Part II : Coronal Mass Ejections & Large-scale Transients

B. J. Lynch [1, 2]

1. Department of Earth, Planetary, and Space Sciences, University of California–Los Angeles
2. Space Sciences Laboratory, University of California–Berkeley

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Outline

- **Introduction Material / Background – what is a CME and *why* does it erupt?**
- **Illustrative Example(s) of Solar Flare + CME Observations**
- **Theoretical Considerations**
- **Role of Magnetic Reconnection during the Eruption Process**
- **Somewhat Recent MHD Modeling Example(s) and Comparison to Observations**

  * in the corona

  * in the heliosphere

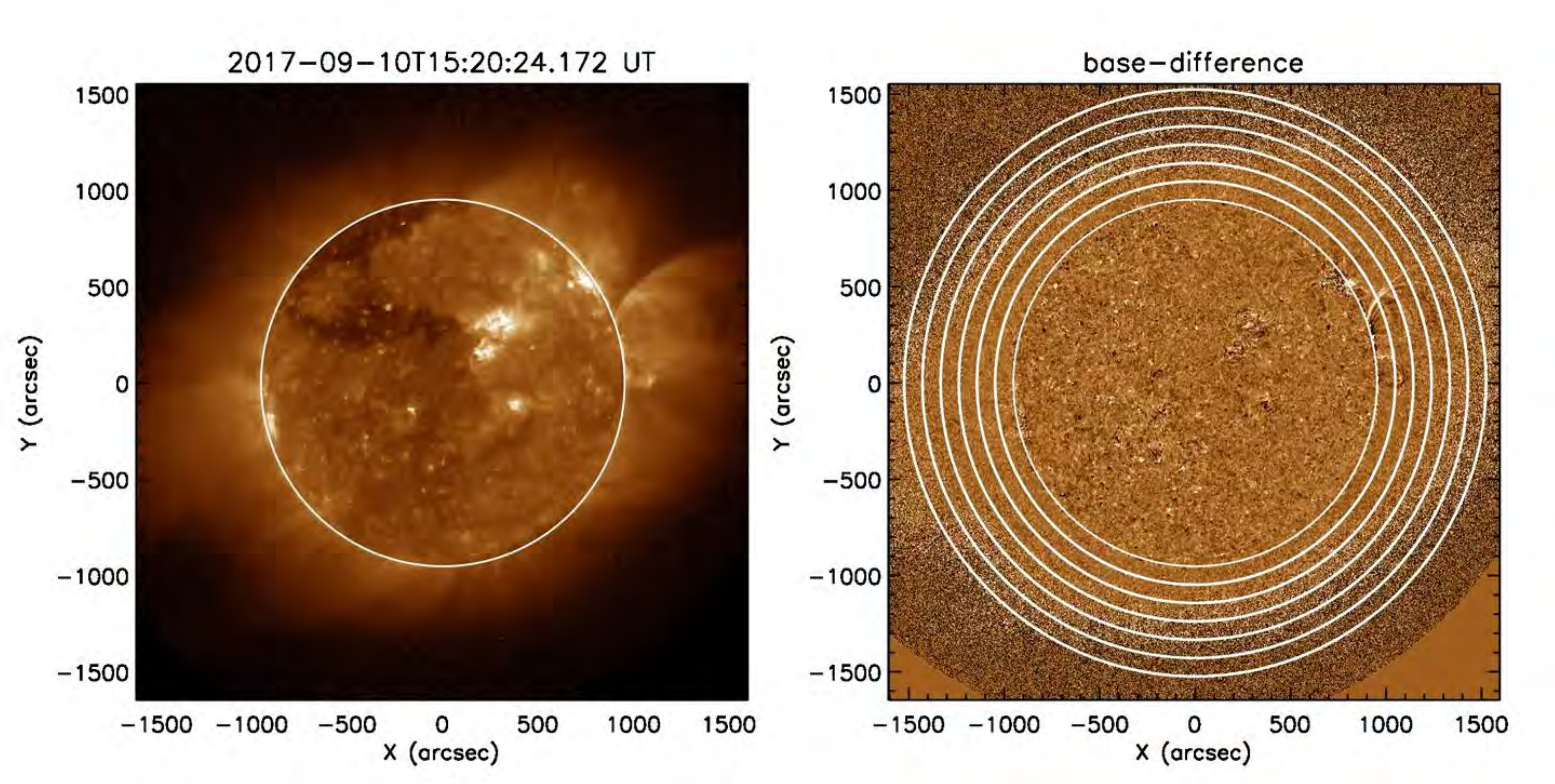
  * on other stars?!

  * some (well-known) issues with heliosphere/in-situ CME & FR modeling
- **Summary & Conclusions & Discussion**

Introduction to Coronal Mass Ejections

Sudden, large eruption of the solar atmosphere into interplanetary space:

A billions tons of matter ($10^{15\text{-}16}$ g) at a million miles per hour (~1000 km/s)!



Introduction to Coronal Mass Ejections

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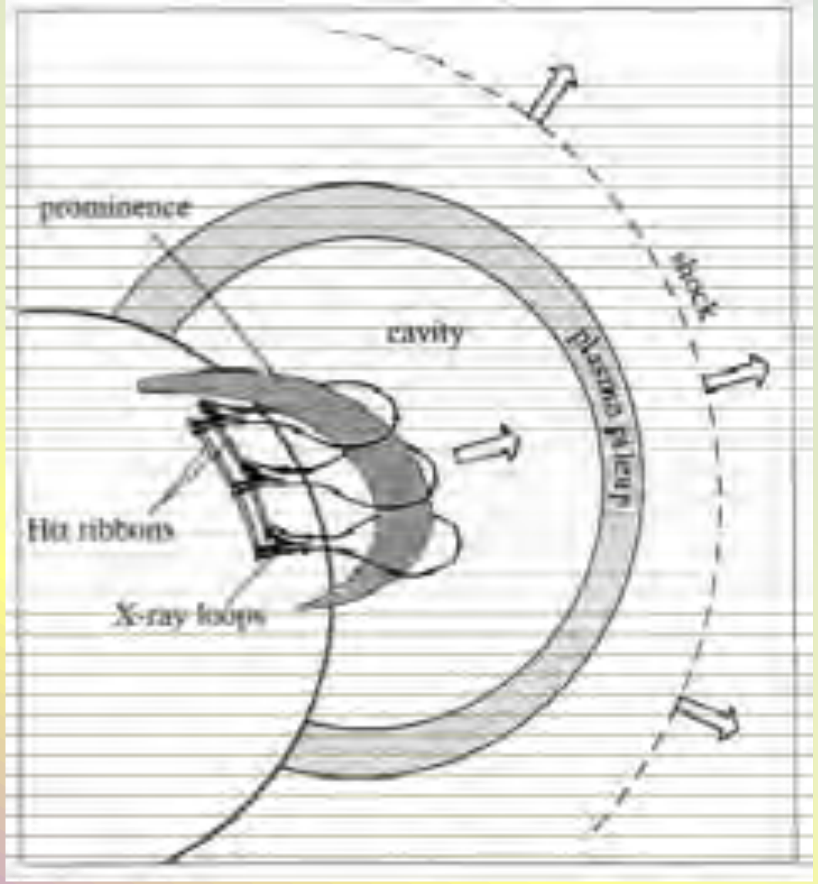
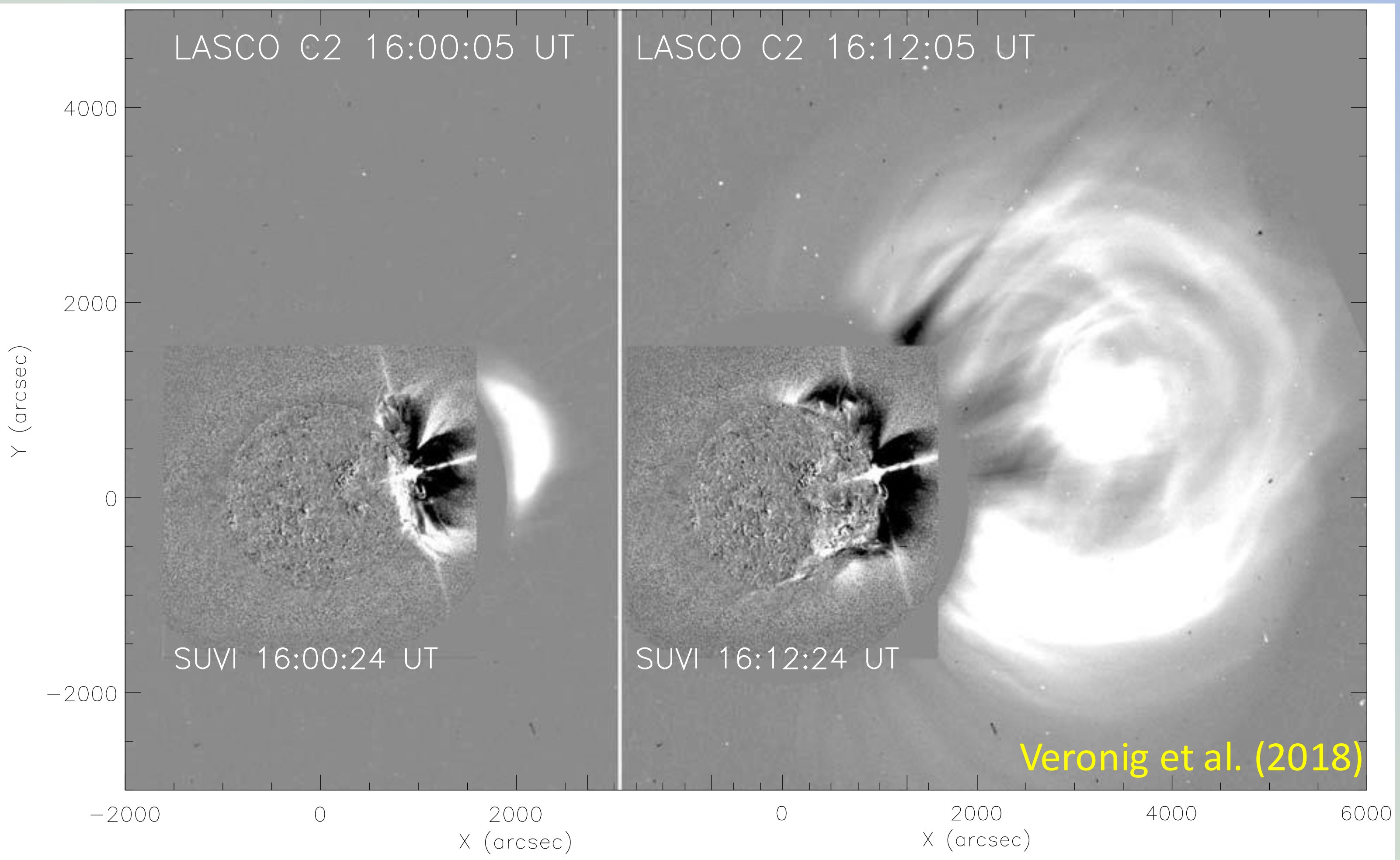
CMEs typically have a 3-part structure in white light: (1) leading edge enhancement, (2) dark cavity, (3) bright core

Often drive coronal and/or interplanetary shocks!

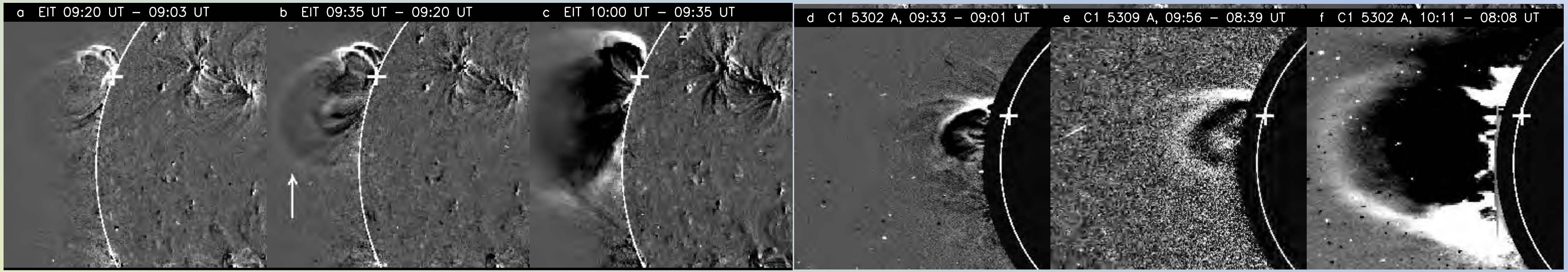


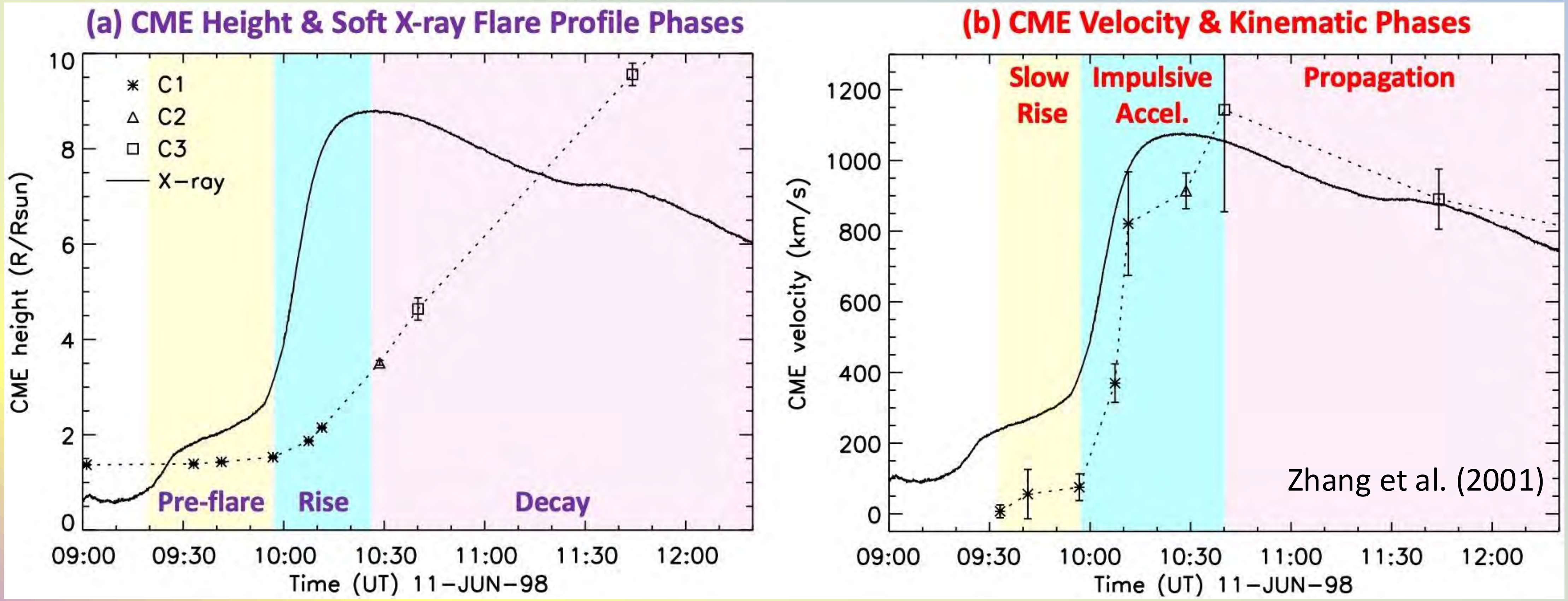
Forbes (2000)



Veronig et al. (2018)

Introduction to Coronal Mass Ejections





CME INITIATION – What Erupts?

- **CORONAL MAGNETIC FIELD AND PLASMA!**
  Must be energetically favorable for field and plasma to erupt and take out a substantial portion of the overlying solar atmosphere

→ Magnetic energy is the only viable source!

Forbes (2000)

Table 1. Energy Requirements for a Moderately Large CME

Parameter	Value
Kinetic energy (CME, prominence, and shock)	10^{32} ergs
Heating and radiation	10^{32} ergs
Work done against gravity	10^{31} ergs
Volume involved	10^{30} cm^3
Energy density	100 ergs cm^{-3}

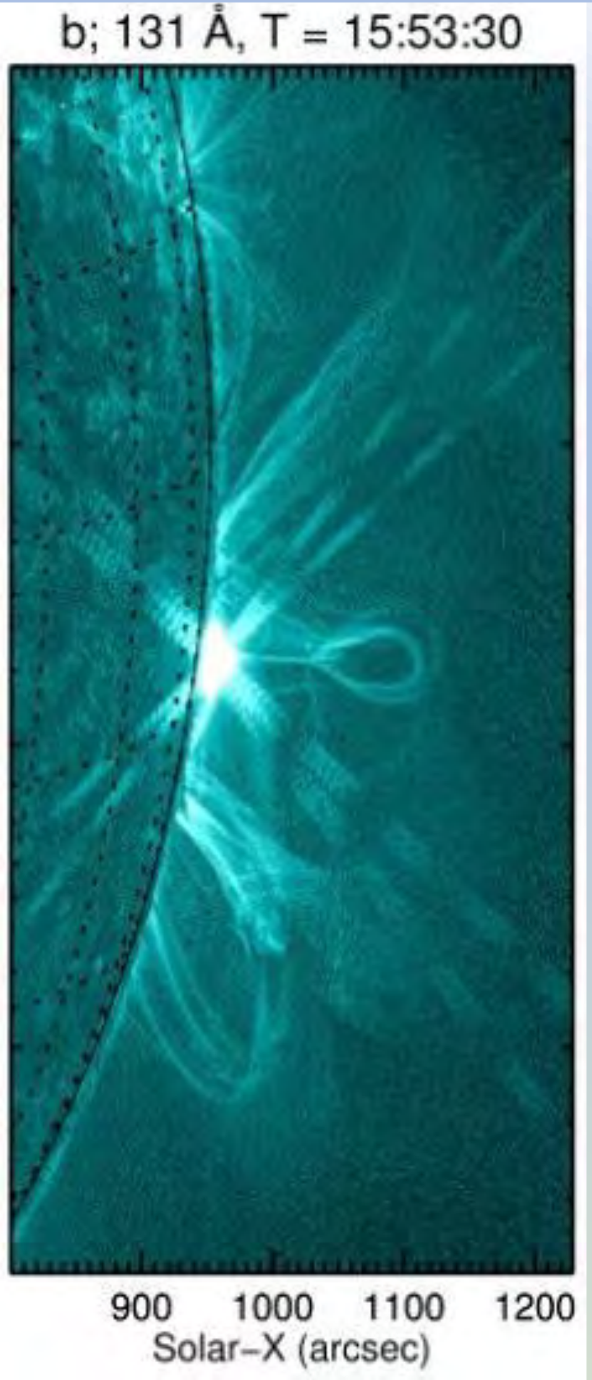
Table 2. Estimates of Coronal Energy Sources

Form of Energy	Observed Average Values	Energy Density ergs cm^{-3}
Kinetic ($(m_p n V^2)/2$)	$n = 10^9$ cm^{-3}, $V = 1$ km s^{-1}	10^{-5}
Thermal (nkT)	$T = 10^6$ K	0.1
Gravitational ($m_p n g h$)	$h = 10^5$ km	0.5
Magnetic ($B^2/8\pi$)	$B = 100$ G	400

CMEs are a problem of *magnetic energy storage and release*

→ gradual/slow STORAGE

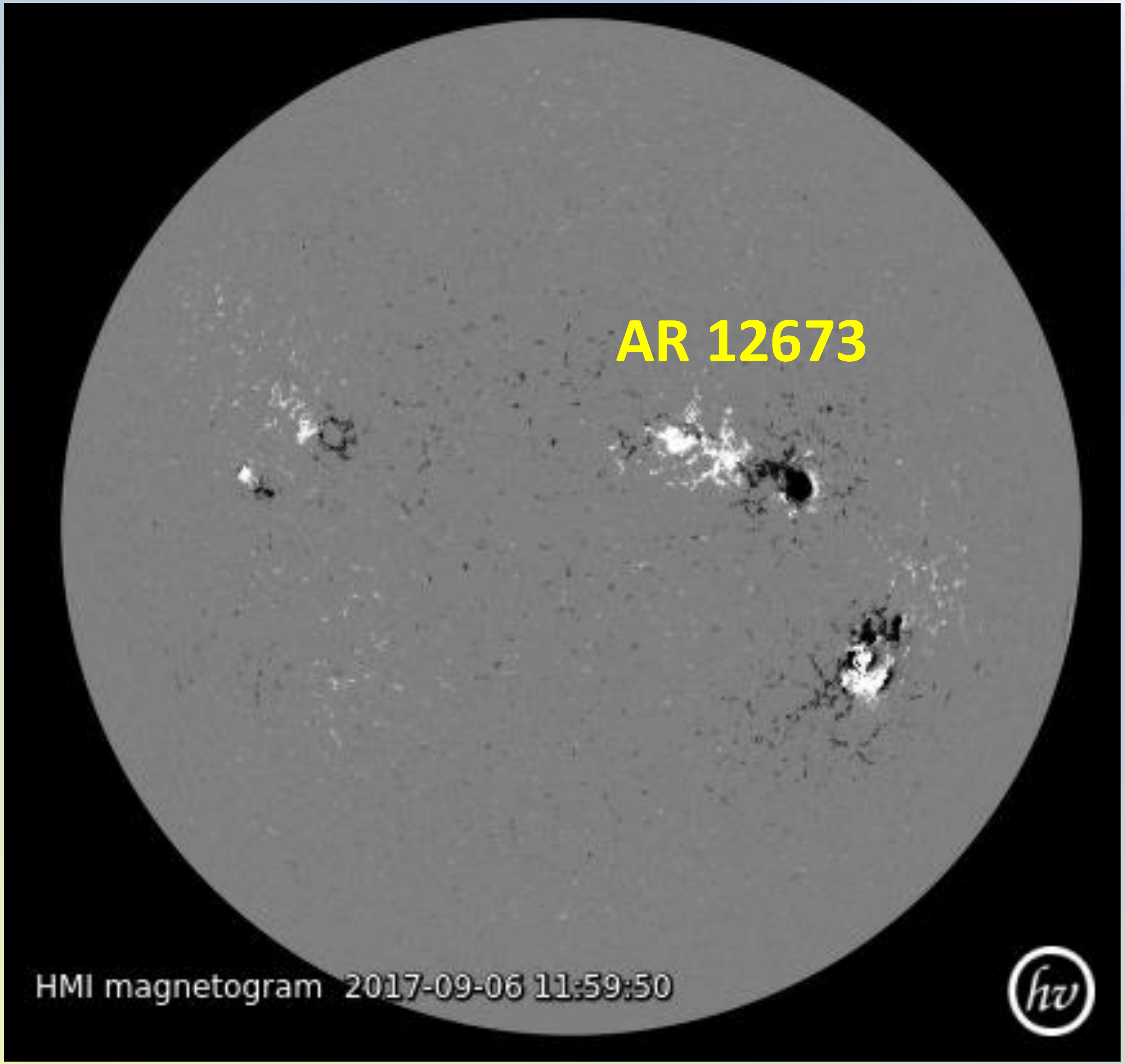
→ rapid/fast RELEASE



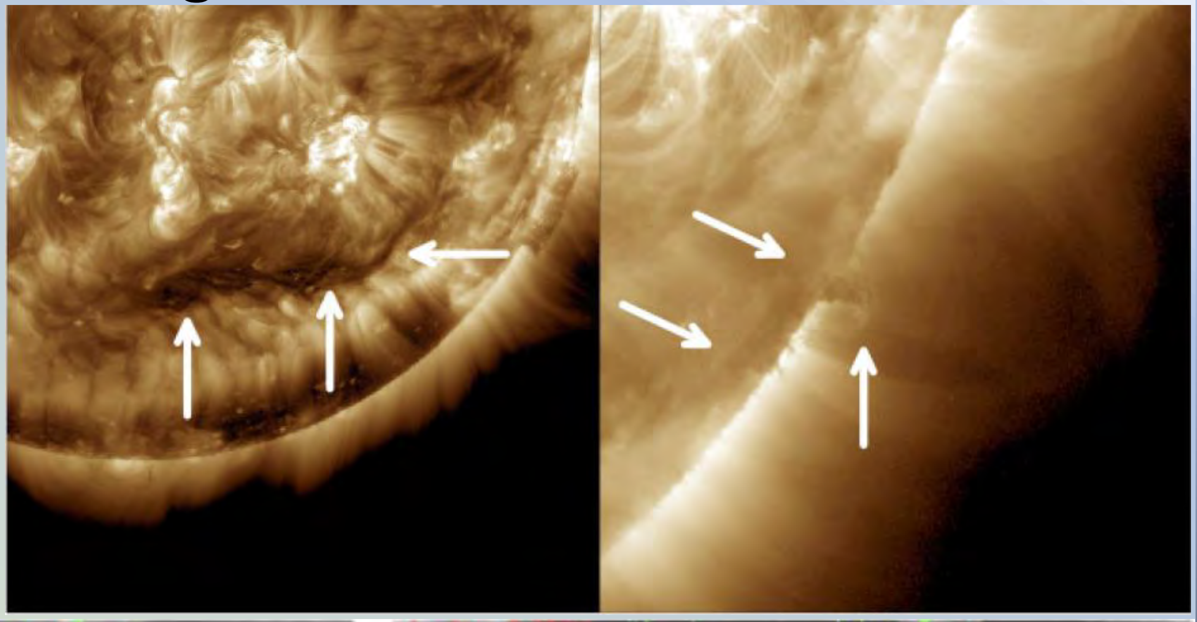
Magnetic Structure of the Filament Channel / Energized Polarity Inversion Line (PIL)

Most flares/CMEs originate in solar active regions---groups of strong-field sunspots. PILs exist between the two magnetic polarities (sign of B_r). As ARs evolve, shearing motions and/or flux emergence and/or flux cancellation gradually energize strong, low lying fields.

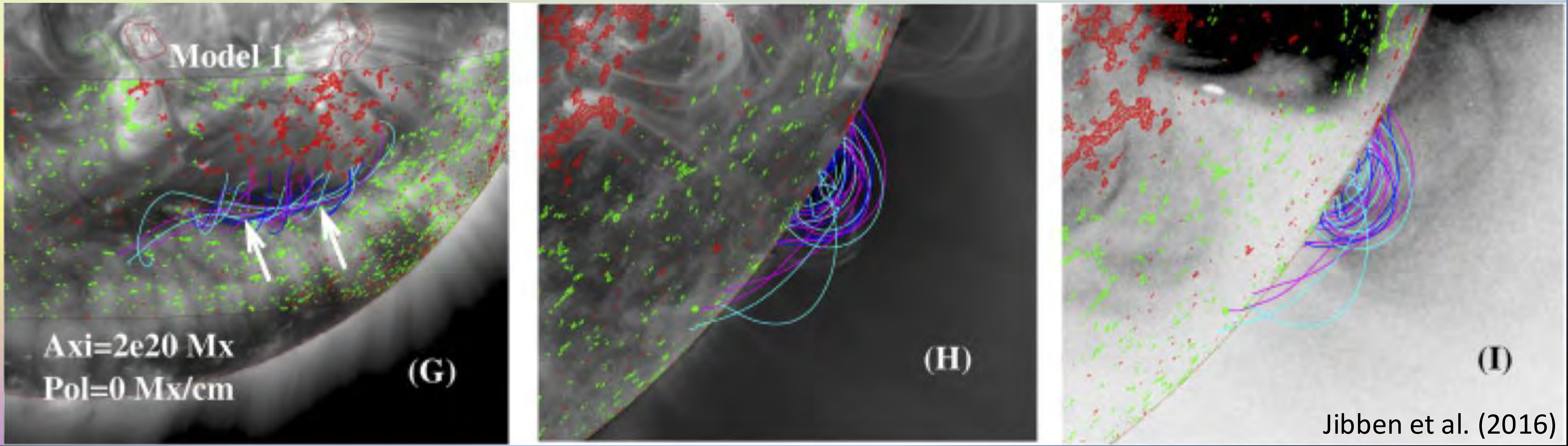
Threshold/instabilities occur, triggering the solar flare+CME rapid release of stored magnetic energy



Magnetic Structure of the Filament Channel / Energized PIL

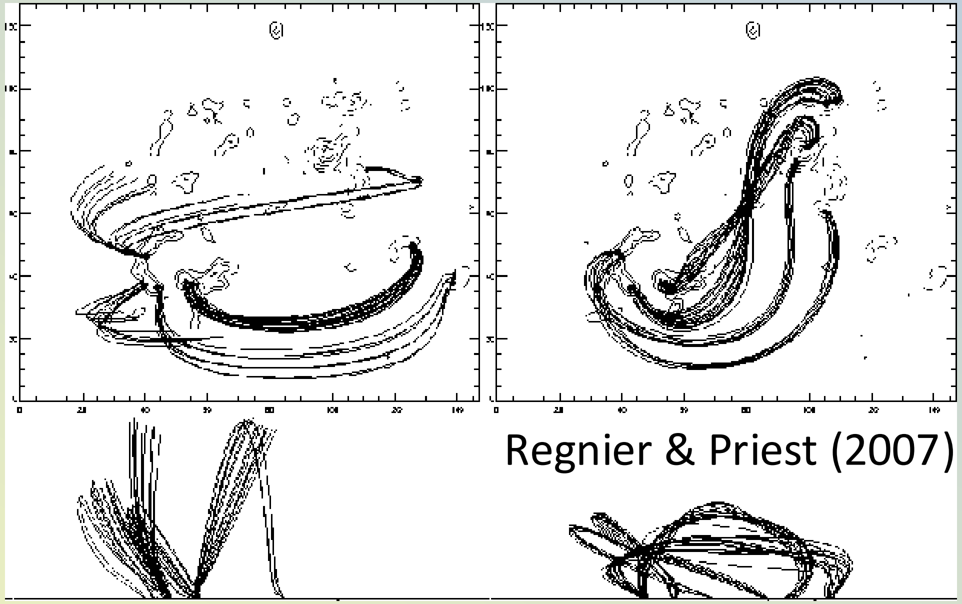


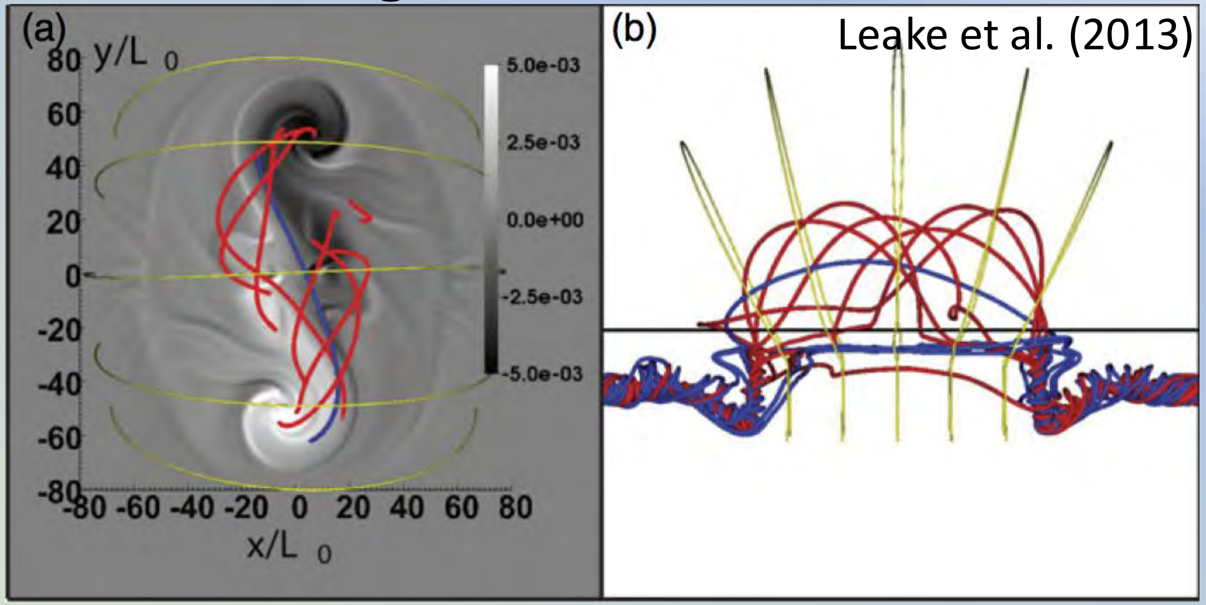
Different models for energized field structures: sheared arcades or weakly twisted flux ropes. CME initiation mechanism(s) only somewhat dependent on details of these structures.

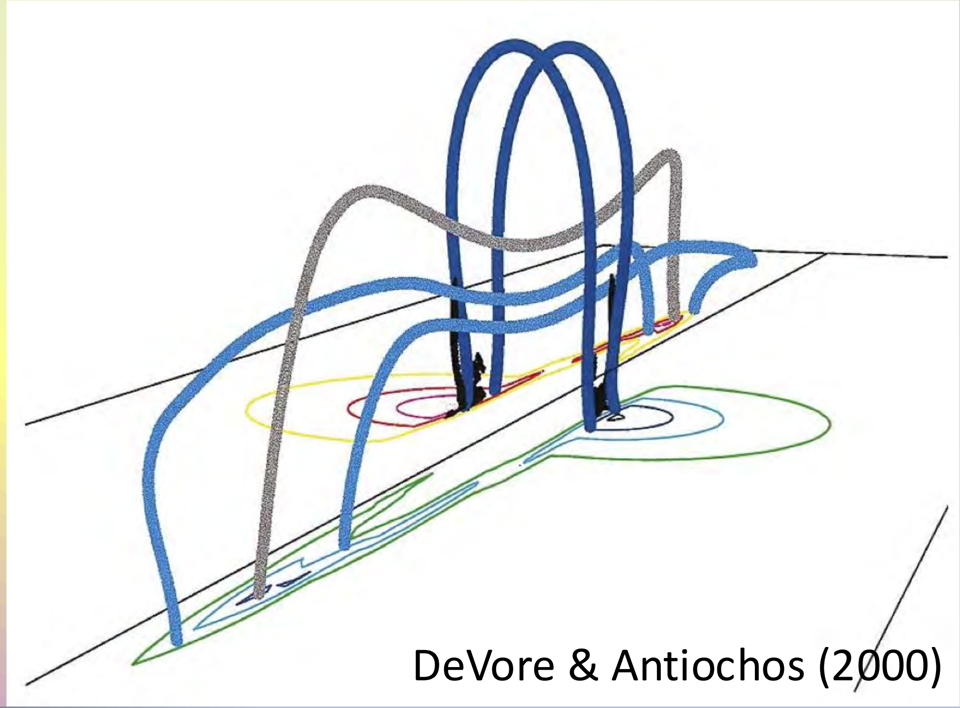


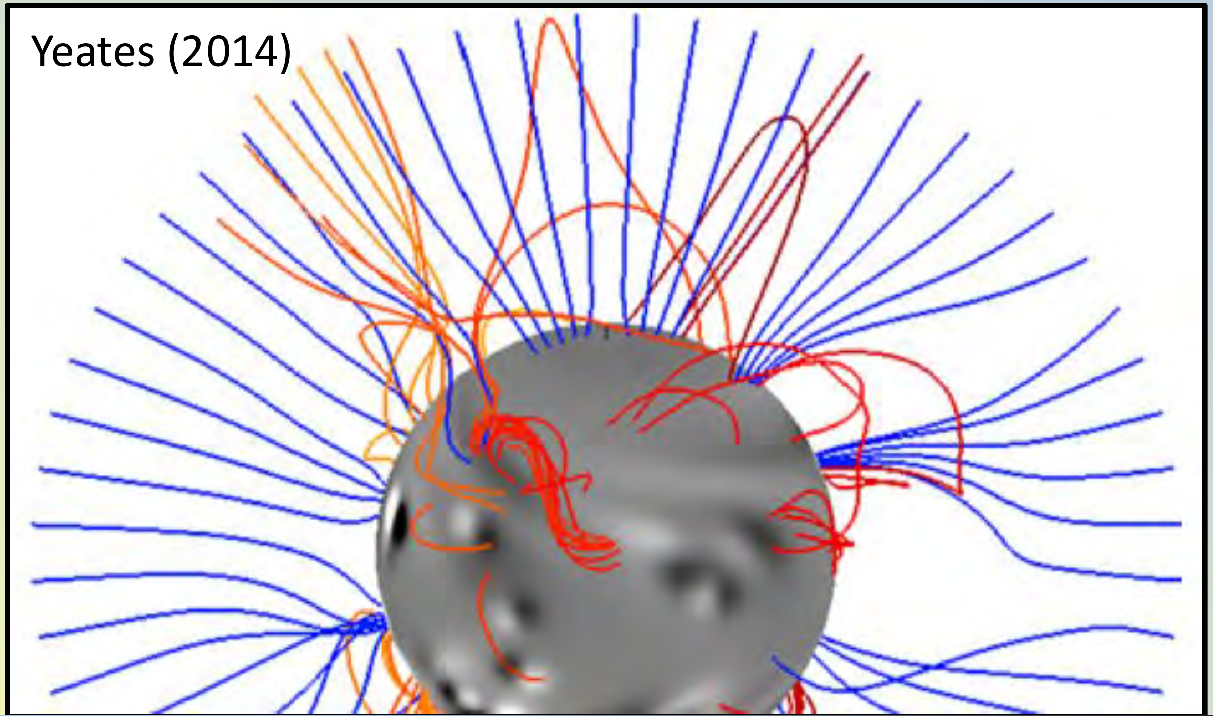
Jibben et al. (2016)

Magnetic Structure of the Filament Channel / Energized PIL



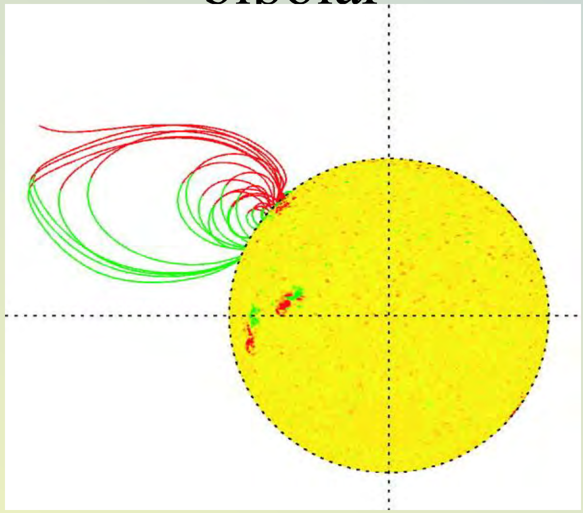


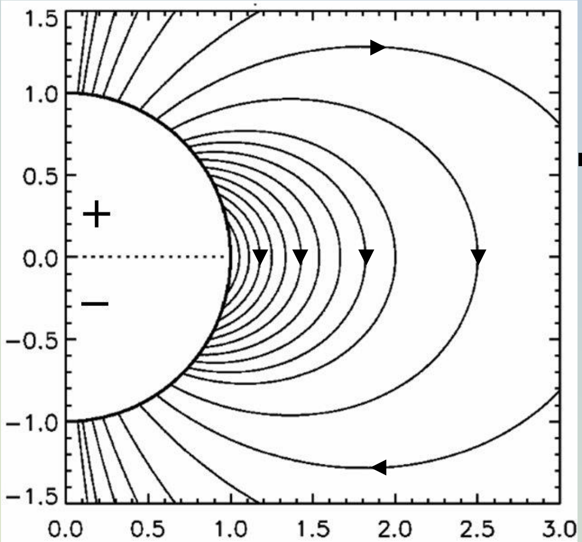


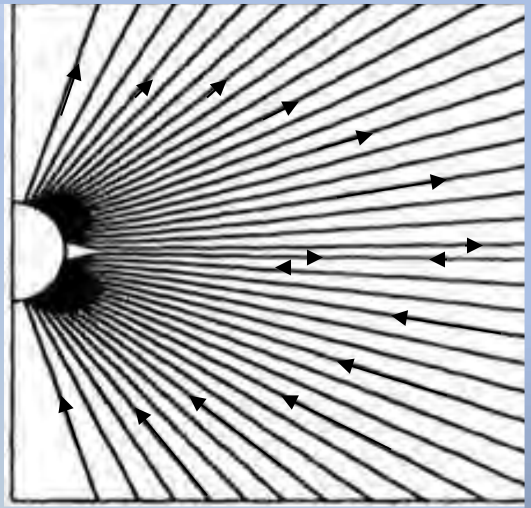


Two Simplest Source Regions → Topology Determines Open State(s)

bipolar

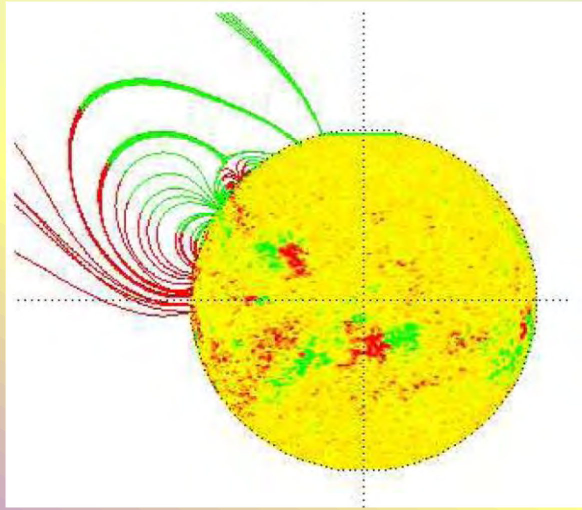


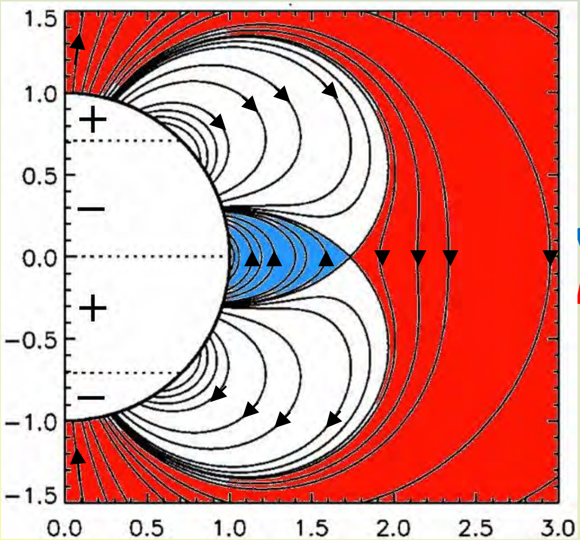




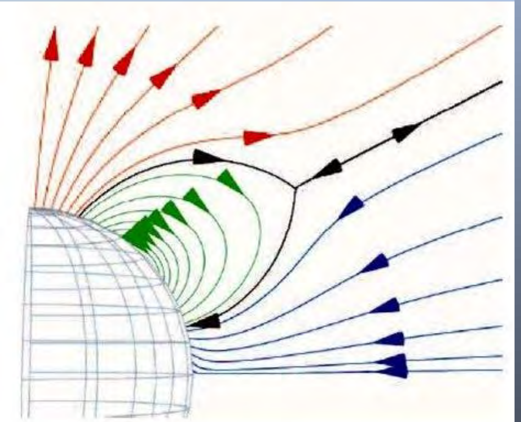
only one Open State possibility

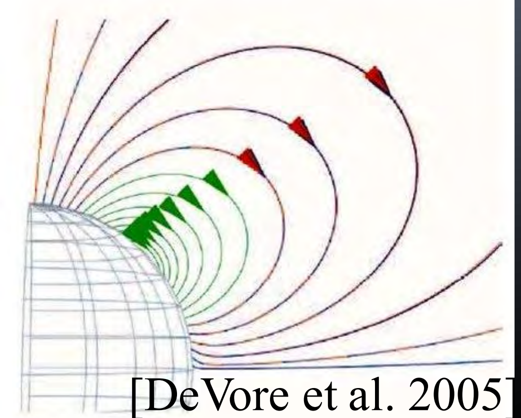
multipolar





ΔE_{mo} : "Maximally Open"
(0% blue-red reconnection)





ΔE_{mc} : "Maximally Closed"
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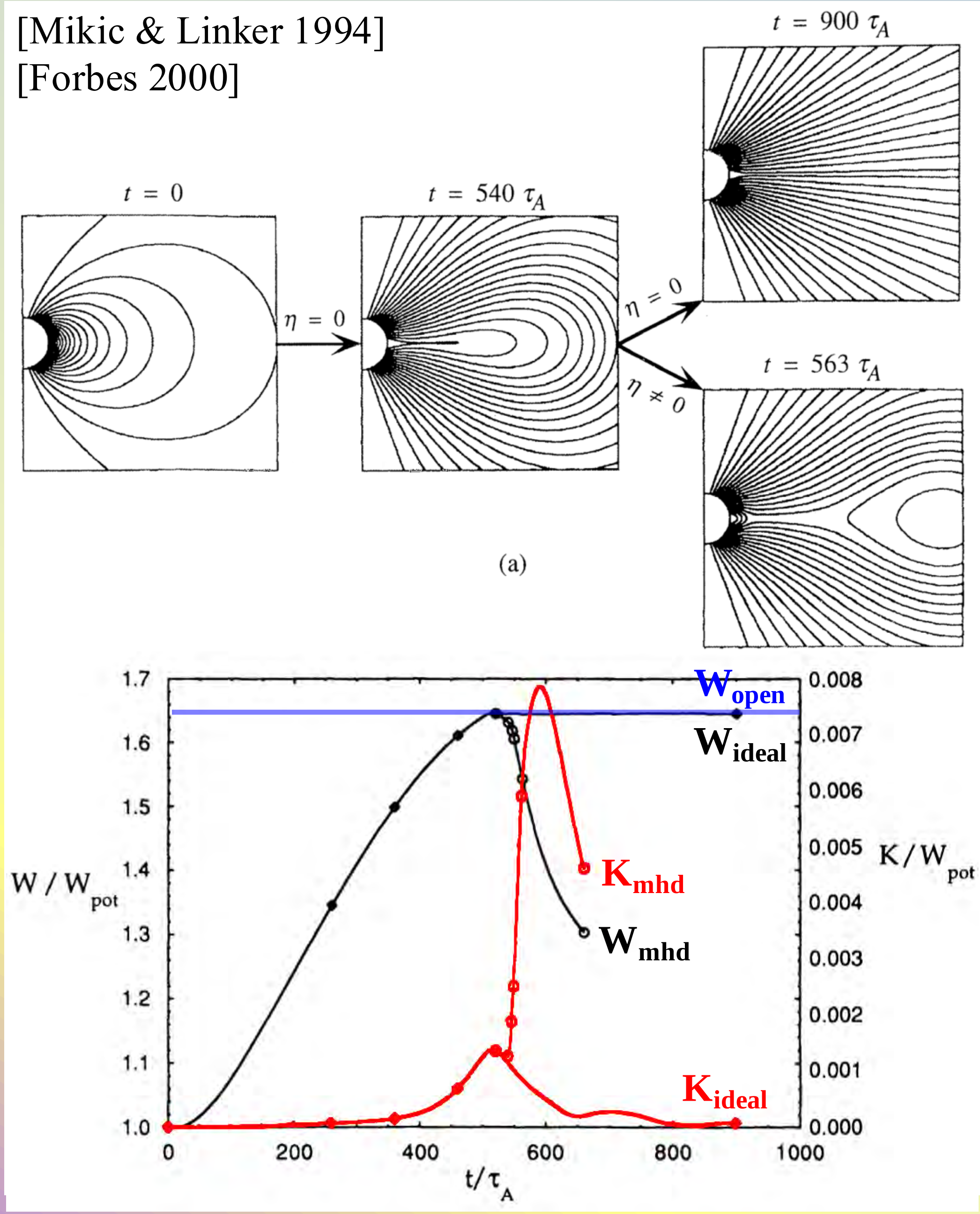
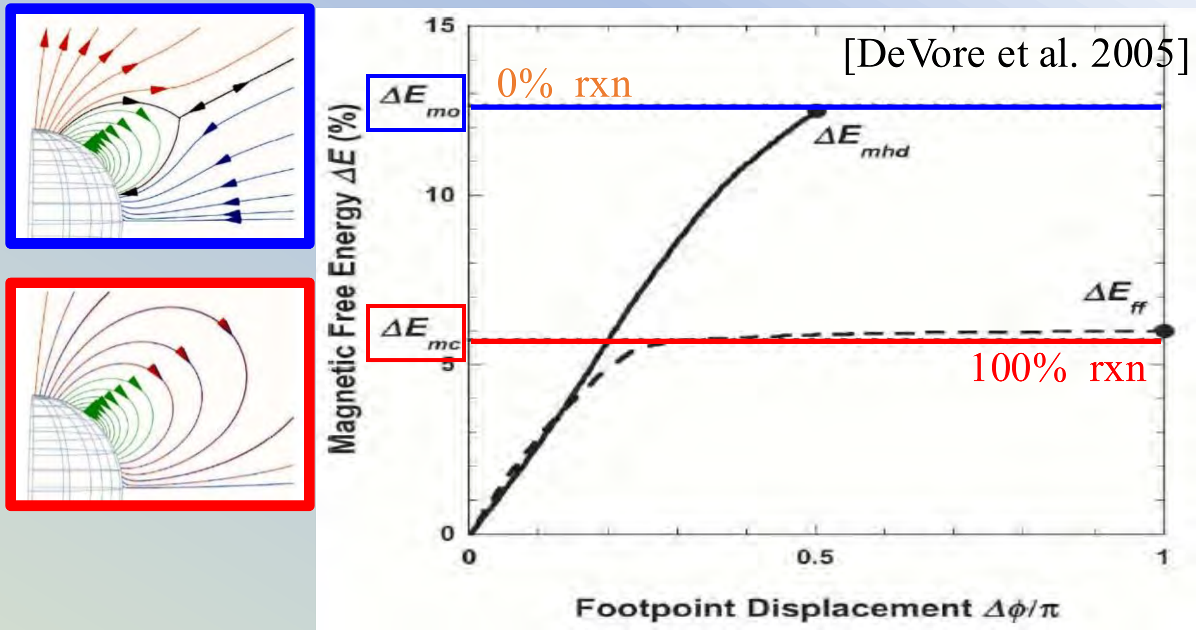
[Li & Luhmann, 2006]

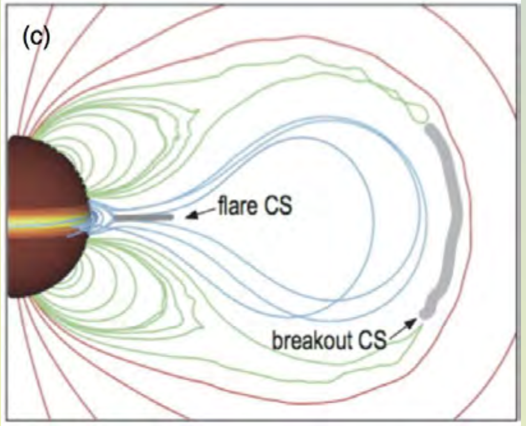
[DeVore et al. 2005]

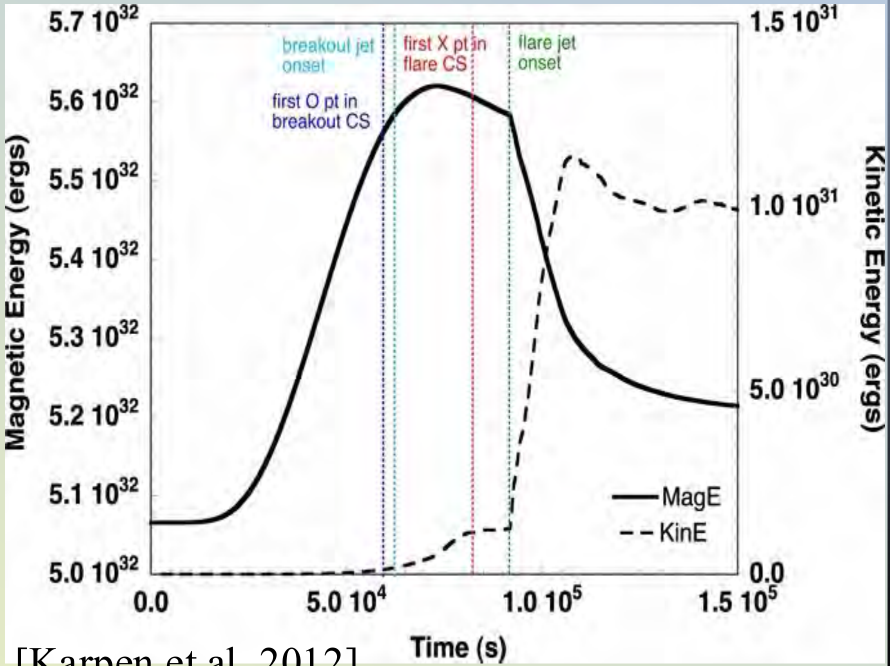
Energy Evolution of Bipolar Configuration (in 2.5D)



Energy Evolution of Multipolar Configuration (in 2.5D)





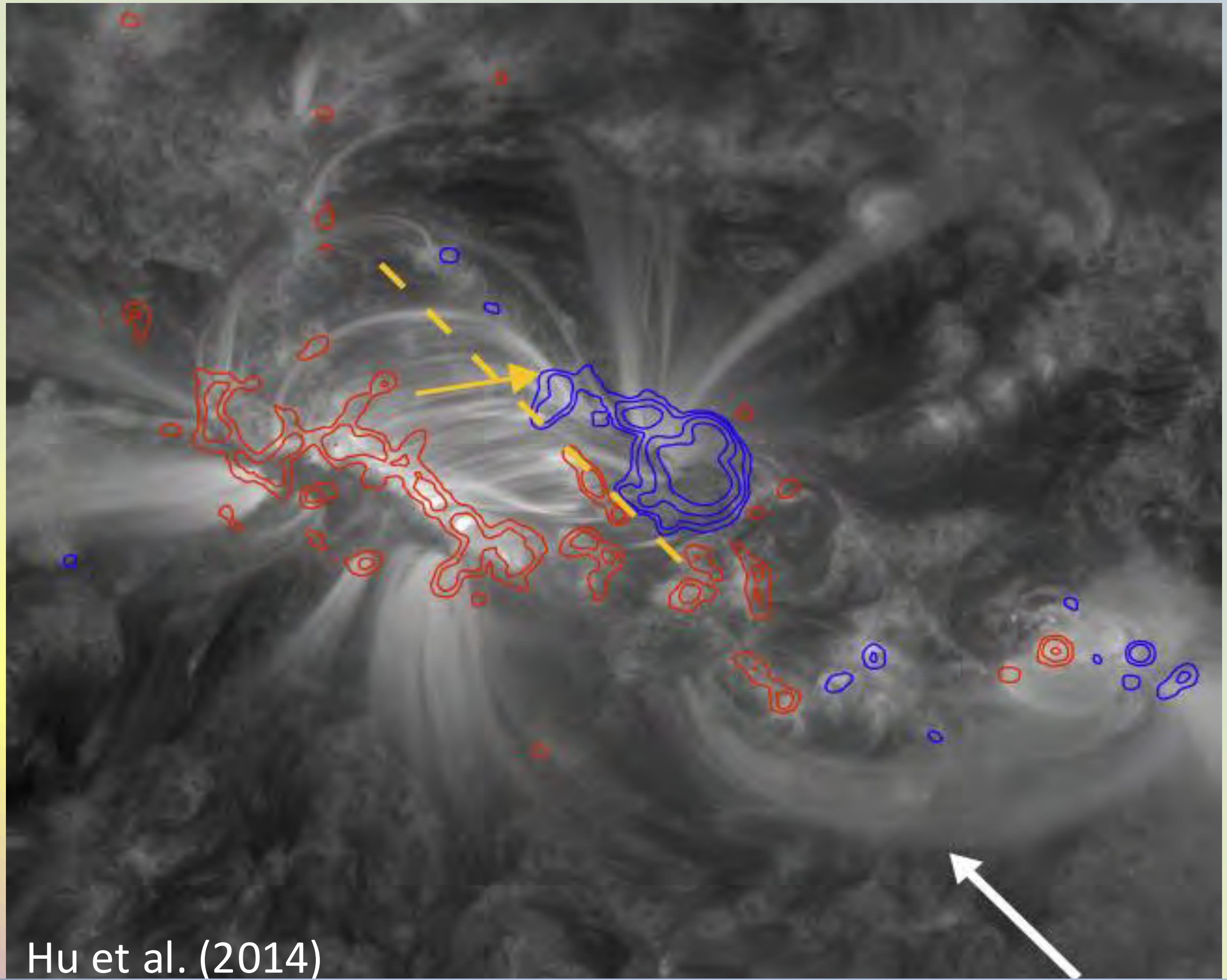


[Karpen et al. 2012]

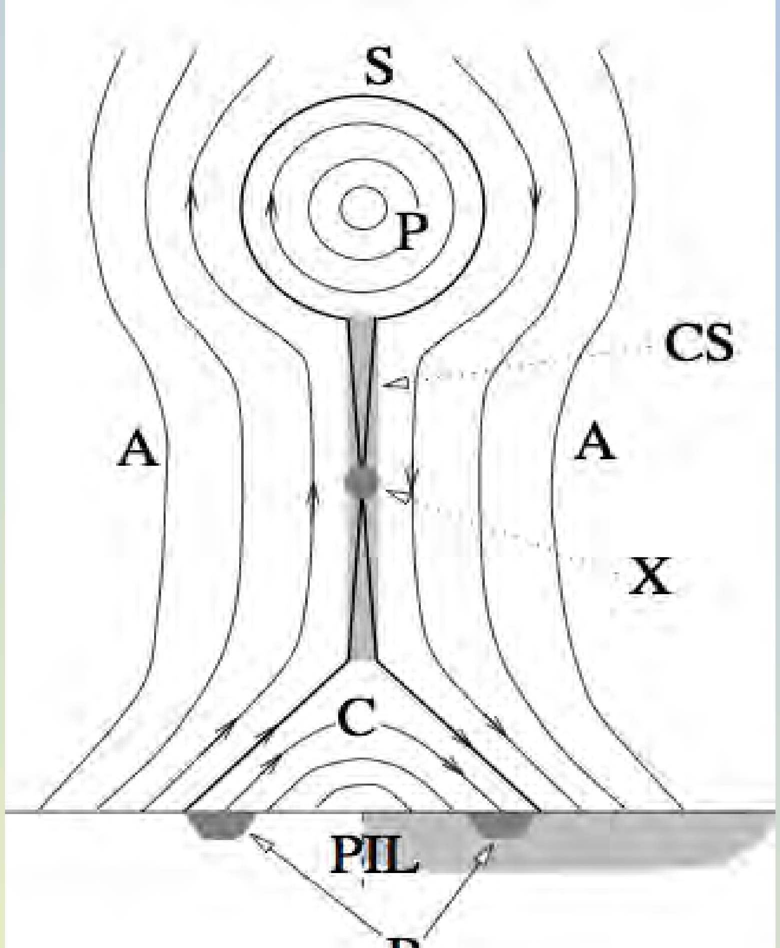
The Standard Model (CSHKP) for Eruptive Flares + CMEs

The long-standing CSHKP model (Carmichael 1964; Sturrock 1966; Hirayama 1974; Kopp & Pneuman 1976) for eruptive solar flares explains many of their generic observed properties

Eruptive flare reconnection builds both the flare-loop arcade and supplies erupting structure with mass, momentum, and magnetic flux

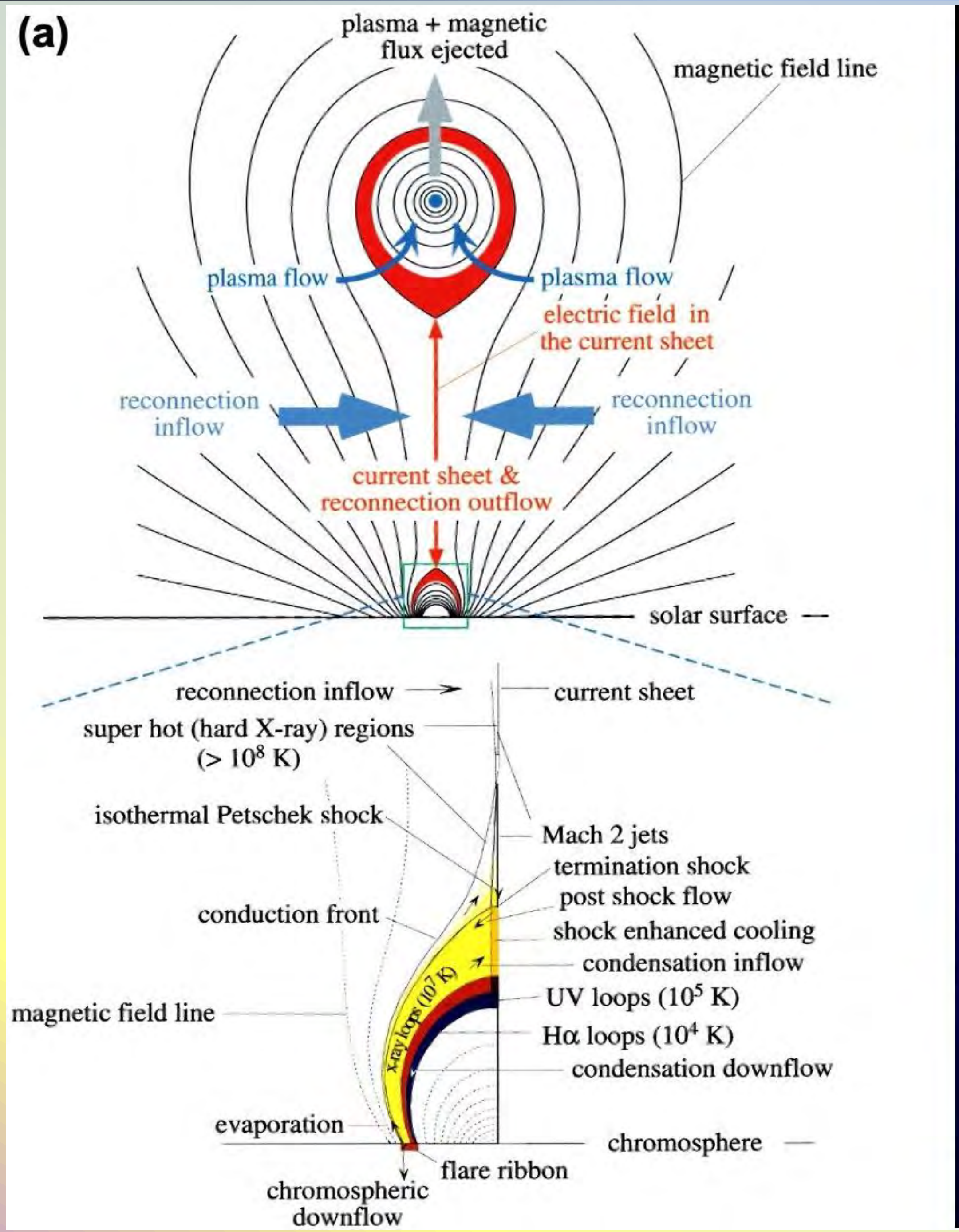


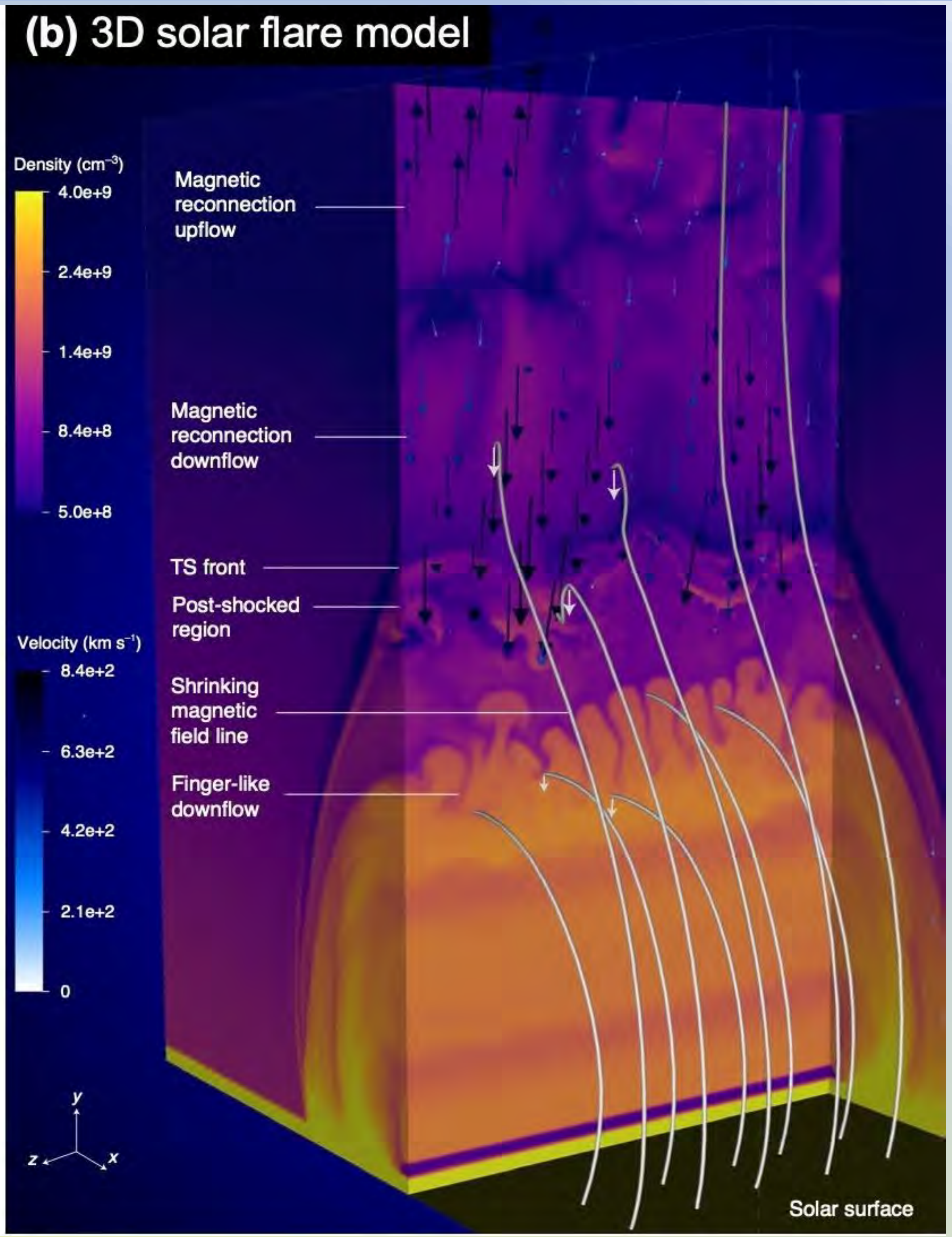
Hu et al. (2014)



Forbes (2000)

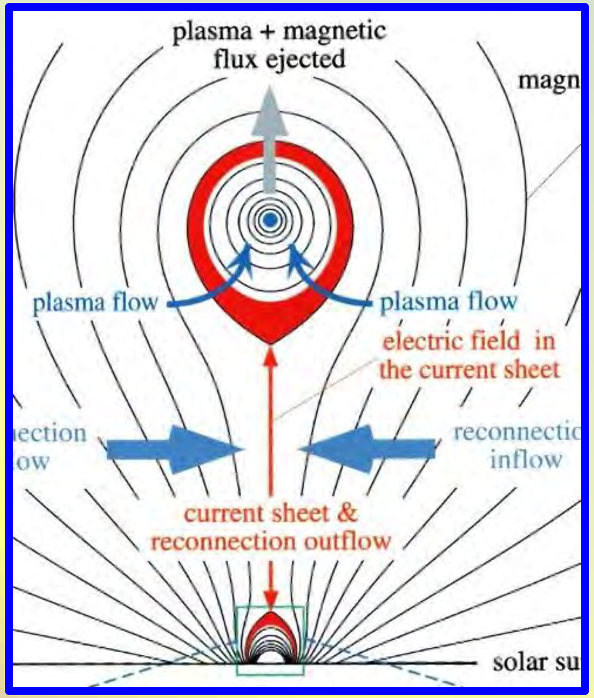
Lin and Forbes (2004)

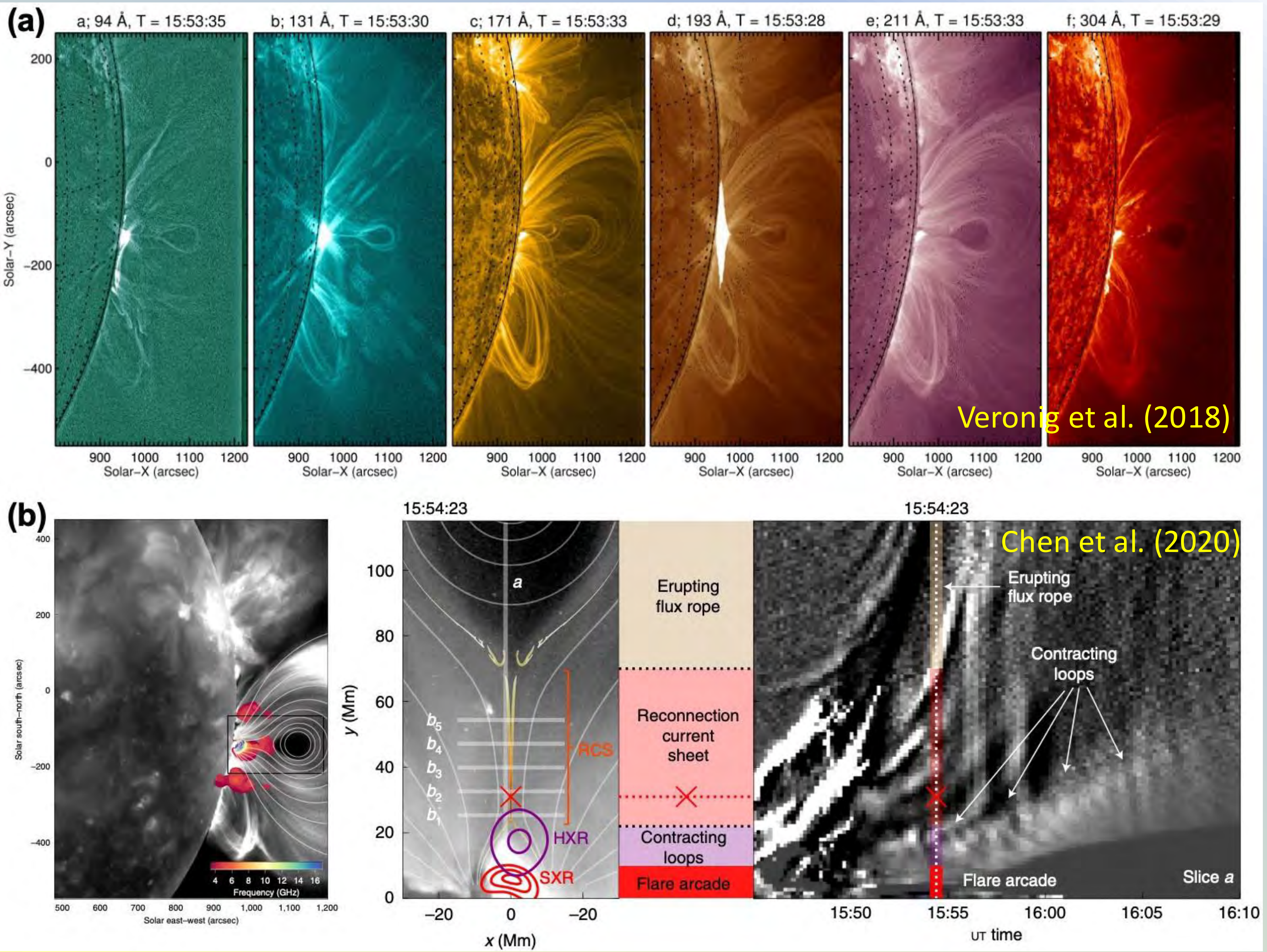




Shen et al. (2022)

How well does the ~50-year old CSHKP model work?





Surprisingly well!

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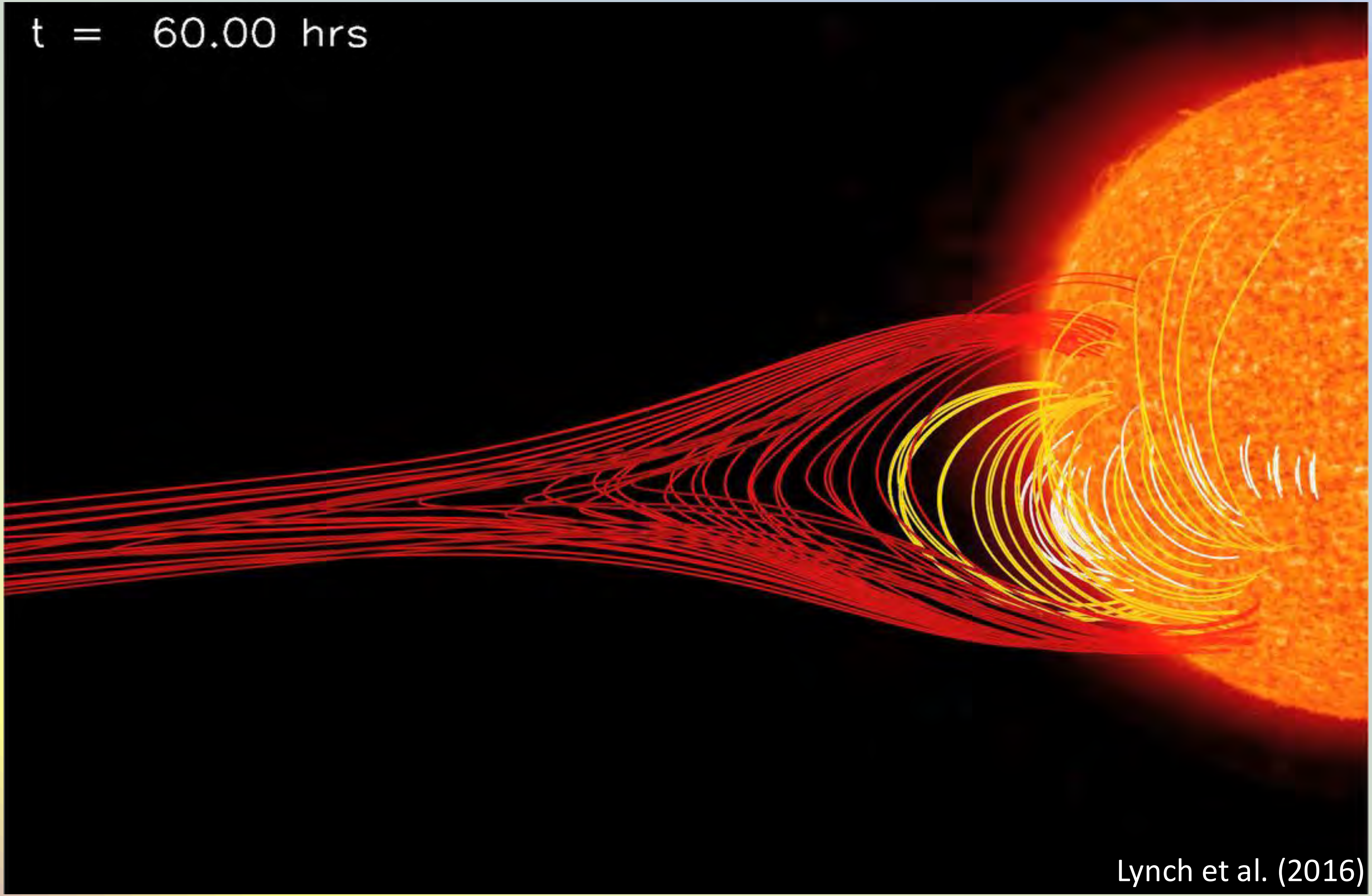


Lynch et al. (2016)

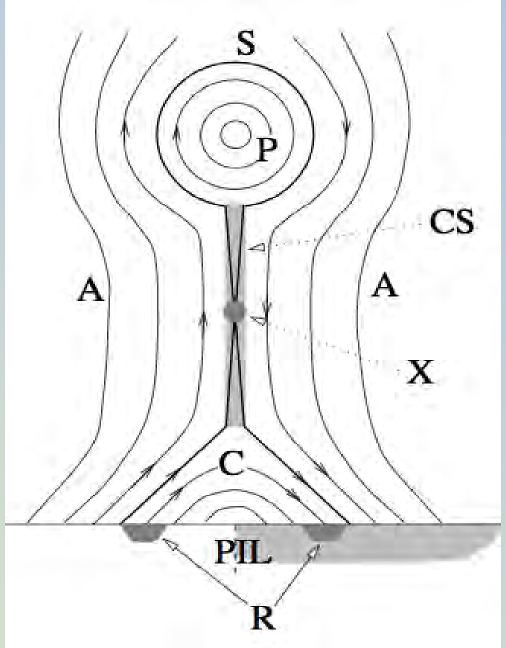
Flare reconnection flux in the standard (CSHKP) model

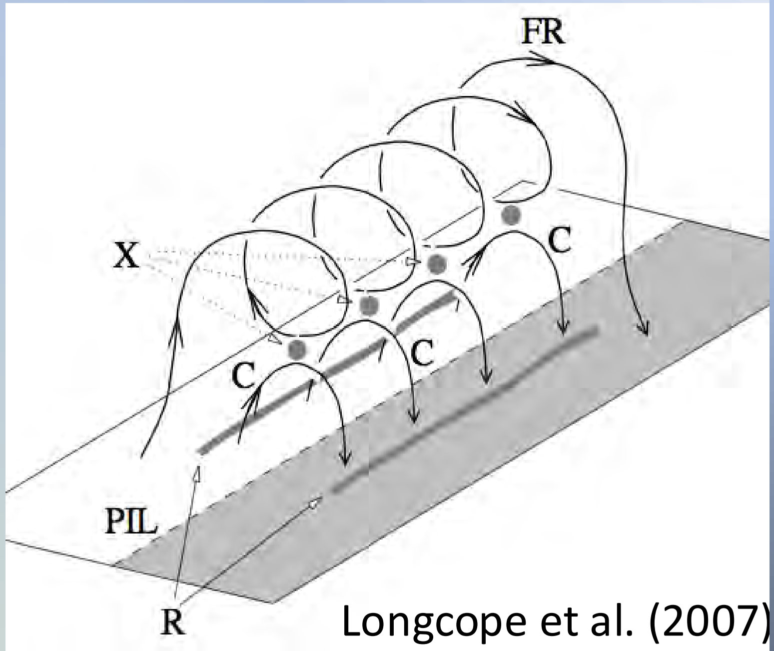
- Quantitative relationship between observed flux swept by flare ribbons and unobserved coronal flux processed through (eruptive) flare reconnection

$$\frac{\partial \Phi}{\partial t} = \frac{\partial}{\partial t}\int B_c\, dS_c = \frac{\partial}{\partial t}\int B_{\rm n}\, dS_{\rm ribbon}.$$

$$\Phi_{\rm ribbon} = \int (\partial\Phi/\partial t)\, dt = \int B_{\rm n} dS_{\rm ribbon}$$

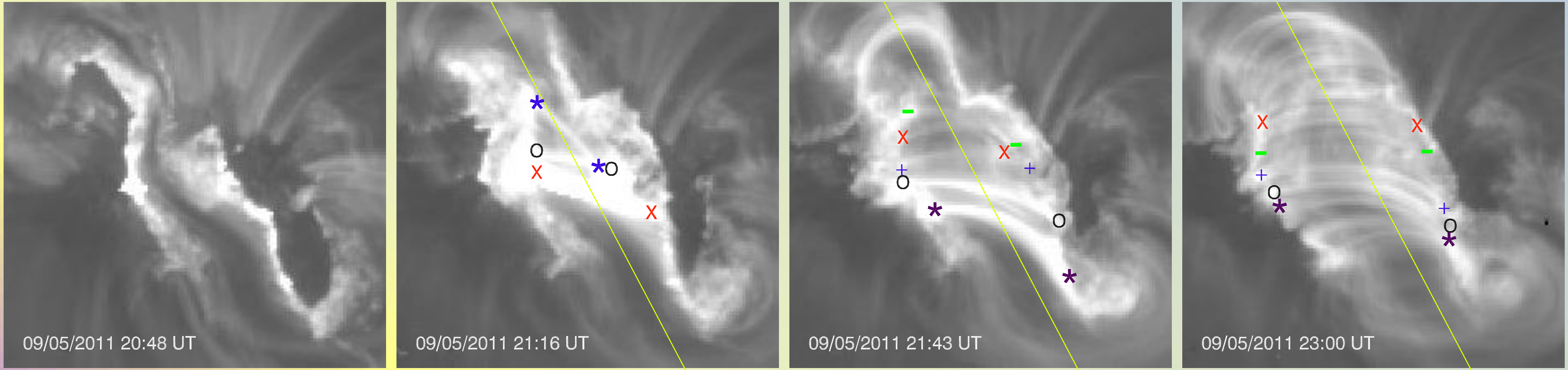
Forbes (2000)





Longcope et al. (2007)

Aulanier et al. (2012)



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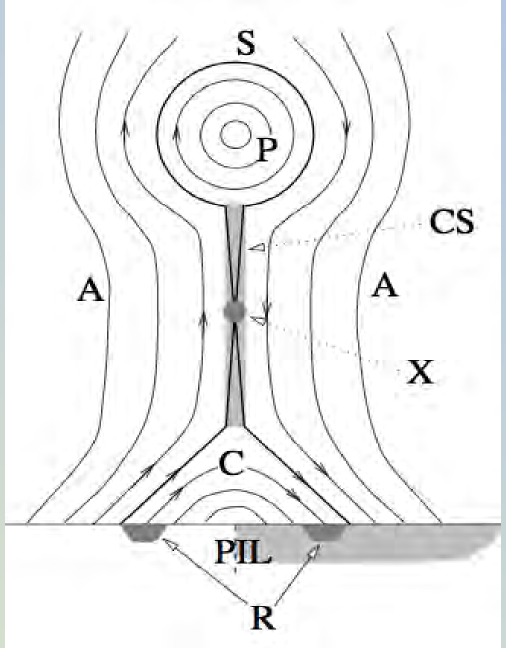
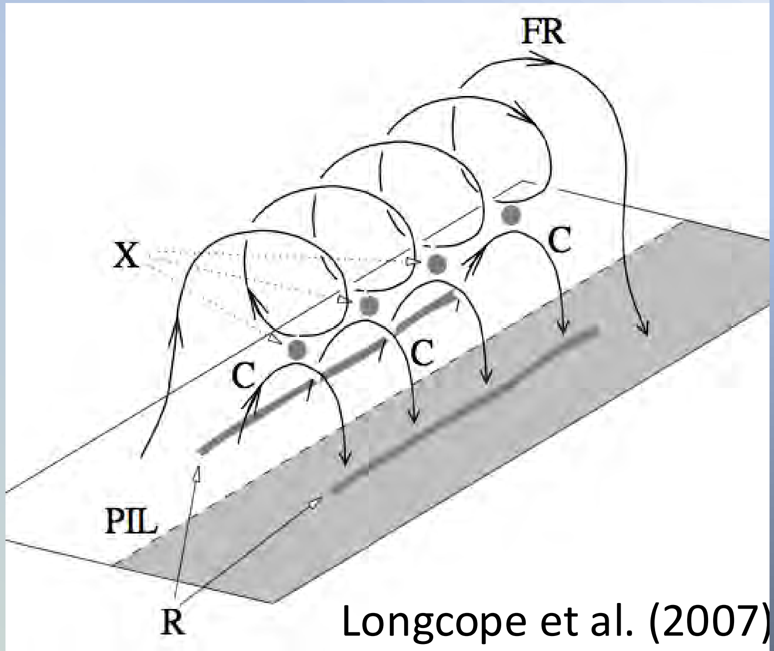
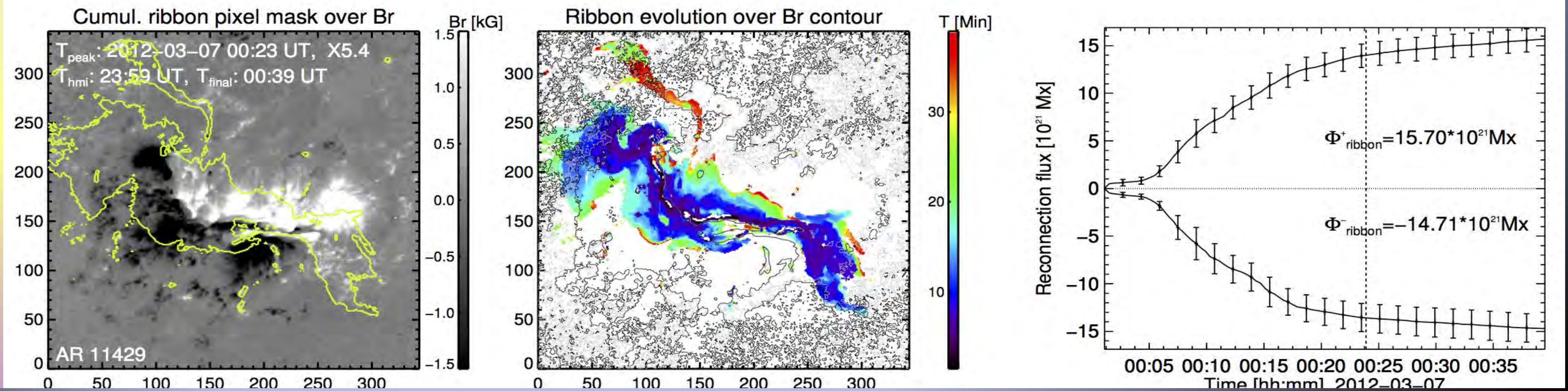
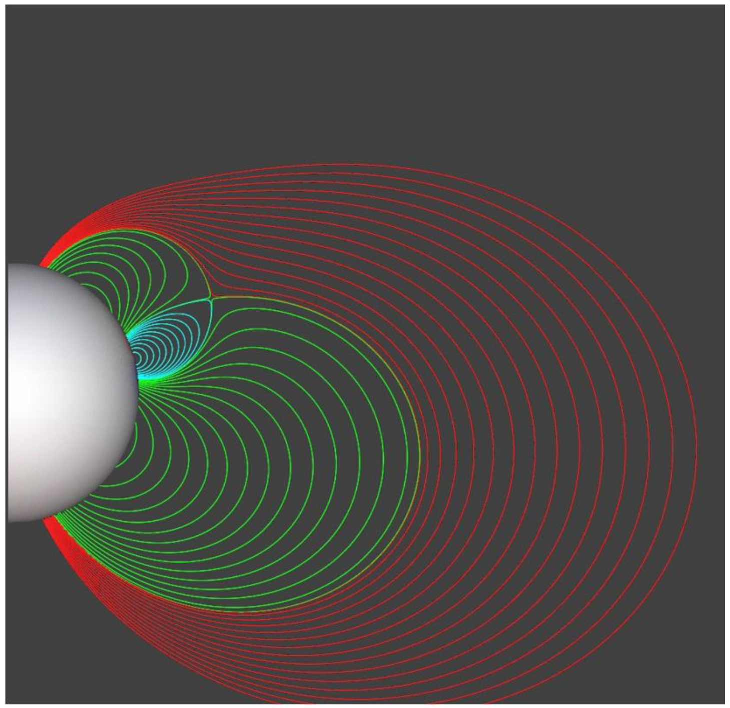


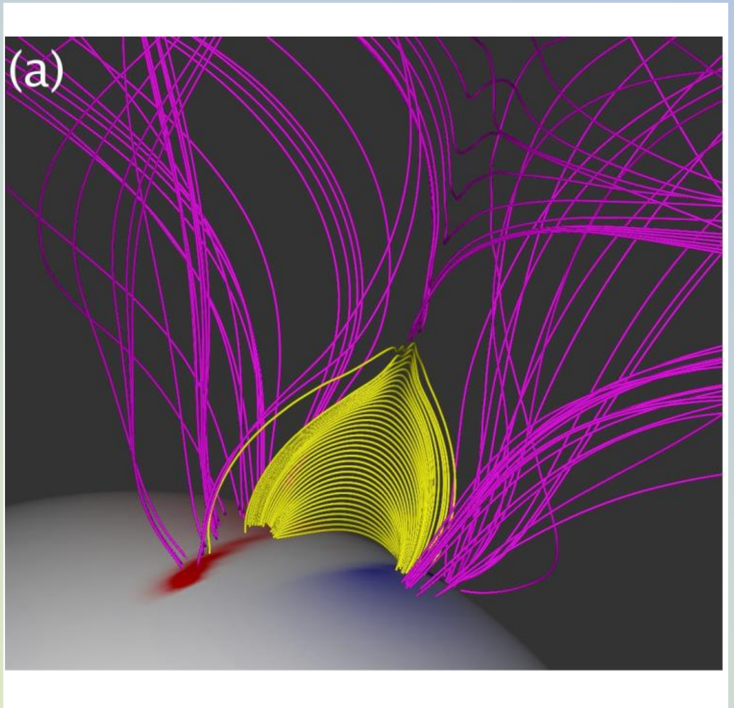


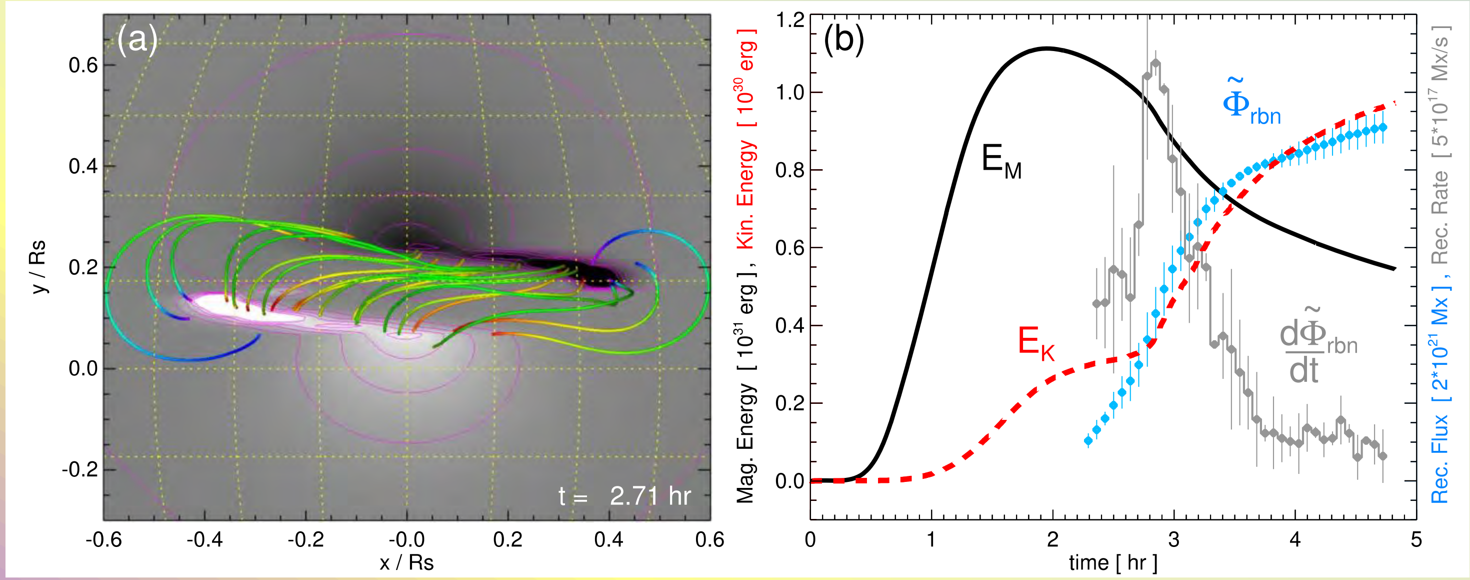
Longcope et al. (2007)

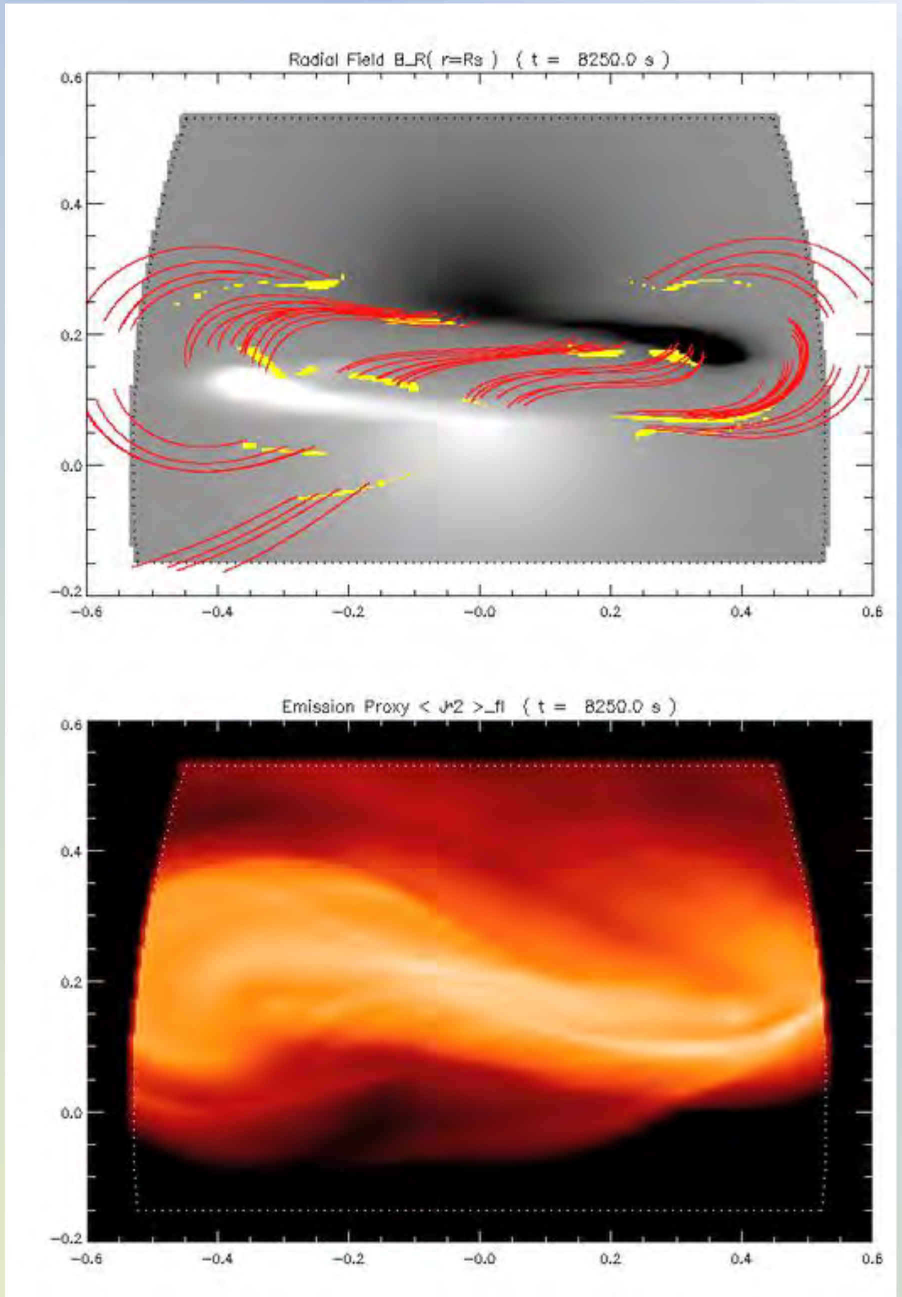
Kazachenko et al. (2017)





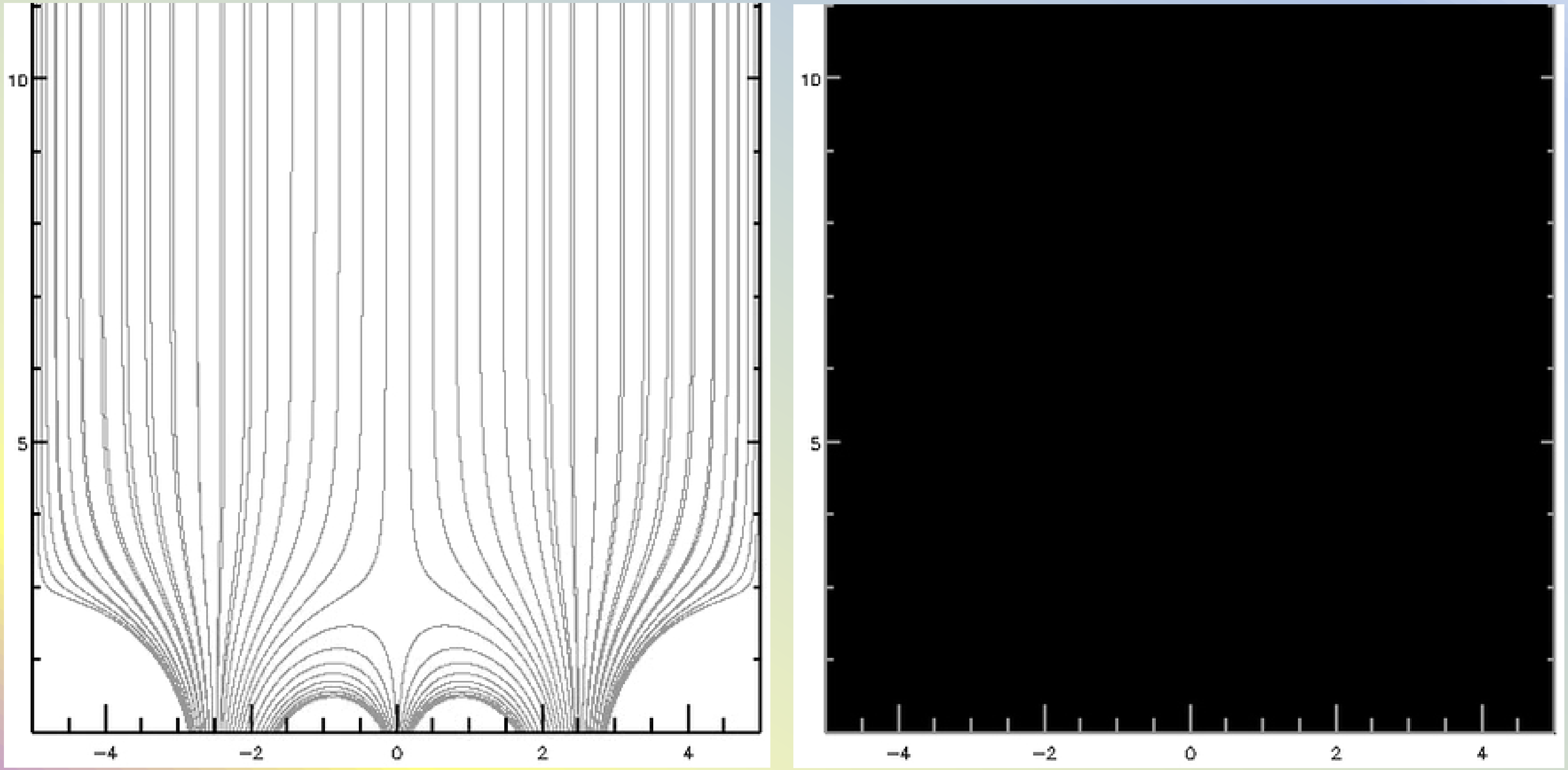

(a)


(a)
y / Rs
x / Rs
t = 2.71 hr
(b)
E_M
E_K
$\tilde{\Phi}_{rbn}$
$\frac{d\tilde{\Phi}_{rbn}}{dt}$
Mag. Energy [10^{31} erg], Kin. Energy [10^{30} erg]
Rec. Flux [$2*10^{21}$ Mx], Rec. Rate [$5*10^{17}$ Mx/s]
time [hr]


Radial Field B_R(r=Rs) (t = 8250.0 s)
Emission Proxy < J^2 >_fl (t = 8250.0 s)

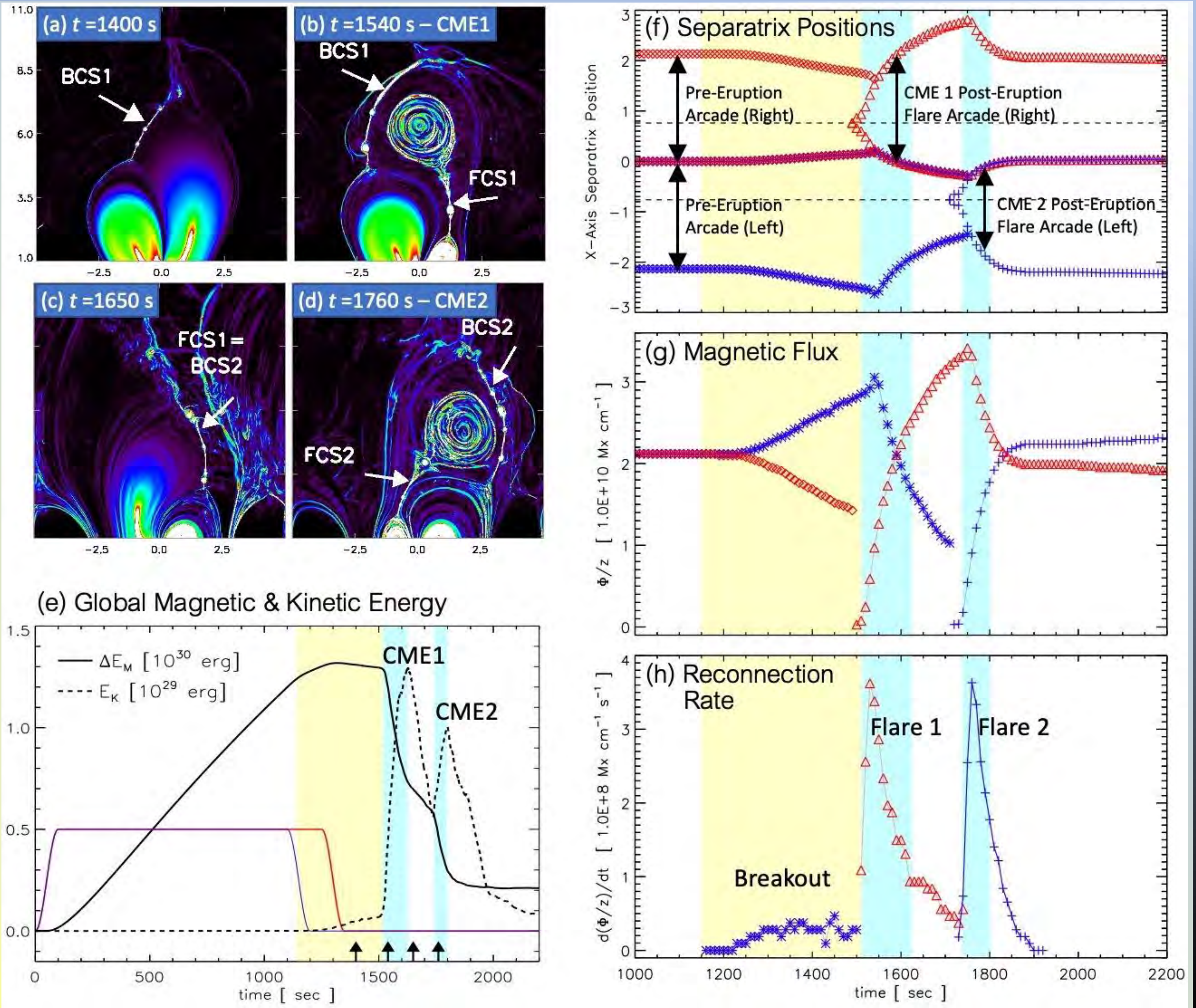
When the source region and eruption is complex?

Sympathetic CME eruptions from a coronal pseudostreamer topology [Lynch & Edmondson 2013]

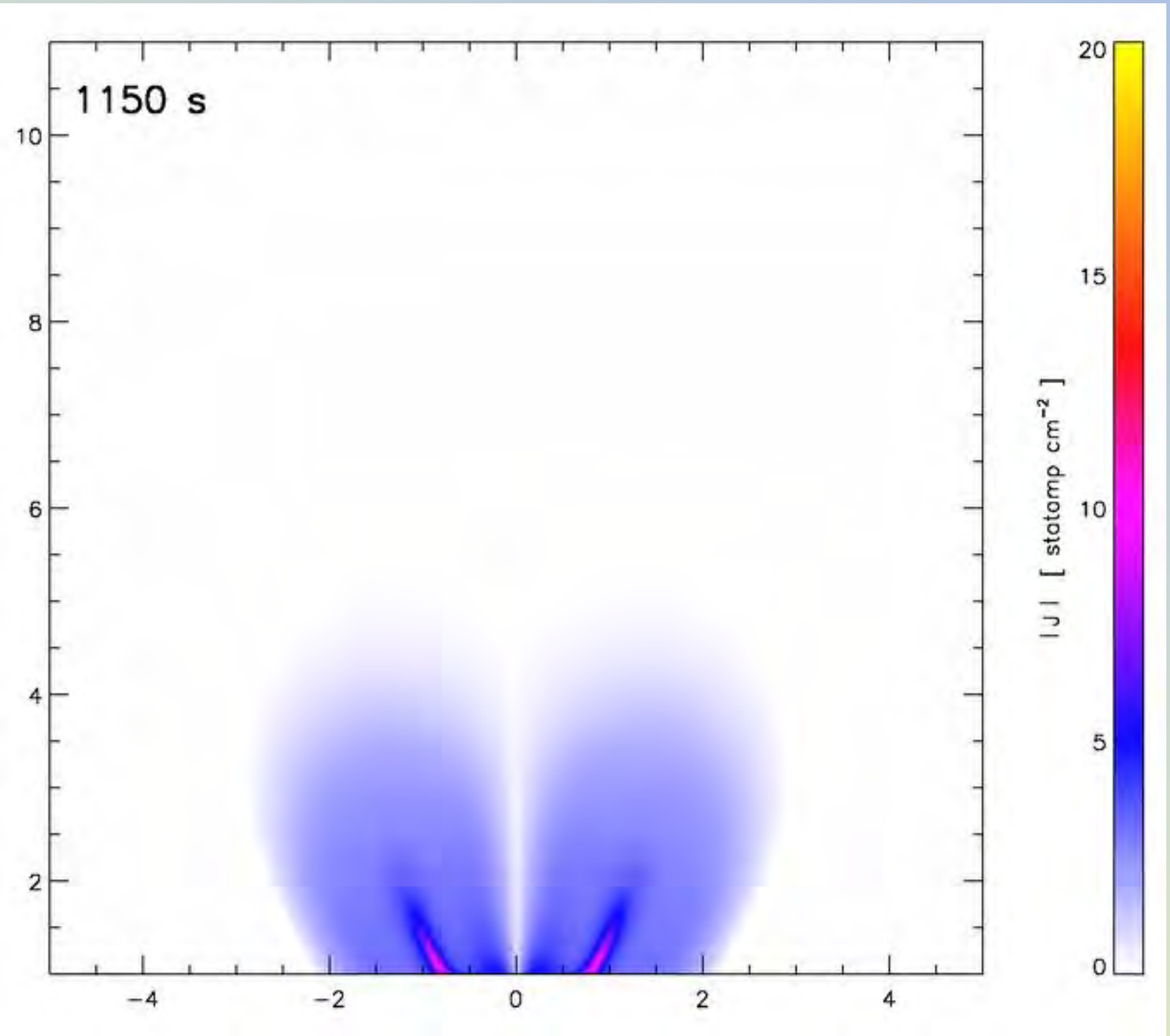


Understanding Sympathetic CME Eruptions via Magnetic Reconnection

- Separatrix motion illustrates magnetic reconnection dynamics and flux transfer
- Quantify reconnection rate
- Direct correspondence between reconnection and global energy evolution (ME, KE). *NOTE SLOW RISE AND IMPULSIVE ACCELERATION PHASE(S) IN EACH CASE.*



Magnetic Reconnection – Plasmoids Everywhere!



(Lynch et al. 2016a)

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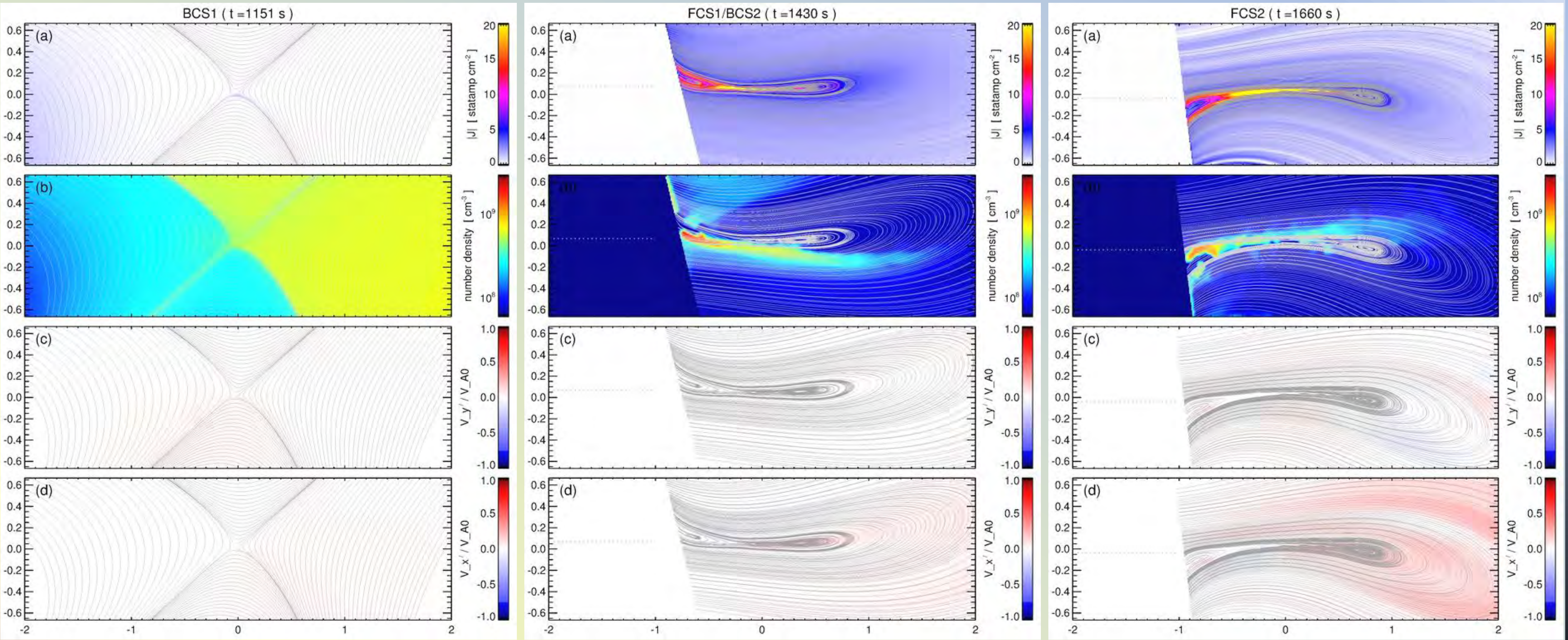

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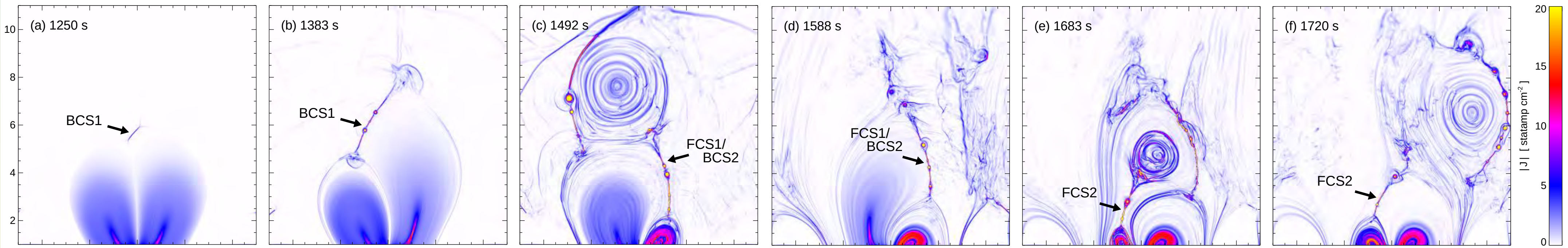
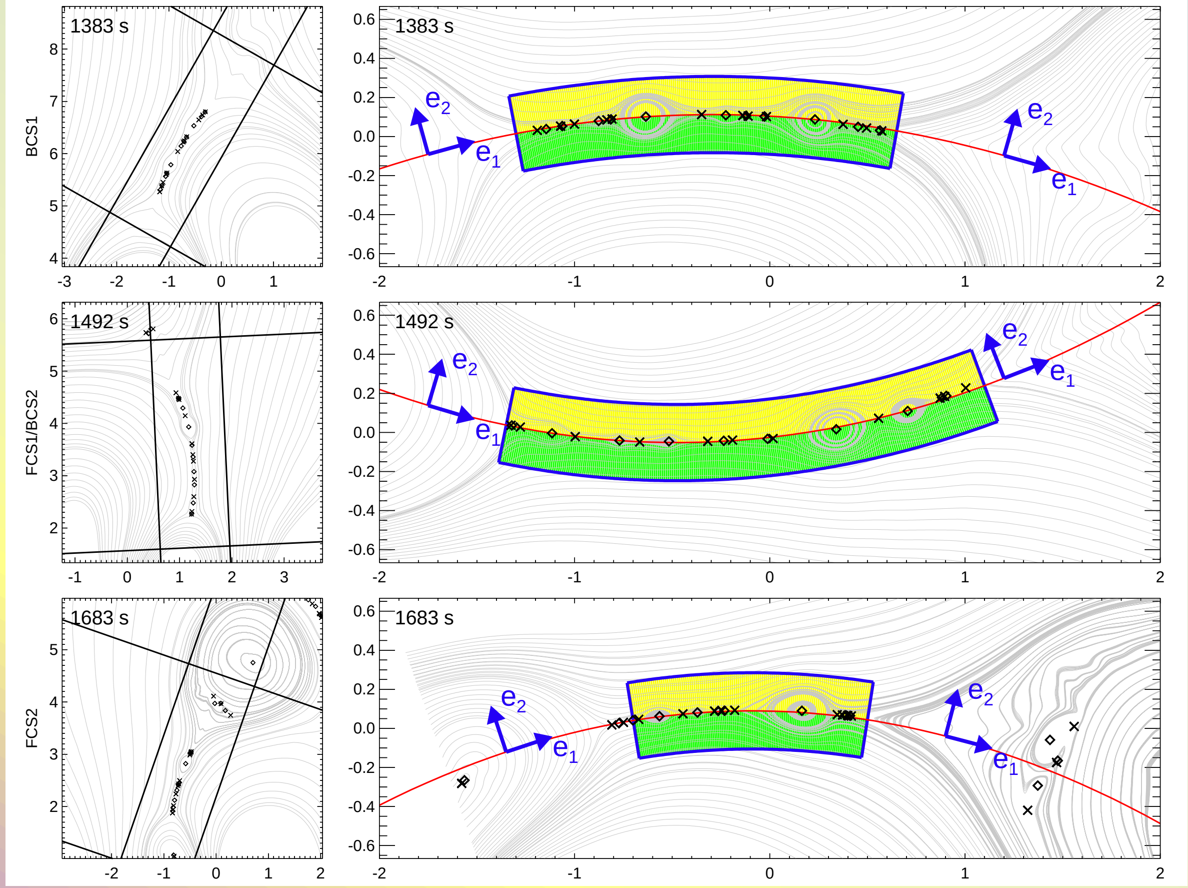
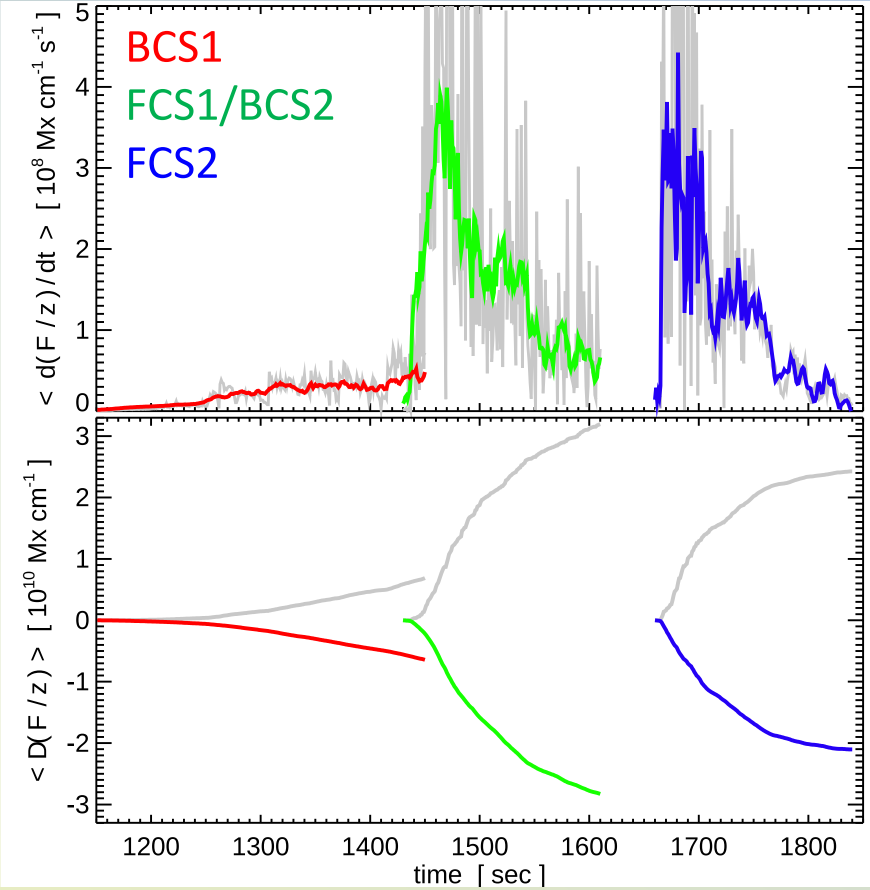


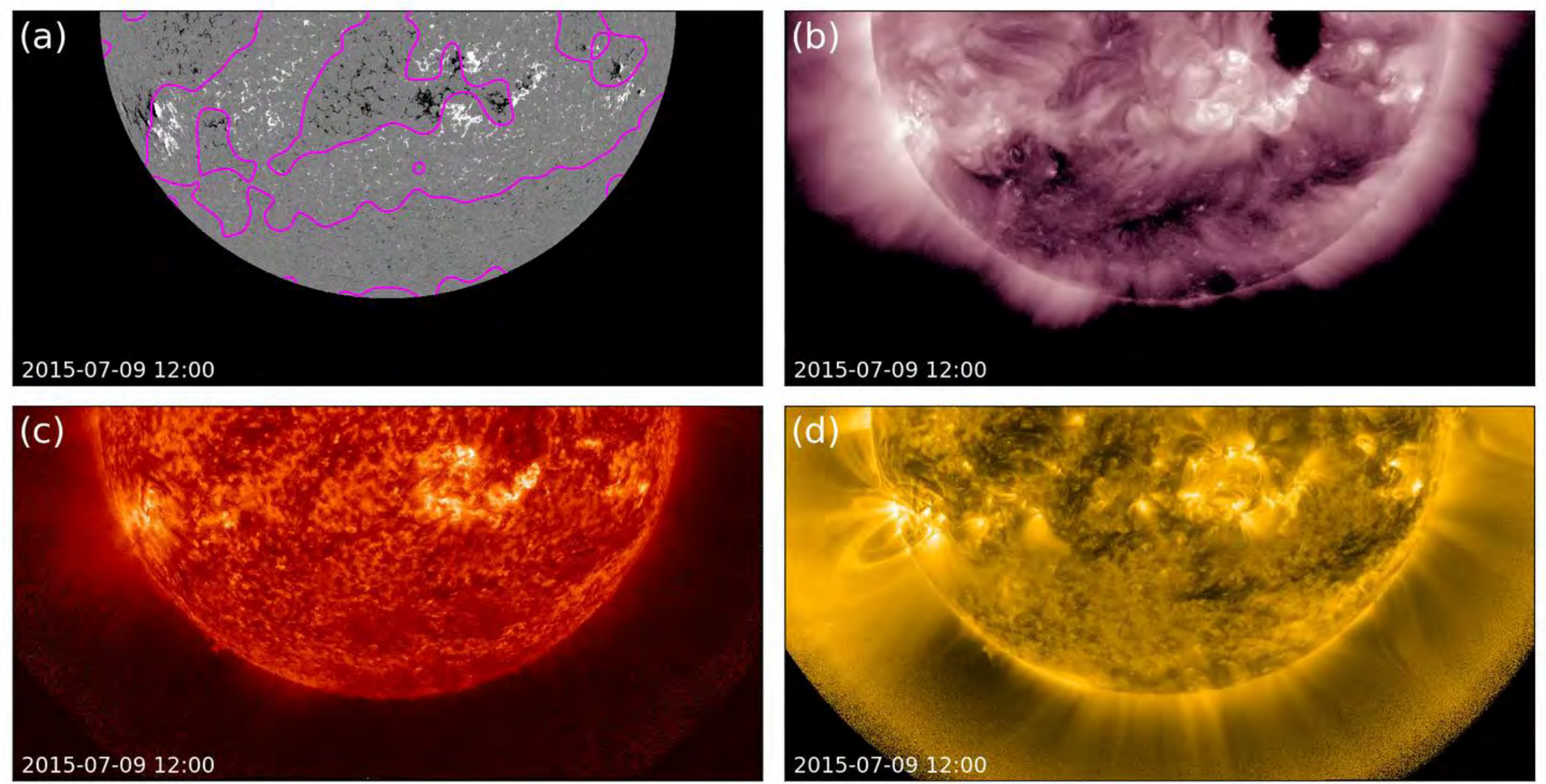




(Lynch et al. 2016a)

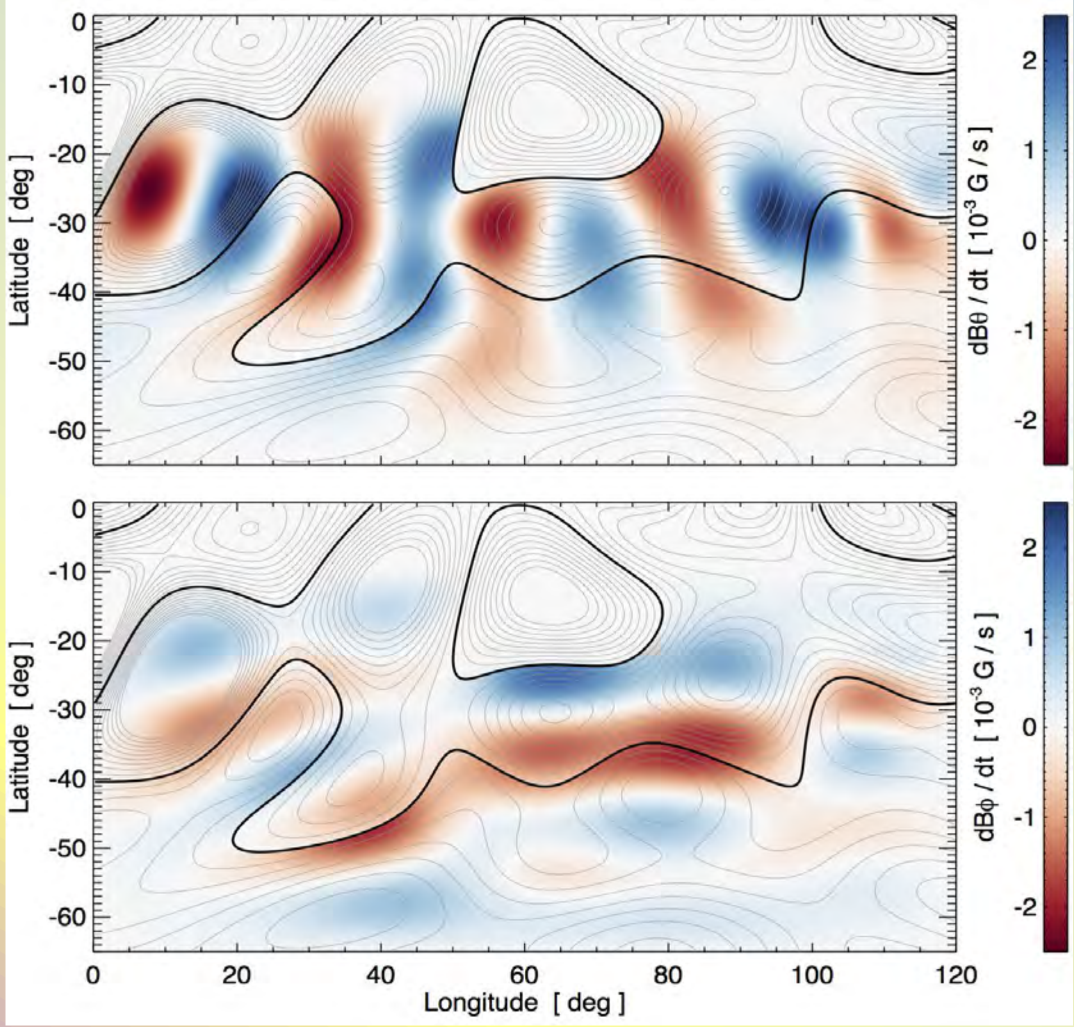
Example of a "realistic" high-latitude filament eruption

Lynch et al. (2021, ApJ 914:39) simulation of 2015 July 9—10 CME



Energizing the Filament Channel w/ STITCH

We employ the **STatistical InjecTion of Condensed Helicity** procedure (STITCH; Dahlin et al. 2019a) to introduce sheared flux along the high-latitude filament channel PIL. A mathematically similar formalism has been used in magnetofrictional modeling to accumulate magnetic free energy in various AR configurations (e.g. Cheung & DeRosa 2012; Pomoell et al. 2019) and over the larger spatial scales of decayed ARs and high-latitude PILs (Mackay et al. 2018).



The STITCH sheared-flux generation is calculated from

$$\frac{\partial \boldsymbol{B}_S}{\partial t} = h^{-1}\left[\boldsymbol{\nabla} \times (\zeta B_r)\,\hat{\boldsymbol{r}}\right] \qquad (1)$$

where $\boldsymbol{B}_S = B_\theta \hat{\boldsymbol{\theta}} + B_\phi \hat{\boldsymbol{\phi}}$ and

$$\zeta(\theta, \phi, t) = K_0 \Theta\,(\theta)\,\Phi\,(\phi)\,T(t) \qquad (2)$$

supplies the spatial and temporal envelope functions that smoothly ramp the helicity condensation region to zero outside the high-latitude filament channel. The (θ, ϕ) dependence is given by

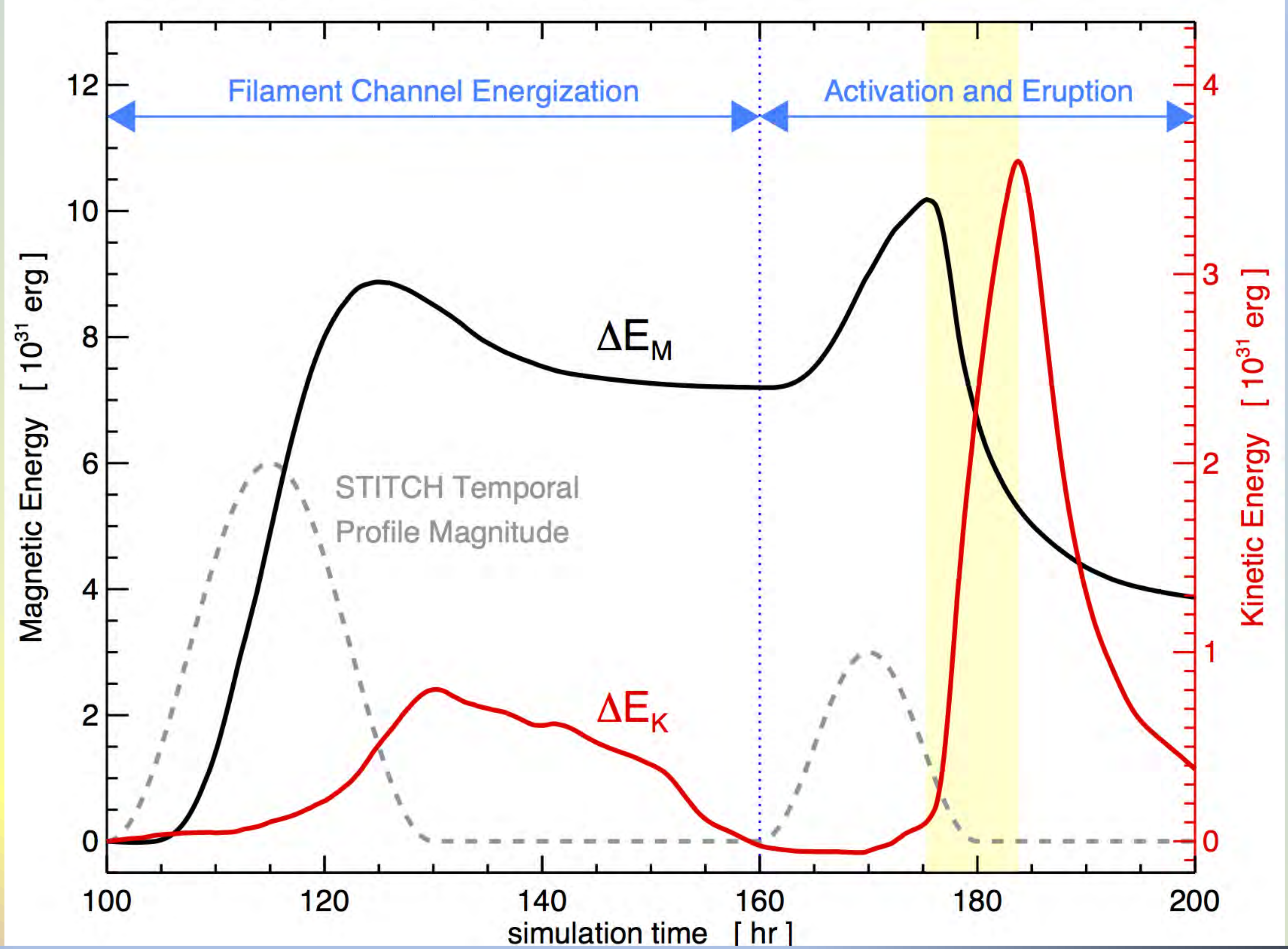
$$\Theta(\theta) = \tfrac{1}{2} - \tfrac{1}{2}\cos\left[2\pi k_\theta \frac{(\theta - \theta_c)}{(\theta_r - \theta_l)}\right], \qquad (3)$$

$$\Phi(\phi) = \sin\left[2\pi k_\phi \frac{(\phi - \phi_c)}{(\phi_r - \phi_l)}\right], \qquad (4)$$

and the temporal dependence by

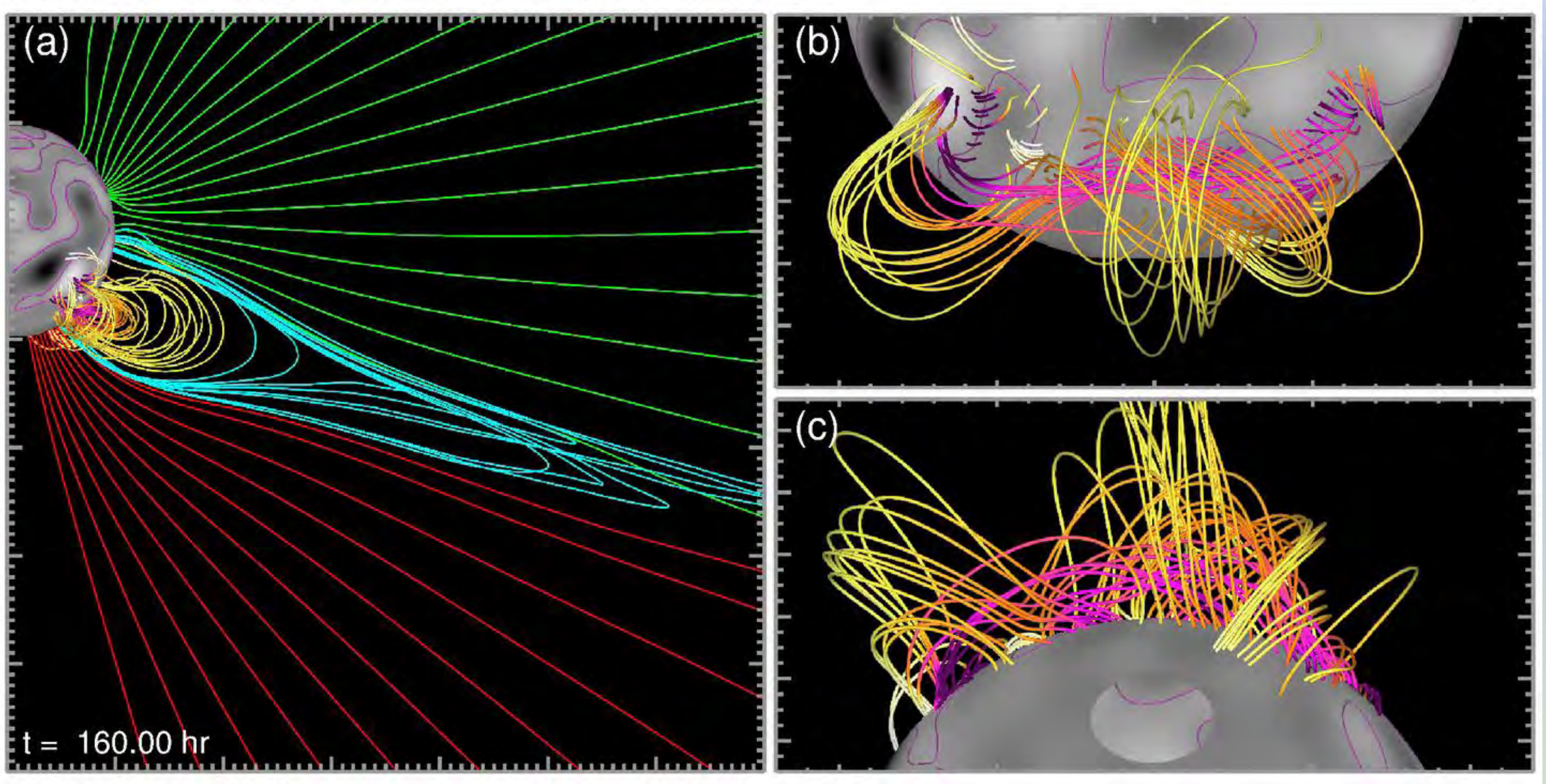
$$T(t) = \tfrac{1}{2} - \tfrac{1}{2}\cos\left[2\pi k_t \frac{(t - t_c)}{(t_r - t_l)}\right]. \qquad (5)$$

Global Magnetic and Energy Evolution

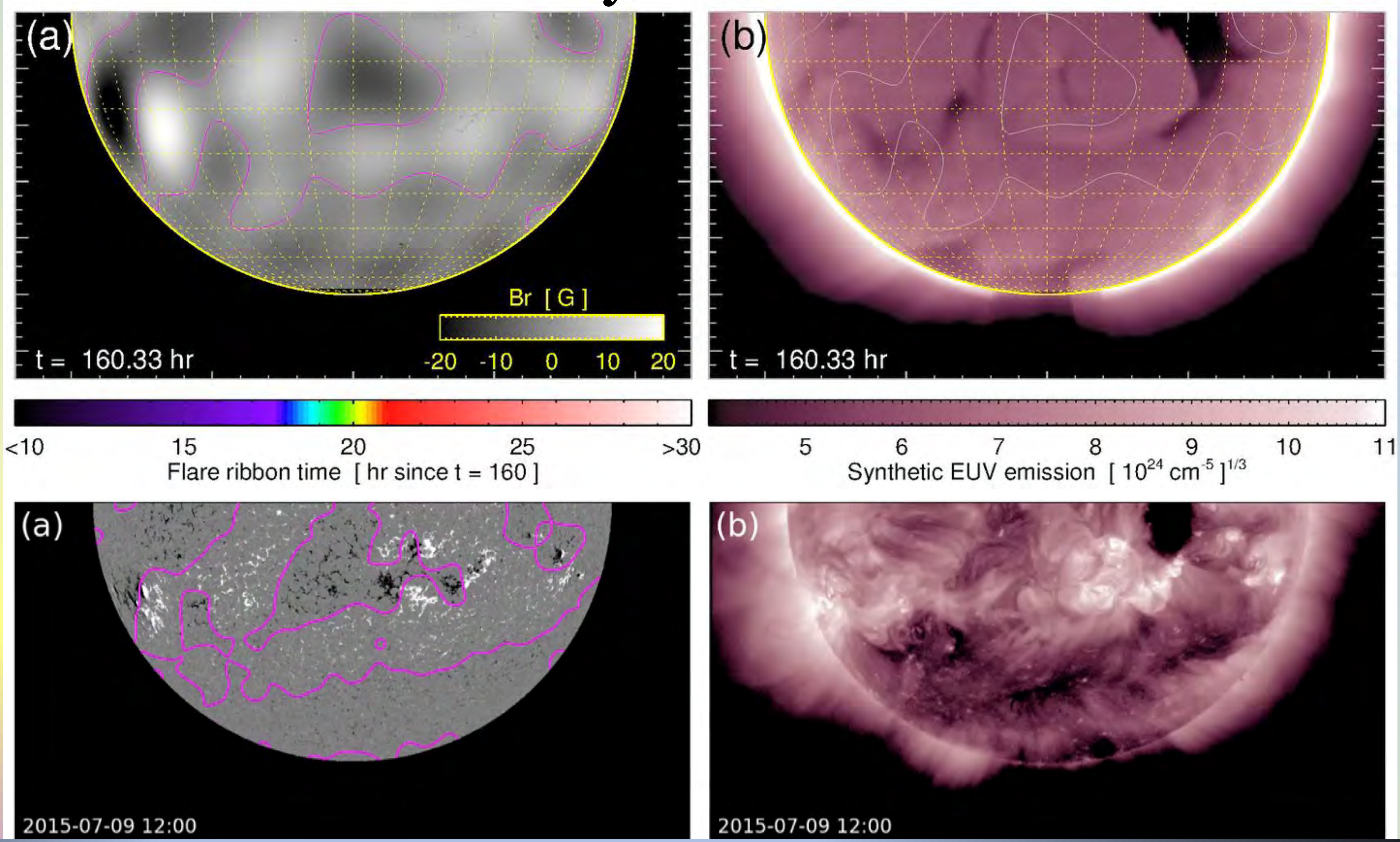


MHD modeling of a high-latitude prominence eruption

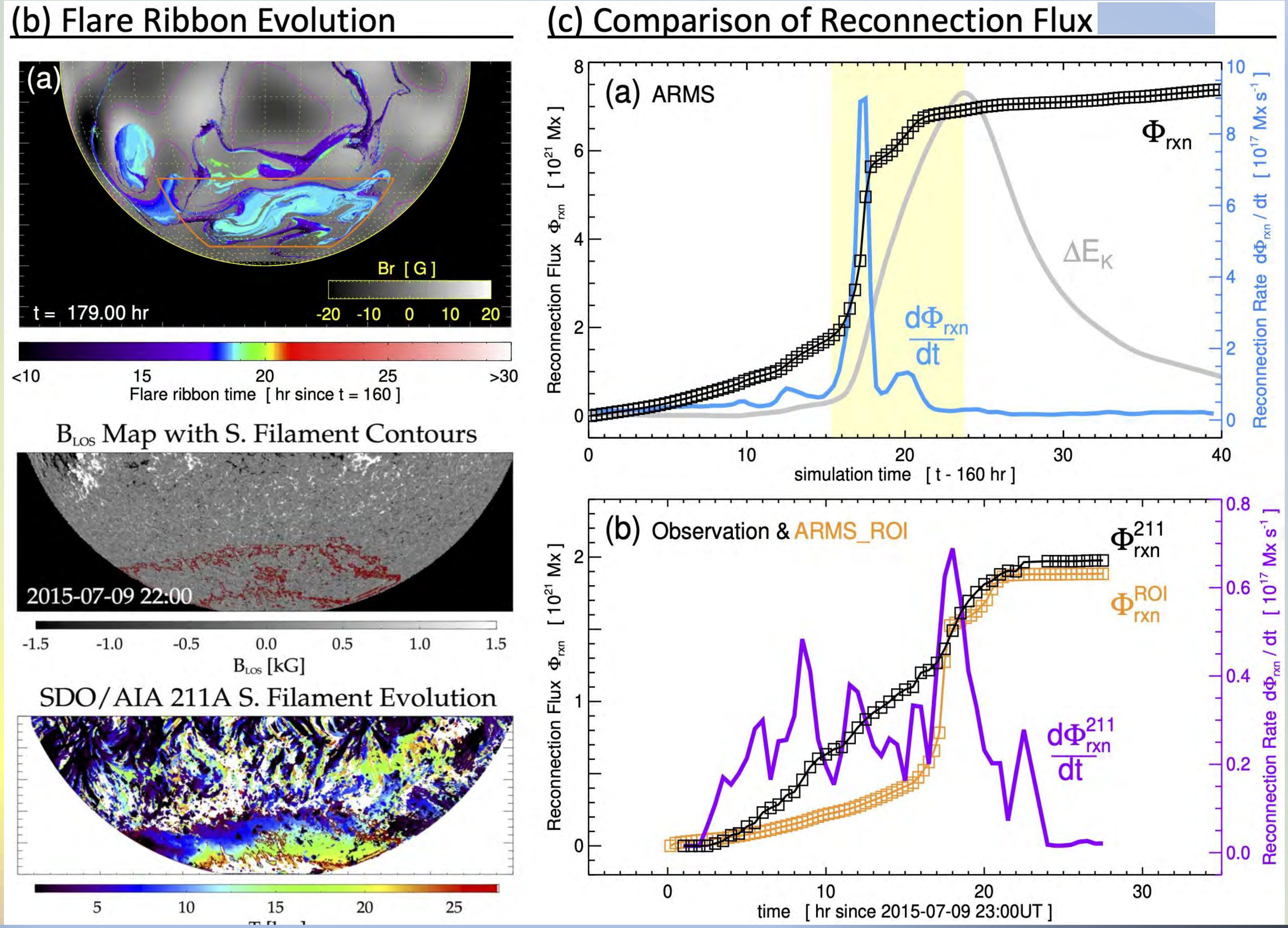
Lynch et al. (2021, ApJ 914:39) simulation of 2015 July 9—10 CME



Flare reconnection flux + synth. EUV in the MHD simulation



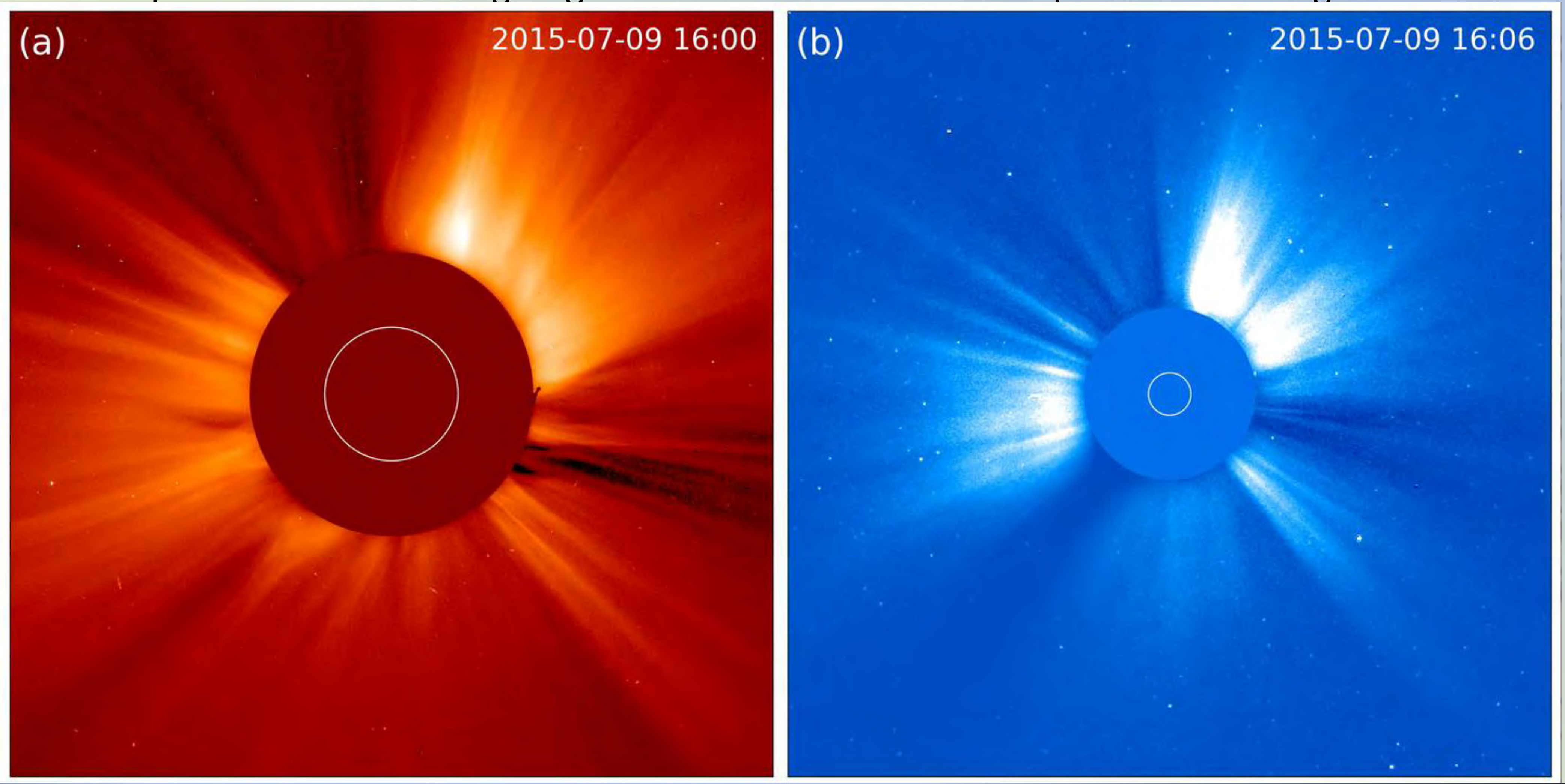
Cf. Reconnection flux w/ observational estimate



SOHO/LASCO C2+C3 — Partial Halo (?) CME Towards South

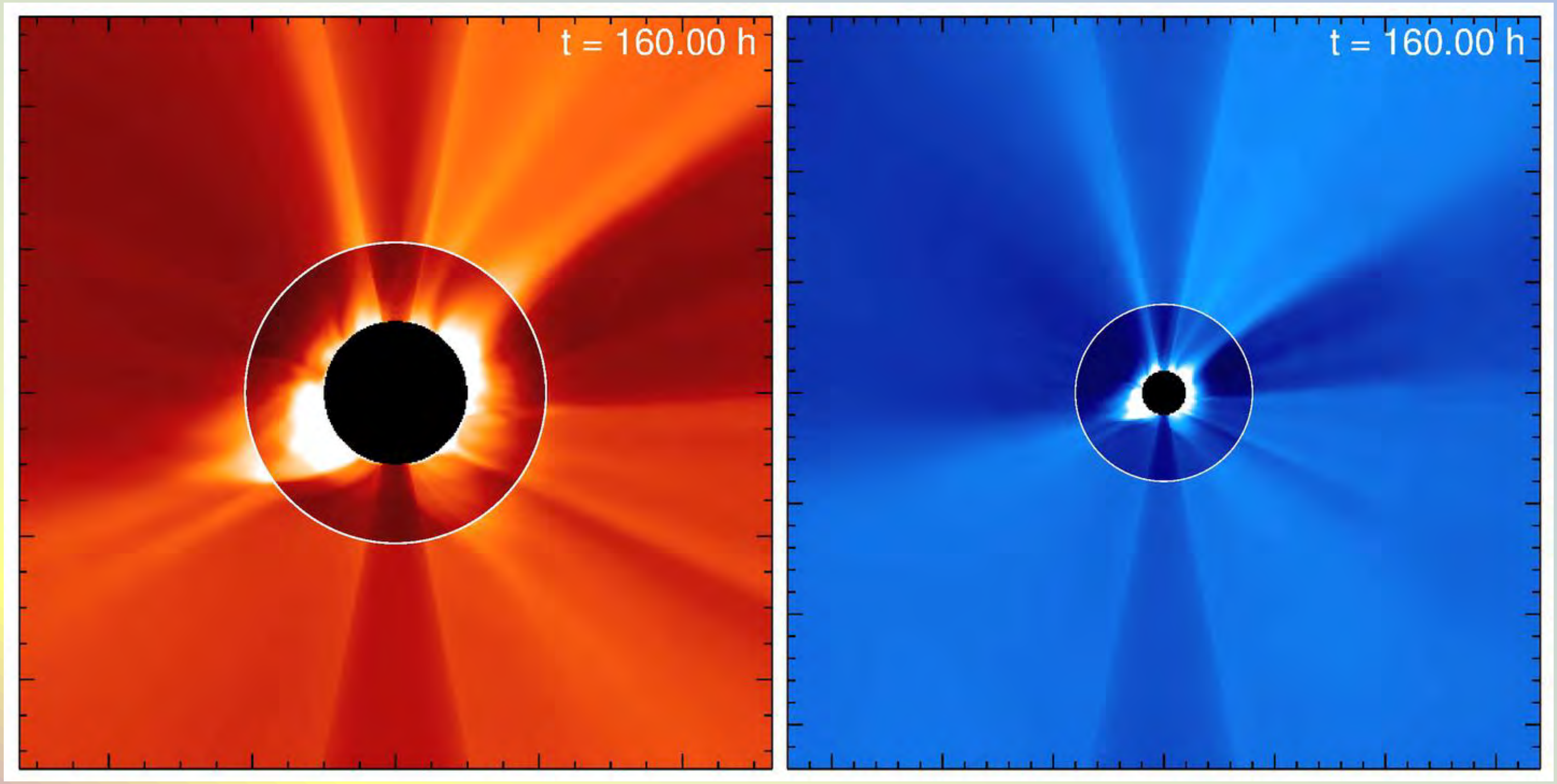
Coronagraph signatures somewhat ambiguous: (1) clear streamer blowout South-East quadrant; (2) some indication of filament material (?) and extended arc-front sweeping from left to right; (3) apparent flux rope eruption South-West quadrant.

→ All part of the same “single” gradual streamer blowout eruption. Camouflaged?

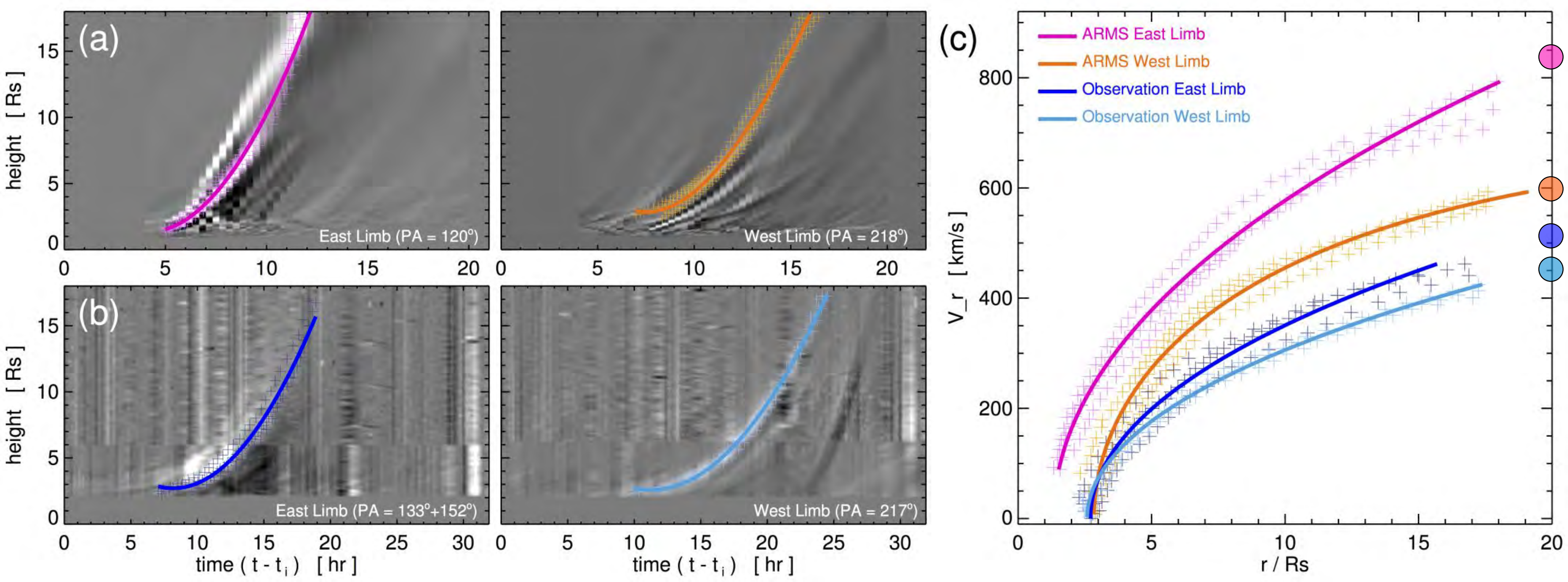


Synthetic White-light Structure

Line of sight integral of Thomson scattered white light from 3D MHD plasma density data.
Calculate WL ratio image I(t)/I(100) as in Vourlidas et al. (2013)



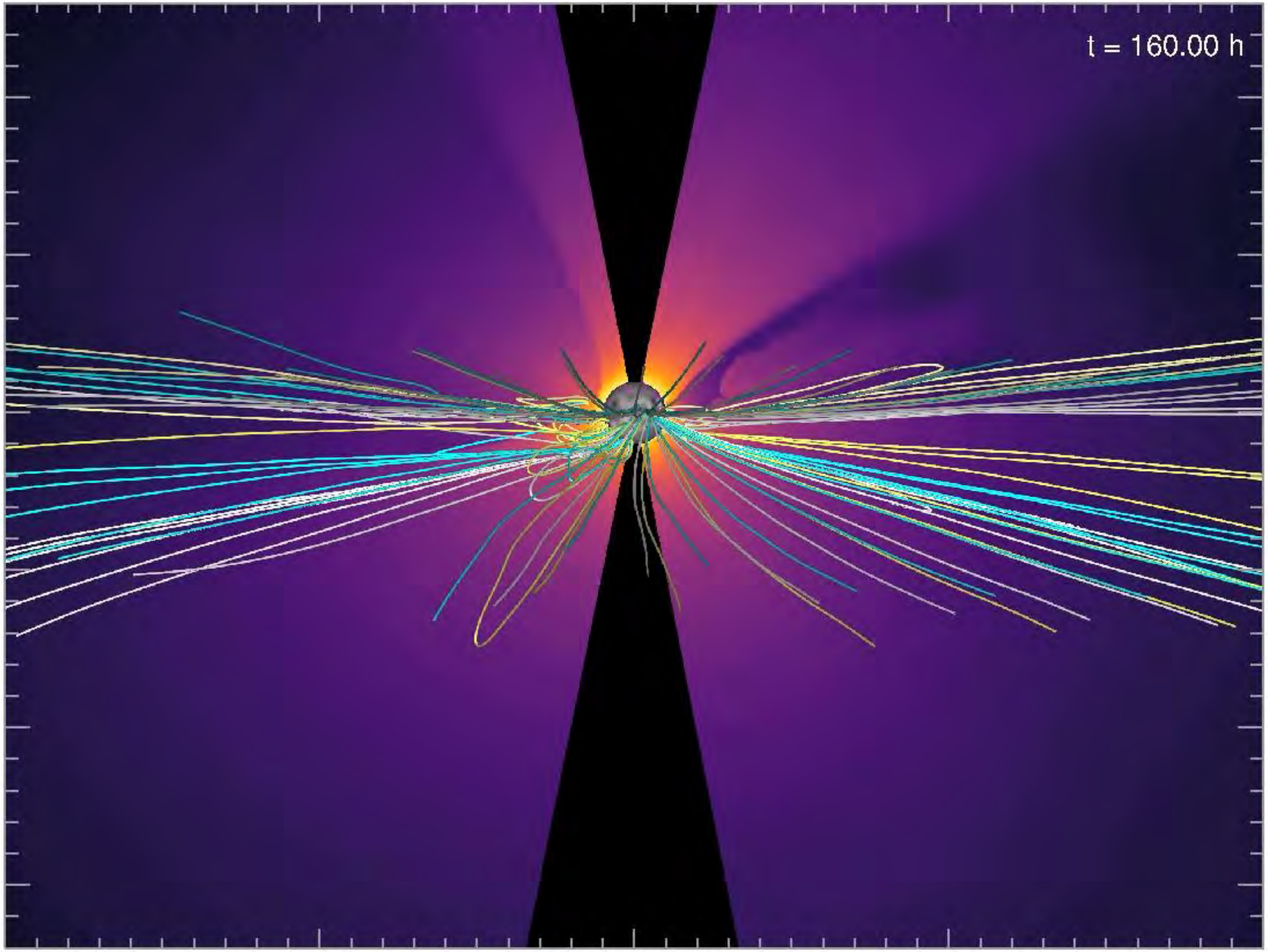
MHD – CME Kinematics: Height-time and Velocity Profiles



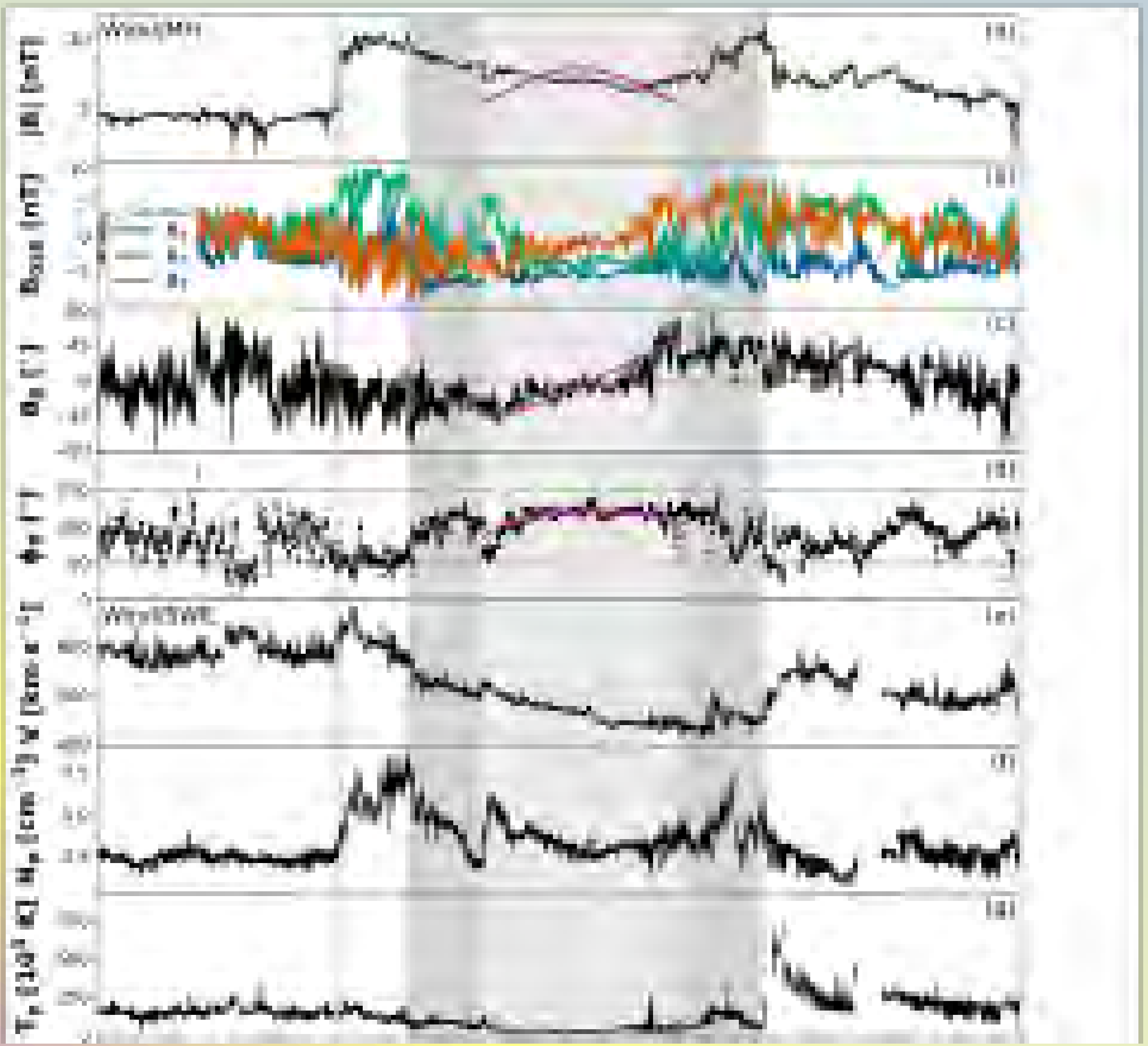
Fit East- & West-limb height-time data in simulation & observations with Sheeley et al. (1999) function:

$$h(t) = r_0 + 2r_a \ln\left[\cosh\left[\frac{v_a(t+t_0)}{2r_a}\right]\right] \qquad v(r) = v_a\left(1 - \exp\left[\frac{-(r-r_0)}{r_a}\right]\right)^{1/2}$$

Height-time profile	t_0	r_0	r_a	v_a	χ^2	$v_{\rm fit}(20R_\odot)$
ARMS East limb	-175.1	1.32	190.4	2733.8	0.077	835.8
ARMS West limb	-178.5	2.84	13.4	707.4	0.115	601.0
LASCO C2/C3 East limb	-24.2	2.71	110.1	1385.1	0.164	528.1
LASCO C2/C3 West limb	-27.3	2.58	102.9	1160.1	0.051	457.8


t = 160.00 h

Modeling the Flux Rope Structure of CMEs/ICMEs

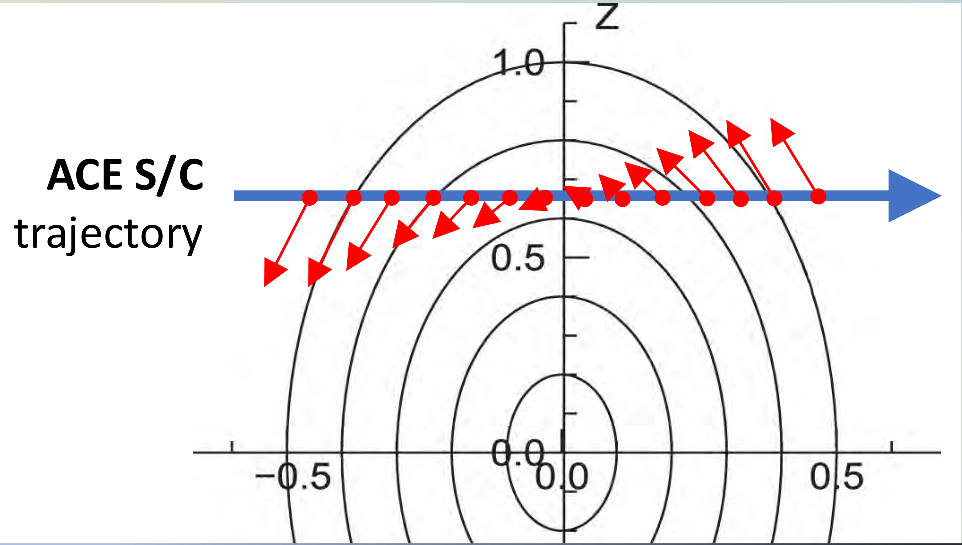


Classic flux rope signatures in field and plasma signatures. Relatively weak field rotation (B_z) and non-zero B_x component imply a large impact parameter. **Flux rope is SWN type (RH).**

[$\phi_0 = 269^o$, $\theta_0 = -12^o$, $\rho_0 = 0.64$, H = +1]

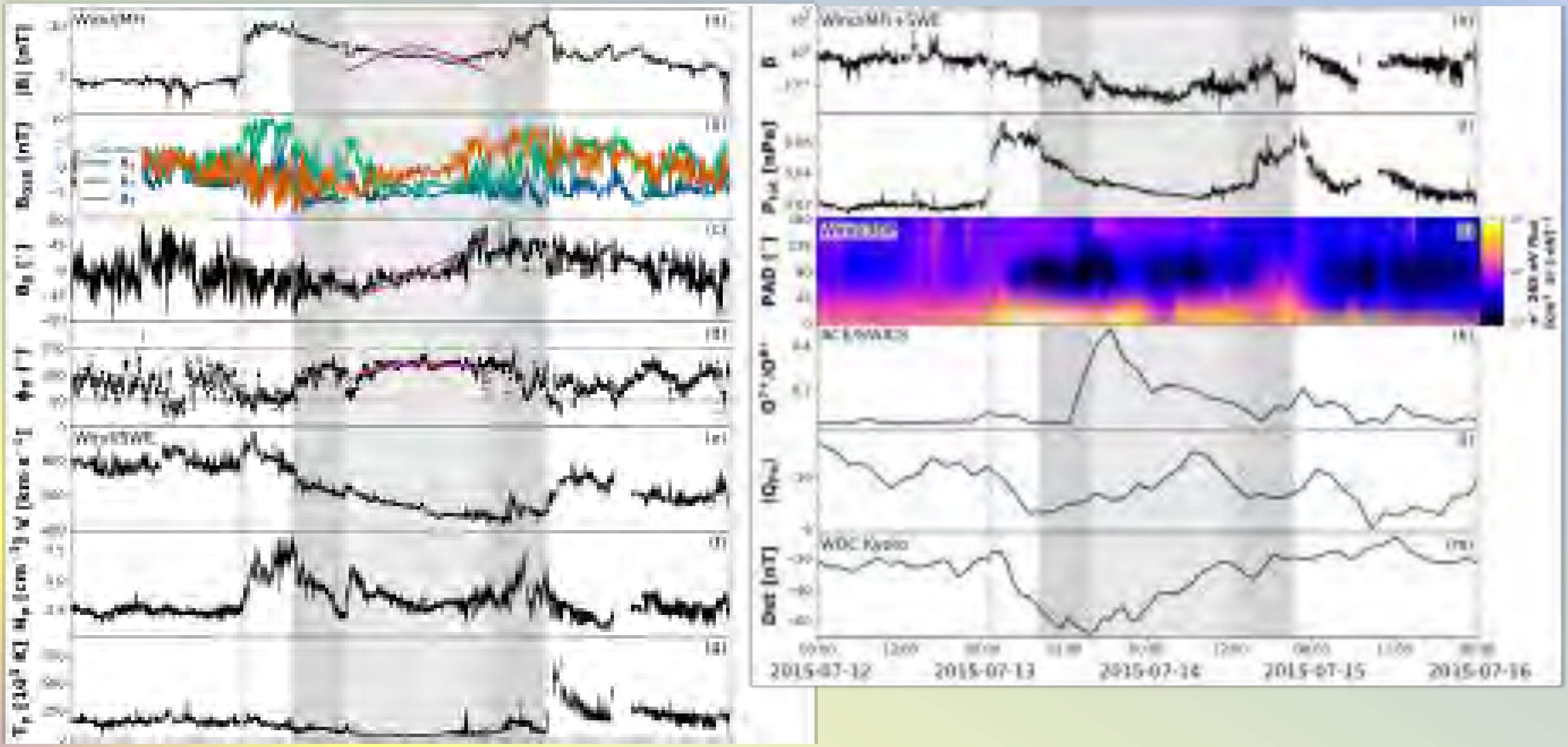
Slow MC/ICMEs channeled into HCS so we expect main FR to be south of ecliptic.

Ambiguous low-coronal signatures and CME association in coronagraphs makes this event *quasi-stealthy* --- or at least "unexpected."



[Palmerio et al. 2023, in press]

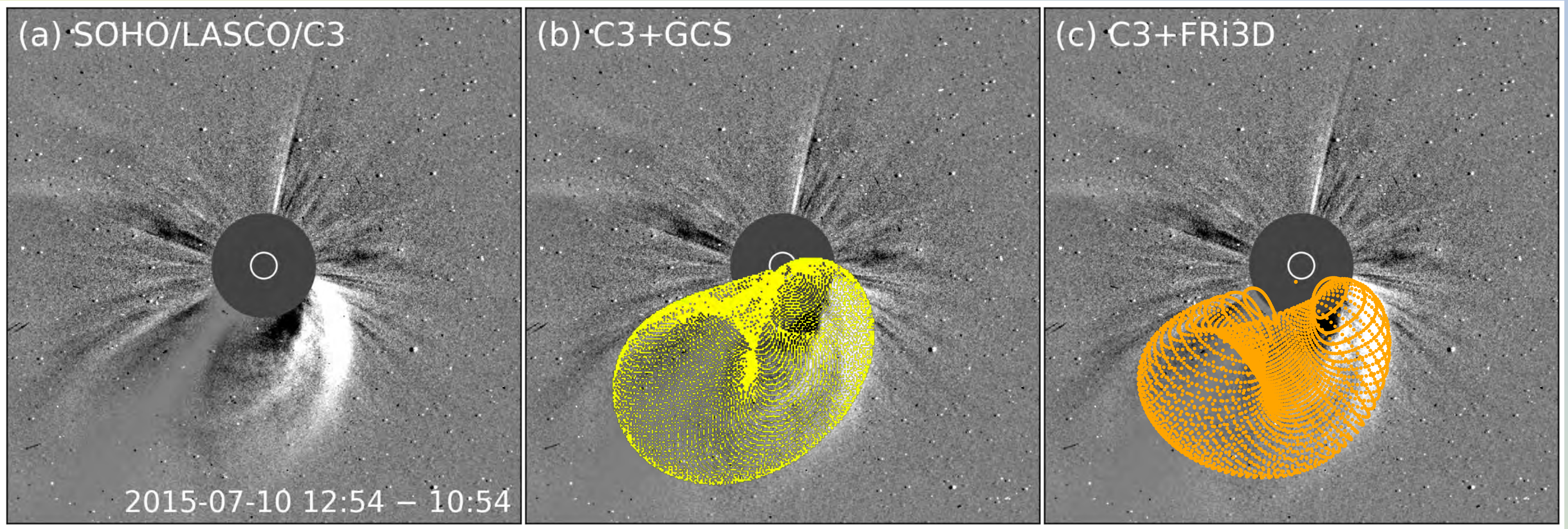
Modeling the Flux Rope Structure of CMEs/ICMEs



[Palmerio et al. 2023, in press]

Modeling the Flux Rope Structure of CMEs/ICMEs

Palmerio et al. (2023, in press) ran EUHFORIA propagation with three different CME/ICME models: Spheroid (elliptical "cone model" pressure-pulse; Scolini & Palmerio 2023, in prep), the Spheromak (Verbeke et al. 2019), and the FRi3D (Maharana et al. 2022) flux rope prescription. Geometric and magnetic parameters for EUHFORIA CME models derived from observational data and consistent with earlier ARMS sim results.



[Palmerio et al. 2023, in press]

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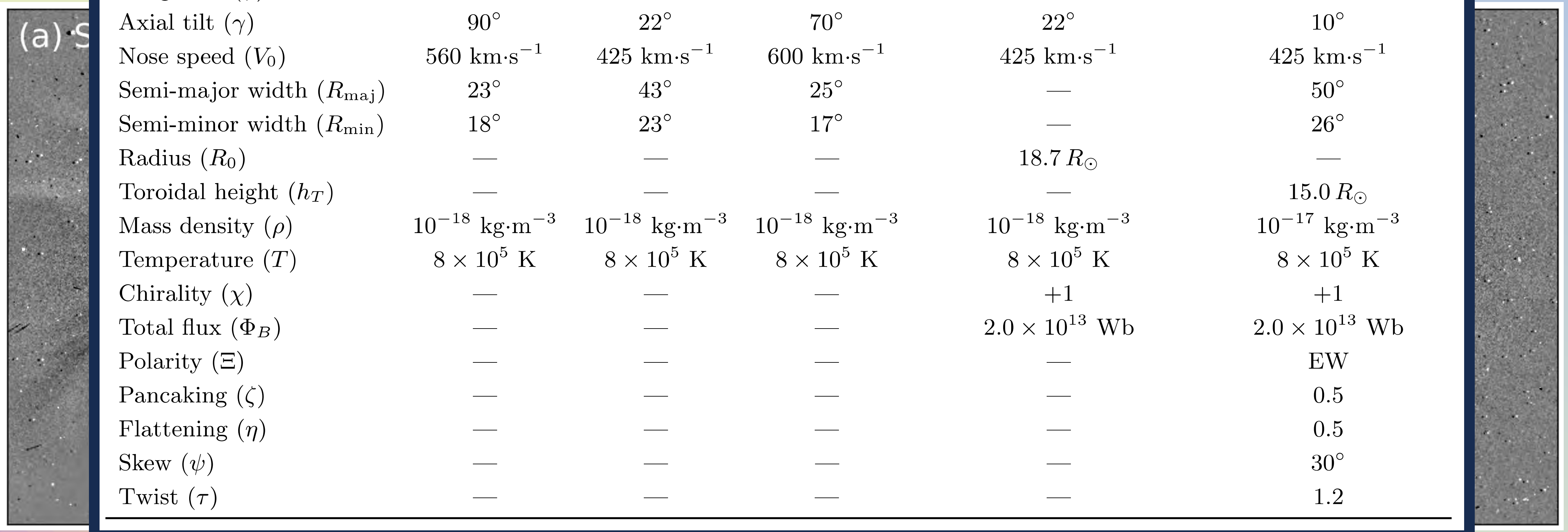
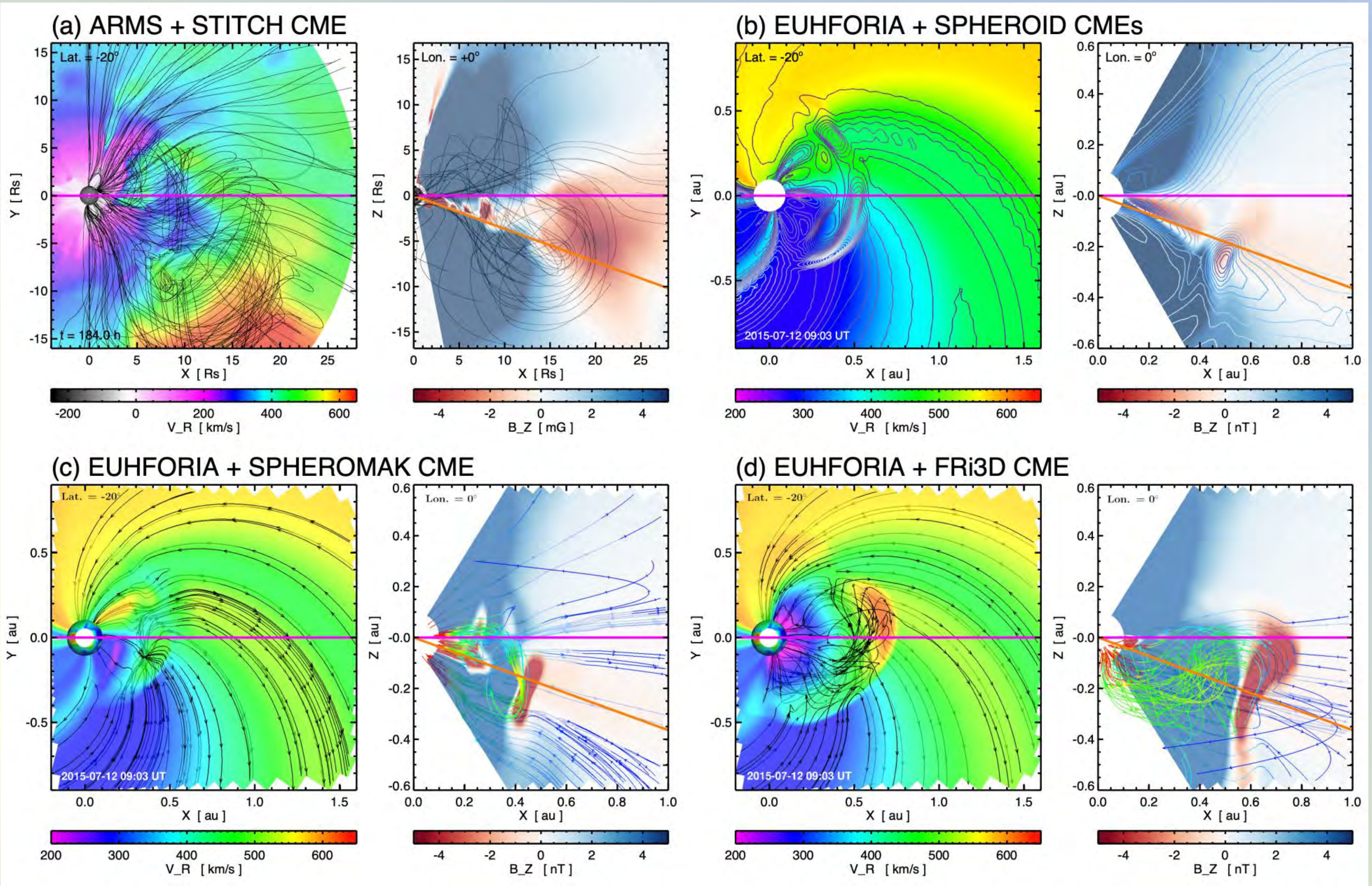
Table 2. List of the input parameters used to inject each CME in the three different EUHFORIA runs. Latitudes and longitudes are reported in Stonyhurst coordinates. The tilt is measured from the solar west direction and is defined as positive for counterclockwise rotations. Note that for the EUHFORIA+Spheroid run, the 2015 July 9 event is initialized in three parts (see Section 3.2.1 for details).

Model version →	EUHFORIA+Spheroid			EUHFORIA+Spheromak	EUHFORIA+FRi3D
↓ Input	Part 1	Part 2	Part 3		
Injection day	2015-07-10	2015-07-10	2015-07-10	2015-07-10	2015-07-10
Time at 21.5 $R_\odot$ (t_0)	08:30	12:54	20:18	12:54	12:54
Latitude (θ)	$-33°$	$-35°$	$-35°$	$-35°$	$-38°$
Longitude (ϕ)	$-32°$	$-18°$	$40°$	$-18°$	$-25°$
Axial tilt (γ)	90°	22°	70°	22°	10°
Nose speed (V_0)	560 $km{\cdot}s^{-1}$	425 $km{\cdot}s^{-1}$	600 $km{\cdot}s^{-1}$	425 $km{\cdot}s^{-1}$	425 $km{\cdot}s^{-1}$
Semi-major width (R_{maj})	23°	43°	25°	—	50°
Semi-minor width (R_{min})	18°	23°	17°	—	26°
Radius (R_0)	—	—	—	18.7 $R_\odot$	—
Toroidal height (h_T)	—	—	—	—	15.0 $R_\odot$
Mass density (ρ)	10^{-18} $kg{\cdot}m^{-3}$	10^{-18} $kg{\cdot}m^{-3}$	10^{-18} $kg{\cdot}m^{-3}$	10^{-18} $kg{\cdot}m^{-3}$	10^{-17} $kg{\cdot}m^{-3}$
Temperature (T)	8×10^5 K	8×10^5 K	8×10^5 K	8×10^5 K	8×10^5 K
Chirality (χ)	—	—	—	+1	+1
Total flux (Φ_B)	—	—	—	2.0×10^{13} Wb	2.0×10^{13} Wb
Polarity (Ξ)	—	—	—	—	EW
Pancaking (ζ)	—	—	—	—	0.5
Flattening (η)	—	—	—	—	0.5
Skew (ψ)	—	—	—	—	30°
Twist (τ)	—	—	—	—	1.2

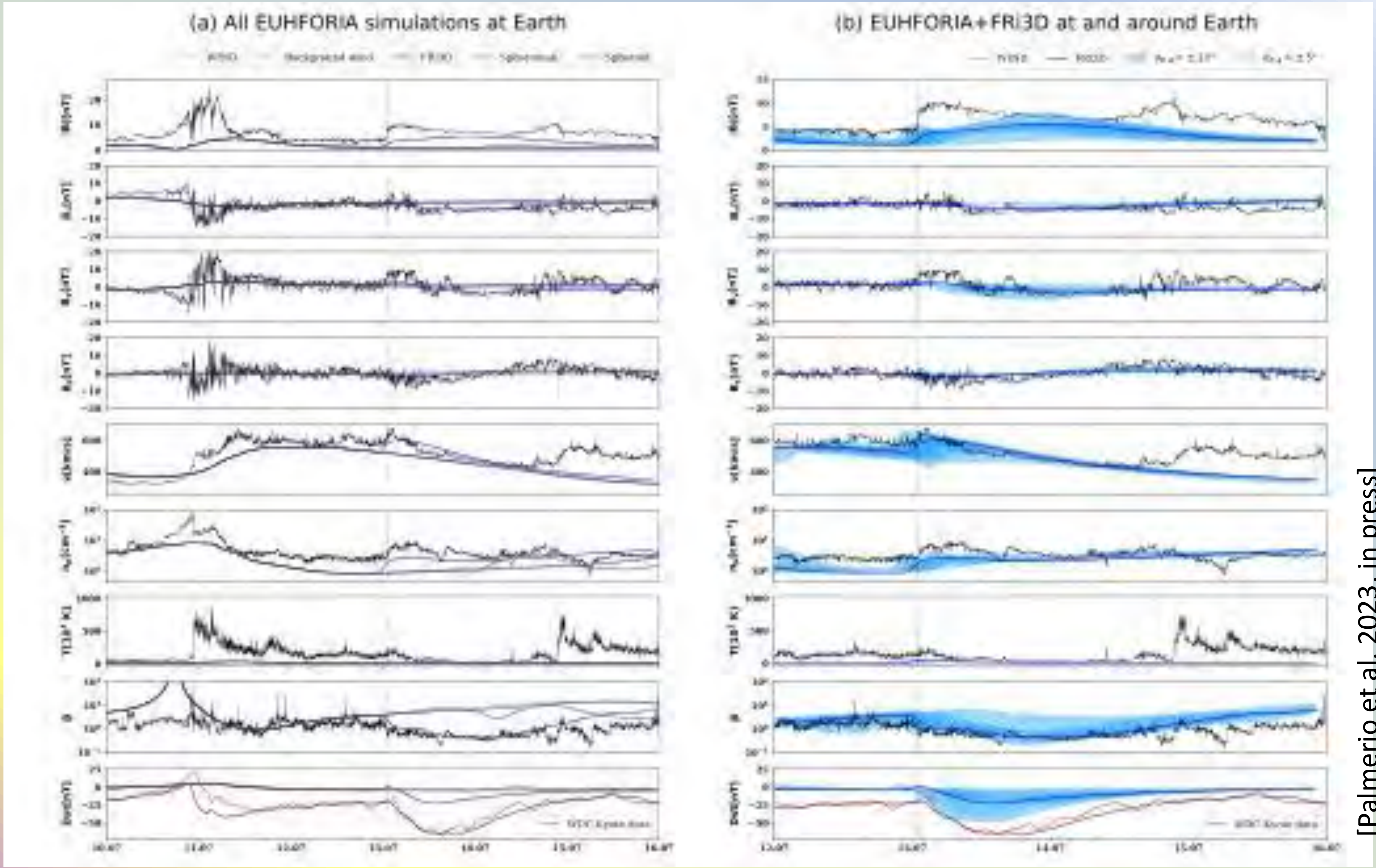


[Palmerio et al. 2023, in press]

Modeling the Flux Rope Structure of CMEs/ICMEs



[Palmerio et al. 2023, in press]



[Palmerio et al. 2023, in press]

Making a Carrington-class stellar superflare + CME

- One of the great things about simulations/modeling --- get to run numerical experiments!

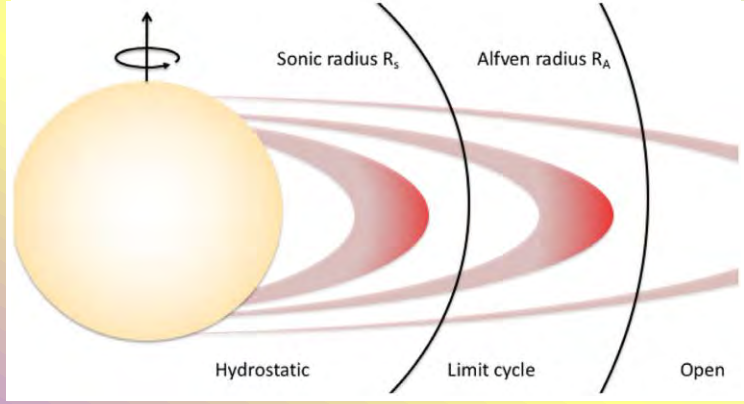
- What happens in extreme/pathological cases?

- For example, what if we were to energize the entire closed-field corona? Can we erupt the entire Sun? Yes! And since that never happens on the Sun in real life, let's call it a stellar superflare and see what happens!

Idealized global streamer blowout case – erupt the whole Sun?

Lynch et al. (2019, ApJ 880:97)

- κ^1 Ceti a 700My solar analog (G5) star: $M_* \sim 1.02 M_\odot$, $R_* \sim 0.99 R_\odot$, $T_{eff} \sim 5700$K (do Nascimento et al. 2016)
- ZDI stellar magnetogram from mid-to-late August 2012 (Rosén et al. 2016)
- Apply energizing (quasi-static) shearing flows to entire streamer belt PIL for maximum possible source region size



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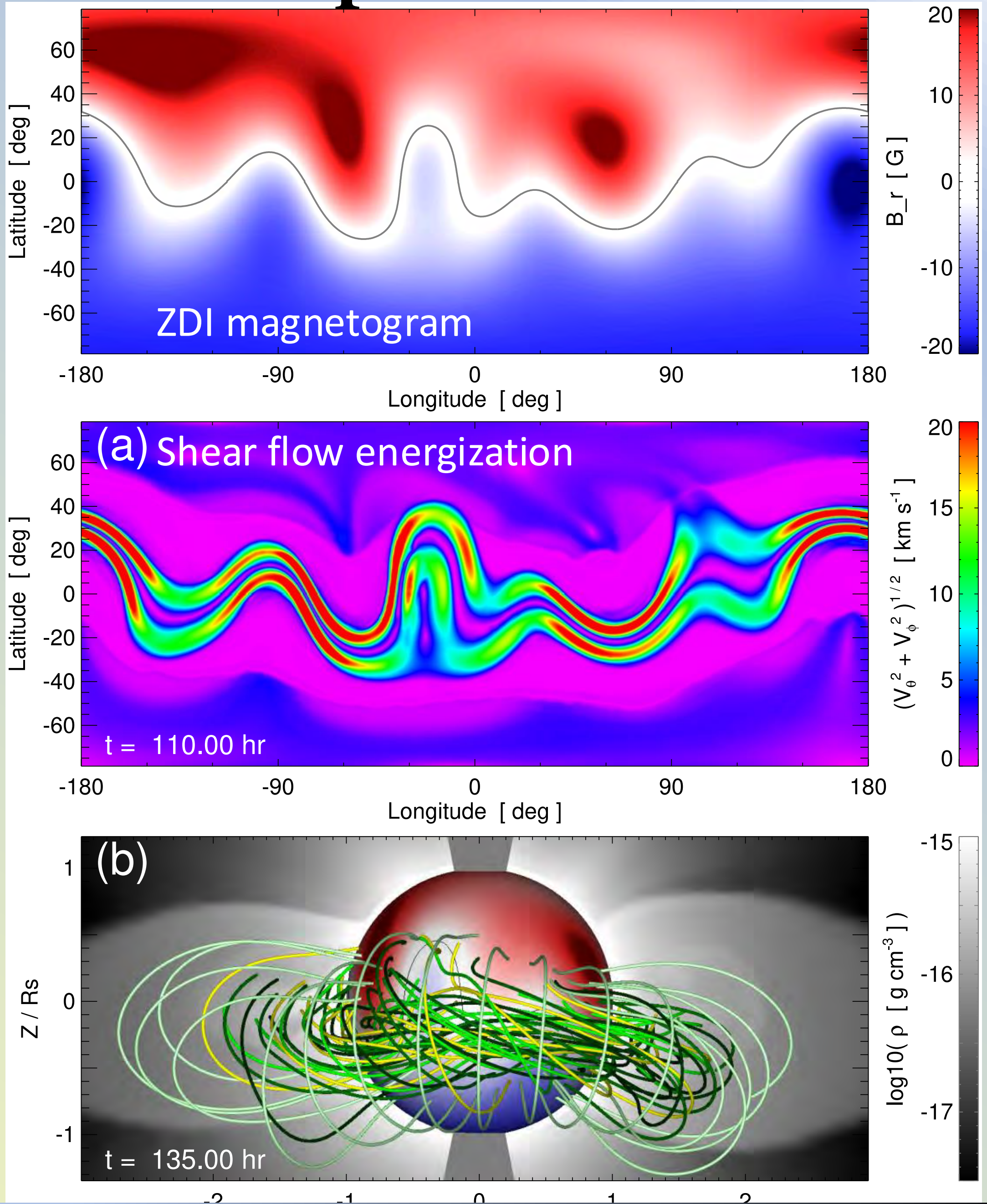
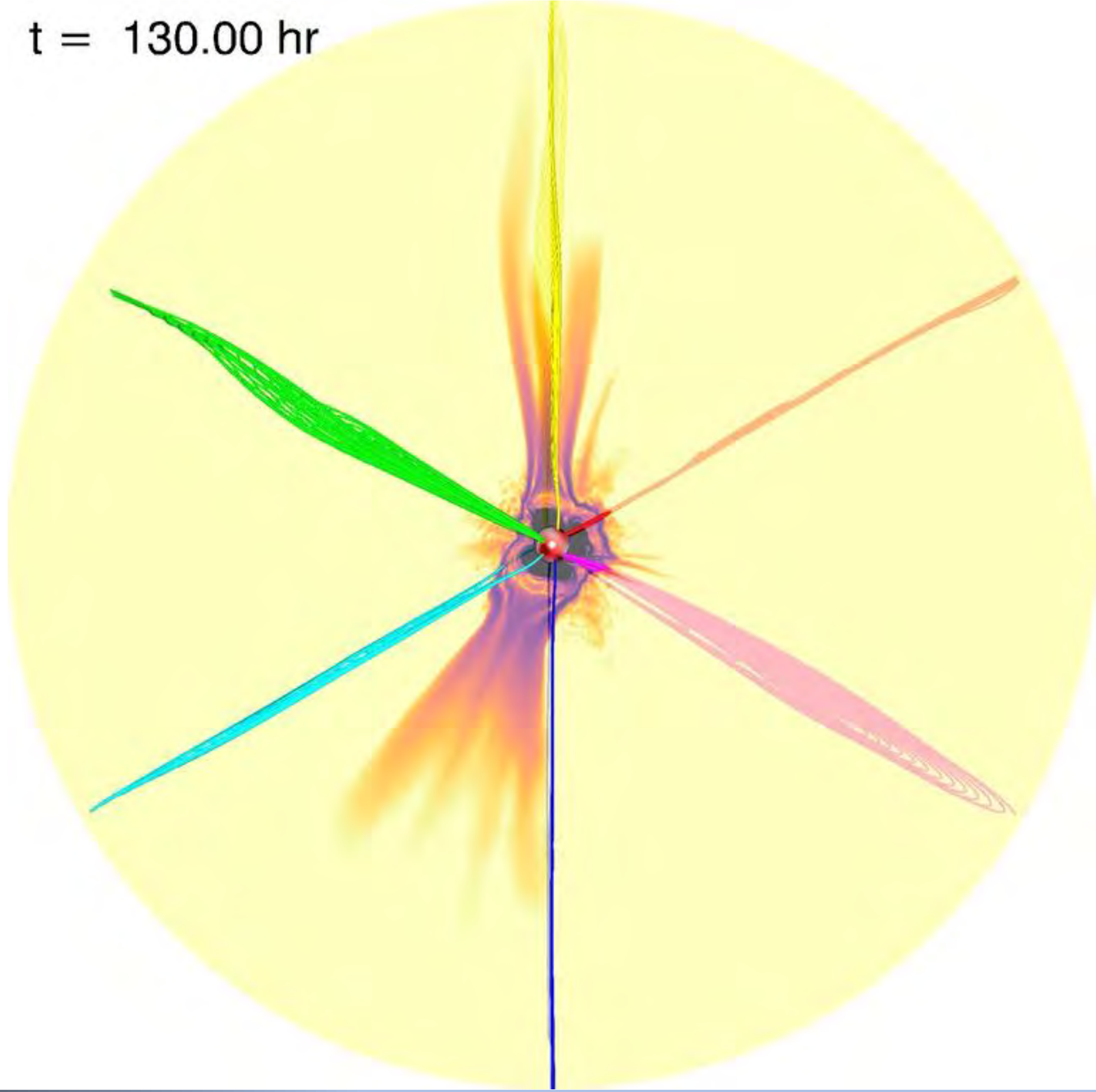
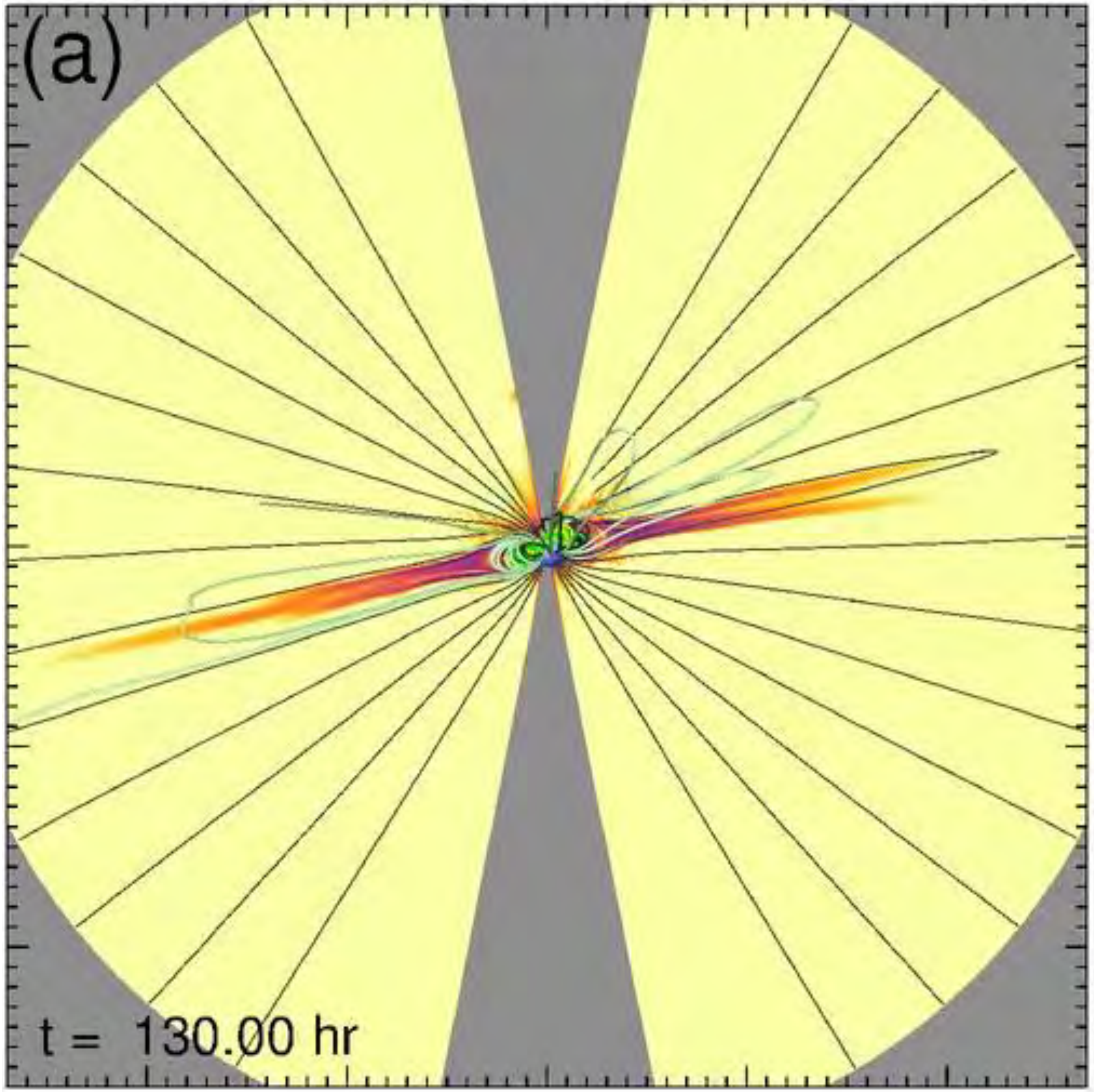


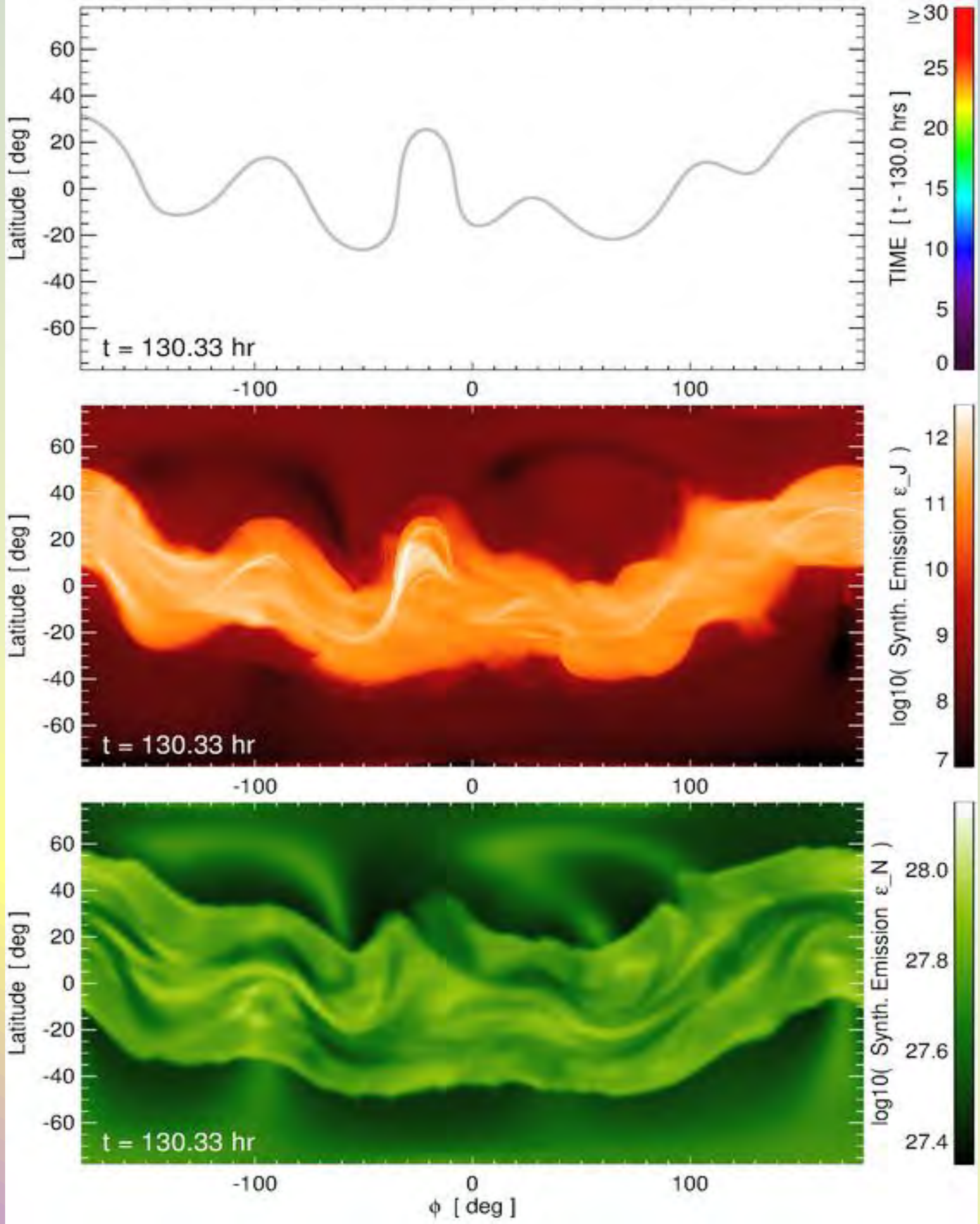
Modeling a stellar superflare+CME from κ¹ Ceti

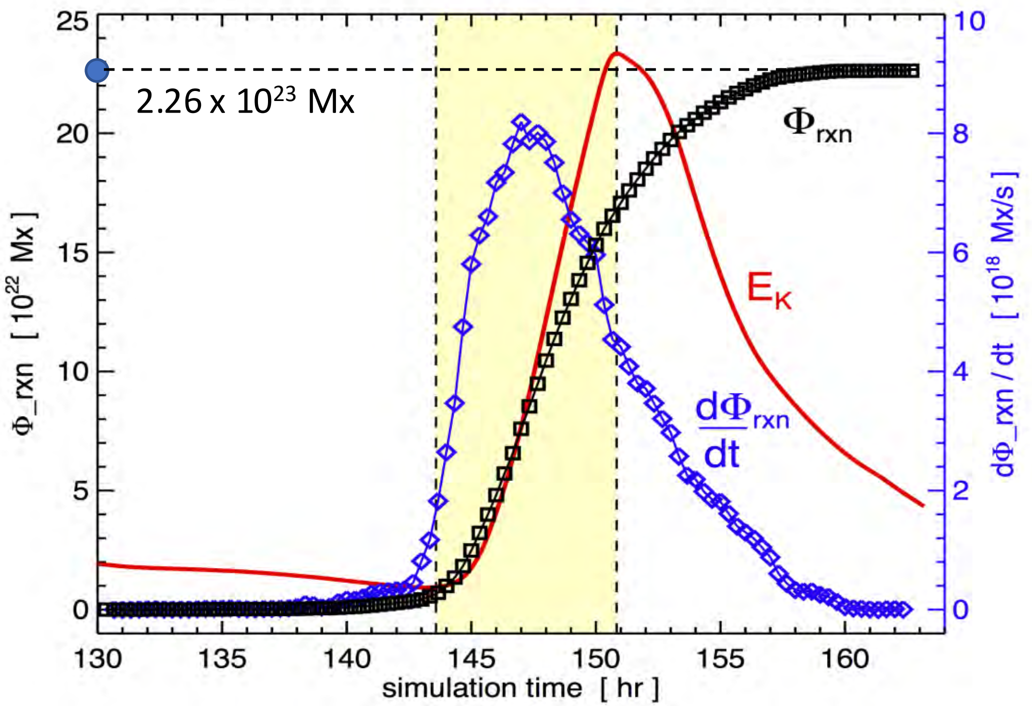
Lynch et al. (2019, ApJ 880:97)

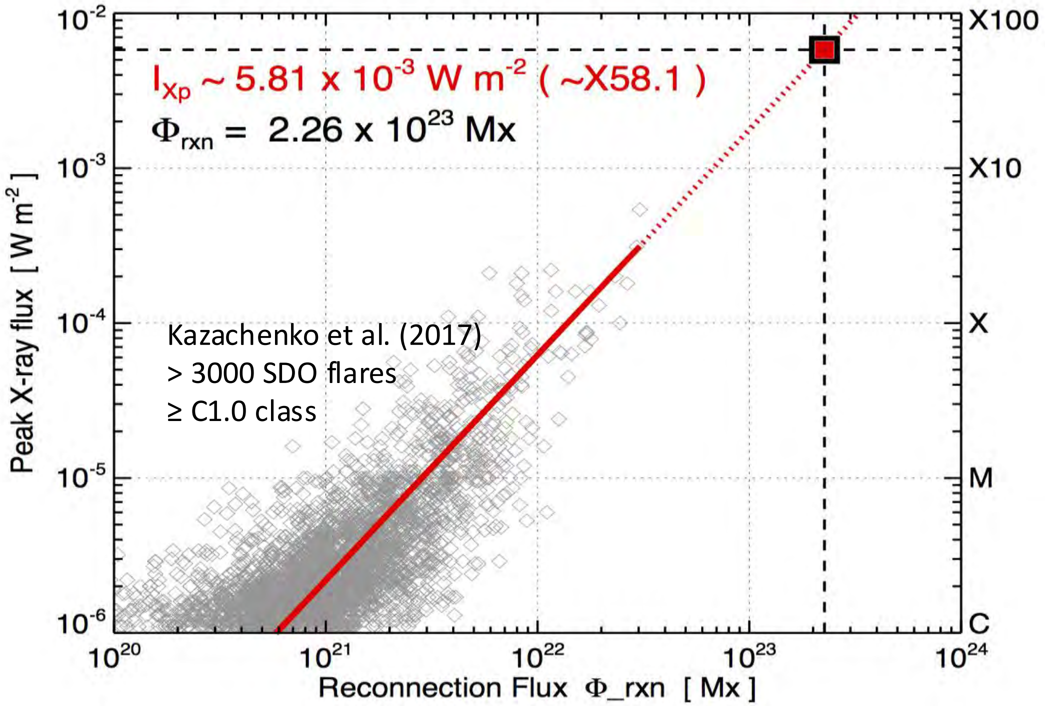




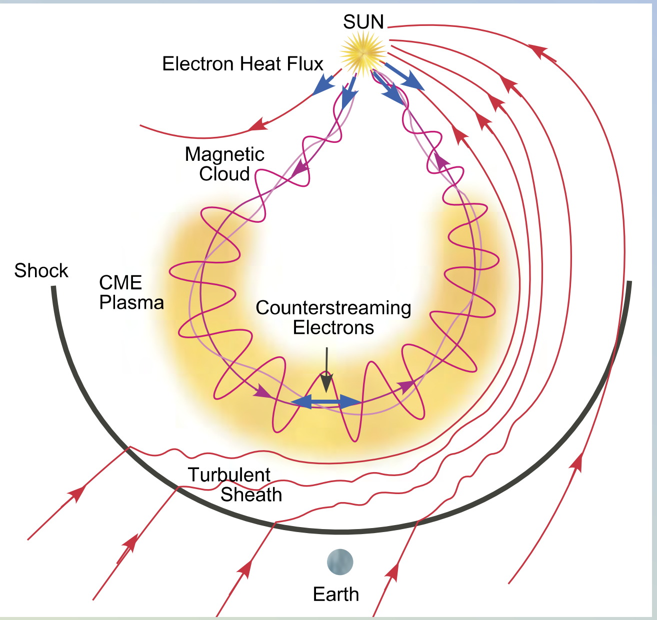
(Solar) SXR vs. Φ_{rxn} Estimate

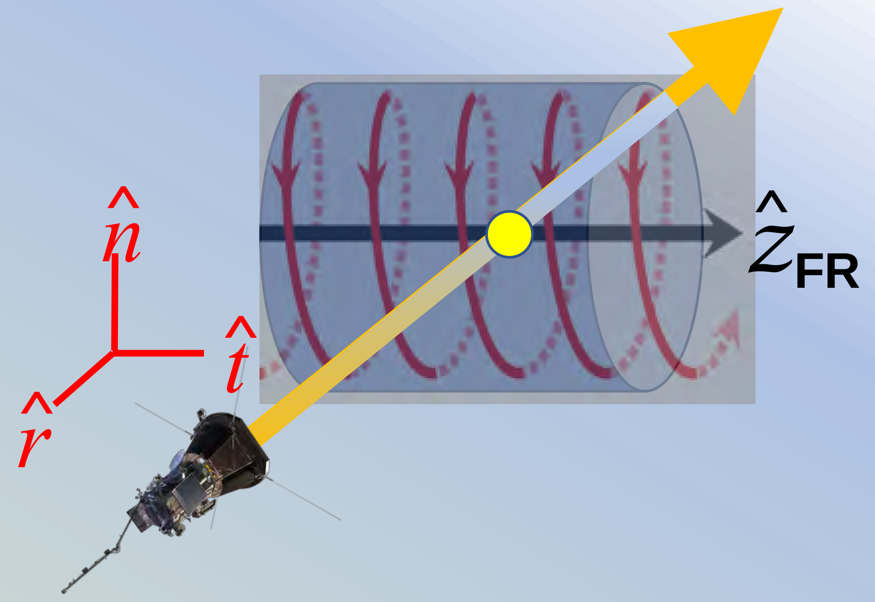






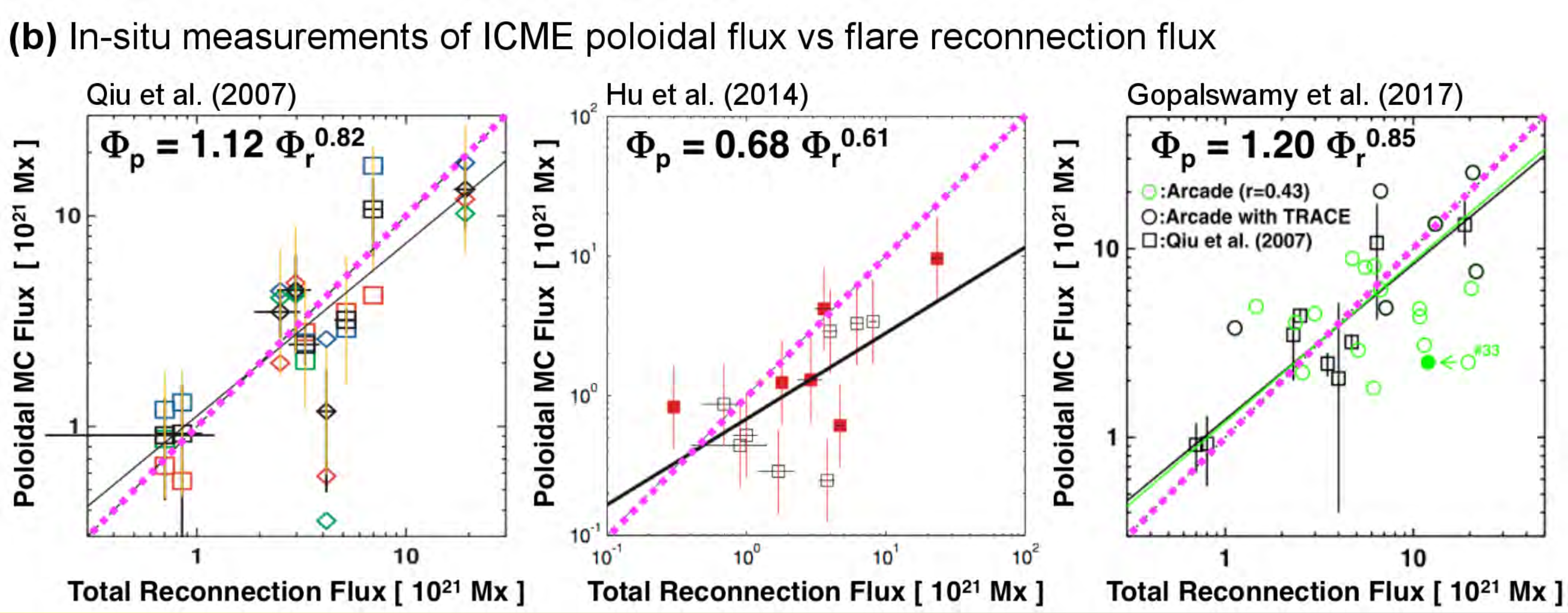
Using Magnetic Flux Content to Make the CME—ICME Connection





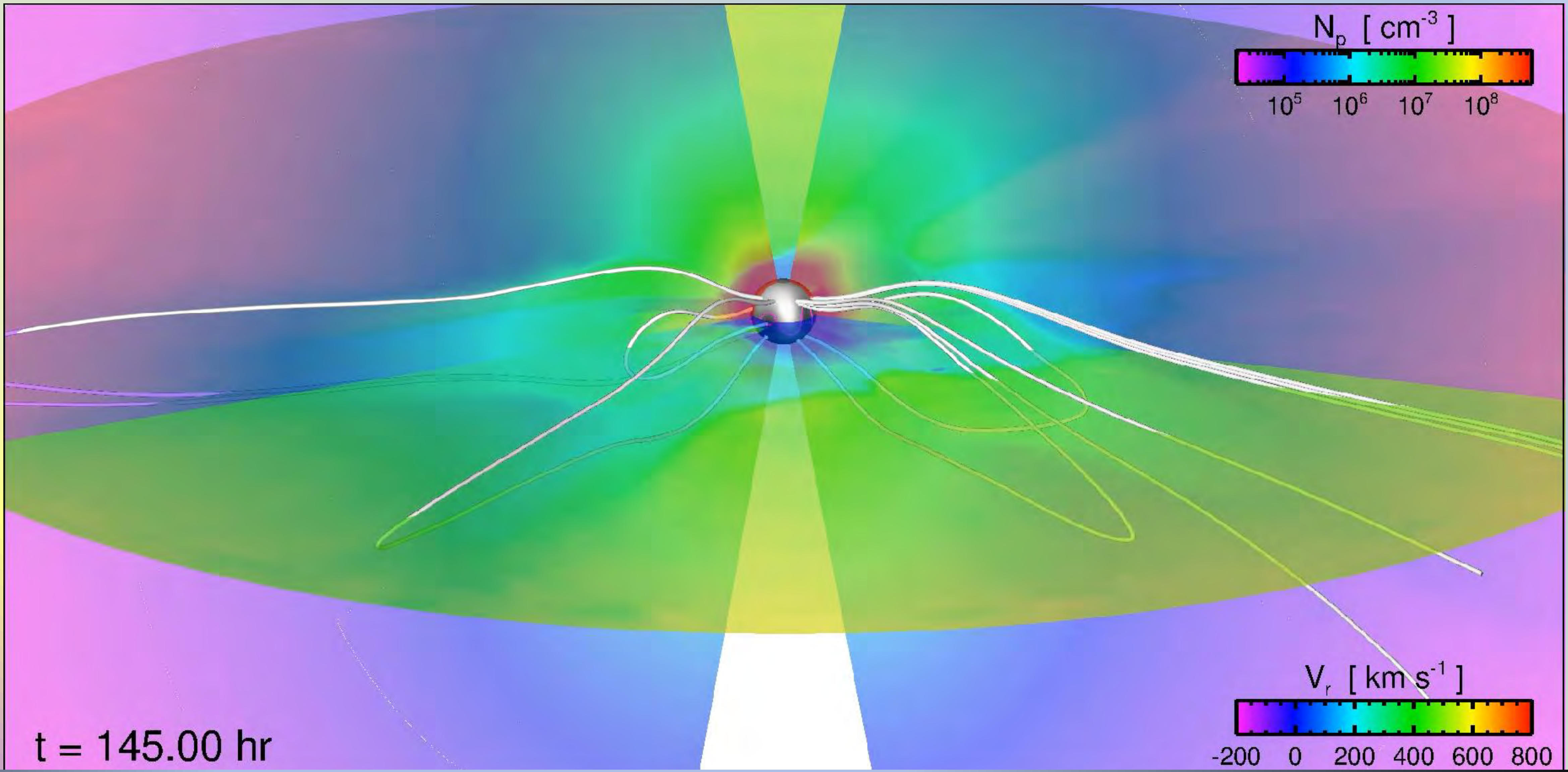
Many CMEs observed in situ with plasma, field, particle measurements appear to have this large-scale "flux rope" morphology

Since, magnetic flux conserved in ideal MHD, is there a direct relationship between solar reconnection flux and observed in-situ CME flux content?



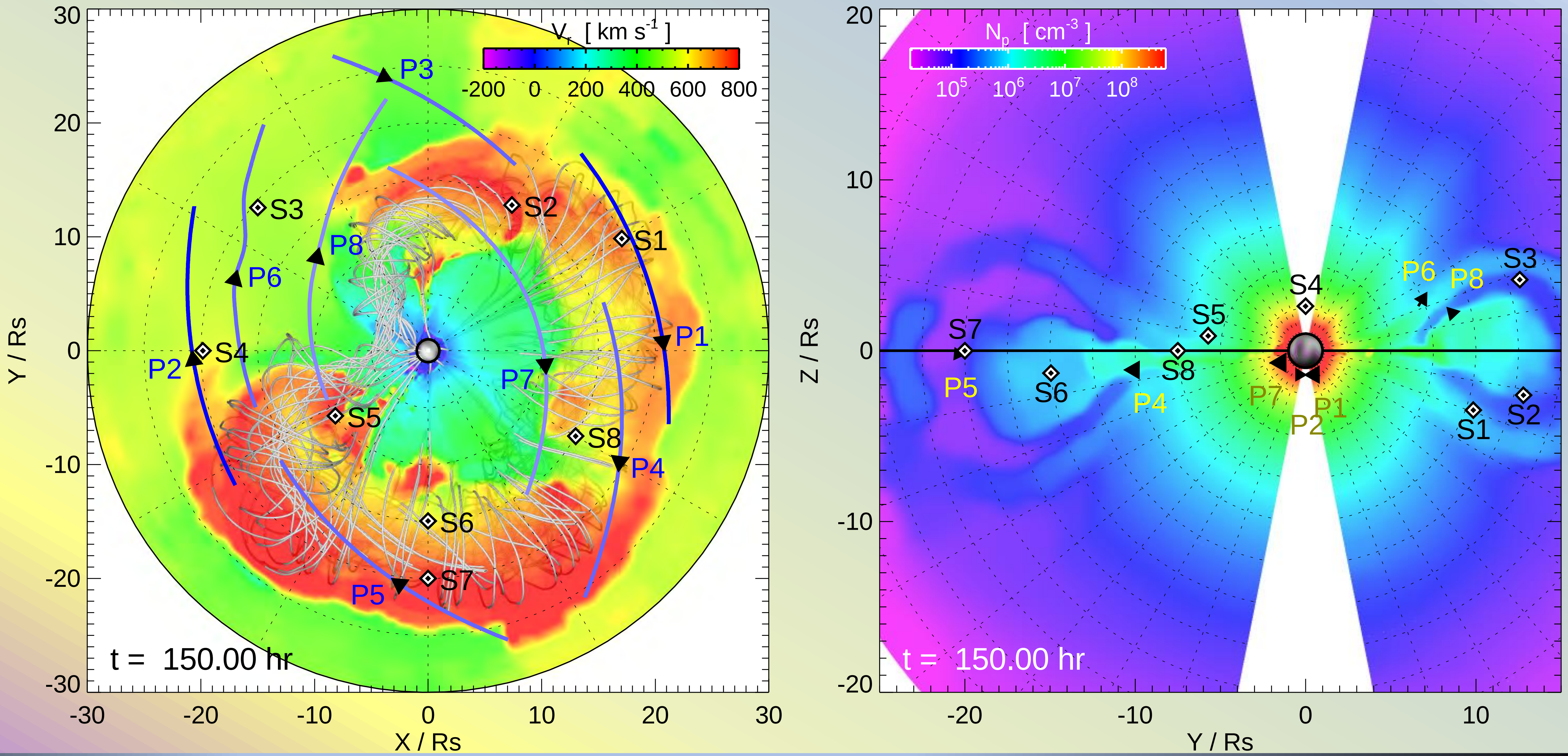
What is the in-situ magnetic structure of CMEs?

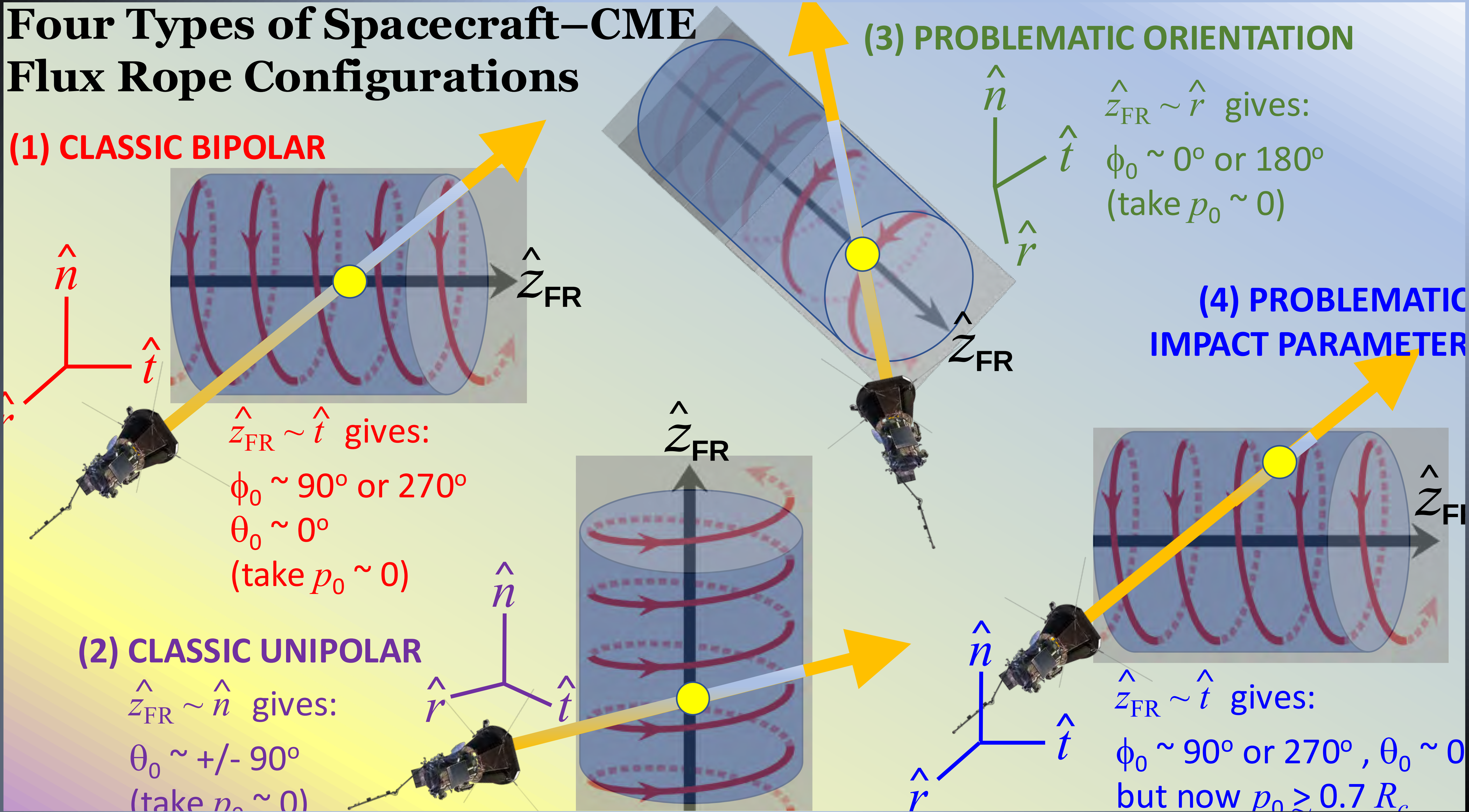
- Launched 360°-wide streamer blowout CME (literally entire streamer erupts, simple model for eruptive stellar superflare)
- Moderate-speed CME with V_r > ~800 km/s. Classic magnetic flux rope CME with 3-part density structure/cross-section



Synthetic Spacecraft Sampling through 4D Simulation Data

- Eight STATIONARY Observers (**S1—S8**) and eight PSP-like MOVING Observers (**P1—P8**)
- PSP-like Observer trajectories derived from PSP Encounters 7, 9, and future Encounter 23 (e.g. $9.8R_\odot < r_{PSP} < 20.4R_\odot$)



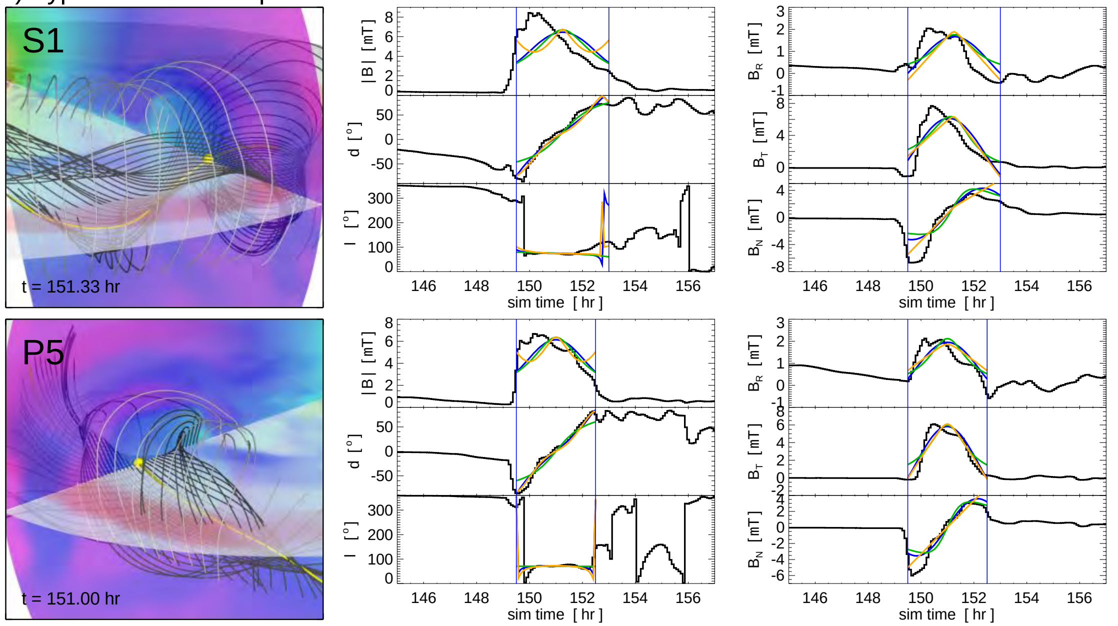


Four Types of Spacecraft–CME Flux Rope Configurations
(1) CLASSIC BIPOLAR
$\hat{n}$
$\hat{t}$
$\hat{z}_{FR}$
$\hat{z}_{FR} \sim \hat{t}$ gives:
ϕ_0 ~ 90° or 270°
θ_0 ~ 0°
(take p_0 ~ 0)
(2) CLASSIC UNIPOLAR
$\hat{z}_{FR} \sim \hat{n}$ gives:
θ_0 ~ +/- 90°
(take p_0 ~ 0)
$\hat{n}$
$\hat{r}$
$\hat{t}$
$\hat{z}_{FR}$
(3) PROBLEMATIC ORIENTATION
$\hat{n}$
$\hat{t}$
$\hat{r}$
$\hat{z}_{FR}$
$\hat{z}_{FR} \sim \hat{r}$ gives:
ϕ_0 ~ 0° or 180°
(take p_0 ~ 0)
(4) PROBLEMATIC IMPACT PARAMETER
$\hat{z}_{FR}$
$\hat{n}$
$\hat{t}$
$\hat{r}$
$\hat{z}_{FR} \sim \hat{t}$ gives:
ϕ_0 ~ 90° or 270°, θ_0 ~ 0
but now $p_0 \geq 0.7 R_c$

In-situ Flux Rope Model Fitting (LFF,GH,CCS) to MHD Data

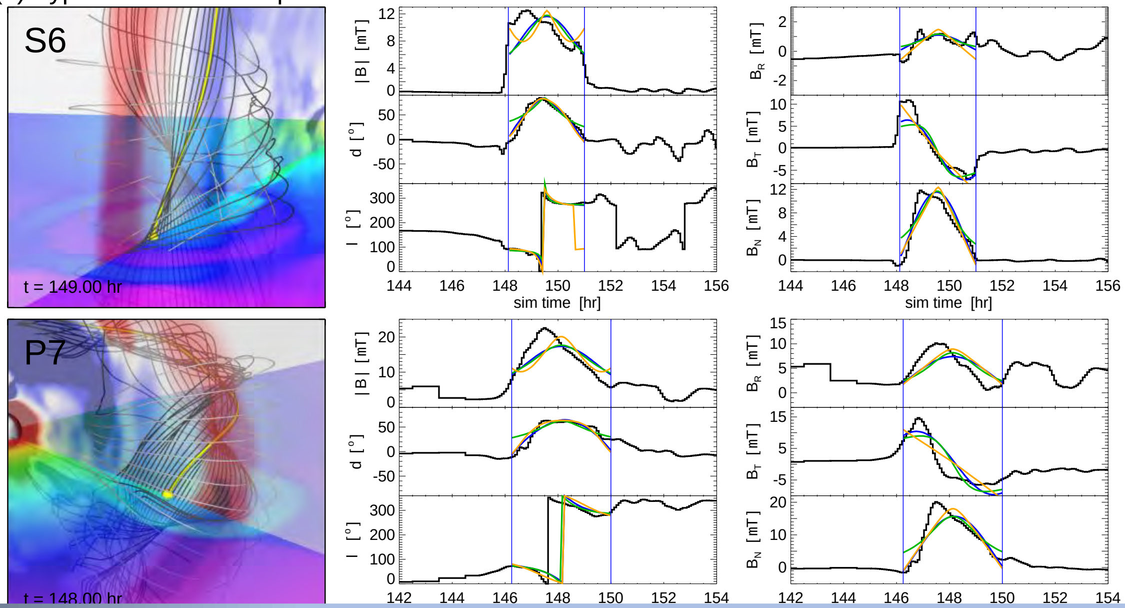
Classic Bipolar

(a) Type 1 -- Classic Bipolar



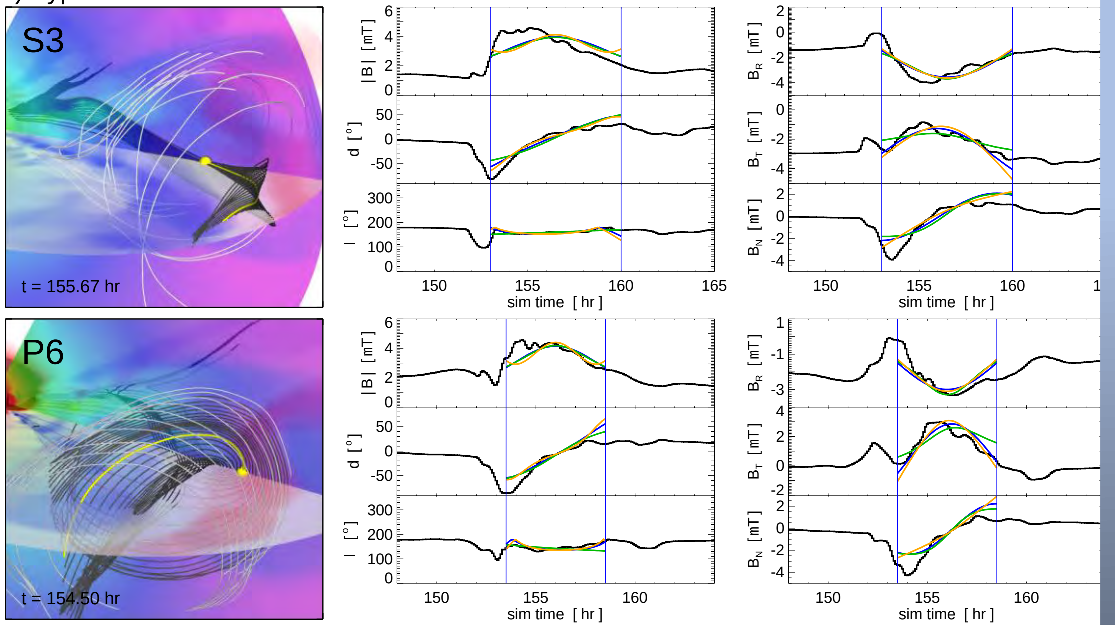
Classic Unipolar

(b) Type 2 -- Classic Unipolar



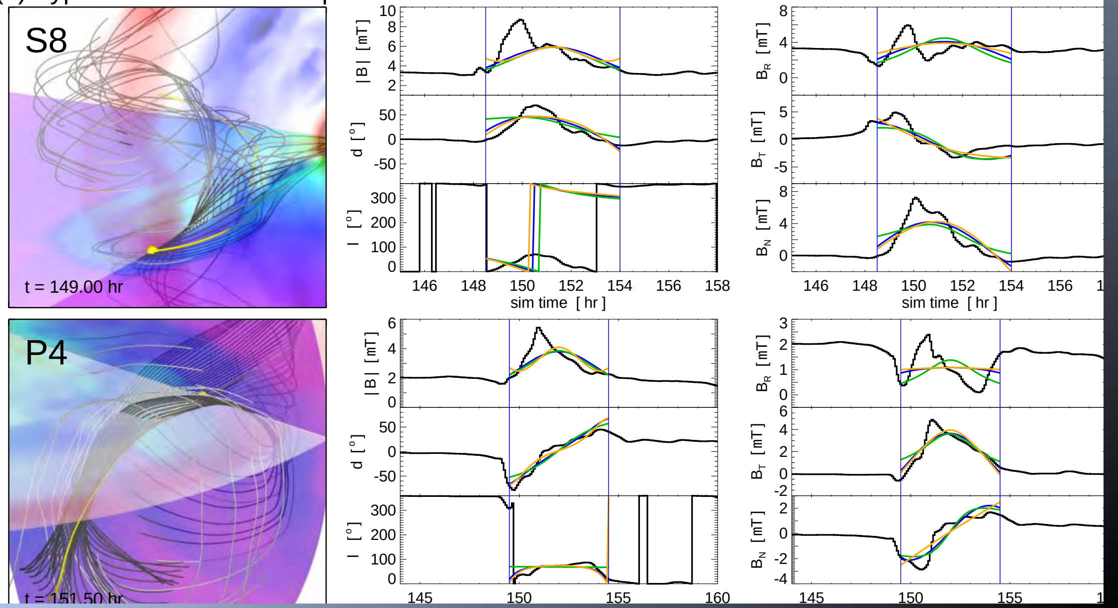
Problem Orientation

(a) Type 3 -- Problematic Orientation



Problem Impact

(b) Type 4 -- Problematic Impact Parameter



Cf. In-situ FR Model Flux Content & MHD Estimates

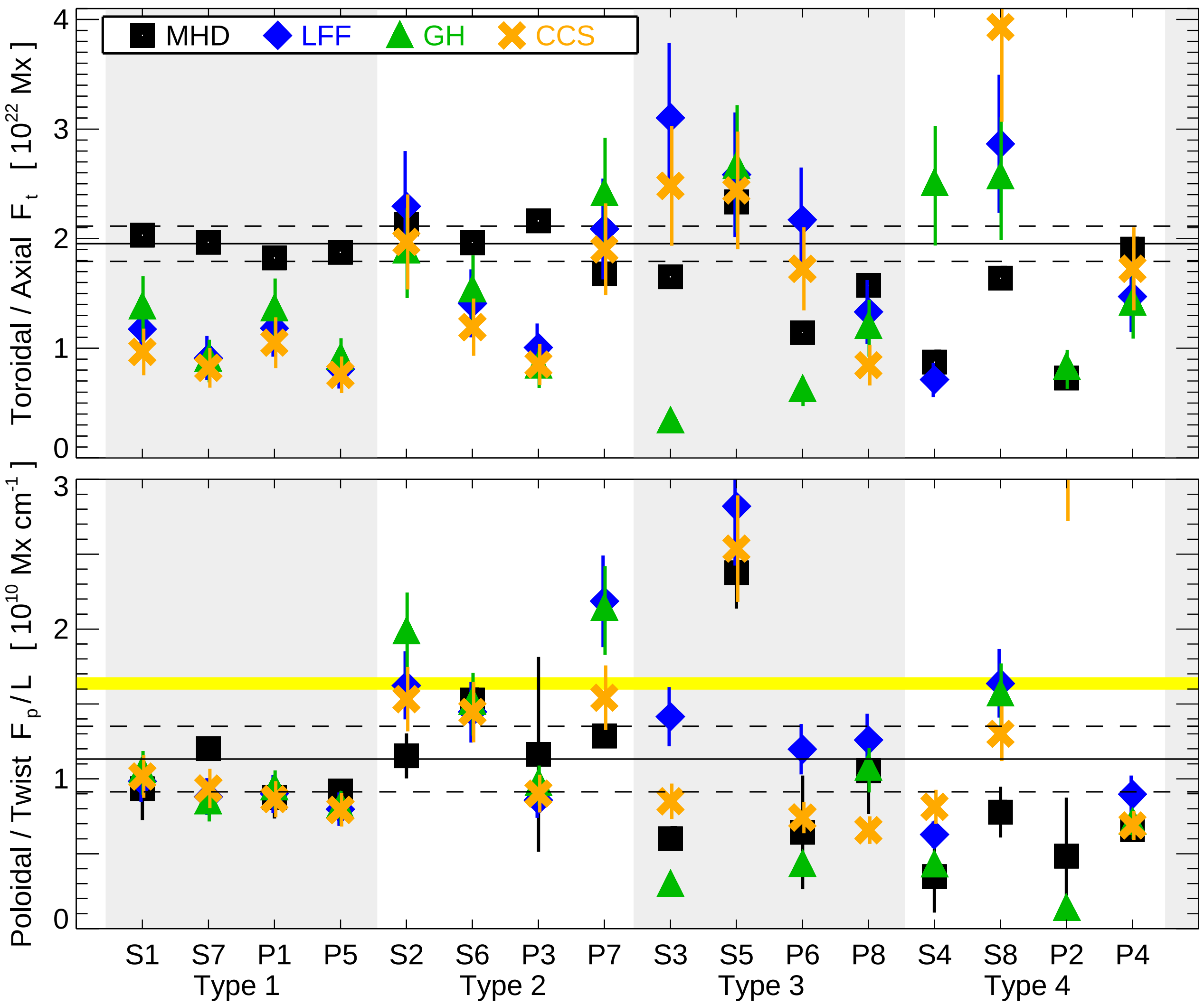
In-situ models have analytic expressions for toroidal/axial flux (Φ_t) and poloidal/twist flux per unit length (Φ_p/L) based on fit parameters. How close are these to MHD values?

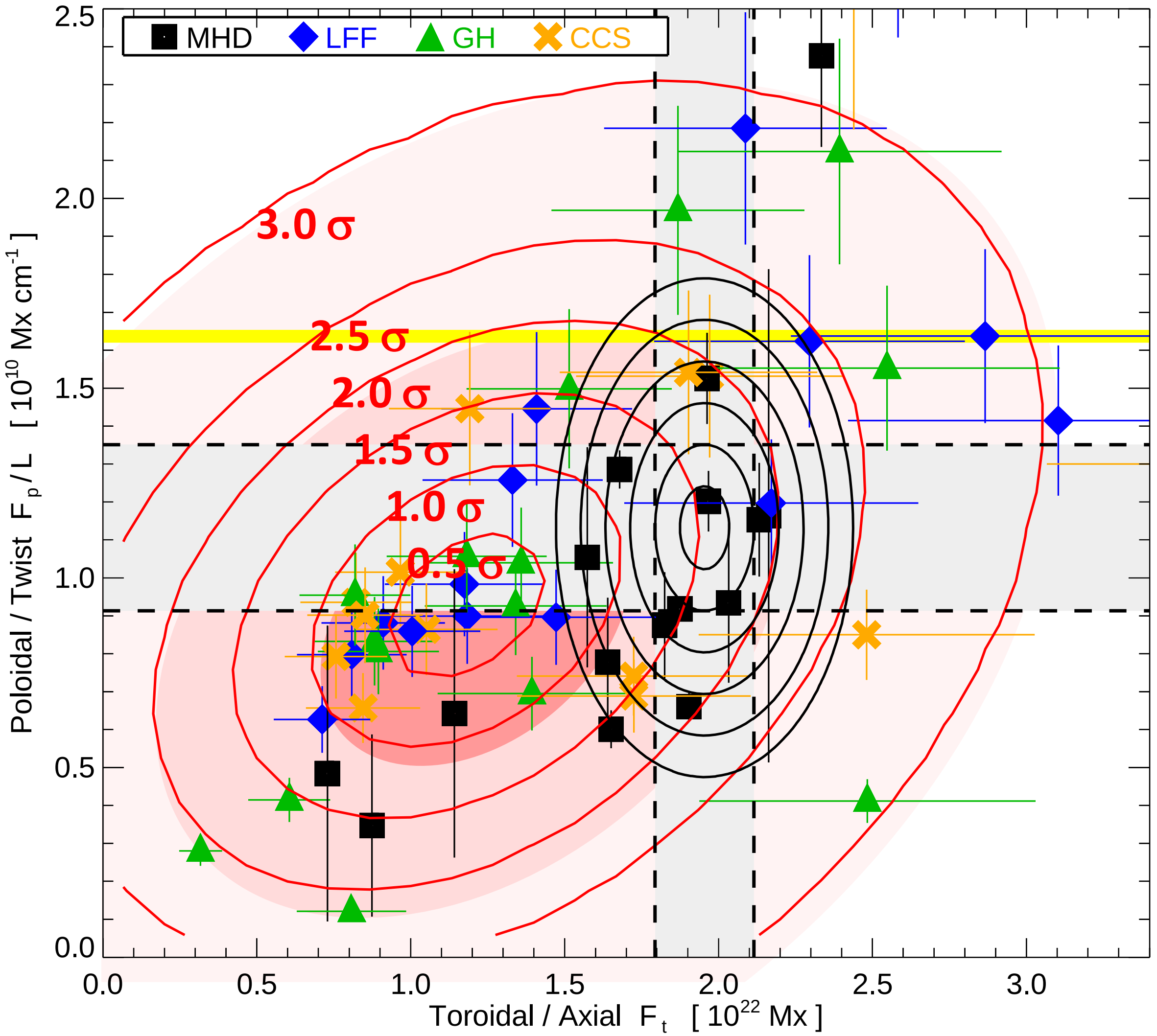
- Classic Type 1&2 cfg better fit than Problematic Type 3&4...

$$\Phi_t^{LFF} = (2J_1(x_{01})/x_{01})B_0\pi R_c^2, \qquad (\Phi_p/L)^{LFF} = (1/x_{01})B_0 R_c,$$

$$\Phi_t^{GH} = \ln\left[1+\tau^2 R_c^2\right] B_0\pi(1/\tau)^2, \qquad (\Phi_p/L)^{GH} = \ln\left[1+\tau^2 R_c^2\right] B_0(1/2\tau),$$

$$\Phi_t^{CCS} = (1/3)B_0\pi R_c^2. \qquad (\Phi_p/L)^{CCS} = (1/4)(\mu_0 j_z^0 R_c) R_c.$$





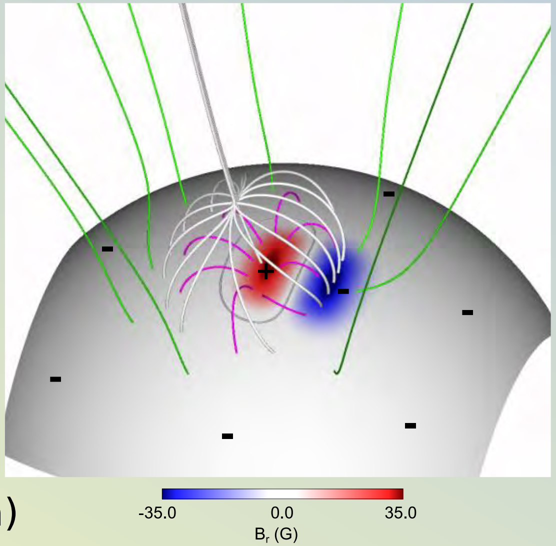
(Idealized) Pseudostreamer CME Eruption

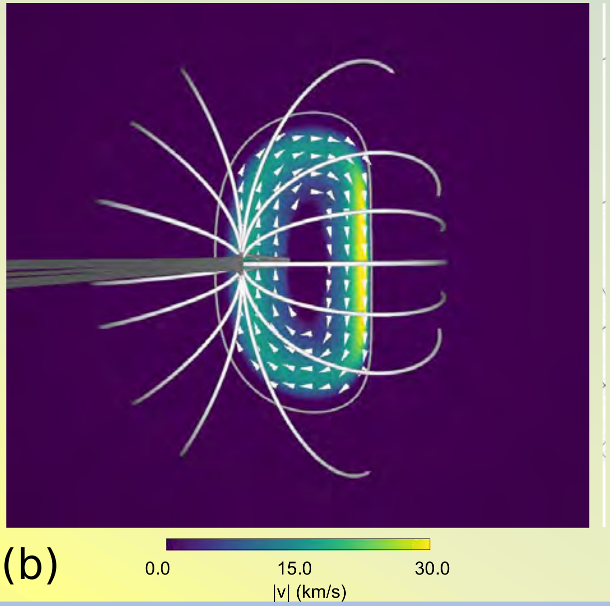
Wyper et al. (2024, in prep) ran an idealized pseudostreamer CME simulation. *Second simplest possible coronal source region!*

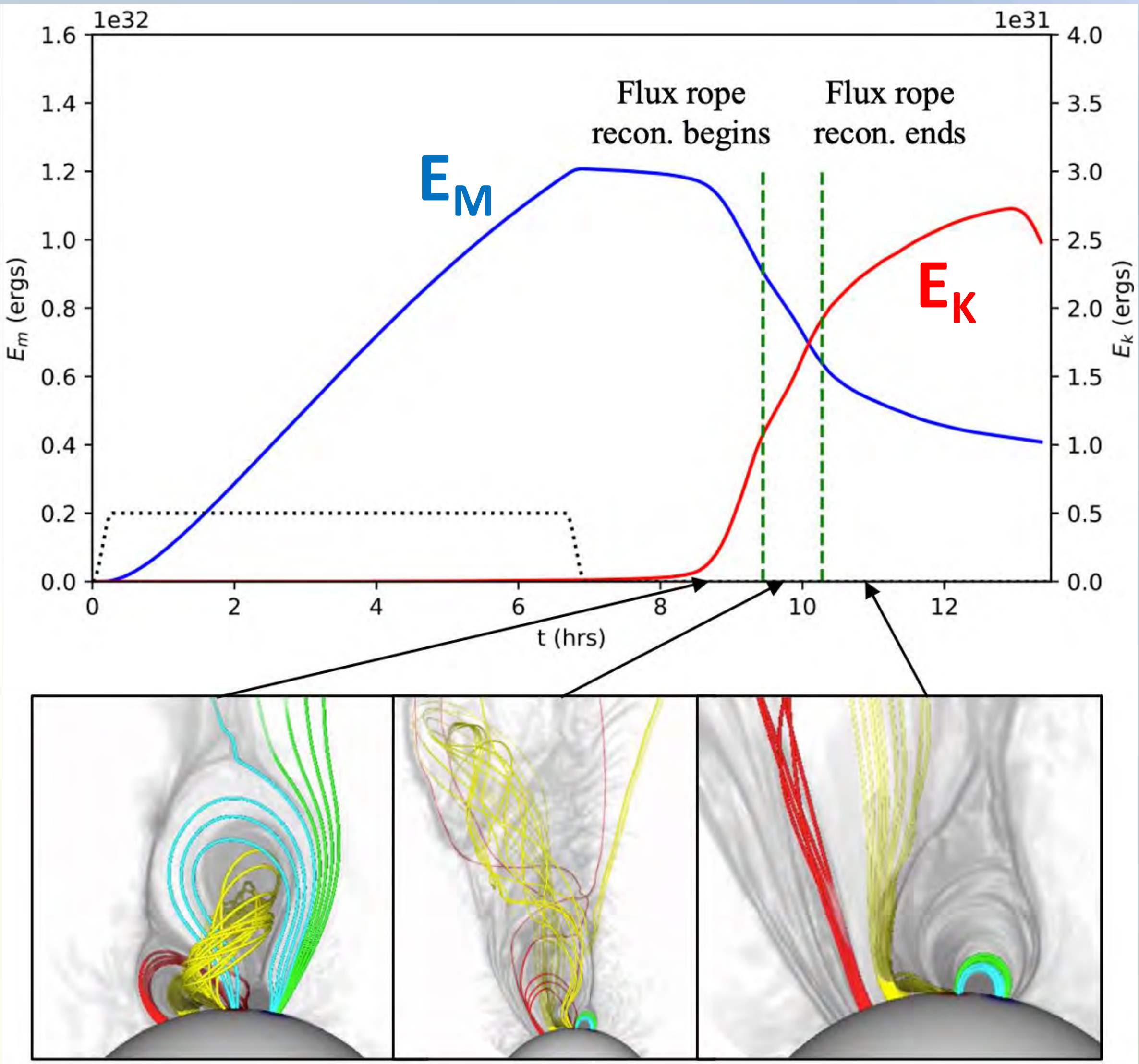
* Uniform, single polarity open field with embedded bipolar AR flux system. Classic spine-fan-separatrix dome boundary between open and closed flux.

* Energize AR flux with idealized, Br-preserving flows at lower boundary. Topologically identical to extremely large "coronal jet" configuration (e.g. see Wyper et al. 2022)

During eruption, one leg of the CME reconnects with open field. This should be universal process in essentially all PS CMEs!

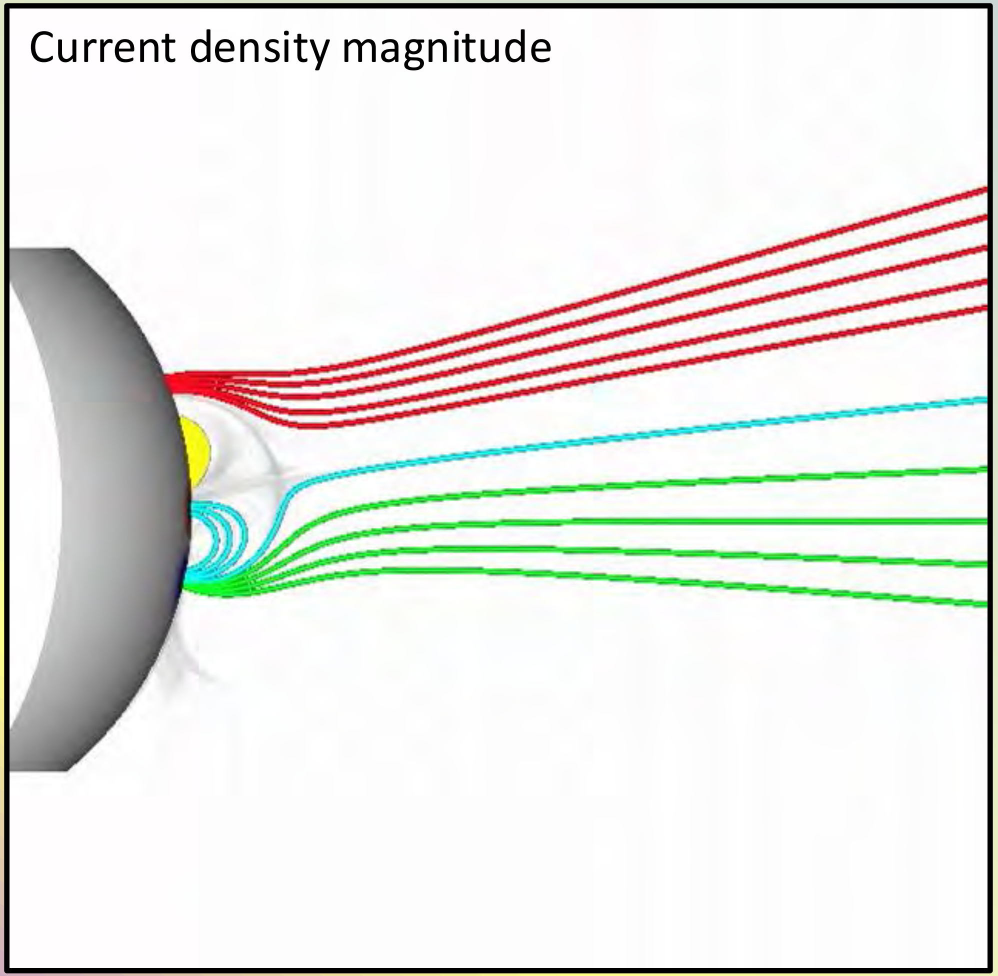


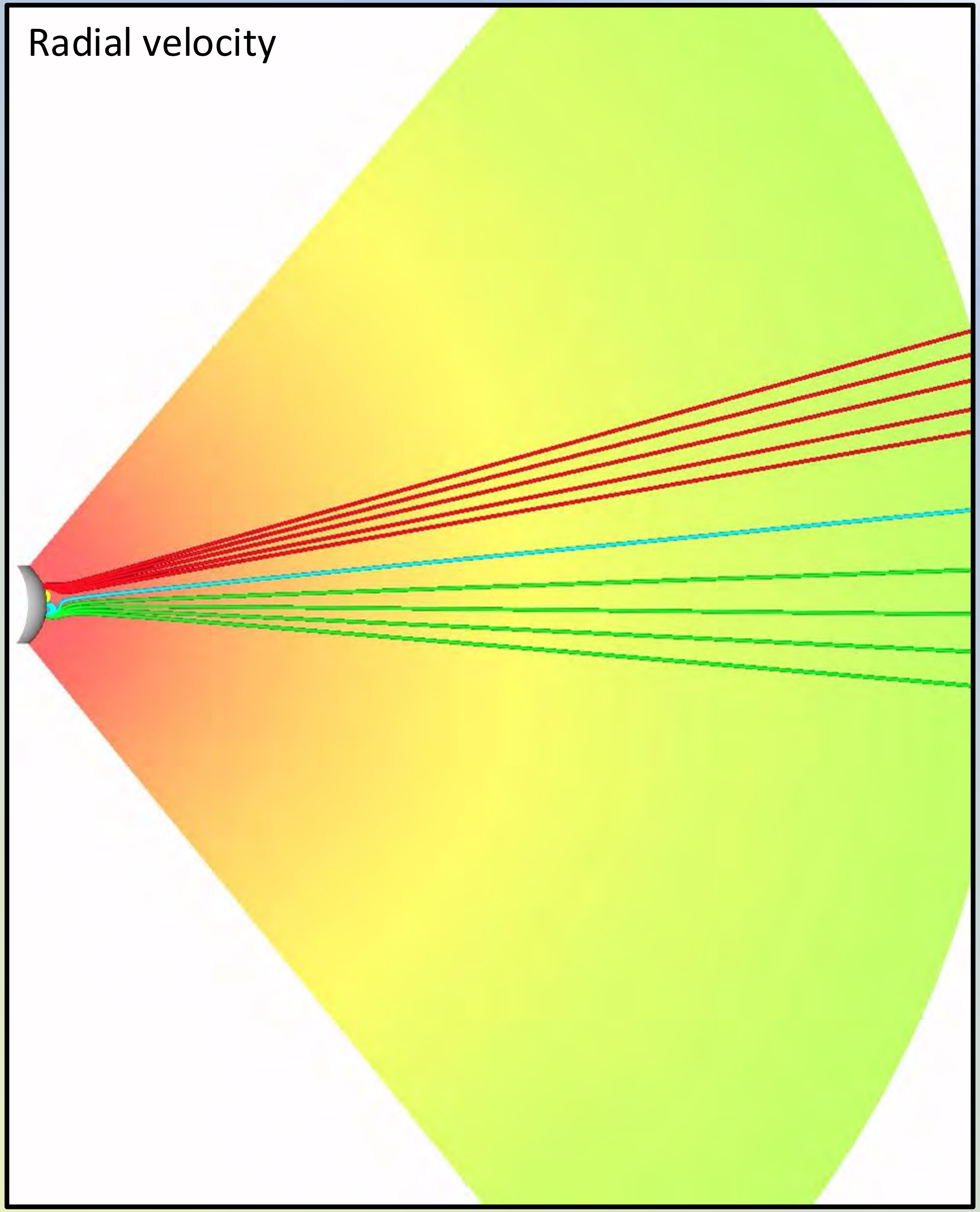




Pseudostreamer CME Eruption

Wyper et al. (2024, in prep) ran an idealized pseudostreamer CME simulation: Classic "magnetic breakout" CME eruption! Eruption dynamics similar to e.g. Masson et al. (2019), Wyper et al. (2021), etc.





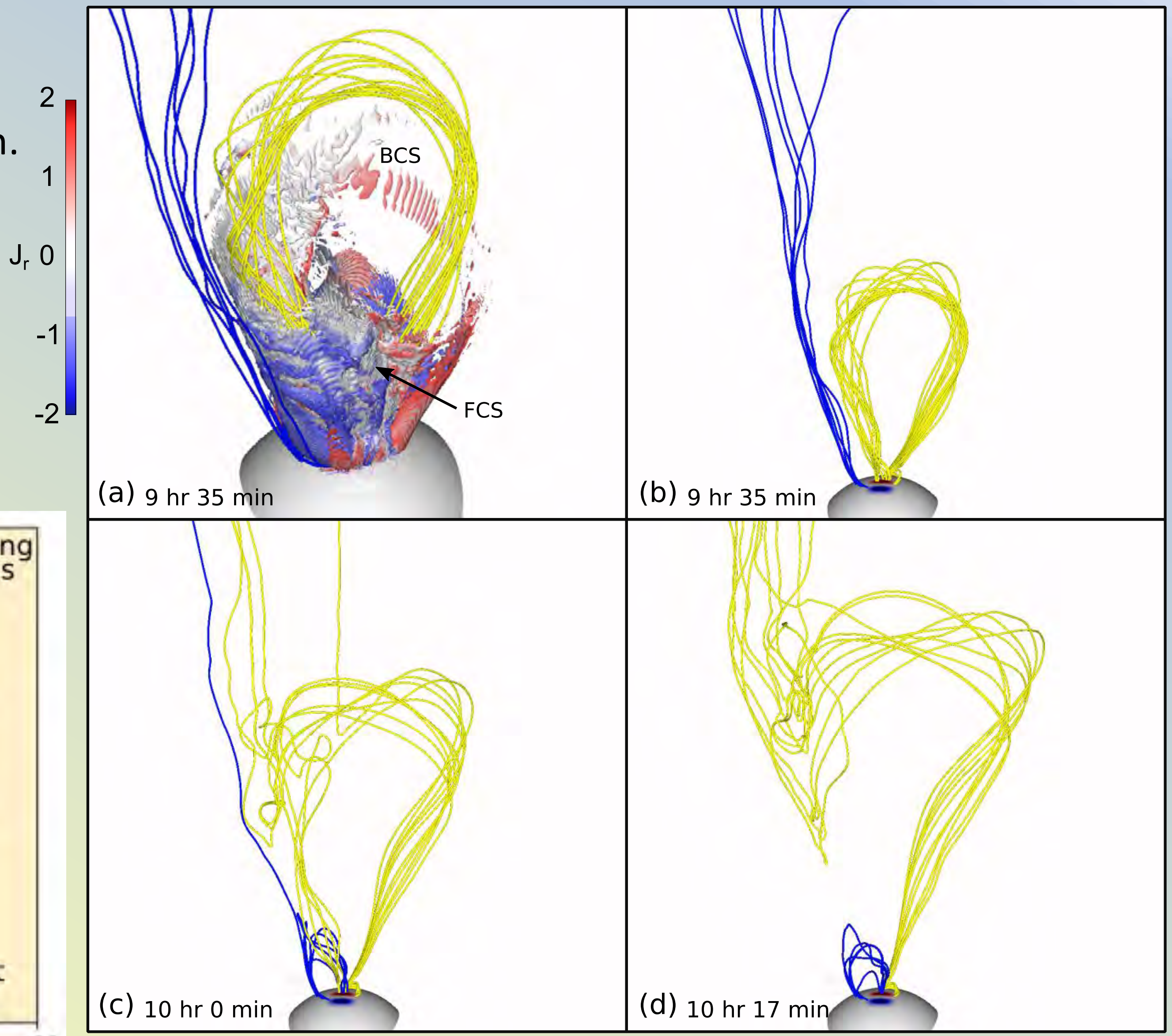
PS CME Eruption: CME Flux Rope Leg "Disconnection"

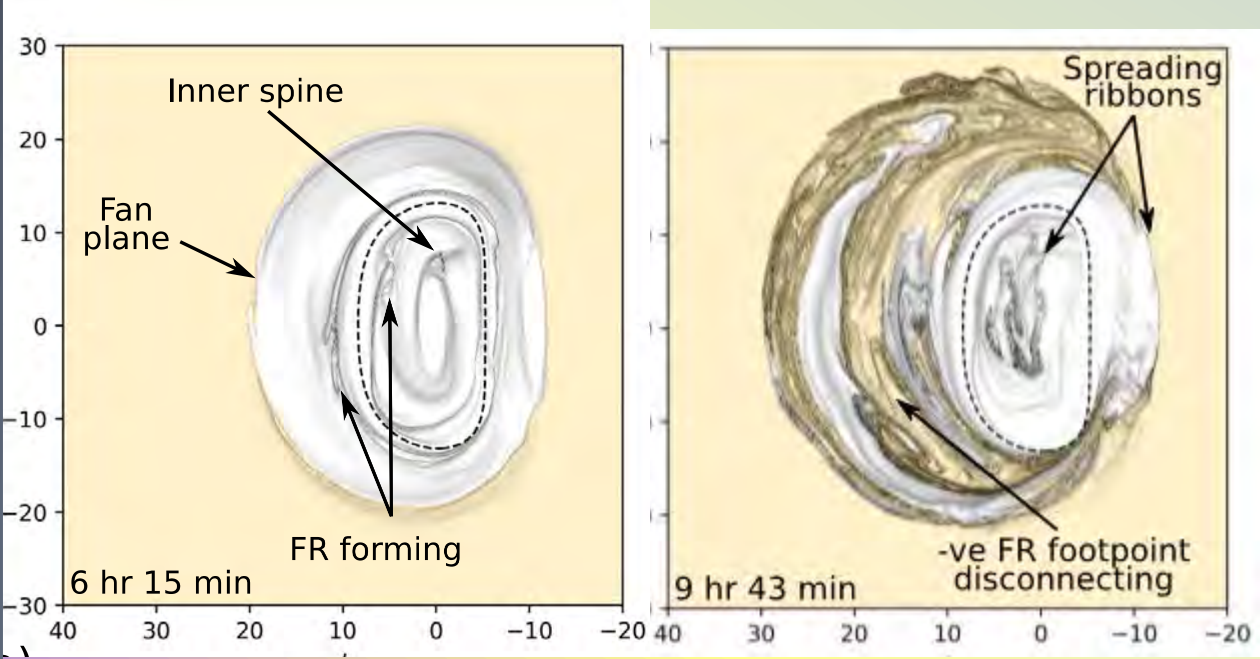
* Simple source region topology still leads to relatively complex eruption. All the same features as CSHKP, just more compact, fully 3D, with no shortage of fine-scale/meso-scale structure generated during reconnection.

* CME flux rope leg disconnection (reconnection with open field) gives rise to large-scale "question mark" topology early on

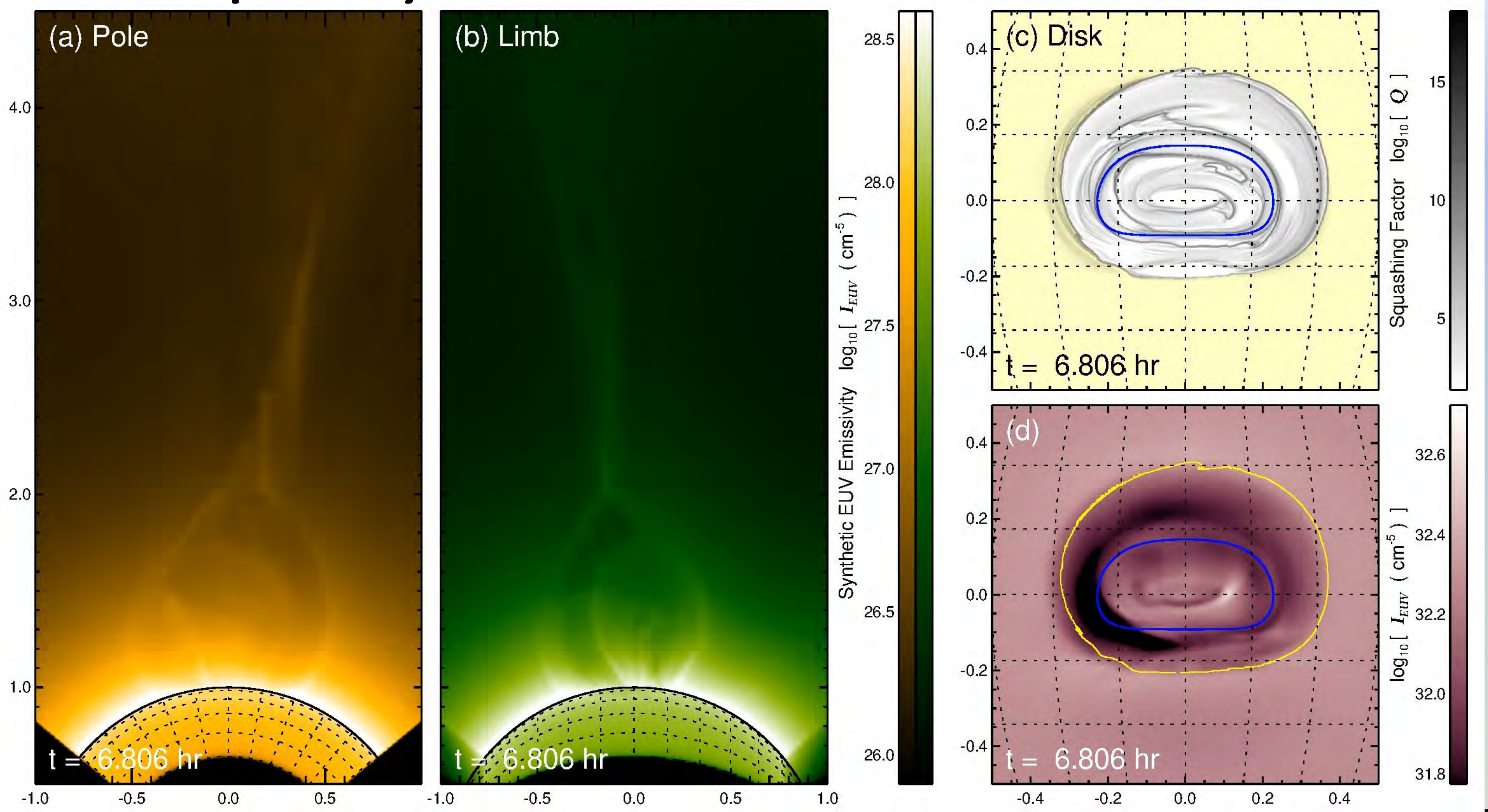
* WHAT DOES THIS LOOK LIKE IN SYNTHETIC OBSERVATIONS? SIMPLE? COMPLEX? BOTH?!?!

Wyper et al. (2024, in prep)





PS CME Eruption: Synthetic EUV Structure

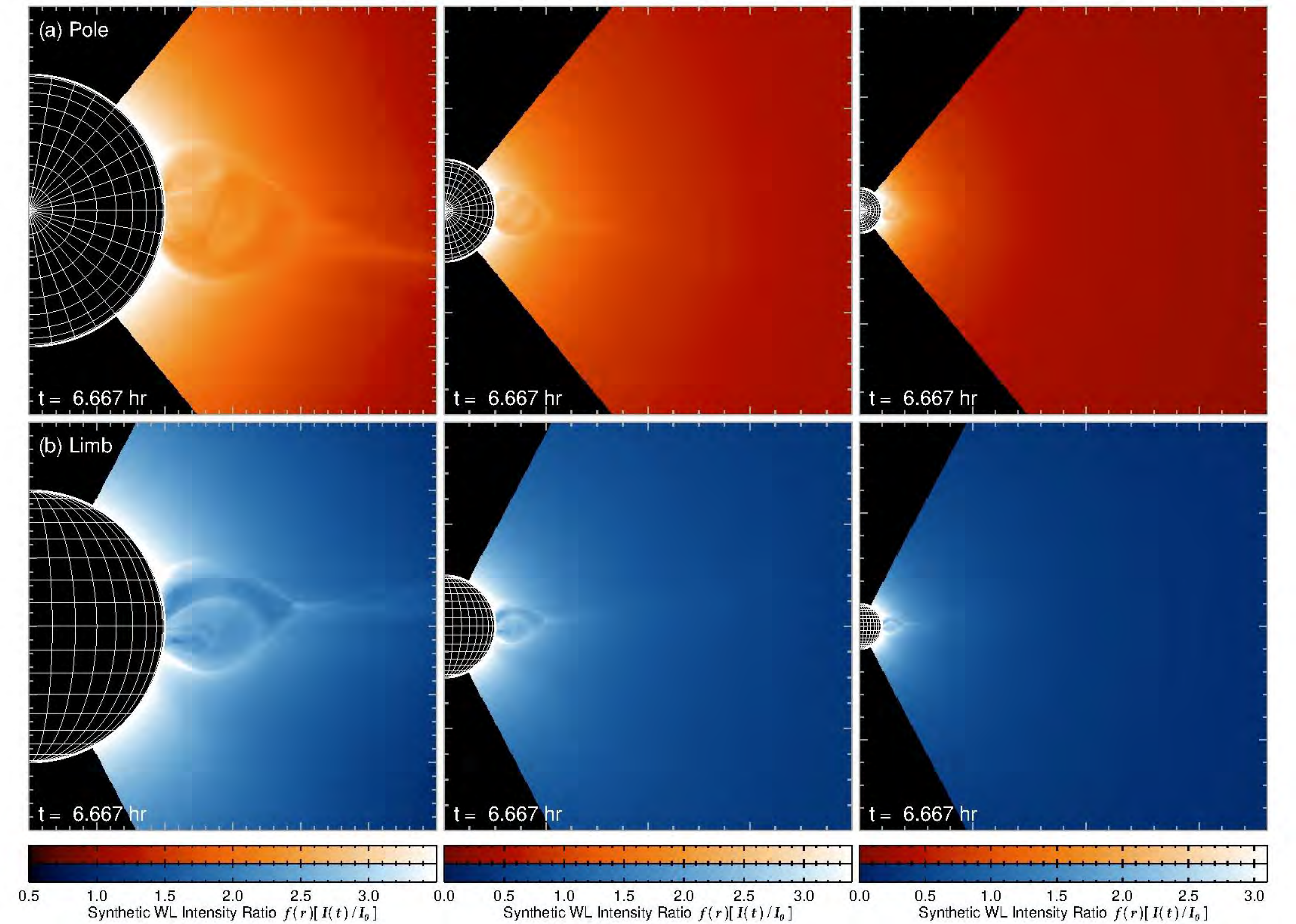


PS CME Eruption: Synthetic WL Structure

Limb View:
narrow jet-like CMEs

Polar View:
broad, fan-shape "unstructured" CMEs

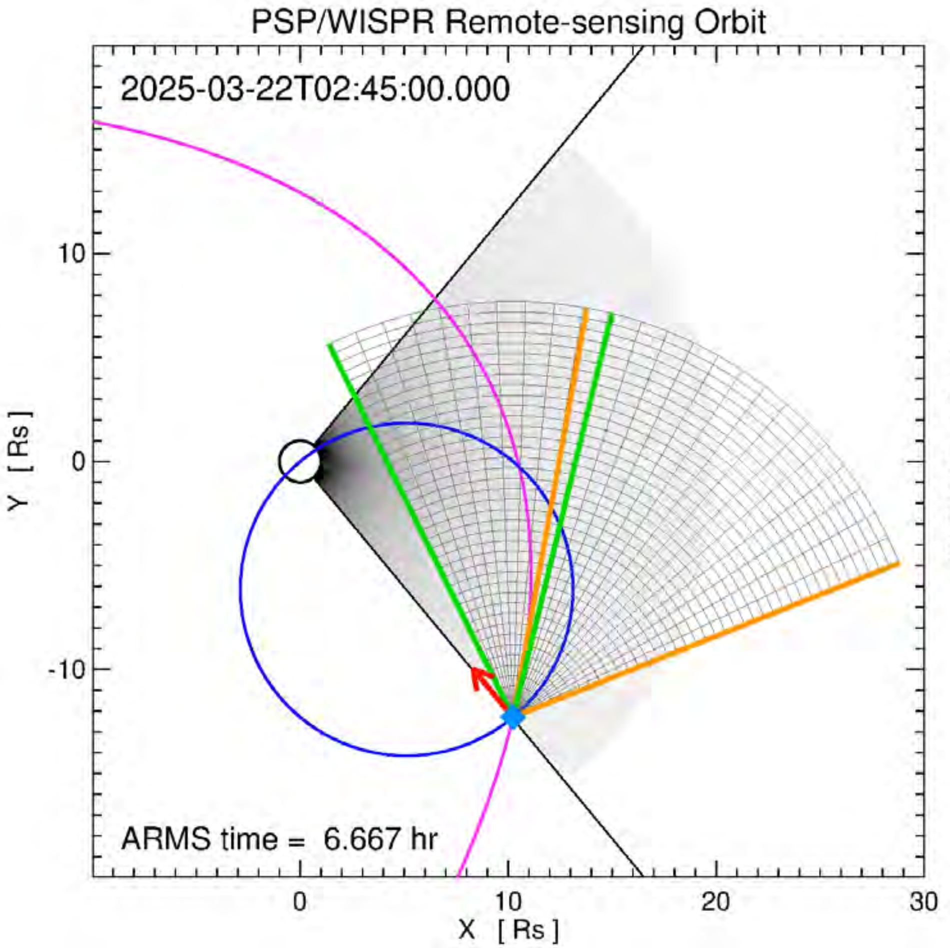
Because of the large-scale twist introduced + released during CME, rxn jet outflow ROTATES in space, mixing "viewpoints"

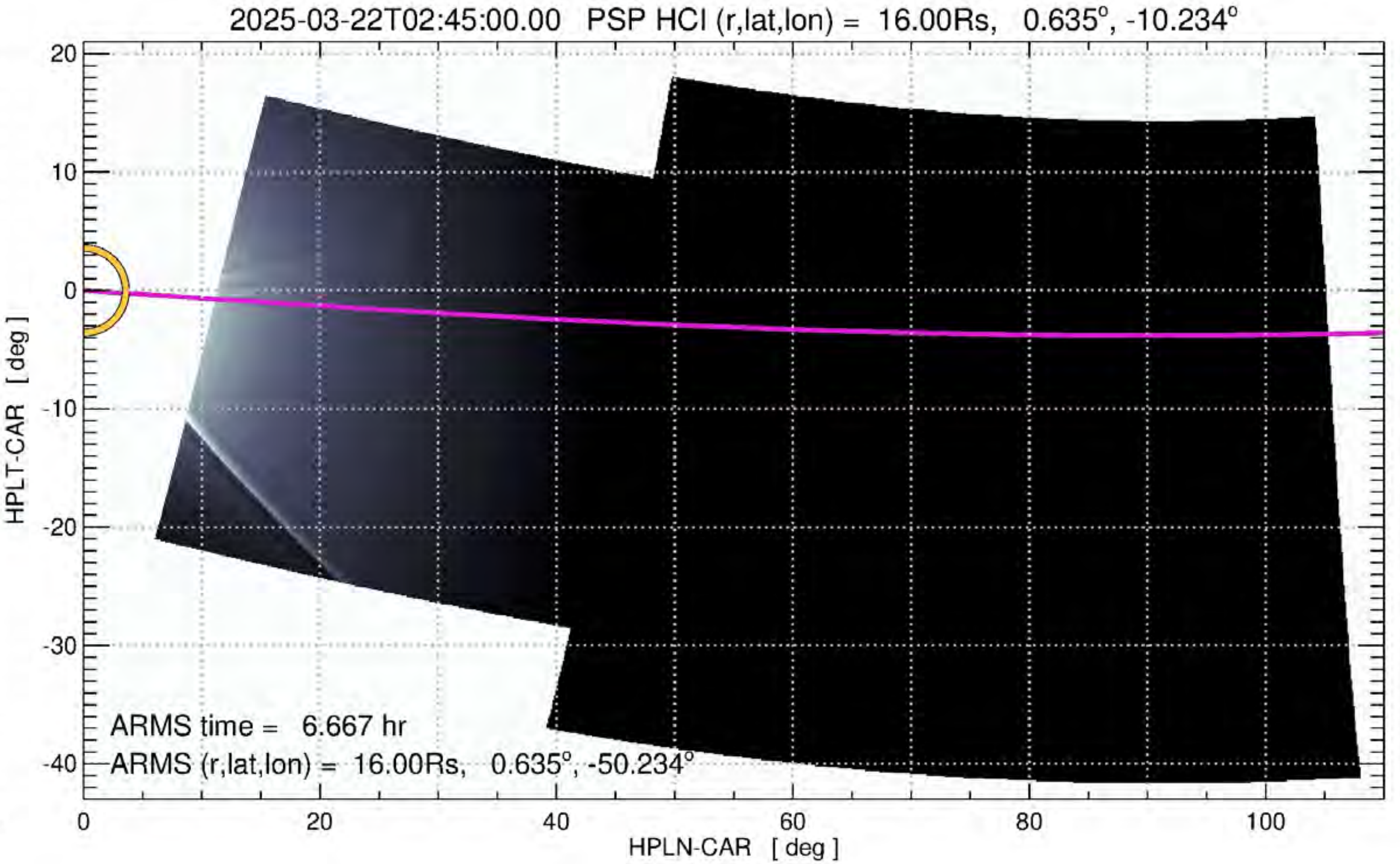


PS CME Eruption: Synthetic WISPR Imaging View

* Let's see what this idealized PS CME would look in Parker Solar Probe/WISPR imaging

Left panel: fake PSP orbit (based on E23 trajectory), rotated and lined up with MHD simulation domain
Right panel: PSP/WISPR-I & WISPR-O FOV white-light intensity (with "enhancement" processing---stay tuned for details)





PSP CME In-situ:
Flank Encounter

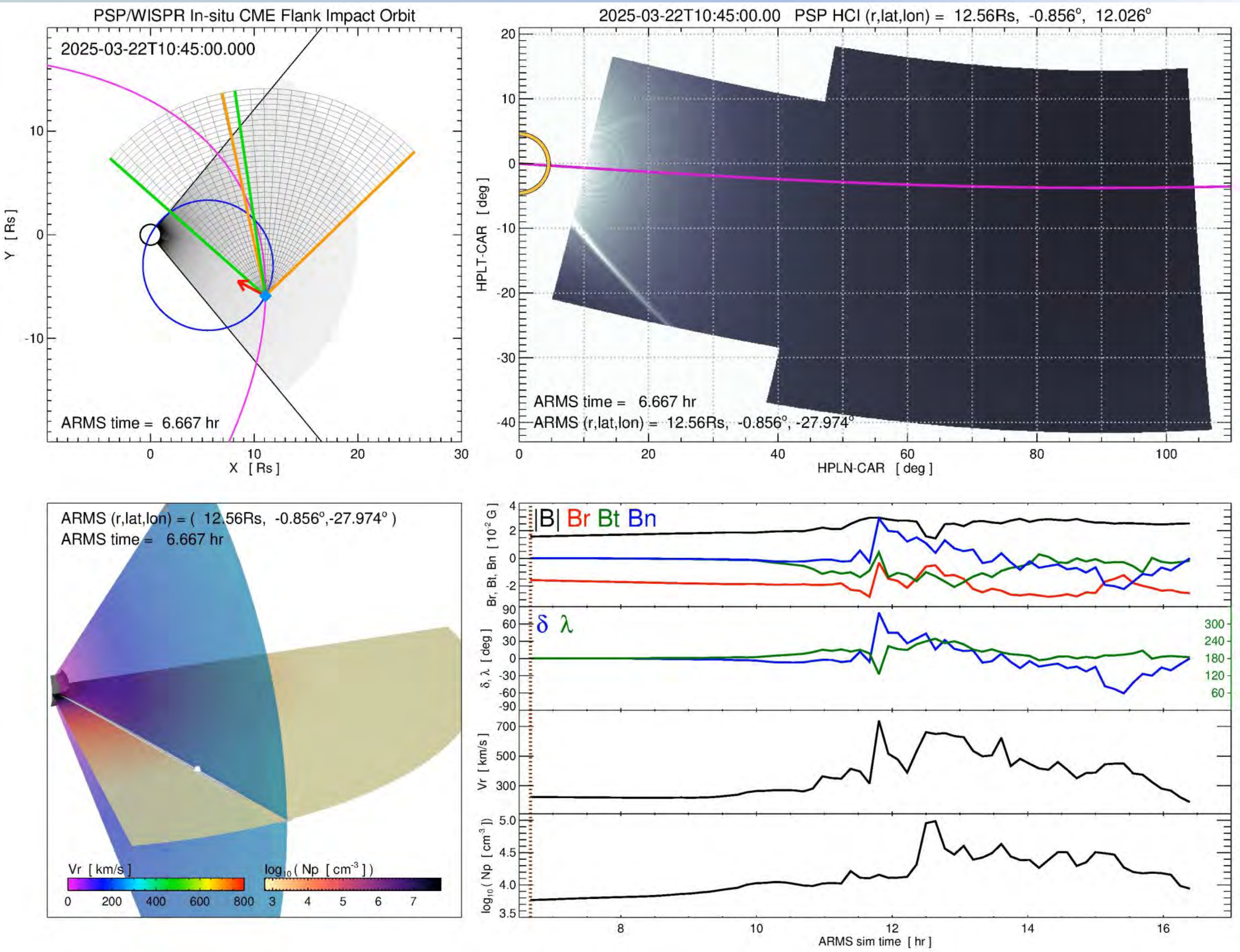
Synthetic spacecraft in-situ observations of bulk plasma & field properties

* Enhanced B magnitude

* Long-duration "rotation" in field components, e.g. δ goes from +60 to -60 deg, BN component bipolar

* Declining speed profile

* Density enhancement (need to double check the plasma β—does this look like a magnetic cloud/flux rope?)



PSP CME In-situ:
Central Encounter

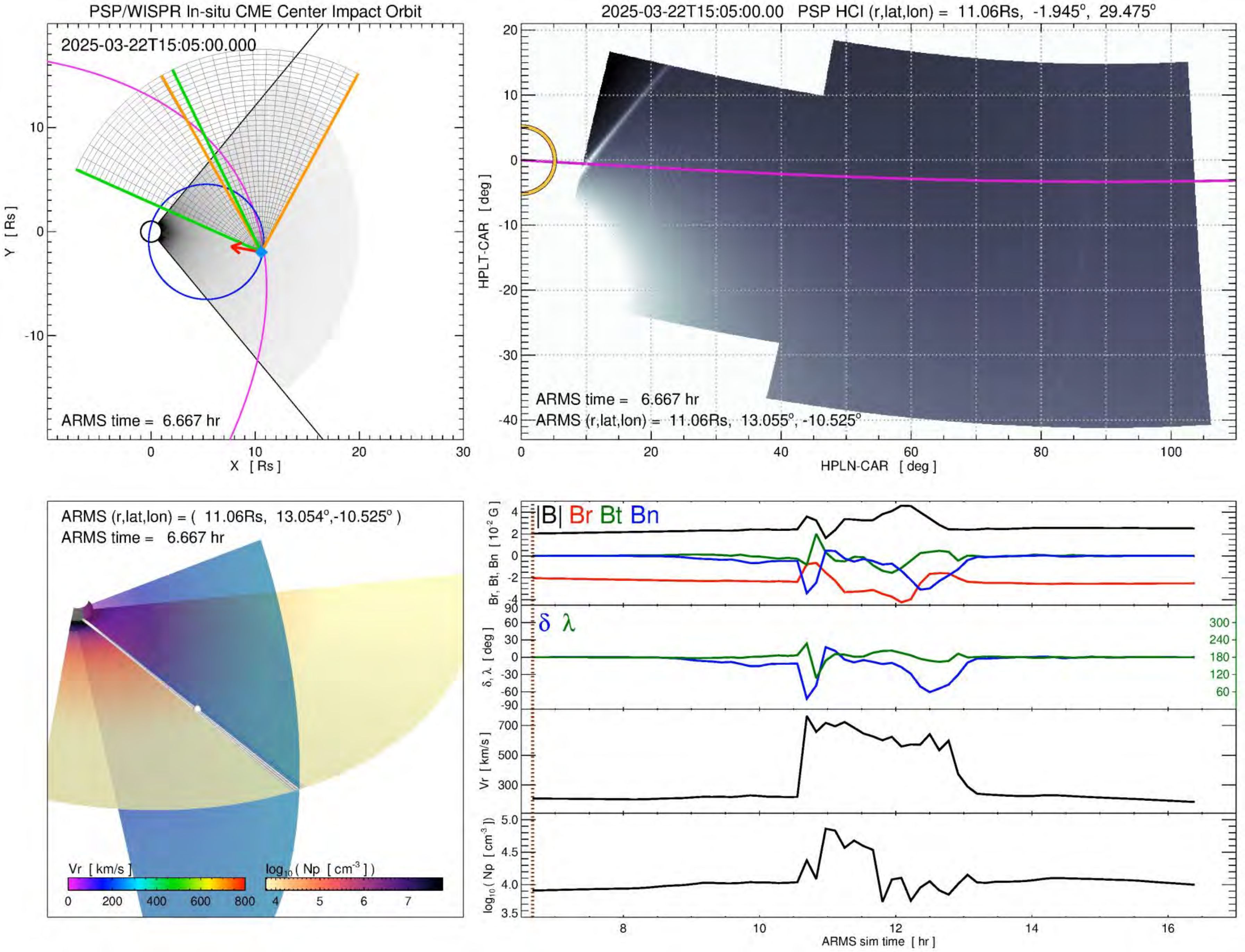
Synthetic spacecraft in-situ observations of bulk plasma & field properties

* Half-sheath, half-ejecta!

* Enhanced B magnitude

* Shorter-duration, rotation in field components, δ goes from 0 to -60 deg and back, BN component unipolar (axis), BR,BT rotation (twist component)

* Density high in sheath, low in magnetic core (low β)!



Modeling the Evolution of ICMEs During Propagation

- "Isolated" CME evolution in a backgound solar wind

  Rotation, ***deflection***, ***deformation*** of original classic 3-part CME/FR structure occurs in both the corona and heliosphere. The good news is that magnitude of these effects may decrease significantly w/ distance?

- CME–solar wind (HCS/HPS) interaction

  Flux "erosion"/reconnection resulting, in part, from interaction with HCS/HPS structure

- CME–solar wind CIR/SIR/fast stream interaction

  In addition to processes above, may also include momentum transfer (increased drag/deceleration CME runs into slower/denser) or compression & acceleration of ejecta (fast wind stream runs into CME), affecting arrival times, possible distortion, etc

- CME–CME Interaction

  Now also includes magnetic reconfiguration of pre-interaction ICMEs

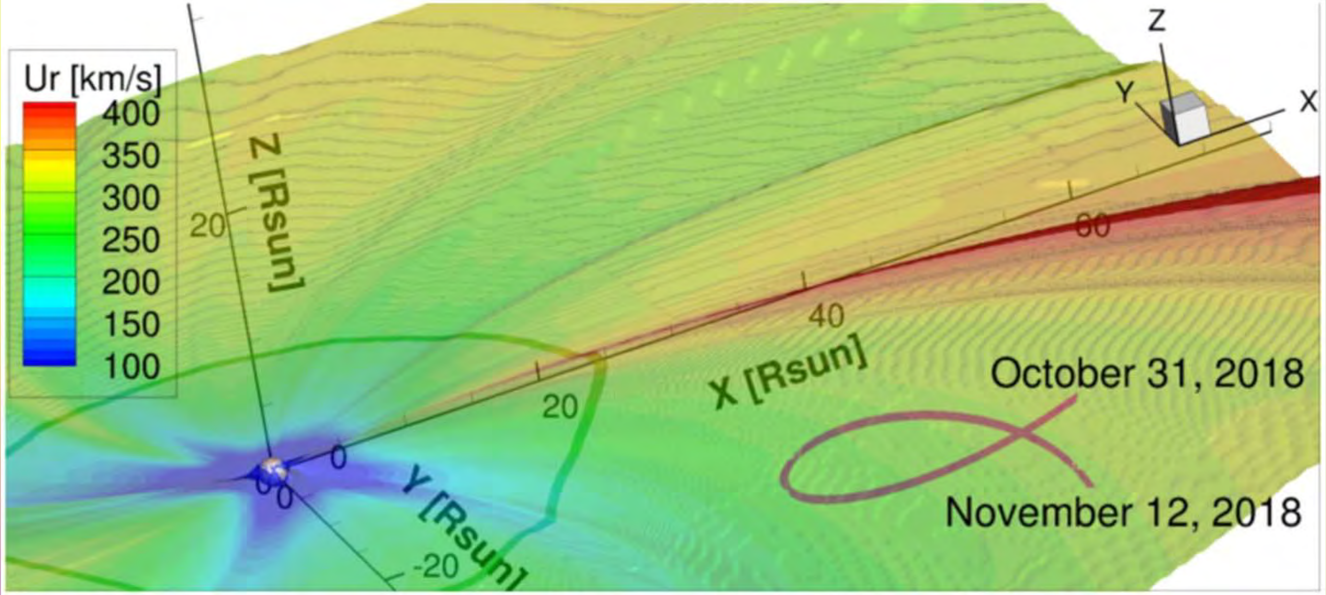
Modeling the Evolution of ICMEs During Propagation

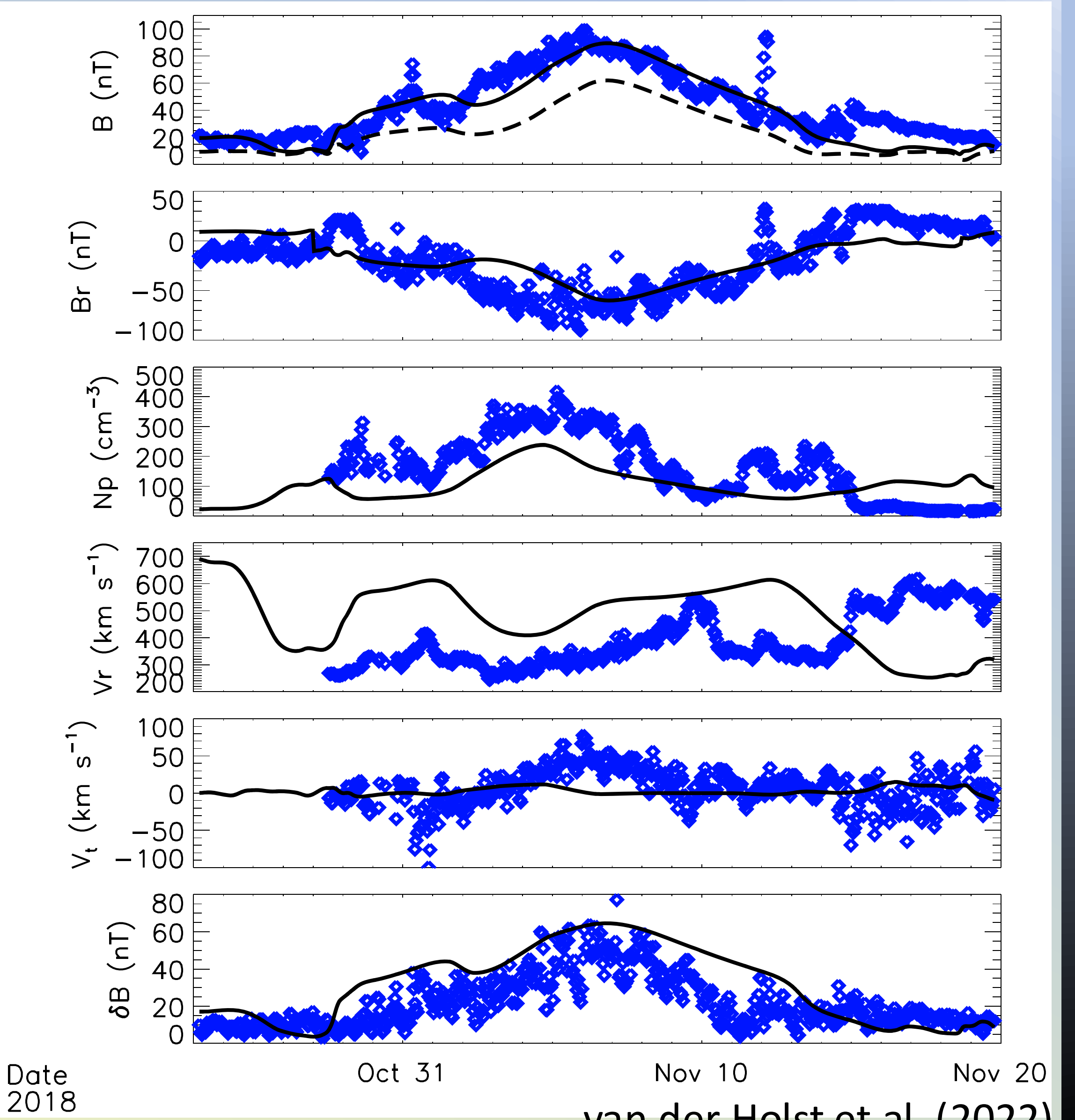
BACKGROUND SOLAR WIND:

van der Holst et al. (2022) using PSP data to constrain/validate AWSoM solar wind model in Michigan SWMF framework. δB is level/magnitude of "turbulence" from wave-heating part of steady-state wind...

(This is about as sophisticated a solar wind treatment as anyone has put into a global MHD model)

Agreement good... but obviously not perfect!



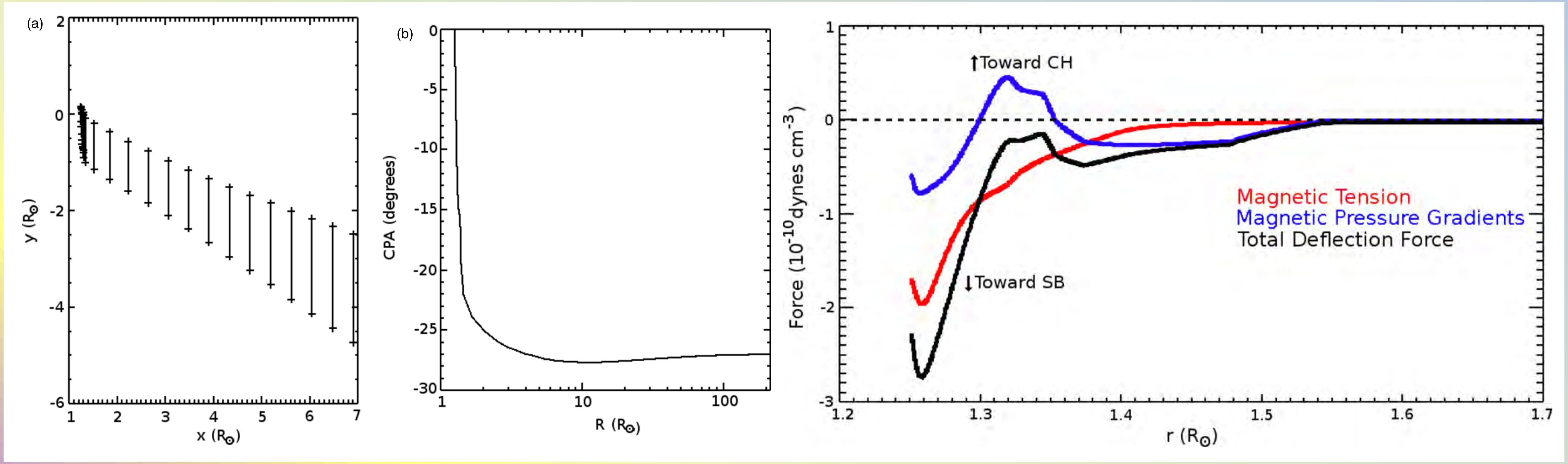


van der Holst et al. (2022)

Modeling the Evolution of ICMEs During Propagation

Rotation, ***deflection***, ***deformation*** of original classic 3-part CME/FR structure occurs in both the corona and heliosphere.

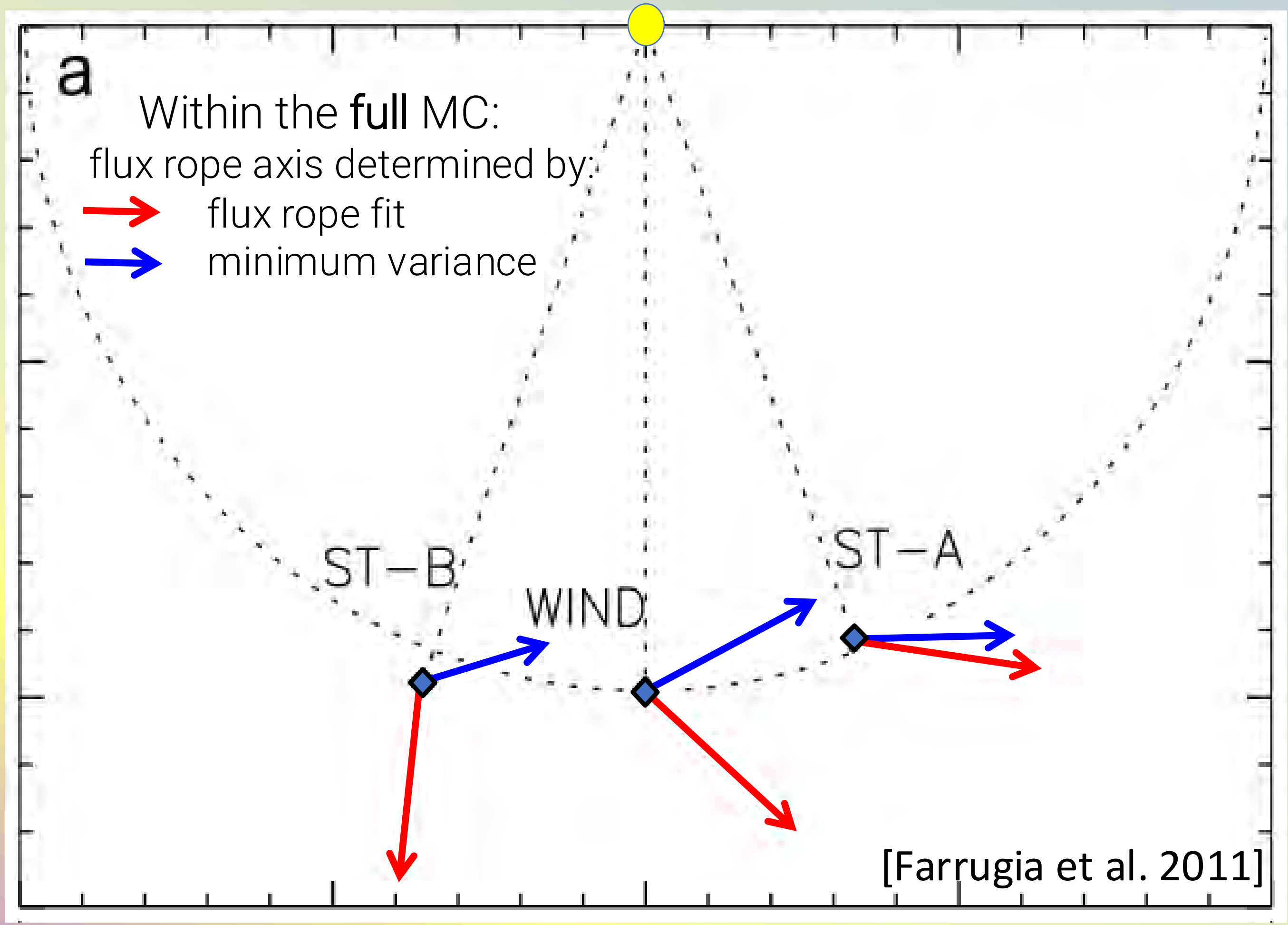
Kay et al. (2013) have developed OSPREI suite of coupled propagation models to tackle CME FR rotation and deflection based on magnetic forces of surrounding coronal field configuration(s). E.g. 30° deflection within 2Rs, by r >10Rs almost no further deflection.



Modeling the Flux Rope Structure of CMEs/ICMEs

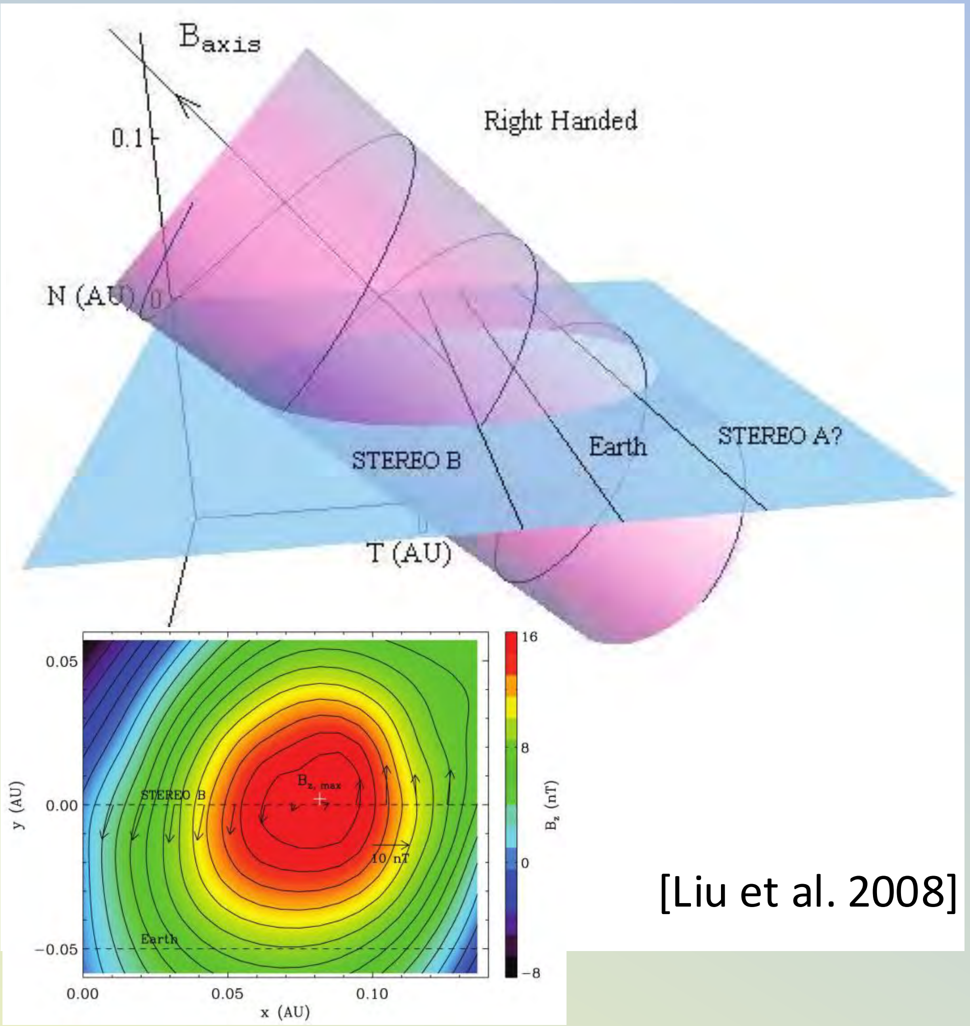
How does the multi-spacecraft/multipoint in-situ observing paradigm improve things?

2007 Nov 19–20 Event



[Farrugia et al. 2011]

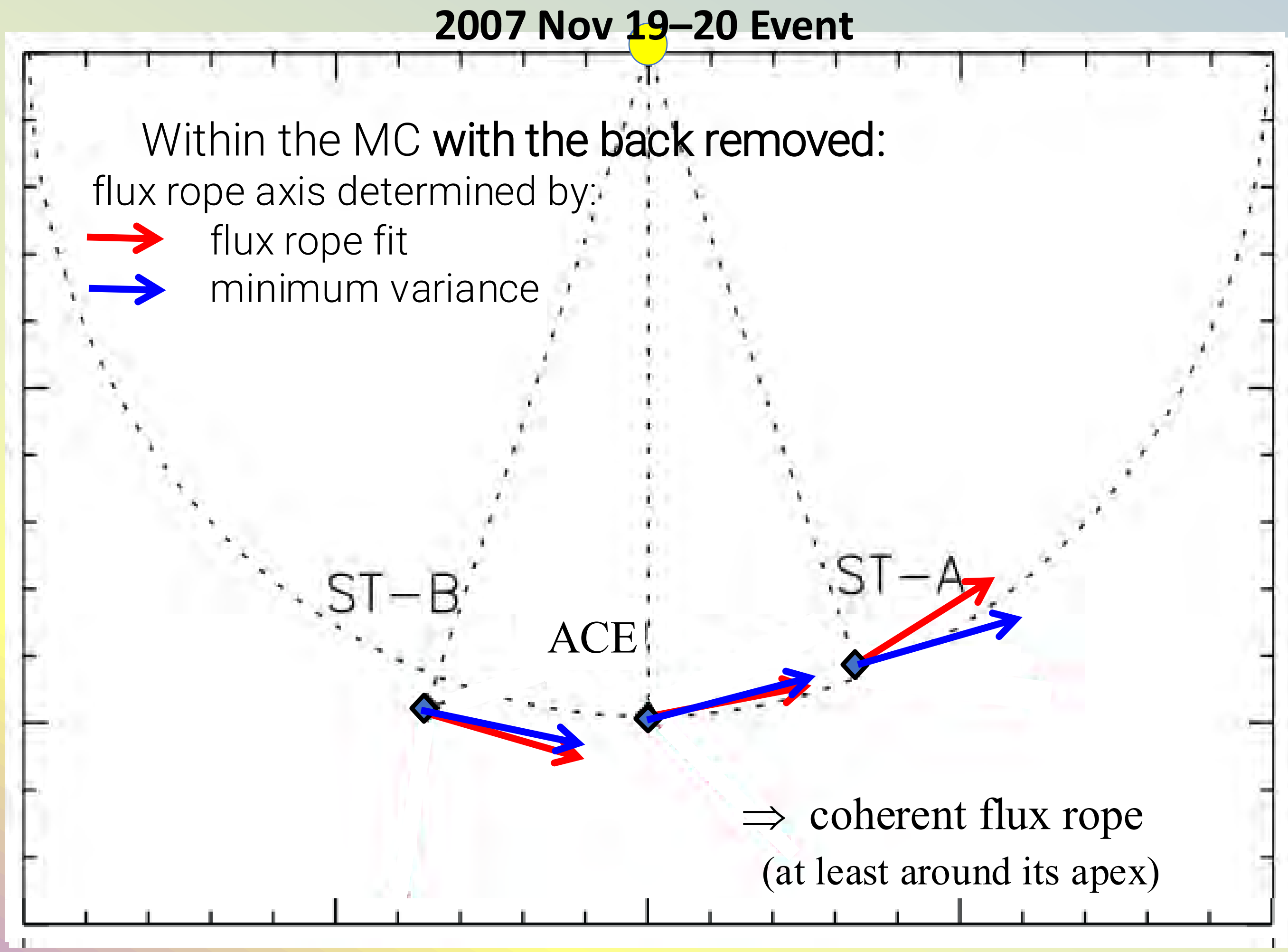
2007 May 22 Event

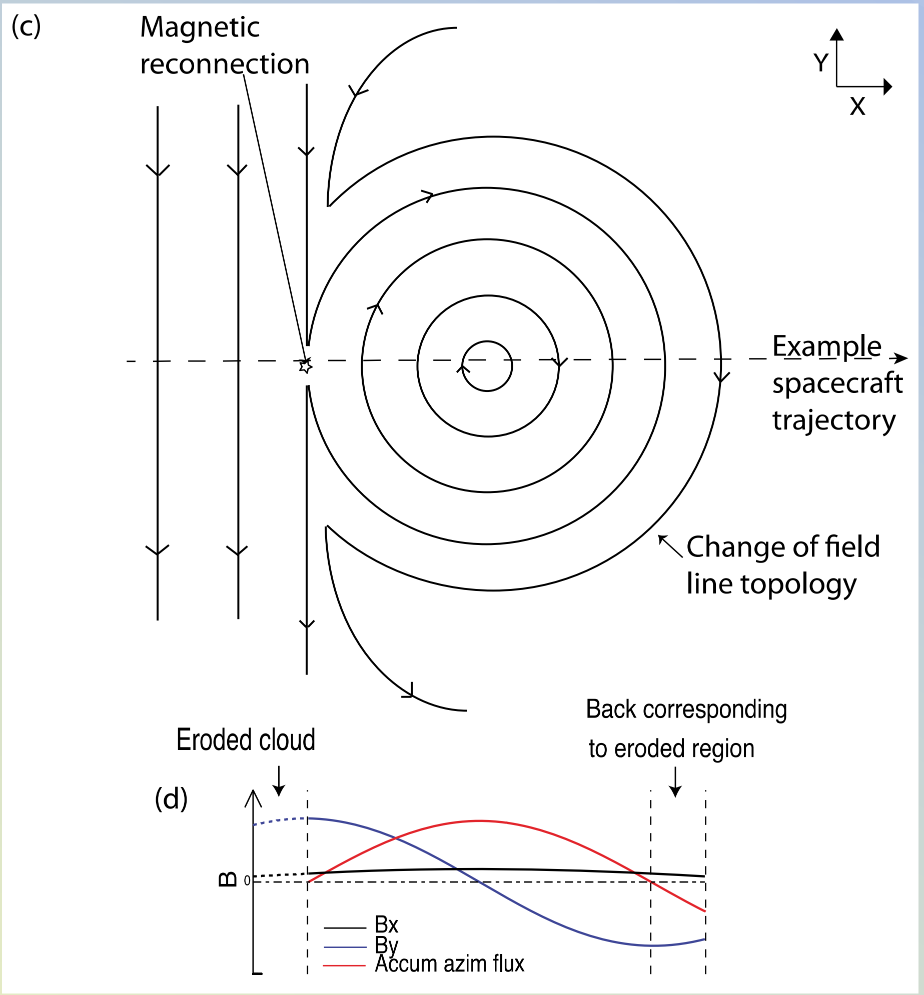


[Liu et al. 2008]

Modeling the Evolution of ICMEs During Propagation

Certain conditions favorable for reconnection between CME & upstream SW, get magnetic flux erosion. Ruffenach et al. (2012) showed this can improve multi s/c fitting tremendously!

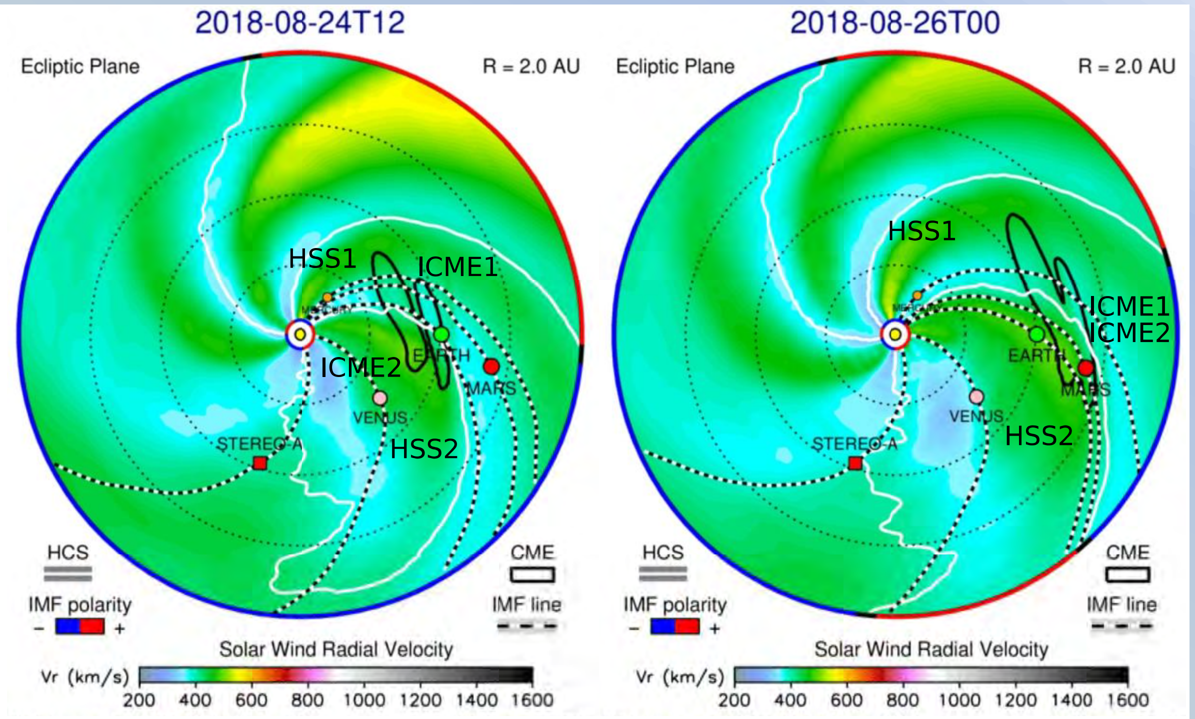


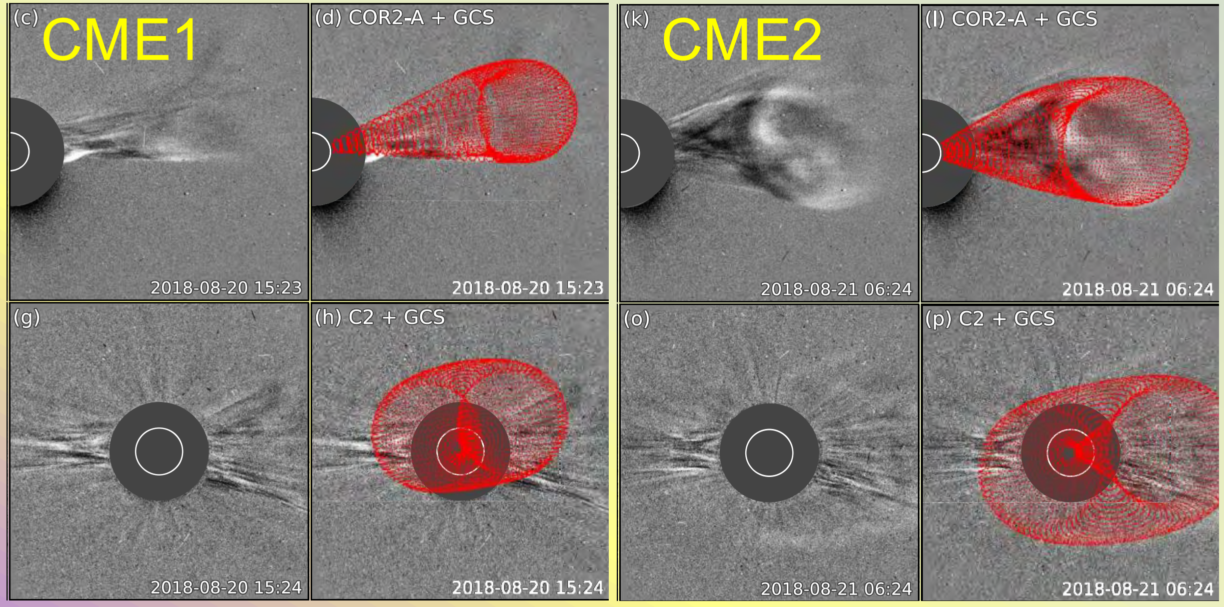


[Ruffenach et al. 2012]

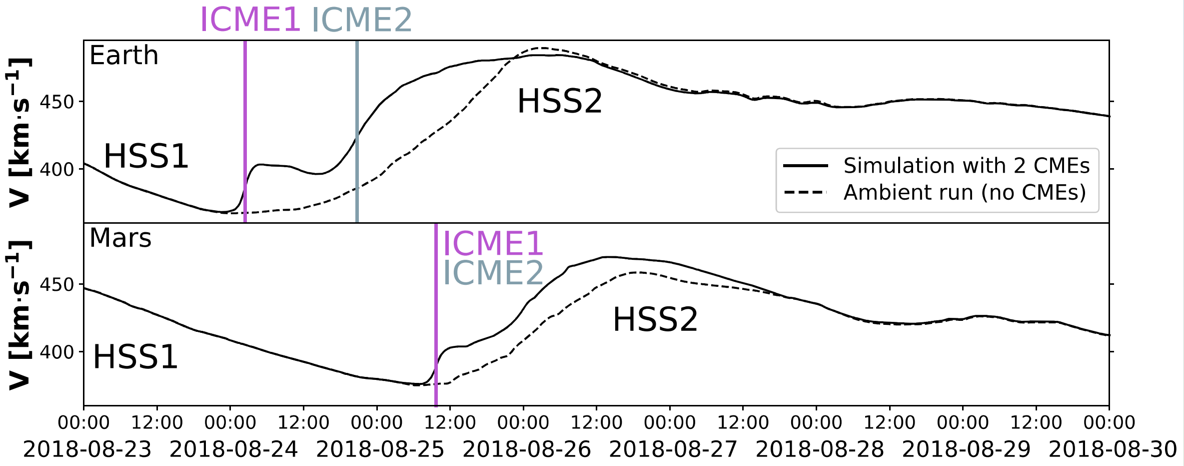
Modeling the Evolution of ICMEs During Propagation

Palmerio et al. (2022) analyzed a series of eruptions in late August 2018 (late declining phase) with cone model ejecta in WSA/Enlil. Two distinct ICMEs at Earth but continued propagation en route to Mars gave a high speed stream (HSS) time enough to run into the second ICME, speed it up, and cause it to either merge/deflect/interact/etc.





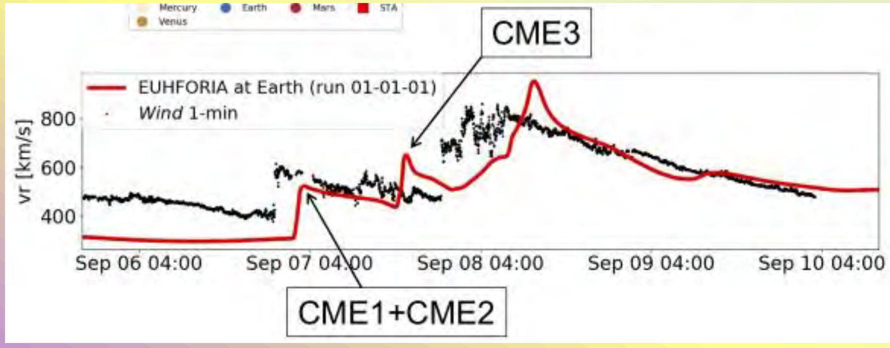
[Palmerio et al. 2022]

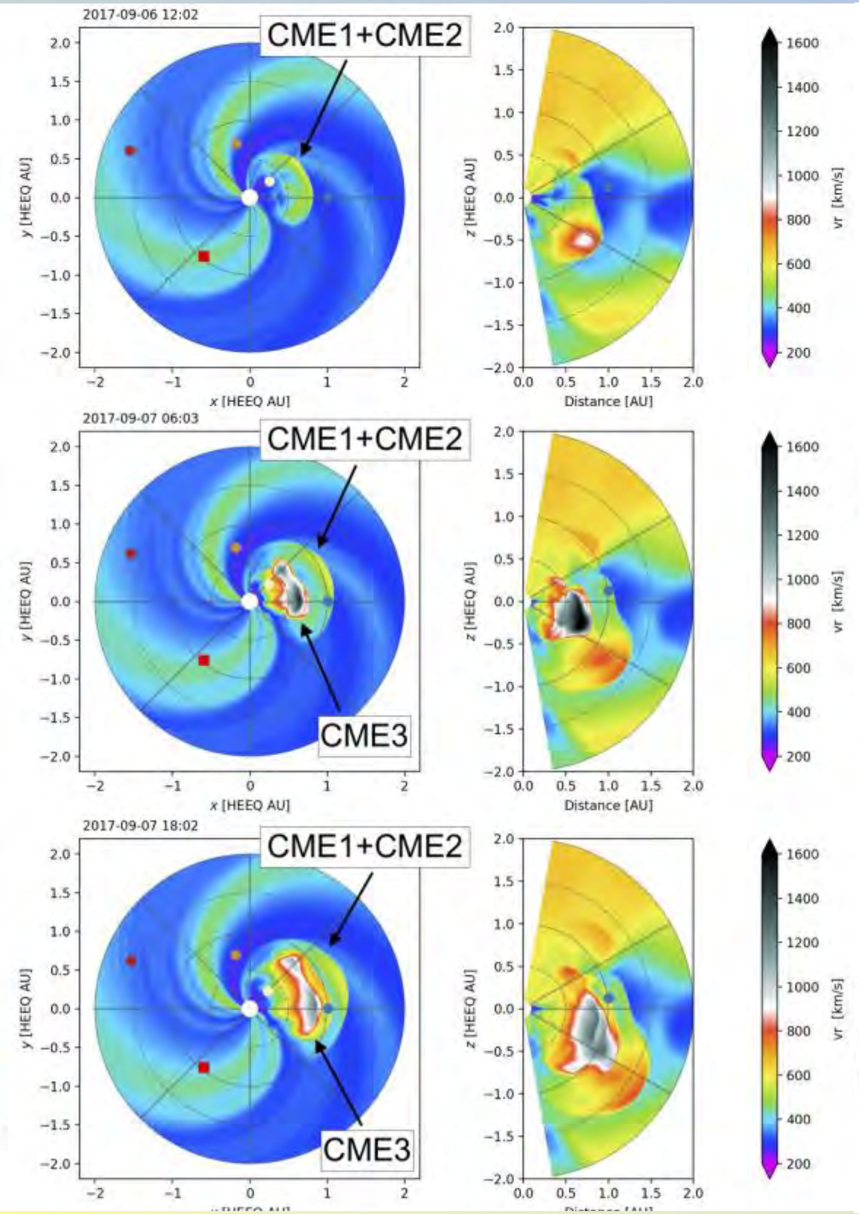


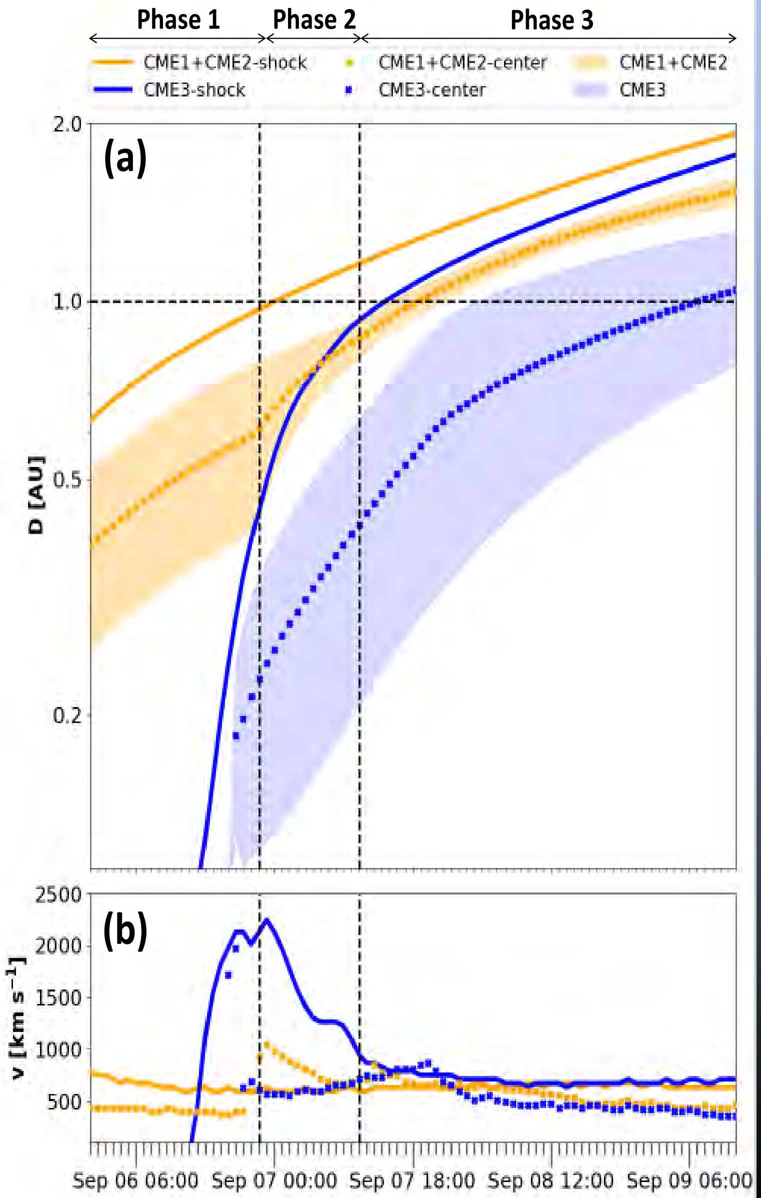
Modeling the Evolution of ICMEs During Propagation

Scolini et al. (2020) simulated the sequence of eruptions during 2017 Sep 4–7 as 3 separate spheromak CMEs. *Data constrained* CME parameters obtained from observed reconnection fluxes: CME1 Φ_{rxn} = 5*10^{21} Mx, CME2 Φ_{rxn} = 5*10^{21} Mx, and CME3 Φ_{rxn} = 1*10^{22} Mx.

Needed all three erruptions to get enhanced geoeffectiveness!







Summary & Discussion Statements

- CMEs: Fundamentally a problem of *gradual* magnetic energy storage and *rapid* energy release
- The standard CSHKP model for eruptive flares/CMEs *does* work
- Numerical modeling lets us study the corona's magnetic field configuration and its dynamical evolution during eruptive transients
- MHD modeling also allows us to connect remote sensing EUV, white-light, X-ray, radio data with in-situ observations of plasma, field, particles
- We're getting the basic/generic/large-scale properties of CME/flux rope eruptions right
- There's a lot of opportunities now to extend space physics understanding to more exotic environments, i.e. other stars, exoplanetary systems, etc.

Summary & Discussion Statements

- Space weather modeling has made good progress! Models are doing great!
- We never actually get everything (anything?!) right—arrival time, **B**(t), n, V, T, etc. Models are doing terrible!
- Increase in model complexity (amount of detailed physics) makes interpretation of modeling results ***almost*** as difficult as looking at real data!

  Lots of opportunity for analysis & deep dive into simulation results

  → Multiple synthetic observers, both in-situ sampling trajectories and remote sensing synthetic WL/EUV/Xray emission viewpoints

- Need more and better data... but even more, we need to apply UNDERSTANDING, INSIGHT, and PHYSICS to our interpretation of data!
- (We also probably need to do a bit better with the simulations)