From multi-decadal solar wind modelling to real-time forecasting, and on moving away from the ecliptic plane

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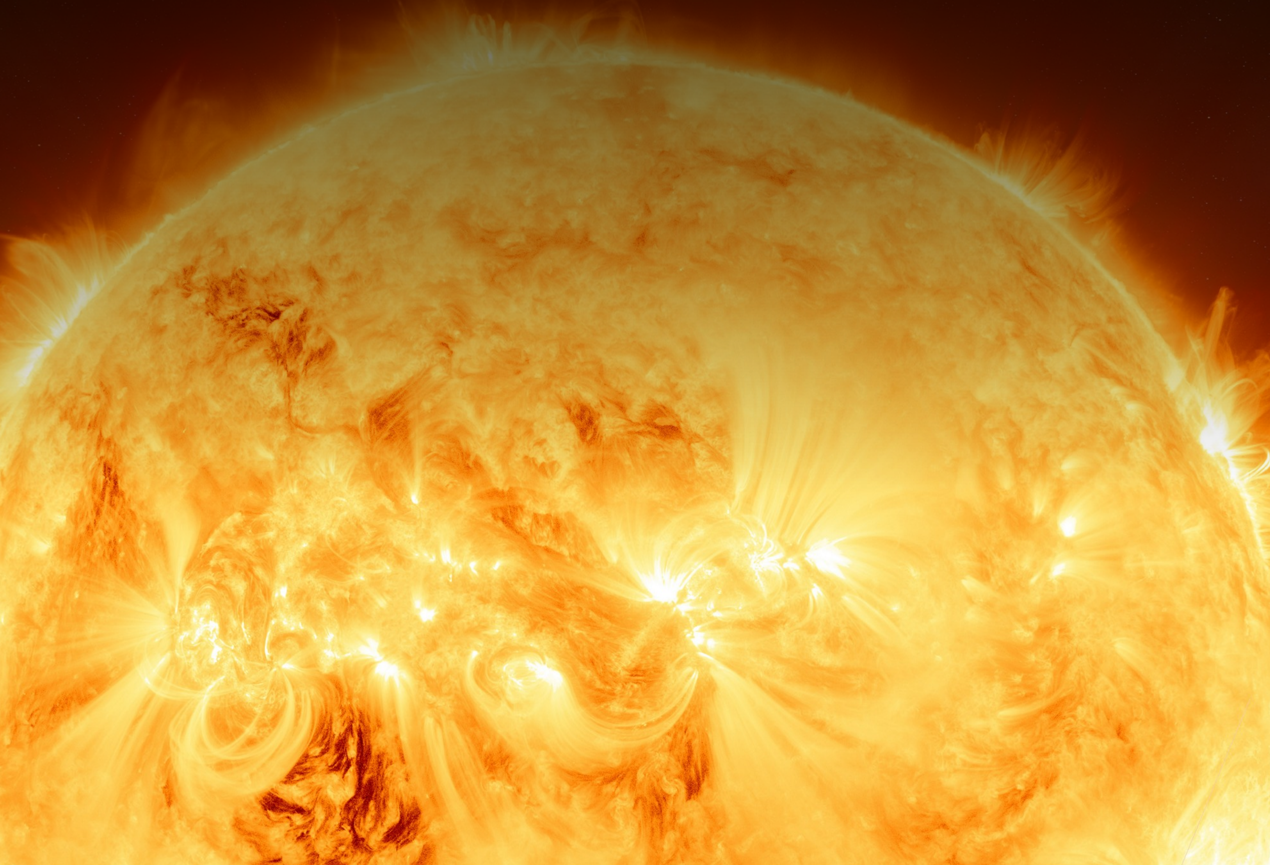
IRAP, U. Toulouse, OMP/CNRS, Infor'Marty



Global solar wind modeling

MULTI-VP: data-driven, physics-based, lighter than full MHD, better than empirical models

Long time-series of solar wind simulations

Two solar cycles+ **CR1920 (03/1997)** to **CR2276 (10/2023)**

Based on WSO + ADAPT/GONG magnetograms

Solar wind sources and flow topology

Tranverse components (lat and lon) below 5 Rs

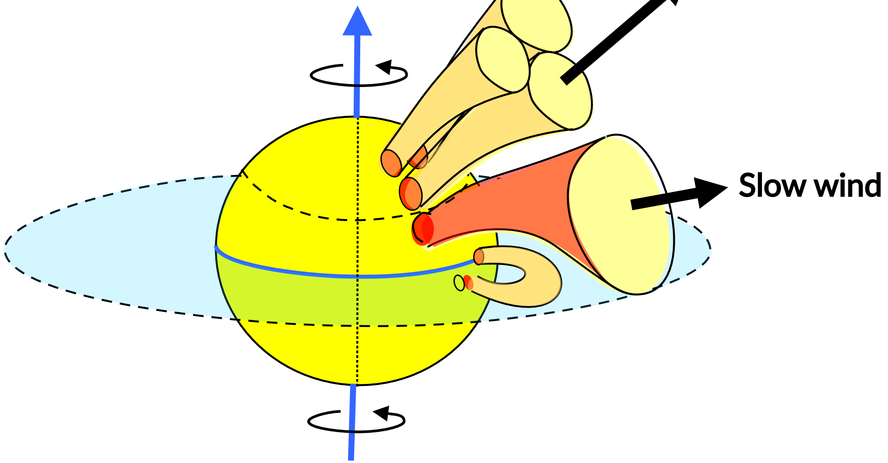
Off-ecliptic in-situ and remote obs

Slow/fast solar wind distribution

Connectivity patterns

Determining solar wind speed

Semi-empirical scaling laws



WSA (Wang-Sheely-Arge)

$$V_{wind} = 265 + \frac{1.5}{(1+f_{ss})^{1/3}} \times$$
$$\times \left[5.8 - 1.6 \exp\left[1 - \frac{\theta_b{}^3}{7.5^3}\right]\right]^{3.5} \text{ km s}^{-1}$$

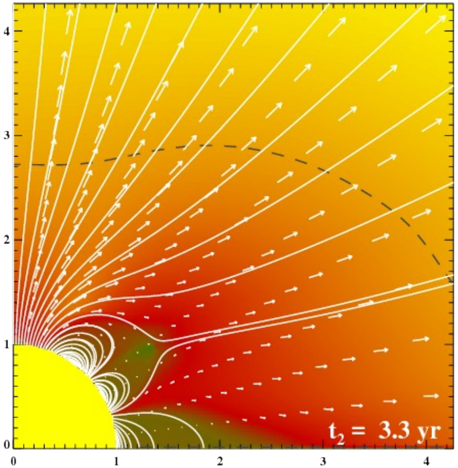
f_{ss}: total flux-tube expansion ratio (Wang, 1995; Velli 2013)
θ_b: distance to coronal hole boundary

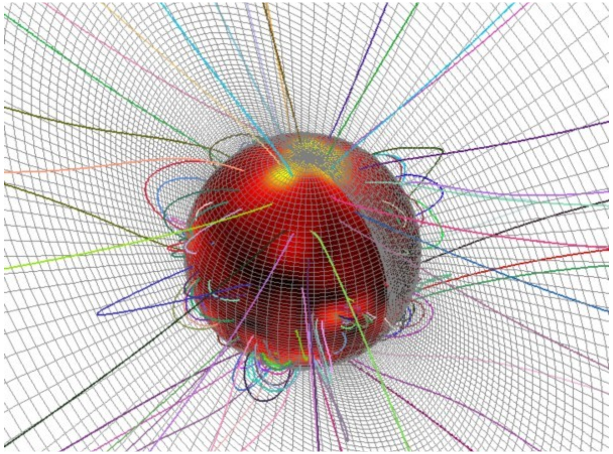
Coronal hole area – wind speed relation

$$V = (80 \pm 2)A + 426 \pm 5.$$

V: wind speed at 1 AU
A: total CH area
(Nolte et al 1976, Vršnak, et al 2007, Tokumaru et al 2016)

Global MHD corona and wind models





More physics, but higher complexity

Full magnetic geometry
(but other simplifications)

CPU-heavy
(especially in the corona)

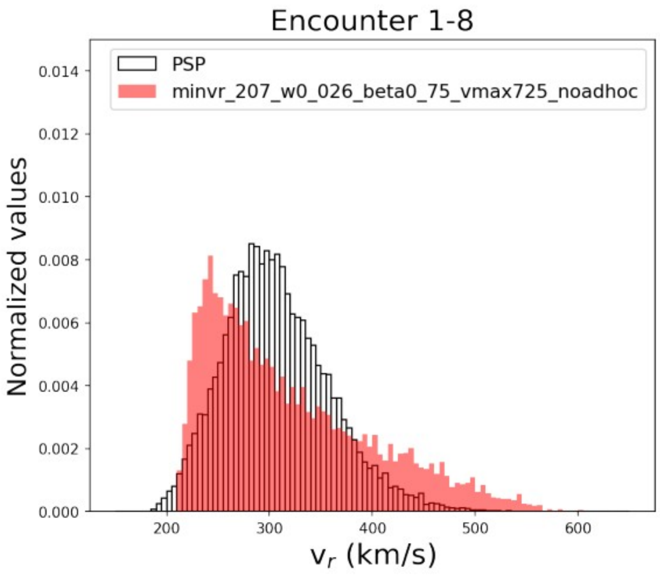
Mikić et al (2011), Gressl et al (2014),
Pinto et al (2011,2013),
van der Holst et al (2015), +

Heliospheric models

HUXt, HELIO1D,
EUHFORIA, ENLIL,
Susanoo

Parker Solar Probe + Solar Orbiter: constraints at mid-heights

Using PSP data to recalibrate semi-empirical laws (WSA)



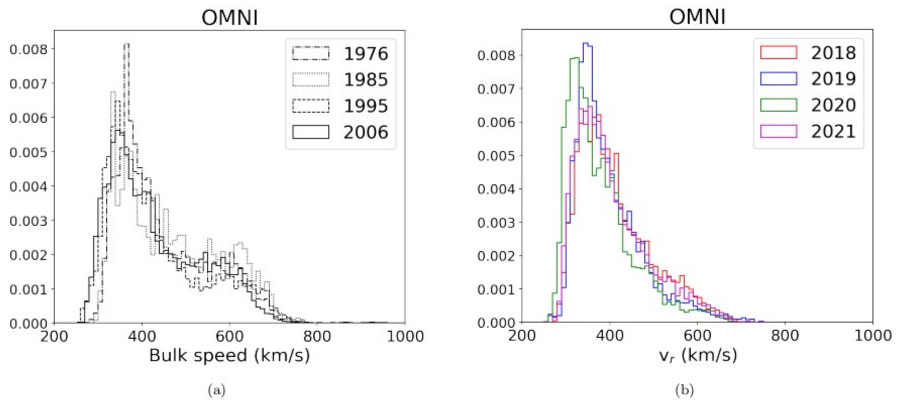
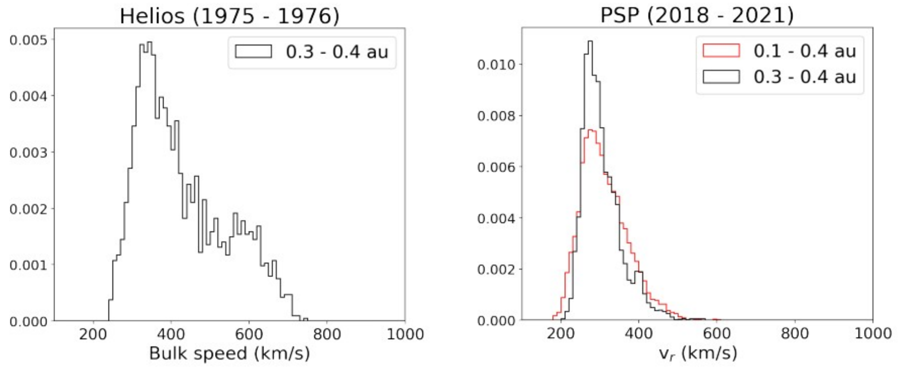


Figure 10. Velocity distributions at Earth based on OMNI data for years during different solar minimum periods. Panel (a): yearly velocity distributions during past consecutive solar minima. Panel (b): yearly velocity distributions during the latest solar minimum.



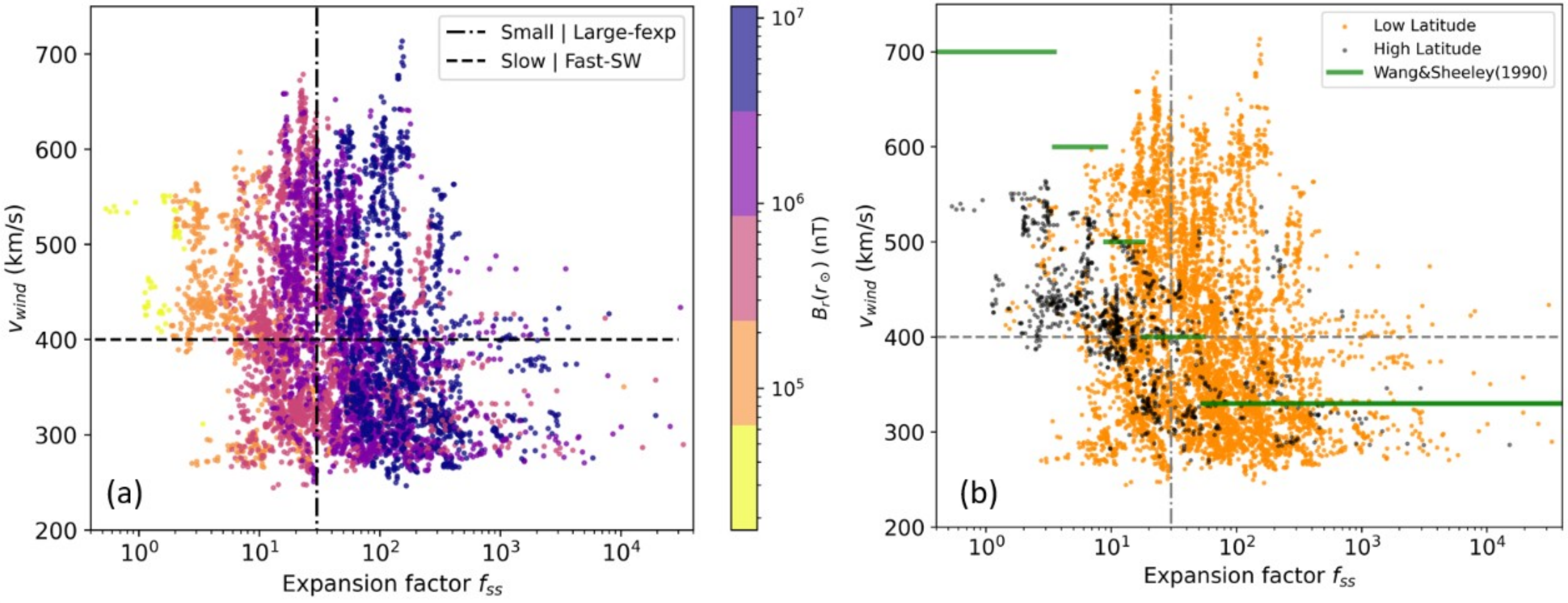
Standard WSA, difficulties:

- predictions @ PSP, SolO, Earth can be incorrect/inconsistent
- current calibration dates from HELIOS era
- can PSP help?
- inconsistencies b/w different heliocentric distances remain

Samara, et al (ApJ, 2024)

Solar wind speed and flux-tube geommetry

Parker Solar Probe wind speeds vs. expansion factor



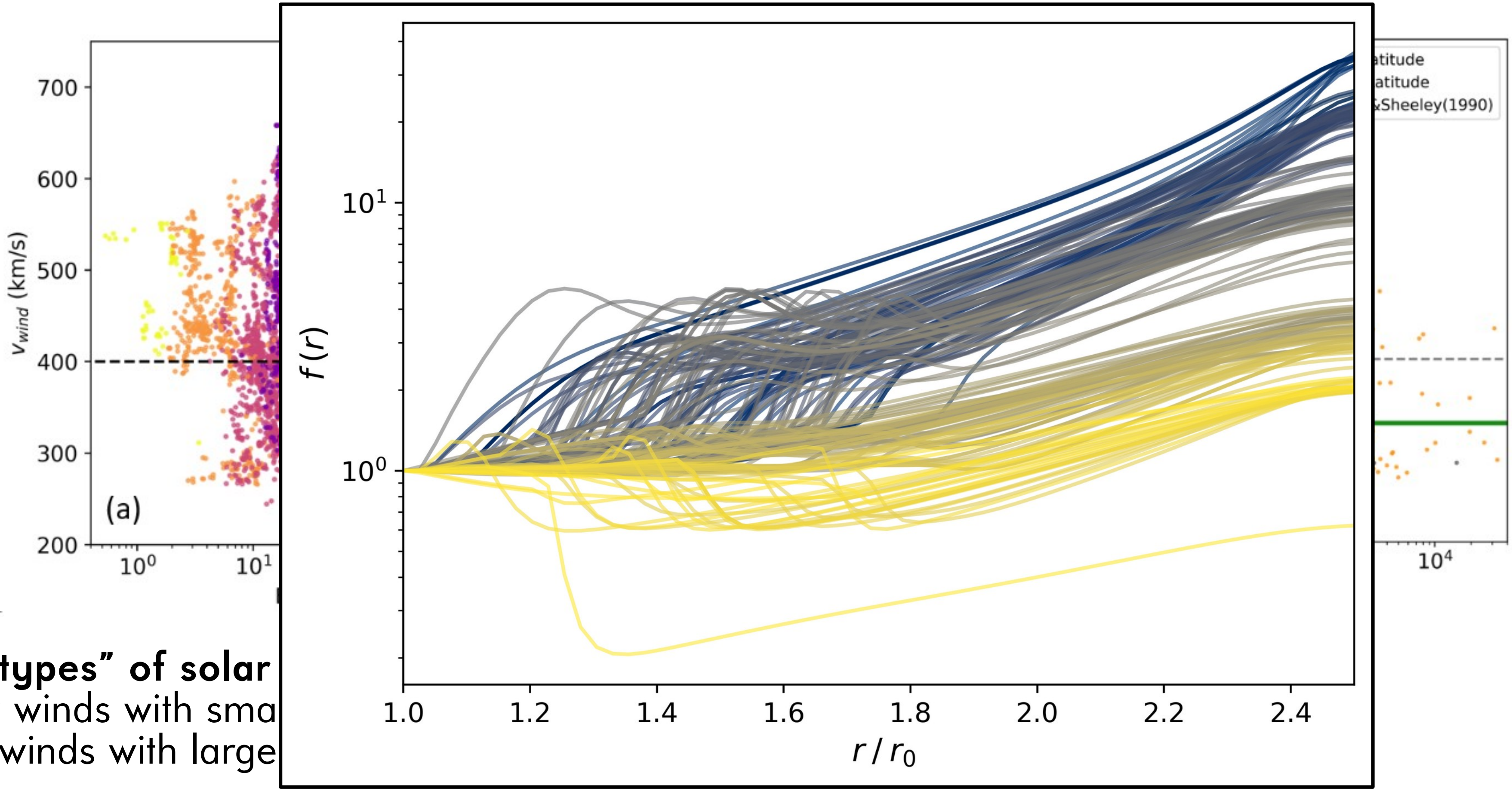
Two "types" of solar wind flow not predicted by standard WSA

- slow winds with small expansion factors
- fast winds with large expansion factor

(Dakeyo et al, *2024*)

Solar wind speed and flux-tube geommetry

Parker Solar Probe wind speeds vs. expansion factor

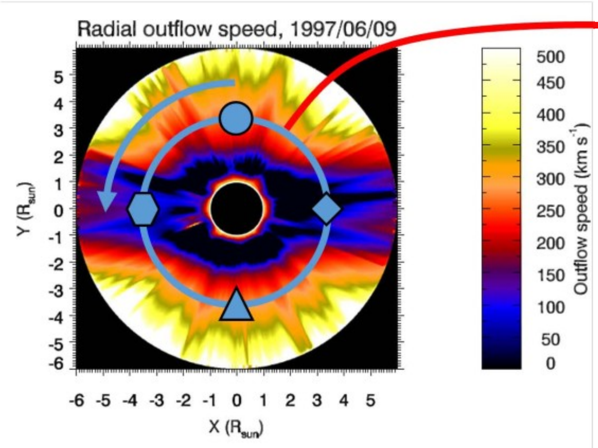


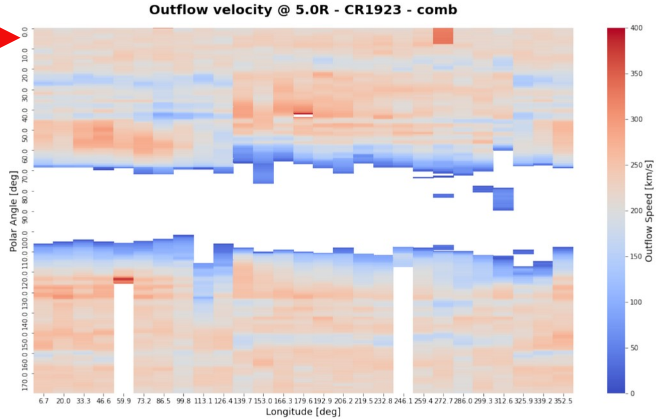
Two “types” of solar
- slow winds with sma
- fast winds with large

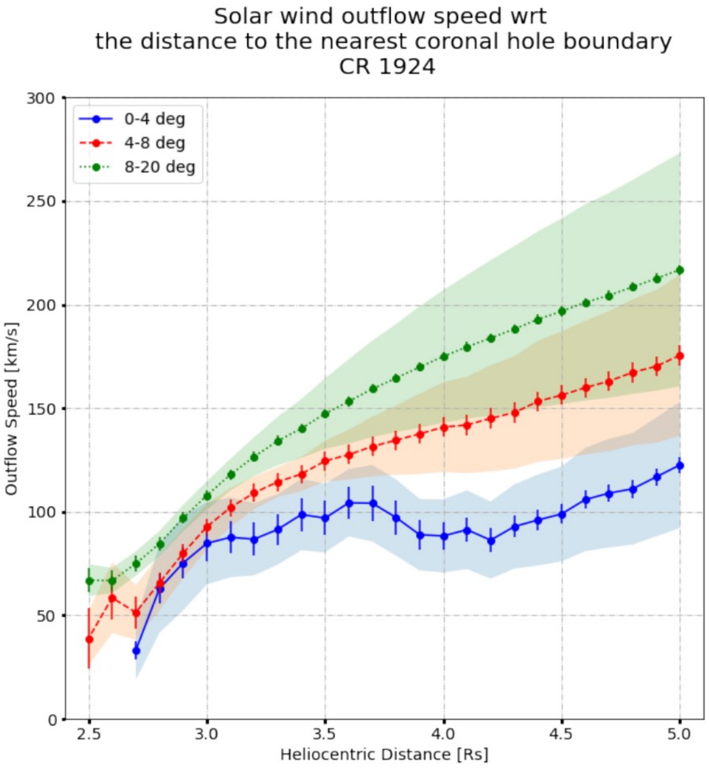
(Dakeyo et al, *2024*)

UVCS slow wind flow mapping (outlook for SolO/Metis)

PFSS/SCS mappings to UVCS wind flow maps (CR 1923–1924)







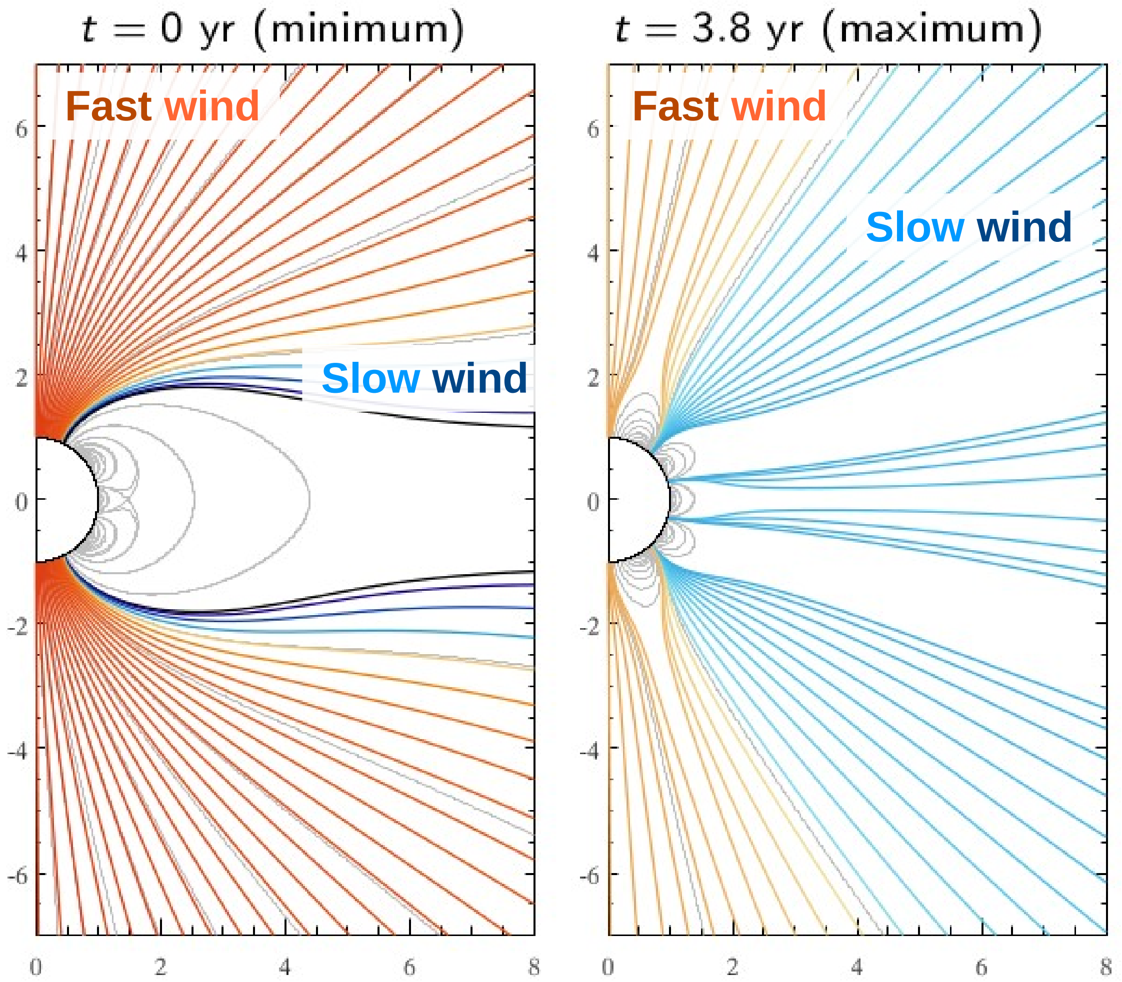
Solar wind speed profile from SoHO/UVCS

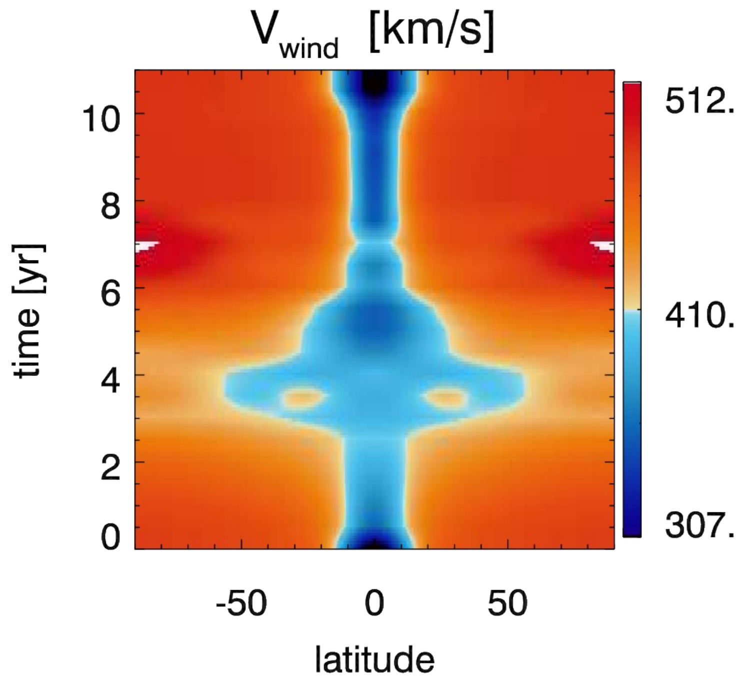
- wind speed vs. heliocentric distance
- profiles measures along flow/magnetic field lines
- trends: lower speed gradients close to CH boundaries
- slow/boundary layer streams more variable and complex

Casti, et al (2023)

Solar wind speed and flux-tube geometry

Global MHD simulations of the solar dynamo, corona and solar wind (11 yr cycle)





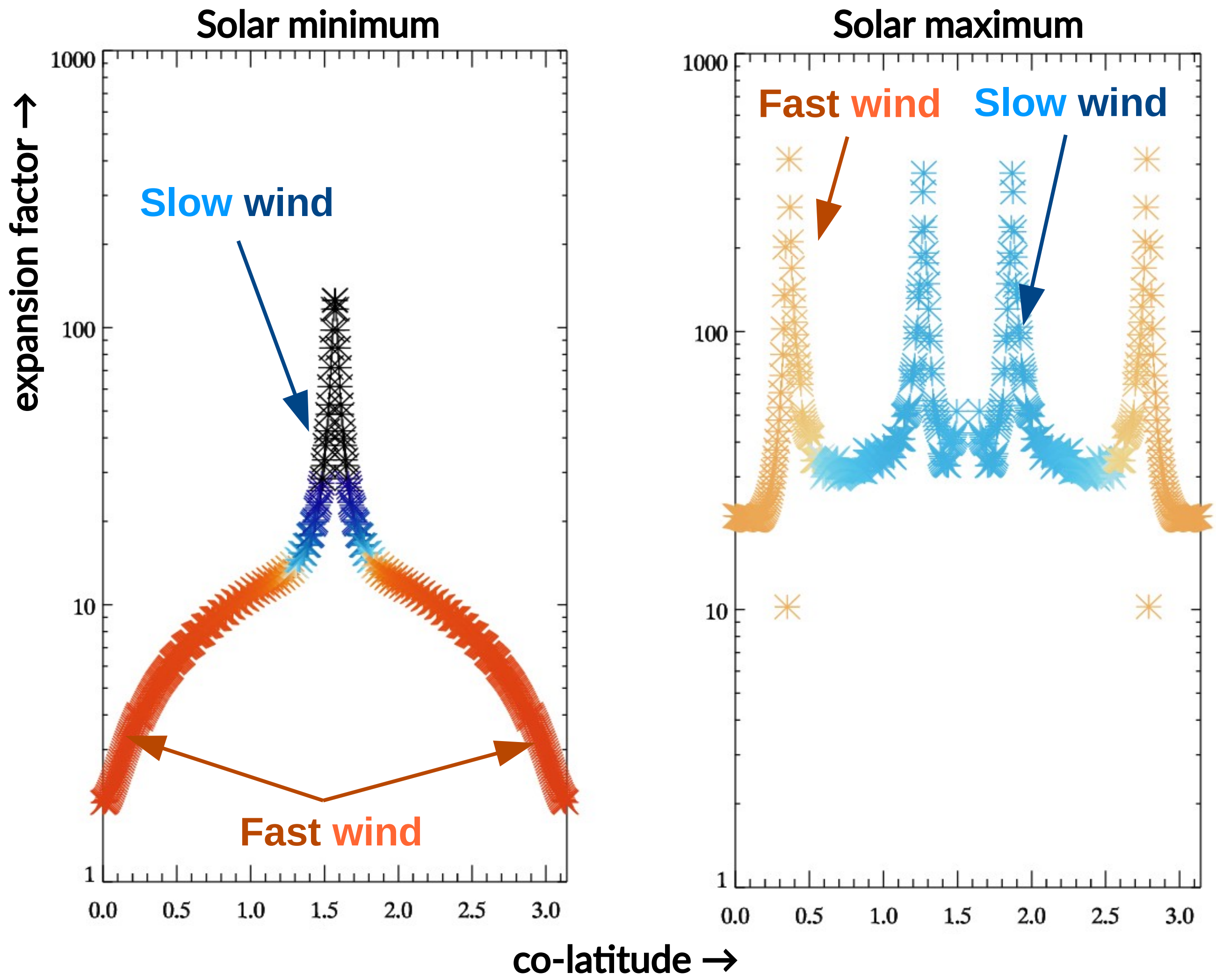
Wind speed distribution

↕

Magnetic geometry

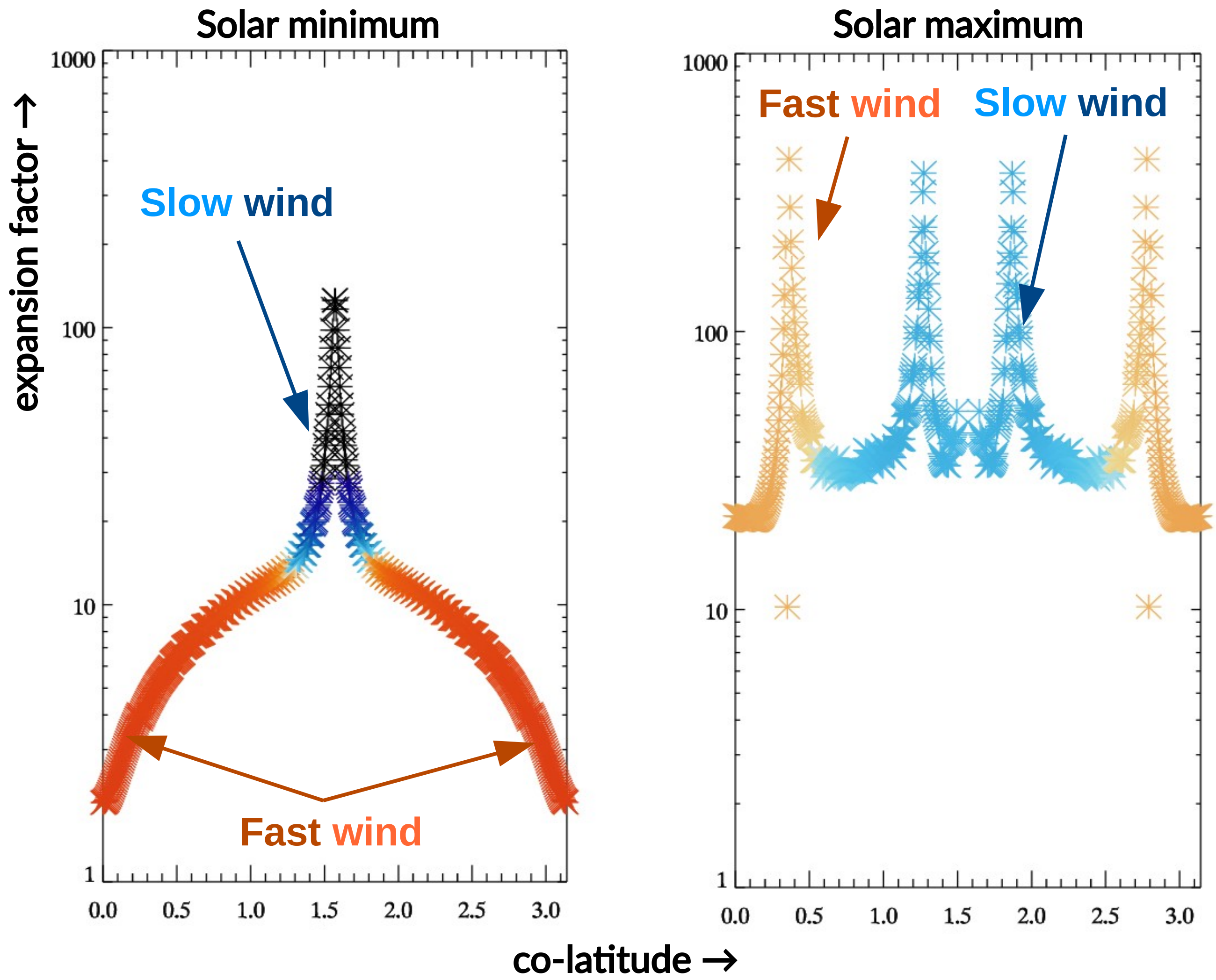
Pinto, et al (2011)
Pinto, Brun, Rouillard (2016)

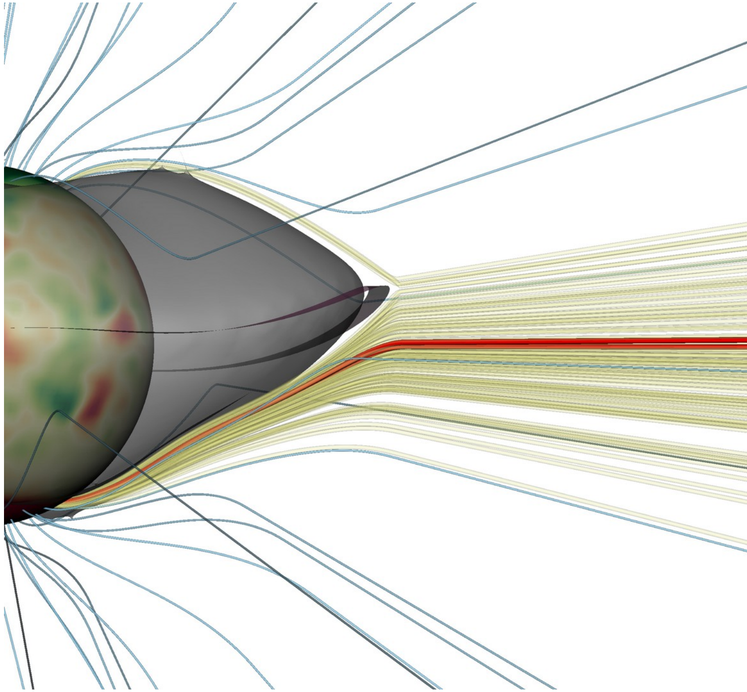
Solar wind speed and flux-tube geommetry



Pinto, Brun, Rouillard (2016)
Li, et al (2011)
Peleikis, et al (2016)

Solar wind speed and flux-tube geommetry





Pinto, Brun, Rouillard (2016)
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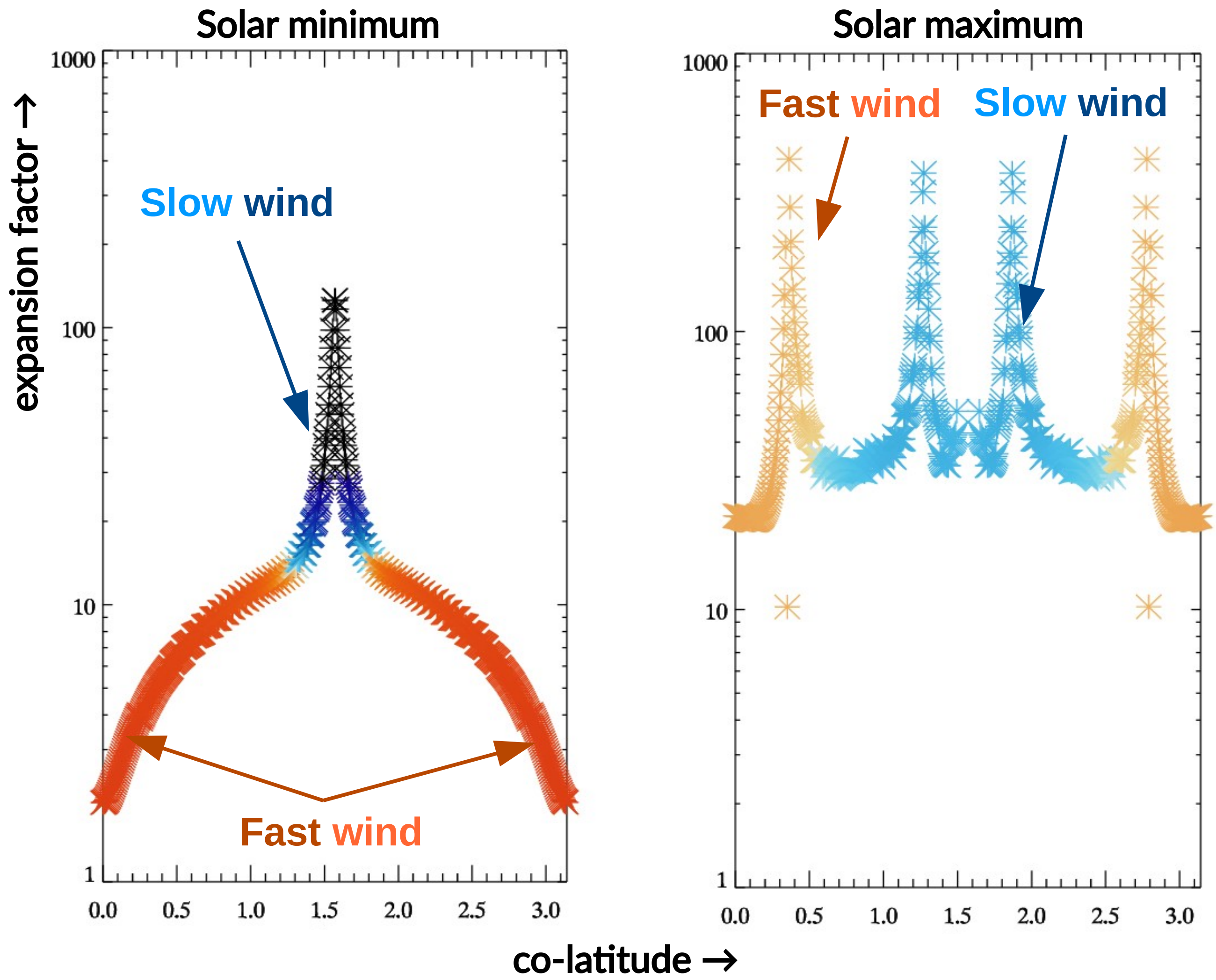
Solar wind speed and flux-tube geommetry



Flux-tube geometry:

- expansion profiles
- fieldline inclination

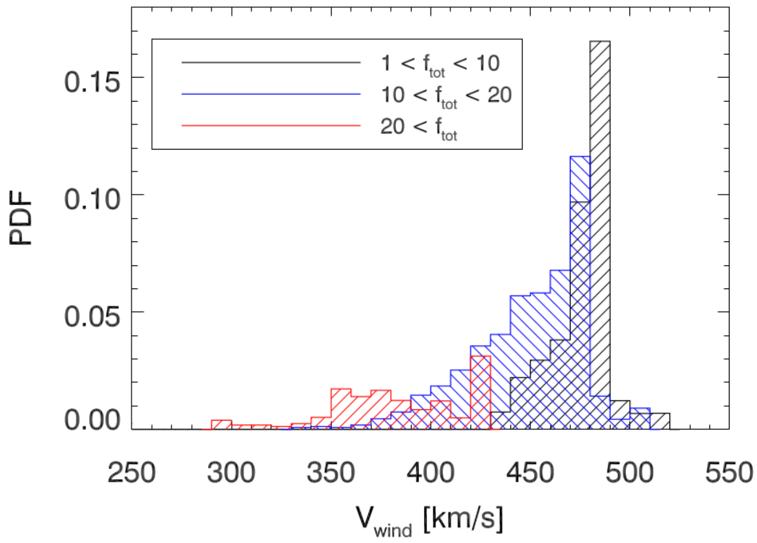
$$\partial_s v = \frac{v}{1 - M^2}\left[\frac{GM_\odot m_p}{2r^2 k_b T}\cos(\alpha) - \frac{1}{A}\partial_s A\right]$$

α: inclination angle
A: flux-tube cross-section

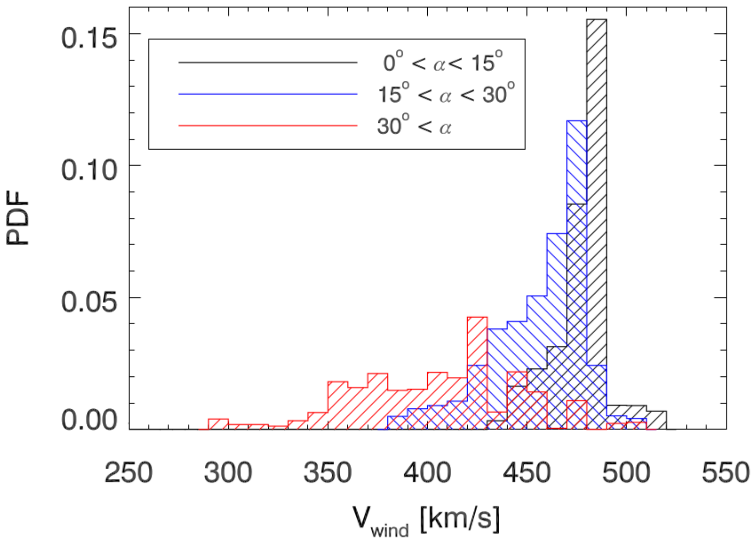
Pinto, Brun, Rouillard (2016)
Li, et al (2011)
Peleikis, et al (2016)

Solar wind speed and flux-tube geommetry

Speed - expansion factor



Speed - field-line inclination



Both flux-tube over-expansion and inclination influence the wind flow acceleration.

$$\partial_s v = \frac{v}{1 - M^2}\left[\frac{GM_\odot m_p}{2r^2 k_b T}\cos(\alpha) - \frac{1}{A}\partial_s A\right]$$

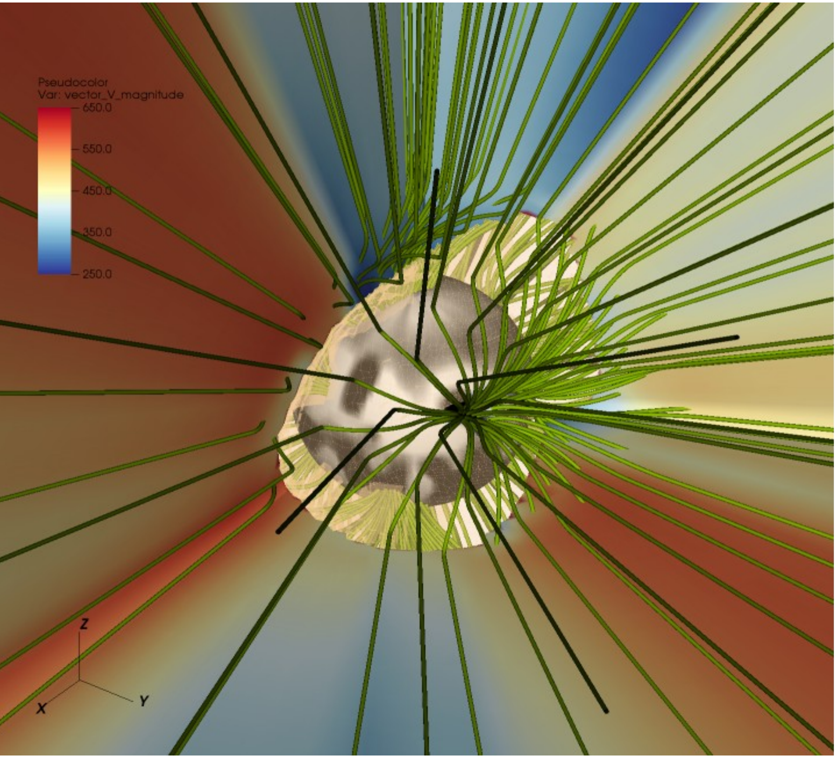
α: inclination angle

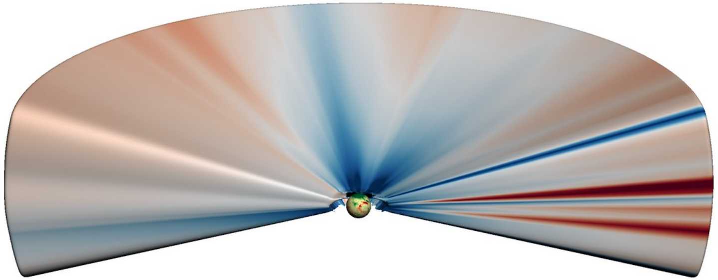
A: flux-tube cross-section

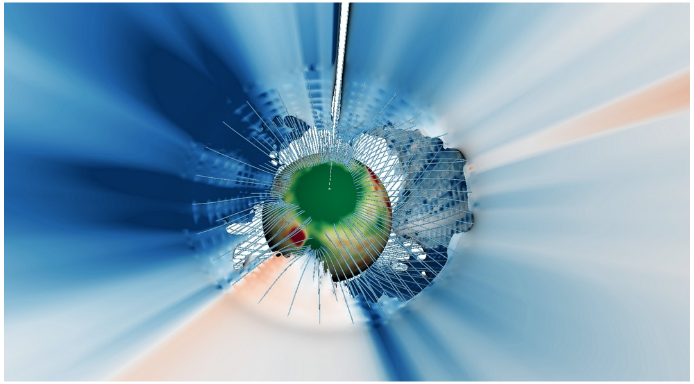
(Pinto, Brun, Rouillard, 2016;

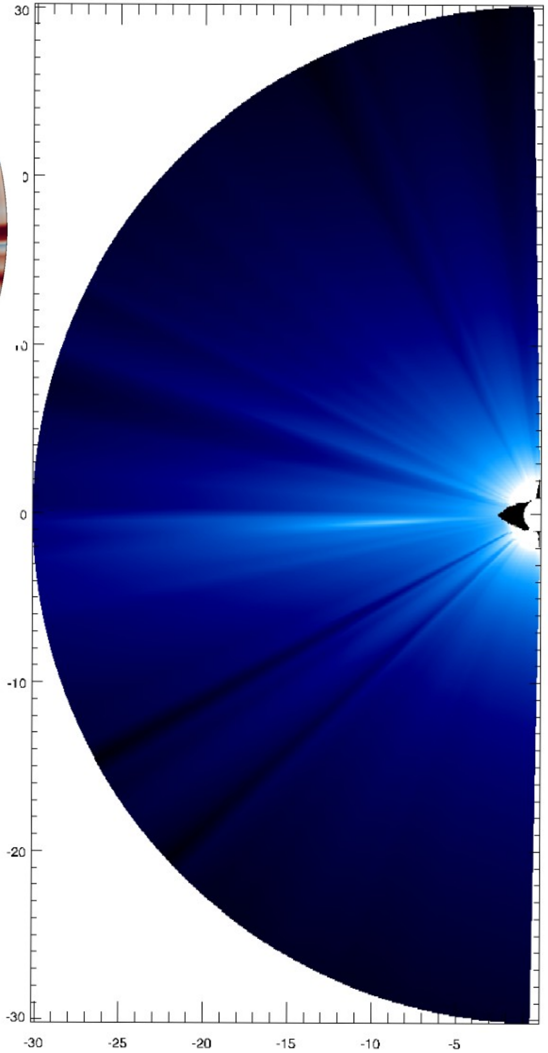
see also Li, et al., 2011, Lionello, et al., 2014)

MULTI-VP solar wind model





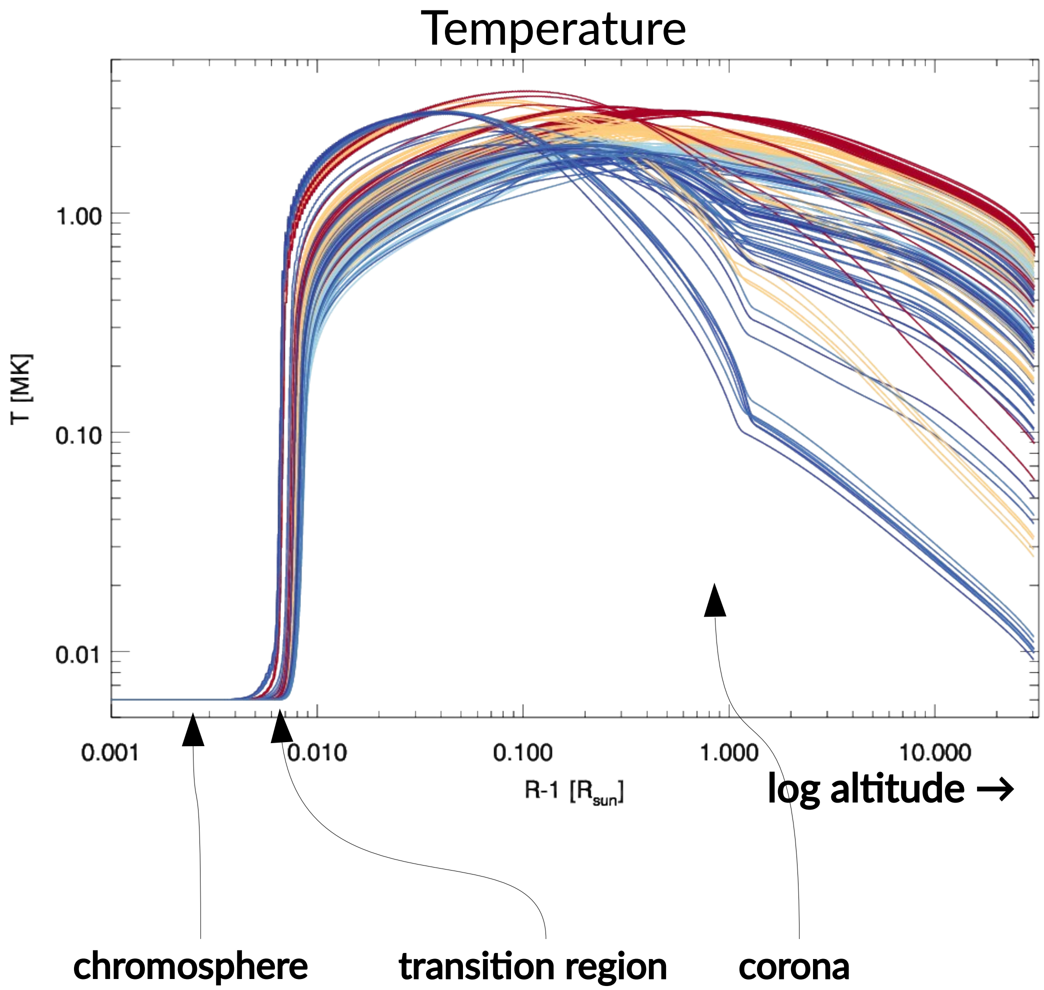


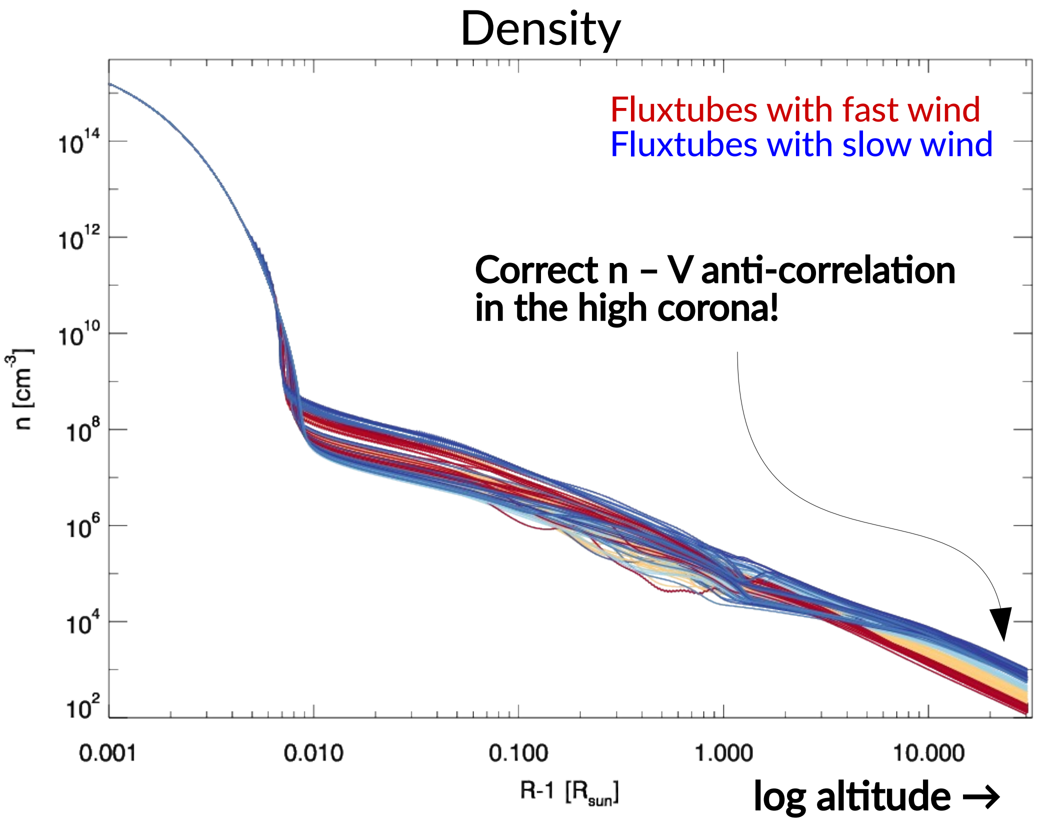


Solar wind speed (250 – 650 km/s)
Surface mag. field (neg. – pos. polarity)

MULTI-VP:
data-driven background solar wind model, physics-based (heating, radiative losses, conduction; Pinto, Rouillard, 2017)

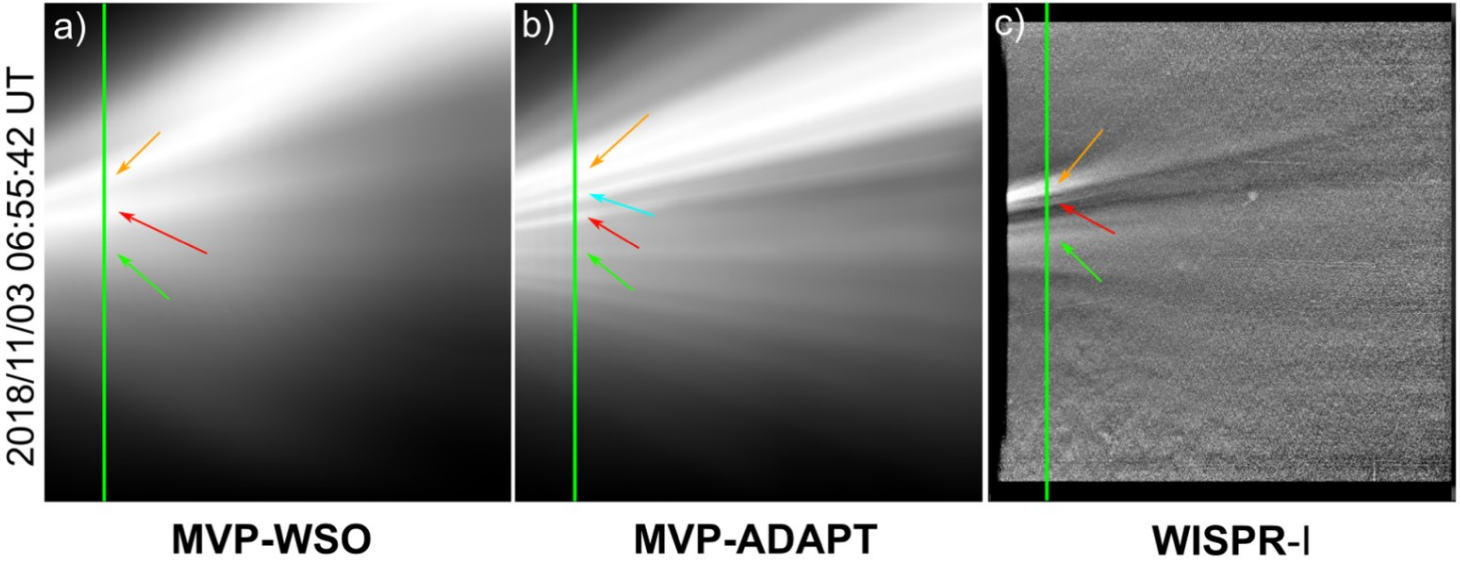
MULTI-VP solar wind model





Pinto, Rouillard, ApJ (2017)

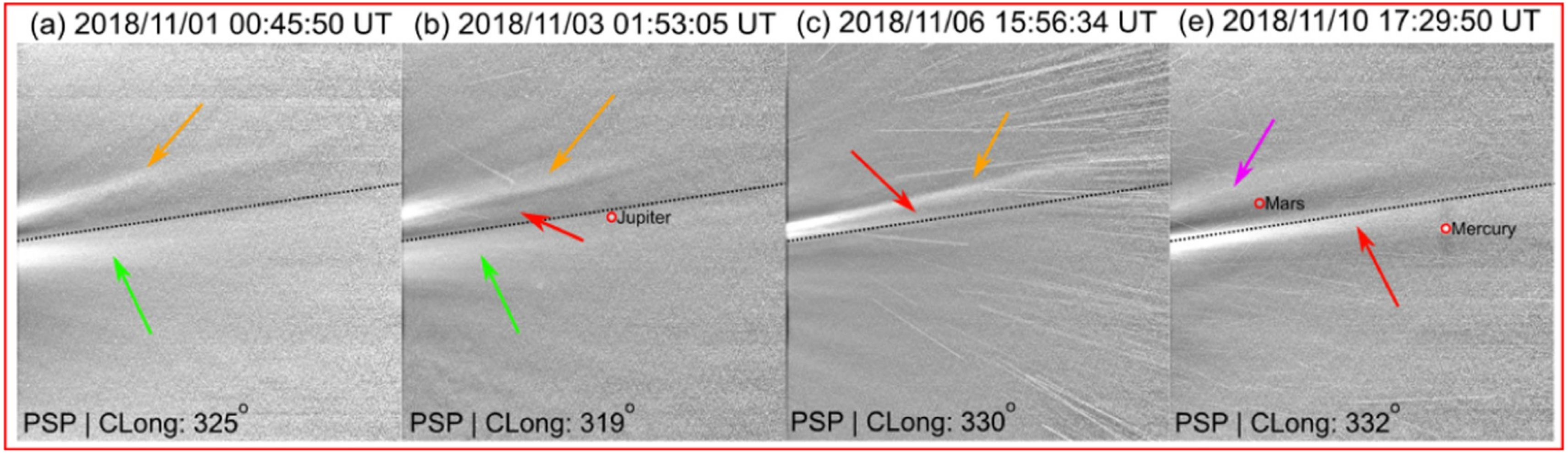
PSP E01, MULTI-VP synthetic WISPR FoV



Synthetic MULTI-VP white-light

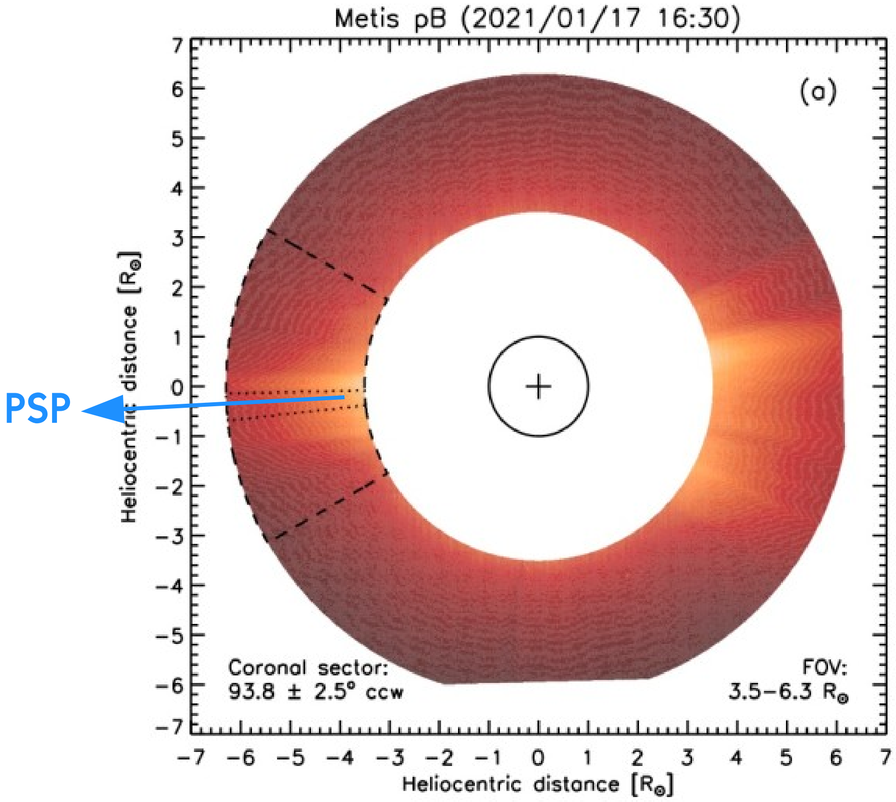
Parker Solar Probe/WISPR FoV

(Poirier et al, 2020)

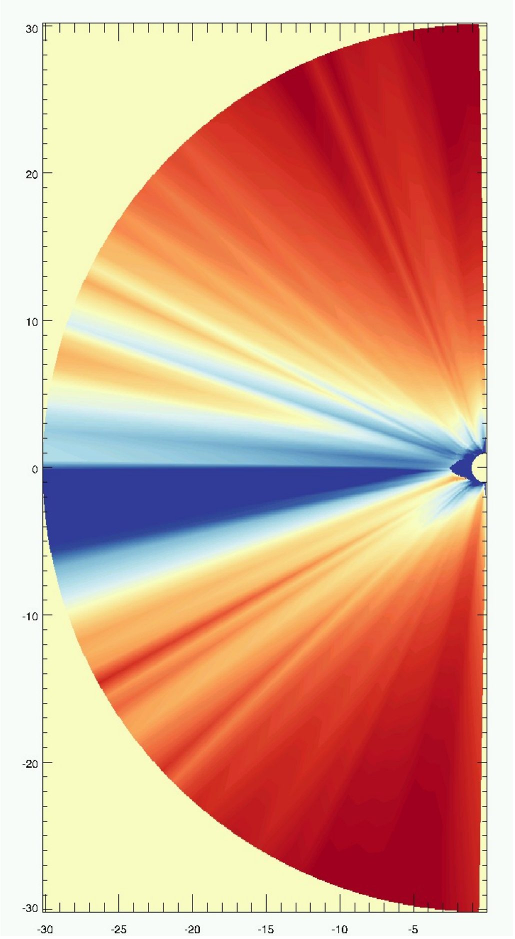


SO/PSP quadrature event 01/2021

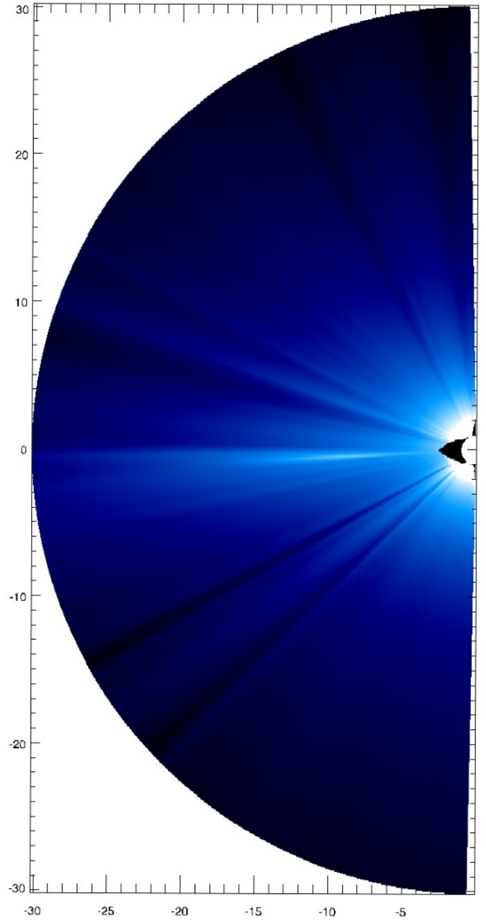
PSP / Solar Orbiter quadrature (Jan 2021)



Wind speed



log(density)

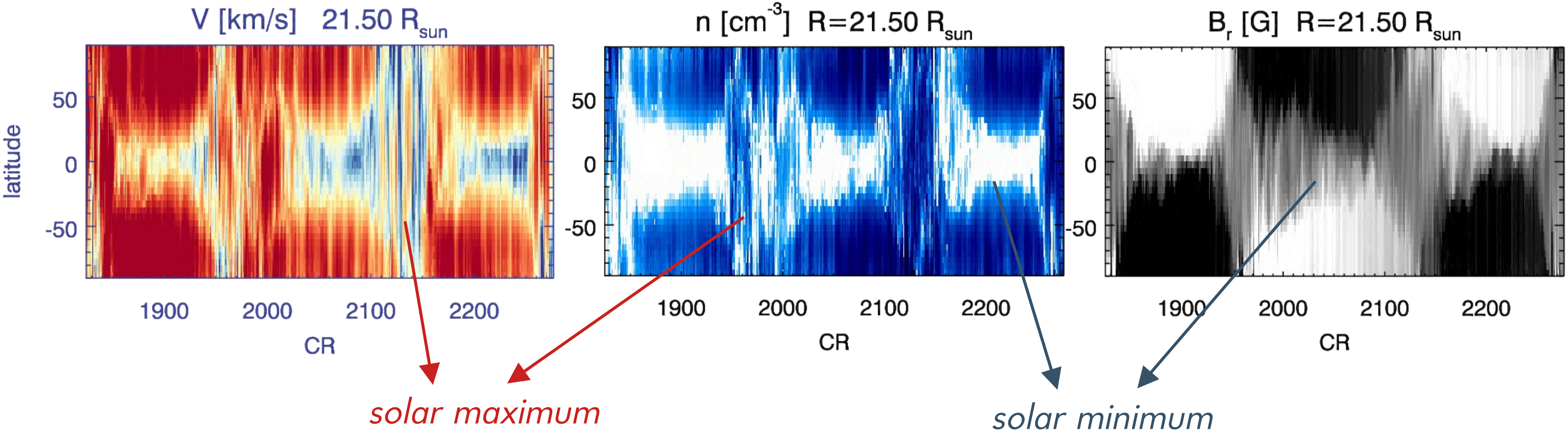


(Pinto et al, in prep.)

MULTI-VP solar wind model

Long time-series of full MULTI-VP runs
based on WSO synoptics maps

Latitude – time (Carrington rotation) maps of V, n and B at 0.1 AU



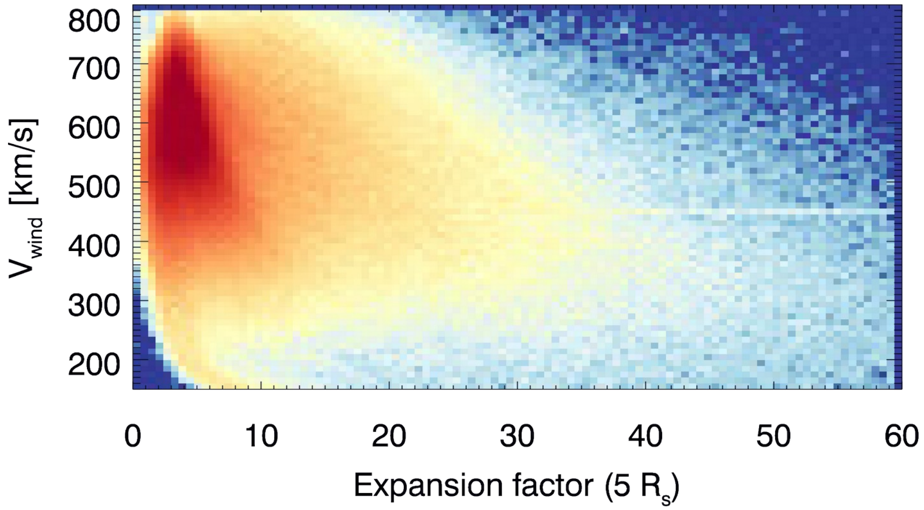
(Pinto, et al, *in prep;* cf. IPS surveys Tokumaru et al 2021; Finley, et al 2023; UVCS butterfly diagrams by Bemporad et al, 2025)

MULTI-VP: a new look at the expansion vs. speed issue

All MULTI-VP runs (1996 to 2023)

(all latitudes and longitudes)

Wind speed at 0.1 AU vs. f_{exp} at 5 R_{sun}



→ no anti-correlation b/w speed and expansion factor

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All MULTI-VP runs (1996 to 2023)

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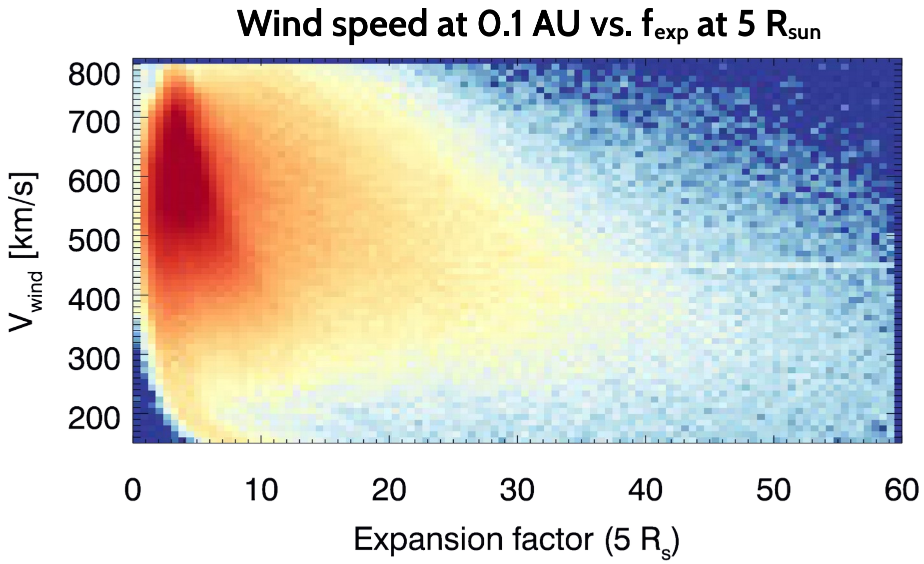

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PCA analysis of MULTI-VP profiles suggests that field-line inclination is a strong predictor of solar wind flow type, confirming previous theory-based work (Barros, et al, 2025; Façoso et al, 2025)

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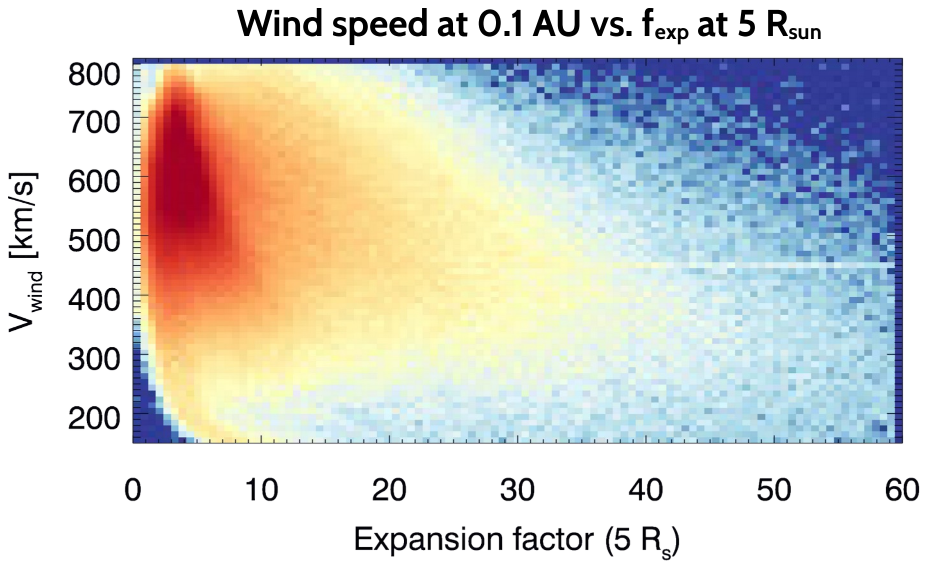

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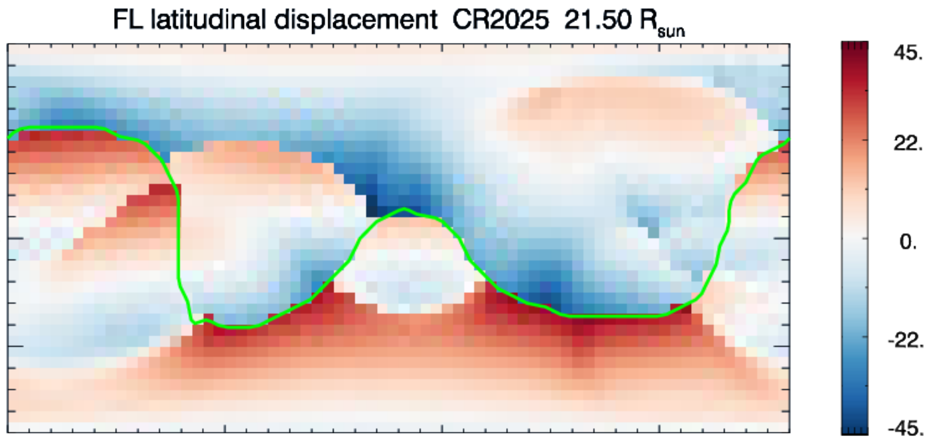
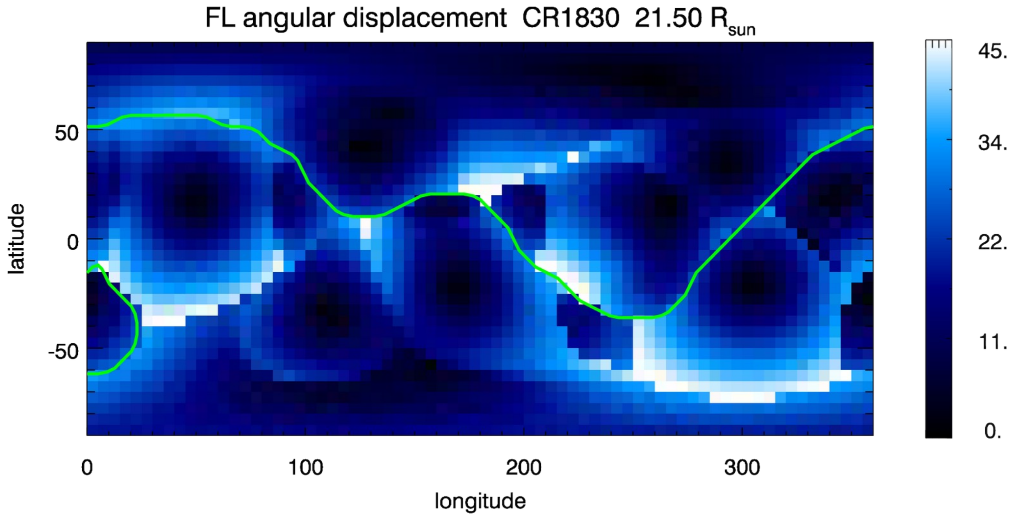
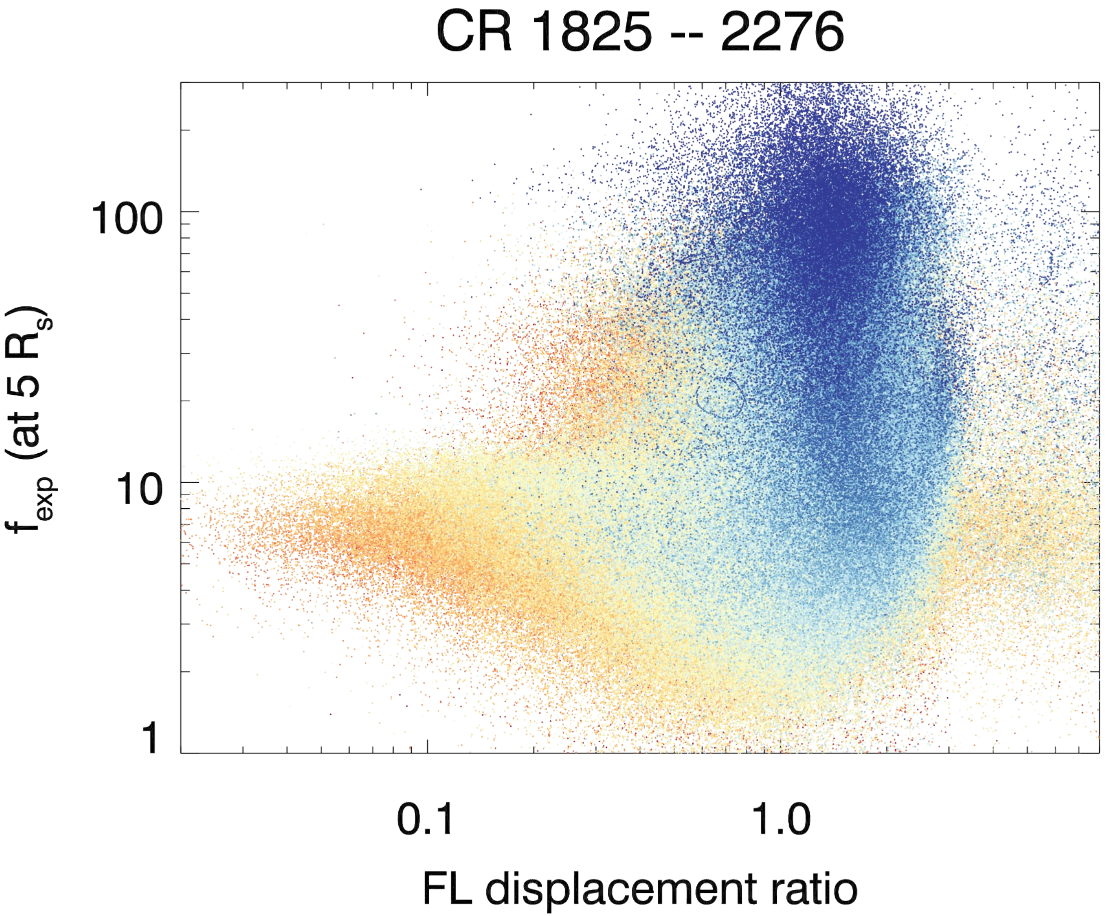




MULTI-VP: a new look at the expansion vs. speed issue

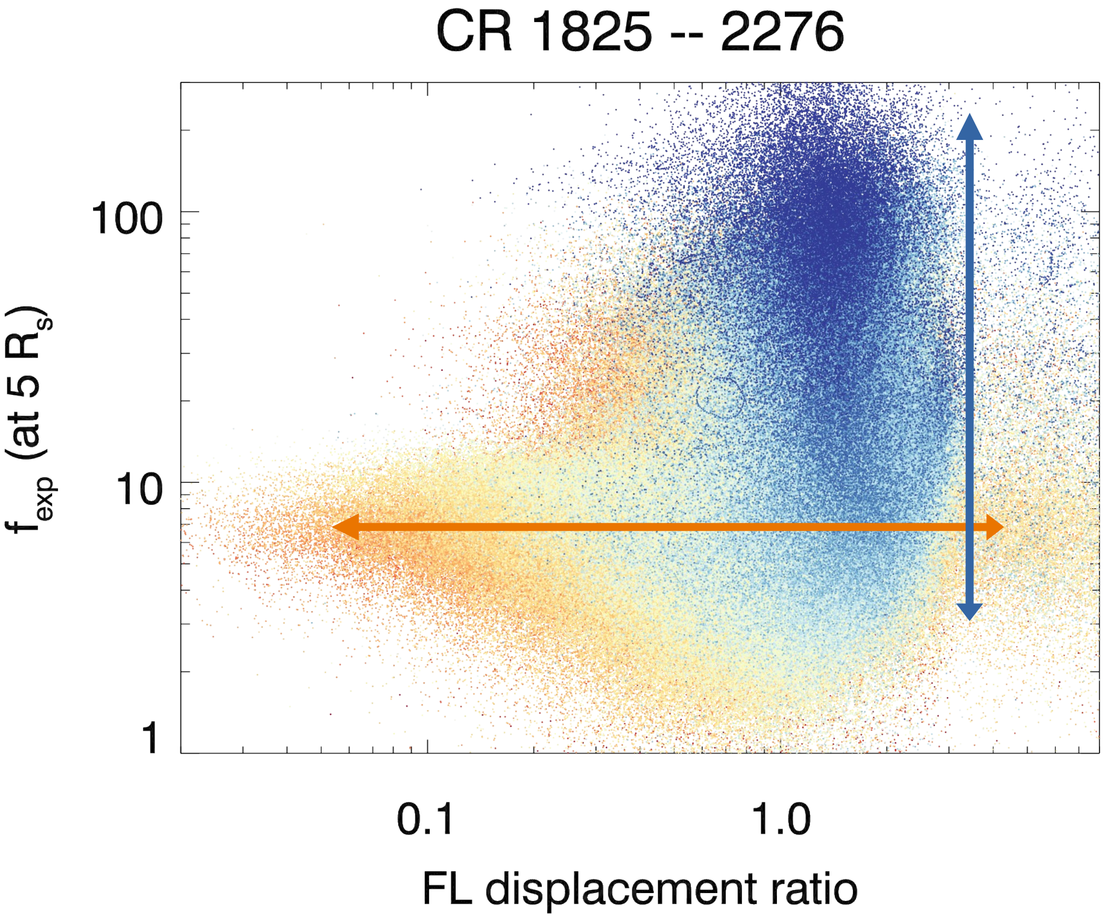


Standard expansion factor f_{exp}

Total cumulated transverse field-line deviation
(normalised by radial coordinate)

Colour scale: wind speed (200 – 800 km/s)

MULTI-VP: a new look at the expansion vs. speed issue



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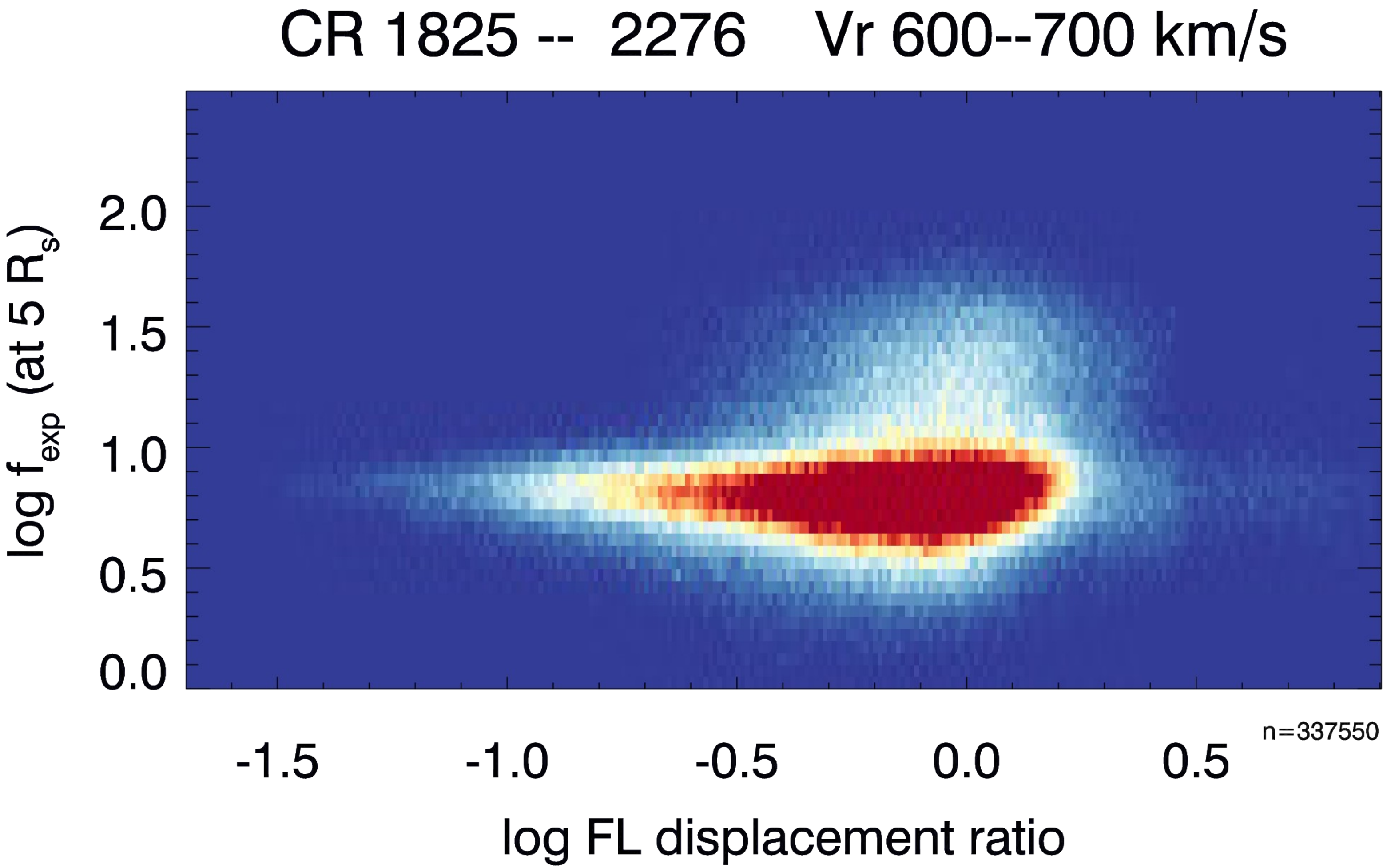
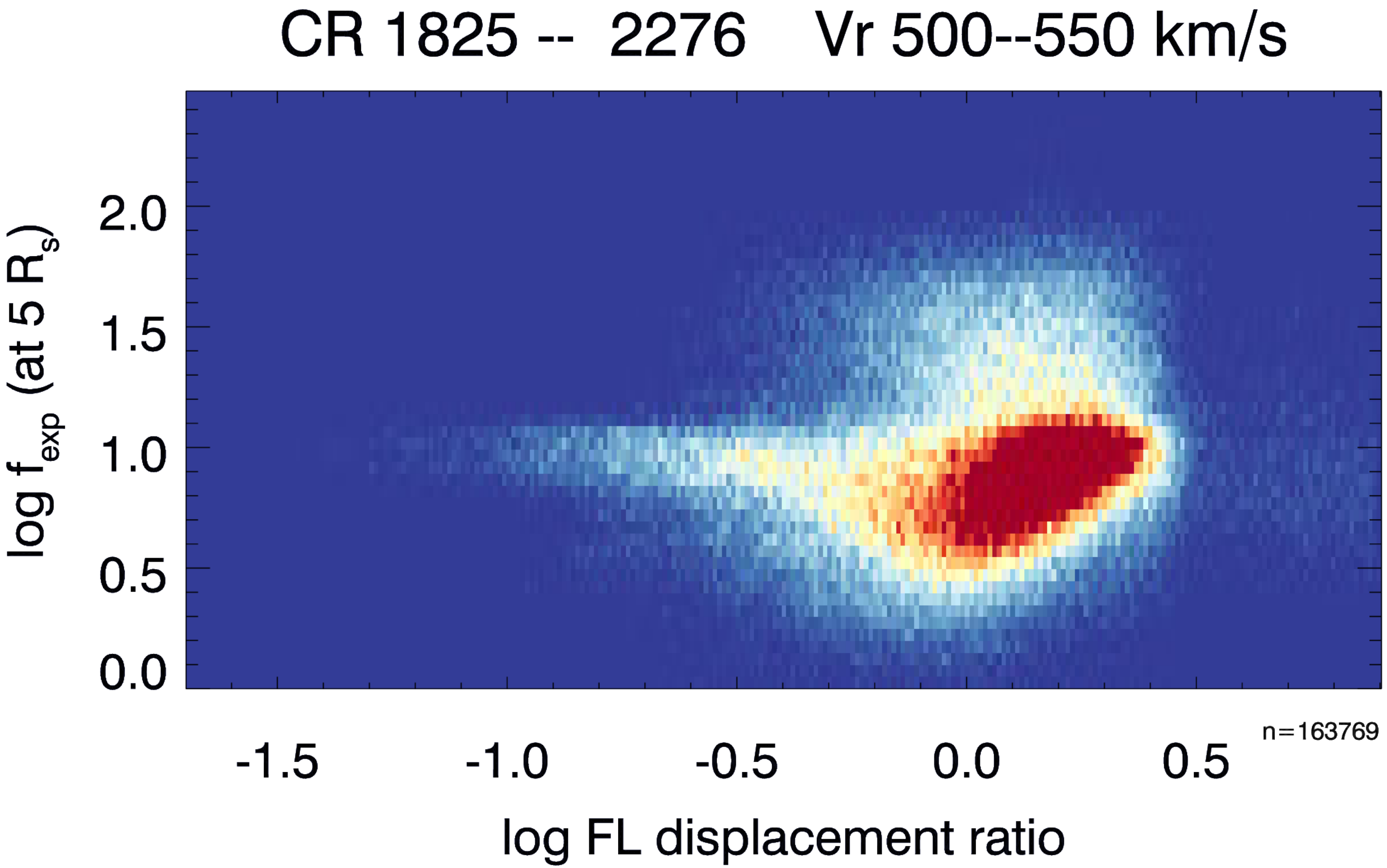


Only very **fast wind**:

- most points align horizontally

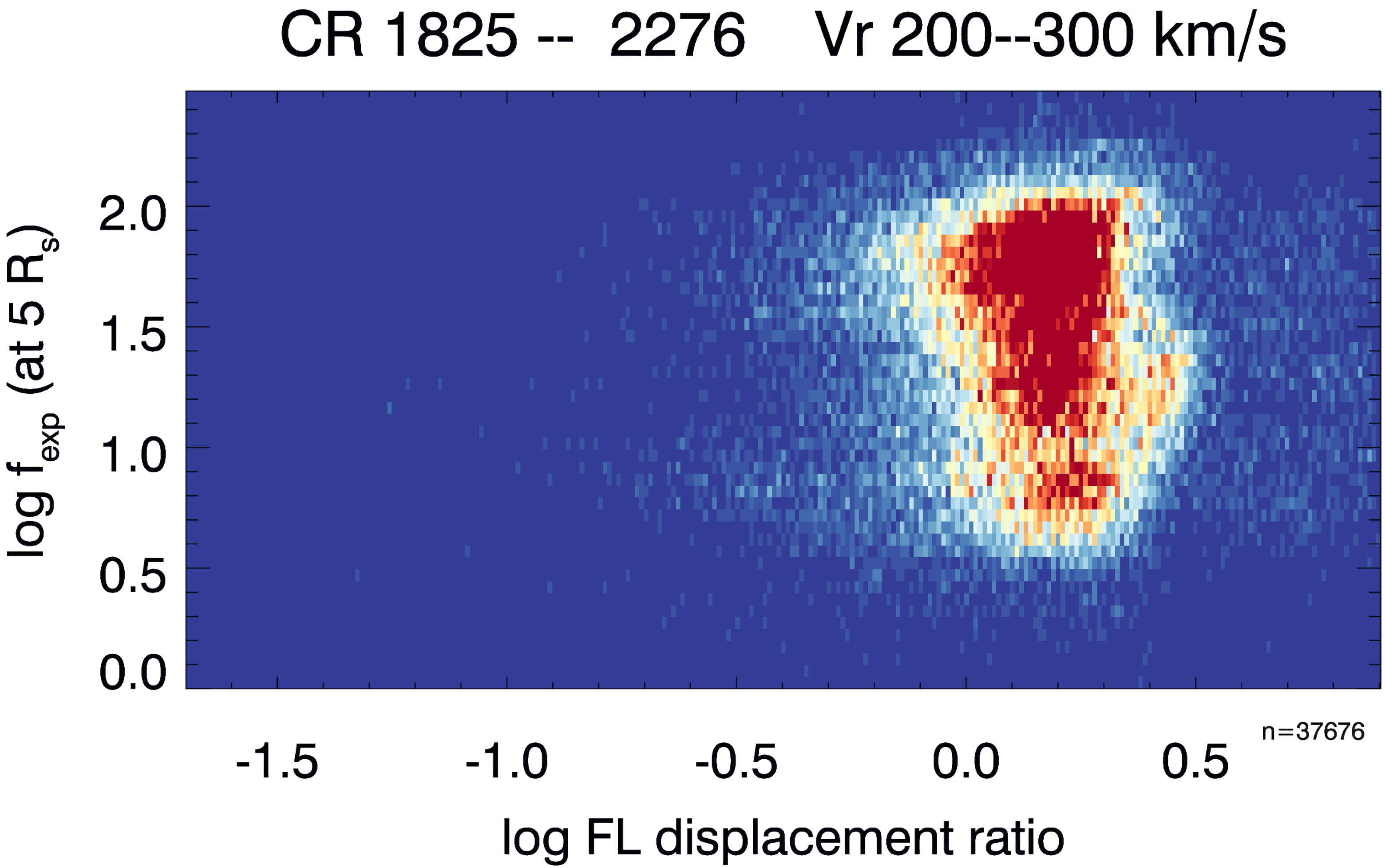
- **f_{exp} more predictive of solar wind speed**

MULTI-VP: a new look at the expansion vs. speed issue



Moderate wind speeds

MULTI-VP: a new look at the expansion vs. speed issue

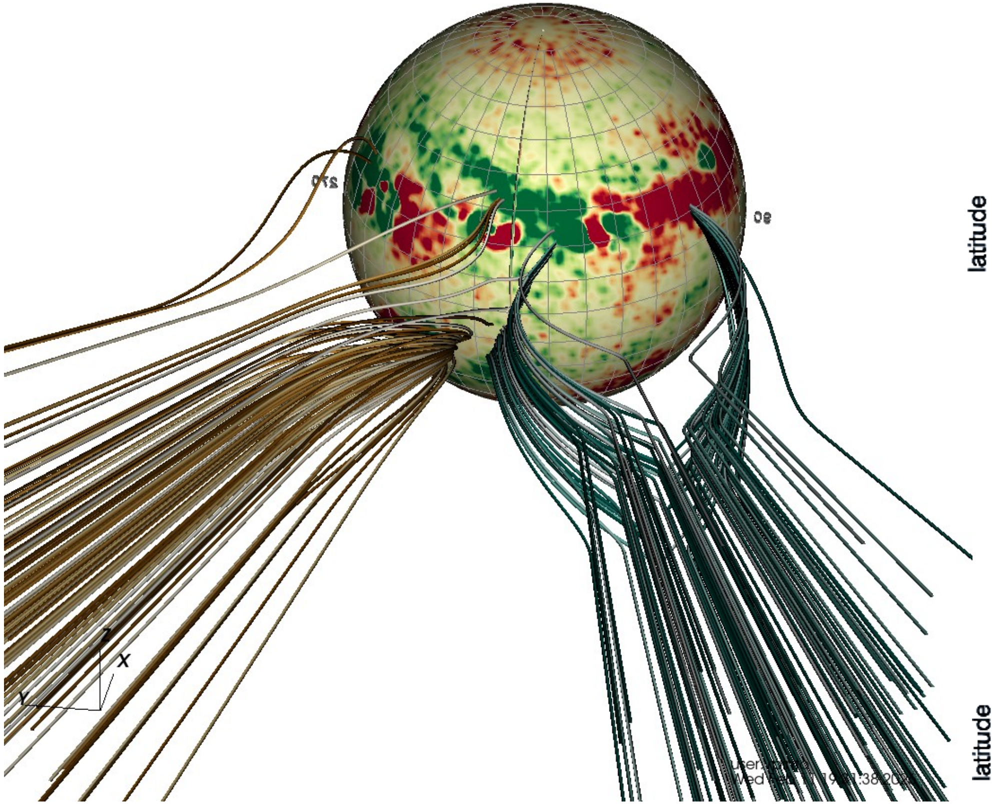


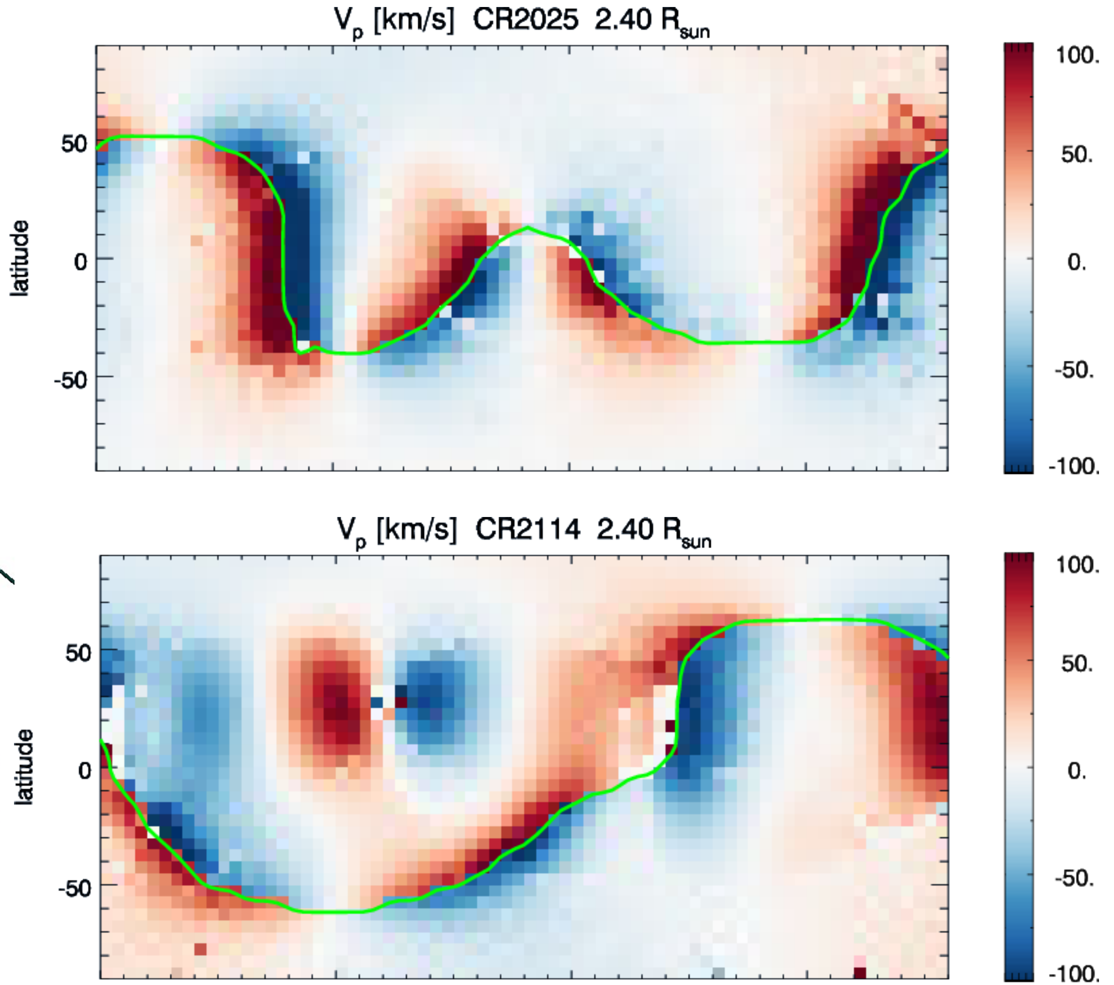
Only very **slow wind**:

- most points align vertically

- **inclination/field line displacements more predictive of wind speed**

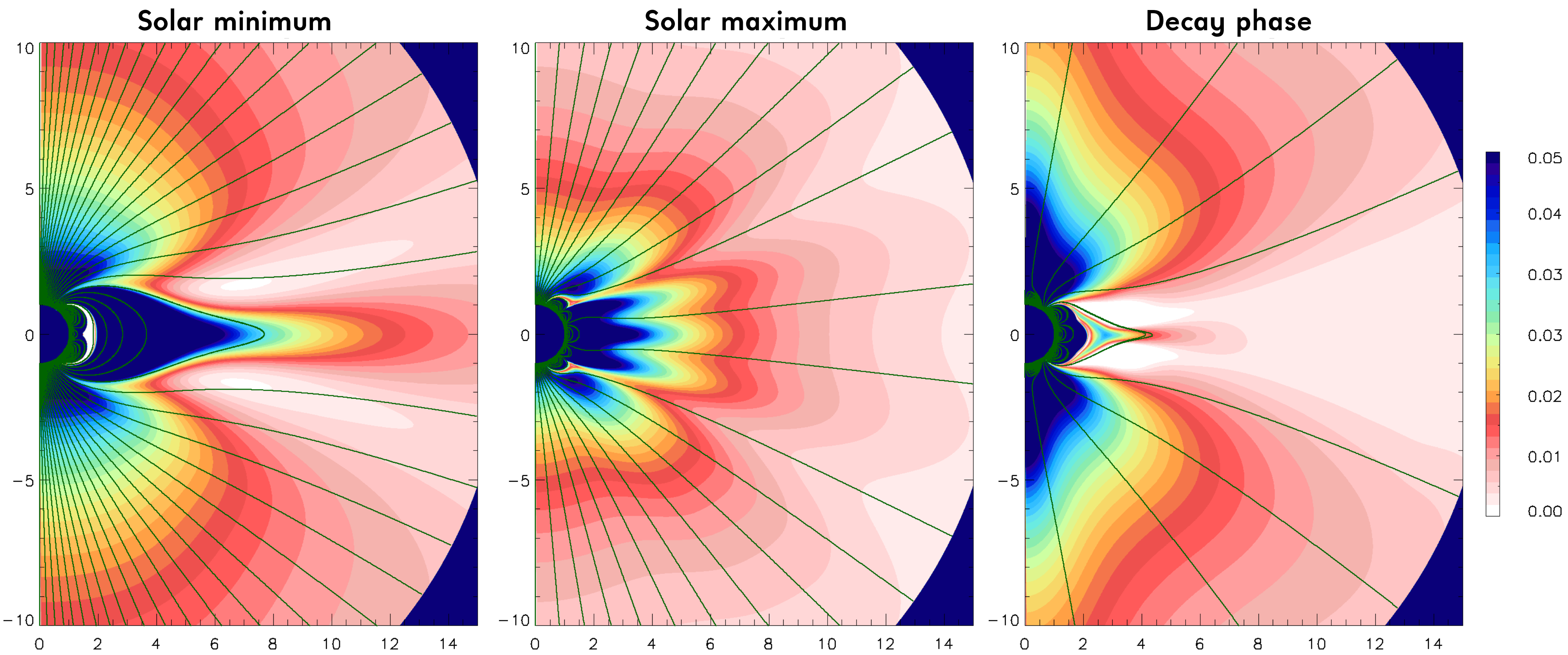
Coronal topology and azimuthal flows





→ Some wind flows are accelerated **backwards** or **forwards** in respect to the **global rotation direction**

Rotation rate, full solar corona



Coronal rotation ≠ surface rotation

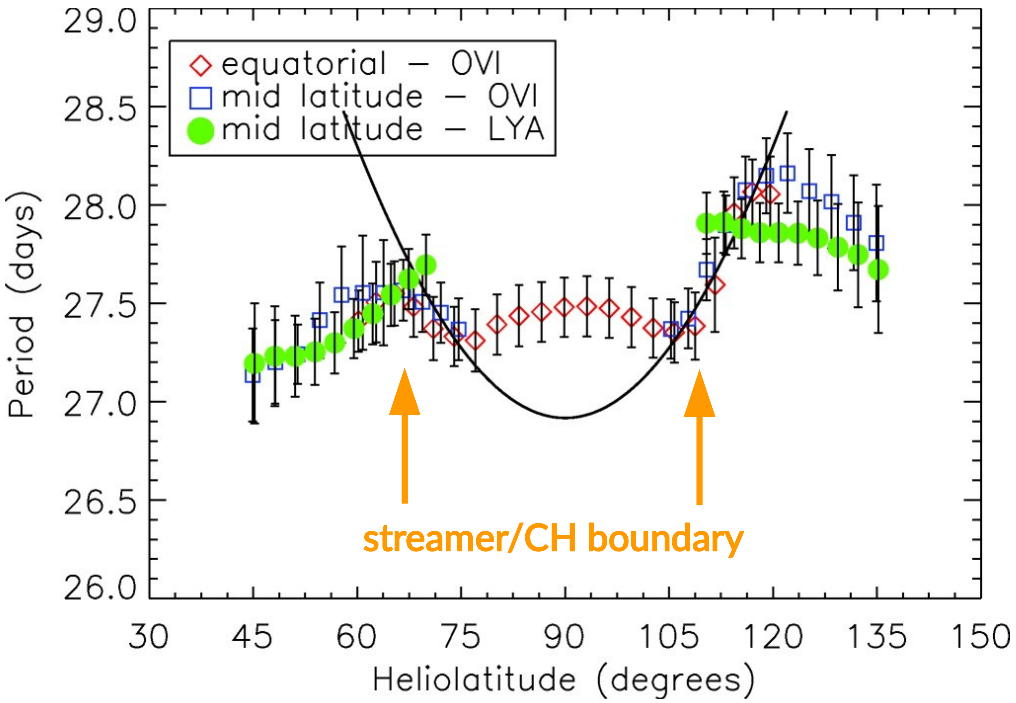
Enhanced shear at CH boundaries

Fast / slow rotation

Rotation rate Ω(r, θ)
(normalised units)

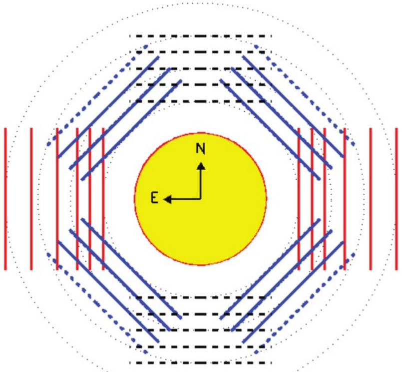
(Pinto, et al, A&A 2021; doi:10.1051/0004-6361/202040180)

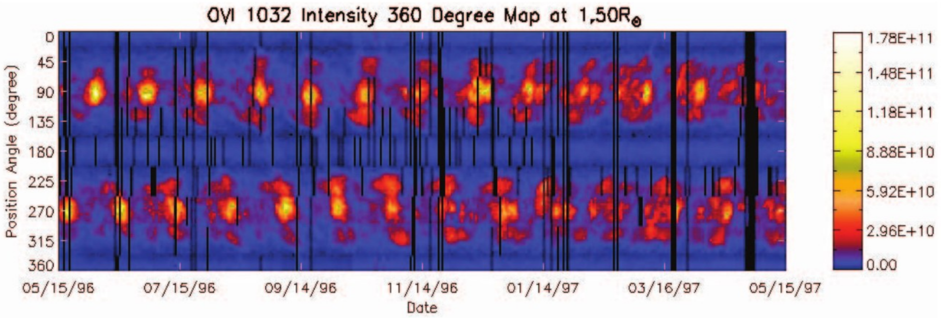
Differential rotation in the corona, observations

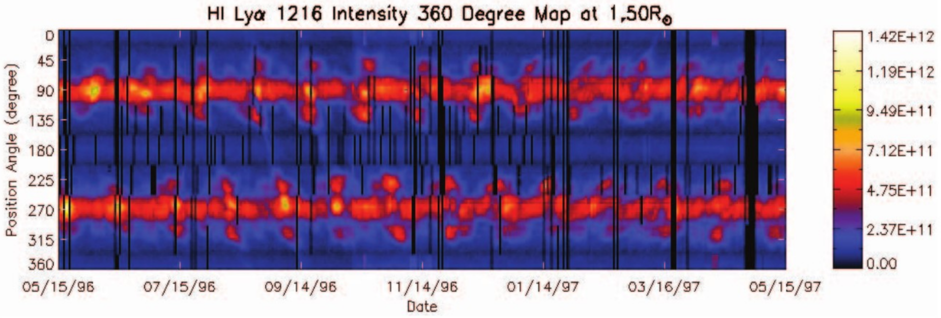


UVCS derived rotation periods (at 1.5 R_{sun}), solar minimum

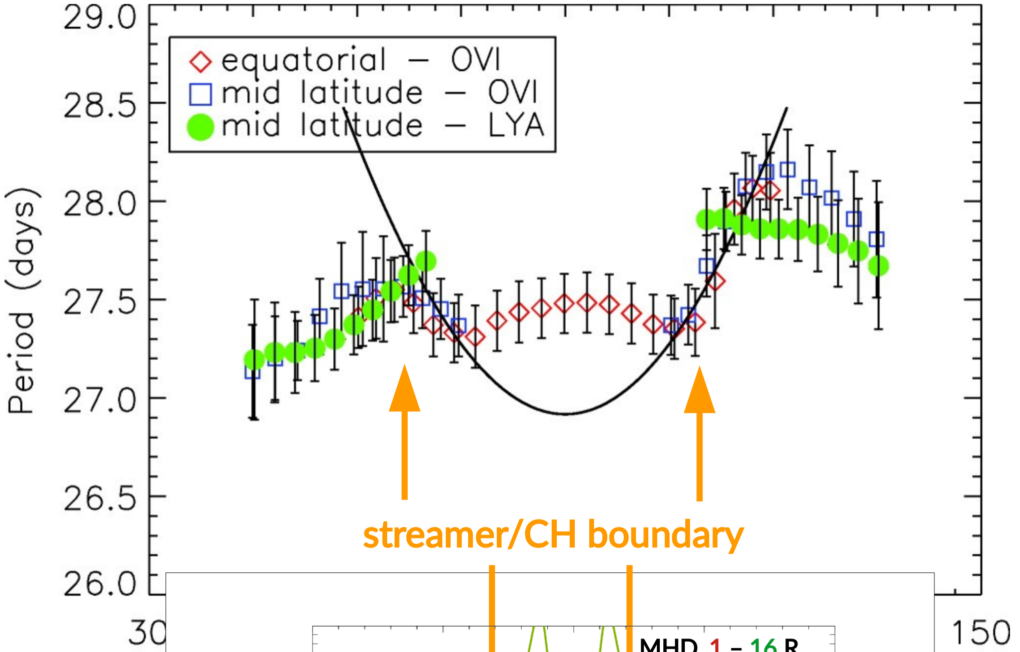
(Giordano & Mancuso, ApJ 2008)

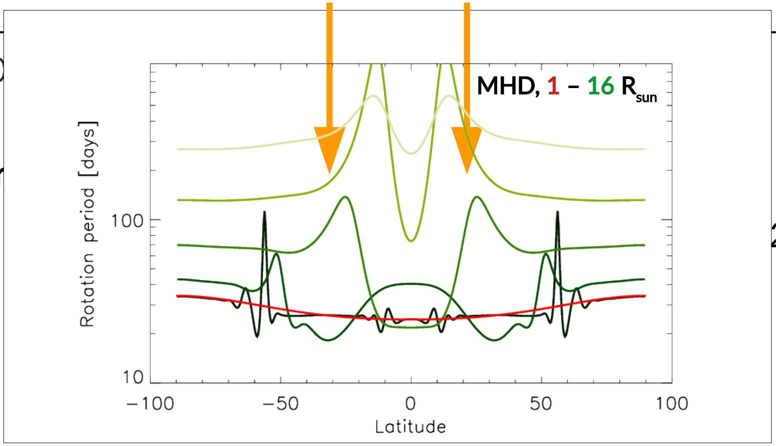






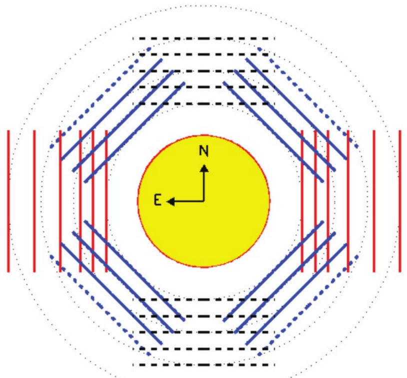
Differential rotation in the corona, observations

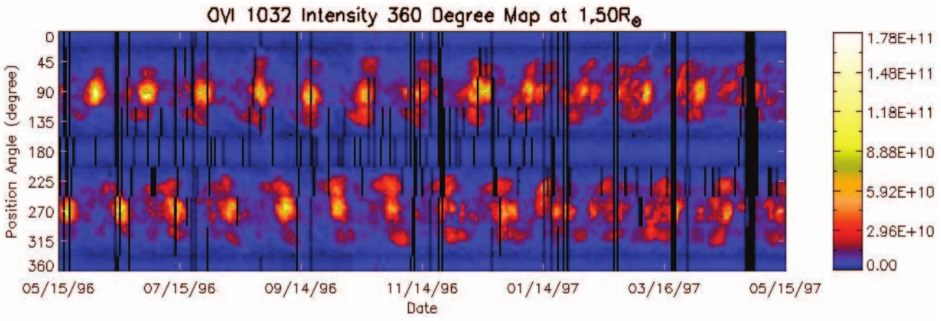


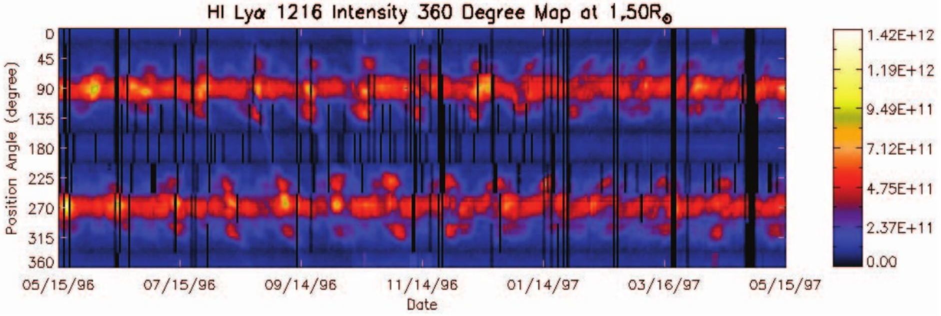


UVCS der

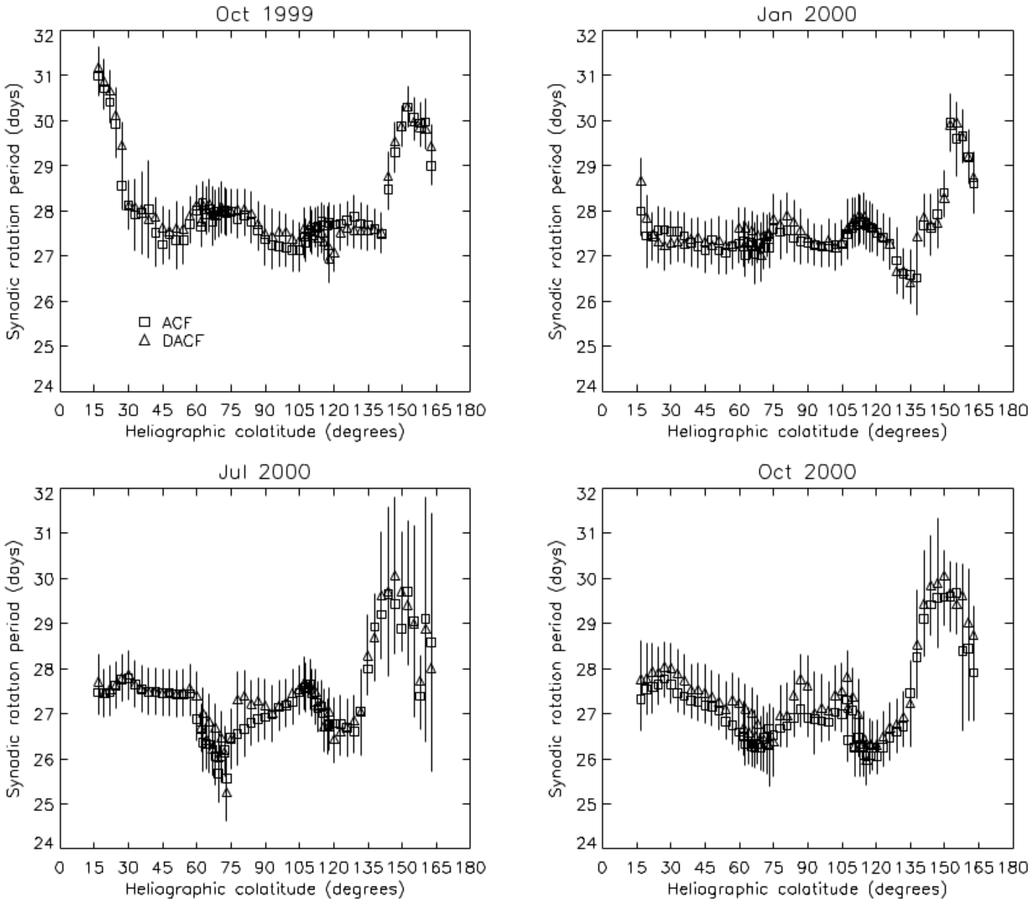
2008)

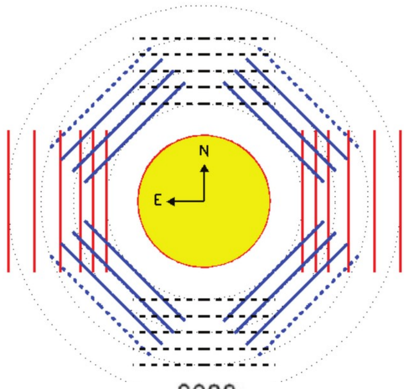


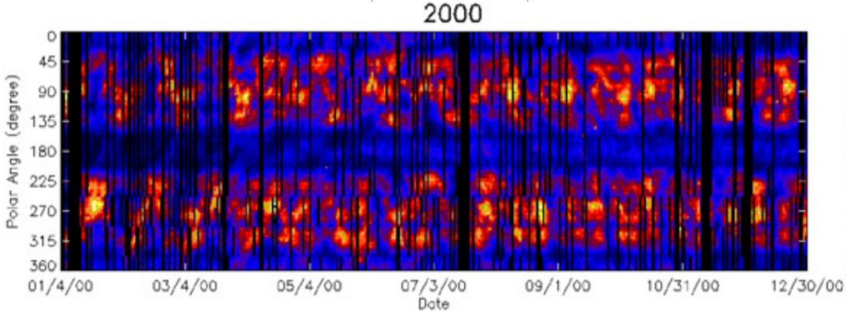


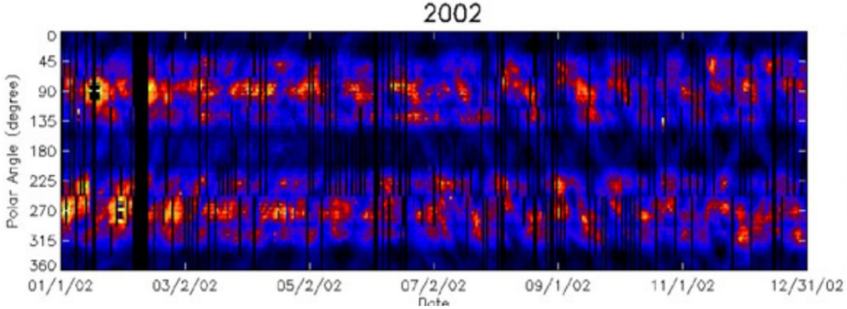


Differential rotation in the corona, observations





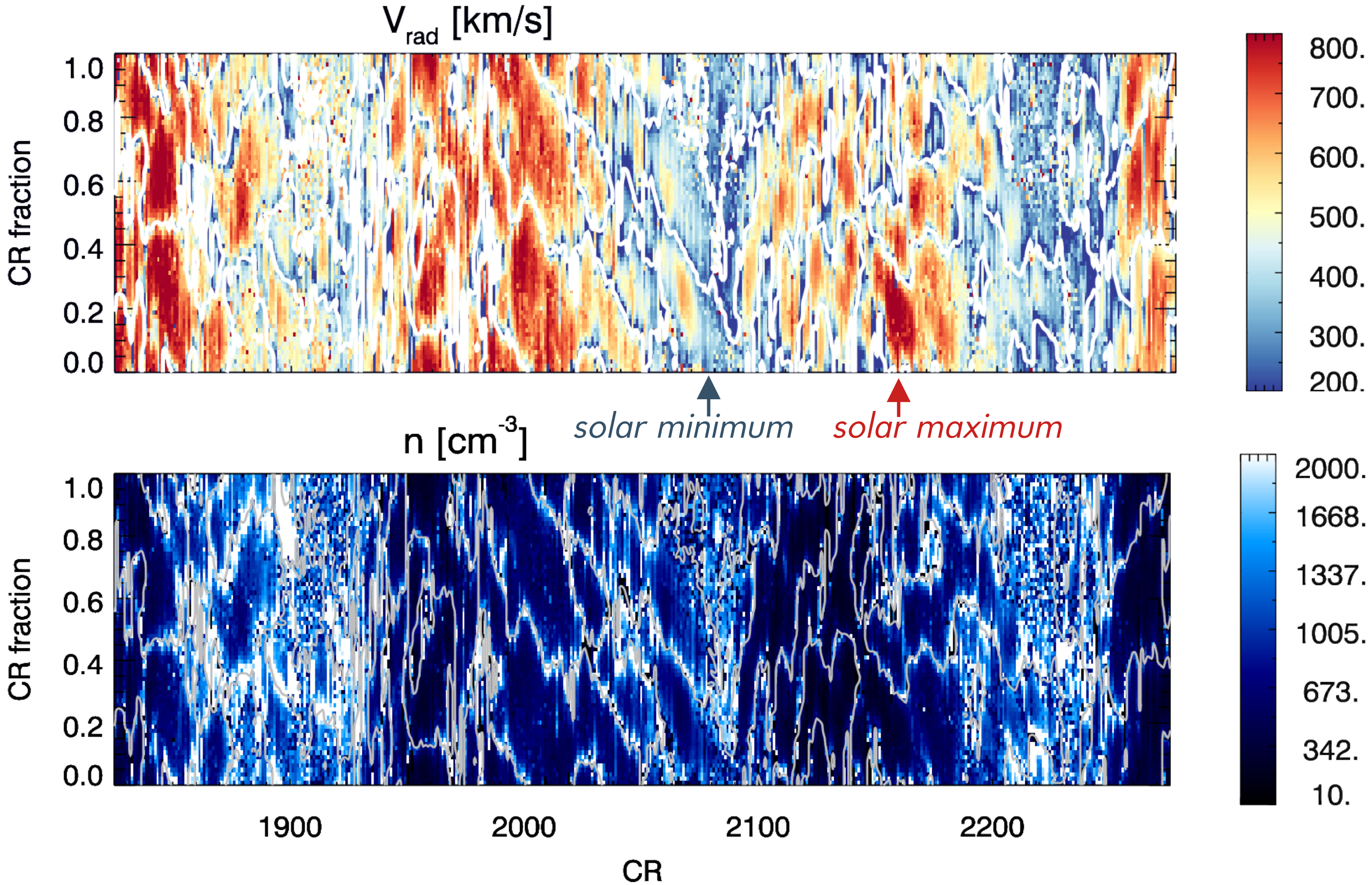




UVCS derived rotation periods (at 1.5 R_{sun}), solar maximum

(Mancuso & Giordano, ApJ 2011)

Earth-directed solar wind



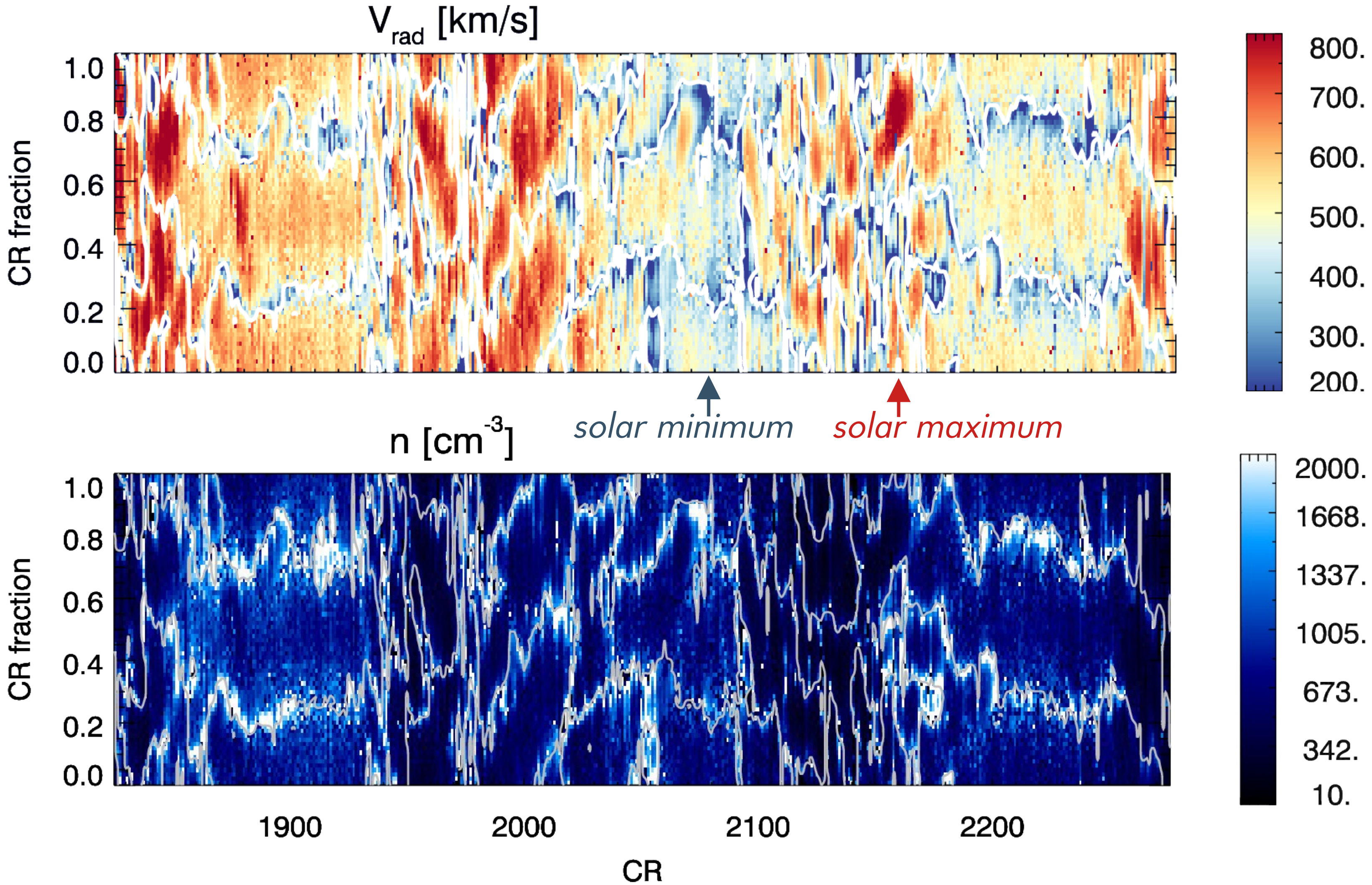
CR stackplots

y: CR progression
x: time

Light grey lines: polarity reversals

(cf. Luhmann et al, 2023; stackplots with OMNI data)

Off-ecliptic orbit (30 deg)



CR stackplots

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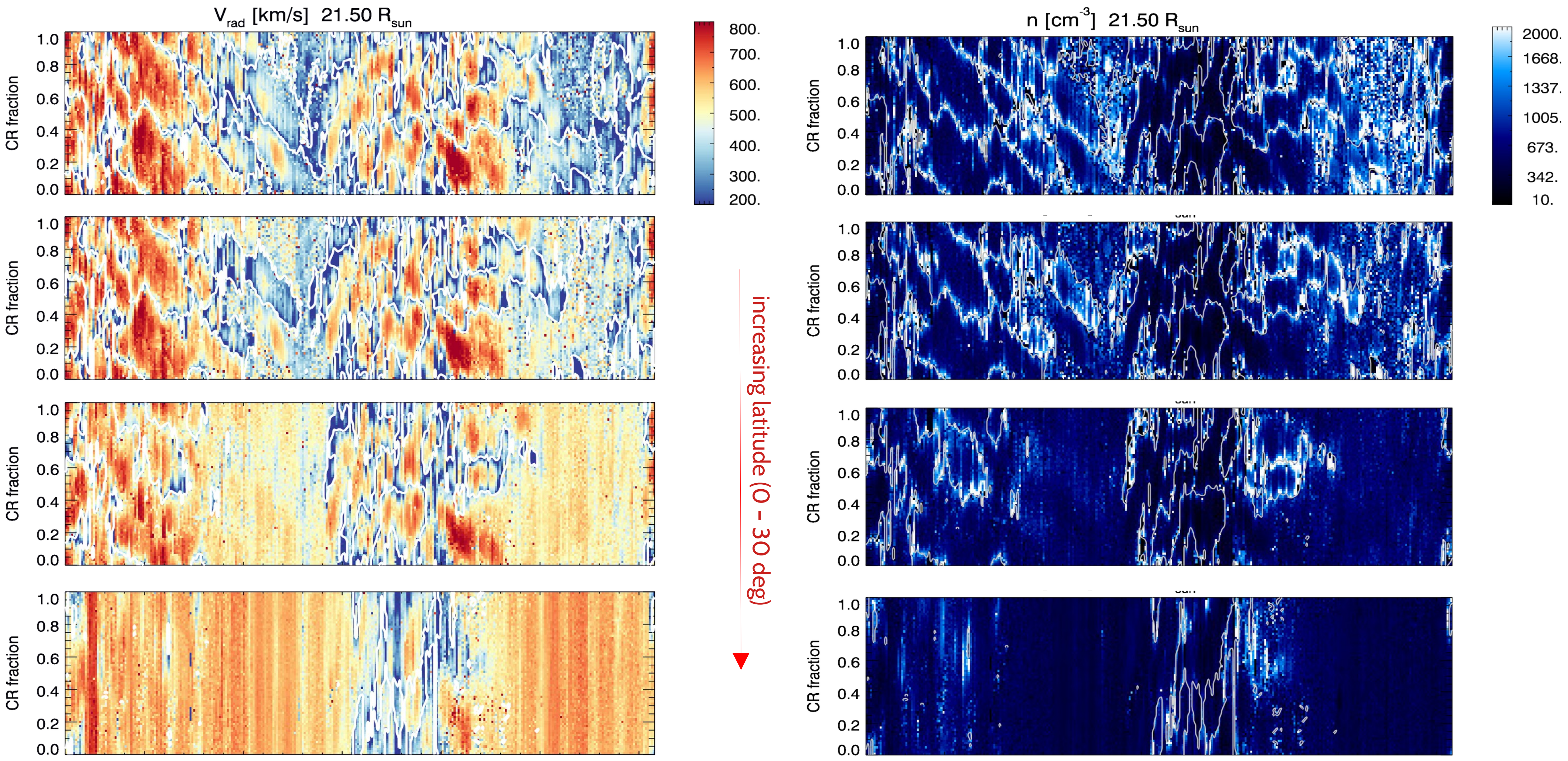
Solar wind and density, varying latitudes



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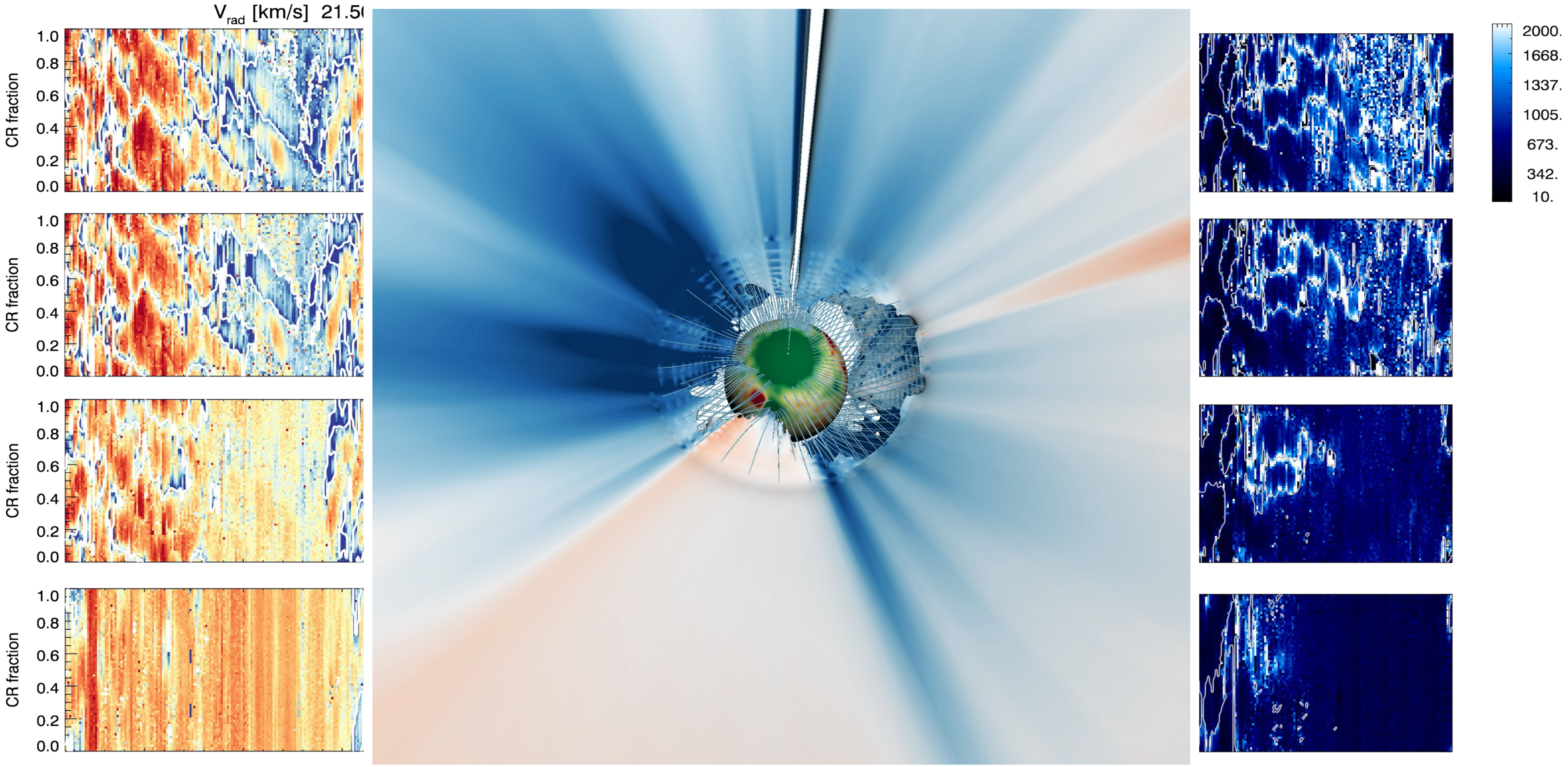
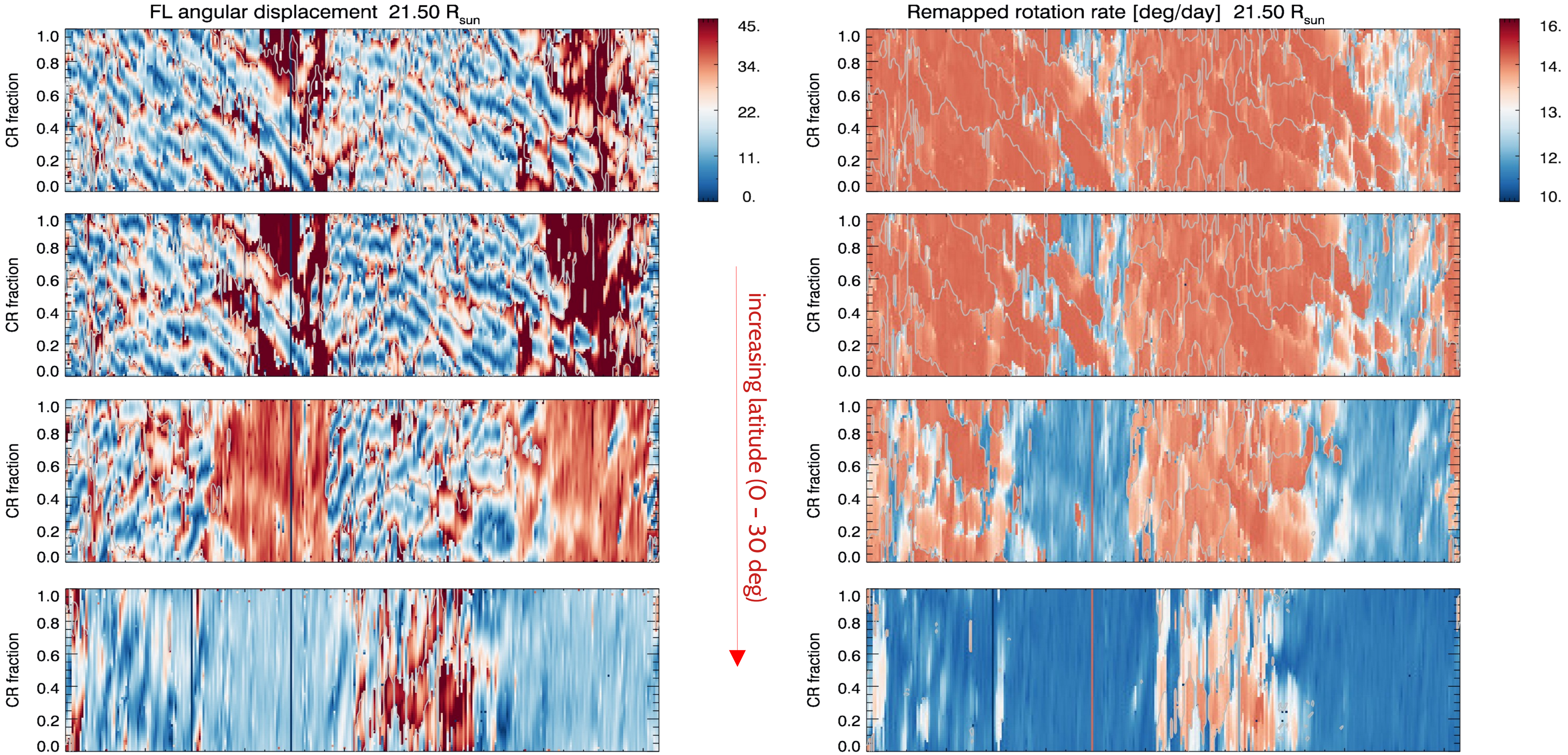
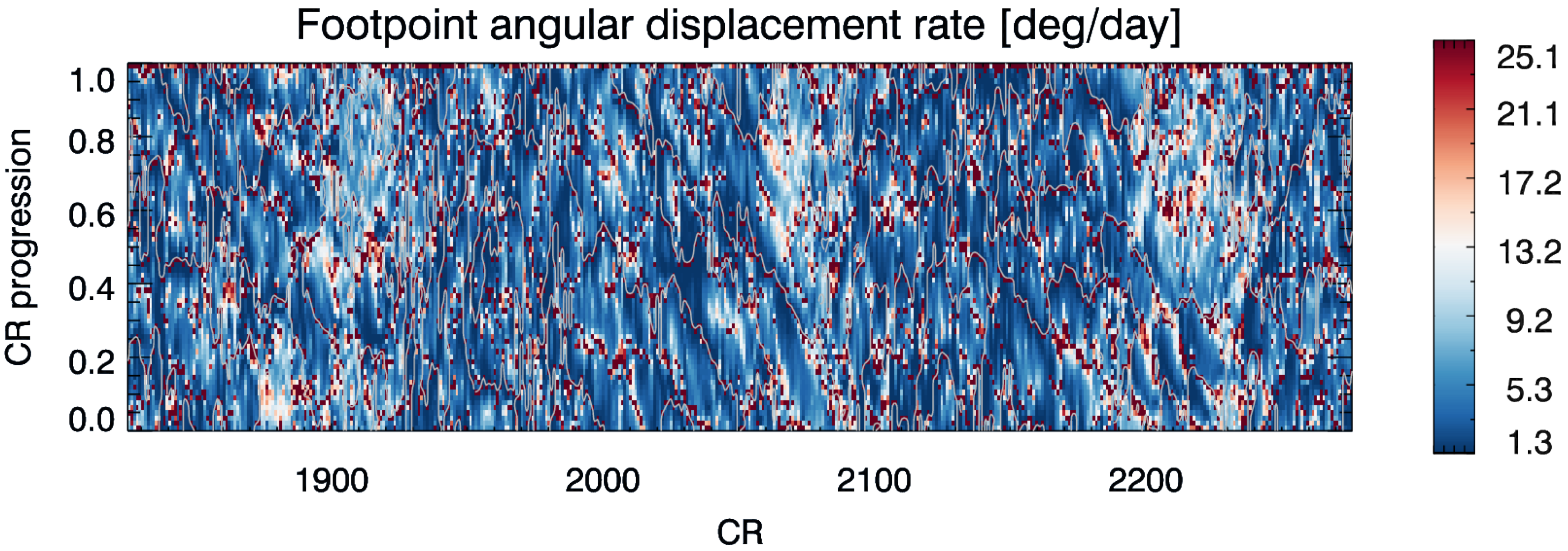


Surface to corona angular displacement, varying latitudes



Connectivity switches

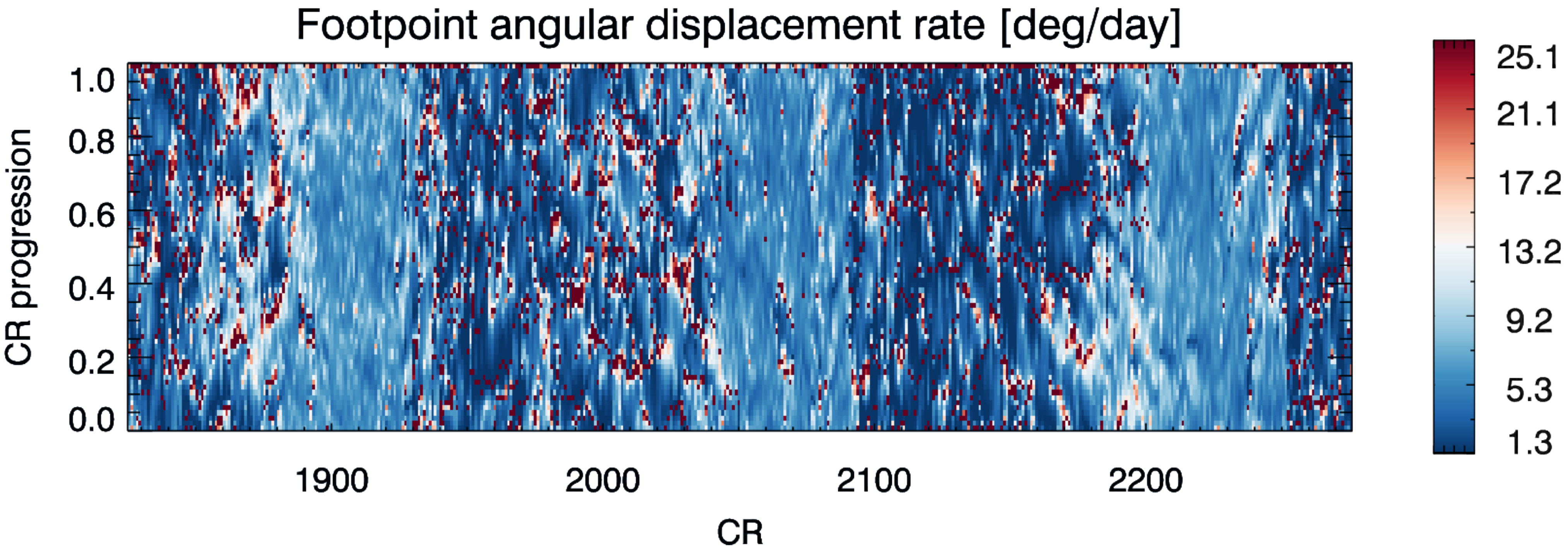


Connectivity switches

Rate of angular displacement of footpoints/solar wind sources.
Grey lines: magnetic polarity reversals (HCS crossings).

Large connectivity jumps occur frequently **away from the HCS** (switches b/w same polarity CH, pseudo-streamers)

Connectivity switches



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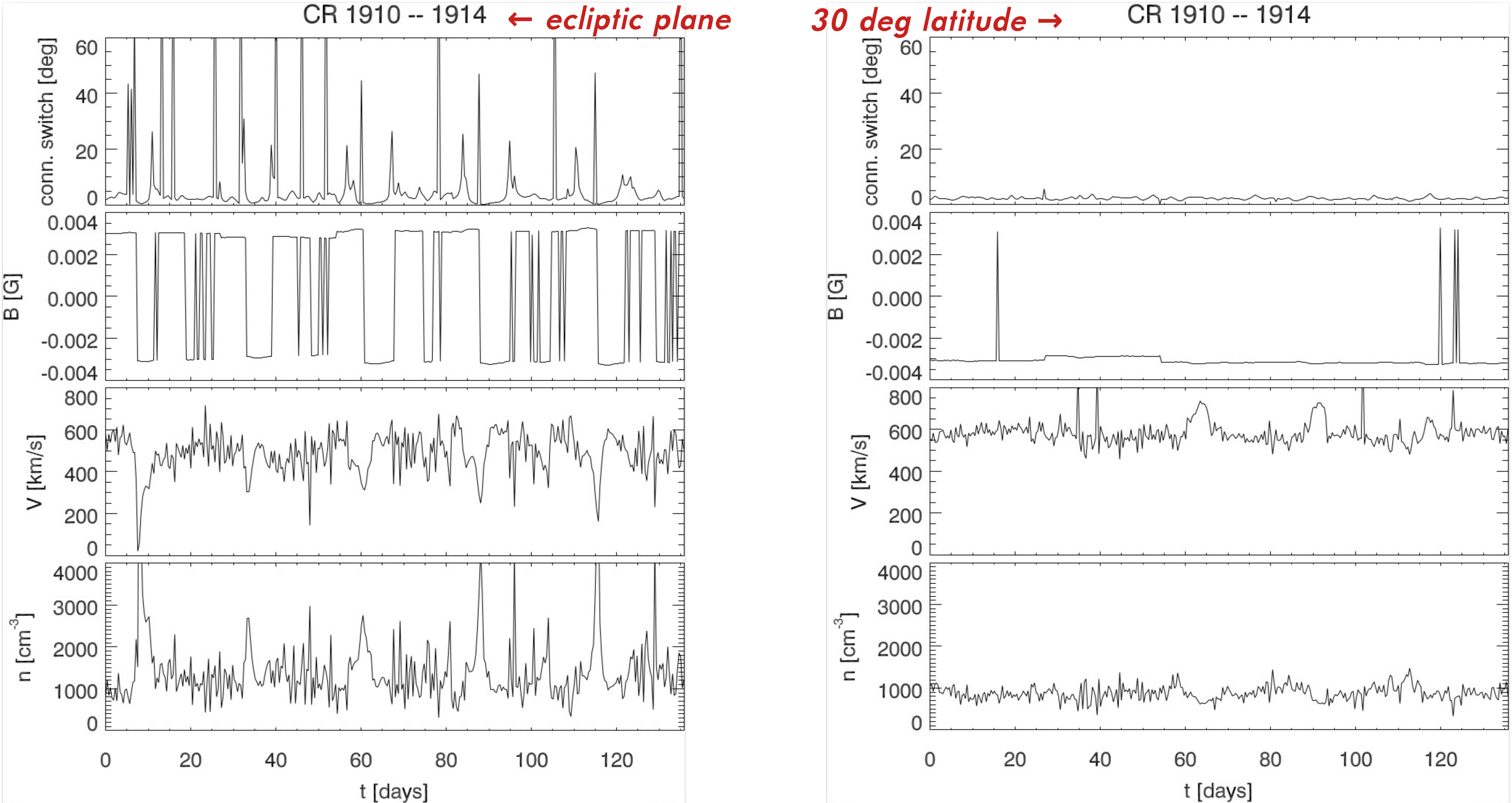
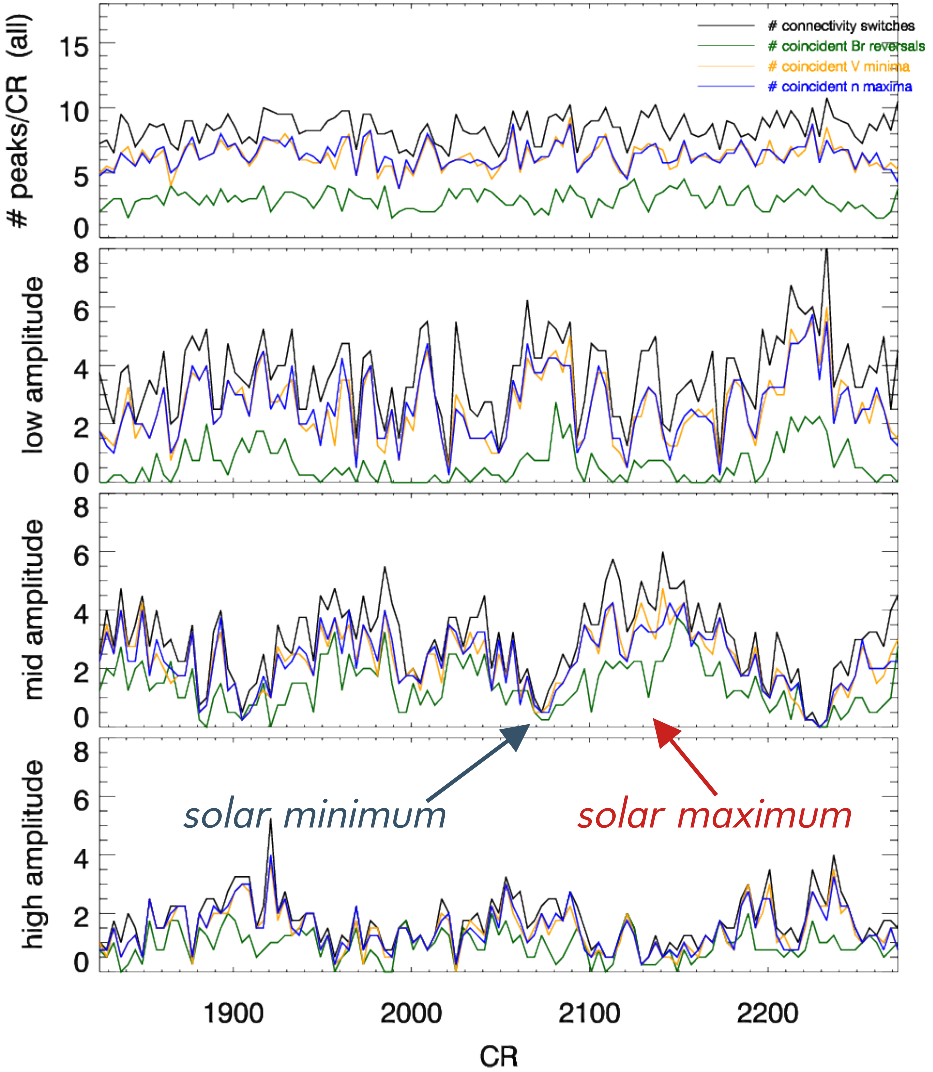


Connectivity switches

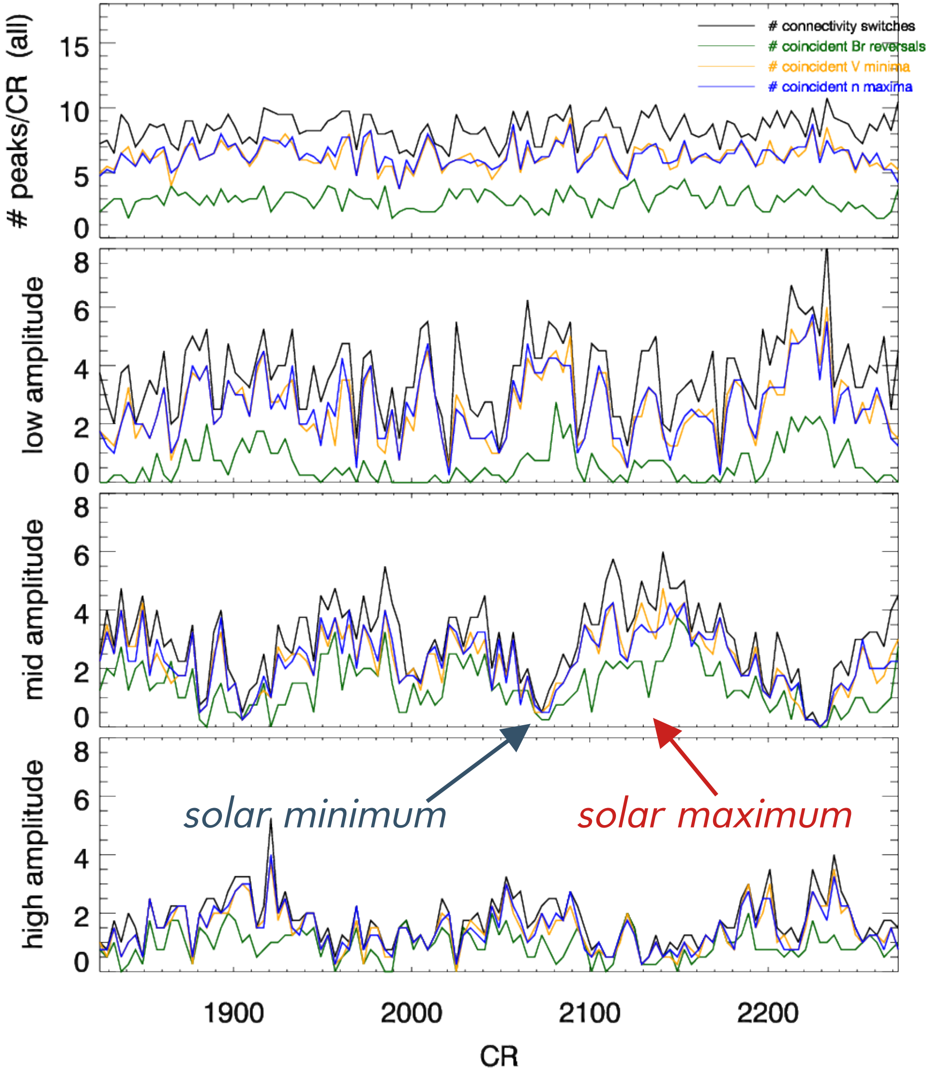


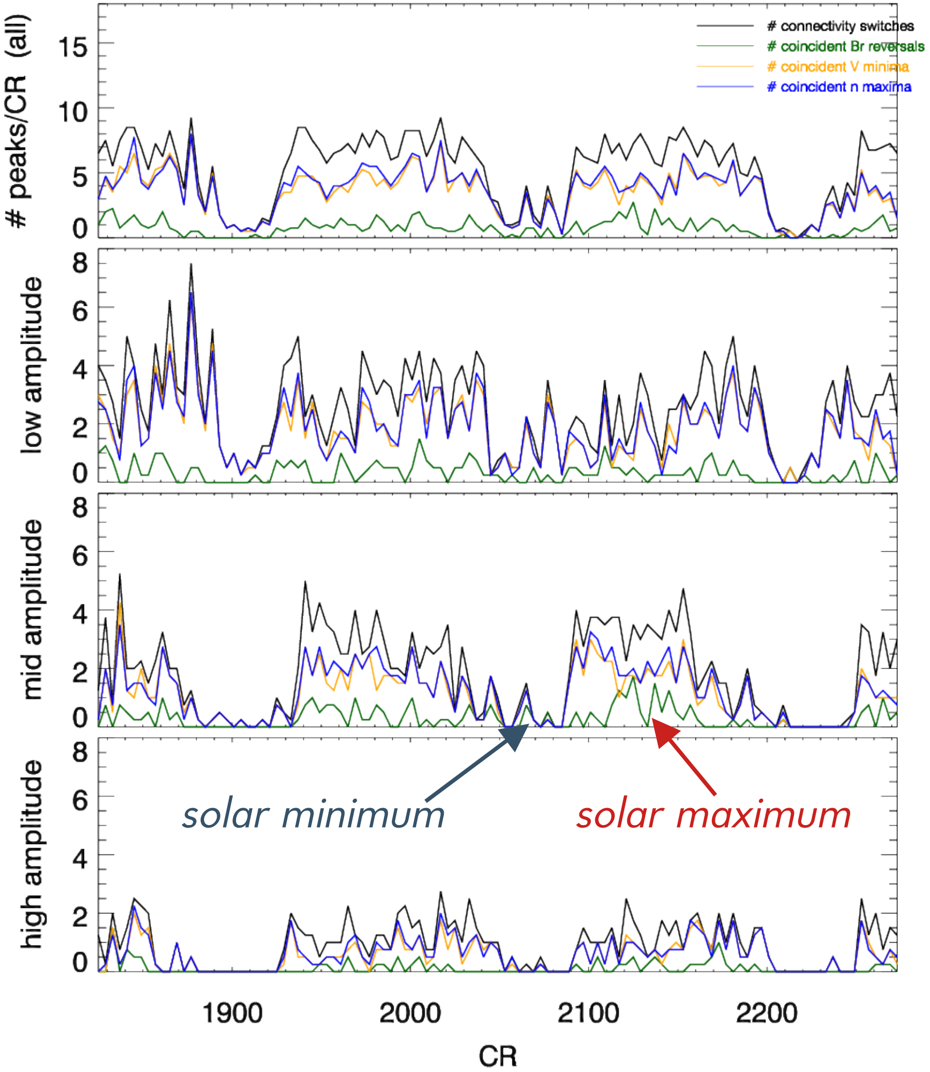
Connectivity switches vs. B, V and n

Large connectivity switches can be associated with polarity reversals, and (more often) to local minima of V and maxima of n.

The relative fraction of each depends on latitude and on solar cycle phase.

Connectivity switches





Conclusions