# Cosmic ray solar modulation studies using GRAPES-3

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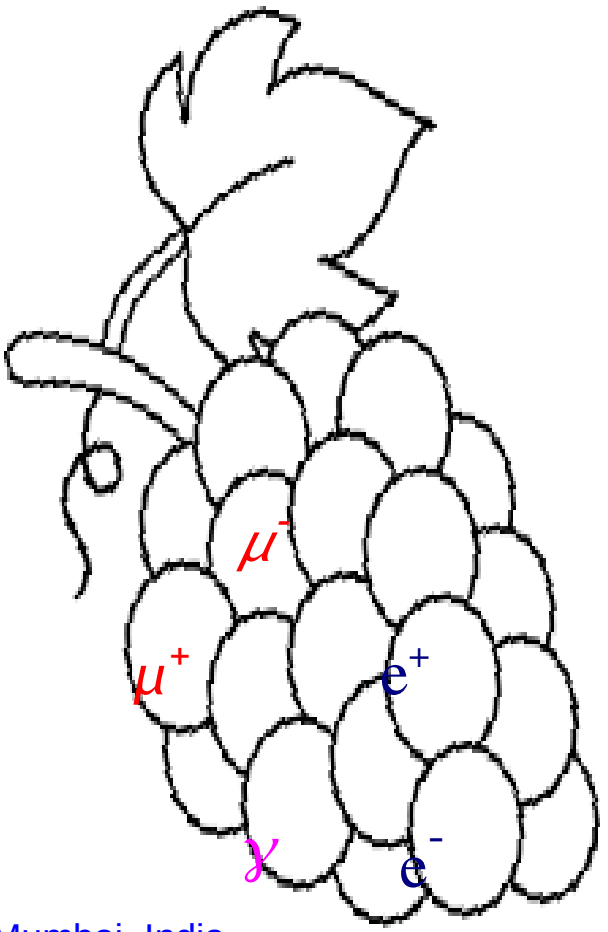
# GRAPES-3->Gamma Ray Astronomy at PeV EnergieS Phase-3

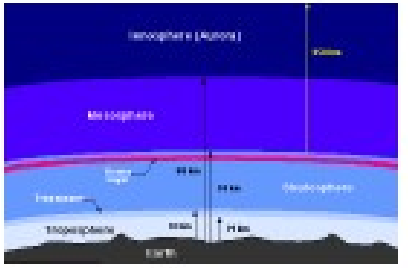




1. Tata Institute of Fundamental Research, Mumbai, India
2. Osaka City University, Osaka, Japan
3. Aichi Institute of Technology, Toyota, Japan
4. J.C. Bose Institute, Kolkata, India
5. Indian Institute of Science and Engineering Research, Pune, India
6. Indian Institute of Technology, Kanpur, India
7. Chubu University, Kasugai, Aichi, Japan
8. Hiroshima City University, Hiroshima, Japan
9. Kochi University, Kochi, Japan
10. Aligarh Muslim University, Aligarh, India
11. North Bengal University, Siliguri, India
12. Vishwakarma Institute of Information Technology, Pune, India

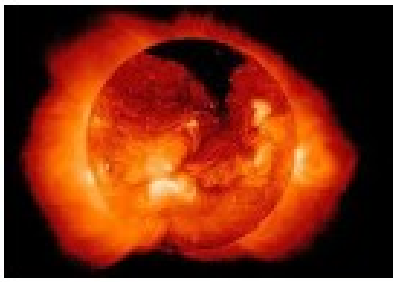
# Objective: Universe at high energies

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



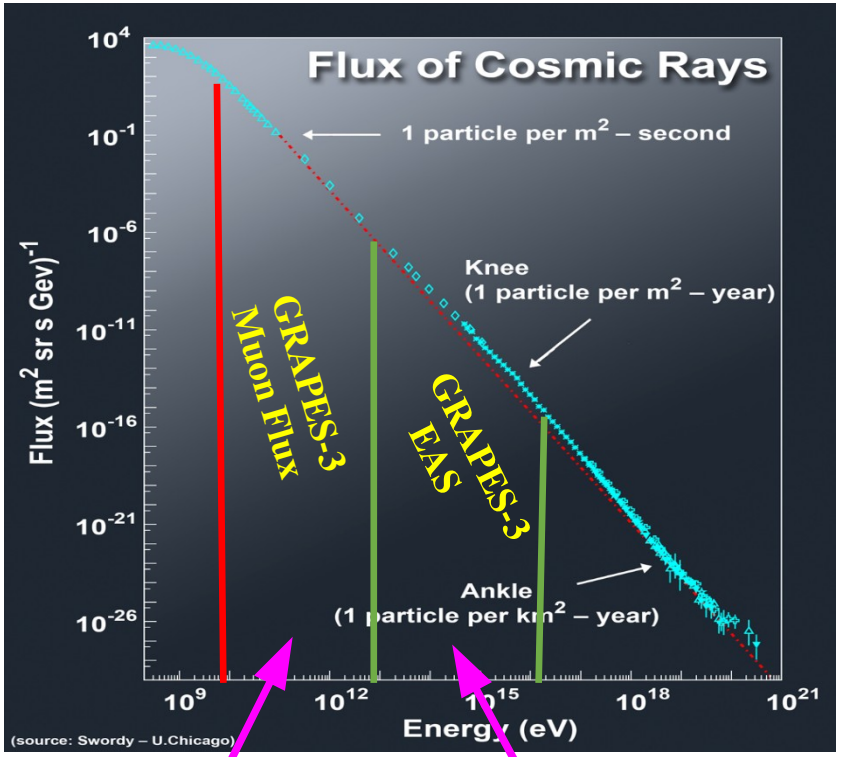
2. Solar flares, Coronal Mass Ejections
   Energy ~10 GeV  Scale ~$10^{11}$-$10^{13}$ cm



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

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





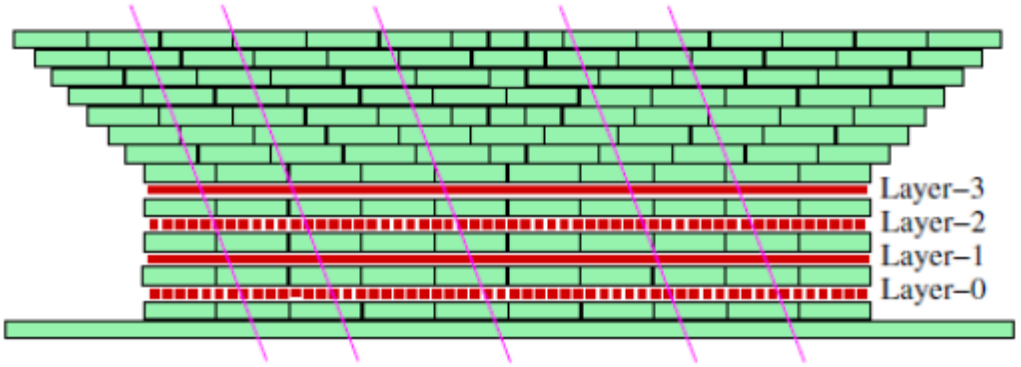

**4 billion muons/day** (High Statistical Accuracy)

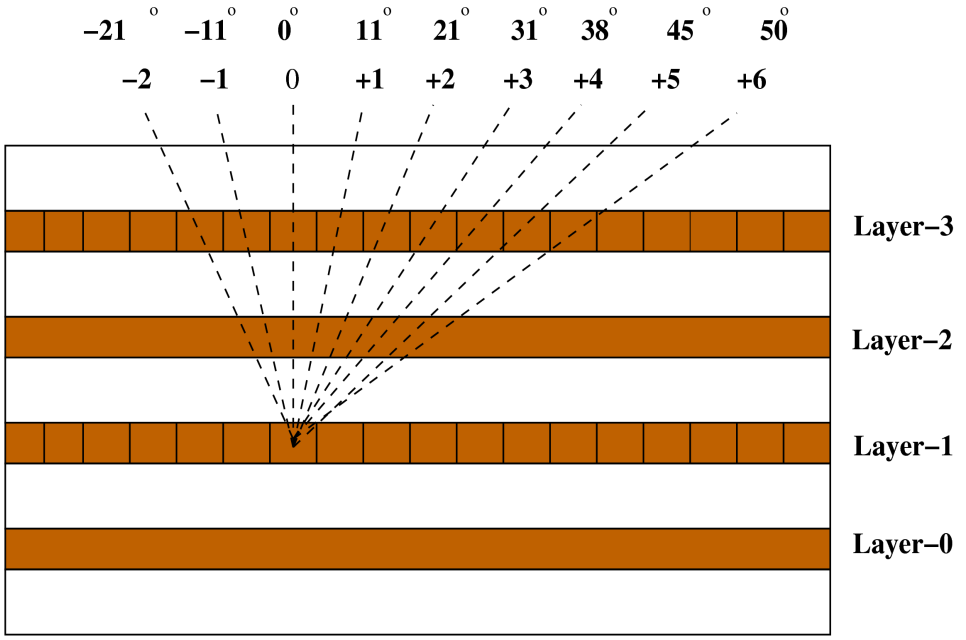
**Heliospheric Science**
**Atmospheric acceleration**

**3 million EAS events /day** (**Energy and Direction**)

**Spectrum and elemental Composition**

**Gamma Ray Astronomy**



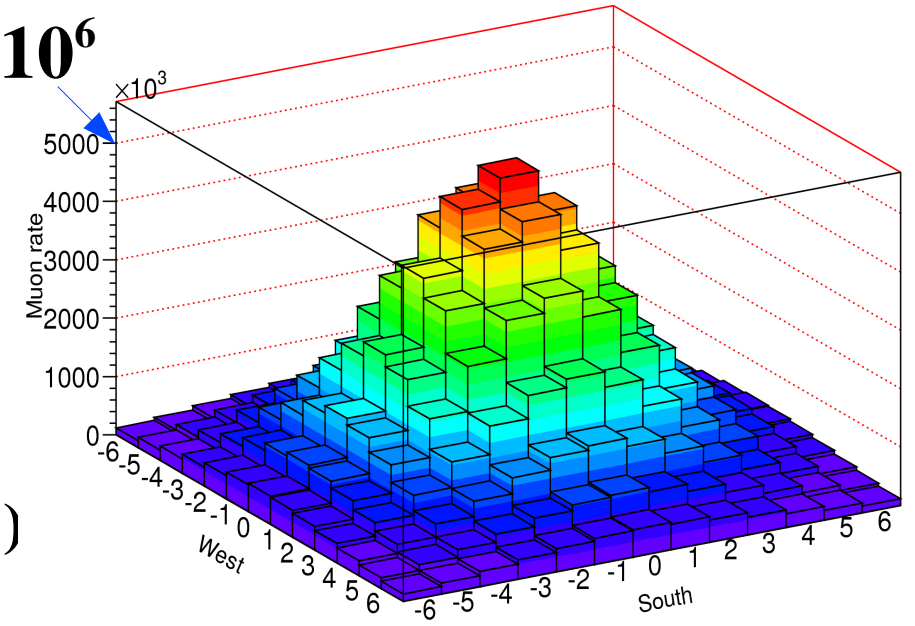

**Trigger:**

4-layer coincidence trigger

- clean muon events

**Energy threshold = 1 GeV sec(θ)**

**5 x $10^6$**



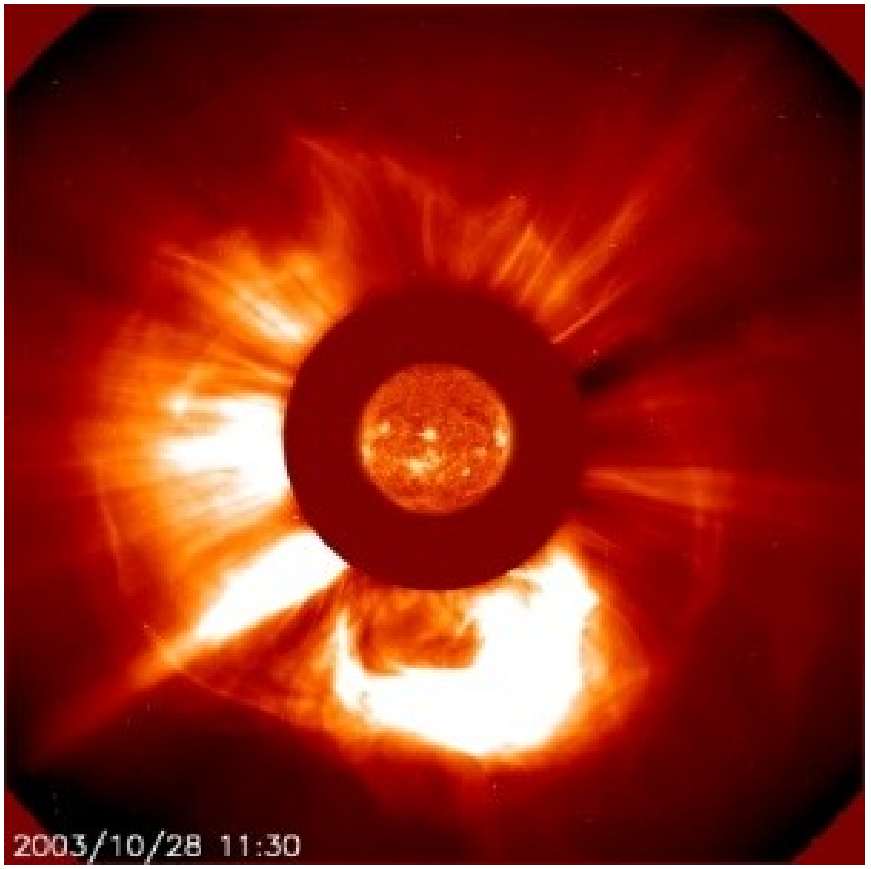

**24 x 7 observation**

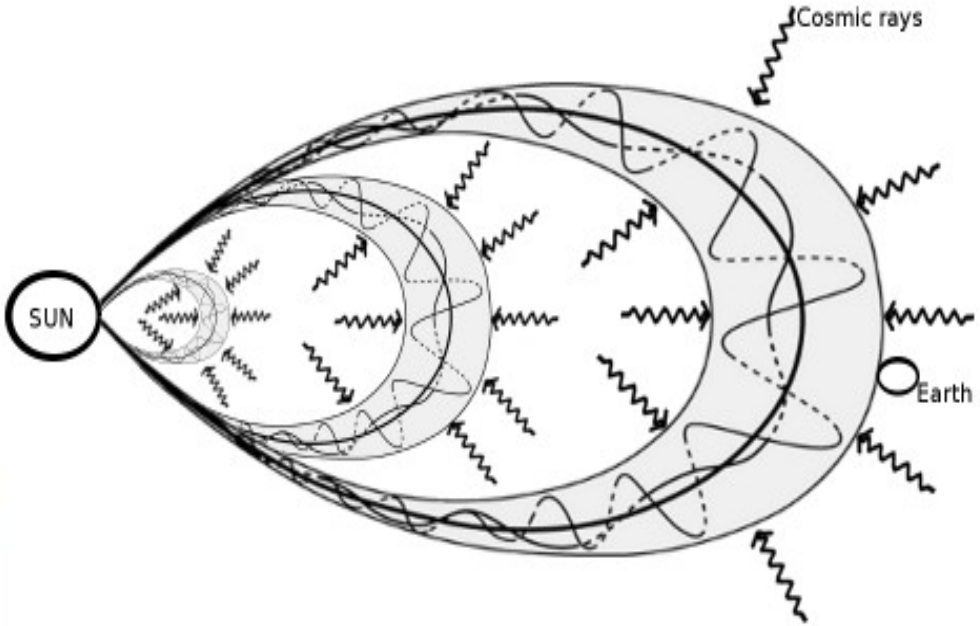
**Field of View = 2.3 sr**

**Map = 13 x 13 angular bins**

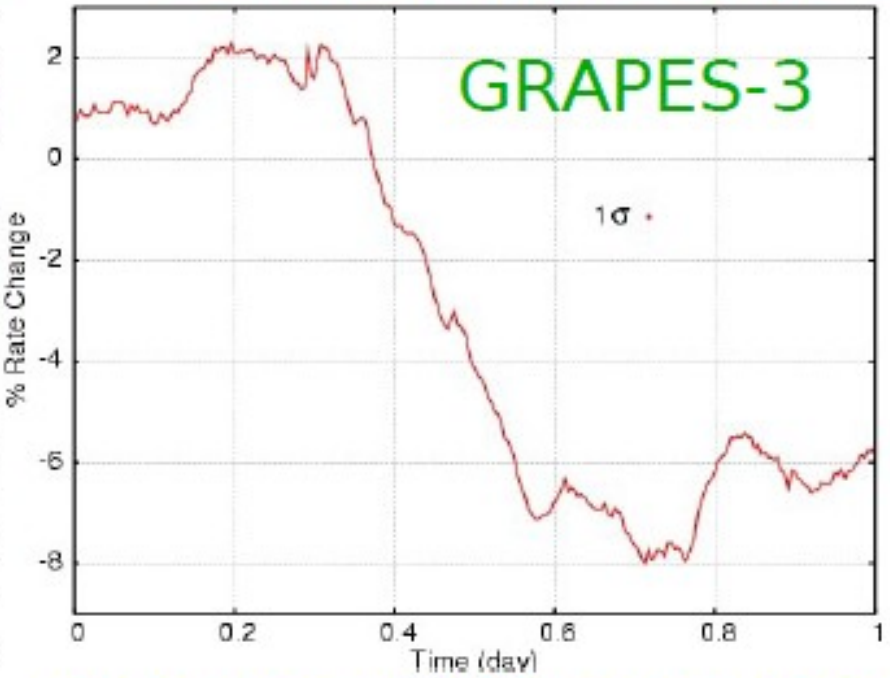
**Statistics : 4 billion muons /day (~0.001%)**

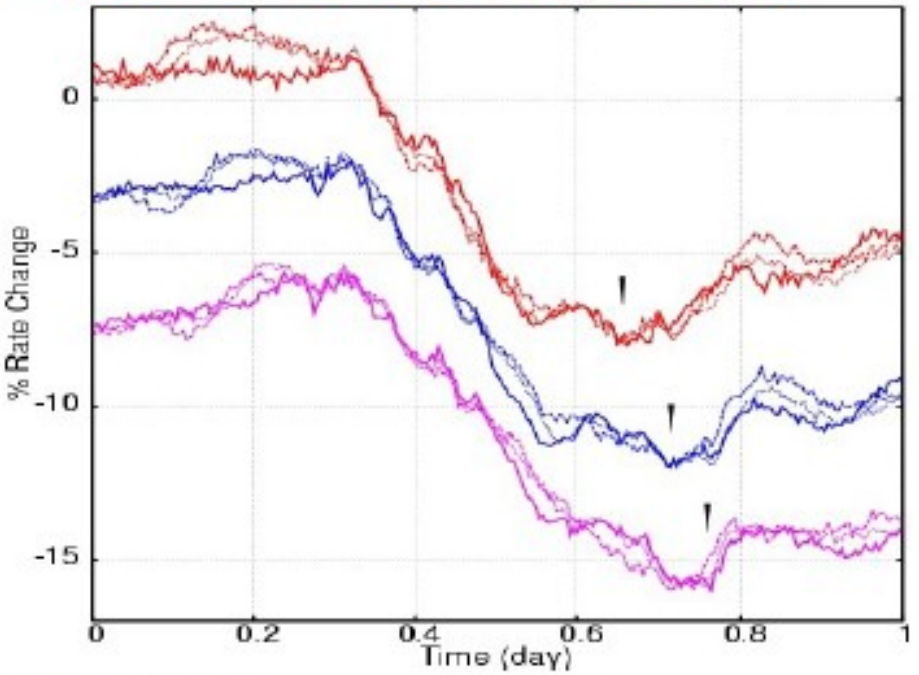
# Coronal Mass Ejection (CME)



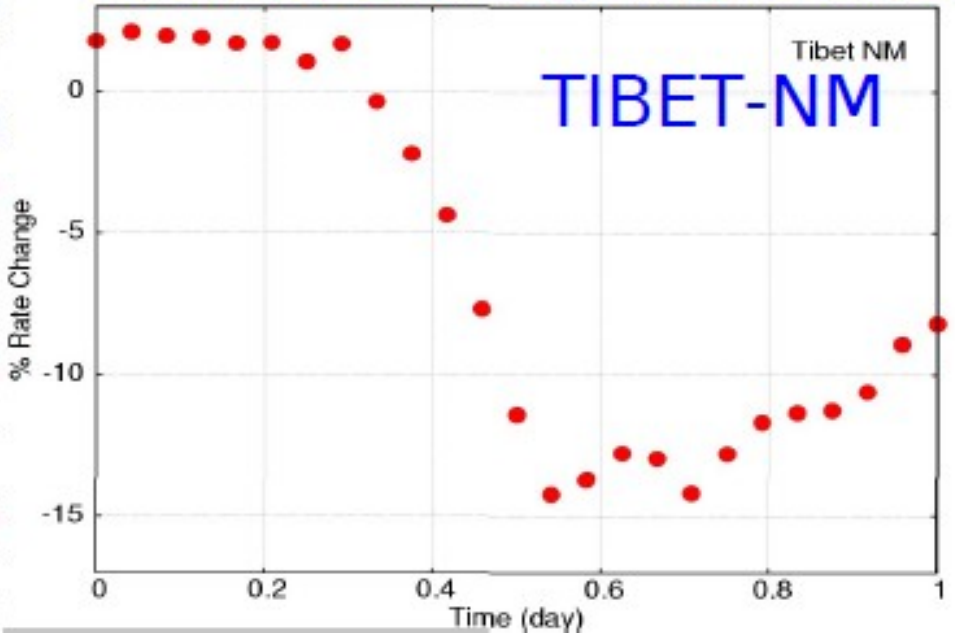



# Coronal Mass Ejection (28 October 2003)




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

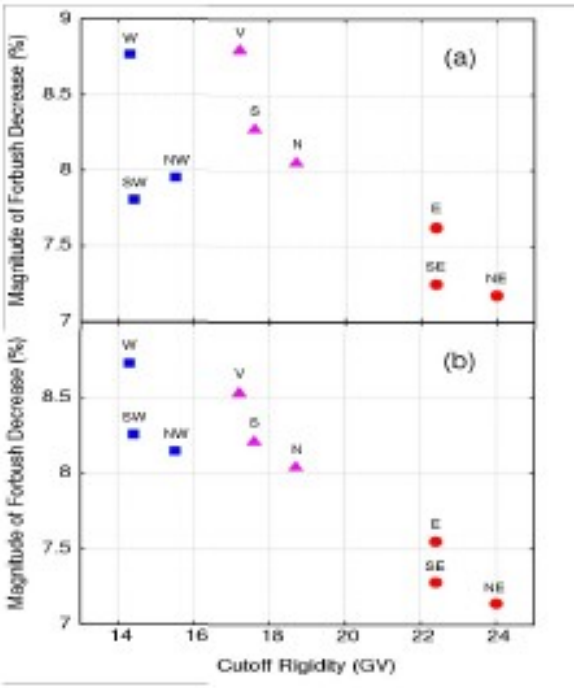



$A(r) = K \times r^{-\gamma}$

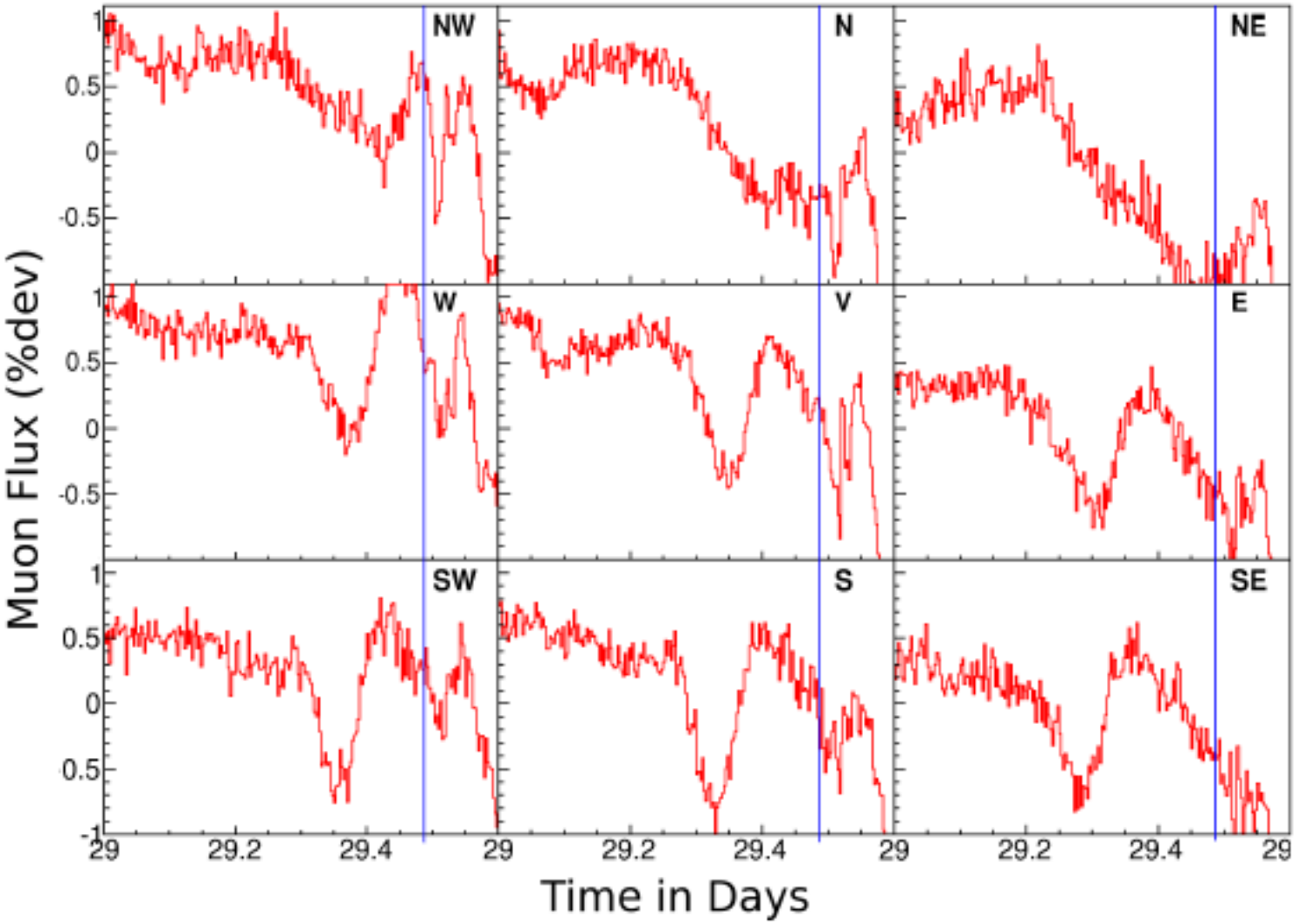
$K = (12.3 \pm 0.3)\%$

$\gamma = (0.53 \pm 0.04)$

$\gamma = 0.4 - 1.2$



# Precursor Associated with CME on 29 Oct 2003



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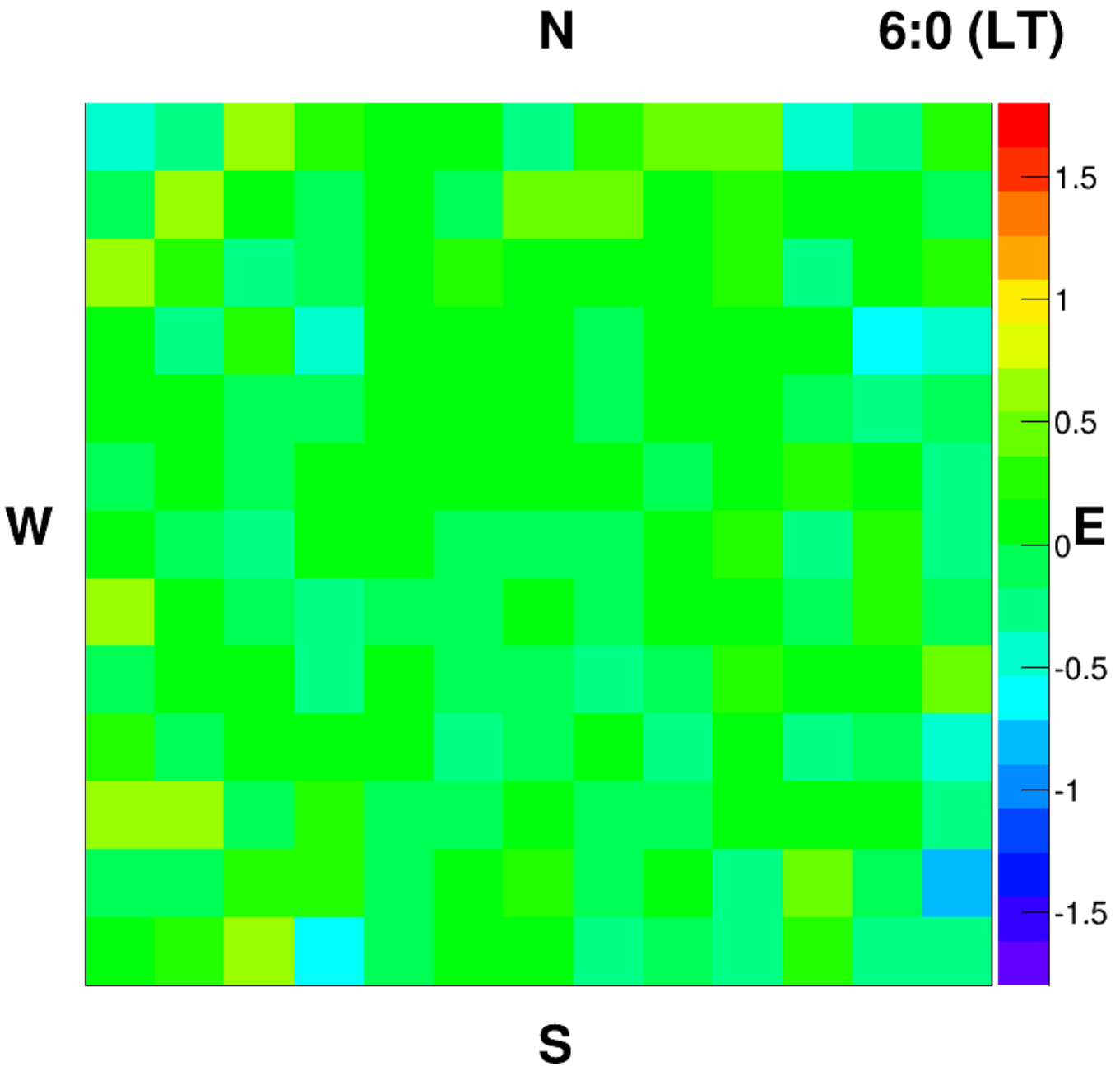
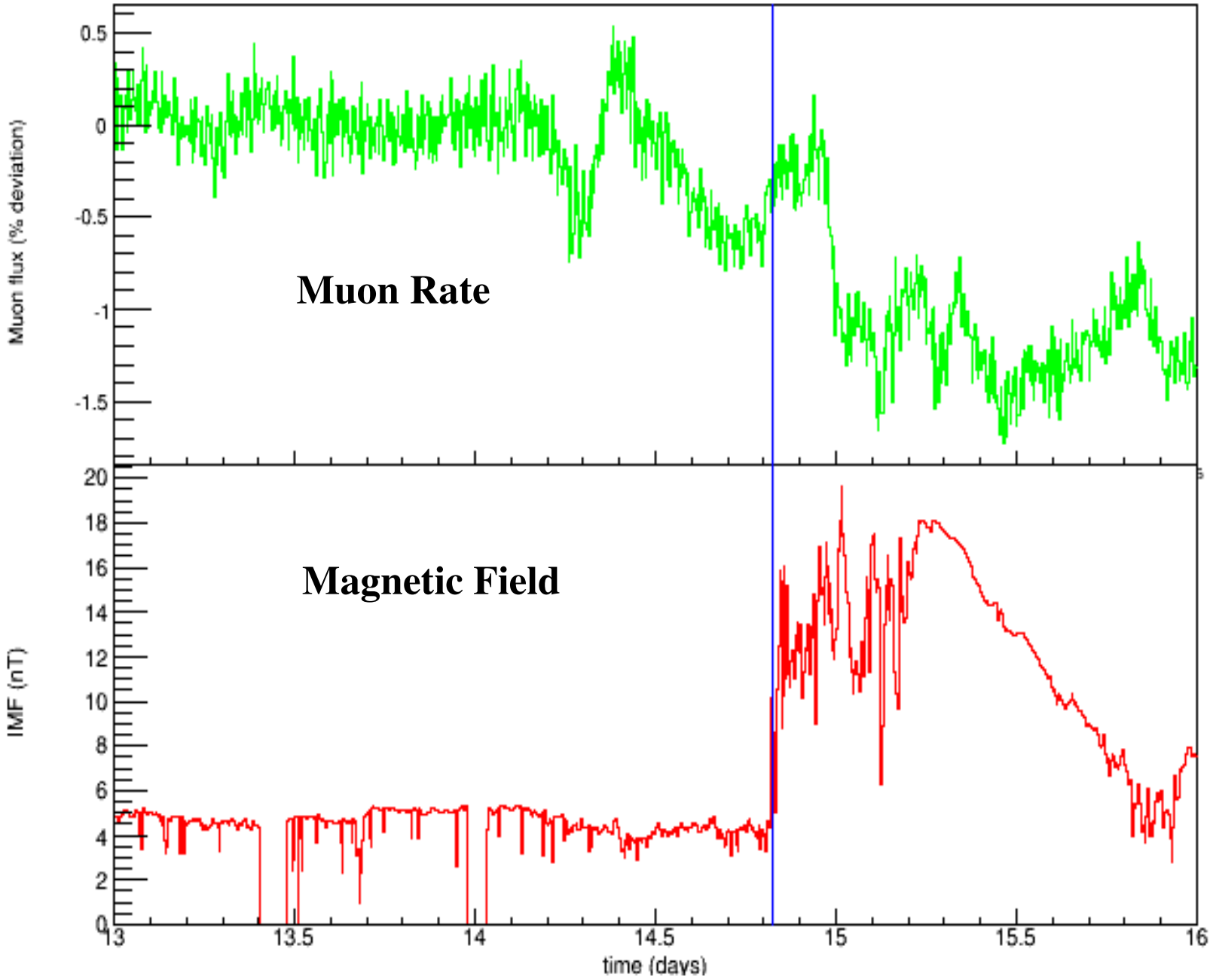
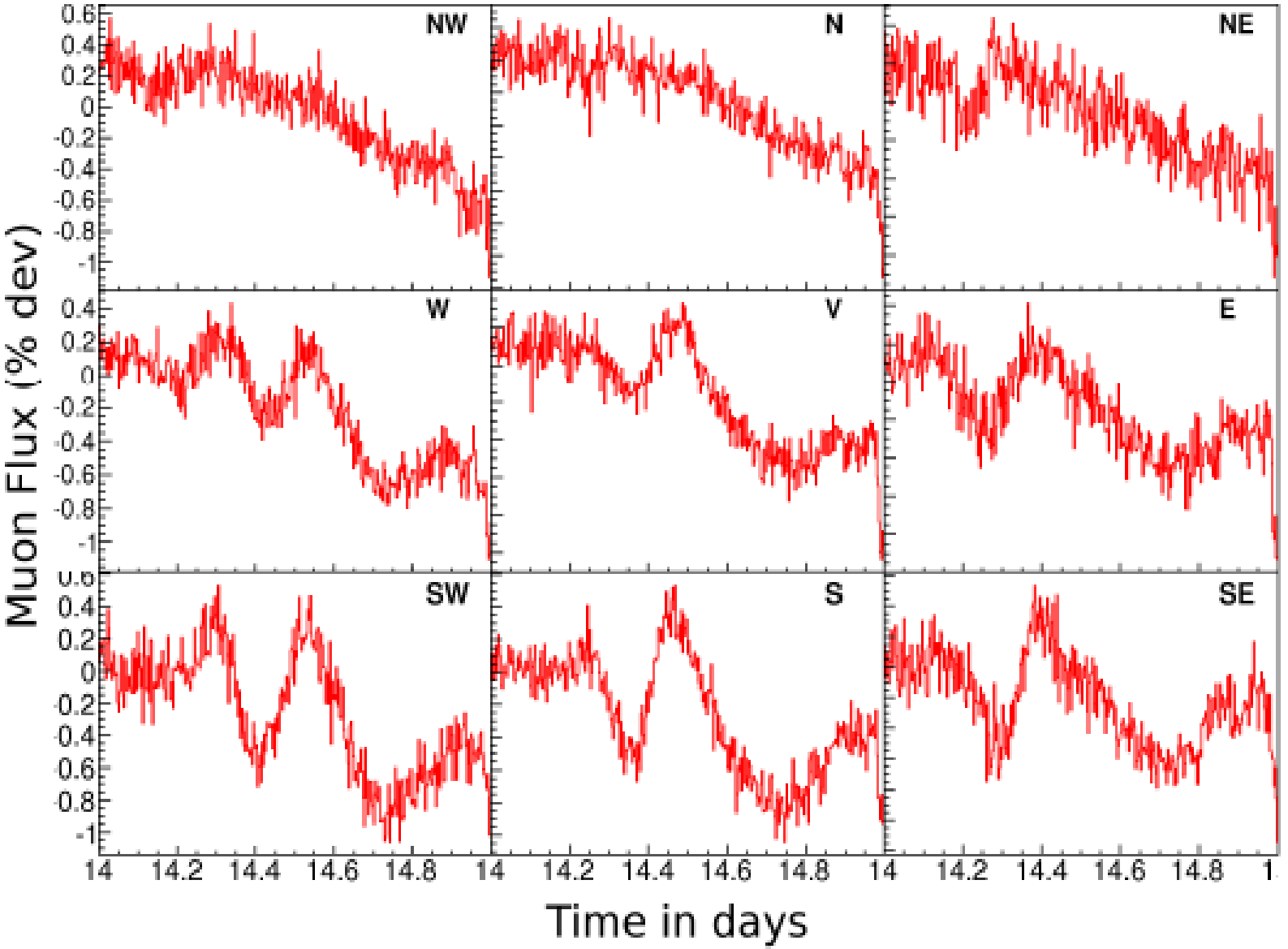


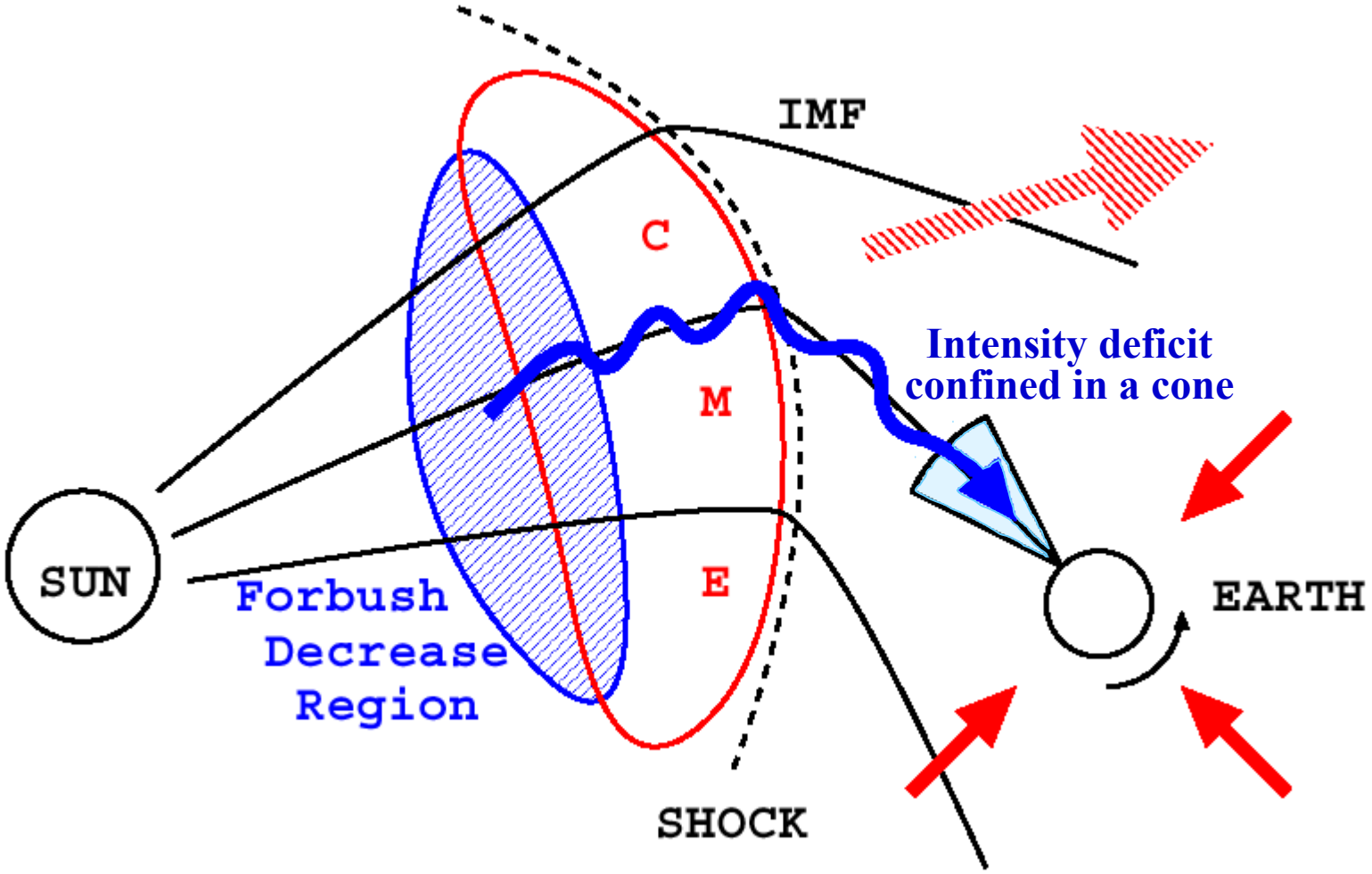
# Precursor Associated with CME on 14 Dec 2006



# Precursor Associated with CME on 14 Dec 2006



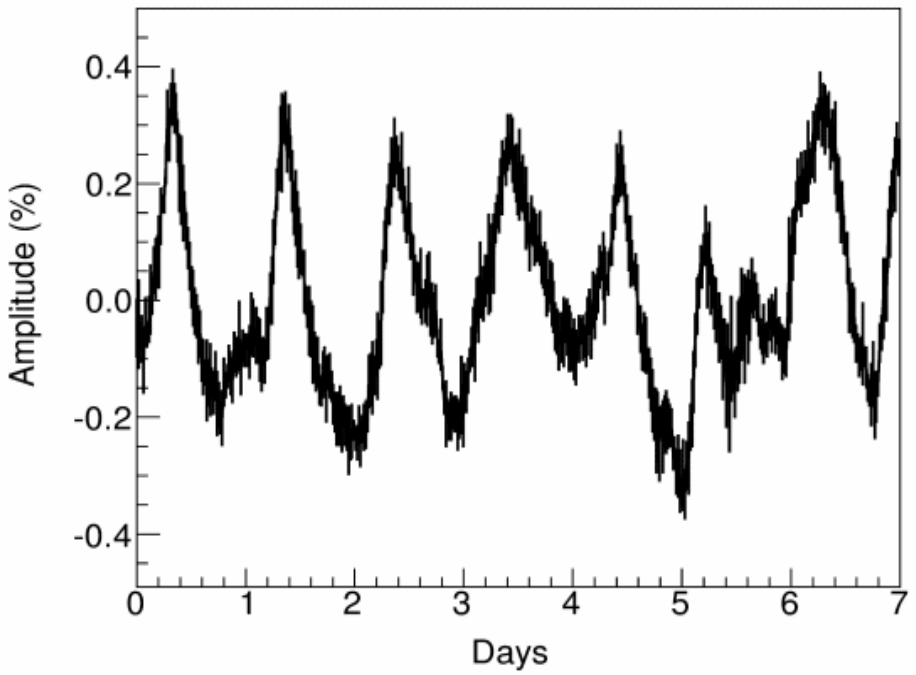
# Loss Cone Precursor to an ICME



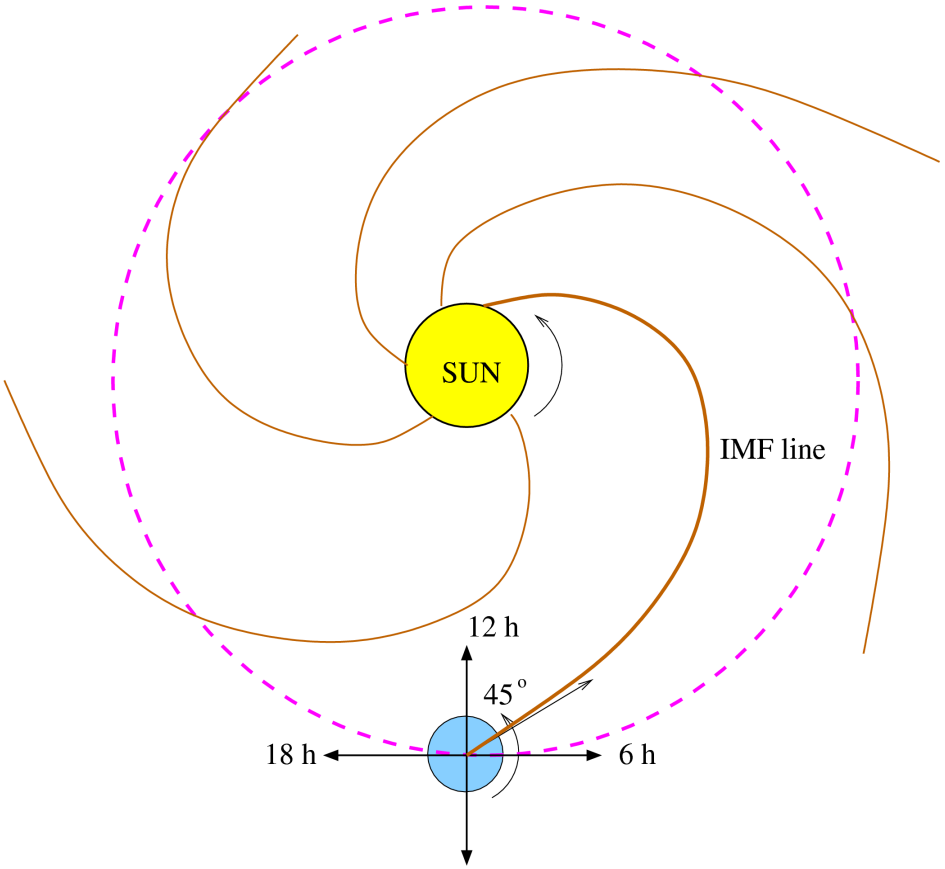

**Precursors can provide advance warning of 5-10 hours**

# Solar Diurnal Anisotropy

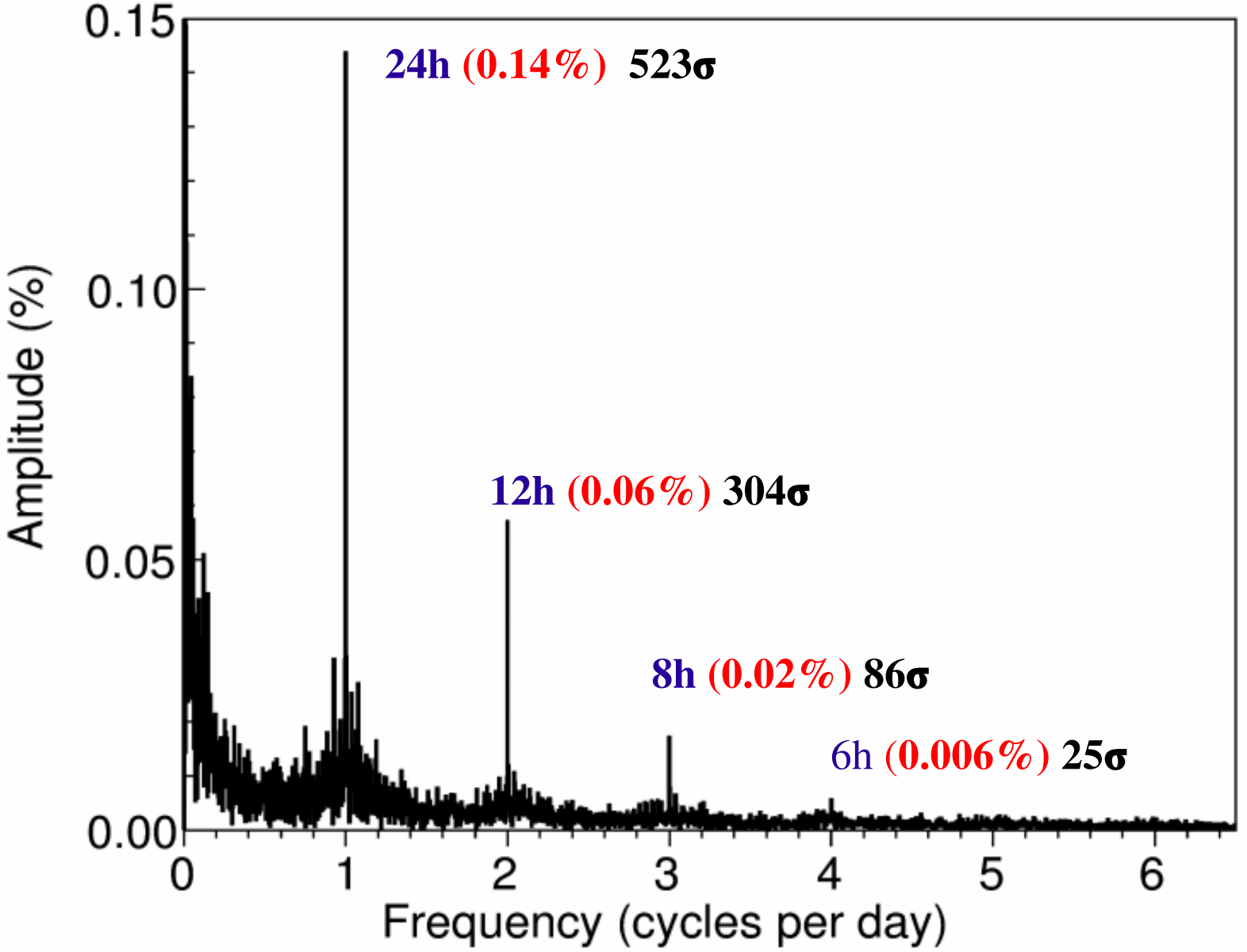
## GRAPES-3 muon data



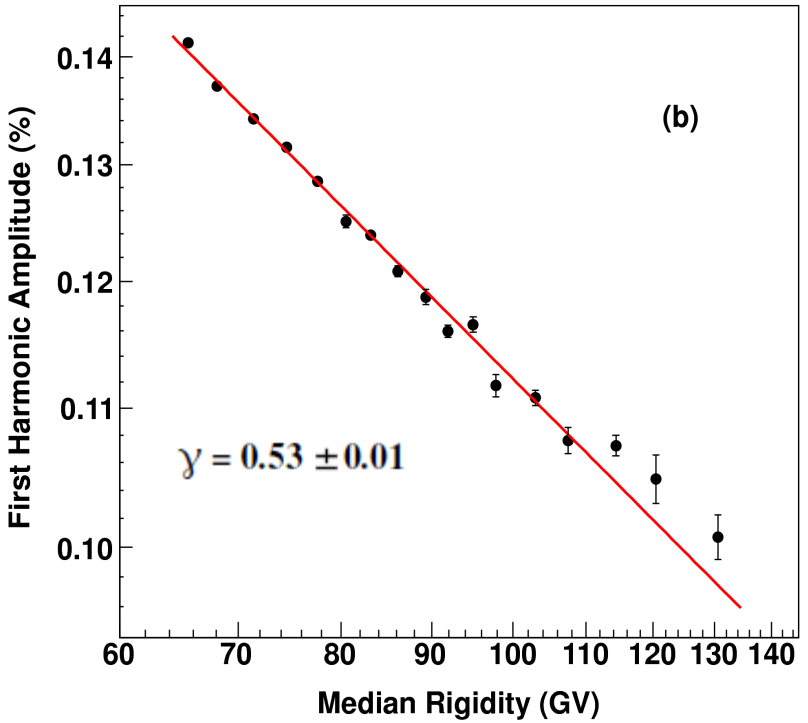

## Diffusion-Convection model (Parker 1964)

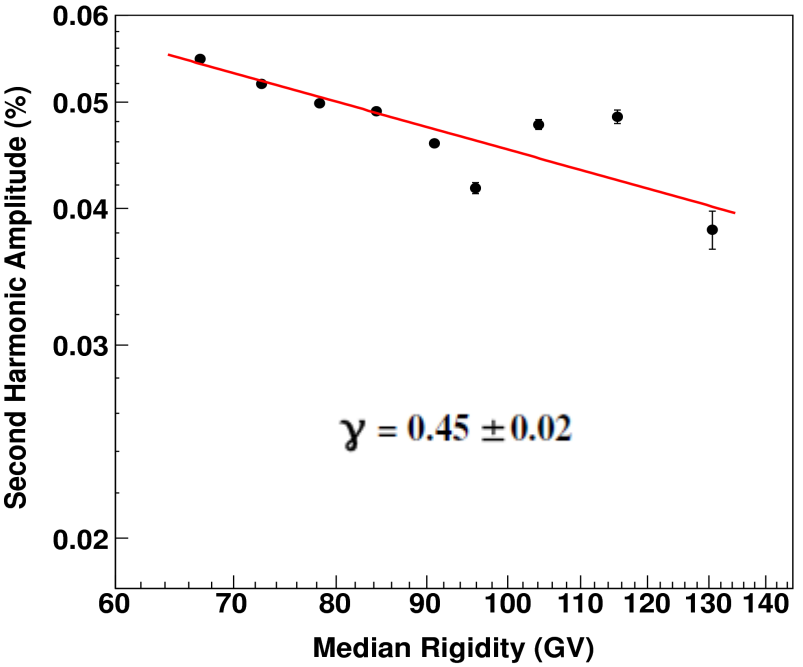


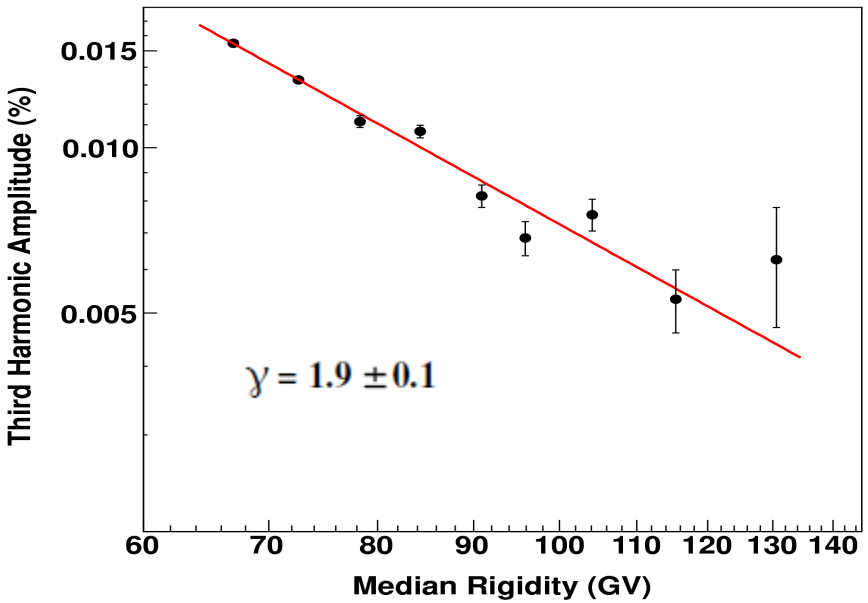
# Harmonics of diurnal anisotropy (one year data)

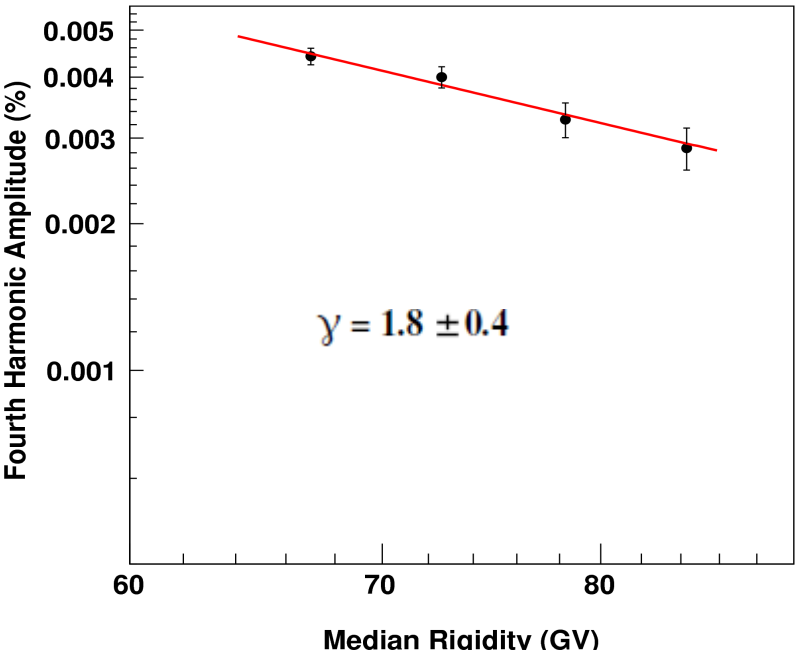


$$A(R) = K R^{-\gamma}$$

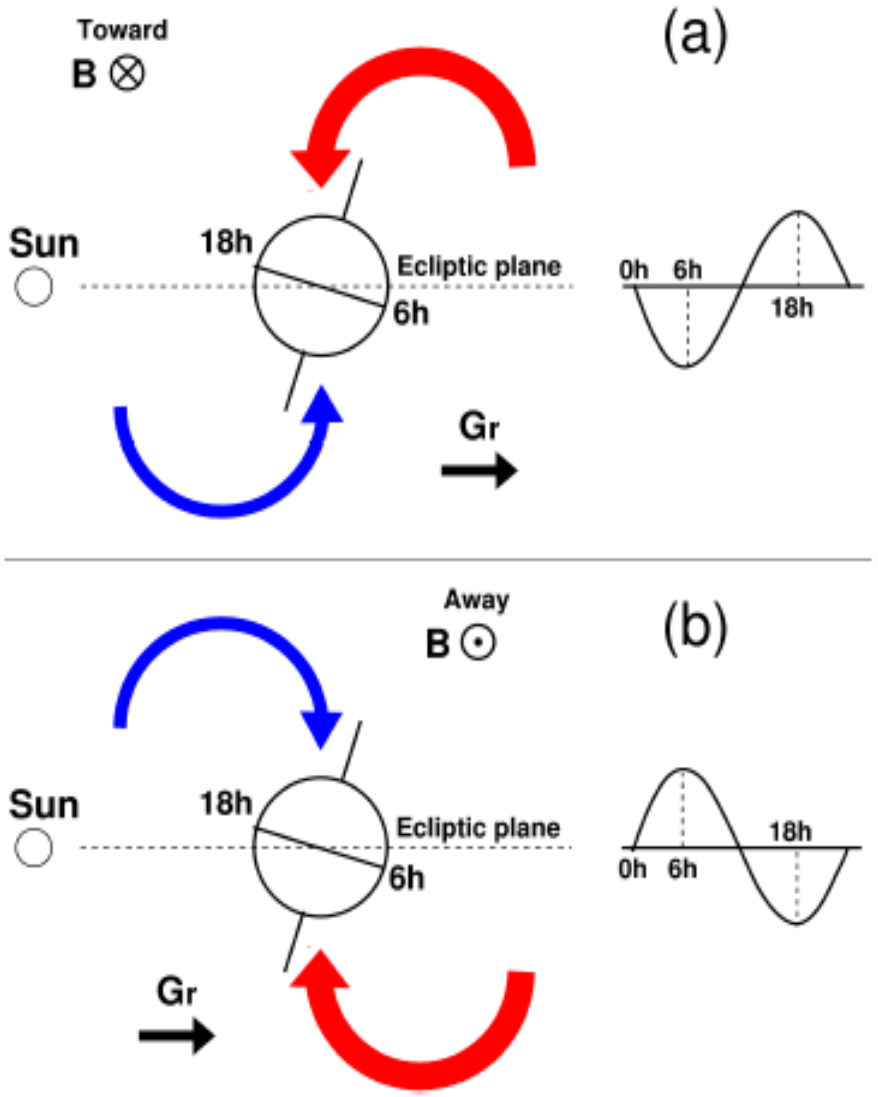

(b)
First Harmonic Amplitude (%)
0.14
0.13
0.12
0.11
0.10
γ = 0.53 ±0.01
60 70 80 90 100 110 120 130 140
Median Rigidity (GV)


Second Harmonic Amplitude (%)
0.06
0.05
0.04
0.03
0.02
γ = 0.45 ±0.02
60 70 80 90 100 110 120 130 140
Median Rigidity (GV)


Third Harmonic Amplitude (%)
0.015
0.010
0.005
γ = 1.9 ±0.1
60 70 80 90 100 110 120 130 140
Median Rigidity (GV)


Fourth Harmonic Amplitude (%)
0.005
0.004
0.003
0.002
0.001
γ = 1.8 ±0.4
60 70 80
Median Rigidity (GV)

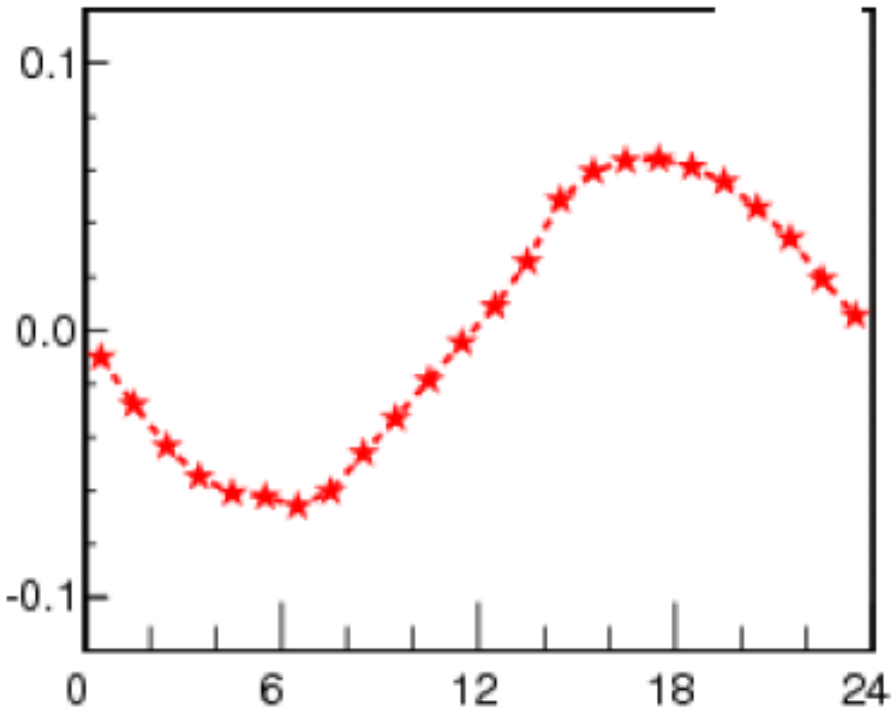
# Swinson Flow Amplitude (%)




GRAPES-3 6-Yr Data 2000-2005

A = (0.0644 +/- 0:0008)% 80σ

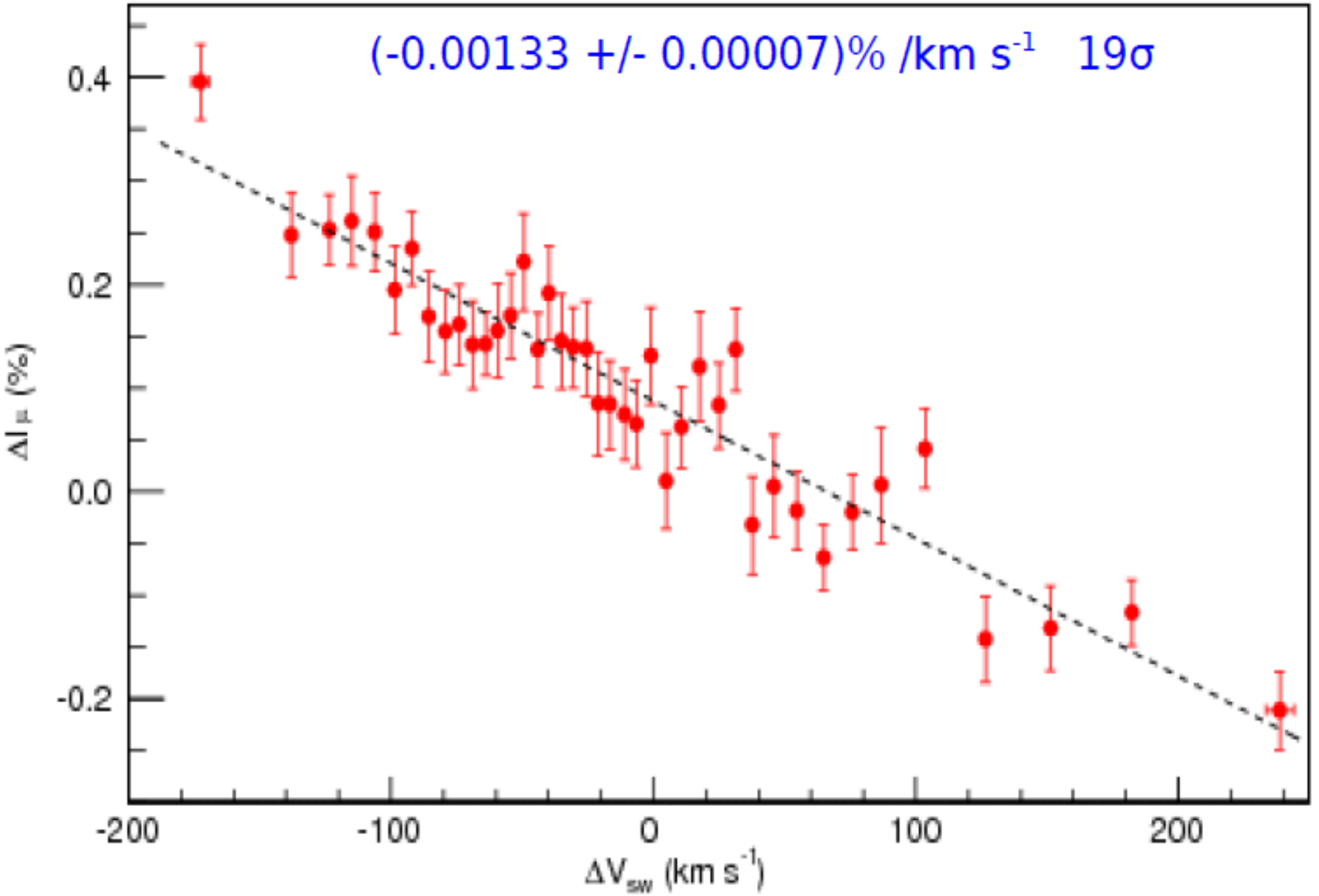
ψ = (17:70 +/- 0:05) h




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

# Cosmic Ray-Solar Wind Correlation

## GRAPES-3 6-Yr Data 2000-2005



# SUMMARY

**Sensitive detection of FD precursors could serve as useful advance indicator of imminent space weather disturbances.**

**Most precise measurement of solar diurnal anisotropy of first, second, third and fourth harmonic including spectra**

**Precise measurement of Swinson flow amplitude at 80σ**

**Dependence of CR on solar wind velocity shown (19σ)**

# THANK YOU

Owens (1981), and Bieber & Pomerantz (1983):
Higher harmonics as the manifestation of the same physical process that is responsible for the generation of the first harmonic. Due to the anisotropic scattering of particles by the irregularities in IMF, the shape of this variation acquires a non-sinusoidal character which when subjected to a Fourier analysis produces higher harmonics.

The unambiguous observation of third and fourth harmonics in the GRAPES-3 data seems to favor this class of models.

# Phase of Harmonics by Fourier Series Method