

# Particle Accelerations – Spectra and their associated CMEs

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IUCAA, Pune  
7 September 2011

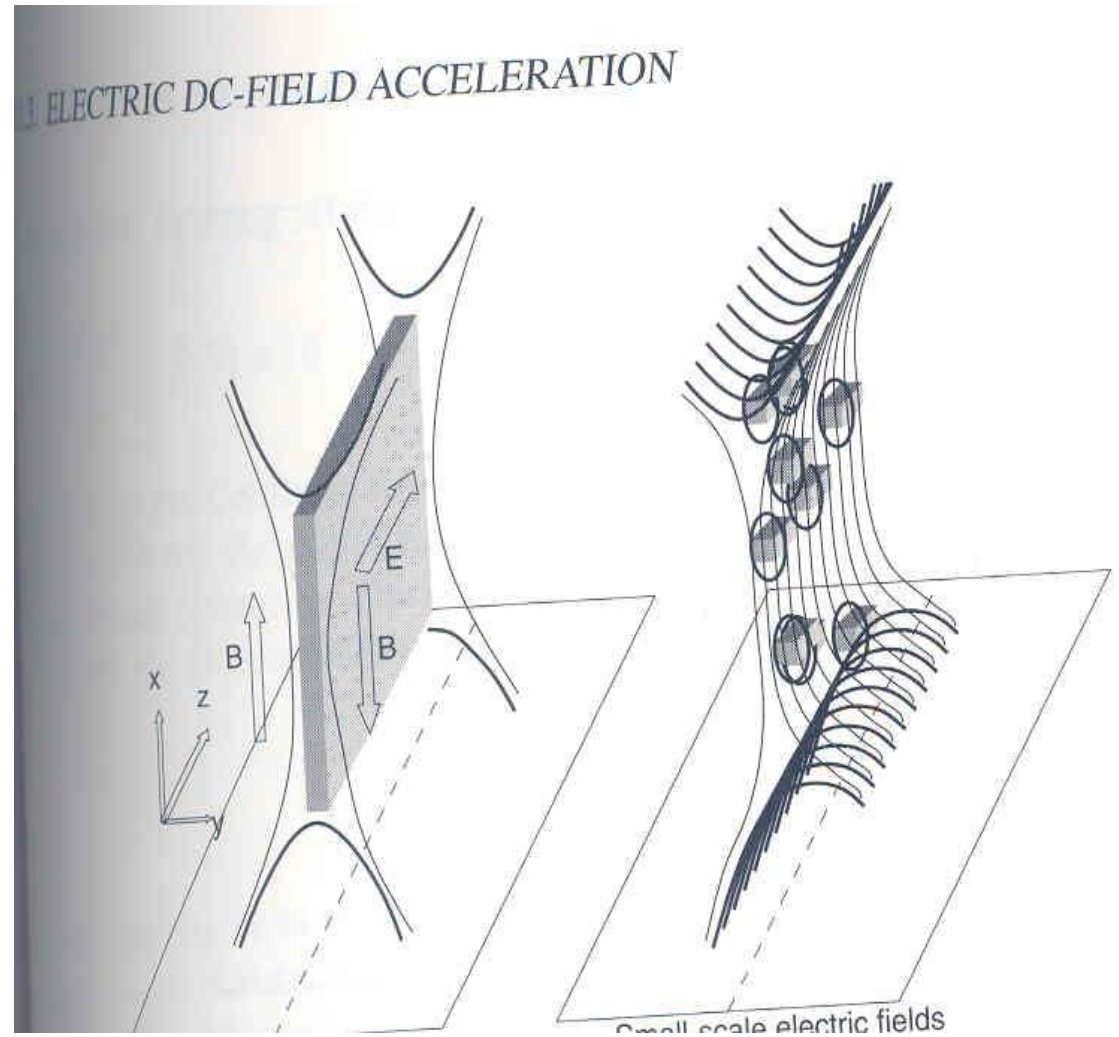


# Outline of the talk

- **Some basics particle acceleration mechanisms**
  - **DC electric field acceleration**
  - **Shock acceleration**
  - **Radio emission**
- **Solar Flares and energetic particle events**
  - **CME association – particle profile**
  - **CME propagation and particle spectrum**

# DC Electric Field Acceleration

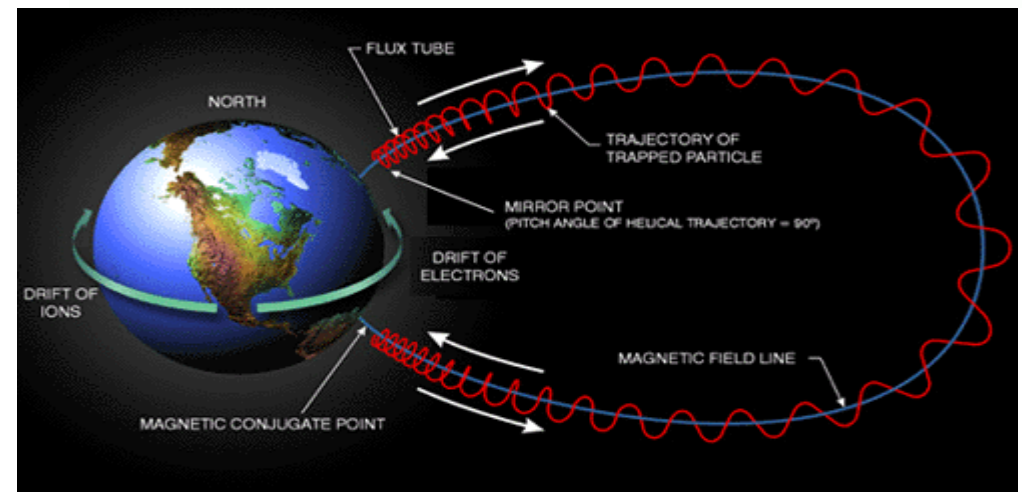
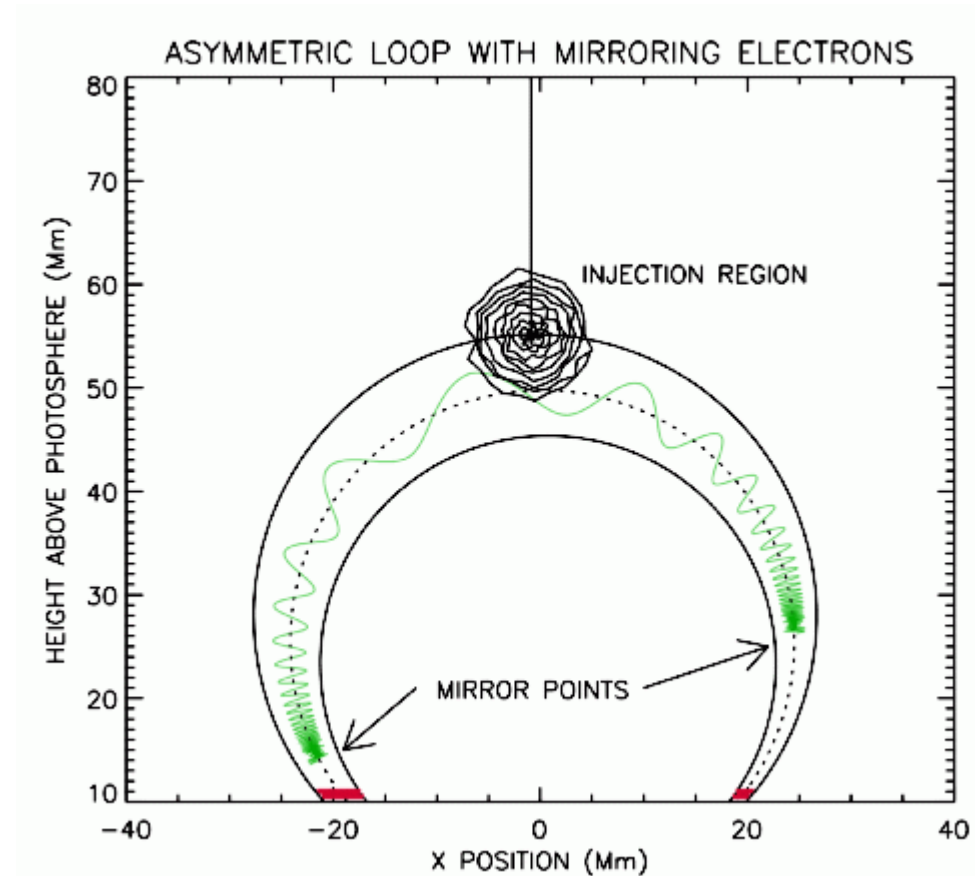
Acceleration in *static electric fields* which are generated in current sheets during magnetic reconnection processes.



# Magnetic Mirroring effect

- Tendency for charged particles to bounce back from the high field region
- Particles with a pitch angle greater than a critical value will be reflected, those with a smaller pitch angle will escape.
- Adiabatic invariant

$$\mu = \frac{\frac{1}{2}mv_{\perp}^2}{B}$$

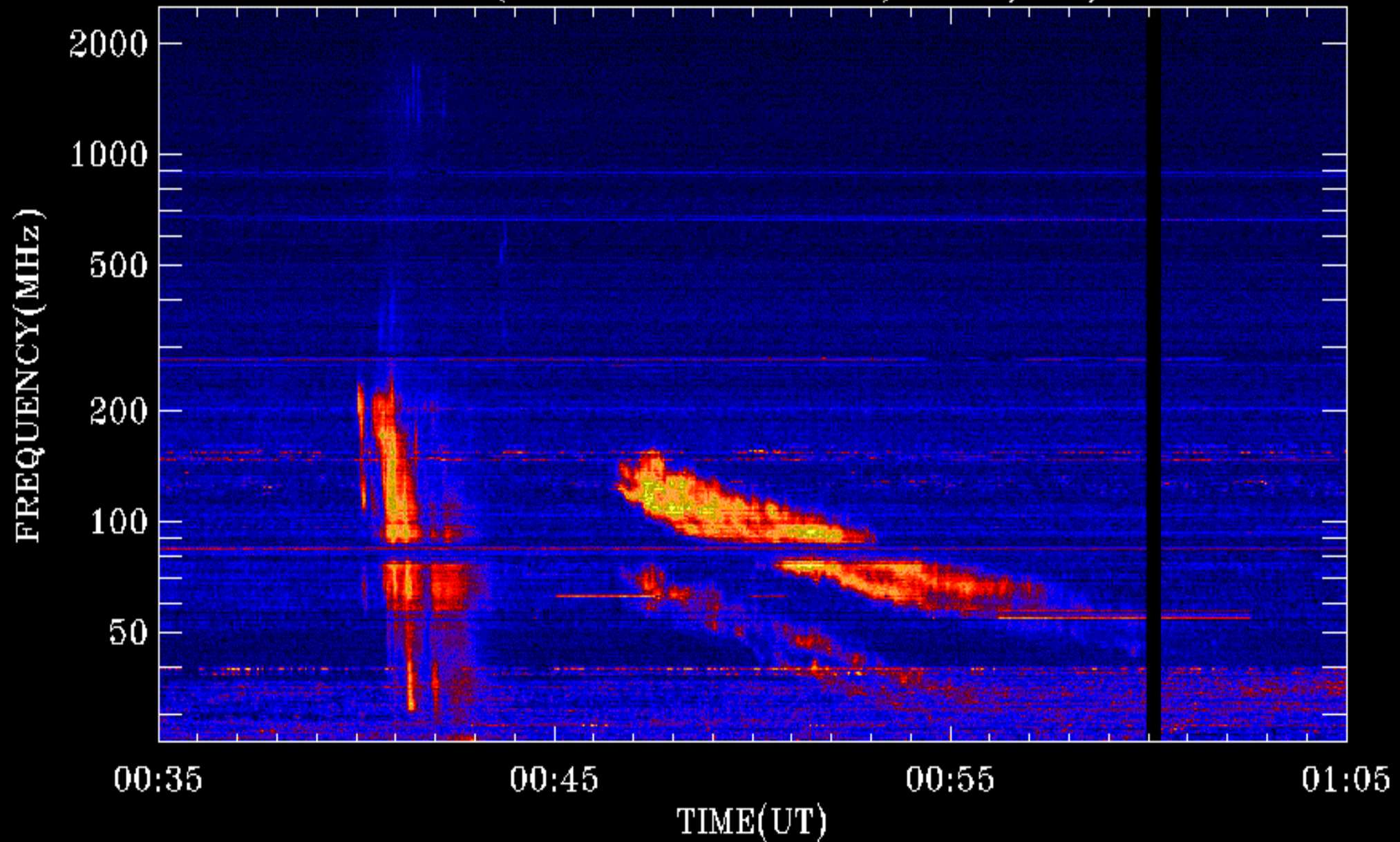


# Shocks

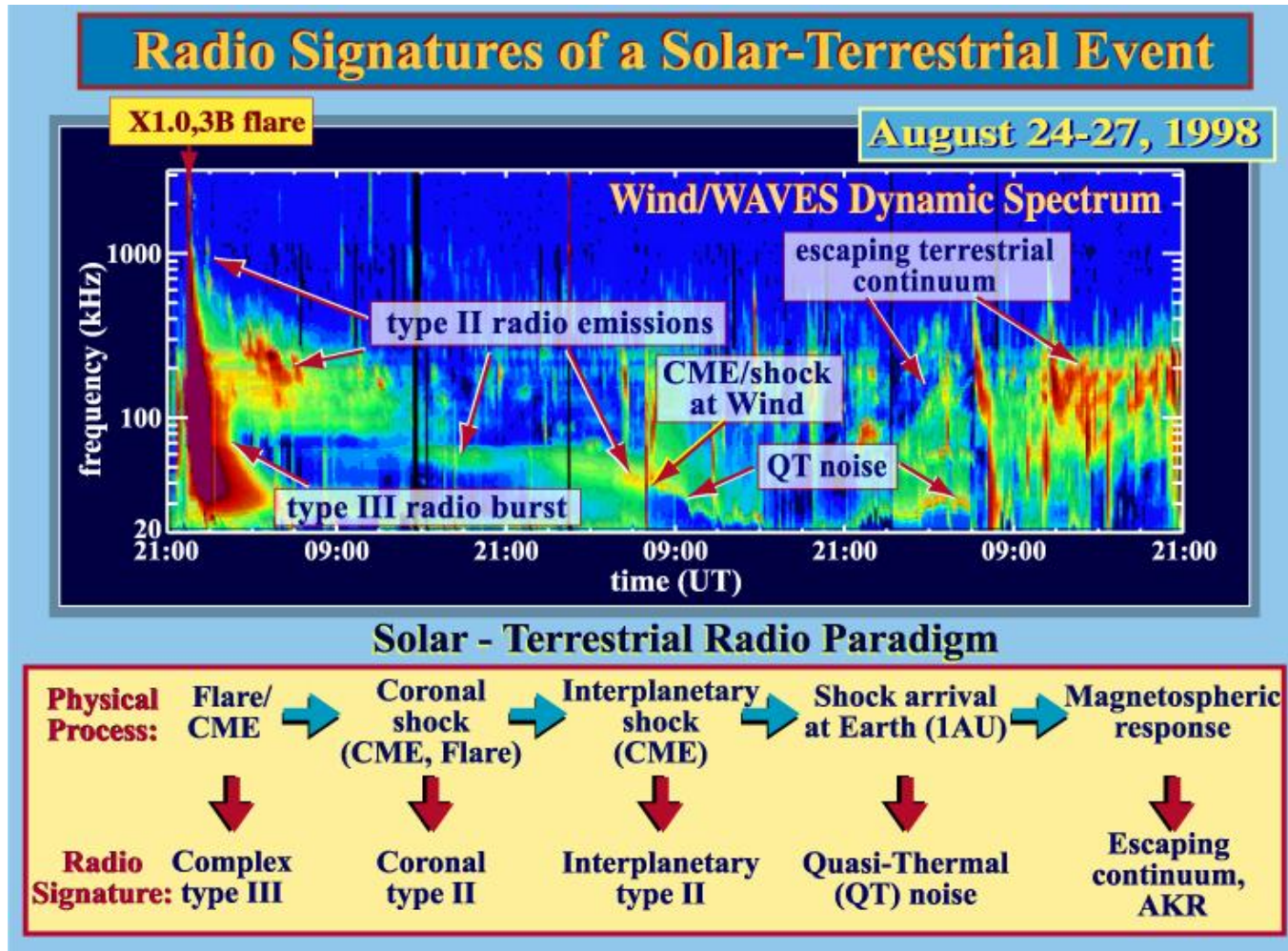
- **Shocks are places where plasma and field go through dramatic changes in density, temperature, field strength, and/or flow speed.**
- **Play important role in the solar corona and interplanetary space, since they are able to accelerate the particles up to high energy.**
- **In solar corona , these can be produced by either by blast waves due to huge pressure pulse accompanying the flare or as a piston driven shocks i.e. Bow shock of a propagating/rising CME.**

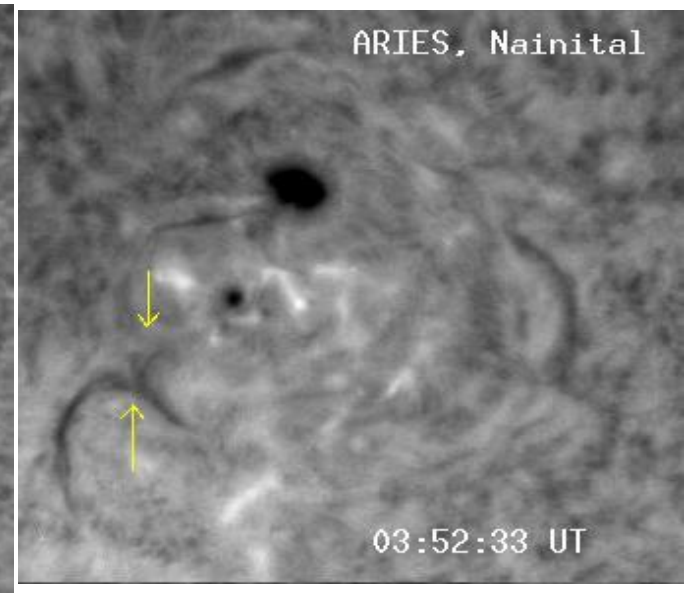
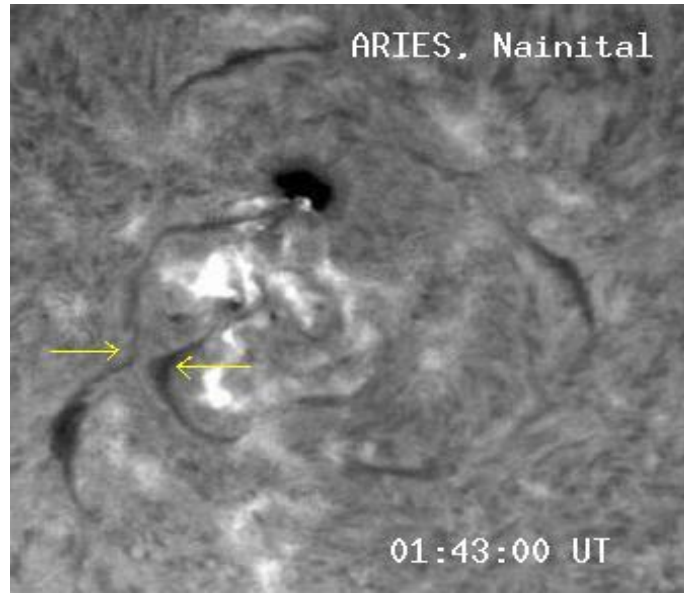
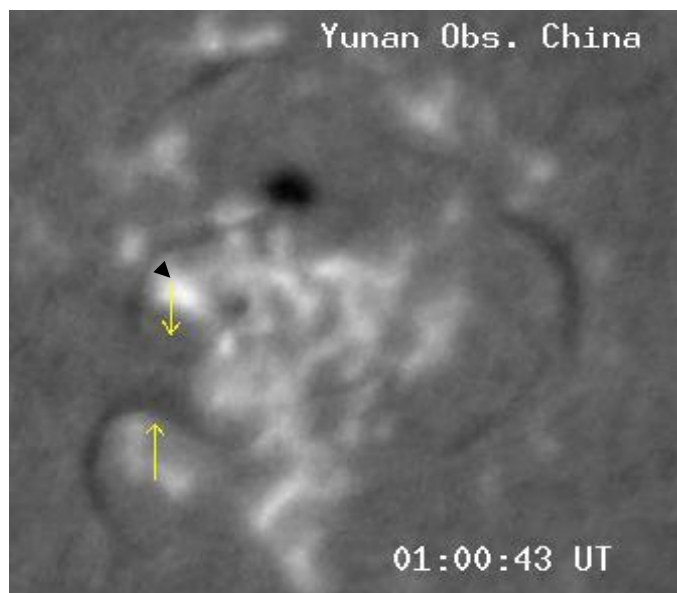
# Type II and III Bursts

*HiRAS* (25–2500MHz R+L) 93/10/26



# Shock acceleration in CMEs and Type II burst



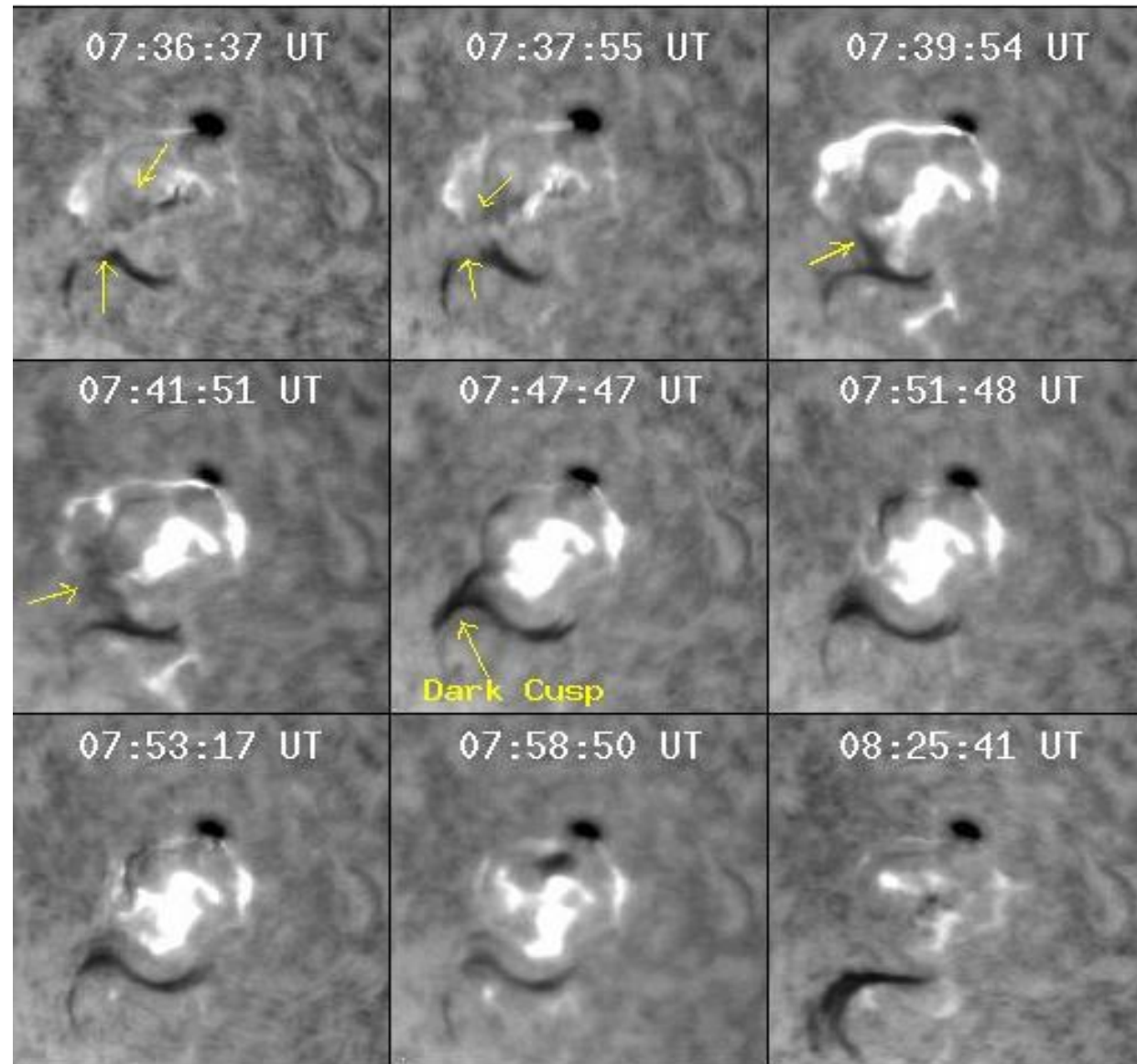
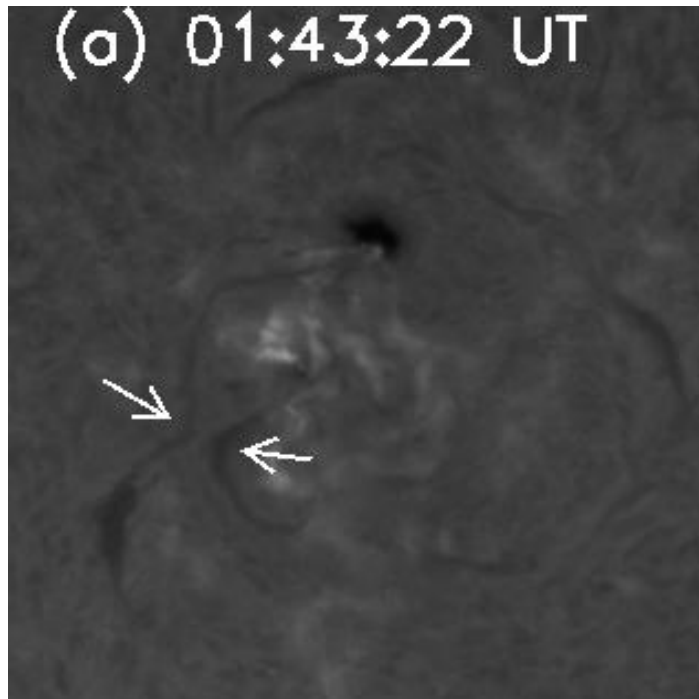


**Changes in orientation of filament  
- signature of magnetic reconnection.**



# Evolution of 2B/M9.6 Flare in $H\alpha$

Impulsive flare starts with two filaments reconnection and dark cusp formed during impulsive/maximum phase.



# Solar Energetic Particle (SEP) Events



**Associated with explosive phenomenon on the Sun**

- **SEP events – 2 types – Impulsive and Gradual**
  - Impulsive events have their origin at rapid short duration flares ( $\leq 30$  min. duration)
  - Dominated by electrons,  $^3\text{He}$ , and heavy ions
  - Flare energy release processes play a key role in particle acceleration
- **Gradual Events**
  - Associated with large/fast coronal mass ejection (CME) events
  - Rich in protons
  - CME-driven shock accelerates particle in the IP space

# SEP Events and their CMEs

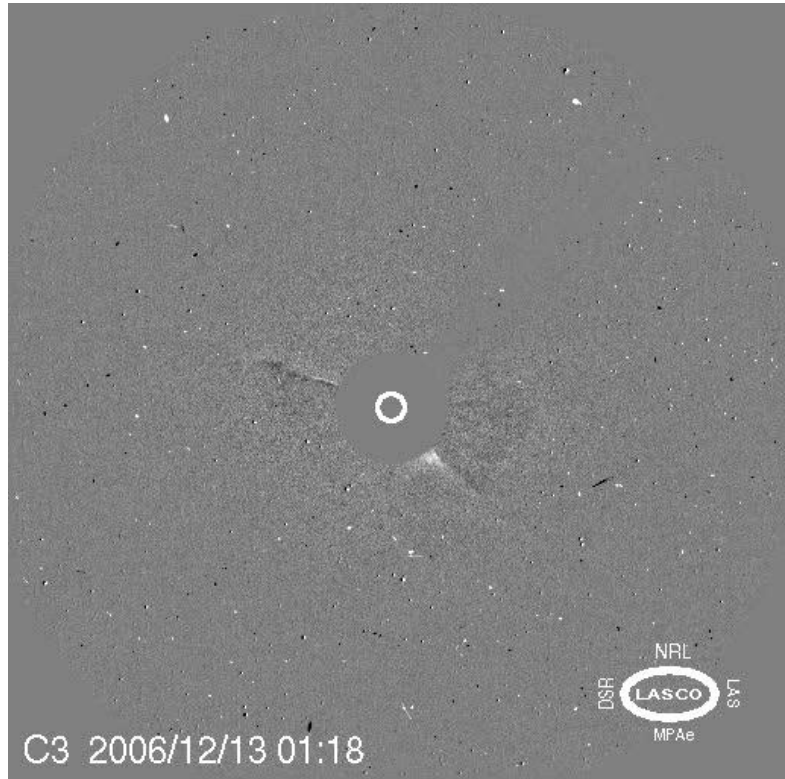
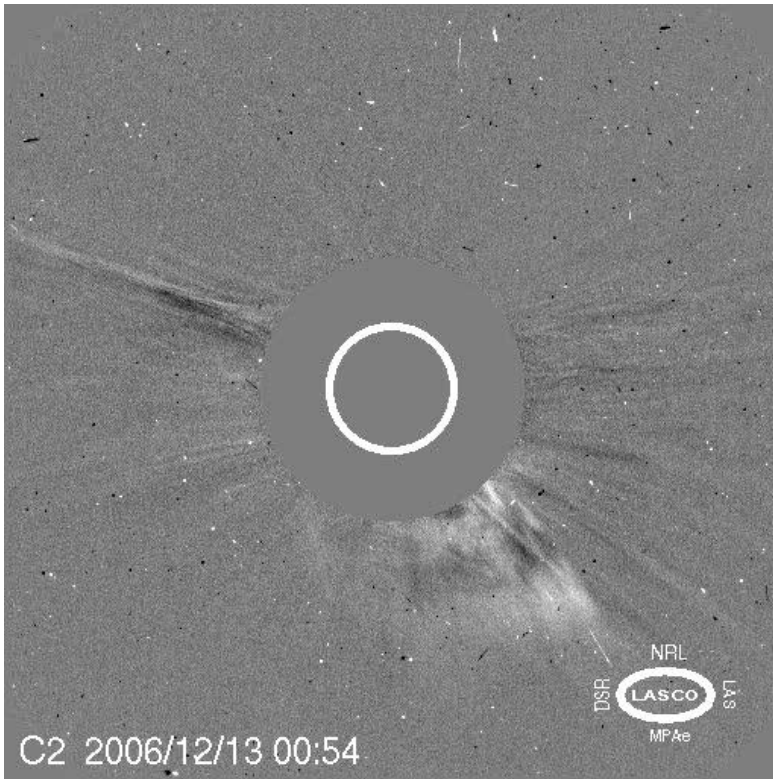
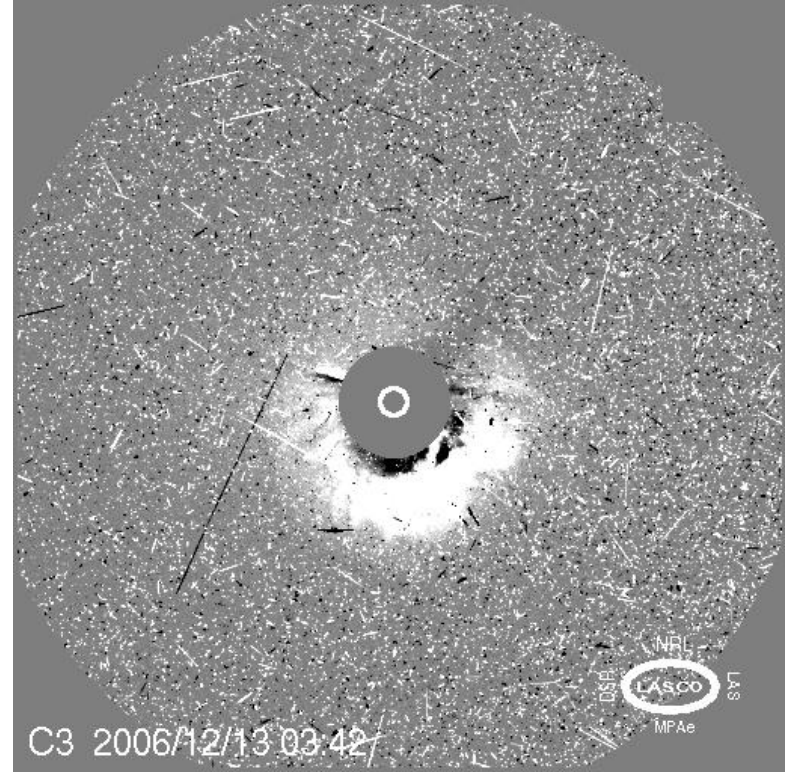
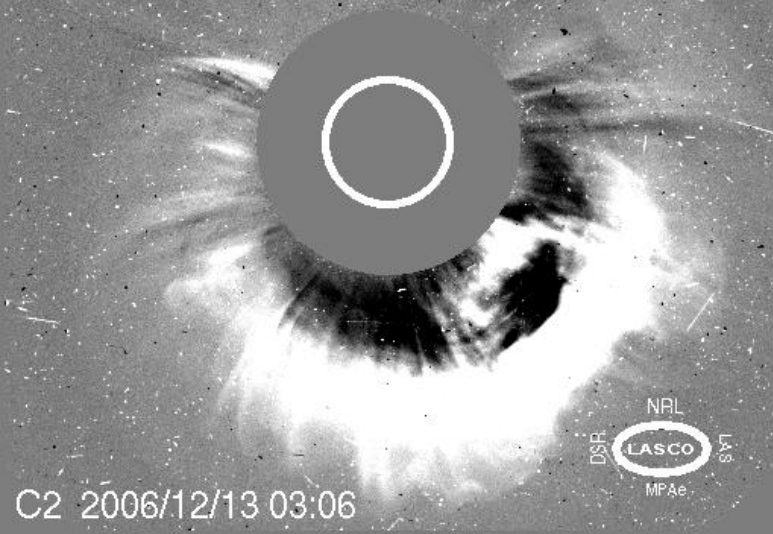
- **We consider 57 intense SEP events during 1989-2006**
  - Events of flux  $>1$  proton/s/cm<sup>2</sup>/sr/MeV at 50 MeV
  - Cover periods during solar cycles 22 and 23
  - 31 of them caused Ground Level Enhancements (GLEs)
- **Associated with intense flares plus large and fast CMEs**
  - Most of them are associated with X-class flares
  - Halo and partial halo CMEs (width  $>180$  degrees)
  - Fast CMEs – average initial speed  $>1000$  km/s
- **Most of them produced strong shock at 1 AU**
- **Particle Spectrum in the energy range 10 – 100 MeV**
  - Spectral evolution between Sun and Earth (i.e., from CME onset to shock arrival at 1 AU) is studied.

**13 December 2006 Flare/CME**

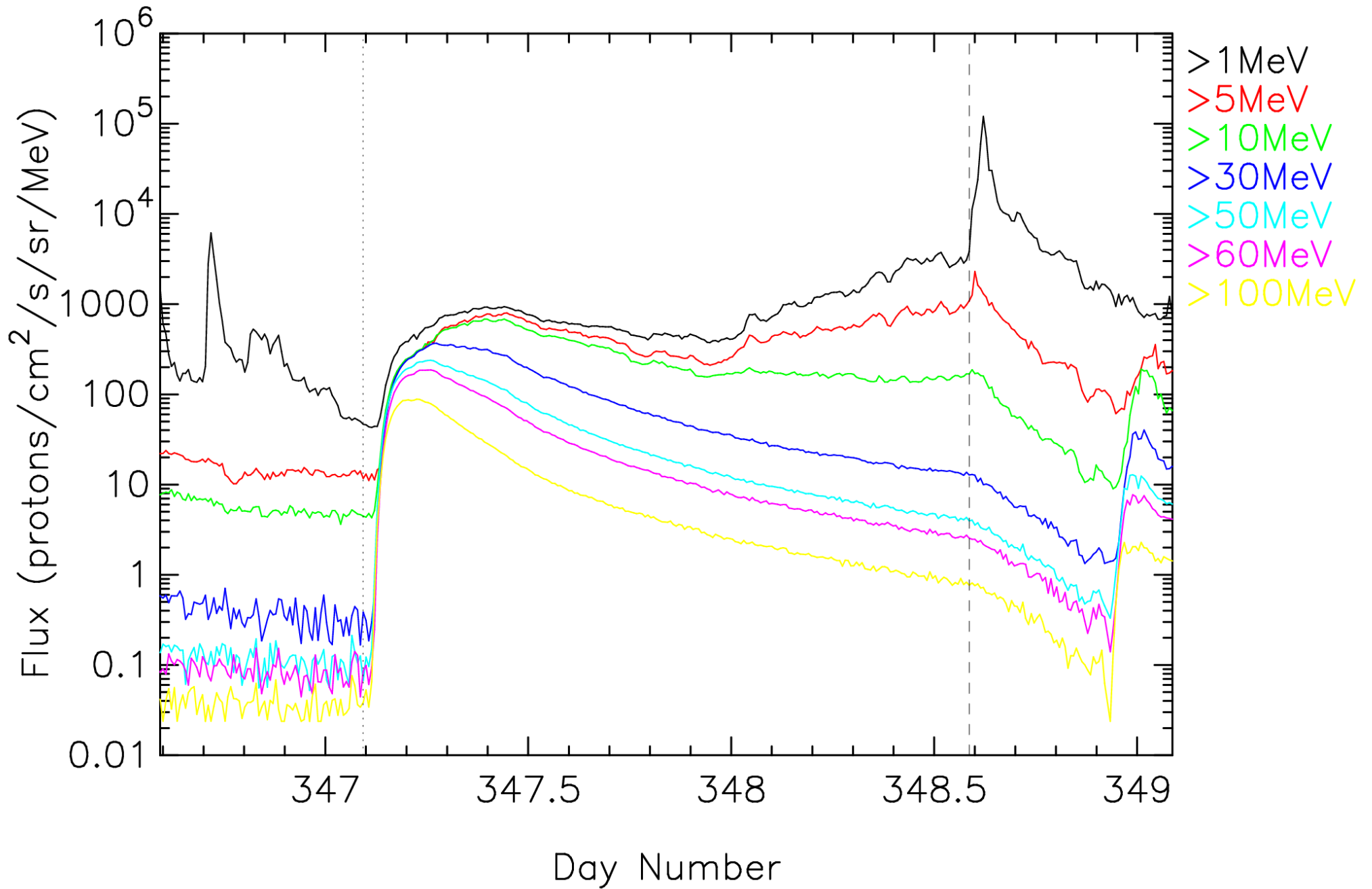
**X3.4 S05W23**

**Halo CME, speed ~1775 km/s**

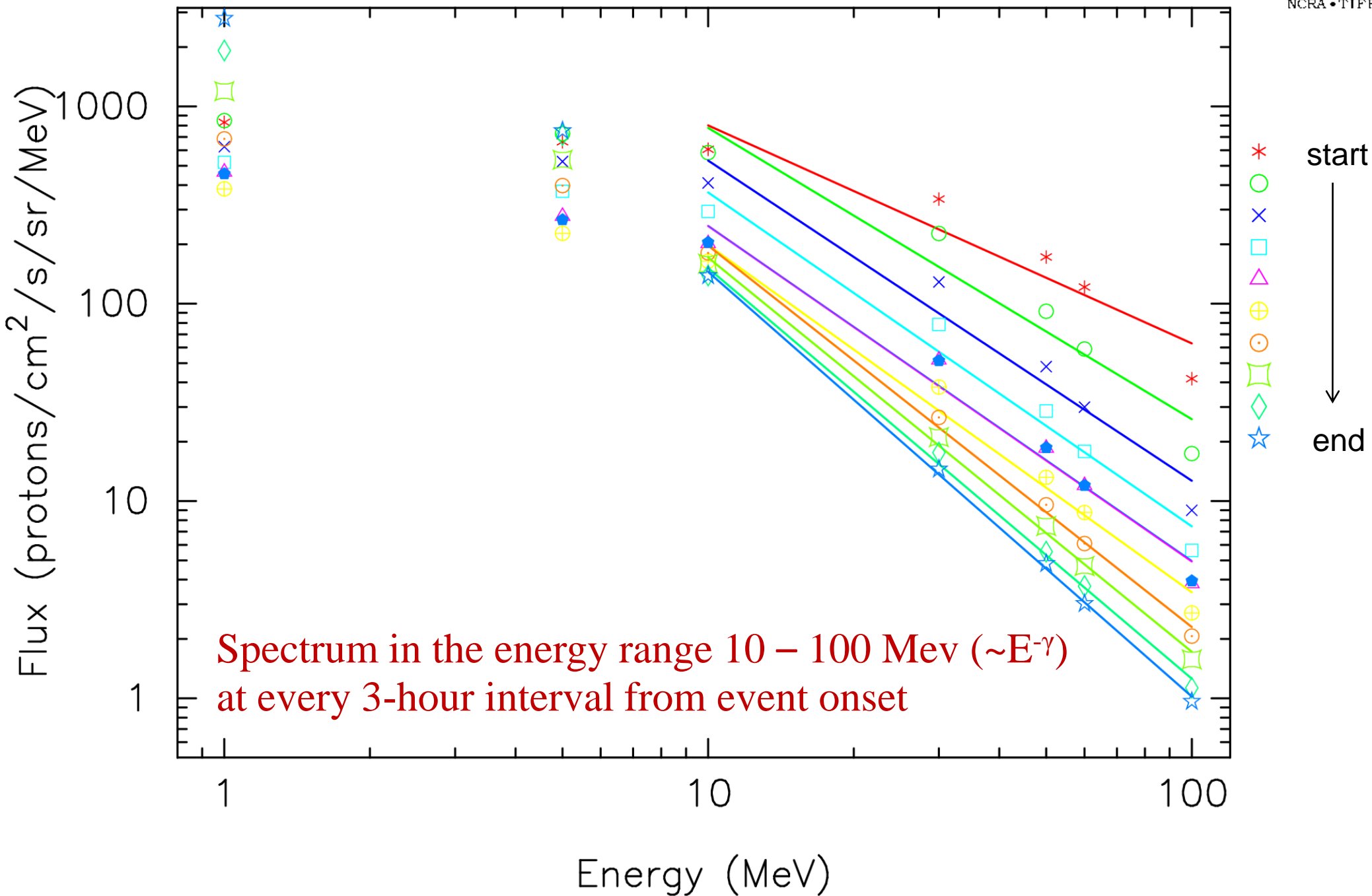
LASCO



13DEC2006

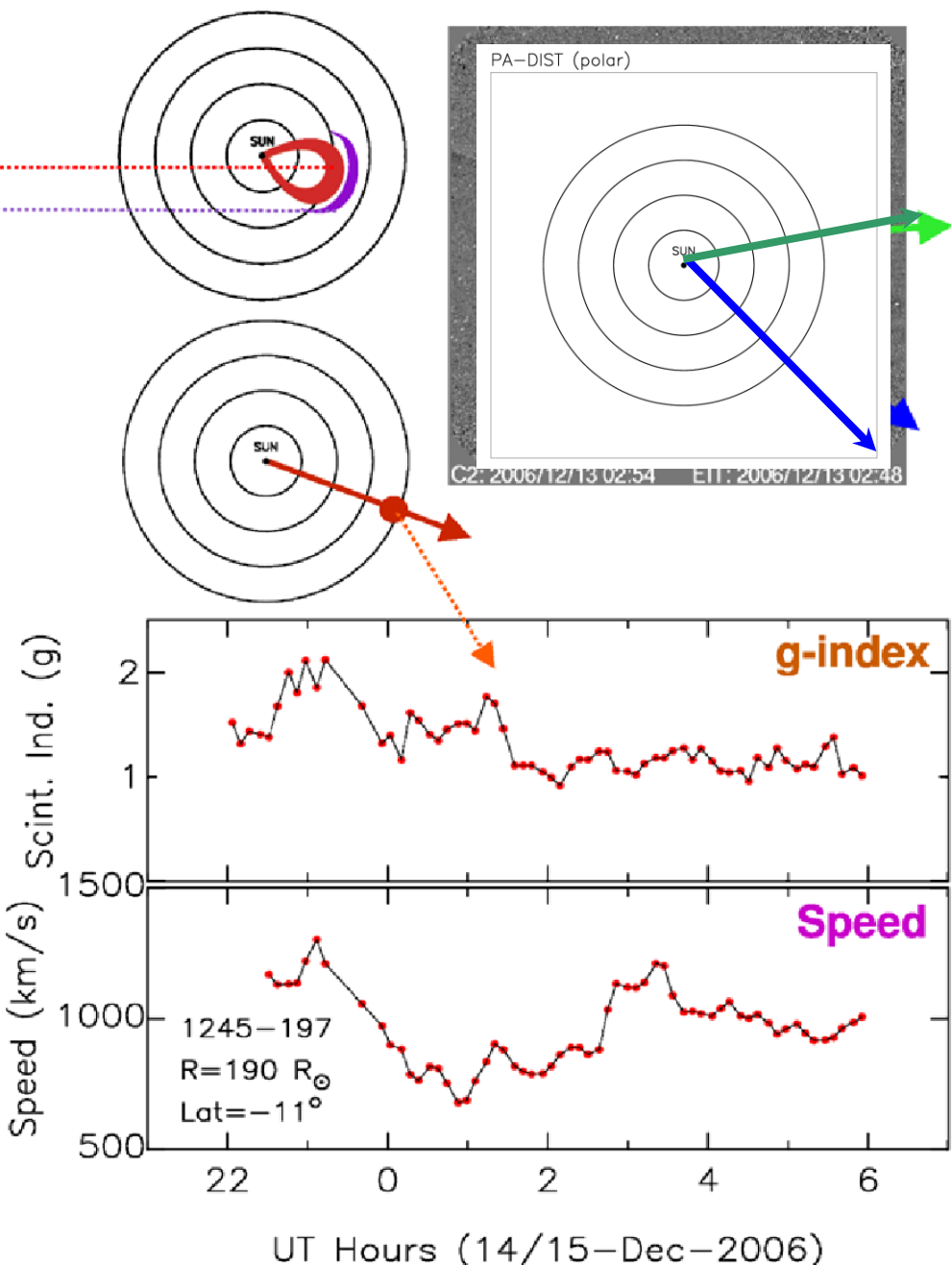
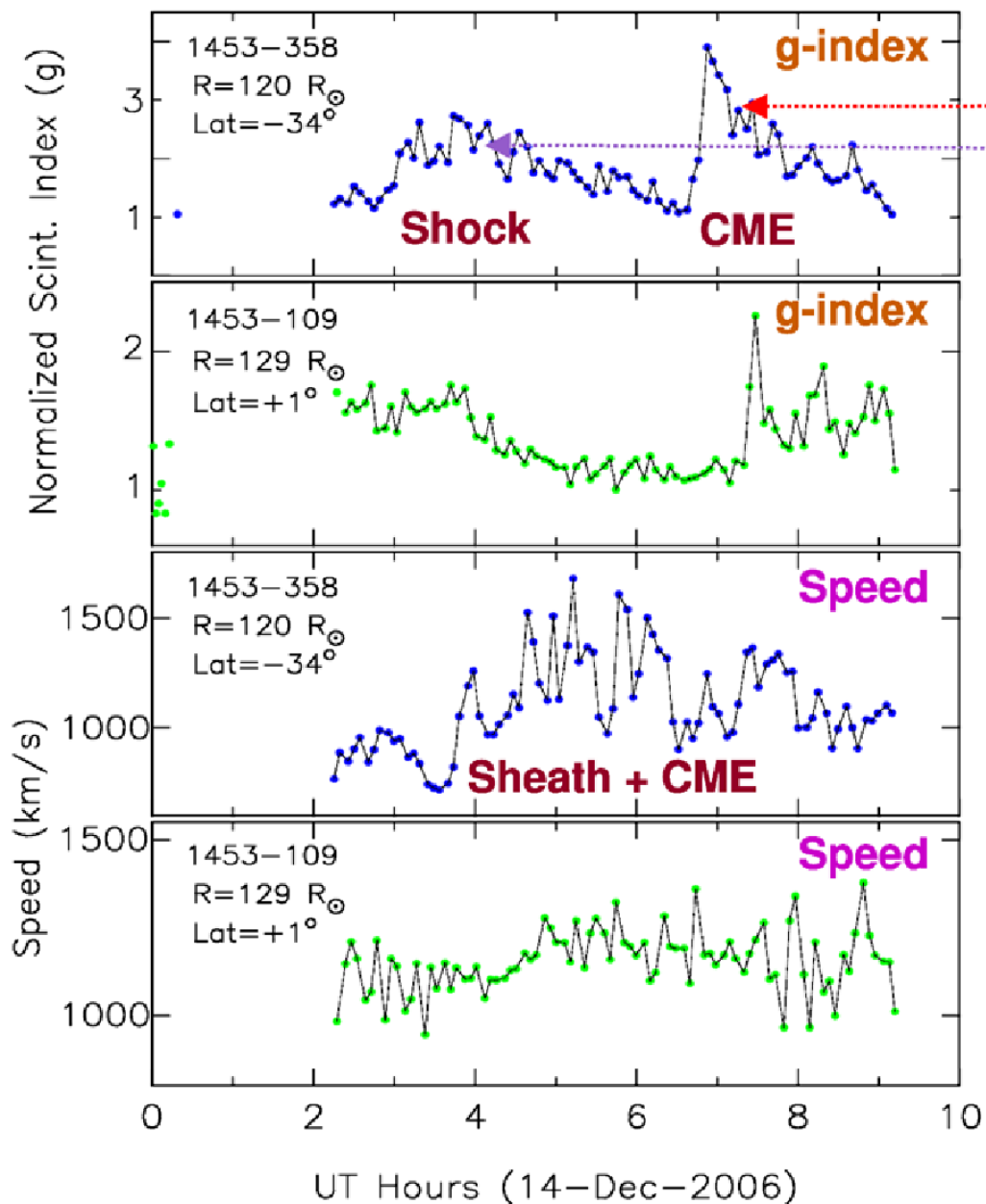


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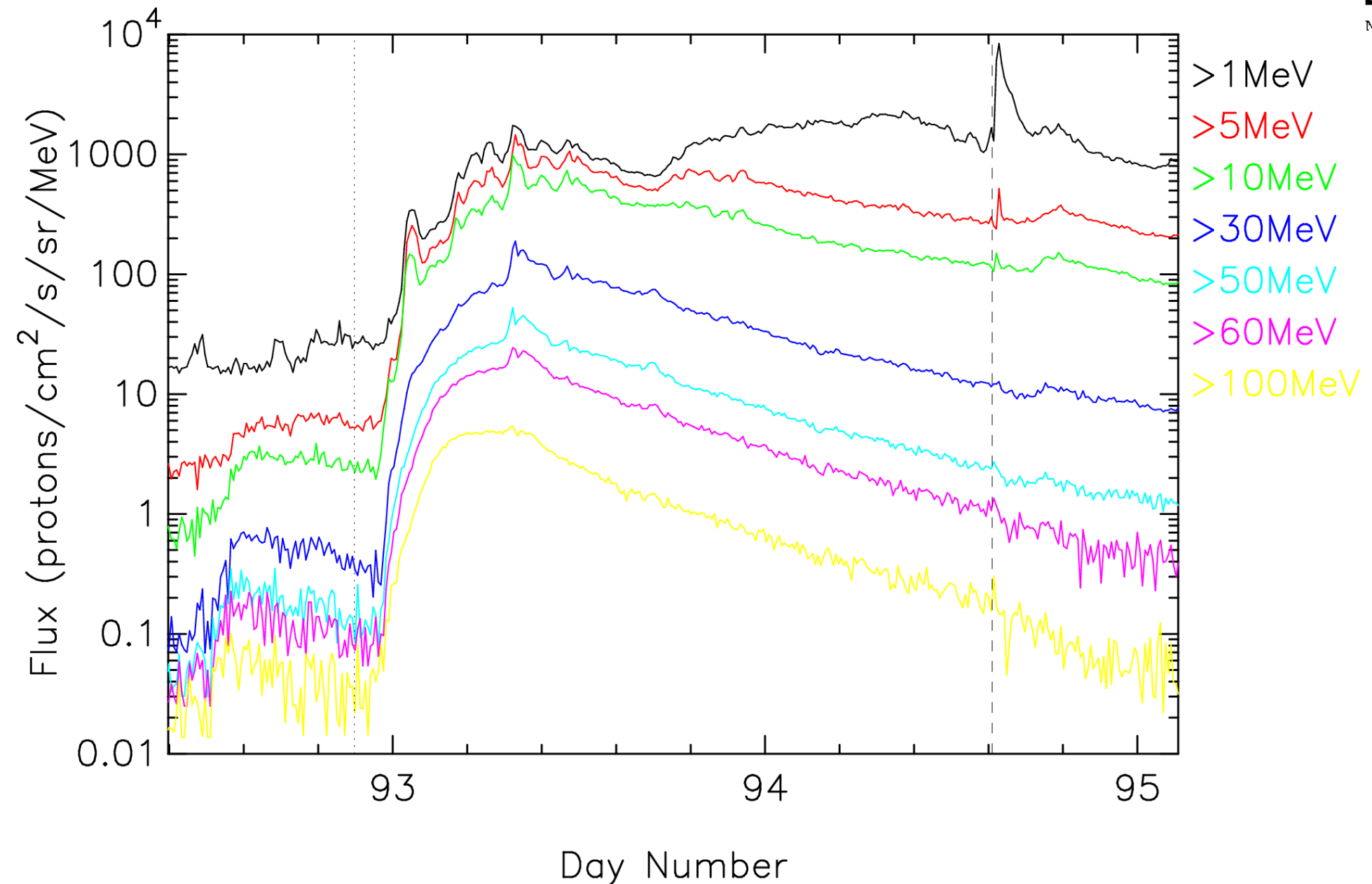




# CME on December 13, 2006



02APR2001

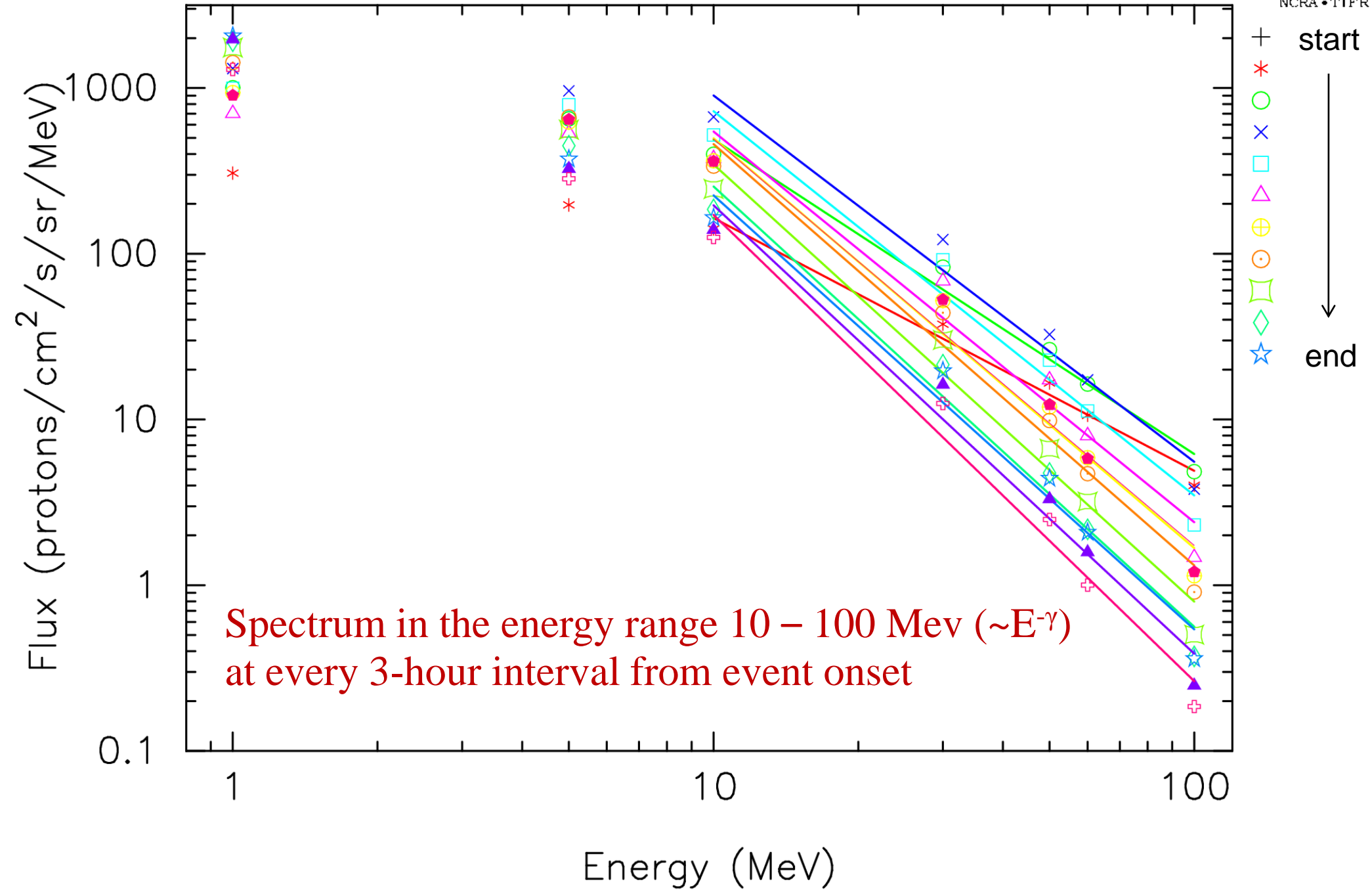


**When the magnetic connectivity between particle acceleration site and Earth is well established – flux profiles at different energies peak nearly same time**

02APR2001



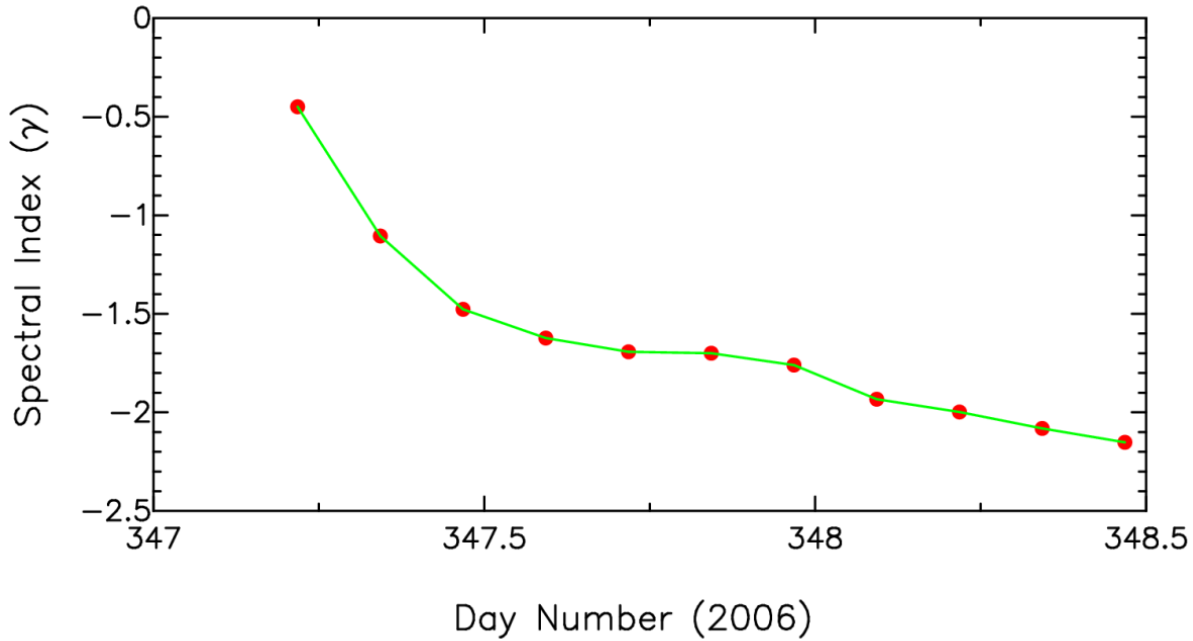
NCRA • TIFR



13DEC2006



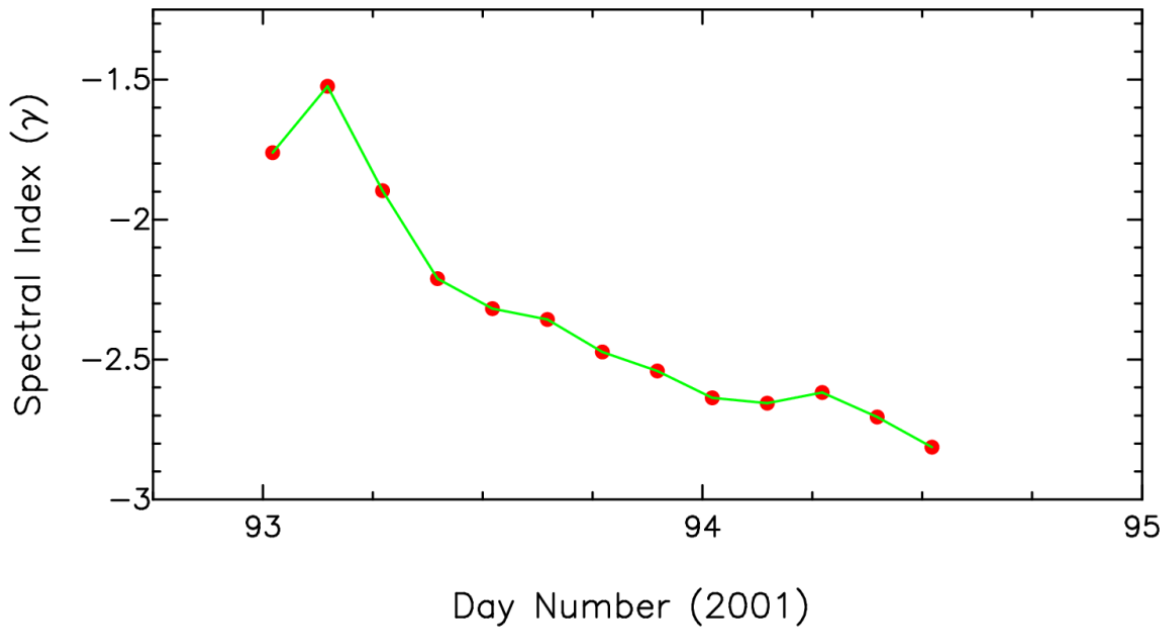
NCRA • TIFR



**$E^{-\gamma}$  (10 – 100 MeV range)**

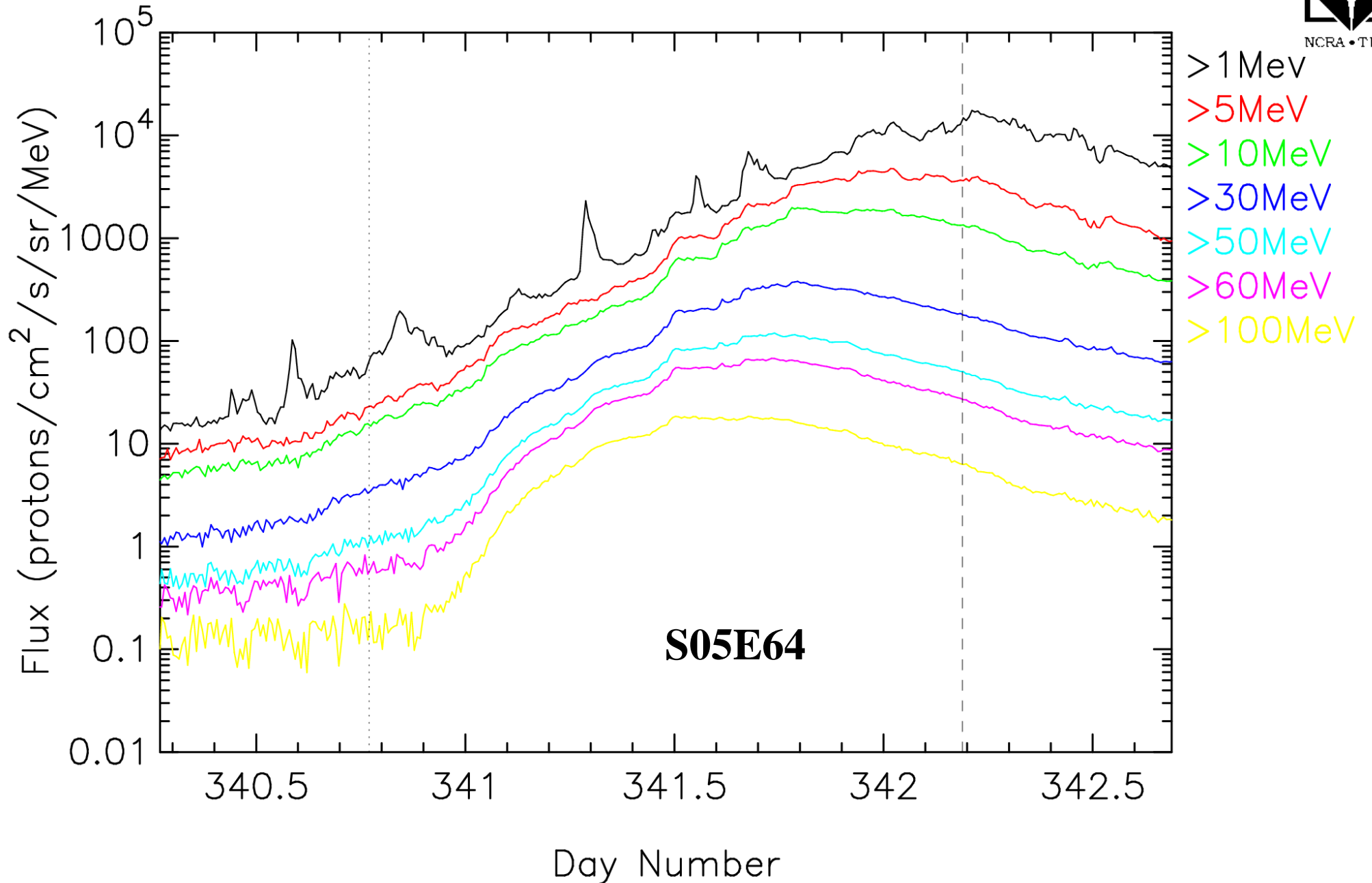
**Spectral index ( $\gamma$ ) between particle onset and Shock arrival at 1 AU**

02APR2001



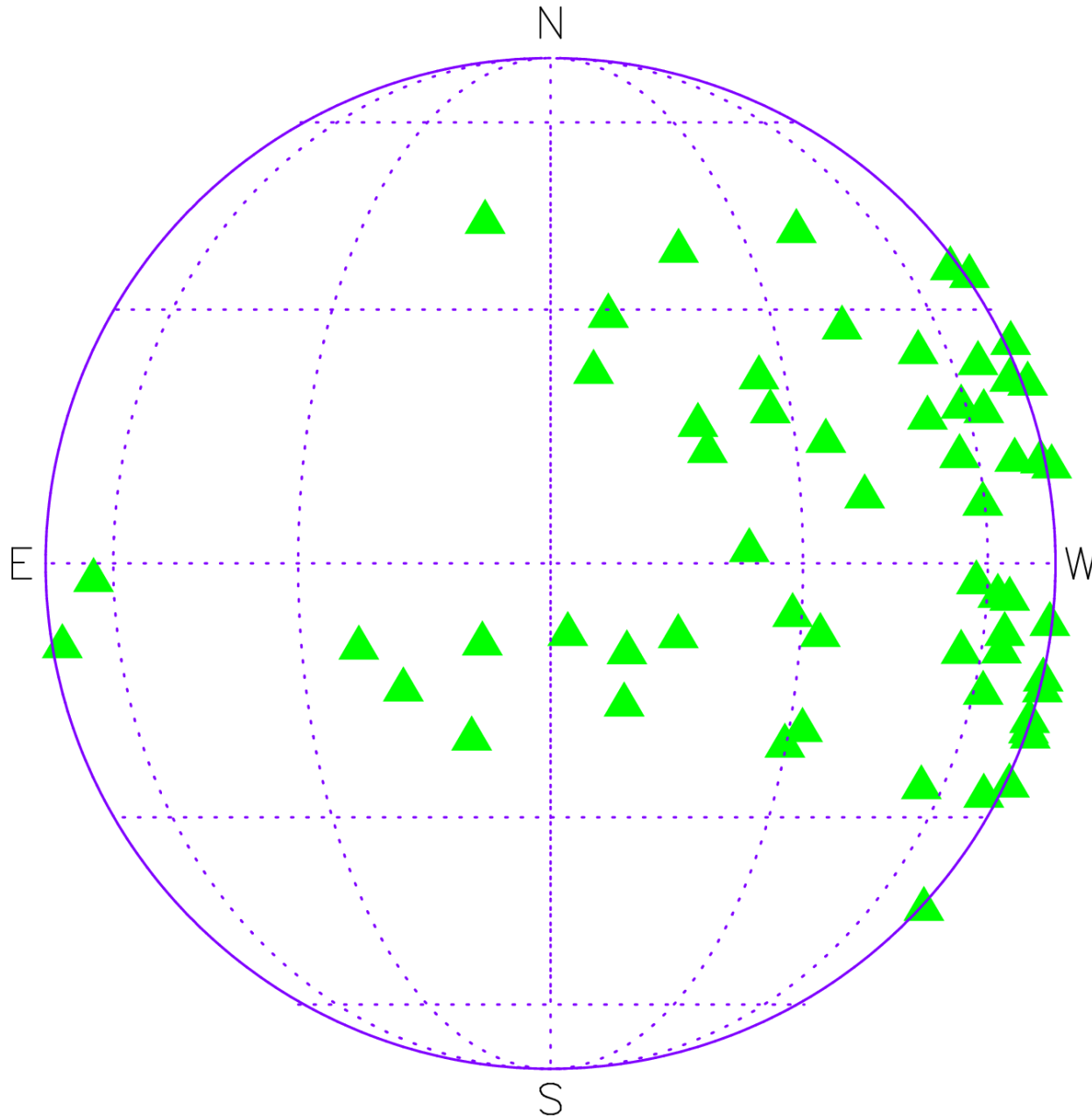
**Spectrum steepens with distance from the Sun and steepening differs**

06DEC2006

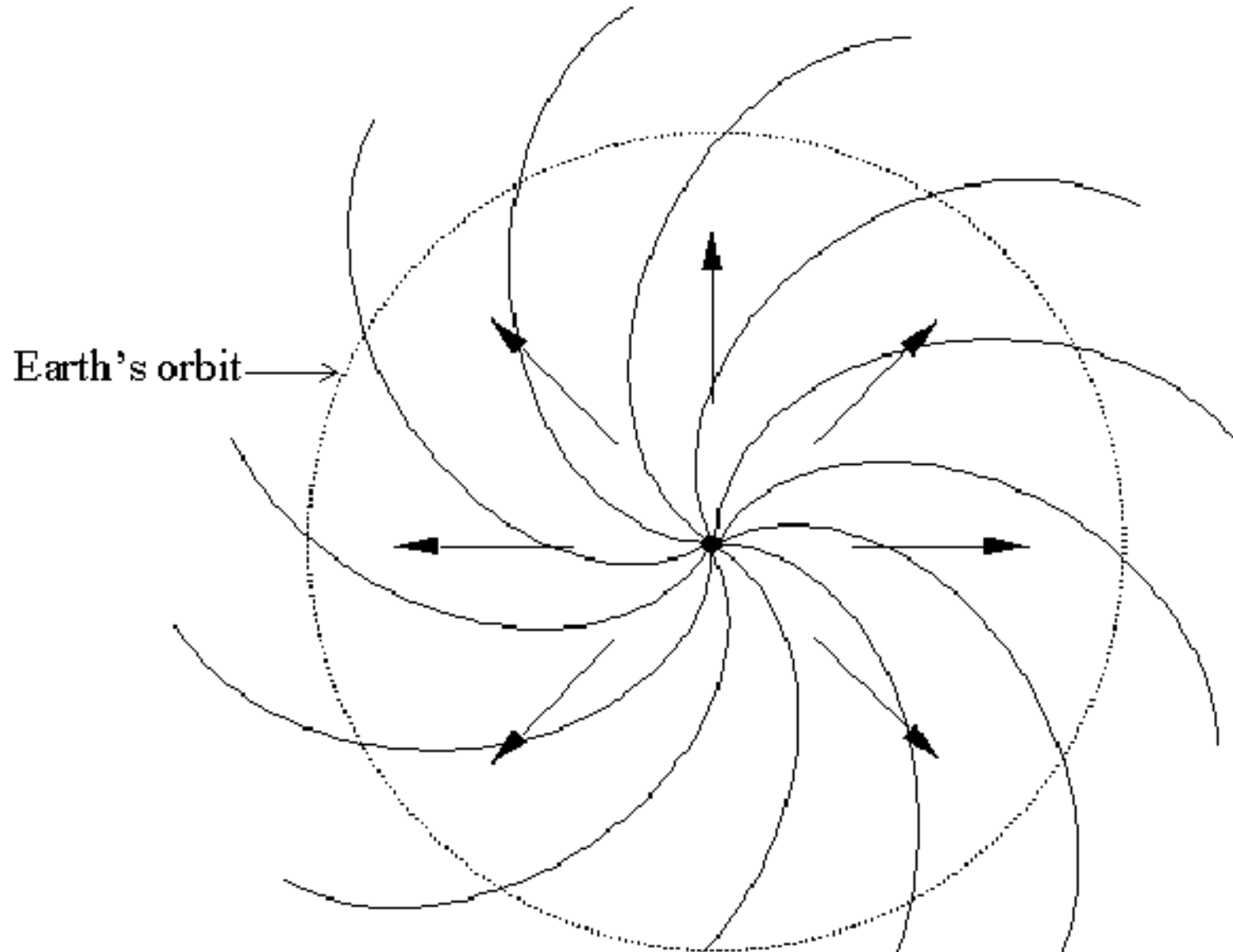


**Development of magnetic connectivity with time and peaking of flux profile**

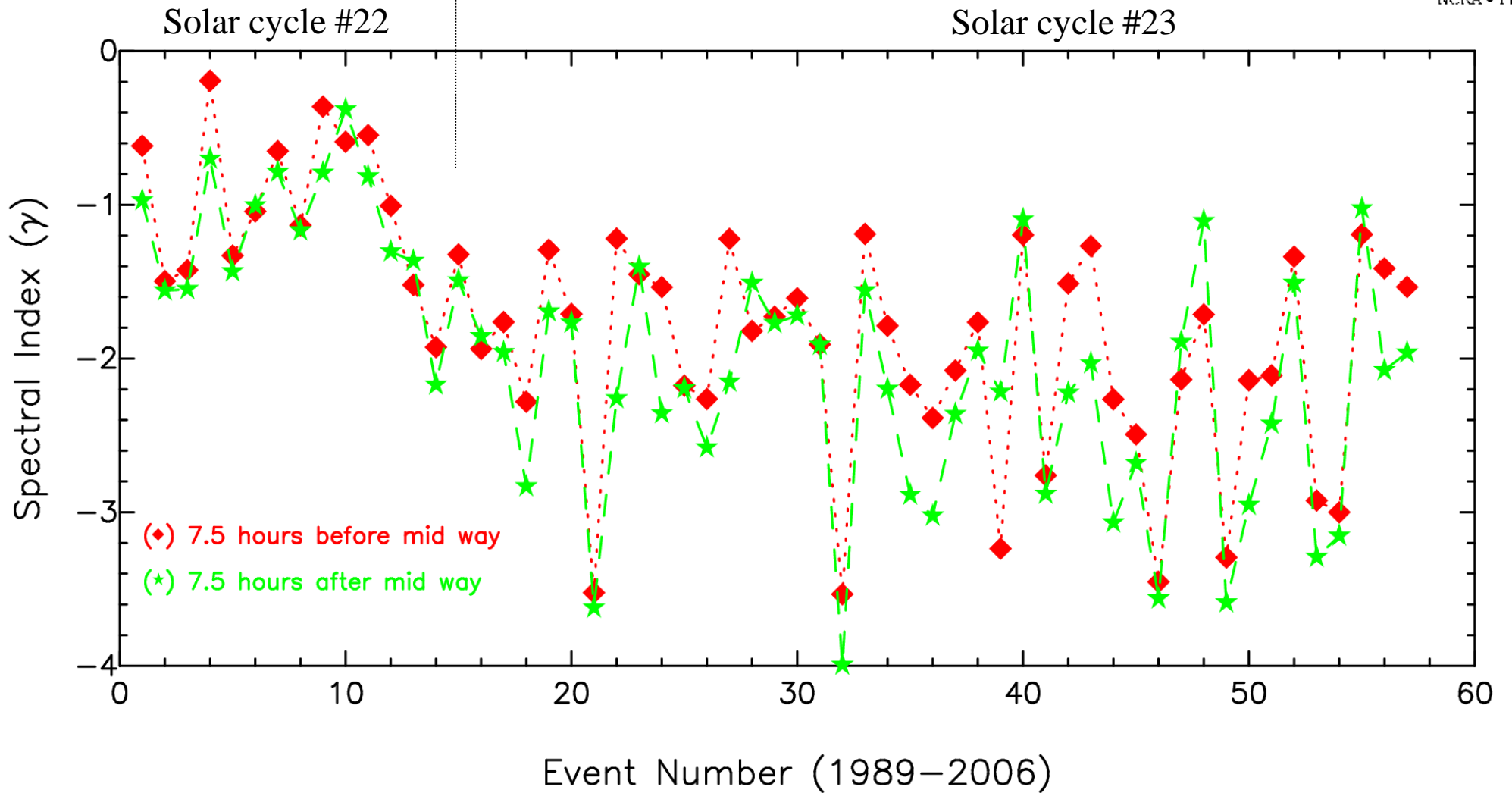
# Location of SEP events between 1989 and 2006



- Origin of particle events crowded to the western hemisphere of the Sun ( $>10^{\circ}$  east longitude)**
- Suggests the required magnetic connectivity between particle acceleration site and earth



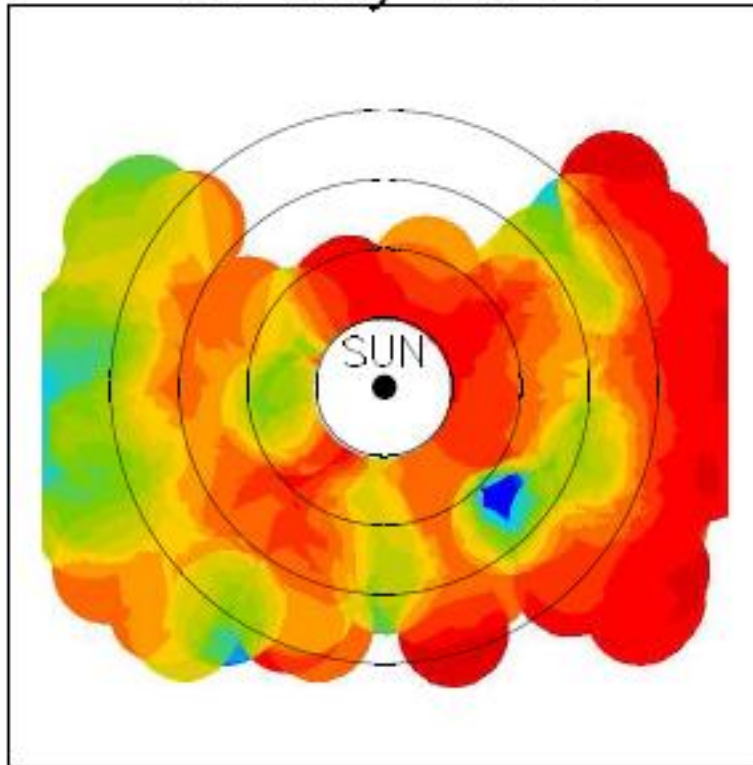
Coronal magnetic field and properties of the solar wind are intimately related. In the closed field regions flow speed is low. In the open field sites, i.e., above the coronal holes, the speed tends to be high.



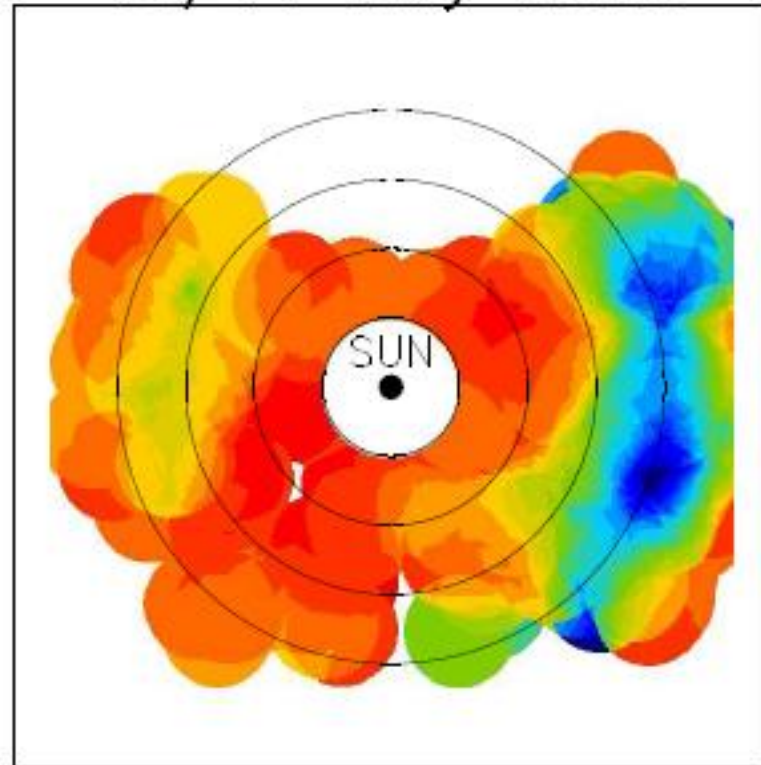
**Events associated with fast/wide CMEs show spectral evolution ( $\gamma$ ) in the range 0.5 – 2.5; Particle events observed during solar cycle 22 are flatter than events of cycle 23**

# IPS images of 14 July 2000 CME

15 July 2000



15/16 July 2000



## Radial profile of the CME in LASCO and IPS FOV

- At distances  $< 100 R_{\odot}$ 
  - $V_{\text{CME}} \sim R^{-0.08}$
- and
- At distance  $> 100 R_{\odot}$ 
  - $V_{\text{CME}} \sim R^{-0.72}$

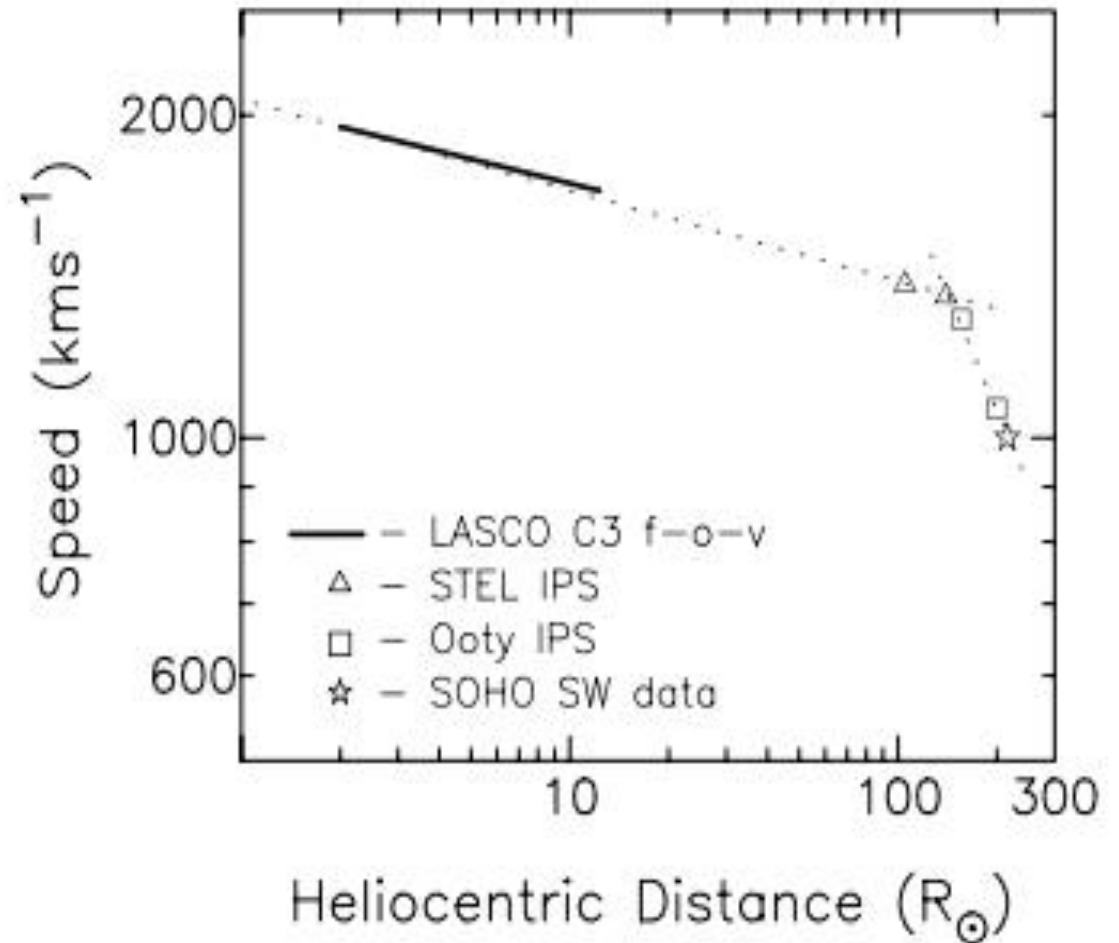
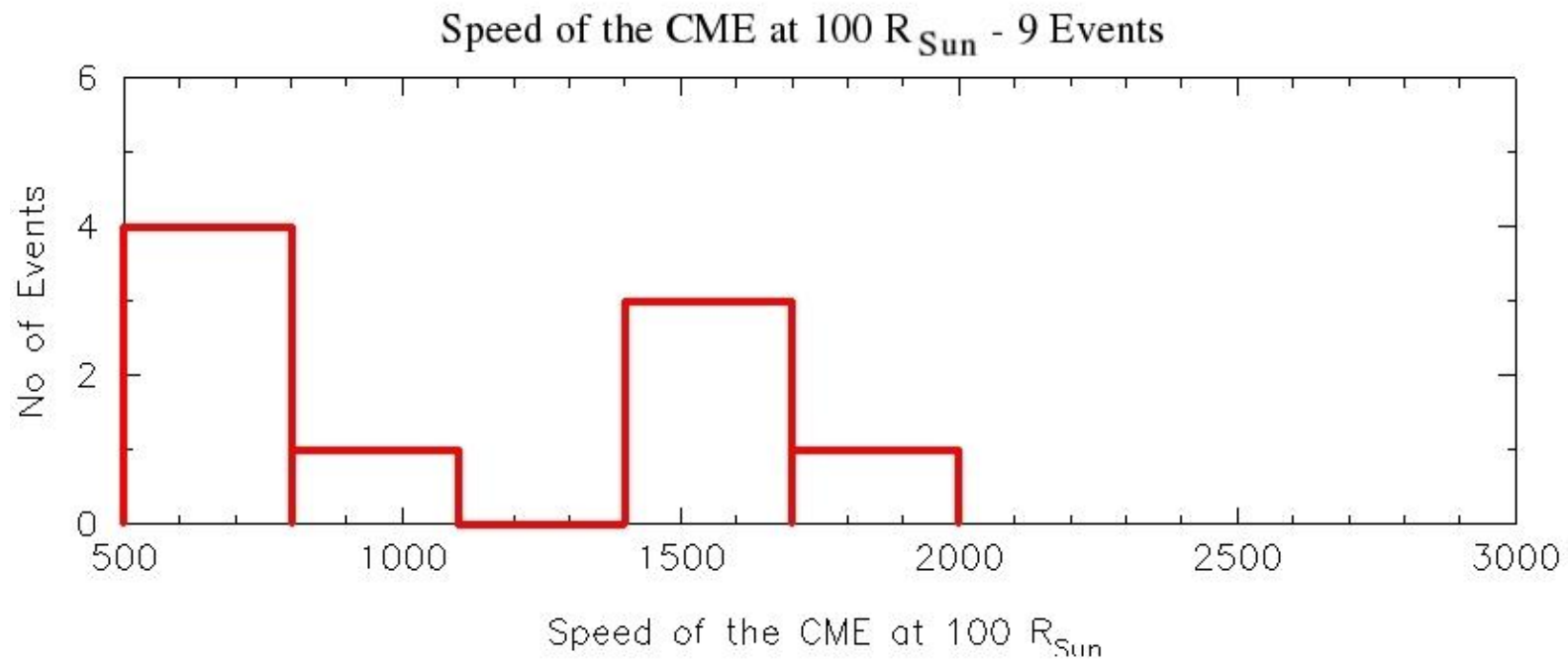
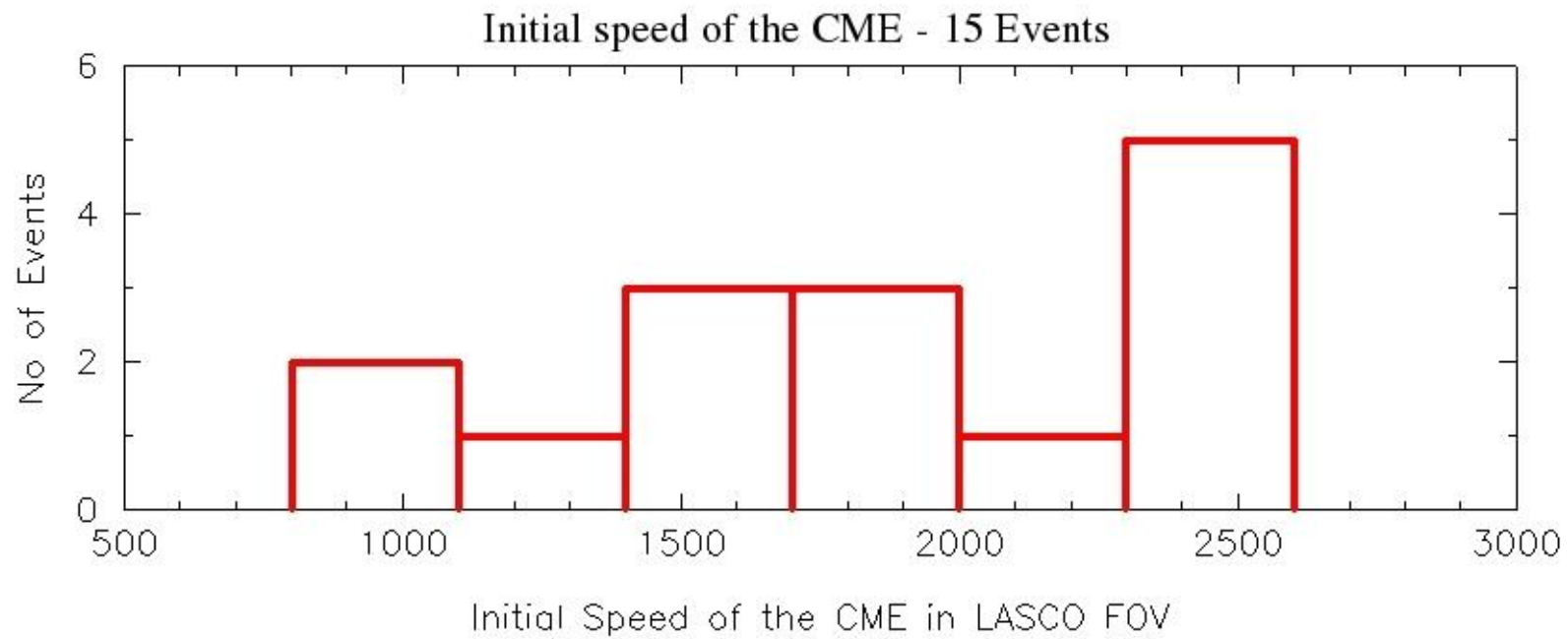
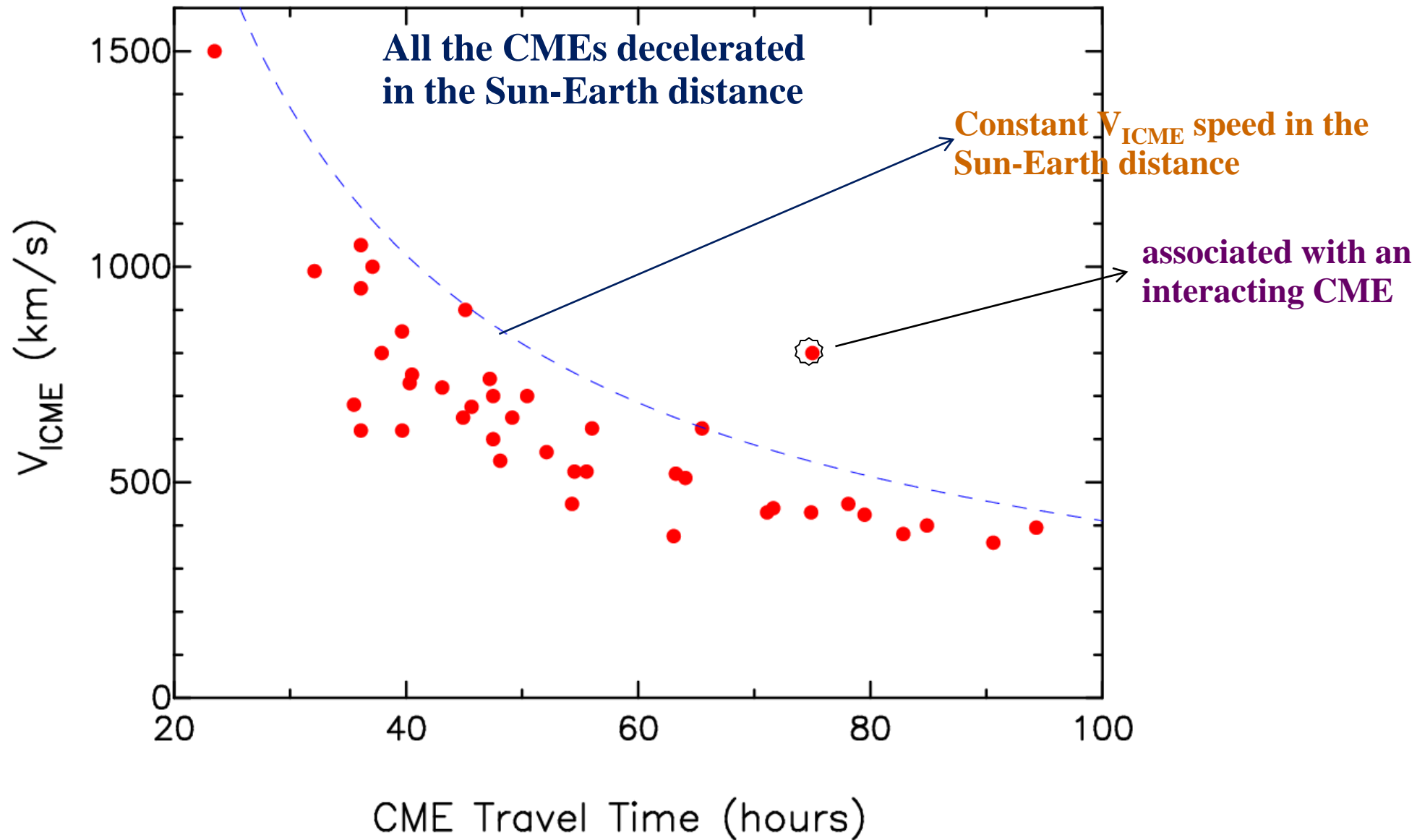
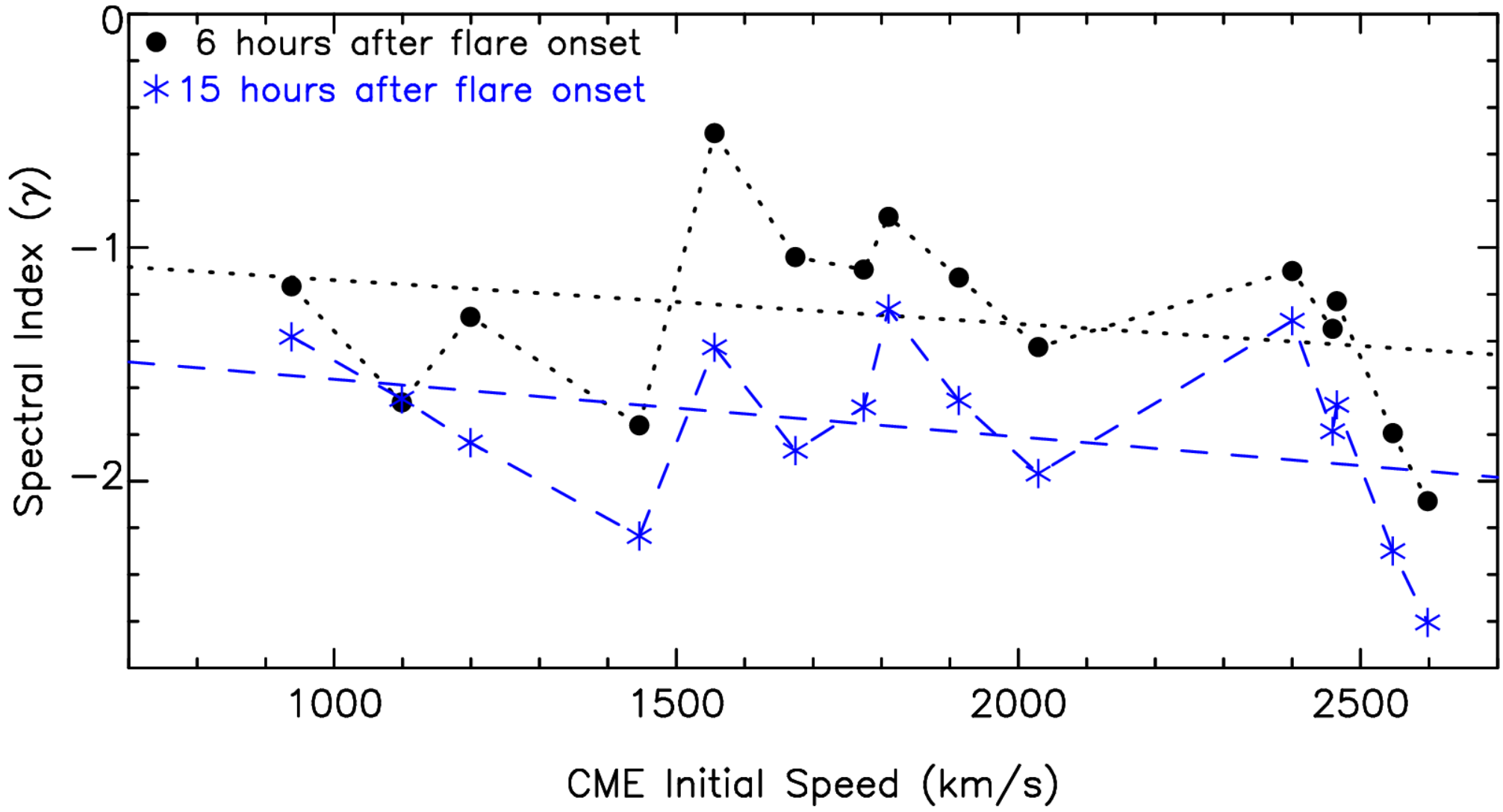


FIG. 11.—Estimated speed of the traveling CME at various distances from the Sun. The thick line indicates CME measurements in the field of view of the LASCO coronagraphs. The speed estimates are obtained from the space-time information obtained from the onset of the CME disturbance at different observational windows. The radial variation of speed seems to follow two-part power-law deceleration, (1) at  $R < 100 R_{\odot}$ ,  $V_{\text{CME}} \sim R^{-0.08}$  and (2) at  $R > 100 R_{\odot}$ ,  $V_{\text{CME}} \sim R^{-0.72}$ .



# CME Propagation – “Sun-Earth” distance





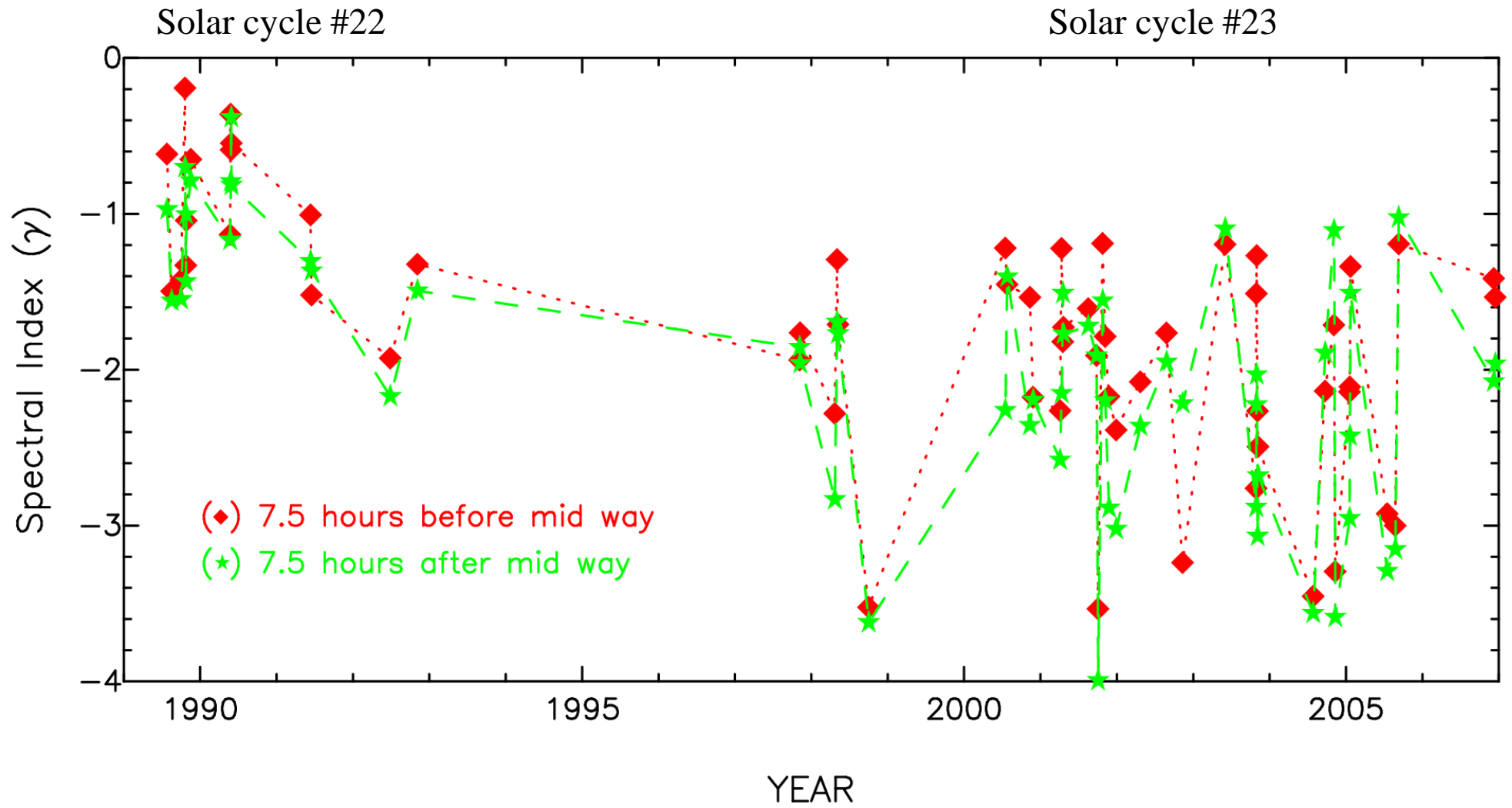
# Summary



- In general, the energy spectrum steepens with distance from the Sun
- **SEP events associated with intense flares and fast/wide CMEs are flatter than events originated from slow CME**
  - they show only marginal steepening in the Sun-Earth space
  - Whereas, events of slow CME (or less intense flare) steepen heavily (i.e., rapidly) with distance from the Sun
- Acceleration of low-energy protons (<50 MeV) seems to be efficient in front of the IP shock than high energy particles – it also can lead to steepening of the spectrum with distance from the Sun.
- For CMEs having excess internal magnetic energy, the SEP spectrum shows no significant change or flattens with distance from Sun
- The initial speed of the CME may not play significant role in the spectral evolution – it requires more work!

**Thank You**

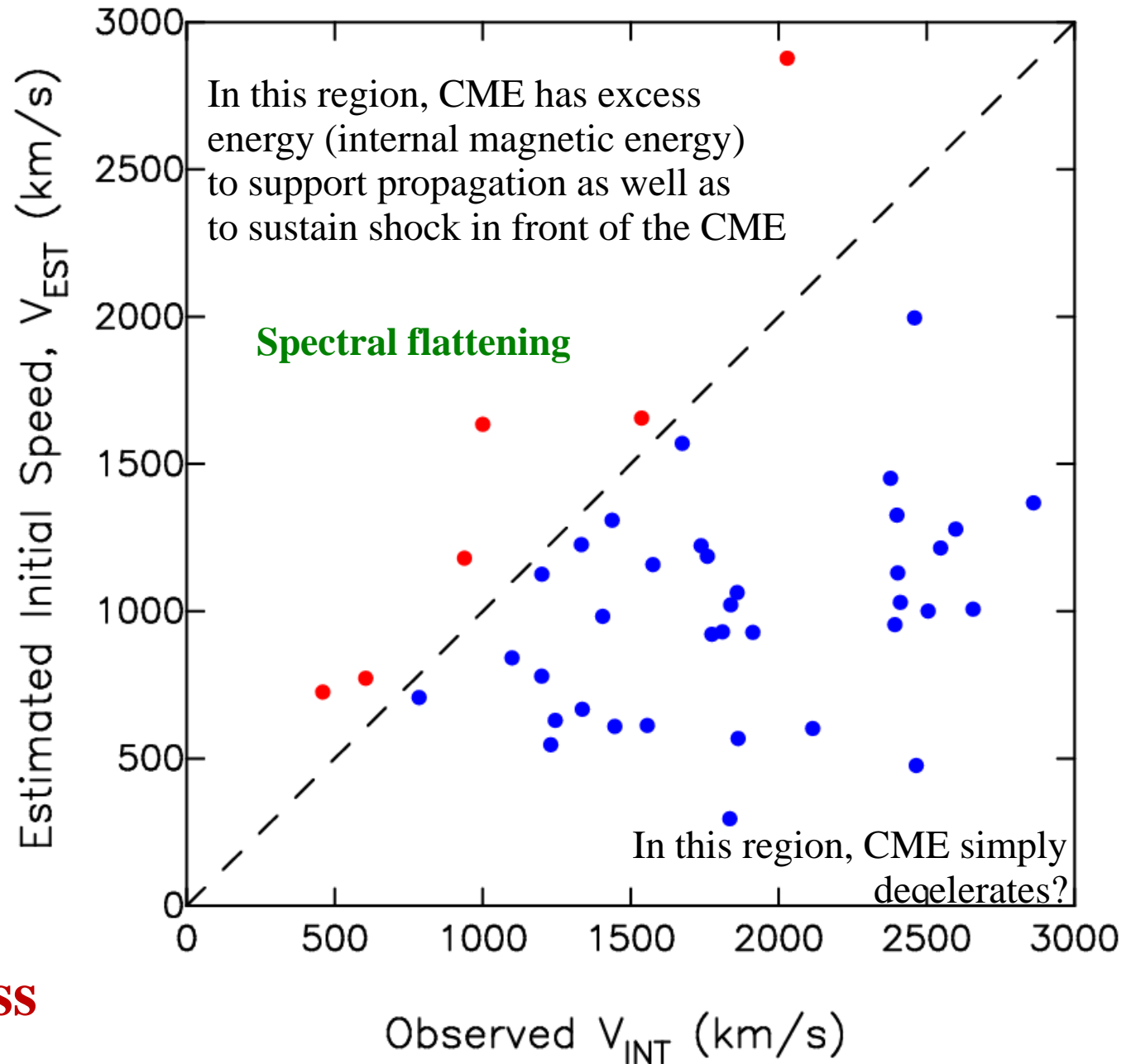
**Thank You**



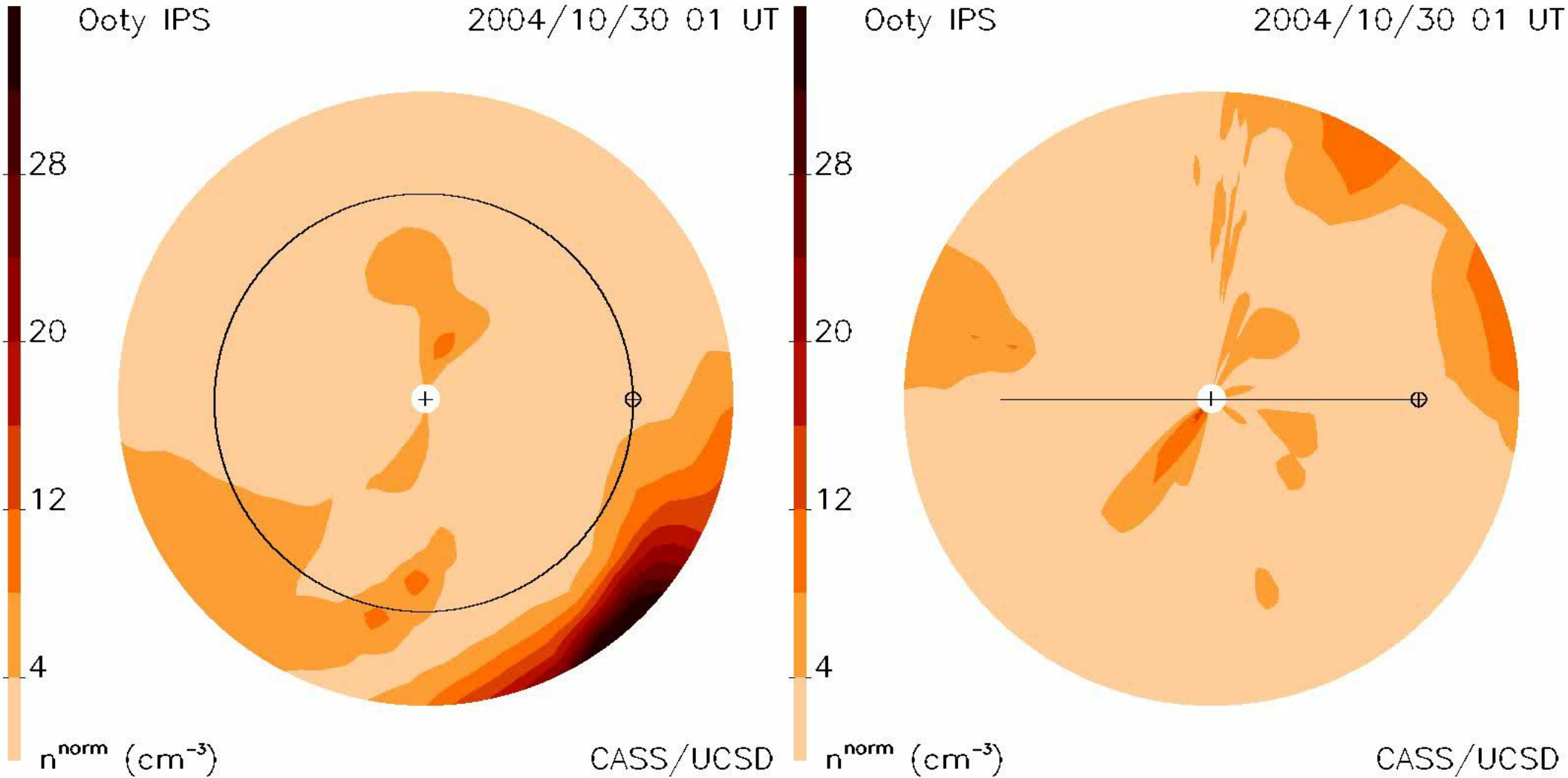
$$V_{AVG} = \frac{\sim 1 \text{ AU}}{\text{CME Travel Time}}$$

$$= \frac{V_{EST} + V_{ICME}}{2}$$

$V_{EST} > V_{INI}$   
**CME possesses excess**

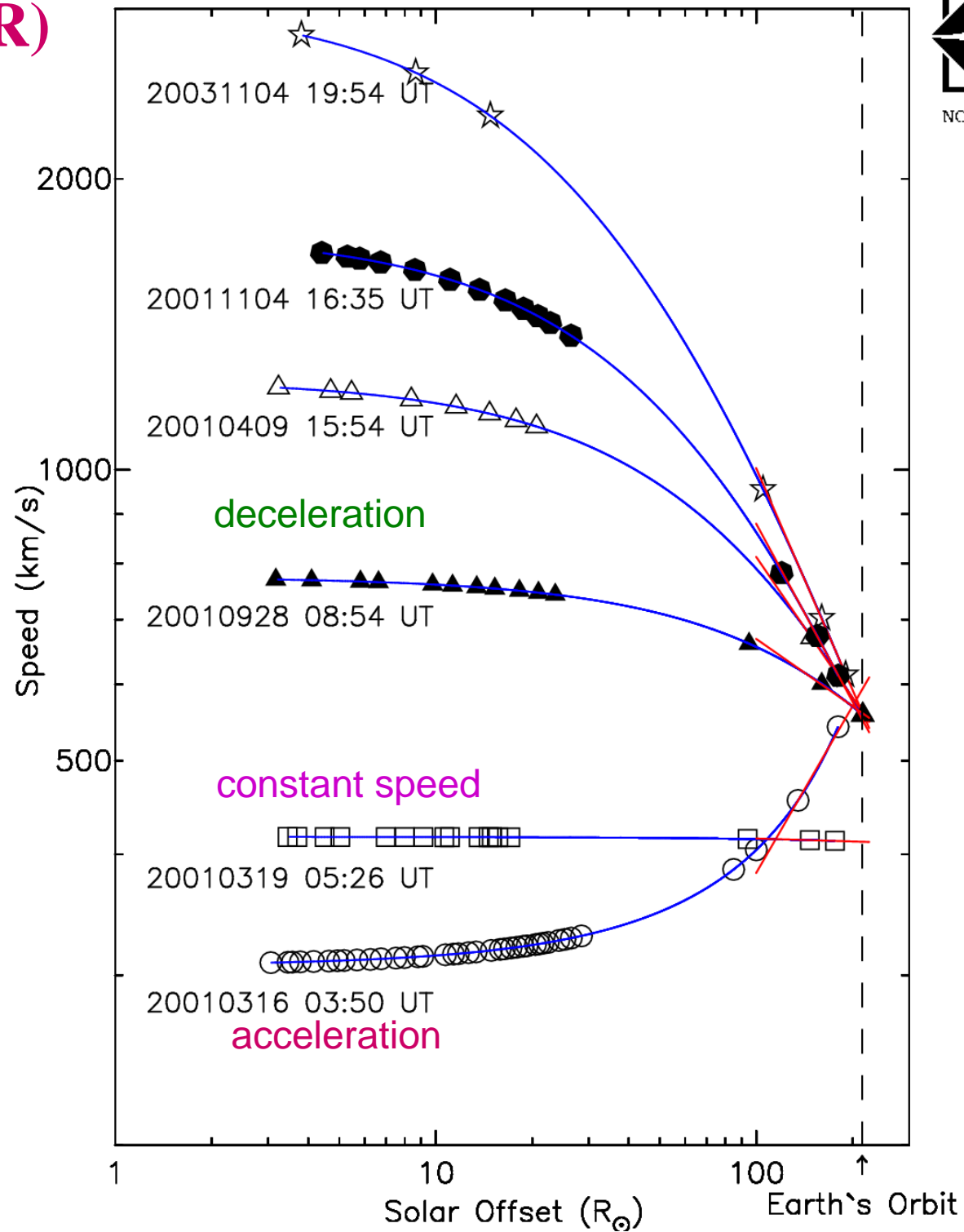


# Current 3D Ooty Density Reconstruction

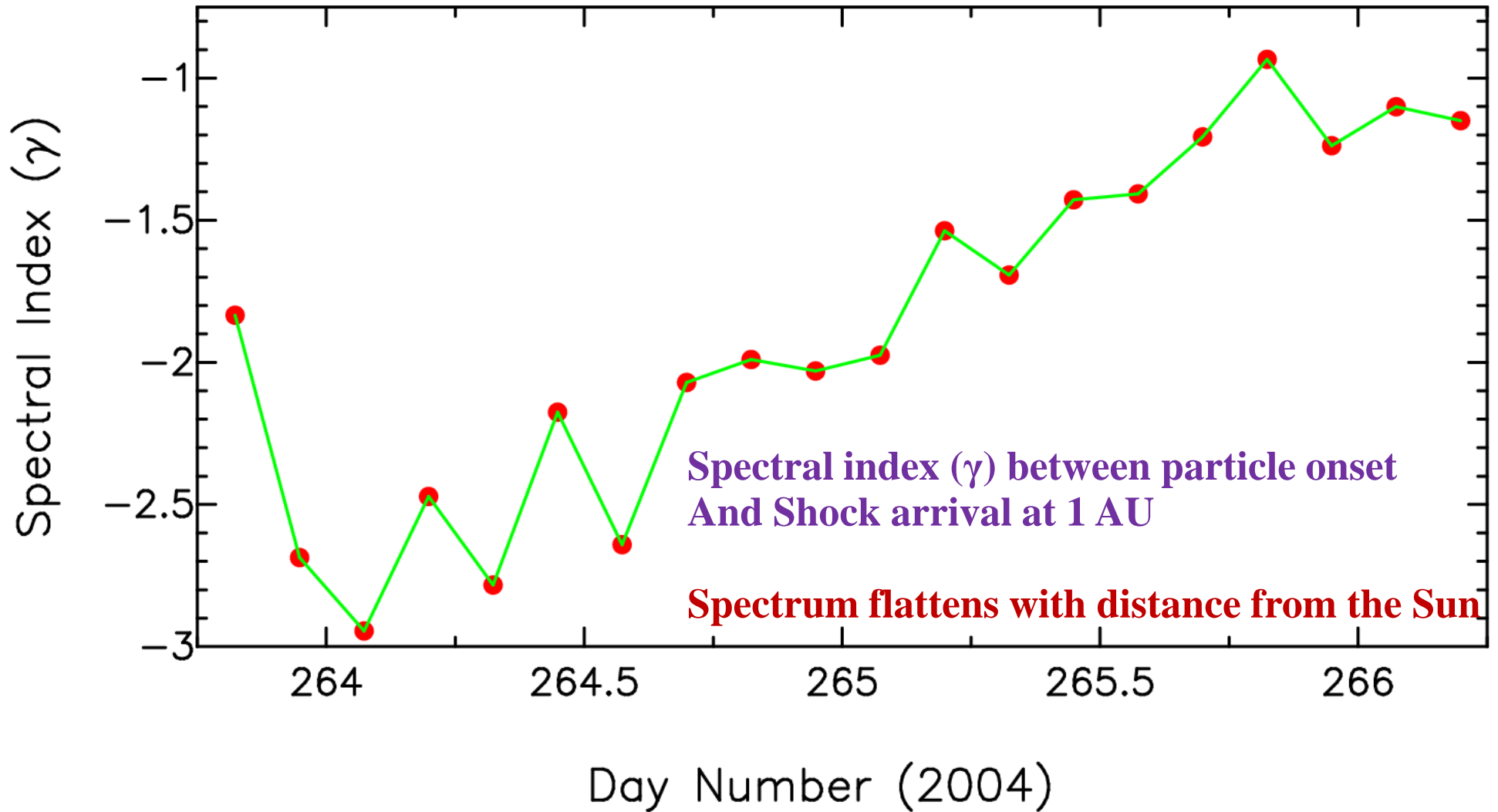


The left movie shows an ecliptic cut through the 3D Ooty IPS density reconstruction and the right movie show a meridional cut (from East of the Sun-Earth line) of the same; both with the Earth on the right-hand side and it's orbit shown in each case

# Speed Profiles: $V_{CME}(R)$



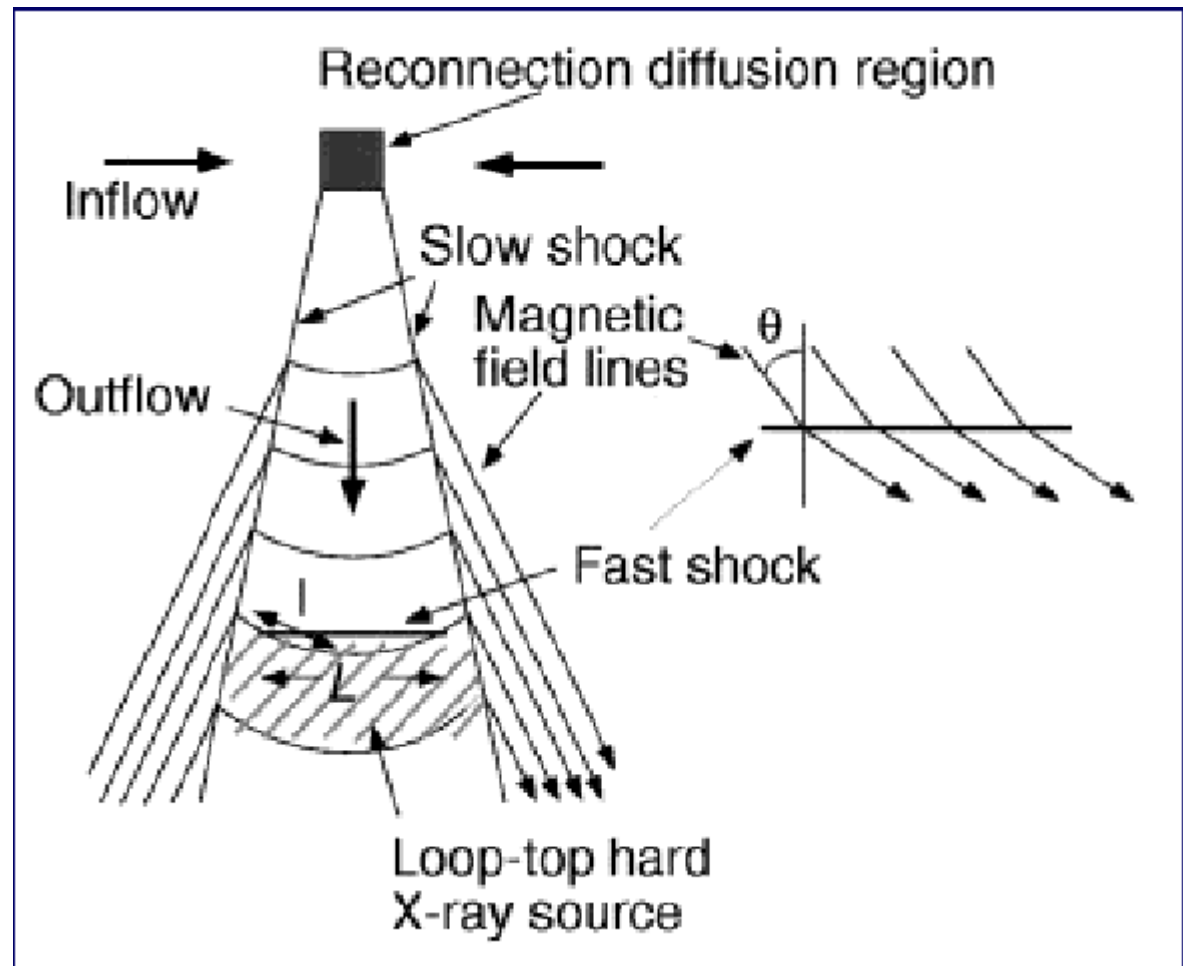
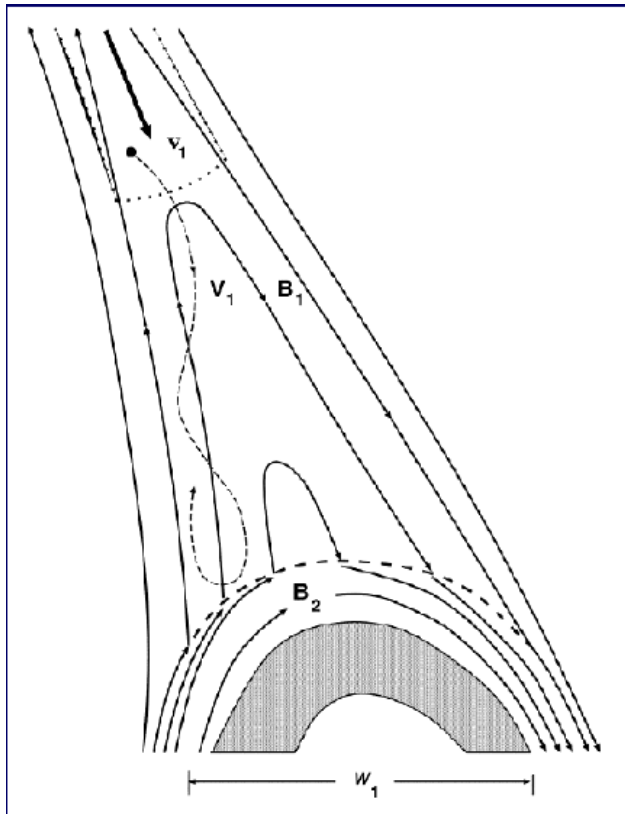
19SEP2004



# Relativistic Particle Energies

- Thermal electrons in solar corona ( $T \sim 1\text{MK}$ ) have non-relativistic speeds  $v/c \sim 0.018$
- If such an electron is accelerated about 4 times the thermal speed so  $v/c \sim 0.07$  (still non relativistic), but can produce radio emission at plasma frequency.
- Hard X-ray are produced by electrons with typical energies of  $\sim 20\text{-}100\text{ keV}$ , they are mildly relativistic having  $v/c \sim 0.2\text{-}0.5$
- Gyrosynchrotron emission & electron bremsstrahlung in gamma ray are produced by highly relativistic electrons with energies of  $\sim 0.3\text{-}10\text{ MeV}$  & relativistic speed  $\sim 0.8\text{ c}$

# Shock acceleration in coronal flare



Somov & Kosugi (1997)

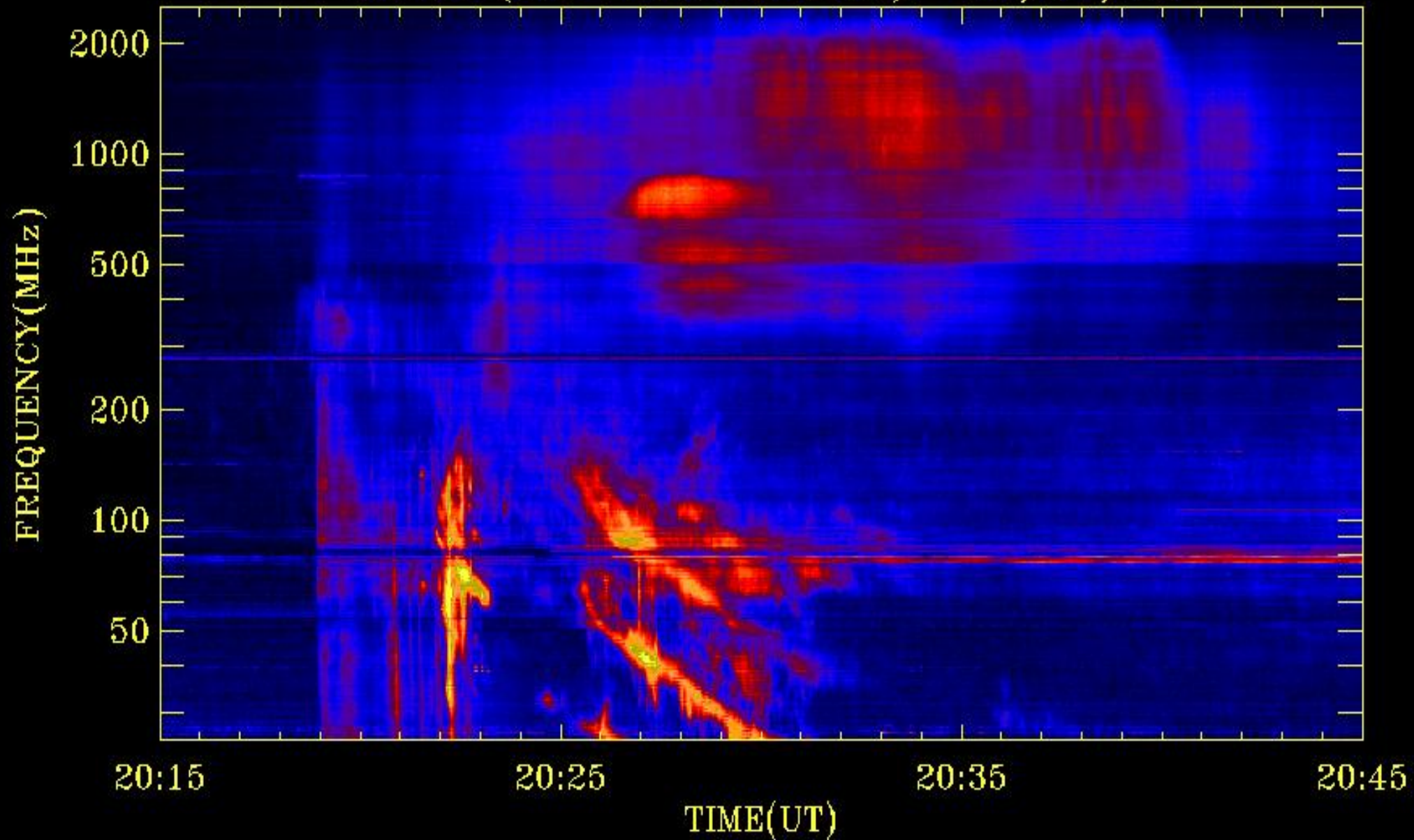
Tsuneta & Naito (1998)

## Applications of shock acceleration to solar flares :

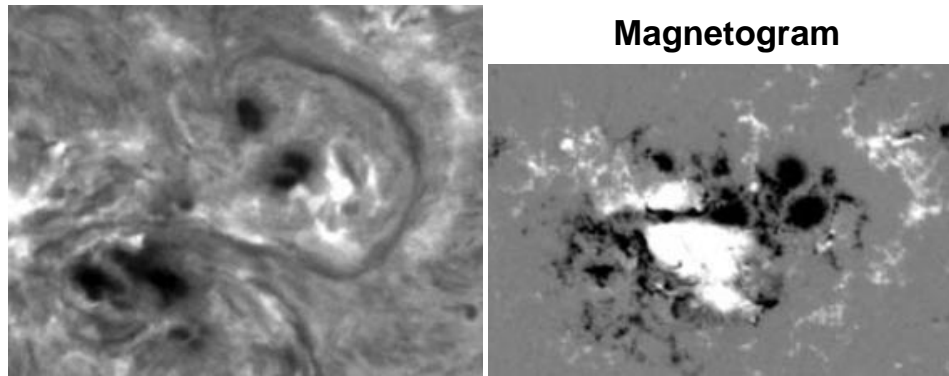
- First-order Fermi in mirror trap in flare loop cusp
- Fast shock in reconnection outflow above flare loop
- Type II as shock front signature in interplanetary space

# Type II, III, and IV Bursts

*HiRAS* (25–2500MHz R+L) 97/07/25

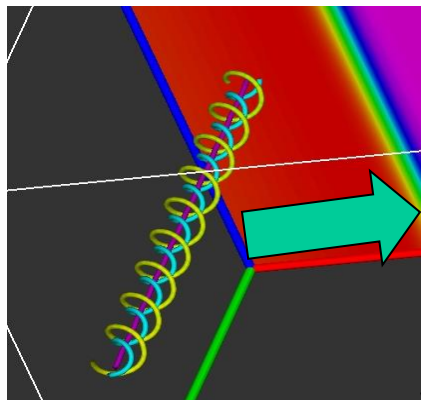


# Energetic Flare and CME (October 2003)

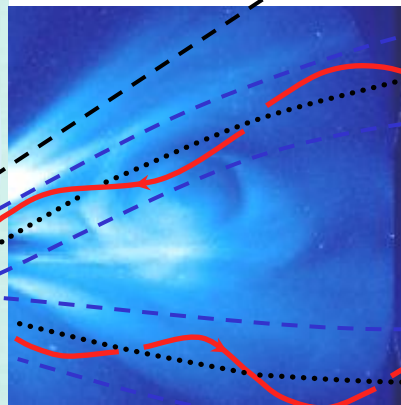
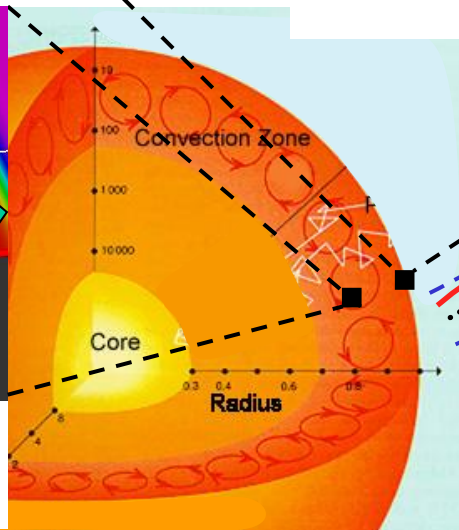


Active Region  
486

(Schmieder et al 2006,  
Mandrini et al 2006,  
Dasso et al 2007)

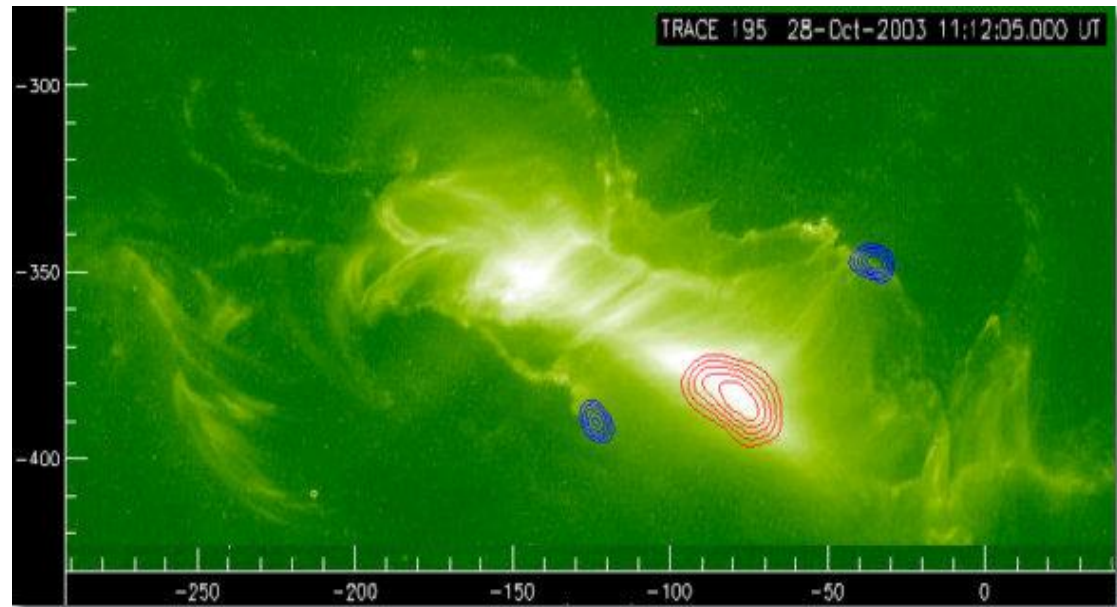
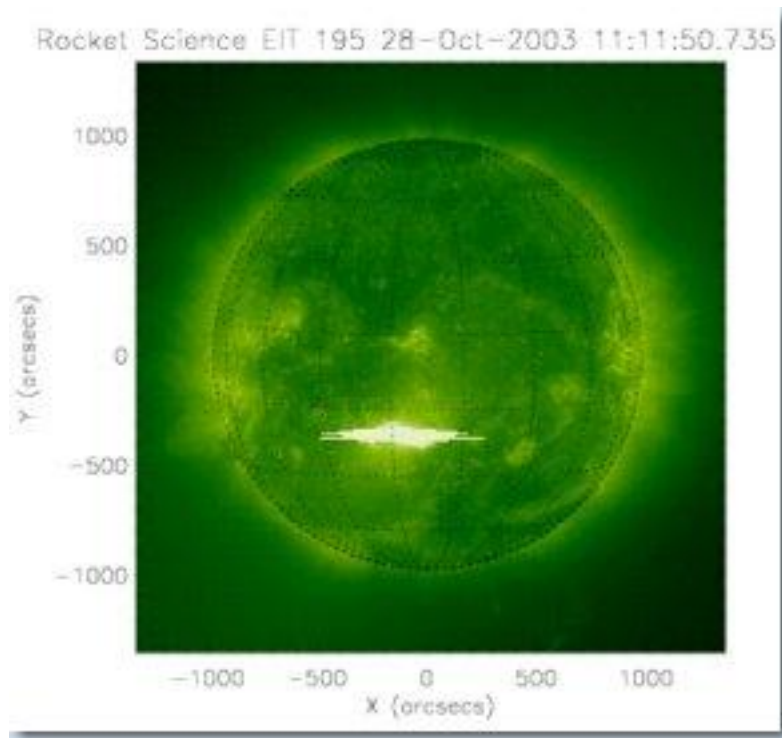


Emerging  
Flux tube

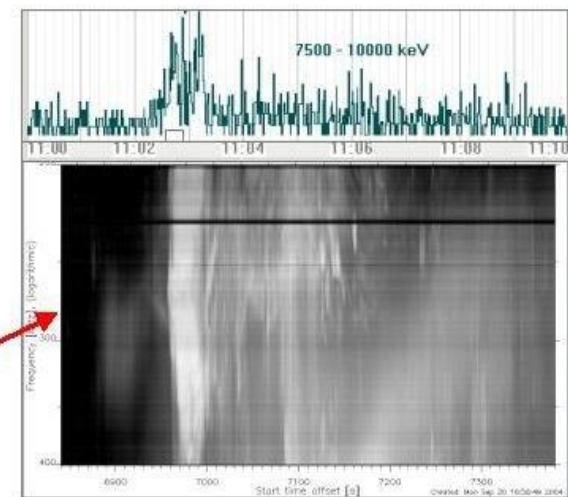
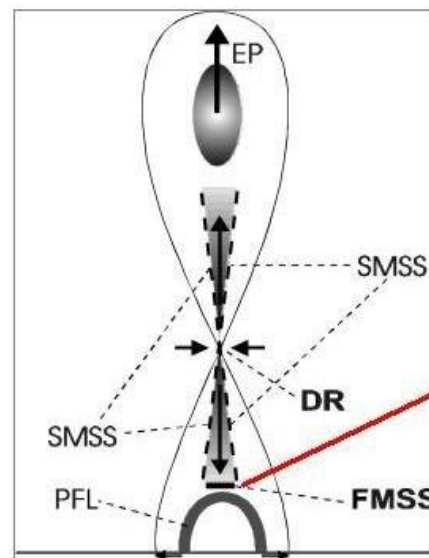


Ejection  
  
CME

# X17-Flare/CME on 28 October 2003

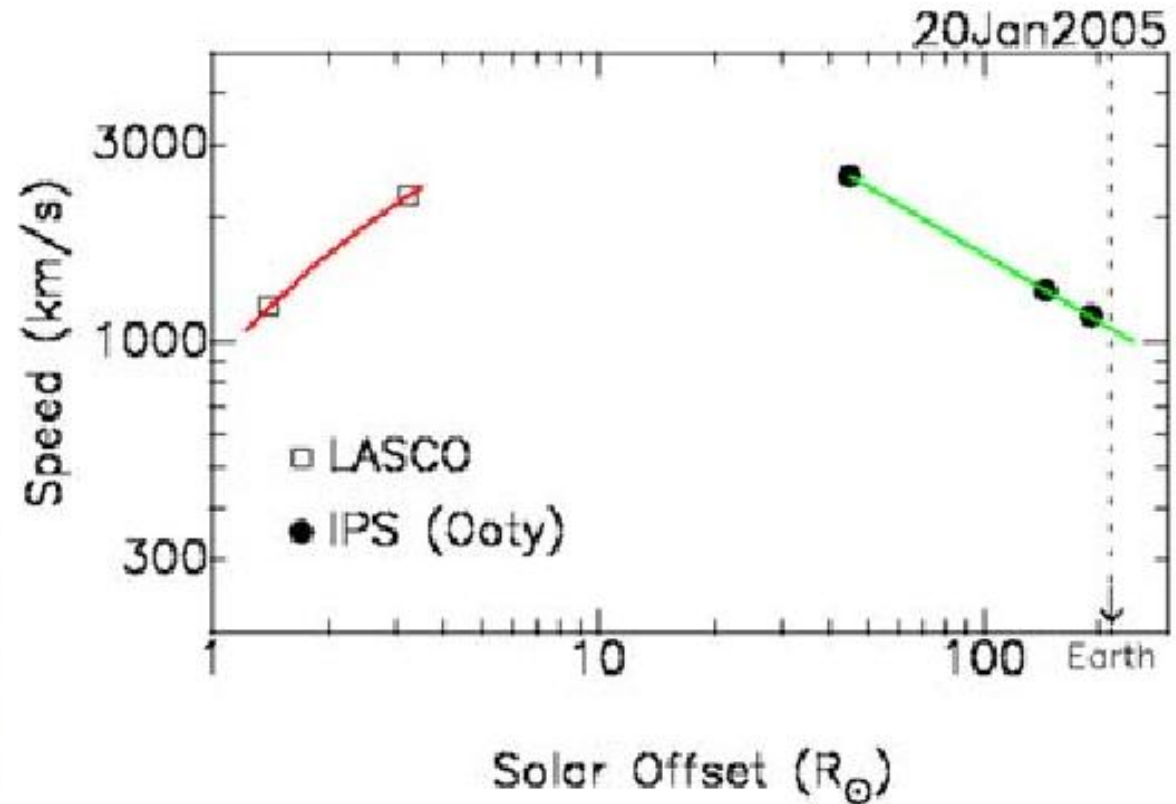
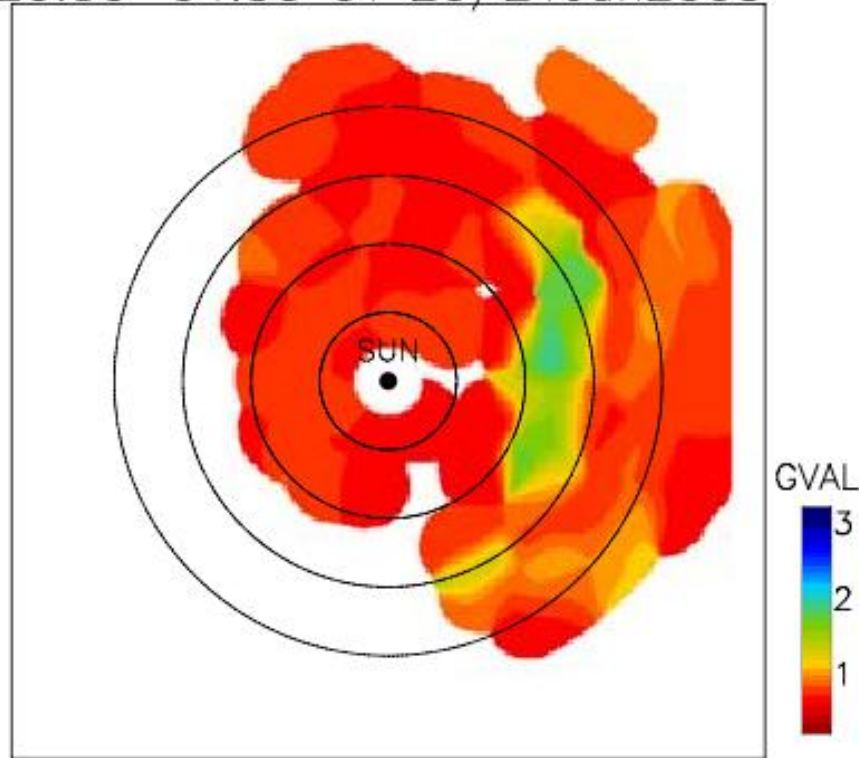


1. electrons are energized by shock drift acceleration
2. observed photon fluxes in the range 7.5-10 MeV are well explained



# IPS Image and Radial profile of the CME occurred on 2005 Jan 20

20:30–04:30 UT 20/21Jan2005



Ooty scintillation image (left) and CME speeds (right) from the estimations by Gopalswamy *et al.* (2005) and the measurements from the Ooty interplanetary scintillation observations during 20–21 January 2005.

Pohjolainen, Manoharan, et. al. 2007 *Sol. Phys.*