

# Shocks in Corona and Solar Energetic Particles

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Forbush, S., Phys. Rev.  
Lett., 70, 771, 1946

“...unusual increases...  
nearly simultaneous with a  
solar flare...”

“...may have been caused  
by charged particles  
actually being emitted by  
the Sun...”

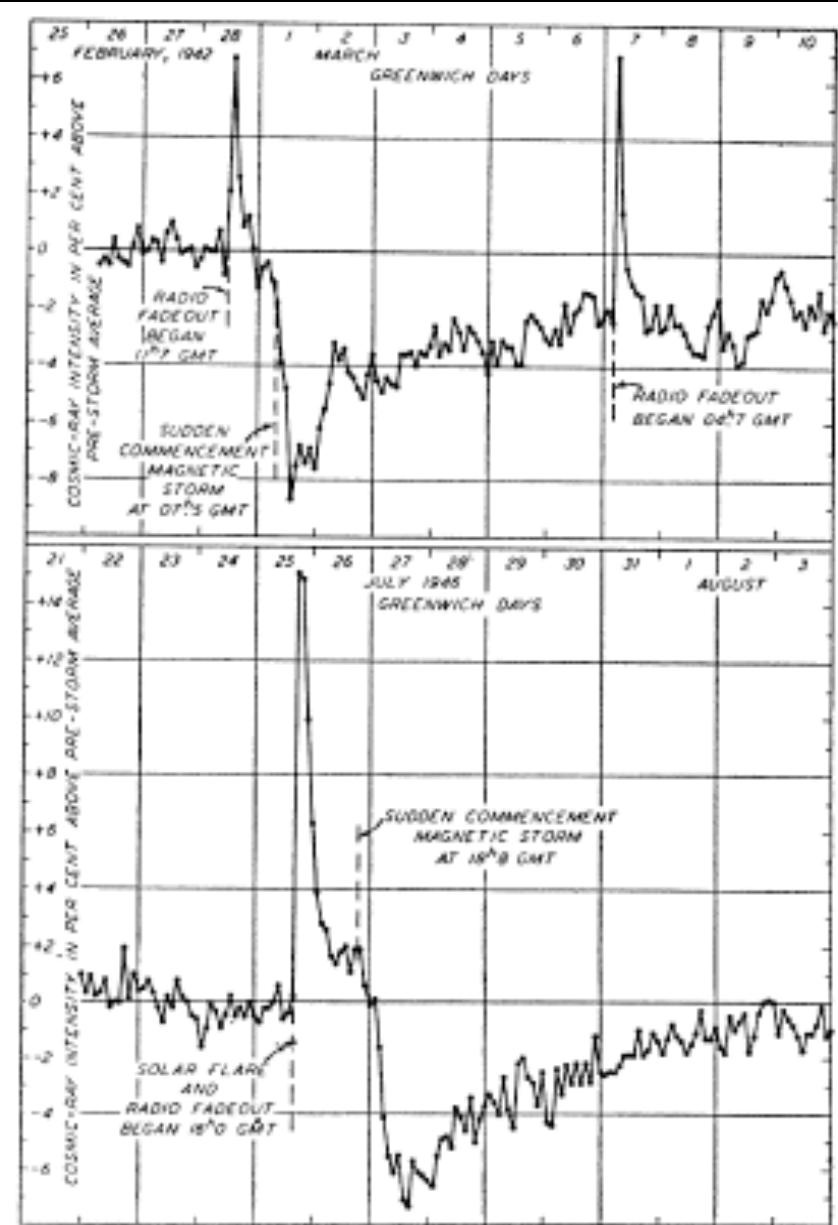


FIG. 1. Three unusual increases in cosmic-ray intensity at Cheltenham, Maryland, during solar flares and radio fadeouts.

# **The Sun is the most energetic particle accelerator in the solar system:**

- Ions up to ~ 10s of GeV*
- Electrons up to ~100s of MeV*

## **Acceleration occurs in transient energy releases, in two (!) processes:**

- Large Solar Flares, in the lower corona*
- Fast Coronal Mass Ejections (CMEs), in the inner heliosphere, ~2-40 solar radii*

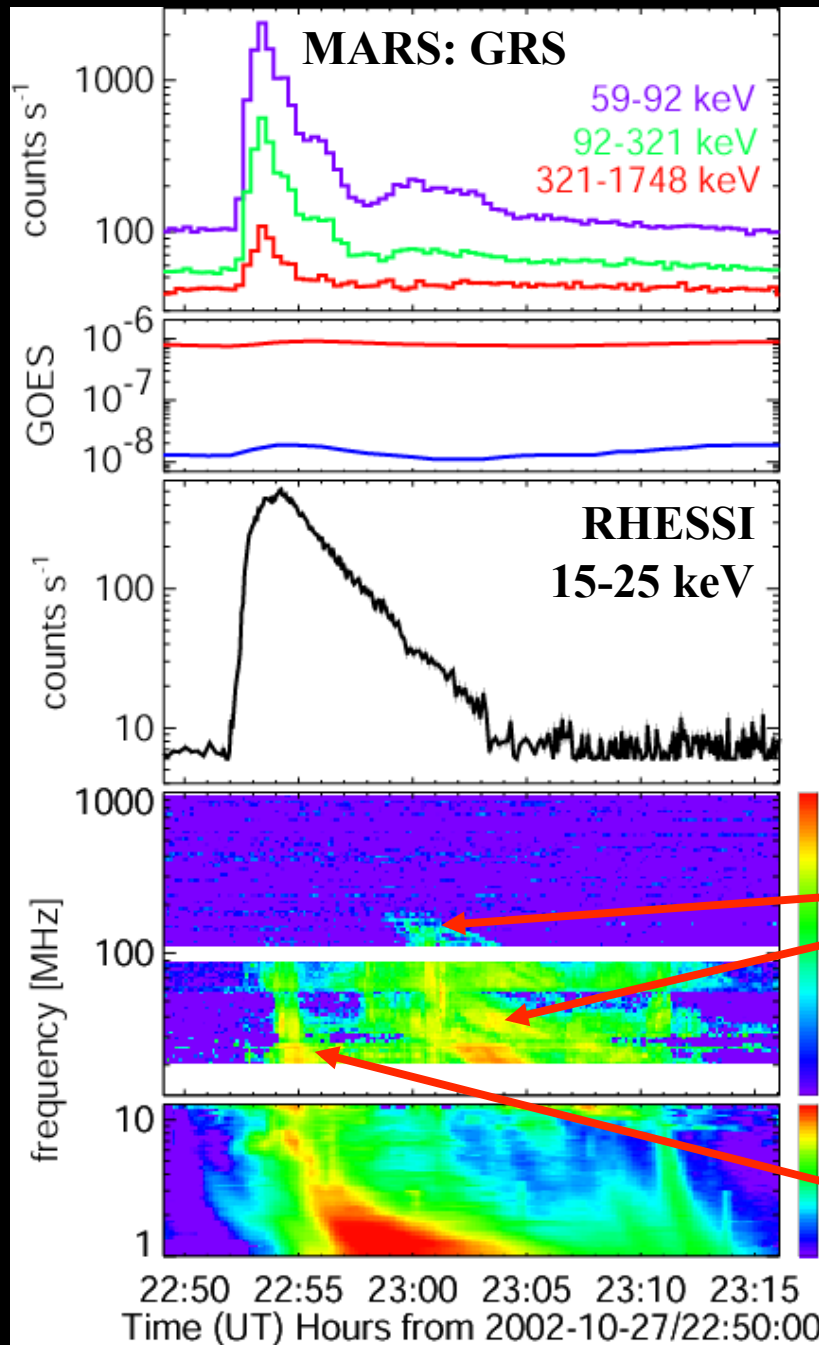


Apr 17 2002 23:59:32

# radio observations

no emission at high frequencies!  
→ density  $\sim 10e8 \text{ cm}^{-3}$

RHESSI HXR emission  
correlated with type III,  
not with type II (shock)

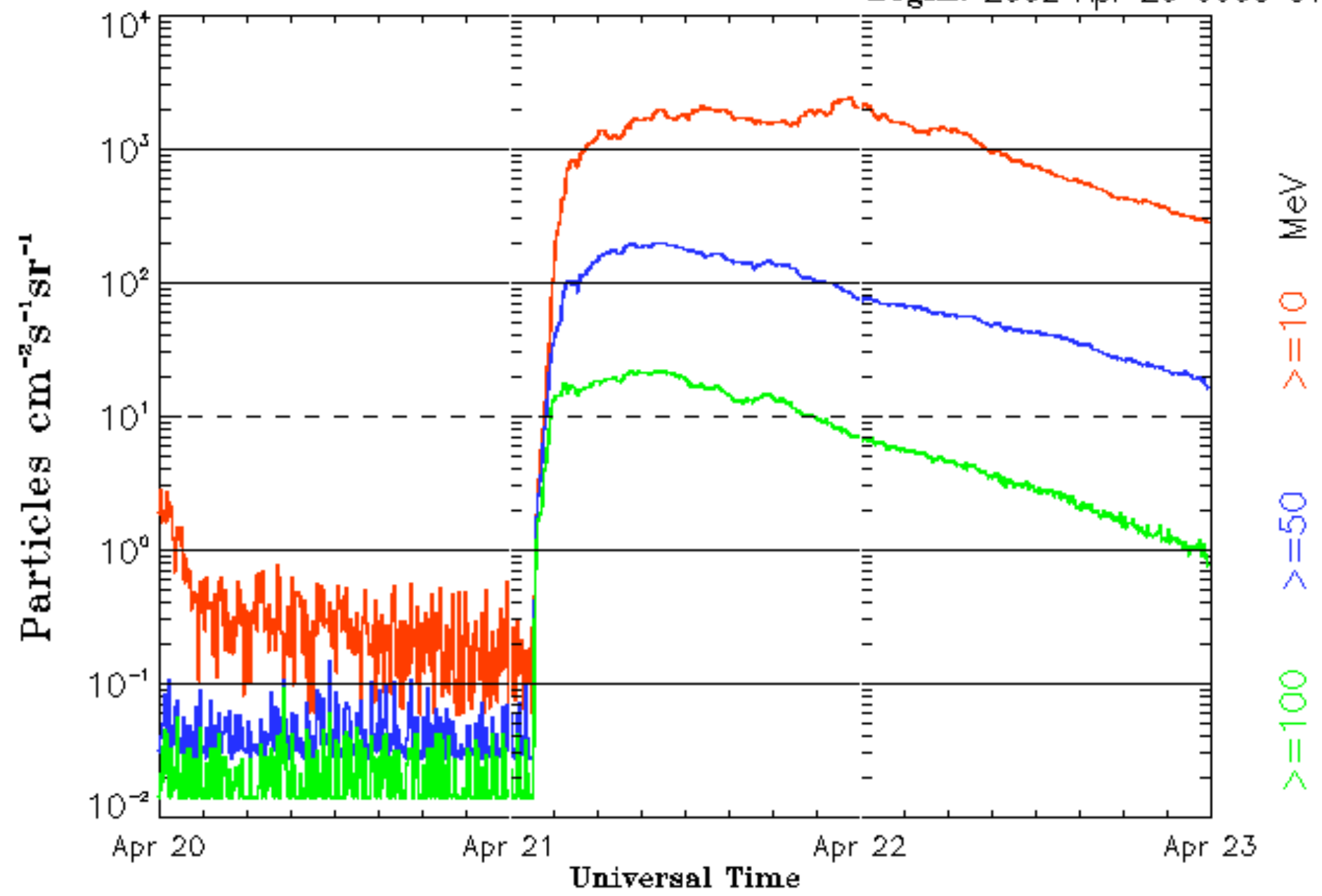


type II

type III starts at 100 MHz  
( $n \sim 1e8 \text{ cm}^{-3}$ )

# GOES8 Proton Flux (5 minute data)

Begin: 2002 Apr 20 0000 UTC

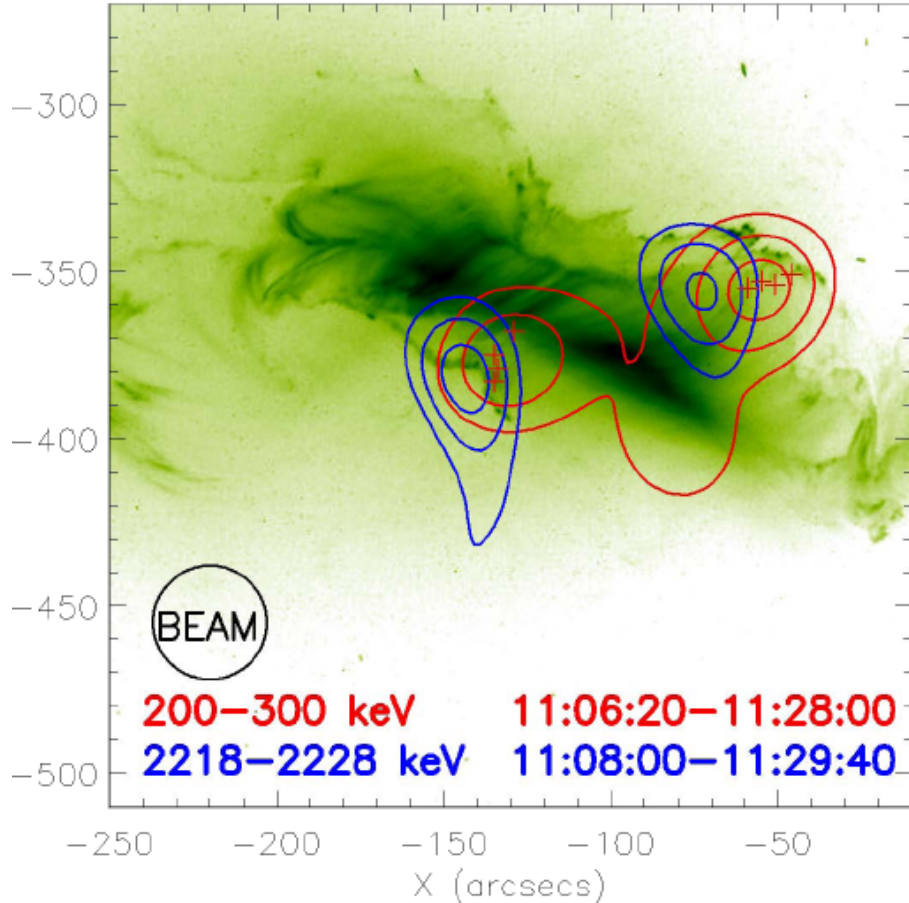


Updated 2002 Apr 22 23:56:05 UTC

NOAA/SEC Boulder, CO USA

# Solar Flare Particle Acceleration by Magnetic Reconnection

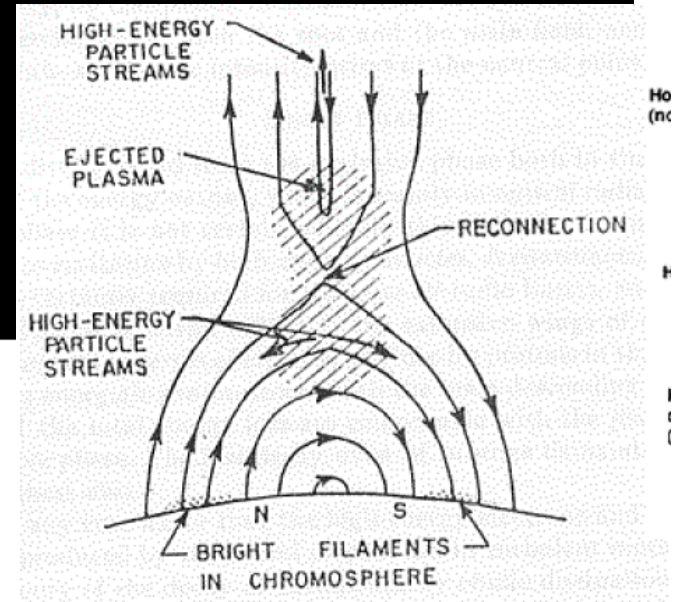
TRACE 195A 28-Oct-2003 11:11:02



## Protons vs Electrons

>~30 MeV p  
(2.223 MeV  
n-capture line)

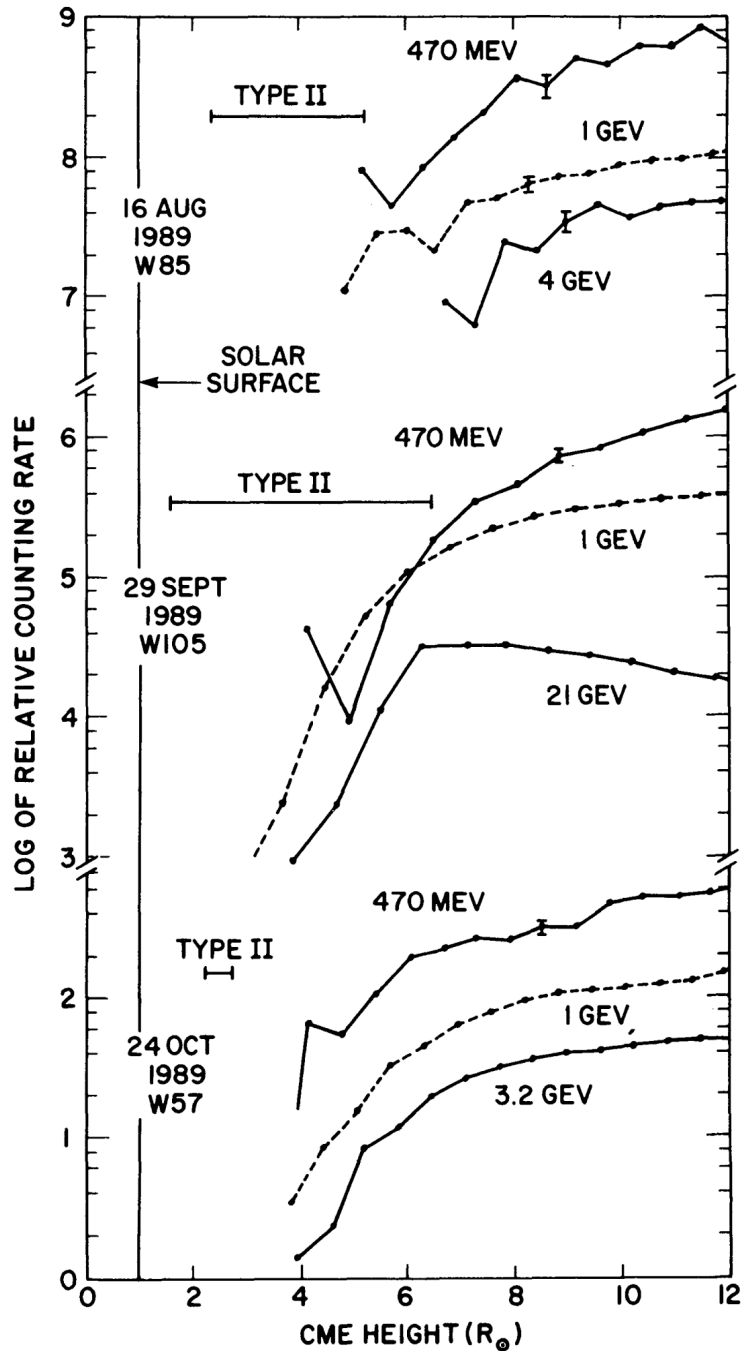
> 0.2 MeV e  
(0.2-0.3 MeV  
bremsstrahlung X-  
rays)



Sturrock 1966

(Hurford et al., 2006)

# Ion acceleration



Kahler 1994:

Compare ion release time near Sun with CME front altitude

◇ CME is already several Solar radii away from the Sun



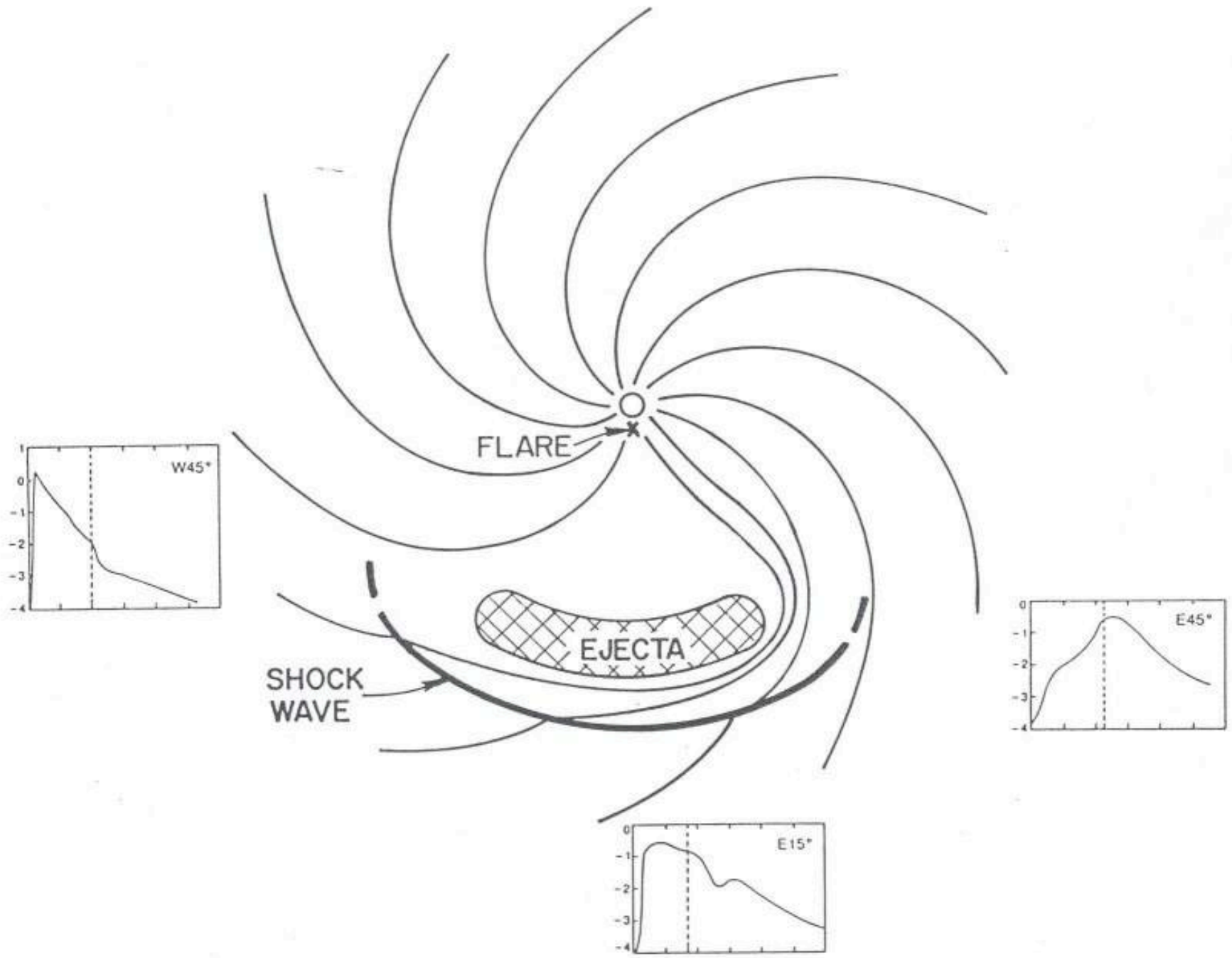
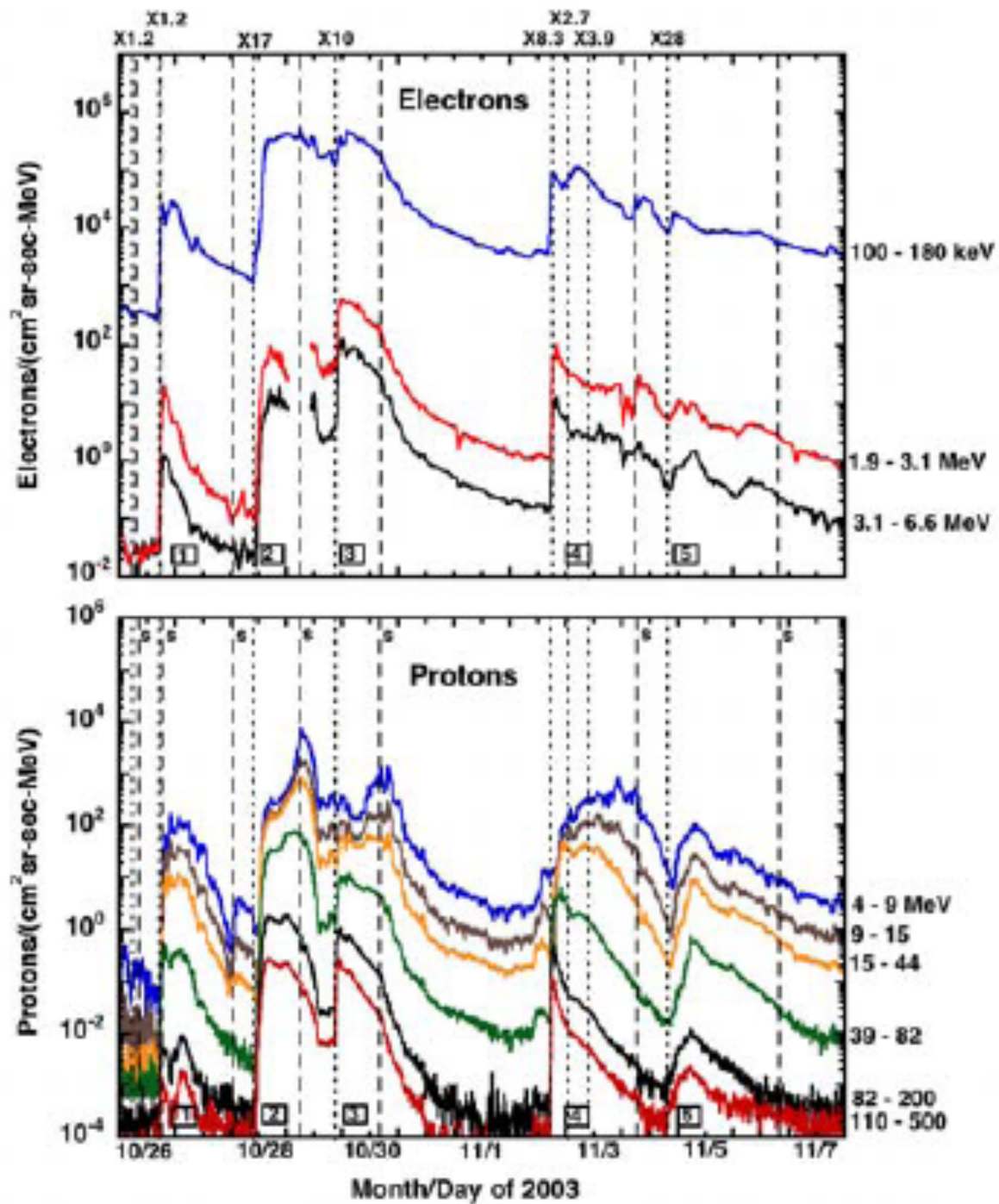


Figure 2.

## Large (L)SEP events - tens/year at solar maximum

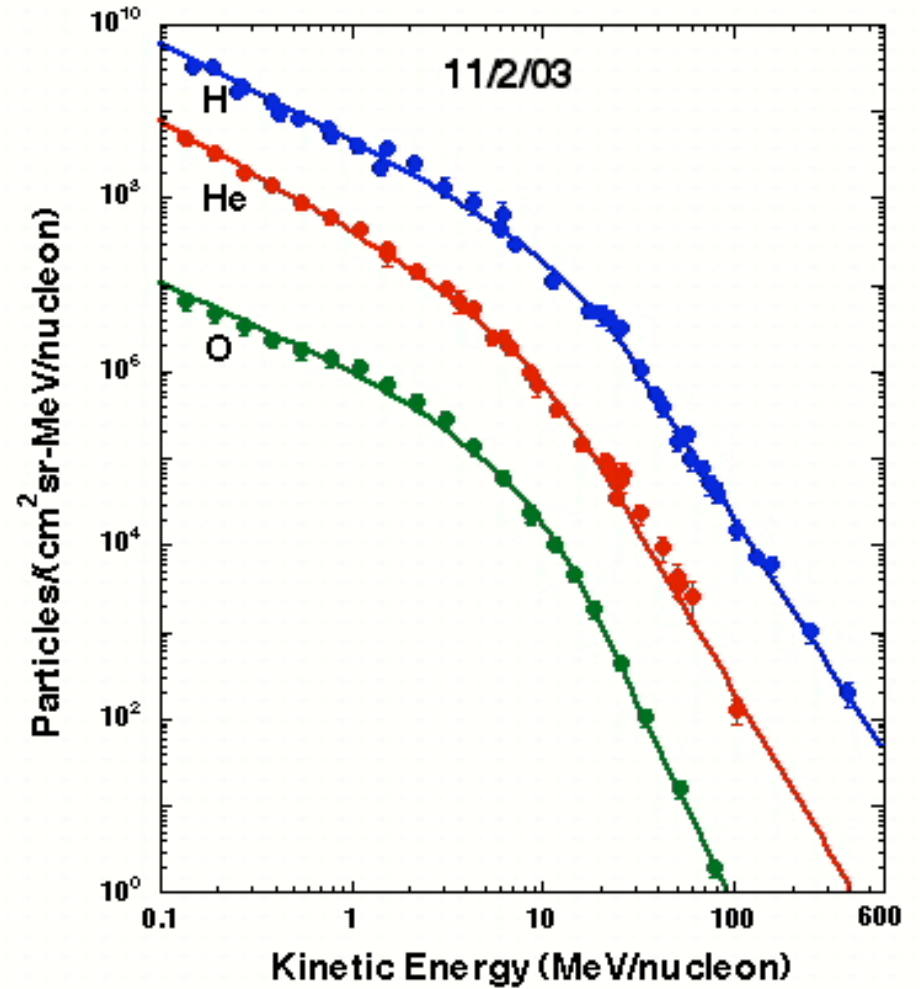
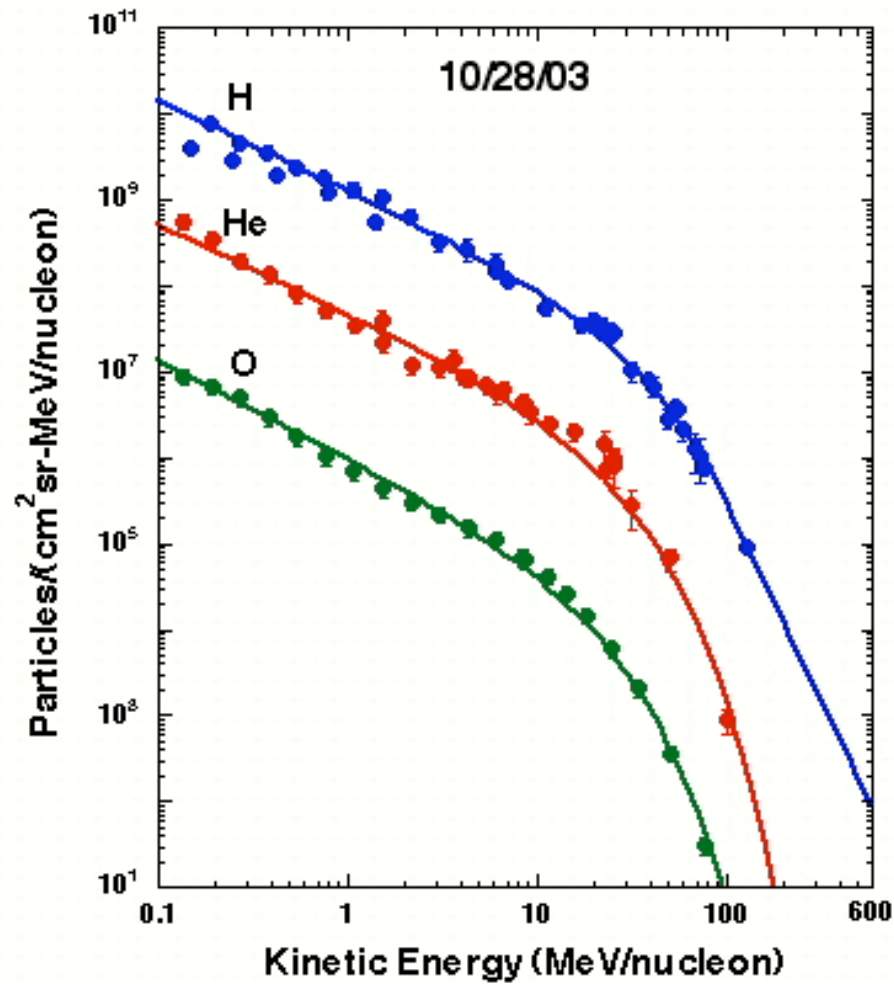
- **>10 MeV protons (small e/p ratio)**
- **Normal coronal composition**  
(but sometimes  $^3\text{He}$  &  $\text{Fe/O}$  enhanced)
- **Normal coronal charge states,  $\text{Fe}^{+10}$**   
(but sometimes enhanced )
  
- **SEPs seen over  $>\sim 100^\circ$  of solar longitude**
  
- **associated with:**
  - **Fast Coronal Mass Ejections (CMEs)**
  - **Large flares (but sometimes missing)**
  - **Gradual (hours) soft X-ray bursts**  
(also called Gradual SEP events)

**\* Acceleration by fast CME driven shock wave  
in inner heliosphere, 2-40 solar radii**



Mewaldt et al  
2004

# H, He, and O Spectra at 1 AU from ACE/GOES/SAMPEX

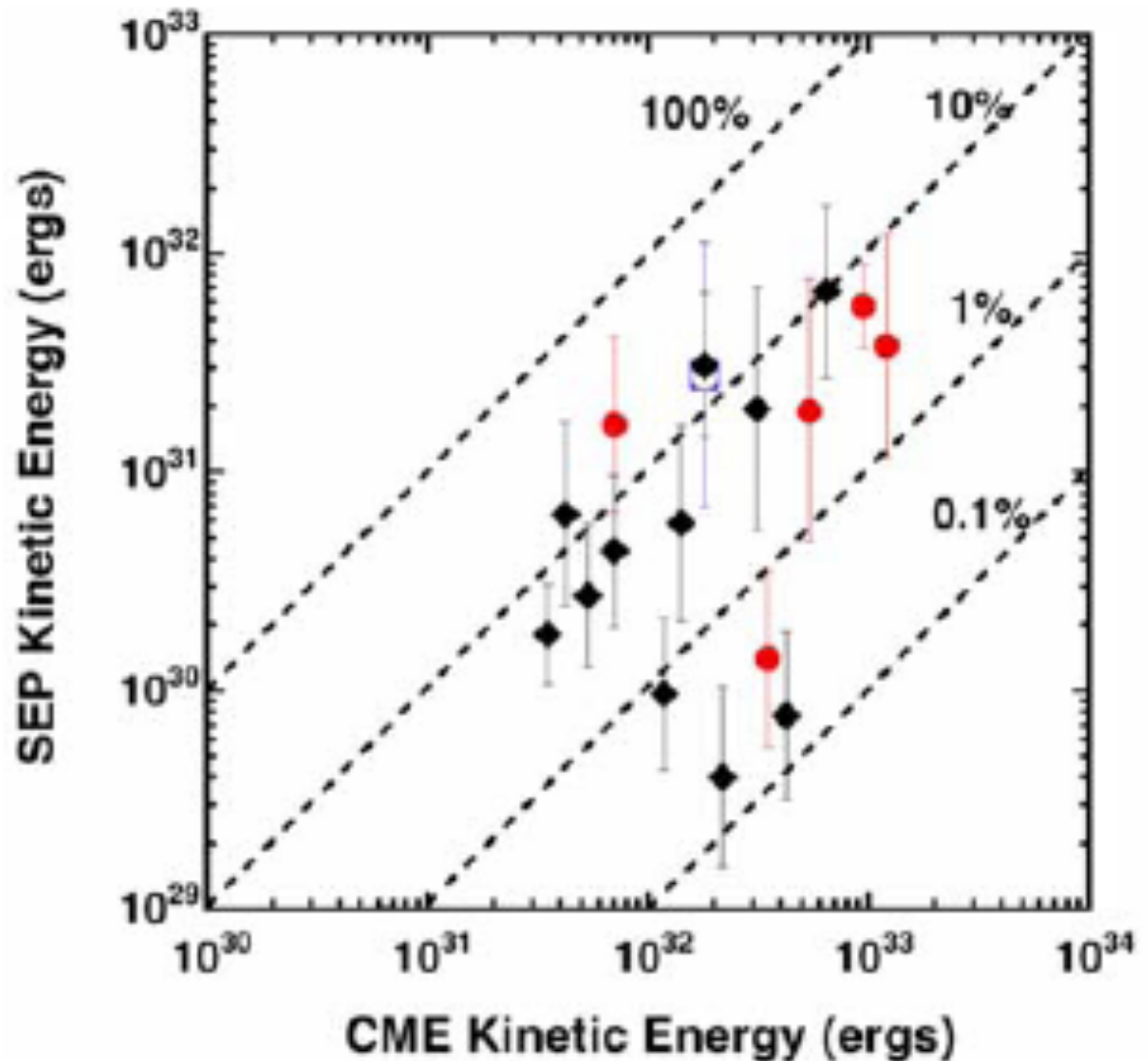


***(Mewaldt et al. 2004)***

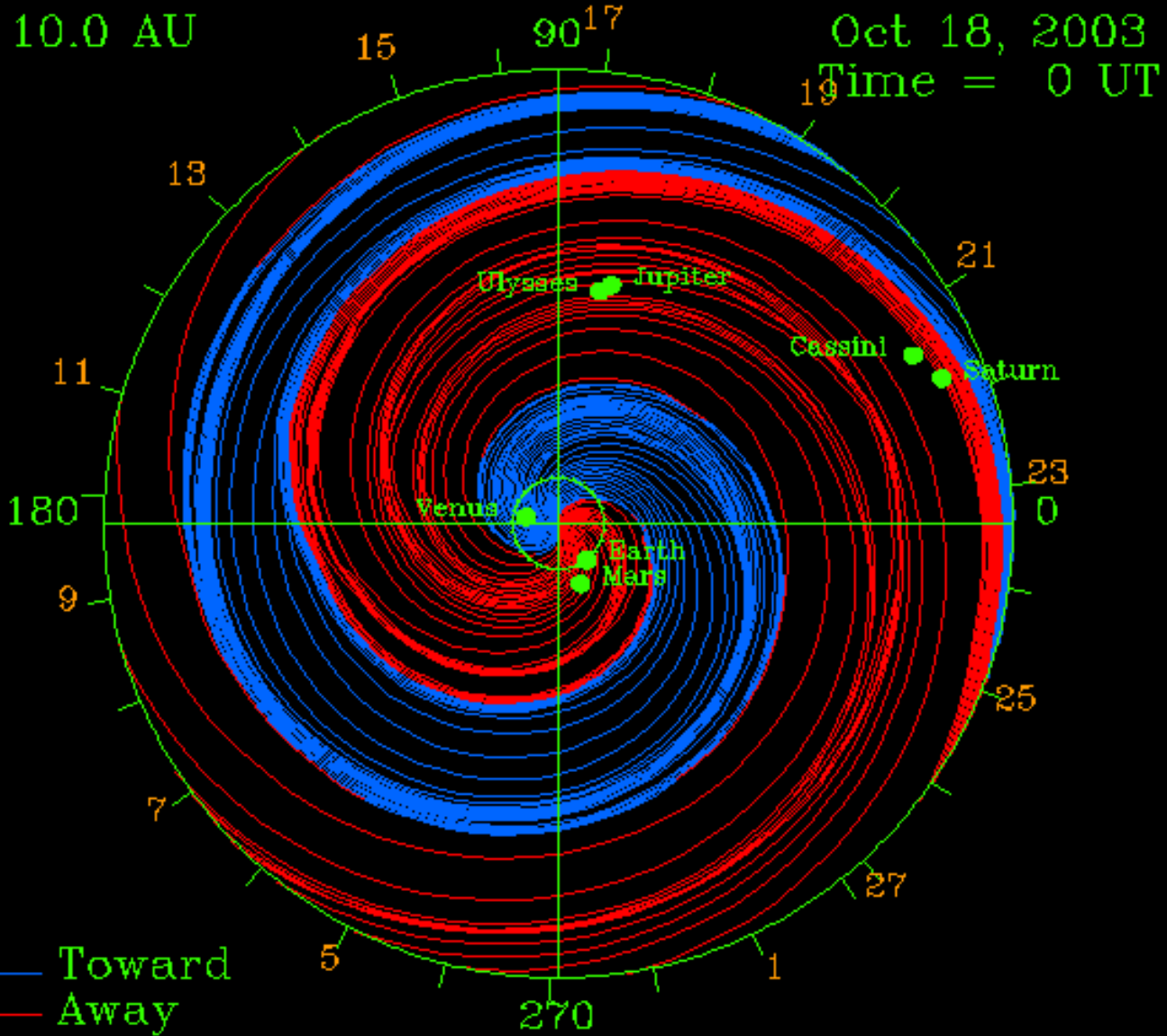
## Mewaldt et al, 2005

If these SEPs are accelerated by CME-driven shocks, they use a significant fraction of the CME kinetic energy (up to 20%)

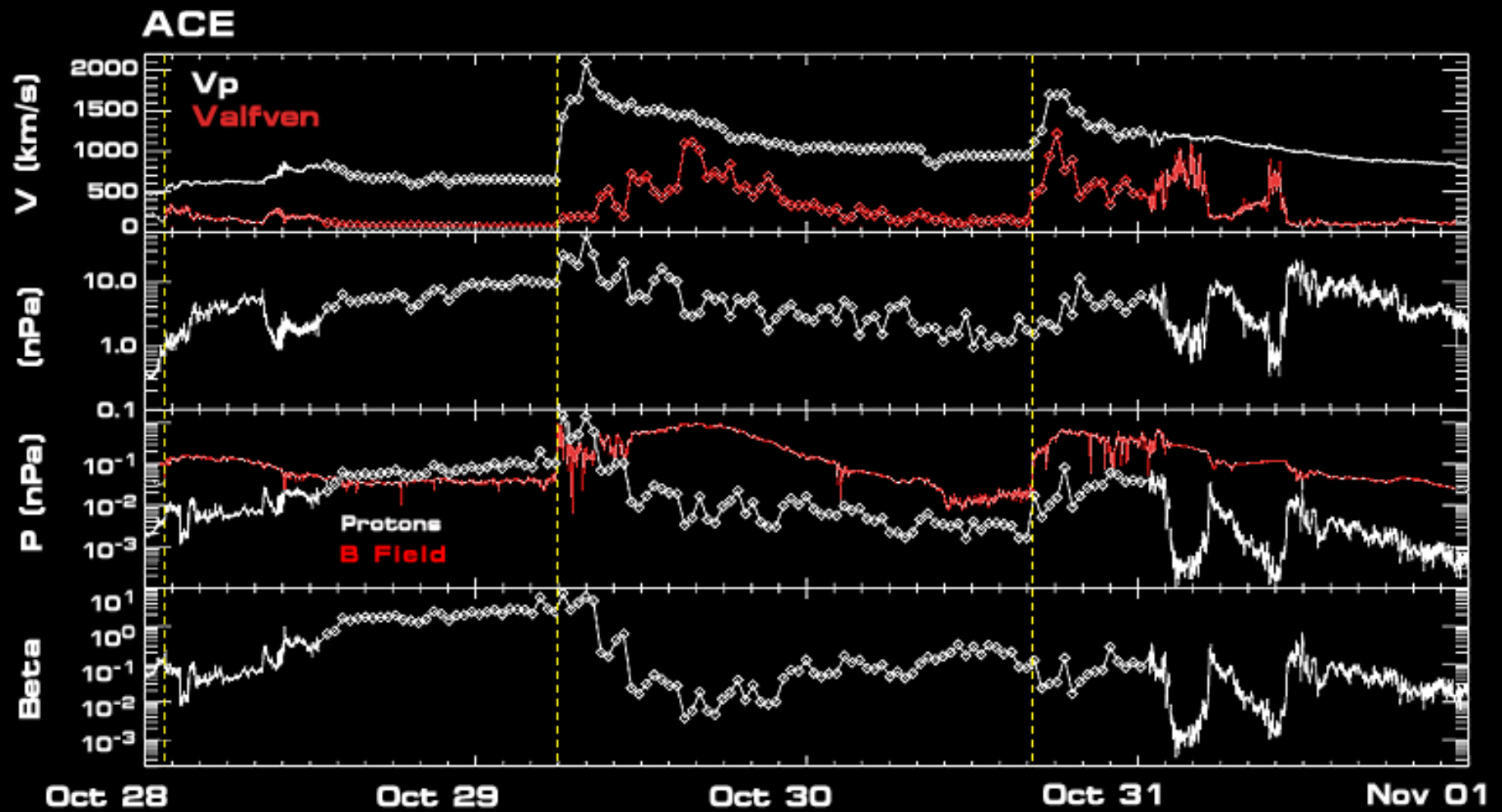
(see also Emslie et al. 2004).

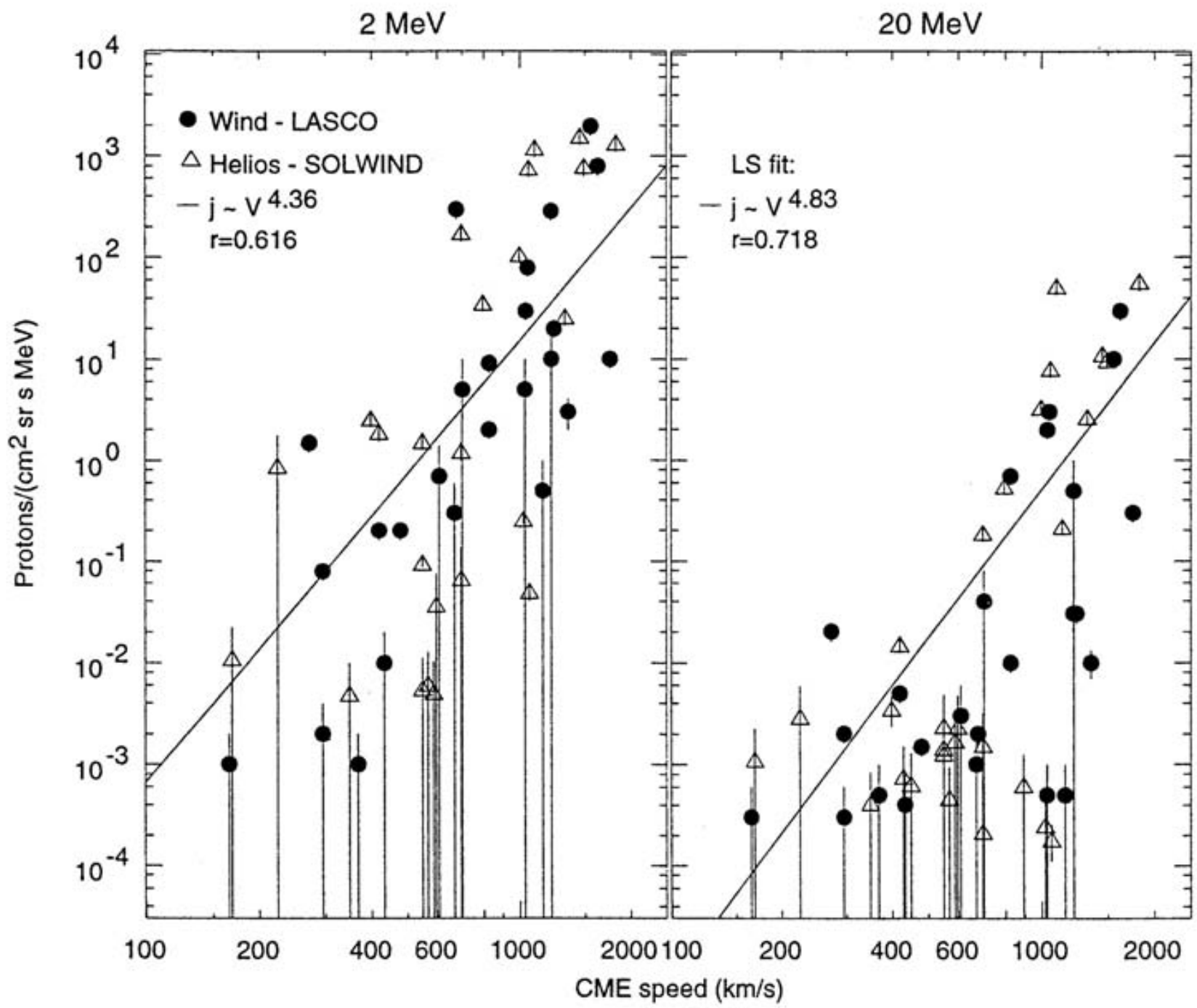


# Equatorial Plane IMF



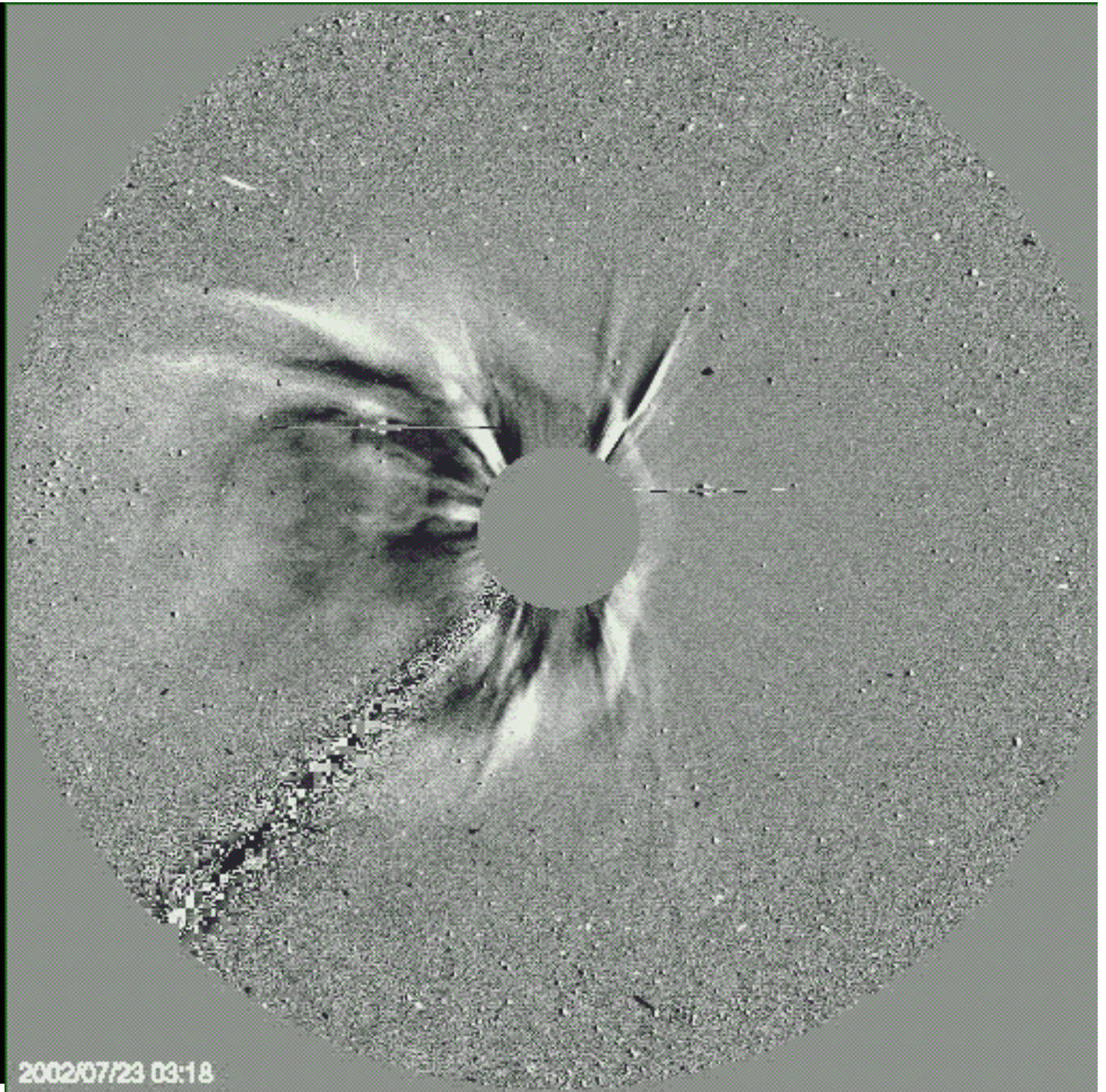
# Zurbuchen 2004



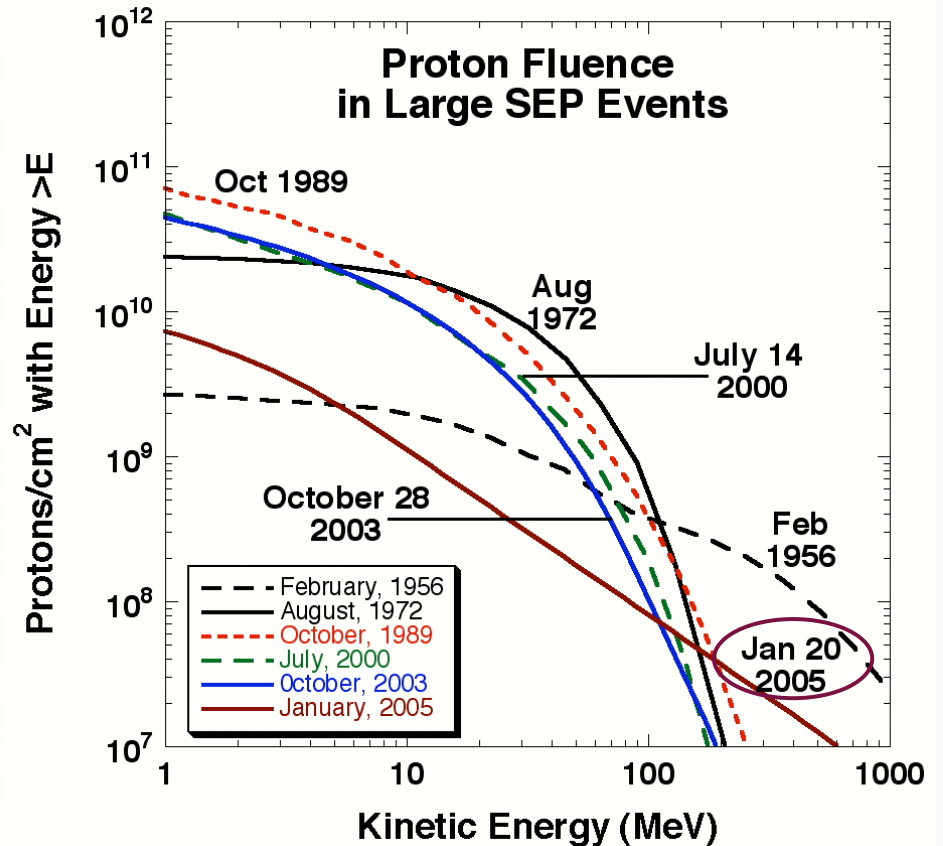
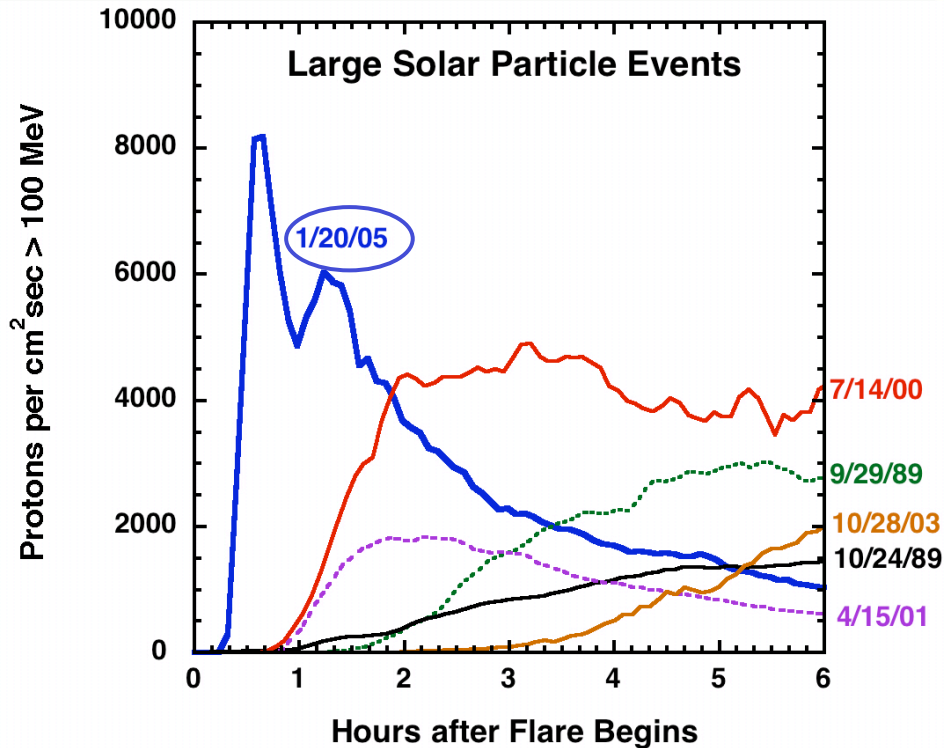




Gopalswamy  
et al. 2004



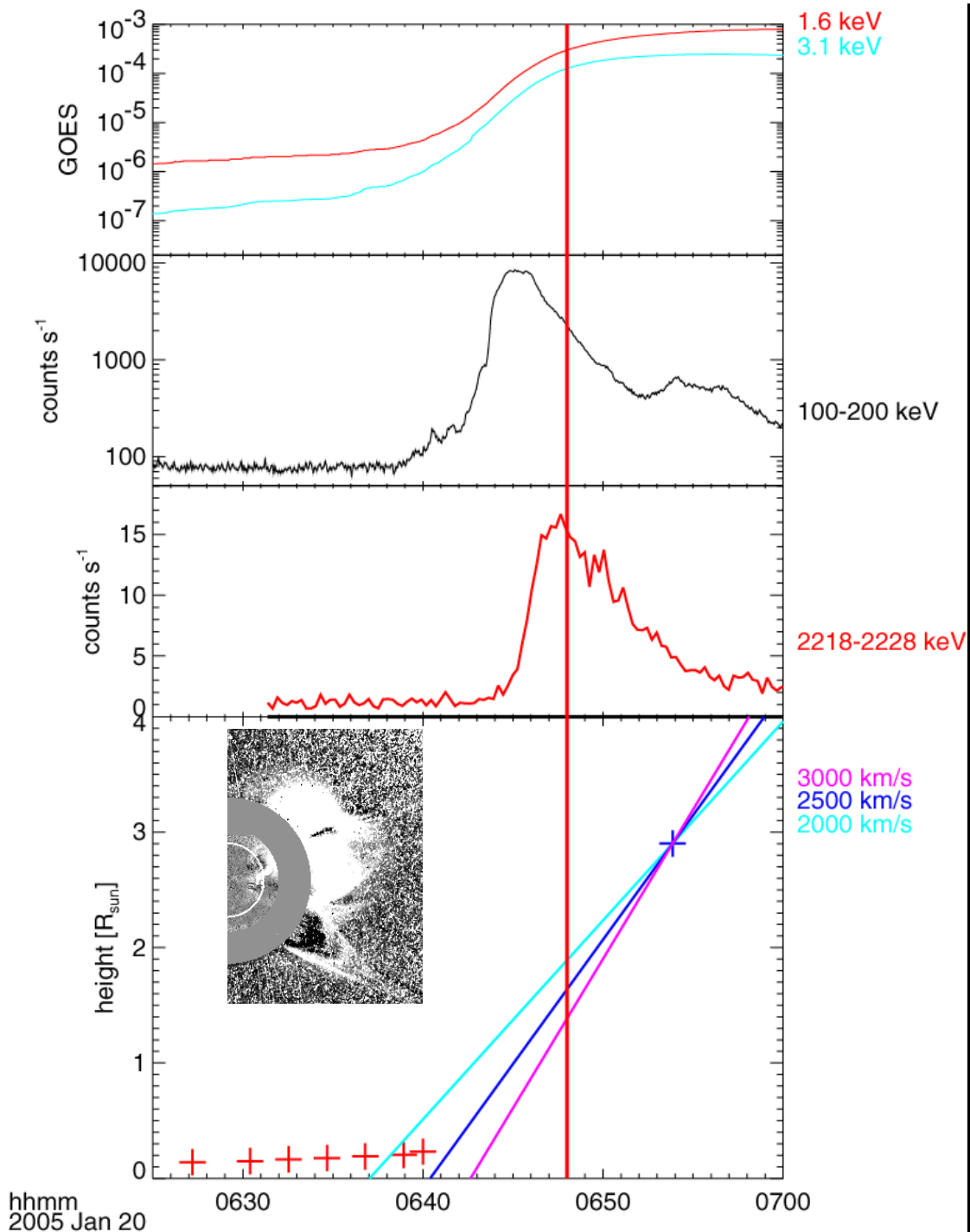
# January 20, 2005 SEP event



**Very short time to maximum intensity (30 min)**

**Very hard spectrum**

**(from Mewaldt et al. 2005)**



## Timing

**Red vertical line  
(06:48UT):**

**Solar release time assuming first  
arriving particles travel at  $v=c$   
along  $L=1.2$  AU**

**HXR peak at 06:45:00UT**

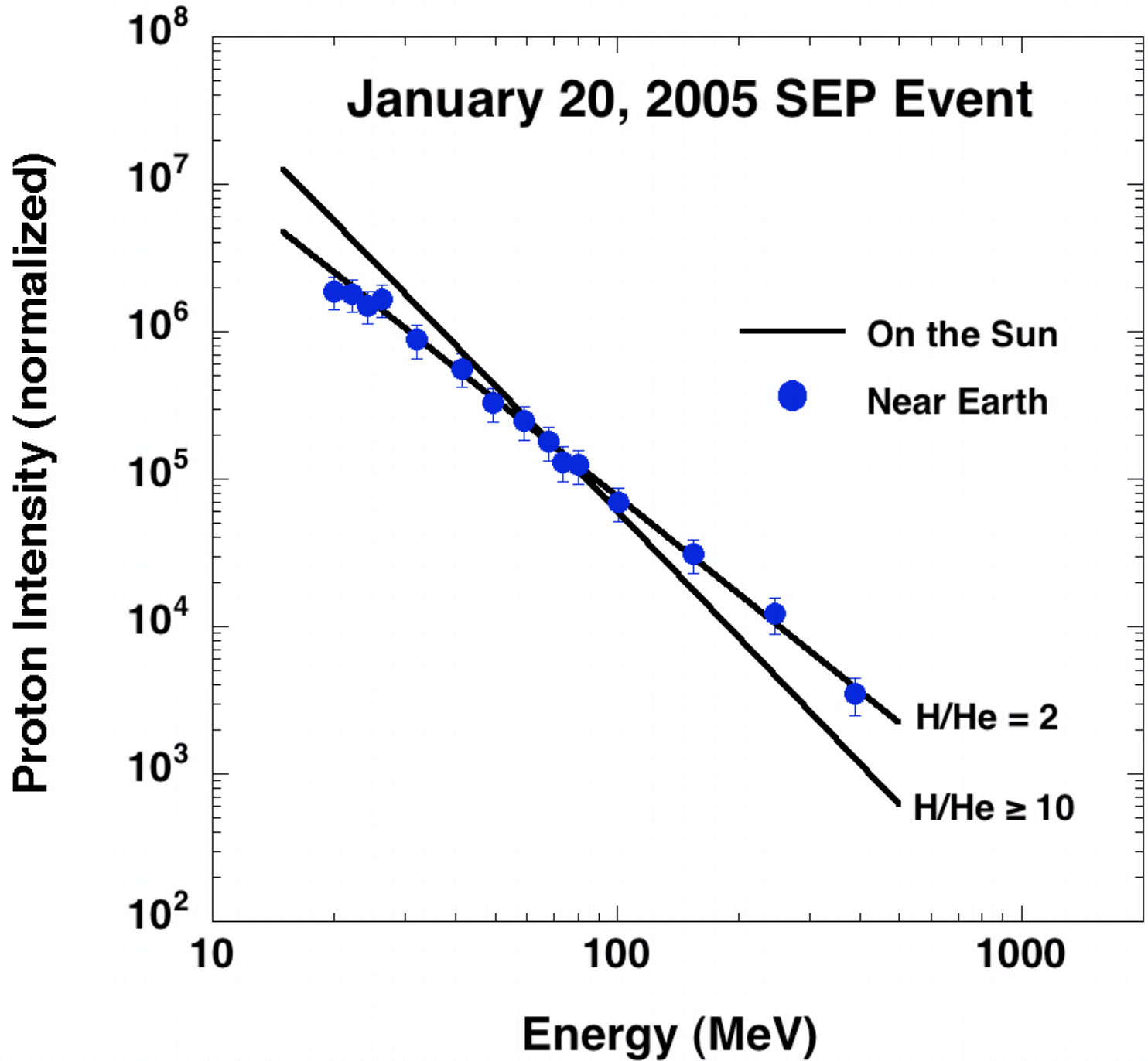
**2.2 MeV peak at  
0647:30UT**

**06:54UT: CME at  $\sim 3$  R<sub>sun</sub>**

**Line: 2500 km/s CME  
speed**

**Proton  
spectrum:**

**RHESSI  
Gamma-rays  
(lines)  
vs  
SEPs at 1AU  
(blue points)**



# NASA Solar Probe Plus ESA Solar Orbiter



APL

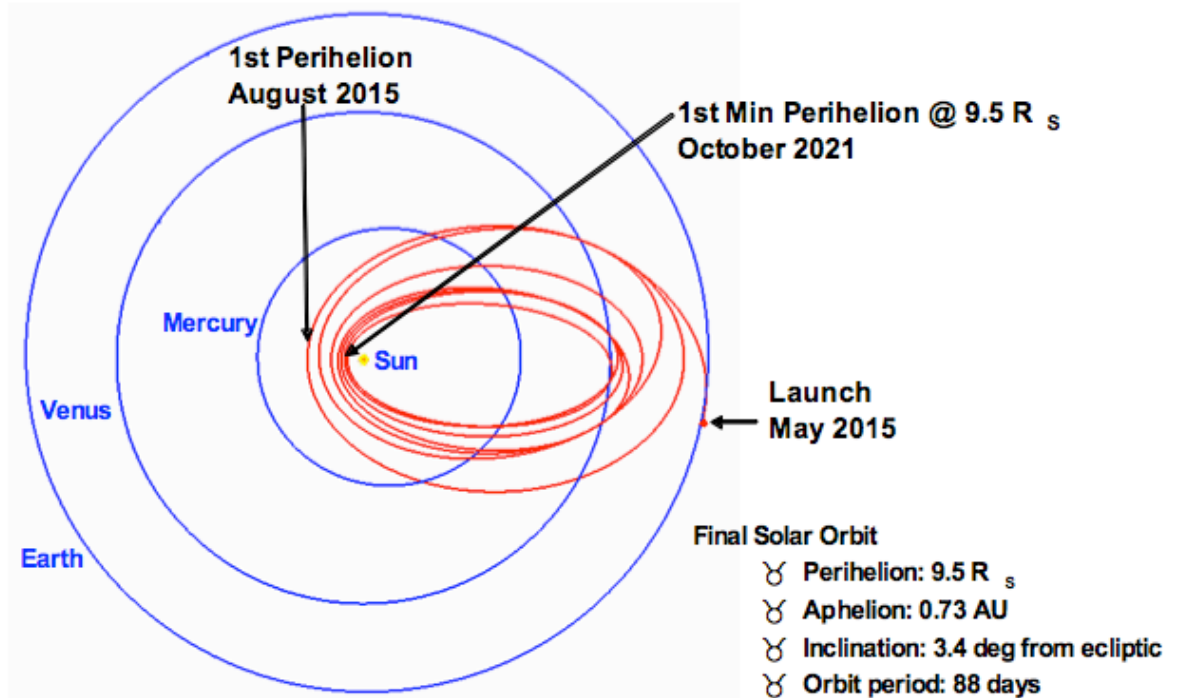
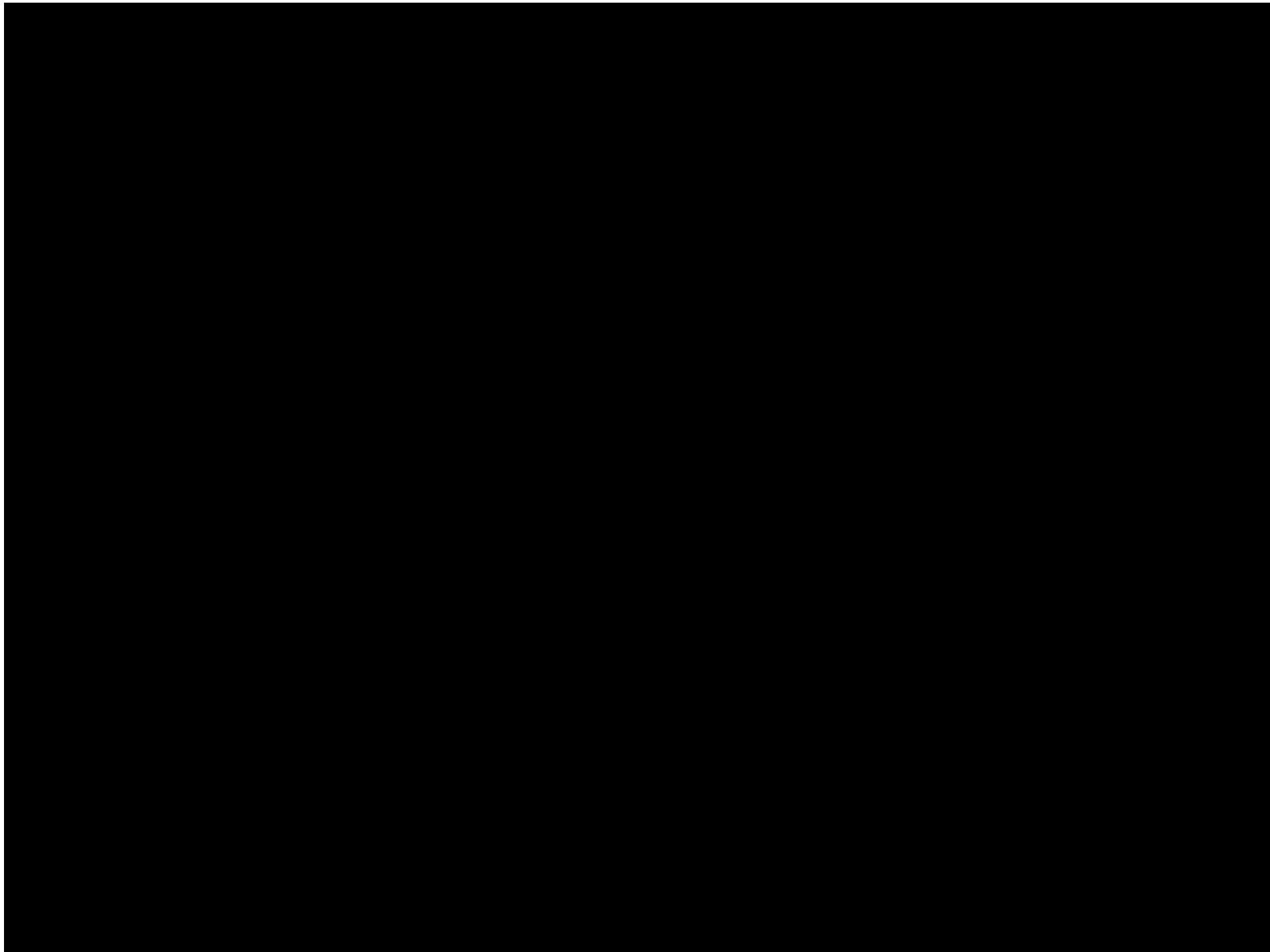
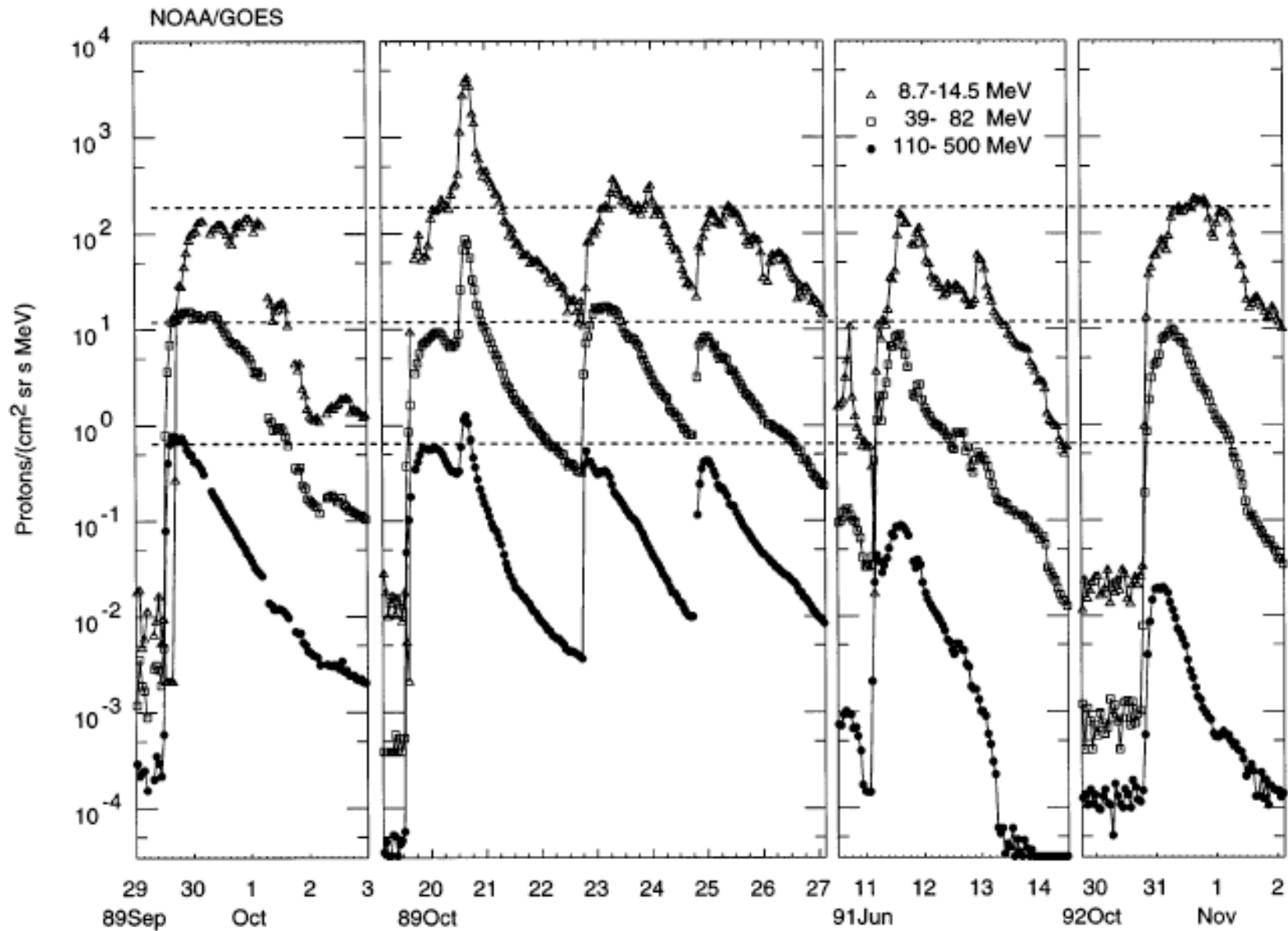


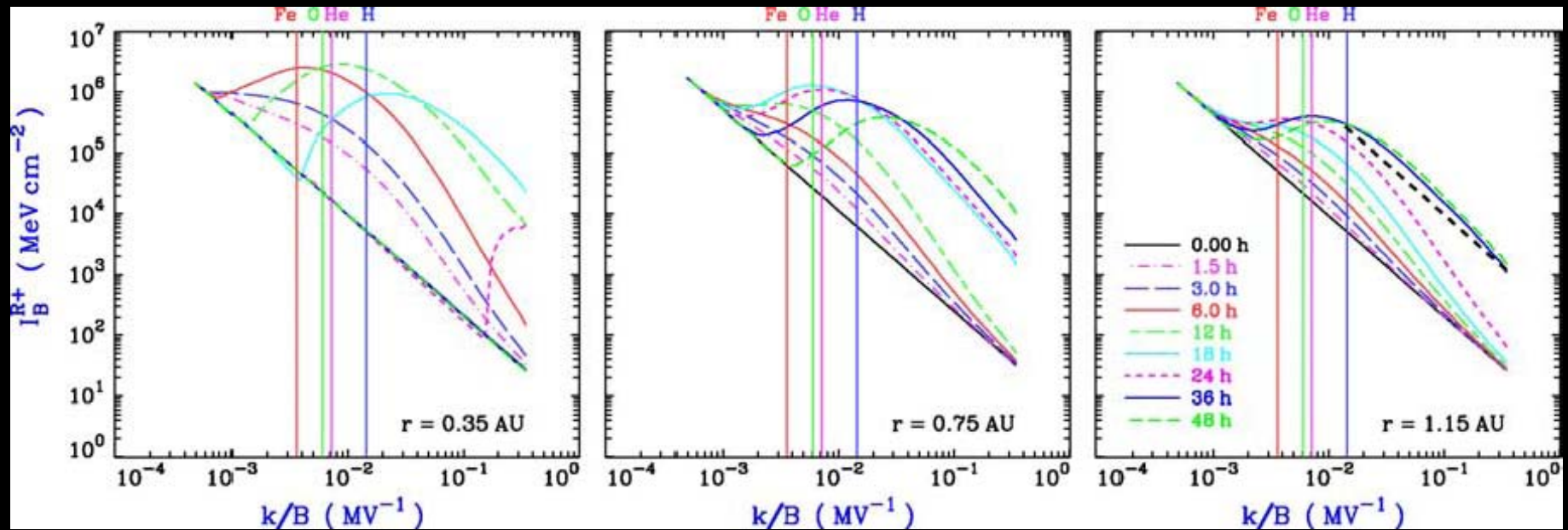
Figure 4-1. Baseline Solar Probe+ trajectory.



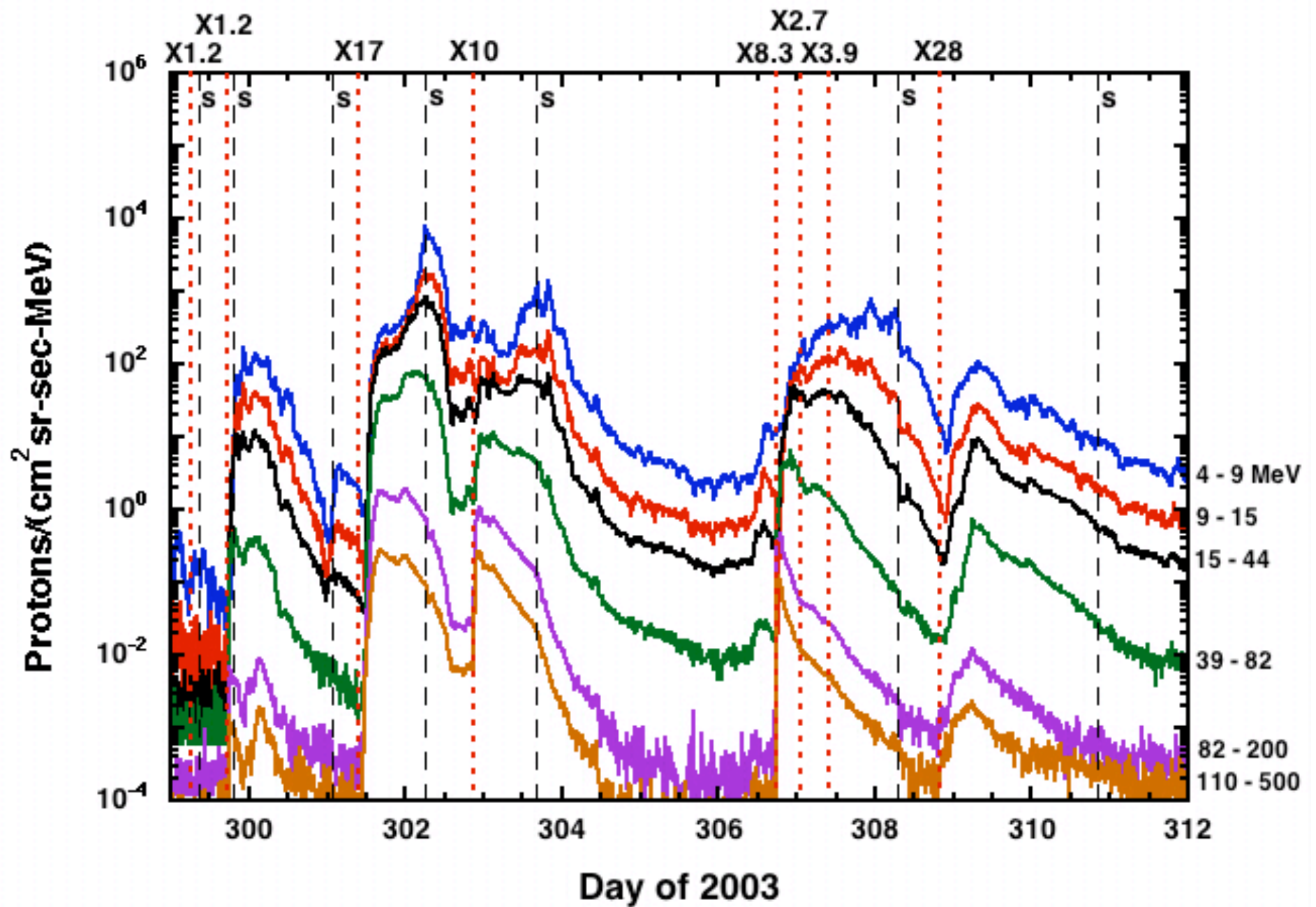
# Reames & Ng 1998



# Computed wave spectra (Leamon et al 1998)







Mewaldt et al 2005