Solar Probe Plus and Solar Orbiter joint science opportunities and campaigns

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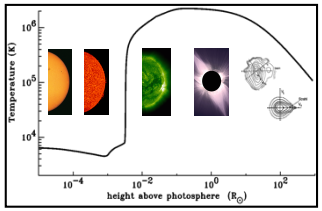
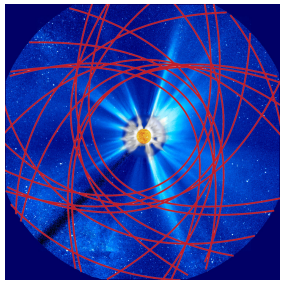
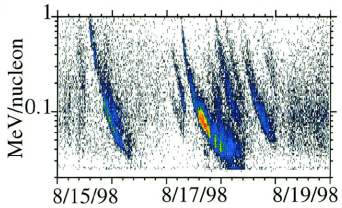
SPP Science Objectives



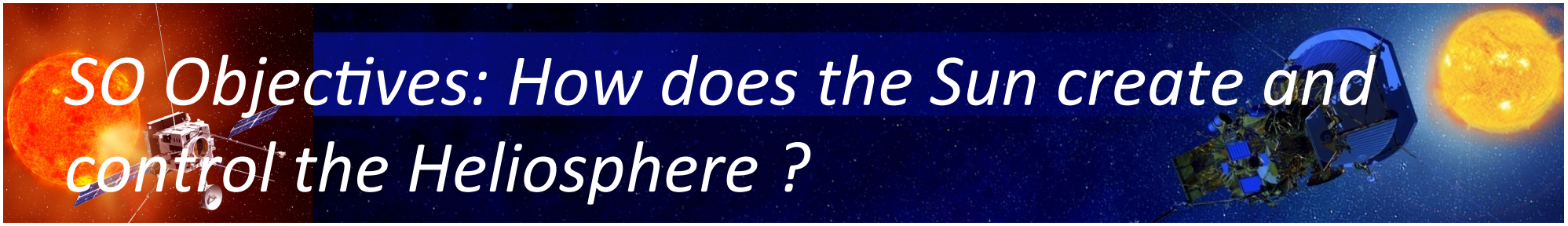
+ Trace the flow of energy that heats the corona and accelerates the solar wind (overlap SO 1.



+ Determine the structure and dynamics of the magnetic fields at the sources of the fast and slow solar wind



+ Determine what mechanisms accelerate and transport energetic particles



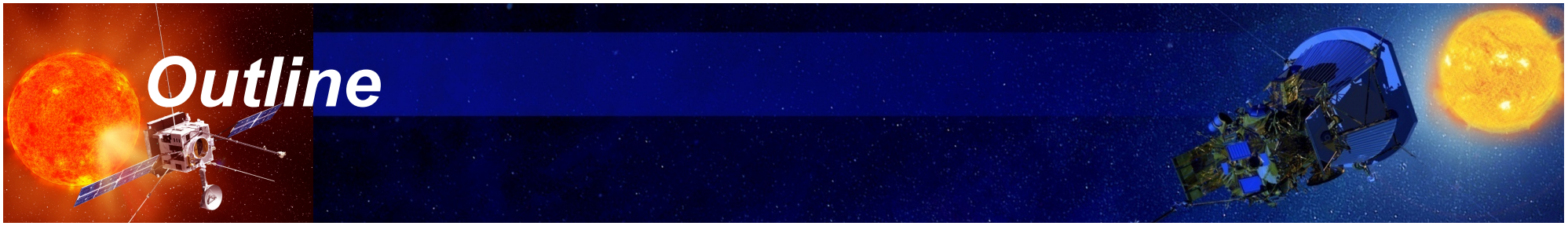
SO Objectives: How does the Sun create and control the Heliosphere ?

Q1) How and where do the solar wind plasma and magnetic field originate in the corona?

Q2) How do solar transients drive heliospheric variability?

Q3) How do solar eruptions produce energetic particle radiation that fills the heliosphere?

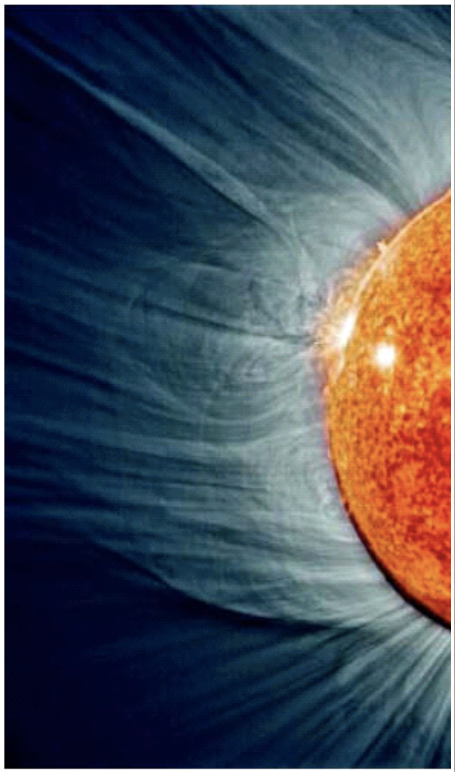
Q4) How does the solar dynamo work and drive connections between the Sun and the heliosphere?

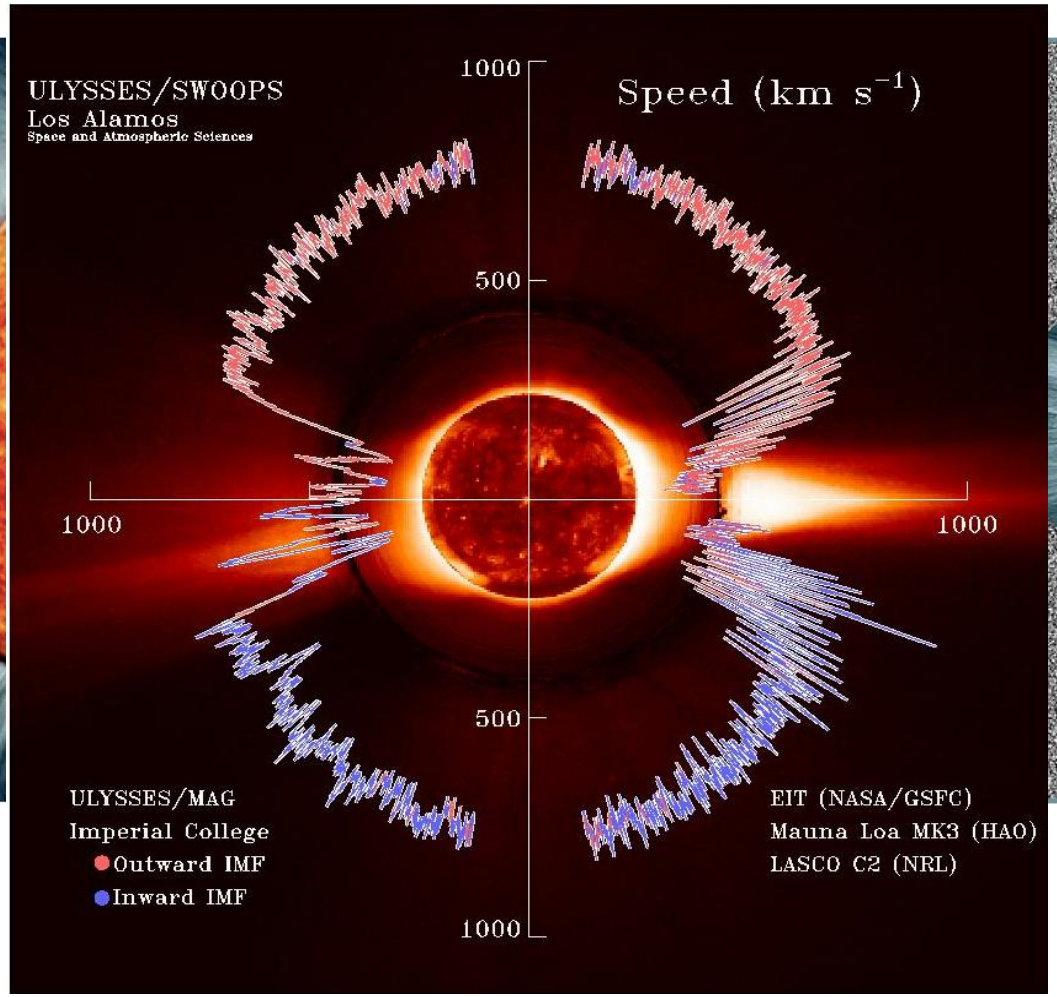


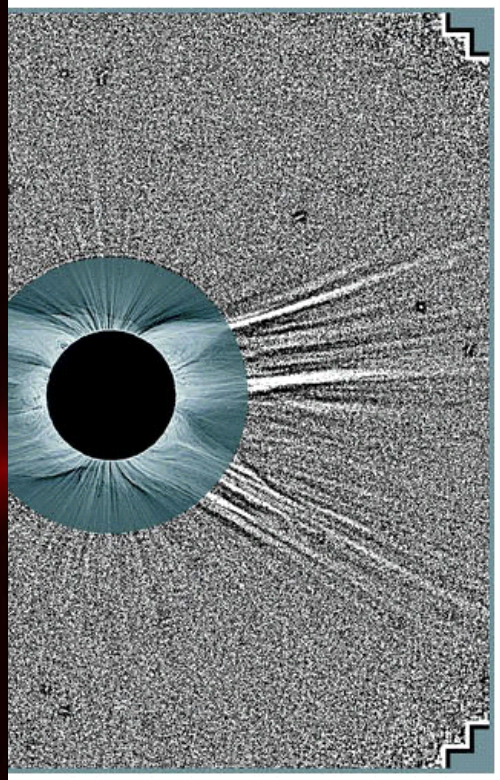
- **Solar Probe Plus and Solar Orbiter objectives:** ***understanding the source regions of the solar wind, of the heliospheric magnetic field and of solar energetic particles.***

I will discuss here some questions of coronal heating, sw acceleration, source regions of the solar wind, and origins and propagation of transients, within the framework of SPP/SO synergies in their observations driven by differences in orbits and instrumentation.

Solar corona, wind and magnetic activity

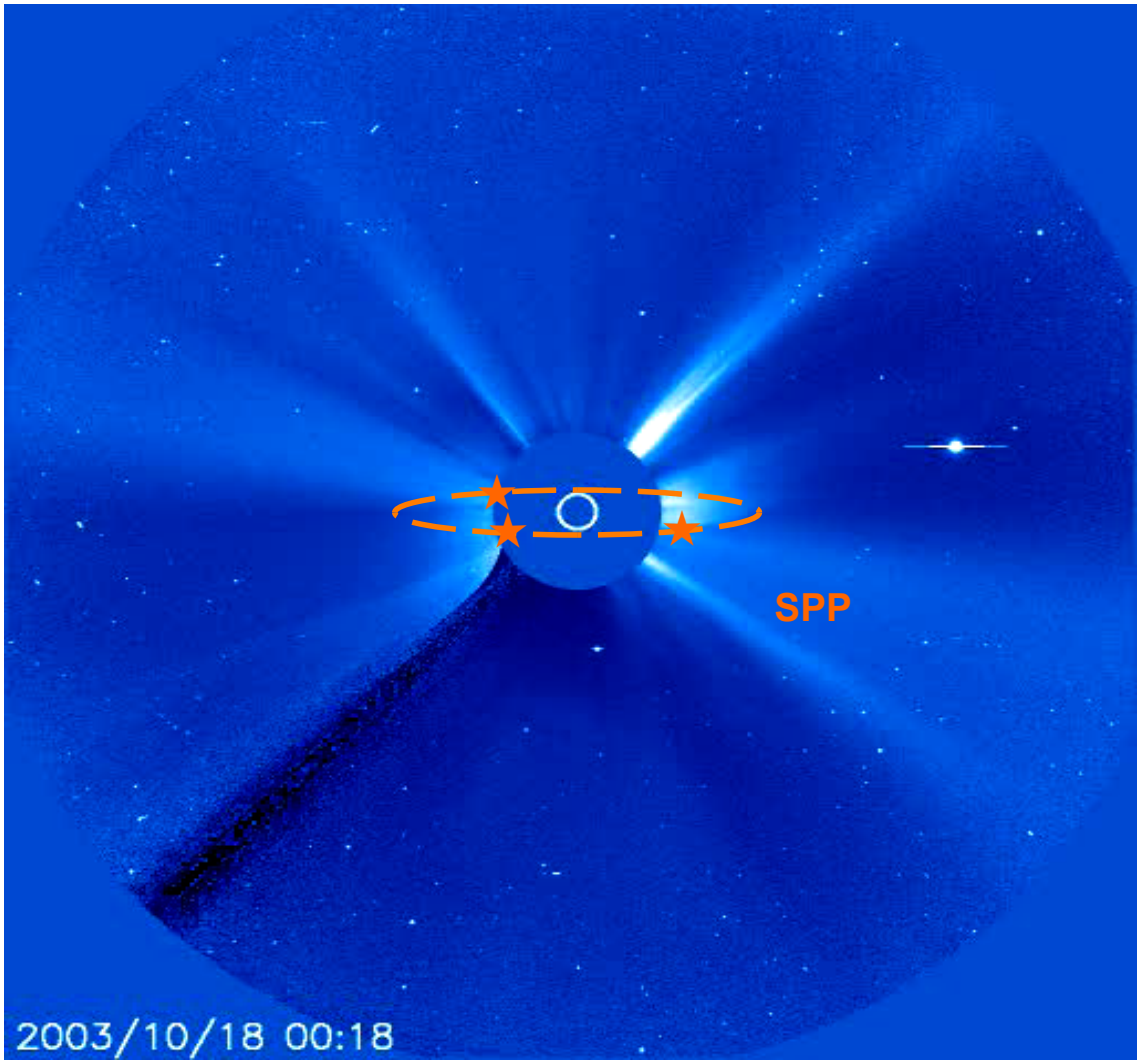




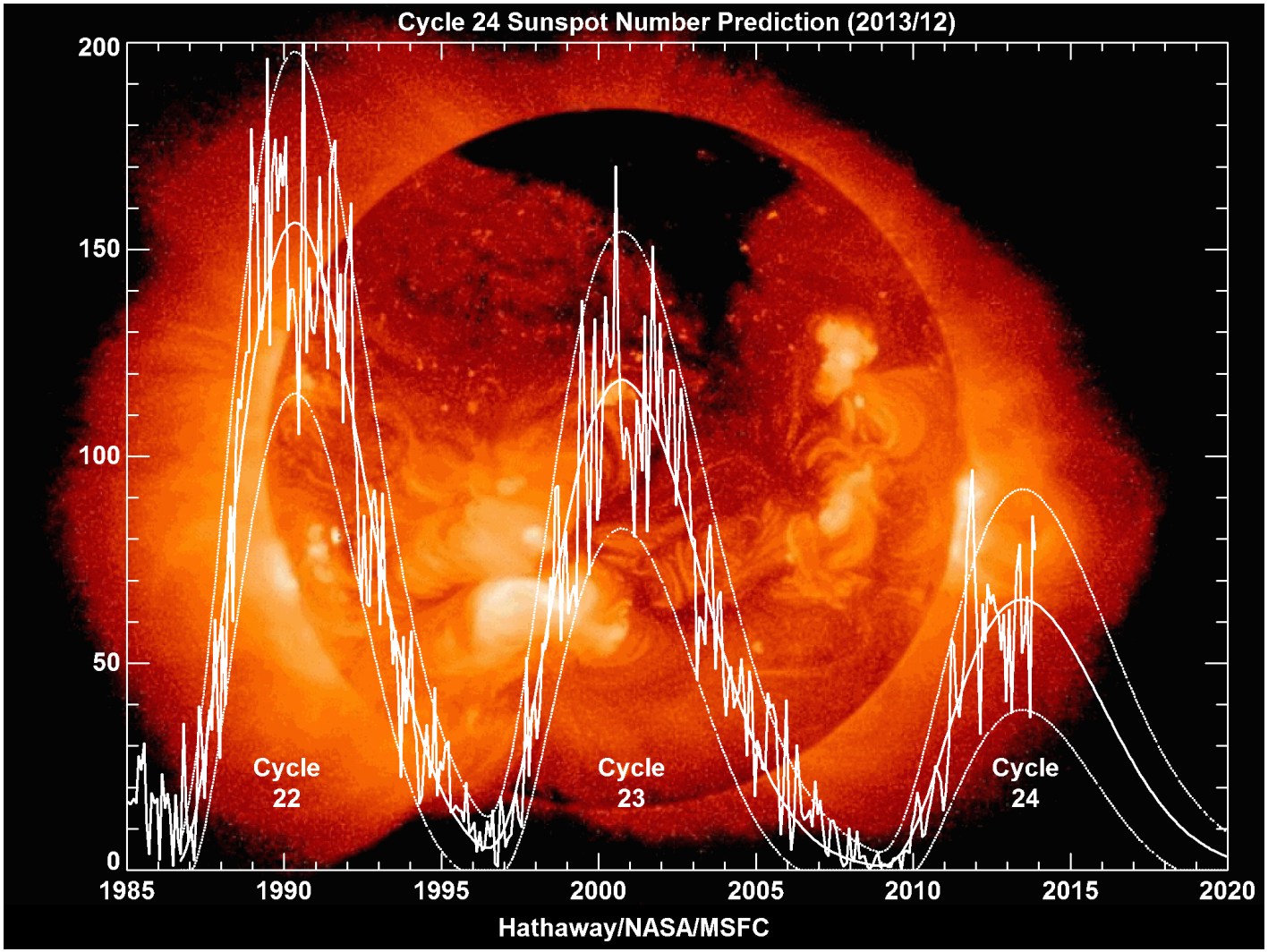


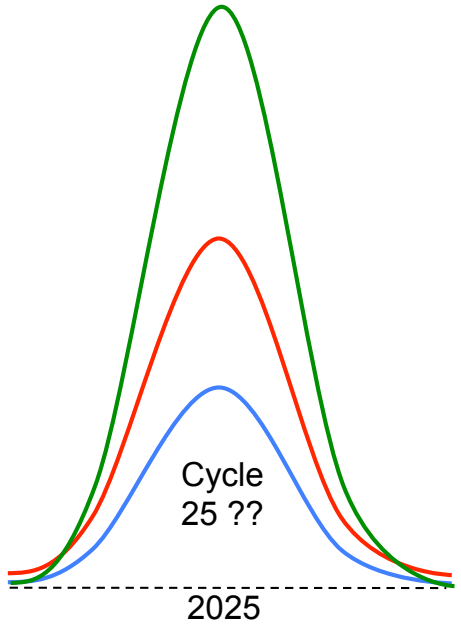
Intrinsically time-depedent outflow

★ Possible SPP positions at 9.86 R_S perihelion

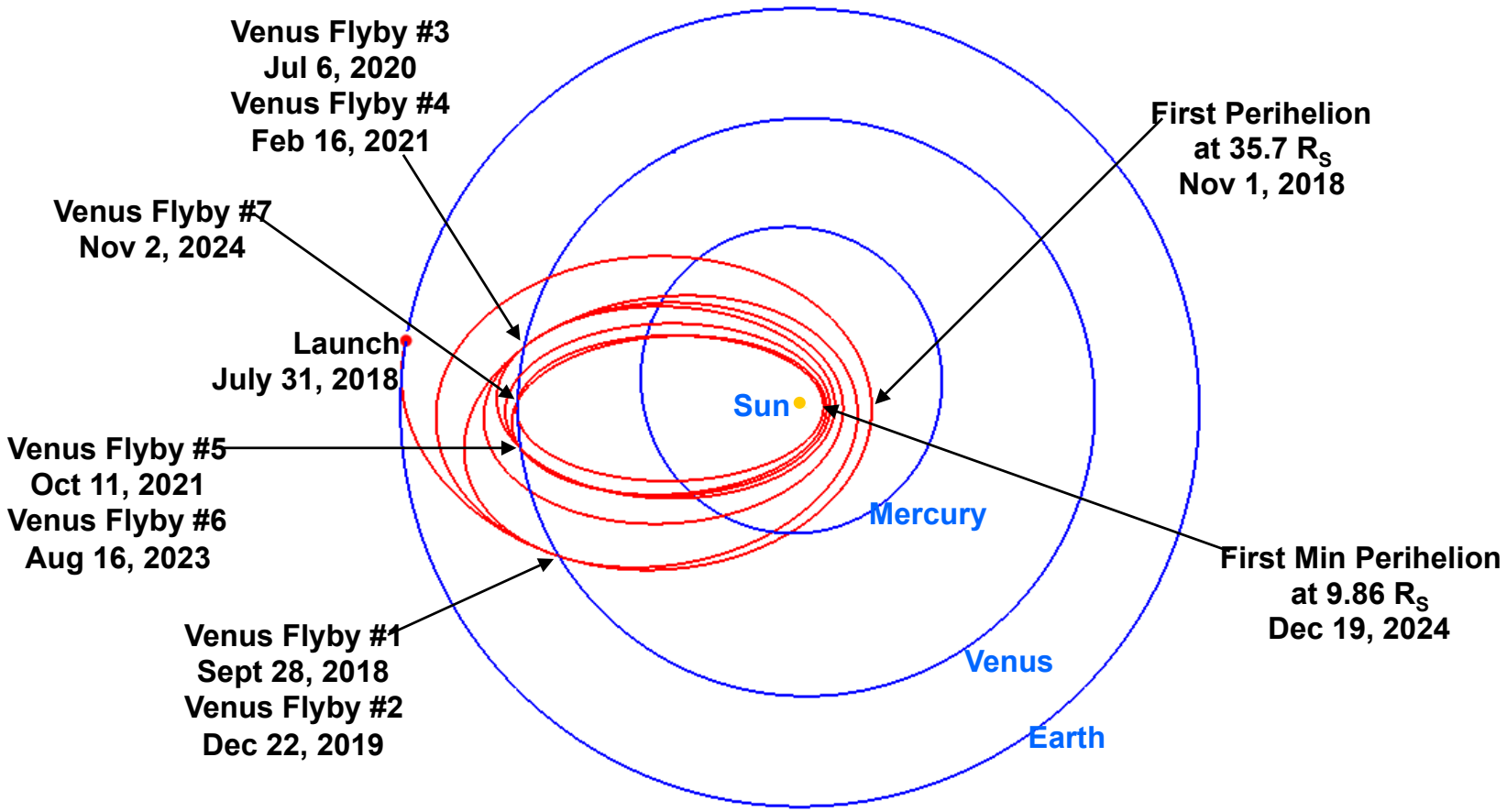


Solar Cycle: SPP will be going from minimum to ascending phase?

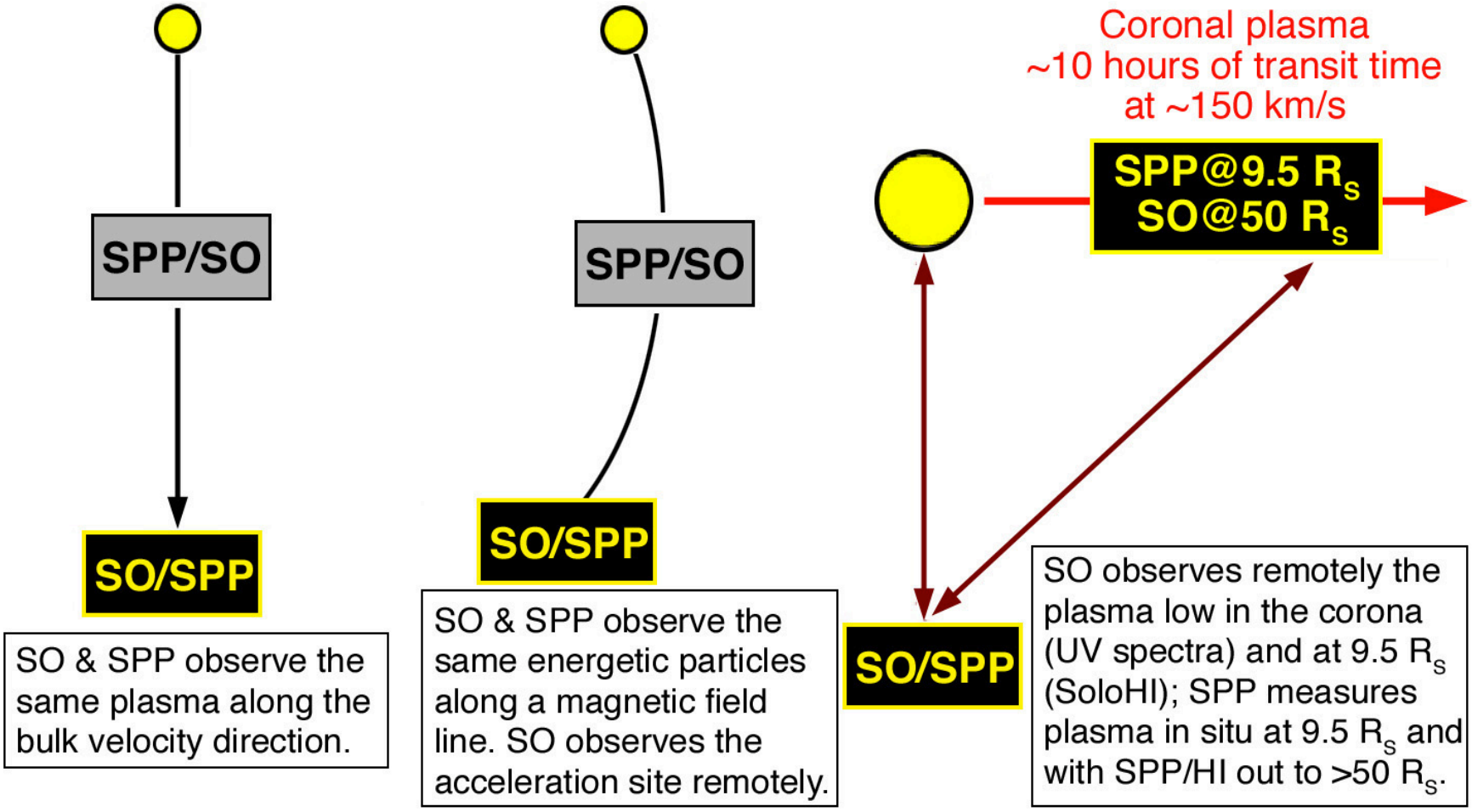




SPP Mission Trajectory

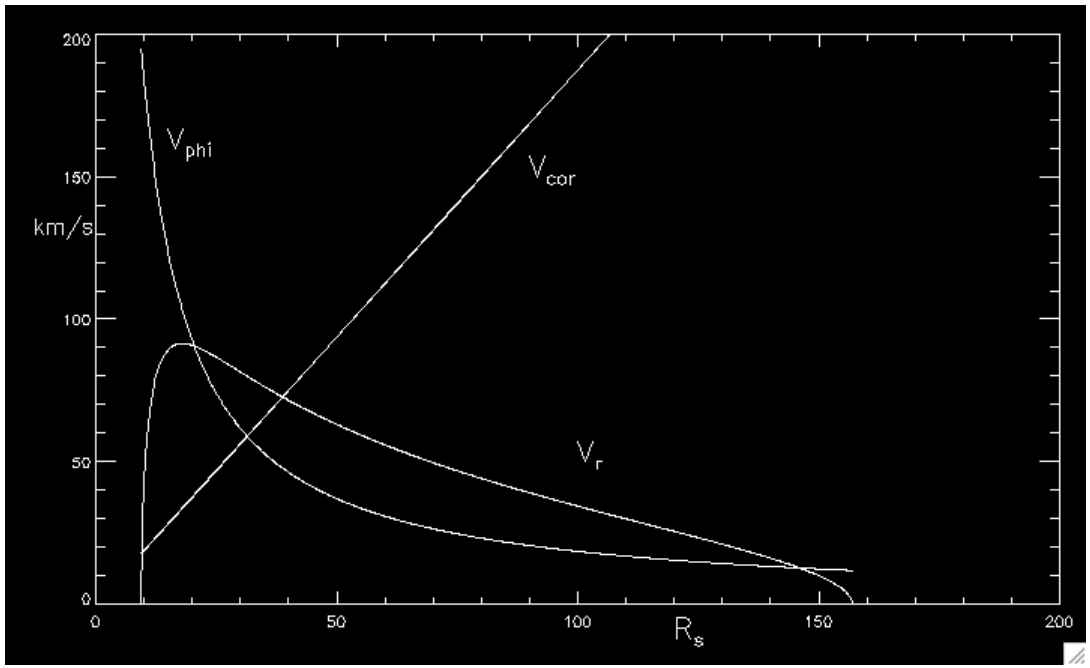


Joint SO/SPP Observations



Solar Probe Plus mission profile

Radial Scan (SR) (between 23 and 37 R_S; 2 days), to sample the same solar wind stream for an extended interval while the spacecraft is in quasi-corotation with the Sun.



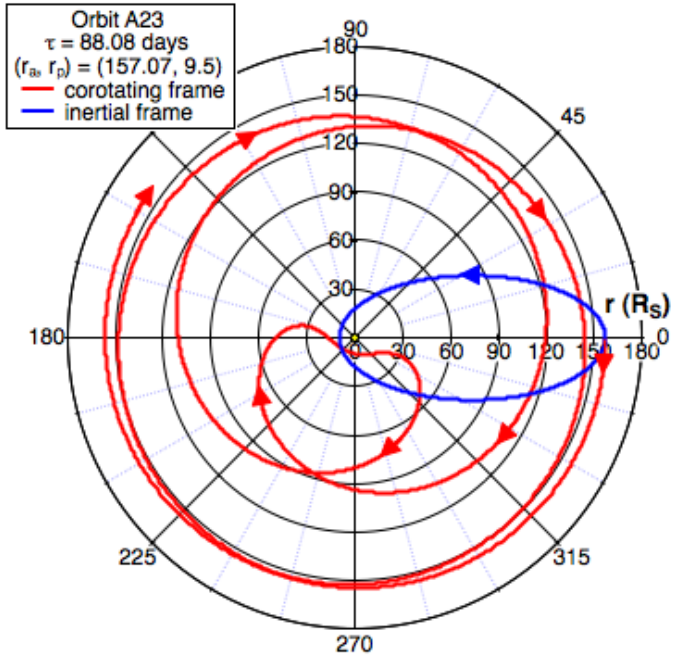
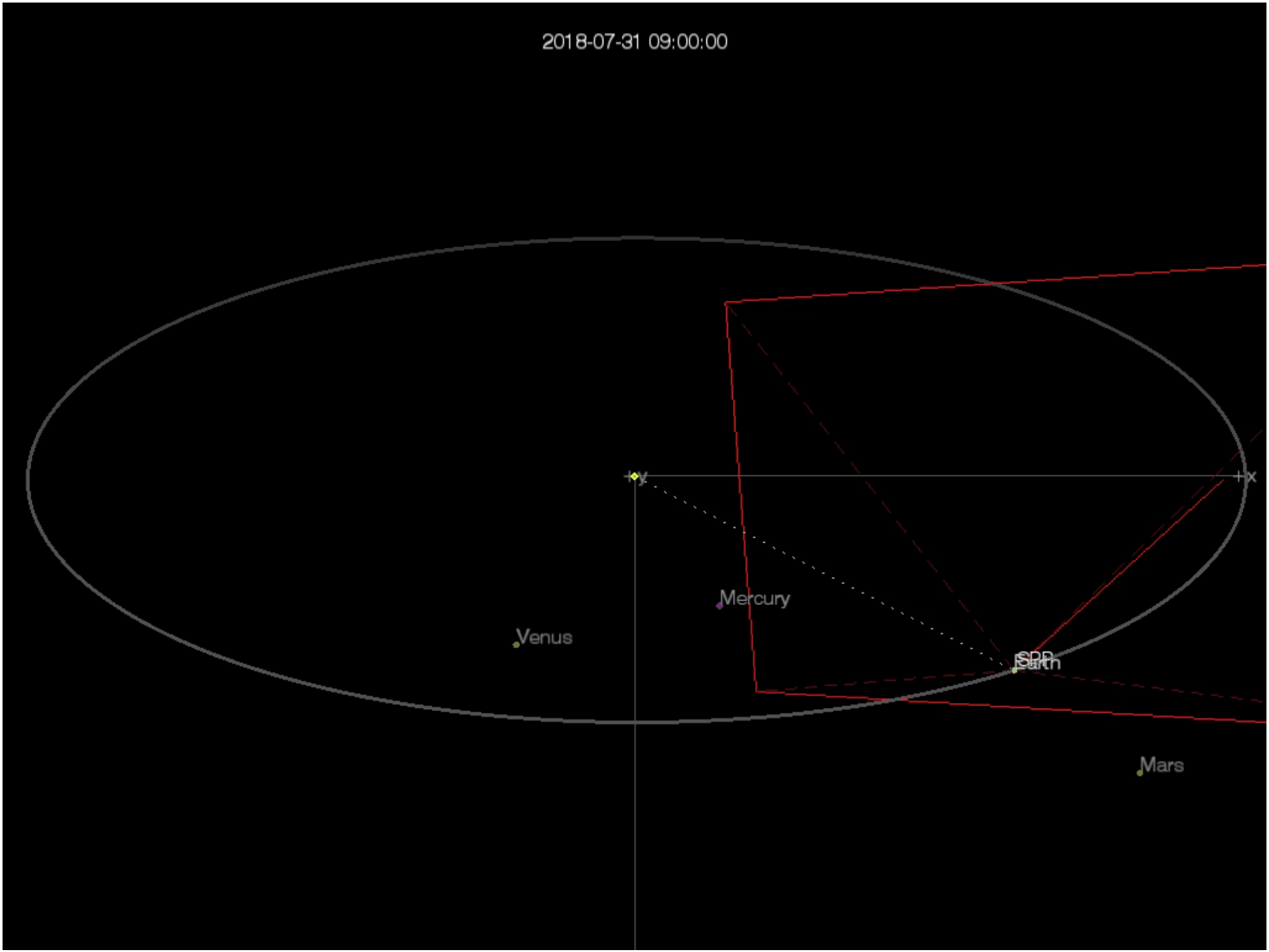


Figure: Decker and Lario 2011


2018-07-31 09:00:00
+y
+x
Mercury
Venus
Earth
SDD
Mars

Trace the flow of the energy that heats the solar corona and accelerates the solar wind

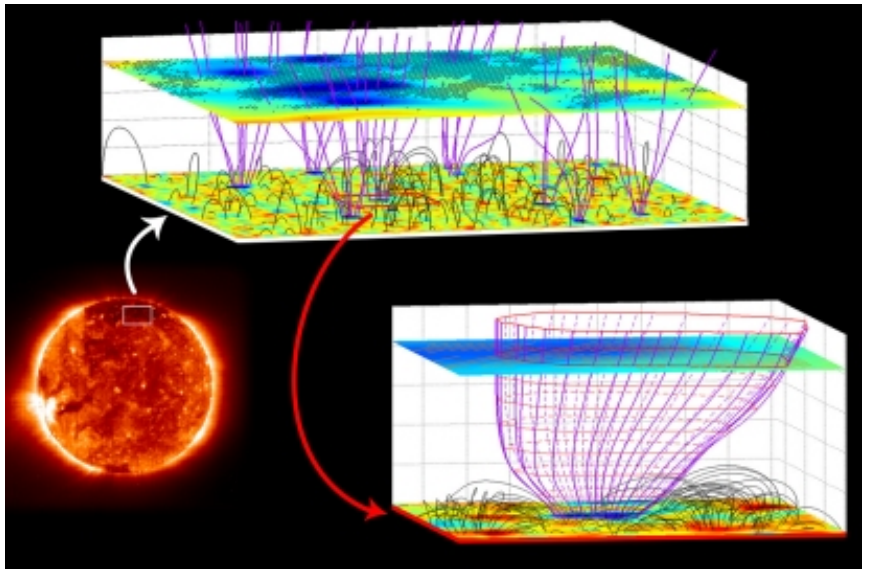
$$\nabla * \left\{ \rho \vec{V} \left(\frac{V^2}{2} + \frac{\gamma p}{(\gamma - 1)\rho} - \frac{GM_\odot}{R} \right) - \frac{(\vec{V} \times \vec{B}) \times \vec{B}}{4\pi} + \vec{F}_c \right\} + q_R = 0$$

$\vec{F}_c = -\kappa \nabla T$ *or some other prescription (collisionless)*

q_R *radiative loss*

$$F_0 = F_m + F_q + F_{rad} + F_{sw}$$

$$\frac{V_\infty^2}{2} = \frac{1}{\dot{M}} \left(F_{m,0} - F_{rad,\infty} \right) - \frac{V_g^2}{2}$$



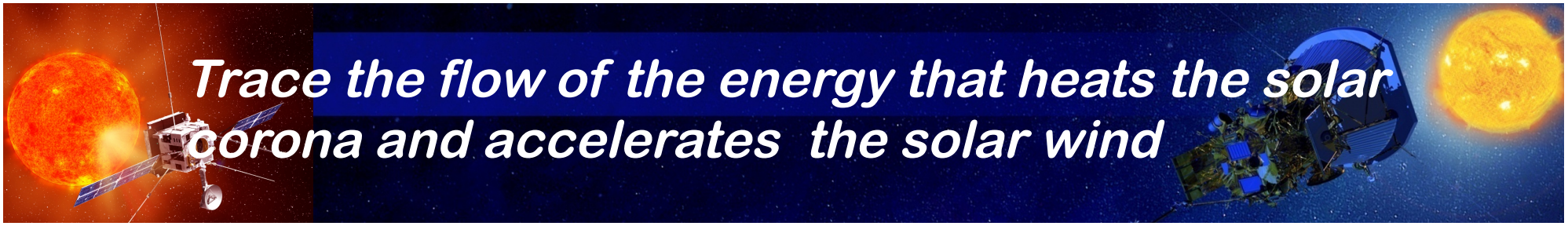
Photospheric motions produce field line tangling and emerging flux resulting in a Poynting flux crossing the photosphere:

$$\vec{S} = \frac{c}{4\pi}\vec{E}\times\vec{B} \qquad \vec{E} = -\frac{1}{c}\vec{V}_{ph}\times\vec{B}$$

$$\vec{S}\cdot\vec{n}_{ph} = \frac{B_{\perp}^{2}}{4\pi}\vec{V}_{ph}\cdot\vec{n}_{ph} - \frac{\vec{B}\cdot\vec{n}_{ph}}{4\pi}\vec{V}_{ph\perp}\cdot\vec{B}$$

Emerging Flux **Waves and Turbulence**

Source of heliospheric energy flux



Trace the flow of the energy that heats the solar corona and accelerates the solar wind

Coronal heating / Solar Wind Acceleration models (from Kasper)

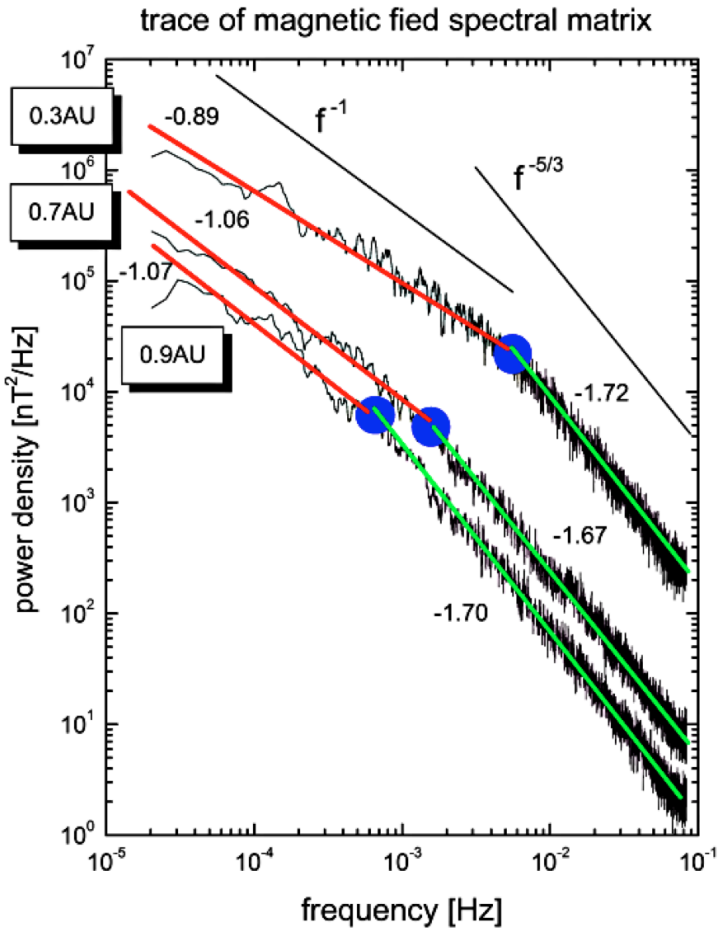
Mechanism	(1) Ion Cyclotron[a]	(2) Turbulent Cascade[b]	(3) Shock Steepened Acoustic modes[c]	(4) Reconnection and nano-flares[d]	(5) Filtration[e]
Process	Ion-cyclotron wave damping	Turbulent cascade, spectral coupling, and dissipation	Compressive waves, wave steepening, shock dissipation	Large and small-scale reconnection, convective motions	Kappa distributions
Signatures in the solar wind	high frequency fluctuations at ion-cyclotron frequency, i+ $T_{\perp} > T_{\parallel}$	low-frequency waves, spectral breaks, dissipation range	Ion beams, compressible low-frequency waves and shocks	High speed i+ beams and bidirectional plasma jets, enhanced e- strahl	Ions and electrons have unusual peaked VDFs
Identifying Signature	p+ flow angles, 2D i+ and e- VDF at 64 Hz cross-correlated with E and B power spectra		n and V at 1% accuracy to detect weak shocks	Flow angles and i+ beams at 30 Hz	dE/E < 5% to resolve VDF, p+ and e- halo

[a]Hollweg, 2008; Cranmer, 2000; Hollweg and Isenberg, 2002; Isenberg, 2001; Galinsky and Schevchenko, 2000; Marsch and Tu, 2001; [b]Matthaeus, Zank et al., 1999; Dmitruk et al., 2002; Cranmer et al., 2007; Chandran et al., 2009; [c]Bruner, 1978; Ulmschneider, 1985; [d]Parker, 1979, 1987; Sturrock, 1999; Priest et al., 2002; Axford and McKenzie, 1992; Cargill and Klimchuk, 2004; Schrijver et al., 1997; [e]Scudder, 1994; Pierrard and Lamy, 2003

Trace the flow of energy that heats the solar corona and accelerates the solar wind

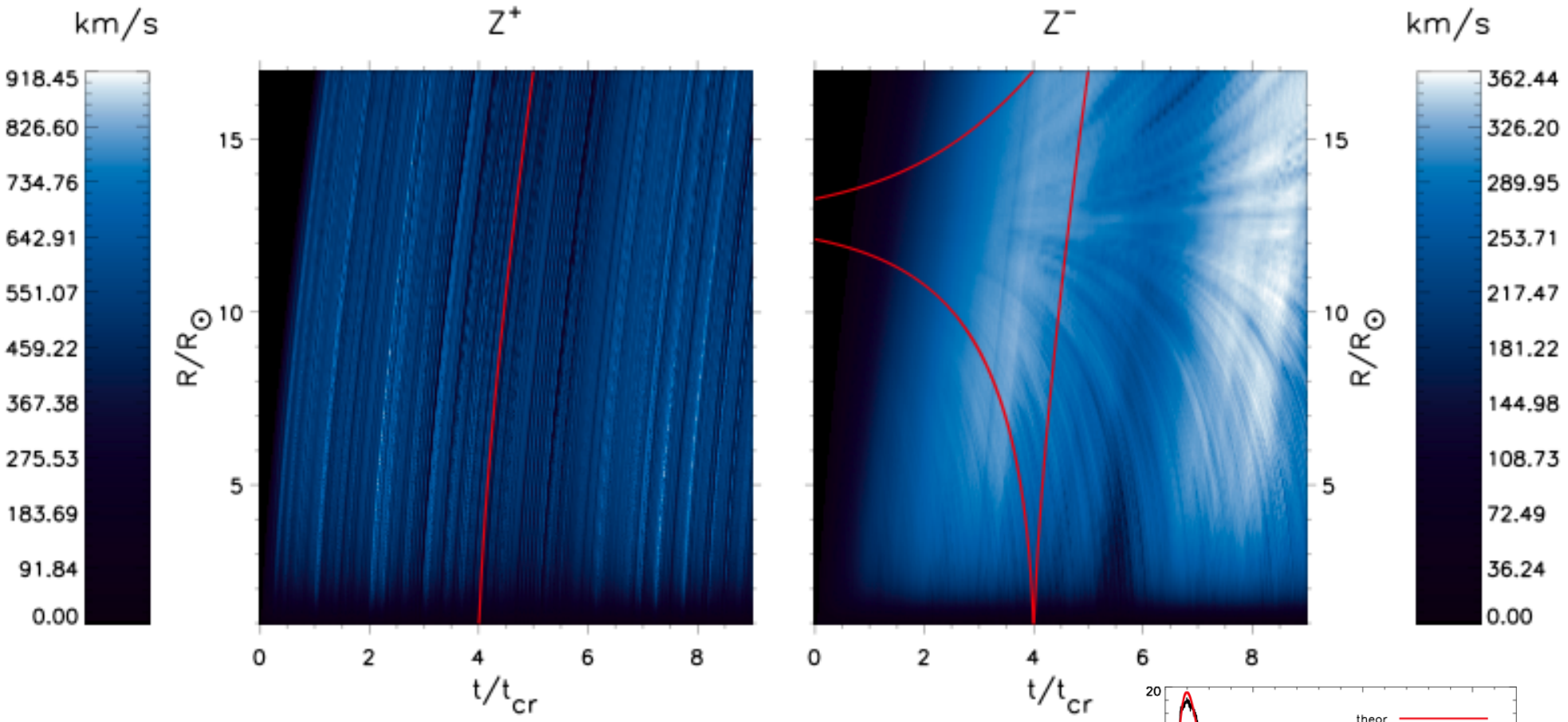
$$\frac{\partial z^{\pm}}{\partial t} + [(U \pm V_a)\cdot\nabla]z^{\pm} + (z^{\mp}\cdot\nabla)(U \mp V_a) + \frac{1}{2}(z^{-} - z^{+})[\nabla\cdot V_a \mp \frac{1}{2}(\nabla\cdot U)] =$$

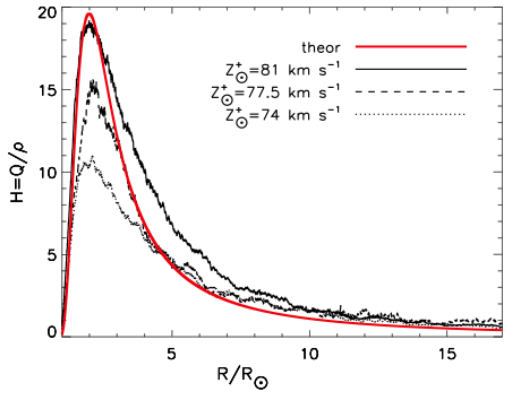
$$-(z^{\mp}\cdot\nabla)z^{\pm} - \frac{1}{\rho}\nabla p_{tot}$$



$$z^{-} << z^{+} \qquad \delta\rho/\rho << 1 \qquad \delta|B| << |b|$$

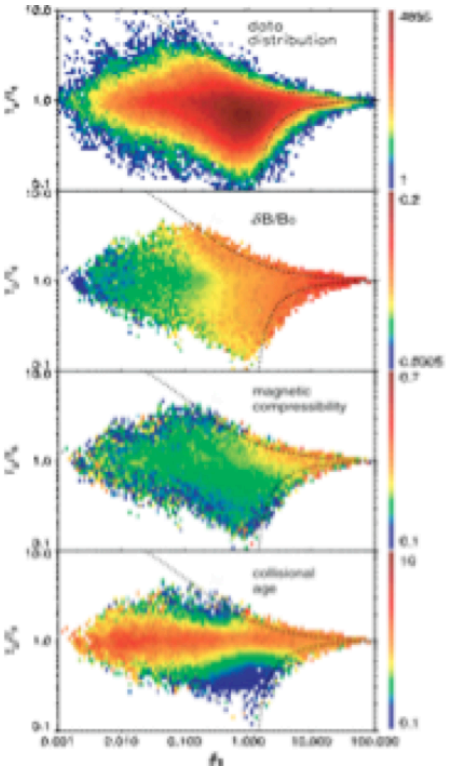
Trace the flow of energy that heats the solar corona and accelerates the solar wind

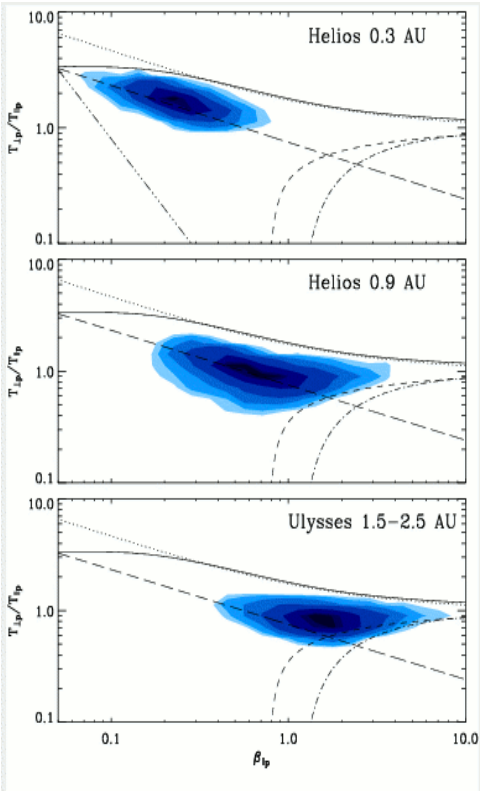


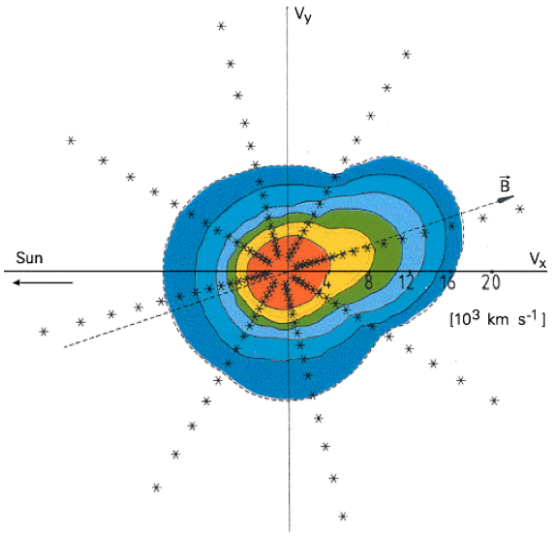


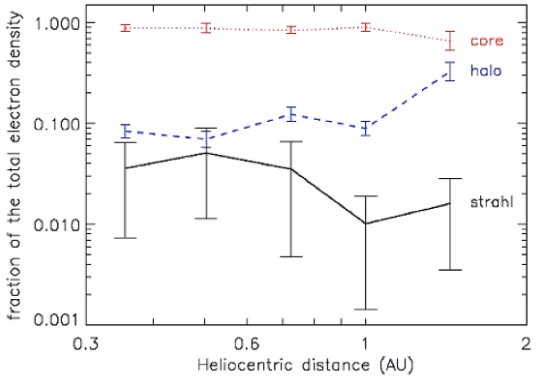
Shell model for the nonlinear terms

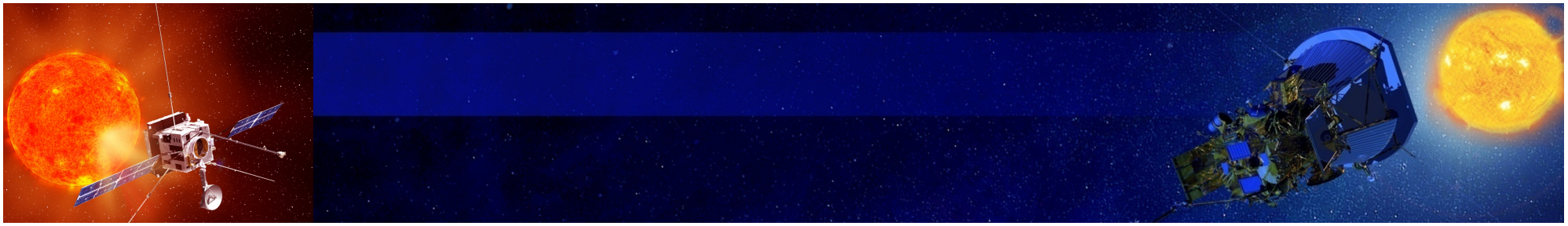
Trace the flow of energy that heats the solar corona and accelerates the solar wind





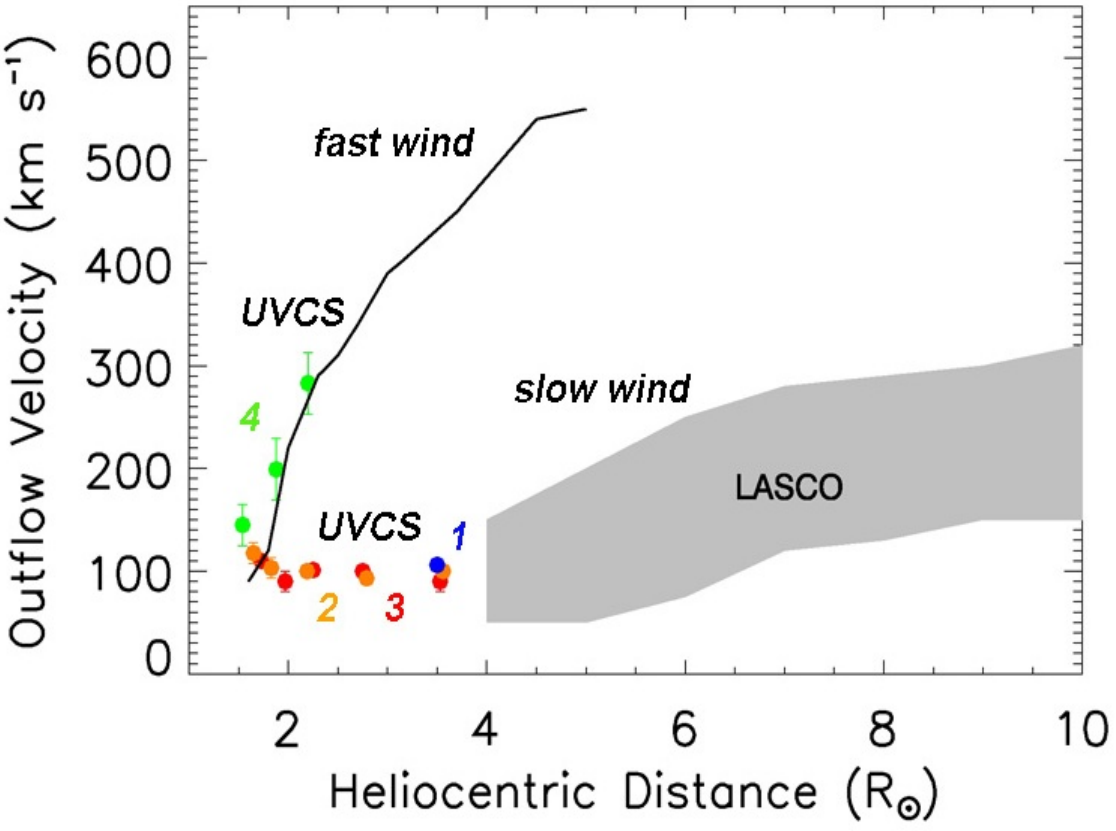


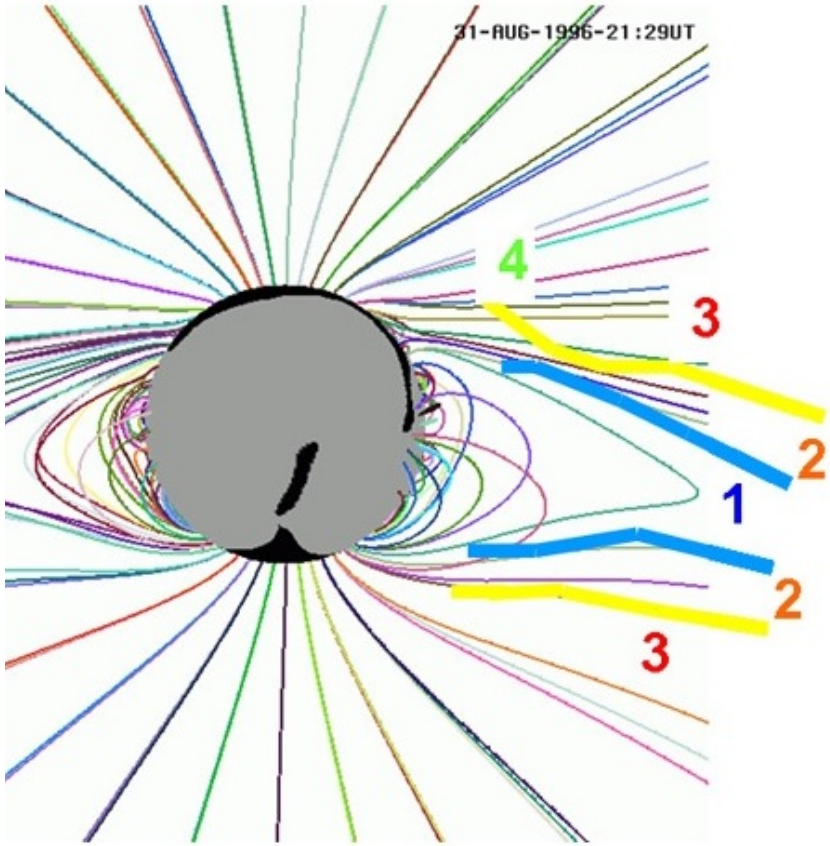




- ***Where and how does the sharp gradient in speeds develop close to the Sun?***
- ***Is there a steady component of the slow (and fast) wind or is its origin always intermittent in nature?***
- ***Where does the heliospheric current sheet form and how stable is it close to the Sun?***
- ***What is the distribution of CME origins and is there a continuum from large CMEs to small blobs of plasma?***

Where and how does the sharp gradient in speeds develop close to the Sun?

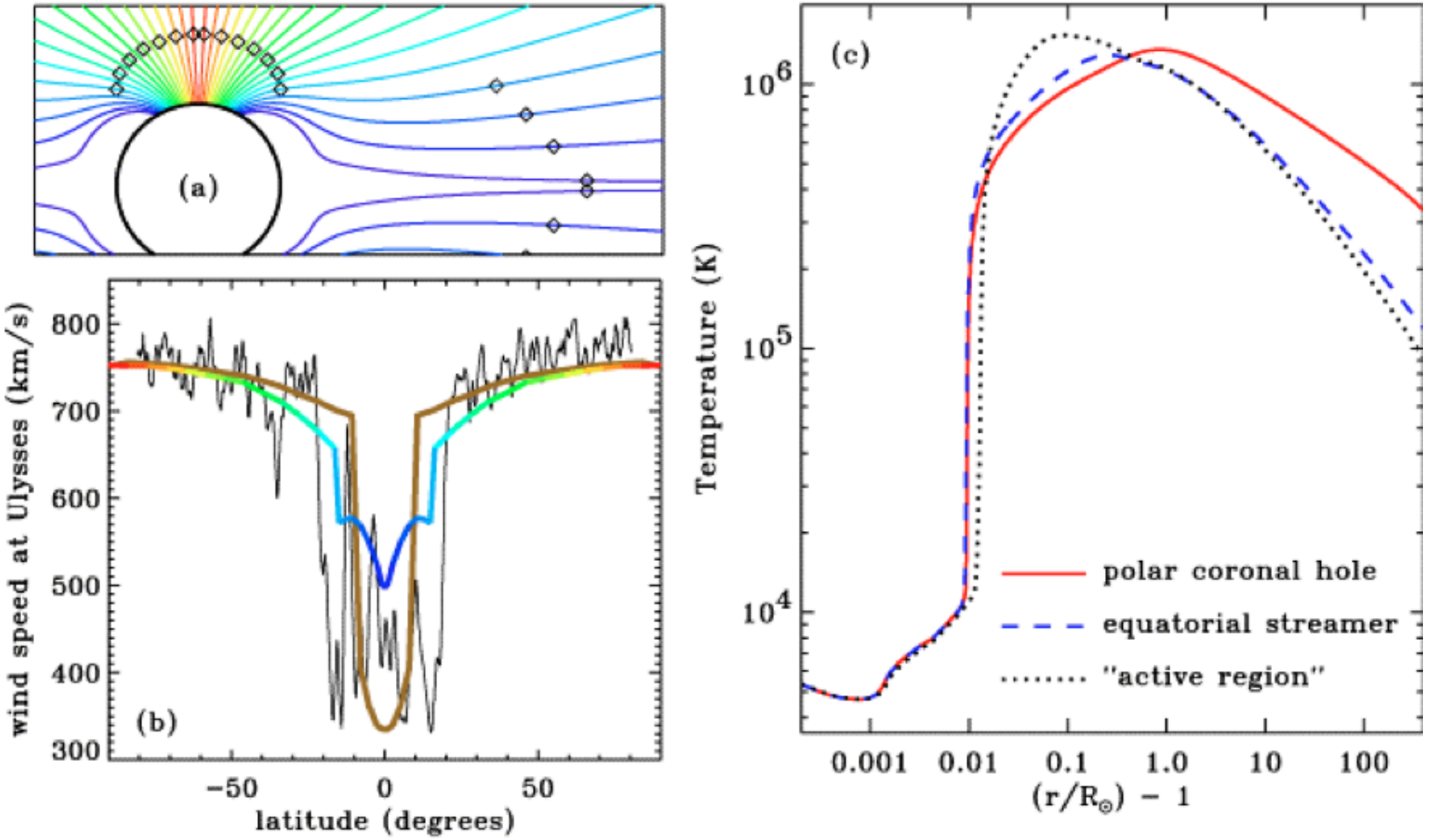




Antonucci et al., Telloni et al. 2007-2009

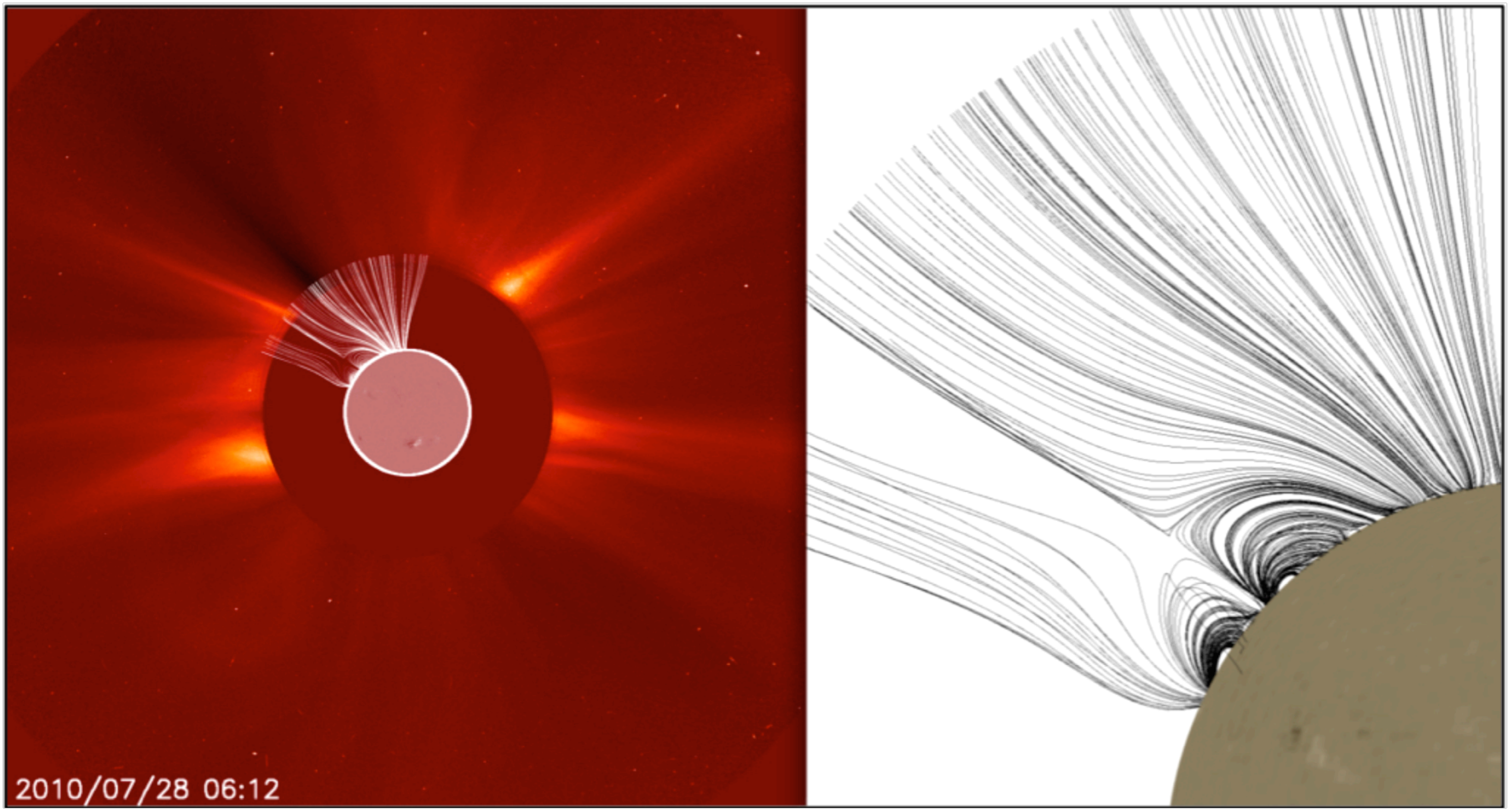
UVCS on SOHO suggest slow/fast separation already in place by 9 Rs

Where and how does the sharp gradient in speeds develop close to the Sun?

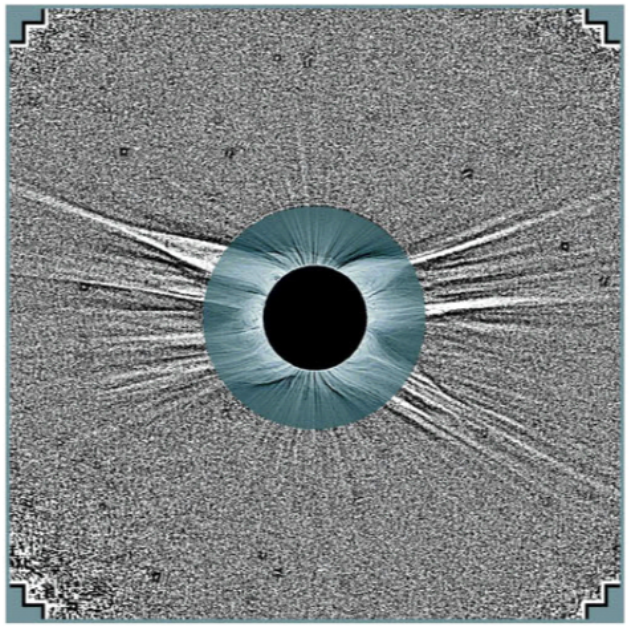


Cranmer et al. 2008

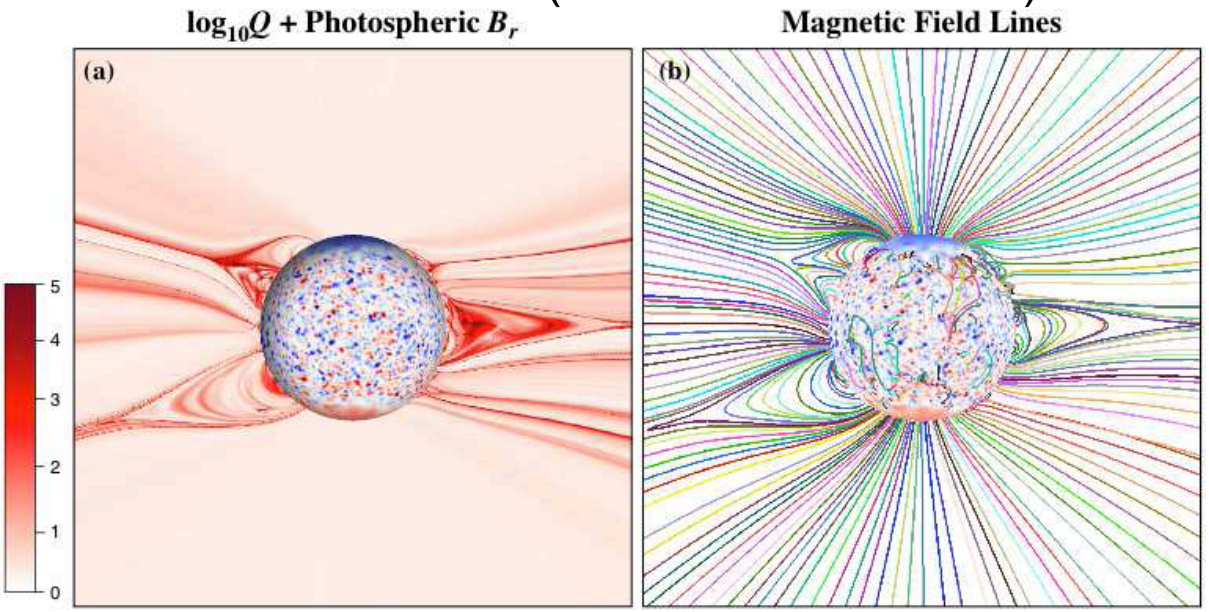
Pseudostreamers are a second defining feature of the corona



Connection between coronal sources, streamer belt, and heliospheric current sheet



(Antiochos et al. 2011)



- In situ measurements of solar wind state: temperature, density, velocity, He/H, magnetic field strength, turbulence
- Remote imaging of local and global structures with WISPR
- Connect to solar observations and models

Pseudostreamer interchange reconnection as a wind source: jet-like vs blobs?

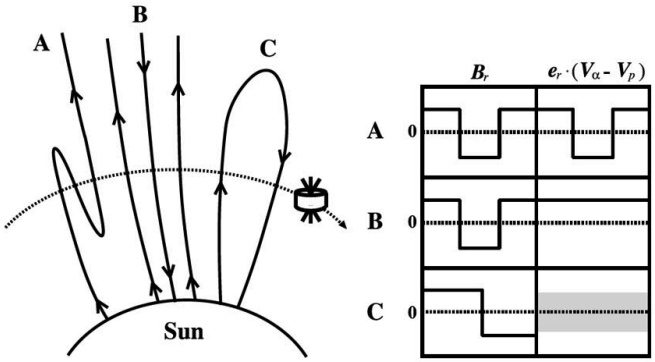
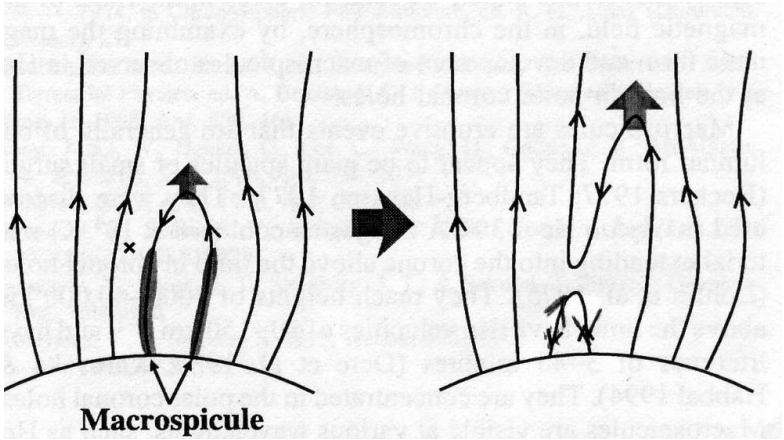
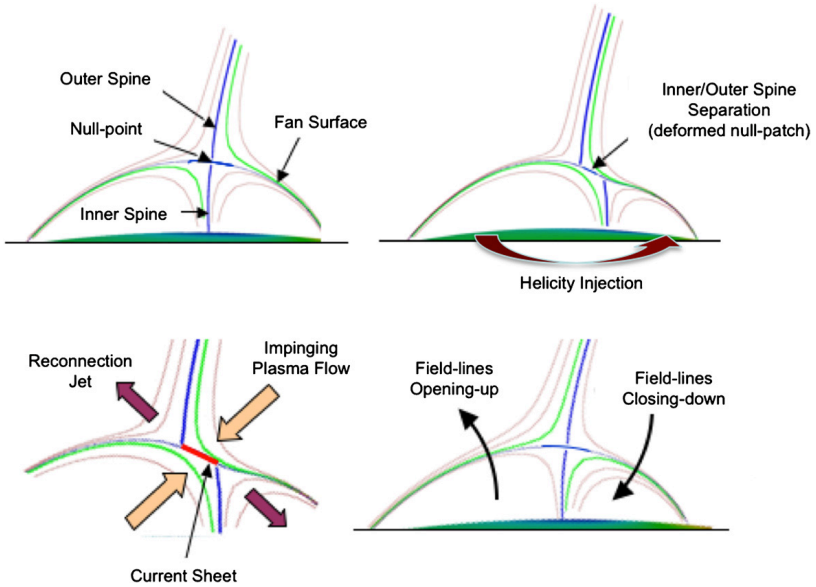
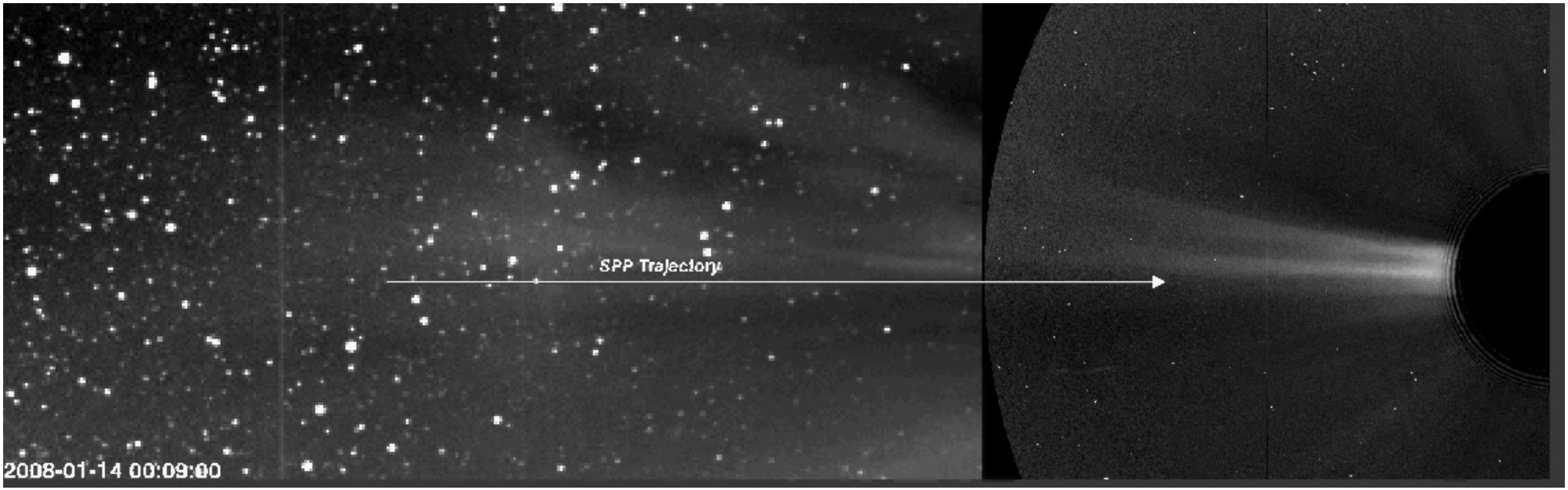


Figure 1. (left) Cartoon of three possible configurations across discontinuities in the radial magnetic field. (right) Diagrams of the variation in radial magnetic field strength and alpha particle-proton differential streaming in the radial direction across the three classes of discontinuities.



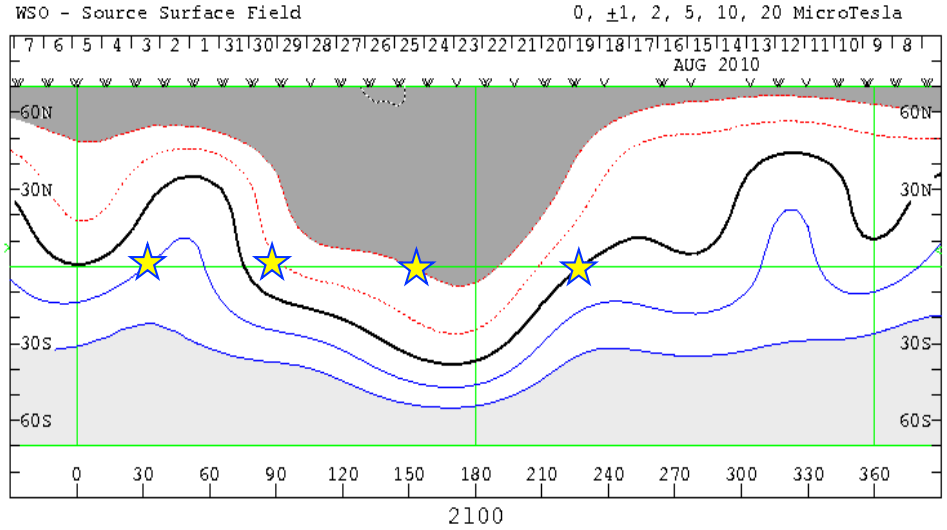


Solar Probe will directly sample wind



Coronal Magnetic Topology: Streamers and Pseudostreamers. Fast, slow and hybrid wind.
Presence of pseudostreamers (PS)
a) extreme-high and extreme-low-proton-flux wind is associated with PS; "hybrid" type of outflow;
b) intermediate proton speed but high electron temperature; c) spikes of proton density may represent PS plasma sheets; d) wind measurements; All above will allow to determine the structure and dynamic of the plasma and mag. fields at the sources of the solar wind. And also will answer the question how the processes in the corona affect the properties of the solar wind in heliosphere.
Presence of streamers. a) not extreme-high densities and regular slow solar wind

Heliospheric current sheet



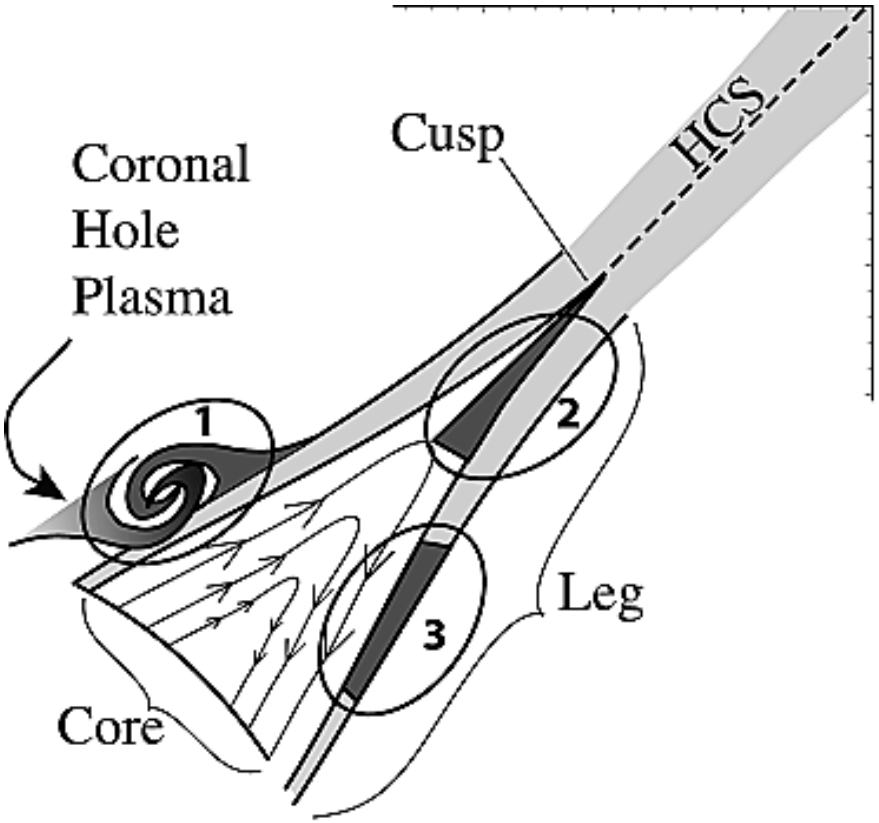
Where is the HCS is formed? At which distances from the Sun? Properties and structure of HCS? SPP can give answers.

SPP can answer the question - Does the HCS play a key role in the CME propagation? Presence of CME plasma and shocks at SPP position.

Heliospheric current sheet (HCS) position and properties:

1. HCS associated with high-density and low velocity solar wind;
2. Sector boundary - magnetic filed direction is changes;
3. He/H ratio dips sharply at plasma sheets associated with sector boundaries;
4. turbulence?

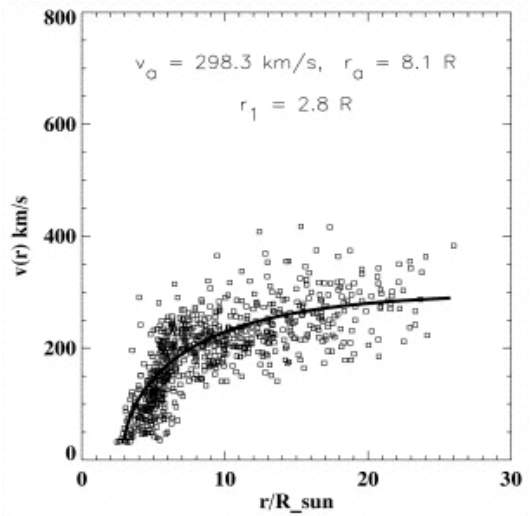
Other slow wind ideas and possible discriminators

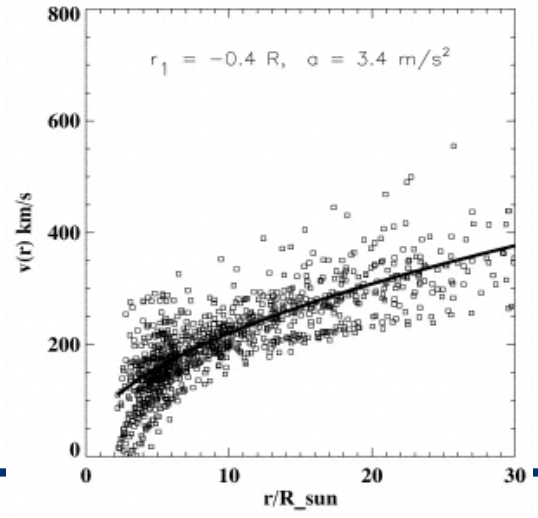


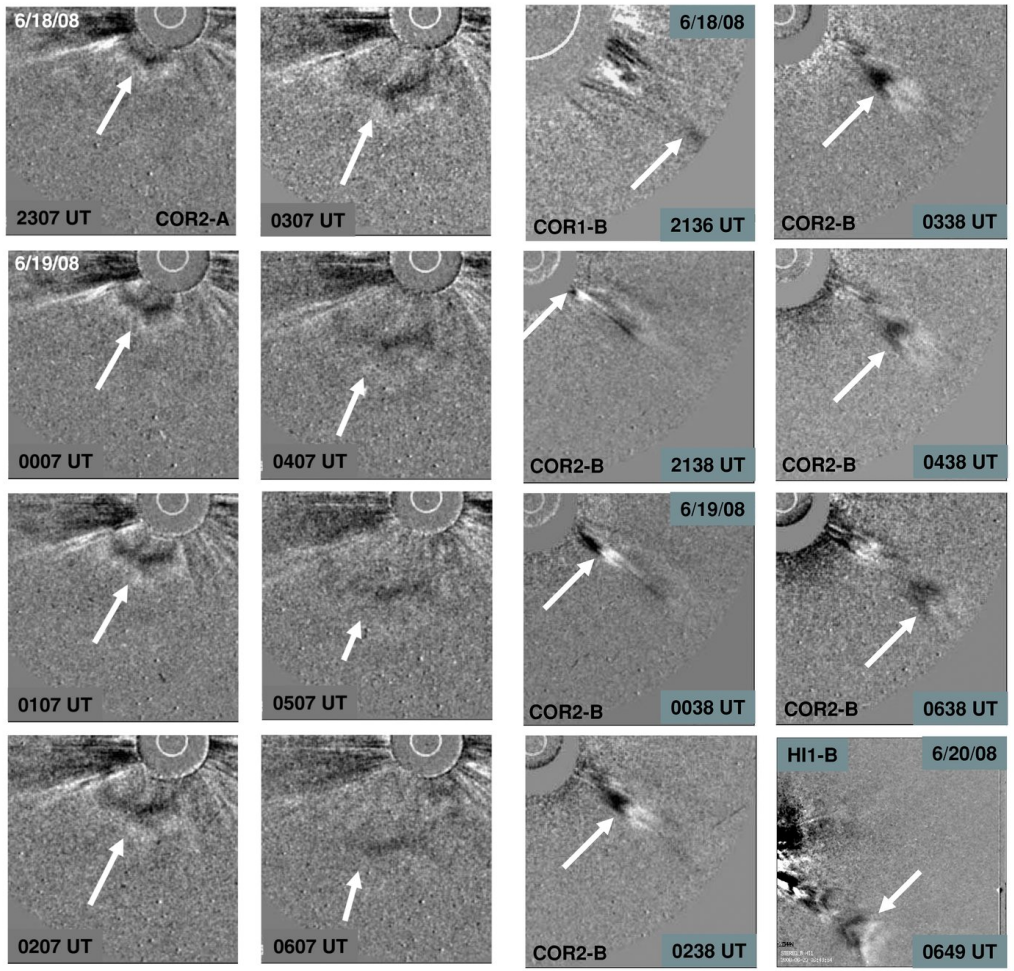
Helium depletion around heliospheric current shees

(1) Mixing of plasma inside the brightness boundary with that from adjacent coronal holes.
(2) Plasma from just one side in the core, just below the cusp, so as to produce a He/H depletion lying to one side of the HCS.
(3) Quasi-steady flow from the legs of streamers (Suess et al 2009)

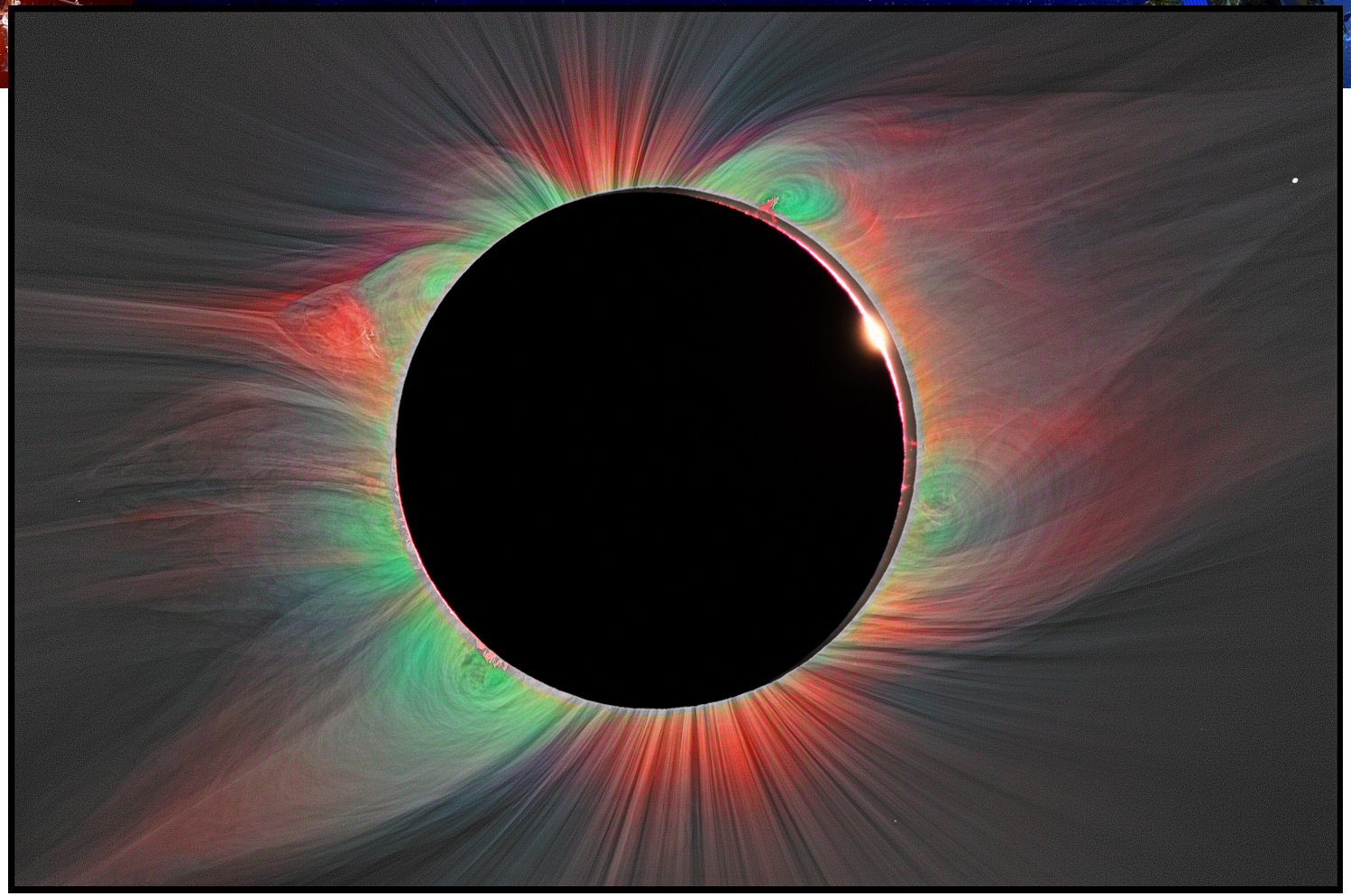
"Blobs" from Heliospheric current sheet have flux-rope like nature





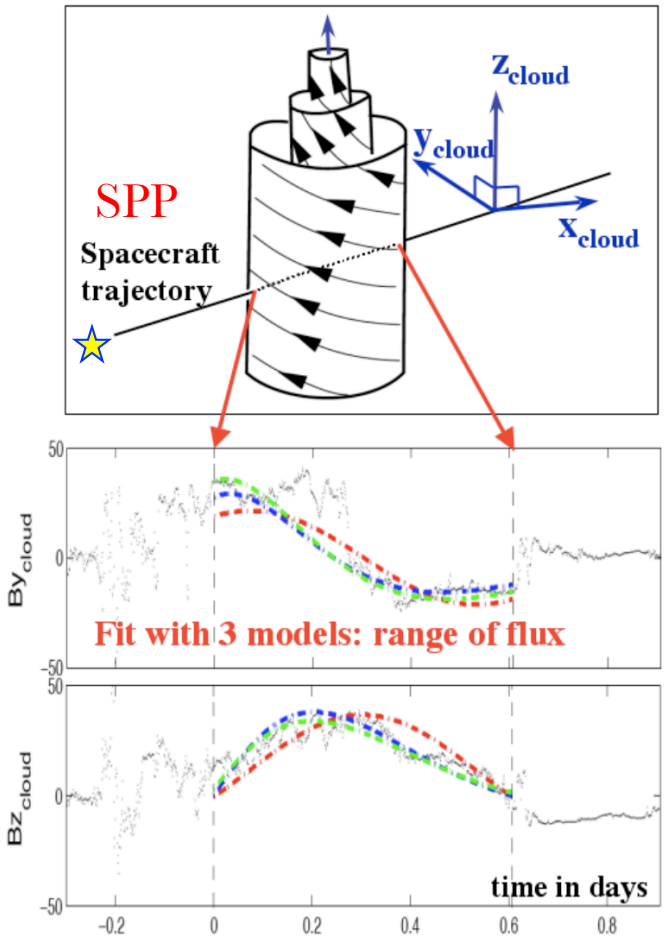


Back to structure in the solar corona

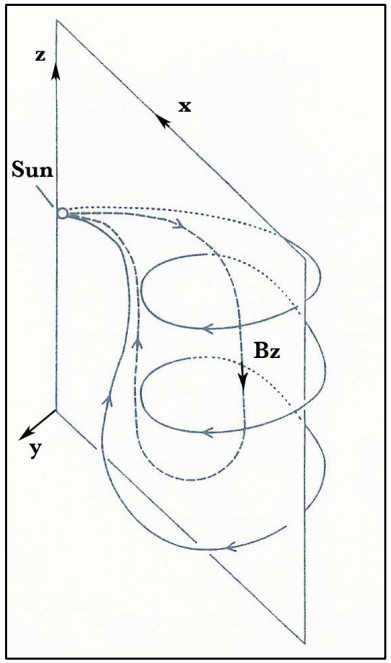


Eclipse: RED 1.1 10^6 K *Iron X-XI (RED)* GREEN 2 10^6 K *XIII-XIV (GREEN)*
Expanding corona is dominated by Te = 1.1 10^6 K Cavity around CMEs very hot
(Habbal et al 2010, 2013)

CMEs and their contribution acceleration



Mandrini et al., 2007



Gosling, 1990
Bothmer & Schwenn, 1998

Counterstreaming:

- ICME suprathermal electrons ≥ 80 MeV (Gosling 1990);
- H-alpha filaments (Zirker et al., 1998; Lin et al., 2003, 2007, 2013);
- Hi-C 195 Å (Alexander et al., 2013)
- SDO/corona AIA 193, 173 Å, limb prominences (Panasenco et al., 2013)

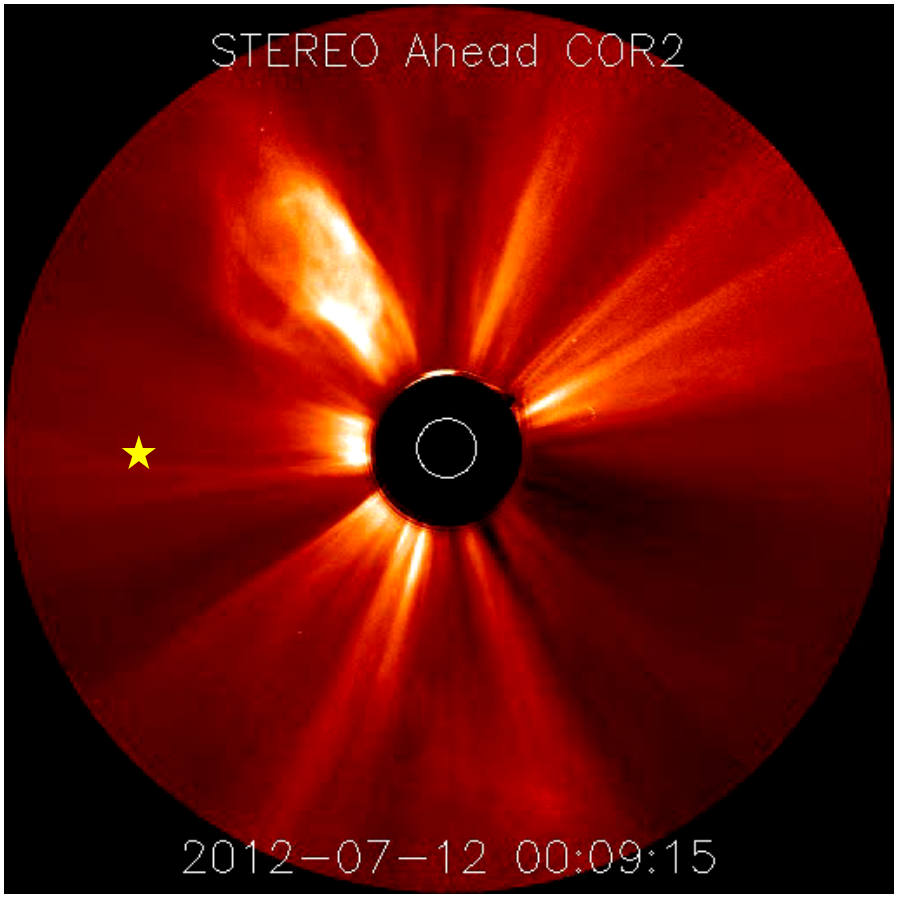
CME shock, cavity, core…

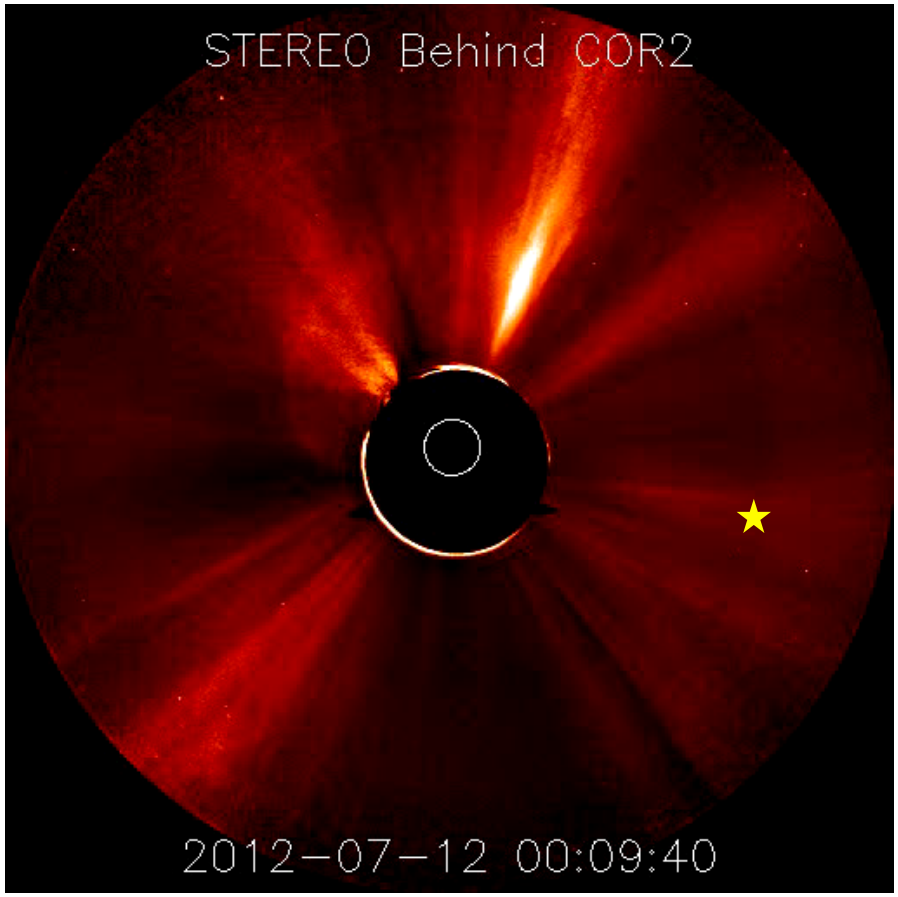
Plasma of the core (prominence plasma), very rarely observed at 1AU. SPP will measure density, etc.

Helicity/Chirality

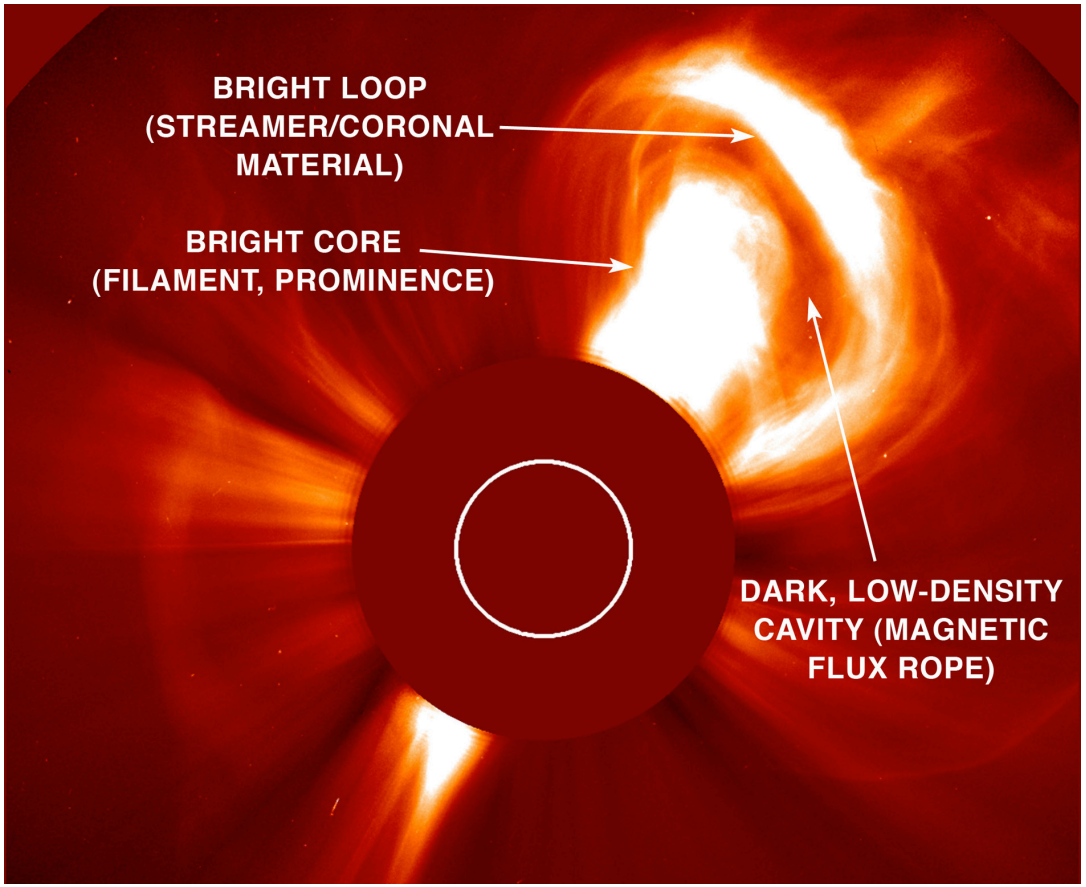
Bx, By, Bz components… Compare with the source of CMEs

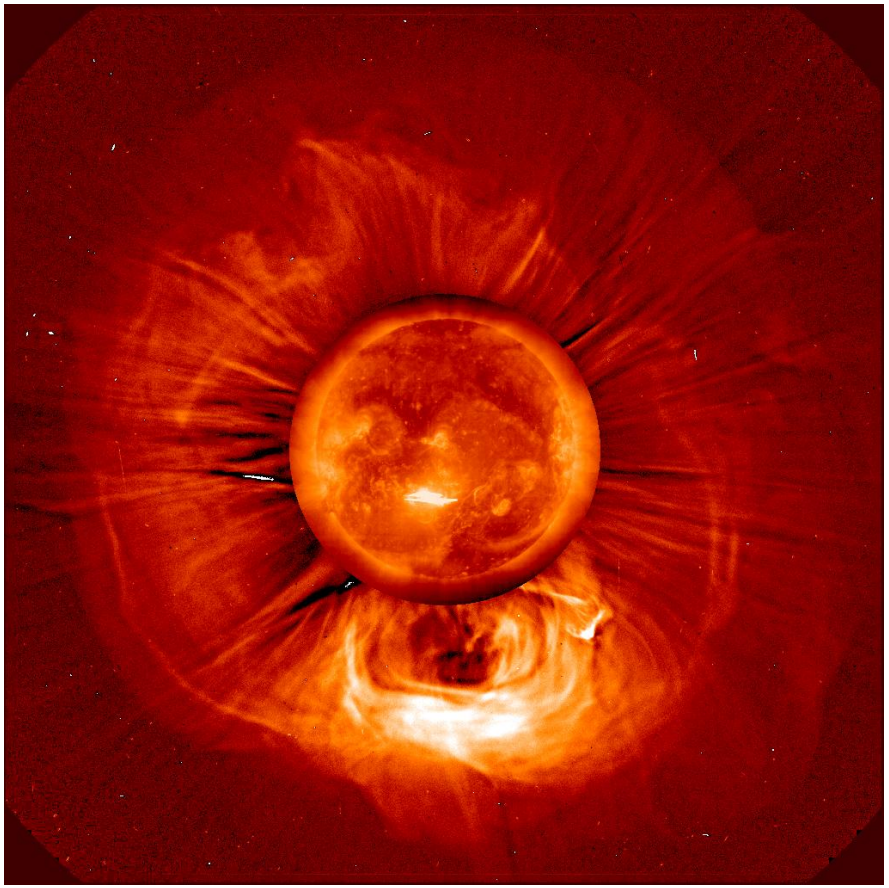
CMEs


STEREO Ahead COR2
2012-07-12 00:09:15


STEREO Behind COR2
2012-07-12 00:09:40

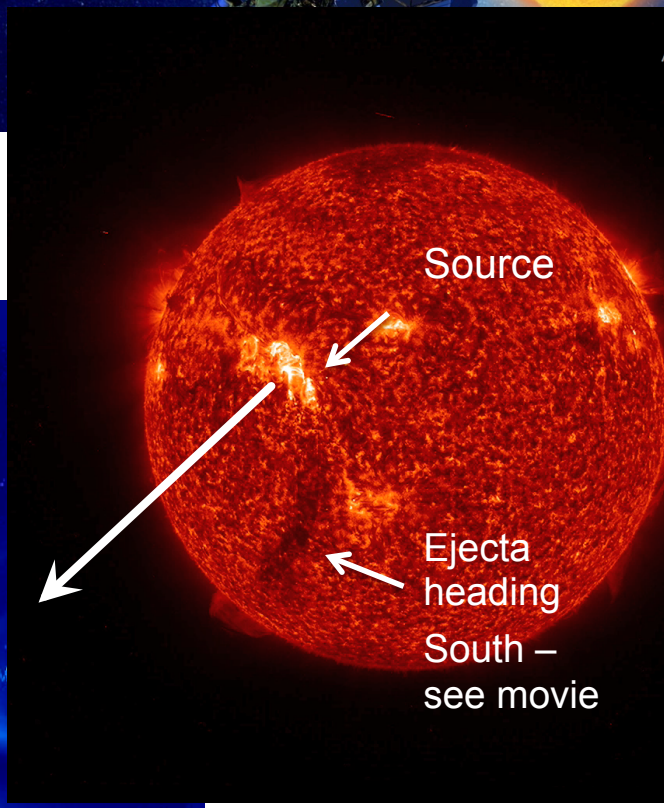
Shock formation and propagation close to the sun

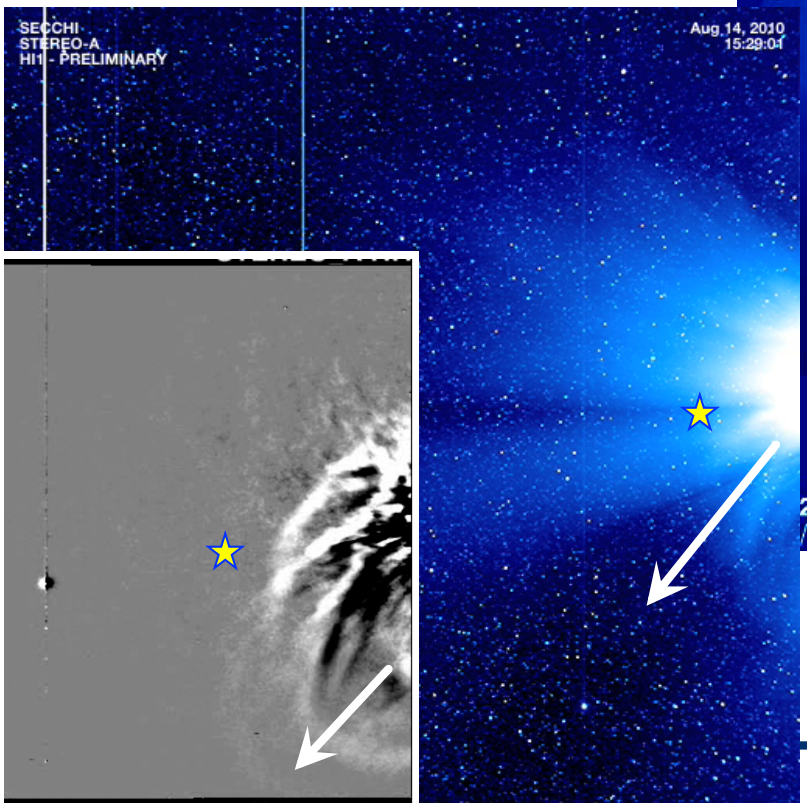


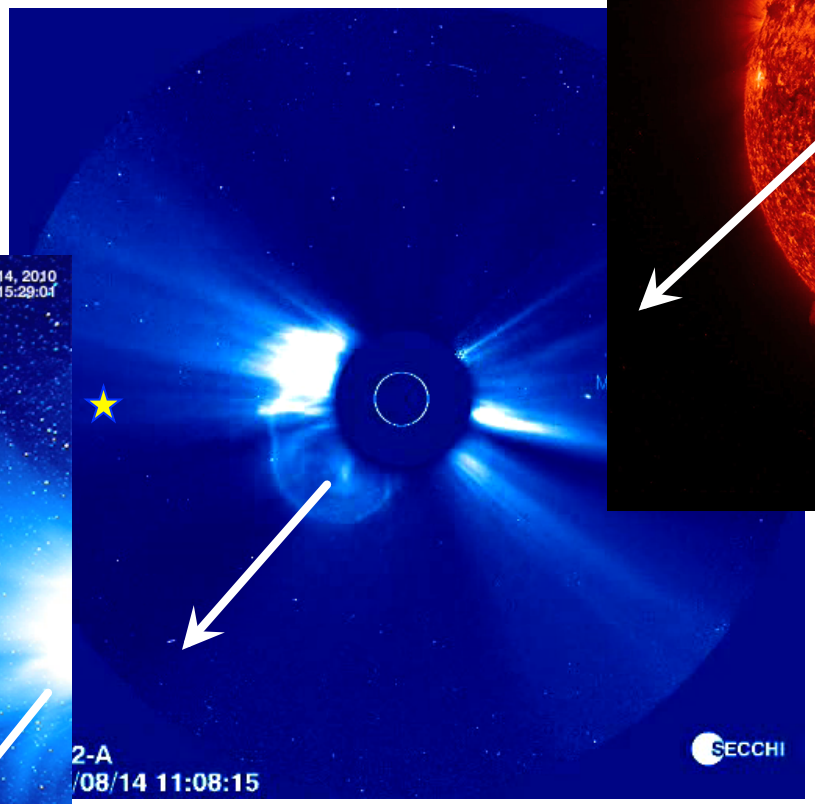


CMEs & HCS

CME (14 Aug 2010) propagates in straight line S20-S30, well south of the heliospheric current sheet, but **NOT** radially from source!

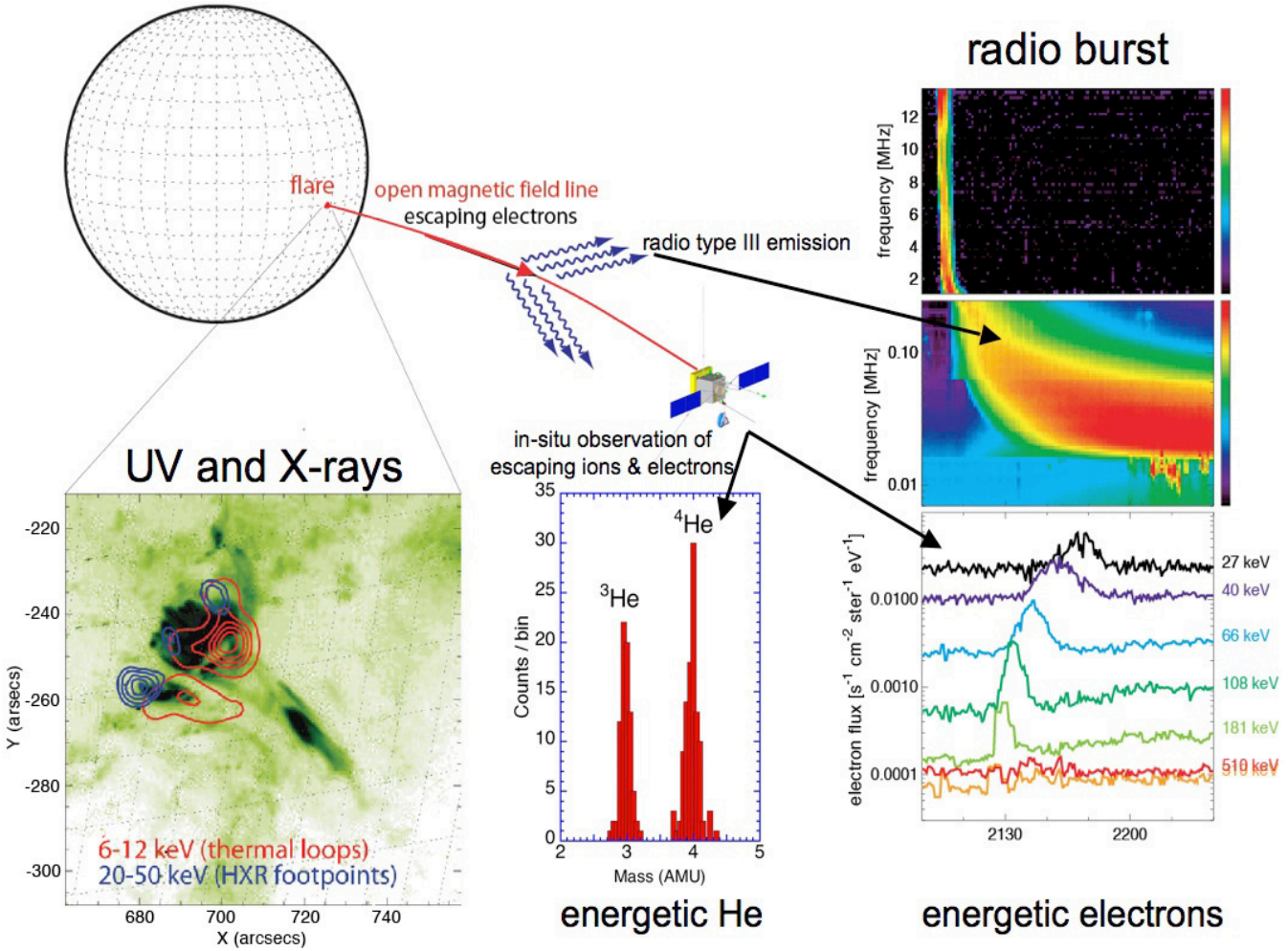




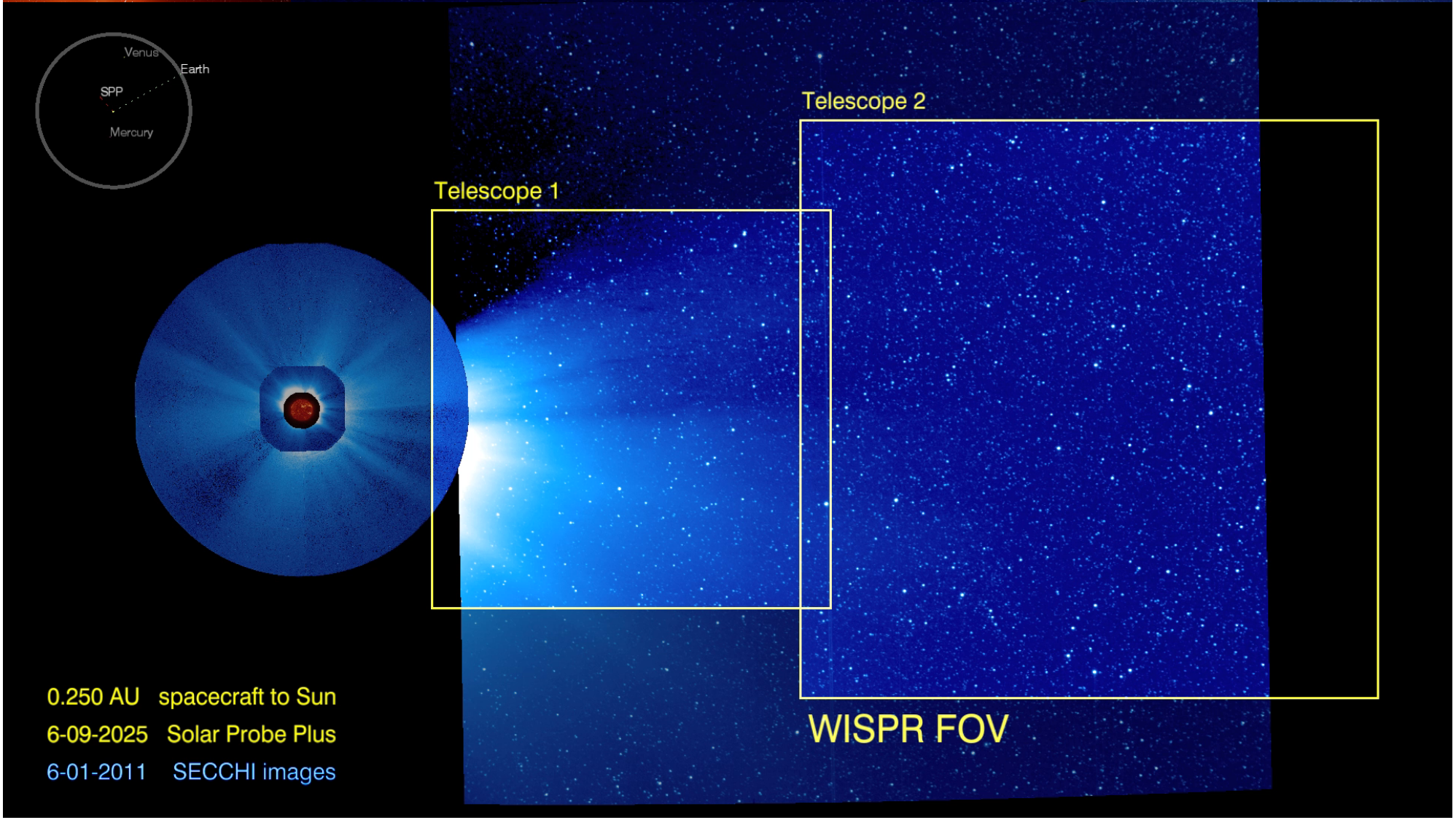


Liewer et al., in progress

Particle acceleration close to the sun



WISPR Field of View in orbit



SPP/SO Encounter configurations

SPP Perihelion	Date	SO/Earth position	SPP Distance	Time within 30	20	15	10
1	01/11/2018	SO 100 E 90 West	35.8	0	0	0	0
	25/11/2018	S/SO/E conjunction					
2	31/03/2019	E 45 East SO 105 East	35.8	0	0	0	0
	04/04/2019	S/SPP/E conjunction	~40 Rs				
	08/08/2019	S/SPP/SO conjunction	~0.4 AU				
3	28/08/2019	E 170 East SO 105 East	35.8	0	0	0	0
4	24/01/2020	S/SPP/SO/E conjunction	27.9	60.4	0	0	0
	04/12/2020	S/SO/SPP conjunction	~0.65 AU				
	22/05/2020	S/SPP/SO conjunction	~0.4 AU				
5	02/06/2020	E 120 West SO 120 East	27.9	60.5	0	0	0
	06/11/2020	S/SPP/E conjunction	~0.45 AU				
	23/08/2020	S/SPPE conjunction	~0.65 AU				
6	22/09/2020	S/SPP/SO conjunction E 105 East	20.4	104.1	0	0	0
	18-19/12/2020	SO/SPP close longitude	~0.6 AU				
7	13/01/2021	S/SPP/Earth 12/01 SO 105 West	20.4	104.1	0	0	0

SPP Perihelion	Date	SO/Earth position	SPP Distance	Time within 30	20	15	10
	10-21/05/2021	SO-E-SPP 360	~0.5 AU				
9	05/08/2021	SPP/S/E (occ) conj SO 120 West	16	108.6	47.8	0	0
	15/09/2011	S/SO/E conj SPP 40 East	~0.6-0.7 AU				
10	16/11/2021	S/SPP/SO 15/11 S/SPP/E 16/11	13.3	107.3	55.1	24.5	0
	01/03/2022	S/SO/E					
11	21/02/2022	S/SPP/E conj SO 140 West	13.3	107.3	55.1	24.5	0
	25/05/2022	S/SPP/SO conj FRS E 130 East					
12	28/05/2022	SO/SPP/E 360 31/05 S/SPP/E con FRS	13.3	107.3	55.1	24.5	0
13	01/09/2022	SO/SPP 90 SPP/E 135 02/09 S/SPP/SO conj FRS	13.3	107.3	55.1	24.5	0
	10/07/2022	S/SO/SPP conj	~0.7 AU				
14	07/12/2022	03/12 S/SPP/SO 05/12 S/SPP/E FRS	13.3	107.3	55.1	24.5	0
15	13/03/2023	E/S/SO 100 S/SPP/SO S/SPP/E conj	13.3	107.3	55.1	24.5	0
	17/04/2023	S/SO/E "conj"					
	05/08/2023	S/E/SO-SPP quad SPP Aph S/SO/SPP conj	~0.7 AU				
16	17/06/2023	SPP/E/SO 360 23/06 S/SPP/E conj	13.3	107.3	55.1	24.5	0
	13/08/2023	S/SPP/E Aph conj	~0.7 AU				

SPP Perihelion	Date	SO/Earth position	SPP Distance	Time within 30	20	15	10
17	23/09/2023	16/09 S/SPP/E conj - 23/09 S/SPP/SO "conj"	11.5	105.1	56.9	32.1	0
18	24/12/2023	Xmas conj/perihelion !!!	11.5	105.1	56.9	32.1	0
	13/03/2024	S/SO/E "conj" antipodes SPP	~0.3 AU				
19	25/03/2024	S/SPP/E conj and S/SPP/SO "conj"	11.5	105.1	56.9	32.1	0
20	25/06/2024	FRS S/SPP/SO "conj" 24/06 E antip	11.5	105.1	56.9	32.1	0
	02/07/2024	S/SPP/E	~0.3 AU				
	07/08/2024	S/SPP/E	~0.7 AU				
	19/09/2024	S/SPP/E SO 45 East	~0.3 AU				
21	25/09/2024	SPP/S/SO conj E 100 East	11.5	105.1	56.9	32.2	0
22	19/12/2024	18/12 S/SPP/SO "conj 19/12 S/SPP/E conj	**9.9**	102.5	57	35.2	4.2
	08/02/2025	S/SO/E "conj"					
	14/15/02/2025	Inner heliospher SPP - SO 3D					
23	18/03/2025	S/SPP/E conj SO at 180	**9.9**	102.5	57	35.2	4.2
24	14/06/2025	E far side SO necessary	**9.9**	102.5	57	35.2	4.2
		Total		**2130.3**	**936.7**	**437.7**	**12.6**

SO-SPP JO WG Members

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	A. Szabo	NASA Project Scientist
	N. Fox	APL Project Scientist
	D. Lario	
	S. Bale	FIELDS
	W. Matthaeus	ISIS
	J. Kasper	SWEAP
	A. Vourlidas	WISPR
SO	D. Muller/I. Zouganelis	ESA- Project Science
	C. St-Cyr	NASA Project Scientist
	T. Horbury	MAG
	M. Maksimovic	RPW
	C. Owen	SWA
	J. Rodriguez Pacheco	EPD
	S. Fineschi	METIS
	J. Woch	PHI
	A Zukhov	EUI
	S. Krucker	STYX
	A. Vourlidas	Solo-HI
	A. Fludra/D. Hassler	SPICE

Conclusions

Solar Orbiter & Solar Probe Plus promise to be a great opportunity for discovery for the origins of the Heliosphere:

coronal heating and solar wind acceleration,

sources of the solar wind and solar magnetic field,

energetic particle acceleration,

first measurements of dust environment close to the sun.