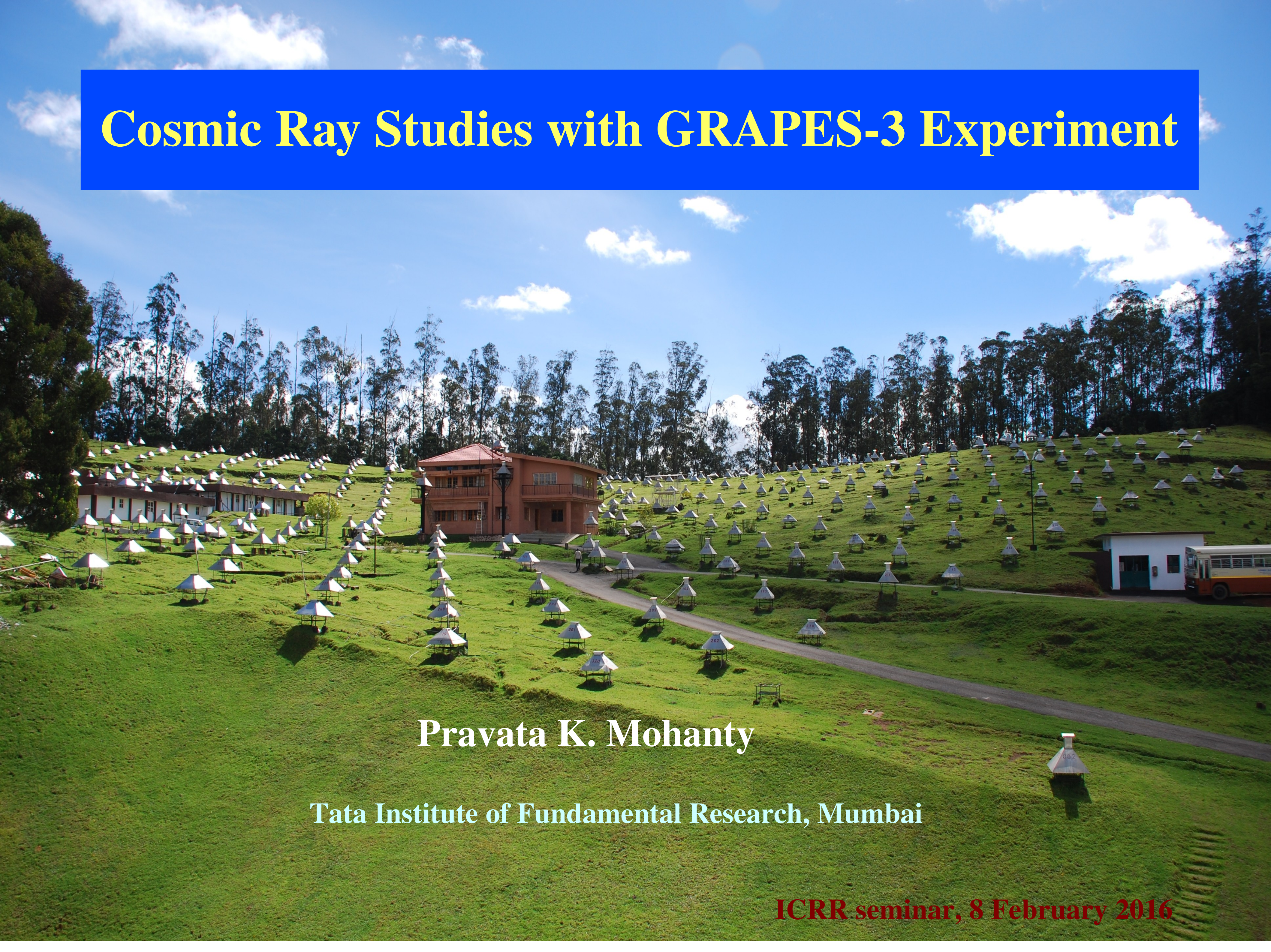
Cosmic Ray Studies with GRAPES-3 Experiment



Pravata K. Mohanty

Tata Institute of Fundamental Research, Mumbai

ICRR seminar, 8 February 2016

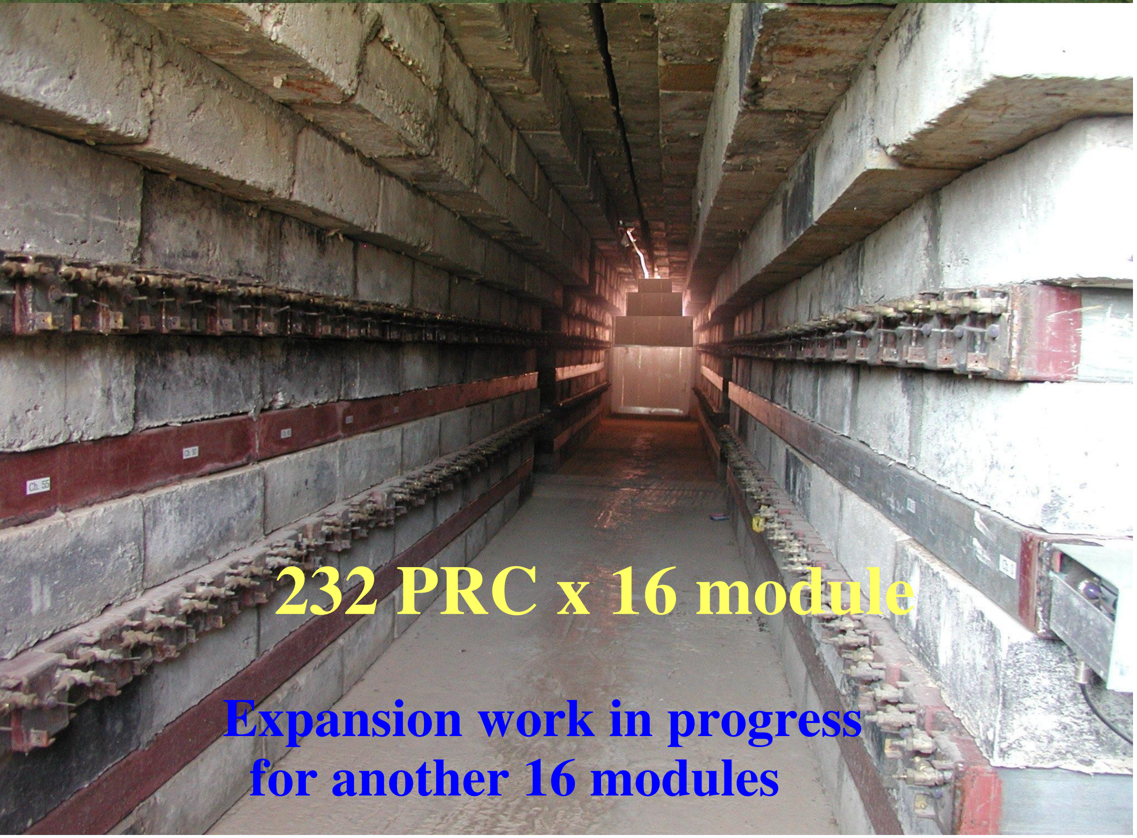
Outline

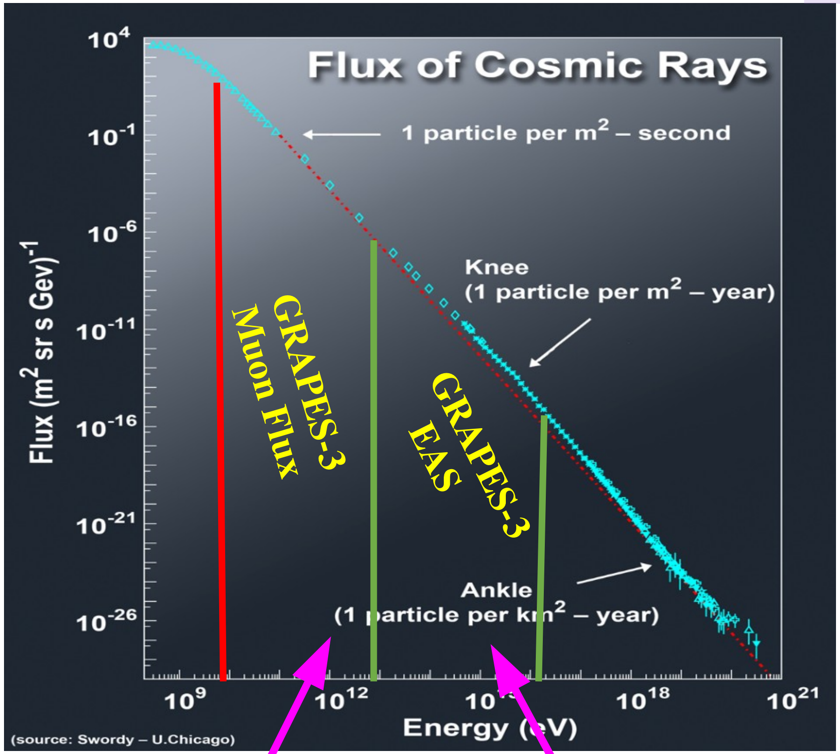
PART-I

- Overview of the GRAPES-3 Experiment
- Measurements of Solar Diurnal Anisotropy
- Forbush Decrease precursor events
- Thundercloud acceleration of muons

PART-II

- R&D of scintillator detectors
- GRAPES-3 C++/ROOT based data analysis framework





4 billion muons/day

(High Statistical Accuracy)

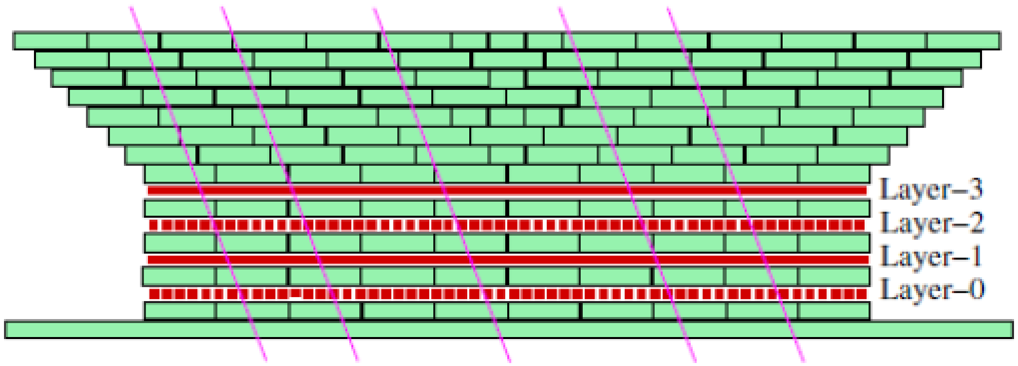
- Solar phenomena
- Thundercloud acceleration

3 million EAS events /day

(Energy and Direction)

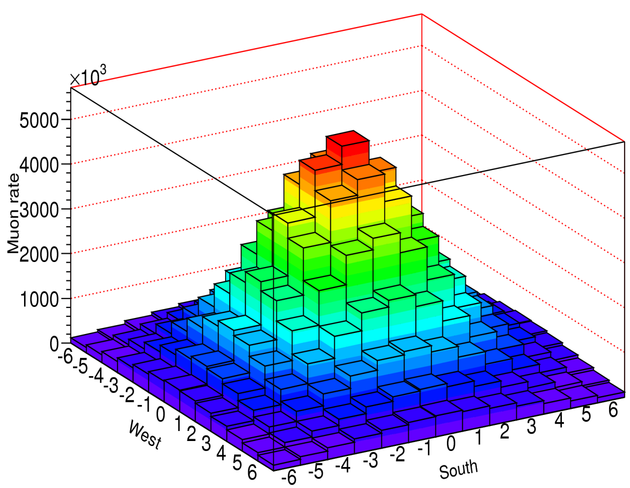
- **Spectrum and elemental composition ($10^{13} – 10^{16}$eV)**
- **Diffuse ray studies**

Features of Muon Detector

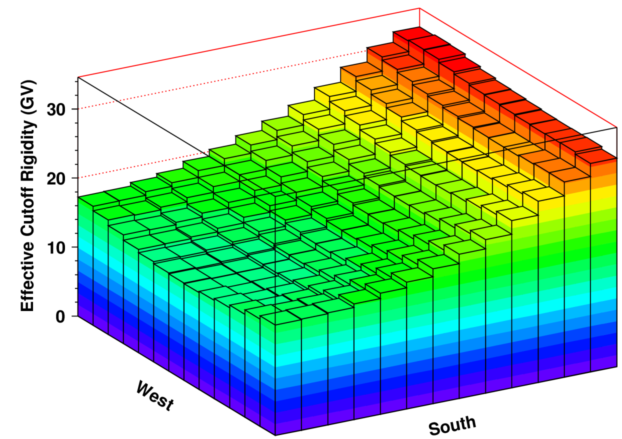


$E_\mu > 1$ GeV sec(θ)

Total field of view : 2.3 sr
Number of Directions : 13 x 13 (169)
Angular Resolution : 2 to 6°
Muon Rate : 5×10^4 / s
Basic time resolution : 10 s
Statistical Accuracy (1 h) : 0.01%

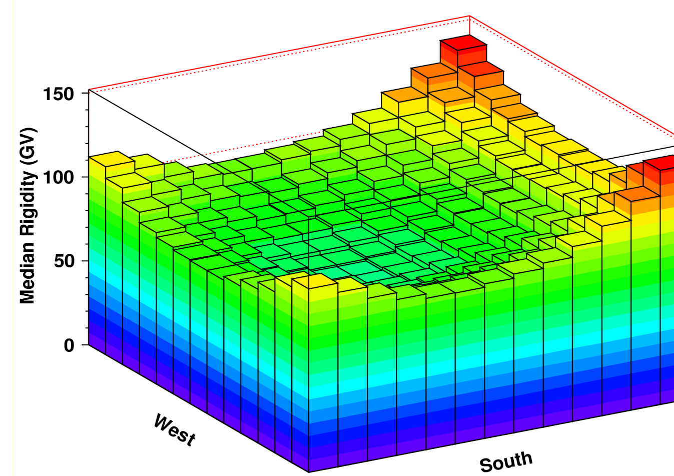


Cutoff rigidity map



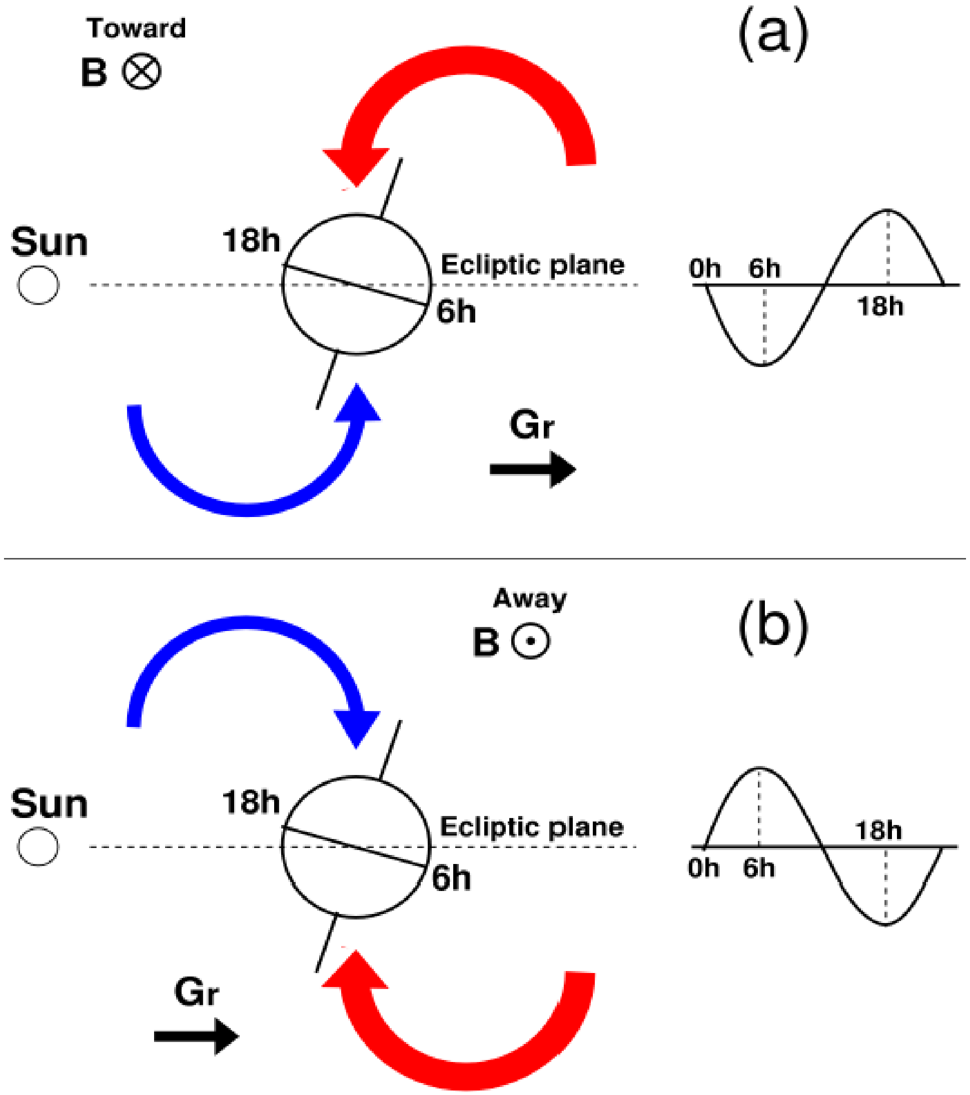
14 – 32 GV

Median rigidity map



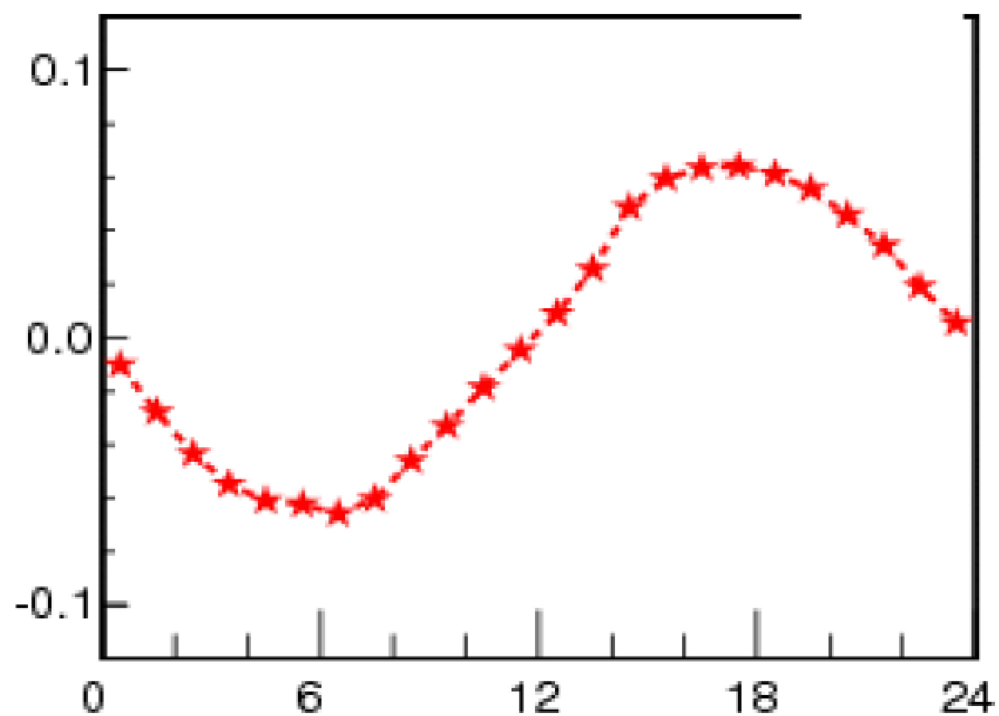
65 – 140 GV

Swinson Flow Amplitude (%)



GRAPES-3 6-Yr Data 2000-2005

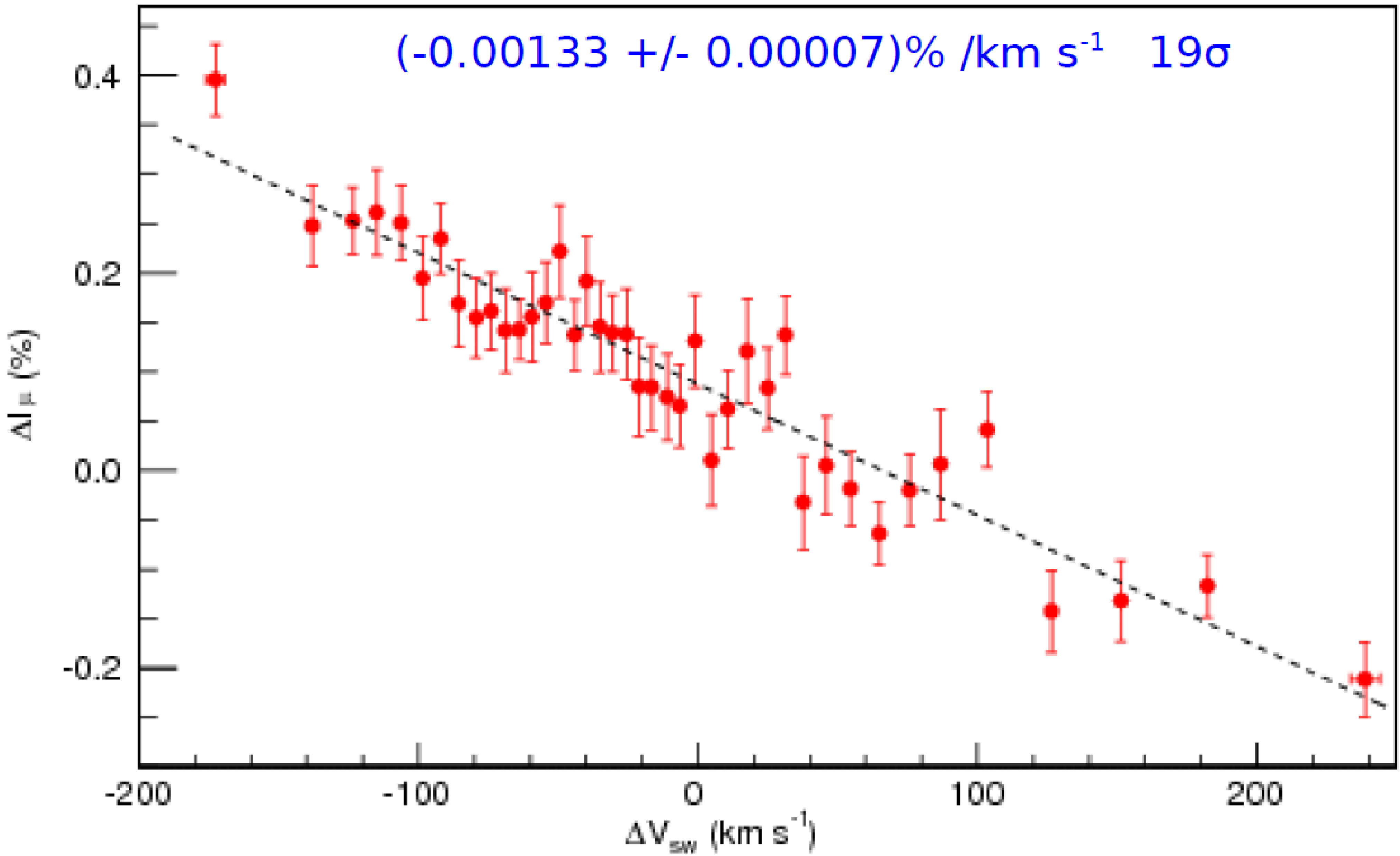
A = (0.0644 +/- 0:0008)% 80σ
ψ = (17:70 +/- 0:05) h



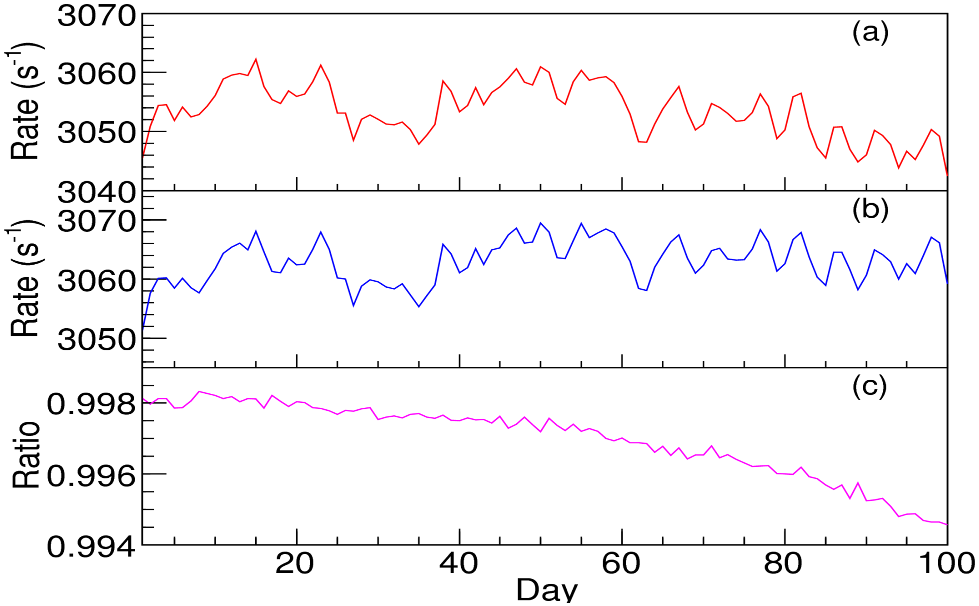
H. Kojima et al., Astropart. Phys. **62** 21 (2015)

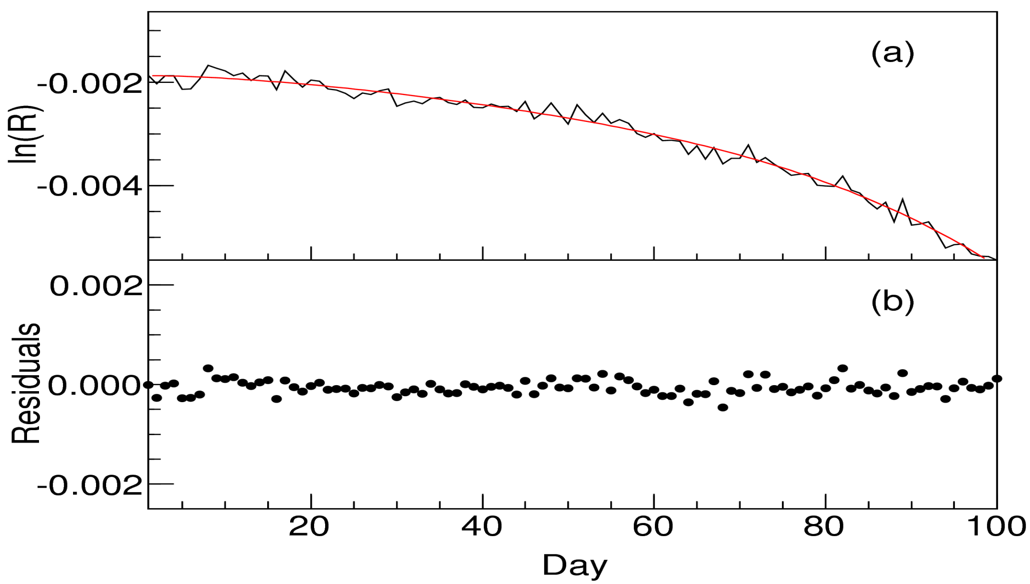
Cosmic Ray-Solar Wind Correlation

GRAPES-3 6-Yr Data 2000-2005



Efficiency corrections





$$R(t) = R_0\epsilon(t)$$

$$\epsilon(t) = 1 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4$$

$$r_{ij}(t_k) = \frac{R_{0i}(1 + a_{1i}t_k + a_{2i}t_k^2 + a_{3i}t_k^3 + a_{4i}t_k^4)}{R_{0j}(1 + a_{1j}t_k + a_{2j}t_k^2 + a_{3j}t_k^3 + a_{4j}t_k^4)}$$

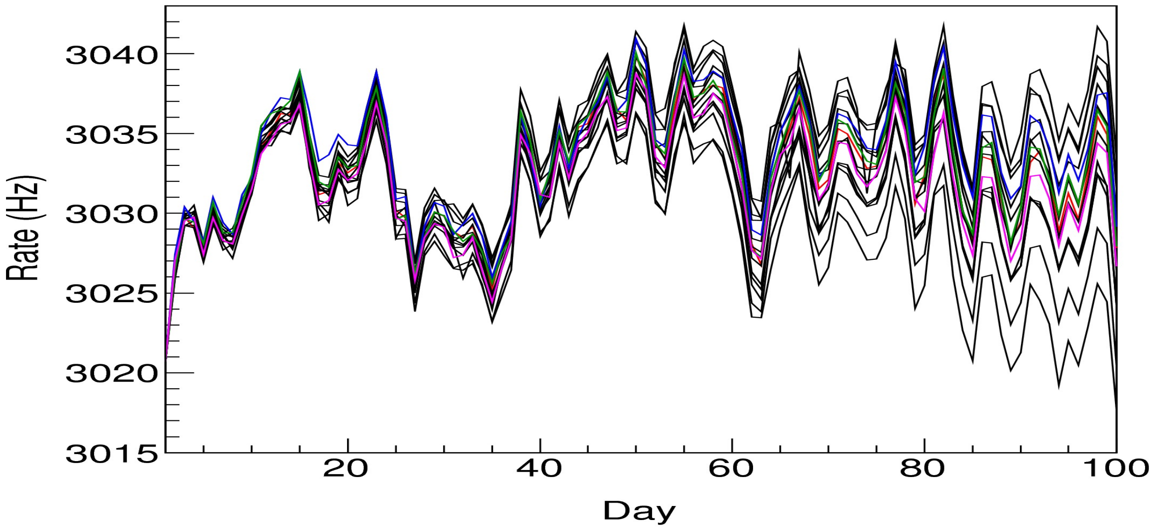
$$ln(1+x) \simeq x$$

$$Ga = b$$

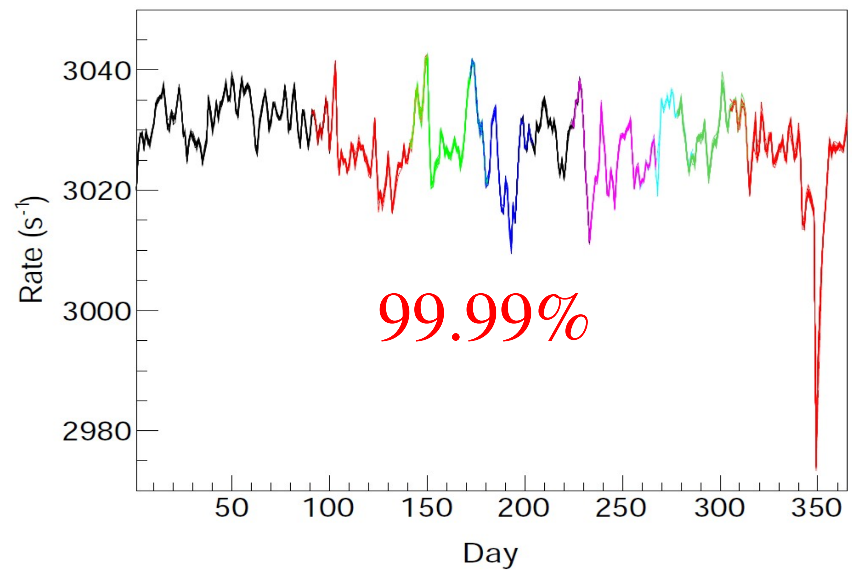
120 x 100 days = 12000 linear equations to be solved to get 80 coefficients for 16 mod.

Solved using SVD decomposition

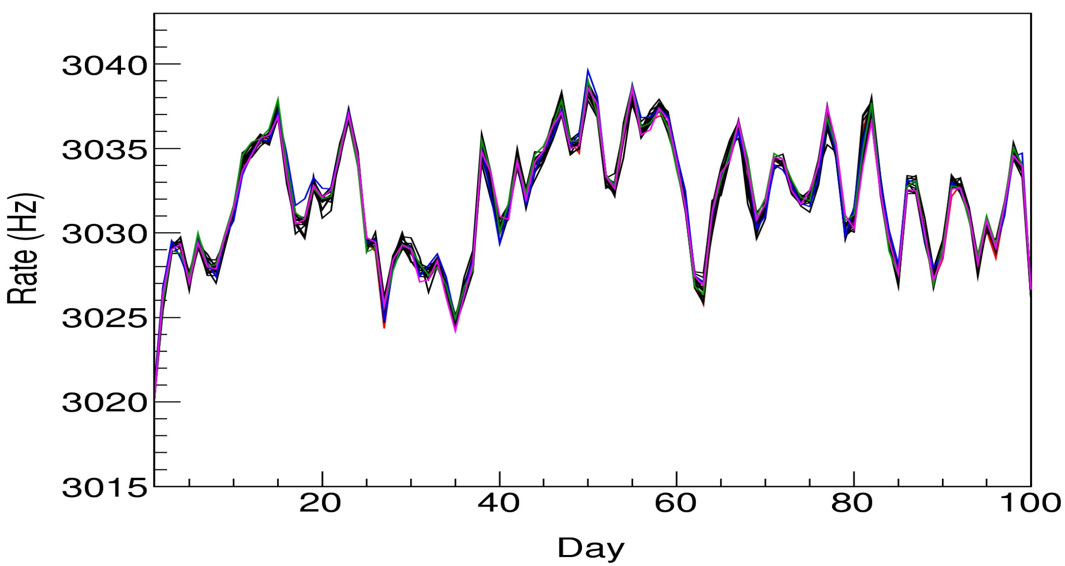
Before correction

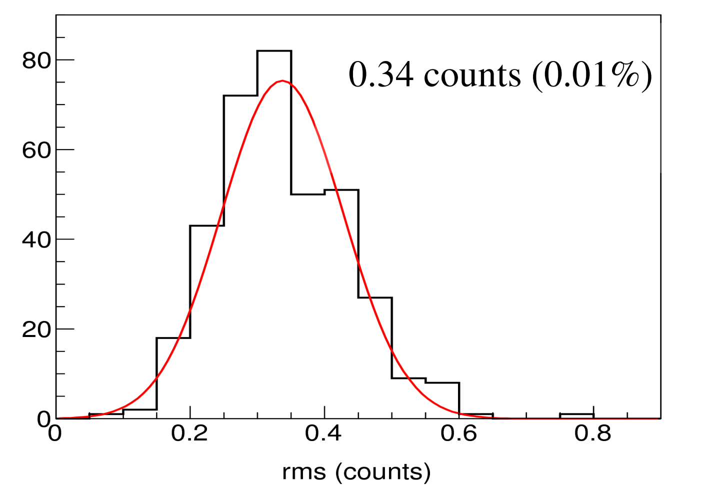


Full 2006 data after correction



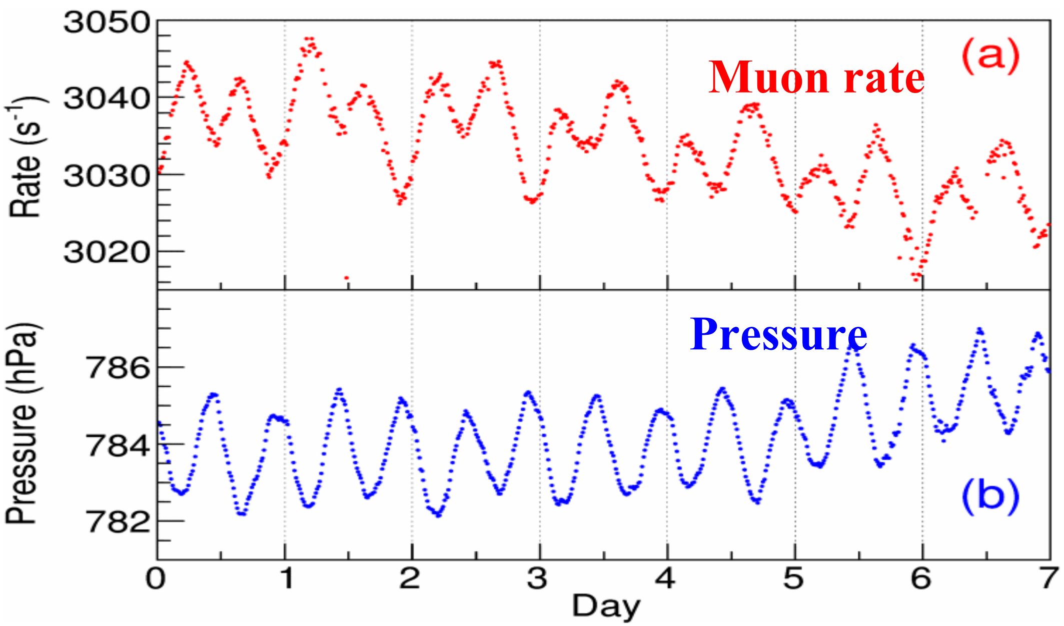
After correction

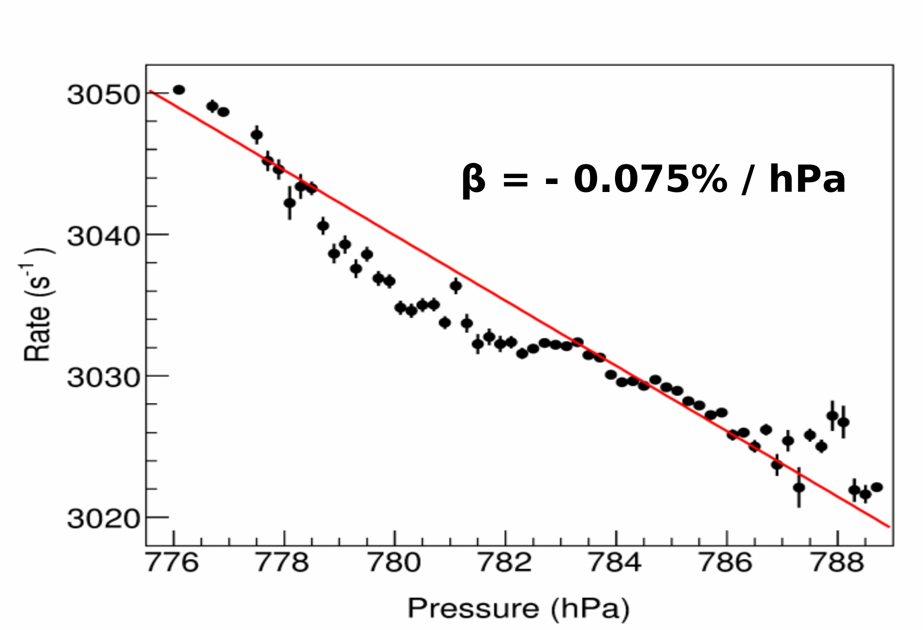


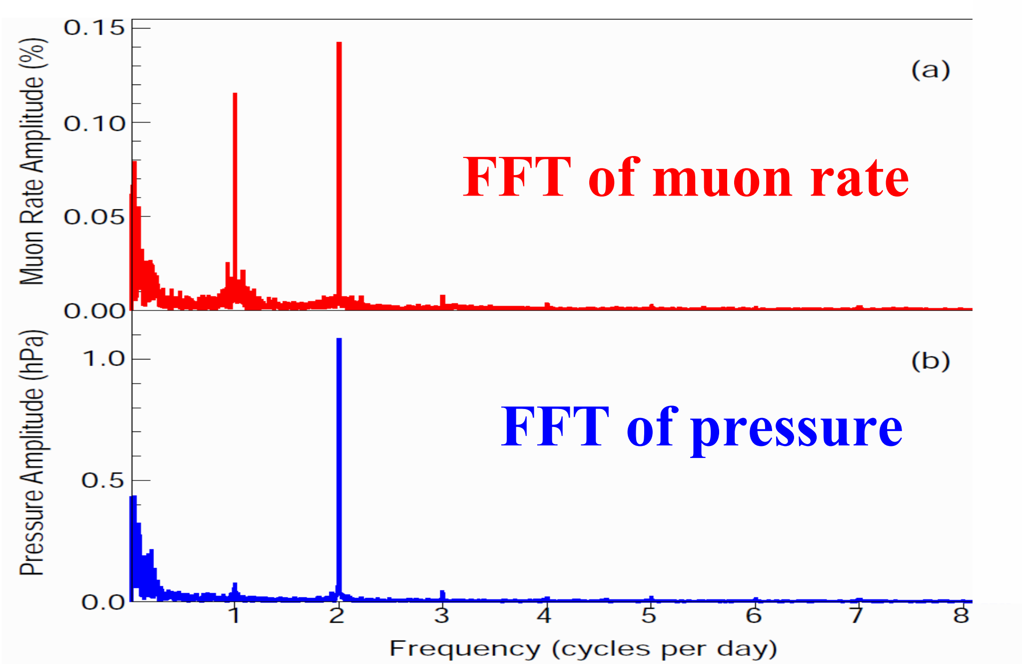


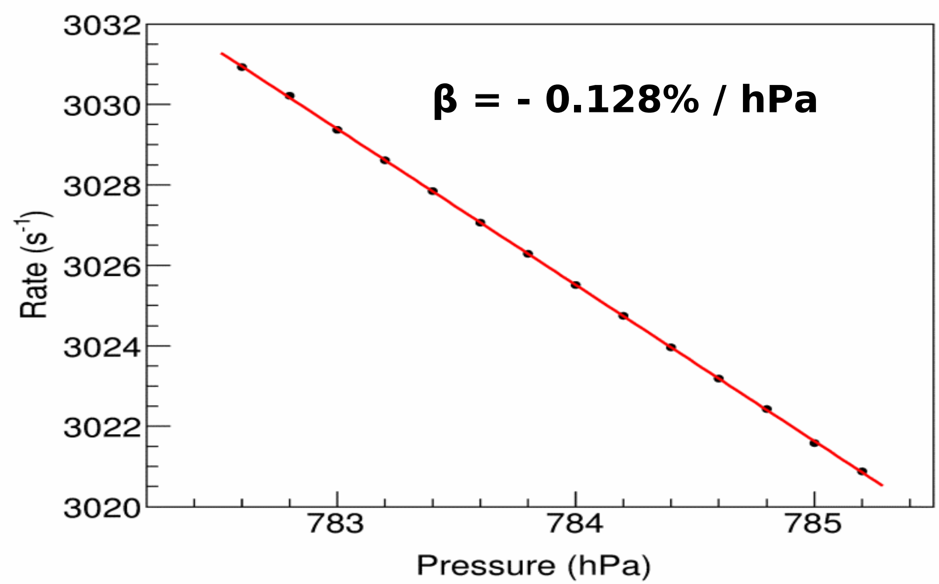
Analysis completed from 2004 - 2013

Atmospheric pressure corrections



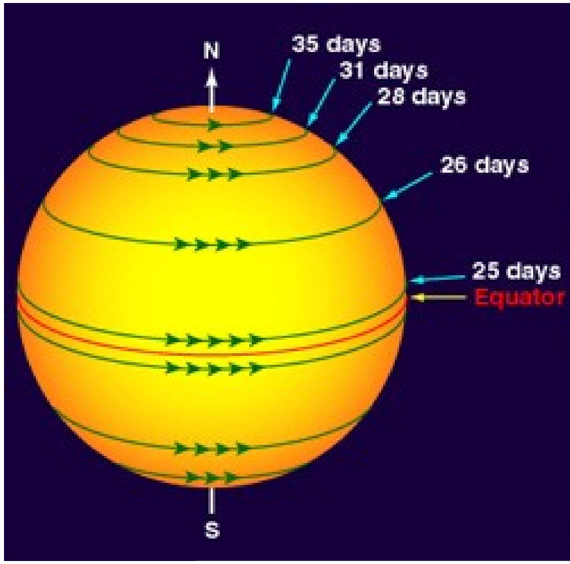


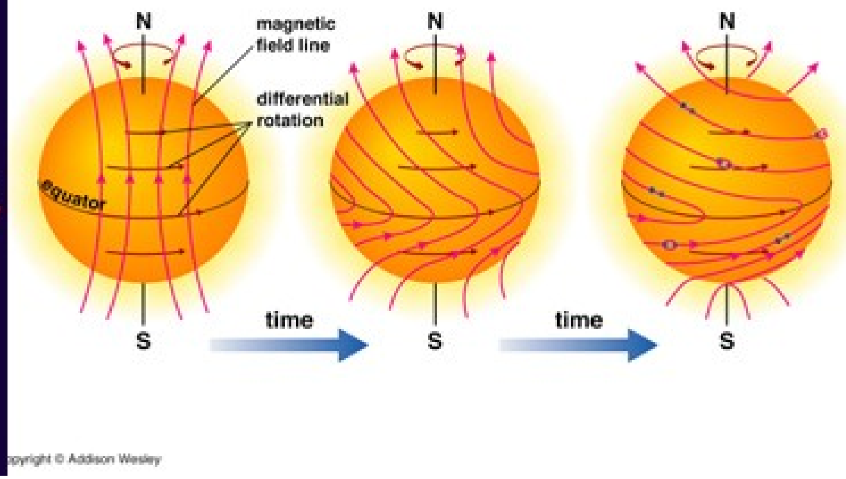




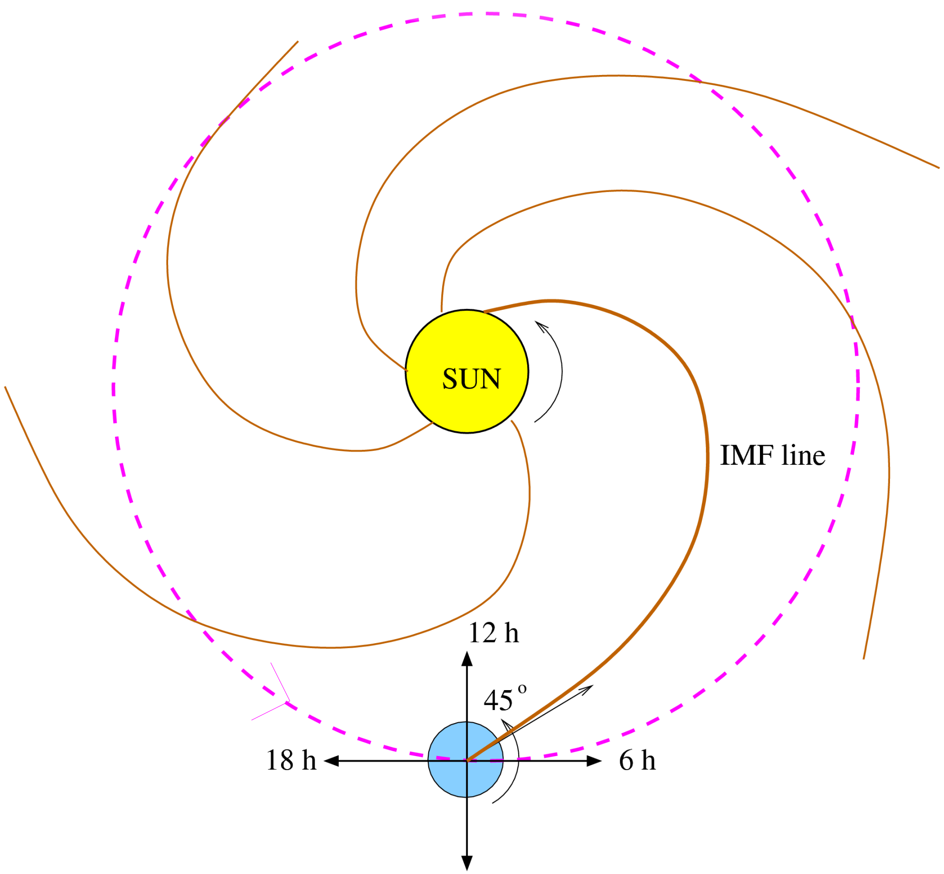
Paper Submitted to Astroparticle Physics

Solar Diurnal Anisotropy

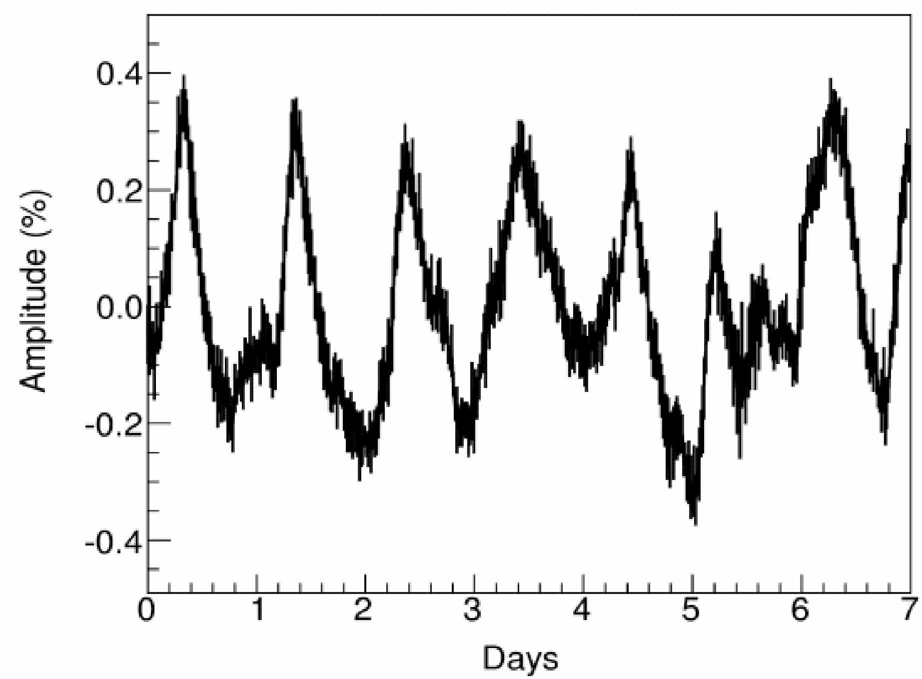




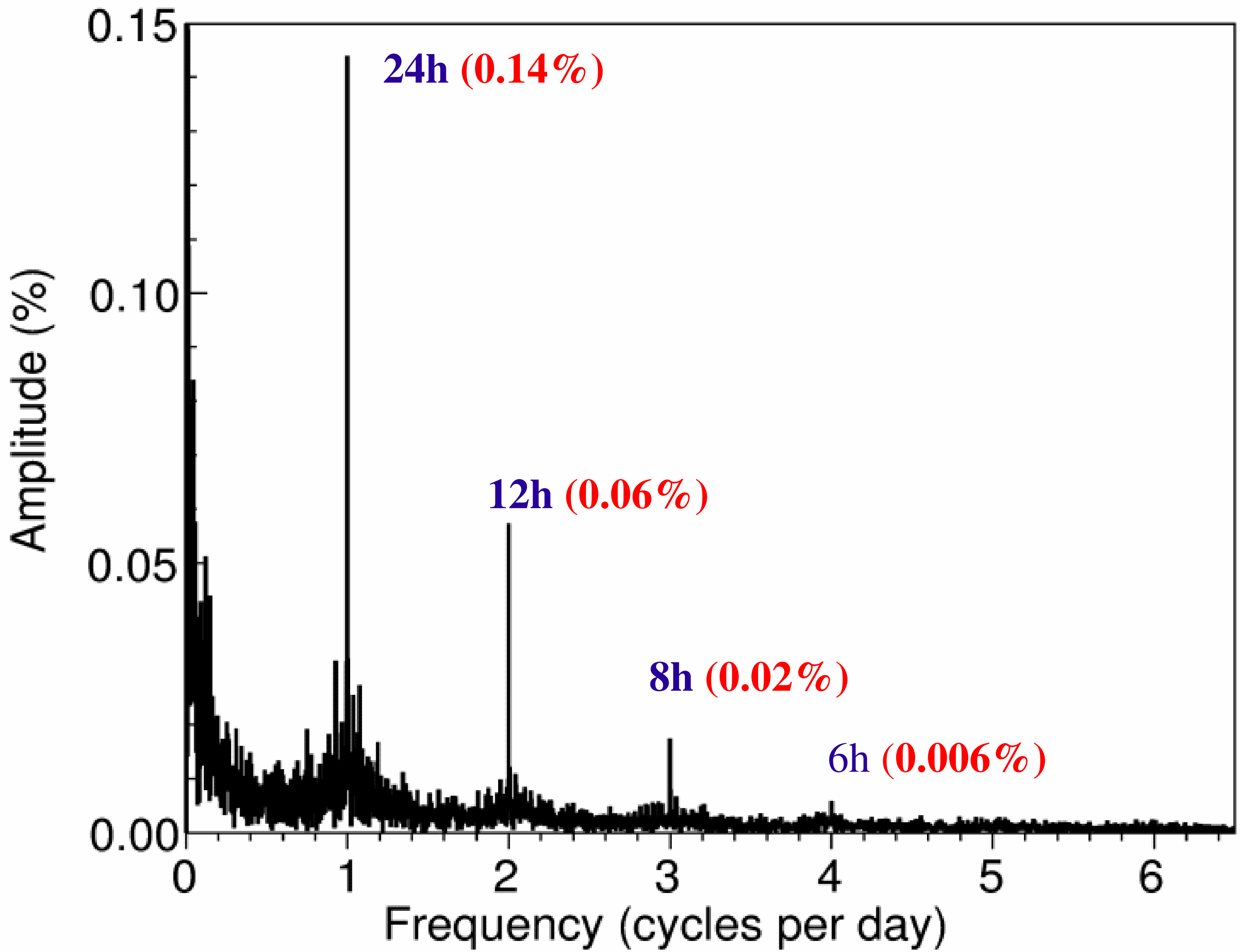
Diffusion-Convection Model



GRAPES-3 Muon data

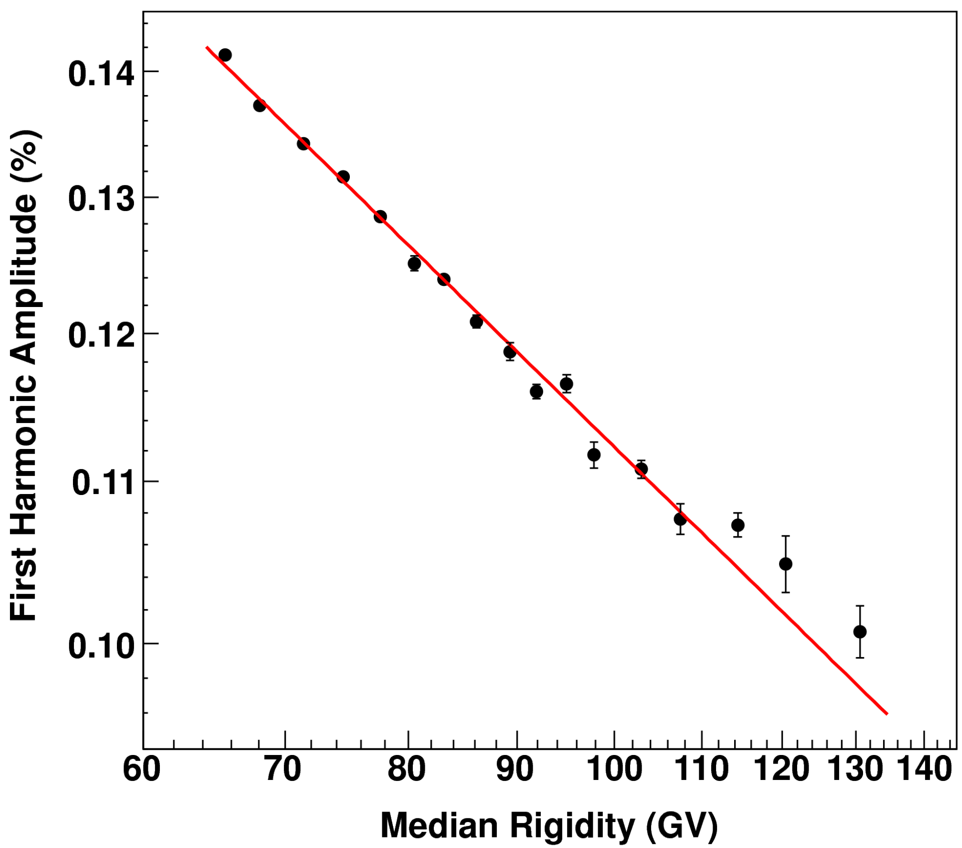


Harmonics of solar diurnal anisotropy using FFT (Median Rigidity: 65 – 70 GV)



Rigidity Spectrum of SDA

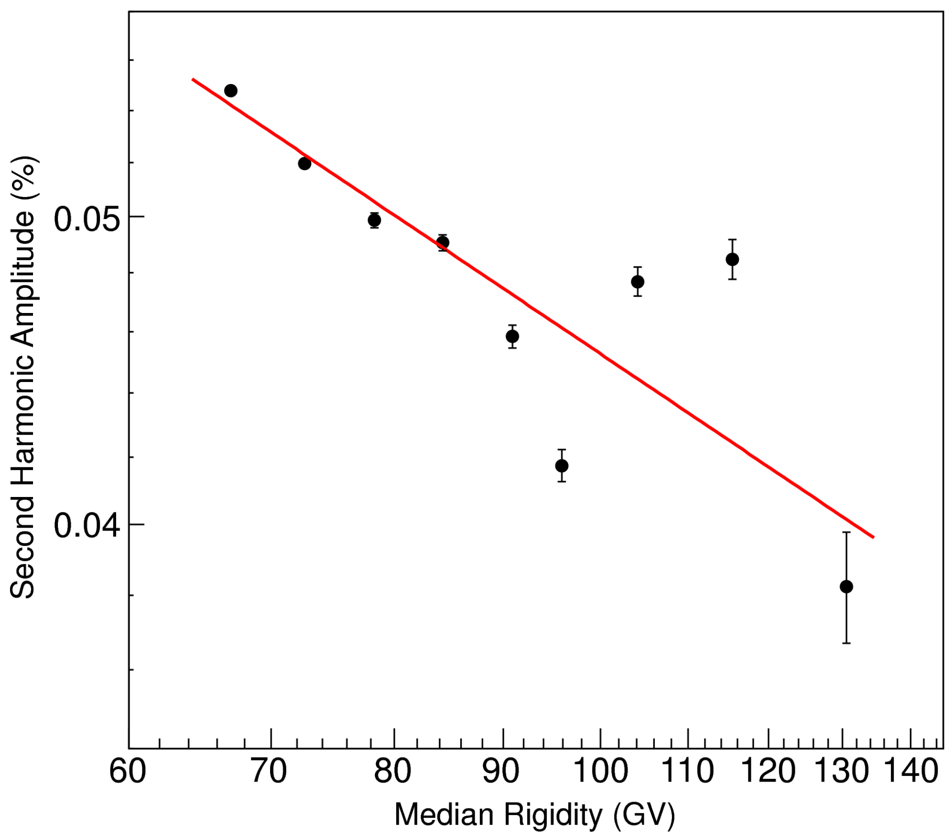
First Harmonic



$$A(R) = K R^{-\gamma}$$

$K = 1.3 \pm 0.1$, $\gamma = 0.53 \pm 0.01$

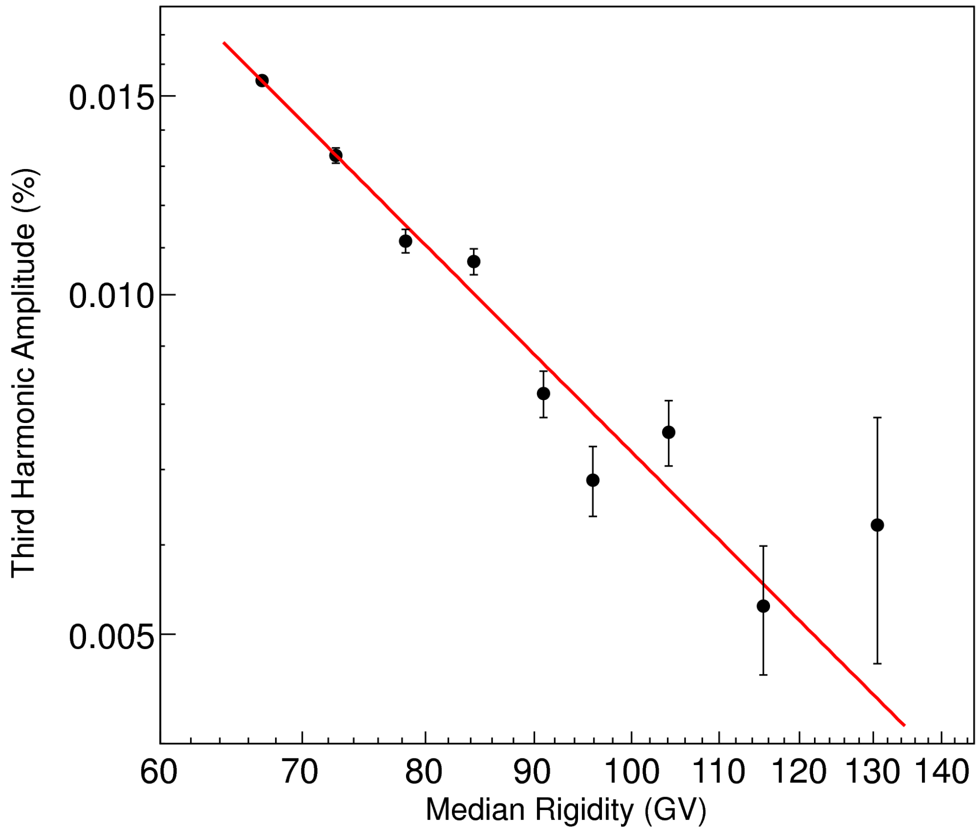
Second Harmonics



$\gamma = 0.45 \pm 0.02$

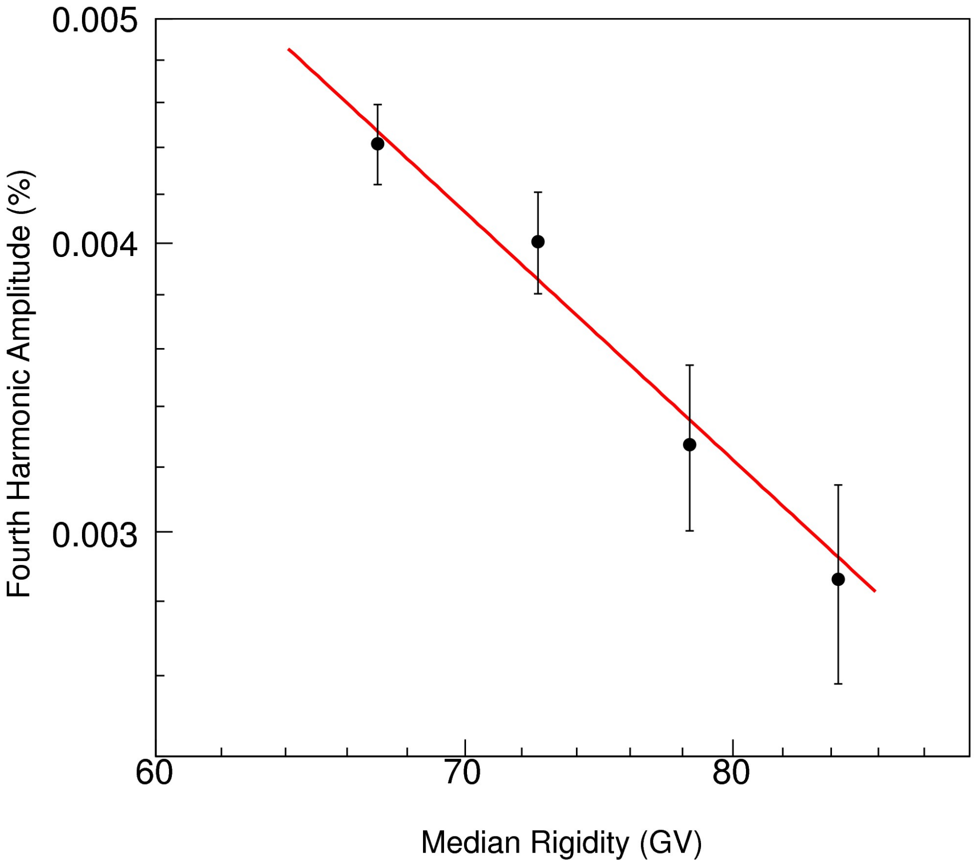
Rigidity Spectrum of SDA

Third Harmonic



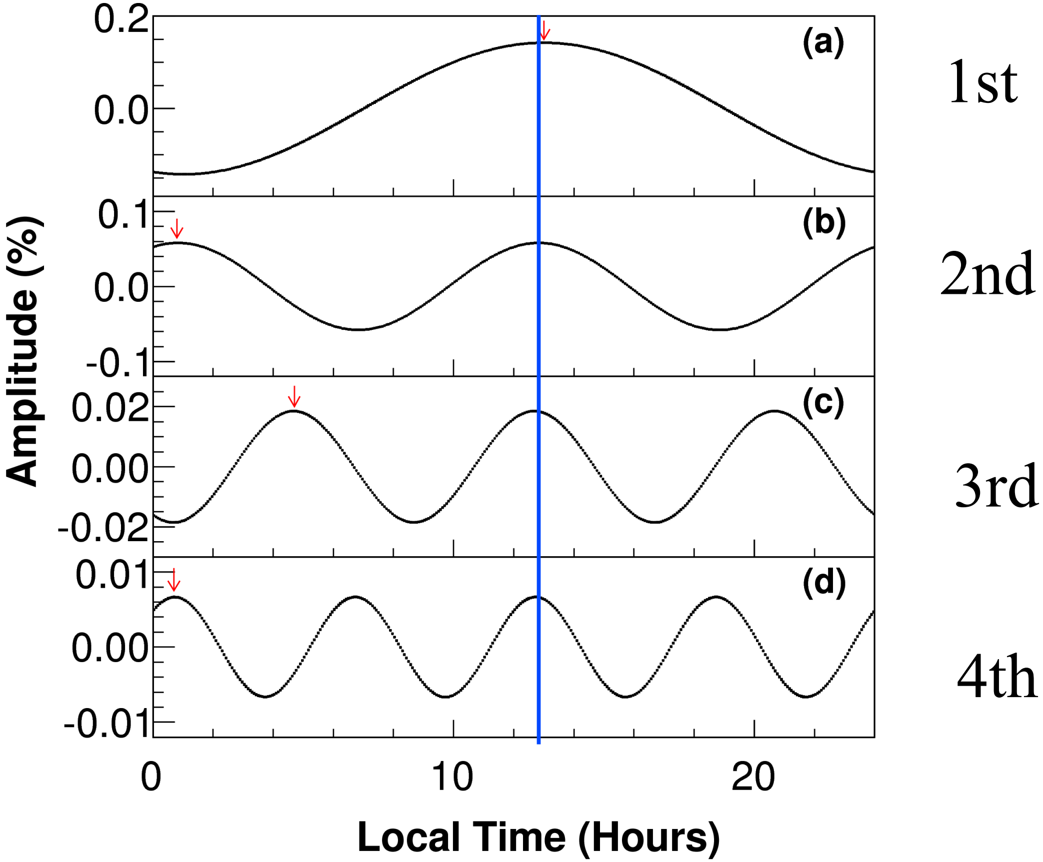
$\gamma = 1.9 \pm 0.1$

Fourth harmonic

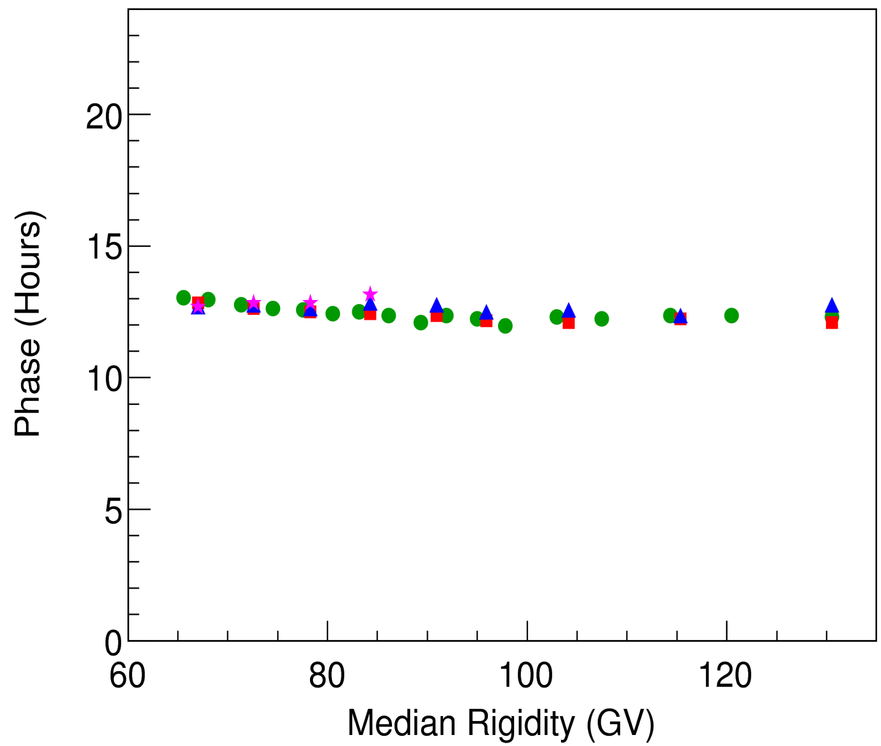


$\gamma = 1.8 \pm 0.4$

Phase of Harmonics



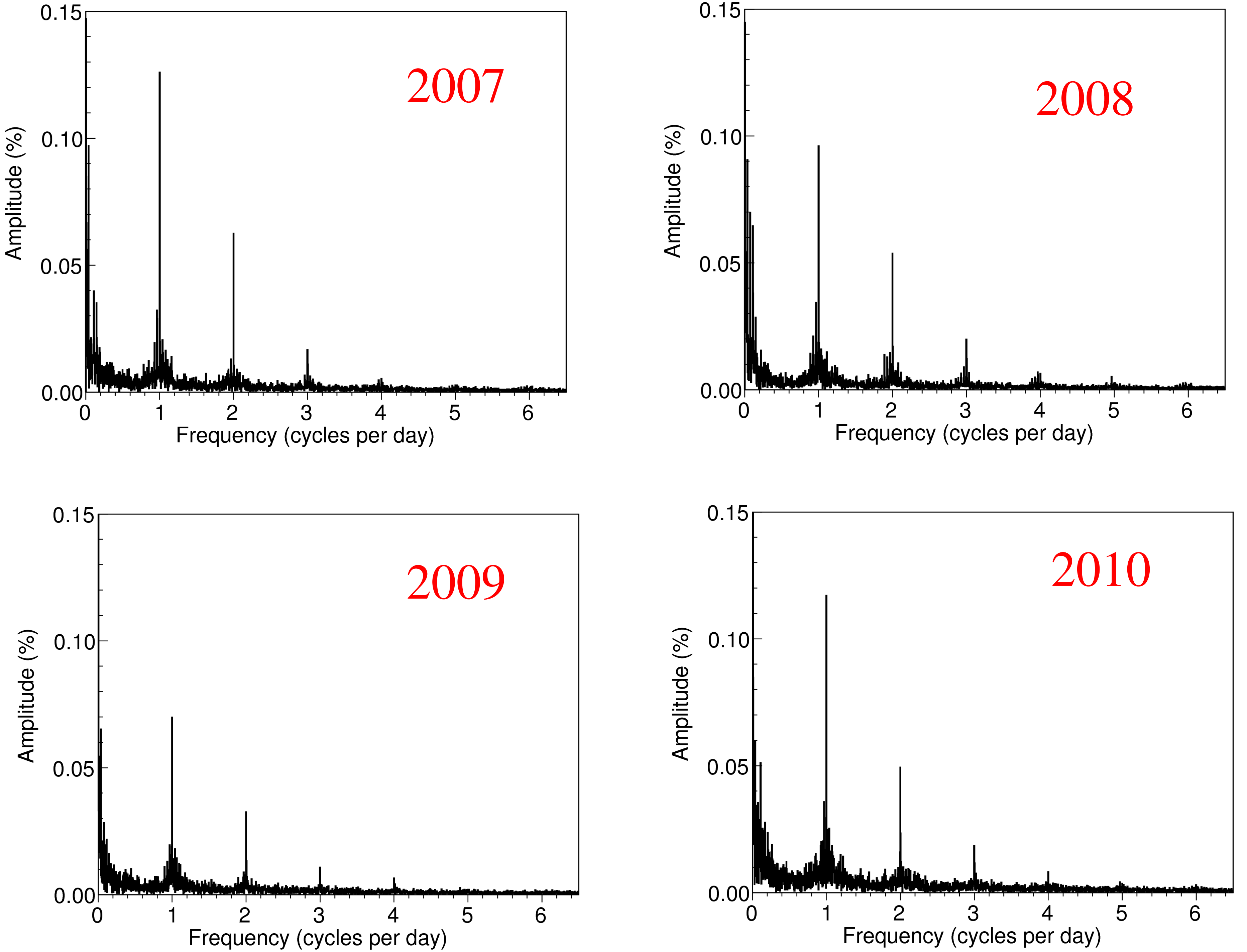
Rigidity dependence



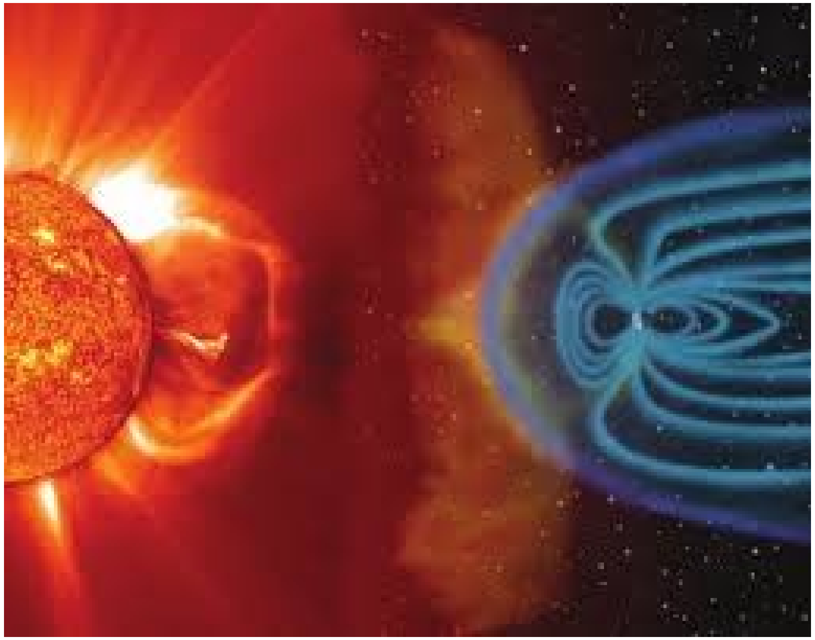
Comparison with similar experiment (2006 data)

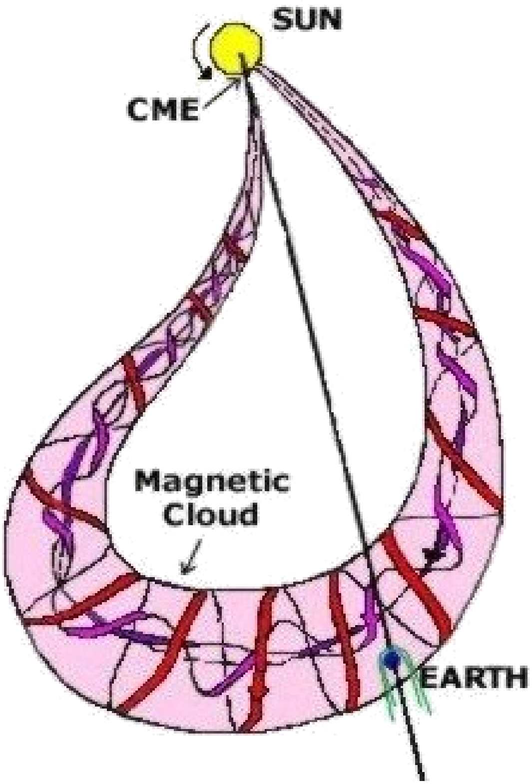
Harmonic	Amplitude (%)		Phase (hours)	
	GRAPES-3	Nagoya	GRAPES-3	Nagoya
1	0.132%	0.105%	12.4 h ± 0.3 h	12.3 h
2	0.054%	0.051%	12.4 h ± 0.3 h	12.7 h
3	0.014%	0.017%	12.7 h ± 0.2 h	12.7 h
4	0.004%	----	12.9 h ± 0.2 h	------

Solar Diurnal Harmonics 2007 - 2010



Coronal Mass Ejection (CME)

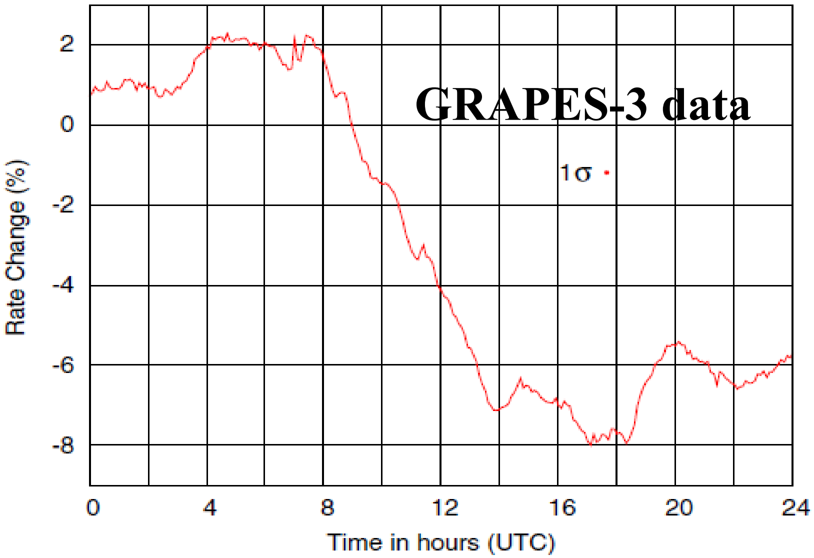




Strong Southward oriented IMF favors magnetic reconnection process which can trigger severe geomagnetic storm that can cause failure of large power grids, satellite communications, radio blackouts.

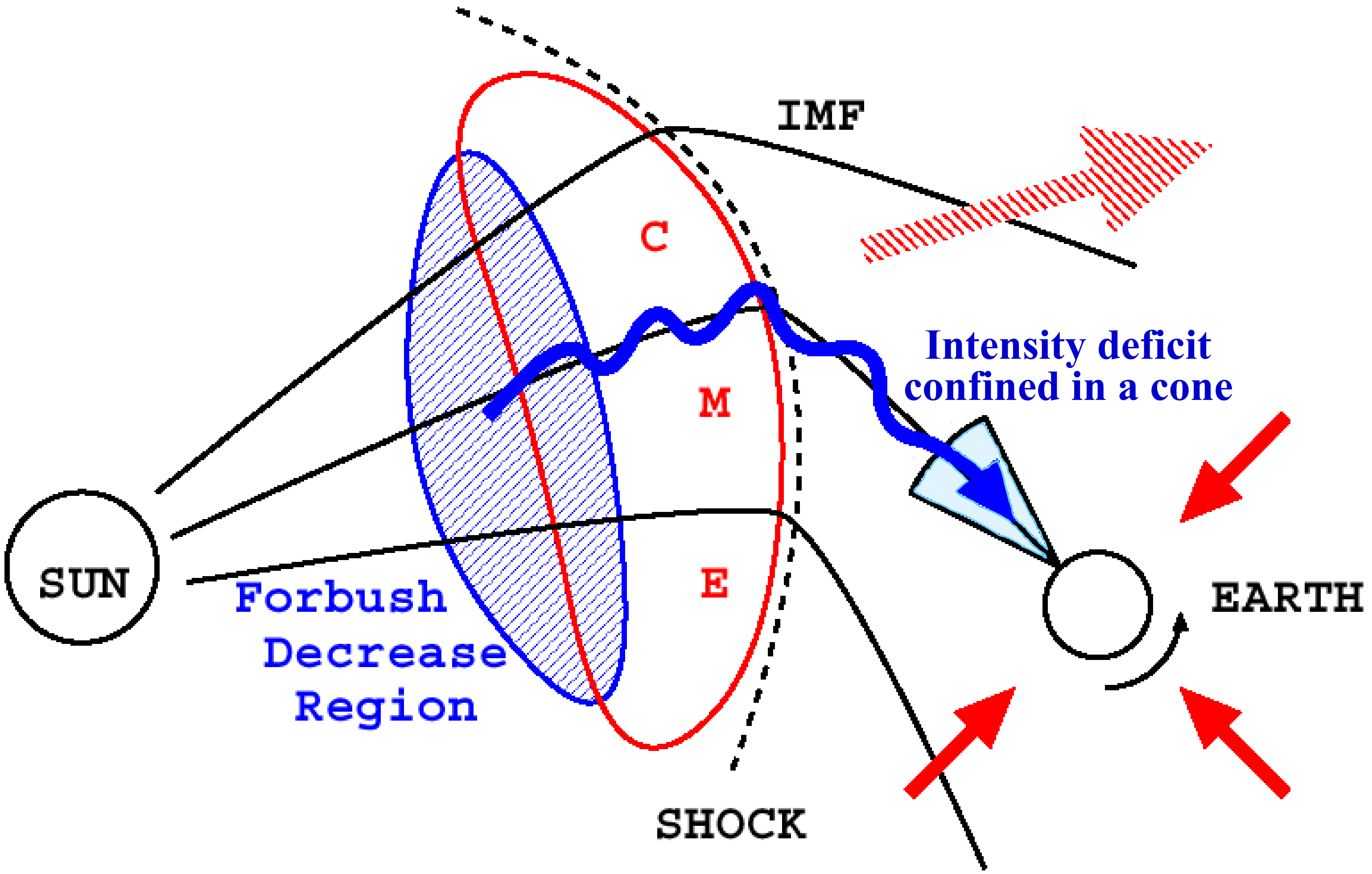
Spacecrafts such as ACE, WIND which are located ~ 1.5 million km (L1 point) can provide advance intimation of CME of about an hour

Forbush decrease (29th October 2003)



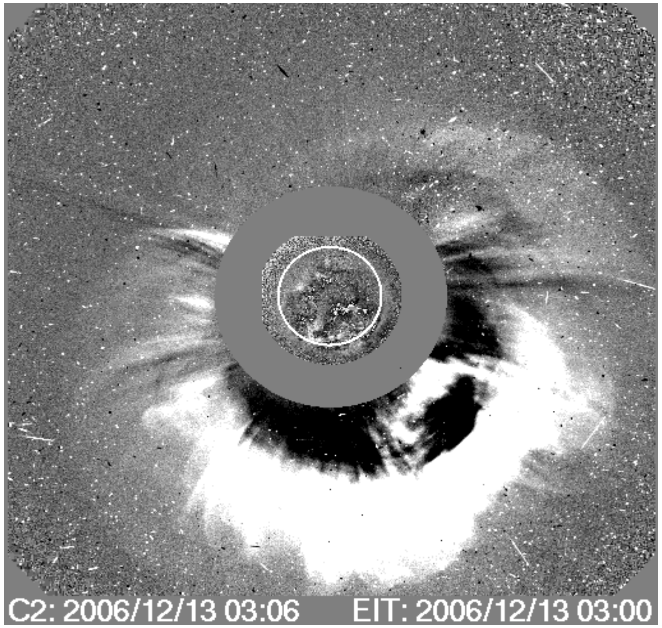
T. Nonaka et al., PRD, 74 (2006) 052003

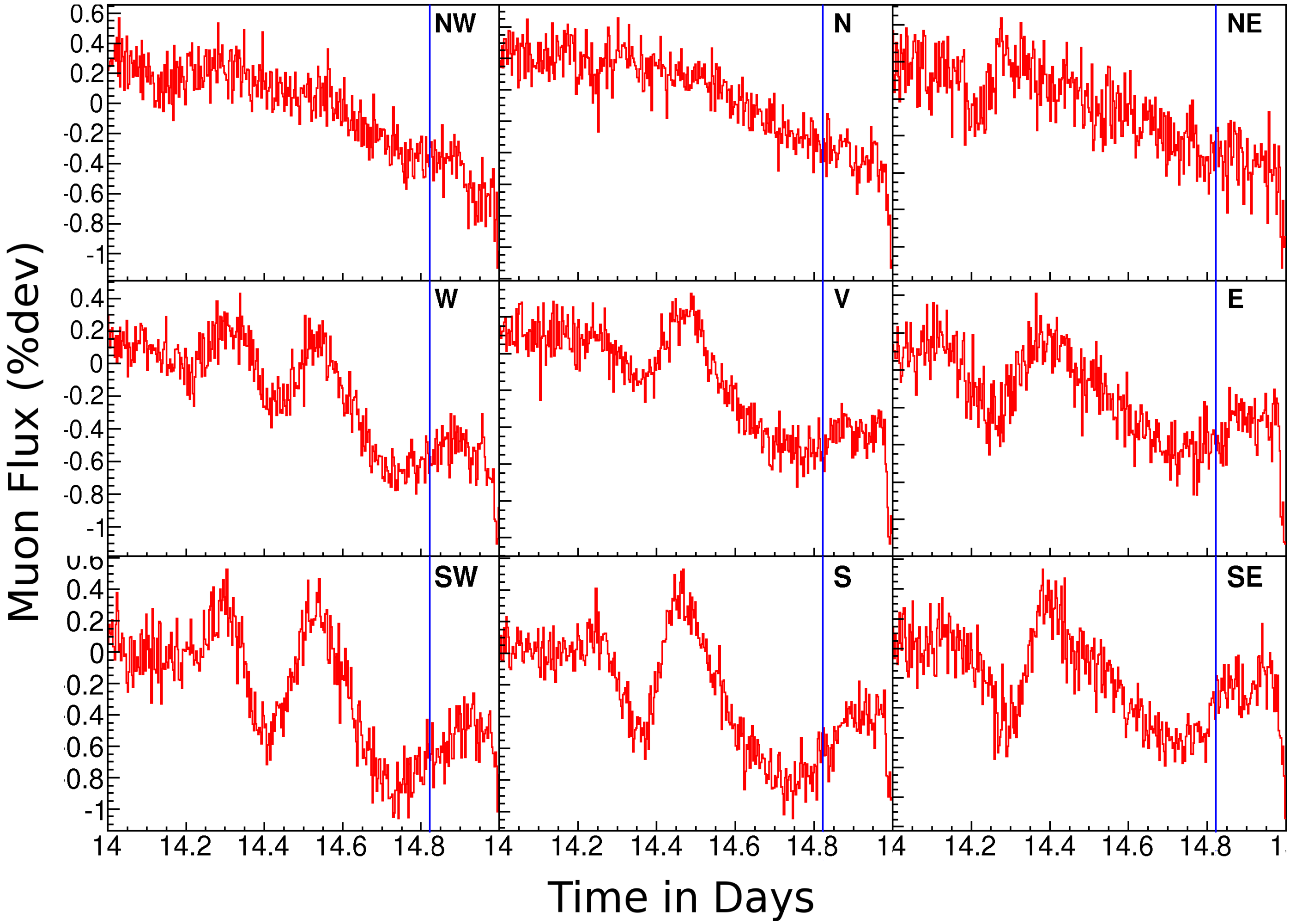
Loss Cone Precursor to an ICME



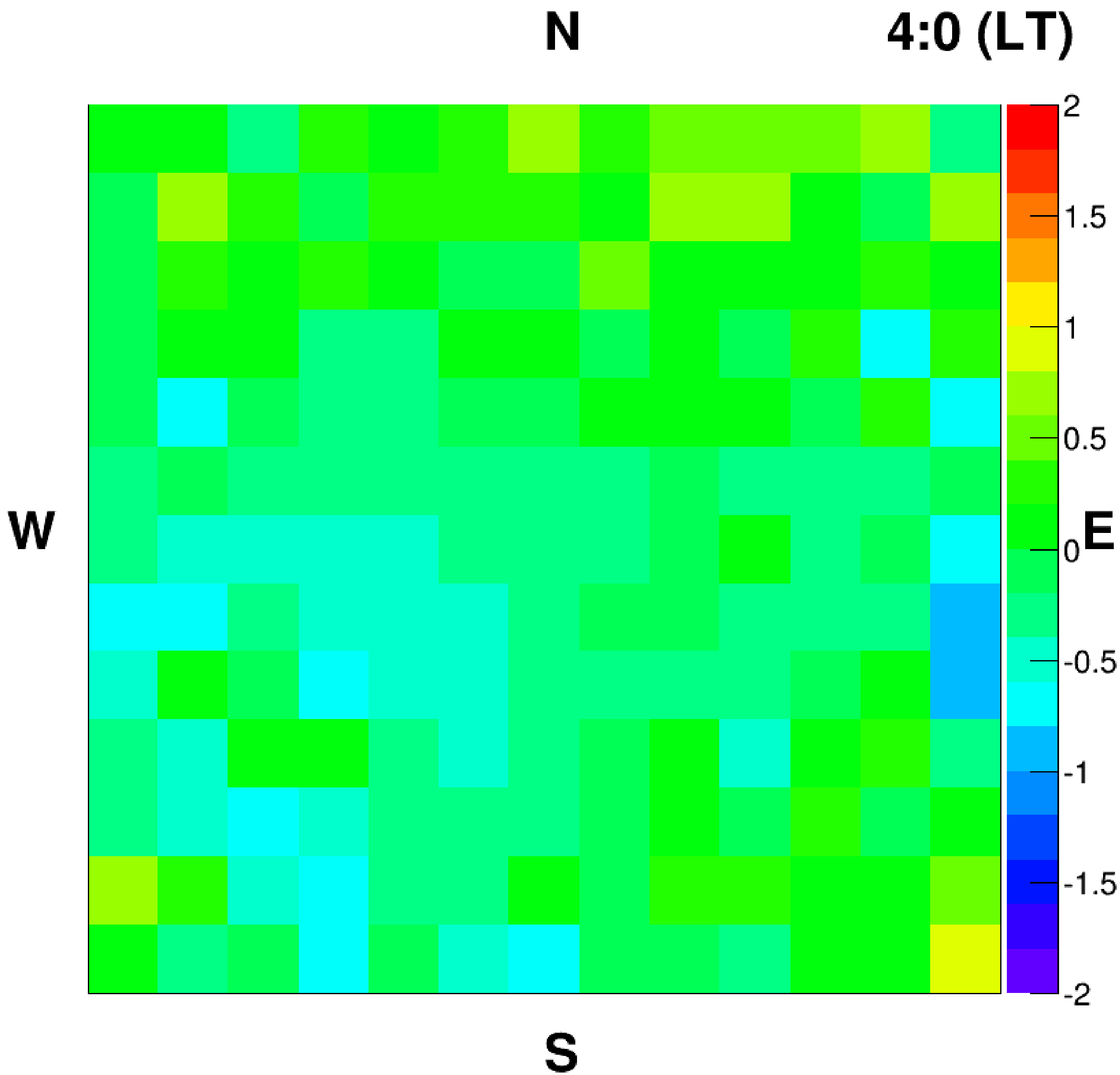
Precursors detected by muon telescopes can provide advance warning more than 5 hours.

Precursor observed by GRAPES-3 on 14 December 2006

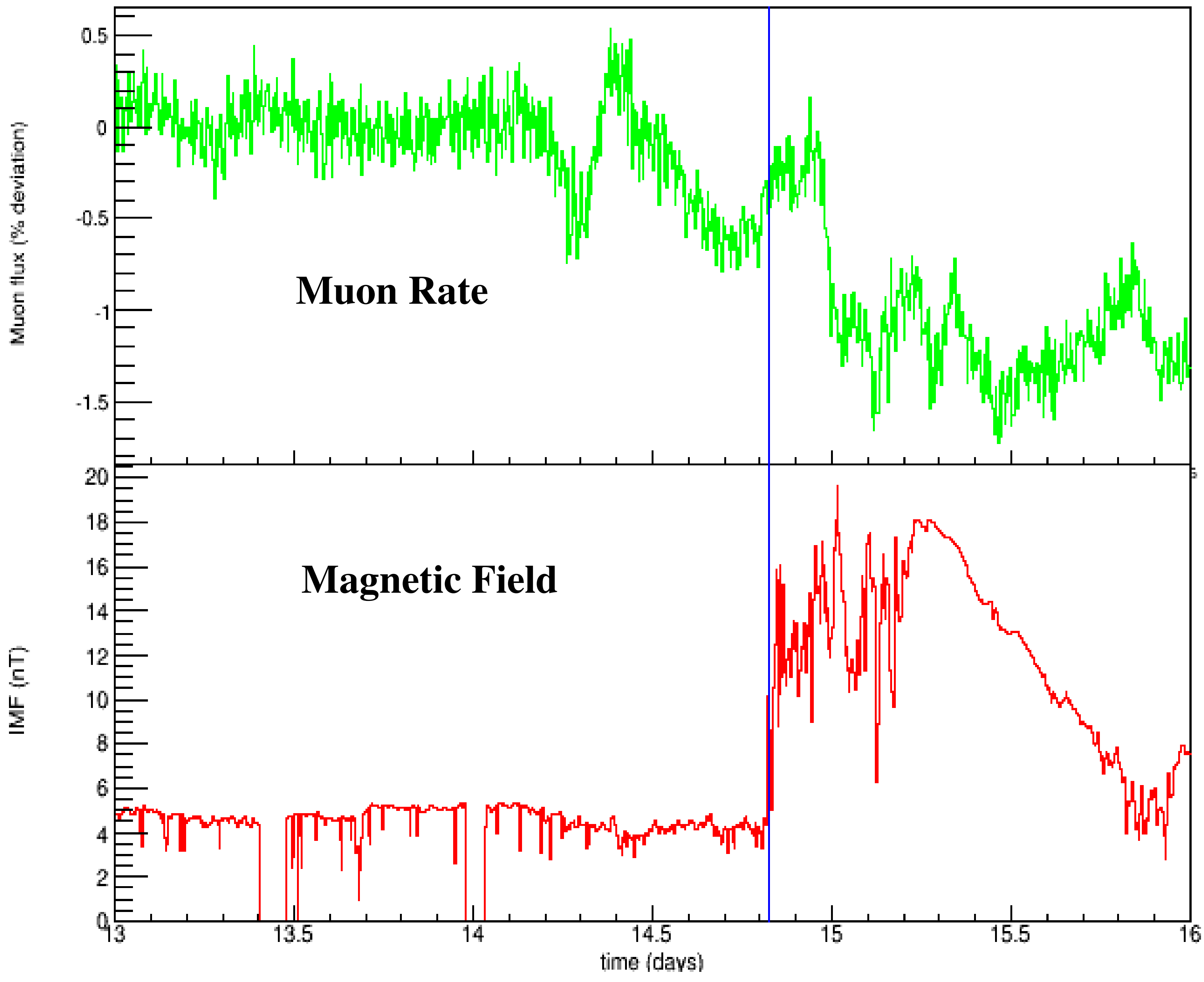




Precursor on 14 December 2006

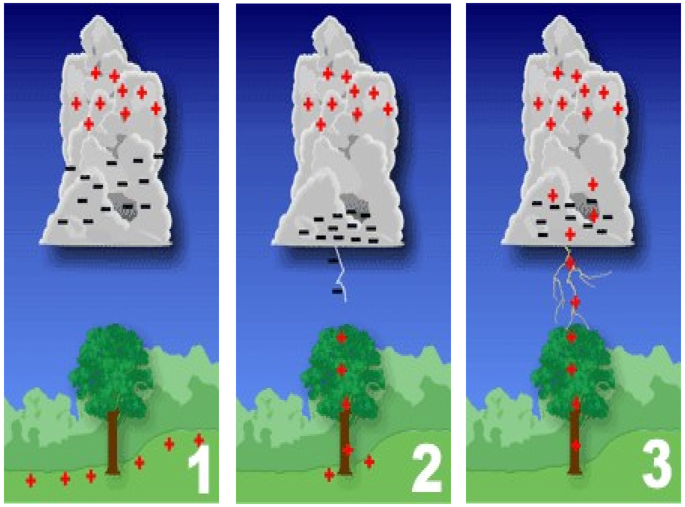


Precursor on 14 December 2006



Thundercloud acceleration

Thunderclouds may gain potential ~ Giga-Volts turning the atmosphere into a giant natural particle accelerator

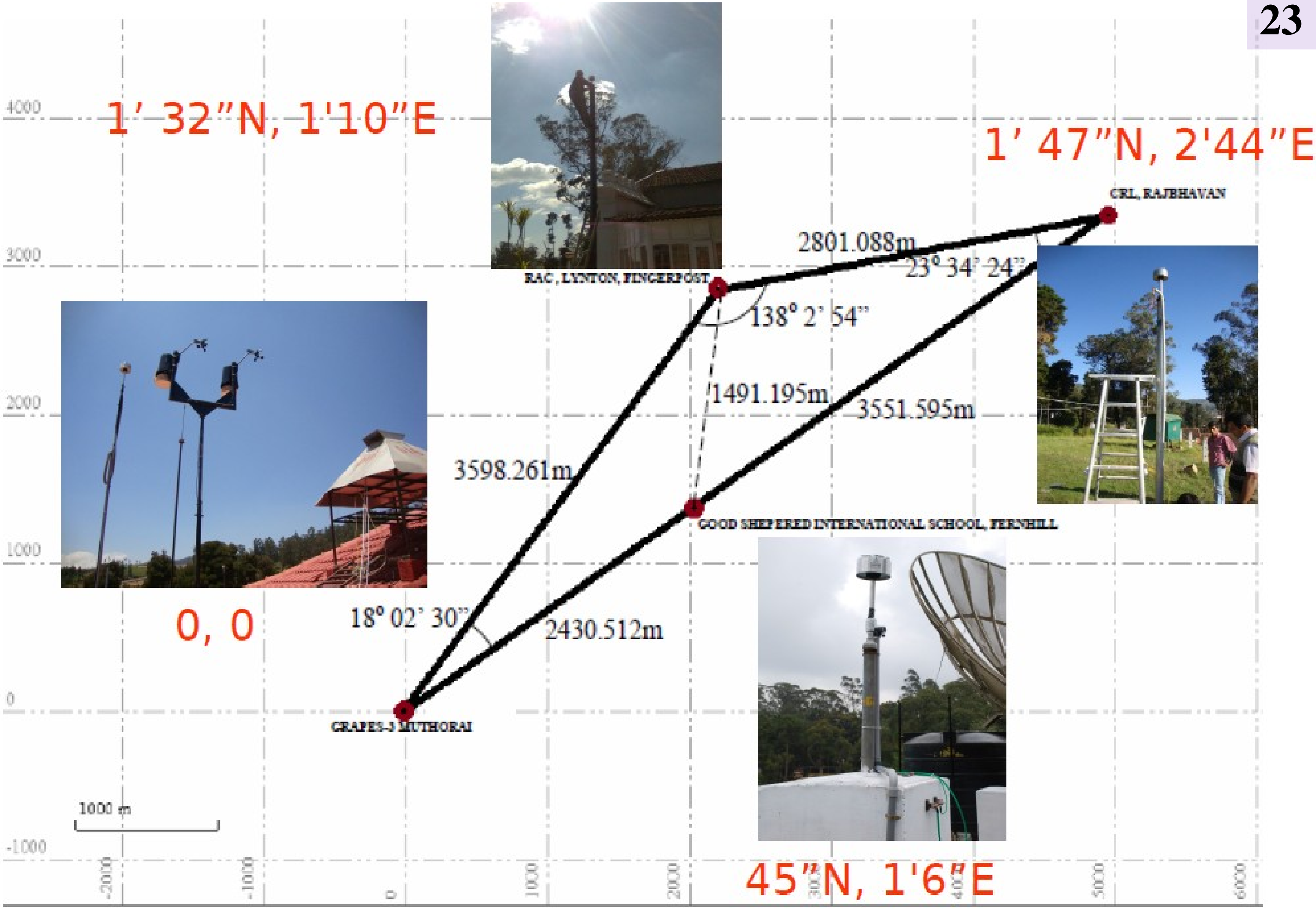


C. T. R. Wilson, the acceleration of beta-particle in strong electrical fields of thunderclouds, Proc. Cambridge Philos. Soc. 22, 534, (1925).

Terrestrial Gamma Ray Flashes (TGFs)

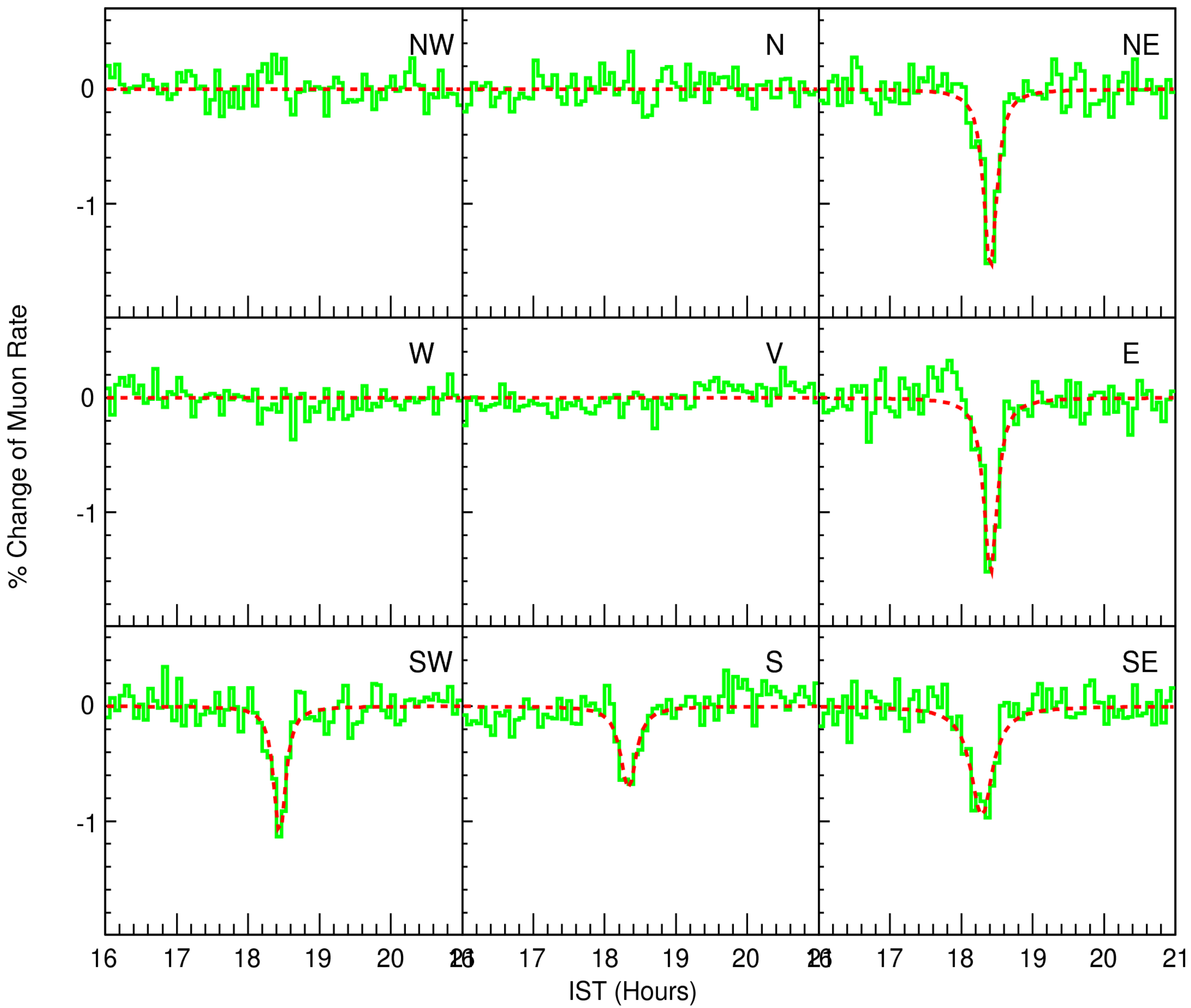
First observation by BATSE in CGRO (Fishman, Science, 264 (1994) 5163)

Recent observation by AGILE up to 100 MeV (Tavani, PRL, 106 (2011) 018501)

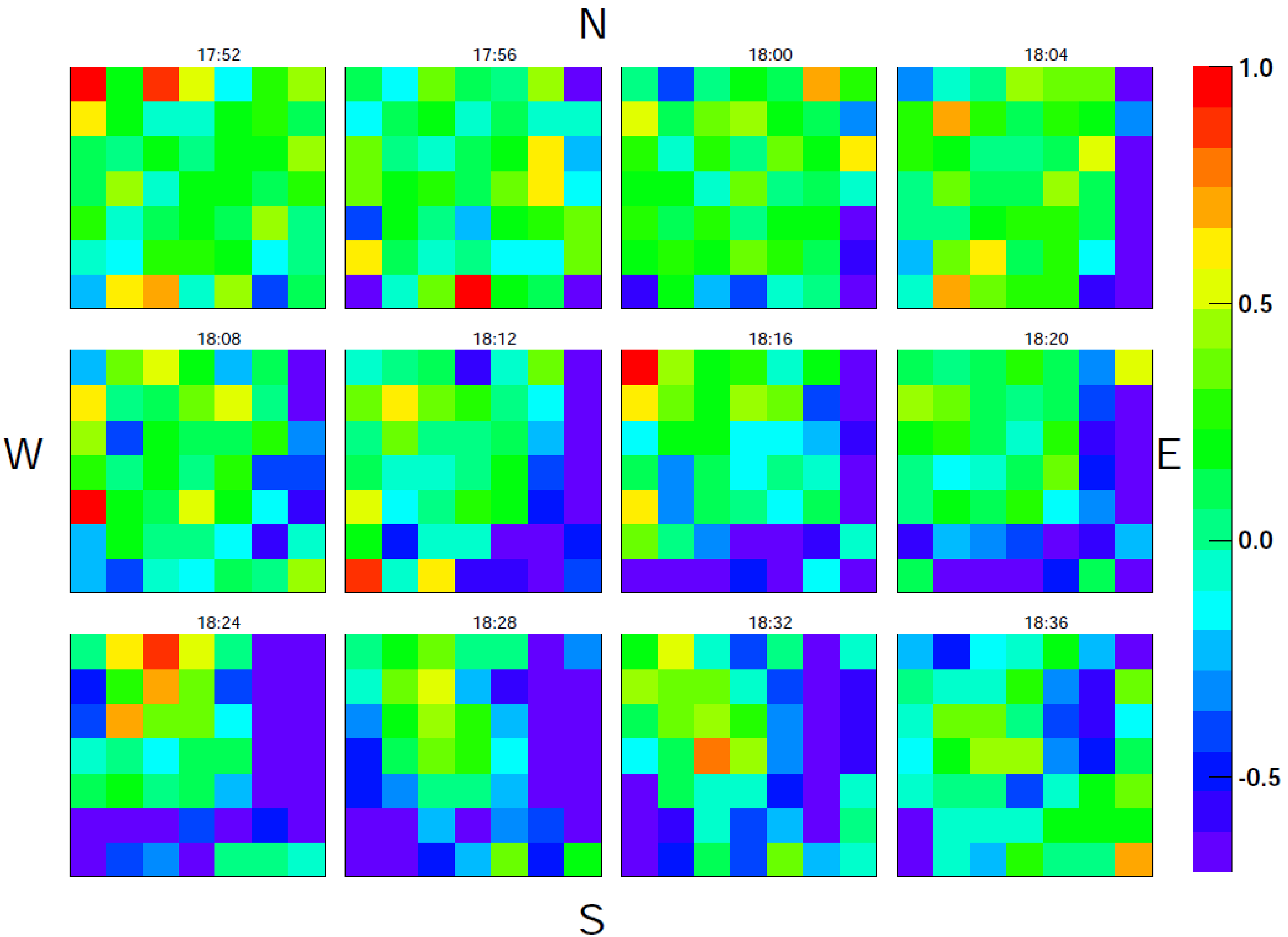


GRAPES-3 Lat. = 11° 23' 26" N Long. = 76° 39' 50" E

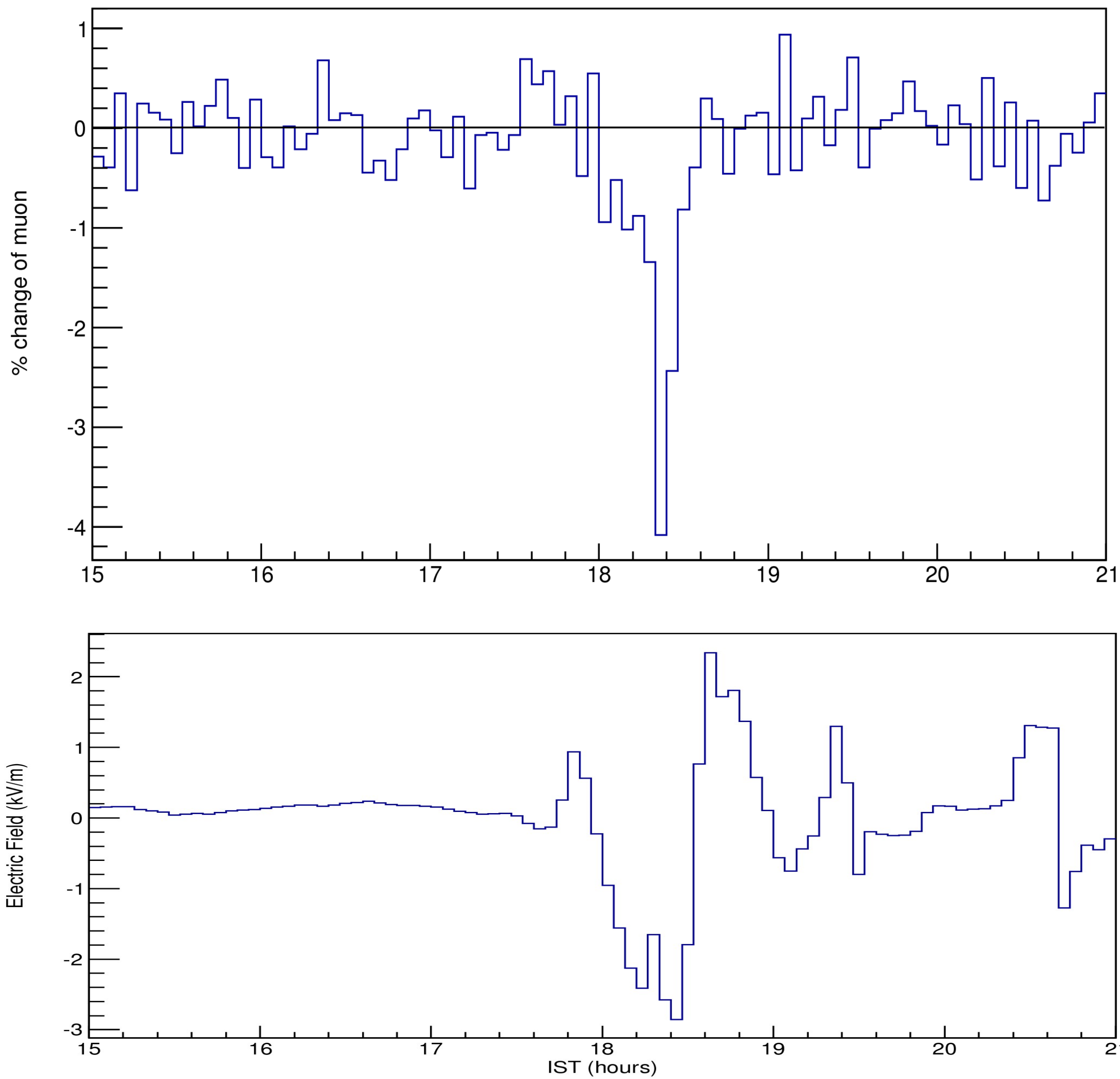
30 Sept 2015 Event



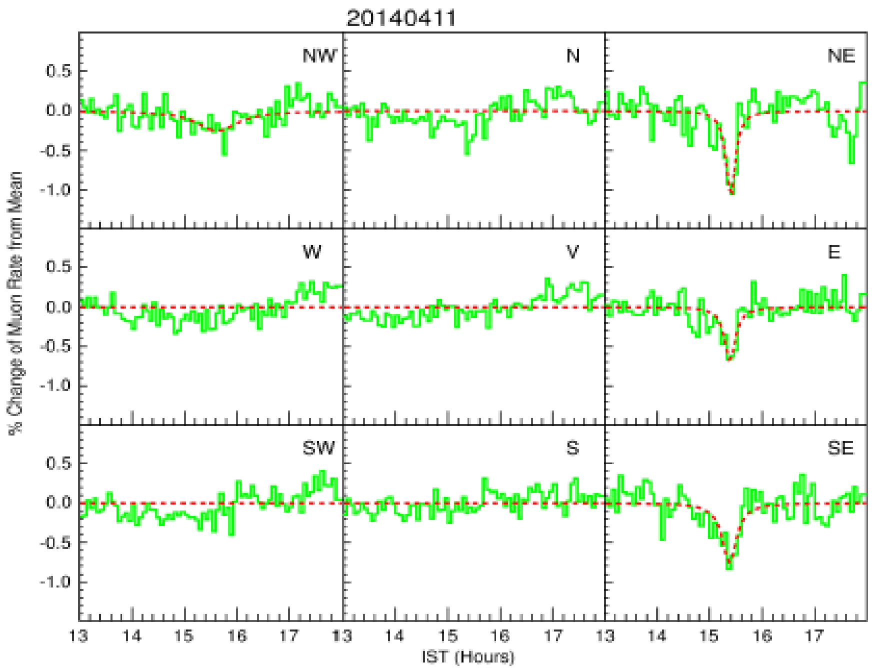
30 Sept 2015 Event

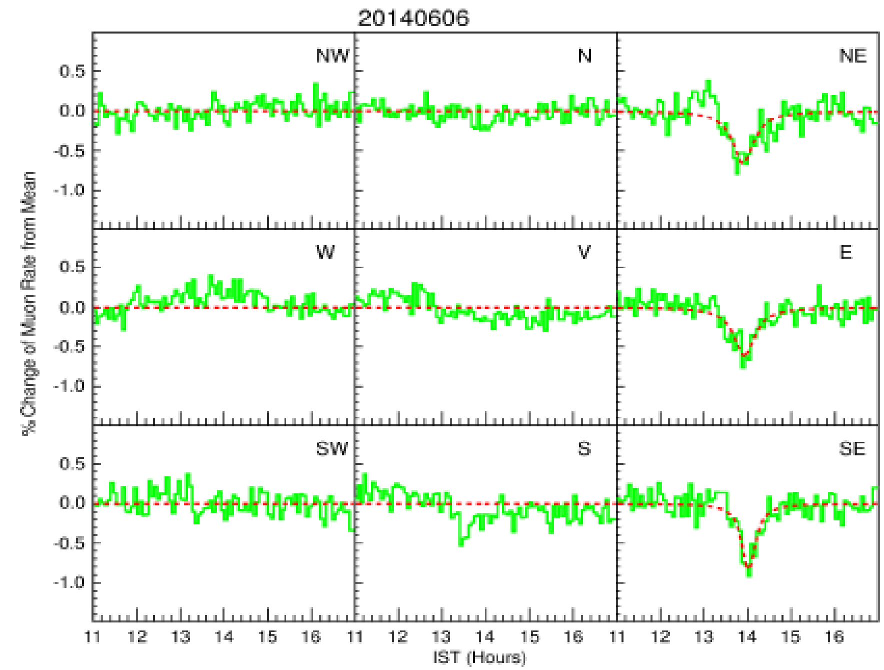


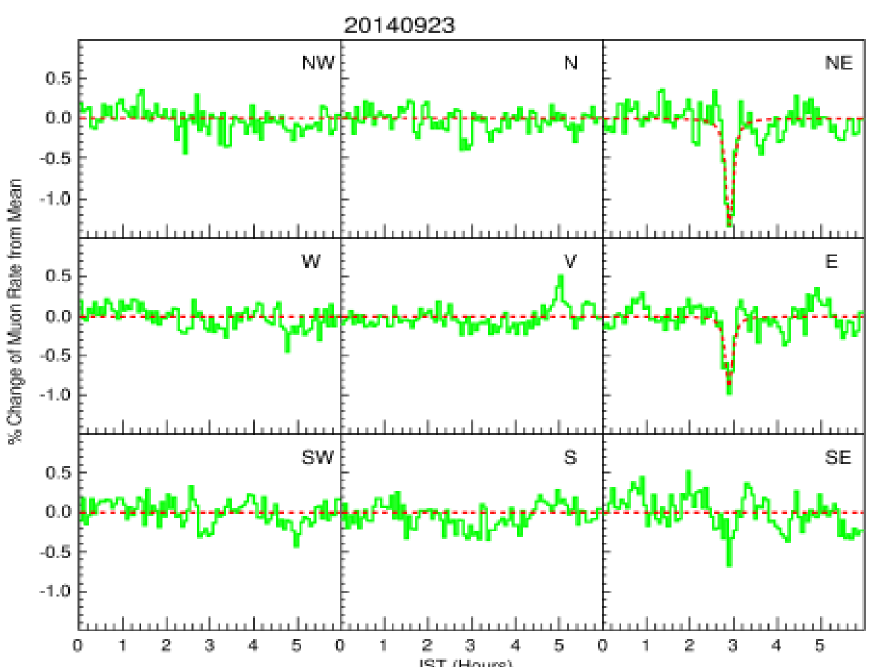
30 Sept 2015 Event

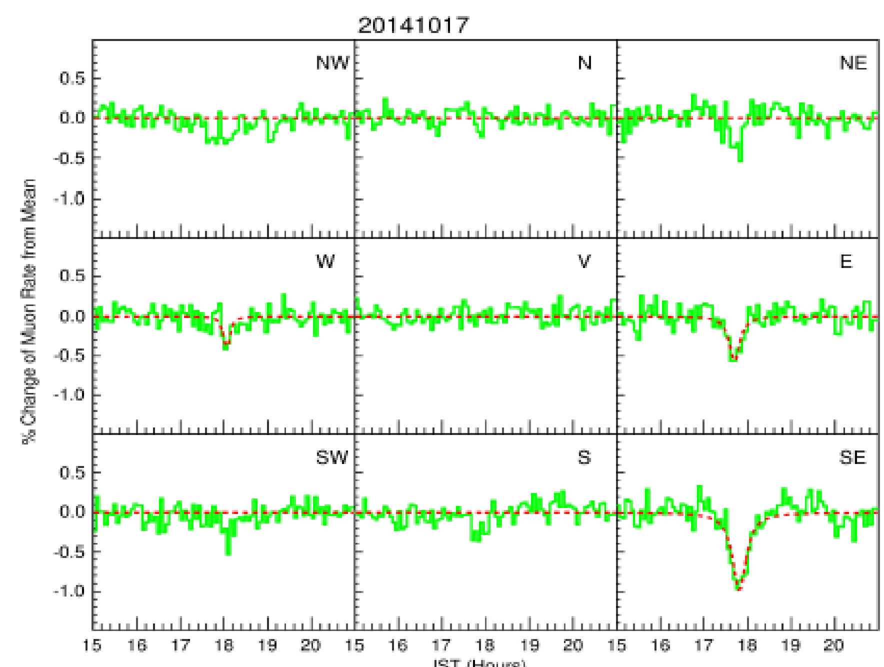


Events mainly from eastern directions









Events during 2006 to 2010

NW 11	N 06	NE 59
W 01	V 01	E 07
SW 15	S 03	SE 80

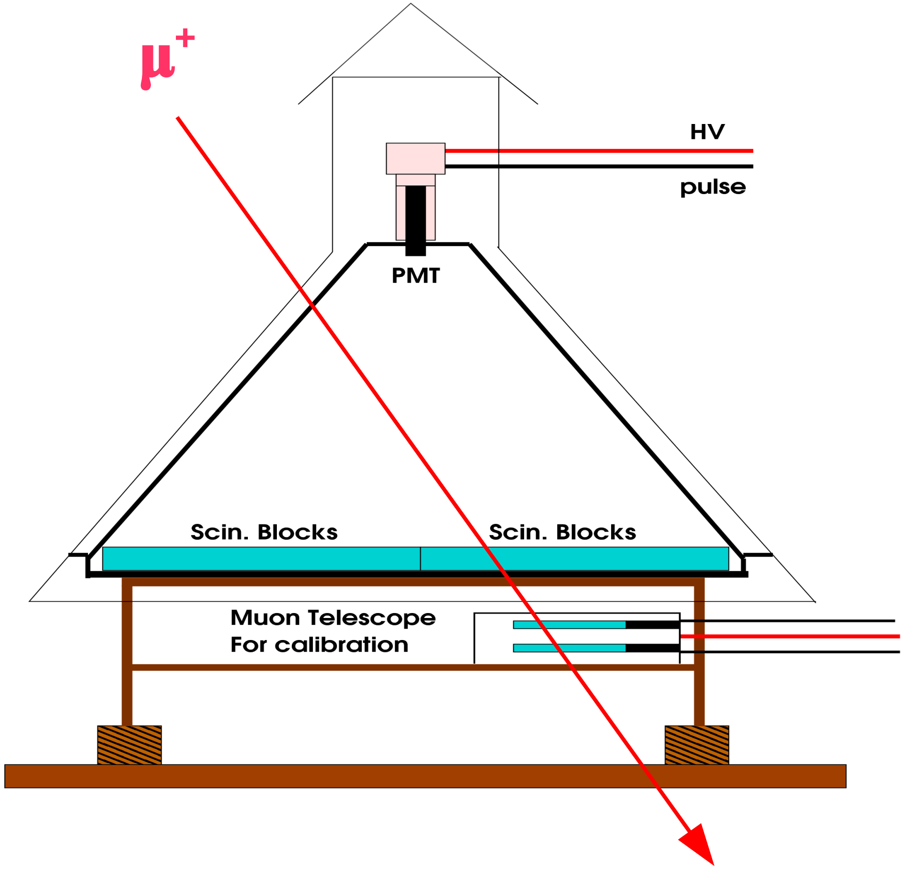
Events from eastern direction: 146/183 = 80%

PART – II

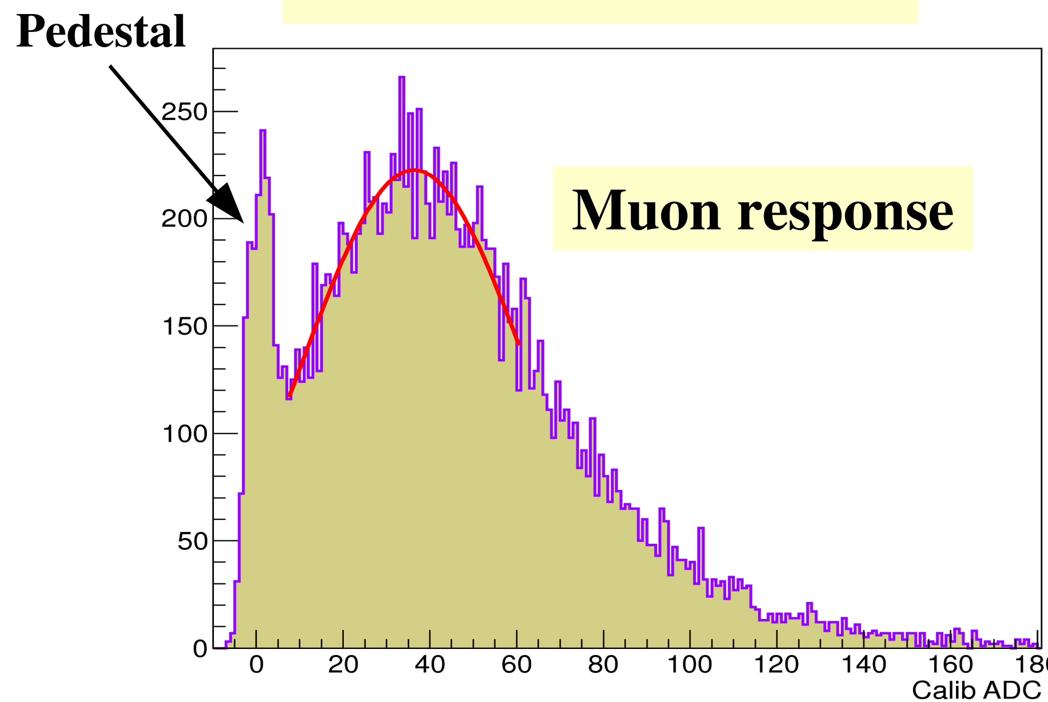
R&D of scintillator detectors

GRAPES-3 data analysis framework

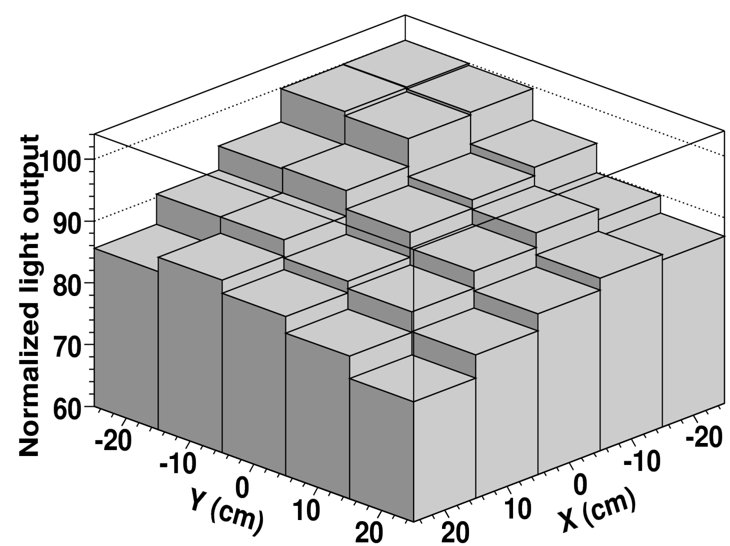
Old scintillator detector



Low Photo-electron Yield (3-5)
(Poor Signal to Noise Separation)



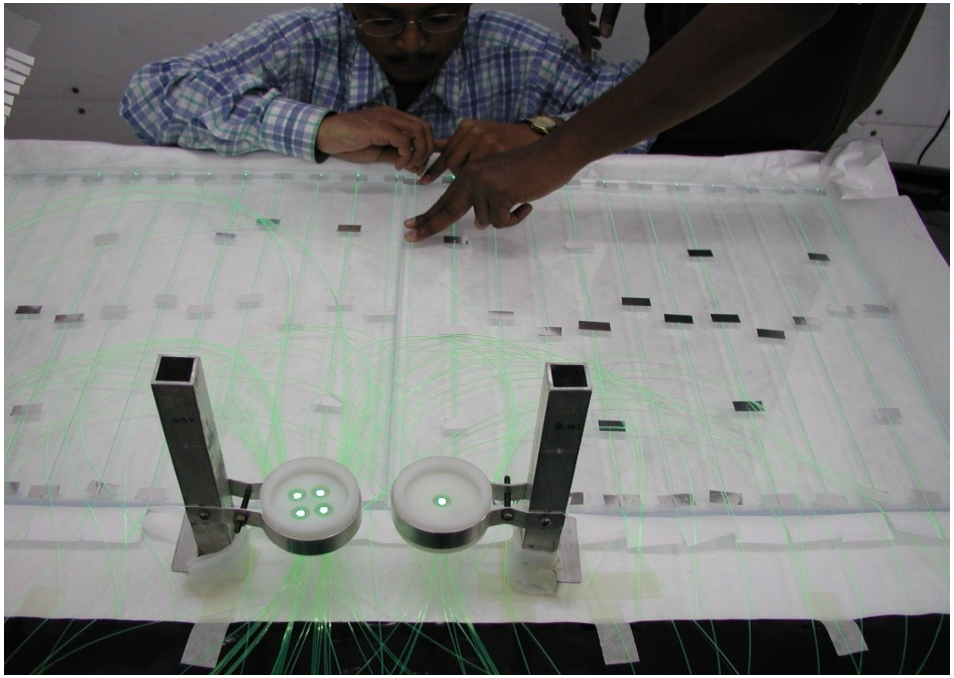
Large Non-uniform Response (~ 30%)



Expansion of the Array with a better detector

- Increase photo-electron yield
- Better spatial uniformity
- Increase the dynamic range
  (to several thousands particles / m^2)

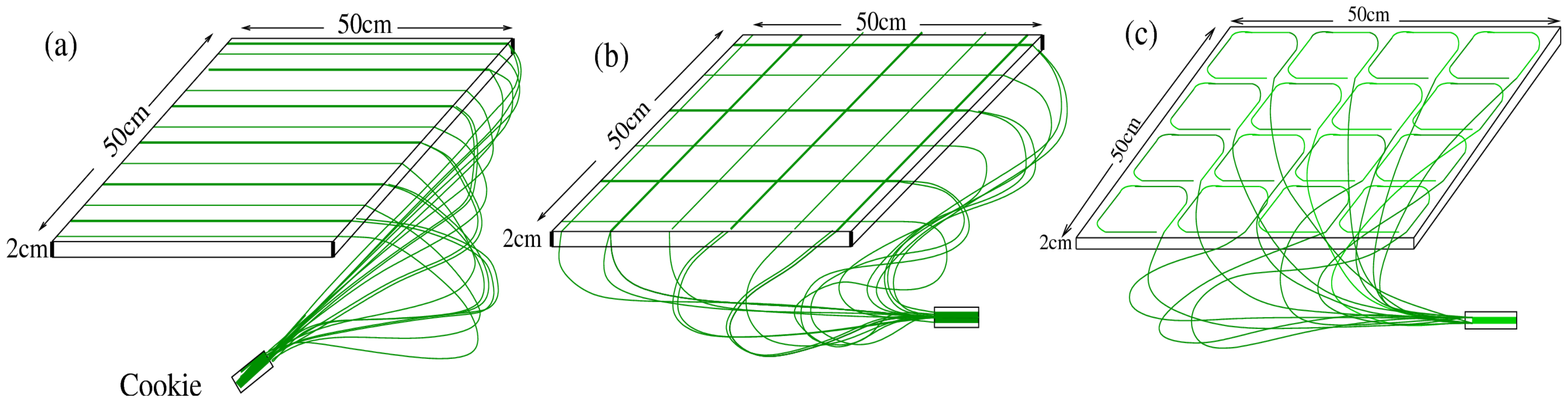
New design



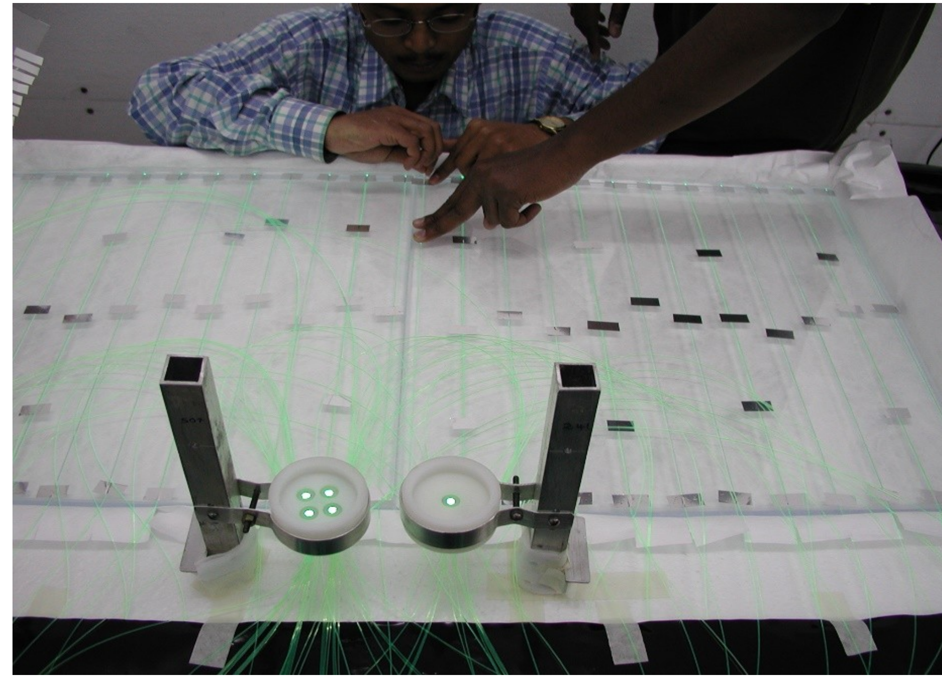
Parallel

Matrix

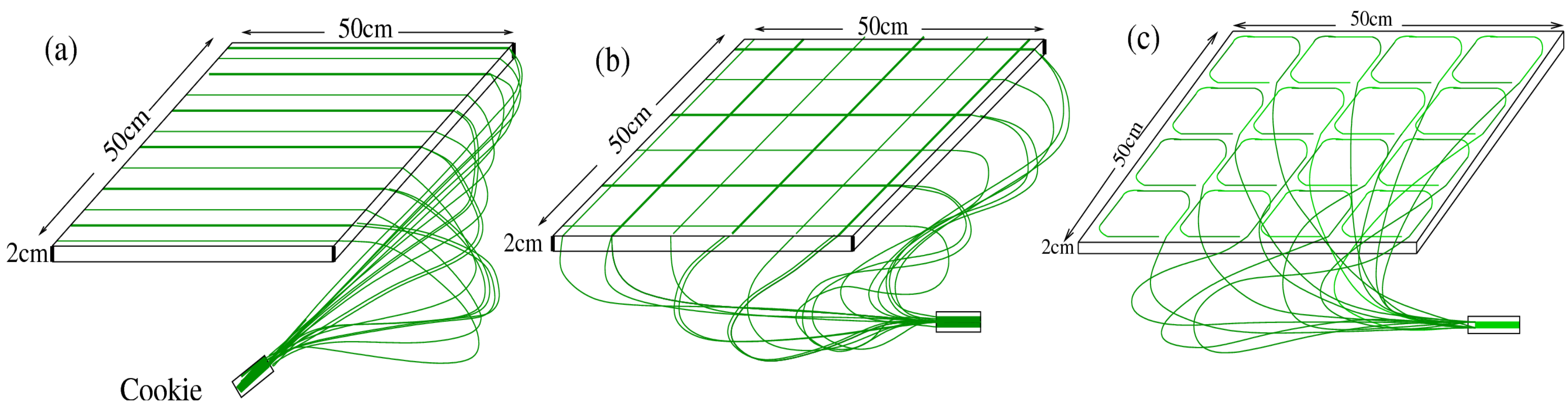
σ



New design

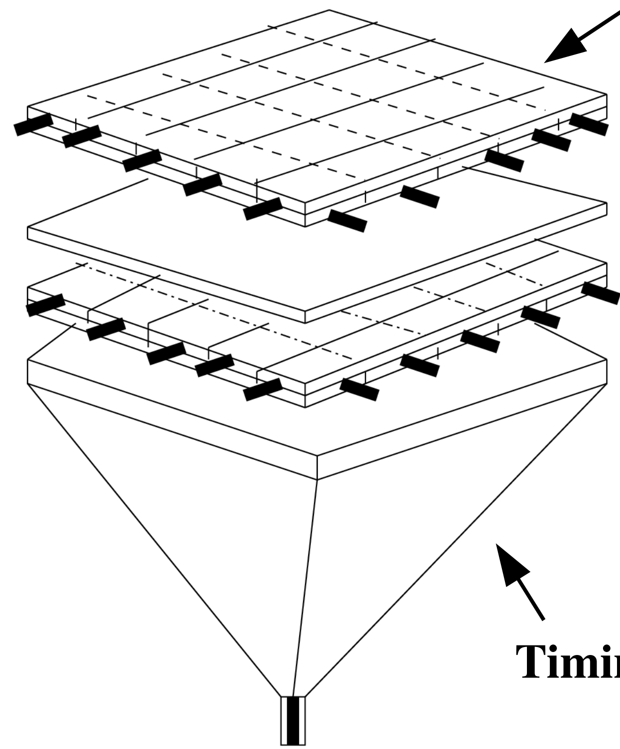


Parallel **Matrix** **σ**



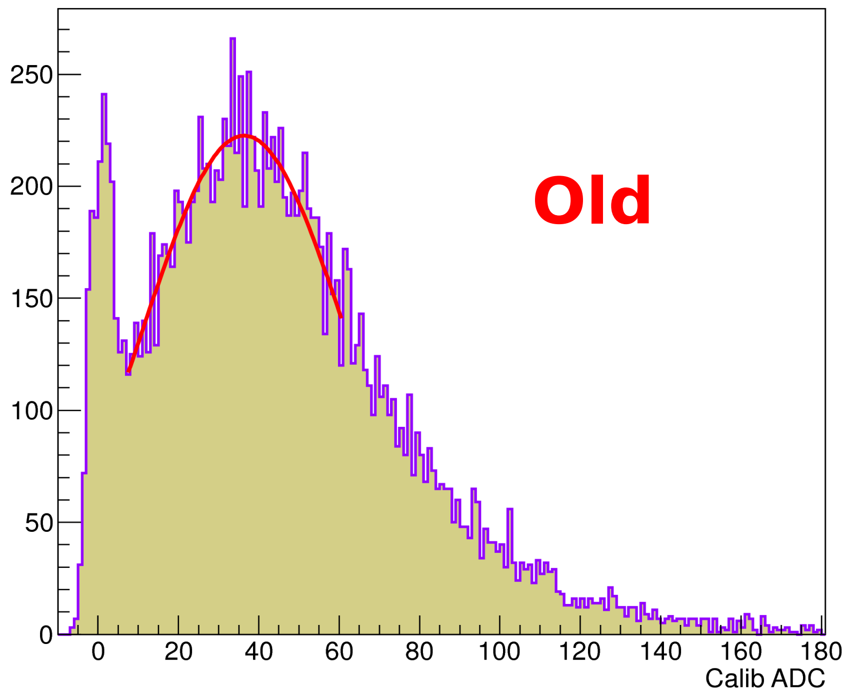
Measurement set-up

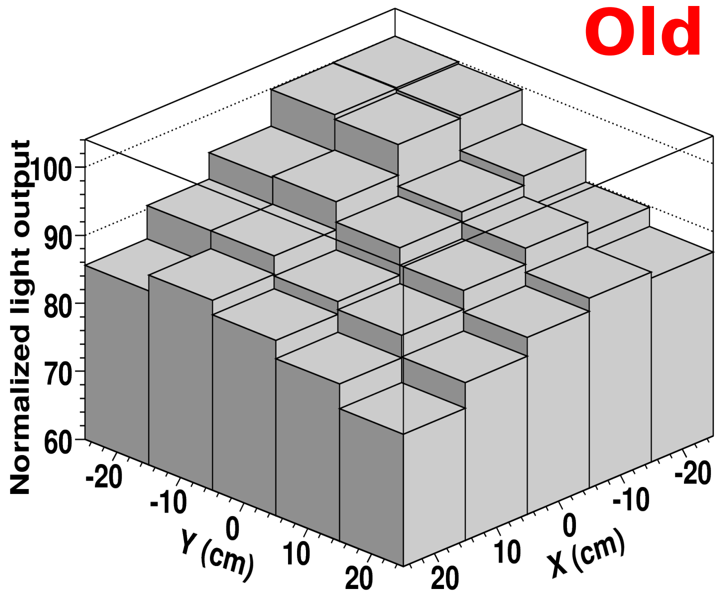
Muon trigger set-up

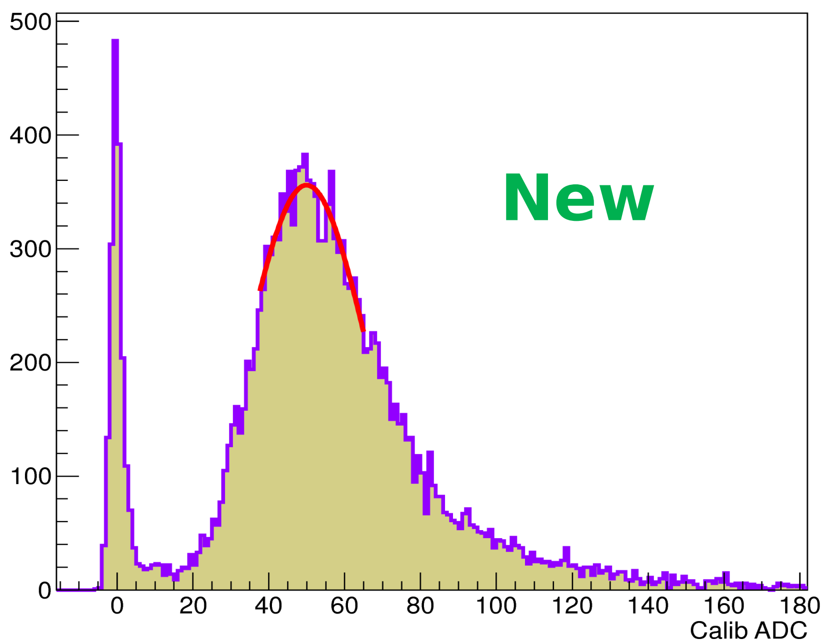


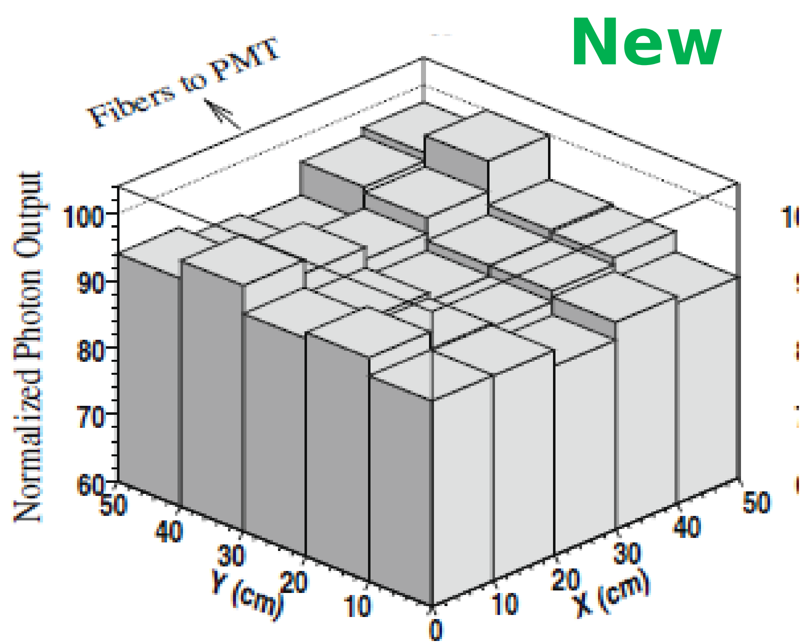
Measurement Parameters

1. Photon yield
2. Uniformity
3. Time Response









P.K. Mohanty et al. Astropart. Phys. 31 (2009) 24

Monte Carlo simulation: G3sim

1: Generation and propagation of muons

$$\frac{dN_\mu}{d\Omega} \propto \cos^2\theta.$$

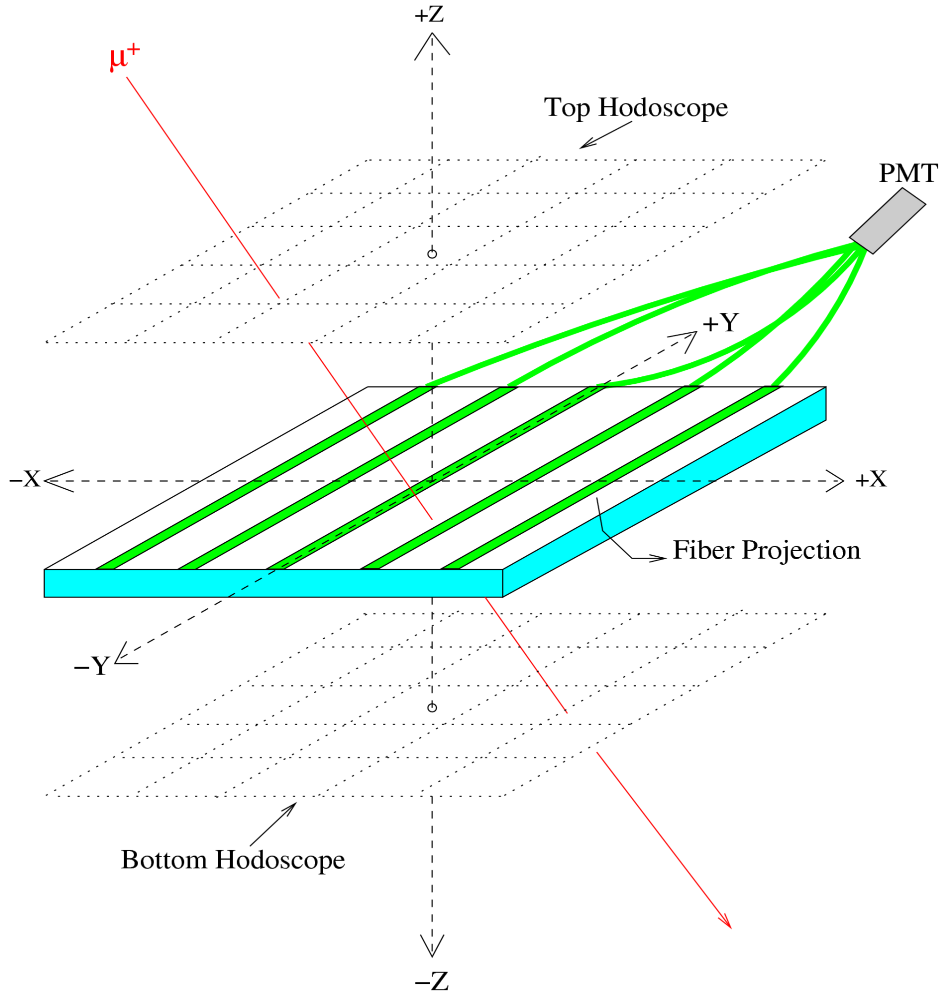
2: Energy loss (dE/dX) calculation using Landau distribution

3: Generation of photons in scintillator.

4: Propagation of photons in scintillator using basic laws of reflection and considering attenuation loss and loss due to imperfect surface

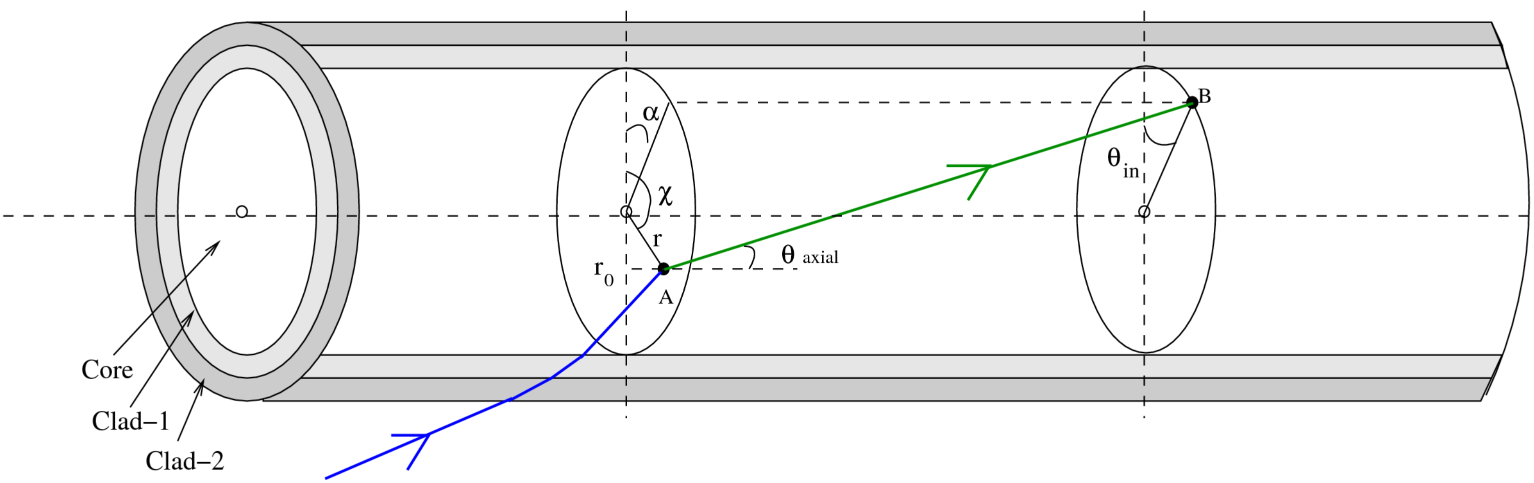
5: Capture, trapping and propagation of photons in WLS fiber considering meridional and skew ray modes

6: Convolution of PMT responses.



Probability distributions and uniform random numbers (0 to 1) used to model each process

Photon Trapping in Fiber



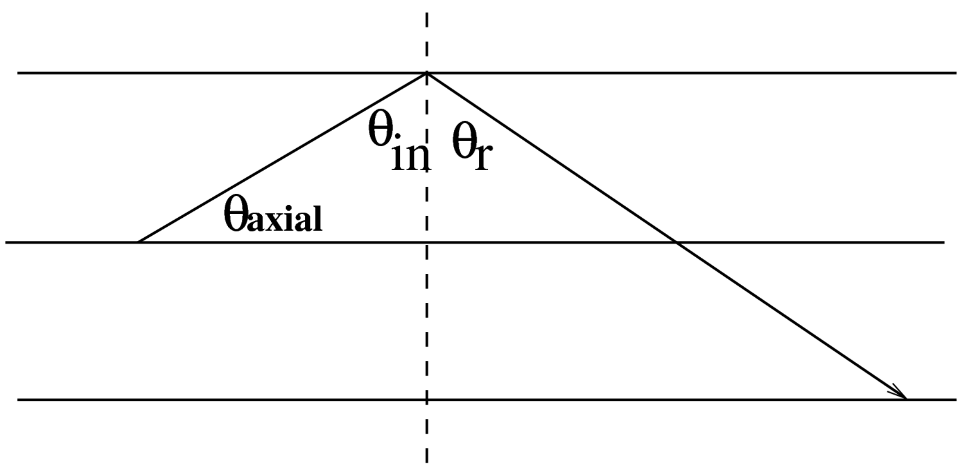
Core: 0.94mm
Refractive index = 1.59

Inner clad: 0.03mm
Refractive index = 1.49

Outer clad: 0.03mm
Refractive index = 1.42

Meridional rays

Incident, normal and reflected ray lie in the same plane



$$\cos(\theta_{in}) = \sin(\theta_{axial})$$

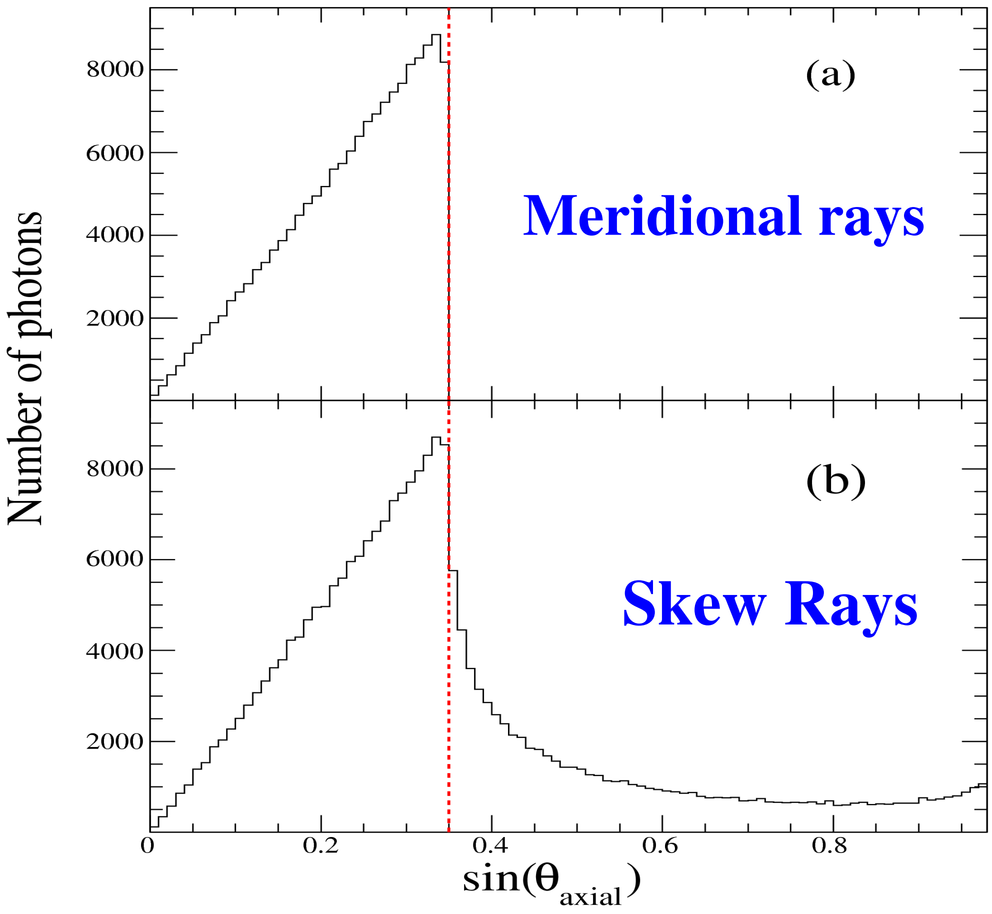
Skew Rays

do not lie in the same plane

$$\sin(\theta_{axial}) = \cos(\theta_{in})\left\{1 + \left(\frac{r/r_0 \sin(\chi - \alpha)}{1 - r/r_0 \cos(\chi - \alpha)}\right)^2\right\}^{1/2}$$

Ref: N.S. Kapany, Fiber Optics: Principles & Applications, Academic Press London & New York (1967)

Axial angle distribution of trapped photons



Trapping Efficiency of meridional rays = 3.2 %

With inclusion of skew rays, trapping efficiency = 4.8%

Input parameters

TABLE I. Simulation parameters.

Photon conversion	100 eV
Maximum reflections	150
Scintillator ETIR	0.93
Tyvek reflectivity	0.90
Fiber reflectivity	0.9999
Path-length step	0.01 cm
λ_{scint}	100 cm
λ_{WLS}	350 cm
η_{scint}	1.59
η_{core}	1.59
η_{clad-1}	1.49
η_{clad-2}	1.42
η_{air}	1.00
Min, Max (X Y Z)	−25 25 −25 25 −1 1 cm

Photon Statistics (50 cm x 50 cm x 2cm)

TABLE II. Photon statistics.

Produced in scintillator	46 000	
Escaped from scintillator	11 500	
Absorbed in scintillator	30 000	
Entered WLS fiber	4500	→ 10%
Escaped from WLS fiber	3850	
Trapped in WLS fiber	650	
Absorbed in WLS fiber	450	
Arrived at the PMT	200	→ 0.4%

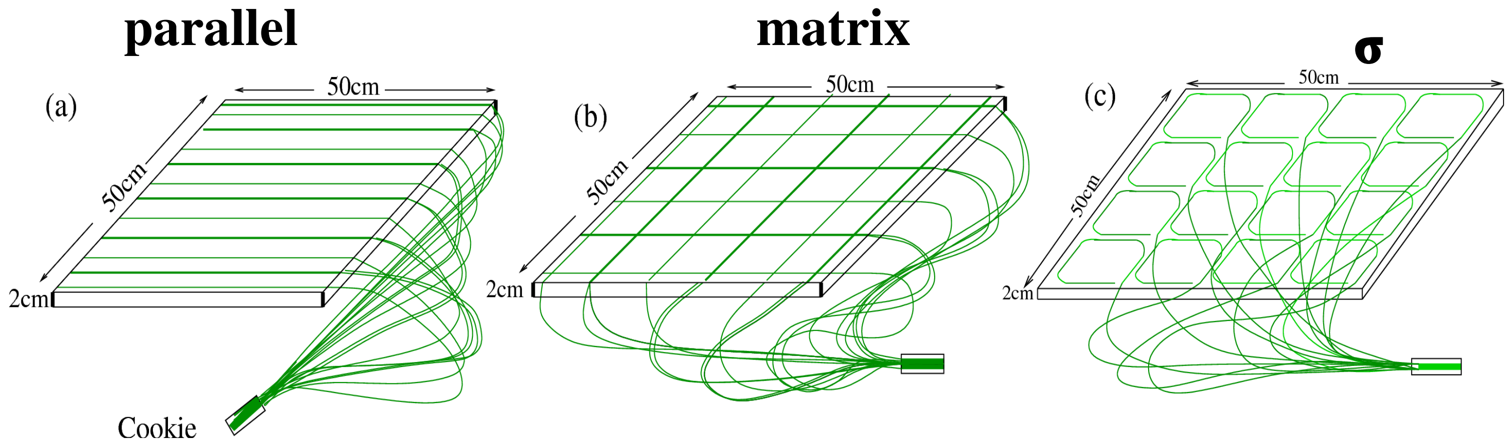
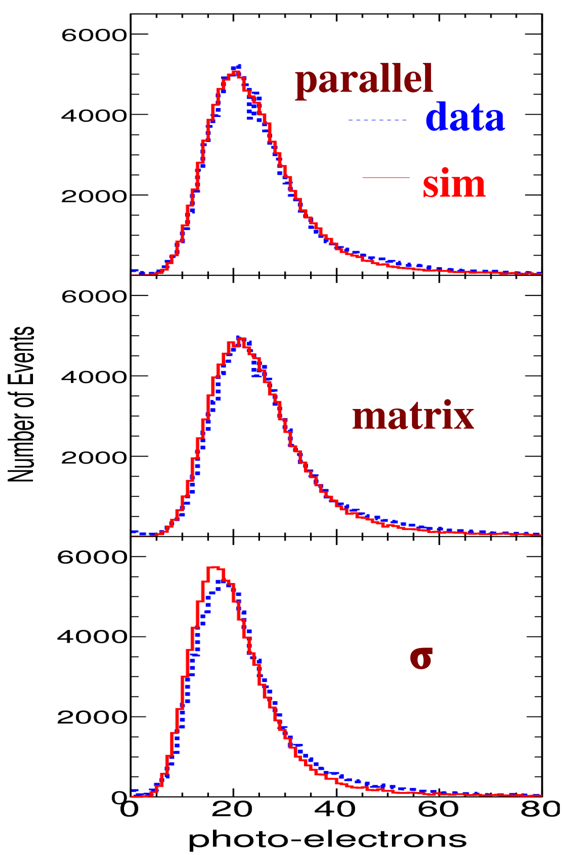
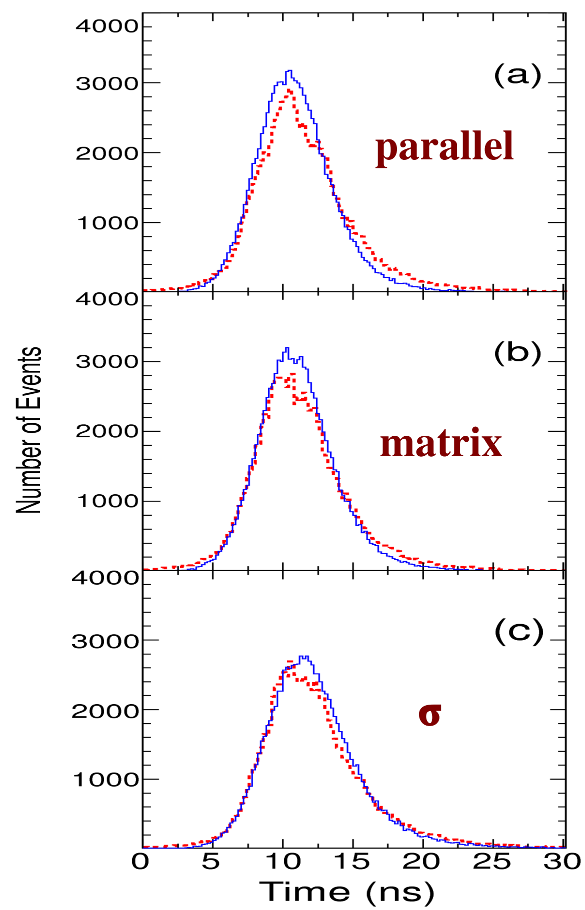


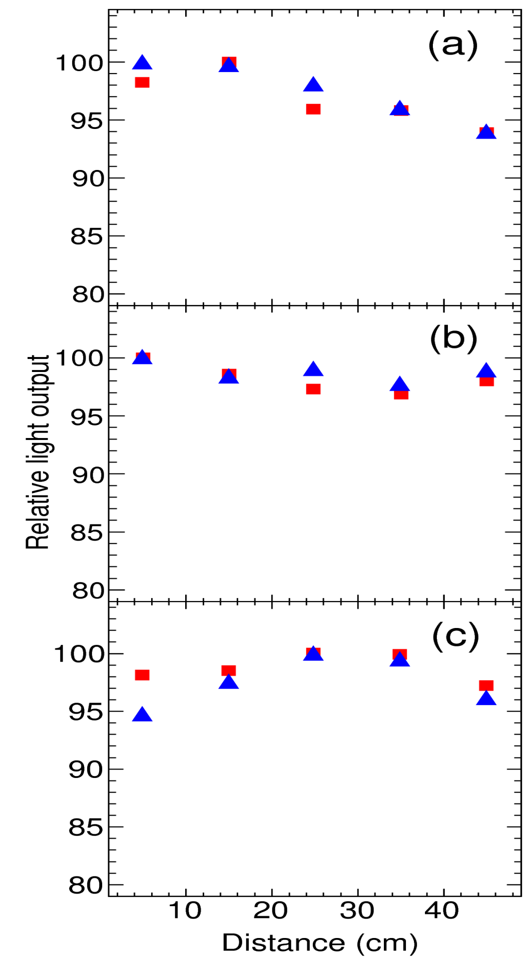
Photo-electron Yield



Time Response



Uniformity



Summary of groove comparisons

Photo-electron yield

Groove	Fiber-length(cm)	Photo-electrons
Parallel	900	20.5
Matrix	900	21.7
σ	656	17.9

RMS non-uniformity (%)

Groove	Experiment	Monte Carlo
Parallel	2.7	2.0
Matrix	2.1	1.6
σ	3.5	3.3

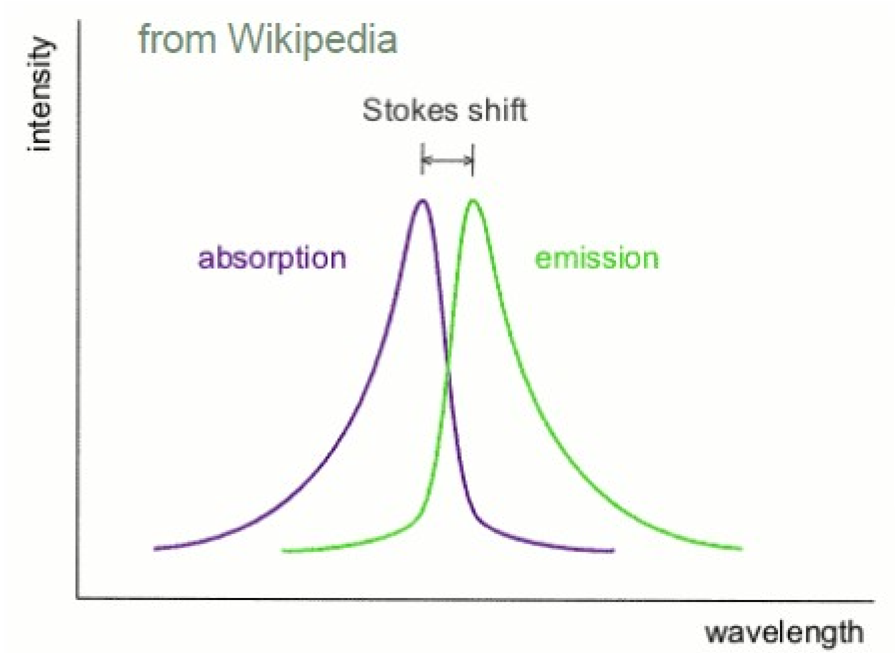
Time Response (ns)

Groove	Experiment	Monte Carlo
Parallel	2.5	2.3
Matrix	2.4	2.3
σ	2.4	2.4

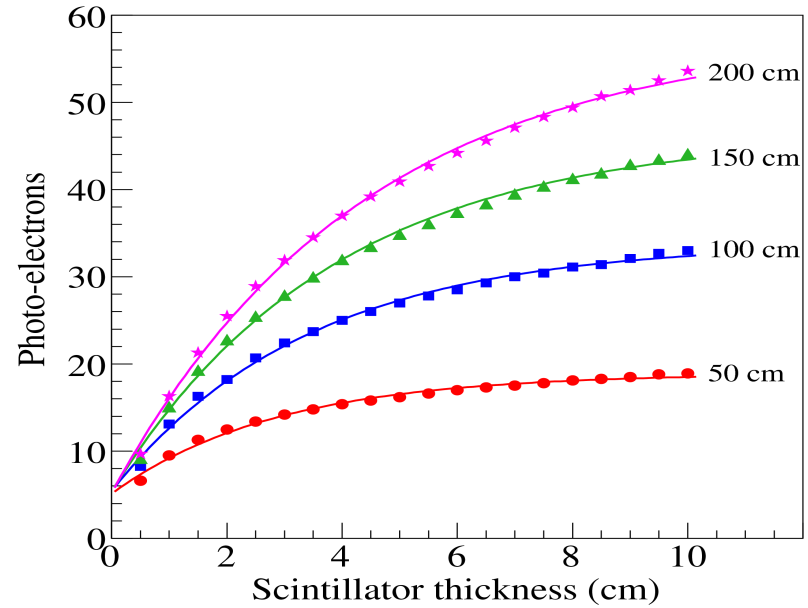
Parallel groove design selected for final configuration because of ease in fabrication

Attenuation

Self Absorption



$$N(x) = N(0)e^{-x/\lambda_{sc}}$$



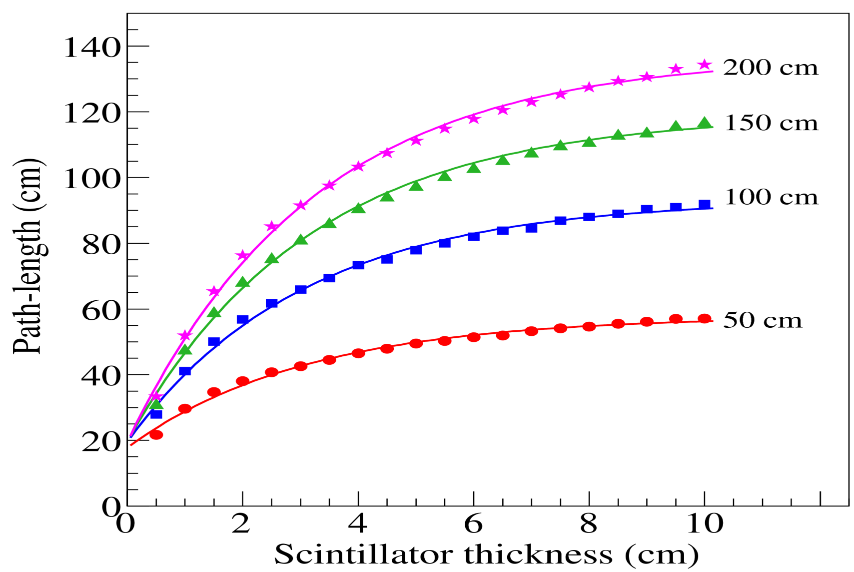
200cm

150cm

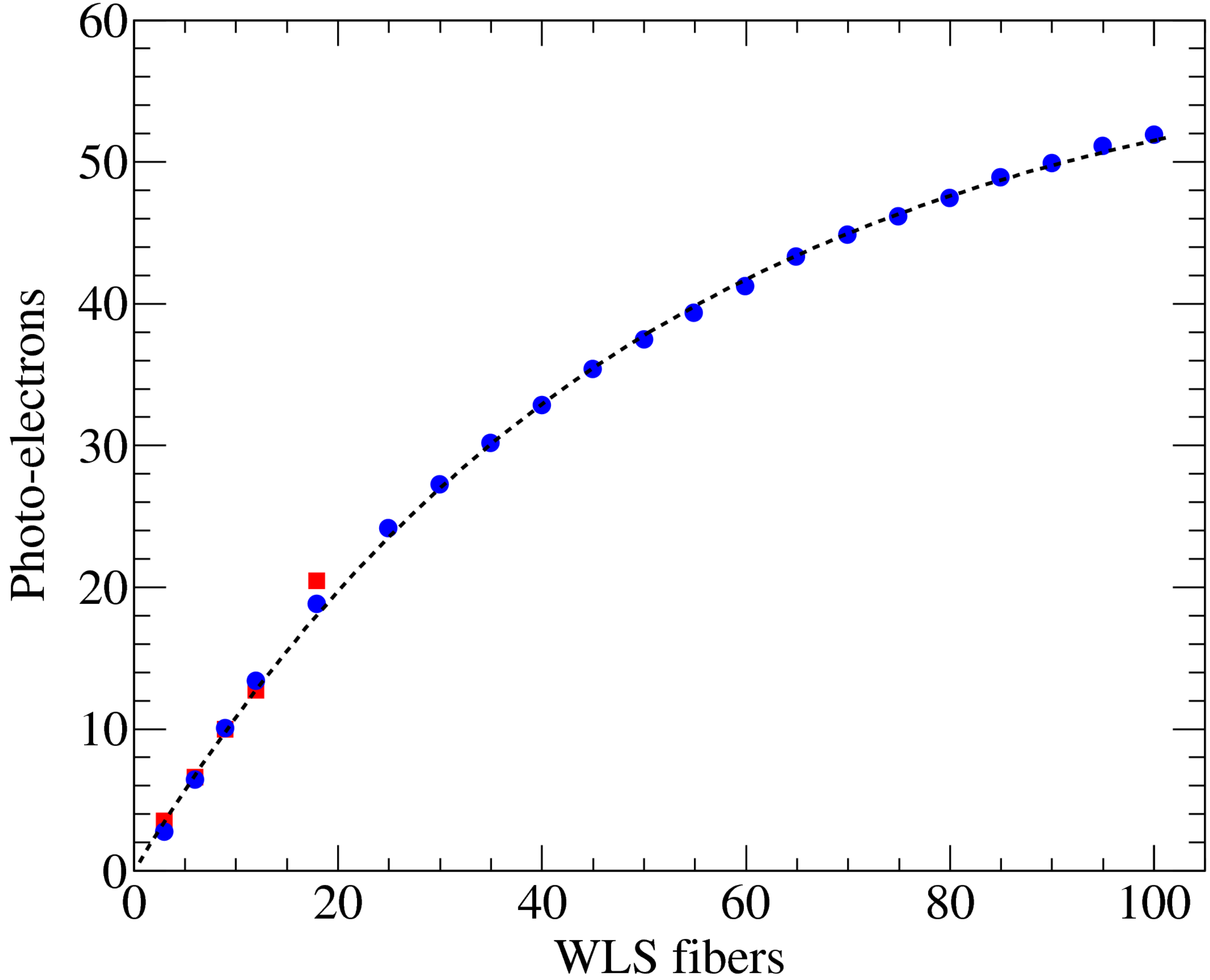
100cm

50cm

FIG. 6. Mean photo-electrons as function of thickness for $\lambda = 50, 100, 150, 200$ cm. Data fitted by PE = a - b$\times$ $e^{(-x/c)}$. Y-axis intercept a - b = (5.2 $\pm$ 0.5) and c = (3.6 $\pm$ 0.5) cm.



Photon-electron with number of fibers



G3sim configuration file

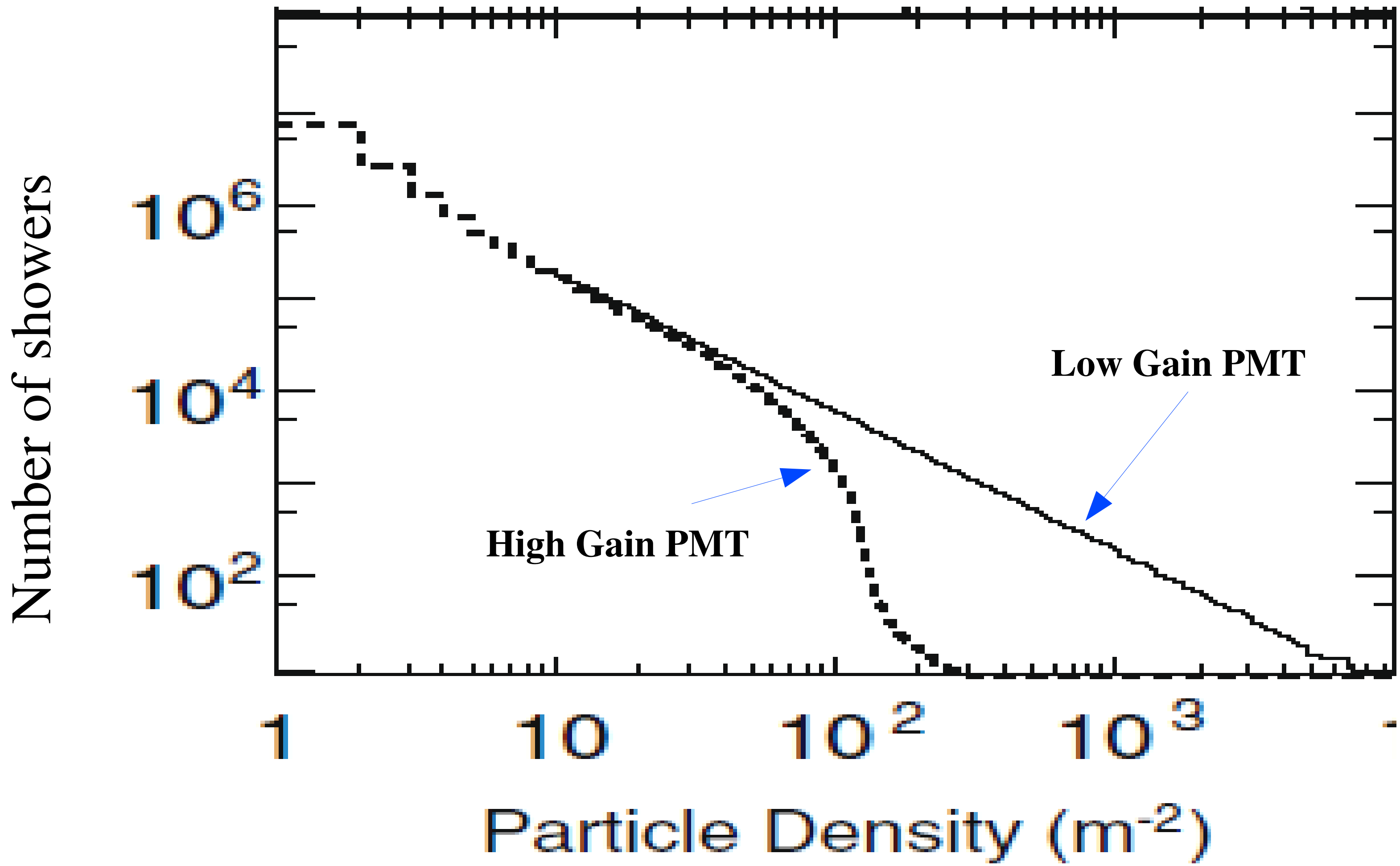
RunNumber	1
NumberOfEvents	50000
PhotonConversionEnergyeV	100
PathLengthStepcm	0.01
ETIRScintillator	0.93
ReflectivityFiber	0.9999
ReflectivityDiffuseReflector	0.9
RefractiveIndexScintillator	1.59
RefractiveIndexFiberCore	1.59
RefractiveIndexFiberInnerClad	1.49
RefractiiveIndexFiberOuterClad	1.42
AttenuationLengthScintillatorcm	100
AttenuationLengthFibercm	350
ScintillatorDecayTimens	1.5
FiberDecayTimens	6.1
PMTQuantumEfficiencySpectrumFileOption1	PMTQuantumEfficiencySpec.dat
PMTPeakQuantumEfficiencyOption2	-1
PMTSinglePhotoElectronDistributionWidth	0.2
PMTTransitTimeJitterns	1.0
PMTWindowTransmissionCoefficient	0.93
FiberEmissionWaveLengthSpectrumFileOption1	WLSFiberEmissionSpec.dat
FiberPeakEmissionWaveLengthnmOption2	-1
GeometrySpecificationFile	GeometrySpecification.dat
OutputfileDirectoryWithPath	/home/grapes/g3simpaper_work/program/version2

G3sim consists of 1200 lines of C++ code.

G3sim code is available on request
(contact: pkm@tifr.res.in)

P.K. Mohanty et al. Rev. Sci. Instrum. 83 (2012) 043301.

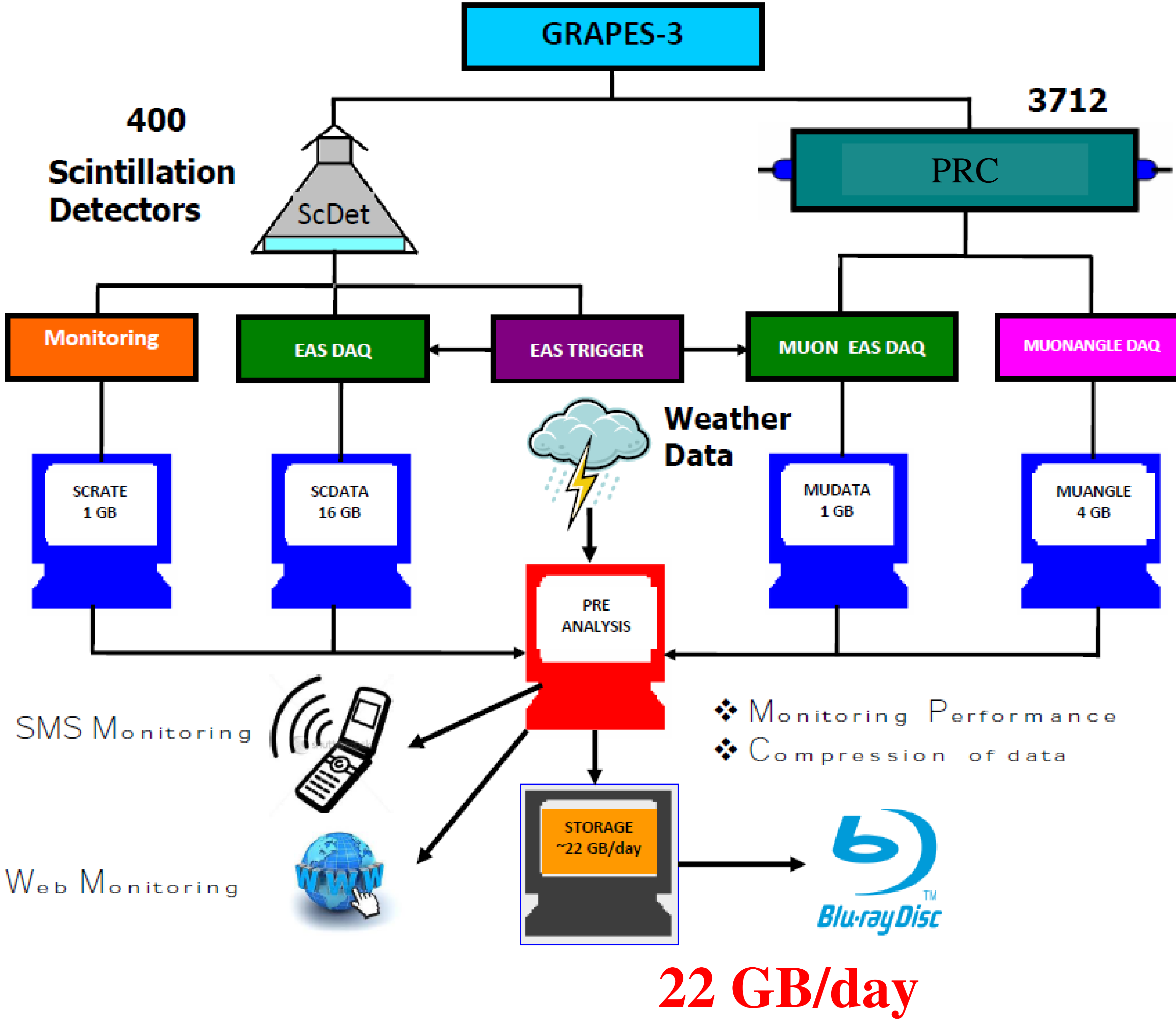
Enhanced dynamic range with two PMT design



More details:

"Measurement of some EAS properties using new scintillator detectors developed for the GRAPES-3 experiment",

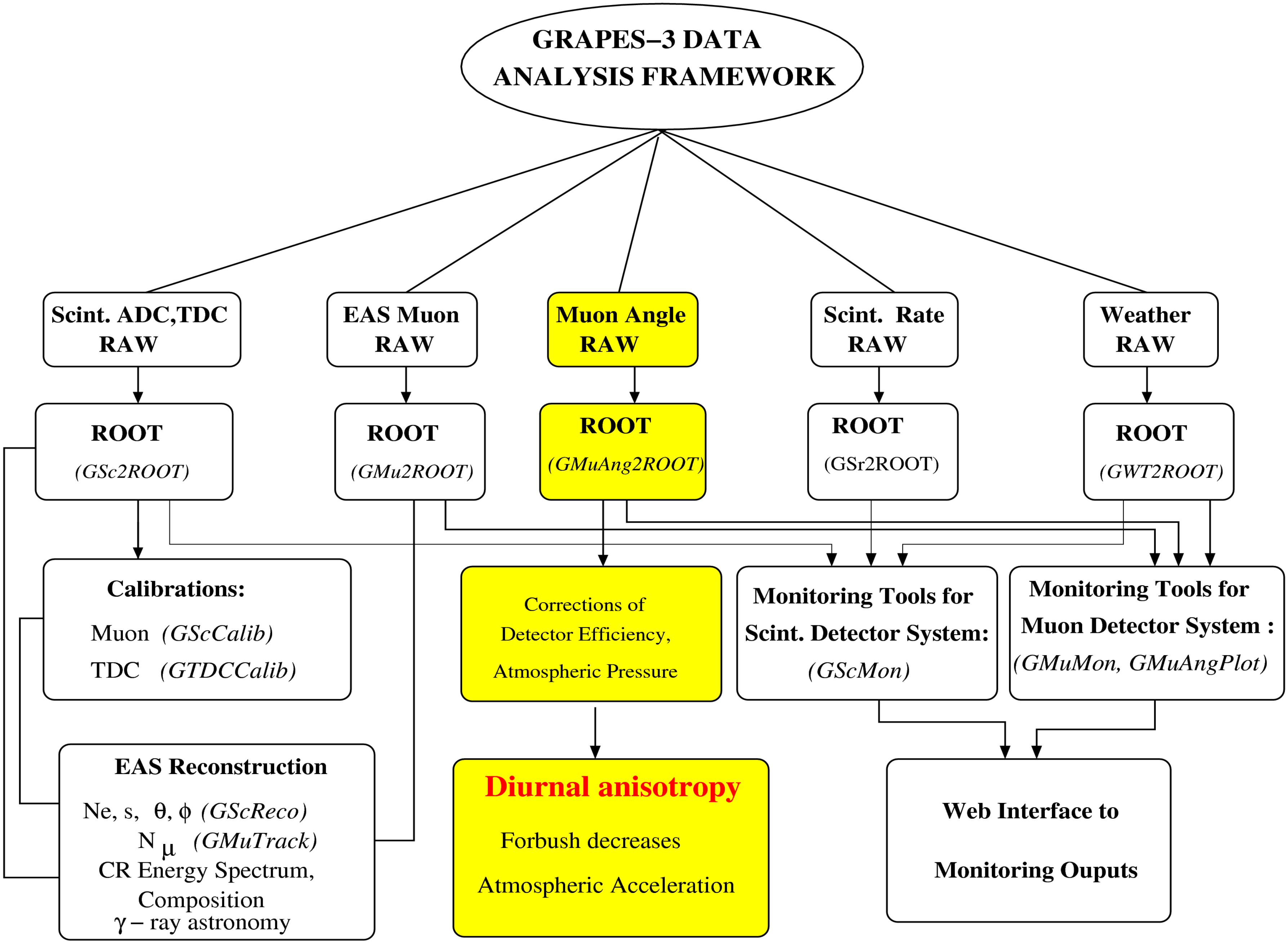
P. K. Mohanty et al., Astropart. Phys. 31 (2009) 24.


GRAPES-3
400
Scintillation
Detectors
ScDet
3712
PRC
Monitoring
EAS DAQ
EAS TRIGGER
MUON EAS DAQ
MUONANGLE DAQ
Weather
Data
SCRATE
1 GB
SCDATA
16 GB
MUDATA
1 GB
MUANGLE
4 GB
PRE
ANALYSIS
SMS Monitoring
Web Monitoring
Monitoring Performance
Compression of data
STORAGE
~22 GB/day
Blu-ray Disc
22 GB/day

Data Analysis Framework

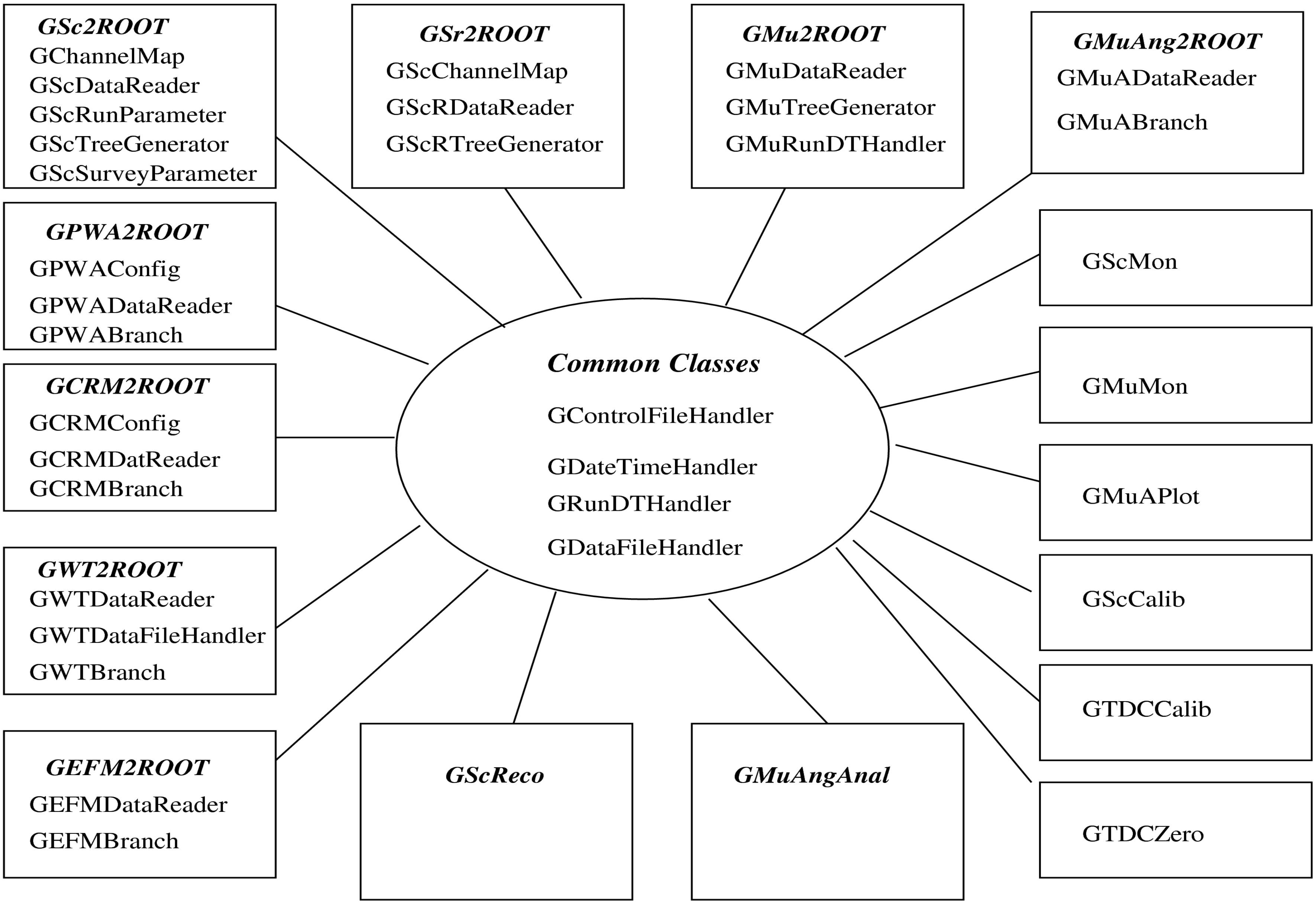
An object oriented software framework was created for the GRAPES-3 data using popular graphics and analysis tool ROOT with the following philosophy

- **Efficient storage and access of various data streams using ROOT tree**
- **Efficient monitoring of data quality**
- **Portability of data to the collaboration.**
- **Adaptation to the data system with short learning curve and more time devoted for detailed analysis for a new member**
- **Involvement of more people in parallel development**

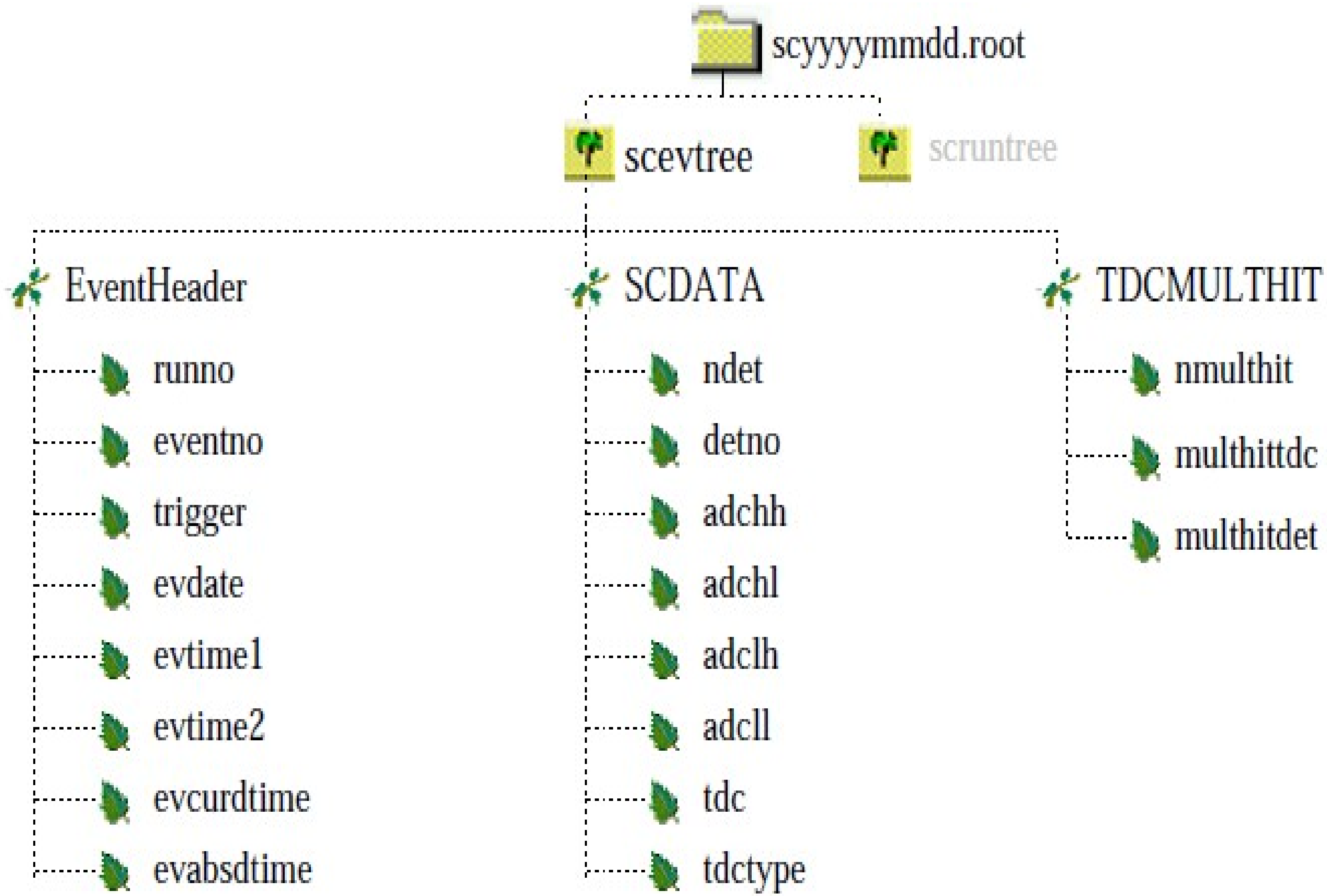


~ 1 00 000 lines of code

Effort spread over 5 years

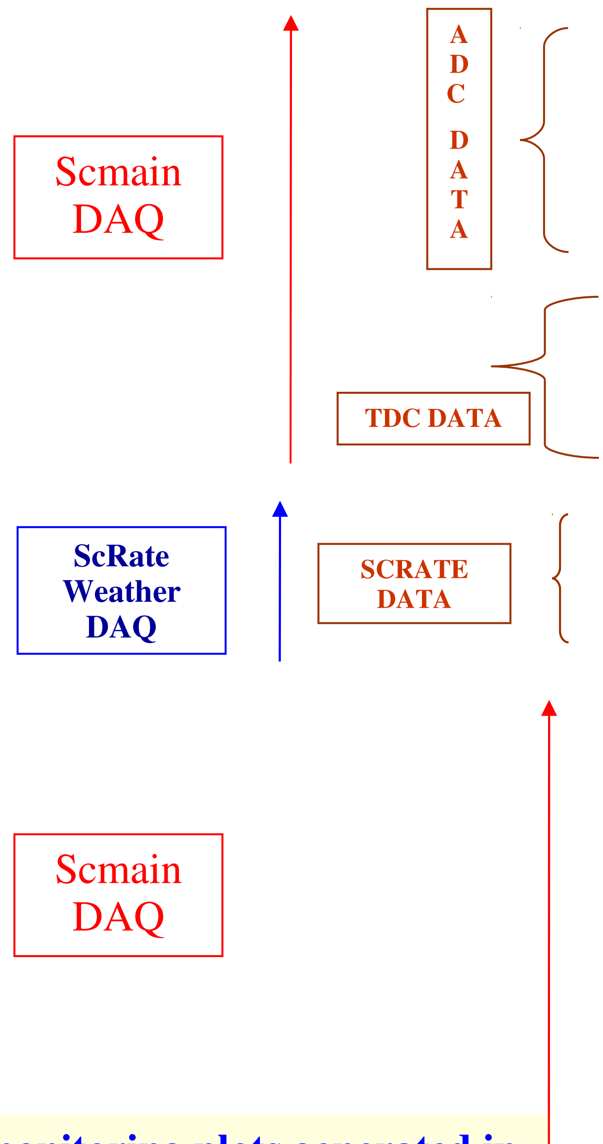

GSc2ROOT
GChannelMap
GScDataReader
GScRunParameter
GScTreeGenerator
GScSurveyParameter
GSr2ROOT
GScChannelMap
GScRDataReader
GScRTreeGenerator
GMu2ROOT
GMuDataReader
GMuTreeGenerator
GMuRunDTHandler
GMuAng2ROOT
GMuADataReader
GMuABranch
GPWA2ROOT
GPWAConfig
GPWADataReader
GPWABranch
GCRM2ROOT
GCRMConfig
GCRMDatReader
GCRMBranch
Common Classes
GControlFileHandler
GDateTimeHandler
GRunDTHandler
GDataFileHandler
GScMon
GMuMon
GMuAPlot
GScCalib
GTDCCalib
GTDCZero
GWT2ROOT
GWTDataReader
GWTDataFileHandler
GWTBranch
GEFM2ROOT
GEFMDataReader
GEFMBranch
GScReco
GMuAngAnal

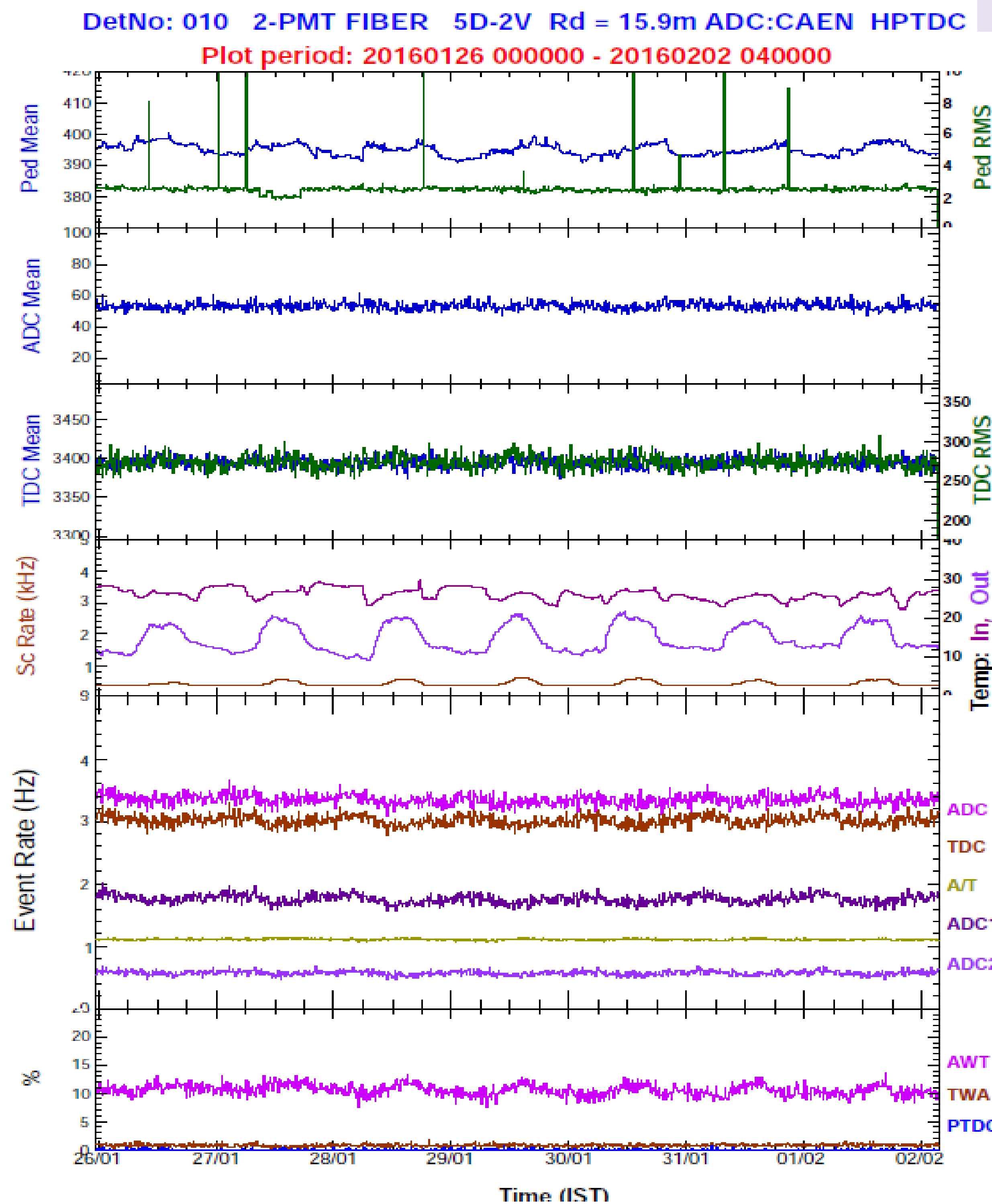
ROOT Tree structure for scintillator data



10 GB RAW DATA => 1.5 GB ROOT DATA per day

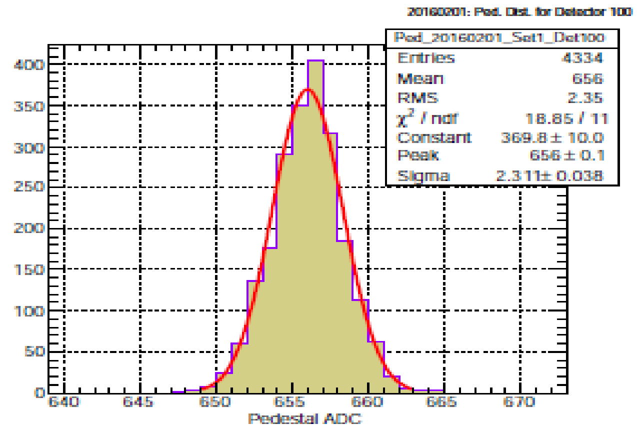
Inbuilt compression, no explicit uncompression while retrieval

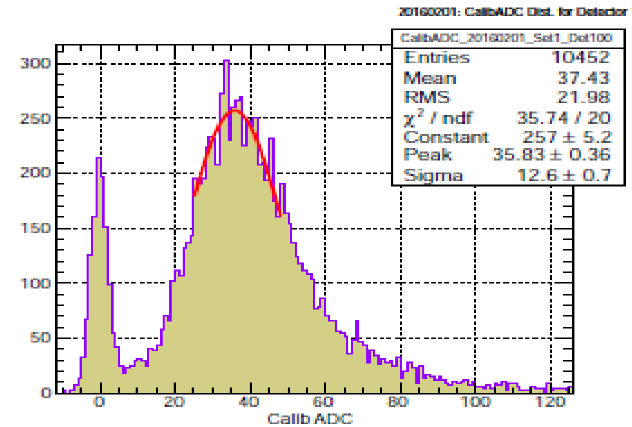


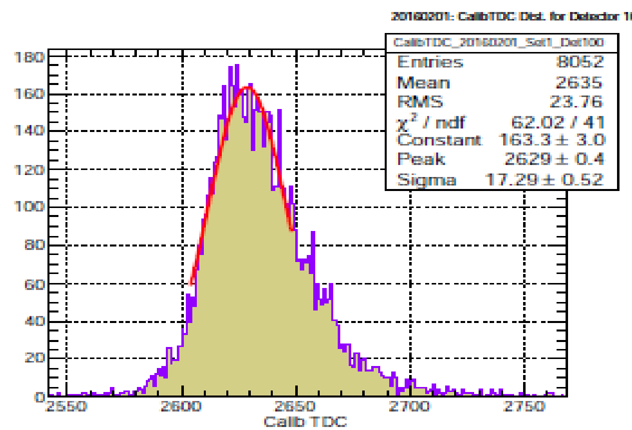


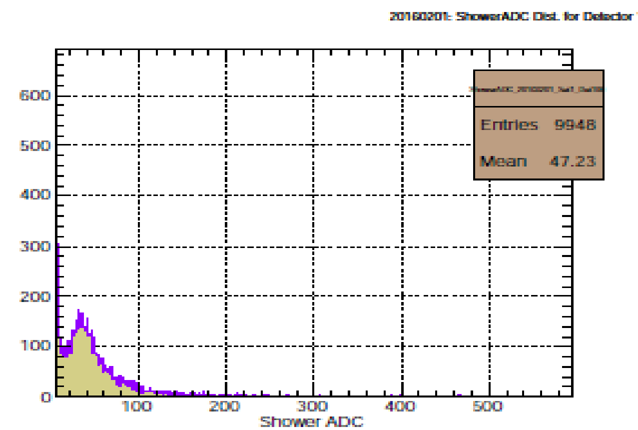
All monitoring plots generated in automated way before 9 AM

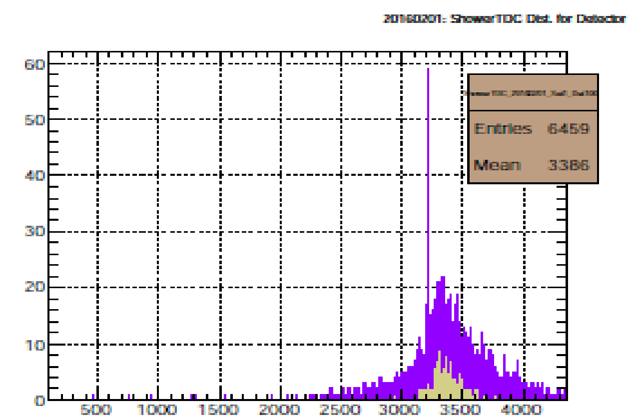
Muon calibration











Date: 20160201

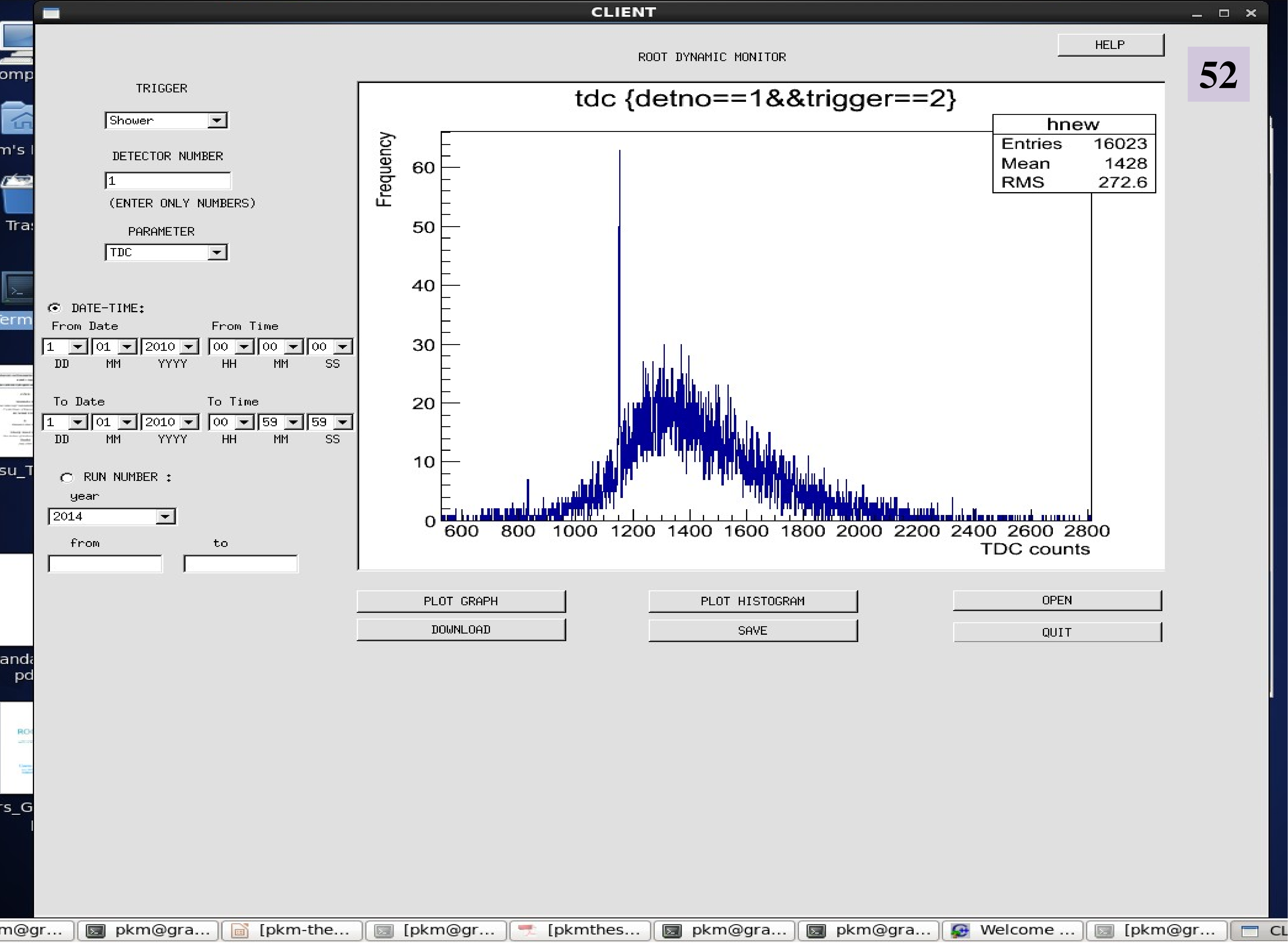
Detector: 100

Run Number: 18786 to 18802

Fit Flag: 111

Det/Cable Type: 2-PMT FIBER-5D2V

ADC/TDC Type: CAEN-HPTDC-v1.1


CLIENT
ROOT DYNAMIC MONITOR
HELP
TRIGGER
Shower
DETECTOR NUMBER
1
(ENTER ONLY NUMBERS)
PARAMETER
TDC
DATE-TIME:
From Date
From Time
1 01 2010 00 00 00
DD MM YYYY HH MM SS
To Date
To Time
1 01 2010 00 59 59
DD MM YYYY HH MM SS
RUN NUMBER :
year
2014
from
to
tdc {detno==1&&trigger==2}
hnew
Entries 16023
Mean 1428
RMS 272.6
Frequency
0 10 20 30 40 50 60
600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800
TDC counts
PLOT GRAPH
PLOT HISTOGRAM
OPEN
DOWNLOAD
SAVE
QUIT

Summary

1. Unique measurement of diurnal anisotropy. Demonstration of unprecedented sensitivity of GRAPES-3 detector
2. Exploiting the GRAPES-3 sensitivity for space weather studies
3. Continuing our effort to understand atmospheric acceleration
4. GRAPES-3 has now efficient shower detectors and expected to provide better measurement of shower parameters
5. The new data analysis frame work made the analysis convenient and fast. Inclusion of more people for analysis


THANK YOU
094
130
172
093
063
129
171