High Energy Astro-Particle Physics:
An Experimental Perspective

Sunil K. Gupta
gupta@grapes.tifr.res.in

WAPP-2011, Darjeeling, 28 December 2011

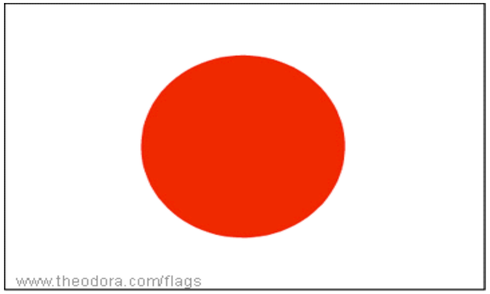
- Introduction and Motivation
- The GRAPES-3 Experiment
- Technology Development
- Scientific Results
- Future Plans

GRAPES-3 Collaboration

(Gamma Ray Astronomy at Pev Energies Phase-3)

An India Japan Scientific Experiment

WAPP-2011, Darjeeling, 28 December 2011



S.K. Gupta, H.M. Antia, S.R. Dugad, I. Mazumdar, P.K. Mohanty, P.K. Nayak, A. Iyer, P. Jagadeesan, A. Jain, S.D. Morris, B.S. Rao, K.C. Ravindran, Y. Hayashi, S. Kawakami, T. Matsuyama, S. Ogio, H. Kojima, R. Koul, V.K. Dhar, K. Venugopal, S. Das, S.K. Ghosh, P. Joarder, P. Subramanian, P. Jain, A. Oshima, H. Tanaka, S. Shibata, U.D. Goswami, S. Panda, S. Ahmad, Badruddin, R. Hasan, A. Bhadra, R.K. Dey, S.K. Sarkar, C.S. Garde

1. Tata Institute of Fundamental Research, Mumbai, India
2. Osaka City University, Osaka, Japan
3. Aichi Institute of Technology, Toyota, Japan
4. Bhabha Atomic Research Centre, Mumbai, India
5. J.C. Bose Institute, Kolkata, India
6. Indian Institute of Science and Engineering Research, Pune, India
7. Indian Institute of Technology, Kanpur, India
8. National Astronomical Observatory of Japan, Tokyo, Japan
9. IPMU, University of Tokyo, Tokyo, Japan
10. Chubu University, Kasugai, Japan
11. University of Dibrugarh, Dibrugarh, India
12. Indian Institute of Science and Engineering Research, Bhopal, India
13. Aligarh Muslim University, Aligarh, India
14. North Bengal University, Siliguri, India
15. Vishwakarma Institute of Information Technology, Pune, India

Motivation

Almost every interesting object in sky producing E-M radiation (radio, optical γ-rays, X-rays) results from interaction of H.E charged particles with matter or radiation field

Understanding of any phenomena in H.E astrophysics requires production and acceleration of charged particles be understood

Charged particles	---->	engine
EM emission	---->	exhaust

Our galaxy contains 10^{11} stars, interstellar space is permeated with magnetic field, gas clouds, dust, MBR, CR

Energy density of these components are

1. Magnetic field ~ 1 eV/cm^3
2. K.E of Gas ~ 1 eV/cm^3
3. Cosmic rays ~ 1 eV/cm^3
4. Star light ~ 1 eV/cm^3
5. MBR ~ 1 eV/cm^3

there seem to be Equipartition of energy

CR play role → Evolution of galaxy

Highest energy accelerator at FERMILAB $E = 10^{12}$ eV

In near future (2009) $E = 7x10^{12}$ eV CERN

Nature reaches $E = 10^{20}$ eV ~ 14000 / day (Earth)

How does nature produce these particles?

How does it accelerate them?

- Cosmic rays are the highest energy particles present in nature
- Cosmic rays have been observed over an extraordinary range of energies

10^8 - 10^{20} eV   12 order of magnitude

$E_{C.R} < 10^{12}$ eV   space based detectors

$E_{C.R} > 10^{12}$ eV   ground based detectors

- At lower energies C.R are mostly charged particles of various nuclei

P ~ 90%

He ~ 7-8%

C, N, O,..... Si, S,...... Fe,....... etc ~ 2-3%

e^-, γ $\leq \gamma \leq$ 1%

- CR are basically energetic charged particles with a good representation from the entire periodic table
- *Due to this huge energy range a variety of experimental techniques, are used to detect and measure them*

Cosmic rays discovered in 1912 by Victor Hess aboard hot air balloon using simple instruments. Set the explorer tradition for future experiment

Unlike most branches of physics, experiments are in well maintained and nicely equipped labs, most cosmic ray (CR) experiments are at diverse and remote sites around the earth and beyond

Geographic Location	Examples		Country
SEA LEVEL	KASKADE EAS		GERMANY
	AUGER EAS		ARGENTINA
MOUNTAINS	2.2 km	GRAPES-3	OOTY
	4.3 km	ASγ	TIBET
	3.0 km	MILAGRO	USA
UNDERGROUND	3 km	KGF EXPT	(closed)
	1 km	SUPER-K	JAPAN
UNDERWATER	1 km	LAKE BAIKAL	RUSSIA
	1 km	NESTOR	GREECE

Geographic Location	Examples		
UNDER ICECAP	2.3 km	ICE CUBE	1 km^3
BALLOONS	35 km	JACEE	USA/JAPAN
	35 km	ISOMAX	USA/GERMANY
SPACE	200 km	AMS, SPACE SHUTTLE	
	10^6 km	ACE, NASA	
	> 100 AU	VOYAGER MISSION	
ACCELERATORS	L3 COSMICS	CERN, TIFR	

Early Experiments on Ships going round the Earth, on aircraft flying at High Altitudes etc.,

Prerequisite:

A Astro-Particle Physicist is adventurous, won't mind venturing out beyond the safety of Home Institution

Experimental Observations:

(1) CR flux is constant in time

(2) CR flux is isotropic

It is now established that in energy range 10^{14} – 10^{16} eV CR are produced within the galaxy (Milky way)

Galactic magnetic field in gas clouds in interstellar space has random orientations, which deflect CR particles complete randomizing their direction

CR motion $\longrightarrow$ Diffusion $\longrightarrow$ Isotropic flux with constant intensity

Larmor radius ~ 1 LYR 10^{15}eV at 3μG

Magnetic trapping in galaxy

- CR flux isotropic constant
- Increases the flux in galaxy by increasing storage time – lifetime

T ~ $10^7 – 10^8$ yrs - 10^5 yrs galactic size

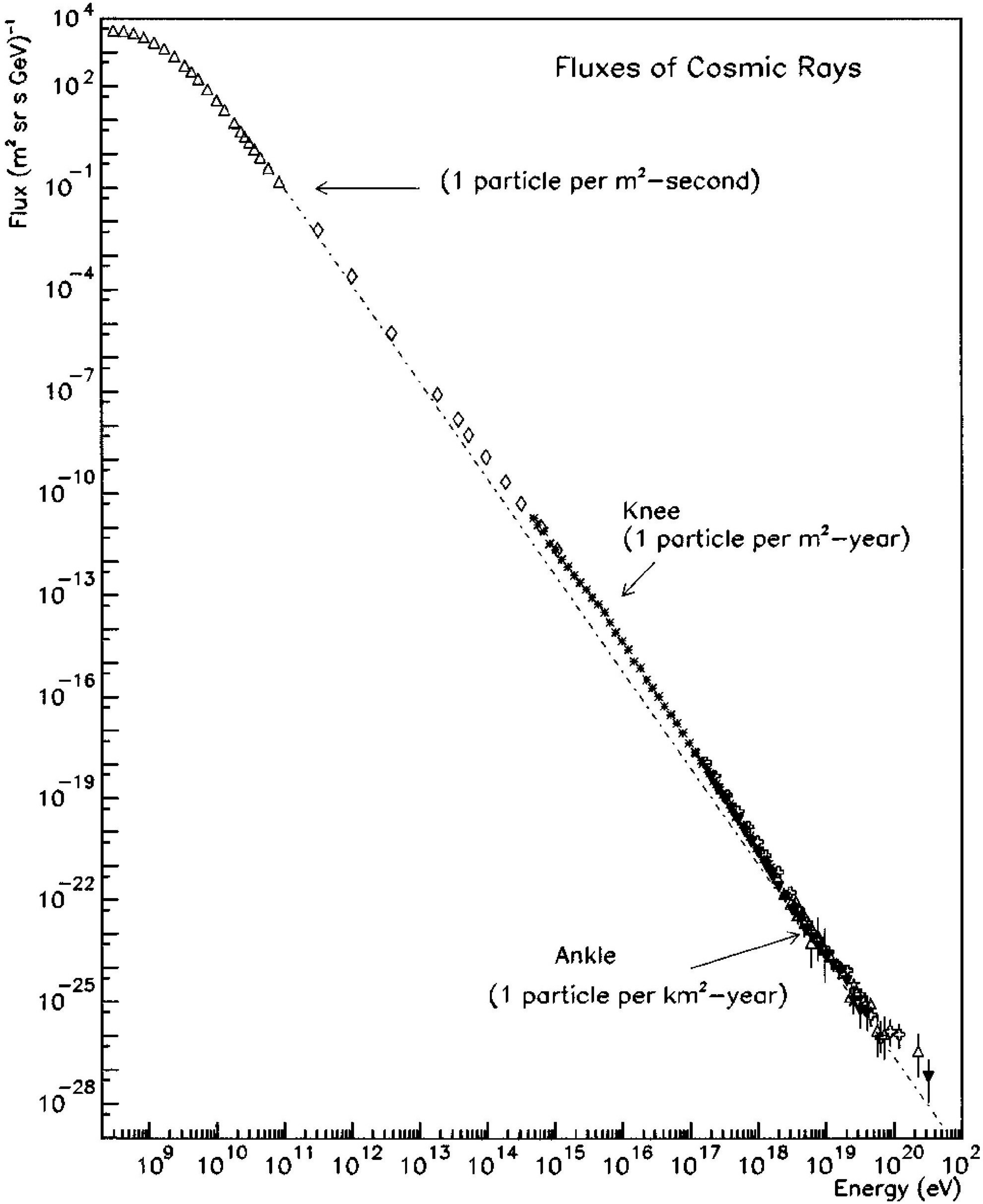
Trapping of CR in galaxy randomizes direction → direct identification of source difficult

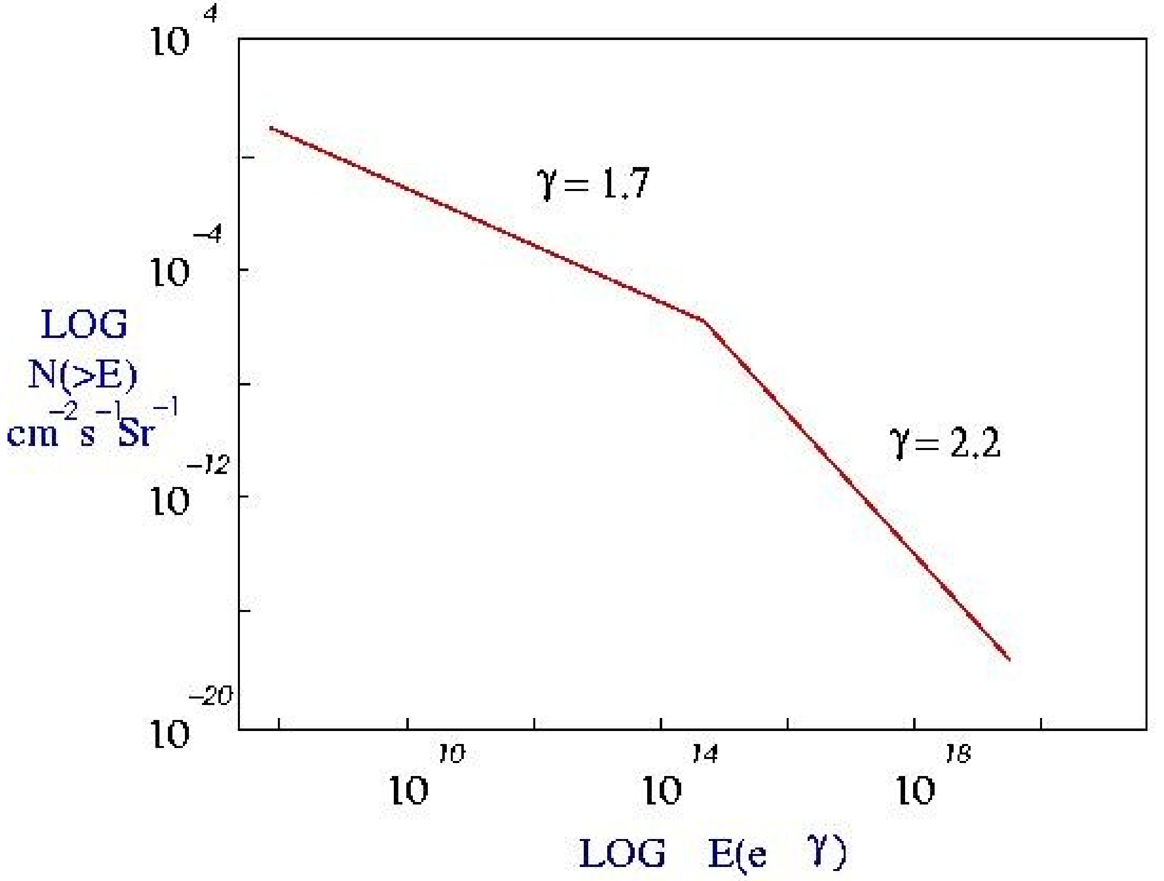
But significant information on sources of CR and on medium of propagation is present in the

(1) The energy spectrum of CR

(2) Nuclear composition of CR

(3) γ - ray flux in CR


Fluxes of Cosmic Rays
Flux (m² sr s GeV)⁻¹
(1 particle per m²-second)
Knee
(1 particle per m²-year)
Ankle
(1 particle per km²-year)
Energy (eV)
10^4
10^2
10^-1
10^-4
10^-7
10^-10
10^-13
10^-16
10^-19
10^-22
10^-25
10^-28
10^9
10^10
10^11
10^12
10^13
10^14
10^15
10^16
10^17
10^18
10^19
10^20
10^21



$N(>E) = kE^{-\gamma}$

Spectrum Very Steep X 10 Energy % 50 Flux

At $\geq 10^{14}$ eV Flux = 1 particle m^{-2} hr^{-1}

At $\geq 10^{15}$ eV = 1 particle m^{-2} $week^{-1}$

At $\geq 10^{20}$ eV = 1 particle km^{-2} $century^{-1}$

Objective: Universe at high energies

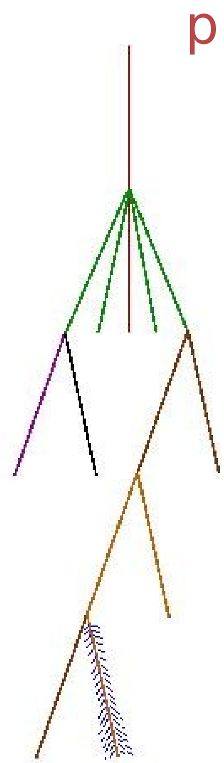
Acceleration, propagation of high energy particles,
Extreme conditions may require new physics ...

1. Acceleration in atmospheric electric field
   Energy ~100 MeV   Scale ~10^5-10^6 cm

2. Solar flares, Coronal Mass Ejections
   Energy ~10 GeV   Scale ~10^{11}-10^{13} cm

3. Galactic Cosmic Rays at " Knee "
   Energy ~1 PeV   Scale ~10^{21}-10^{23} cm

4. Diffuse multi-TeV γ-rays
   Energy ~100 EeV   Scale ~10^{24}-10^{26} cm



$p + p \rightarrow p + p + \pi^{+} + \pi^{-} + \pi^{0}$

$\pi^{+} \rightarrow \mu^{+} + \upsilon_{\mu}$ 2×10^{-8} s

$\pi^{0} \rightarrow \gamma + \gamma$ 10^{-16} s

$\gamma \rightarrow e^{+} + e^{-}$

$e^{-} \rightarrow e^{-} + \gamma$

Phenomenon of Extensive Air Shower
Particles multiply and at lower altitudes one gets

1. Electrons, Positrons & Gamma rays called E-M component (90 %)
2. Muon (μ^{+}, μ^{-})called Muon or Penetrating Component (8 – 10 %)
3. Pions, Kaons etc called Hadronic Component (1 %)
4. Neutrinos (υ_{μ},$\bar{\upsilon}_{\mu}$,υ_{e},$\bar{\upsilon}_{e}$) largely pass through the Earth undetected

At E = 10^{14} eV
At Mountain level (Ooty) ~ 20000 particles spread over an area of ~ 1000 m^{2}

Detection and Measurement of Cosmic Rays:

HE particles produce a shower of electromagnetic (e^+, e^-, γ) particles, muons (μ^+, μ^-) and other particles.

Measurement of electron density and time (ns) in shower provides an estimate of energy and direction of primary particle.

Measurement of muon density in the shower provides information on the composition of primary particle. It also allows discrimination between γ and protons.

The muons are also sensitive to flux of solar energetic particles and be used to study solar and atmospheric phenomena.

GRAPES-3: A powerful tool for Astroparticle Physics.

Conventional array with highest density of detectors

Basic Detector Component:

400 - Plastic Scintillator detectors (1 m^2 area)

4000 - Proportional Counters (6m x 0.1m x 0.1m) deployed in four crossed layer configuration as 1 GeV muon detector of area 560 m^2.

N
© 2007 Europa Technologies
Image © 2007 DigitalGlobe
©2007 Google™
298 ft
Pointer 11°23'25.54" N 76°39'49.48" E elev 7223 ft
Streaming |||||||||| 100%
Eye alt 8167 ft

400 Plastic Scintillator detectors (1 m^2 area)

560 m^2 muon detector (E_μ=1 GeV)


112
113
114
073

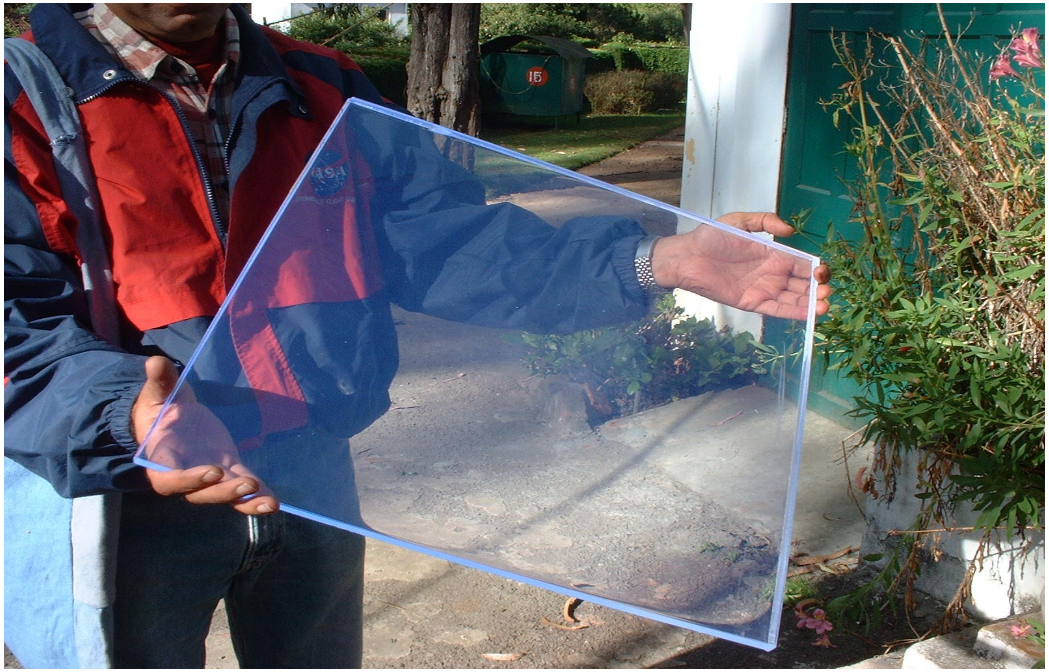
#2 MO
3,28,42

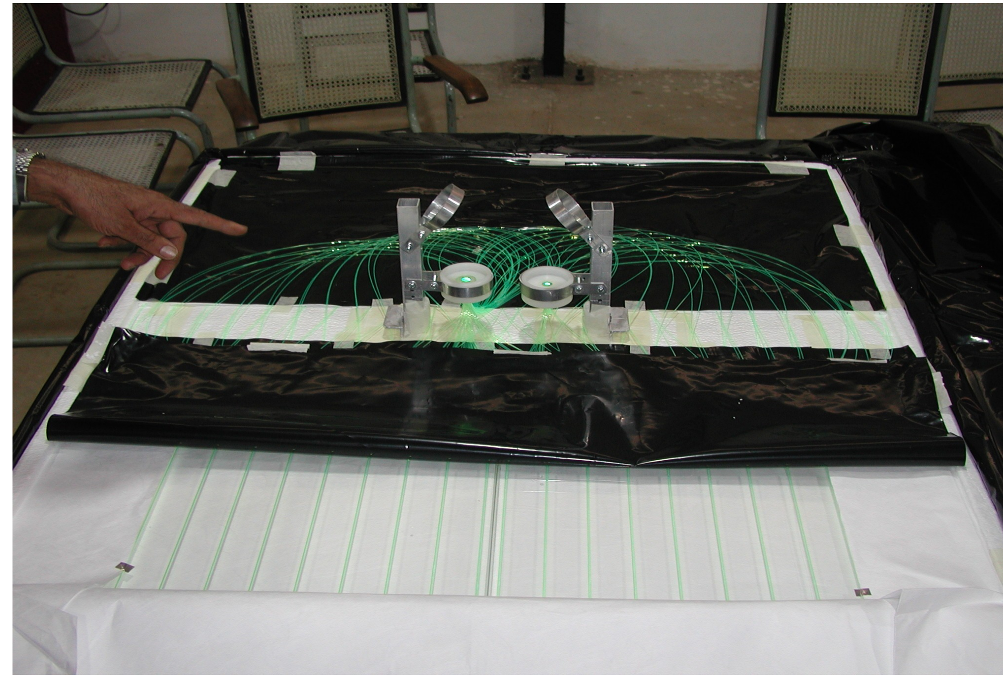
In-house technology for the Fabrication of Various Detector Components

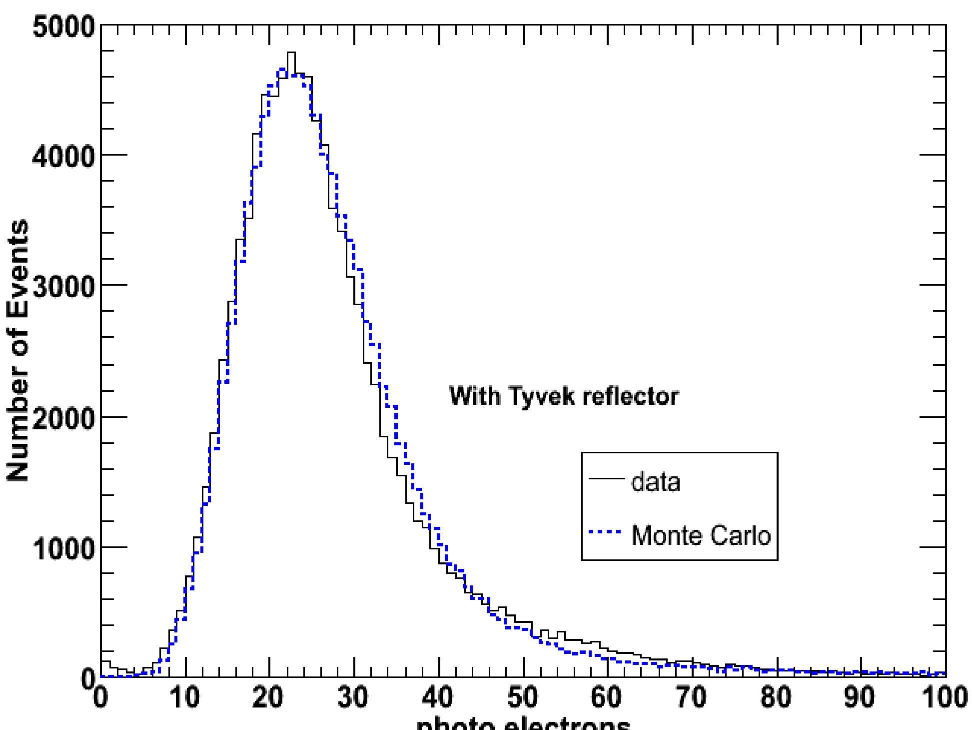
Plastic Scintillator development:

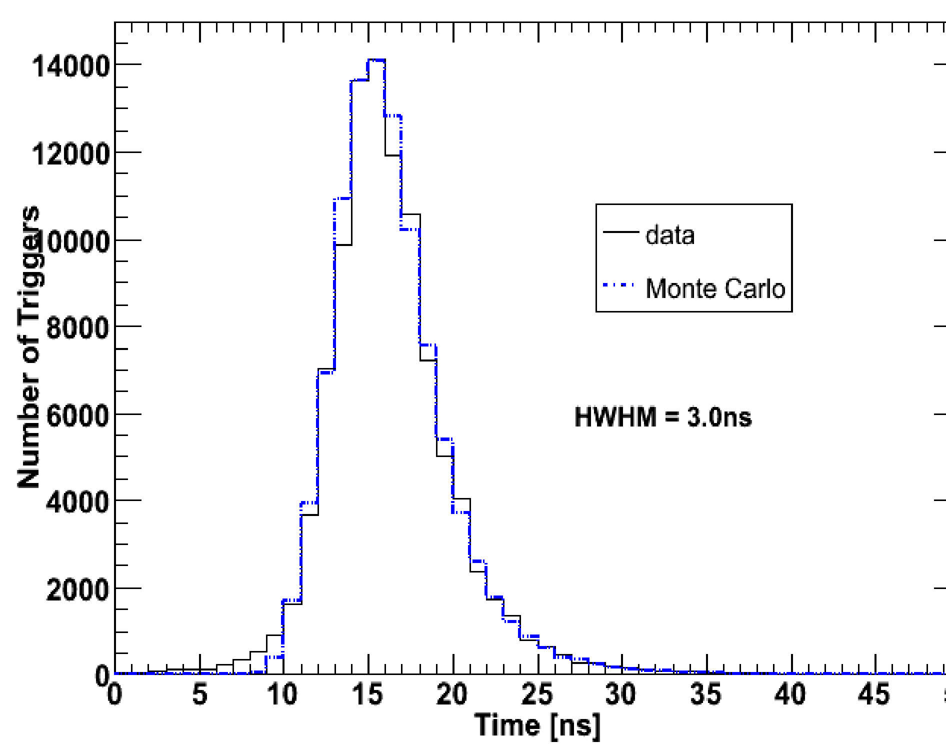
Decay Time= 1.6 ns
Light Output = 85% Bicron (54% anthracene)
Timing 25% faster
Atten. Length $\lambda = 100$cm
Cost ~10% of Bicron
Max Size 100cmX100cm
Total > 2000

CERN, Osaka, IUAC Delhi, Bose, VECC, BARC etc.

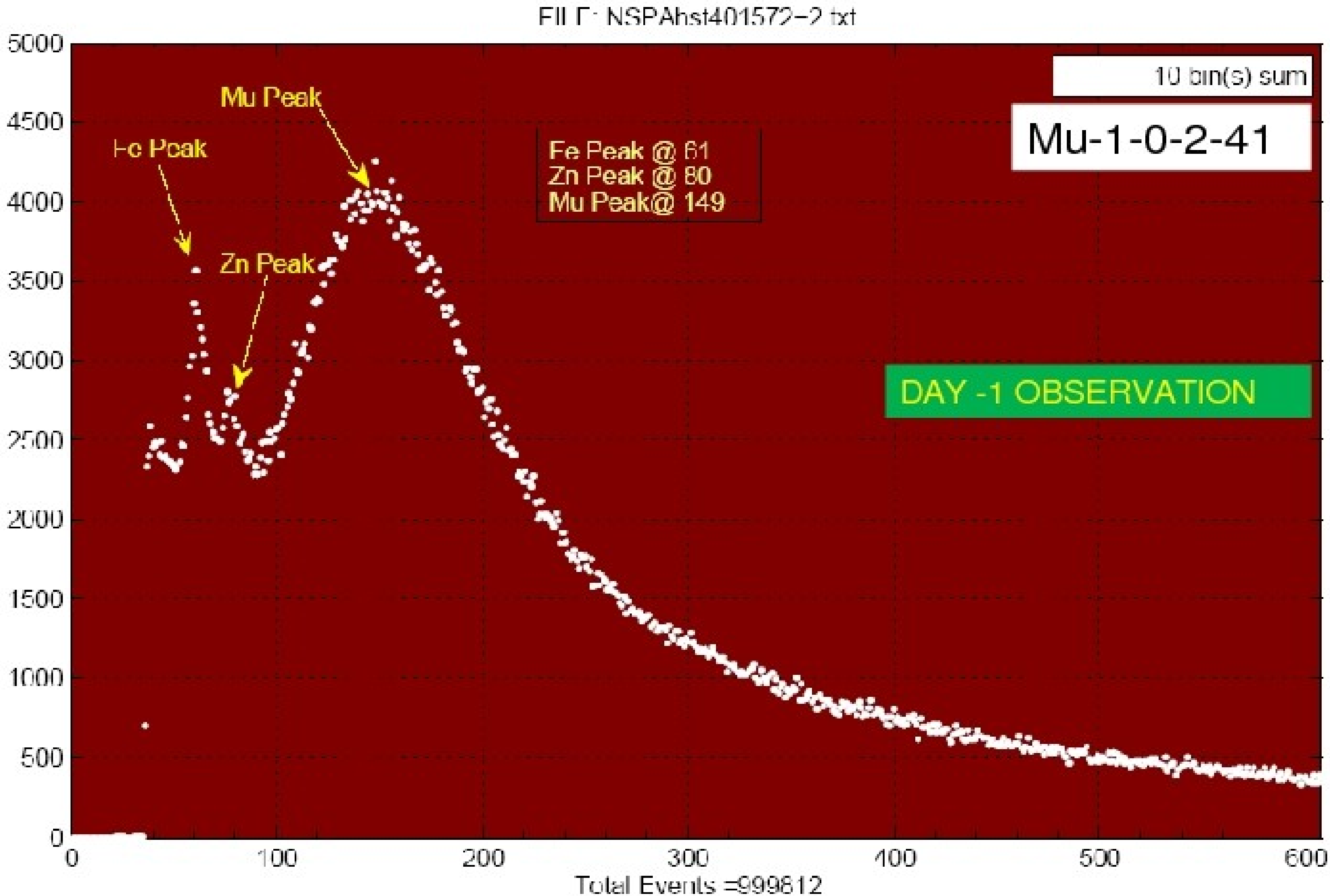





Number of Events
photo electrons
0
1000
2000
3000
4000
5000
0
10
20
30
40
50
60
70
80
90
100
With Tyvek reflector
data
Monte Carlo

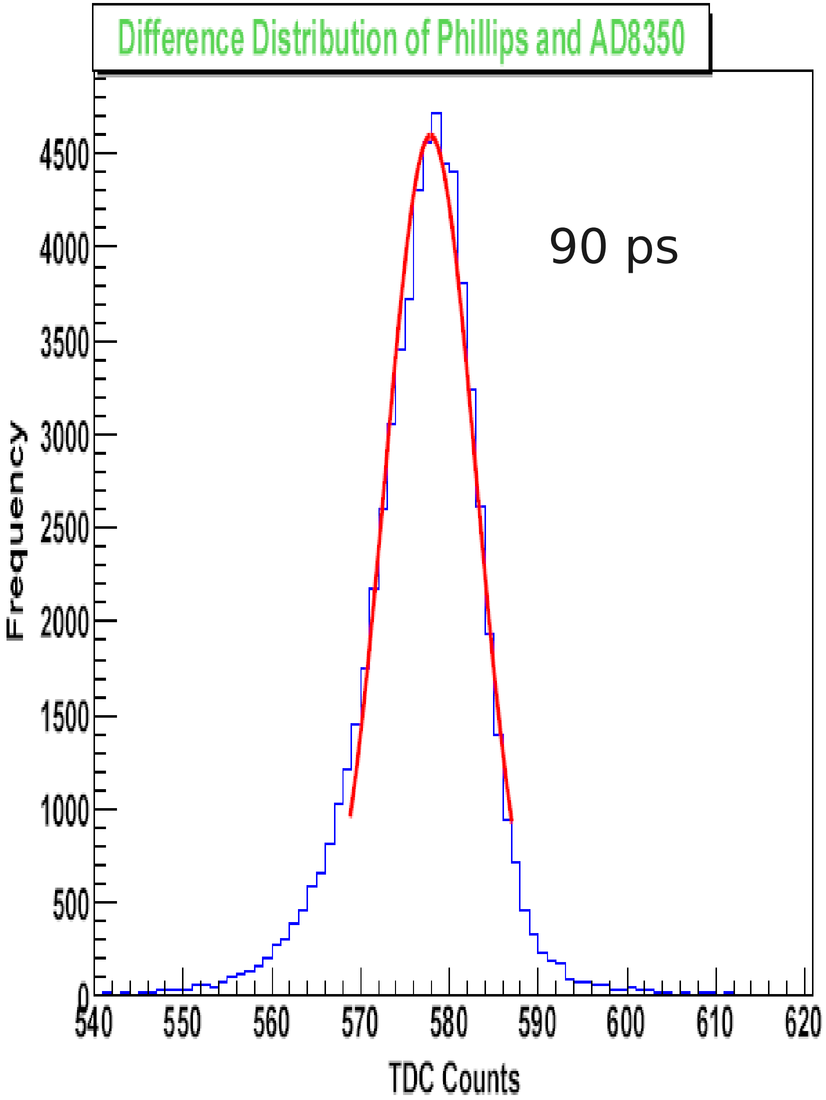

Number of Triggers
Time [ns]
0
2000
4000
6000
8000
10000
12000
14000
0
5
10
15
20
25
30
35
40
45
50
data
Monte Carlo
HWHM = 3.0ns

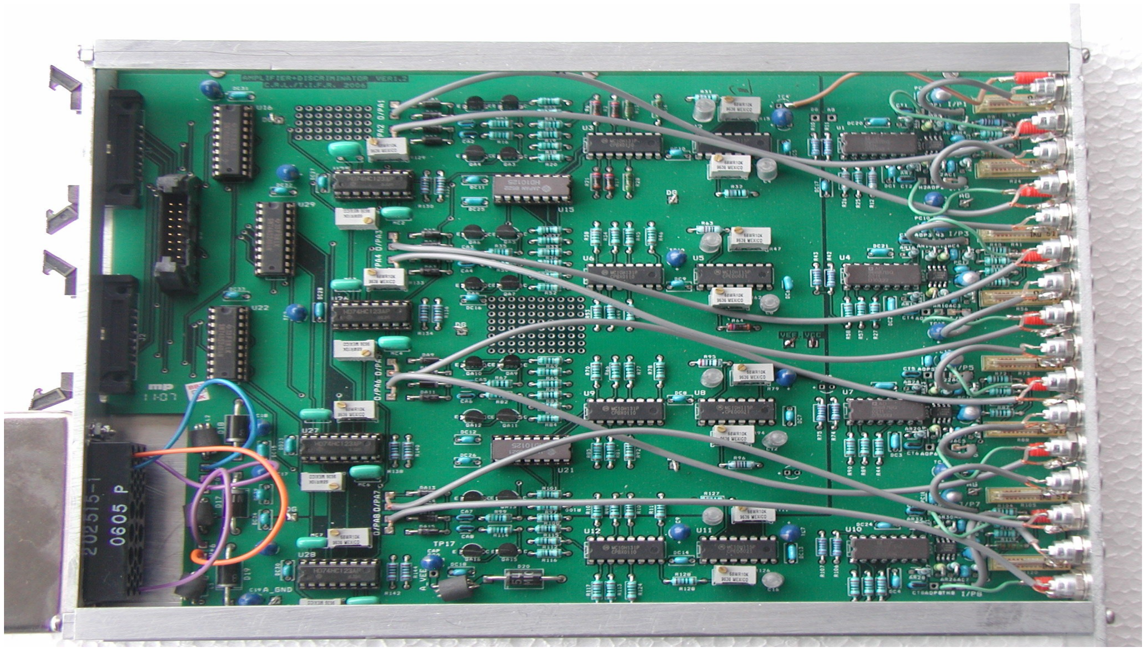
Proportional Counter Test Setup



FILE: NSPAhst401572-2.txt
10 bin(s) sum
Mu-1-0-2-41
Mu Peak
Fe Peak
Zn Peak
Fe Peak @ 61
Zn Peak @ 80
Mu Peak@ 149
DAY -1 OBSERVATION
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
500
600
Total Events =999812

Amplifier-Discriminator response using muons

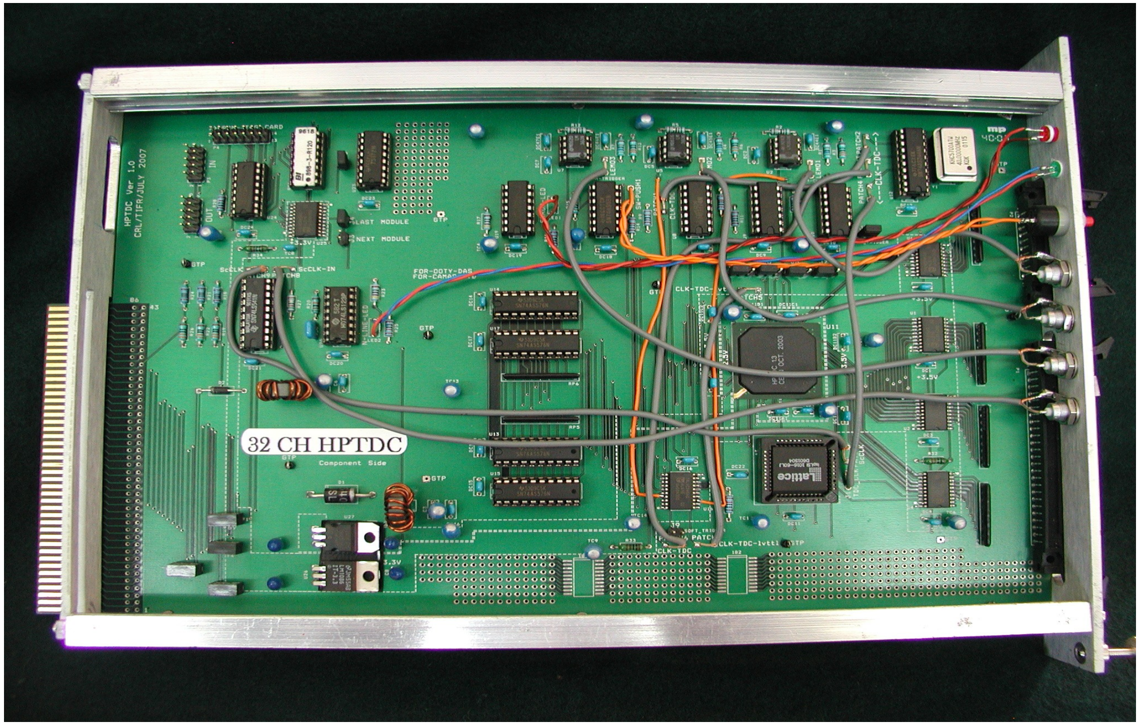


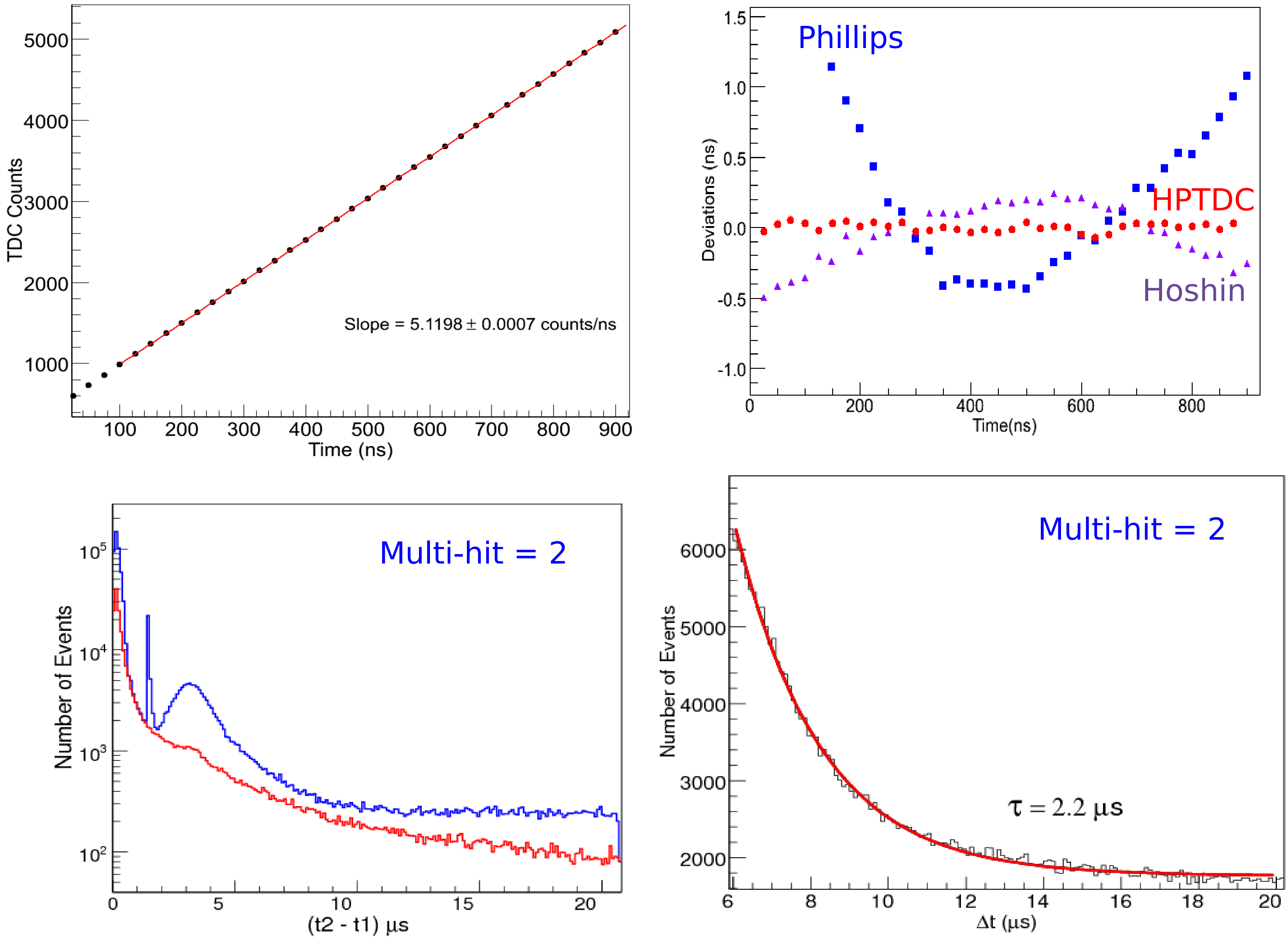


Performance of HPTDC (Stop Watch)

32 Channels
100 ps time resolution
Multi-hit capability
Huge dynamic range (100 ps - 50 μs)
Trigger mode (avoids delay cables)

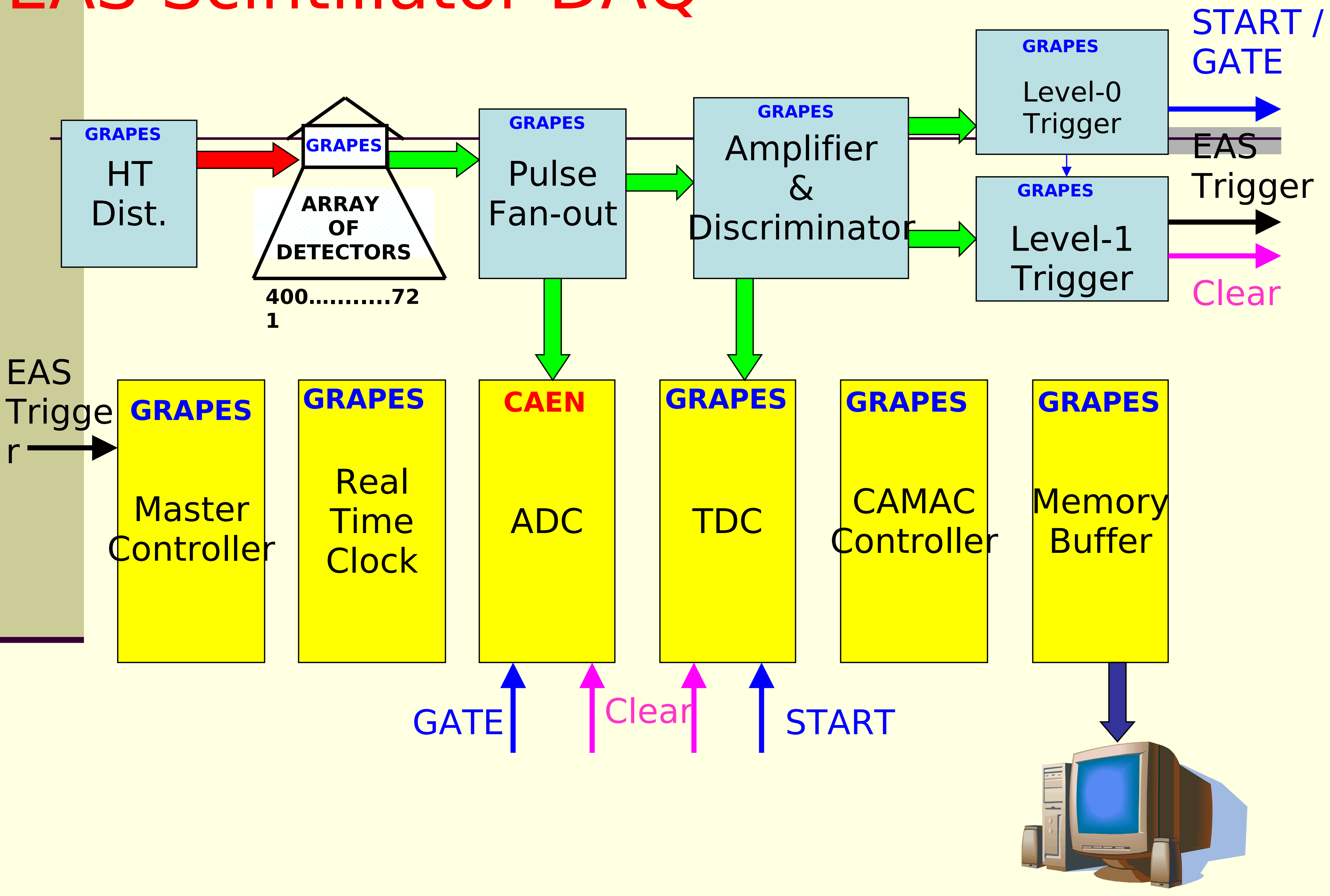
Requests: Atomic, Chemistry, Biology in TIFR, Oulu Finland, IUAC Delhi, Bose Institute, BARC etc.





TDC Counts
Time (ns)
Slope = 5.1198 ± 0.0007 counts/ns
Phillips
HPTDC
Hoshin
Deviations (ns)
Time(ns)
Multi-hit = 2
Number of Events
(t2 - t1) μs
Multi-hit = 2
τ = 2.2 μs
Number of Events
Δt (μs)

EAS Scintillator DAQ



DATA RECORDED:

1) Arrival Time of Shower Particles at Each Detector

2) Number of Particles at Each Detector

3) Real Time of Shower

4) Number of Muon (>1 GeV) in 560 m^2 Detector

EAS Rate ~ 30/sec

We Record ~ 15×10^9 bytes/Day

Analysis: Since Shower is initiated by a single particle and since all secondary particles are relativistic entire shower travels down at the speed of light in the direction of primary

$$ct_i = lx_i + my_i + nz_i$$

c = Velocity of Light

(x_i, y_i, z_i) Coordinates of ith Detector

(l, m, n) Direction Cosines of EAS

Needs a minimum of 3 Detectors to find (l, m, n) consequently the direction in space (θ, φ).

EAS have well Defined Density Distribution as a Function of Radial Distance in Shower Plane

$$\rho(r,s,Ne) = \frac{Ne}{R_m^2} \frac{\Gamma(4.5-s)}{2\pi\,\Gamma(s)\,\Gamma(4.5-2s)} \left(\frac{r}{R_m}\right)^{(s-2)} \left(1+\frac{r}{R_m}\right)^{(s-4.5)}$$

It Actually Behaves as

$$\rho(r) \propto \left(\frac{1}{r}\right)^{n}$$

r < 10 m n ~ 1

r < 50 m n ~ 2

r < 200 m n ~3

Observed Densities at Each Detector is Fitted to Extract Parameters 'N_e', 's' etc.,

Ne = Total no of Charged Particles

s = Age of the Shower

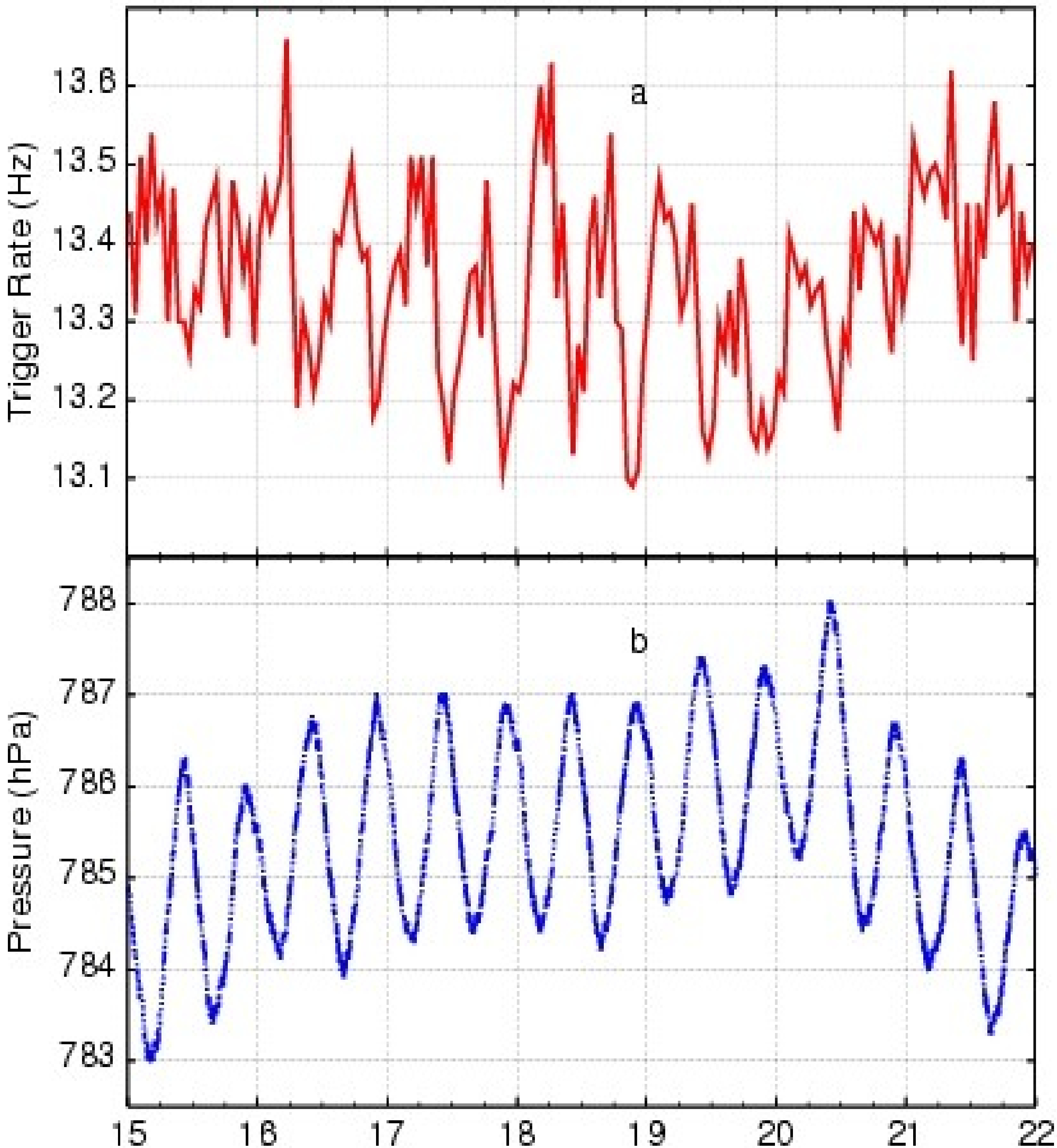
Complications due to Large Fluctuations from Shower to Shower even for Identical Primaries

We have a major Data Processing Program to Analyze Individual Showers using Data

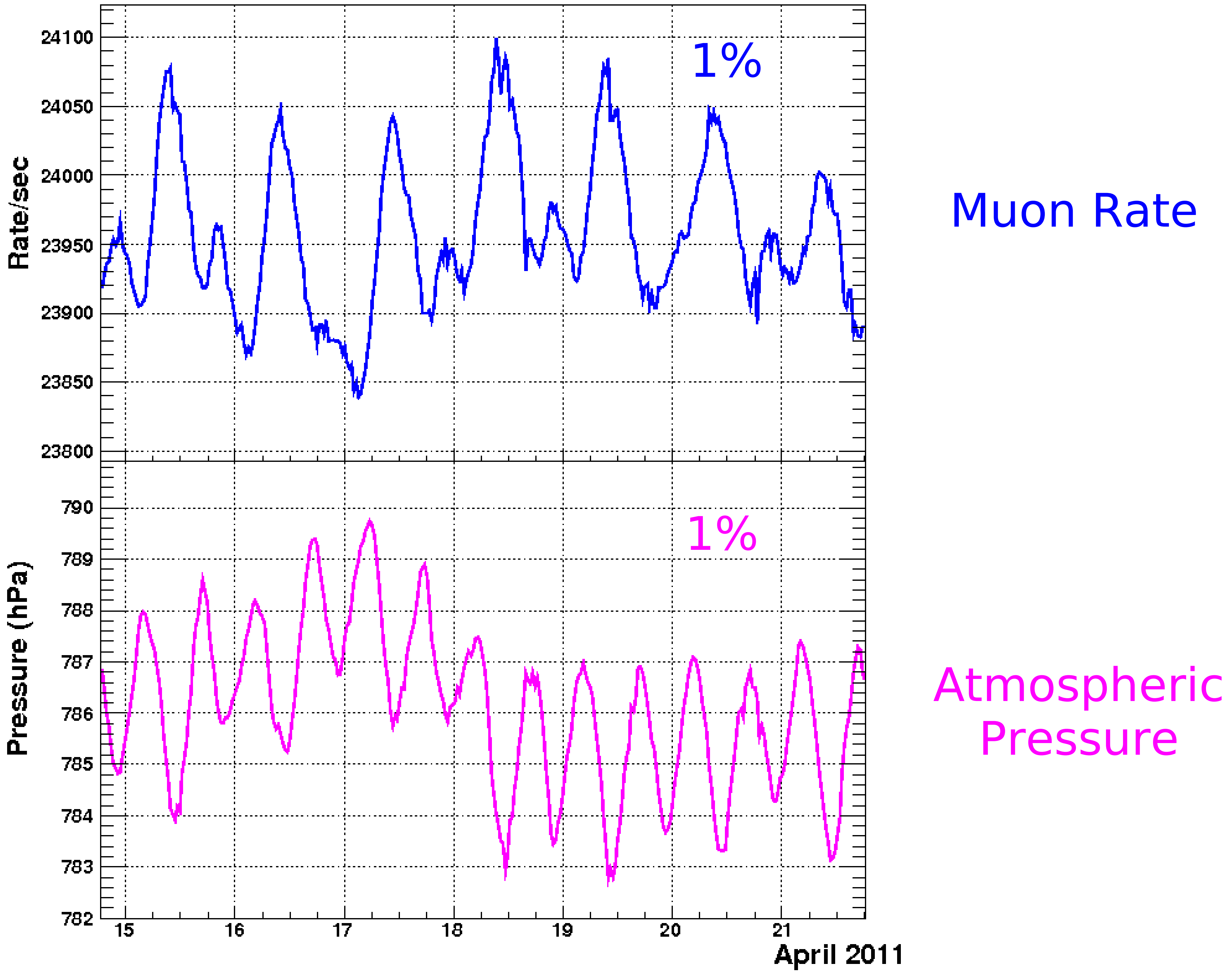
Finally Ne, s, θ, φ, (x, y), t From ~ >400 Scintillators

3×10^6 /day 10^9/yr ~ 3712 Proportional Counters

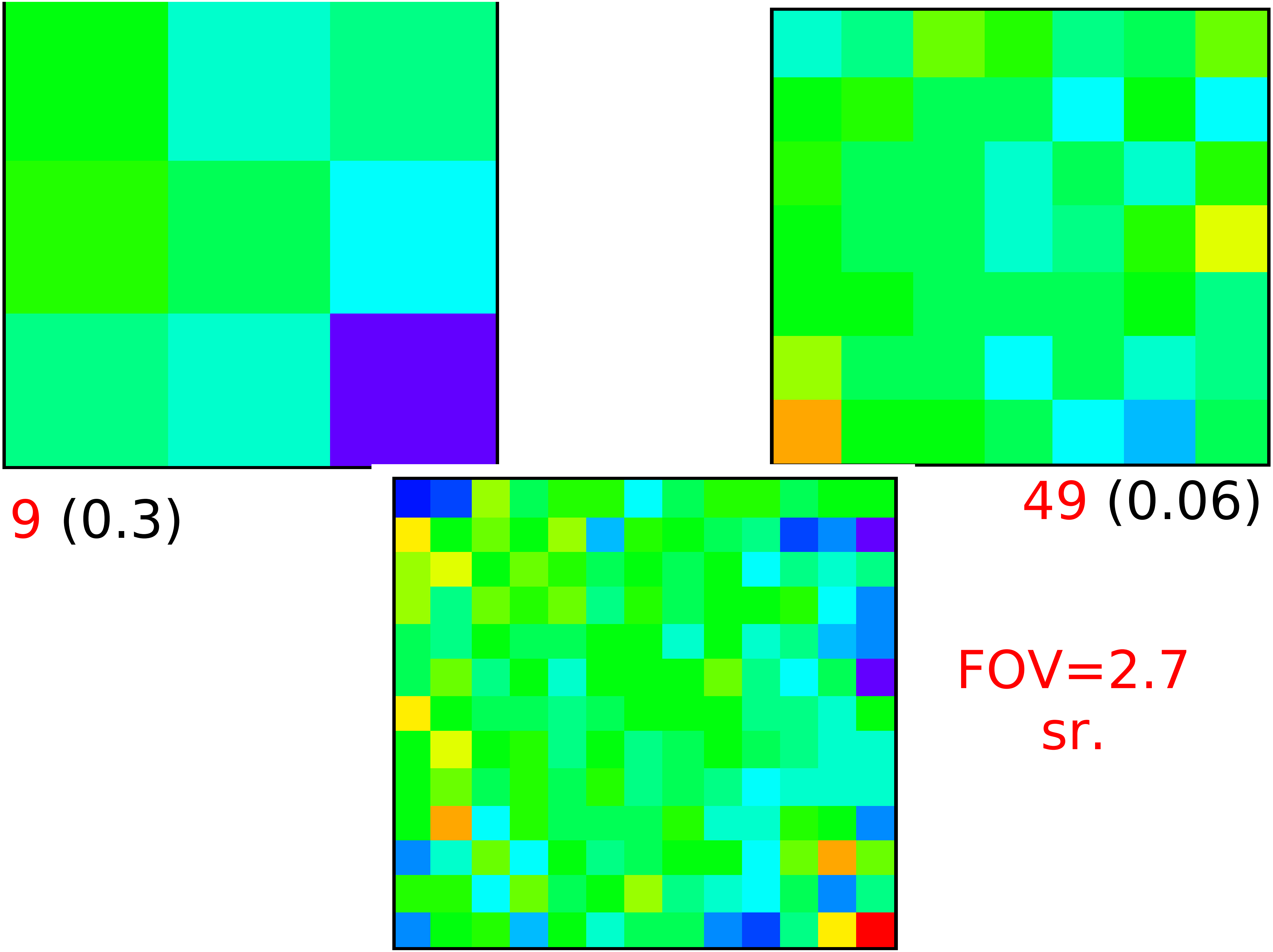
GRAPES-3 Results

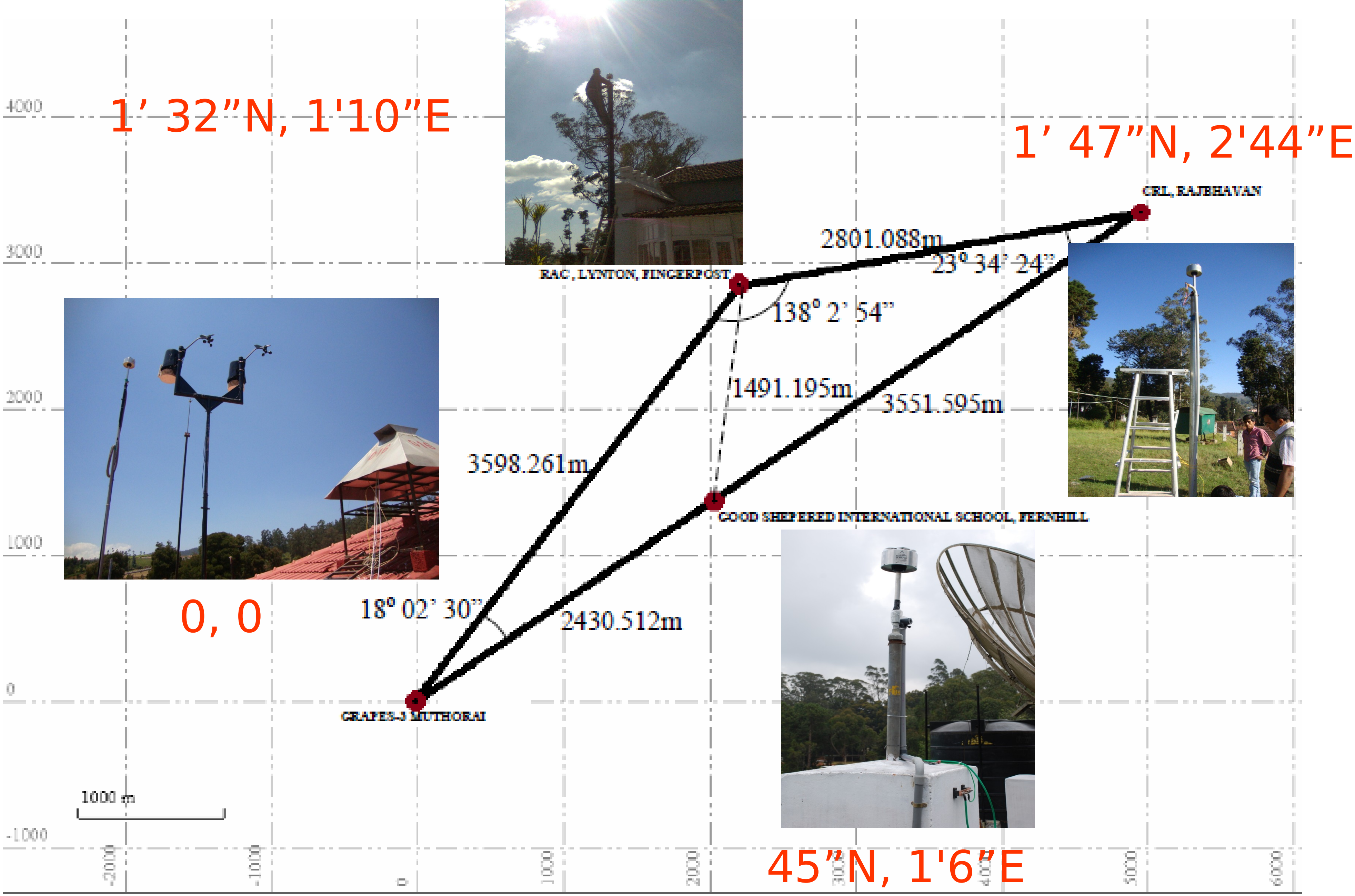


Trigger Rate (Hz)
13.6
13.5
13.4
13.3
13.2
13.1
a
Pressure (hPa)
788
787
786
785
784
783
b
15
16
17
18
19
20
21
22



Rate/sec
24100
24050
24000
23950
23900
23850
23800
1%
Muon Rate
Pressure (hPa)
790
789
788
787
786
785
784
783
782
1%
Atmospheric Pressure
15
16
17
18
19
20
21
April 2011


9 (0.3)
49 (0.06)
FOV=2.7
sr.


1’ 32”N, 1'10”E
1’ 47”N, 2'44”E
CRL, RAJBHAVAN
RAC, LYNTON, FINGERPOST
2801.088m
23° 34’ 24”
138° 2’ 54”
1491.195m
3551.595m
3598.261m
GOOD SHEPERED INTERNATIONAL SCHOOL, FERNHILL
0, 0
18° 02’ 30”
2430.512m
GRAPES-3 MUTHORAI
1000 m
45”N, 1'6”E
4000
3000
2000
1000
0
-1000
-2000
-1000
0
1000
2000
5000
6000


CRL, RAJBHAVAN
RAC, LYNTON, FINGERPOST
Anna Nagar
Ooty
उदगमंदलम
GOOD SHEPERD SCHOOL, FERNHILL
Elk Hill
Fern Hill
GRAPES-3, MUTHORAI
Image © 2011 DigitalGlobe
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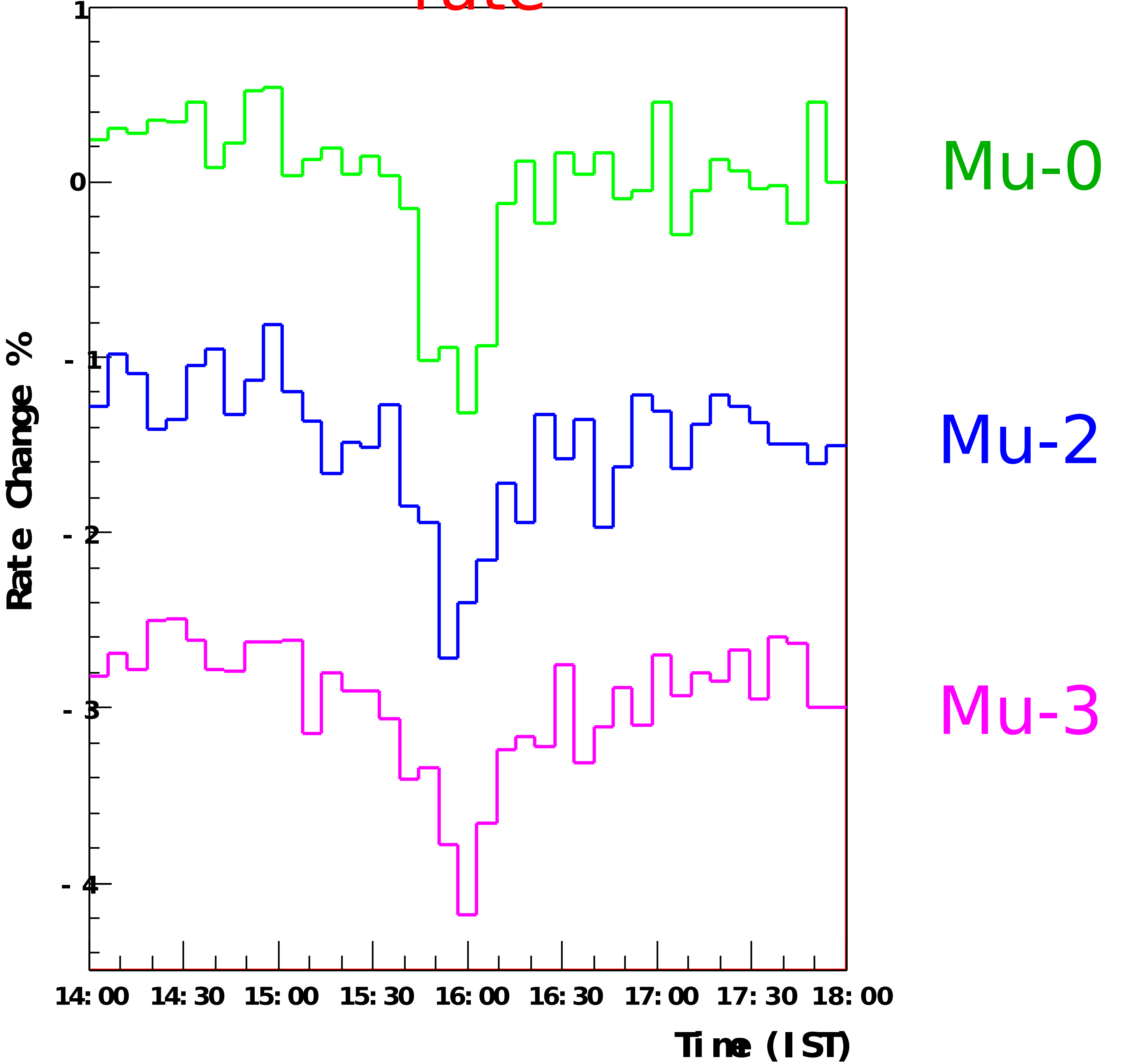
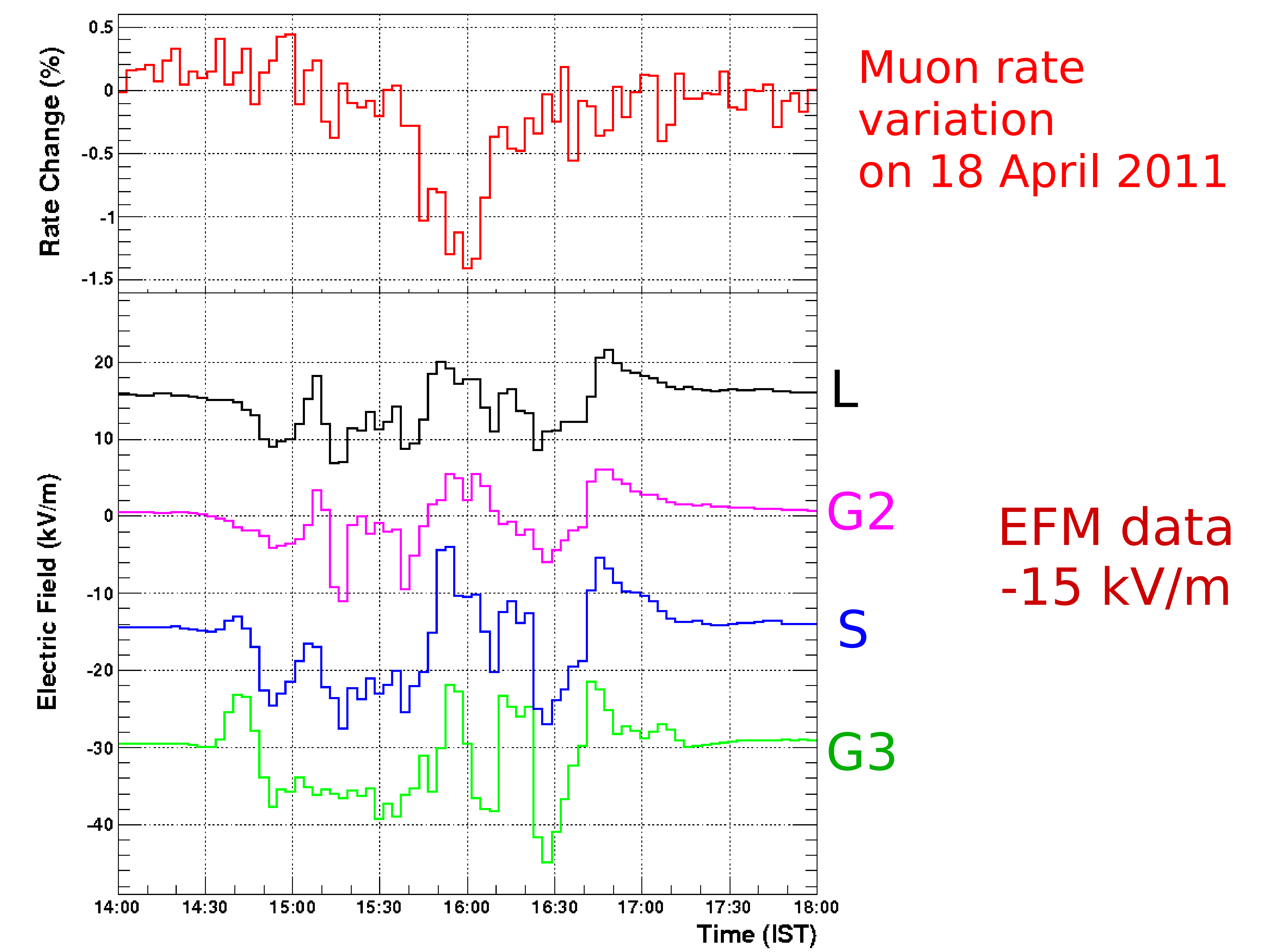
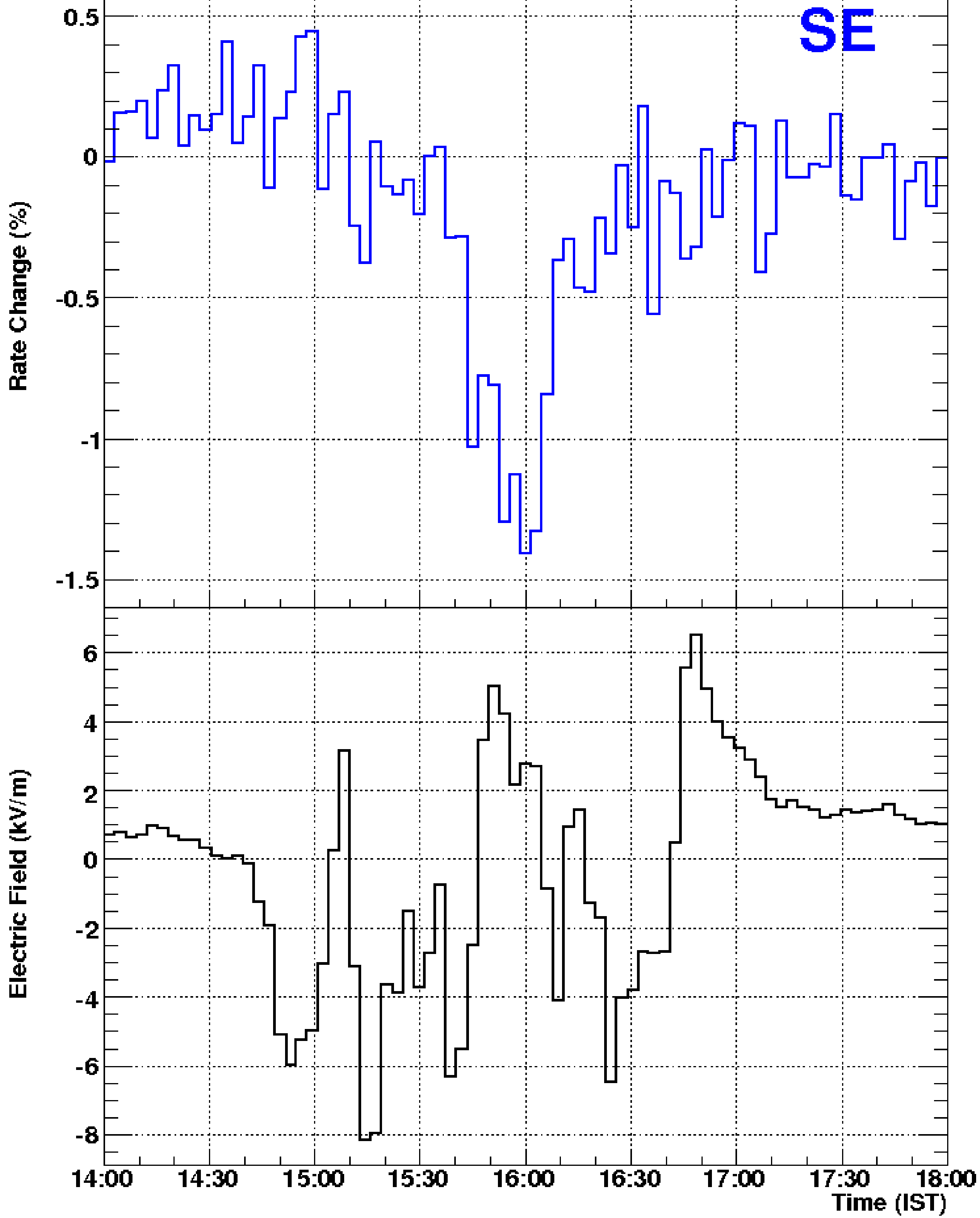
©2010 Google
Imagery Date: 1/31/2006
2006
11°24'53.26" N 76°40'19.74" E elev 2246 m
Eye alt 8.55 km

% change in Muon rate

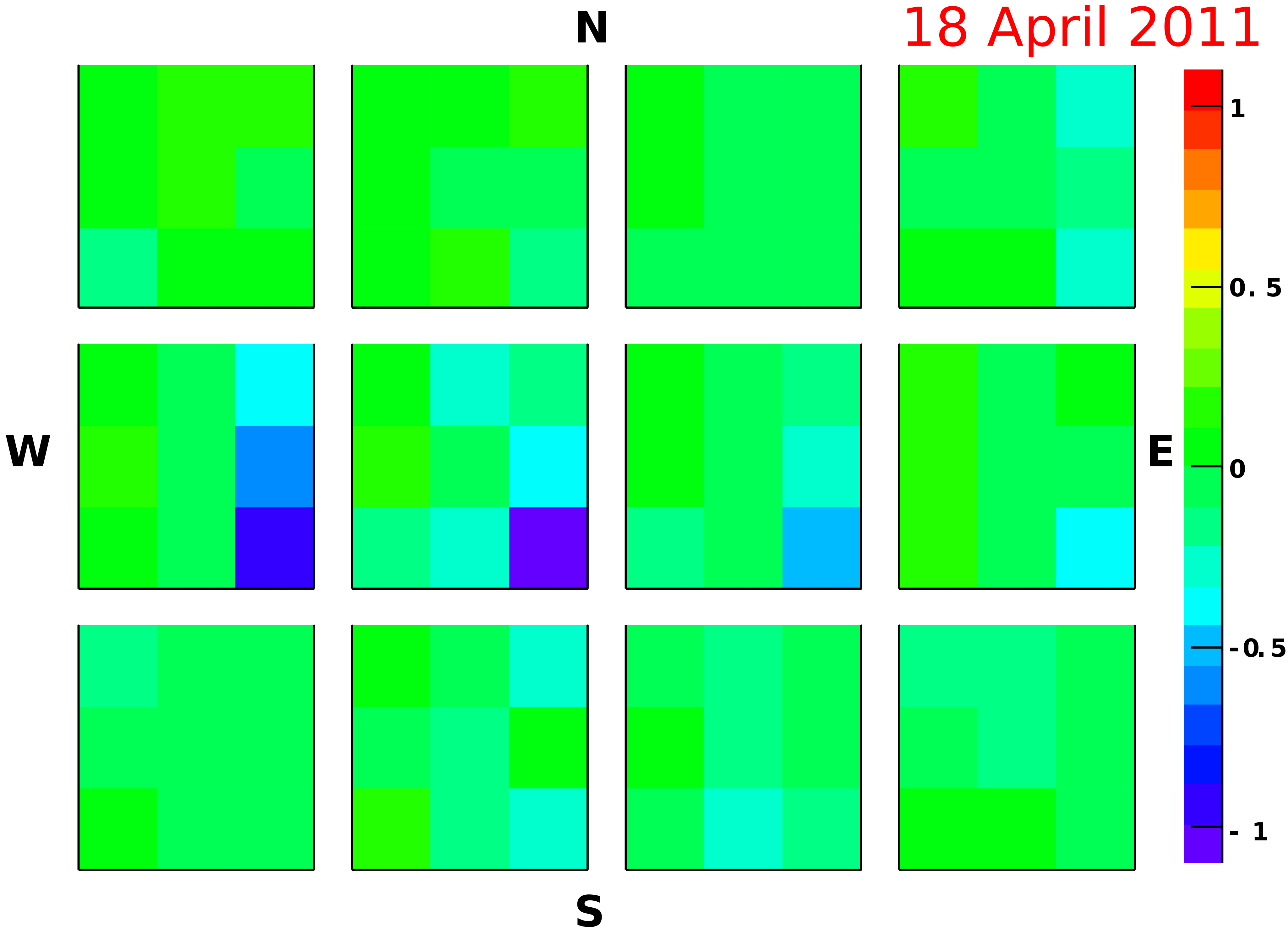


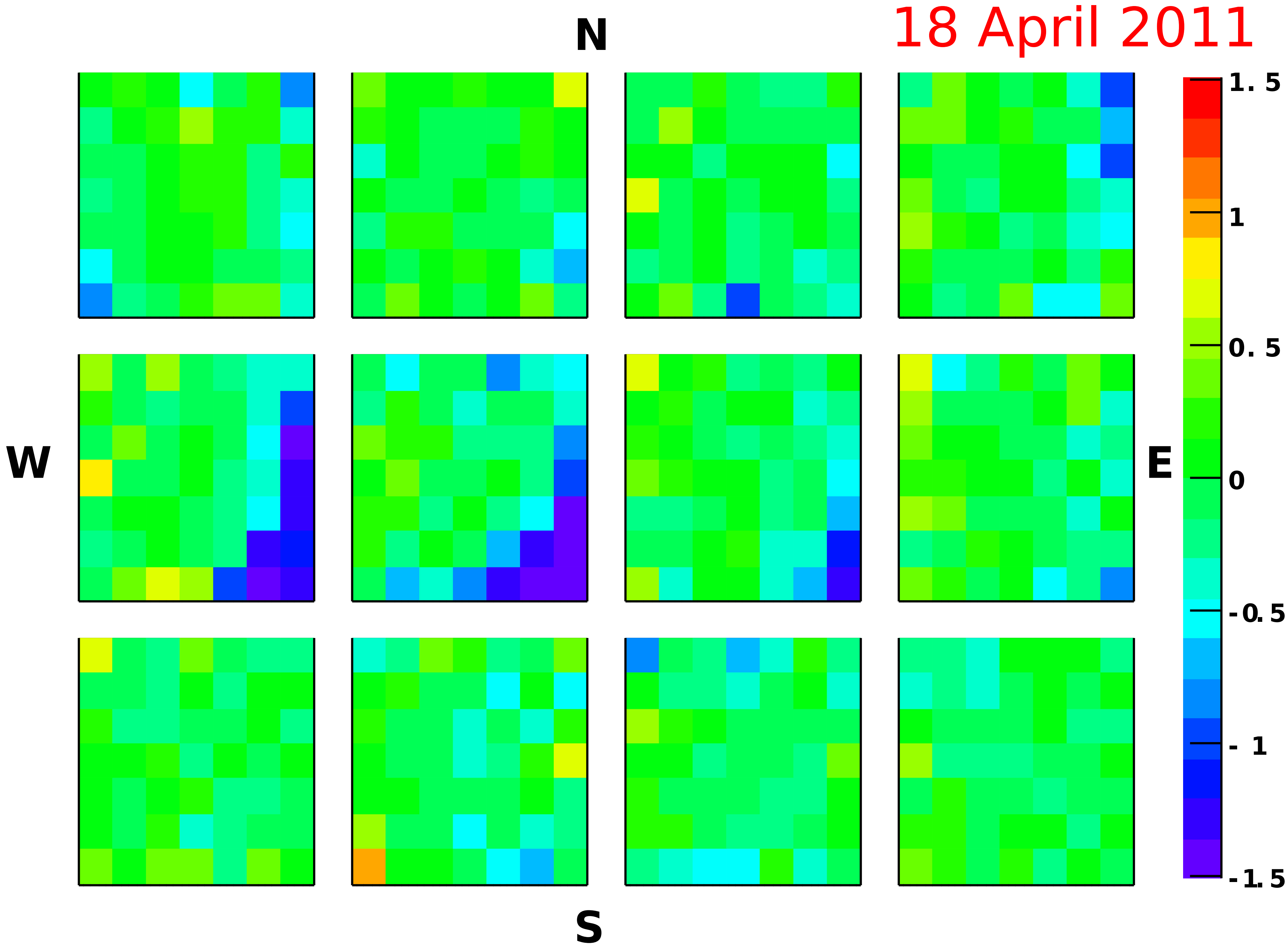
Mu-1 out of action

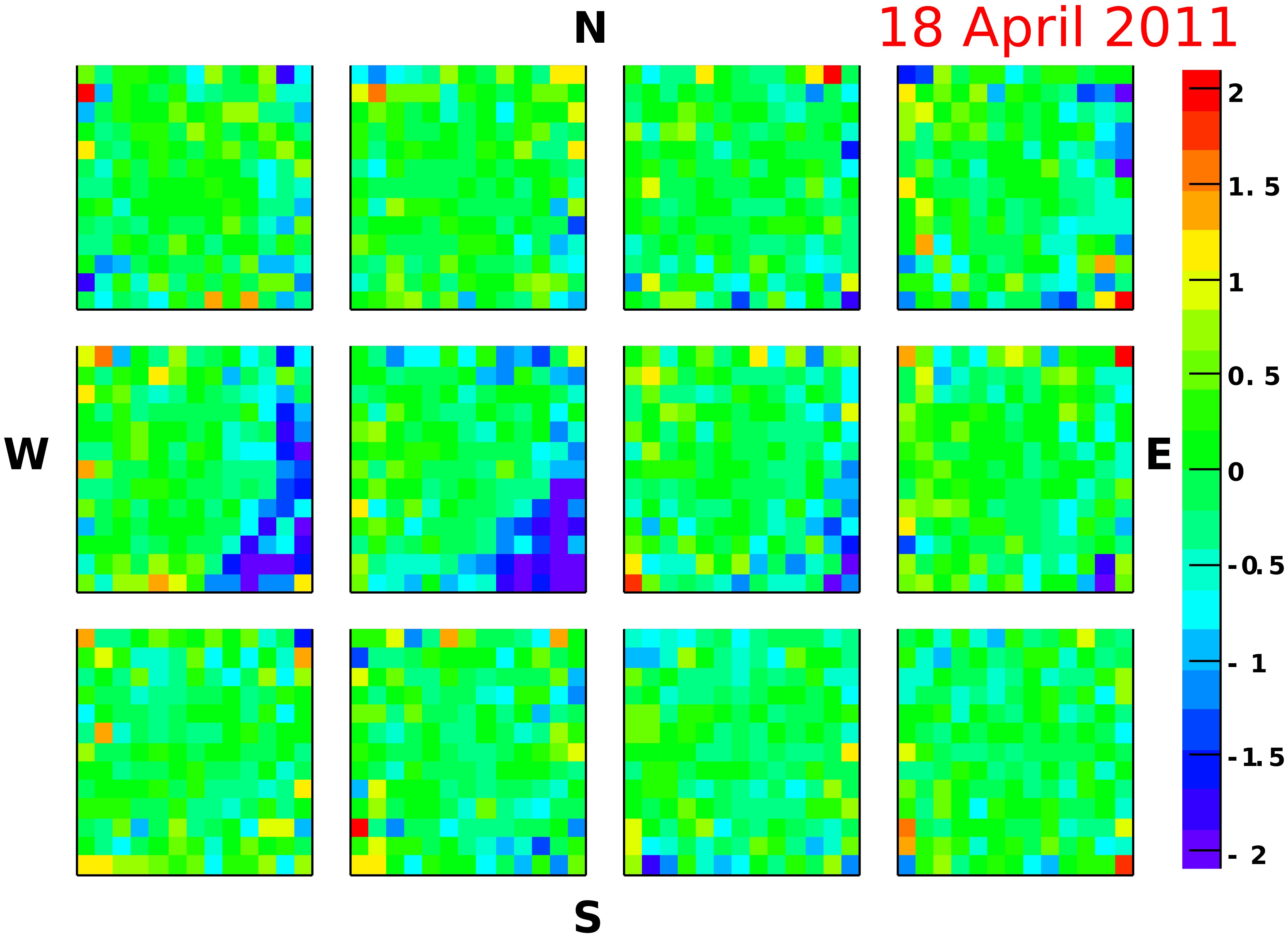

Muon rate
variation
on 18 April 2011
Rate Change (%)
0.5
0
-0.5
-1
-1.5
Electric Field (kV/m)
20
10
0
-10
-20
-30
-40
L
G2
S
G3
EFM data
-15 kV/m
14:00
14:30
15:00
15:30
16:00
16:30
17:00
17:30
18:00
Time (IST)



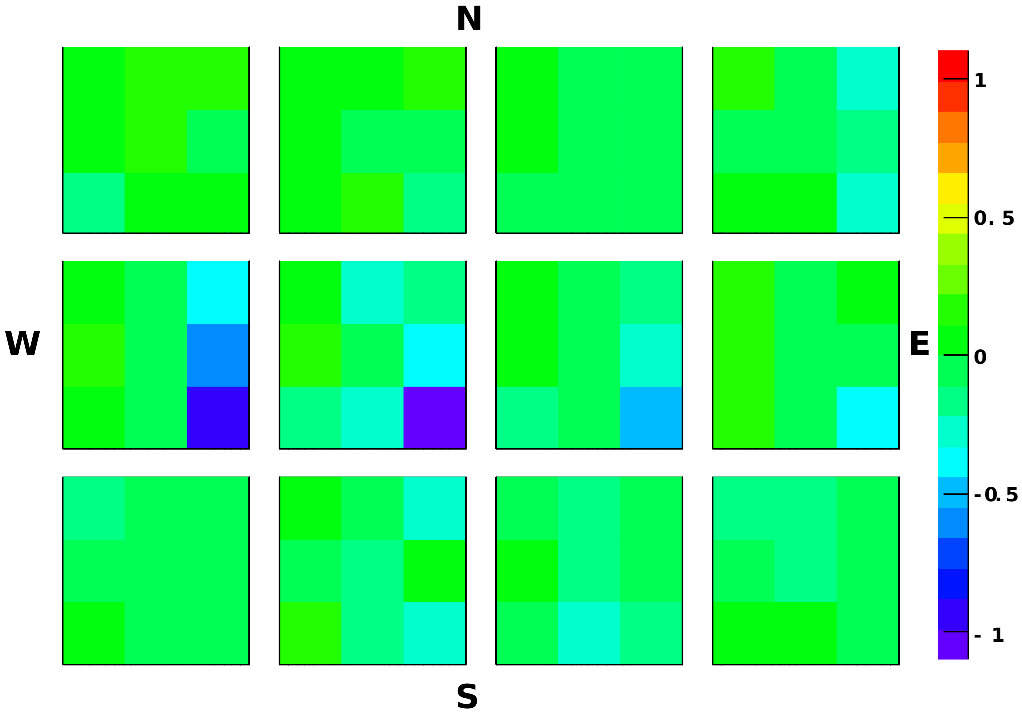
18 April
2011

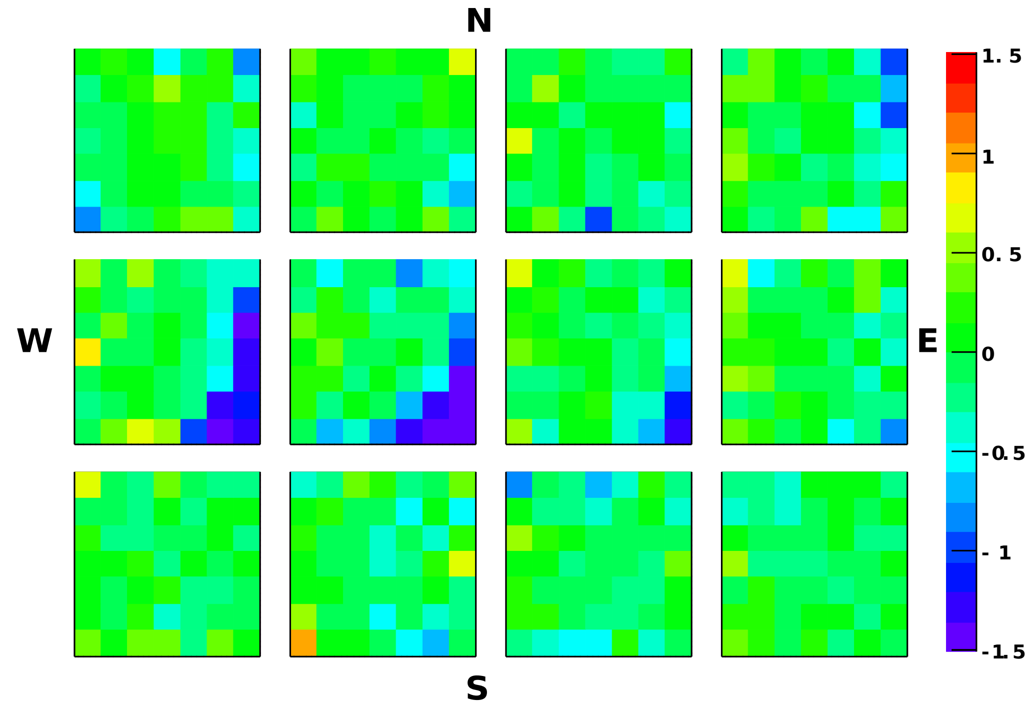

18 April 2011
N
W
E
S
1
0. 5
0
- 0. 5
- 1

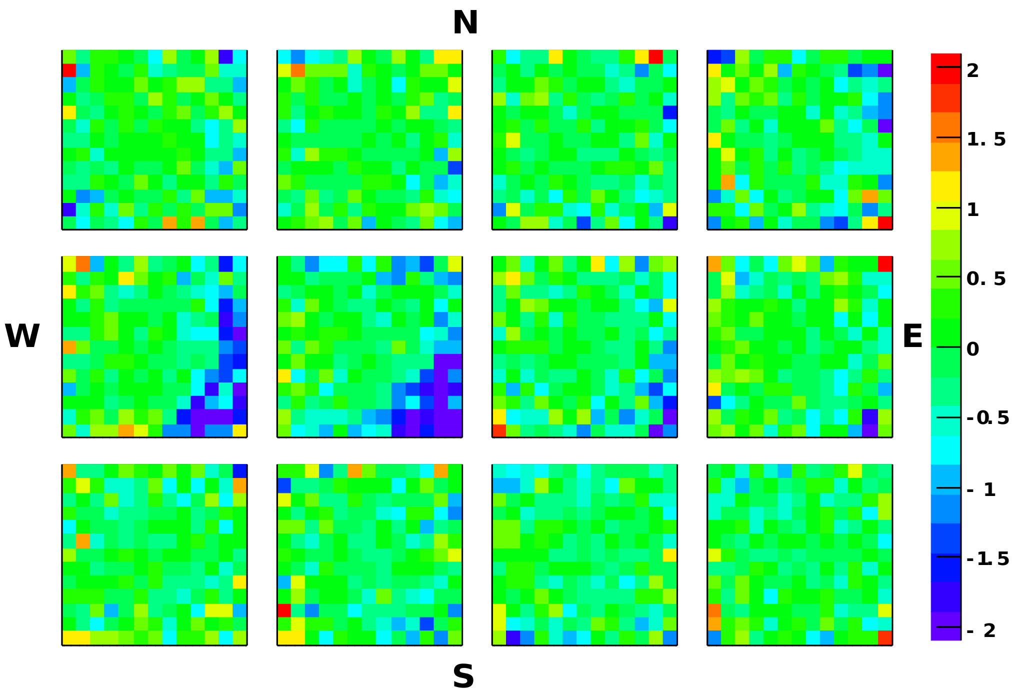

18 April 2011
N
W
E
S
1. 5
1
0. 5
0
-0.5
- 1
-1.5



18 April 2011
N
W
E
S
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2

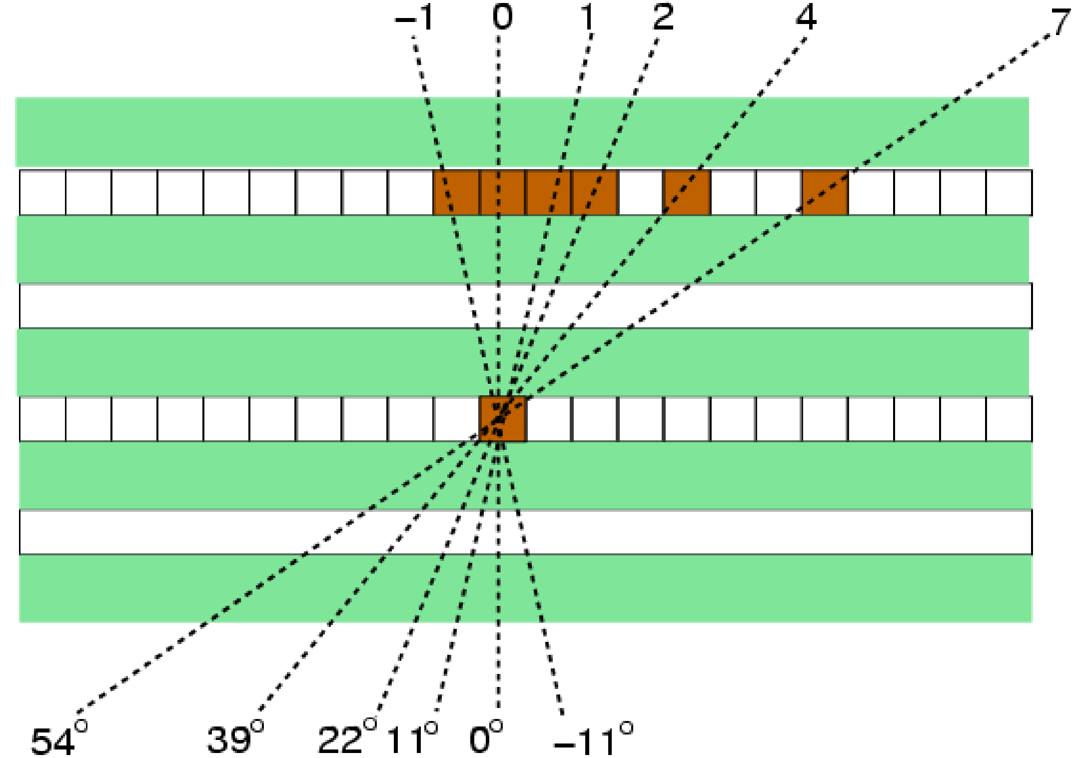


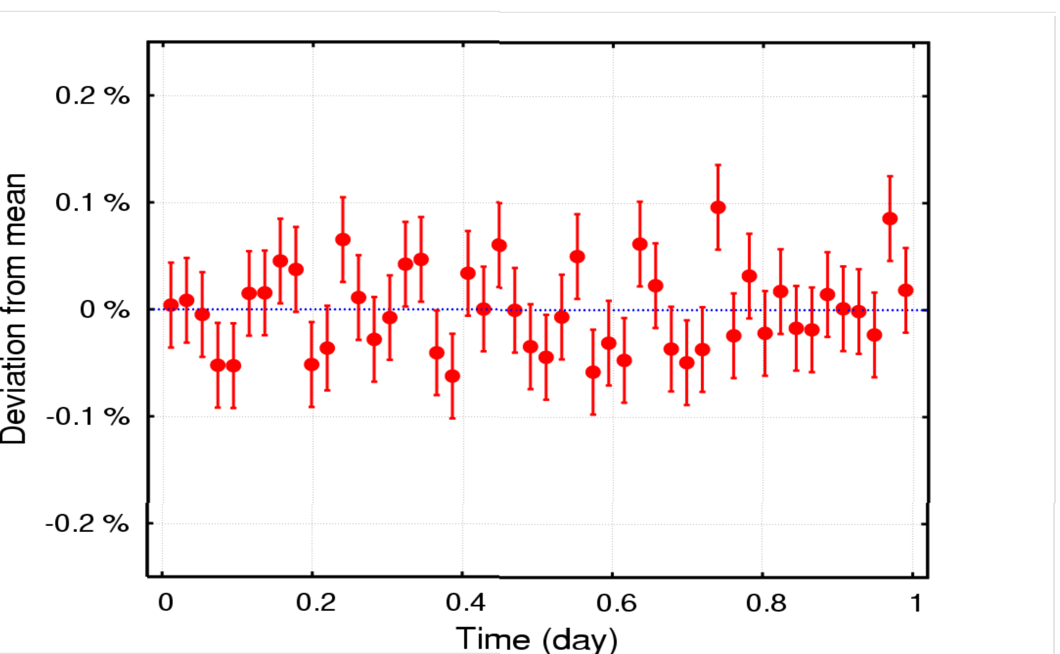


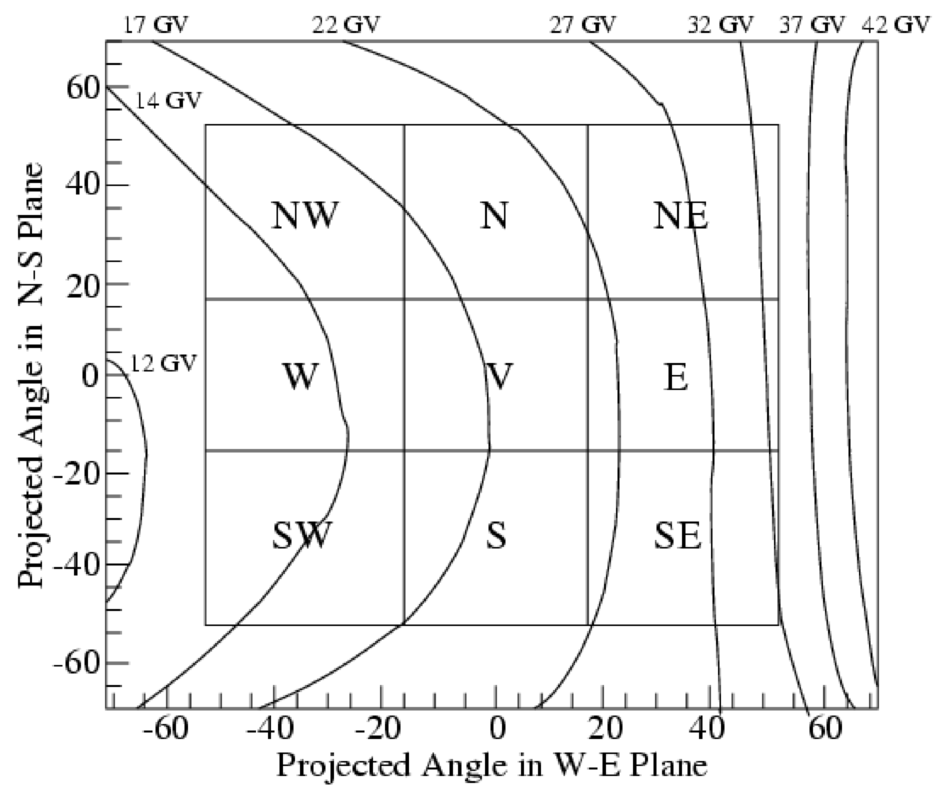


Thunderstorm
18 April 2011

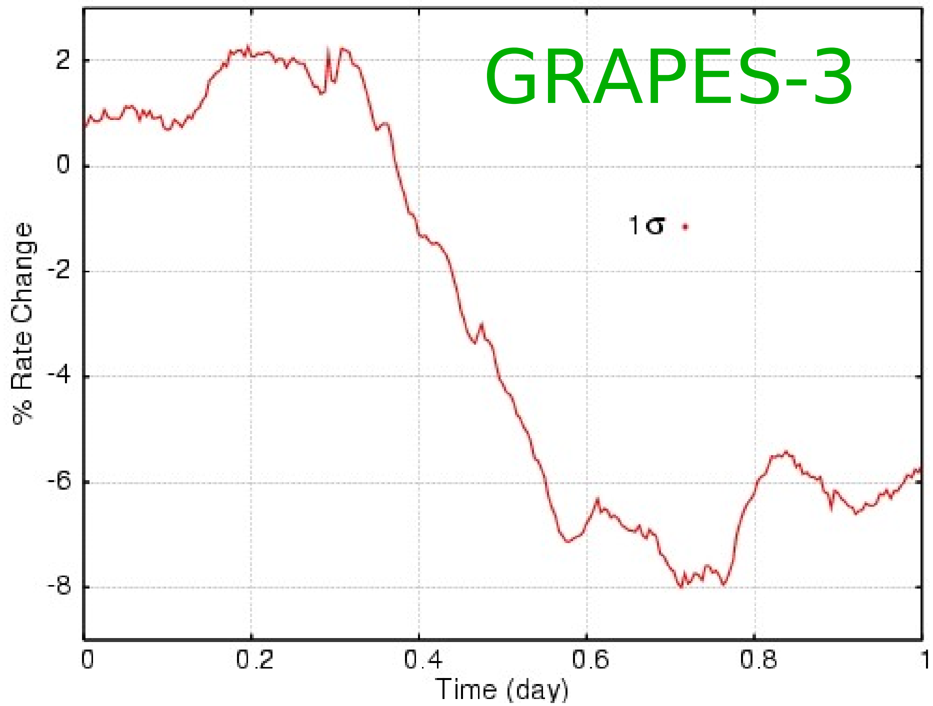

Solar
phenomena

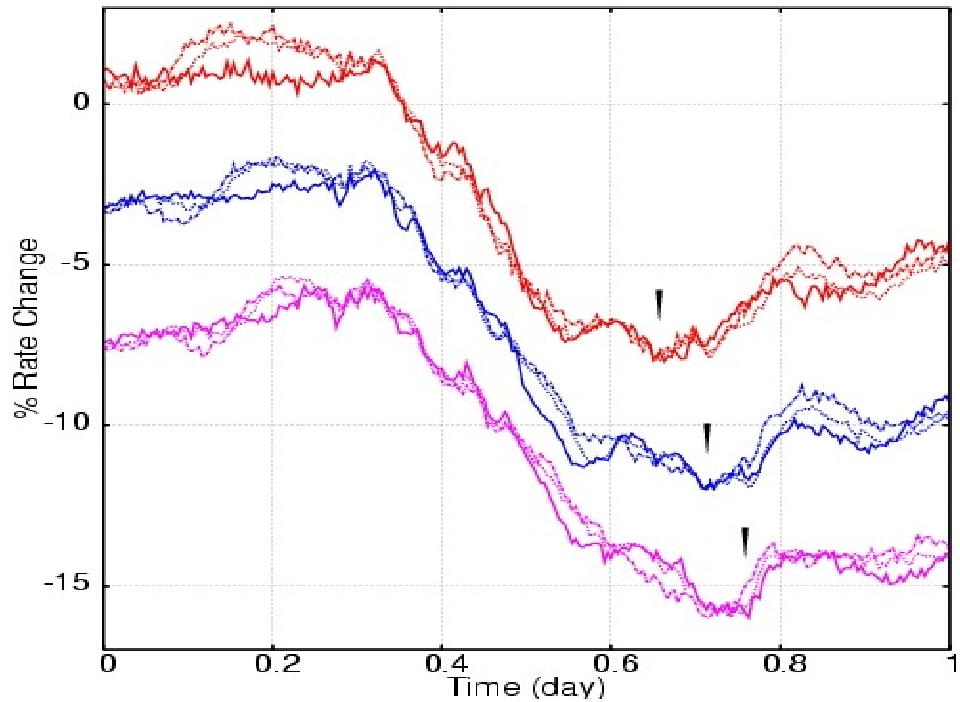

−1
0
1
2
4
7
54°
39°
22°
11°
0°
−11°

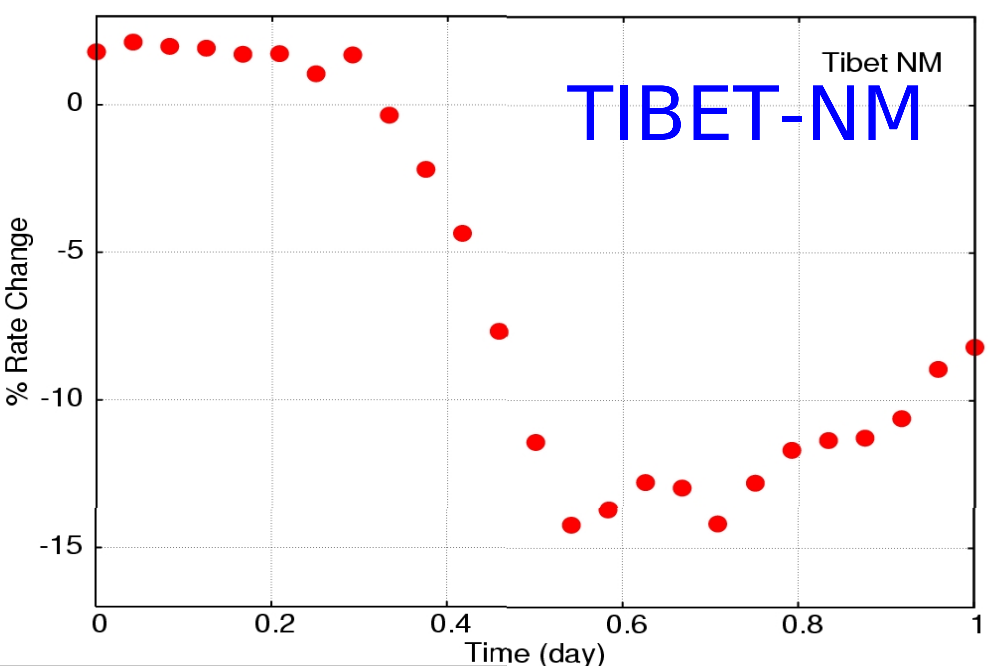

Deviation from mean
0.2 %
0.1 %
0 %
-0.1 %
-0.2 %
0
0.2
0.4
0.6
0.8
1
Time (day)

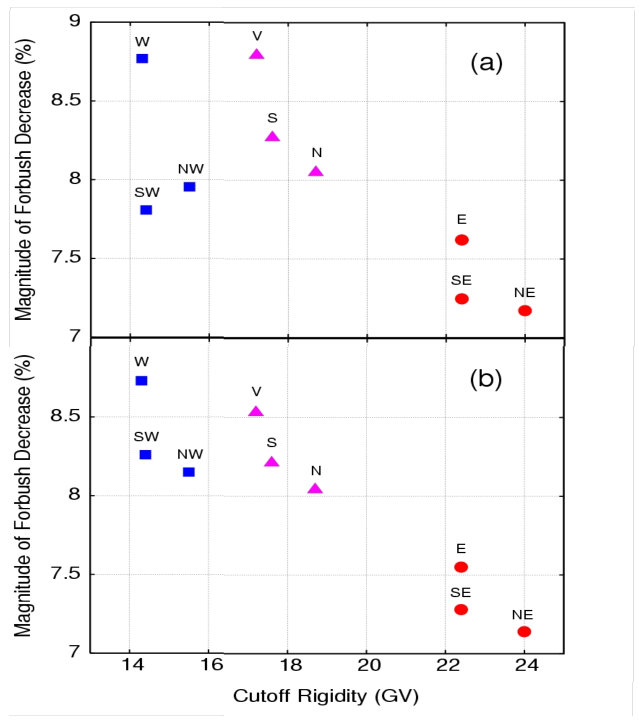

17 GV
22 GV
27 GV
32 GV
37 GV
42 GV
14 GV
12 GV
NW
N
NE
W
V
E
SW
S
SE
Projected Angle in N-S Plane
Projected Angle in W-E Plane
60
40
20
0
-20
-40
-60
-60
-40
-20
0
20
40
60

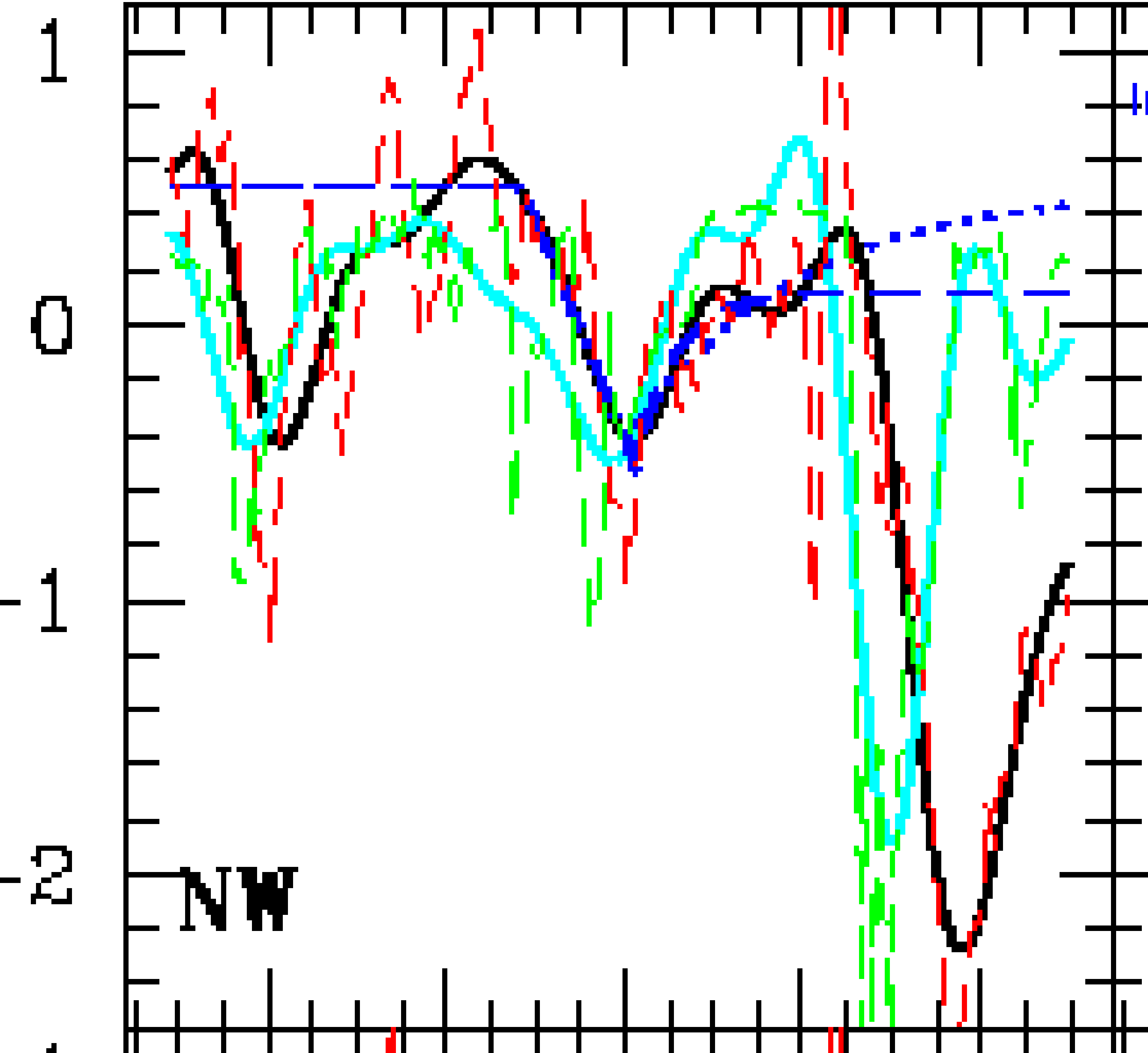
Coronal Mass Ejection (28 October 2003)





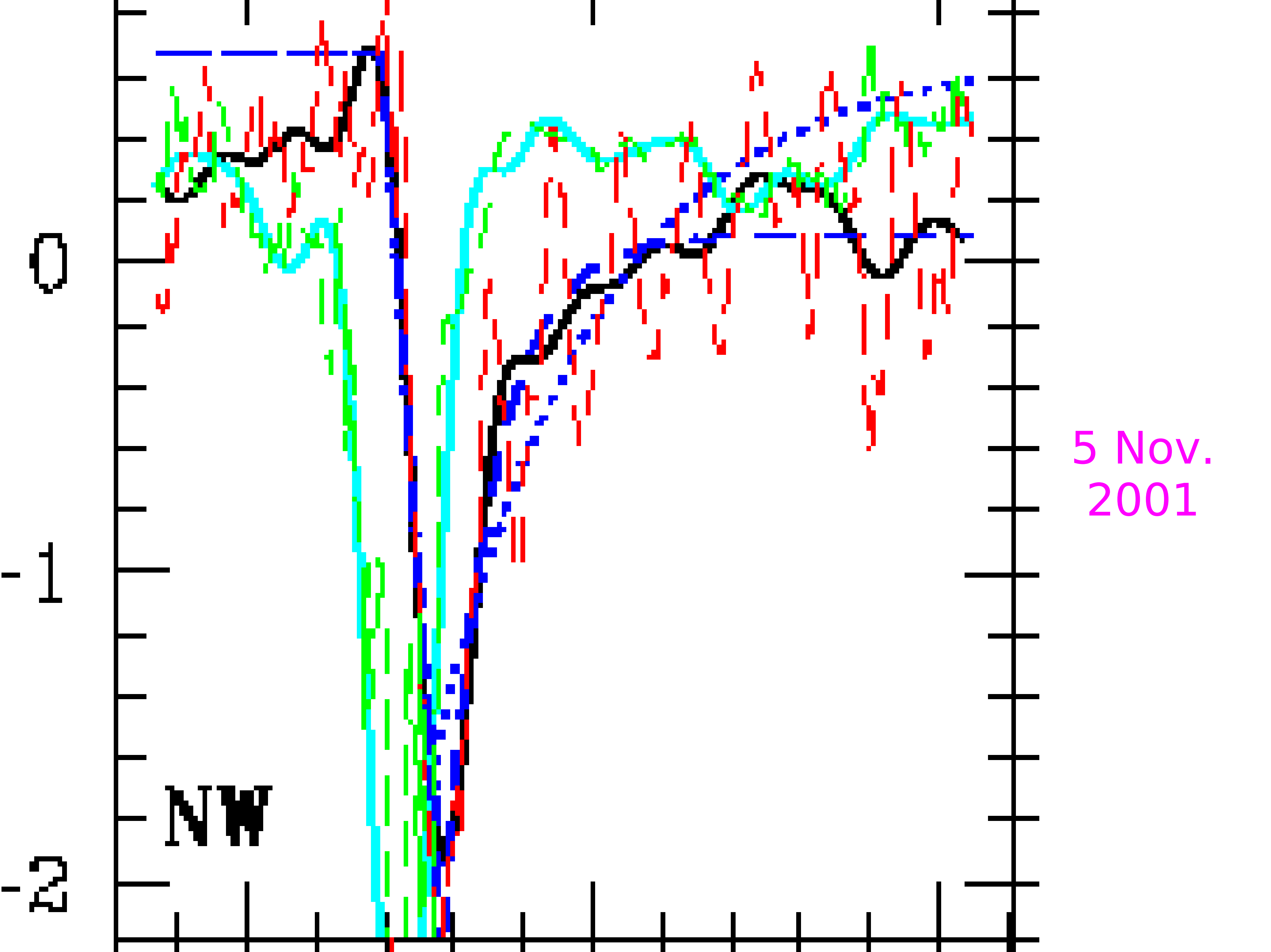




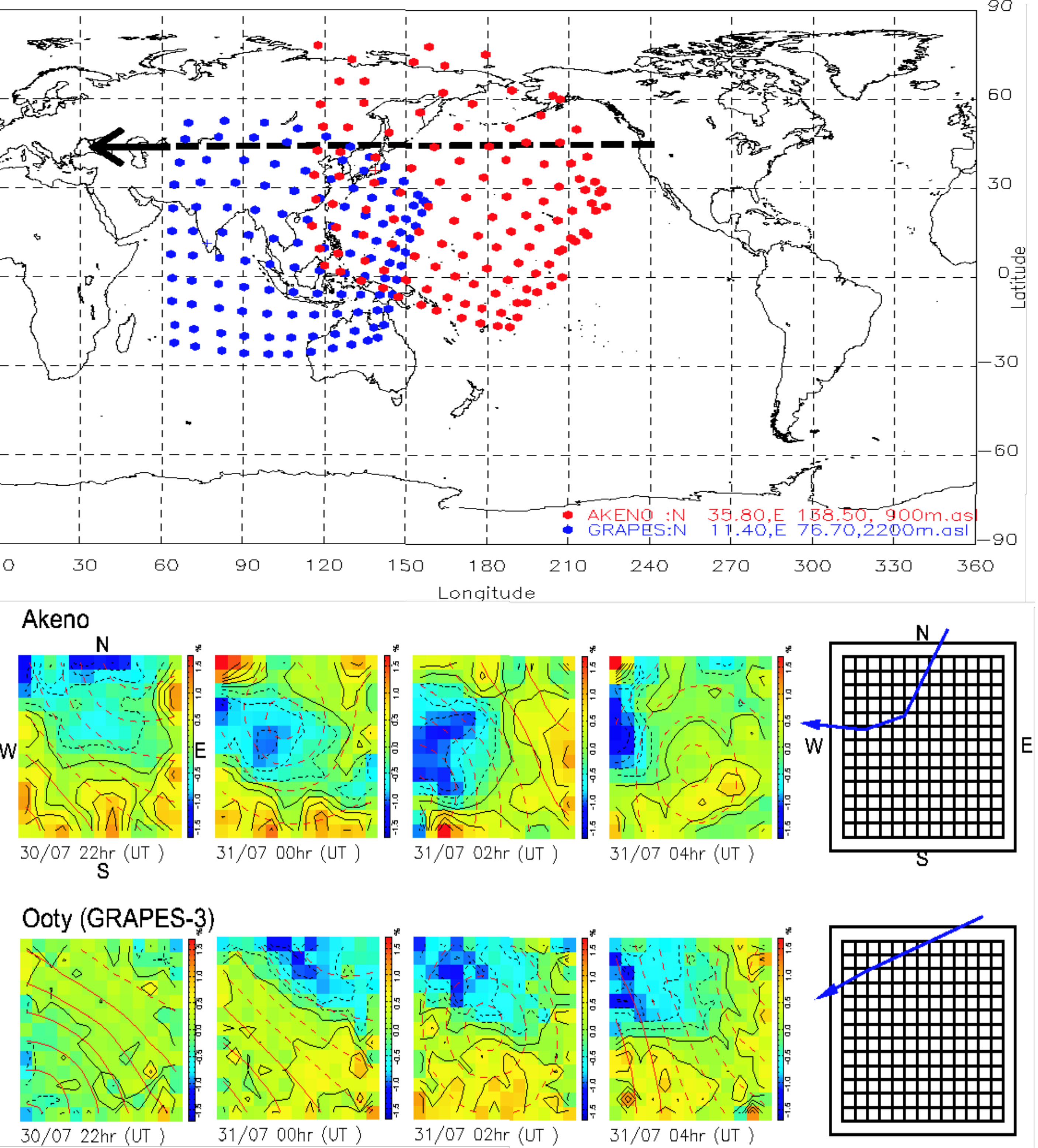


Study of Interplanetary Space from the Earth

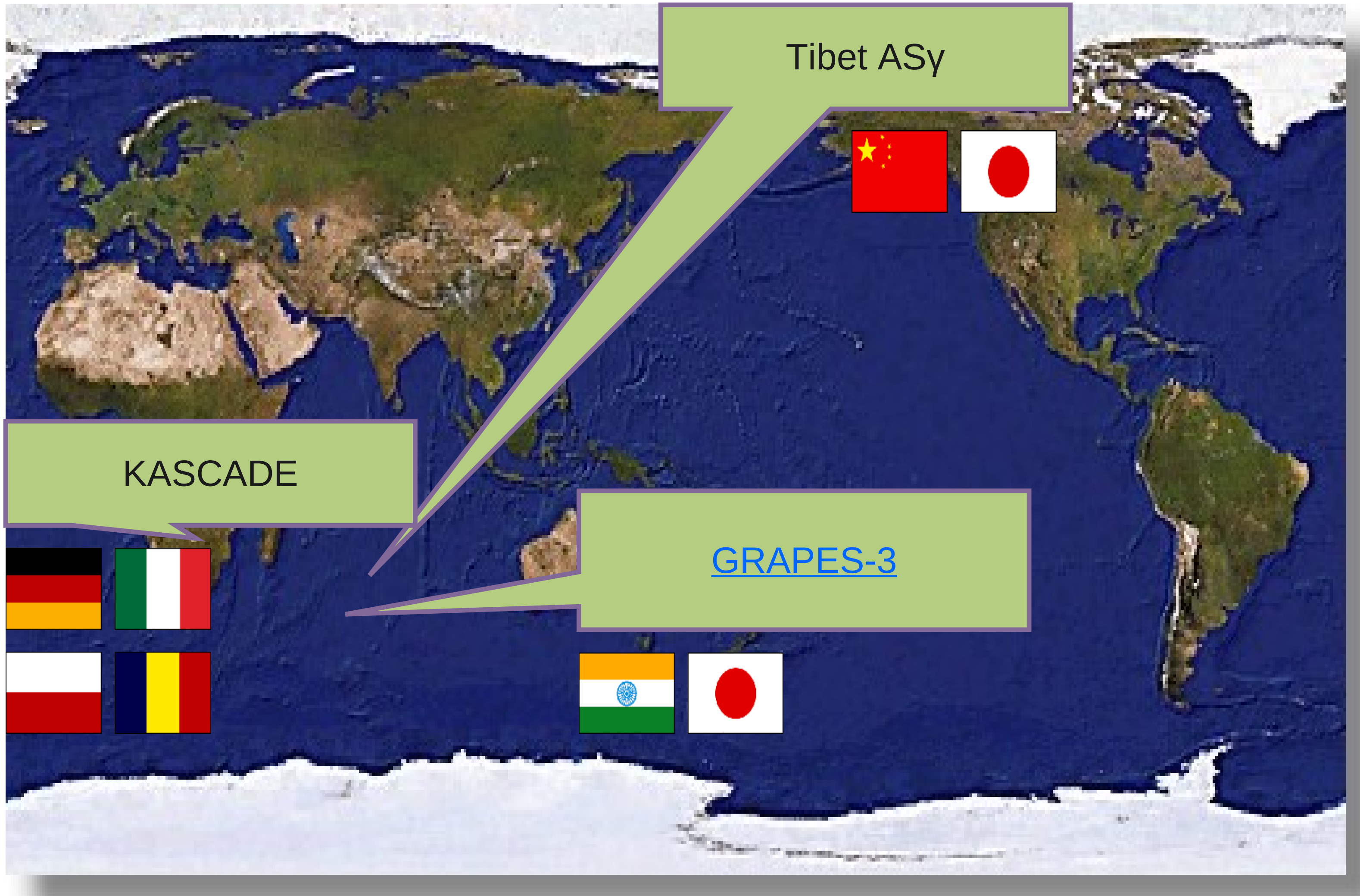
7 April 2001



0
-1
-2
NW
5 Nov.
2001

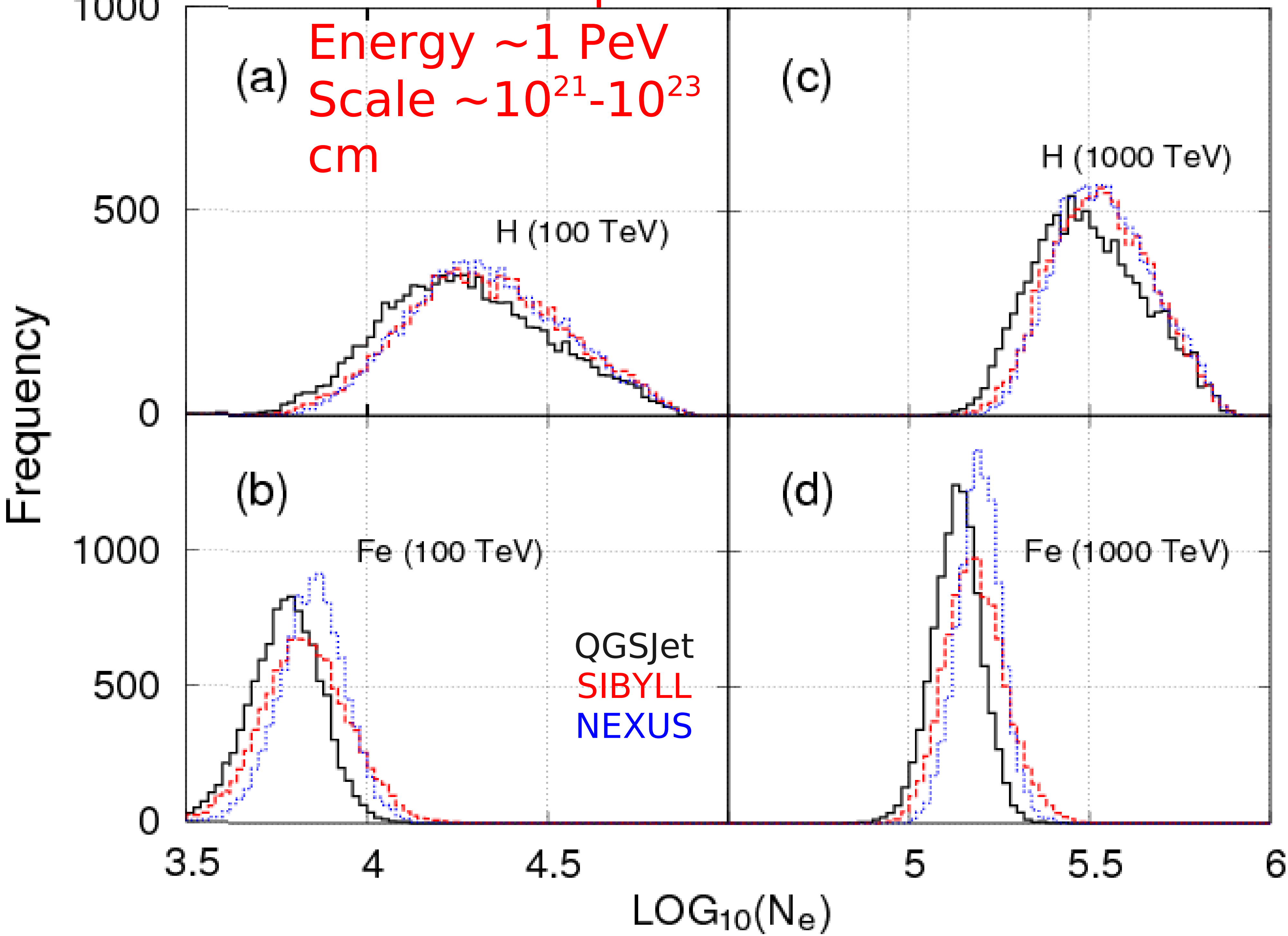

AKENO :N 35.80,E 138.50, 900m.asl
GRAPES:N 11.40,E 76.70,2200m.asl
Longitude
Latitude
Akeno
N
W
E
S
30/07 22hr (UT)
31/07 00hr (UT)
31/07 02hr (UT)
31/07 04hr (UT)
Ooty (GRAPES-3)
30/07 22hr (UT)
31/07 00hr (UT)
31/07 02hr (UT)
31/07 04hr (UT)

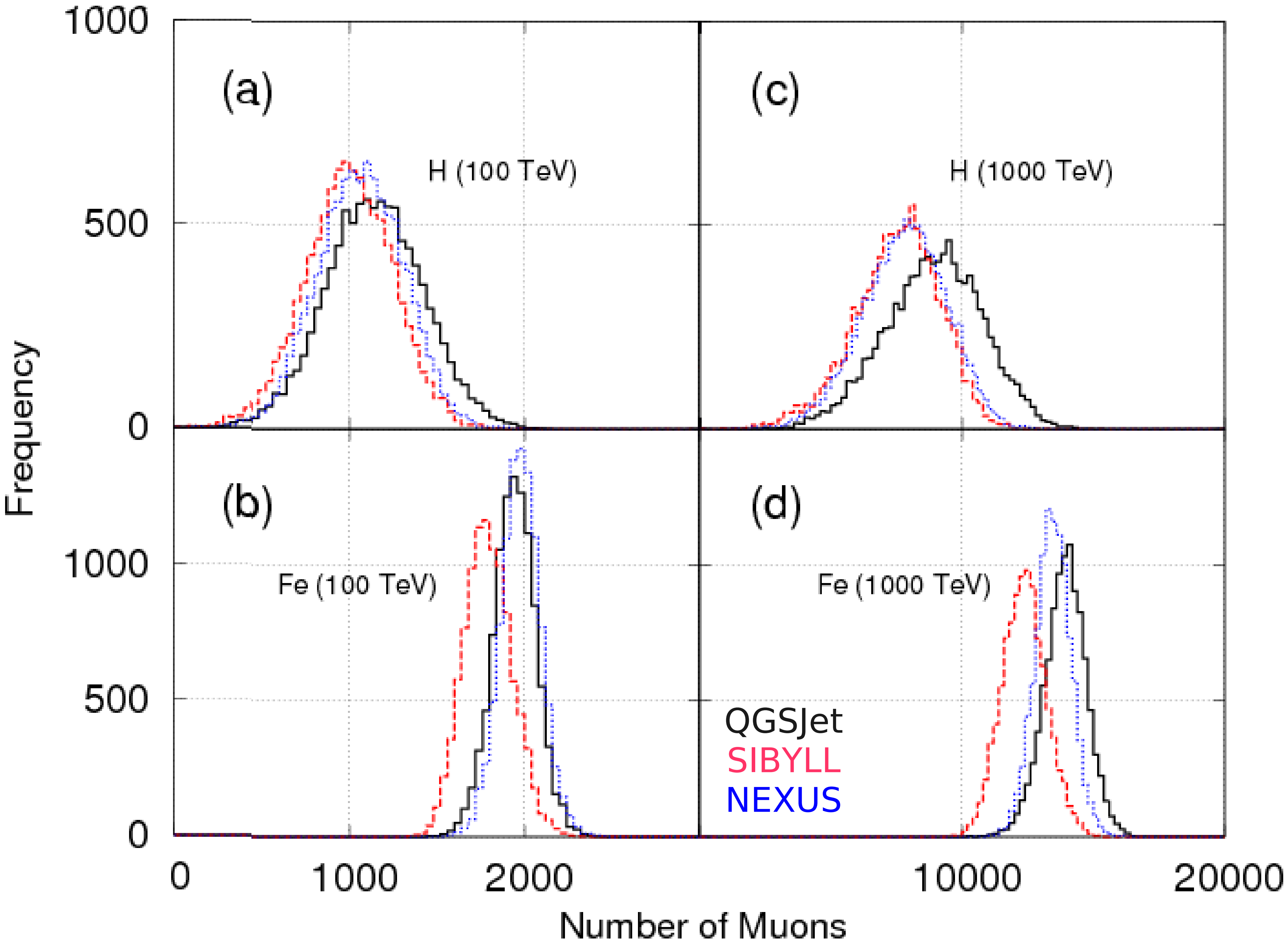
Air Shower Experiments



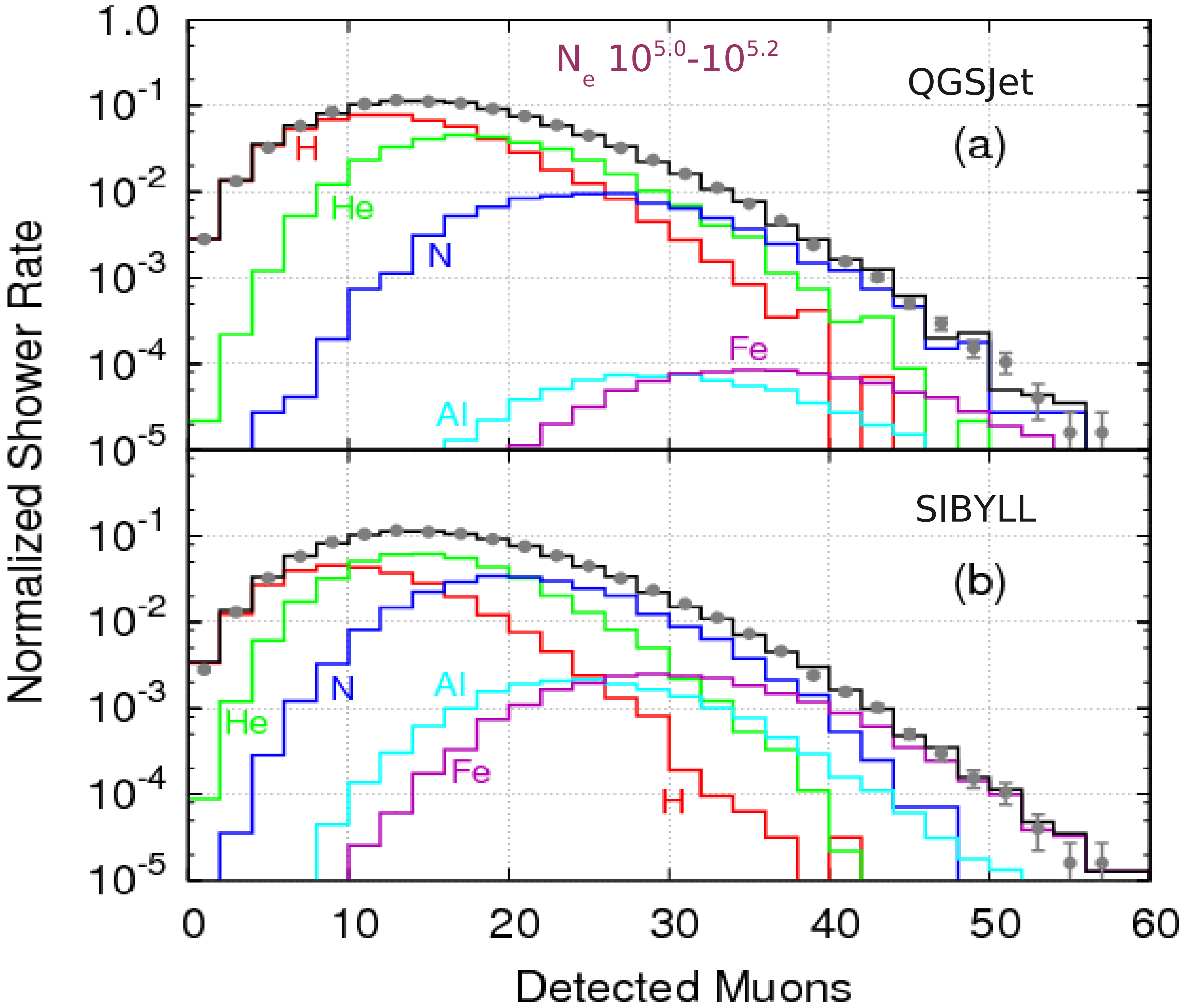
GRAPES-3 has a dense array and large muon detector at high altitude.

Composition Studies



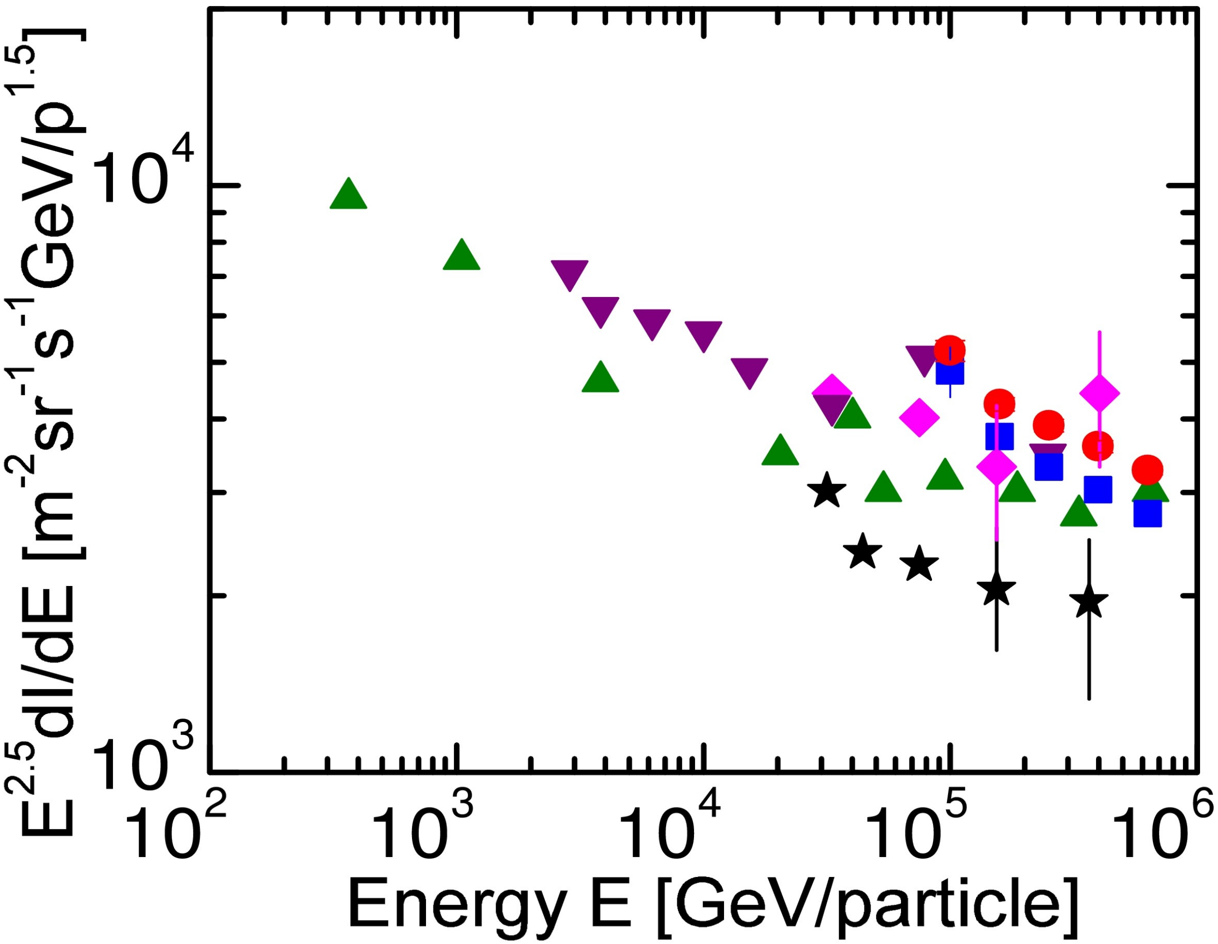


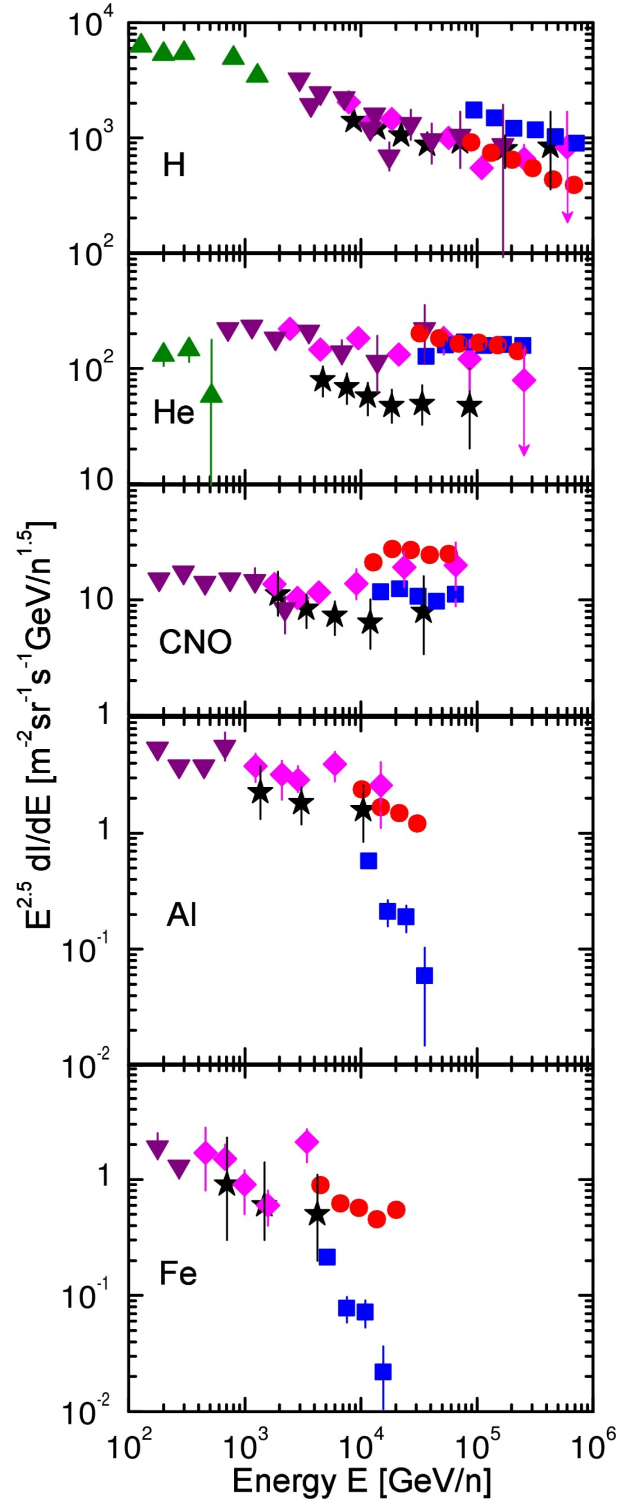
Frequency
Number of Muons
(a)
H (100 TeV)
(b)
Fe (100 TeV)
(c)
H (1000 TeV)
(d)
Fe (1000 TeV)
QGSJet
SIBYLL
NEXUS
0
500
1000
0
1000
2000
10000
20000

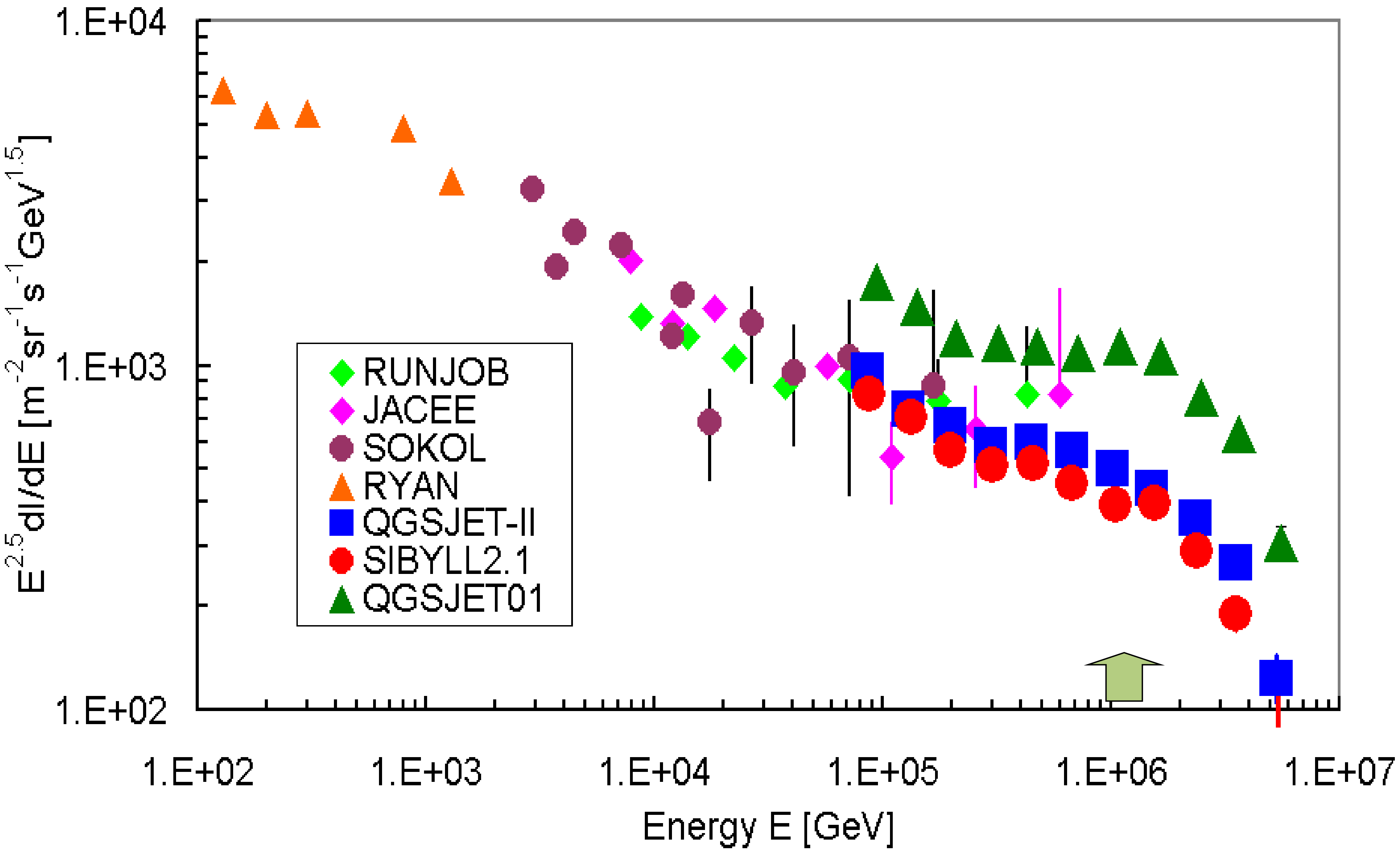


N_e $10^{5.0}$-$10^{5.2}$
QGSJet
(a)
H
He
N
Fe
Al
SIBYLL
(b)
N
Al
He
Fe
H
Normalized Shower Rate
Detected Muons
1.0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
10
20
30
40
50
60

All particle energy spectrum

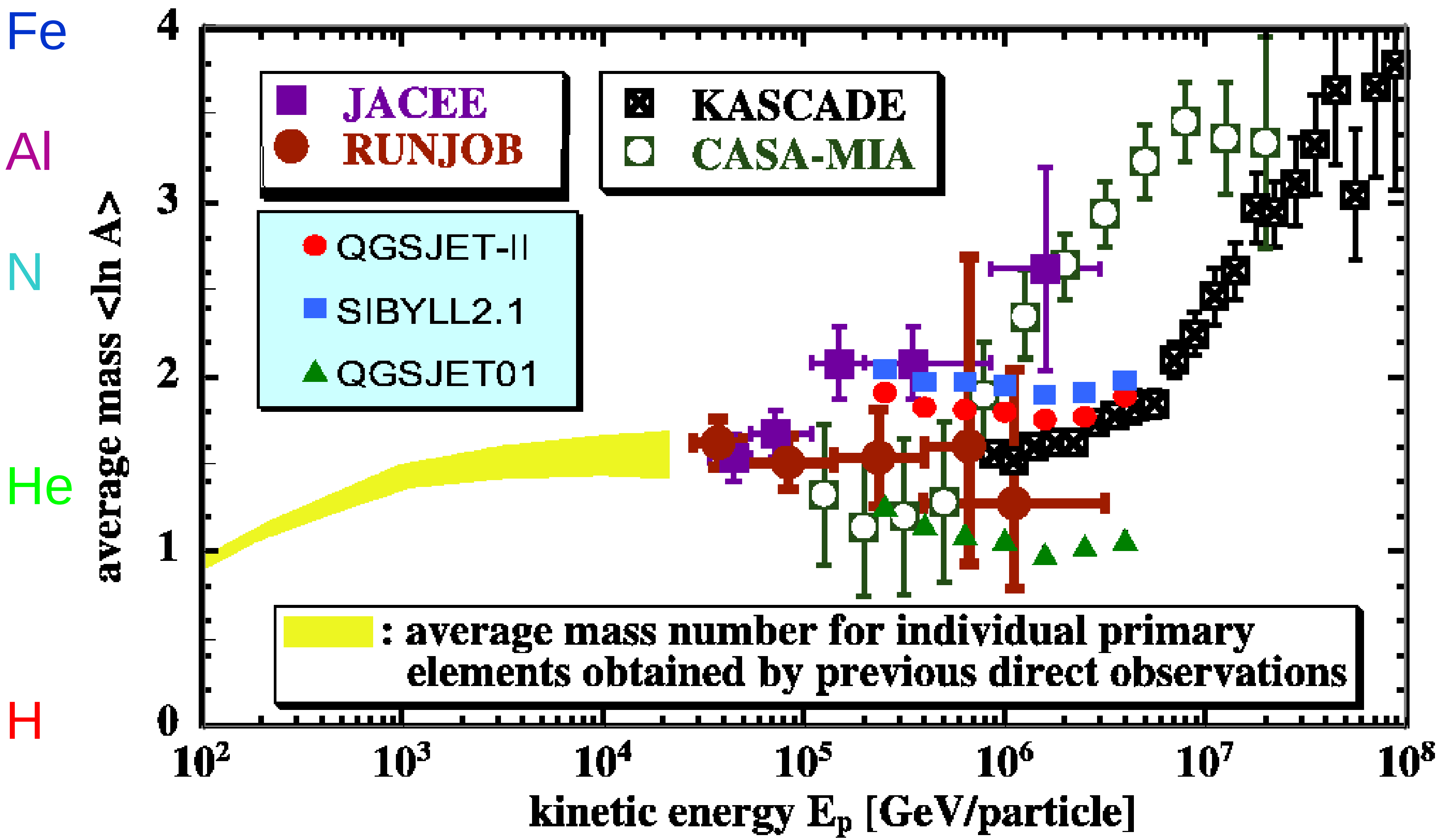




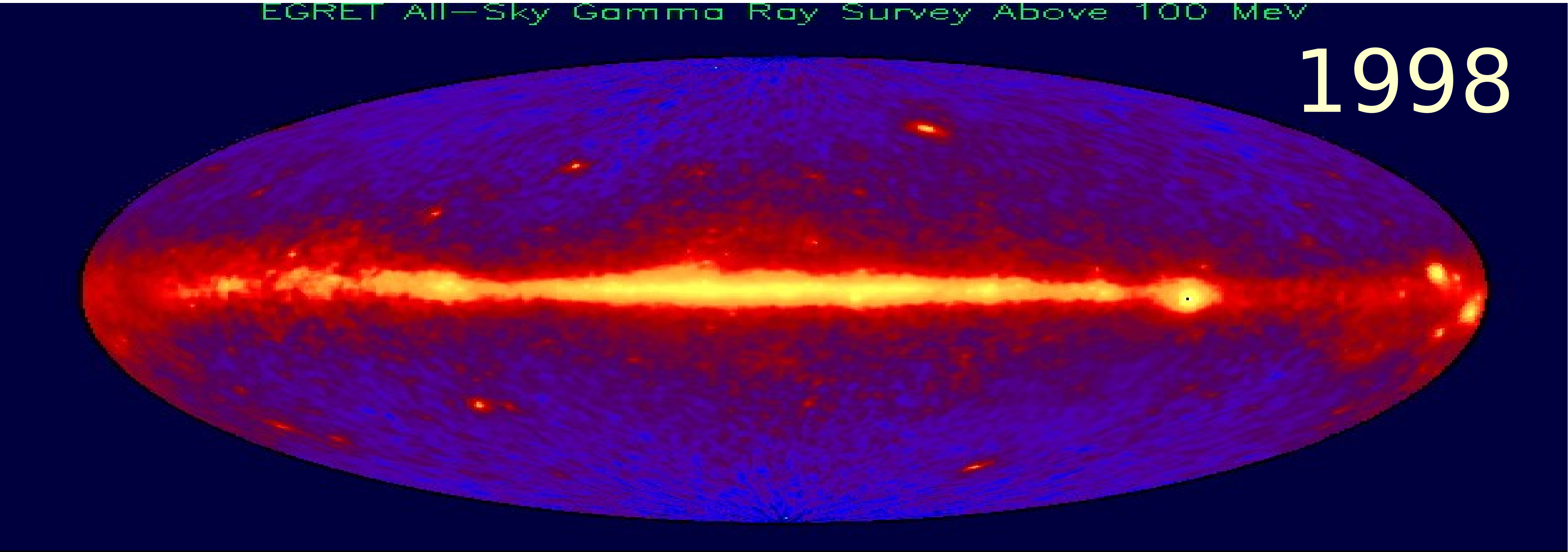


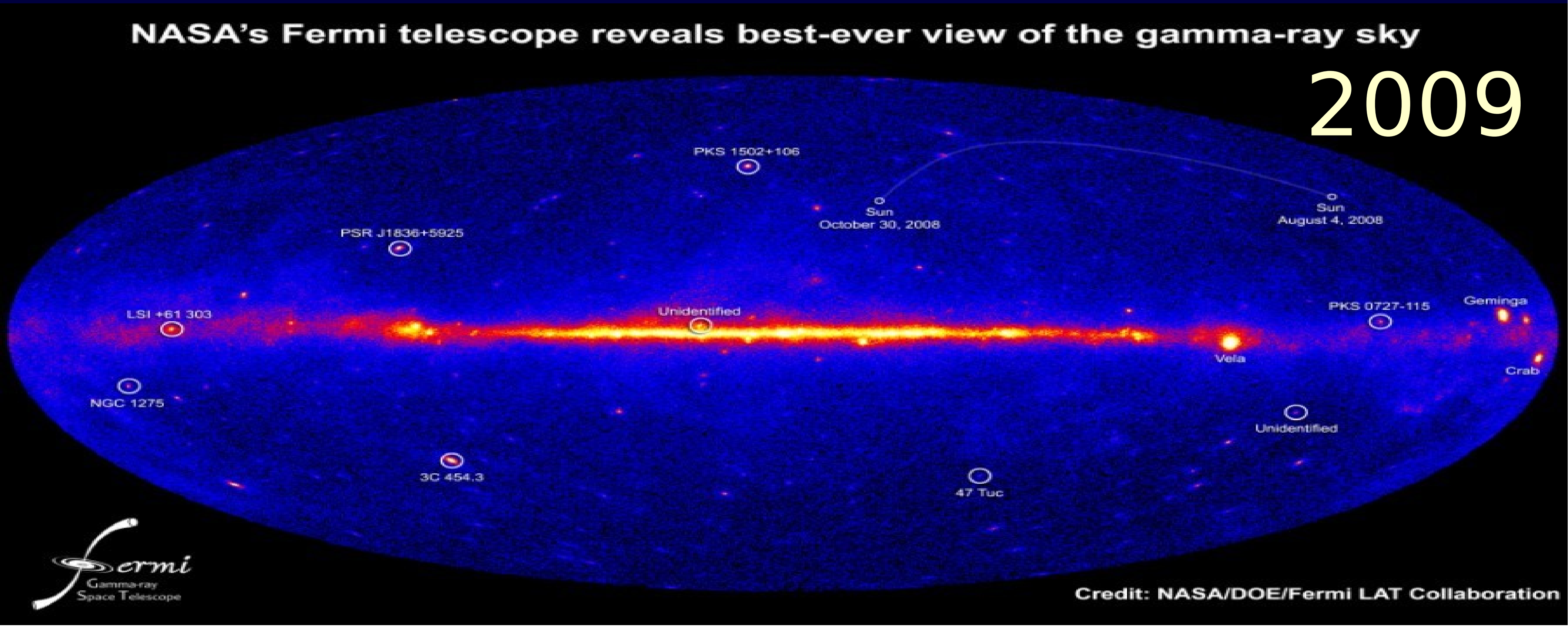
Comparison with direct measurements is possible

Mean Mass Number



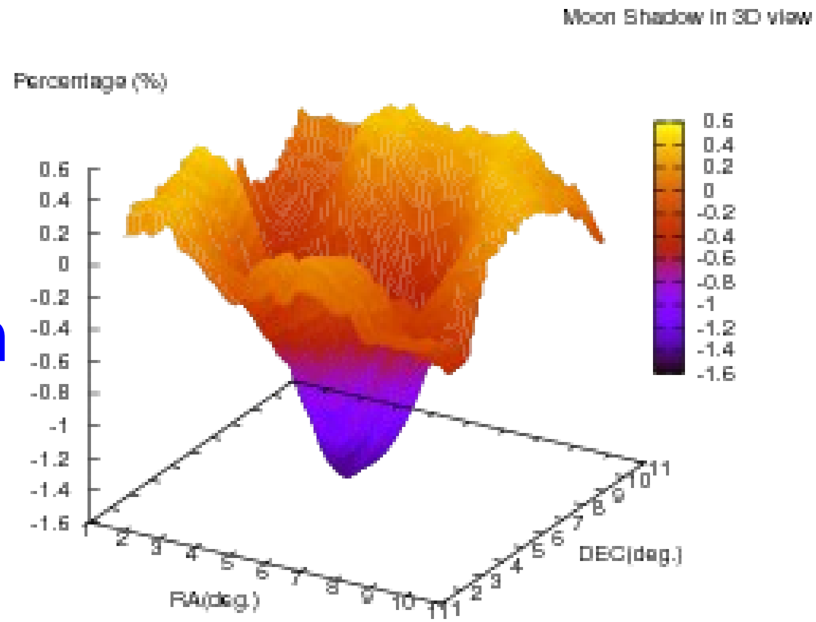
Lower threshold enables data to compare with direct measurements.


EGRET All-Sky Gamma Ray Survey Above 100 MeV
1998


NASA's Fermi telescope reveals best-ever view of the gamma-ray sky
2009
PKS 1502+106
Sun
October 30, 2008
Sun
August 4, 2008
PSR J1836+5925
LSI +61 303
Unidentified
PKS 0727-115
Geminga
Vela
Crab
NGC 1275
Unidentified
3C 454.3
47 Tuc
Fermi
Gamma-ray
Space Telescope
Credit: NASA/DOE/Fermi LAT Collaboration

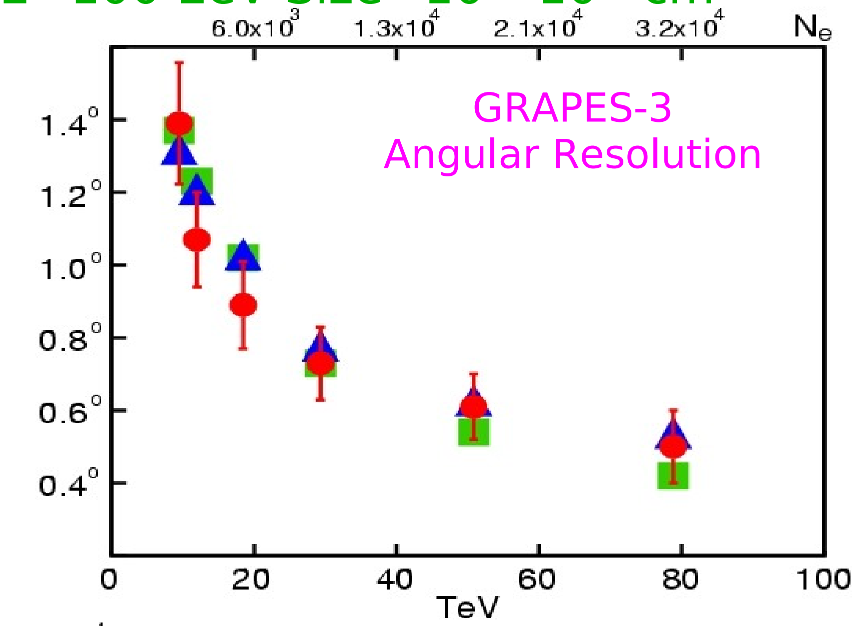
Moon Shadow

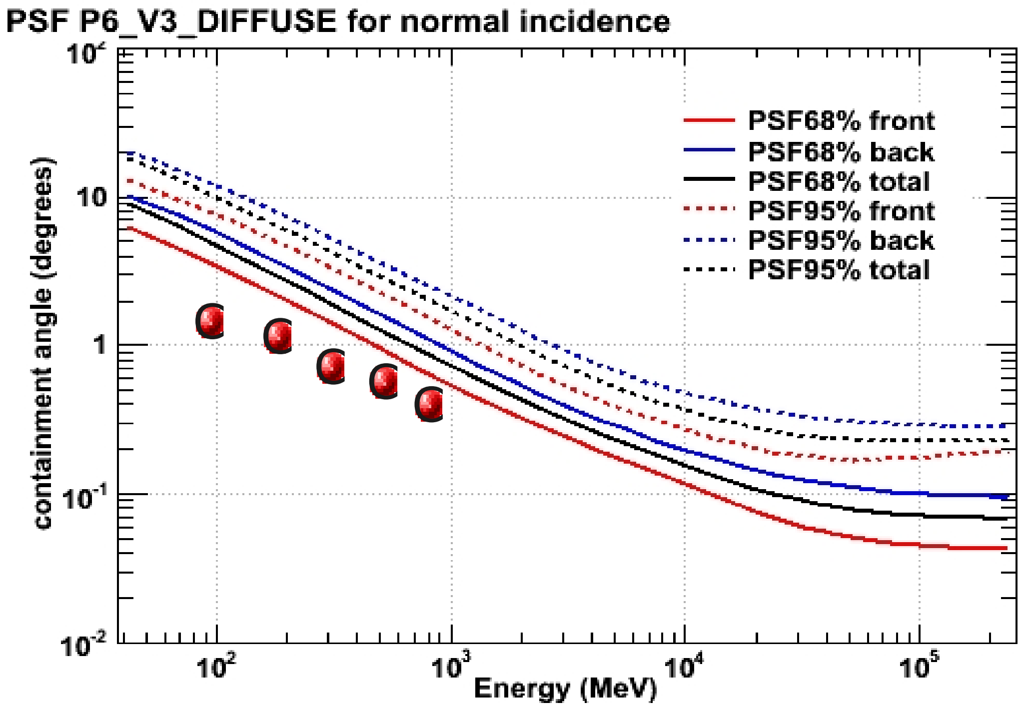
Moon

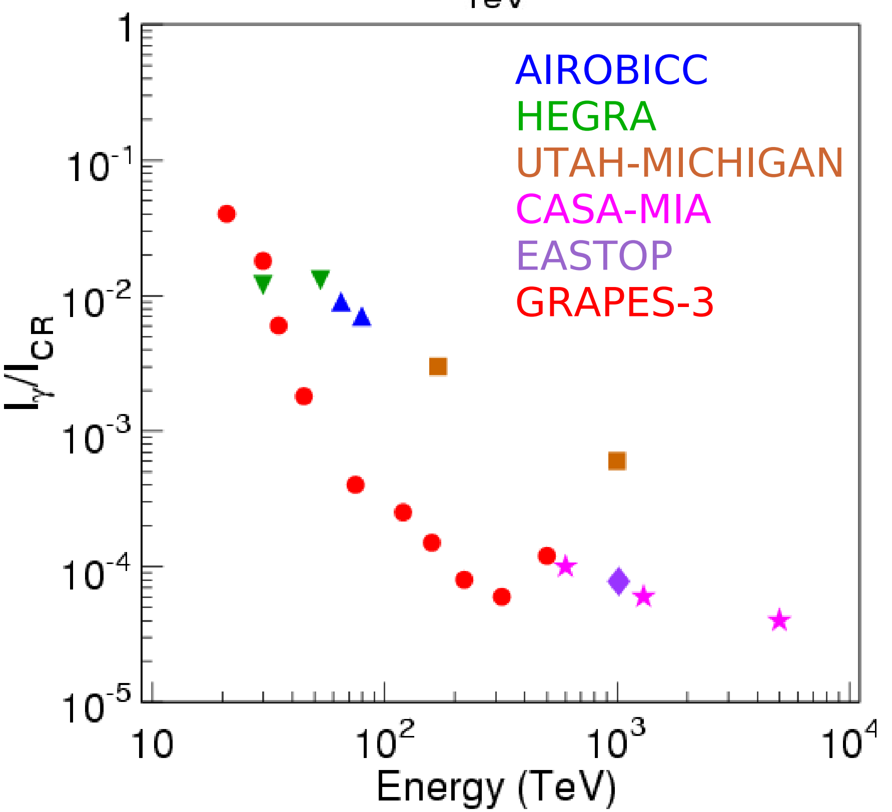


γ-ray astronomy σ_θ = 25'

E~100 EeV Size~10^{24}-10^{26} cm







Future Expansion Plans

Electric field and γ-ray measurements along with correlated study of muon variation

Double muon detector 560 ---> 1120 m^2

Imaging Cerenkov telescope

Expansion to ~0.25 km^2

Neutron monitors for solar studies


Thanks

Backup Slides

MILESTONES:

DST-DAE Vision 2020 meeting accorded highest priority to the GRAPES-3 experiment.., 7-8 April 2006

GRAPES-3 activity to be utilized as a nucleating centre for astroparticle physics.., Panel Report, 19 December 2006

Future activity at Ooty will offer a basis for a national facility in this area of science.., DHEP Review Report, 17 January 2008

With enhanced resources in manpower and funding would allow success on all three fronts, namely, science, R&D, training and education

GRAPES-3 Publications during 2005-2010:

(1) S.K. Gupta et al. Nucl. Instr. and Meth. **A 540** 311-323 (2005)

(2) S.K. Gupta et al. Pramana **65** 273-283 (2005)

(3) S.C. Tonwar et al. Int. J. Mod. Phys. A **20** 6852-6854 (2005)

(4) Y. Hayashi et al. Nucl. Instr. and Meth. **A 545** 643-657 (2005)

(5) S.C. Tonwar et al. Nucl. Phys. B Proc. Suppl. **151** 477-480 (2006)

(6) T. Nonaka et al. Phys. Rev. D **74** 52003 (2006)

(7) H. Tanaka et al. Nucl. Phys. B Proc. Suppl. **175-176** 280-285 (2008)

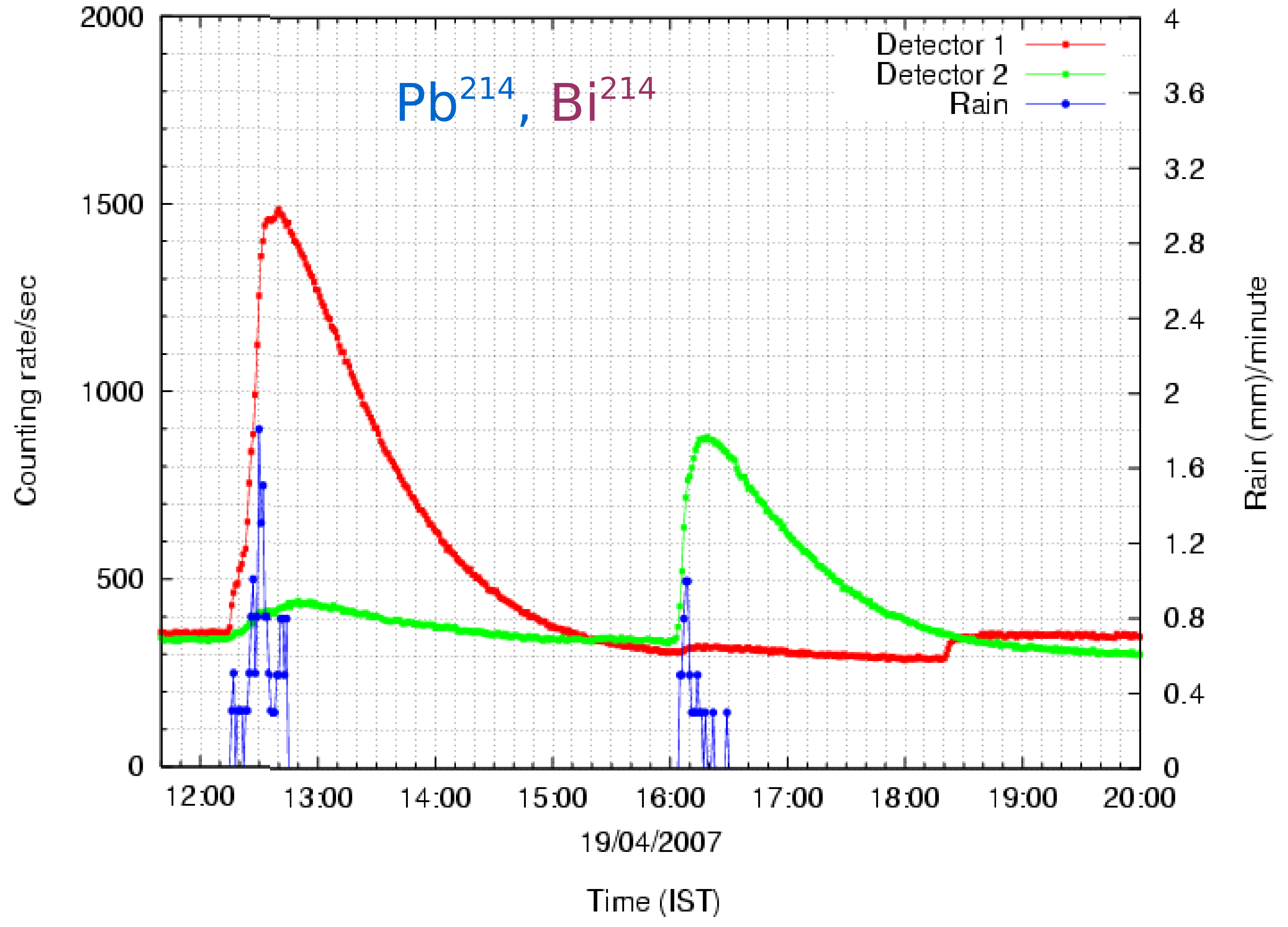
(8) P.K. Mohanty et al. Astropart. Phys. **31** 24-36 (2009)

(9) P. Subramanian et al. Astron. Astrophys. **494** 1107-1118 (2009)

(10) P.K. Nayak et al. Astropart. Phys. **32** 286-293 (2010)

(11) S.K. Gupta et al. Nucl. Phys. B Proc. Suppl. **196** 153-156 (2009)

(12) A. Oshima et al. Astropart. Phys. **33** 97-107 (2010)



Pb214, Bi214
Detector 1
Detector 2
Rain
Counting rate/sec
Rain (mm)/minute
2000
1500
1000
500
0
4
3.6
3.2
2.8
2.4
2
1.6
1.2
0.8
0.4
0
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
19/04/2007
Time (IST)

The main, naturally occurring radioactive nuclei is U^{238} which is present in the soil in very very small concentration ~1 part in 10^9. The decay chain of U^{238} results in production of other radioactive nuclei as shown below,

$$
{}_{92}U^{238} \xrightarrow[4.5\times10^{9}\ \mathrm{yr}]{\alpha} {}_{90}Th^{234} \xrightarrow[24.1\ \mathrm{day}]{\beta} {}_{91}Pa^{234} \xrightarrow[70.2\ \mathrm{sec}]{\beta} {}_{92}U^{234} \qquad (T_{1/2})
$$

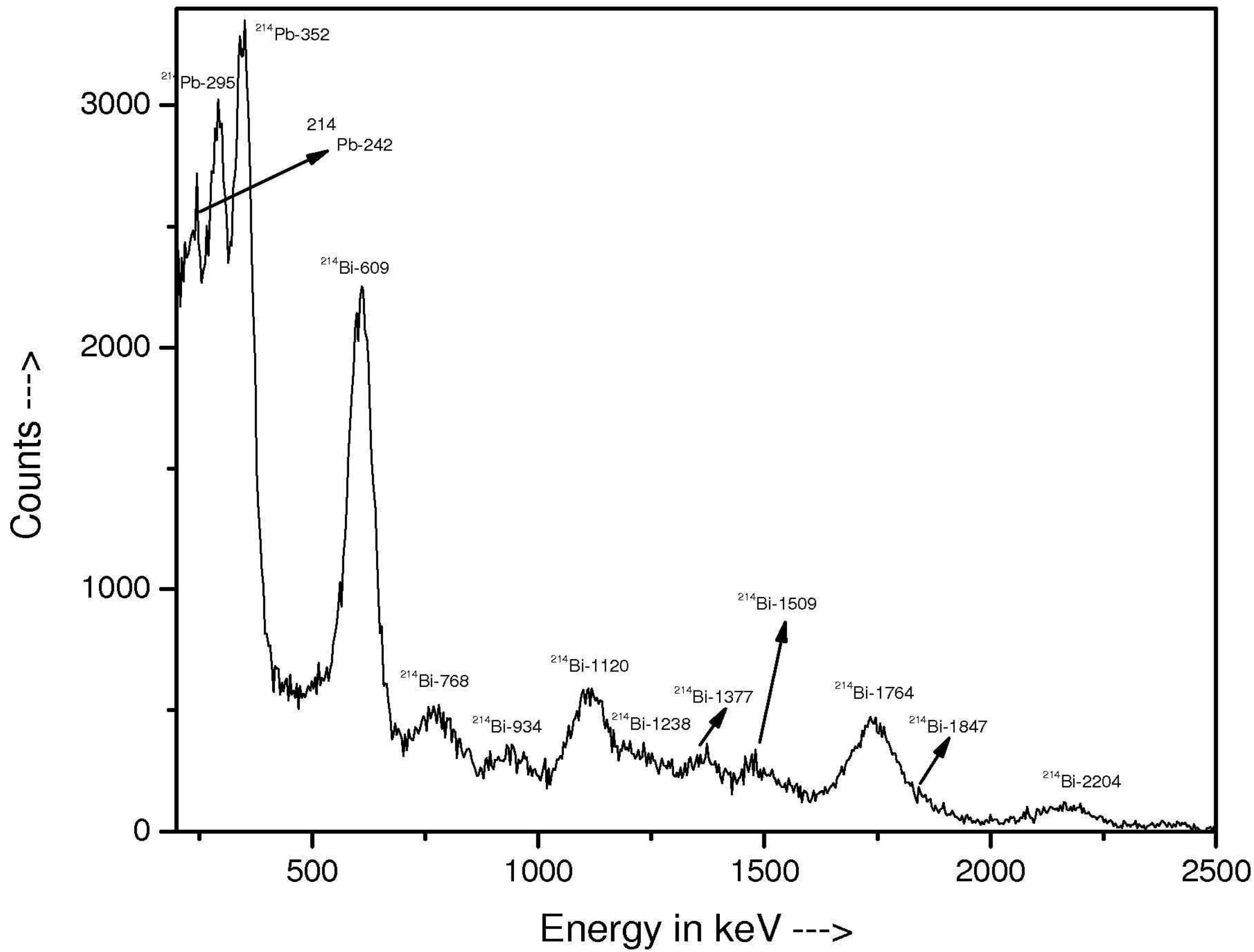
$$
{}_{92}U^{234} \xrightarrow[2.5\times10^{5}\ \mathrm{yr}]{\alpha} {}_{90}Th^{230} \xrightarrow[7.5\times10^{4}\ \mathrm{yr}]{\alpha} {}_{88}Ra^{226} \xrightarrow[1600\ \mathrm{yr}]{\alpha} {}_{86}Rn^{222} \qquad (T_{1/2})
$$

Daughter product of U^{238} is Rn^{222} a gas, that escapes from the soil into the atmosphere where it mixes in the air due to its half-life of 3.82 days, before decaying into Po^{218}. The decay chain of Rn^{222} is schematically shown below. Radon daughter products are heavy metals are precipitated along with rain-fall. The radon daughter nuclei Pb^{214} ($T_{1/2}$=26.8 minutes) and Bi^{214} ($T_{1/2}$=19.9 minutes) are the two most important radioactive nuclei,

$$
{}_{86}Rn^{222} \xrightarrow[3.8\ \mathrm{day}]{\alpha} {}_{84}Po^{218} \xrightarrow[3.1\ \mathrm{min}]{\alpha} {}_{82}Pb^{214} \xrightarrow[26.8\ \mathrm{min}]{\beta} {}_{83}Bi^{214} \qquad (T_{1/2})
$$

$$
{}_{83}Bi^{214} \xrightarrow[19.9\ \mathrm{min}]{\beta} {}_{84}Po^{214} \xrightarrow[164\ \mu s]{\alpha} {}_{82}Pb^{210} \xrightarrow[22.2\ \mathrm{yr}]{\beta} {}_{83}Bi^{210} \qquad (T_{1/2})
$$

$$
{}_{83}Bi^{210} \xrightarrow[5.01\ \mathrm{day}]{\beta} {}_{84}Po^{210} \xrightarrow[138.4\ \mathrm{day}]{\alpha} {}_{82}Pb^{206} \qquad (T_{1/2})
$$



214Pb-352
214Pb-295
214
Pb-242
214Bi-609
214Bi-768
214Bi-934
214Bi-1120
214Bi-1238
214Bi-1377
214Bi-1509
214Bi-1764
214Bi-1847
214Bi-2204
3000
2000
1000
0
500
1000
1500
2000
2500
Counts --->
Energy in keV --->

Acceleration of Cosmic Rays:

Charged particles can only be accelerated in presence of an electric field

Two classes of Mechanism

1) Betatron Acceleration:

Particles are accelerated in homogeneous magnetic field which is increasing with time

$$P^2_{\perp} / B = \text{constant} \qquad P^2_{\perp} \propto B \quad (\textit{Adiabatic constant})$$

If particles leave before field decreases → Net Acceleration

2) FERMI Acceleration:

Acceleration in collision with magnetic clouds collisions with moving magnetic gas clouds

$$\Delta E \sim u/c\, E \qquad u = \textit{velocity of cloud}$$

Gain if approaching 1st order

Loss if receding

Not Very Efficient

Fermi Acceleration 2nd order or Stochastic *Acceleration*:

In collisions with randomly moving magnetic field clouds there is 'net' statistical acceleration due to greater probability of 'head-on' collisions than 'overtaking'/'passing' collisions and energy gained

$\equiv \Delta E = u^2/c^2\ E$ $u \ll c$ $\Delta E_{2nd} \ll \Delta E_{1st}$

C.R particles are continuously accelerated in interstellar medium   Rate of change of Energy $dE/dt = \alpha\ E$

Probability of a particle with age t, t+dt

$dW = 1/T e^{-t/T}\, dt$ *T = mean age in cloud*

$N(E)dE = k\ E^{-(1+1/\alpha T)}$

$N(E)\ dE = kE^{-\gamma}$ $\gamma = (1 + 1/\alpha T)$

Power Law Spectrum

In Interstellar Space Energy Gain ~ 10

Sites of C.R. Acceleration

1) Supernova Shocks from explosion and in remnants provide sites suitable for acceleration of C.R

$$E \sim 10^{16} - 10^{17} \text{ eV}$$

By repeated crossing of shock front. Stochastic Acceleration is possible

S.N. Rate of Energy Release ~ 10^{41} -10^{42} erg/s

C.R Rate of Energy Pumped in Galaxy ~ $10^{40} - 10^{41}$ erg/s

2) Acceleration in compact objects such as Pulsars, X-Ray Binaries etc

Electric Fields ~ V X B ~ 10^{16} v/m

C.R Energies ~ 10^{17} eV possible

Summary talk:
The experimental situation

Alan Watson
University of Leeds

a.a.watson@leeds.ac.uk

Weihai: 14th ISVHECRI, 22 August 2006

My conclusions

- **Tibet data are statistically limited (177 events in 3 year
and require an understanding of emulsion chambers**

- **GRAPES data should be analyzed using KASCADE
methods of deconvolution**

- **KASCADE group should show their results along with
direct measurements. These are not 'perfect' right now
but better data will come and they may 'guide the though
The KASCADE data are not perfect either!**

- **What will the conclusion on composition be:
KASCADE and GRAPES or Tibet?**

Do we need hadronic interaction models to find out?

What is going on at the knee (~ 3 PeV)?

- Very detailed observations:

  KASCADE, GRAPES and Tibet Array

  $N_{e,}N_{\mu}$ EAS + Emulsion Chambers

- Close to where there are accelerator measurements

- Close to where there are direct data

Surely we should have a clear result by now

– but unfortunately ‘NO’