GRAPES Collaboration

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S.K. Gupta, Atul Jain, A.V. John, D.K. Mohanty,
P.K. Mohanty, S.D. Morris, K.C. Ravindran, K. Sivaprasad,
B.V. Sreekantan, S.C. Tonwar and K. Viswanathan
Tata Institute of Fundamental Research
Mumbai 400005, India

Y. Hayashi, Y. Ishida, N. Ito, S. Kawakami,
T. Matsuyama, T. Nonaka, A. Oshima, M. Sasano,
S. Tamaki, H. Tanaka and T. Yoshikoshi
Graduate School of Science, Osaka City University
Osaka 558-8585, Japan

K. Fujimoto and H. Kojima
Nagoya Women's University
Nagoya 467-8610, Japan

High Energy Cosmic Ray Astrophysics with the GRAPES Experiments at Ooty

(Gamma Ray Astronomy at PeV EnergieS)

Ooty (Udhagamandalam) : a mountain resort town in the state of Tamil Nadu in southern India, $11^o23'N$, 77^oE, 2200m altitude (800 g cm^{-2})

An India-Japan Collaboration Project

PHYSICS OBJECTIVES:

- Determination of the energy spectrum of primary cosmic ray flux from $10^{13.5}$ eV to $10^{16.5}$ eV, overlapping with direct measurements below 10^{14} and extending well beyond the *knee*.
- Determination of the nuclear composition of primary flux using observations on muon multiplicity distributions with the $560m^2$ area tracking muon detector $(E_\mu \geq 1GeV)$.
- Search for steady/episodic sources of cosmic γ-rays.
- Search for high energy γ-ray bursts.
- Study of modulation of atmospheric muon flux due to Solar wind and search for flux of high energy protons in association with large CME's.

- Ultra-High Energy Cosmic Rays - Outstanding Problems
  (a) Knee in the spectrum at $E_o \sim 3 \times 10^{15}$ eV.
  (b) Ankle at $E_o \sim 3 \times 10^{18}$ eV.
  (c) Particle flux above the GZK cut-off energy.
- Physics of the KNEE
  (a) High energy physics or astrophysics.
  (b) Source or acceleration or propagation.
- Experimental considerations - only indirect studies are possible - observations on Cherenkov photons, e/γ, μ or hadrons in extensive air showers.
- Studies on correlations between electrons and muons with large area detectors - sensitivity to composition.
  - High energy muons - muon detectors placed deep underground (KGF) or magnet spectrometers at shallow depths (MSU and L3+C).
  - Low energy muons using arrays of muon detectors for studies on correlations between N_μ and N_e for showers (CASA, EAS-TOP and KASCADE).
  - Low energy muons using large area modular muon detectors for studies on muon multiplicity distributions for various selection cuts on the electron component (EAS-TOP, KASCADE, GRAPES-2 and GRAPES-3).

Primary Composition at 10^{14} ev/particle.

Table 5.1 An estimate of the composition of arrived nuclei at 10^{14} eV/particle.

Group of nuclei	P	He	CNO	Ne-S	Fe-group
A	1	4	14	24	56
E (GeV/n)	10^5	2.5×10^4	7.14×10^3	4.17×10^3	1.79×10^3
Flux estimate (GeV/n)	1.3×10^4	2×10^3	1.2×10^2	3×10^1	7
Flux calculated (GeV/particle)	1.3×10^{14}	2.26×10^4	1.22×10^4	7.81×10^3	8.02×10^5
Relative Abundance	20	36	19	12	13

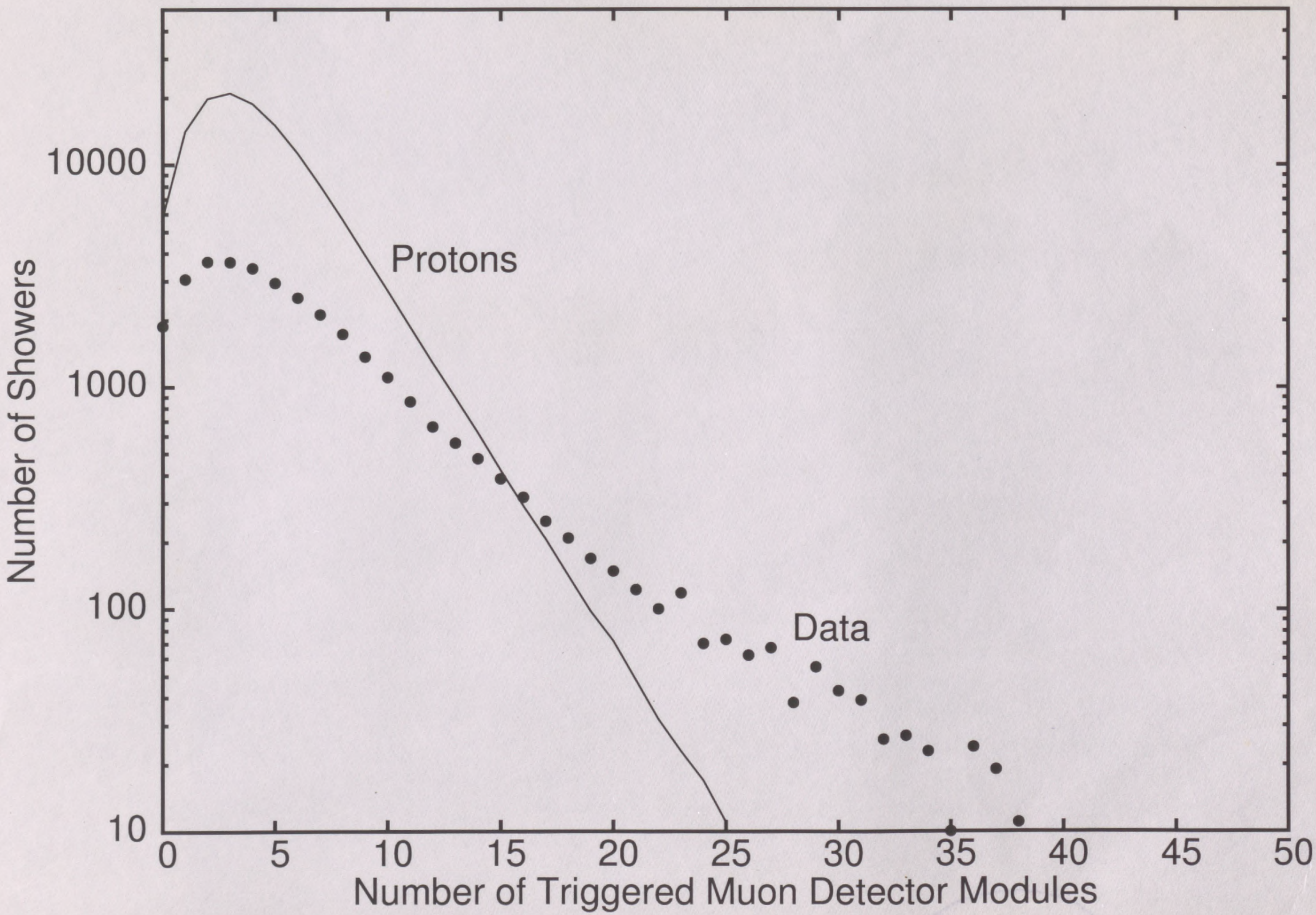
Simon Swordy's estimate based on different experiments (JACEE)

Compared to the proportions at 10^{12} ev,

(i) The relative proportion of H Compared to protons increases with energy

(ii) A possible C around 10^{14} ev. (Sudden Steepening of the p

T-10


Number of Showers
10000
1000
100
10
Protons
Data
0
5
10
15
20
25
30
35
40
45
50
Number of Triggered Muon Detector Modules

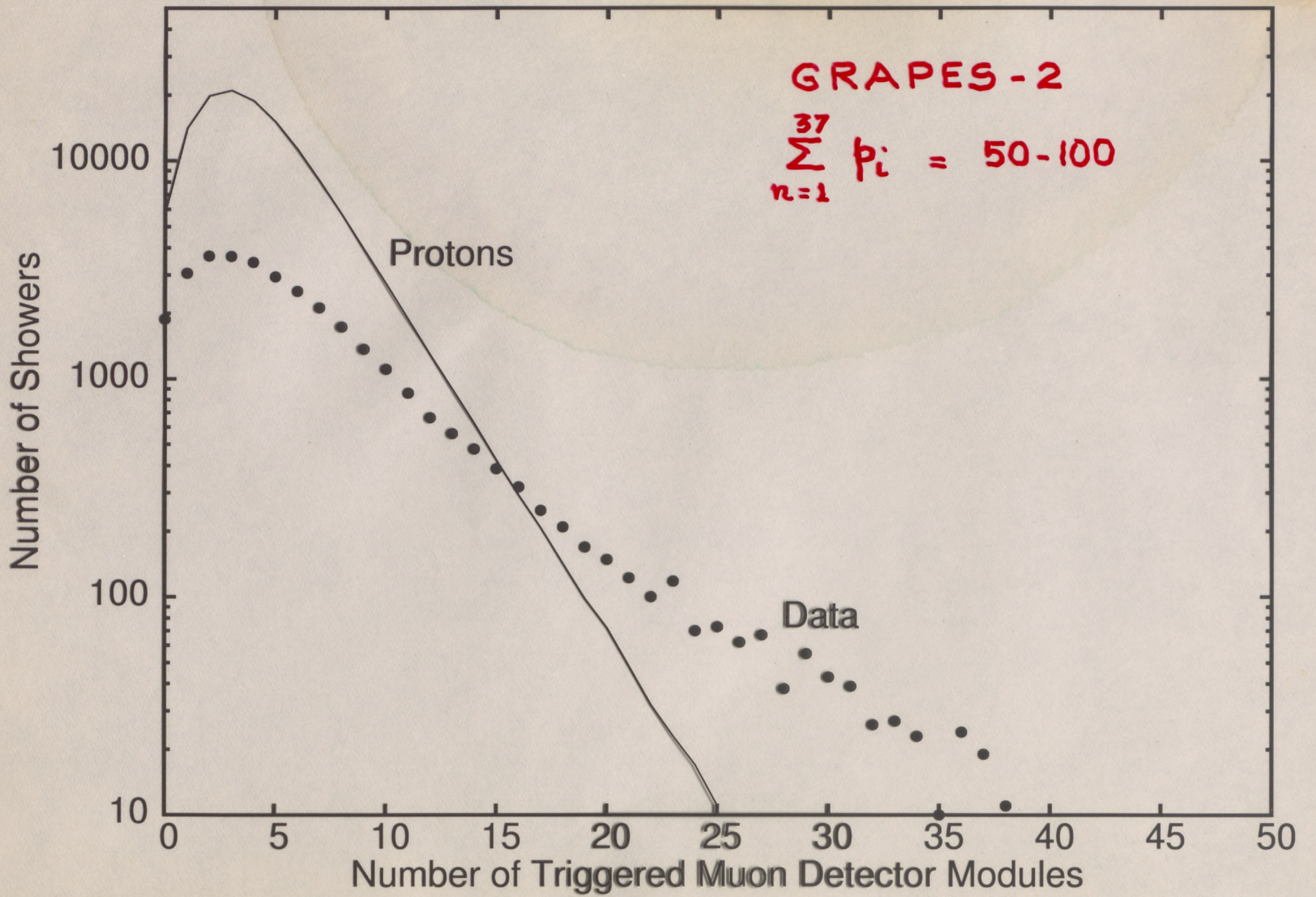
Primary Composition 10^{14} ev - 10^{15} ev.

Table 6.3: Fractional contents of primary cosmic ray flux contributed by the 5 nuclear groups in the energy range, from 100 to 1,000 TeV, for various composition models.

Group	Protons (%)	α Particles (%)	CNO Nuclei (%)	Si group Nuclei (%)	Fe group Nuclei (%)
Constant Mass Composition	41.84	23.74	13.50	9.52	11.39
Linsley Composition	52.59	19.23	11.06	7.79	9.33
Maryland Composition	20.92	12.23	18.55	21.98	26.32
Ooty Composition	27.39	22.75	13.22	12.11	24.53

- Maryland Composition matches through simulations the observed delay distribution of N-particles in EAS.
- The Ooty Composition matches the observed multiplicity distribution of muons in EAS.

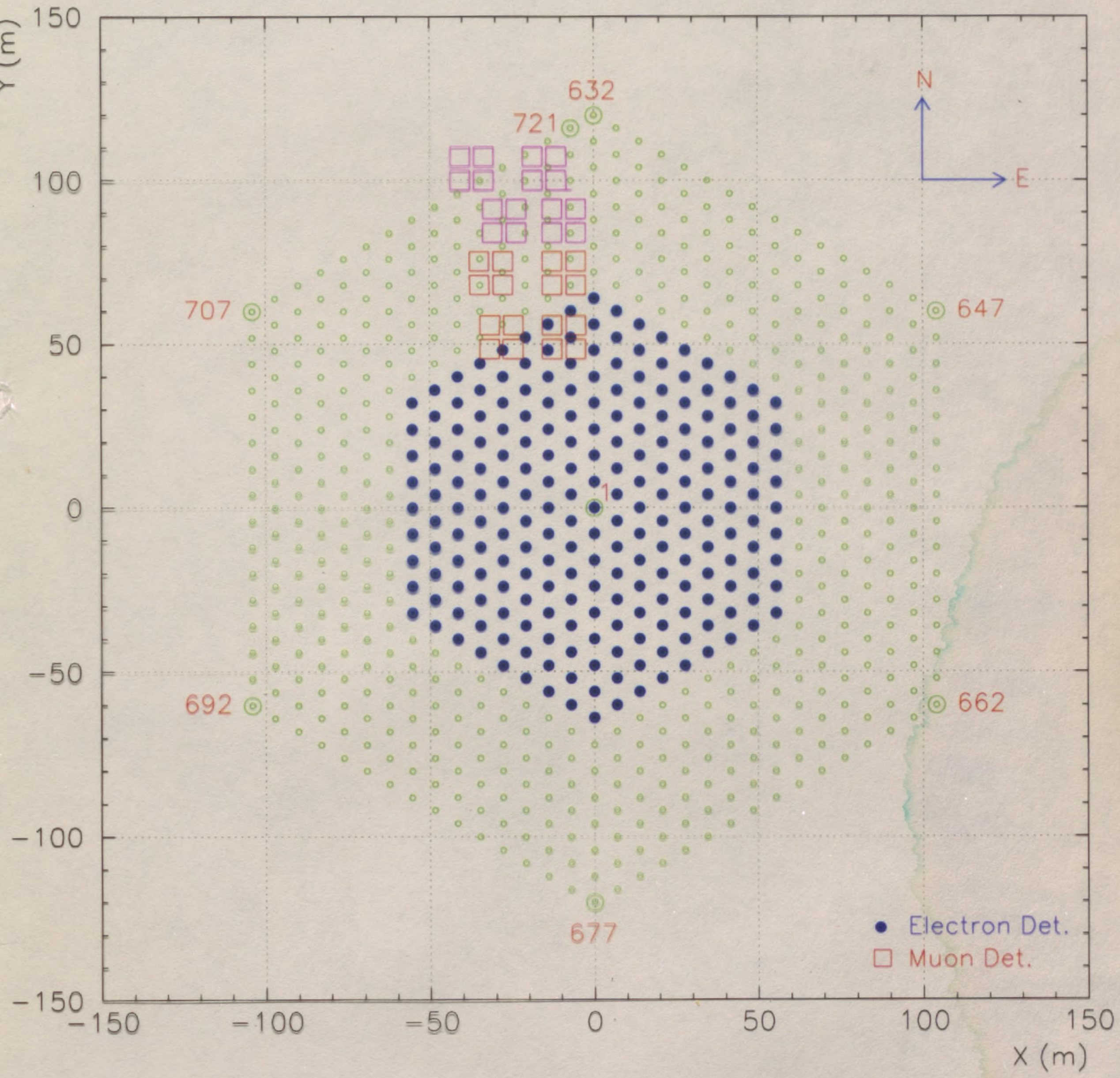
Ph. D. Thesis of R. Srivatsan
(1994)

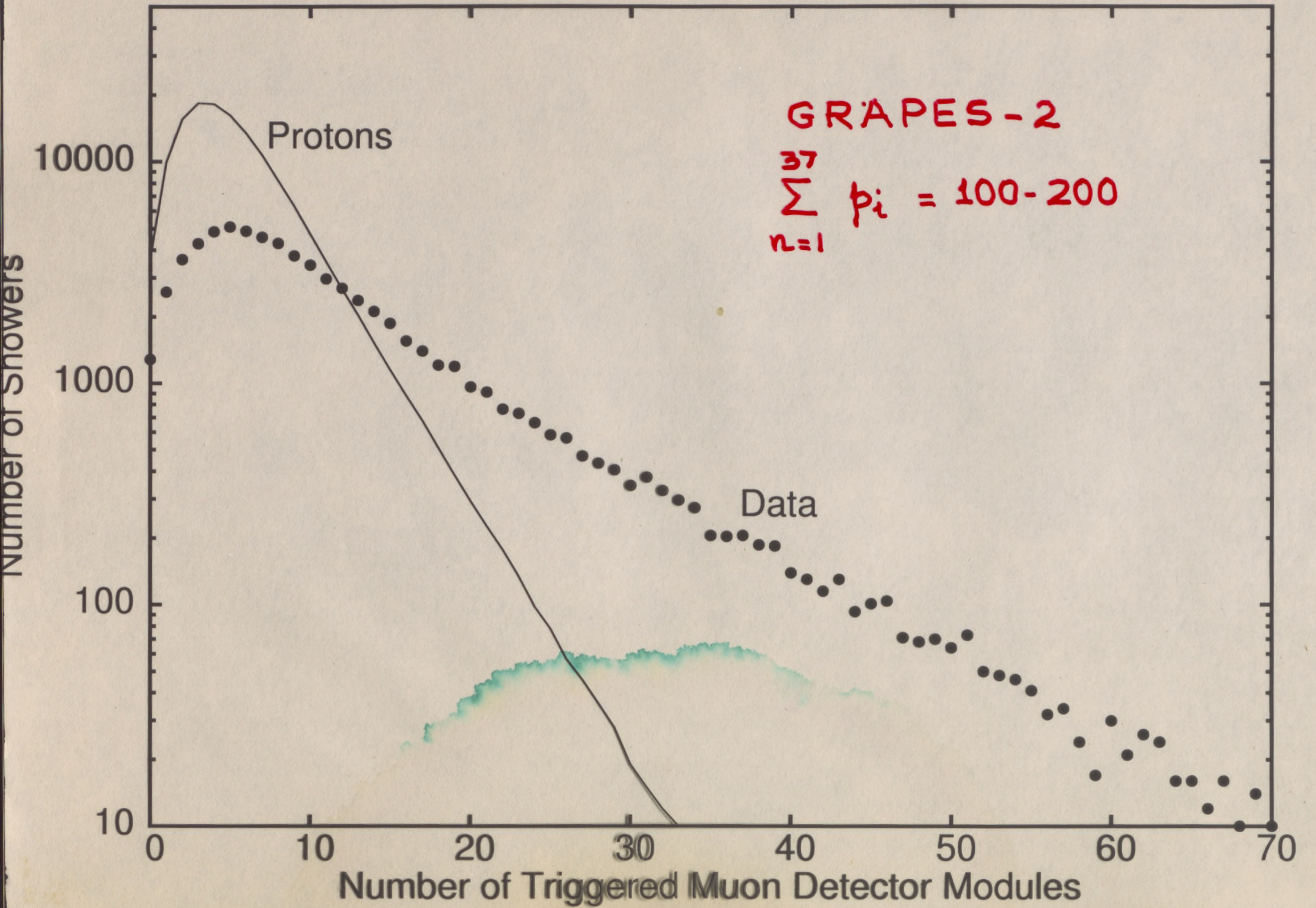


GRAPES - 2

$\sum_{n=1}^{37} p_i = 50\text{-}100$

GRAPES-3 Array (Radio Astronomy Centre campus, Ooty) - May 2003

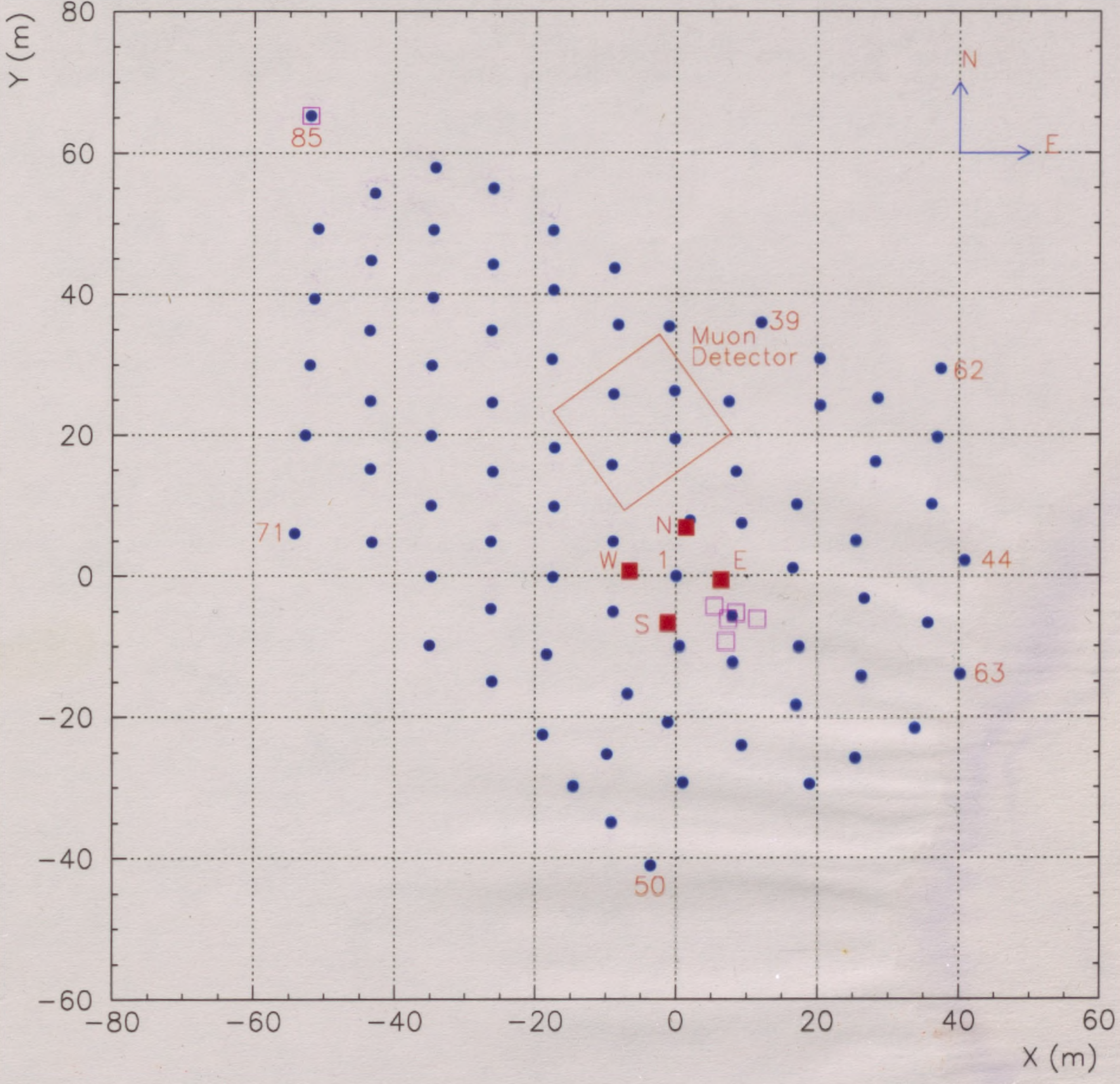




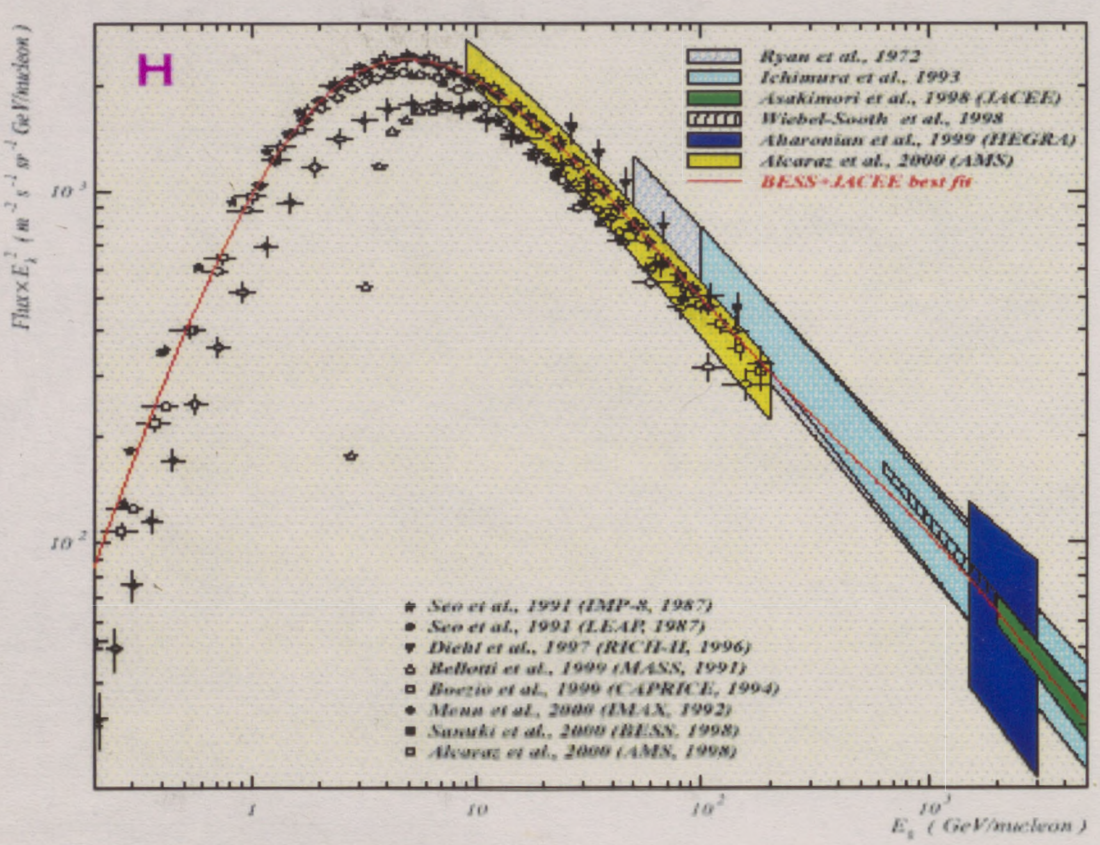
GRAPES-2

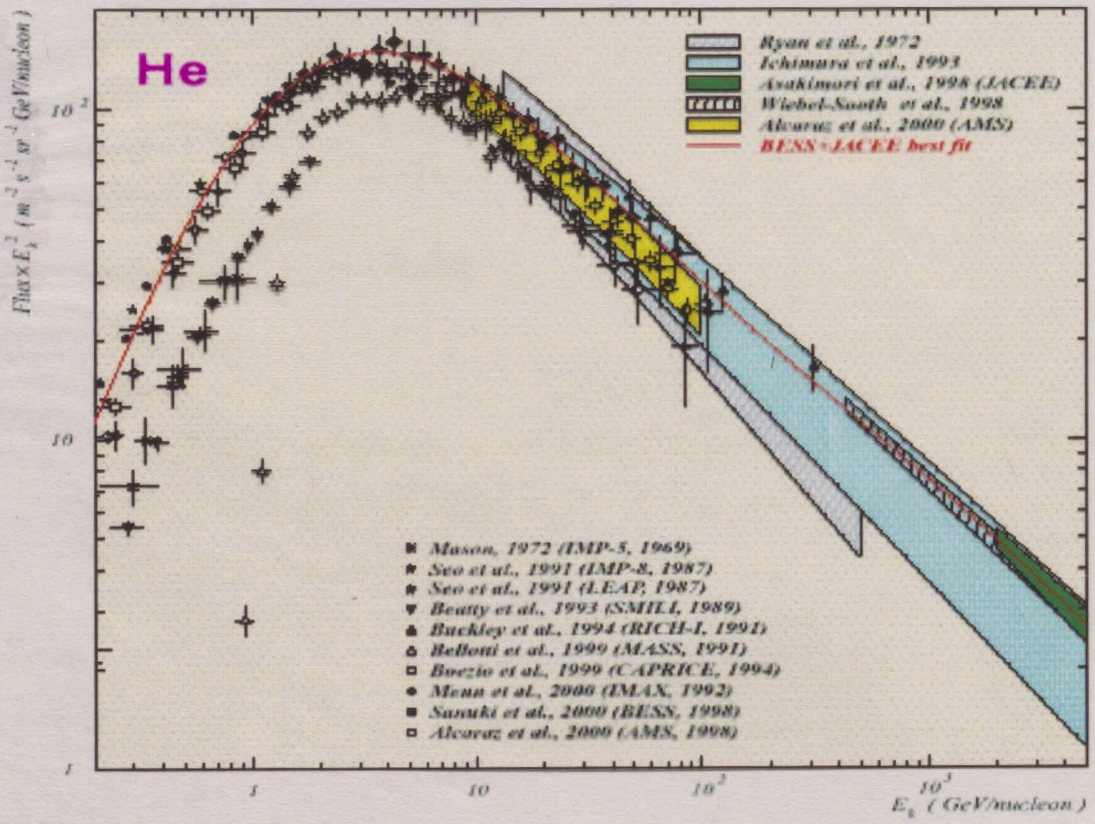
$\sum_{n=1}^{37} p_i = 100-200$

GRAPES-2 Array (Raj Bhavan campus, Ooty)



- 100-detector shower array spread over $\sim 5000 m^2$ area; hexagonal configuration with 10 m inter-detector spacing.
- 192-module, 200 m^2 area muon detector, $E_\mu \geq 1 GeV$.
- Shower trigger, based on the 4-fold N.E.W.S. coincidence, optimized for selection of small showers with their cores near the centre of the array.
- Shower trigger rate $\sim 6\ min^{-1}$, energy threshold $\sim$ 30 TeV.


H
Ryan et al., 1972
Ichimura et al., 1993
Asakimori et al., 1998 (JACEE)
Wiebel-Sooth et al., 1998
Aharonian et al., 1999 (HEGRA)
Alcaraz et al., 2000 (AMS)
BESS+JACEE best fit
Seo et al., 1991 (IMP-8, 1987)
Seo et al., 1991 (LEAP, 1987)
Diehl et al., 1997 (RICH-II, 1996)
Bellotti et al., 1999 (MASS, 1991)
Boezio et al., 1999 (CAPRICE, 1994)
Menn et al., 2000 (IMAX, 1992)
Sanuki et al., 2000 (BESS, 1998)
Alcaraz et al., 2000 (AMS, 1998)
Flux× E_k^2 (m^-2 s^-1 sr^-1 GeV/nucleon)
10^3
10^2
1
10
10^2
10^3
E_k (GeV/nucleon)


He
Ryan et al., 1972
Ichimura et al., 1993
Asakimori et al., 1998 (JACEE)
Wiebel-Sooth et al., 1998
Alcaraz et al., 2000 (AMS)
BESS+JACEE best fit
Mason, 1972 (IMP-5, 1969)
Seo et al., 1991 (IMP-8, 1987)
Seo et al., 1991 (LEAP, 1987)
Beatty et al., 1993 (SMILI, 1989)
Buckley et al., 1994 (RICH-I, 1991)
Bellotti et al., 1999 (MASS, 1991)
Boezio et al., 1999 (CAPRICE, 1994)
Menn et al., 2000 (IMAX, 1992)
Sanuki et al., 2000 (BESS, 1998)
Alcaraz et al., 2000 (AMS, 1998)
Flux× E_k^2 (m^-2 s^-1 sr^-1 GeV/nucleon)
10^2
10
1
1
10
10^2
10^3
E_k (GeV/nucleon)

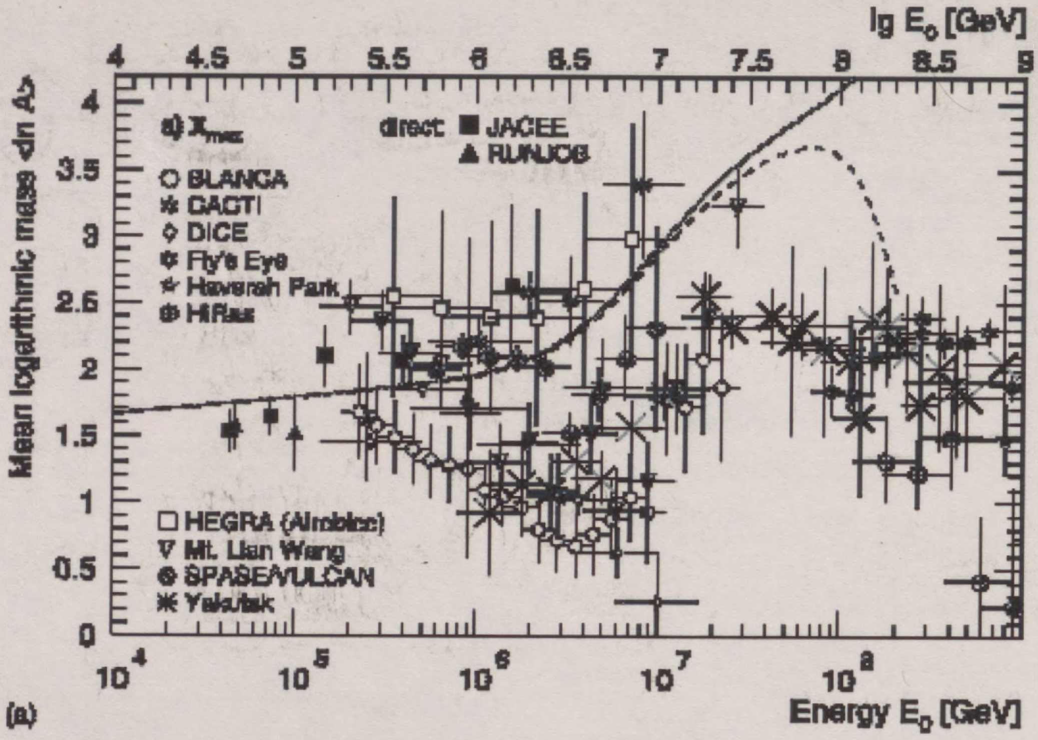
Primary Composition 10^{15} ev - 10^{16} ev.

Table 6.4: Fractional contents of primary cosmic ray flux contributed by the 5 nuclear groups in the energy range, from 1,000 to 10,000 TeV, for various composition models.

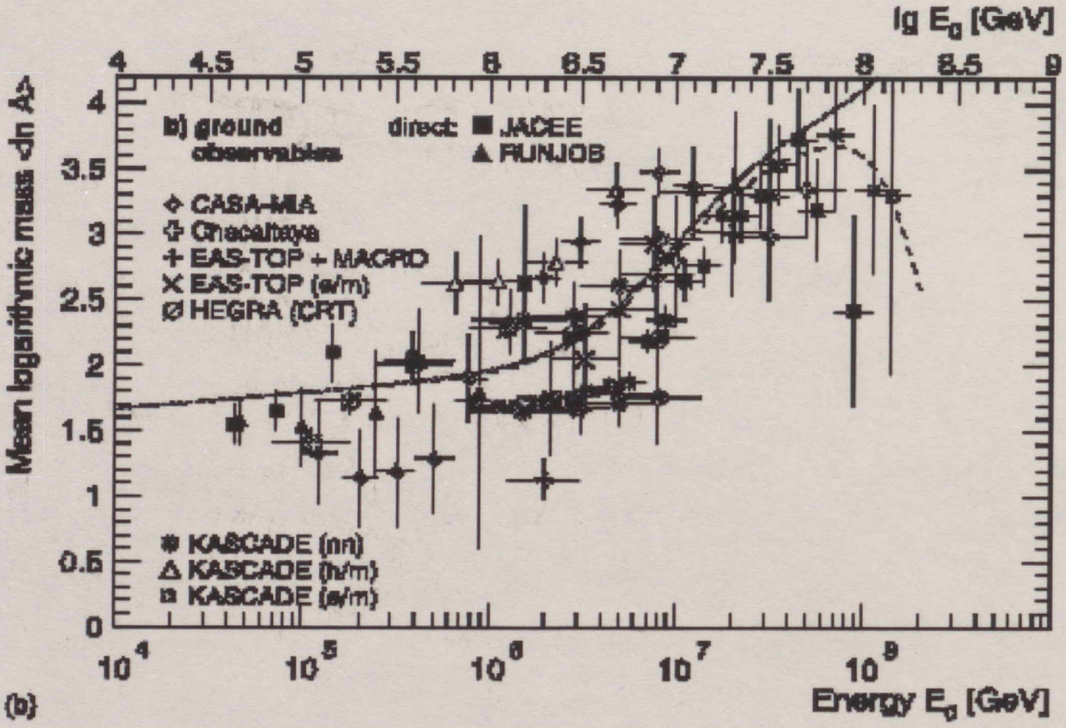
Group	Protons (%)	α Particles (%)	CNO Nuclei (%)	Si group Nuclei (%)	Fe group Nuclei (%)
Constant Mass Composition	41.02	23.97	13.73	9.68	11.59
Linsley Composition	76.35	6.29	6.38	4.93	6.05
Maryland Composition	6.19	3.98	15.91	31.71	42.22
Ooty Composition	10.47	14.59	14.82	16.69	43.42

Note the drastic change in the proton Composition in the Maryland and Ooty Compositions (beyond 10^{15} ev.)

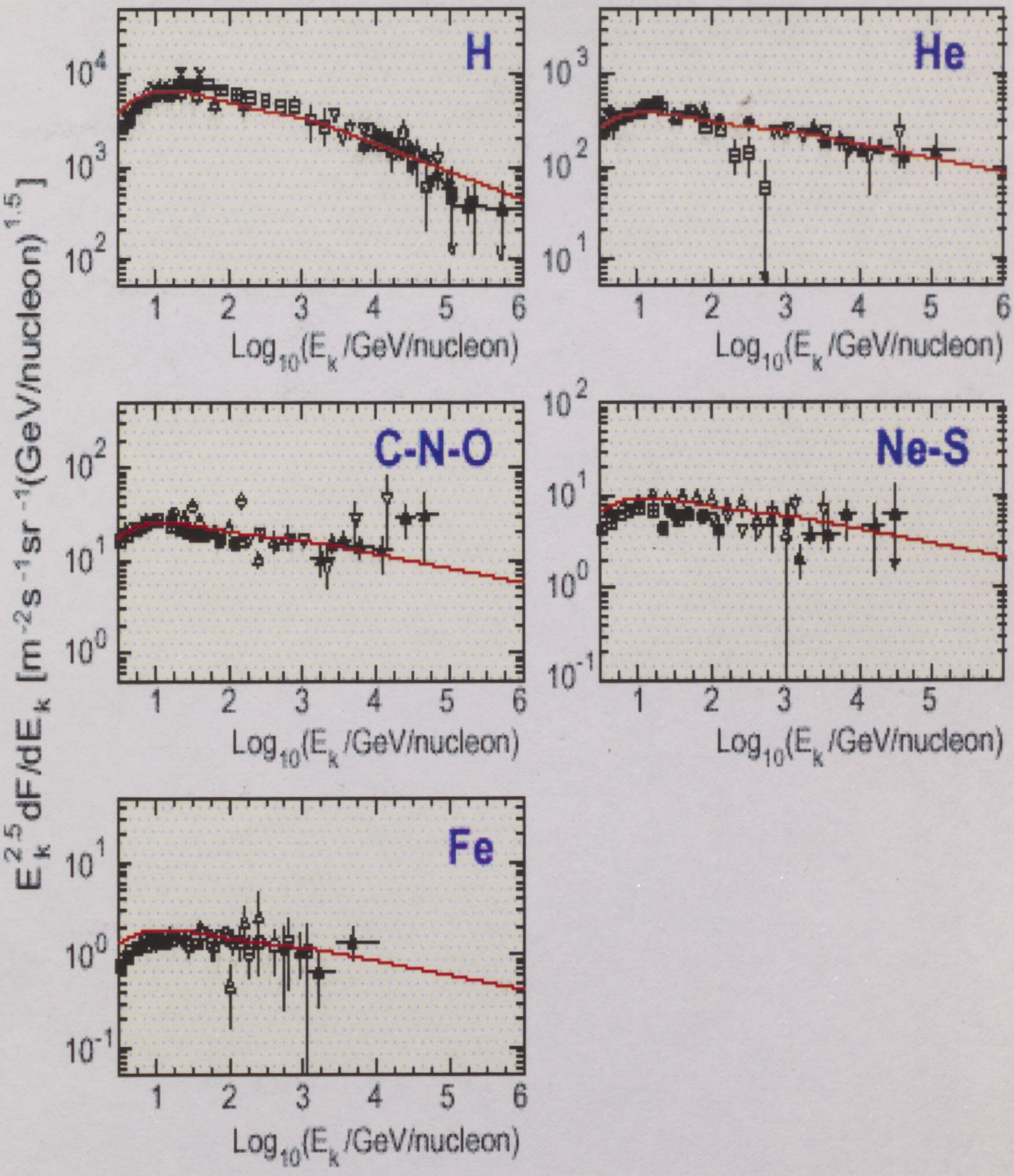
Ph.D Thesis of R. Srivatsan.
(1994.)



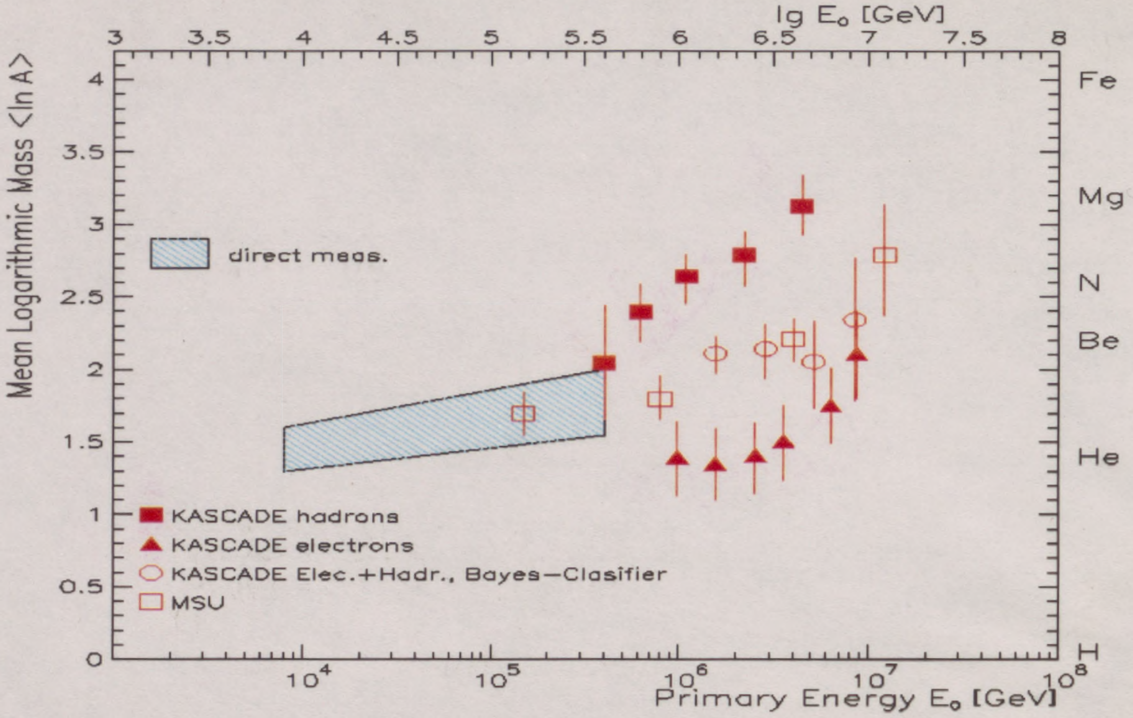
- Observations on $X_{max} \rightarrow \bar{A}$ decreasing with $E_\circ$??



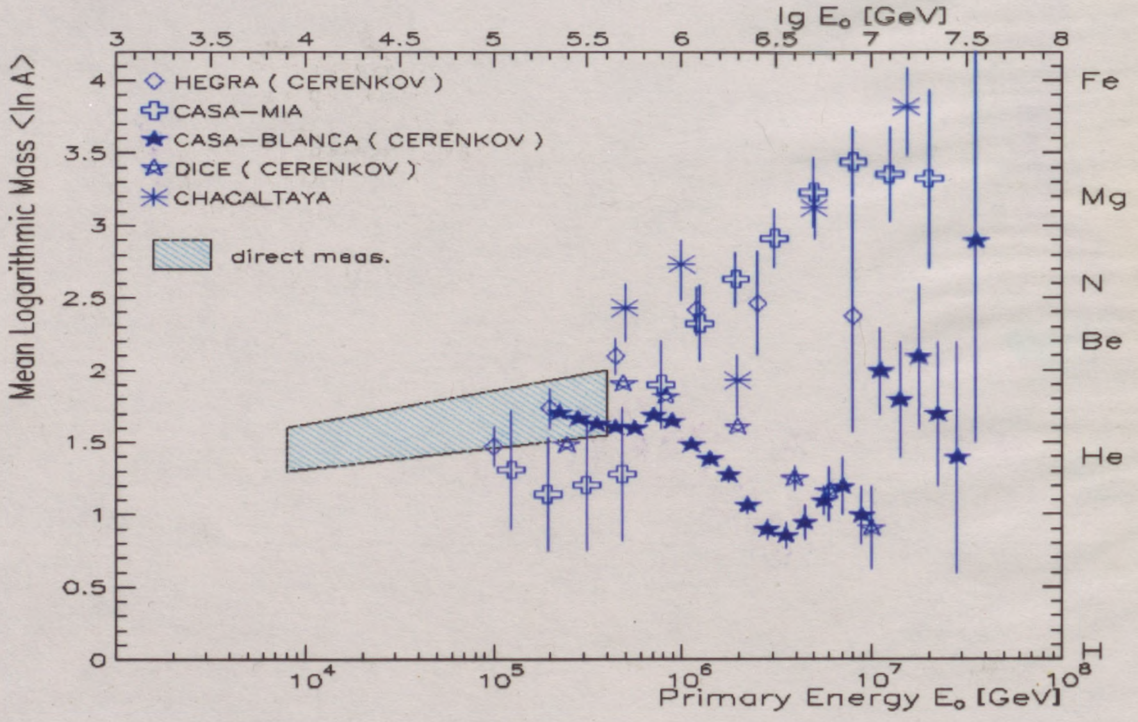
- Electrons, muons and hadrons $\rightarrow \bar{A}$ increasing with $E_\circ$??



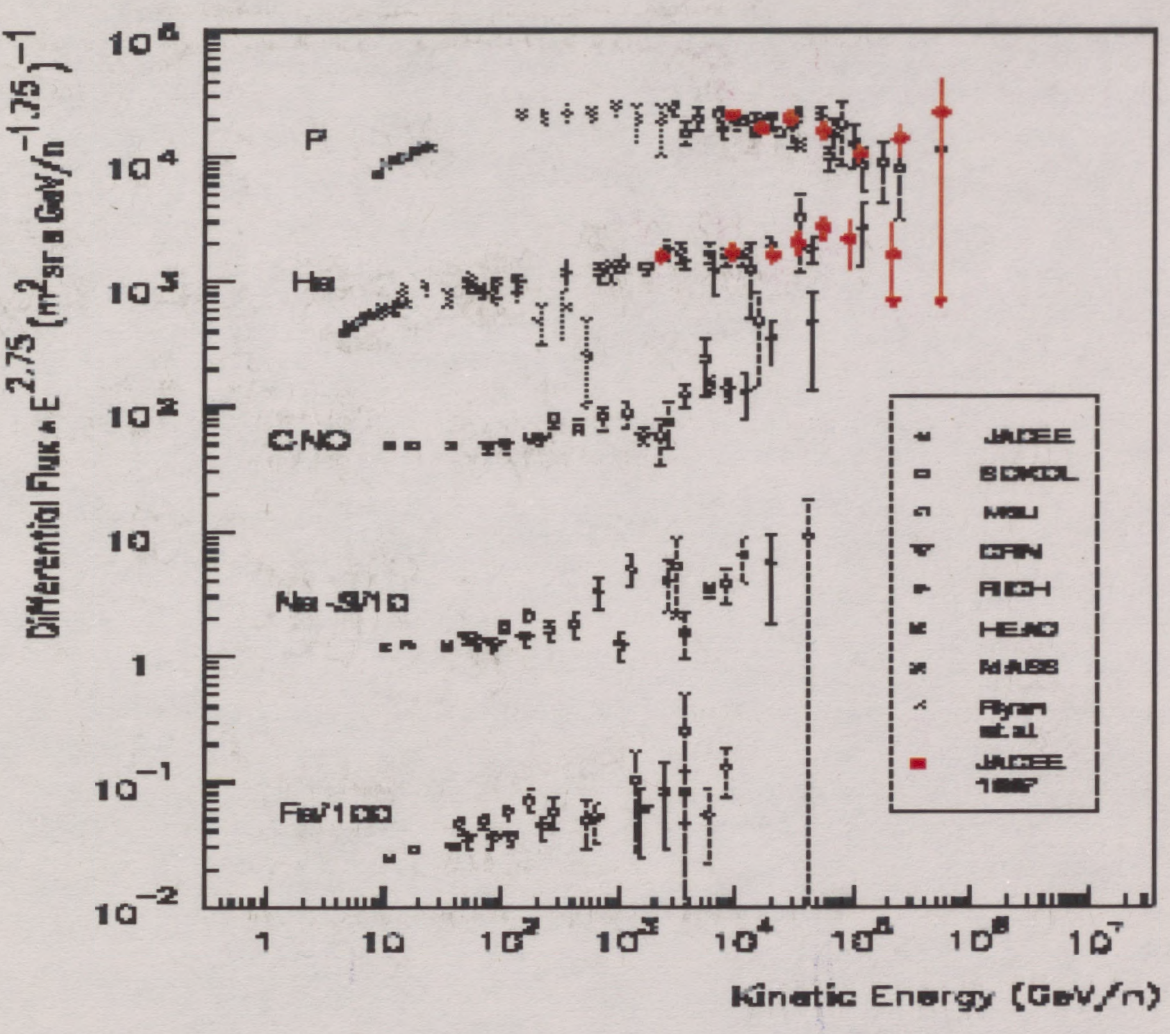
- The absolute flux at energy ~ 1 TeV of various nuclear groups may be considered to be known only to an accuracy of only about ±20%.



- Observations on shower electrons and hadrons.



- Observations on $N_\mu - N_e$ and Cherenkov photons.



- With direct measurements on the energy spectra for various nuclear groups available only at energies less than $\sim 10^{14}$ eV from detectors flown aboard balloon or satellite-borne platforms, it is rather difficult to predict the shapes of these spectra at air shower energies. However, it is good to anchor the spectra for various nuclear groups at energies where relatively more reliable data is available, for example, at 1 TeV/nucleus. These spectra show that there are significant differences between the values of the spectral index for various nuclear groups with the heavy nuclei (Ne-Fe group) having a relatively flatter spectrum, which has significant implications for the composition around the knee and its possible interpretation.

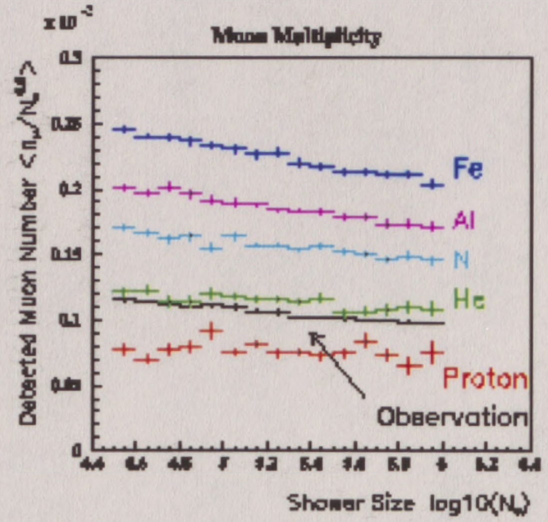


Fig. 3. Average number of detected muon with shower size. Observation is shown in black and compared with MC results.

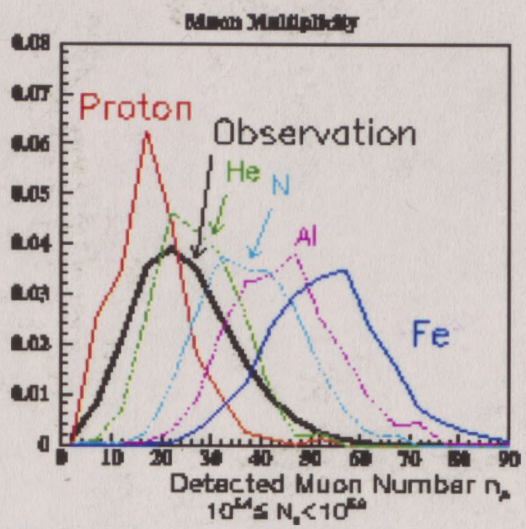


Fig. 4. Distribution of detected muon number with size. Observation is shown in black and others are MC results.

SIMULATION OF THE EXPERIMENT

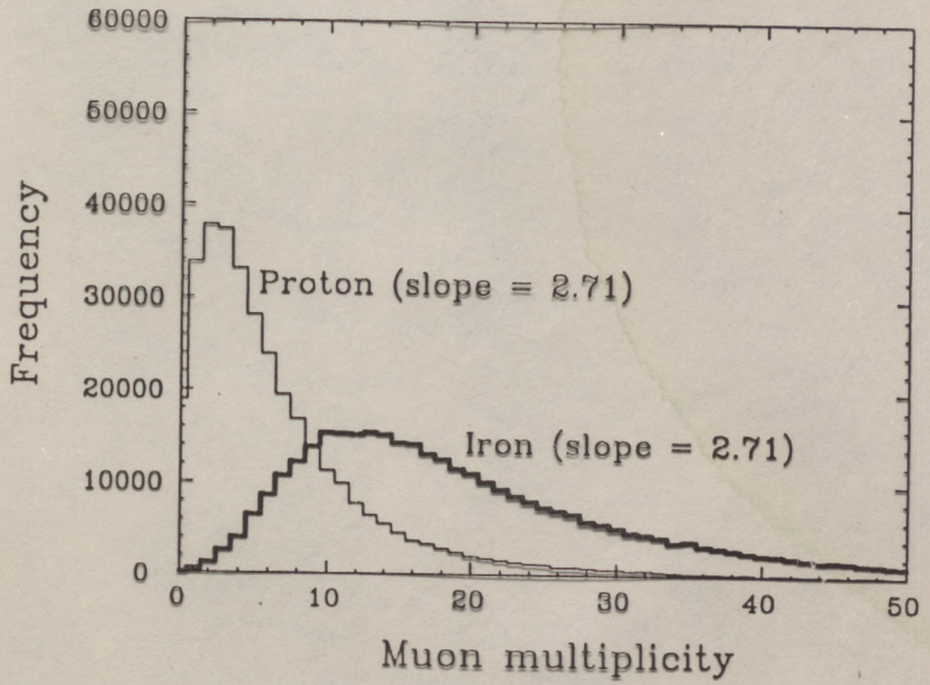
(i) INPUT : Primary energy spectra, N(E) dE = $K_i E^{-\gamma_i}$ dE, for 5 primary nuclear species, H (A=1), α (A=4), N (A=14), Si (A=28) and Fe (A=56), specified by the 'Composition Model' under consideration.

Normalisation of spectra (K_i) at a total energy of 1 TeV with measurements obtained from direct experiments, JACEE,CRNE, etc.

(ii) Simulation of showers in the atmosphere for zenith angle (θ) between 0° and 45°.

(iii) Simulation of electron detector response to shower particles laterally spread according to NKG distribution and selection of showers satisfying the NEWS trigger criterion.

(iv) Simulation of muon detector response to muons ($E_\mu \geq 1$ GeV), laterally spread according to Greisen distribution to obtain the expected muon multiplicity distribution.



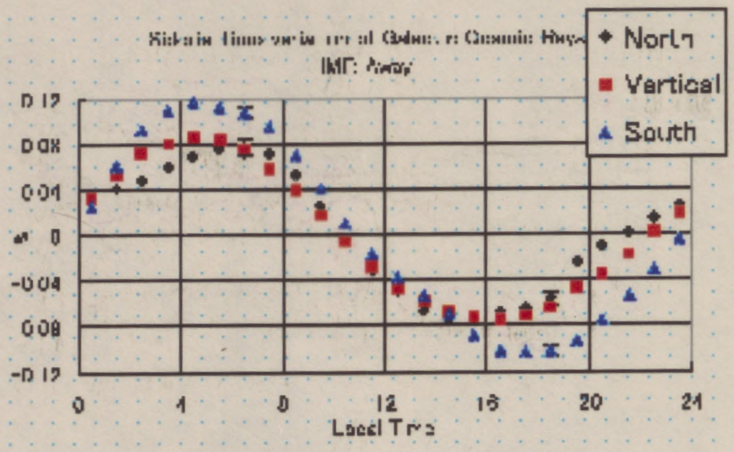


Fig.2 Sidereal time variation of Cosmic rays (Away)

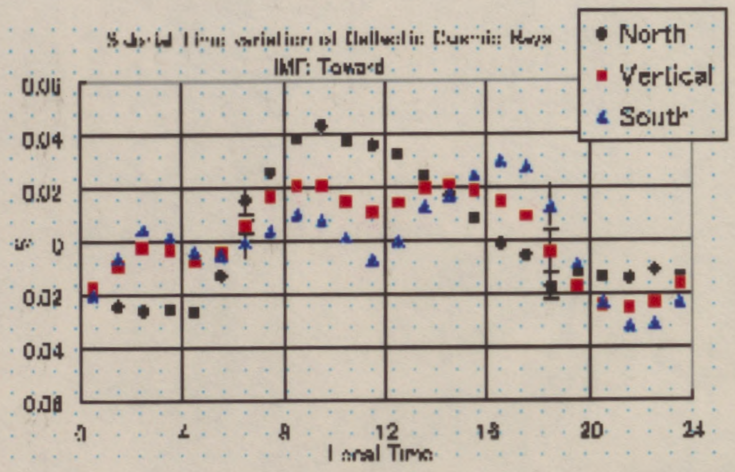


Fig.3 Sidereal time variation of Cosmic rays (IMF: Toward)

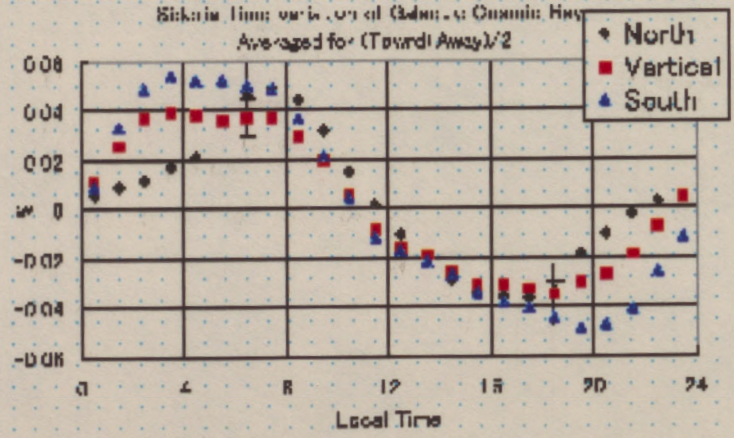


Fig.4 Sidereal time variation of Cosmic rays (Toward+Away)/2

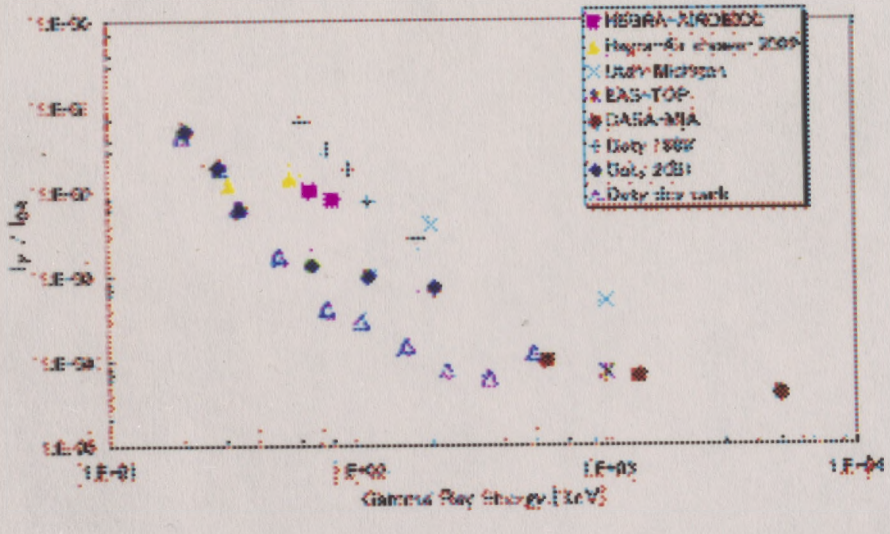


Fig. 2. Upper Limit of Isotropic Gamma Ray

OOTY INDIA

GRAPES-3 EXPT.

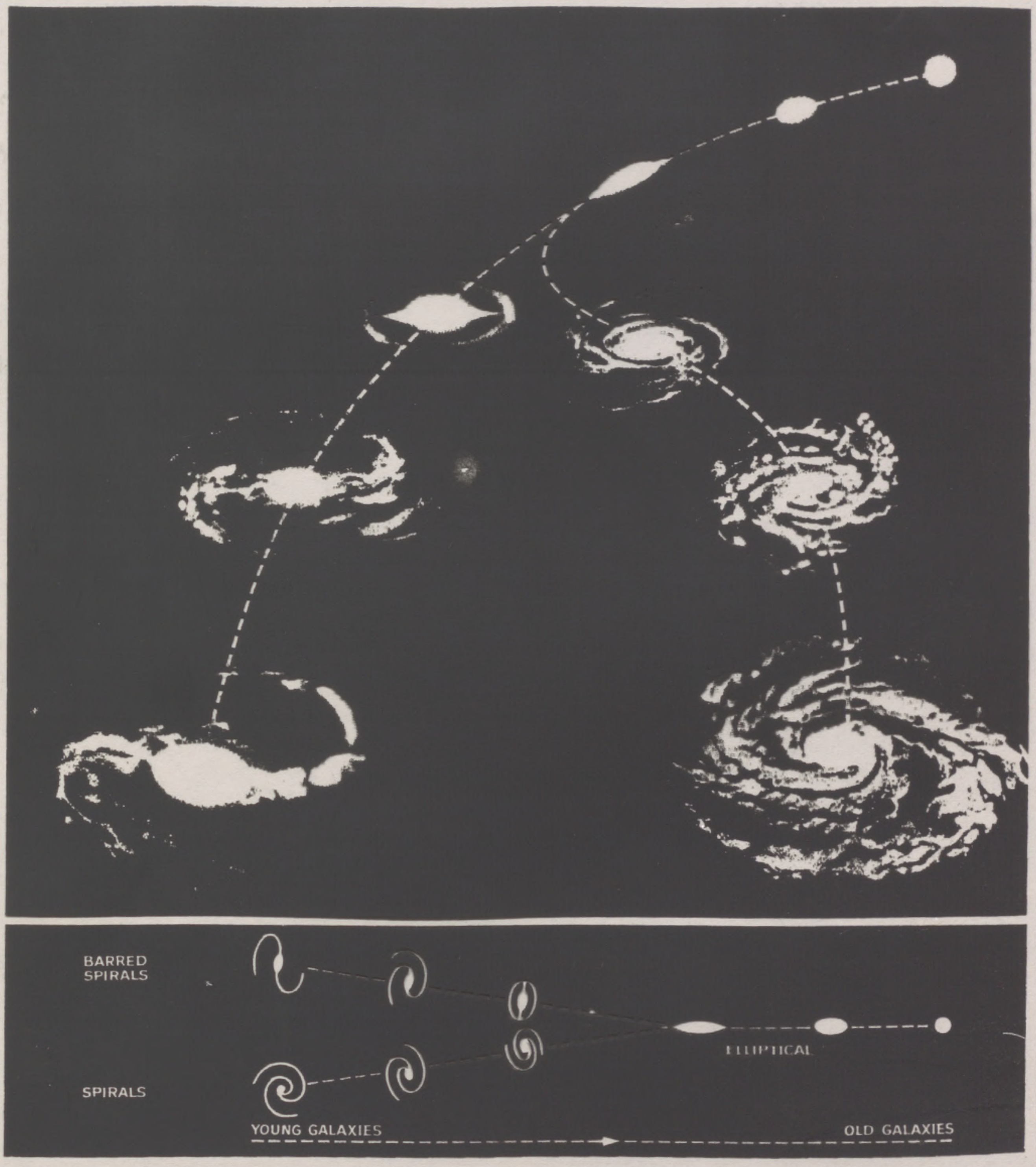
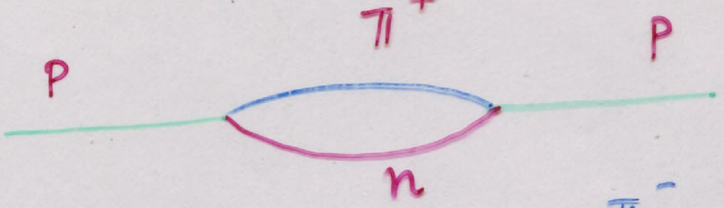
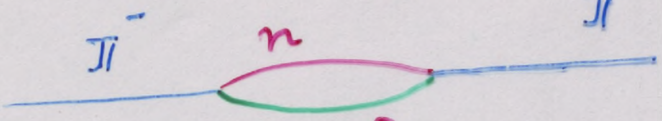
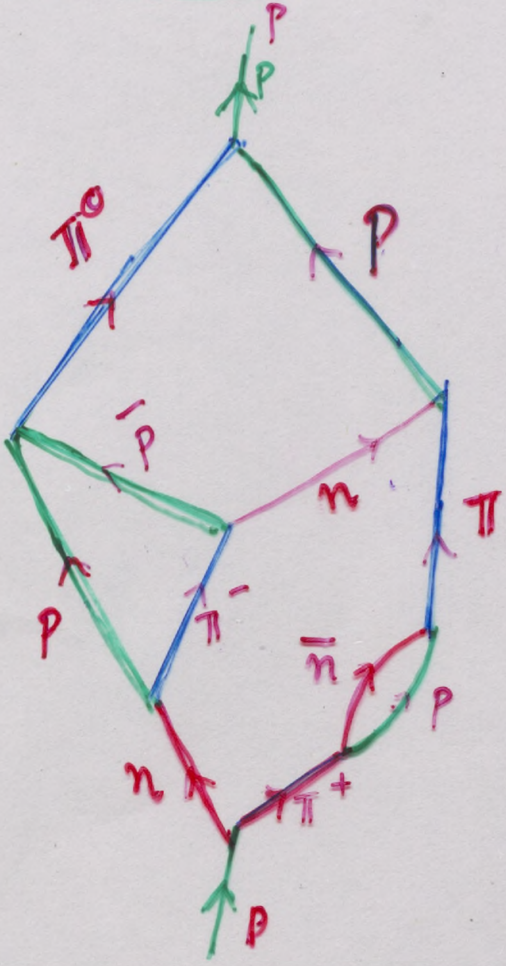


Fig. 733 — Evolution of galaxies

Virtual States







What is Vacuum?

Repository of all fundamental particles (discovered and yet to be discovered) in negative energy states.