Evolution of the slow solar wind during a solar cycle

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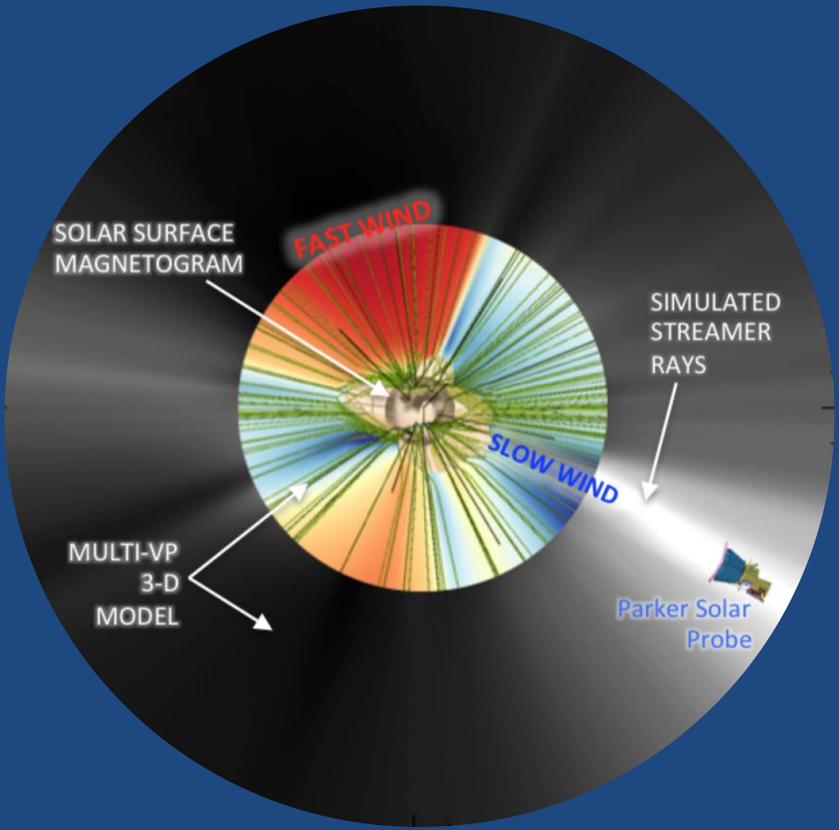
IRAP, CNRS, Toulouse



While it is certain that the fast solar wind originates from coronal holes, where and how the slow solar wind (SSW) is formed remains an outstanding question in solar physics.

The slow wind is a messy story!

Several possible origins:

-> the slow wind forms like the fast wind along open field lines!

-> the slow wind forms via continual plasma exchanges between the open and closed corona

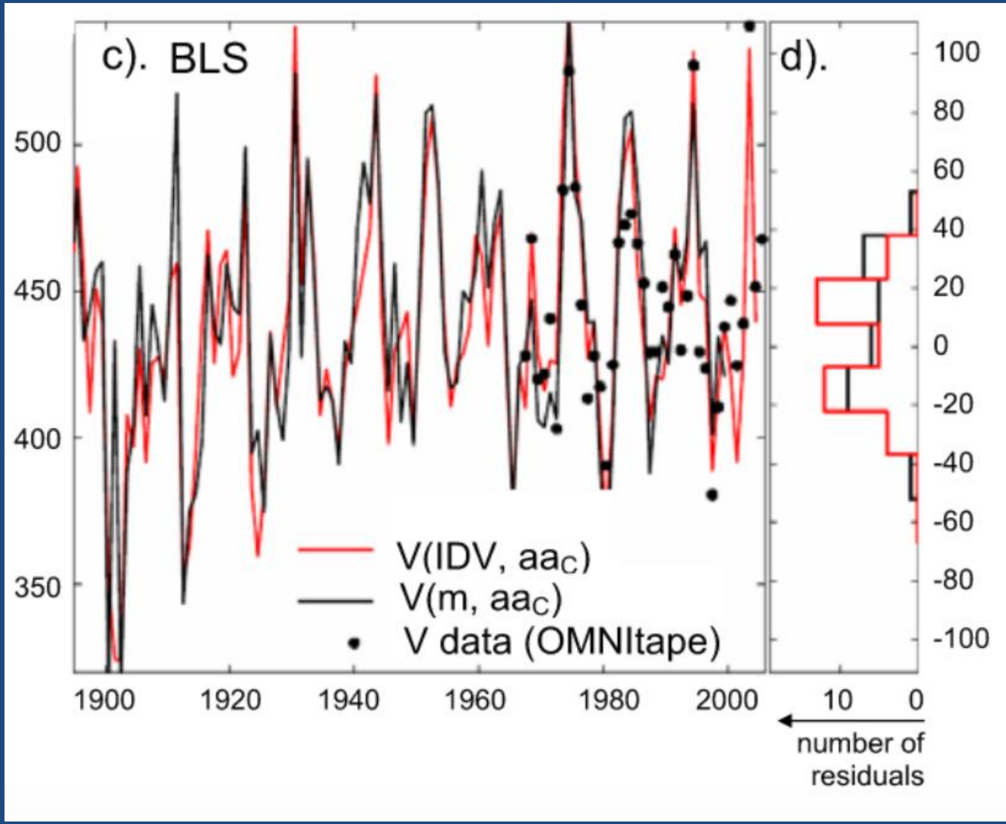
-> a component certainly forms via transient releases at the tip of streamers

Outline

- Intro on slow solar wind and implication for long-term evolution of the slow wind
- State-state theories for the origin of the slow wind
- Dynamic theories for the origin of the slow wind

Why should we care about the slow solar wind here?

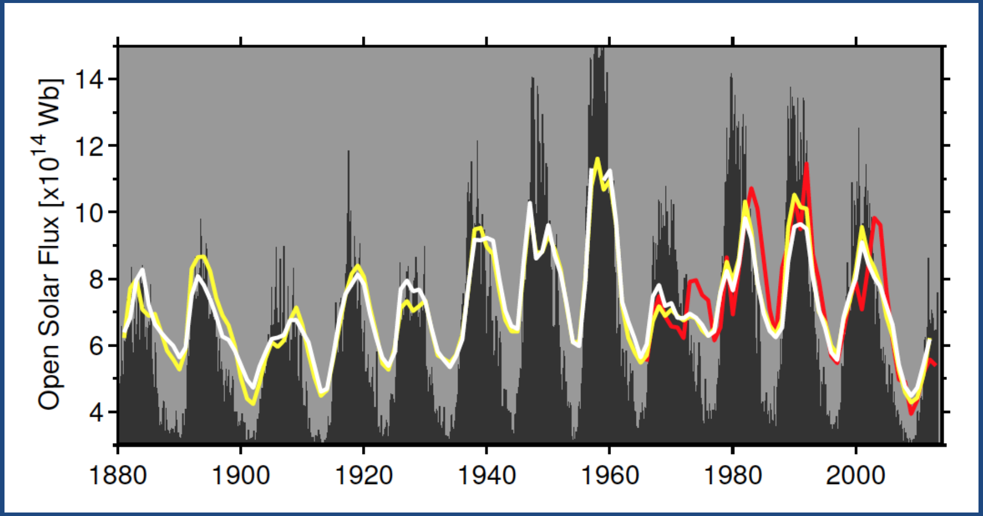
1) There are long-term trends in solar wind properties including solar wind speed:



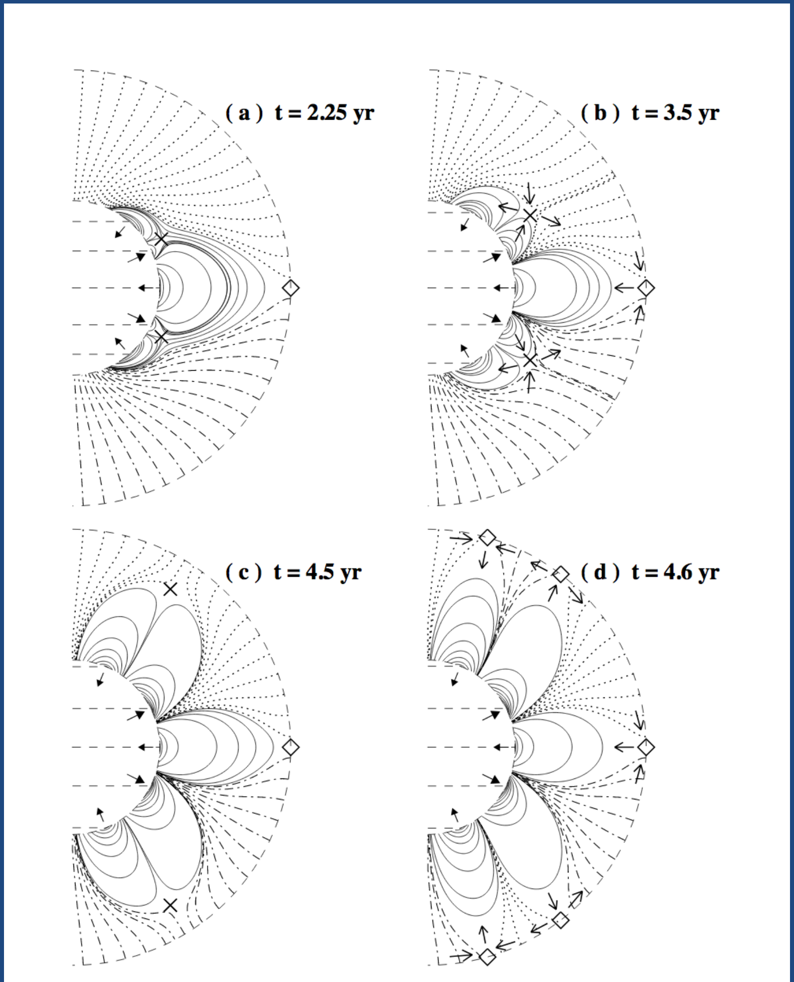
[16] **Acknowledgments.** A.P.R. thanks both Kalevi Mursula and Georgeta Maris for inviting him to the exciting "Second International Symposium on Space Climate" held in Sinaia, Romania, September 2006 when some key ideas of this paper were formulated.

Rouillard et al. 2007
See also : Cliver et al.
Mursula et al. 2016

2) The slow wind source hosts most of the emergence and shedding of open flux over different timescales:



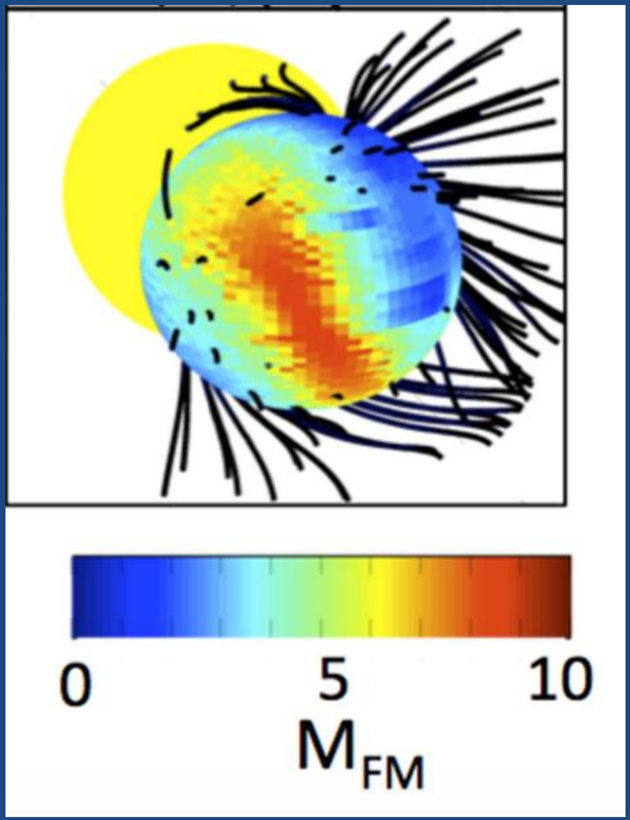
Lockwood et al. 2013



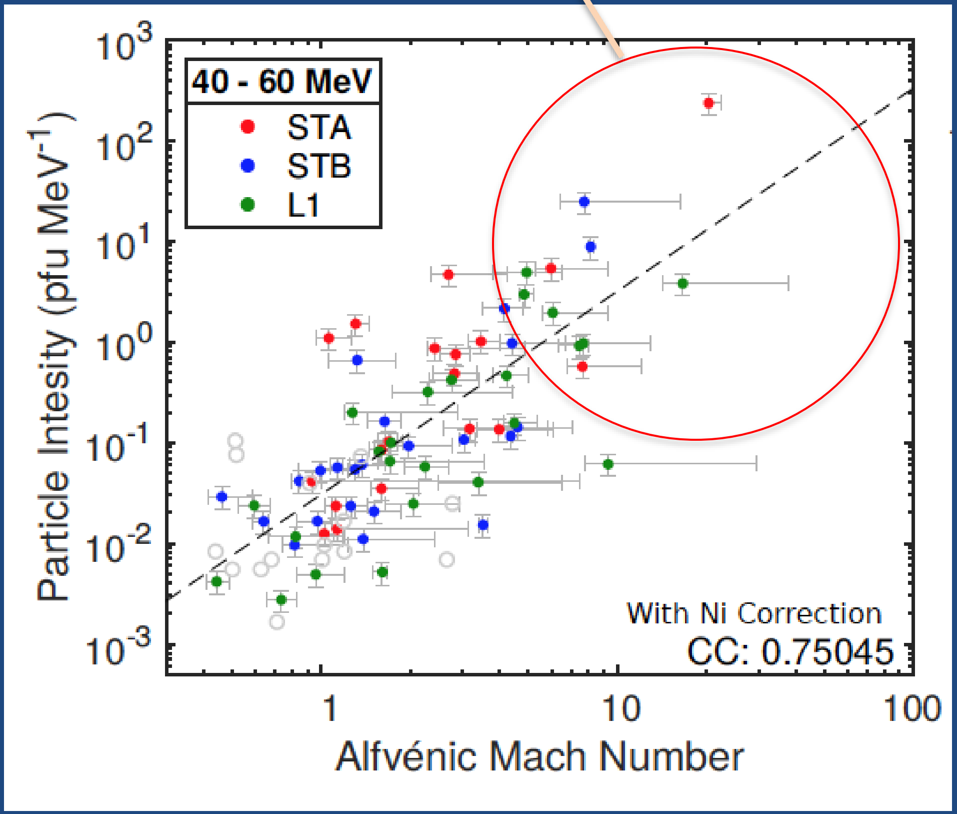
Wang et al. 2003

3) The slow wind is likely to hosts CME propagation and very strong particle acceleration

High-energy particles produced near the tip of streamers

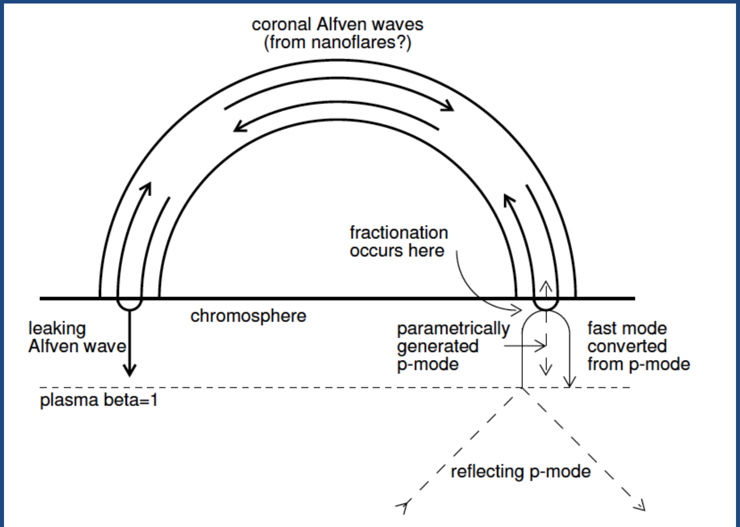


Rouillard et al. 2016

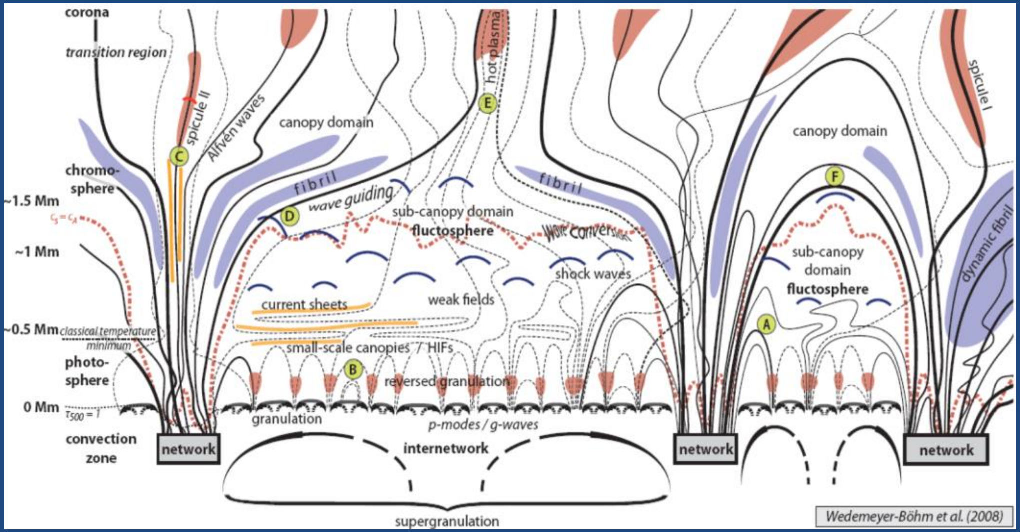


Kouloumvakos et al. 2019

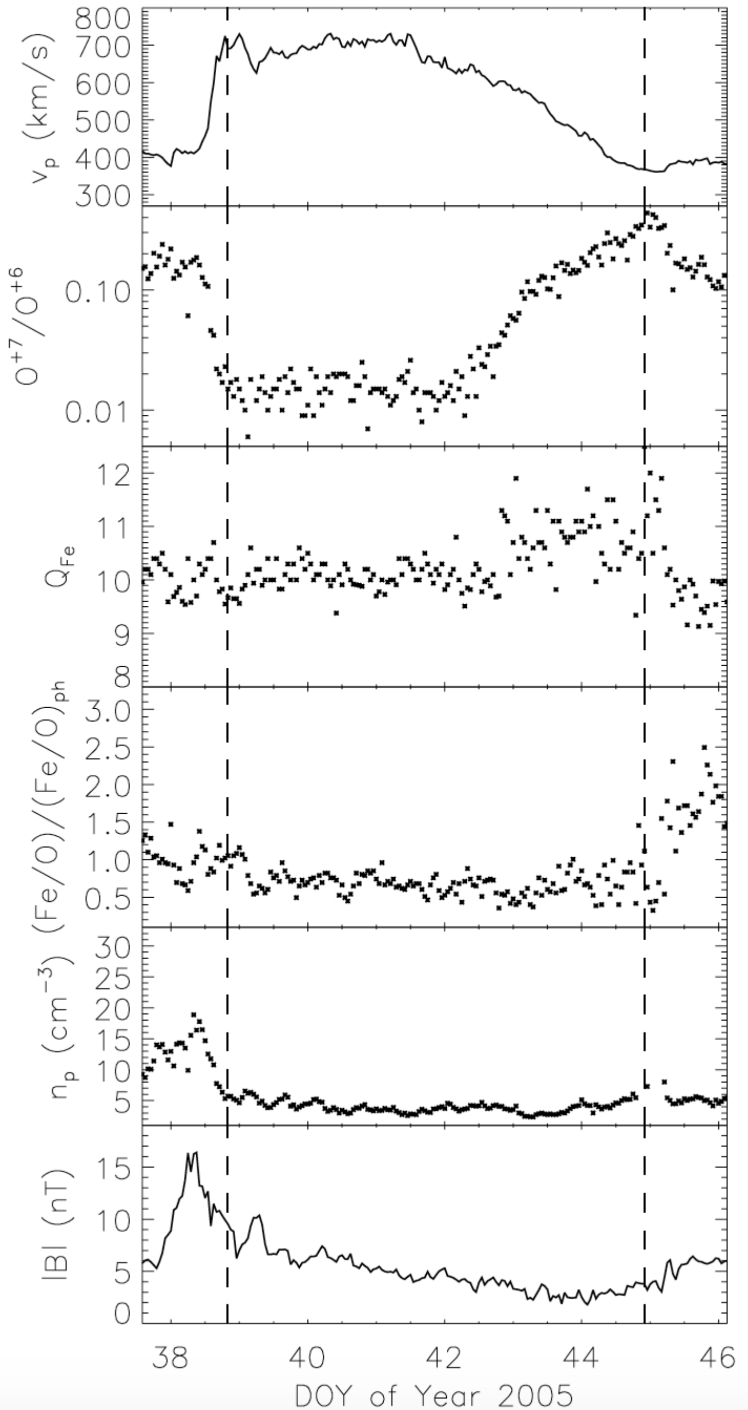
4) Lots of fascinating MHD instabilities, kinetic physics and wave-particle interaction to study heating rate and composition of the slow wind.



Laming et al. 2009

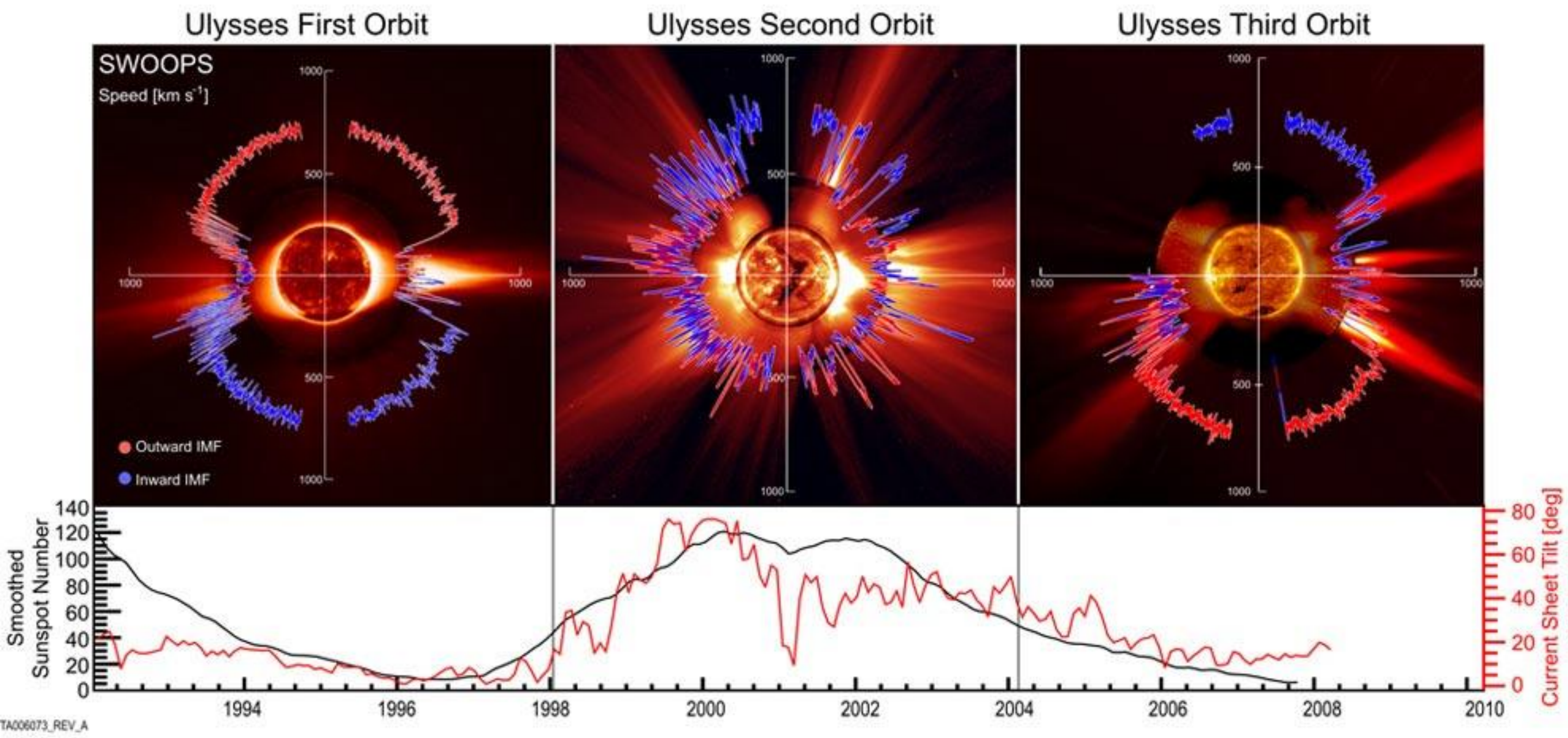


Wedemeyer-Bohm et al. 2008

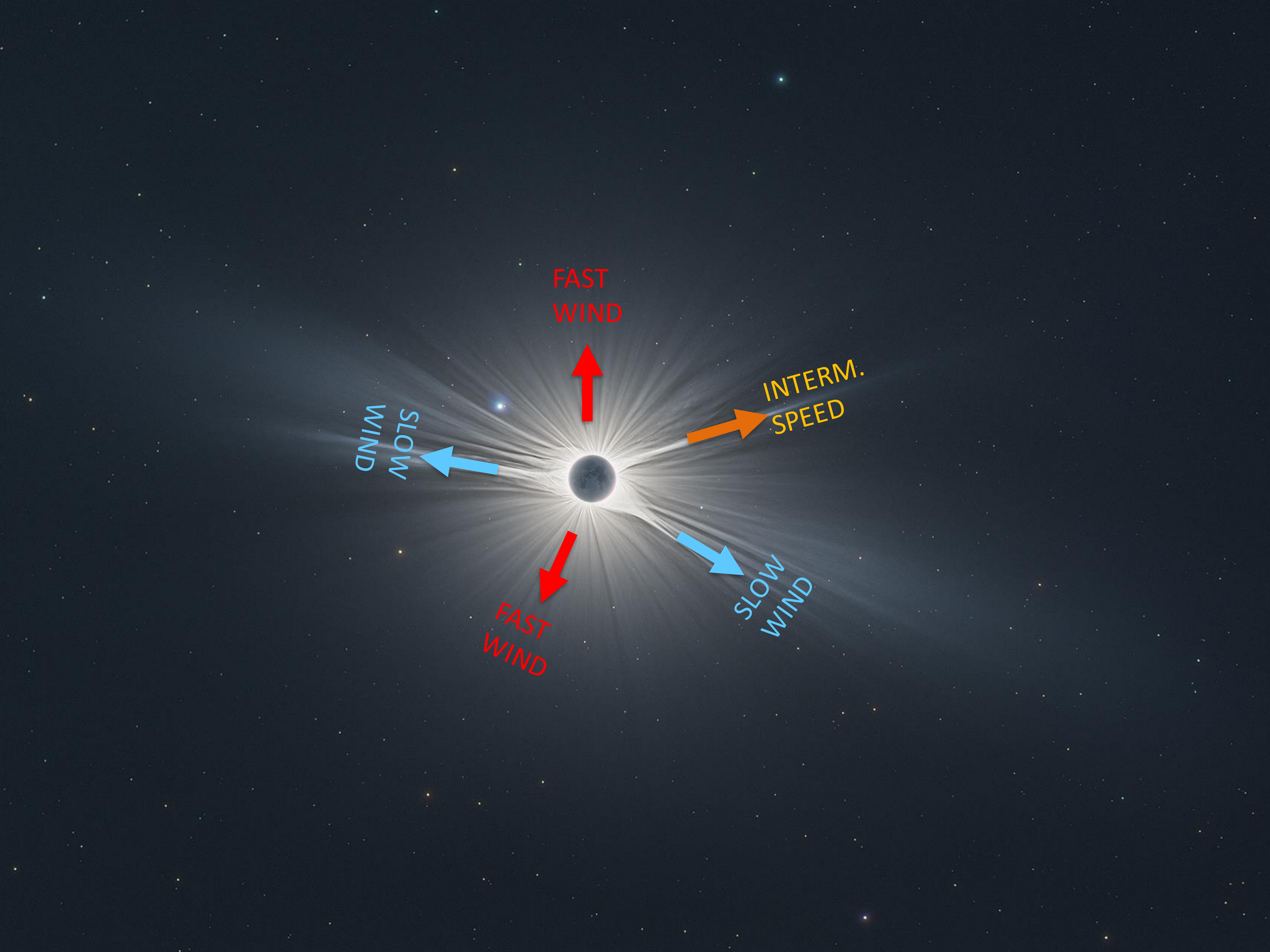


v_p (km/s)
800
700
600
500
400
300
O^{+7}/O^{+6}
0.10
0.01
Q_{Fe}
12
11
10
9
8
$(Fe/O)/(Fe/O)_{ph}$
3.0
2.5
2.0
1.5
1.0
0.5
n_p (cm^{-3})
30
25
20
15
10
5
|B| (nT)
15
10
5
0
38
40
42
44
46
DOY of Year 2005

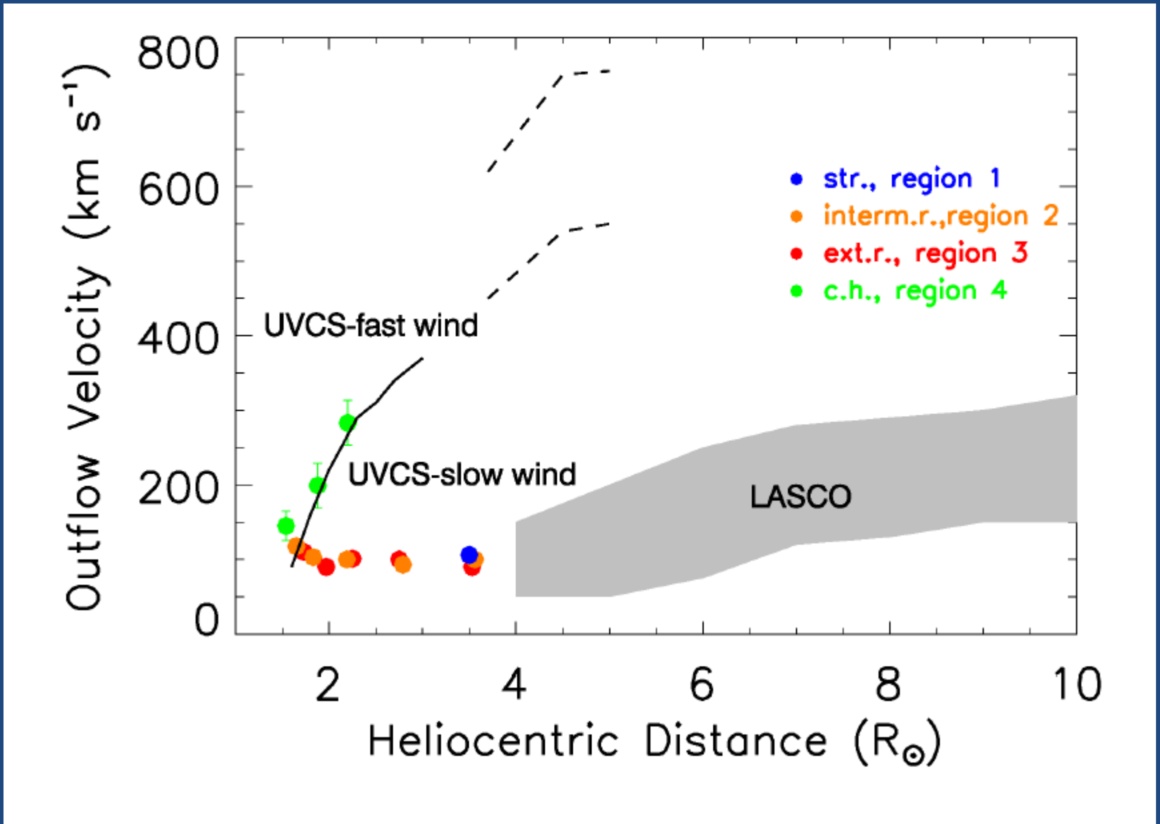
Ko et al. 2018



McComas et al. 2008

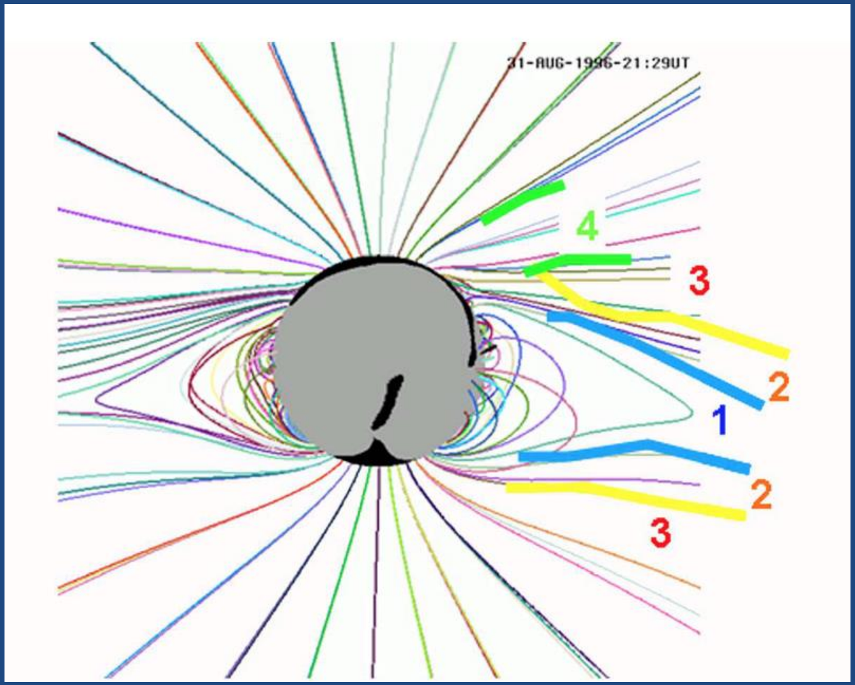

FAST
WIND
INTERM.
SPEED
SLOW
WIND
FAST
WIND
SLOW
WIND

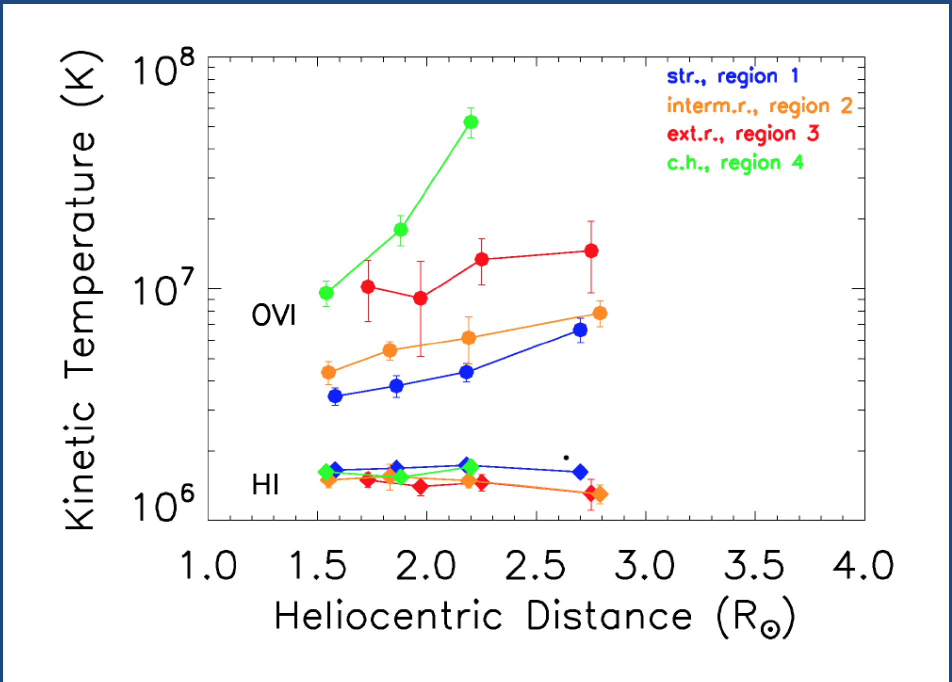
Contrasting the origins of slow and fast solar winds:



Abbo et al. 2010

Differnetial ion heating is weaker in the source region of the slow wind:





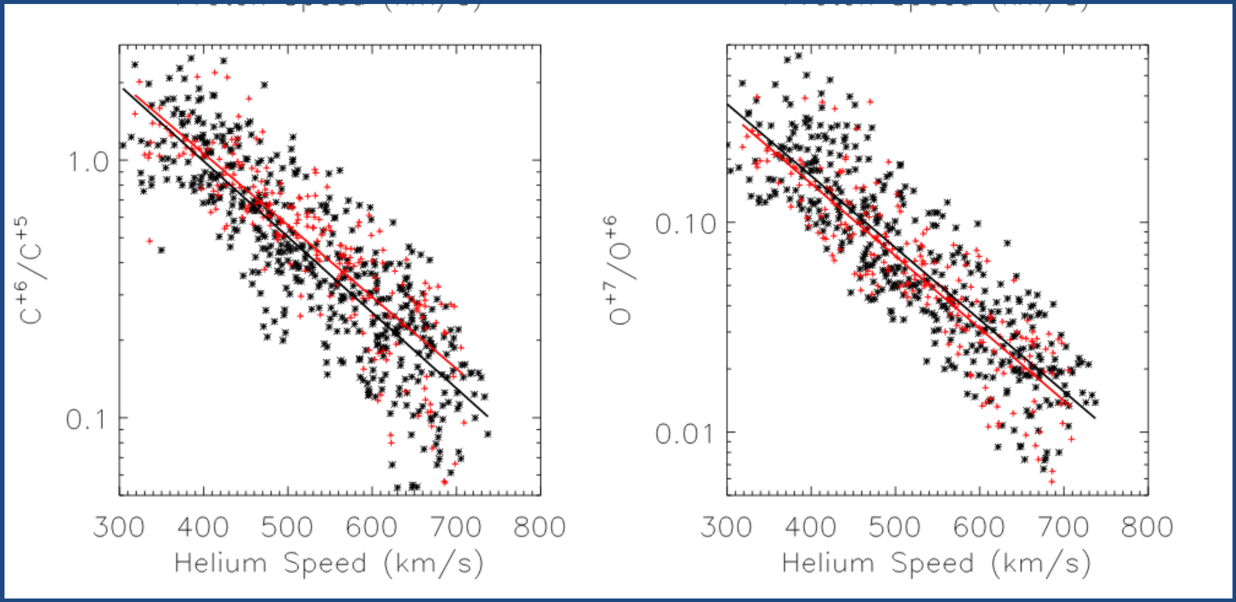
Abbo et al. 2013

But temperature anisotropy is therefore also found in the streamer edges and coronal hole boundaries with values in the range of 1.3-2 (Frazin et al, 2003; Susino et al, 2008).

-> Alfvén wave driven solar wind models highly popular

The source region of the slow solar wind has hot electrons!

The ionic charge states are largely fixed in the inner corona (generally below 10Rs), as opposed to density and temperature which change dynamically during the transit in the heliosphere.

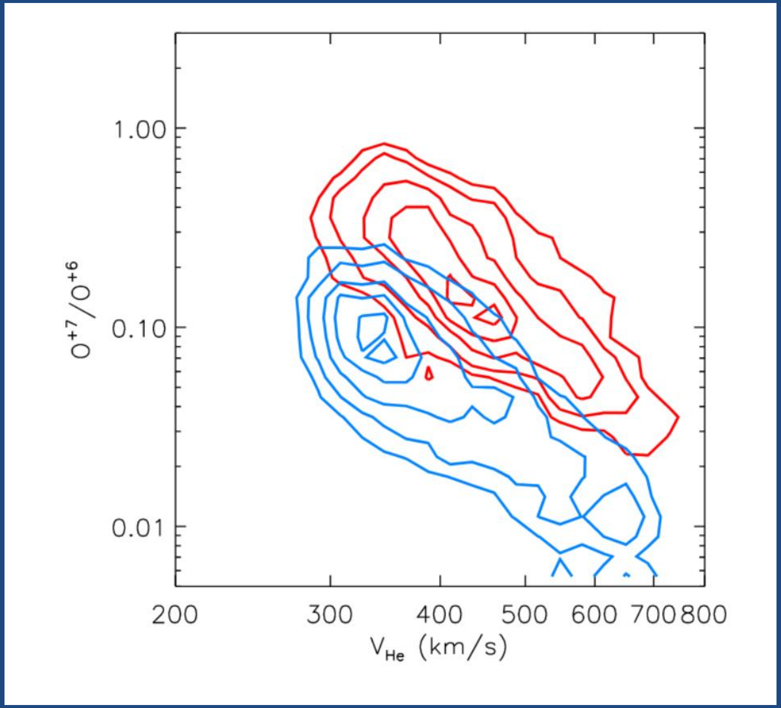


Ko et al. 2014

Long-term temperature decrease at the source of the wind:

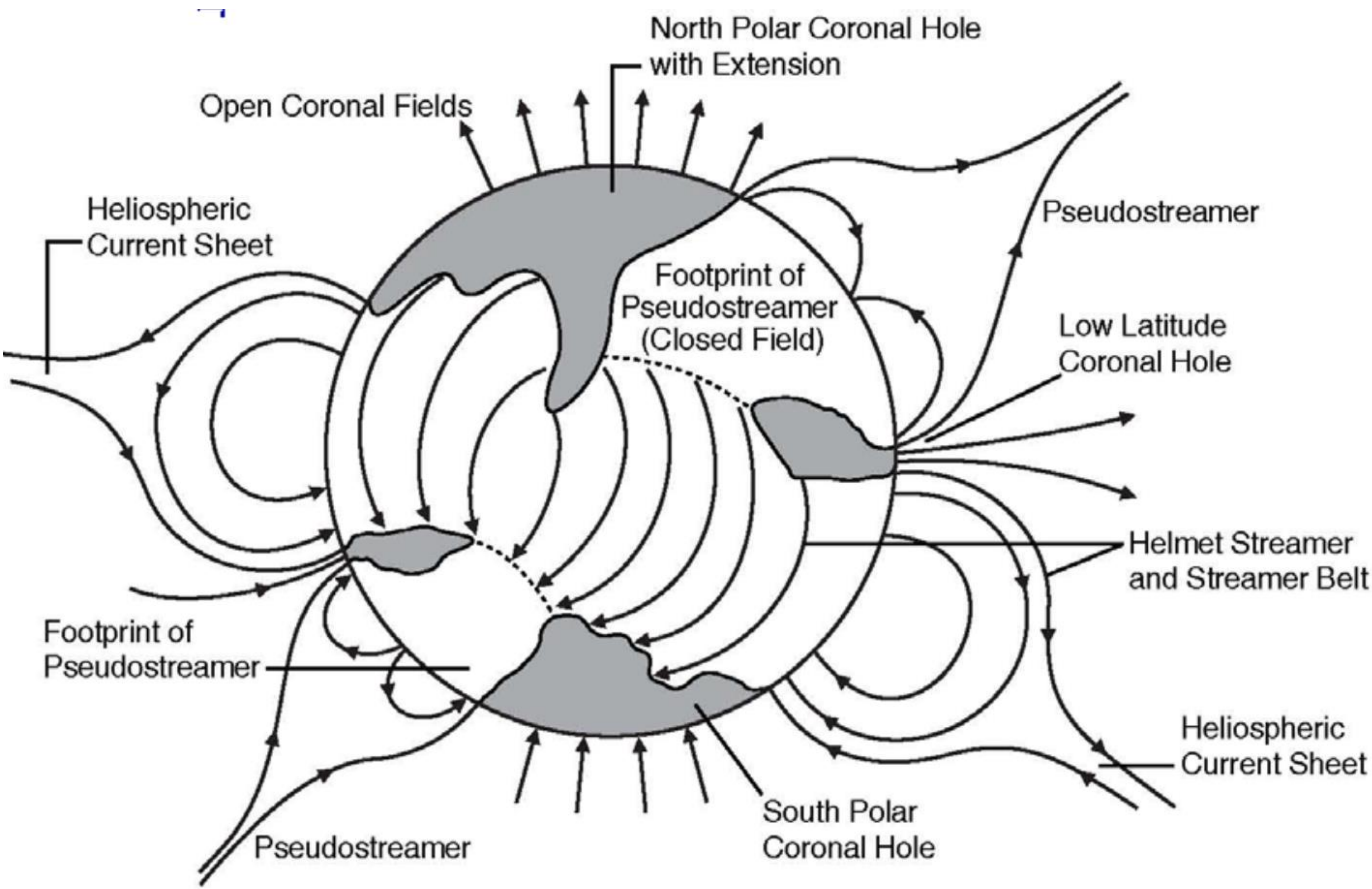
Solar wind ionization states in both fast and slow wind decrease during the declining phase of cycle 23, which should be in some way related to the decreasing solar magnetic field:

-> less magnetic energy would be available to power the wind (Schwadron et al, 2011).

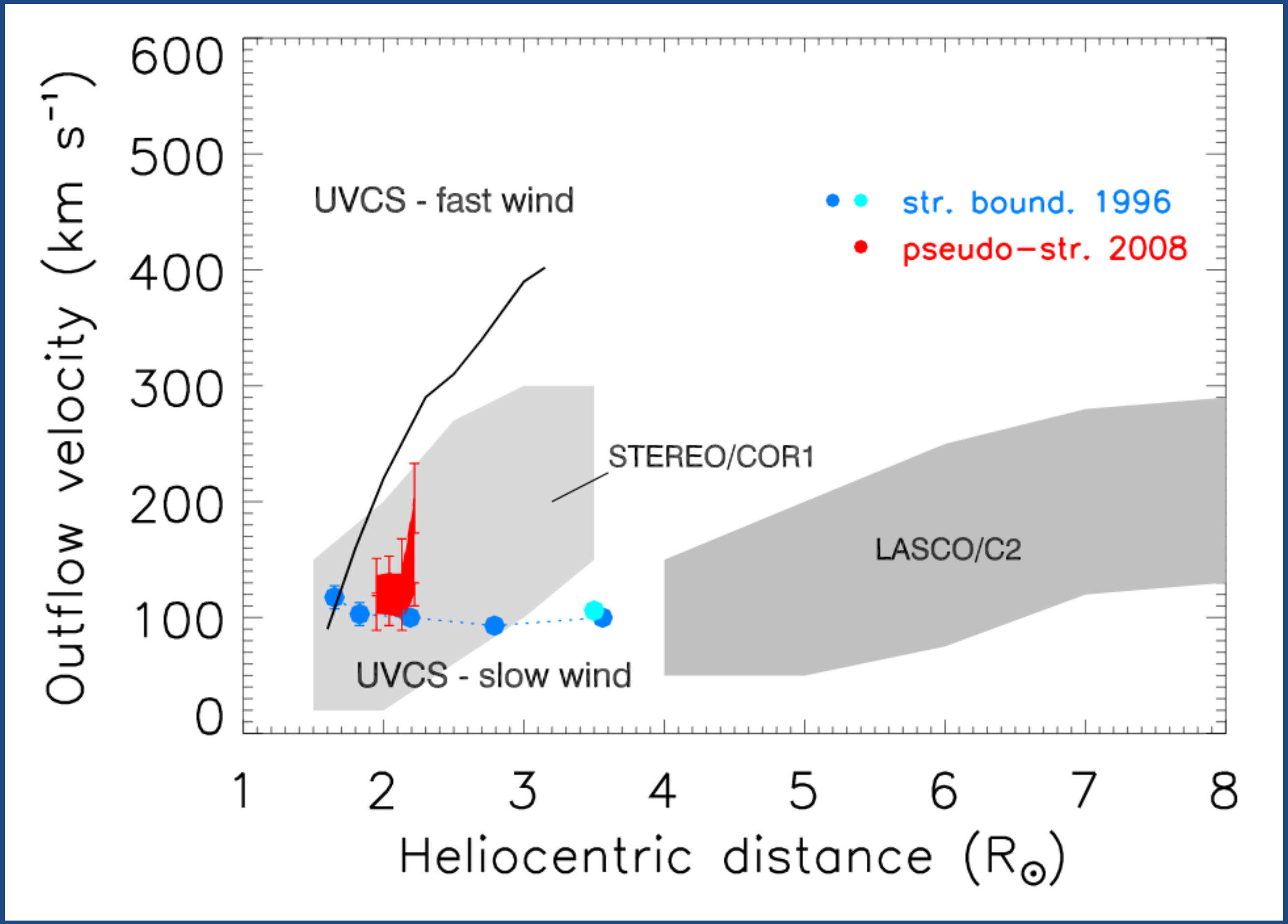


Ko et al (2014)

Abbo et al. 2016


North Polar Coronal Hole
with Extension
Open Coronal Fields
Heliospheric
Current Sheet
Footprint of
Pseudostreamer
(Closed Field)
Pseudostreamer
Low Latitude
Coronal Hole
Helmet Streamer
and Streamer Belt
Footprint of
Pseudostreamer
Heliospheric
Current Sheet
South Polar
Coronal Hole
Pseudostreamer

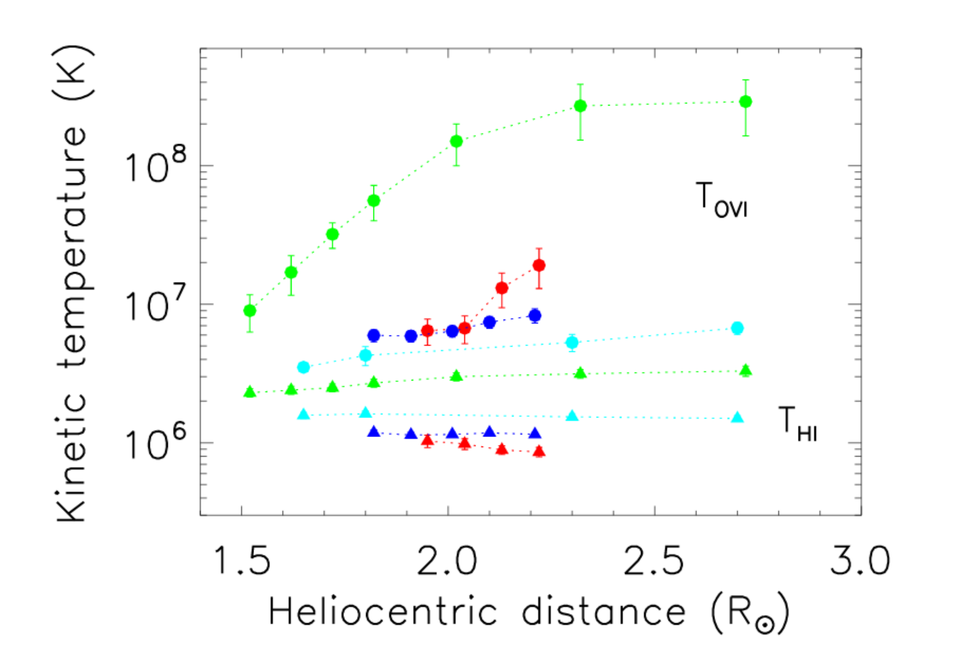
Slow solar wind from unipolar streamers:



Abbo et al. 2015

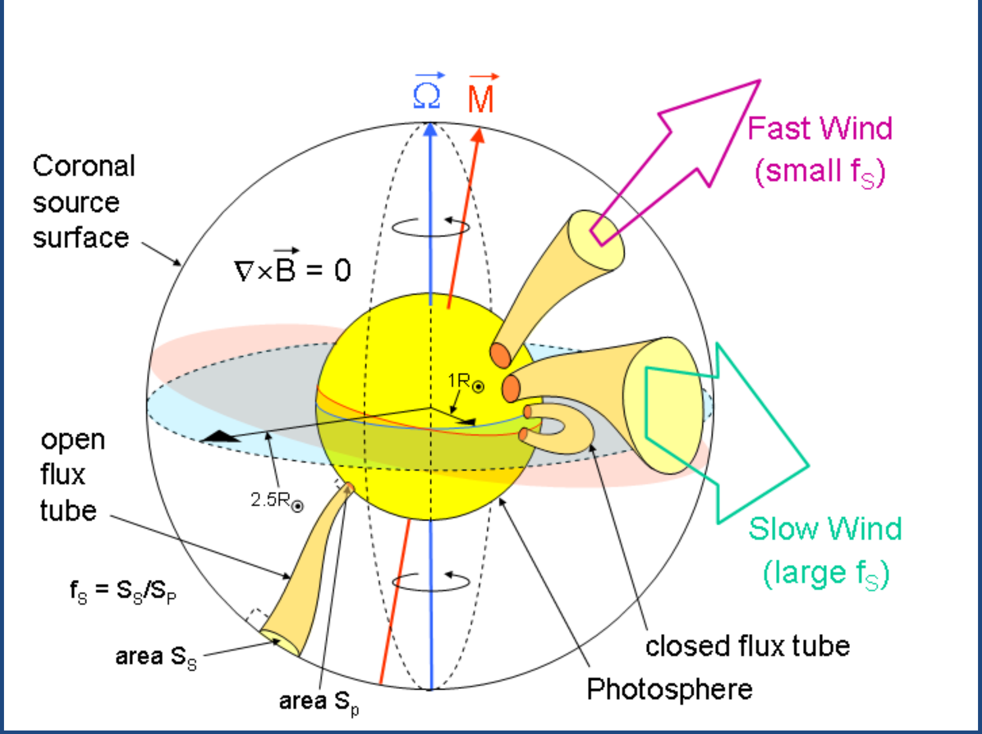
Slow solar wind from unipolar streamers:

-> pseudo-streamers produce a ”hybrid” type of outflow that is intermediate between slow and fast solar wind and they are apossible source of slow/fast wind in not dipolar solar magnetic field configuration.



Abbo et al. 2015

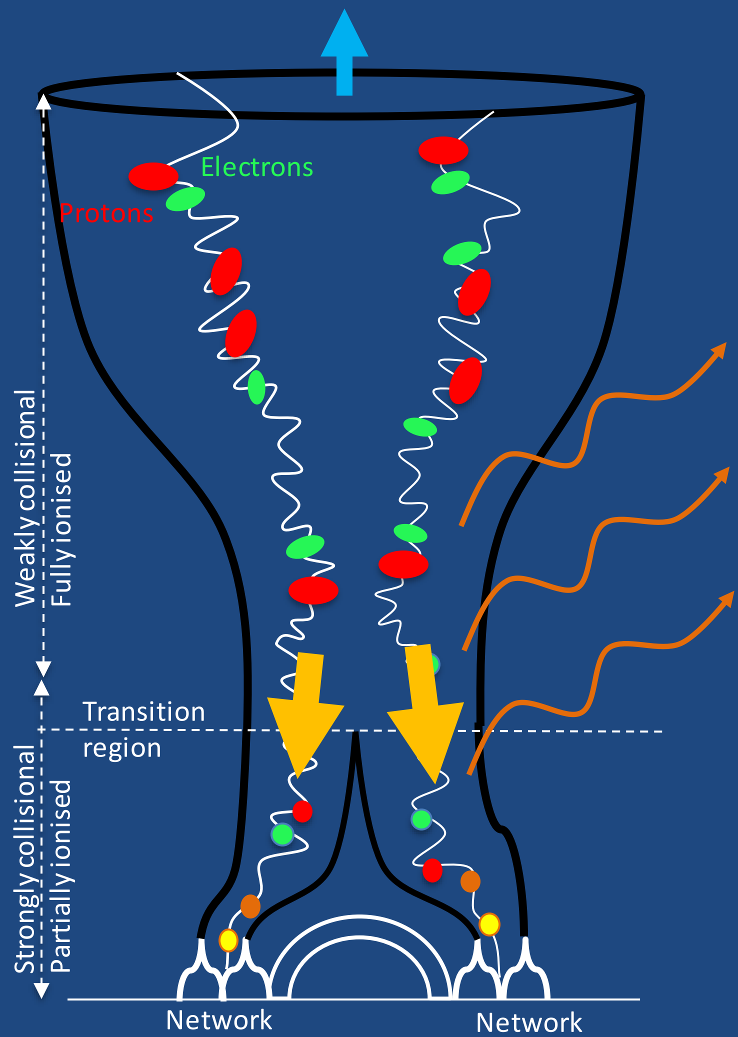
Flux expansion factor theory:



Wang and Sheeley 1990, 1991, 1994,
Wang et al. 2008

Basic ingredients to model a 'realistic' solar wind:

- suppose the simplest single fluid model with an isotropic distribution function to reproduce (roughly!) coronal temperatures and solar wind moments:



Ingredients:

Anisotropic thermal conduction (extra term or can be included by solving for electrons),

Radiative cooling (usually a function),

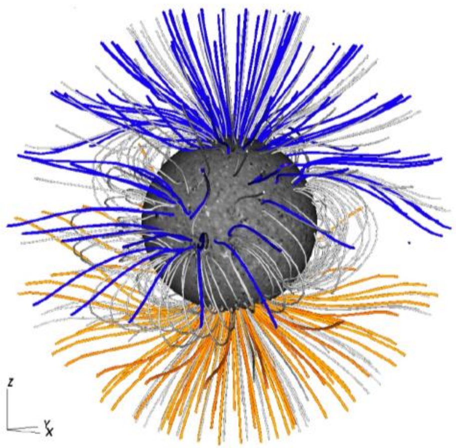
Some heating (choose your favourite!)

+ an unknown additional contribution to momentum (wave pressure?, electric fields?)

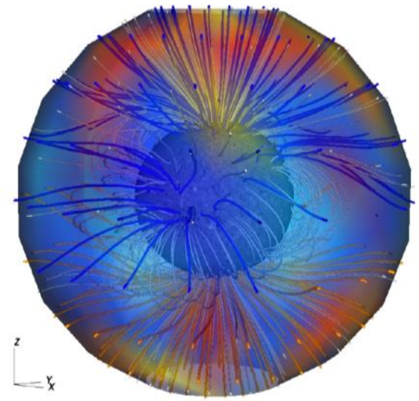
-> V,T,N compare reasonably well with observations.

Hansteen et al. 1996, Cranmer et al. 2007, Verdini and Velli 2007, Downs et al. 2009, Lionello et al. 2009)

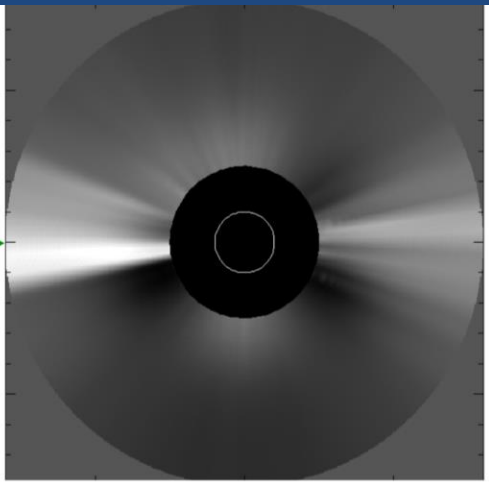
Photosphere to corona solar wind models run with realistic thermodynamics and high-resolution magneto-static models (PFSS, NLFF):



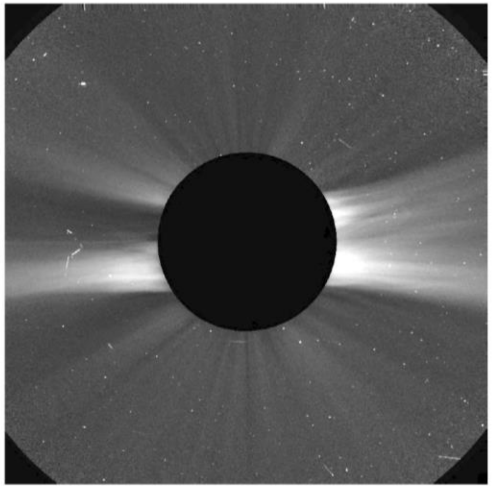
PFSS (or NLFF)



3-D solar wind plasma



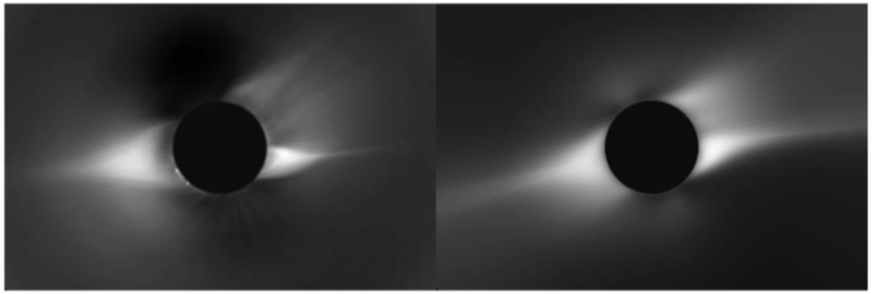
Synthetic imagery



SOHO C2

Pinto and Rouillard (2017)

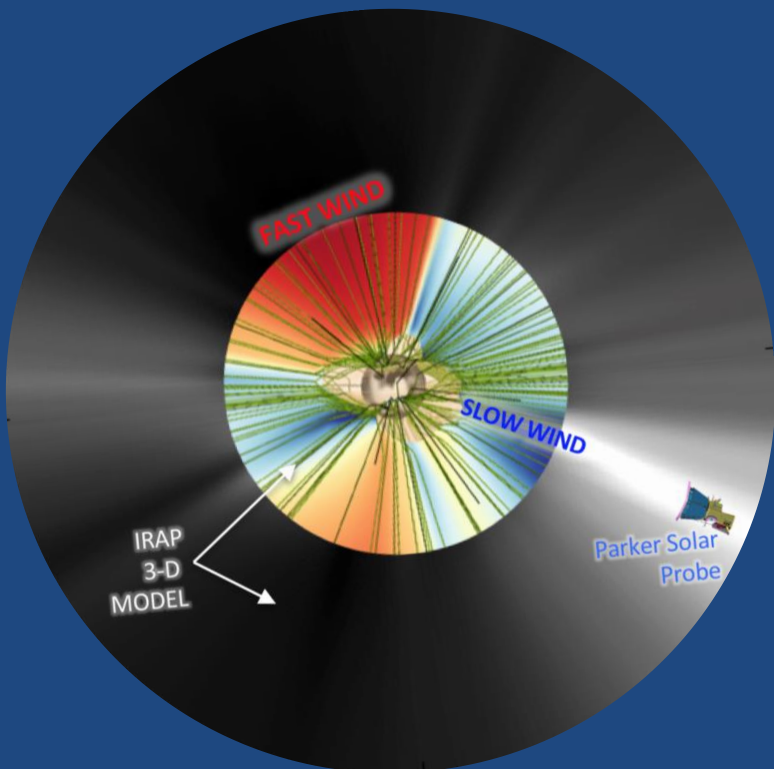
Done by MHD modellers on smoothed magnetograms:



To compare simulations with remote-sensing observations

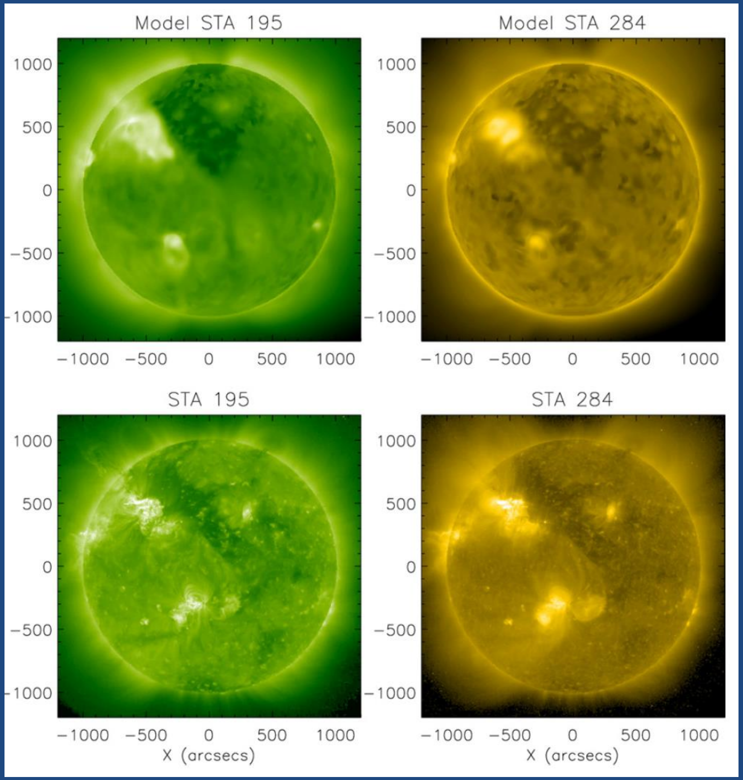
- We need ‘Realistic magnetic fields’
- To fill in the 3-D volume inside our instruments’ field of view

3-D (MULTI-TUBE), 1-D flows



Pinto and Rouillard 2017
-> Provides space-weather forecasts

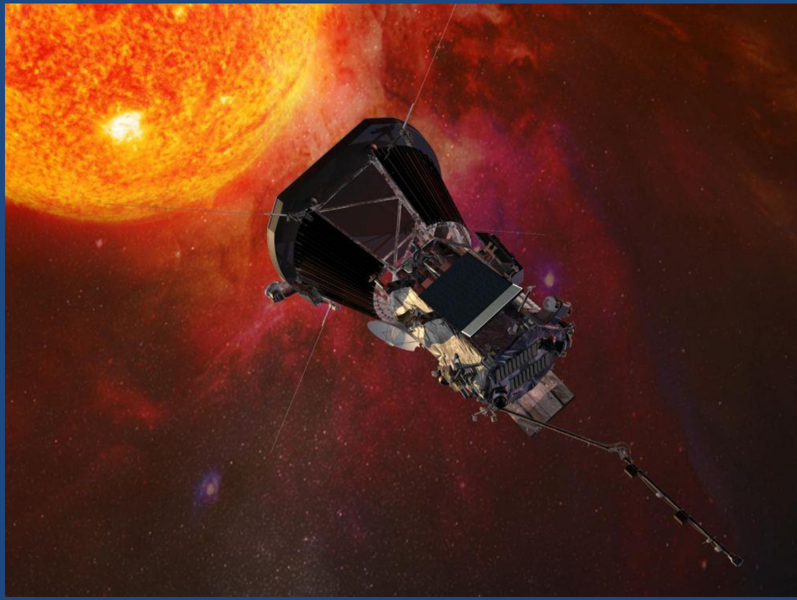
Full 3-D MHD

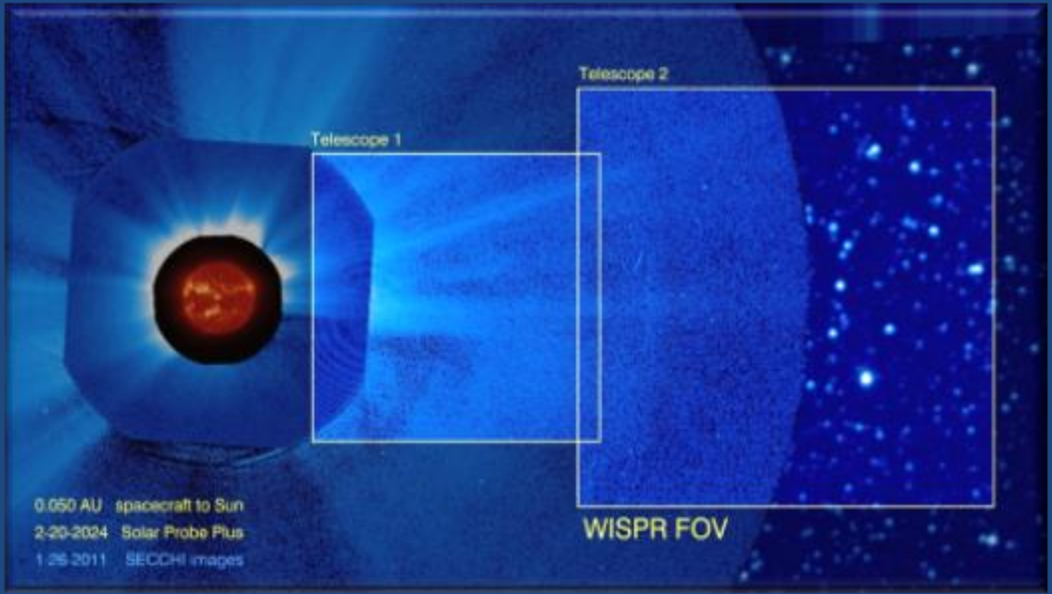


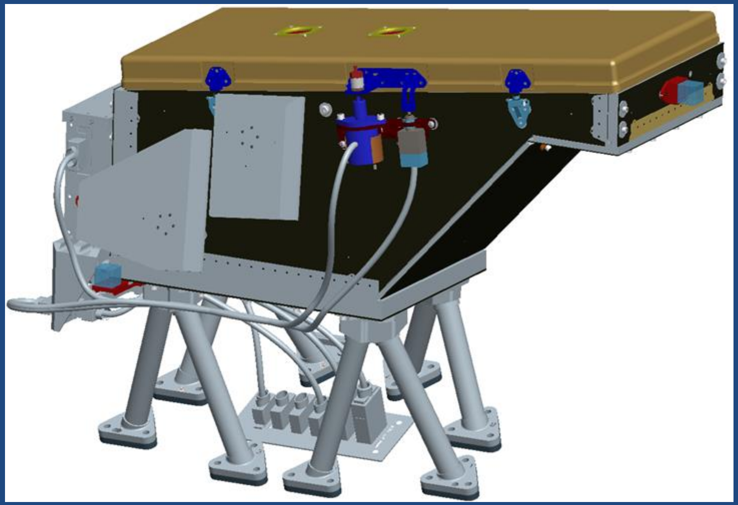
AWSoM is awesome!

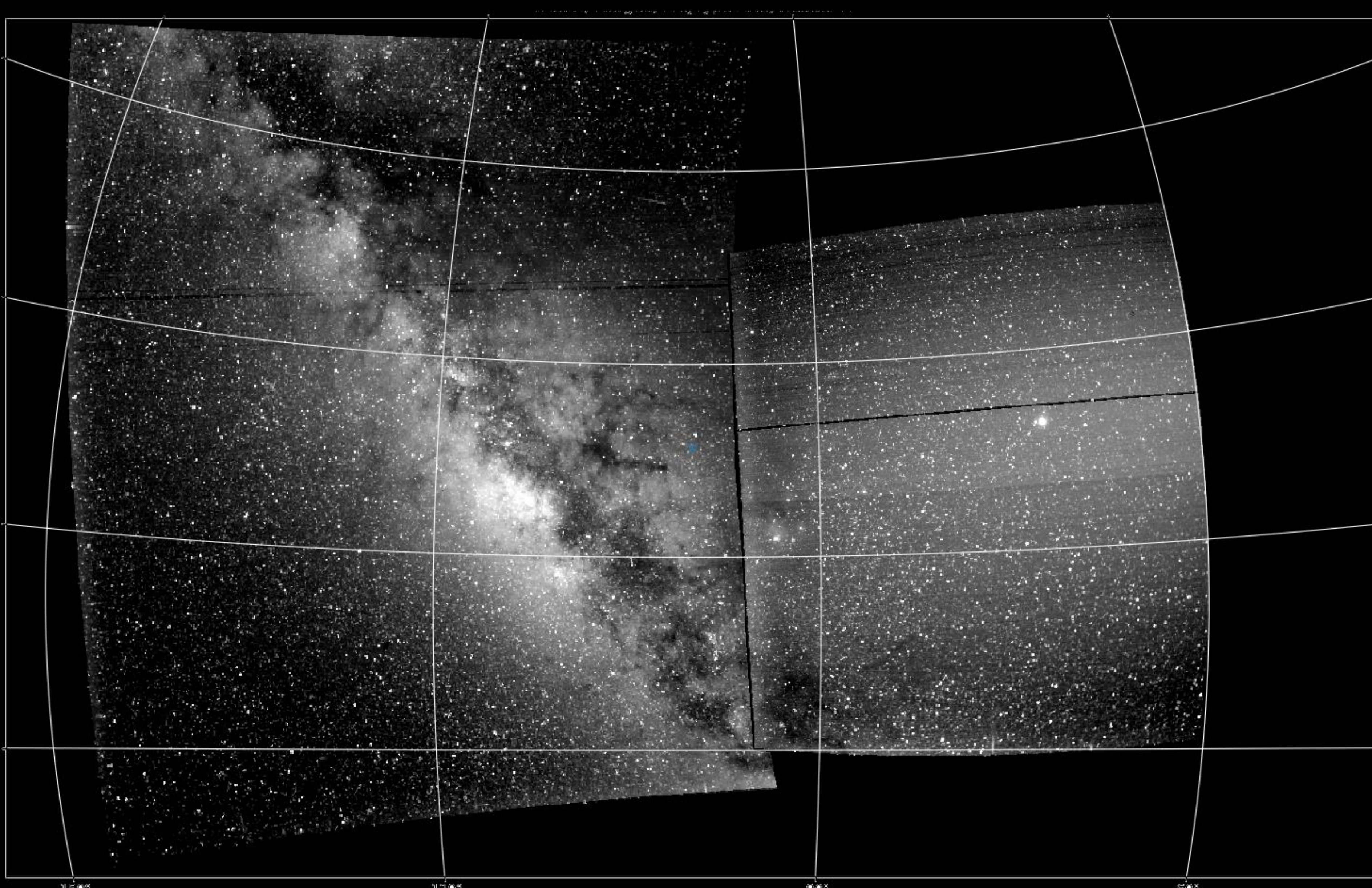
Van der Holst 2014
Lionello et al. 2009, Downs et al. 2009
Reville et al. 2018

- Wide-Field Imager : 13.5º - 105º from the Sun.
- Visible Light Observations.
- Next-Generation 2k x 2k APS Sensor.
- Smallest Heliospheric Imager to-date.
- Heritage: *STEREO*/HI, *Solar Orbiter*/SoloHI

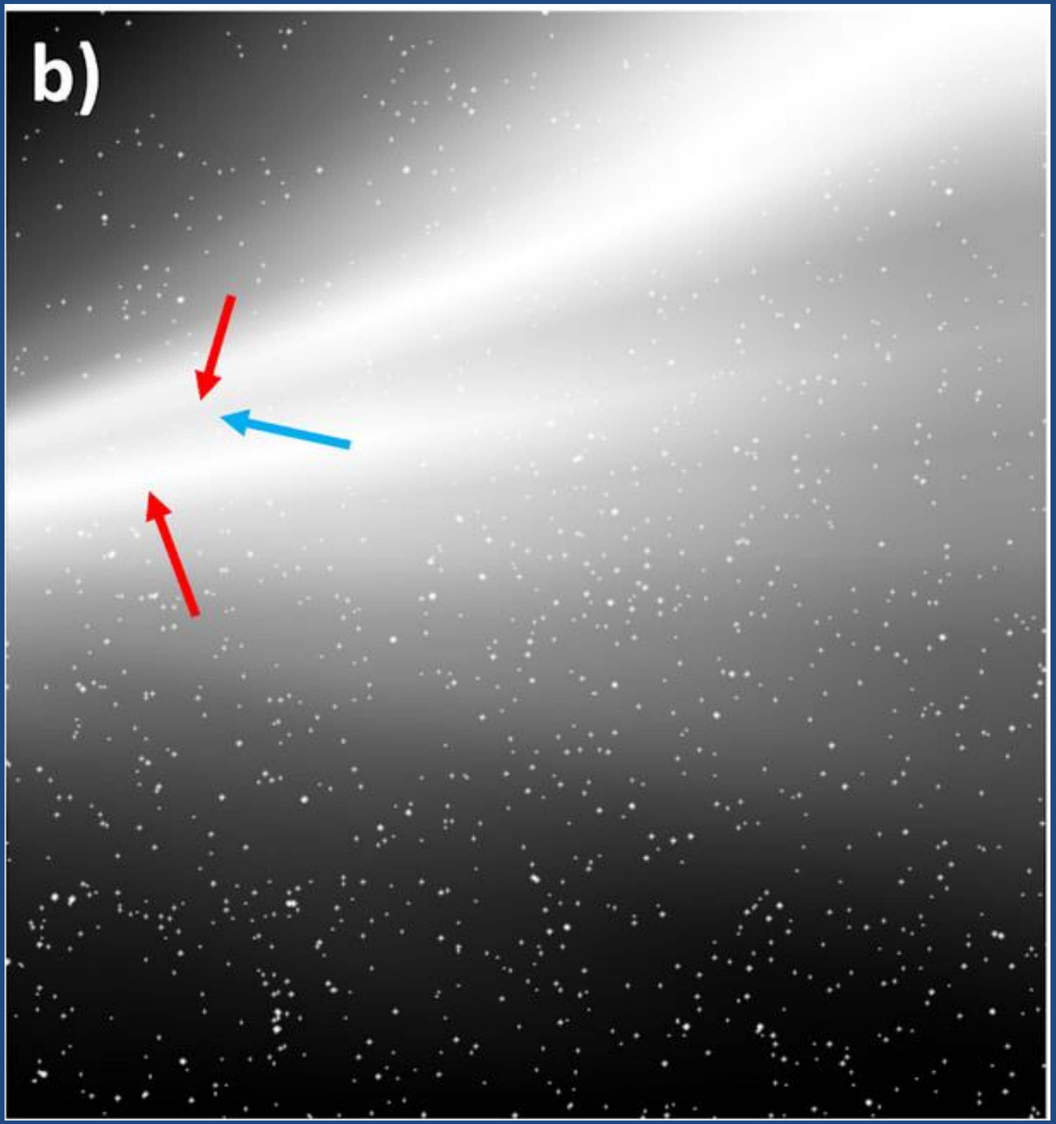








IRAP MHD model prediction for Parker Solar Probe



See PSP Nature special issue (Nov 2019) to evaluate our predictions.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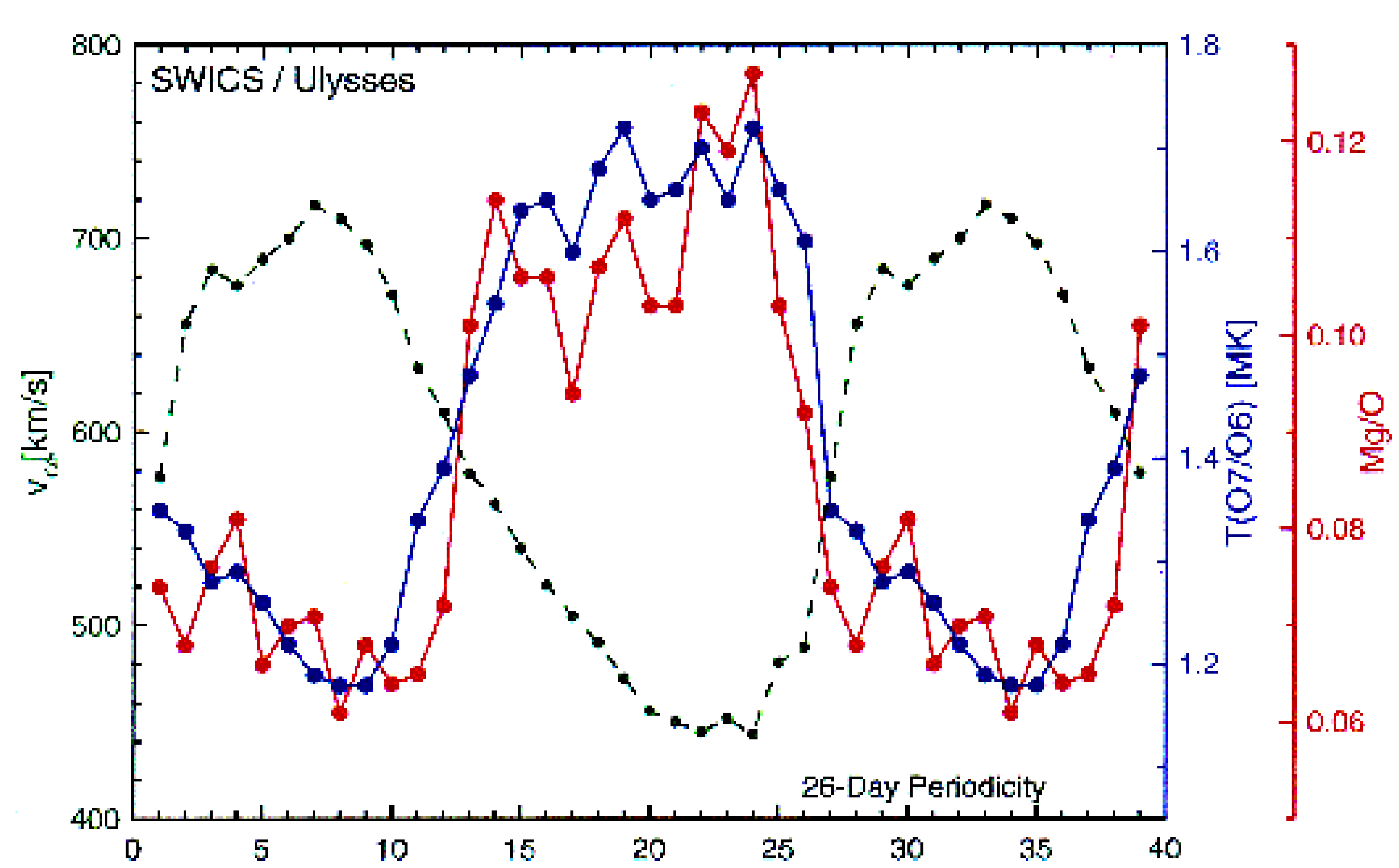
MHD simulations cannot explain both source temperature and brightness of the corona

Michican Ionisation Code (MIC, Landi and co-workers) + AWSoM 3-D MHD (Oran et al. 2015):

- Reproduces the relative charge states of the slow and fast winds,
- Emissions of different ions difficult to re-produce,
- Excursions from average charge state are not explained (footpoint exchange?)

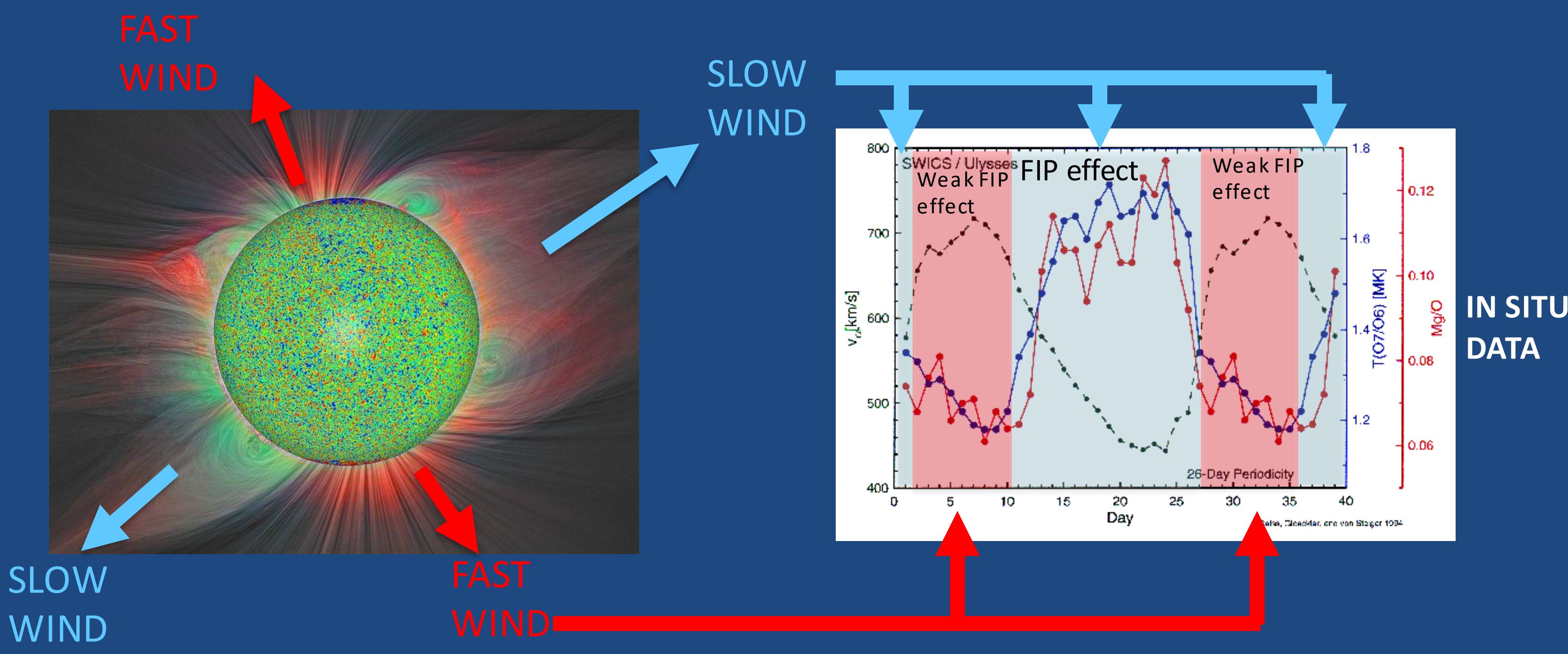
-> supra-thermal electrons (3MK) improve the agreement between observed and synthetic fluxes of 10 emission lines considered here.

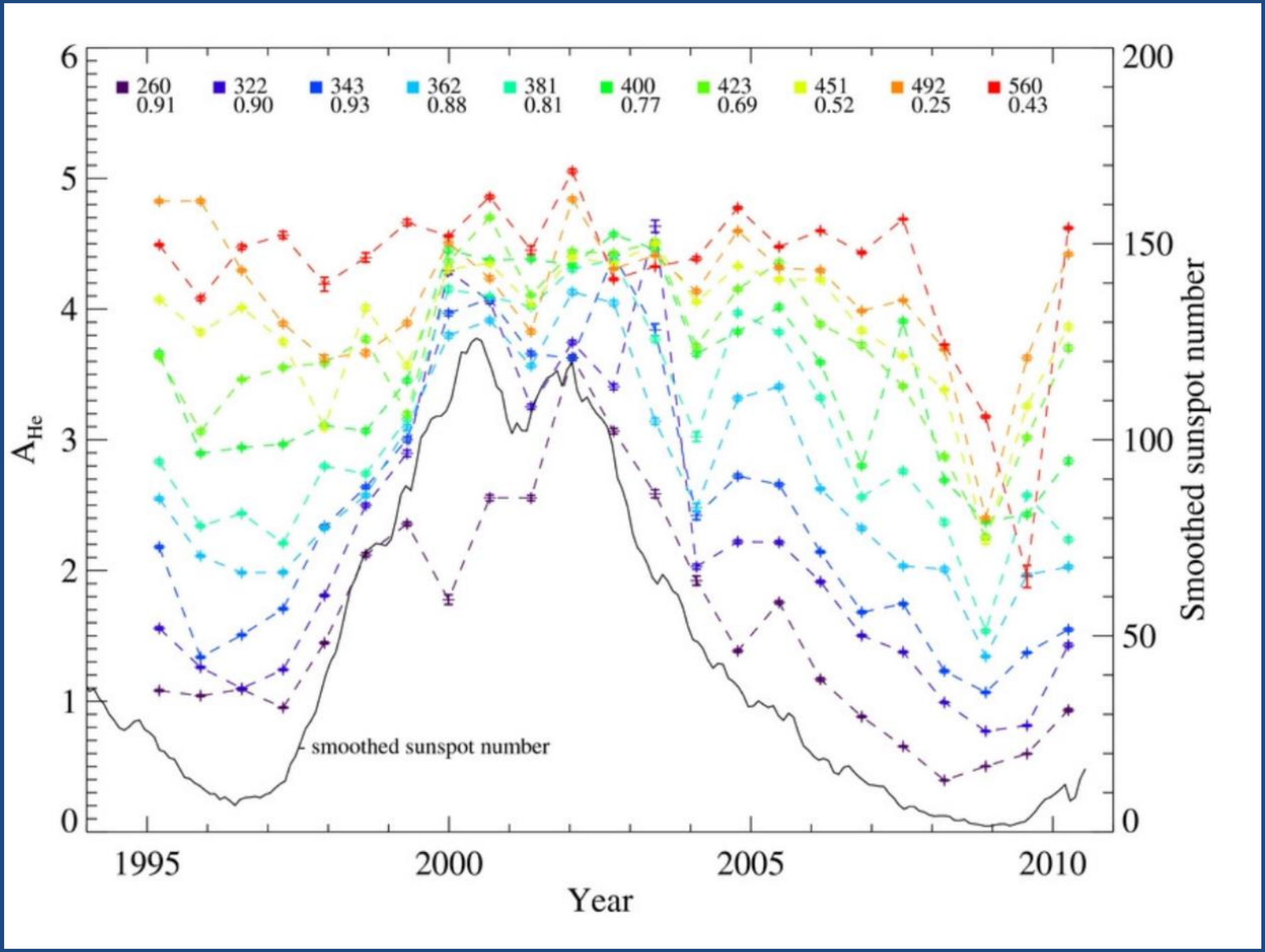


Geiss et al. 1996

Can we model the composition of the solar wind?

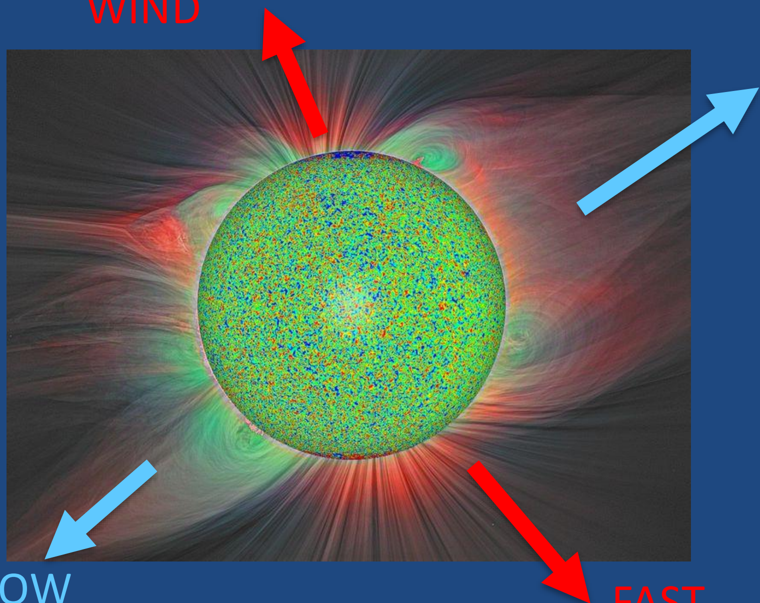
How do we address the FIP effect?





Kasper et al. 2007

Slow and fast solar winds are very different!



- 4 x photospheric Fe/O abundance ratio
- Depleted He abundance
- Small proton T anisotropy
- High iron charge states
- Intermittent structures

(see Rouillard et al. 2010, 2011)

- Photospheric Fe/O and He abundance ratio
- Large proton T anisotropy
- Low carbon and oxygen charge states

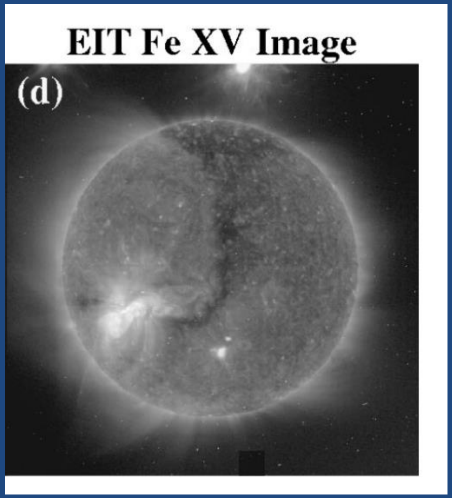
On M-stars= Opposite abundance anomaly to solar slow wind and loops.

No model is yet capable of simulating coronal composition in 3-D!

The slow wind forms along flux tubes that are adjacent and likely to interact with closed loops:

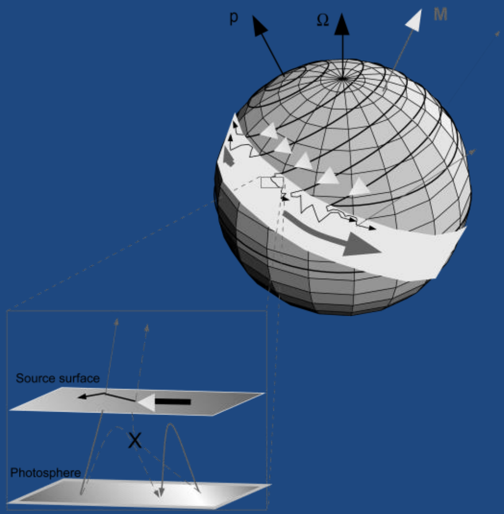
Rigid rotation of coronal holes

e.g. Elephant trunk



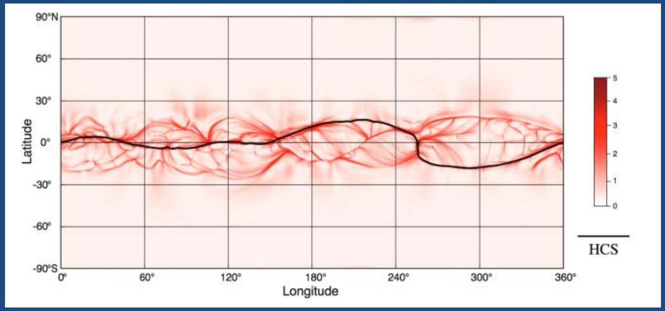
Wang, Nash, Sheeley (late 80s)

Fisk field



Fisk (1996)

S-Web

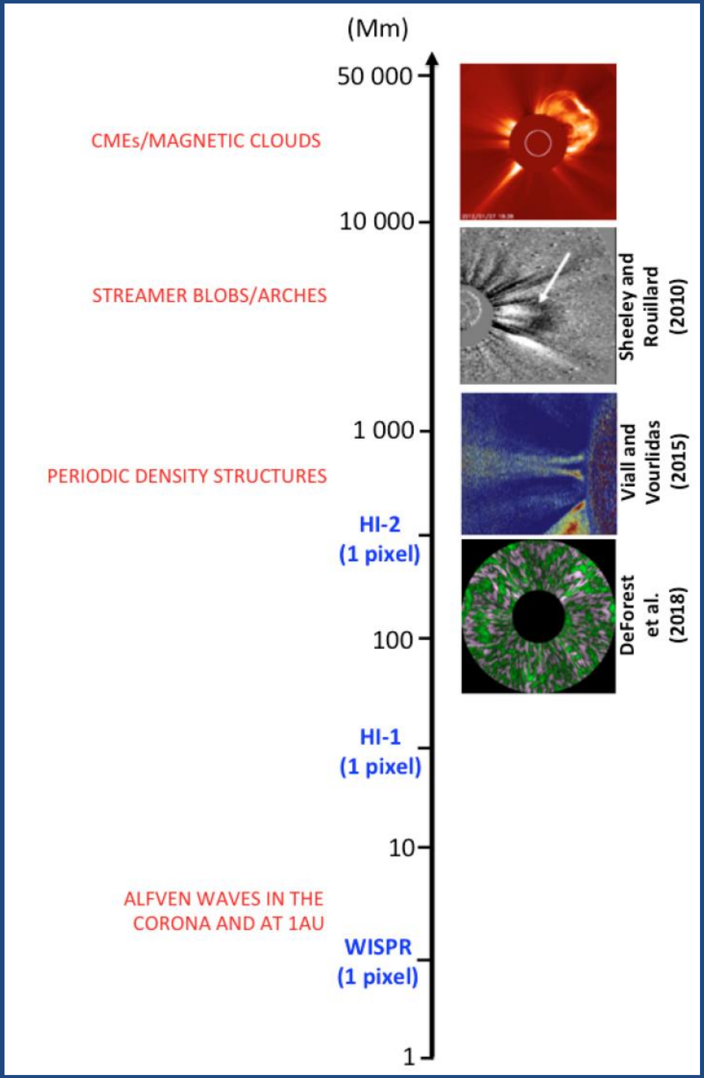


Antiochos et al. 2008


PSI Prediction 08/14/2017 - Terrestrial North up

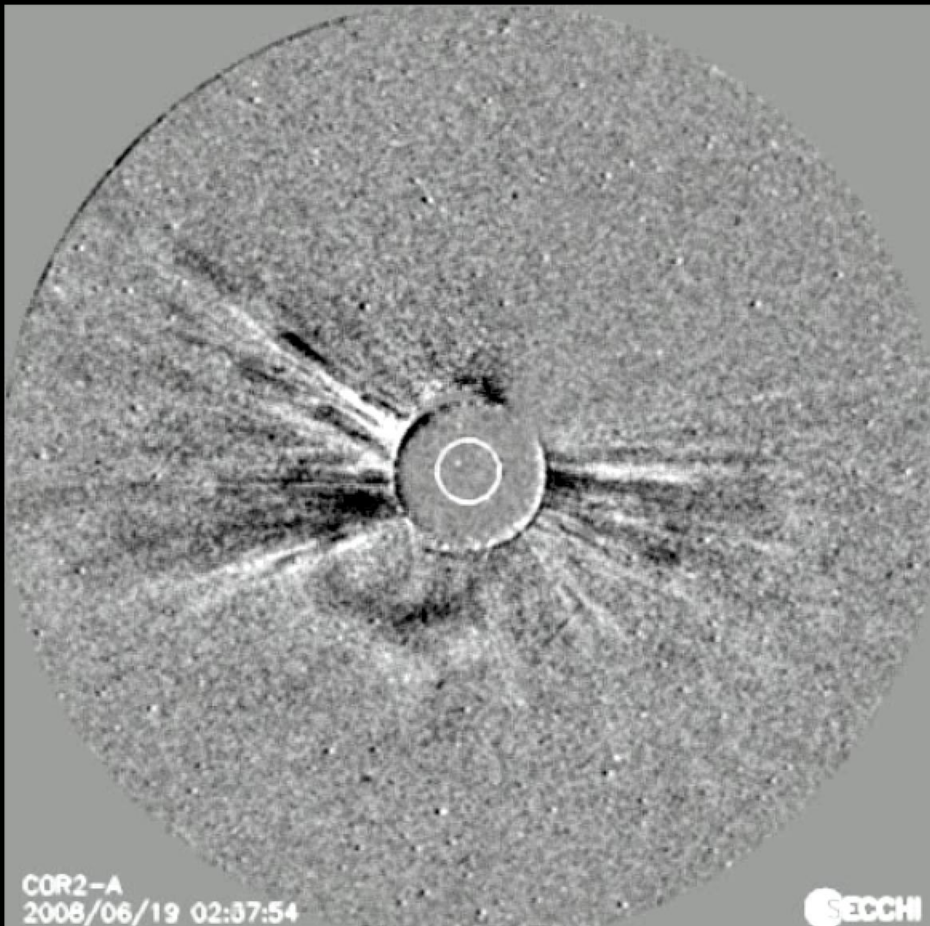
Can we find signatures of this release process in remote-sensing?

Scales, scales, scales ...

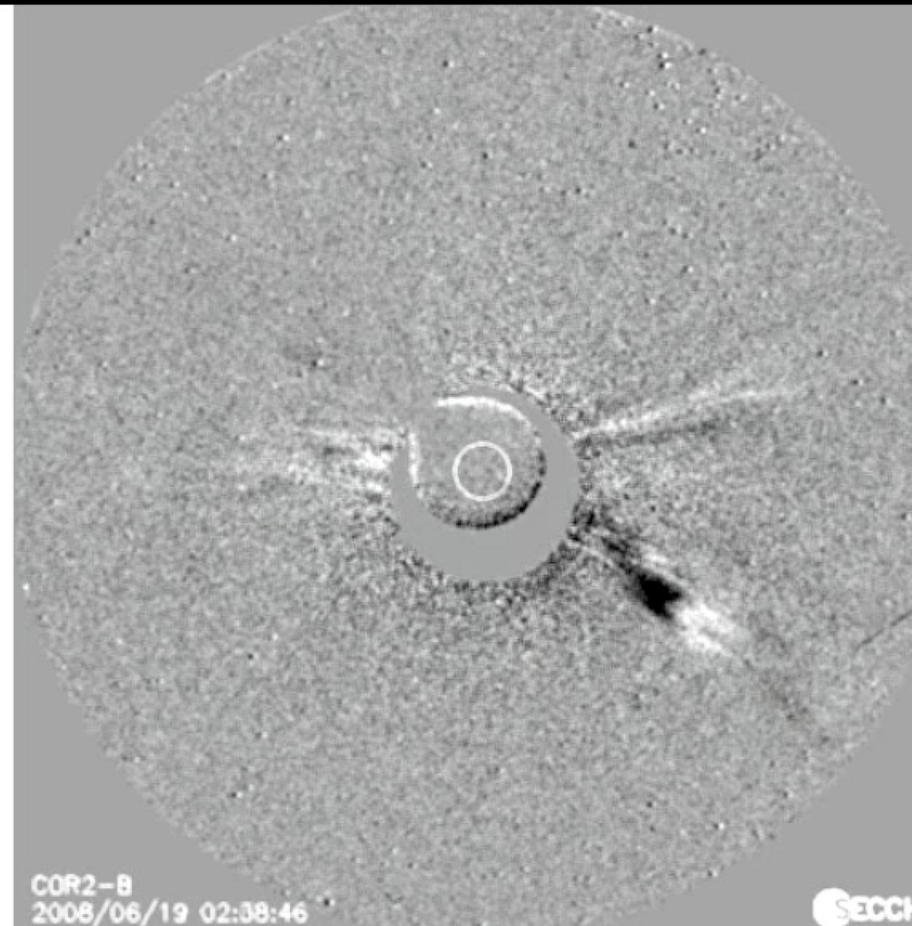


Rouillard et al. 2019

COR-2A

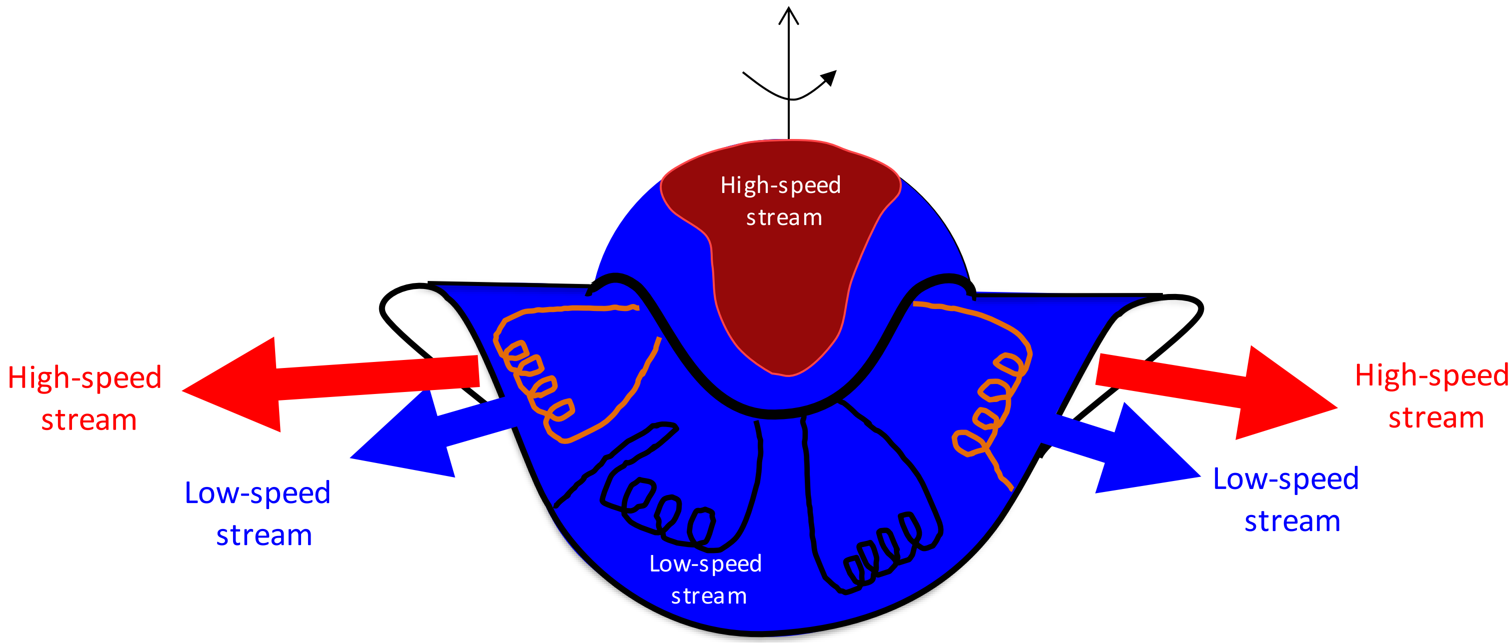


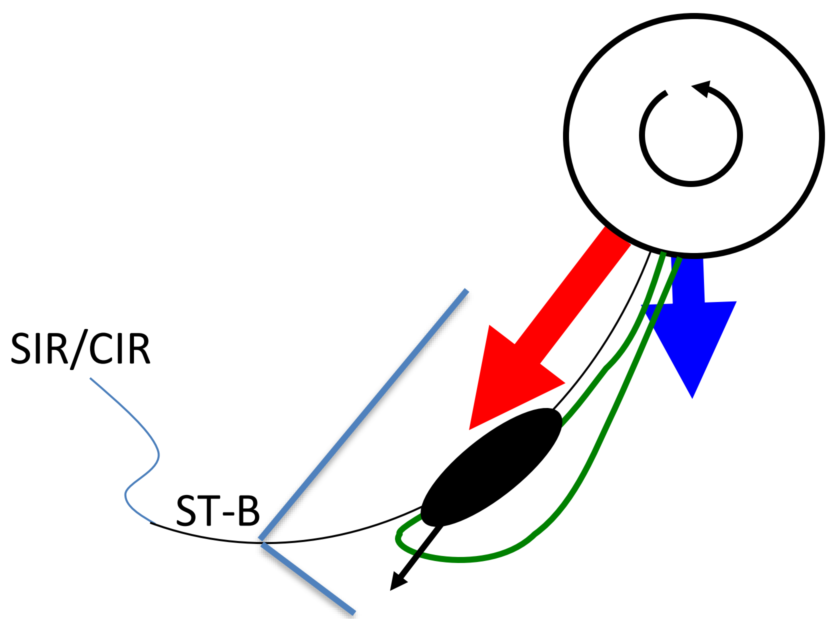
COR-2B



Arc-like structures emitted over
20-40 degrees PA range

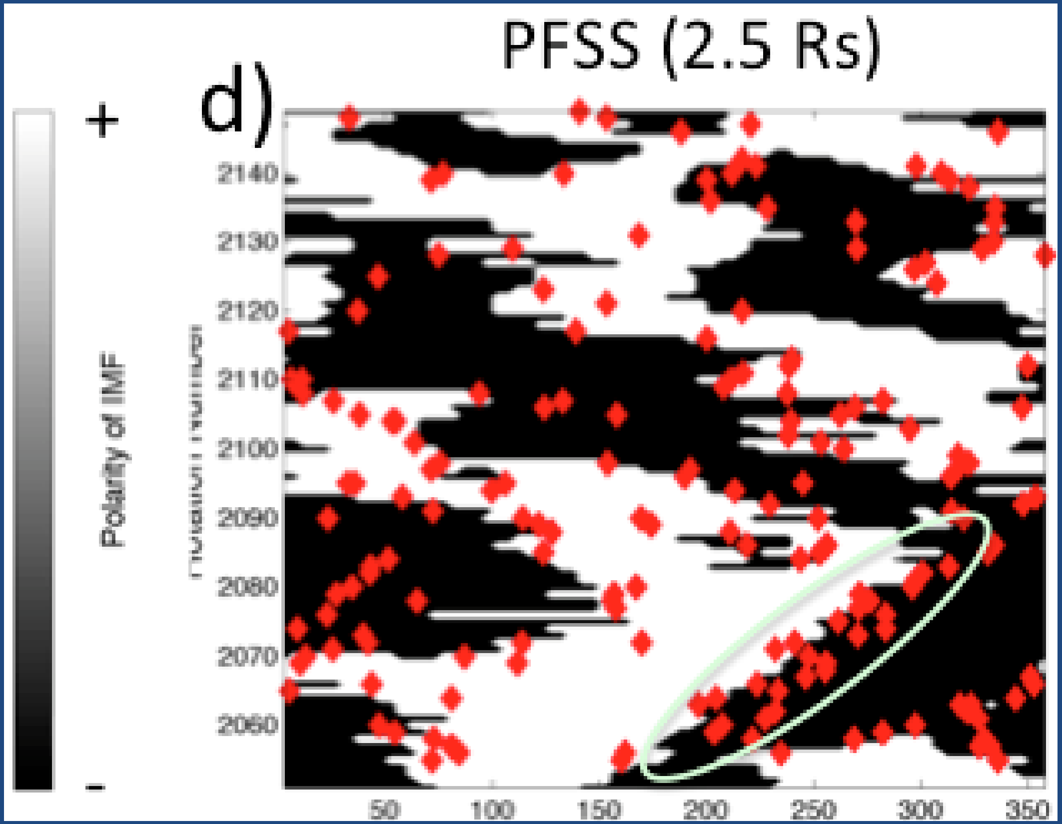
2-3 edge-on blobs per day
Sheeley et al. 2008



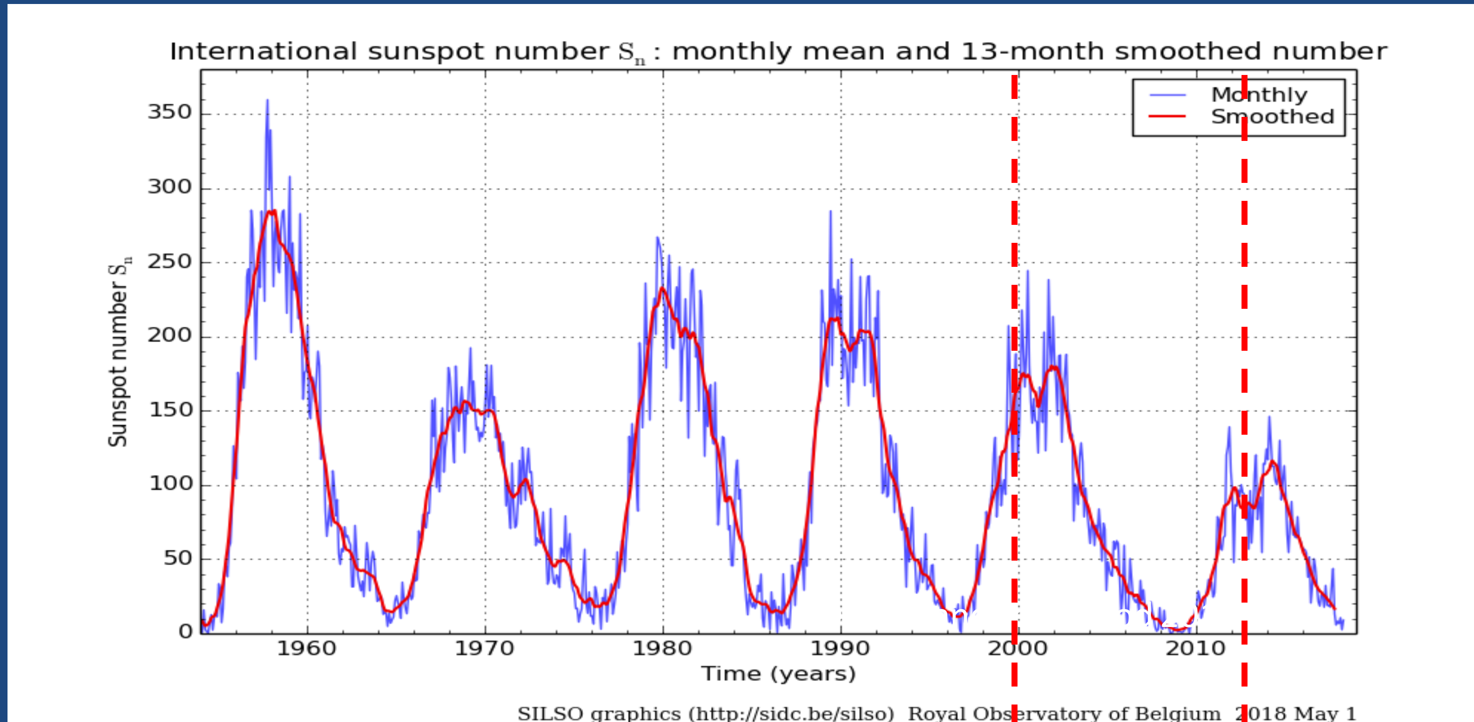


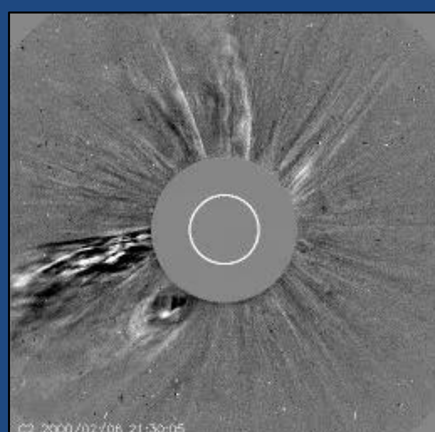
Rouillard et al. (2011a)

If blobs are produced high up in the corona and are flux ropes then can we detect inward motions (i.e. analogous to the SADs in EUV)?

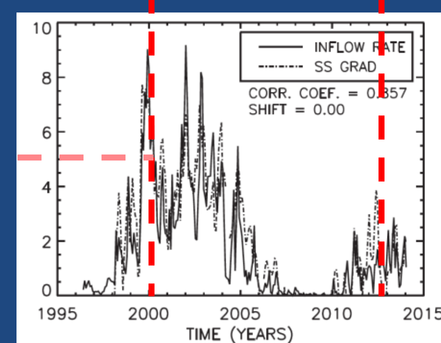


Plotnikov et al. (2016)

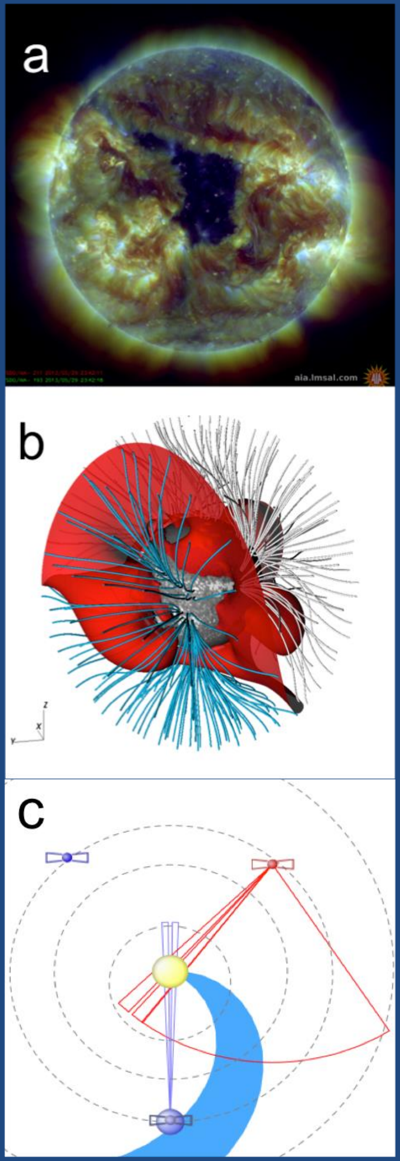


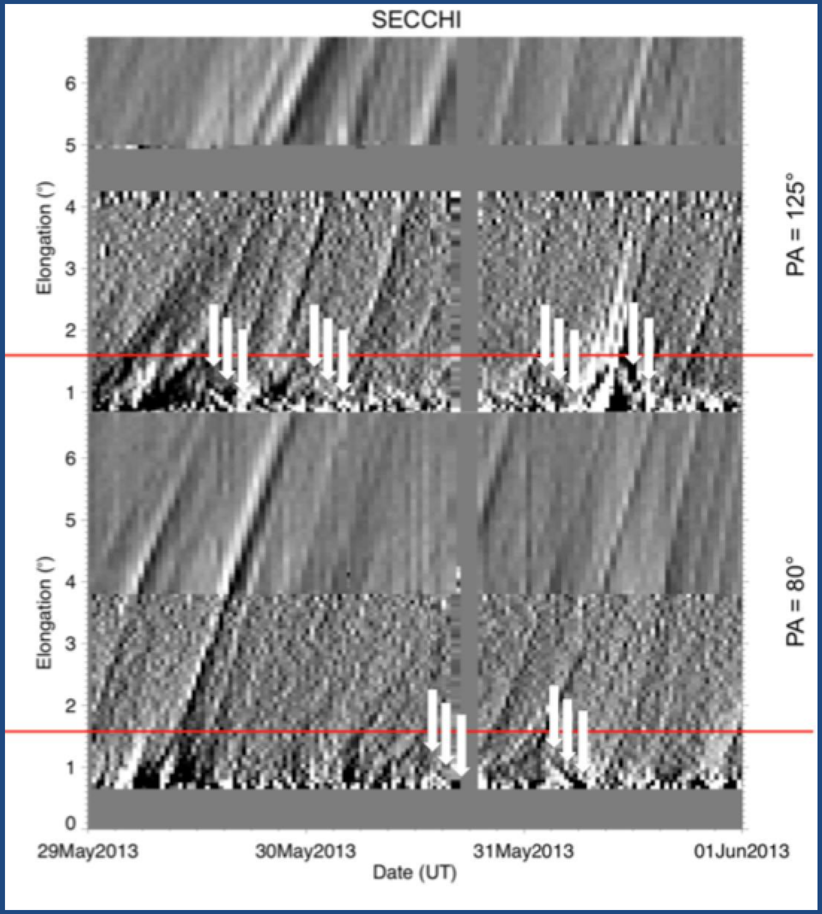


Sheeley and Wang 2001



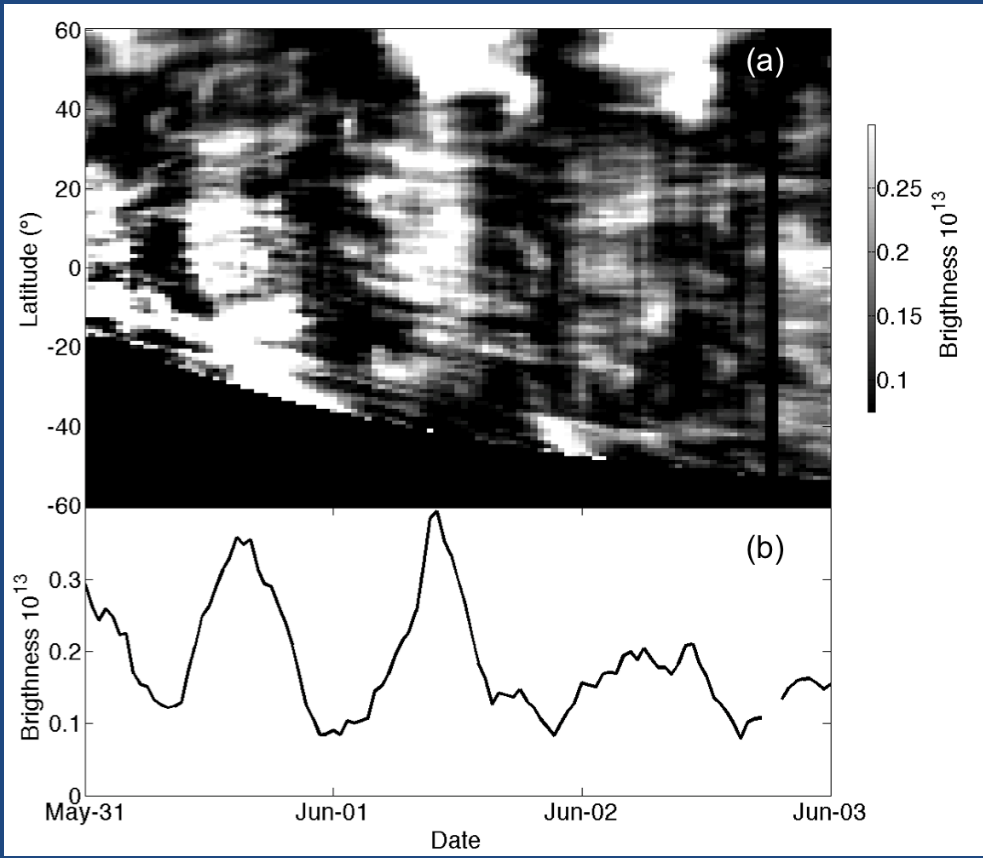
Sheeley and Wang 2014

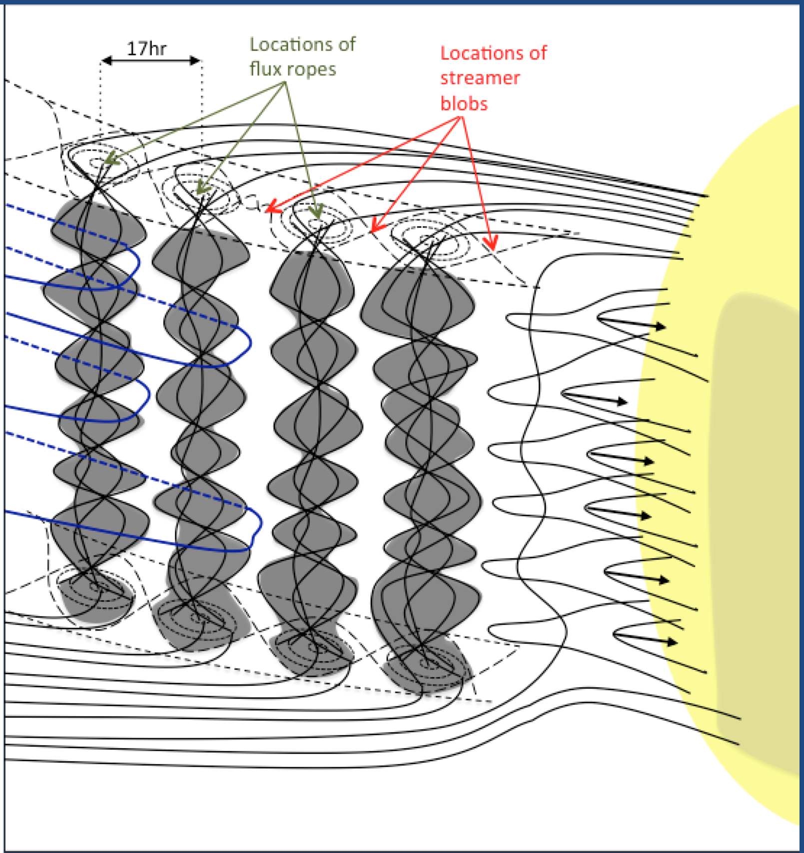




The release of many blobs had inflows associated with them.

Sanchez-Diaz et al. 2016

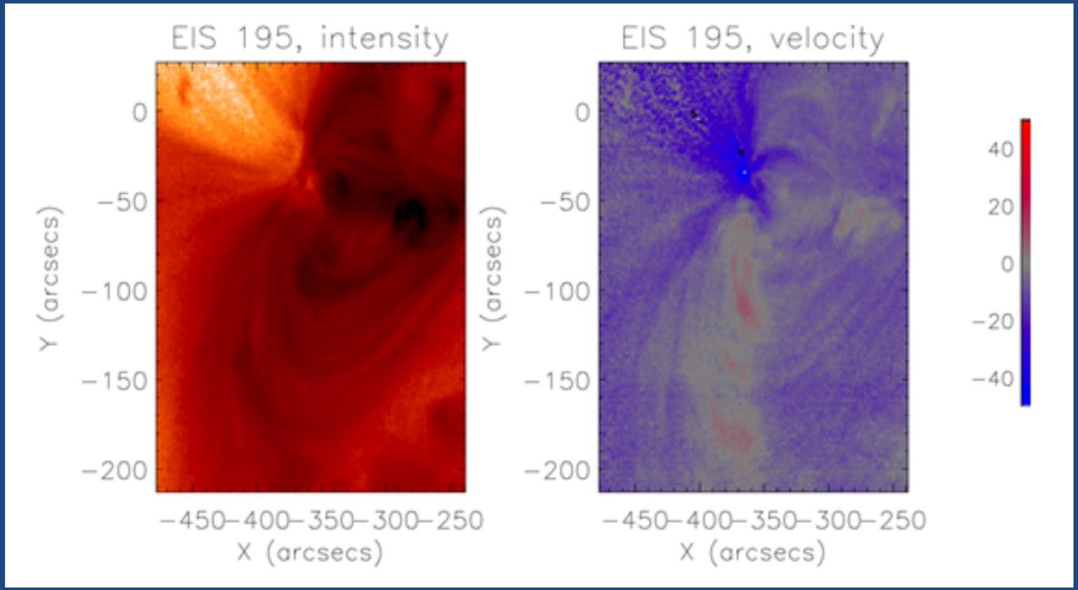




Sanchez-Diaz et al. 2017bc

-> Analysis of in situ data: Sanchez-Diaz et al. 2019

Upflows are seen by Hinode on the edges of active regions

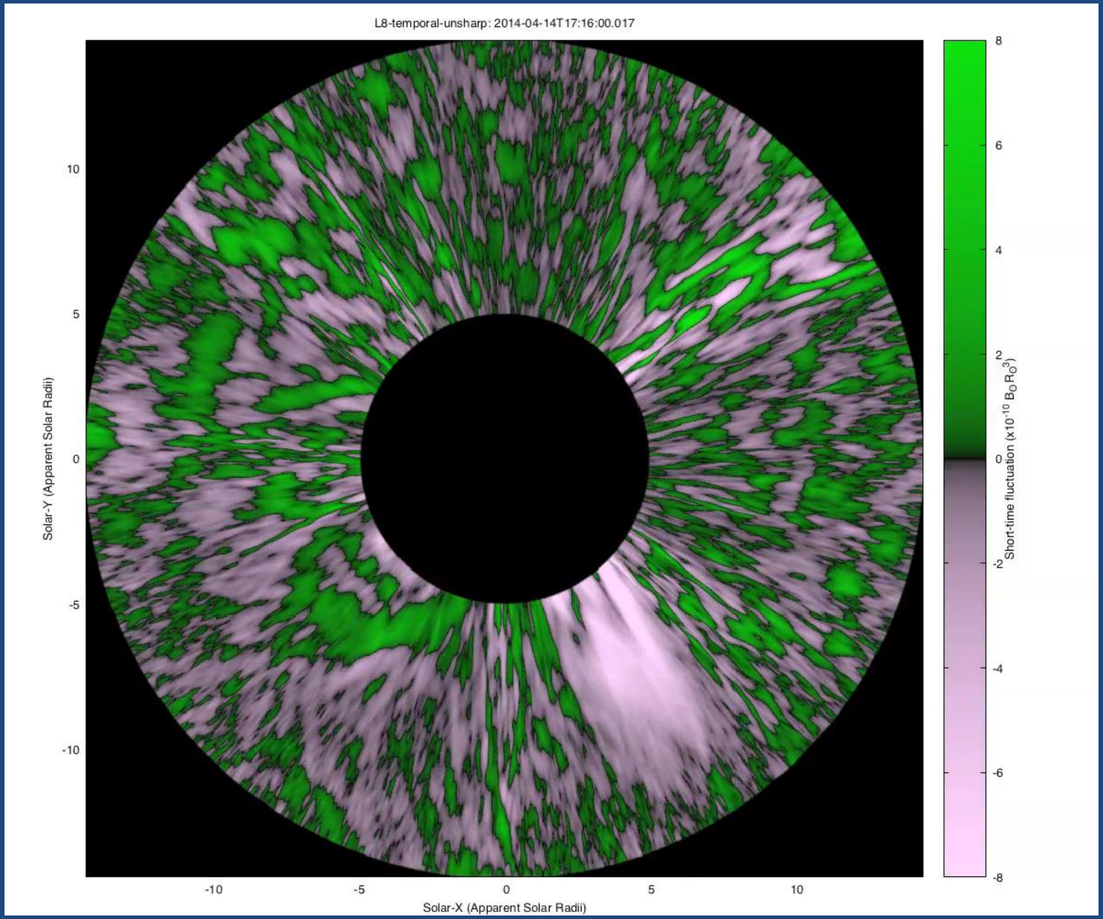


Harra et al. 2008

It was estimated that this up owing plasma could form around 25% of the SSW (Harra 2008)

However! Considering the small field of view of Hinode/EIS, it is challenging to make a direct link to the solar wind and therefore to determine whether these up flows actually become out flows leaving the Sun.

What about far from the current sheet?

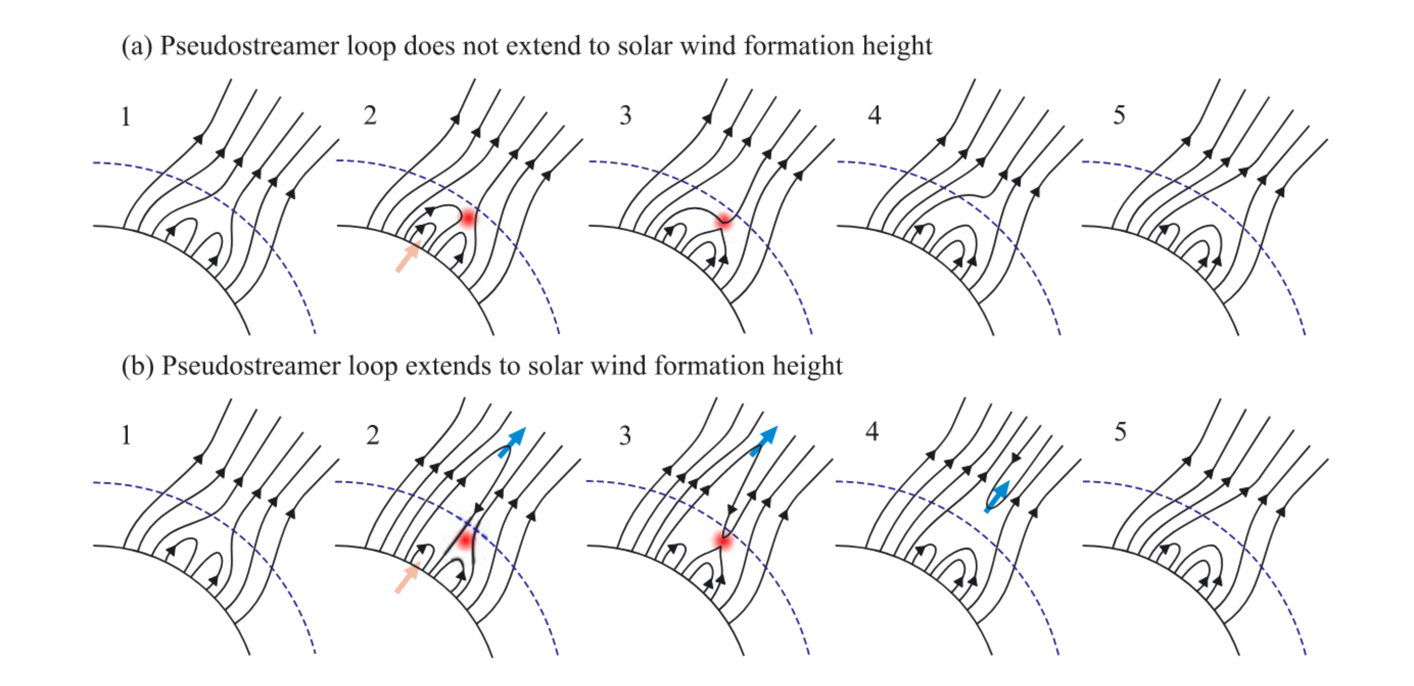


DeForest et al. 2018


© Nicolas Lefaudeux 2017

Analysis of the near-Earth solar wind during the period 1998–2011 reveals that inverted HMF is present approximately 5.5% of thetime and is generally associated with slow, dense solar wind and relatively weak HMF intensity.

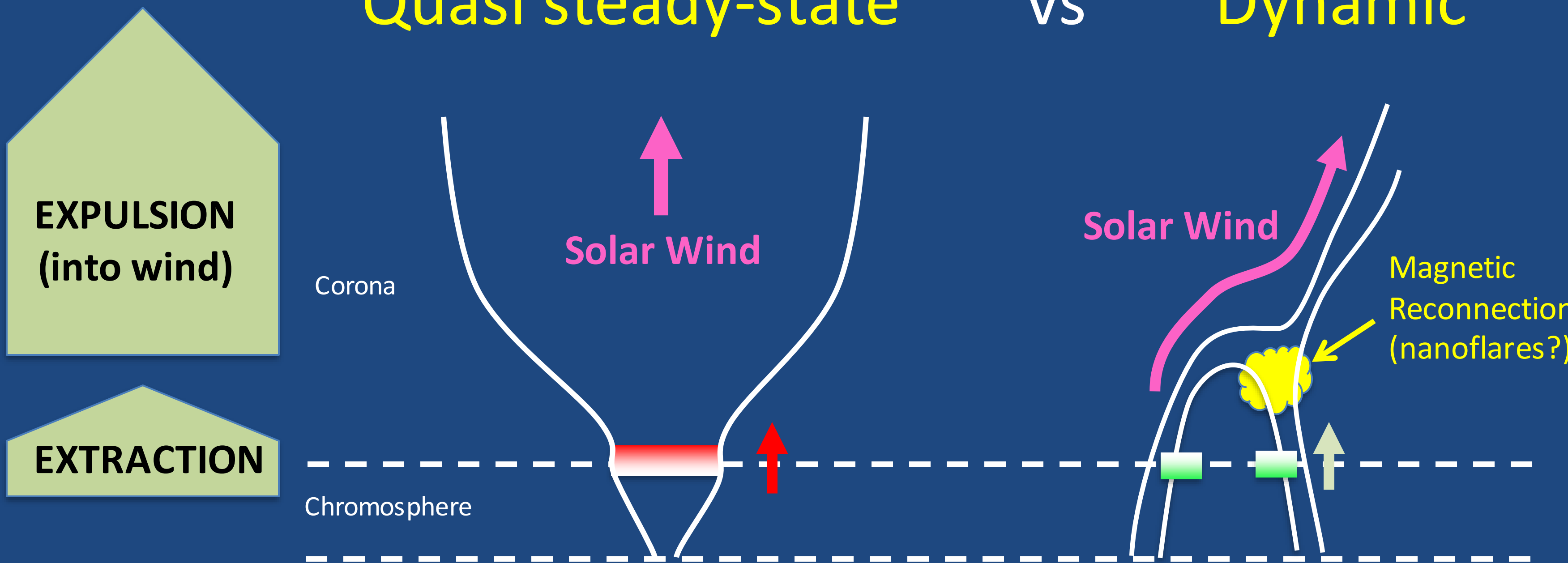
Inverted HMF is mapped to the coronal source surface -> a strong association with bipolar streamers containing the heliospheric current sheet, as expected, but also with unipolar or pseudostreamers, which contain no current sheet.



Owens et al. 2013

Stay tuned to PSP results!

Quasi steady-state vs Dynamic



Diagnostics

(Spectroscopy/In situ)

Composition → Multi-species model (H, e^-, He, Fe, C, O)

Ionisation states → Coupling of photo/collisional ionization

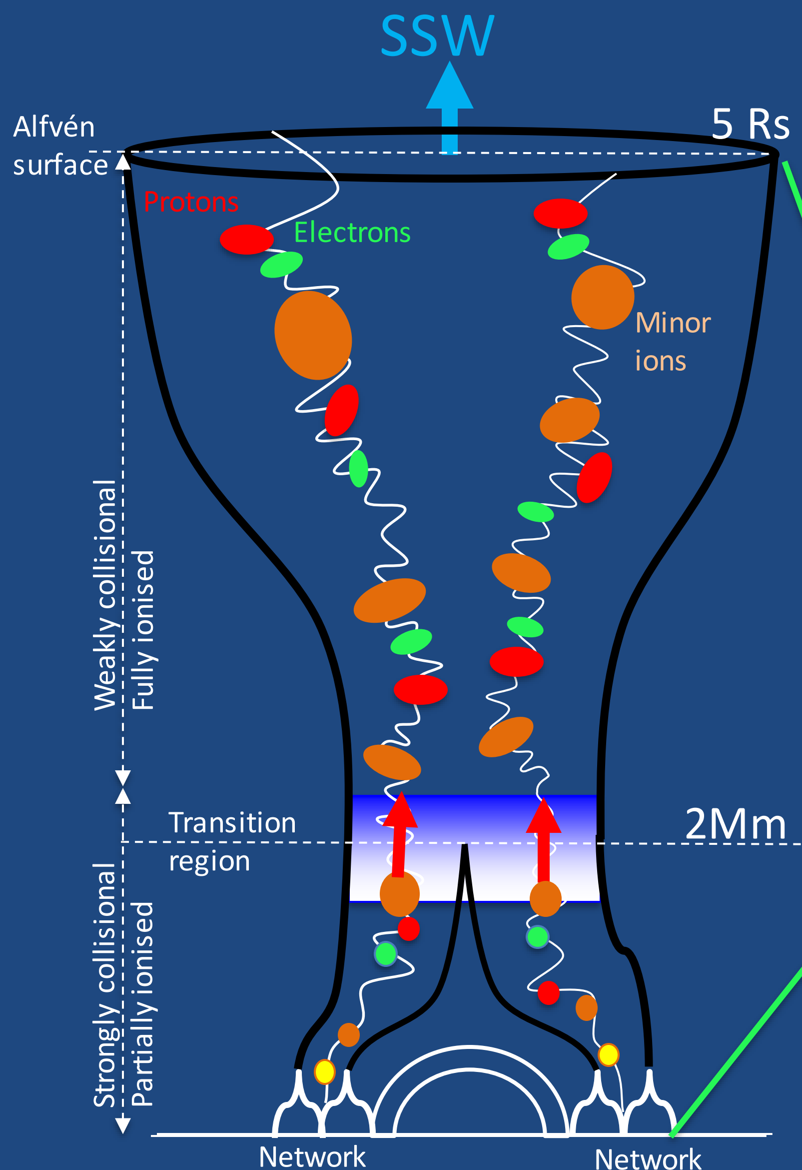
Temperature anisotropies → Include elements of kinetic plasma physics

A unique approach at modelling the 3-D multi-species anisotropic corona!

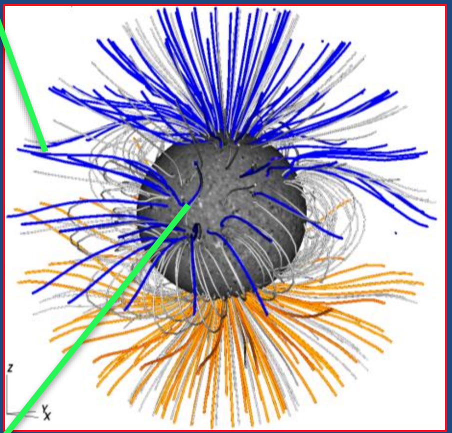
Kinetic-Fluid solver
Lavarra, Rouillard et al.
(In Prep. 2018)

CORONAL PHYSICS
(plasma/wave transport/heating, non-thermal tails)
(Postdoc-1)

CHROMOSPHERIC PHYSICS
NON-LTE processes
(radiative transfer)
(PhD-1)



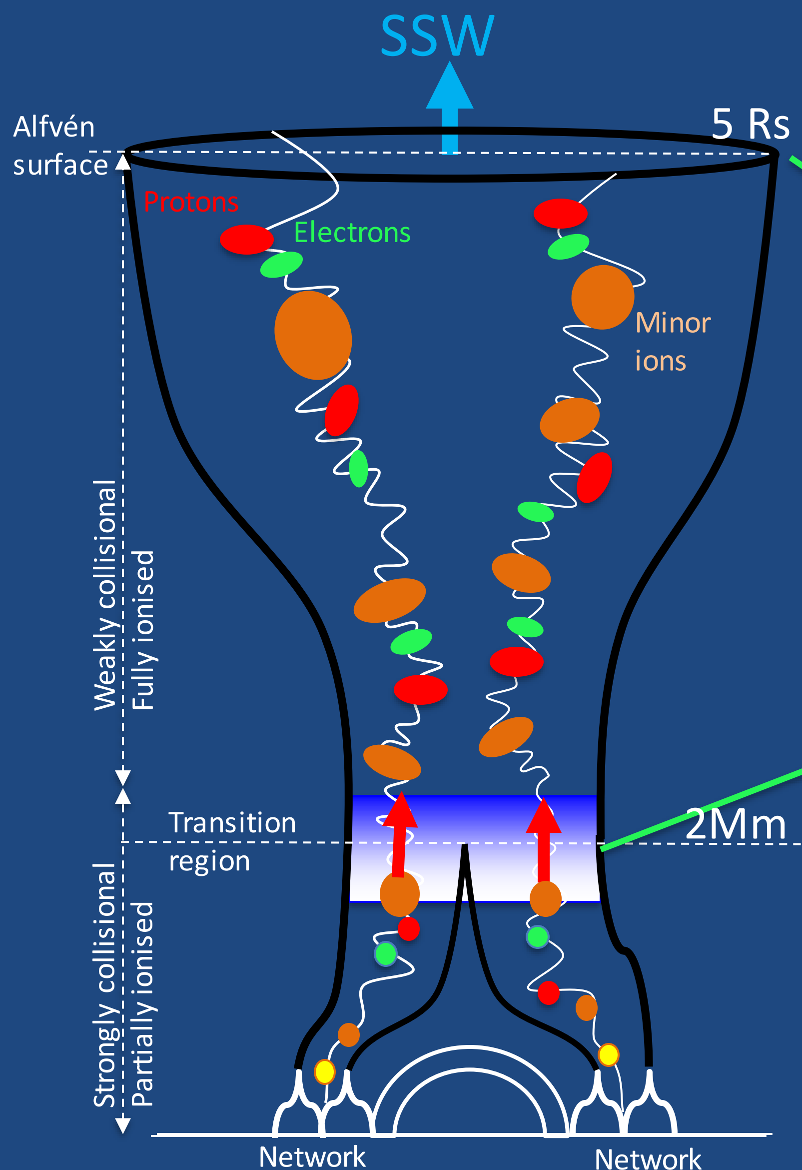
Testing **static** origin of slow solar wind



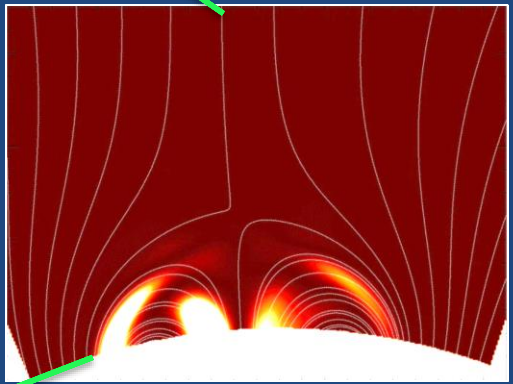
First 3-D multi-species corona
(PhD-1, Postdoc-1, Postdoc-3)

Testing the dynamic origin of the slow solar wind!

How variable is the slow wind composition?



Testing **dynamic** origin of slow solar wind



First dynamic multi- species model of corona

Couple to 2.5-D MHD (PhD-2, Postdoc-3)

Couple to 3-D MHD (Postdoc-2)

(Based on 2.5-MHD: Pinto, Rouillard 2016)

Merci!