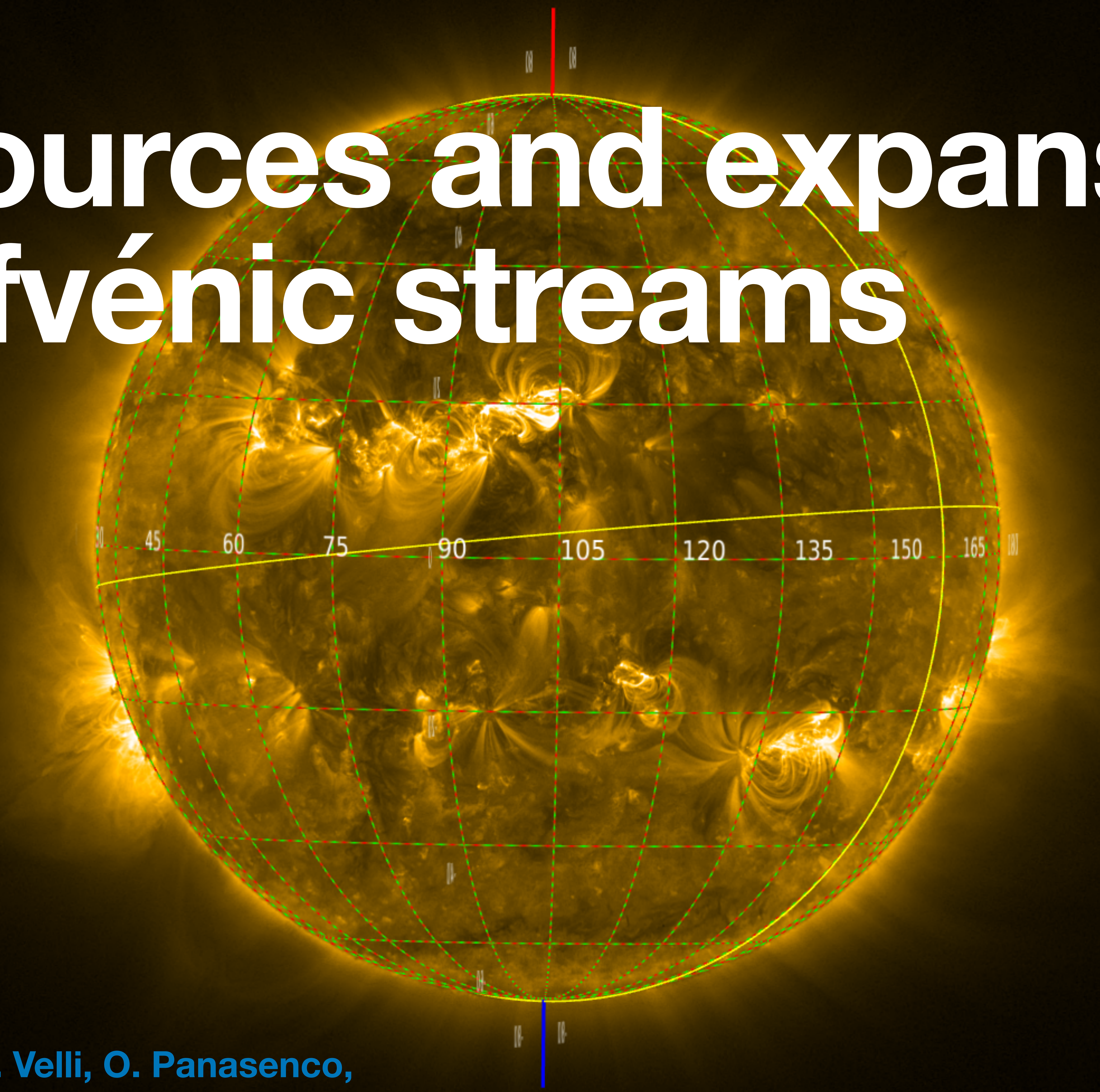
Solar sources and expansion of slow Alfvénic streams



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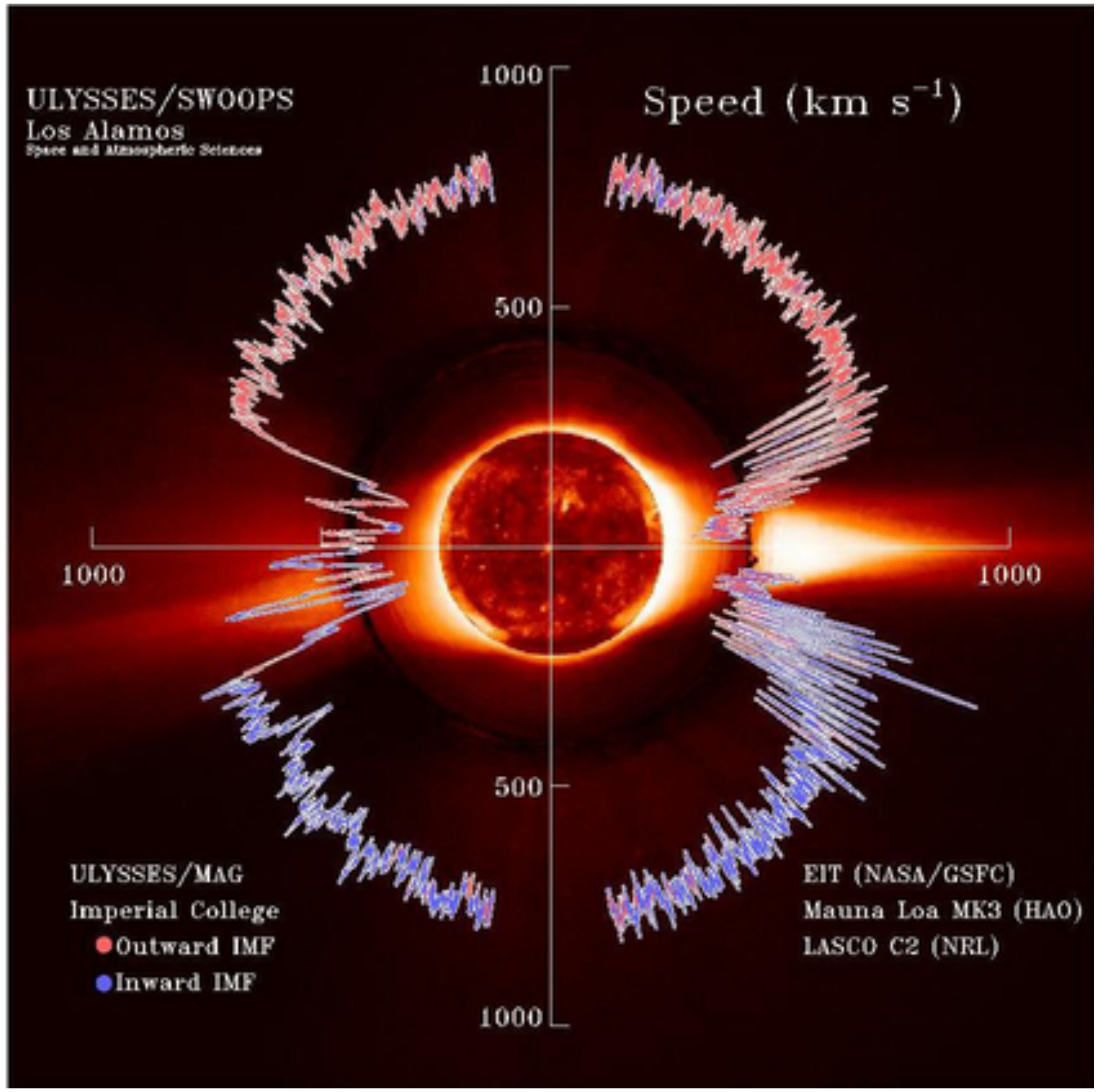
Solar Orbiter Teams

Slow and fast solar wind

Waves properties in different streams

$$H_c = \frac{2\delta \mathbf{v} \cdot \delta \mathbf{b}}{\delta v^2 + \delta b^2}$$



Ulysses Observations
[McComas et al. 2003, 2008]

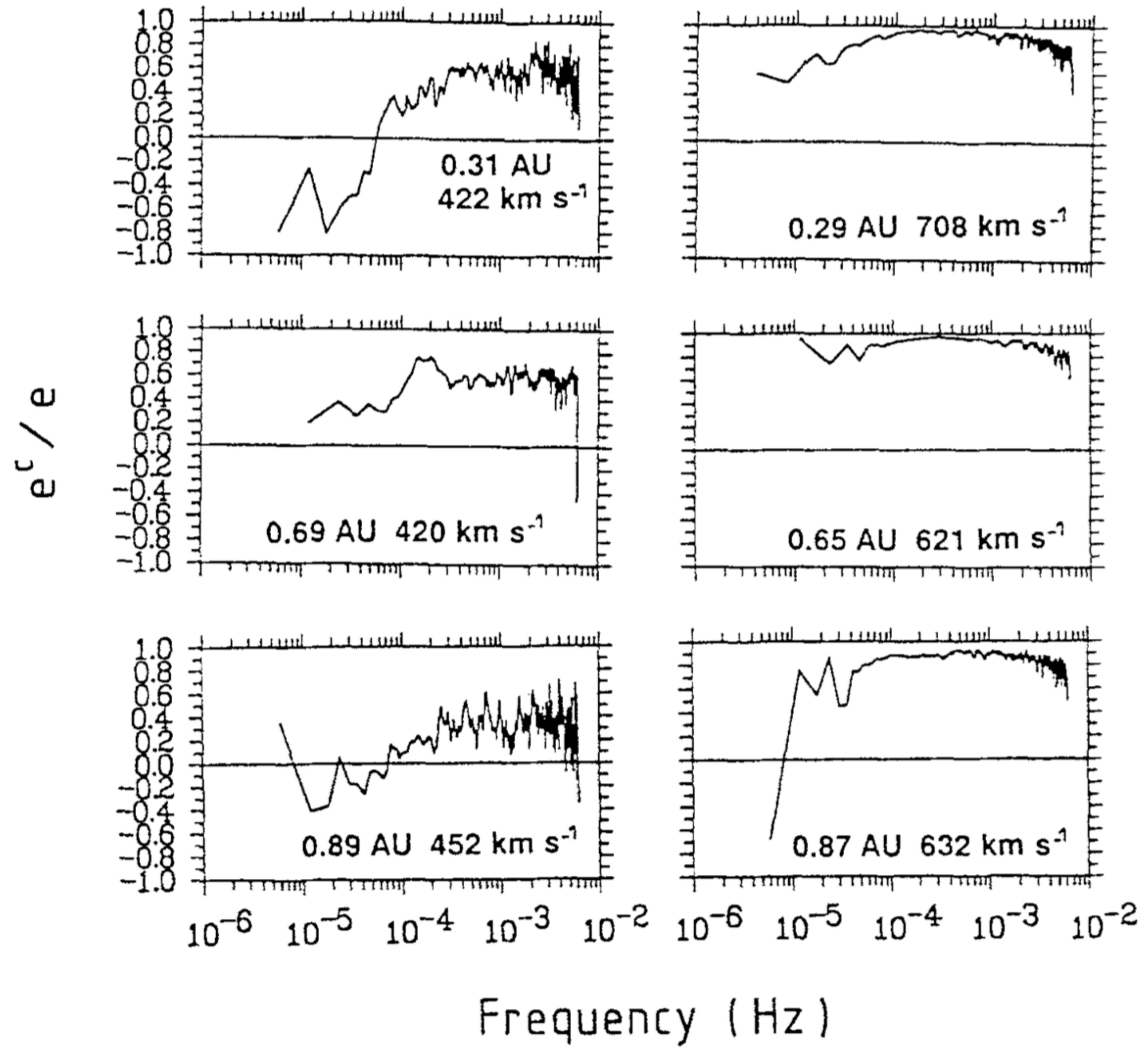


Fig. 2-4. Normalized cross helicity as a function of heliocentric distance and solar wind flow speed as indicated. The right-hand column is for the recurrent high-speed stream studied by Villante (1980) and Bavassano *et al.* (1982). The left-hand column is for the neighbouring low-speed wind streams (adopted from Marsch and Tu, 1990a).

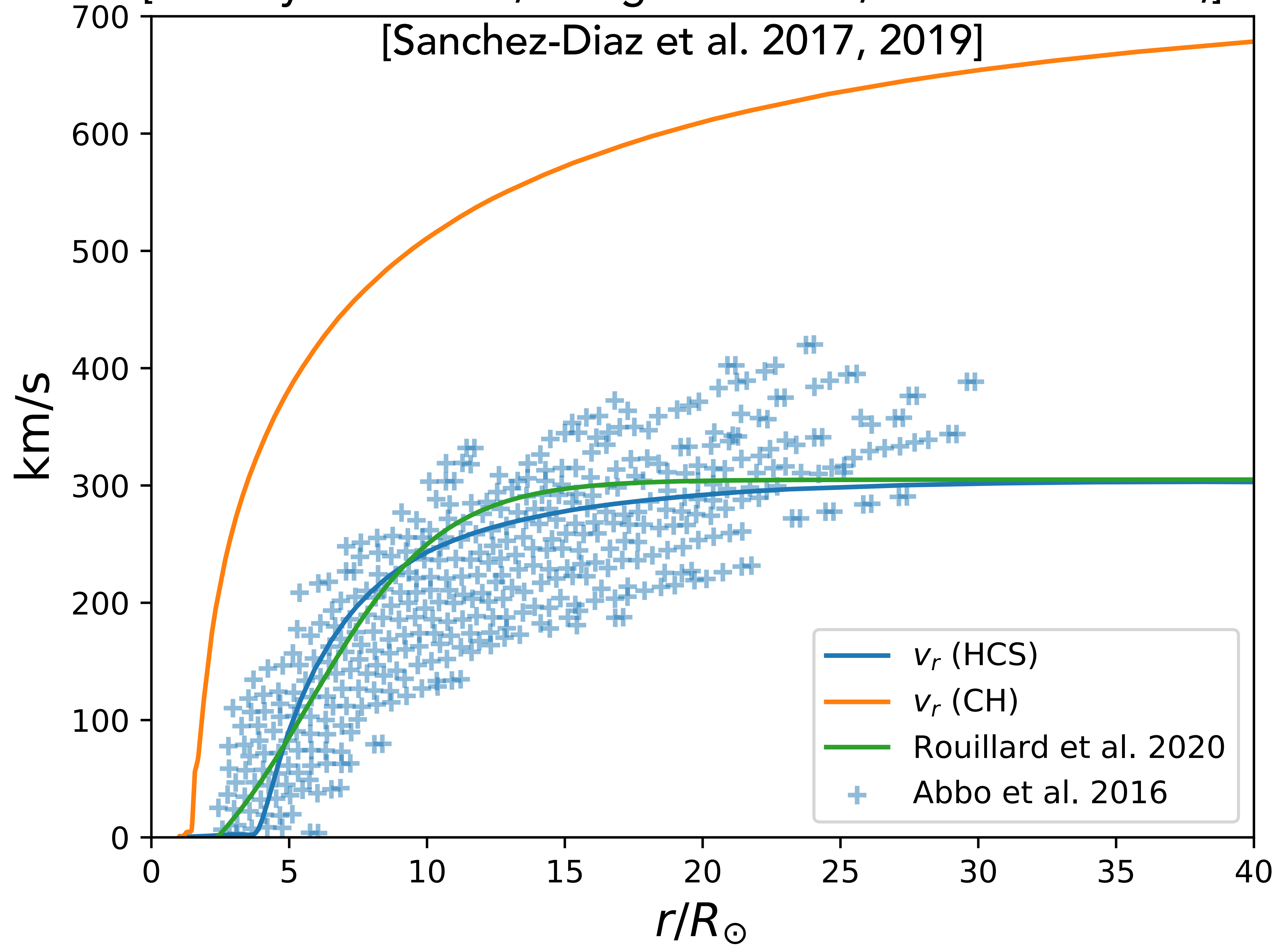
Helios
[Tu & Marsch 1995]

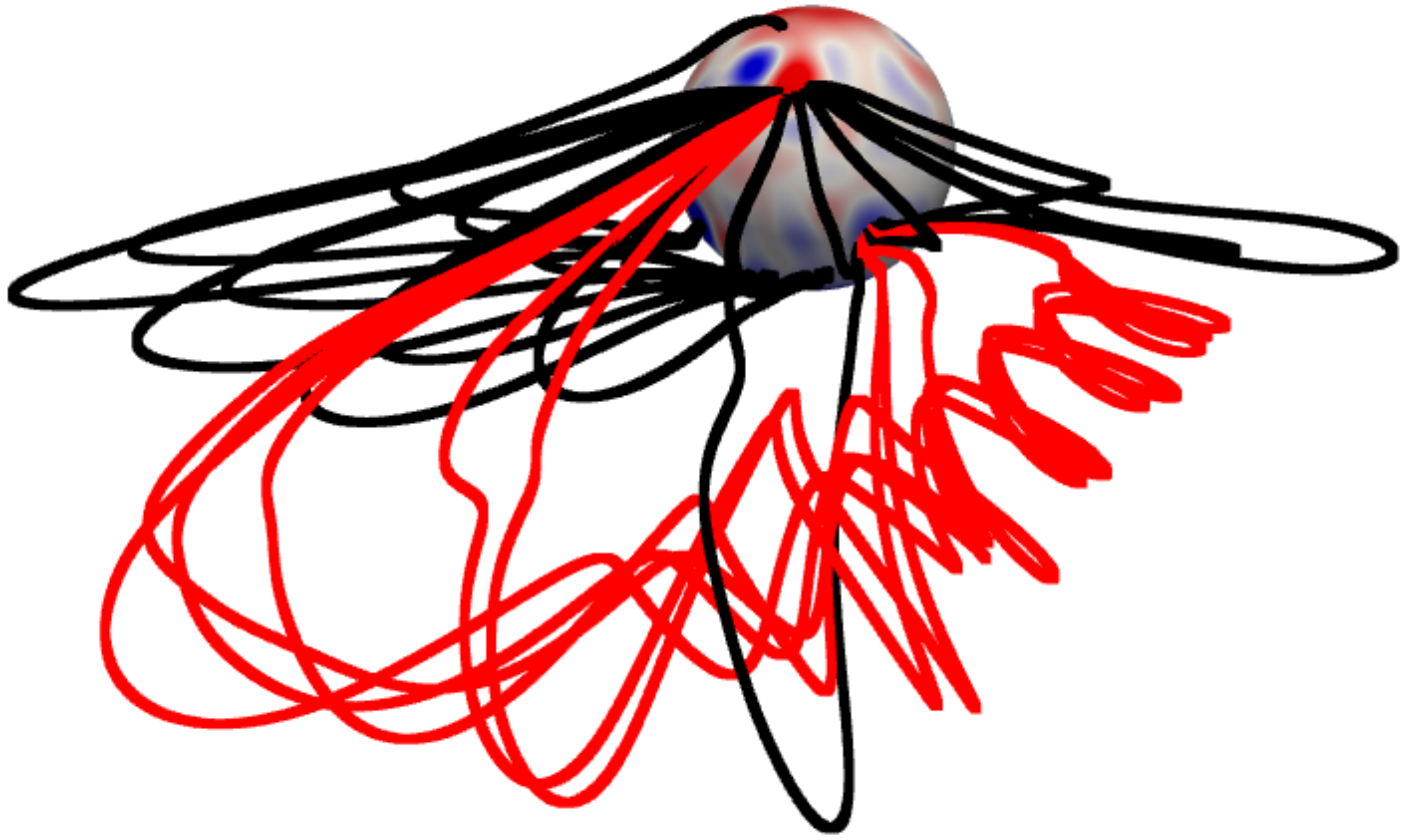
The dynamic slow solar wind

The reconnecting HCS

- Propagating blobs have observed for ~3 decades in coronagraphs and heliospheric imagers
- Seems propagating (advected?) by the slow solar wind in the vicinity of the HCS

[Sheeley et al. 1997, Wang et al. 1998, Abbo et al. 2016,]
[Sanchez-Diaz et al. 2017, 2019]





- The coronal helmet streamers are unstable to a thermal ballooning mode that extends the streamers and pinches the HCS
- Tearing instability is then triggered to create the flux ropes and density perturbations at characteristic frequencies.

[Endeve et al. 2003, 2004, Rappazzo & Velli 2005]
[Higginson & Lynch 2018, Réville et al. 2020, 2022]

The dynamic slow solar wind

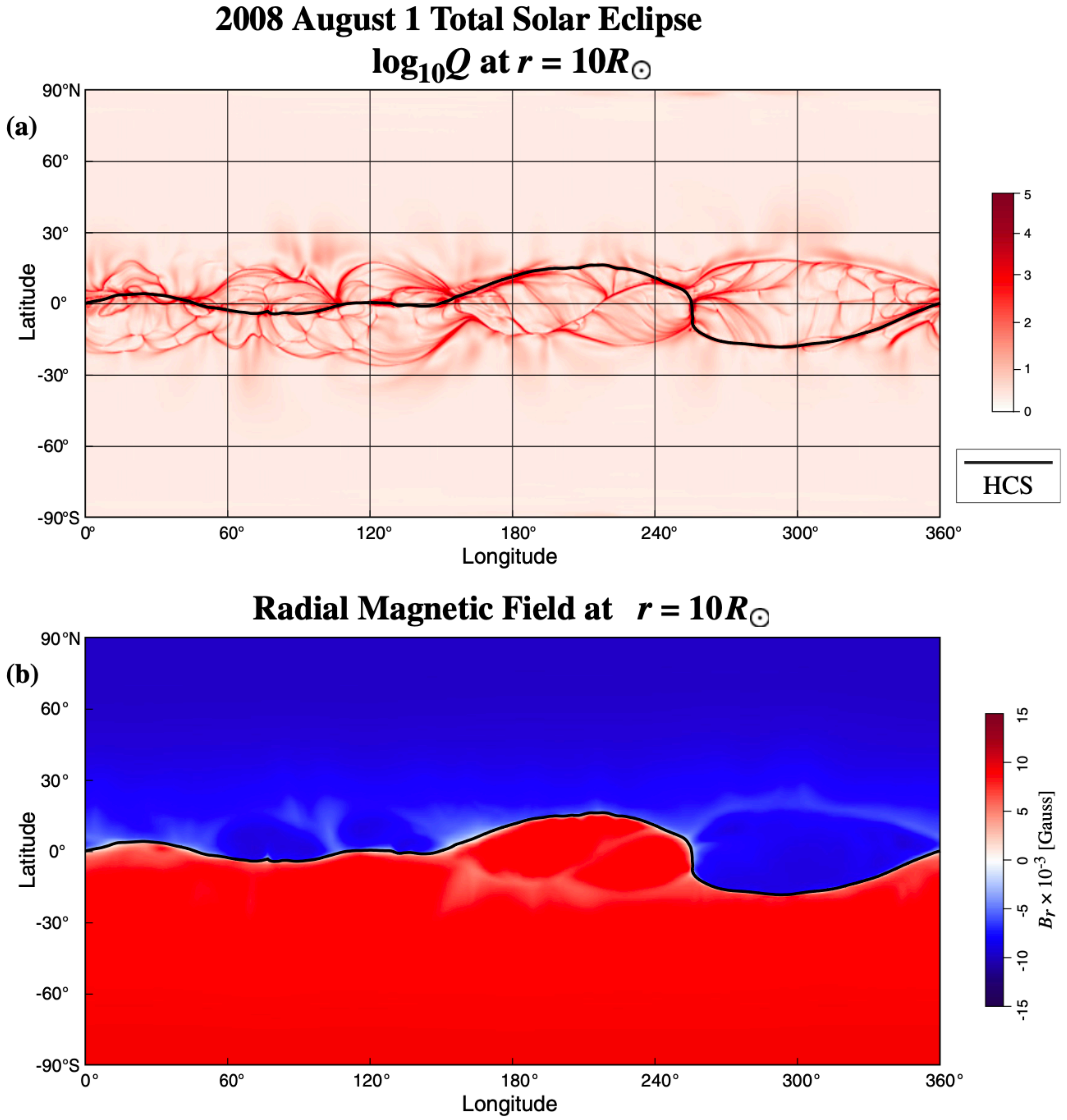
The S-Web and quasi-separatrices

- The HCS is a true separatrice and associated with slow wind
- The corona and solar wind is organized in regions of same origins separated by the HCS and quasi-separatrices that together form the S-Web
- The squashing factor can be used to localize these boundaries :

$$Q = \left|\frac{B_{ss}}{B_r}\right| \frac{R_{ss}^2}{R_\odot^2} \left[\left(\frac{\sin\Theta}{\sin\theta}\frac{\partial\Phi}{\partial\phi}\right)^2 + \left(\sin\theta\frac{\partial\Phi}{\partial\theta}\right)^2 + \left(\frac{1}{\sin\theta}\frac{\partial\Theta}{\partial\phi}\right)^2 + \left(\frac{\partial\Theta}{\partial\theta}\right)^2 \right]$$

[Priest & Démoulin 1995, Démoulin et al. 1996]
[Titov & Démoulin 1998, Titov et al. 2002, Titov 2007]

[Antiochos et al. 2011]



Does all the slow wind comes from the S-Web? In particular the Alfvénic wind?

Mass loading in the corona

Energetics of the expanding wind

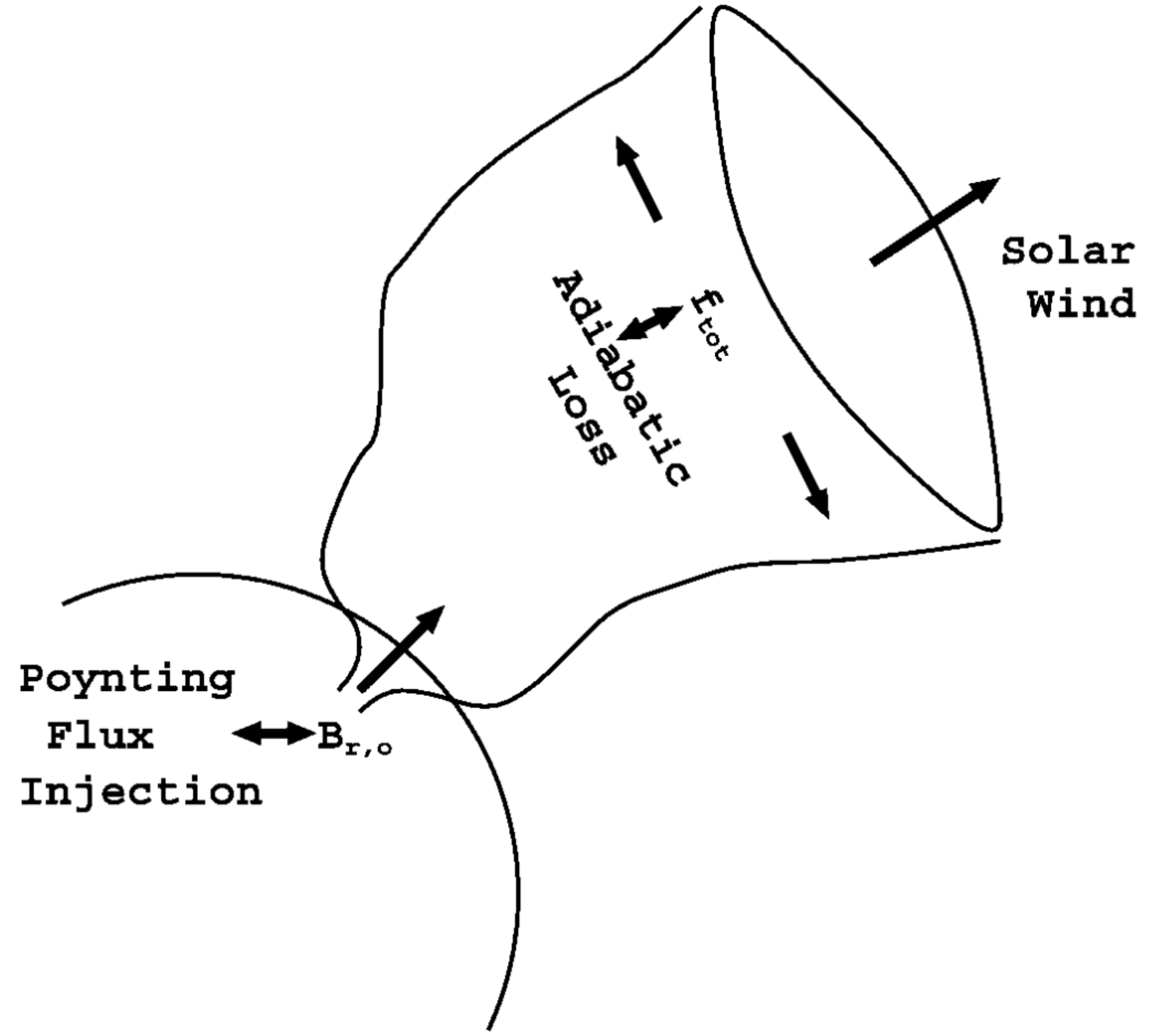
- Expansion has been shown to be anti-correlated with the terminal wind speed

[Wang & Sheeley 1991]

TABLE 2

CORRESPONDENCE BETWEEN RANGES OF f_s AND CHARACTERISTIC VALUES OF v_w

f_s	v_w (km s^{-1})
<3.5	700
3.5–9	600
9–18	500
18–54	400
>54	330



- Balancing the input Poynting flux at the base with the mass flux at 1 AU:

$$v_{1AU} = \sqrt{2\left(-\frac{R_\odot^2}{4\pi\rho v r^2}\frac{B_\odot}{f_{\exp}}\langle\delta B_\perp \delta v_\perp\rangle + \frac{\gamma}{\gamma-1}RT_c - \frac{GM_\odot}{R_\odot}\right)}$$

[Suzuki 2006]

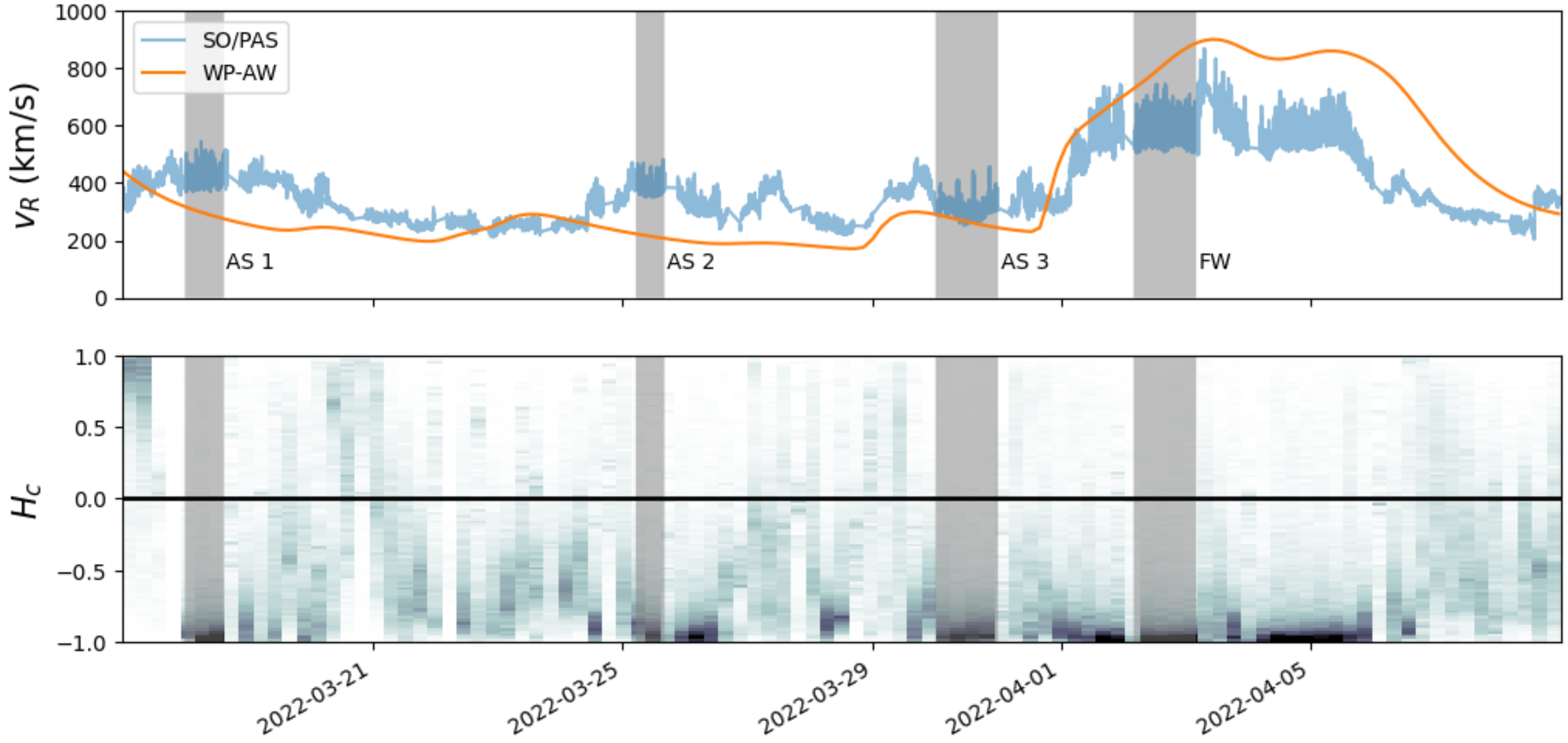
- Given similar wave amplitude and constant mass loss, the terminal velocity depends scales as the square root of B0/fexp

- But expansion also changes the base velocity i.e. the mass loss, and the coronal temperature [Velli 2010]

Solar Orbiter observations

March 2022 intervals

- Solar Orbiter in situ observation (MAG & PAS GM)
- Three slow alfvénic streams followed by one fast alfvénic streams
- High cross helicity for all intervals (~0.8 for AS, 0.95 for FW)
- MHD model well predicts the transition from slow to fast wind (orange line)

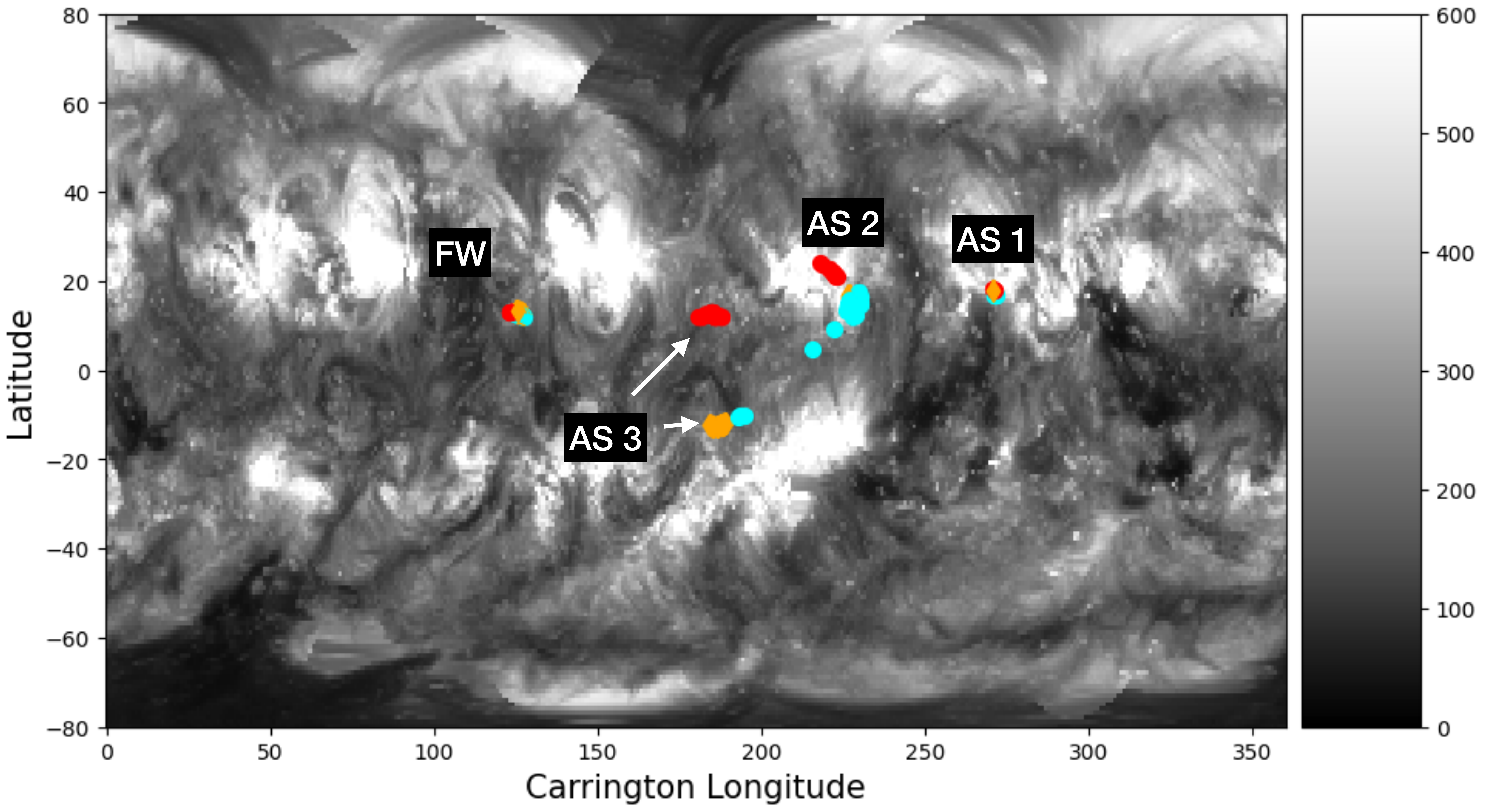


[D'Amicis et al., 2024, Baker et al. 2023, Réville et al. 2024]

Solar wind sources

PFSS and MHD (AW driven) model

- PFSS model (IRAP connect-tool) **red**
- PFSS model (single ADAPT BC) **orange**
- Global MHD model w/ turbulence transport from the photosphere up to 30 Rs (WindPredict-AW) **cyan**
- PFSS and MHD agrees when based on the same map
- Following the MHD simulations AS 1 and FW come from coronal holes (and probably AS 2)
- Expansion is higher in AS 1 than FW, but hard to say for the two others



[Réville et al. 2020, Parenti et al. 2022, Réville et al. 2024]

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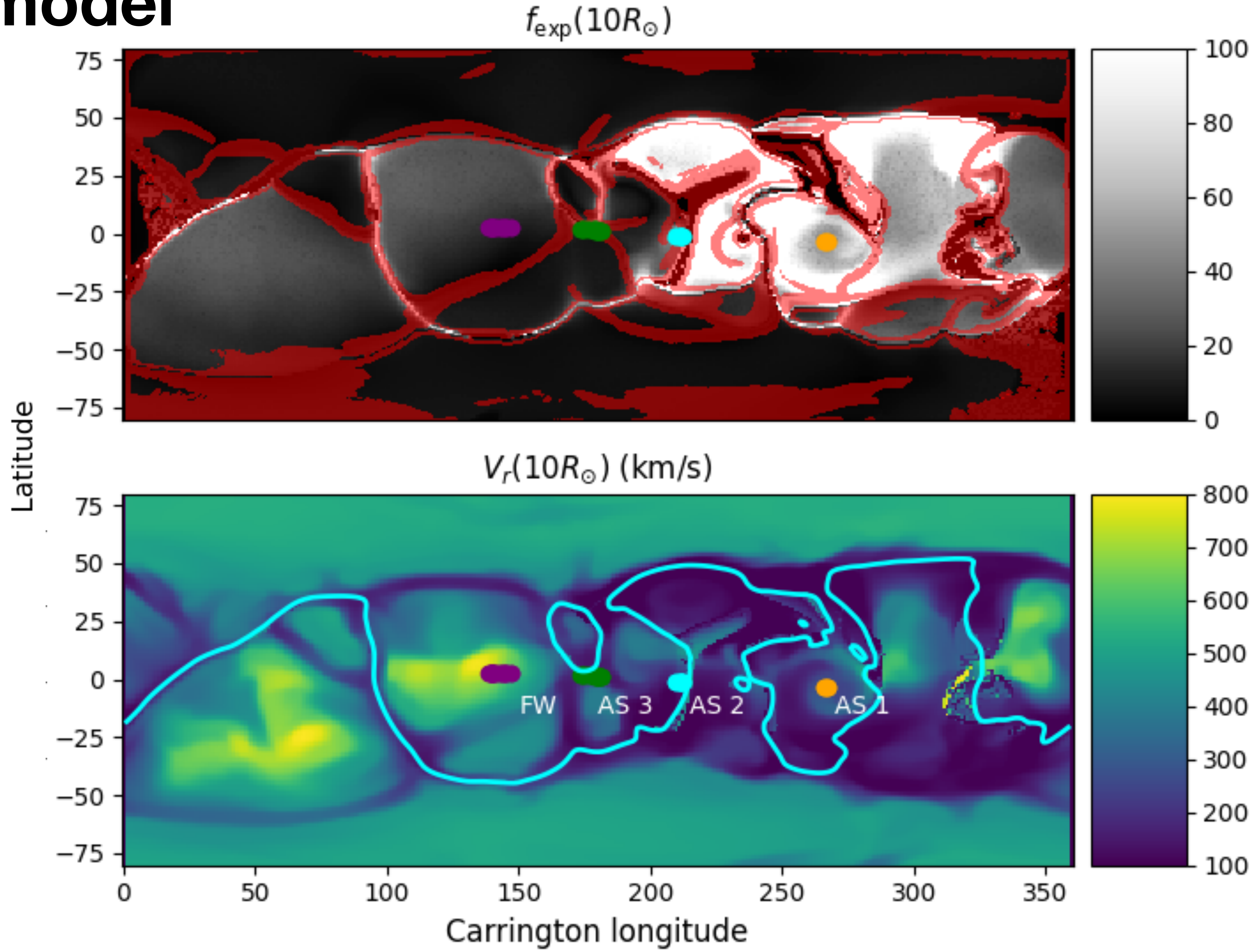


[Réville et al. 2020, Parenti et al. 2022, Réville et al. 2024]

Expansion properties

Is high expansion factor always indicative of slow winds?

[Réville & Brun 2017]

- For all intervals (except AS1), the ratio B0/fexp seems better correlated with wind speed
- This has been reported in interplanetary scintillations observations [Kojima et al. 2004]
- In PFSS models expansion stops at rss ~2.5 Rs
- In MHD (and reality) expansion goes on up to 10 Rs
- How to chose the height of expansion?

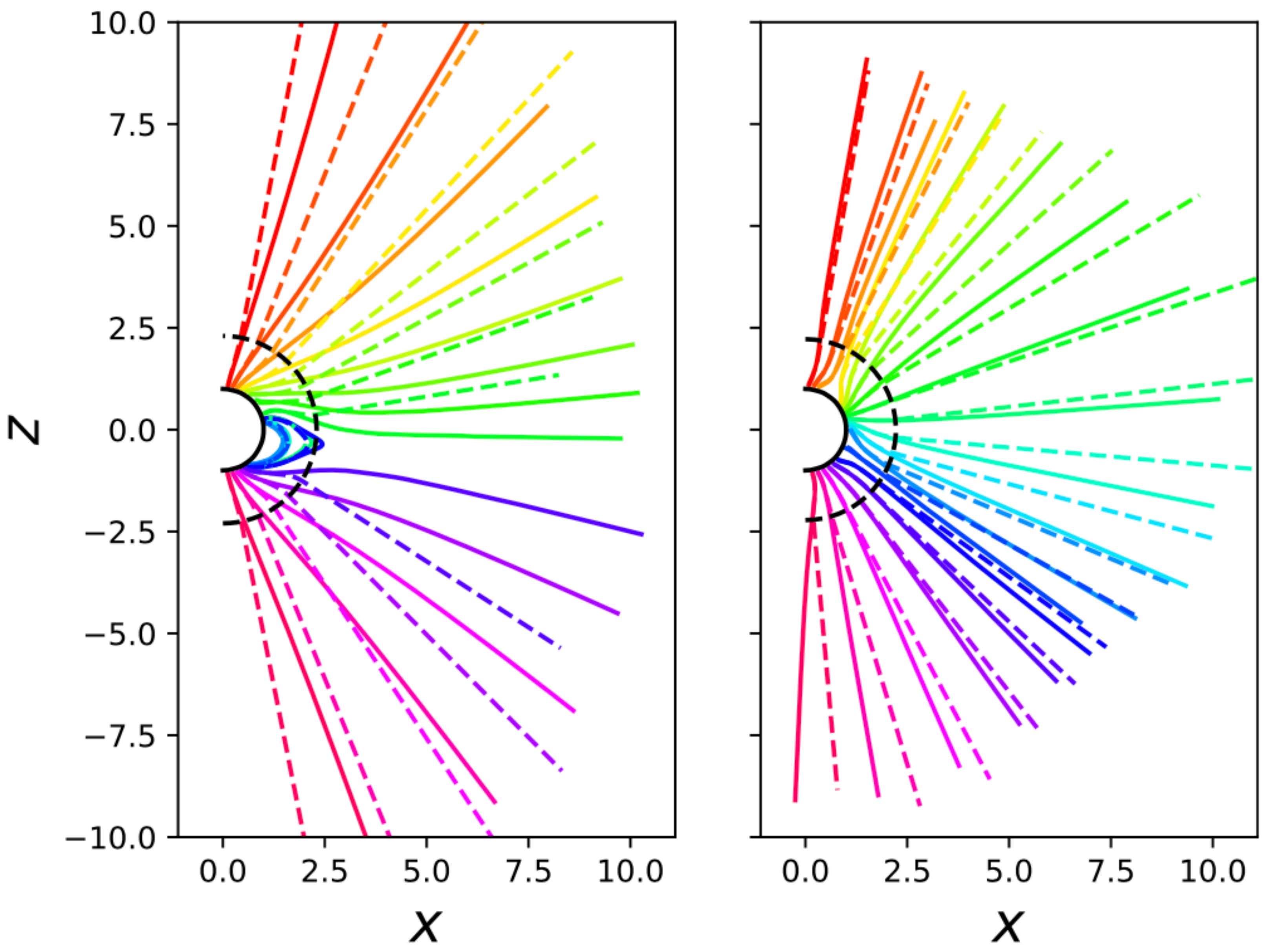


TABLE 1. Characteristics of the studied Alfvénic streams

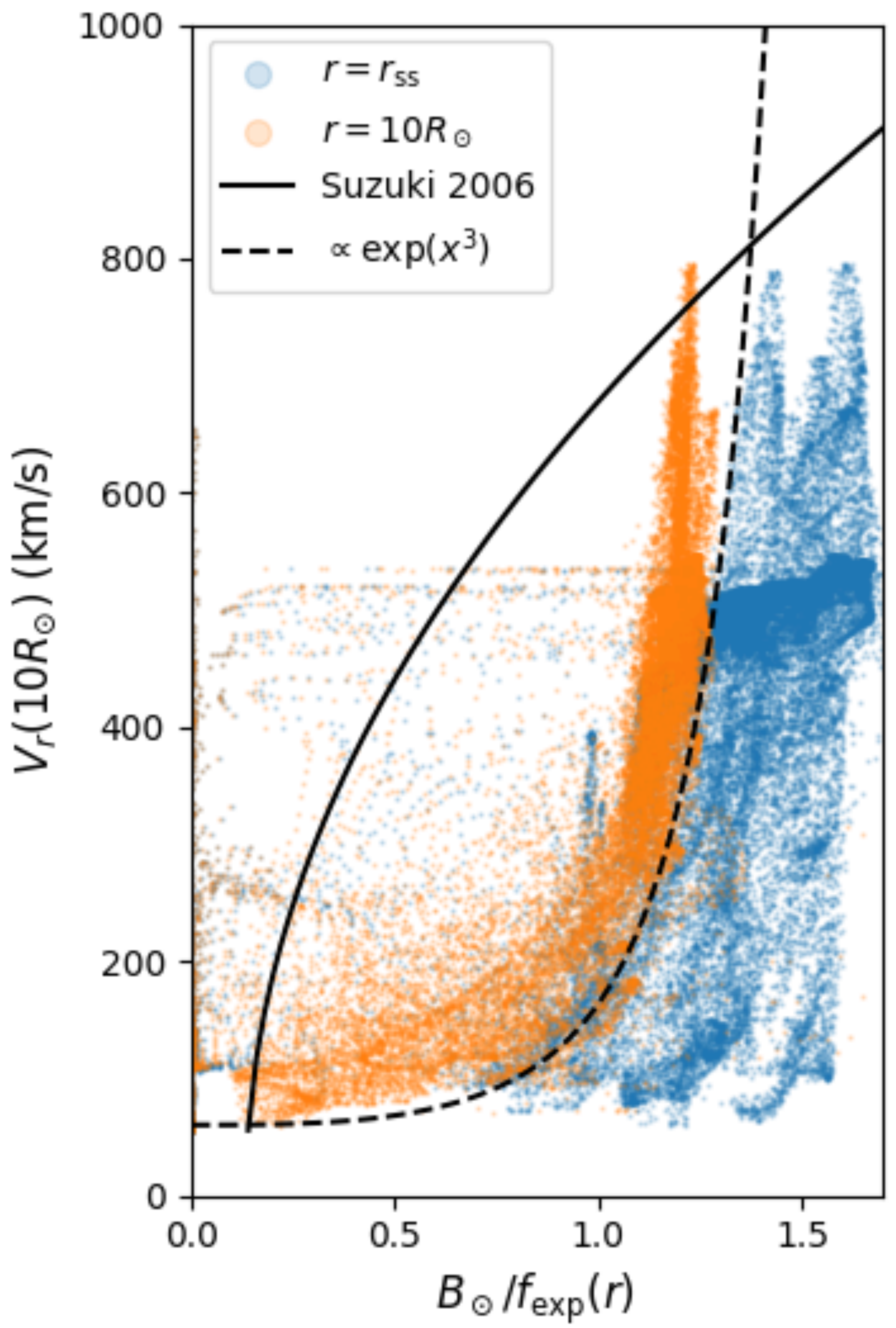
	$\langle v_r \rangle$ (km/s)	$\langle H_c \rangle$	$\langle f_{ss} \rangle$	$\langle B_\odot / f_{ss} \rangle_{PFSS}$ (G)	$\langle f_{ss\|MHD} \rangle$	$\langle B_\odot / f_{ss} \rangle_{MHD}$ (G)	$\langle B_\odot / f_{tot} \rangle_{MHD}$ (G)
AS 1	412	-0.88	958 (1065)	0.08 (0.07)	54.5	1.3	1.4
AS 2	385	-0.85	17.3 (48.2)	0.5 (0.3)	22.7	0.8	0.5
AS 3	310	-0.84	12.4 (21.4)	0.6 (0.35)	12.5	0.9	0.6
FW	570	-0.94	26.5 (27.8)	0.9 (0.75)	15.0	1.4	1.2

Scaling of the terminal wind speed

SS vs total expansion

- In the MHD model, the wind speed is positively correlated to B0/fexp
- The expansion at 10 Rs provides a better correlation
- The growth is much faster than predicted by Suzuki's law
- Simulation suggests an exponential scaling as suggested by Velli (2010).

$$v_{1AU} = \sqrt{2\left(-\frac{R_\odot^2}{4\pi\rho v r^2}\boxed{\frac{B_\odot}{f_{\mathrm{exp}}}}\langle\delta B_\perp \delta v_\perp\rangle + \frac{\gamma}{\gamma-1}RT_c - \frac{GM_\odot}{R_\odot}\right)}$$



[Pinto et al. 2016, Réville & Brun 2017, Réville et al. 2024]

Summary

- Close-in observations of the solar wind has revealed more and more intervals of Alfvénic slow wind.
- Using Solar Orbiter data, PFSS and MHD modeling, we identified some sources and profiles of the expanding solar wind for intervals in March/April 2022.
- Our study suggests that sources for the slow Alfvénic wind are in majority coronal holes but may also lie at HCS/QSLs.
- The ratio B0/fexp seem the best correlated parameter to classify fast/slow alfvénic streams, when fexp is taken at 10Rs, and with a very strong dependance (exponential).