Identifying the Source Complexity of a Complex Ejecta

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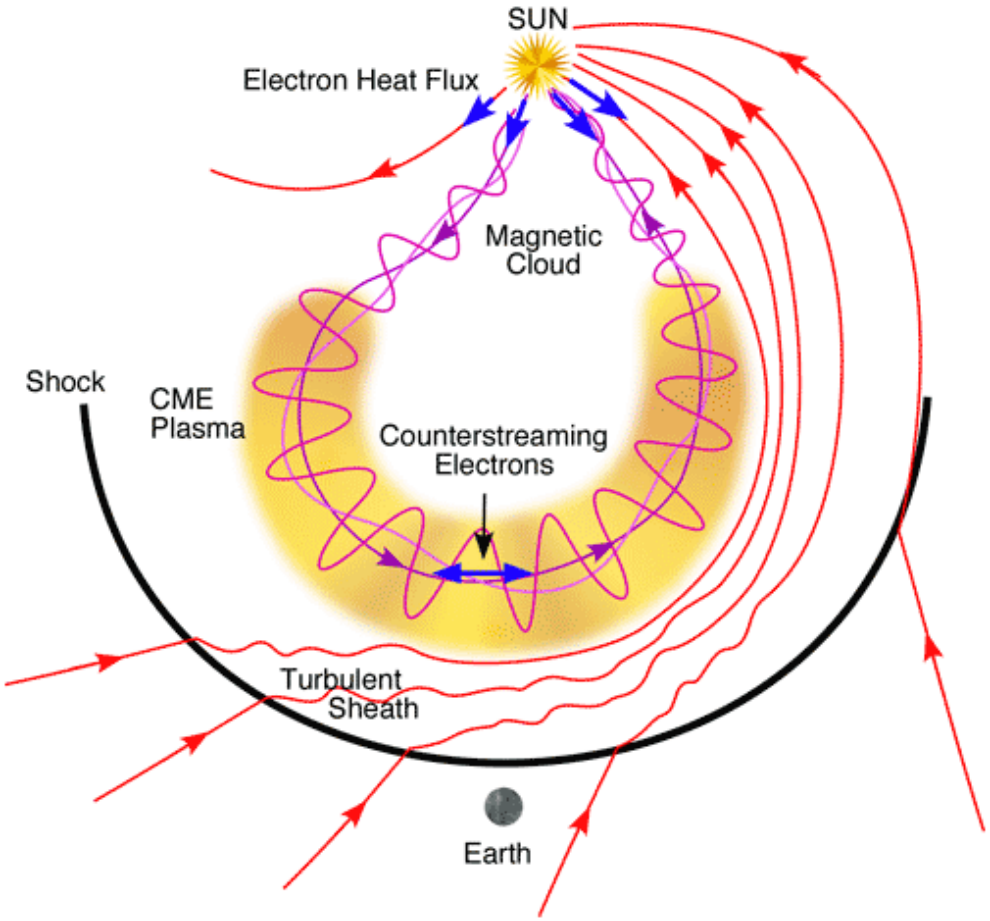
Enigma of complex ejecta

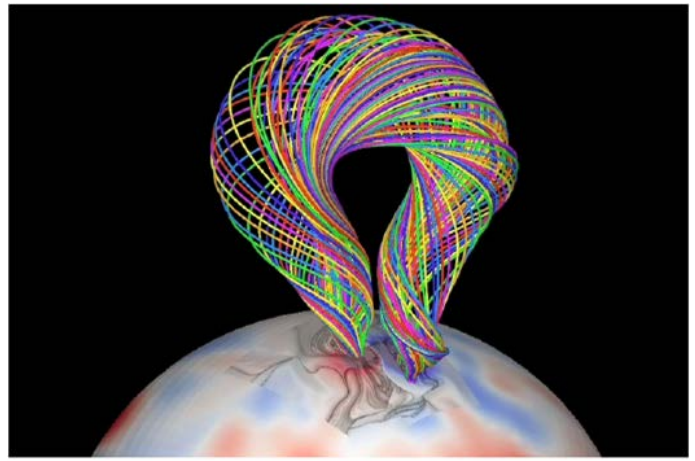
- Conventional thinking: most of CMEs are magnetic flux ropes

- Reality: only 1/3 of ICMEs are magnetic clouds
  - CME-CME Interaction
  - Glancing encounter with S/C
  - Complex source?



Magnetic Flux Rope: Introduction

- Definition
  - A bundle of magnetic field lines collectively winding around a common axis
- Implication
  - Similar magnetic connectivities within the rope?
  - A boundary separating twisted from untwisted field?
- Methods
  - Quantify magnetic connectivity
  - Quantify magnetic twist

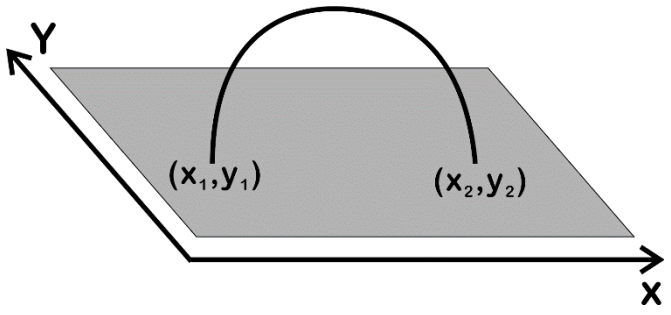


Courtesy of V.S. Titov

Quantifying Magnetic Connectivity

- Field line mapping $\Pi_{12} : \mathbf{r}_1(x_1,\ y_1) \mapsto \mathbf{r}_2(x_2,\ y_2)$
- Jacobian associated with the mapping

$$D_{12} = \left[\frac{\partial \mathbf{r}_2}{\partial \mathbf{r}_1}\right] = \begin{pmatrix} \partial x_2/\partial x_1 & \partial x_2/\partial y_1 \\ \partial y_2/\partial x_1 & \partial y_2/\partial y_1 \end{pmatrix} \equiv \begin{pmatrix} a & b \\ c & d \end{pmatrix}$$



- **Squashing Factor Q** (Titov et al. 2002, JGR)

$$Q \equiv \frac{a^2 + b^2 + c^2 + d^2}{|\det D|}$$

- Quasi-Separatrix Layers : $Q \gg 1$
- Separatrix Surfaces: $Q \to \infty$

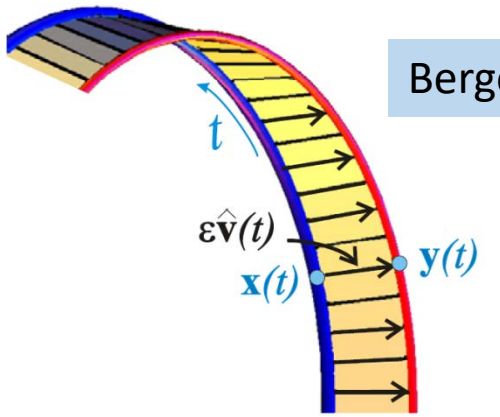
Rapid change in magnetic connectivity

Quantifying Magnetic Twist

Liu et al. 2016, ApJ

Geometric Twist: # of turns of a curve winding about axis

$$T_g = \frac{1}{2\pi} \int_{x(s)} \hat{T}(s) \cdot \hat{V}(s) \times \frac{d\hat{V}(s)}{ds} ds$$



Berger + Prior 2006

Twist of a Field Line: generalized from a cylindrical flux tube

$$T_w = \int_{y(s)} \frac{\mu J_\parallel}{4\pi |B|} ds = \int_{y(s)} \frac{(\nabla \times \boldsymbol{B}) \cdot \boldsymbol{B}}{4\pi B^2} ds$$

$$\lim_{\varepsilon \to 0} T_w(\varepsilon) = T_g - \int_{x(s)} \frac{c_3}{2\pi B} ds$$

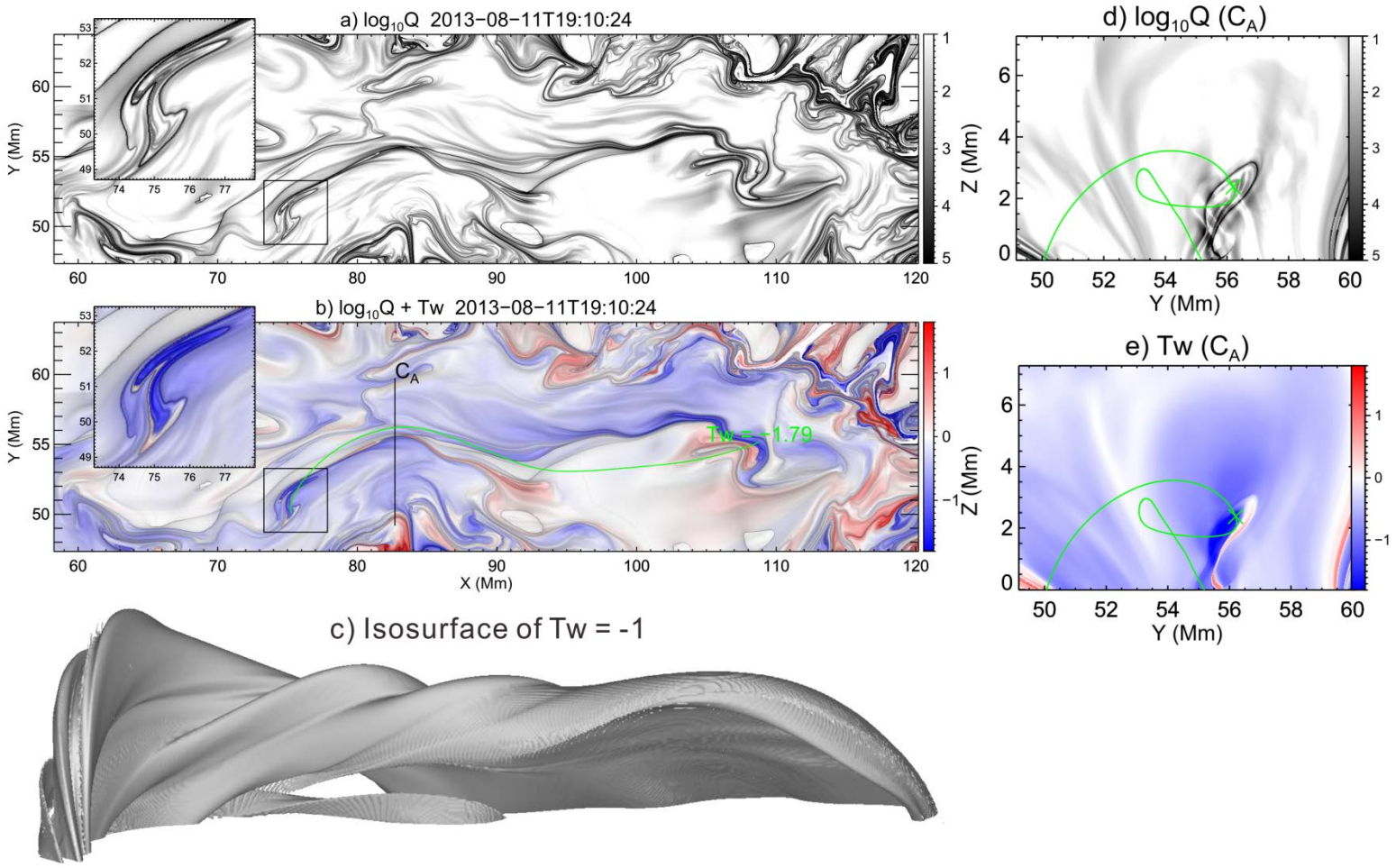
$$\mathbb{S} \cdot \hat{V} = c_1 \hat{T} + c_2 \hat{V} + c_3 \hat{T} \cdot \hat{V}$$

$\mathbb{S}$ - symmetric part of the field gradient tensor $\partial \boldsymbol{B} / \partial \boldsymbol{r}$

$c_3 = 0$ at the axis in cylindrical symmetry

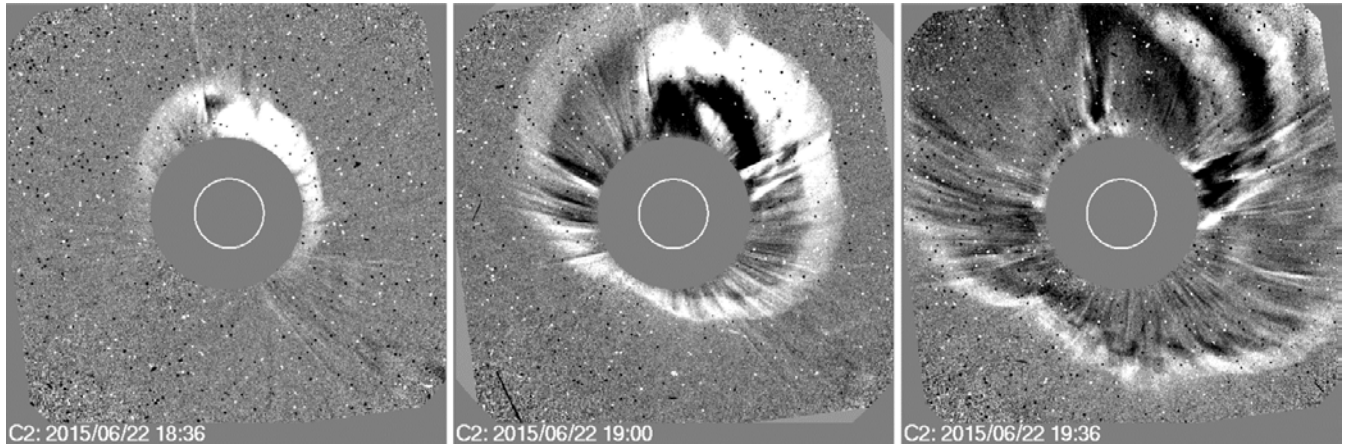
Combining Q and Tw

Liu et al. 2016, ApJ



- MFR criteria: a 3D region of enhanced twist ($|Tw| \geq 1$) bounded by high-Q surfaces (QSLs)
- Axis criteria: $|Tw|$ achieves extremum at the axis

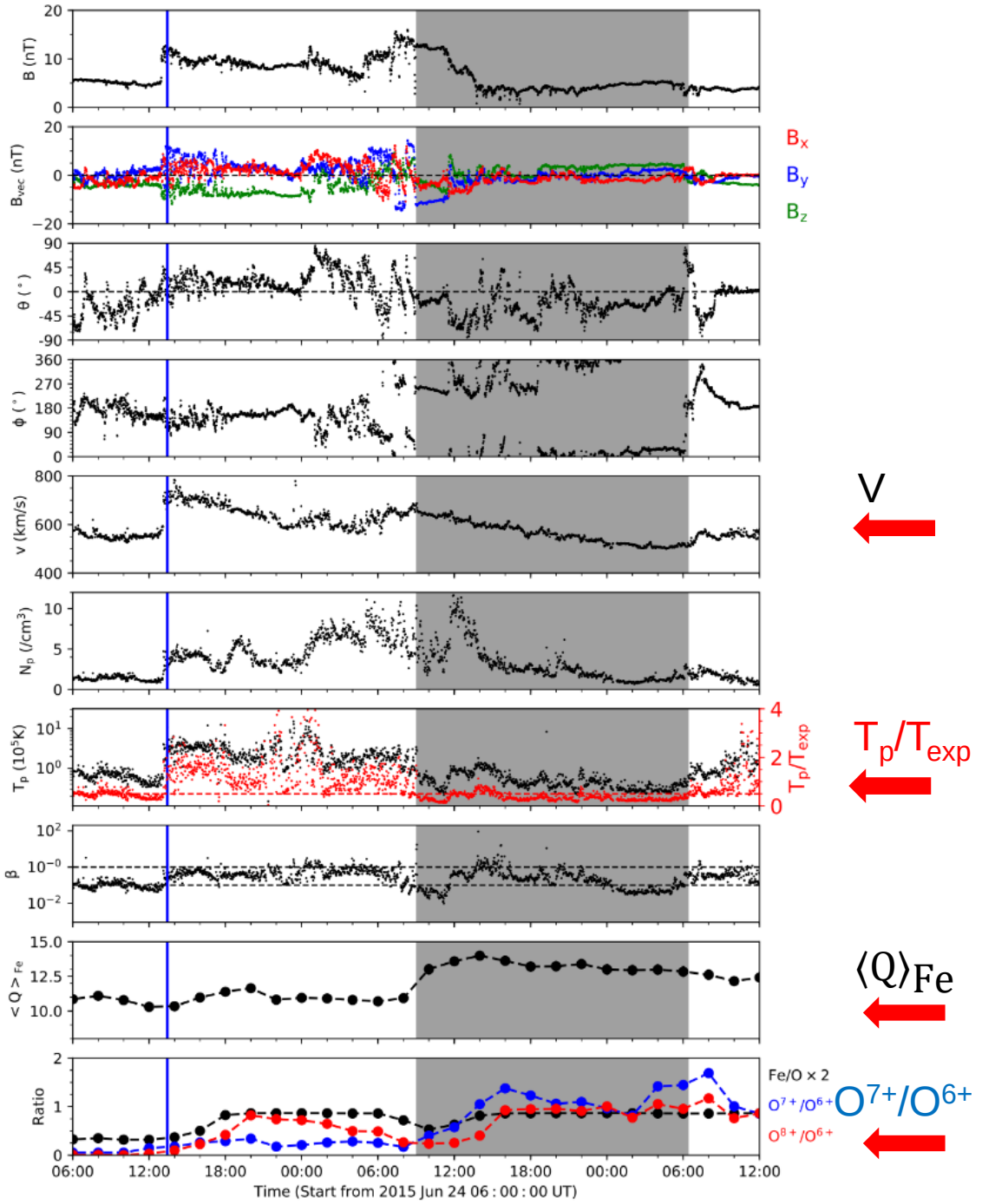
CME and unexpectedly moderate geoeffect



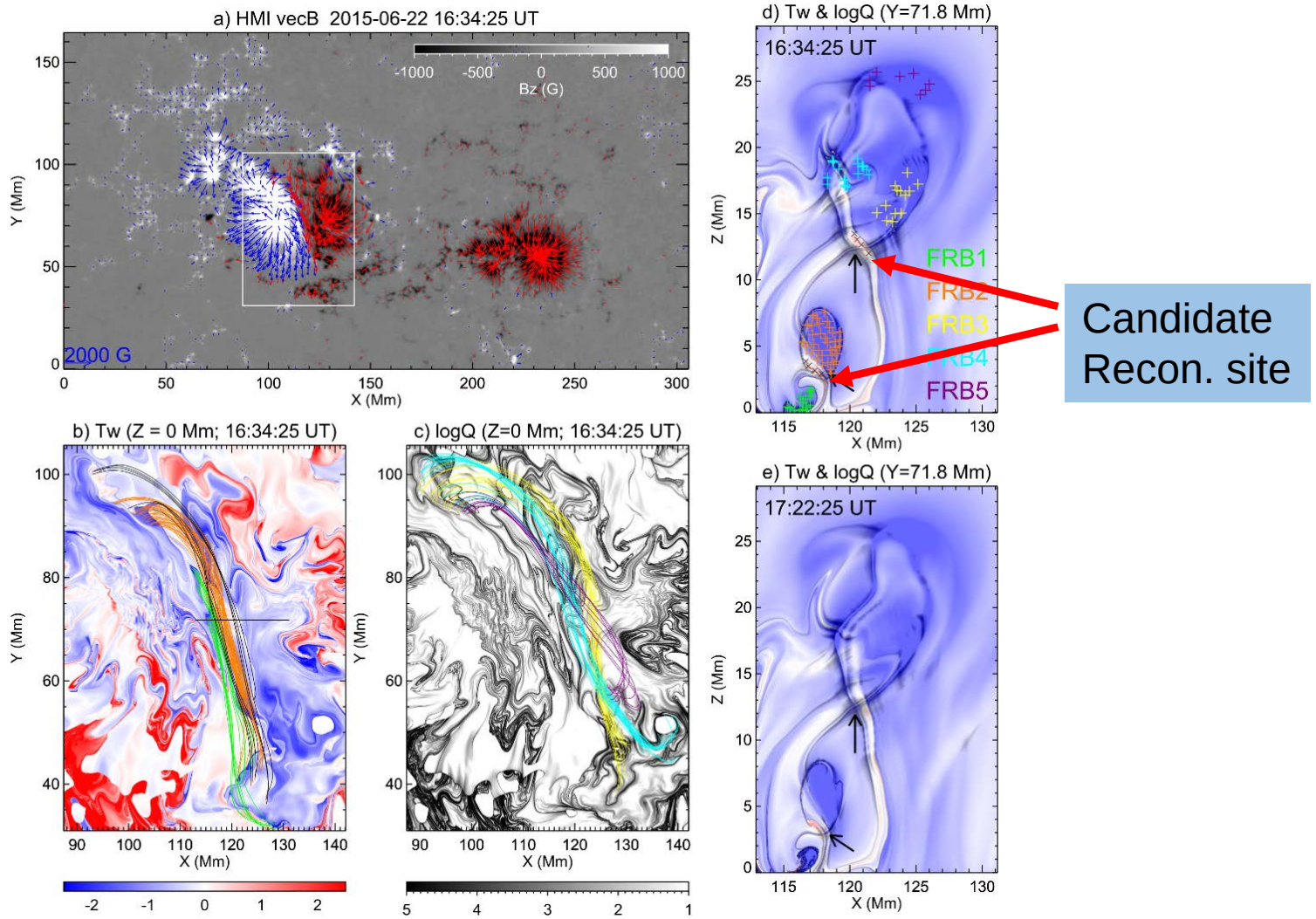
Earth-directed
Full halo
Fast (1200 km/s)

?

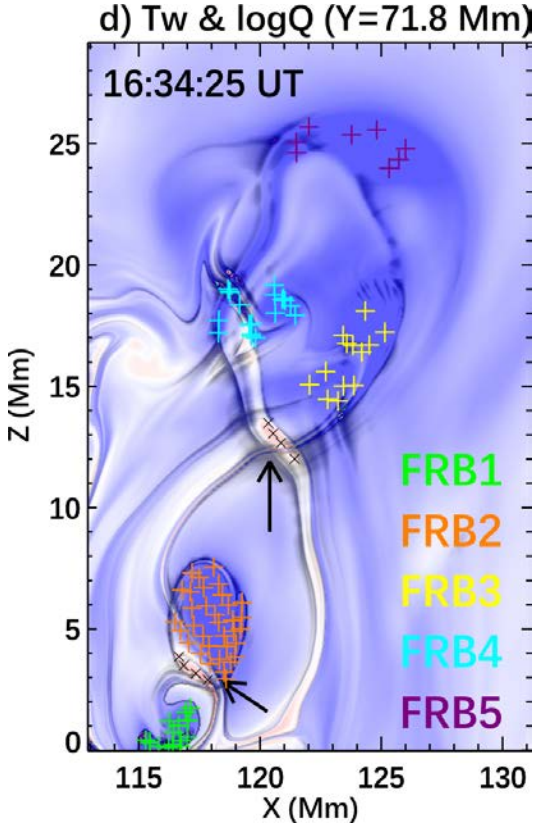
$Dst_{min} \approx -80$ nT

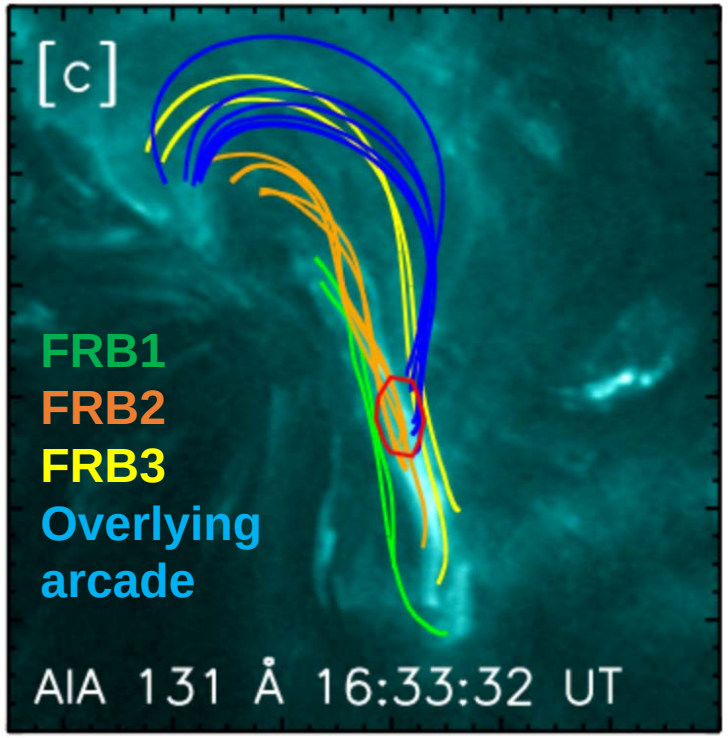


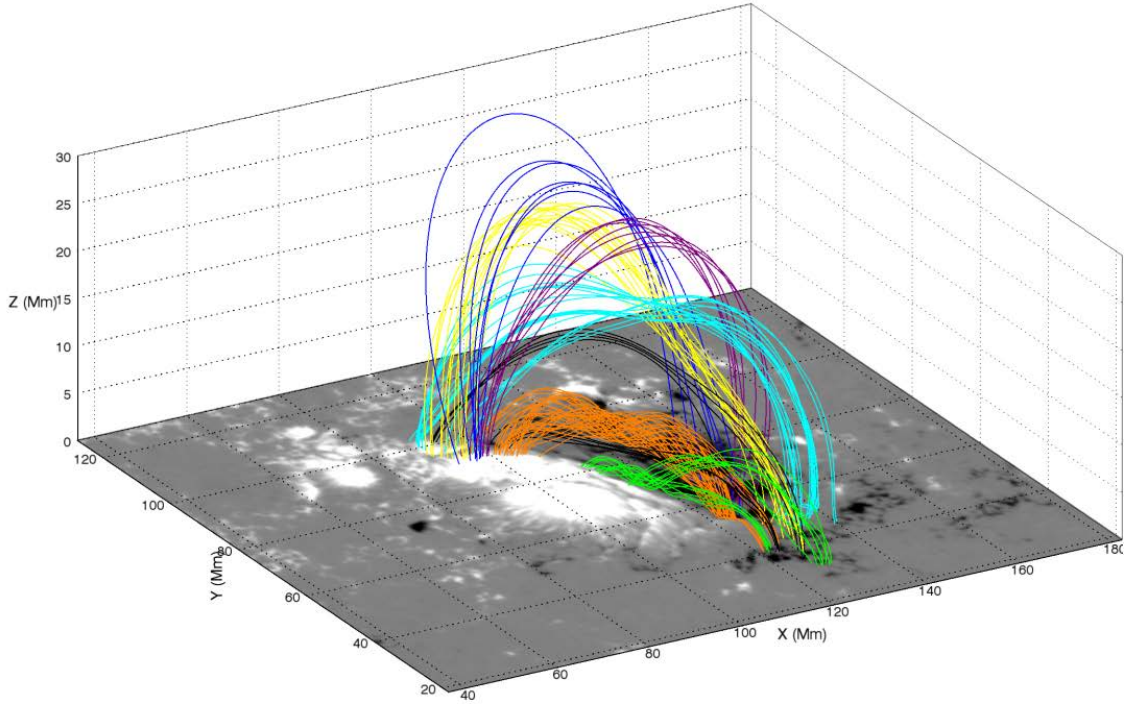
Multi-Flux-Rope System

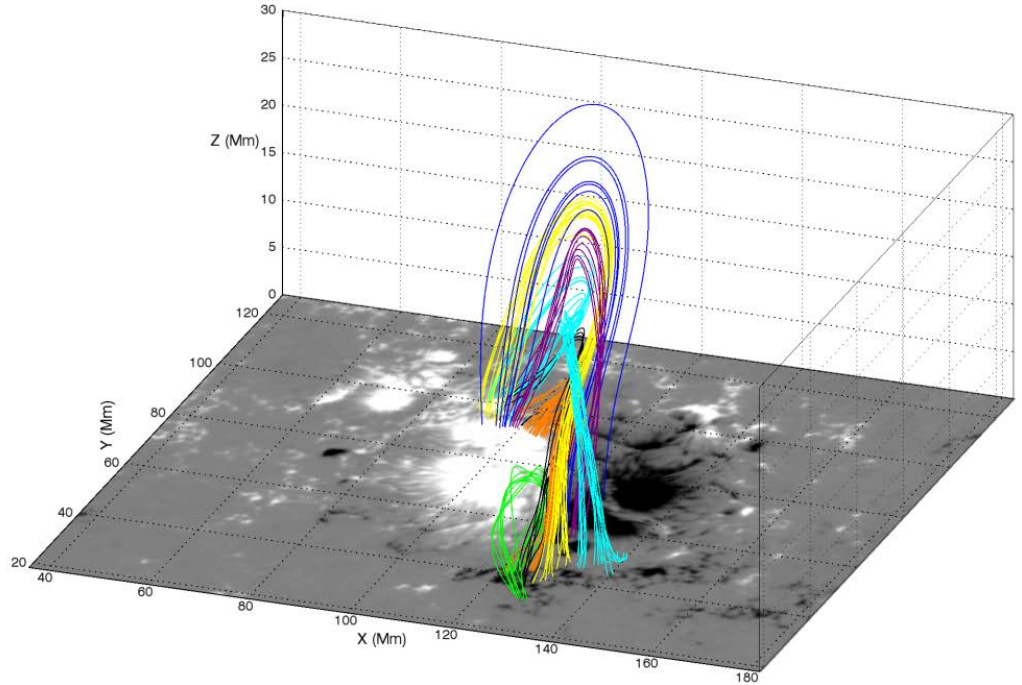


Braiding sub-flux-ropes

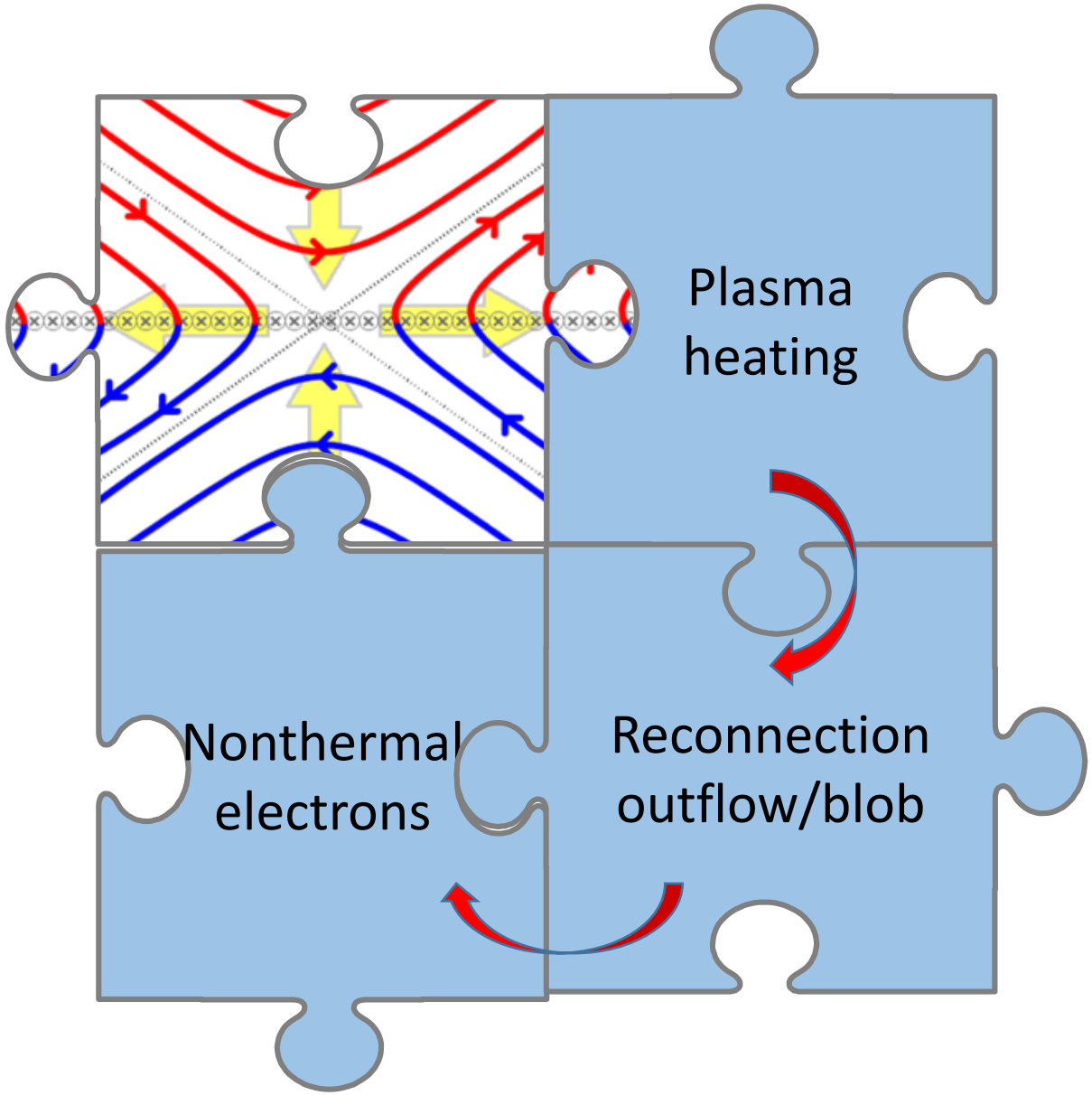






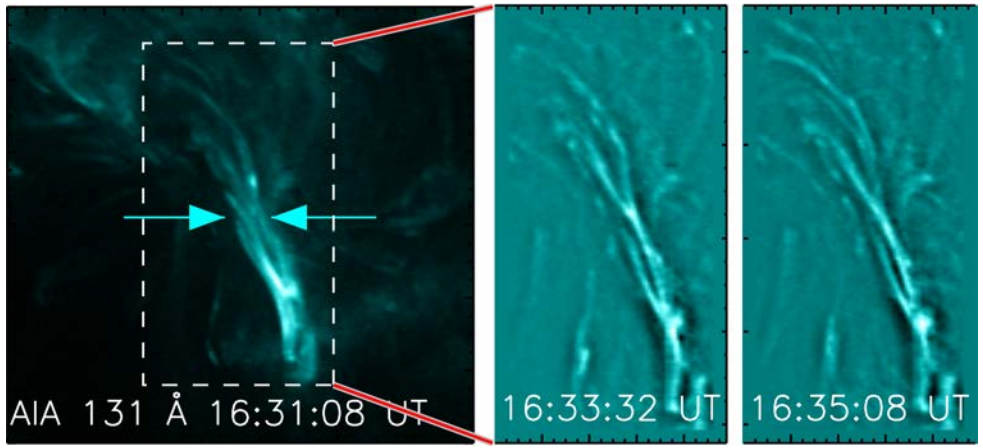


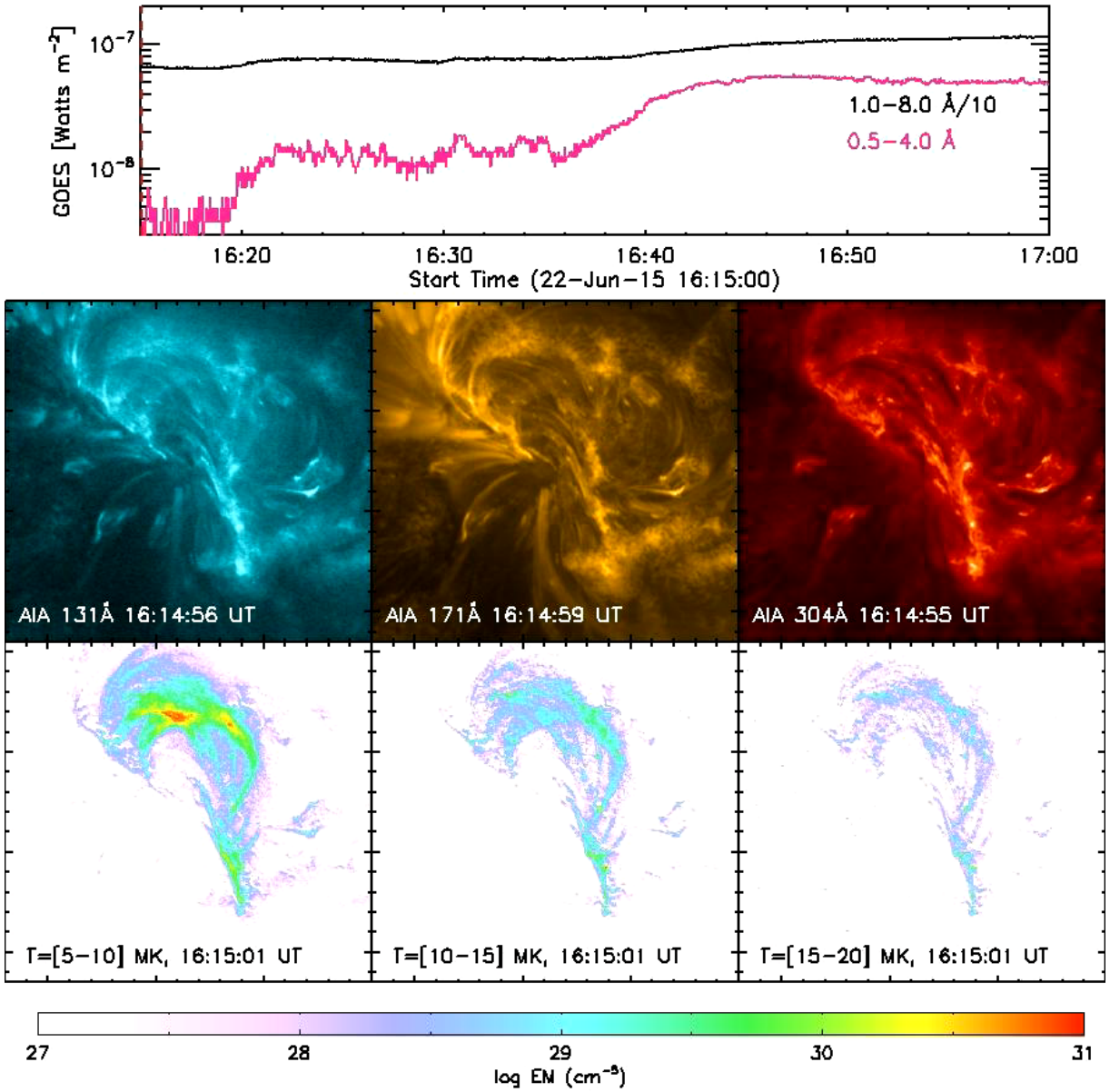
Seeking Evidence of Magnetic Reconnection



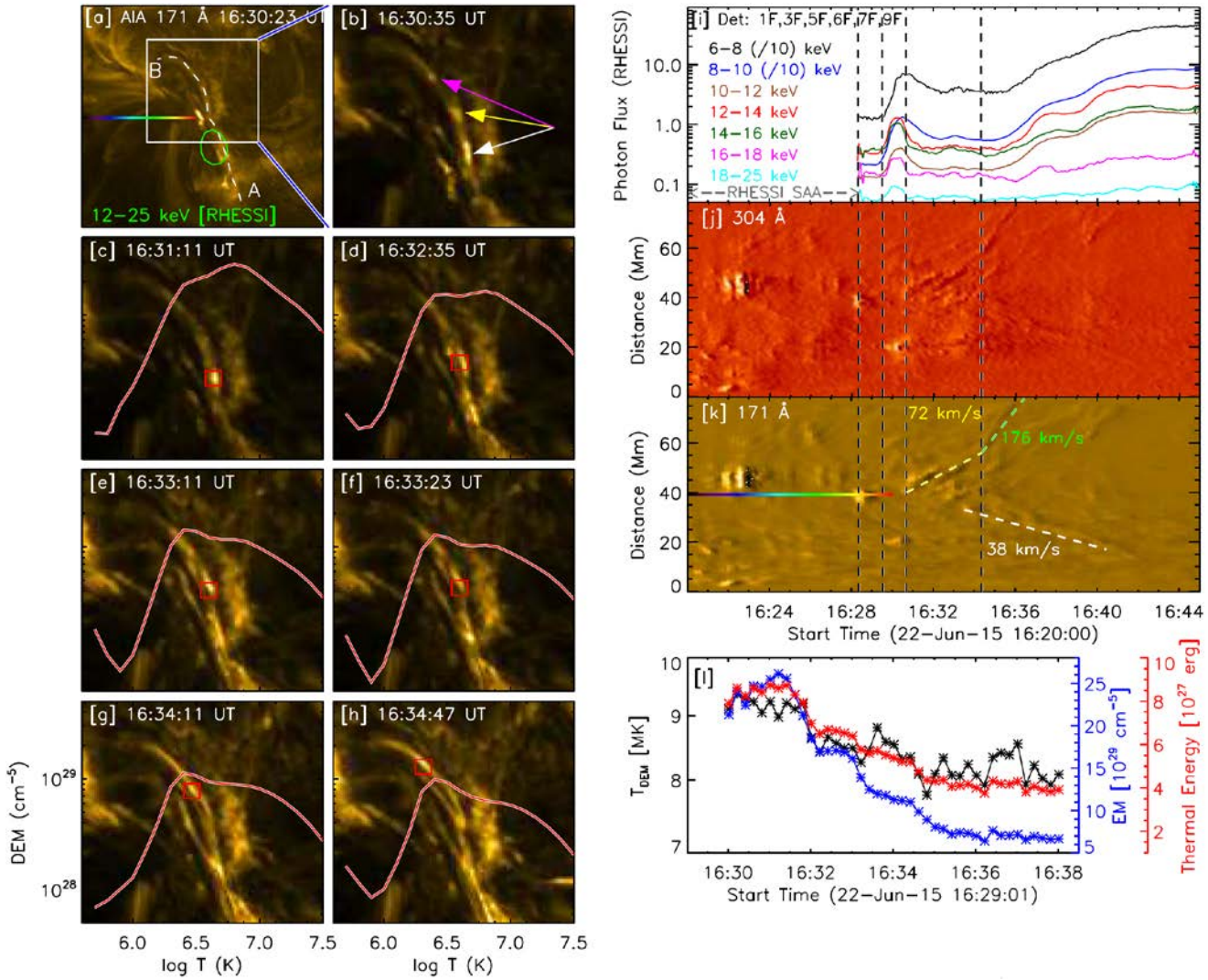
Braiding & Plasma Heating

- Braiding of multi-threads in 131Å
- Plasma heated up 20 MK in a C1.1 flare before M6.5



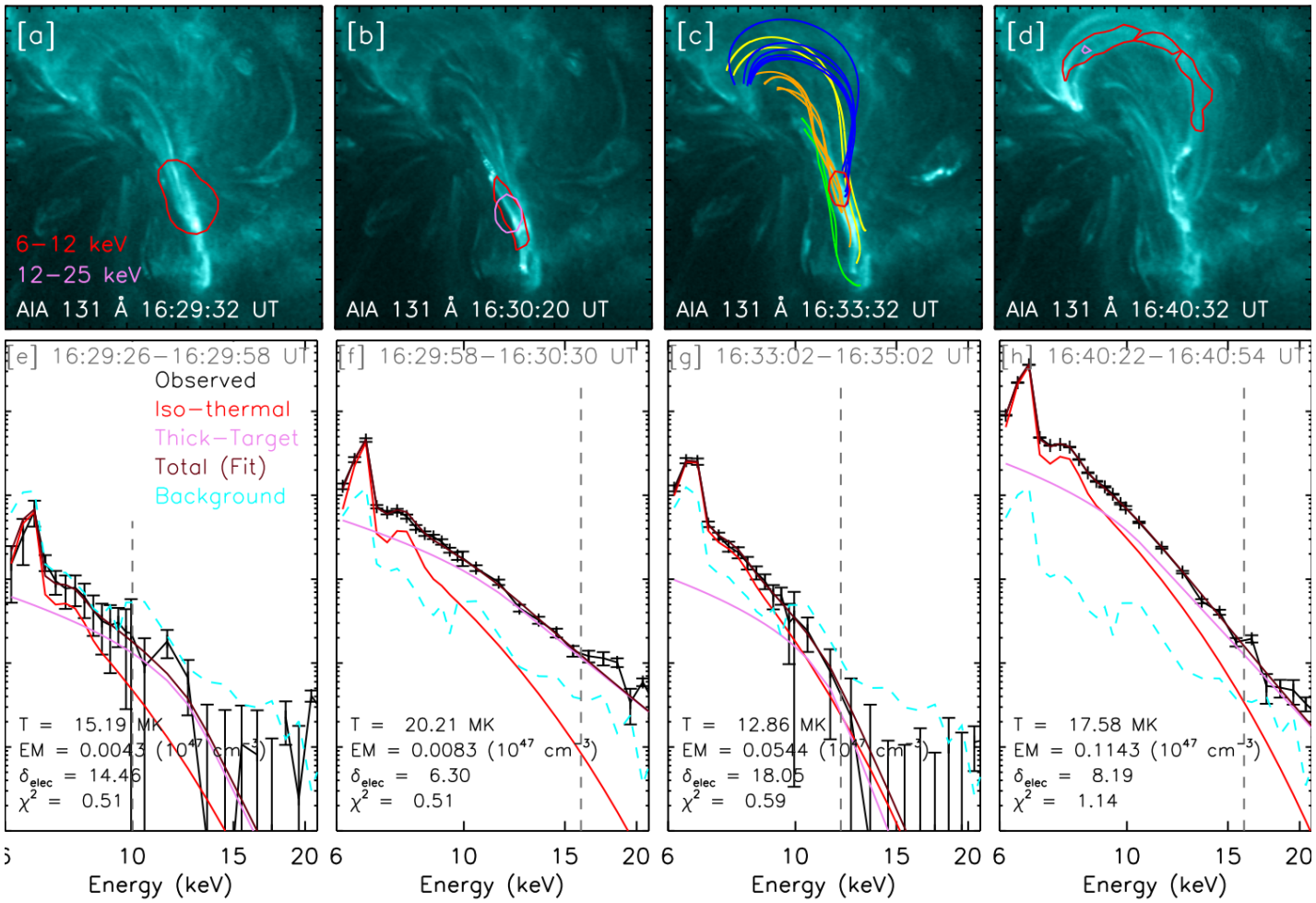


Reconnection outflow

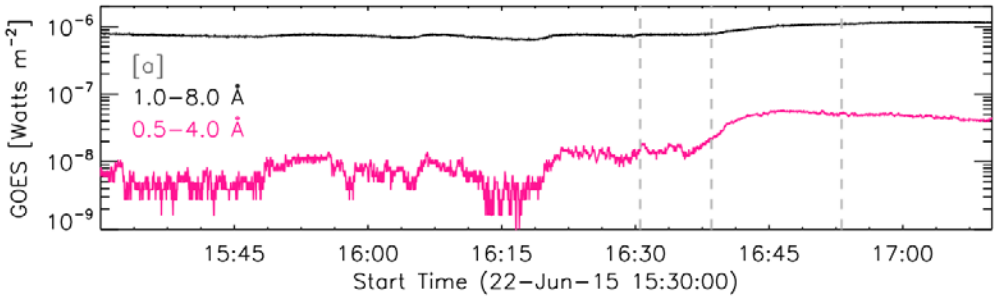


- Bidirectional outflow in the form of blobs
- Blobs are multi-thermal with a 10 MK component

Nonthermal HXR electrons



- **Preflare phase**: significant nonthermal component (power-law index $\delta = 6.3$)
- **Main phase**: Essentially thermal (exponential)



Conclusion

- Complex ejecta may **inherit complexity** from the source

- Time to start thinking about **internal structure and reconnection** if we are to understand CMEs and to predict their geoeffects.

Awasthi, Liu*, et al. 2018, ApJ