Tracing the magnetic connectivity from the Sun into the heliosphere: a multi-messenger approach

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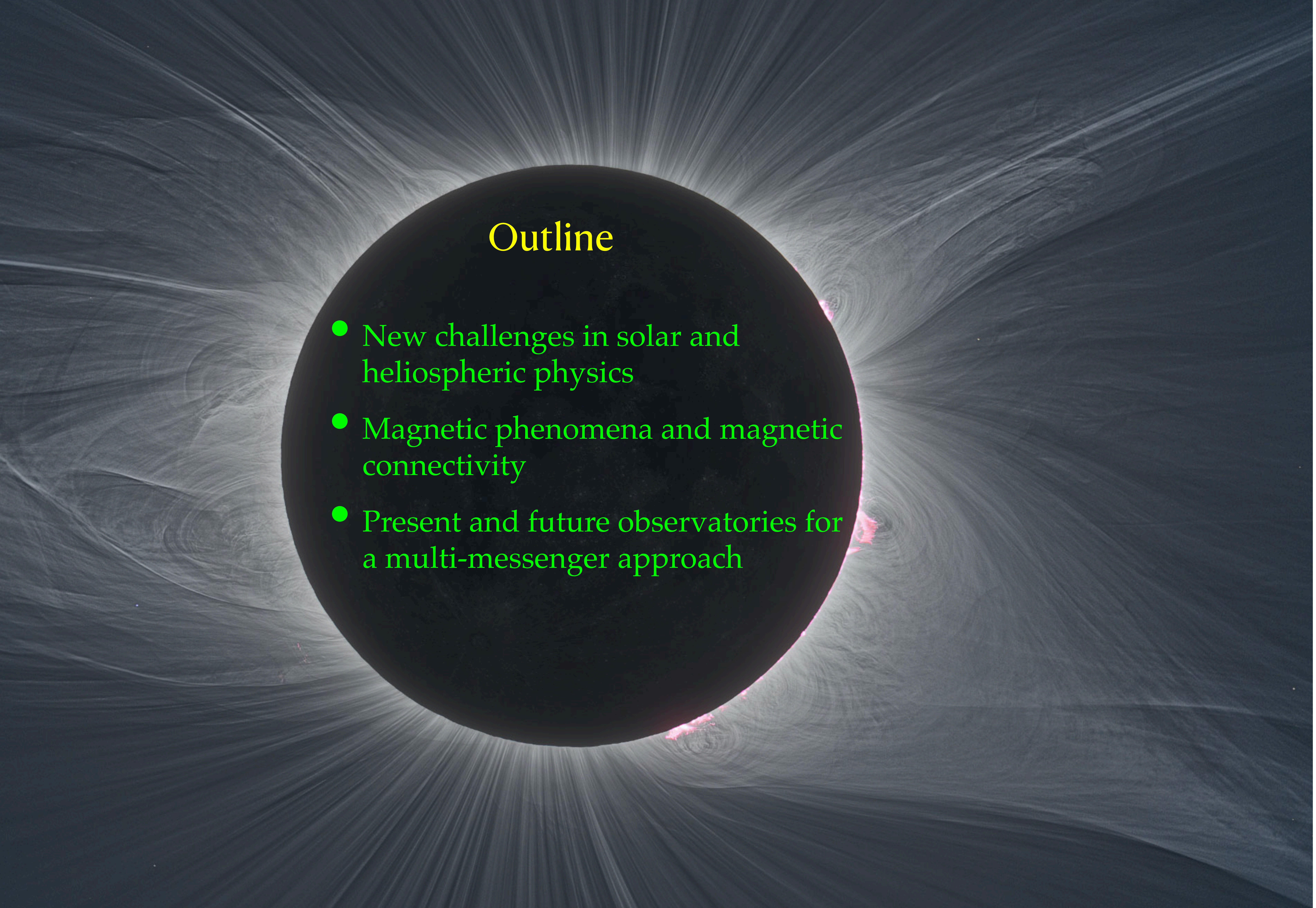


Outline

- New challenges in solar and heliospheric physics
- Magnetic phenomena and magnetic connectivity
- Present and future observatories for a multi-messenger approach

Solar corona during the Great American Eclipse, August 21, 2017

(nearing solar minimum)

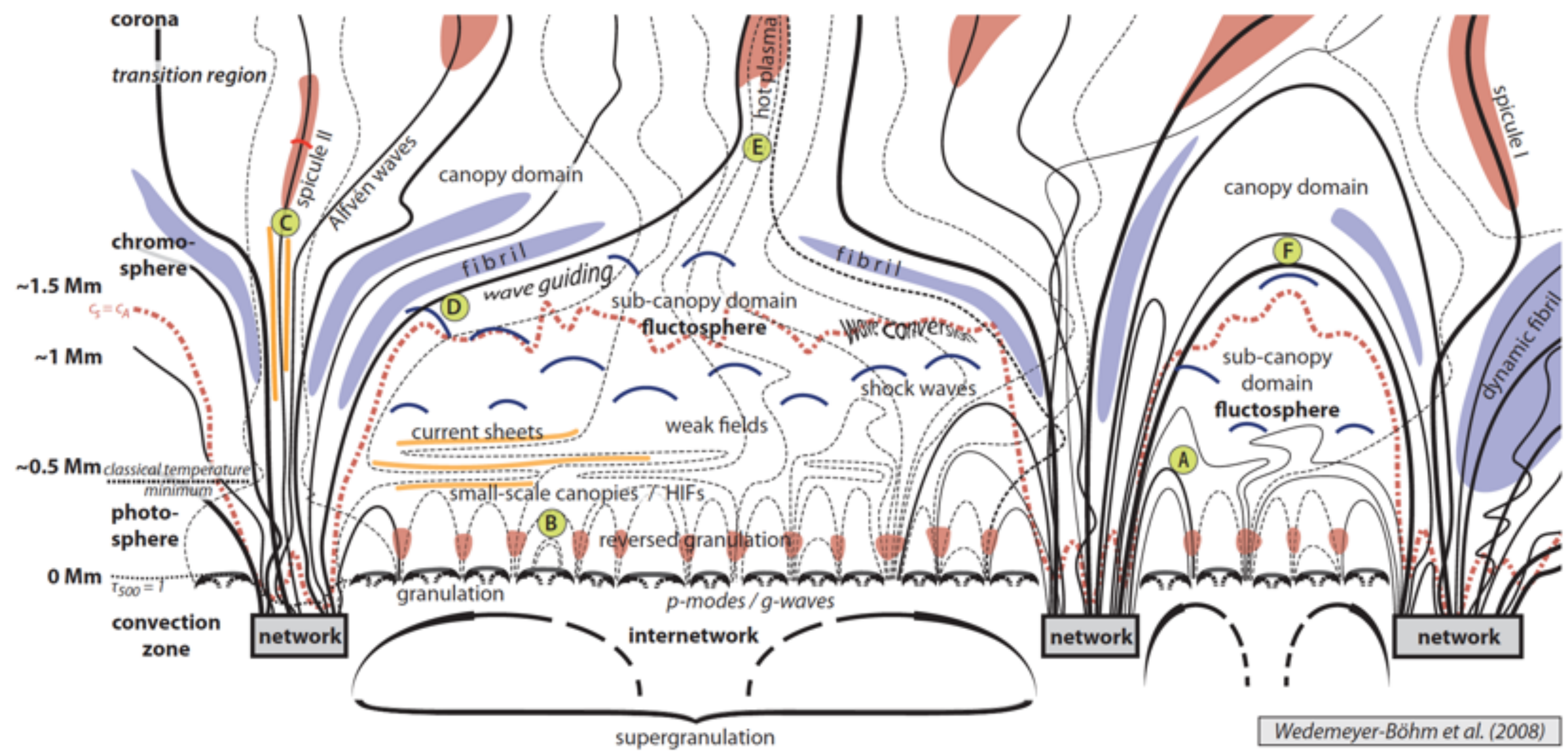
Open problems and new challenges - 1

- Coronal heating
- Solar dynamo
- Flares: what triggers them?
- Coronal Mass Ejections (CMEs): what triggers them?
- What drives the solar wind? What is the origin of slow solar wind?
- Can we understand how magnetic reconnection in the chromosphere, transition region and corona supplies energy and accelerates flows and jets? *
- How do CMEs evolve through the corona and inner heliosphere?
- What are the properties of the magnetic field and solar convection at high solar latitudes? *

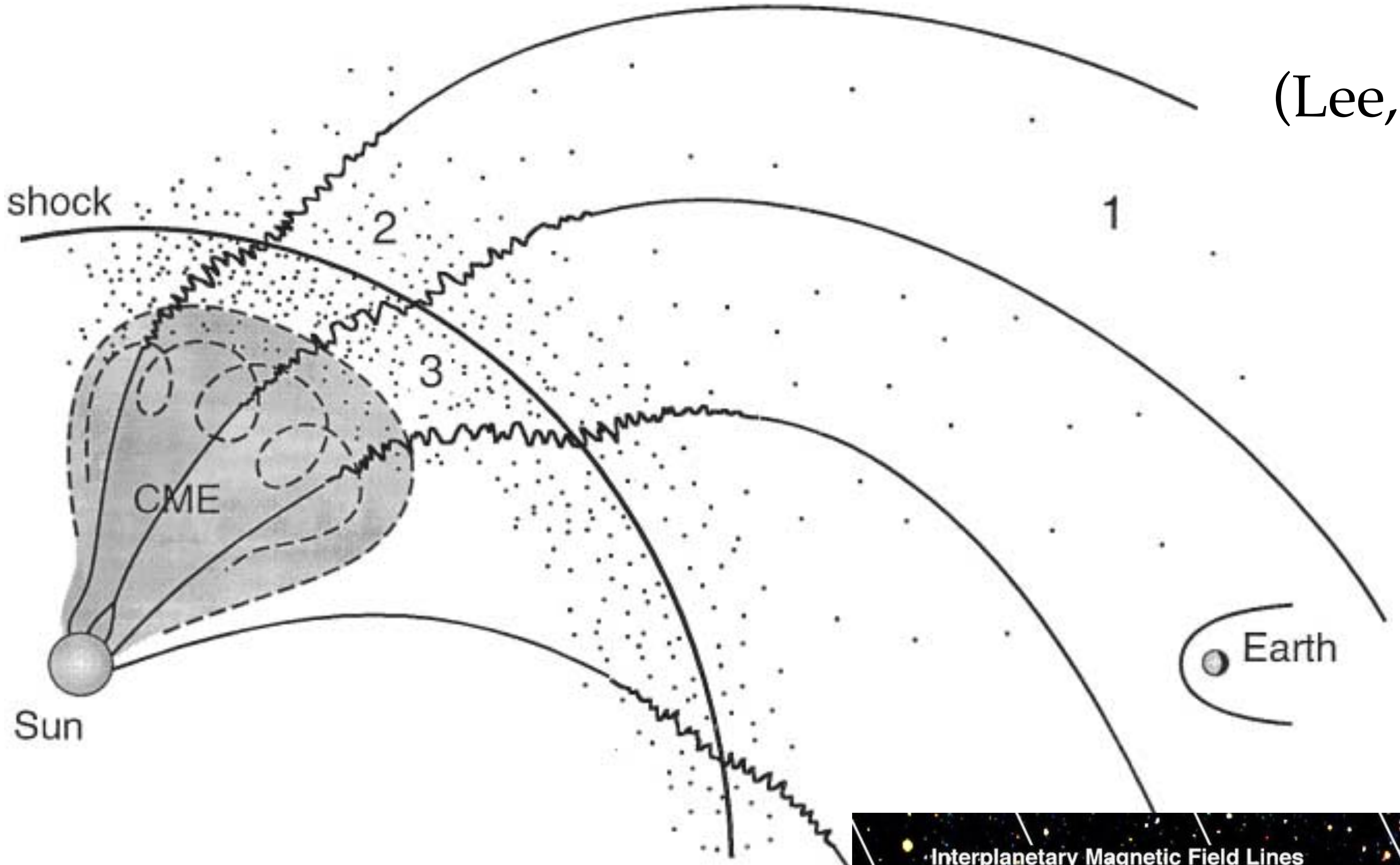
Open problems and new challenges - 2

- How and where do shocks form in the corona?
- Where are shocks most efficient in accelerating particles?
- How do energetic particles propagate parallel and perpendicular to the direction of the heliospheric magnetic field?
- What is the exact influence of magnetic turbulence on particle propagation and plasma heating?
- How much are waves and turbulence amplified around shocks, and how is this influencing particle acceleration?
- What are the conditions in the solar wind which cause the strongest geomagnetic storms?

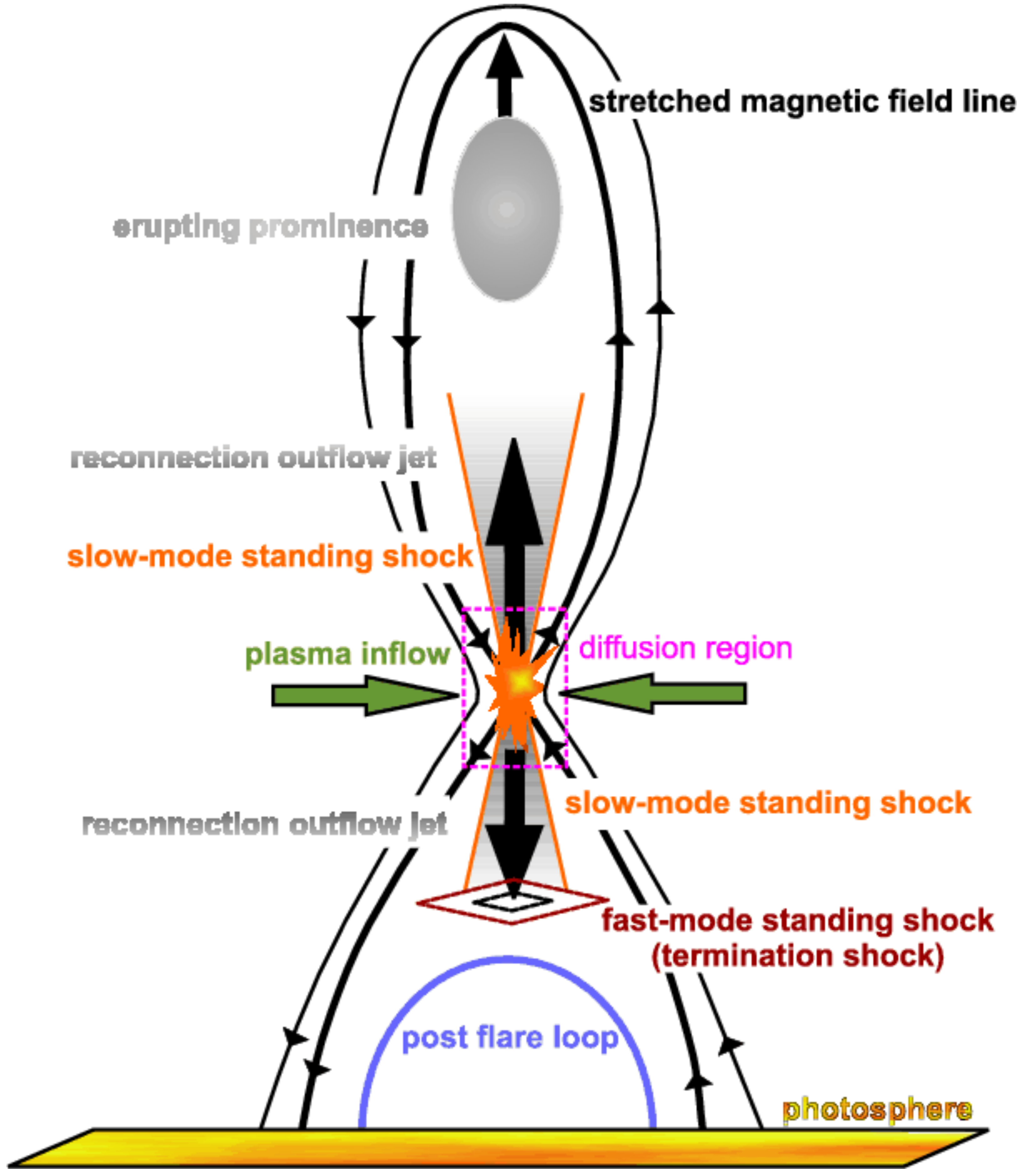
The magnetic field shapes most of plasma structures and controls energy exchange phenomena



Magnetic connectivity and magnetic reconnection:



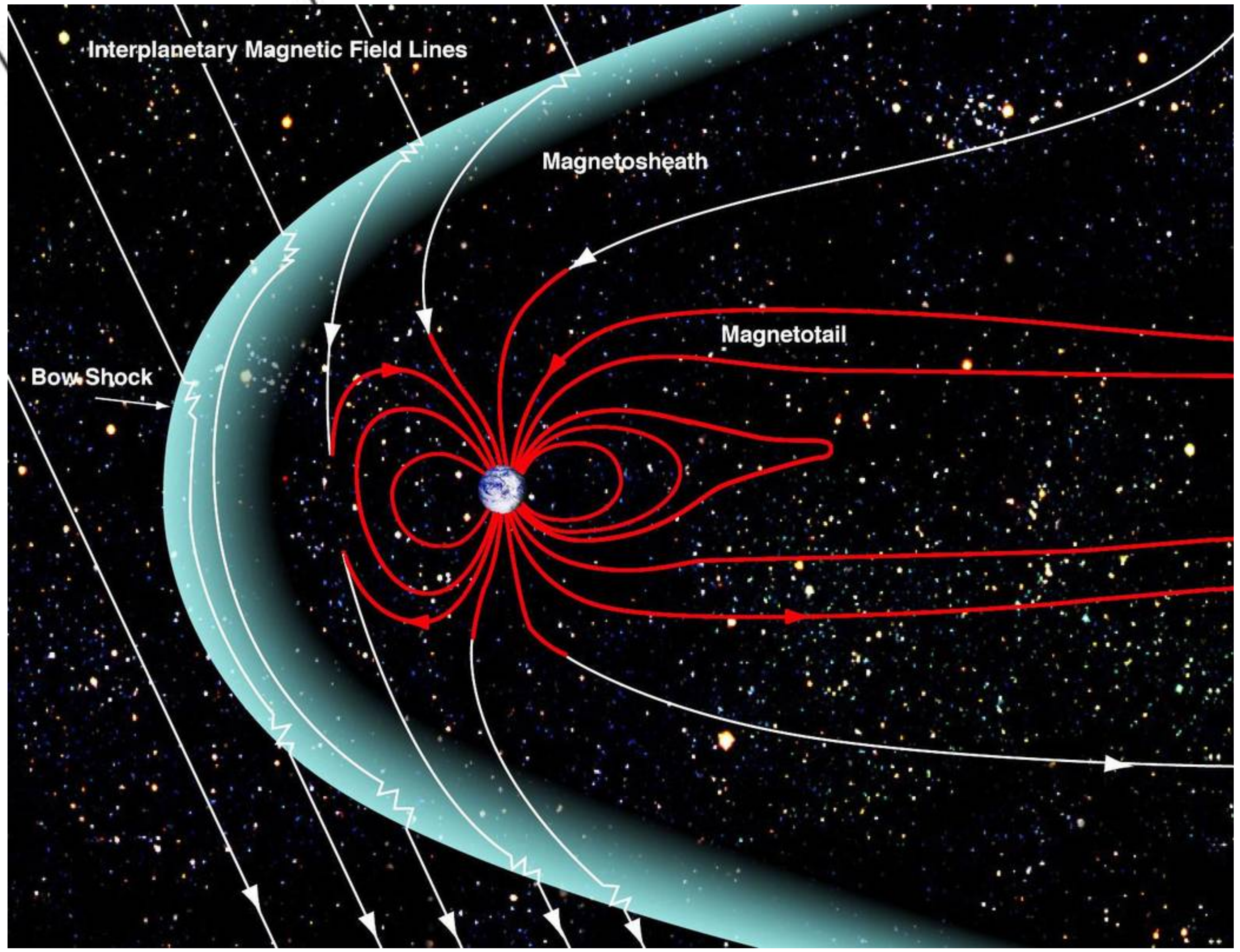
(Lee, 2005)



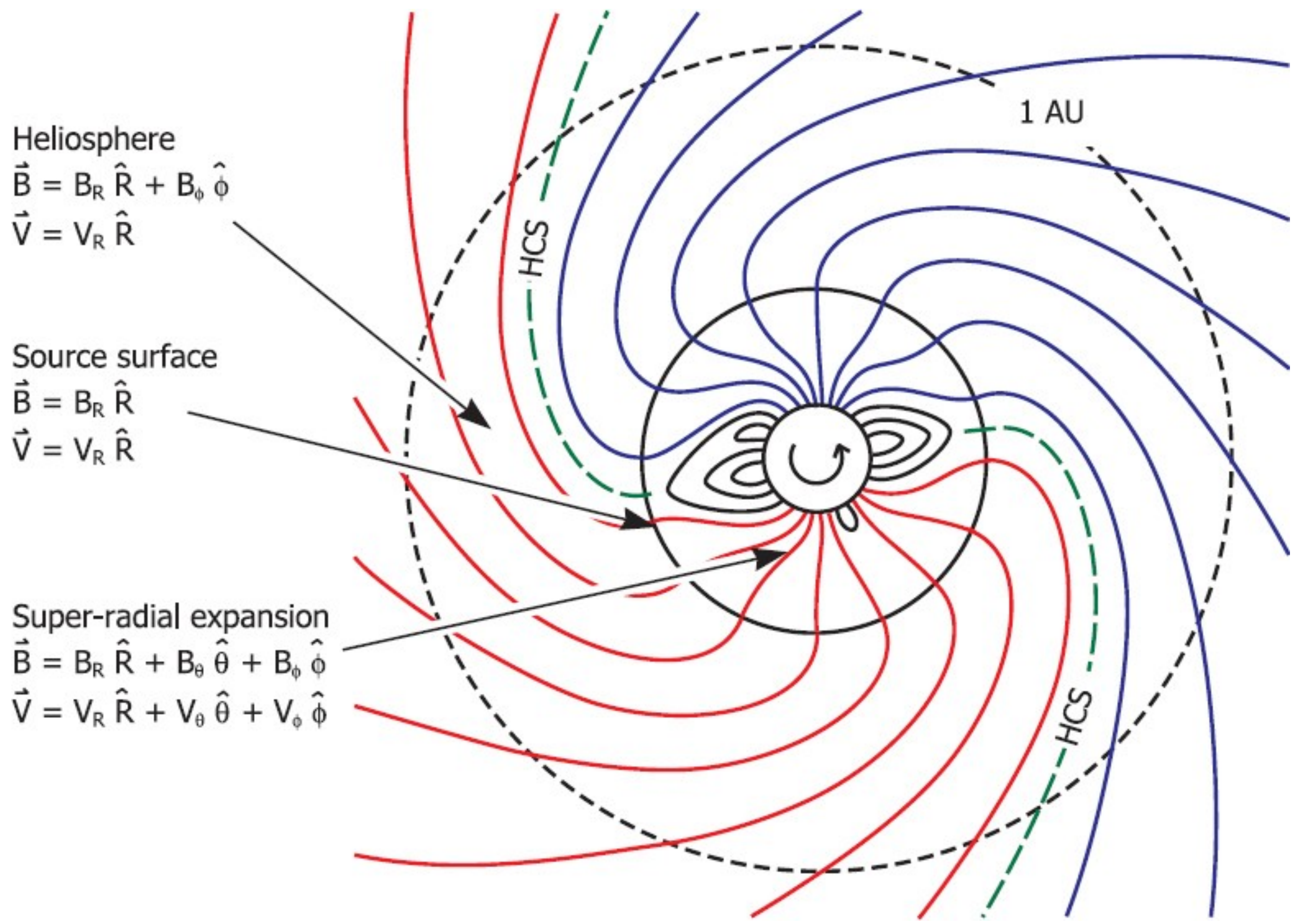
Flare scheme by Mann et al. (2009)

We live in a magnetic universe!

Understanding the magnetic connectivity is essential for energy flows and Space Weather predictions

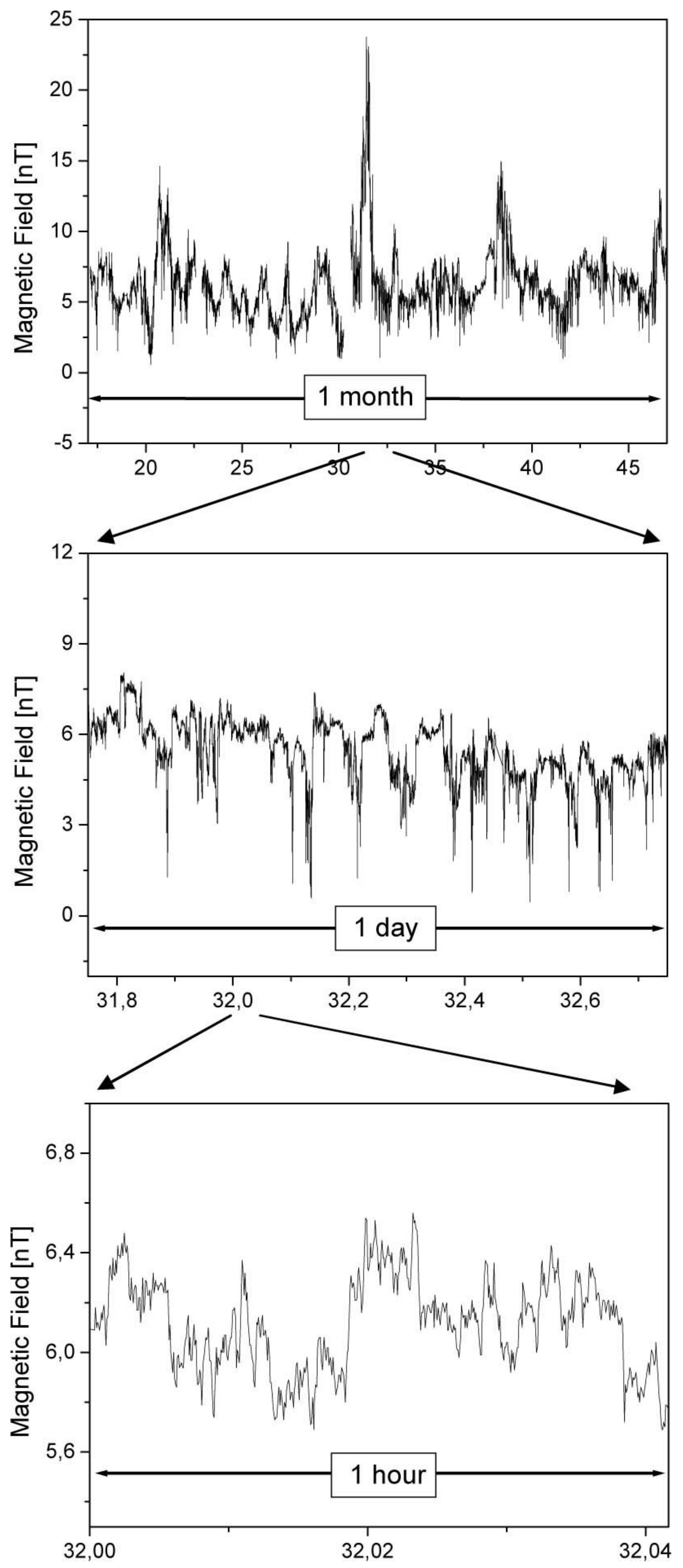


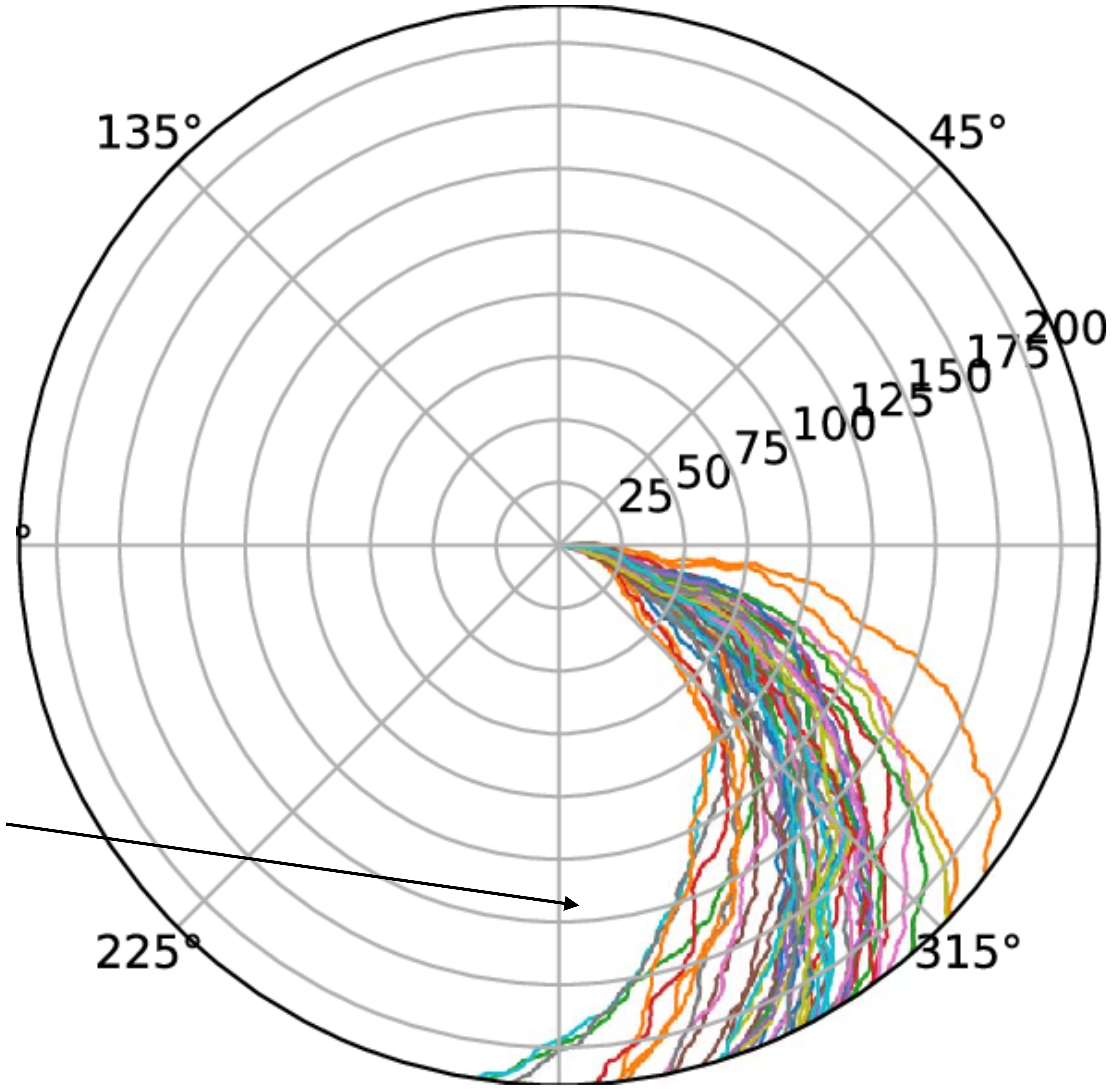
Magnetic turbulence is ubiquitous in astrophysical plasmas, and makes the magnetic connection from the Sun to Earth very complex



Heliospheric magnetic field (Owens and Forsyth, 2013) …

… plus magnetic turbulence (Bruno and Carbone, 2013)





Laitinen et al., ApJ 2023

It is crucial to have in-situ measurements of magnetic field and plasma properties at many heliographic longitudes.

We need to know the magnetic field in all of these environments

Parker Solar Probe is exploring the inner heliosphere, and will reach distances as small as 10 $R_\odot$.

Among PSP discoveries, the magnetic switchbacks of heliospheric magnetic field and the large rotational velocity at small radial distances:

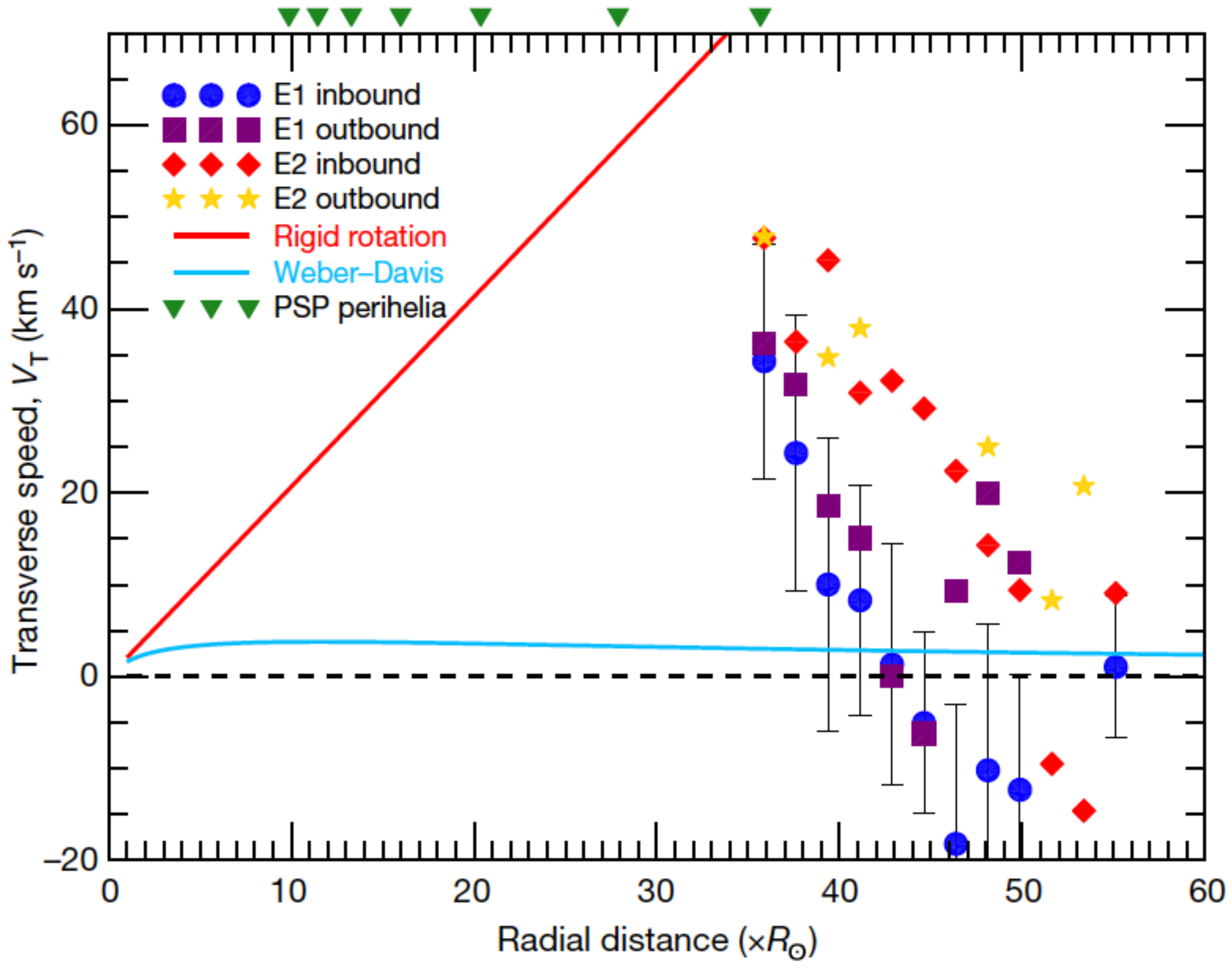
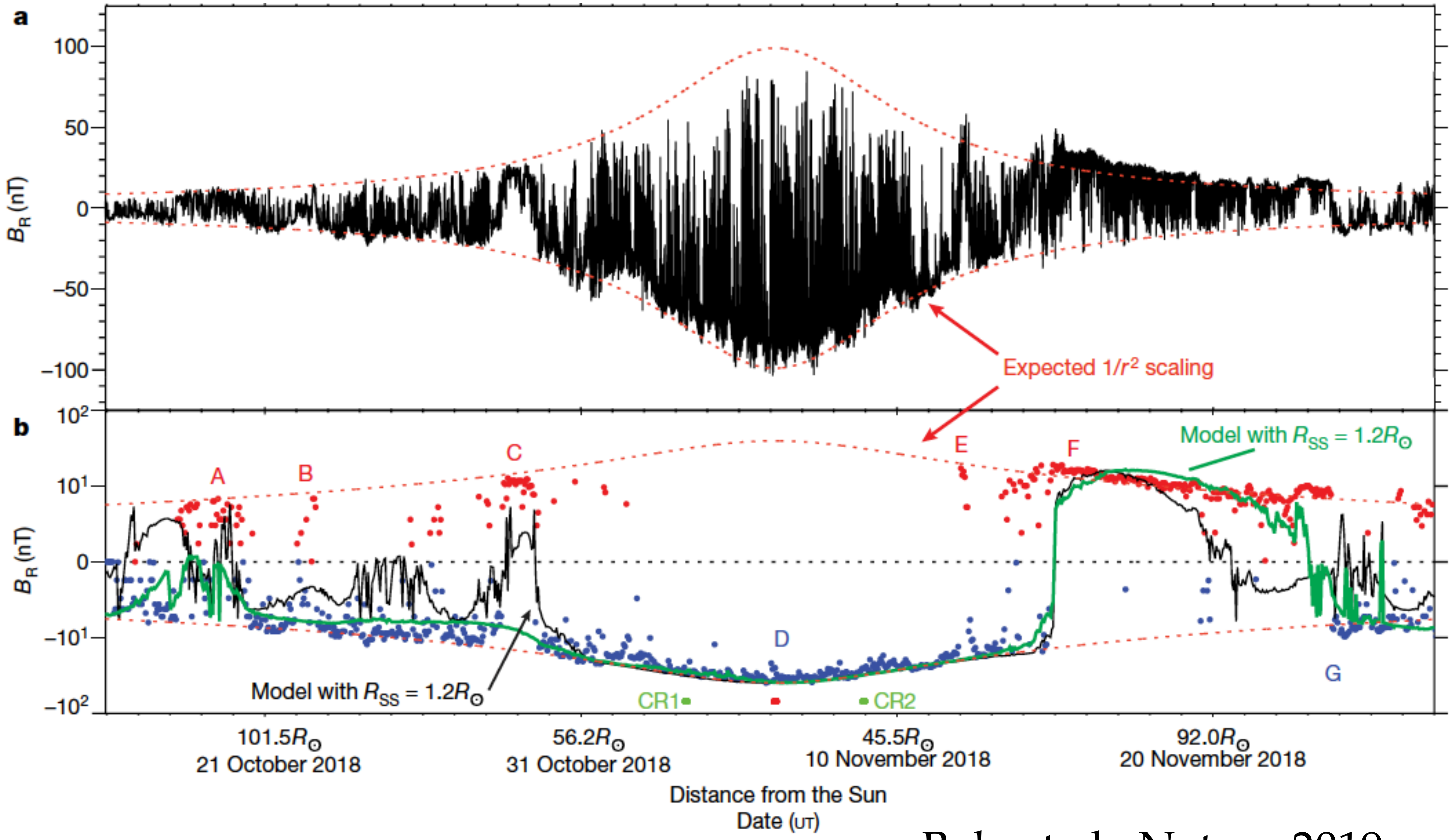


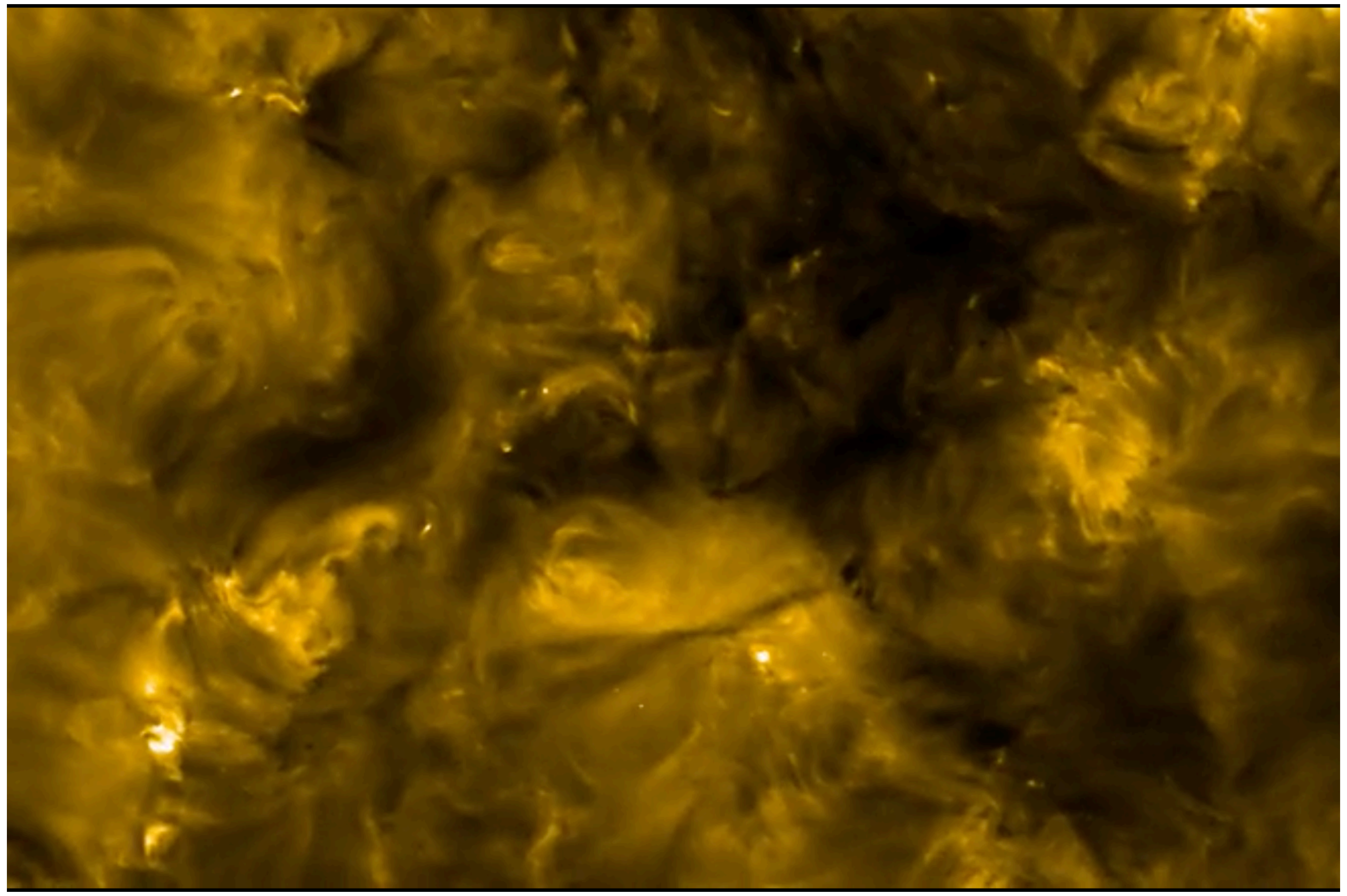
Fig. 4 | Large circulation of solar wind observed near the Sun. Averaged rotational (or azimuthal) flow, V_{pT}, over 1.75$R_\odot$ intervals during E1 (inbound in



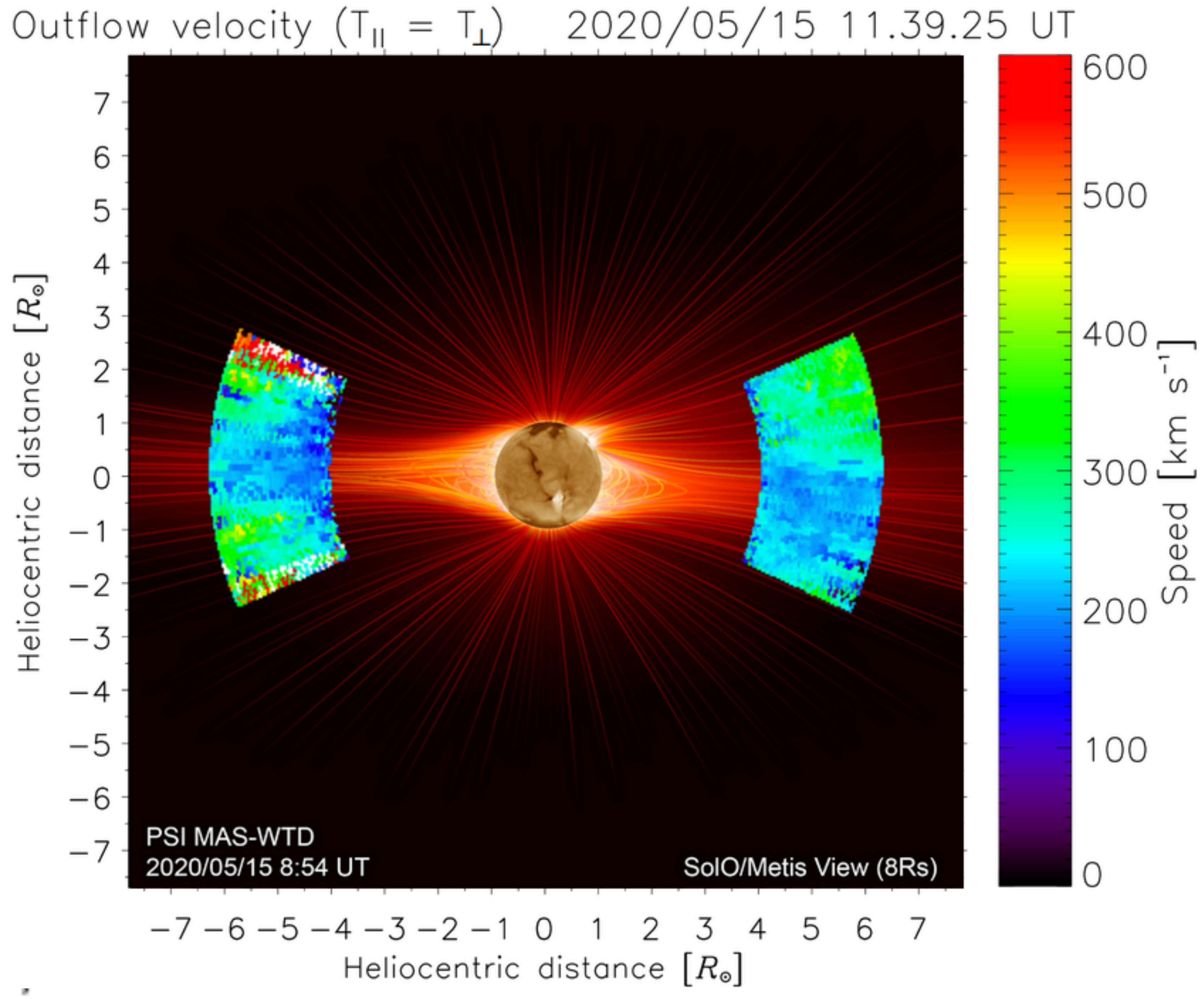
Bale et al., Nature 2019

Kasper et al., Nature 2019

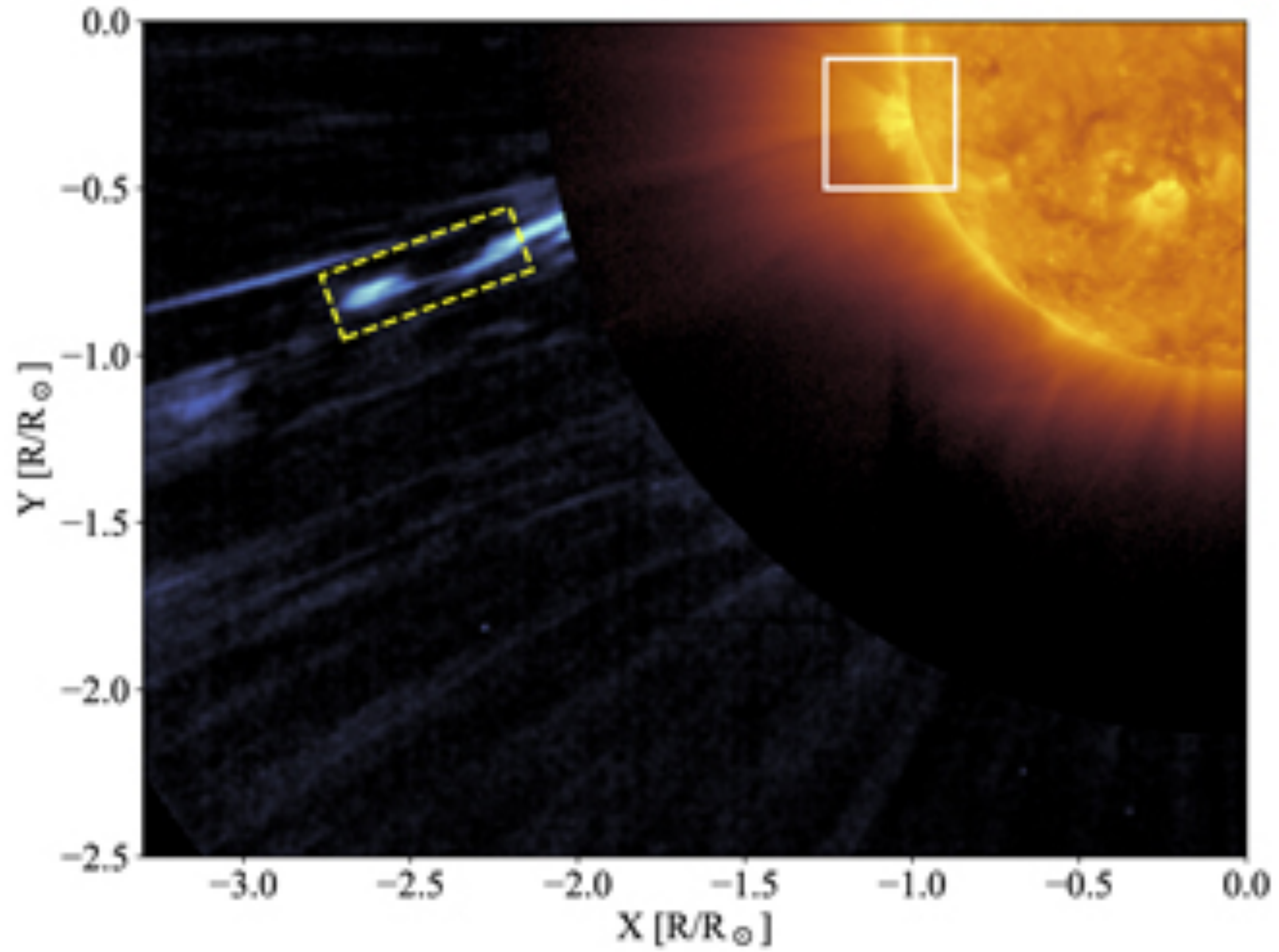
Solar Orbiter is bringing imaging instruments closer than ever to the Sun



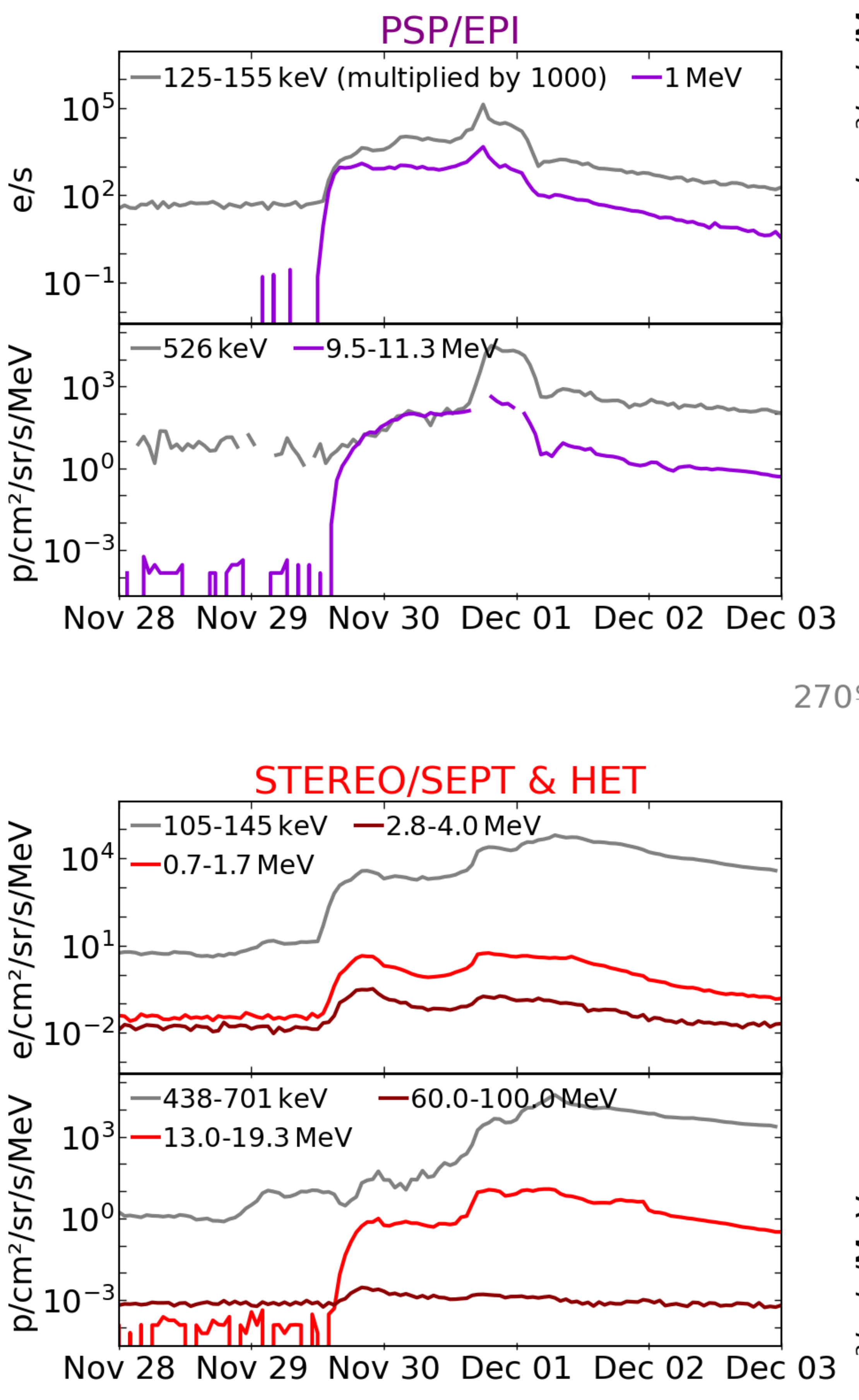
Campfires in the low corona seen by EUI on May 2020, at about 0.5 au, which imply magnetic reconnection on small scales

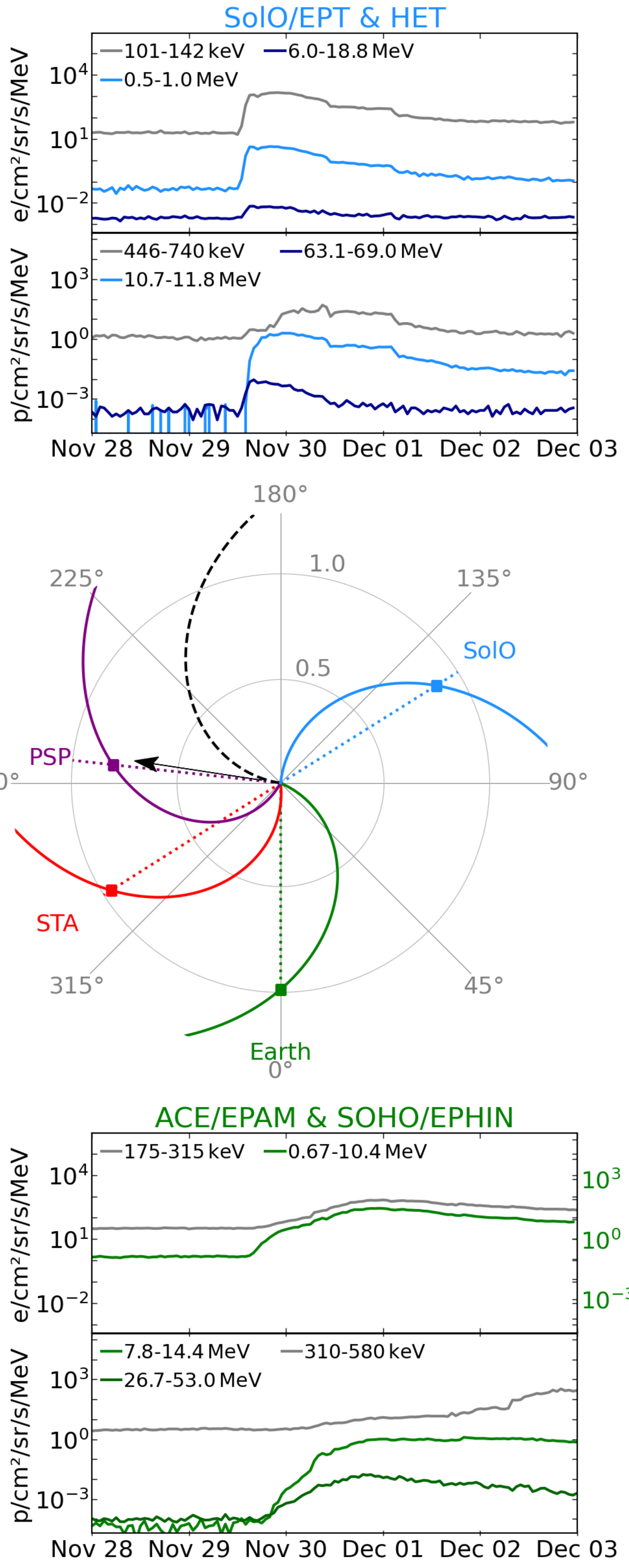


First radial velocity maps of the corona by Metis (Romoli et al. 2021)



First observation of a magnetic switchback in the corona by Metis (Telloni et al., ApJL 2022)



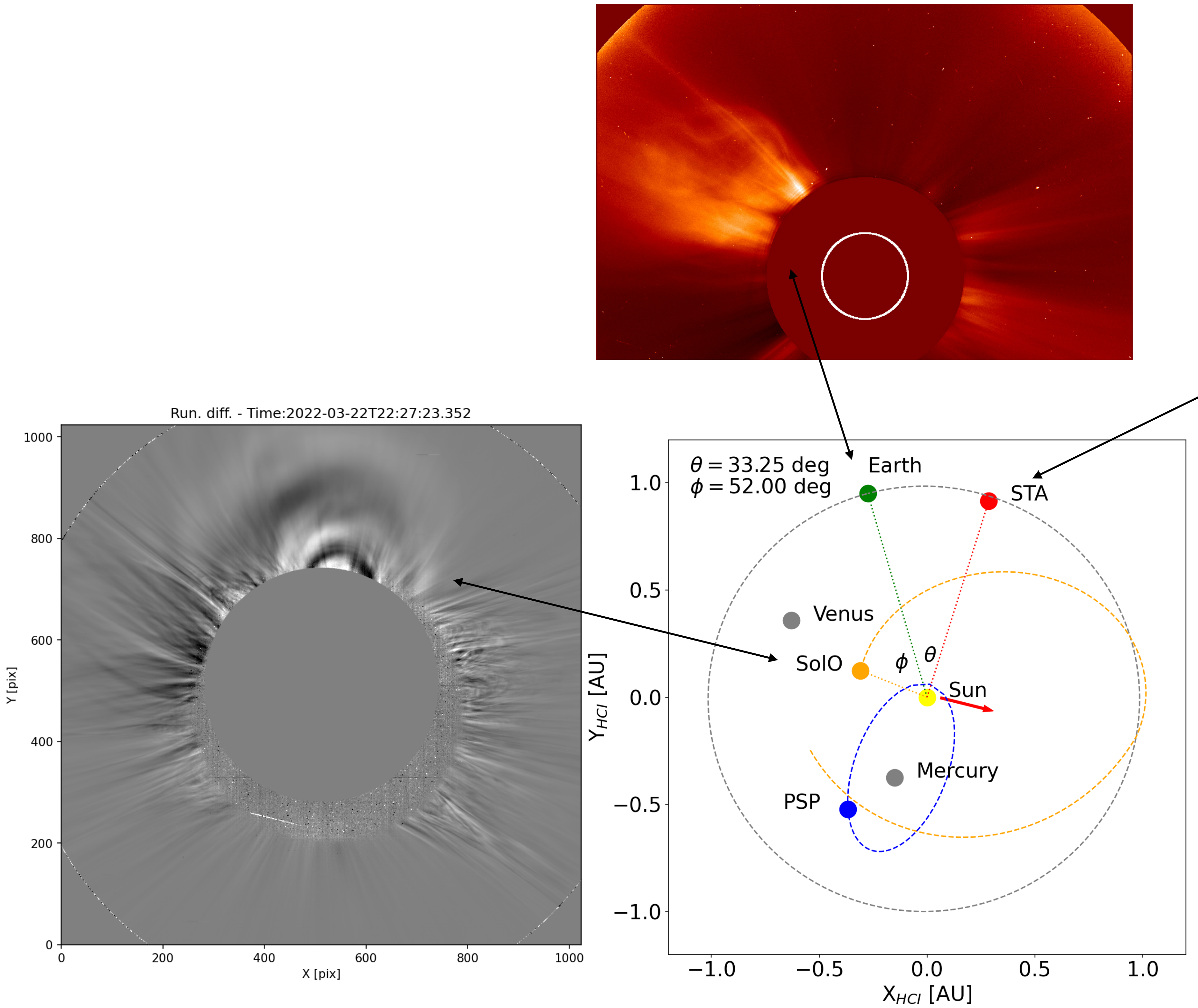


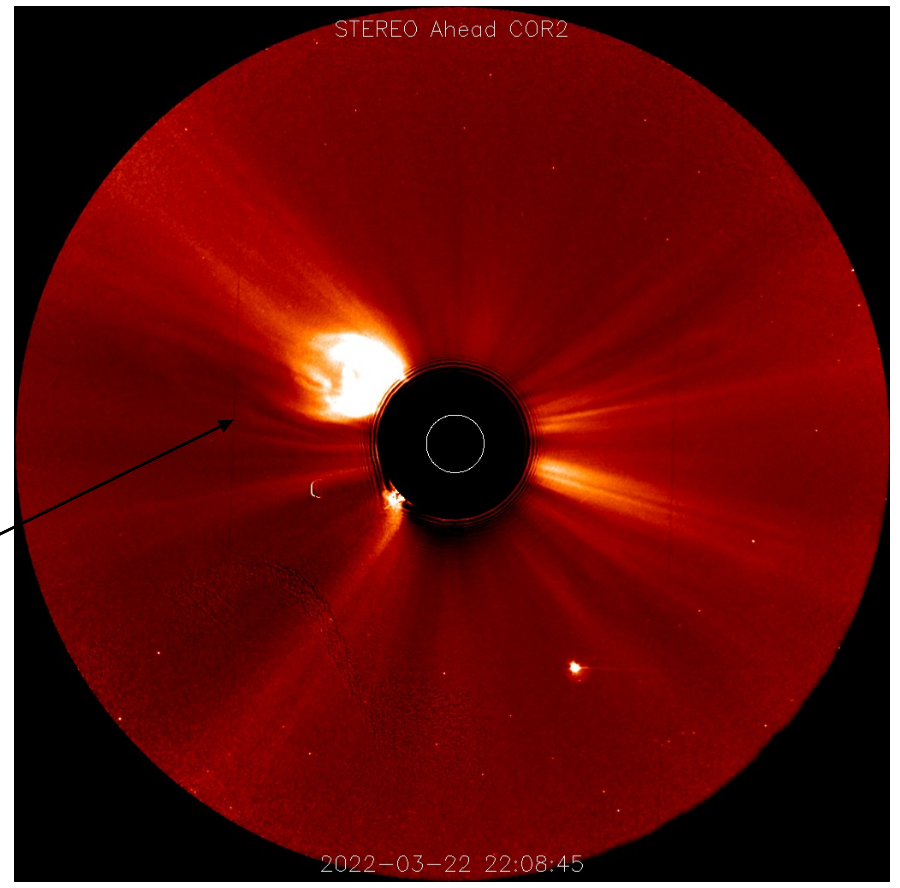
Kollhoff et al., A&A 2021

A constellation of spacecraft allows for a multi-messenger approach to magnetic connectivity in the heliosphere.

Spacecraft already operative include SOHO, STEREO-A and -B, PSP, Solar Orbiter, SDO, Bepi-Colombo, ACE, Wind, and more.

The Chinese probe ASO-S and the Indian probe Aditya-L1 are going to join this fleet soon.

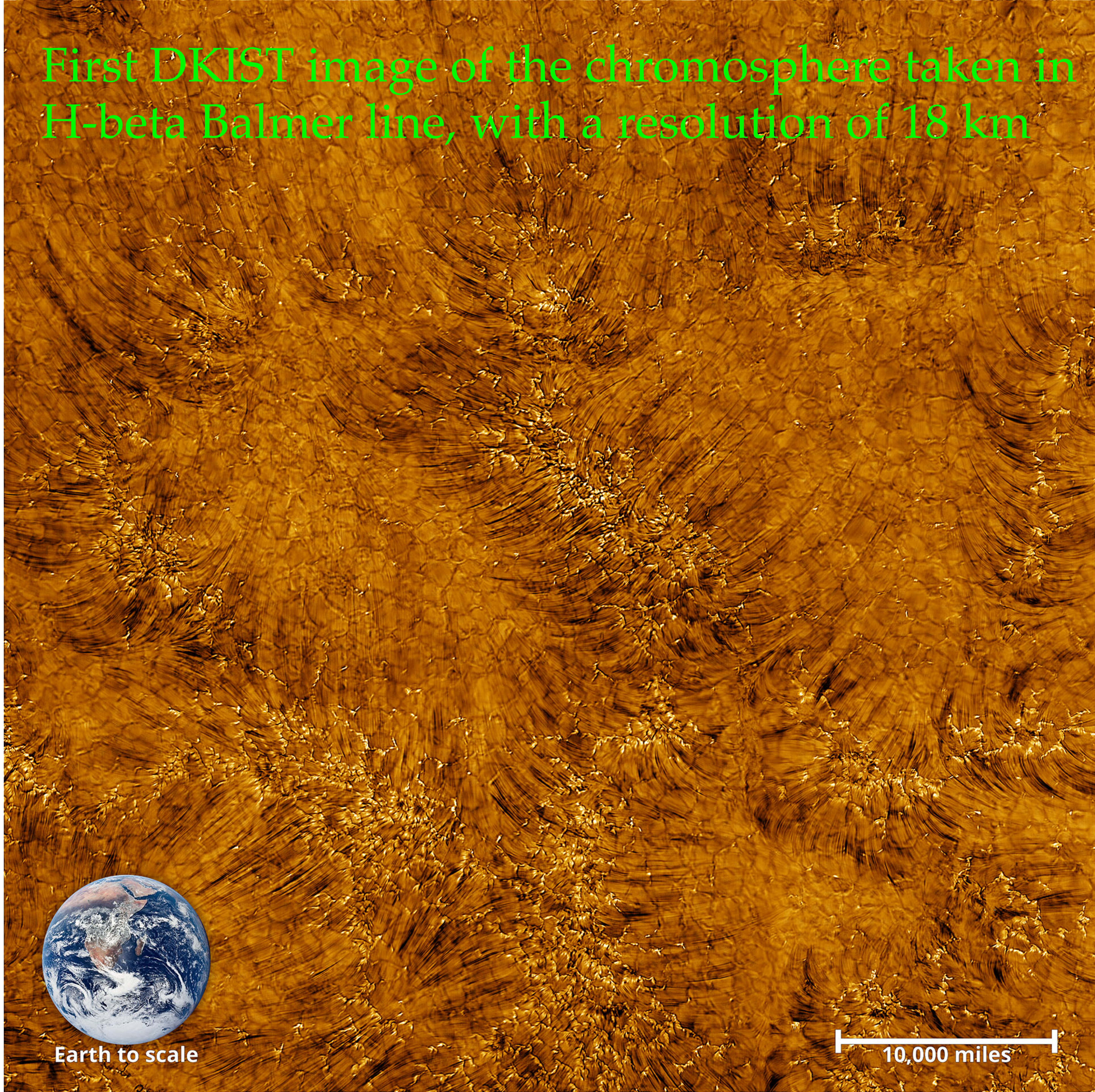




Zimbardo et al., submitted

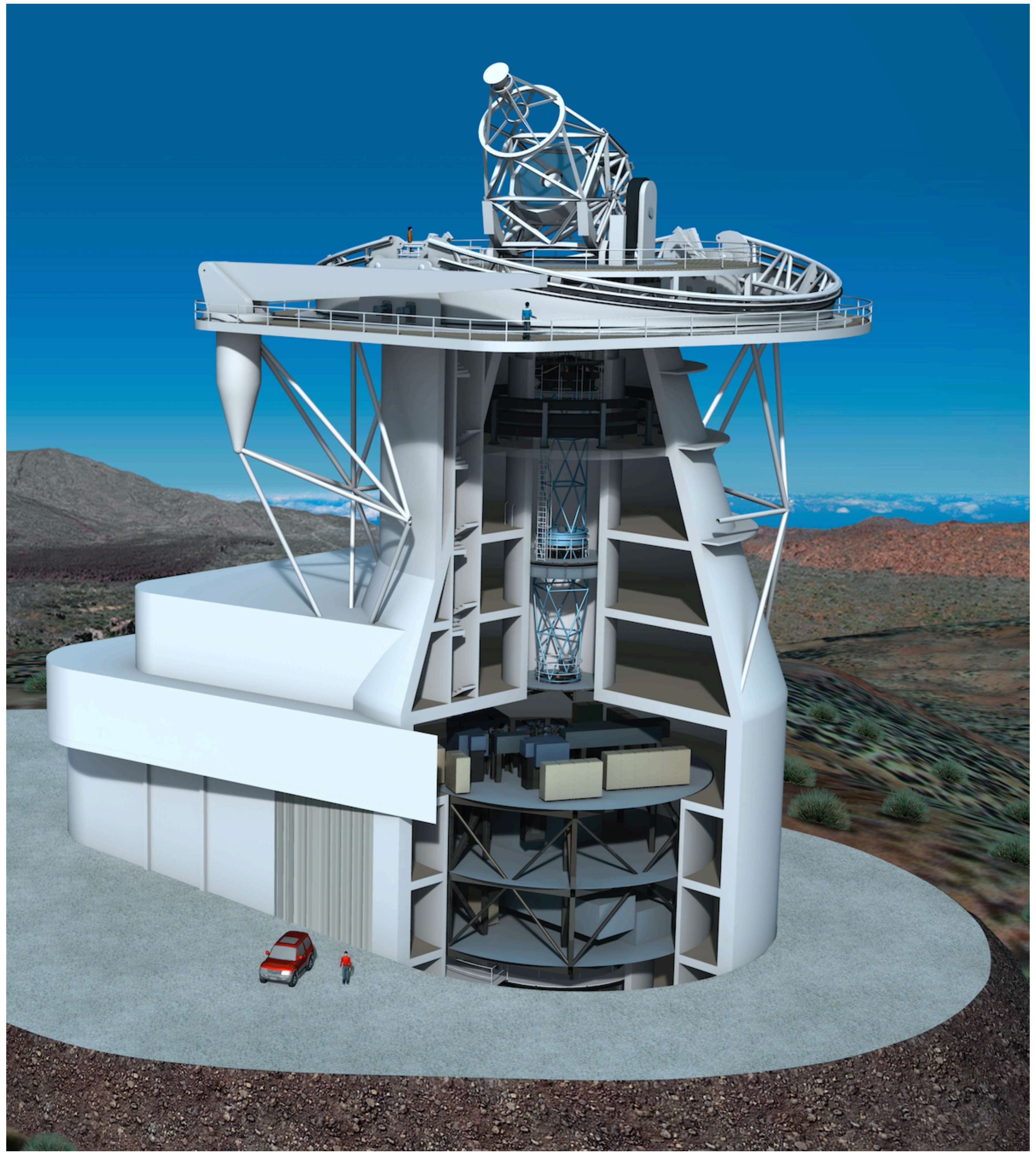
New capabilities for measuring the magnetic field in the chromosphere and low corona will soon be made available by the DKIST solar telescope in the Hawaii islands

DKIST can observe on disk and off-limb several Helium lines, and the spectropolarimetric capabilities will allow to determine the vector magnetic field with unprecedented detail. This will complement the in-situ measurements by PSP and Solar Orbiter.

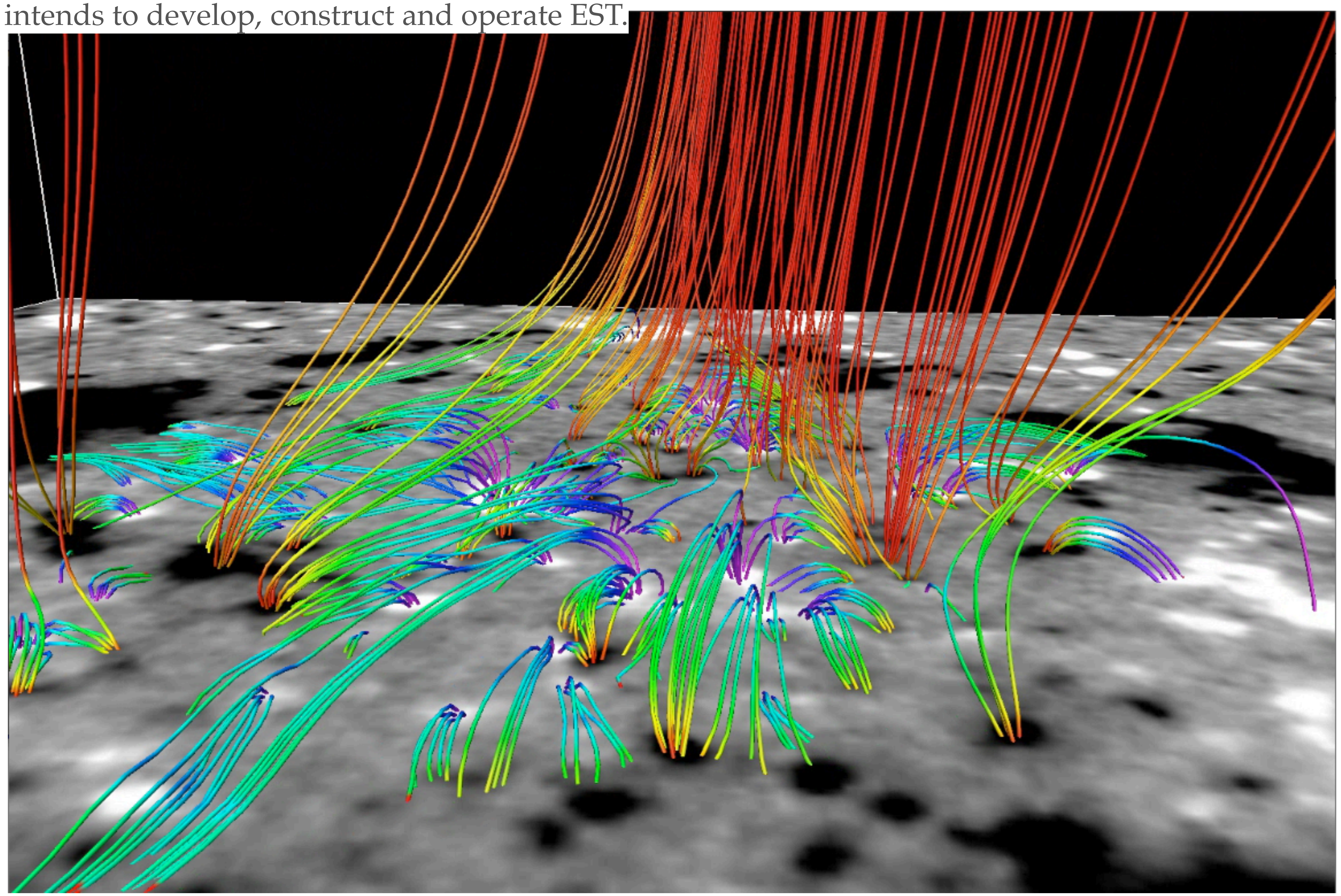


The advanced capabilities of PSP, Solar Orbiter and DKIST will be completed by the European Solar Telescope (EST)

- EST will have a 4.2-m primary mirror and the latest technology available, giving astronomers the most powerful tool ever conceived for observing the Sun.
- EST will be deployed in the Canary Islands, a first-class location thanks to the sky quality and excellent conditions for astronomical observations.
- The European Association for Solar Telescopes (EAST) is the entity promoting the project and intends to develop, construct and operate EST.



EST in Canary Islands will complete the sun coverage by DKIST at Hawaii (separation of 150° in longitude).



Magnetic tiny loops in the quiet sun (Credits: M. Gosic (IAA-CSIC), M. Cheung (LMSAL), L. Bellot Rubio (IAA-CSIC)
Observations: Hinode (ISAS/JAXA, NAOJ, NASA; STFC, ESA), HOP 151)

The new ESA mission PROBA-3, to be launched in 2024

Proba stands for the 'PRoject for OnBoard Autonomy' and the decision has been taken to make an expanded use of autonomous on-board control procedures for this mission.

PROBA-3 carries the ASPIICS coronagraph with the occulter on one satellite and the detector on the other, separated by 144 m. This will allow to study the corona closer to the rim than ever before.

Proba-3 is ESA's – and the world's – first precision formation flying mission. A pair of satellites will fly together maintaining a fixed configuration as a "large rigid structure" in space to prove formation flying technologies.
Beside its scientific interest, the mission will be a perfect instrument to measure the achievement of the precise positioning of two spacecraft. It will be enabled using a wide variety of new technologies.

Plasma Observatory

Unveiling plasma energization and energy transport in the near-Earth plasma environment through multiscale observations

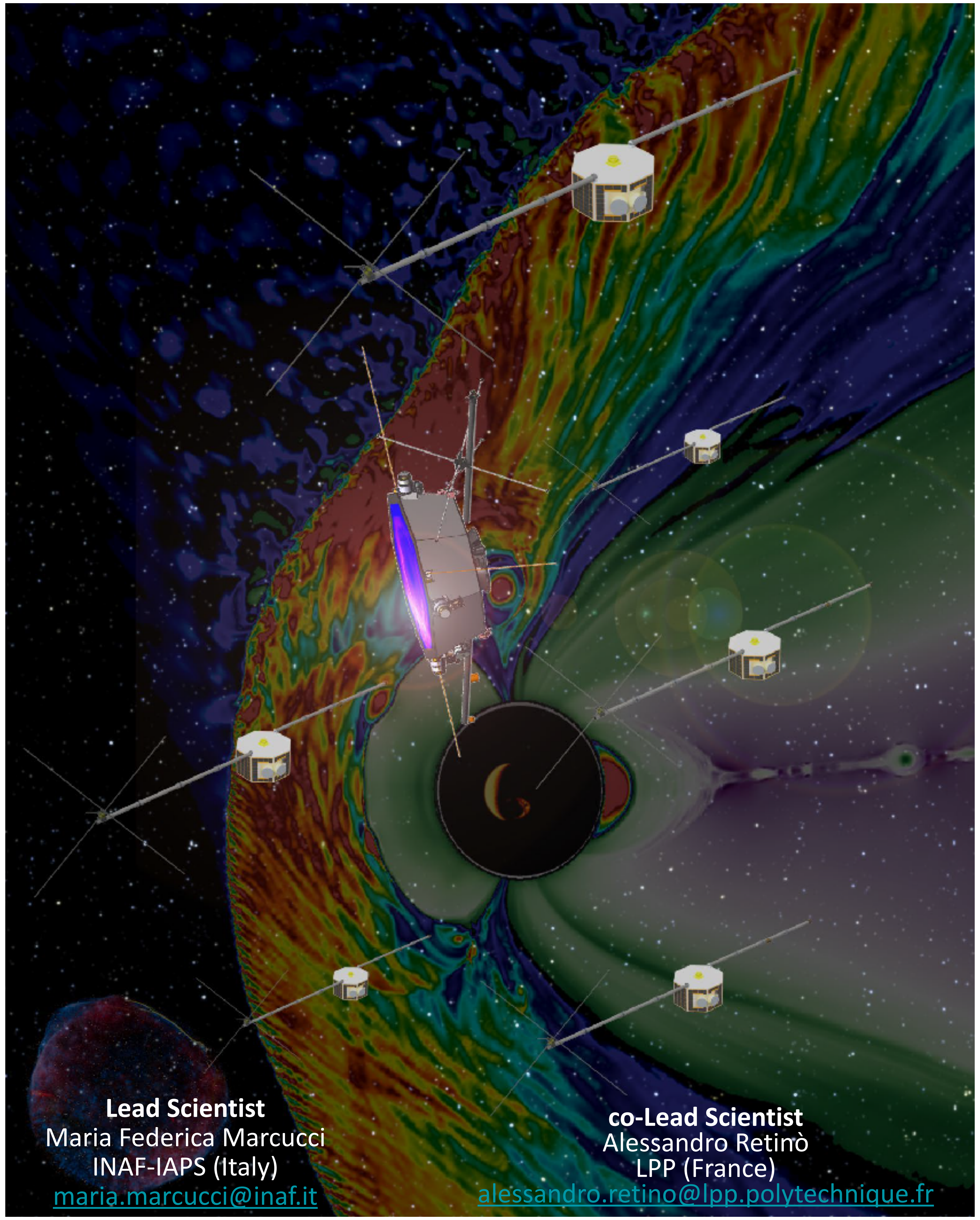
ESA M7 candidate currently in competitive Phase 0.

Targets the two ESA Voyage 2050 themes for ESA-led M Mission: *Magnetospheric Systems* and *Plasma Cross-scale Coupling*

Large scientific community: 350+ researchers from 25 countries (17 in Europe) including US, Japan and China

Payload team including 10 ESA countries with key US and Japanese contributions

- First multi-scale measurements tailored to the Magnetospheric System. Constellation of one mothercraft and 4 to 6 small daughtercraft, resolving scales from fluid to sub-ion (SC separation from~30 to ~ 5000 km).
- HEO 8 RE×18 RE orbit (15°inclination) covering Key Science Regions in the Magnetospheric System where the strongest plasma energization and energy transport occur: foreshock, bow shock, magnetosheath, magnetopause, magnetotail current sheet, and transition region.
- Scientific measurements:
  - *Single point.* 3D electric and magnetic fields and 3D particle distributions measured with cadence to resolve sub-ion scales in 1 point.
  - *Multipoint.* 3D electric and magnetic fields and 3D particle distributions measured with cadence to resolve ion and fluid scales in 7 points.



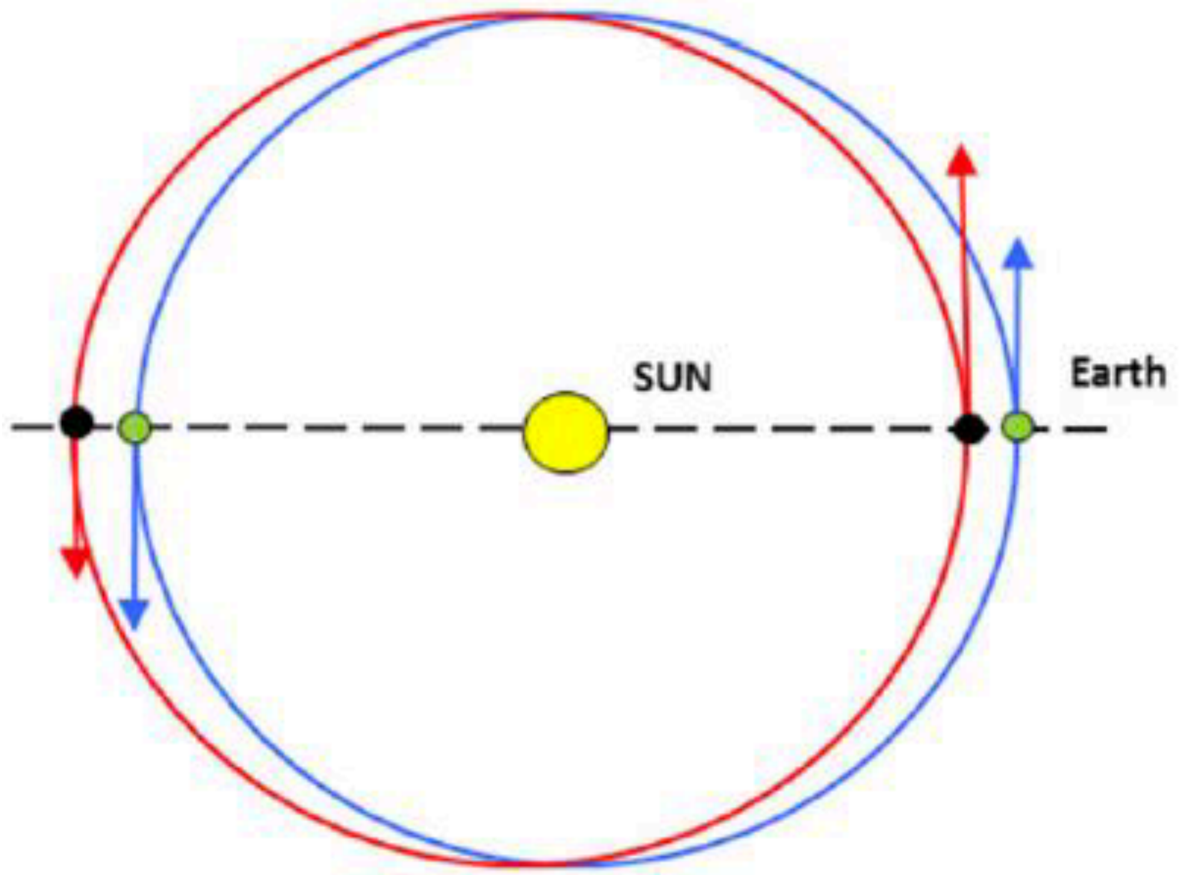
Magnetosphere in a hybrid-Vlasov simulation (M. Palmroth), the CAD drawing of Plasma Observatory mothercraft (OHB-DE) and daughtercraft (Argotec - IT), SN 1006 (X-ray: NASA/CXC/Rutgers/G.Cassam-Chenai, J.Hughes et al.; Radio: NRAO/AUI/NSF/GBT/VLA/Dyer, Maddalena & Cornwell; Optical: Middlebury College/F.Winkler, NOAO/AURA/NSF/CTIO Schmidt & DSS). Courtesy: Walter Puccio, IRF, SE

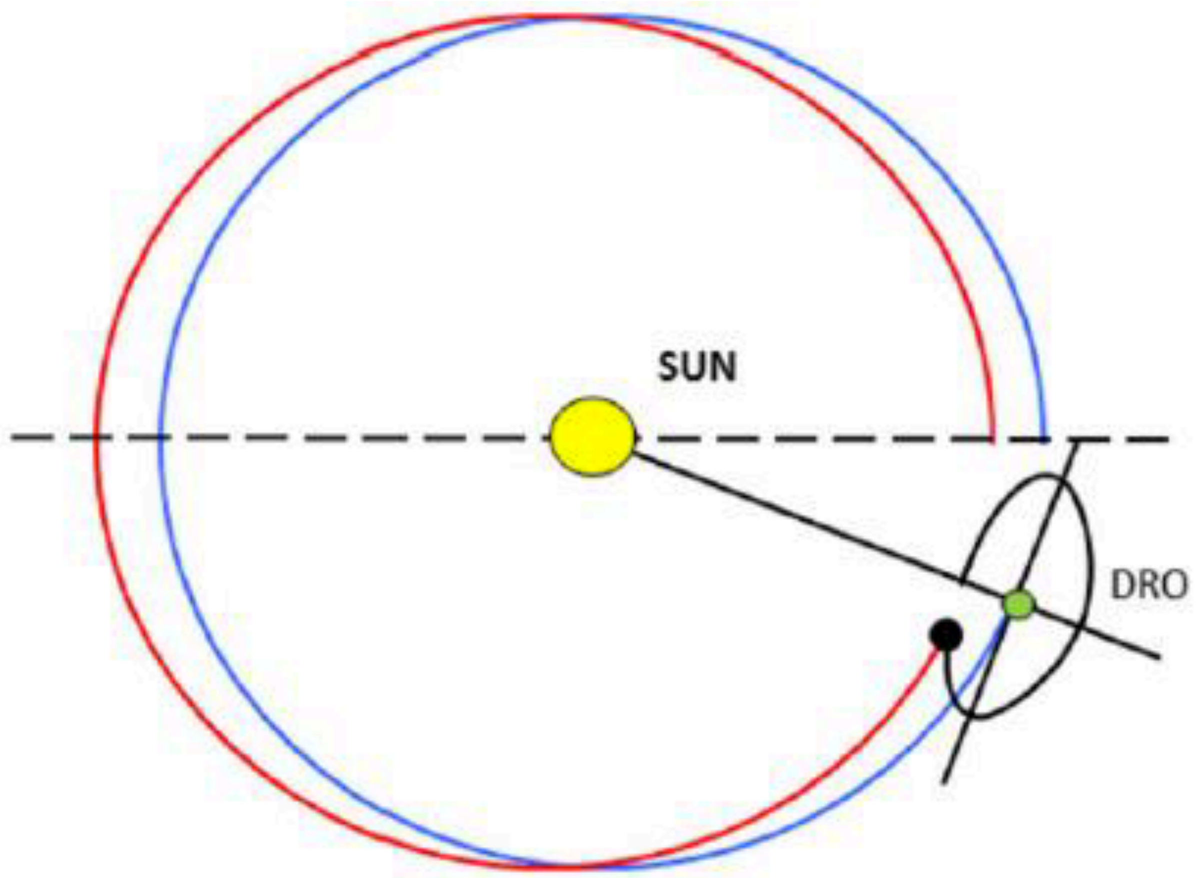
For Space Weather predictions, beside solar monitoring, it is essential to have measurements in the solar wind upstream of the Earth

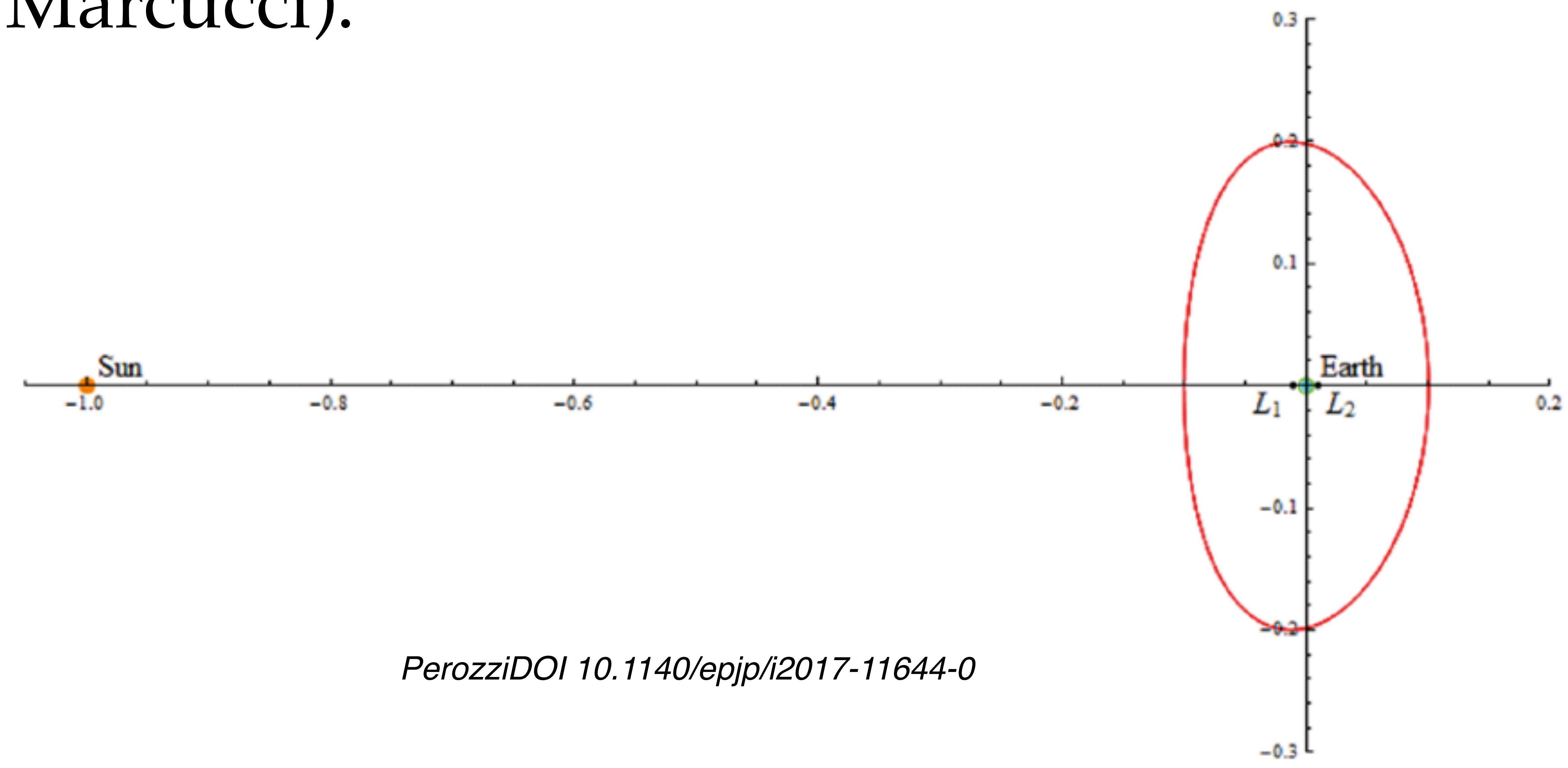
In a comprehensive review paper, Vourlidas, Patsourakos, and Savani (2019) (Predicting the geoeffective properties of coronal mass ejections: current status, open issues and path forward. Phil. Trans. R. Soc. A 377: 20180096) summarize the infrastructures needed Space Weather: they recommend to

Deploy in situ monitors ahead of L1, optimally at 0.3 AU from Earth, to measure directly the CME magnetic properties with approximately 24 h warning time.

This can be achieved by Distant Retrograde Orbits (DRO): two bodies are revolving around a common primary body, and apparently one is orbiting the other. **The HENON mission** (currently in phase B) of ASI uses this concept to design a cubesat orbiting the Earth at around 0.1 AU upstream of the Earth (Project leader M.F. Marcucci).





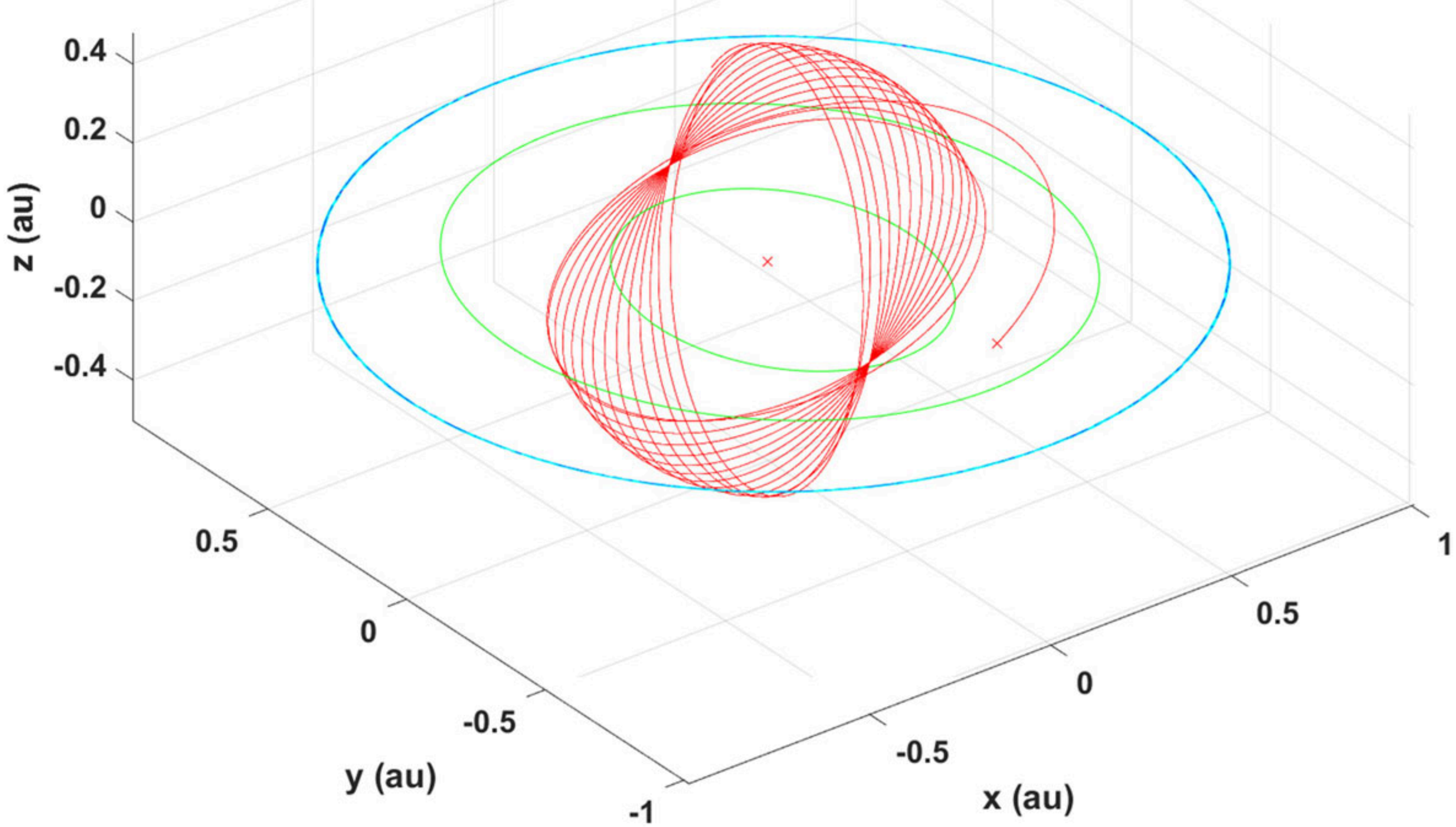


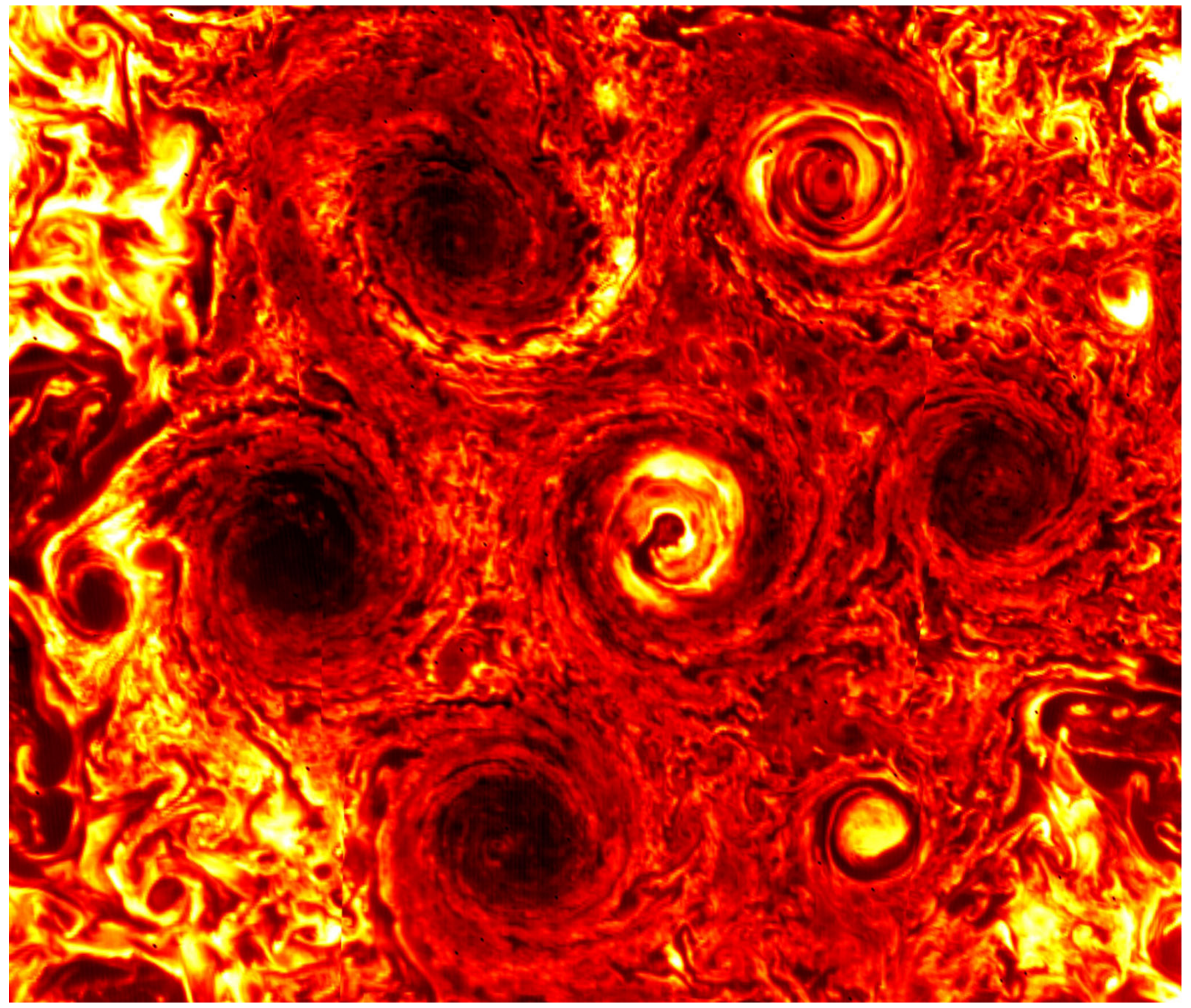
PerozziDOI 10.1140/epjp/i2017-11644-0

Nevertheless, we miss observations from new vantage points:

- Solar Orbiter will gradually reach solar latitudes of 33°, but we miss a full polar view of Sun poles.
- A solar polar mission would allow an unprecedented opportunity to study solar convection at the poles, solar dynamo, the transfer of magnetic flux during solar cycle, the polar magnetic field and solar wind, and the solar irradiance at high latitudes.
- Primary objectives of a solar polar mission are: (i) To study the interior of the solar polar regions to uncover the key role of magnetic flux transport in the solar cycle (ii) To study the global mass-loss of a star through discrete mass ejection processes (iii) To determine solar irradiance at all latitudes (iv) To explore solar activity at the poles and the impact on the solar wind.
- Several concepts of solar polar missions have been proposed, which require further development of technologies like solar sails and ion engines (Harra et al., 2022).

Post-Venus Gravity Assist solar sail trajectory to a polar orbit (Harra et al. 2022).



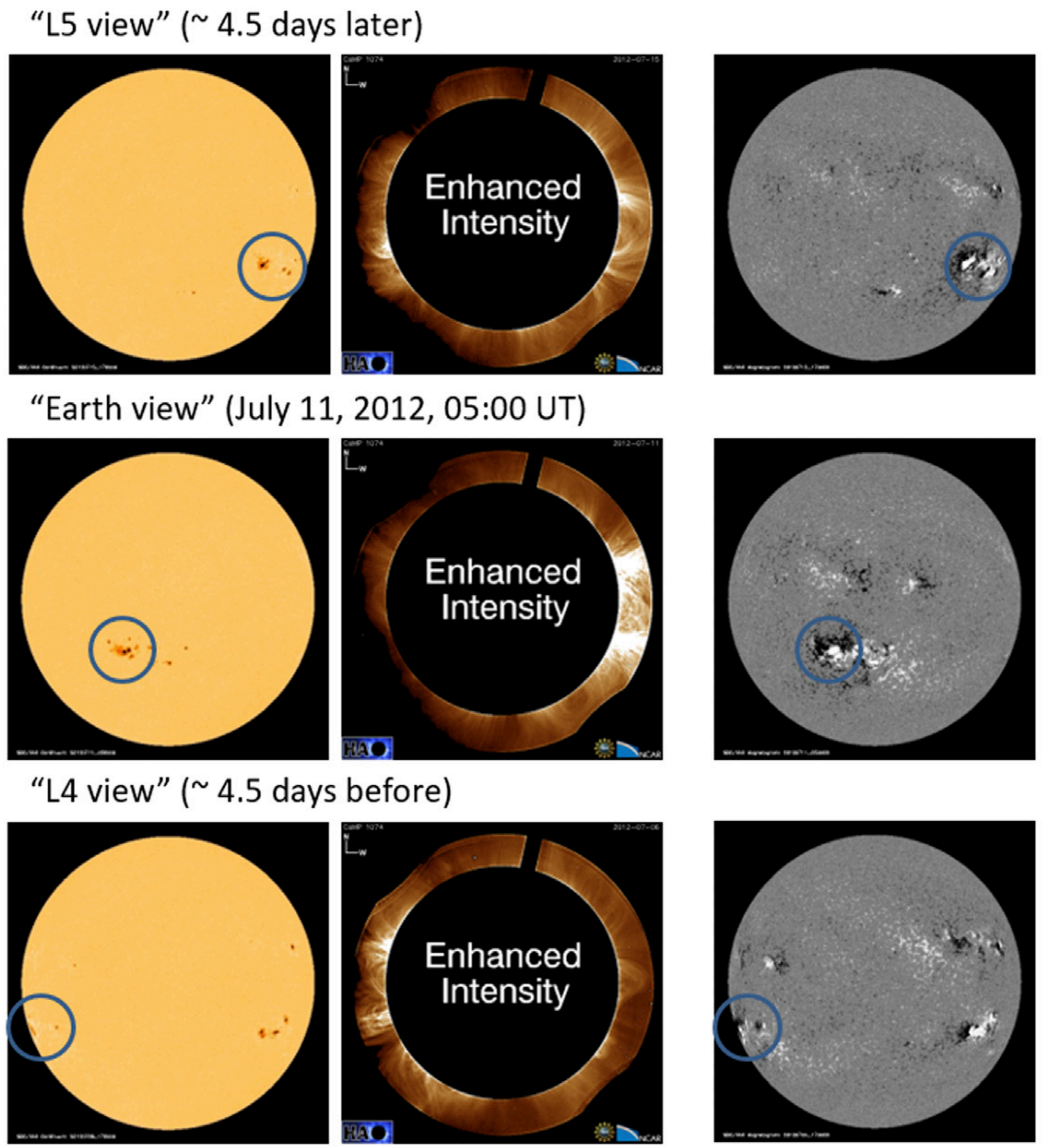


As inspiration, look at Jupiter images by the Juno spacecraft:

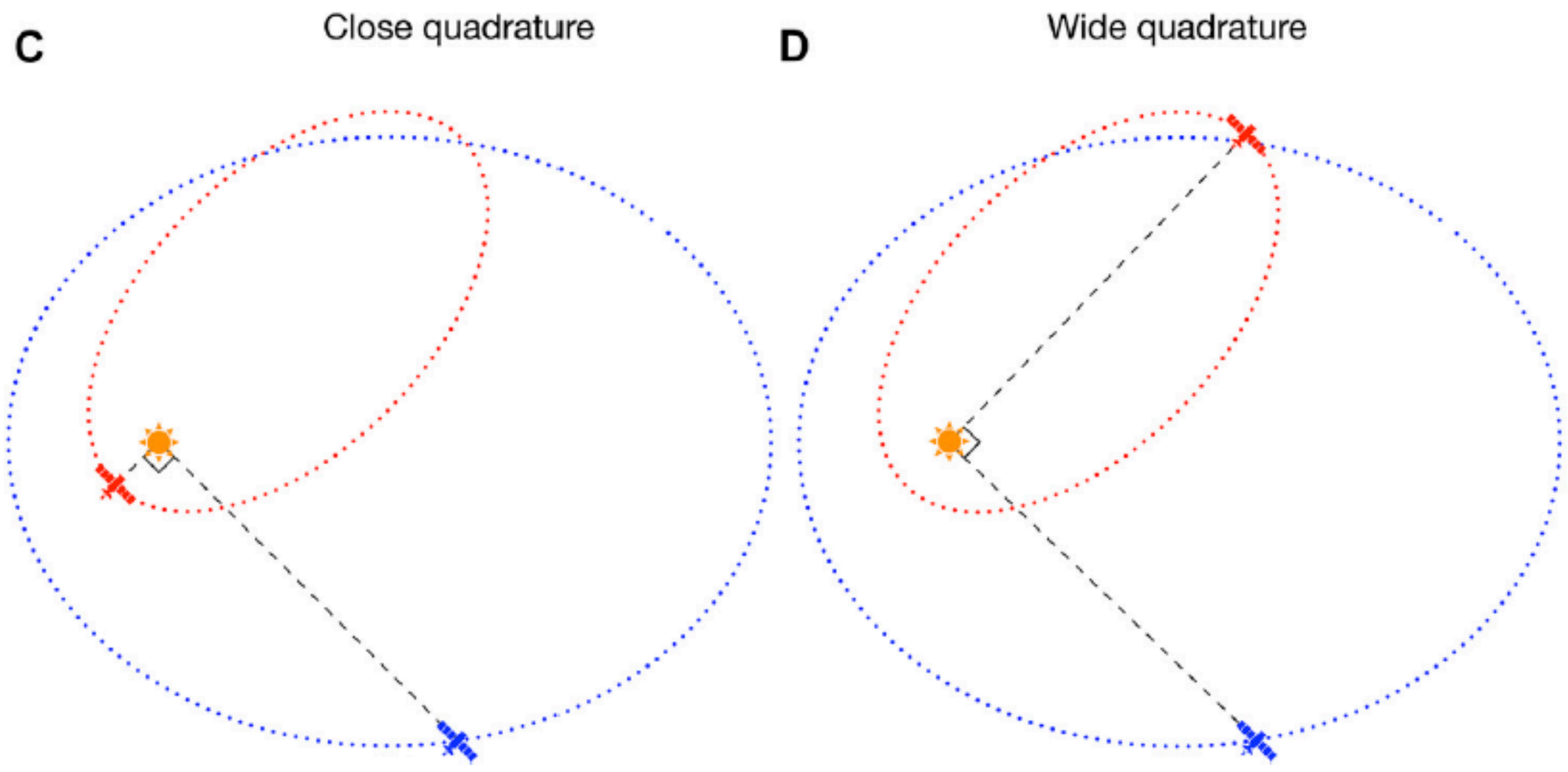
South Pole, infrared

New concepts for missions at L4 and L5 and in quadrature

Spacecraft in Lagrangian points L4 and L5 (Bemporad, 2022): data provided by such a twin mission will allow to follow the evolution of magnetic fields from inside the Sun (with stereoscopic helioseismology), to its surface (with photospheric magnetometers), and its atmosphere (with spectropolarimeters).



Spacecraft in quadrature: SQUARE^2 (Telloni 2022): the combined use of remote-sensing and in-situ instrumentation aboard the twin SQUARE2 probes would allow the connection of the locally sampled solar-wind plasma flow with its coronal drivers.



Conclusions

These future observatories, together with those already operating, will form a formidable constellation for multi-messenger tracing of the magnetic connectivity and for Space Weather predictions.