COLLAGE 2019

Solar Wind; Flux Emergence

Xudong Sun (UH/IfA)

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Outline

- The magnetic solar wind
- Crash course on flux emergence

The Magnetic Solar Wind

Material partially from S. Bale's 2018 CPAESS summer school lecture

Parker's Solar Wind

- Momentum equation for steadily expanding, spherically symmetric corona:

$$v\frac{dv}{dr} + \frac{1}{\rho}\frac{dP}{dr} + \frac{GM_\odot}{r^2} = 0$$

- Isothermal, perfect gas (dT/dr = 0) & constant mass loss rate ($\rho v r^2 = C$)

$$\frac{dP}{dr} = \frac{RT}{\mu}\frac{d\rho}{dr}$$

$$\frac{1}{\rho}\frac{d\rho}{dr} = -\frac{1}{v}\frac{dv}{dr} - \frac{2}{r}$$

- Solving for:

$$(v^2 - v_c^2)\frac{1}{v}\frac{dv}{dr} = 2\frac{v_c^2}{r^2}(r - r_c)$$

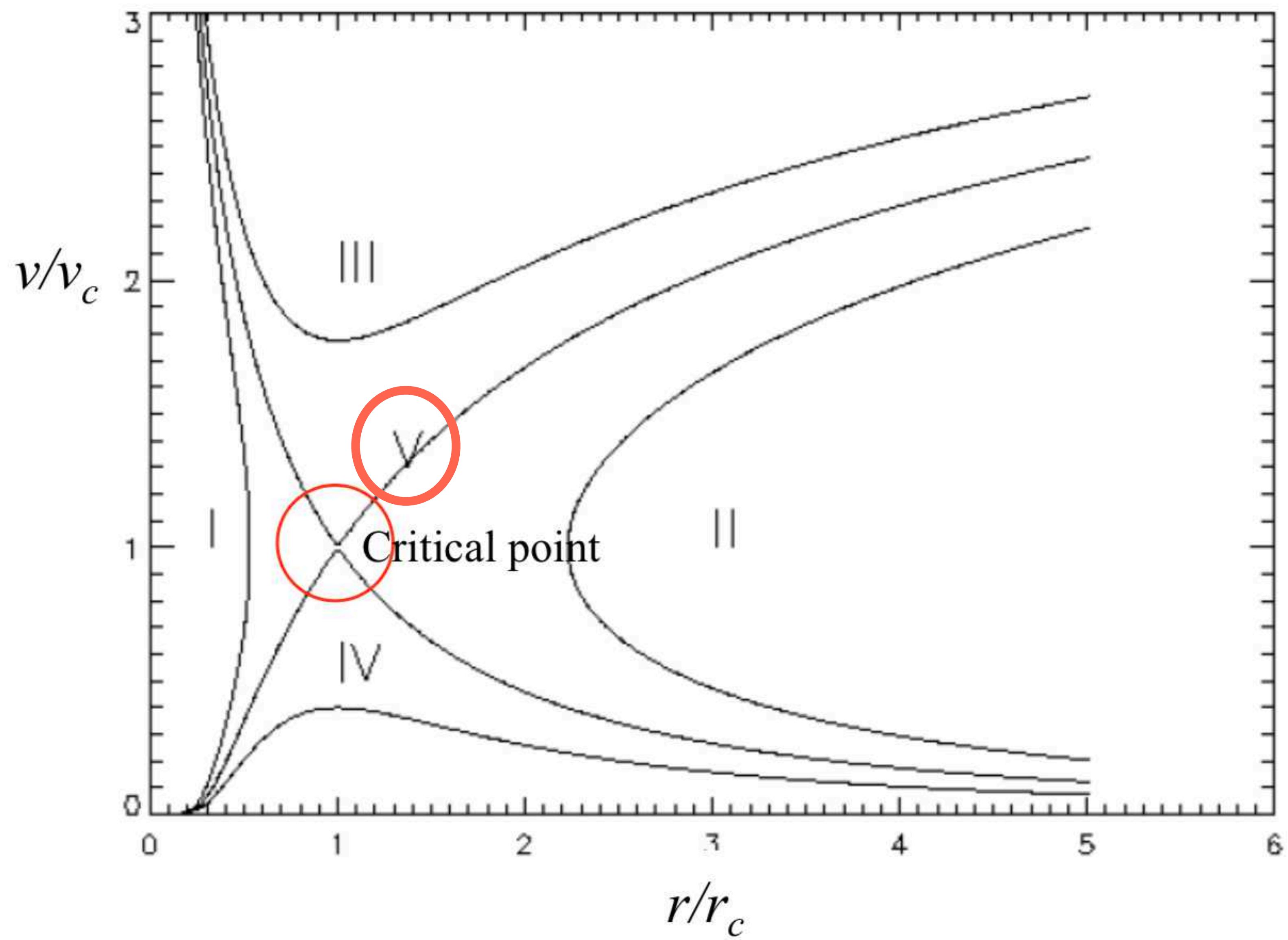
$$v_c = \sqrt{RT/\mu}, \;\; r_c = GM_\odot/2v_c^2$$

Parker (1958)

Parker's Solar Wind

- Solution:

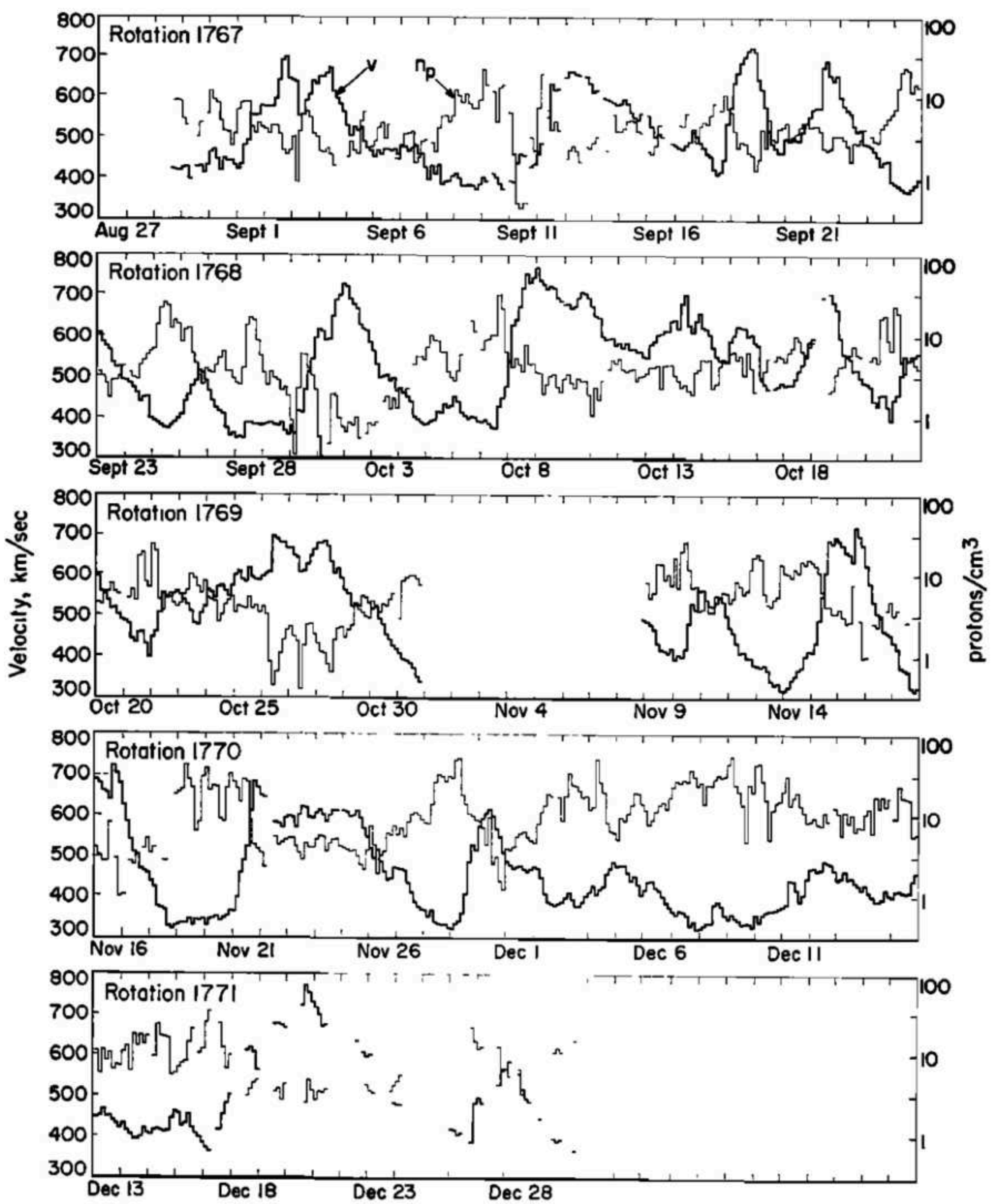
$$\left(\frac{v}{v_c}\right)^2 - \ln\left(\frac{v}{v_c}\right)^2 = 4\ln\left(\frac{r}{r_c}\right) + 4\left(\frac{r}{r_c}\right) + C$$



Parker (1958)

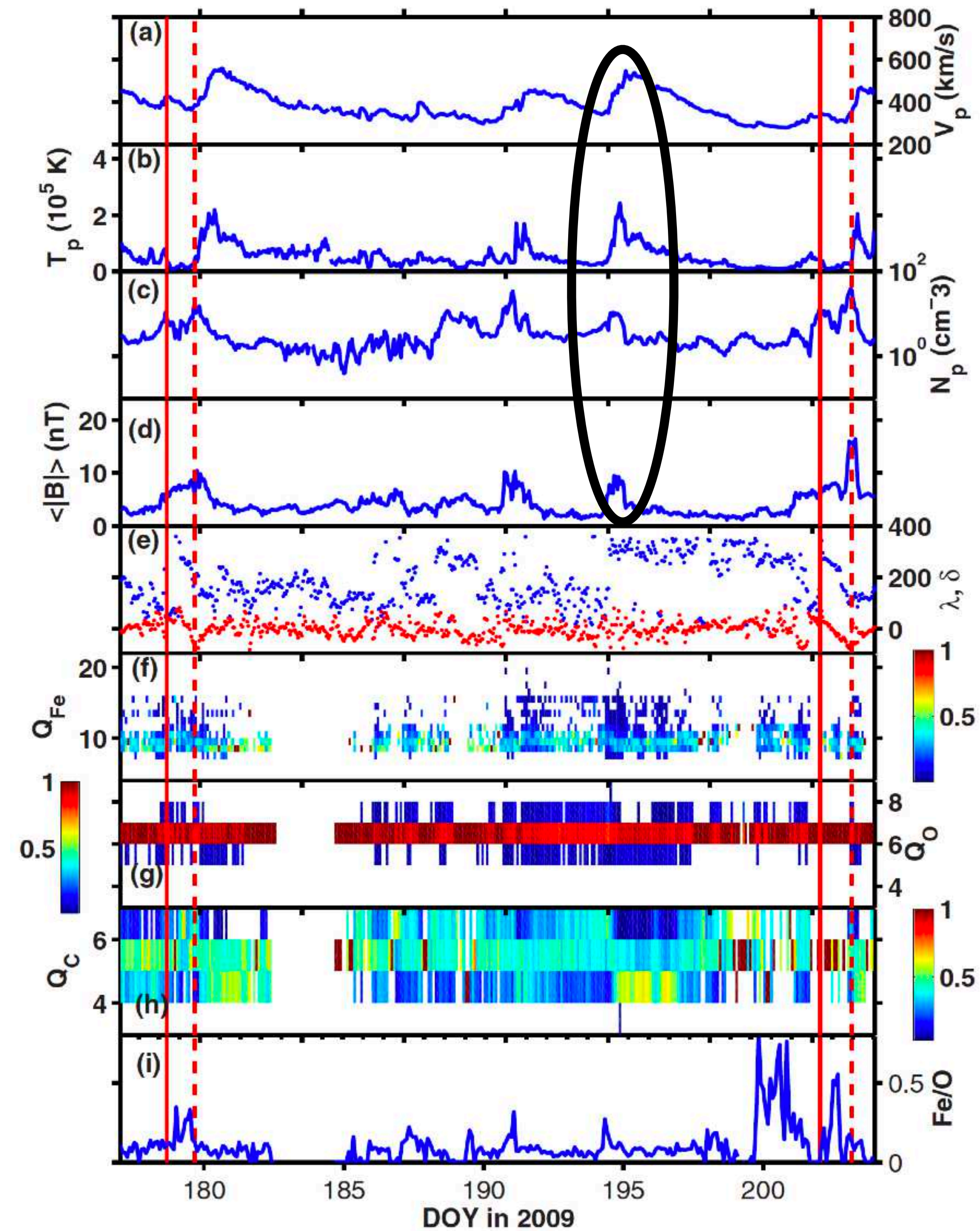
In Situ Measurement

Mariner 2



Neugebauer & Snyder (1965)

ACE



Lepri et al. (2013)

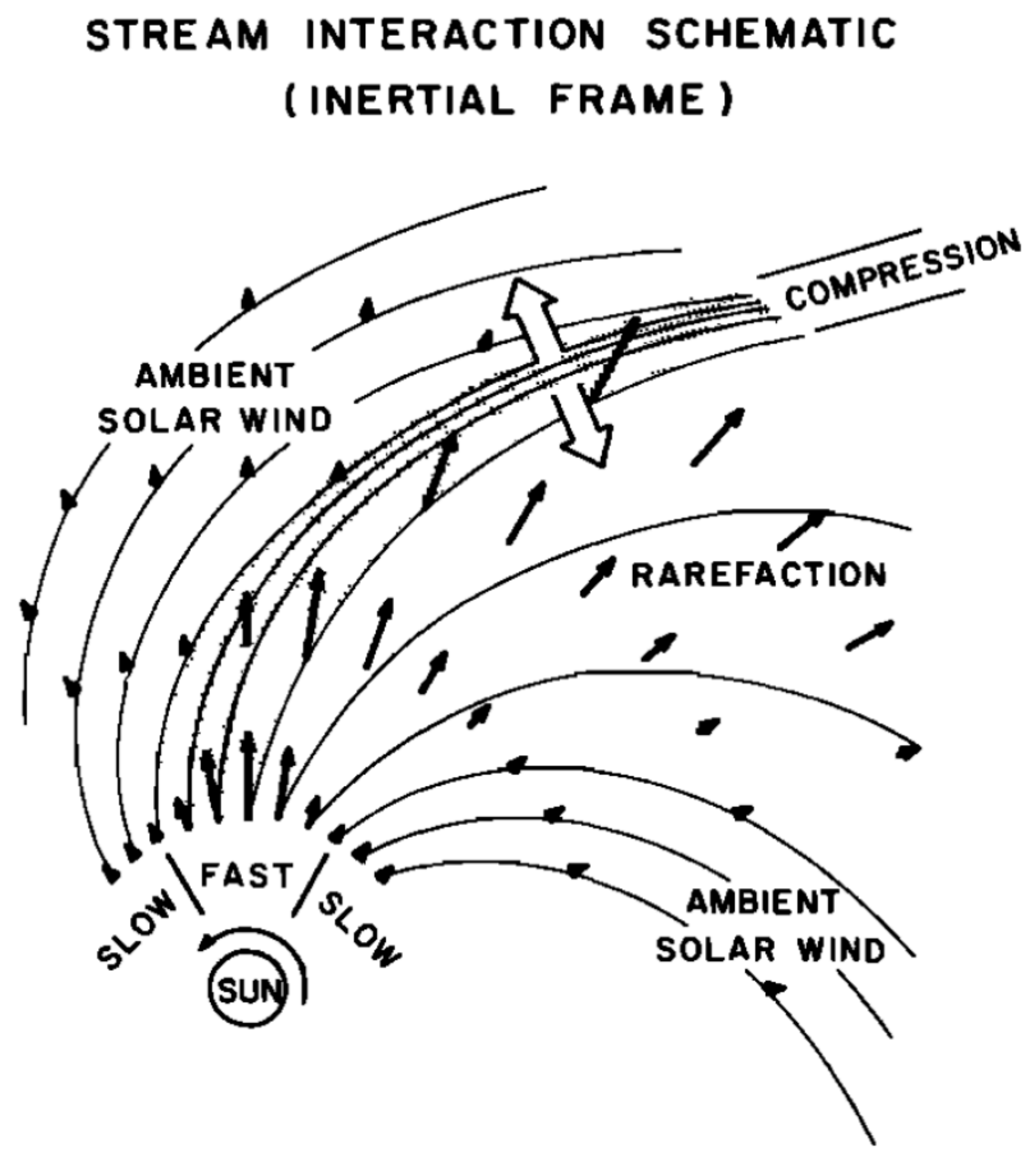
Alfvén Surface & Stream Interaction

- Alfvén surface: kinetic energy greater than magnetic energy

$$\frac{1}{2}\rho v^2 = \frac{B^2}{8\pi}$$

  Occurs at a few tens of solar radii

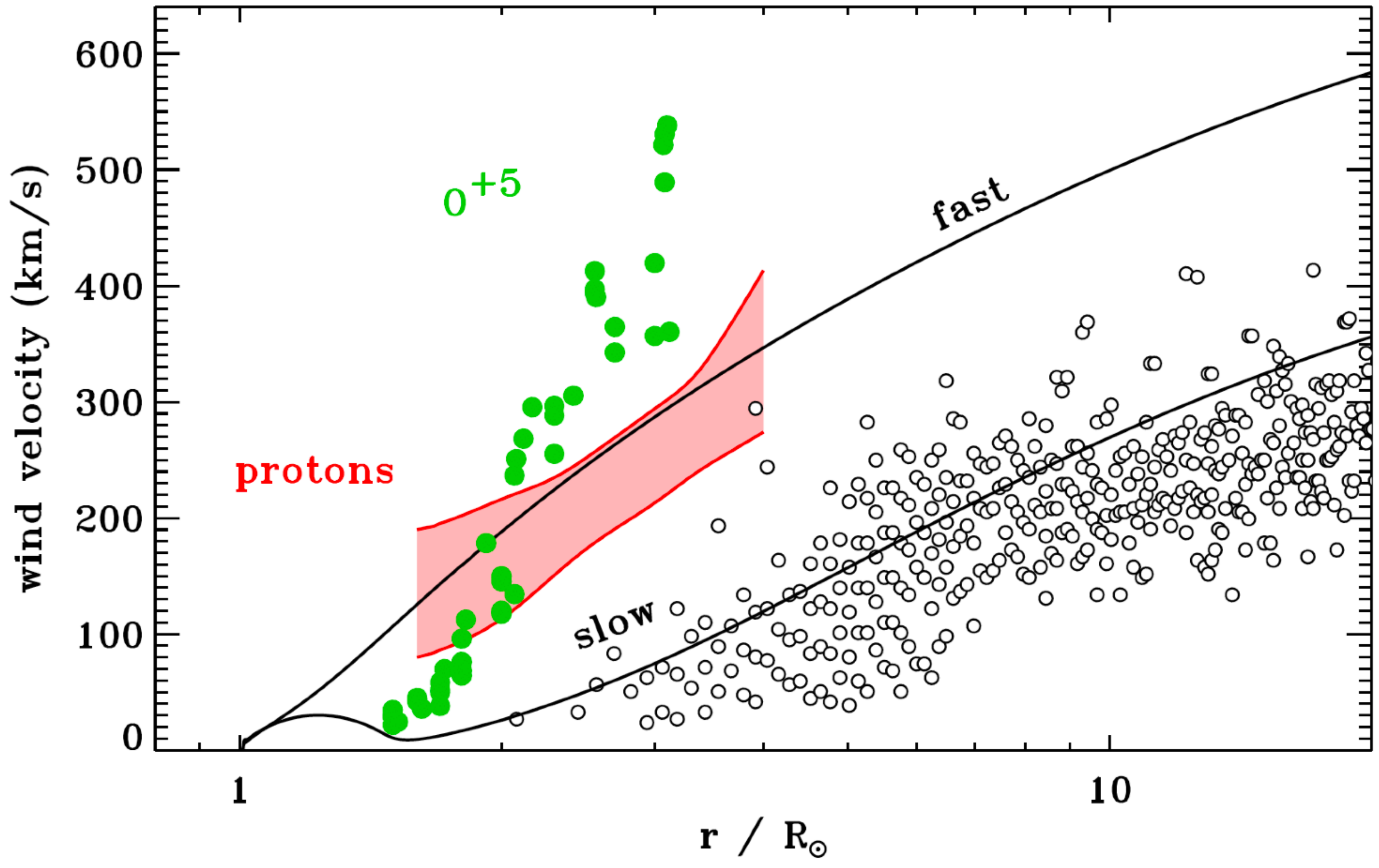
- Stream (co-rotating) interaction region: faster SW stream catches up with slower stream and compresses plasma



Pizzo (1978)

Solar Wind Acceleration

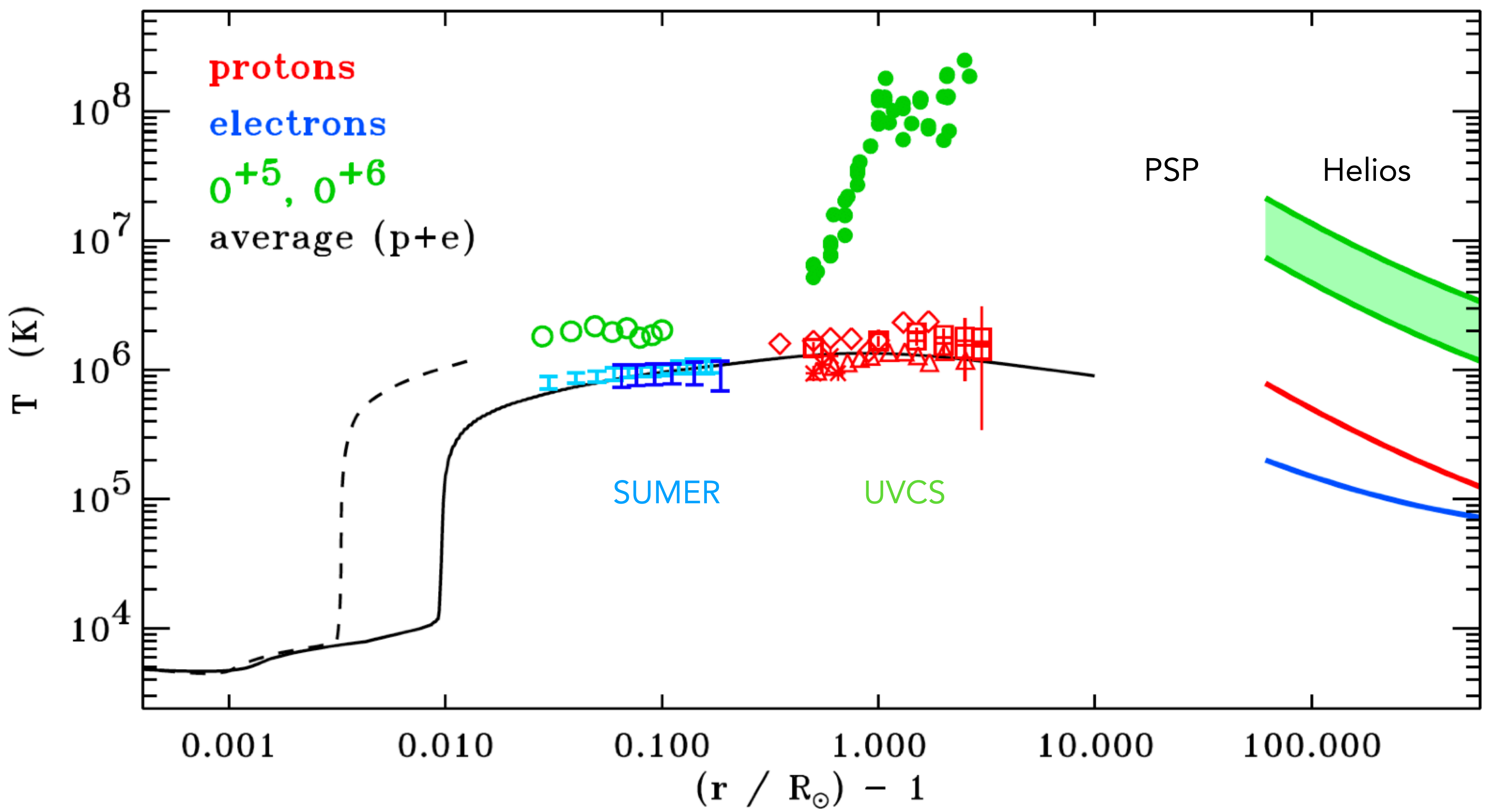
- Fast wind: relatively uniform
- Slow wind: impulsive
- Minor ion species show enhanced acceleration



Cranmer (2009)

Solar Wind Temperature

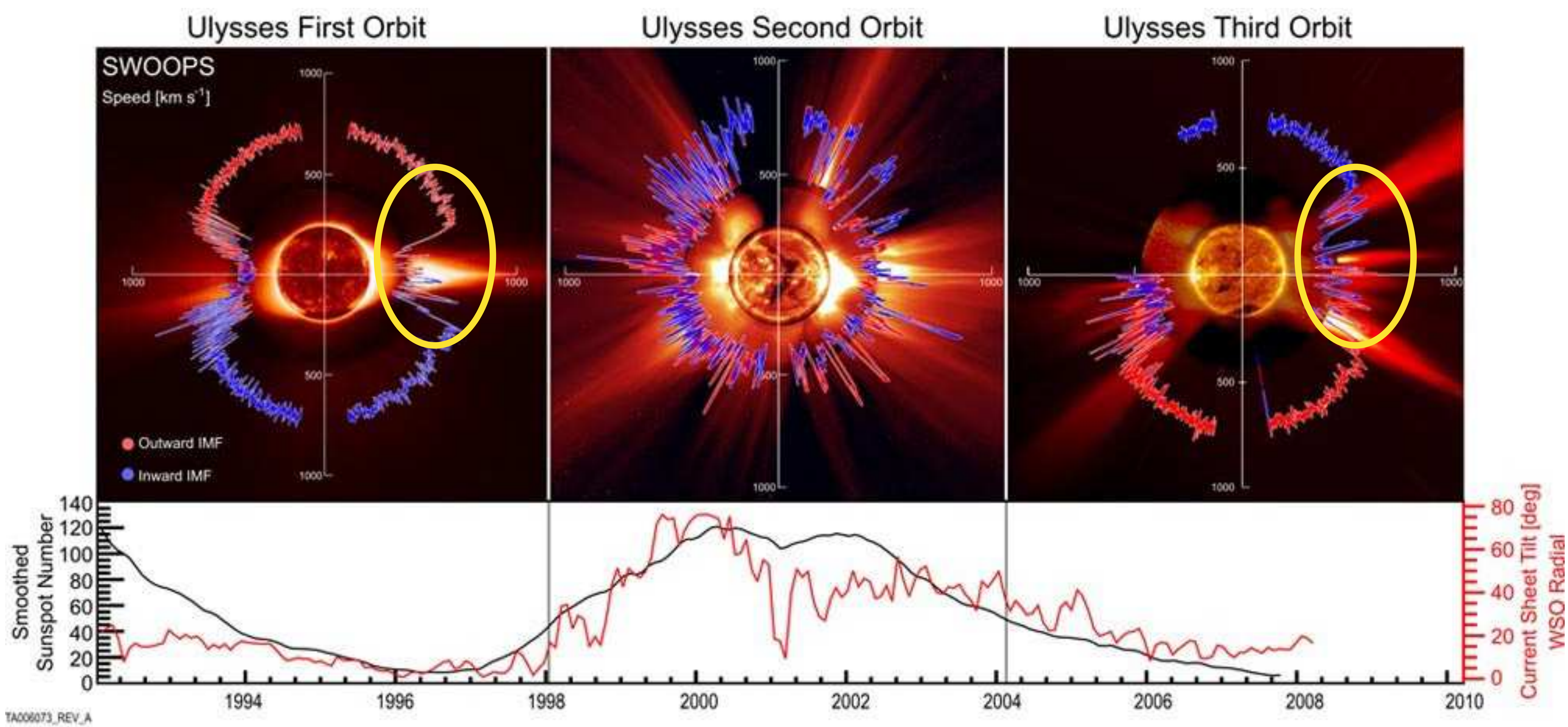
- Minor ions selectively heated in direction perpendicular to *B*
- Different ion compositions
- Gap of 10 - 60 R_{sun} will be probed by *Parker Solar Probe* (*PSP*)



Cranmer (2009)

Bimodal Structure

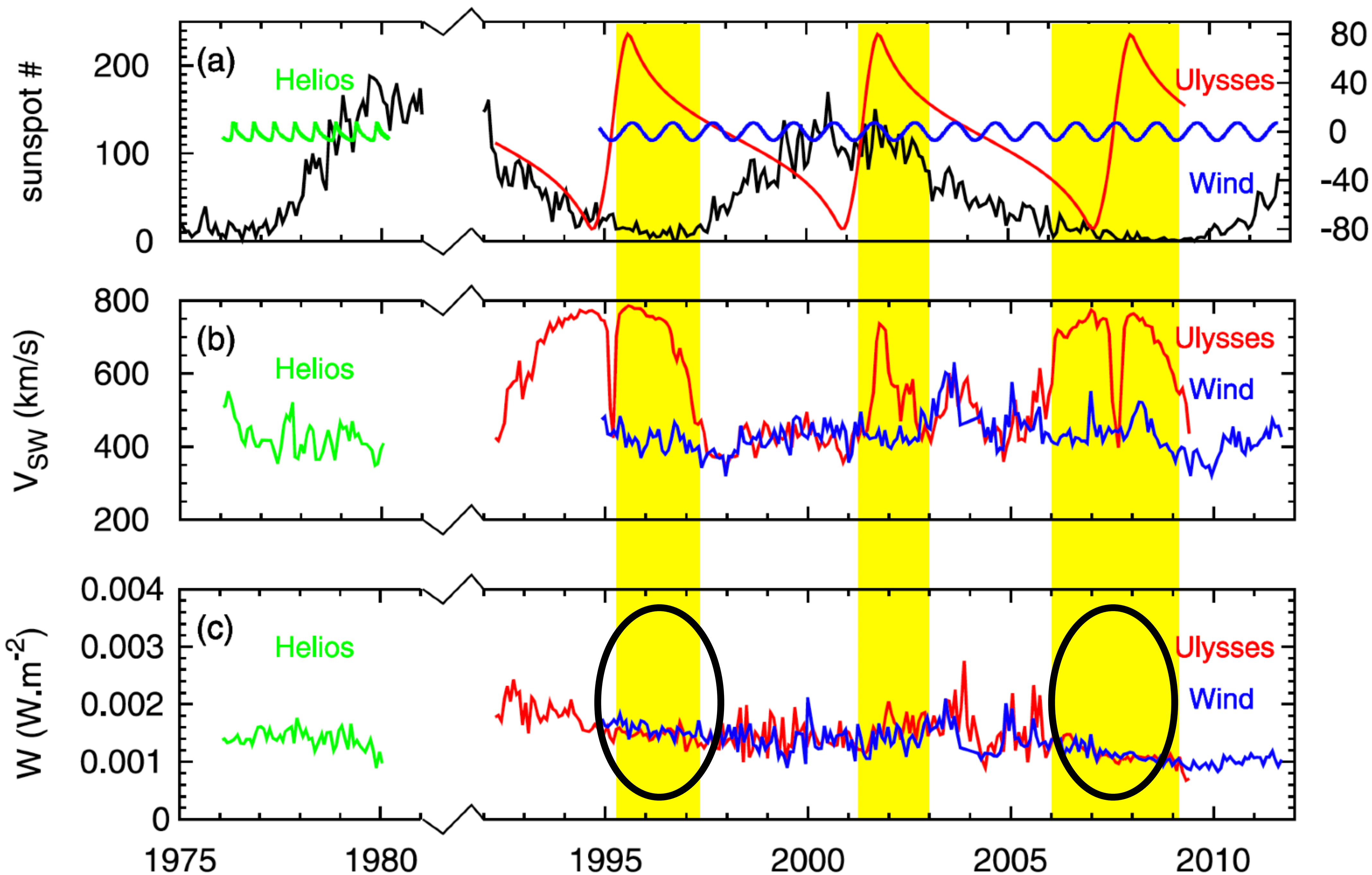
Directly dependent of coronal field structure



McComas et al. (2008)

Constant Energy Flux

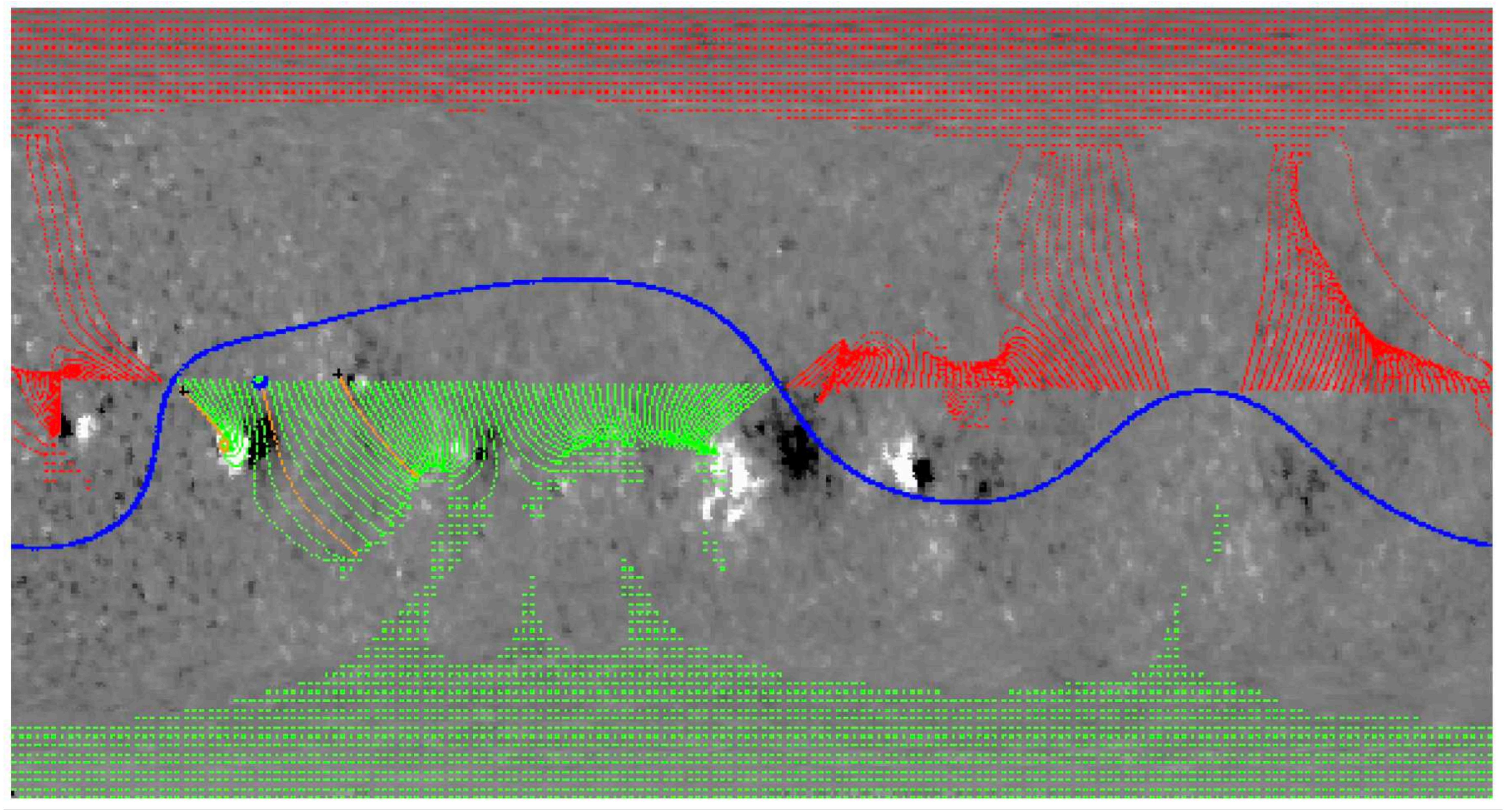
$$W = \rho V \left(\frac{1}{2} V^2 + \frac{M_{\odot} G}{R_{\odot}} \right)$$



Le Chat et al. (2012)

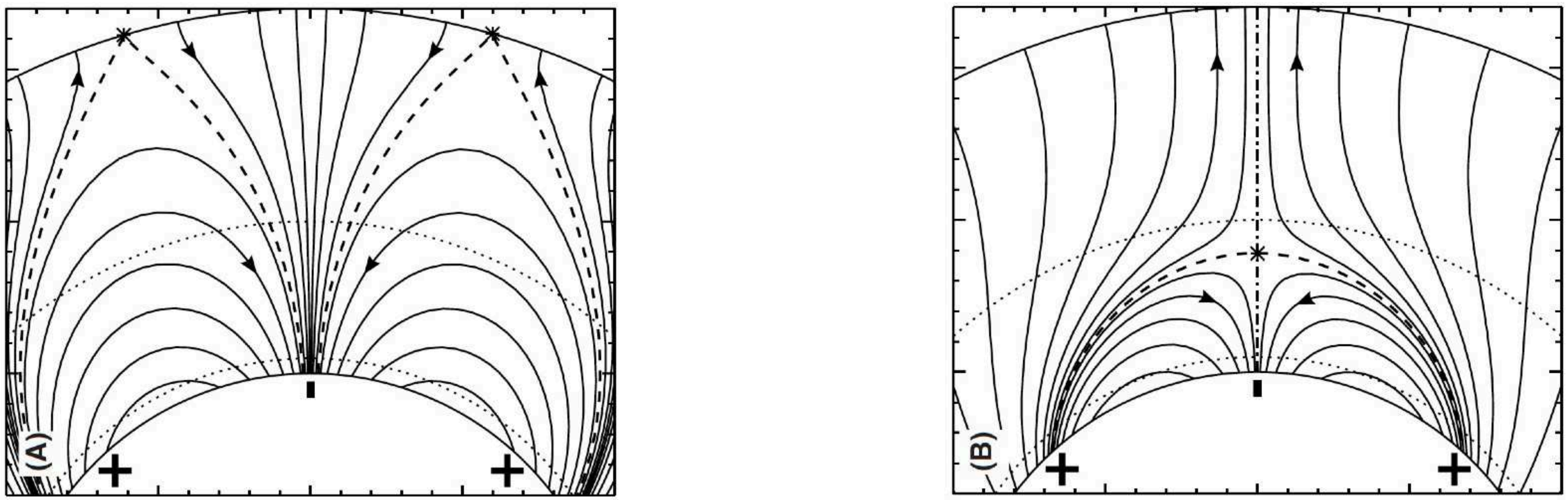
Magnetic Connectivity

Mapping of open field along Sun-Earth line

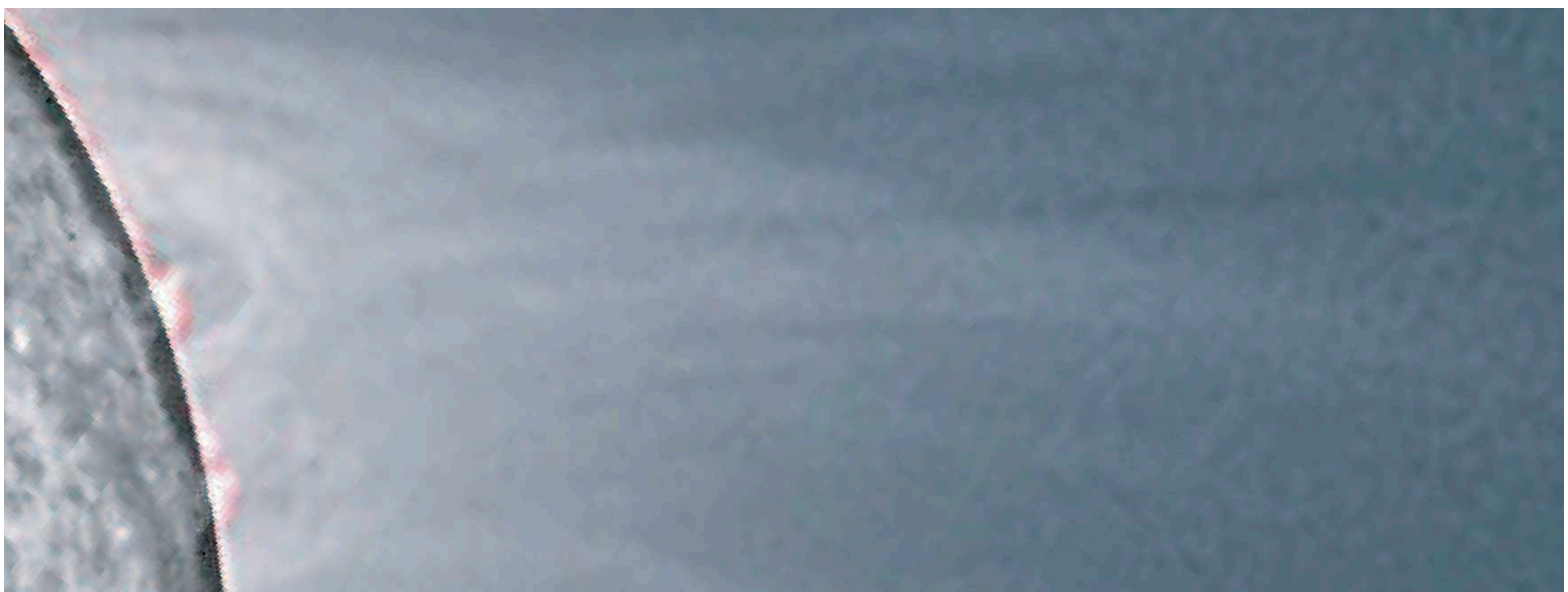


NSO/*GONG*

Streamer & Pseudo-Streamer



Rachmeler et al. (2014)



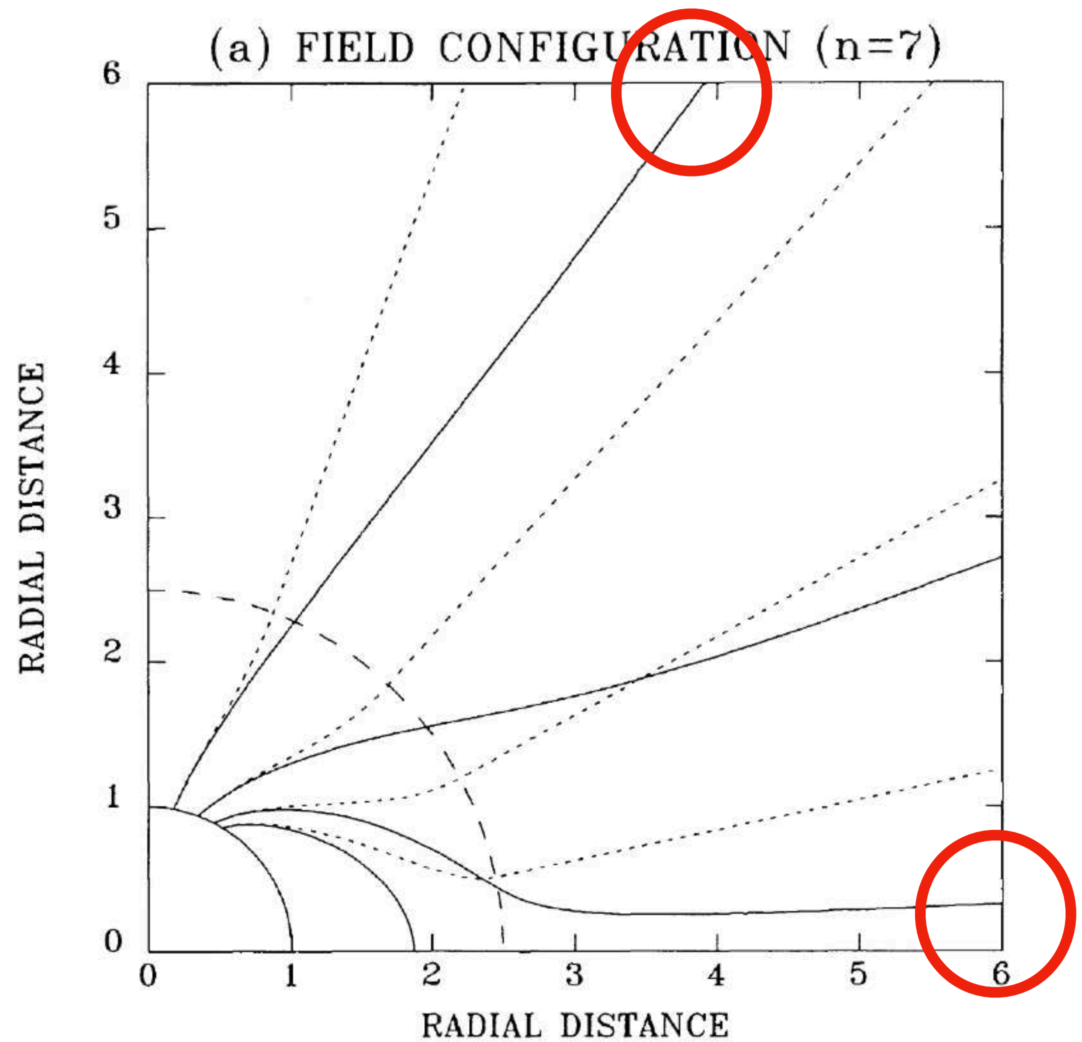
Wang et al. (2007)

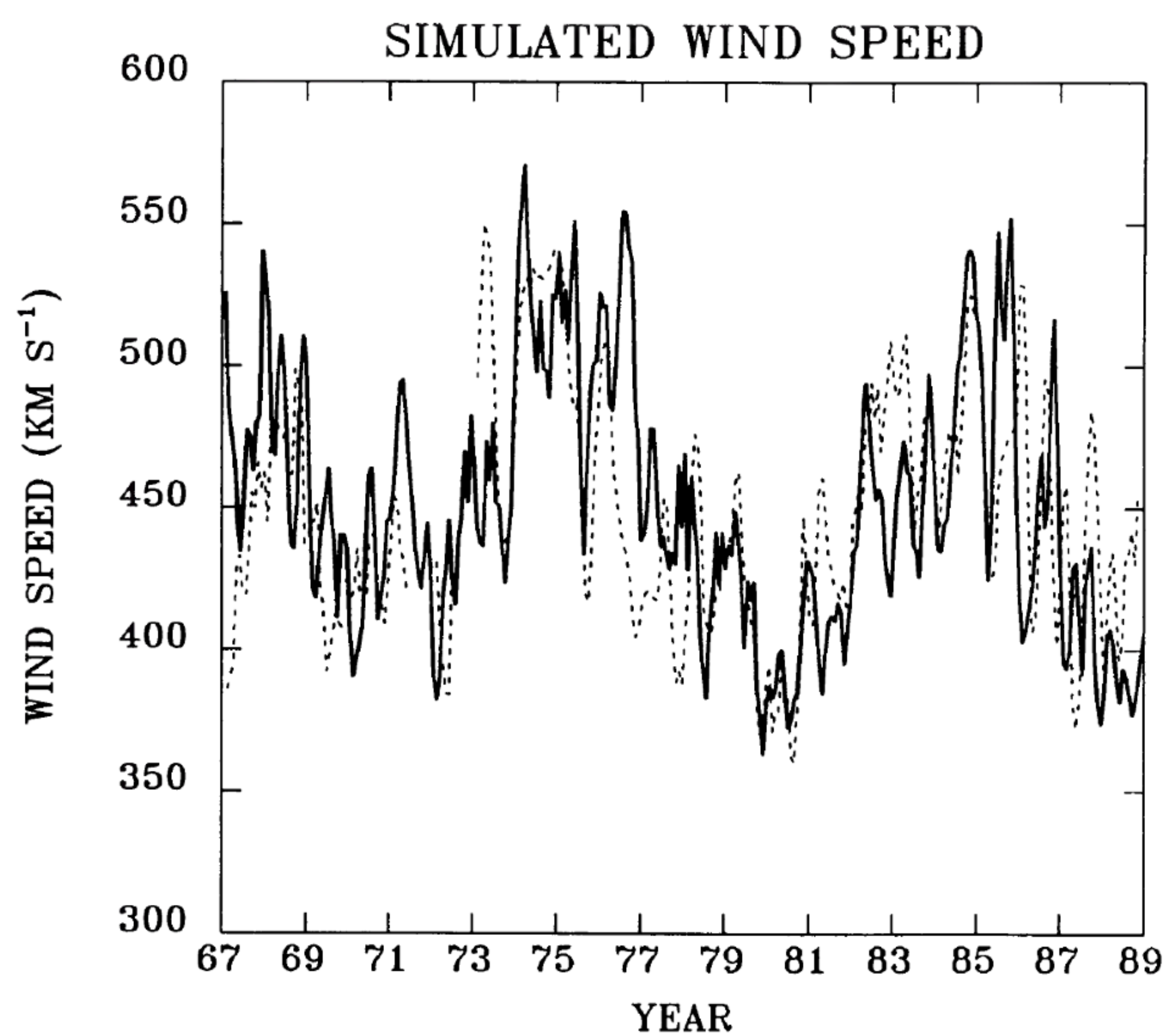
Flux Tube Expansion

$$f = \frac{B_r(R_\odot)R_\odot^2}{B_r(R_s)R_s^2} \propto V^{-\alpha}$$

Wang & Sheeley (1990)

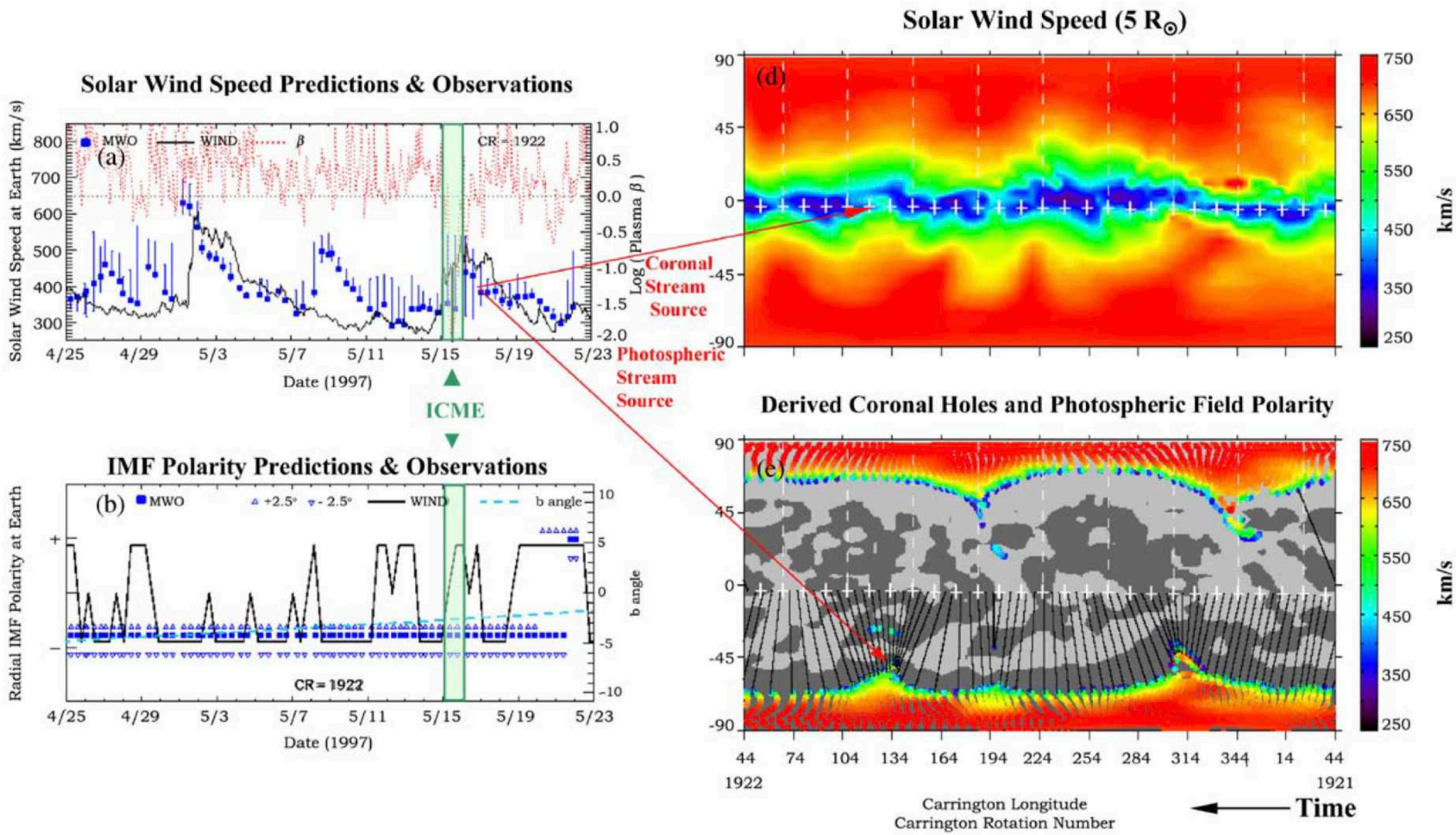
f_s	v_w (km s^{-1})
<3.5	700
3.5–9	600
9–18	500
18–54	400
>54	330





Wang-Sheeley-Arge (WSA) Model

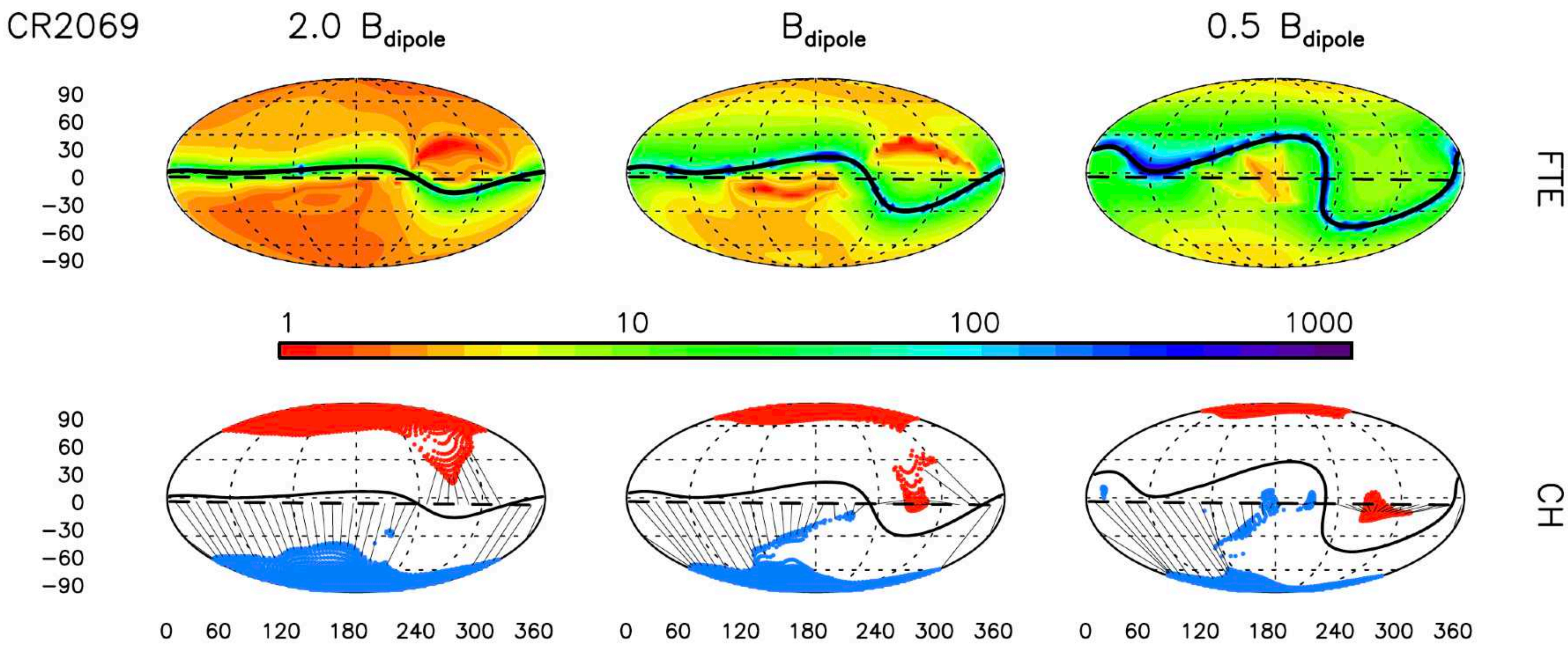
$$V(f) = 267.5 + \frac{410}{f^{2/5}}$$



Arge & Pizzo (2000); Arge et al. (2004)

The Critical Polar Field

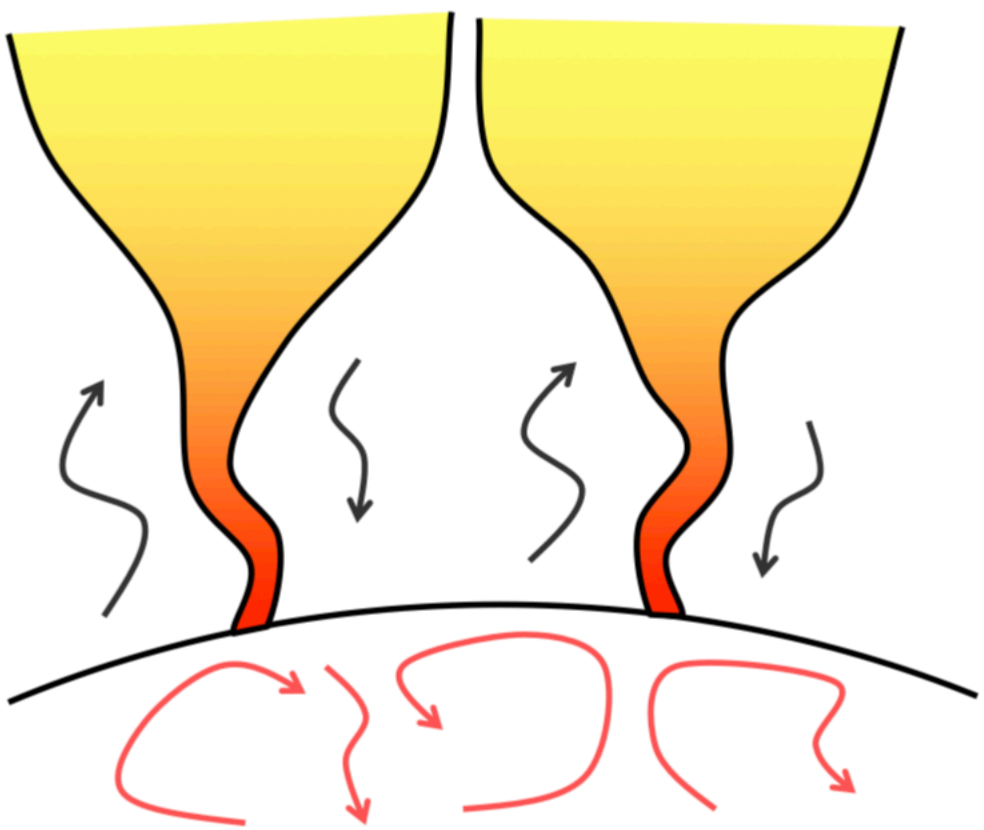
- Coronal structure & *f* critically depends on dipole (polar) field
- Polar field not well observed



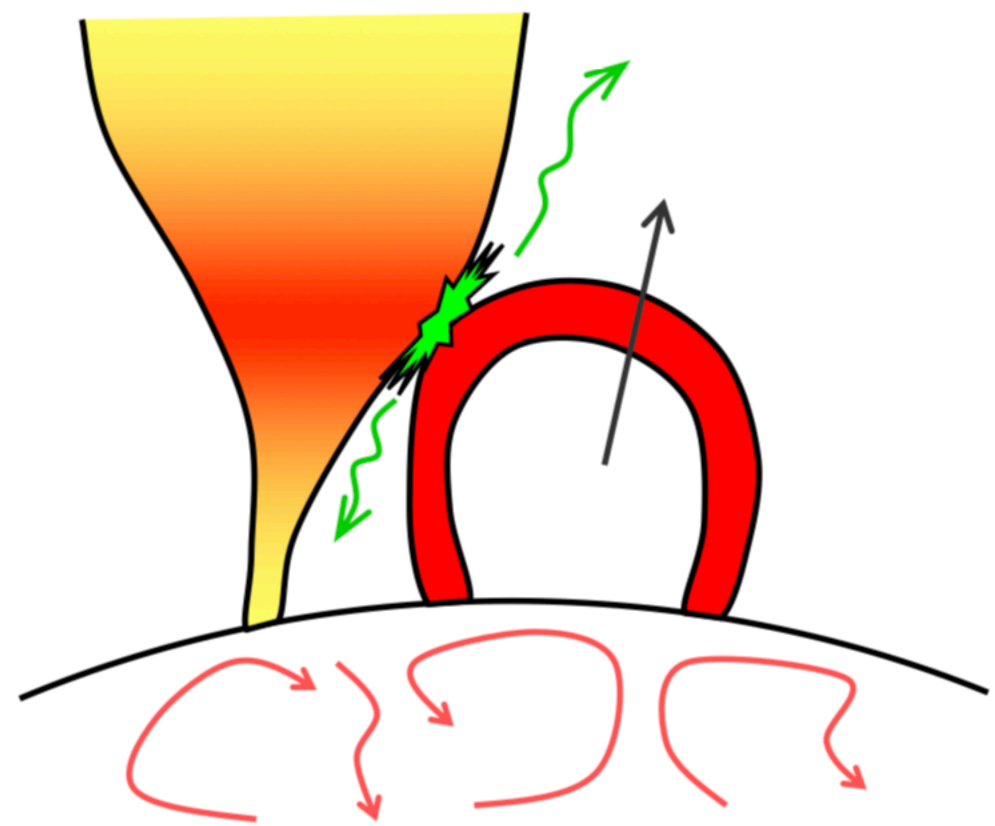
Sun et al. (2008)

SW Origins

Wave & Turbulence



Reconnection



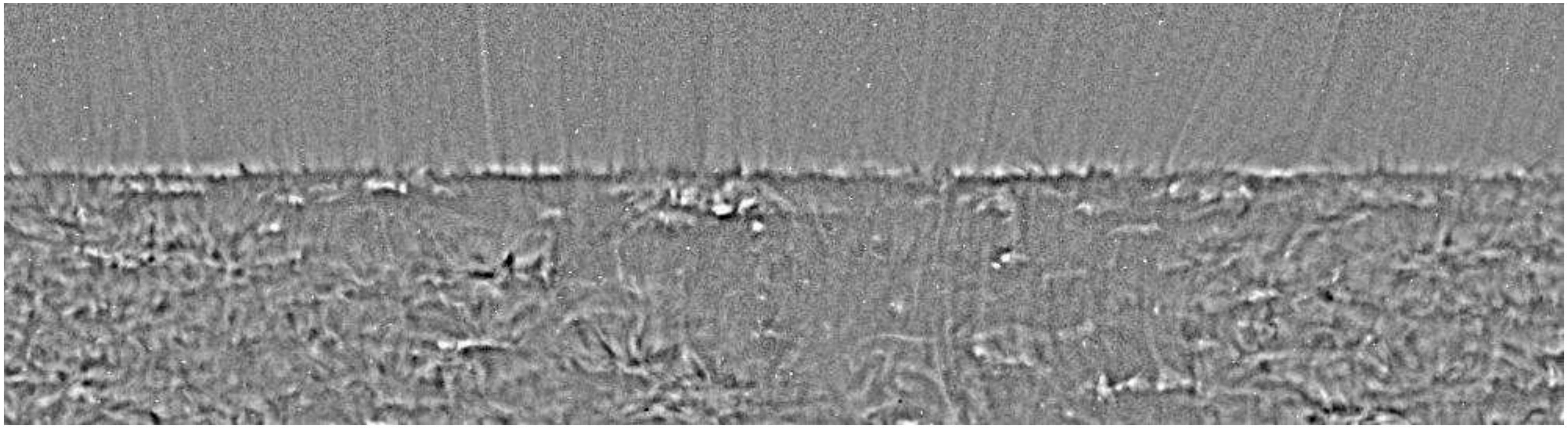
Courtesy S. Cranmer

- Alfvén wave damping
- Open field region: coronal holes

- Reconnection
- Close/open field boundary: coronal hole/ streamer edge; active region edge

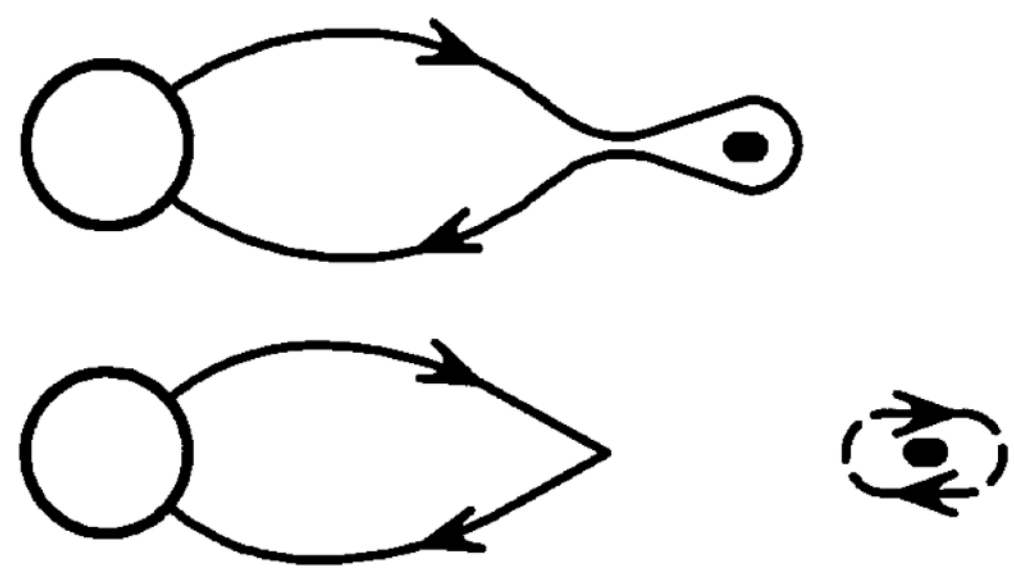
Alfvén Waves & Streamer Blobs

AIA 17.1 nm



McIntosh et al. (2011)

LASCO C3 difference

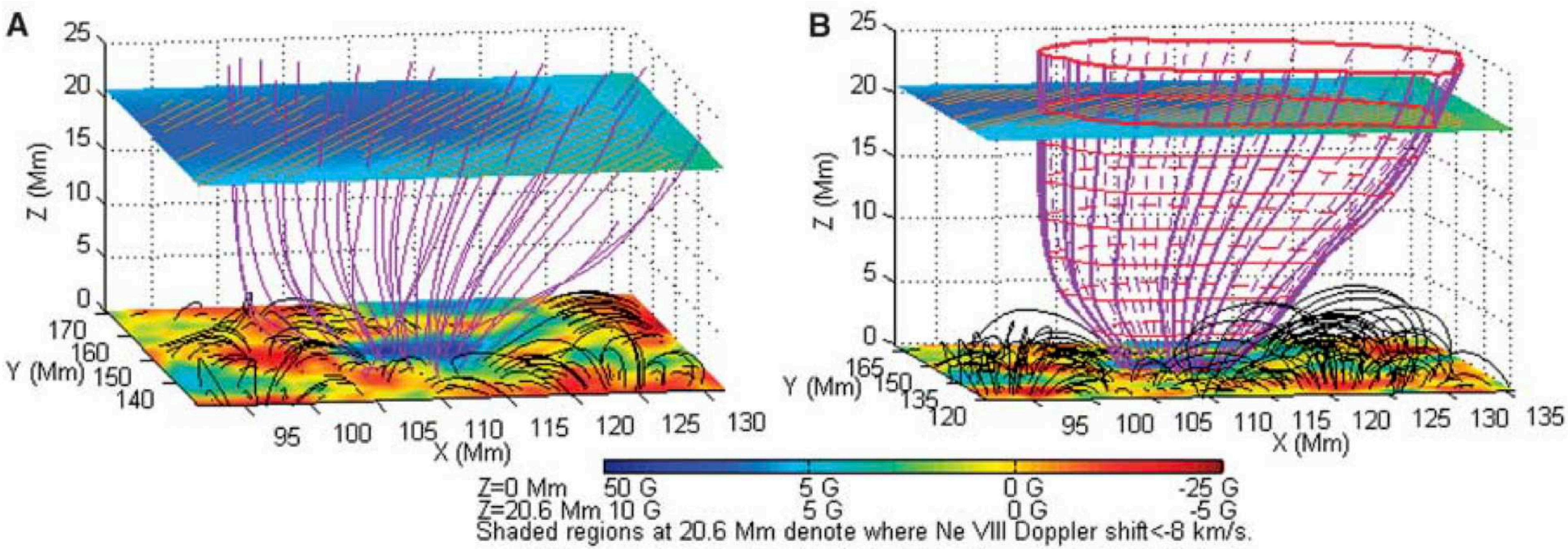


Wang et al. (2000)

CH Winds

- Ubiquitous outflow in coronal EUV lines with v > 10 km/s
- Corresponded well with open field “magnetic funnels”

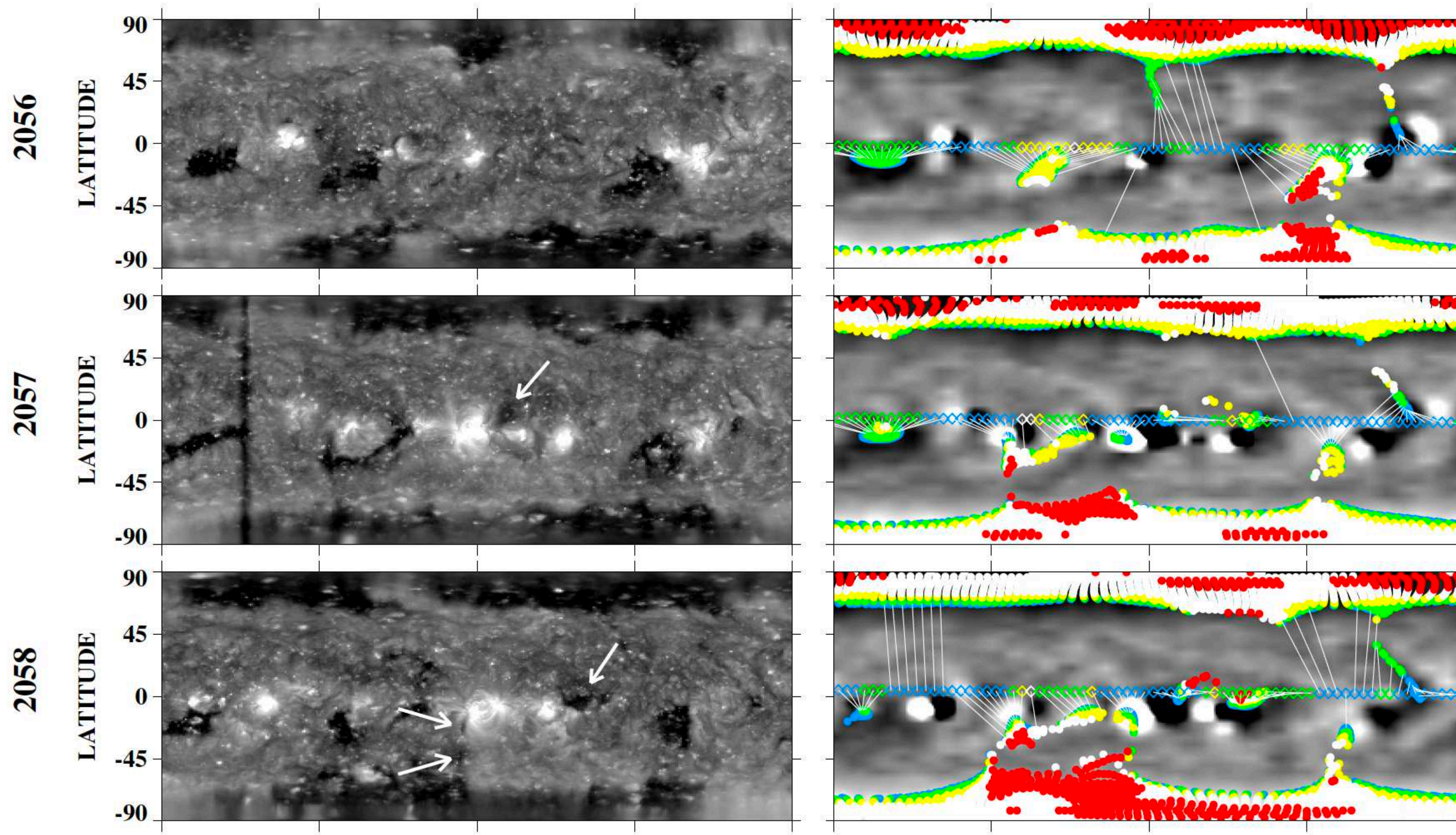
SoHO/SUMER Ne VIII 77 nm in Polar CH



Tu et al. (2005)

CH Winds

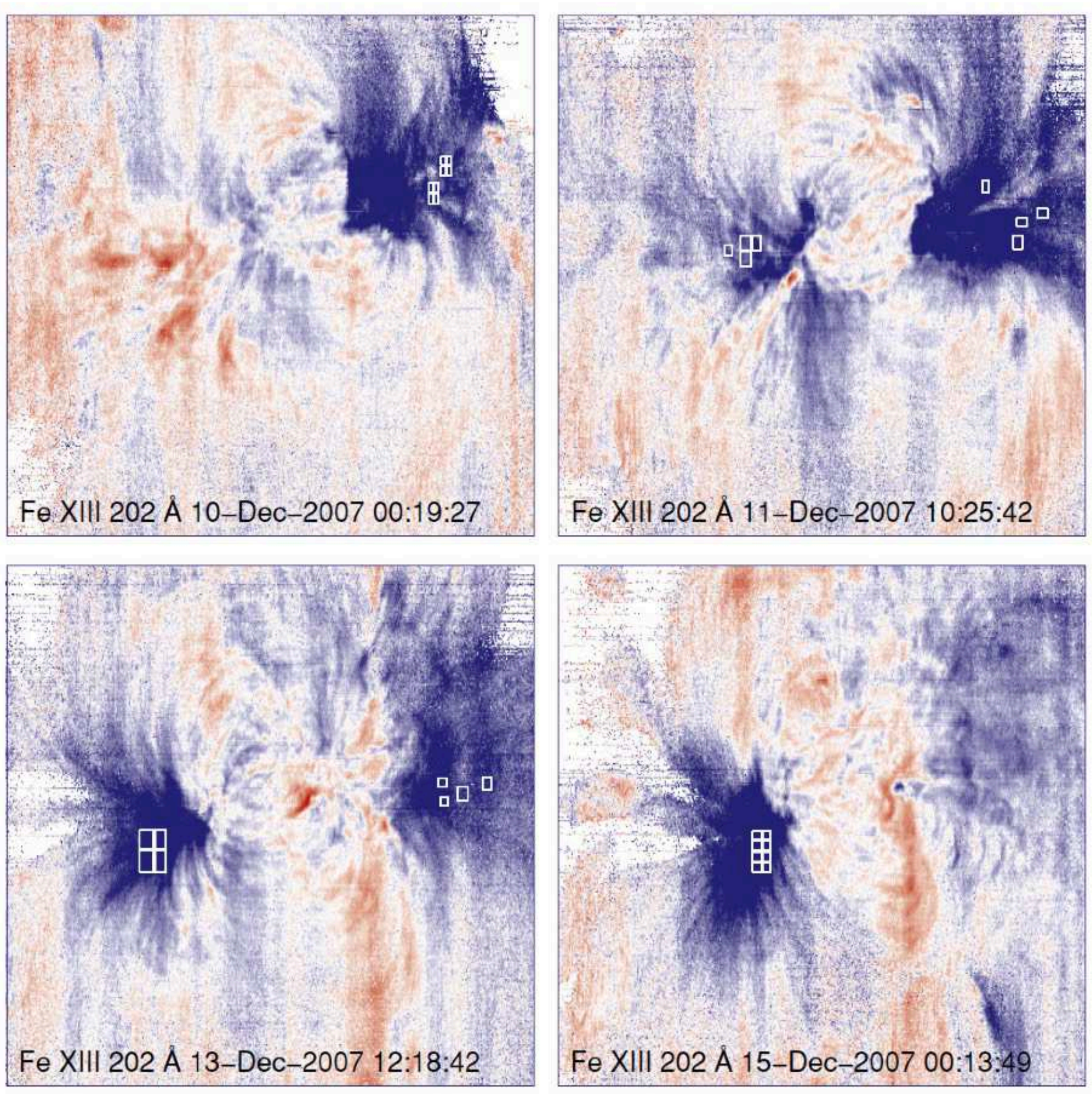
Decayed AR turns into low-lat CH



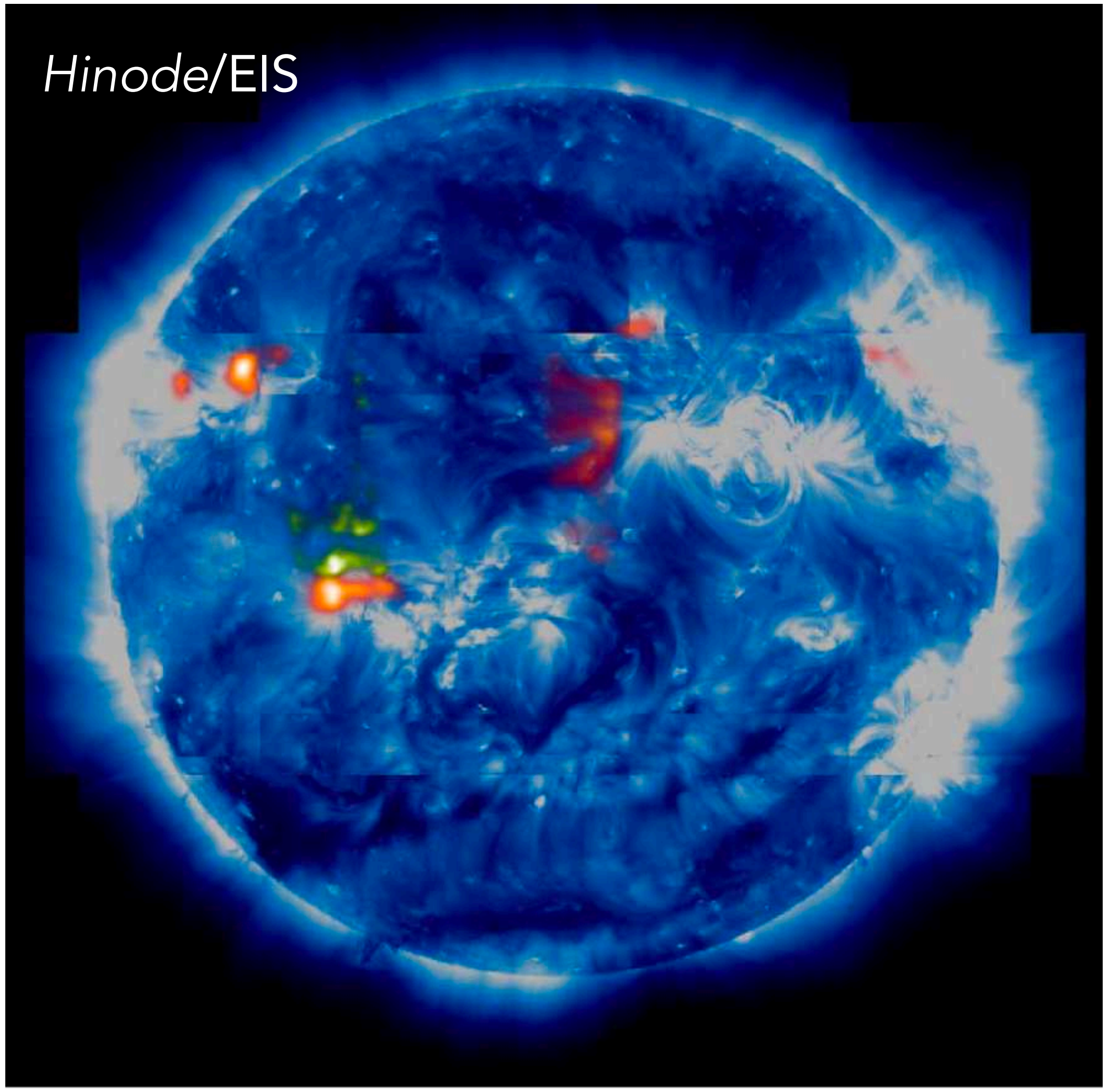
Wang et al. (2010)

Non-CH Winds

- Outflows from edge of ARs based on EUV Doppler observation
- Combining magnetic modeling and spectral diagnostics



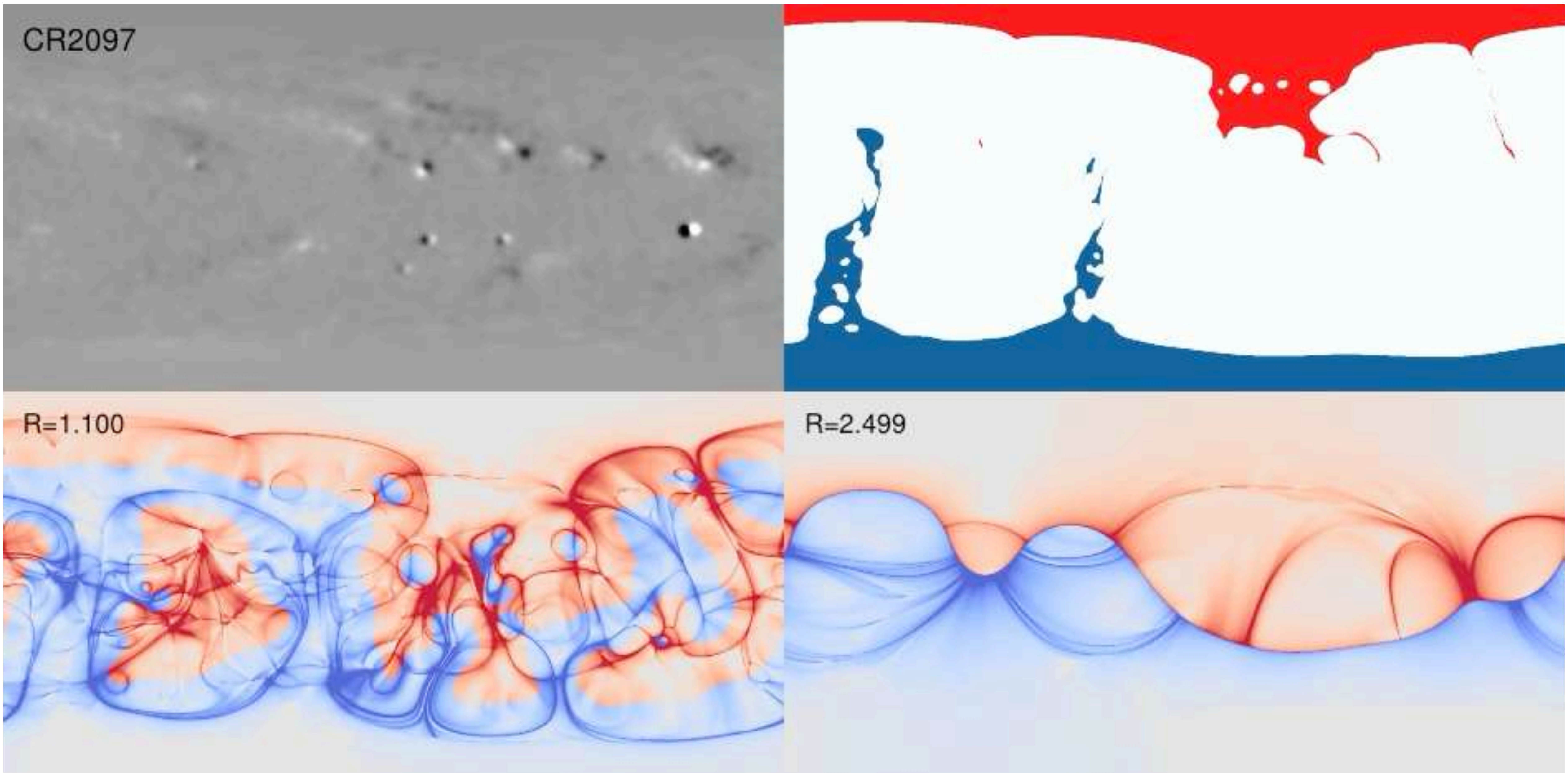
Brooks & Warren (2011)



Brooks et al. (2015)

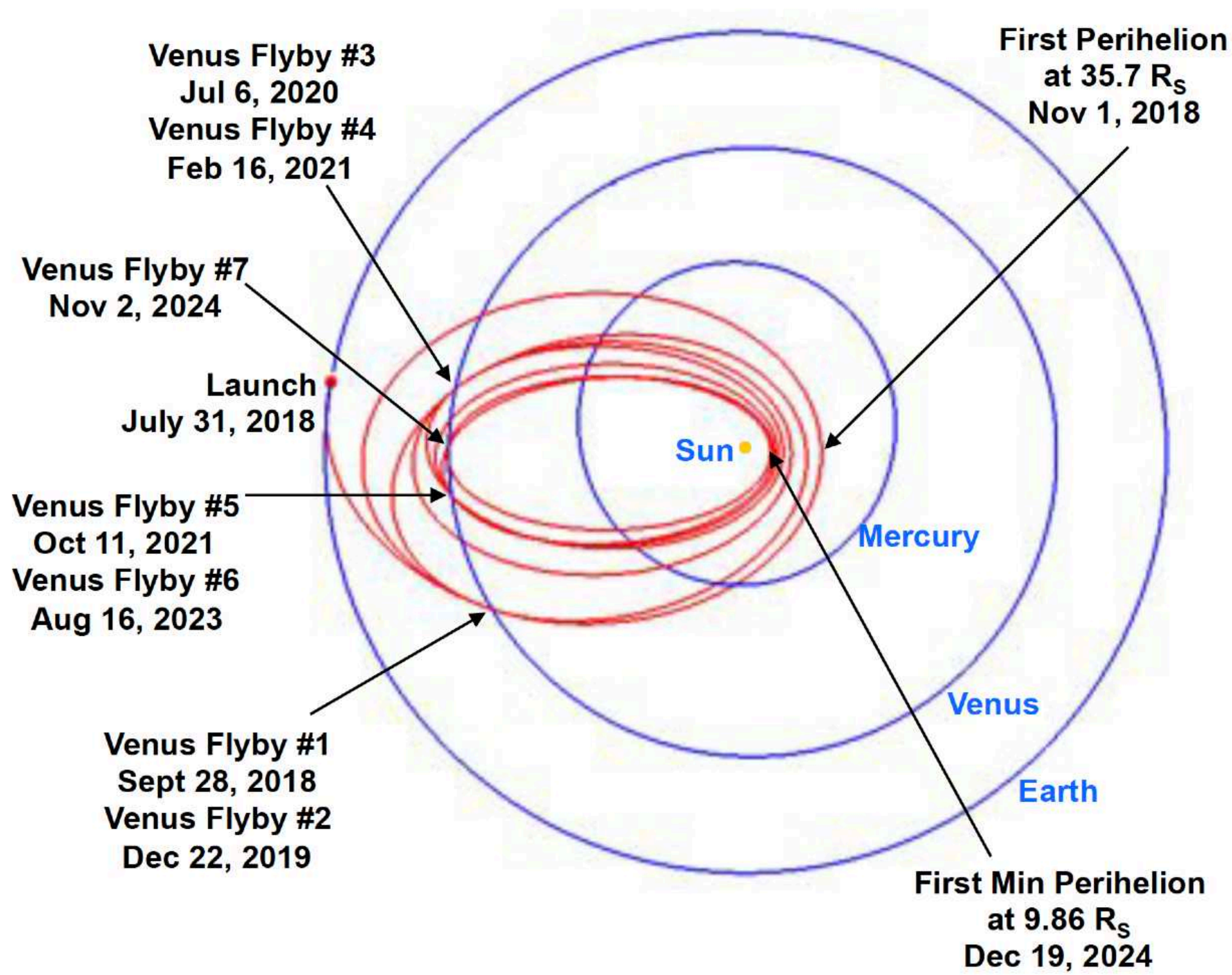
The "*S*-Web" Model

Squashing Degree Based on HMI & PFSS



http://hmi.stanford.edu/QMap/

Parker Solar Probe (PSP)



- Repeated 7 Venus gravity assists to lower orbit to reach the Sun
- Switching between resonant and non-resonant Venus encounters to minimize mission duration
- Orbit phasing matched between flybys so that no deep space maneuvers are required
- Multiple solar encounters at various distances
- Solar distances not beyond Earth for a solar powered spacecraft

Courtesy S. Bale

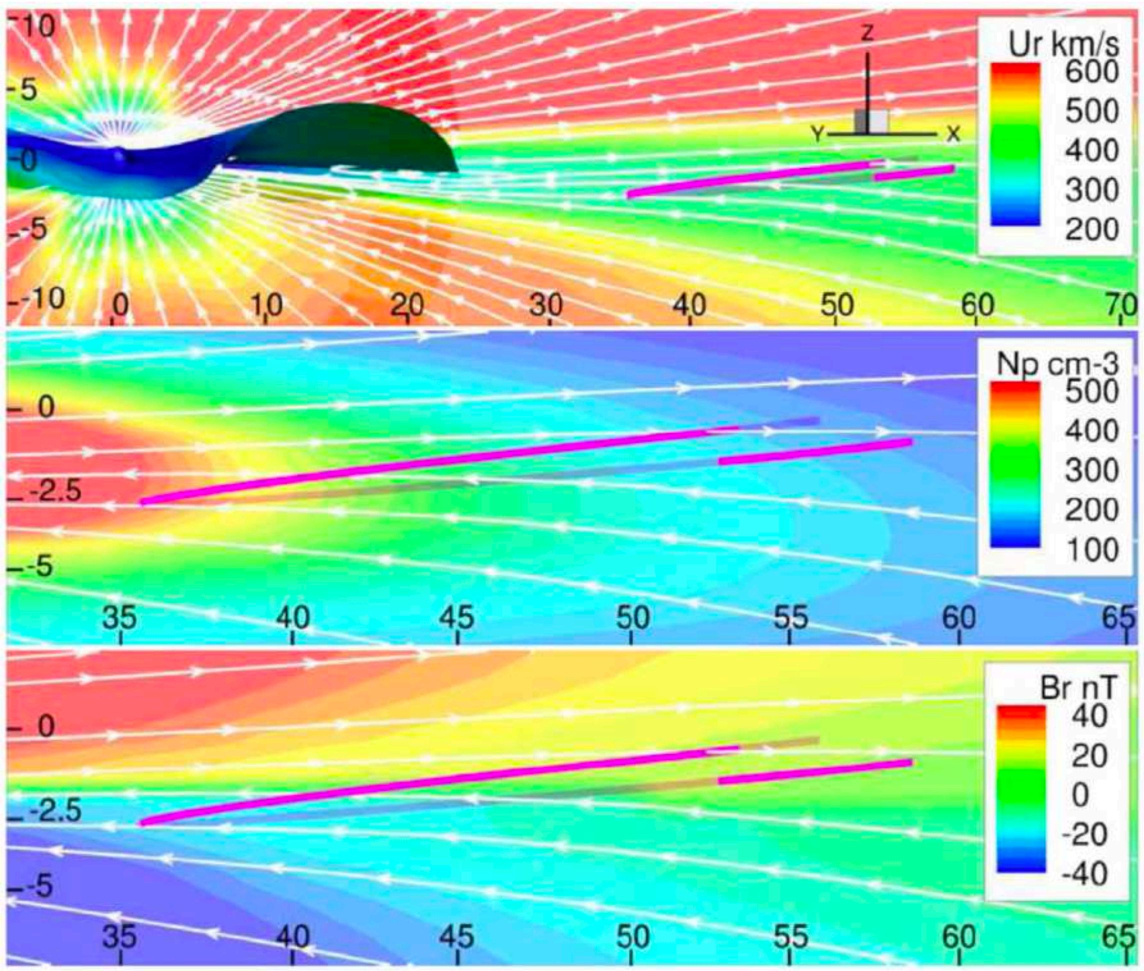
Parker Solar Probe (PSP)

L1 Science Objectives	Sample Processes	Needed Measurements	Instruments
1. Trace the flow of energy that heats and accelerates the solar corona and solar wind. 2. Determine the structure and dynamics of the plasma and magnetic fields at the sources of the solar wind. 3. Explore mechanisms that accelerate and transport energetic particles.	- heating mechanisms of the corona and the solar wind; - environmental control of plasma and fields; - connection of the solar corona to the inner heliosphere. - particle energization and transport across the corona	- electric & magnetic fields and waves, Poynting flux, absolute plasma density & electron temperature, spacecraft floating potential & density fluctuations, & radio emissions - energetic electrons, protons and heavy ions - velocity, density, and temperature of solar wind e-, H+, He++ - solar wind structures and shocks	FIELDS - Magnetic Field - Electric Field - Electric/Mag Wave ISOIS - Energetic electrons - Energetic protons and heavy ions - (10s of keV to ~100 MeV) SWEAP - Plasma e-, H+, He++ - SW velocity & temperature WISPR - White light measurements of solar wind structures

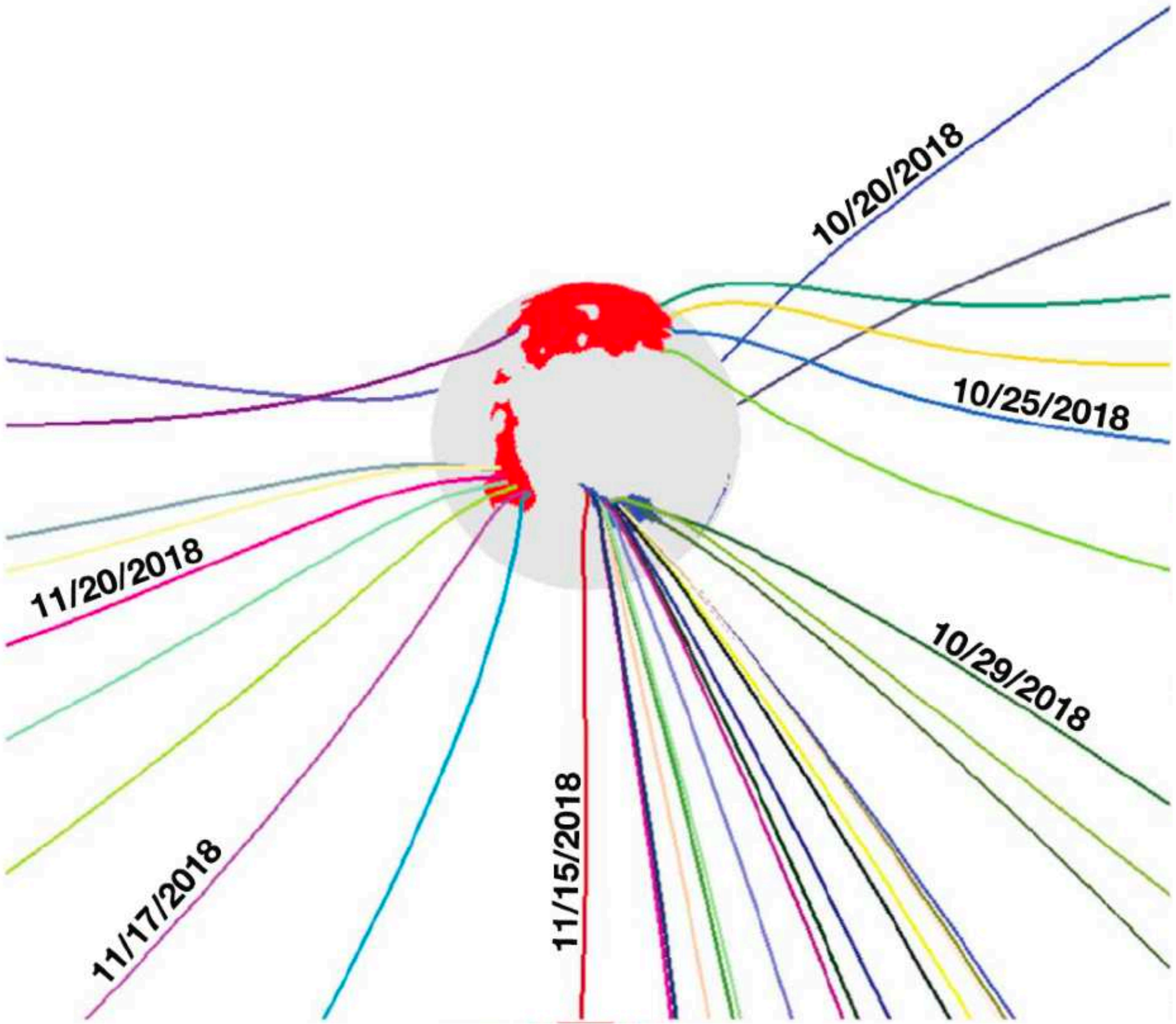
Courtesy S. Bale

PSP as Testbed for Models

MHD Prediction of 1st Perihelion
With Alfvén wave driven SW



van der Holst et al. (2019)



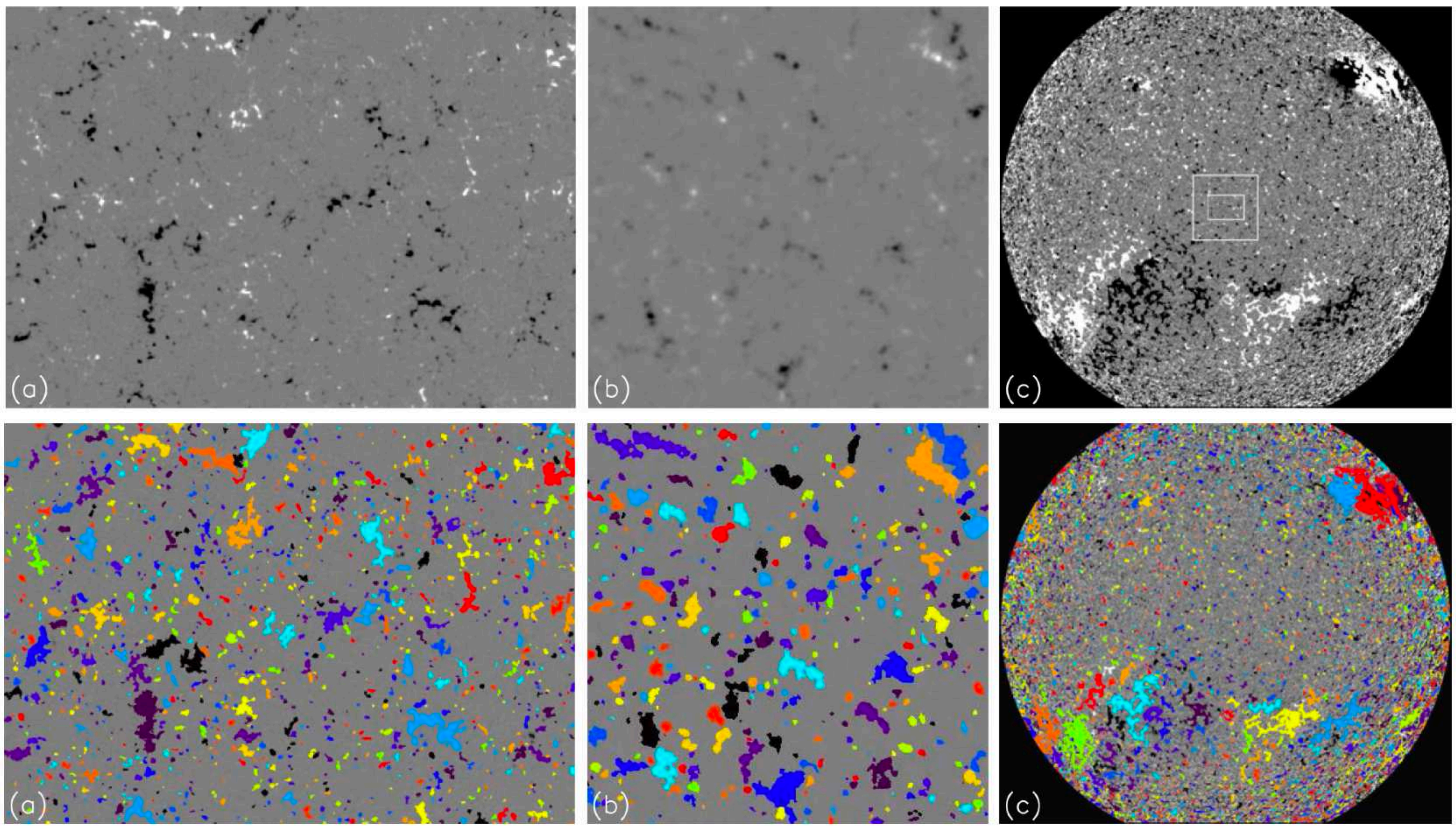
Riley et al. (2019)

Crash Course on Flux Emergence

See Cheung & Isobe (2014) for review

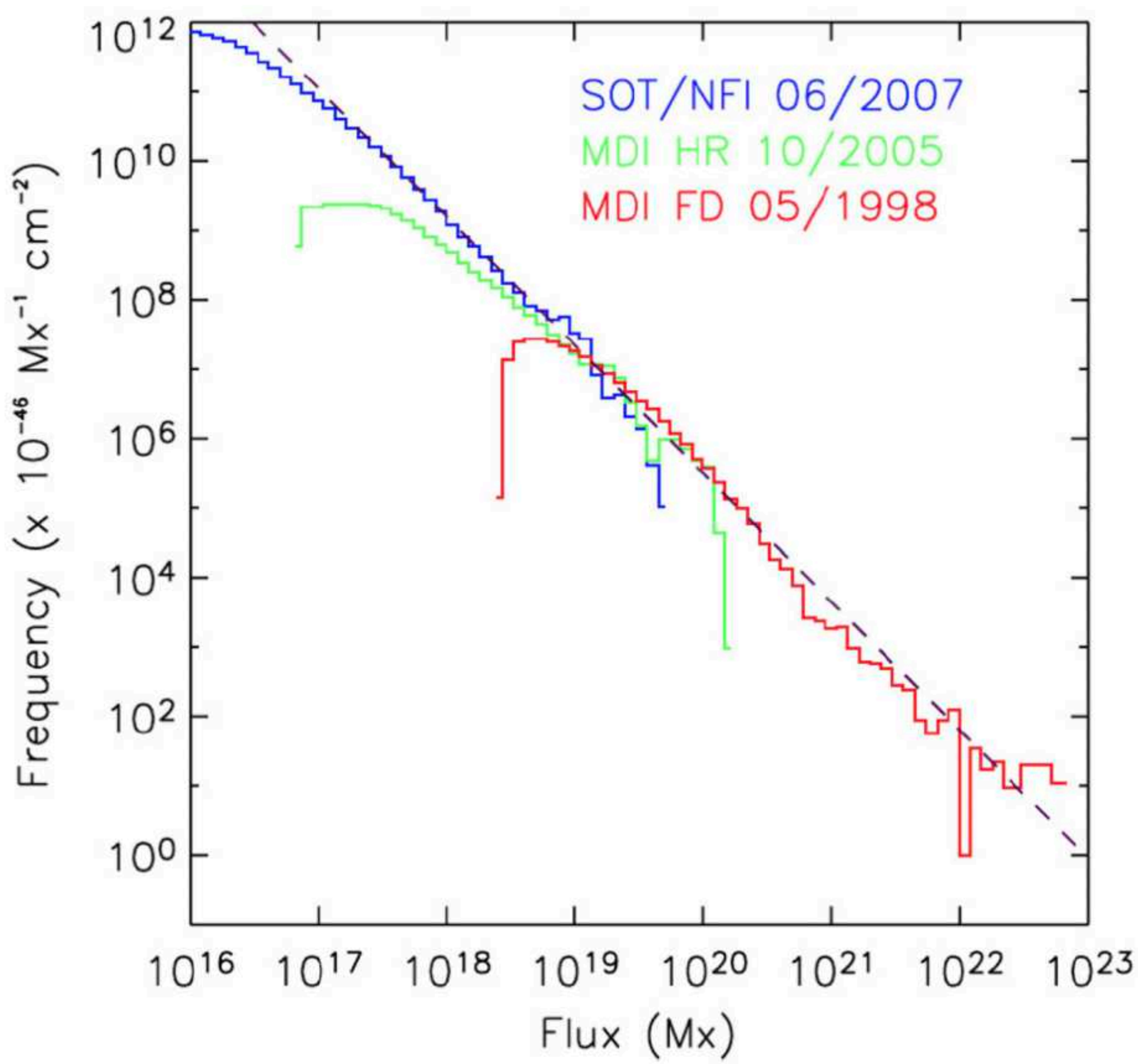
Flux Emergence: Two Dynamos?

- AR flux is highly cycle dependent; quiet Sun flux less so
- Are global dynamo & surface dynamo two different processes?



Parnell et al. (2009)

Flux Emergence: Continuous Scales



Harvey (1993); Hagenaar et al. (2003)
Parnell et al. (2009); Thornton & Harvey

- Continuous power law: slope -1.85
- QS flux dominates: 10^4 x AR!
- Continuous dynamo process with different Rossby numbers:

$$Ro = \frac{P_{\rm rot}}{\tau_{\rm conv}}$$

Buoyant Rise of Flux Tubes

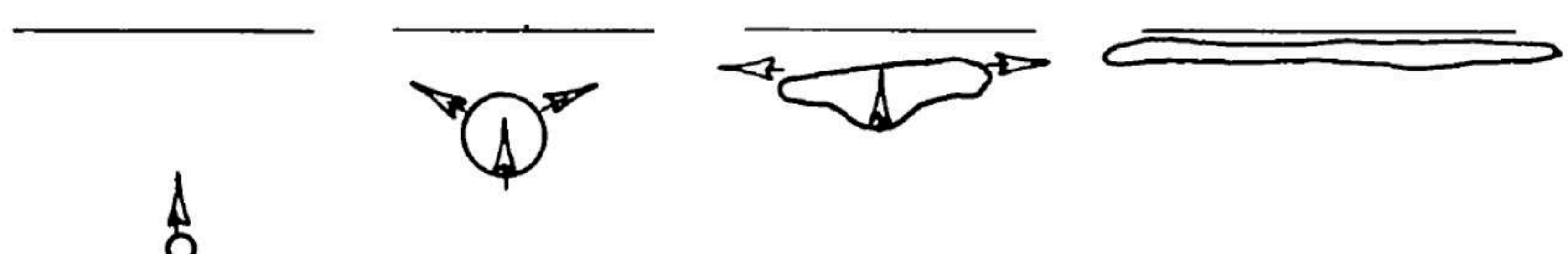
- Density deficiency due to increased magnetic field

$$p_i + \frac{B^2}{8\pi} = p_o$$

- Steep stratification leads to decreasing pressure scale height

- Stratification unstable to convective perturbation in near surface layer

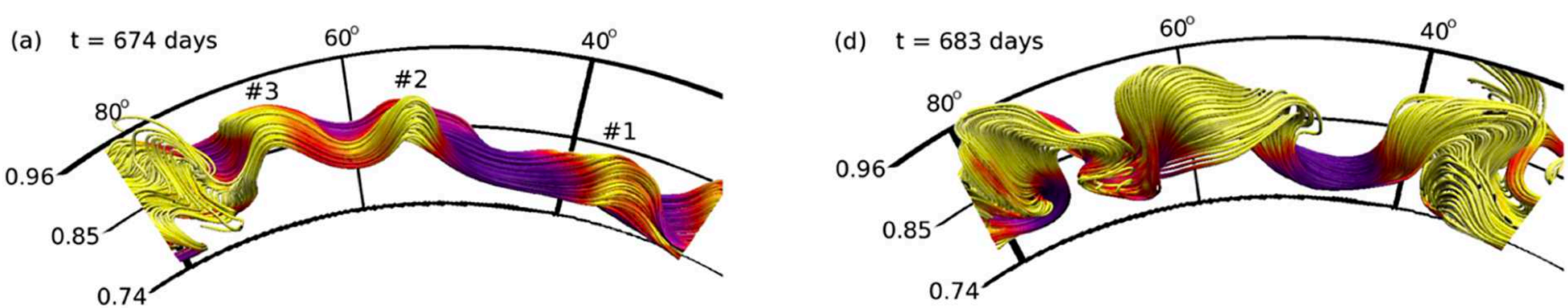
$$\frac{\partial \rho_{\rm ad}}{\partial z} < \frac{\partial \rho}{\partial z}, \text{ or } \left.\frac{d\ln T}{d\ln p}\right|_s < \frac{d\ln T}{d\ln p}$$



Spruit (1987)

ARs from Convection Zone

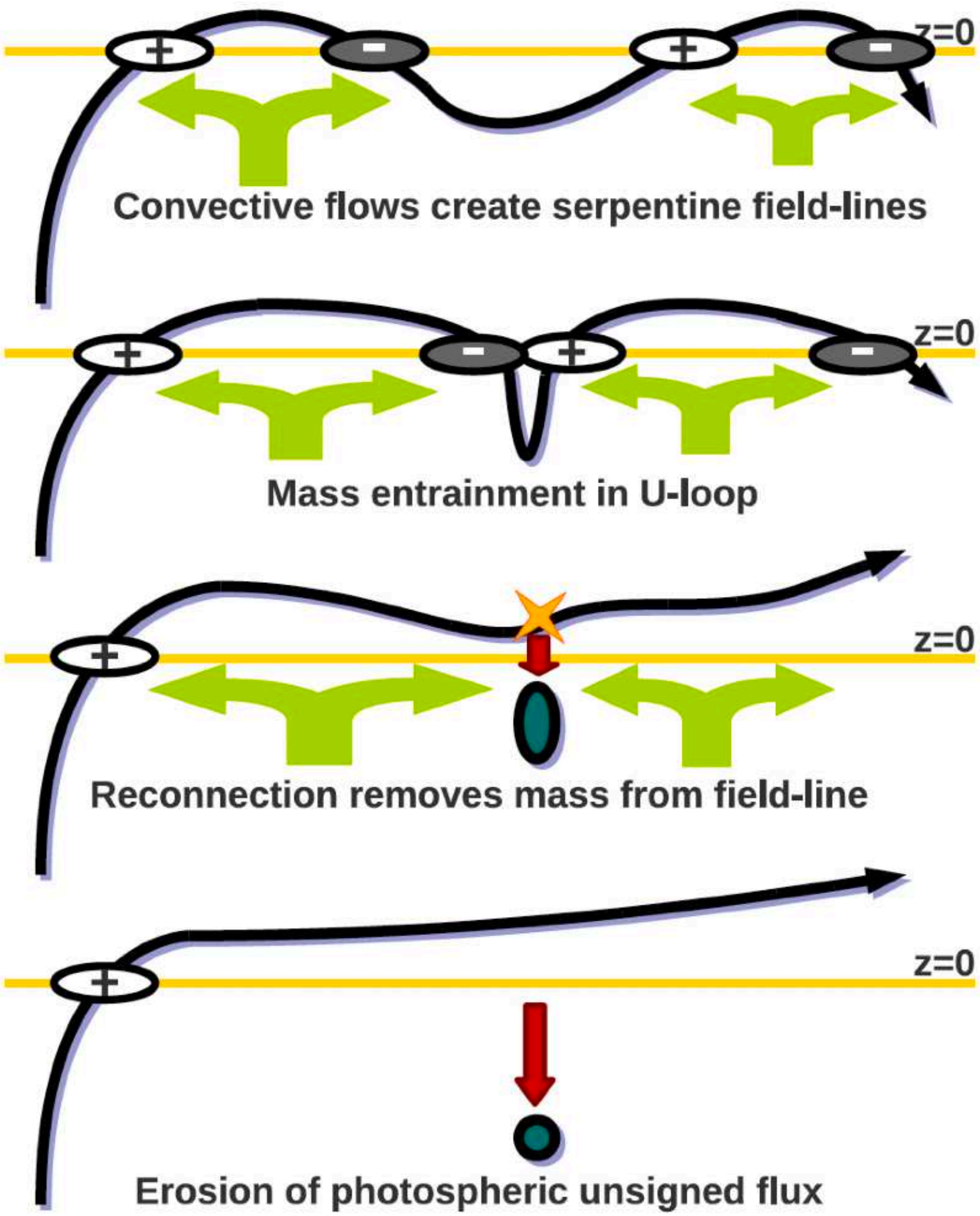
- Strong field strength needed to stay coherent: ~ 10 kG
- Easily undergo magnetic buoyancy instabilities
- Large scale structure (small *Ro*) modulated by Coriolis force
- Will develop twist due to interaction with turbulence & kinetic helicity (Long cope & Klapper 1997; Longcope et al. 1998)

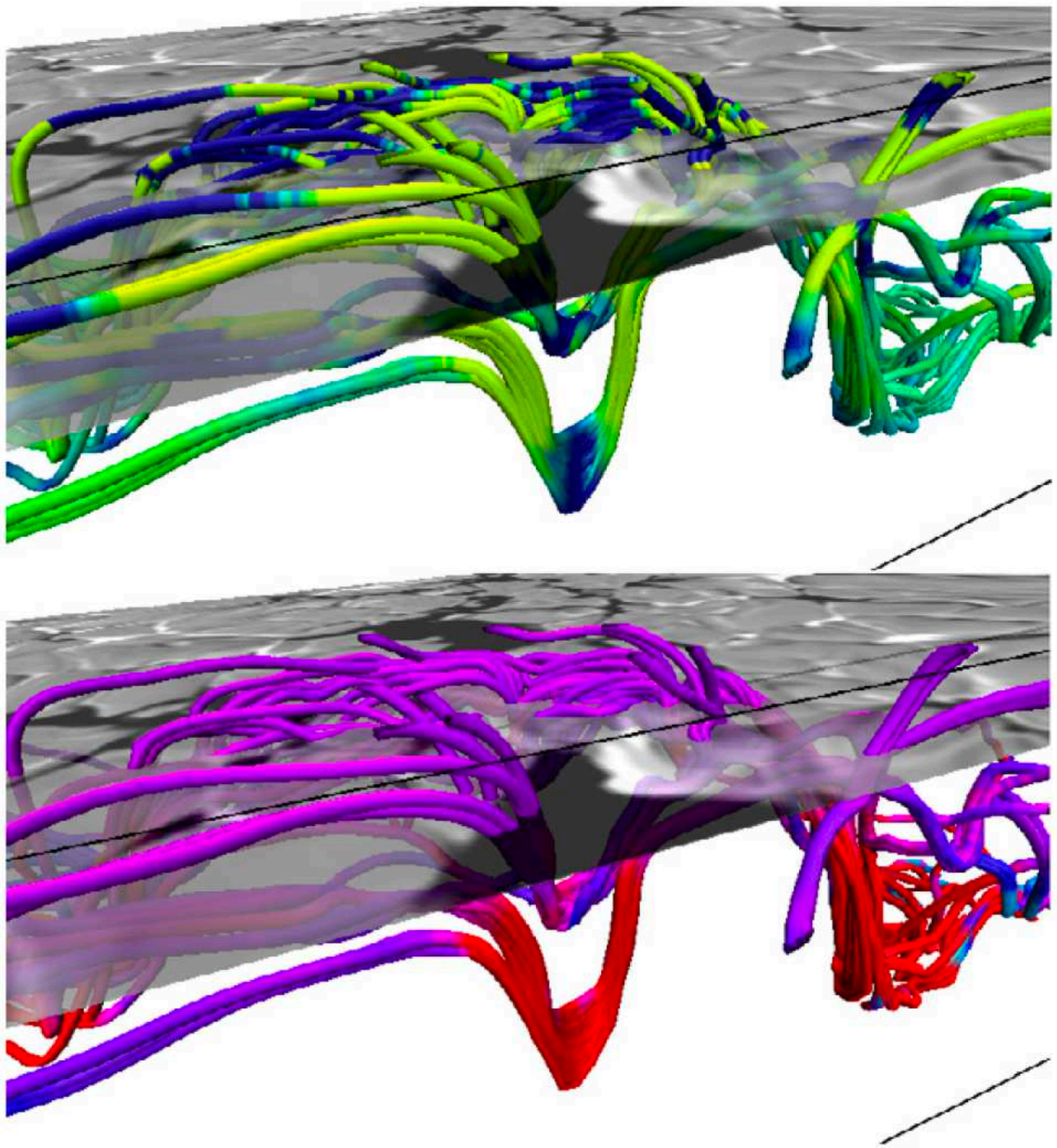


Nelson et al. (2014)

Emerging Through Surface

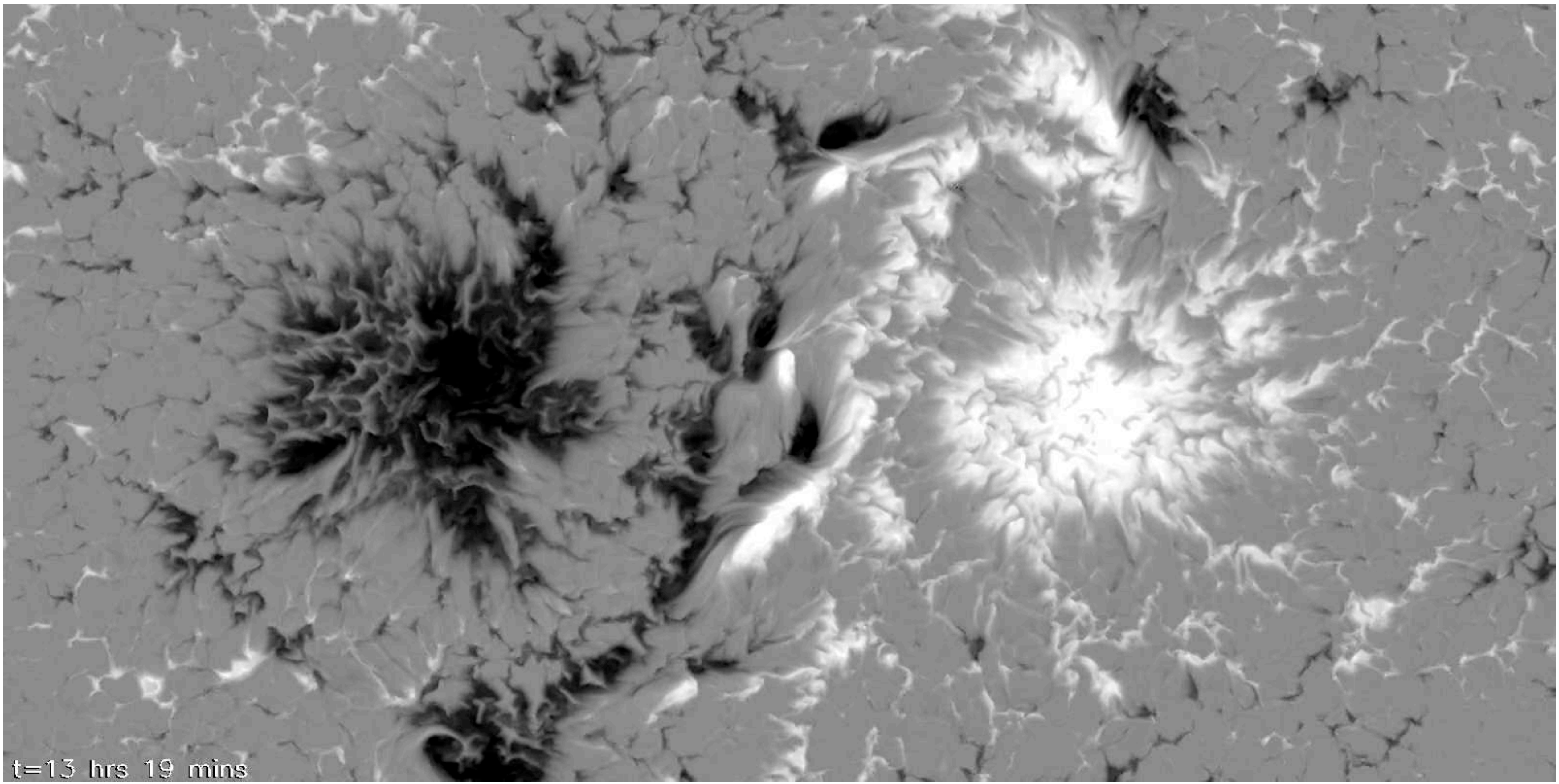
Interaction with surface convection & mass riddance





Cheung et al. (2010)

Flux Emergence Simulation



Cheung et al. (2010)

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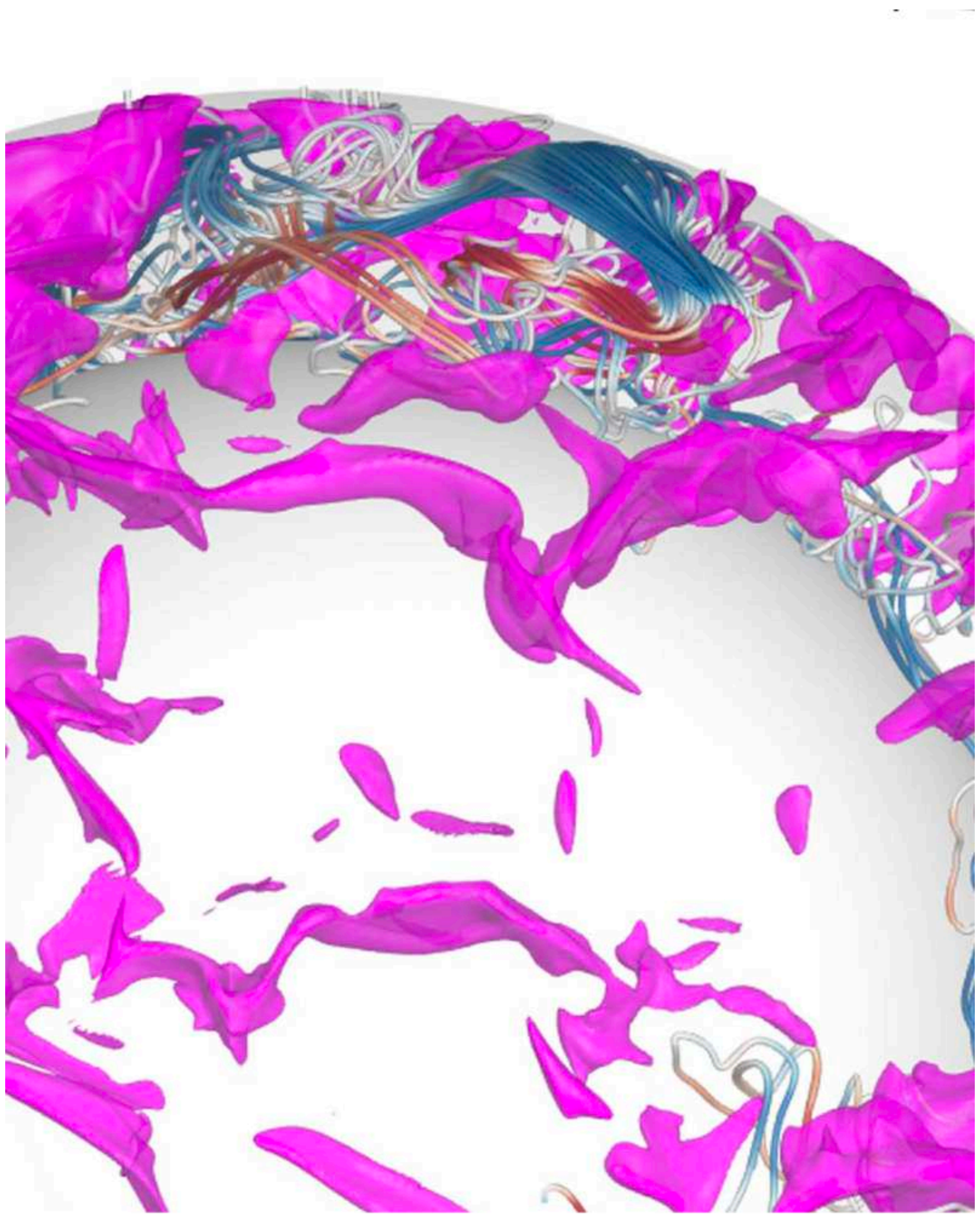
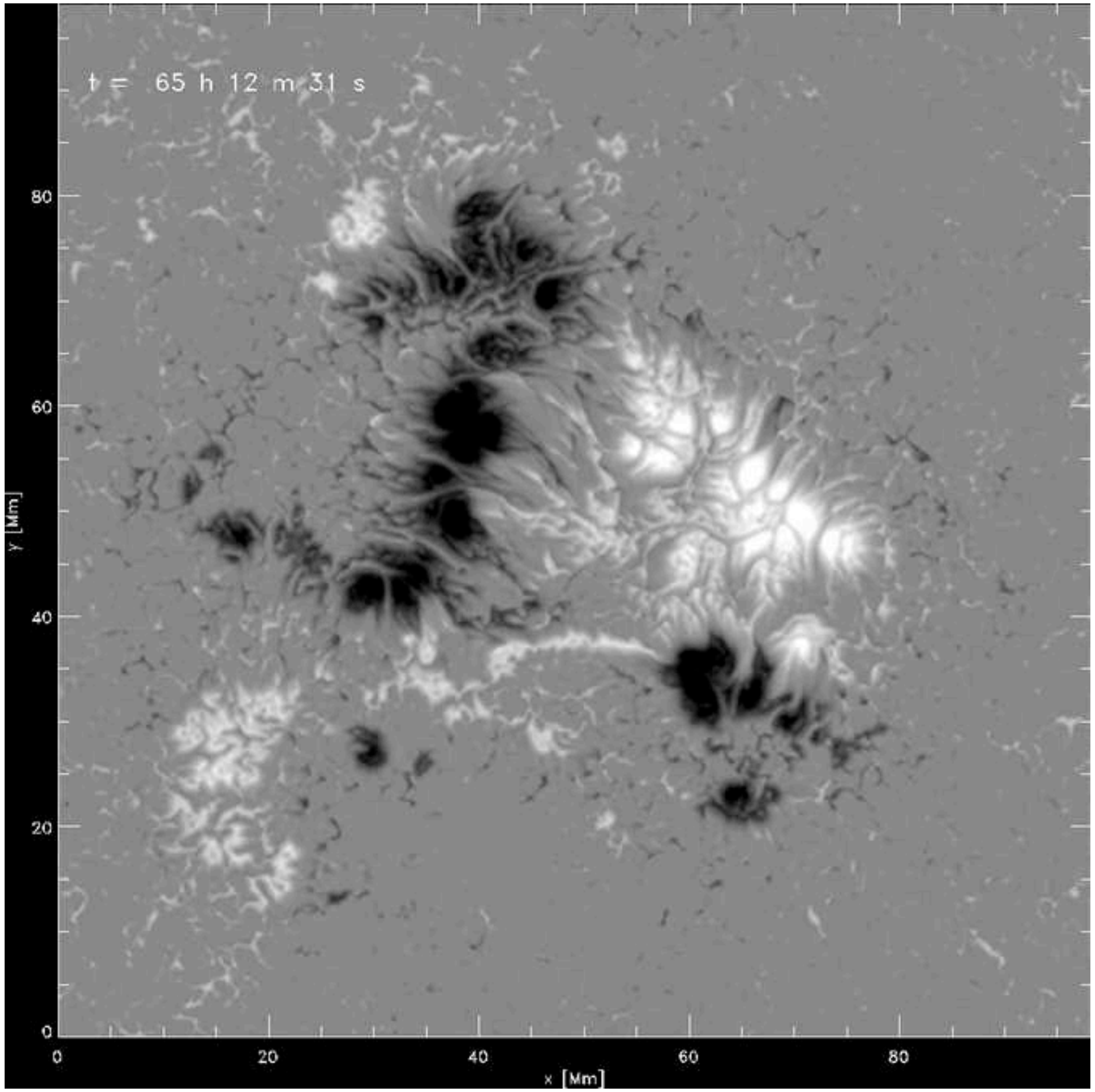
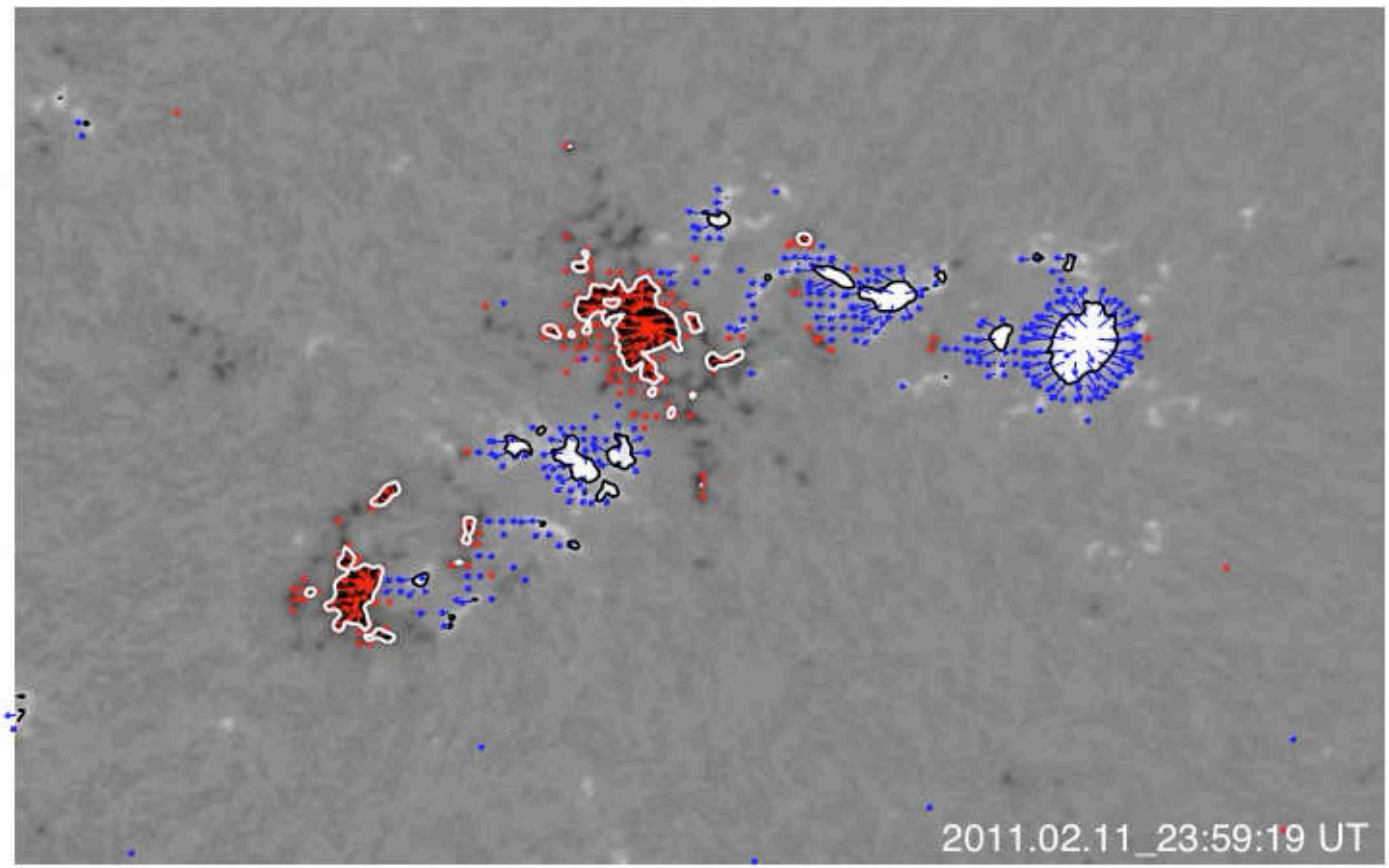




Chen et al. (2017)

Flux Emergence Observation

HMI vector field



Sun et al. (2012)