MULLARD SPACE SCIENCE LABORATORY

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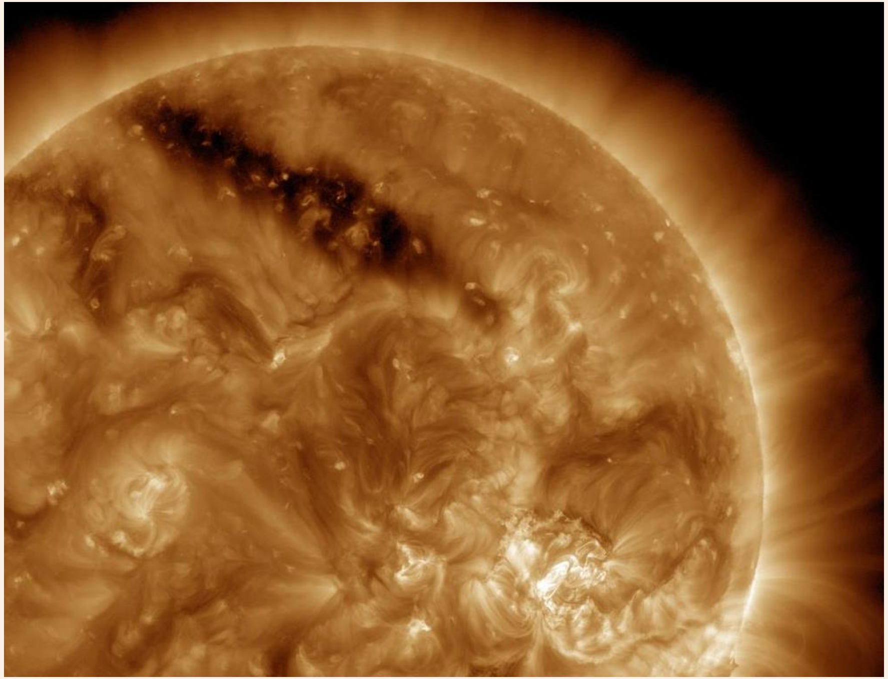
solar orbiter

The solar wind from the Sun to the Earth: a multi-scale plasma



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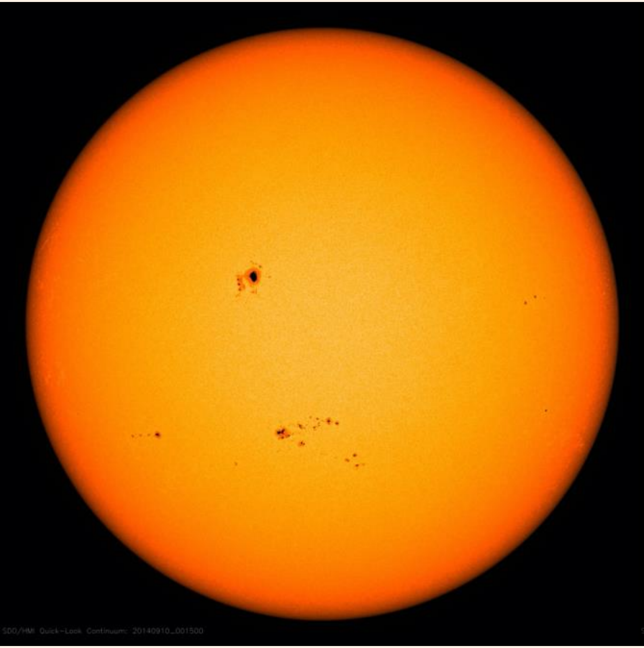
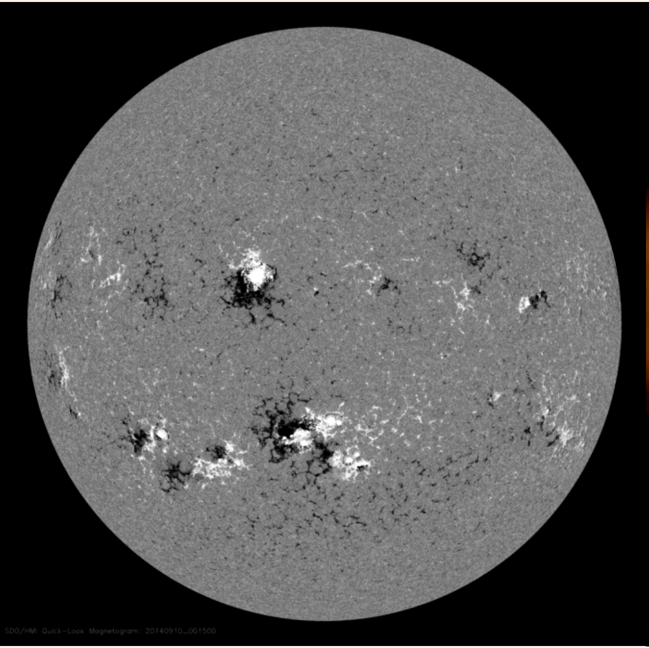
Mullard Space Science Laboratory (@MSSLSpaceLab)

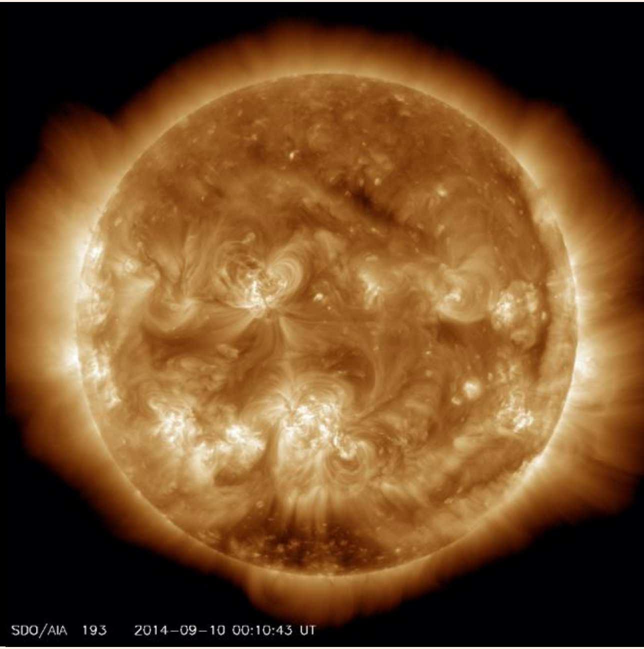
02 November 2021

@DVerscharen

The Sun

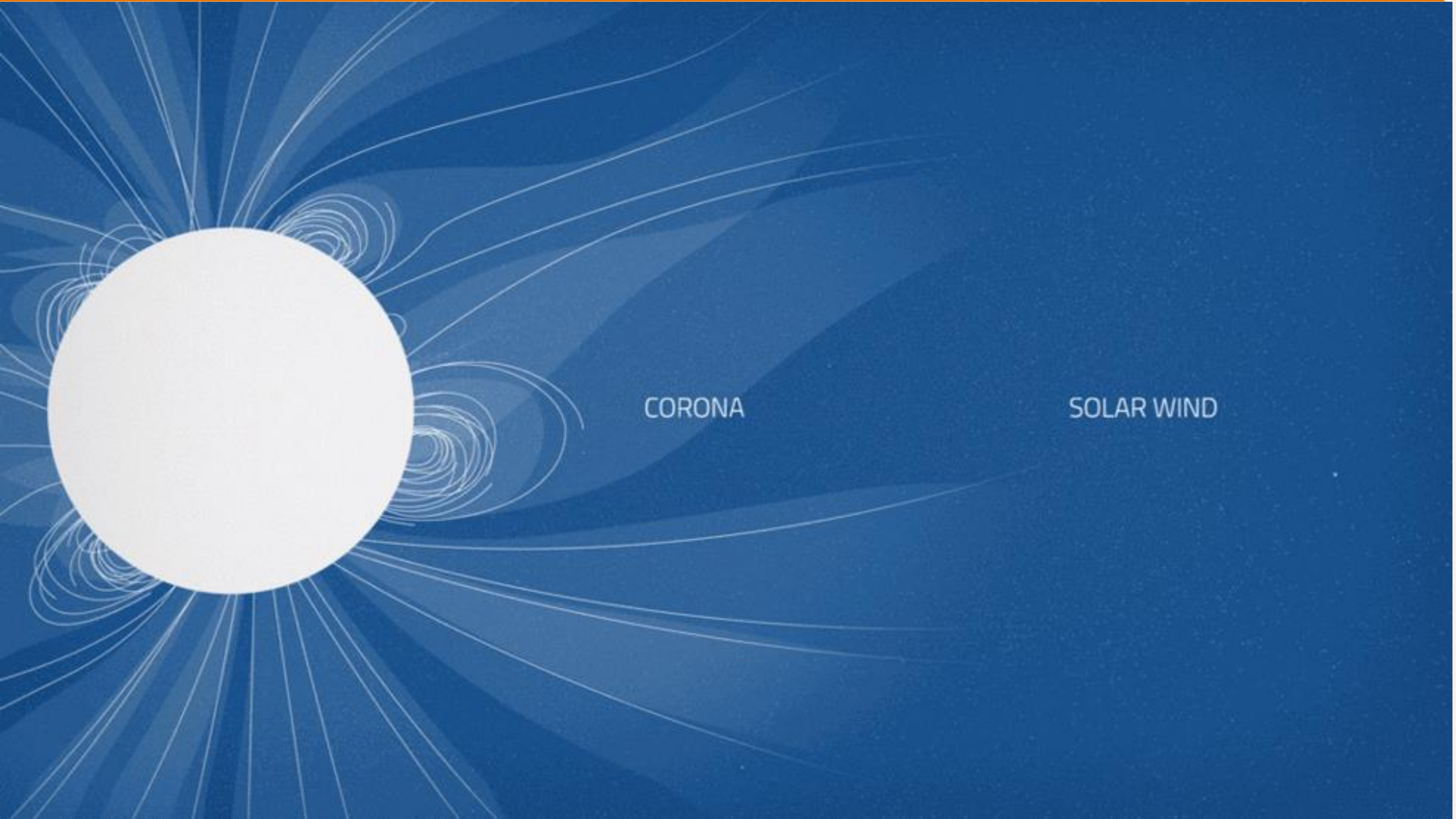






Credit: NASA/SDO

The corona: a hot plasma that escapes into space as the solar wind

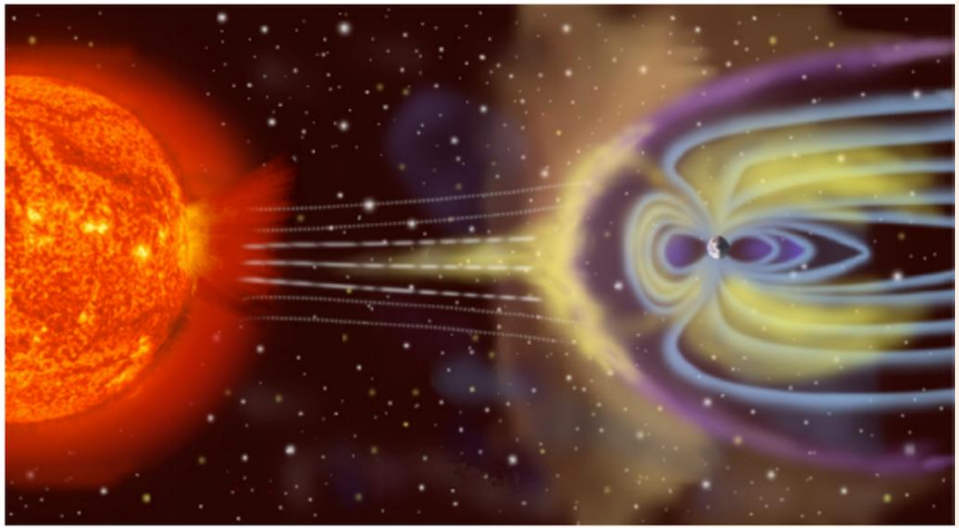


Credit: NASA/GSFC/Lisa Poje

The solar wind: a collisionless space plasma

Typical solar-wind parameters at 1 au:

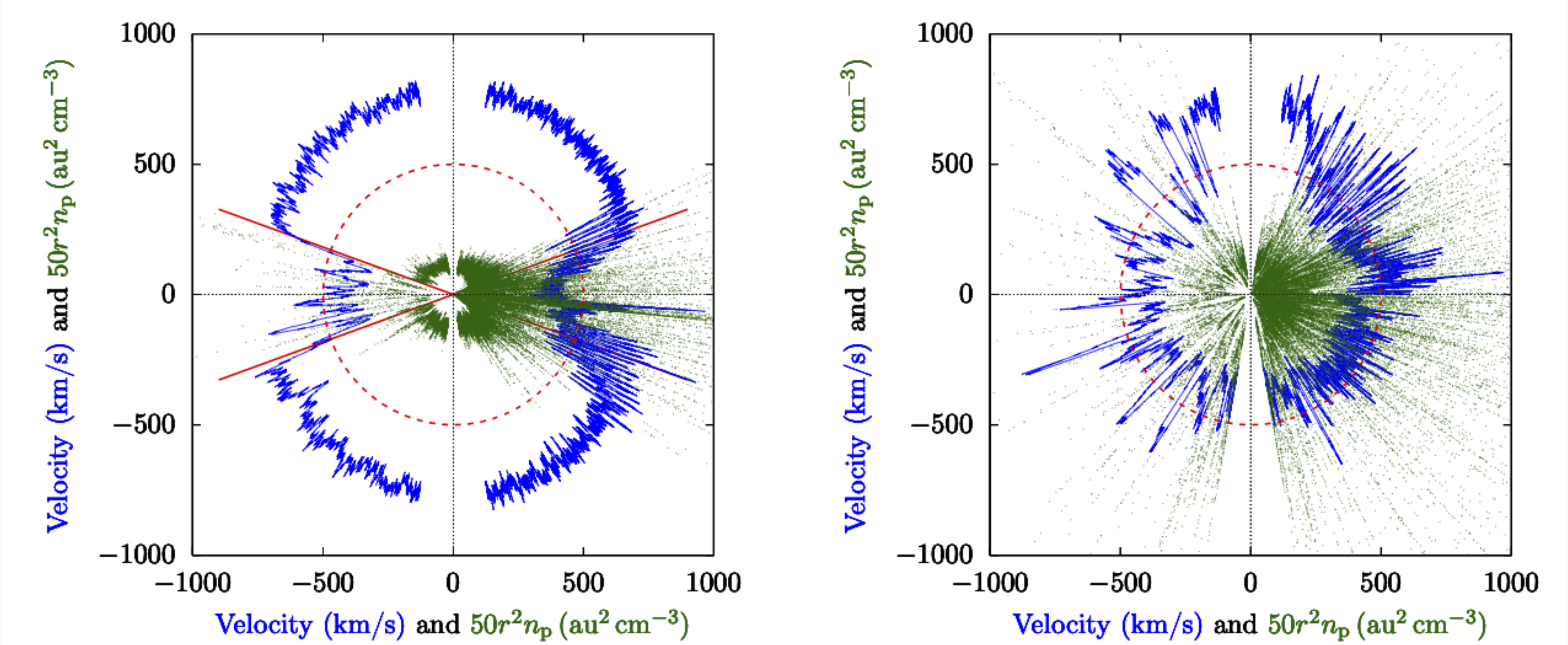
- Flow speed: about 500 km/s
- Magnetic field strength: a few nT
- Proton temperature: about 10^5 K
- Plasma-β: about unity
- Collisional mean free path: about 1 au



Credit: ESA

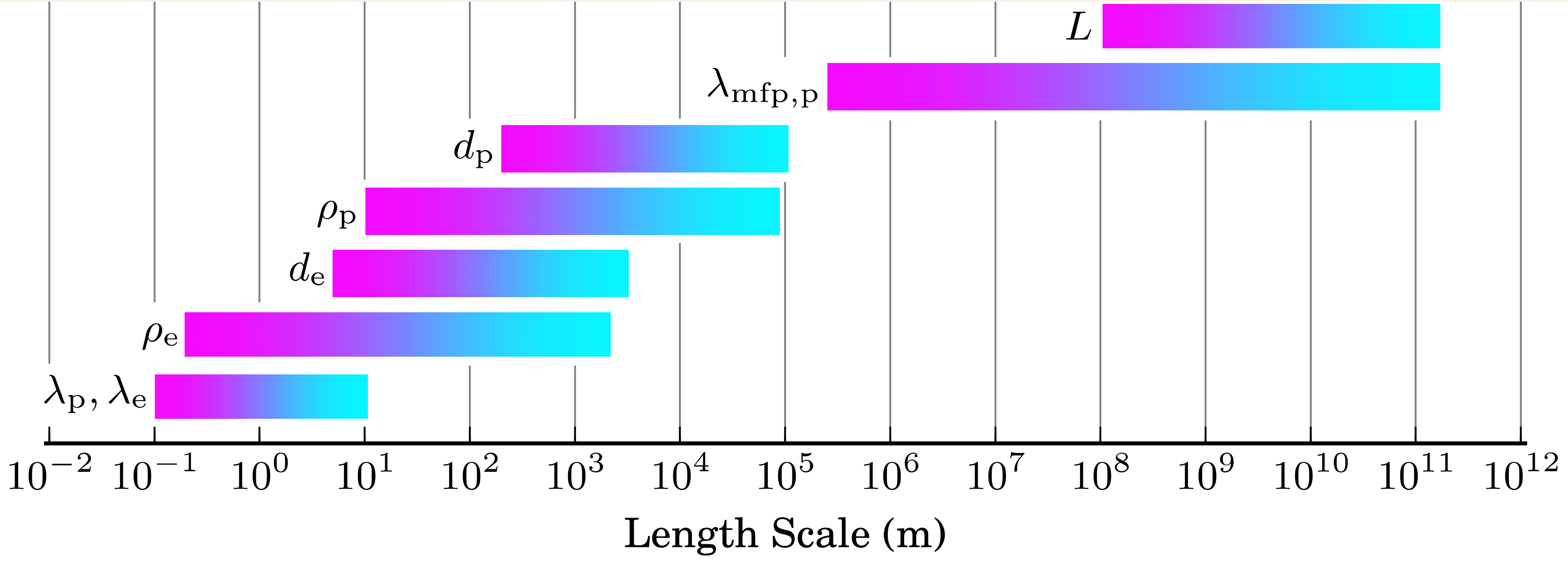
The solar wind is (mostly) a collisionless plasma.

Ulysses observations



(Verscharen et al. 2019)

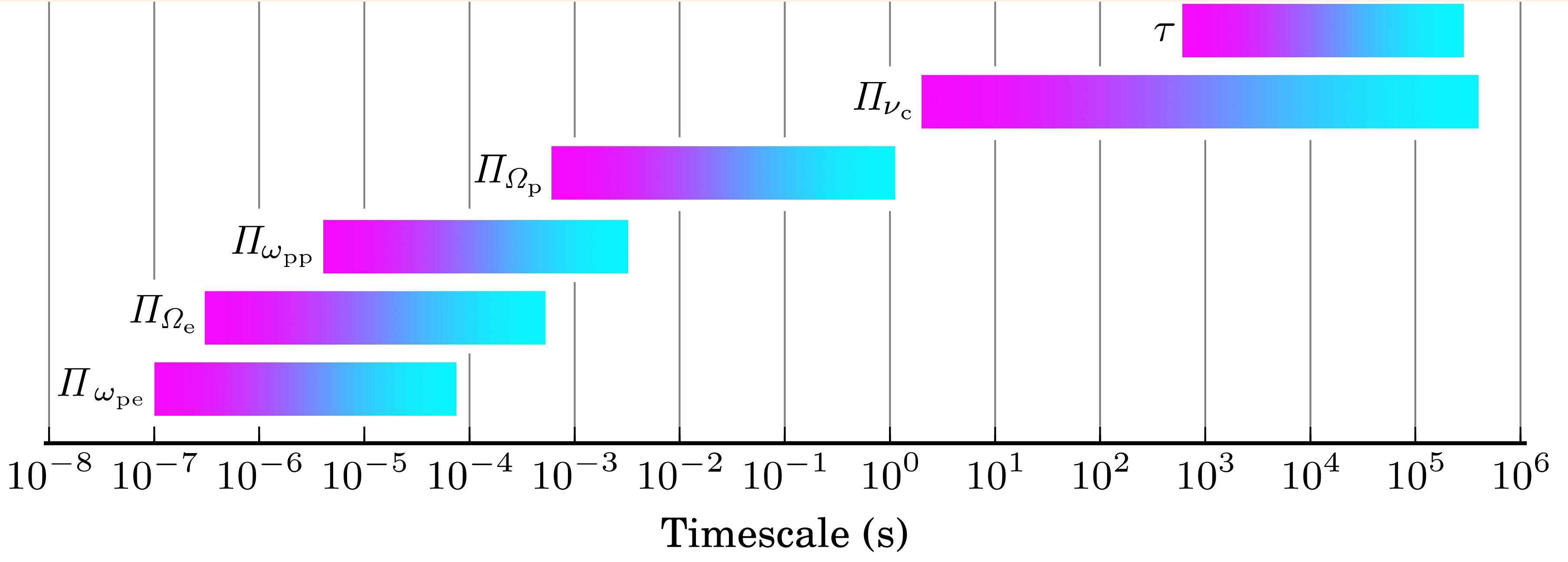
What does "multi-scale" mean?



λ_j: Debye length, ρ_j: gyro-radius, d_j: inertial length, $\lambda_{mfp,p}$: collisional mean free path,
L: system size

(Verscharen et al. 2019)

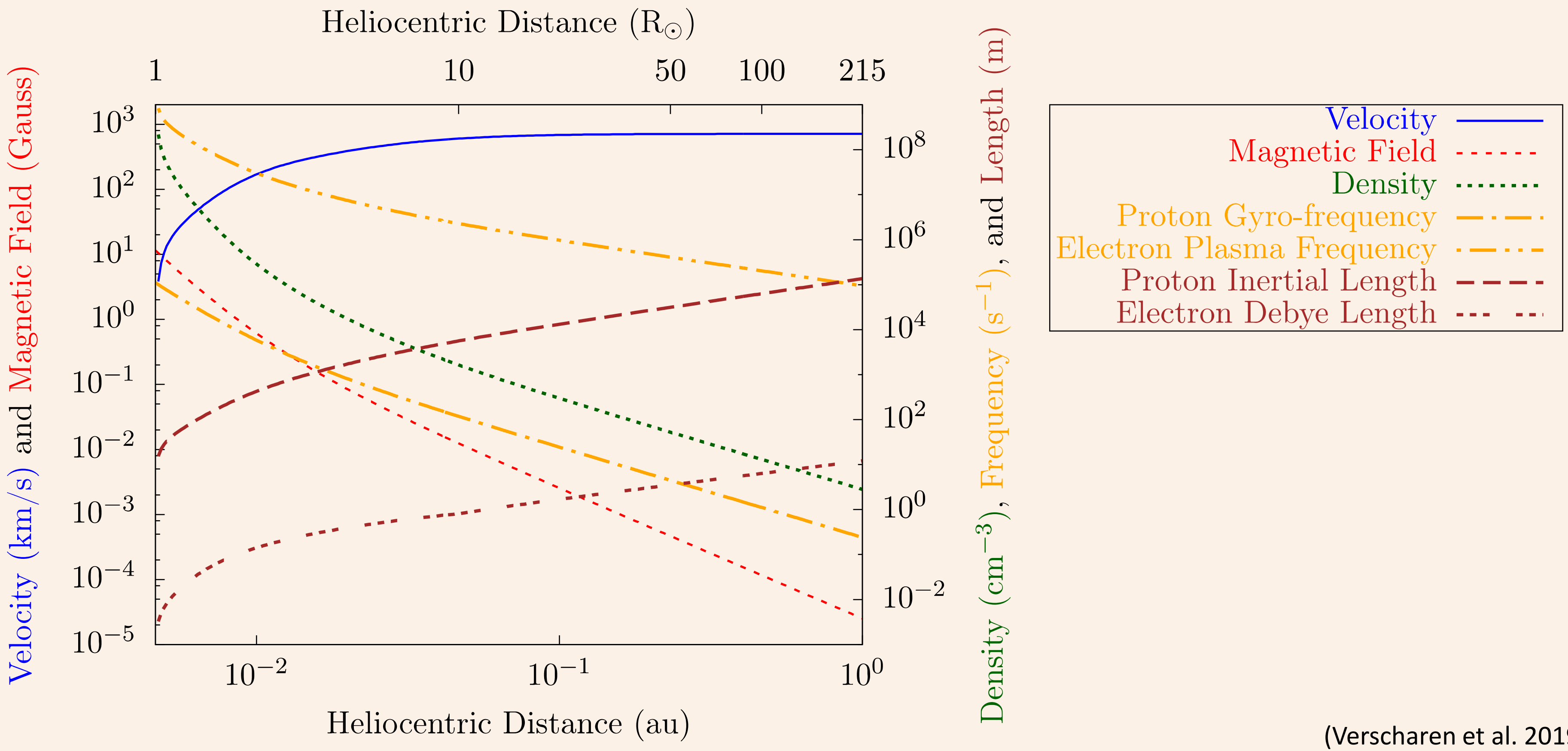
What does "multi-scale" mean?



$\Pi_{\omega_{pj}}$: plasma-oscillation period, Π_{Ω_j}: gyro-period, Π_{ν_c}: collisional time scale,
τ: expansion time

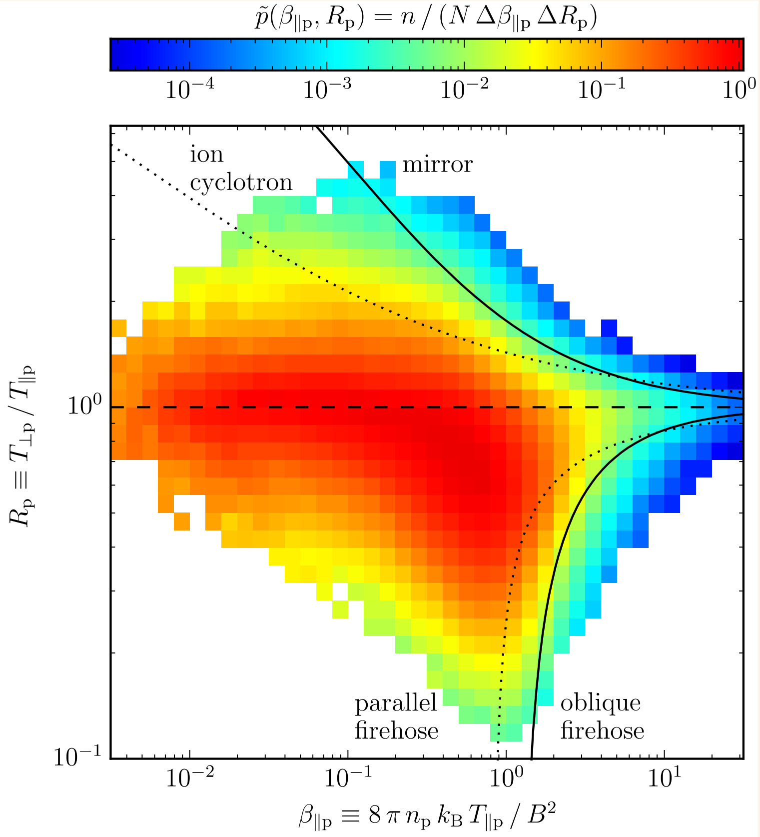
(Verscharen et al. 2019)

Parameters and scales change significantly with distance from the Sun



(Verscharen et al. 2019)

Deviations from equilibrium drive plasma instabilities

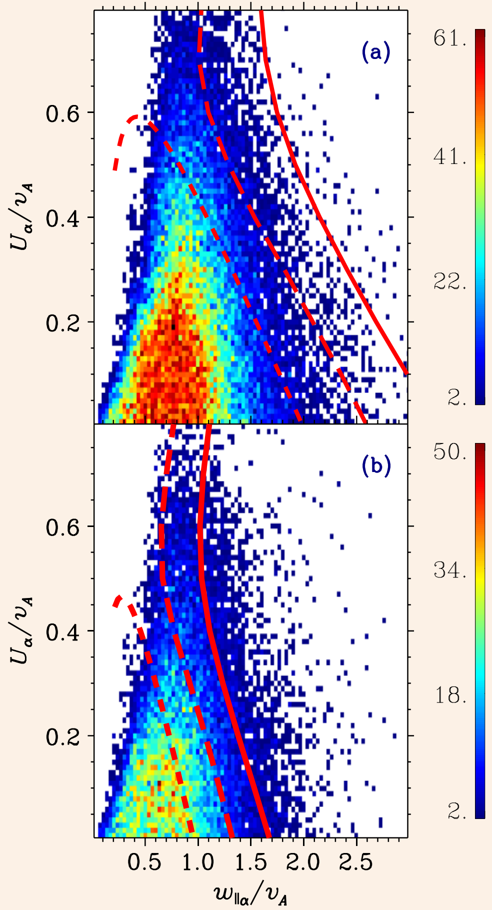


Proton temperature anisotropy can drive small-scale fluctuations in the electromagnetic fields:

- Ion-cyclotron
- Mirror-mode
- Parallel firehose
- Oblique firehose

(Verscharen et al. 2019)

Deviations from equilibrium drive plasma instabilities



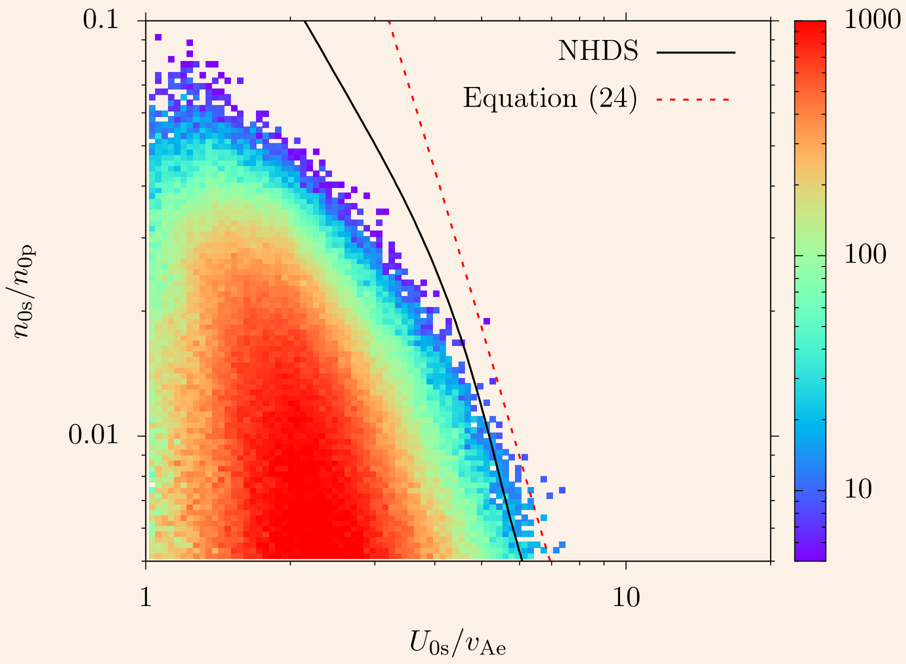
α-particle drift can drive small-scale instabilities:

- Ion-cyclotron wave
- Fast-magnetosonic/whistler wave
- Oblique Alfvén wave

These instabilities are energetically important (more to follow)

(Bourouaine, DV, et al. 2013)

Deviations from equilibrium drive plasma instabilities

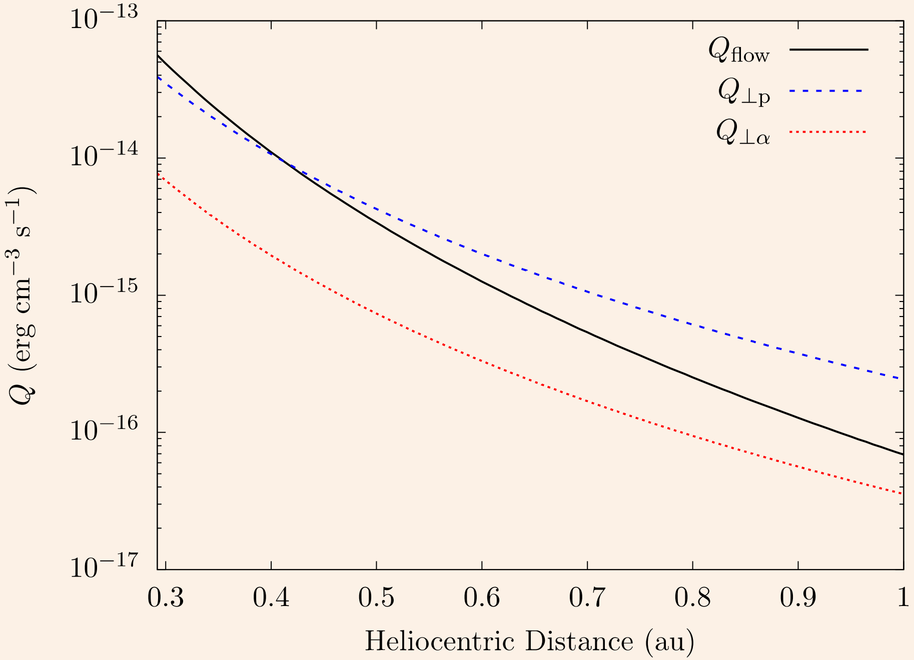


Electron drift can drive (even smaller) small-scale instabilities:

- Oblique fast-magnetosonic/whistler wave
- Whistler heat-flux
- Kinetic Alfvén wave
- Electrostatic electron-beam
- Ion-acoustic wave

(Verscharen et al. 2019b)

Instabilities have an impact on the large-scale properties of the solar wind

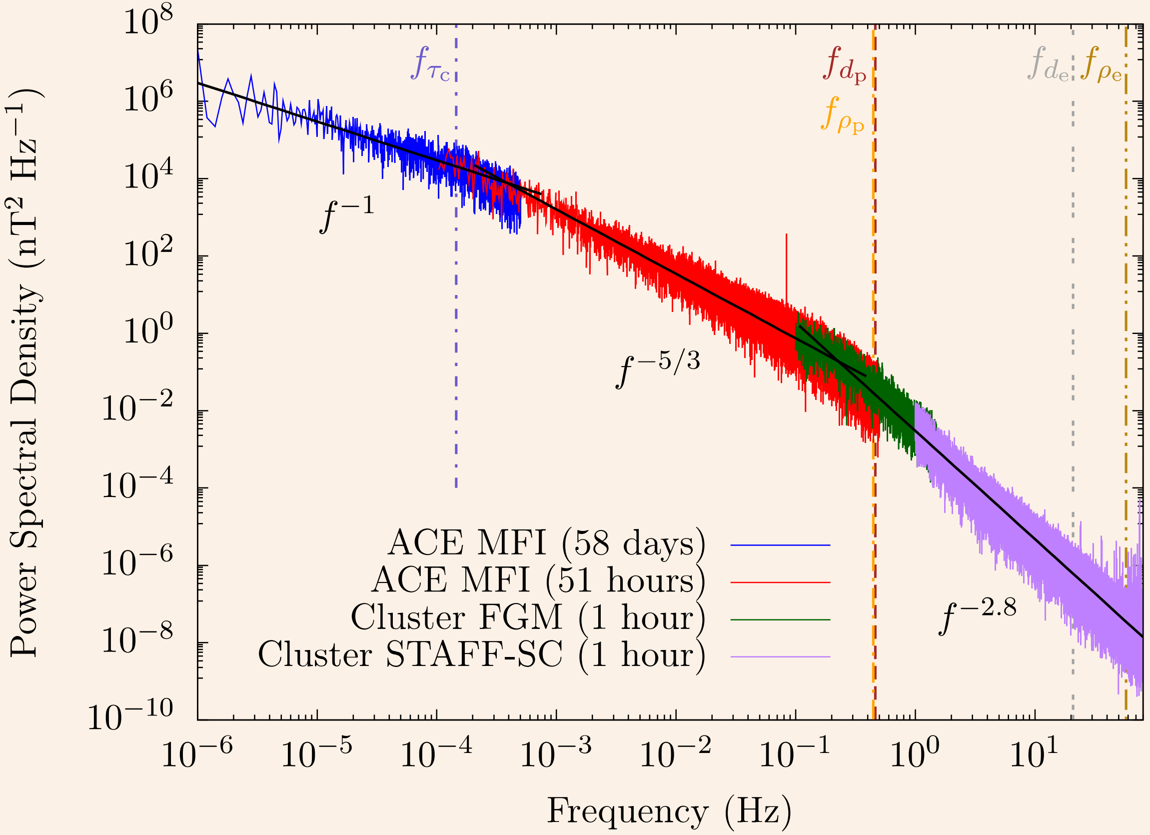


- As the background changes, the thresholds for kinetic instabilities also change.
- This leads to a quasi-continuous excitation of these instabilities.
- Quasi-continuous release of energy and cross-scale coupling.

Comparable to the energy required to explain observed particle heating (especially close to the Sun).

(Verscharen et al. 2015)

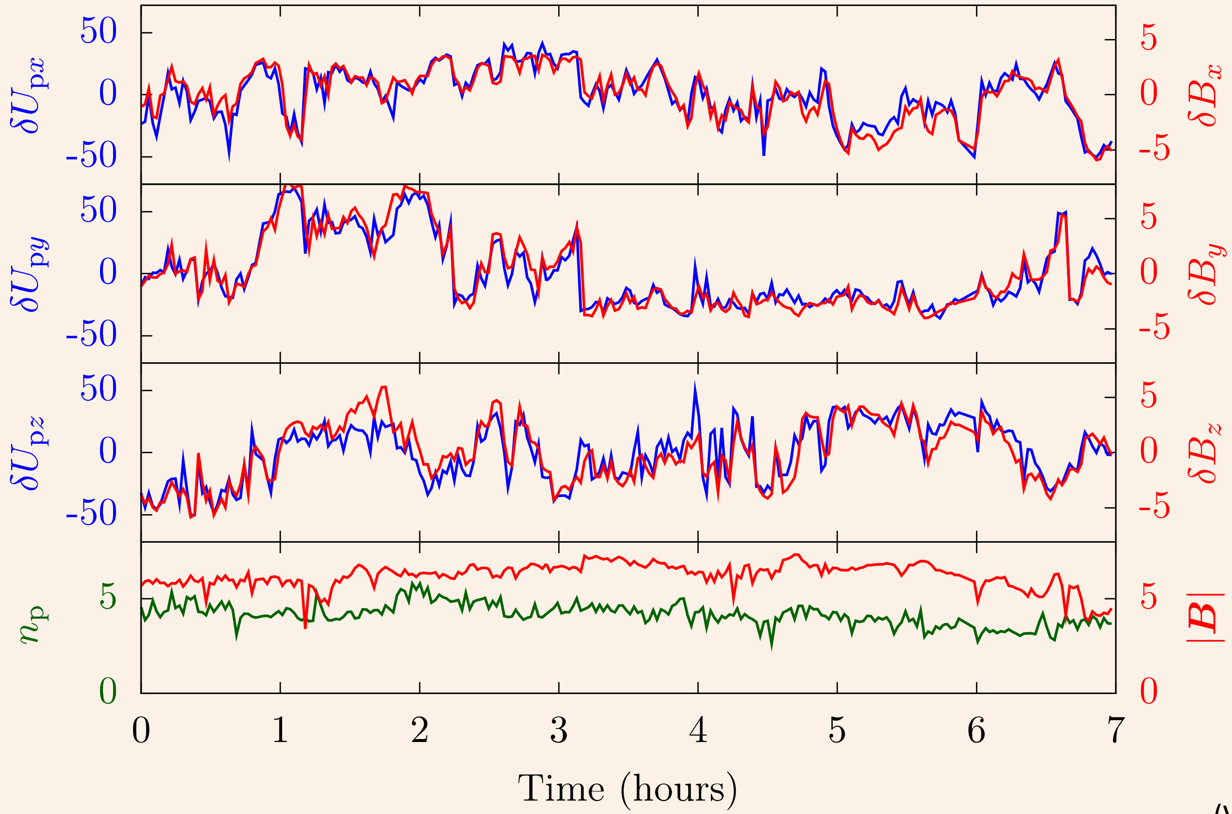
Plasma turbulence: a multi-scale process



- Collisionless plasmas are almost always turbulent.
- Fourier spectrum shows characteristic power-laws.
- Behaviour changes at plasma scales.

(Verscharen et al. 2019)

Plasma turbulence: mostly non-compressive, Alfvénic fluctuations



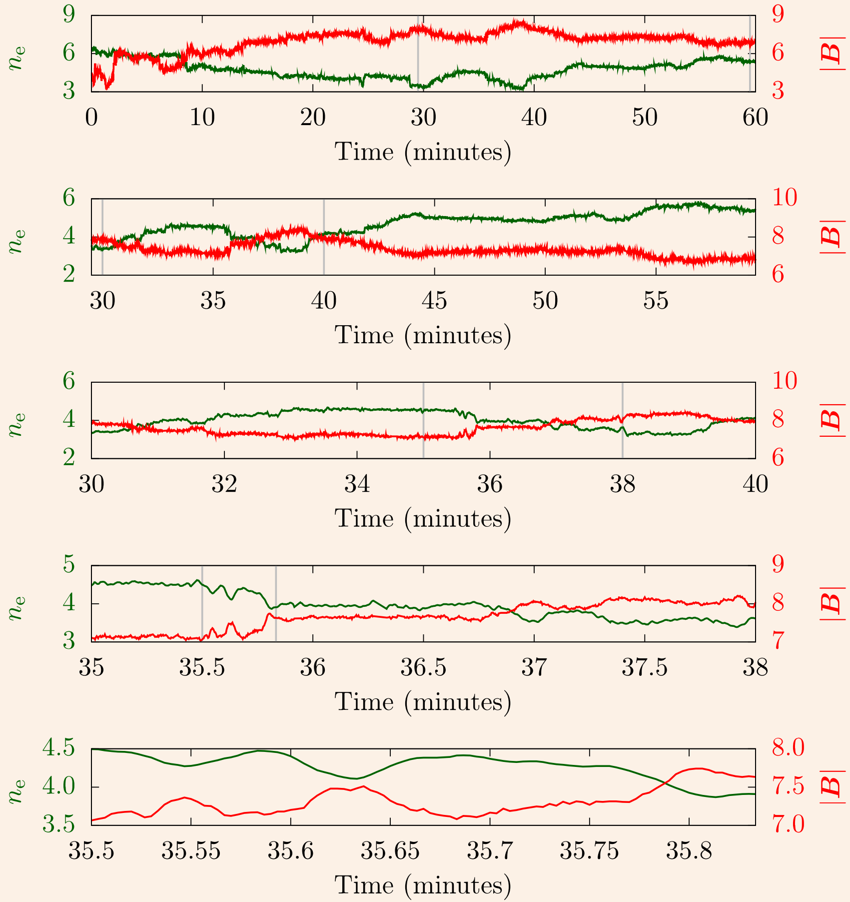
Alfvénic correlation:

$$\frac{\delta \vec{U}}{v_A} = \mp \frac{\delta \vec{B}}{B_0}$$

Density and B-magnitude fluctuations are small.

(Verscharen et al. 2019)

Plasma turbulence: minor compressive component

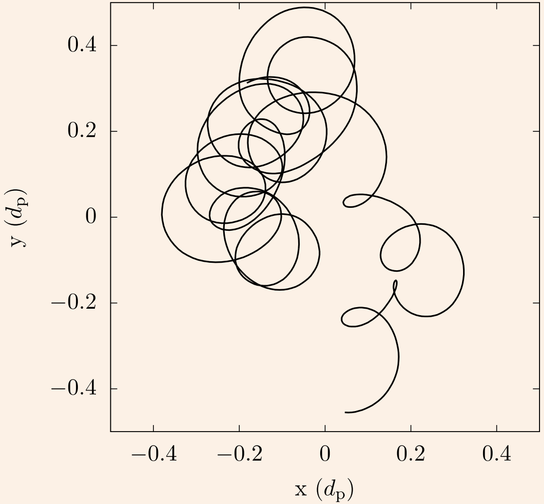


Anti-correlation between density and B-magnitude.

(Verscharen et al. 2019)

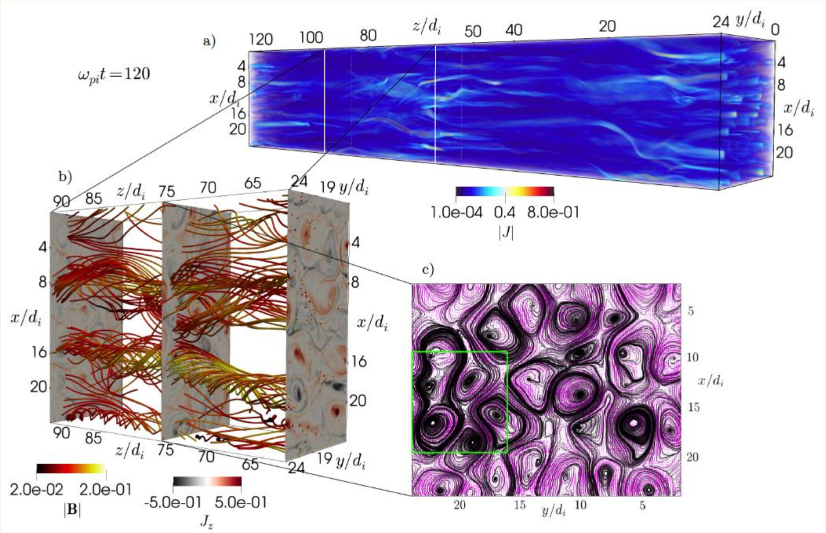
Why is turbulence important?

Test-particle calculation



(Verscharen et al. 2019)

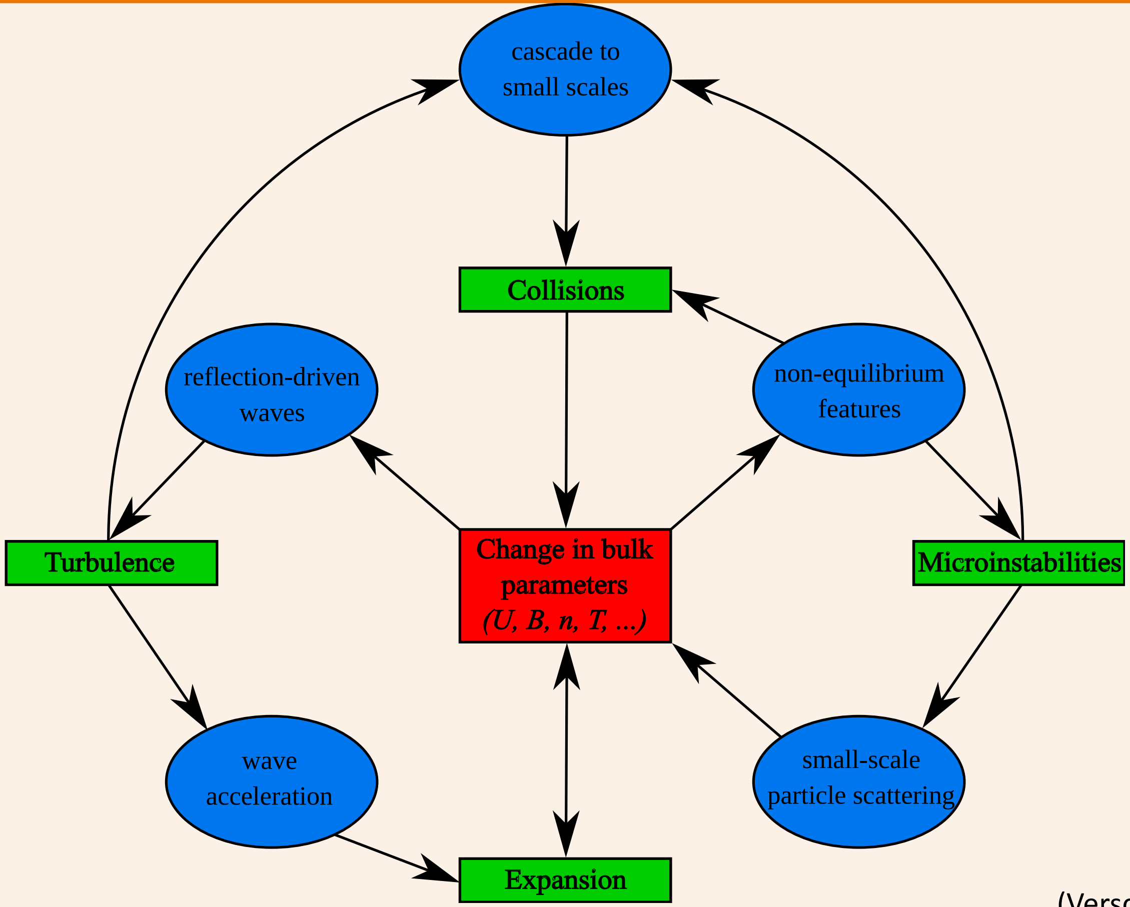
Large-scale simulation



(Agudelo Rueda, DV, et al. 2021)

- Turbulence dissipates and heats the plasma.
- Turbulence scatters energetic particles.
- Turbulence defines the background conditions for instabilities and all space-weather events.

Multi-scale couplings in the solar wind



Multi-scale couplings go in both directions.

We require modern space missions and improvements in super-computing to understand these couplings:

- Explore new parts of the heliosphere
- Smaller scales require higher resolution
- Joint campaigns are becoming more important

(Verscharen et al. 2019)

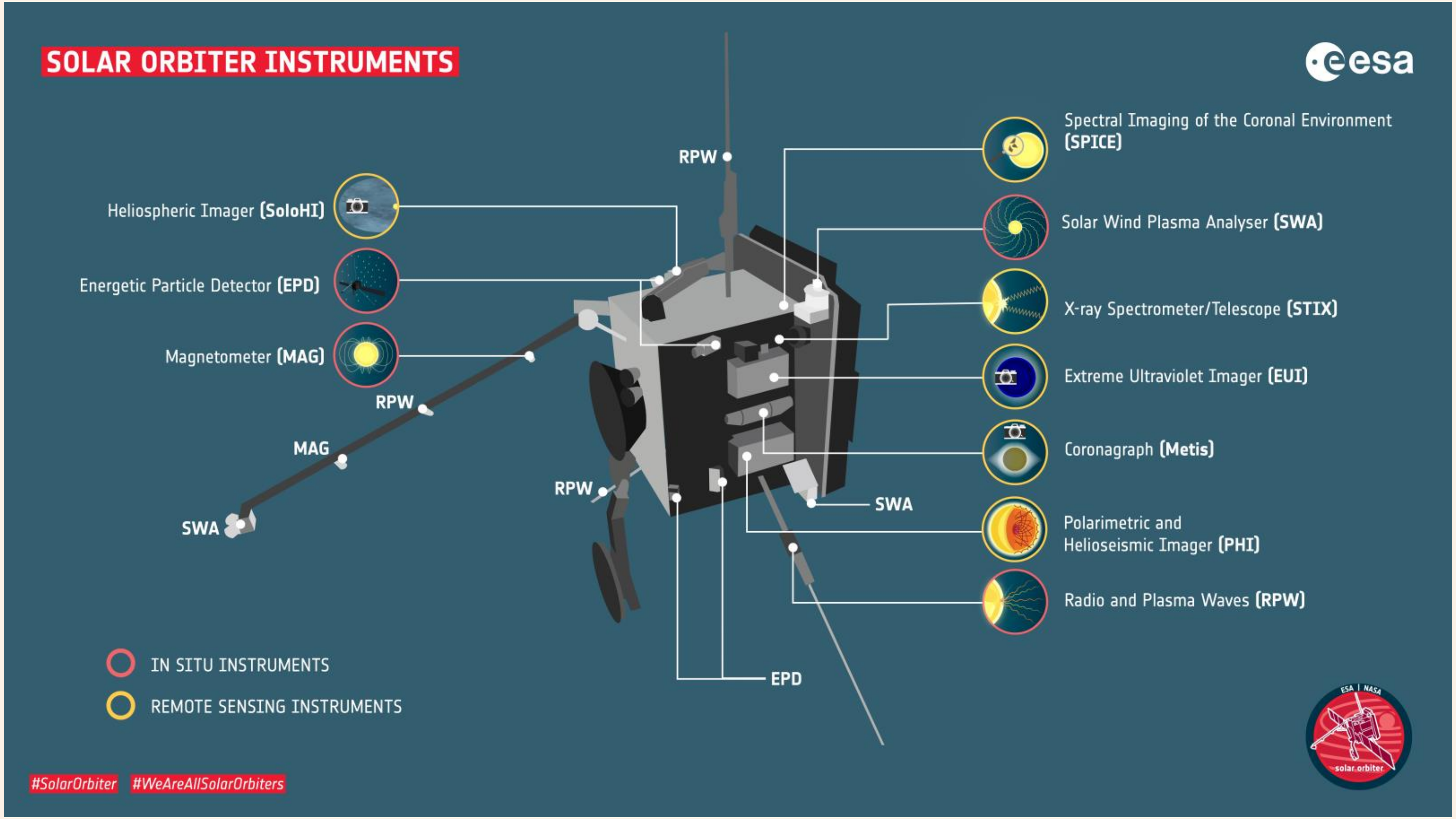
Solar Orbiter: a science mission to study the Sun and the solar wind

Credit: ESA/ATG medialab

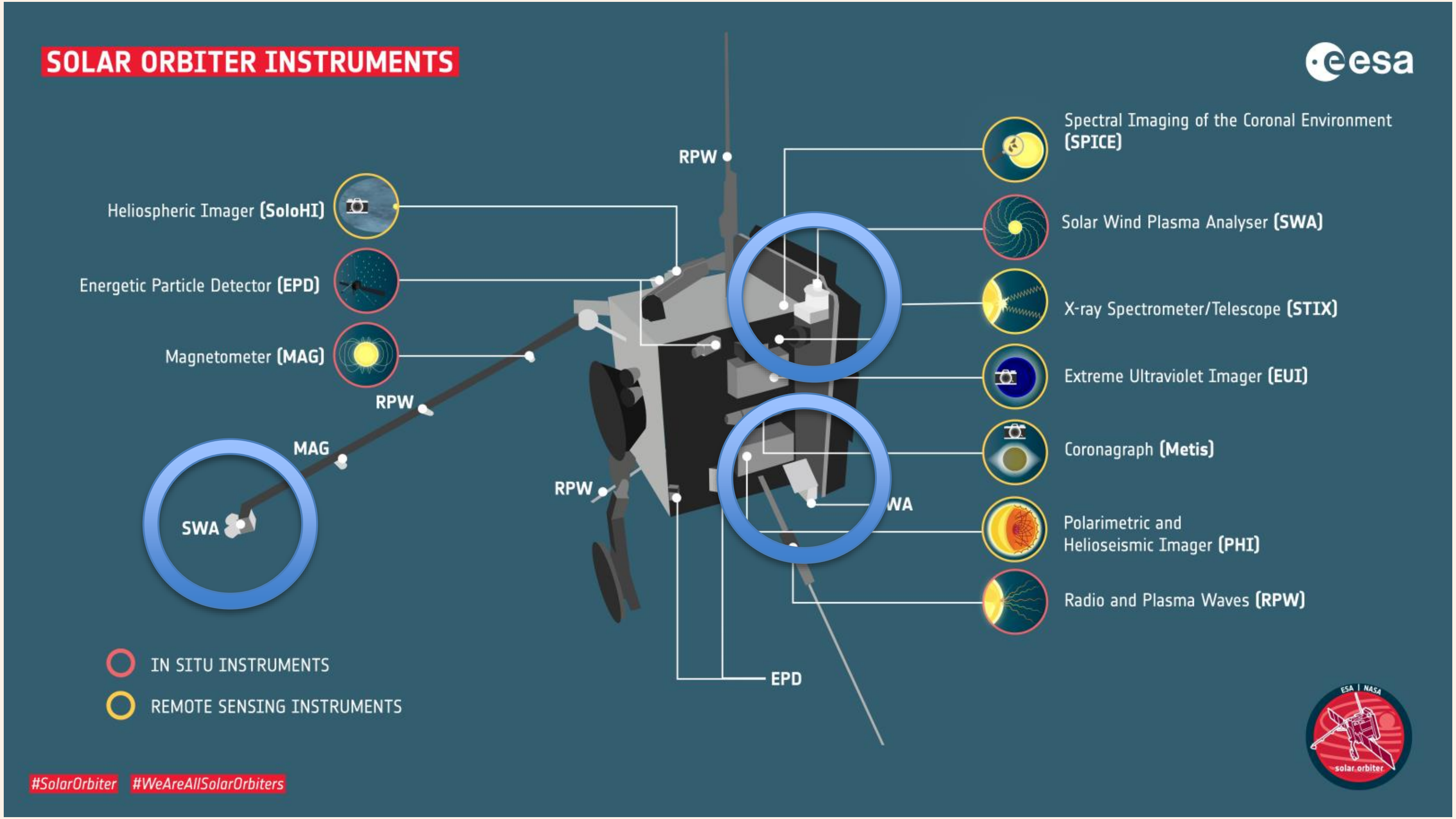
Key science questions for Solar Orbiter:

1. What drives the **solar wind**?
2. What happens in the **polar regions**?
3. How is the **magnetic field** generated?
4. How do **eruptive events** (flares, CMEs) impact the solar system?

Solar Orbiter – combining remote-sensing and in-situ measurements



SWA – Solar Wind Plasma Analyser (led by UCL/MSSL)



SWA – Solar Wind Plasma Analyser (led by UCL/MSSL)

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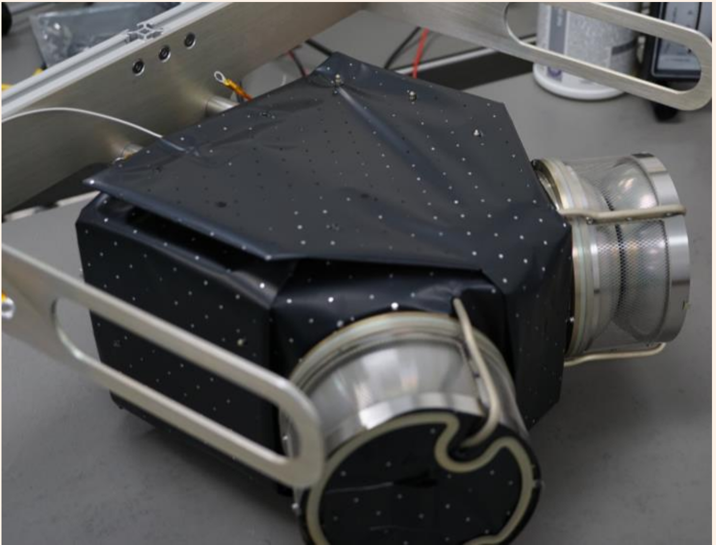
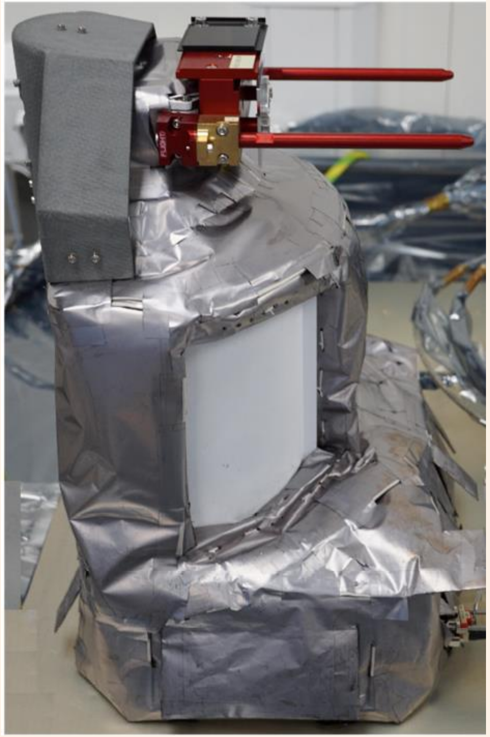
Electron Analyser System
(built at UCL/MSSL)



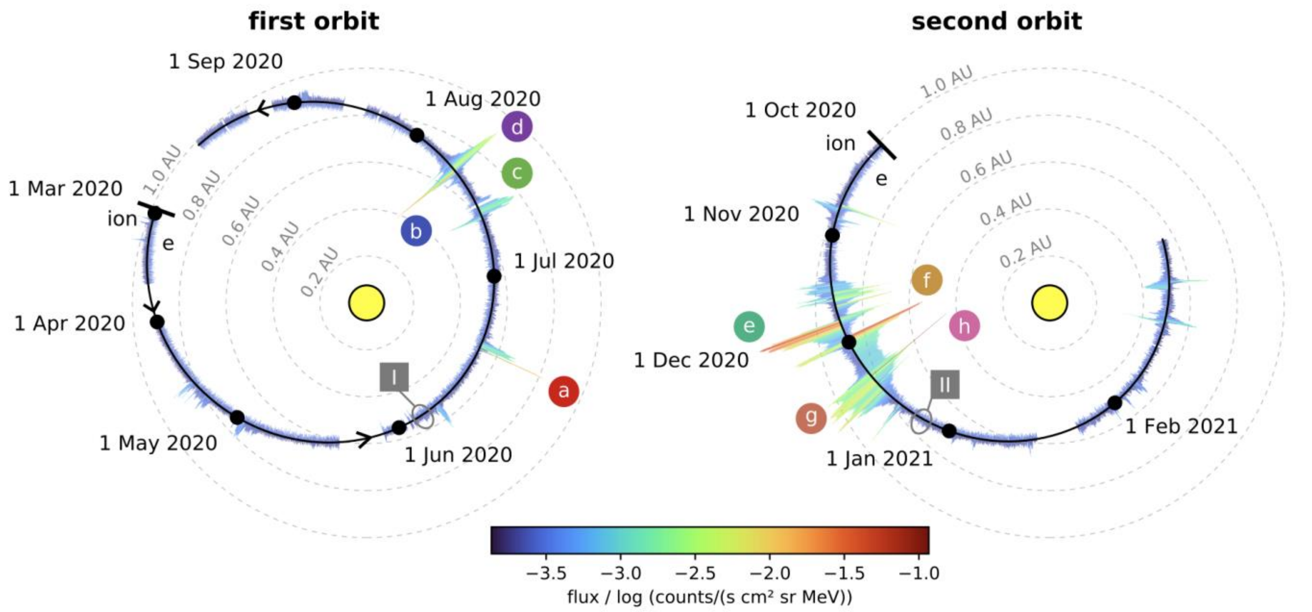
Proton-Alpha Sensor

Heavy Ion Sensor
(provided by NASA)



Solar Orbiter launched successfully in February 2020

EPD science: overview of the first year of energetic-particle measurements



EPD consists of 4 sensors.

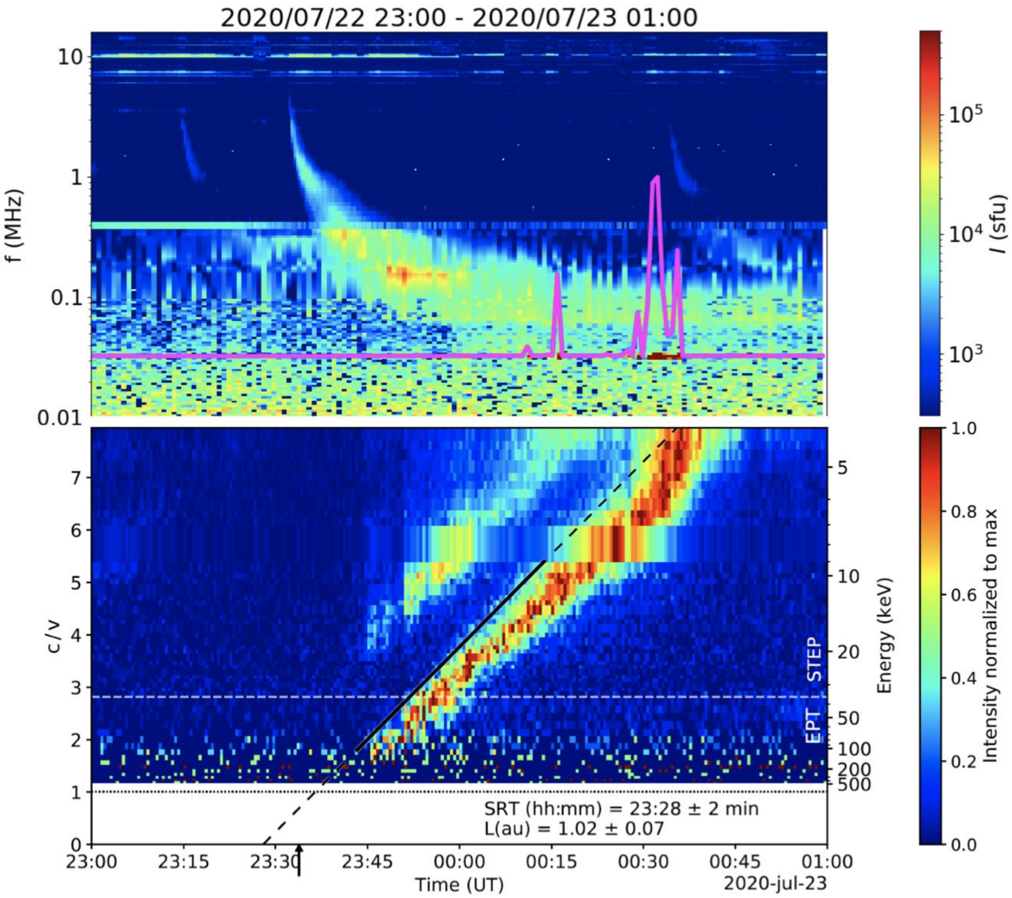
It measures electrons from 4 keV to 30 MeV and ions from 4 keV to 500 MeV/nuc (including some compositional capability).

Some events detected, more studies in A&A special issue.

EPD/EPT data: ions at 124-218 keV (outer), electrons at 54-101 keV (inner)

(Wimmer-Schweingruber et al., 2021)

EPD science: near-relativistic electron events



Type III radio burst are generated by energetic electron beams.

RPW radio spectrum observed in association with an electron event.

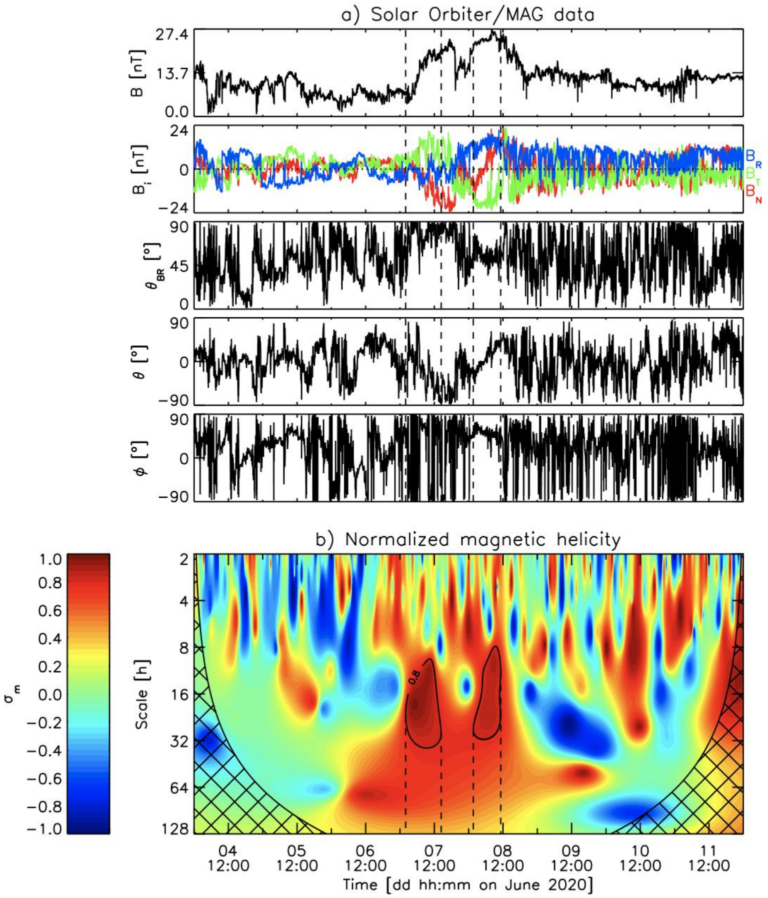
Magenta line: spectral flux at plasma frequency -> locally generated Langmuir waves!

Electron dispersion plot shows arrival of accelerated electrons.

Studies of particle transport.

(Gómez Herrero et al., 2021)

MAG science: large-scale structures – HCS and 2 CMEs



A sharp HCS crossing observed on 07 June.

Before and after the HCS crossing, two helical structures are seen.

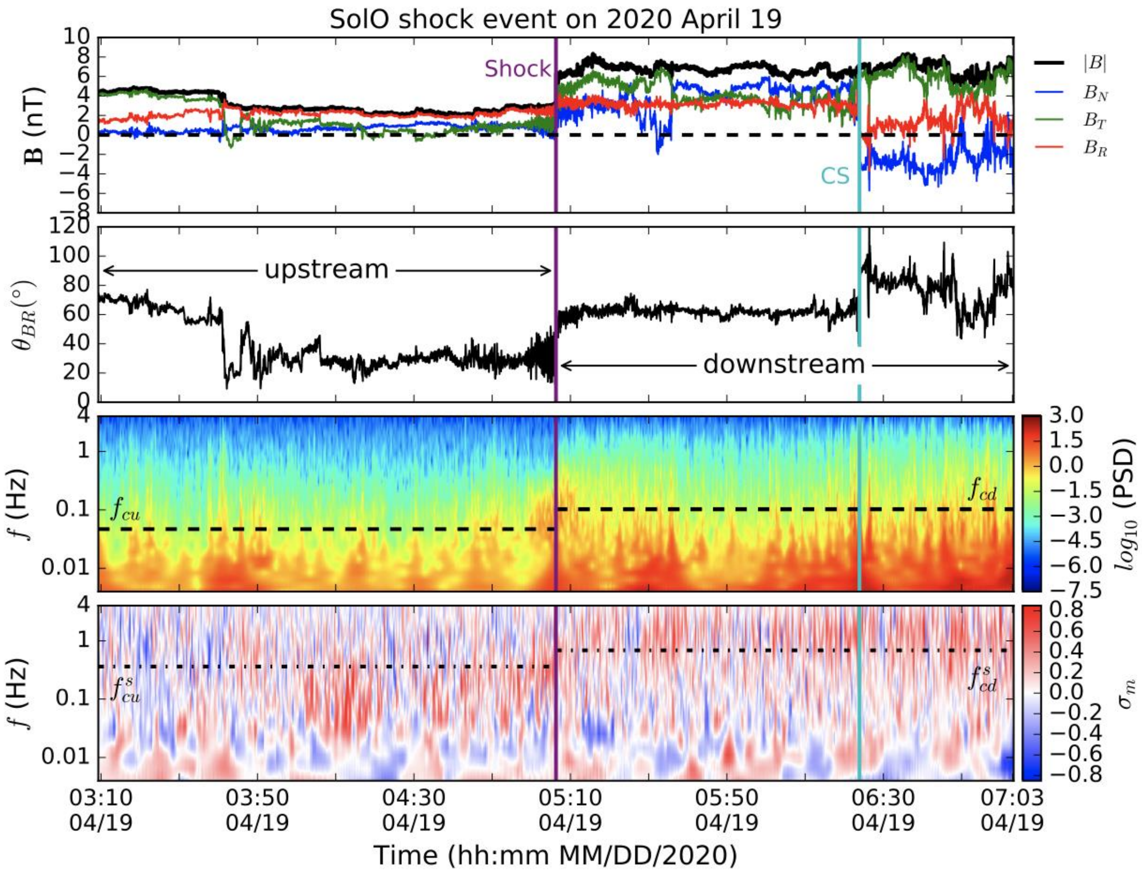
Normalised magnetic helicity spectrogram confirms these large-scale magnetic-field structures.

These structures are identified as two interacting CMEs, separated by the HCS.

Signatures for magnetic reconnection (supported by MHD simulations).

(Telloni et al., 2021)

MAG science: turbulence and waves at a CME-driven shock



Multiple MAG turbulence studies.

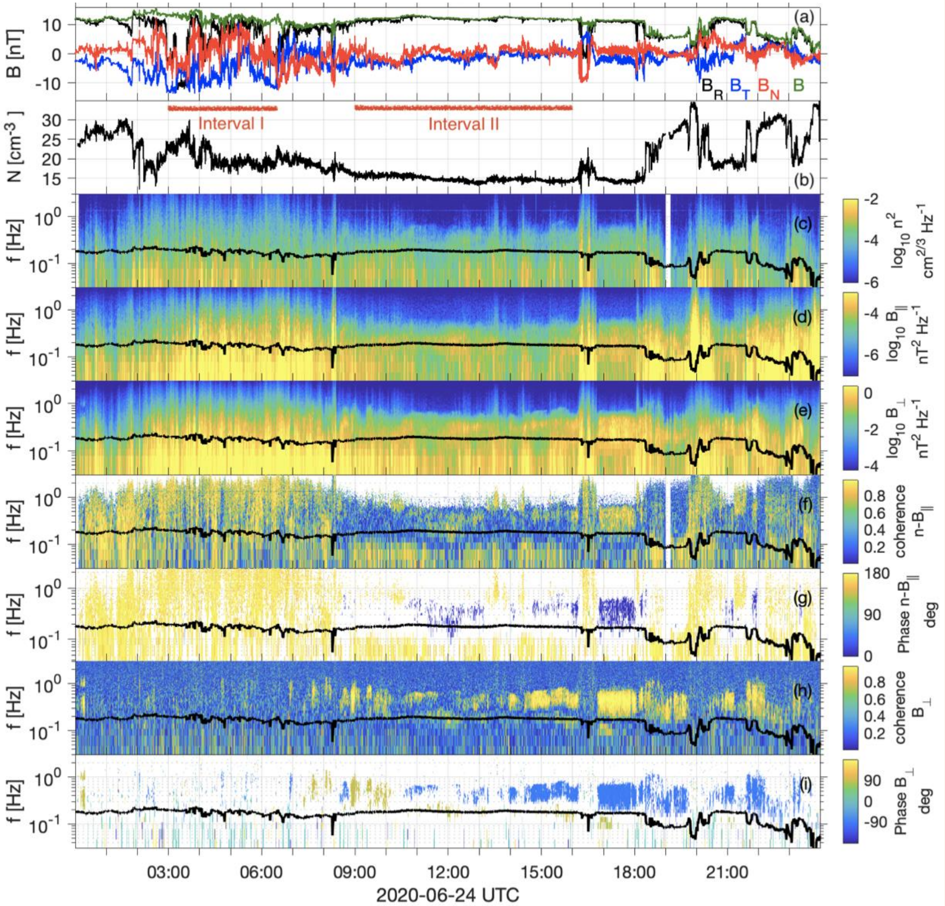
Higher turbulence level downstream -> shock amplification.

Prior to shock, positive helicity signal at 0.1 Hz; i.e., right-hand polarised waves.

After crossing, these waves exist at higher frequencies (transmitted or locally generated?).

(Zhao et al., 2021)

RPW science: density fluctuations due to turbulence and waves



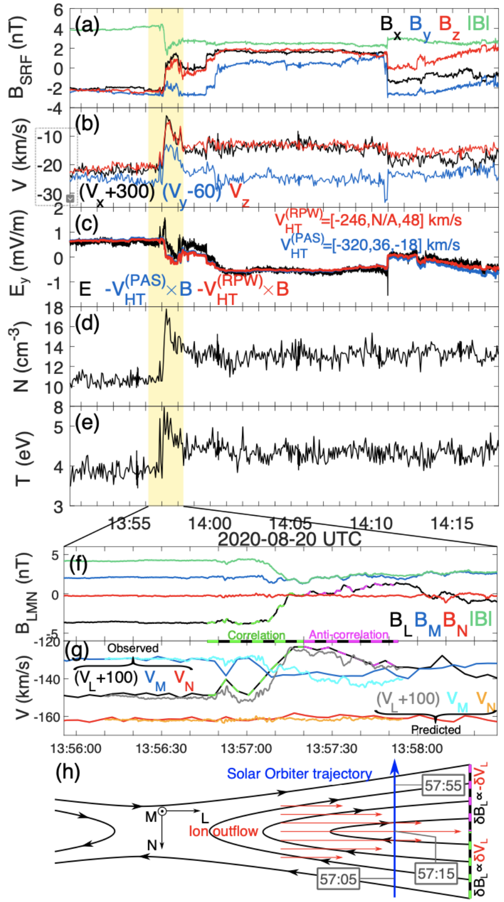
RPW delivers an independent and fast measurement of the electron density based on probe-to-spacecraft potential and QTN measurements.

Interval I: high level of turbulence.

Interval II: presence of weakly-compressive ion-cyclotron waves.

Combination with MAG data allows wave identification.

(Khotyaintsev et al., 2021)



RPW measures (in addition to B-field fluctuations and the potential) also the electric field.

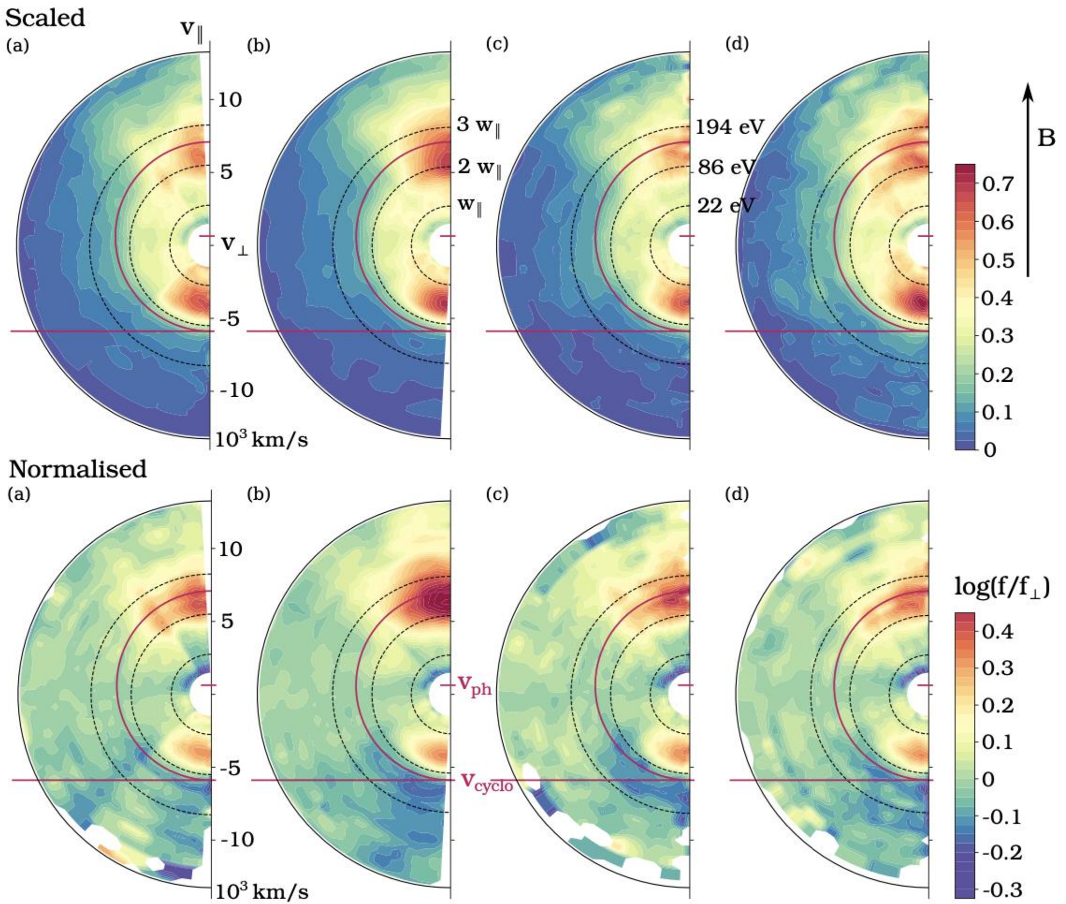
De Hoffmann-Teller frame analysis of reconnecting current sheets by combining RPW with SWA/PAS.

Convection electric field from particle data and measured electric field agree very well.

Correlation and anti-correlation between V and B is consistent with expectation for reconnection event.

(Steinvall et al., 2021)

SWA science: high-cadence electron observations



SWA has three sensors: PAS, EAS, and HIS.

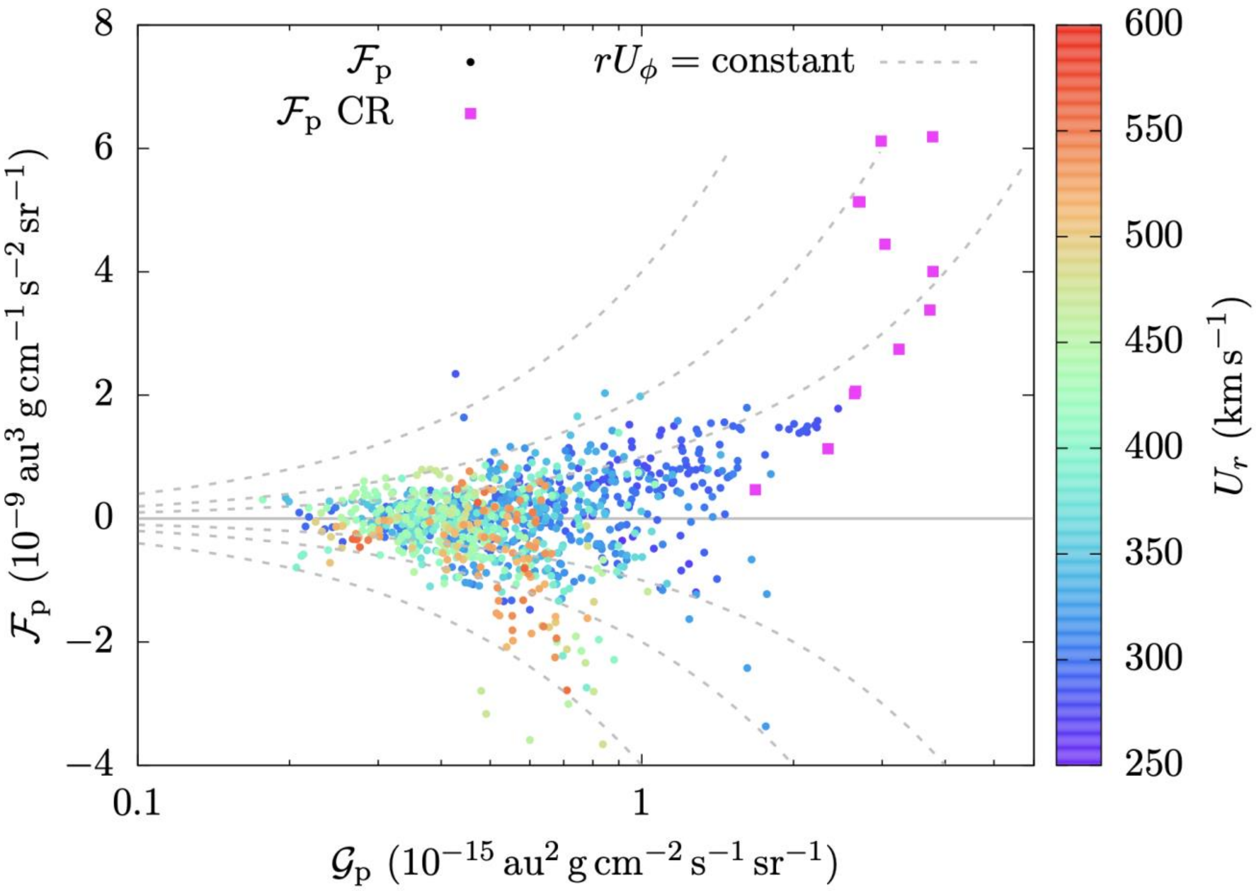
EAS burst-mode data provides pitch-angle distributions with 0.125 s cadence.

High-resolution pitch-angle data reveal sporadic sunward electron deficit in the solar wind.

Combined with RPW measurements of B-field fluctuations, a new whistler-wave instability is found.

(Bercic, DV, et al., 2021)

SWA science: angular-momentum loss of the solar wind



Angular-momentum flux

$$\mathcal{F}_\mathrm{p} = r^3 \rho U_r U_\phi$$

and mass flux

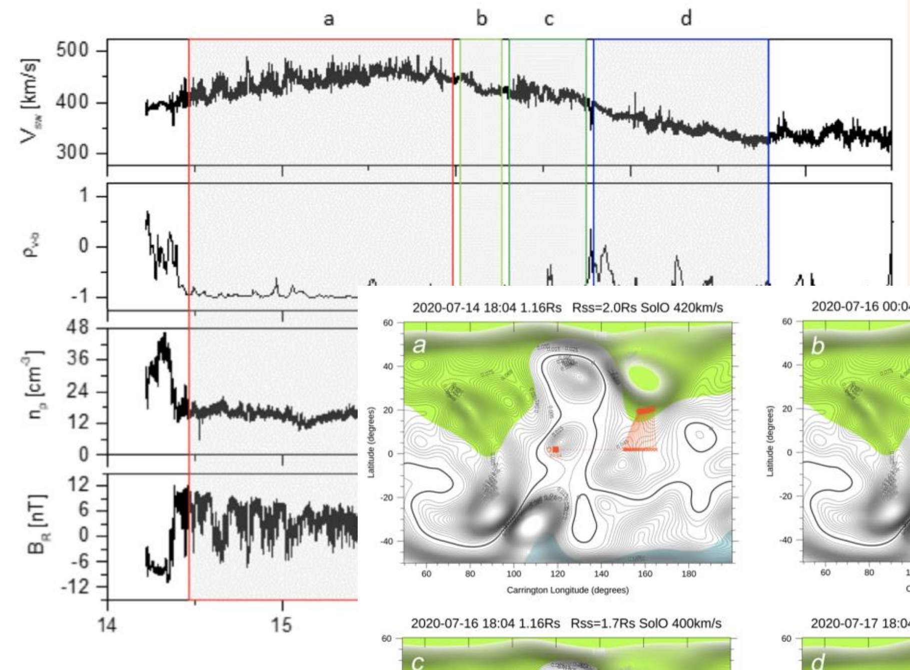
$$\mathcal{G}_\mathrm{p} = r^2 \rho U_r$$

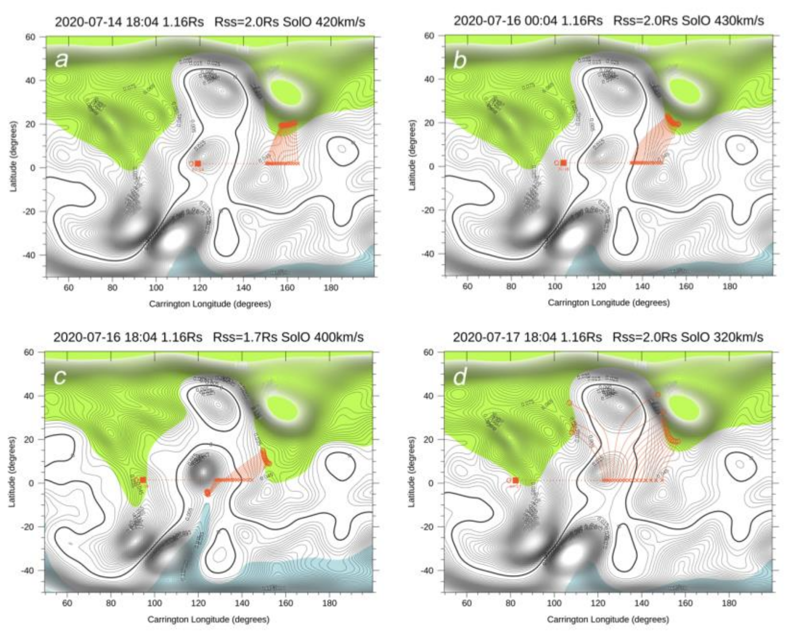
show systematic offset to net angular-momentum loss in slow (high-G) wind.

Compression region (CR) has the same angular momentum per unit mass as slow wind.

(Verscharen et al., 2021)

Connection science: slow Alfvénic solar wind and its source regions





In-situ measurements of the solar wind and Alfvénic fluctuations are combined with connectivity model (PFSS model).

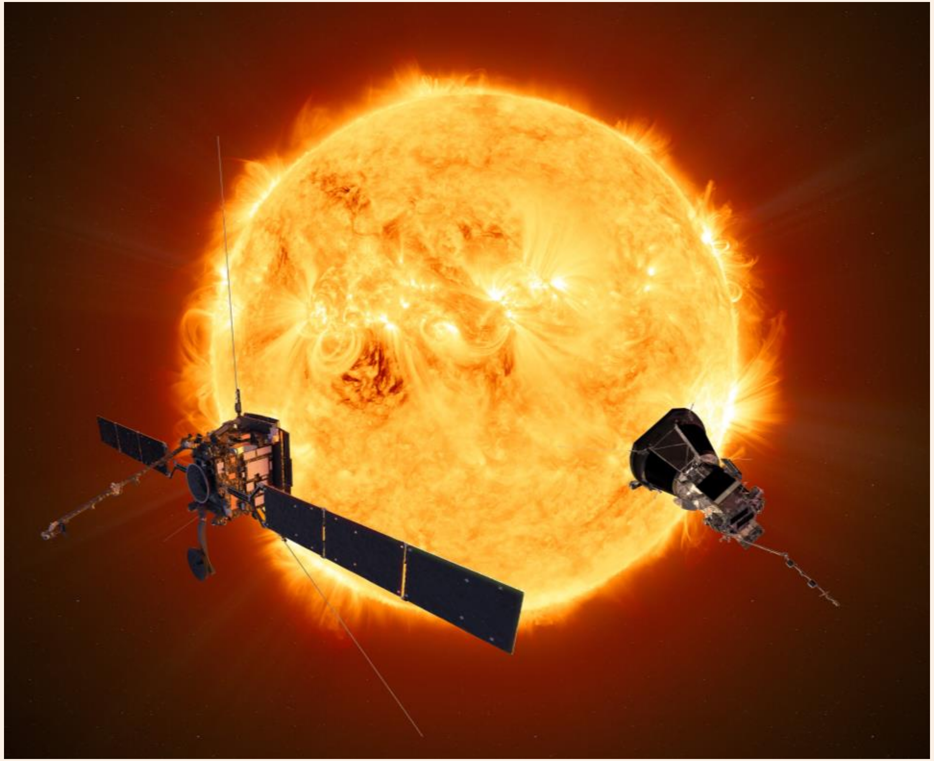
Transitions between coronal holes, helmet streamers and pseudostreamers identified in the source regions.

In the future, remote observations will be combined with in-situ measurements to understand solar-wind source regions.

(D'Amicis, DV, et al., 2021)

The solar wind from the Sun to the Earth: a multi-scale plasma

UCL



Credit: ESA/ATG medialab

@DVerscharen

The solar wind is a multi-scale plasma that fills the interplanetary space.

It is the background for *all* space-weather events.

Solar Orbiter links remote-sensing observations with in-situ measurements to cover the multi-scale physics of the inner heliosphere.

This is a very exciting time for solar and space physicists across the world!