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# Modeling the solar cosmic ray event of 13 December 2006 using ground level neutron monitor data

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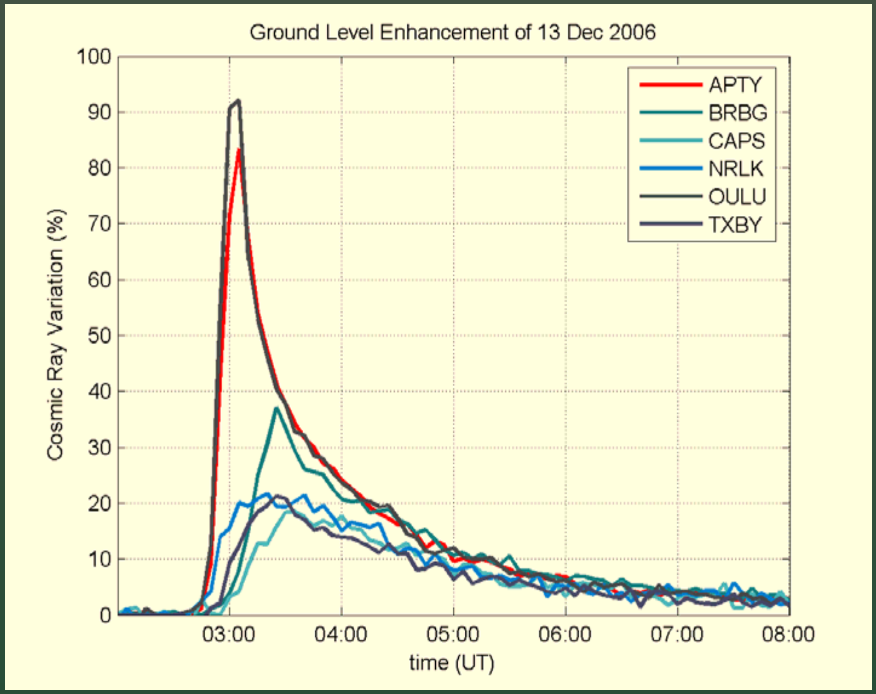
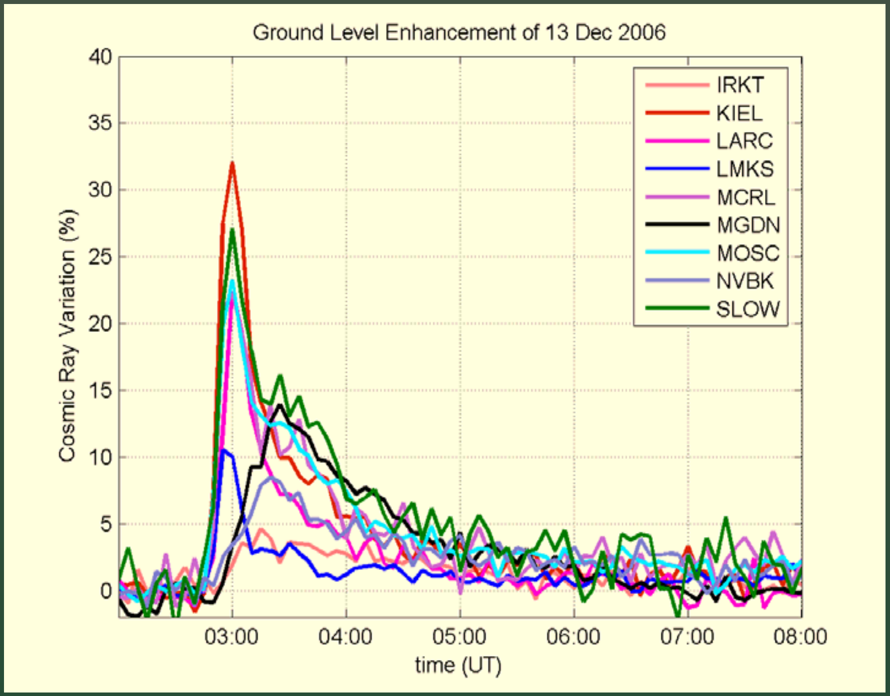
# Overview

- The GLE of 13 December 2006
- The NM-BANGLE Model
- Application to GLE 70
- Results of modeling
- Comparison between GLE69 and GLE70
- Conclusions

# GLE 70
# 13 December 2006



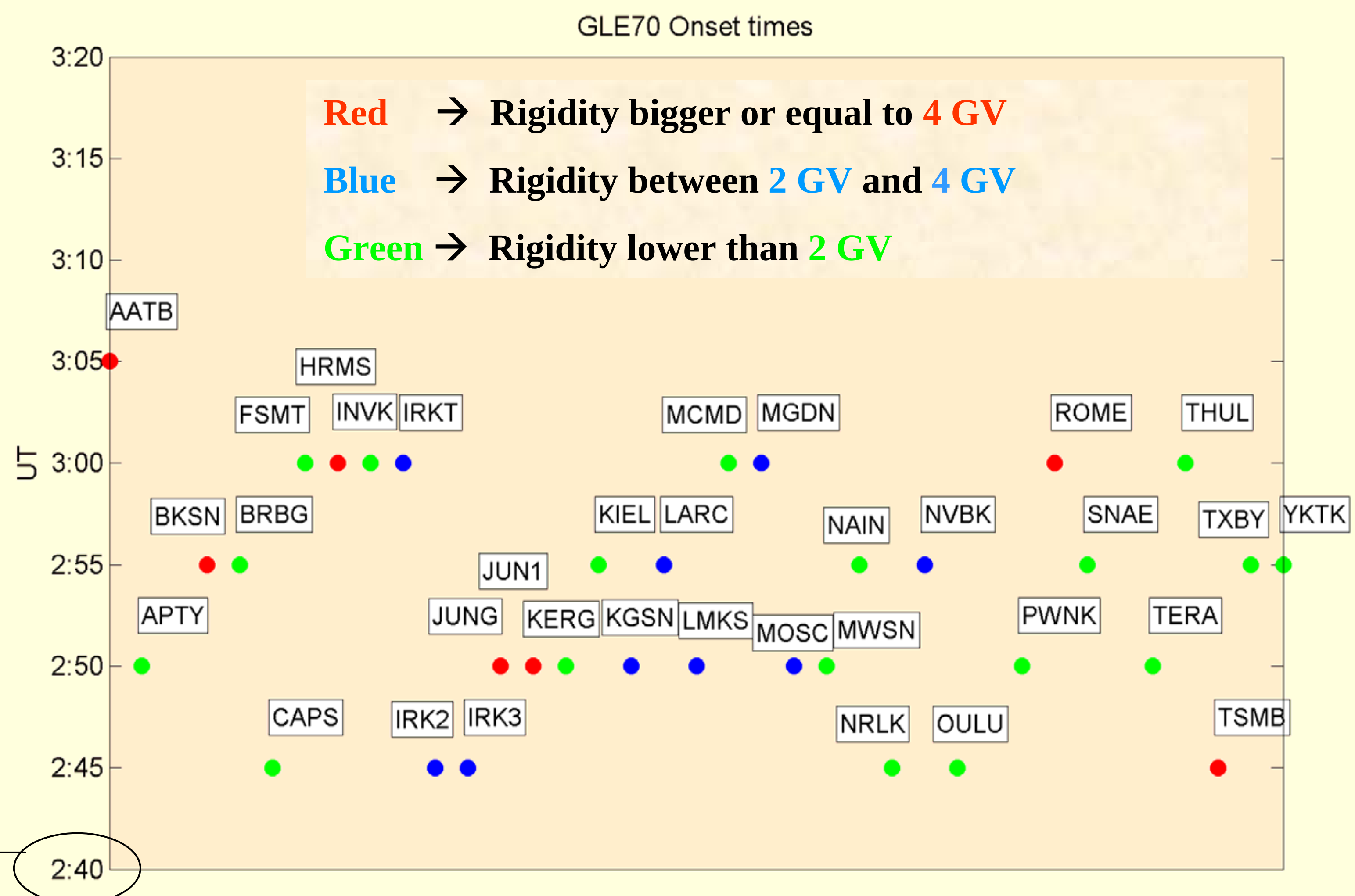




Increase of

~ 92.1 % (**Oulu**)

~ 83.4 % (**Apatity**)

# GLE 70 Onset Times




Time of Flare maximum

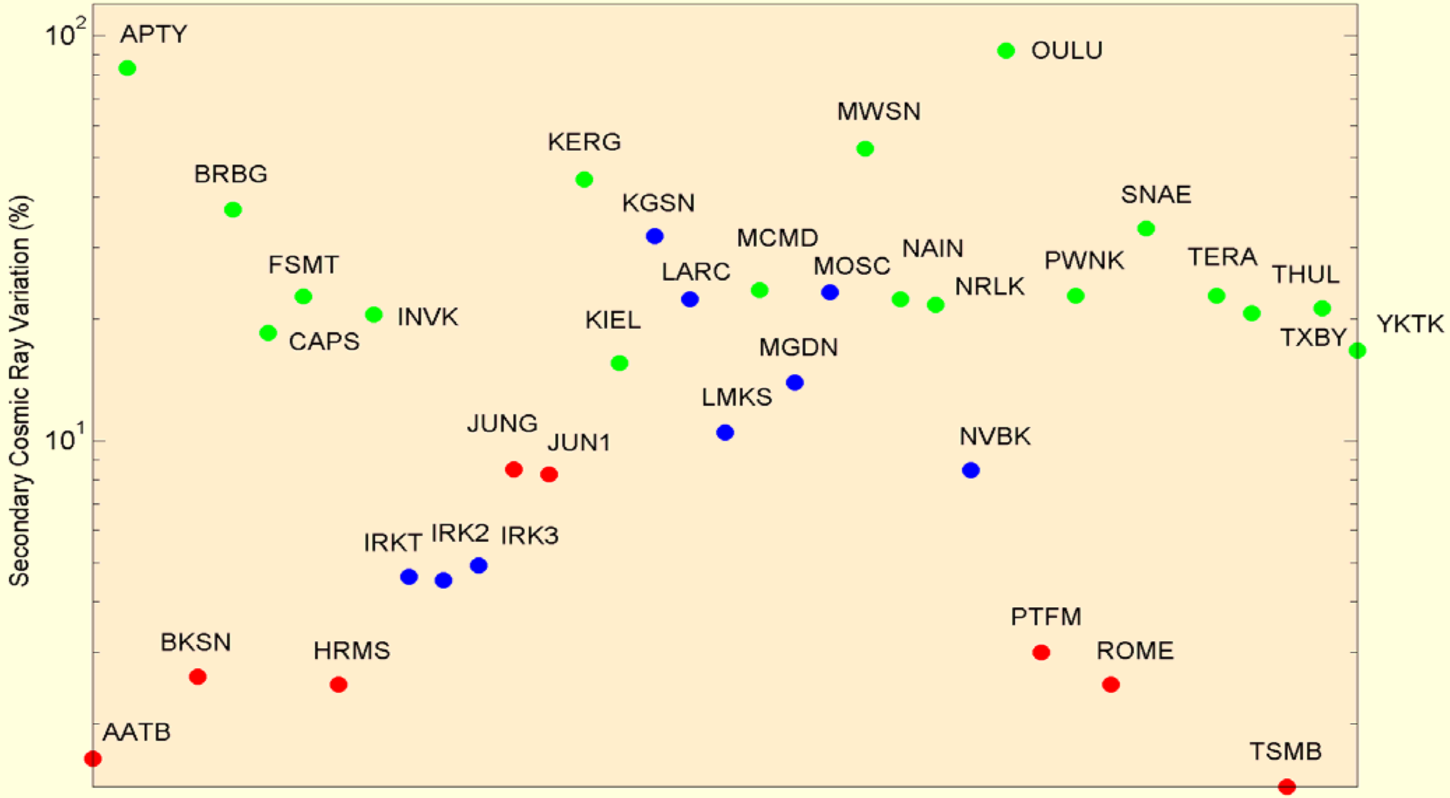
**13 Dec 2006**

# GLE 70 Maxima

**Red** → **Rigidity bigger or equal to 4 GV**

**Blue** → **Rigidity between 2 GV and 4 GV**

**Green** → **Rigidity lower than 2 GV**




**13 Dec 2006**

# GLE 70 Characteristics

(derived from analysis of CR data from 37 NM stations)

One of the **biggest GLEs in 23rd cycle** (behind Apr. 15 2001 and Jan. 20 2005 only) in minimum phase of solar cycle.

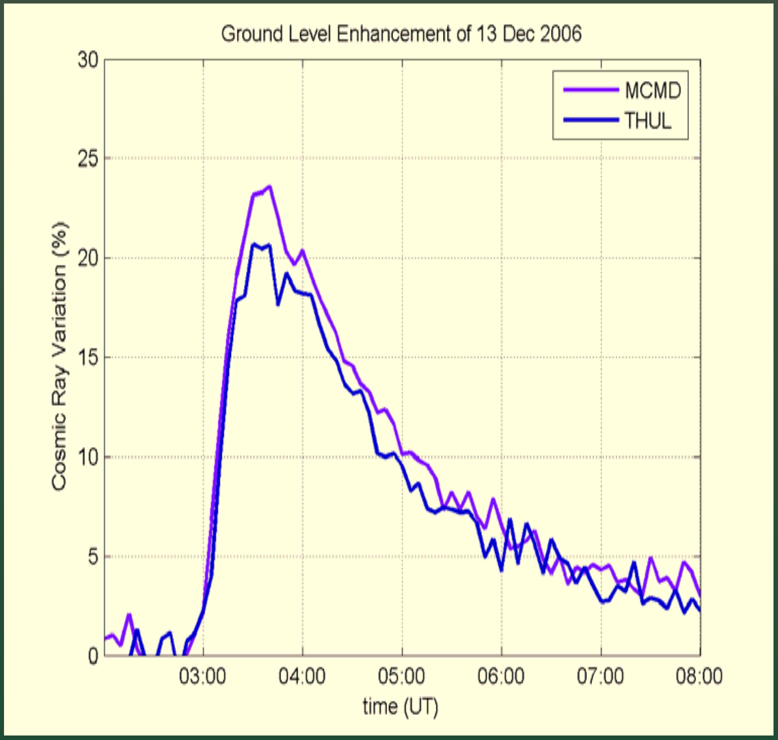
- Slow and unpronounced onset for so big GLE. It is difficult to define surely onset time (2:45-2:52 UT).

- Biggest maximum was recorded at Oulu Neutron Monitor Station (92.1 %).

- Anisotropic enhancement.

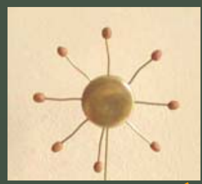
- Maximum enhancement was registered not at sub-polar stations as usual, but at lower latitudes→ Source of anisotropy near ecliptic plane.

- No big North –South Asymmetry.

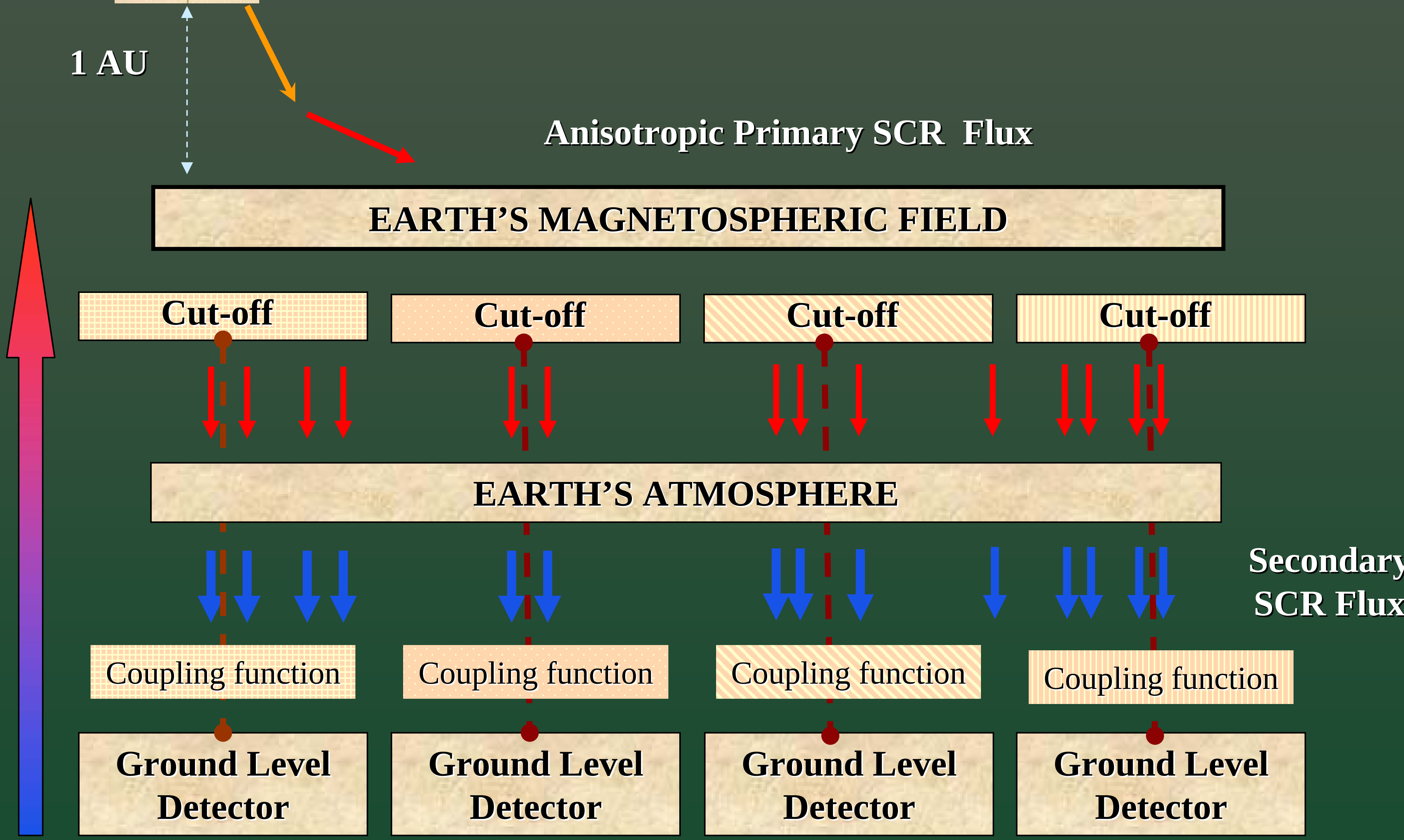


# The NM-BANGLE Model

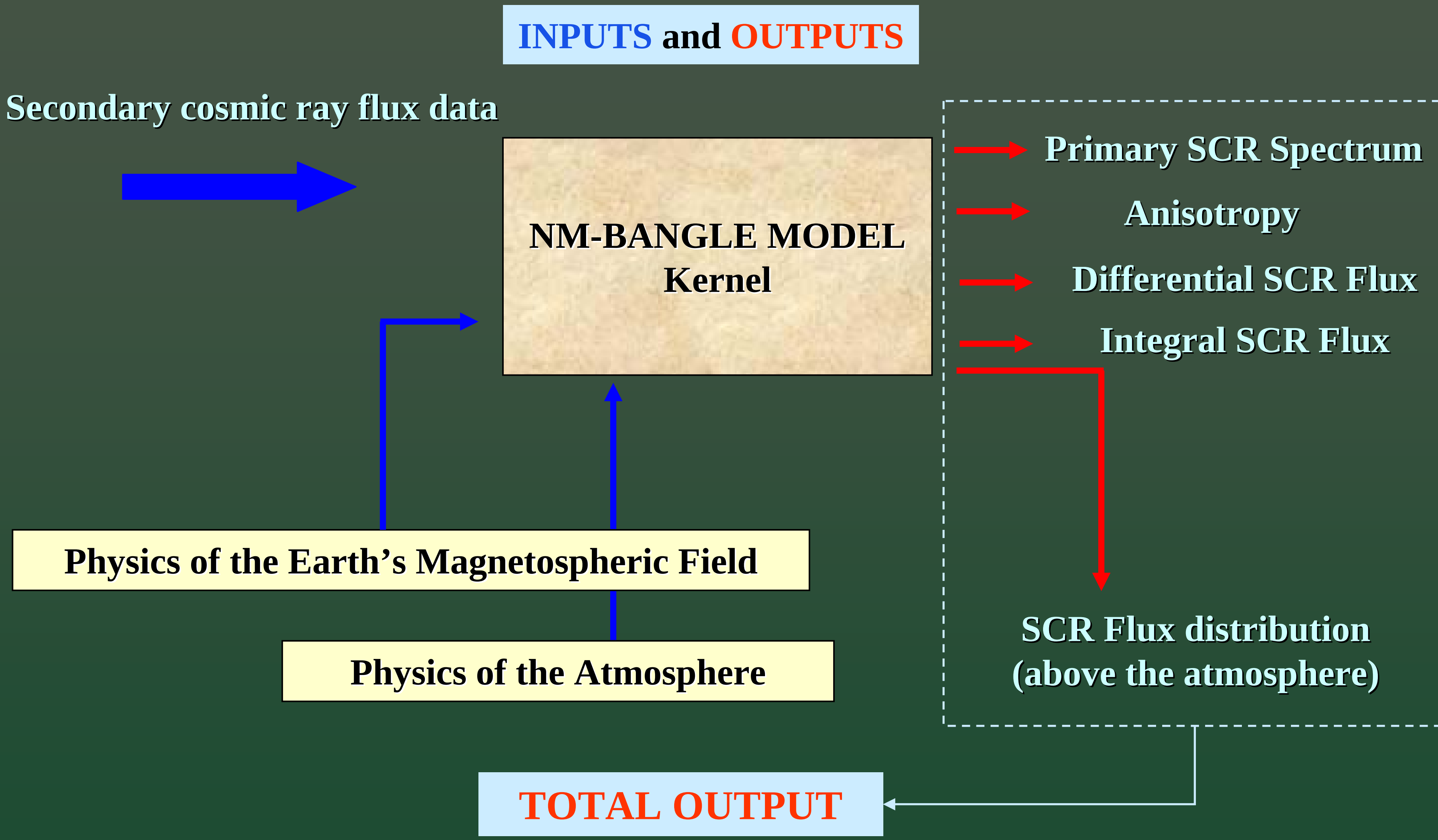
## Neutron Monitor Based Anisotropic GLE Model



*(Plainaki et al., J. Geophys. Res., 2007)*



# The NM-BANGLE Model




a **multi-dimensional** GLE picture that gives an important contribution to understanding the physics of solar cosmic ray particles under extreme solar conditions.

# The NM-BANGLE Model

Neutron Monitor Coupling function

$$\frac{\Delta N(R_c,h,t,t_0)}{N_0(R_c,h,t_0)} = \frac{\int_{R_c}^{R_u} W(R,h,t_0)\,\frac{\delta D}{D_{GCR}}(t,R)\,dR}{\int_{R_C}^{R_u} W(R,h,t_0)\,dR}$$

**Solar Cosmic Rays** differential spectrum

Secondary Cosmic Ray Variation

Galactic Cosmic Ray Background

- **Solar Cosmic Ray Spectrum**:

$$\delta D = b \cdot f(R,E) \cdot \Psi$$

**anisotropy function**

For $f(R,E)$ and $\Psi$ there is a variety of choices depending on the **characteristics** of each specific GLE event.

Power-law rigidity dependence gives: $f(R) = R^{\gamma}$

# The NM-BANGLE Model

## ➢ Solar Cosmic Ray Anisotropy

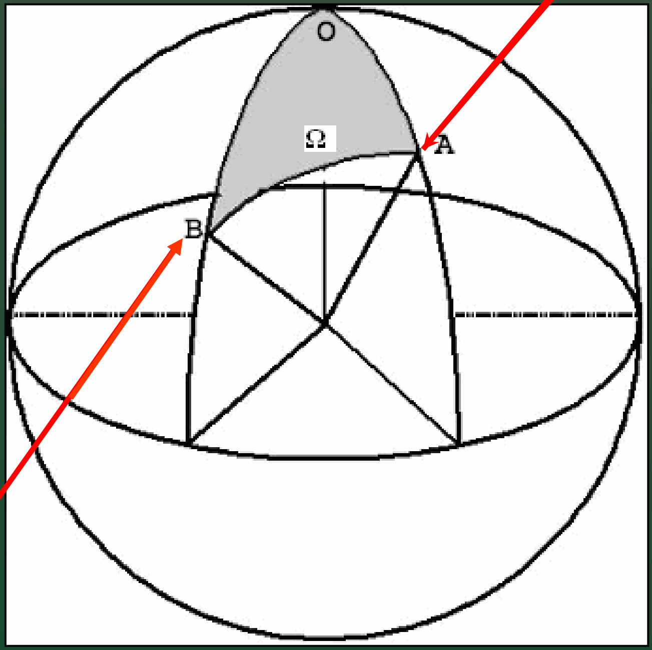
One “good” choice for anisotropic GLE events is:

$$\Psi(\Omega) = \exp(-n^2 \sin^2 \Omega)$$

axis-symmetric **anisotropy function**

Definition of angular parameter $\Omega$

**Point of observation defined by the asymptotic coordinates of the NM Station**




**Location of the anisotropy source**

# The NM-BANGLE Model

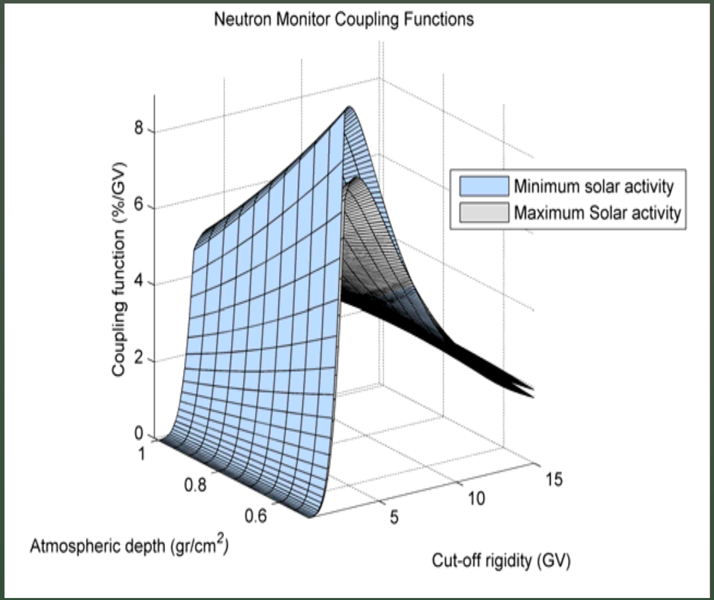
- **Neutron monitor coupling functions**:

$$W(R,h,t_0)dR = \begin{cases} W_T(R,h,t_0)dR, & E \geq 2GeV \\ W(R=2.78GV,h,t_0)\left(\dfrac{E}{2GeV}\right)^{3.17} dR, & E < 2GeV \end{cases}$$

where

$$W_T(R,h,t_0) = a\cdot(k-1)\cdot\exp(-a\cdot R^{-k+1})R^{-k}$$

is the **Dorman** function *(Dorman, 2004; Clem and Dorman, 2000; Belov and Struminsky, 1997; Belov et al., 2005)*




Taking into consideration long-term variation and/or possible Forbush effect, coupling functions become:

$$W(R,h,t_0)dR = \begin{cases} W_T(R,h,t_0)[1+\delta_{t0}(R)]dR, & E \geq 2GeV \\ W(R=2.78GV,h,t_0)\left(\dfrac{E}{2GeV}\right)^{3.17} dR, & E < 2GeV \end{cases}$$

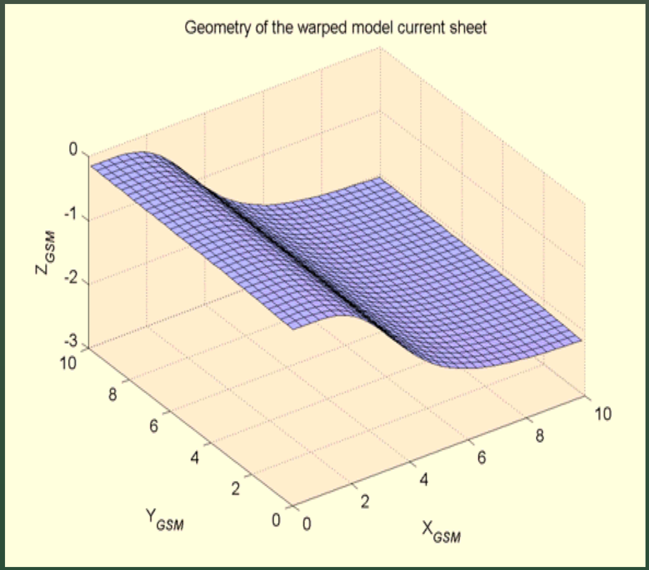
where $\delta_{to}(R)$ is a typical GCR spectrum

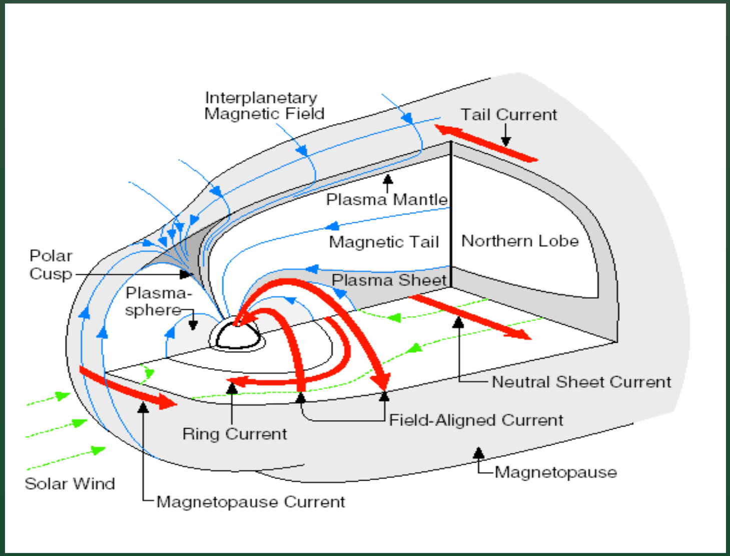
# Magnetospheric field modeling

The NM-BANGLE model uses Tsyganenko 1989 model for describing the Earth's magnetospheric field (T89c)

The main contributions to the Earth's magnetic field come from:

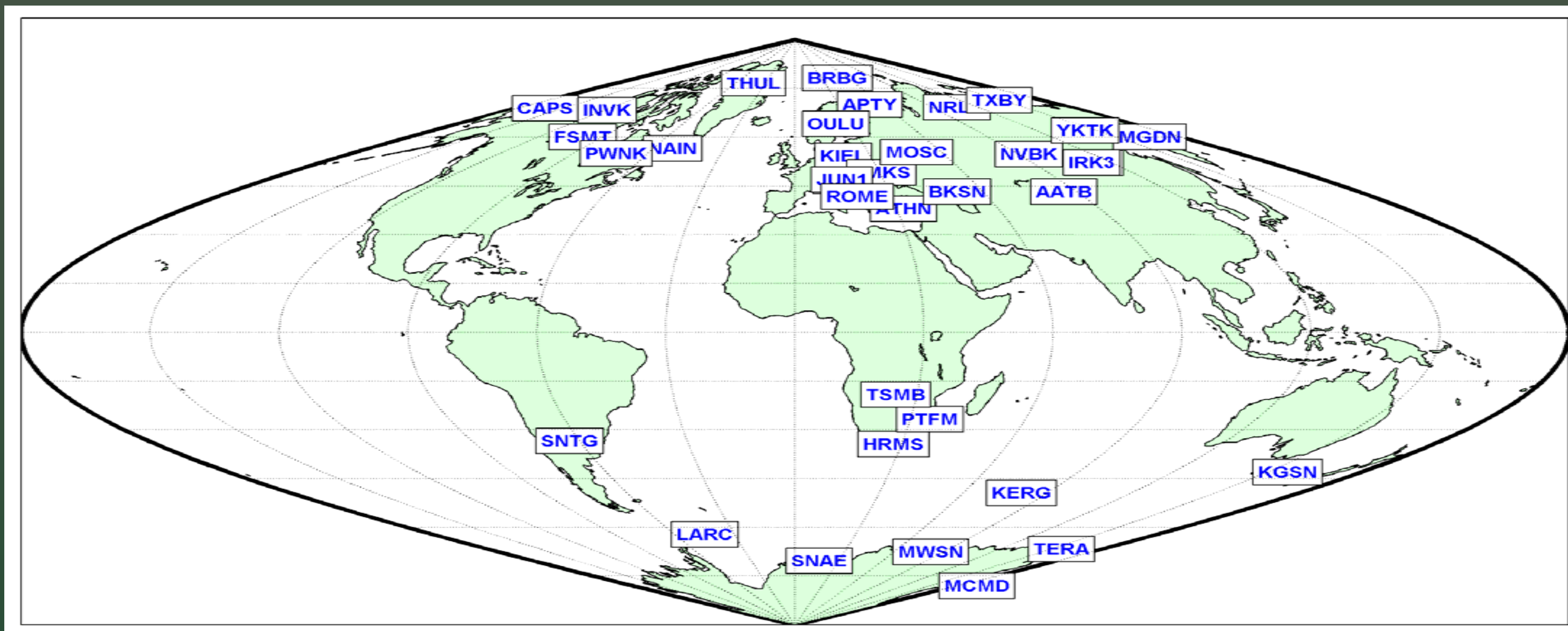
- The **Ring Current** System
- The **Tail Current** System
- The **Magnetospheric Boundary Sources**
- The **Chapman-Ferraro** Current systems at the magnetopause




**Warping effect** of the tail current sheet in two dimensions due to the geodipole tilt

# NM-BANGLE Model Application




- Five minute data from **37 NM stations** widely distributed around the Earth
- Magnetospheric field configuration according to Tsyganenko89 model
- Calculation of the Neutron Monitors asymptotic directions of viewing.
- Levenberg-Marquardt non-linear optimization algorithm

# Results of Modeling

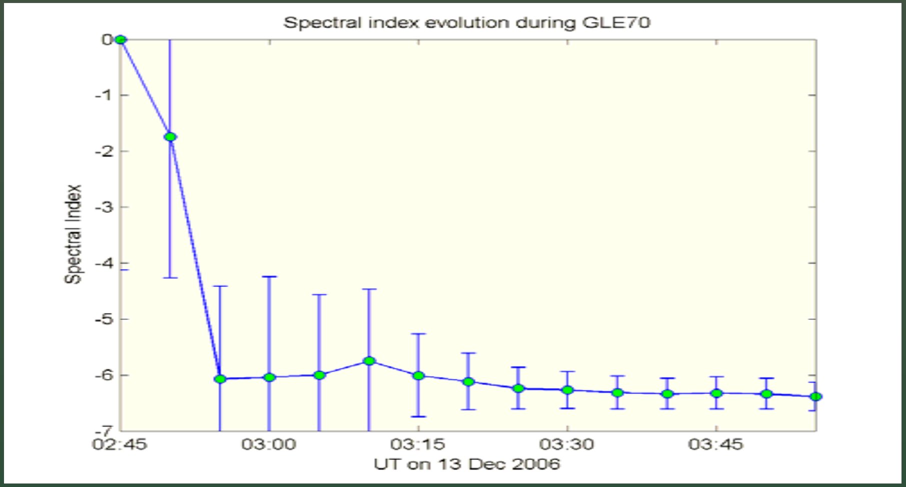
## Rigidity Spectrum

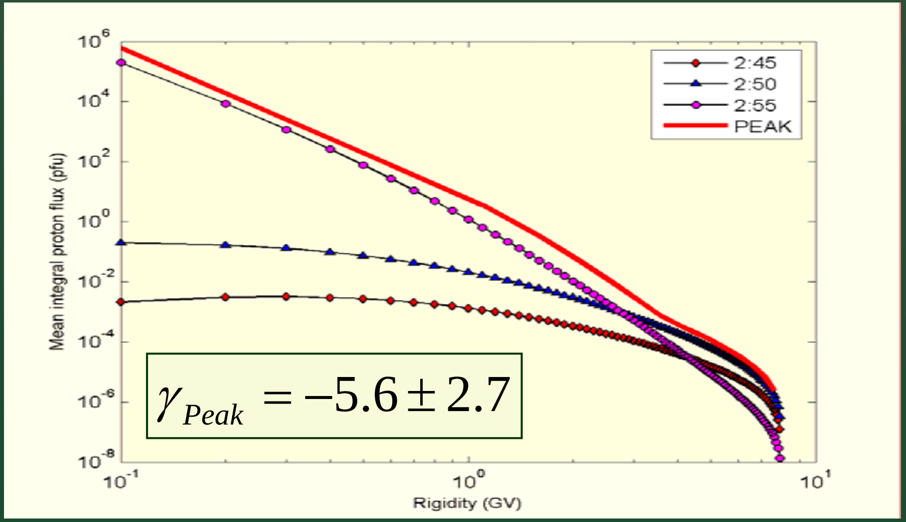
- Contribution of **higher energy** particles in 2:45 – 2:50 UT

- Initially **hard spectrum-** significantly **softer** in the third 5min-interval.

- **Peak spectrum** quite close to power law

- Even in case of a full scatter-free propagation the peak spectrum cannot be affirmed to be very representative of the injection spectrum shape because of the possible **influence of the IMF →** Additional study required



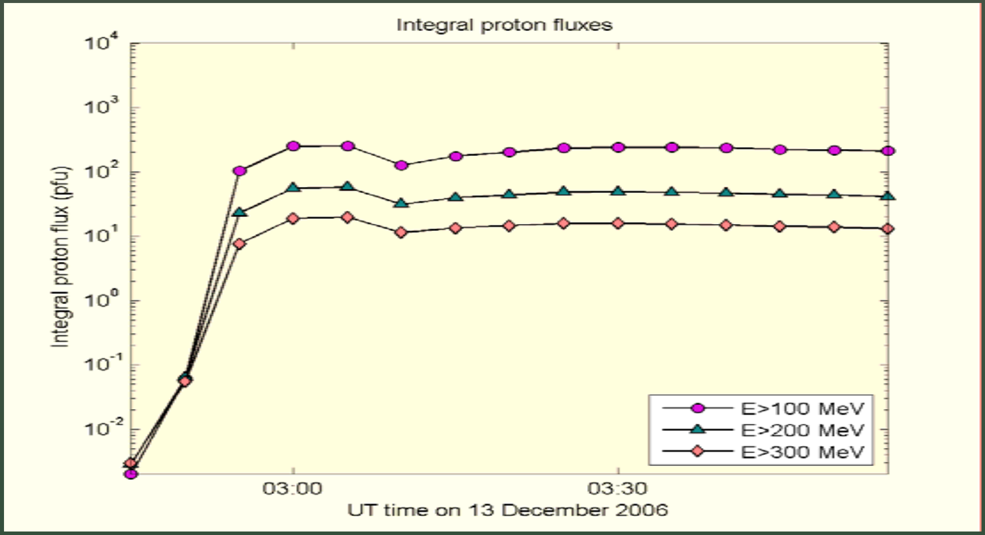
# Integral proton fluxes

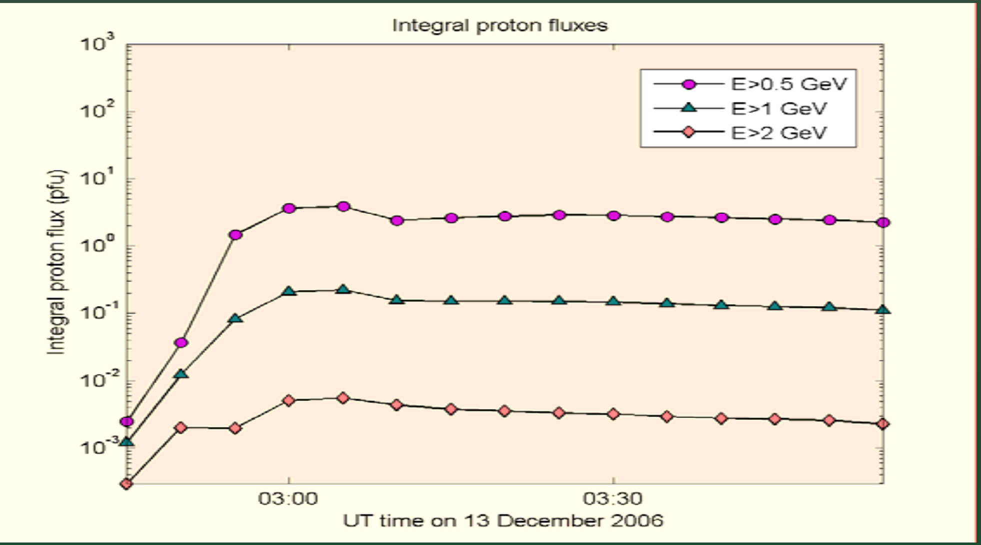
- Big mean integral flux during the first time intervals of the event

- Good agreement between calculated mean integral flux and satellite observations.

- According to our model, all three fluxes of lower energy particles remain at a high level during the first hour of the event. This is also testified by the satellite observations.

- The estimated flux for particles with energy >100 MeV exceeds only by a factor of ~2 the flux recorded on 29 September 1989 (~600 pfu) and on 14 July 2000.




Results displayed for energies greater than 100 MeV, 200 MeV and 300 MeV are obtained by extrapolation

# Anisotropy

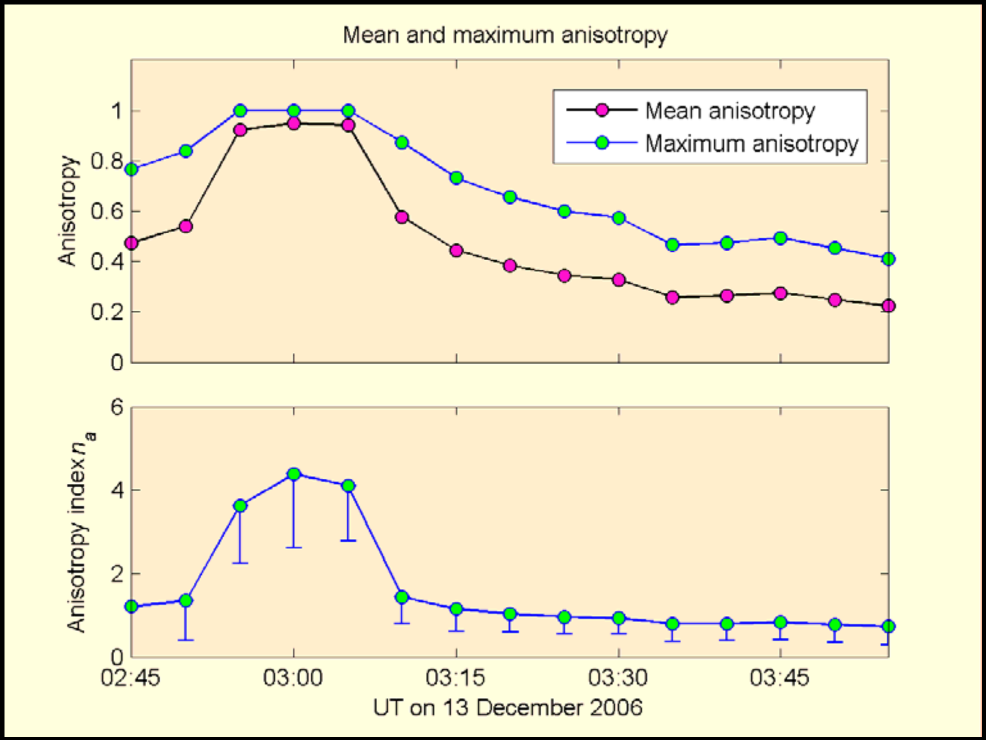
According to the NM-BANGLE Model solar particles arrived mostly from equatorial-southern directions

- Strong anisotropy in the beginning phase of the event . Maximum anisotropy value on the maximum of the event.

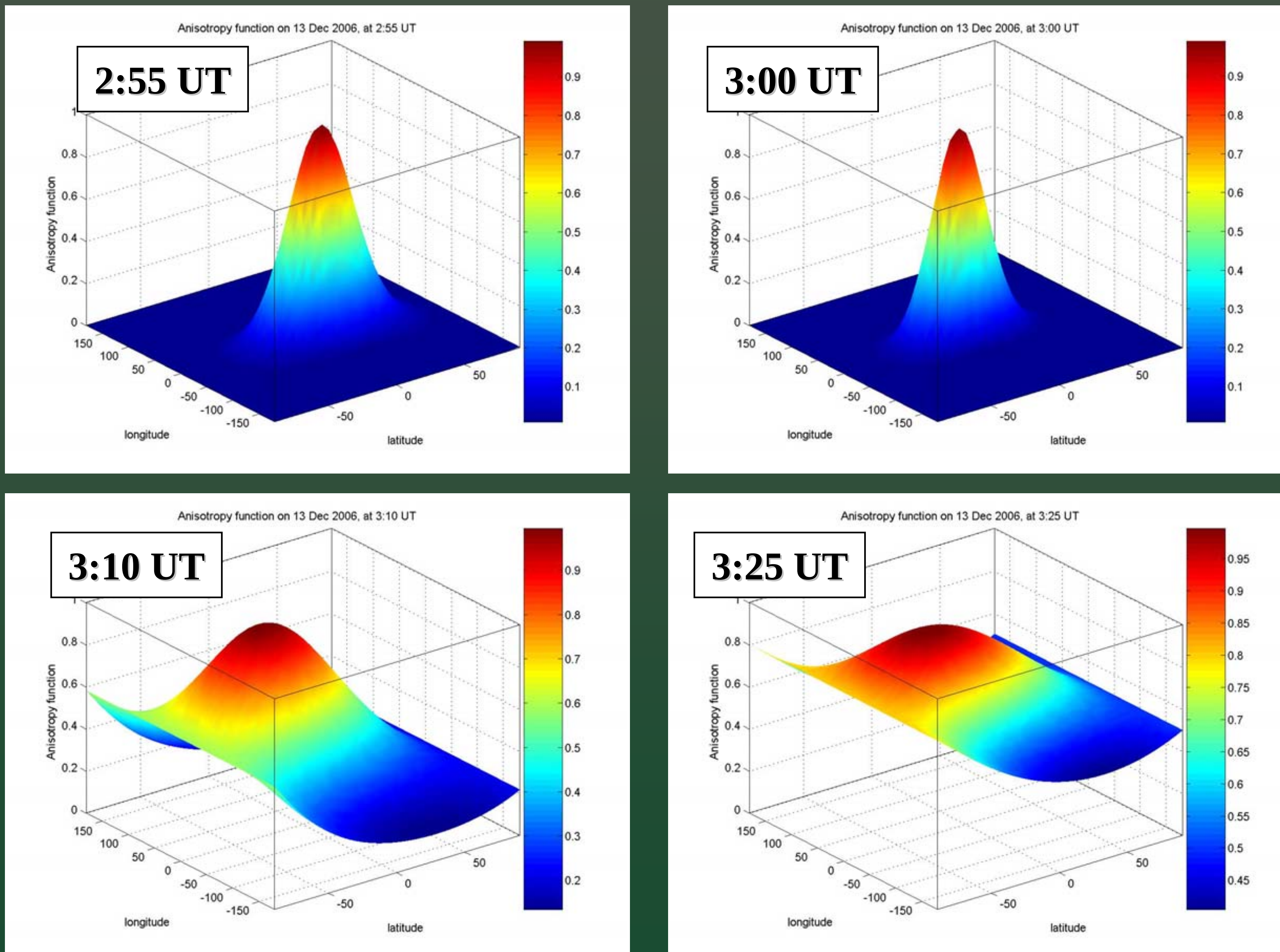
- Values of the anisotropy contribution in mean and maximum fluxes, on maximum, are similar.

- The angular distribution is narrow during the time interval 2:55 UT – 3:05 UT, with an index taking values between 3.7 and 4.

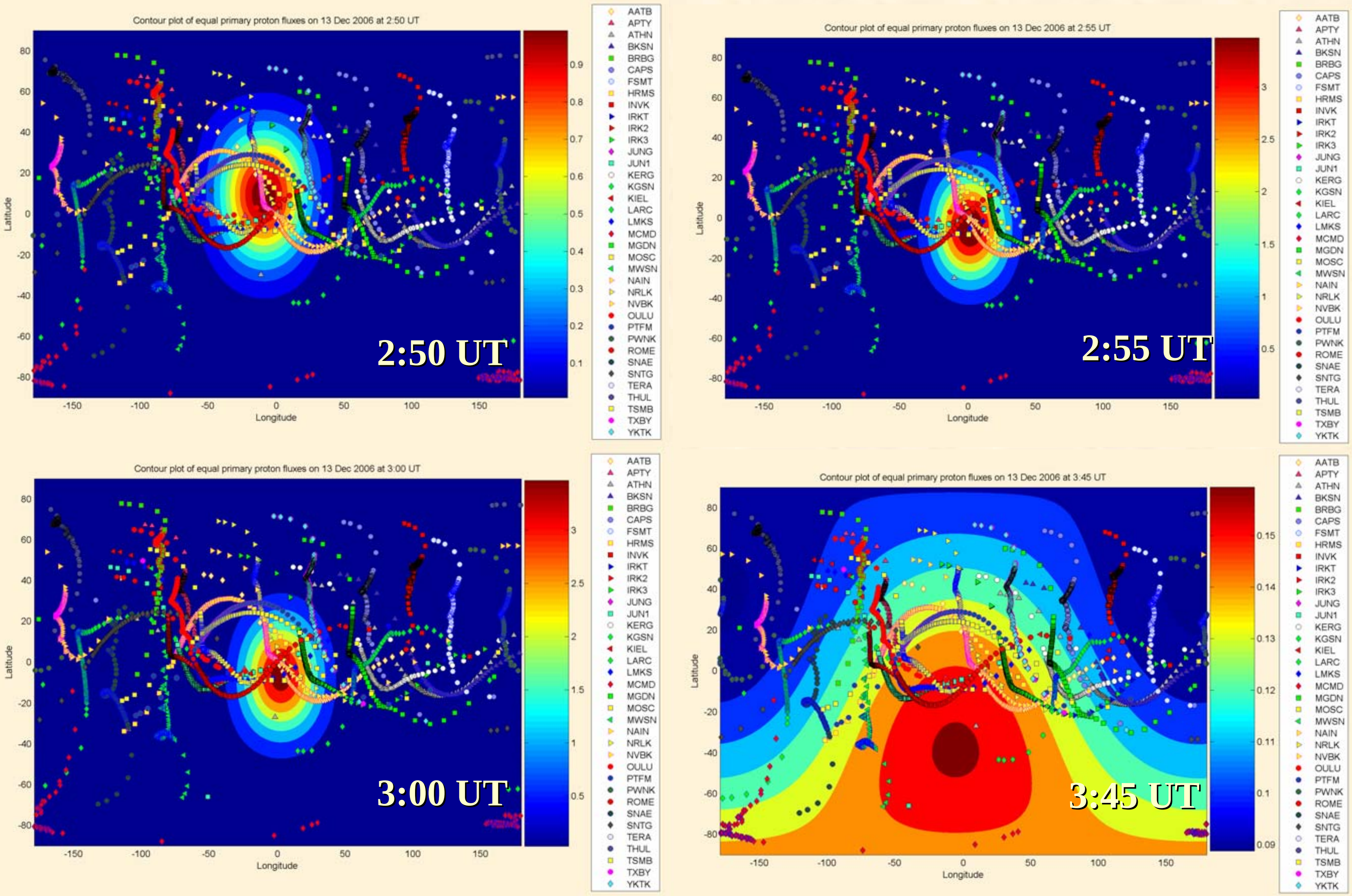
- After 3:10 UT anisotropy index becomes smaller (~1), suggesting a **wider angular distribution** of SCR particles



# Longitudinal distribution of the anisotropic flux on 13 December 2006



# Contour areas of equal fluxes of particles with rigidity>1 GV together with NM asymptotic viewing directions



# Comparison between GLE69 (20 Jan 2005) and GLE70 (23 Dec 2006)

## Similarities

- They were both big anisotropic enhancements recorded by the majority of the NM of the worldwide network.
- In the initial phase of both events **narrow particle beams** of solar cosmic rays arrived at the Earth.
- Initially **hard spectrum** in both cases, **significantly softer** during later phases.

## Differences

- **Maximum enhancements** differed by **2 orders** of magnitude (GLE69-Max~3200%, GLE70-Max~92%)
- The anisotropy source was located **near the equator** during GLE70, whereas in case of GLE69 it was placed to **southern locations**.
- Maximum of GLE70 was recorded at **sub-polar stations**, whereas GLE69 maximum was registered at **South Pole**.
- The solar cosmic ray particle beam assumed in NM-BANGLE Model was **more narrow** in case of GLE69 than in GLE70.

# Conclusions

- On 13 December 2006, the neutron monitors whose asymptotic directions viewed the anisotropy source recorded big enhancements (e.g. Apatity, Oulu).

- The initially narrow solar particle beams widened with time resulting in big enhancements recorded by other NMs as well.

- Anisotropy remained in relatively high levels during the first hour of the event.

- The source of anisotropic flux was located near the ecliptic plane. The position of the anisotropy source changed with time, moving to southern locations.

- The estimation of the integral flux for primary cosmic ray particles with energy >100 MeV on the basis of our model is in good agreement with the satellite observations.

## Special thanks to all Neutron Monitor Groups for kindly providing their data

**Websites**

***http://cosray.phys.uoa.gr***

***http://users.uoa.gr/~cplainak/index.htm***

***email: cplainak@phys.uoa.gr***