Working Group 6, WG6:
‘Solar Energetic Particles (SEPs)’

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Scientific Objectives

The main objective of this Working Group, directly aligned with the ISEST science objectives, is the **improvement of our understanding of the origin, acceleration and transport of energetic particles in the heliosphere**, in association with **Coronal Mass Ejections (CMEs)** and **Corotating Interaction Regions (CIRs)** propagation and evolution.

Issues Reported Here

- SEP release time and Radio bursts
- Potential SEP acceleration by shock compression
- Particle acceleration by magnetic Islands in the heliosphere

Scientific Questions *(cntd.)*

A. Kouloumvakos, A. Nindos, E. Valtonen, C.E. Alissandrakis, O. Malandraki, P. Tsitsipis, A. Kontogeorgos, X. Moussas, and A. Hillaris

- What are the properties of SEP events as inferred from their associated radio emission?

Motivation

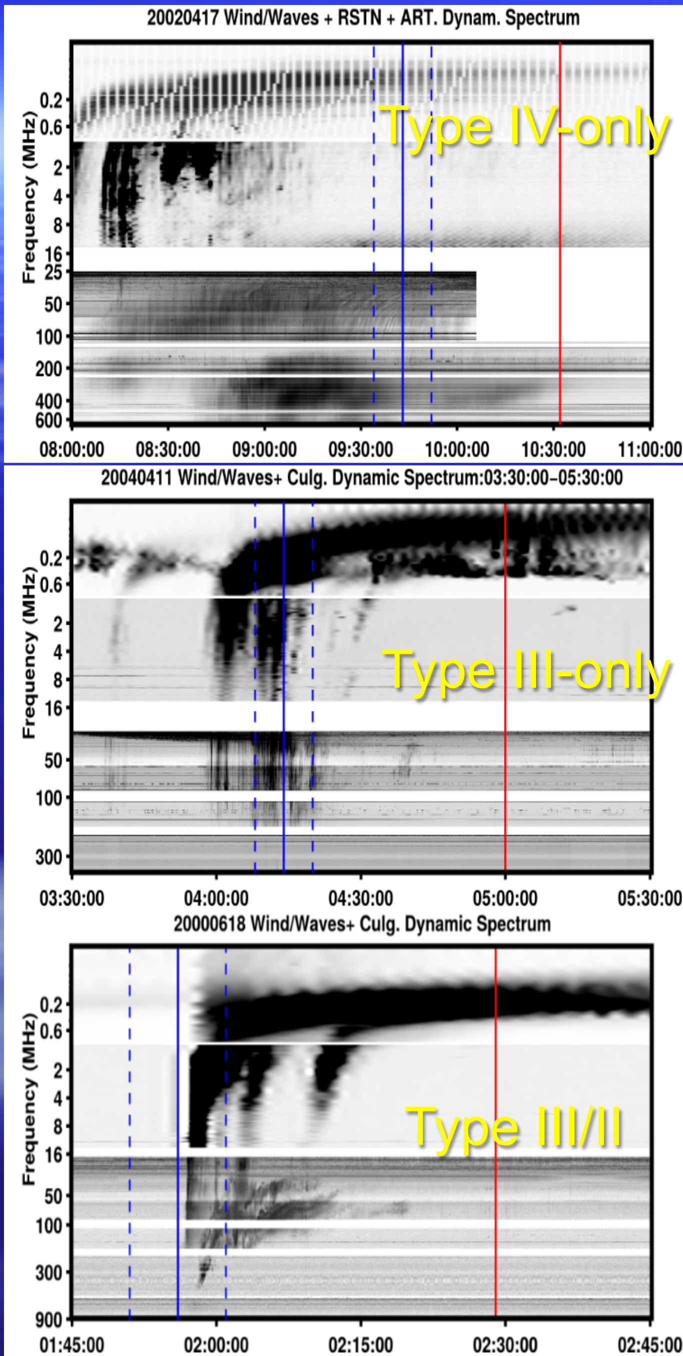
We constrained the particle acceleration and release processes in Solar Energetic Particle (SEP) Events, using the:

- Association of SEP events with Transient Radio Emissions.
- Timings between the energetic proton release time and
  - Type-III related electrons
  - Energetic electrons

Also Miteva, Samwe, Malandraki..

- Energetic Proton release height

SEP Radio Associations



Radio Association Cases:

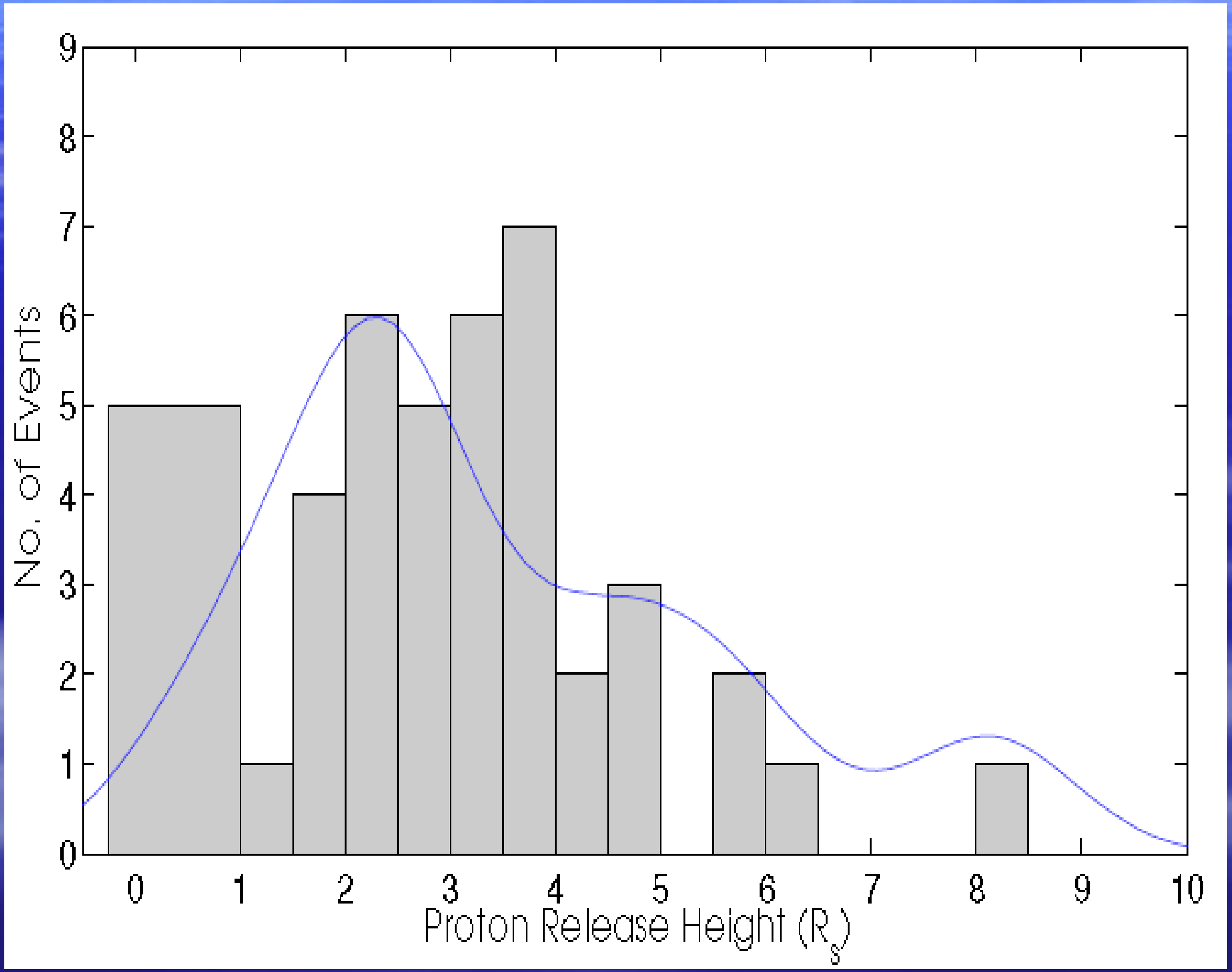
	III/II	III	II	mix/IV-c	Total	No Assoc.
†	25	18	7	15	65	18
	38%	28%	11%	23%	100%	
‡	34	10	0	21	65	0
	52%	16%	0%	32%	100%	

†: Radio association rates *within* proton release window.
‡: Radio association rates within ±1 h. from proton release time.

- Both flare- and shock-related particle release processes are observed in at least 25 cases (38%).
- 18 cases (28%) associated with flare-related particle release processes
- 7 cases (11%) associated with shock-related particle release processes.

Kouloumvakos et al. 2015

SEPs with type IIs: Proton Release Heights



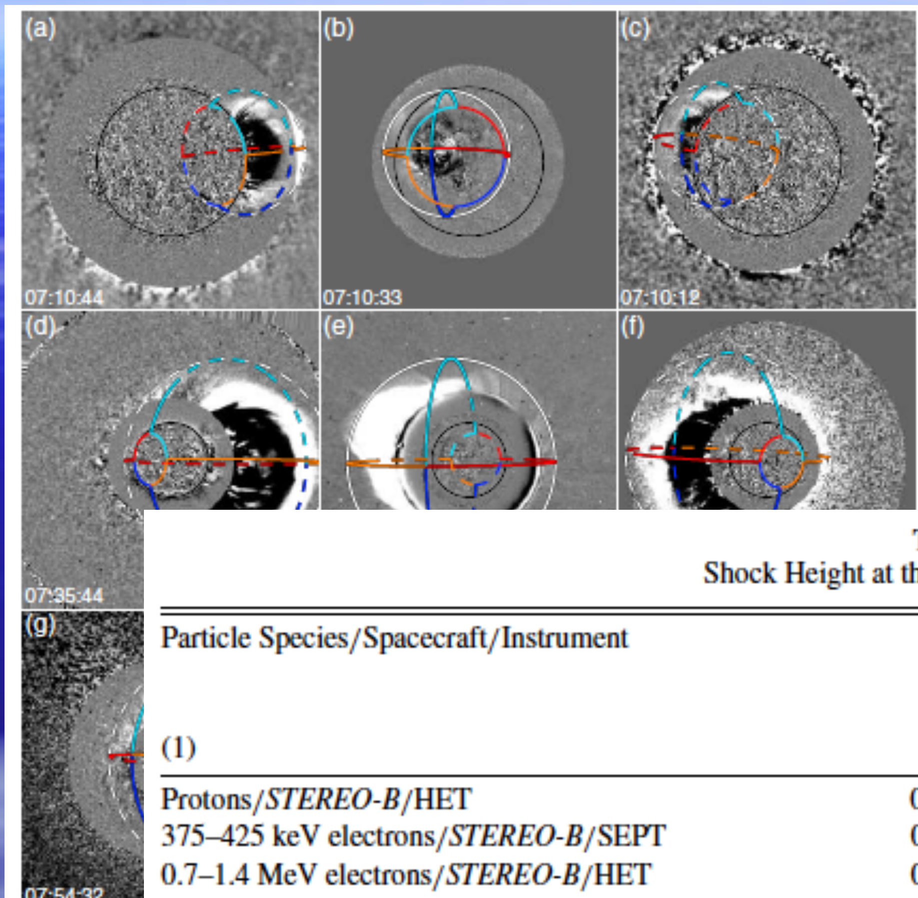
Used information for the height of the LASCO CME leading edge.

Extrapolated (or interpolated) their projected height-time measurements to the time of the proton release as estimated from the VDA.

The proton release for the type II associated cases typically occur at heights from 2.0 to 3.5 R.

Trace The Origin Of SEPs In The Low Corona

e.g. Lario et al. 2014. also Rouillard et al. 2012



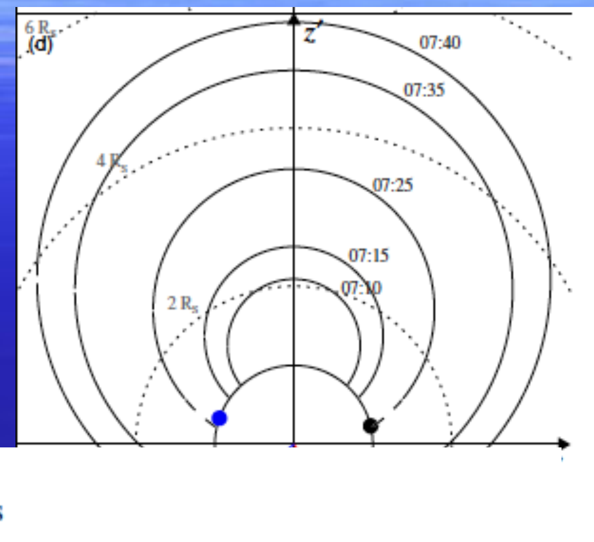


Table 2
Shock Height at the Particle Release Times

Particle Species/Spacecraft/Instrument (1)	Estimated Release Time (UT)[a] (2)	Shock Height above Sun Surface[b] (3)	θ_{nr} (4)
Protons/*STEREO-B*/HET	07:10 ± 4 minutes (VDA)	$\lesssim 0.13\ R_\odot$	74 ± 04°
375–425 keV electrons/*STEREO-B*/SEPT	07:16 ± 2 minutes (TSA)	$\lesssim 0.62\ R_\odot$	69 ± 13°
0.7–1.4 MeV electrons/*STEREO-B*/HET	07:17 ± 2 minutes (TSA)	$\lesssim 0.72\ R_\odot$	69 ± 14°
60–100 MeV protons/*STEREO-B*/HET	07:26 ± 3 minutes (TSA)	$1.20 \pm 0.80\ R_\odot$	53 ± 16°
Protons/*SOHO*/ERNE	07:58 ± 9 minutes (VDA)	$3.68 \pm 1.27\ R_\odot$	33 ± 06°
Near-relativistic electrons/*WIND*/3DP	07:45 ± 5 minutes (VDA)	$2.57 \pm 0.90\ R_\odot$	36 ± 07°
175–315 keV electrons/*ACE*/EPAM/DE	07:47 ± 2 minutes (TSA)	$2.73 \pm 0.65\ R_\odot$	35 ± 05°
0.25–0.70 MeV electrons/*SOHO*/EPHIN	07:35 ± 2 minutes (TSA)	$1.52 \pm 0.63\ R_\odot$	45 ± 08°

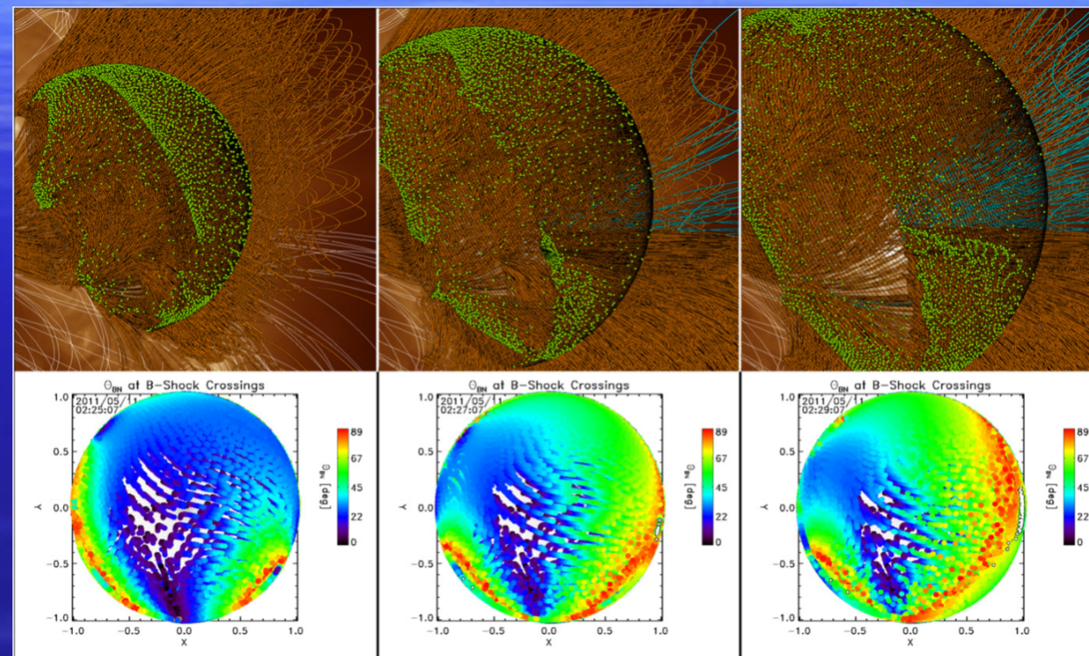
Step 1
to extr
time/d

Step 3: Estimate shock location at time of particle injection.

Understand the shock type at SEP injection site

Kozarev et al. (2015)

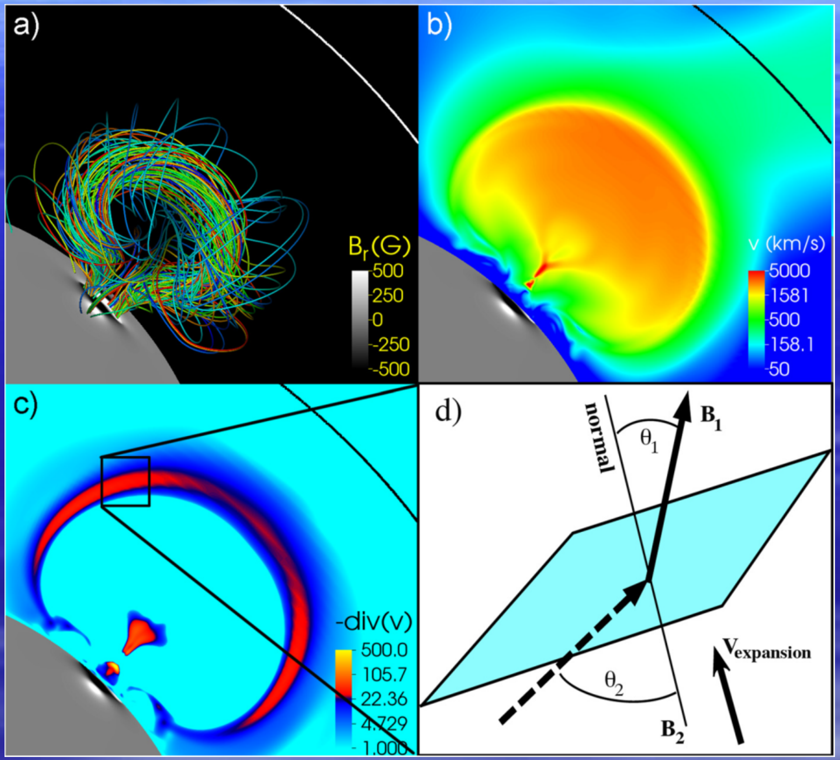
- Estimates of $\theta_{Bn\ i}$in the low corona are possible.
- Can lead to better modeling (and understanding) of the SEP intensities/evolution.
- **Open Questions:**
  - What's the best B-field model to use?
    - PFSS is likely unreliable.
  - Needs to be validated with more events.



Top row: three snapshots of the time-dependent coupled PFSS+CSGS model, showing the interaction of the spherical geometric shock front model with the PFSS coronal fields. The AIA 193Å channel image is shown for reference, for each time step. On top of it we have plotted the field lines—colored orange (closed) or blue (open) if interacting with the shock surface, white otherwise. The shock surface mesh is plotted in green. The orange dots represent the points of interaction Bottom row: for each step of the shock evolution, we produced a map of the position of the field interaction with the shock. The colors correspond to the value of the angle θBN between 0◦ and 90◦. Open field-crossing symbols are open circles (their centers are white).

What is the role of compression on SEP production?
Schwandron et al 2015)

- Lateral expansion of the CME, low in the corona, drives shocks and accelerates particles.
- Validates early interpretations from Patsourakos et al. (2009) and Patsourakos, Vourlidas, & Kliem (2010).
- **Open Questions:**
  - How common is this mechanism?
  - Is an EUV bubble (shock proxy) a necessary condition for SEPs?
  - What is the role of the flare-accelerated particles?



Configuration in the low corona based on MAS simulations (Schwadron et al. 2014) showing a strong compression driven by the expansion of a CME. The strong compressions on the flank of the CME create the conditions that lead to rapid particle acceleration. The configuration of the erupting magnetic flux rope (panel (a)) is shown with associated photospheric field strength Br in grayscale on the solar surface. The CME accelerates rapidly to plasma speeds (panel (b)) of thousands of km s−1 low in the corona. As a result of the CME's rapid acceleration, strong compressions and shocks are formed showing a large negative velocity divergence, ∇ °E u (panel (c)) expressed in code units corresponding to 7 ´ 10-4 s−1. The box in panel (c) is blown out (panel (d)) to indicate the plane of the shock of compression and a magnetic flux bundle piercing the shock. In panel (d), note the magnetic field normal angles q1 and q2 upstream and downstream from the shock or compression. The expansion velocity driving these compressions is also shown

Heliospheric Superthermal Particles

- Particle can be accelerated locally in the solar wind.
- acceleration due to a magnetic reconnection at current sheets +
- re-acceleration in magnetically confined areas filled with dynamically changing small-scale magnetic islands

Olga Khabarova, Gary Zank, Gang Li, Olga Malandraki

Can magnetic reconnection accelerate particles to keV-MeV energies in the solar wind?

Acceleration of particles in current sheets due to the magnetic reconnection was considered in many works: Büchner et al, 2010; Zelenyi et al., 2013; Drake et al. 2010, 2013; Lapenta 2012; Teumann & Baumjohann, 2013 etc..

YES

Energization of particles up to MeV in the Earth's magnetotail [Zelenyi, Lominadze & Taktakishvili (1990); Ashour-Abdalla et al. (2011)], but it is still disputable for the HCS, because of some lack of observations.

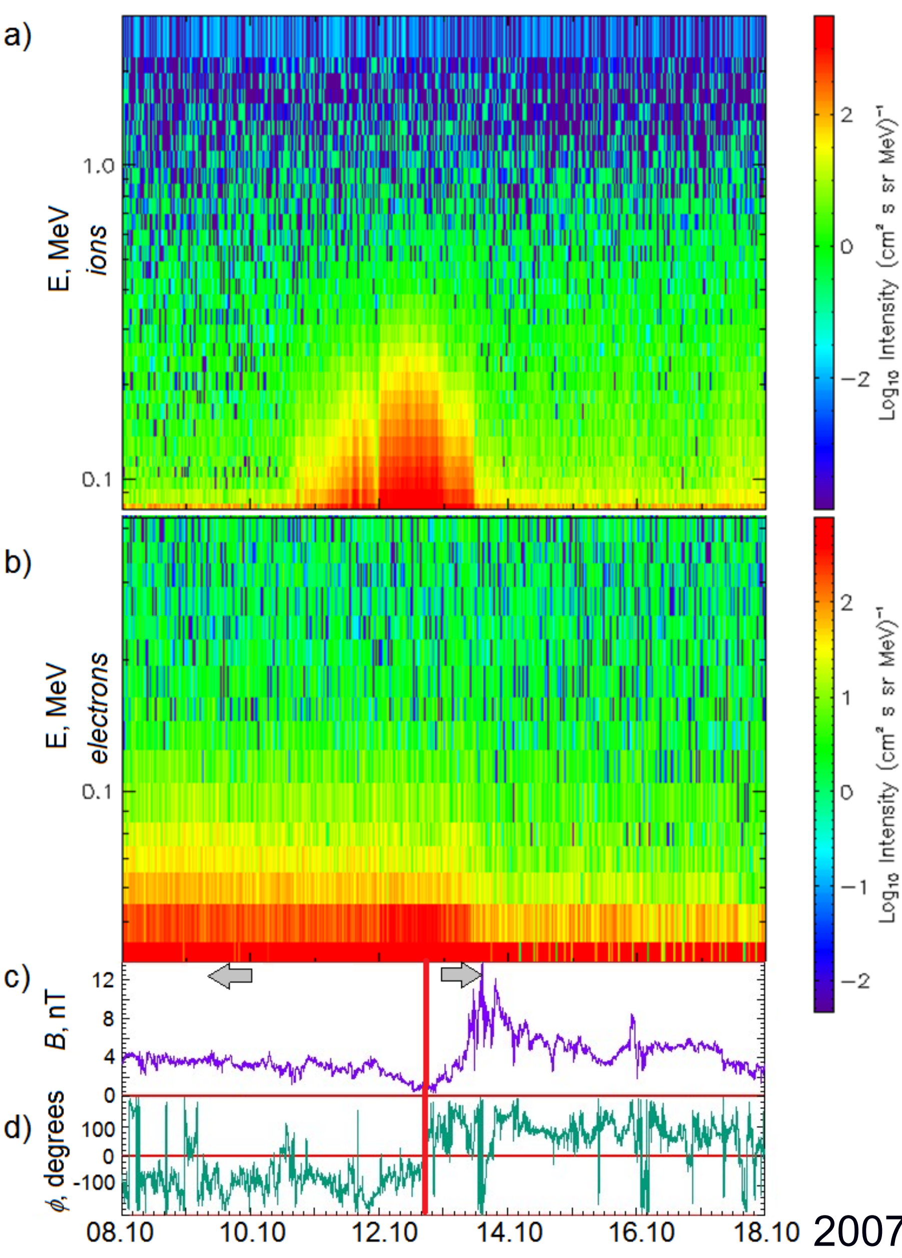
Goldstein, Matthaeus & Ambrosiano (1986): the maximum energy achievable during the magnetic reconnection at the heliospheric current sheet (HCS) should be **~100 keV.**

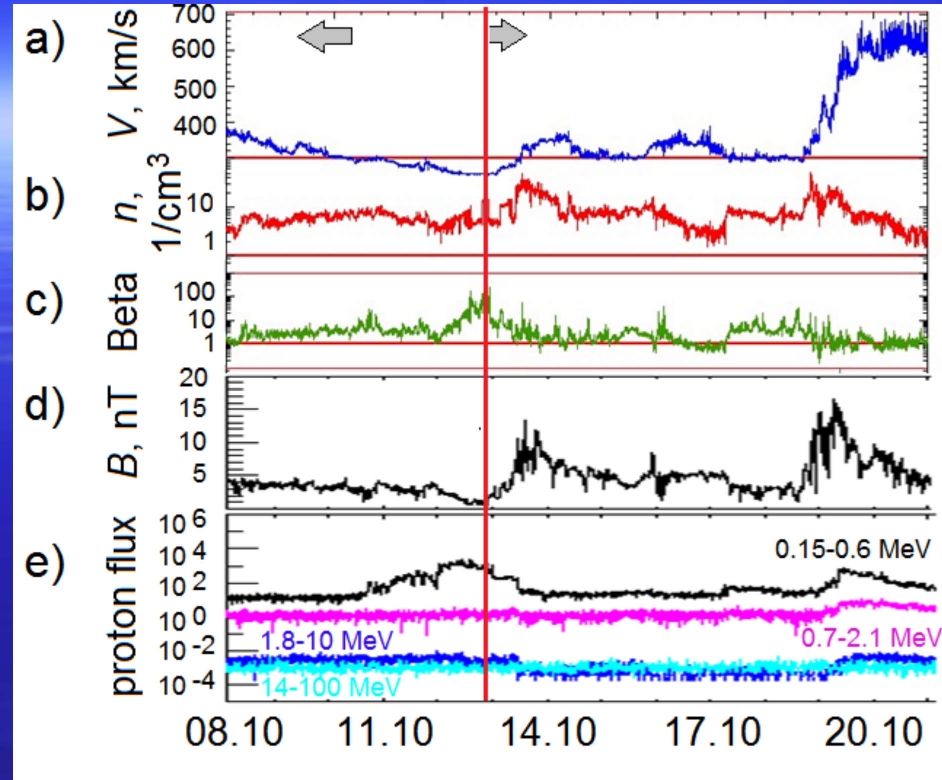
Zharkova & Khabarova (2012; 2015): the maximum energy achievable during the magnetic reconnection at the HCS may be ~ keV for electrons and ~MeV for ions.

NO

Gosling, J. T., R. M. Skoug, D. K. Haggerty, and D. J. McComas (2005): **Absence of energetic particle effects associated with magnetic reconnection exhausts in the solar wind.** Geophys. Res. Lett., 32, L14113, doi:10.1029/2005GL023357.

Evidence for particle acceleration near the heliospheric current sheet





Zharkova & Khabarova, AnnGeo, 2015

Protons accelerated to 1 MeV, and electrons – to keV are sometimes observed near the HCS. Events can last from minutes to hours. Murphy et al. (1993); Sanderson (1997); Lanzerotti & Sanderson (2001), Zharkova & Khabarova (2012; 2015)

Magnetic island contraction and merging can accelerate particles

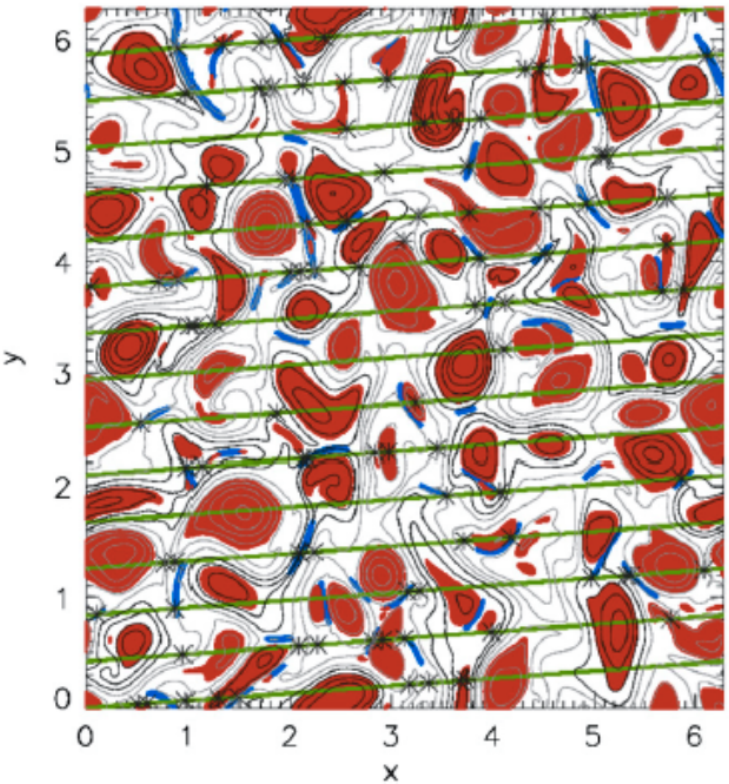


Fig. 2. A contour map of the out-of-plane vector potential (field lines) for $a > 0$ (black contour lines) and $a < 0$ (gray contour lines). The superposed colors represent magnetic islands (red) and strong current regions (blue) identified with a cellular automata technique (Servidio et al., 2009). Green lines represent a sample path through the simulation box. Gray stars are placed at the center of a discontinuity, selected in this case by the PVI method. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The dominant charged particle energization processes are

1) the electric field induced by **magnetic island merging**,
2) **magnetic island contraction**.

In both cases, the magnetic island topology ensures that charged particles are trapped in regions where they can experience repeated interactions with either the induced electric field or contracting magnetic islands.

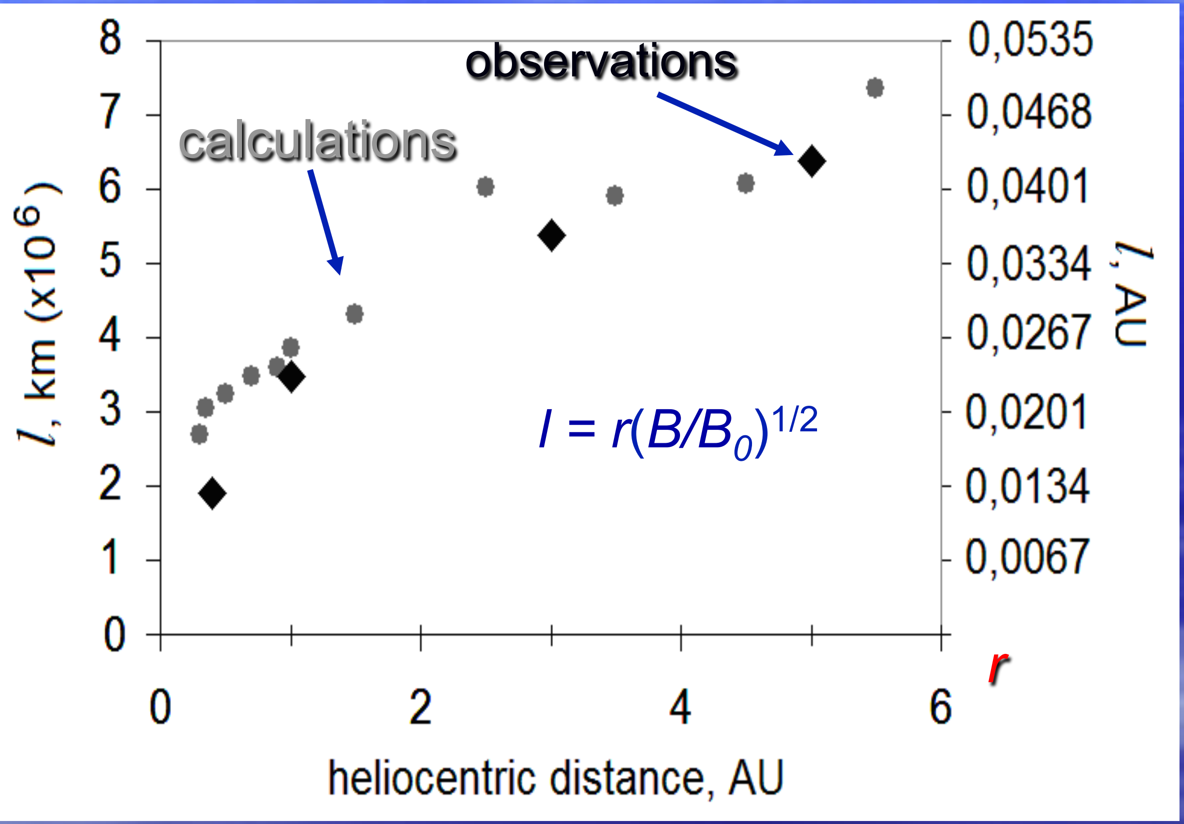
Greco, A., Servidio, S., Matthaeus, W. H., & Dmitruk, P. 2010, Planet. Space Sci., 58

Zank, le Roux, Webb, Dosch, Khabarova. Astrophysical Journal, V.797, 2014 ;

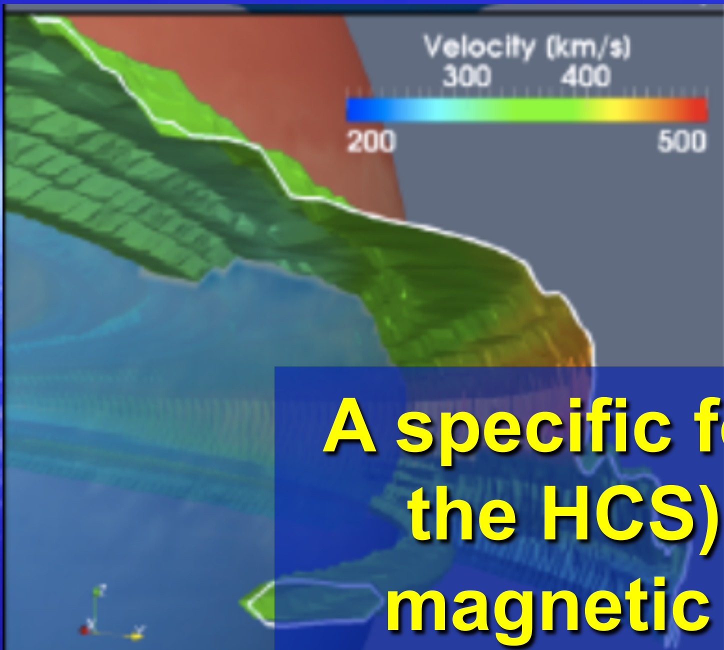
le Roux, Zank, Webb, Khabarova Astrophysical Journal, V.799, 2015

Small-scale magnetic islands (l ~ 0.01-0.1 AU) observed near the heliospheric current sheet

Khabarova, Zank, Li, le Roux, Webb, Dosch, Malandraki, ApJ, 2015



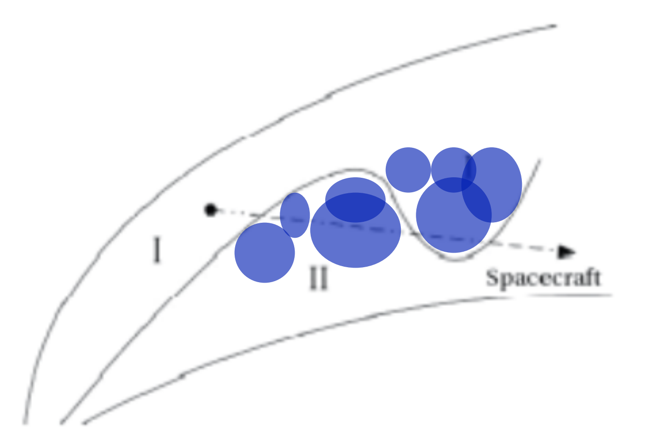
Averaged magnetic island width l versus heliocentric distance r as observed by Cartwright & Moldwin (2010) (black diamonds) and calculated through the $l(B,r)$ dependence (1) (grey circles).

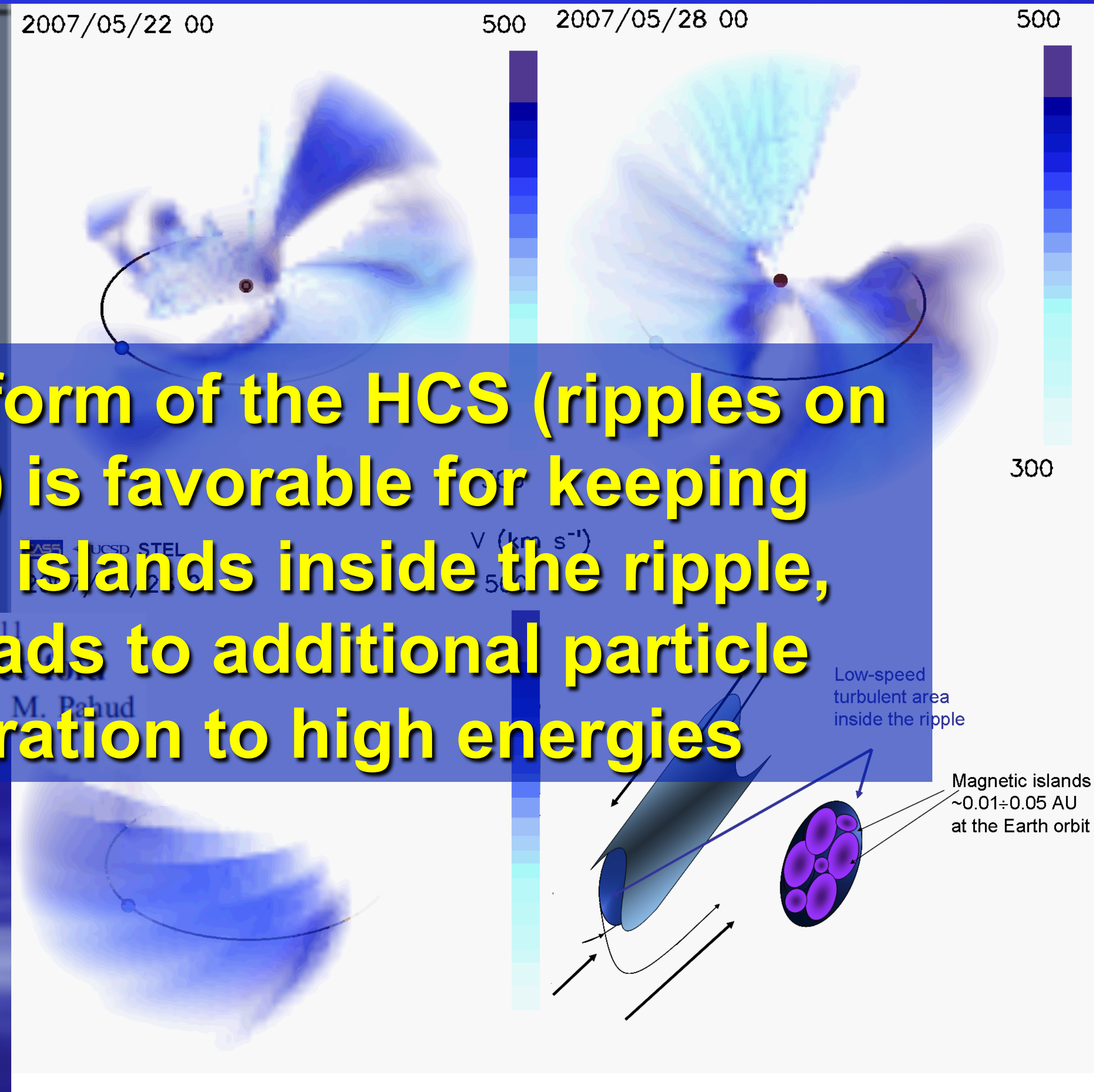


A specific form of the HCS (ripples on the HCS) is favorable for keeping magnetic islands inside the ripple, which leads to additional particle acceleration to high energies

GEOPHYSICAL RESEARCH LETTERS, VOL. 38, L14107, 2011
Disruption of a heliospheric current sheet fold
V. G. Merkin, J. G. Lyon, S. L. McGregor, and D. M. Pahud

THE ASTROPHYSICAL JOURNAL, 766:2 (6pp), 2013
L. ARNOLD, G. LI, X. LI, AND Y. YAN

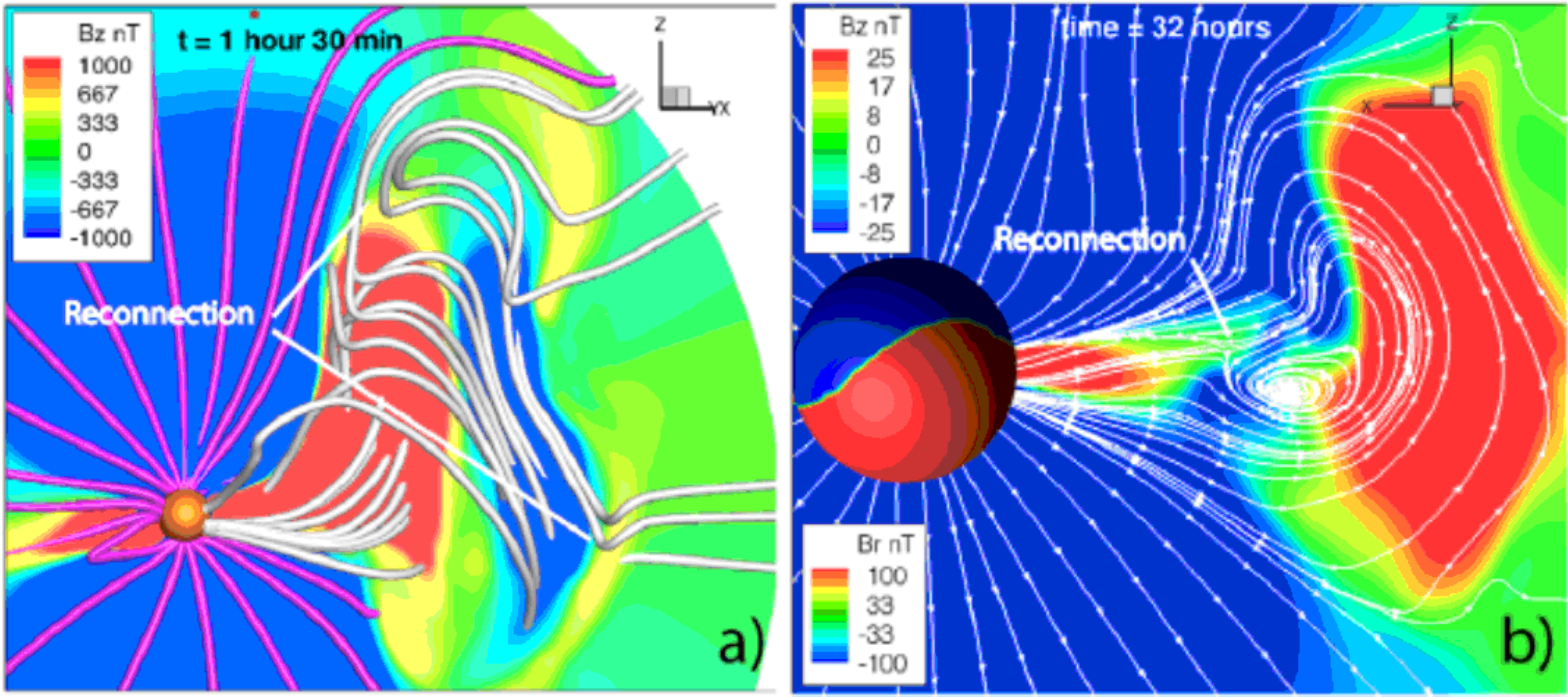




Khabarova, Zank, Li, le Roux, Webb, Dosch, Malandraki, ApJ, 2015

Application of the idea to the HCS-ICME/CIR interaction

W B Manchester IV *et al* Plasma Phys. Control. Fusion **56** (2014)

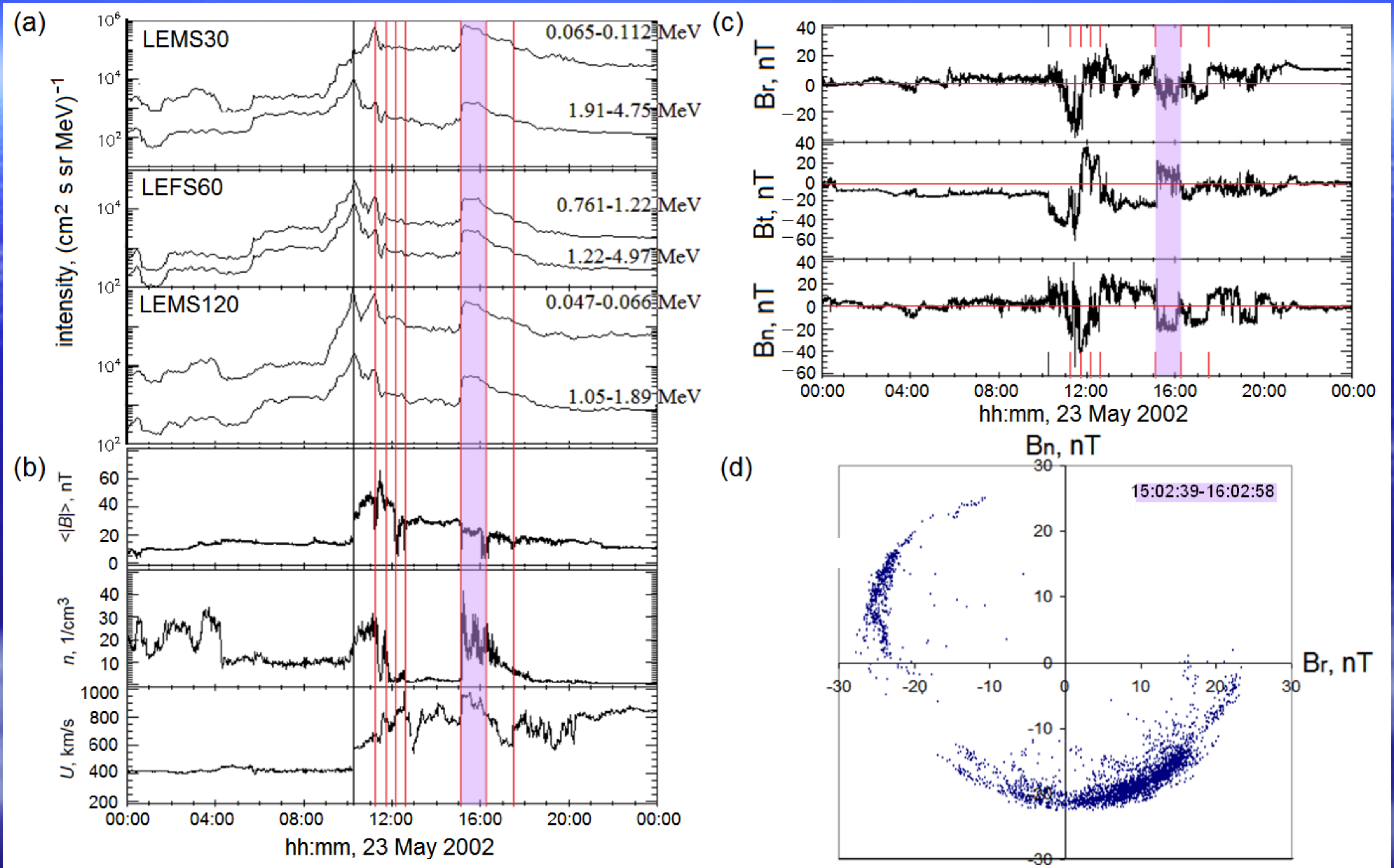


Magnetic reconnection

a) at the leading edge of an ICME; b) behind the ICME

Conditions favorable for island contraction - interaction of the HCS with CMEs/CIRs

The HCS-ICME interaction. A post-CME case



Particle acceleration associated with islands near the HCS (an **after -CME case**)

Khabarova, Zank, Li, le Roux, Webb, Dosch, Malandraki, ApJ, 2015

Khabarova, Zank, Li, le Roux, Webb, Malandraki, Zharkova, J. of Physics: Conference Series, 2015

The HCS-ICME interaction. A pre-CME case

The case of a rippled HCS that surrounded an ICME. The energetic particle flux enhancements are observed not during the ICME, but in the areas filled with magnetic islands. (STEREO-B)

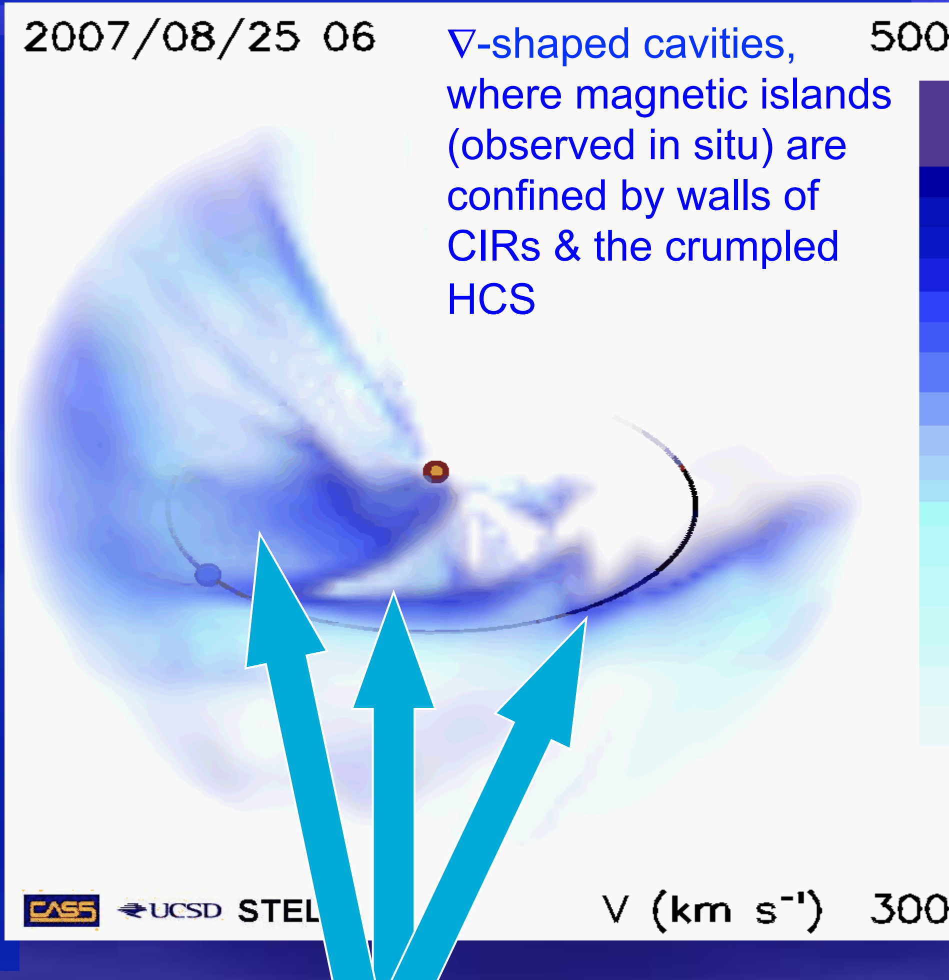
The HCS-CIR interaction

In August 2007, a pair of Corotating Interaction Regions (CIRs) was observed by the pair of STEREO s/c and the ACE & WIND near Earth s/c.

Interpretation by Wu et al. (*Z. Wu et al. ApJ, 781, 2014*):
there were two couples of forward/reverse shocks in the U-shape system of CIRs with the curved-inward IMF lines. Particles are accelerated by reflection from the shocks.

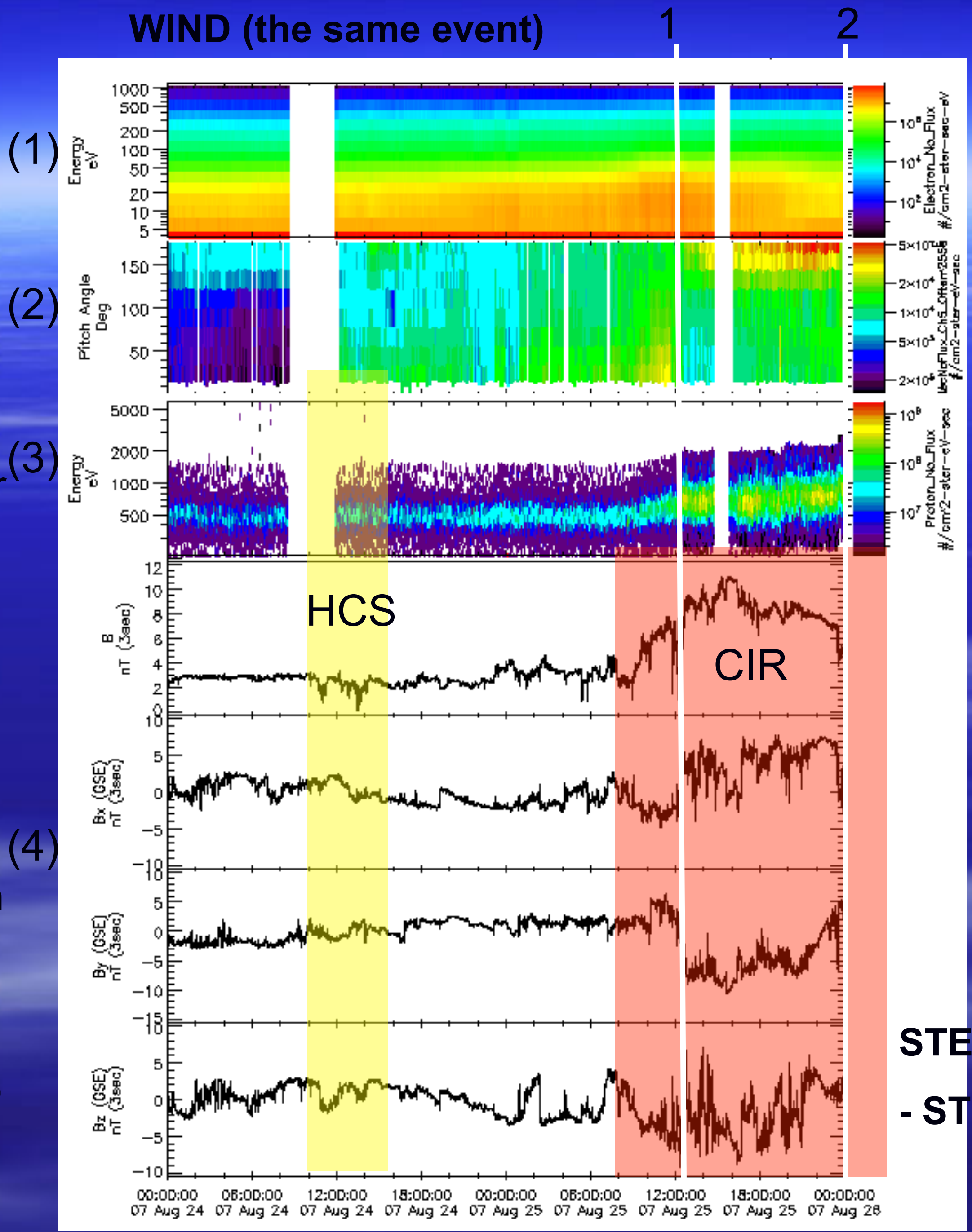
Our interpretation:

According to STEL observations, there were several nabla-shaped cavities formed by the consequence of streams from coronal holes and CMEs. This lead to plasma confinement between the heliospheric current sheet (HCS) and current sheets belonged to CIRs. The HCS and strong local current sheets together with magnetic islands localized inside the ∇ -shaped cavities played significant role in particle acceleration, which was local.



WIND (the same event)

Change of the IMF direction at the HCS is seen in (2) and (4), the particle flux increase (both for electrons and ions) is observed before the CIR1 arrival (red). The most impressed variations of energetic particle flux is related to the area between current sheets inside CIR. The area is full with magnetic islands, separated by smaller-scale current sheets.



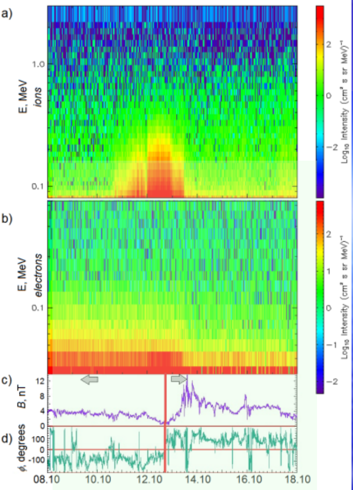
(1) electron flux spectrogram,
(2) pitch angle distribution at 255eV,
(3) ion flux spectrogram,

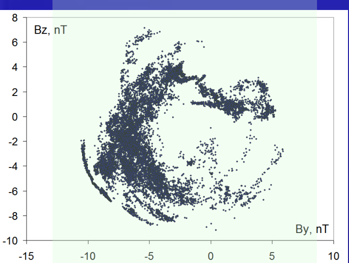
(4) IMF components

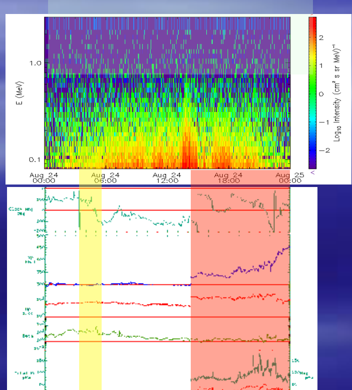
STEREO-B – WIND/ACE –

- STEREO A - Ulysses

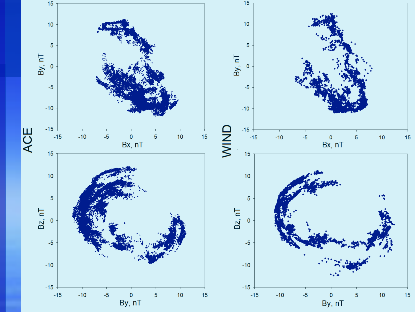
Conclusions

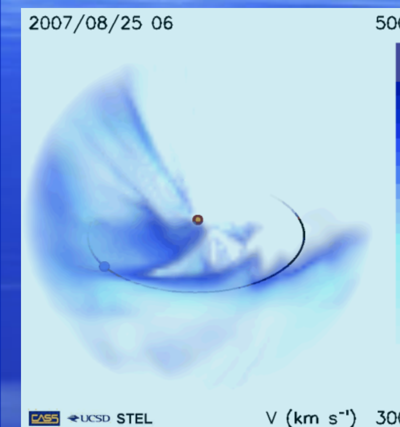


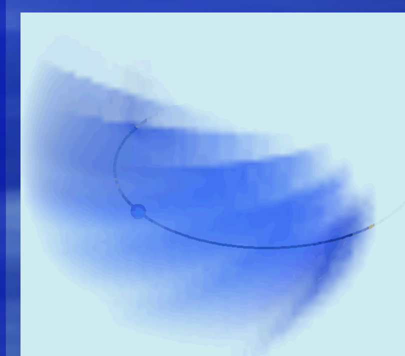


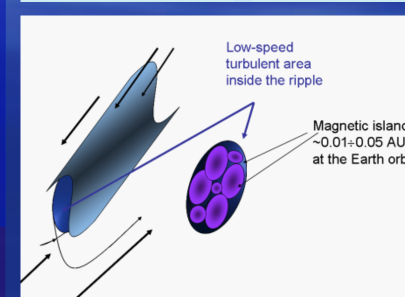


- - Particles may be effectively accelerated in areas filled with magnetic islands which are bounded typically by two magnetic walls such as the HCS from one side and current sheets at the edge of an ICME or CIR from the other side.
- - The HCS itself can confine the magnetic islands because of its plissé-like profile.
- - Initial particle acceleration due to magnetic reconnection at the HCS may be insufficient to reach MeV energies, but the presence of magnetic islands near the HCS offers the possibility of re-accelerating particles in the ways discussed in Zank et al. (2014) and Le Roux et al. (2015).









Suggested Science Objectives & Methods for WG6

- Trace the origin of SEPs
  - METHOD: Via 3D reconstructions of shock envelope
- Understand the shock type at SEP injection site
  - METHOD: Estimate the shock normal angle to B-field via 3D reconstruction of shock envelope and B-field model (PFSS). E.g. see Kozarev et al (2015).
  - What is the role of compression on SEP production? - - METHOD: Measure CME lateral expansion low in the corona
  - GLE from shock nose: latitudinal connectivity
  - FE vs. GLE spectrum: shock formation heights
  - FE vs. GLE spectrum: shock formation heights
  - Solar Cycle effect on SEPs