Tracing Heliospheric Structures to Their Solar Origin

Robert Wimmer-Schweingruber
wimmer@physik.uni-kiel.de
Christian Albrechts University Kiel
Kiel, Germany
for the Solar Orbiter Team

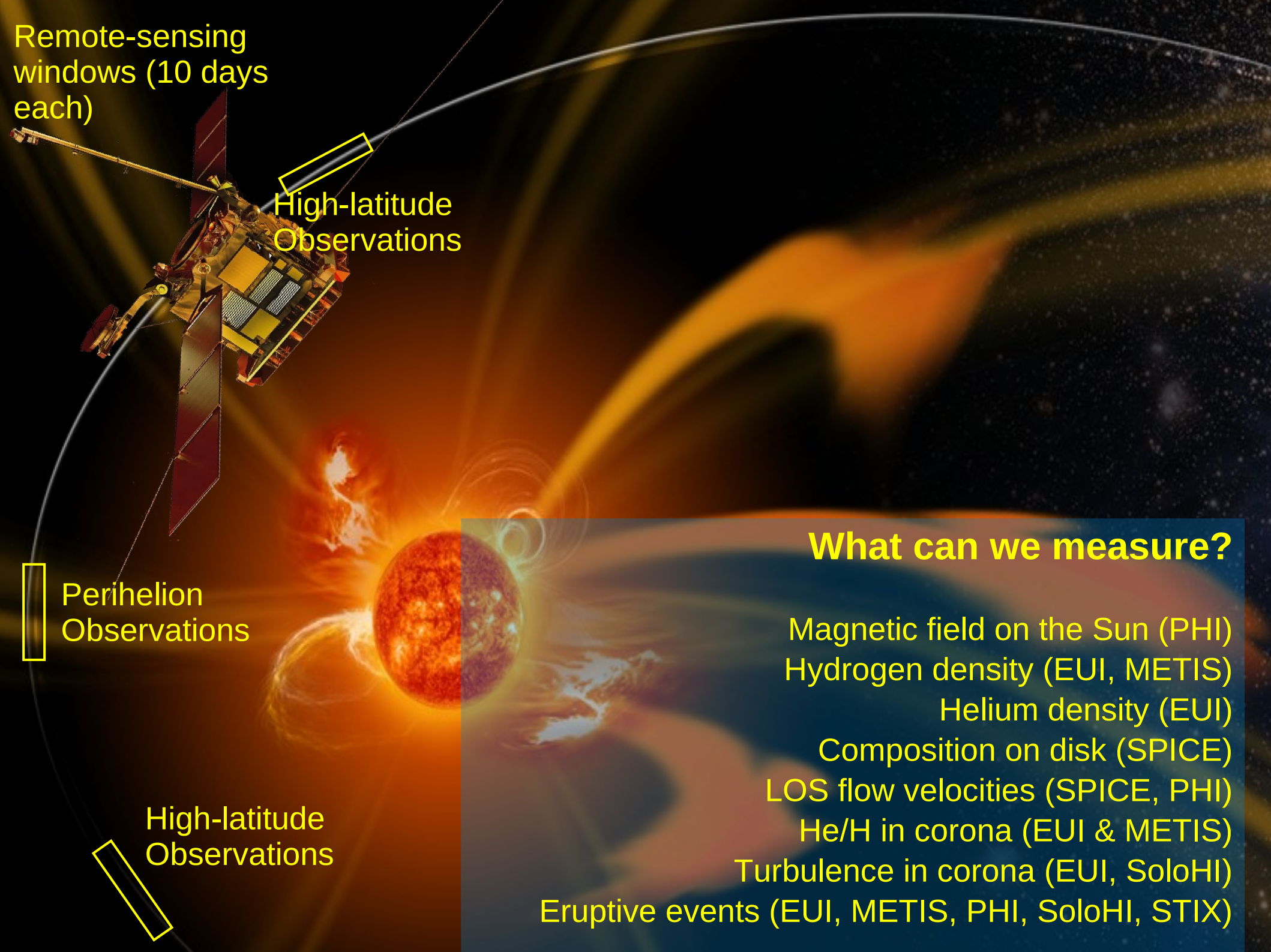
Tracing Heliospheric Structures to Their Solar Origin

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

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)

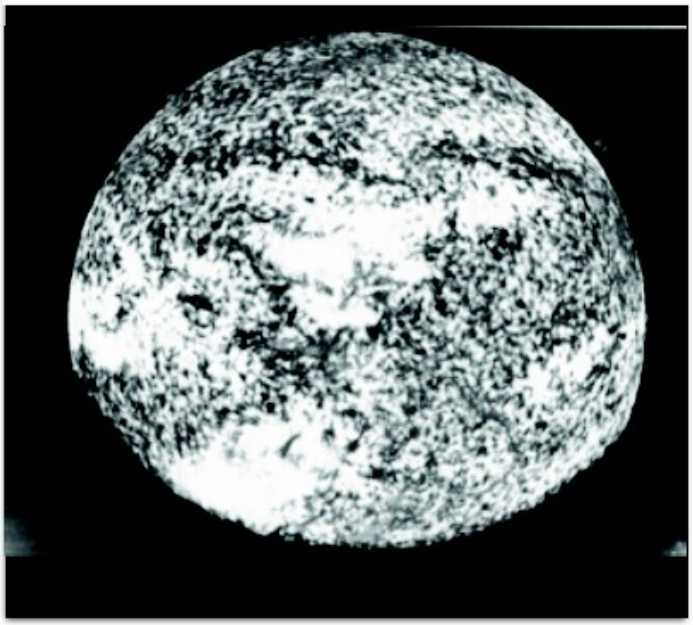
Remote-sensing windows (10 days each)

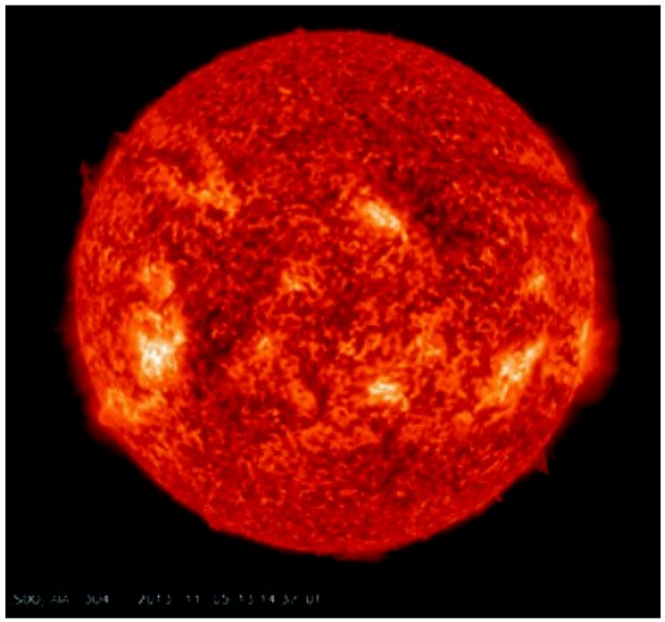
High-latitude Observations

TRC (Bonnet et al, 1980)

SDO/AIA

PROBA2/SWAP





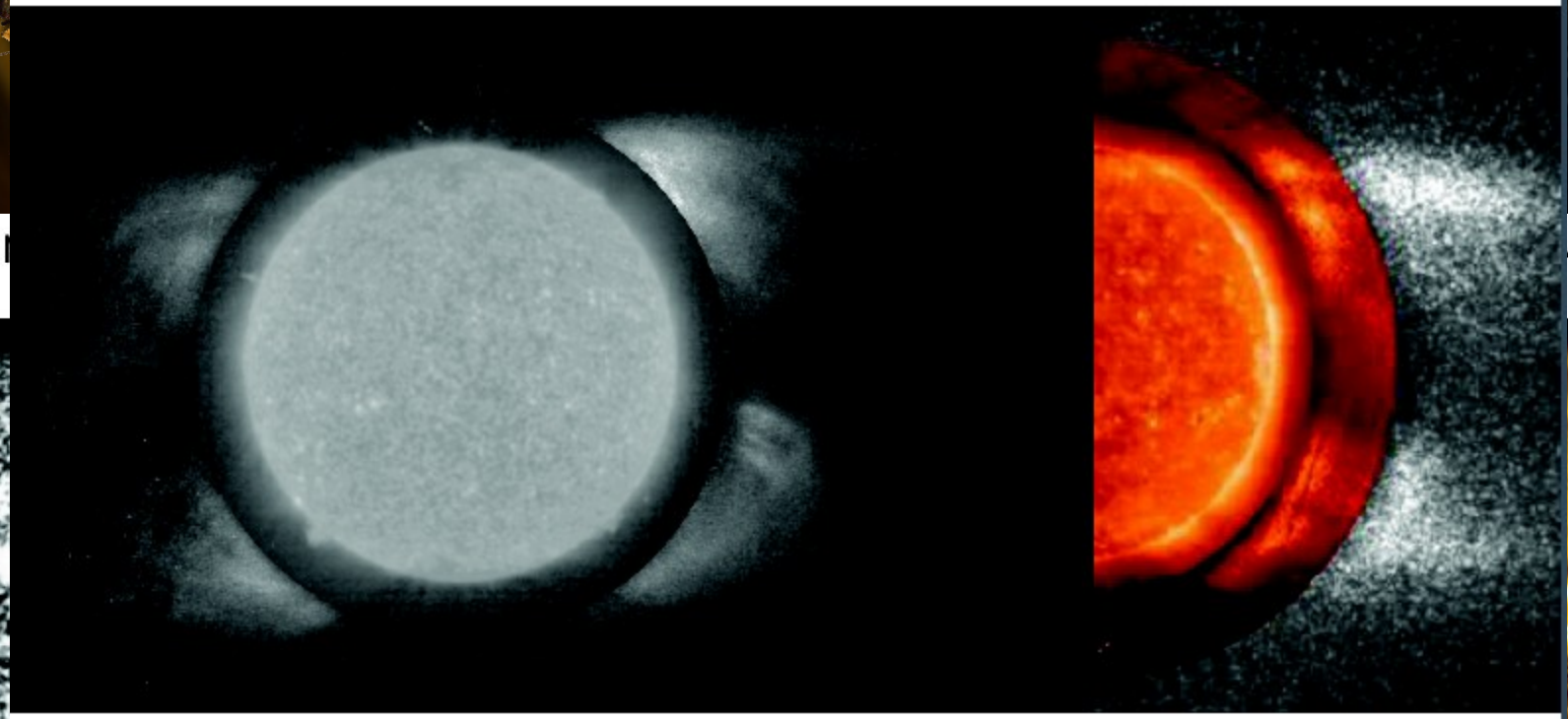
H Lyman alpha 121.6nm
chromosphere

He II 30.4nm
transition region

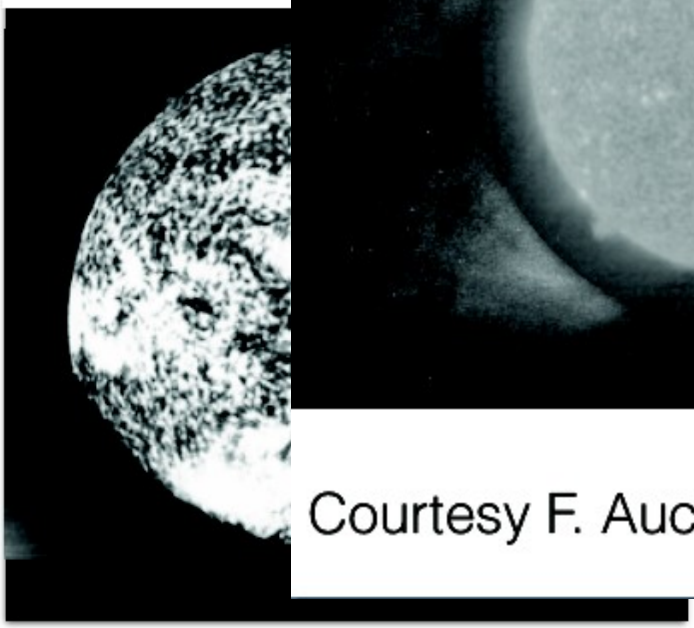
Fe IX, X, XI ~ 17nm
low corona

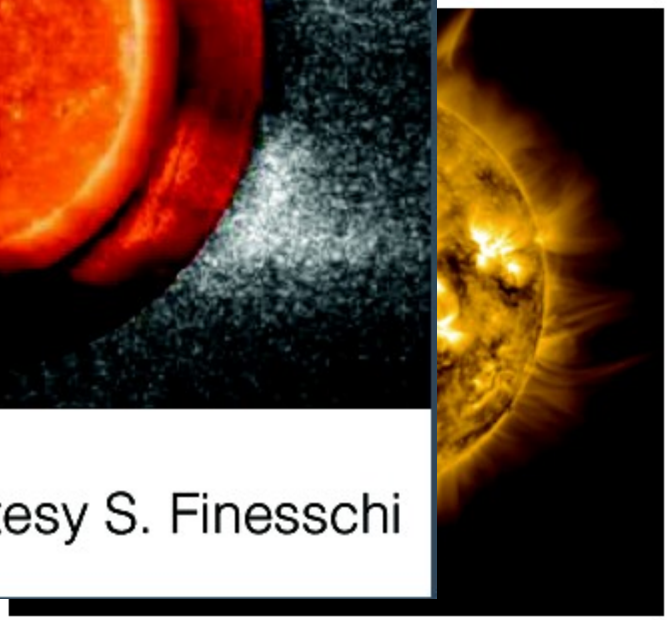
Remote-sensing windows (10 days each)

EIT HECOR SCORE



TRC (Bonn AP





Courtesy F. Auchere

Courtesy S. Finesschi

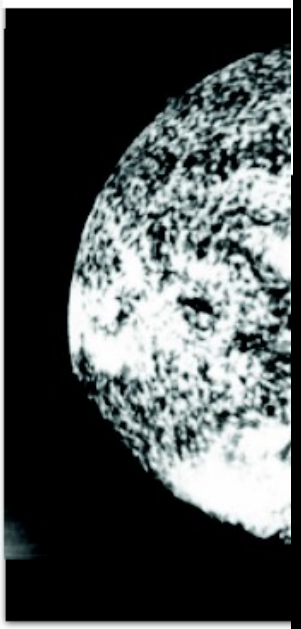
H Lyman alpha 121.6nm
chromosphere

He II 30.4nm
transition region

Fe IX, X, XI ~ 17nm
low corona

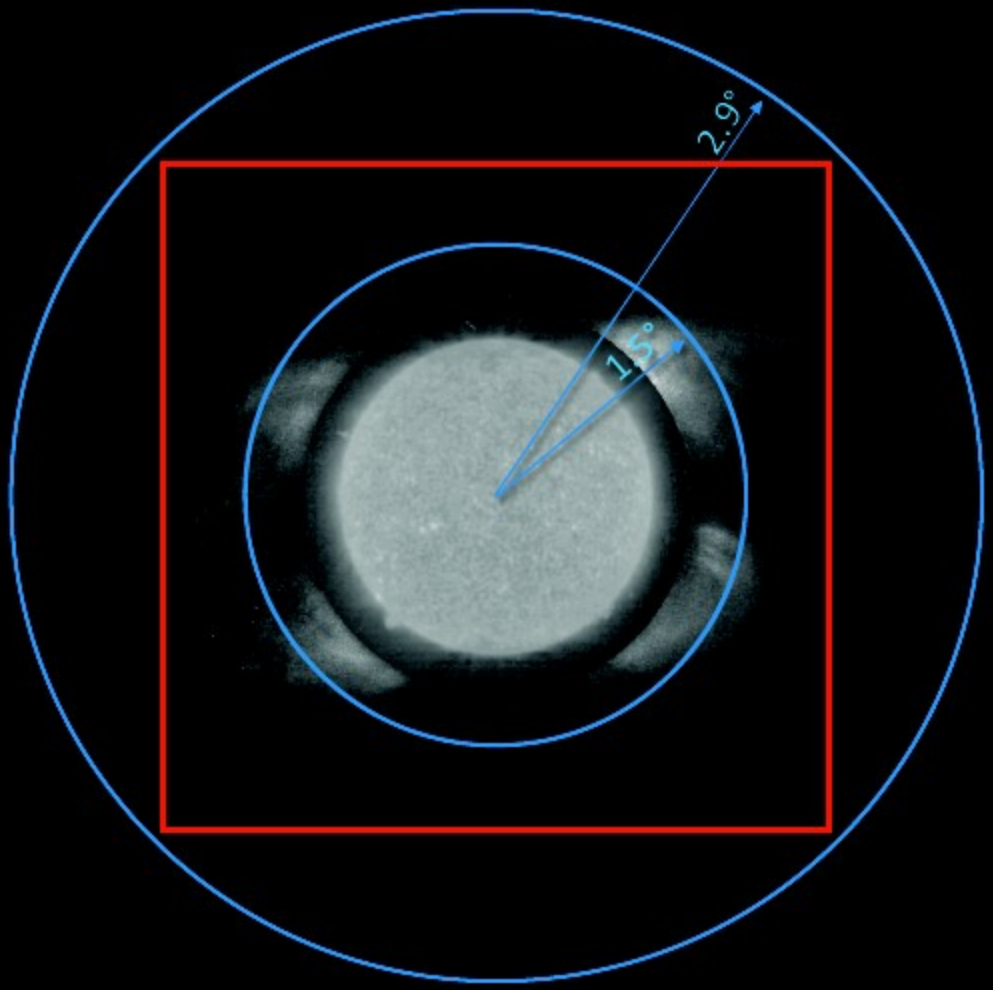
Remote-sen
windows (1
each)

TRC (Bonn

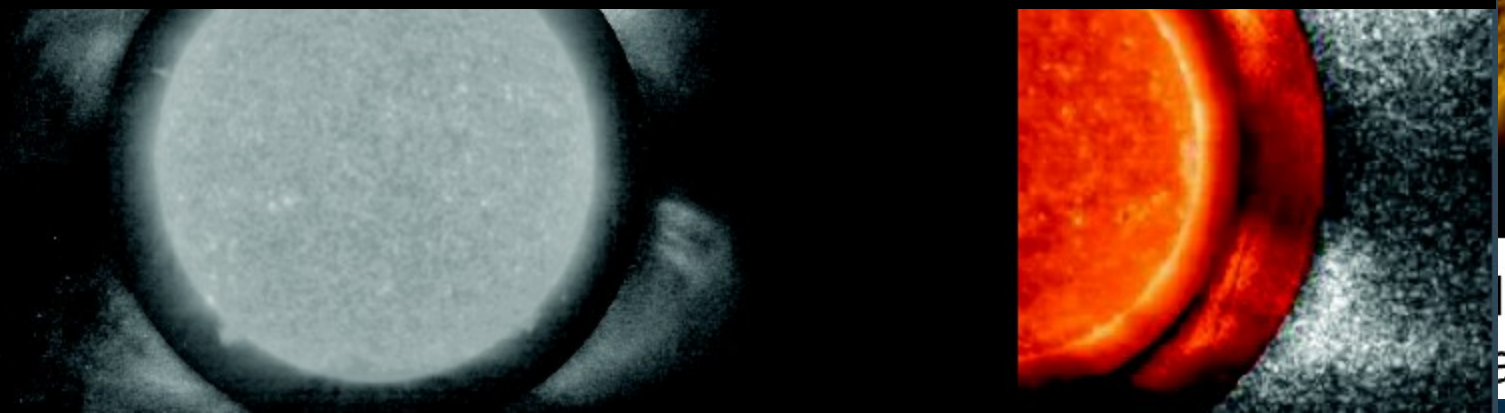


H Lyman a
chron

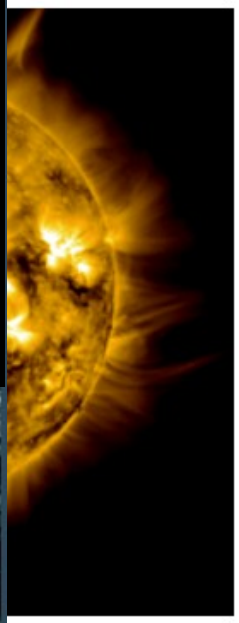
FSI & METIS: 30.4 @ 0.28 AU



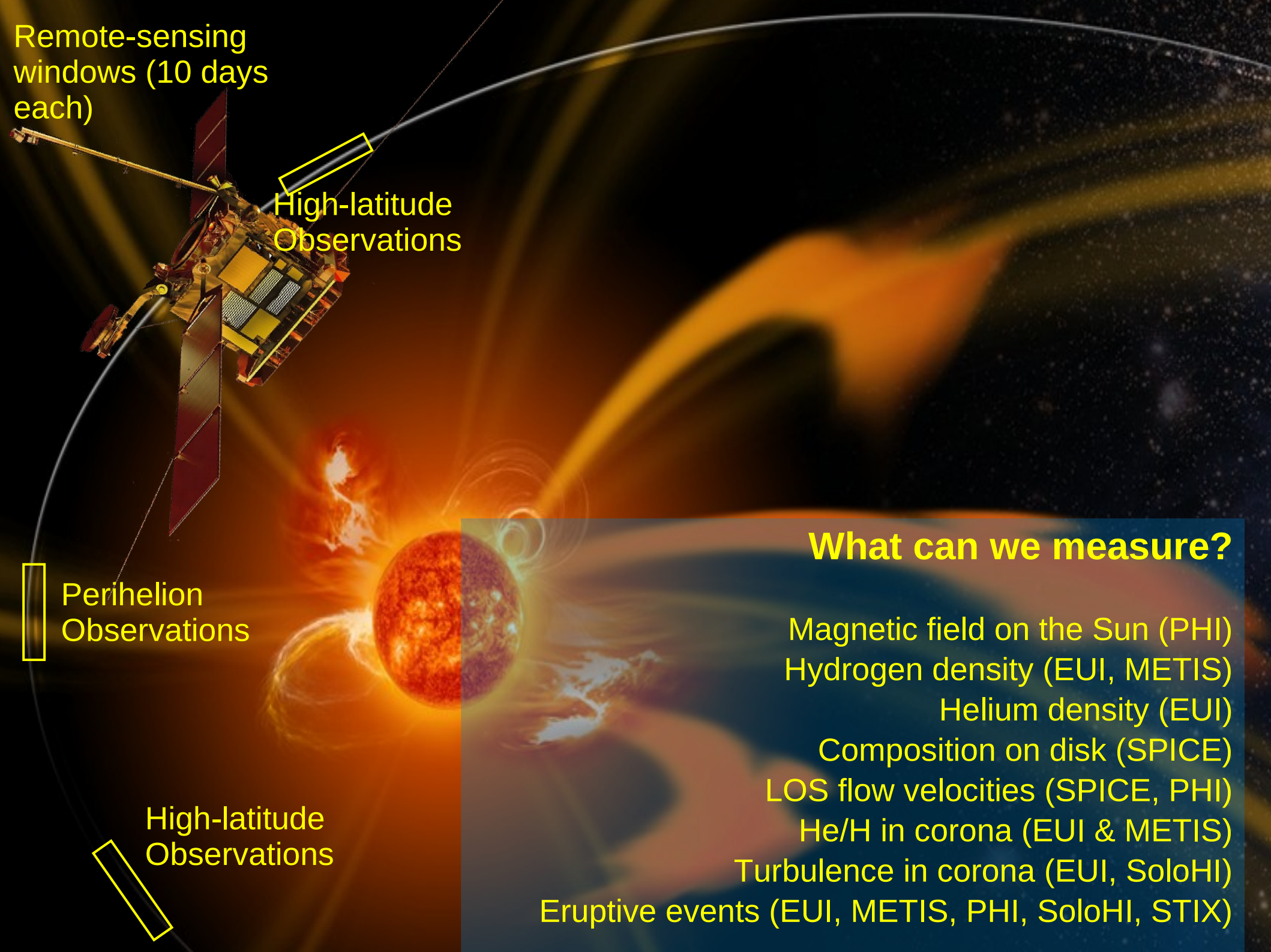
SP+

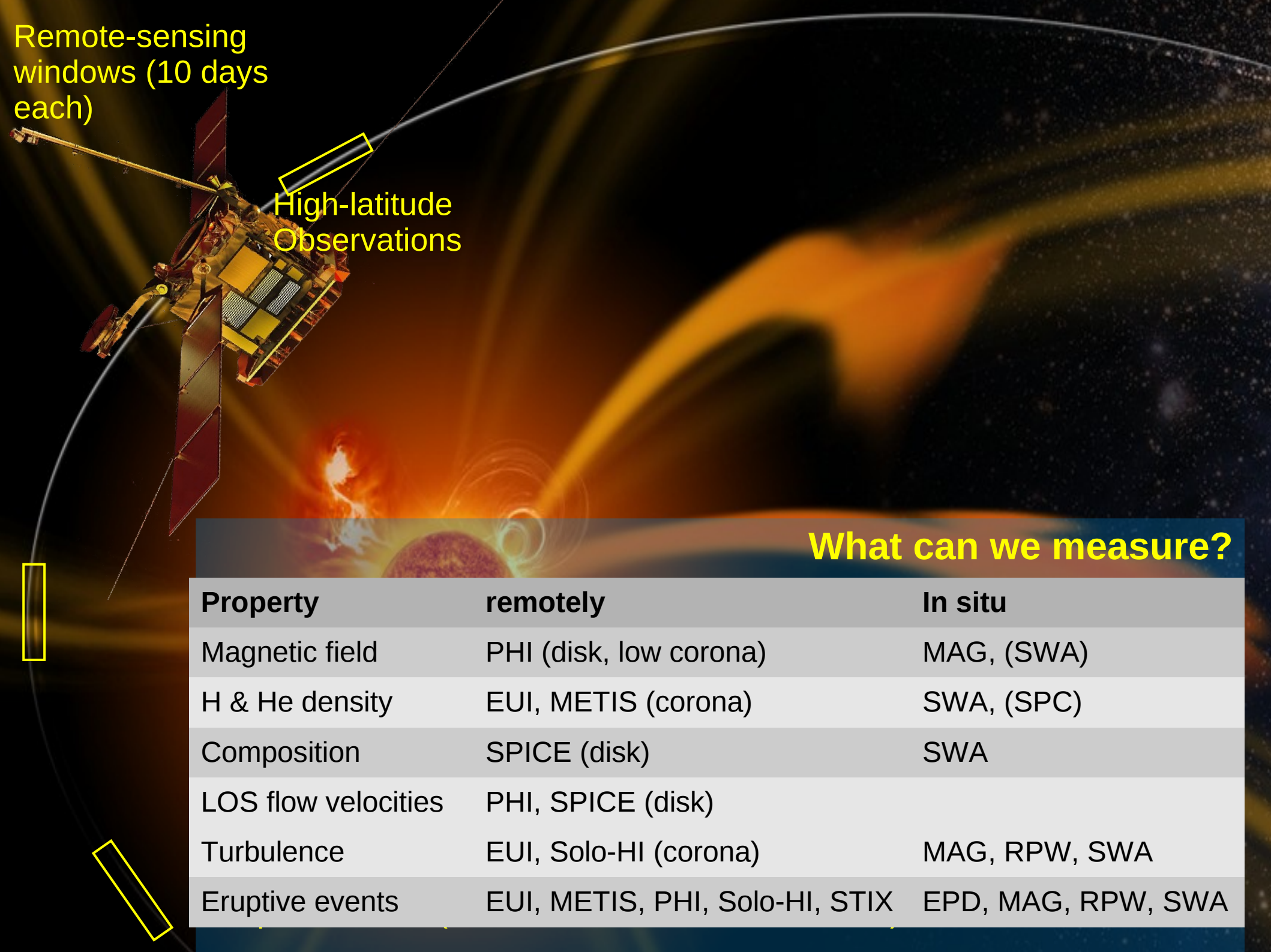


AP



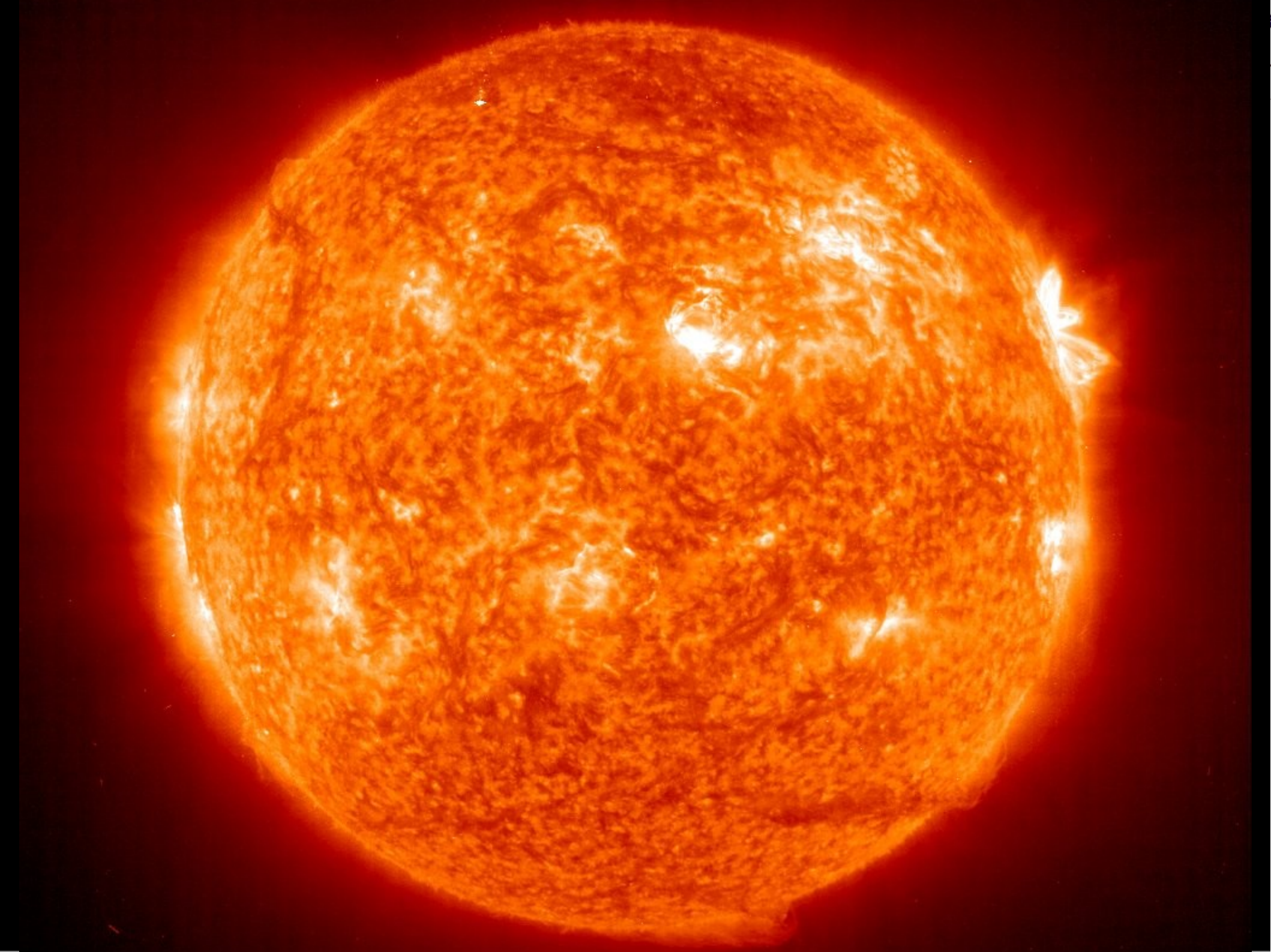
17nm
a


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)

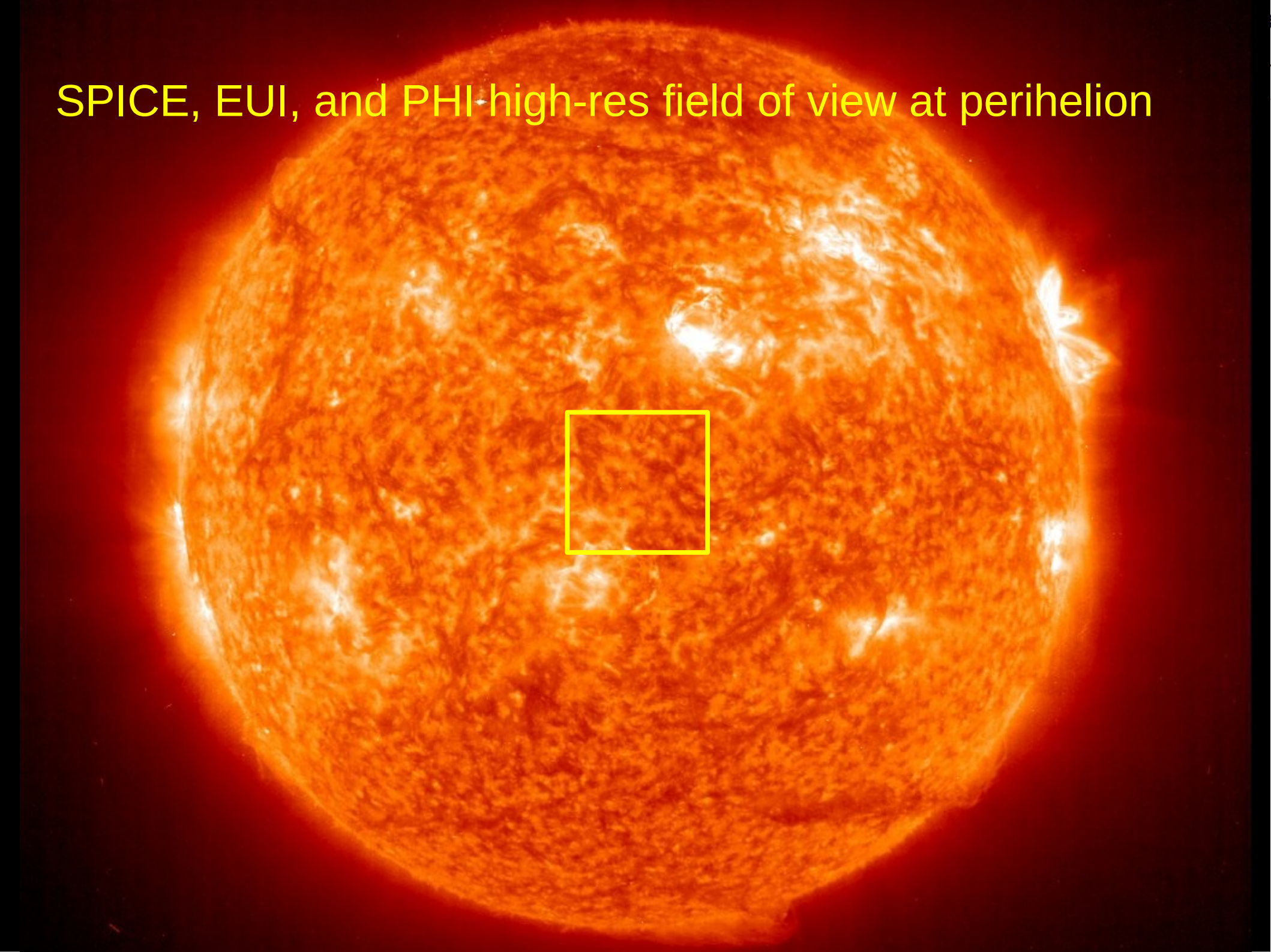


What can we measure?

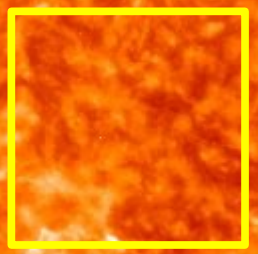
Property	remotely	In situ
Magnetic field	PHI (disk, low corona)	MAG, (SWA)
H & He density	EUI, METIS (corona)	SWA, (SPC)
Composition	SPICE (disk)	SWA
LOS flow velocities	PHI, SPICE (disk)	
Turbulence	EUI, Solo-HI (corona)	MAG, RPW, SWA
Eruptive events	EUI, METIS, PHI, Solo-HI, STIX	EPD, MAG, RPW, SWA



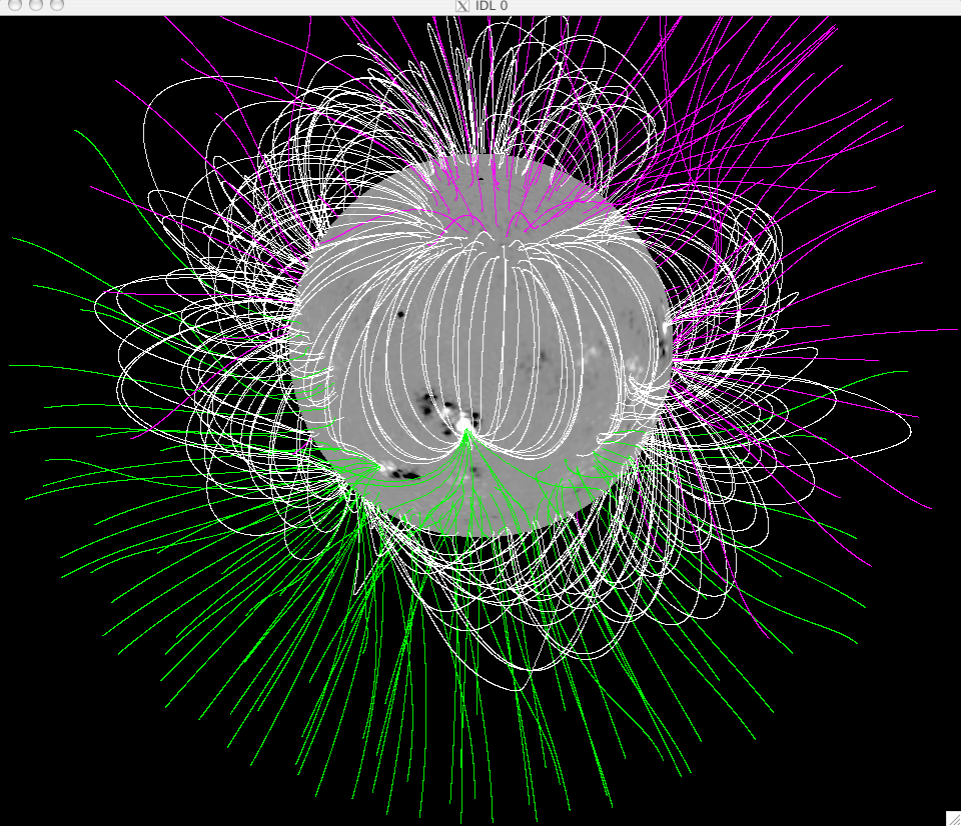
SPICE, EUI, and PHI high-res field of view at perihelion

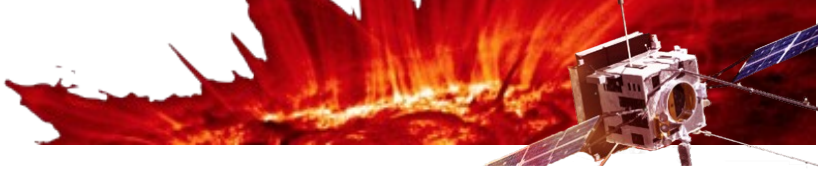


3% of disk at perihelion:
- approx. 18 degrees as seen from Sun center
- apparent solar rotation rate at perihelion is ~ 6°/day
- thus, same source region remains in box for ~ 3 days
- typical travel time: 60 r_{sun}/400 km/s = 1.25 days
- typical travel time: 60 r_{sun}/300 km/s = 1.6 days



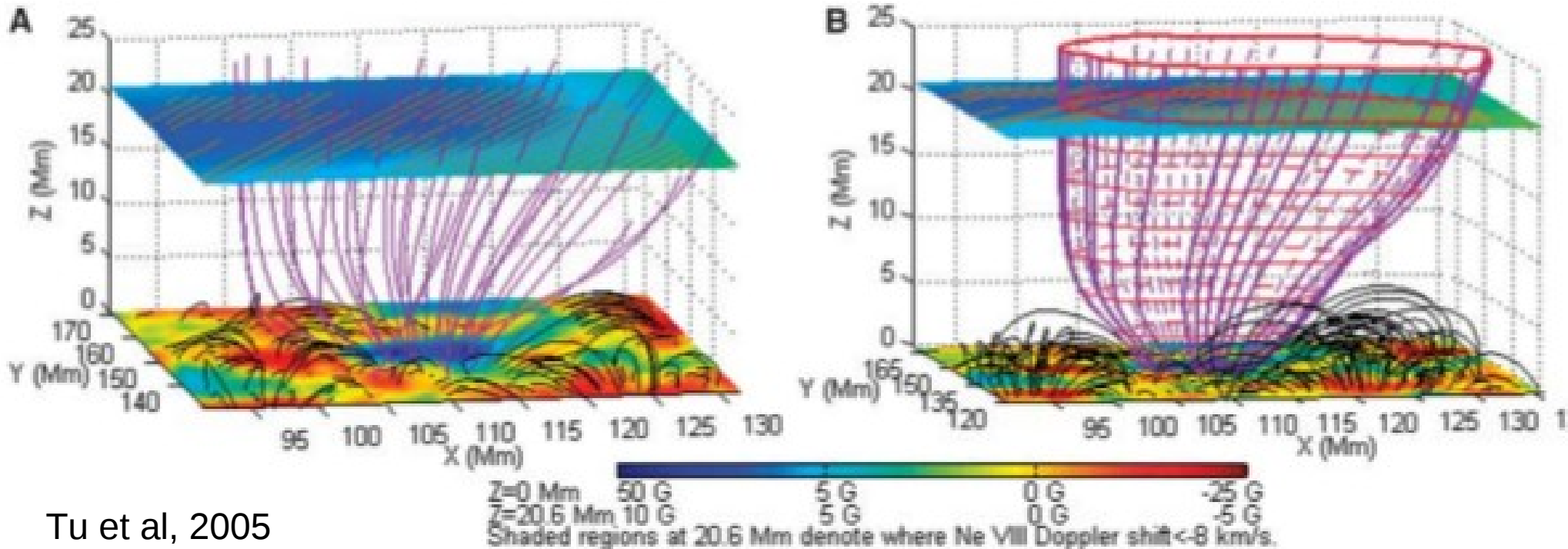
Mapping the origin of the solar wind looks feasible
if it comes the disk center.
BUT: Does it? Well, that's what Solar Orbiter is all about.



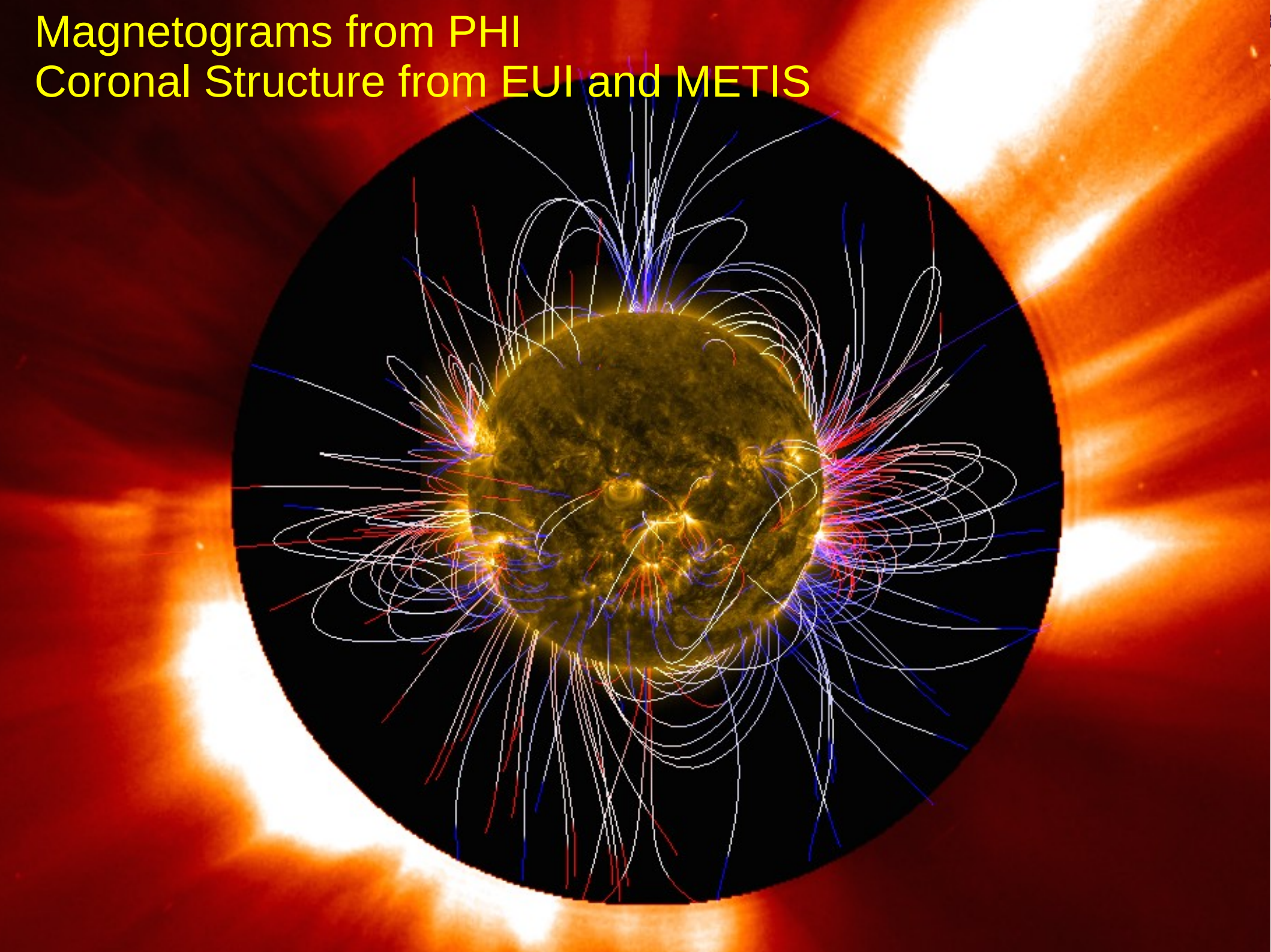


The problem lies in the super-radial expansion of flux tubes.

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

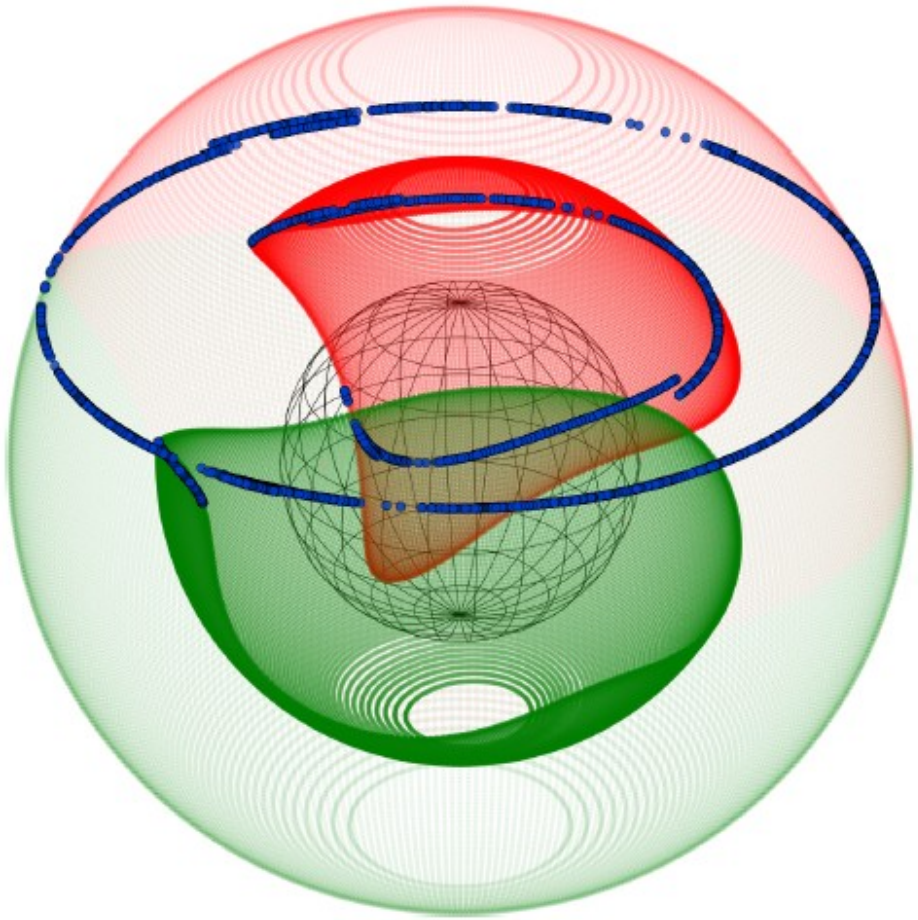


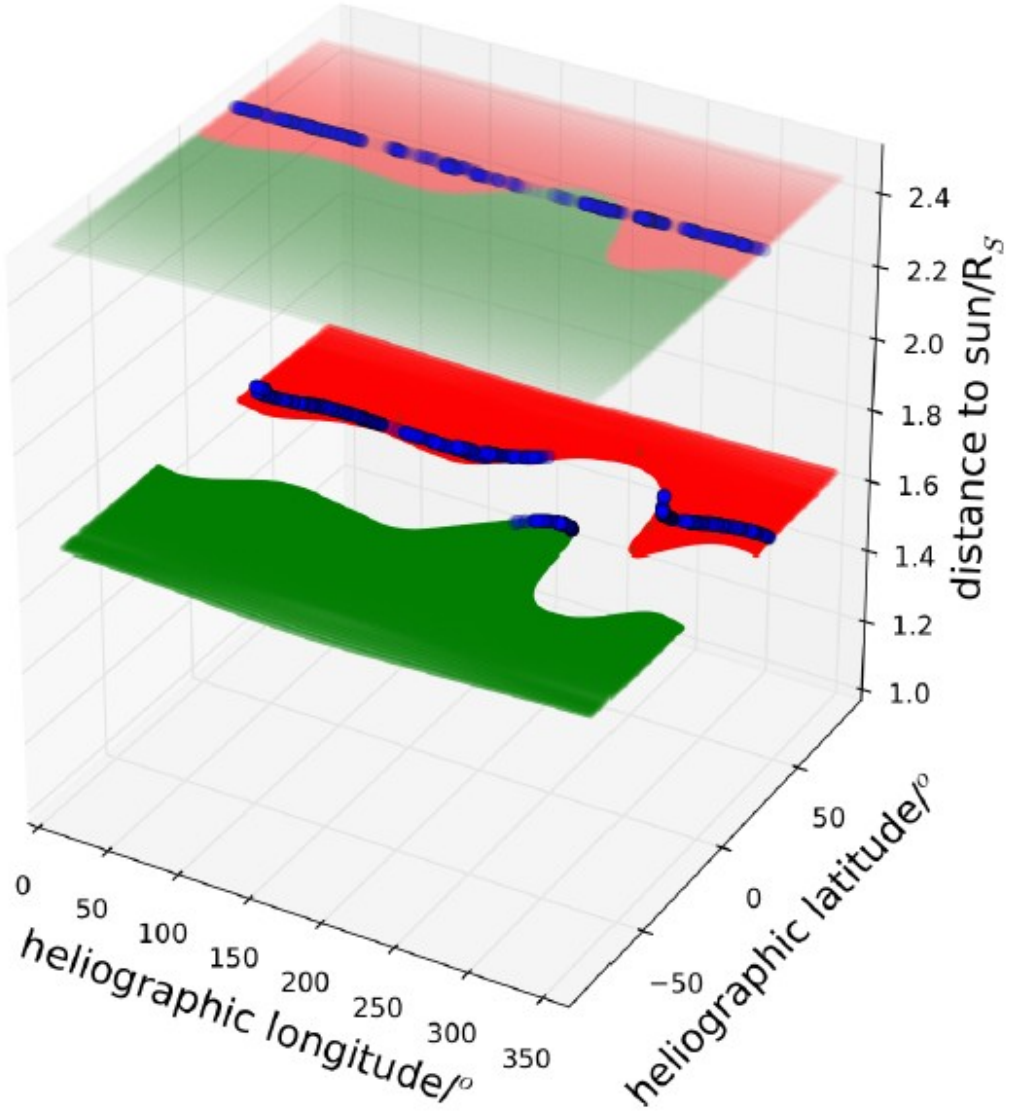
Tu et al, 2005


Magnetograms from PHI
Coronal Structure from EUI and METIS

The Third “Instrument”: Models

For instance map solar wind back to coronal & chromospheric origin

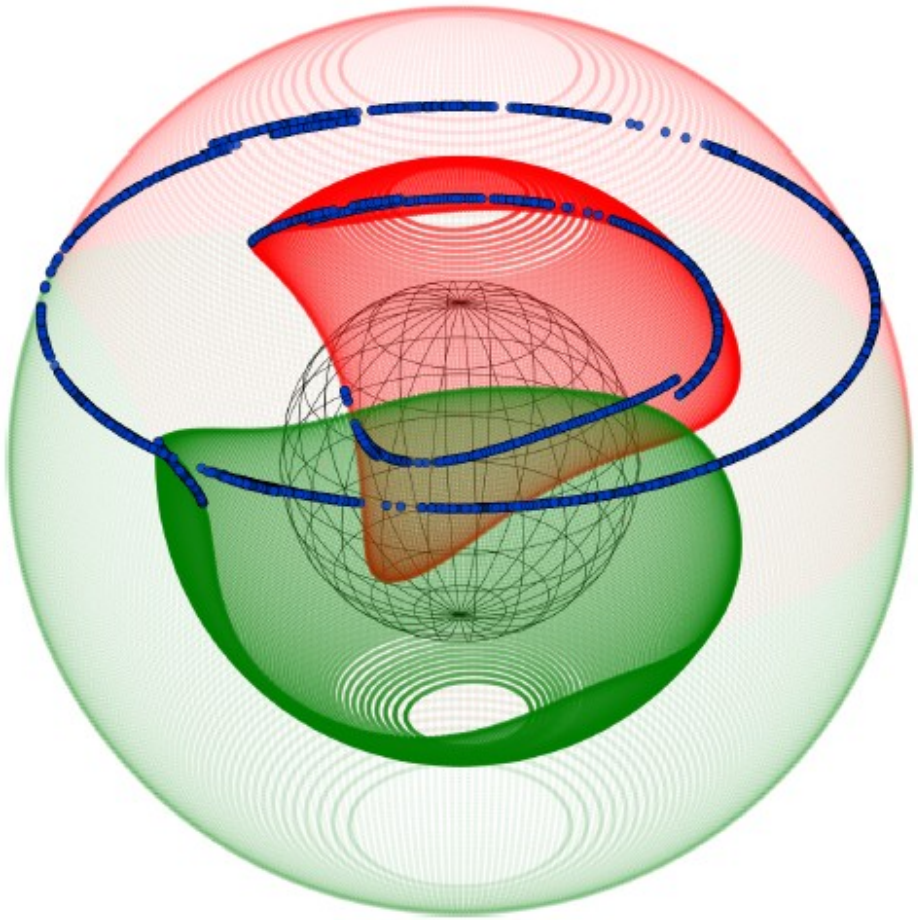


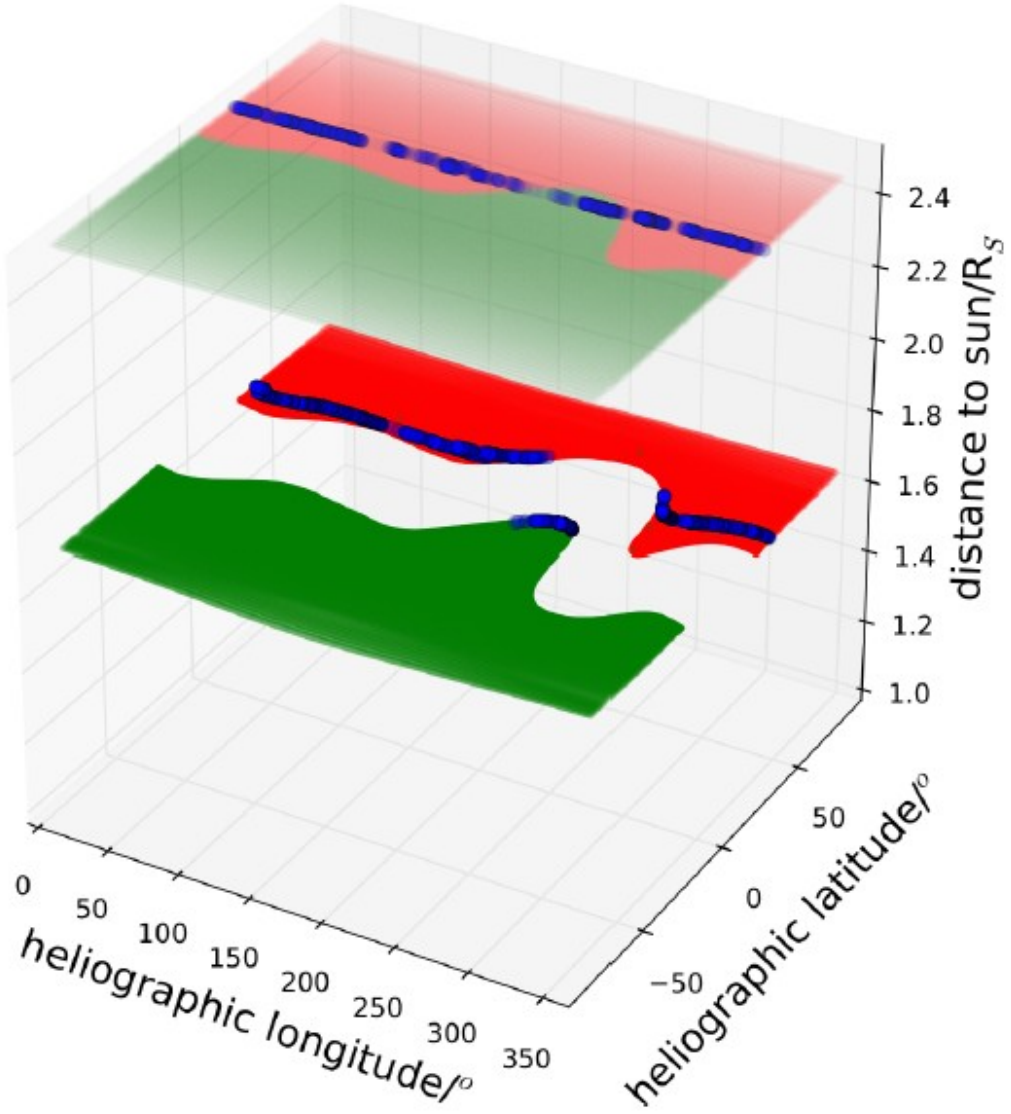


(Peleikis et al., SH31B-03
Kruse et al., SH13A-4080)

The Third “Instrument”: Models

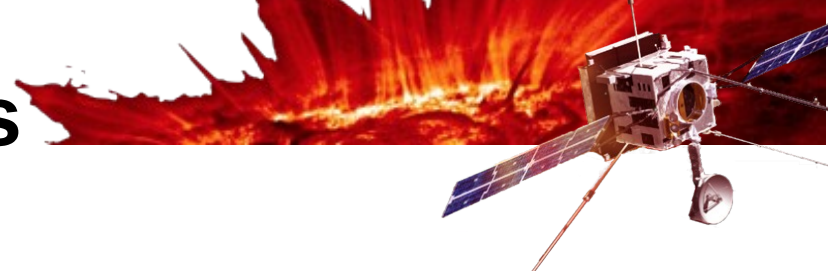
For instance map solar wind back to coronal & chromospheric origin





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

The Third "Instrument": Models

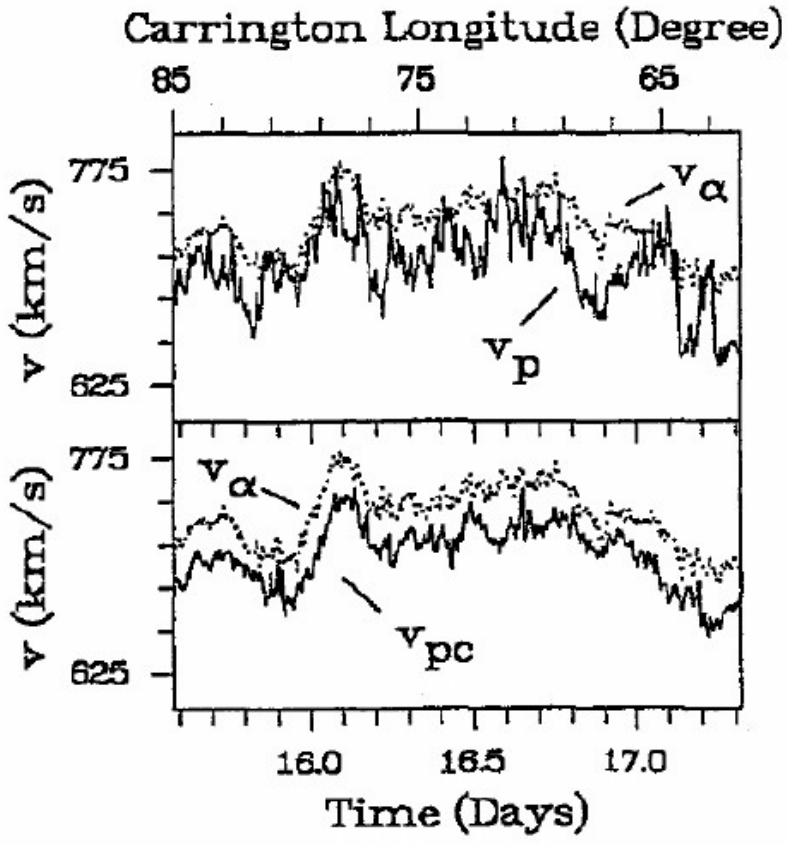


For instance map solar wind back to coronal & chromospheric origin

Removal of the Alfvén-Waves Influence from the Proton Velocity

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

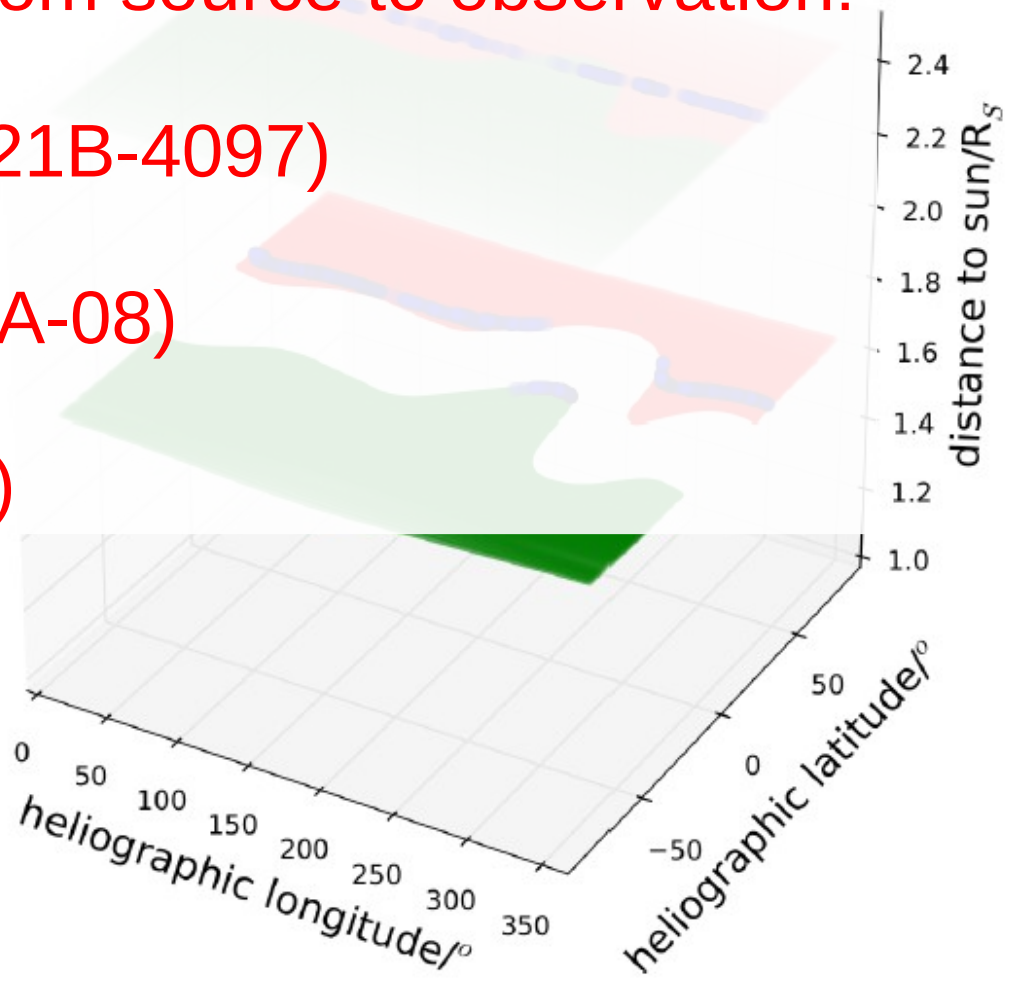
For instance map solar wind back to coronal & chromospheric origin

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

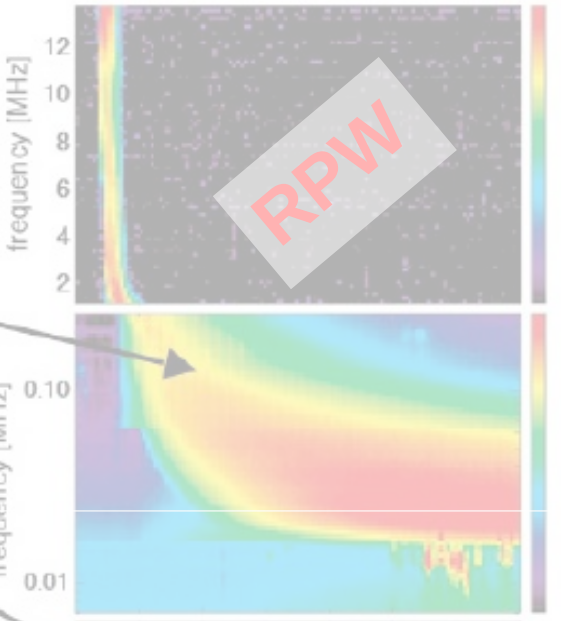
SO & SP+

magnetic field line
escaping electrons
radio type III emission

MAG, SWA

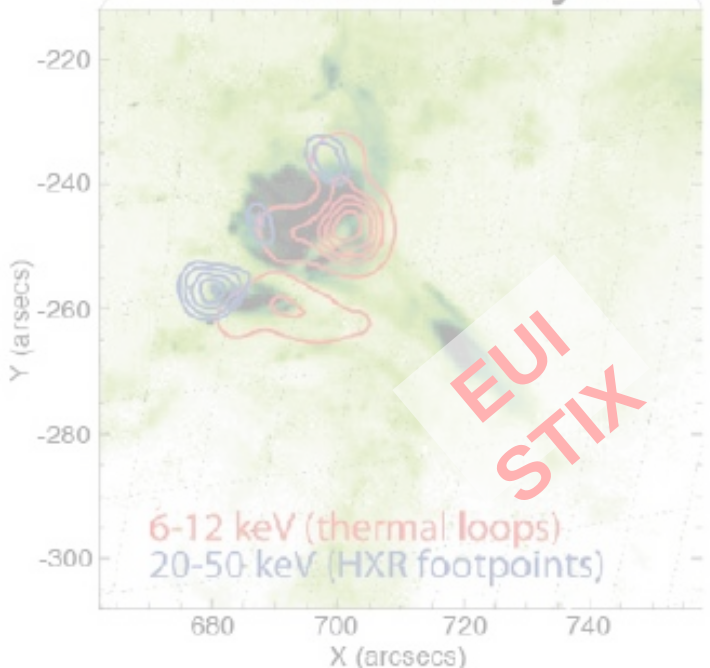
in-situ observation of
escaping ions & electrons

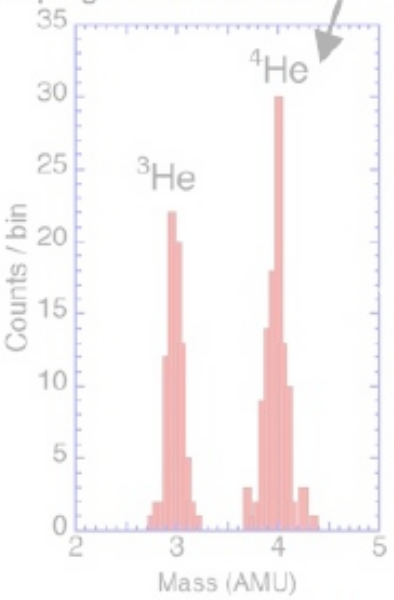
radio burst



SO

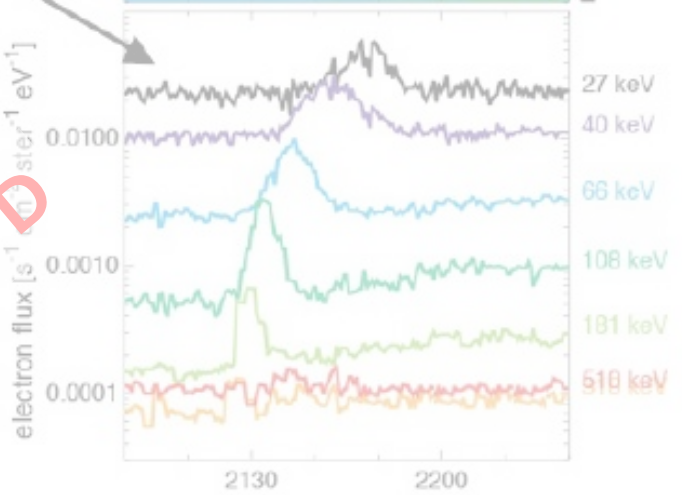
UV and X-rays





energetic He

EPD

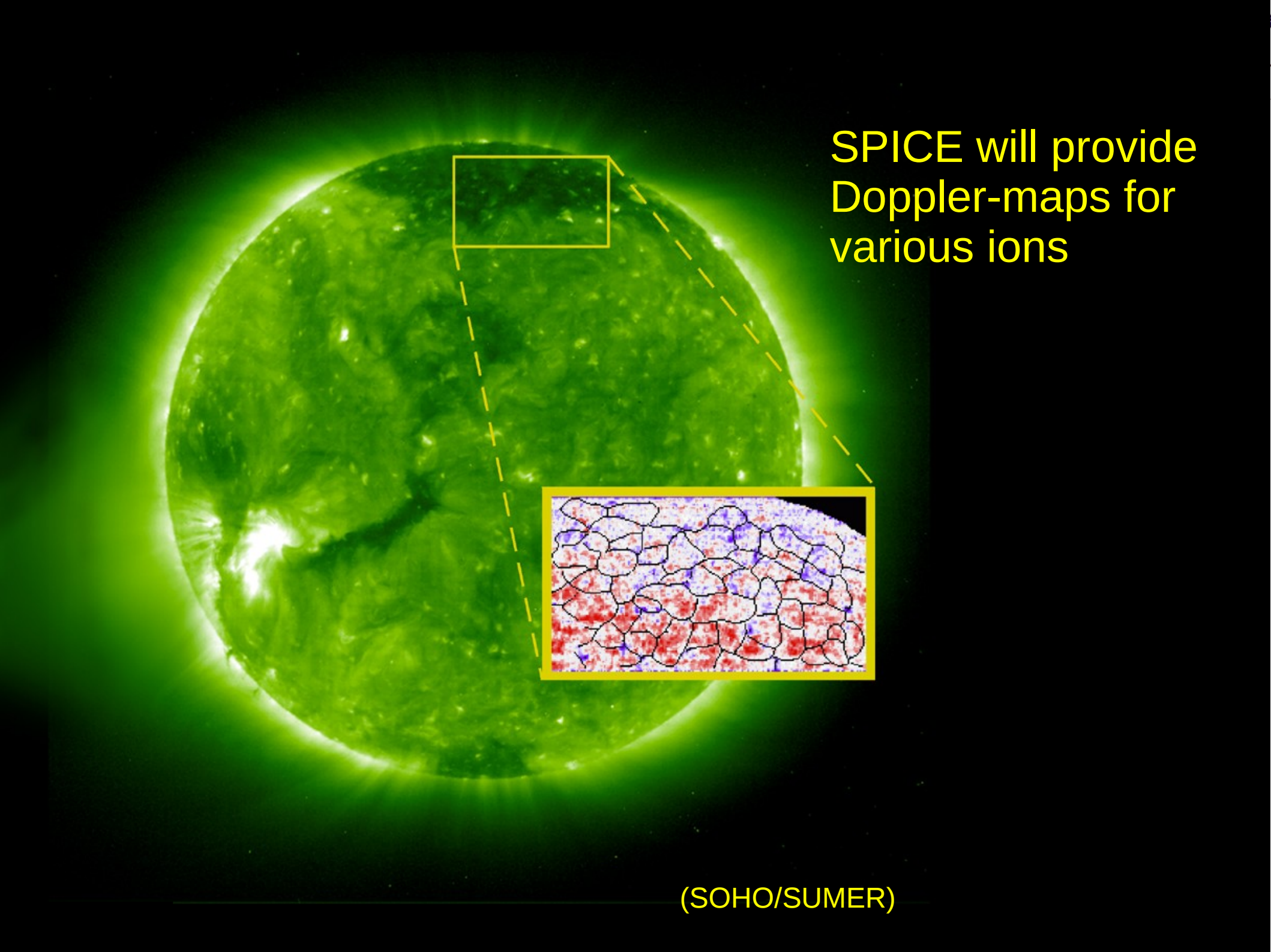


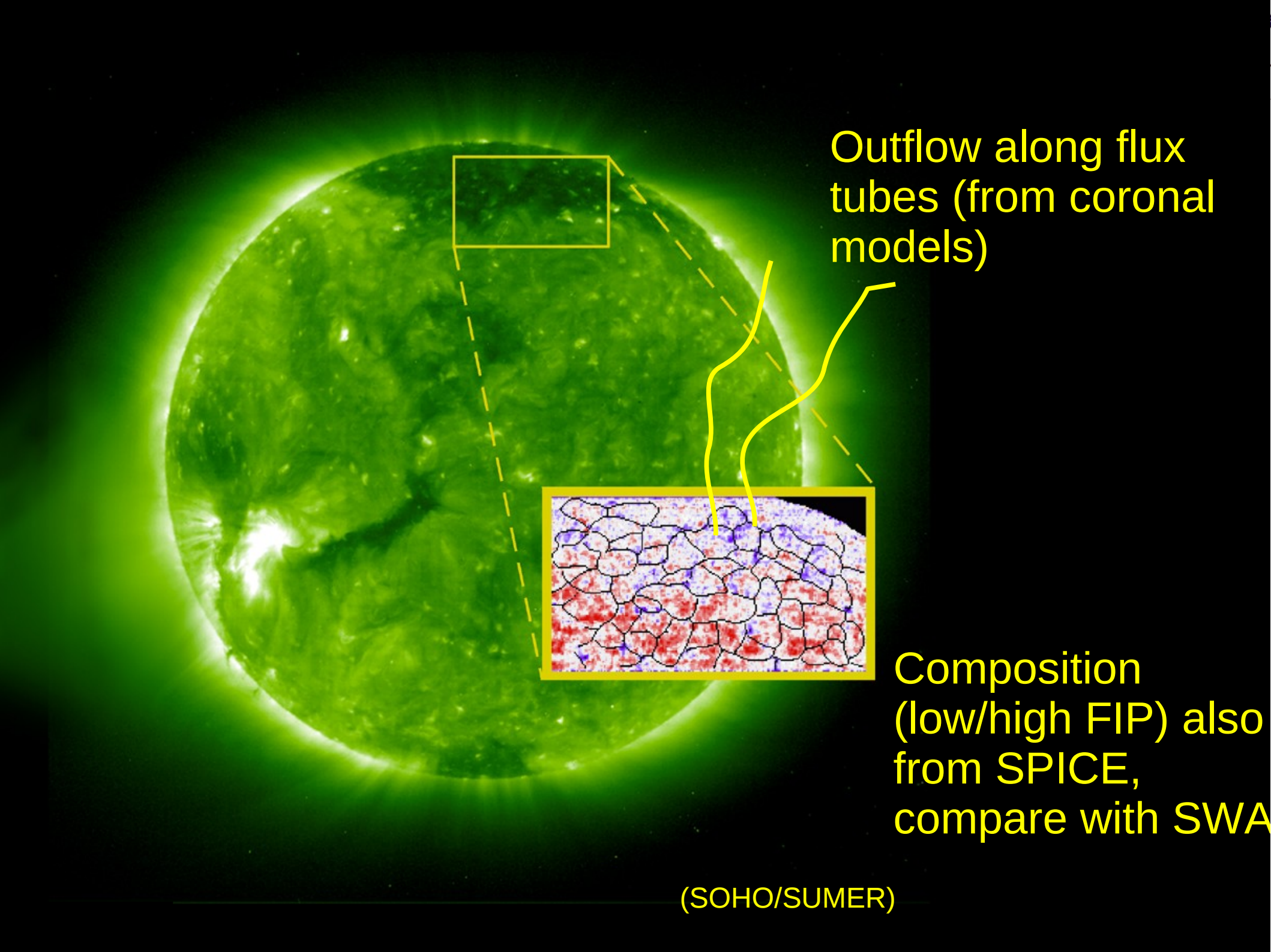
energetic electrons

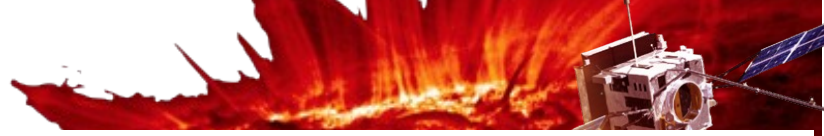
Processes that affect solar wind composition:

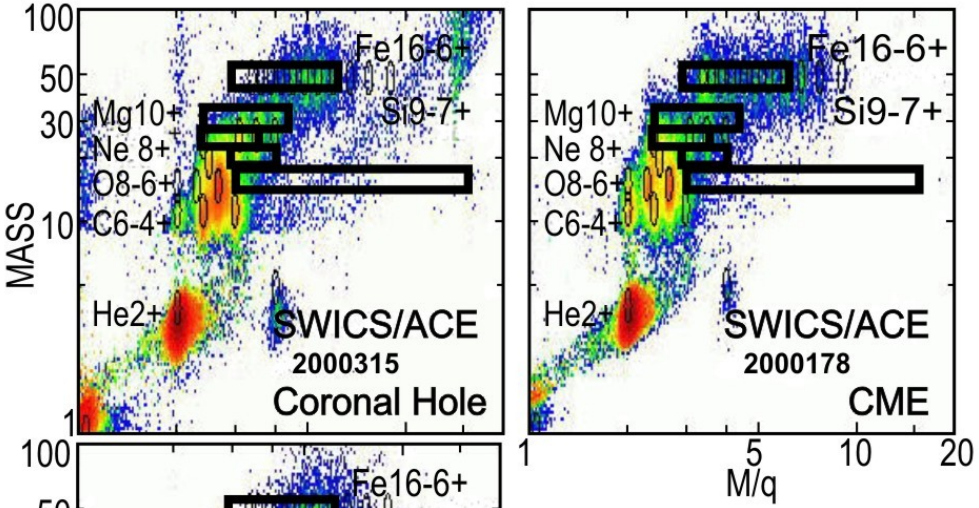
Process	Location	Elemental	Ionic	Seen in situ?	Origin understood?
FIP effect	Chromosphere, foot points of loops	yes	?	yes	no
Heating	Corona, loops, foot points of loops	Possibly small effect?	yes	yes	no
Gravitational stratification	streamers	yes	no	no	yes
Coulomb drag	Coronal expansion	Yes, especially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

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


SPICE will provide Doppler-maps for various ions
(SOHO/SUMER)

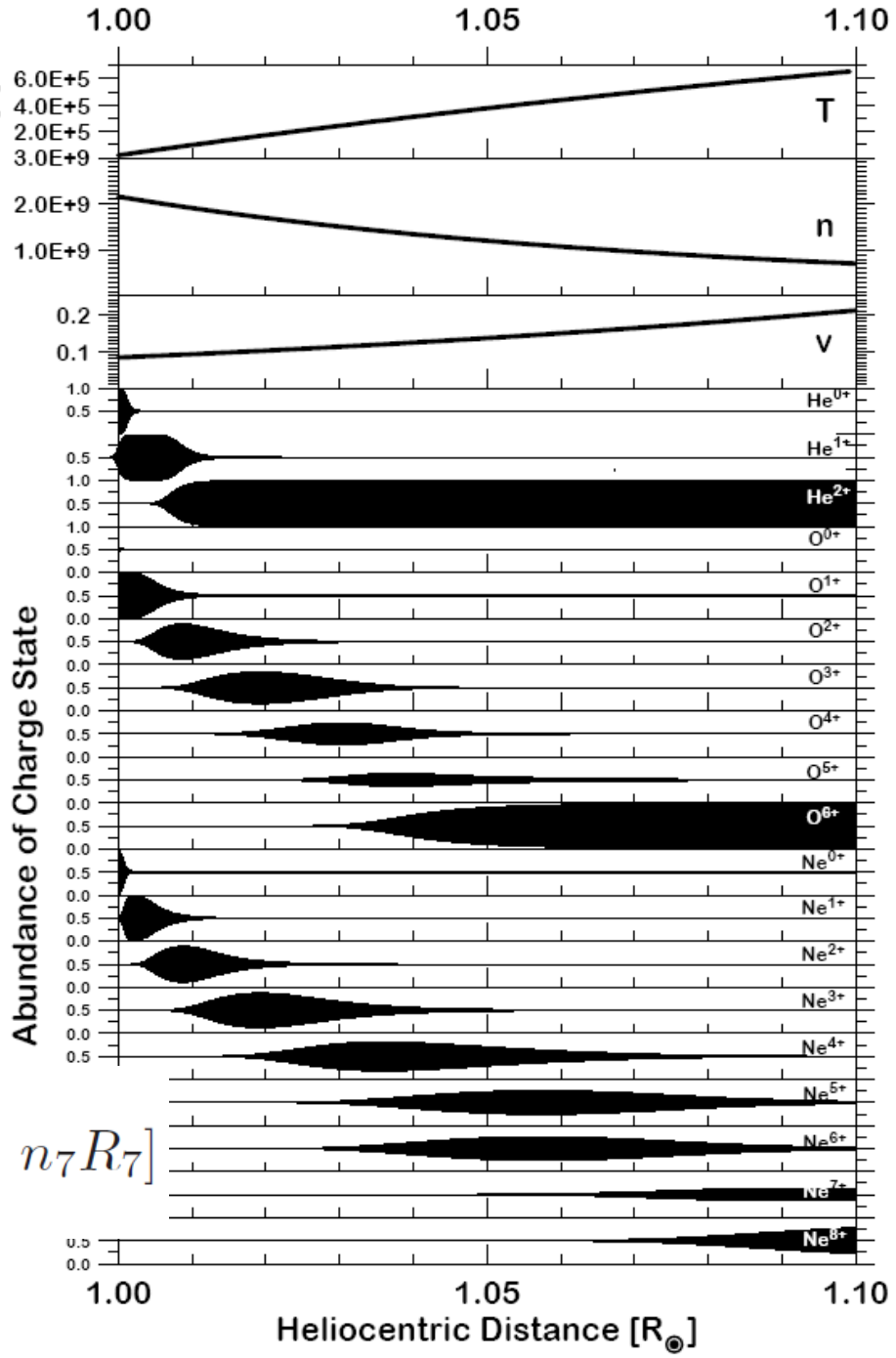

Outflow along flux tubes (from coronal models)
Composition (low/high FIP) also from SPICE, compare with SWA
(SOHO/SUMER)





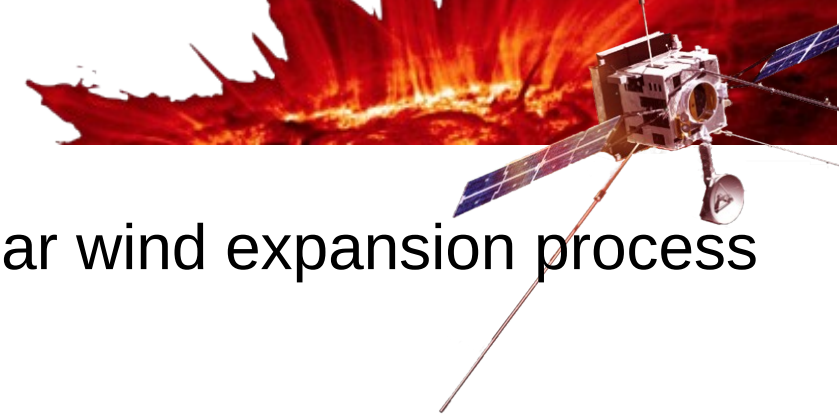
TA005918_SPICE

Charge states are continuously modified by ionization and re-combination. Both are proportional to coronal electron density.

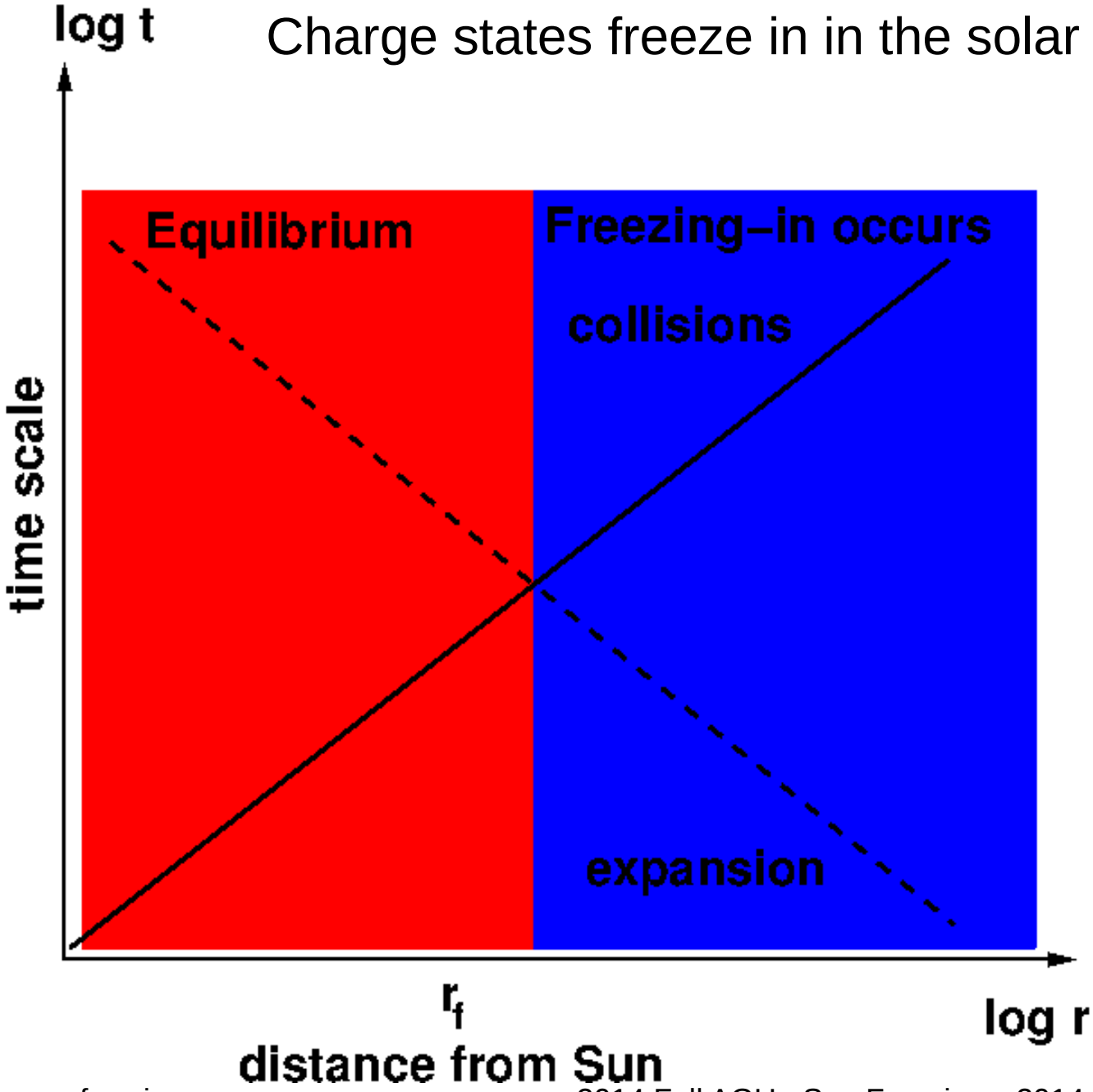


$$\frac{\partial n_6}{\partial t} + \vec{\nabla}\left(n_6 \vec{u}_6\right) = n_e \left[n_5 C_5 - n_6 \left(R_6 + C_6\right) + n_7 R_7\right]$$

Bochsler, 2007

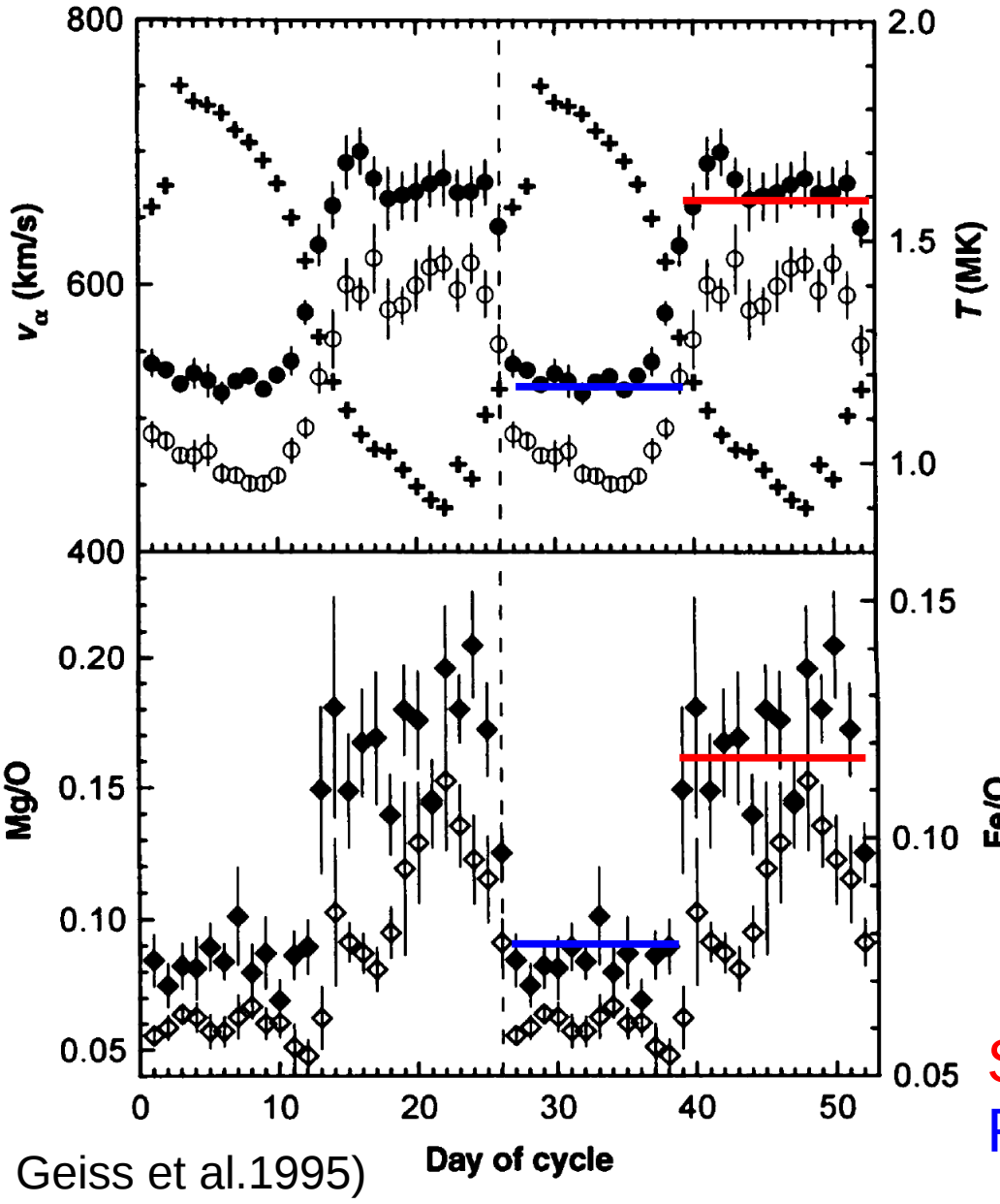


Charge states freeze in in the solar wind expansion process



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.



Geiss et al.1995)

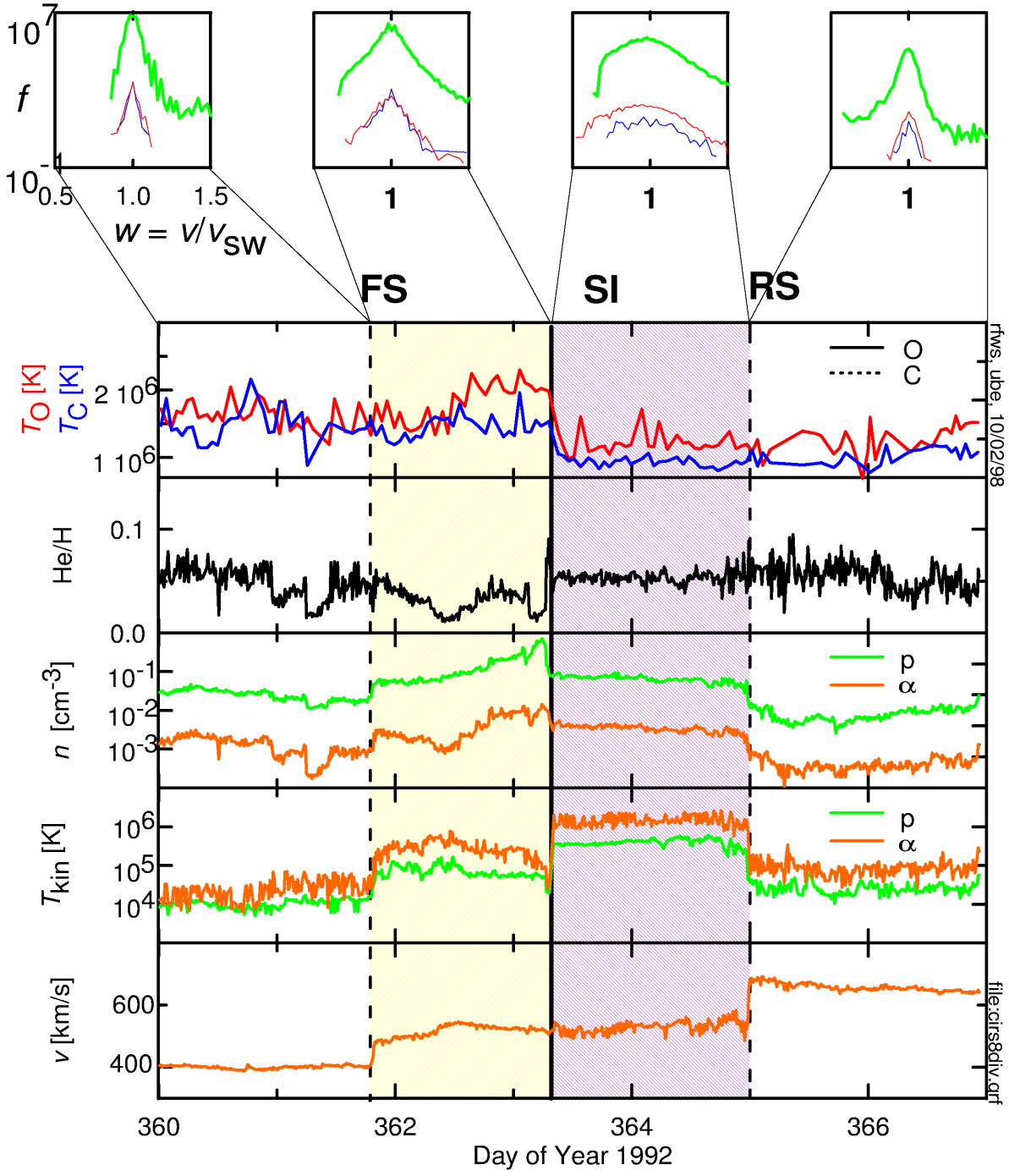
Slow wind hot (source?)

Fast wind cool (coronal hole)

What links chromosphere and corona?

Slow wind strongly FIPped

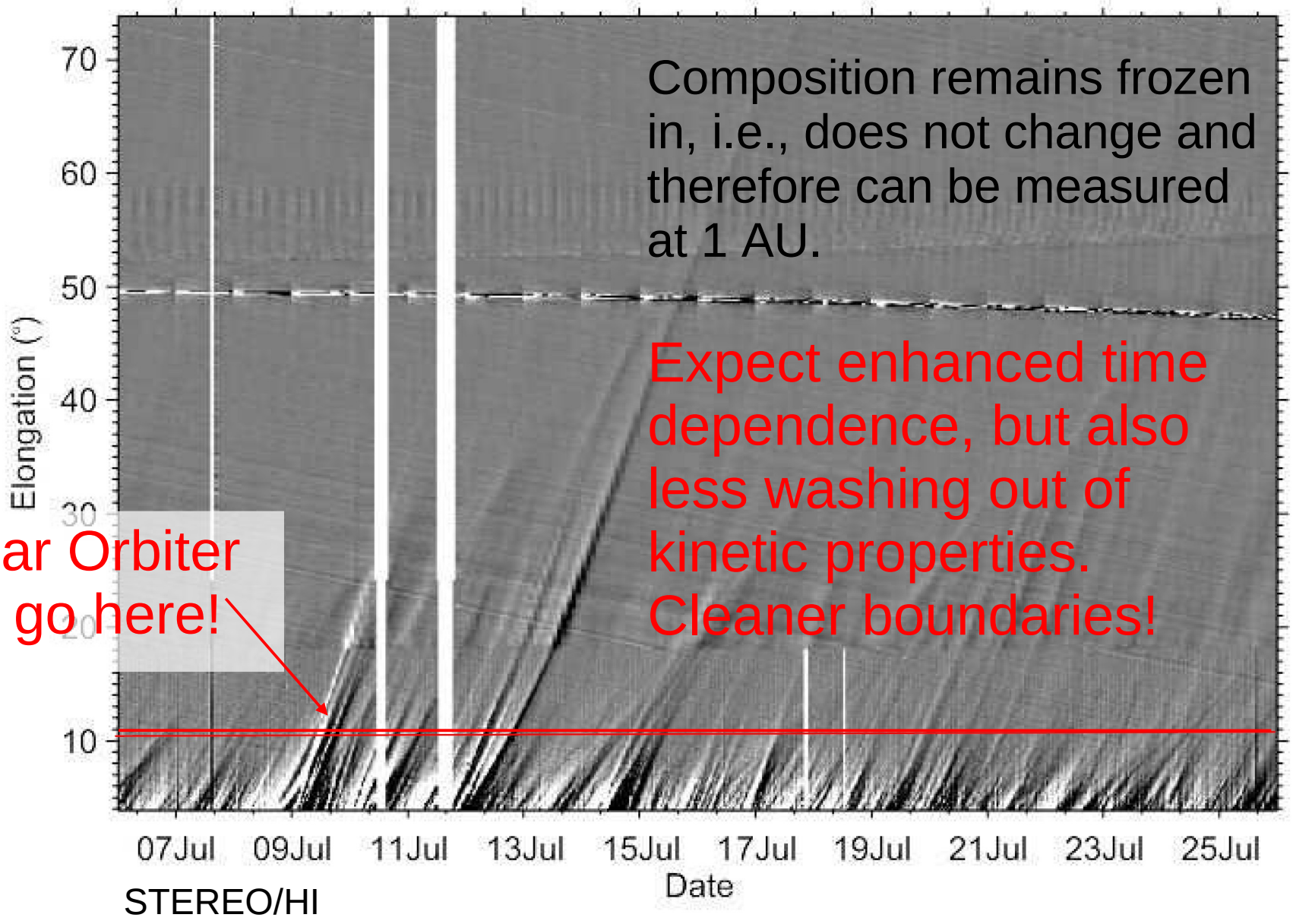
Fast wind weakly/barely FIPped

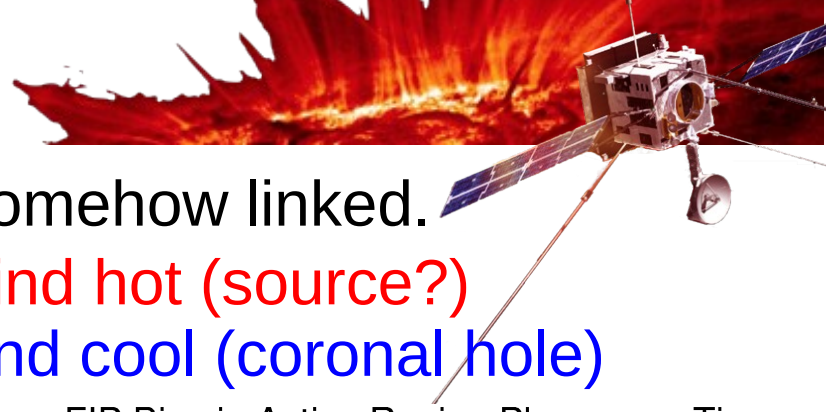


Individual streams can be identified in-situ by many independent methods:
- magnetic field
- plasma data
- specific entropy
- composition

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.

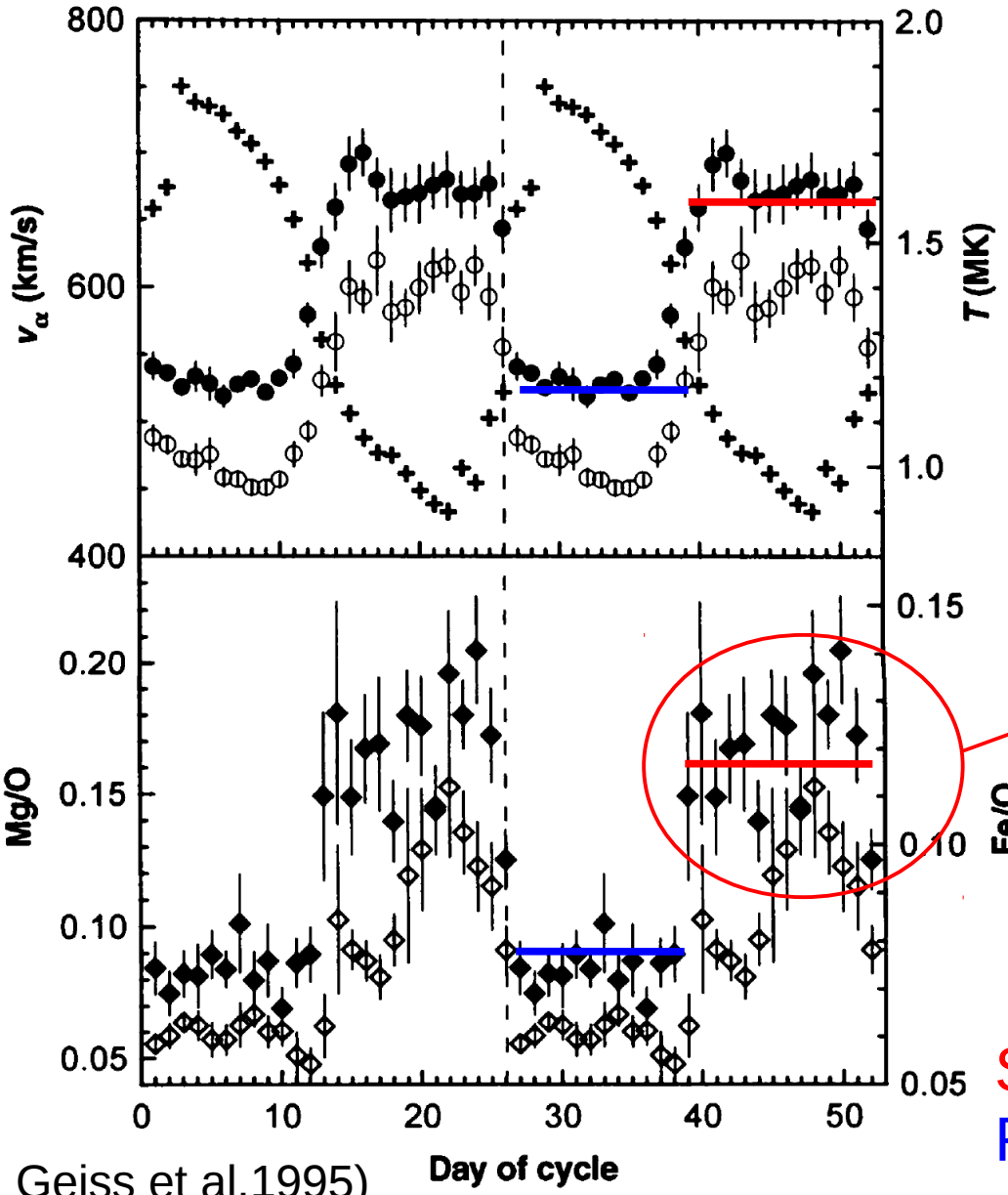

Composition remains frozen in, i.e., does not change and therefore can be measured at 1 AU.
Expect enhanced time dependence, but also less washing out of kinetic properties. Cleaner boundaries!
Solar Orbiter will go here!
Elongation (°)
70
60
50
40
30
20
10
07Jul
09Jul
11Jul
13Jul
15Jul
17Jul
19Jul
21Jul
23Jul
25Jul
Date
STEREO/HI



Charge-state and elemental composition somehow linked.

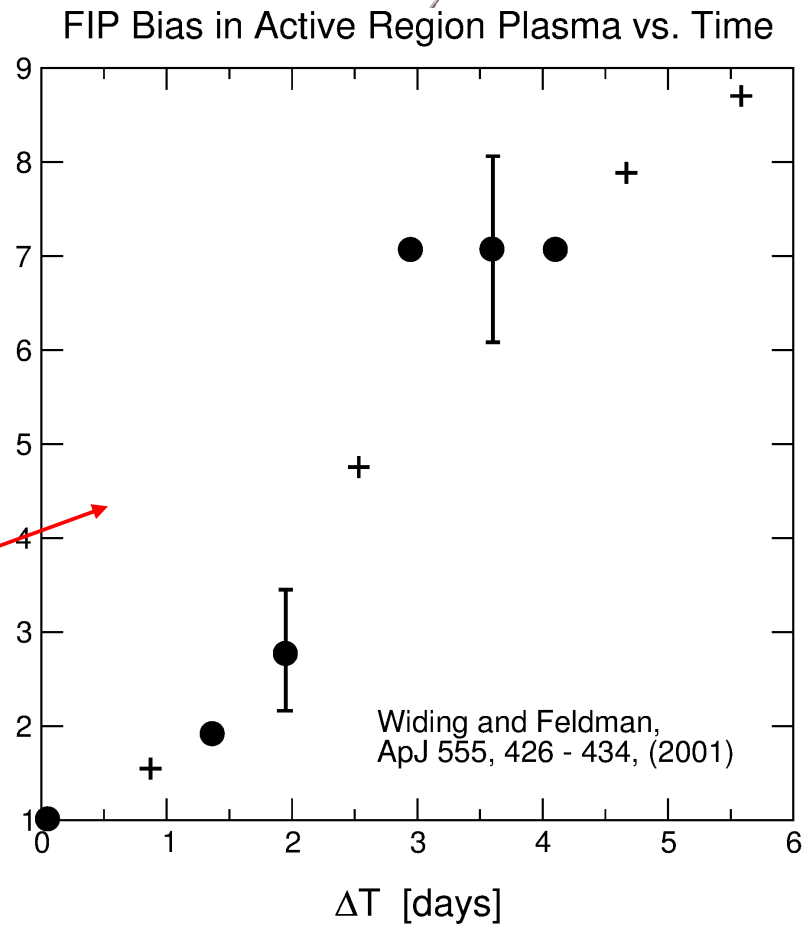
Slow wind hot (source?)

Fast wind cool (coronal hole)



Geiss et al.1995)

What links chromosphere and corona?



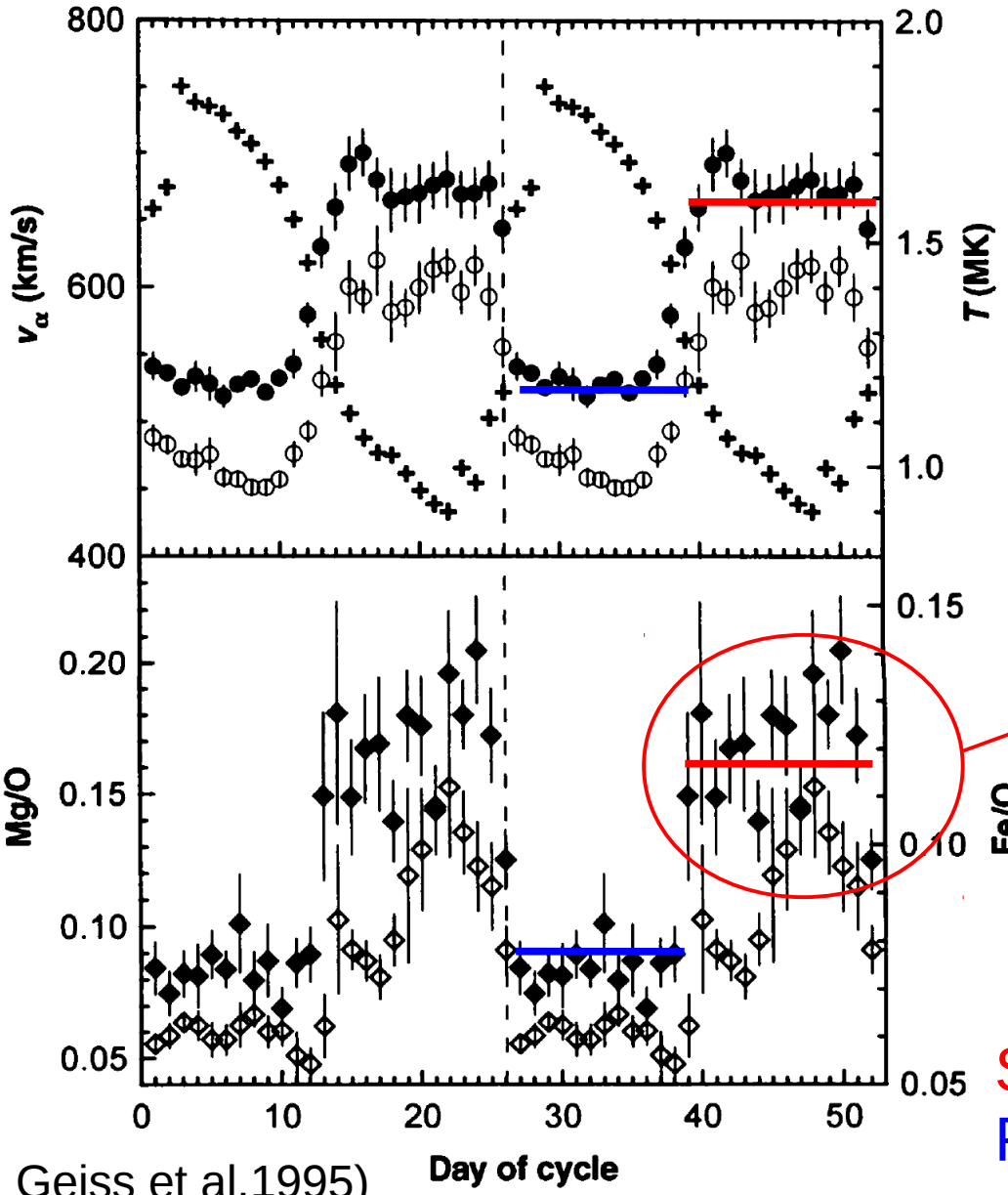
Slow wind strongly FIPped

Fast wind weakly/barely FIPped

Charge-state and elemental composition somehow linked.

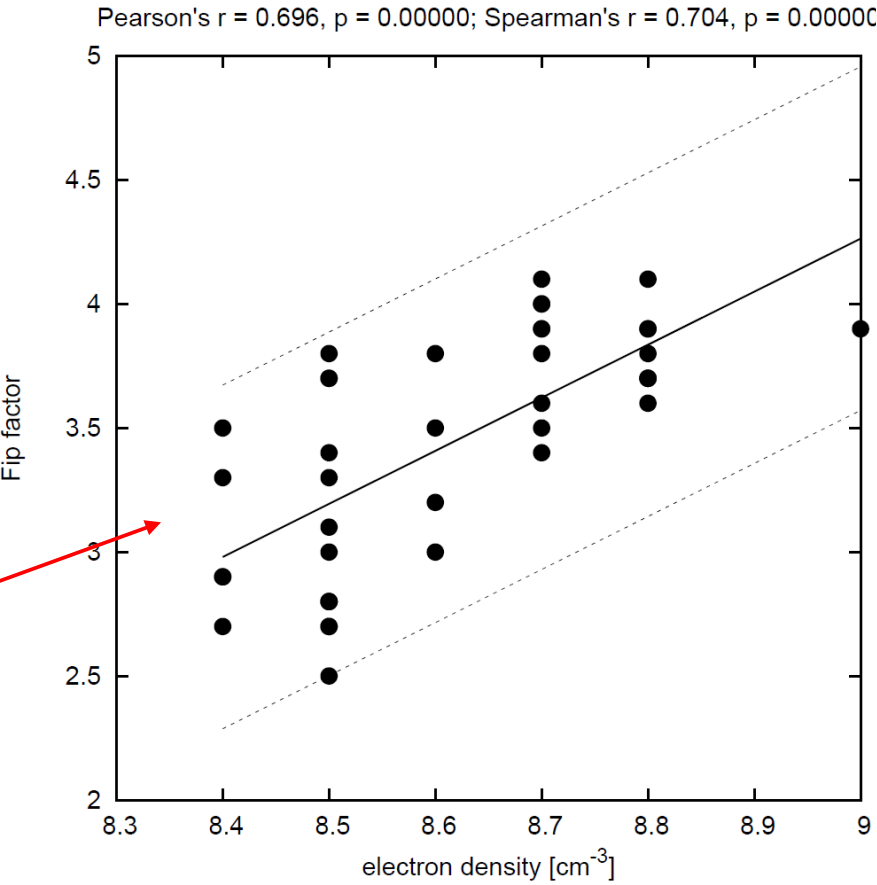
Slow wind hot (source?)

Fast wind cool (coronal hole)



Geiss et al.1995)

What links chromosphere and corona?

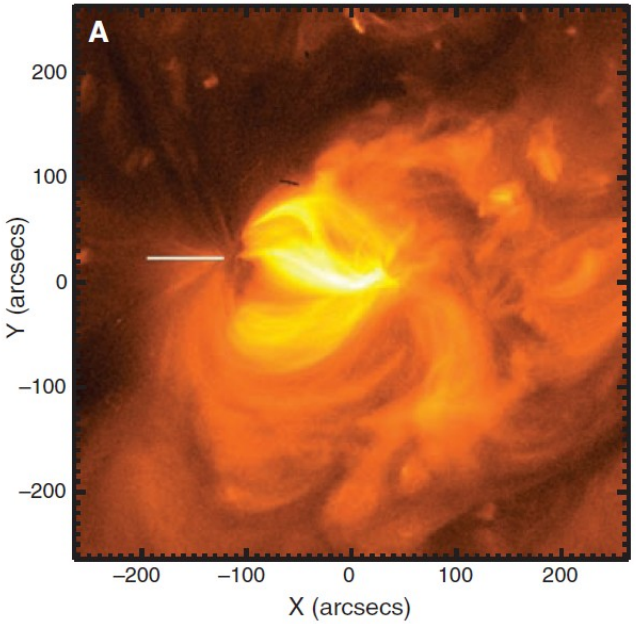


Brooks and Warren, 2011

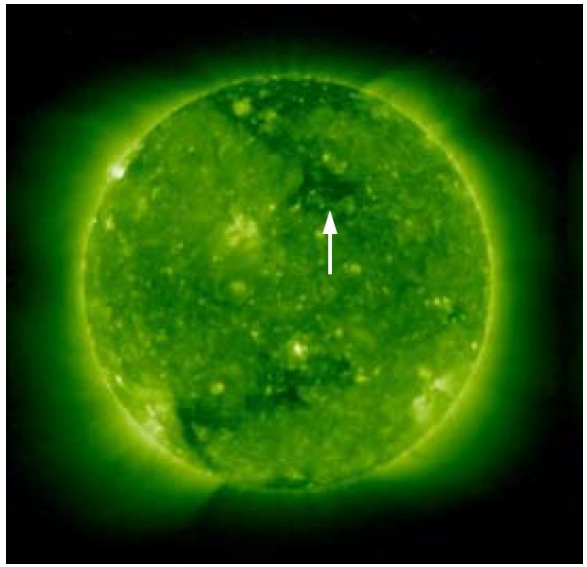
Slow wind strongly FIPped

Fast wind weakly/barely FIPped

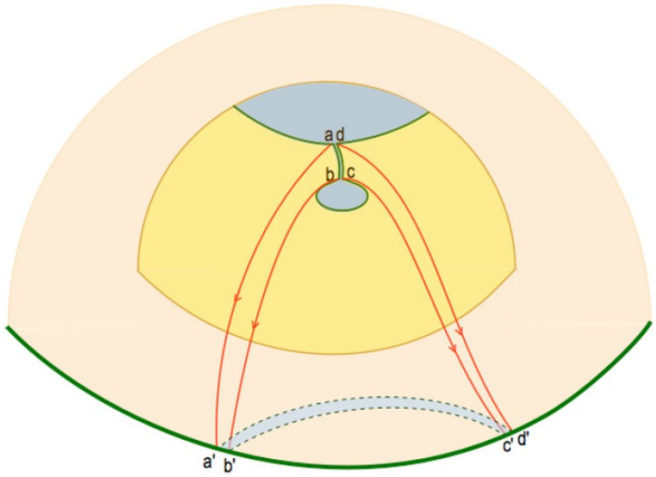
Origin of the Slow Solar Wind?



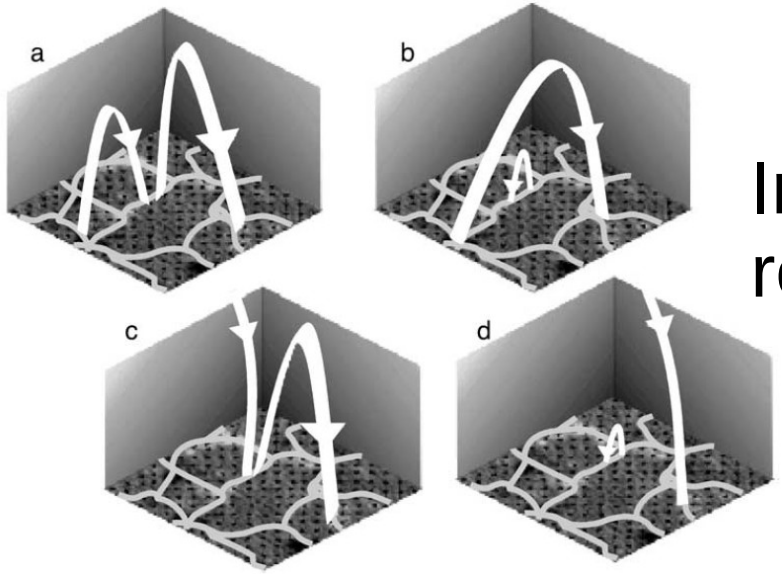
Edges of
Active regions



Edges of
Coronal holes



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



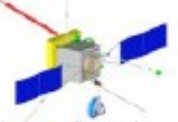
Interchange
reconnection

Solar Orbiter works best with all instruments together

SO & SP+

magnetic field line
escaping electrons
radio type III emission

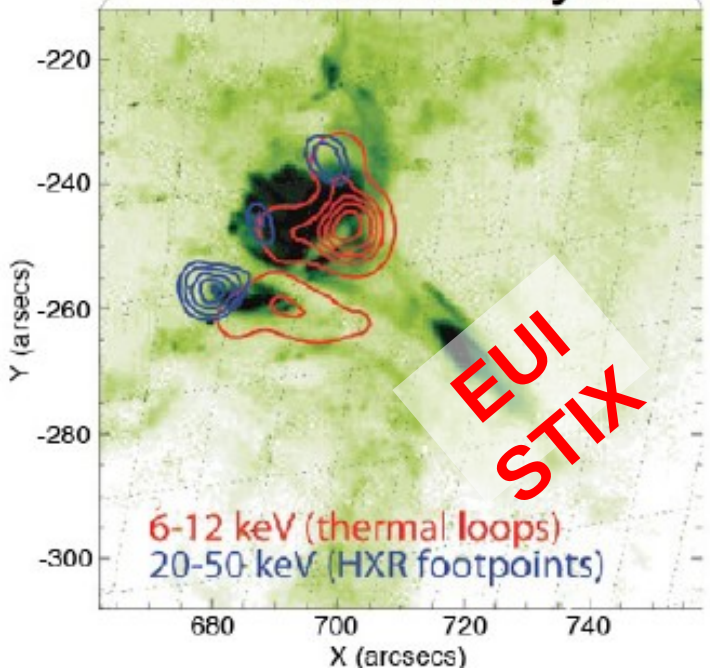
MAG, SWA

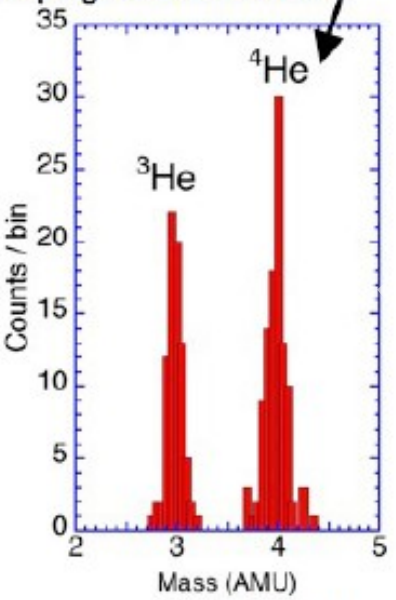


in-situ observation of
escaping ions & electrons

SO

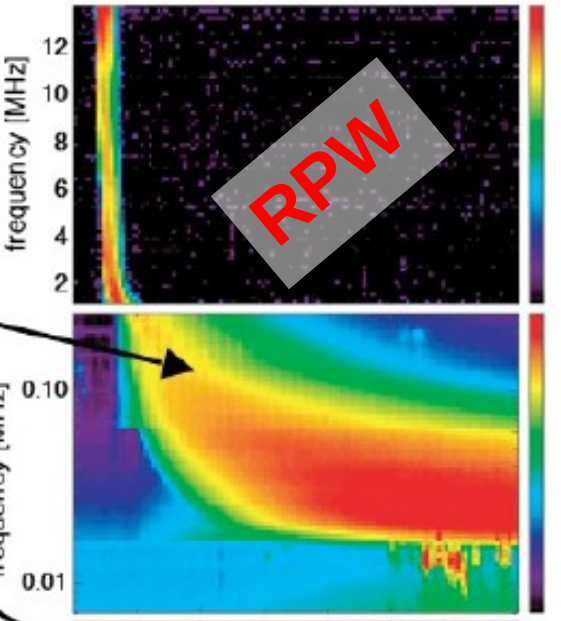
UV and X-rays



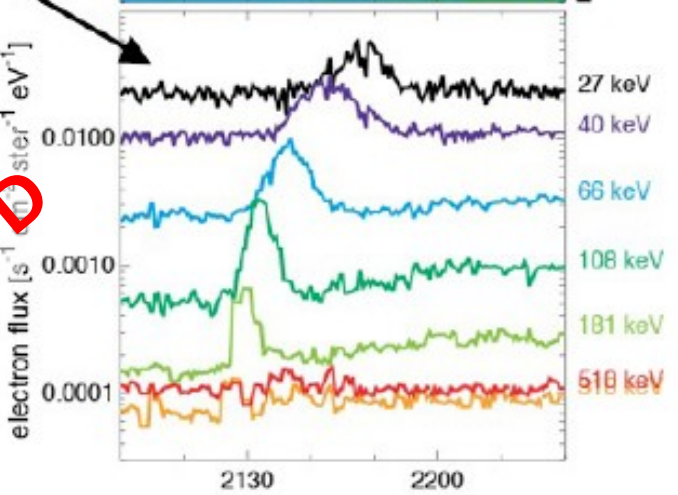


energetic He

radio burst

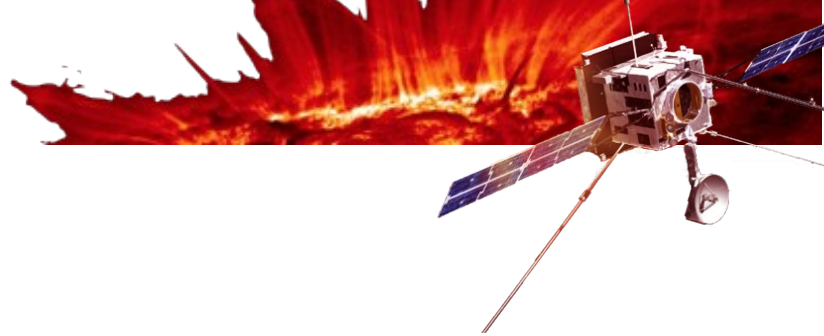


EPD

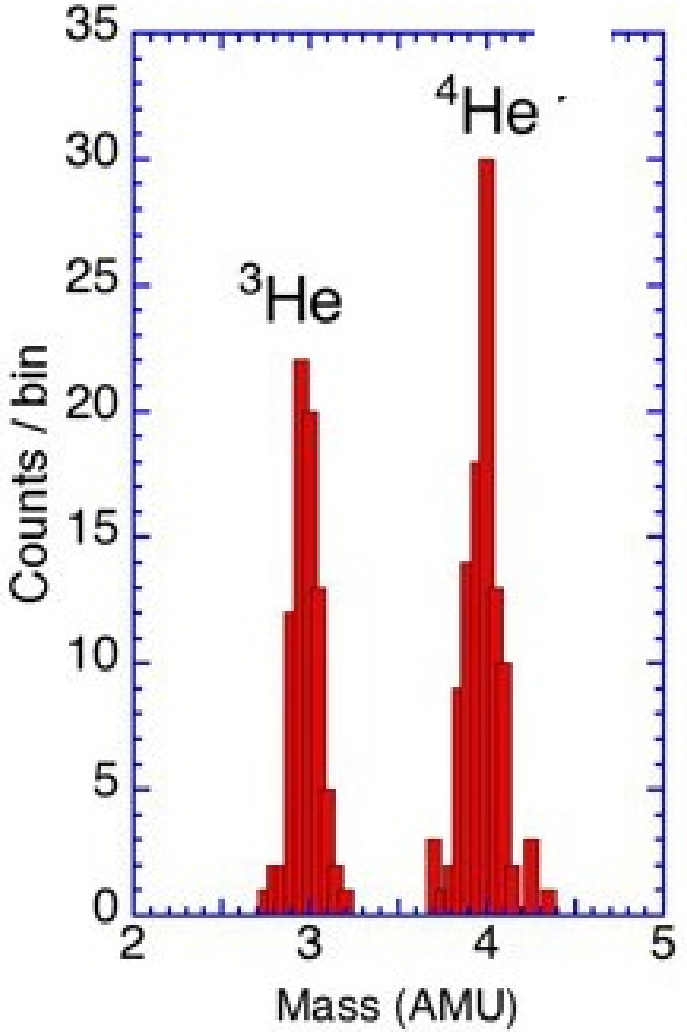


energetic electrons

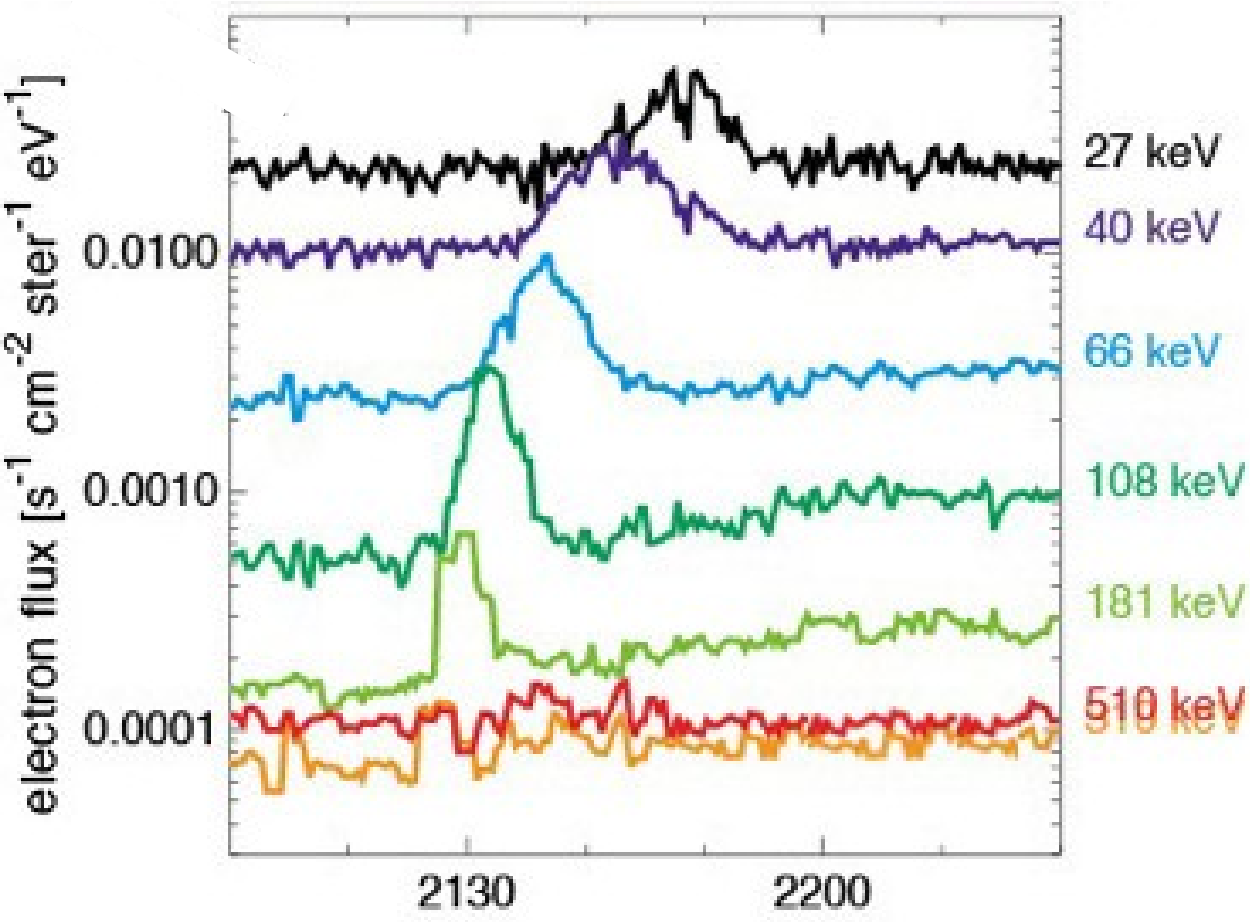
Information from EPD



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



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



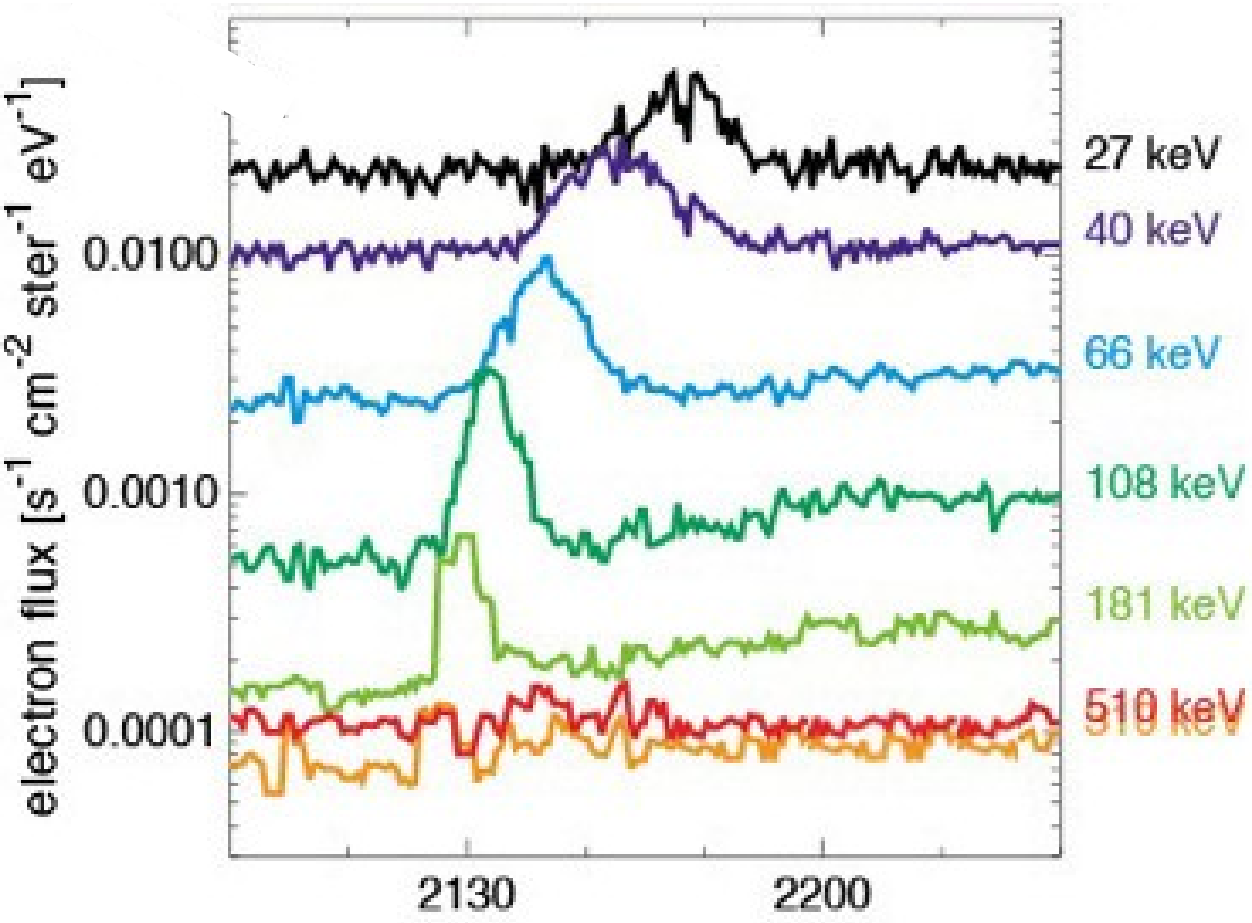
Information from EPD

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

For good connection:
→ ^{3}He, 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).

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



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

Thanks to Solar Orbiter & SP+ Teams, funding agencies, tax payers.