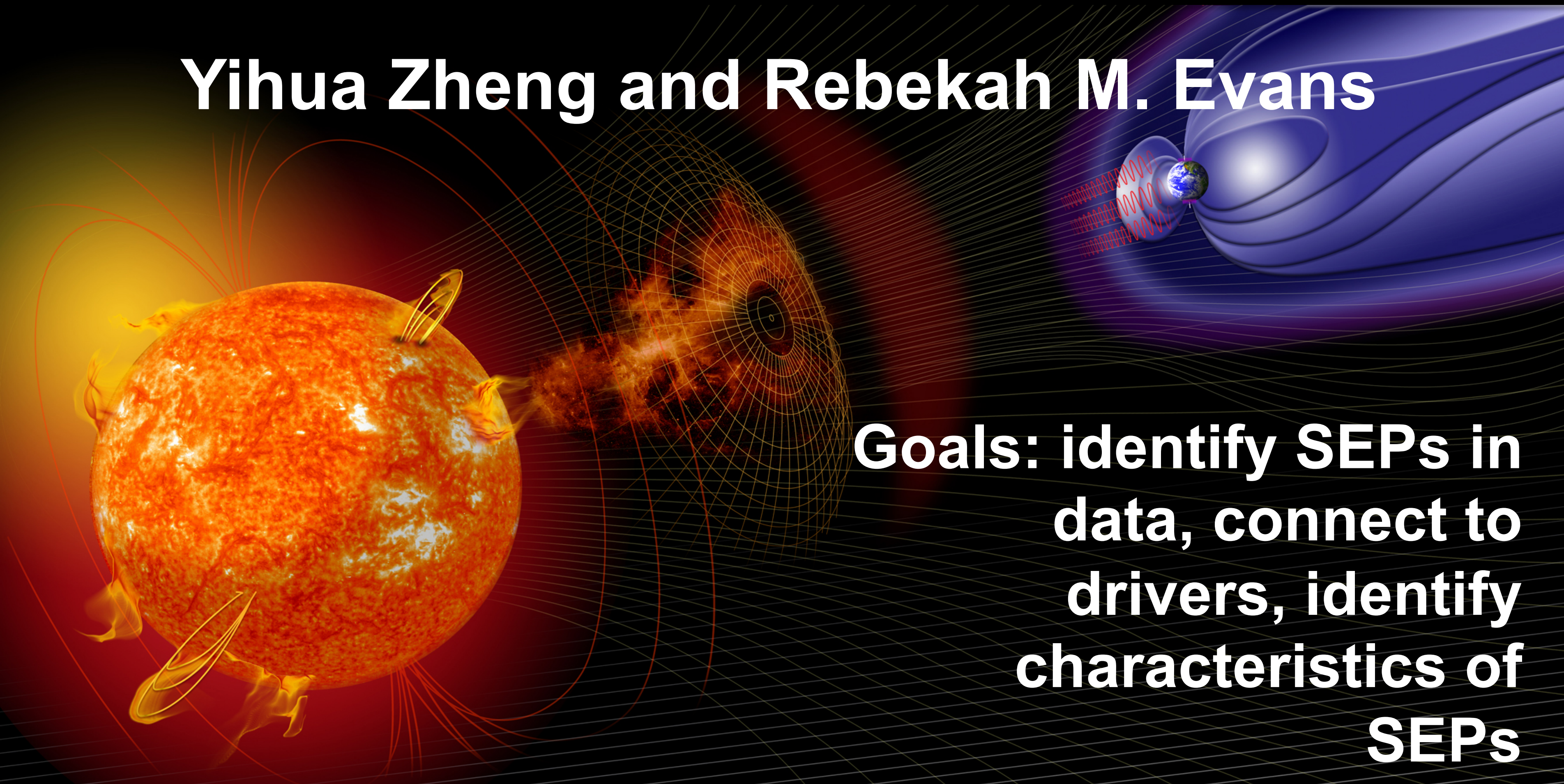
Solar Energetic Particles (SEPs)

Yihua Zheng and Rebekah M. Evans

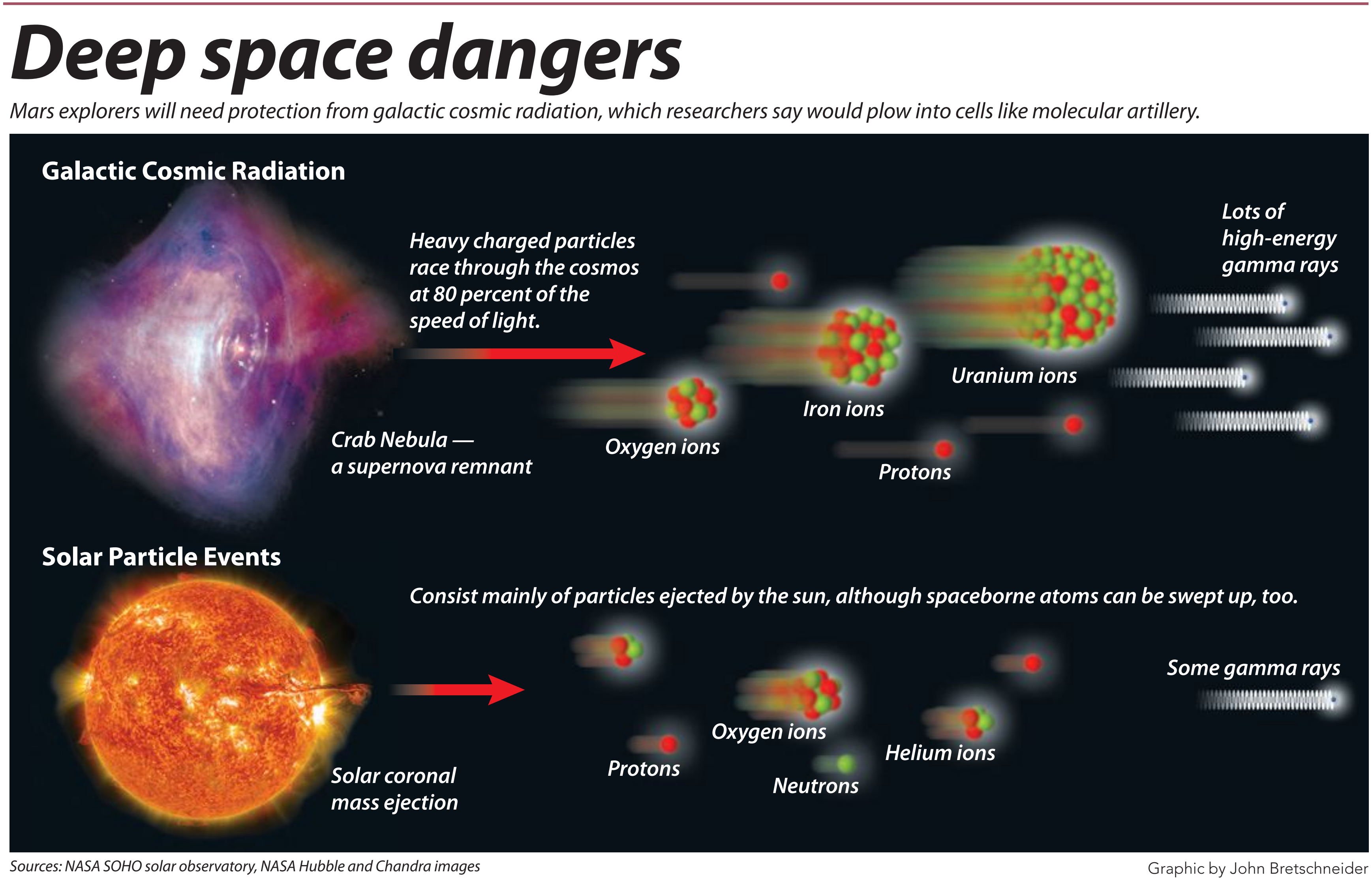


Goals: identify SEPs in data, connect to drivers, identify characteristics of SEPs

June 3, 2014

SW REDI Boot Camp

SEPs – important source of space radiation: hard to predict



What are they?

Definition:

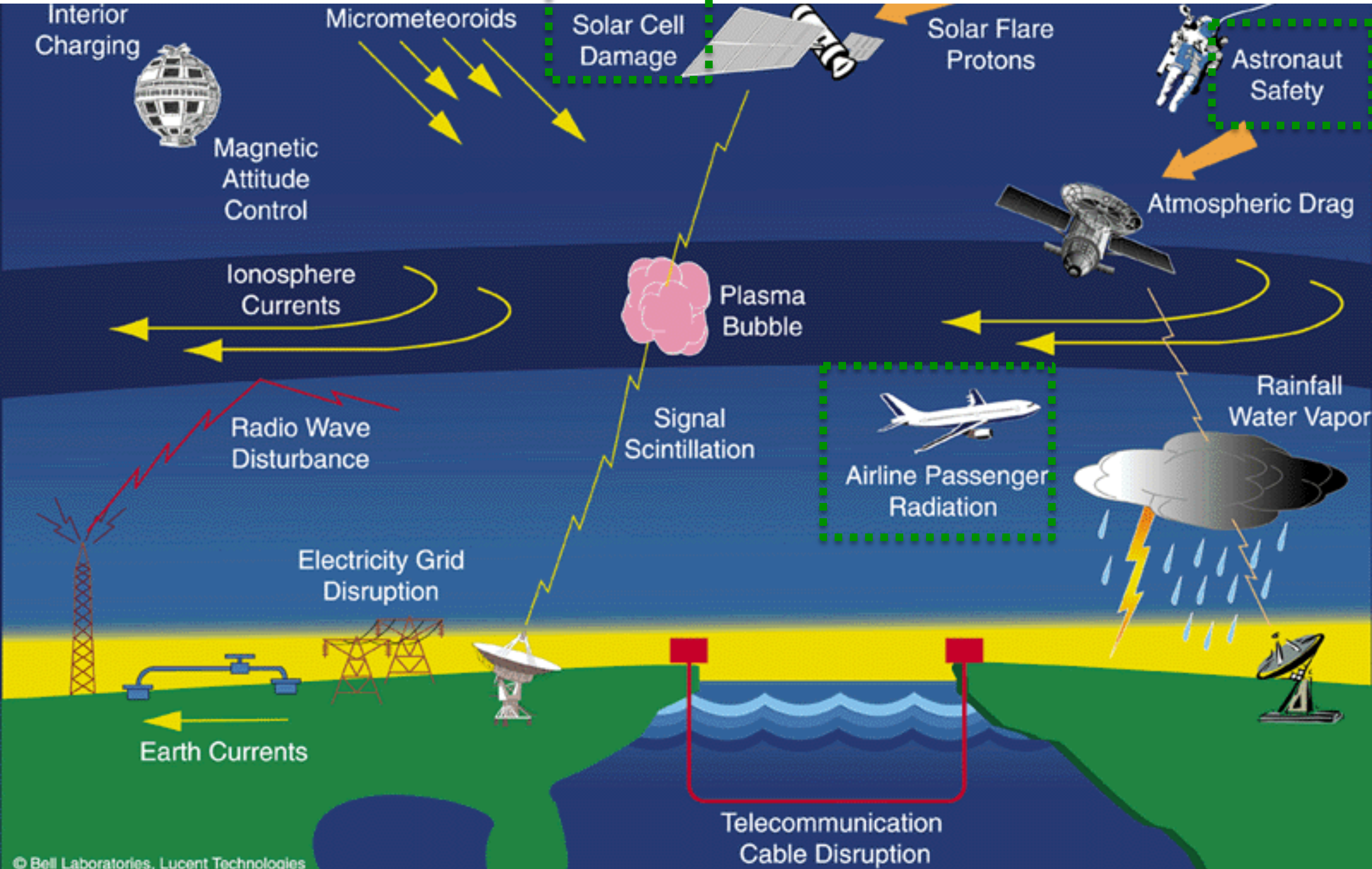
Energetic charged particles (such as electrons and protons) traveling much faster than ambient particles in the space plasma, at a fraction of the speed of light (relativistic!).

They can travel from the Sun to the Earth in one hour or less!

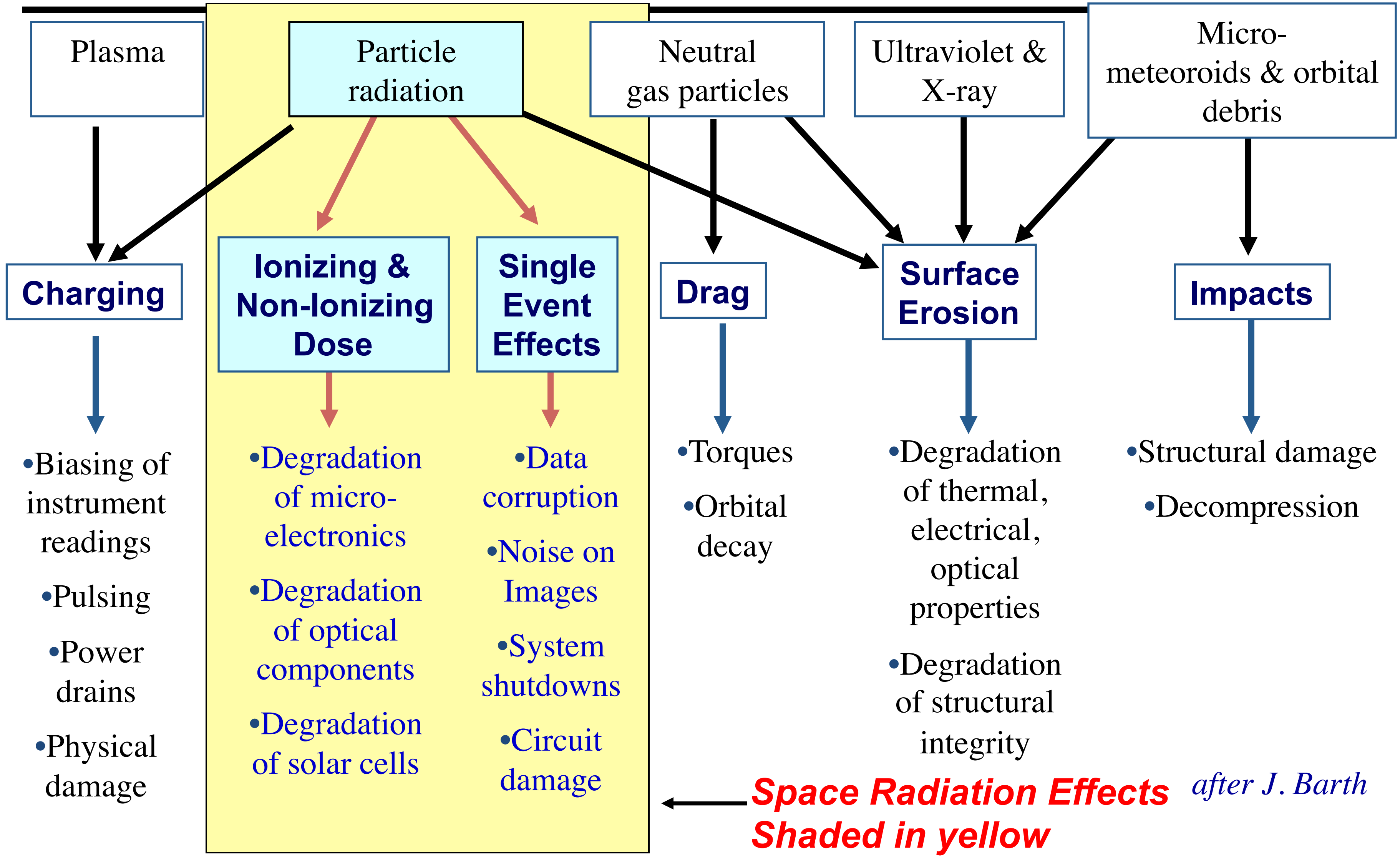
The term "SEP" usually refers to protons.

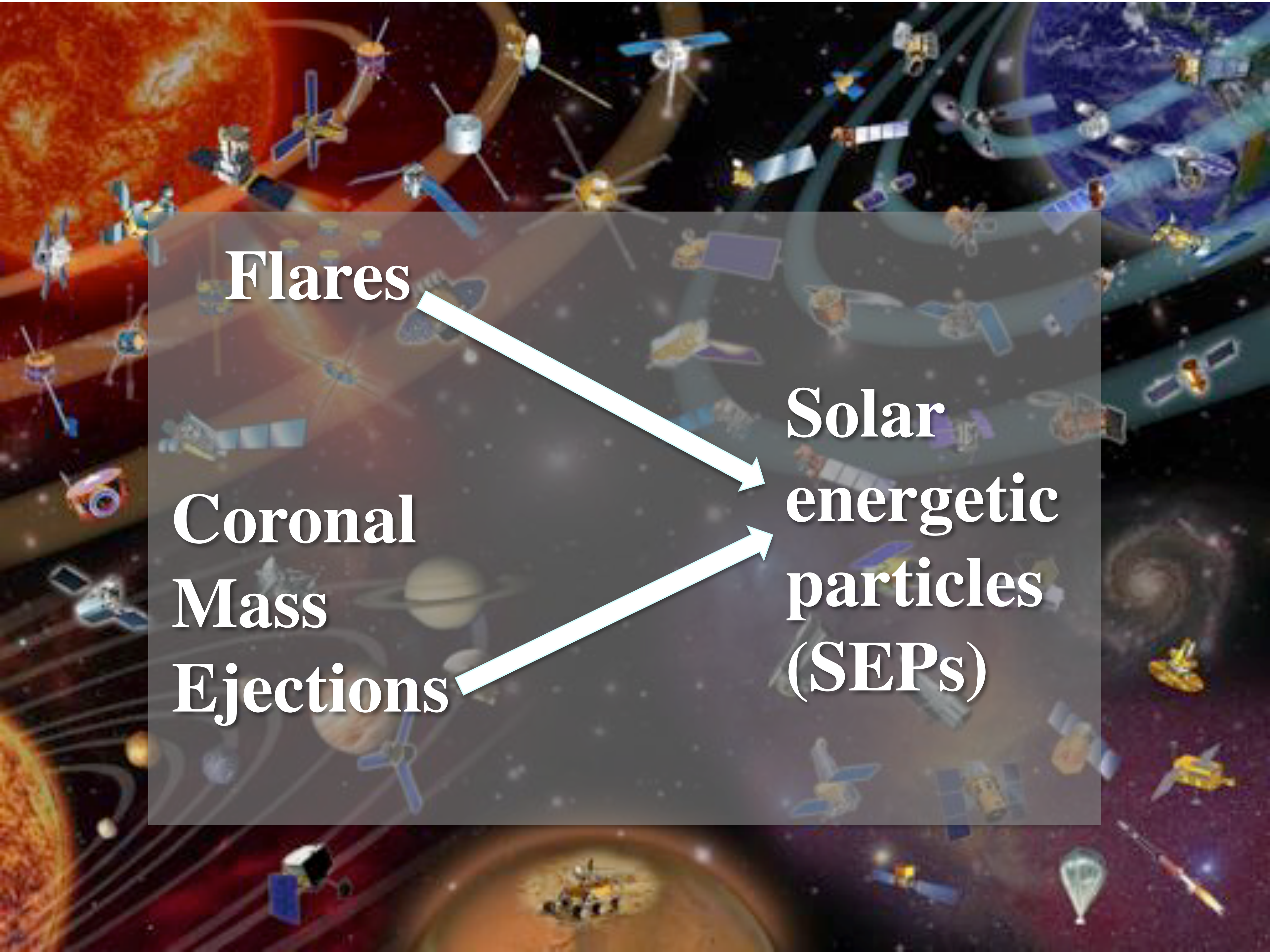
Why do we care?

Radiation hazards for spacecraft,
human in space and airline passenger safety



Space Environments and Effects on Spacecraft

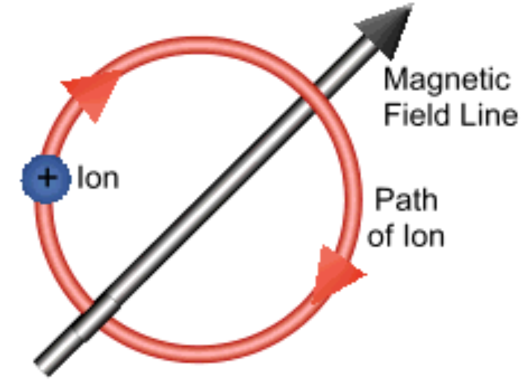



Flares
Coronal
Mass
Ejections
Solar
energetic
particles
(SEPs)

SEPs: ion radiation storms

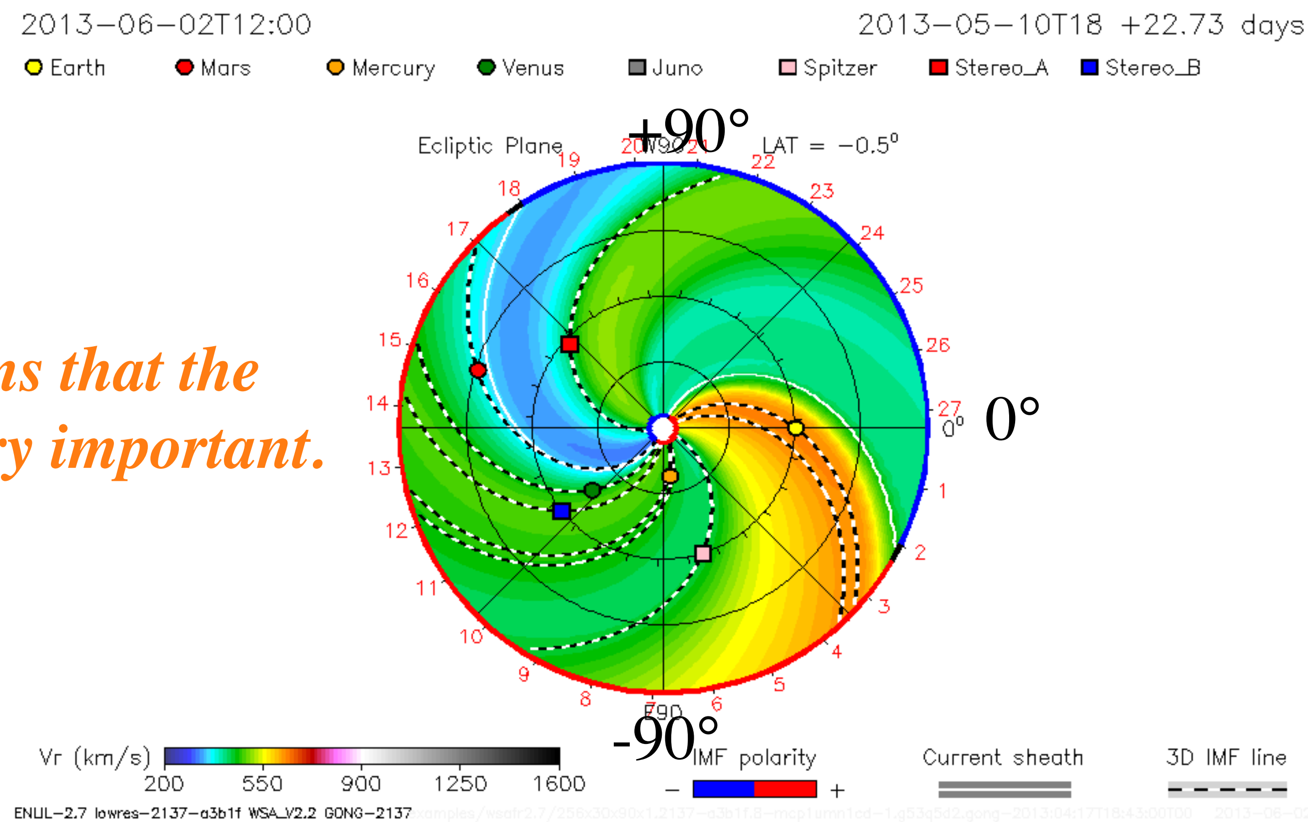
Potentially affect everywhere in the solar system

Magnetic fields guide SEPs



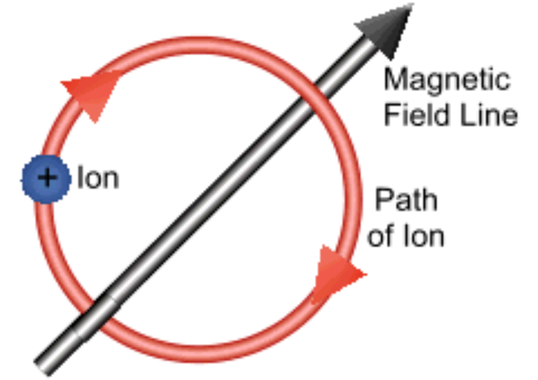
Charged particle motion* is confined by the magnetic field.

This means that the source is very important.



*in a substantially strong B

Magnetic fields guide SEPs



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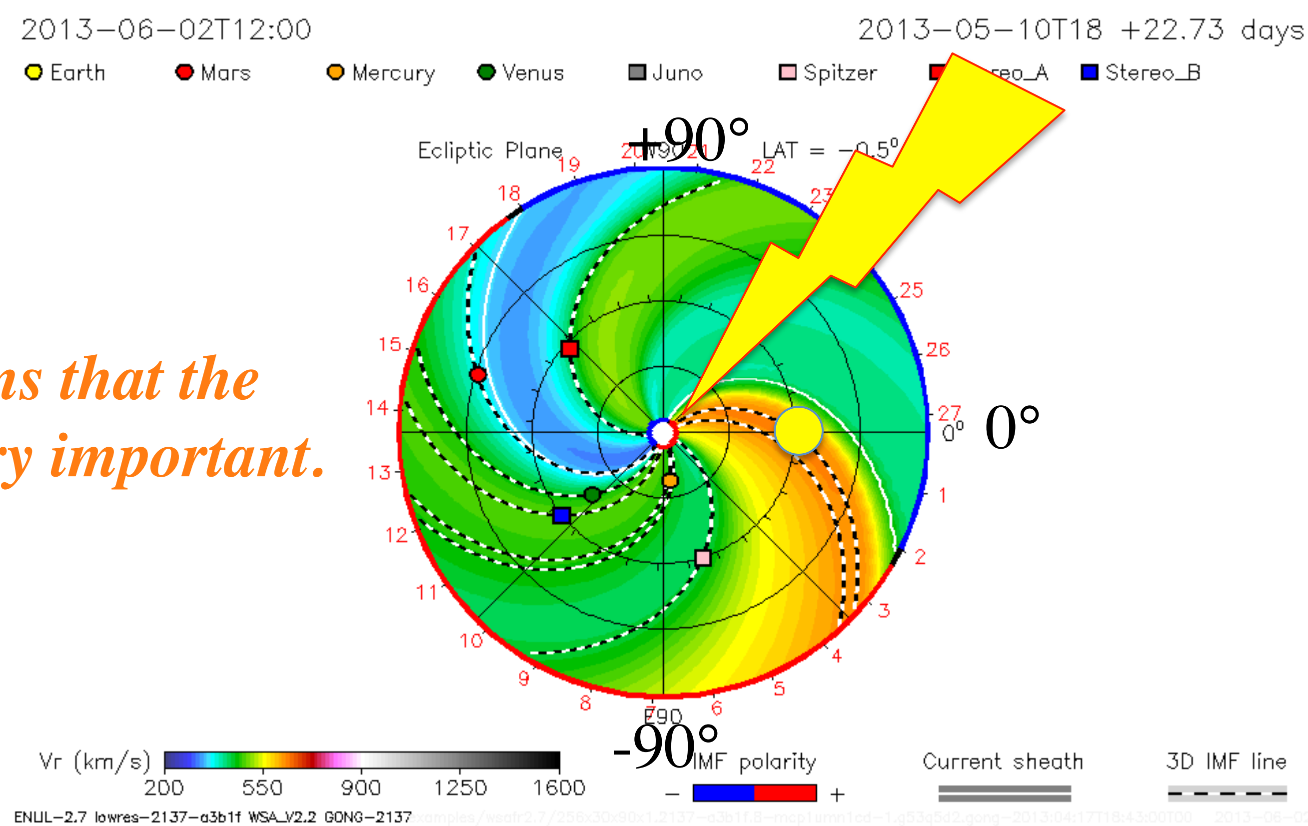

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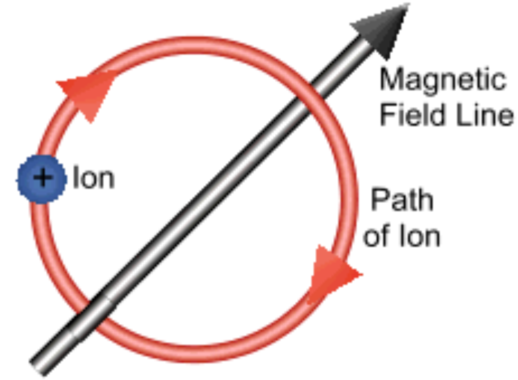
Magnetic fields guide SEPs



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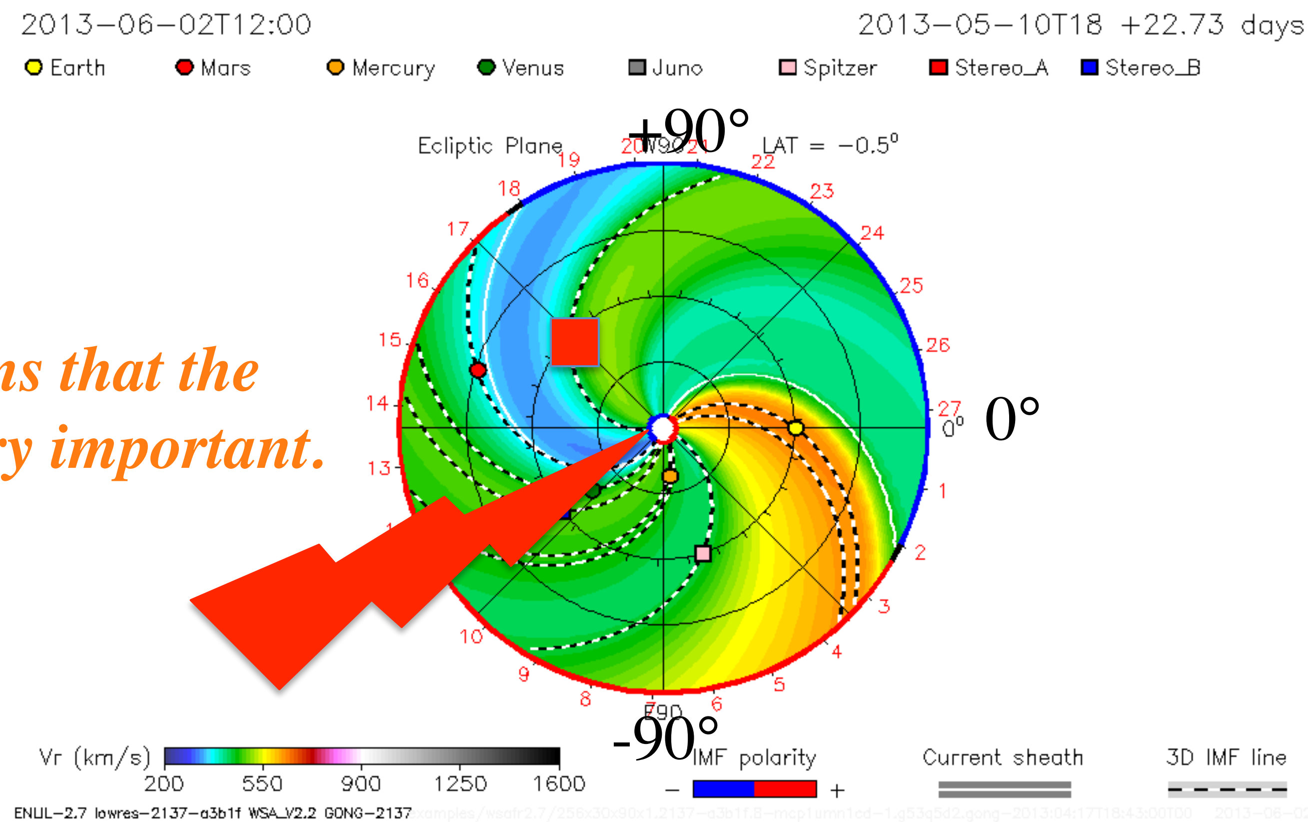

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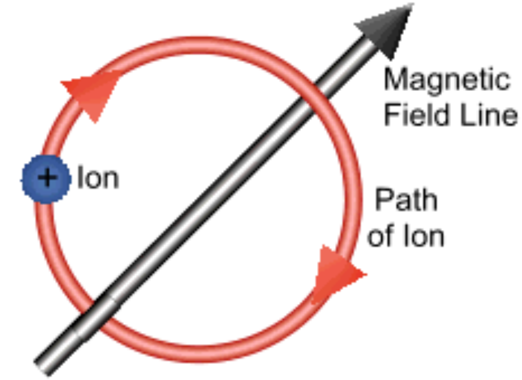
Magnetic fields guide SEPs



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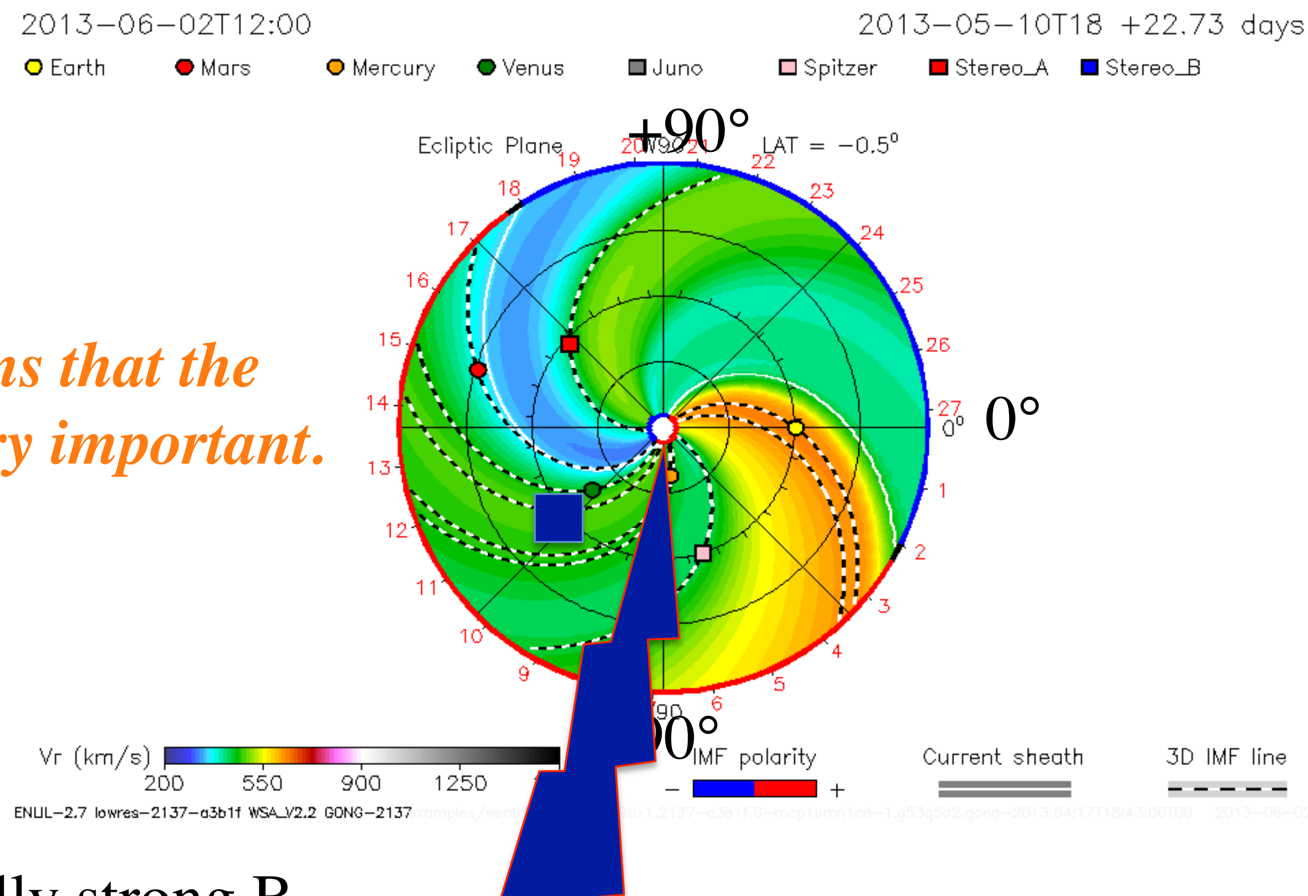
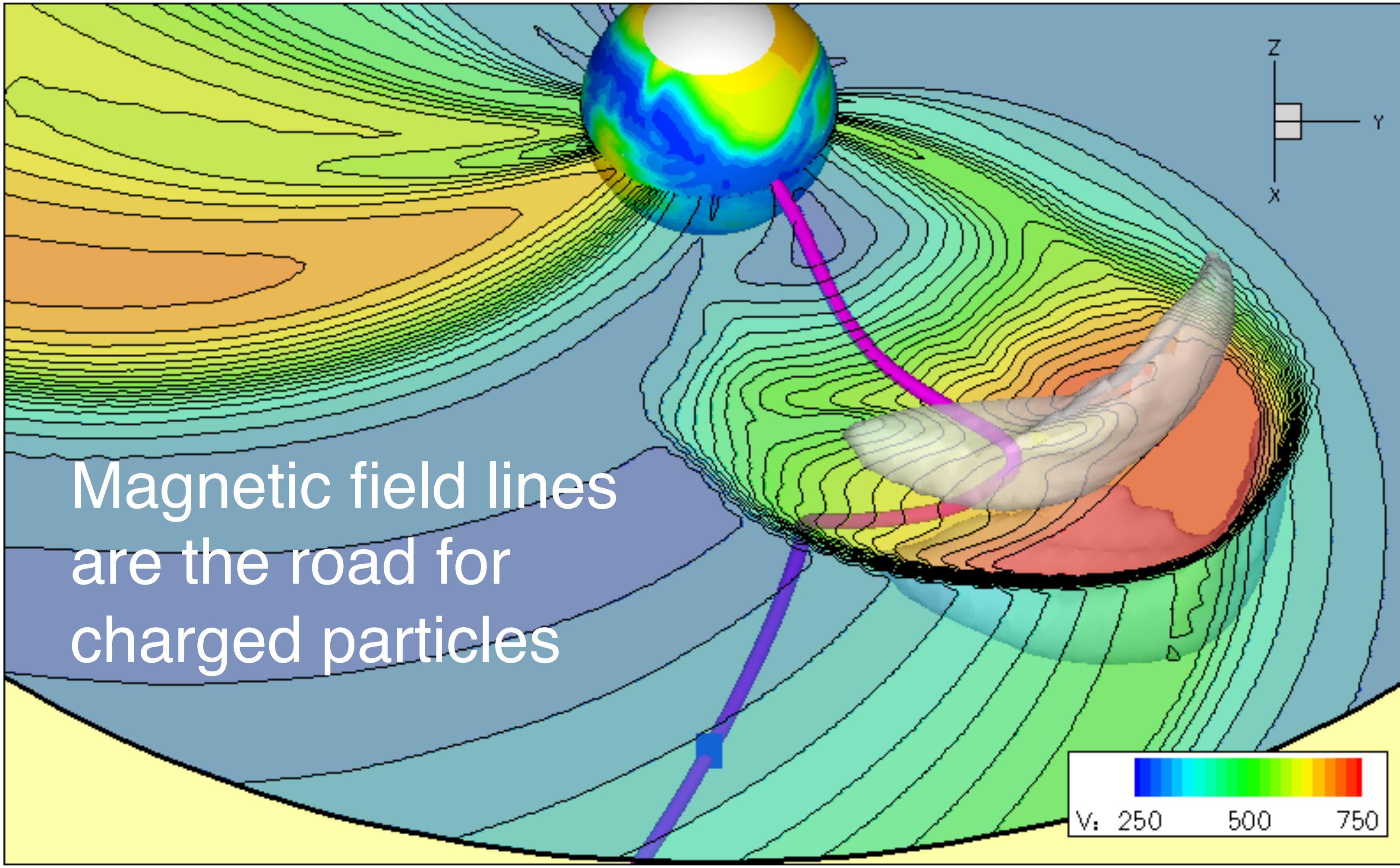


*in a substantially strong B

CMEs Can Widen Longitudinal Extent of SEP Events



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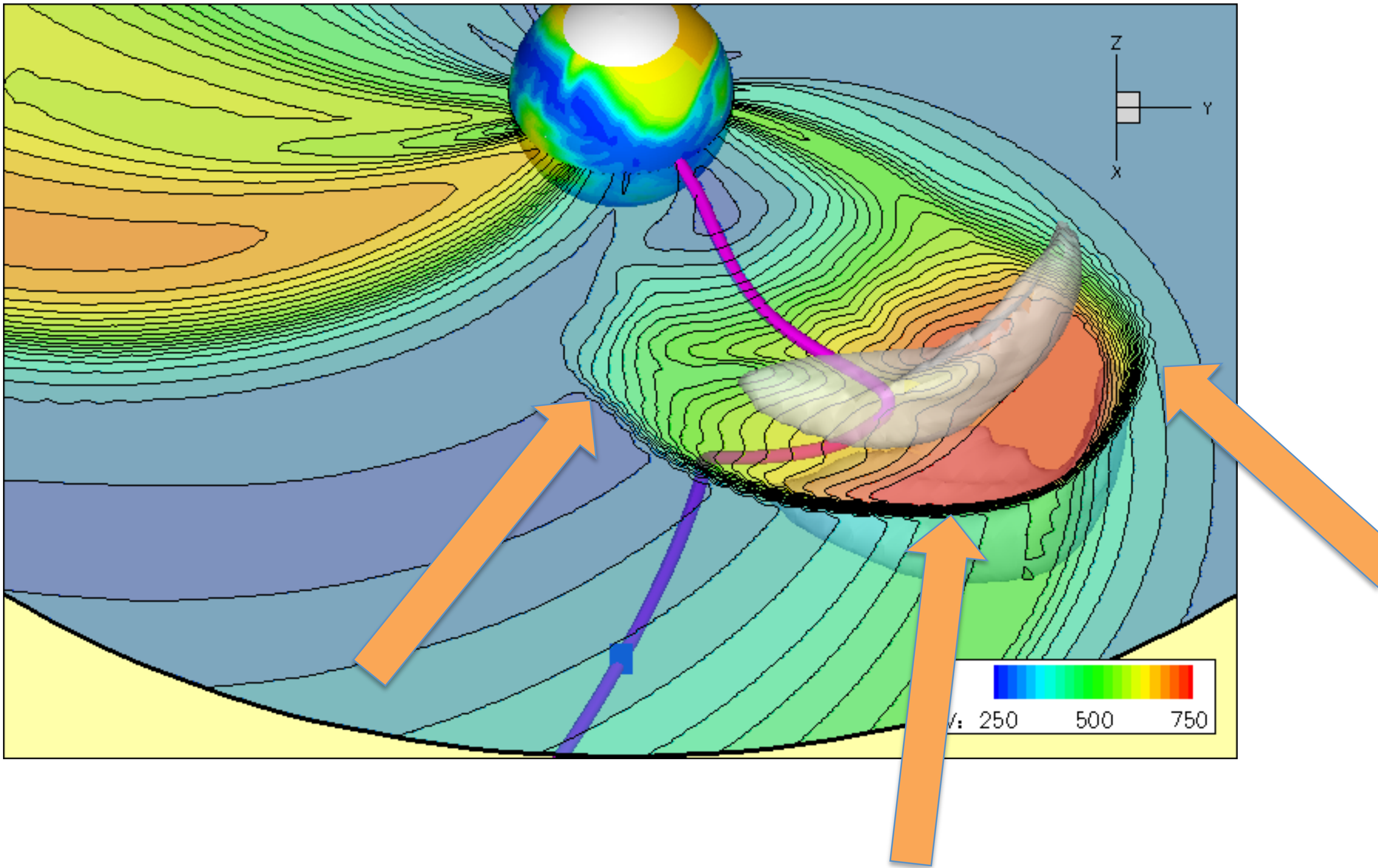


How Do We Monitor SEP Levels?

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

Track the particle flux at different locations.

Flux units: pfu, pfu/MeV

- ***Heliosphere with STEREO In-situ Measurements of Particles and CME Transients (IMPACT)***
  - ***Differential energy band; Units measured, some energy ranges are:***
- ***Upstream of Earth with SOHO/COSTEP***
  - ***Units measured, some energy ranges are:***
- ***Geostationary Orbit with GOES***
  - ***Integral flux, Units measured, some energy ranges are: pfu particle flux unit***

Another useful quantity:

Fluence = flux integrated over the entire event.

Important for biological effects (flights)

SEP Intensity

Event magnitudes:

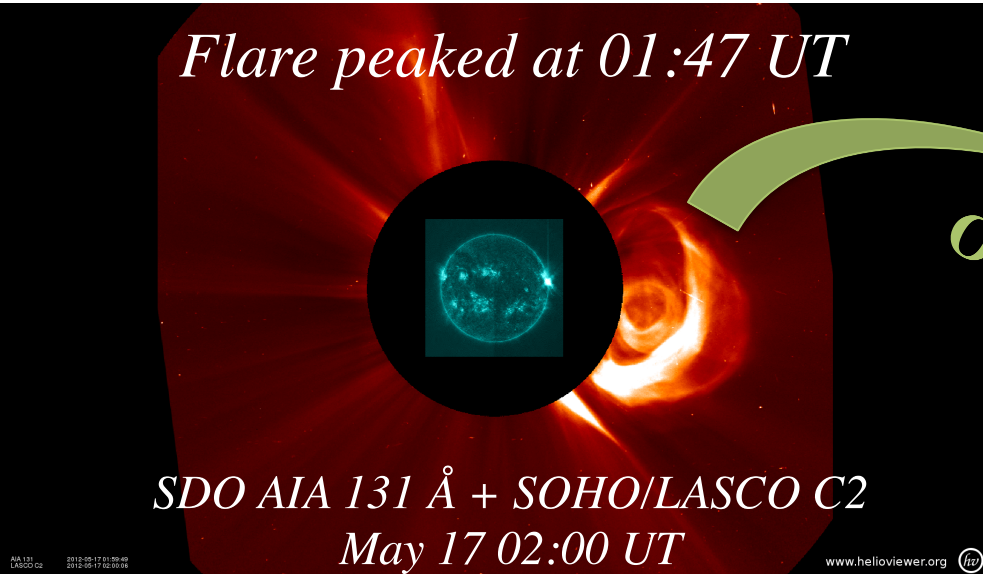
> 10 MeV/nucleon integral fluence: can exceed 10^9 cm^{-2}

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

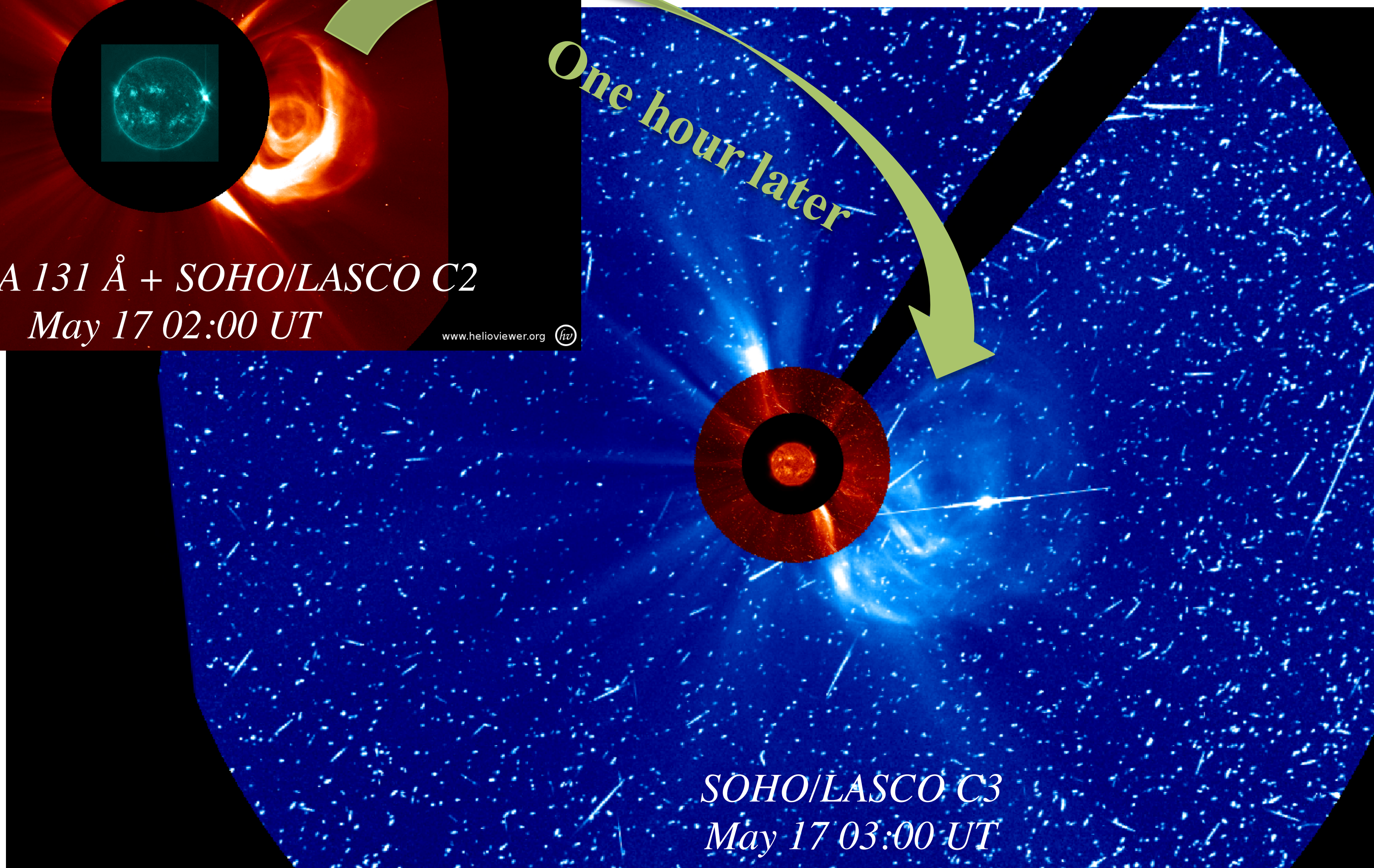
PARTICLE SNOW!

Coronagraph acting as particle de

☺



One hour later

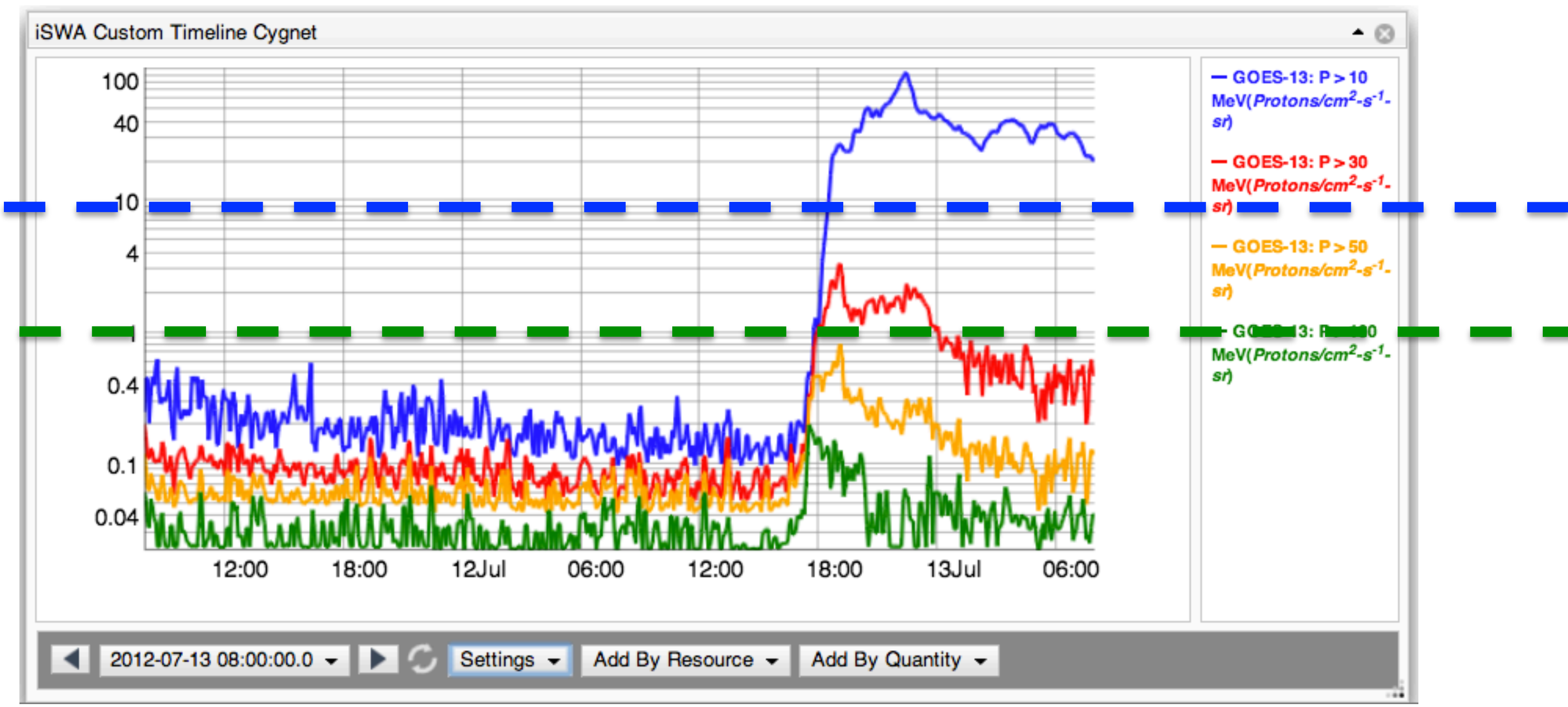


How do we define an SEP Event?

SWRC: SEP event detections are defined as:

GOES Proton E > 10 MeV channel > 10 pfu

GOES Proton E > 100 MeV channel > 1 pfu



How Do We Quantify an SEP Event?

NOAA Space Weather Scale for Solar Radiation Storms

Category		Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Scale	Descriptor	Duration of event will influence severity of effects		
Solar Radiation Storms			Flux level of >= 10 MeV particles (ions)*	Number of events when flux level was met (number of storm days**)
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

Human Safety in Space

- GCR
- **SEP**

Johnson Space Center/Space Radiation Analysis Group (SRAG)

Limit: the > 100 MeV flux exceeding 1pfu

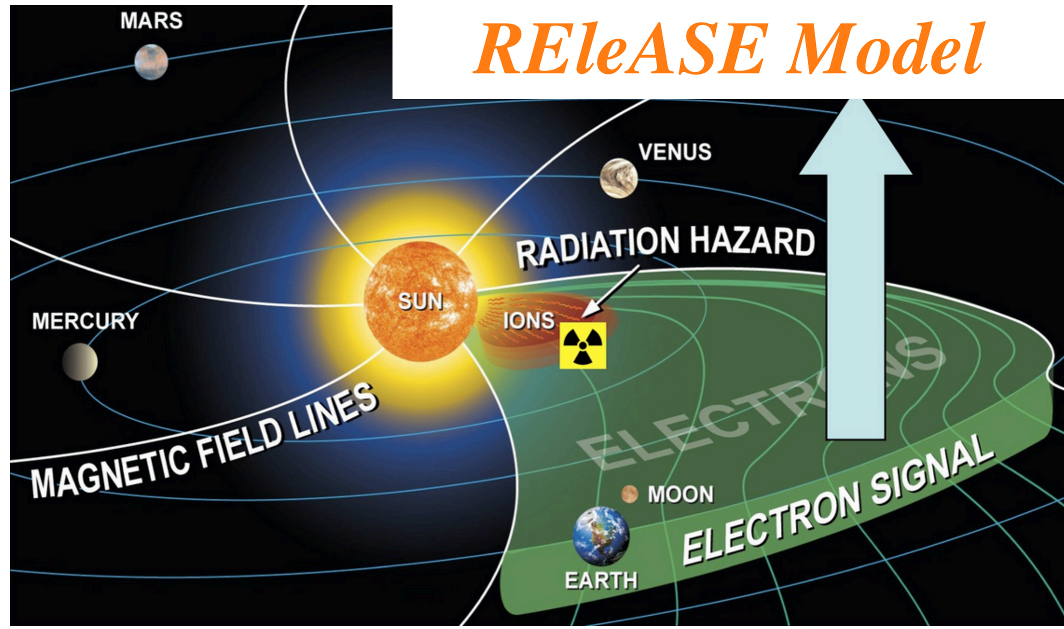
(1 pfu = 1 particle flux unit= 1/cm^2/sec/sr)

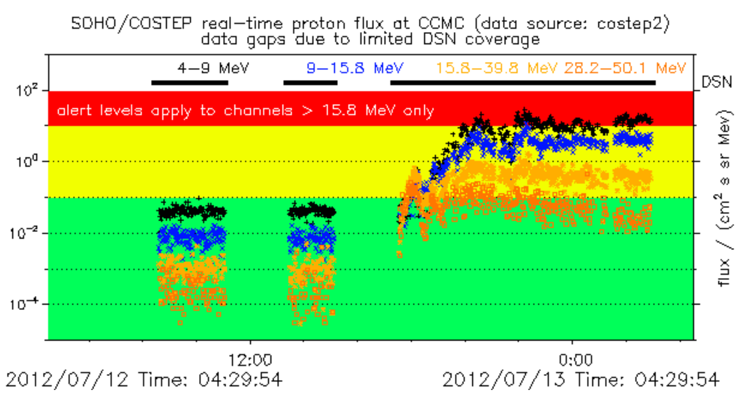
- All clear (EVA –extravehicular activity)

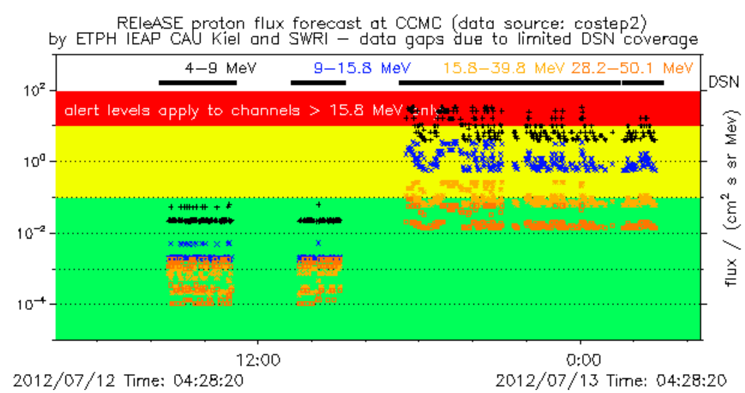
Can we predict SEP events?

Uses detection of high energy *electrons* to predict arrival of high energy *protons*

Data source: SOHO COSTEP







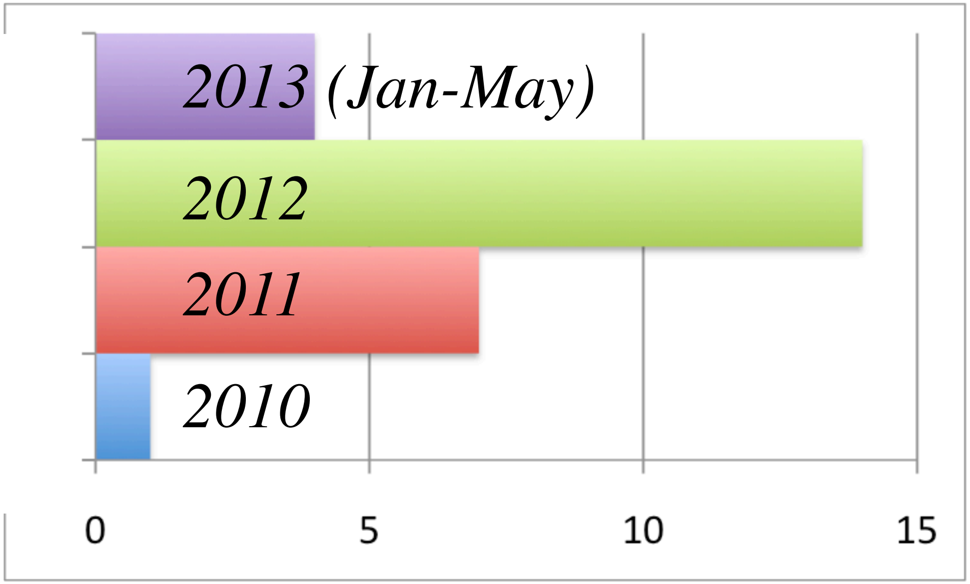
How Often Do SEP Events Occur?

SEP event detections in the near-Earth environment

(GOES 13, Proton E > 10 MeV channel)

2007-2009: Zero Events - Solar Minimum Indeed!

Total Events



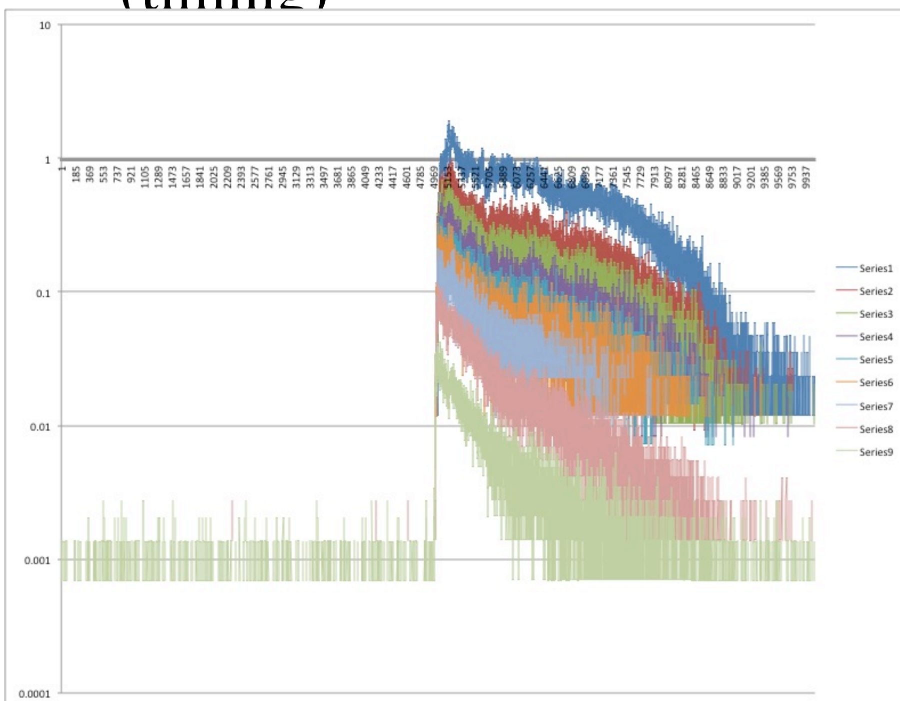
Since March 2011

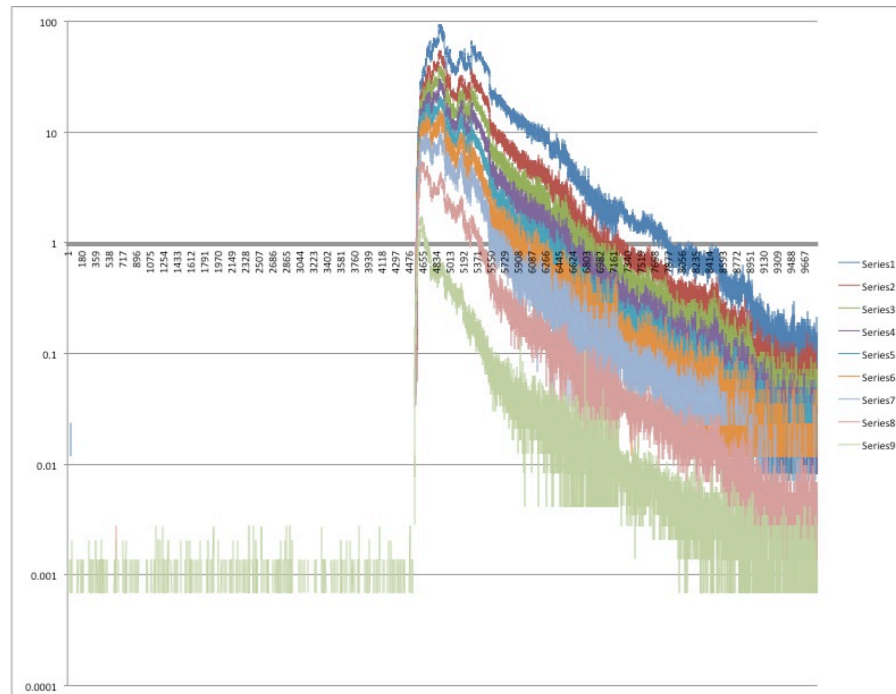
STEREO A: 16

STEREO B: 11

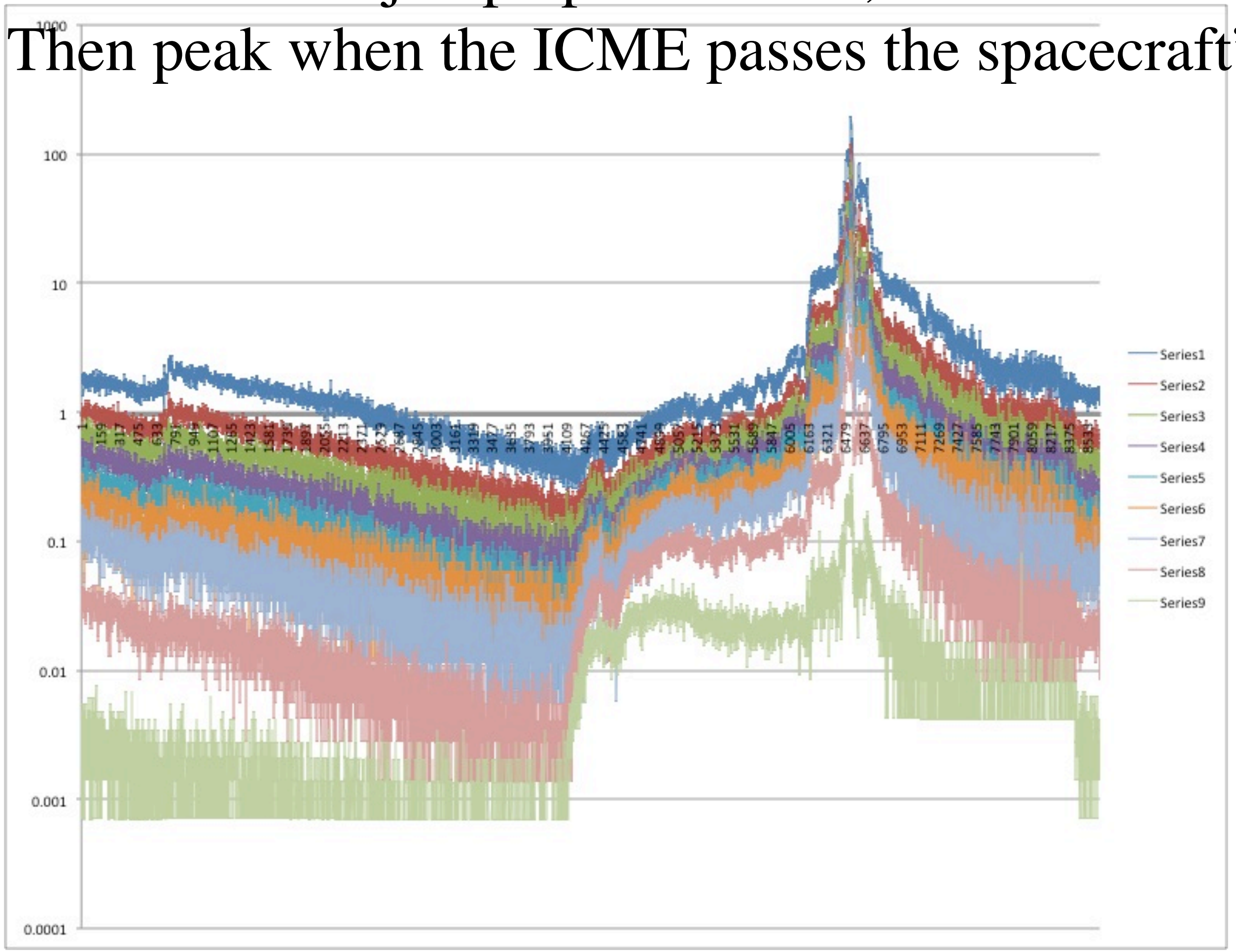
Recognizing profile shapes of SEP flux and associating it with the source/driver

Impulsive: The "peak at the beginning due to flare, fall off" – indicates how well connected you are to the source (timing)

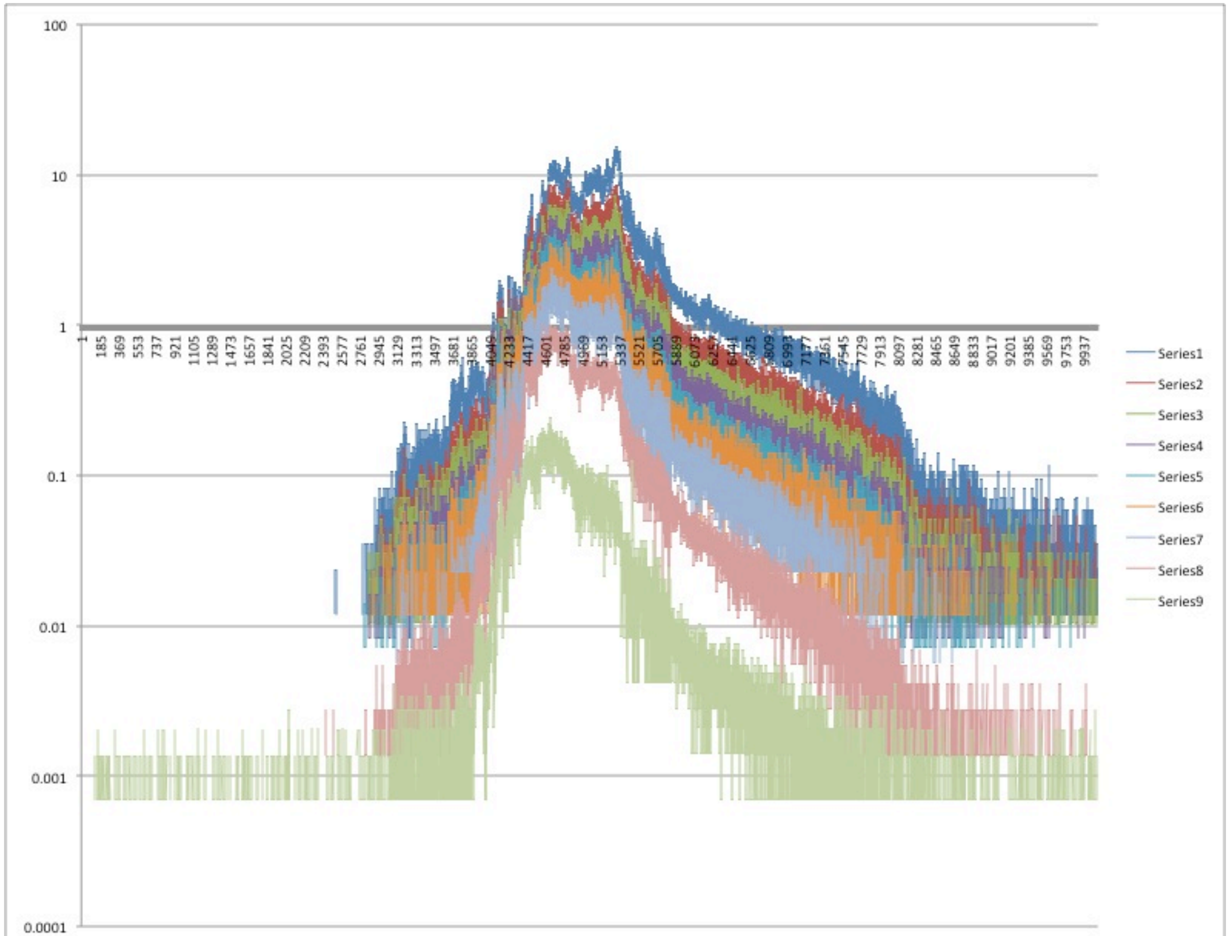




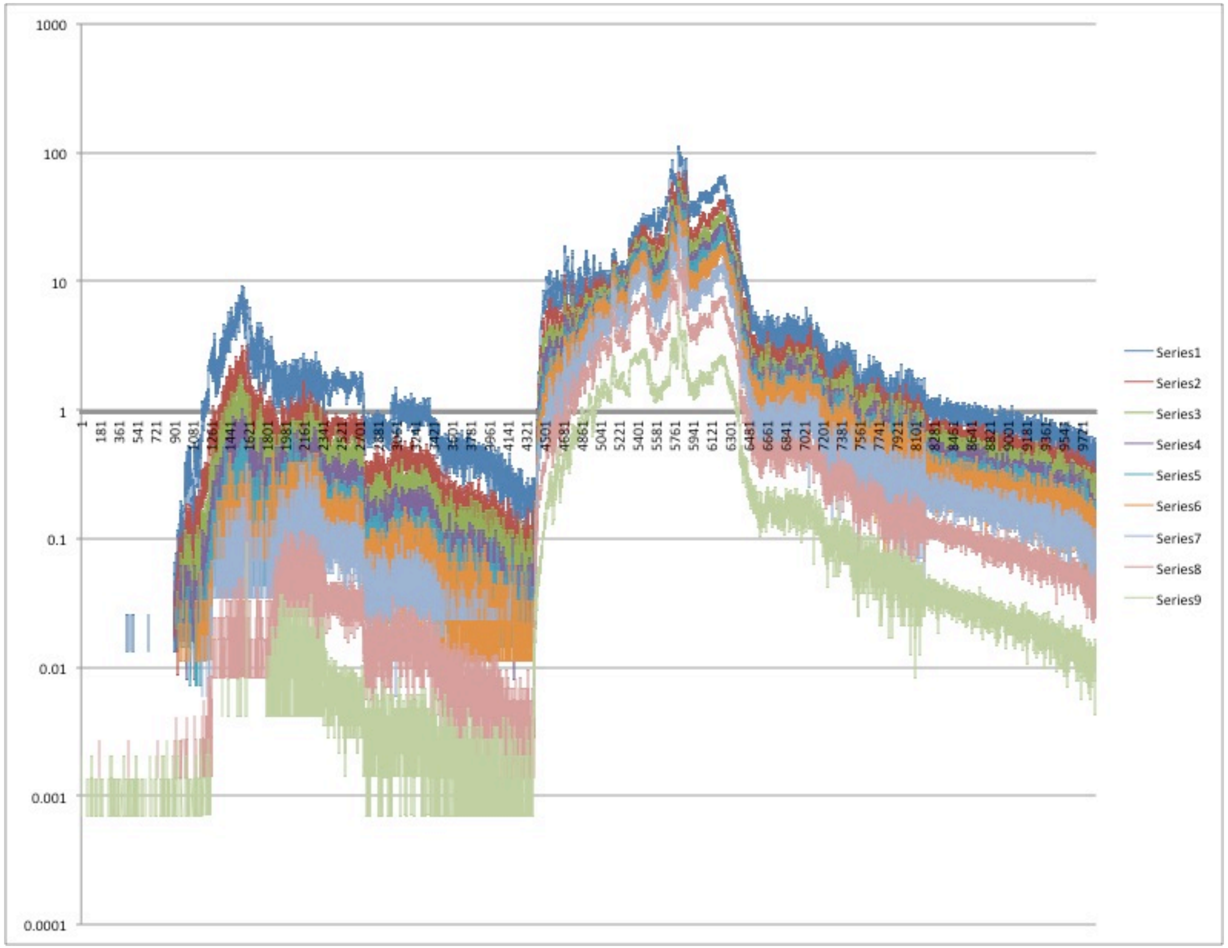
Gradual: The "jump up from flare, slow rise
Then peak when the ICME passes the spacecraft"



The "slow rise then peak, (slow rise can let you know that you are not well connected
ICME doesn't hit spacecraft so falls off"

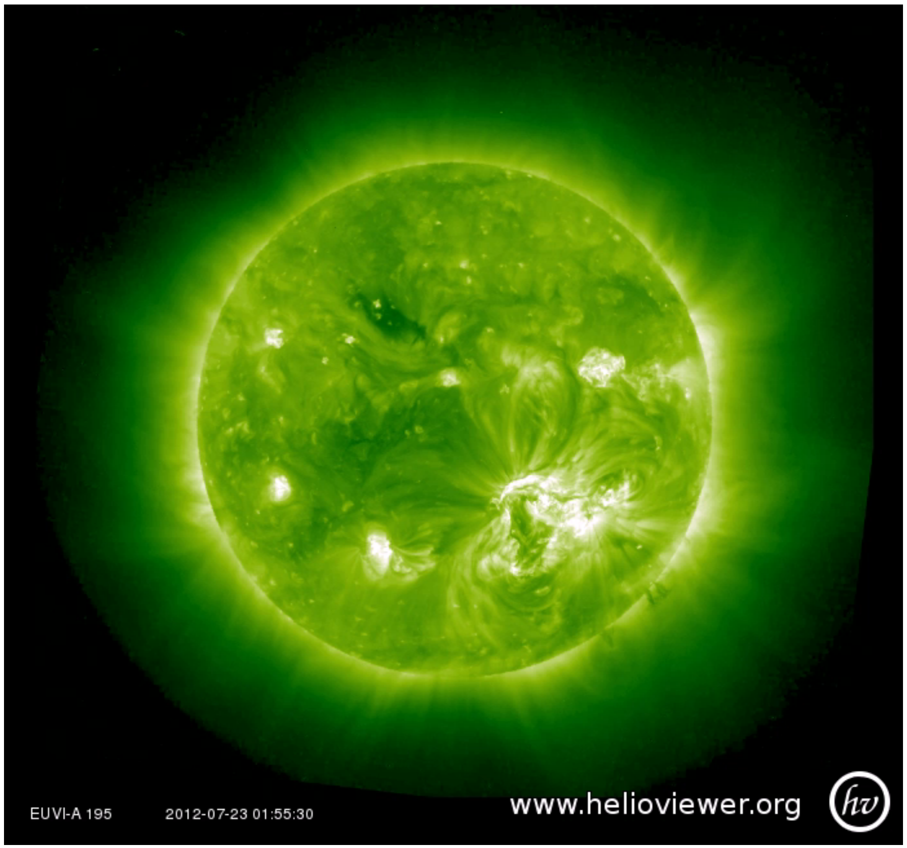


The “multiple event weirdness”

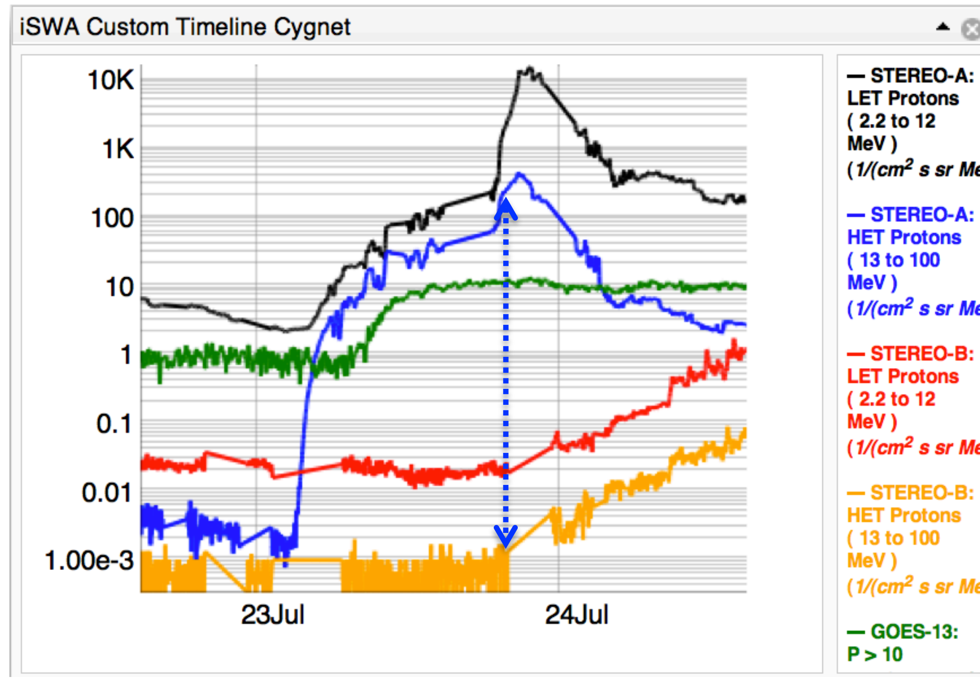


July 23, 2012

Example where is reaches one spacecraft, then later another…



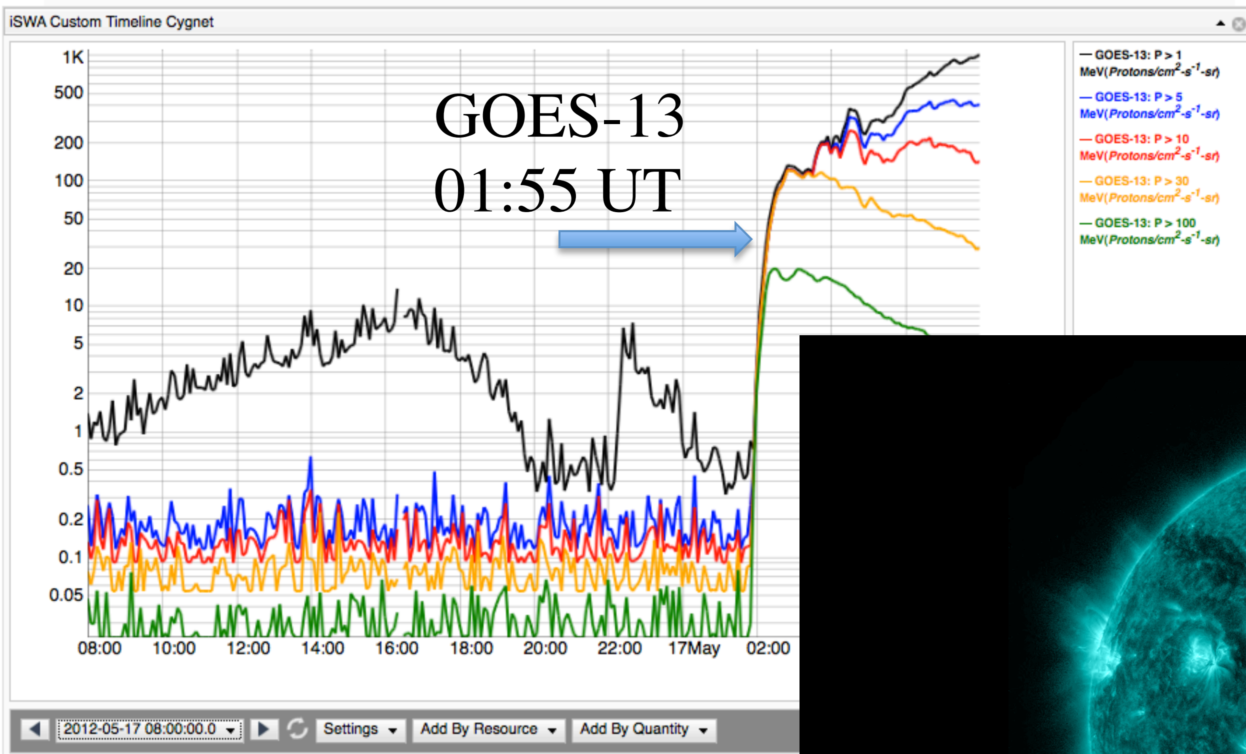
July 23 flare as seen in STEREO A EUVI 195



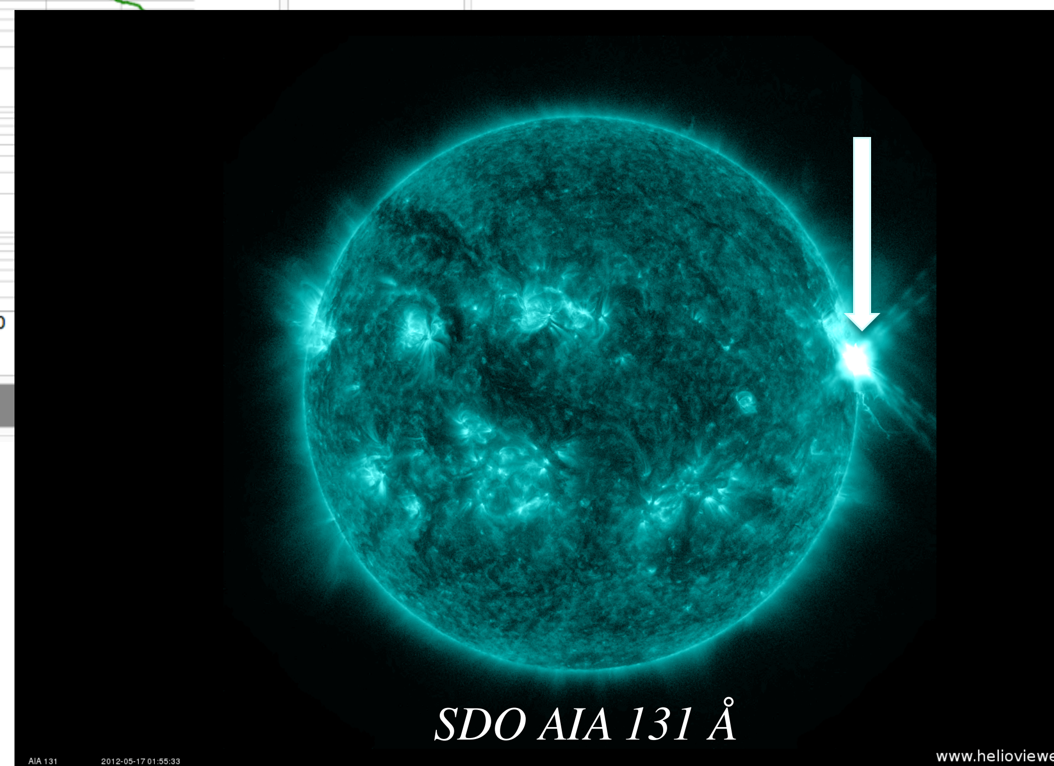
Increase of more than 5 orders of magnitude at STEREO A

SEP event also detected by GOES, and later enhancement seen at STEREO B (possibly due to IPS)

For Earth – Best Connection is 45-60 degree west



Energetic proton fluxes elevated for >12 hours

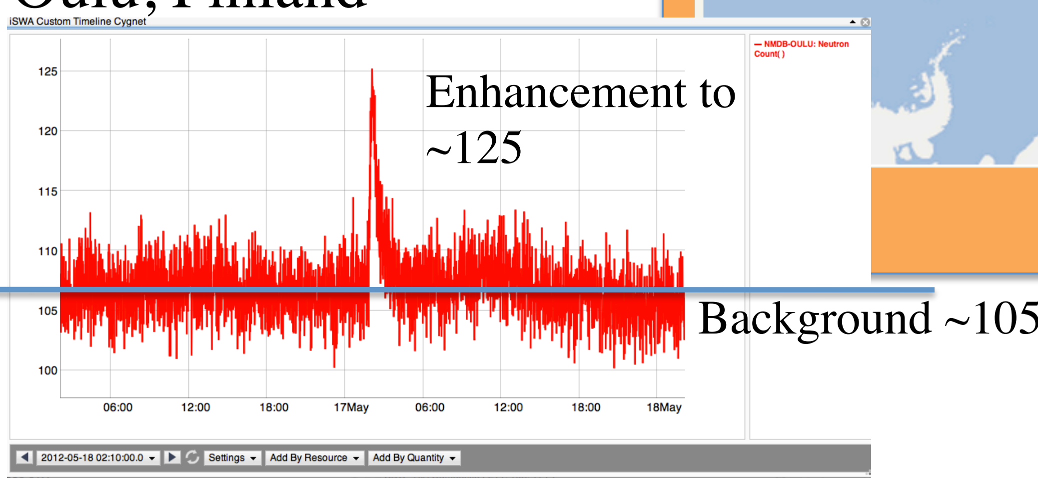


Ground Level Enhancement

A subset of SEP events, a GLE event occurs when extremely high energy protons (>500 MeV/nuc) penetrate the Earth's atmosphere. Collisions with atoms generate secondary particles that are measured at neutron monitoring (NM) stations on the ground.

NM Stations *(http://www.nmdb.eu)*

Neutron Monitoring Station in Oulu, Finland



What causes strongest SEP events?
Or, how do the drivers relate to the SEP Flux?

Difficult to distinguish GLE from traditional SEP events:

- Complexity of Active Region (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)
- Seed particles
  - -Known to have harder spectrum

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

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

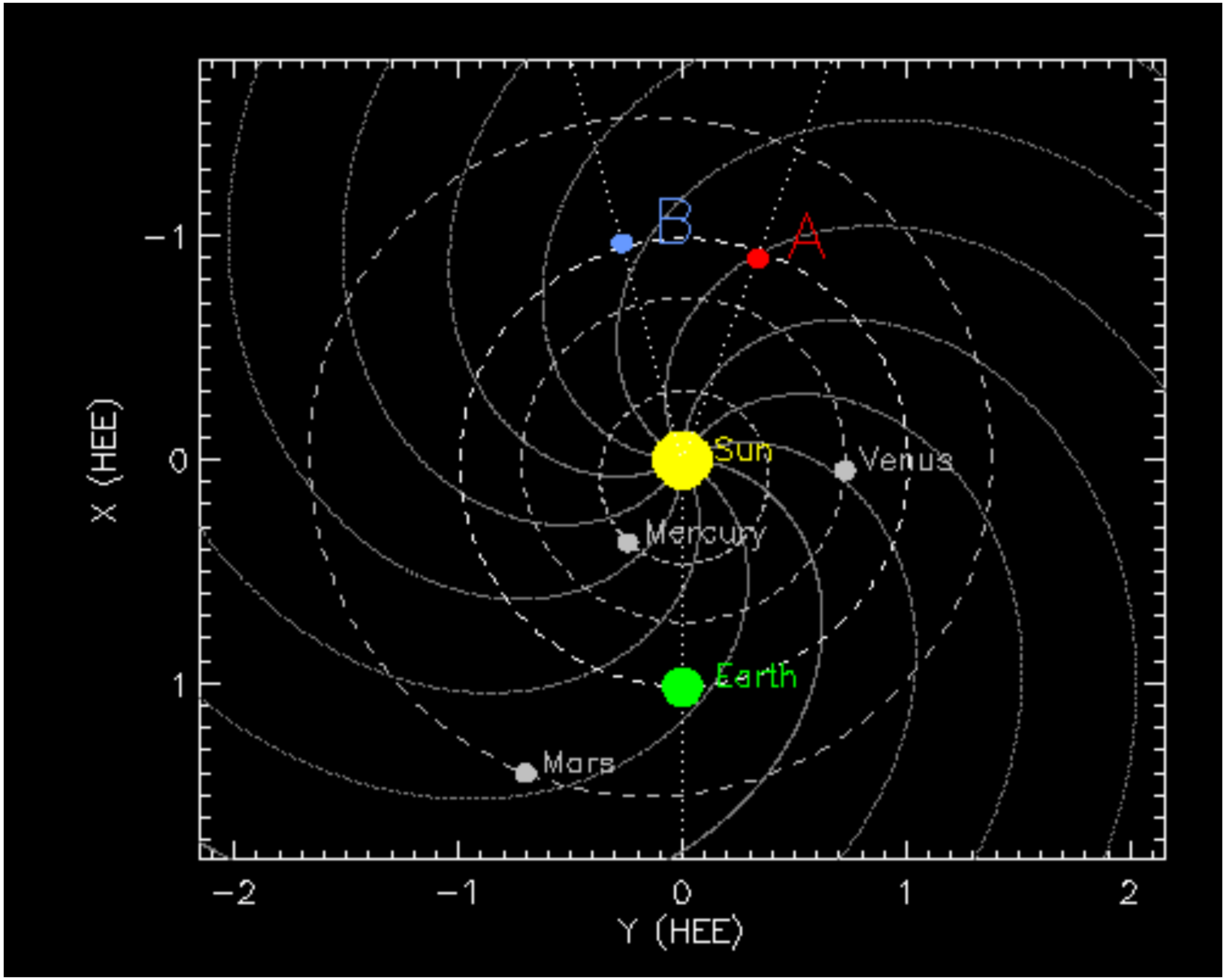
CME-driven shocks are thought to play important role in low (<3R_s) corona

- Only imaged in mid-high corona (*Ontiveros & Vourlidas 2009*)
- Type II radio bursts
- Multiple CME events – doesn't apply for May 17 event

Exceptions to every rule!

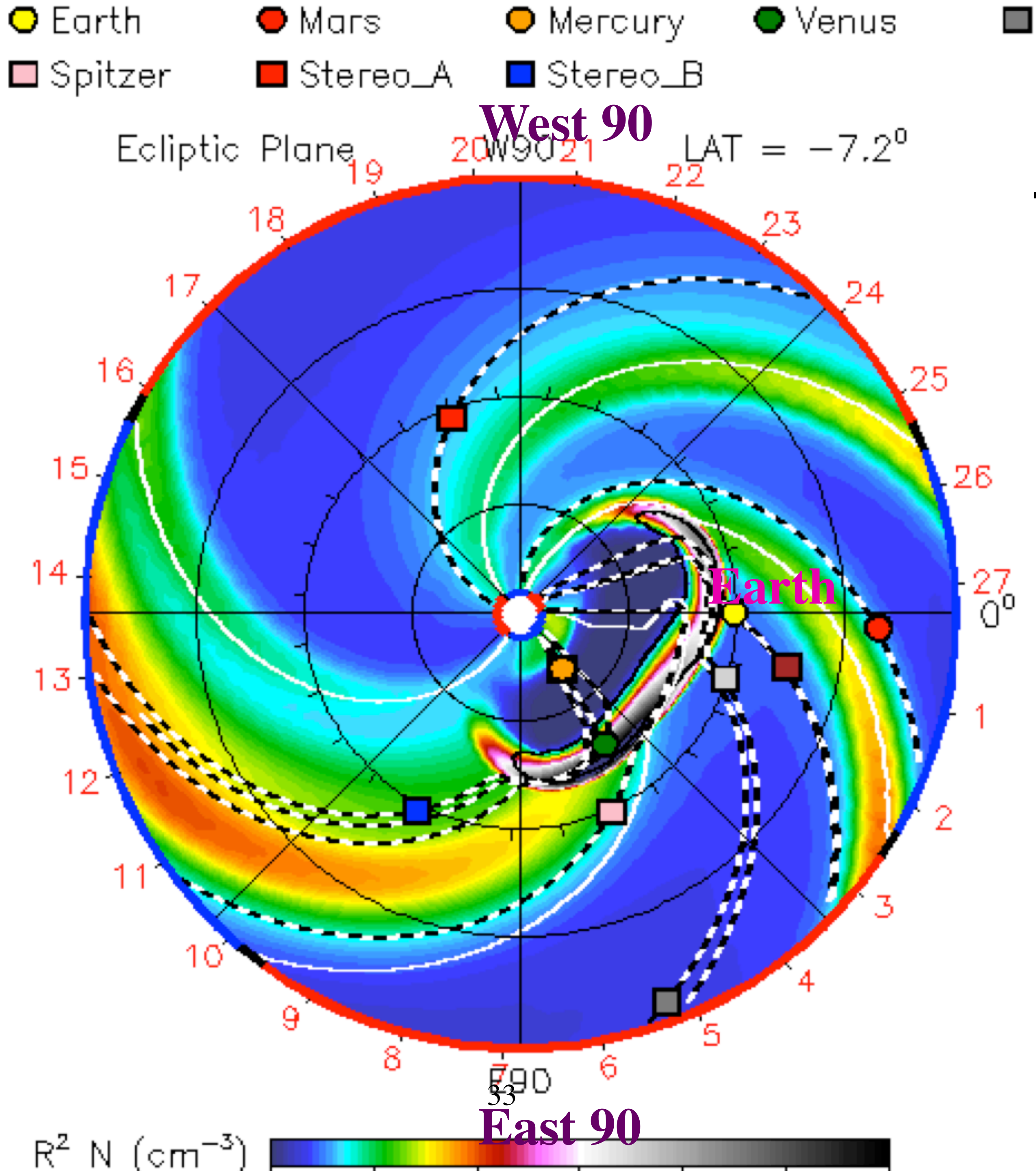
September 28, 2012 – whole heliosphere event – C3.7 flare

Where are NASA assets now?

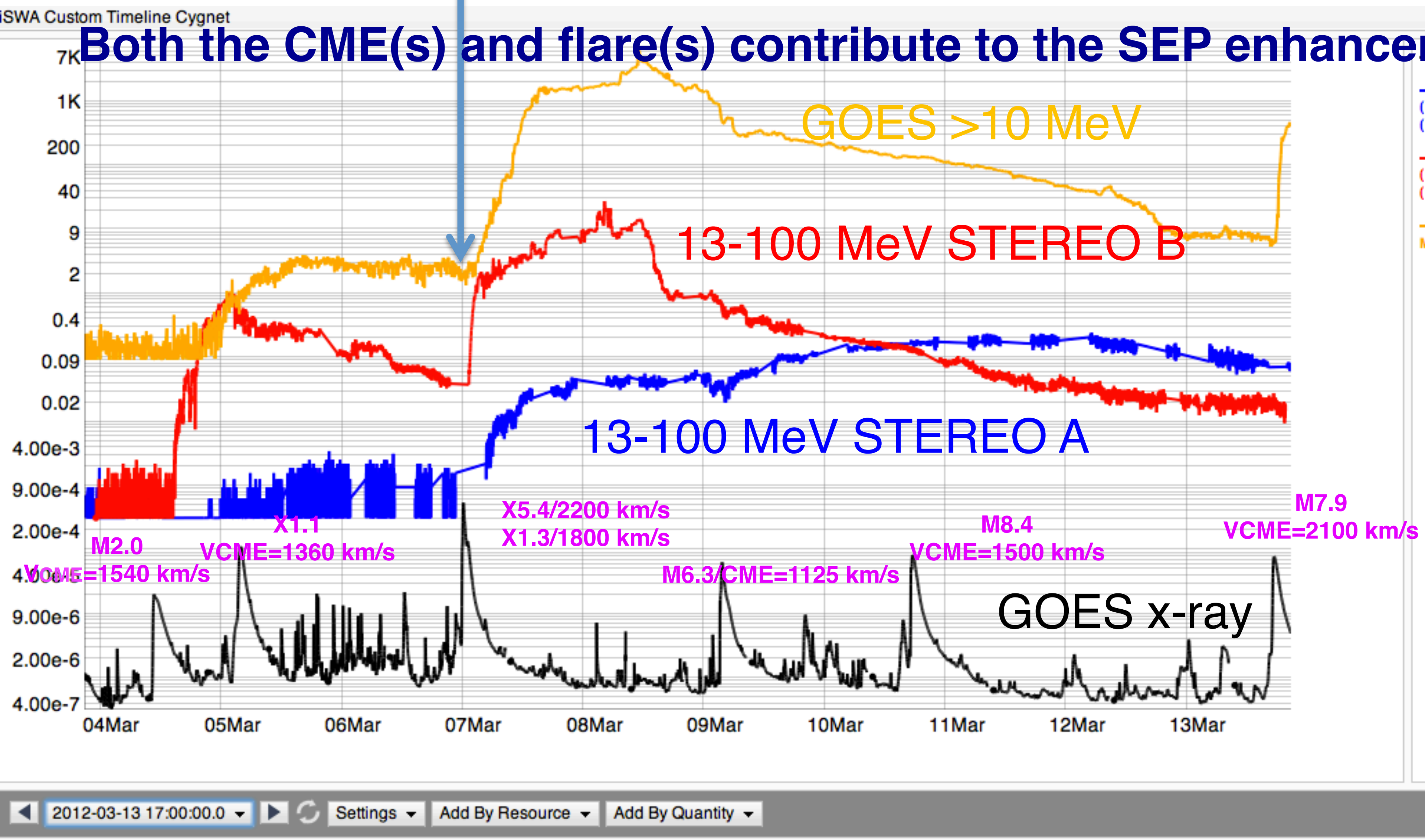


Mars and Earth are aligned! Share a similar magnetic connectivity

We may lose real-time SEP at STEREOs


Earth
Mars
Mercury
Venus
Spitzer
Stereo_A
Stereo_B
West 90
Ecliptic Plane
LAT = −7.2°
W90
E90
Earth
0°
East 90
R² N (cm⁻³)

SEP: proton radiation



SEP Layout

http://bit.ly/alert_SEP_layout

Summary

- **Our goal is to understand extreme energetic particle events**
- We use a new solar wind model driven by Alfvén waves coupled to a kinetic model of particle acceleration and transport, acting on observed quiet time particle spectra (scaled back to the corona)
- We find strong acceleration
- Acceleration can vary wildly from different regions of the CME due to interaction with structures in the corona, so **using a single CME speed as a hard predictor of particle acceleration will not work**
- Is it more about the magnetic connectivity of the observer than the properties of the CMEs and flares?
  - 2012 May 17 GLE event suggests it could be

- ***The events from Solar Cycle 24 provide interesting cases to test our model – can we explain the May 17 and July 23 observations?***