Highly Structured Solar Wind

Multi-source Connectivity

SO & PSP IAU Paper

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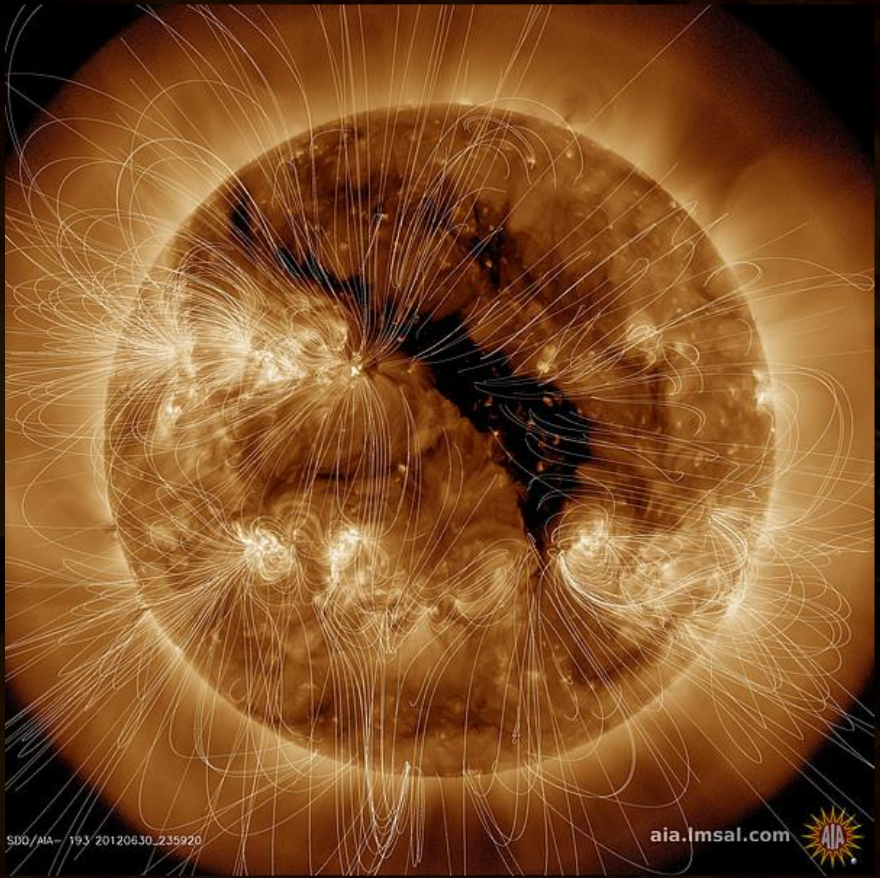
@slyardley

L'Aquila International School: Cross-Scale Coupling of Heliospheric Systems ✦ 12-16th May 2025

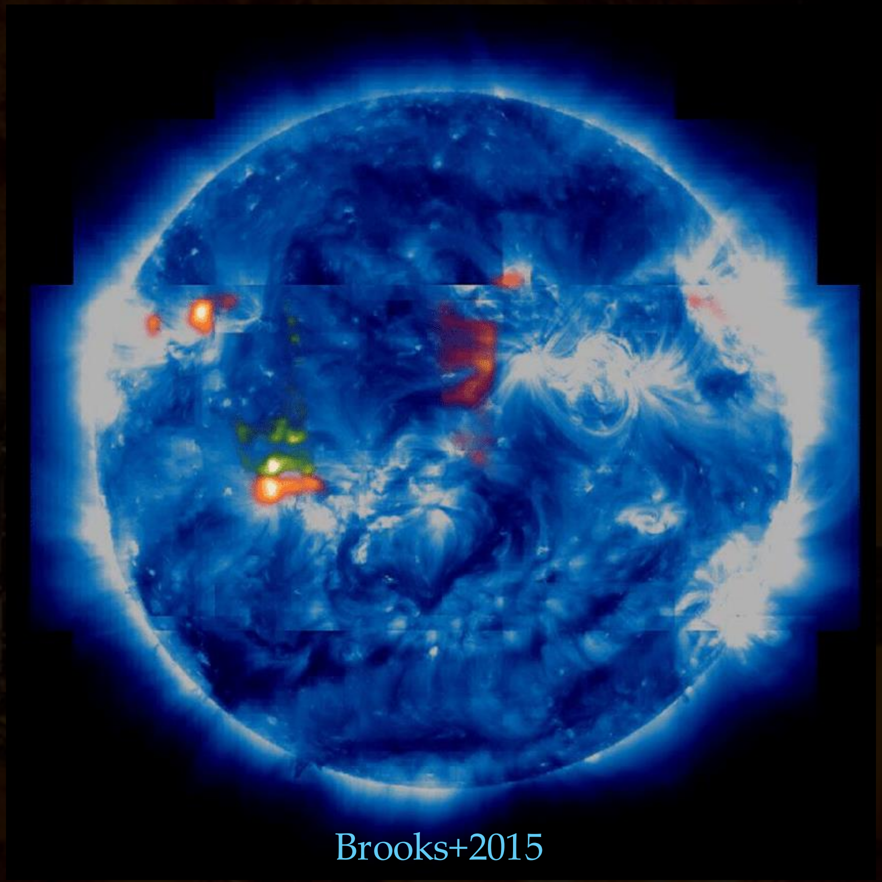
Sources of the Solar Wind

Fast Solar Wind > 500 km/s



Origins => Coronal Holes

Slow Solar Wind $\lesssim$ 500 km/s



Origins => ???

Active Region/Coronal Hole boundaries

Small low-latitude coronal holes

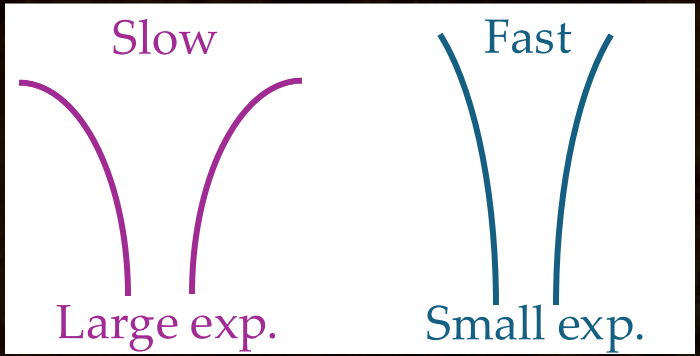
Coronal Helmet Streamers

Solar Wind Formation Mechanisms

Expansion factor

Flux tube expansion
<=> solar wind speeds

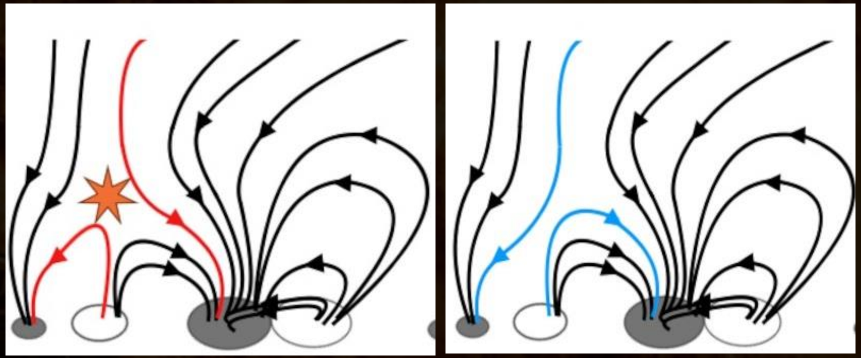
Wang+2009



Interchange Reconnection

Magnetic reconnection at open-closed magnetic field boundaries

e.g. Fisk 1999, Crooker 2002

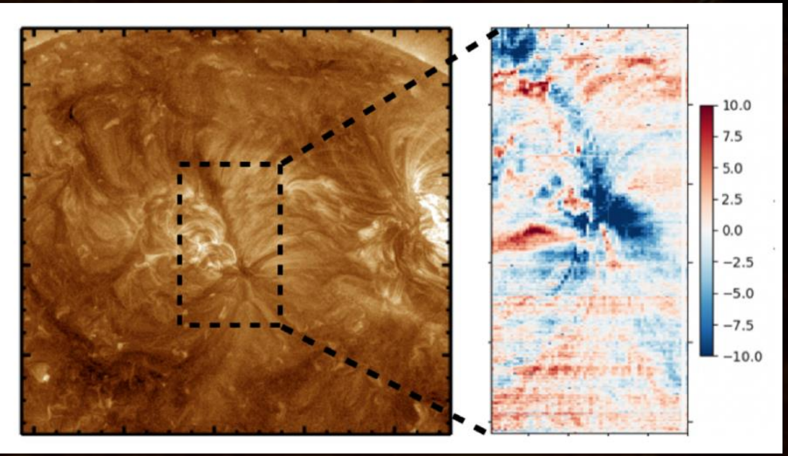


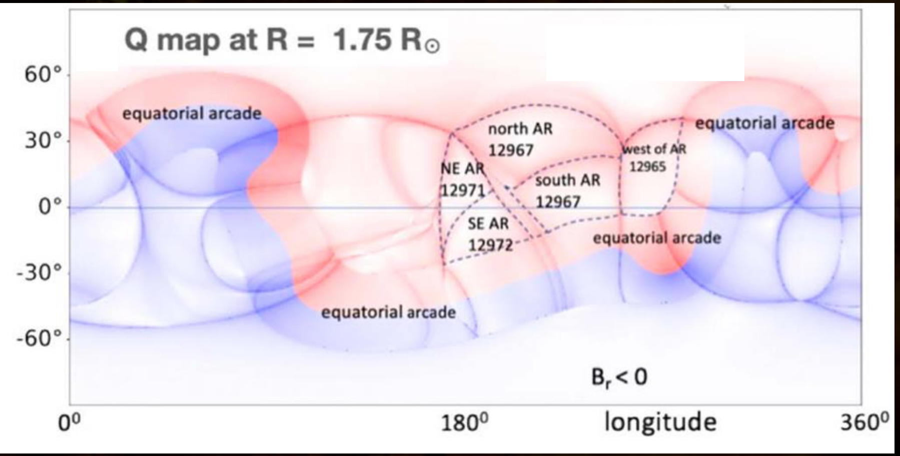
Brooks & Yardley 2021

S-web

Combination of the two models

Antiochos+2011

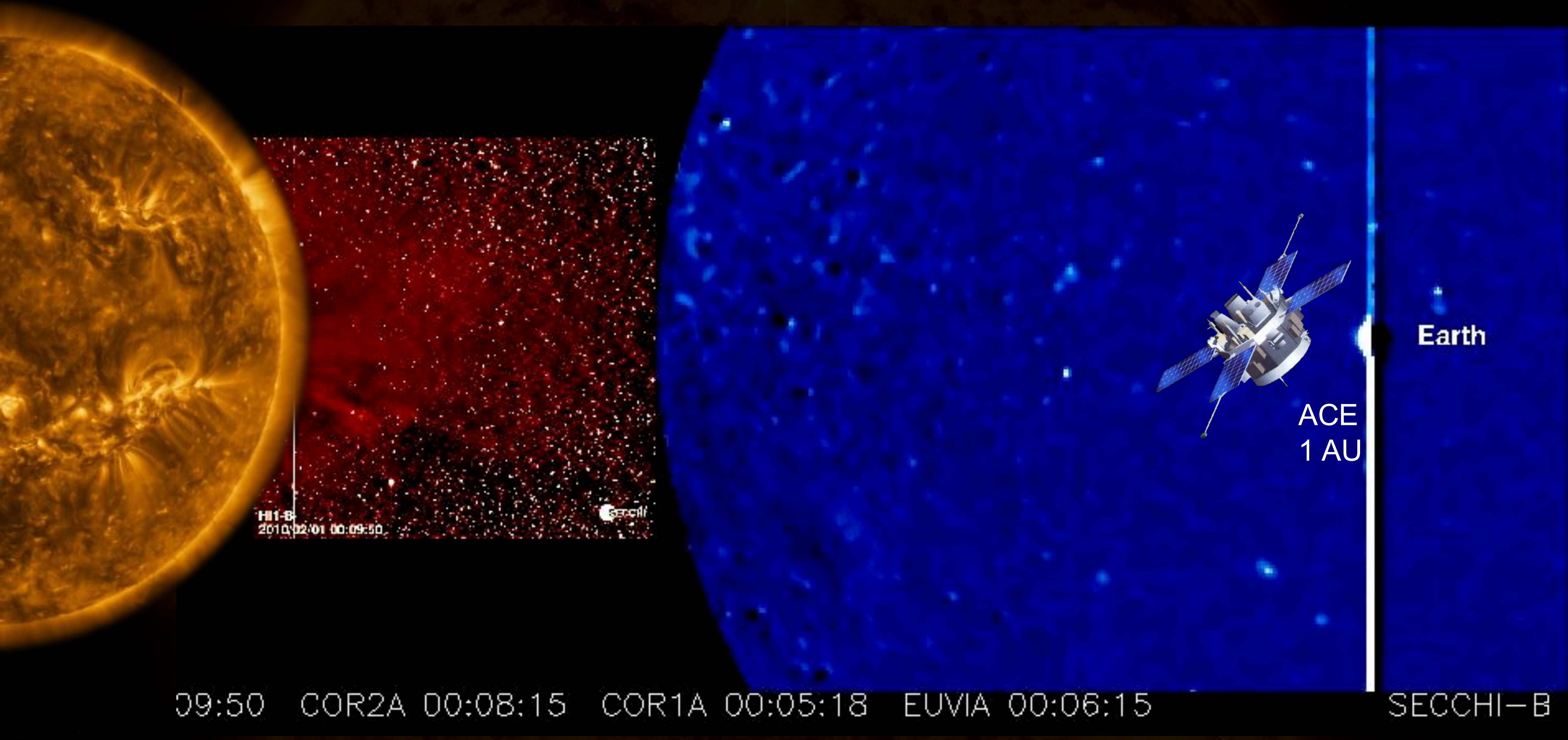




Baker+2023

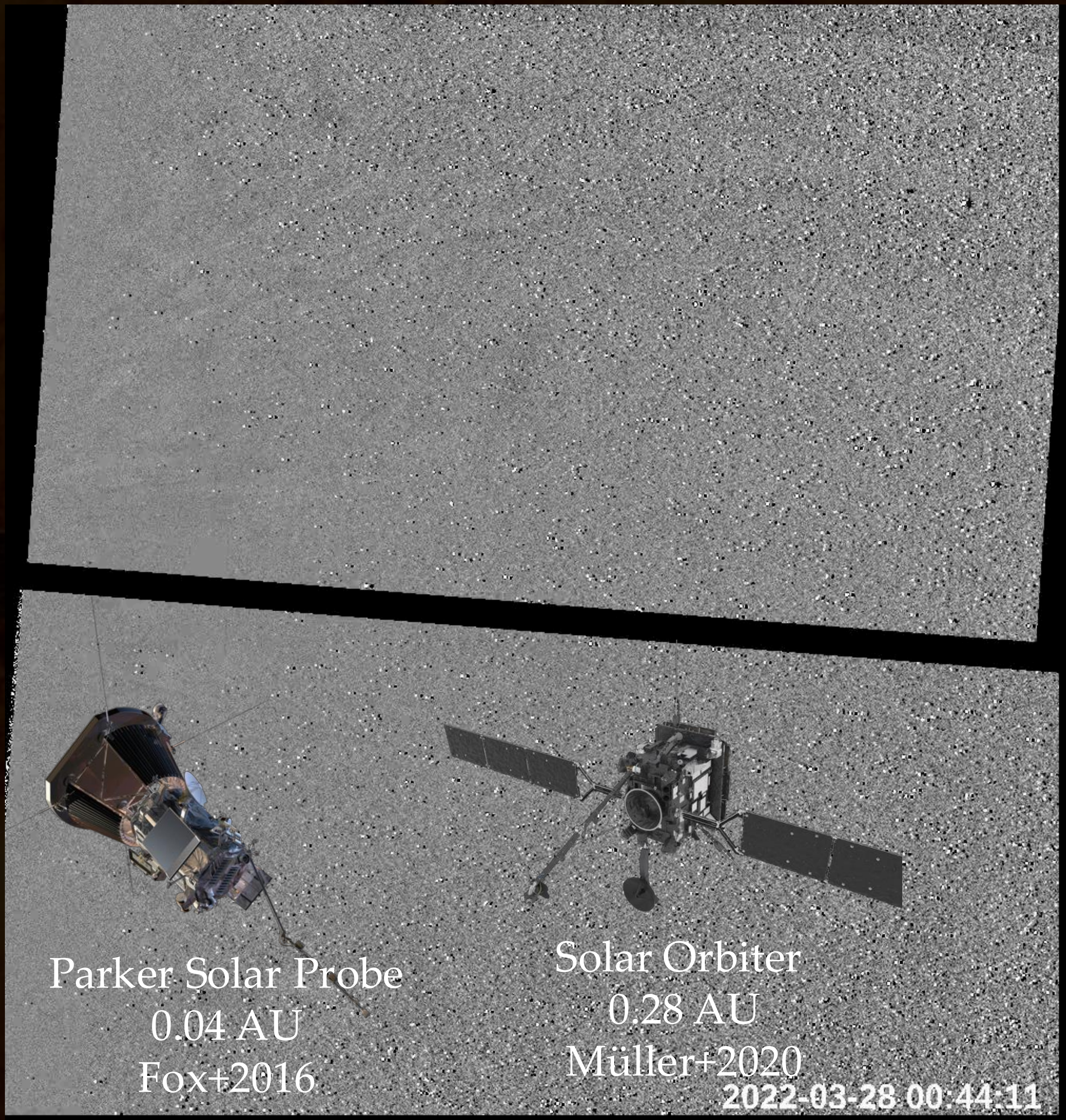
Solar Wind Variability

What drives heliospheric variability?



Solar Wind Variability

Small-scale variability is lost at large distances from the Sun

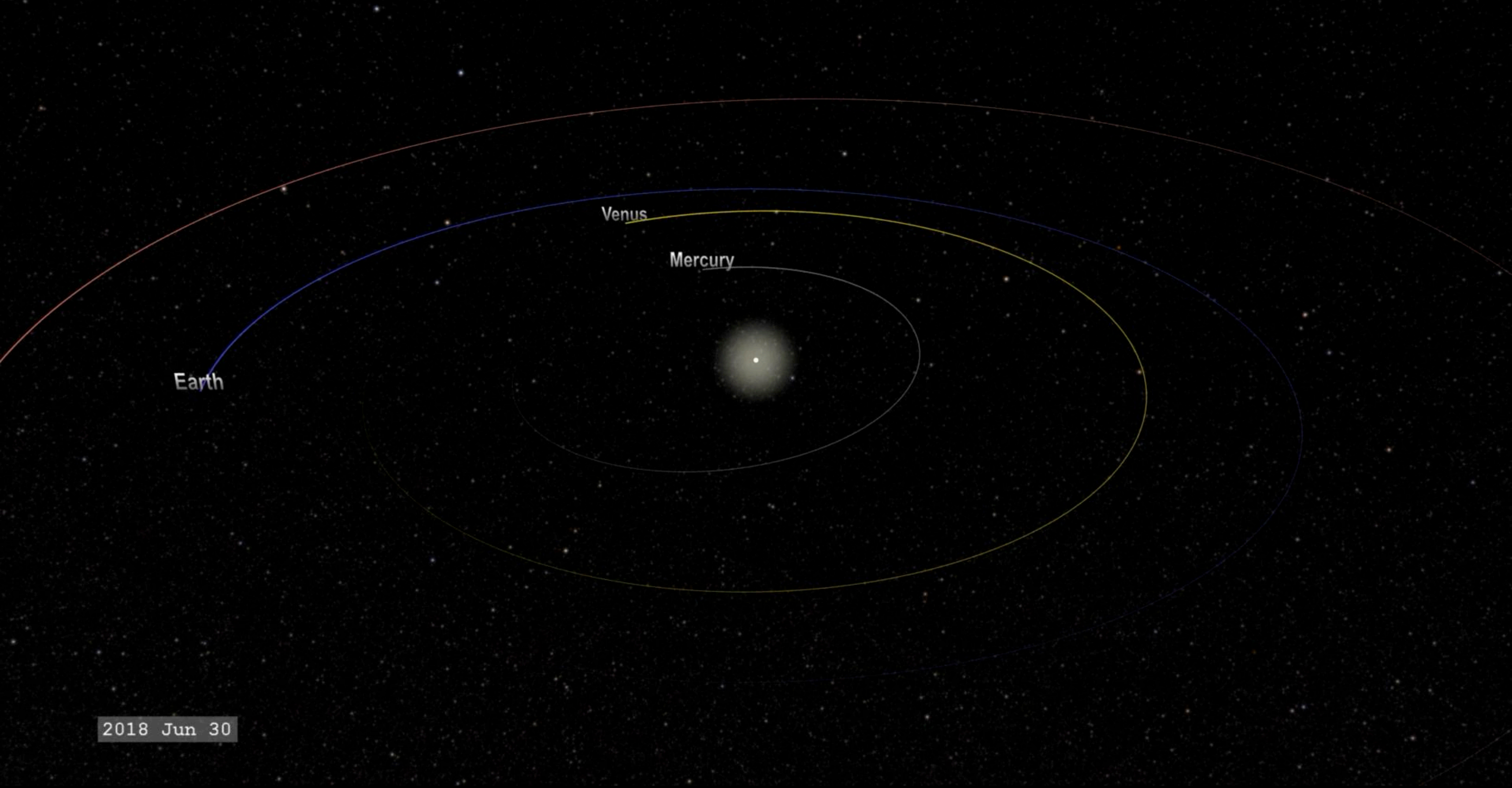


Two complementary spacecraft studying the Sun at close proximity

Providing solar wind measurements in the inner heliosphere coupled with close up views of the solar atmosphere

Solar wind: Abbo+2016, Cranmer+2017, Viall+2020

Solar Orbiter & Parker Solar Probe Orbits



EXTREME EXPLORATION WITH SOLAR ORBITER AND PARKER SOLAR PROBE

Solar Orbiter

42 million
kilometres to the Sun
at closest approach

10 instruments
to observe the turbulent solar surface, its hot outer atmosphere, and changes in the solar wind

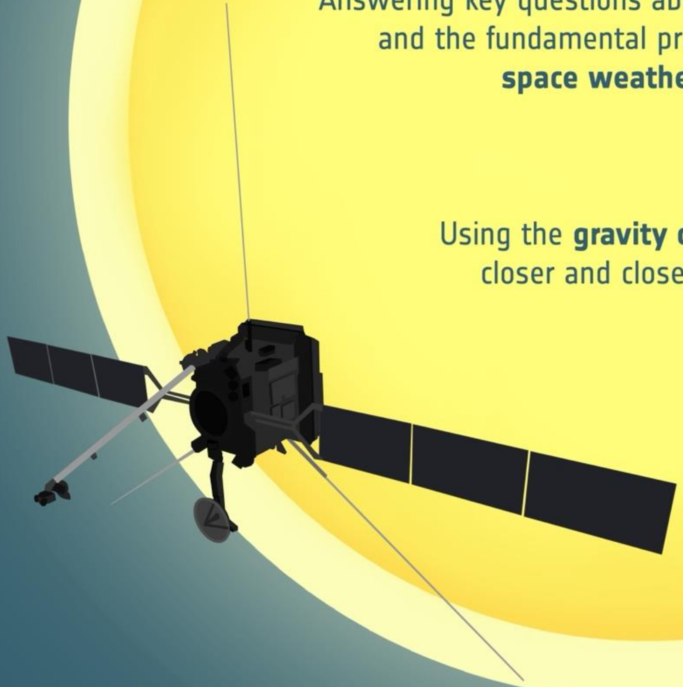
Combination of **in situ** and **remote sensing** observations

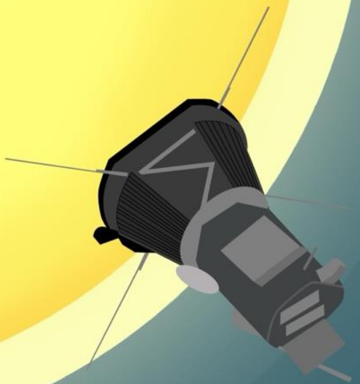
first images
of the Sun's poles: the key to understanding the Sun's activity and solar cycle

Providing **complementary measurements** and putting each other's **data in context**

Answering key questions about **how our star works** and the fundamental processes that lead to **space weather at Earth**

Using the **gravity of Venus** to get closer and closer to the Sun





Parker Solar Probe

6.2 million
kilometres to the Sun
at closest approach

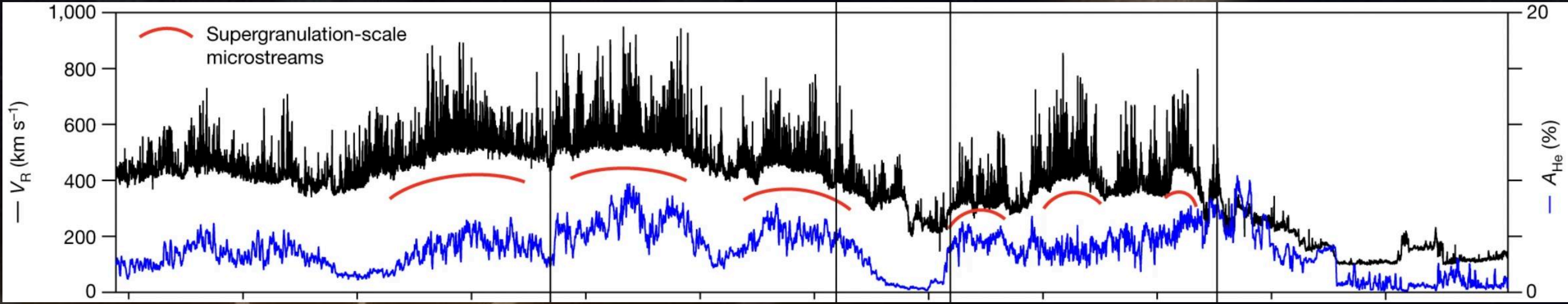
4 instruments
to study magnetic fields, plasma, energetic particles and solar wind

Flies through the Sun's inner atmosphere to trace how energy flows through the corona

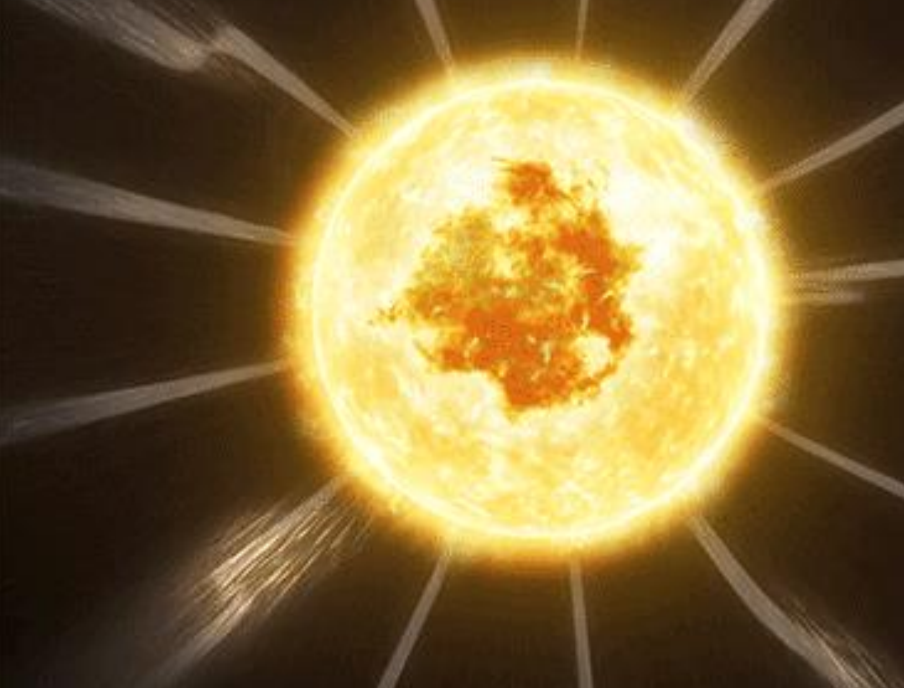
#SolarOrbiter #WeAreAllSolarOrbiters

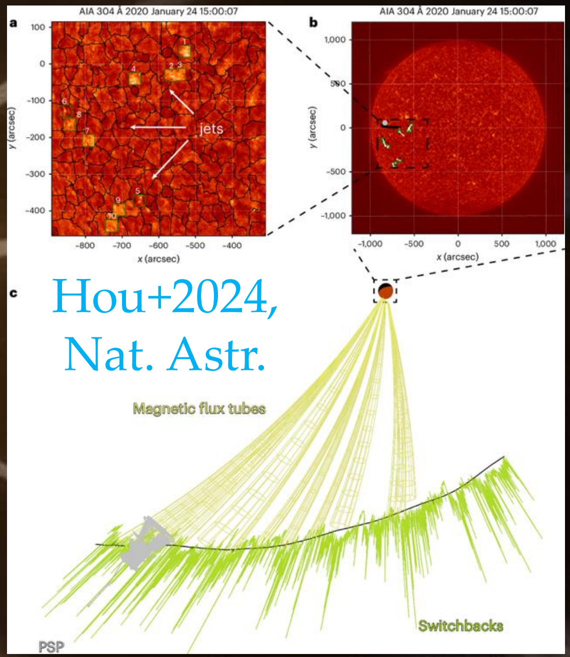
Magnetic Switchbacks

Ubiquitous reversals in the magnetic field accompanied with velocity spikes

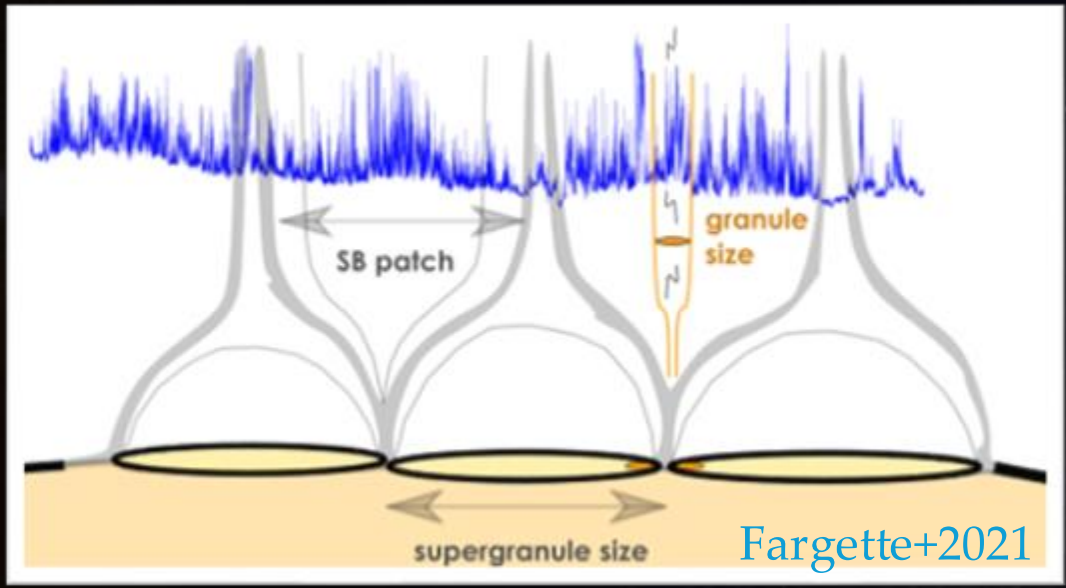


e.g. Bale+2019, Kasper+2019, Dudok de Wit+2020, Horbury+2020, Bale+2021, Federov+2021, Telloni+2022





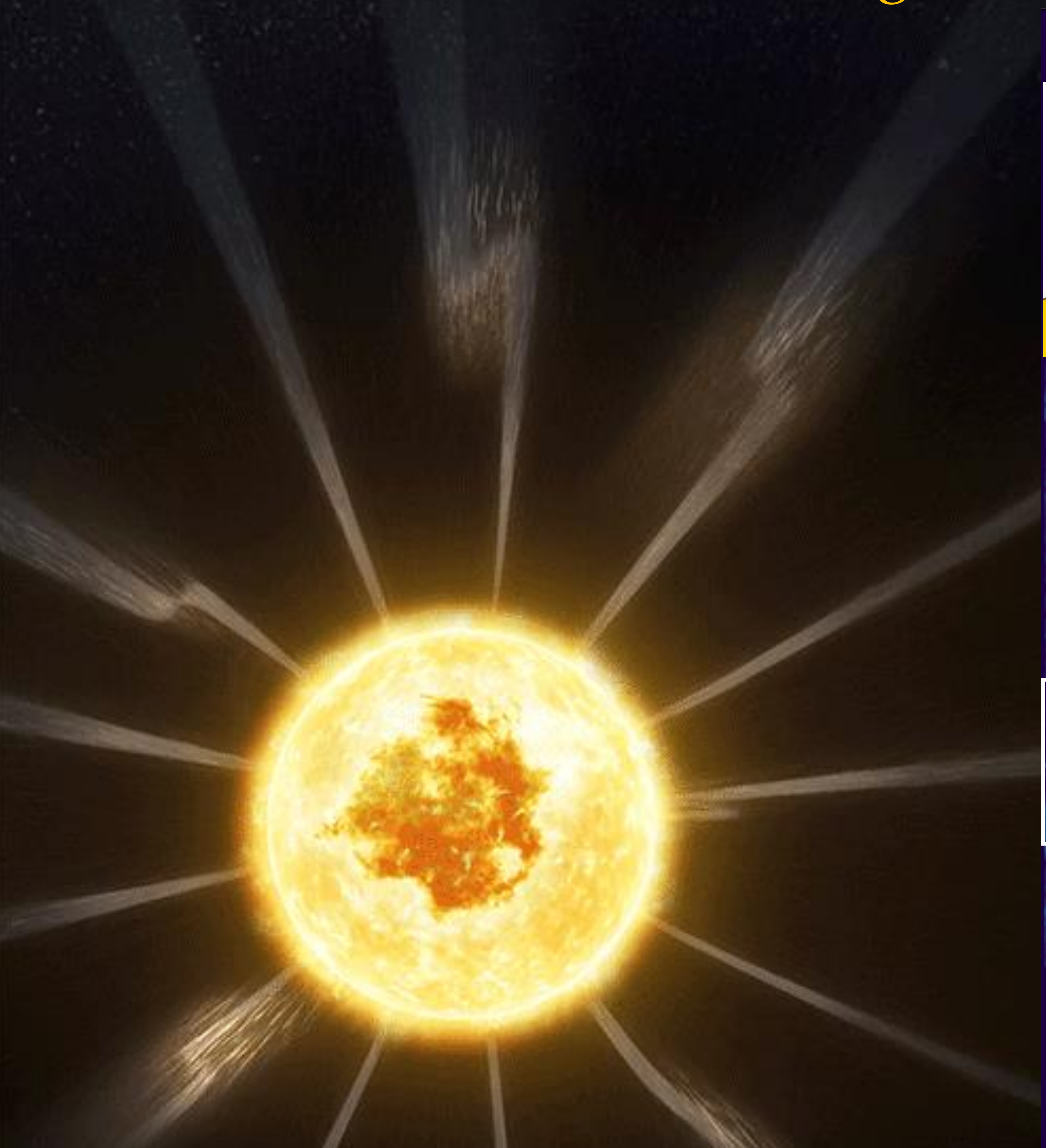
Hou+2024, Nat. Astr.

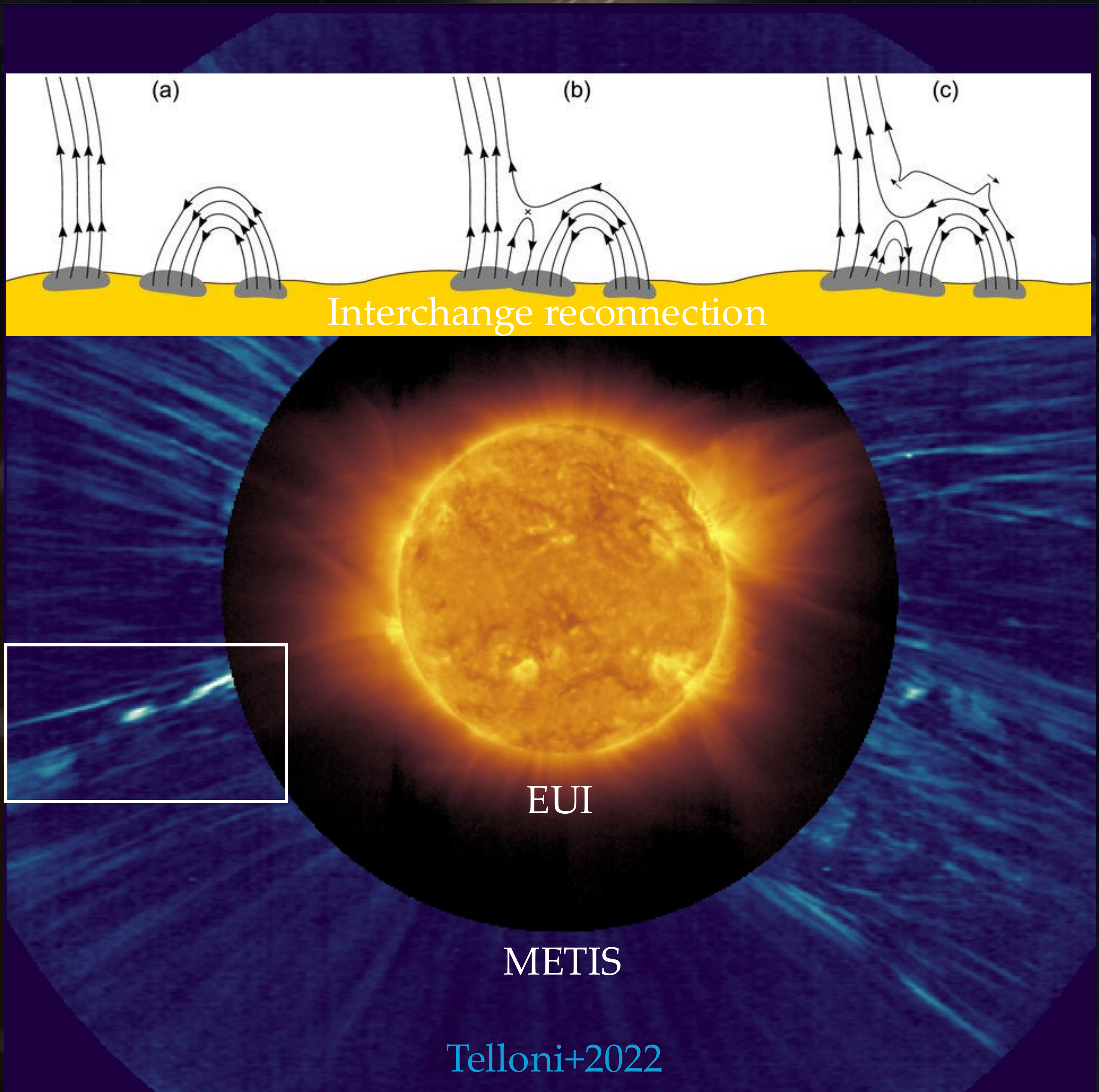


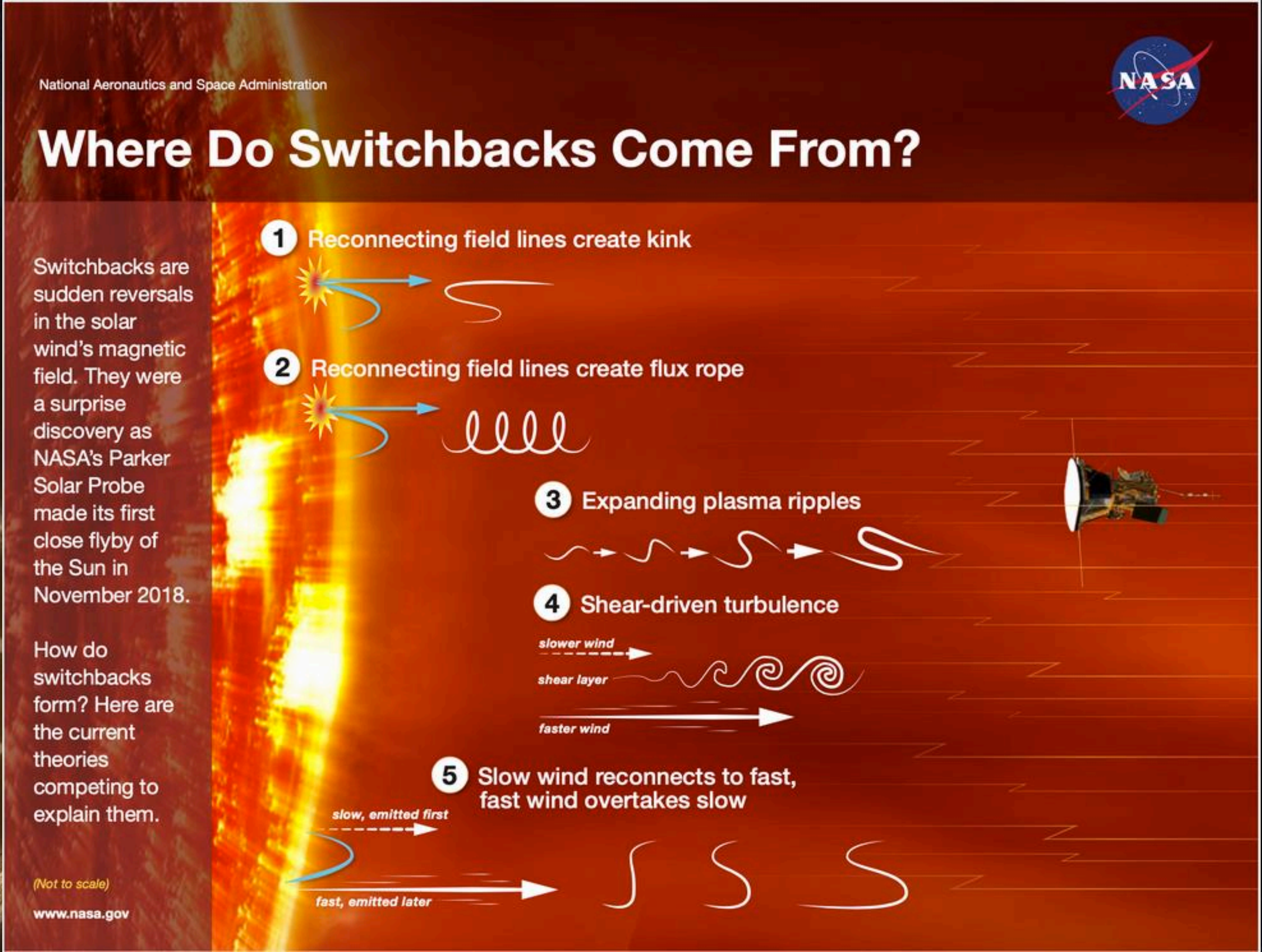
Fargette+2021

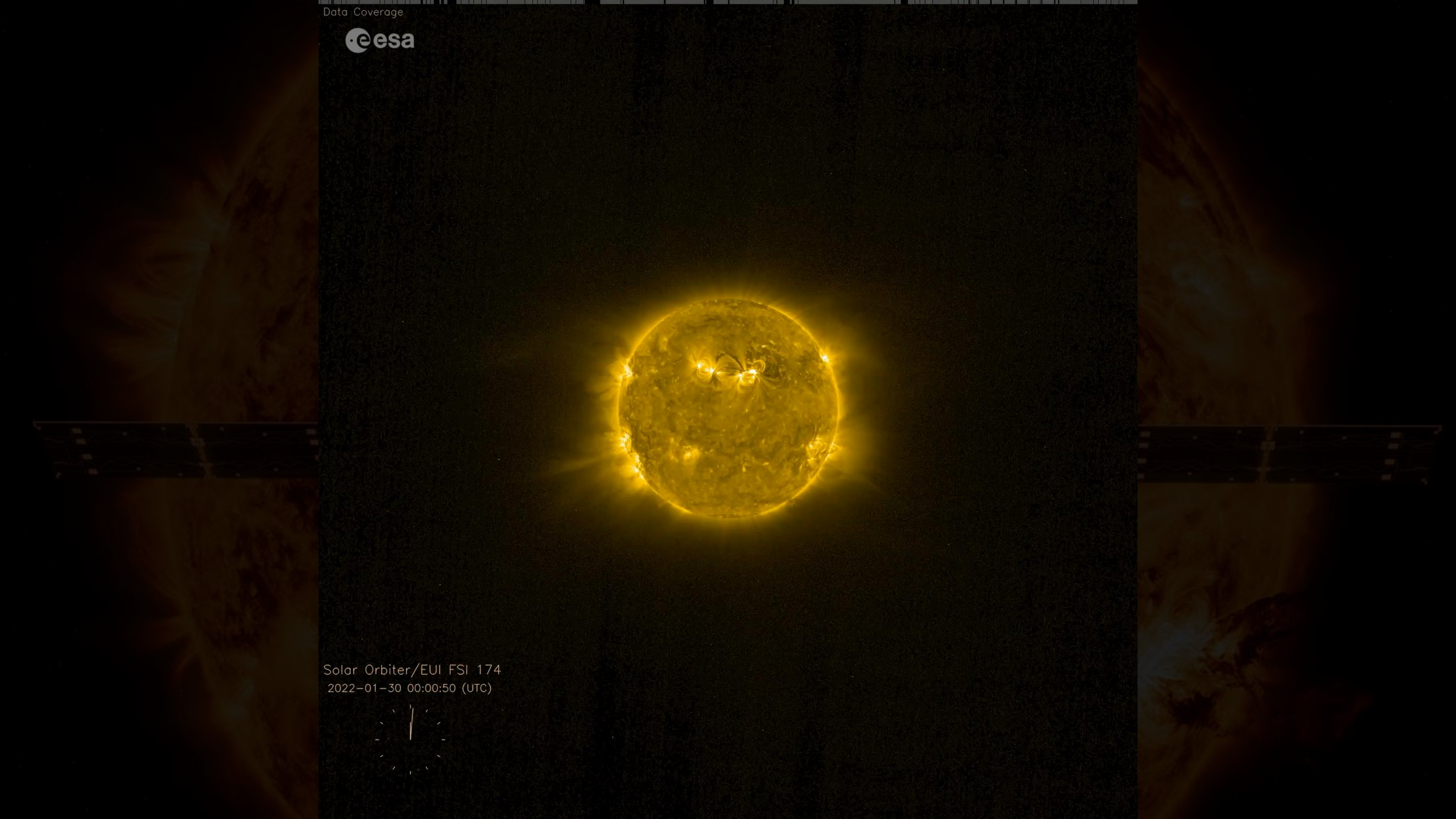
Switchback patches modulated by supergranules

Magnetic Switchbacks



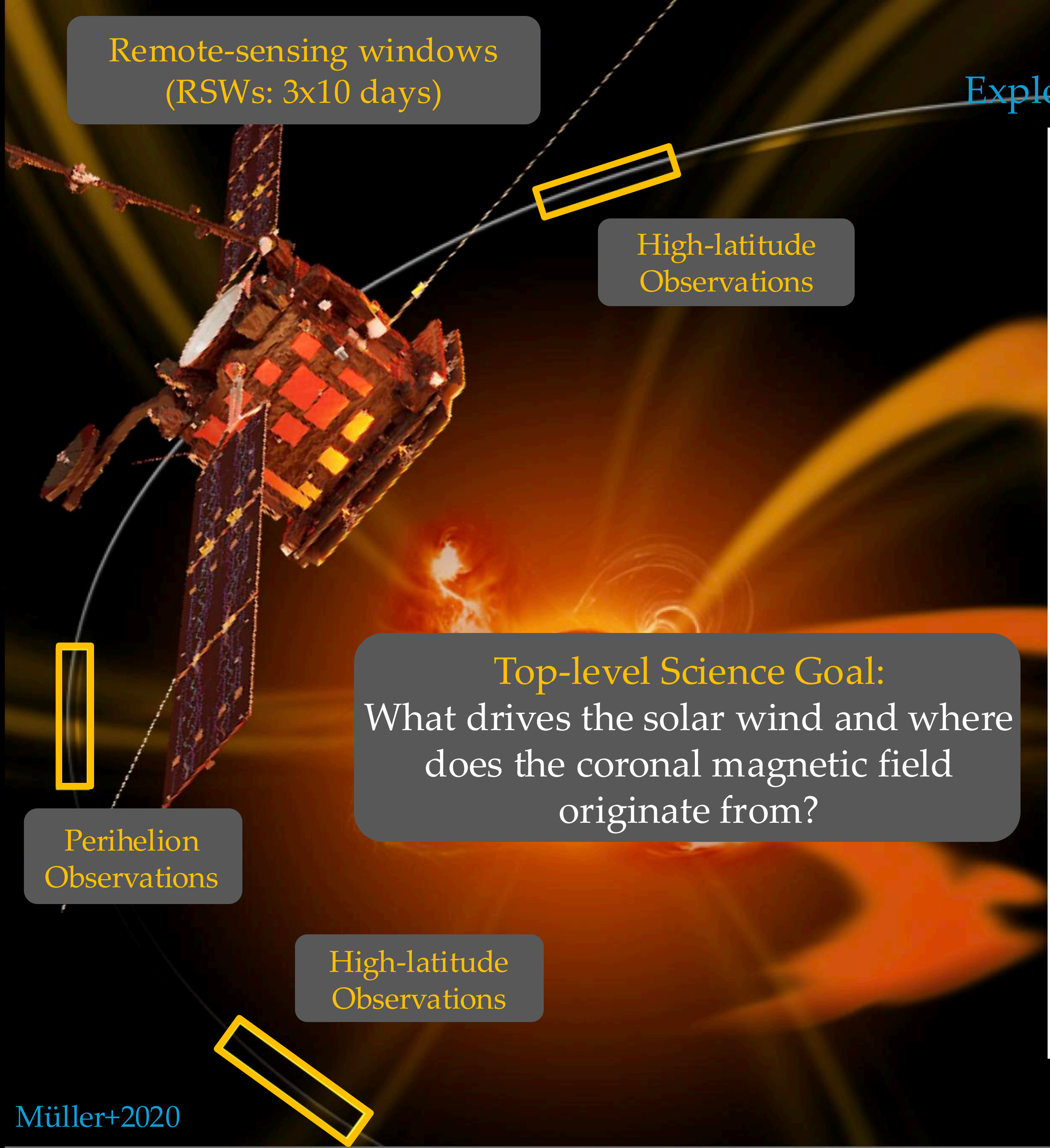



National Aeronautics and Space Administration
NASA
Where Do Switchbacks Come From?
Switchbacks are sudden reversals in the solar wind's magnetic field. They were a surprise discovery as NASA's Parker Solar Probe made its first close flyby of the Sun in November 2018.
How do switchbacks form? Here are the current theories competing to explain them.
1 Reconnecting field lines create kink
2 Reconnecting field lines create flux rope
3 Expanding plasma ripples
4 Shear-driven turbulence
slower wind
shear layer
faster wind
5 Slow wind reconnects to fast, fast wind overtakes slow
slow, emitted first
fast, emitted later
(Not to scale)
www.nasa.gov

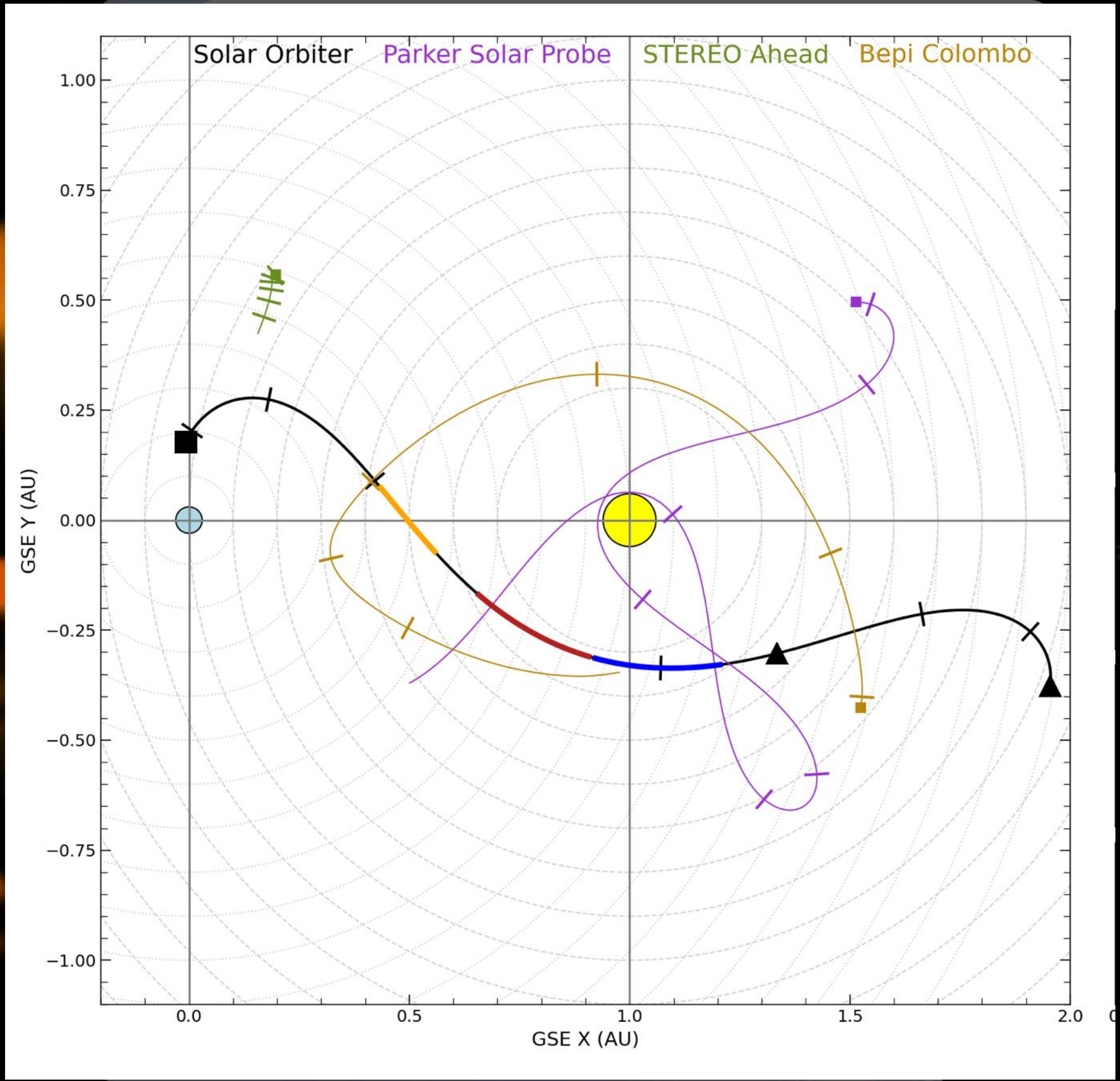

Data Coverage
esa
Solar Orbiter/EUI FSI 174
2022-01-30 00:00:50 (UTC)

Solar Orbiter Mission

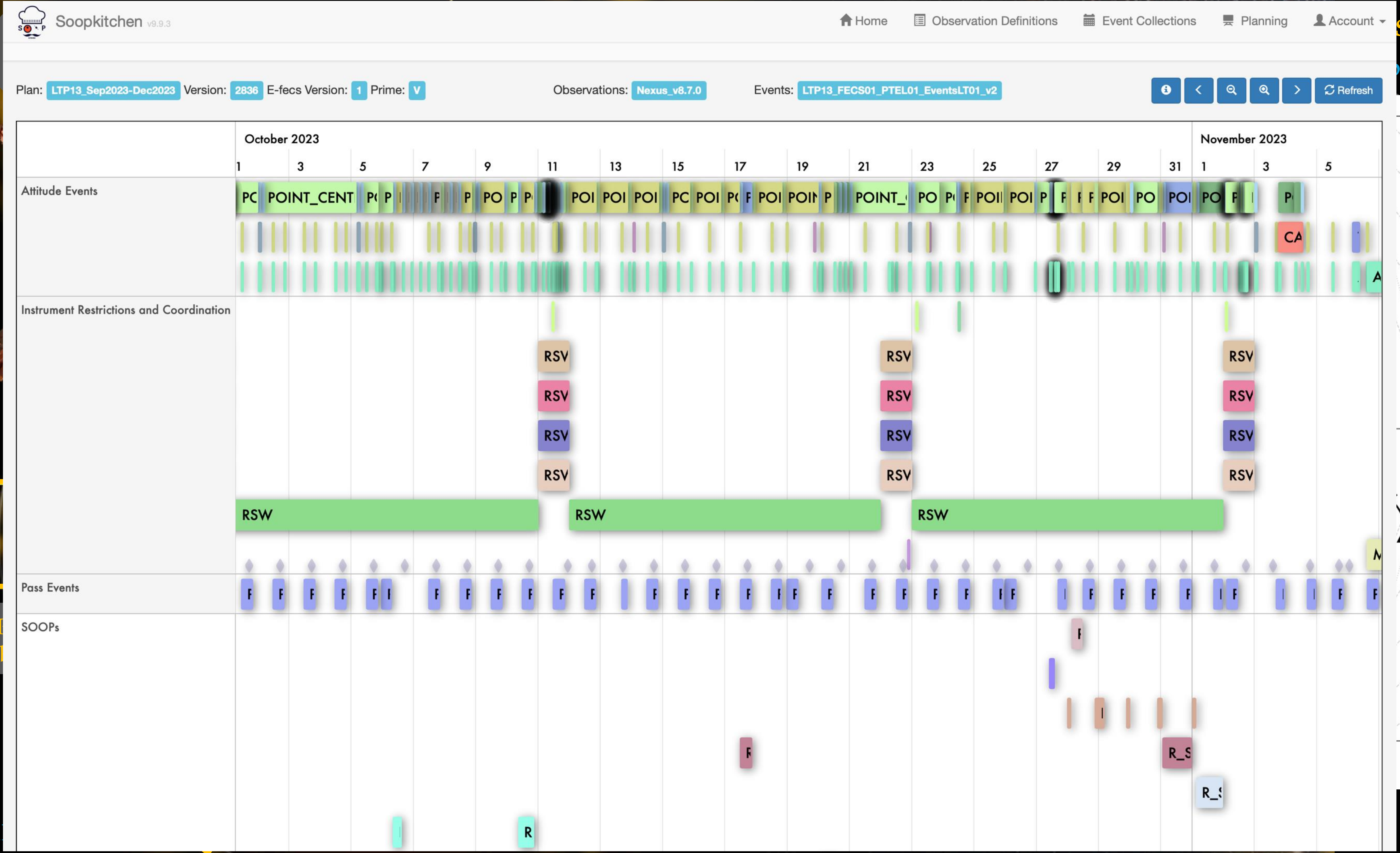
Exploring the connection between the Sun and the heliosphere



Top-level Science Goal:
What drives the solar wind and where does the coronal magnetic field originate from?



Müller+2020



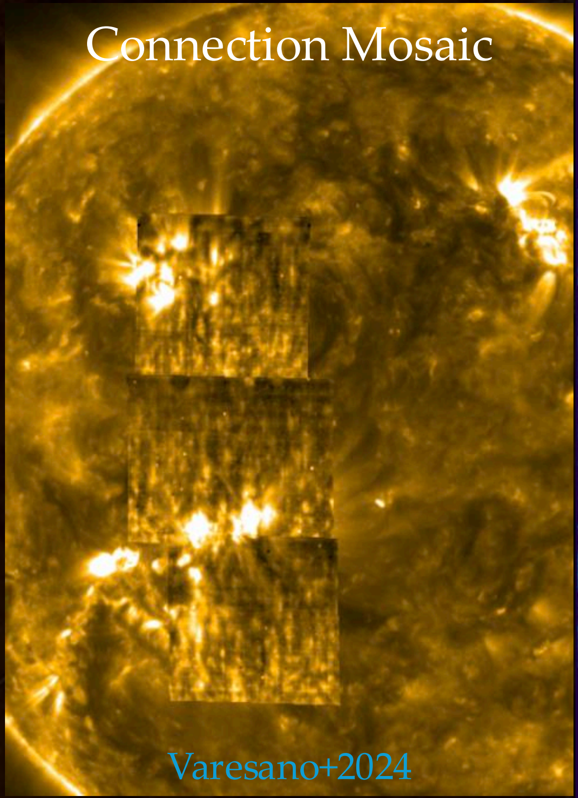
Soopkitchen v9.9.3
Home
Observation Definitions
Event Collections
Planning
Account
Plan: LTP13_Sep2023-Dec2023
Version: 2836
E-fecs Version: 1
Prime: V
Observations: Nexus_v8.7.0
Events: LTP13_FECS01_PTEL01_EventsLT01_v2
Refresh
October 2023
November 2023
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 1 3 5
Attitude Events
POINT_CENT
POINT_
CA
Instrument Restrictions and Coordination
RSV
RSW
Pass Events
SOOPs
R_S

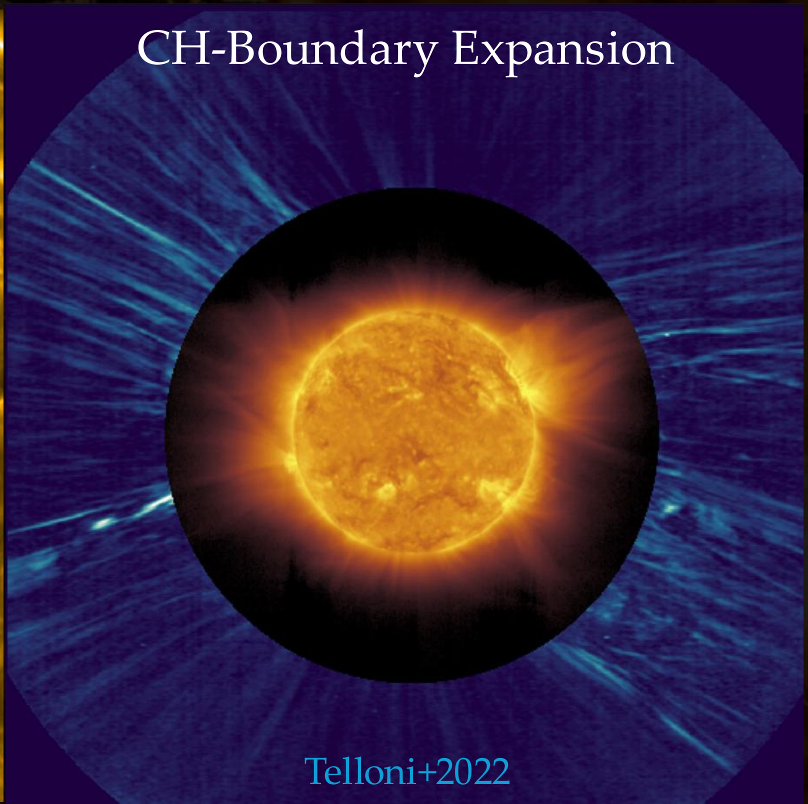
Solar Wind Related SOOPs

L_SMALL_MRES_MCAD_Ballistic-Connection
L_SMALL_MRES_MCAD_Connection-Mosaic
L_SMALL_HRES_HCAD_Fast-Wind
L_SMALL_HRES_HCAD_Slow-Wind-Connection
L_BOTH_MRES_MCAD_Farside-Connection
L_BOTH_HRES_LCAD_CH-Boundary-Expansion
R_SMALL_HRES_HCAD_PDF-Mosaic

https://www.cosmos.esa.int/web/solar-orbiter/soops-summary

Zouganelis+2020





Solar Wind Related SOOPs

L_SMALL_MRES_MCAD_Ballistic-Connection
L_SMALL_MRES_MCAD_Connection-Mosaic
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L_BOTH_HRES_LCAD_CH-Boundary-Expansion
R_SMALL_HRES_HCAD_PDF-Mosaic

https://www.cosmos.esa.int/web/solar-orbiter/soops-summary

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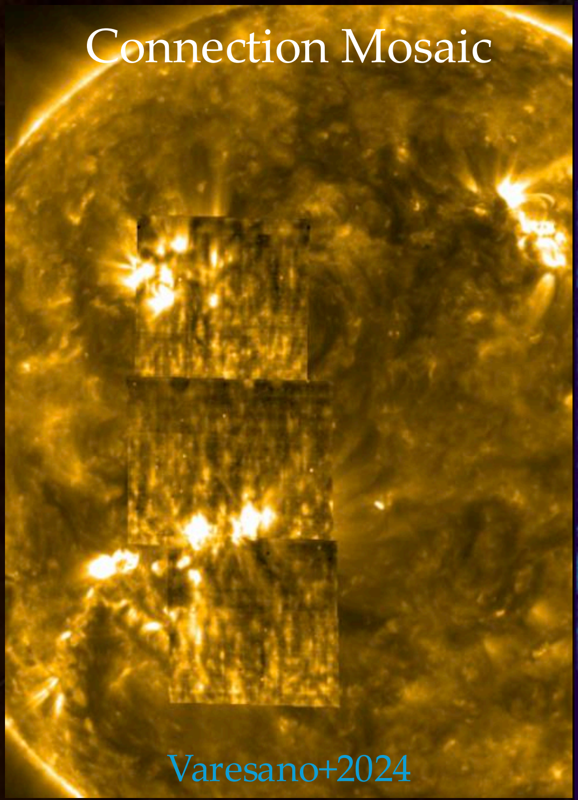
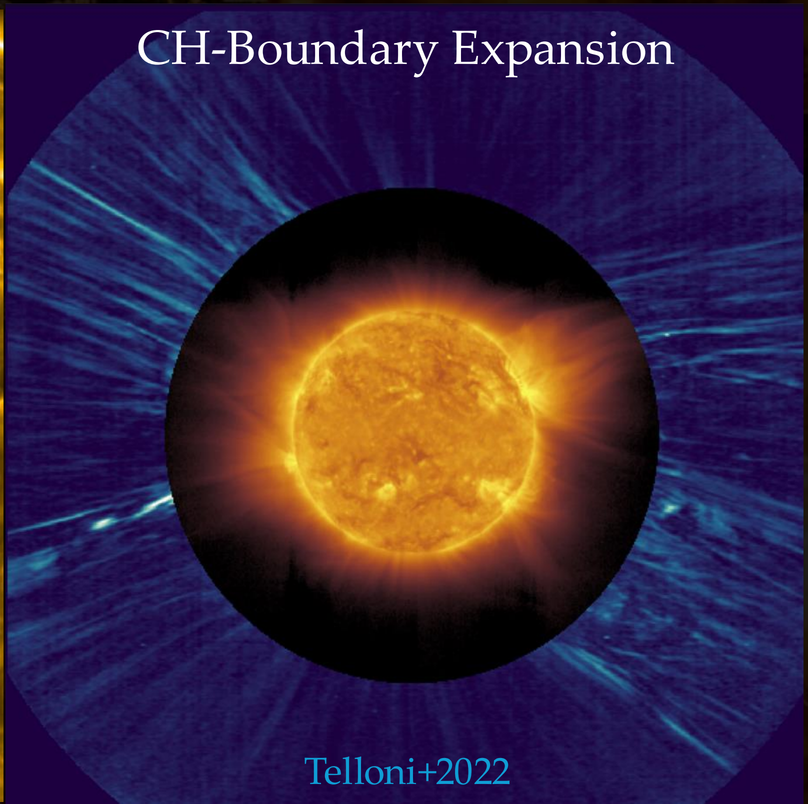
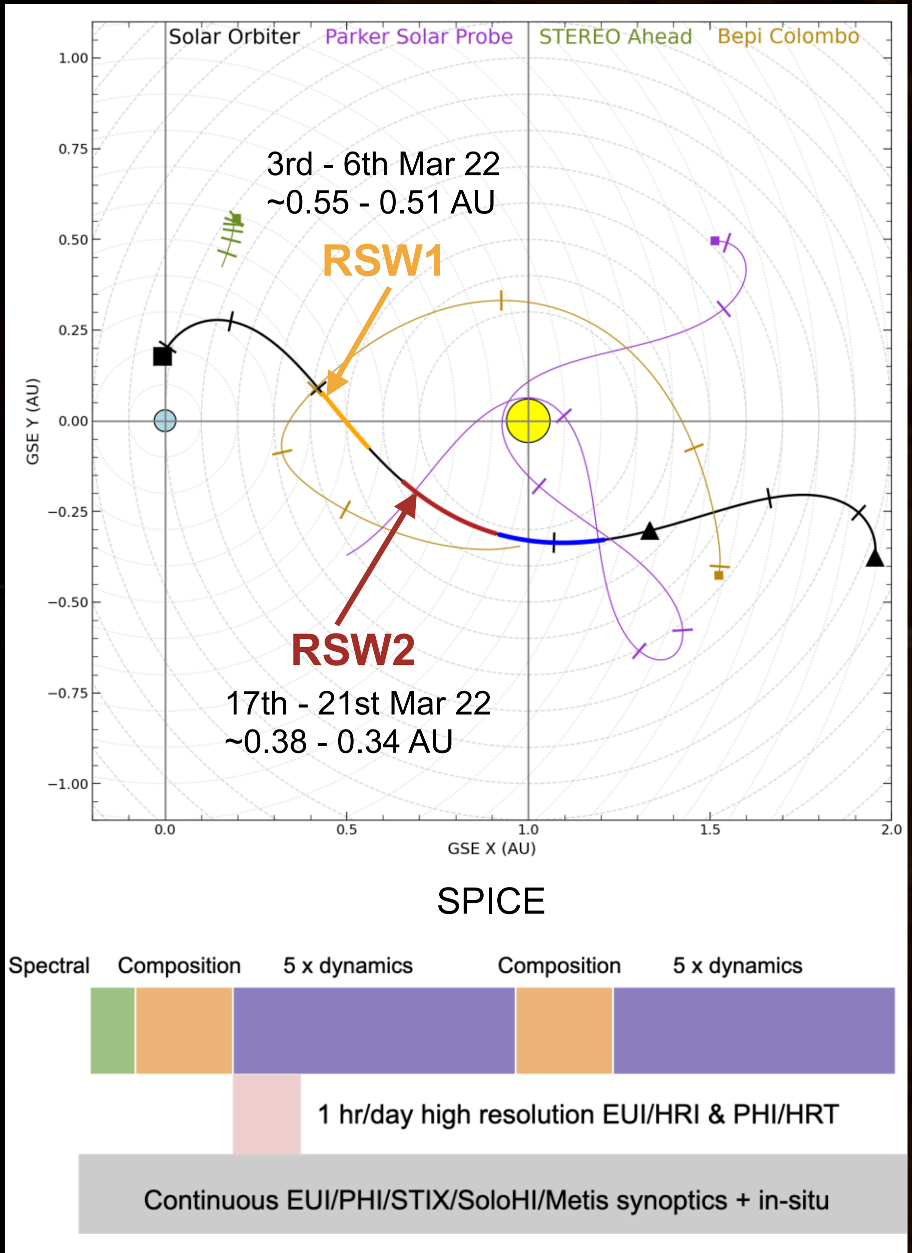




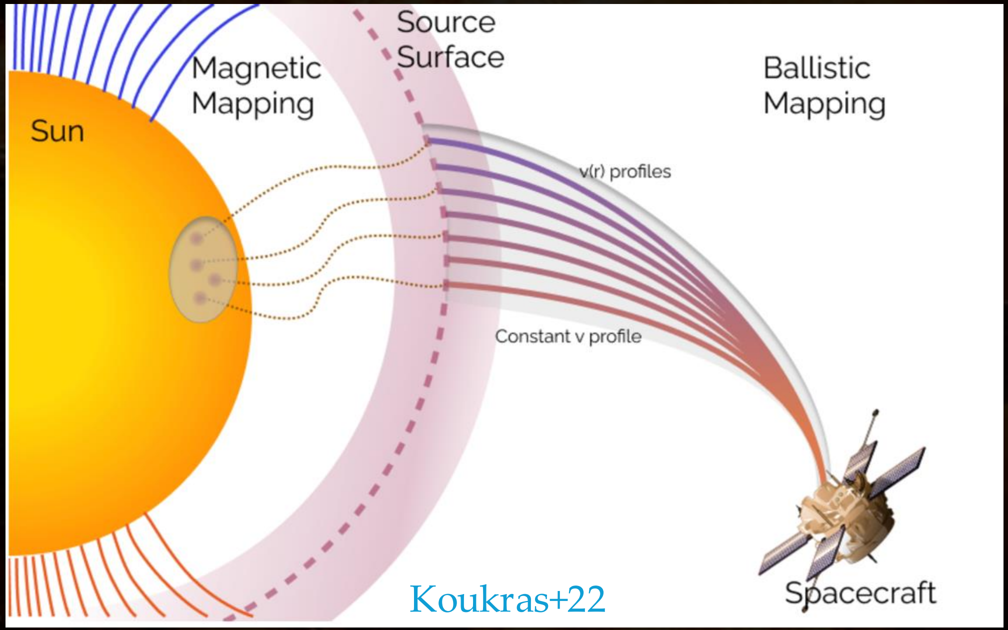
Slow Solar Wind Connection Science SOOP

L_SMALL_HRES_HCAD_Slow-Wind-Connection



Science Goal: Slow solar wind release mechanisms at open-closed magnetic field boundaries

Target: Active Region/Coronal Hole Boundaries



Depends upon connectivity of spacecraft!

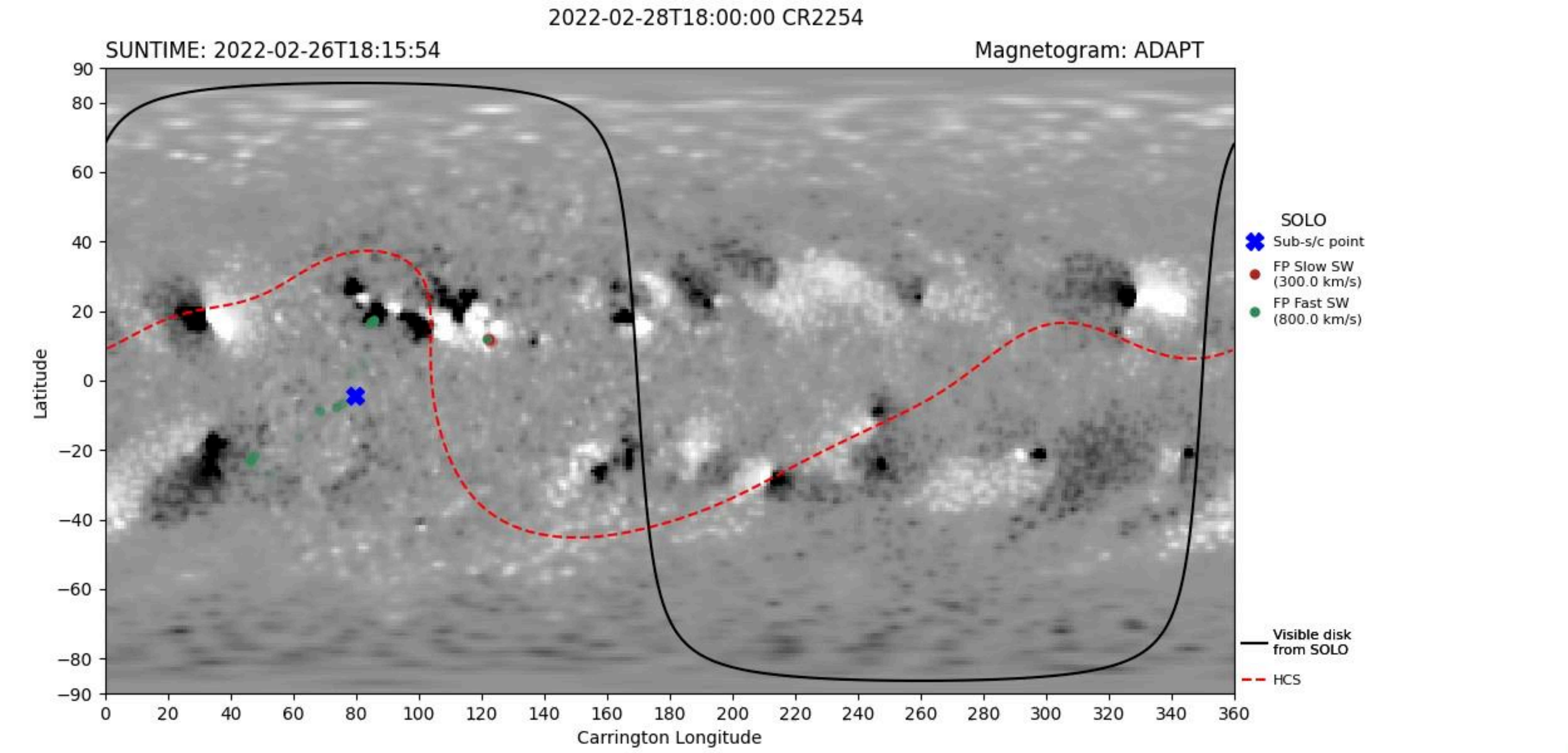
(Rouillard+2020)

Supporting observations from

Hinode & **IRIS**

Yardley+2023

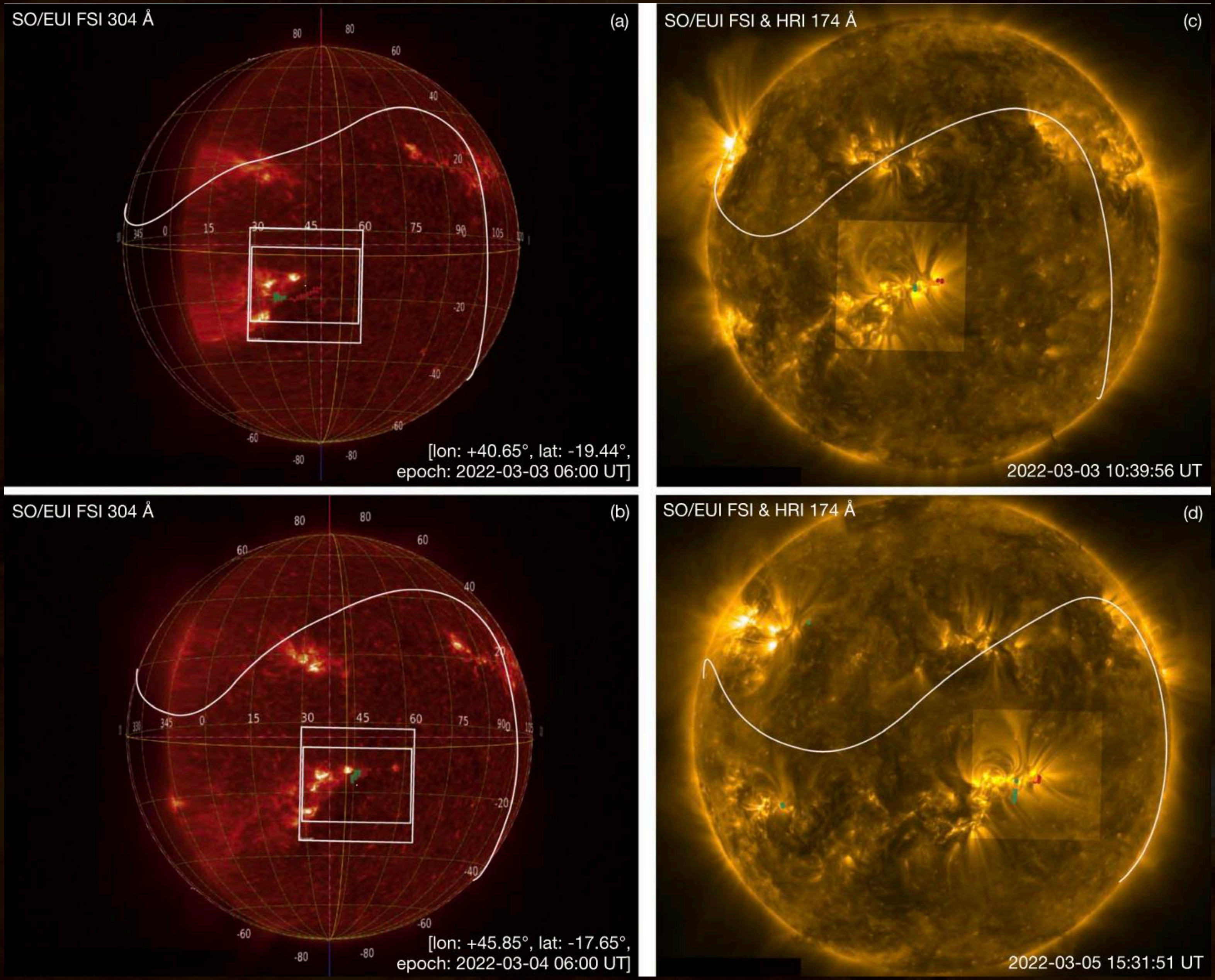
Magnetic Connectivity Tool (RSW1)



http://connect-tool.irap.omp.eu/

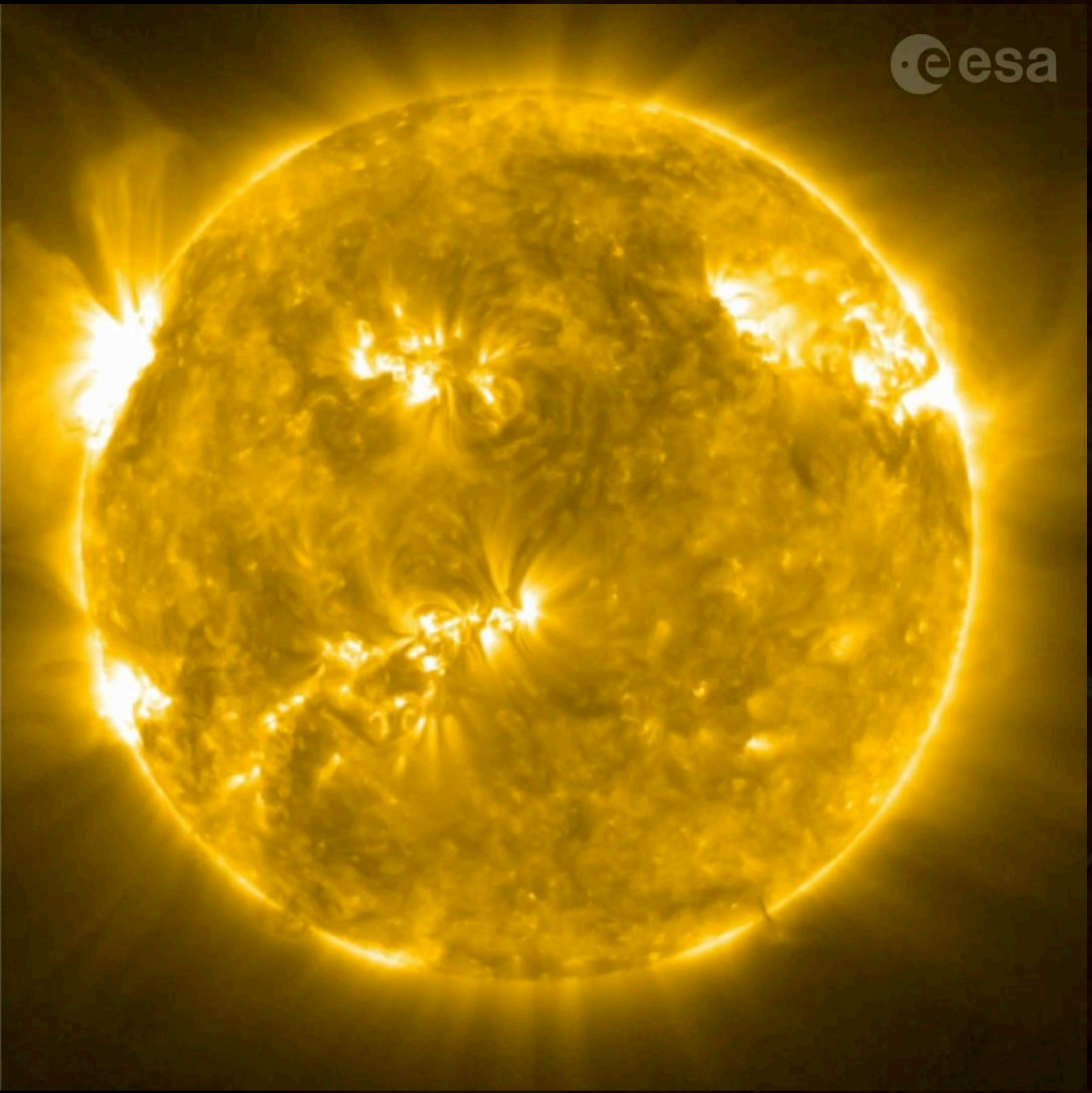
Rouillard+2020

Target Selection for RSW1



Yardley+2023

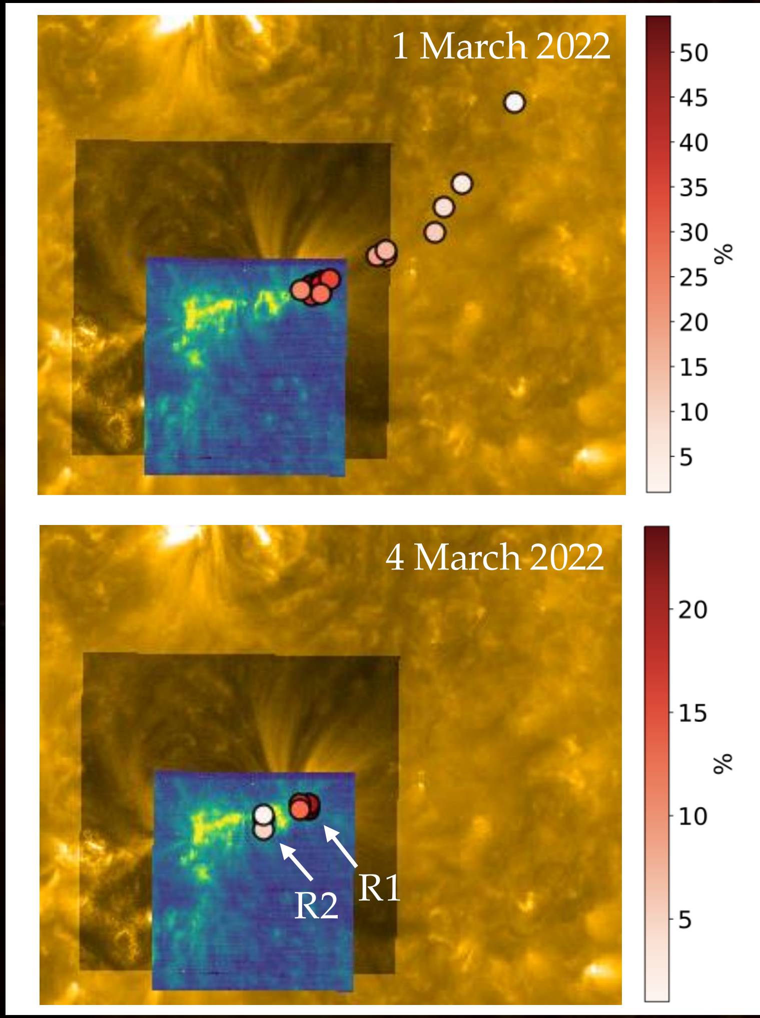
Multi-source connectivity drives solar wind variability



Magnetic connectivity of Solar Orbiter transitions across
the CH-AR complex
Solar wind travel time ~ 2-3 days

Yardley, Brooks, D’Amicis, Owen, Long, Baker, Démoulin, Owens, Lockwood+2024, Nat. Astr.

Multi-source connectivity drives solar wind variability



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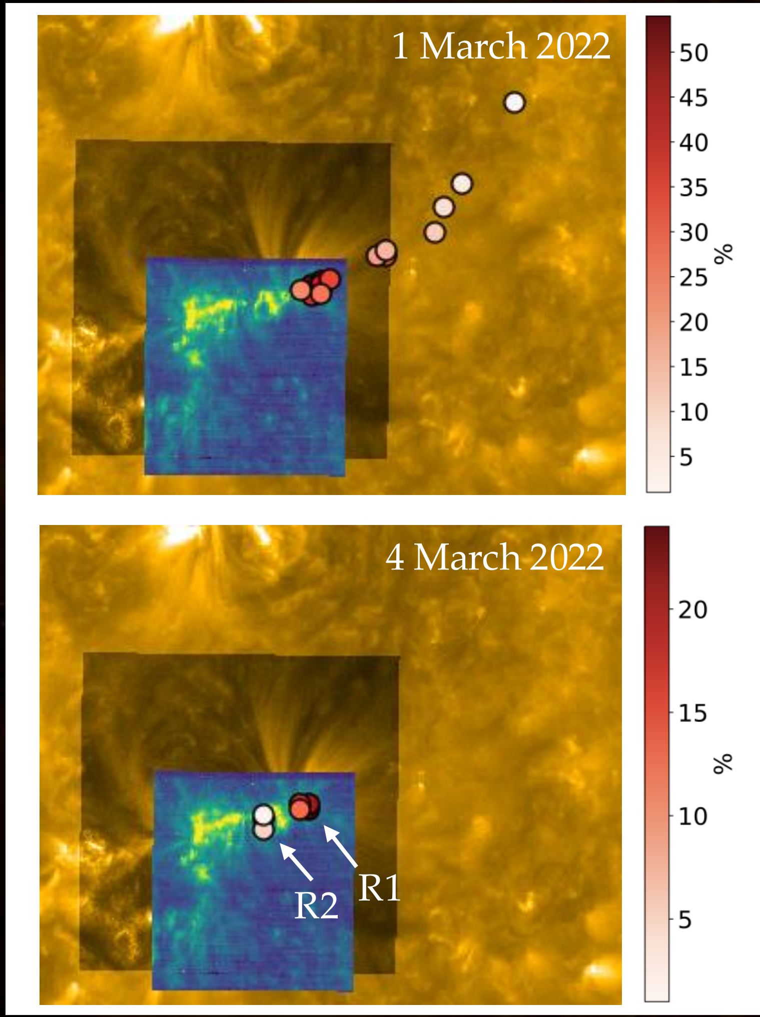
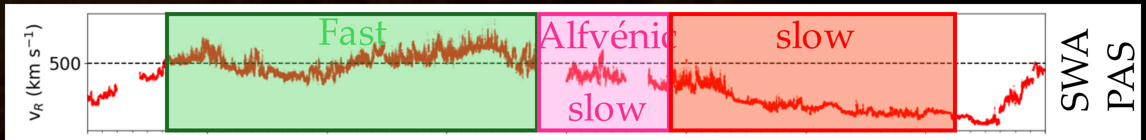
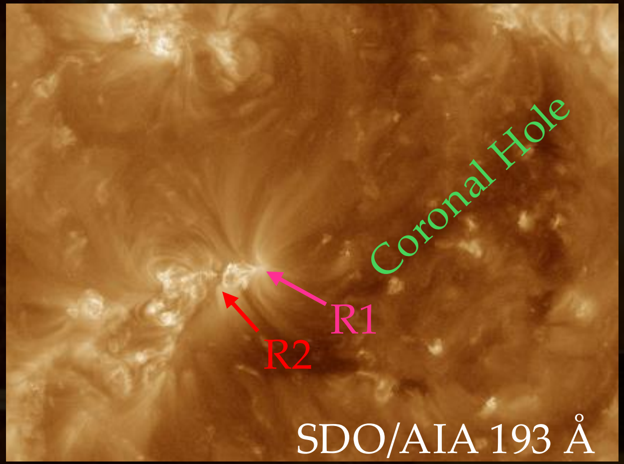




All types of solar wind



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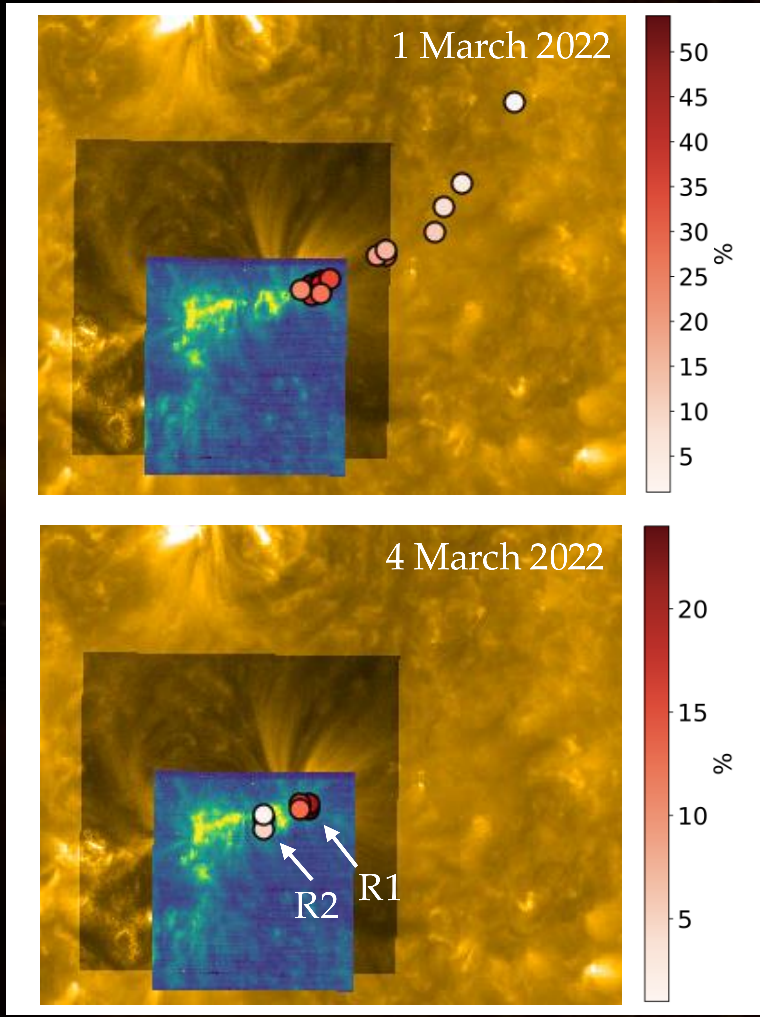
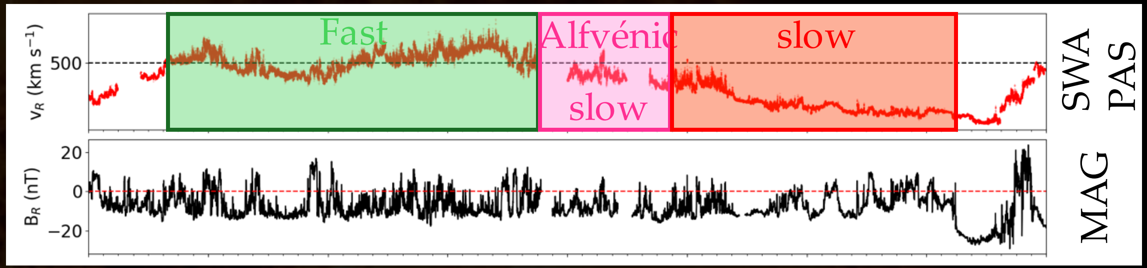
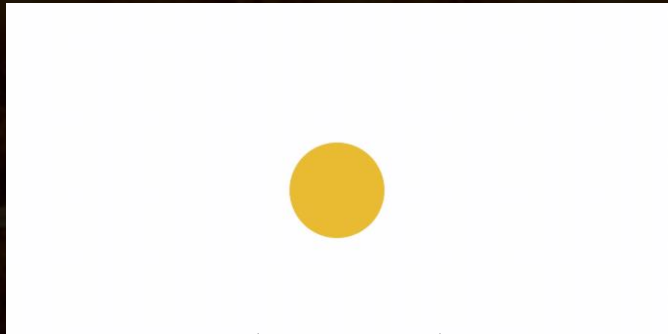




Negative B_R consistent with sources


Credit: Ronan Laker

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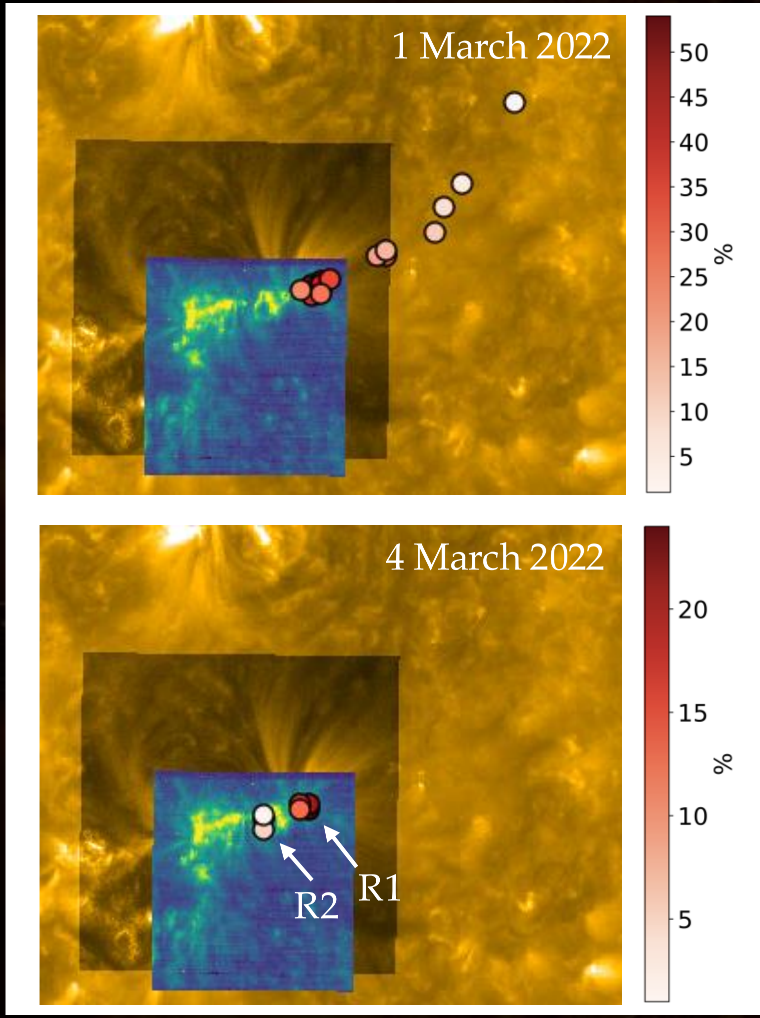

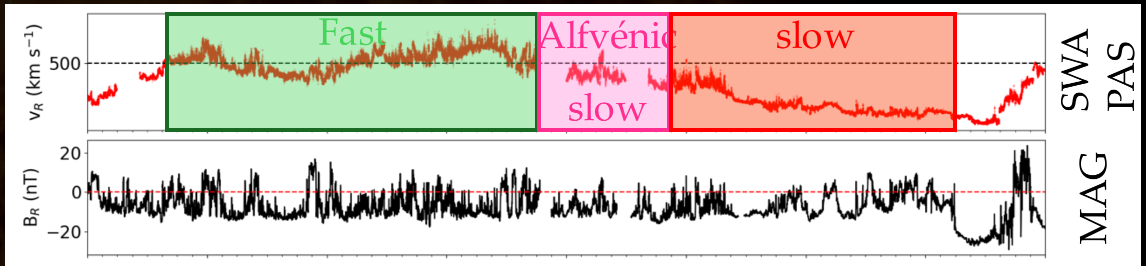

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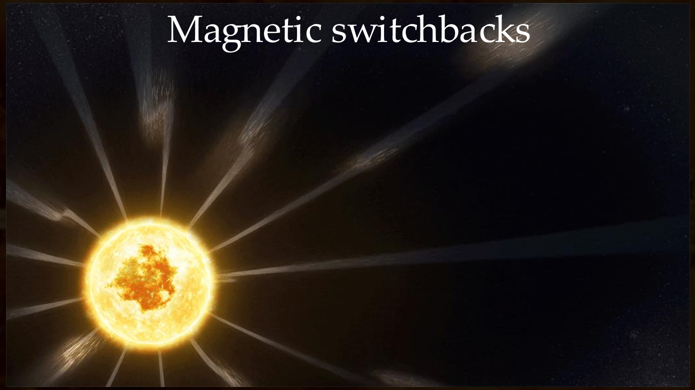

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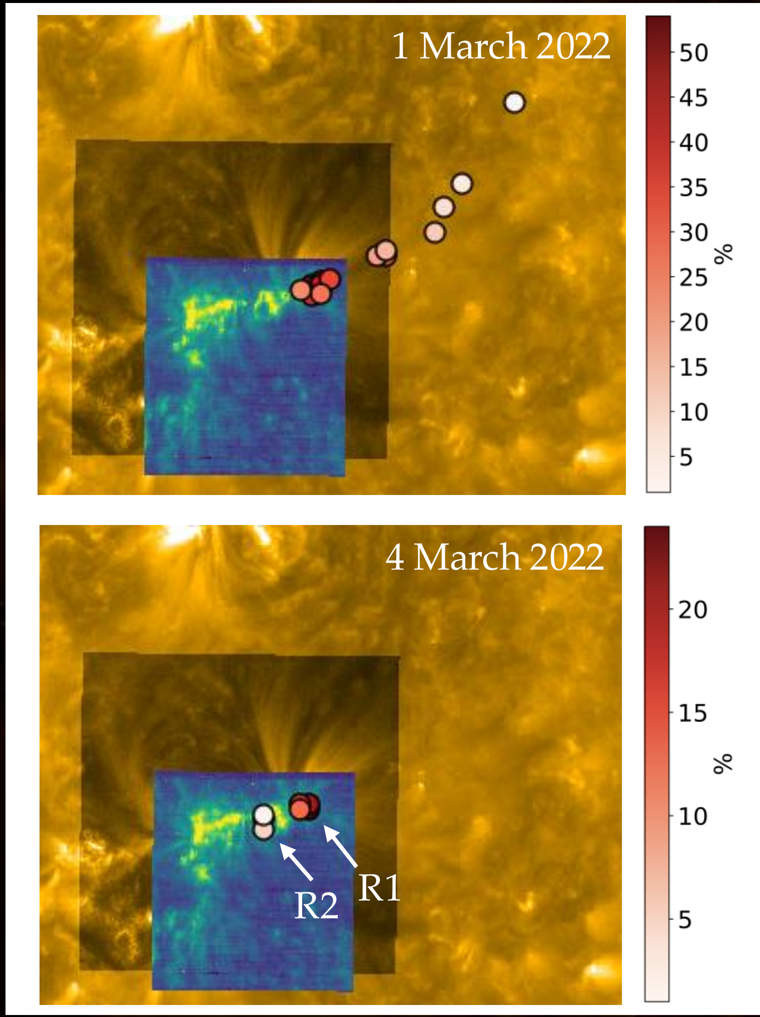
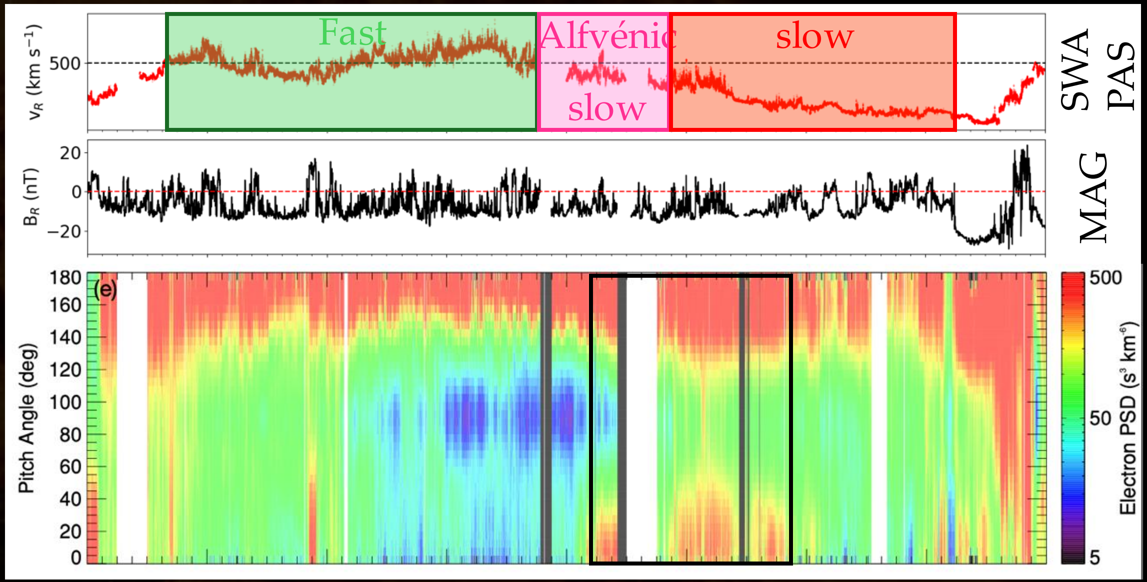
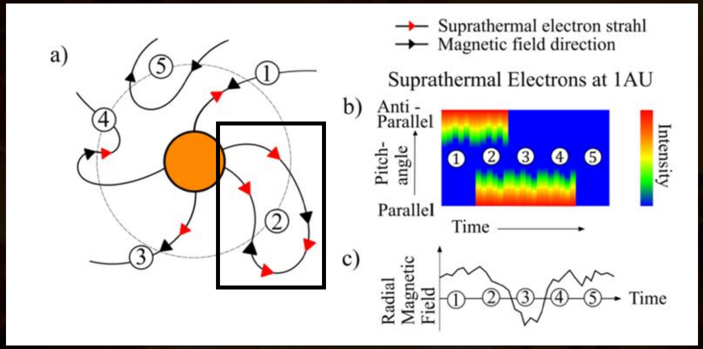




Outward & anti-parallel, with bi-directional streams



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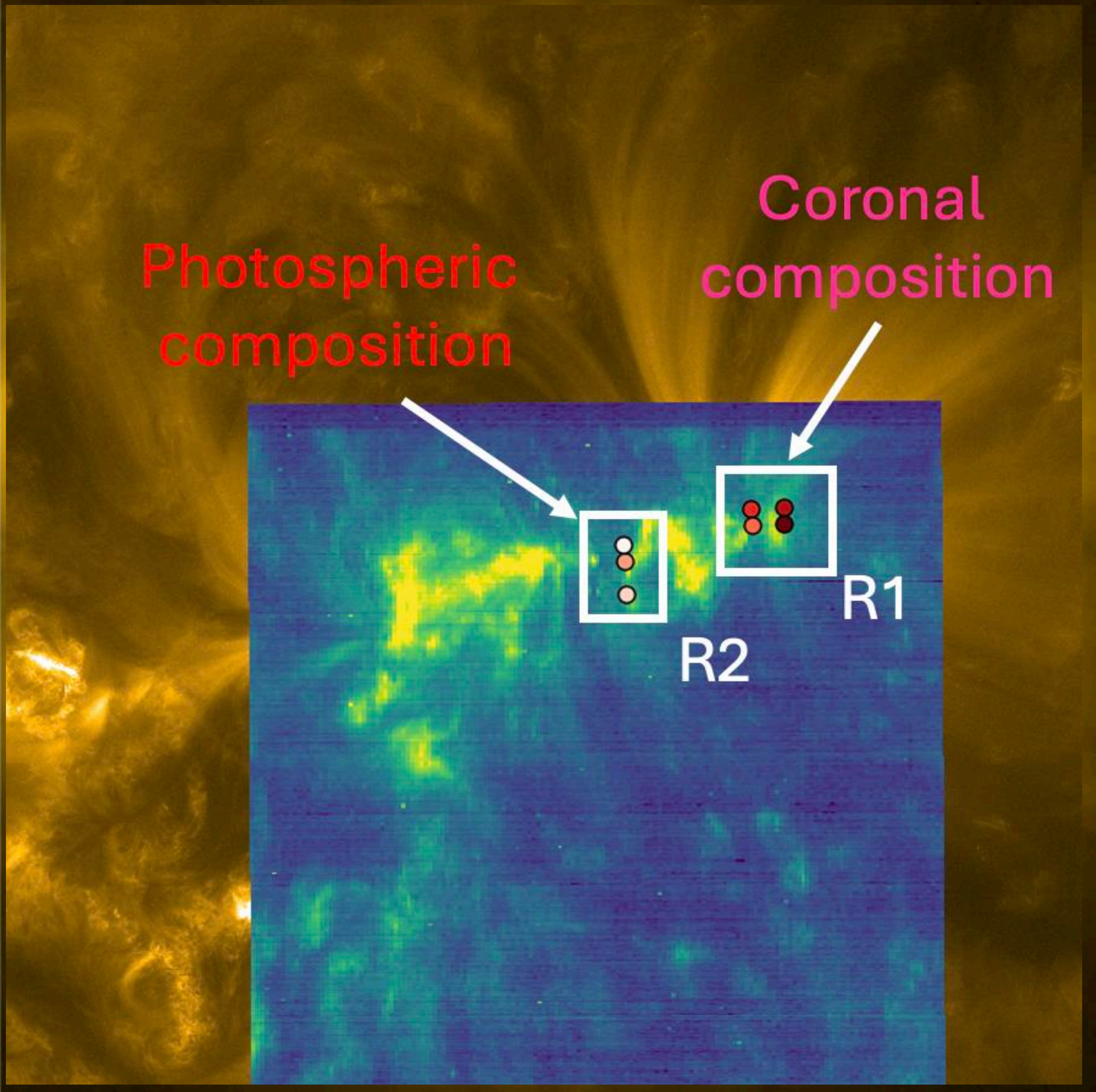

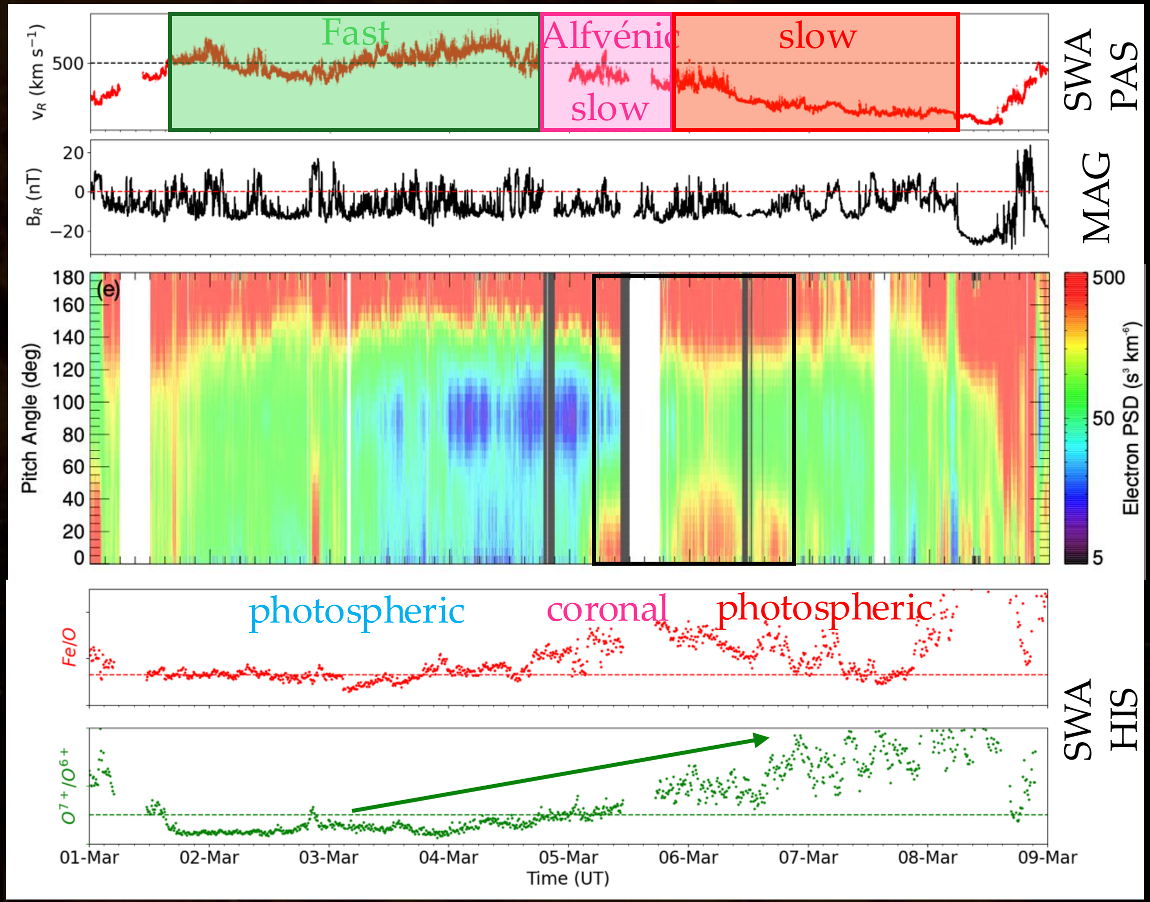

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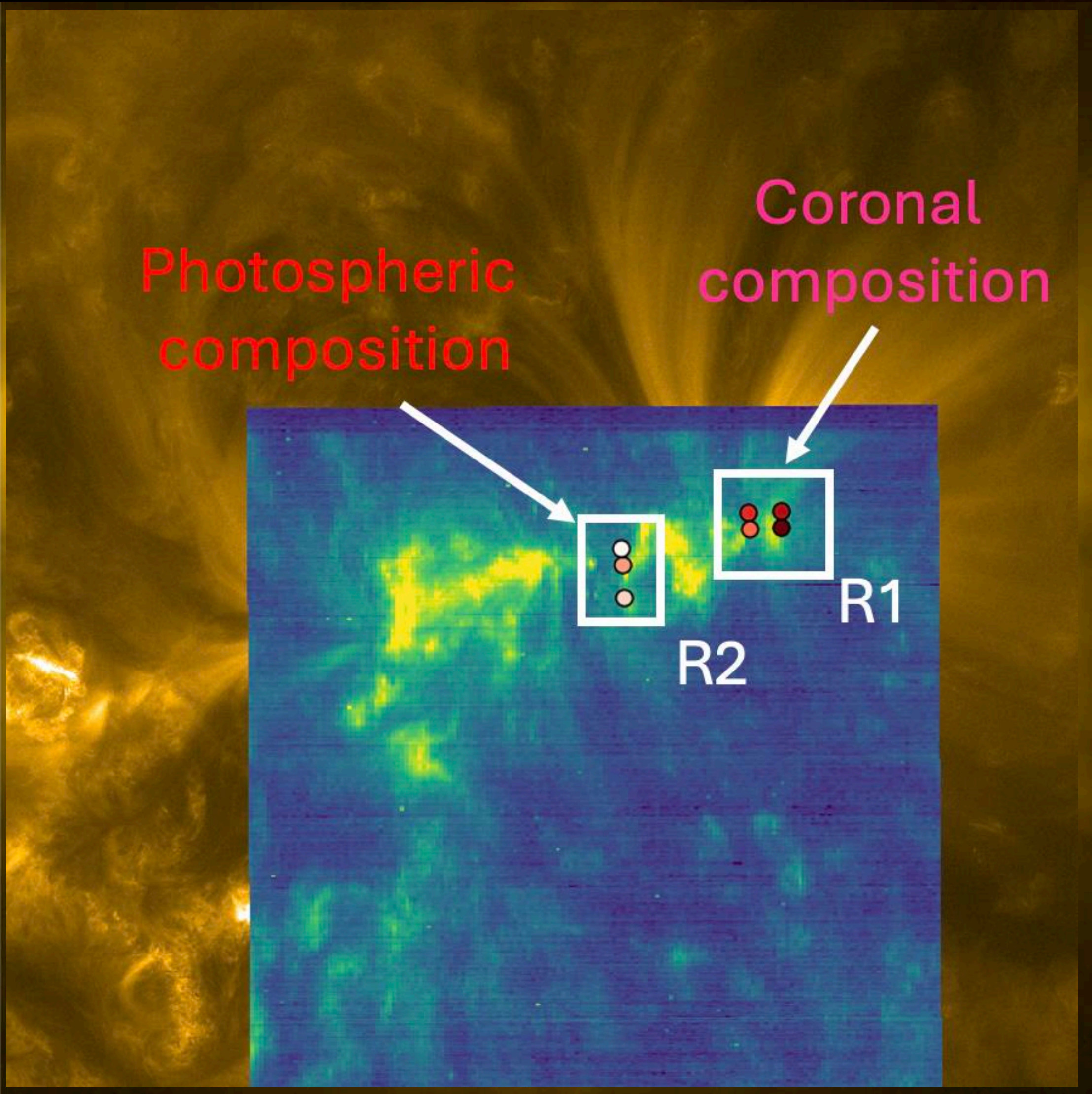

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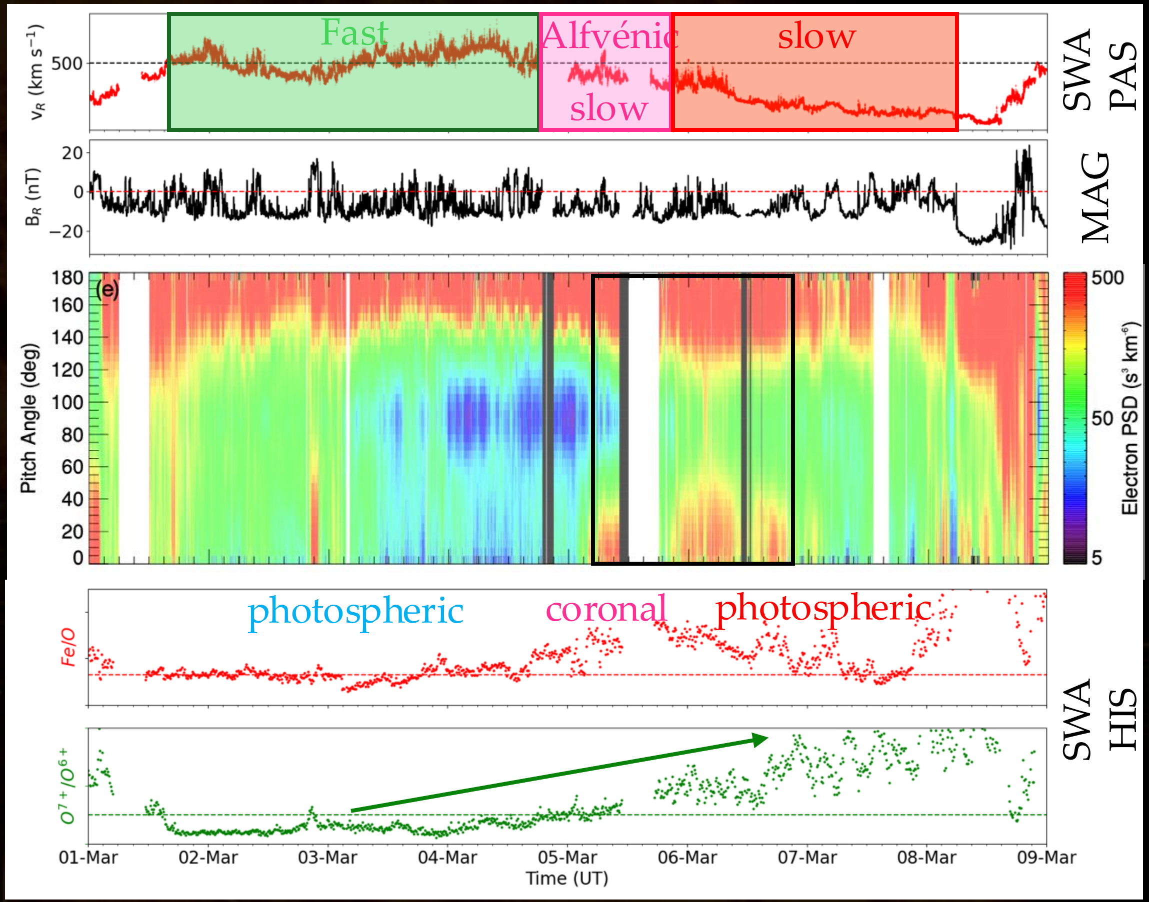
Solar wind travel time ~ 2-3 days



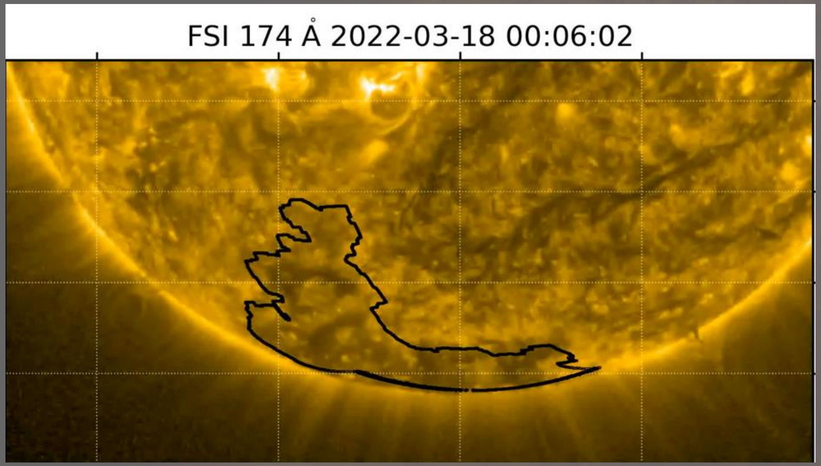
Small-scale variability is driven by the changing connectivity across multiple sources, where the topology also changes due to interchange reconnection at closed-open field boundaries

Yardley, Brooks, D'Amicis, Owen, Long, Baker, Démoulin, Owens, Lockwood+2024, Nat. Astr.

High-Resolution Observations from other RSWs

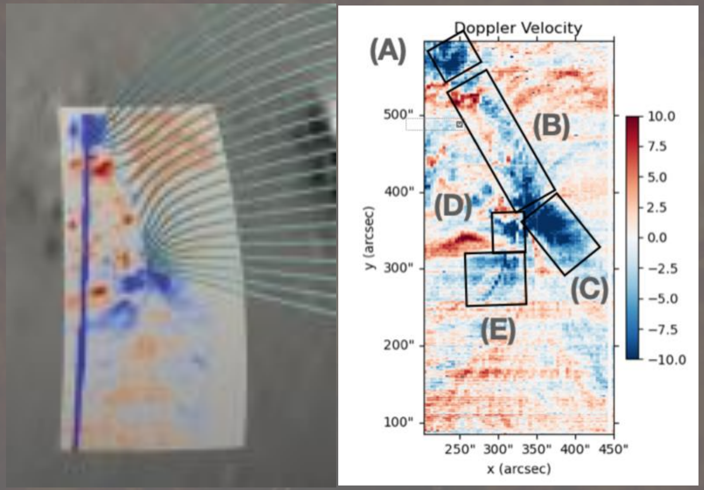
RSW2: 17-22 March 2022, RSW7: 30 March - 4 April 2023, RSW9: 21 – 24 April 2023

Merging of a CD & polar CH



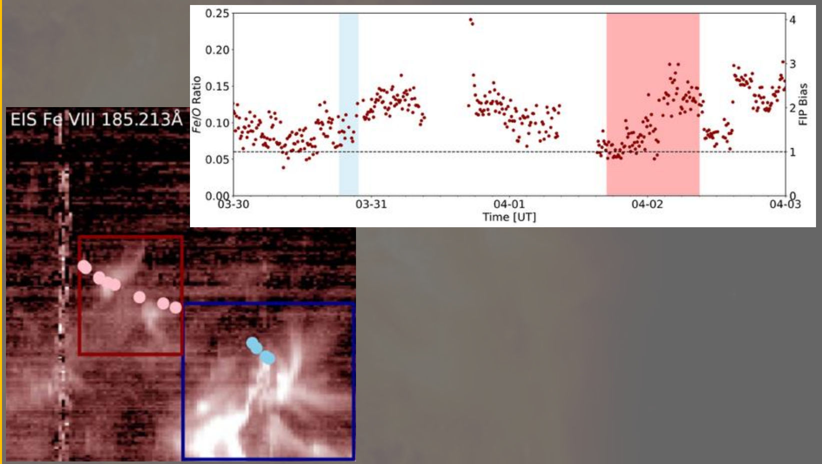
Component reconnection primary driver
Similar upflow profiles after merging
Jets inside CD similar to CH
(Ngampoopun+2023, ApJ, 950, 2, 150)

Observational Evidence of S-Web



Super-radial expansion of narrow corridor
Interchange reconnection provides at corridor boundaries allows plasma to escape
(Baker+2023, ApJ, 950, 1, 65)

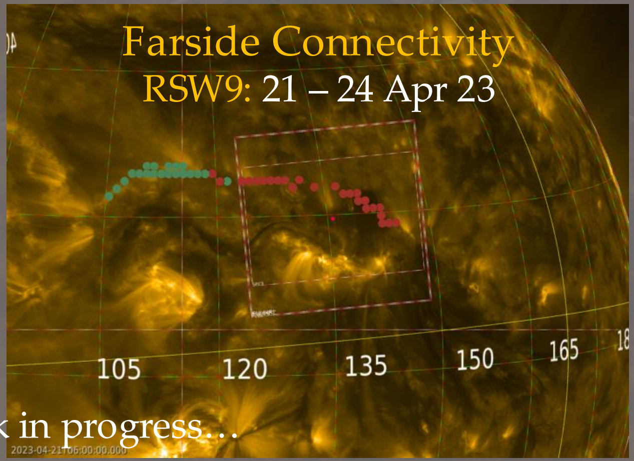
SPICE/EIS abundance diagnostic



Fe/Ne FIP bias diagnostic from combined SPICE/EIS data
Diagnostic useful for Solar-C/EUVST
(Brooks+2024, 976, 2, 188, ApJ)

Farside Connectivity

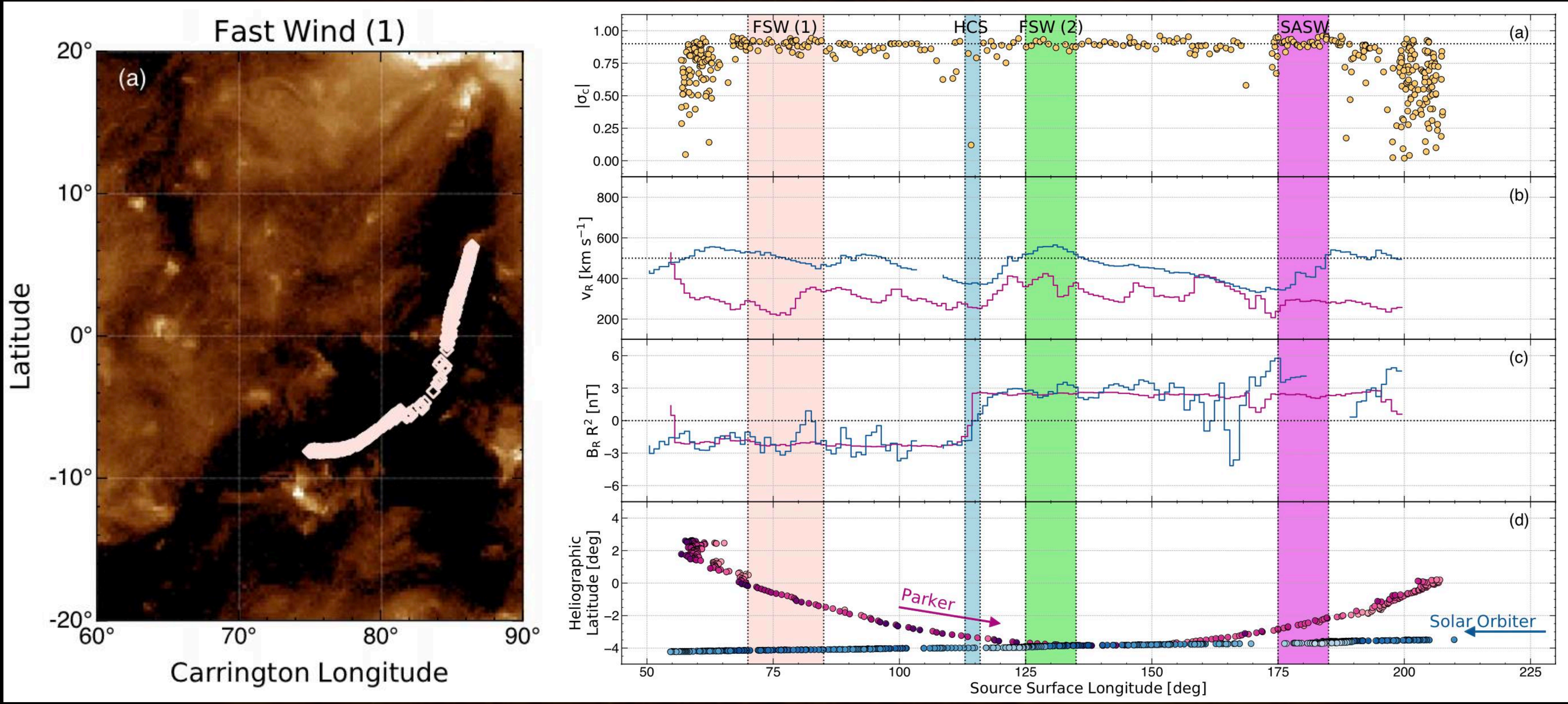
RSW9: 21 – 24 Apr 23



Work in progress…

Solar Orbiter and Parker Solar Probe Conjunction during PSP Encounter 11

Composition and variability of fast and slow Alfvénic solar wind from CHs



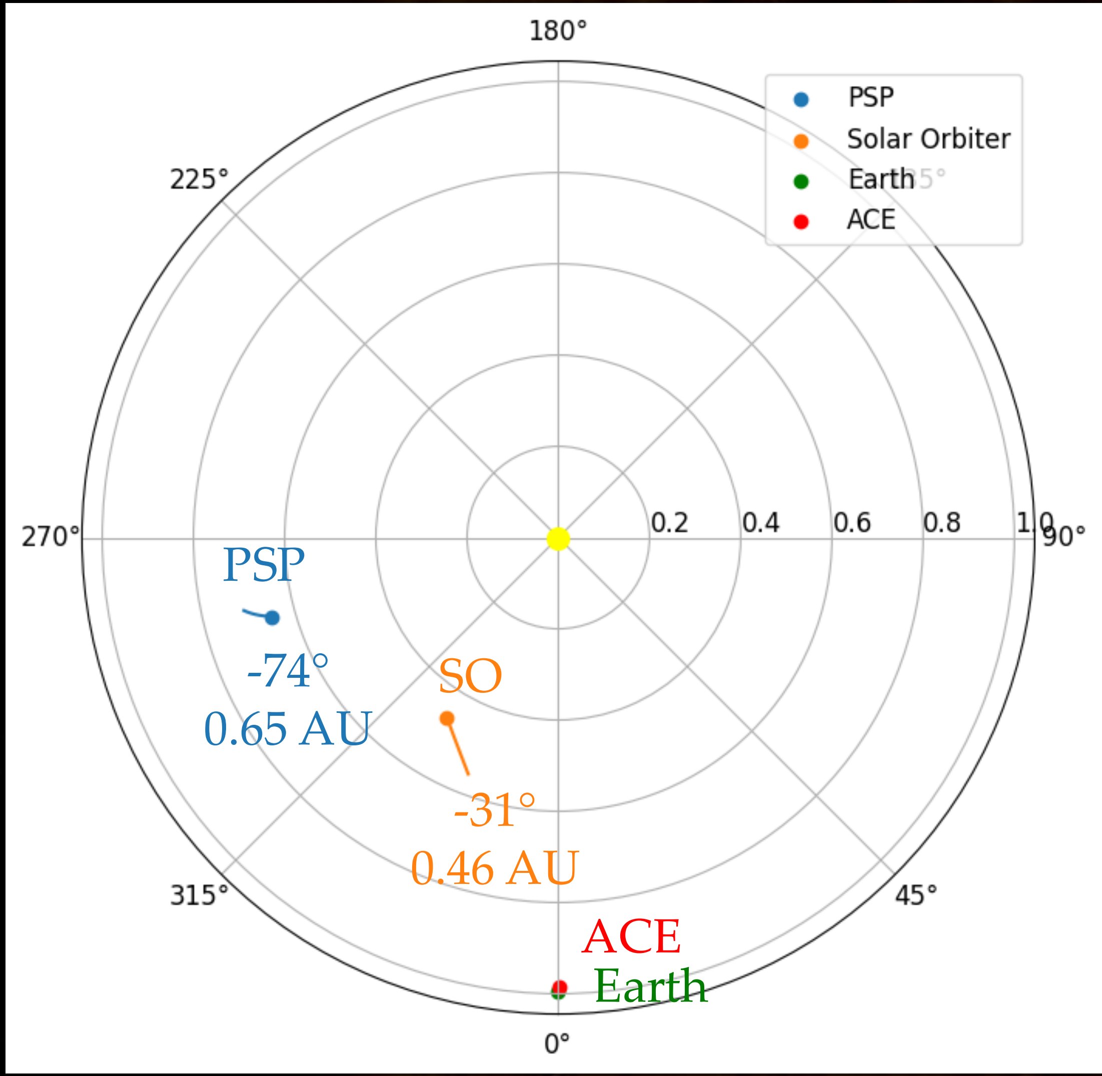
Future multi-spacecraft conjunctions to determine the effects of radial propagation

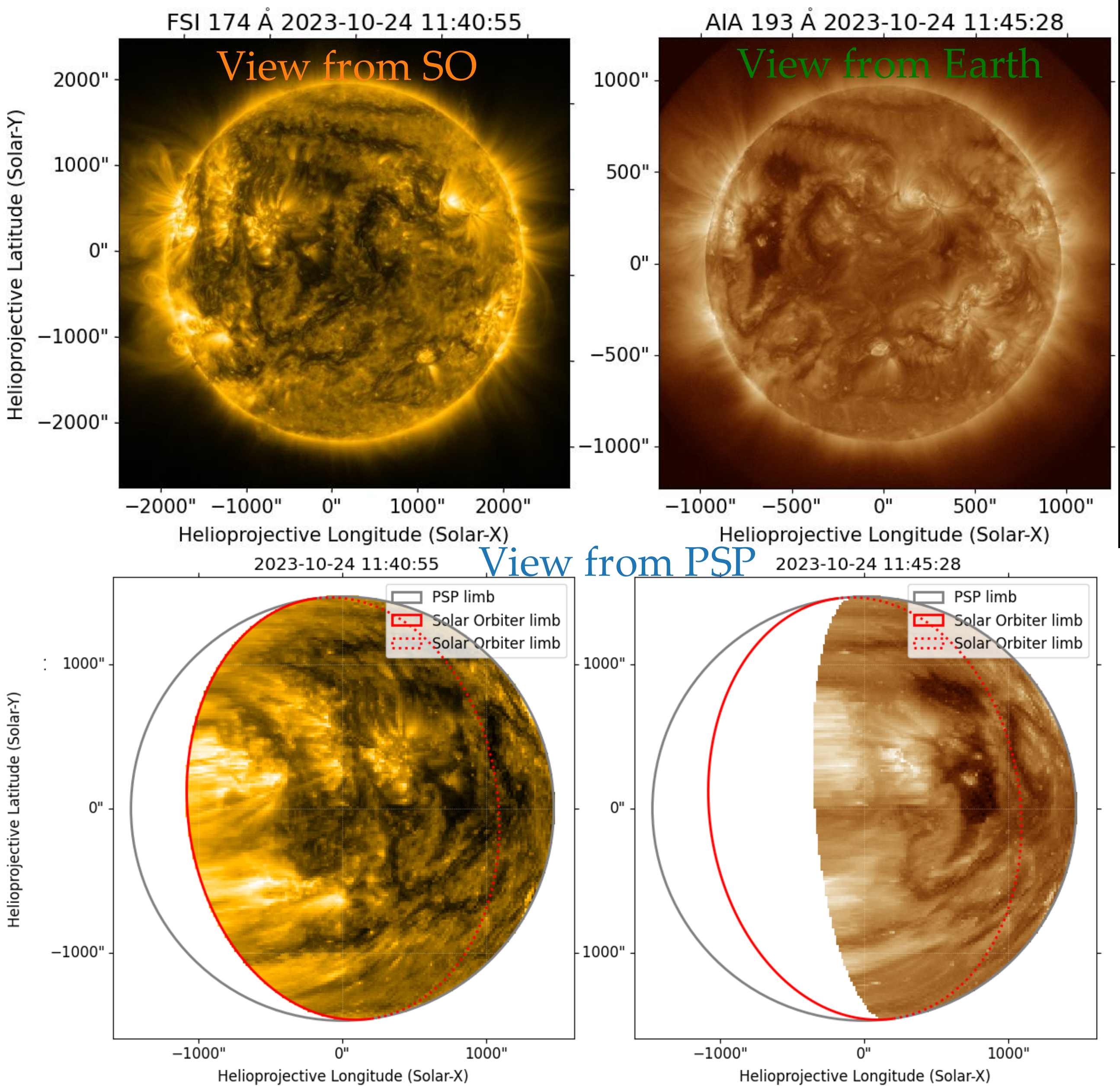
Ervin+2024

Fast Wind SOOP Observations

L_SMALL_HRES_HCAD_Fast-Wind

RSW12: 24th-26th October 2023 (0.46 – 0.50 AU)





SOOP Coordinators: A. James, L. Franci, E. Buchlin, S. Mzerguat

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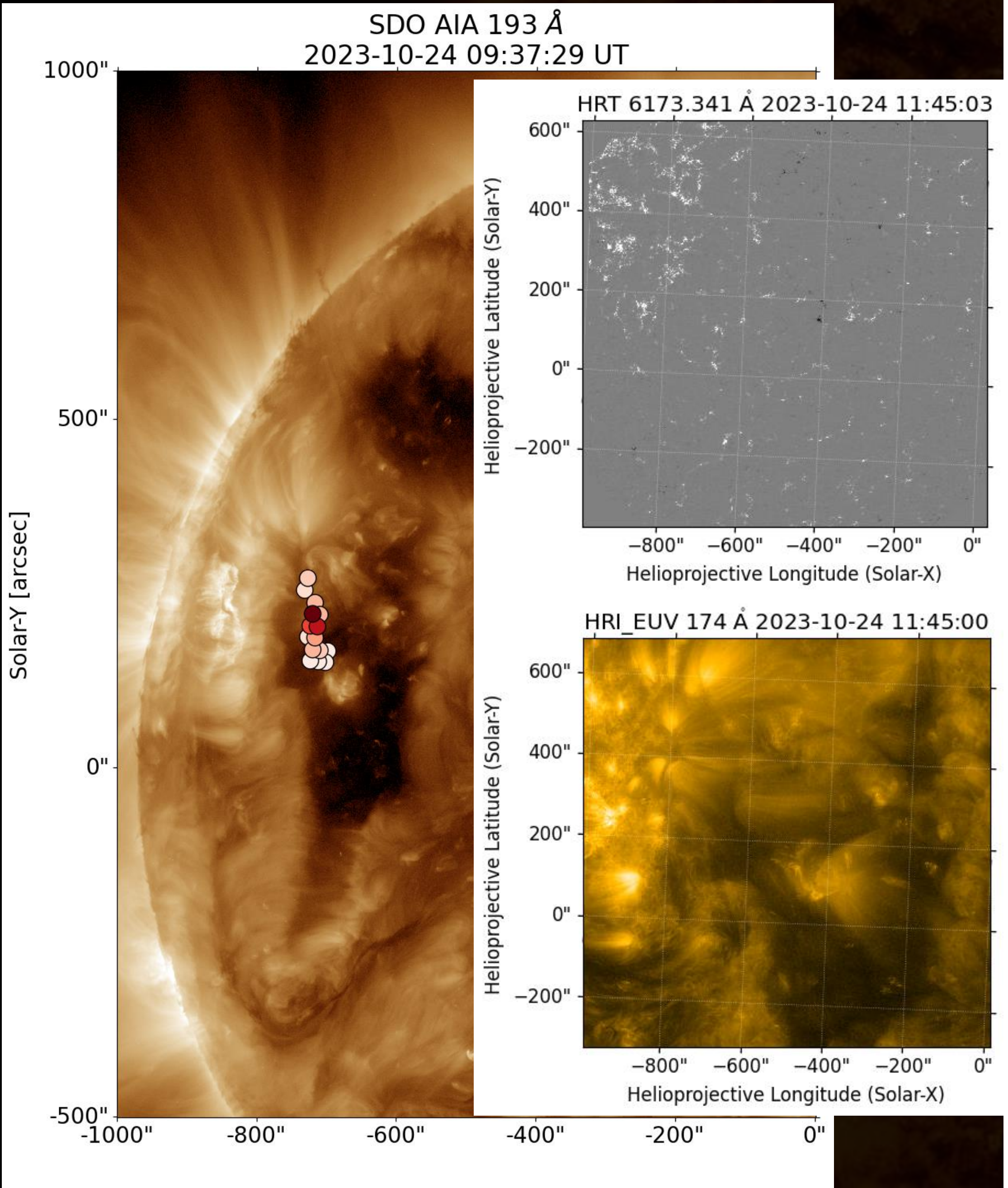

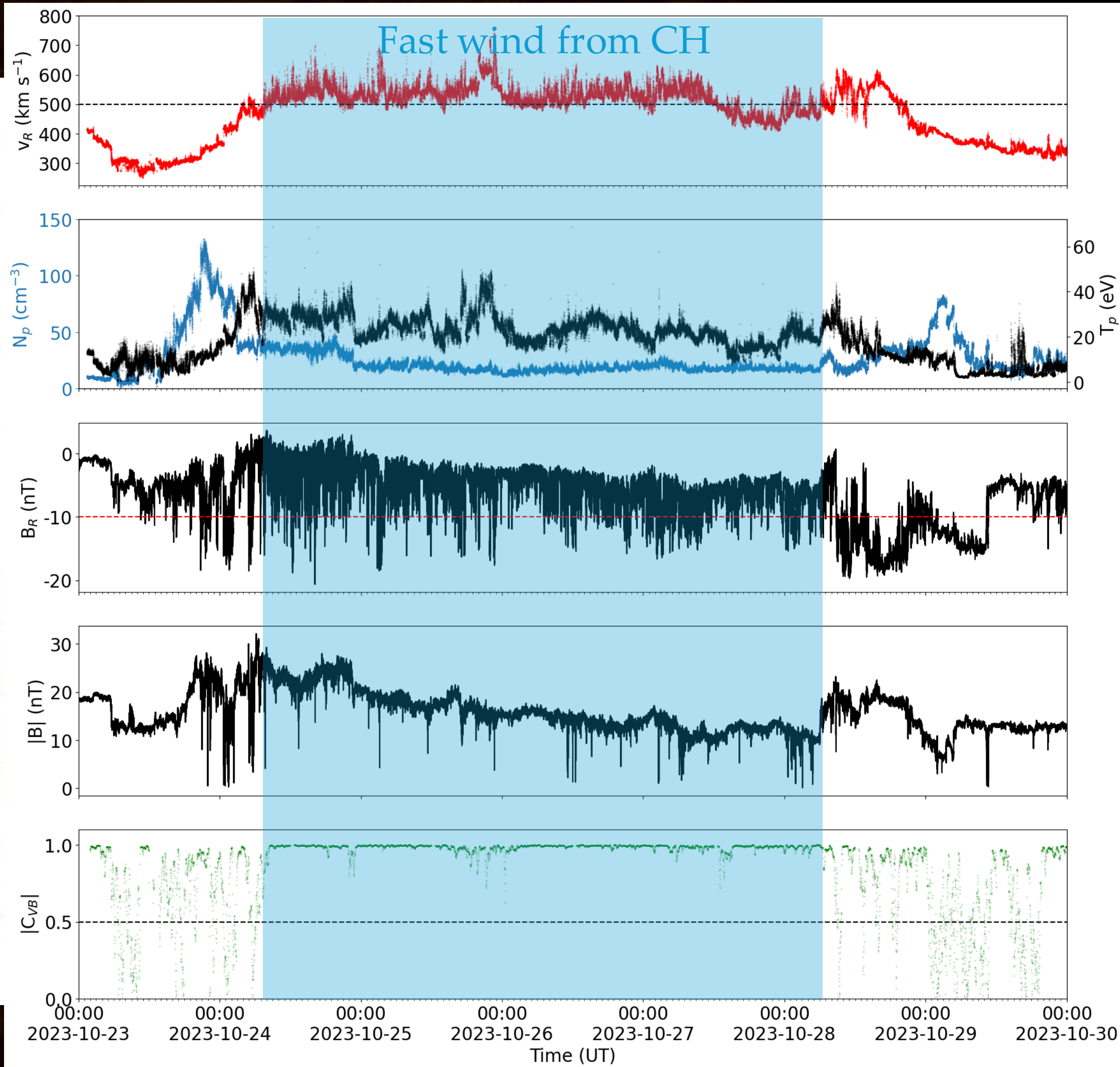

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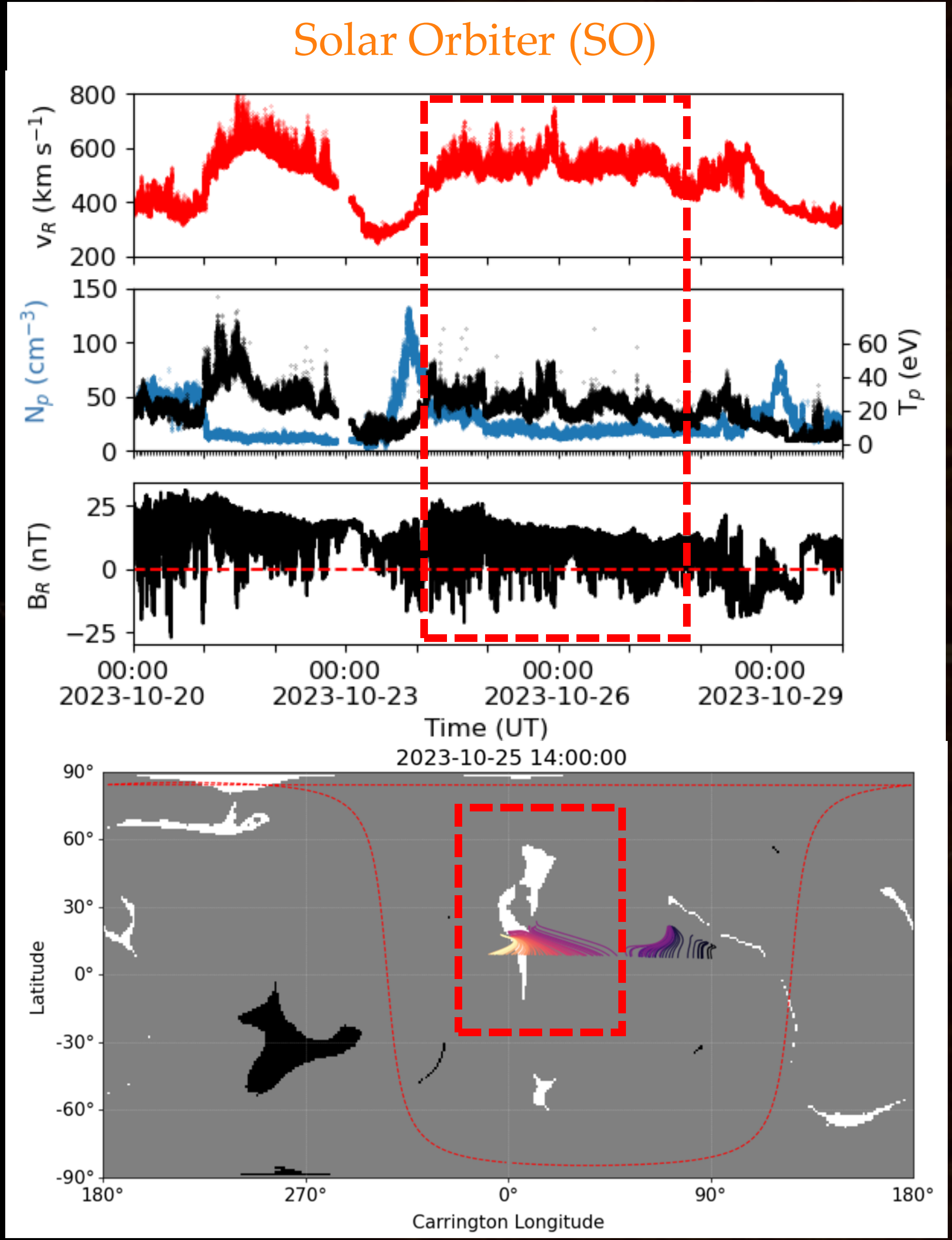
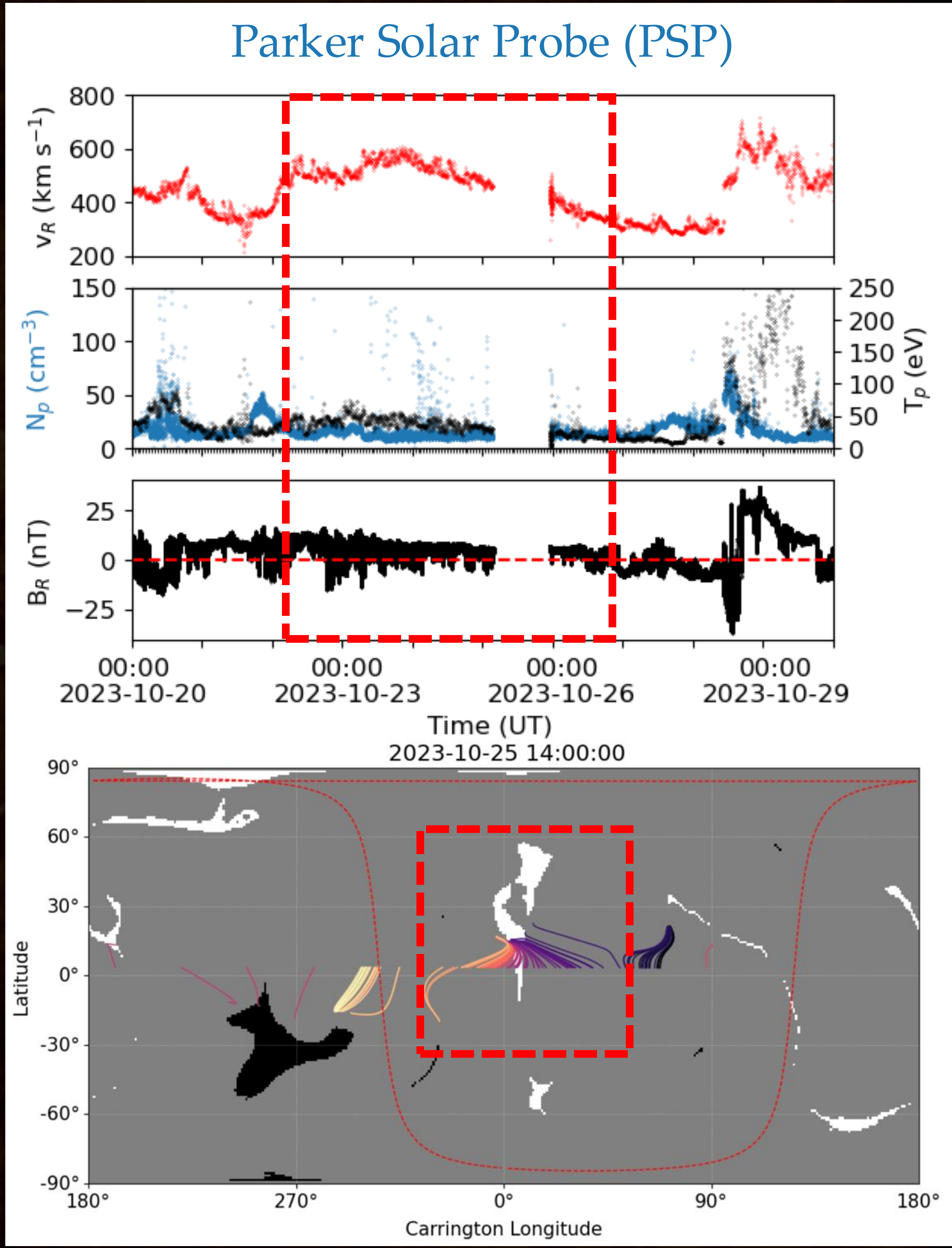


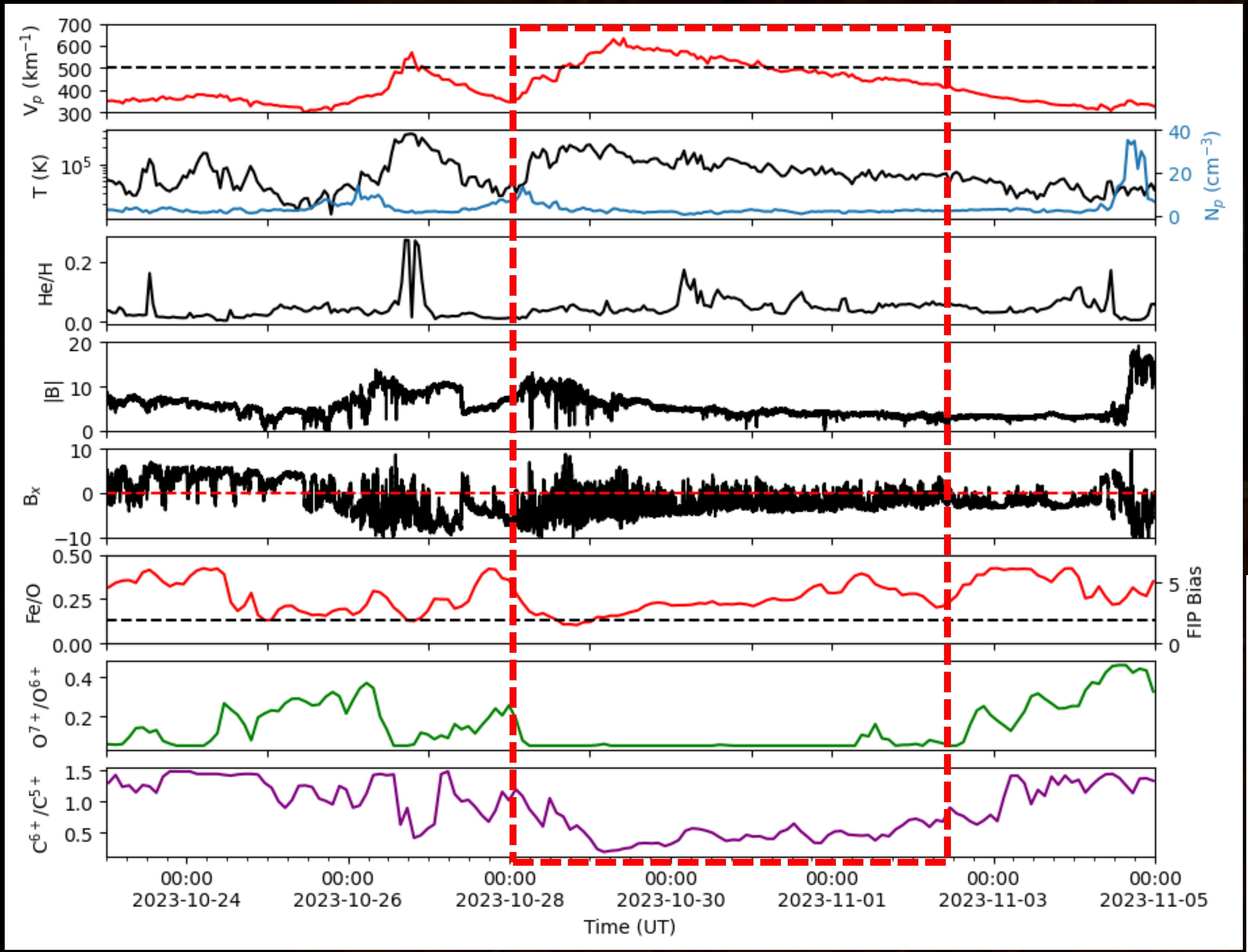


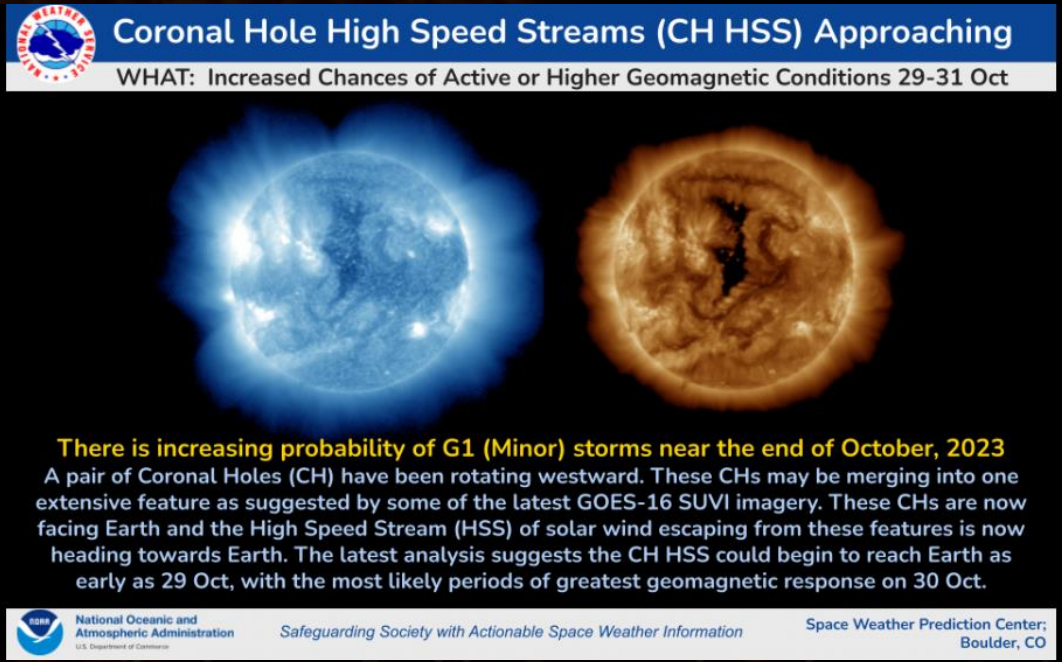
Fast wind stream arrival

PSP:
22nd Oct 23
SO:
24th Oct 23

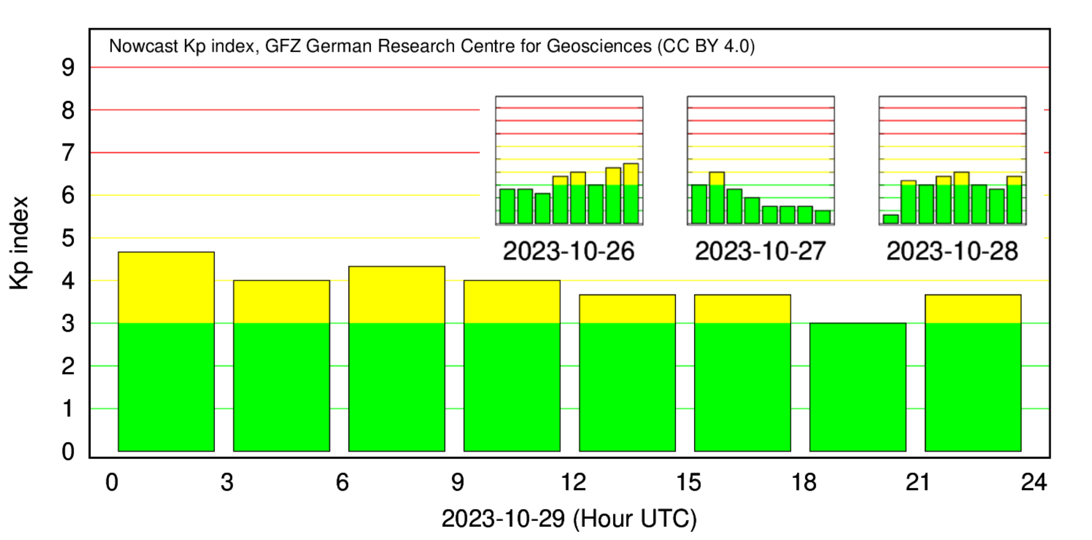
Fast Wind SOOP Observations

Arrival at ACE on 28th Oct 23





G1 (Minor) Storm Watch was issued for 29-31 Oct due to high-speed streams from the CH



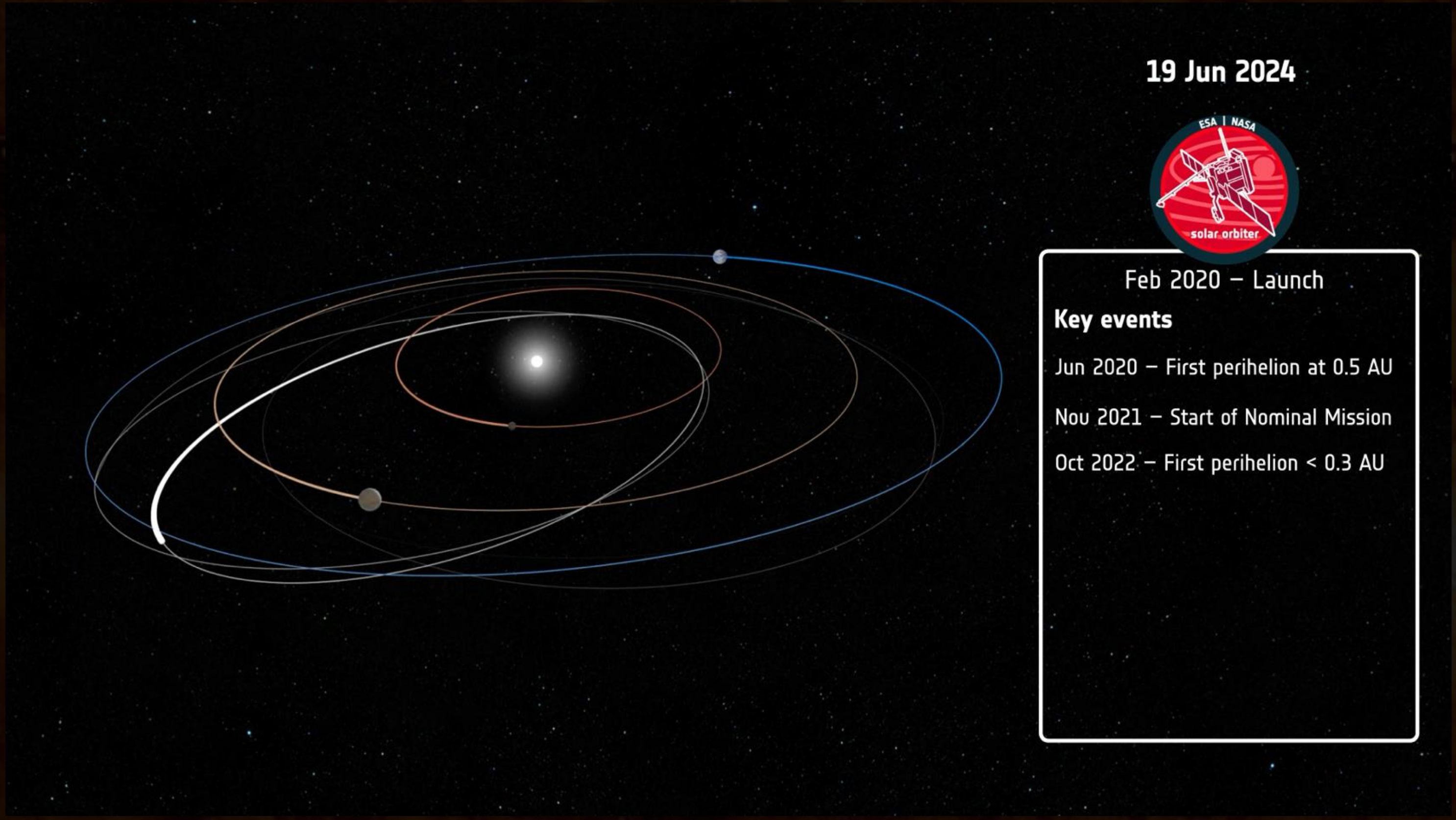
Summary

Importance of multi-spacecraft multi-viewpoint observations in the inner heliosphere for variability of multi-source solar wind

Ongoing analysis of joint observations during SO & PSP alignments

SO to observe the poles (>17° in Mar 2025)

Final 3 PSP Encounters from Dec 2204



SO & PSP Data Analysis Practical

https://bit.ly/3UQEksj