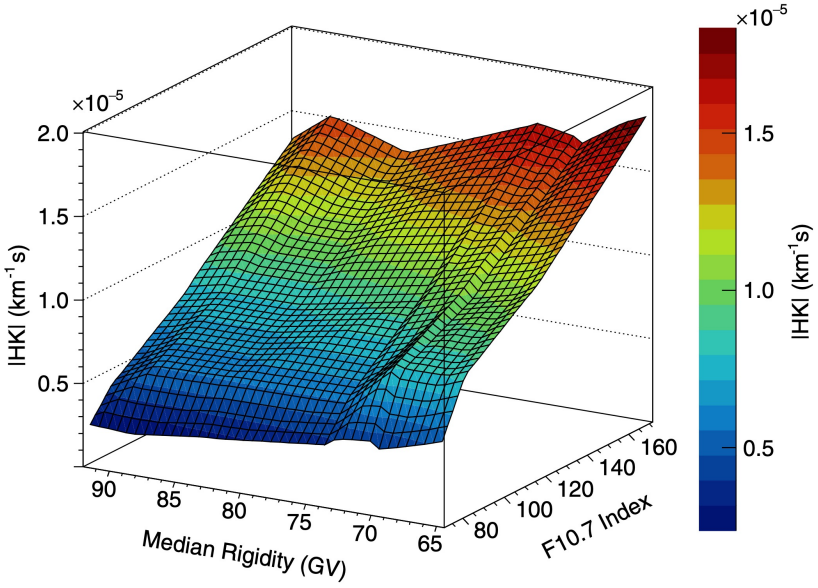
Detection by Scintillators

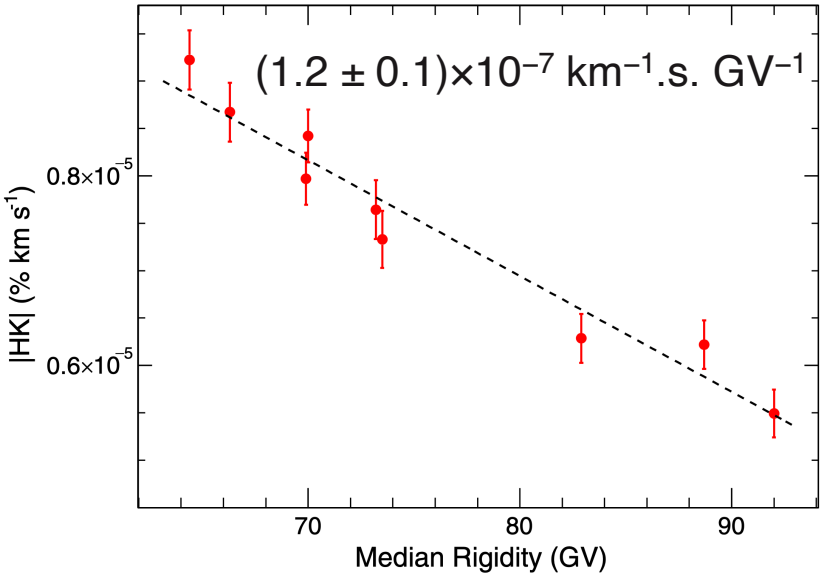


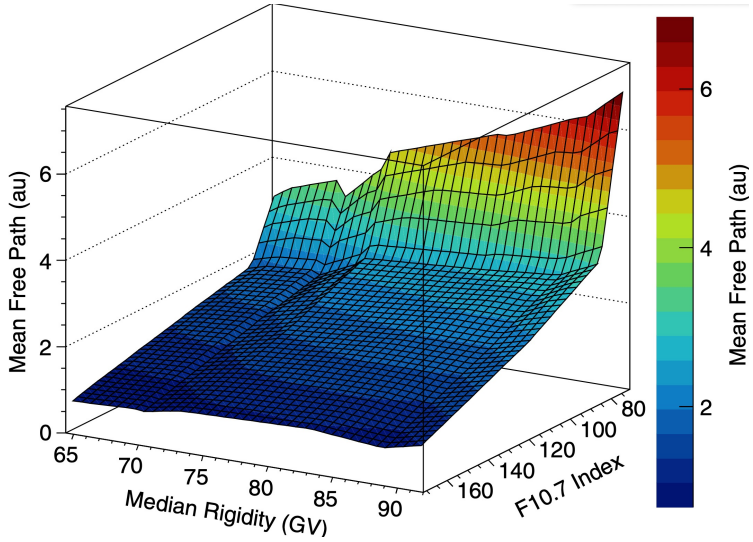
B. Hariharan et al., JASTP 243 (2023) 106005

Dependence of parallel mean free path of GCRs



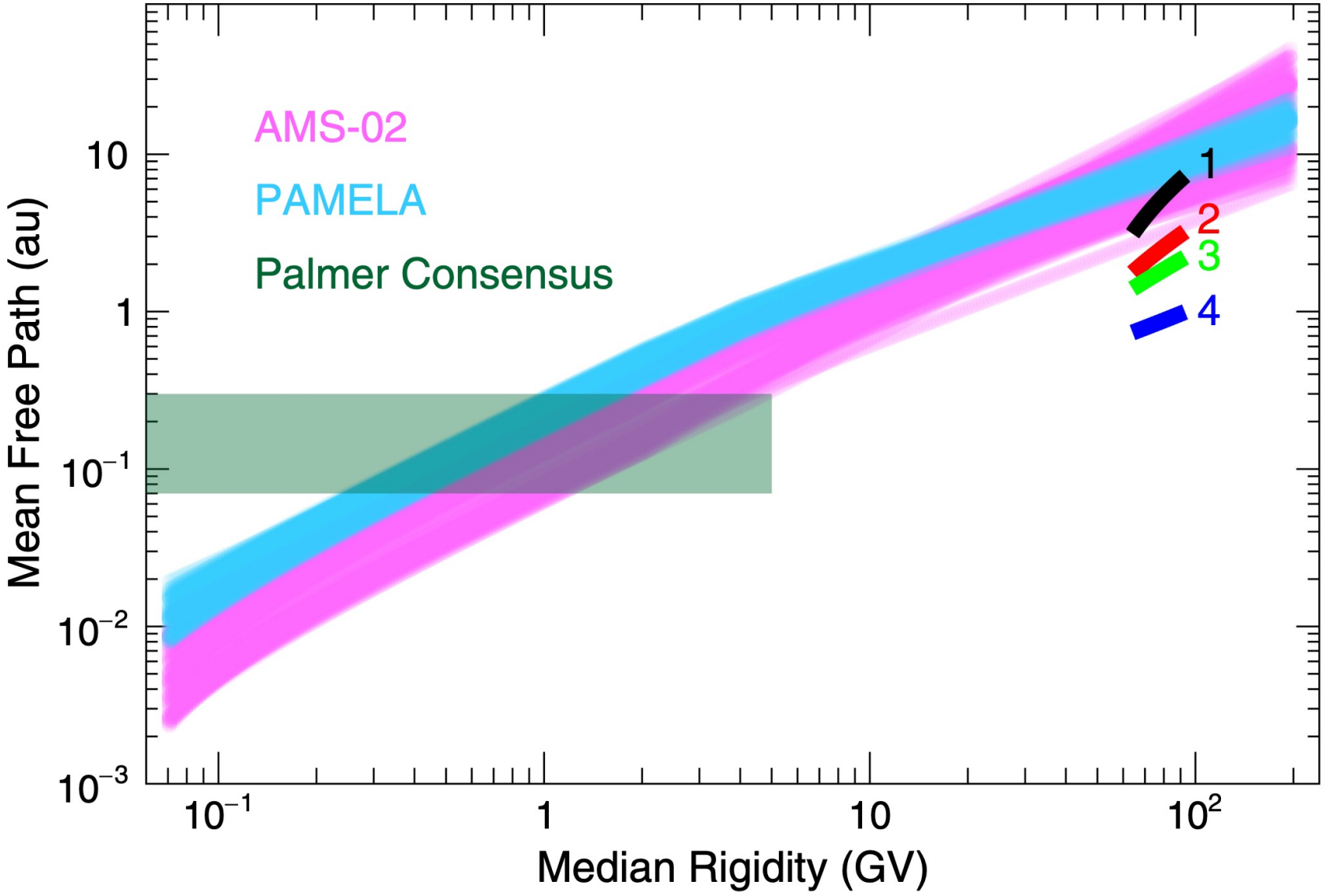






H. Kojima et al., Physical Review D 109, 063011 (2024)

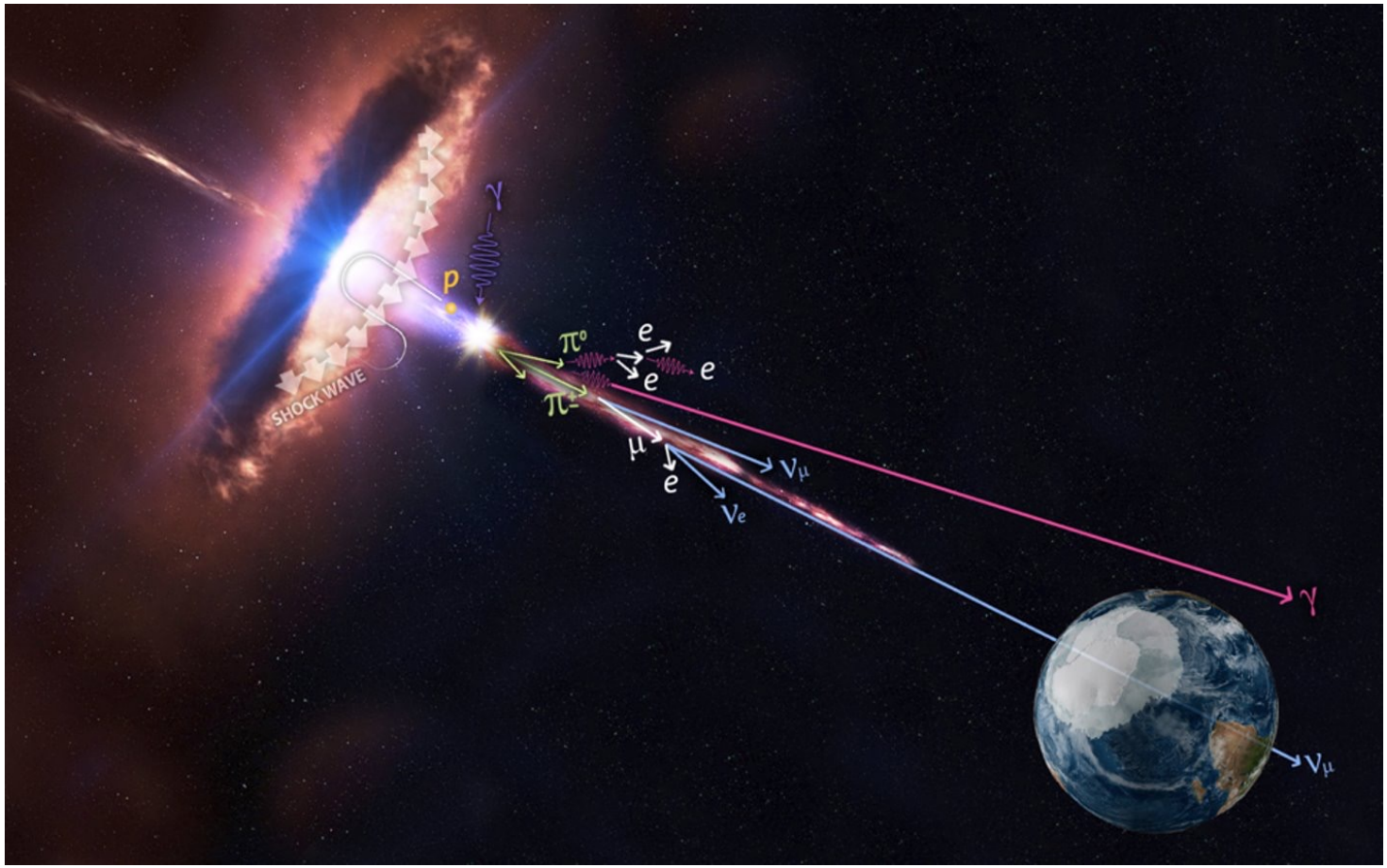
Dependence of parallel mean free path of GCRs



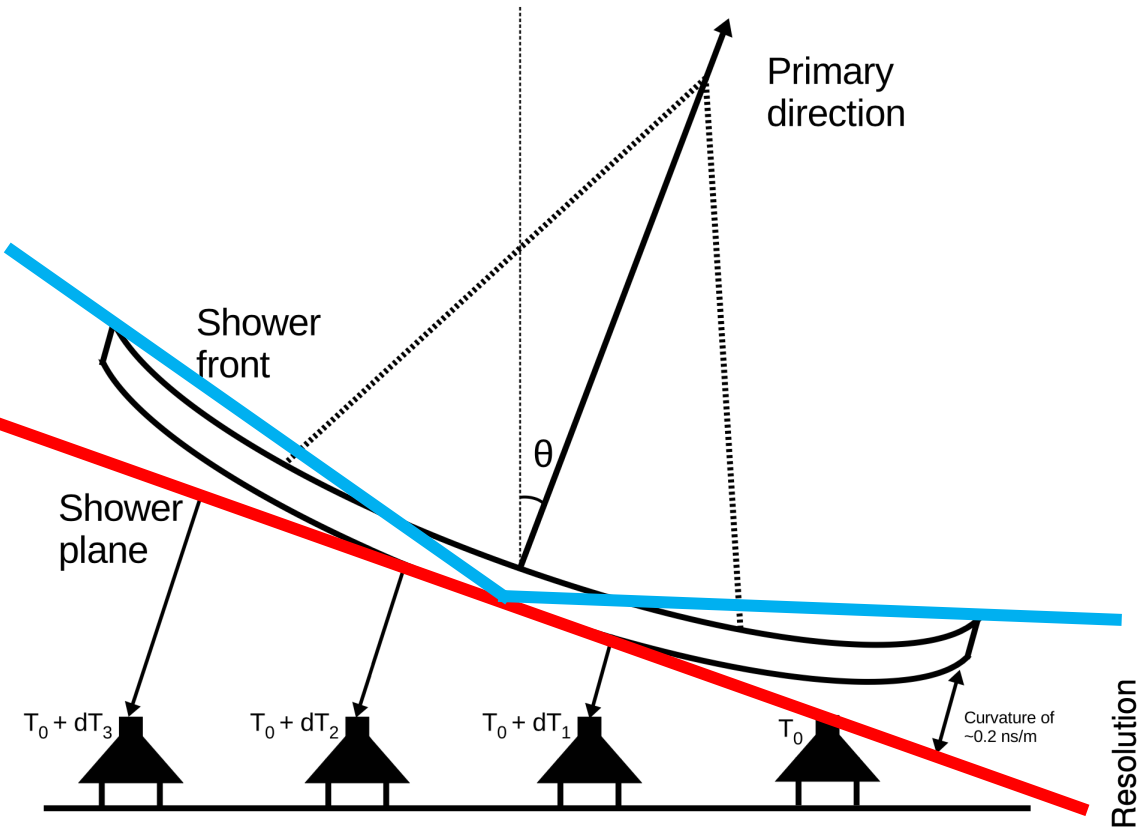
H. Kojima et al., Physical Review D 109, 063011 (2024)

Part III: Cosmic Rays

E = 1 TeV – 10 PeV



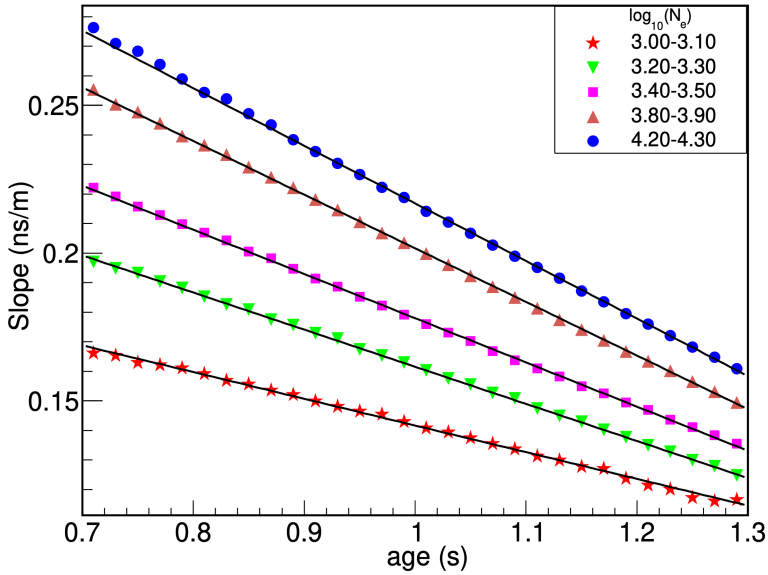
Shower Front Correction

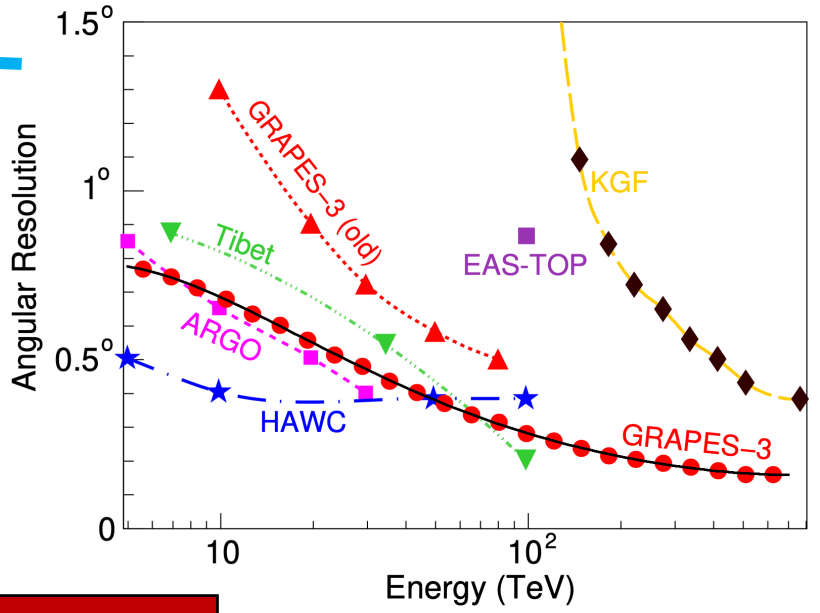


Traditional (Plane fit)

Improved (Cone fit)

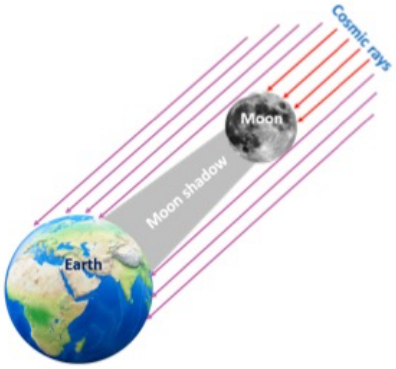
Curvature correction with shower age and size

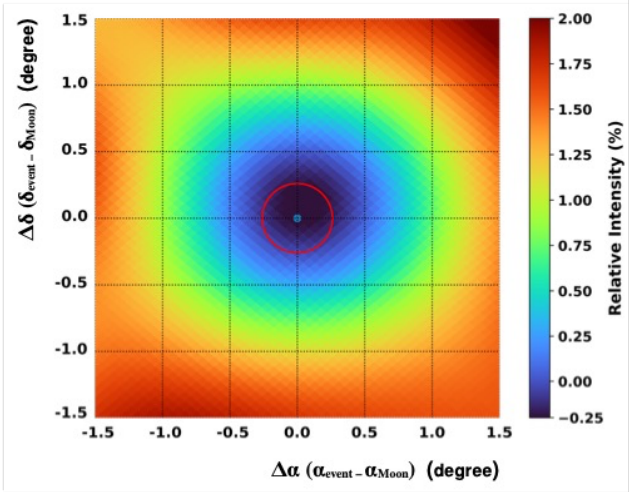




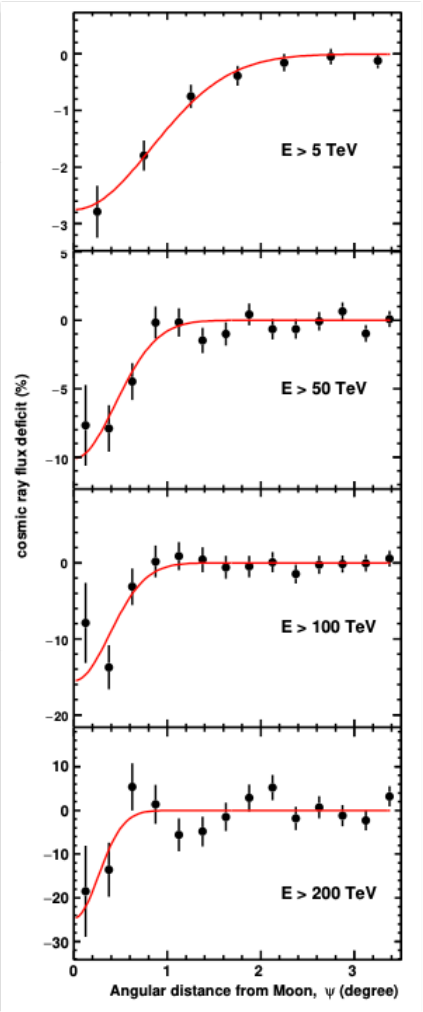
V.B. Jhansi et al., JCAP07(2020)024

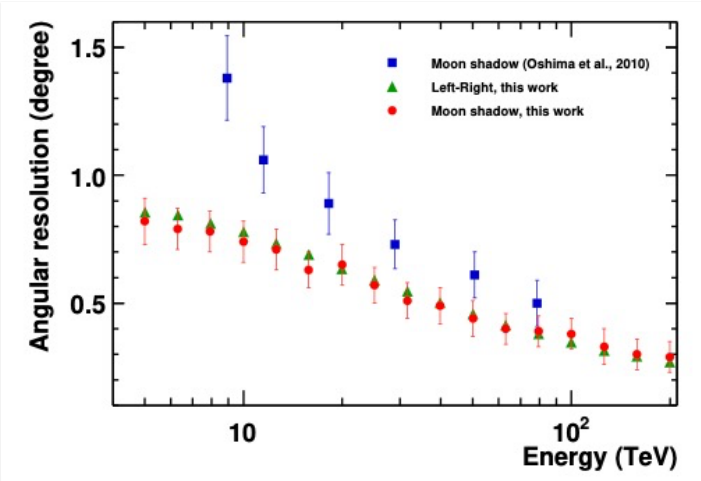
The Moon Shadow

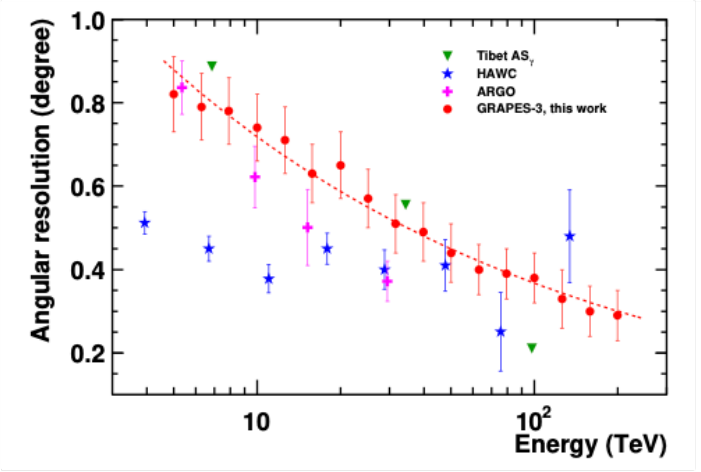




$\alpha = (0.032 \pm 0.004)°$
$\delta = (0.090 \pm 0.003)°$

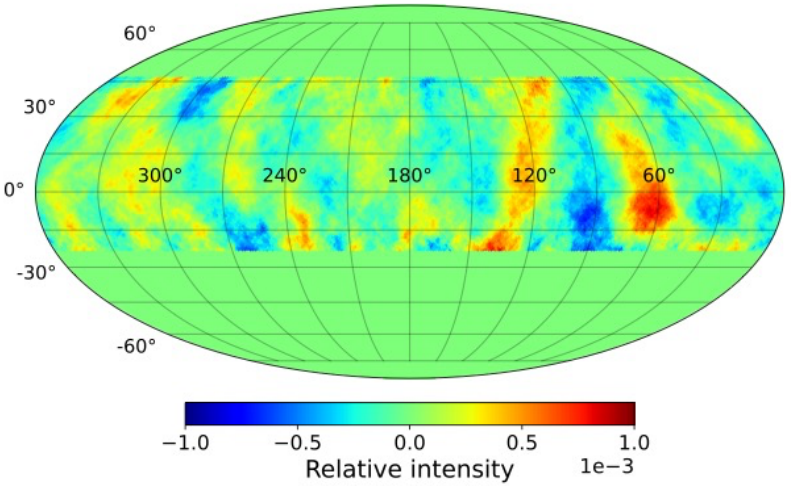






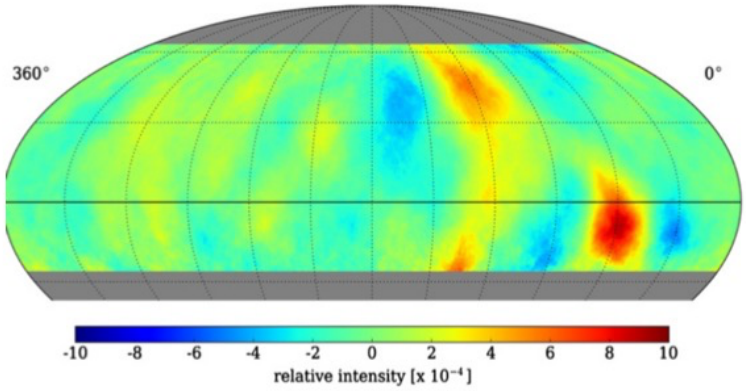
D. Pattanaik et al., PRD 106, 022009 (2022)

Cosmic Ray Anisotropy

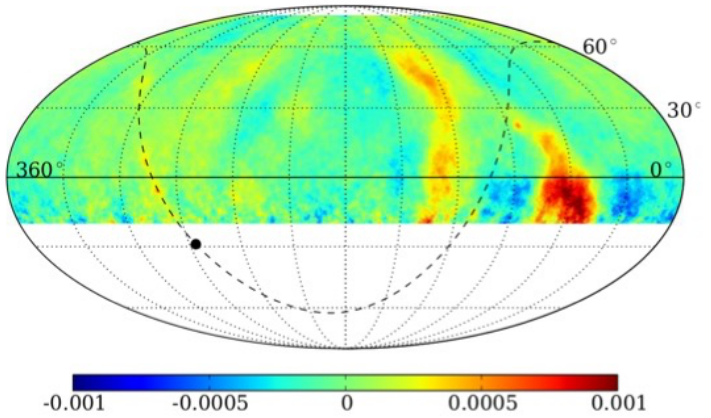


GRAPES-3

HAWC

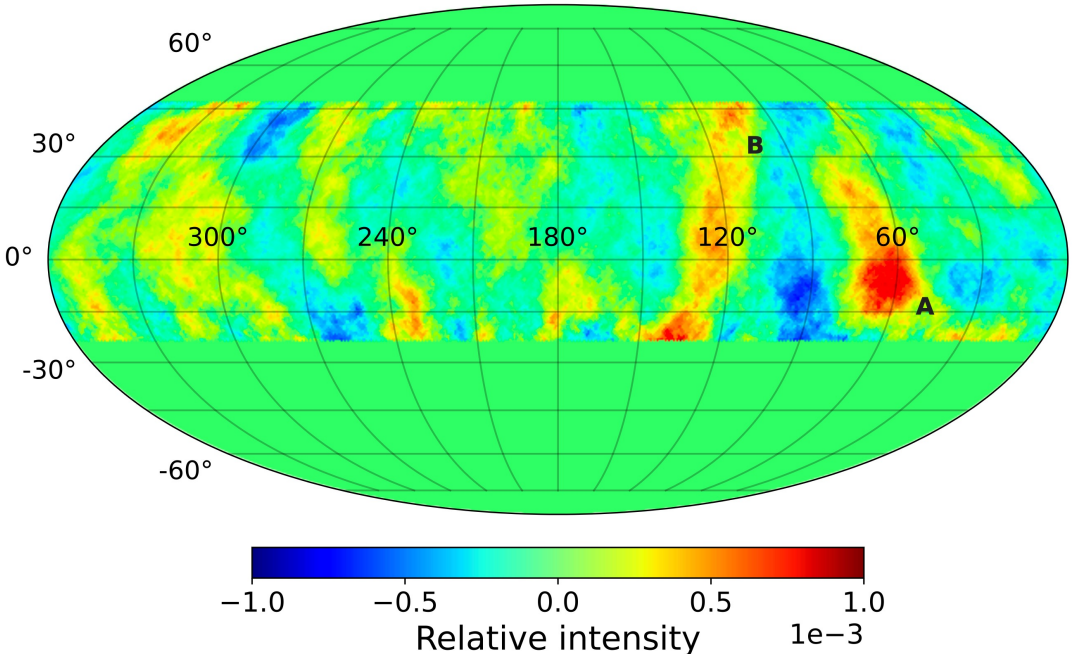


ARGO-YBJ

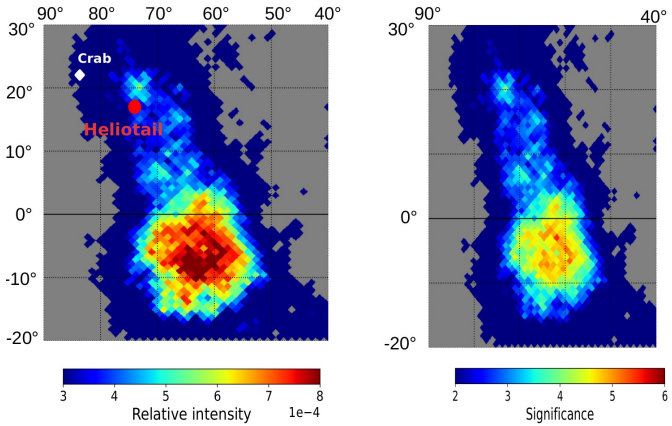


M. Chakraborty et al., The Astrophysical Journal, 961:87 (7pp), 2024

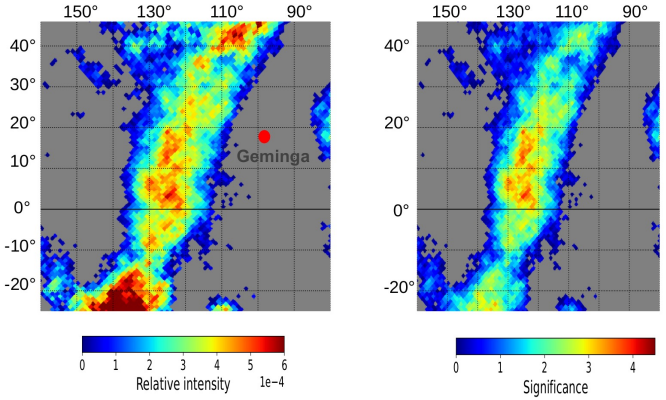
Cosmic Ray Anisotropy



Region A

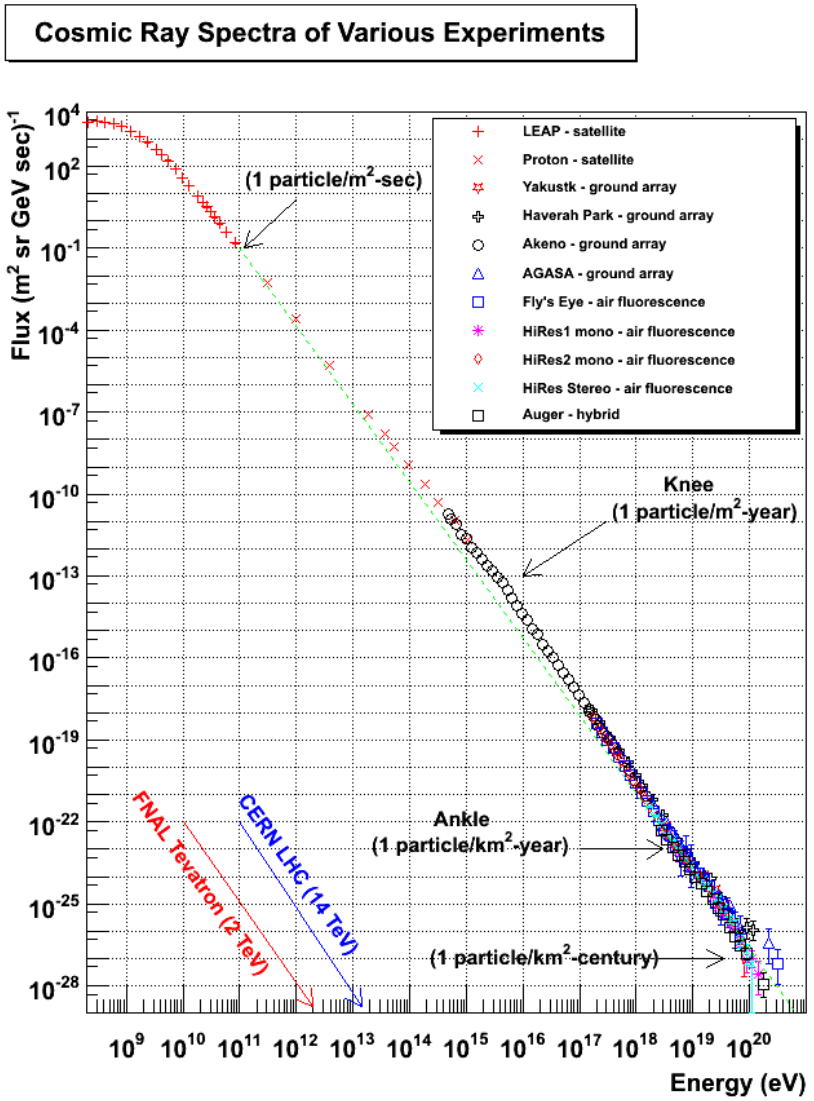


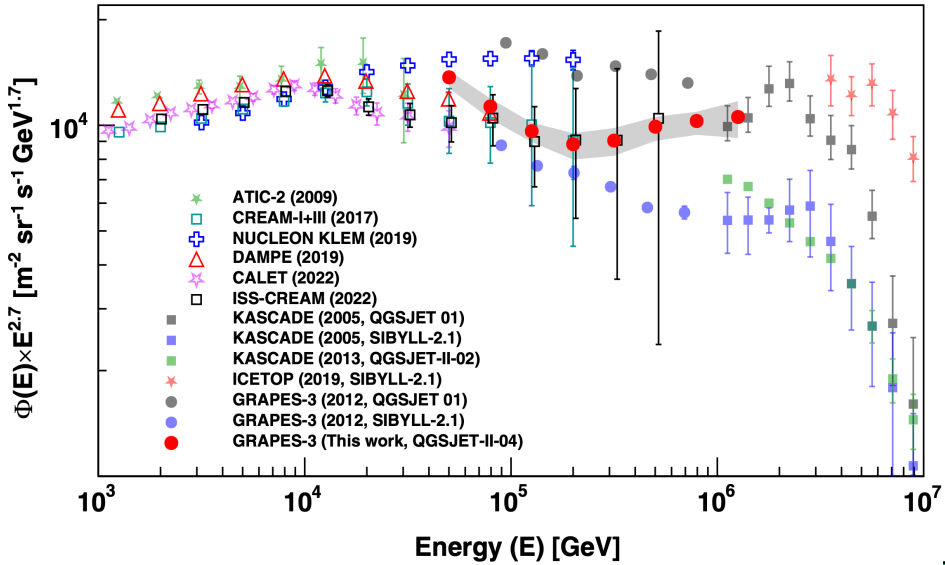
Region B



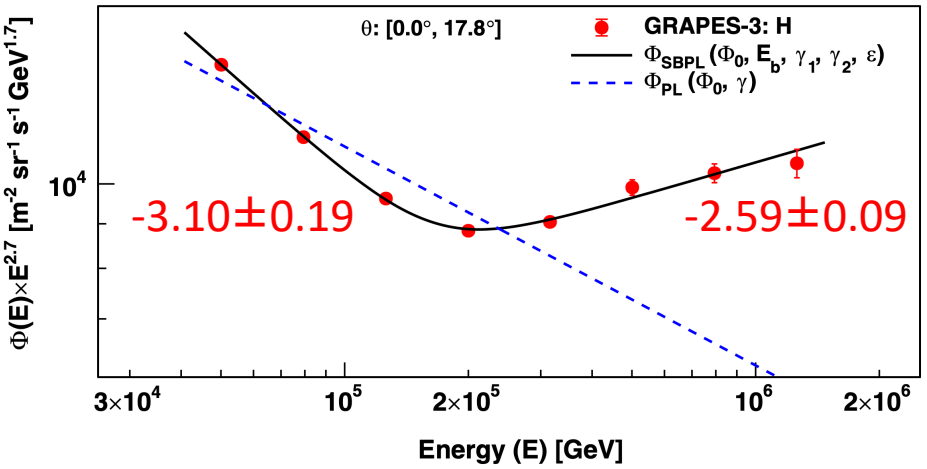
M. Chakraborty et al., The Astrophysical Journal, 961:87 (7pp), 2024

Energy Spectrum





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

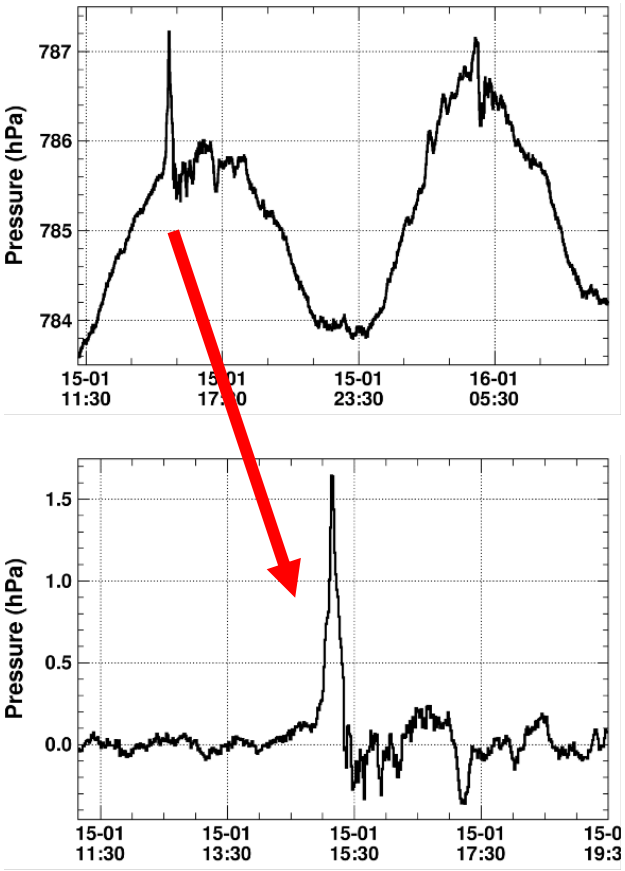


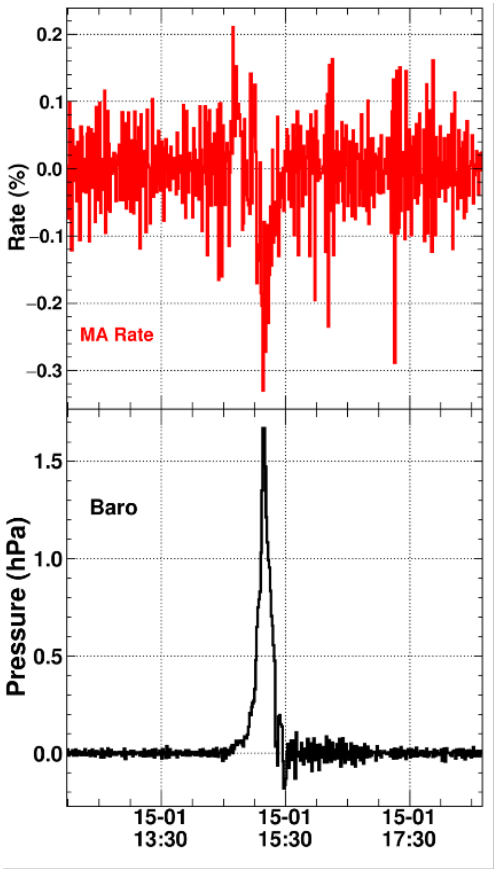
F. Varsi et al., Physical Review Letters 132, 051002 (2024)

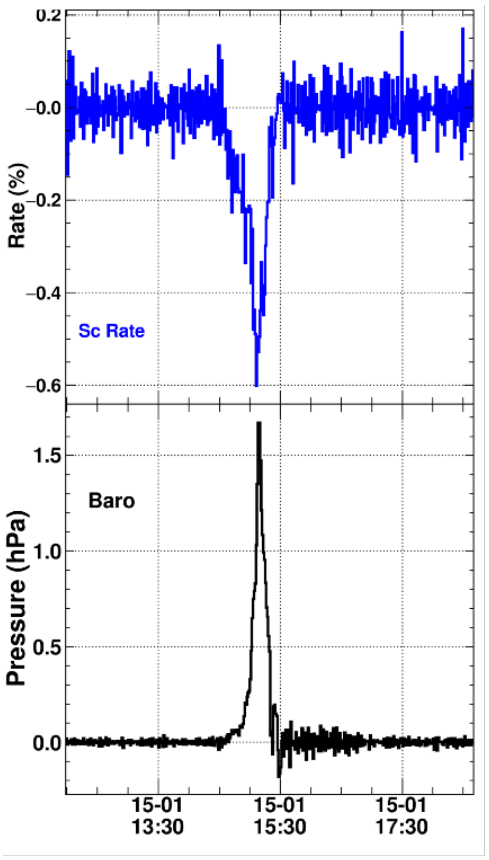
Bonus: Tonga Volcano Eruption

- 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) [13000 km away from GRAPES-3]

Bonus: Tonga Volcano Eruption







15 January 2022

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

Summary

- Ideal for thunderstorm studies
- Ideal for solar studies concerning space weather
- Shower front curvature correction
- Moon shadow (angular resolution and pointing accuracy)
- Small-scale CR anisotropy at TeV scale
- Spectral break at low energy spectrum
- Detection of volcano eruption

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- More in the pipeline (crab search, large scale anisotropy...)