

Tracing Heliospheric Structures to Their Solar Origin

The background of the slide is a composite image. In the center is a bright, orange-yellow sun with visible solar flares and coronal loops. To the left, a solar orbiter satellite is shown in orbit, with its solar panels extended. To the right, a large, stylized, orange-yellow heliospheric structure, possibly a coronal mass ejection or a solar wind stream, is depicted flowing outwards. The overall color scheme is dominated by warm tones of orange, yellow, and red, set against a dark blue/black background representing space.

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Tracing Heliospheric Structures to Their Solar Origin

The background of the slide is a composite image. In the upper left, a satellite with solar panels is shown. In the center, the Sun is depicted as a bright, orange-yellow sphere with visible solar flares and coronal loops. Large, flowing structures of the solar wind, in shades of orange and yellow, are shown emanating from the Sun and filling the background.

The Problem
What can we measure?
Linkage...
The End



Remote-sensing
windows (10 days
each)

The diagram shows a satellite in a highly elliptical orbit around the Sun. The Sun is at the center, depicted as a bright orange and yellow sphere. The satellite is shown in three positions along its orbit, each with a yellow rectangular box indicating a remote-sensing window. The background is a dark space with some nebulae and stars.

High-latitude
Observations

Perihelion
Observations

High-latitude
Observations

The Problem

**How does the Sun create and control the Heliosphere
– and why does solar activity change with time ?**

- 1) What drives the solar wind and where does the coronal magnetic field originate from?
- 2) How do solar transients drive heliospheric variability?
- 3) How do solar eruptions produce energetic particle radiation that fills the heliosphere?
- 4) How does the solar dynamo work and drive connections between the Sun and the heliosphere?

Remote-sensing
windows (10 days
each)

High-latitude
Observations

Perihelion
Observations

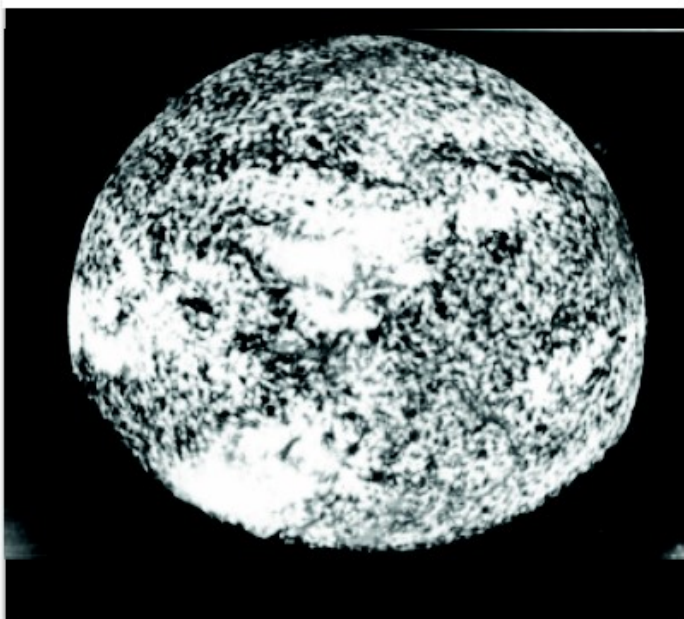
High-latitude
Observations

What can we measure?

- Magnetic field on the Sun (PHI)
- Hydrogen density (EUI, METIS)
- Helium density (EUI)
- Composition on disk (SPICE)
- LOS flow velocities (SPICE, PHI)
- He/H in corona (EUI & METIS)
- Turbulence in corona (EUI, SoloHI)
- Eruptive events (EUI, METIS, PHI, SoloHI, STIX)

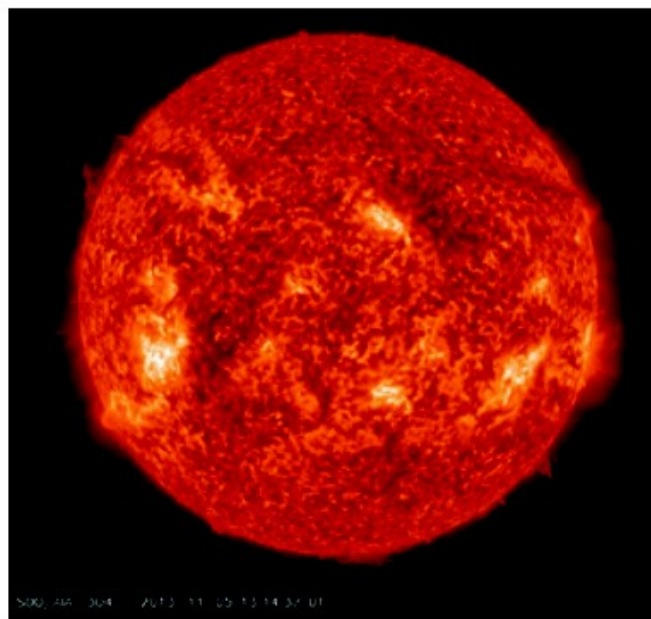


TRC (Bonnet et al, 1980)



H Lyman alpha 121.6nm
chromosphere

SDO/AIA



He II 30.4nm
transition region

PROBA2/SWAP



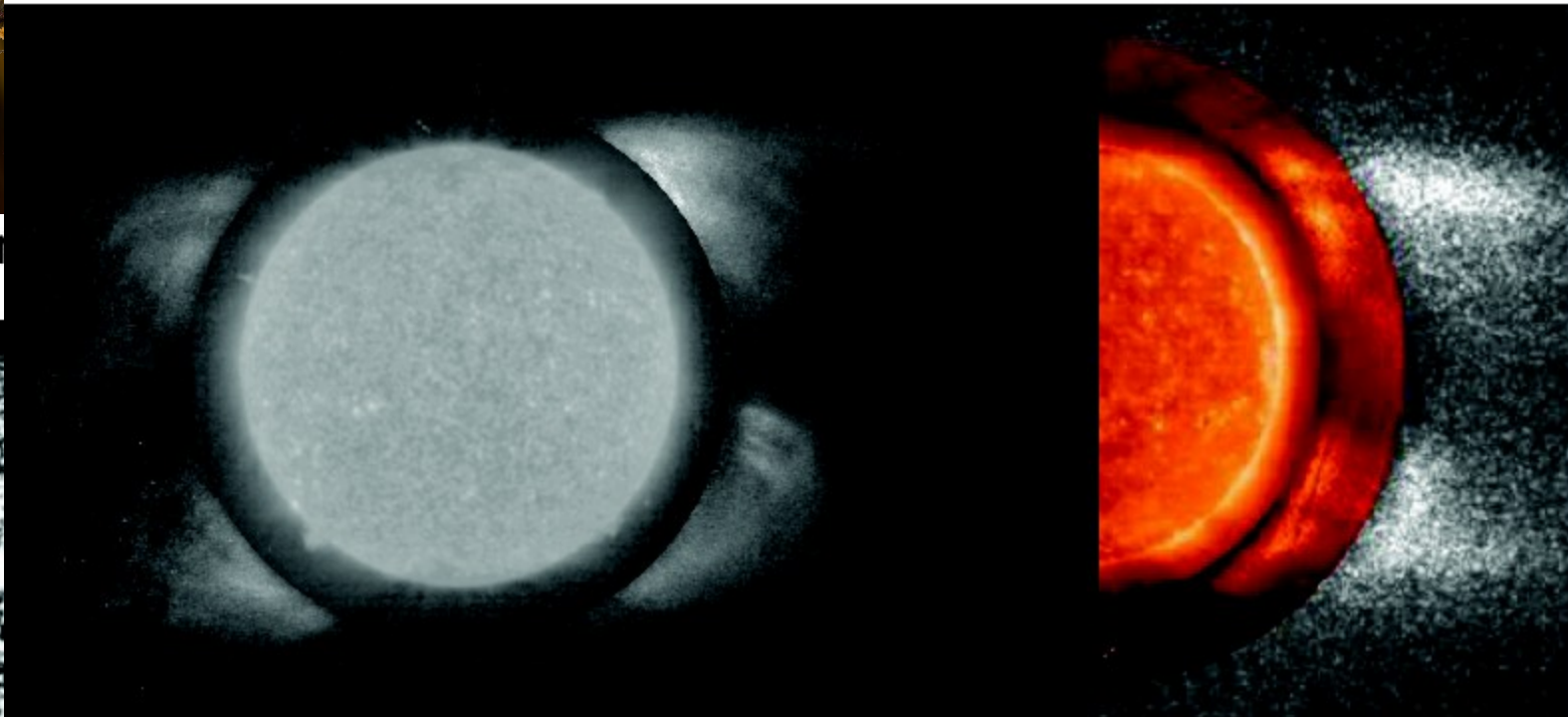
Fe IX, X, XI ~ 17nm
low corona

Remote-sensing
windows (10 days
each)

EIT

HECOR

SCORE



TRC (Bon)

AP

Courtesy F. Auchere

Courtesy S. Finesschi

H Lyman alpha 121.6nm
chromosphere

He II 30.4nm
transition region

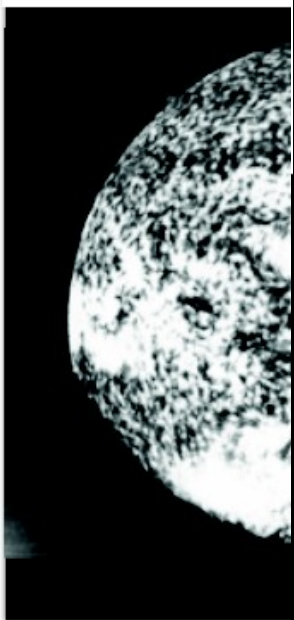
Fe IX, X, XI ~ 17nm
low corona

Remote-sensing windows (1 each)

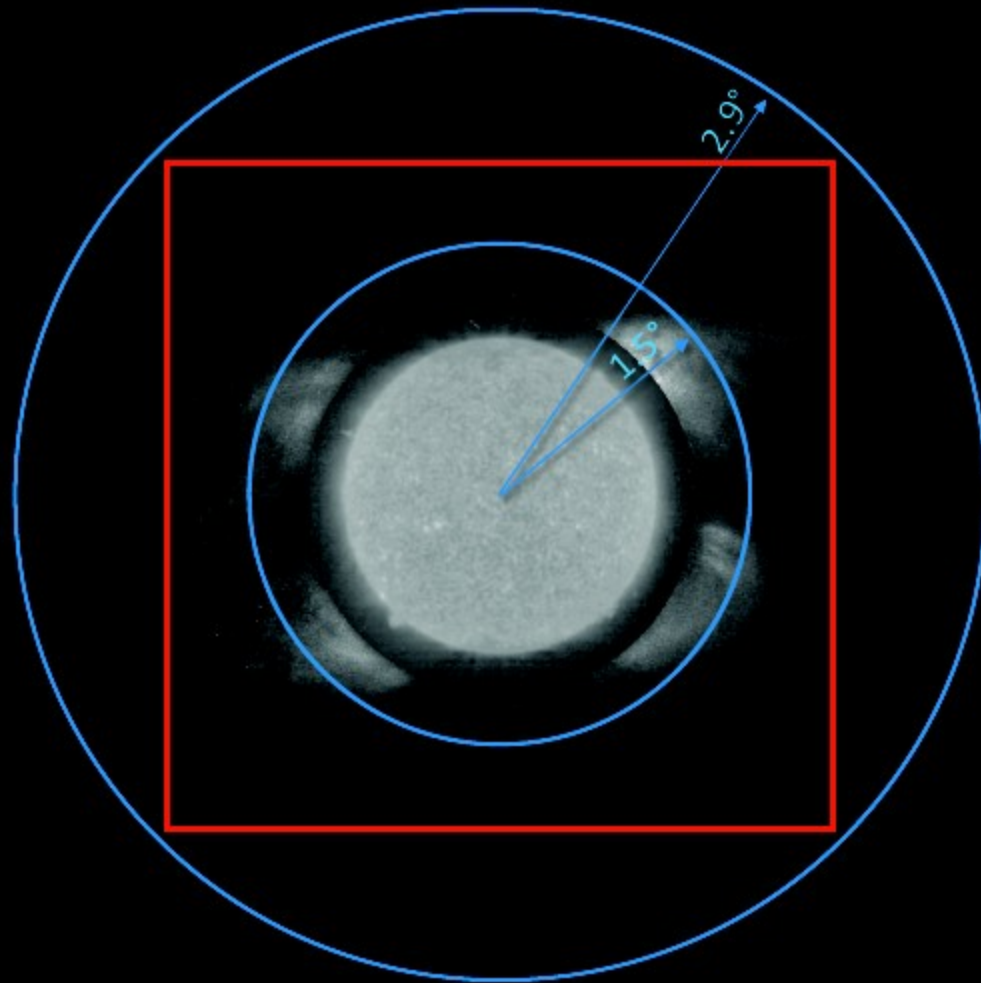
FSI & METIS: 30.4 @ 0.28 AU



TRC (Bonn)



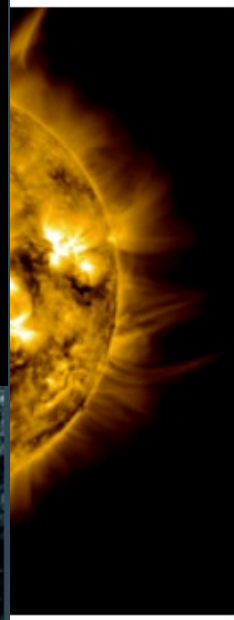
H Lyman α
chrom



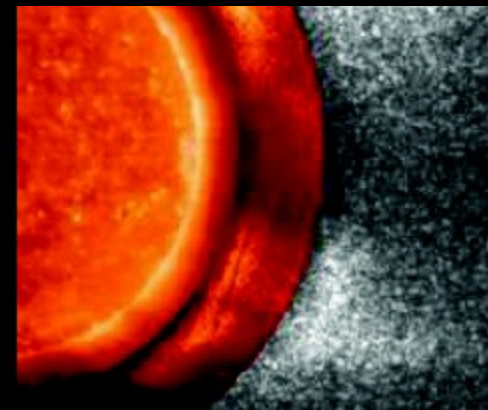
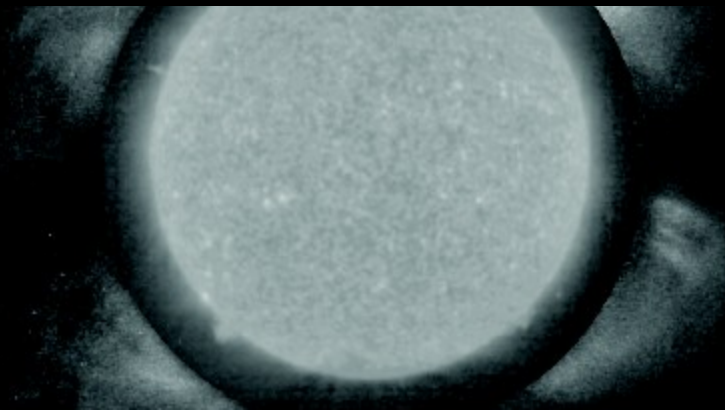
SP+



AP



7nm
a



Remote-sensing
windows (10 days
each)

High-latitude
Observations

Perihelion
Observations

High-latitude
Observations

What can we measure?

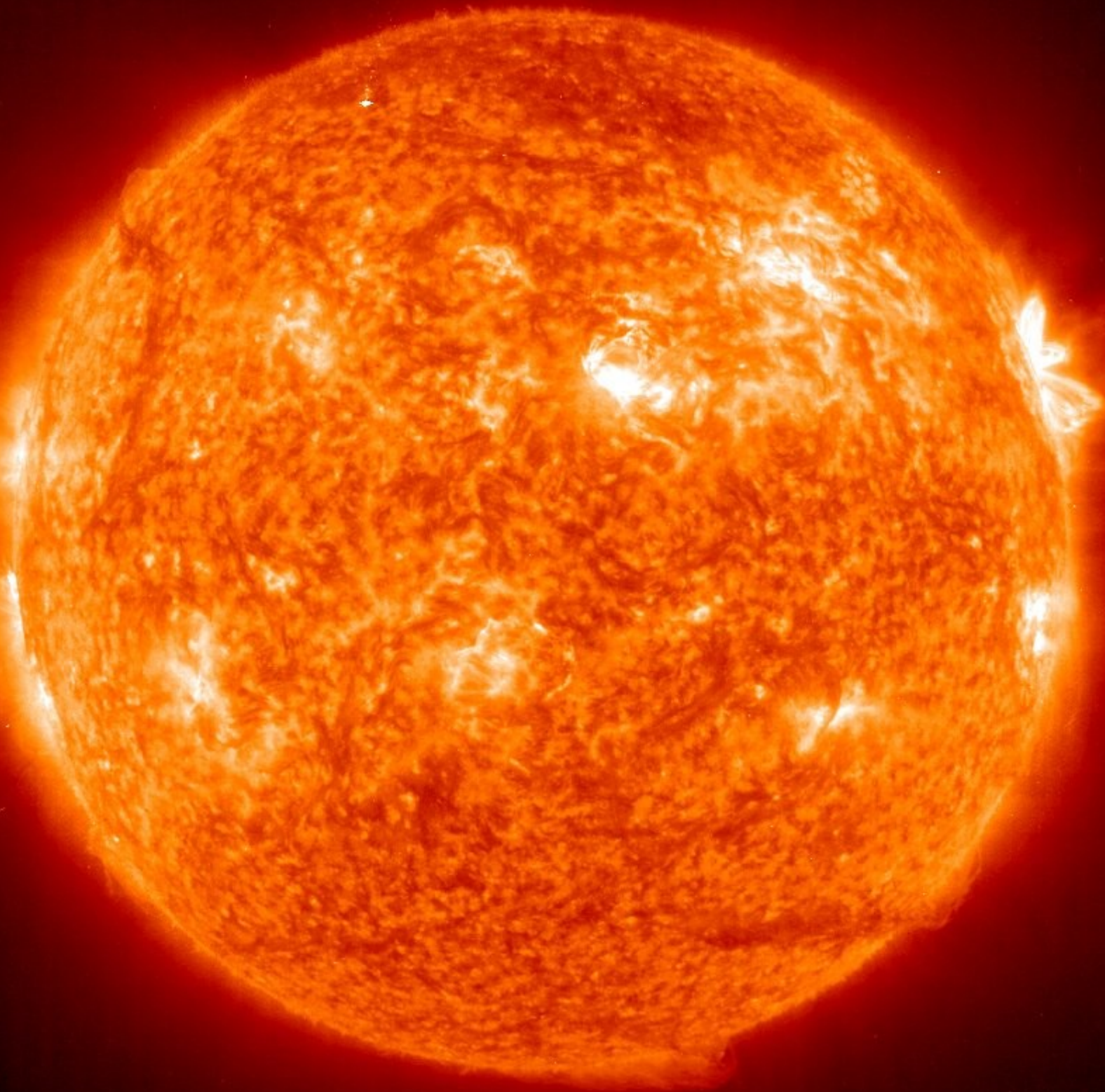
- Magnetic field on the Sun (PHI)
- Hydrogen density (EUI, METIS)
- Helium density (EUI)
- Composition on disk (SPICE)
- LOS flow velocities (SPICE, PHI)
- He/H in corona (EUI & METIS)
- Turbulence in corona (EUI, SoloHI)
- Eruptive events (EUI, METIS, PHI, SoloHI, STIX)

Remote-sensing
windows (10 days
each)

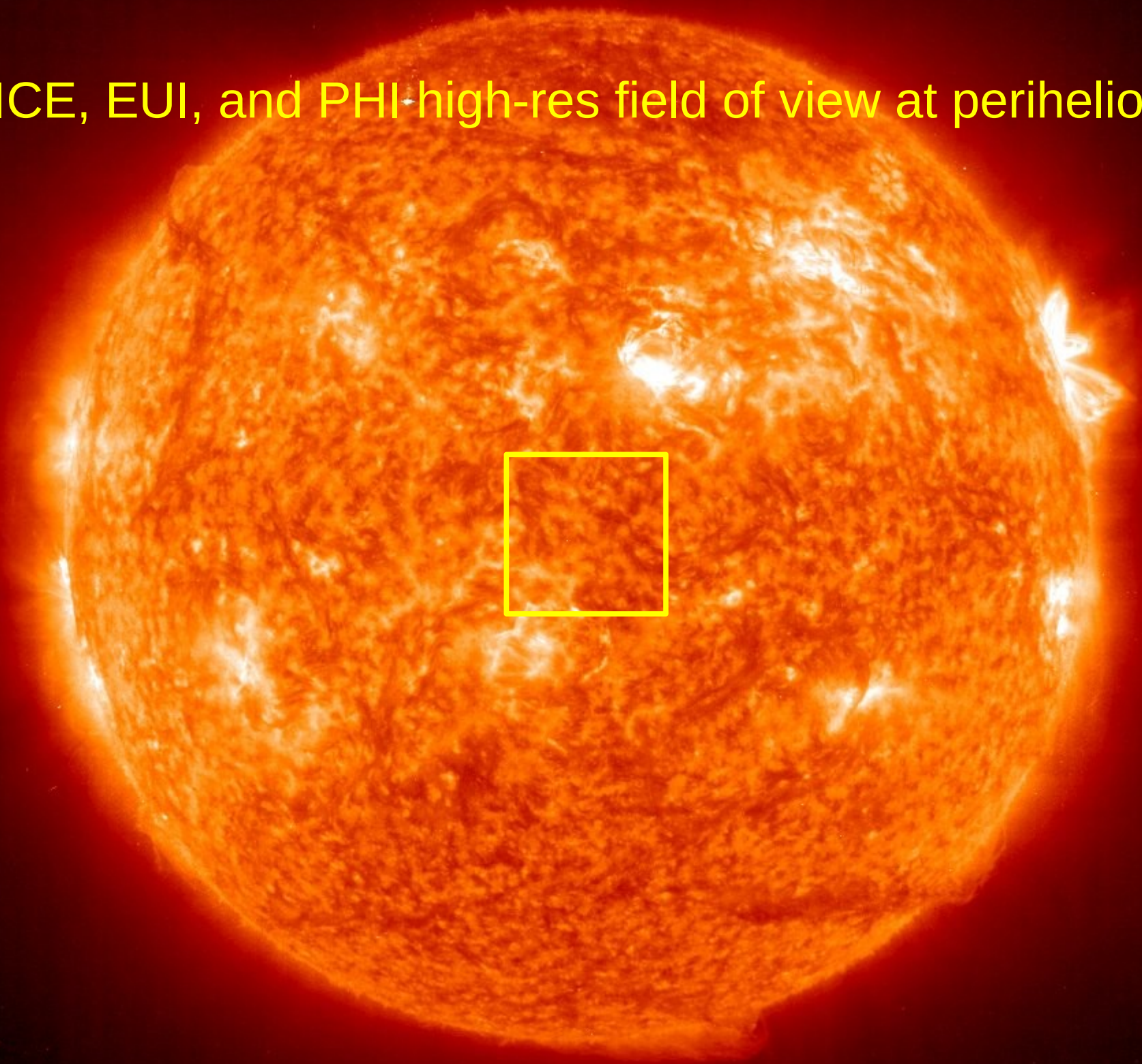
High-latitude
Observations

What can we measure?

Property	remotely	In situ
Magnetic field	PHI (disk, low corona)	MAG, (SWA)
H & He density	EUI, METIS (corona)	SWA, (SPC)
Composition	SPICE (disk)	SWA
LOS flow velocities	PHI, SPICE (disk)	
Turbulence	EUI, Solo-HI (corona)	MAG, RPW, SWA
Eruptive events	EUI, METIS, PHI, Solo-HI, STIX	EPD, MAG, RPW, SWA

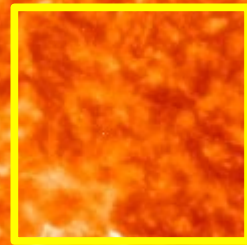


SPICE, EUI, and PHI high-res field of view at perihelion



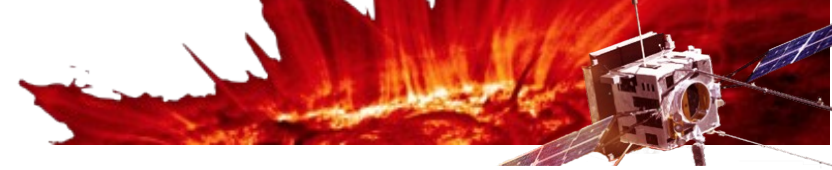
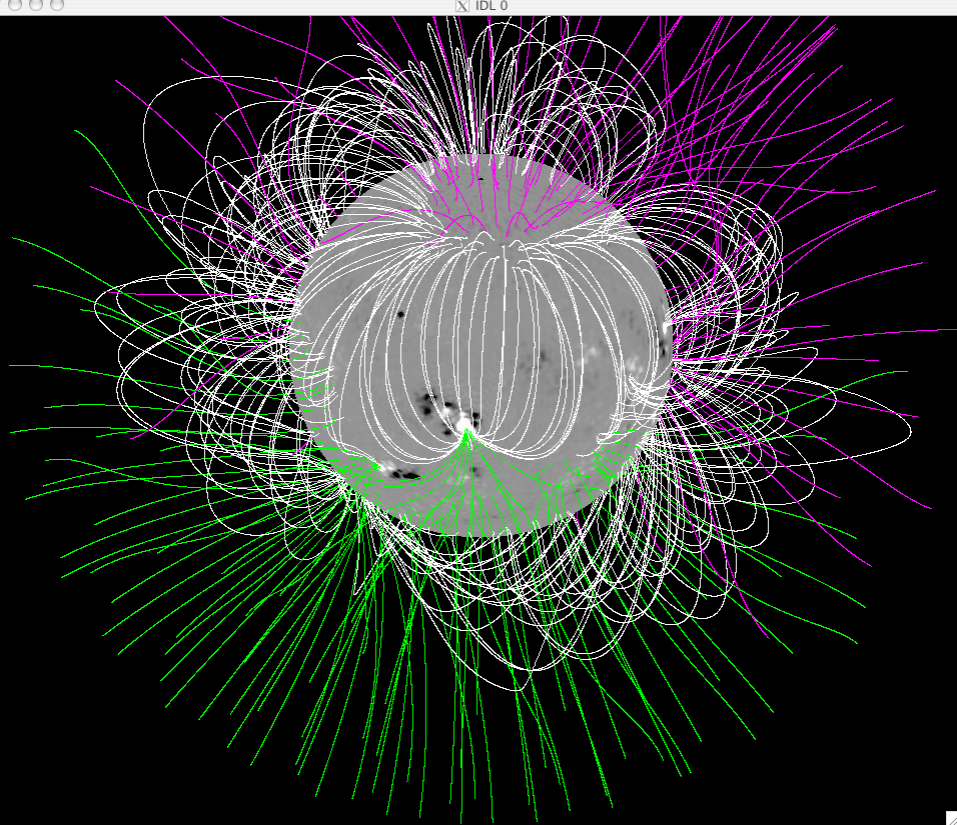
3% of disk at perihelion:

- approx. 18 degrees as seen from Sun center
- apparent solar rotation rate at perihelion is $\sim 6^\circ/\text{day}$
- thus, same source region remains in box for ~ 3 days
- typical travel time: $60 r_{\text{sun}} / 400 \text{ km/s} = 1.25 \text{ days}$
- typical travel time: $60 r_{\text{sun}} / 300 \text{ km/s} = 1.6 \text{ days}$



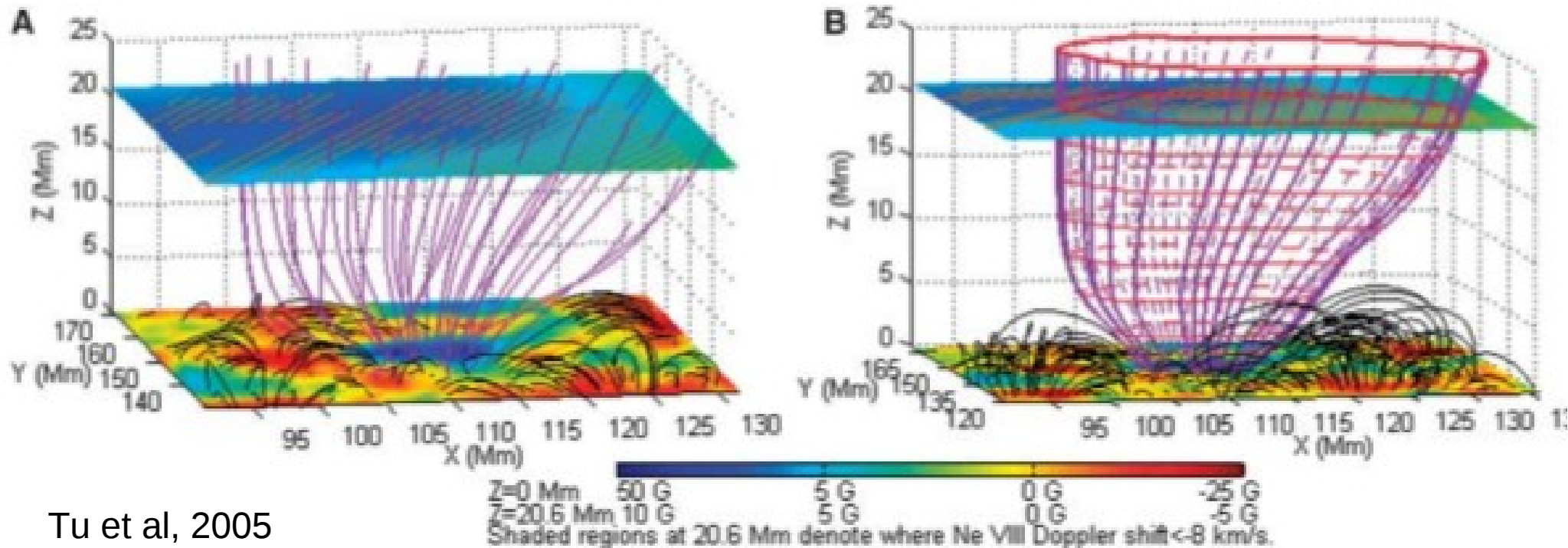
Mapping the origin of the solar wind looks feasible if it comes the disk center.

BUT: Does it? Well, that's what Solar Orbiter is all about.



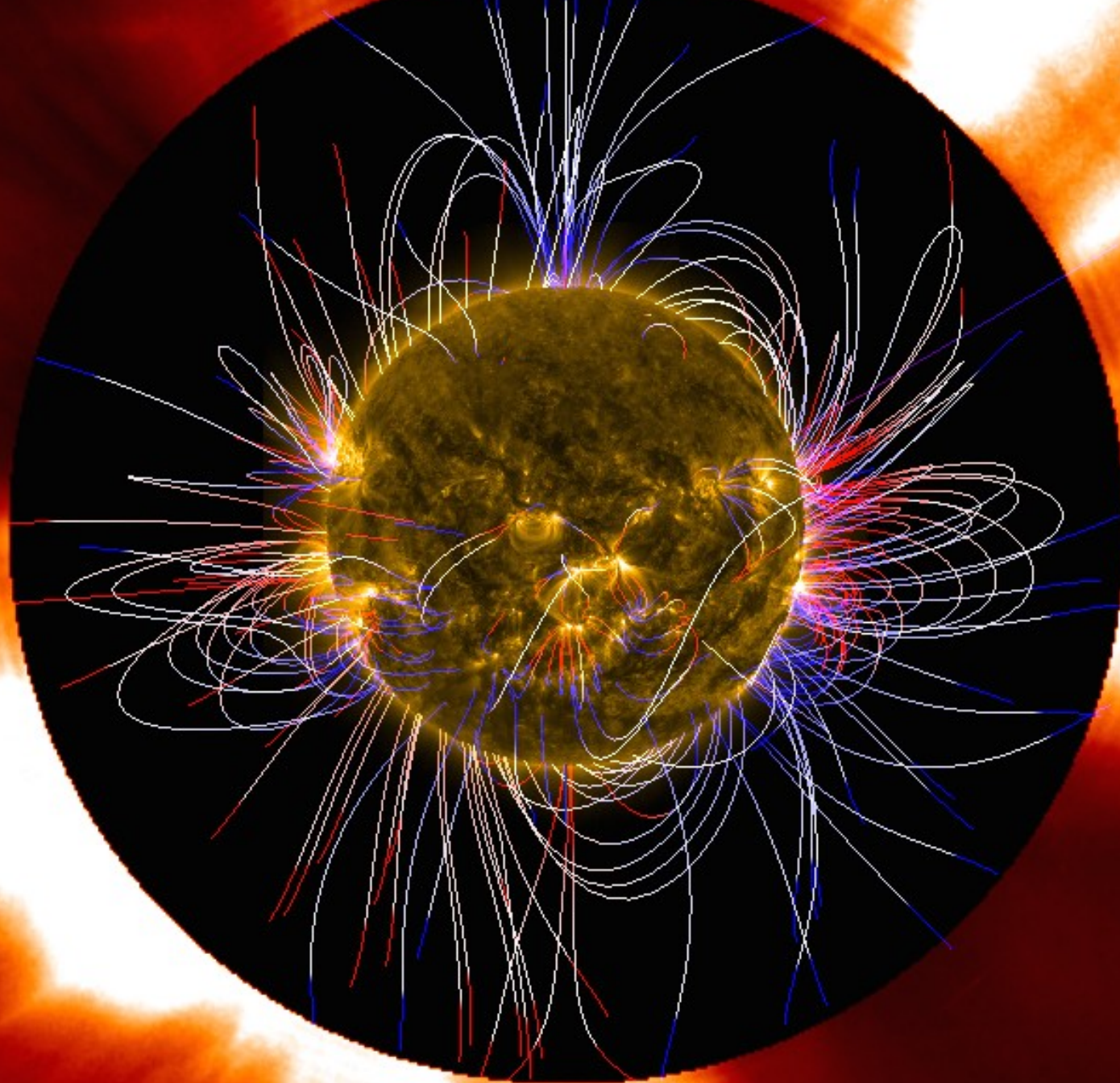
The problem lies in the super-radial expansion of flux tubes.

This is well illustrated by the PFSS 'hairy-ball' model to the left and the coronal funnels shown below.

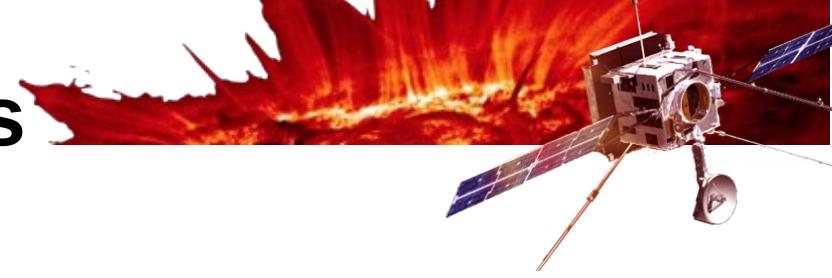


Magnetograms from PHI

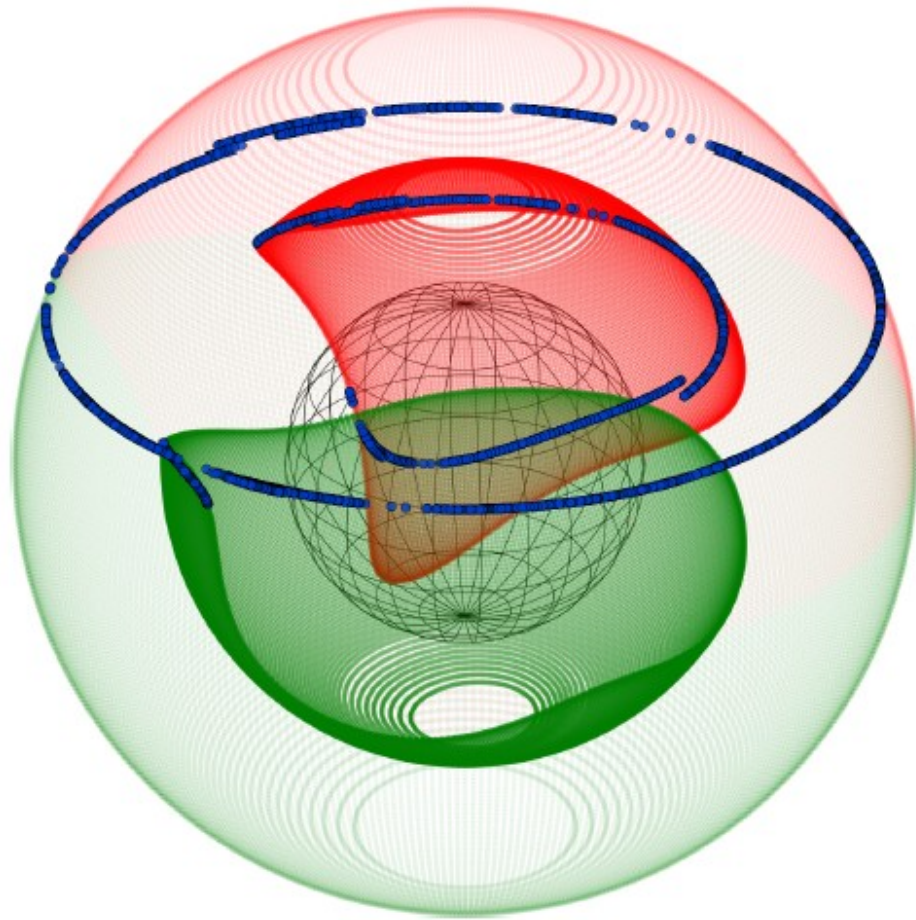
Coronal Structure from EUV and METIS



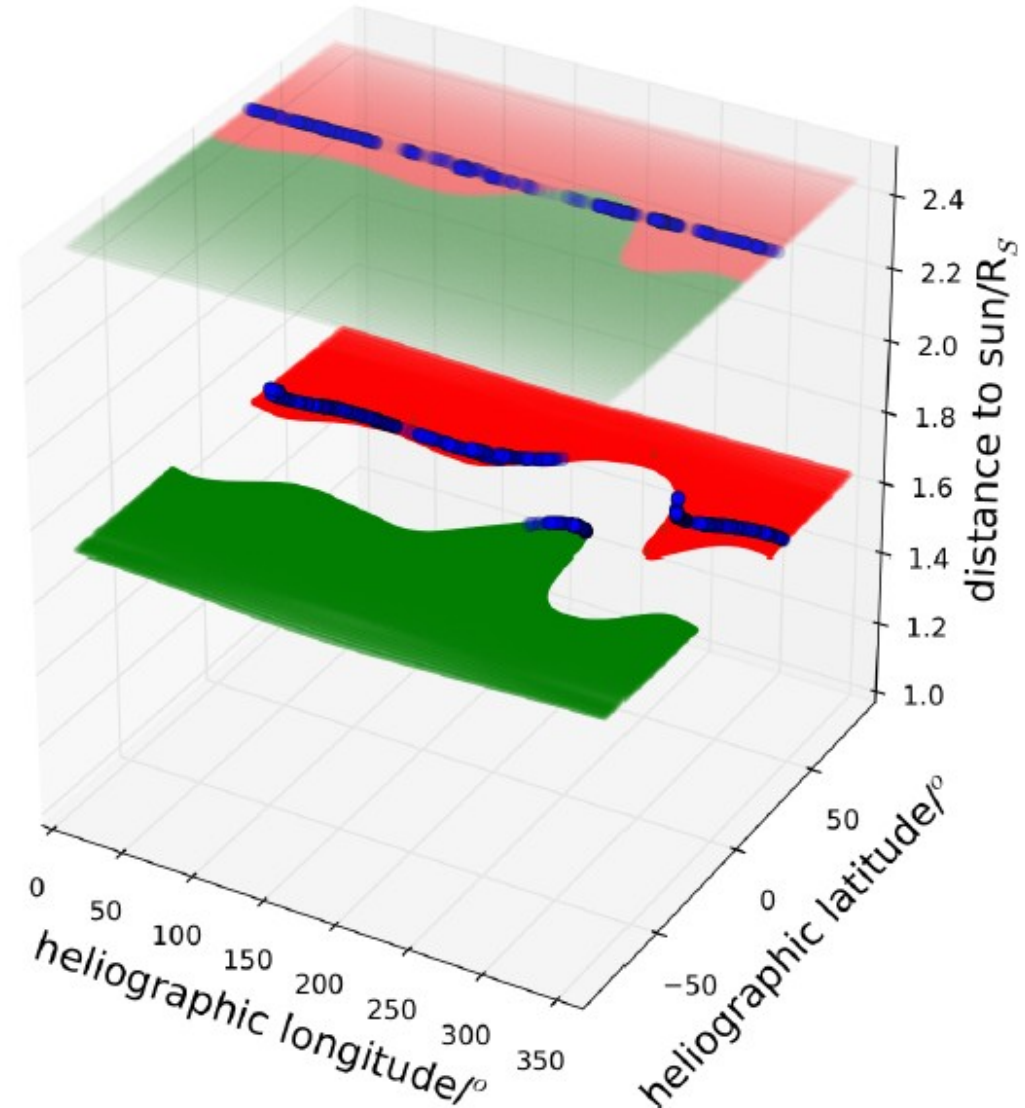
The Third “Instrument”: Models



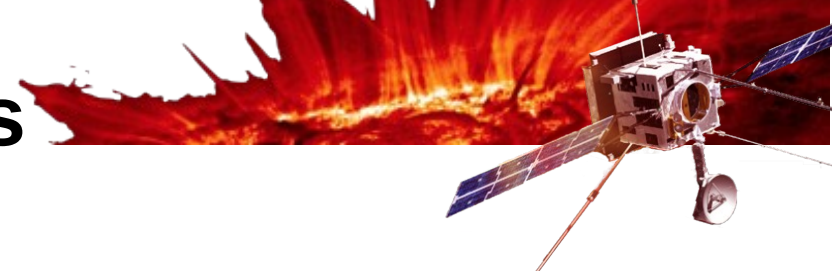
For instance map solar wind back to coronal & chromospheric origin



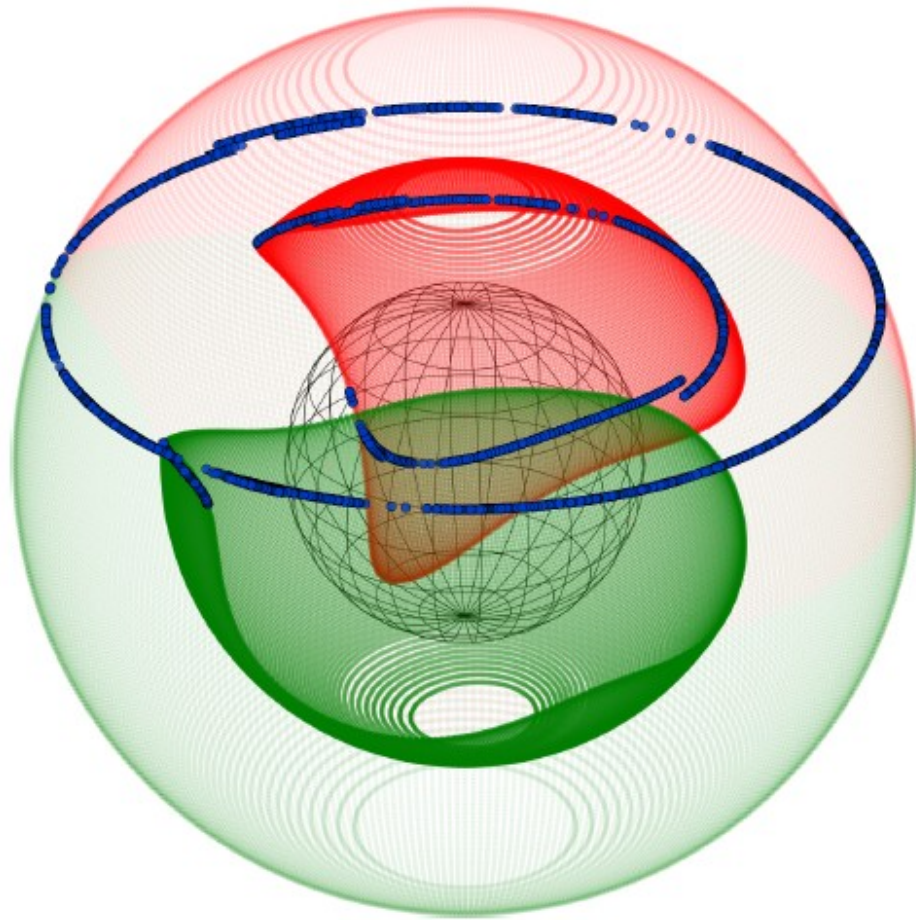
(Peleikis et al., SH31B-03
Kruse et al., SH13A-4080)



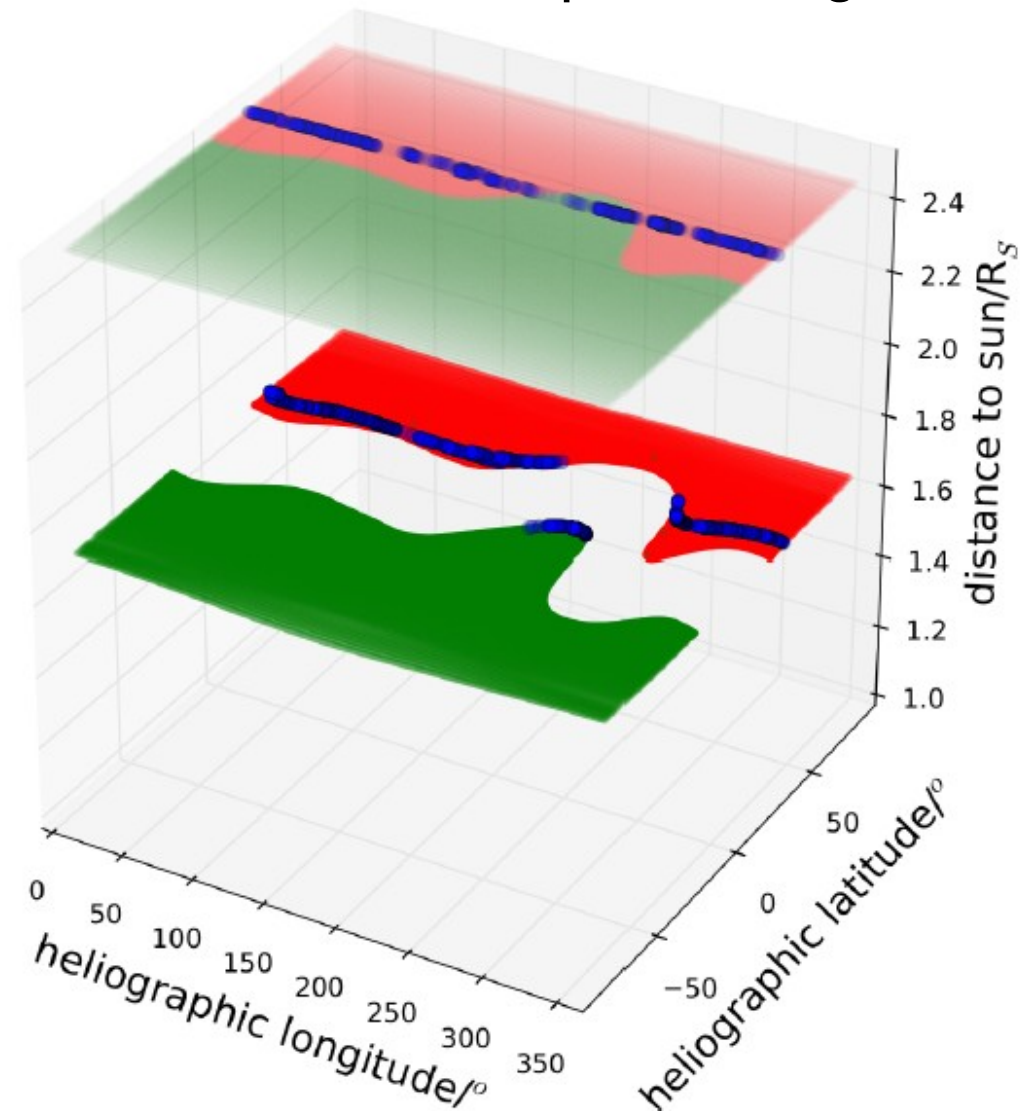
The Third “Instrument”: Models



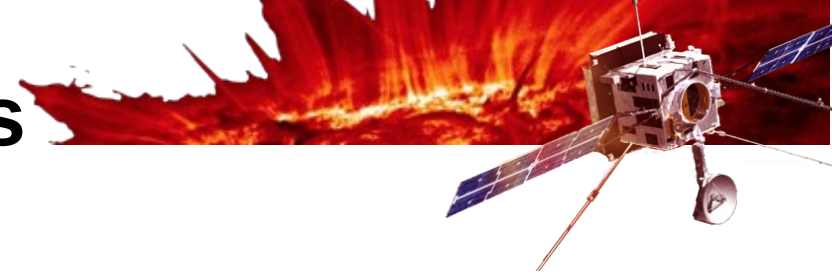
For instance **map** solar wind **back** to coronal & chromospheric origin



(Peleikis et al., SH31B-03
Kruse et al., SH13A-4080)



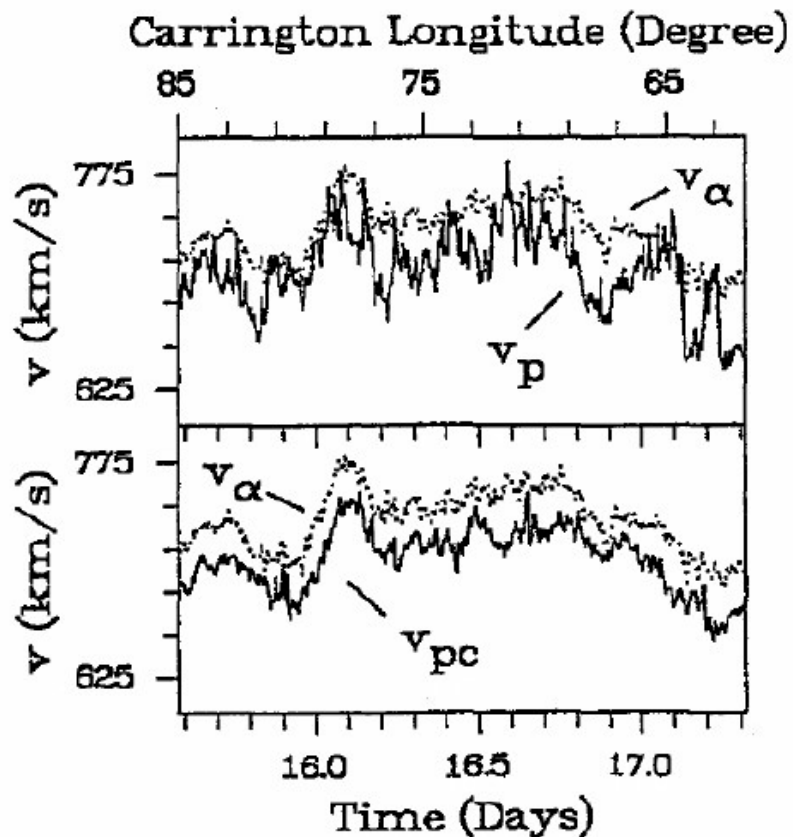
The Third “Instrument”: Models



For instance **map** solar wind **back** to coronal & chromospheric origin

Removal of the Alfvén-Waves Influence from the Proton Velocity

Since Alfvén waves can significantly influence the solar wind velocity, this complicates the search for spatial plasma structures. As already described in /15/, it is possible to remove the influence of the Alfvén waves from the measured proton velocity \vec{v}_p . Hereby is \vec{v}_p a composition of a velocity \vec{v}_{pc} which is **Assumes constant speed from source to observation!** - **Horbury and Matteini (SH21B-4097)**



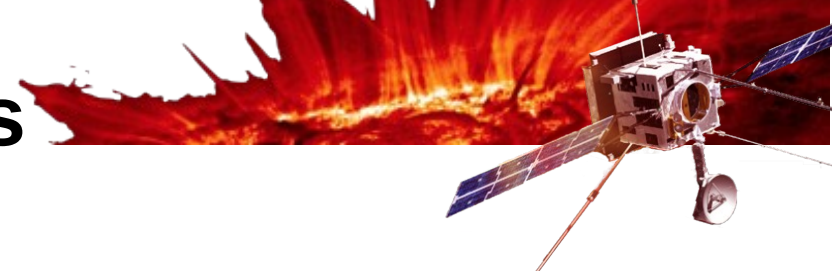
$$\vec{v}_p = \vec{v}_{pc} + \Delta \vec{v}_A.$$

$\Delta \vec{v}_A$ results from

$$\Delta \vec{v}_A = \pm \frac{\Delta \vec{B}}{\sqrt{4\pi\rho}}$$

Thieme et al., Adv. Space Res., v9, (4)127, 1989

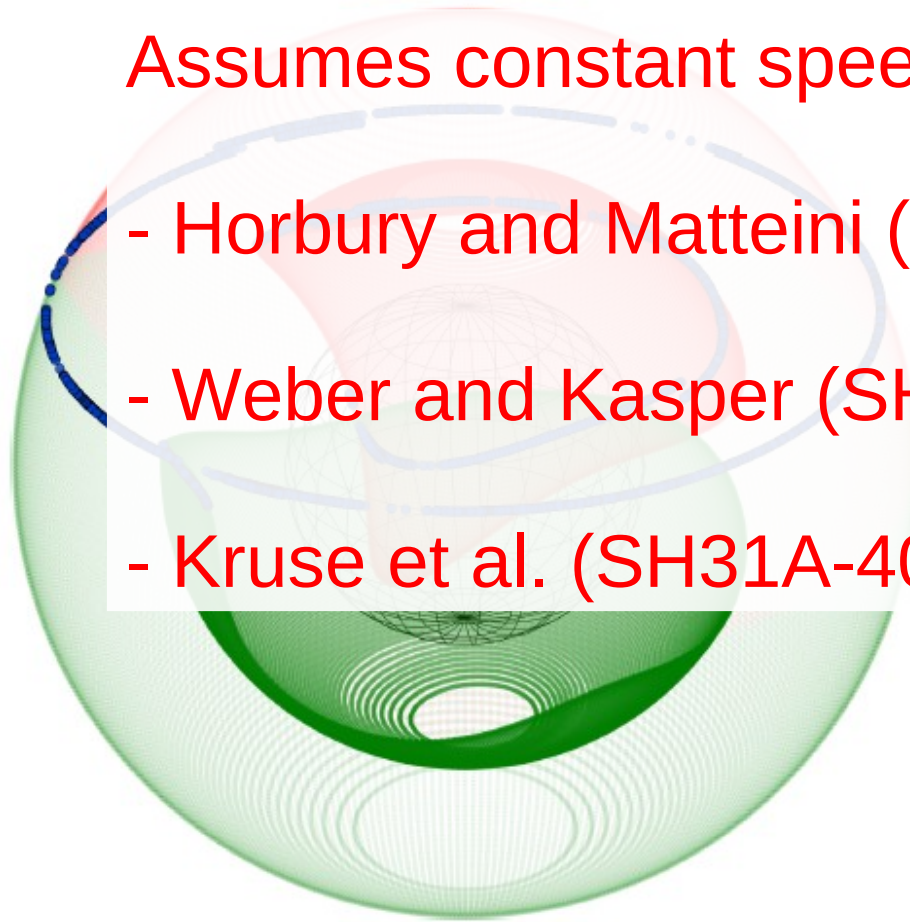
The Third “Instrument”: Models



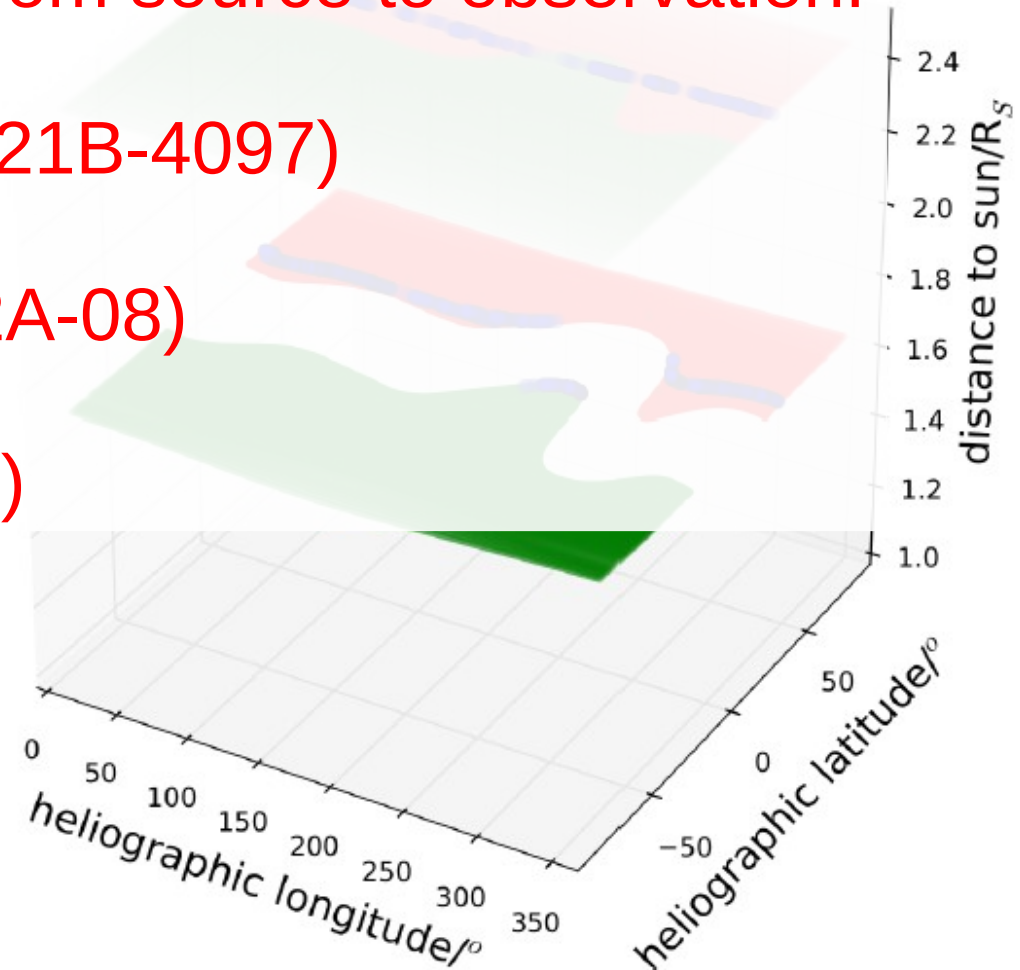
For instance **map** solar wind **back** to coronal & chromospheric origin

Assumes constant speed from source to observation!

- Horbury and Matteini (SH21B-4097)
- Weber and Kasper (SH12A-08)
- Kruse et al. (SH31A-4080)



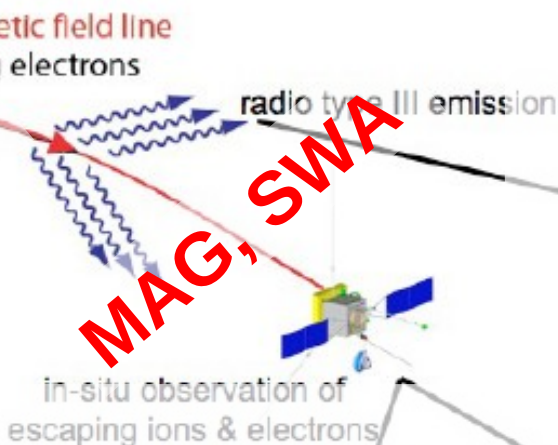
(Peleikis et al., SH31B-03
Kruse et al., SH13A-4080)



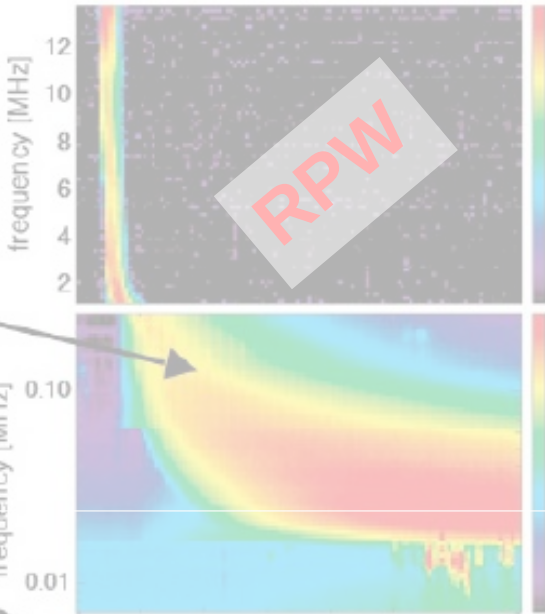
Solar Orbiter works best with all instruments together



SO & SP+

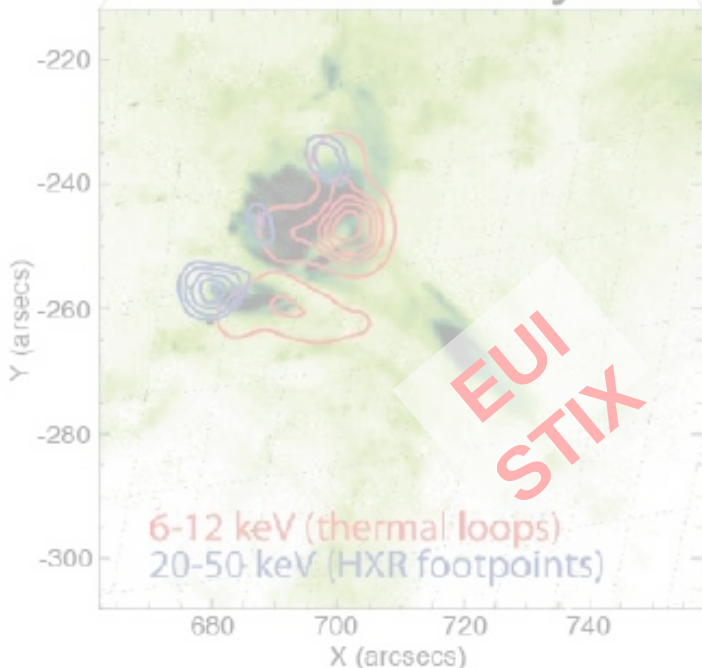


radio burst

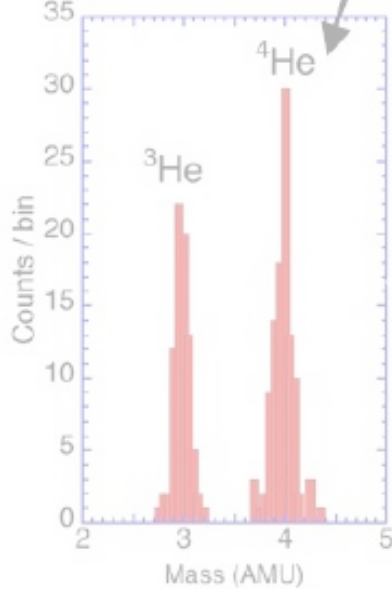


SO

UV and X-rays

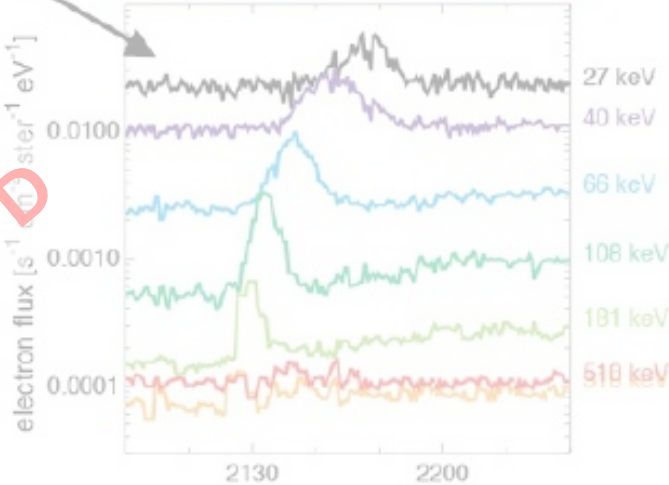


in-situ observation of escaping ions & electrons



energetic He

EPD



energetic electrons

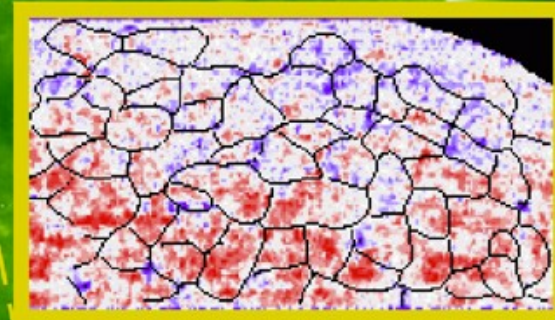


Processes that affect solar wind composition:

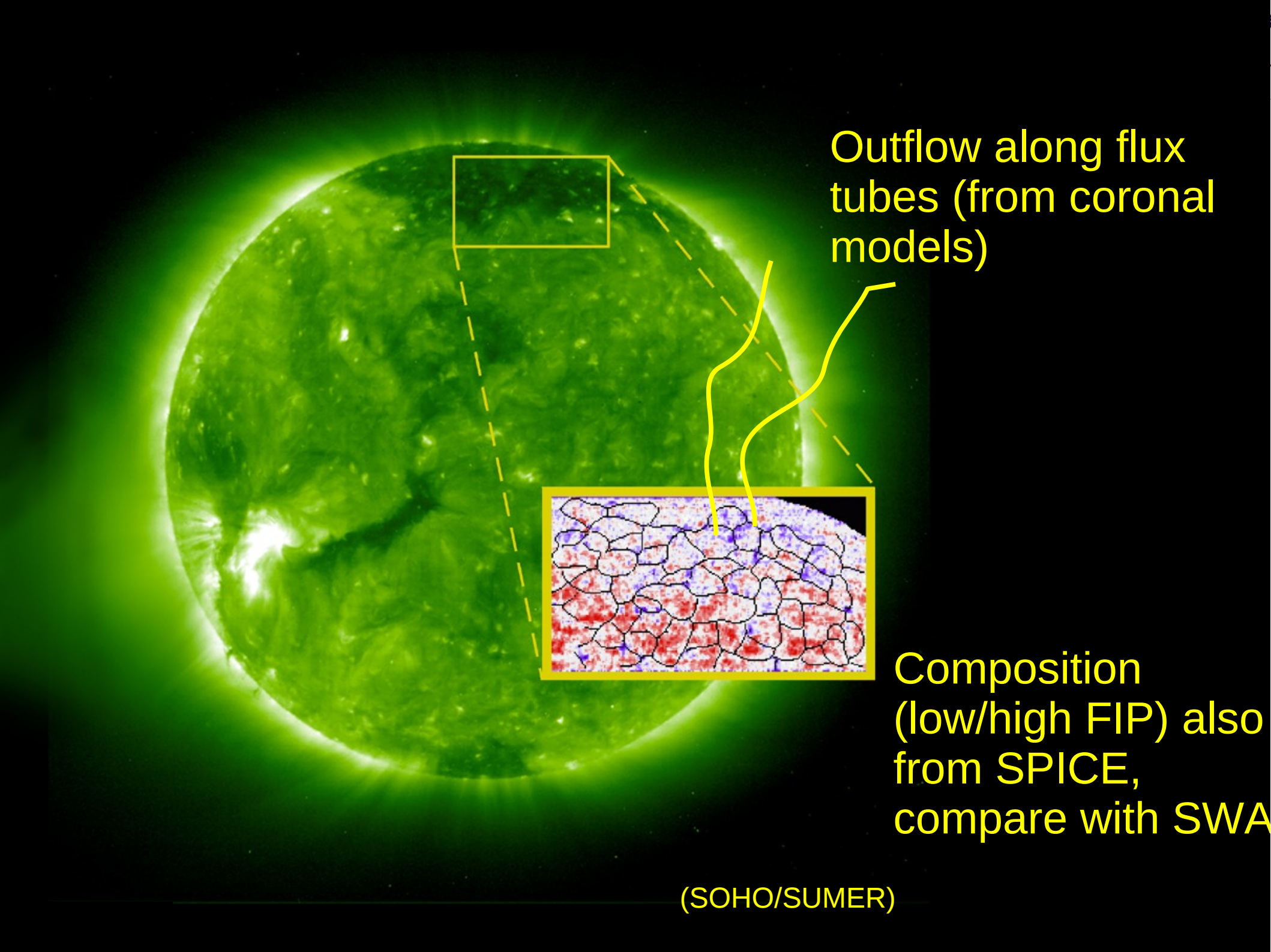
Process	Location	Elemental	Ionic	Seen in situ?	Origin understood?
FIP effect	Chromosphere, foot points of loops	yes	?	yes	no
Heating	Corona, loops, foot points of loops	Possibly small effect?	yes	yes	no
Gravitational stratification	streamers	yes	no	no	yes
Coulomb drag	Coronal expansion	Yes, especially He	no	Yes?	Yes, but does it really act on wind?

Some of these processes can be modeled. Providing simple models, e.g., for FIP, charge states, etc. would be very helpful.

SPICE will provide
Doppler-maps for
various ions



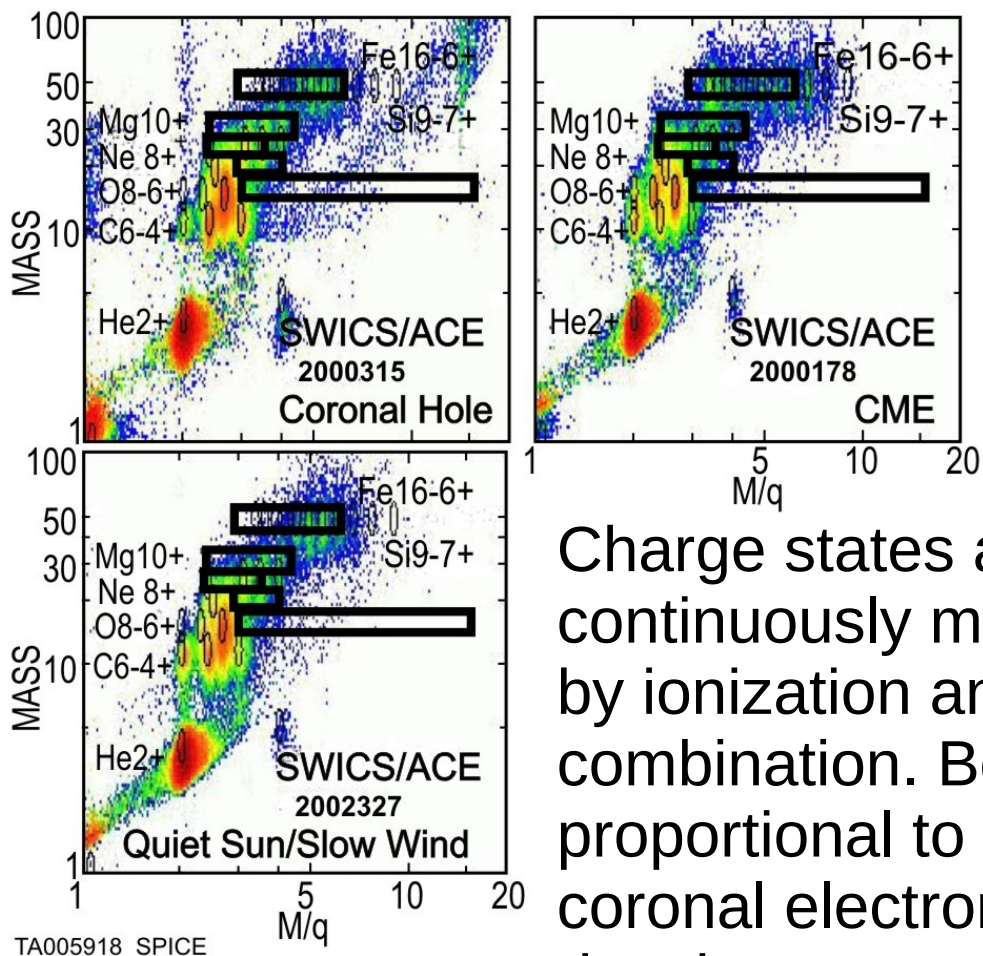
(SOHO/SUMER)

The image shows a green-tinted view of the solar corona from the SOHO/SUMER instrument. A rectangular box in the upper left highlights a specific region. A dashed line extends from this box to a larger inset image in the lower right. This inset displays a color-coded map of elemental composition, with red and blue areas representing different ionization states or abundances, overlaid with a black grid pattern. Two yellow lines point from the text 'Composition (low/high FIP) also from SPICE, compare with SWA' to the inset. Another yellow line points from the text 'Outflow along flux tubes (from coronal models)' to the main image.

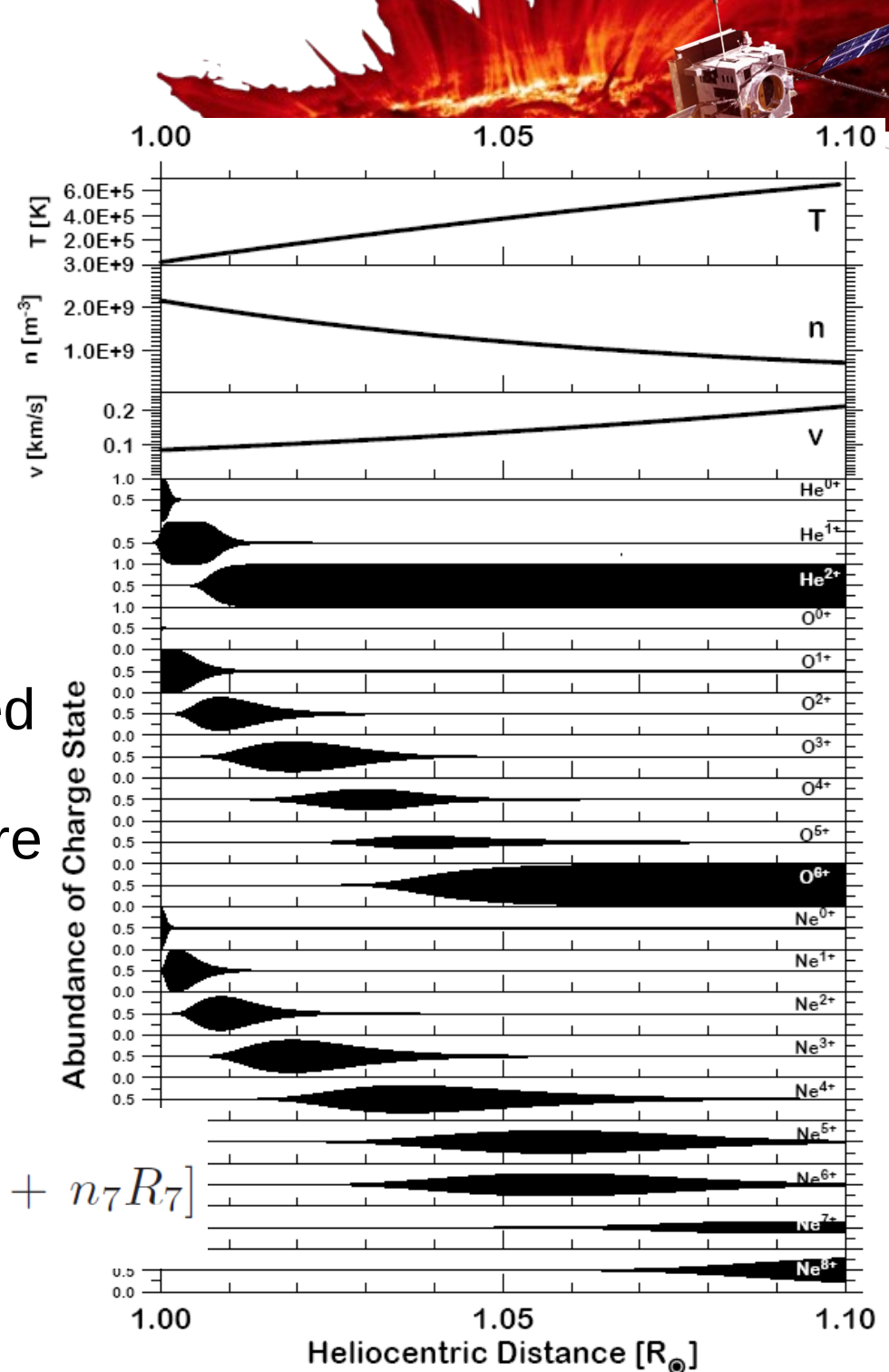
Outflow along flux tubes (from coronal models)

Composition
(low/high FIP) also
from SPICE,
compare with SWA

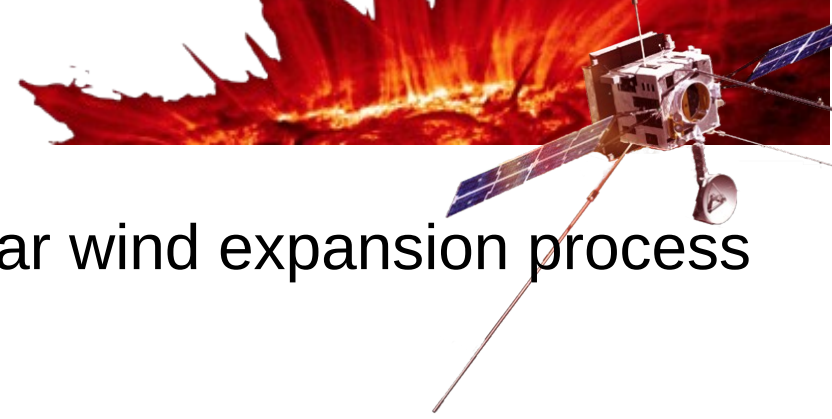
(SOHO/SUMER)



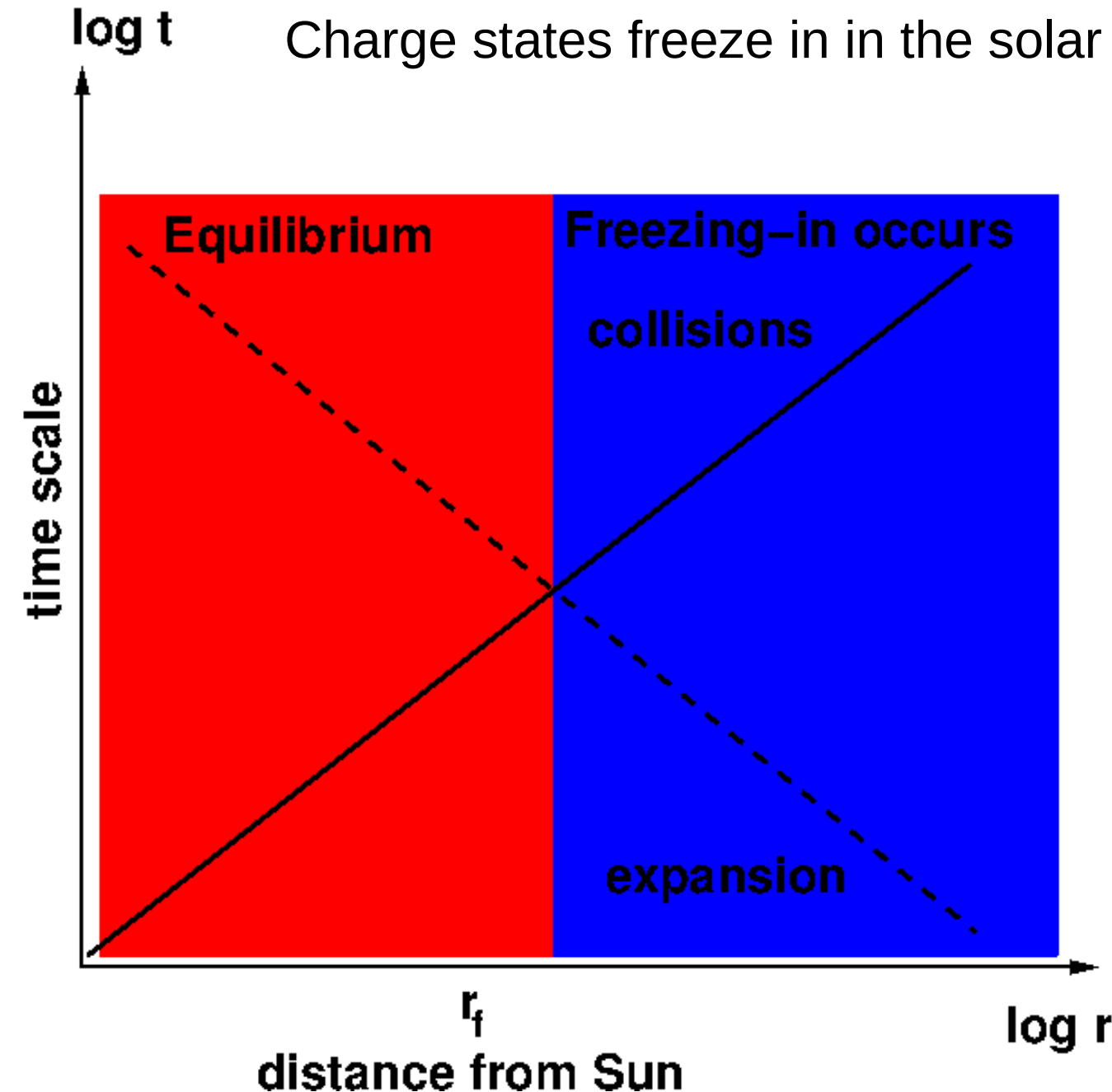
Charge states are continuously modified by ionization and recombination. Both are proportional to coronal electron density.



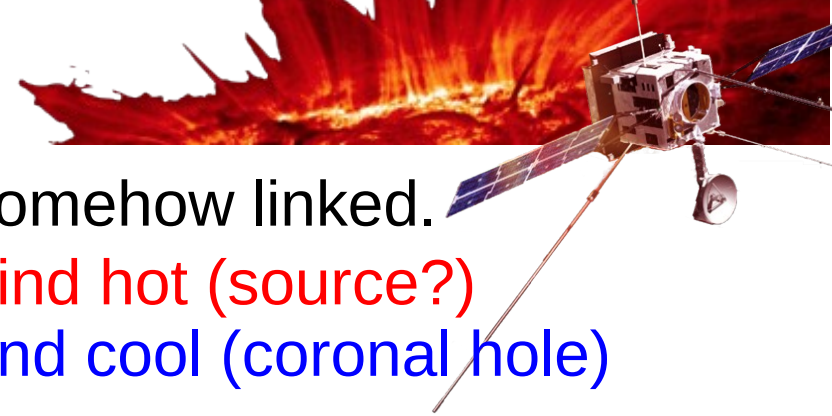
$$\frac{\partial n_6}{\partial t} + \vec{\nabla} \cdot (n_6 \vec{u}_6) = n_e [n_5 C_5 - n_6 (R_6 + C_6) + n_7 R_7]$$



Charge states freeze in in the solar wind expansion process



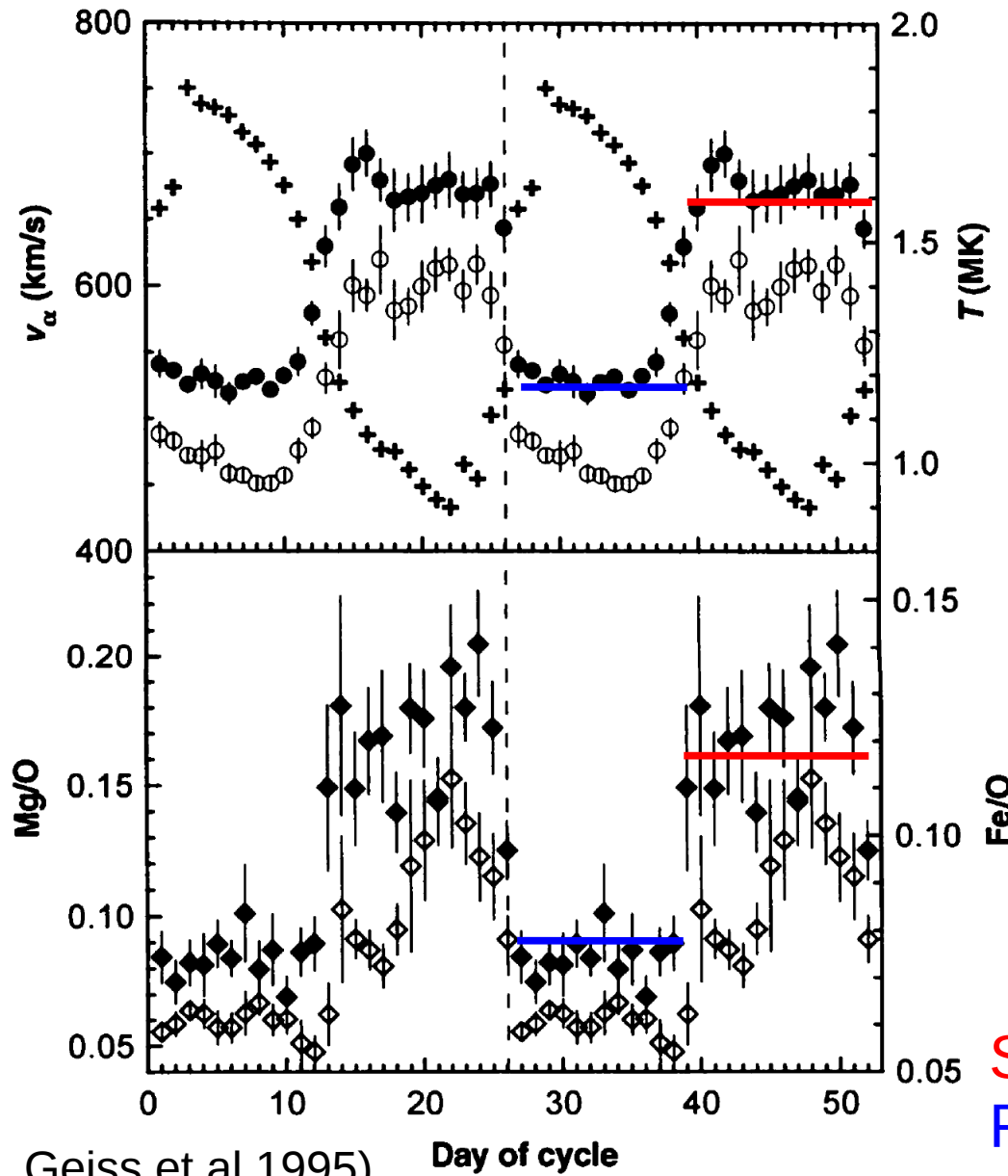
In situ charge states have lost all memory of what happened in deep corona. They retain memory of their last charge modification (charge states frozen in) in the upper corona.



Charge-state and elemental composition somehow linked.

Slow wind hot (source?)

Fast wind cool (coronal hole)

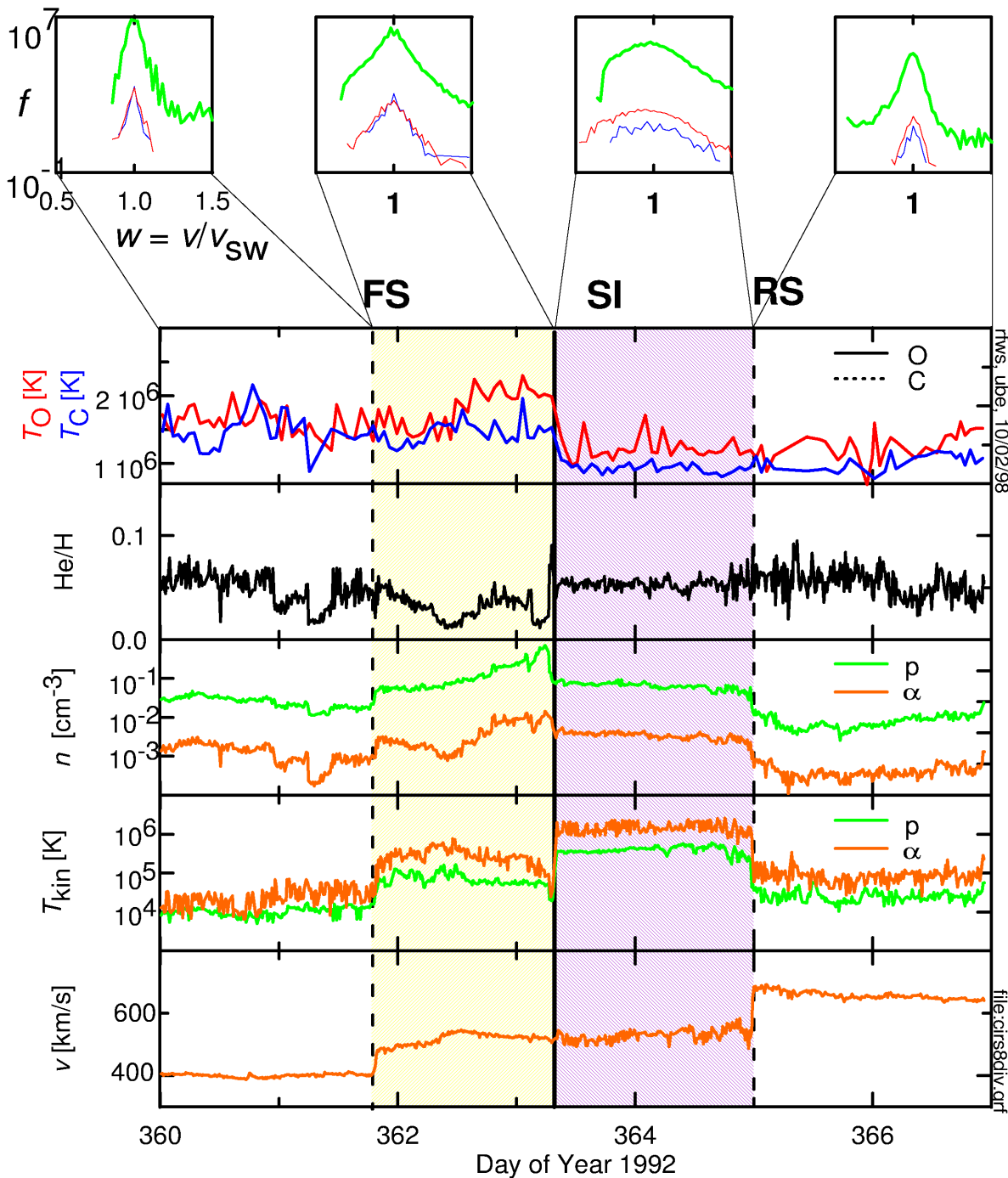
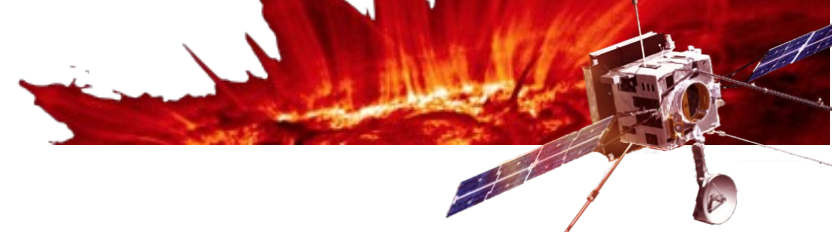


What links chromosphere and corona?

Slow wind strongly FIPped

Fast wind weakly/barely FIPped

Geiss et al.1995)

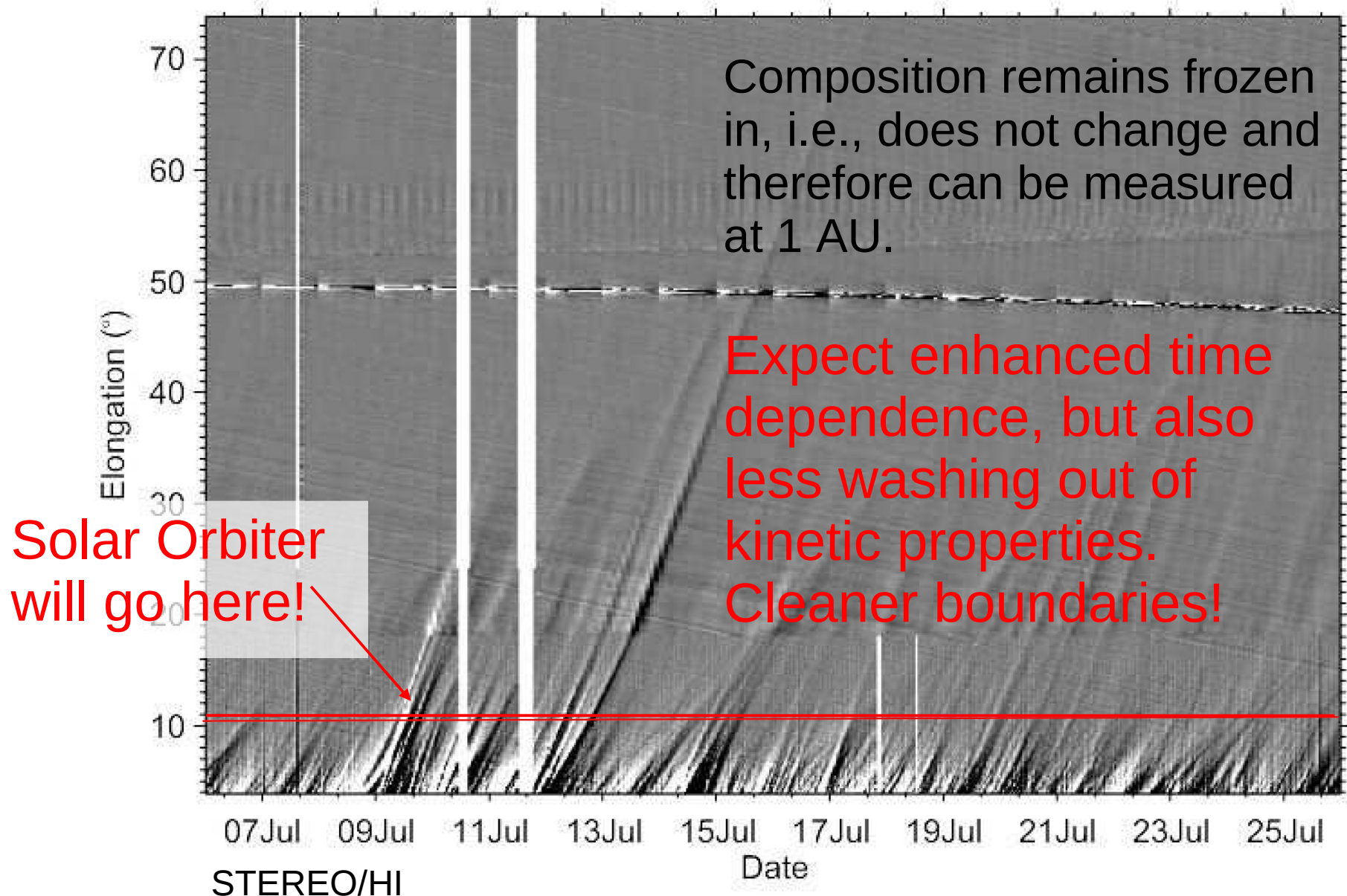


Individual streams can be identified in-situ by many independent methods:

- magnetic field
- plasma data
- specific entropy
- composition

Composition is not altered by kinetic processes and remains conserved once it has been set in chromosphere and corona.
Excellent tracer!

Composition variable, especially in slow wind.

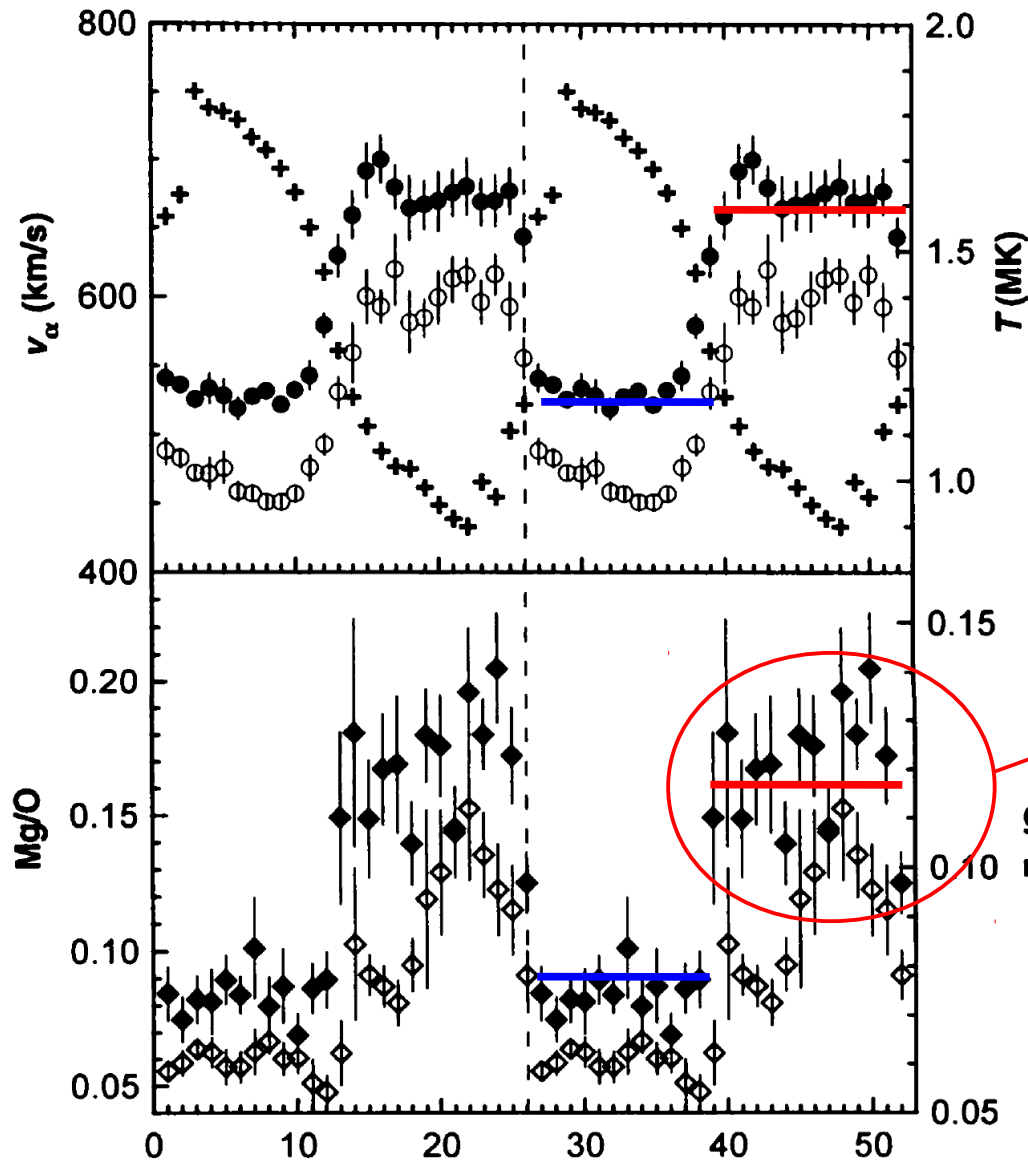




Charge-state and elemental composition somehow linked.

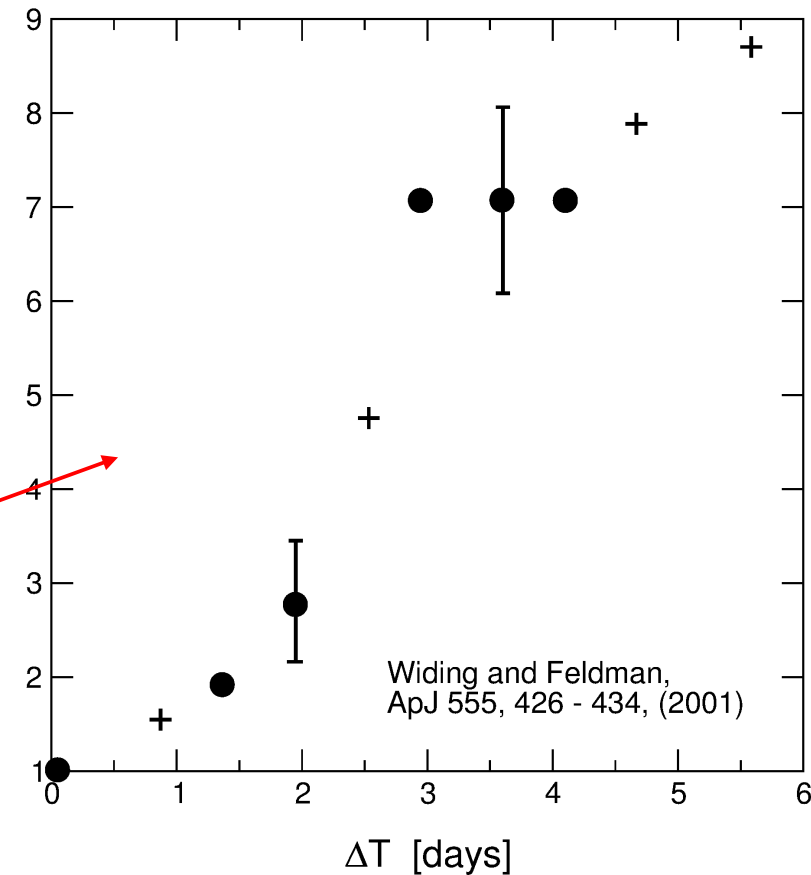
Slow wind hot (source?)

Fast wind cool (coronal hole)



What links chromosphere and corona?

FIP Bias in Active Region Plasma vs. Time



Widing and Feldman, ApJ 555, 426 - 434, (2001)

Slow wind strongly FIPped

Fast wind weakly/barely FIPped

Geiss et al.1995)

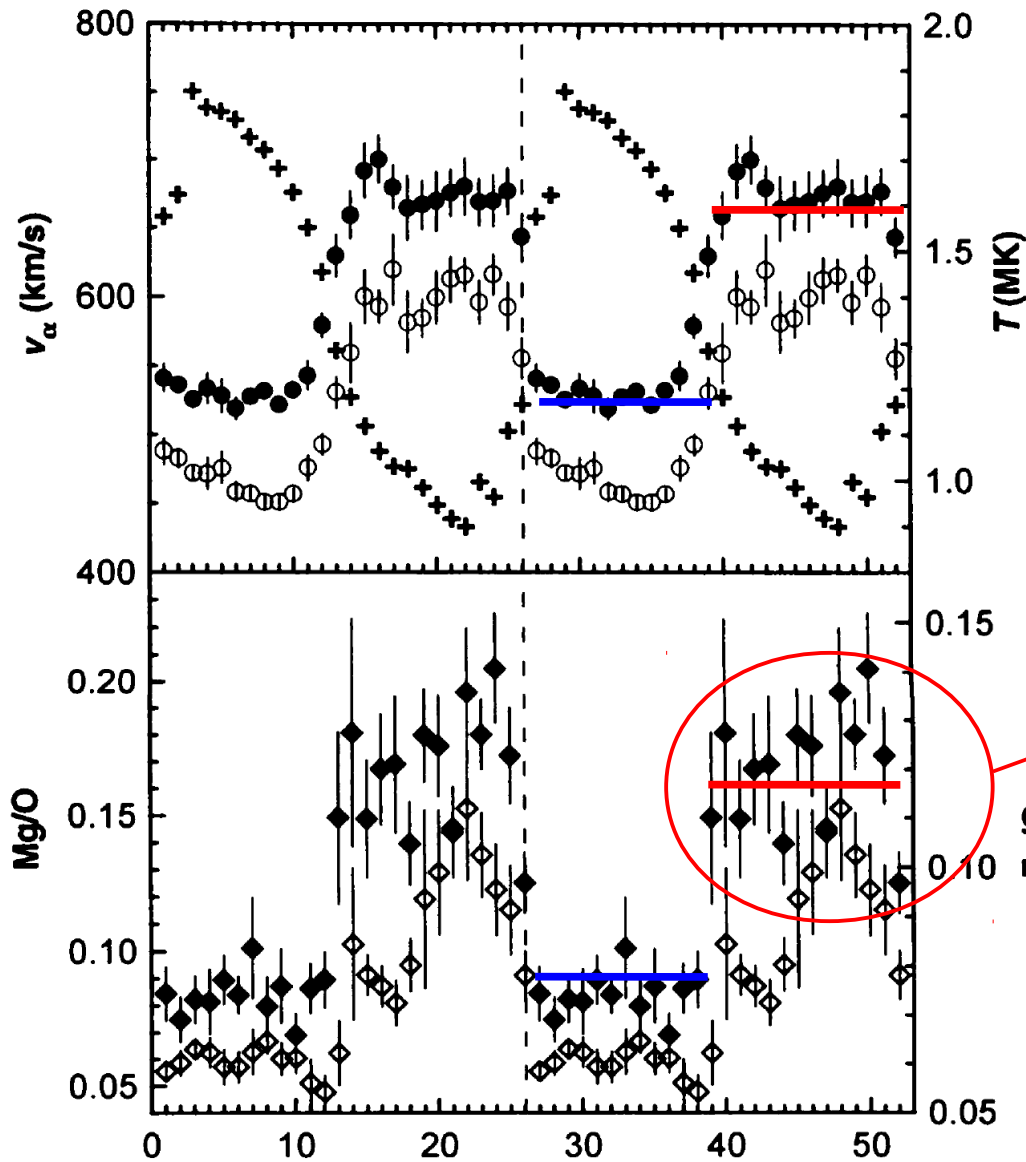


Charge-state and elemental composition somehow linked.

Slow wind hot (source?)

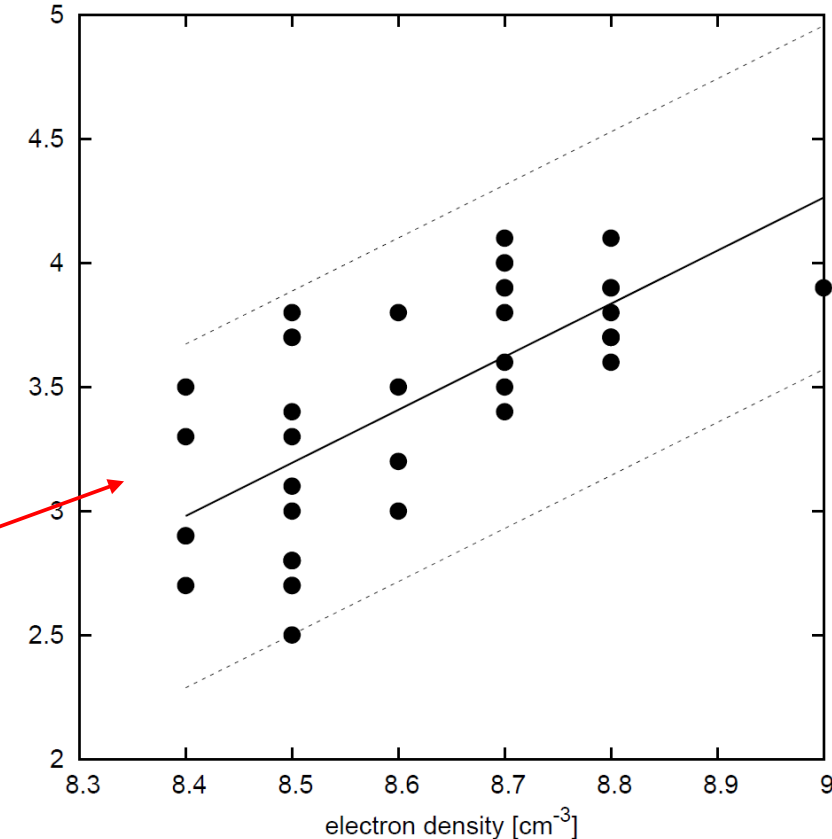
Fast wind cool (coronal hole)

Pearson's $r = 0.696$, $p = 0.00000$; Spearman's $r = 0.704$, $p = 0.00000$



What links chromosphere and corona?

Fip factor



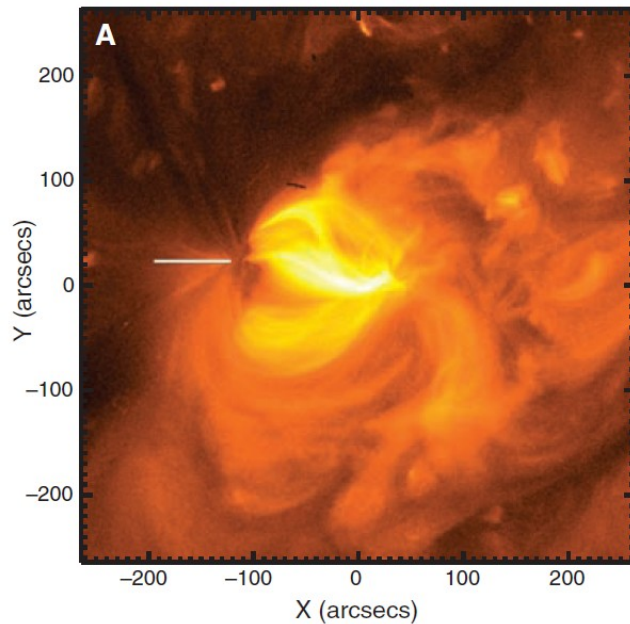
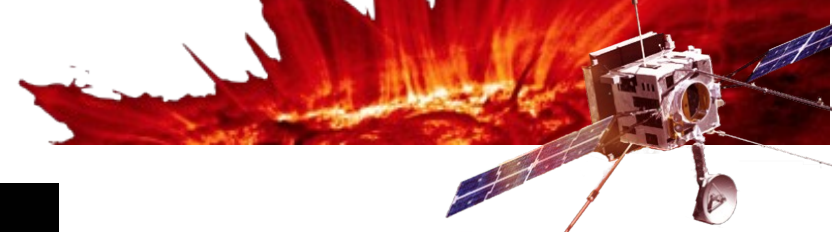
Brooks and Warren, 2011

Slow wind strongly FIPped

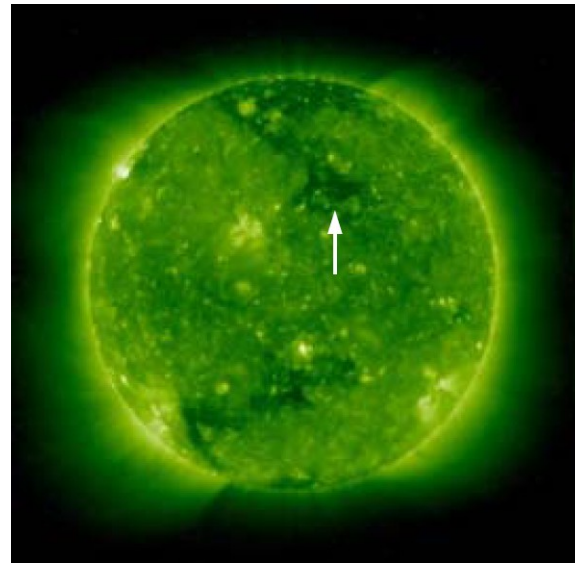
Fast wind weakly/barely FIPped

Geiss et al.1995) Day of cycle

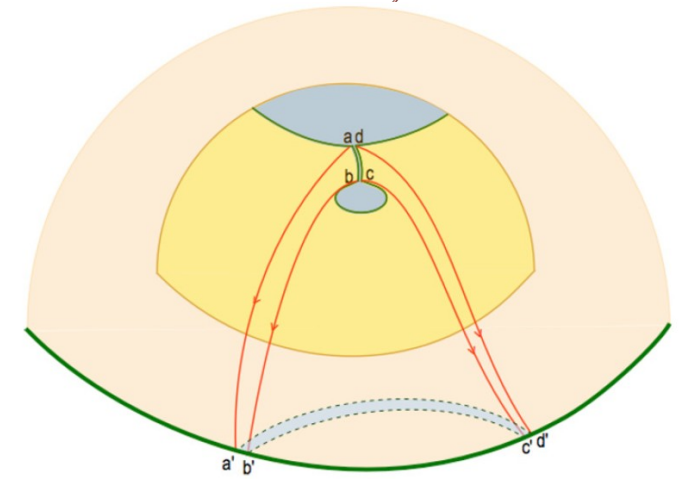
Origin of the Slow Solar Wind?



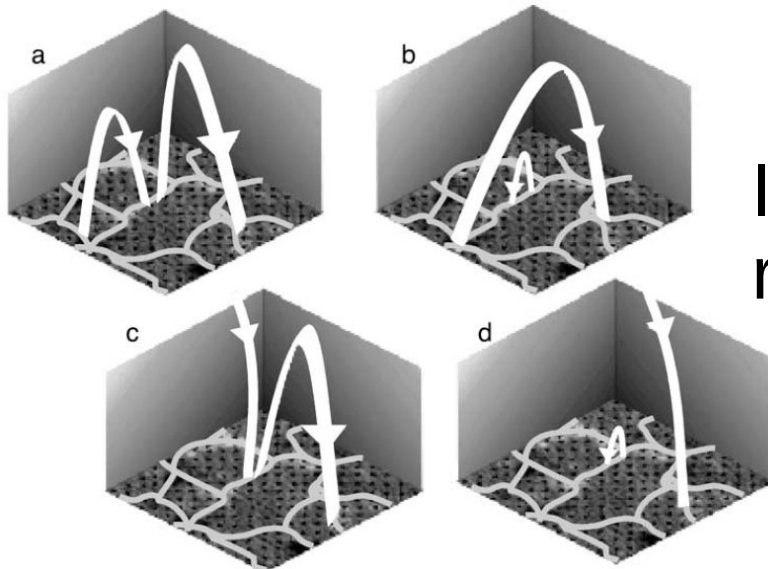
Edges of
Active regions



Edges of
Coronal holes



S-web (coronal hole
extensions provide
open field connection)



Interchange
reconnection

SO

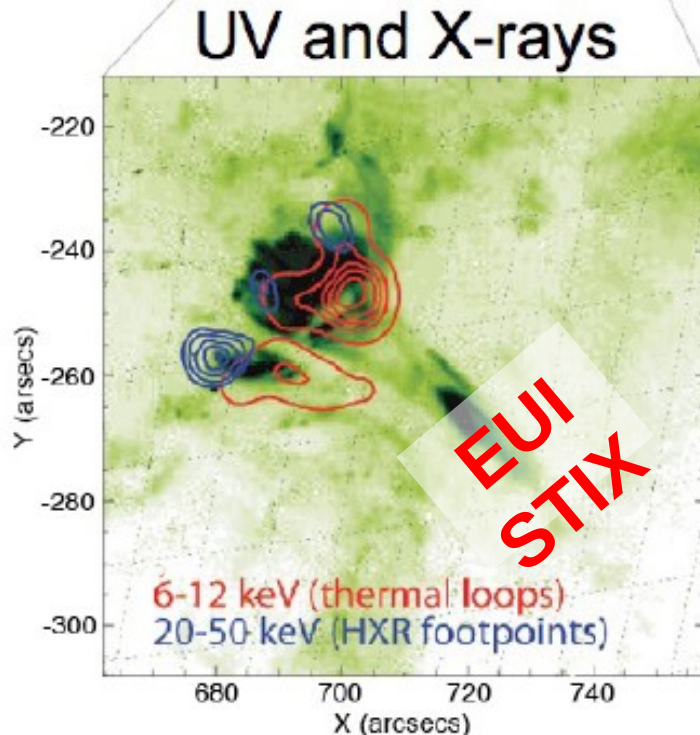
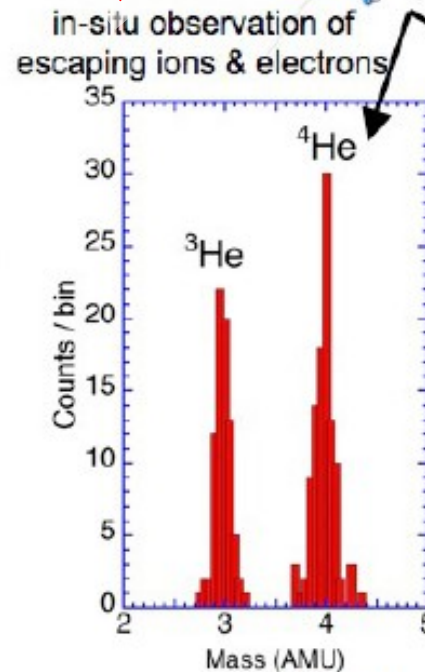
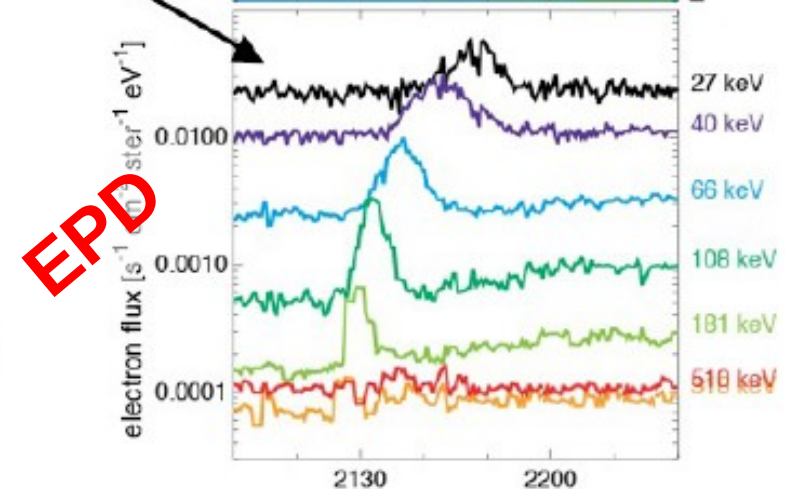
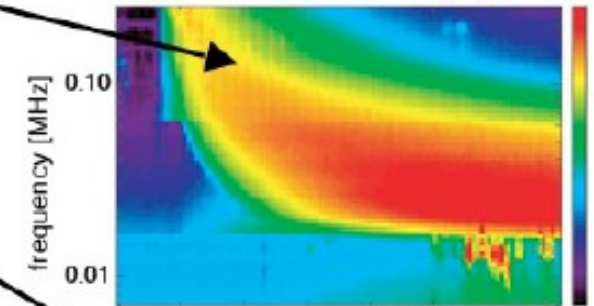


Diagram illustrating a satellite in space. Labels include: magnetic field line, g electrons, radio type III emission, and MAG, SWA.



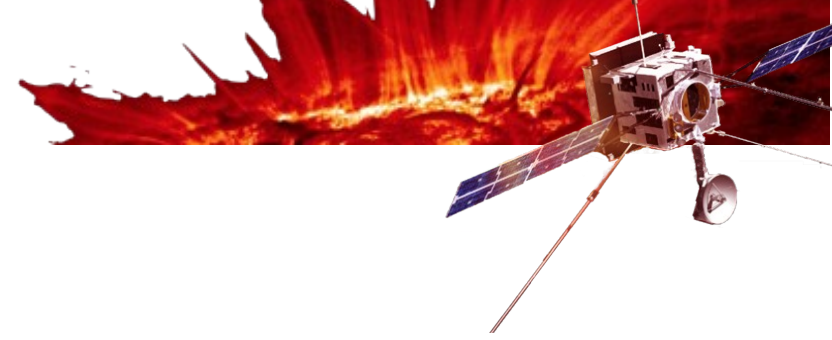
energetic He

A spectrogram of a speech signal. The vertical axis is labeled 'frequency [MHz]' and ranges from 2 to 12. The horizontal axis represents time. A prominent vertical band of high energy is visible on the left side. A large, semi-transparent gray rectangle is overlaid on the spectrogram, containing the text 'RPW' in large, bold, red letters, indicating a watermark.



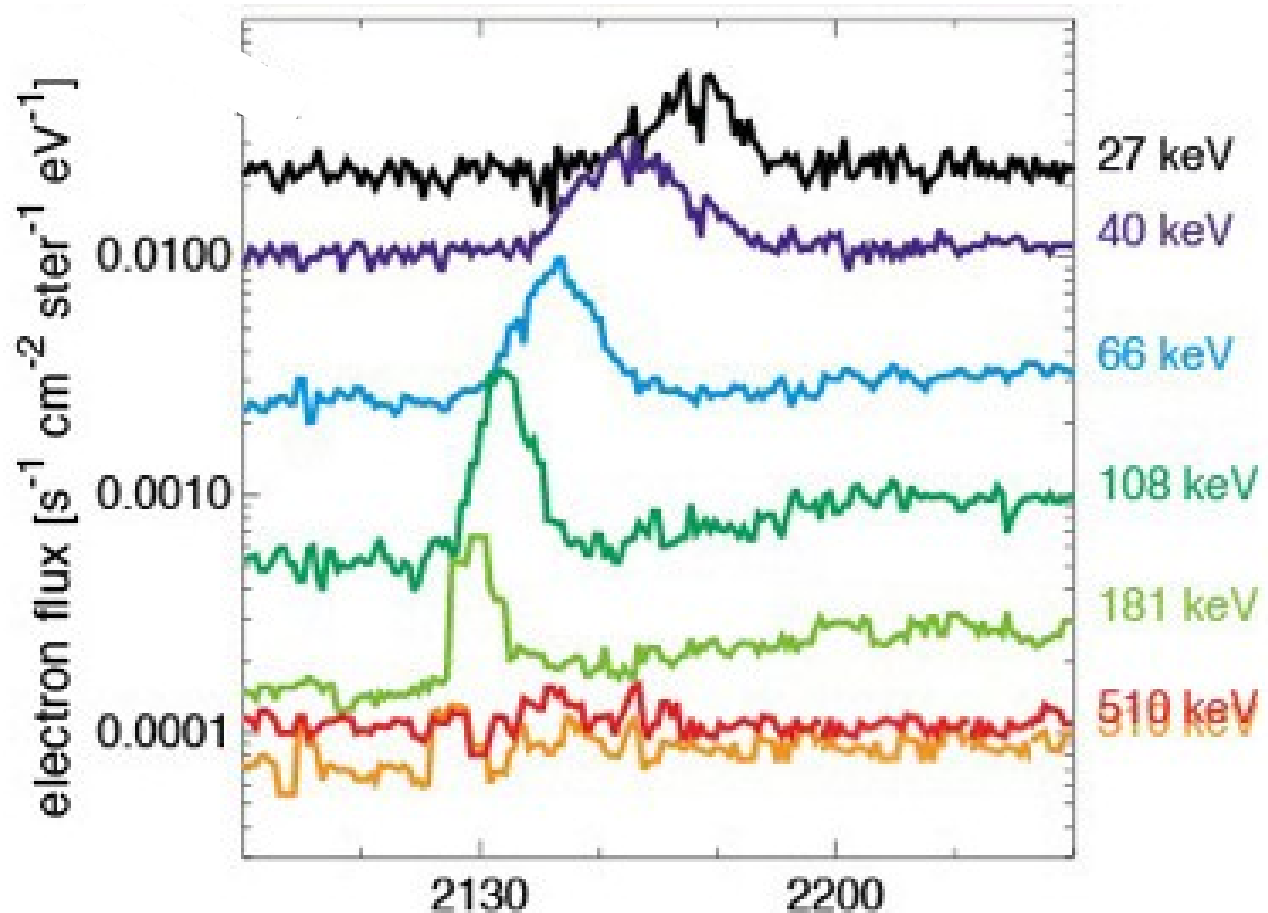
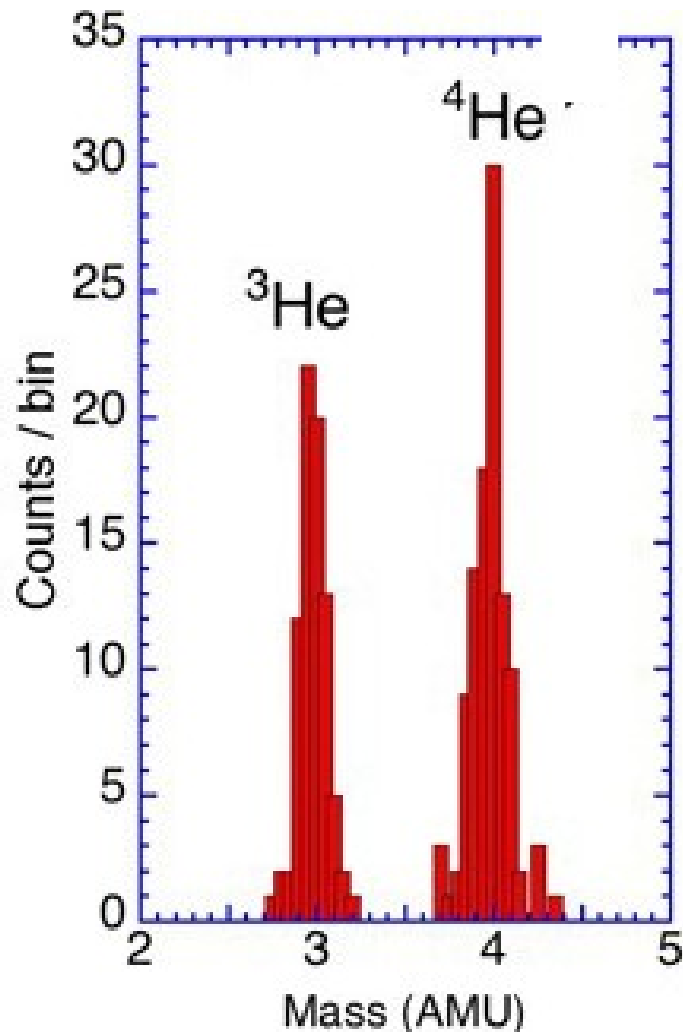
energetic electrons

Information from EPD

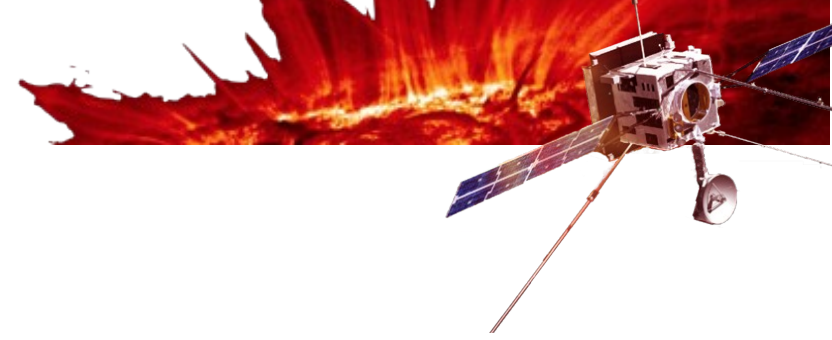


^3He is preferentially accelerated in flares (probably wave-particle interaction) \rightarrow flare origin!

Velocity dispersion indicates rapid acceleration and good connection \rightarrow no time for diffusion!



Information from EPD



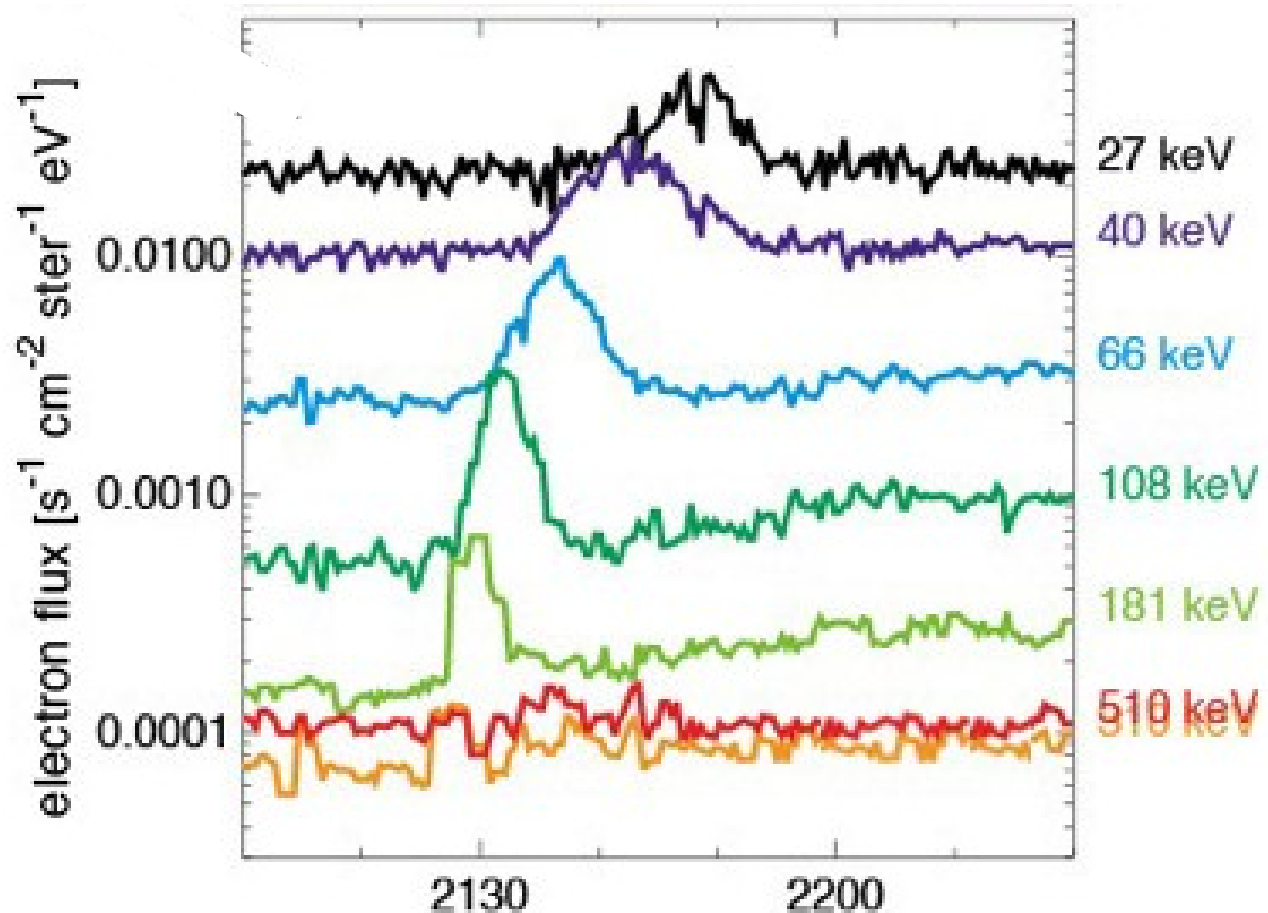
Velocity dispersion also indicates that particles are flowing towards observer from the source. The flow is anisotropic.

Velocity dispersion indicates rapid acceleration and good connection
→ no time for diffusion!

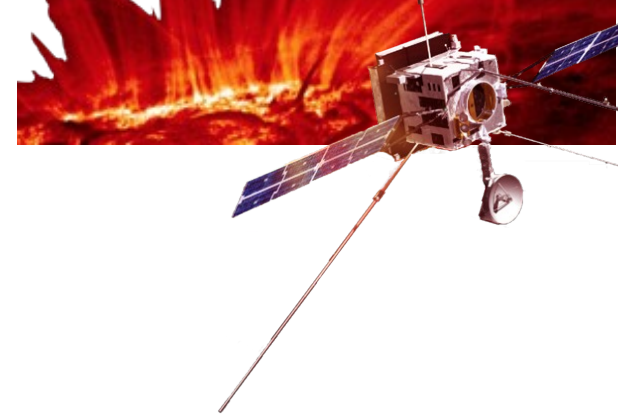
For good connection:

- ^3He , large e/p ratio
- velocity dispersion
- anisotropies
- type III radio emission
- minimal onset delay

Such events are seen at 1 AU, albeit rarely (e.g., Klassen et al. 2011).



Solar Orbiter & the Heliosphere



Need a strong synoptic program to allow linkage.

Need tools that allow user to easily discriminate:

Hot and cool coronal regions:

- provide FIP maps of potential source regions
- provide temperature maps of potential source regions
- do so for more than one Low FIP/High FIP pair.

Line broadening as measure of ion heating and/or turbulence:

- Doppler maps
- coronal turbulence maps

Magnetic connectivity

- Magnetograms → hairy ball models to trace open field
- Timing, magnetic topology, and locations of eruptive events

Modeling must be an integrated “instrument” of Solar Orbiter

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