

Helicity and plasma beta models from the solar atmosphere into interplanetary space

(3rd Helicity Thinkshop, Tokyo, 23.11.2017)



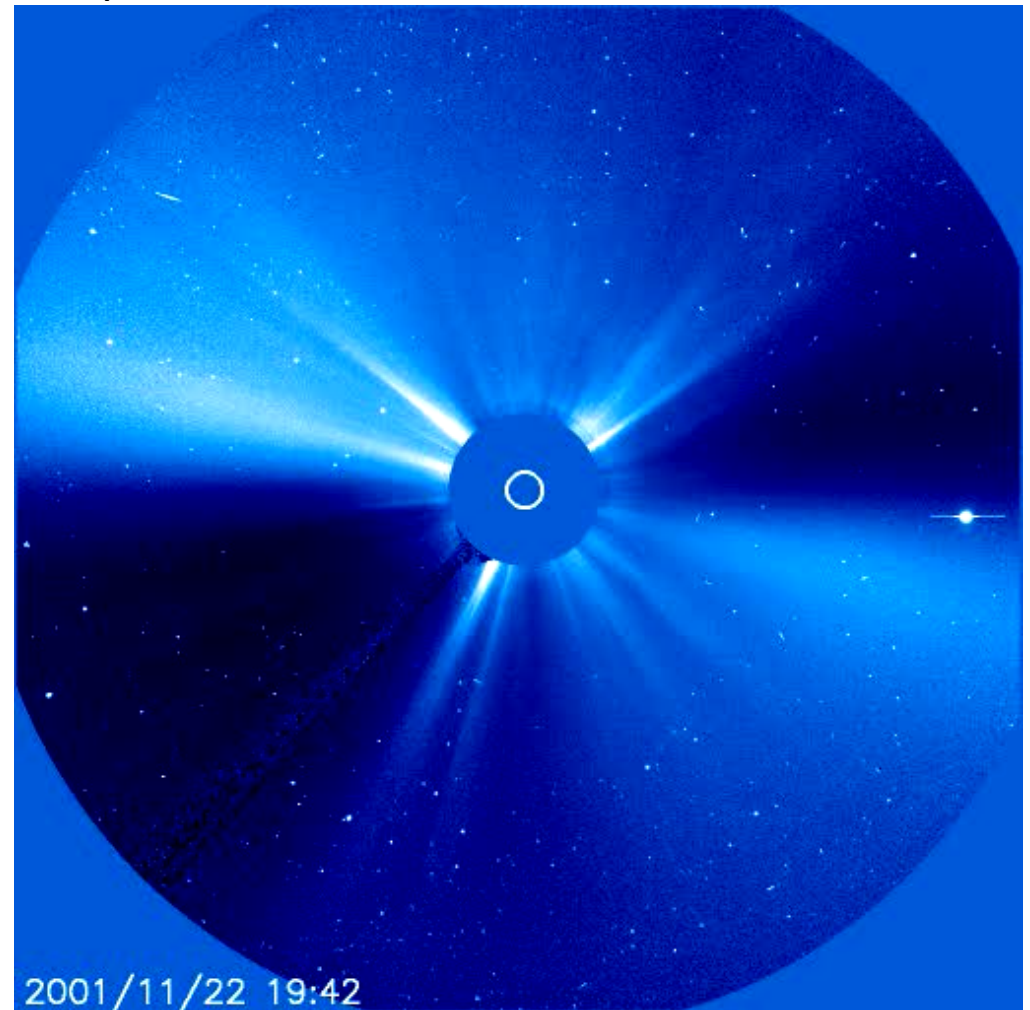
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Overview:

- * Japanese Martial Arts
- * Active Region Corona
- * Plasma Beta
- * Interplanetary CME



STEREO/Lasco, credit: NASA

My definition of good Aikido style

=> obeys energy conservation

=> obeys impulse conservation

=> minimal external forcing

My definition of good Aikido style

=> obeys energy conservation

=> obeys impulse conservation

=> minimal external forcing

=> introduction of (kinematic) helicity!

Attacker (Uke) versus Defender (Nage)



Introduction of helicity in Aikido (Ude Osae - Tenkan)



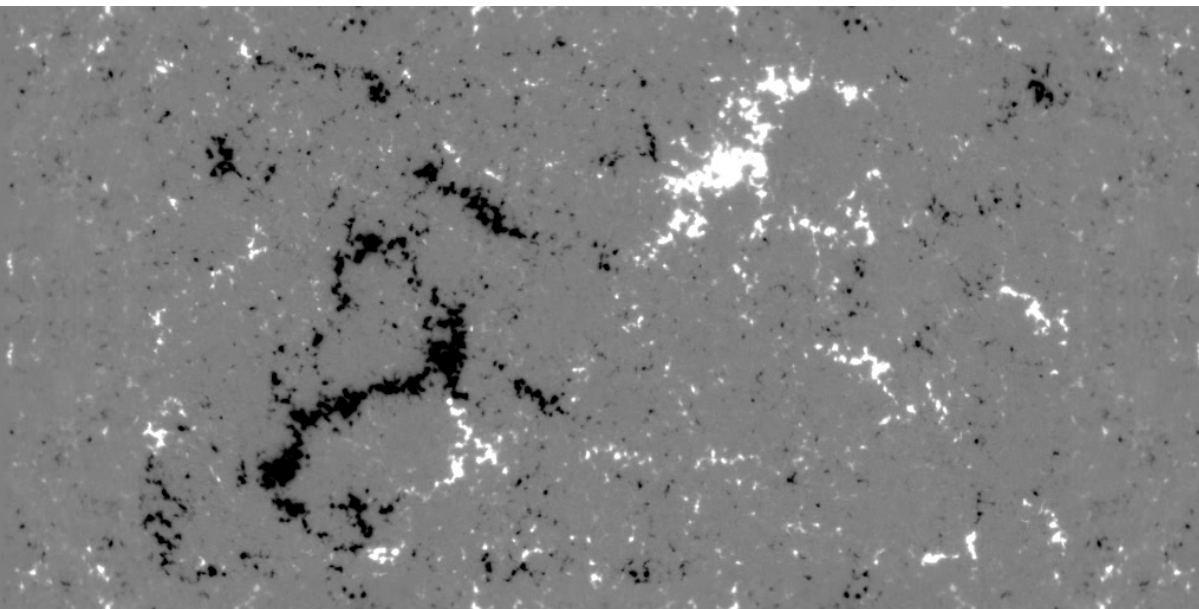
Result of helicity used in Aikido



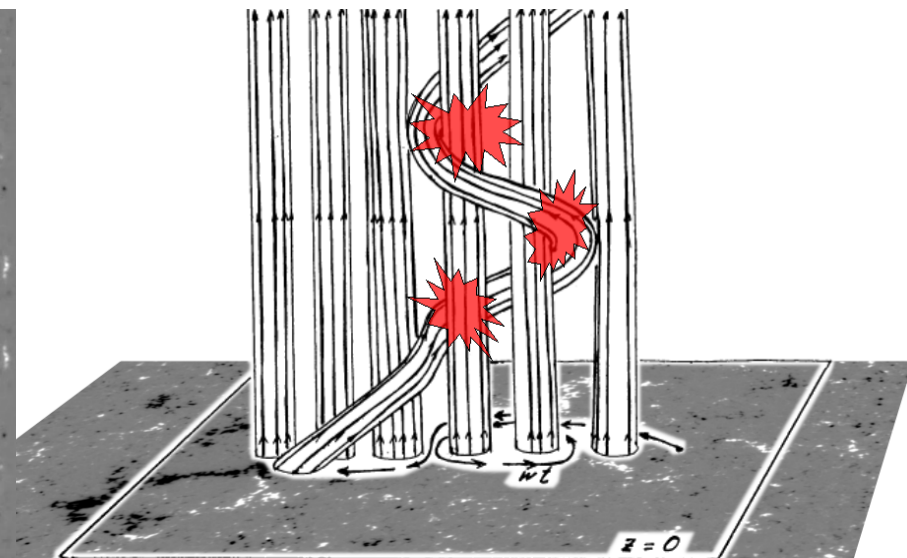
Field-line braiding

➔ Observationally driven forward model:

- Photospheric granulation advects small-scale magnetic fields
- Stress is induced into the magnetic field
- Braiding (or bending) of the field in the corona
- Currents are induced and dissipated to heat the corona



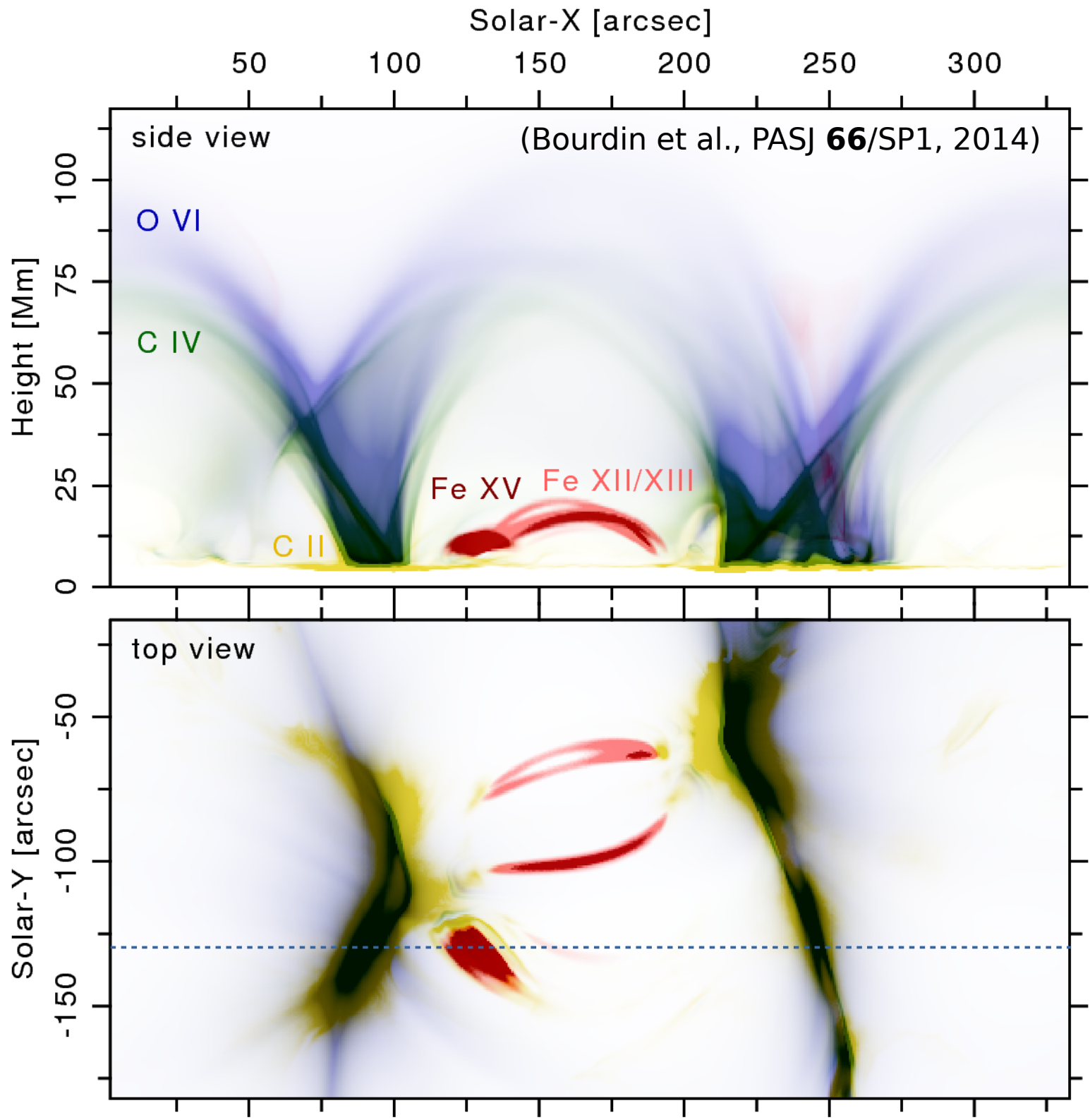
Hinode/SOT observation (14th Nov 2007)



(Parker, 1972, ApJ. 174, 499)

Synthesized emission (CHIANTI)

hot loops in AR core

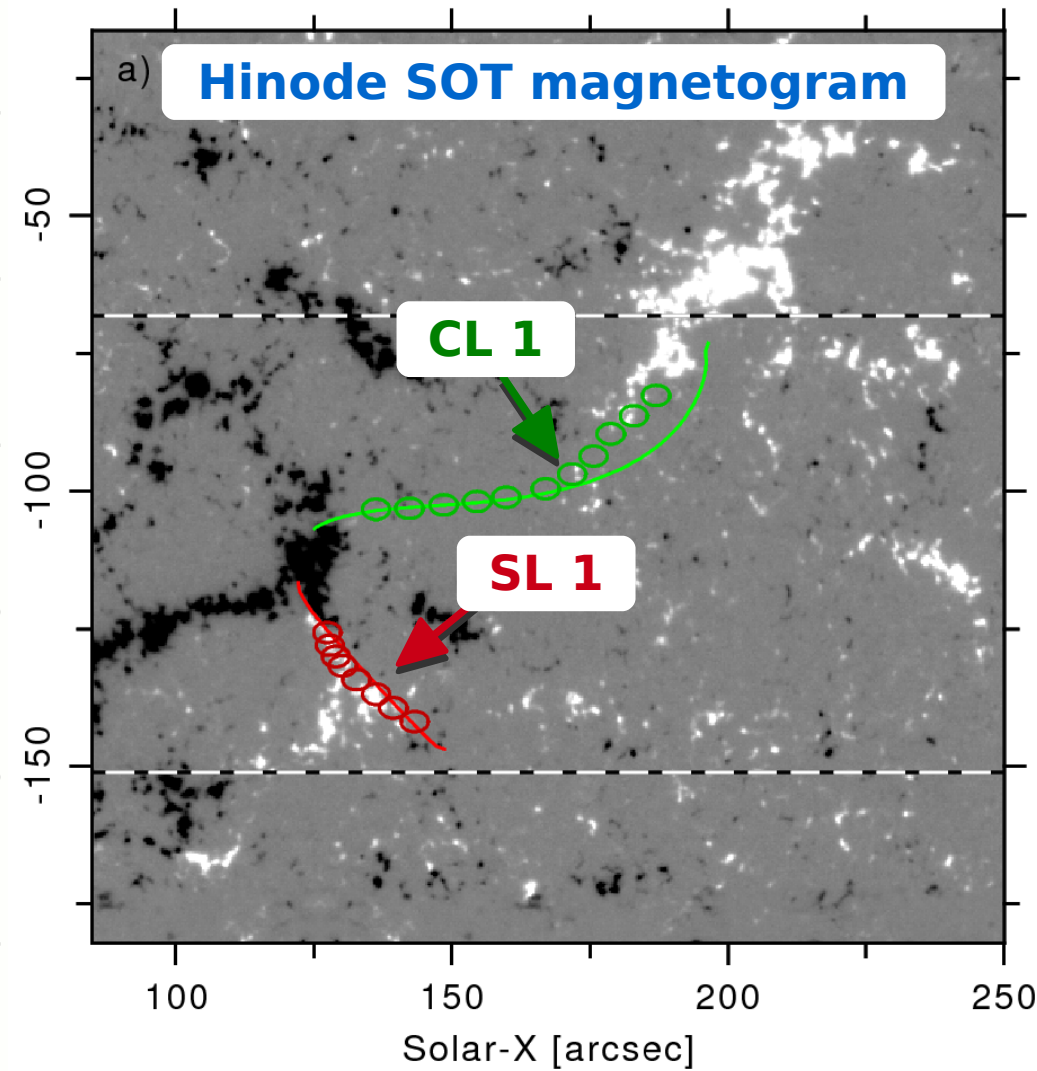
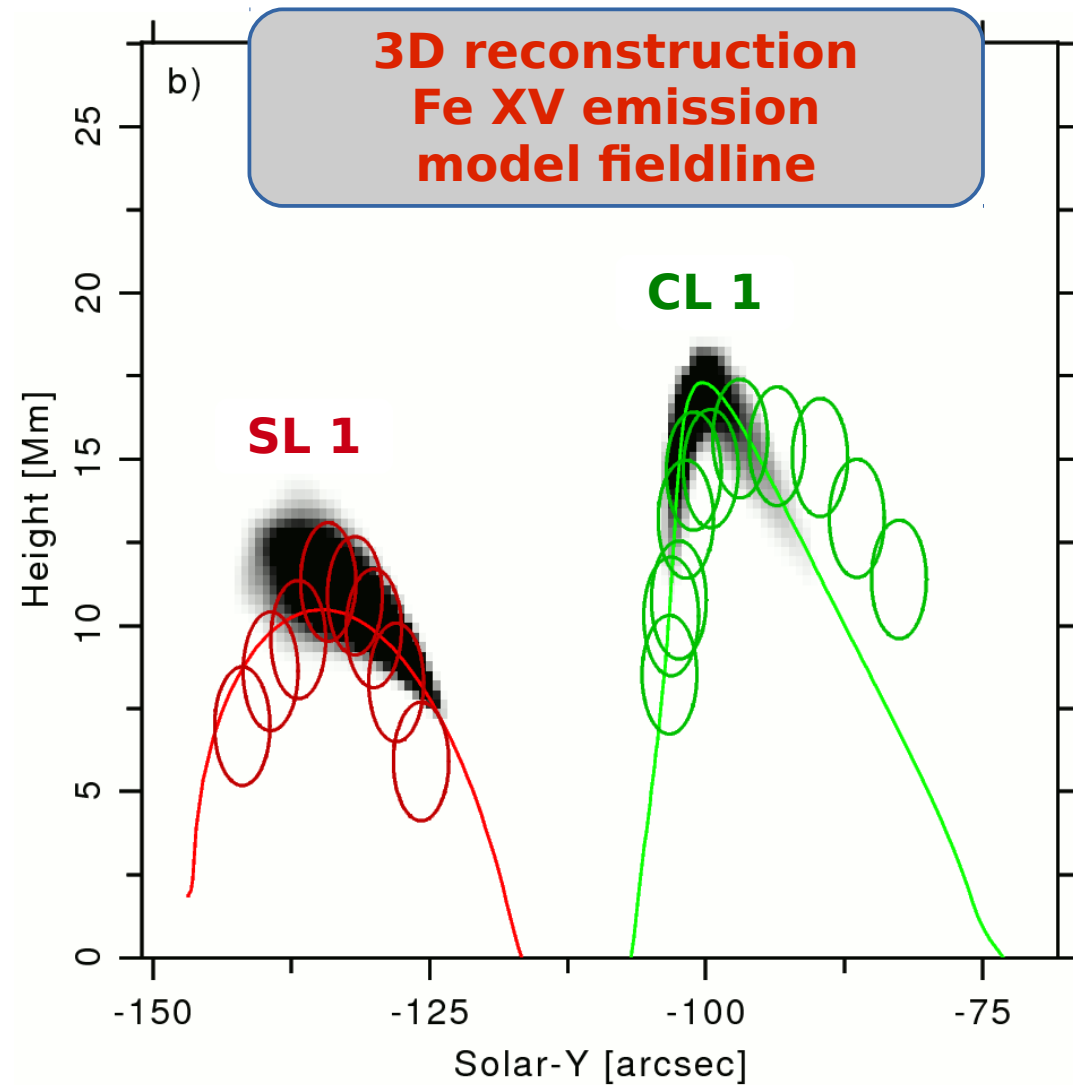


STEREO (3D reconstruction)

(Bourdin et al., A&A **555**/A123, 2013)

➡ 3D structure and height of model loops realistic

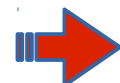
➡ Model fieldlines follow observed loops



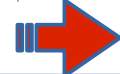
Hinode XRT and SOT observations

(Bourdin et al., A&A **555**/A123, 2013)

Comparison of Doppler-shifts:

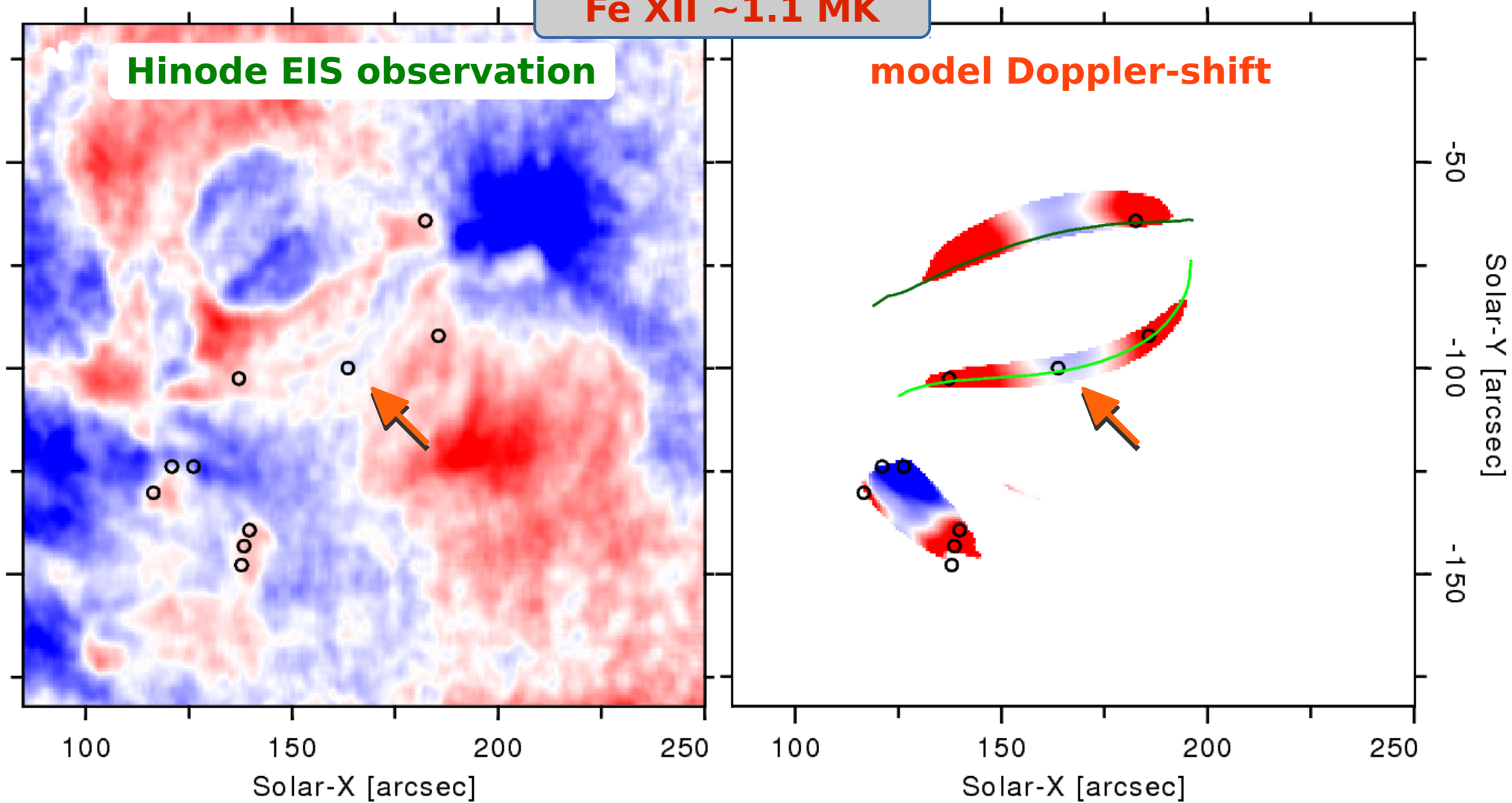


Dynamics match!



Loop top rises: 2 km/s (Solanki, 2003)


Fe XII ~1.1 MK



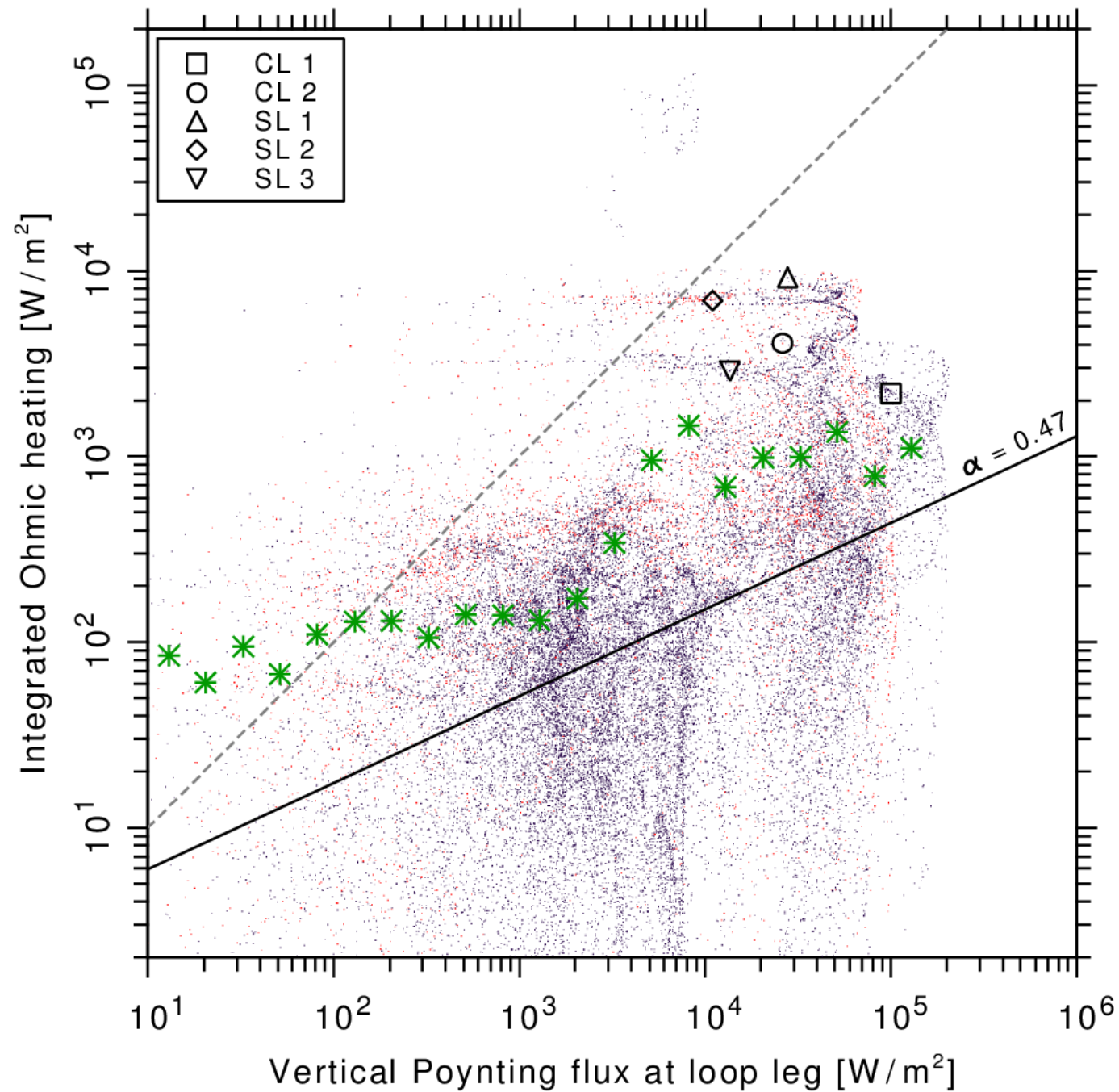
Energy source

(Bourdin et al., A&A **580**/A72, 2015)

**67'000 field lines:
(AR core area)**

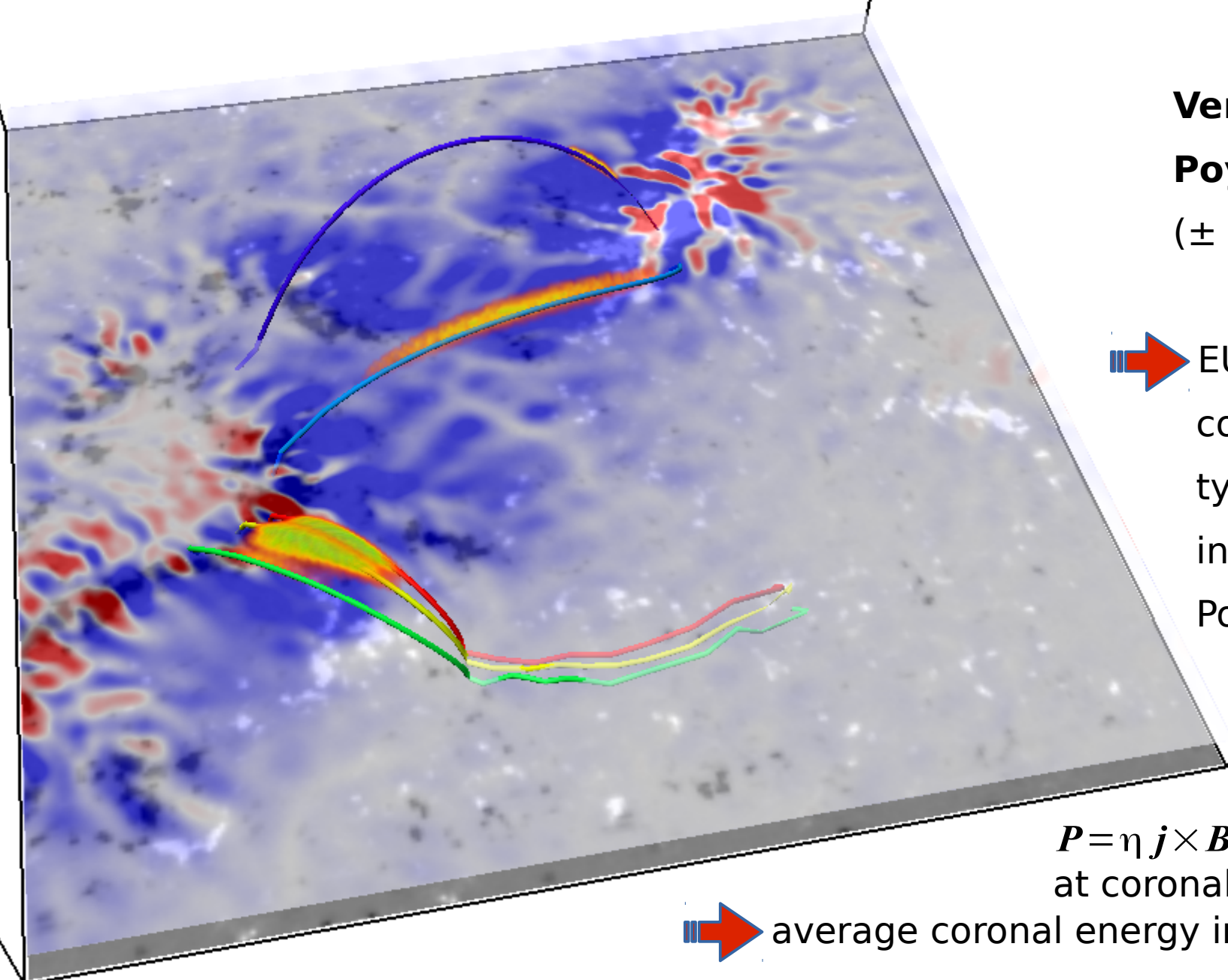
 Integrated
Ohmic heating
scales with
Poynting flux:

$$F_{Ohm} \sim P^{1/2}$$




EUV emission and magnetic fields

(Bourdin et al., A&A **589**/A86, 2016)




**Vertical
Poynting flux**
($\pm 50 \text{ kW/m}^2$)

 EUV-emissive coronal loops typically rooted in upwards Poynting flux

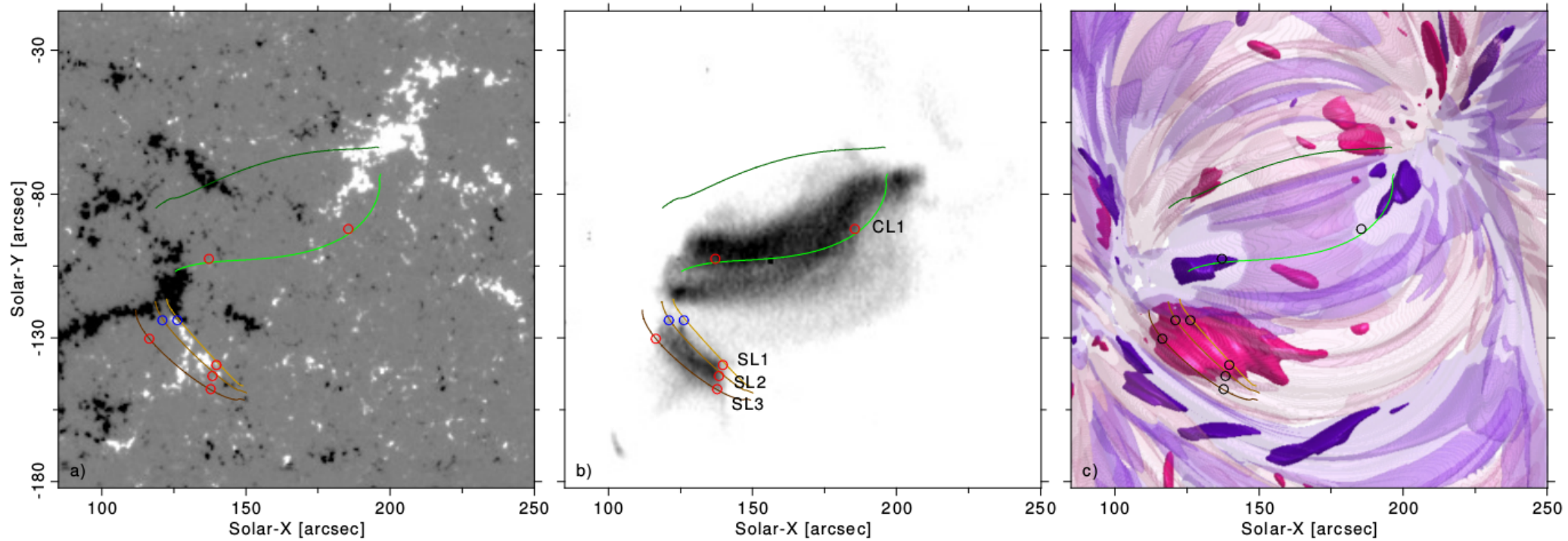
$$P = \eta \mathbf{j} \times \mathbf{B} + (\mathbf{u} \times \mathbf{B}) \times \mathbf{B} / \mu$$

at coronal base: 3 Mm

 average coronal energy input: $\sim 1 \text{ kW/m}^2$

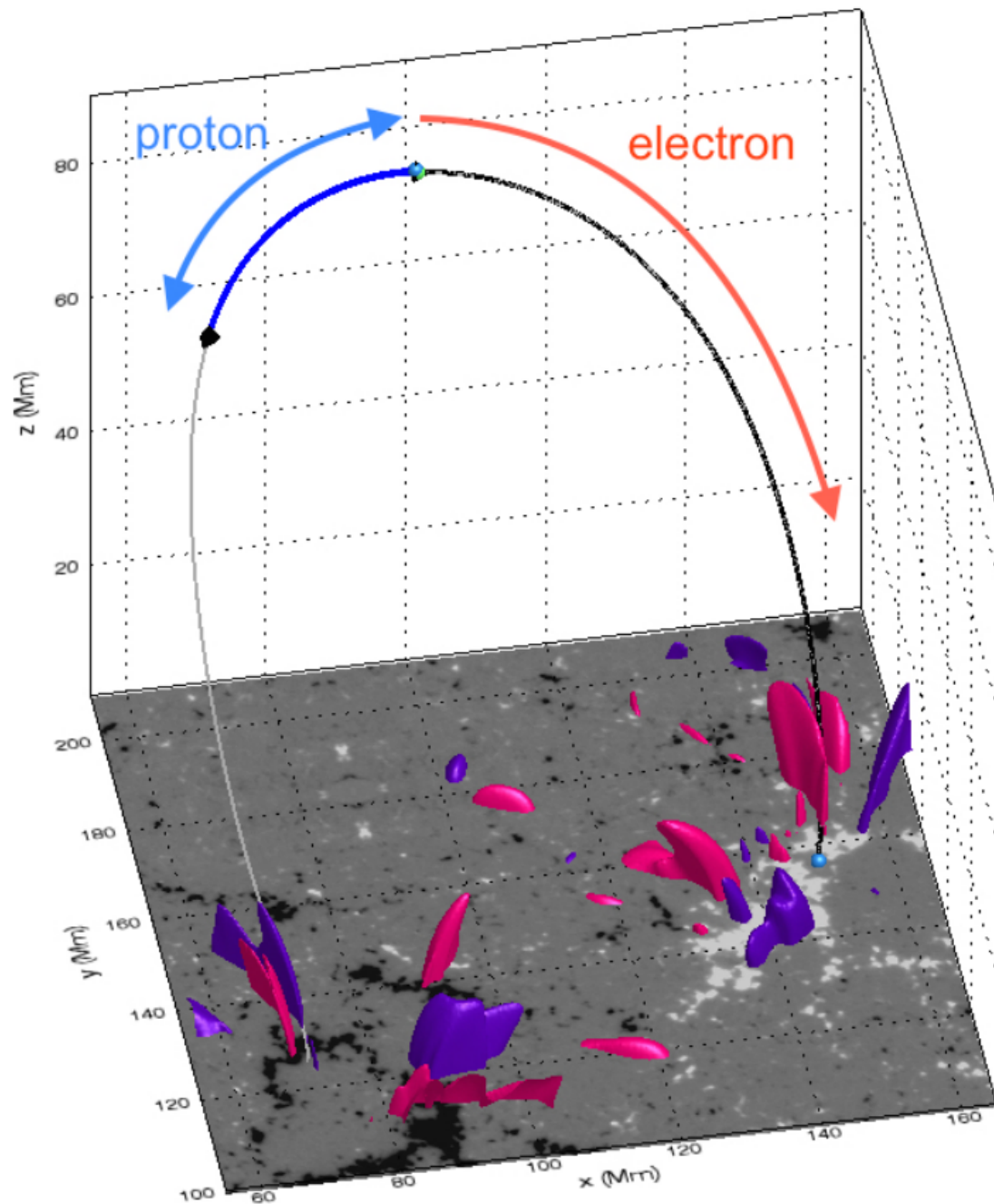
Particle acceleration from electric fields

(Threlfall-Bourdin-Neukirch-Parnell, A&A **587**/A4, 2016)

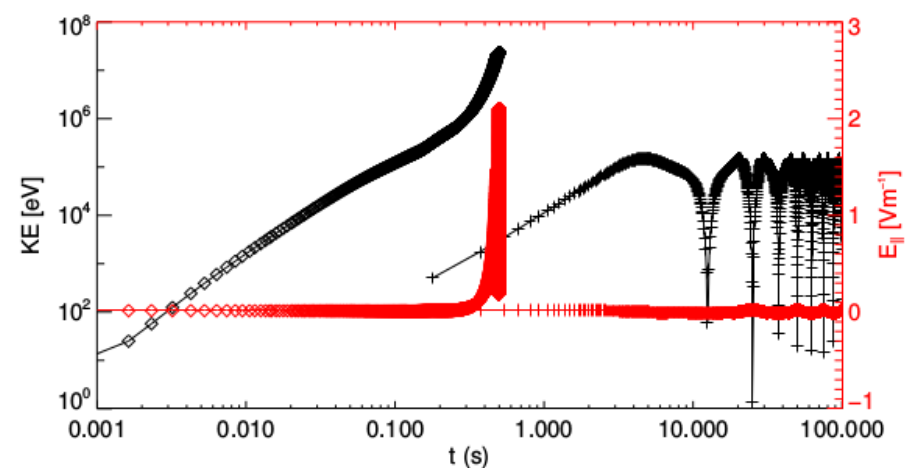


Particle fractioning

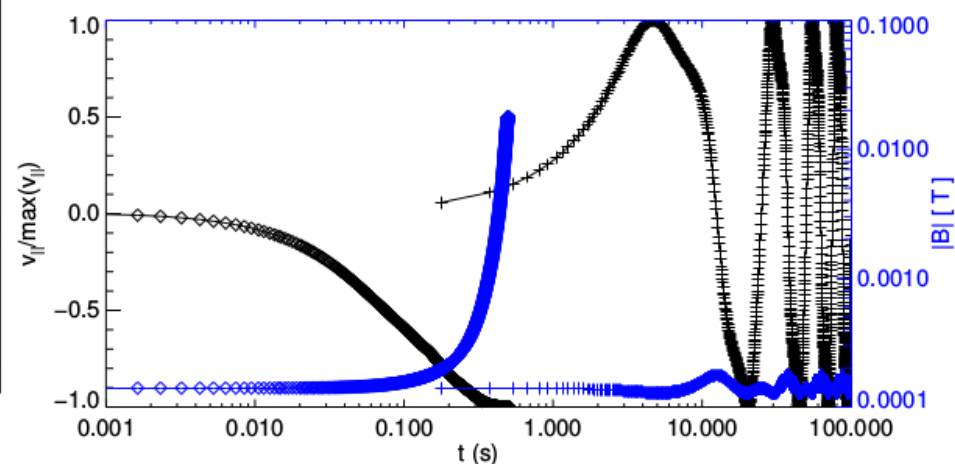
(Threlfall-Bourdin-Neukirch-Parnell, A&A **587**/A4, 2016)



(a) Accelerated proton & electron orbits, initial/final locations, interpolated field lines, regions of strong E_{\parallel} and photospheric magnetogram data.



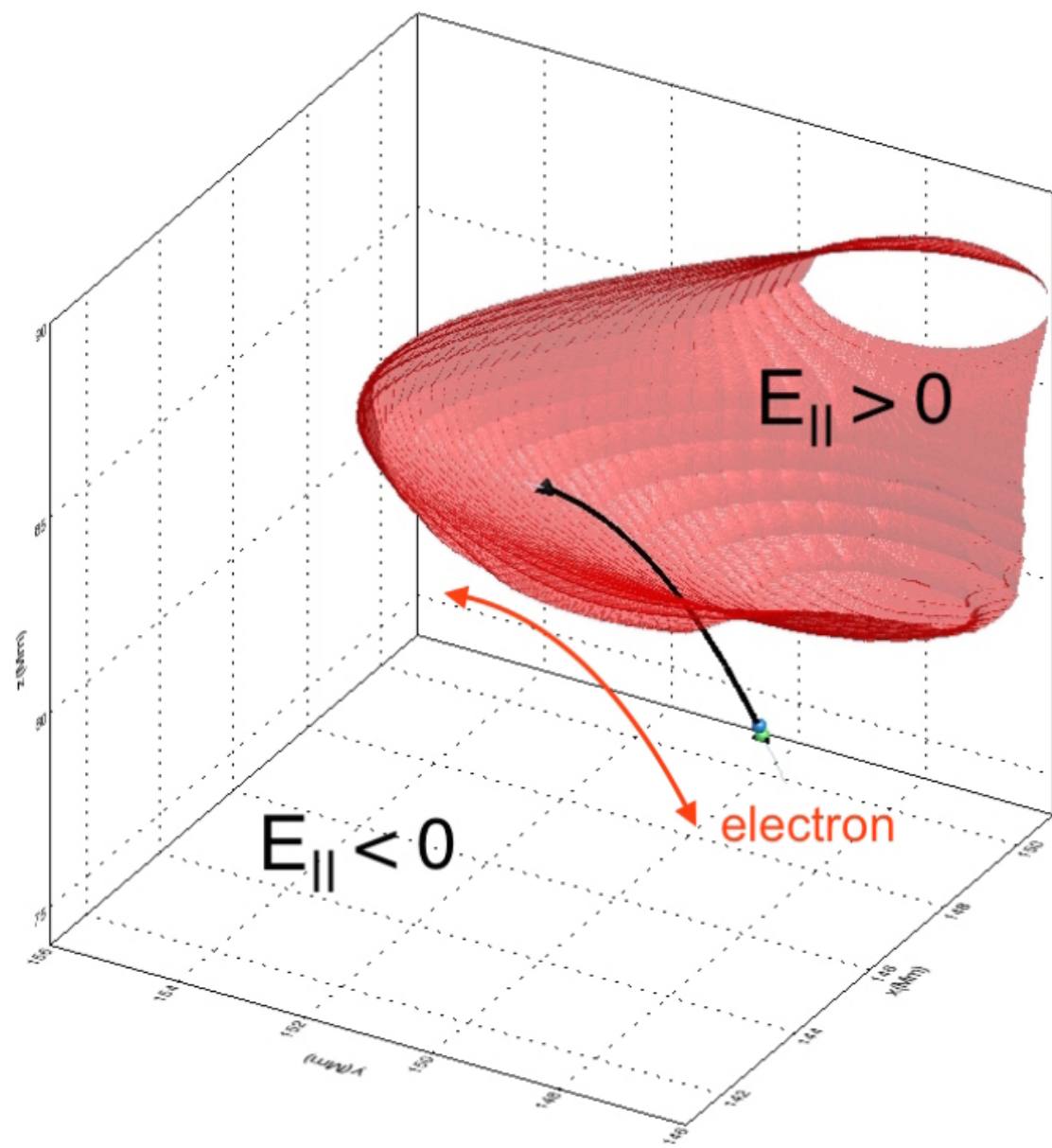
(b) Kinetic energy and E_{\parallel}



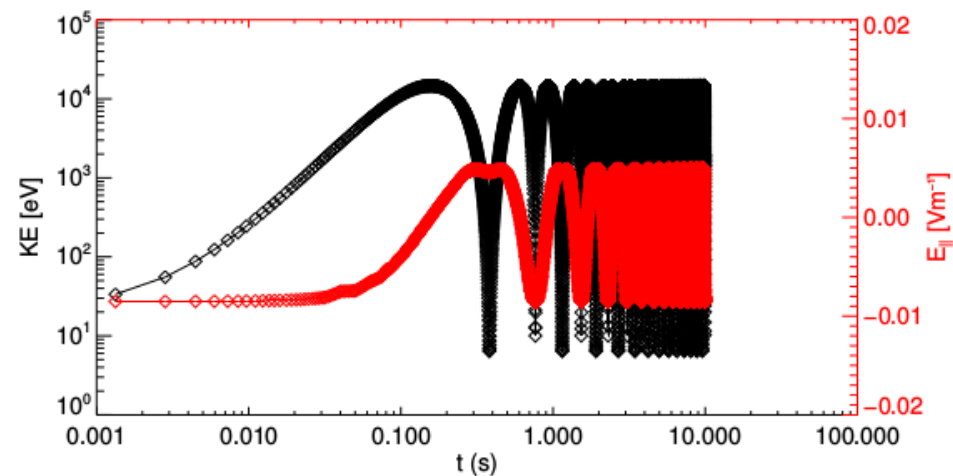
(c) Normalised v_{\parallel} and $|B|$

Trapped electrons

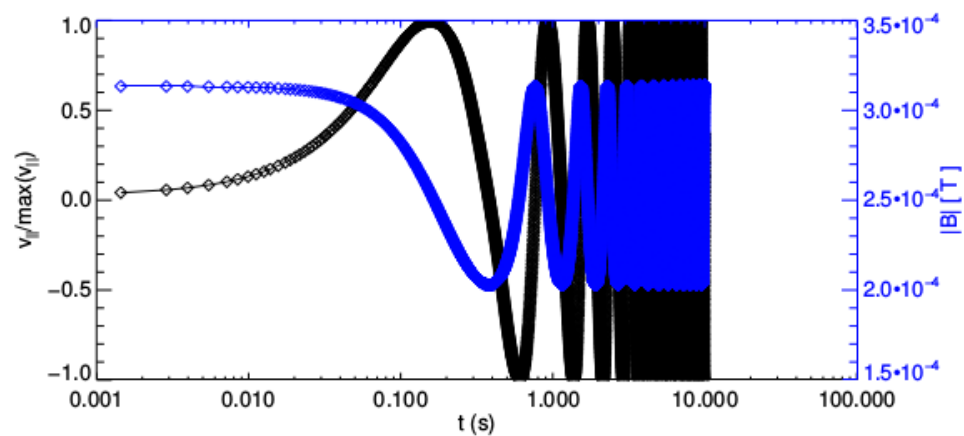
(Threlfall-Bourdin-Neukirch-Parnell, A&A **587**/A4, 2016)



(a) "Trapped" electron orbit (inc. initial/final locations, interpolated field lines, and local contour of $E_{||} = 0$).

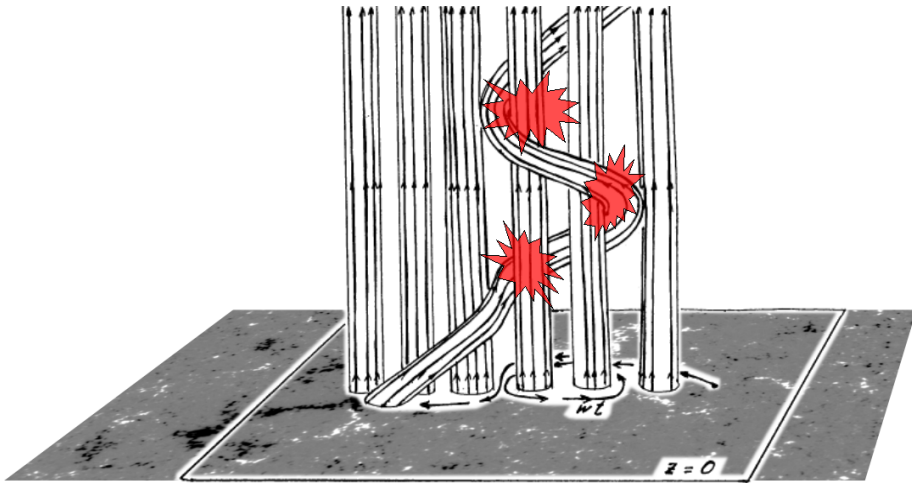


(b) Kinetic energy and $E_{||}$



(c) Normalised $v_{||}$ and $|B|$

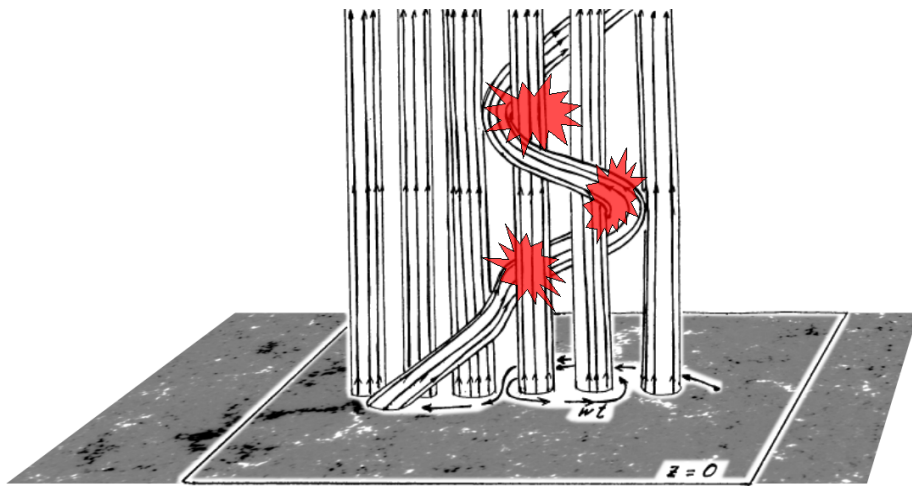
Coronal heating mechanisms:



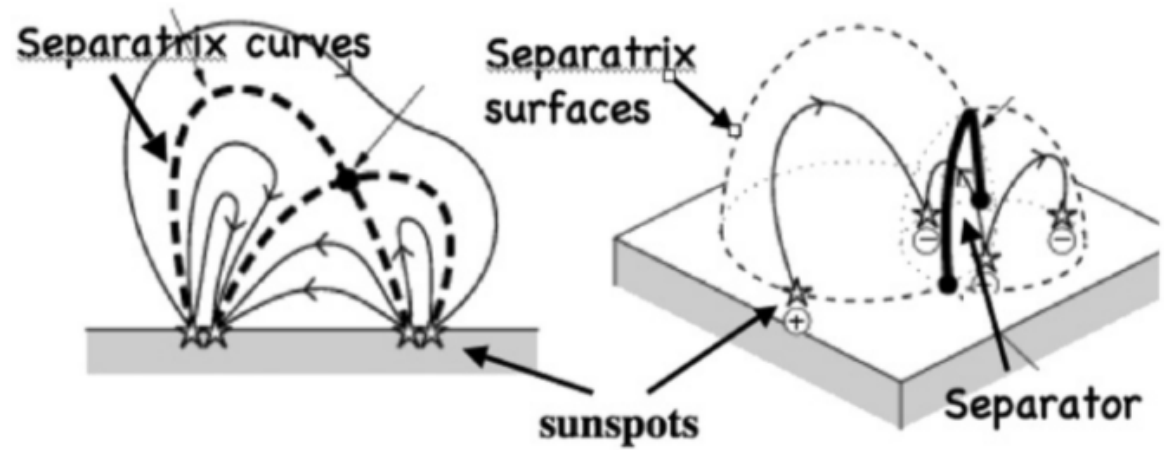
*) Braiding => nanoflares (Parker, 1972)

Coronal heating mechanisms:

*) Coronal tectonics => magnetic shear (Priest, 2011)

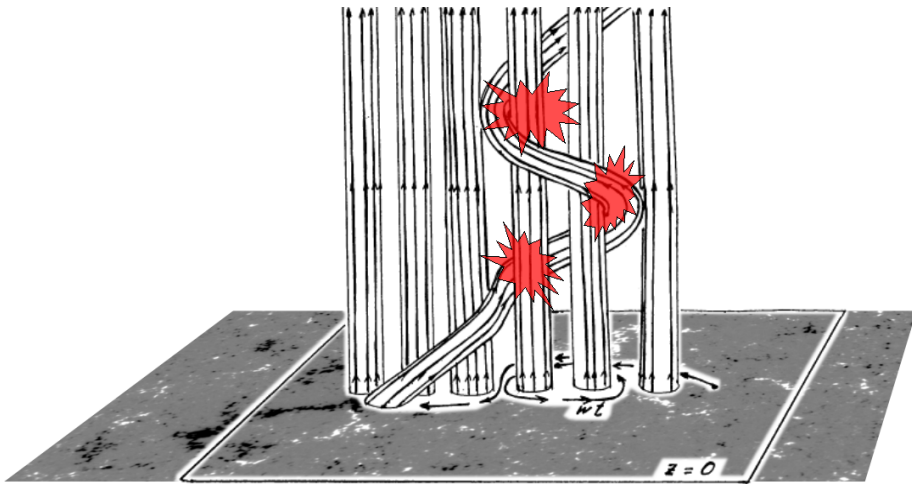
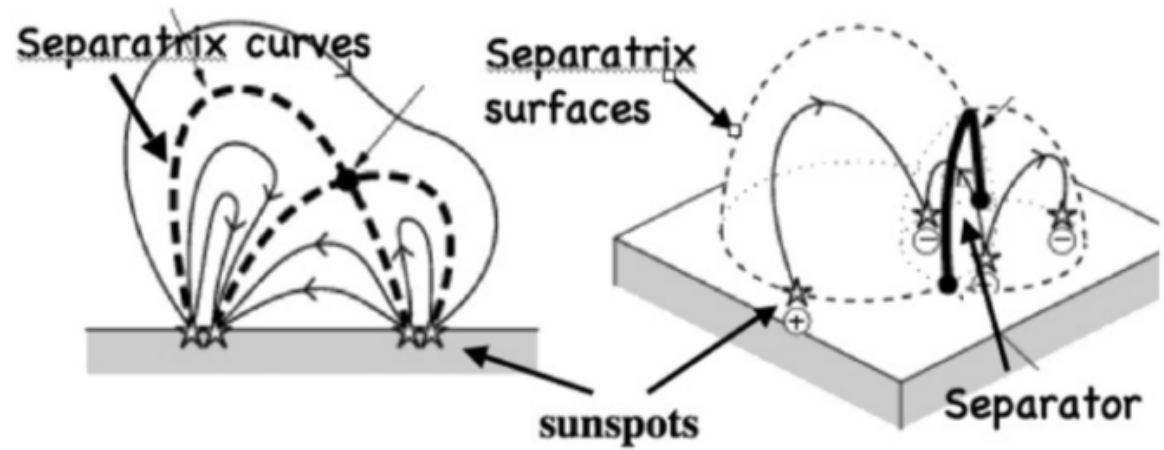


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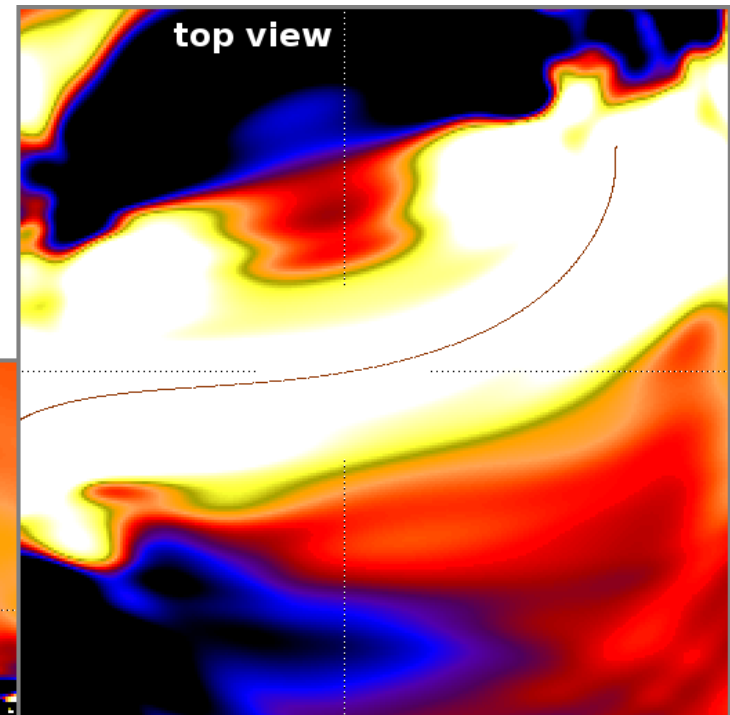
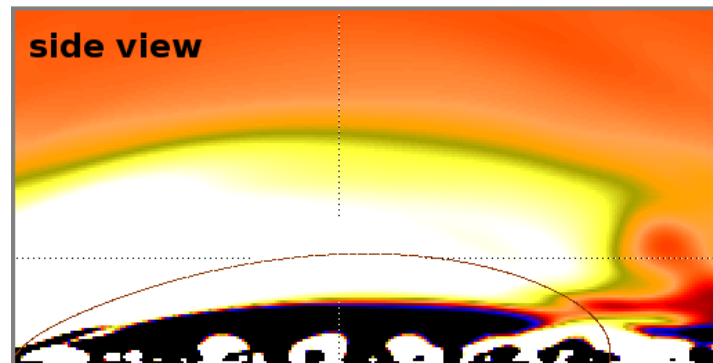


Coronal heating mechanisms:

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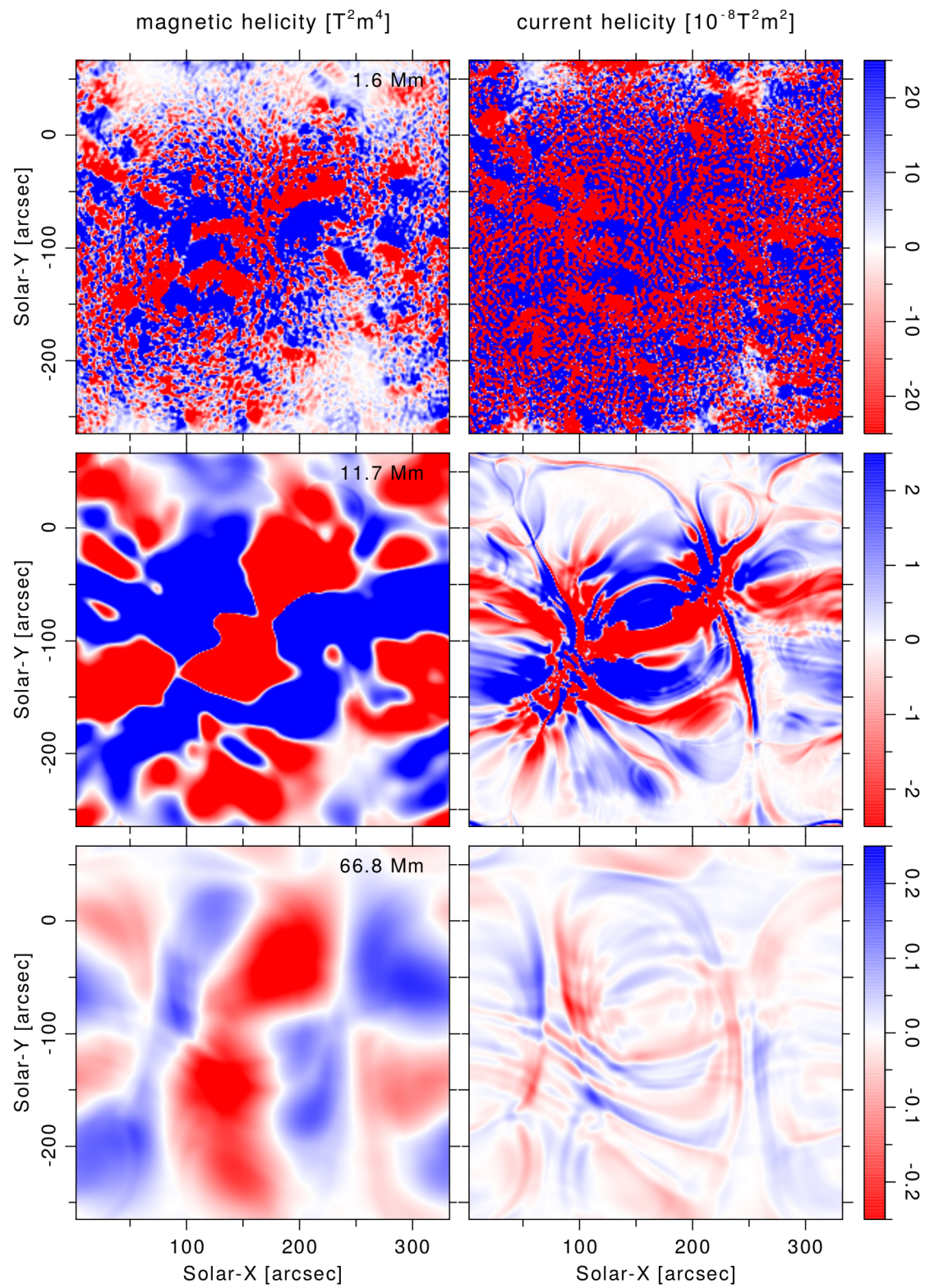


*) Braiding => nanoflares (Parker, 1972)

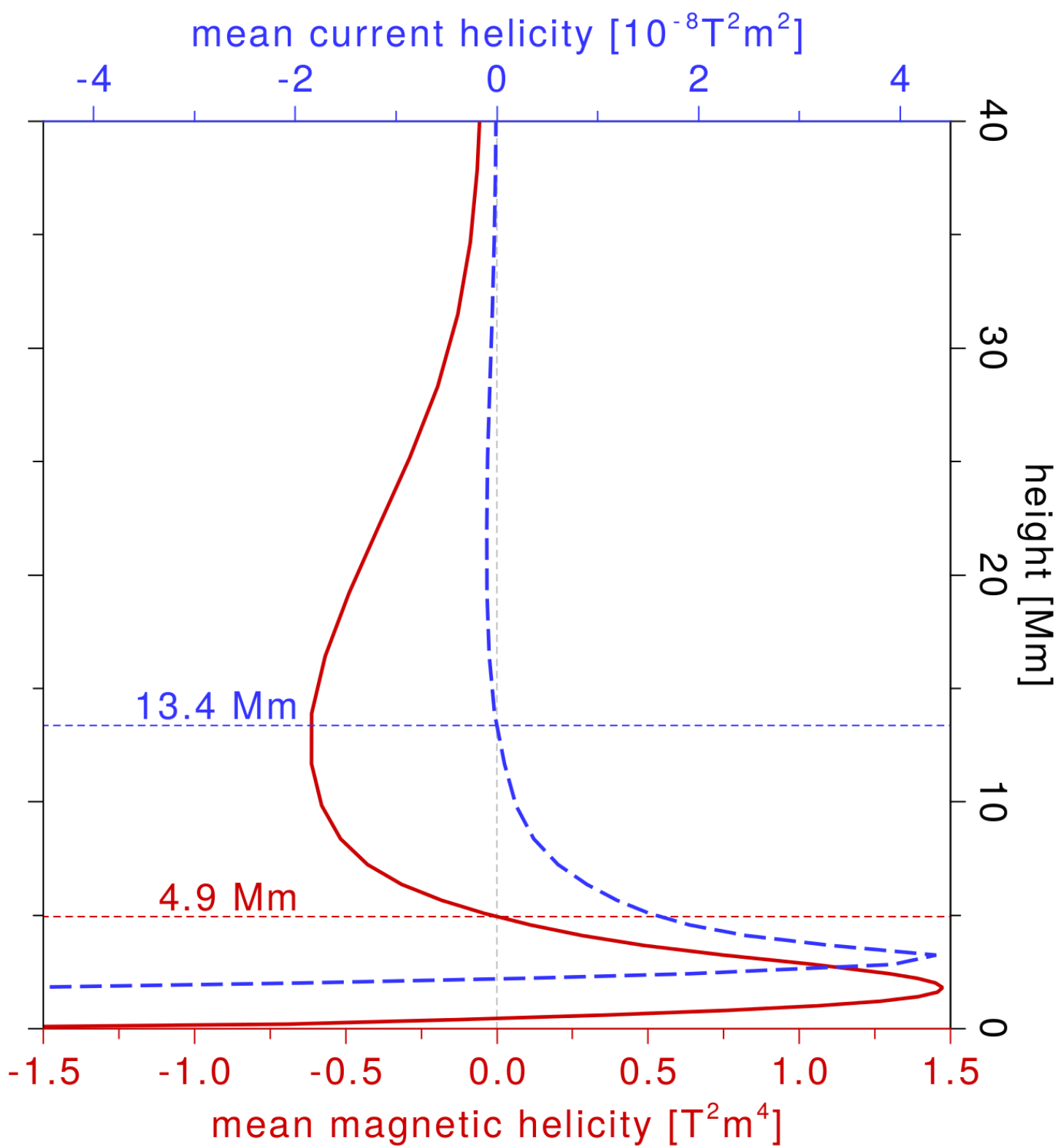


*) Magnetic helicity change => heating (work in progress)

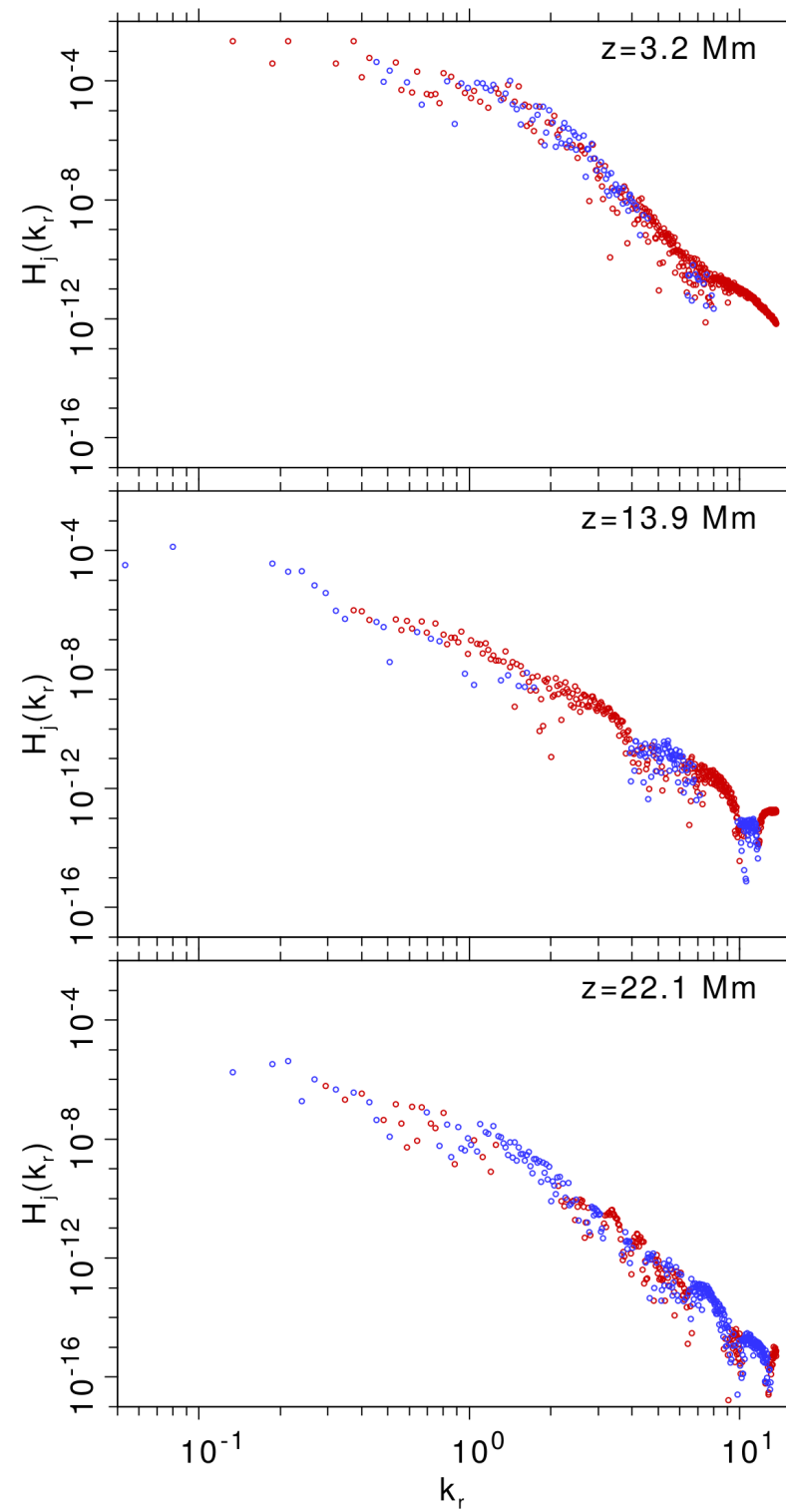
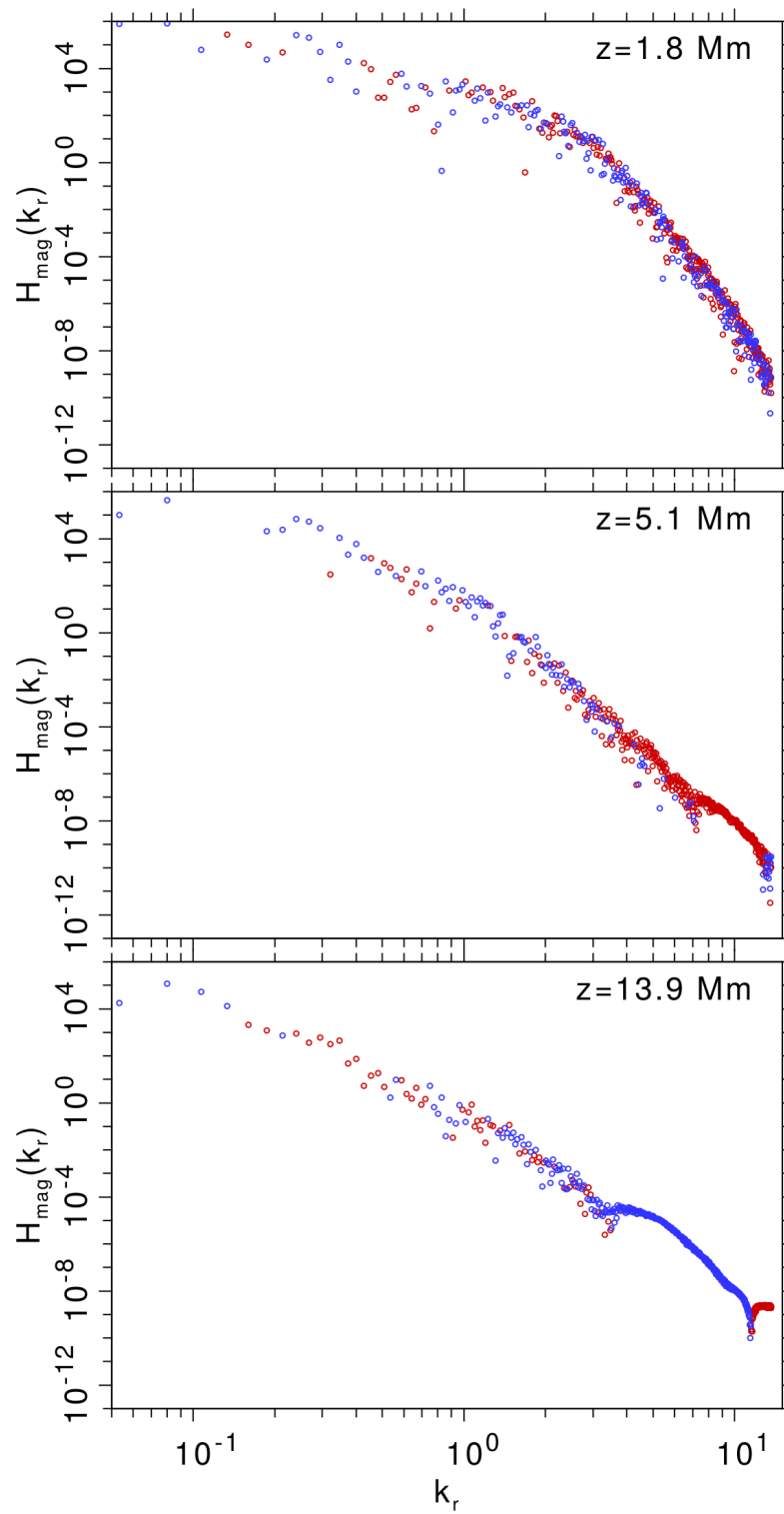
Helicity maps



**Helicity
height
average**



Helicity spectra

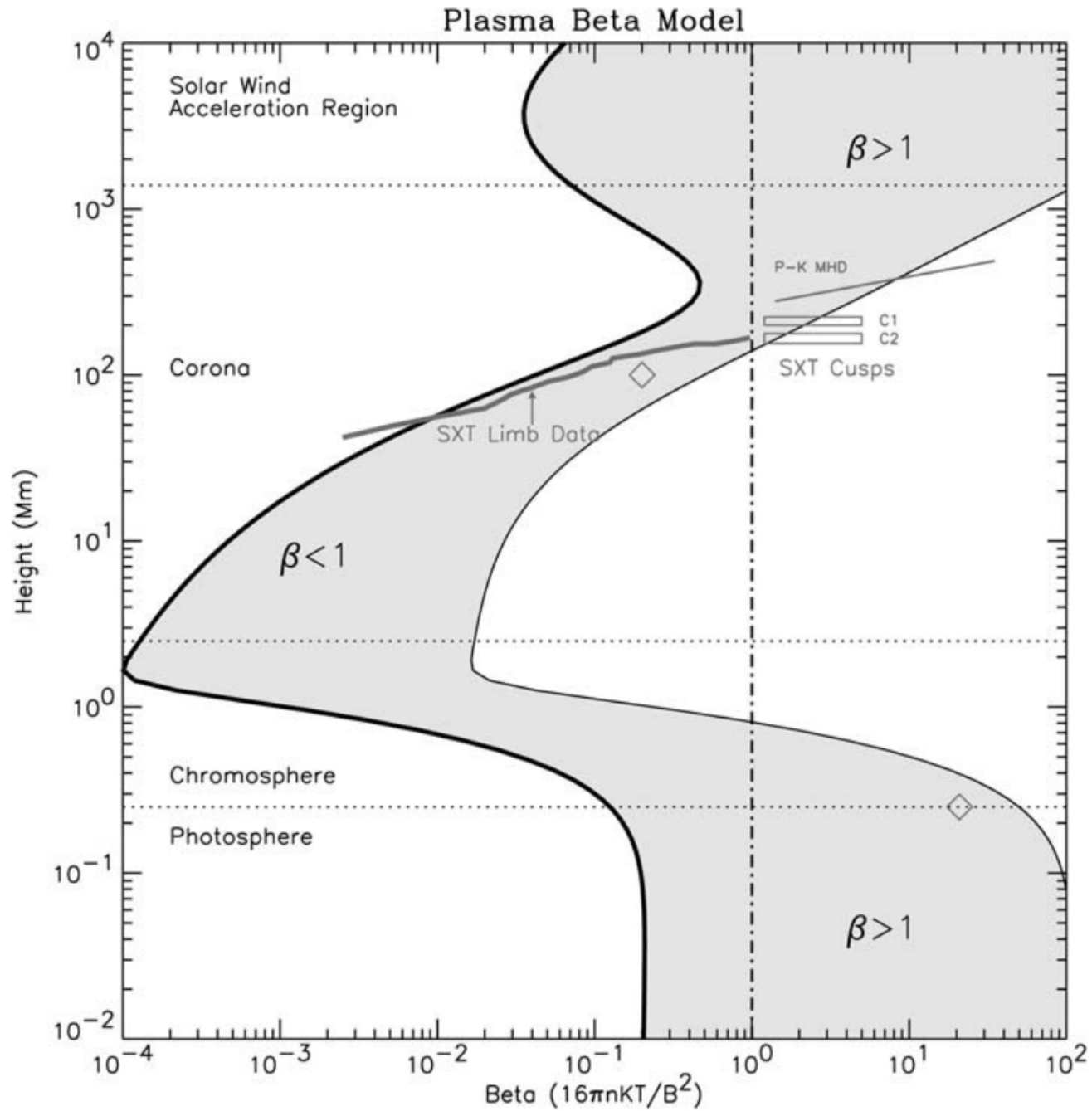


Plasma beta

- ➡ Can a bulk flow advect magnetic field in the corona?
- ➡ How reliable are (non-linear force-free or potential) field extrapolations?
- ➡ What value range of plasma beta do we expect outside of sunspots?

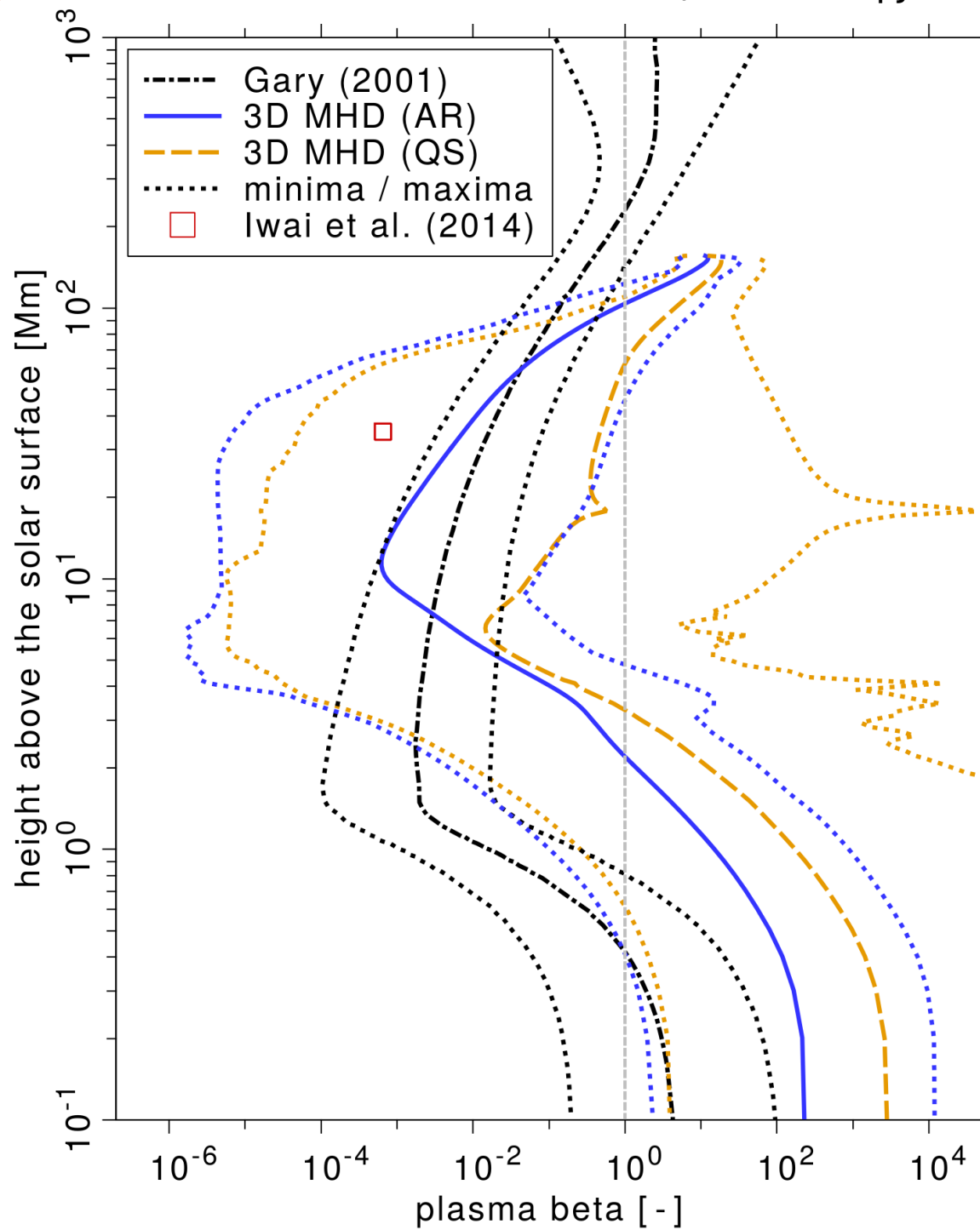
Plasma beta

(Gary, SolPhys **203**, 71-86, 2001)



Plasma beta

(Bourdin, ApJL **accepted**, 2017)



Helicity in an inter-planetary CME shock front

Helicity in an inter-planetary CME shock front

- ➡ Construct simplistic model of helical magnetic field and bulk velocity.
- ➡ Use Helios-2 observation of a magnetic transient event.
- ➡ Compute turbulent transport coefficients and electromotive force.

Helicity in an inter-planetary CME shock front

1) Turn the coordinate system into the solar wind direction:

$$\vec{B}_0 = \begin{pmatrix} 0 \\ 0 \\ B_0 \end{pmatrix}, \vec{U}_0 = \begin{pmatrix} 0 \\ 0 \\ U_0 \end{pmatrix}$$

2) Use Taylor's hypothesis:

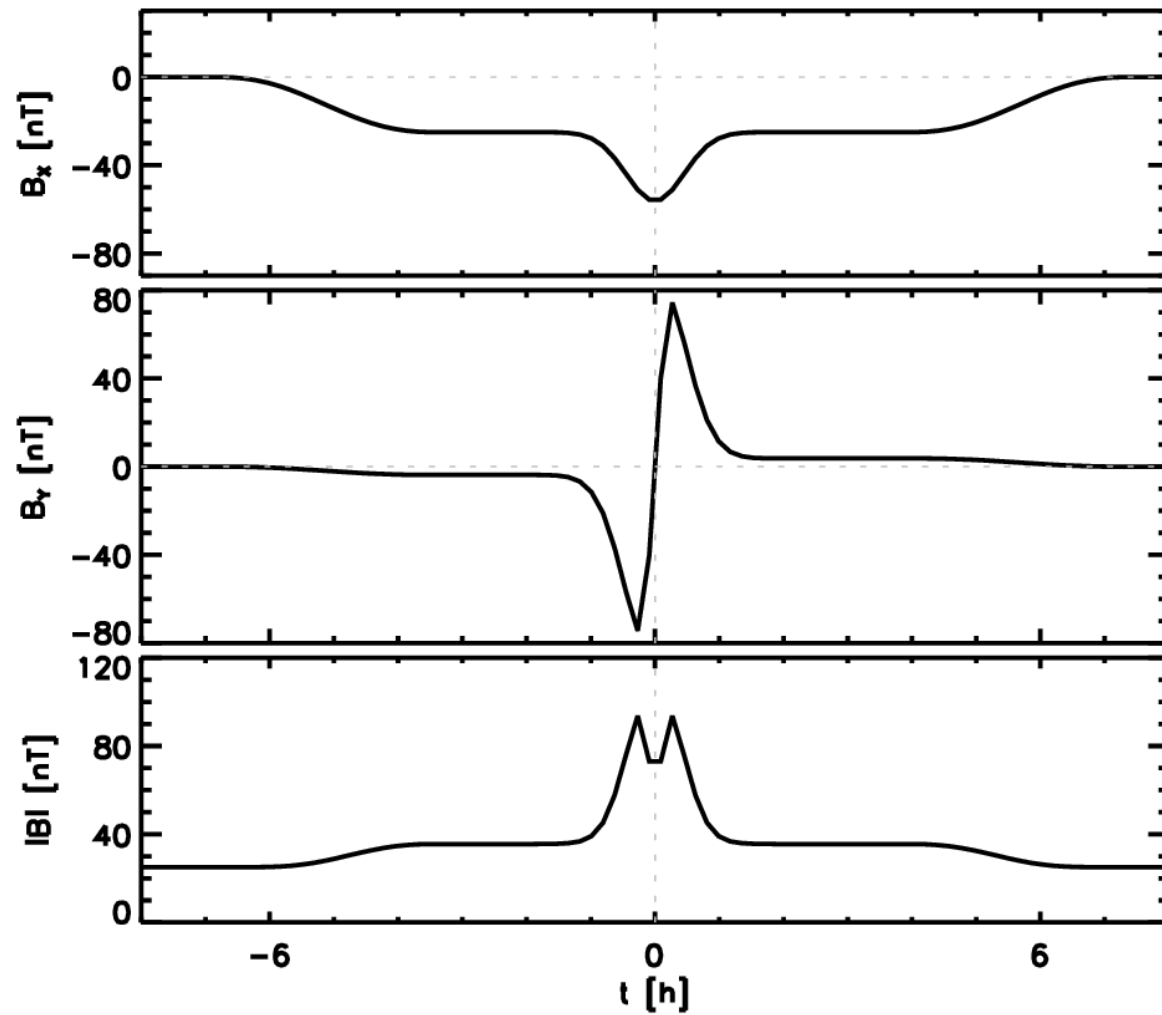
=> transient evolution slower than event passes the spacecraft

=> temporal derivative = spatial derivative along the solar wind

$$\vec{\nabla} = \begin{pmatrix} \partial/\partial x \\ \partial/\partial y \\ \partial/\partial z \end{pmatrix} \rightarrow \frac{1}{U_0} \begin{pmatrix} 0 \\ 0 \\ \partial/\partial t \end{pmatrix} \quad \vec{\nabla} \times \begin{pmatrix} h_x \\ h_y \\ h_z \end{pmatrix} \rightarrow \frac{1}{U_0} \begin{pmatrix} -\partial h_y/\partial t \\ +\partial h_x/\partial t \\ 0 \end{pmatrix}$$

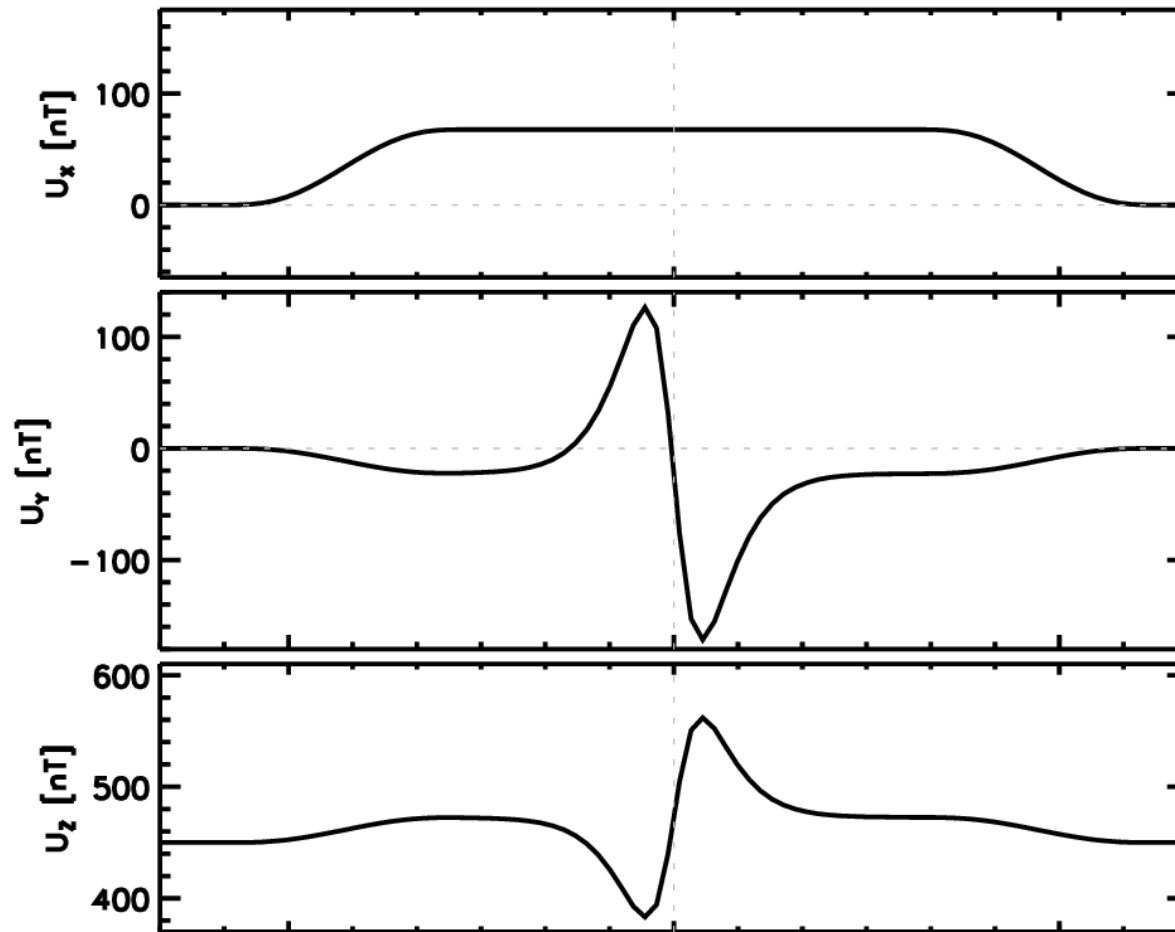
Helicity in an inter-planetary CME shock front

Helical magnetic field as „fluctuation“ on top of the solar wind background



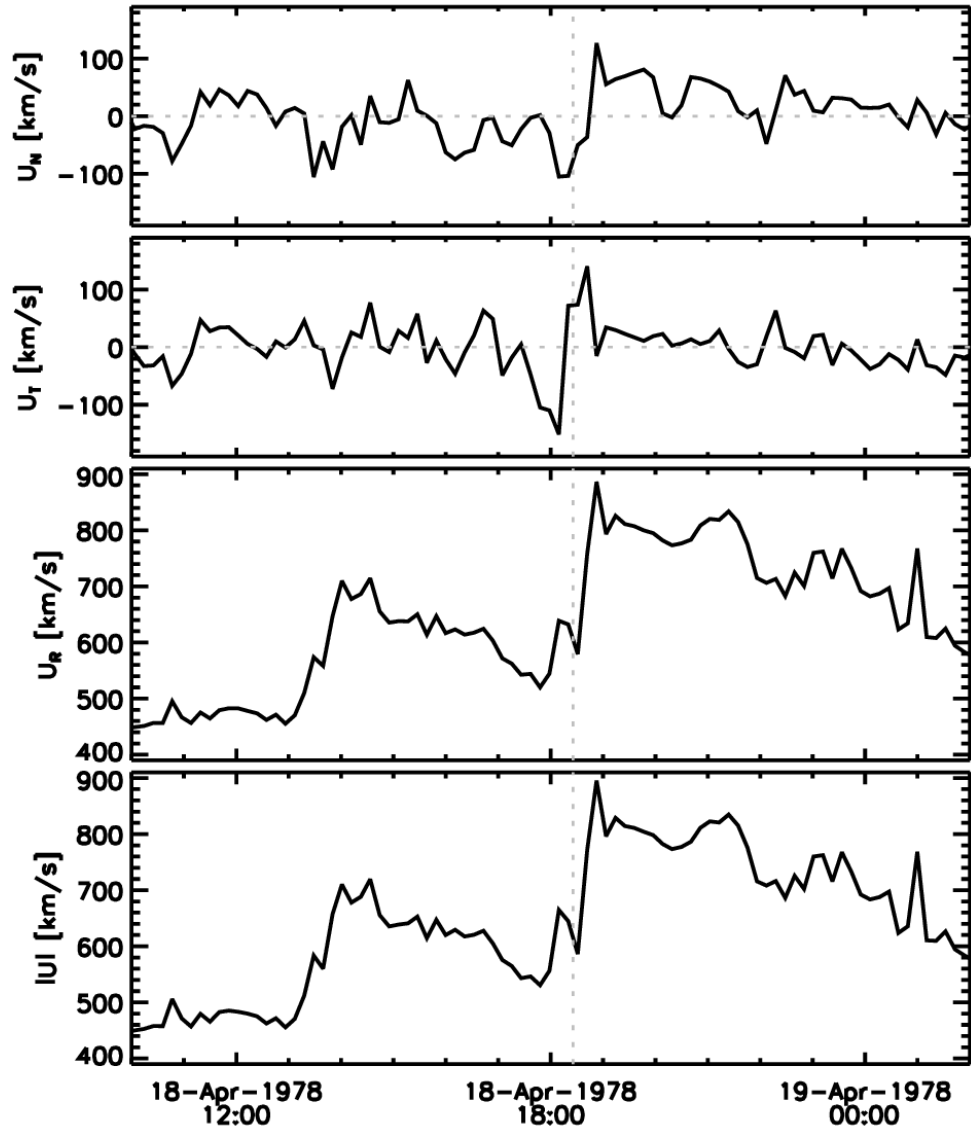
Helicity in an inter-planetary CME shock front

Vortical flow around the shock front with smooth transition

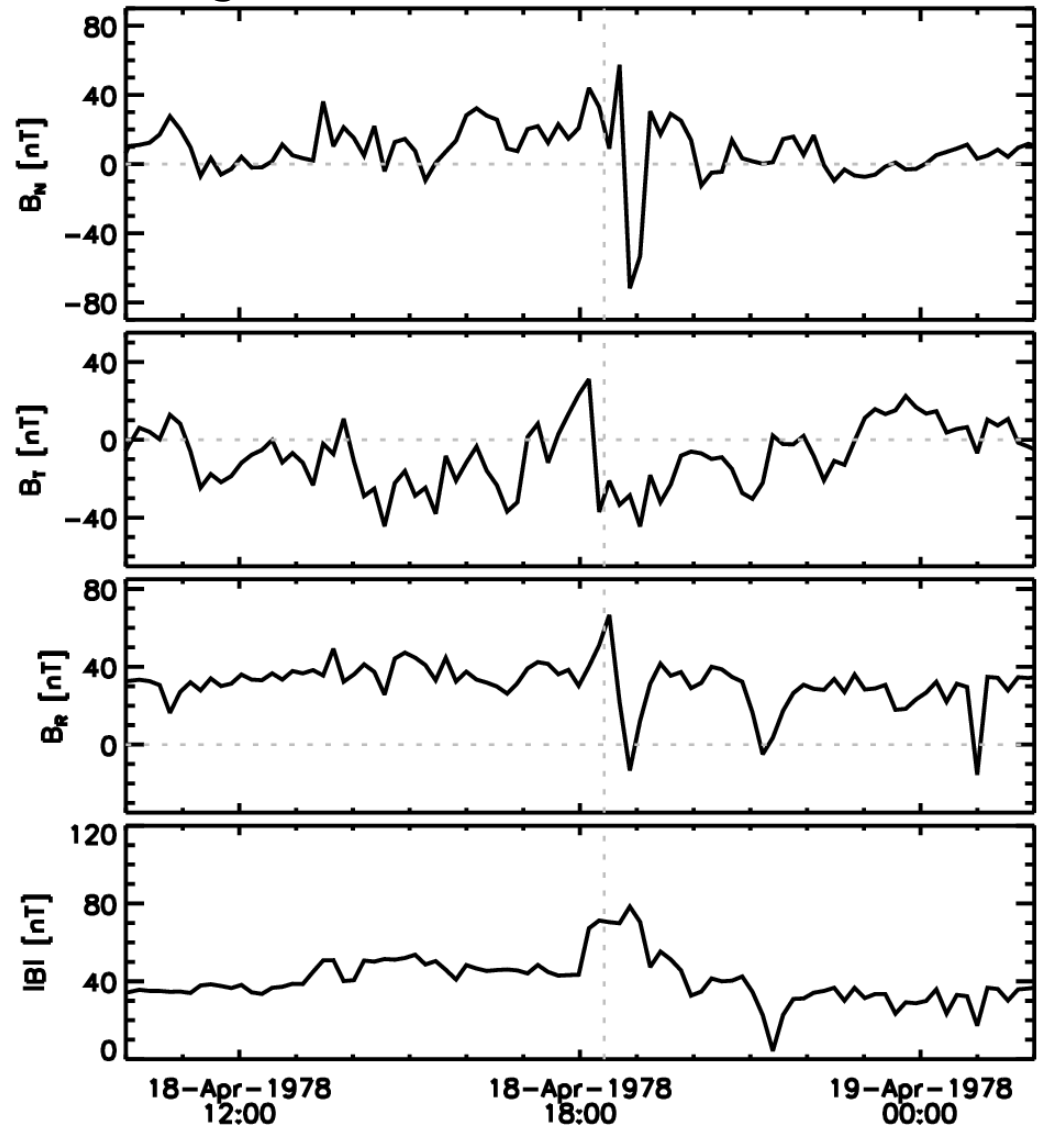


Helios-2 observation (streamwise coordinate system)

Proton bulk flow

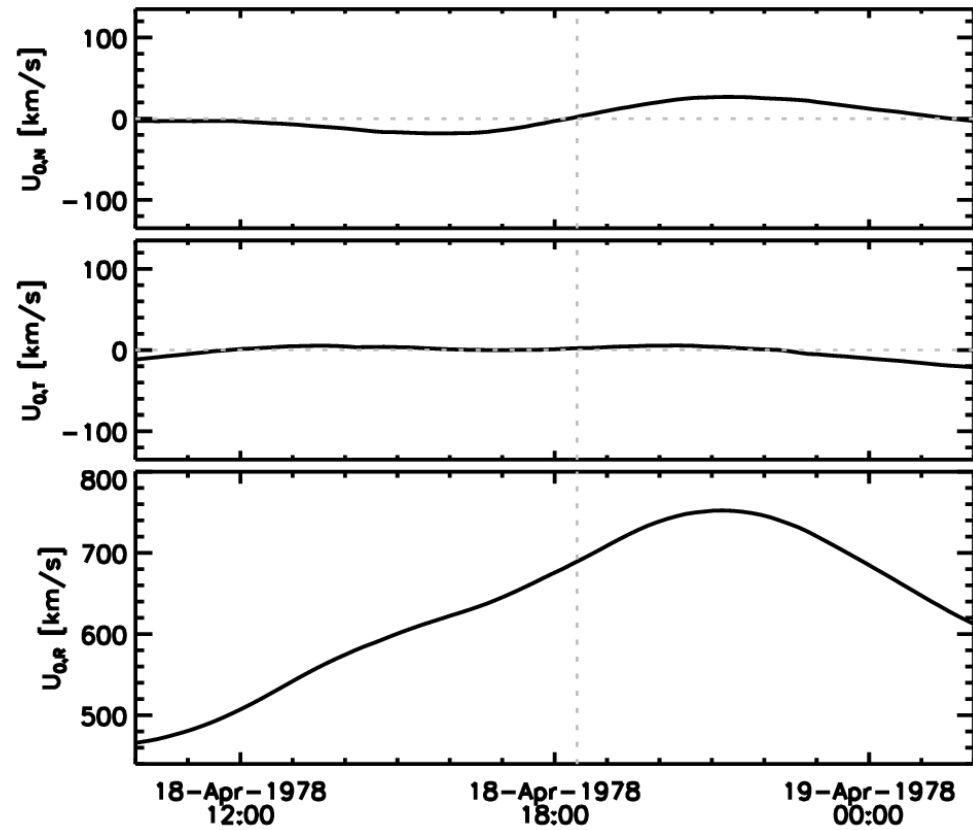


Magnetic field

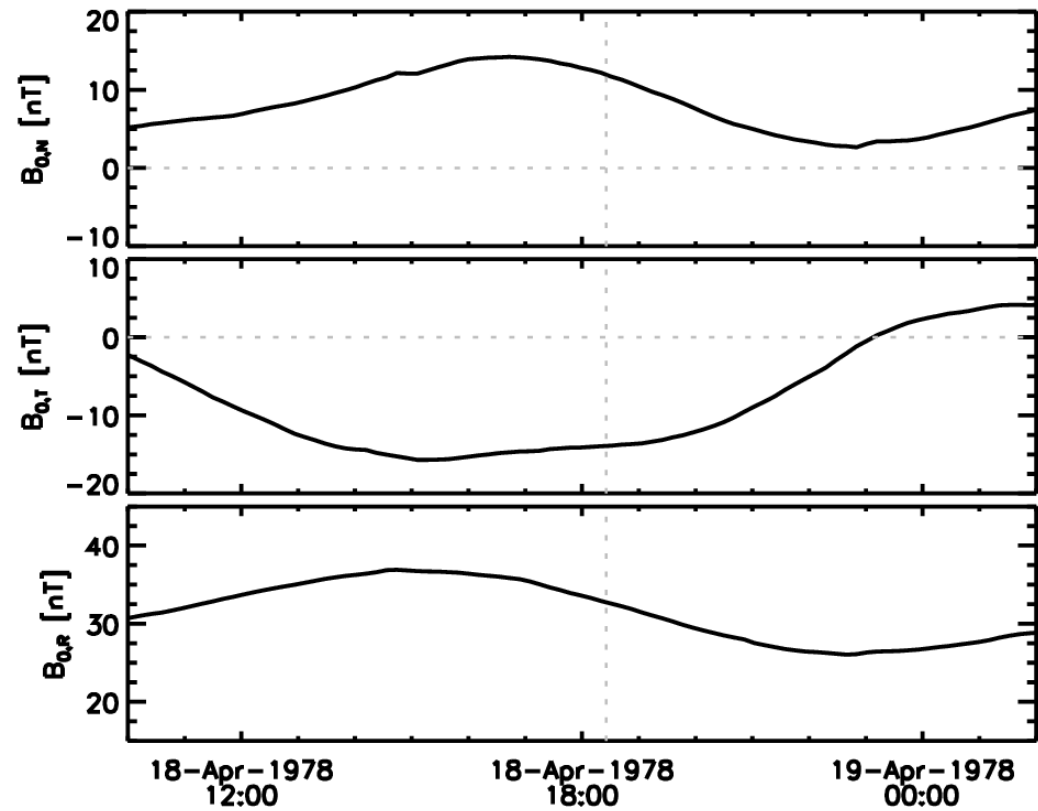


Helios-2 observation (mean field = Gaussian convolution)

Proton bulk flow

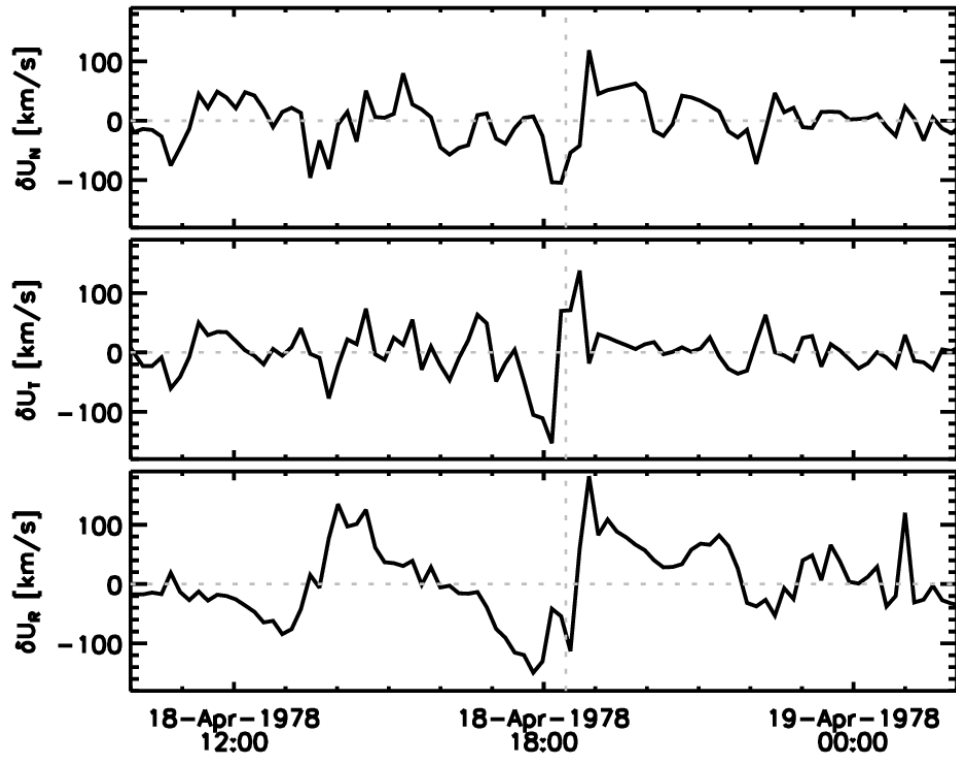


Magnetic field

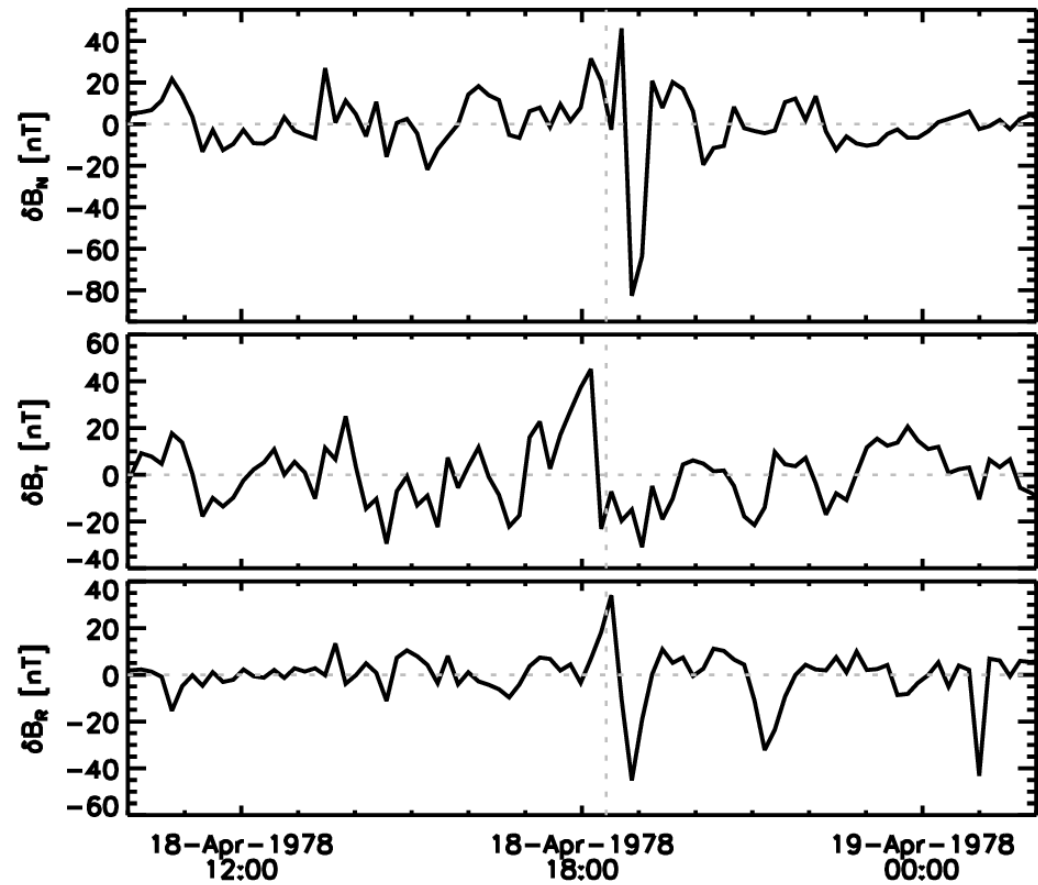


Helios-2 observation (“fluctuation” = observation - mean field)

Proton bulk flow



Magnetic field



Turbulent transport coefficients & Electromotive force

Krause & Raedler (1980):

$$\alpha = \frac{1}{3}\tau \langle -\delta\vec{U} \cdot \delta\vec{\Omega} \rangle$$

$$\beta = \frac{1}{3}\tau \langle \delta\vec{U} \cdot \delta\vec{U} \rangle$$

$$\gamma = \frac{1}{3}\tau \langle \delta\vec{U} \cdot \delta\vec{B} \rangle$$

From Yoshizawa (1990) and Yokoi (2013):

$$\alpha = C_\alpha \tau \langle -\delta\vec{u} \cdot \delta\vec{\Omega} + \delta\vec{b} \cdot \delta\vec{J} \rangle$$

$$\beta = C_\beta \tau \frac{1}{2} \langle |\delta\vec{u}|^2 + |\delta\vec{b}|^2 \rangle$$

$$\gamma = C_\gamma \tau \langle \delta\vec{u} \cdot \delta\vec{b} \rangle$$

From mean-field electrodynamics:

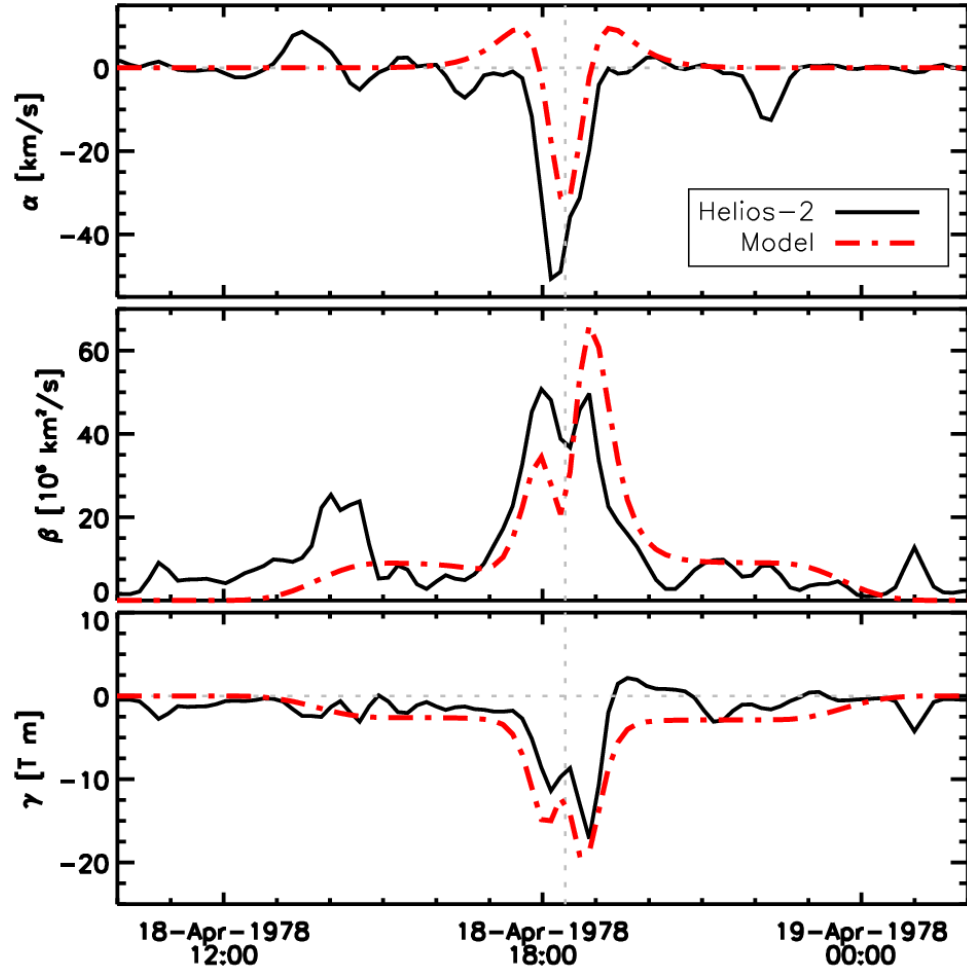
$$\vec{M}_1 = \langle \delta\vec{U} \times \delta\vec{B} \rangle$$

With an adaptation to different length scales of our „fluctuations“:

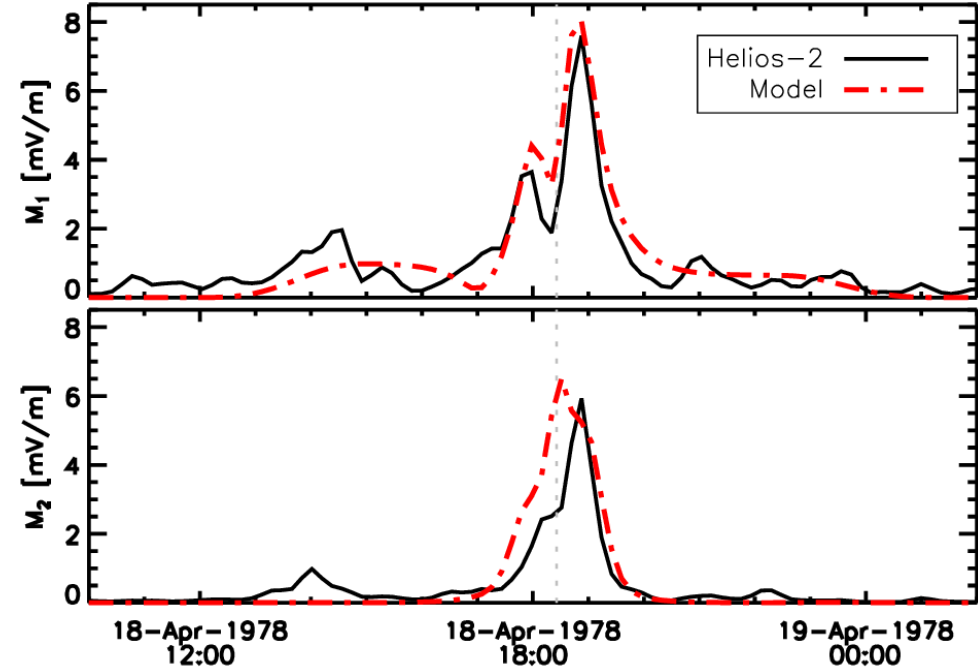
$$\vec{M}_2 = \alpha\vec{B}_0 - \beta(\vec{\nabla} \times \delta\vec{B}) + \gamma(\vec{\nabla} \times \delta\vec{U})$$

Model versus observation

Transport coefficients



Electromotive force



Conclusions

- => Helicity changes along coronal loop, consistent with the heating
- => Plasma beta may practically reach unity at all heights in the corona
- => Simplistic formulations of turbulent transport coefficients and electromotive force can be used to analyse the inner structure of iCME
- => Helical field and vortical flow show good match to observed iCME front

Thank you!