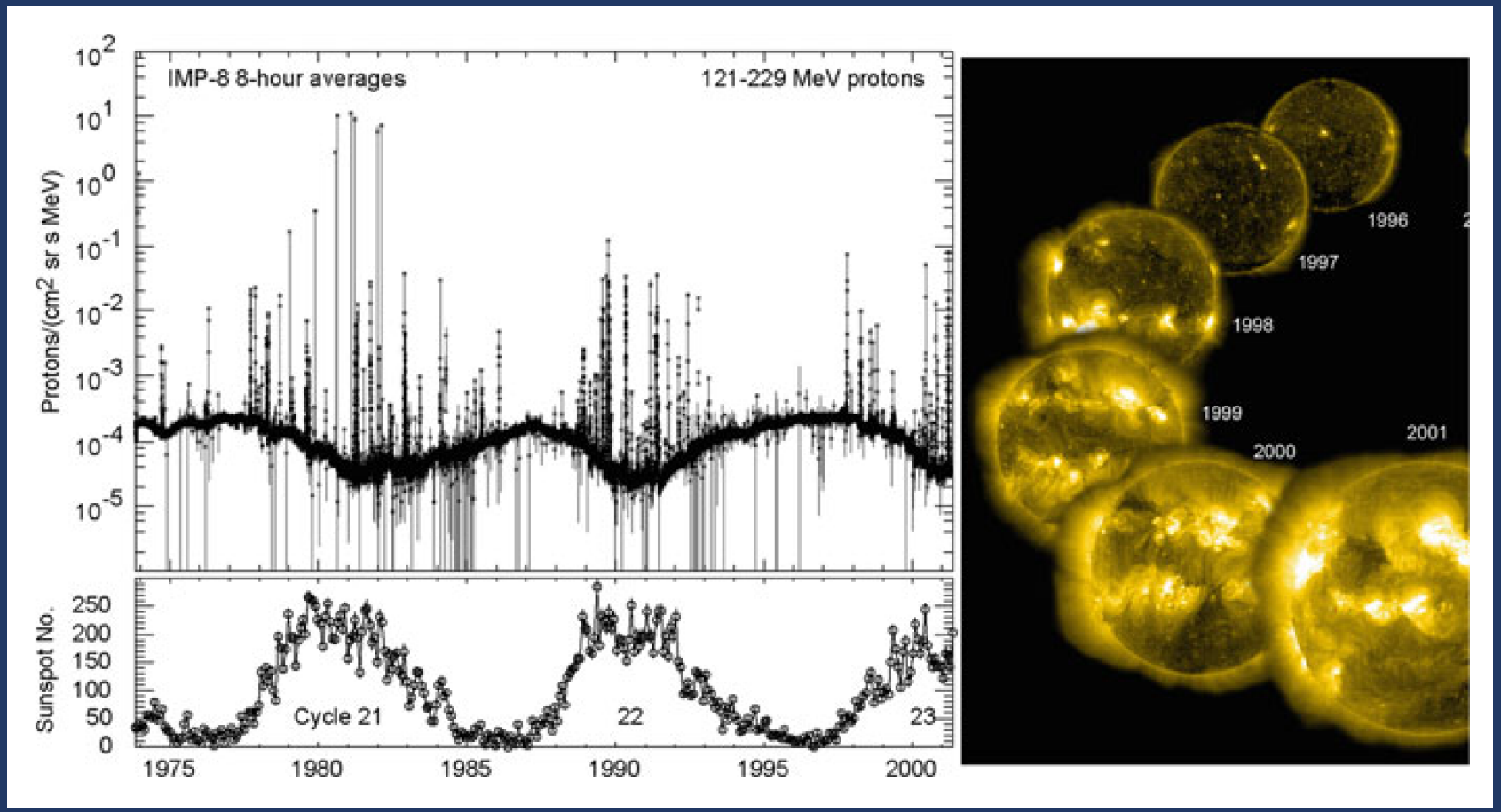
Accélération et transport des particules énergétiques dans la couronne solaire: premiers résultats de Parker Solar Probe et Solar Orbiter

Alexis P. Rouillard, M. Jarry, I. Plotnikov, A. Kouloumvakos, Y. Wu, R. Vainio, A. Warmuth, G. Mann + many collaborators!

SF2A, Mercredi 5 Juin 2024, Ondes de choc en Astrophysiq


IMP-8 8-hour averages
121-229 MeV protons
Protons/(cm2 sr s MeV)
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
Sunspot No.
250
200
150
100
50
0
Cycle 21
22
23
1975
1980
1985
1990
1995
2000
1996
1997
1998
1999
2000
2001

Two possible acceleration sites: solar flares and shock waves

There are two possible acceleration sites:

- one in the low solar corona, where magnetic reconnection seems to be the energizing mechanism
- the other higher up in the Coronal Mass Ejection, possibly by a shock (mediated by turbulence)

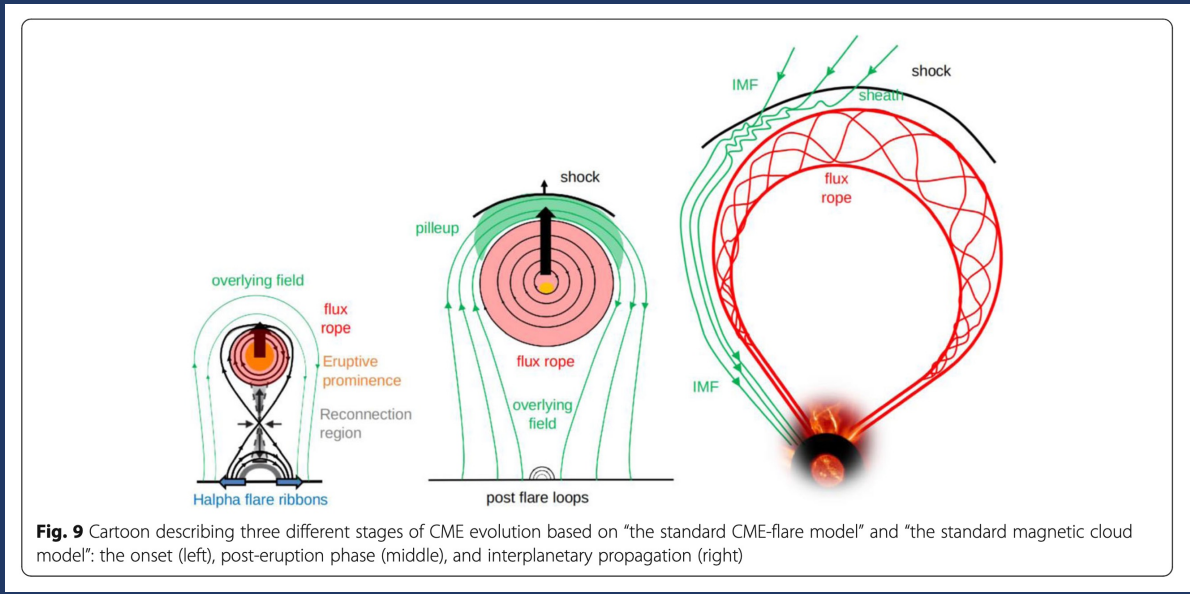
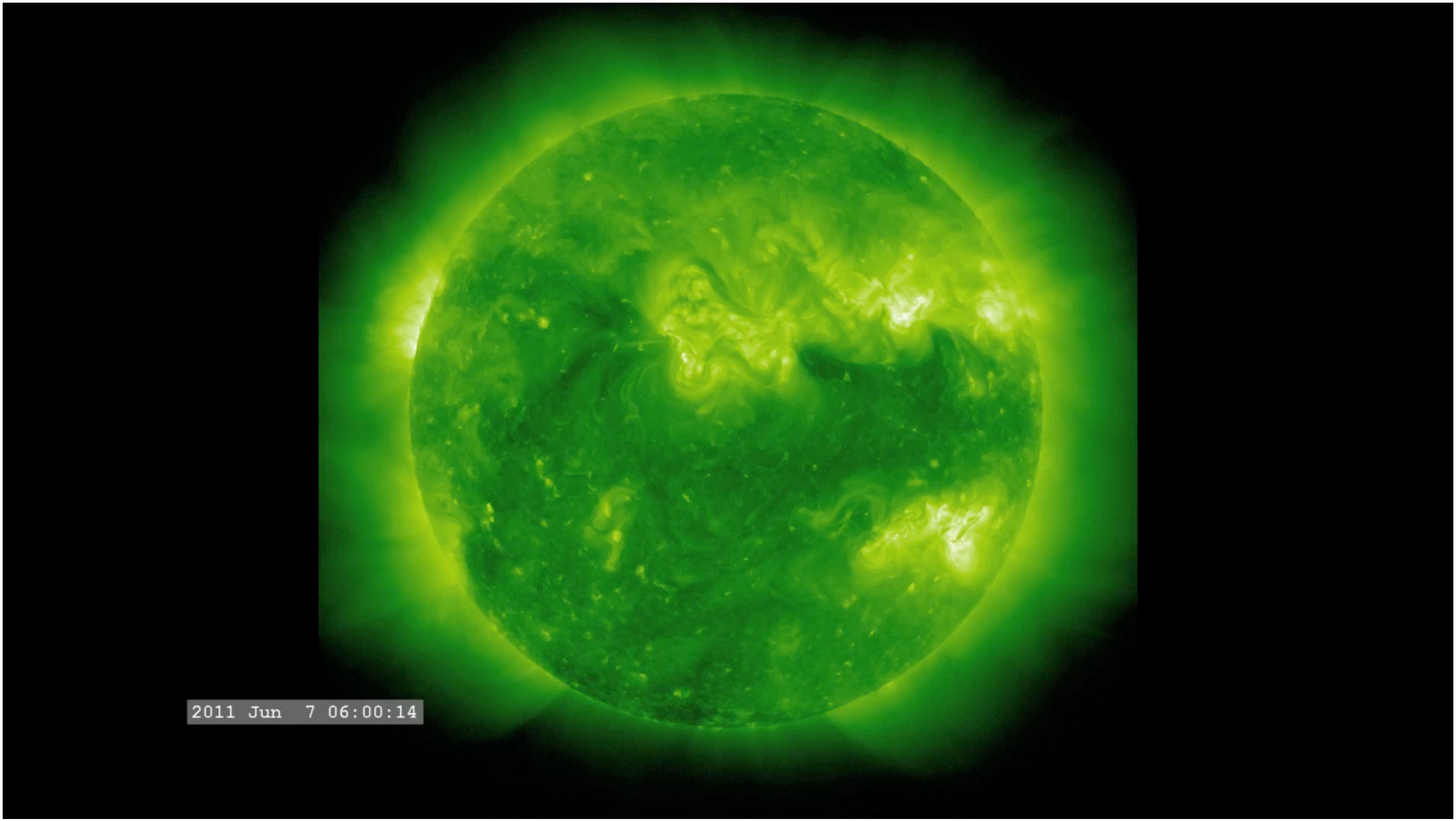


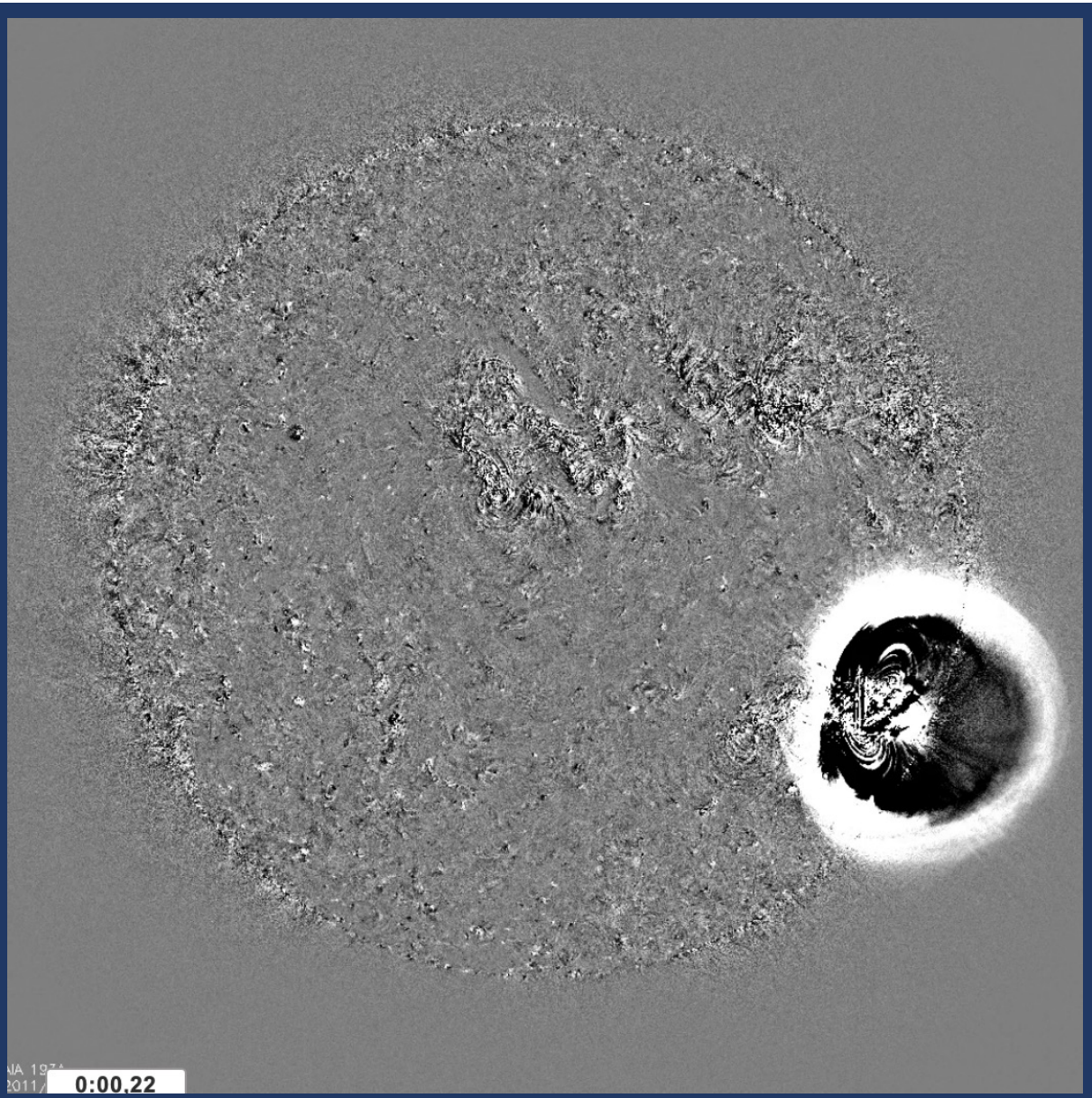
Fig. 9 Cartoon describing three different stages of CME evolution based on "the standard CME-flare model" and "the standard magnetic cloud model": the onset (left), post-eruption phase (middle), and interplanetary propagation (right)

Zhang et al. 2021

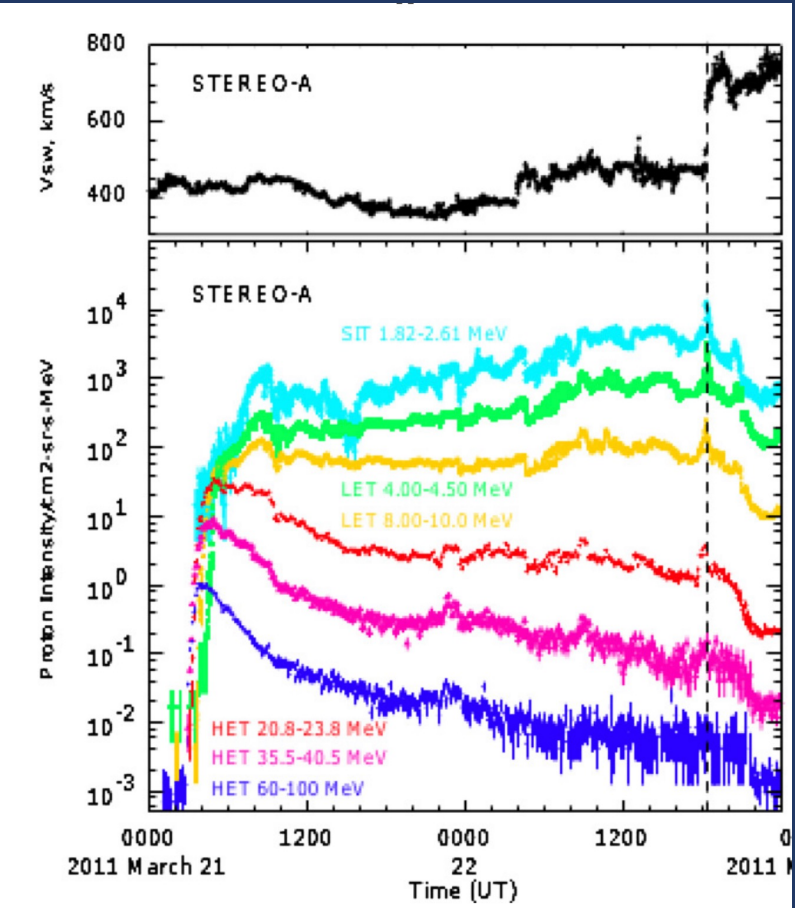
Are radiating particles and SEPs accelerated at only one of these or at both sites?

Are there observations that can answer this question and shed light on the characteristics of the two acceleration mechanisms?

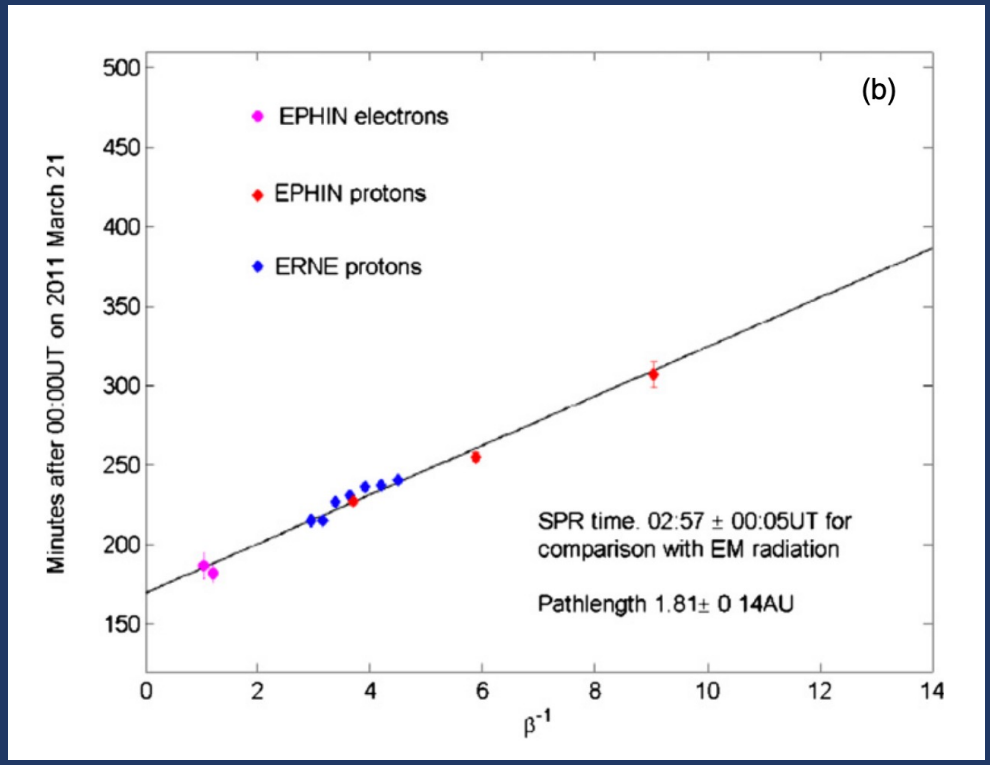

2011 Jun 7 06:00:14


0:00.22

In situ data provide information on timing, energies, composition
(at specific locations in the inner heliosphere)

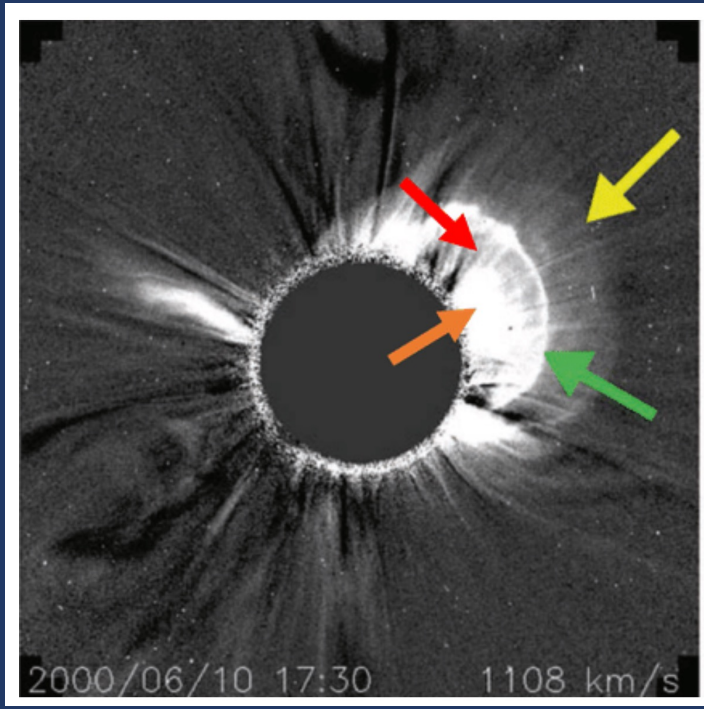


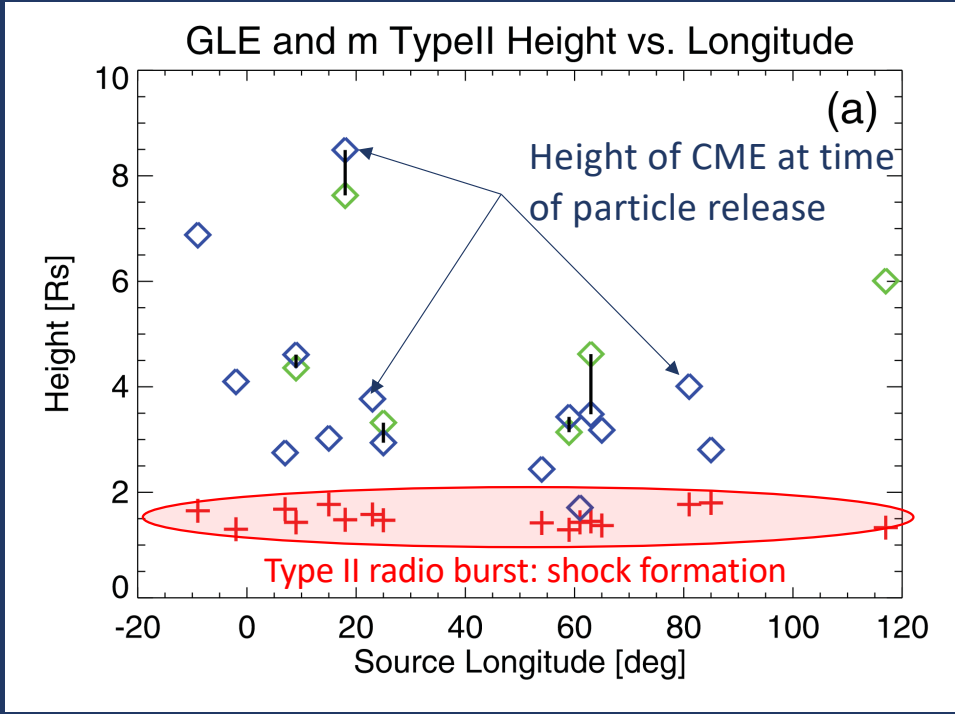
Can determine release time of SEPs using velocity dispersion



Rouillard + 2012

The highest energy events (protons > 1GeV) are produced in the corona (starting between 2 and 9 solar radii)





Gopalswamy et al. 2012

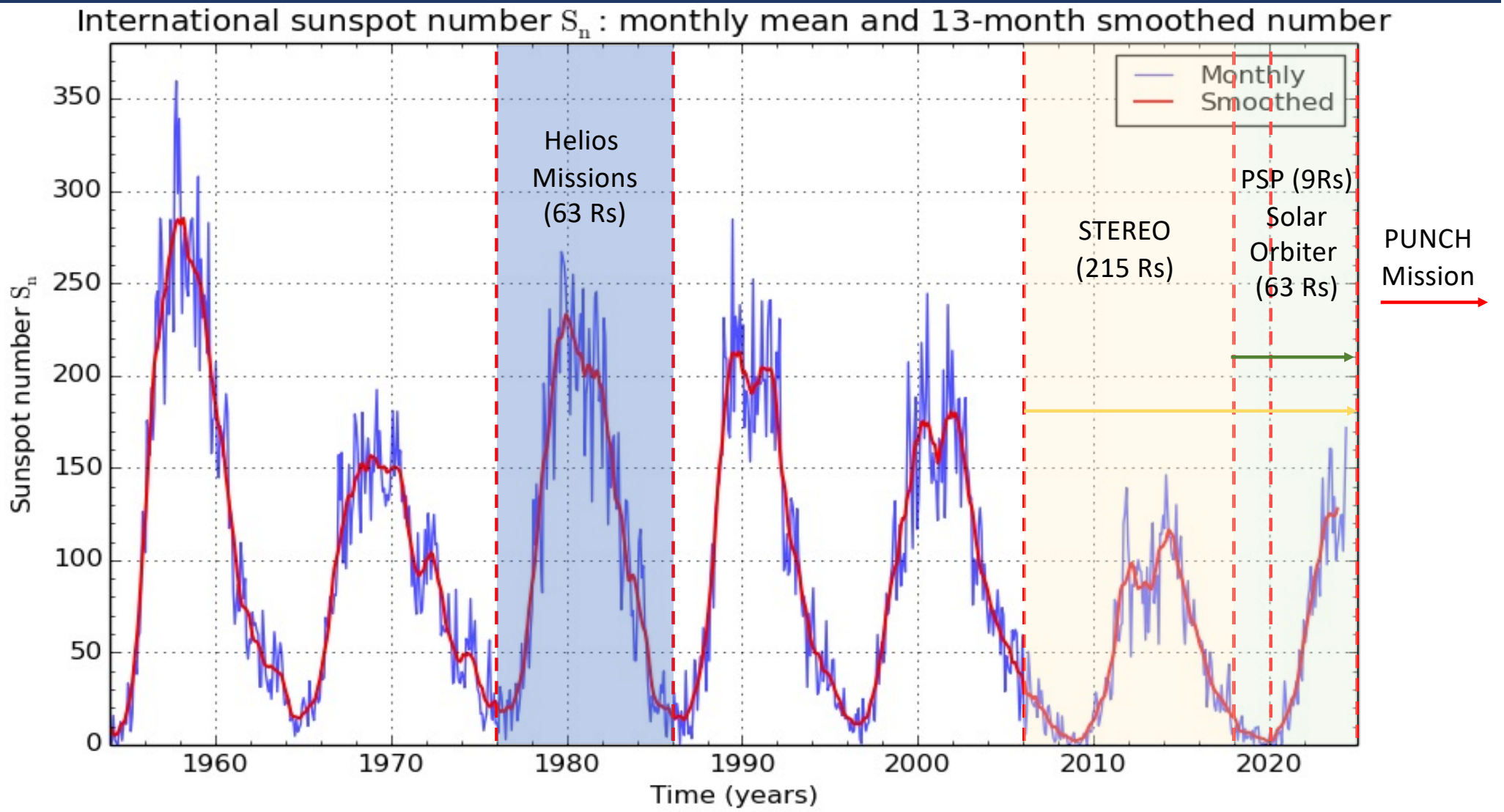
Similar fundamental questions in heliophysics…

… related to acceleration:

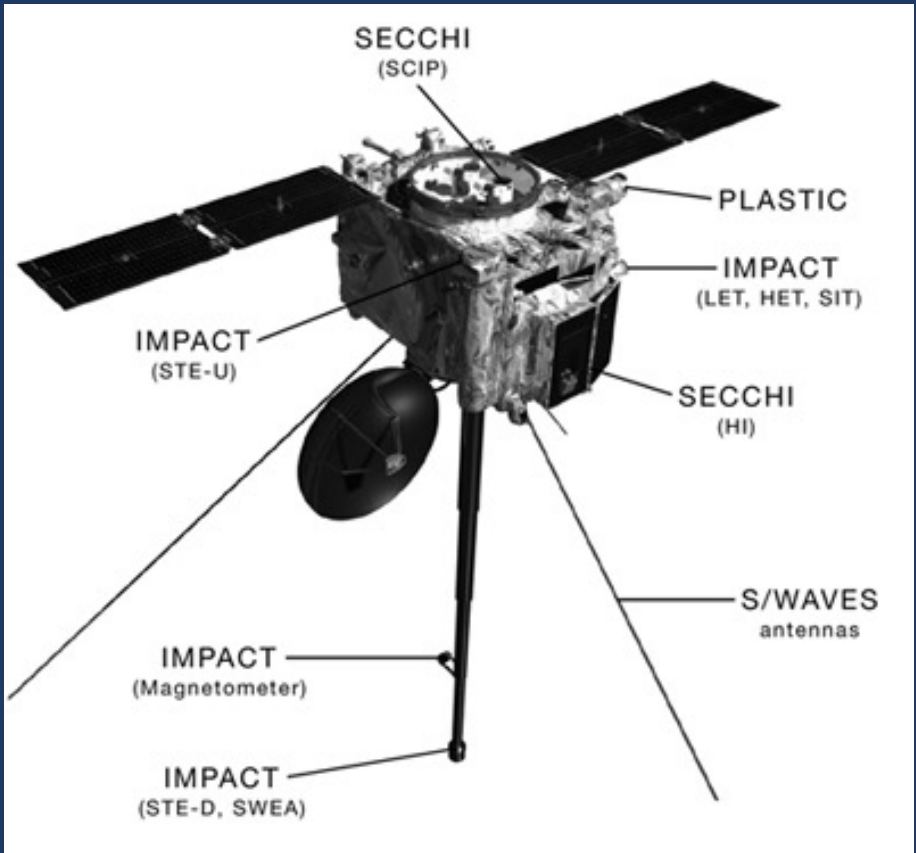
- How are solar energetic particles accelerated to high energy (magnetic reconnection or shock waves)?
- What are the properties of shock waves in the low solar atmosphere (Mach number, geometry) ? Are shocks already super-critical at the release time of high-energy particles?
- How do particles interact with the shock? Can diffusive-shock acceleration (Axford+ 1977; Bell 1978; Blandford & Ostriker 1978,Krymsky 1977) operate in the solar corona?

… related to transport:

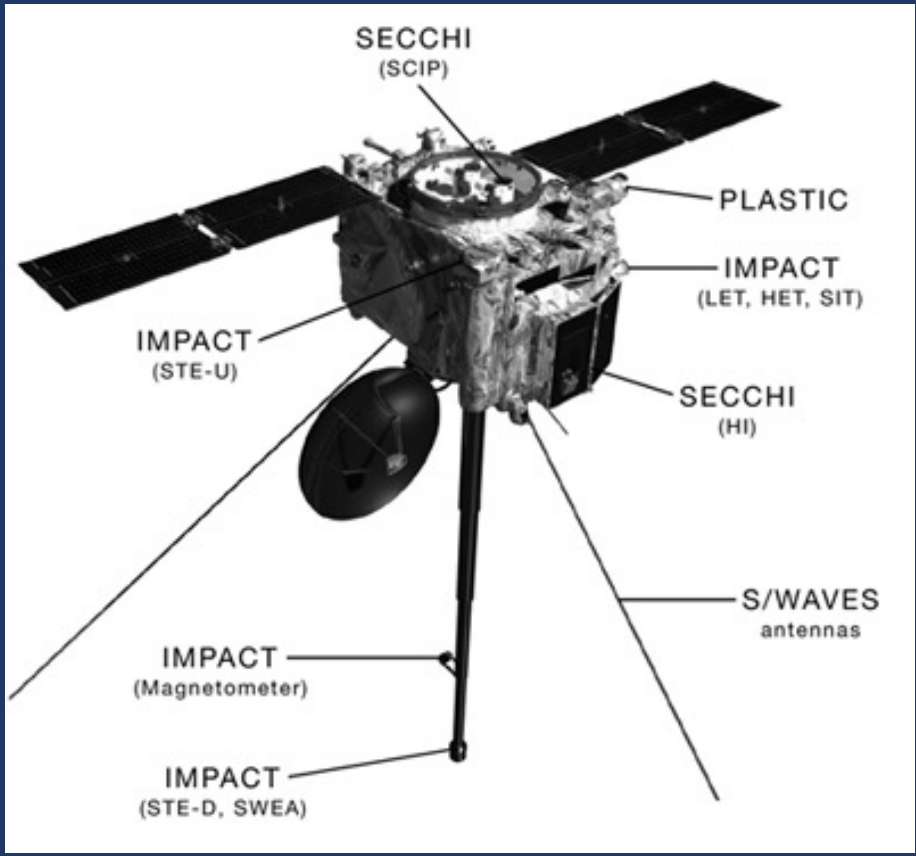
- How do accelerated particles propagate in the inner heliosphere? (transport parallel vs perpendicular to magnetic field lines). What is the effect of dynamical processes in the solar wind?


International sunspot number S_n : monthly mean and 13-month smoothed number
Monthly
Smoothed
Helios
Missions
(63 Rs)
STEREO
(215 Rs)
PSP (9Rs)
Solar
Orbiter
(63 Rs)
PUNCH
Mission
Sunspot number S_n
Time (years)
0
50
100
150
200
250
300
350
1960
1970
1980
1990
2000
2010
2020

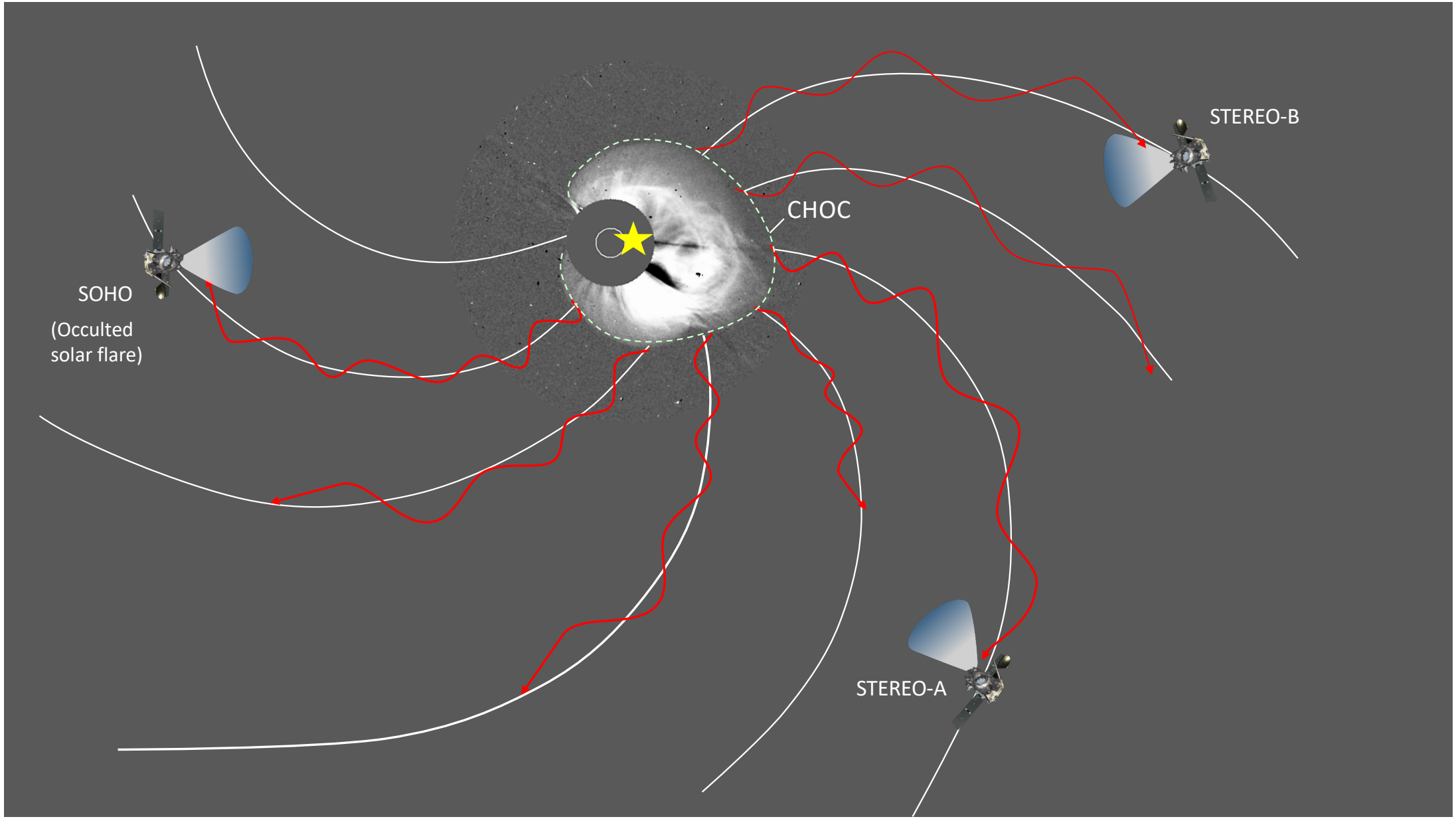
STEREO-A

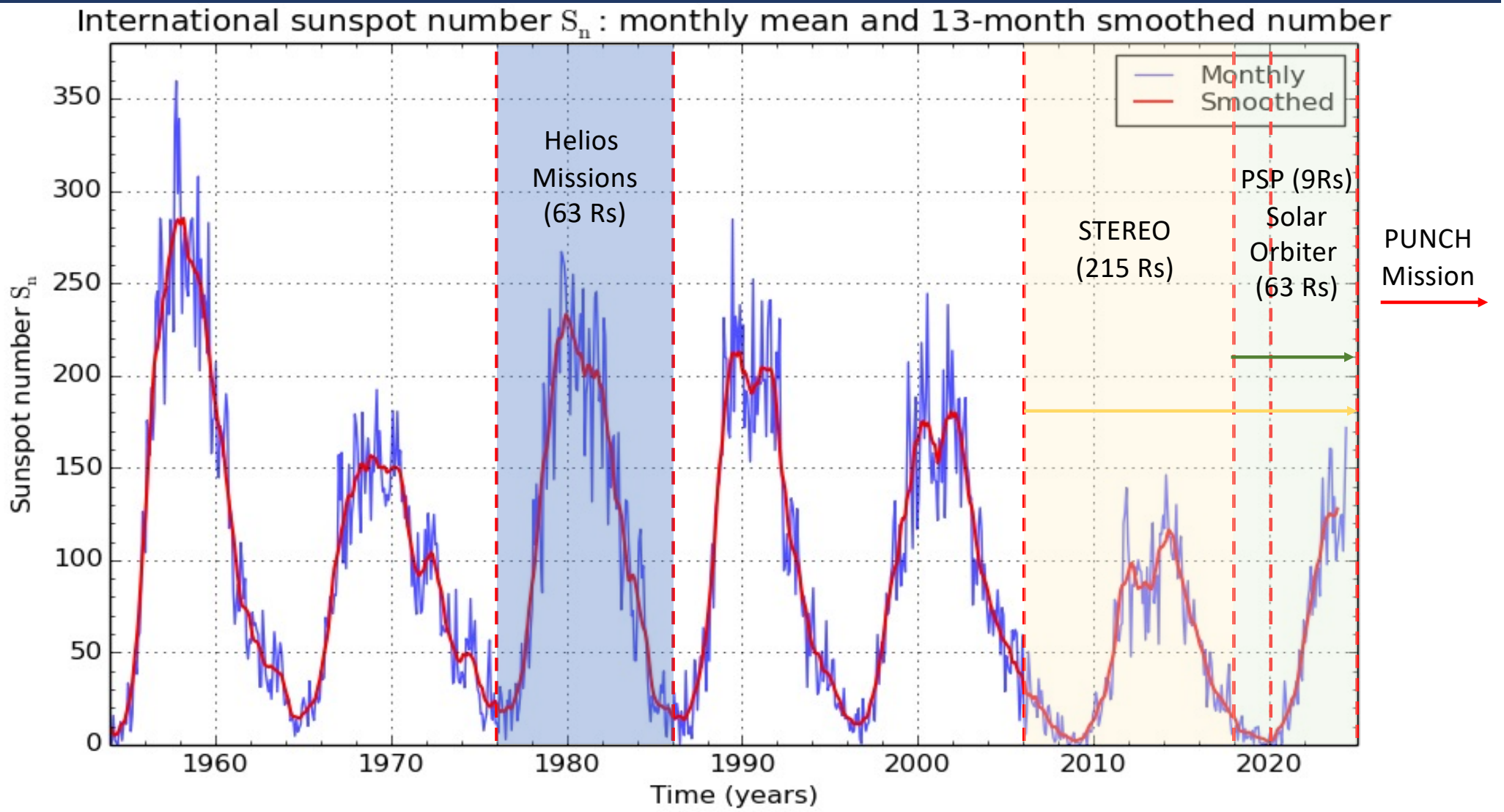


STEREO-B



Launch 2006 STEREO-A still operating, STEREO-B lost in 2014 at superior conjunction


STEREO-B
CHOC
SOHO
(Occulted
solar flare)
STEREO-A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Time (years)
0
50
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300
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1960
1970
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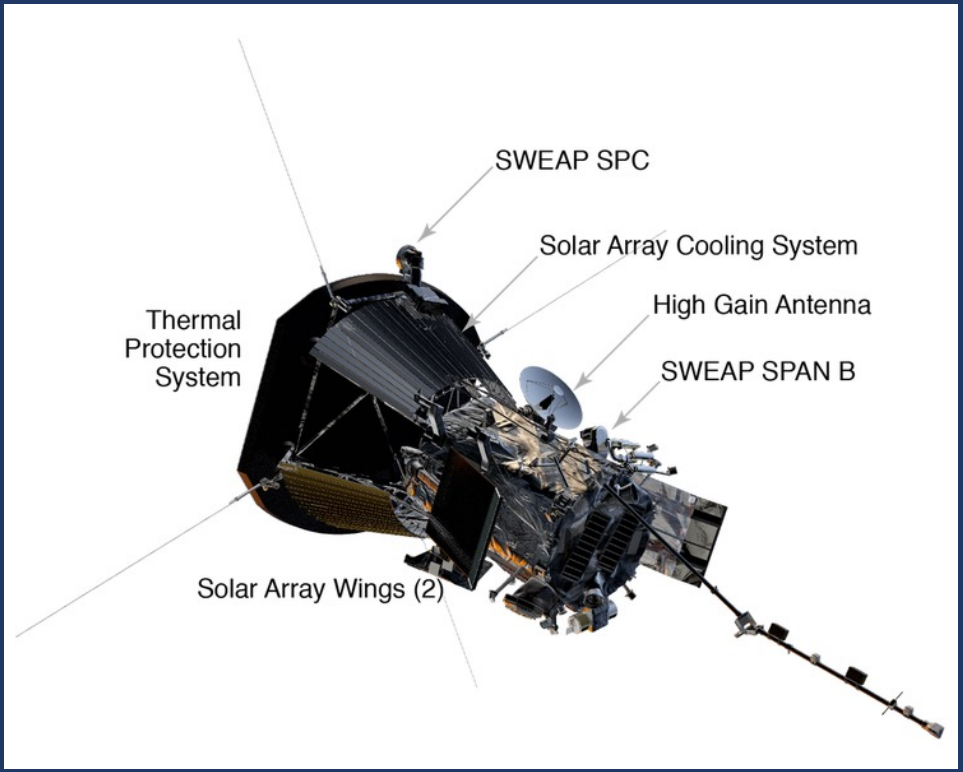
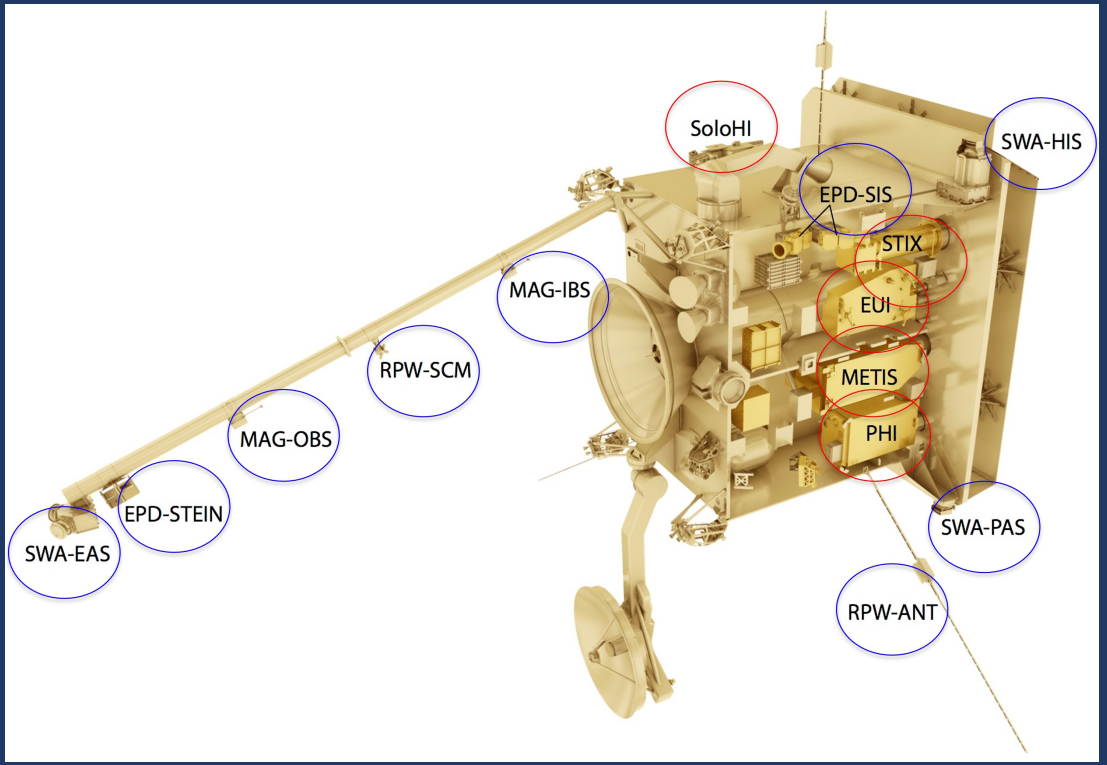
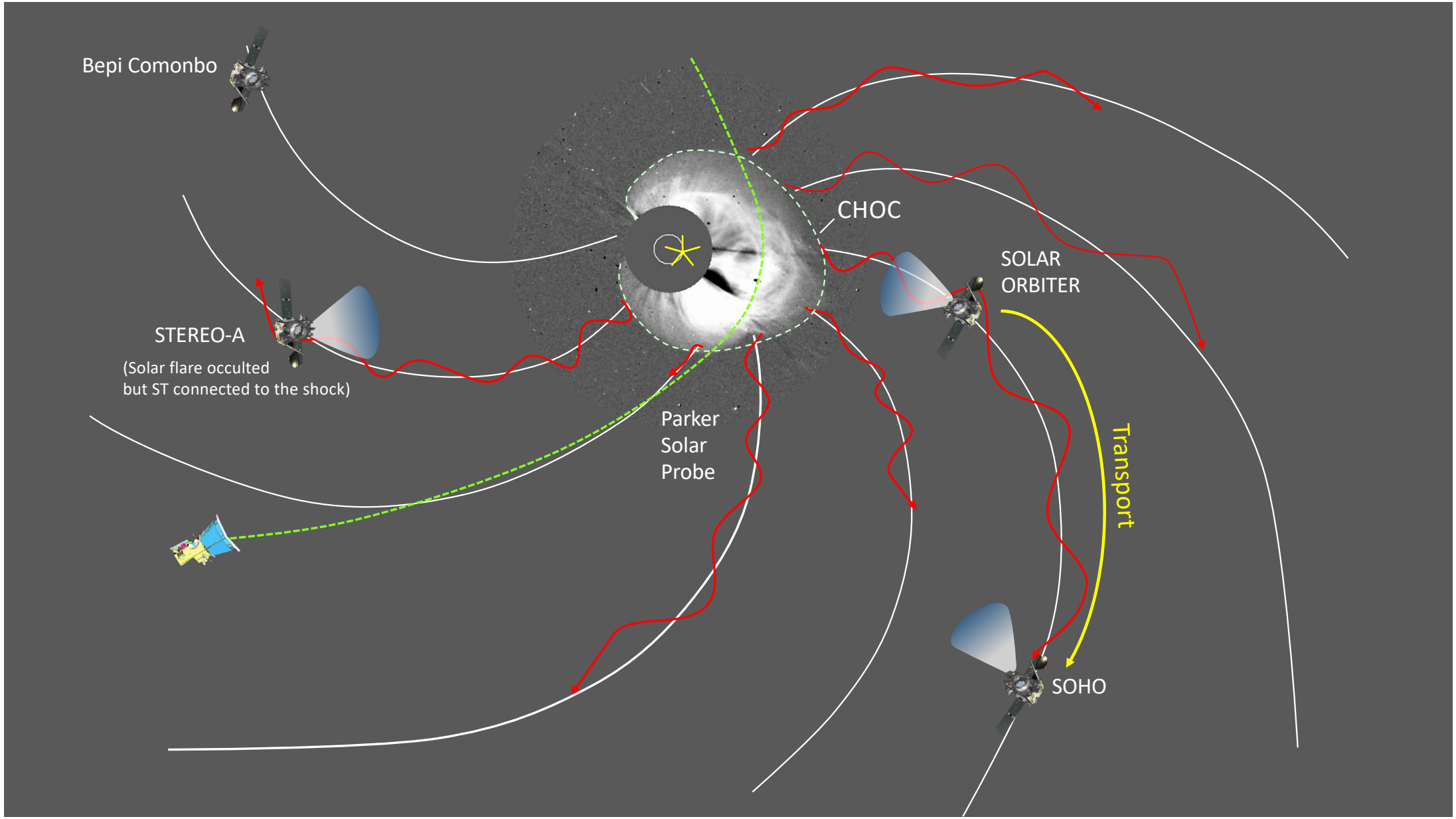
2020

Parker Solar Probe

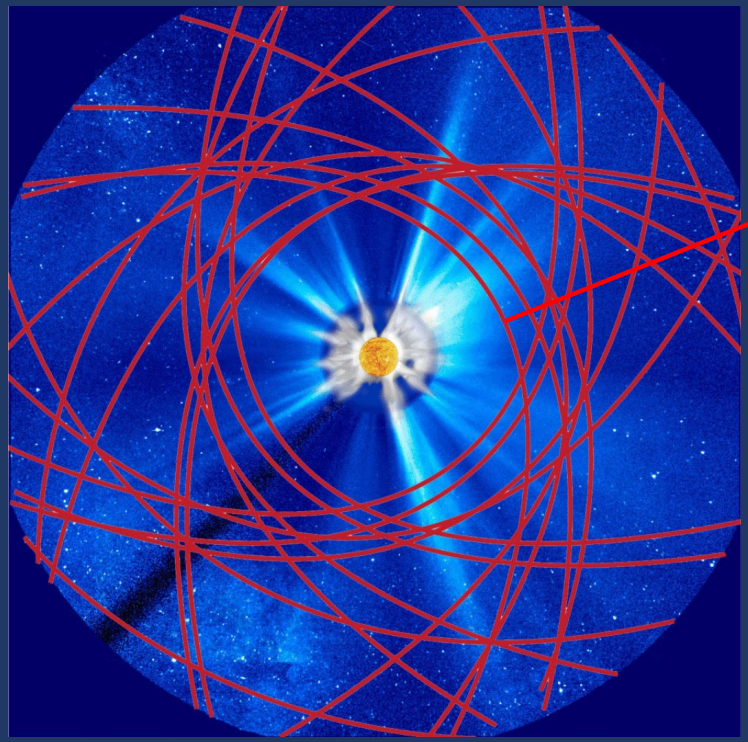


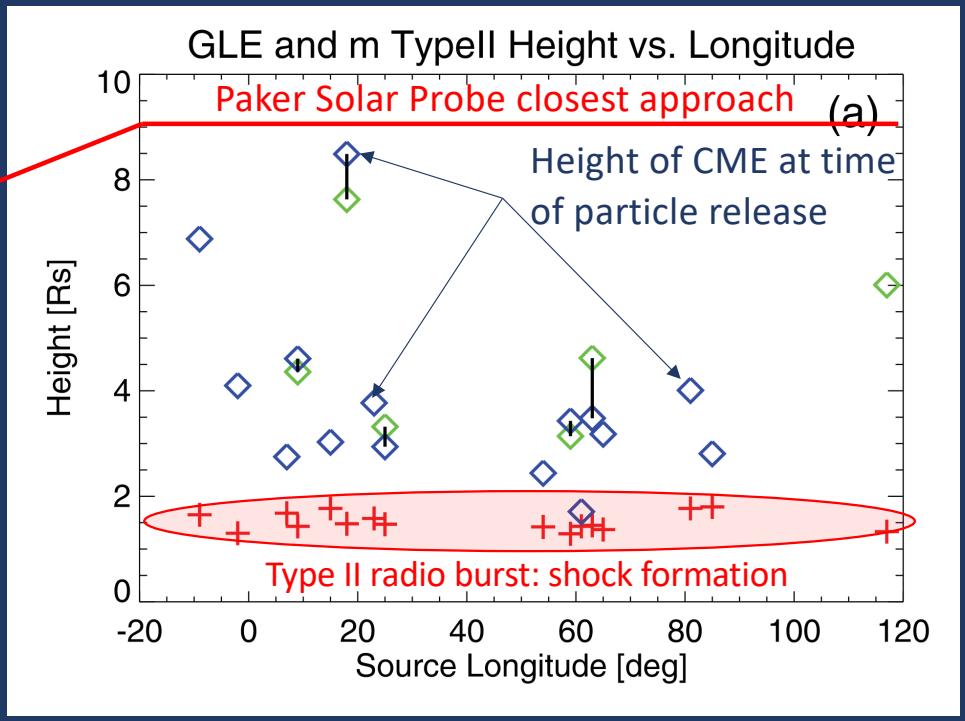
Parker Solar Probe




Bepi Comonbo
CHOC
SOLAR
ORBITER
STEREO-A
(Solar flare occulted
but ST connected to the shock)
Parker
Solar
Probe
Transport
SOHO

Parker Solar Probe will remain above 9Rs !



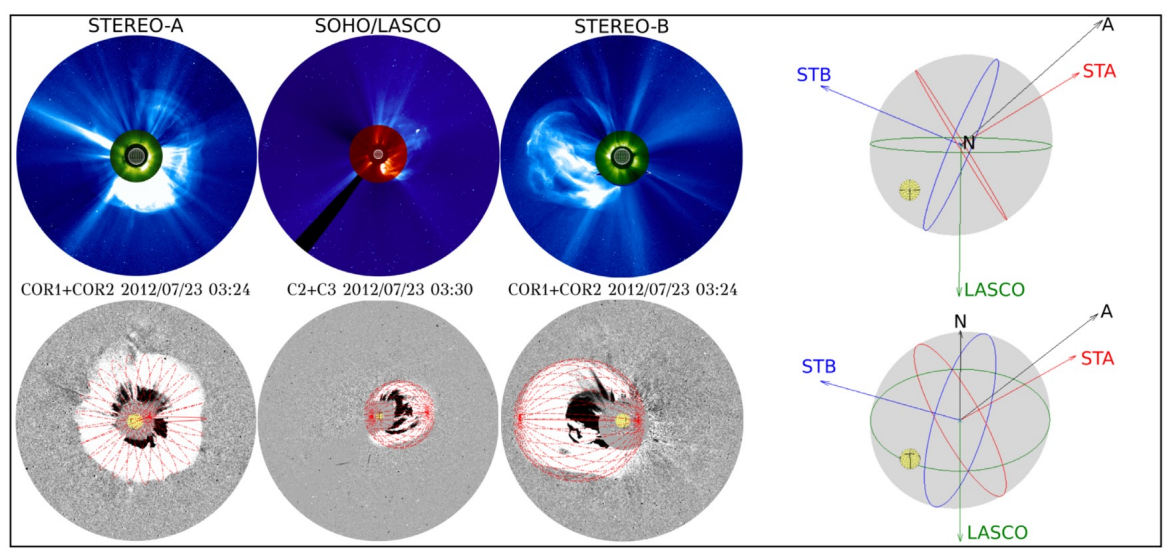


Gopalswamy et al. 2012

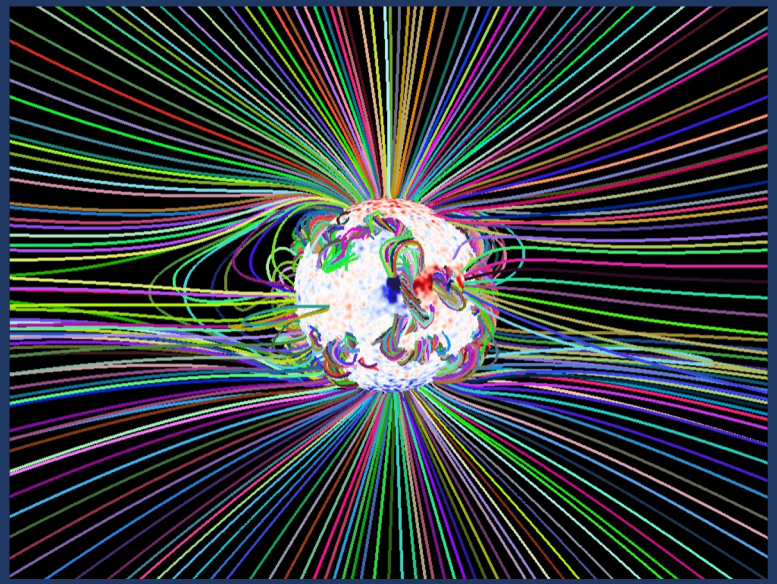
Our toolkit (1/2)

I. Derive shock properties (Mach number, geometry) in the low solar atmosphere:

- Triangulate shock waves in solar imagery => derive 3-D expansion speeds, etc..
- 3-D MHD modelling of the background corona => conditions encountered by shock wave

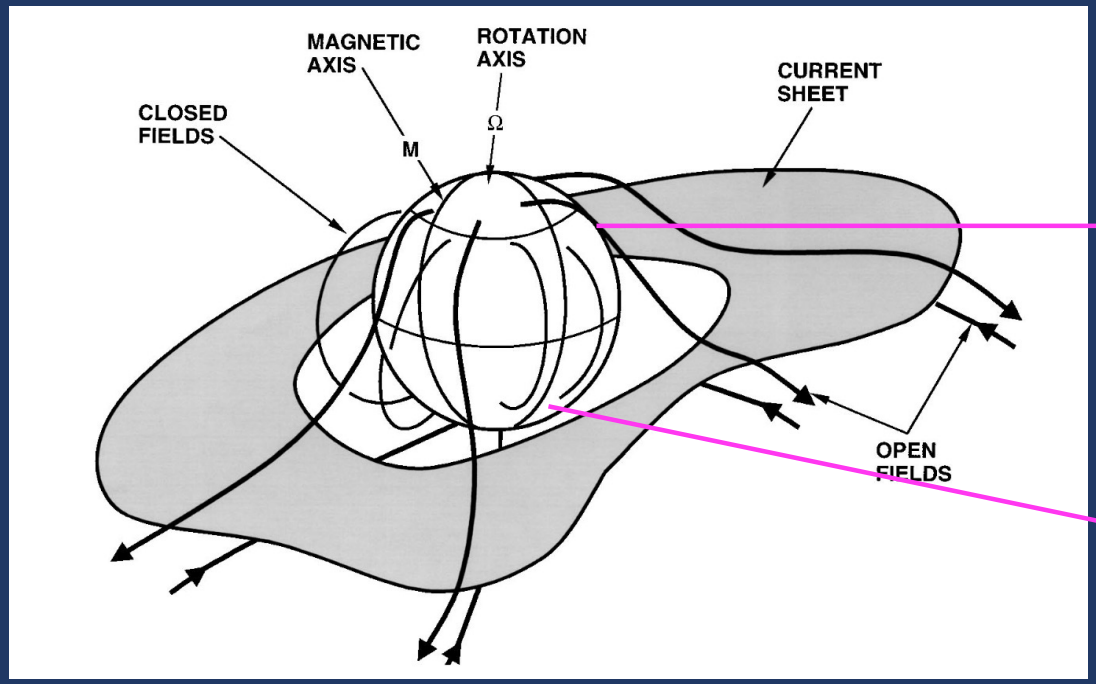


e.g. Rouillard+ 2016, Kouloumvakos+ 2019

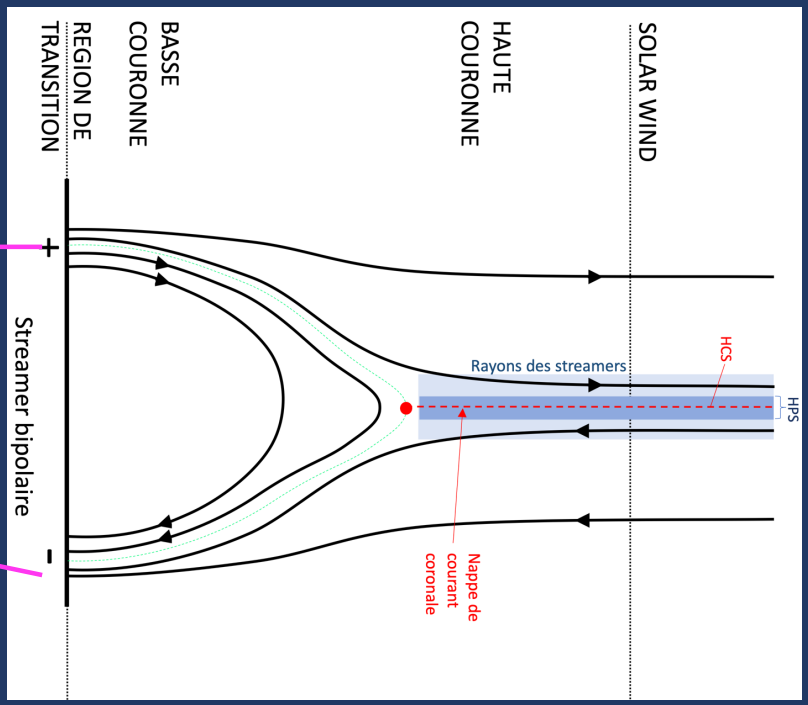


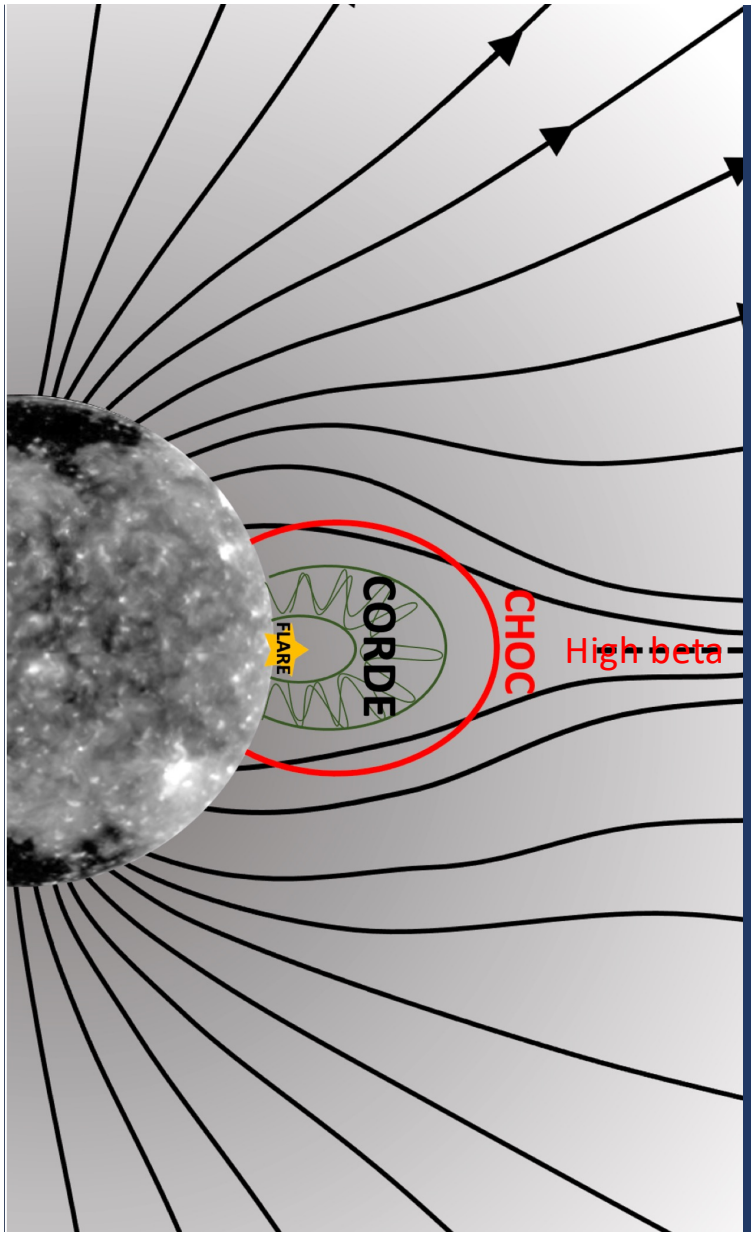
Credit: Predictive Sciences Inc

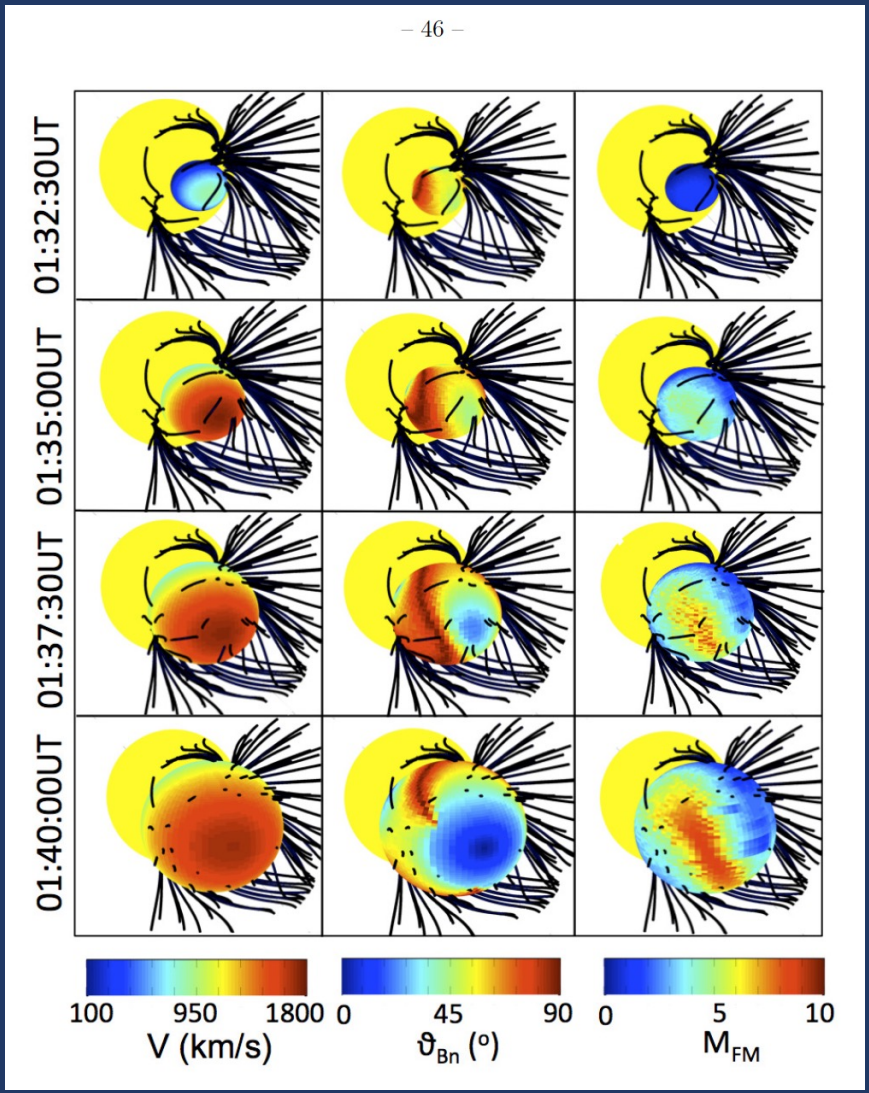
Heliospheric Current Sheet



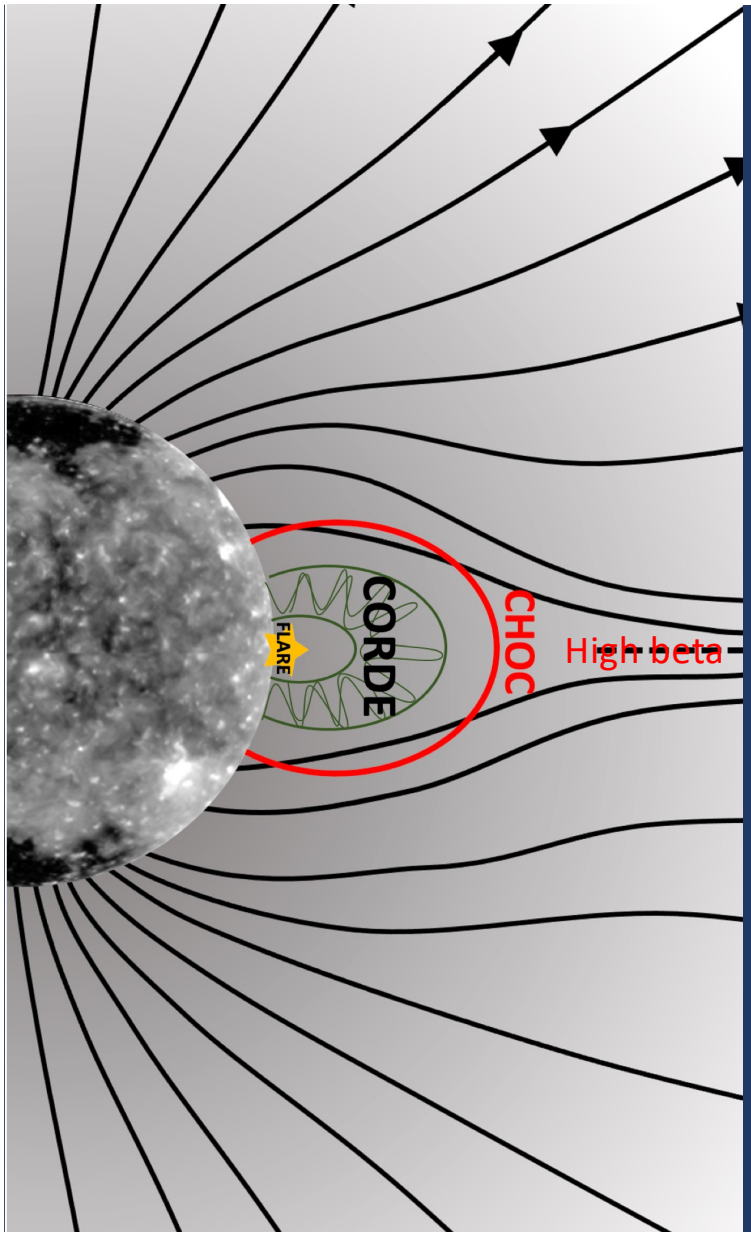
Helmet streamer

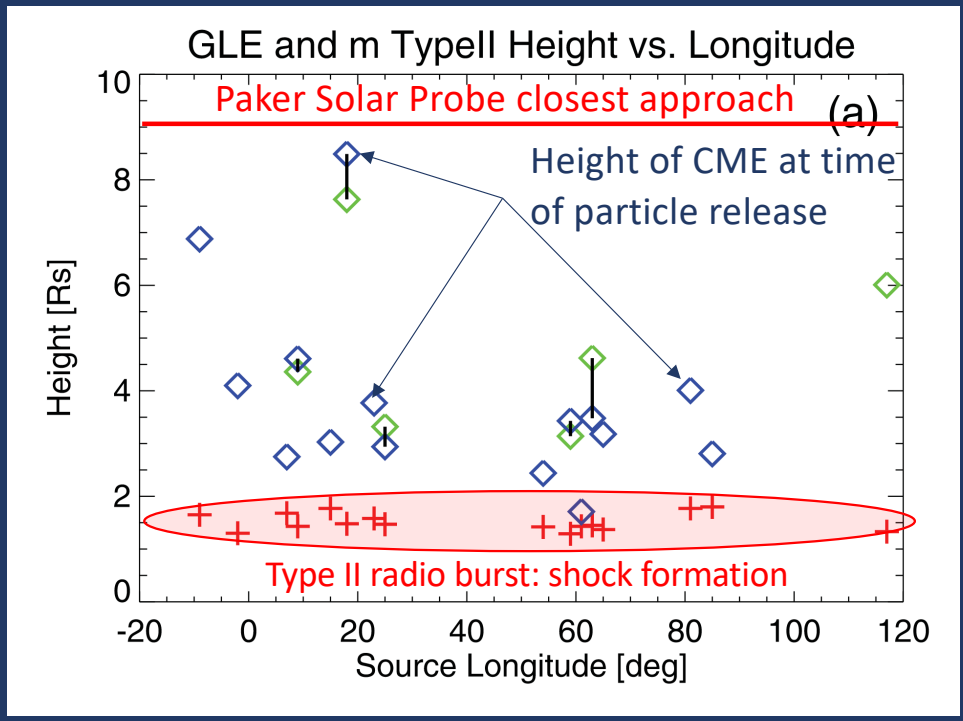






Rouillard + 2016



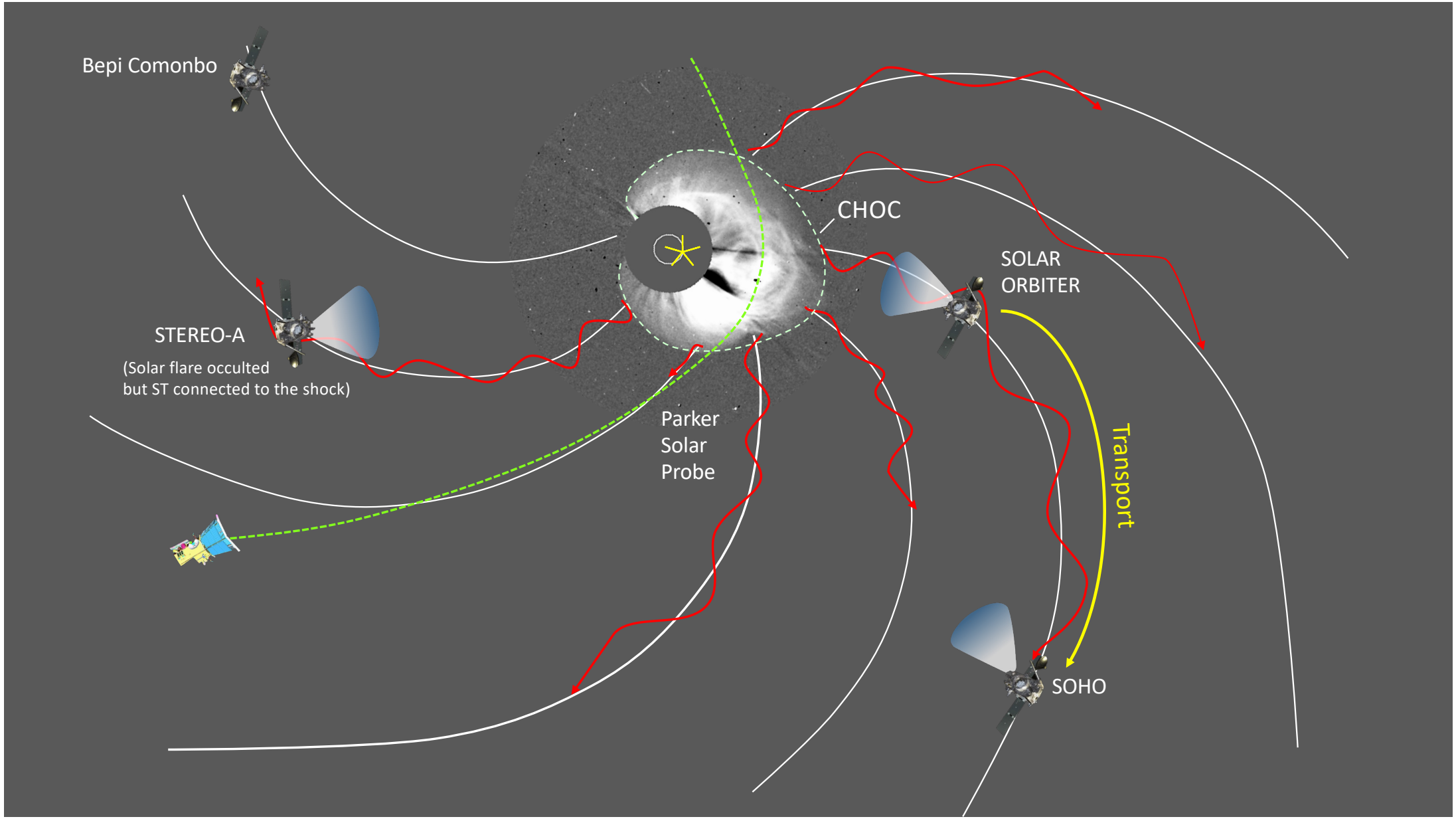


Gopalswamy et al. 2012

Our toolkit (2/2)

II. Derive how particle detectors connect magnetically to the expanding shock:

- Exploit in situ data to evaluate solar wind conditions at particle onset (wind type, etc…)
- Exploit solar wind (MHD, etc…) modelling to trace magnetic field lines between detector and shock wave


Bepi Comonbo
CHOC
SOLAR
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STEREO-A
(Solar flare occulted
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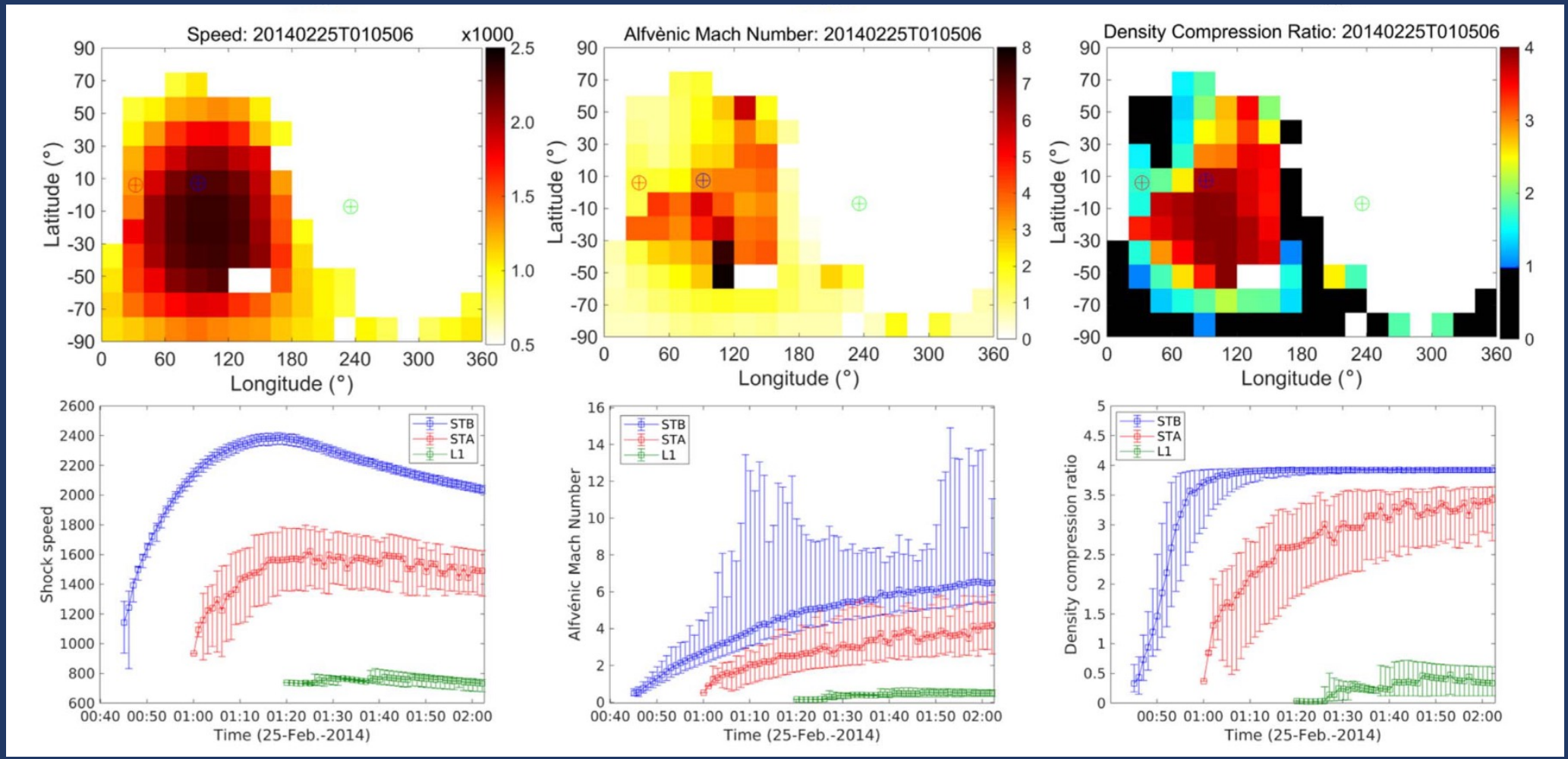
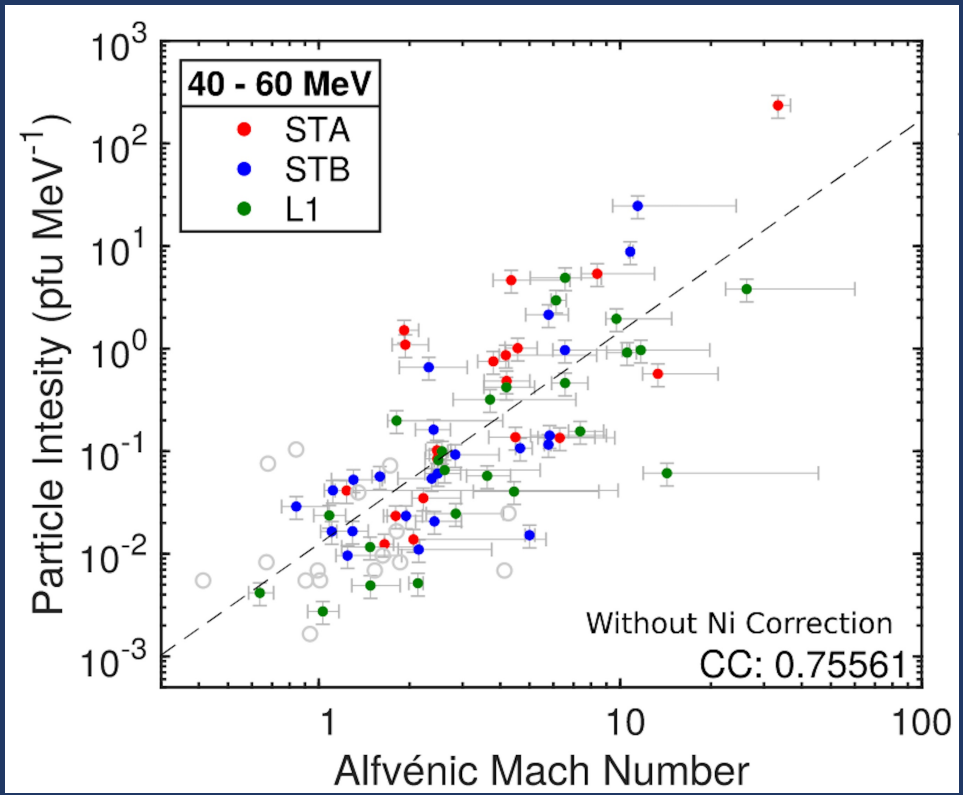
Solar
Probe
Transport
SOHO



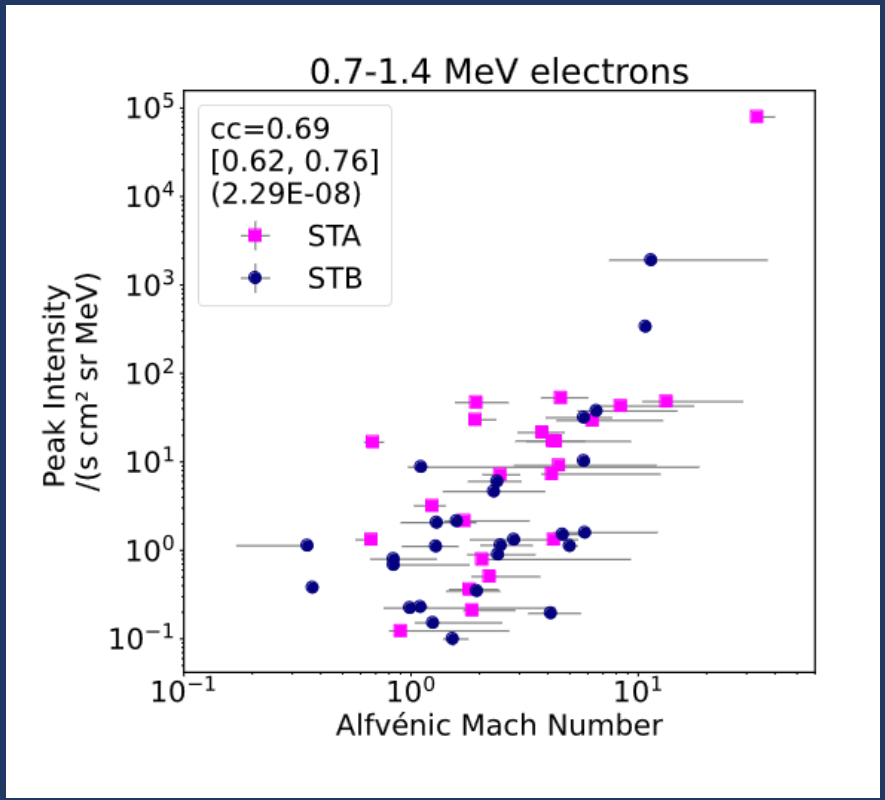
Rouillard et al. 2016
Kouloumvakos et al. 2019

Protons



Kouloumvakos + 2019

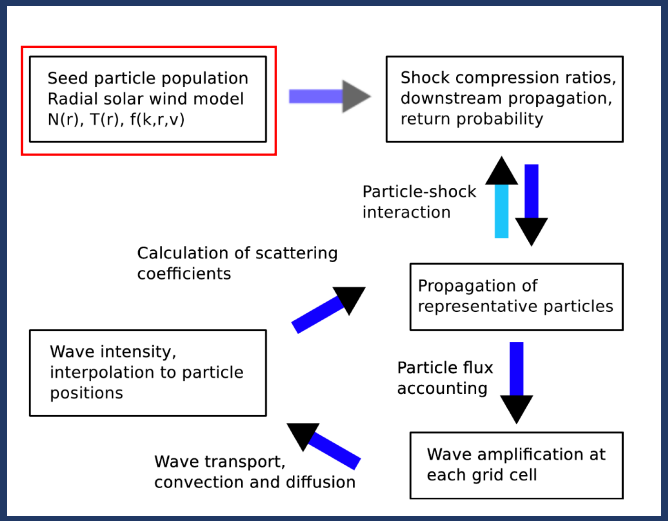
Electrons

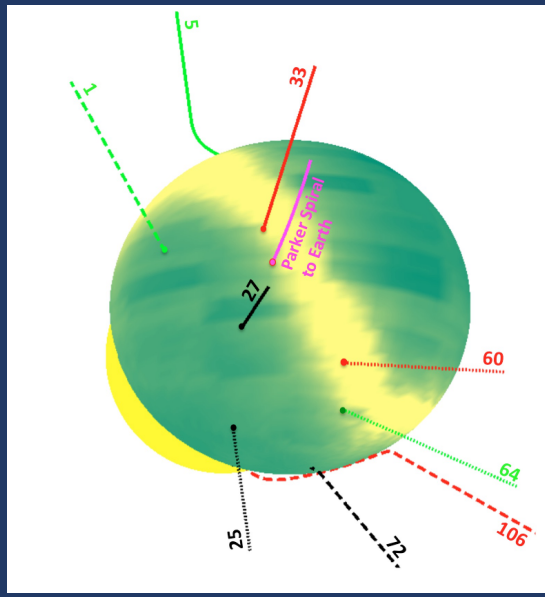


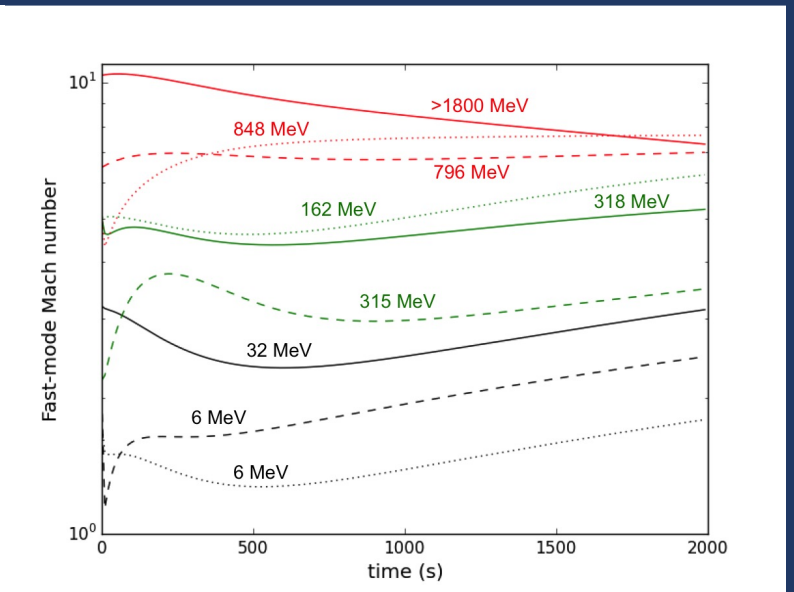
Dresing + 2022

We suppose the existence of a pool of suprathermal particles present in the solar corona available to enter the acceleration process.

Pre-accelerated particles induce a streaming instability which amplifies magnetic fluctuations in the vicinity of the shock.







Rouillard+ 2016

Afanasiev Vainio, Rouillard 2018

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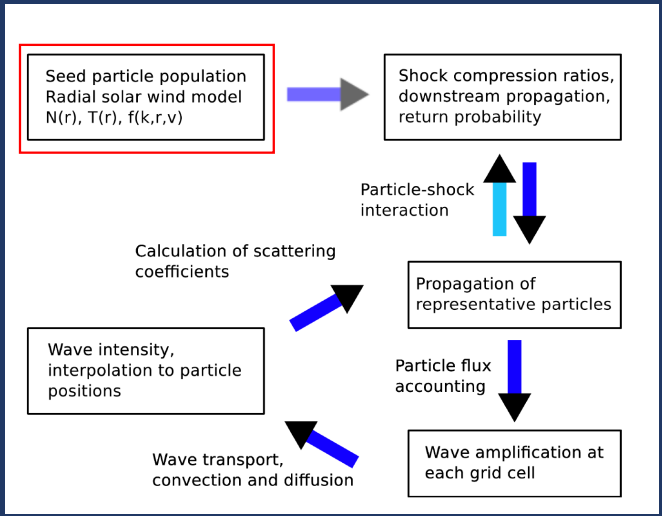
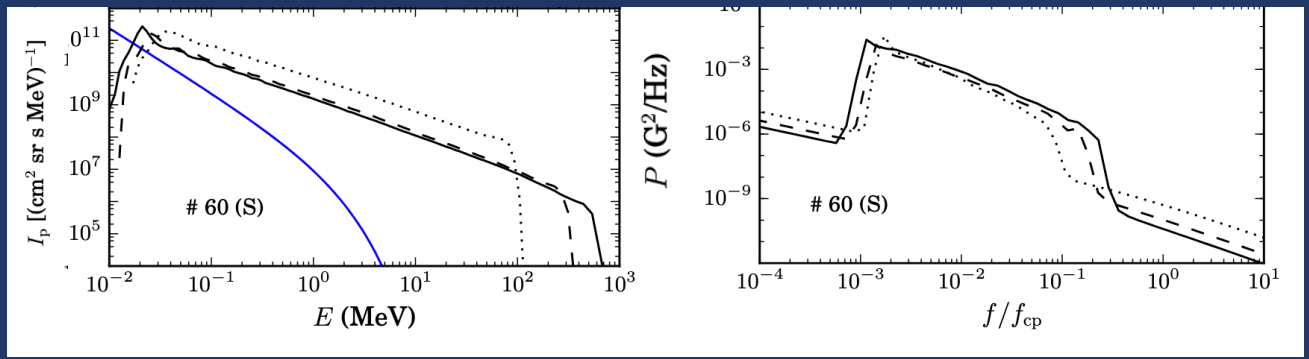
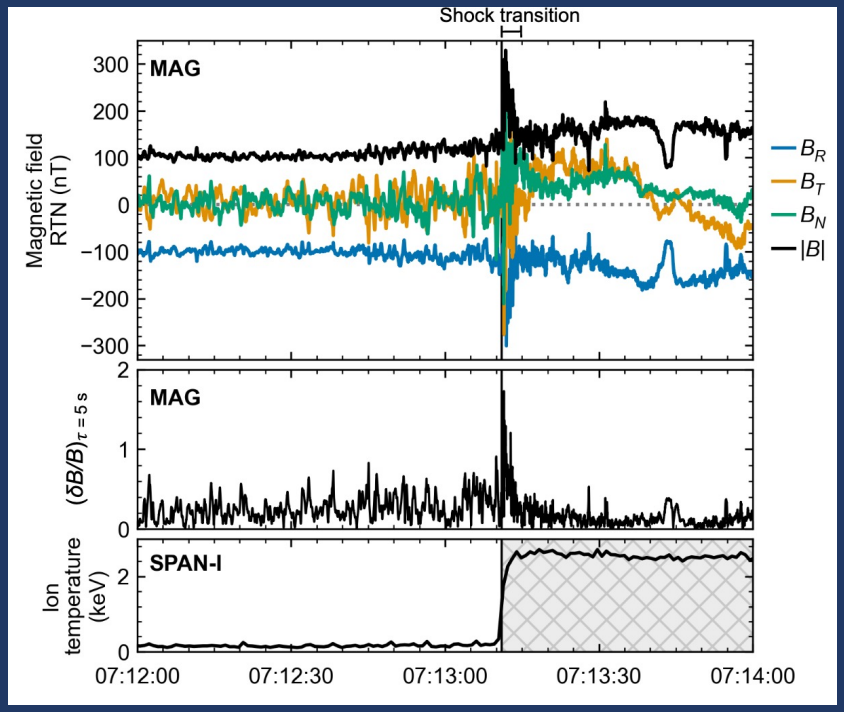




Afanasiev Vainio, Rouillard 2018

Acceleration of electrons and ions by an “almost” astrophysical shock in the heliosphere



On March 13, 2023, PSP encountered a 3000 km/s strong shock (MA at 50 Rs with near-parallel geometry strong shock (MA ~ 9.1 ± 1.35), Low-β plasma (~ 0.16 ± 0.031)

- Amplification of the magnetic field and intensification of fluctuations in the vicinity of the shock
- Measured local acceleration of electrons, with energies ranging from tens of keV (sub-relativistic) to 6 MeV (ultra-relativistic)
- Observed absence of ions at energies below ~1 MeV far from the shock but increase towards the shock indicative of particle trapping
- quasi-perpendicular ramp-overshoot region reflecting ions

Jebaraj et al. 2024

Transport of particles ∥ and ⊥ to magnetic field lines:

- The diffusion tensor can be expressed in terms of its ∥ and ⊥ diagonal coefficients and the off-diagonal coefficients related to gradient/curvature drifts

$$\kappa_{ij} = \kappa_{\perp}\,\delta_{ij} - \frac{(\kappa_{\perp} - \kappa_{\parallel})B_i B_j}{B^2} + \epsilon_{ijk}\,\kappa_A \frac{B_k}{B}$$

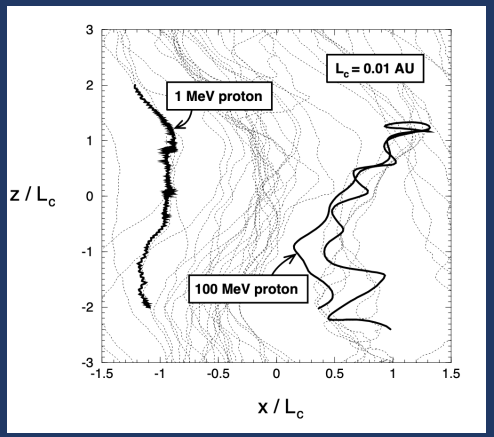
- Since the mean free path is much larger than the particle gyroradius
  => ⊥ transport often considered negligible…

$$\frac{\kappa_{\perp}}{\kappa_{\parallel}} = \frac{1}{1 + (\lambda_{\parallel}/r_g)^2}$$

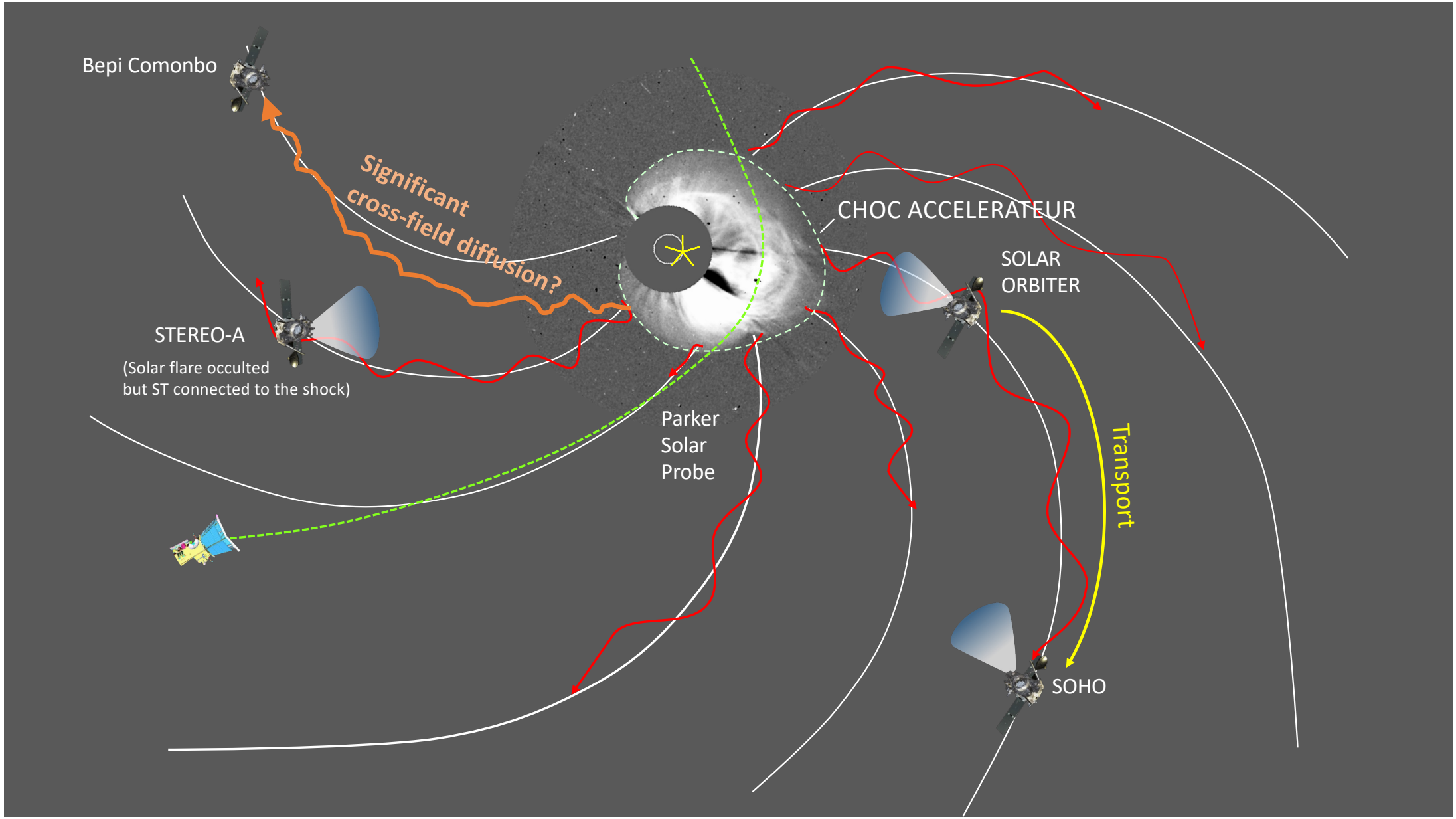
Yet the transport of energetic particles perpendicular to B plays a critical role for a number of important processes (e.g. DSA at quasi-perp shocks).

Perpendicular transport of particles:

- Particle transfer across field: scattering offmagnetic irregularities or drift
- Particle displacement relative to mean field: field-line random walk (Jokipii 1968)



Giacalone and Jokipii 1999


Bepi Comonbo
Significant
cross-field diffusion?
CHOC ACCELERATEUR
SOLAR
ORBITER
STEREO-A
(Solar flare occulted
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Parker
Solar
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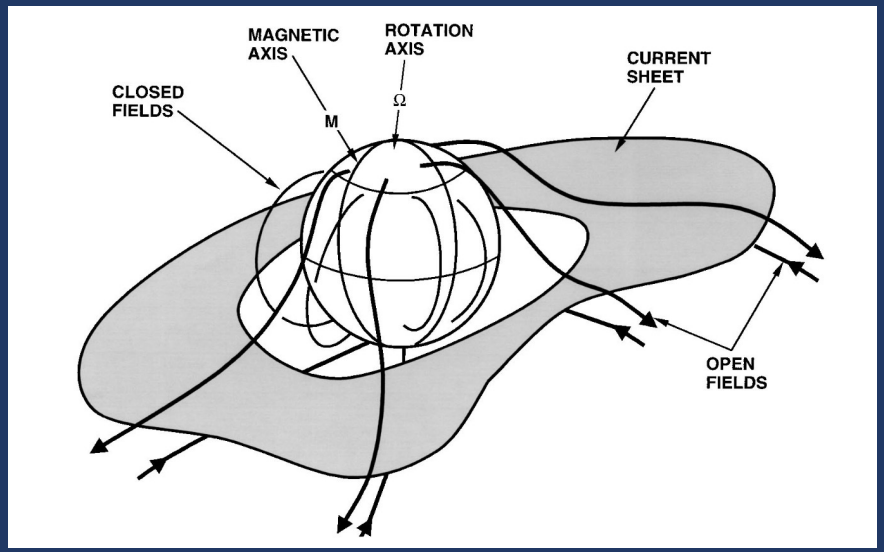
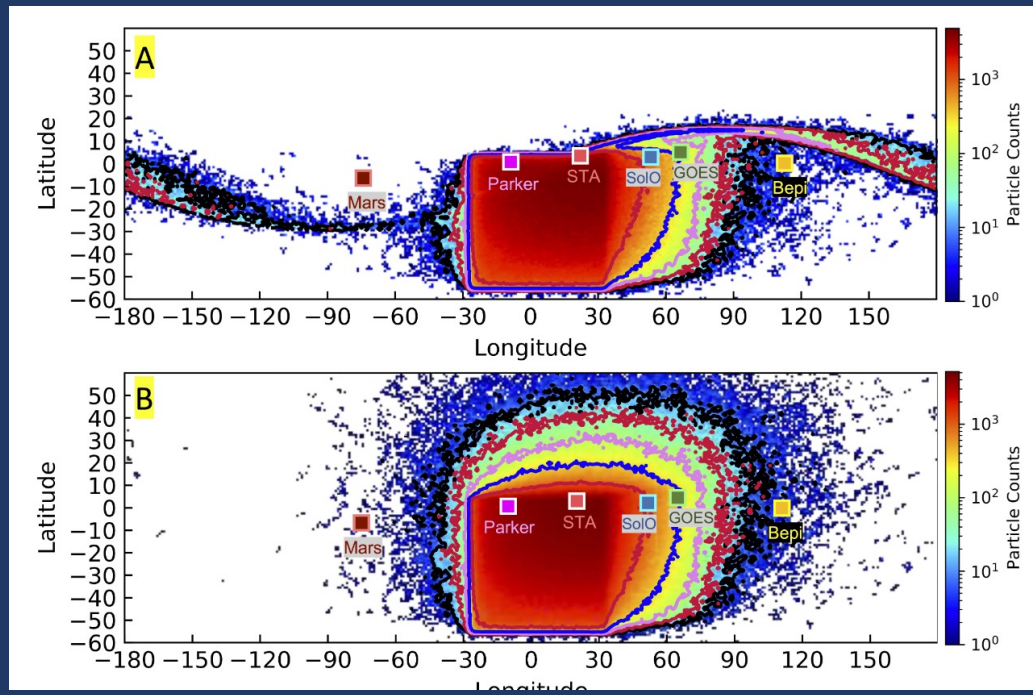
Transport
SOHO

Longitudinal particle transport in the heliospheric current sheet:

Heliospheric Current Sheet



Smith (1993)

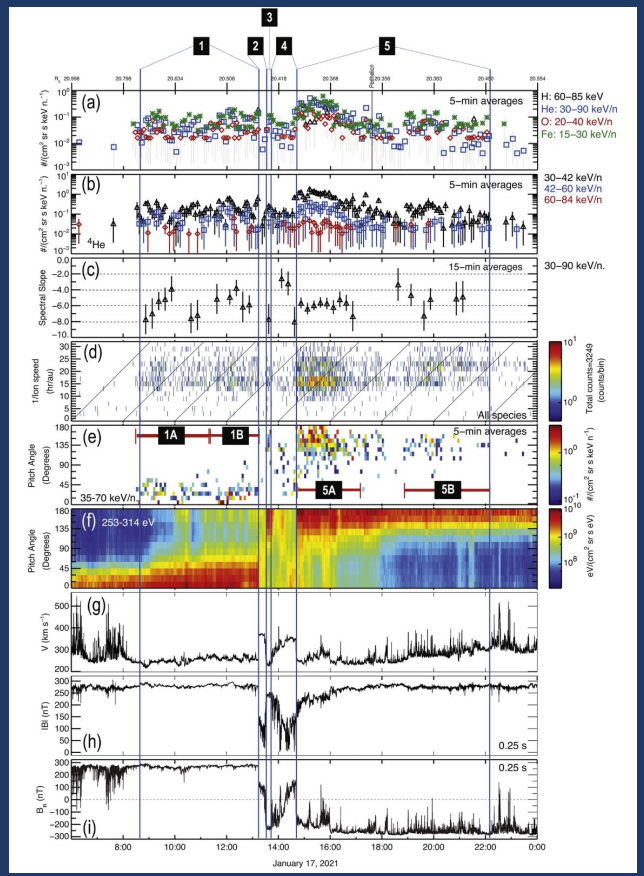


Kouloumvakos + 2023

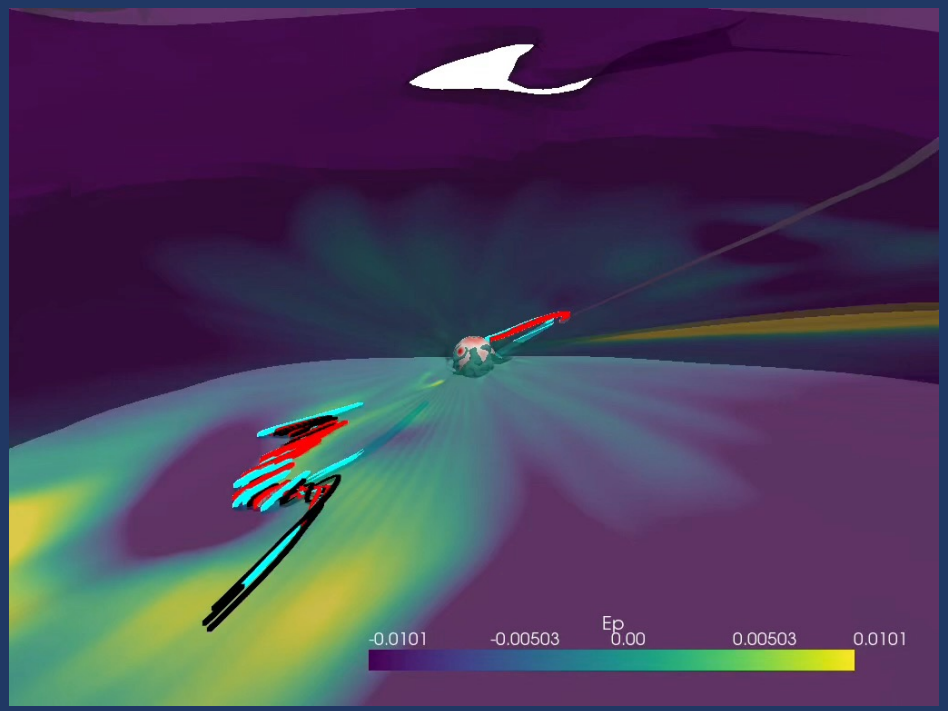
Turbulence-associated perpendicular transport is not included in these simulations and motion across the magnetic field seen in our results is mainly due to drift and HCS effects (see Dalla et al. 2020).

How does the dynamic HCS modulate shock conditions?

Production of suprathermals in the HCS



Desai et al. 2024



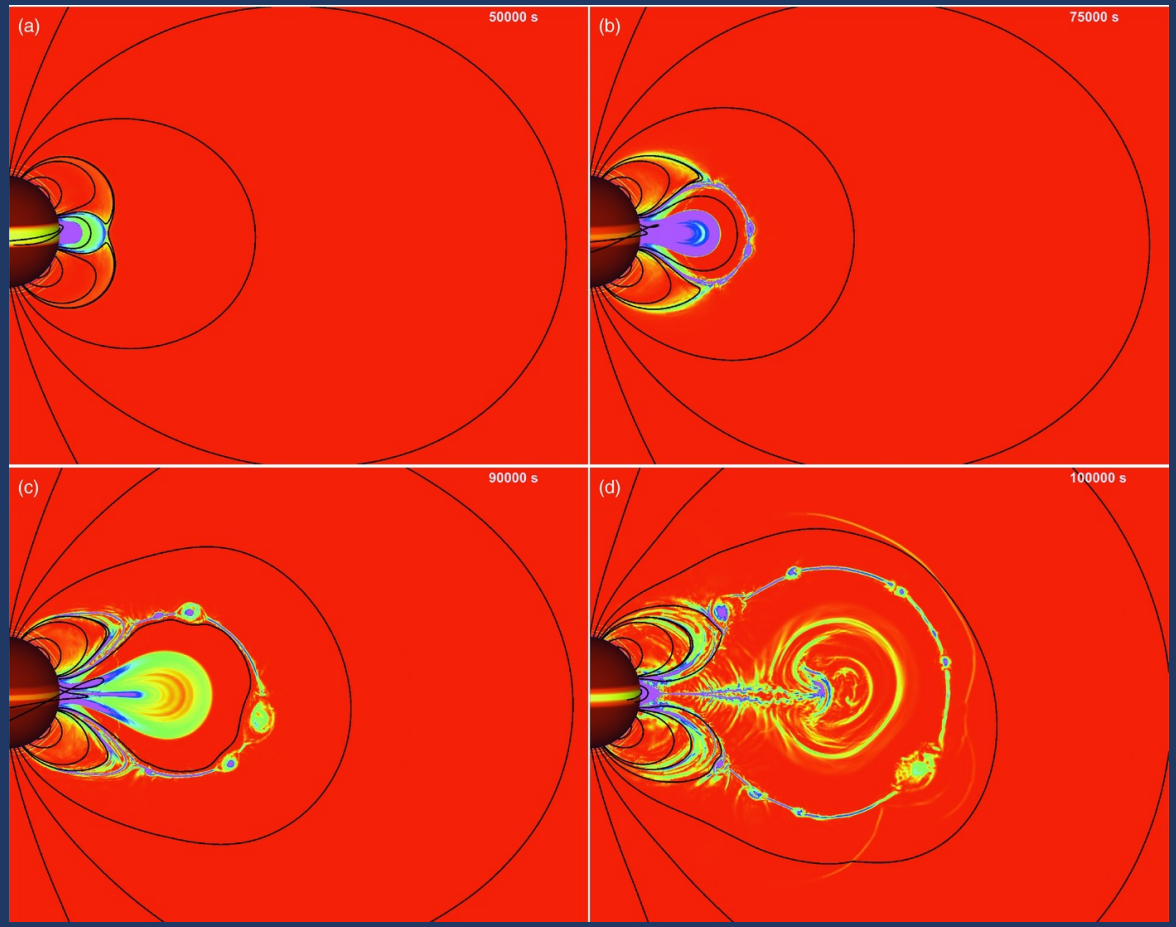
Réville et al. 2022

- 10–100 keV nucleon−1 suprathermal H, He, O, and Fe ions associated with crossings of the HCS at radial distances of <0.1 AU with PSP.
- no velocity dispersion => produced close to PSP

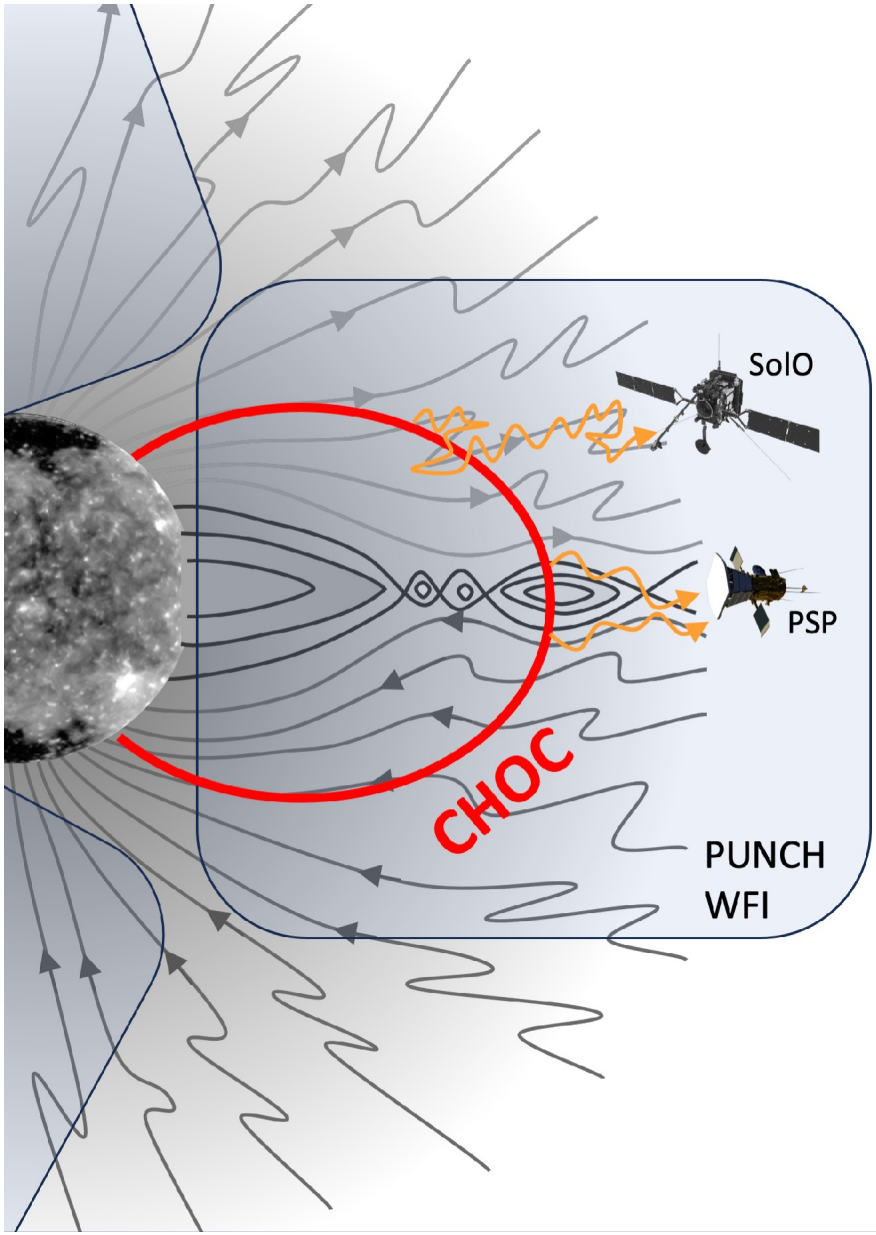
What is the state of the turbulent sheath behing the shock ?

Presence of vorticies and reconnection-induced nmagnetic islands in very high resolution 3-D MHD simulations

Do these islands also provide seed particles for the acceleration process?



Karpen + 2015



Conclusions and Future Work

- The last decades provide strong support to the acceleration of solar particles by shock waves
- Modelled conditions at the shock surface are favourable for DSA to operate in the solar corona:
  - hopefully PSP will interesect a very strong shock to check for the presence amplified Alfvén waves upstream of the shock
  - How are suprathermal (seed) particles produced: flaring activity, in the dynamic background solar wind.
- Additional important information from high-energy EM radiation (Fermi LAT/GBM, Solar Orbiter STIX): not discussed today!

Other open questions:

- How are shock properties modified by the highly transient corona/solar wind measured by Parker Solar Probe and Solar Orbiter? => NASA PUNCH high-resolution imaging (from 2025!)
- How is particle transport modified by the dynamic solar wind?