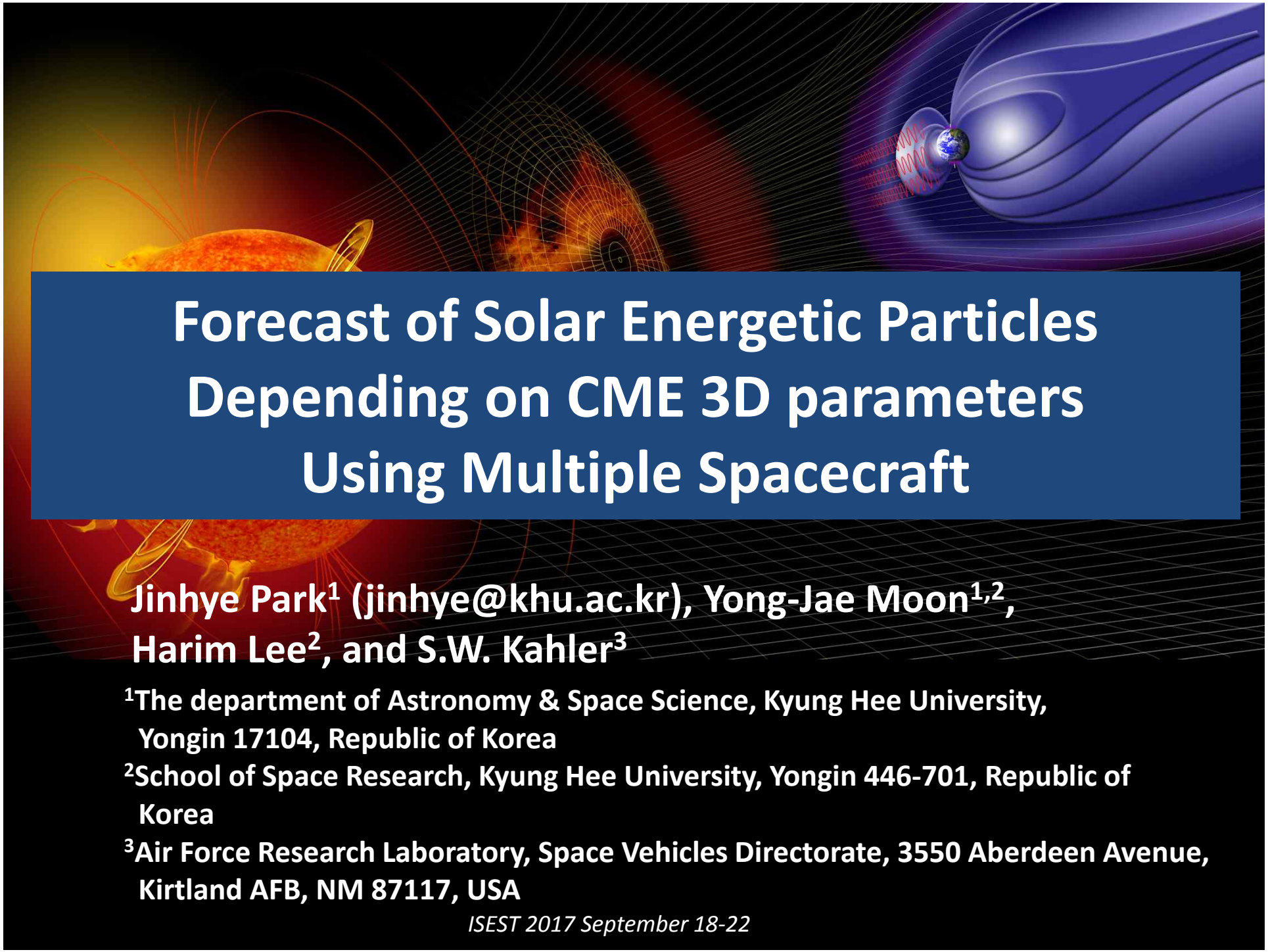

Forecast of Solar Energetic Particles Depending on CME 3D parameters Using Multiple Spacecraft

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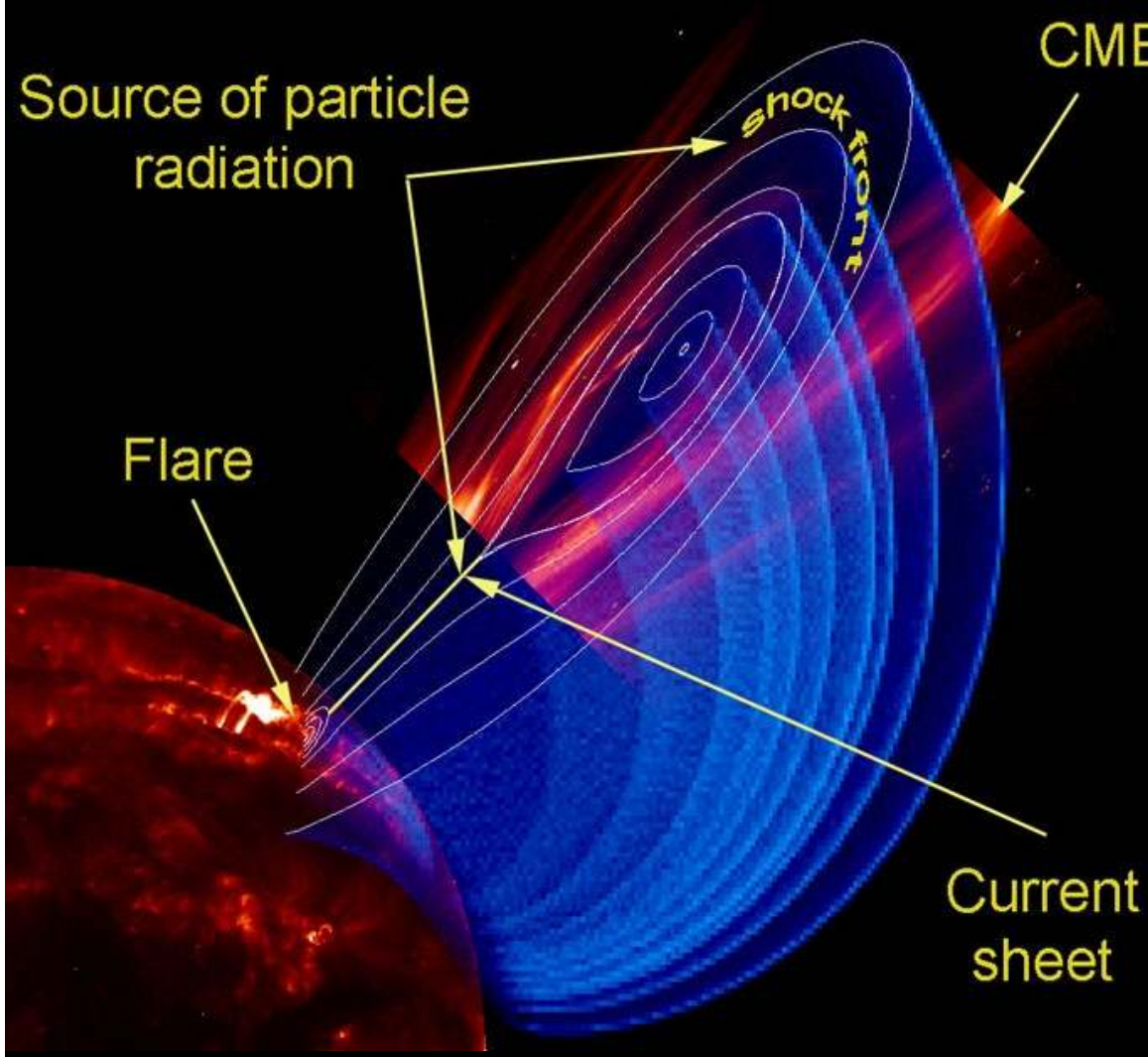
Content

1. Introduction

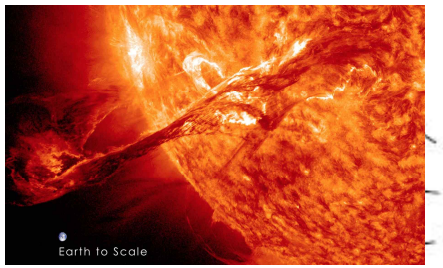


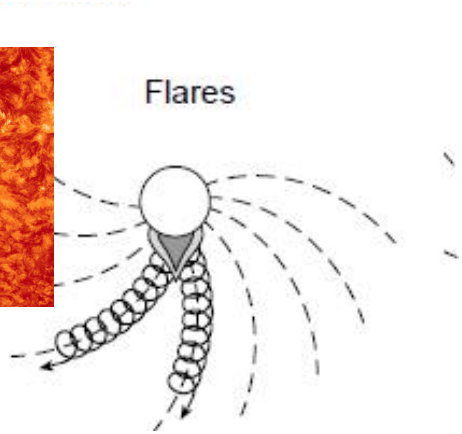
Solar Energetic Particles (SEPs)

They consist of protons, electrons and heavy ions with the energy range from hundreds and thousands keV to MeV.

SEPs are accelerated in flare reconnection regions and/or by CME-driven shocks.

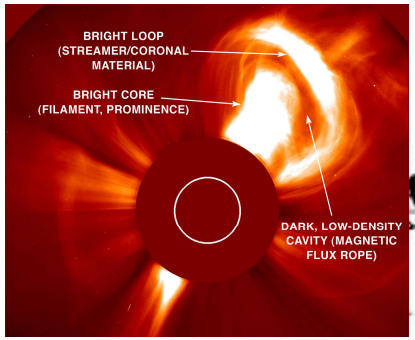
Impulsive

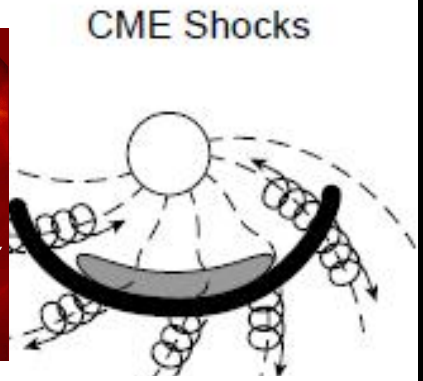




- H-alpha and X-ray flares
- Type III radio bursts
- Short duration, lasting several hours
- Magnetically well-connected
- Longitude cone : < 30°
- Electron-rich

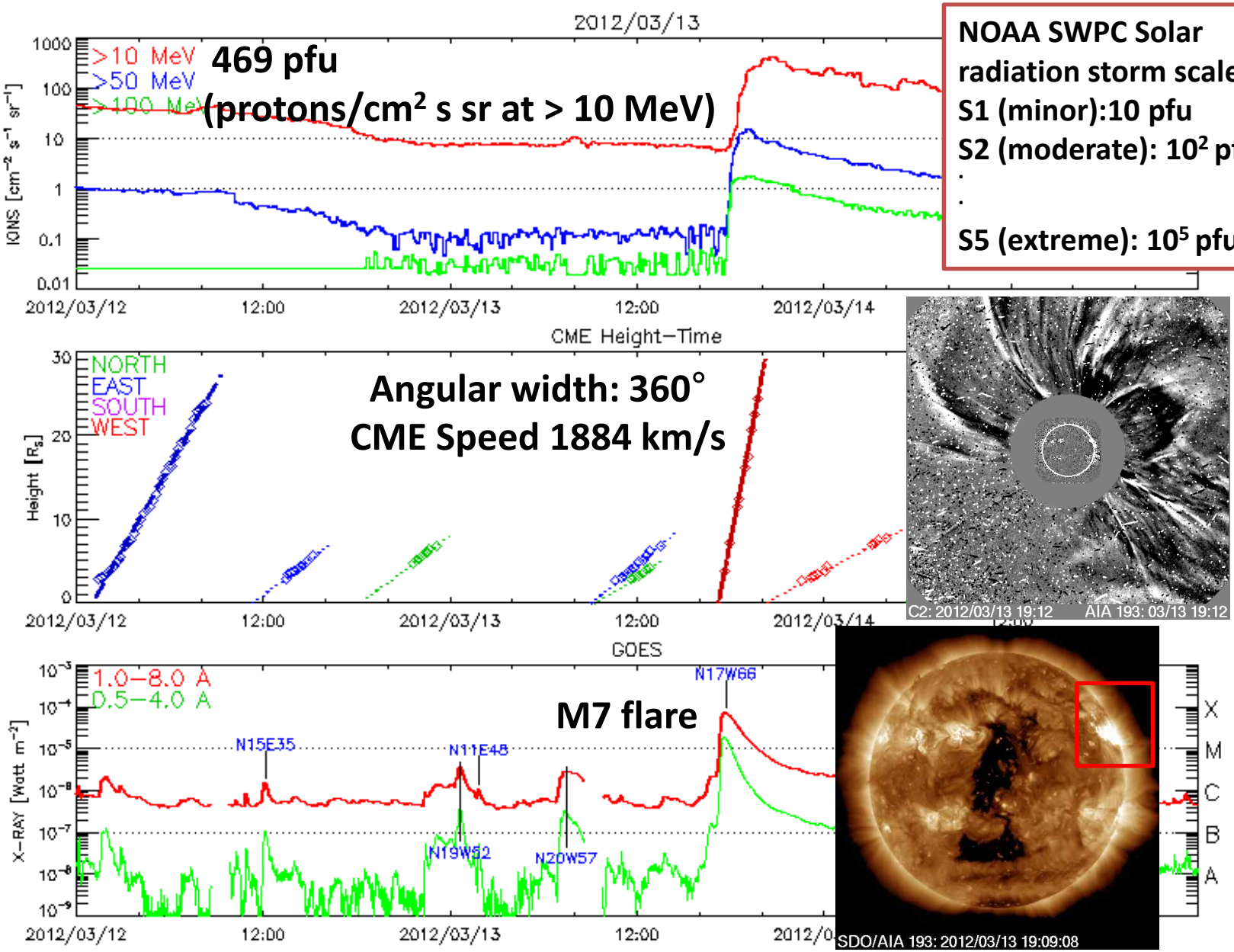
Gradual





- Gradual X-ray flares and the CME shock
- Type II and IV radio burst
- Long duration, lasting several days
- Board range of heliolongitude.
- Longitude cone : ~ 180°
- Proton-rich

SEP event on 2012 March 13



NOAA SWPC customer survey on high-priority space weather forecast (2003)

Priority	Model	Customer example
1	SEP forecast	Commercial airlines HF communication Satellite launch Manned space flight
2	Regional geomagnetic activity forecast and nowcast	Electric power Commercial airlines HF communication
2	Relativistic electron forecast for International space station	Manned space flight
3	Ap prediction	Various military/Civilian users
3	Ionospheric disturbance forecast and nowcast	Navigation(GPS) Explorations Surveying
4	Dst prediction	Various military/ Civilian users

SEP occurrence probability depending on CME 2D parameters

- CME speed and angular width (# of SPEs/# of CMEs), 1997-2006

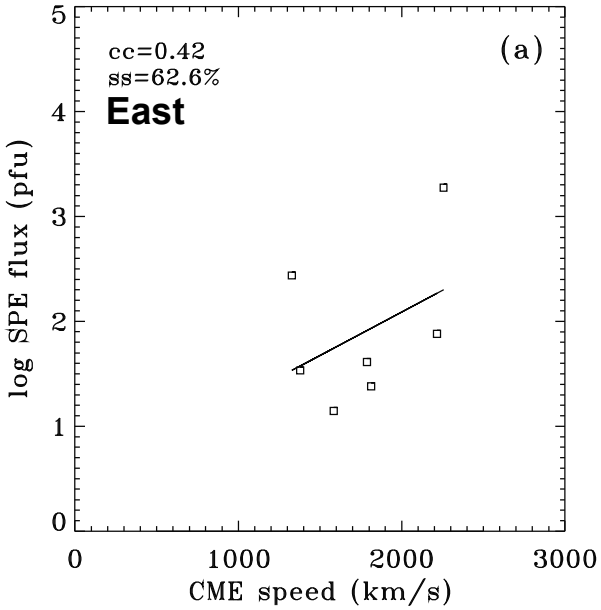
CME	400 ≤ V <1000km/s	1000≤ V<1500km/s	V ≥ 1500km/s
Partial CME (120° – 359°)	0.9% (4/434)	8.2% (8/89)	20.7% (6/29)
Halo CME	5.9% (11/185)	21.3% (19/89)	36.1% (30/83)

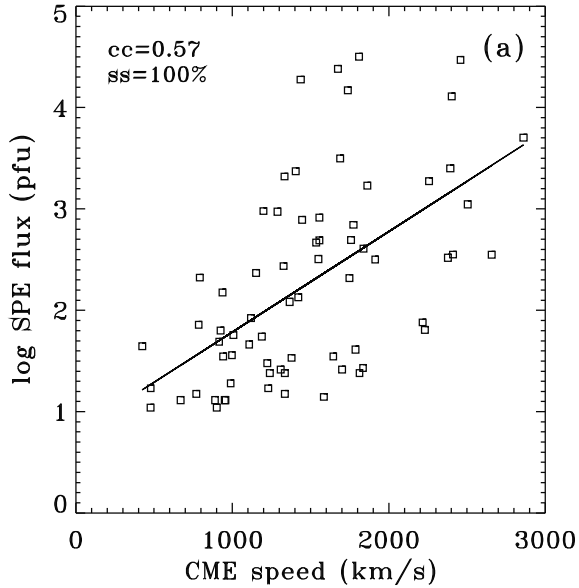
- CME speed and location (# of SPEs/# of CMEs)

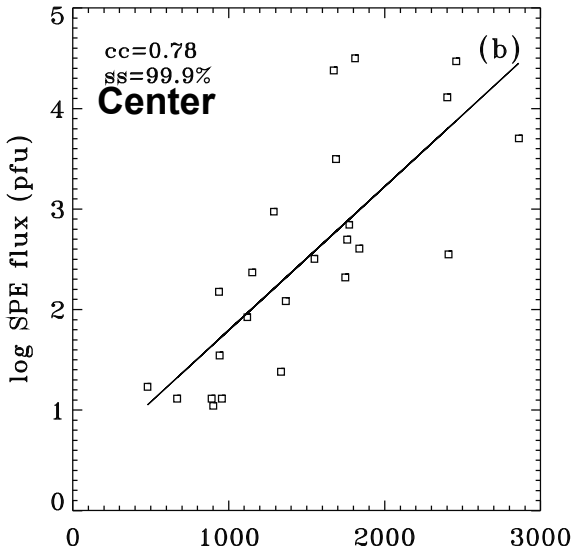
	400 ≤ V <1000km/s	1000≤ V<1500km/s	V ≥ 1500km/s
East	0% (0/91)	5.6% (2/36)	17.2% (5/29)
Center	4.2% (6/42)	12.5% (5/40)	57.1% (12/21)
West	8.7% (9/104)	25.0% (12/48)	44.8% (13/29)

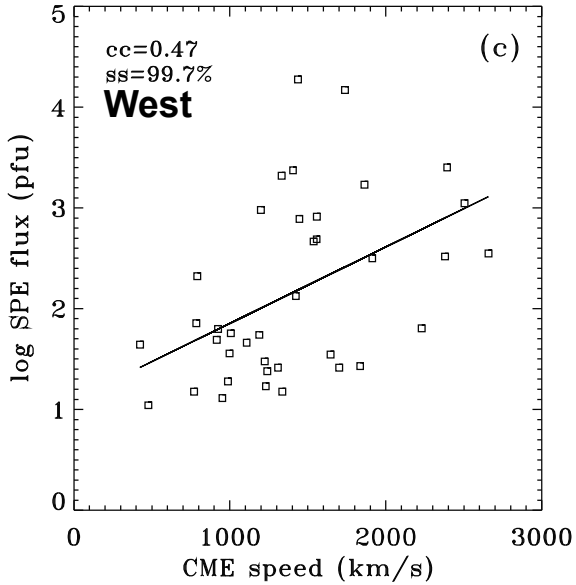
Relationship between CME 2D speed and SEP peak flux

depending on longitude









(Park et al., 2012)

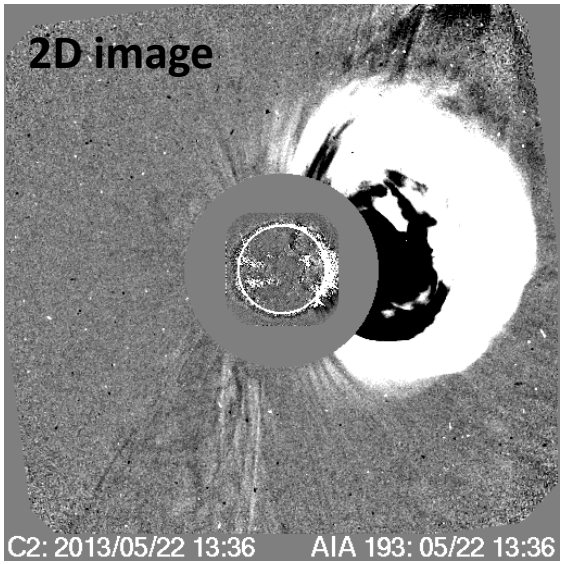
2. Motivation

2D speed
2D angular width
Longitude

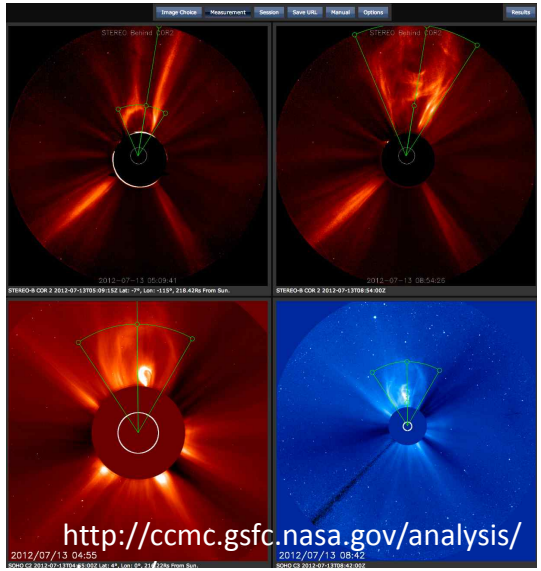
SEP

3D speed
3D angular width
Longitudinal separation angle

Single spacecraft observation



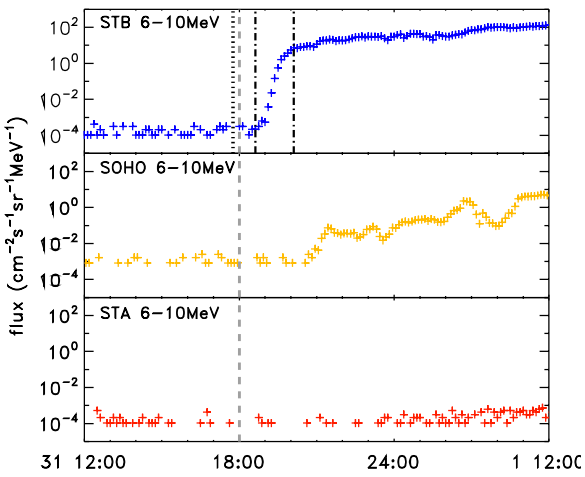
Multi-spacecraft observations



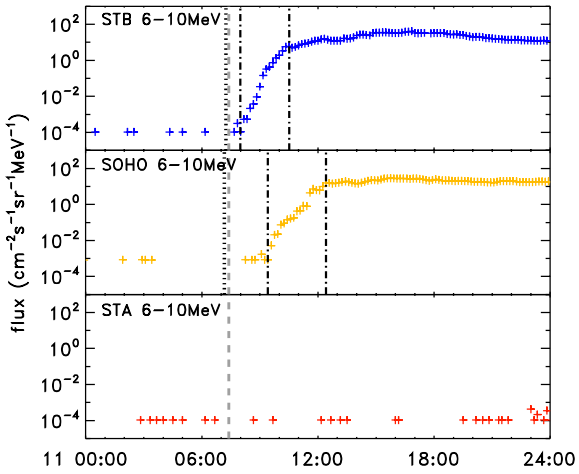
3. Data and Analysis

3.1 SEP peak flux

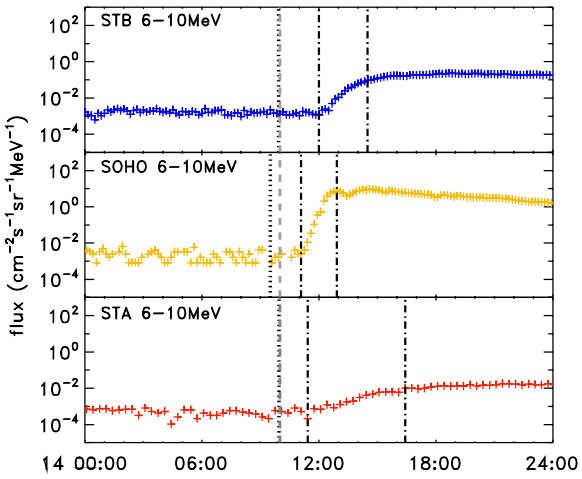
18 events from 2010 to 2013



The event of 2012 August 31



The event of 2013 April 11



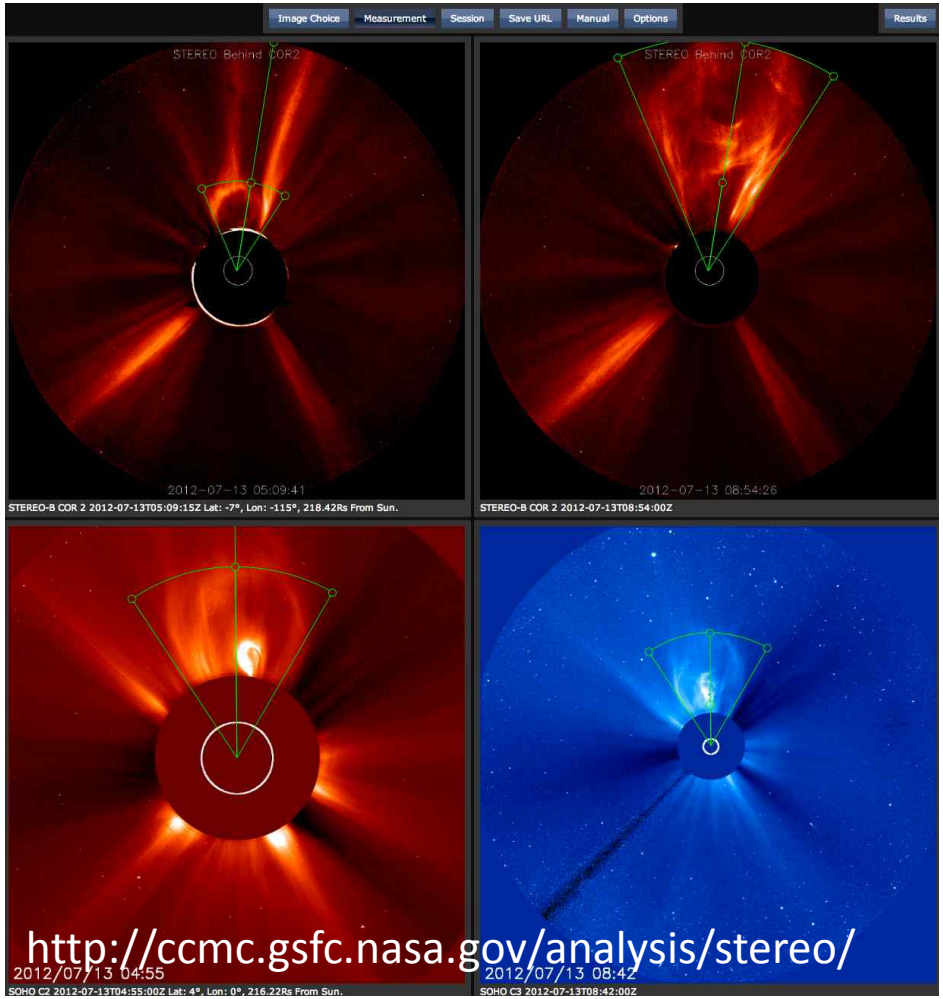
The event of 2010 August 14

STEREO LET and SOHO ERNE: 10 min in the 6-10 MeV proton channel

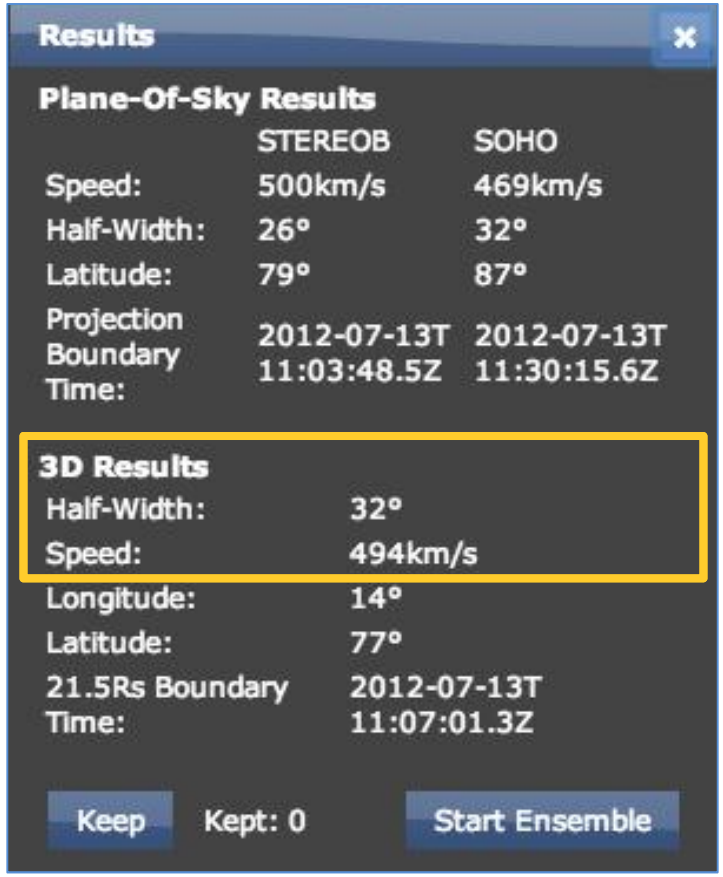
The peak times and peak fluxes are chosen as the points at the top of the of the steep flux rise, which appeared just after the solar eruption, which is marked by the second dash-dot line in Figures.

3.2 CME 3D parameters obtained by StereoCat

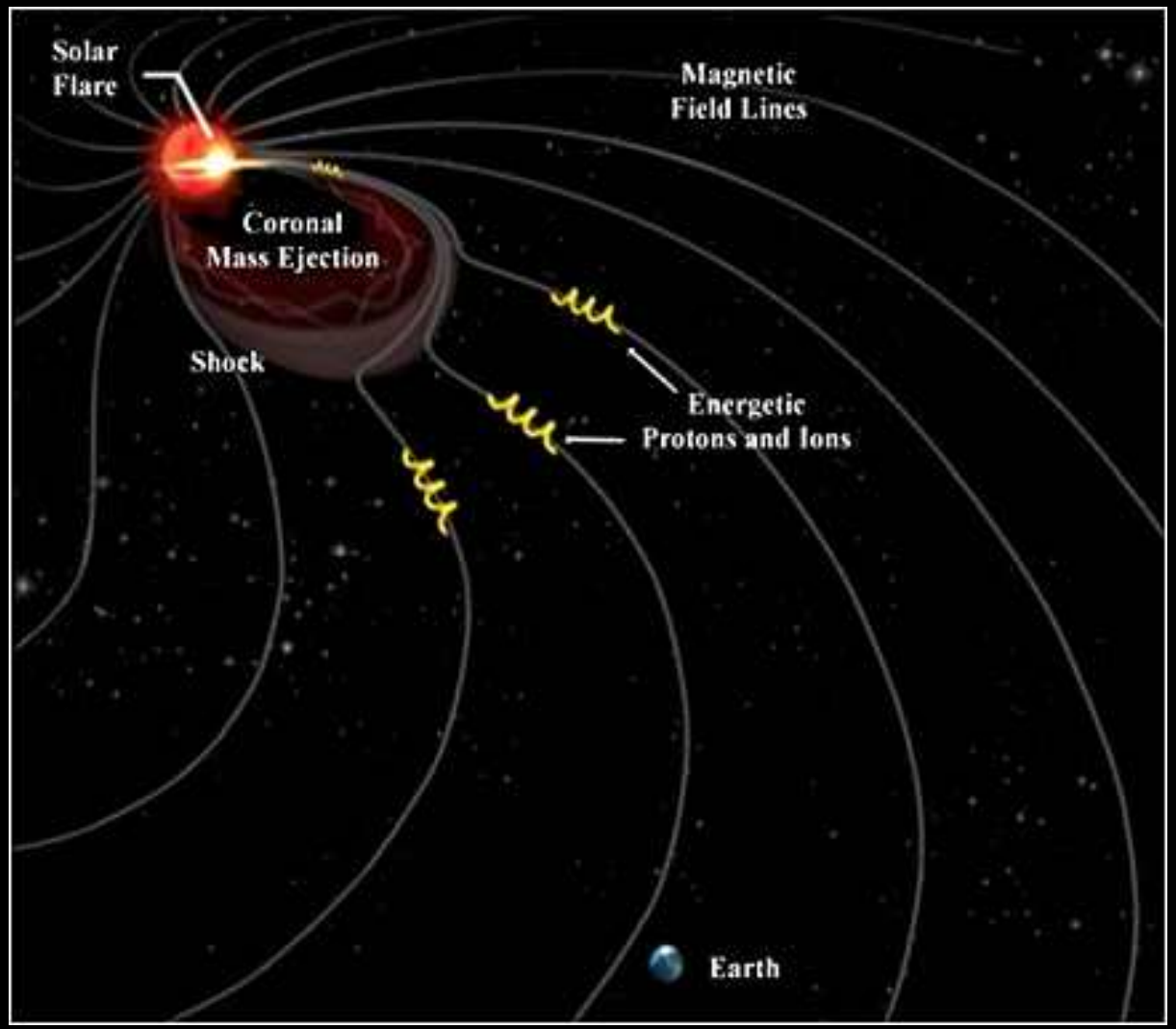
1) Selecting two sequential coronagraphs from SOHO/LASCO C3, STEREO-A and B/SECCHI COR2
2) Measuring the outer edges of a CME



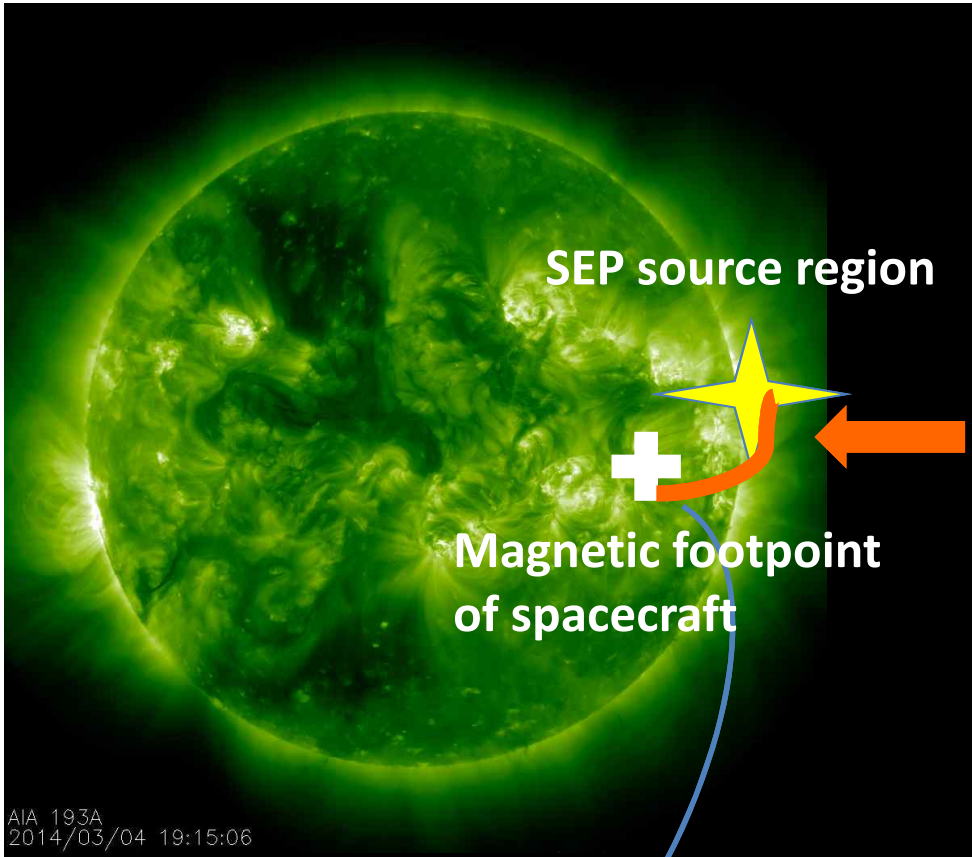
http://ccmc.gsfc.nasa.gov/analysis/stereo/



3.3 Longitudinal separation angle



Credit: http://spaceweather.uma.es/solarstorms.html



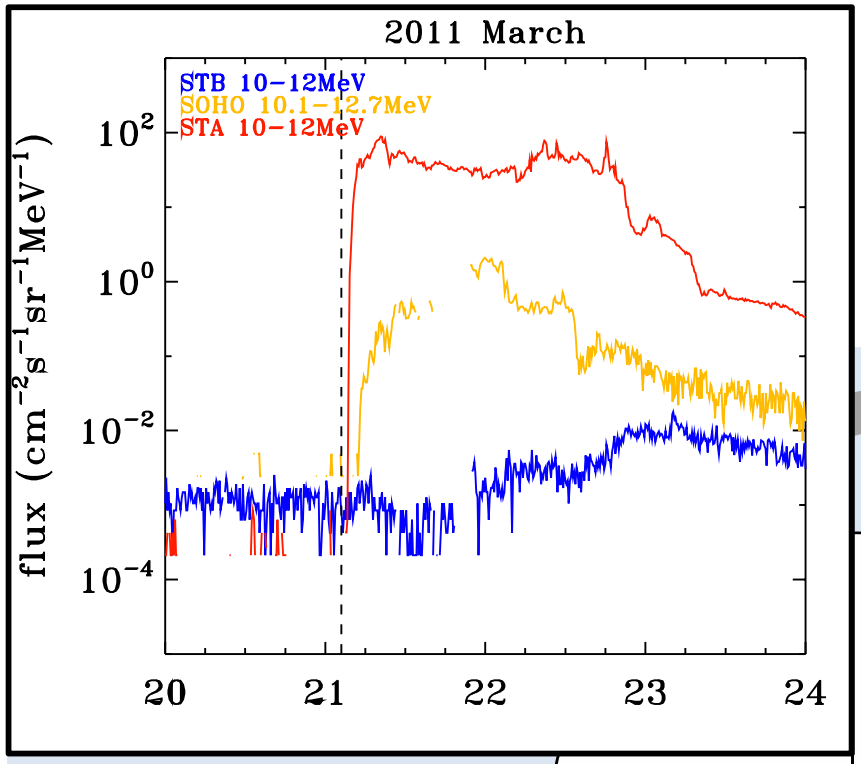
Longitudinal separation angle: longitudinal angles from source regions of SEPs to the photospheric magnetic footpoints of spacecraft

The magnetic footpoint of the spacecraft at $2.5R_{\odot}$ is calculated by assuming a Parker spiral, given by the equation

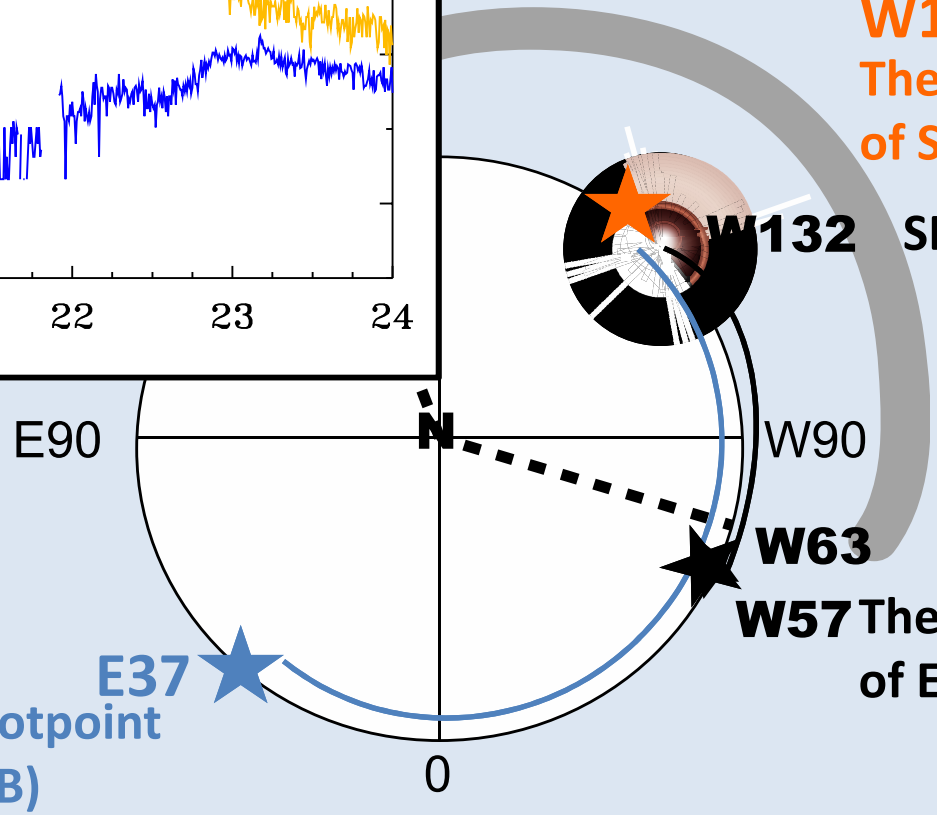
$$\phi = D_{\Omega}/V_w + \phi_0.$$

ϕ : the magnetic footpoint of spacecraft
Φ_0: spacecraft longitude
D : the distance to the Sun
Ω: the Carrington period of 27.3 days
V_w : the solar wind speed

Magnetic footpoint: W50~70° depending on solar wind speed (300~800km/s)



2011 March 21



W142
The magnetic footpoint of STEREO-A (STA)

W132 **SEP Source region**

W63

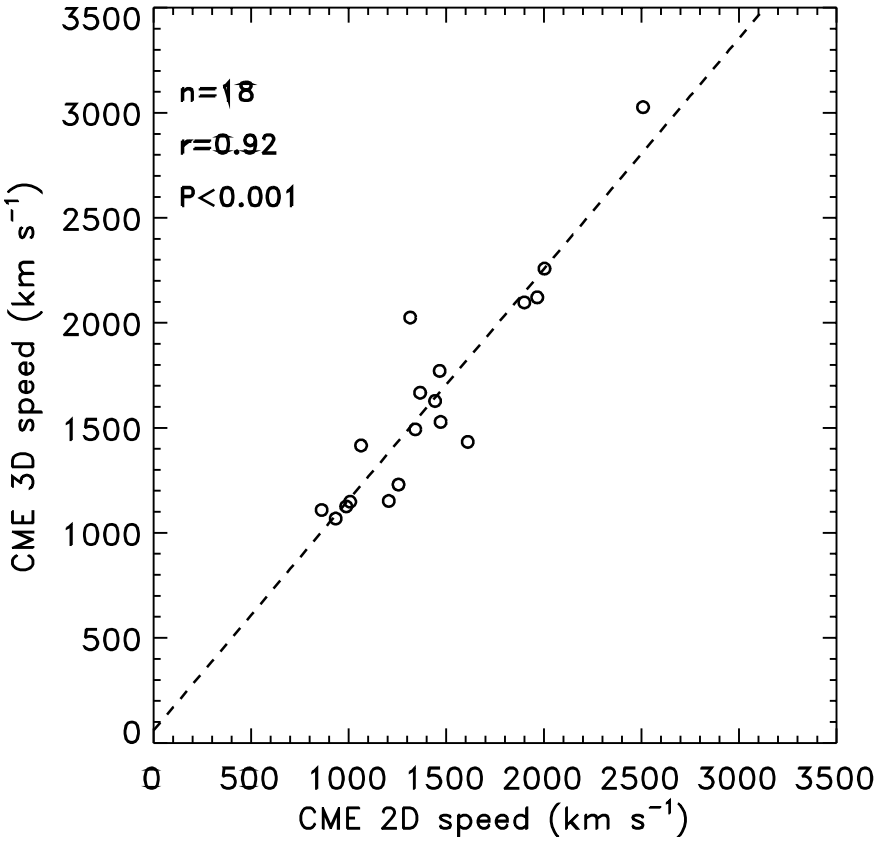
W57 **The magnetic footpoint of EARTH (E)**

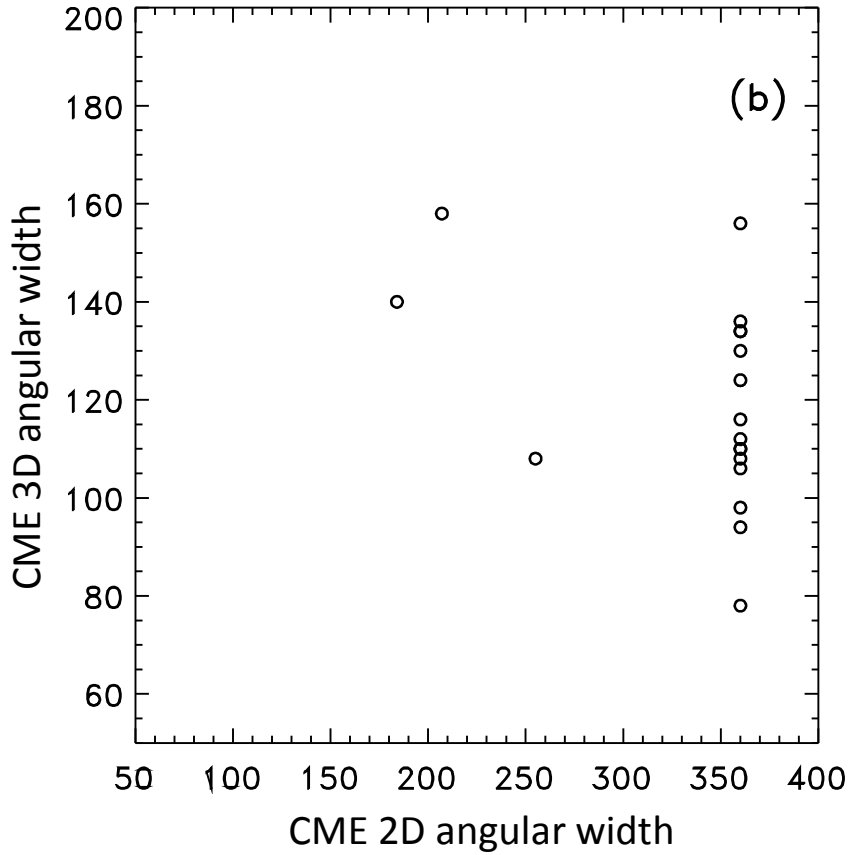
STB θs: 169°
E θs: 75°
STA θs: 10°

E37
The magnetic footpoint of STEREO-B (STB)

4. Result

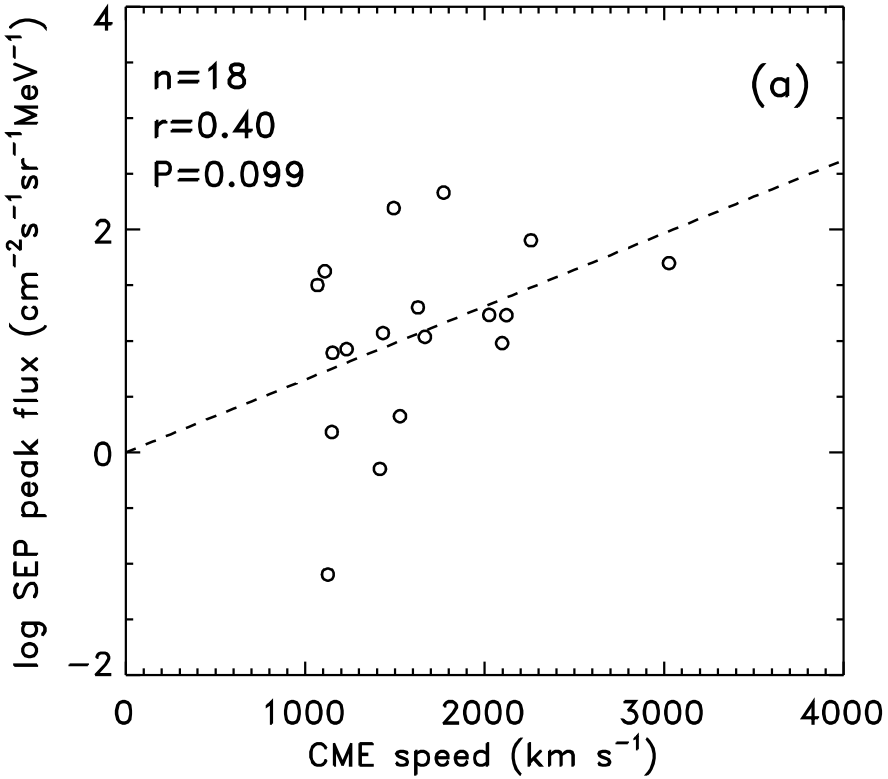
4.1 CME 3D Vs 2D parameters

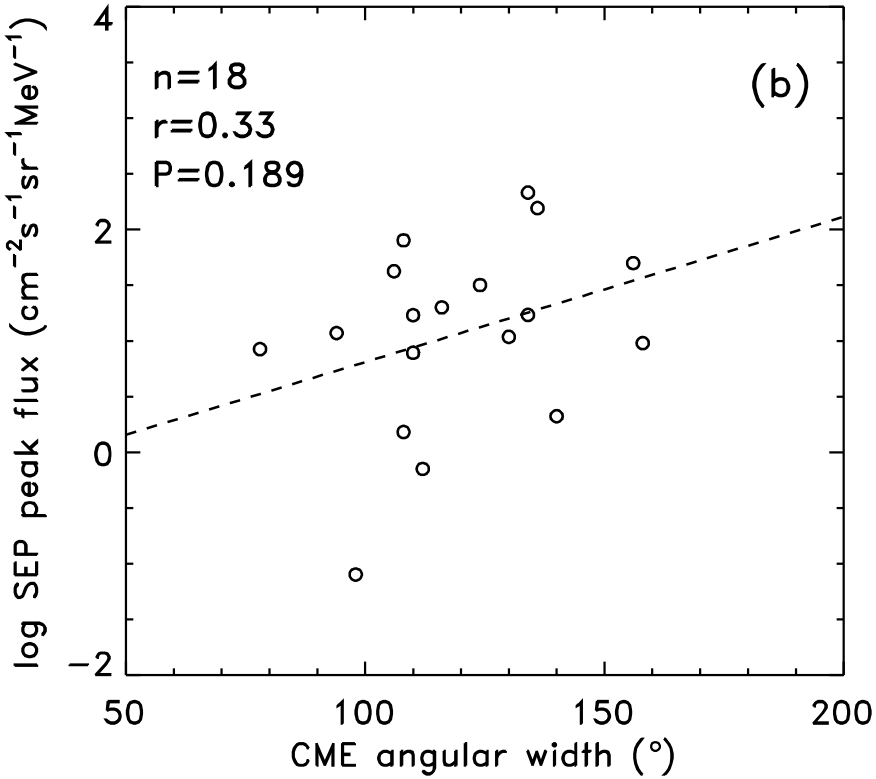




4.2 Relationship between SEP peak flux and CME 3D parameters

CME 3D speed as well as 3D angular width

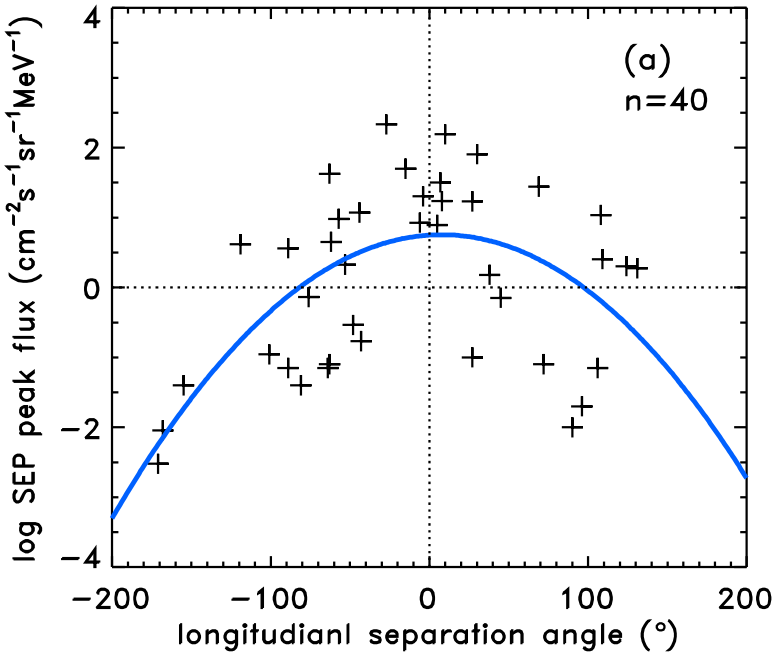


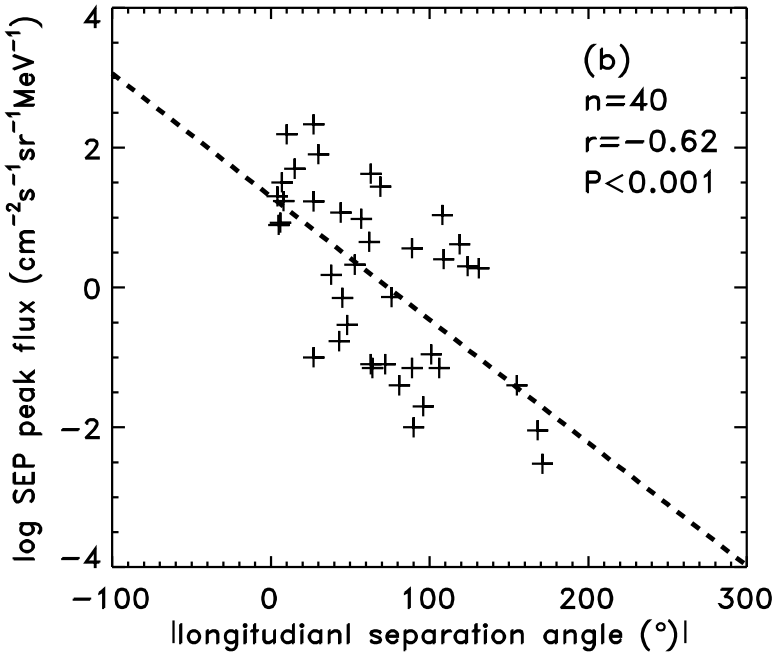


(Park et al. 2017)

The dashed line represents a linear square fit. In the figure, n, r, and p represent number of data, correlation coefficient, and p-value, respectively.

Relationship between SEP peak flux and longitudinal separation angle





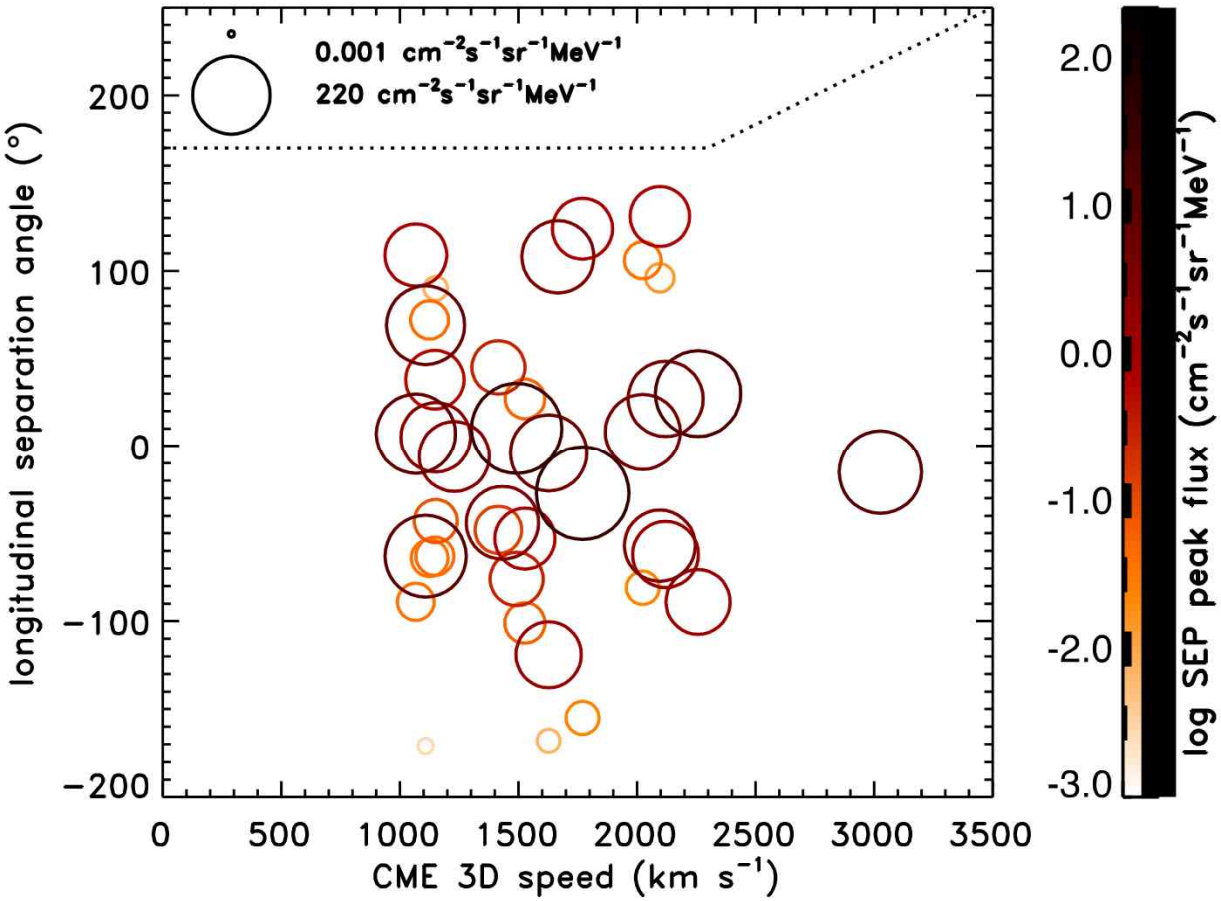
$$I_P = I_0 \mathrm{e}^{-\mathrm{k}(\theta_\mathrm{s}-\theta_0)^2}$$

I_p:SEP peak flux (cm^{-2} s^{-1} sr^{-1} MeV^{-1})
Θ_s: separation angle in radians
Θ_0: the center of a event in radians (0.13)
I_0 :SEP peak flux at θ_0 (5.67 cm^{-2} s^{-1} sr^{-1} MeV^{-1})
k: 0.71
(1.15, Lario et al. 2006, 2013)

$$I_P = I_0 \, \mathrm{e}^{-\mathrm{k}\theta_\mathrm{s}}$$

I_p: SEP peak flux (cm^{-2} s^{-1} sr^{-1} MeV^{-1})
Θ_s: separation angle in radians
I_0: 19.89 cm^{-2} s^{-1} sr^{-1} MeV^{-1}
k: 2.32
(1.604, Kahler 1982)

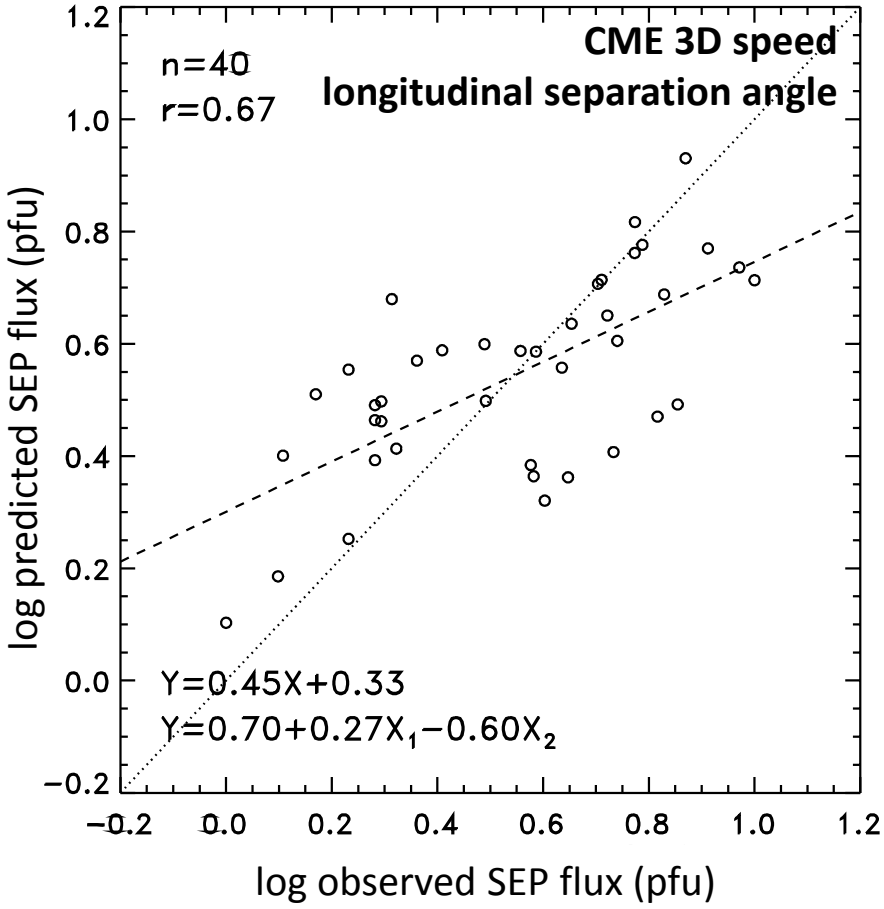
SEP peak flux depending on CME 3D speed and longitudinal separation angle



Stronger peak fluxes (large circles) are mostly located near zero of longitudinal separation angle.

Most of the weaker peak fluxes (small circles) are located either at relatively slow CME 3D speeds (< 1500 km s−1) or large separation angles.

4.3 Prediction of SEP peak flux using multiple regression method



Relative importances of CME 3D parameters

$$\overline{\log_{10} I_p} = 0.70 + 0.27\overline{V_r} - 0.60\overline{\theta_s}$$

I_p:SEP peak flux

V_r: CME 3D speed

Θ_s: separation angle in radian
(Input parameters are normalized)

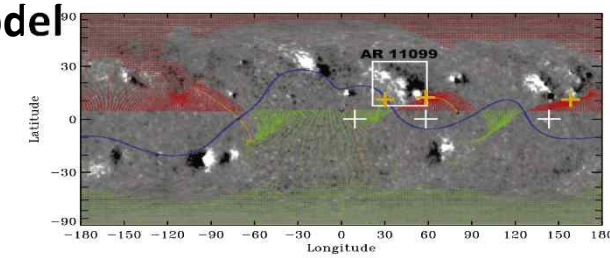
The longitudinal separation angle is the most important parameter, and the CME 3D speed is secondary on SEP peak flux.

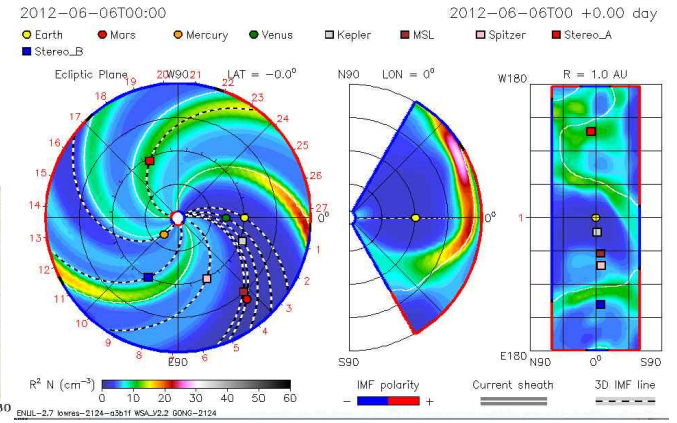
5. Summary

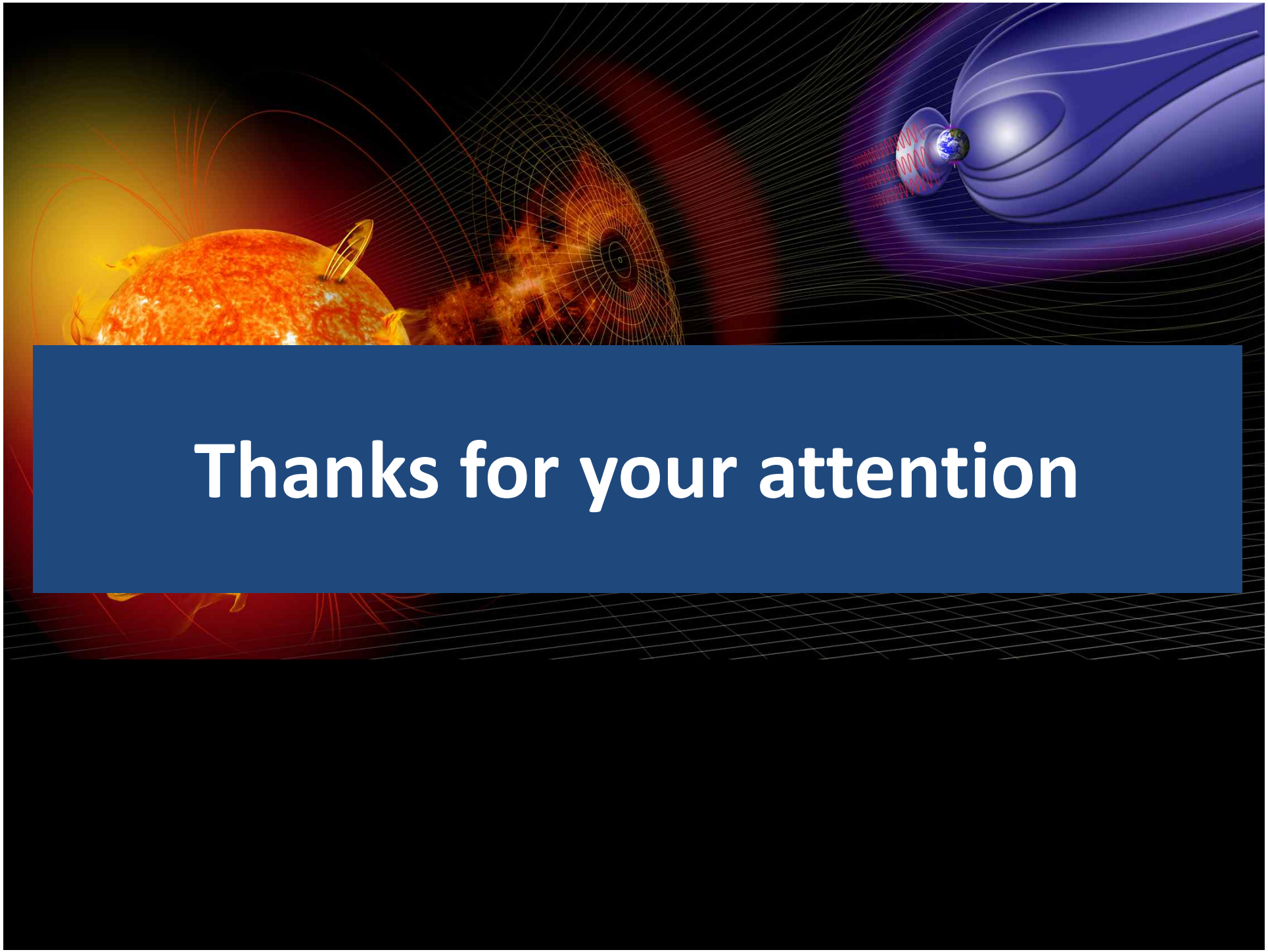
- We find that SEP peak fluxes are associated with CME 3D speed. There is a tendency that the SEP peak fluxes increases with 3D angular widths.
- There is a noticeable anti-correlation (r=-0.62) between SEP peak flux and separation angle.
- The multiple regression method between SEP peak fluxes and CME parameters shows that the longitudinal separation angle is the most important parameter, and the CME 3D speed is secondary on SEP peak flux.

To examine the magnetic connectivity between SEP sources and spacecraft

- Parker spiral approximation + PFSS
- WSA-ENLIL model






Thanks for your attention