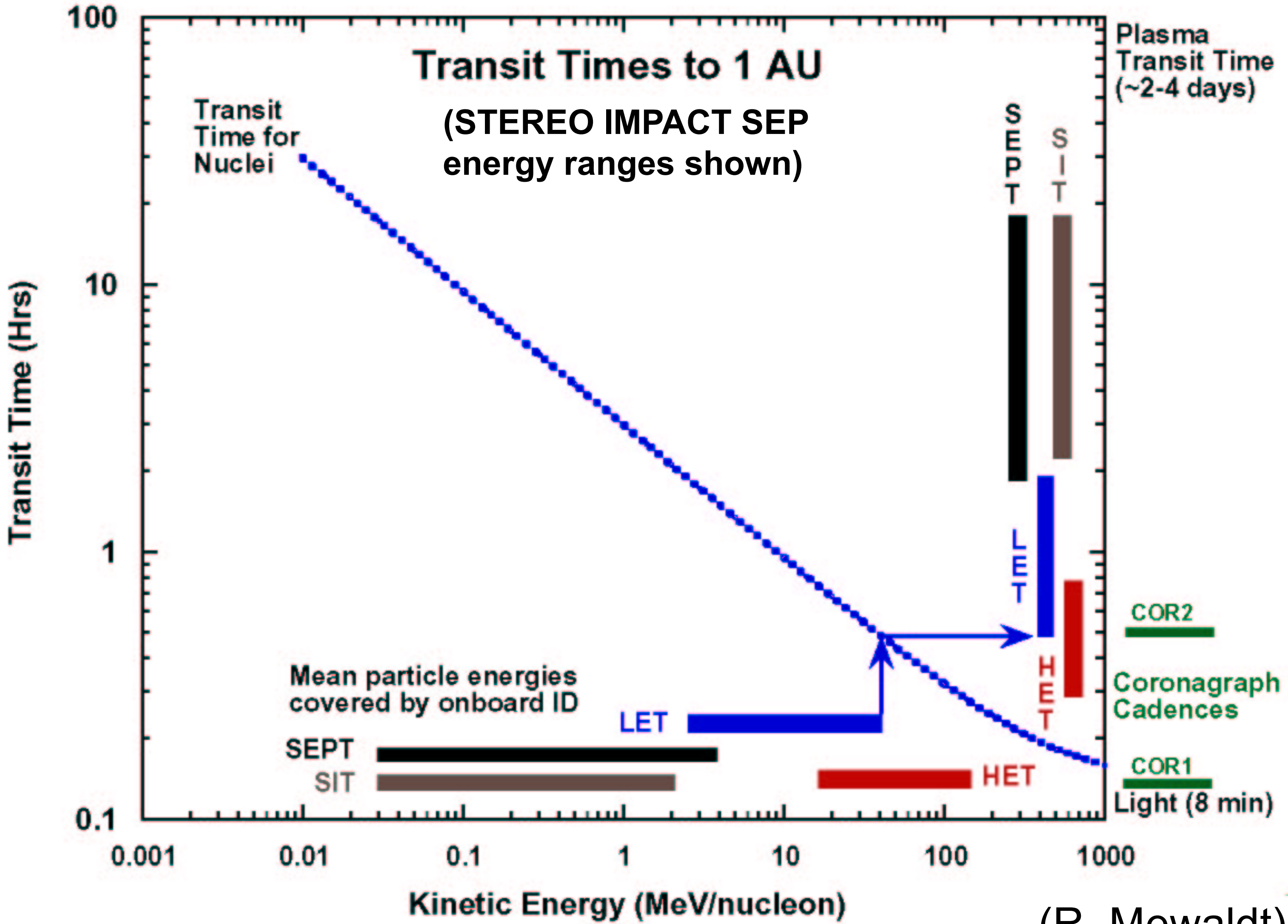
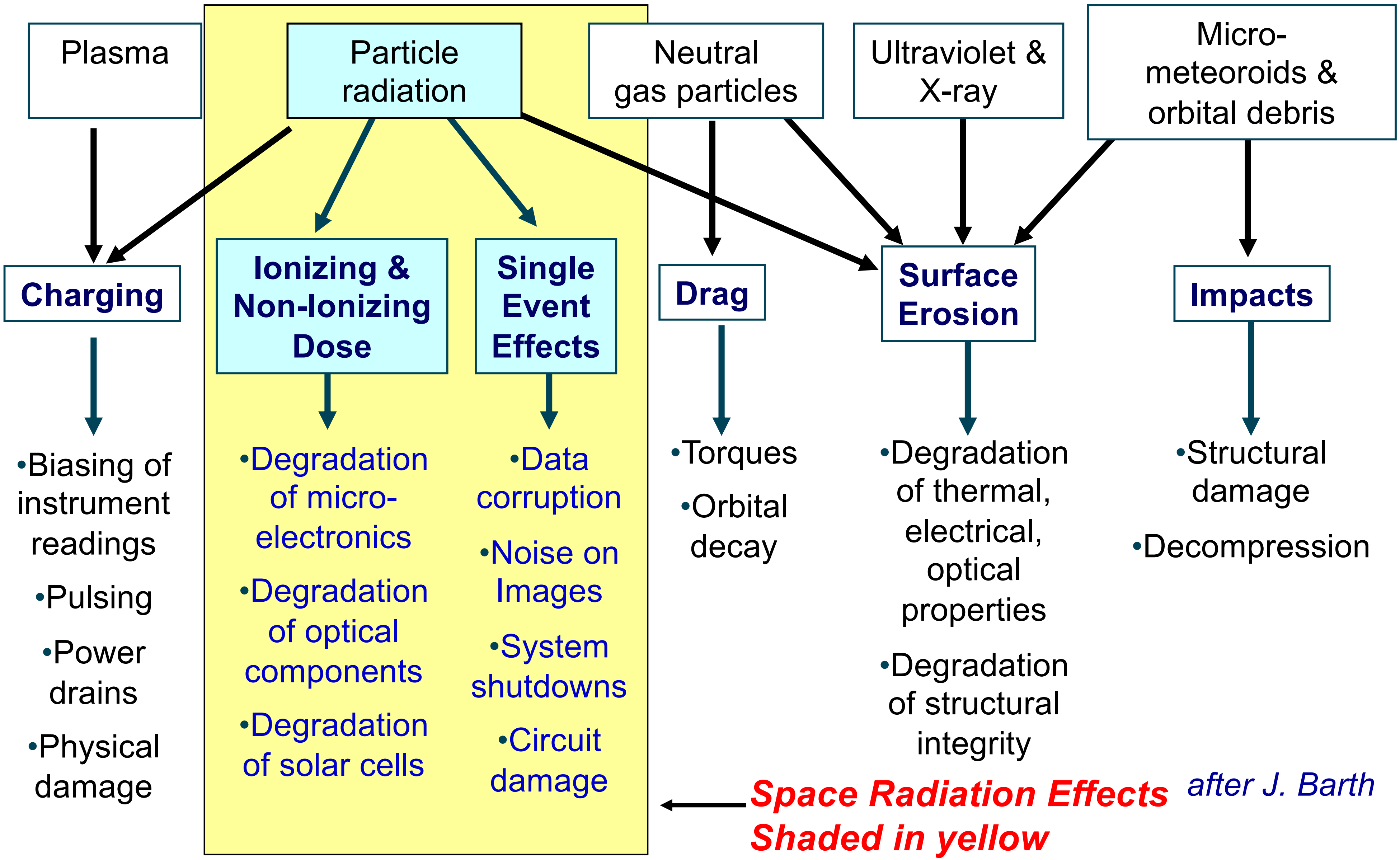
SEPs provide both a **remote diagnostic** of their source(s) and are themselves a space weather hazard of interest to forecasters.



(R. Mewaldt)

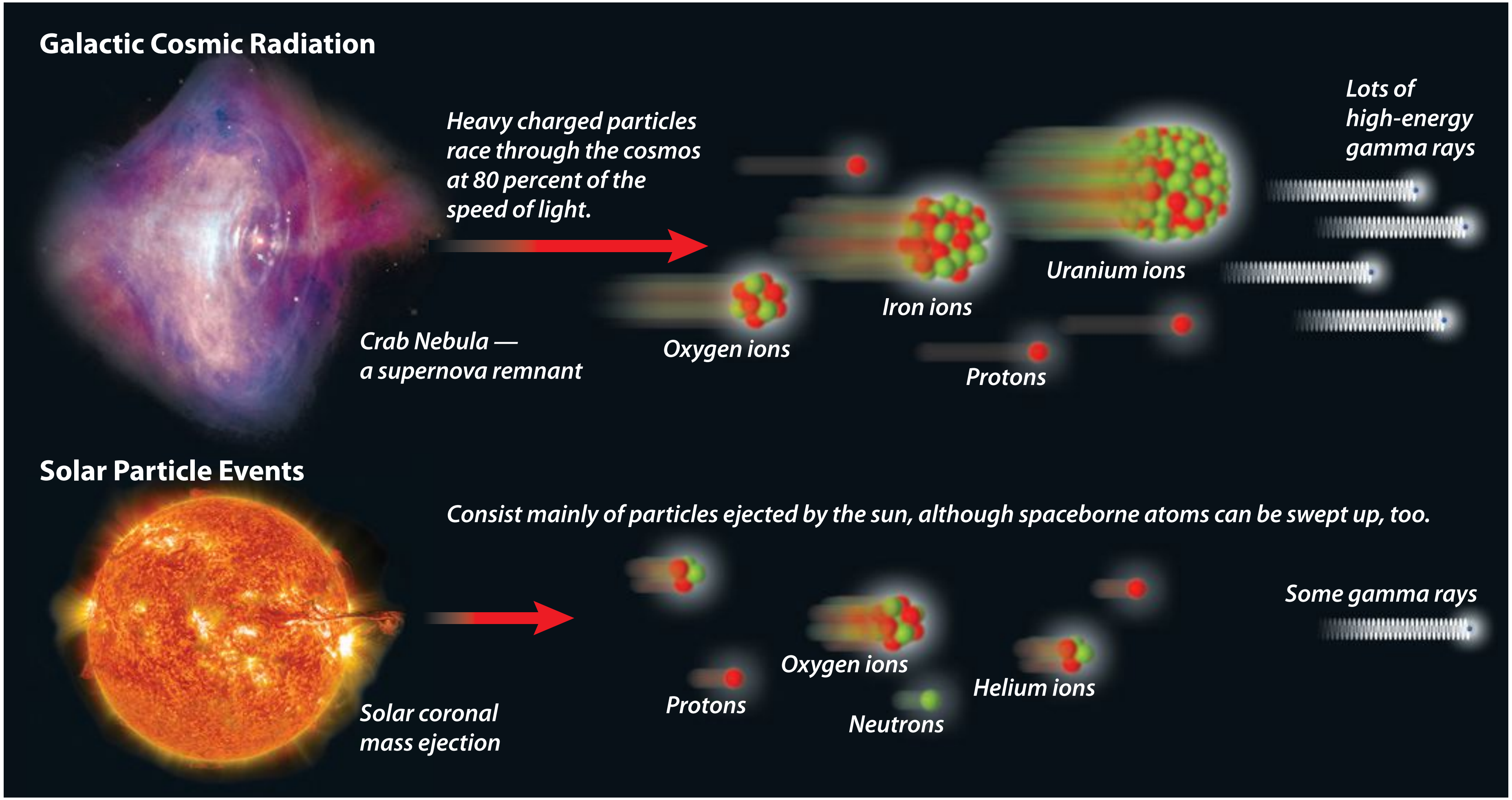
Space Environments and Effects on Spacecraft



SEPs – important source of space radiation: hard to predict

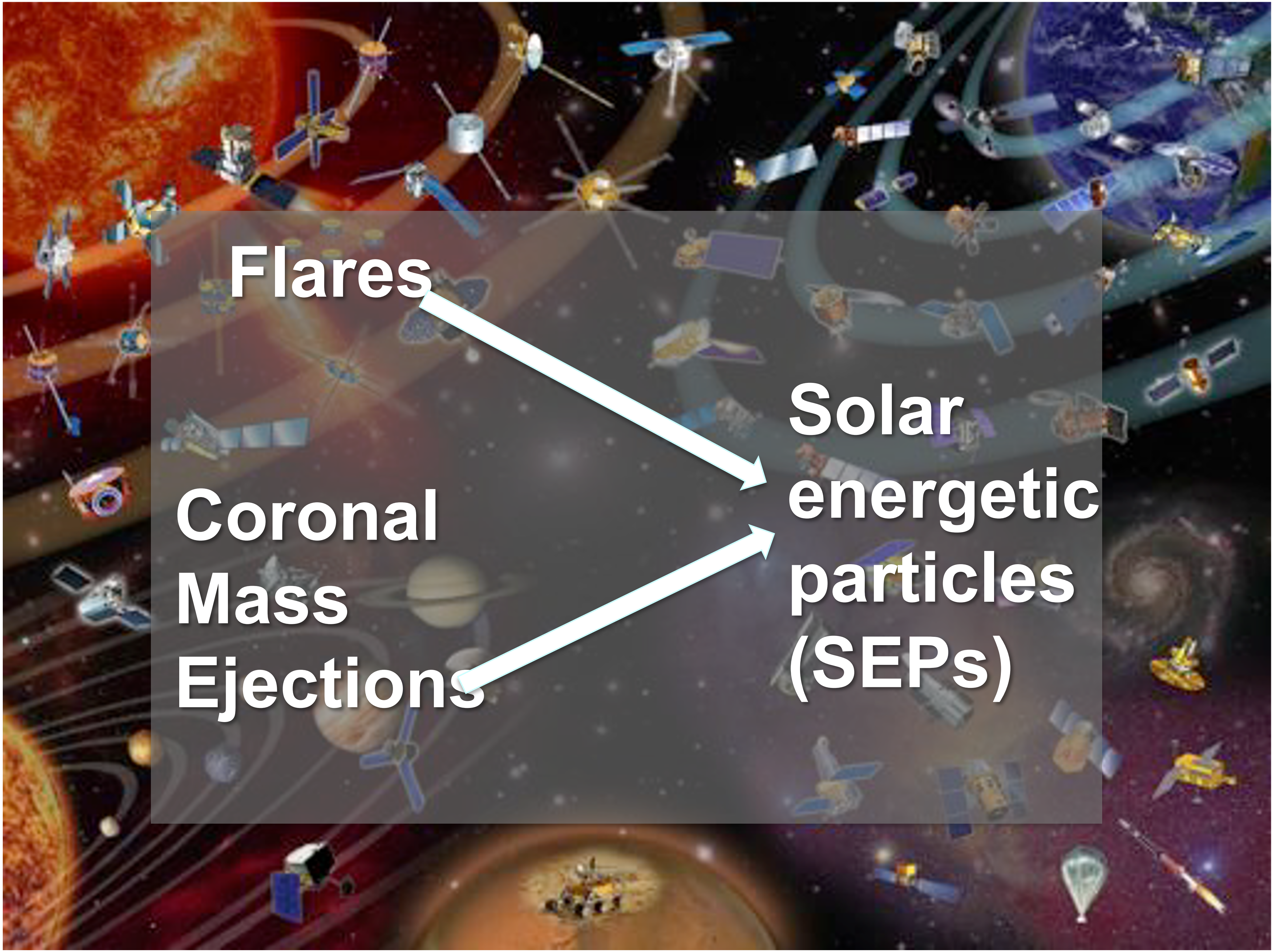
Deep space dangers

Mars explorers will need protection from galactic cosmic radiation, which researchers say would plow into cells like molecular artillery.



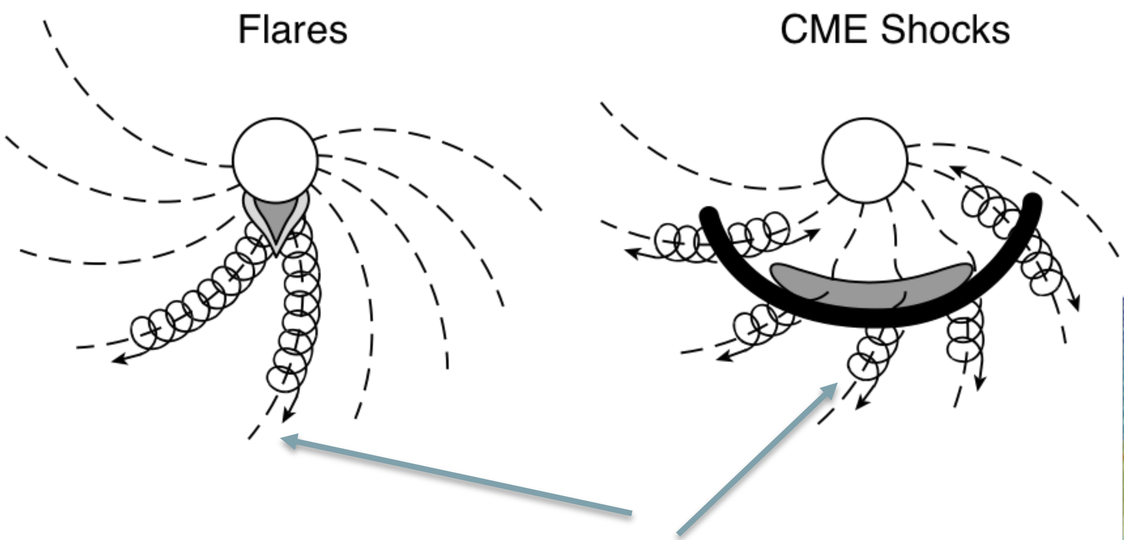
Sources: NASA SOHO solar observatory, NASA Hubble and Chandra images

Graphic by John Bretschneider

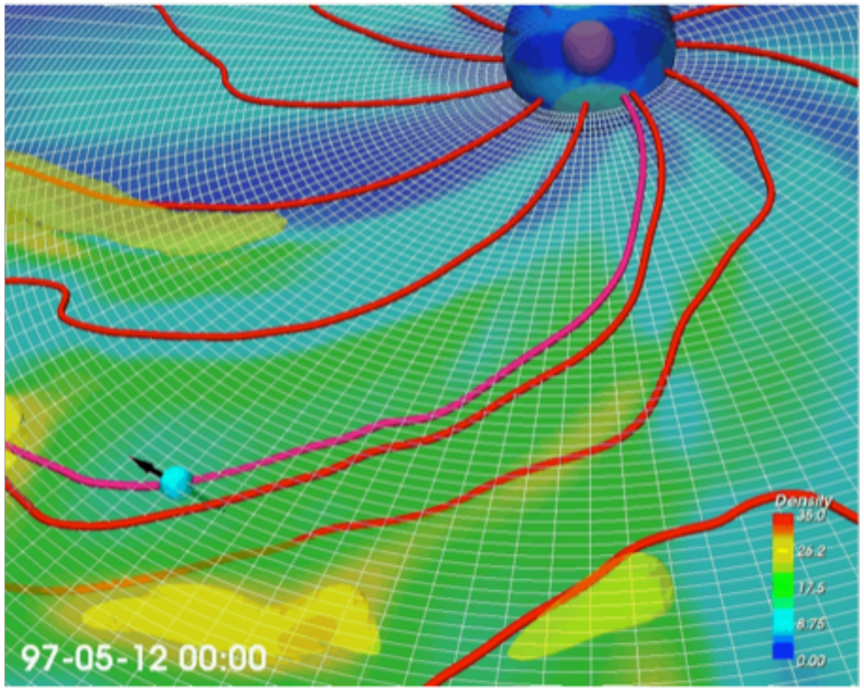

Flares
Coronal Mass Ejections
Solar energetic particles (SEPs)

Flares, CMEs, SEPs and magnetic connectivity

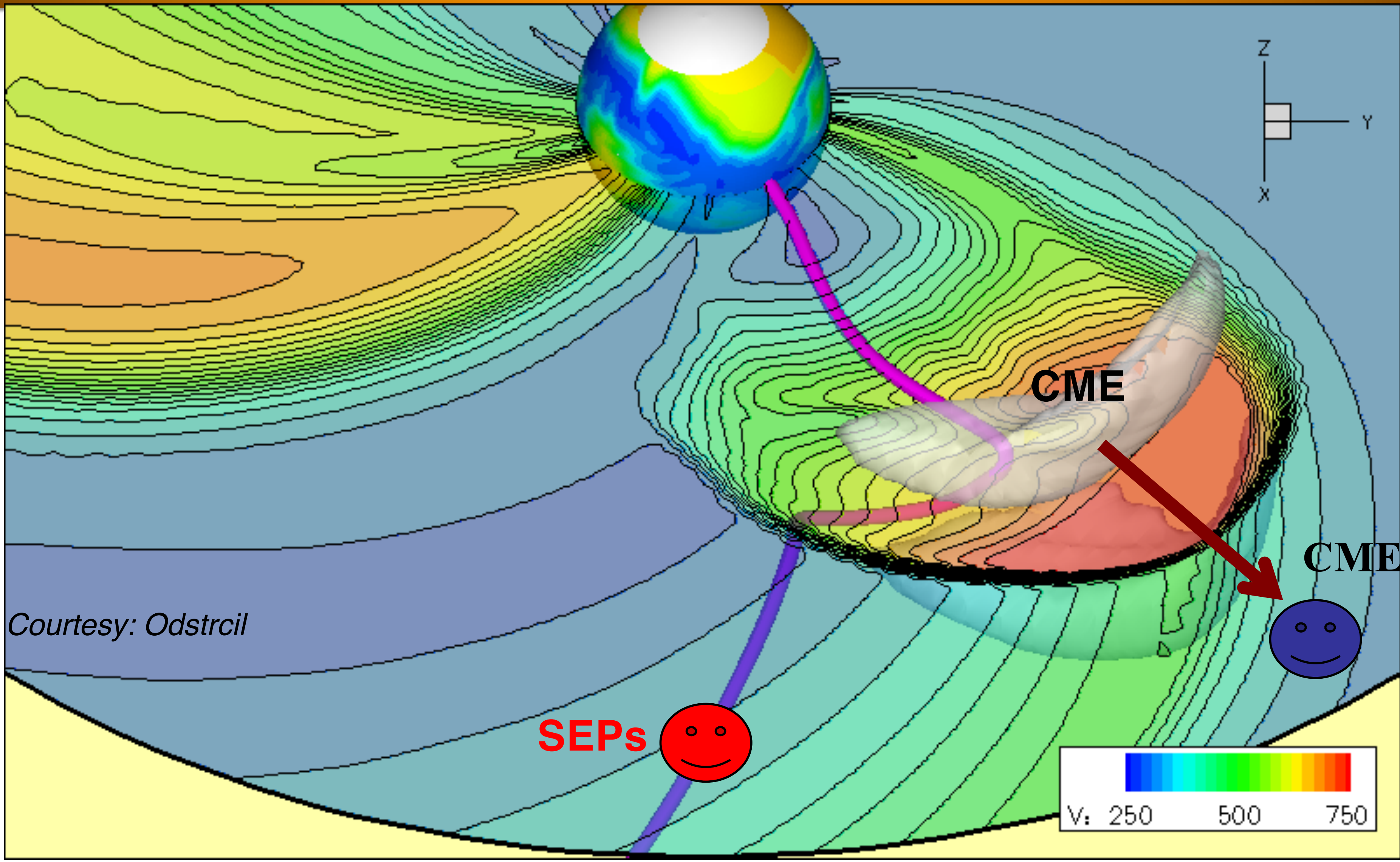
When flares and CME occur, accelerated charged particles start to move along the interplanetary magnetic field lines.



Magnetic connectivity

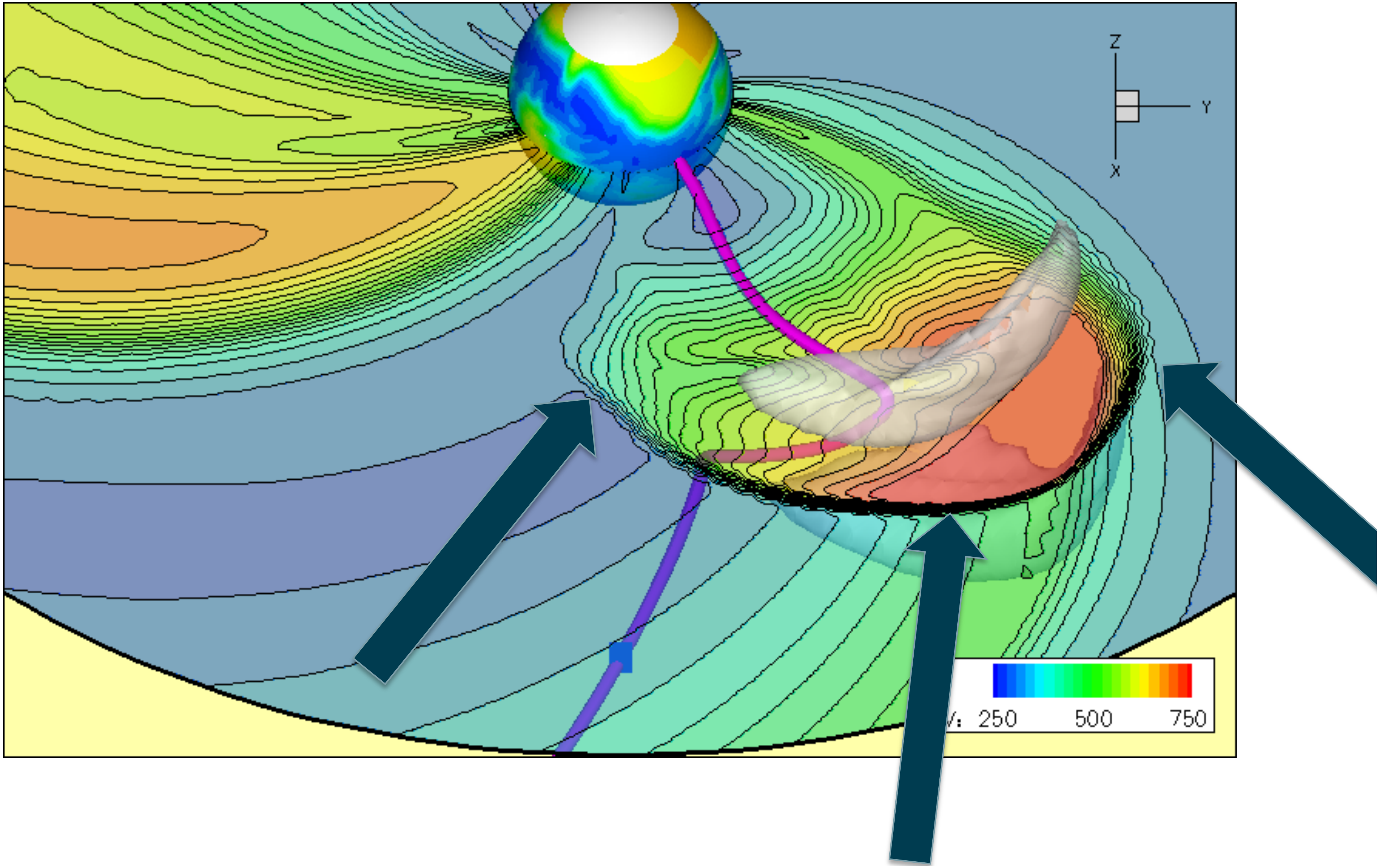


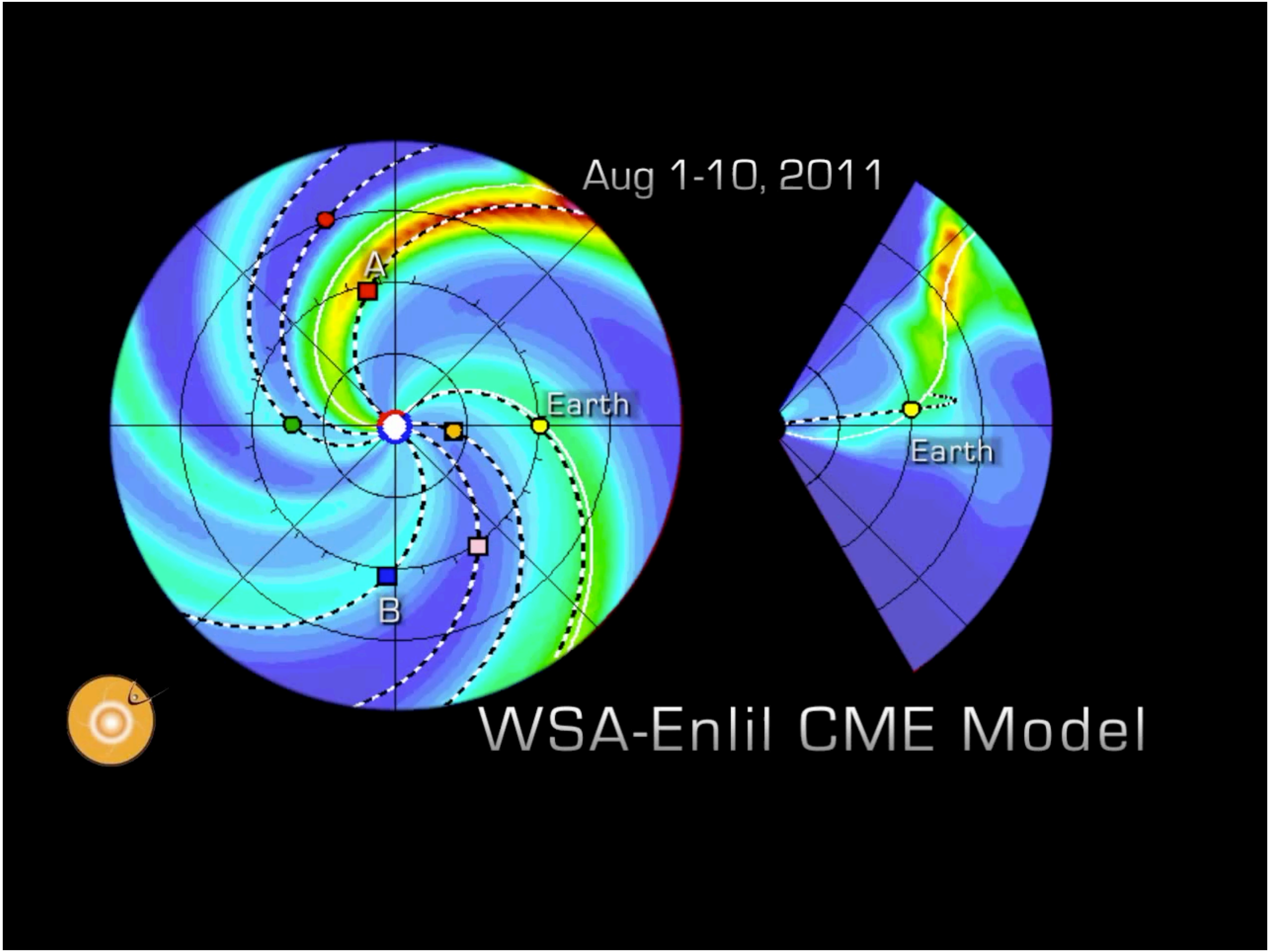
CME and SEP paths may be different



CME: could get deflected, bended, but more or less in the radial direction

CMEs Can Widen Longitudinal Extent of SEP Events

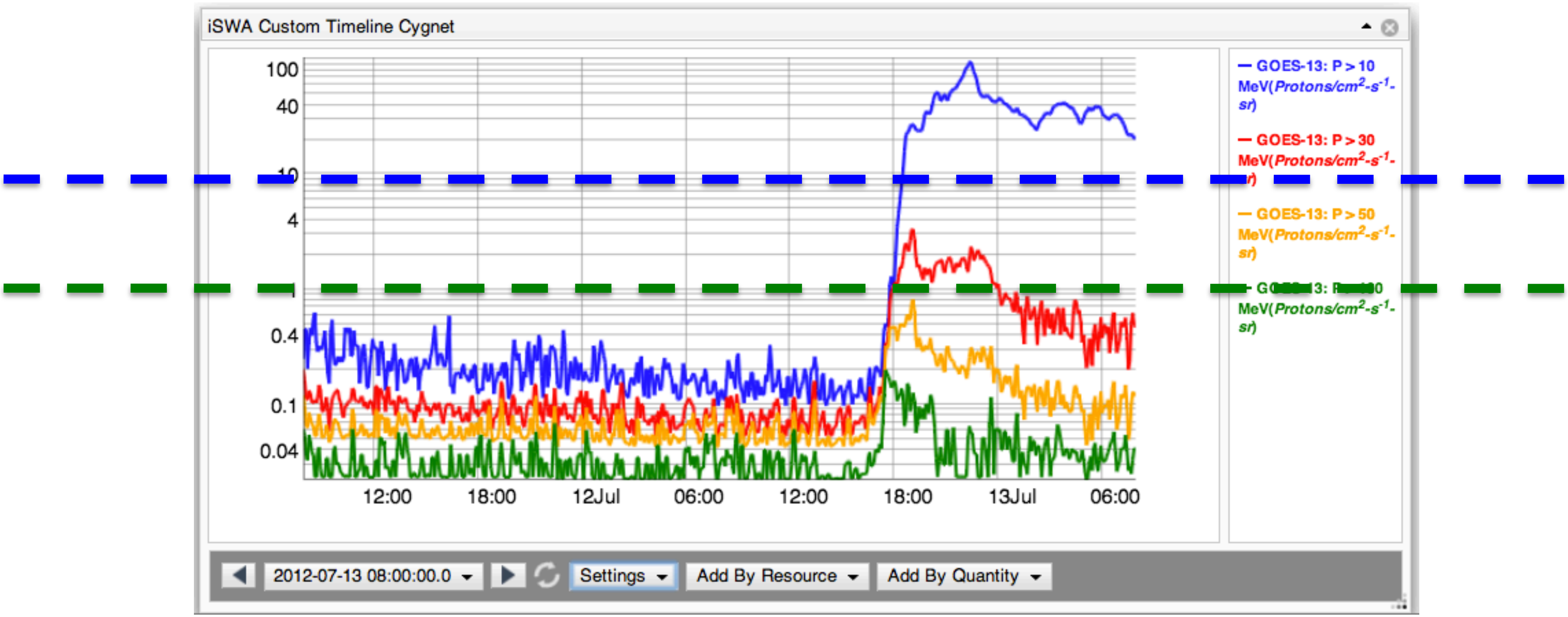



Aug 1-10, 2011
A
B
Earth
Earth
WSA-Enlil CME Model

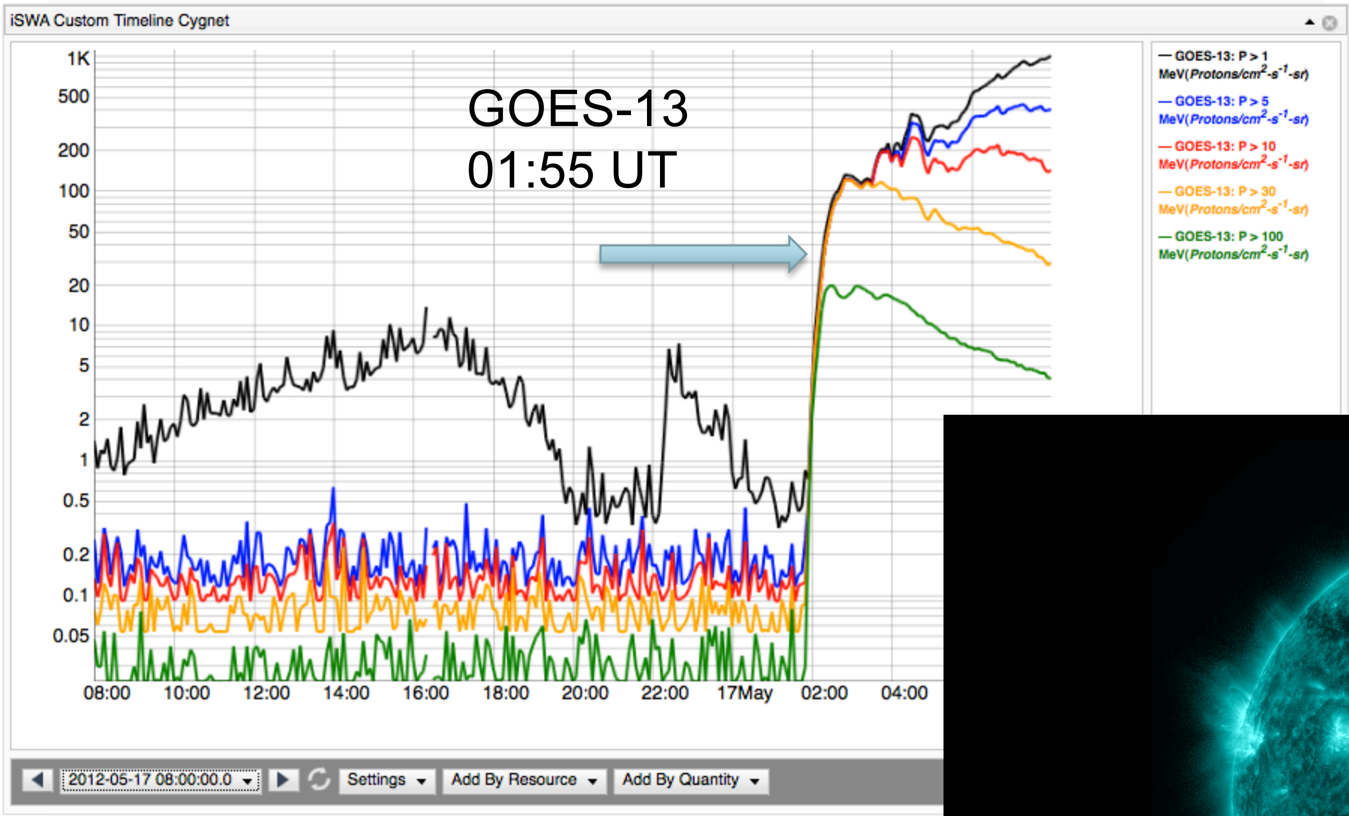
How do we define an SEP Event?

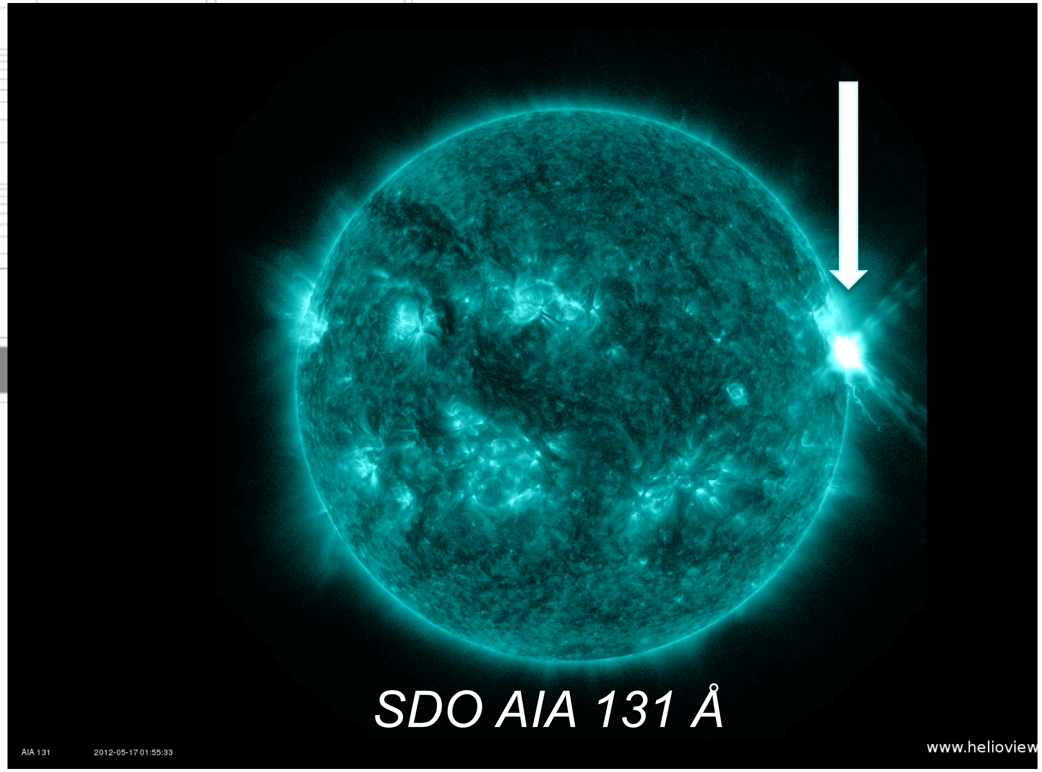
SEP events are defined as:

GOES Proton E > 10 MeV channel > 10 pfu
GOES Proton E > 100 MeV channel > 1 pfu



For Earth – Best Connection is 45-60 degree west





Energetic proton fluxes elevated for >12 hours

How do we monitor SEP Levels

Track the particle flux at different locations.

Units: pfu, pfu/MeV

(1 pfu = 1 **P**article **F**lux **U**nit= 1/cm^2/sec/sr)

- STEREO In-situ Measurements of Particles and CME Transients (IMPACT)
  - Differential energy band; example energy range: 13-100 MeV
- Upstream of Earth with SOHO/COSTEP
  - Differential energy bands; example energy range: 15.8-39.8 MeV
- Geostationary Orbit with GOES
  - Integral flux, example energy ranges: >10 MeV, >100 MeV

Fluence = flux integrated over the entire event - dose

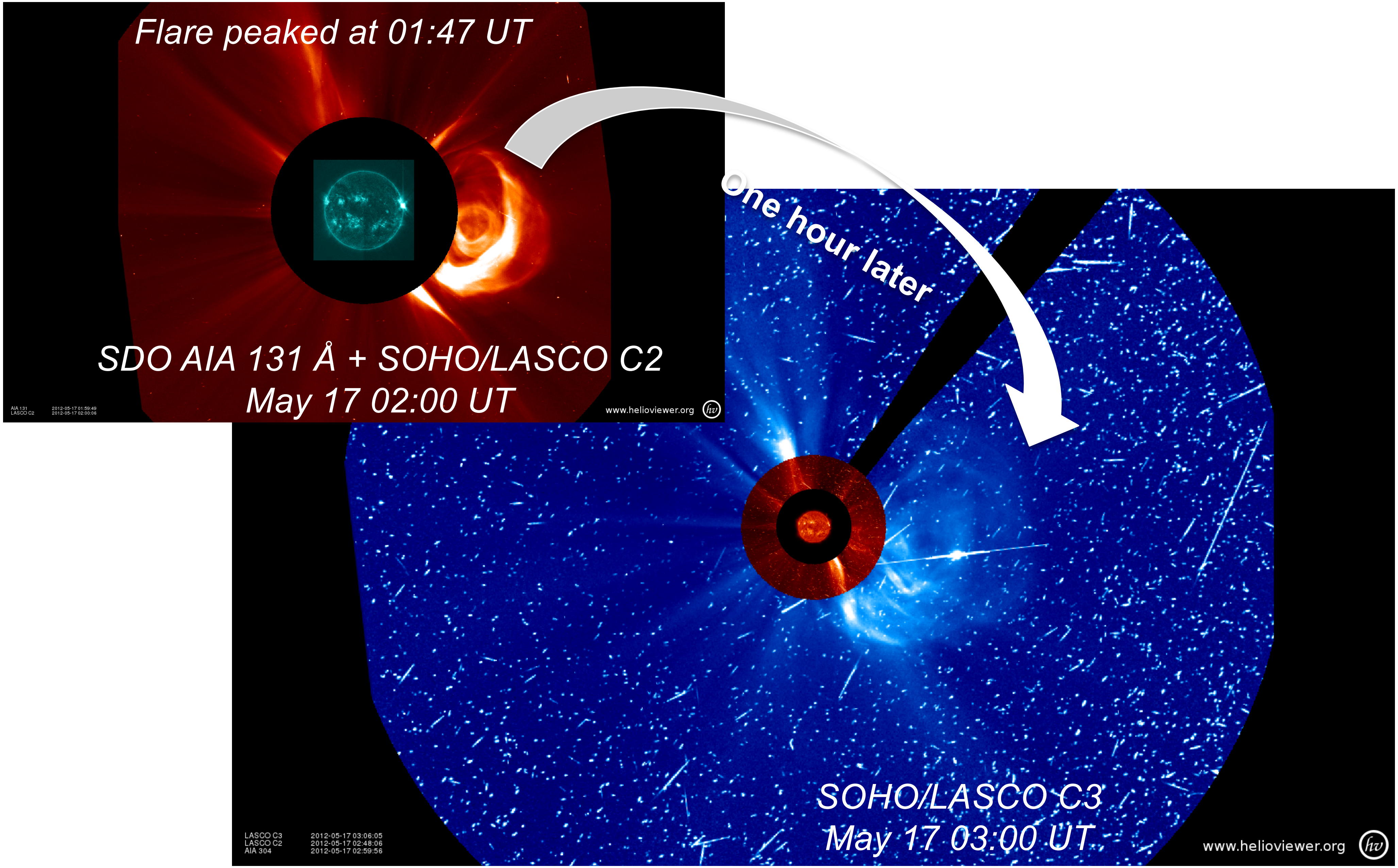
Important for biological effects (flights)

Event magnitudes:

> 10 MeV/nucleon integral fluence: can exceed 10^9 cm^{-2}

> 10 MeV/nucleon peak flux: can exceed 10^5 cm^{-2}s^{-1}

Coronagraph acting as particle detector (SNOW)



NOAA Space Weather Scales

Scale	Description	Effect	**Physical measure** (Flux level of >= 10 MeV particles)	**Average Frequency** (1 cycle = 11 years)
S 5	**Extreme**	**Biological:** Unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** Satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. **Other systems:** Complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	**Severe**	**Biological:** Unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** May experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. **Other systems:** Blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	**Strong**	**Biological:** Radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** Single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. **Other systems:** Degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	**Moderate**	**Biological:** Passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk. **Satellite operations:** Infrequent single-event upsets possible. **Other systems:** Small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S 1	**Minor**	**Biological:** None. **Satellite operations:** None. **Other systems:** Minor impacts on HF radio in the polar regions.	10	50 per cycle

NOAA Space Weather Scales

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
R 5	**Extreme**	**HF Radio:** Complete HF (high frequency) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. **Navigation:** Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 (2 x 10^{-3})	Less than 1 per cycle
R 4	**Severe**	**HF Radio:** HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. **Navigation:** Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	**Strong**	**HF Radio:** Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. **Navigation:** Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R 2	**Moderate**	**HF Radio:** Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes. **Navigation:** Degradation of low-frequency navigation signals for tens of minutes.	M5 (5 x 10^{-5})	350 per cycle (300 days per cycle)
R 1	**Minor**	**HF Radio:** Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact. **Navigation:** Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

Human Safety in Space

- GCR
- **SEP**

Johnson Space Center Space Radiation Analysis Group (SRAG)

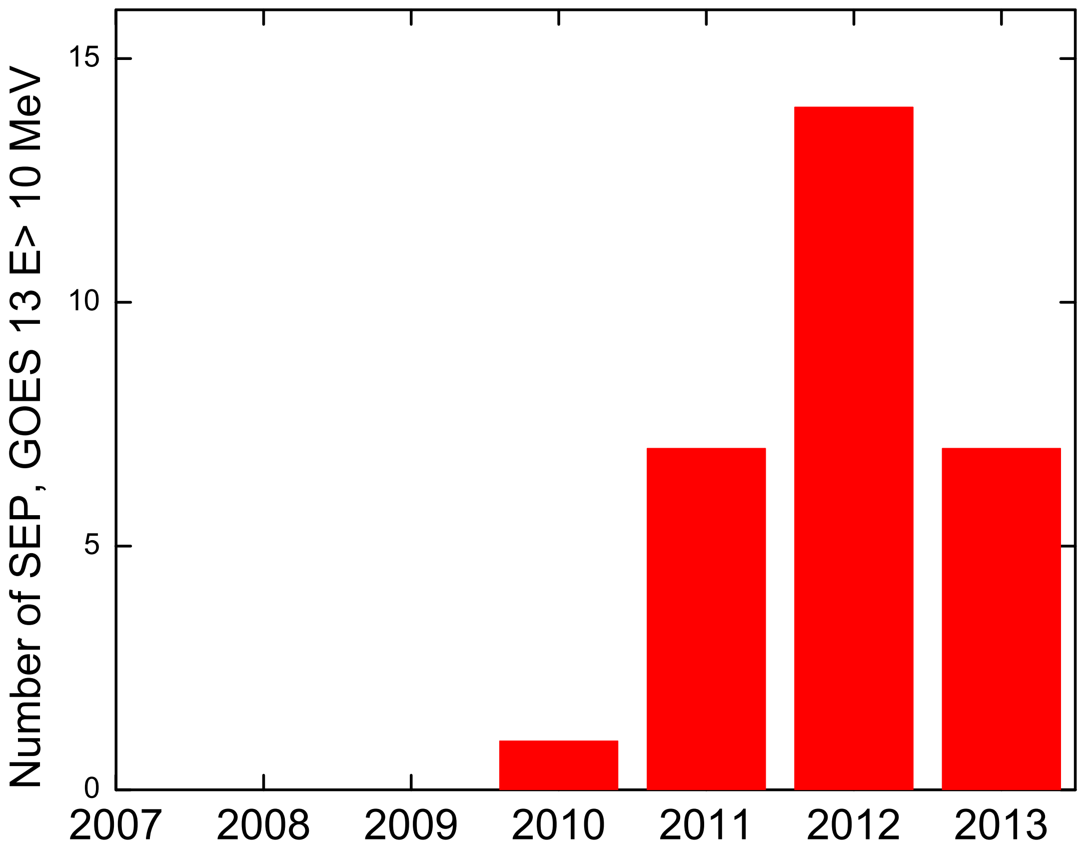
Limit: **the > 100 MeV flux exceeding 1pfu**

(1 pfu = 1 particle flux unit= 1/cm^2/sec/sr)

- All clear (EVA – extravehicular activity)

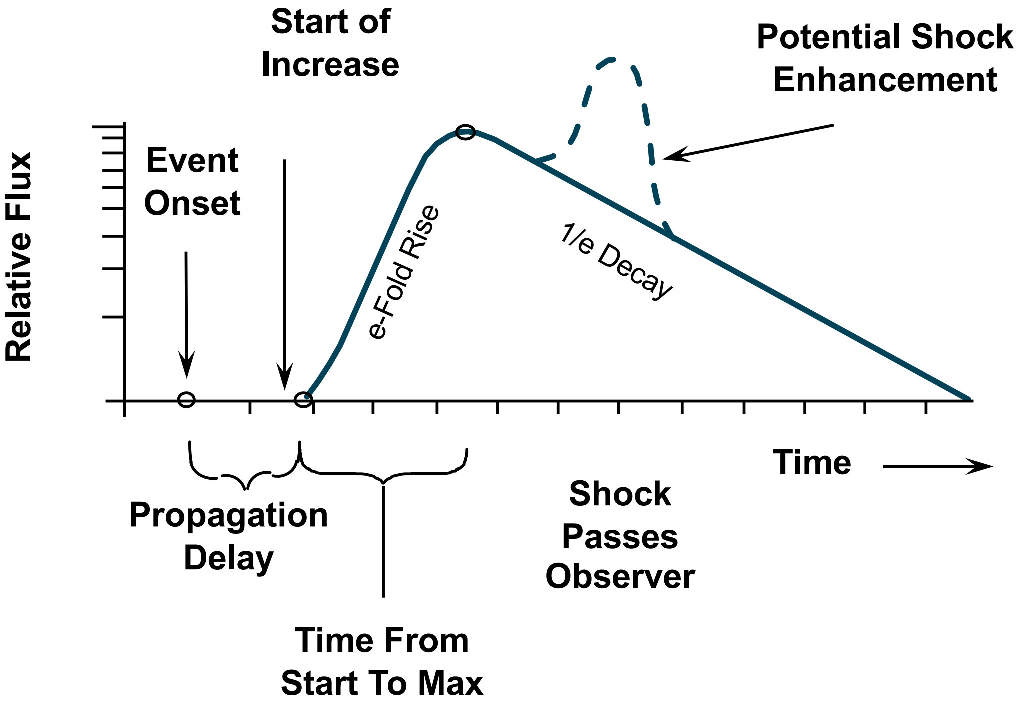
How Often Do SEP Events Occur?

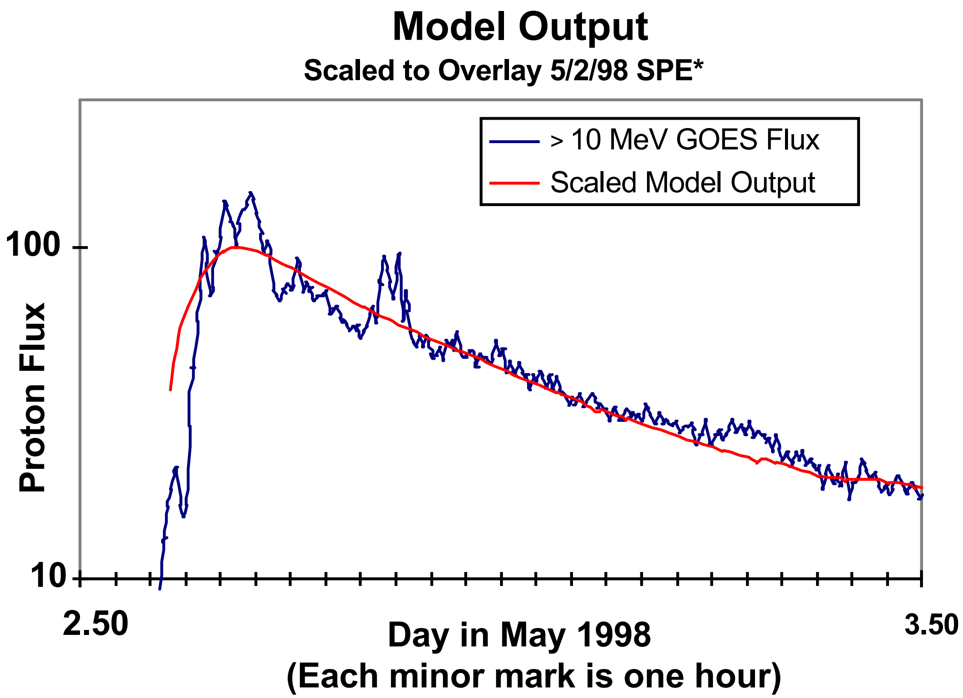
SEP event detections in the near-Earth environment (GOES 13, Proton E > 10 MeV channel)



2007-2009: Zero Events
Solar Minimum Indeed!

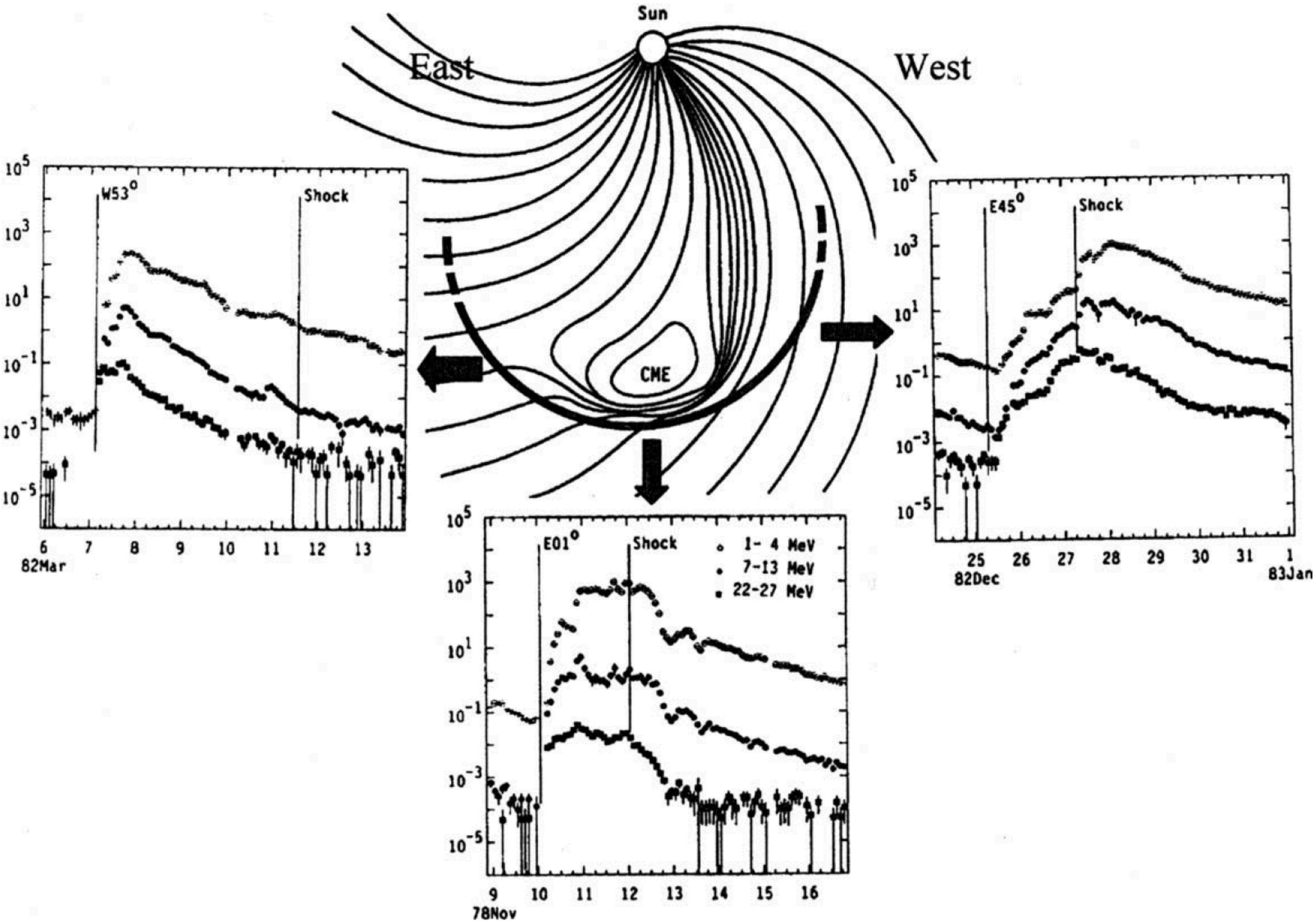
Measure Energetic Particle Flux





Peak flux during an SPE may be two to five orders of magnitude greater than background, within hours of the event onset

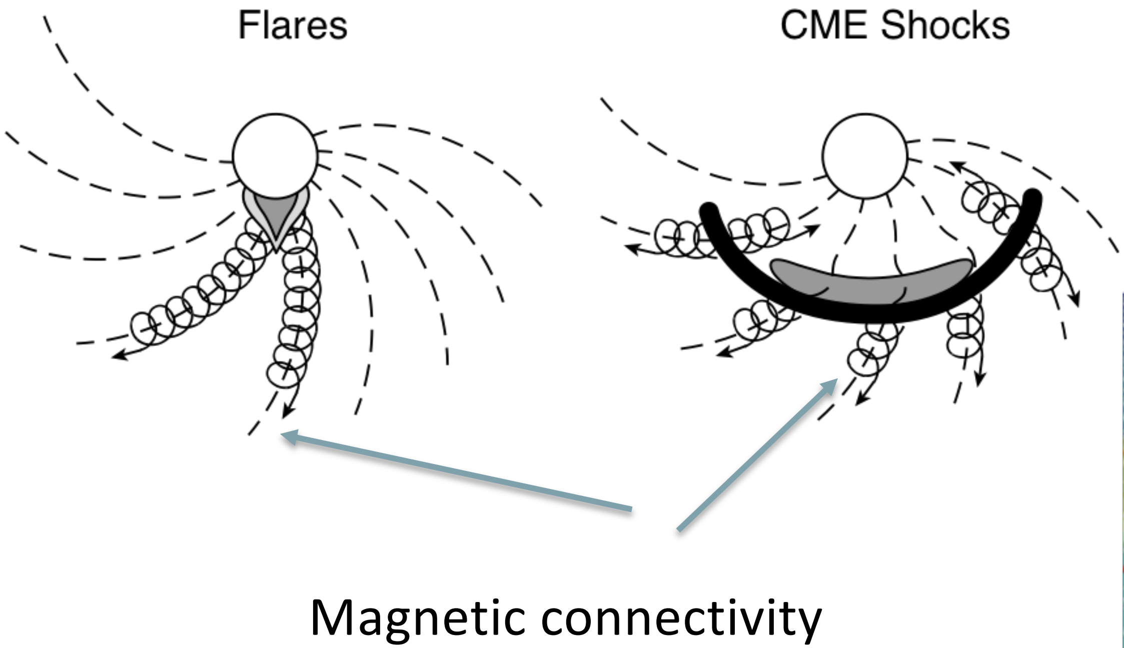
*This was not a fit to the 5/2/98 event.
The event is used only to illustrate results.

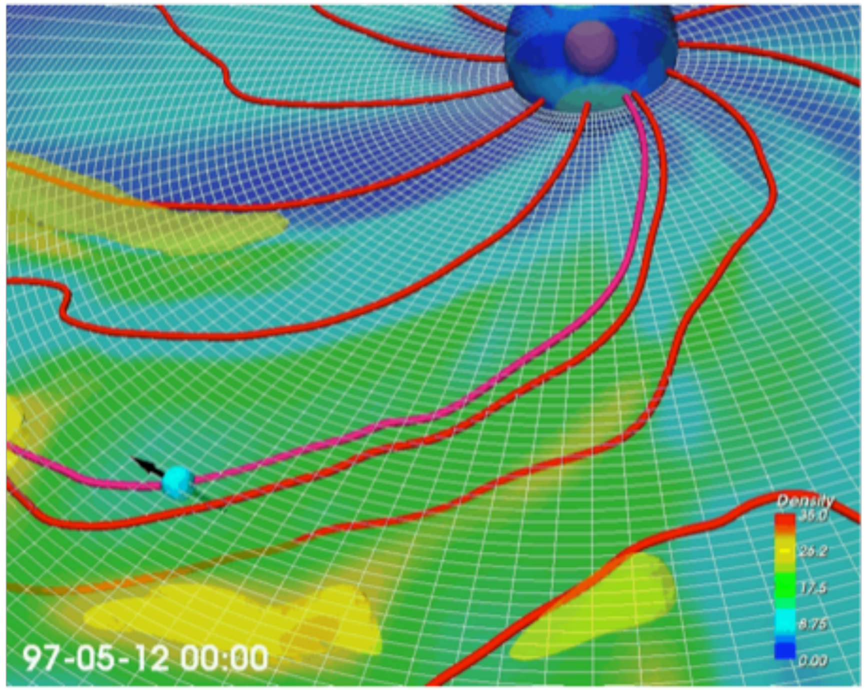


Intensity-time profiles for protons are shown for observers viewing a CME from three different longitudes (Cane et al., 1988; Reames, 1999).

Flares, CMEs, SEPs and magnetic connectivity

When flares and CME occur, accelerated charged particles start to move along the interplanetary magnetic field lines.

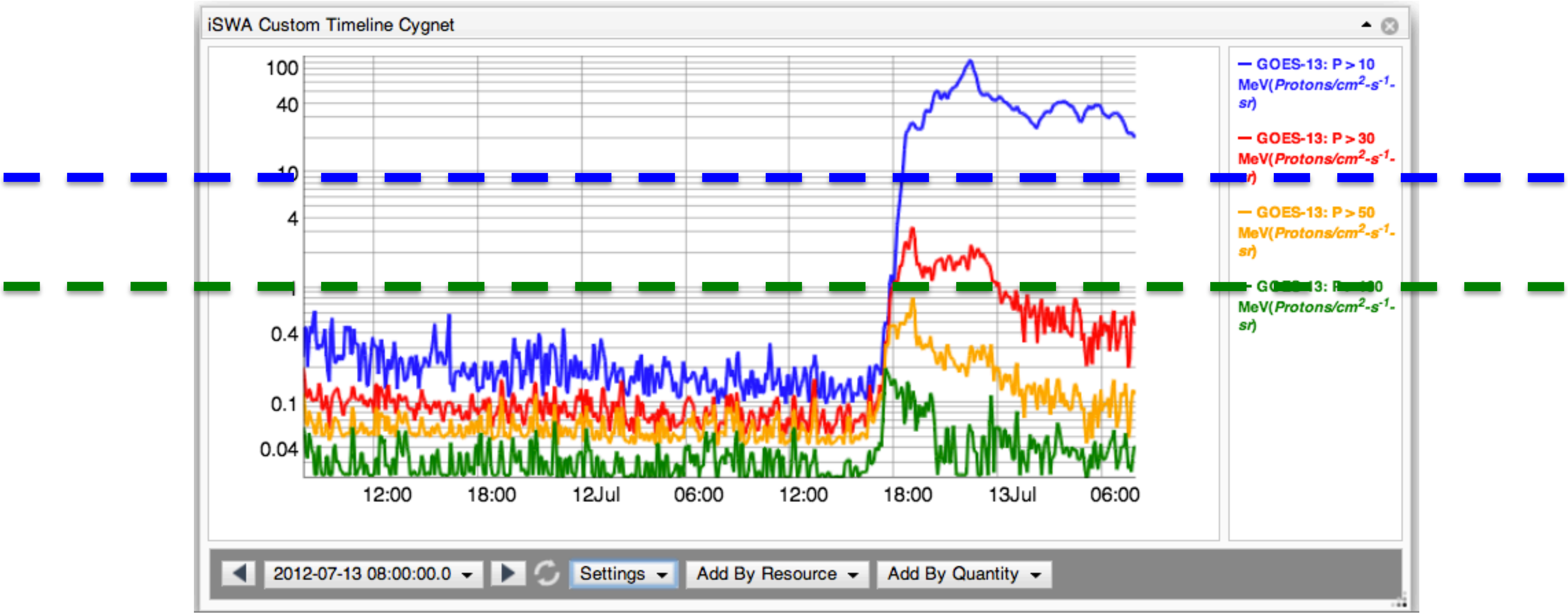




How do we define an SEP Event?

SEP event at GEO

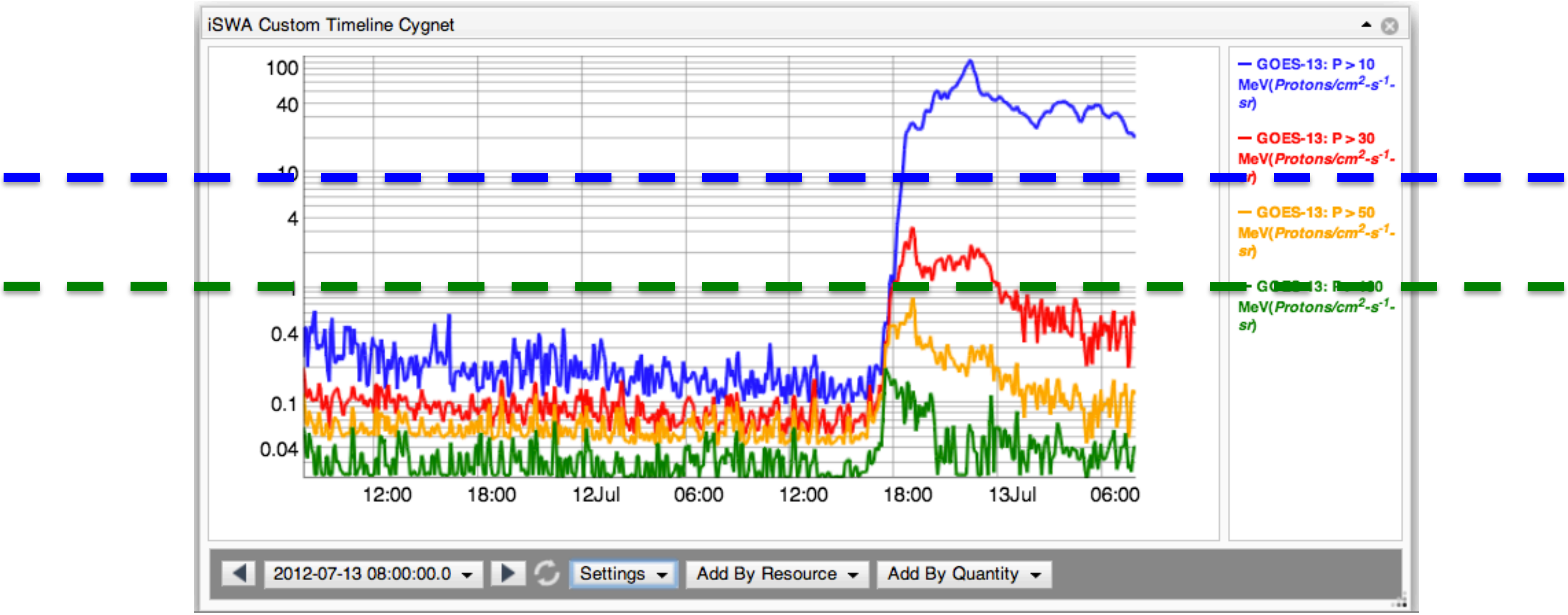
GOES Proton E > 10 MeV channel > 100 pfu !



How do we define an SEP Event?

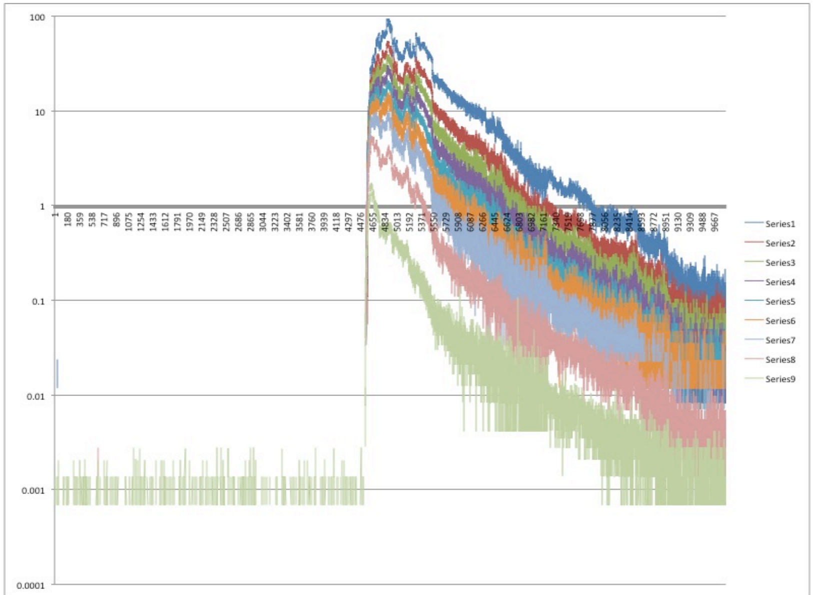
SEP event at GEO

GOES Proton E > 10 MeV channel > 100 pfu !
even E > 30 MeV channel > 3 pfu



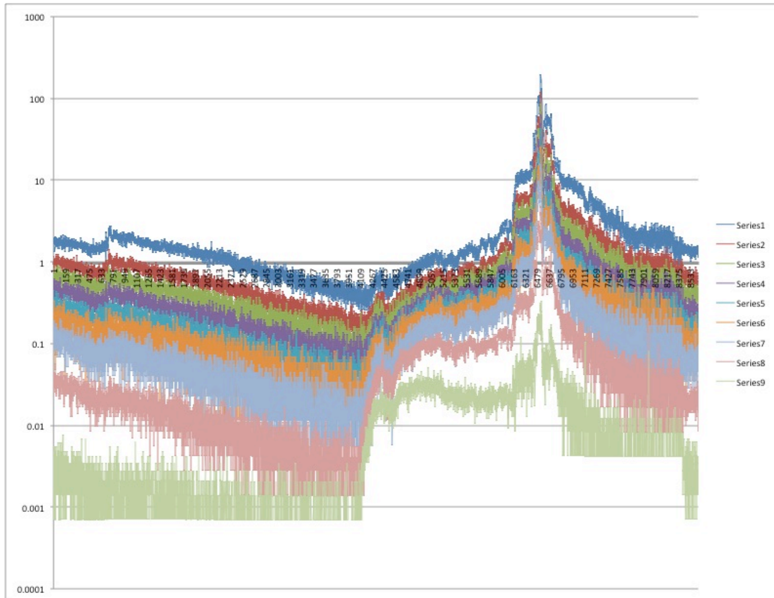
… but: SOHO > 15.8 MeV proton channels 0.1 pfu

Profile Shapes of SEP Fluxes



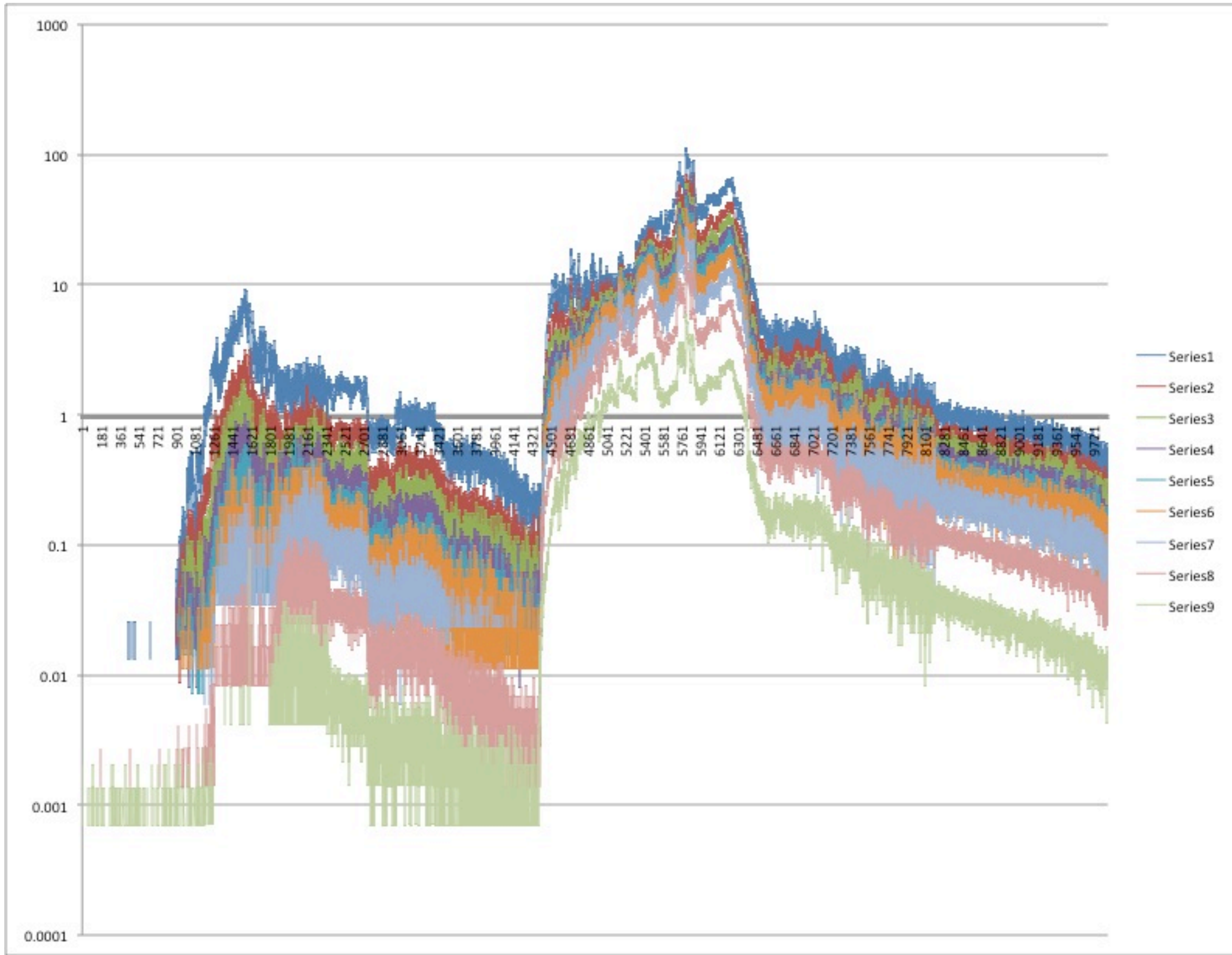
Impulsive SEP event - The peak at the beginning due to flare, all off – indicates how well connected you are to the source (timing)

Gradual SEP event - Slow rise, then peak when the ICME passes the spacecraft



Profile Shapes of SEP Fluxes

The "multiple event weirdness"



What causes strong SEP events?

Complexity of AR

-Most young, more compact

Magnetic connectivity of AR

-About ~50% are well connected

Magnitude of flare

- Average X3.8, but as low as M7.1
- Long duration

Magnitude of CME

- Range of speeds (~2,000 km/s average, but four events <1,500 km/s)

Table 1 GLE events and associated flares and CMEs (adopted from Gopalswamy et al. 2010)

GLE				Flare		CME	
Onset			Max	GOES		POS speed (km/s)	Width (degs)
ID	Date	Time[a]	Int (%)[a]	Class	Location		
55	1997/11/06	12:10	11.3	X9.4	S18W63	1556	360
56	1998/05/02	13:55	6.8	X1.1	S15W15	938	360
57	1998/05/06	08:25	4.2	X2.7	S11W66	1099	190
58	1998/08/24	22:50	3.3	X1.0	N35E09	–[b]	–[b]
59	2000/07/14	10:30	29.3	X5.7	N22W07	1674	360
60	2001/04/15	14:00	56.7	X14	S20W85	1199	167
61	2001/04/18	02:35	13.8	C2.2	S20W116	2465	360
62	2001/11/04	17:00	3.3	X1.0	N06W18	1810	360
63	2001/12/26	05:30	7.2	M7.1	N05W54	1446	>212
64	2002/08/24	01:18	5.1	X3.1	S02W81	1913	360
65	2003/10/28	11:22	12.4	X17	S18E18	2459	360
66	2003/10/29	21:30	8.1	X10	S18W04	2029	360
67	2003/11/02	17:30	7.0	X8.3	S18W57	2598	360
68	2005/01/17	09:55	3.0	X3.8	N14W25	2547	360
69	2005/01/20	06:51	277.3	X7.1	N14W61	3242[c]	360
70	2006/12/13	02:45	92.3	X3.4	S06W23	1774	360

[a] According to the Oulu Neutron Monitor
[b] No SOHO LASCO data
[c] From Gopalswamy et al. (2010). There are different estimates (see Grechnev et al. 2008)

Nitta et al. 2012

Gopalswamy et al. 2012, Li et al. 2012, Mewaldt et al. 20

Flares, CMEs, and the acceleration of solar energetic particle (SEP) events

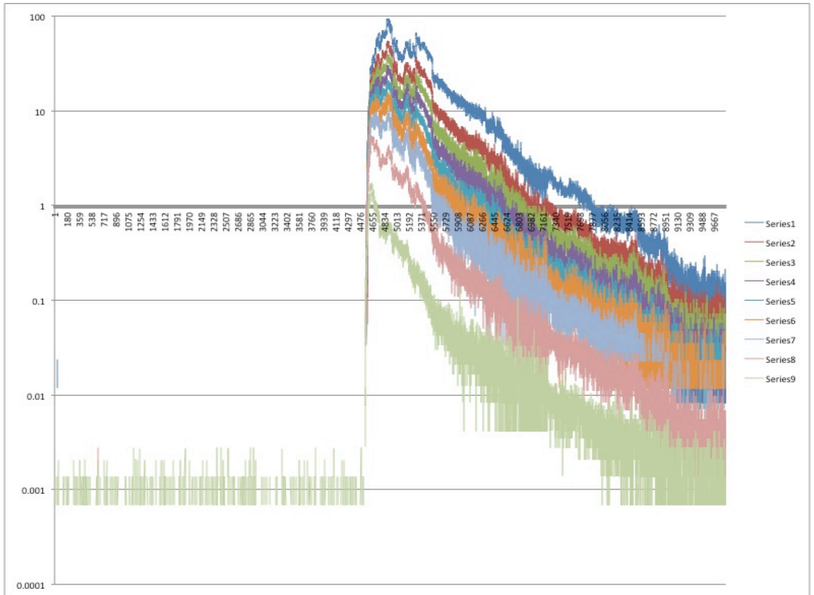
A common idea since 1990 (cf. Reames 1999 SSR 90, 413) :

- numerous small (« impulsive ») SEP are flare-accelerated particles (magnetic reconnection)
- ALL large (« gradual ») SEP events are accelerated at CME shocks

From the report *Managing Space Radiation Risk in the New Era of Space Exploration* (Committee on the Evaluation of Radiation Shielding for Space Exploration, Nat. Res. Council, USA):

*In gradual SPEs, which have large intensities at energies relevant to astronaut radiation safety, **shocks driven by fast CMEs are the dominant accelerator***

Profile Shapes of SEP Fluxes



Impulsive SEP event - The peak at the beginning due to flare, all off – indicates how well connected you are to the source (timing)

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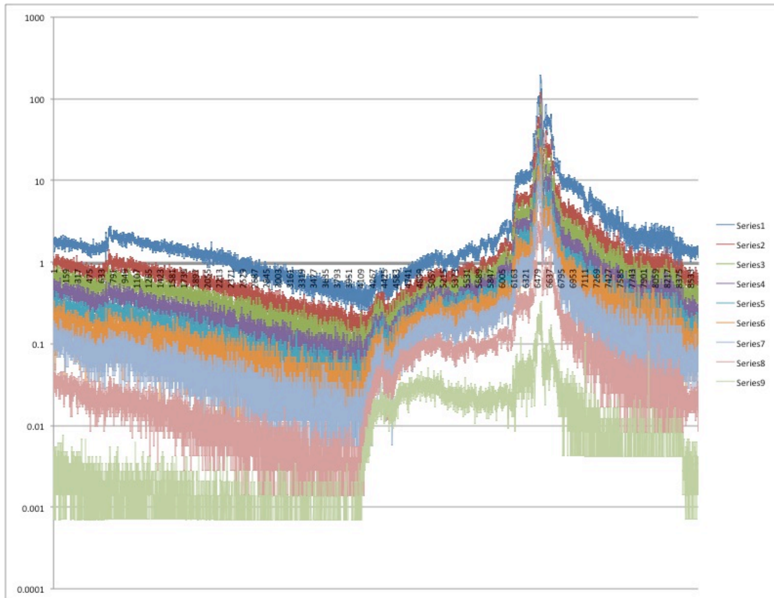
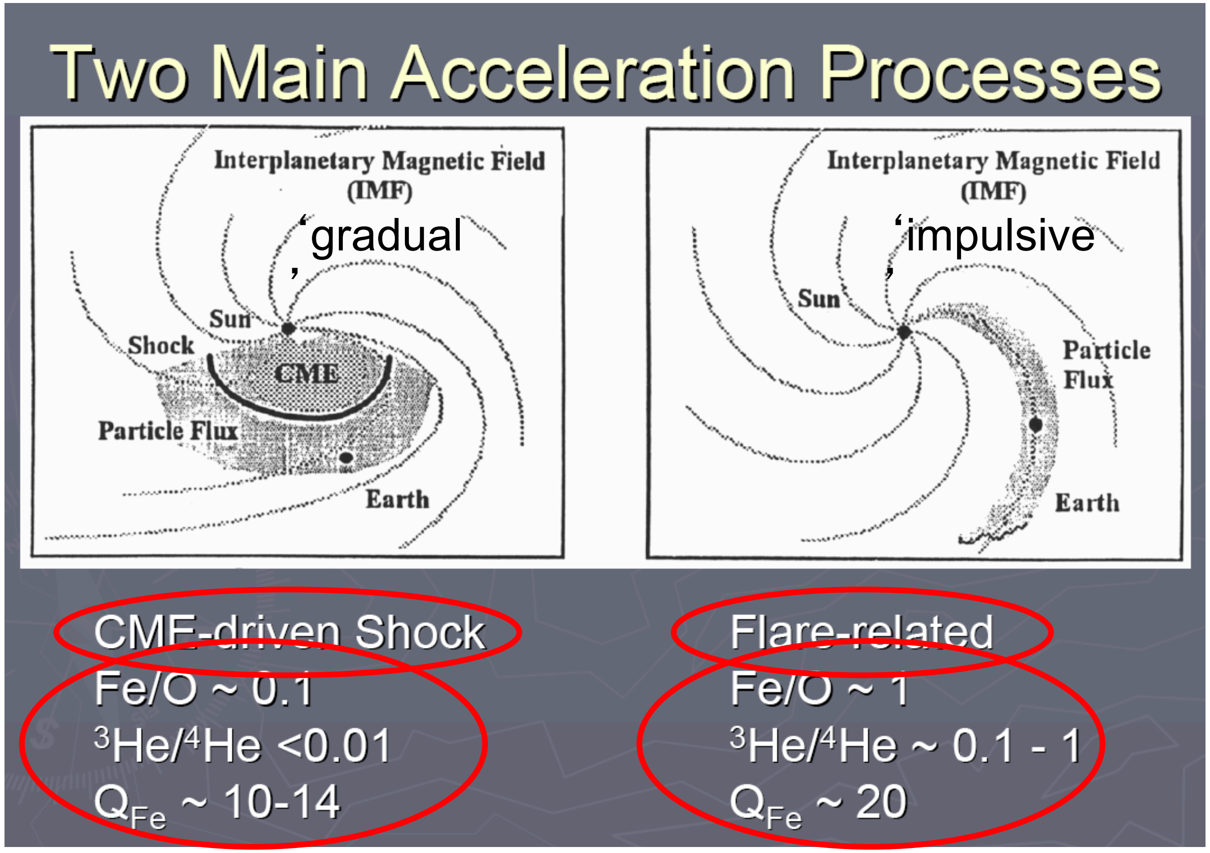


Flares, CMEs, and the acceleration of SEP events: the view of the 1990s

- Reames 1999 SSR 90, 413 : claims a neat separation of “impulsive” (flare-accelerated) and “gradual” (CME shock accelerated) SEP events :

C.M.S. Cohen, 2003 ICRC
Rapporteur paper

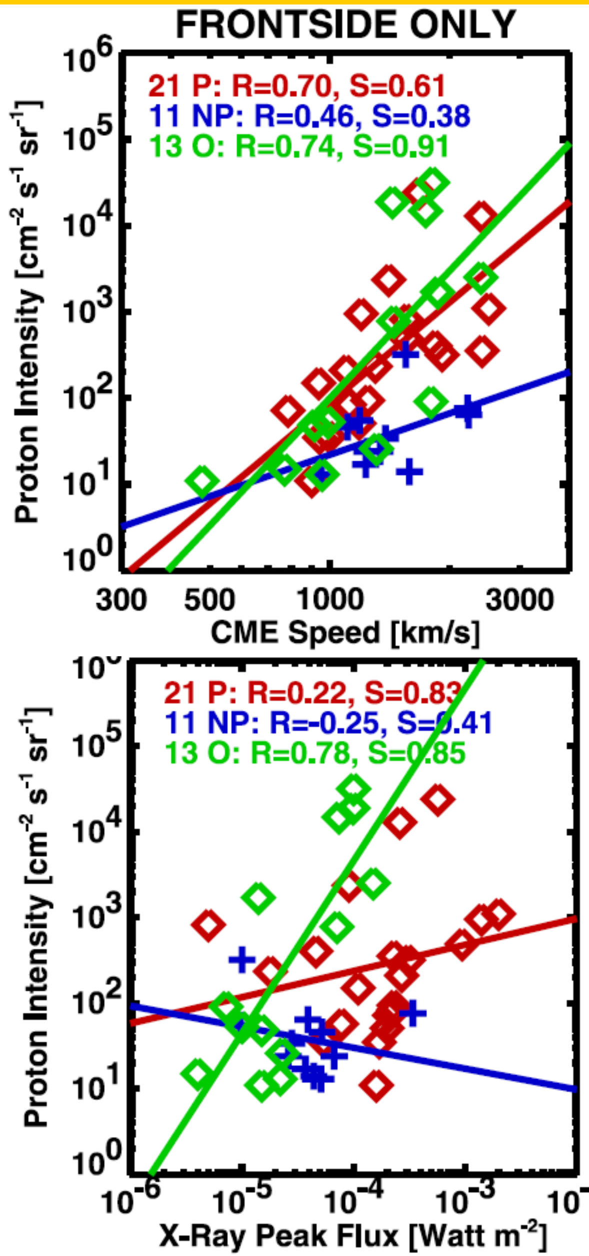


But :

- flares/CMEs in both types of events
- abundances and charge states are energy-dependent

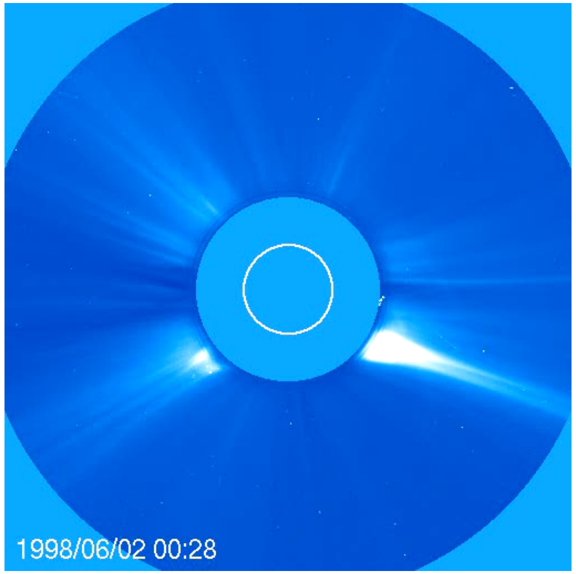
Flares, CMEs, SEP – statistical relationship

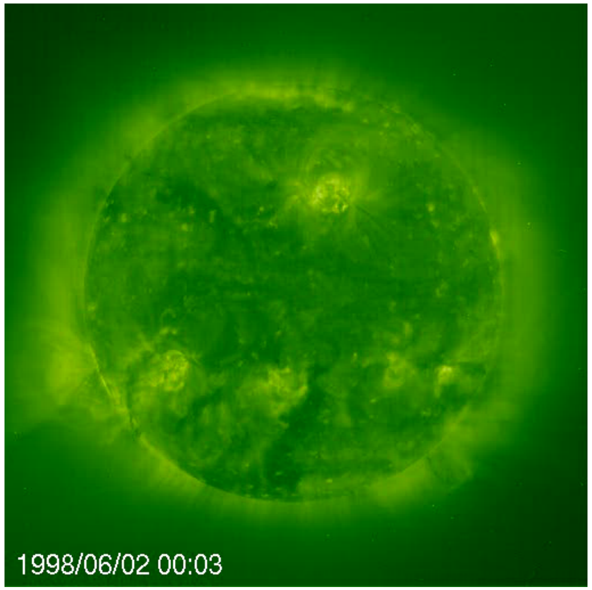
- All large SEP events (GOES) are accompanied by fast/broad CMEs and flares
- There is some correlation - with considerable scatter - between SEP intensity (p>10 MeV) and
  - CME speed
  - Soft X-ray peak flux



Gopalswamy et al. 2004 JGR 109, A12105

Do fast CMEs produce SEP in the absence of flares?

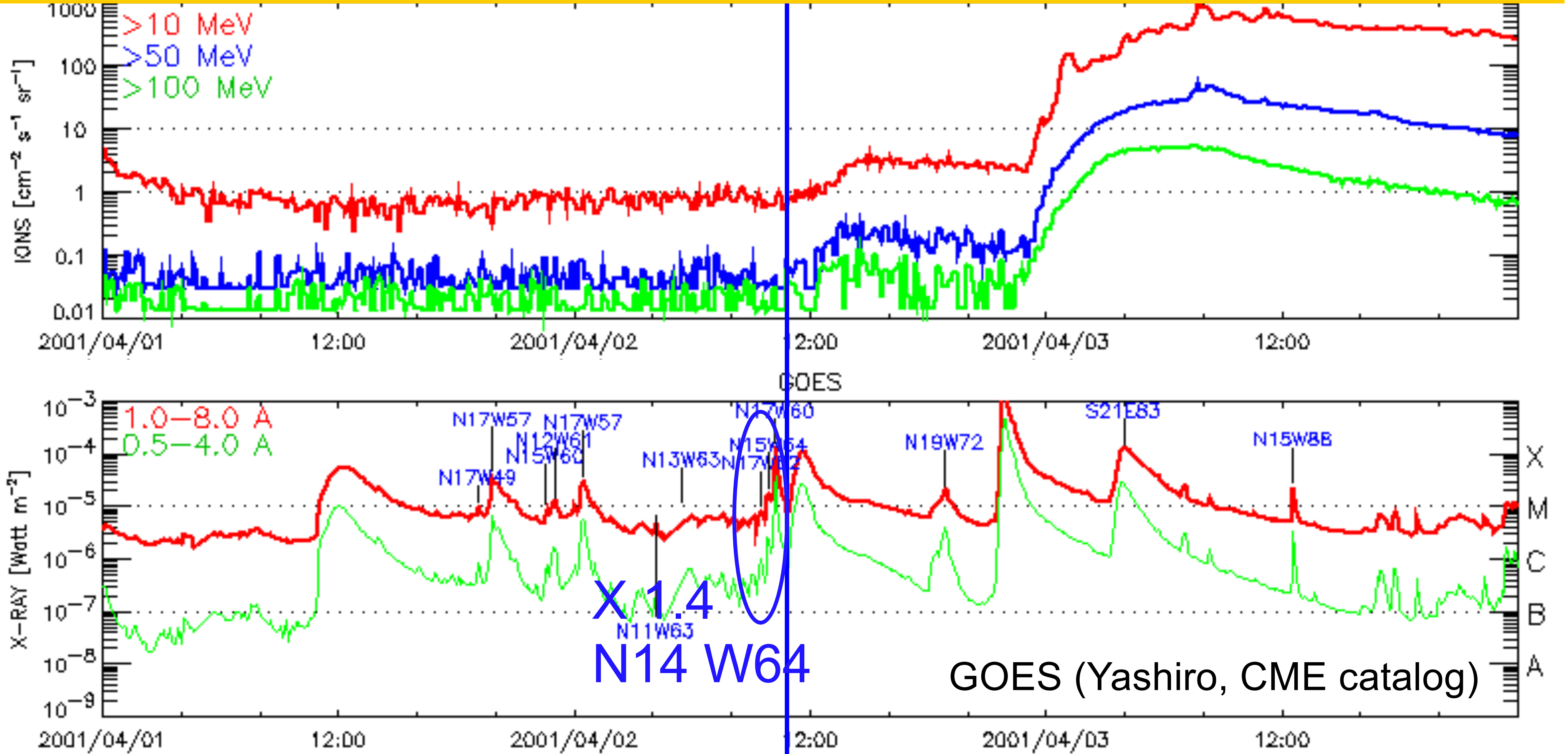


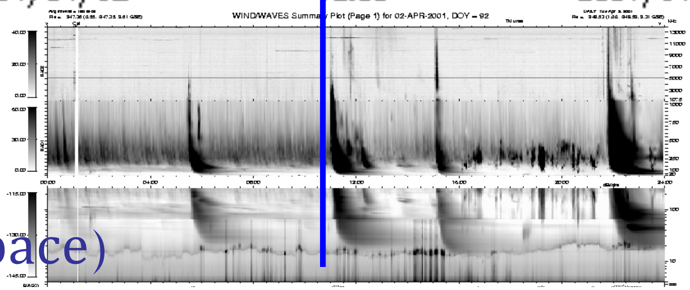


Marqué et al. 2006 ApJ 642, 1222

- Attempt to isolate pure CME-shock-events :
  - Fast (υ>700 km/s) west-limb CME (SoHO): likely to drive shock.
  - EUV manifestations on disk, but no metric radio emission: no evidence for particle acceleration related to a flare (3 events 1996-98).
- SEP from the CME shock ?
  - None detected at GOES.
  - SoHO/COSTEP & ACE/EPAM: weak or 0 (deka-MeV protons, hecto-keV electrons).
- *Indication that CME shock alone is NOT an efficient SEP accelerator*

Do ‘confined’ flares produce SEP in the absence of CMEs ?





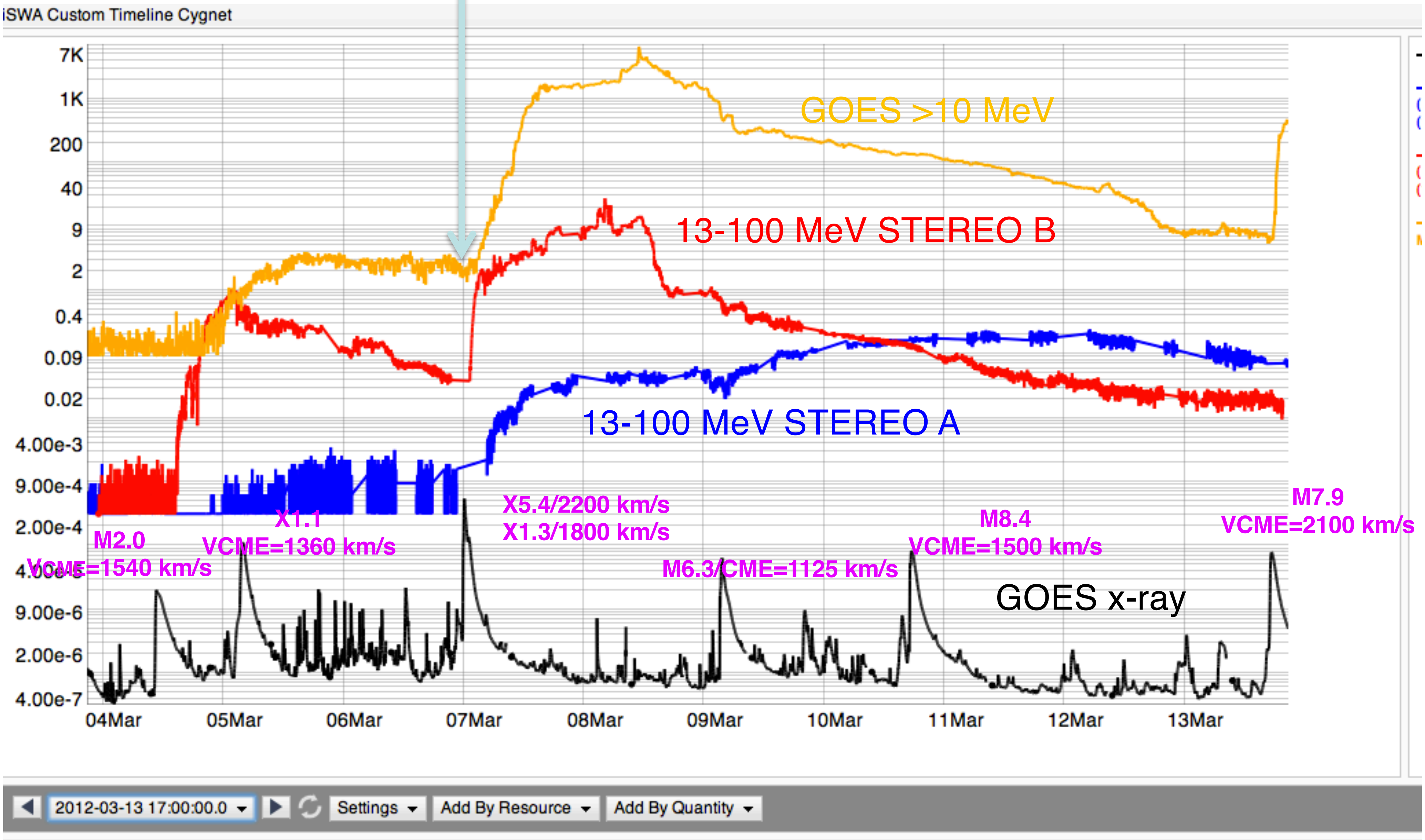
WIND/WAVES

Confined flare:

- no SEP!
- no type III (no e→IP space)

SEP: proton radiation

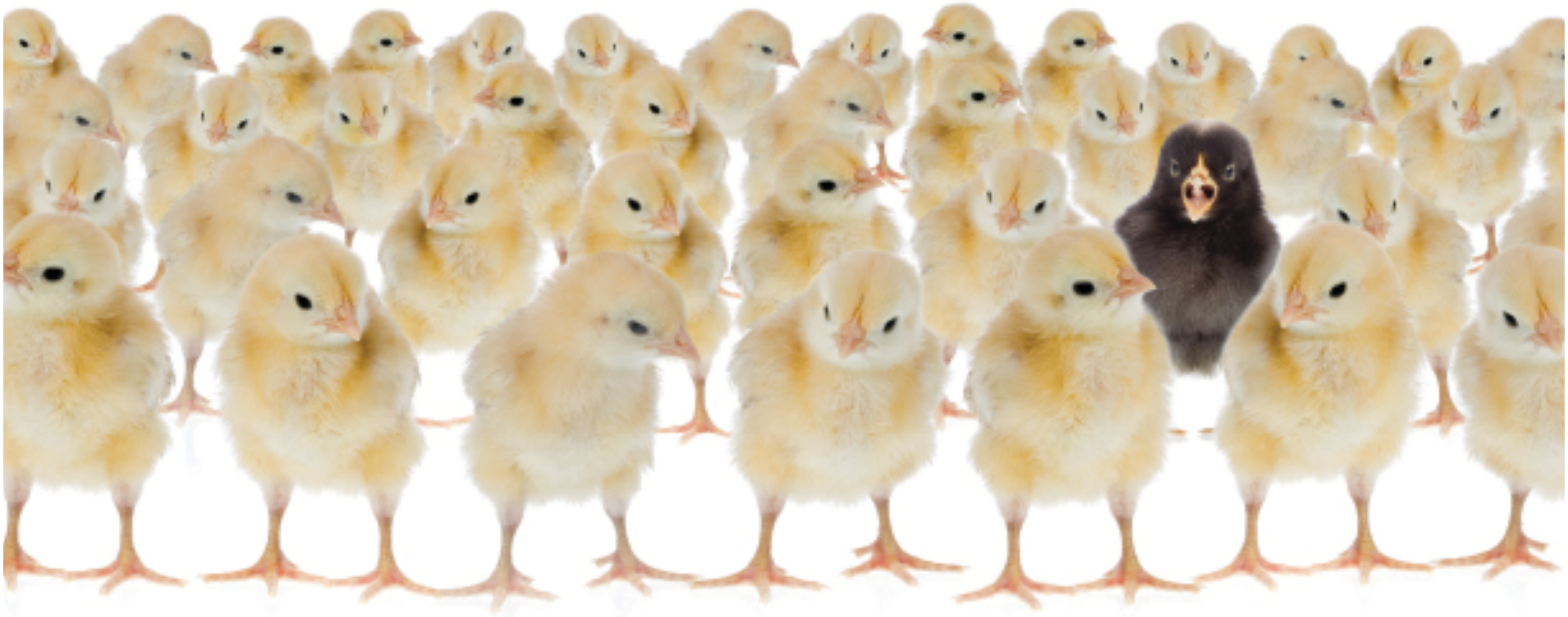
Both the CME(s) and flare(s) contribute to the SEP enhancement

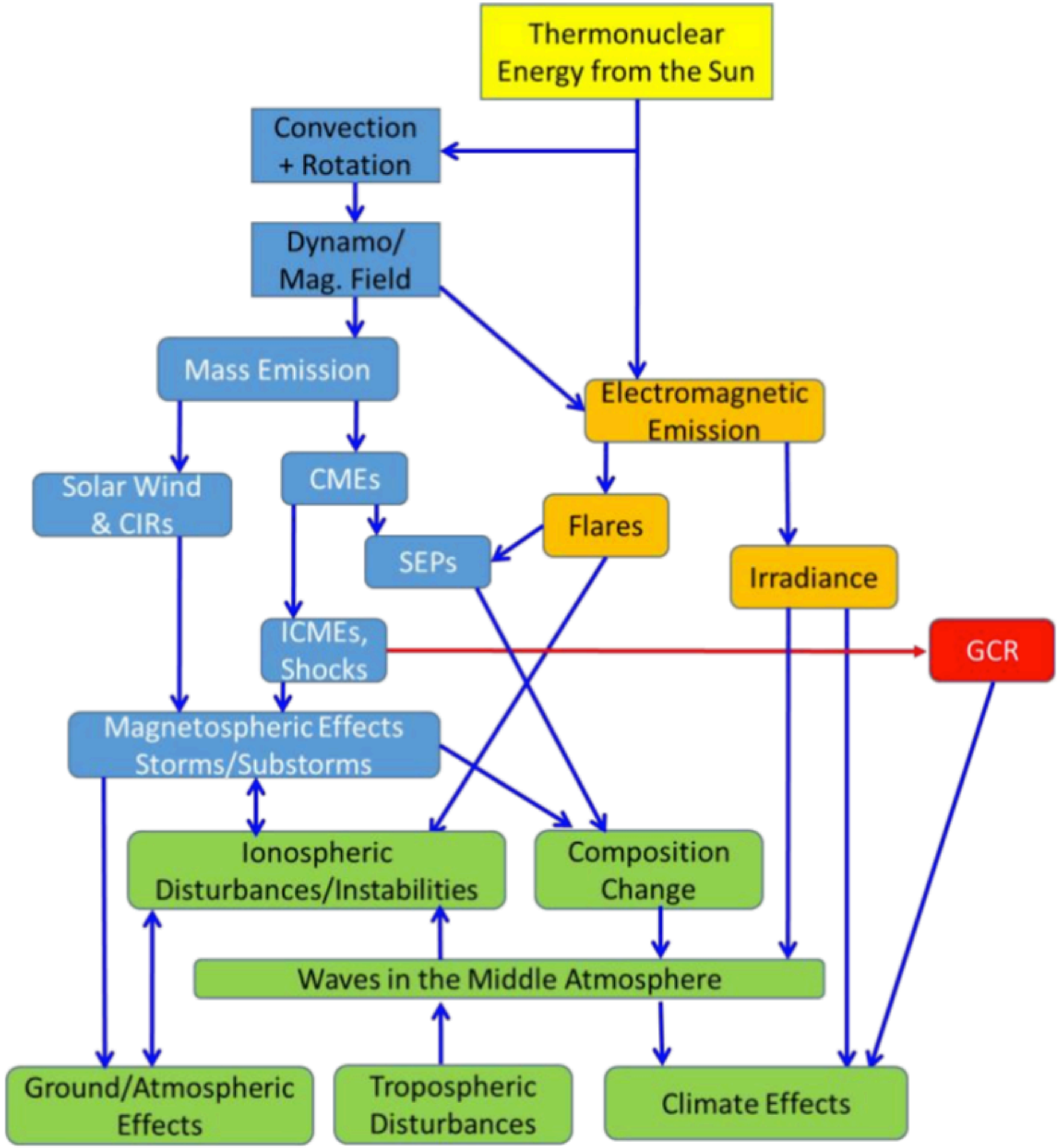


Flares, CMEs and SEP events: a statistical view

- It is difficult to identify ‘pure’ flares or ‘pure’ CMEs.
- But: **flares *and* CMEs appear necessary conditions for SEP events :**
  - no SEP event without particle acceleration signatures in the corona (radio), even when fast CME is observed;
  - no SEP event, even with X-class flares, without a CME.

Ηλιακή μεταβλητότητα
Solar variability




Thermonuclear Energy from the Sun
Convection + Rotation
Dynamo/ Mag. Field
Mass Emission
Electromagnetic Emission
Solar Wind & CIRs
CMEs
Flares
SEPs
Irradiance
ICMEs, Shocks
GCR
Magnetospheric Effects Storms/Substorms
Ionospheric Disturbances/Instabilities
Composition Change
Waves in the Middle Atmosphere
Ground/Atmospheric Effects
Tropospheric Disturbances
Climate Effects