Part I : Coronal Magnetic Structure & Small-scale Transients

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Outline

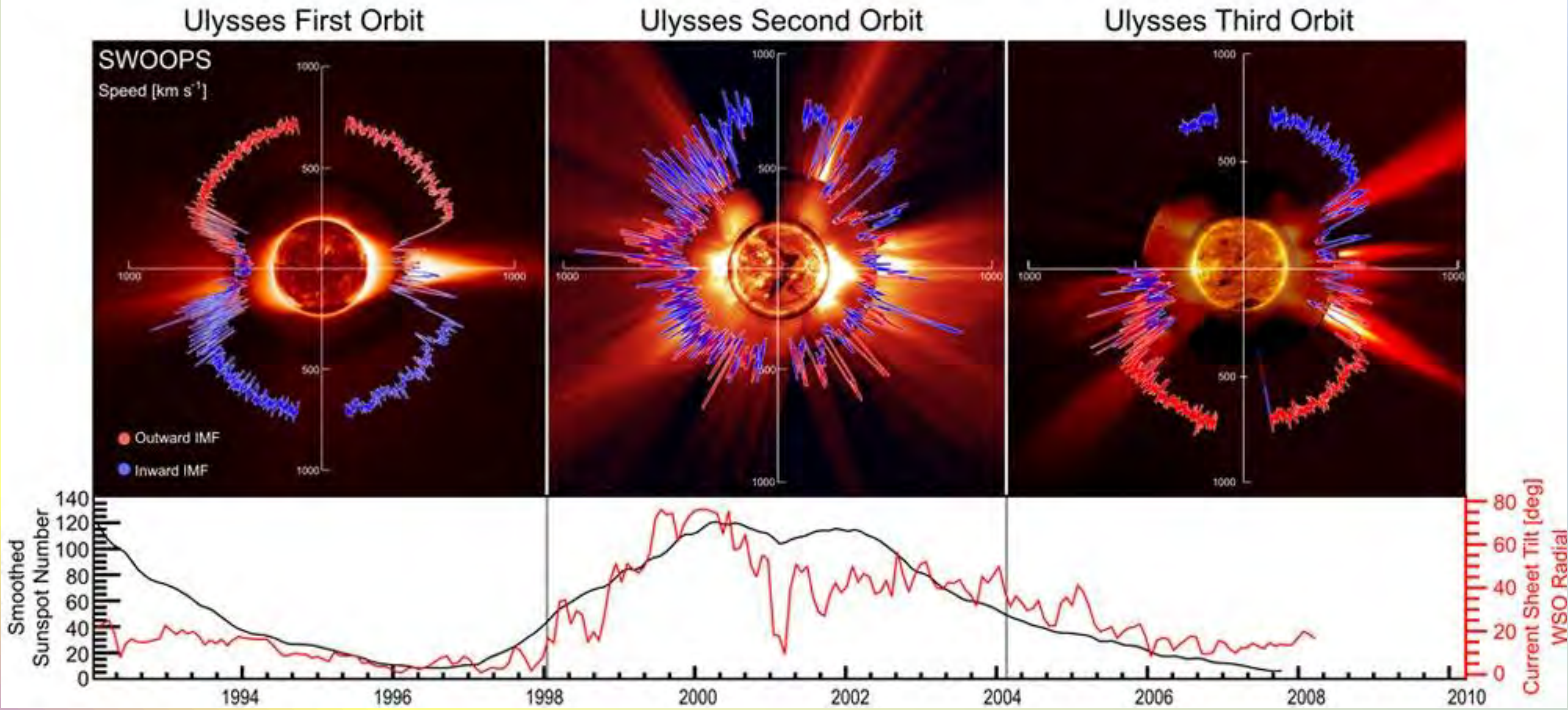
- **Introduction Material / Background**
  - Large-scale Magnetic Structure(s) of the Solar Corona
  - The Solar Wind & the Parker Spiral
  - The "Steady State" Solar Wind & Heliosphere
  - Magnetic Connectivity & Heliospheric Back-mapping
  - The Separatrix Web – A Methodology for Quantifying Magnetic Topology
  - Solar Wind Composition – Tracing the History of In-Situ Solar Wind Plasma

- **Magnetic Reconnection in the Solar Corona**
  - Coronal Dynamics & Generation of Small-scale Solar Wind Transients
  - Helmet Streamer Blobs, Pseudostreamer Outflows, Etc.

- **Assembling the Building Blocks → An Illustrative Example: 2003 April 15-May 13 (CR 2002)**
  - Magnetic Helicity–Partial Variance of Increments (H_m–PVI) Analysis
  - Helmet Streamer Wind Intervals
  - Pseudostreamer Wind Intervals
  - Statistics of Coherent Magnetic Structure(s) w/in S-Web Associated Slow-to-Moderate Speed Solar Wind Intervals

- **Summary & Conclusions**

Coronal Magnetic & Global Solar Wind Structure

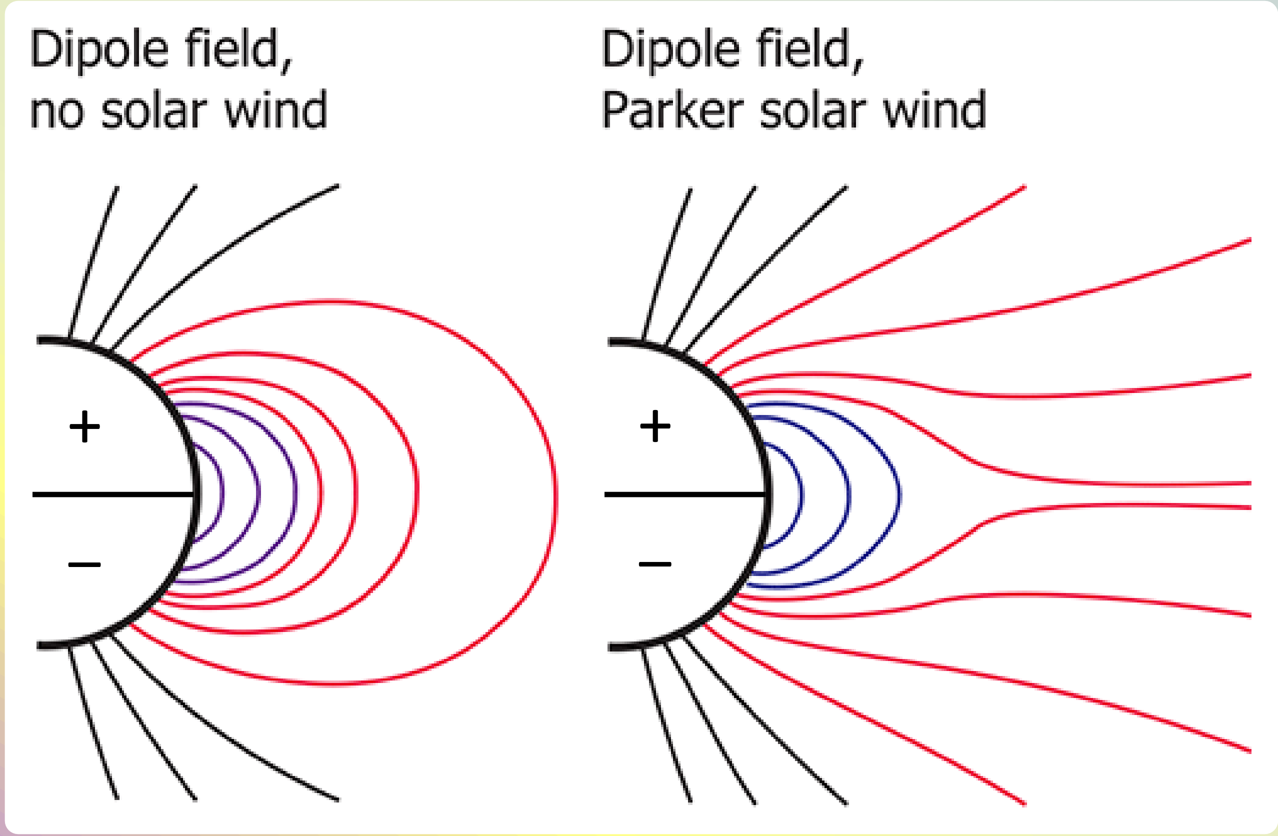


[McComas et al.2008]

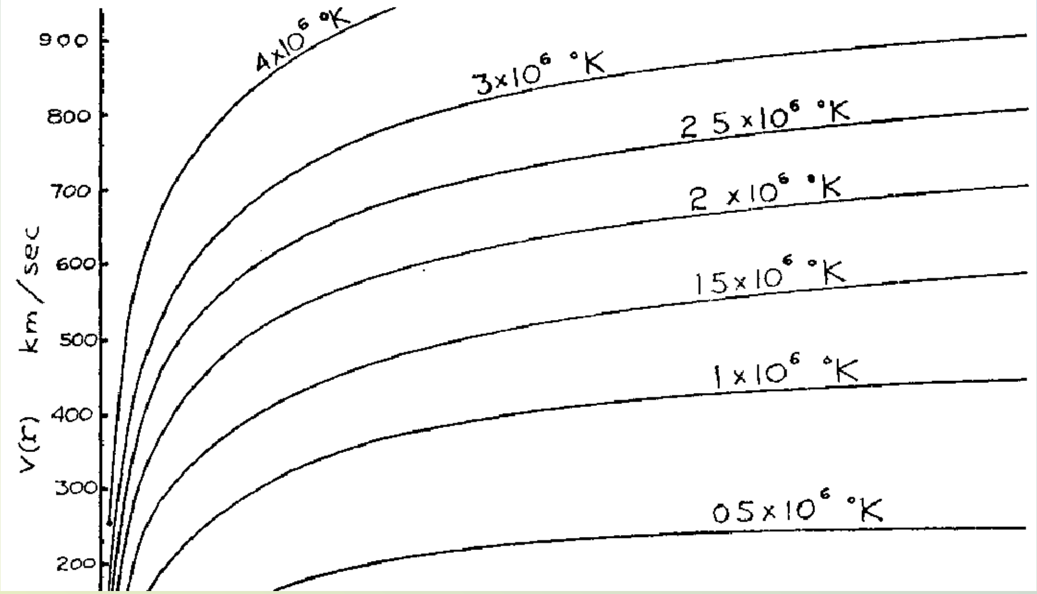
Coronal Magnetic & Global Solar Wind Structure

"It is evident from eclipse photographs that gas-magnetic field interactions are important in determining the structure and dynamical properties of the solar corona and interplanetary medium." [Pneuman & Kopp 1971]

Global field structure more-or-less a magnetic dipole. How do you get a solar corona with helmet streamers? Just heat the plasma! (Just "solve" the coronal heating problem). Parker's famous 1958 isothermal solar wind solution is really all you need to create open magnetic flux regions over the poles and closed flux around the global polarity inversion line.



[Owens 2020 after Pneuman & Kopp 1971]


heir minimum points at the same value of ξ. Thus we mu
, or

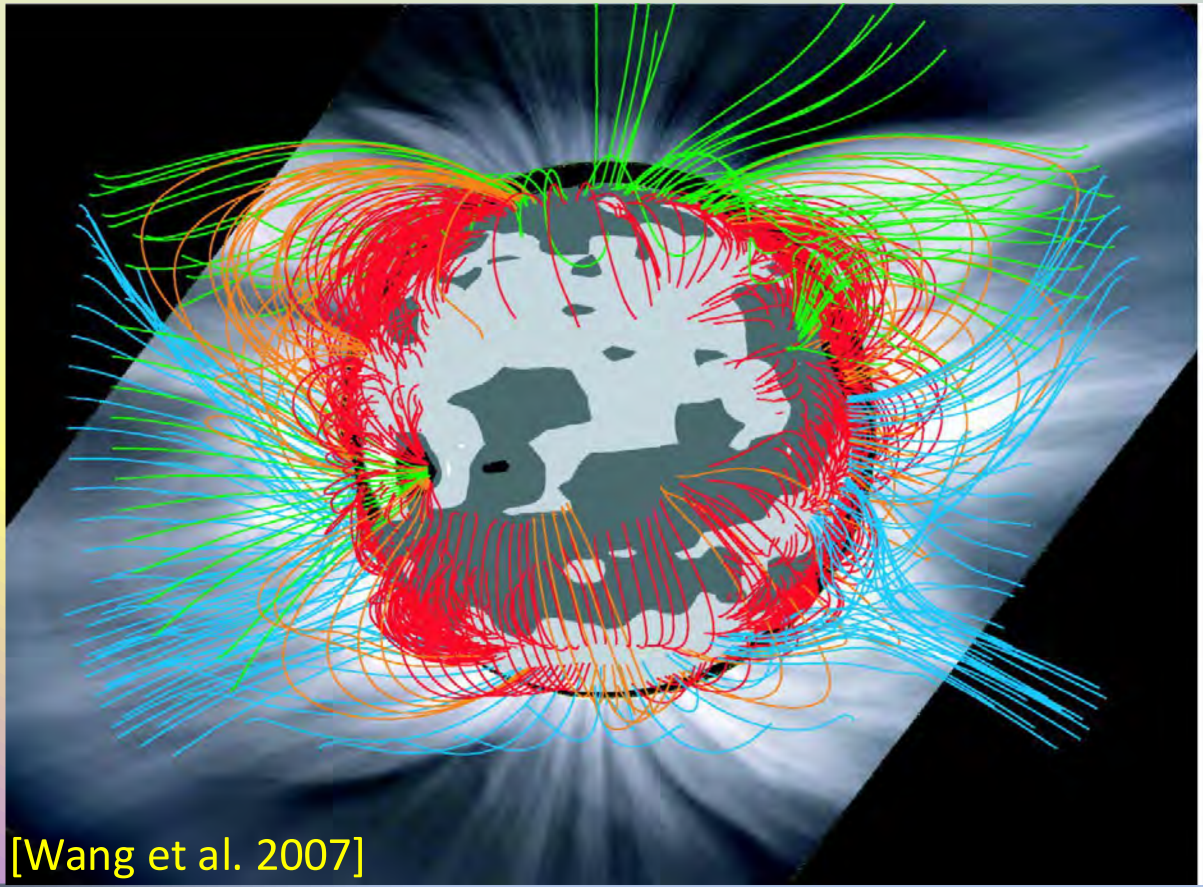
$$\psi_0 - \ln \psi_0 = 2\lambda - 3 - 4 \ln \frac{\lambda}{2}.$$

[Parker 1958]

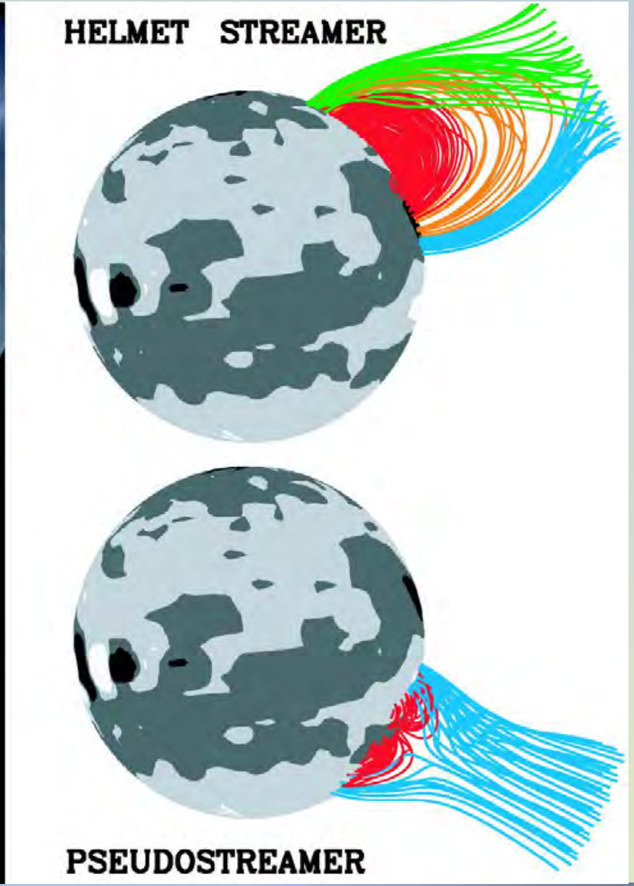
Coronal Magnetic & Global Solar Wind Structure

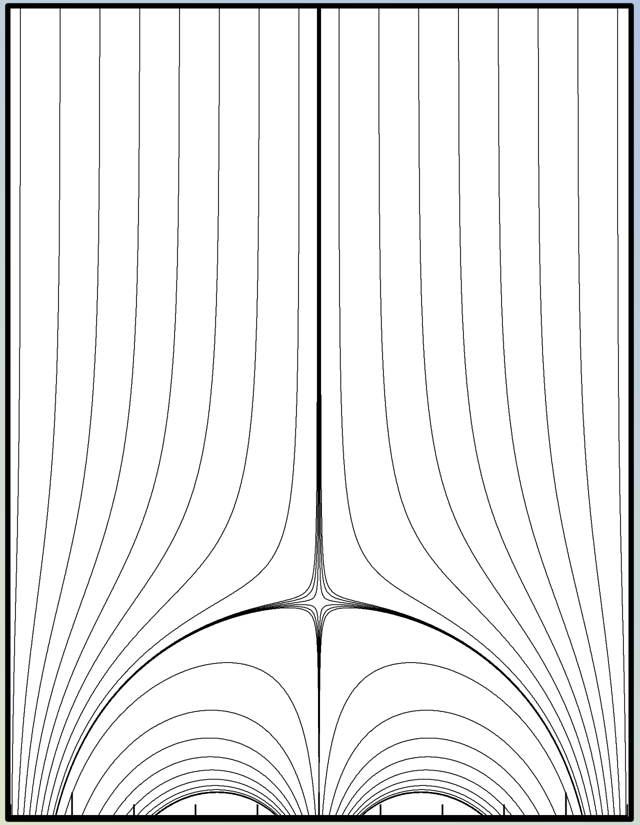
The Sun is obviously more complex than a simple global dipole. What are the second-largest closed flux structures? Coronal pseudostreamers (unipolar streamers) → just make the closed flux a bit smaller and embed it in an open-field region.

In terms of the simplest magnetic field model, the potential field source surface [PFSS; Altschuler & Newkirk 1969; Wang & Sheeley 1992], you can "mimic" open field regions by imposing $\mathbf{B} = (B_r , 0, 0)$ at the source surface R_{ss}. Pseudostreamer flux systems close well before Rss whereas helmet streamers close at R_{ss}.



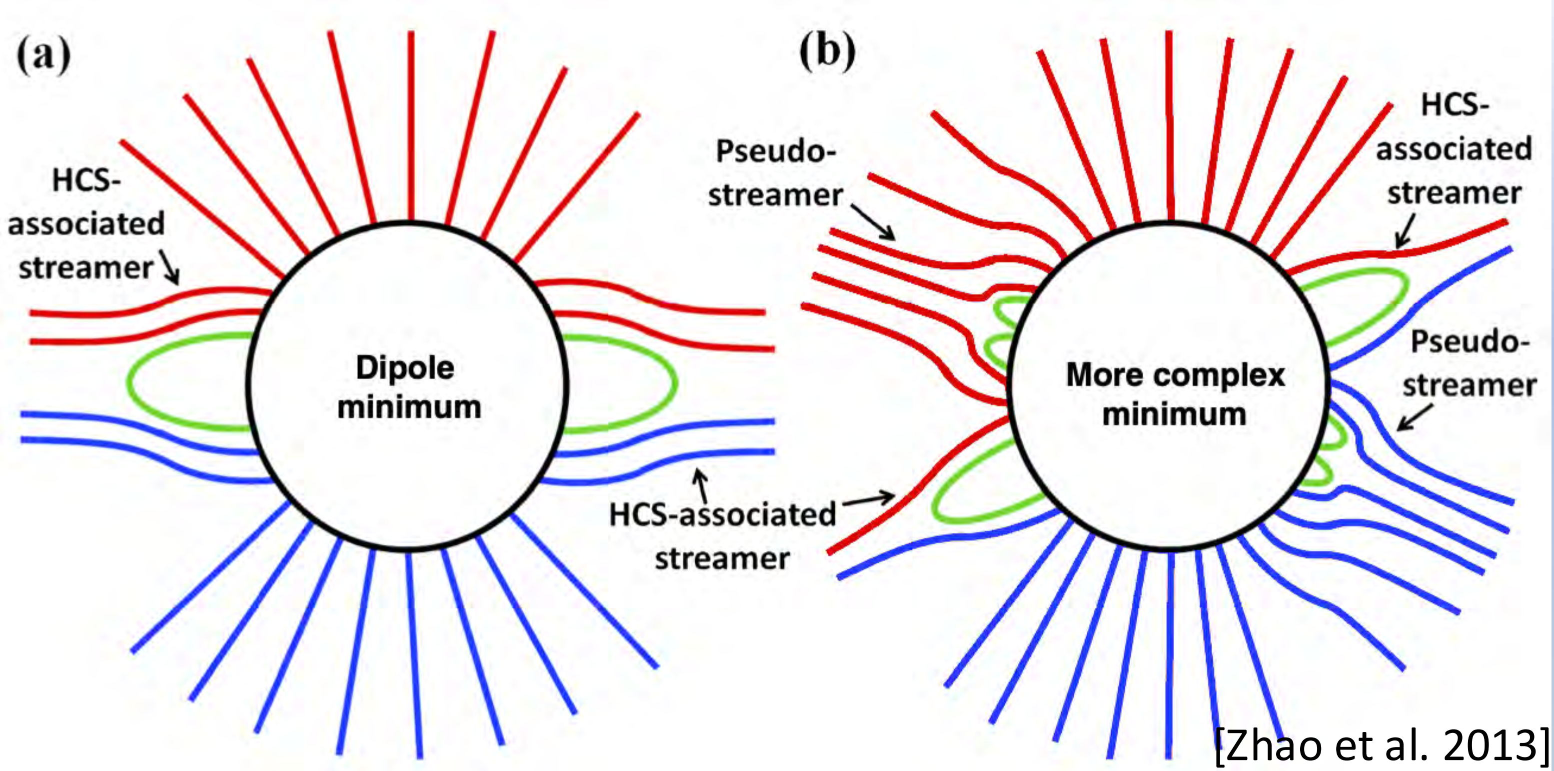
[Wang et al. 2007]



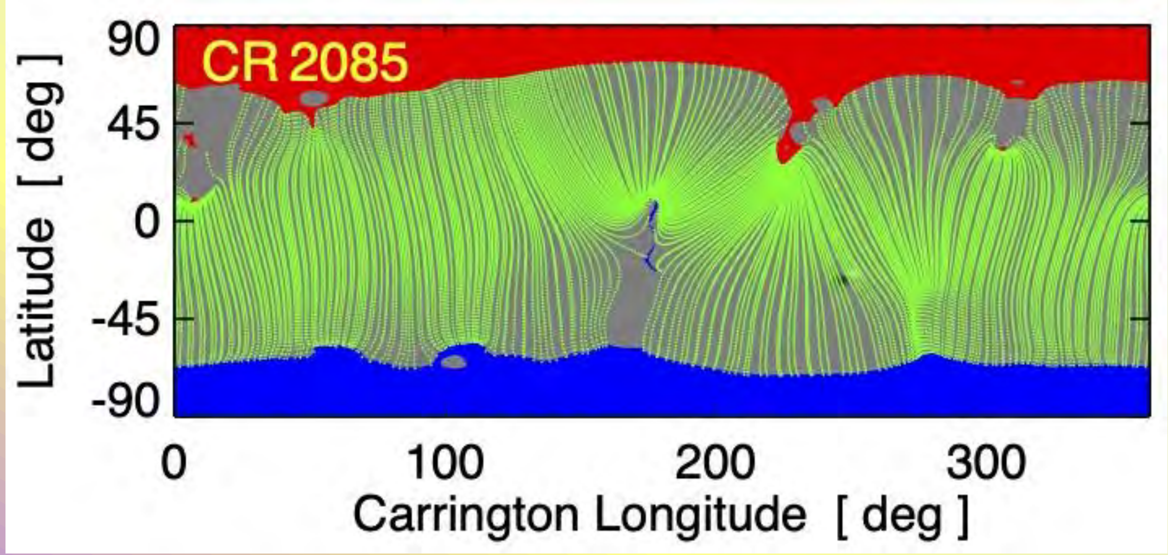


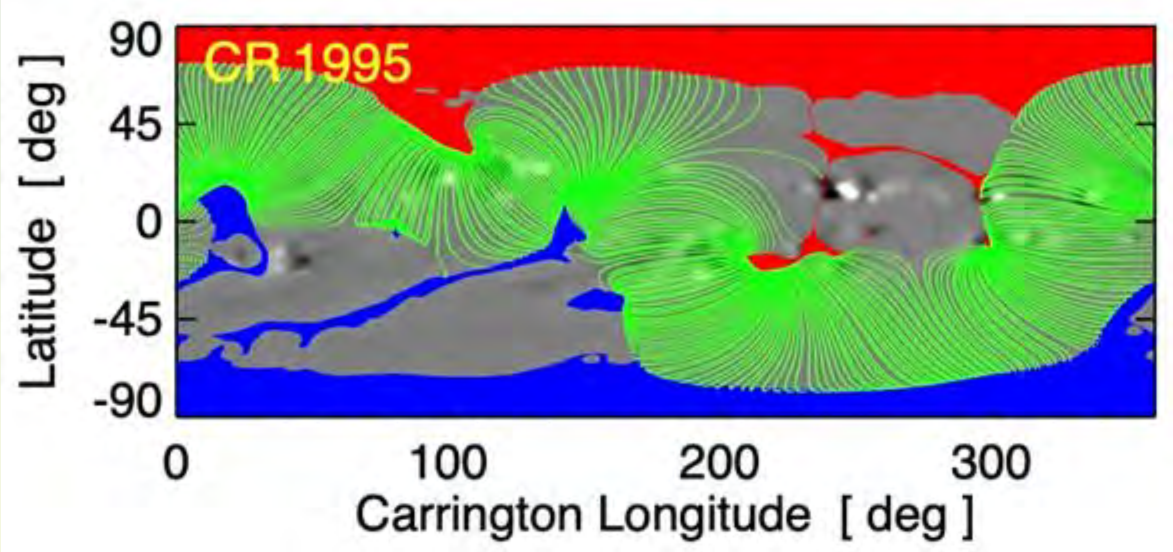
[Lynch & Edmondson 2013]

How good is the PFSS model? It's an extremely simplified model but given the observed photospheric magnetogram data as the lower boundary condition, can generate PFSS solutions for each 27.25-day period (Carrington Rotation) and look at solar cycle evolution. The PFSS model does give global magnetic field structures that reflect some aspects of the overall complexity! Is it right? No. Is it good enough? Depends on what you're trying to do---it does generate helmet streamer and pseudostreamer structures!



[Zhao et al. 2013]





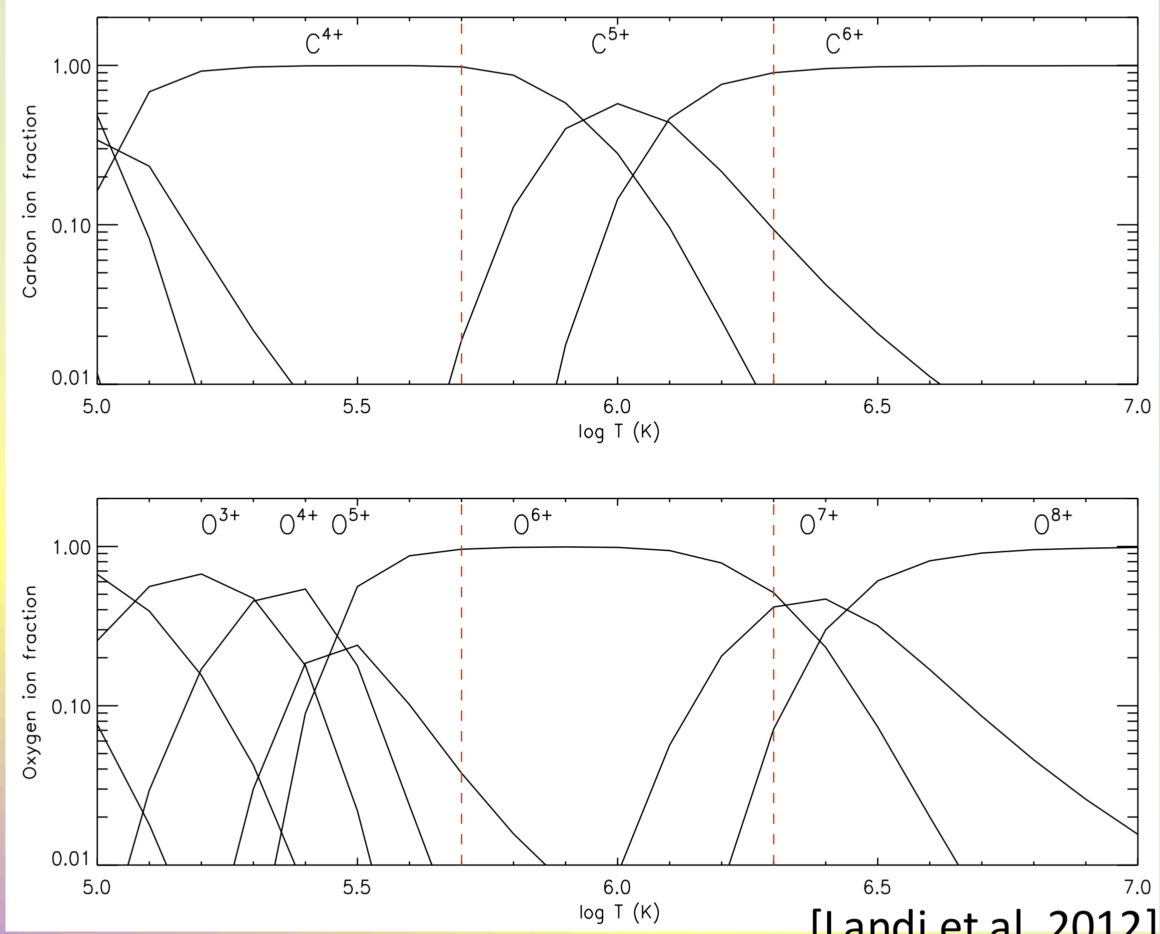
Solar Wind Composition: Tracing Plasma History

$$\frac{dy_i}{dt} = n_e\left[y_{i-1}I_{i-1} + y_{i+1}R_{i+1} - y_i\left(I_i + R_i\right)\right] + y_{i-1}P_{i-1} - y_iP_i$$

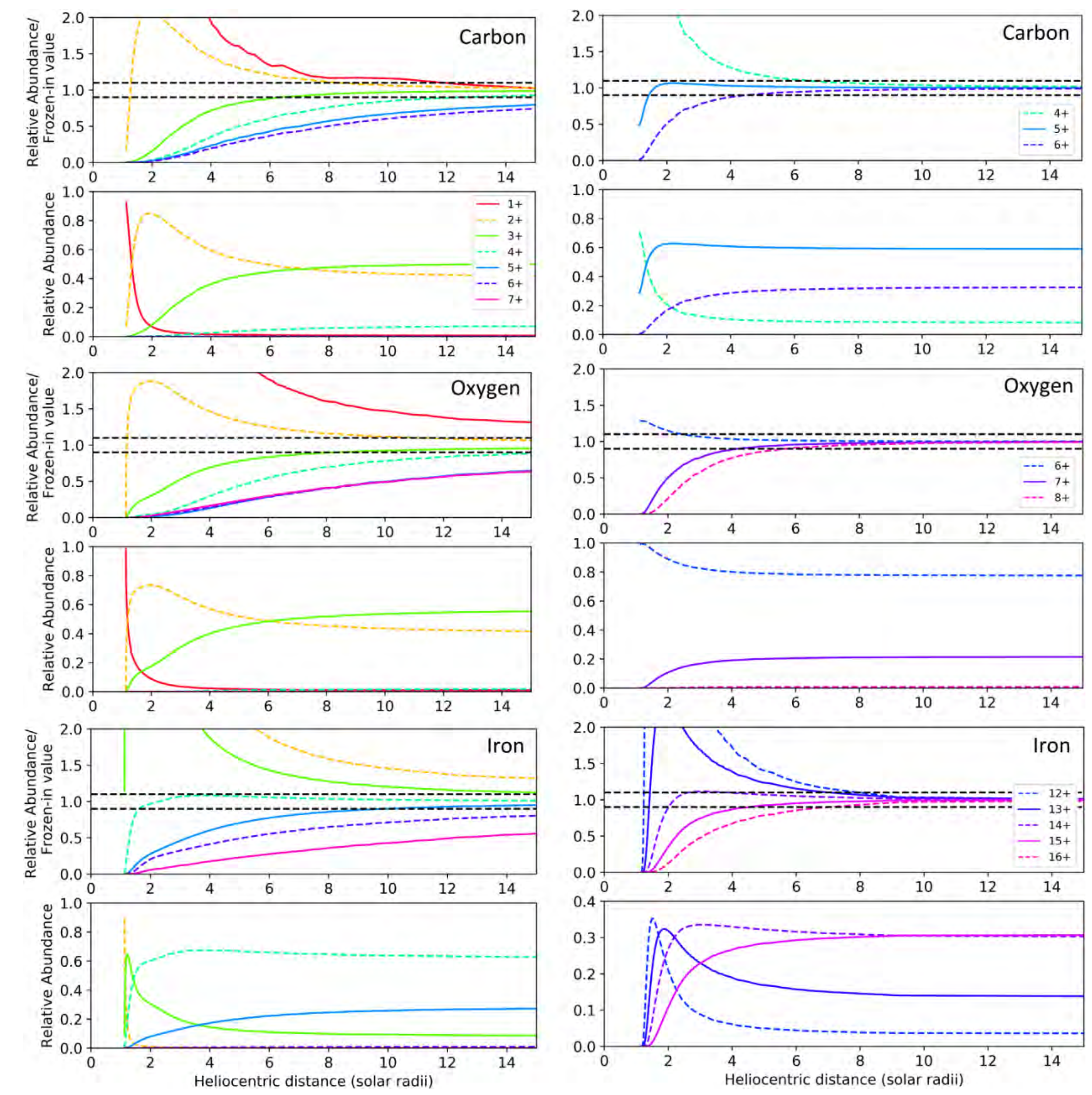
y_i = (fractional) ion density at charge state *i*

I_i, R_i = Ionization, Recombination rates for charge state *i*

P_i = Photoionization for charge state *i*



[Landi et al. 2012]

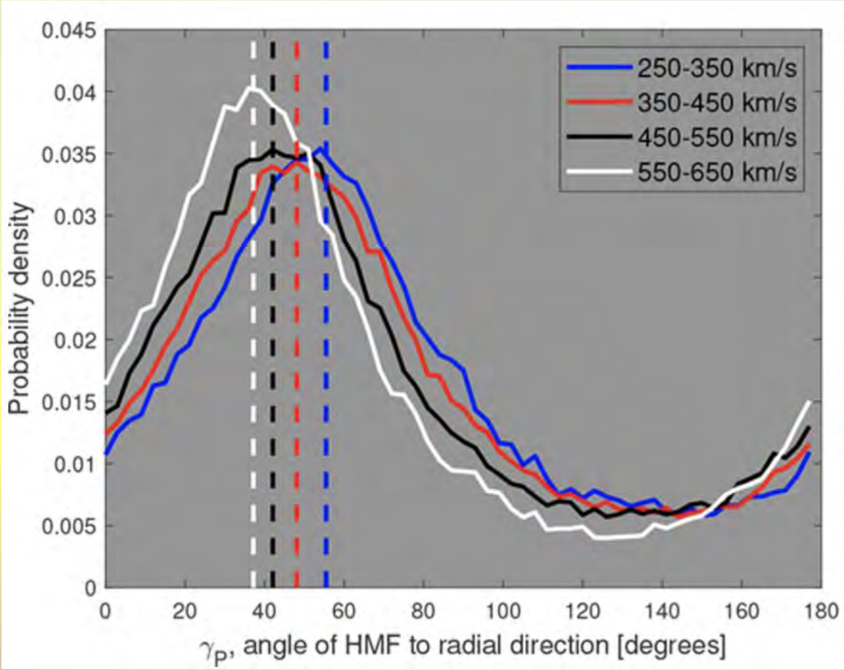


[Rivera et al. 2019]

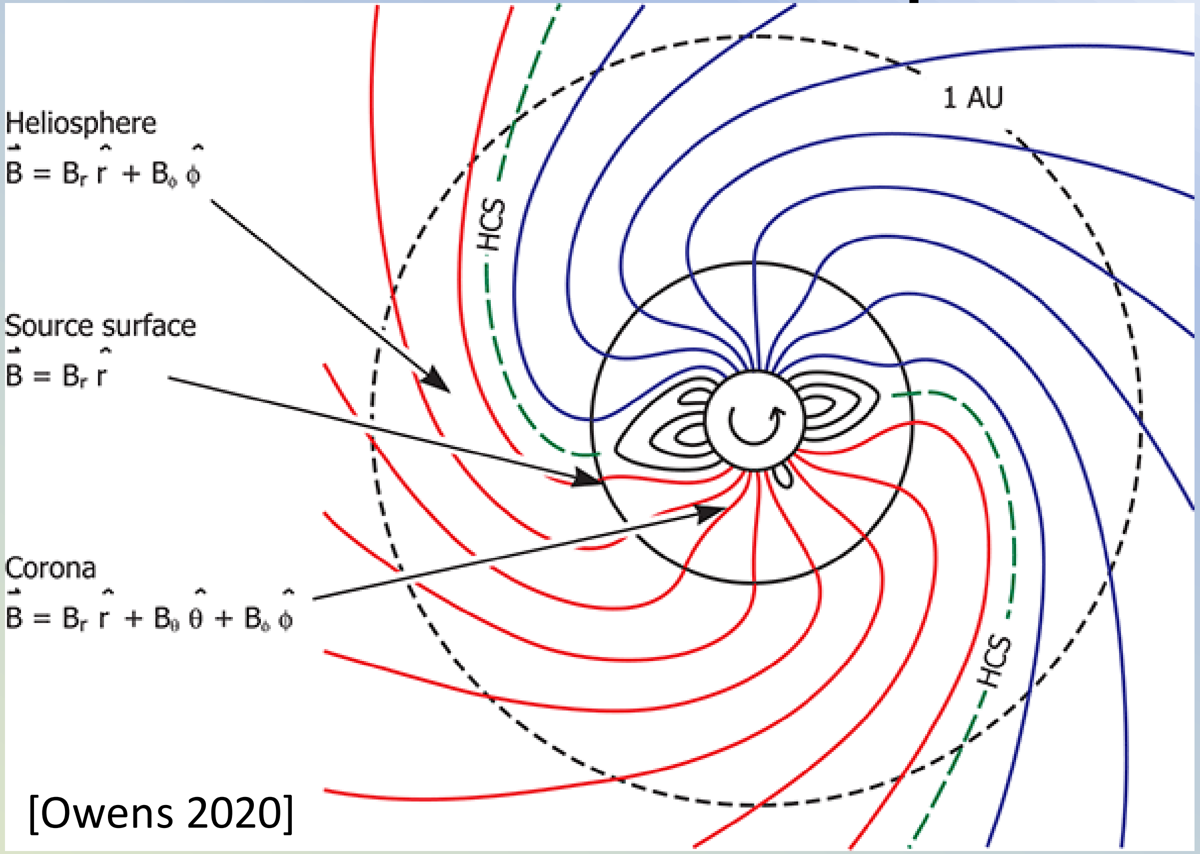
The Parker Spiral: Structure of the Inner Heliosphere

Assume the corona rotates rigidly at angular frequency Ω. Then the PFSS coronal field model solution at R_{ss} (which is purely radial) can be extended into the heliosphere, taking on an Archimedean spiral shape, i.e. the "Parker spiral".

$$\frac{B_\phi(r,\theta,\phi)}{B_r(r,\theta,\phi)} = \frac{v_\phi(r,\theta,\phi)}{v_r} = \frac{-\Omega r \sin\theta}{v_r}$$



[Owens 2020, updated from Owens & Forsyth 2013]



[Owens 2020]

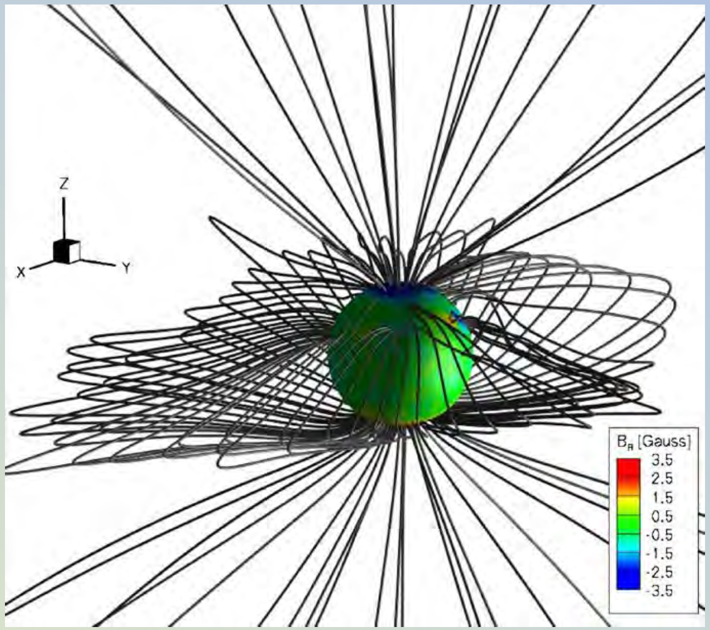
Can calculate the expected angle of the heliospheric magnetic field at 1 AU and get ~45^o for "slow" solar wind ~400 km/s, which is more-or-less what is observed!

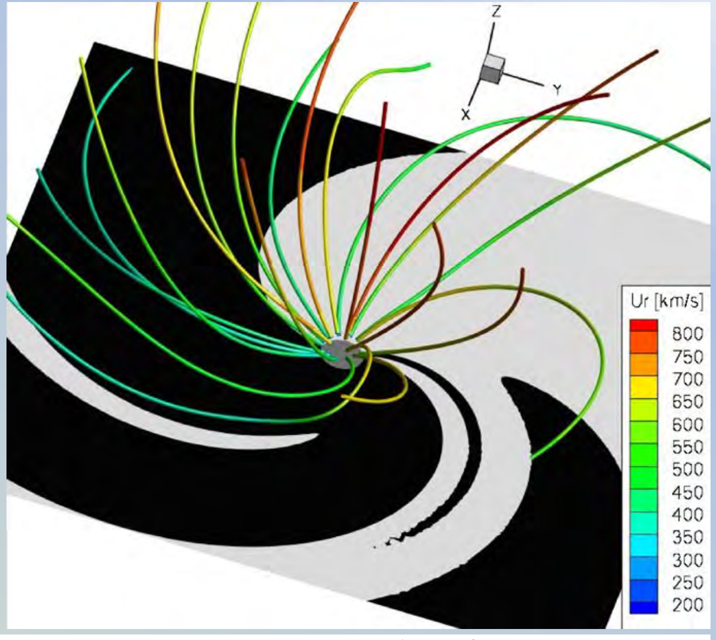
- We now have all the pieces to "connect" in-situ solar wind measurements to where they originate in the solar corona

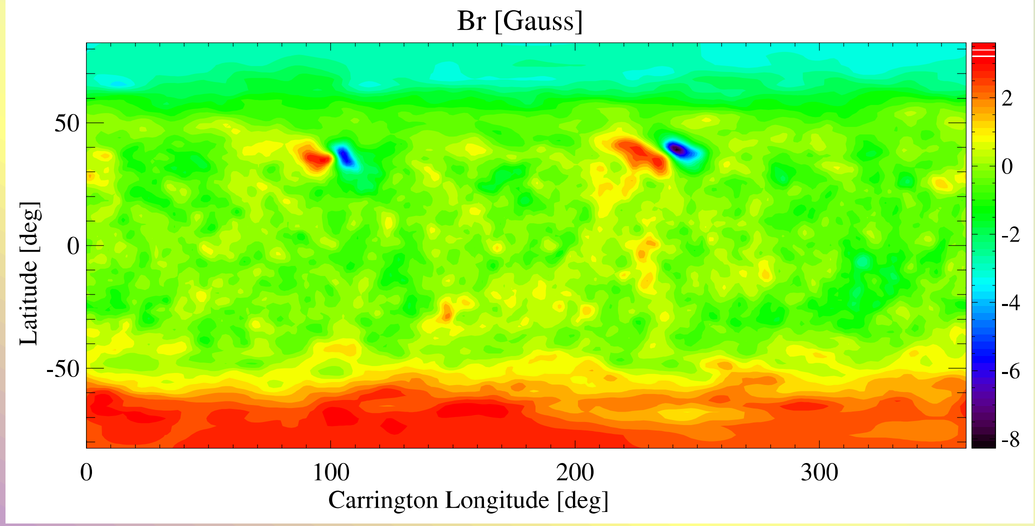
The "Steady State" Solar Wind Picture

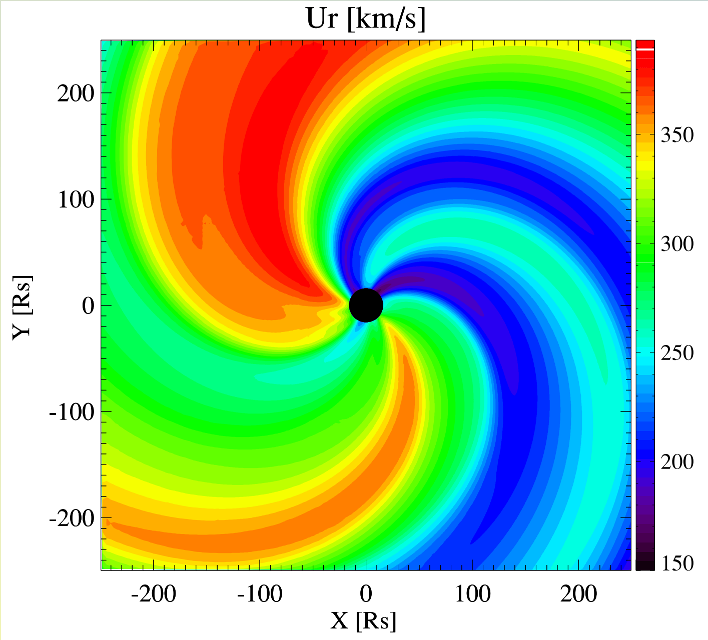
University of Michigan Space Weather Modeling Framework (SWMF) --- one of the most sophisticated, state-of-the-art 3D MHD codes for coronal and heliospheric modeling!

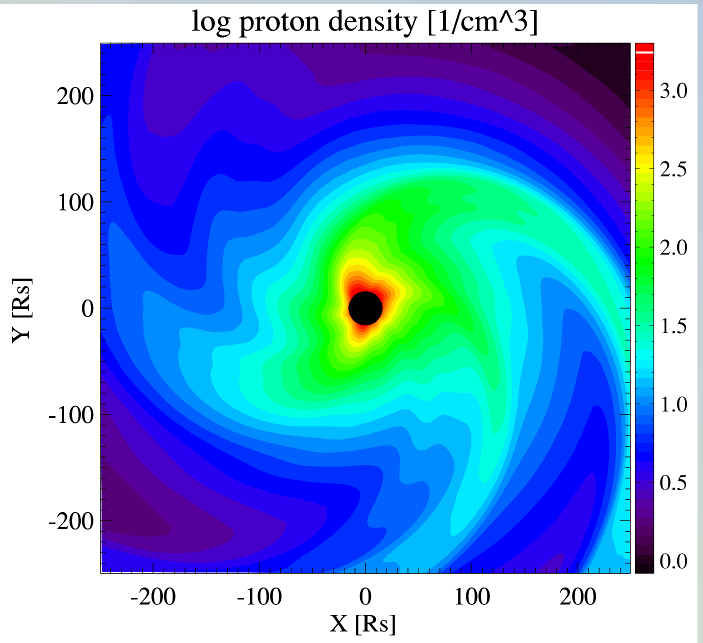
Alfven Solar Wind Model (AWSoM) developed by van der Holst et al. [2014] and colleagues use turbulent dissipation/wave-heating for a more realistic "coronal heating" temperature. Start w/ synoptic magnetogram, heat corona, get 3D density, temperature, velocity distributions throughout inner heliosphere.







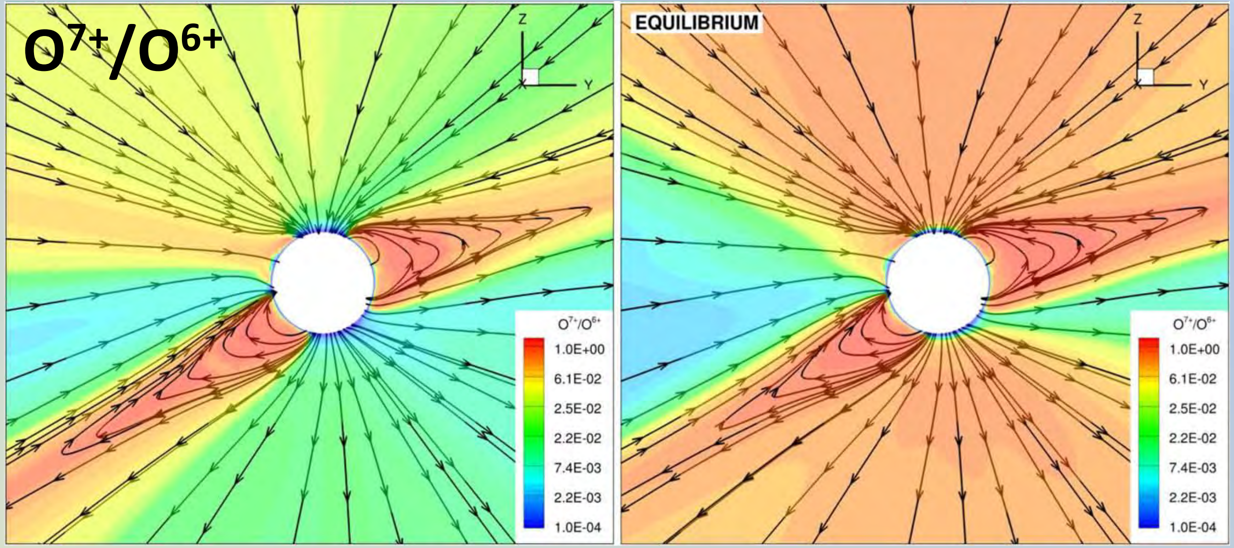


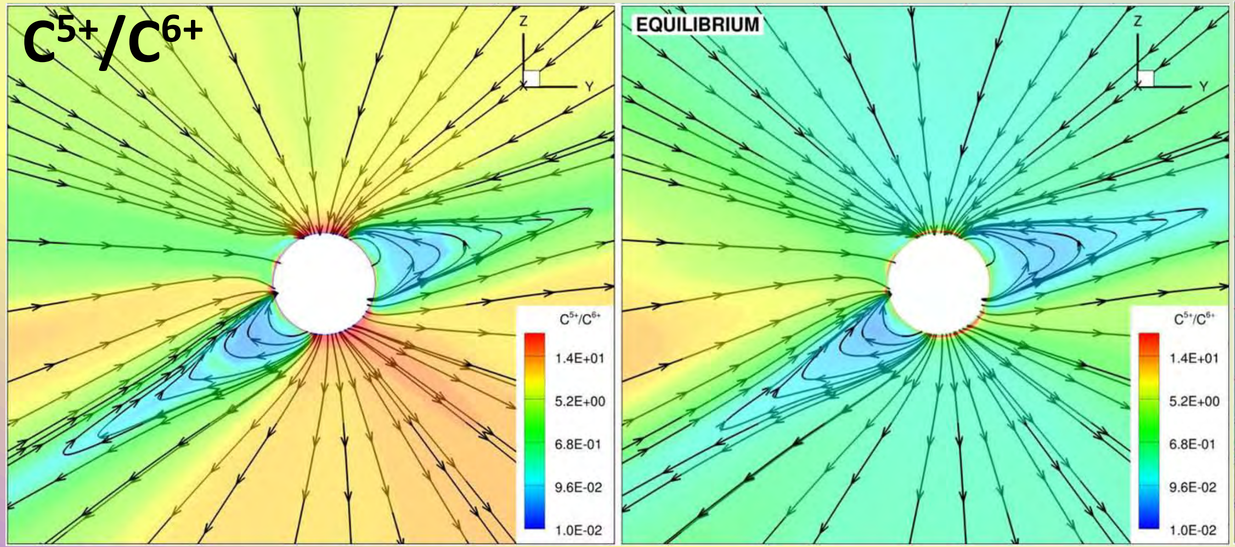


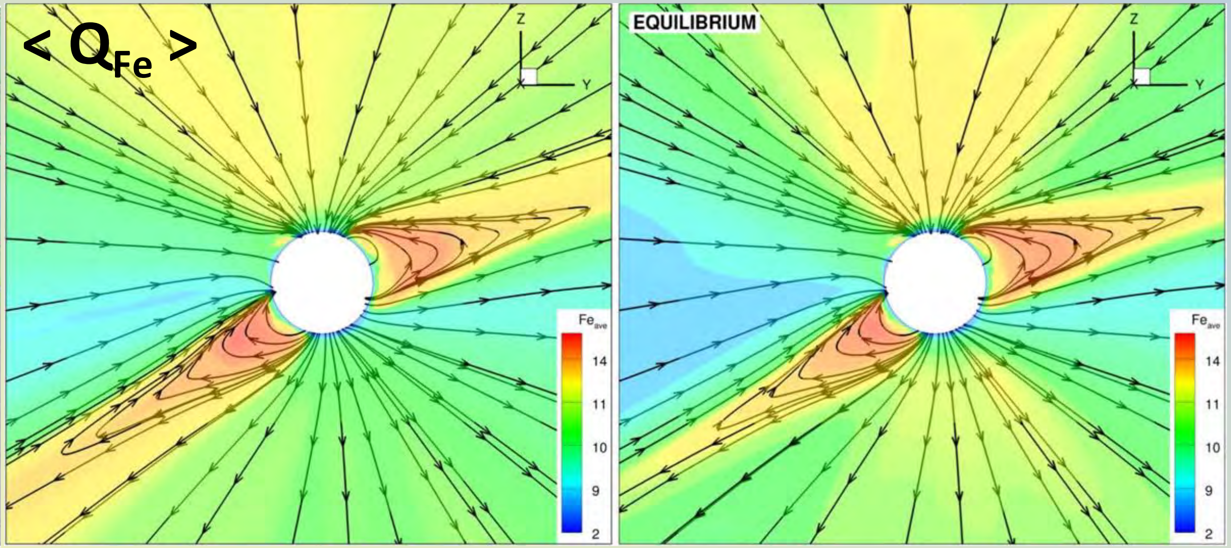
The "Steady State" Solar Wind Picture

Once you have density, velocity, temperature everywhere, can combine these with ionic charge state calculations. E.g., Szente et al. [2022] have used SWMF/AWSoM to model fully 3D ionic charge state distributions for direct comparison with in-situ observations.

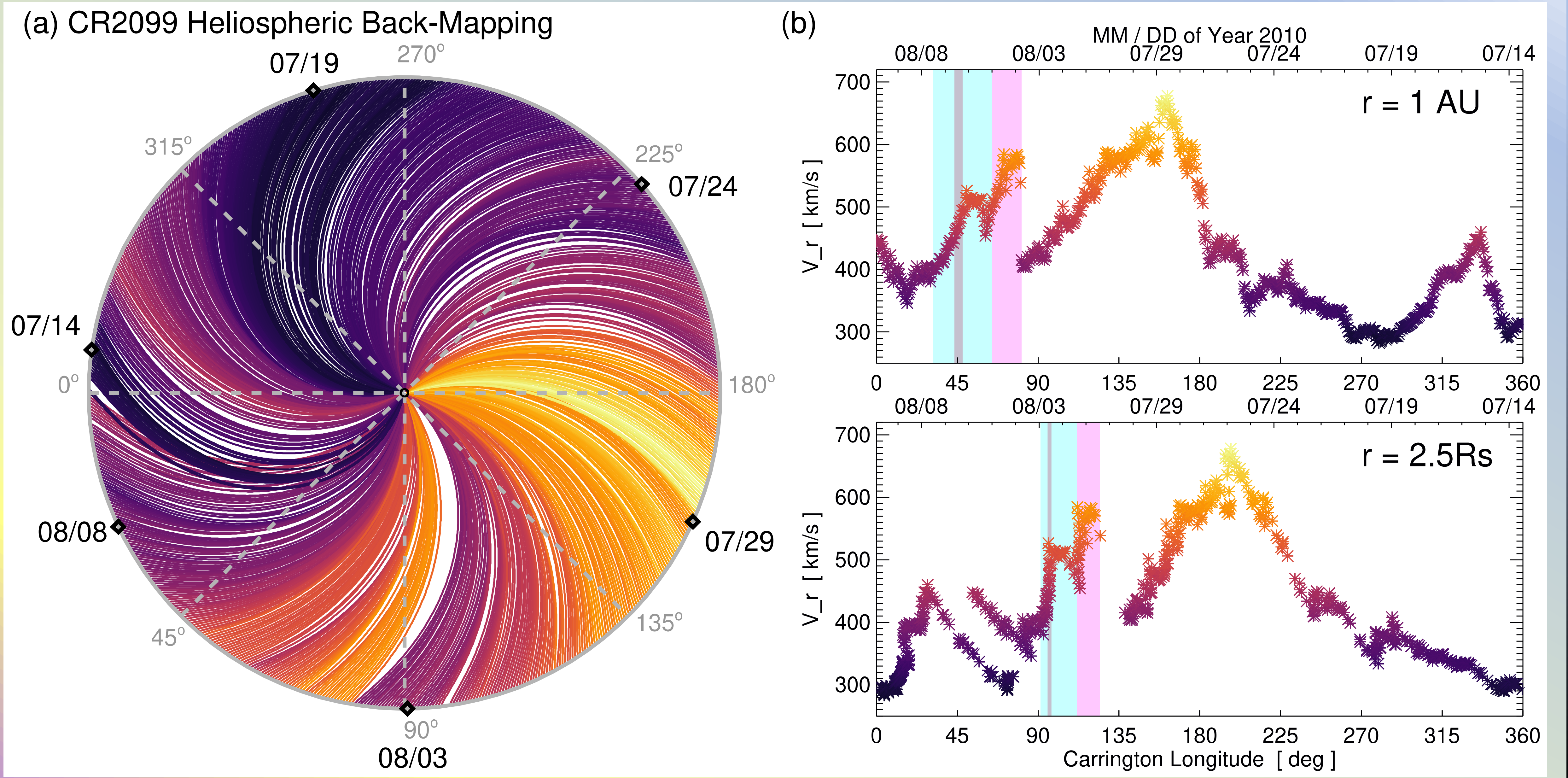
Closed-field plasma within helmet streamer flux systems show elevated O^{7+}/O^{6+} (>1.0), low C^{5+}/C^{6+} (or elevated C^{6+}/C^{5+}), and elevated $\langle Q_{Fe} \rangle$ (>12+). <u>Therefore, plasma originating in closed-flux regions will have distinct composition signatures!</u>



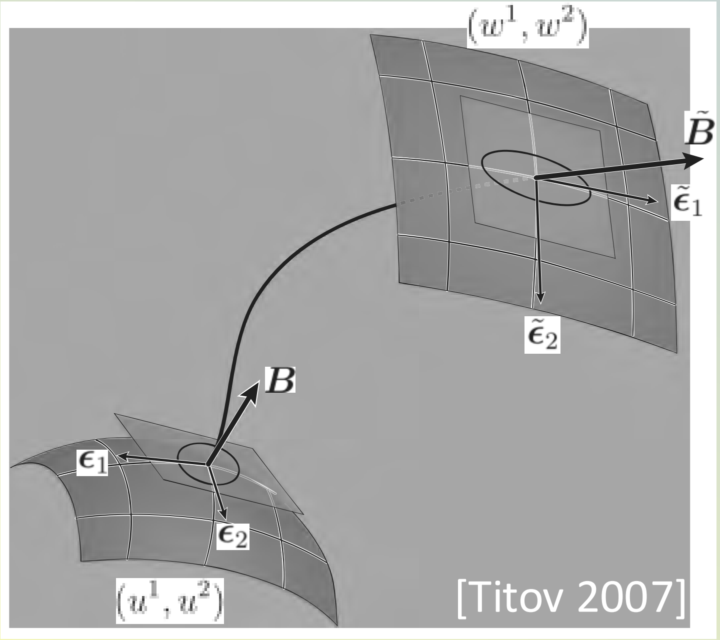




Magnetic Connectivity: Heliospheric Back-Mapping



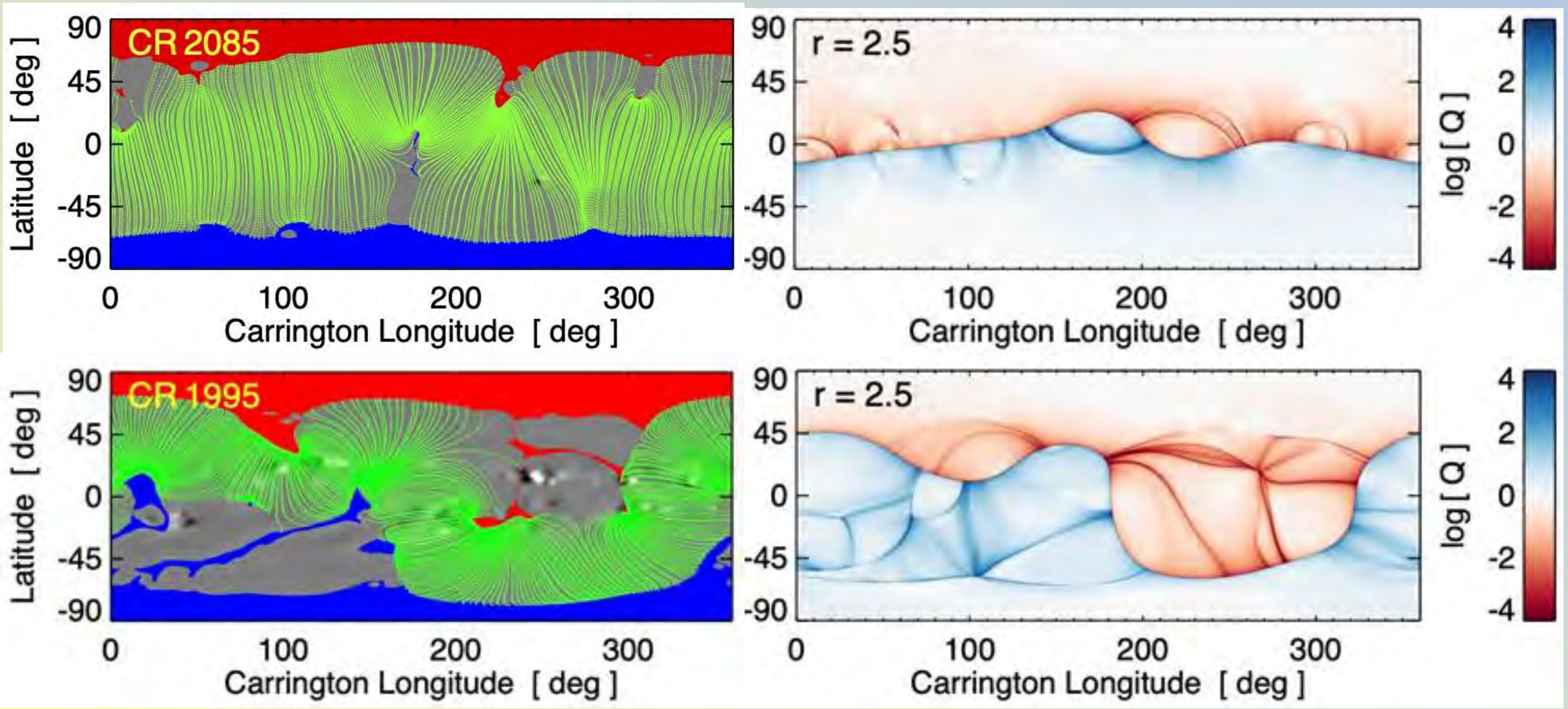
The Separatrix Web – Quantifying Magnetic Topology



Squashing factor developed by **Titov** [**2007**] defined as Q = N^2/Δ

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

Measure field line divergence between field line starting point ($R_\odot, \theta, \phi$) and ending point (R^*, Θ, Φ). Regions of high Q = separatrix surfaces between flux systems: accumulate STRONG current densities, so favorable sites for magnetic reconnection!



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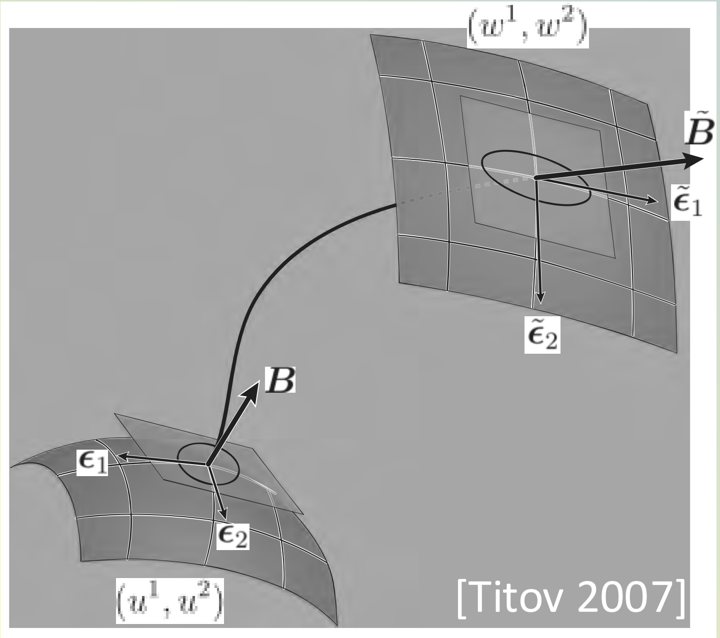

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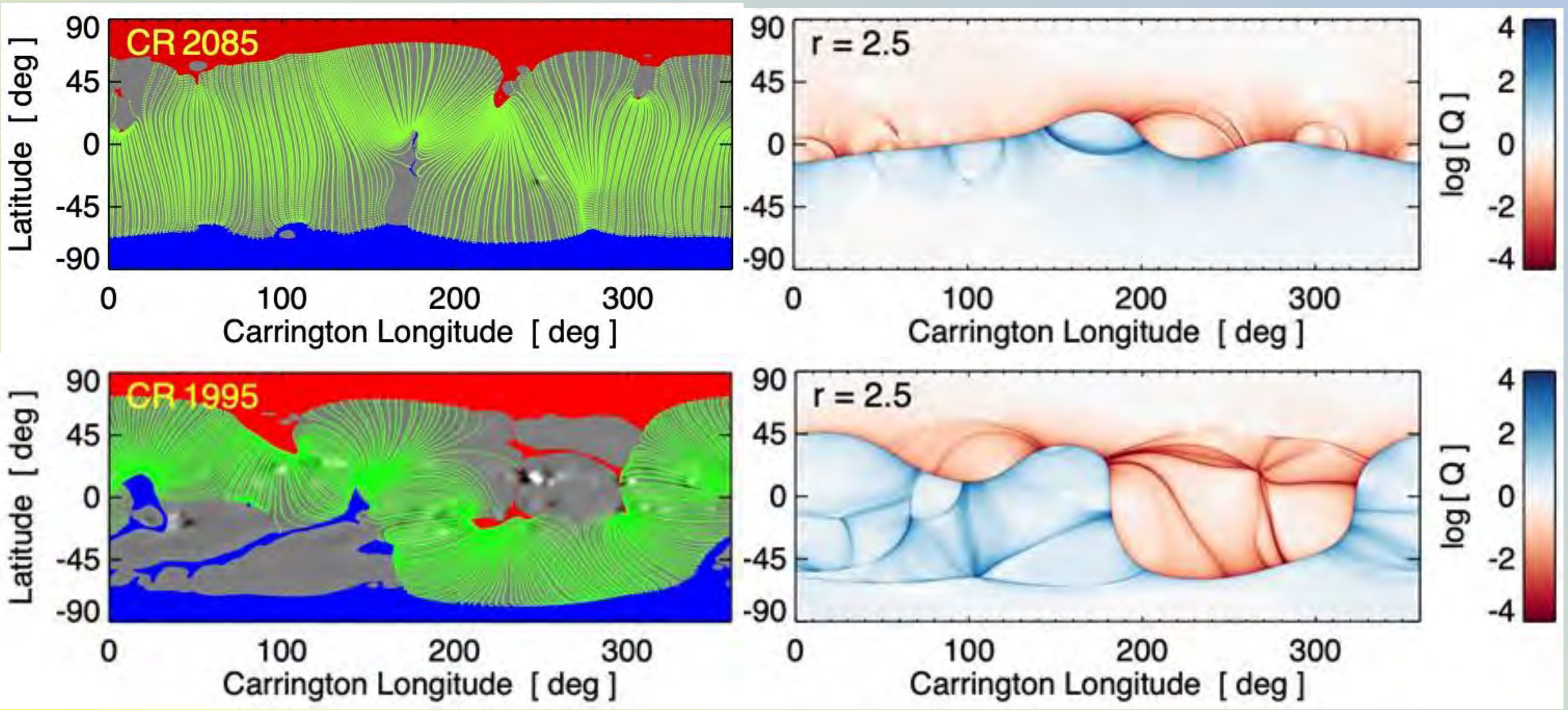
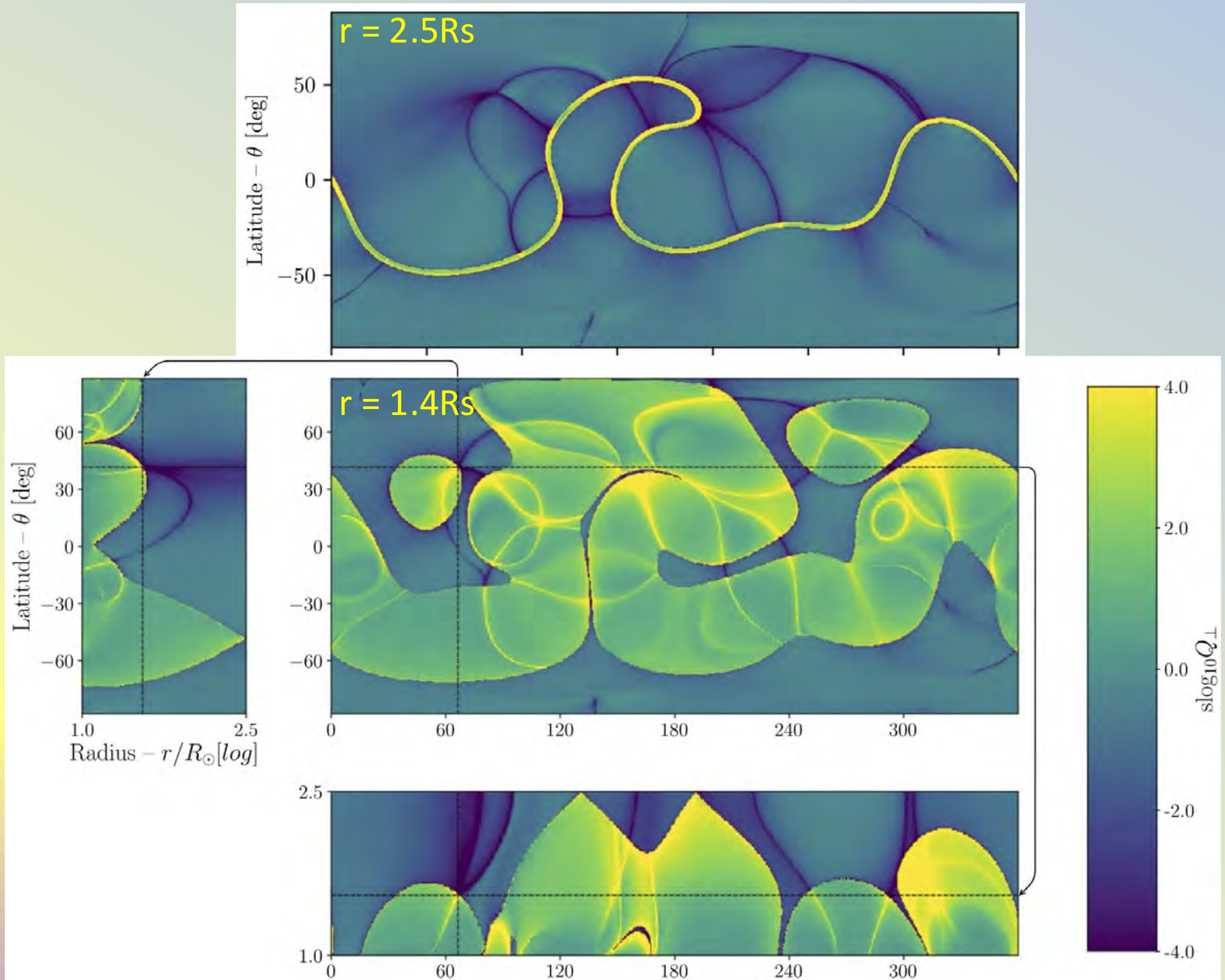
Measure field line divergence between field line starting point ($R_\odot, \theta, \phi$) and ending point (R^*, Θ, Φ). Regions of high Q = separatrix surfaces between flux systems: accumulate STRONG current densities, so favorable sites for magnetic reconnection!

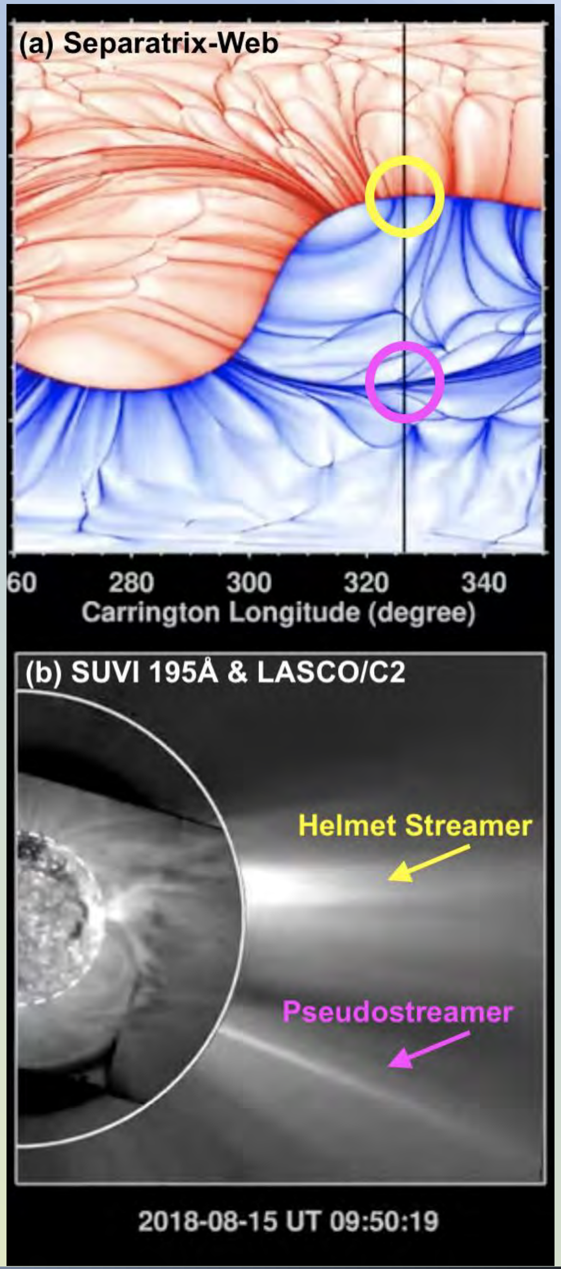
Q-Maps are now a standard data product from HMI team! **Calculated from PFSS solutions using HMI & MDI synoptic maps:**
http://hmi.stanford.edu/QMap/



The Separatrix Web – Quantifying Magnetic Topology

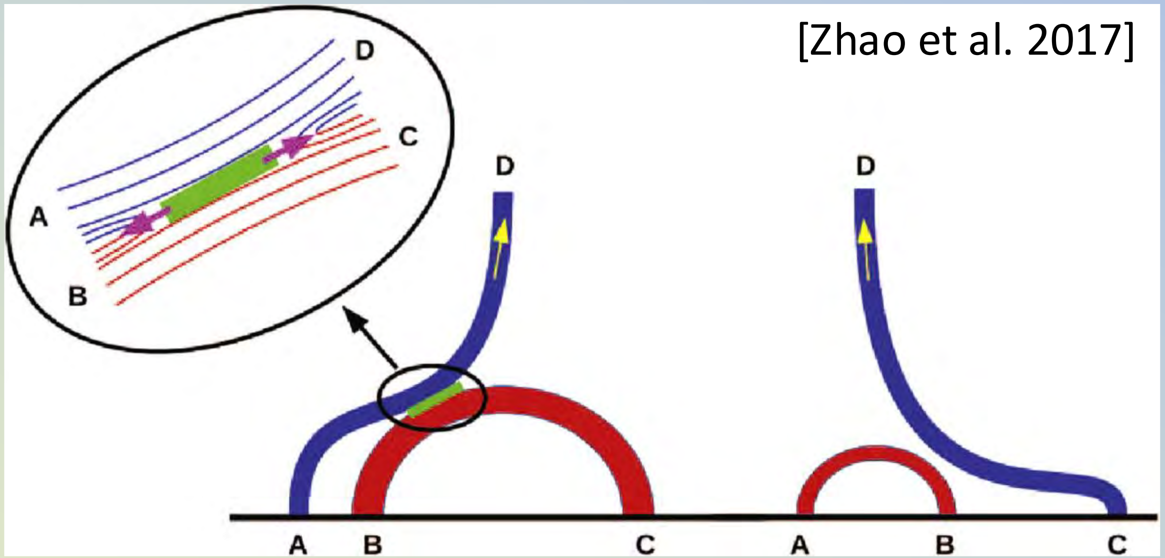


[Scott et al. 2019]

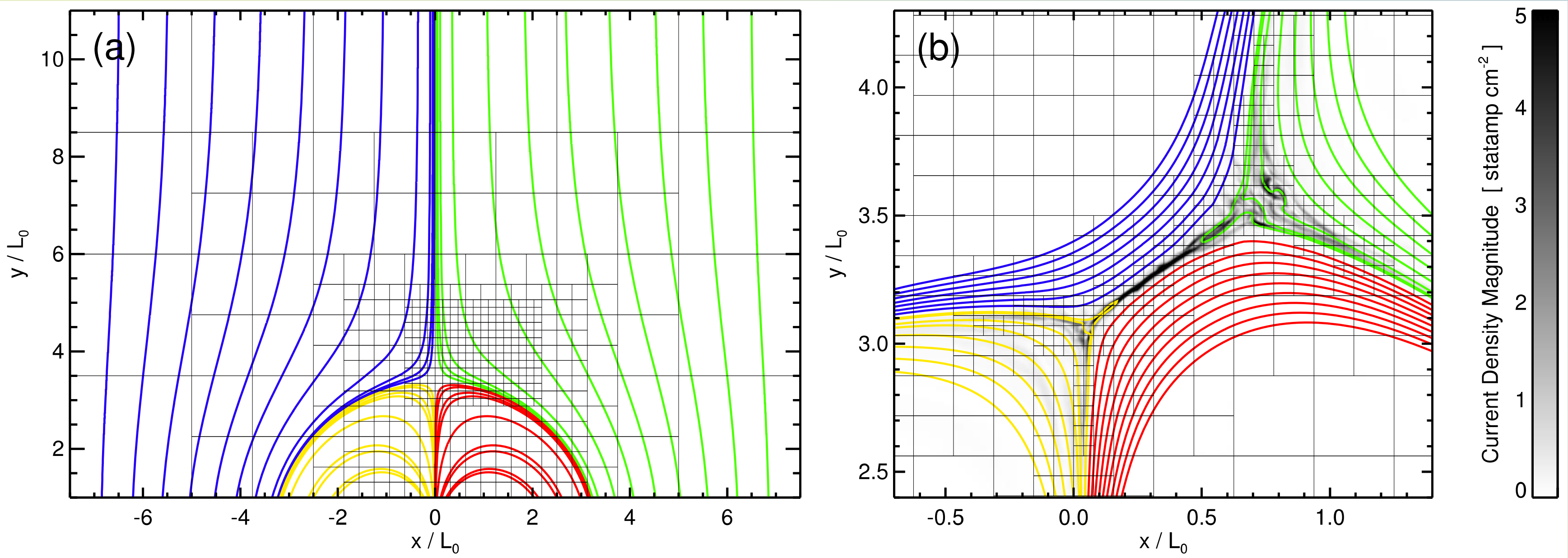


[Chitta et al. 2021]

Magnetic Reconnection (in the Solar Corona)



[Edmondson & Lynch 2017]

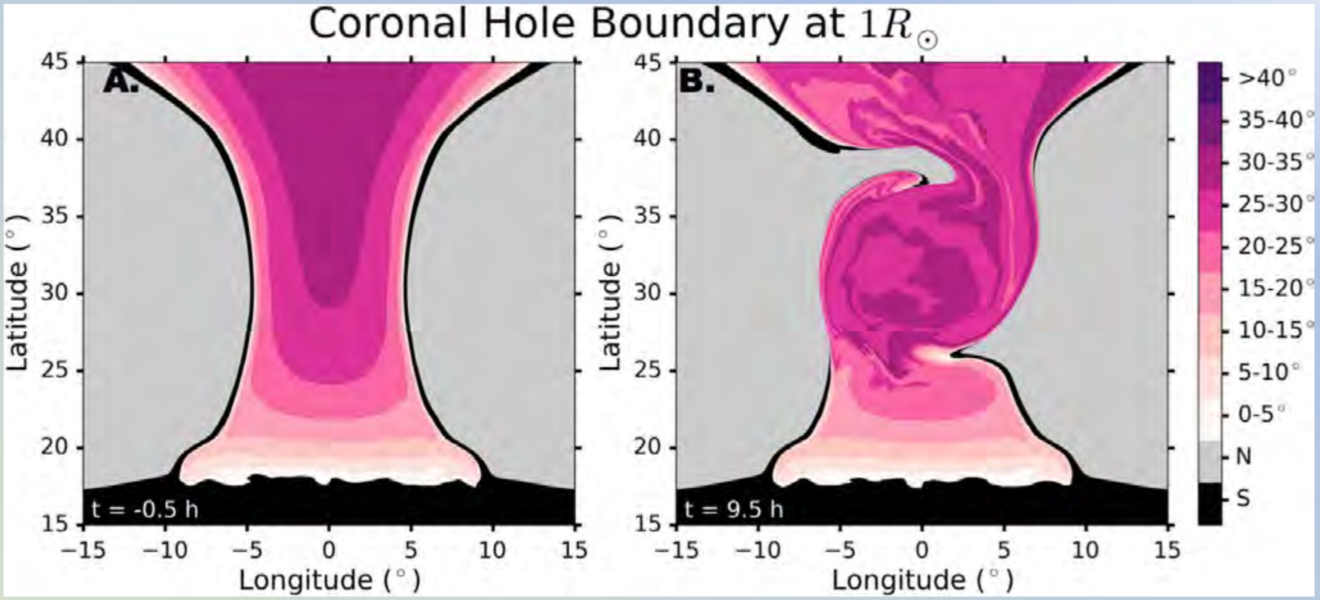


Magnetic Reconnection (in the Solar Corona)

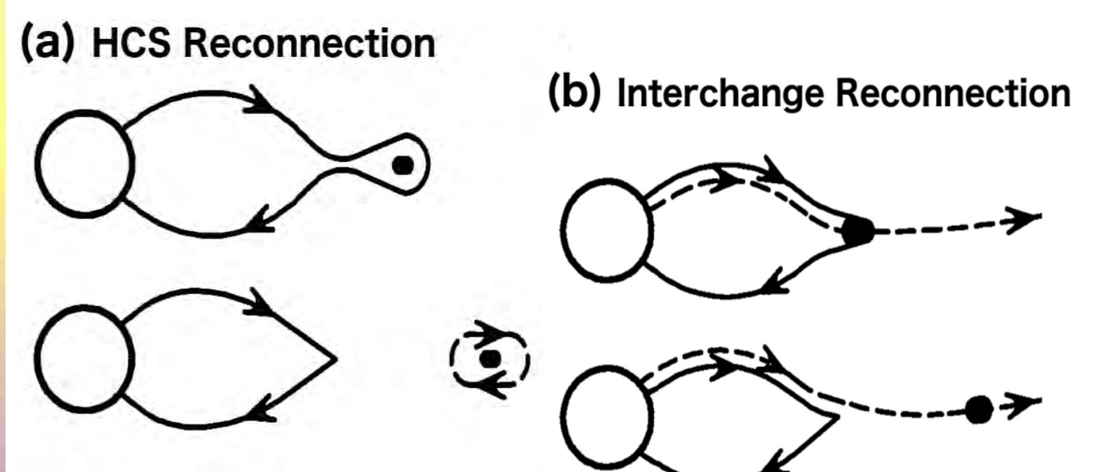
Helmet streamer cusps → HCS. Y-type null point + boundary perturbations = reconnection

Separatrix surface between open and closed:

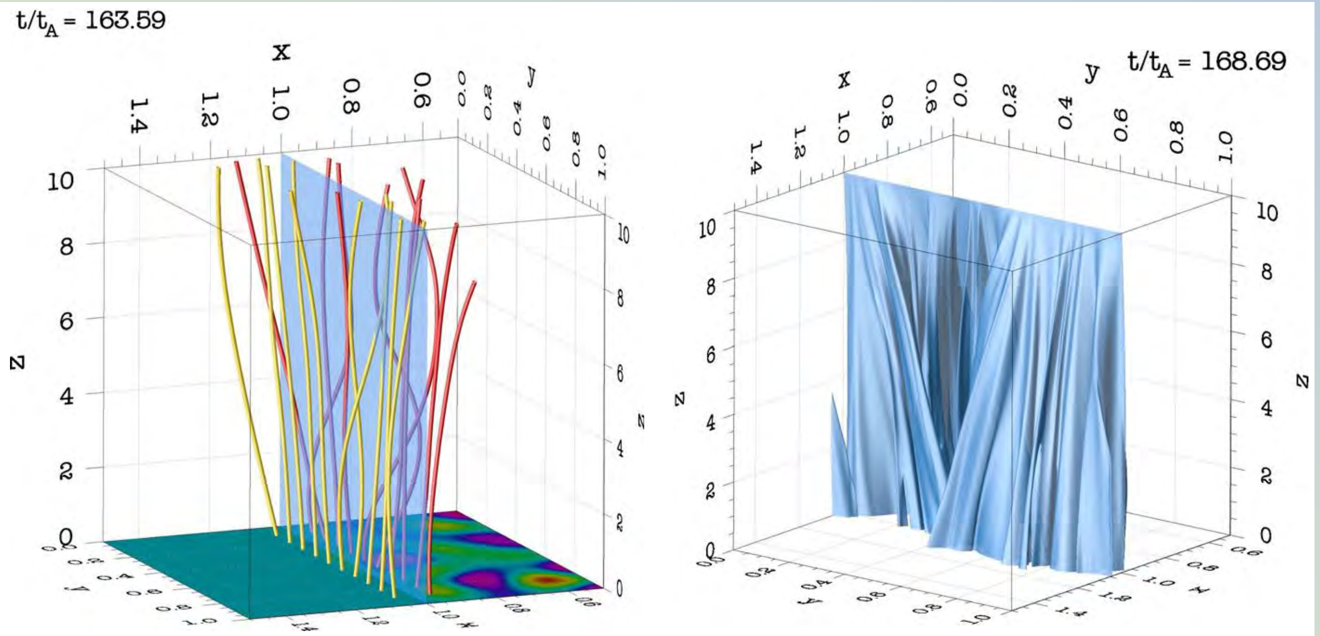
- drastic change in connectivity
- favorable site for currents
- system trying to shed stress/dissipate current structures (to open fields)
- **generation of fine-scale structure!**



[Higginson et al. 2017]

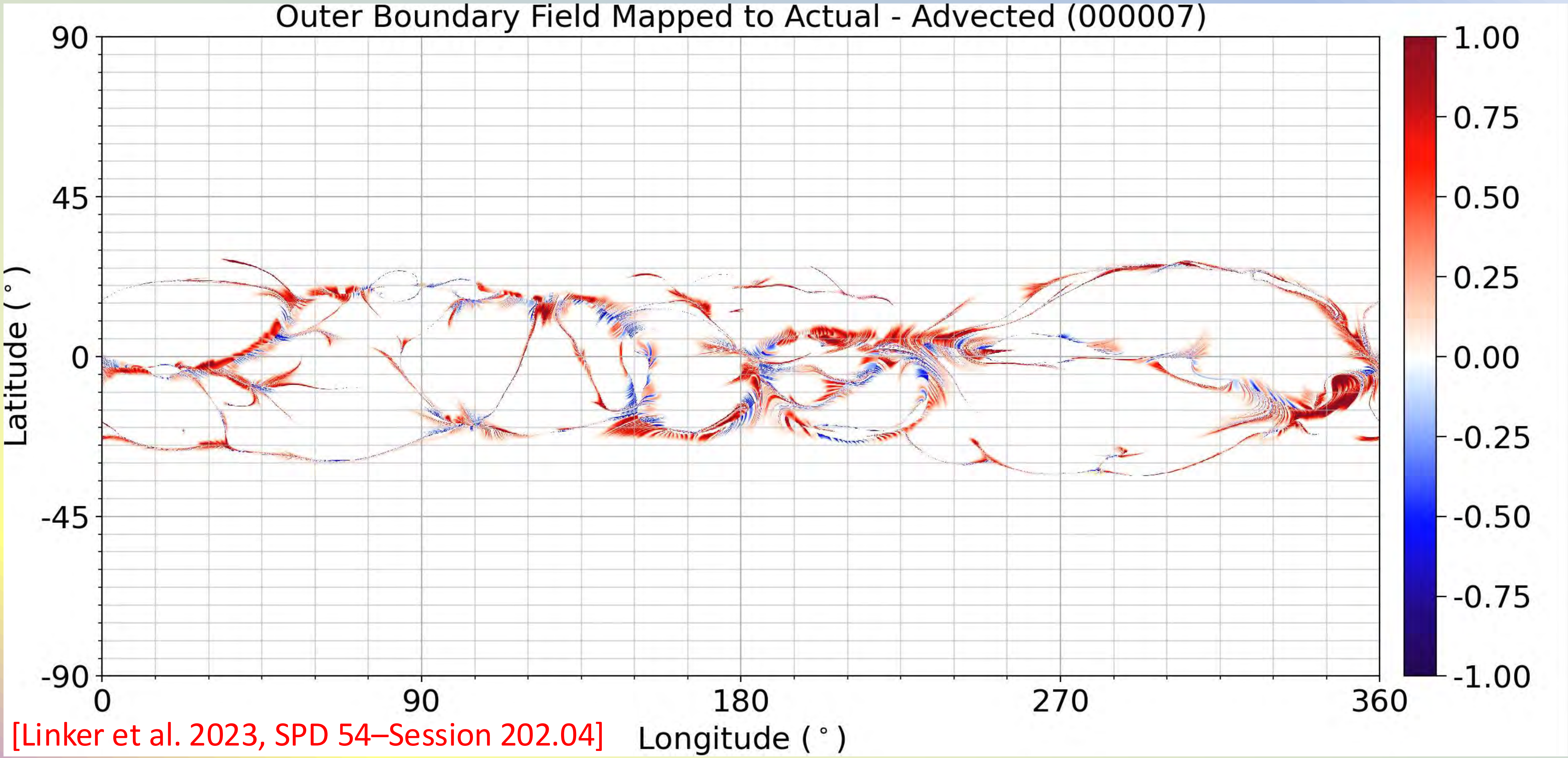


[Wang et al. 2000]



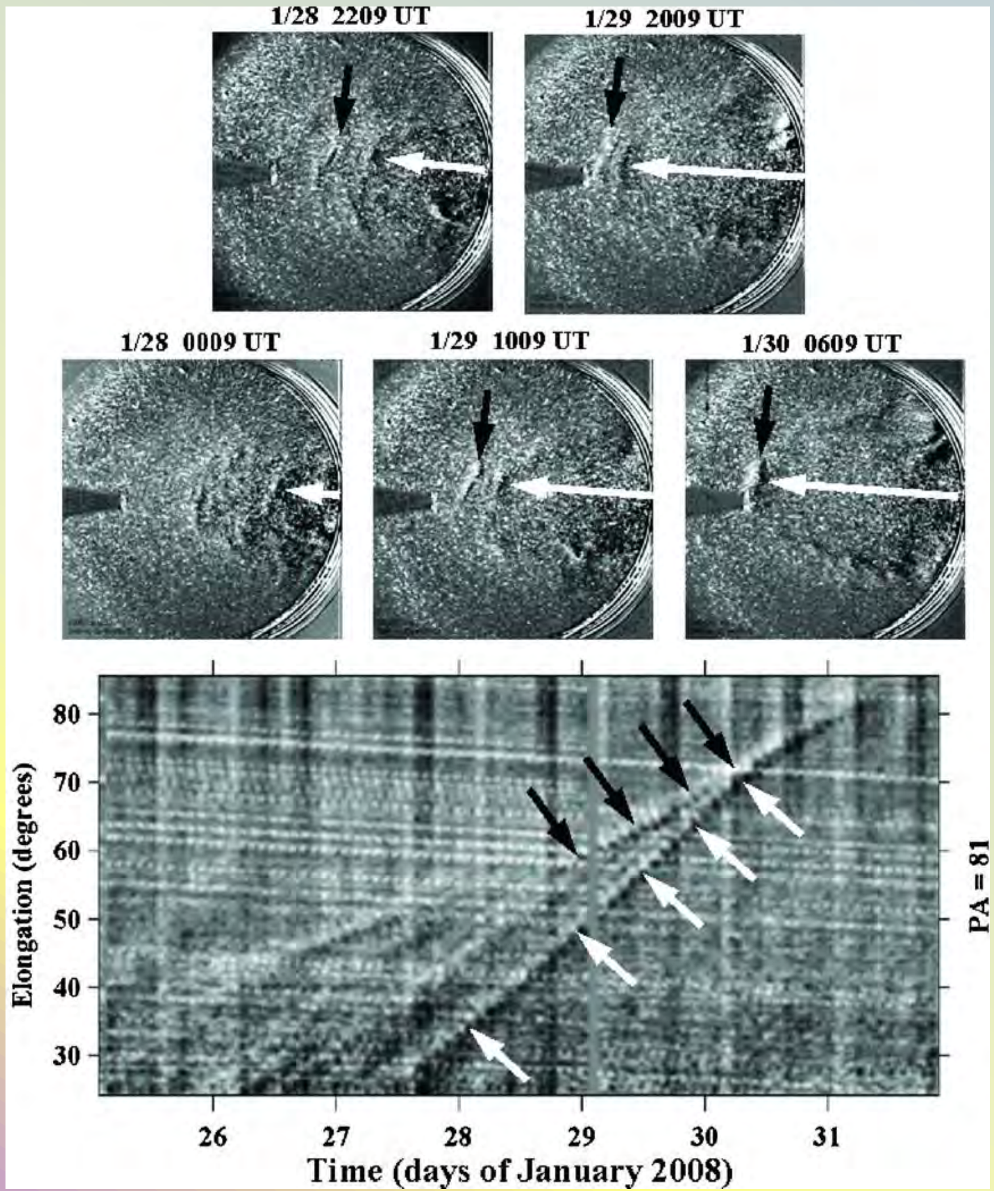
[Rappazzo et al. 2017]

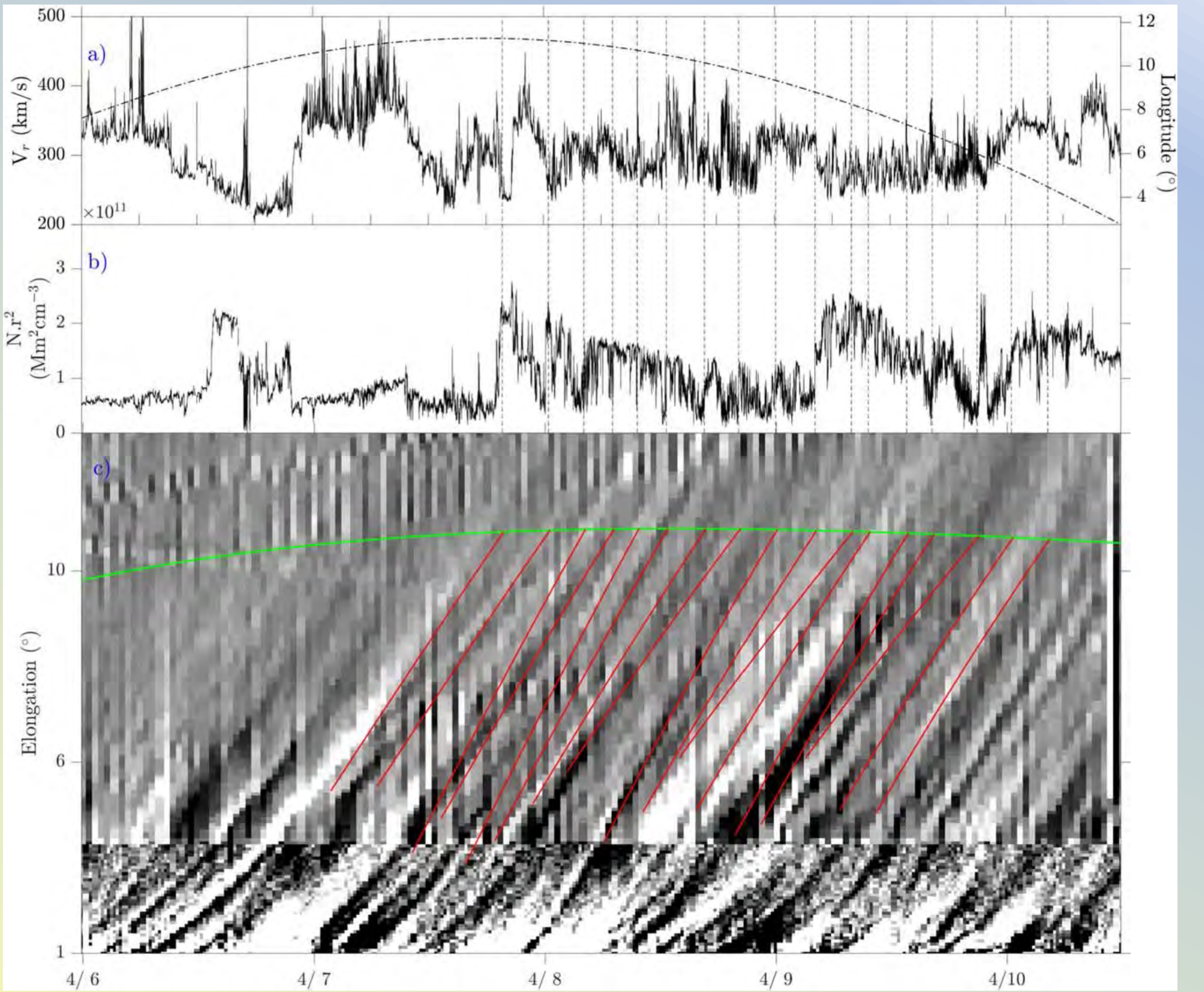
Dynamic Separatrix Web – Magnetic Reconnection



[Linker et al. 2023, SPD 54–Session 202.04]

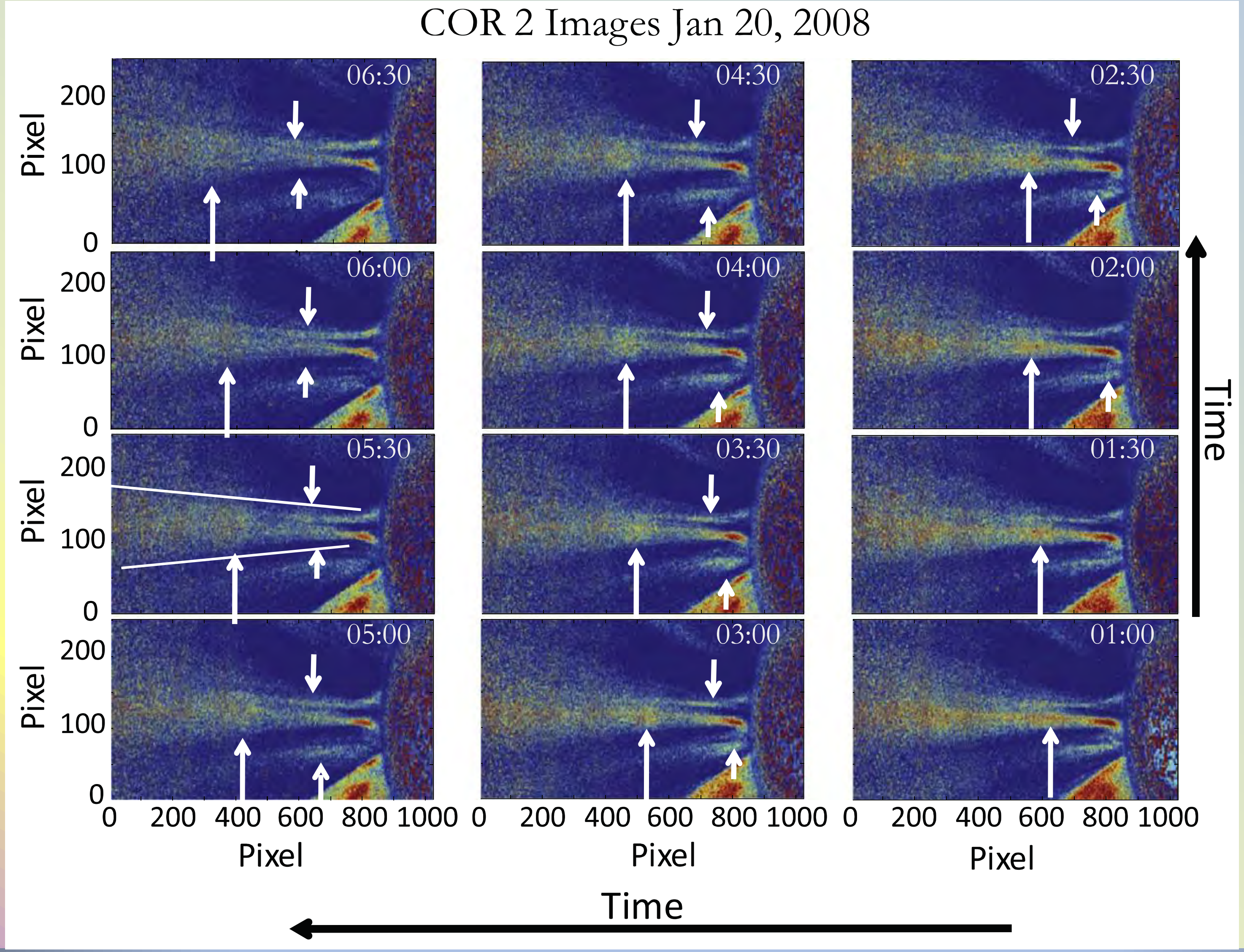
Helmet Streamer "Blobs" (Small Magnetic Flux Ropes)

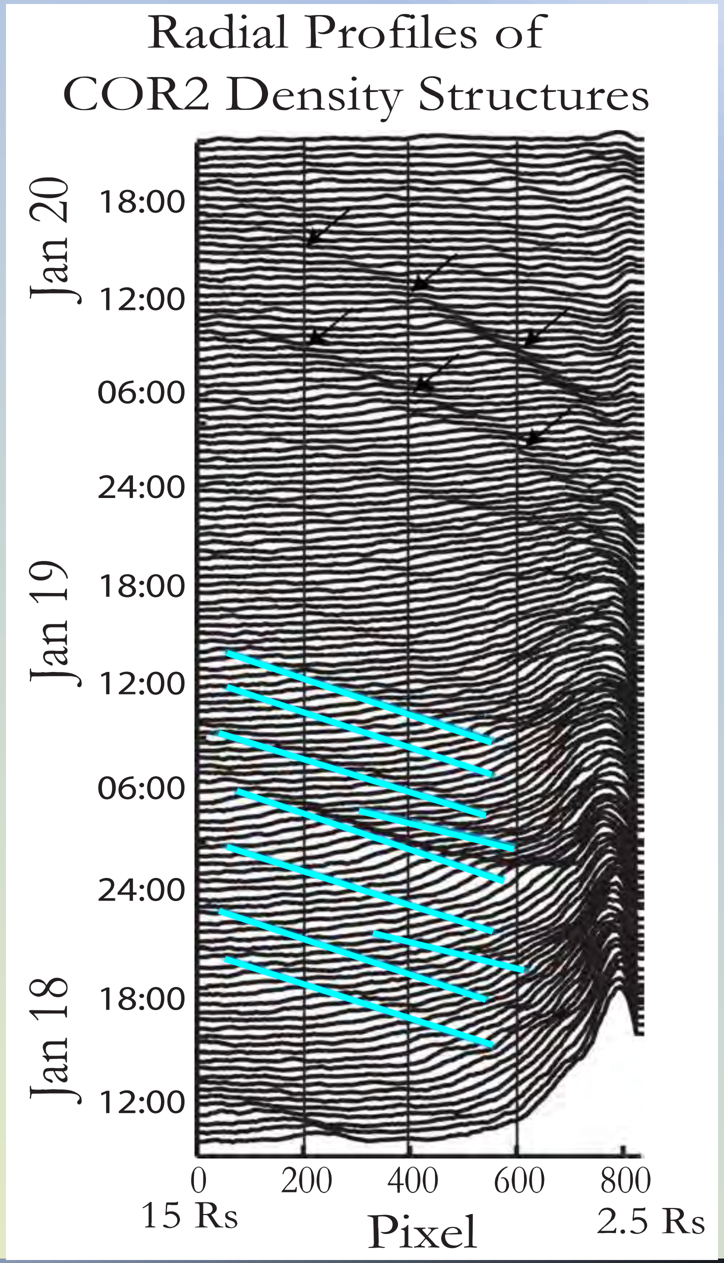




~90 min Structures in Coronagraph + In-situ Data

Viall & Vourlidas [2015] found "a train of ~90 min structures" in STEREO/COR2 white-light coronagraph data

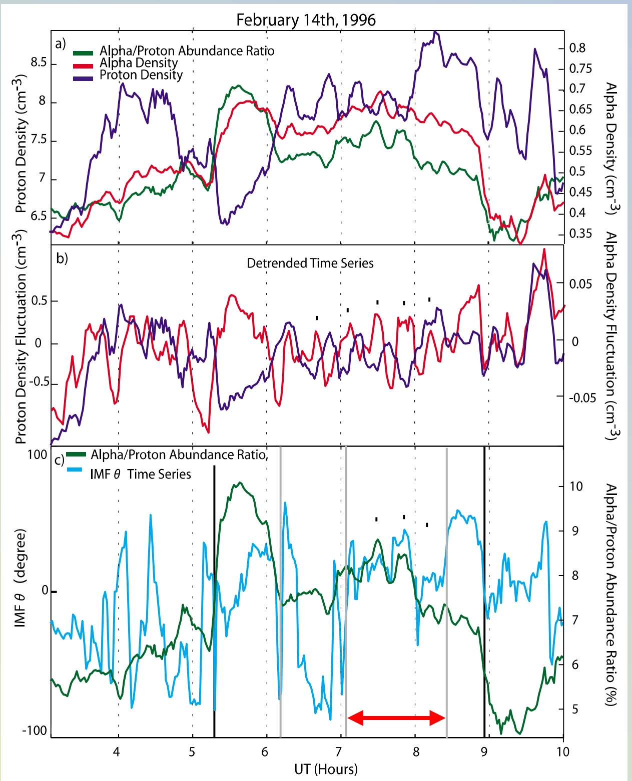




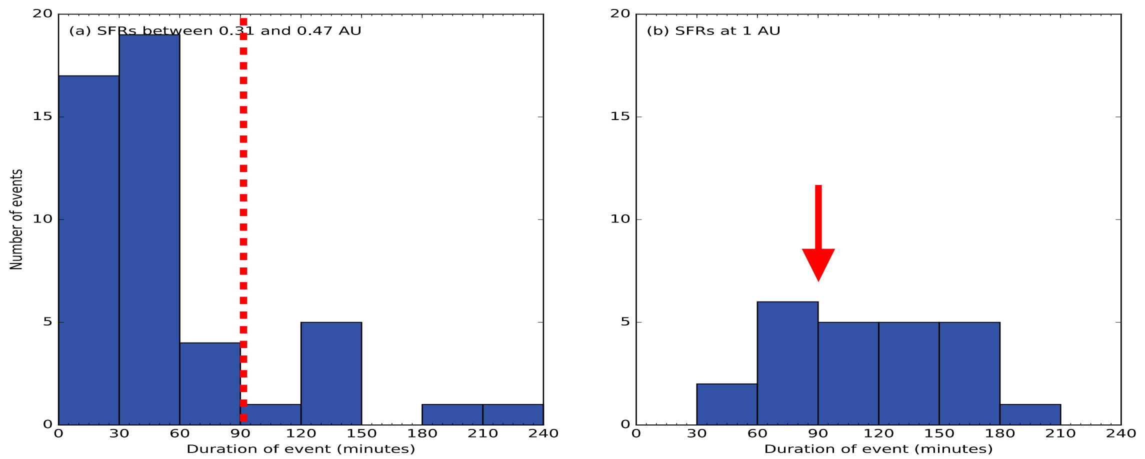
~90 min Structures in Coronagraph + In-situ Data

In addition to periodic proton density structures [Viall et al. 2008, Kepko et al. 2020], Viall et al. [2009] showed that alpha composition also has periodic structures at smaller scales (note 90 min envelope), Kepko et al. [2016] showed ~90 min structure in He, C, O, and Murphy et al. [2020] looked at small FRs in MESSENGER data and compared with earlier 1AU results from Feng et al. [2008] and Cartwright & Moldwin [2008,2010].

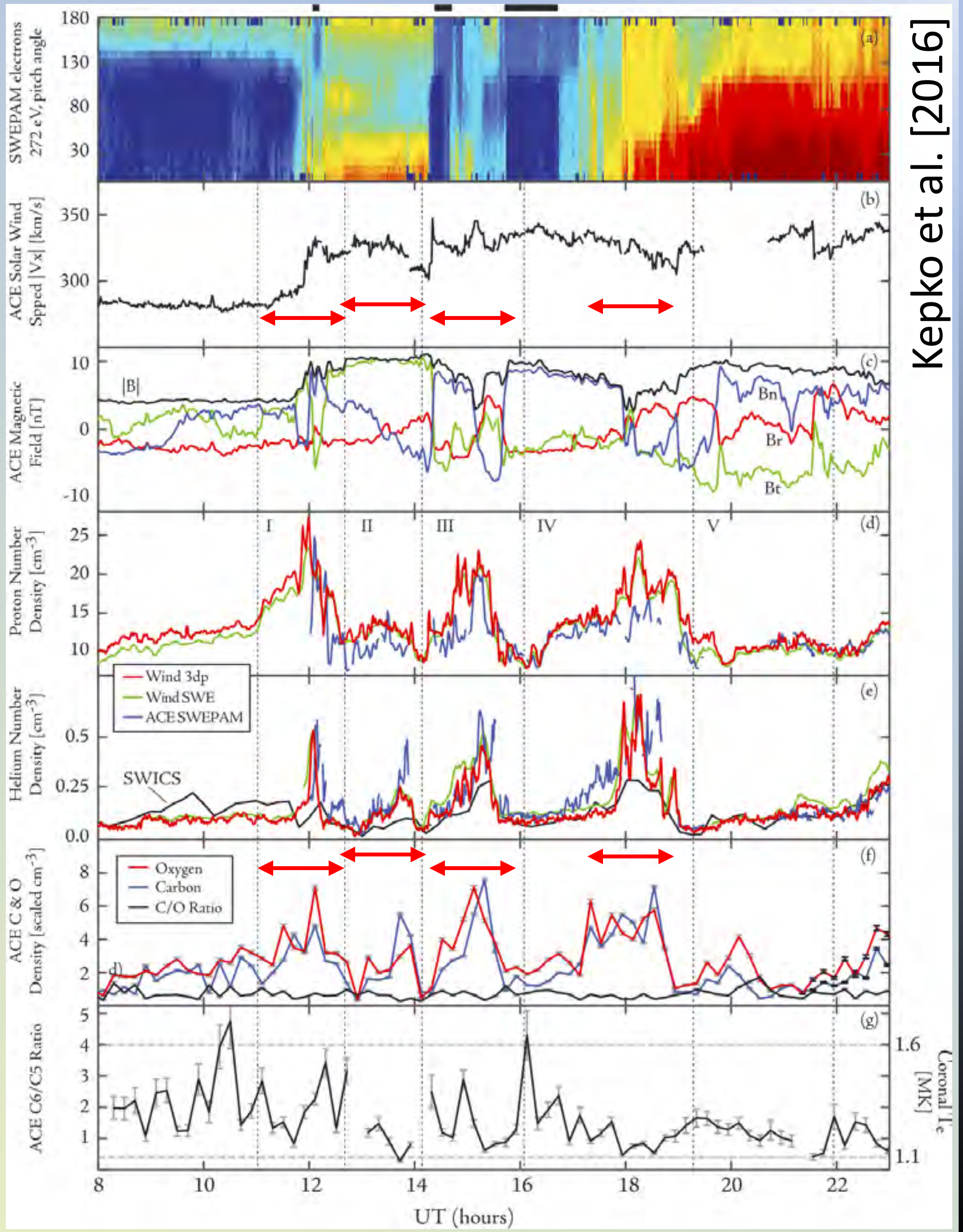
Viall et al. [2009]



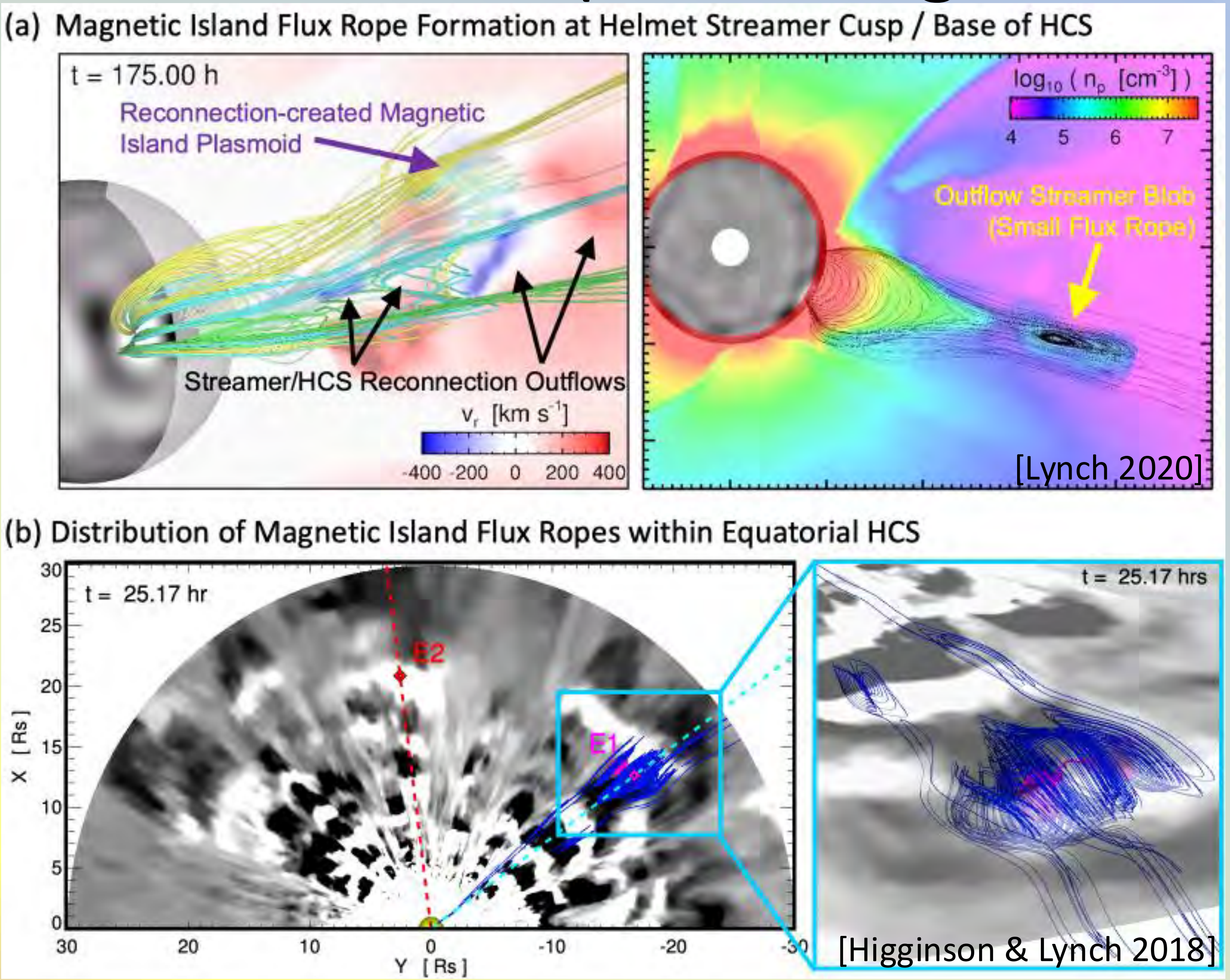
Murphy et al. [2020]



Kepko et al. [2016]



Helmet Streamer "Blobs" (Small Magnetic Flux Ropes)



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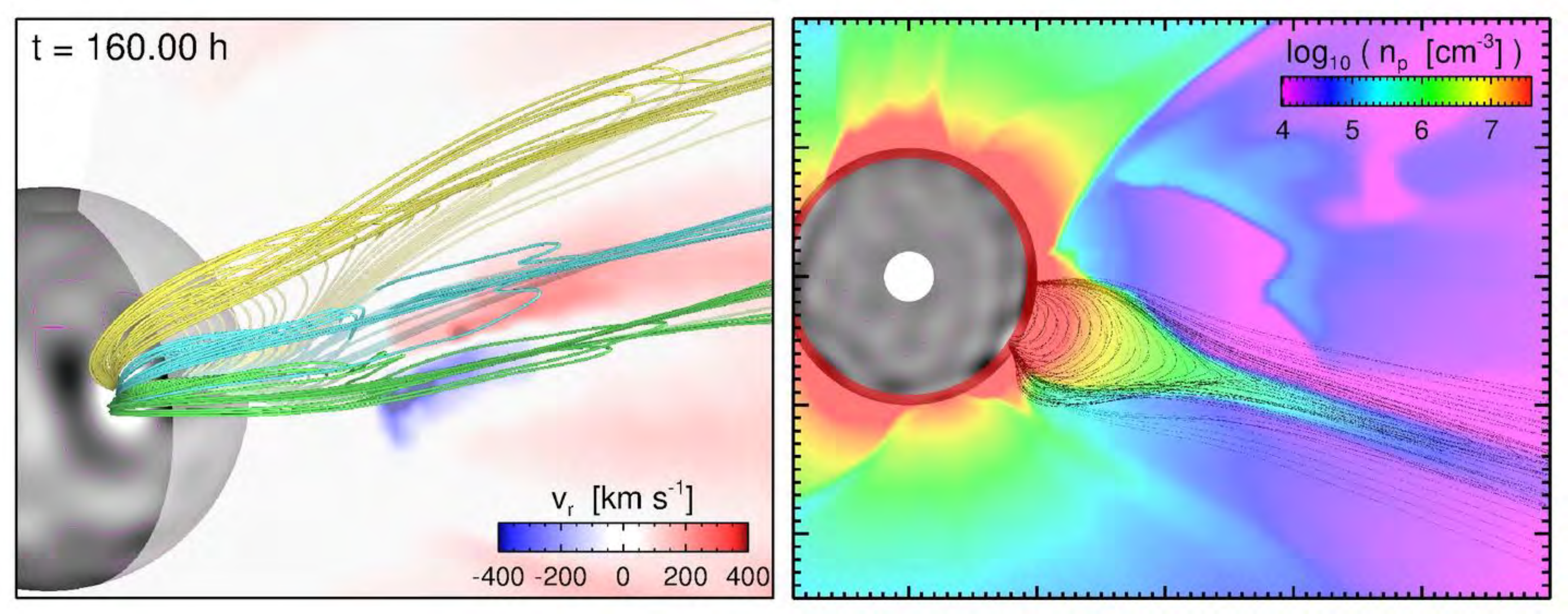
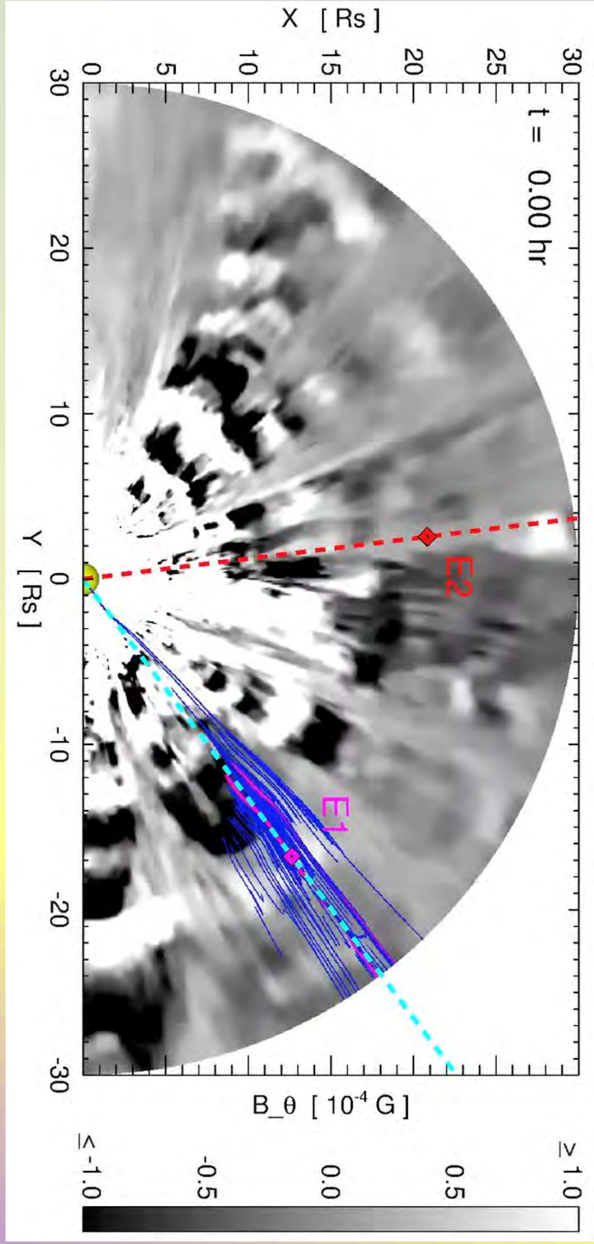
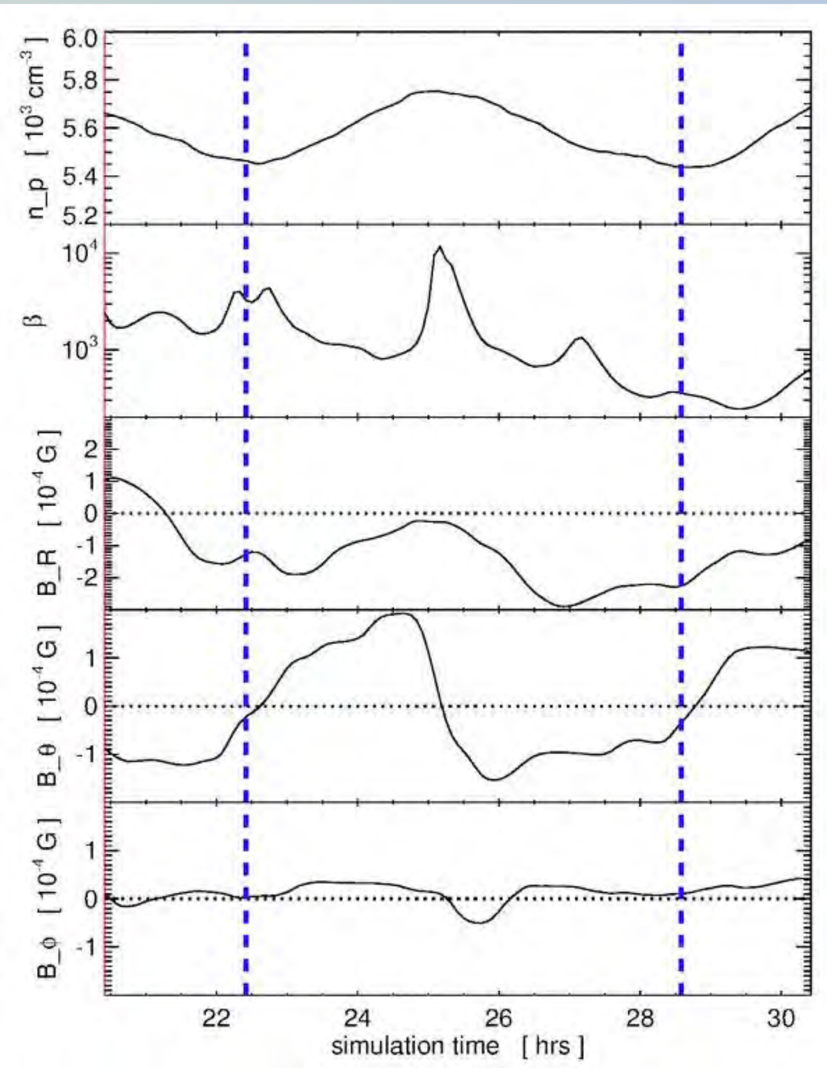
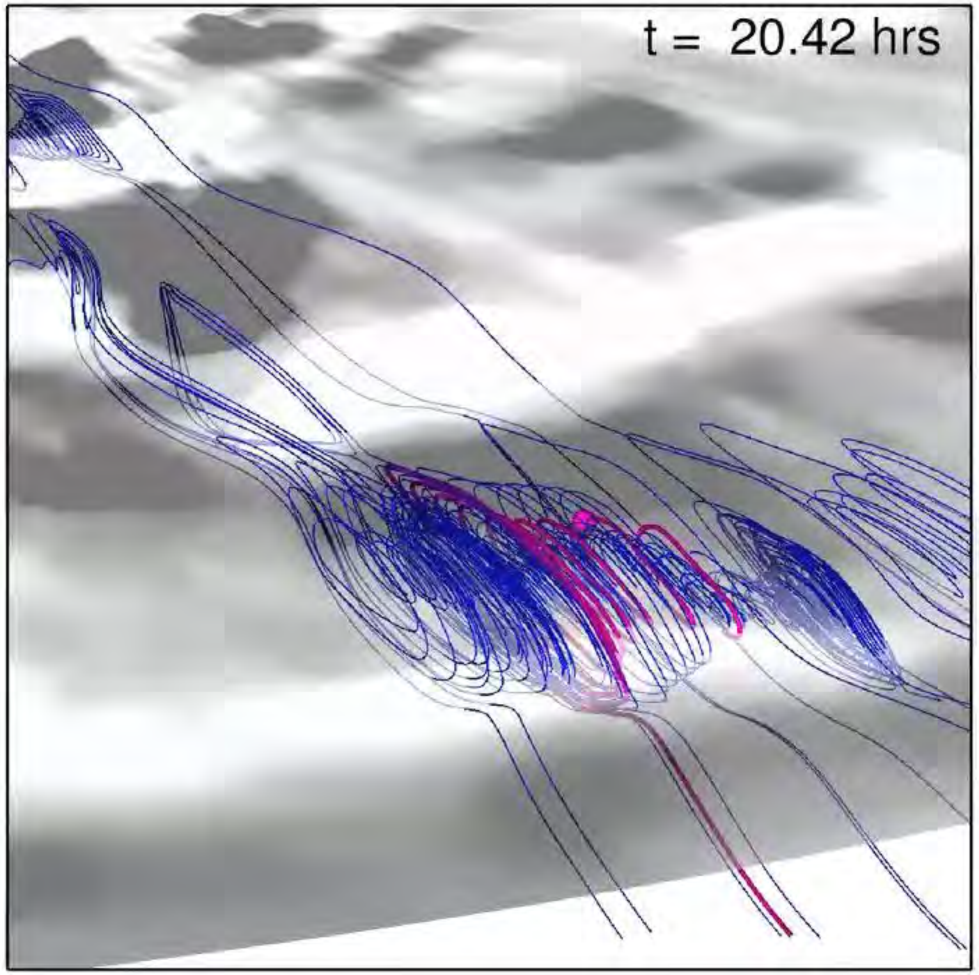


[Lynch 2020]

Helmet Streamer "Blobs" (Small Magnetic Flux Ropes)







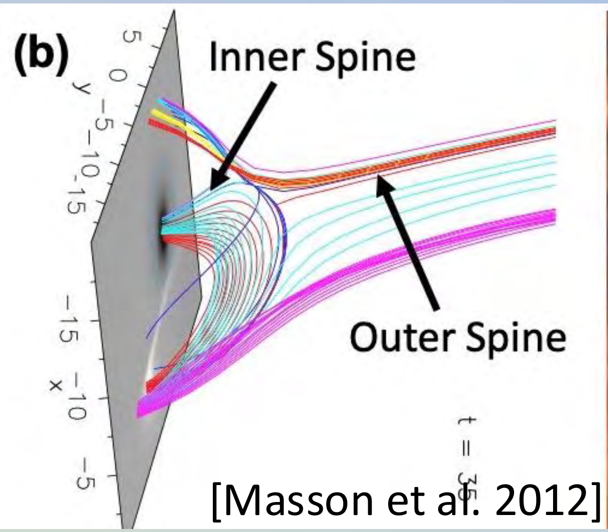
[Higginson & Lynch 2018]

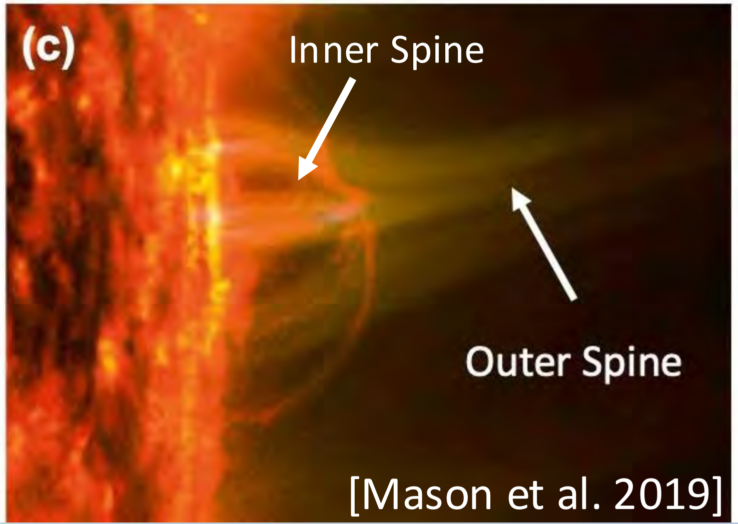
Pseudostreamer Reconnection Outflows

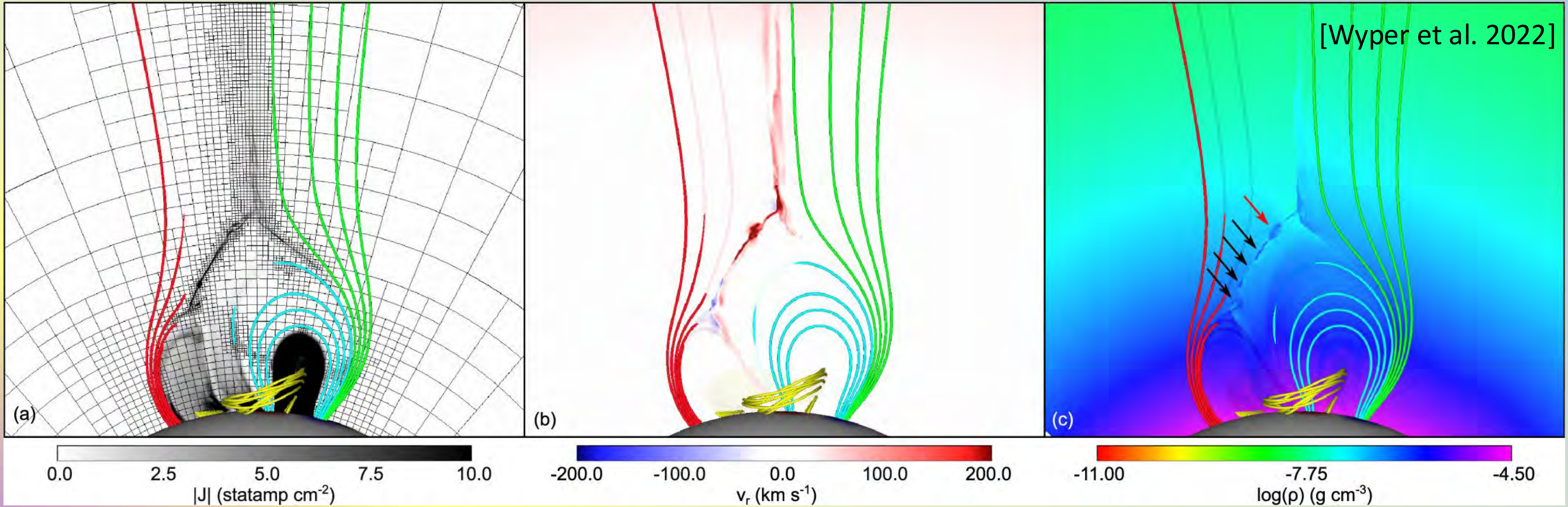
One or more magnetic null points, current layers build up on separatrix boundaries, onset of reconnection to re-distribute stress/current density

→ bulk plasma ouflow w rxn jet

→ structured component from plasmoids



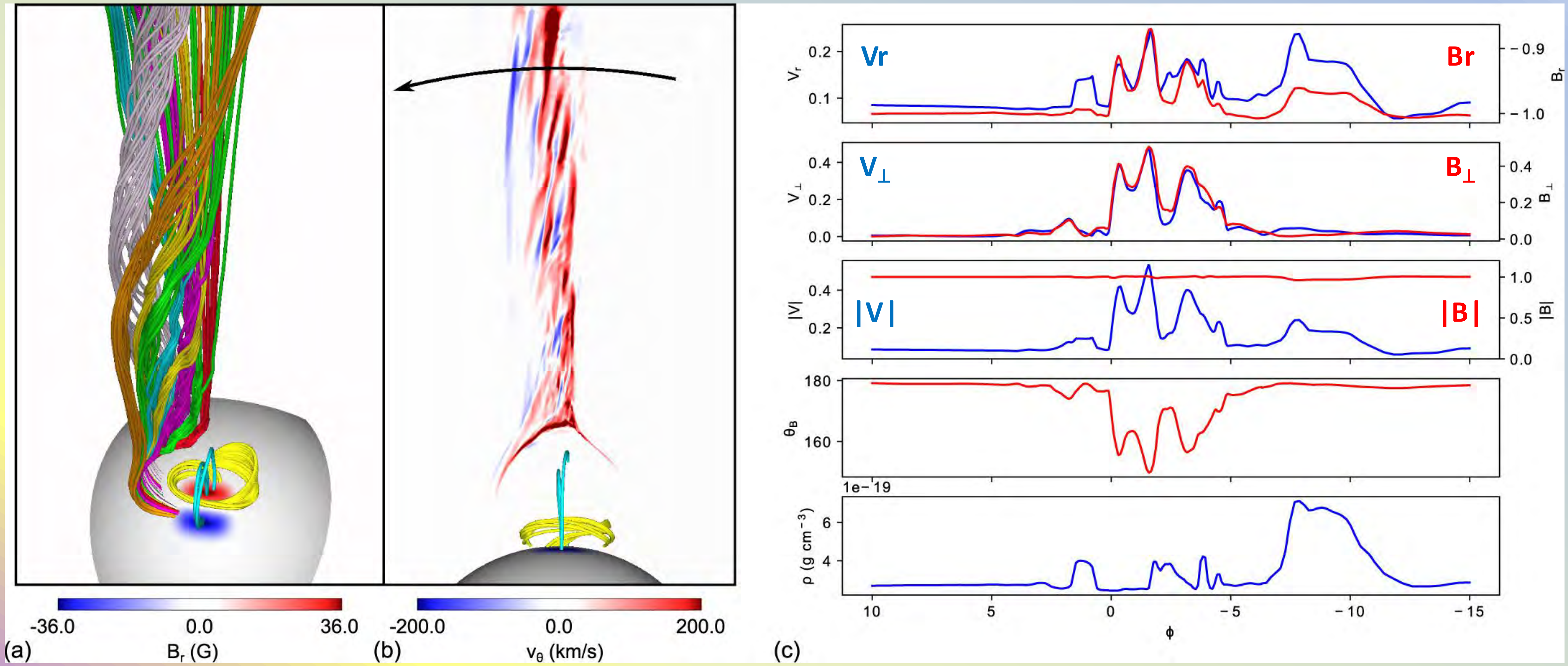




Pseudostreamer Reconnection Outflows

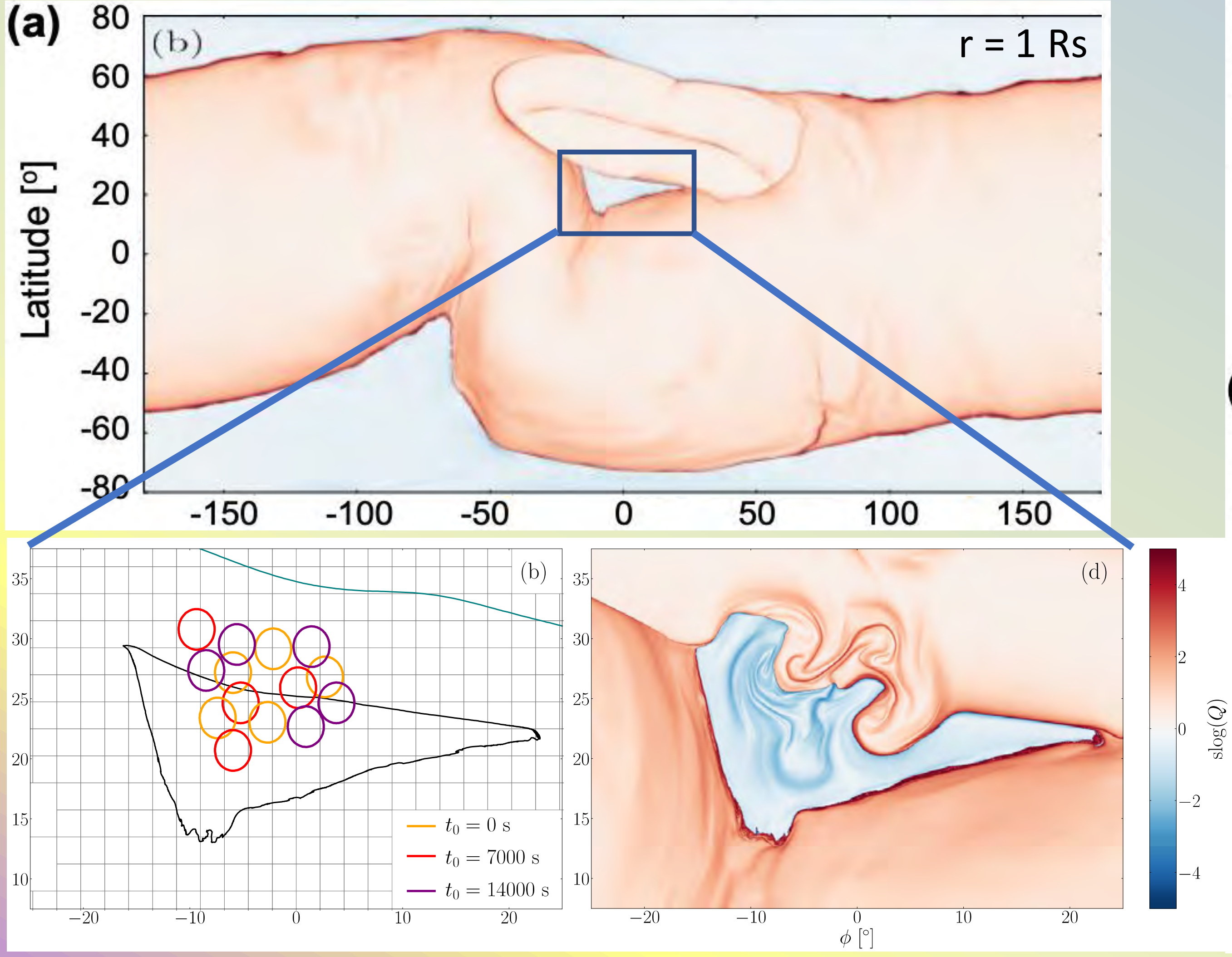
Wyper et al. [**2022**] simulation of plasmoid-unstable interchange reconnection at pseudostreamer current sheet.
Reconnection outflow/waves propagate along S-Web arcs!

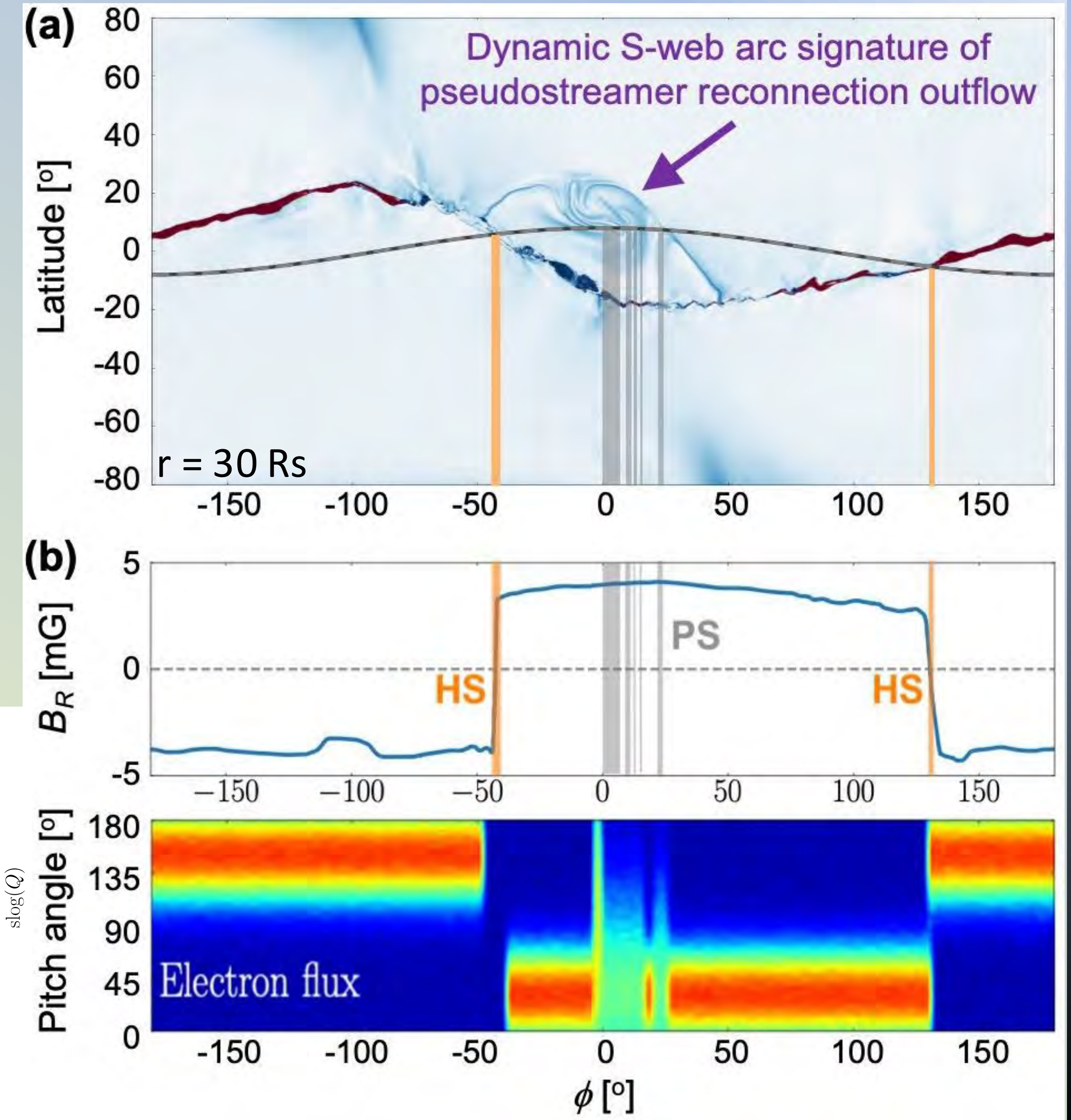
[Wyper et al. 2022]



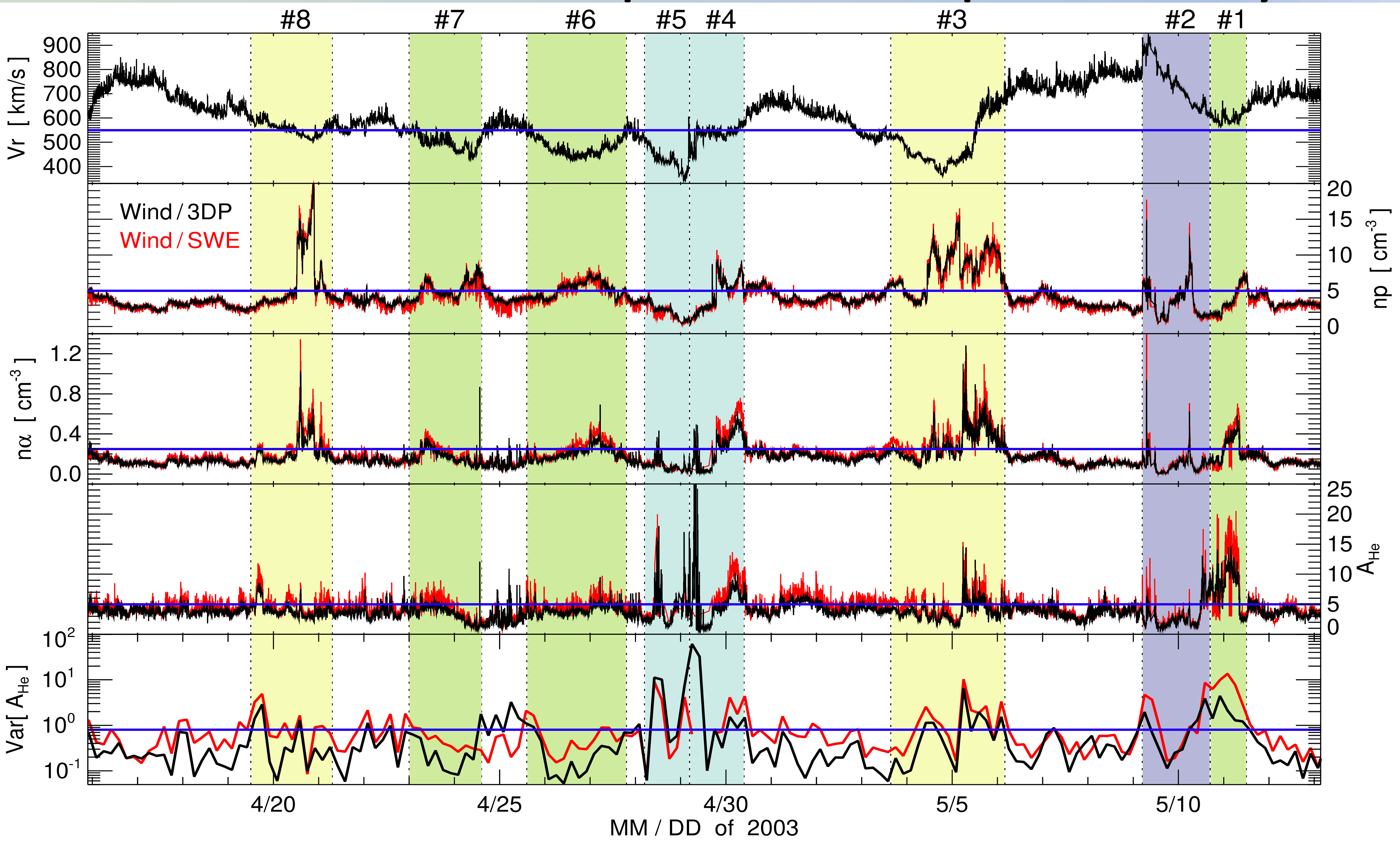
Pseudostreamer Reconnection Outflows

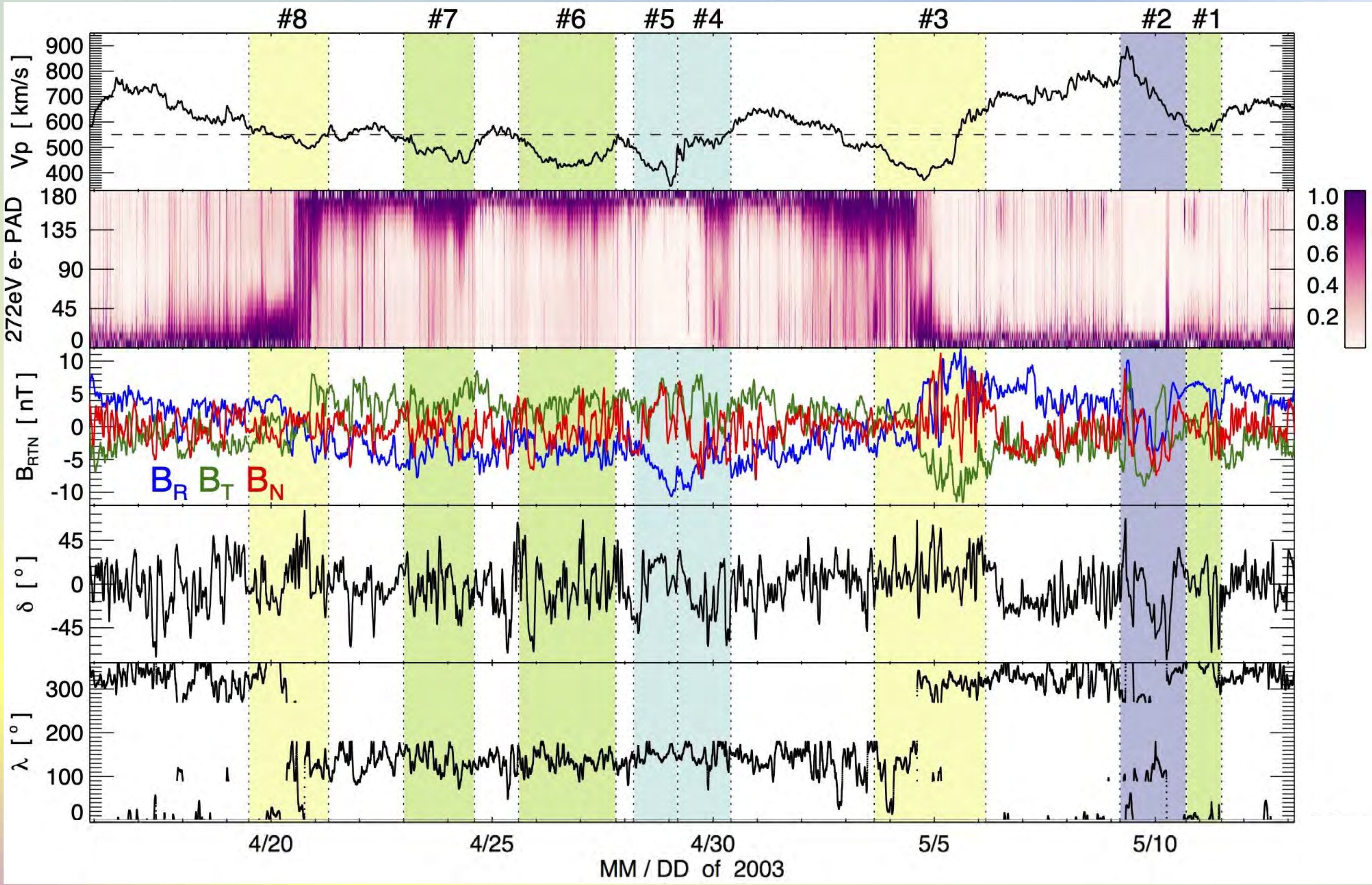
Aslanyan et al. [2022] ran idealized MHD simulation of interchange reconnection at pseudostreamer boundaries



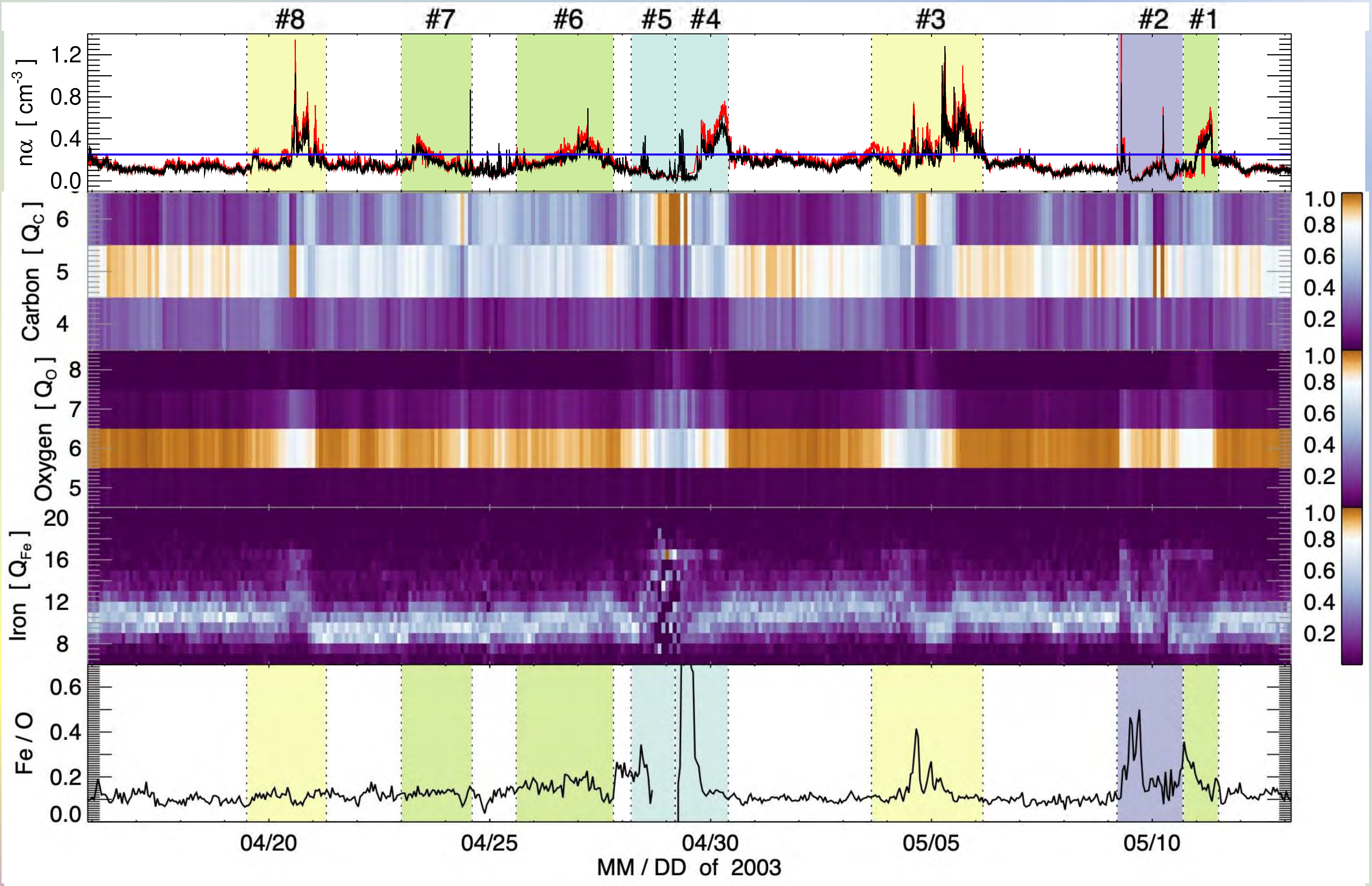


An Illustrative Example: 2003 Apr 15–May 13





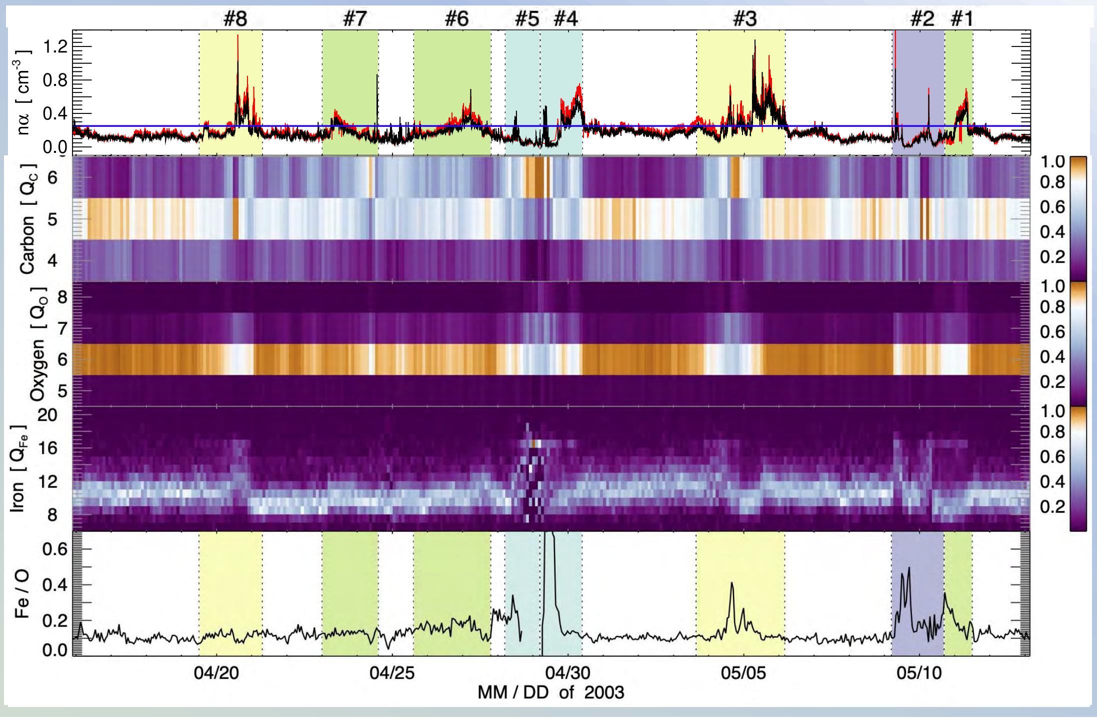
#8
#7
#6
#5
#4
#3
#2
#1
Vp [km/s]
272eV e- PAD
B_{RTN} [nT]
B_R B_T B_N
δ [°]
λ [°]
4/20
4/25
4/30
5/5
5/10
MM / DD of 2003



#8
#7
#6
#5
#4
#3
#2
#1
nα [cm^-3]
1.2
0.8
0.4
0.0
Carbon [Q_C]
6
5
4
Oxygen [Q_O]
8
7
6
5
Iron [Q_Fe]
20
16
12
8
Fe / O
0.6
0.4
0.2
0.0
1.0
0.8
0.6
0.4
0.2
04/20
04/25
04/30
05/05
05/10
MM / DD of 2003

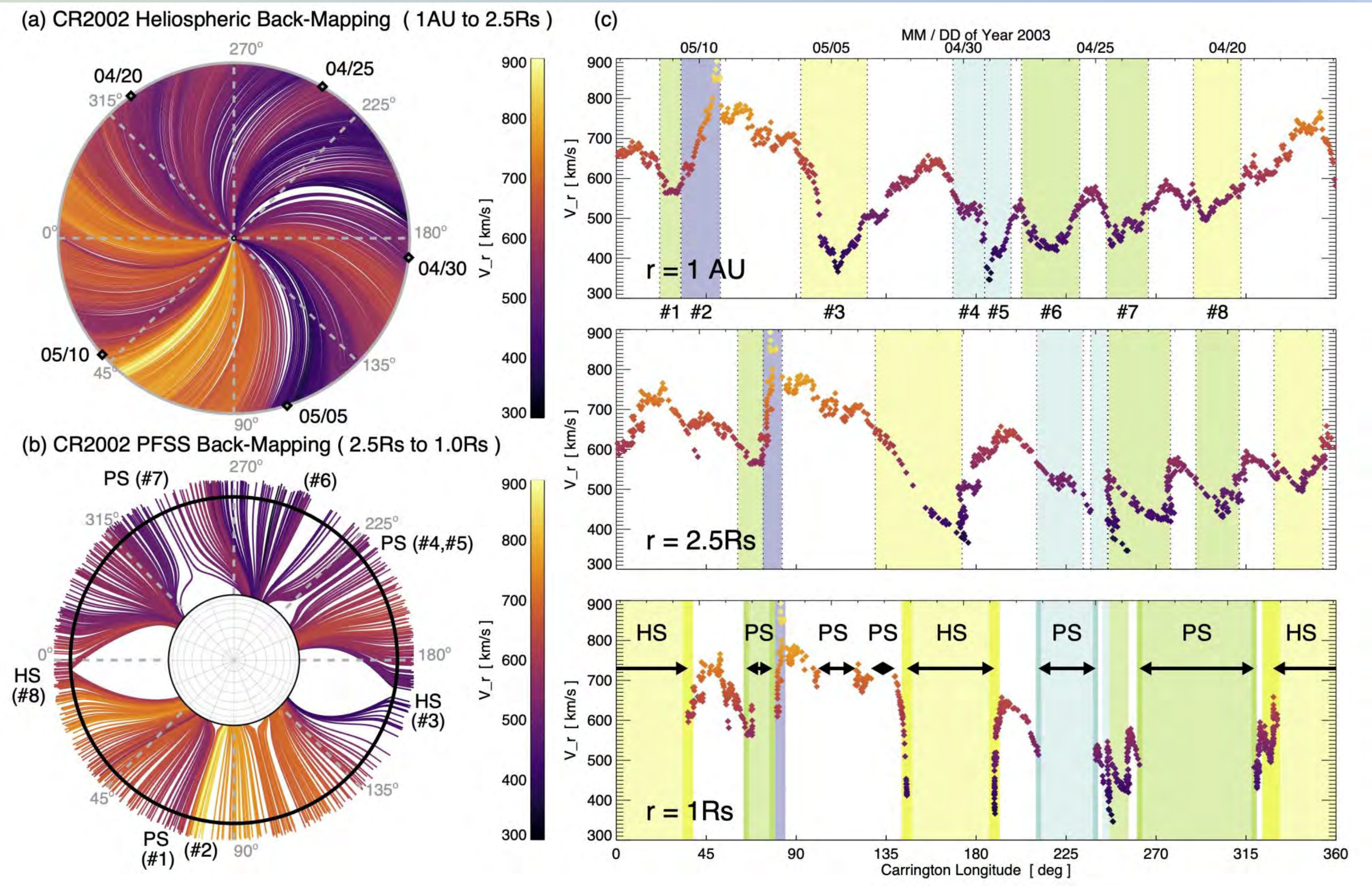
- Every interval has "slower than average" speed (during this CR)
- Most intervals have higher proton density
- "" have higher Alpha to proton abundance ratio
- "" elevated C, O, Fe charge states
- Some have higher Fe/O elemental abundance

- ➔ properties of in-situ plasma that must be related to coronal source region

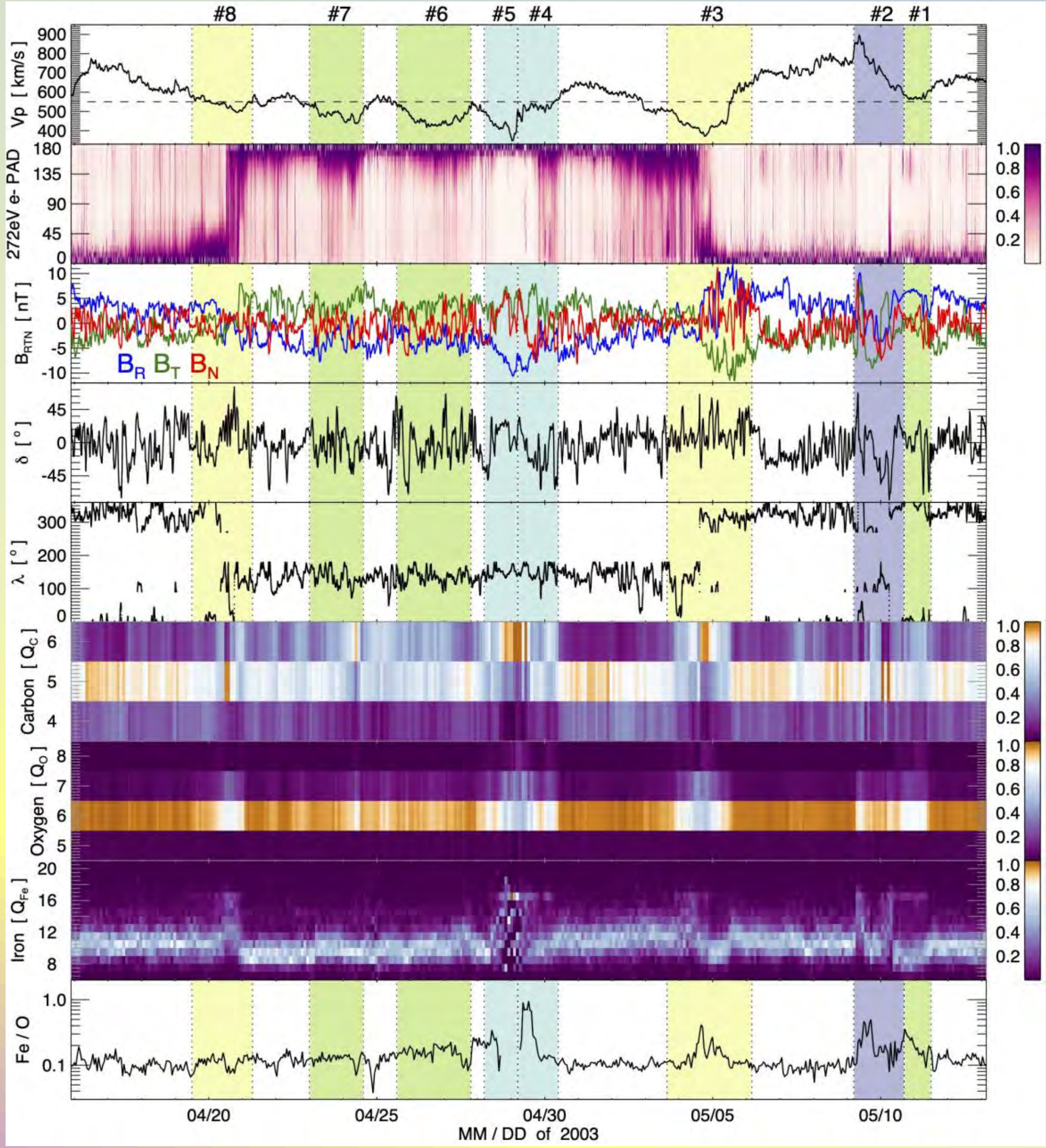


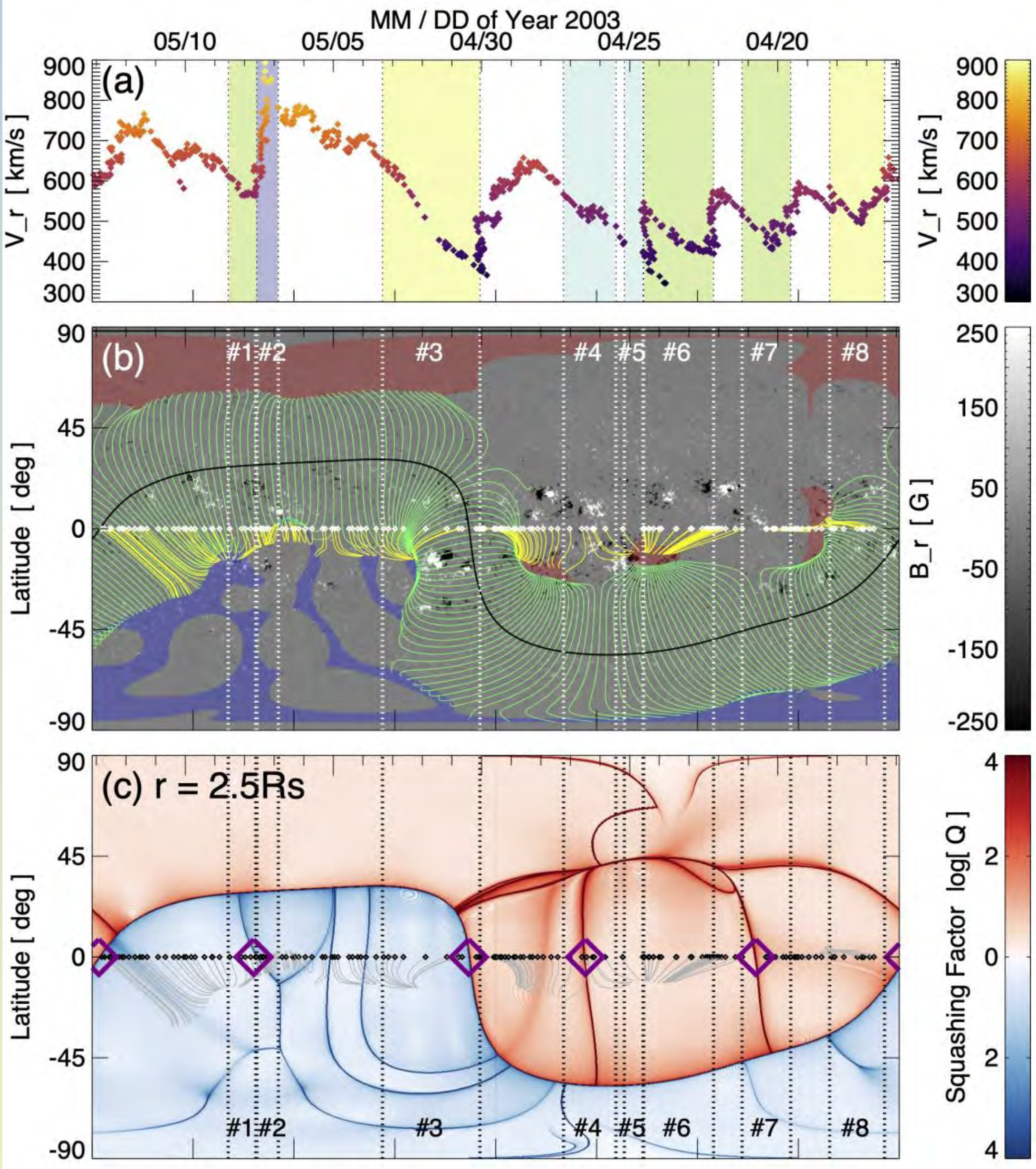
#	Start time DD/MM HH:MM	End time [UT]	Source region	$\langle V_r \rangle$ [km s^{-1}]	$\langle n_p \rangle$ [cm^{-3}]	$\langle A_{He} \rangle$ [%]	$\langle Q_C \rangle$ [4–6+]	$\langle Q_O \rangle$ [5–8+]	$\langle Q_{Fe} \rangle$ [6–20+]	$\langle Fe/O \rangle$
8	04/19 13:58	04/21 05:24	HS (Y)	**556 ± 26**	**6.1 ± 4.1**	**5.1 ± 1.6**	**5.07 ± 0.15**	**6.14 ± 0.08**	**10.82 ± 0.96**	0.11 ± 0.02
7	04/23 00:00	04/24 14:12	PS (G)	**498 ± 32**	**5.2 ± 1.3**	4.4 ± 1.6	**5.19 ± 0.08**	**6.08 ± 0.02**	10.12 ± 0.52	**0.13 ± 0.02**
6	04/25 14:24	04/27 19:12	PS (G)	**478 ± 34**	**5.2 ± 1.1**	**5.0 ± 1.1**	**5.24 ± 0.16**	**6.09 ± 0.05**	9.85 ± 0.32	**0.16 ± 0.03**
5	04/28 04:48	04/29 04:47	PS (T)	**432 ± 45**	2.2 ± 1.0	3.9 ± 1.8	**5.52 ± 0.18**	**6.32 ± 0.16**	**11.83 ± 1.29**	**0.19 ± 0.09**
4	04/29 04:48	04/30 09:36	PS (T)	**534 ± 32**	**4.5 ± 2.3**	**7.6 ± 2.4**	**5.35 ± 0.15**	**6.29 ± 0.14**	**11.07 ± 0.51**	**0.31 ± 0.28**
3	05/03 15:27	05/06 03:56	HS (Y)	**496 ± 95**	**7.9 ± 2.8**	**4.6 ± 1.7**	**5.24 ± 0.24**	**6.20 ± 0.15**	**11.01 ± 0.79**	**0.14 ± 0.07**
2	05/09 04:48	05/10 16:48	ICME (P)	738 ± 89	3.5 ± 2.3	3.2 ± 2.1	**5.06 ± 0.15**	**6.12 ± 0.05**	**11.10 ± 1.14**	**0.21 ± 0.11**
1	05/10 16:48	05/11 12:00	PS (G)	**601 ± 20**	3.6 ± 1.8	**9.4 ± 5.3**	**5.19 ± 0.08**	**6.22 ± 0.08**	10.09 ± 0.25	**0.20 ± 0.07**
Non-interval CR 2002 averages				637 ± 93	4.0 ± 1.9	4.5 ± 1.2	5.01 ± 0.17	6.04 ± 0.09	10.37 ± 0.55	0.11 ± 0.03

Heliospheric Back-mapping to Coronal Source Region(s)



Every Interesting SW Interval → HS/HCS or PS Wind





[Lynch et al. 2023]

Coherent Magnetic Structure via H_m-PVI Method

Use the **Pecora et al.** [**2021**] Magnetic Helicity–Partial Variance of Increments method to identify coherent magnetic structures:

Helicity content (below scale ℓ) estimated with 2-pt correlation function [**Matthaeus & Goldstein 1982**]:

$$H_m^-(x,\ell) = \int_0^\ell ds\, C_{jk}(x,s)\, f(s)$$

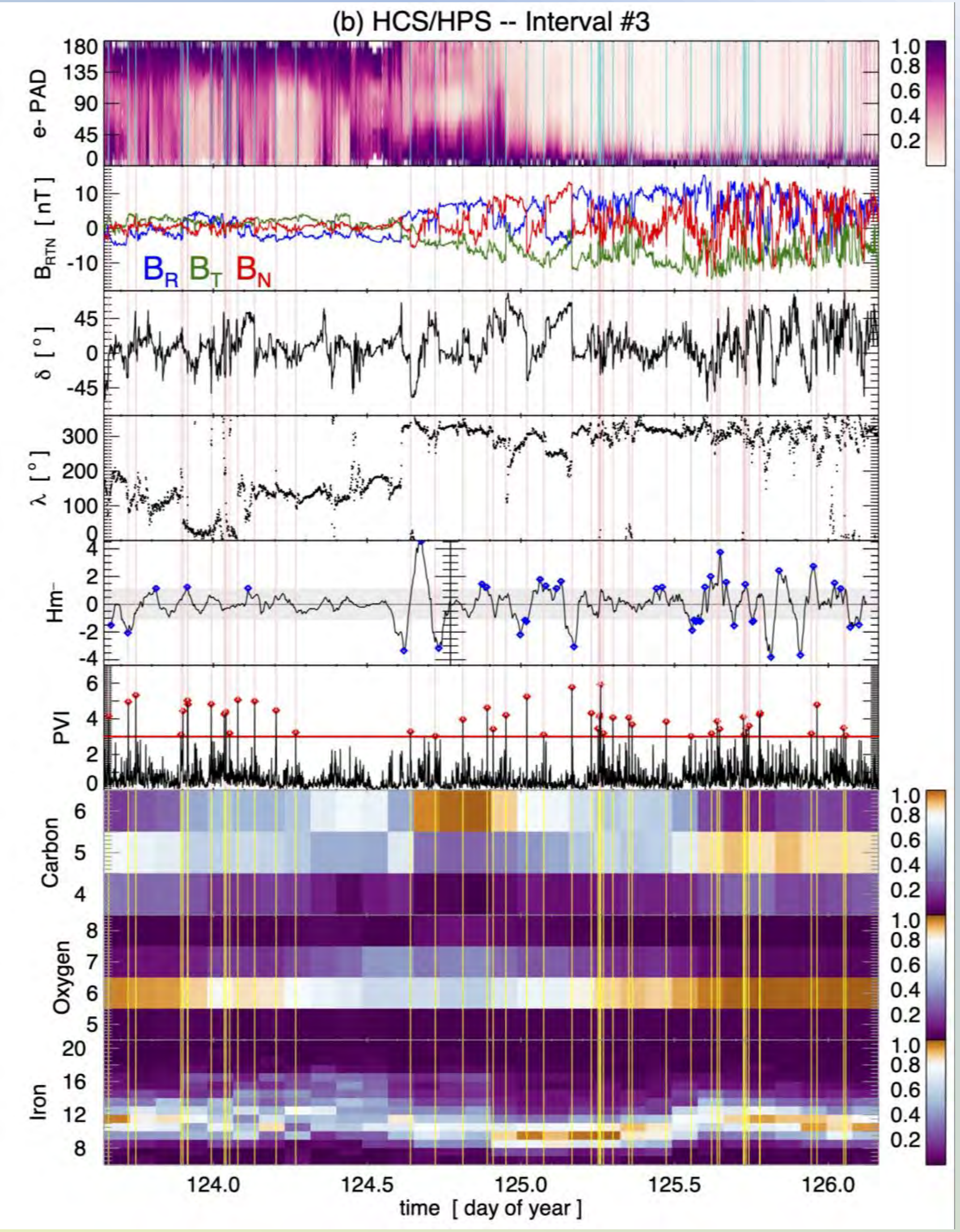
$$C_{jk}(x,s) = \int_{x-\frac{W}{2}}^{x+\frac{W}{2}} d\xi\ \left[B_j(\xi+s)B_k(s) - B_j(s)B_k(\xi+s)\right]$$

$$f(s) = \frac{1}{2} - \frac{1}{2}\cos\left(\frac{2\pi s}{W}\right)$$

Partial Variance of Increments [PVI, e.g. **Greco et al. 2018**] used to identify boundaries/discontinuities:

$$\mathrm{PVI}(t,\tau) = \frac{|\Delta\mathbf{B}(t,\tau)|}{\sqrt{\langle|\Delta\mathbf{B}(t,\tau)|^2\rangle}}$$

$$\Delta\mathbf{B}(t,\tau) = \mathbf{B}(t+\tau) - \mathbf{B}(t)$$

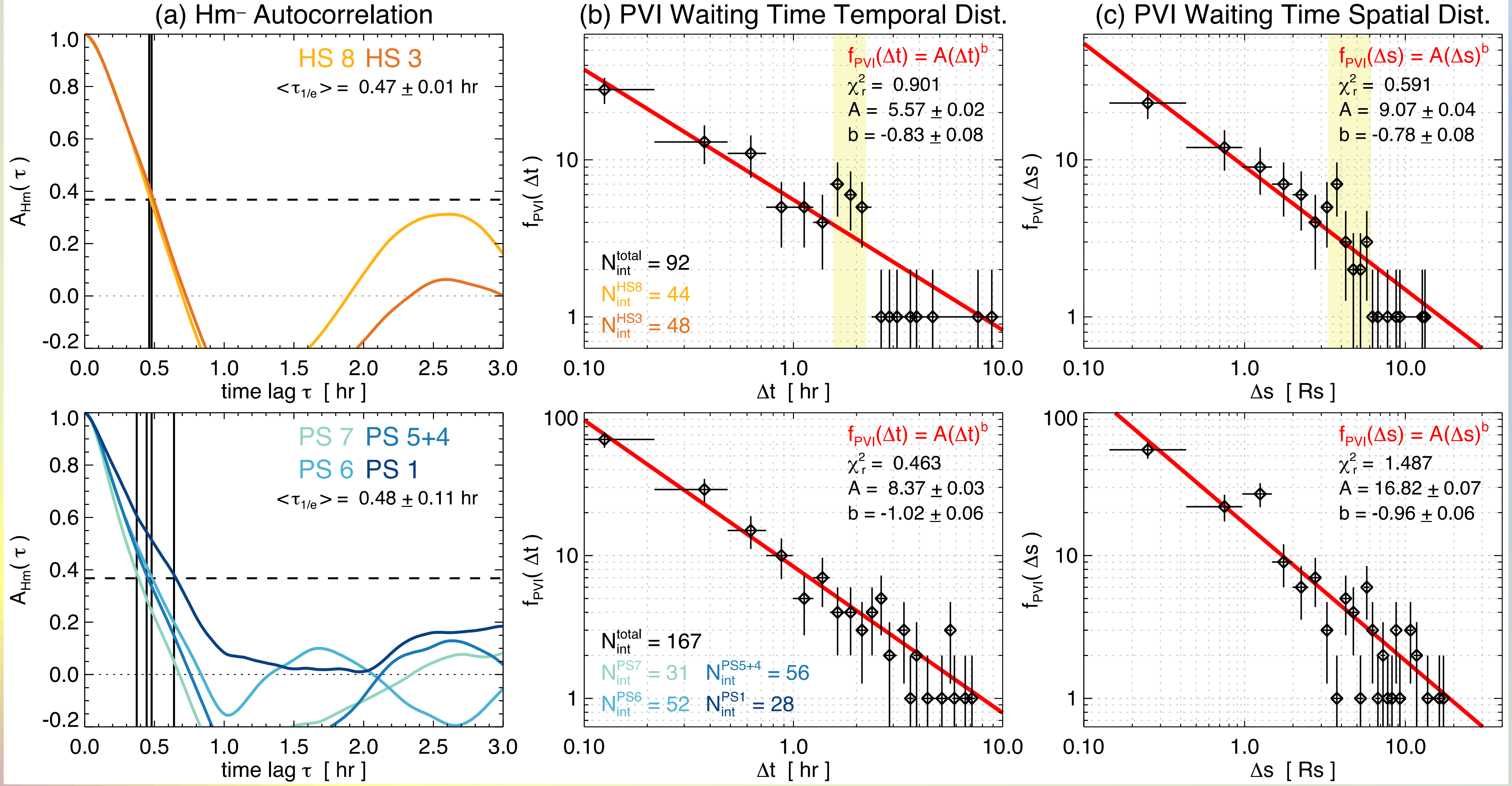


[Lynch et al. 2023]

H_m-PVI Statistics by Interval Type (HS vs. PS)

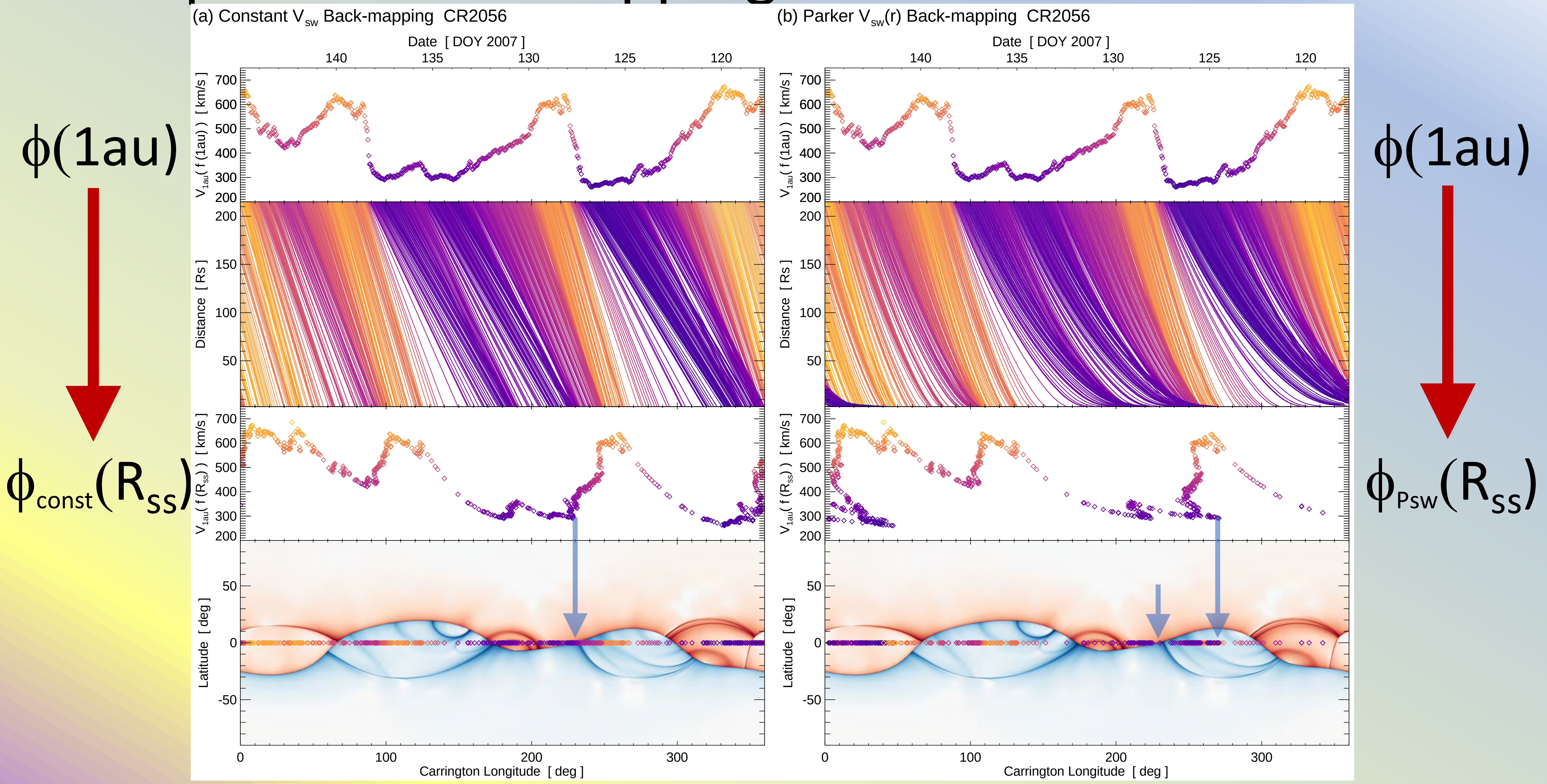
HS:

PS:

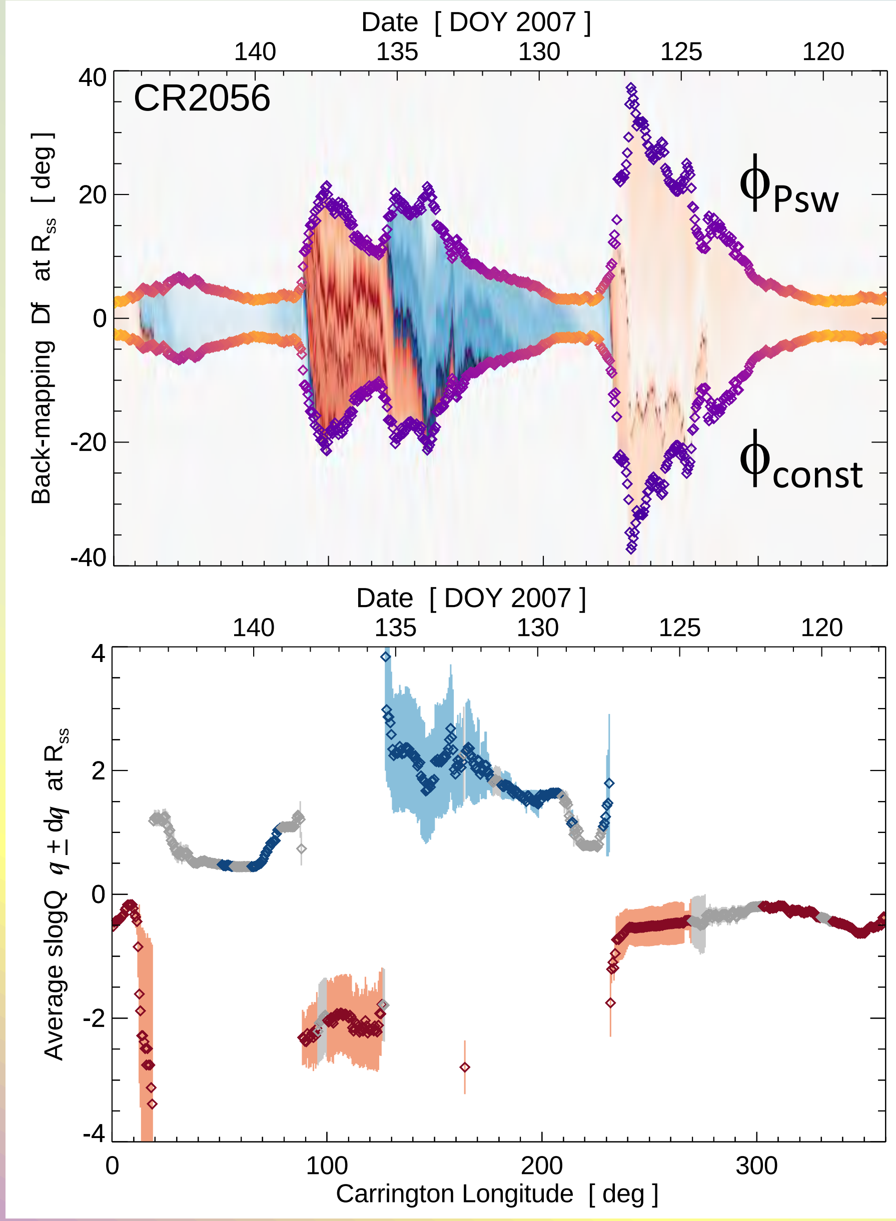


[Lynch et al. 2023]

Heliospheric Back-mapping Revisited



Heliospheric Back-mapping Revisited

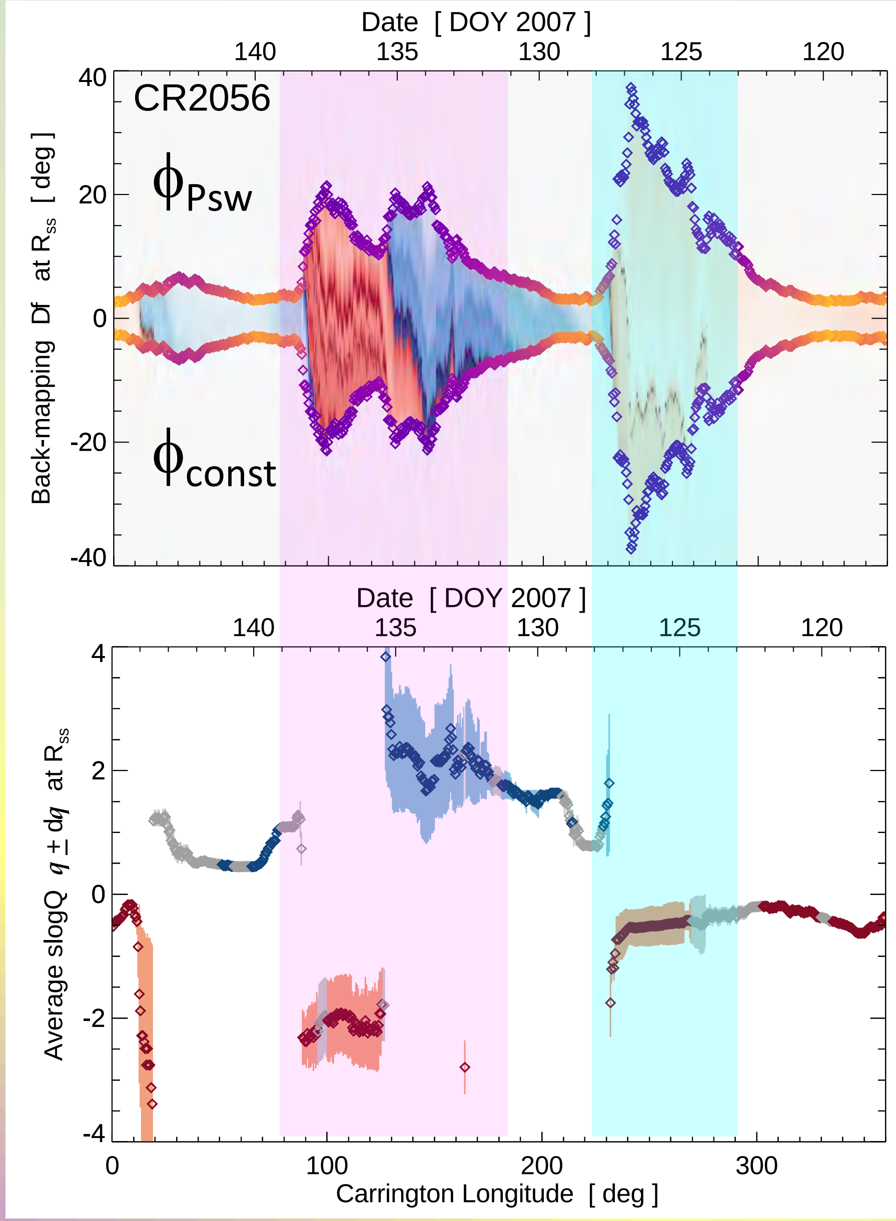


Sample Q-Map values over entire $\Delta\phi$ range [ϕ_{const}, ϕ_{Psw}]
Now both Br/HCS transitions and S-Web arcs show up clearly!

Define a *q(t)* = mean(slog *Q*(ϕ)) and δq = stddev(slog *Q*(ϕ)) time series. Presence of S-Web arc leads to high δq ?!

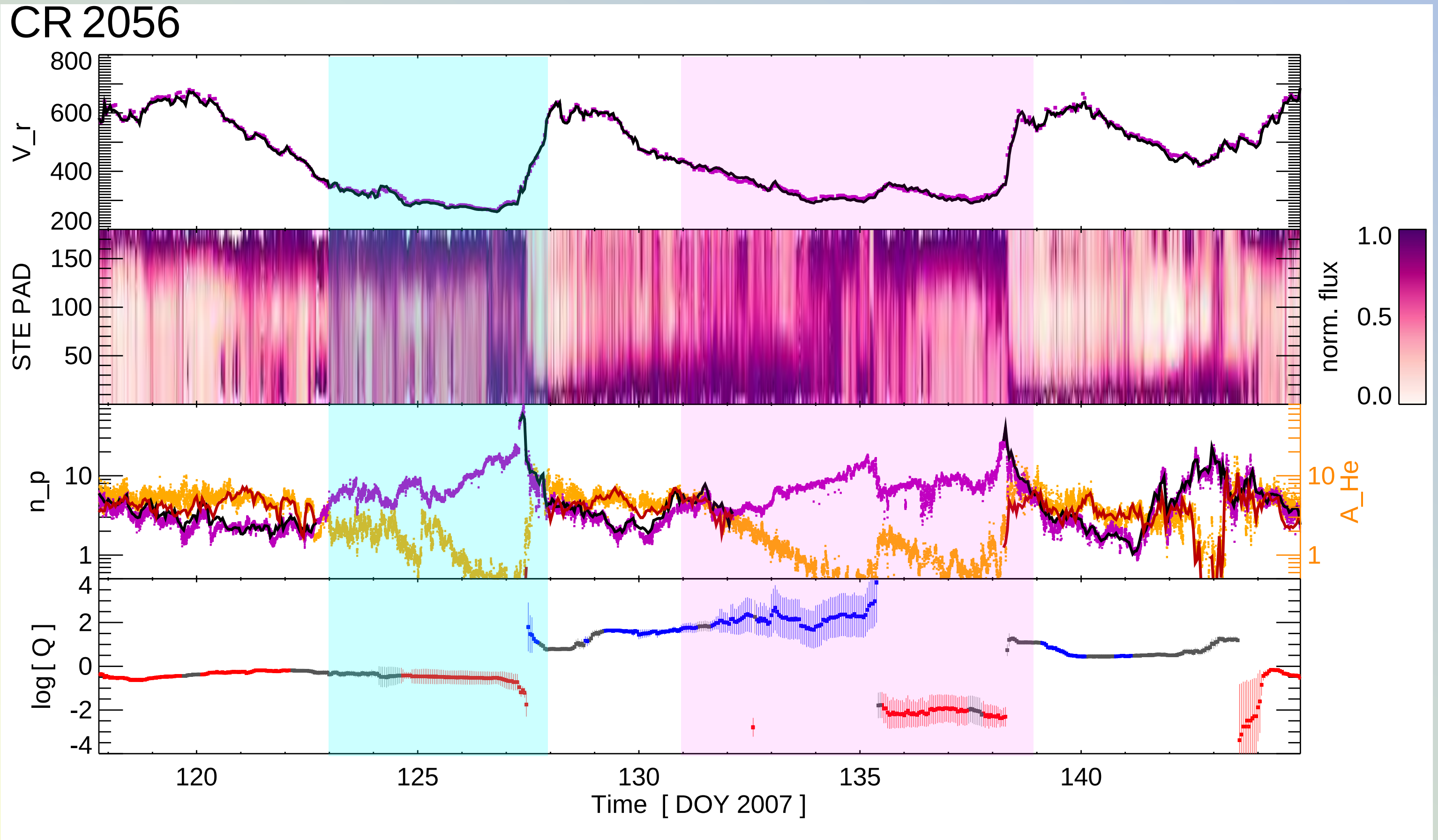
DOES THIS WORK AT ALL FOR ANYTHING OTHER THAN CR2002 ??

Heliospheric Back-mapping Revisited



Sample Q-Map values over entire $\Delta\phi$ range [ϕ_{const}, ϕ_{Psw}]
Now both Br/HCS transitions and S-Web arcs show up clearly!

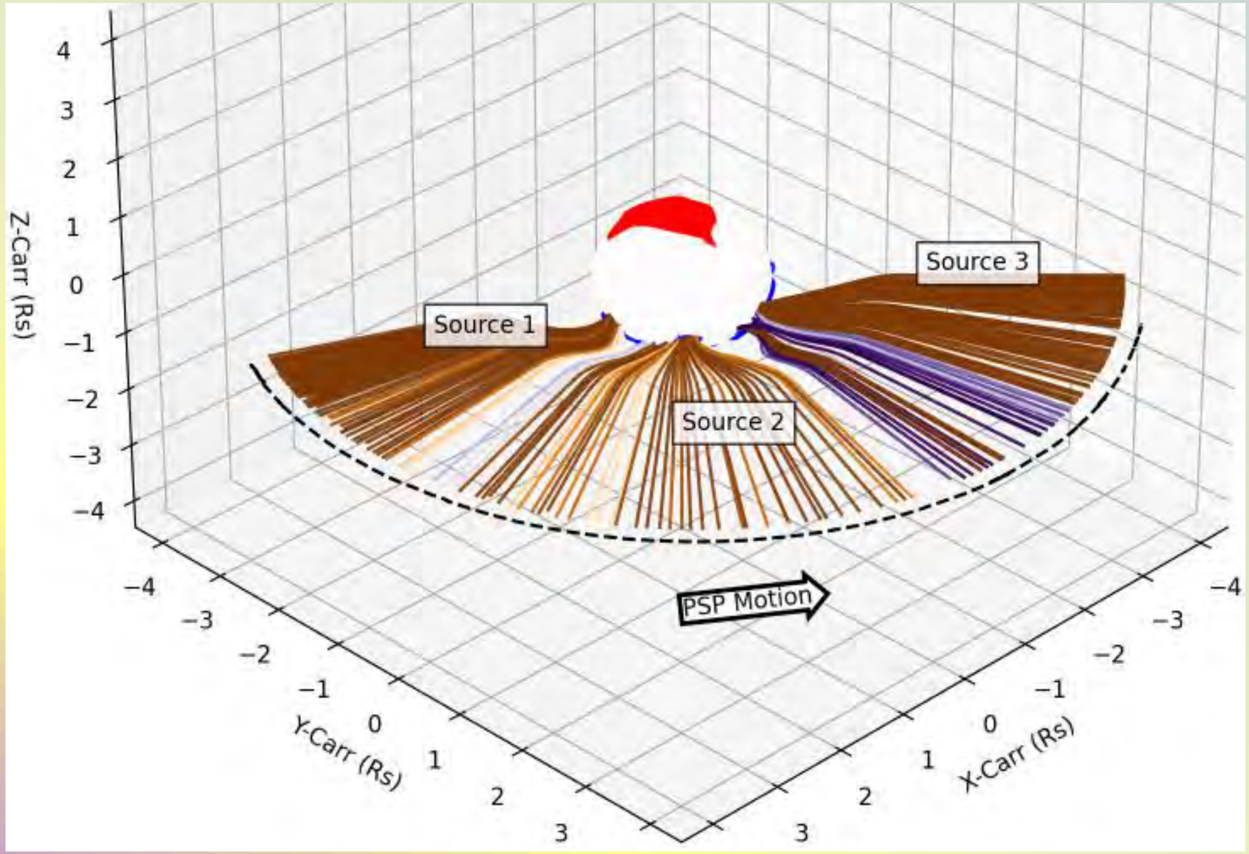
Define a $q(t)$ = mean(slog $Q(\phi)$) and δq = stddev(slog $Q(\phi)$) time series. Presence of S-Web arc leads to high δq ?!

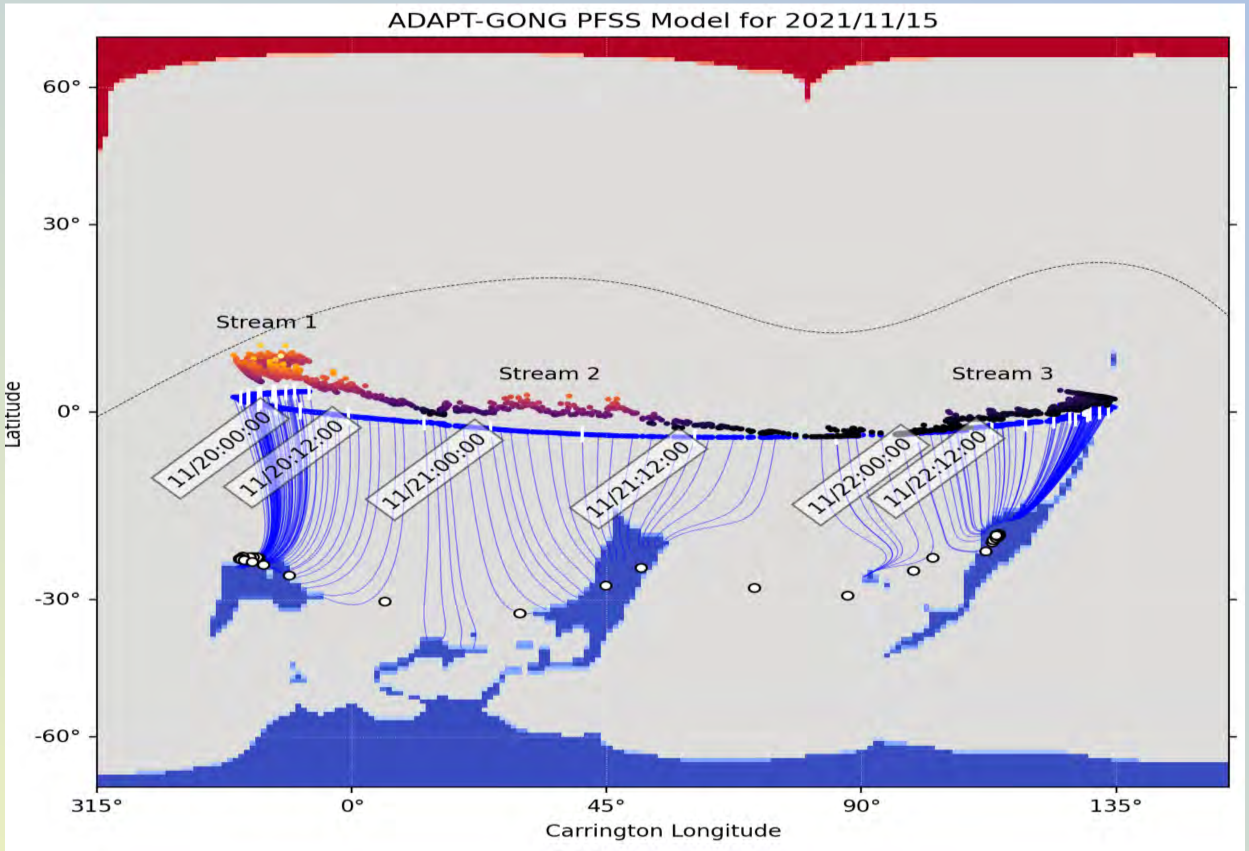


Quick PSP Example of S-Web Solar Wind

Badman et al. [**2023**] looked at PSP Encounter 10 & PFSS Back-Mapping (CR2251)
Three distinct streams from sequence of low-latitude coronal holes
→ Boundaries separating each SW "source" are pseudostreamers and their S-Web arcs!

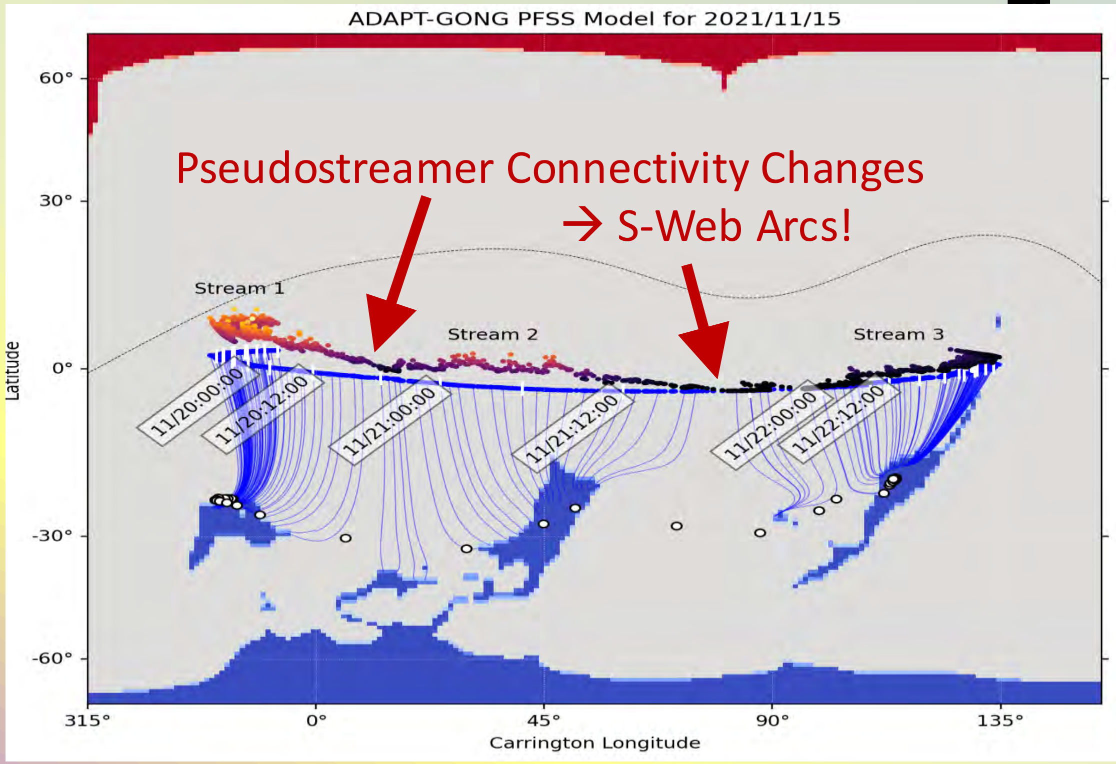
[Badman et al. 2023]

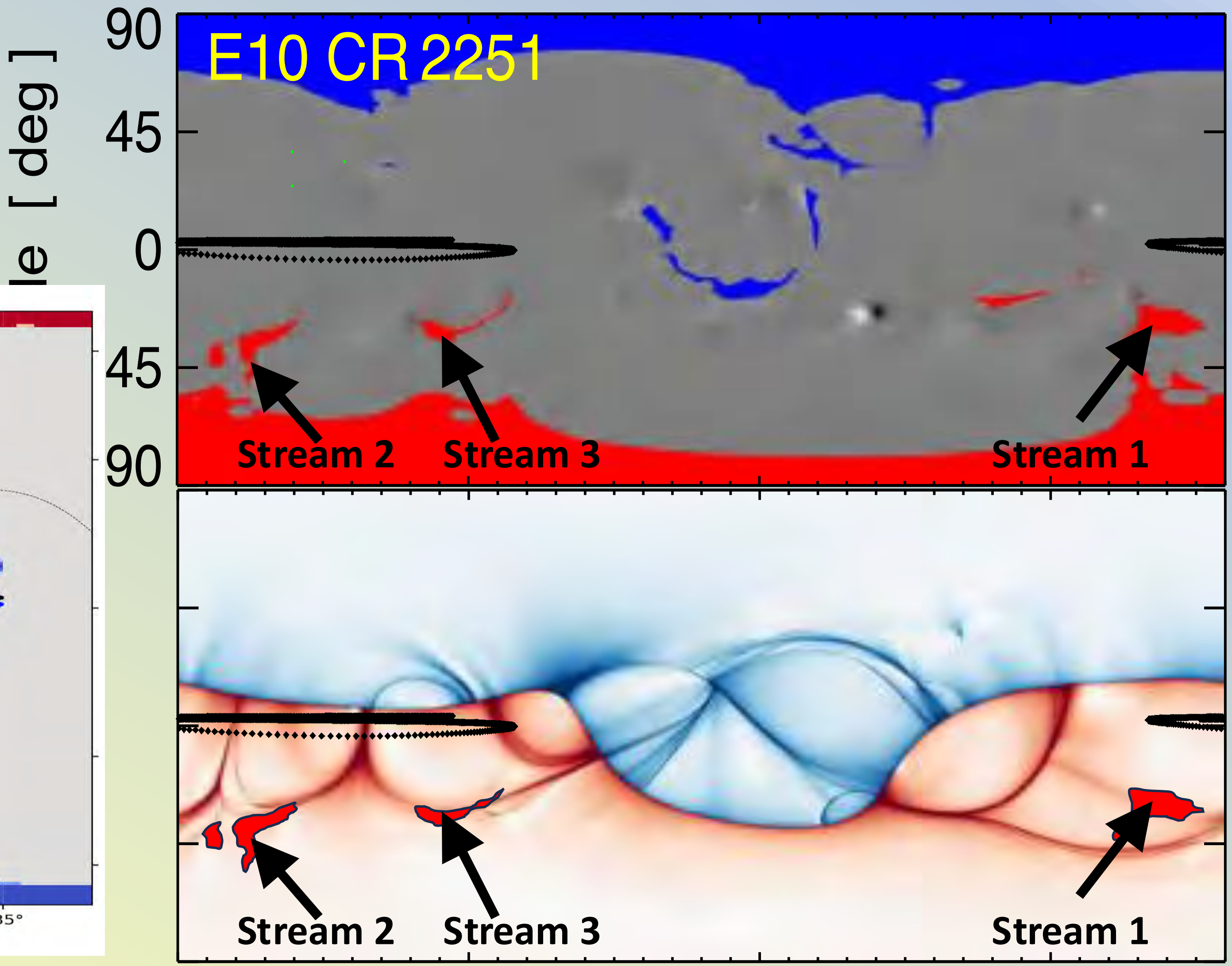




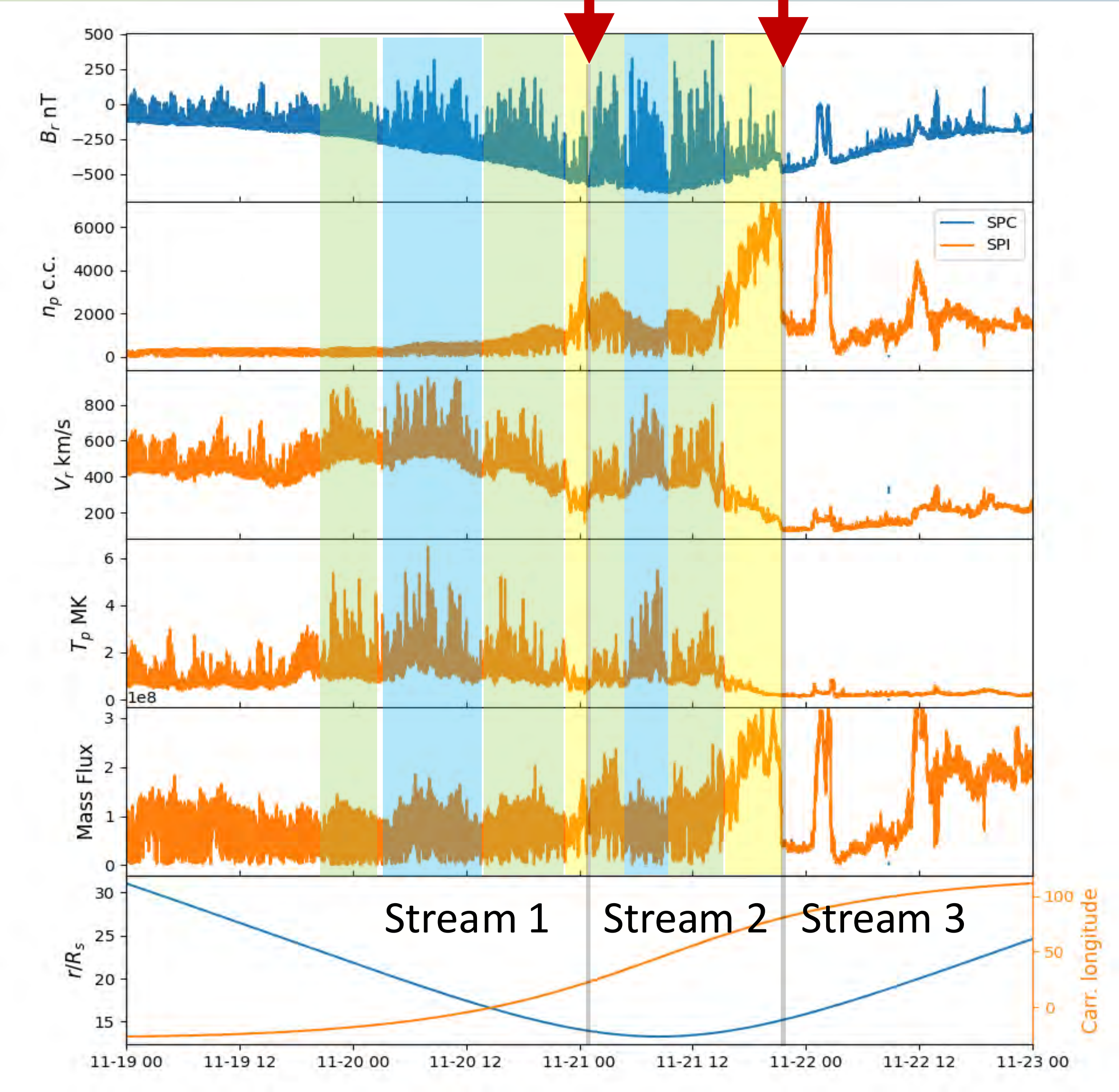
Quick PSP Example of S-Web Solar Wind

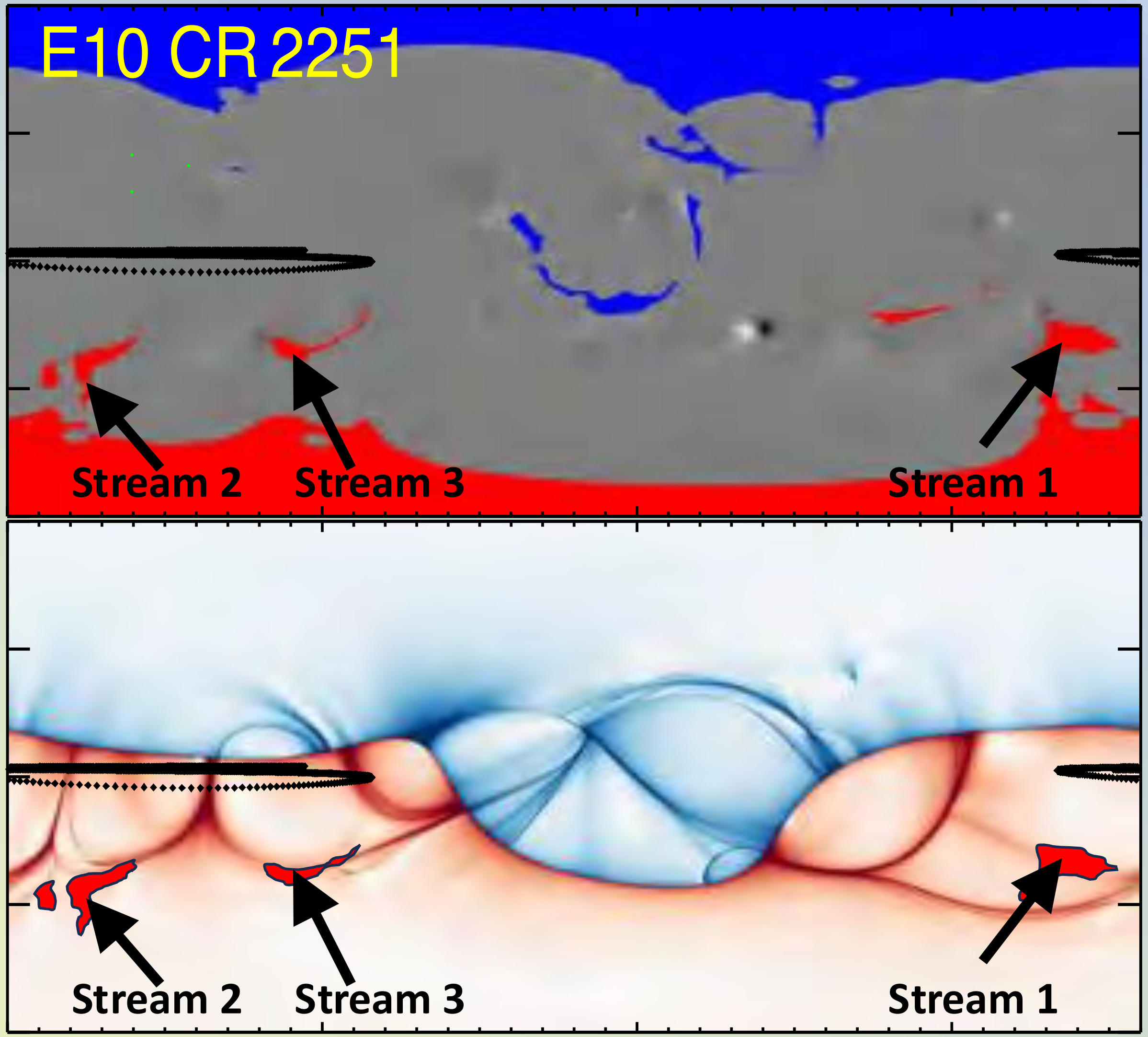
[Badman et al. 2023]



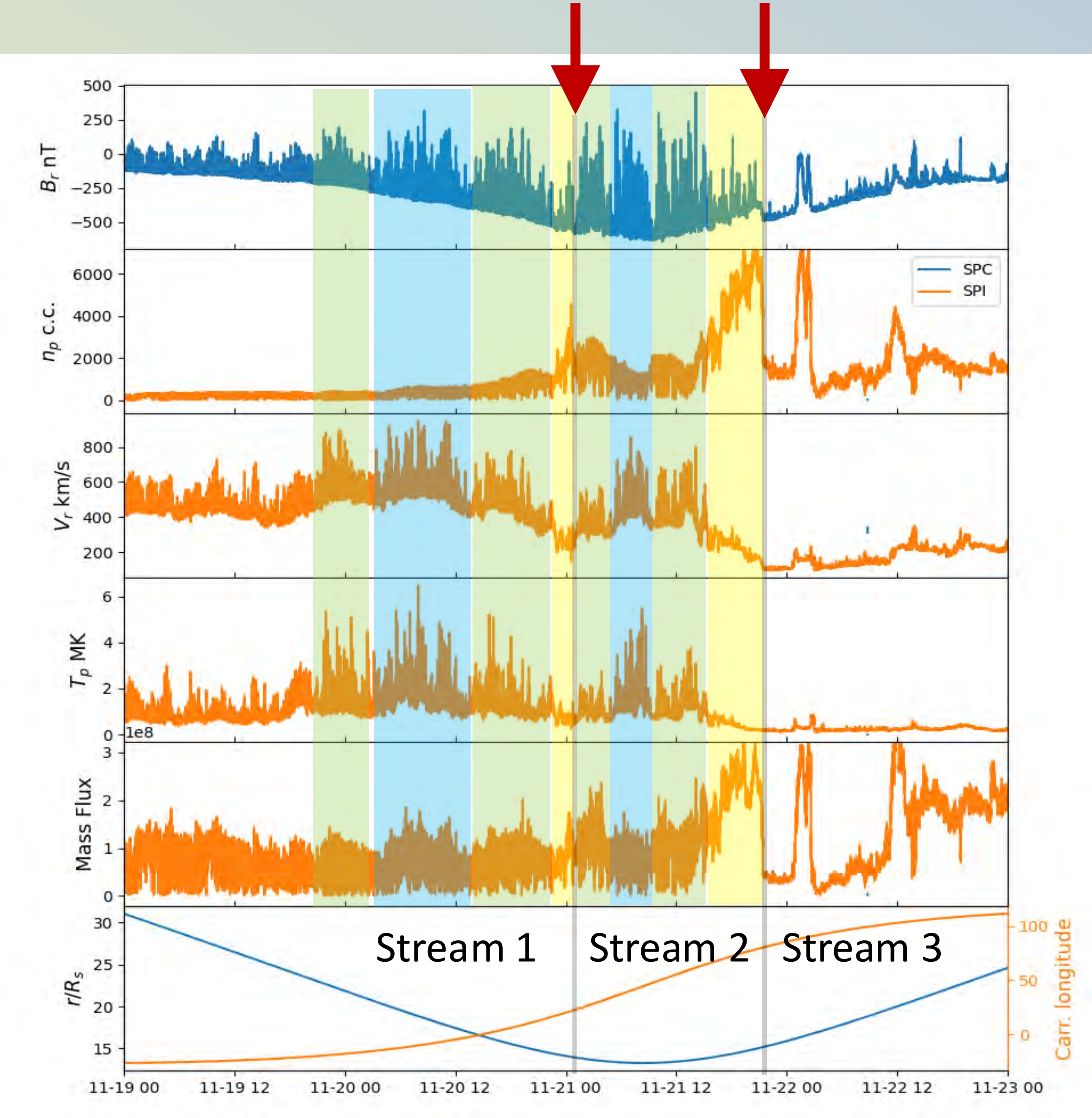


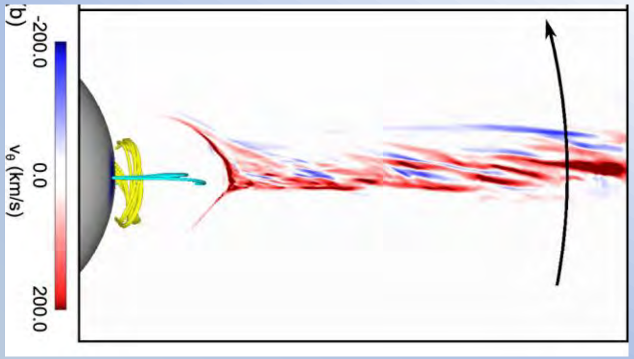
Pseudostreamer Connectivity Changes
→ S-Web Arcs!



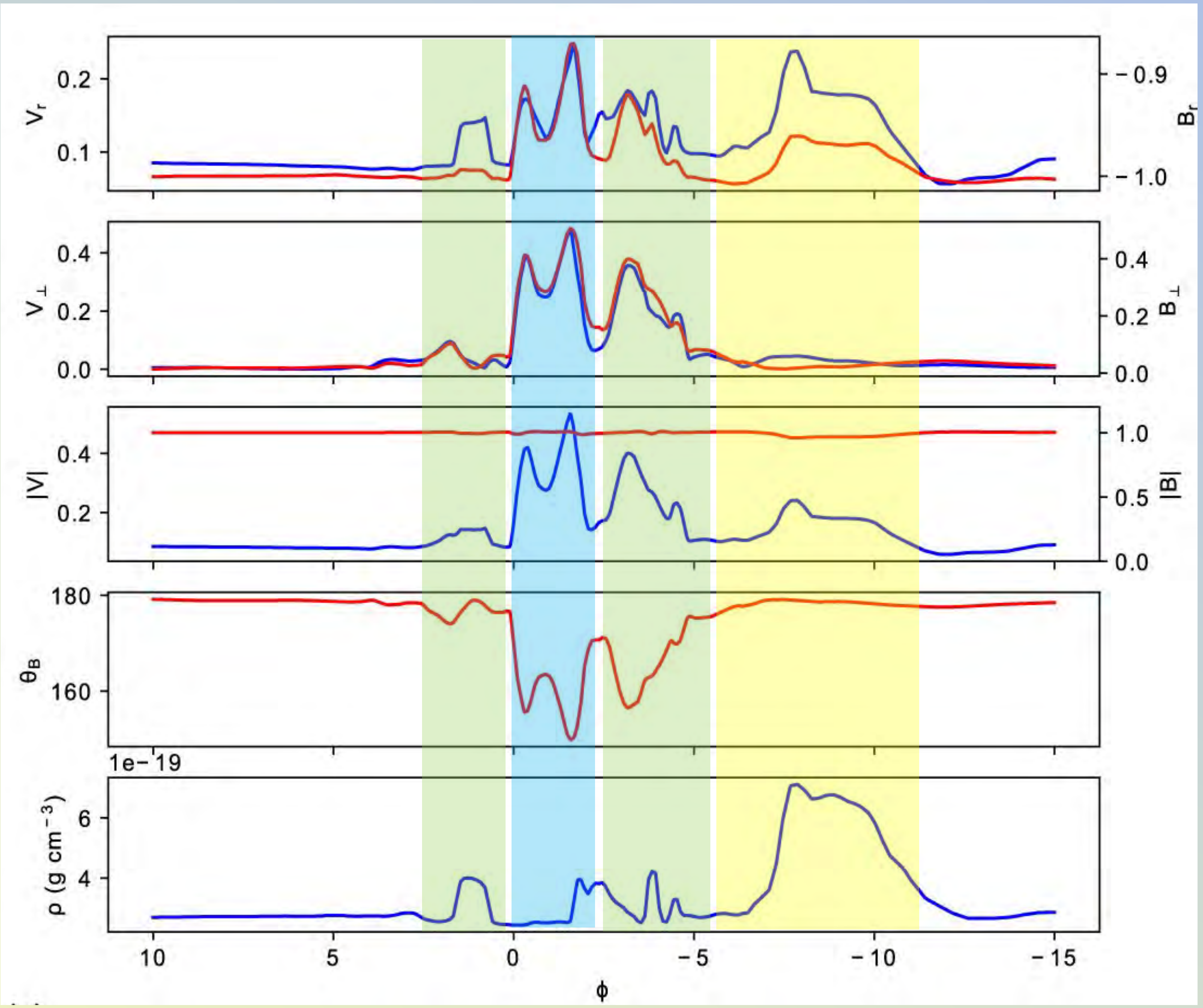


Pseudostreamer Connectivity Changes
→ S-Web Arcs!





[Wyper et al. 2022]



Summary & Conclusions

- Coronal helmet streamer boundaries represent separatrices between open and closed flux systems; even the simplest MHD solar wind model produces a complex set of magnetic reconnection dynamics at streamer cusp & HCS
- Intermittent magnetic island/small FR/plasmoid generation potentially fills entire HCS
- Ionic and elemental charge states during CR2002 highly correlated with S-web arcs/Q-map features and HCS/sector boundary structure. Needs more quantitative analysis
- $N\alpha$ and/or $N\alpha/Np$ is apparently a good proxy for elevated C, O, Fe charge states in the slow solar wind
- Pseudostreamer slow wind also shows enhanced composition variation + broader STE PADs
- Need more simulations of dynamic pseudostreamer evolution, reconnection, and solar wind outflow
- **The characteristic widths of coherent magnetic structures identified from H_m–PVI in HS and PS wind are: $w_{HS} = 0.94 \pm 0.02$ hr, $w_{PS} = 0.92 \pm 0.22$ hr from H_m autocorr and a "streamer blob" component at $\tau_{HS} = 1.625\text{-}2.125$ hr from PVI waiting time—in excellent agreement with the Viall et al. ~90 min timescales of periodic density structures!!!**