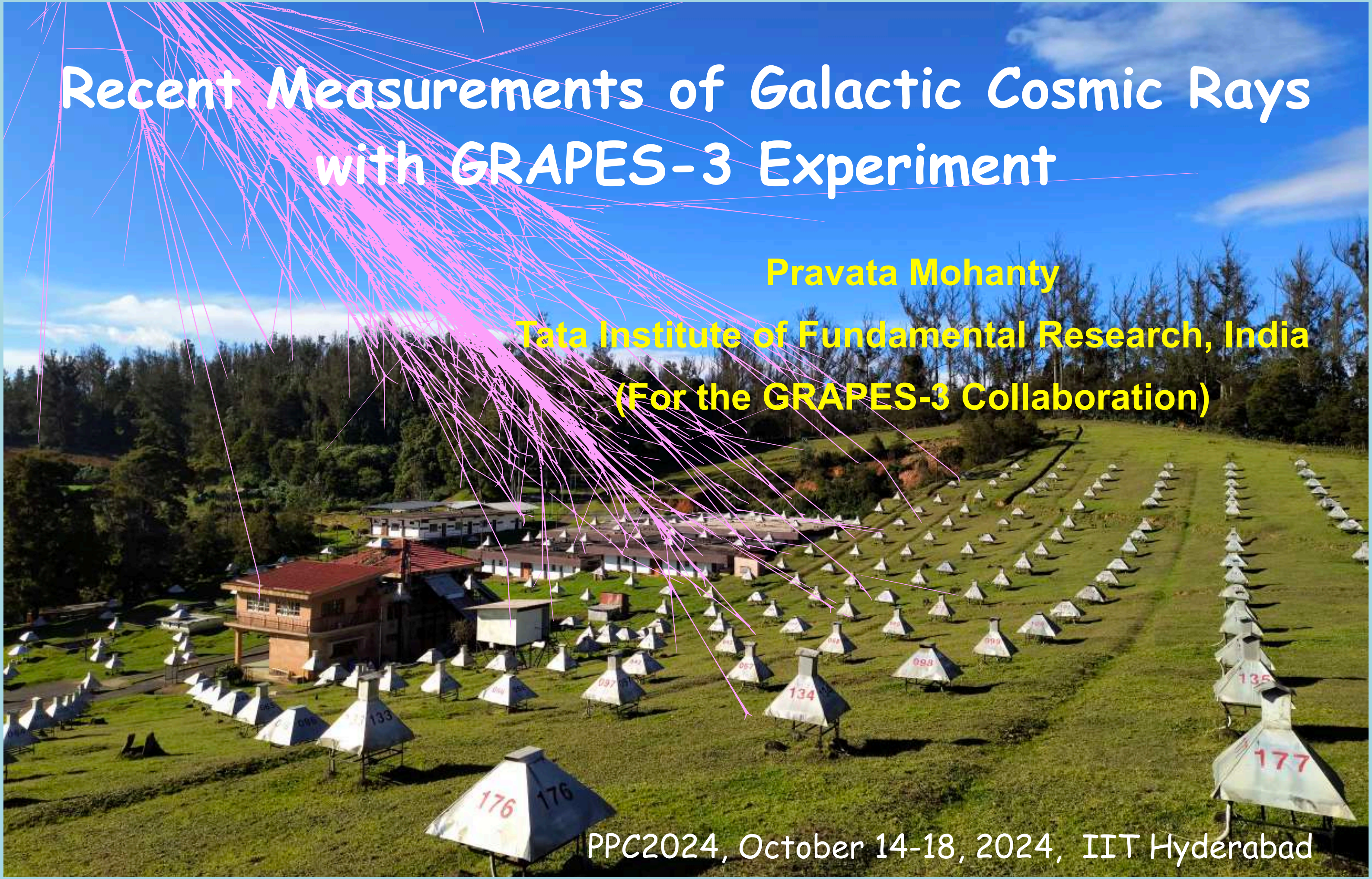
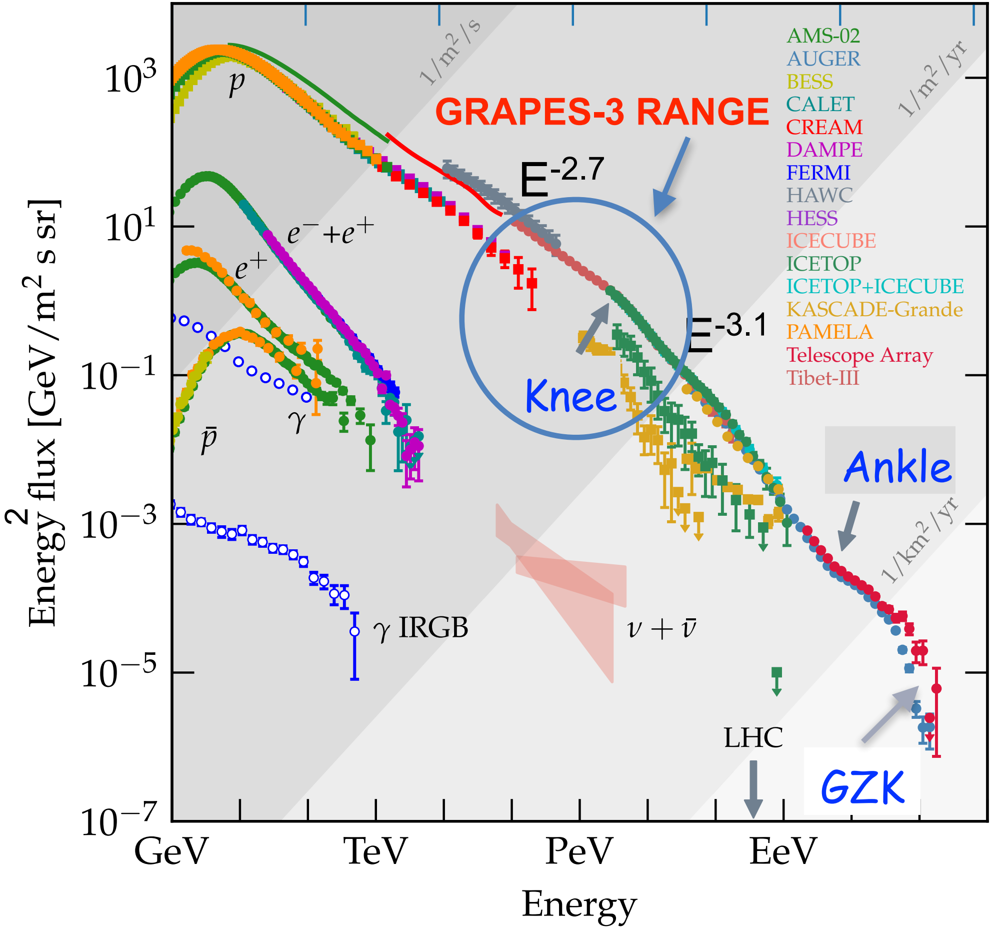
Recent Measurements of Galactic Cosmic Rays with GRAPES-3 Experiment

Pravata Mohanty
Tata Institute of Fundamental Research, India
(For the GRAPES-3 Collaboration)



PPC2024, October 14-18, 2024, IIT Hyderabad

Cosmic Ray Spectrum



Flux of cosmic rays follows a power-law distribution and it decreases rapidly with energy.

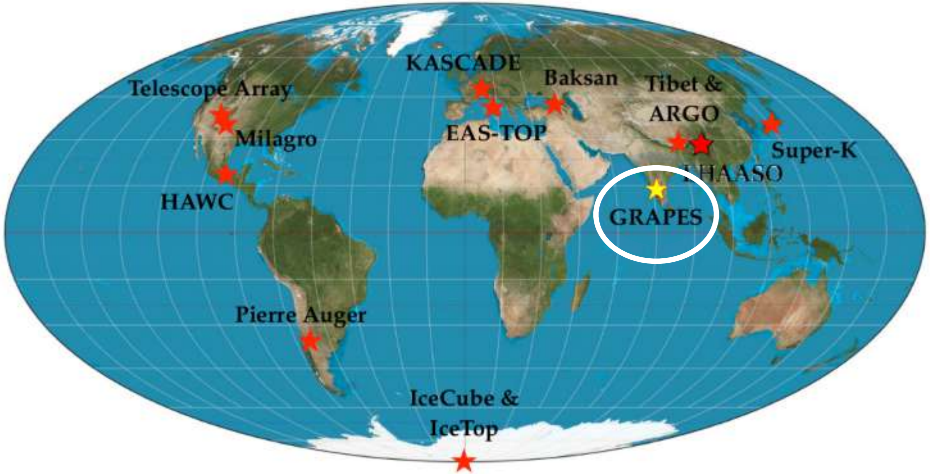
- at 10^{11} eV, 1 particle/m^2 - sec
- at 10^{15} eV, 1 particle/m^2 - year
- at 10^{18} eV, 1 particle/km^2 - year

Knee: Limit of Galactic acceleration
Spectral slope from -2.7 to -3.1

Ankle: Transition to extra-galactic sources

GZK: End of the cosmic ray spectrum
Interaction with 3° K CMB photon

The GRAPES-3 Collaboration



1. Tata Institute of Fundamental Research, Mumbai, India
2. Osaka City University, Osaka, Japan
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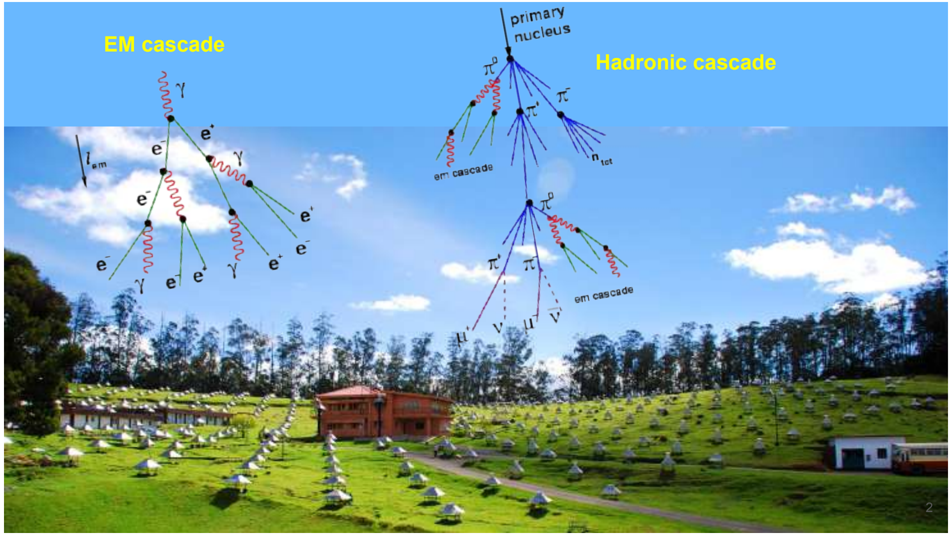
18. Indian Institute of Technology, Indore, India
19. Institute for Cosmic Ray Research, Tokyo U., Japan
20. Amity University, Noida, India
21. Institute of physics, Bhubaneswar, India

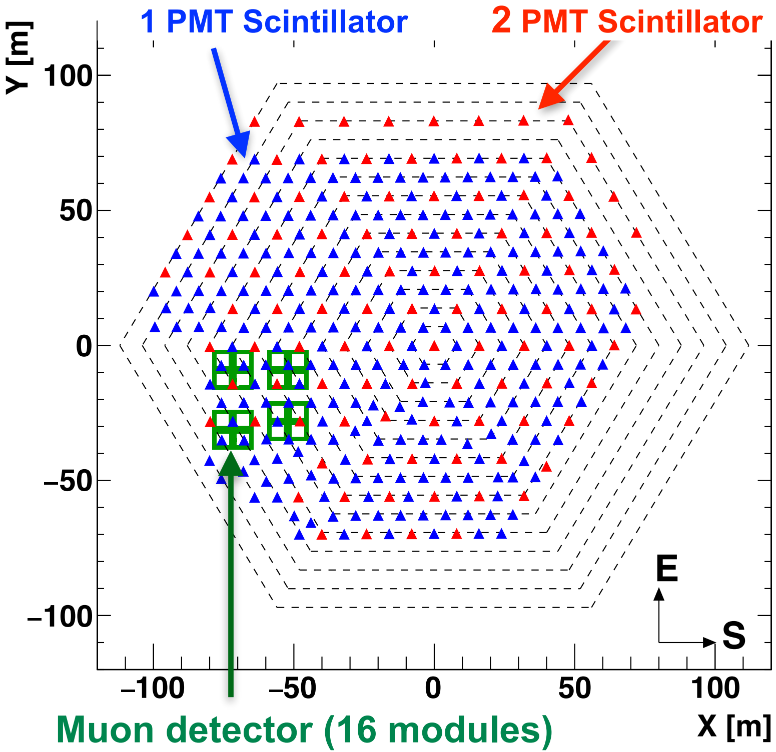
GRAPES-3 is located in Ooty, India

11.4° N lat., 76.7°E lon., 2200 m alt.

The GRAPES-3 experiment in Ooty, India

- 400 plastic scintillator detectors (1 m^2 area) with 8 m inter-separation spread over 25,000m^2
- 560 m^2 muon detector consisting 3712 proportional counters (6m x 0.1m x 0.1m).
- 3 x 10^6 EAS events per day in TeV- PeV range with median energy of 15 TeV.



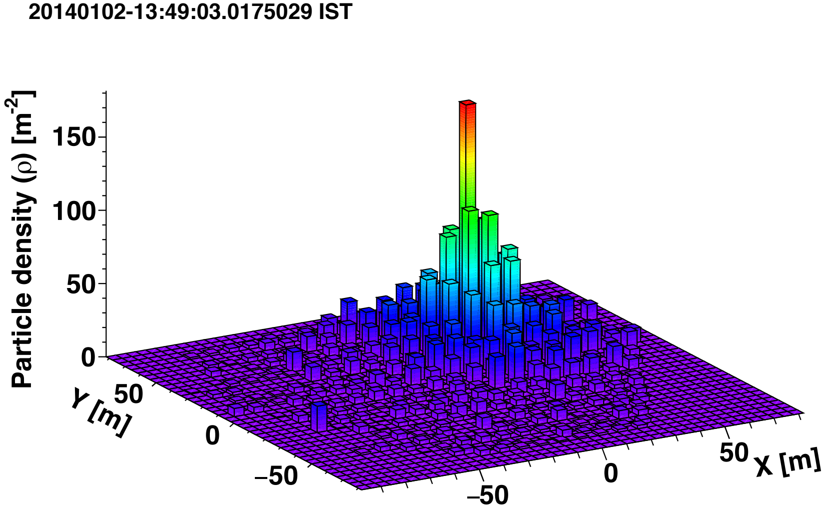


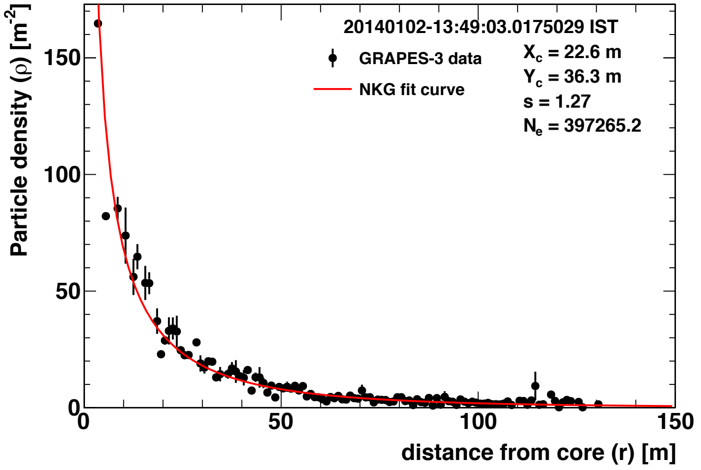
- A shower is triggered if at least 10 scintillator detectors receive signal > 0.5 particle
- Muon detector only records muon component after receiving the shower trigger from scintillators

Shower Reconstruction

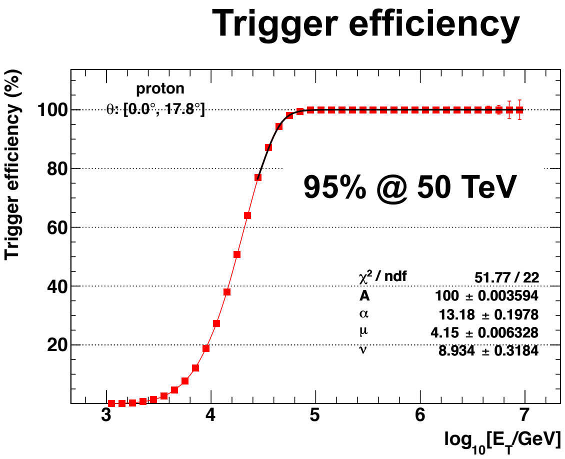
- Shower parameters such as core location (X_c, Y_c), size (N_e) and age (s) are obtained by fitting the observed lateral densities with NKG function as below and directions of the shower (zenith and azimuth) are obtained by fitting a plane front to the observed relative arrival times.

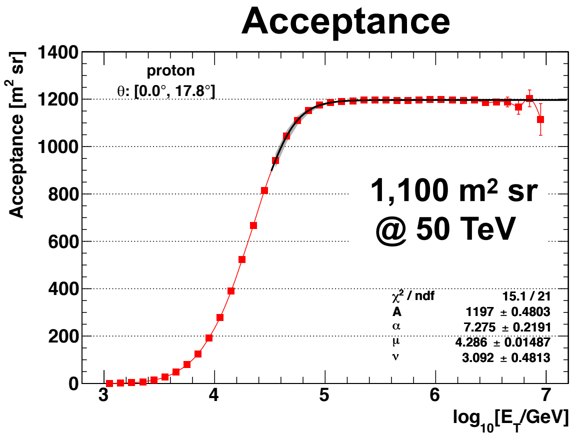
$$\rho_i = \frac{N_e}{2\pi r_m^2} \frac{\Gamma(4.5-s)}{\Gamma(s)\Gamma(4.5-2s)} \left(\frac{r_i}{r_m}\right) \left(1+\frac{r_i}{r_m}\right)^{s-4.5}$$

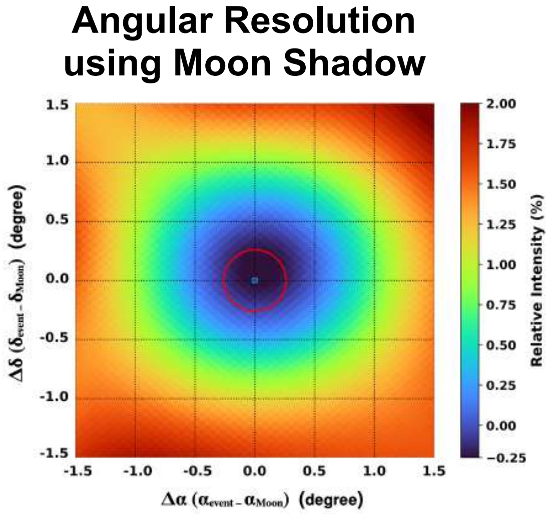


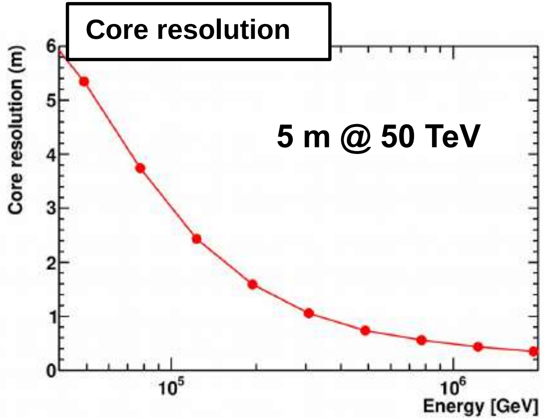


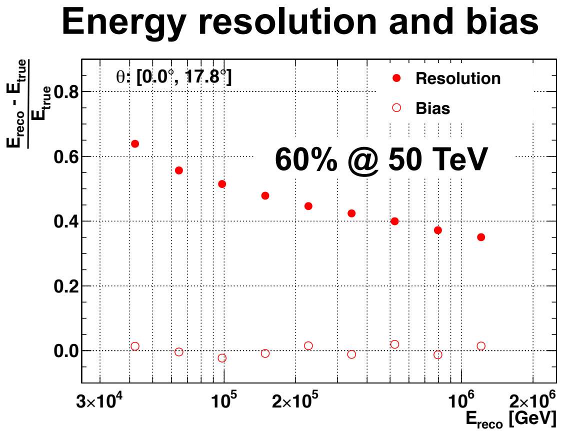
Performances of the scintillator array

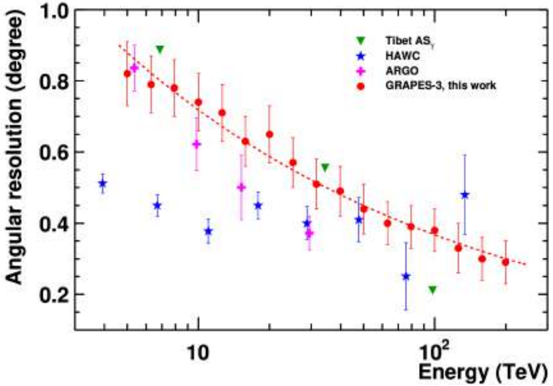








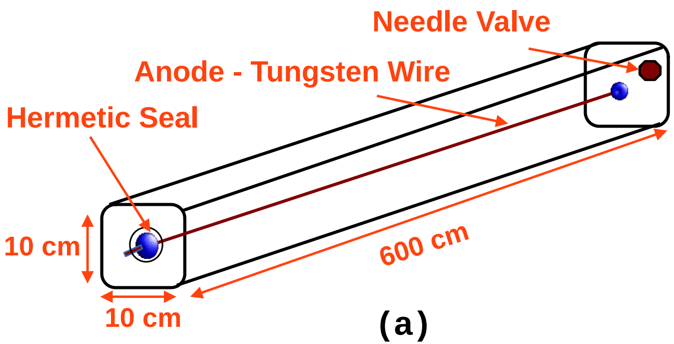




GRAPES-3 muon telescope (560 m²)

- Muon detector consists of 16 modules of 35 m^2 area each.
- Threshold of muons = 1 GeV
- Muons recorded associated with each EAS trigger
- Self triggered muons are recorded in 169 directional bins with 4^o resolution with a statistics of 4 billion muons per day

Proportional counter filled with P10 gas



(a)

Proportional counter fabrication at GRAPES-3. ~4000 successfully made.

Rust removal

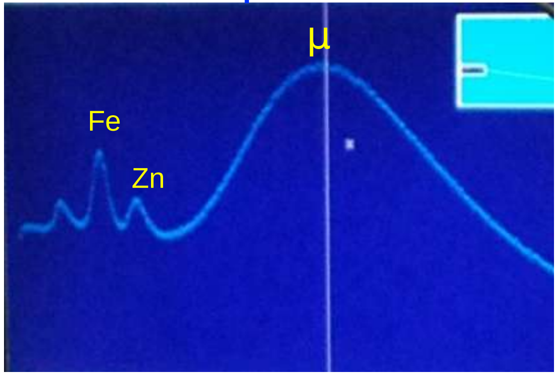
Hermetic seal fixing

Evacuation

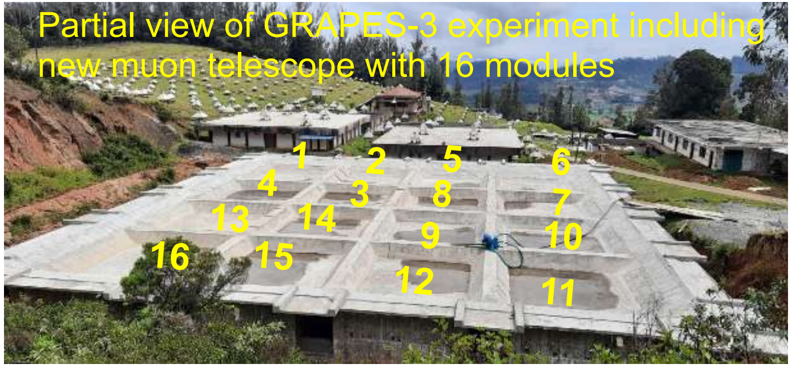
P10 gas filling

Long term test

PRC spectrum

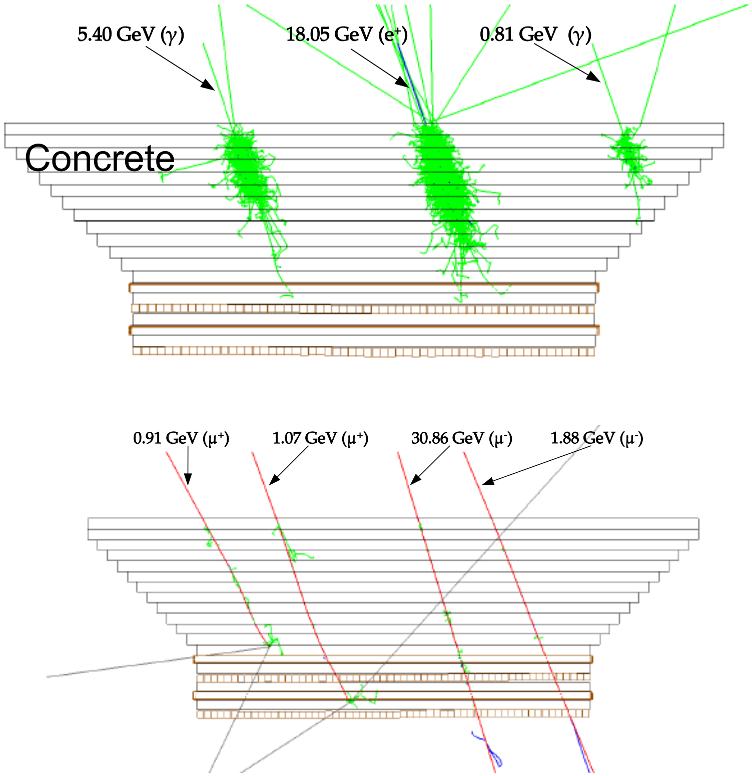


Muon telescope upgrade (560 m² to 1130 m²)

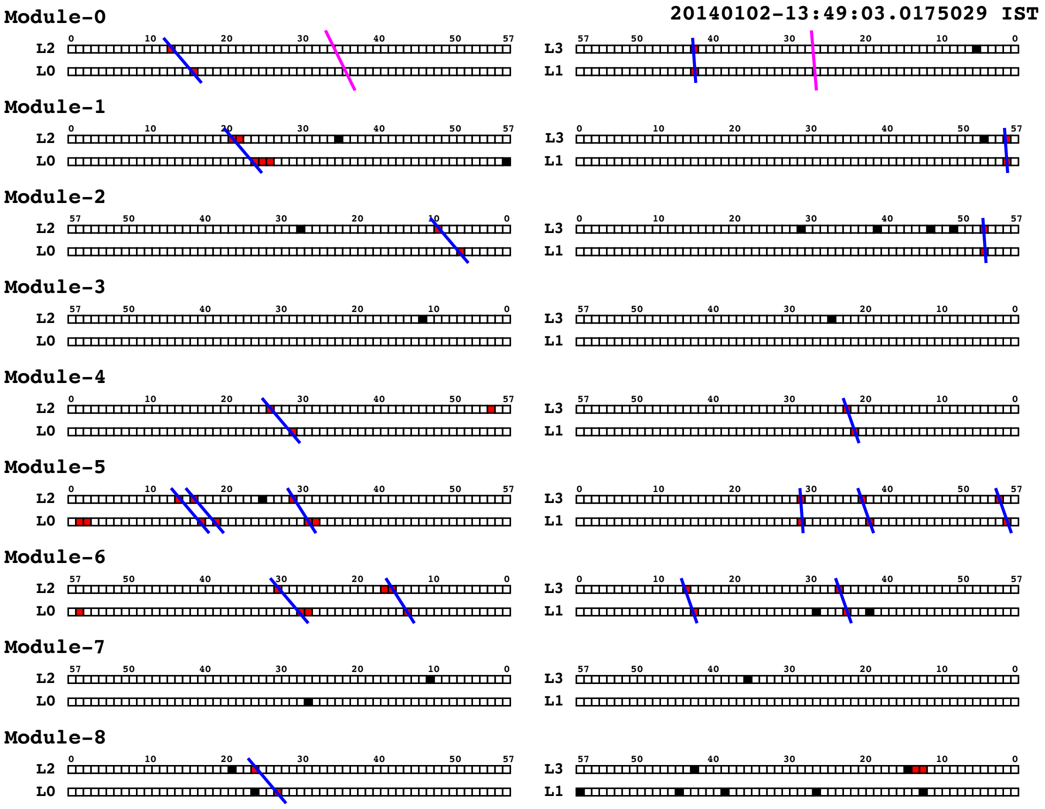


An operational module

Geant4 response of a muon module



Tracking of muons in a shower event

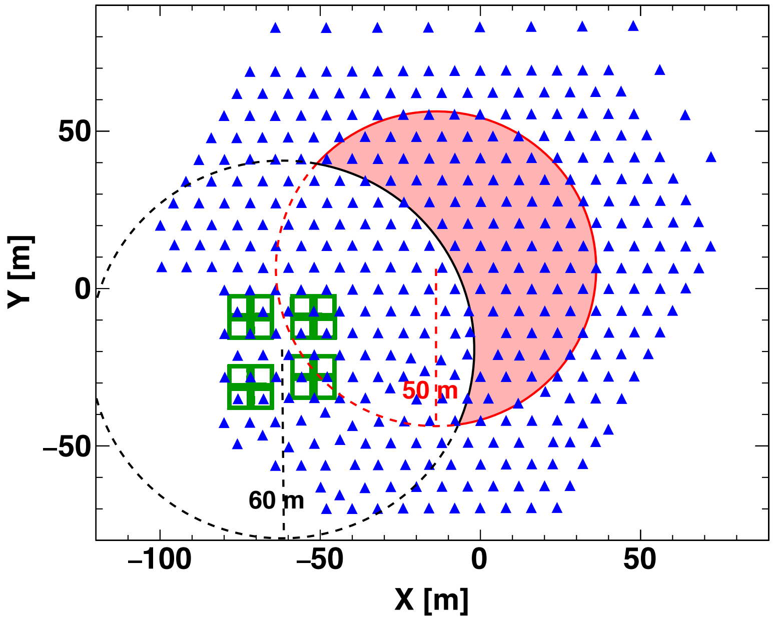


550 gm cm^{-2} of concrete absorber. Threshold for muons = 1 GeV x sec(theta).

Composition Analysis: Data selection and quality cuts

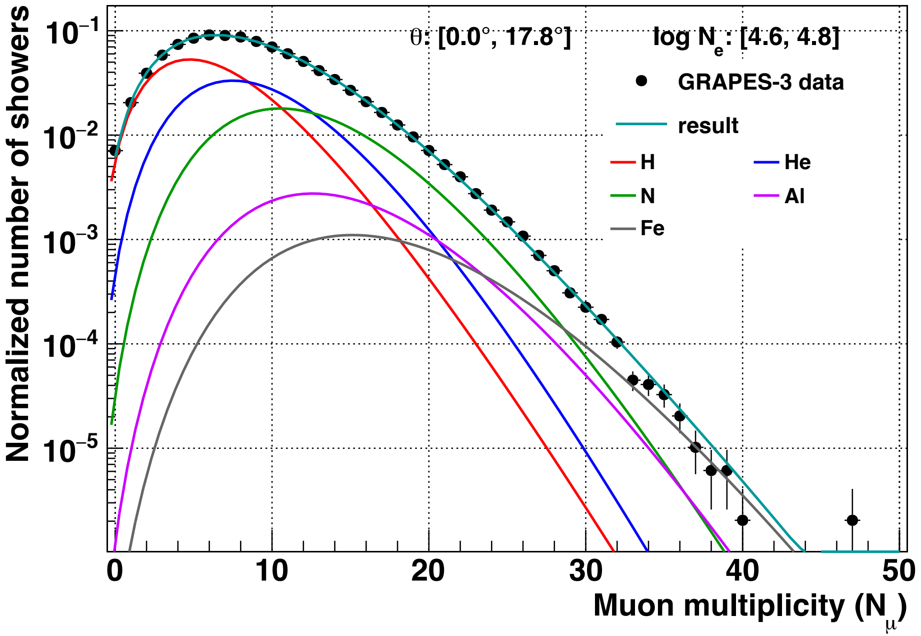
- GRAPES-3 data: 1 January 2014 to 26 October 2015.

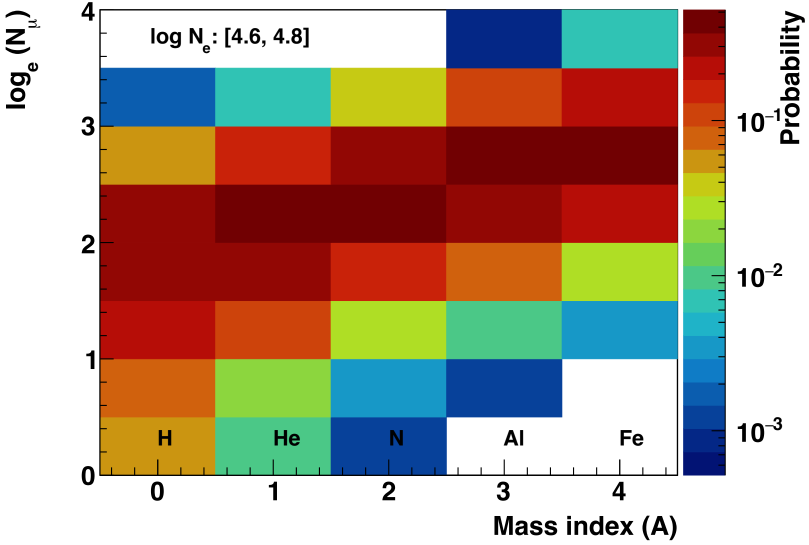
Quality cut	Number of surviving EASs	% of surviving EASs
1. Triggered	1.75×10^{9}	100.0
2. Abnormal days based on N_e spectrum	1.58×10^{9}	90.0
3. Successful event matching & muon tracking	1.17×10^{9}	66.8
4. Angle and NKG reconstruction	8.47×10^{8}	48.3
5. Shower age (s) between 0.02 and 1.98	8.41×10^{8}	48.0
6. Circular area within 50 m radius	3.96×10^{8}	22.6
7. Zenith angle < 17.8°	1.33×10^{8}	7.5
8. Hadron punch-through < 2%	6.27×10^{7}	3.6
9. $10^{4.0} \leq$ Shower size (N_e) < $10^{6.0}$	7.81×10^{6}	0.4



- Showers were selected within 50m from the centre of the array to exclude those landing outside the array while getting mis-reconstructed to be inside the array less than 1%.
- Showers were selected beyond 60 from the centre of the muon modules to restrict the hadron punch-through less than 2%.

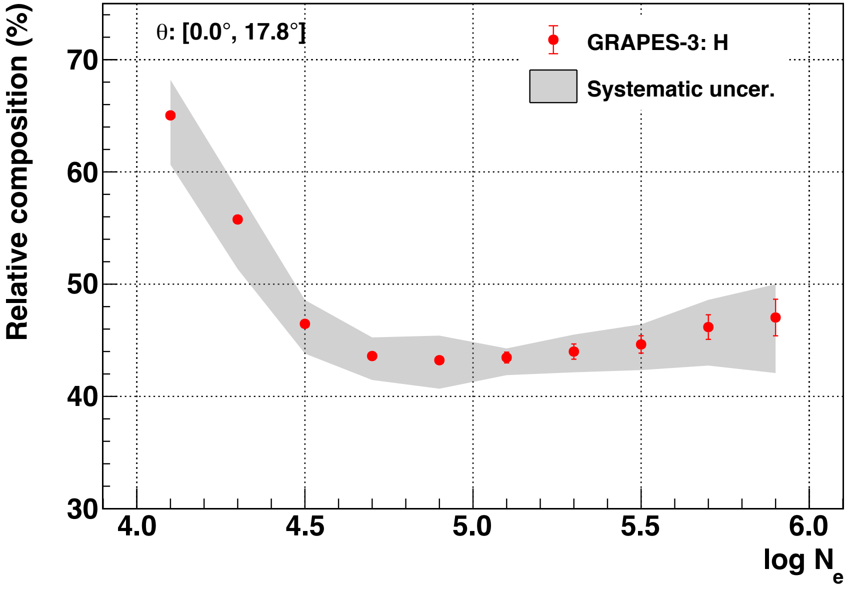
Fitting MMD and Extraction of Composition

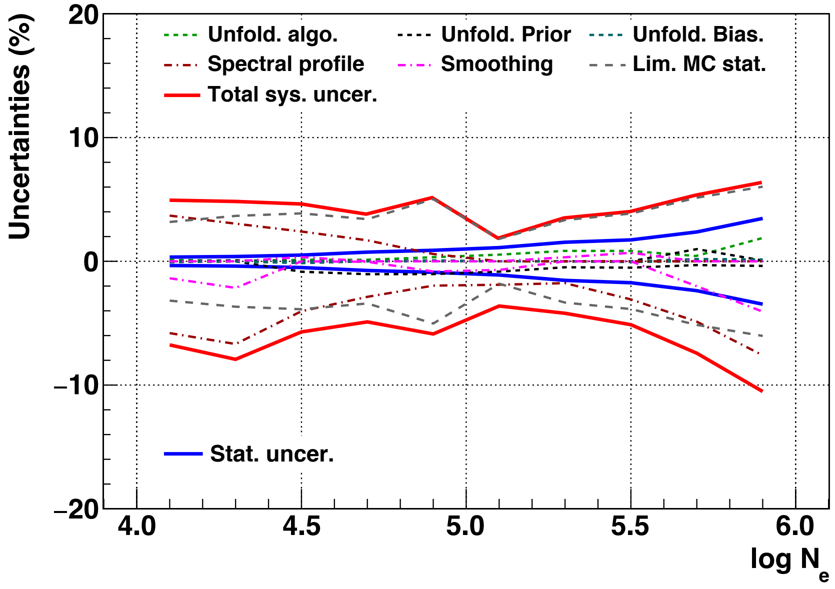




- Observed MMD cannot be described either H or Fe requiring intermediate masses.
- For a given N_e bin, response matrix is generated using MC simulation and Gold's unfolding algorithm is used for relative composition for the five mass groups.

Relative composition of proton primary

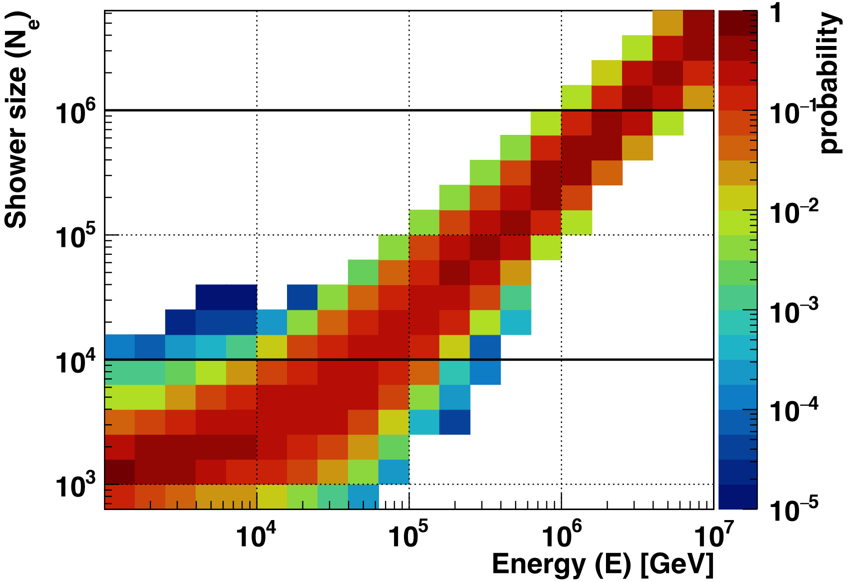


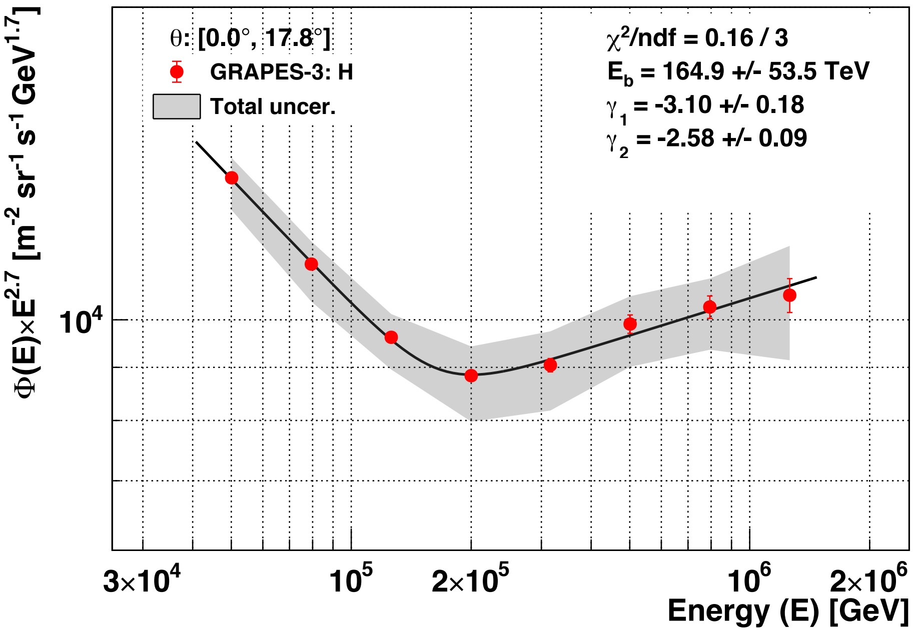


Relative composition for proton primary was obtained for each shower size (N_e) separately.

Systematics uncertainties from different sources. Limited MC statistics and differential spectral profiles are the dominant sources of uncertainties.

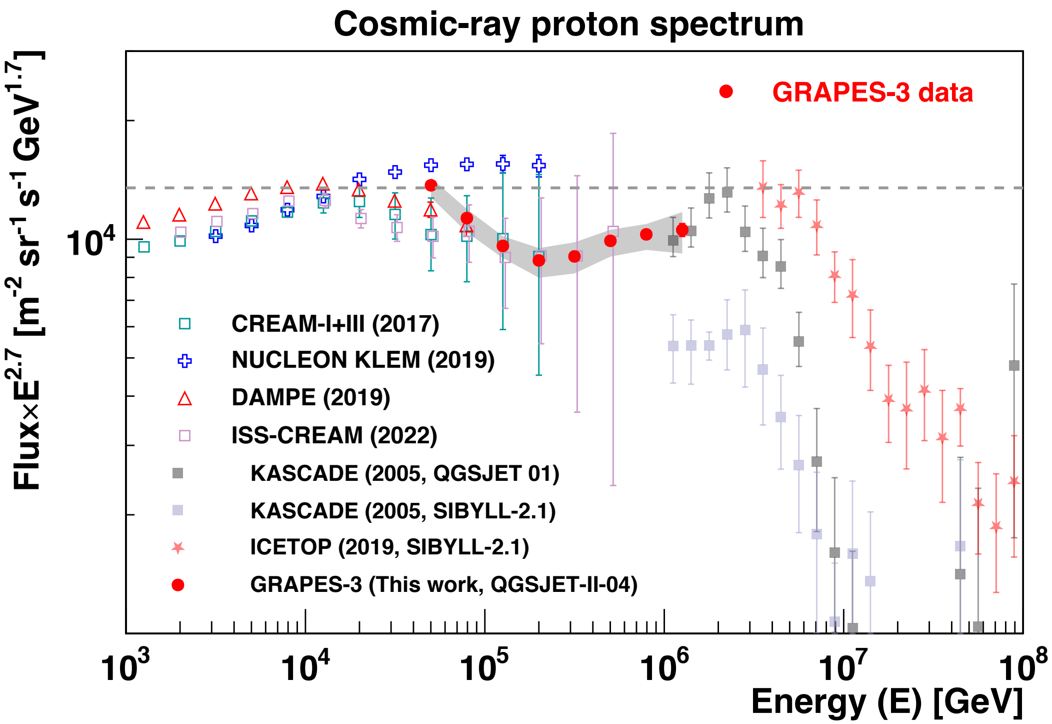
GRAPES-3 Proton Energy Spectrum from 50 TeV - 1.3 PeV





The observed spectral hardening by GRAPES-3 above165 TeV challenges the long-held belief that the spectrum is described by a simple power-law below the Knee.

Comparing with space and ground-based experiments



- Overlap with direct measurements with a flux agreement < 10%
- Observation of a spectral hardening above 165 TeV

F. Varsi et al., PRL 132, 051002 (2024)

PHYSICAL REVIEW LETTERS **132,** 051002 (2024)

Evidence of a Hardening in the Cosmic Ray Proton Spectrum at around 166 TeV Observed by the GRAPES-3 Experiment

F. Varsi,[1] S. Ahmad,[2] M. Chakraborty,[3] A. Chandra,[2] S. R. Dugad,[3] U. D. Goswami,[4] S. K. Gupta,[3] B. Hariharan,[3] Y. Hayashi,[5] P. Jagadeesan,[3] A. Jain,[3] P. Jain,[1] S. Kawakami,[5] H. Kojima,[6] P. Lipari,[7] S. Mahapatra,[8] P. K. Mohanty,[3,*] R. Moharana,[9] Y. Muraki,[10] P. K. Nayak,[3] T. Nonaka,[11] A. Oshima,[6] B. P. Pant,[9] D. Pattanaik,[3,8] S. Paul,[3] G. S. Pradhan,[12] M. Rameez,[3] K. Ramesh,[3] L. V. Reddy,[3] S. Saha,[1] R. Sahoo,[12] R. Scaria,[12] S. Shibata,[6] and M. Zuberi[3]

(GRAPES-3 Collaboration)

[1]*Indian Institute of Technology Kanpur, Kanpur 208016, India*
[2]*Aligarh Muslim University, Aligarh 202002, India*
[3]*Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005, India*
[4]*Dibrugarh University, Dibrugarh 786004, India*
[5]*Graduate School of Science, Osaka Metropolitan University, Sugimoto, Sumiyoshi, Osaka 558-8585, Japan*
[6]*College of Engineering, Chubu University, Kasugai, Aichi 487-8501, Japan*
[7]*INFN, Sezione Roma "Sapienza", Piazzale Aldo Moro 2, 00185 Roma, Italy*
[8]*Utkal University, Bhubaneswar 751004, India*
[9]*Indian Institute of Technology Jodhpur, Jodhpur 342037, India*
[10]*Institute for Space-Earth Environmental Research, Nagoya University, Nagoya 464-8601, Japan*
[11]*Institute for Cosmic Ray Research, Tokyo University, Kashiwa, Chiba 277-8582, Japan*
[12]*Indian Institute of Technology Indore, Indore 453552, India*

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We present the measurement of the cosmic ray proton spectrum from 50 TeV to 1.3 PeV using 7.81×10^6 extensive air shower events recorded by the ground-based GRAPES-3 experiment between 1 January 2014 and 26 October 2015 with a live time of 460 day. Our measurements provide an overlap with direct observations by satellite and balloon-based experiments. The electromagnetic and muon components in the shower were measured by a dense array of plastic scintillator detectors and a tracking muon telescope, respectively. The relative composition of the proton primary from the air shower data containing all primary particles was extracted using the multiplicity distribution of muons which is a sensitive observable for mass composition. The observed proton spectrum suggests a spectral hardening at ∼166 TeV and disfavors a single power law description of the spectrum up to the Knee energy (∼3 PeV).

DOI: 10.1103/PhysRevLett.132.051002

Coverage

https://www.eurekalert.org/news-releases/1033228

https://phys.org/news/2024-02-kink-proton-spectrum-knowledge-cosmic.html

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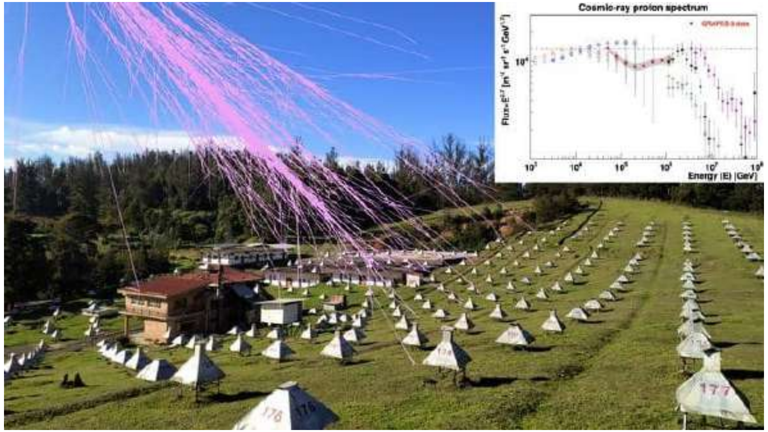
physicsworld

ASTROPARTICLE PHYSICS RESEARCH UPDATE

Kink in cosmic ray spectrum puzzles astrophysicists

15 Feb 2024

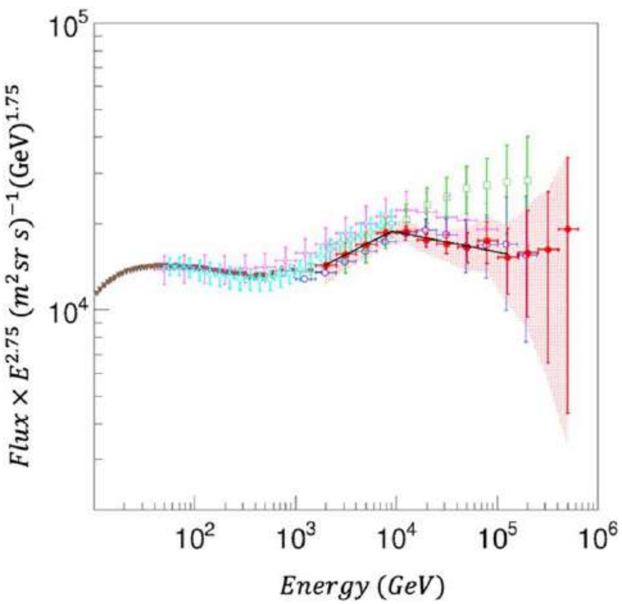


Kinky particles: the GRAPES-3 experiment in Ooty, India depicted with a simulated cosmic ray shower. The inset shows the cosmic ray proton spectrum measurement by GRAPES-3 along with observations by other space and ground-based experiments. (Courtesy: TIFR)

Using observations from the GRAPES-3 muon detector, physicists in India and Japan have explored a poorly understood region of the cosmic ray energy spectrum in unprecedented detail. Fahim Varsi at the Indian Institute of Technology Kanpur and colleagues identified a previously unseen feature in the form of a kink in the spectrum. The observations suggest a need to rethink the origins of cosmic rays.

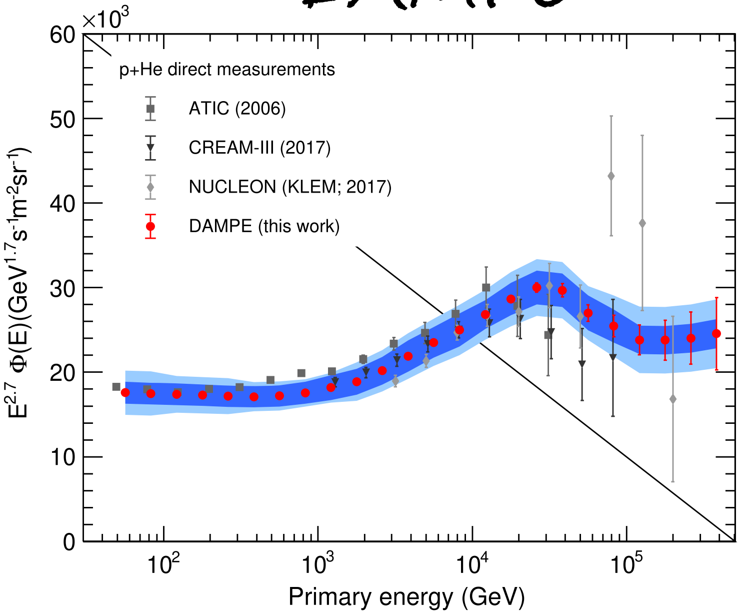
Indication of this feature by other experiments

ISS-CREAM



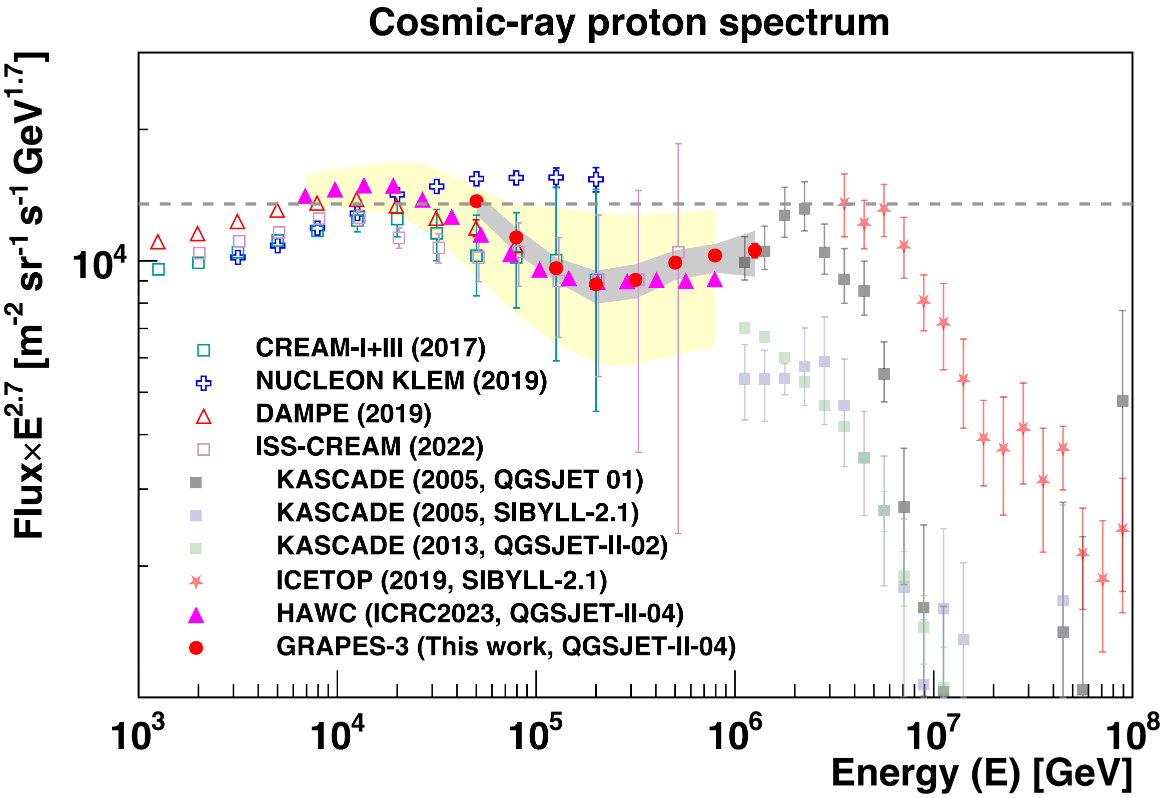
ISS-CREAM proton data suggest a spectral hardening above 164 TeV although the statistical errors are very large APJ 2022

DAMPE



DAMPE proton + helium data suggests a hardening above 150 TeV PRD 2024

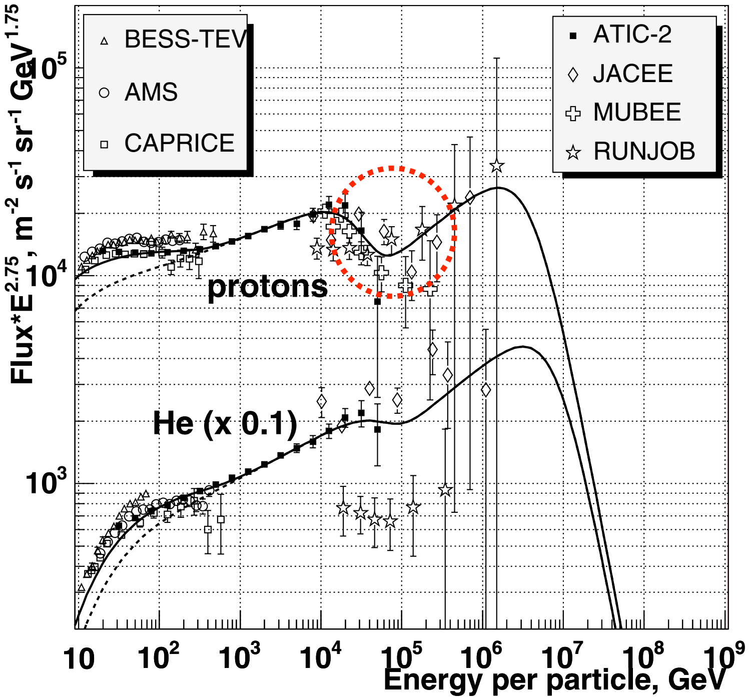
HAWC data (ICRC2023) shows a similar profile although systematic uncertainties are large.



Three component model of cosmic ray spectra from 10 GeV to 100 PeV

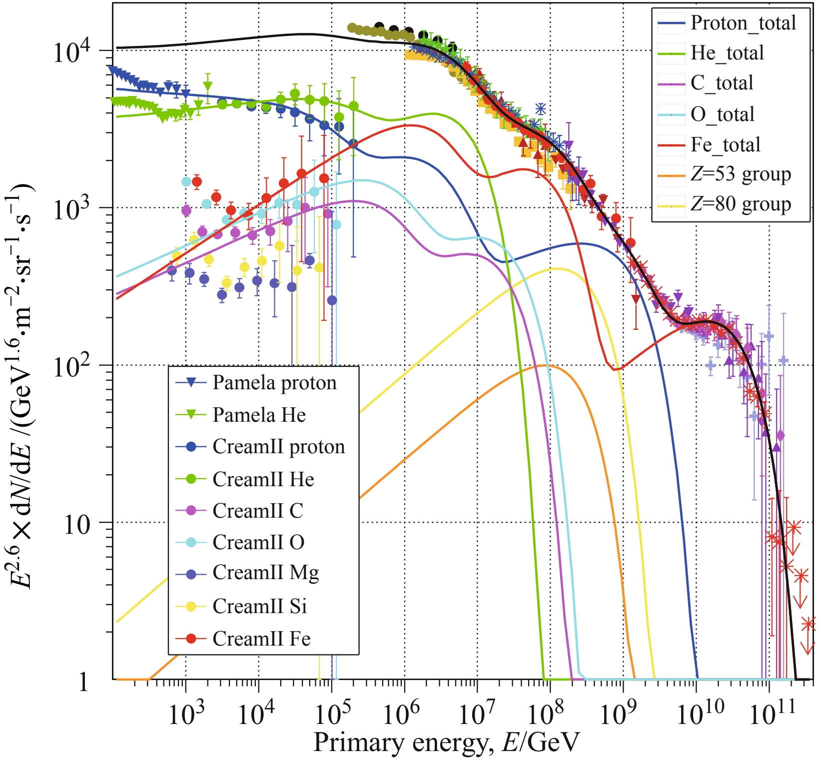
A&A 458, 1-5 (2006), V. I. Zatsepin and N. V. Sokolskaya

- The model assumed one class of sources (SNRs) terminates its effective acceleration at ~50 TeV
- The second source class, presumably supernovae within the local supper bubble accelerates cosmic rays up to rigidity of 4 PeV, producing the Knee.
- Assumed contribution of nova stars below ~300 GeV.



Gaisser-Stanev-Tilav (GST) model of cosmic ray composition

T.K. Gaisser, T. Stanev, S. Tilav, Front. Phys. 2013, 8(6):748-758



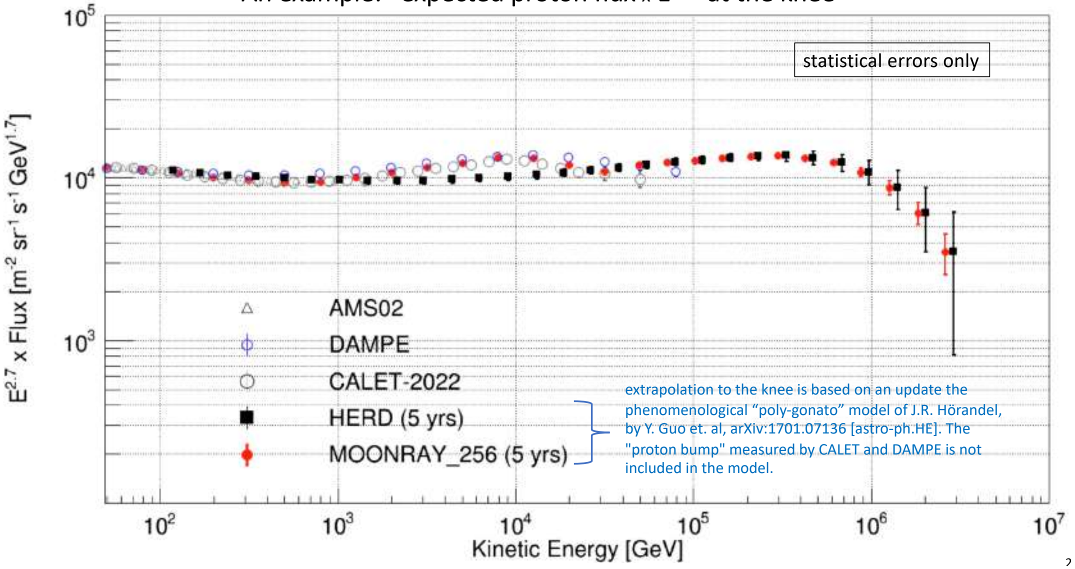
	p	He	C	O	Fe	$50 < Z < 56$	$78 < Z < 82$
Pop. 1:	7000	3200	100	130	60		
$R_c = 120$ TV	1.66 1	1.58	1.4	1.4	1.3		
Pop. 2:	150	65	6	7	2.3	0.1	0.4
$R_c = 4$ PV	1.4	1.3	1.3	1.3	1.2	1.2	1.2
Pop. 3:	14				0.025		
$R_c = 1.3$ EV	1.4				1.2		
Pop. 2*:	150	65	6	7	2.1	0.1	0.53
$R_c = 4$ PV	1.4	1.3	1.3	1.3	1.2	1.2	1.2
Pop. 3*:	12				0.011		
$R_c = 1.5$ EV	1.4				1.2		
Pop. 4*:	1.2						
$R_c = 40$ EV	1.4						

Population 1 has cutoff at 120 TV

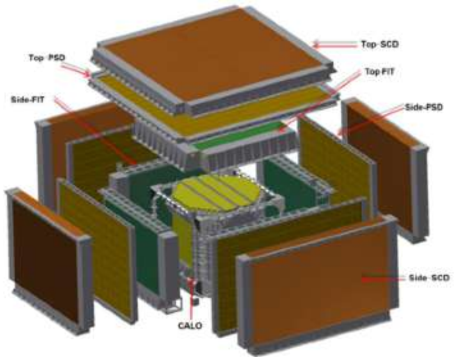
Population 2 has cut off at 4 PV

Future space-based experiments can reach up to Knee

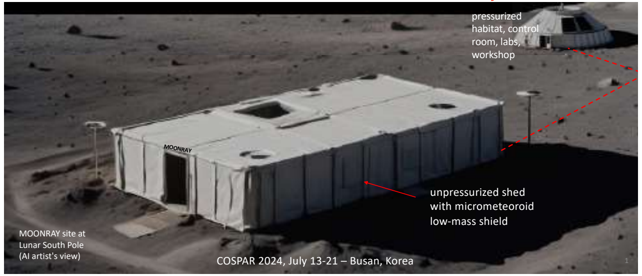
An example: expected proton flux x $E^{2.7}$ at the knee



HERD

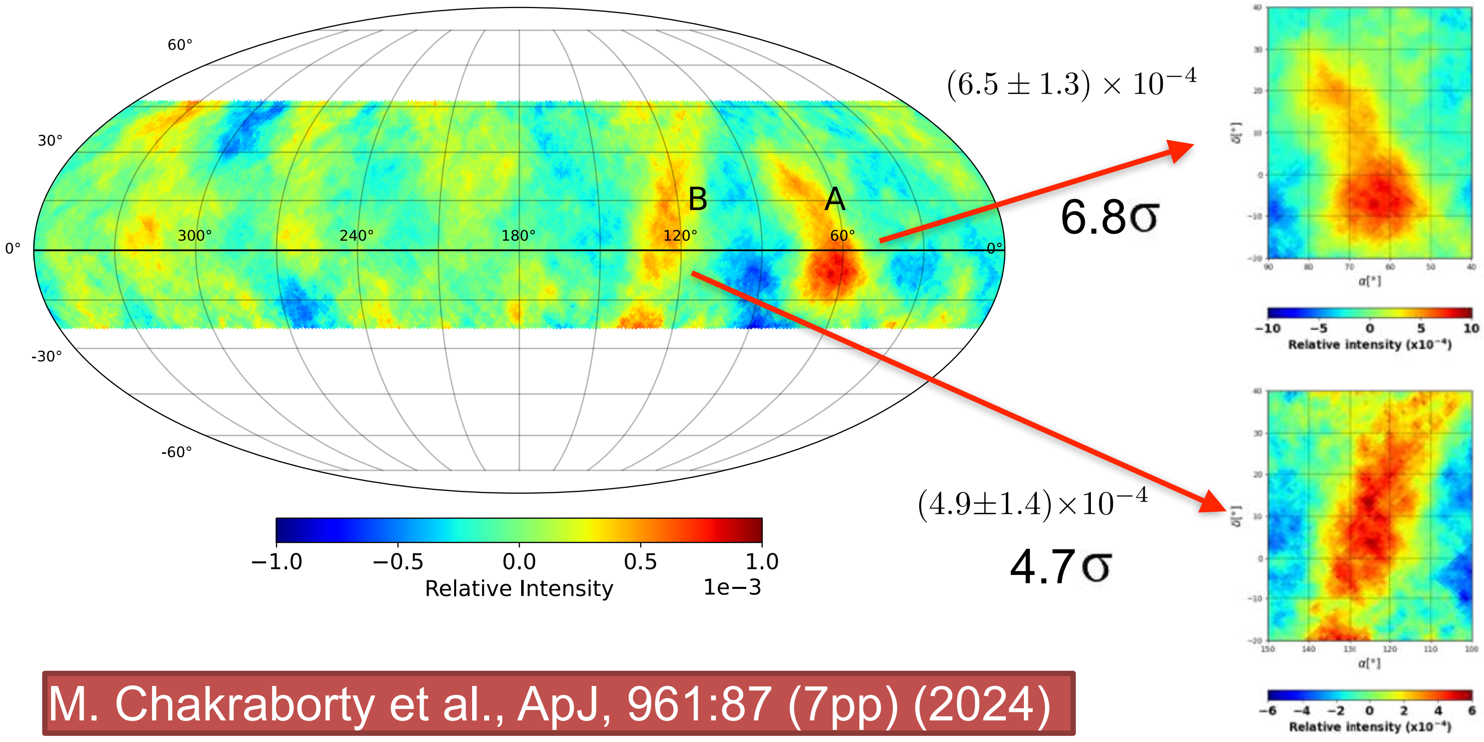


MOONRAY



Cosmic ray anisotropy results from GRAPES-3

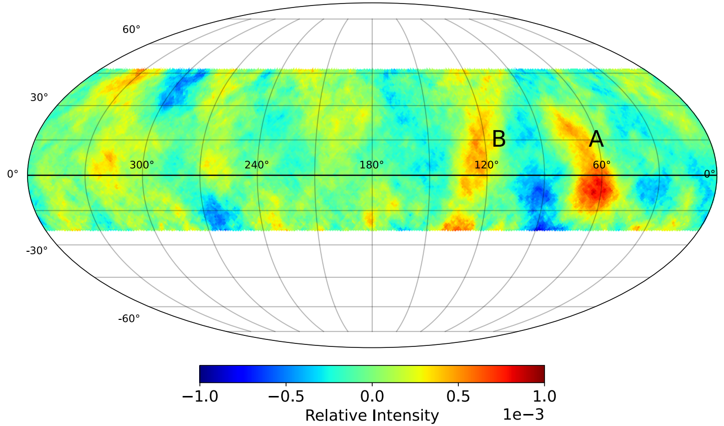
Analysis was performed using 3.7 billion cosmic ray events spanning 4 years at median energy of 16 TeV. Time scrambling method is used for background map generation.



M. Chakraborty et al., ApJ, 961:87 (7pp) (2024)

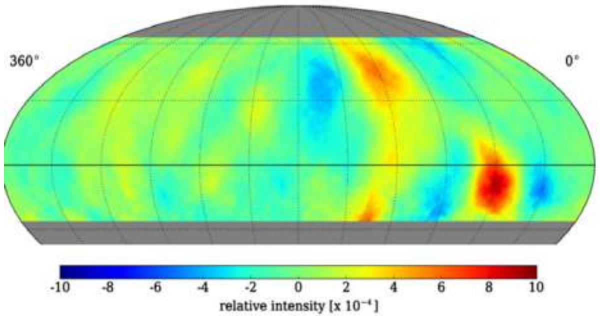
Comparison with other experiments

GRAPES-3



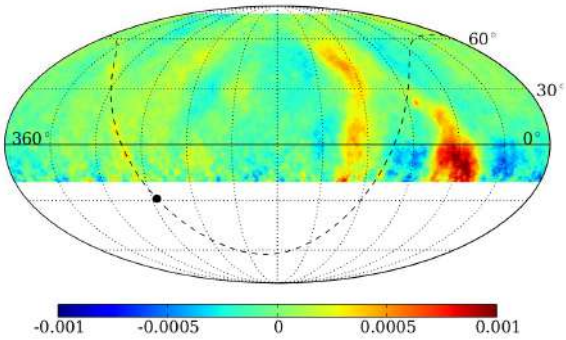
	Region A ($\times 10^{-4}$)	Region B ($\times 10^{-4}$)
ARGO-YBJ	10.0	5.0
HAWC	$(8.5 \pm 0.6 \pm 0.8)$	$(5.2 \pm 0.6 \pm 0.7)$
GRAPES-3	$(8.9 \pm 2.1 \pm 0.3)$	$(5.6 \pm 1.8 \pm 0.1)$

HAWC



(a) HAWC

ARGO-YBJ



(b) ARGO-YBJ

Summary and future outlook

- We have measured cosmic ray proton spectrum below the Knee overlapping with direct measurements.
- We have observed a spectral hardening in the proton spectrum above 165 TeV.
- We have observed two small-scale anisotropic structures from near equatorial location.
- Analysis for extraction of spectrum for other elements below and above the knee is in progress.
- Analysis of large-scale anisotropy is in progress
- We hope the upgrade of the muon telescope together with scintillator array expansion can provide enhanced sensitivity for cosmic ray composition and gamma ray studies

Thank you for your attention