Solar Energetic Particles within the STEREO era: 2007-2012

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Outline

Motivation

Solar Terrestrial Relations Observatory - STEREO

Instrumentation

Compilation of the STEREO Catalogues

Why are STEREO Catalogues Useful?

- Multi-spacecraft event case studies
- Statistical results

Summary

Motivation

Create comprehensive
Solar **E**nergetic **P**article Event lists
[Catalogues] based on **STEREO** recordings

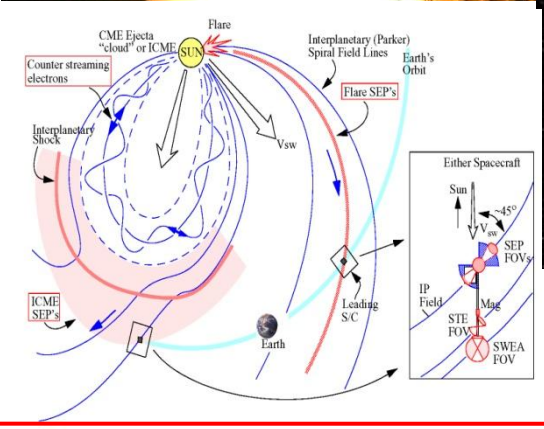
(Req#1) | SEP event catalogues (optimally) should provide:

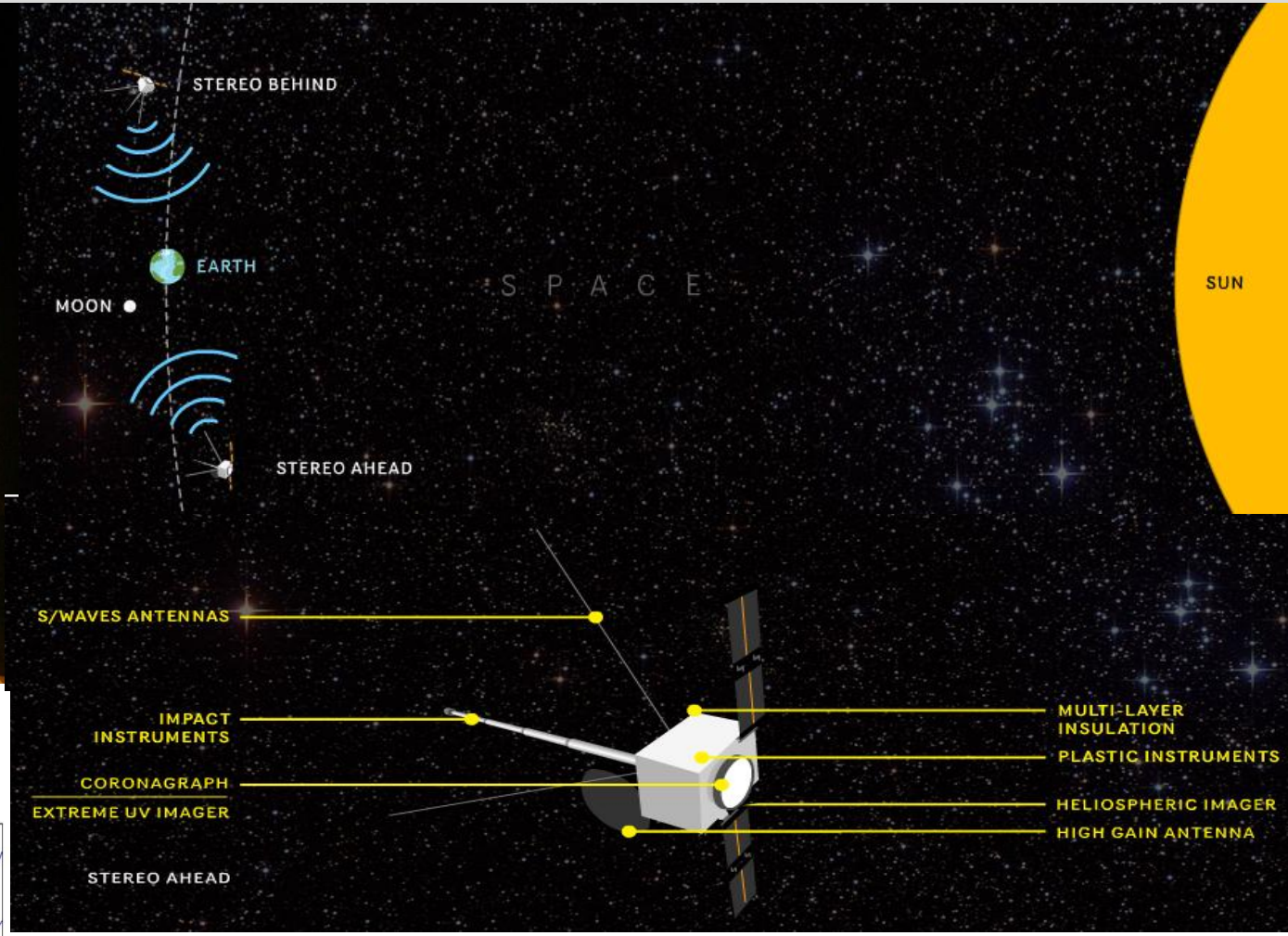
- the event characteristic parameters (year, month, day, onset and peak time)
- information on the s/c, the species and the energy channels used
- reports on the importance of the SEP event

(Req#2) | A complete description of an SEP requires:

- reports on parameters of the solar activity that can be associated with each SEP event
- the solar source associated with an SEP event identified by the active region number and the coordinates of the flare on the solar disk
- observational data accompanying the source activity (i.e. soft X-rays, hard X-ray bursts in different energy ranges, solar radio emissions, radio bursts)

Solar Terrestrial Relations Observatory-STEREO





http://stereo.gsfc.nasa.gov/launch.shtml *Luhman et al., 2008*

http://www.solarstormwatch.com/mission_briefing/the_stereo_spacecraft

Instrumentation

stereo - impact

In-situ Measurements of Particles and CME Transients (IMPACT)

Low Energy Telescope (LET)

p: 1.8-10 (15) MeV

He: 4-10 (15) MeV/n

heavy ions

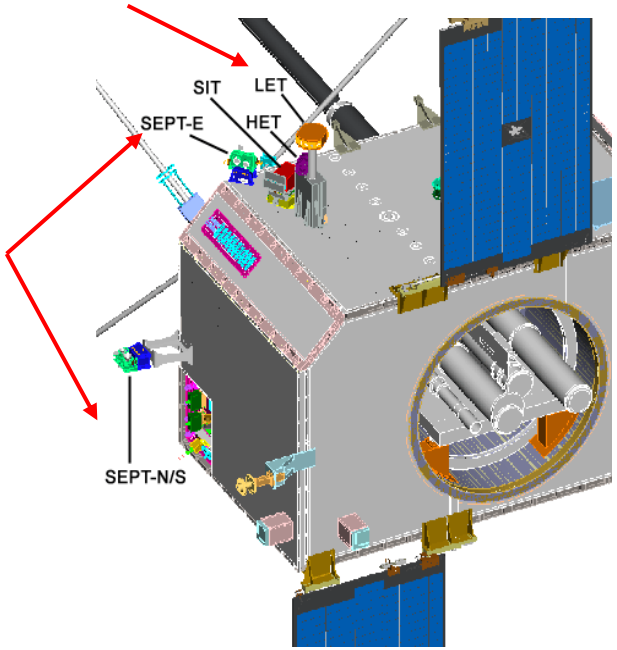
Two 133° x 29° view cones

Solar Electron Proton Telescope (SEPT)

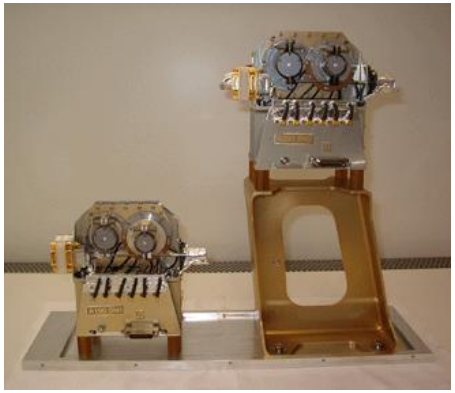
e-: 0.065-0.43 MeV

ions: 0.084-6.5 MeV

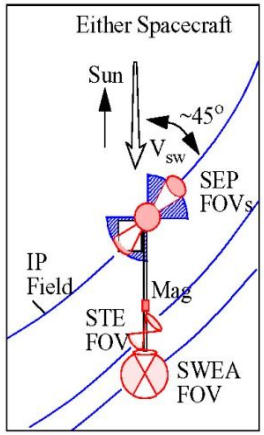
52° and 52.8° view cones; four directions



Mewaldt et al., 2008



Müeller-Mellin et al., 2008



Luhman et al., 2008

Compilation of the STEREO catalogues

Criteria

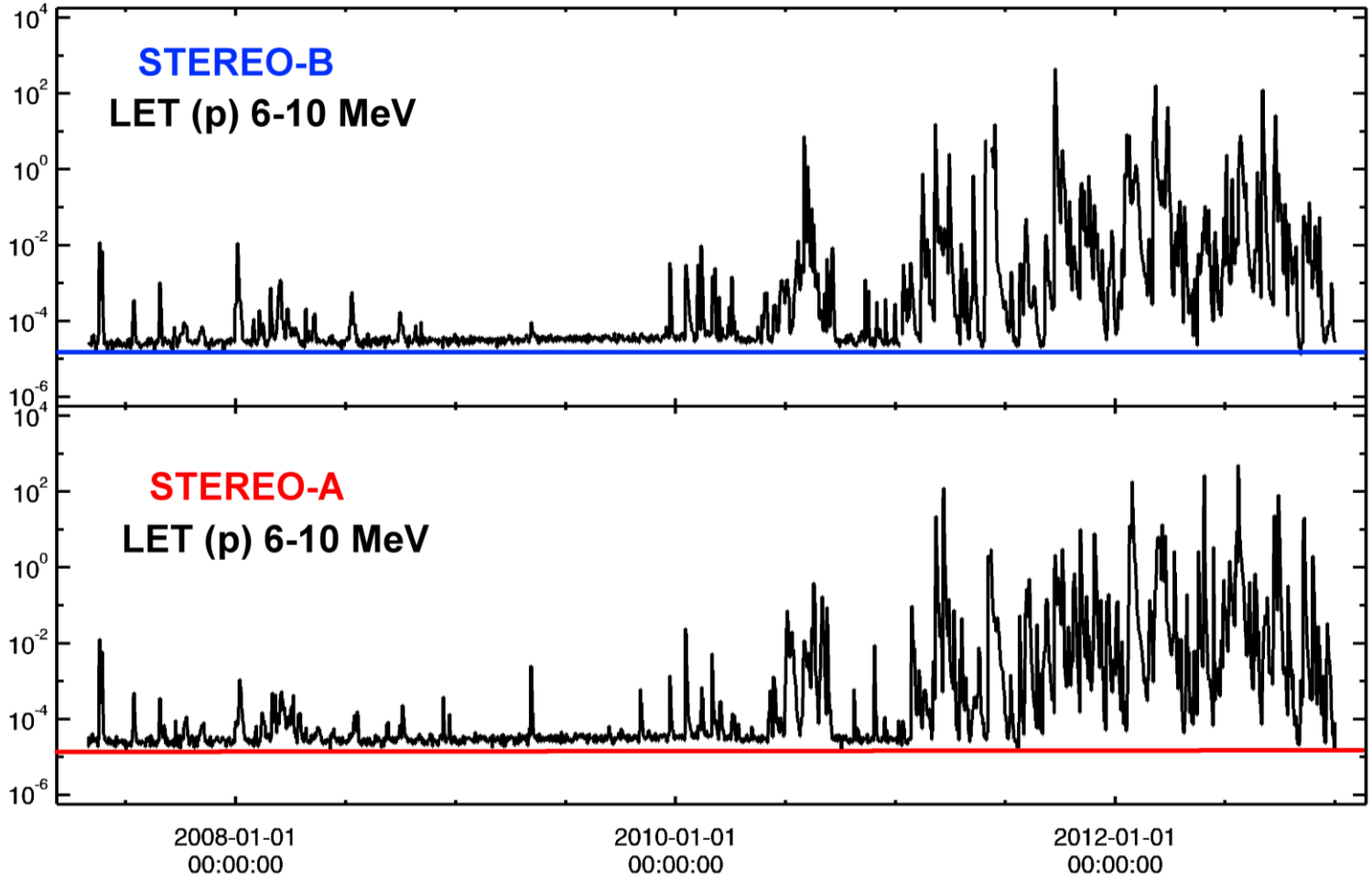
- Selection of events using **STEREO/LET protons** with **6 MeV < E <10 MeV**:

  - Increases **above background**
  - No other **intensity threshold** applied
  - Cross-check with **electrons** (SEPT)
  - Cross-check with **CIRs/SIRs /ICMEs/Shocks**

Papaioannou et al., 2013a;b

Compilation of the STEREO catalogues

A. Increases above background



Procedure

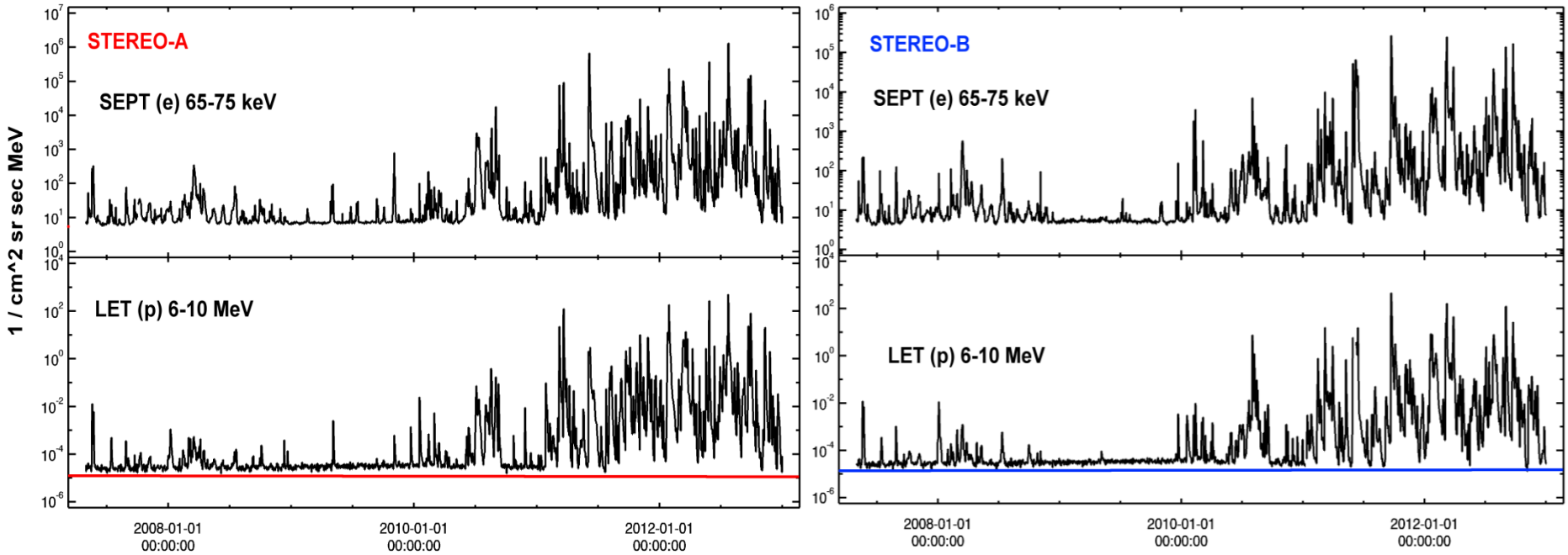
- All enhancements above the quiet time background have been tabulated

Background

- 2 x 10^{-5} particles [cm^{-2} sr^{-1} s^{-1} MeV^{-1}]

Compilation of the STEREO catalogues

B. Cross-check with electrons (SEPT)



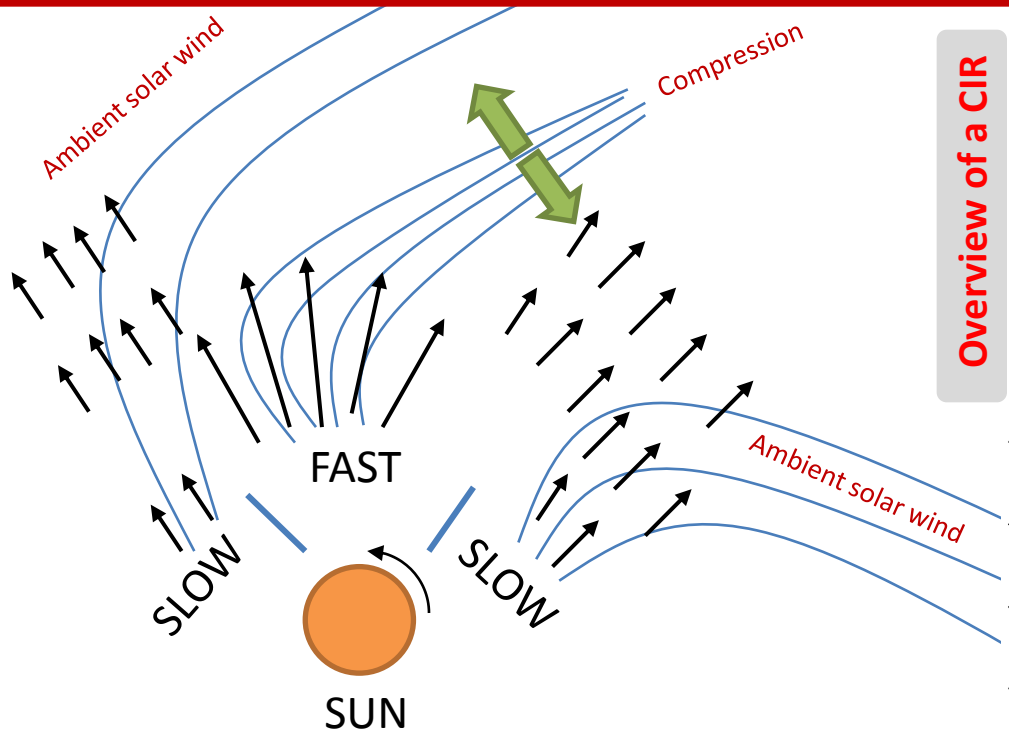
Electrons

- **A parallel scanning of the near-relativistic SEPT electrons for the same time period (i.e. 2007-2012) has been performed**

Papaioannou et al., 2013b

Compilation of the STEREO catalogues

C1. Cross-check with CIRs/SIRs

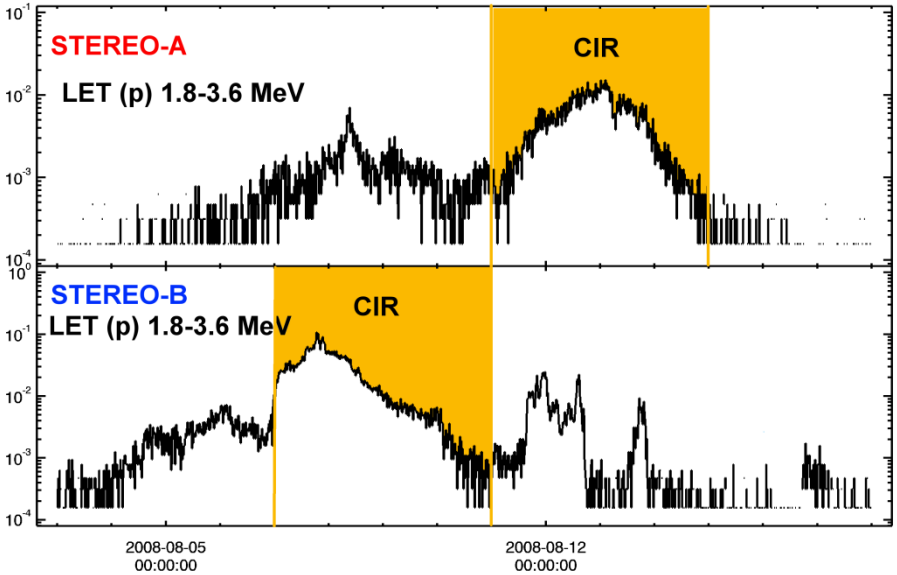


$$t_A - t_B = \frac{\Phi_A - \Phi_B}{\Omega} + \frac{r_A - r_B}{u_{SW}}$$

figure adapted by Gosling & Pizzo, 1999 [Papaioannou, 2012]

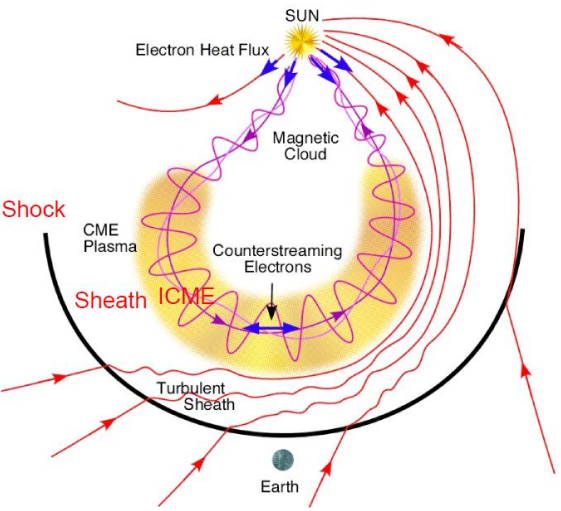
Overview of a CIR

- **Two dominant solar wind speeds:**
  - Fast: ≈ 700 km s-1
  - Slow: ≈ 350 km s-1
- **Interactions between these form CIRs**
- **Seen as enhancements in SEP measurements**
- **Prevalent during solar minimum**



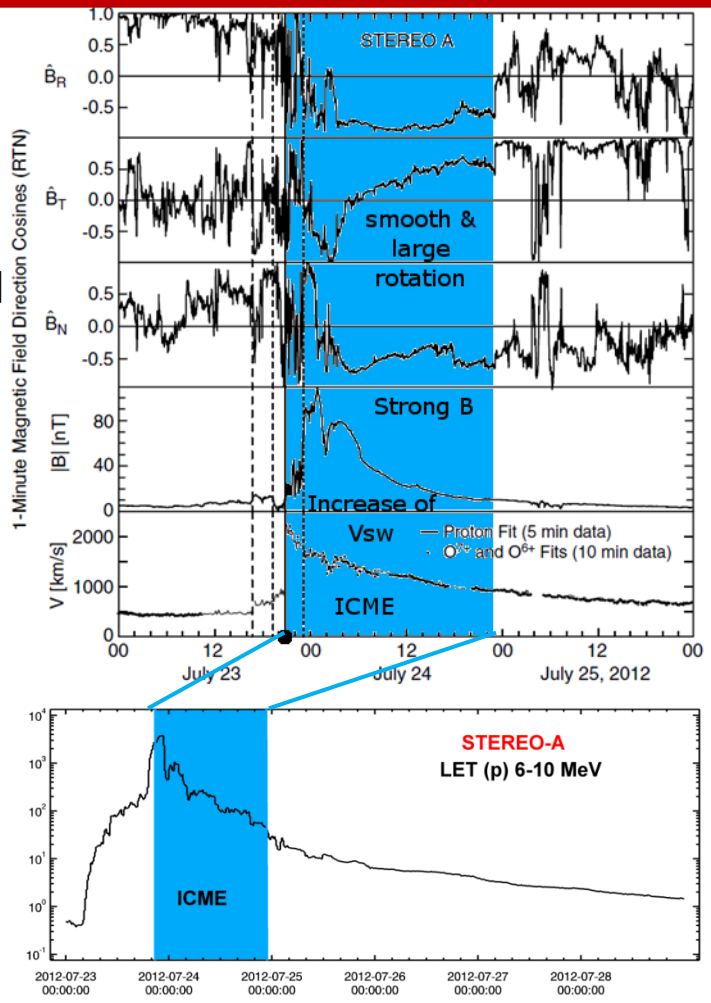
Compilation of the STEREO catalogues

C2. Cross-check with ICMEs/Shocks



Signatures of ICMEs (Magnetic field)

- **Smooth rotation**
  - – > 30^0
- **Strength of the magnetic field**
  - – > 10 nT
- **Presence of MCs**
  - – ~ 30% of ICMEs



➡ **Need to know the IP conditions through which particles propagated**

Details: N. Agueda, *this Splinter*

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http://www-ssc.igpp.ucla.edu/~jlan/STEREO/Level3/STEREO_Level3_Shock.pdf
http://www-ssc.igpp.ucla.edu/~jlan/STEREO/Level3/STEREO_Level3_SIR.pdf
http://www-ssc.igpp.ucla.edu/~jlan/STEREO/Level3/STEREO_Level3_ICME.pdf

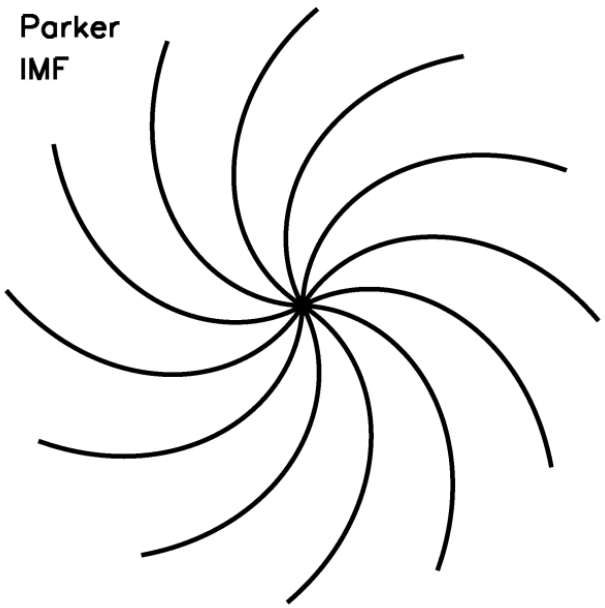
Zurbuchen & Richardson., 2006

Russel et al., 2013

Time-Shifting Analysis (TSA)

Calculating the path travelled by the particles

✓Calculation of the nominal Parker (or Archimedean) spiral



$$L(u_{sw}) = z(r_{S/C}) - z(R_{\odot})$$

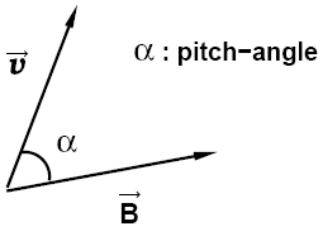
$$z(r) = \frac{a}{2}\left[\ln\left(\frac{r}{a} + \sqrt{1+\frac{r^2}{a^2}}\right) + \frac{r}{a}\sqrt{1+\frac{r^2}{a^2}}\right]$$

$$a = u_{sw}/\Omega_{\odot} \qquad 2\pi\Omega_{\odot}^{-1} = 24.47\ \mathrm{d}$$

Vainio et al., 2013

Time-Shifting Analysis (TSA)

Propagation of the particles



- **Scatter-free propagation**

✓For the first arriving particles we assume α=0° and μ=1.

$$\mu = \cos\alpha$$

$$t_{\mathrm{rel}}(E) = t_{\mathrm{onset}}(E) - 8.33\,\frac{\mathrm{min}}{\mathrm{AU}}\,L\beta^{-1}(E)$$

- **NR Electrons**

✓Onset time for **STEREO/SEPT** @ **55-85 keV**

✓Velocity of **SEPT electrons**, based on mean energy 68.4 keV: **0.47c**

- **LET Protons**

✓Onset time for **STEREO/LET** @ **6-10 MeV**

✓Velocity of **LET protons** based on mean energy 7.75 MeV : **0.12c**

Malandraki et al., 2012

STEREO/LET Catalogues

STEREO-A *Sample*

Home
Event catalogues
Login
Username:
Password:
Log in

Event catalogues

Event catalogue selection

Event catalogue: SEPServer STEREO-A Catalogue

SEPServer STEREO-A Catalogue		SEP Observations						Solar observations		Spacecraft Location			Comments
		LET Protons (6-10 MeV)			SEPT Electrons (55-85 keV)								
Event #	Date	p^- onset	p^- peak time	p^- peak value	e^- onset	e^- peak time	e^- peak value	Start time	Stop time	*R* (AU)	Helio Long. (deg)	Helio Lat. (deg)	
0	19.05.2007	16:45	23:45	2.25E-02	13:50	18:05	7.28E+02	12:30	15:00	0.959666	5.672	-1.434	
1	23.05.2007	10:25	3:45 (DOY 144)	1.32E-02	6:30	10:25	5.56E+02	7:00	10:00	0.959303	6.017	-0.903	
2	05.04.2008	20:20	21:00	1.50E-03	16:32	16:45	4.56E+02	12:00	24:00	0.951614	24.119	-4.192	
3	11.12.2008	11:50	13:30	1.90E-03	9:58	10:36	2.46E+01	8:00	11:00	0.967227	42.068	-5.346	
4	02.05.2009	-	-	-	20:02	20:46	8.21E+02	18:00	22:00	0.957439	47.472	1.849	
5	05.05.2009	10:30	13:30	7.40E-03	8:44	9:25	5.03E+02	8:00	11:00	0.957262	47.719	2.243	
6	03.11.2009	5:20	8:20	2.60E-03	3:57	4:25	2.78E+03	3:00	6:00	0.966748	62.382	-3.489	
7	05.11.2009	8:00	13:00	8.00E-04	0:16	3:06	4.29E+02	23:00 (DOY 309)	2:00	0.966819	62.439	-3.701	
8	22.12.2009	8:20	15:50	4.20E-03	6:26	7:26	3.40E+01	4:00	7:00	0.966624	63.904	-0.108	
9	17.01.2010	7:40	15:00	5.03E-02	5:18	9:15	2.44E+02	3:00	6:00	0.964979	64.68	-7.057	
10	08.02.2010	-	-	-	8:28	12:53	9.10E+01	7:00	10:00	0.963003	65.28	-5.695	

LET (p)
Onset; peak time, peak value

SEPT (e)
Onset; peak time, peak value

Solar data
Start & stop time

Position data
Radial distance (AU), Long.; Lat.

Papaioannou et al., 2013b

Why are STEREO Catalogues Useful ?

Exploitation of the Catalogues

[1]

Make use of the Catalogues for the identification of *single* multi-spacecraft events

Analyze specific case studies

[2]

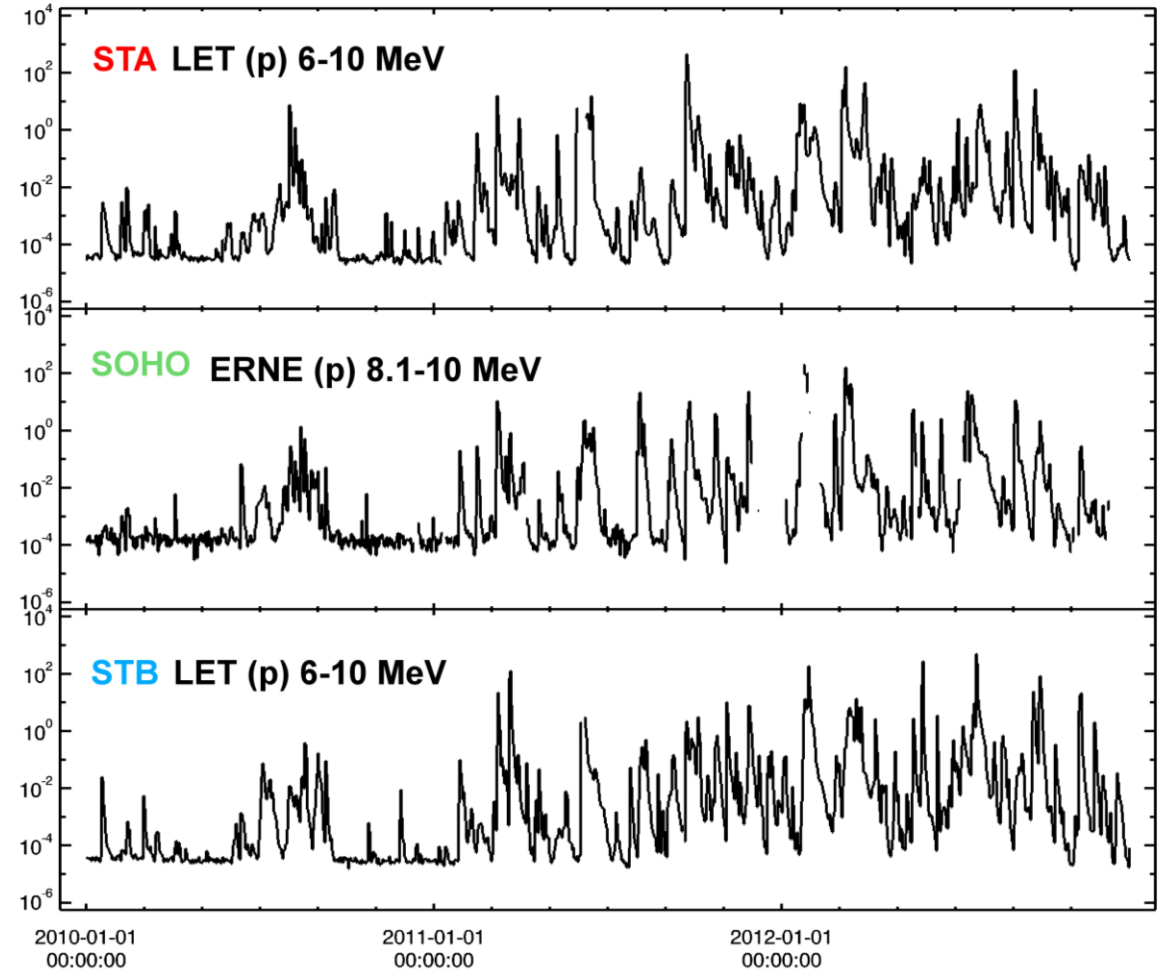
Take advantage of the *bulk* of the events in the Catalogues to derive statistical results

Use the whole sample or make subsets of SEP events for statistical analysis

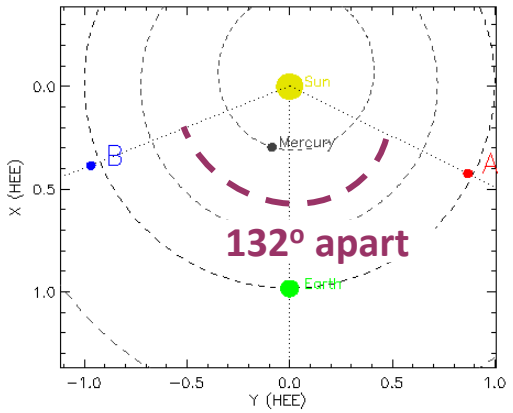
☺ Explore the limitations, test the theories and verify the particle origin, acceleration and transport processes at the Sun and in the inner heliosphere.

The Multi-spacecraft Approach – STEREO era

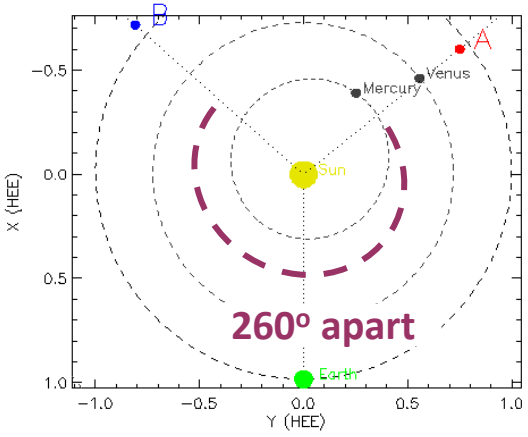
SEPServer STEREO Catalogues



STA, EARTH & STB in 2010 (Beginning of the scanning)

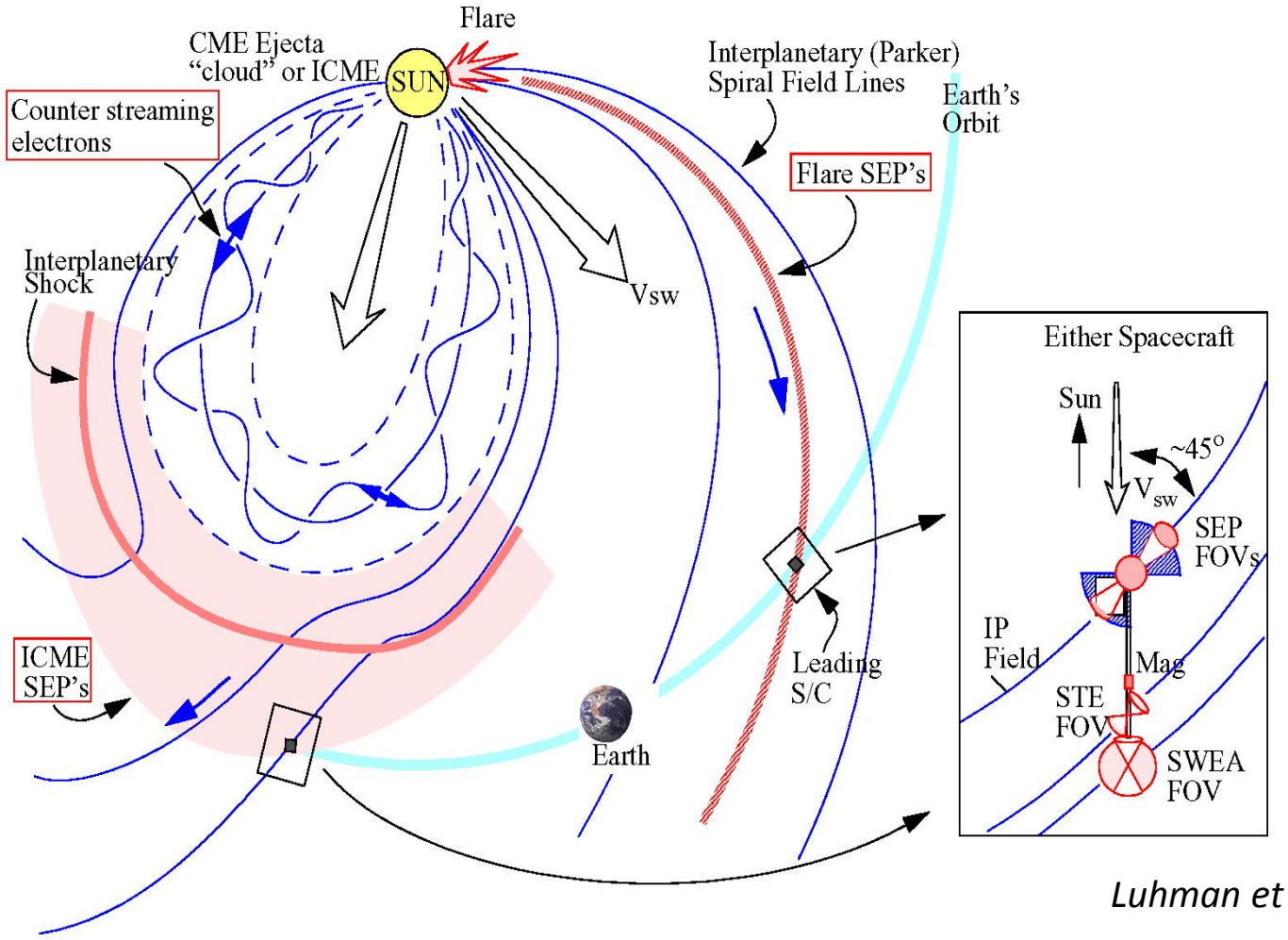


STA, EARTH & STB in 2012 (End of the scanning)



The Multi-spacecraft Approach – STEREO era

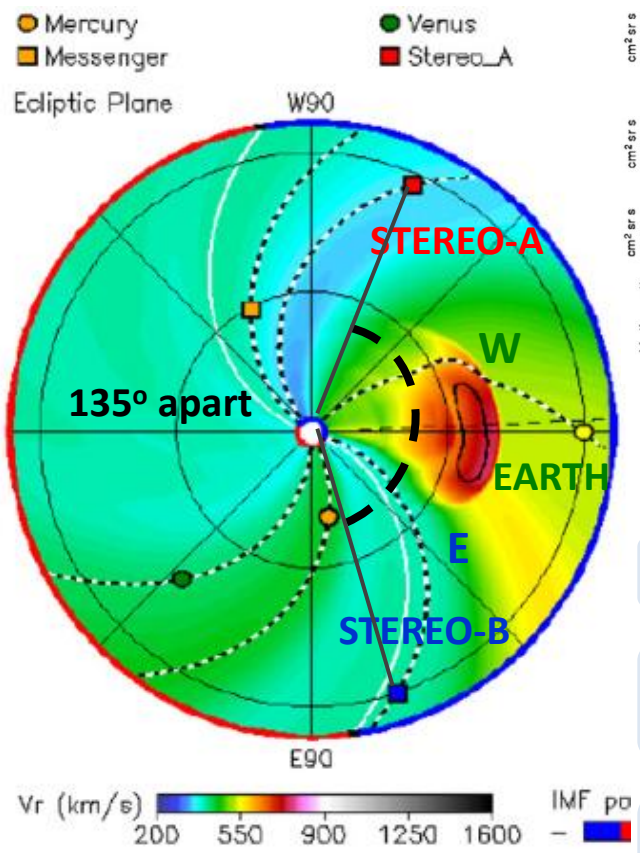
STEREO's added value: 3 points of continuous observations



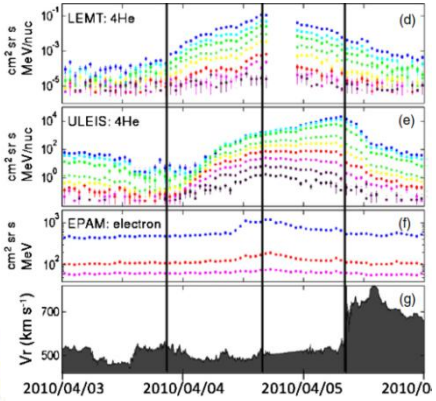
Luhman et al., 2008

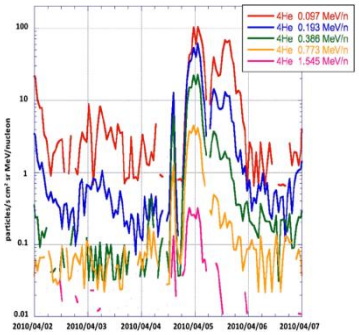
The Multi-spacecraft Approach – STEREO era

03 April 2010 | Multi-spacecraft Wide Spread Event I



Rouillard et al., 2011





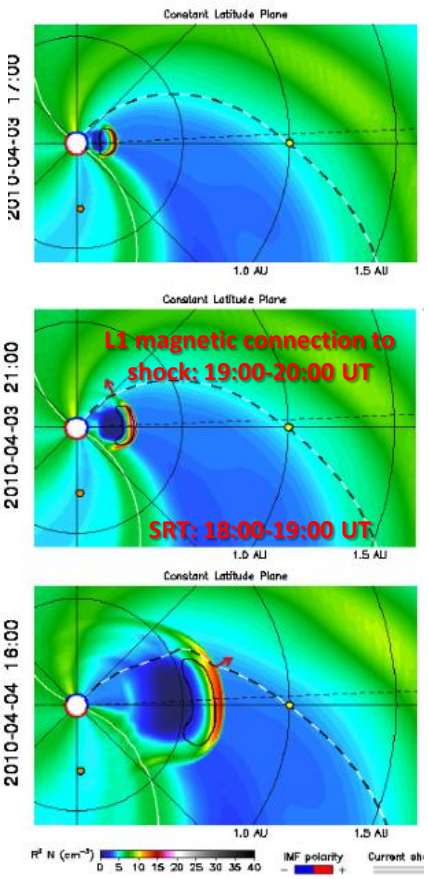
EARTH – STB ~15h Onset Delay

CME injection time – SEP @ EARTH ~12h

Longitudinal Separation – Flare & STB foot point 113°

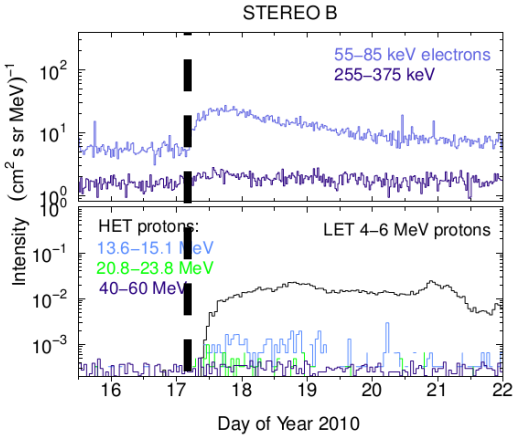
Longitudinal Separation – Flare & SOHO foot point 161°

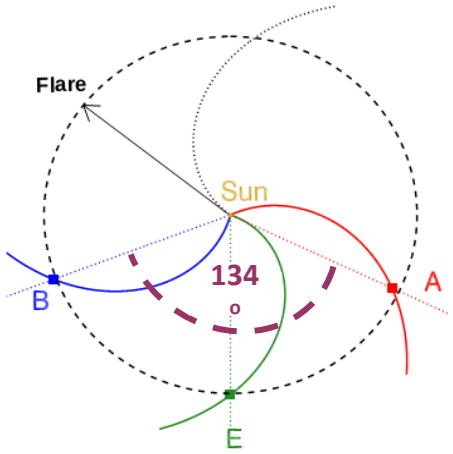
EARTH

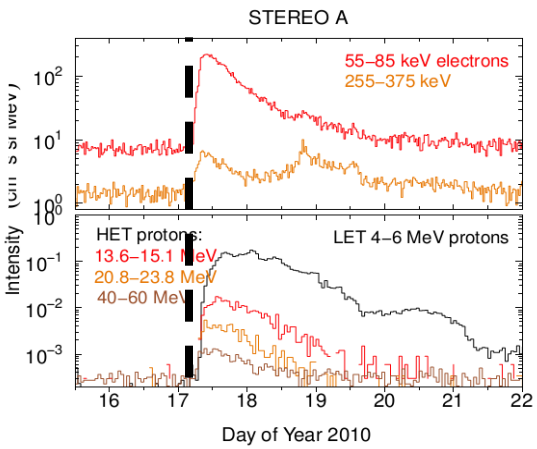


The Multi-spacecraft Approach – STEREO era

17 January 2010 | Multi-spacecraft Wide Spread Event *II*







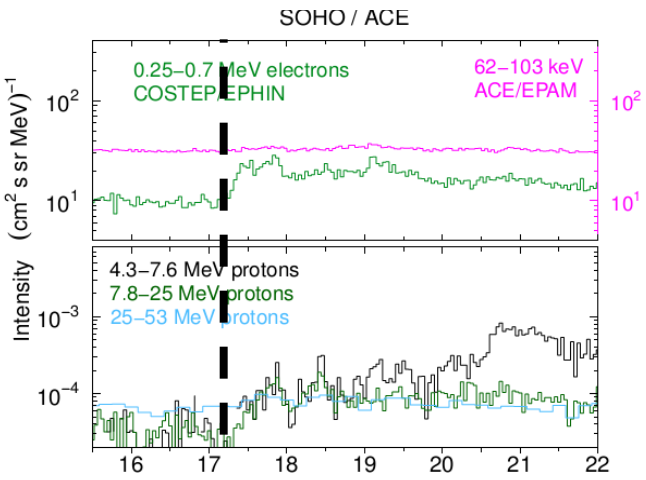
STB – Onset time: 4:30±24 min

Longitudinal Separation – Flare & STB foot point 113°

Longitudinal Separation – Flare & SOHO foot point 161°

Longitudinal Separation – Flare & STA foot point 117°

Dresing et al., 2012



EARTH – Onset time: 6:16±57 min

STA – Onset time: 4:55±24 min

Flare onset time – SEP @ STB *49min*

Flare onset time – SEP @ EARTH ~*2.5h*

Flare onset time – SEP @ STA *74min*

The Multi-spacecraft Approach – STEREO era

Multi-spacecraft - Wide Spread Event

Event Date	Ref.	Interpretation	Other events
03.04.2010	Rouillard et al., 2011	**Shock Evolution**	**21.03.2011** Rouillard et al., 2012
17.01.2010	Dresing et al., 2012	**Perpendicular Diffusion**	**17.05.2012** Heber et al., 2013
07.02.2010	Wiedenbeck et al., 2013 Wiedenbeck et al., 2011	**Cross-Field Transport**	Reames, 2013 Tan et al., 2013

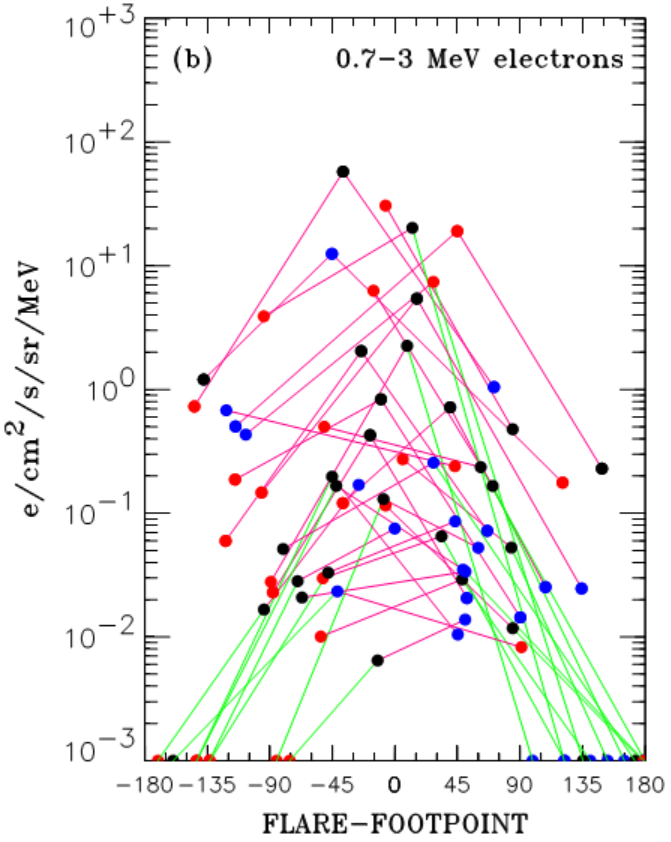
✓**A lot of new information leads to new knowledge and to new [old] questions on the source, acceleration and propagation of SEPs** ☺

✓ **Thorough examination of single case studies, in view of Multi-spacecraft measurements within STEREO era will hopefully shed light to these questions !**

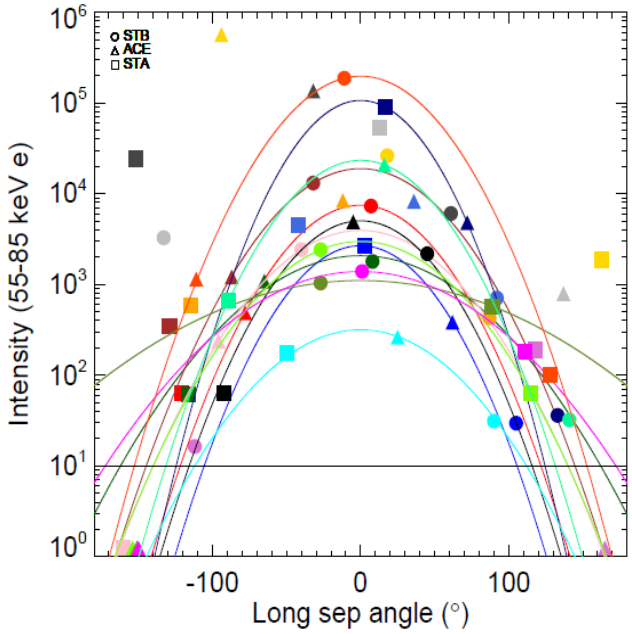
Malandraki, 2013

Statistical Studies

Longitudinal Spread of SEPs



Lario et al., 2013



Dresing et al., 2013

➡ **Details: B. Heber, *this Splinter***

- Peak intensity dependence: **$\exp(-k(\phi-\phi_0)^2/2\sigma)$**
- Asymmetric angular distribution shifted to the east (**$\phi_0<0$**)

Summary

Two SEP lists have been compiled

STEREO A / LET (SEPT)

STEREO B / LET (SEPT)

Time-shifting analysis (TSA)

STA & STB: SEPT electrons

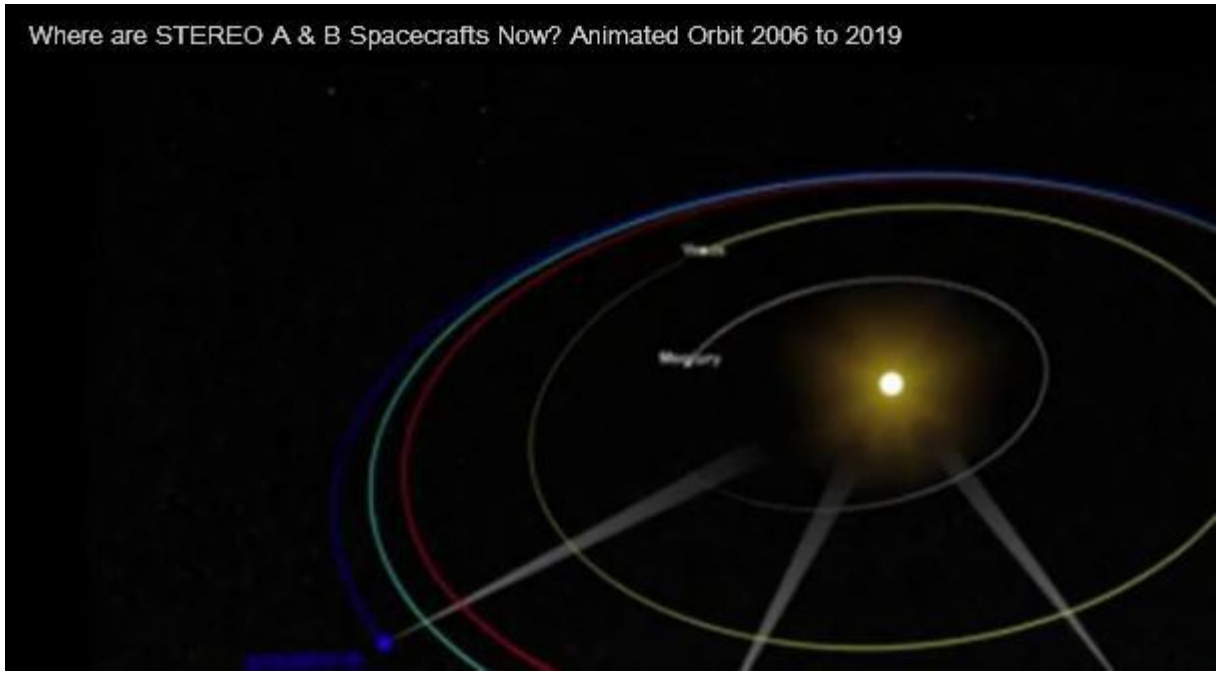
Solar Associations

Wind/WAVES, STEREO/WAVES, ARTEMIS, NRH, CMEs (LASCO and STEREO), SXRs, HXRs

The STEREO SEP event Catalogues

Facilitate the extended investigation on particle acceleration and transport processes at the Sun and in the inner heliosphere through ***specific case studies*** and ***statistical analysis*** of a large sample of well defined events

Thank you ☺



Video Credit: NASA Multimedia

Acknowledgments The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreement n◦ 262773 (SEPServer)

Special thanks to N. Vimer, O. E. Malandraki and N. Crosby for the invitation