The links among the Sun systems: flares, CMEs, and solar winds

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Credit: NASA/SDO/AIA/S. Doran

Chapters

Chapter 1: Observing the Sun's variability through the centuries

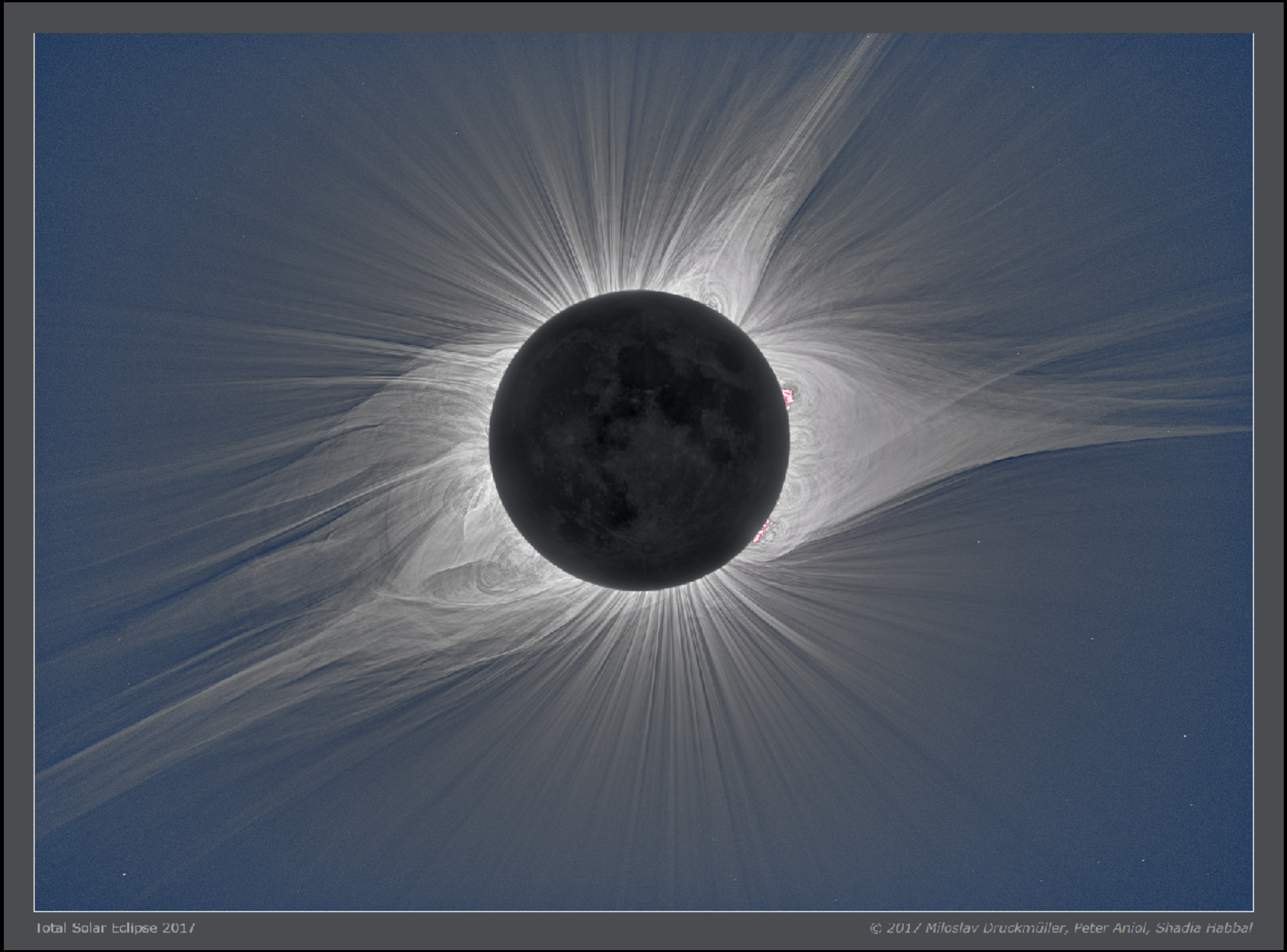
A. The Sun's variability through the naked eye
B. The Sun's variability through a (ground) telescope
C. The space telescopes era

Key idea: our understanding of the Sun has changed over time.. with variability since at every layer of the Sun's atmosphere.

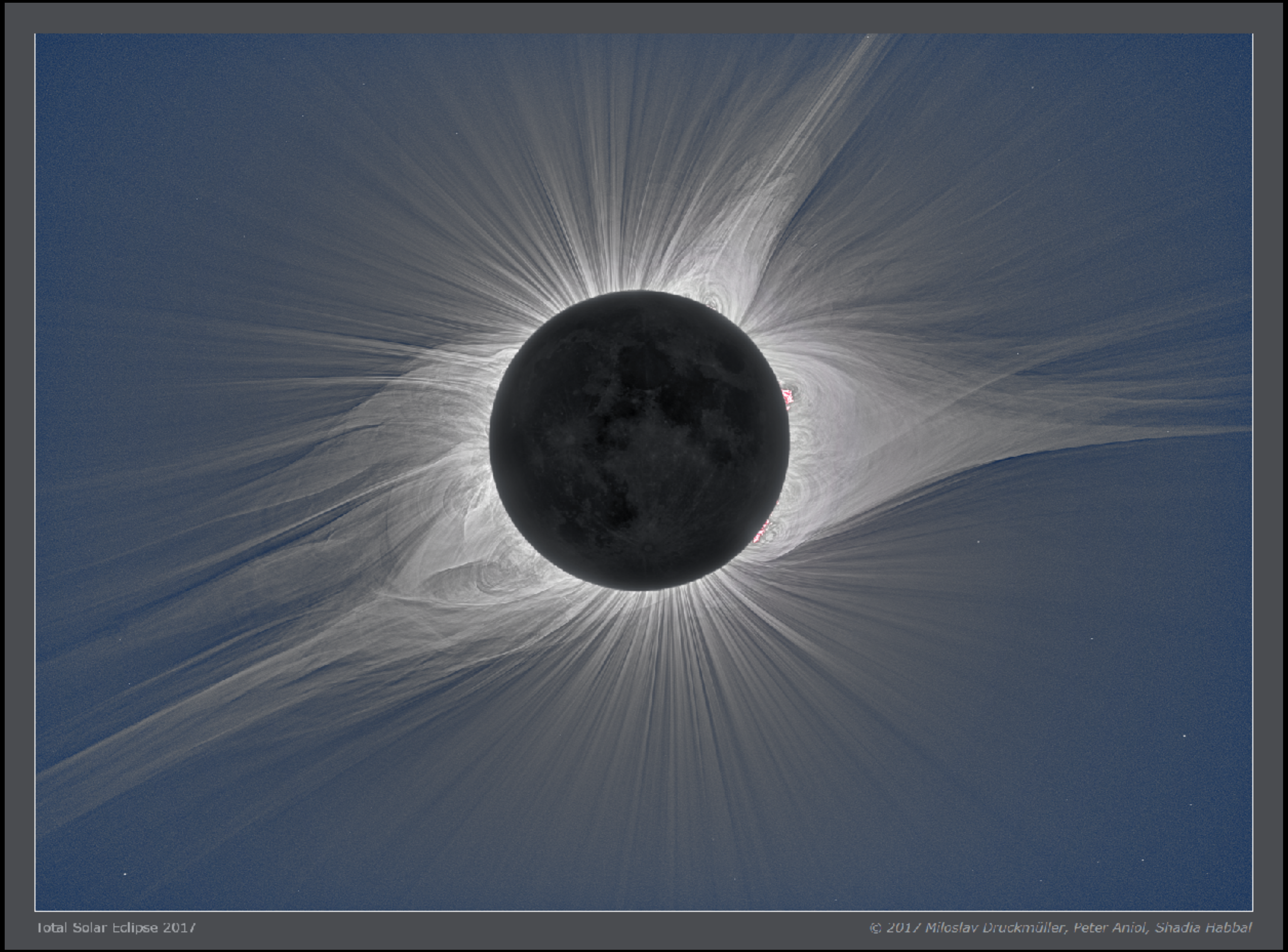
A. The Sun's variability through the naked eye

Chap 1

A. The Sun's variability through the naked eye



↳A. The Sun's variability through the naked eye



❖1st record of the mention of the corona: Byzantin historian Leo Diaconus mentions the corona

> Observation of total eclipse of 22 December 968 from Constantinople (now Istanbul, Turkey)

❖Possible interpretation of a prominence description in Chinese court records

> ~28 BC by Chinese astronomers during the reign of Emperor Cheng of the Western Han Dynasty.

❖1st unambiguous description of prominences = Russian Chronicle of Novgorod

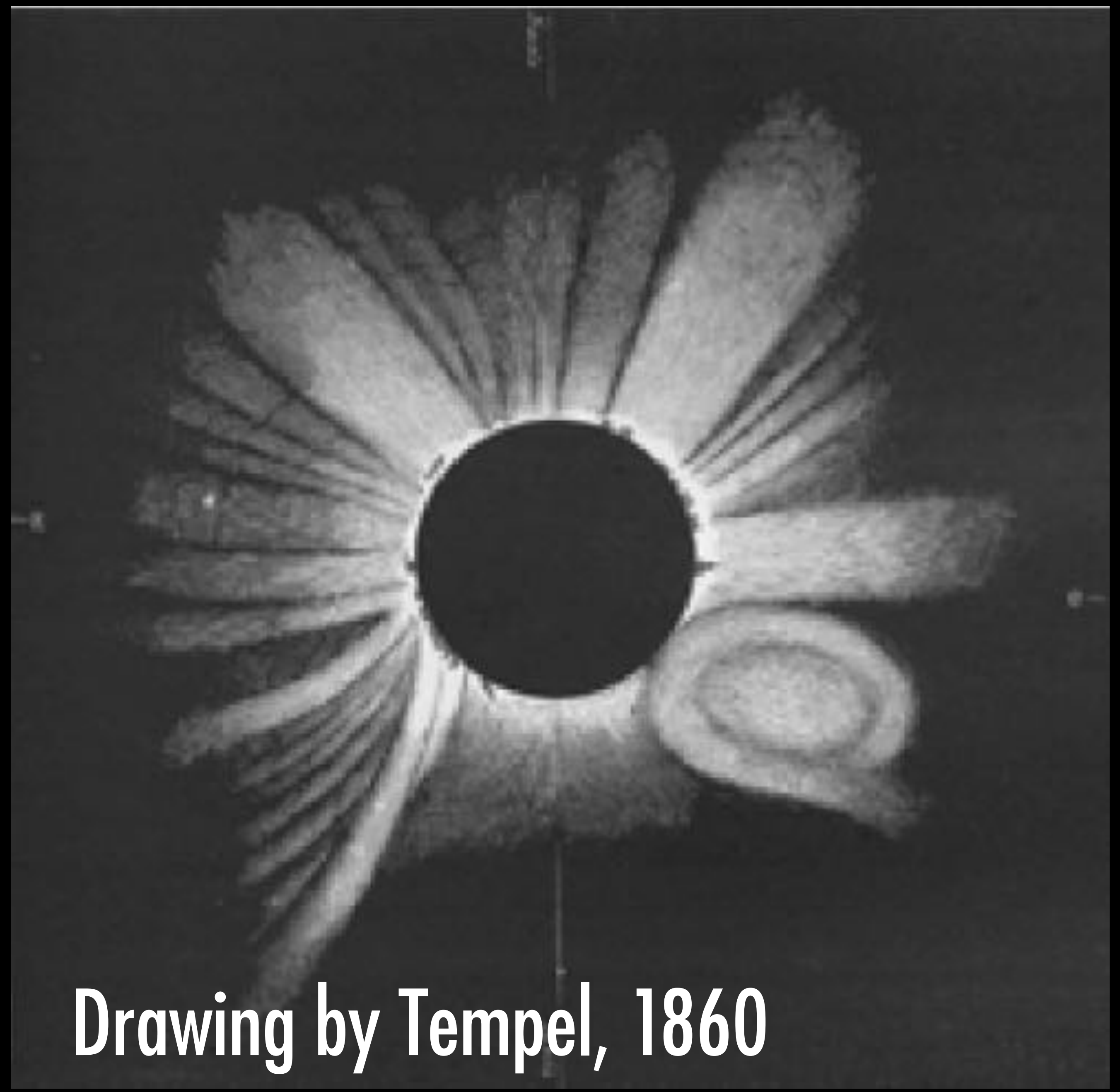
> Observation of 1 May 1185 solar eclipse

Chap 1

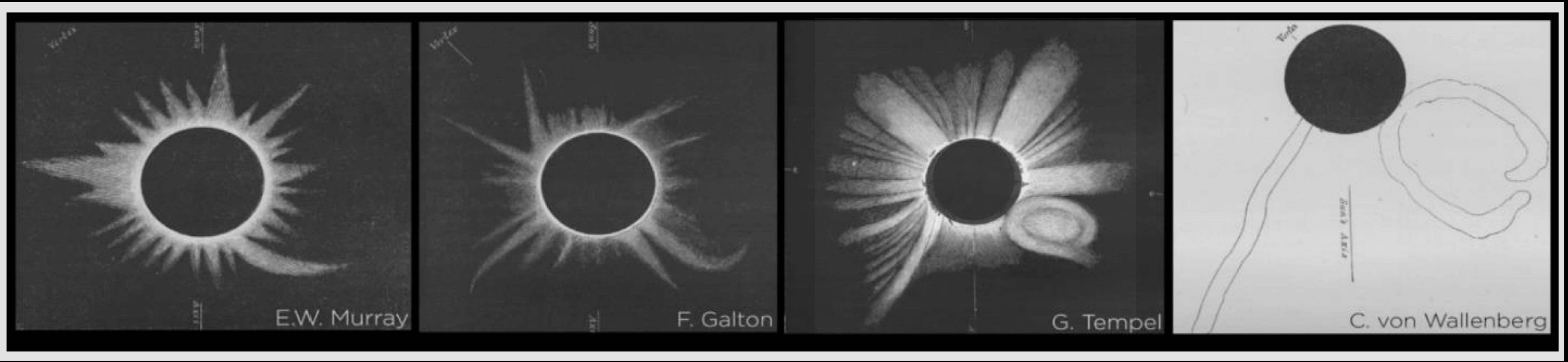
↳A. The Sun's variability through the naked eye

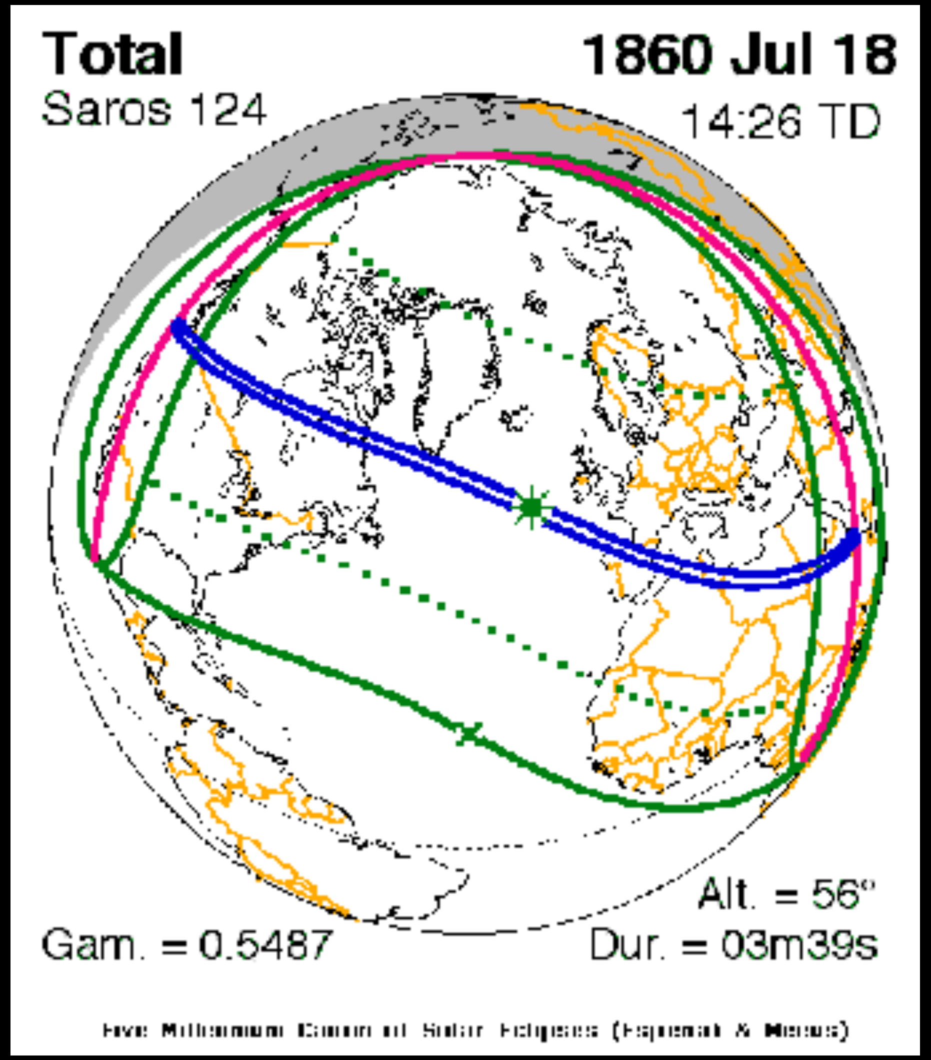
❖Shape of the overall coron
changes over time

❖Possibility to see some
interesting structures!


Drawing by Tempel, 1860

A. The Sun's variability through the naked eye



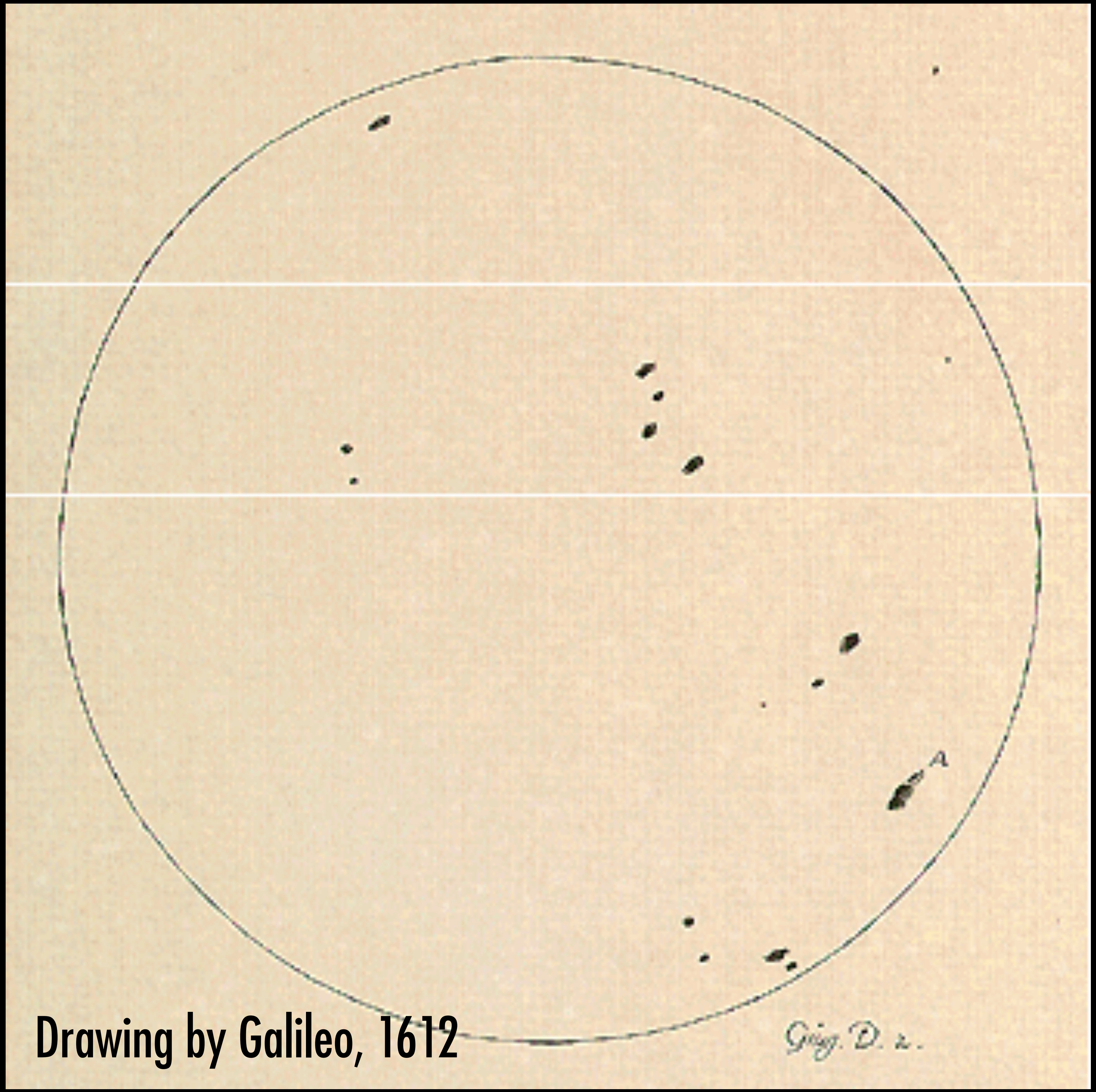


Not all observers saw the same structure!

➡First evidence of a coronal mass ejection

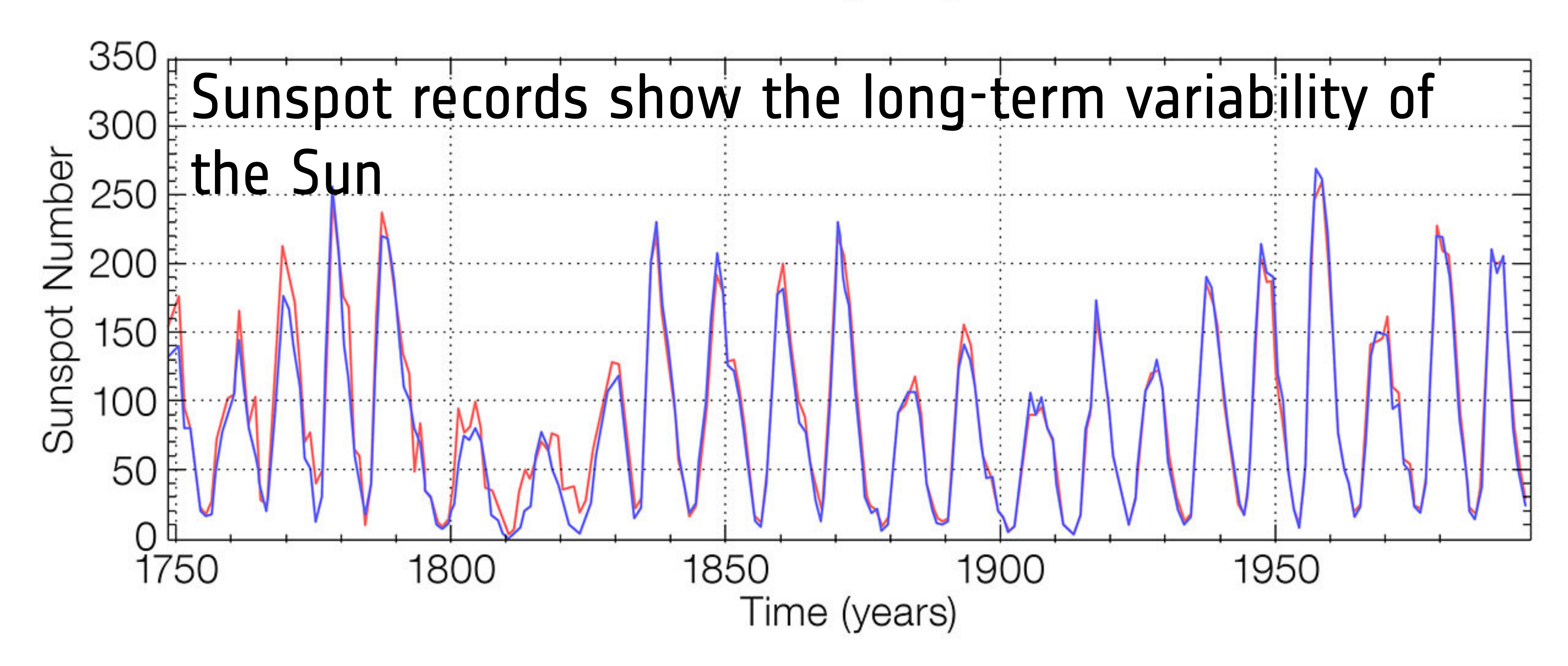
Material being expelled from the Sun and seen in as a disappearance in the corona

B. The Sun's variability through a (ground) telescope

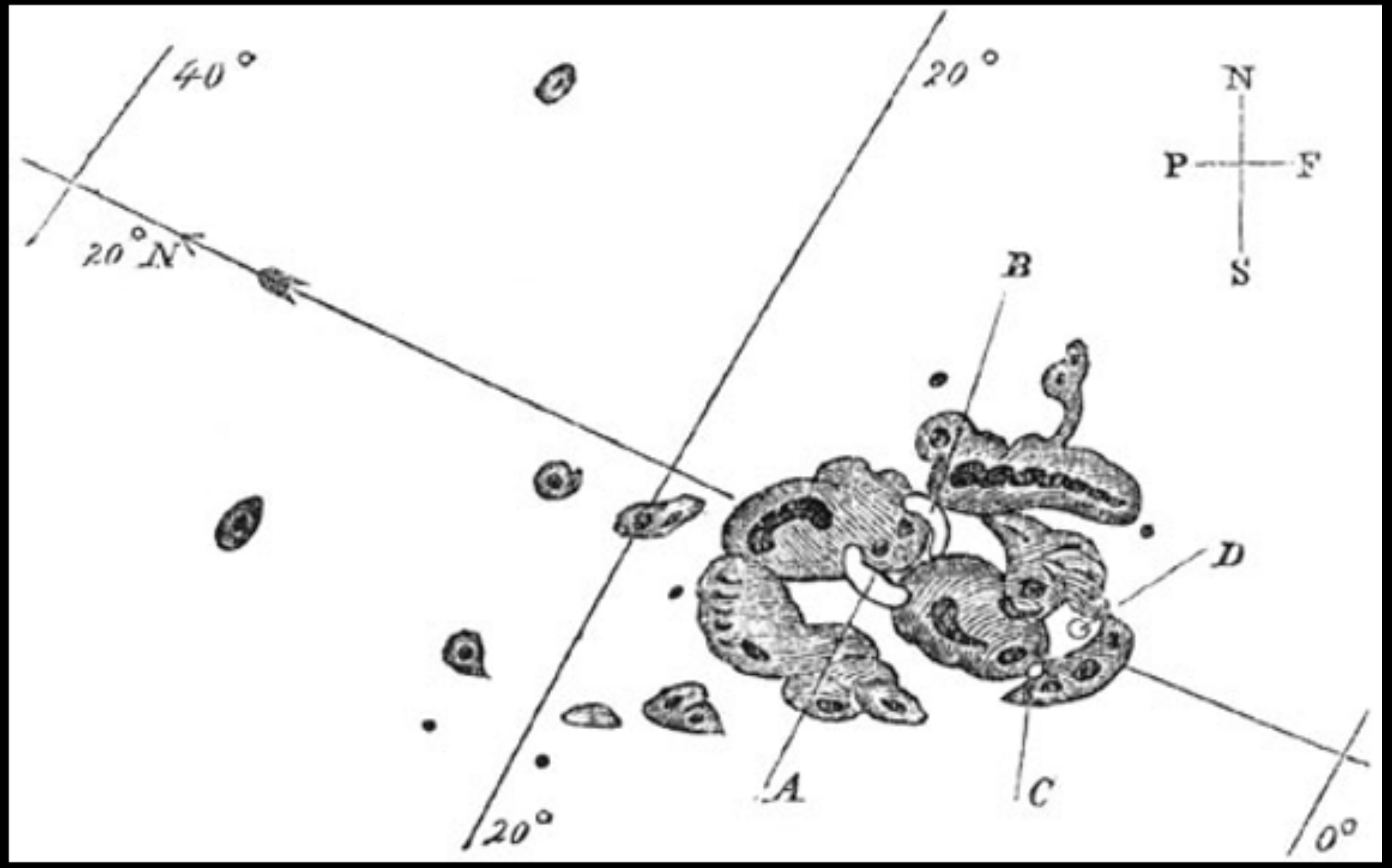


Drawing by Galileo, 1612

Interpretation of what could be the 1st sunspot drawing, by John of Worcester around 1128



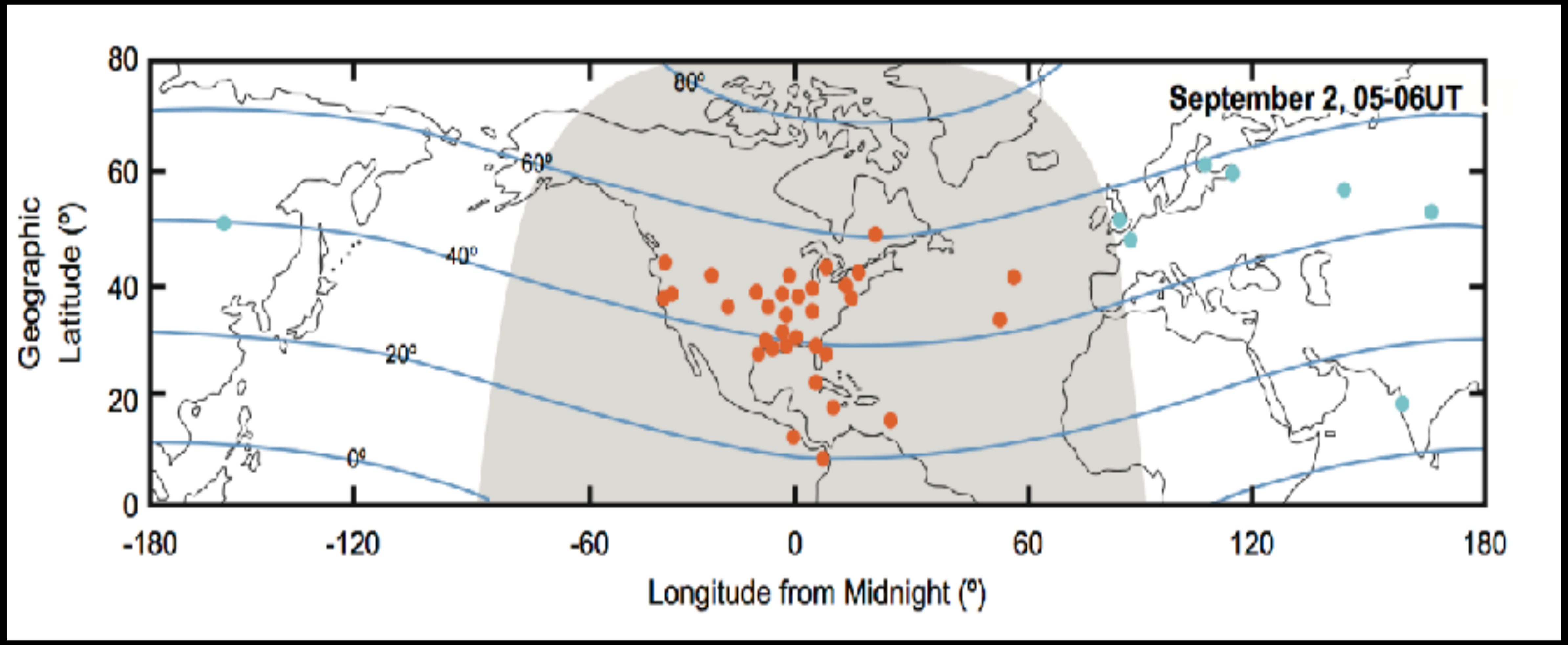
↳B. The Sun's variability through a (ground) telescope



Carrington / Hodgson event (1859)

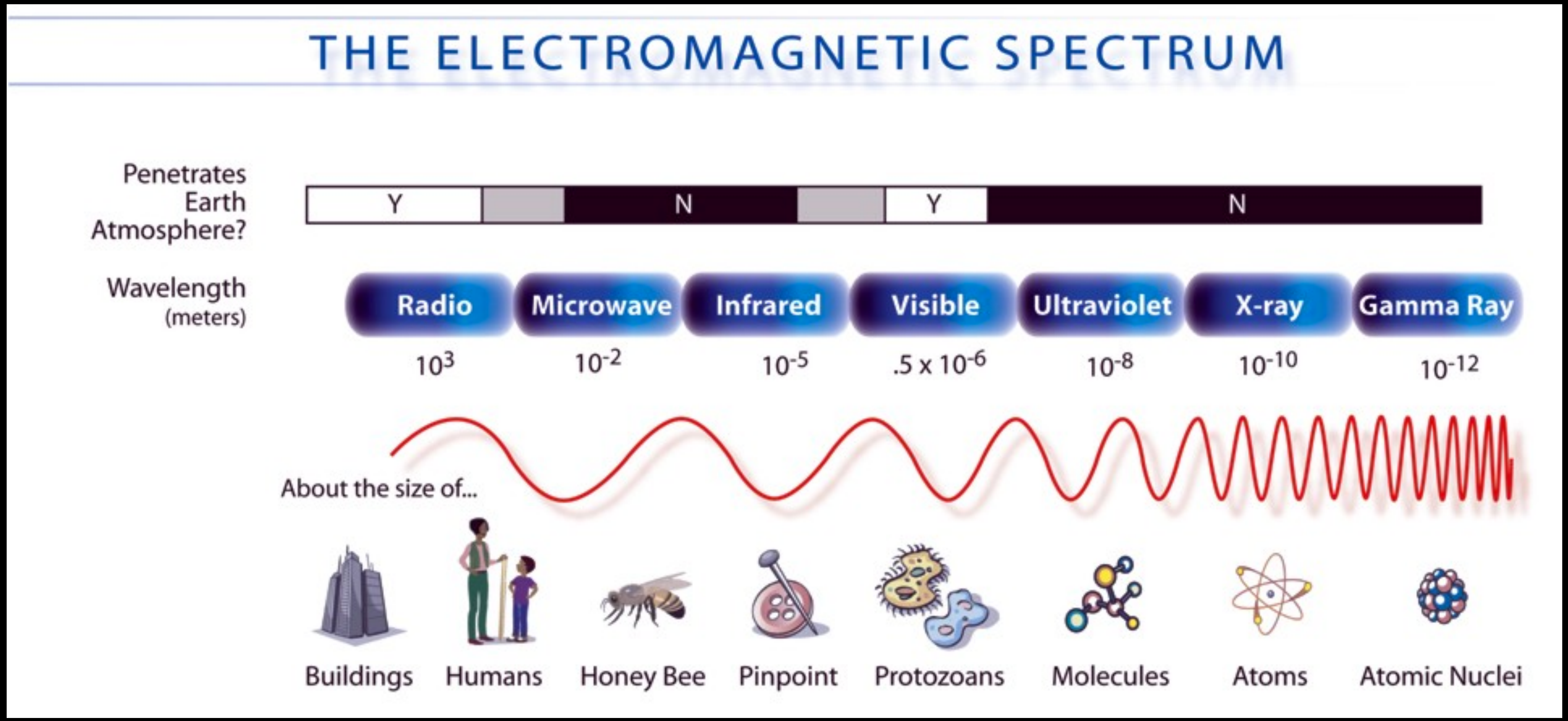
Clear step in understanding the variability AT the Sun and AT Earth with more global network

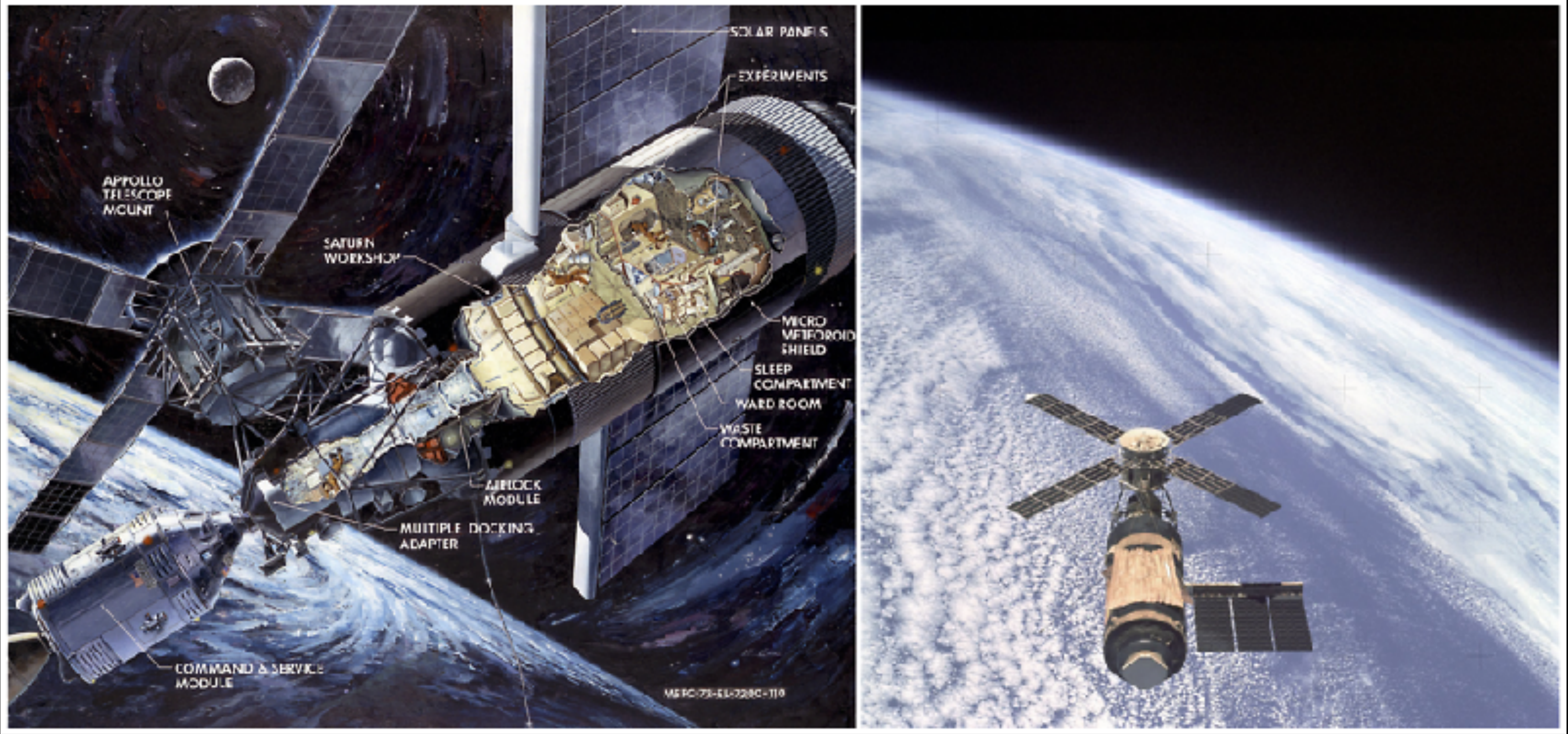
> Solar + magnetic observations, aurora observations all the way to Mexico, consequences on society (telegraph)



A good recent example: May 11 2024 event!

C. The space telescopes era

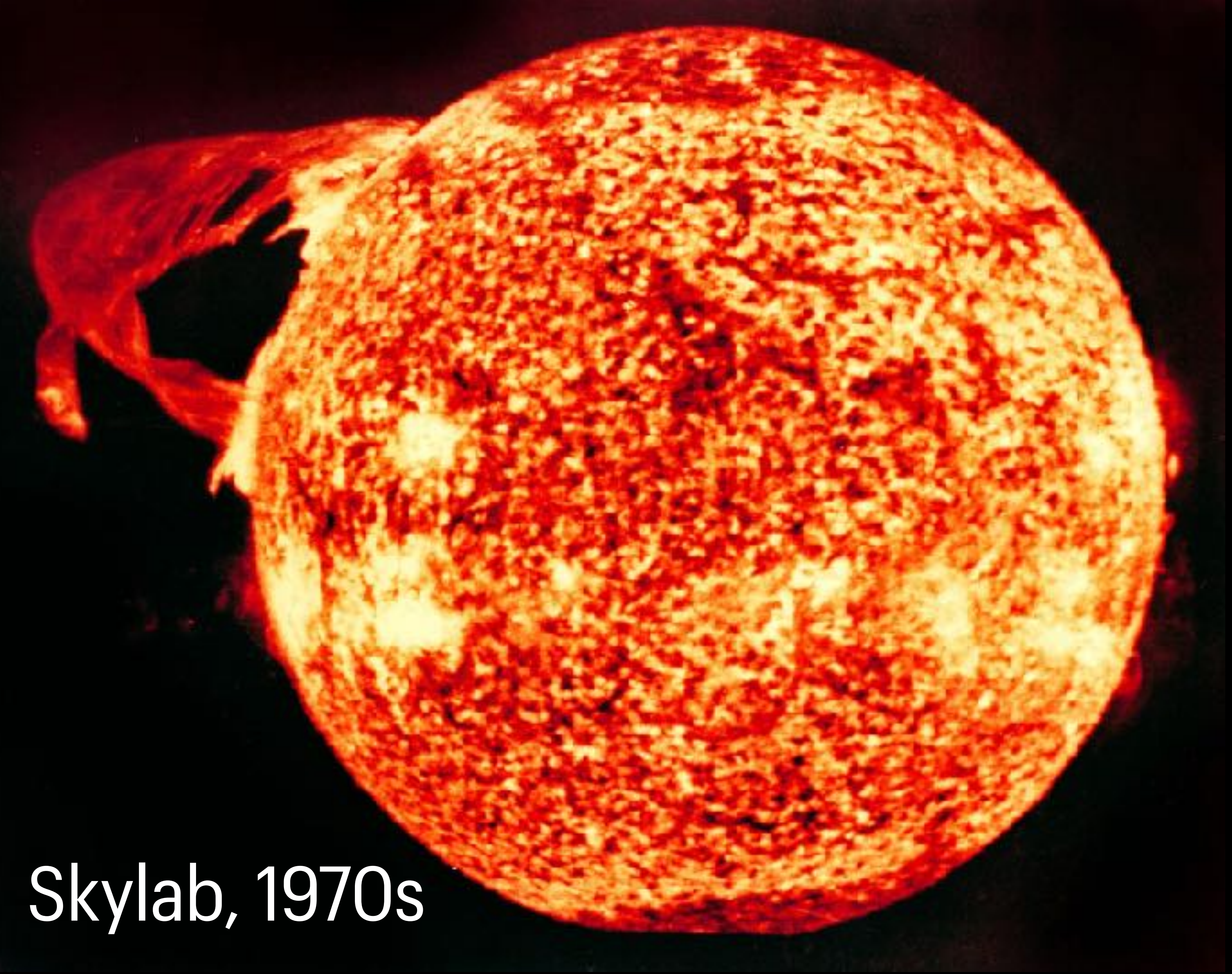




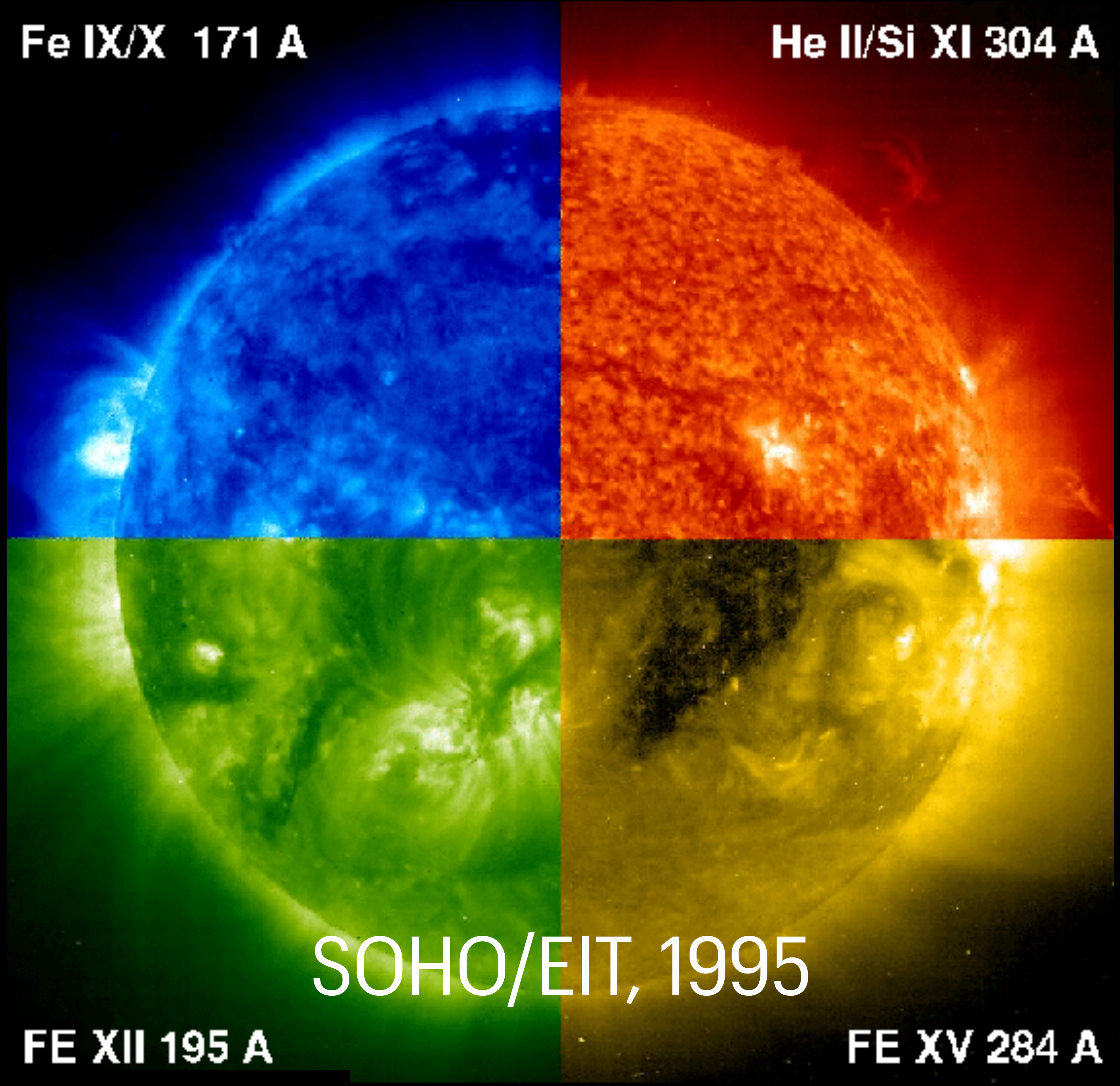
Space telescopes = Accessing wavelengths that we cannot detect from the ground

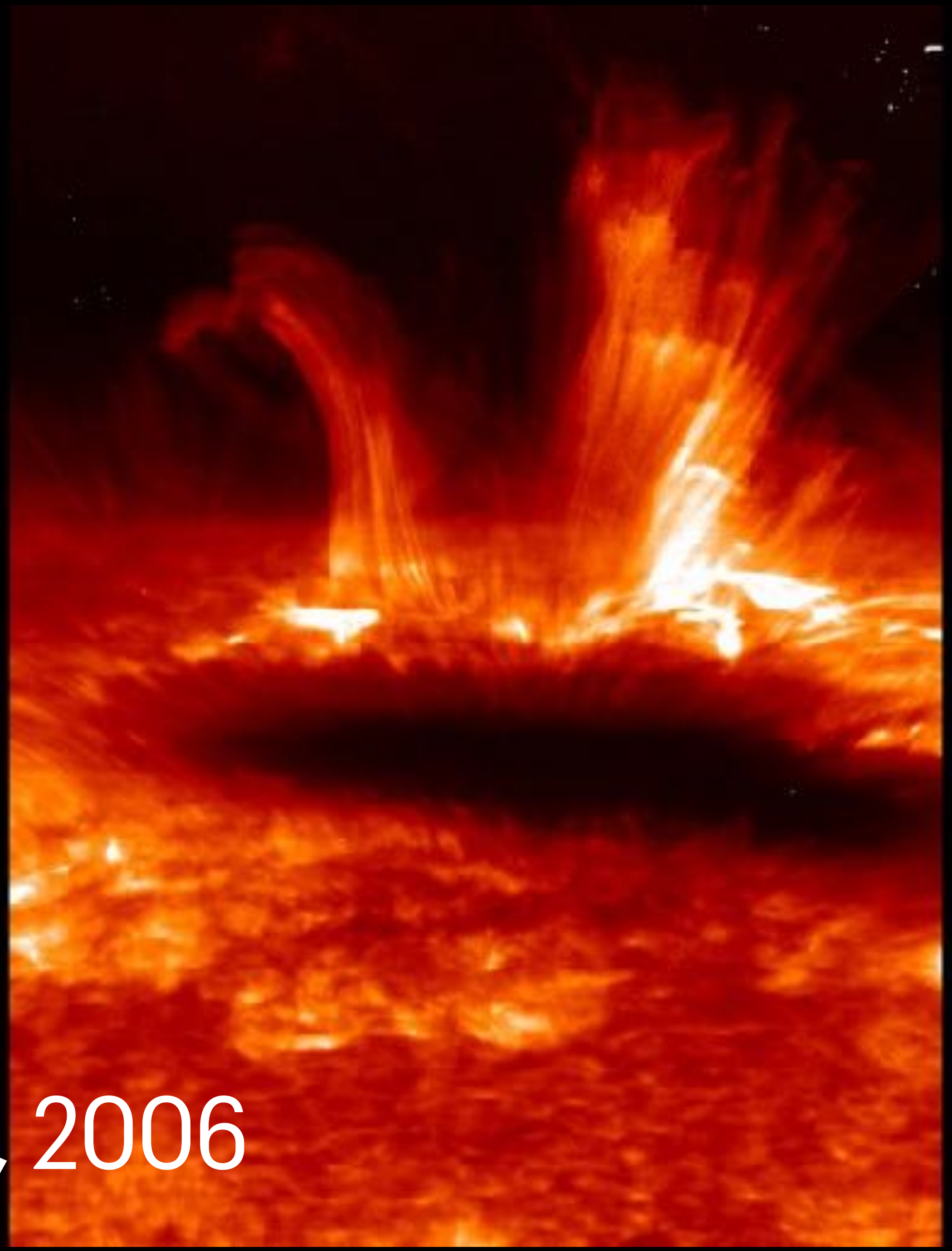
1st dedicated solar observatory on the 1st space station: SKYLAB (Nasa, 1973-1974)

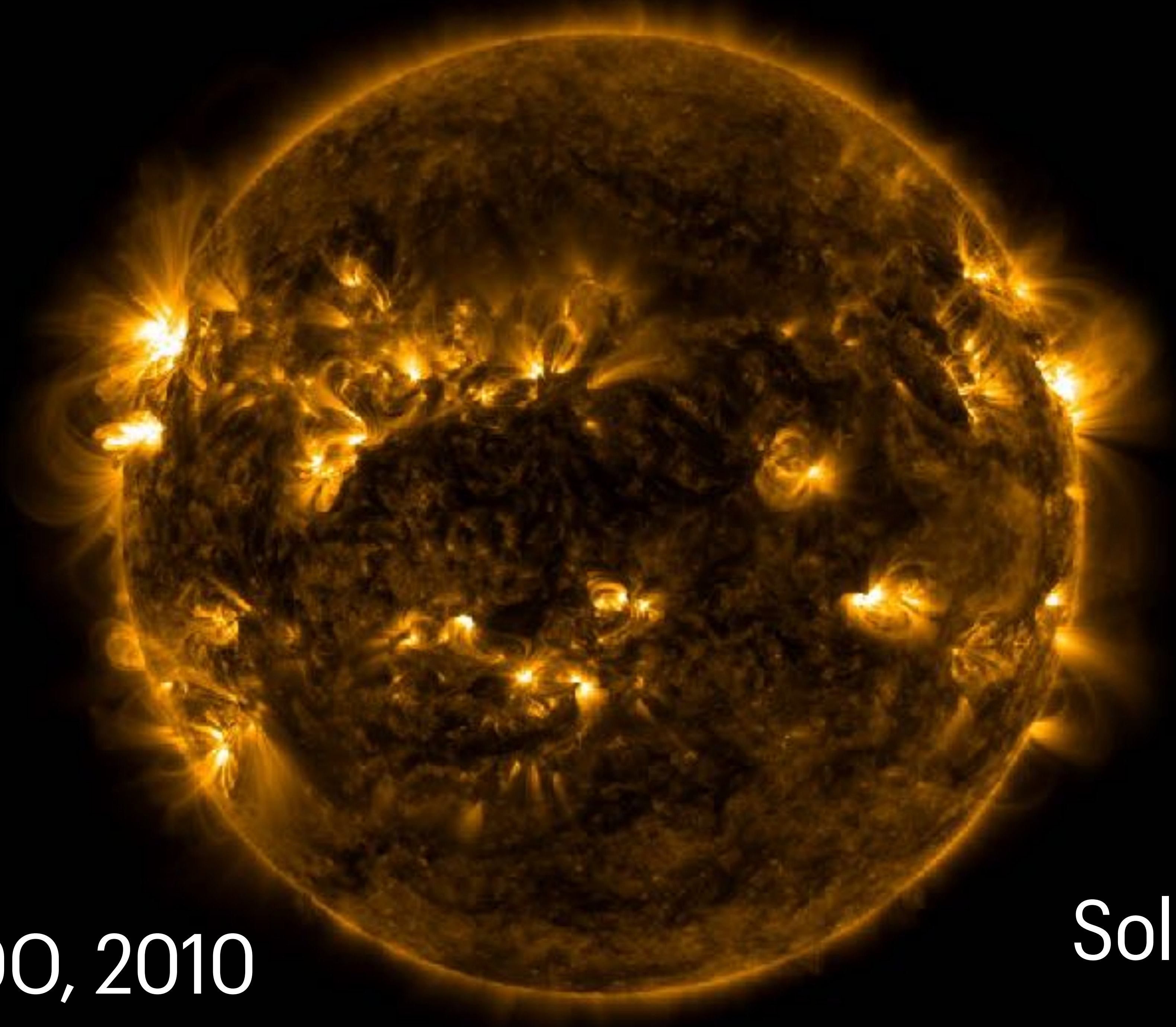
> Recommendation: go see the Apollo telescope at the Udvar-Hazy museum (Washington DC)!

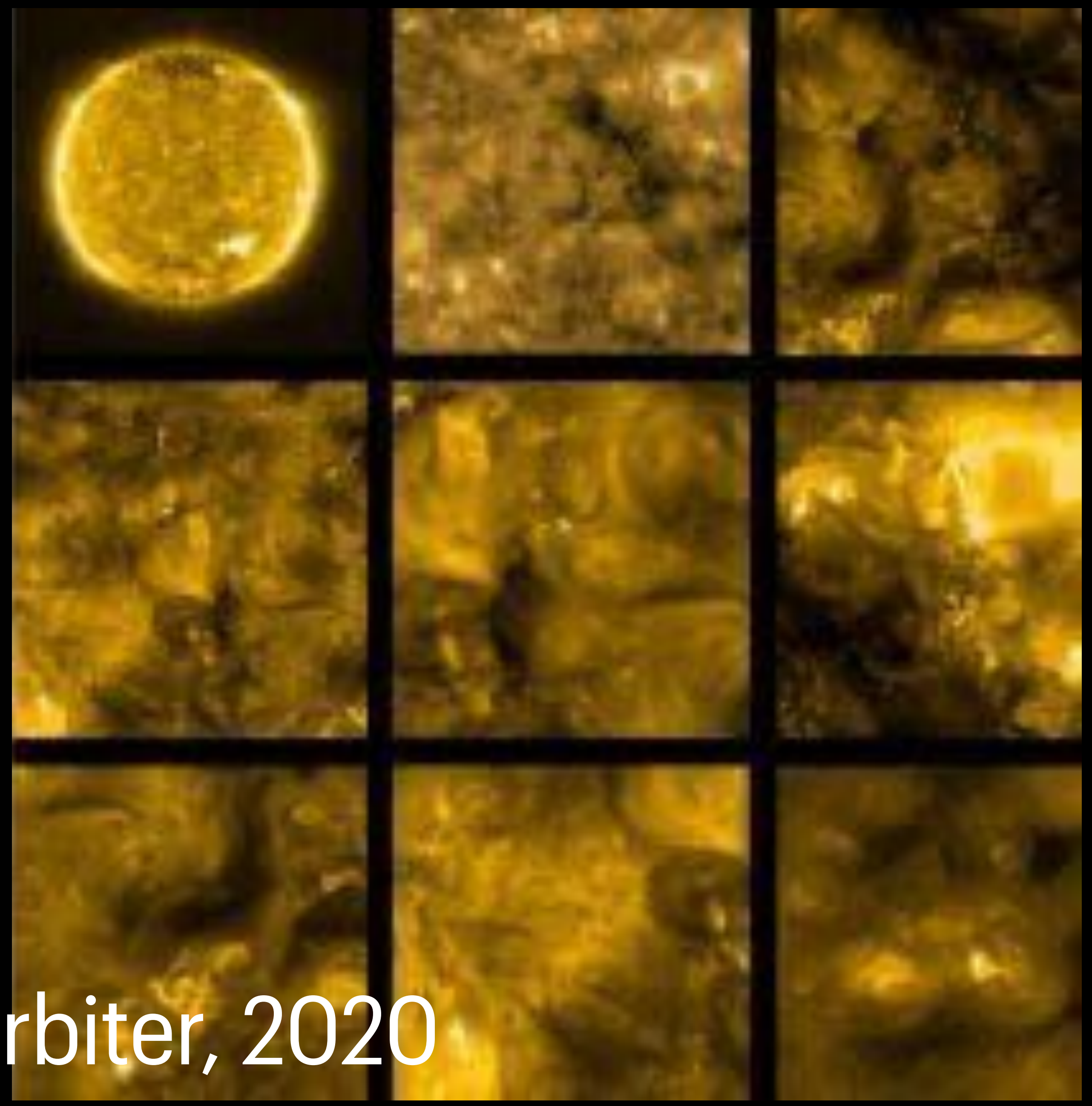

Skylab, 1970s


Yohkoh, 1991


Fe IX/X 171 A
He II/Si XI 304 A
SOHO/EIT, 1995
FE XII 195 A
FE XV 284 A


Hinode, 2006


SDO, 2010


Solar Orbiter, 2020

Chap 1

C. The space telescopes era

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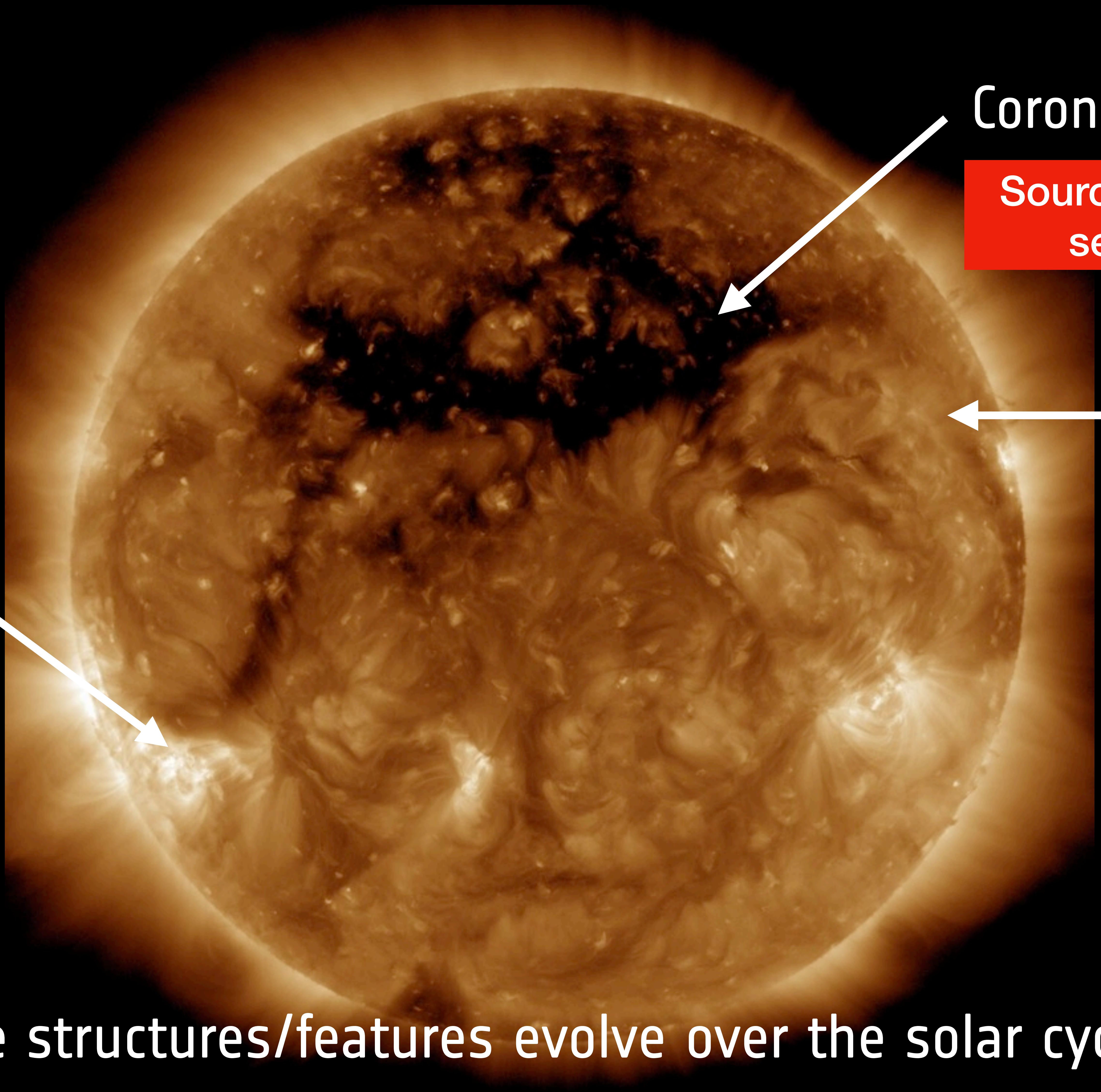


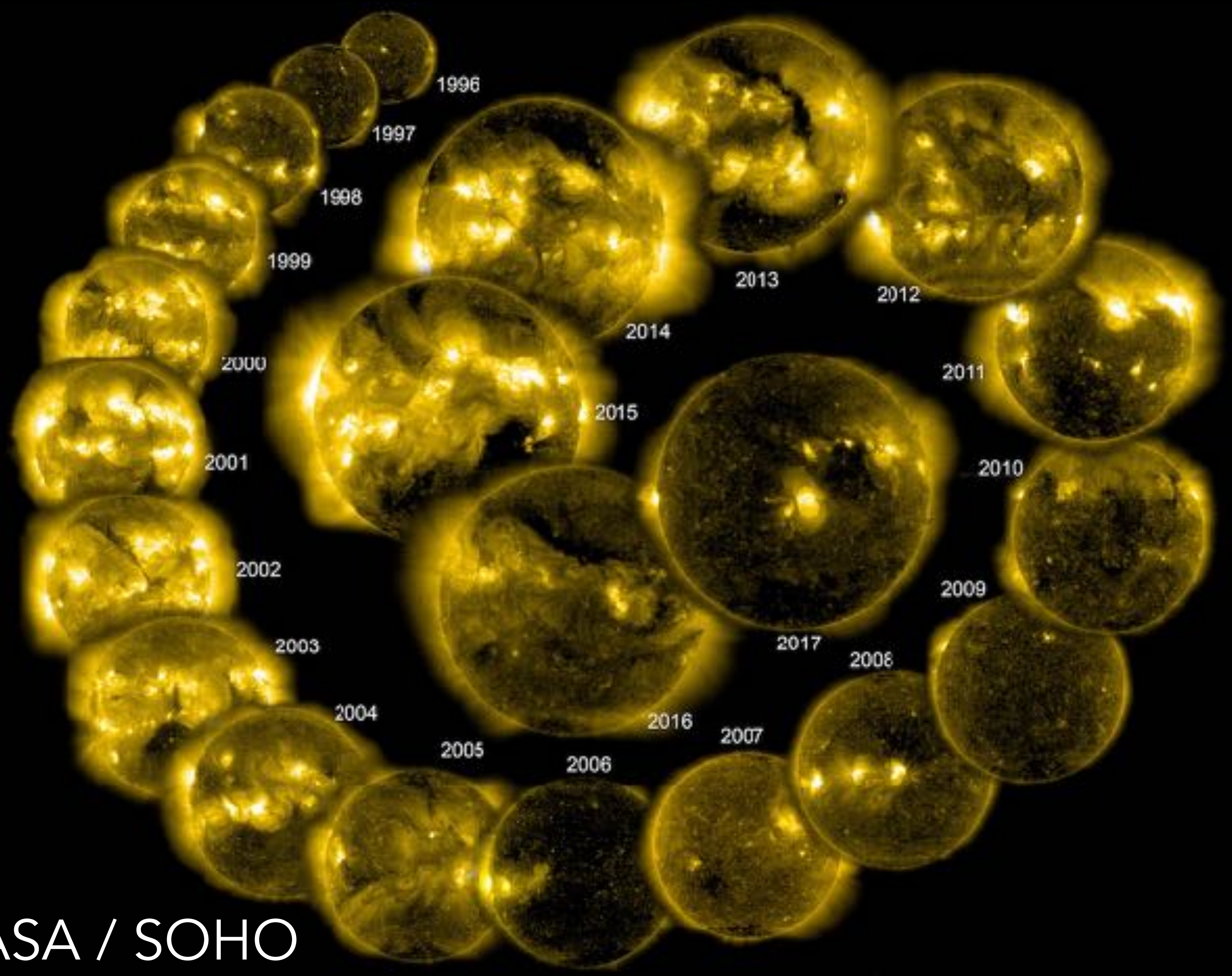
Coronal holes

Sources of fast solar winds => see S. Yardley's lecture

Quiet Sun

Active regions

All of these structures/features evolve over the solar cycle!



ESA / NASA / SOHO

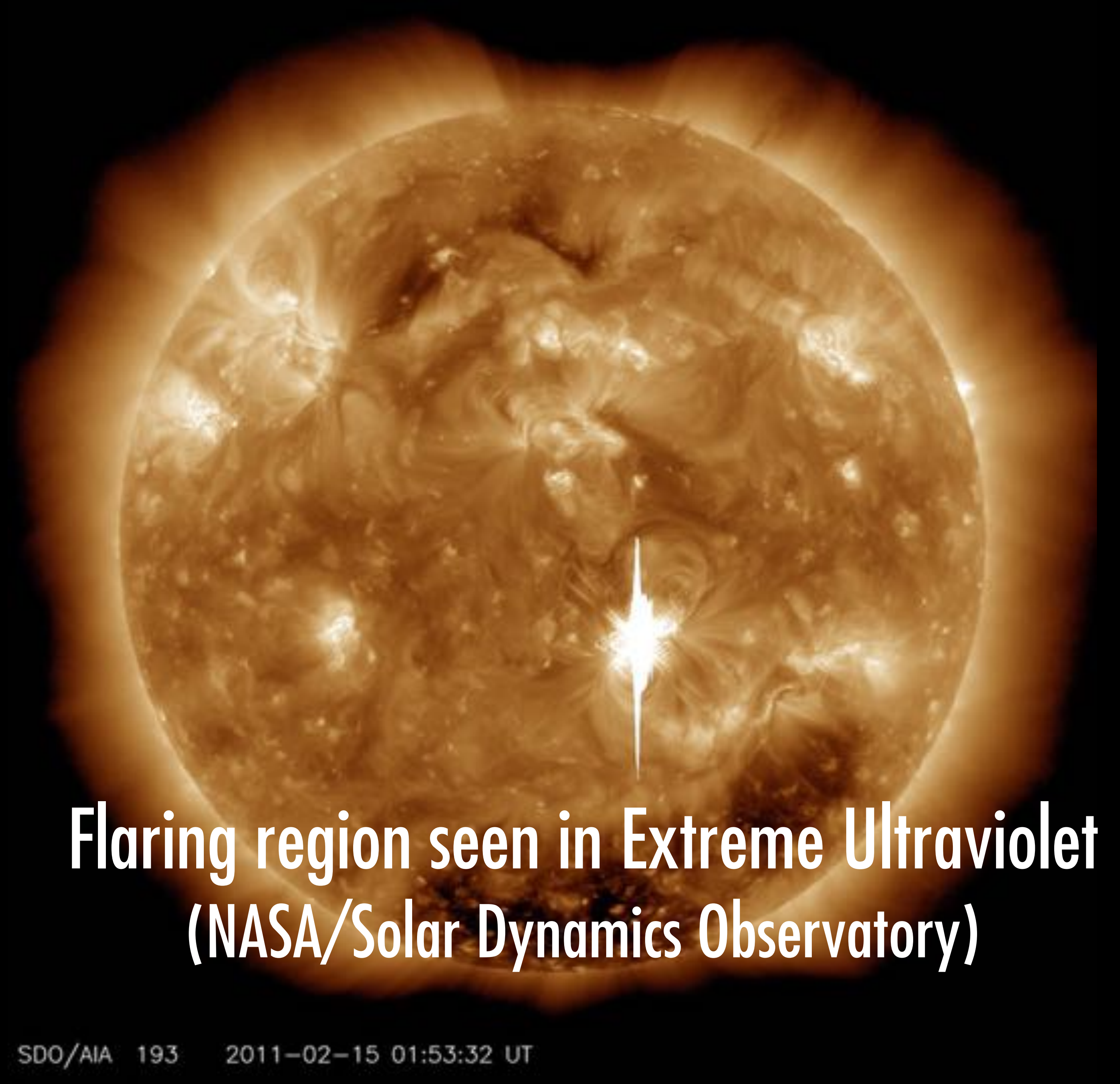
Chapter 2: Flaring events, from observations to modelling

A. Anatomy of a flare
B. Eruptive vs confined flares
C. Phenomenology
D. Where does the flare energy come from?

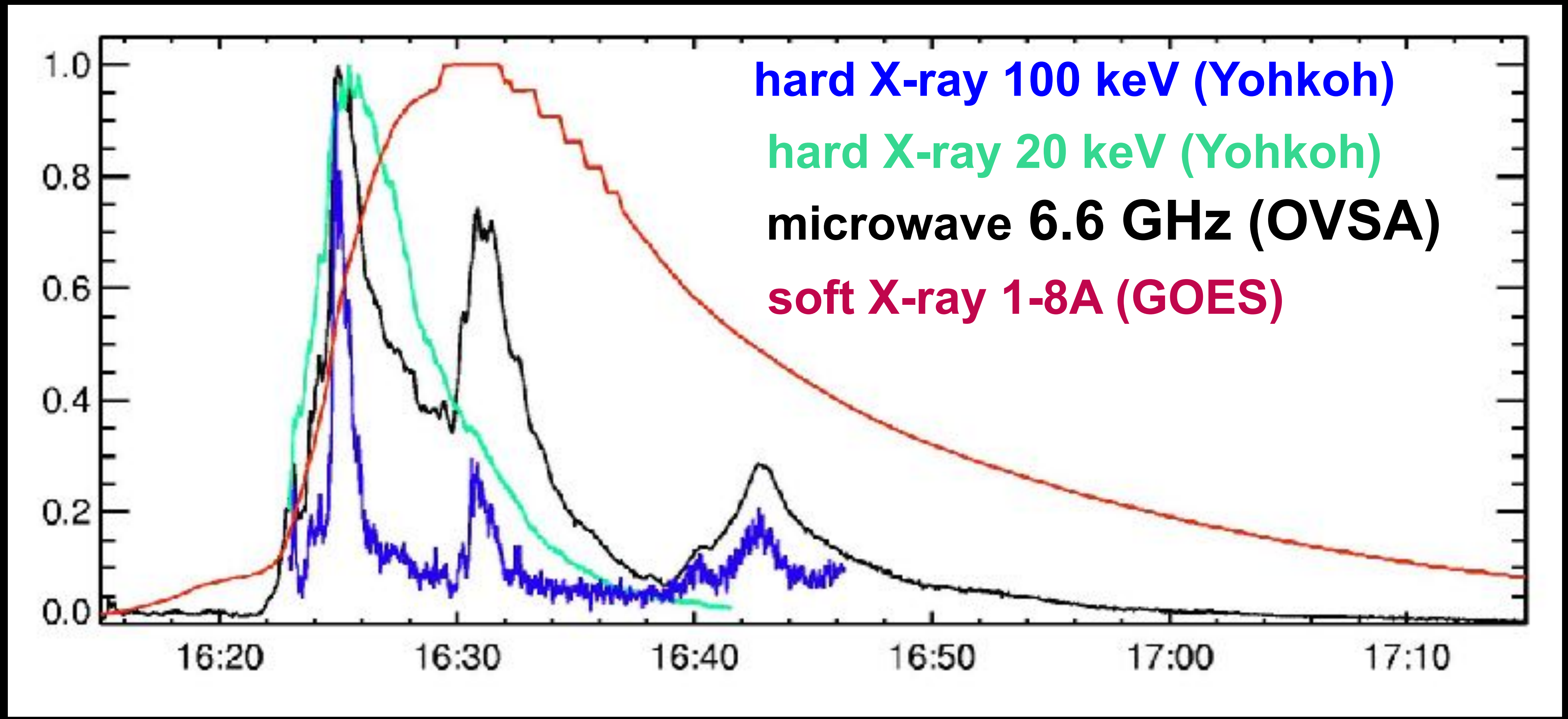
Key idea: understanding the difference between flares and CMEs, and the fundamental structures where the flare energy is stored

A. Anatomy of a flare

« Flare »: sudden brightening in solar atmosphere



Flaring region seen in Extreme Ultraviolet
(NASA/Solar Dynamics Observatory)

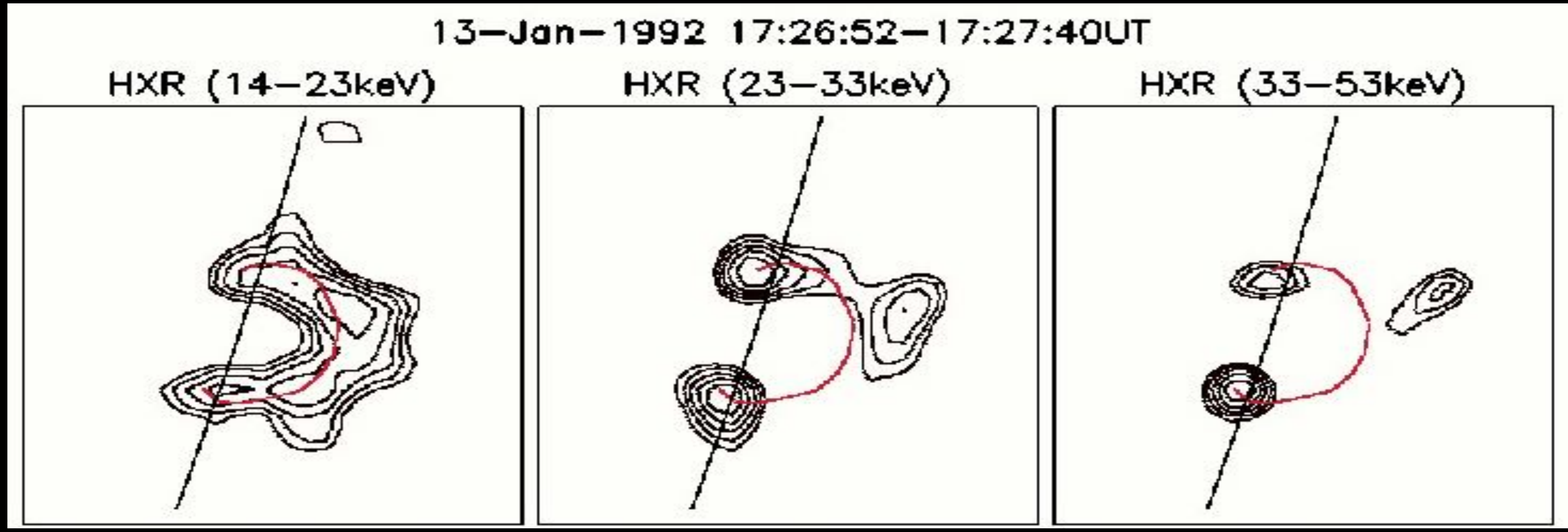


Qiu et al. (2004)

- ❖ Large number of non-thermal electrons (not detected in the non-flaring hot corona)

Accelerated particles

Masuda et al. (1994), Hudson et al. (2001), Sui et al. (2003)

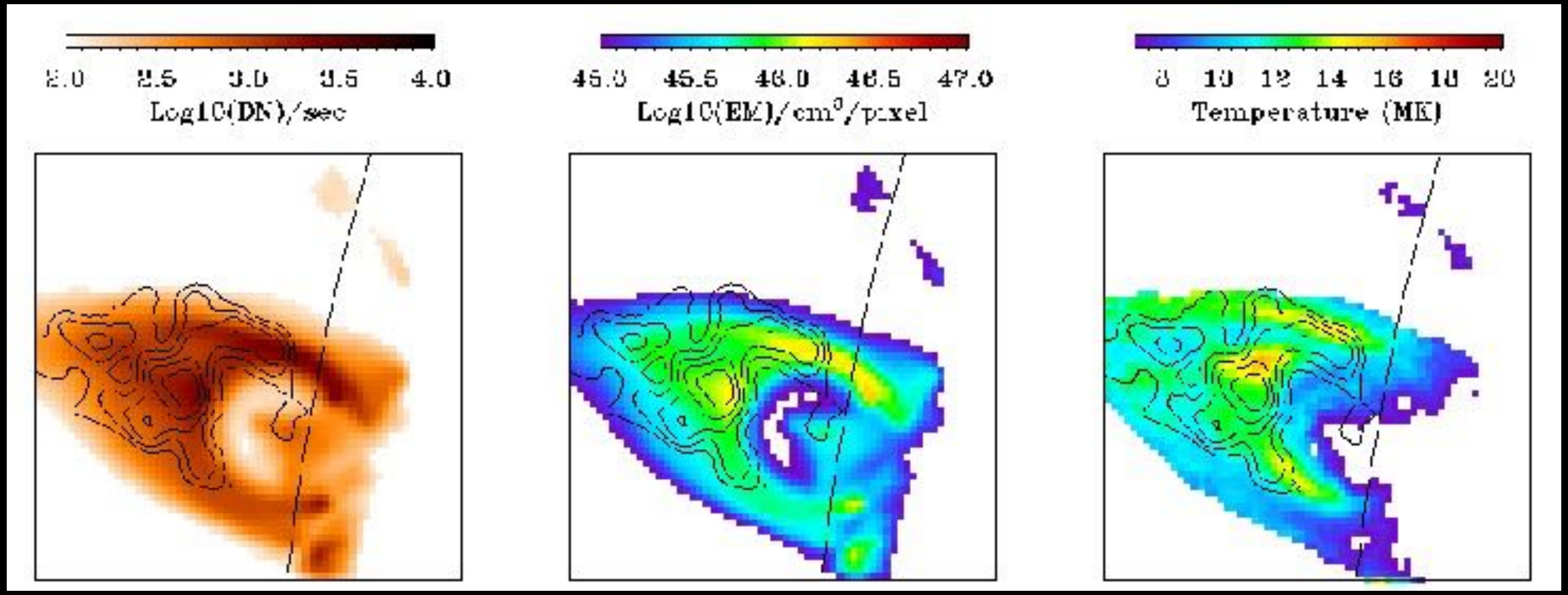


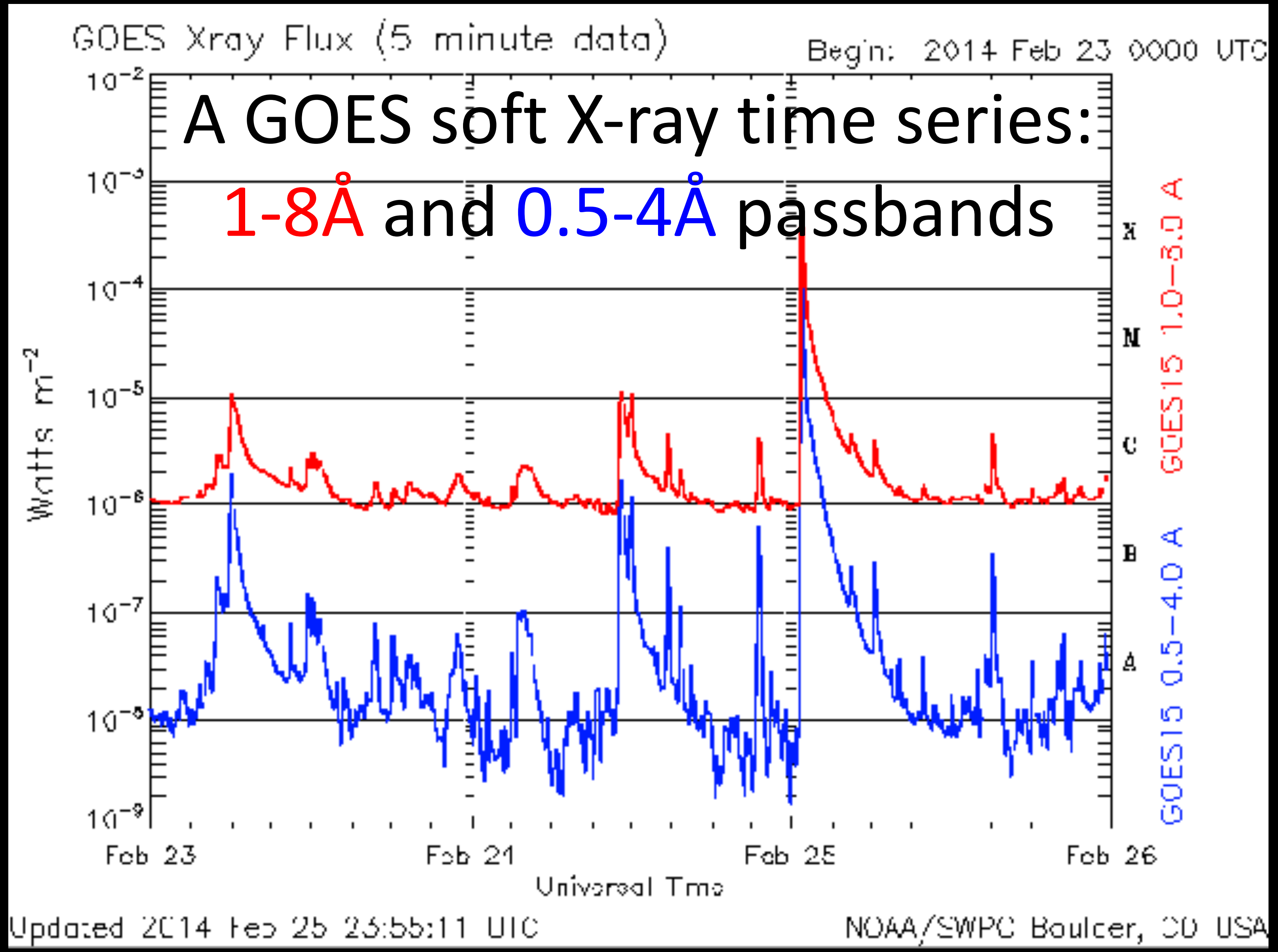
- ❖ Increase in radiation
- ❖ Intermittent energy dissipation

A. Anatomy of a flare

SXR high temperature ridges along outer or newly formed loops:
heating takes place

Tsuneta et al. (1996)





- Classified by energy range (Depends on peak of X-ray flux)

GOES class	1-8Å peak W/m^2
A	$>10^{-8}$
B	$>10^{-7}$
C	$>10^{-6}$
M	$>10^{-5}$
X	$>10^{-4}$
-	$>10^{-3}$

Largest flare:

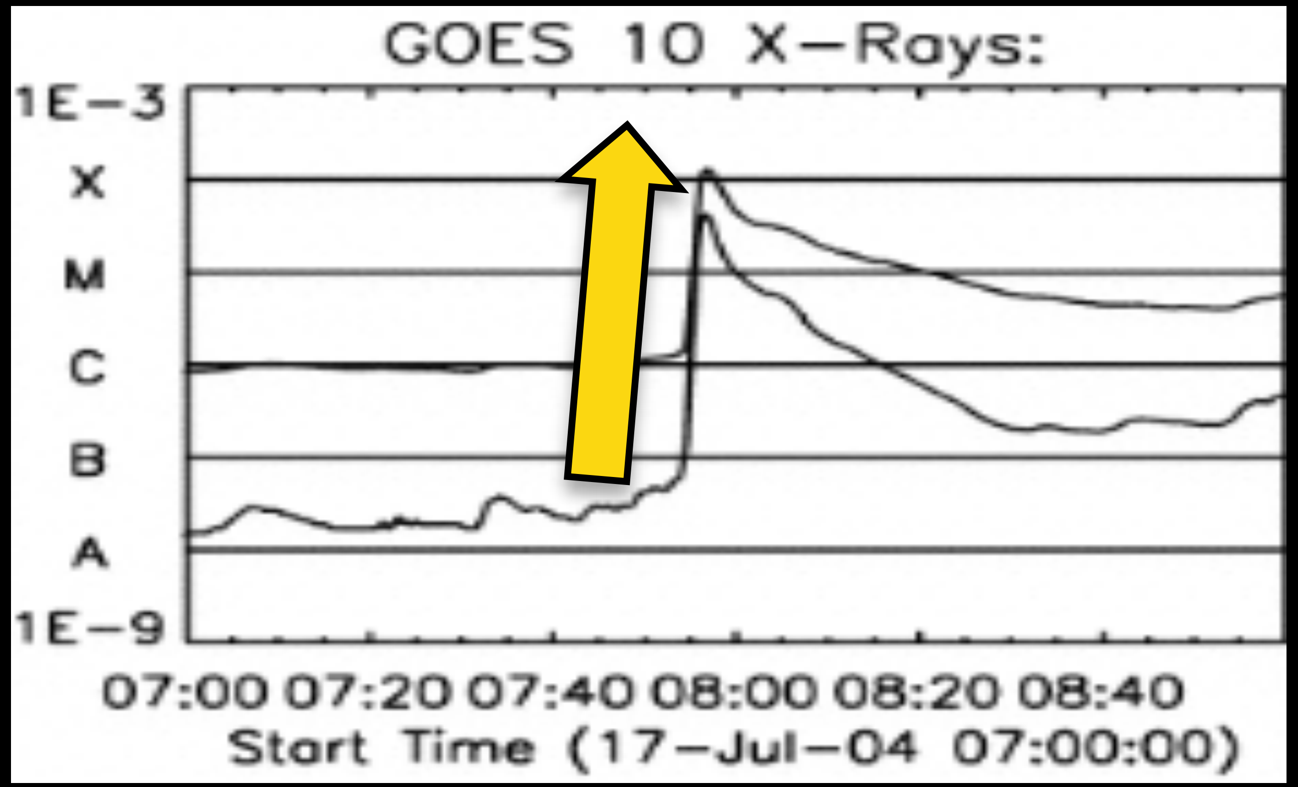
Halloween flare (Nov 4 2003) 10^33 erg X28

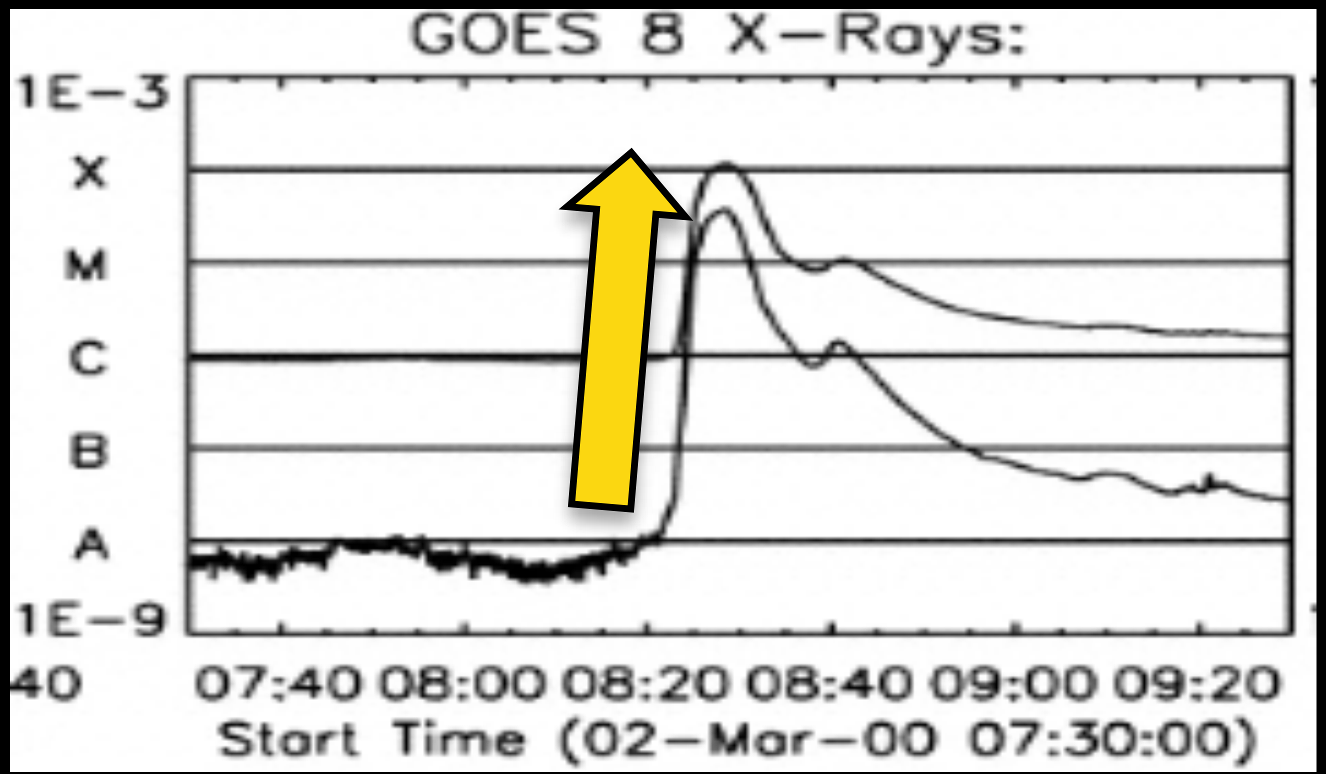
Super flares?

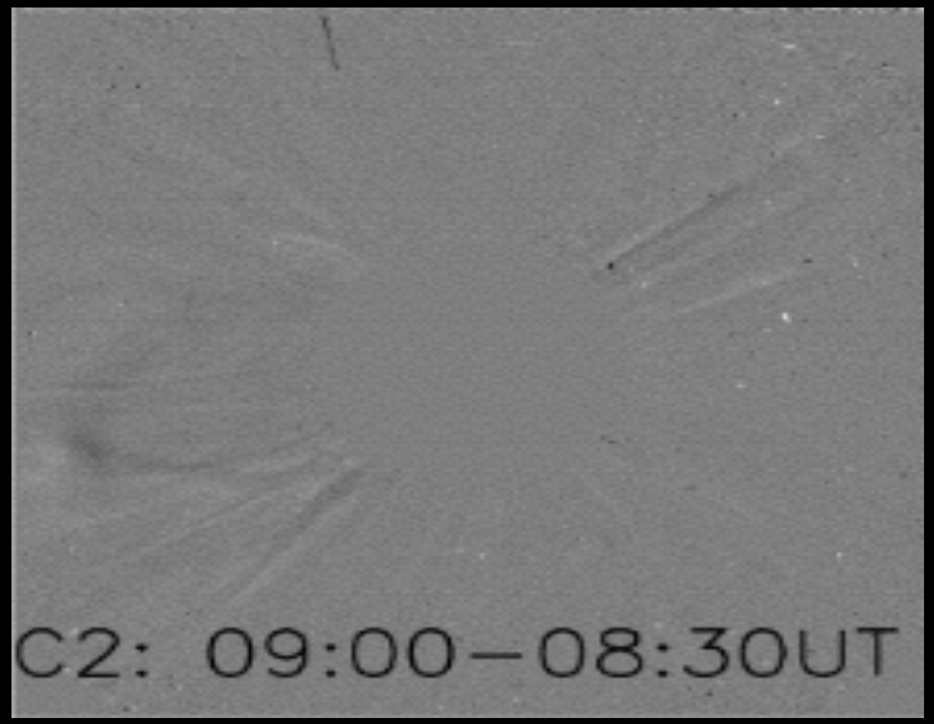
Up to 3.10^36 erg

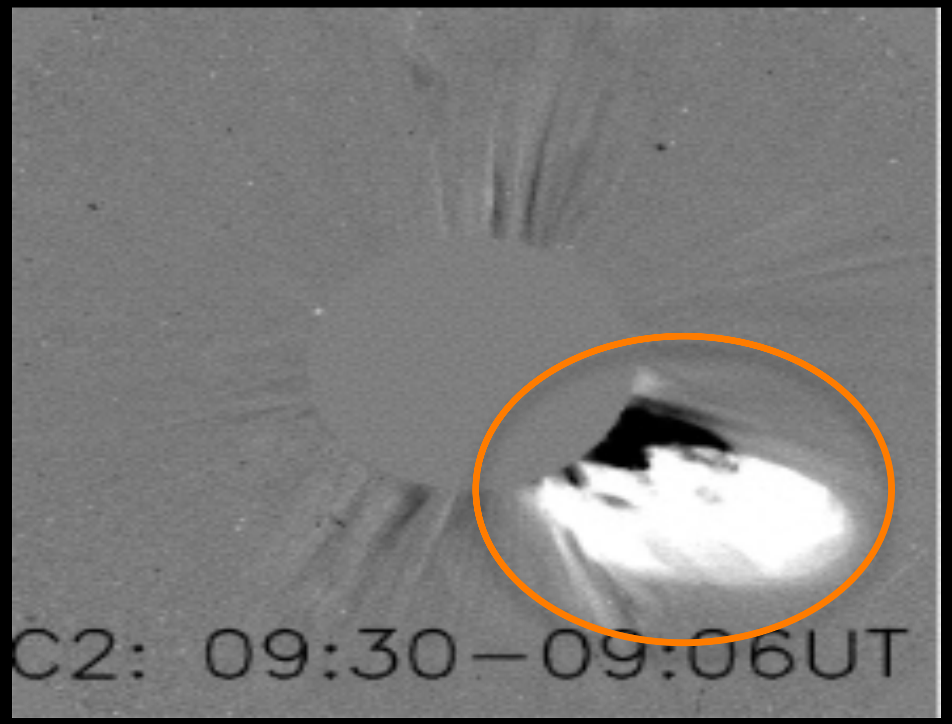

6000 °C
50 000 °C
600 000 °C
1.25 M °C
10 M °C
If in the visible continuum = white light flare
Visible
304
171
193
131

B. Eruptive vs confined flare





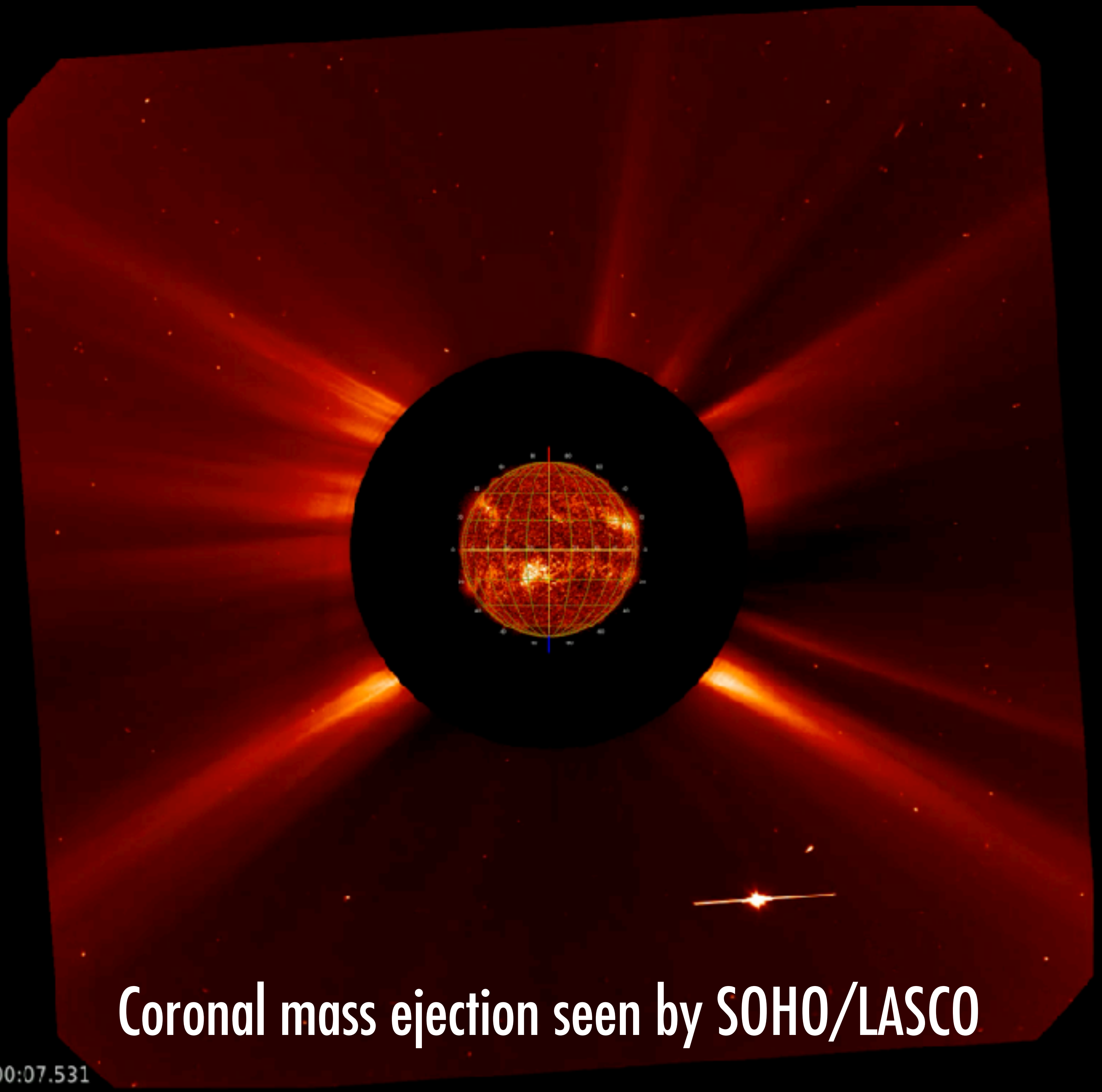




Confined

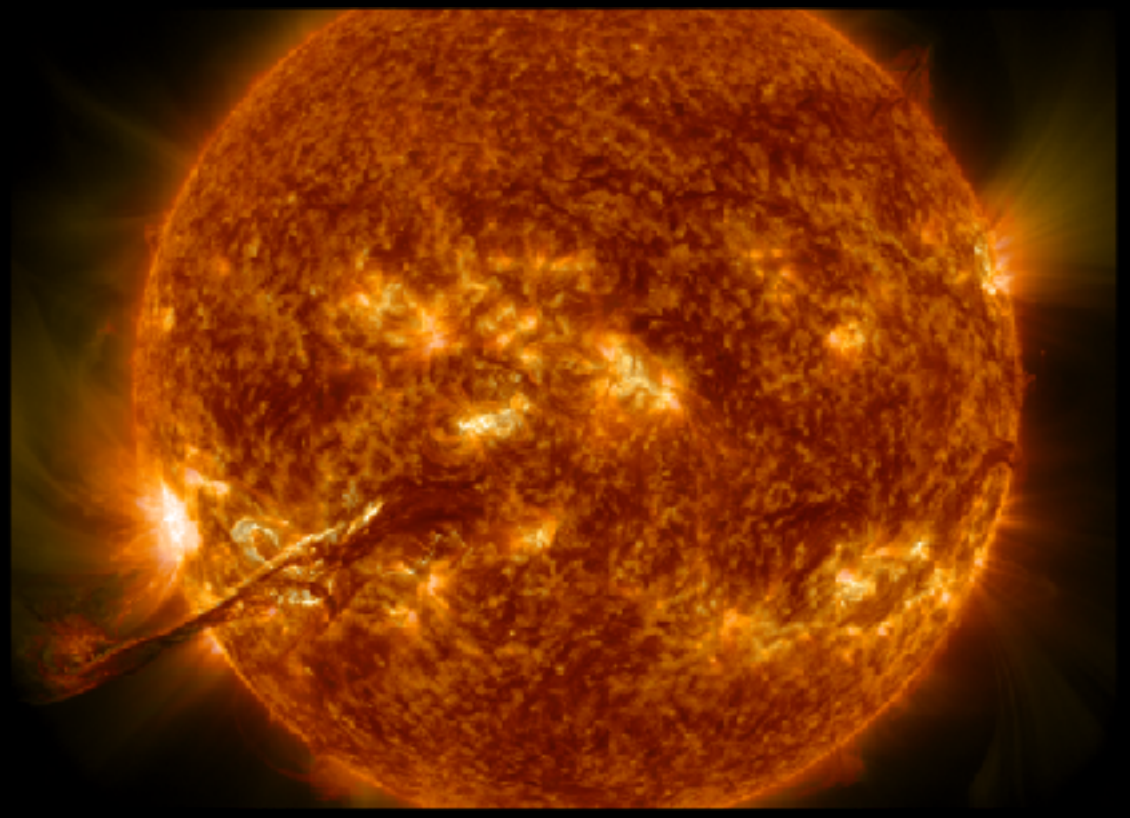
Eruptive

Difference between 2 coronagraph images



Coronal mass ejection seen by SOHO/LASCO

2022-04-02T10:00:07.531



B. Eruptive vs confined flare

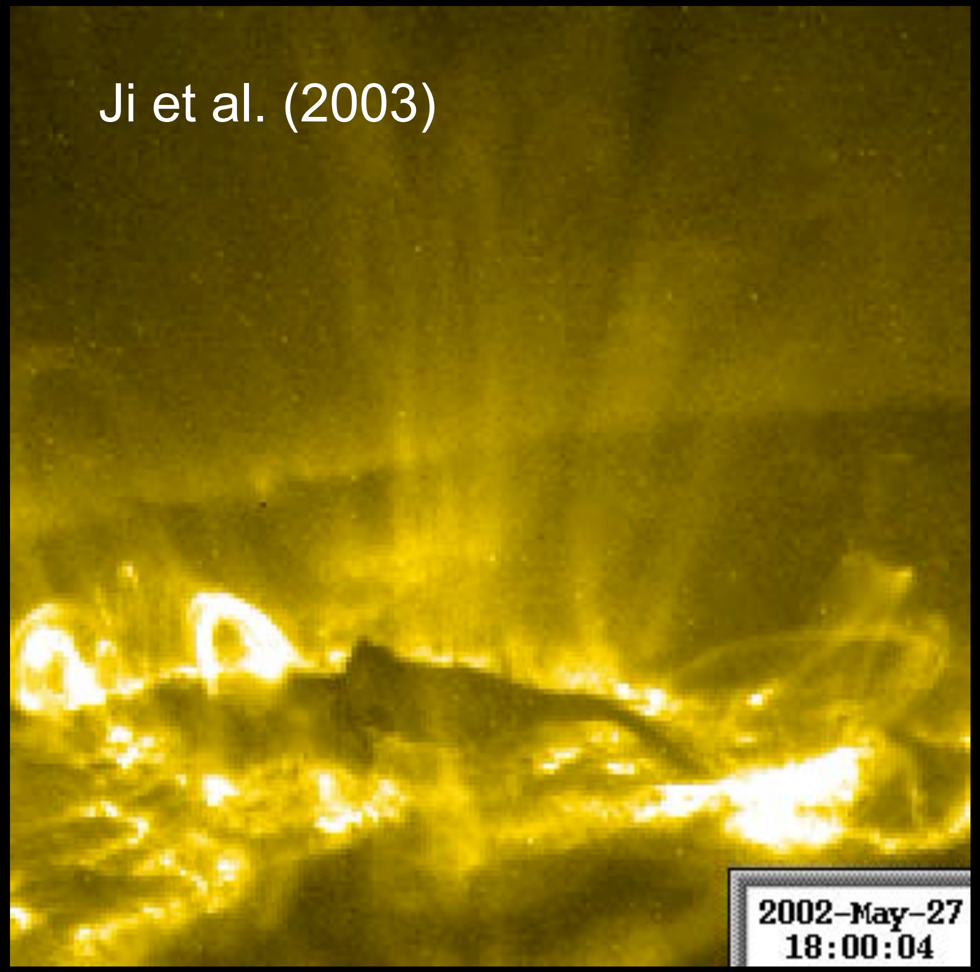
Table 5.1. *Flare classifications*

GOES class	1-8Å peak W/m^2	Hα class	Hα Area *Millionths of hemisphere*	CME fract.[a] *percent*	Events/year *max/min*
A	$>10^{-8}$	-	-	-	-
B	$>10^{-7}$	S	<200	-	-
C	$>10^{-6}$	1	>200	20	>2000/300
M	$>10^{-5}$	2	>500	50	300/20
X	$>10^{-4}$	3	>1200	90	10/one?
-	$>10^{-3}$	4	>1200	100	few?/none?

[a]Yashiro et al. (2005) (approximate values)

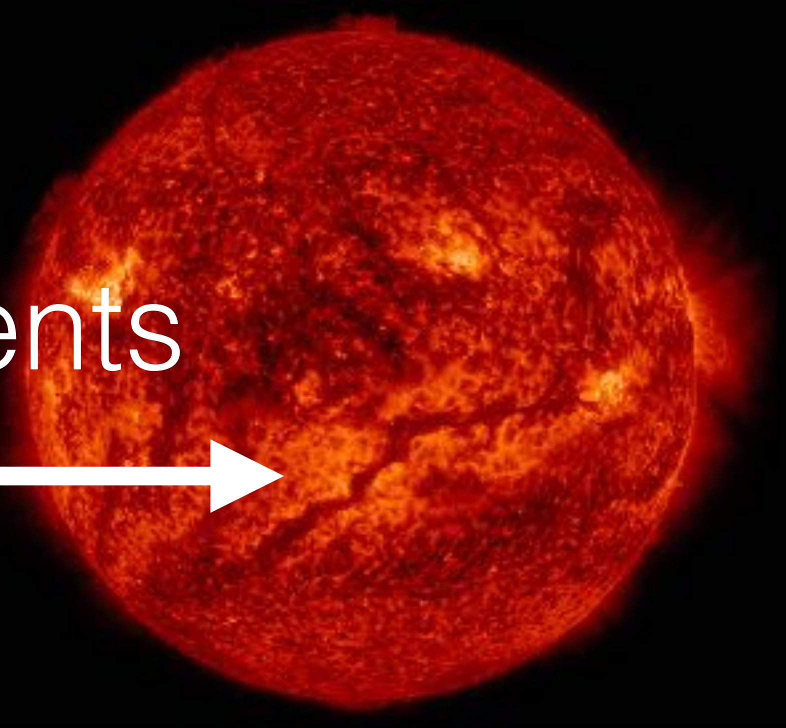
From *Heliophysics II*, eds. Schriver & Siscoe

CME fraction not always the same!
(! Number could also be due to bias of detection)



Sometimes = failed filament eruption

Filaments



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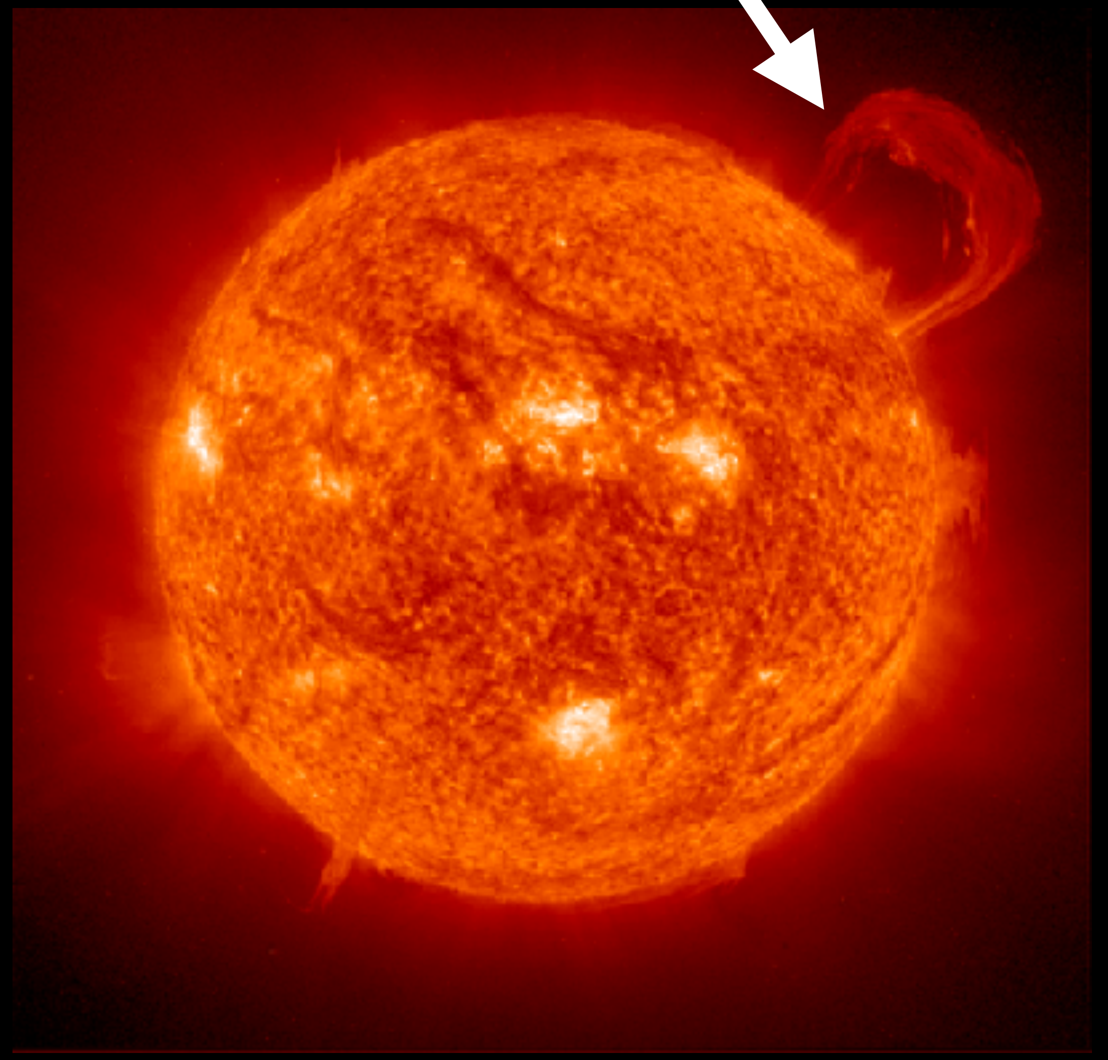
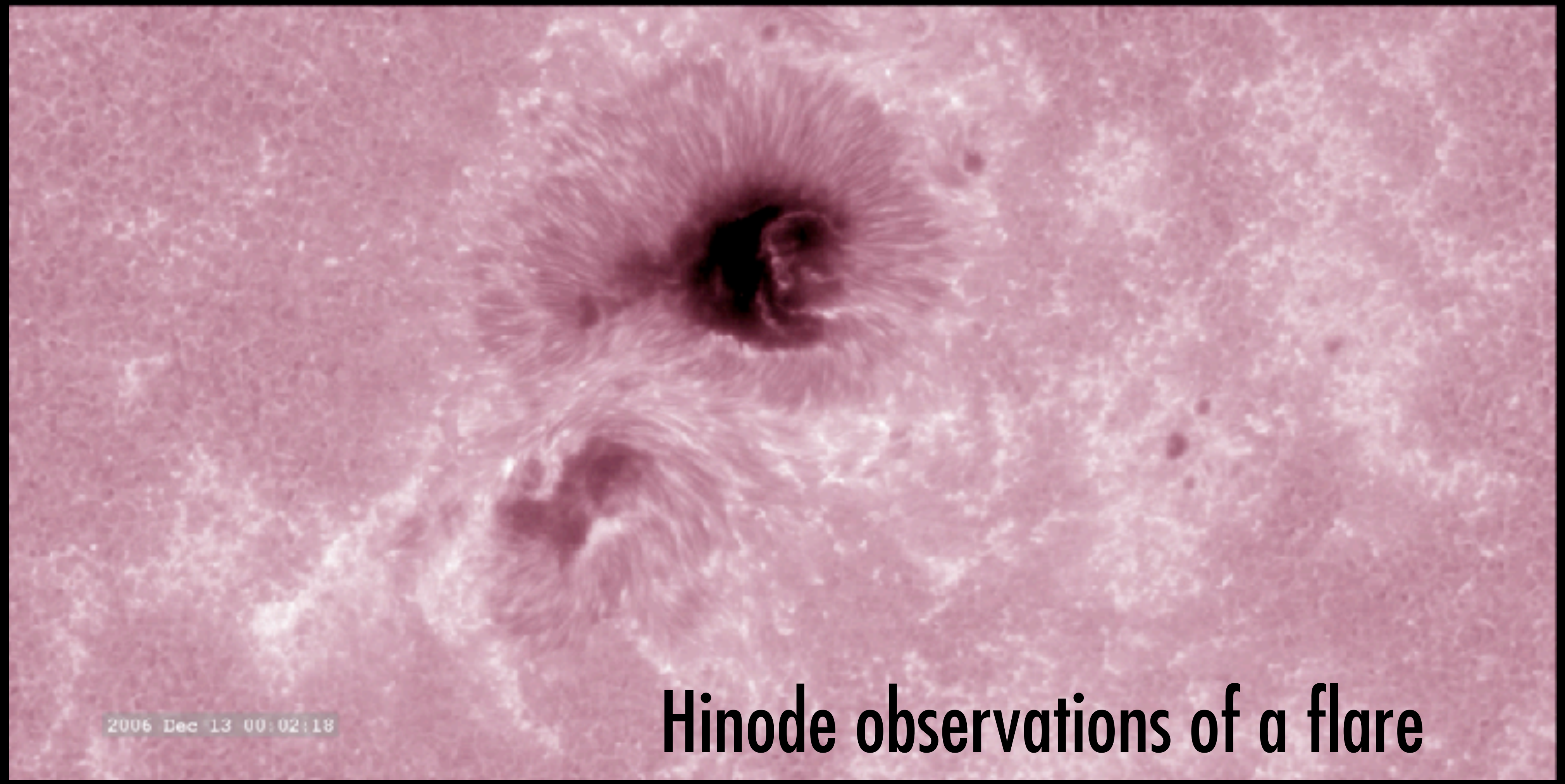
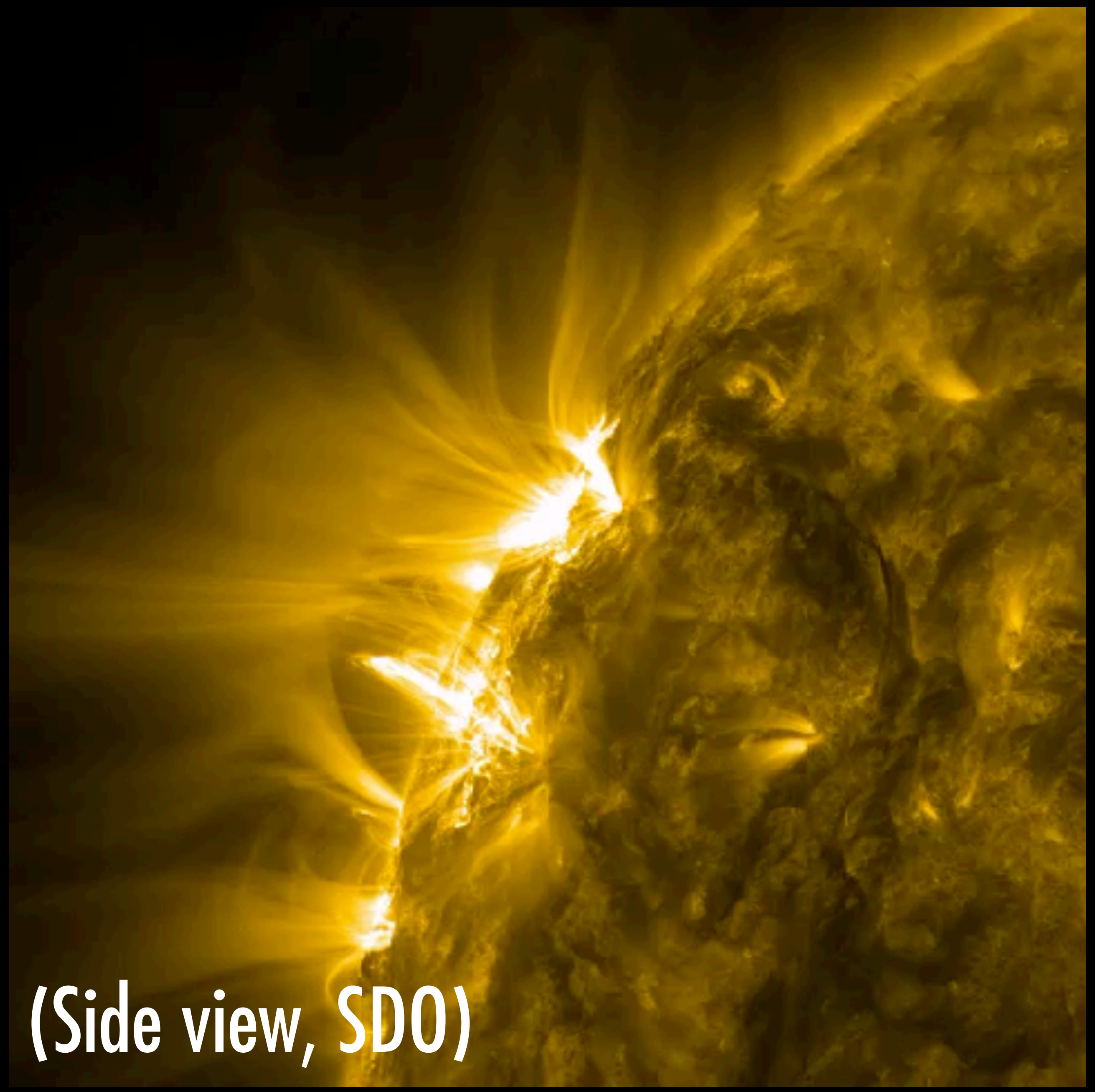
Prominences



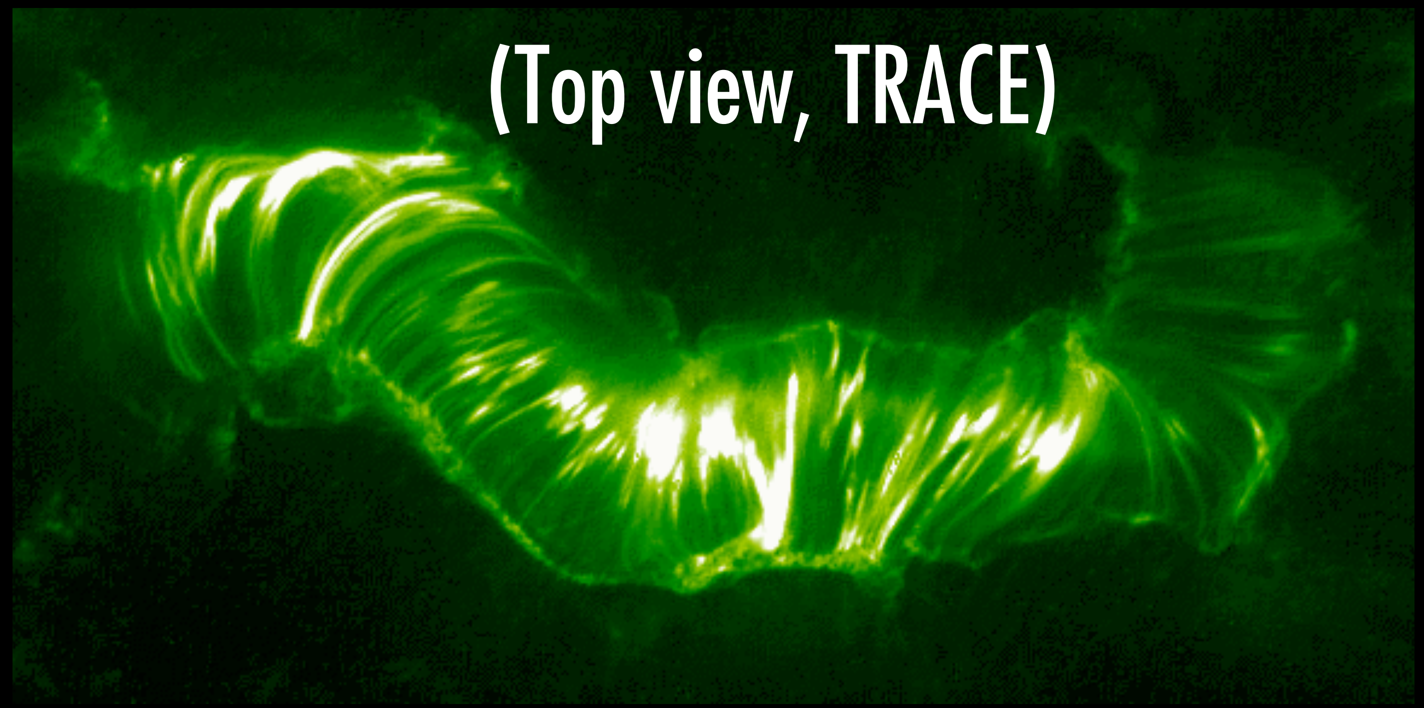
C. Phenomenology



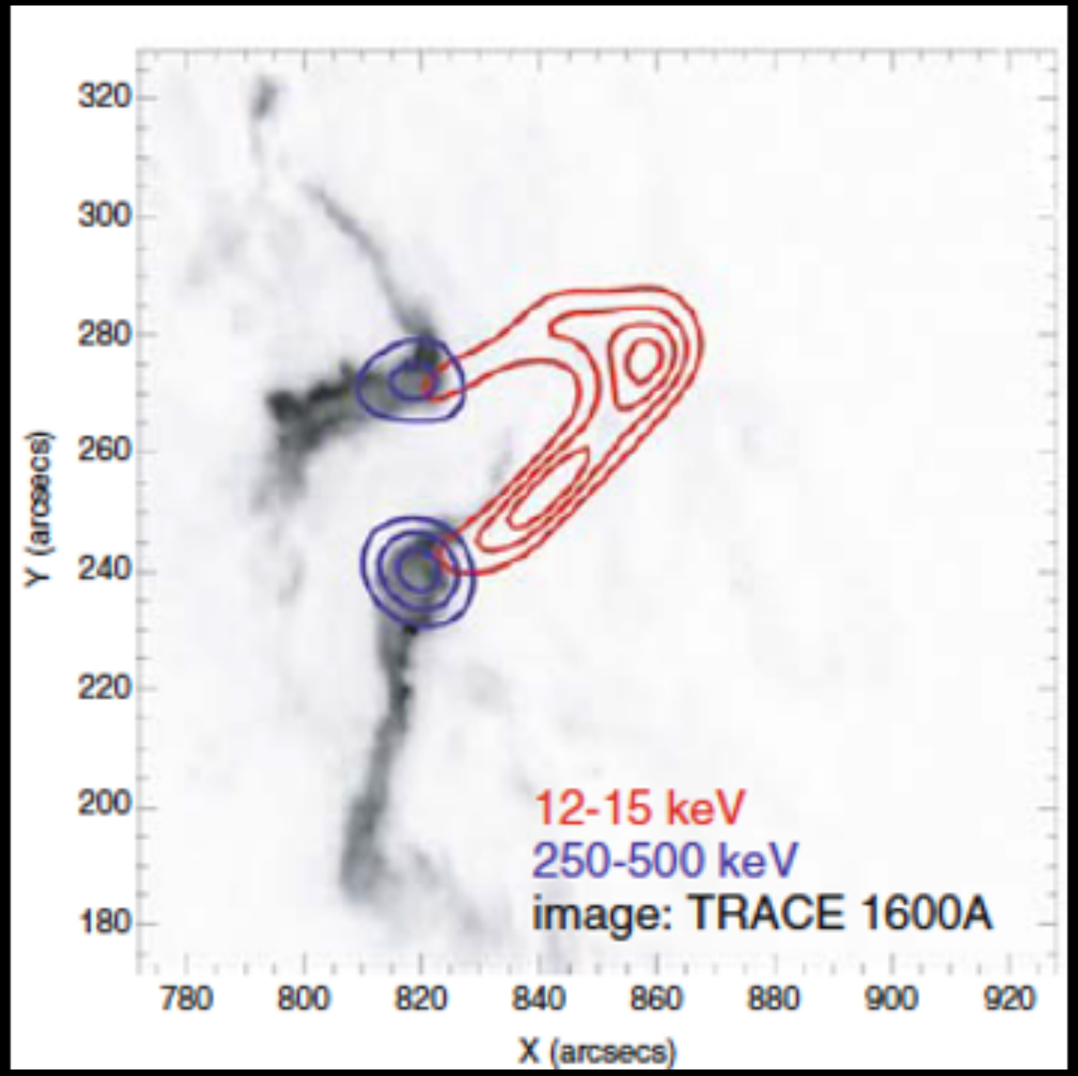
❖Associated with strong magnetic field regions



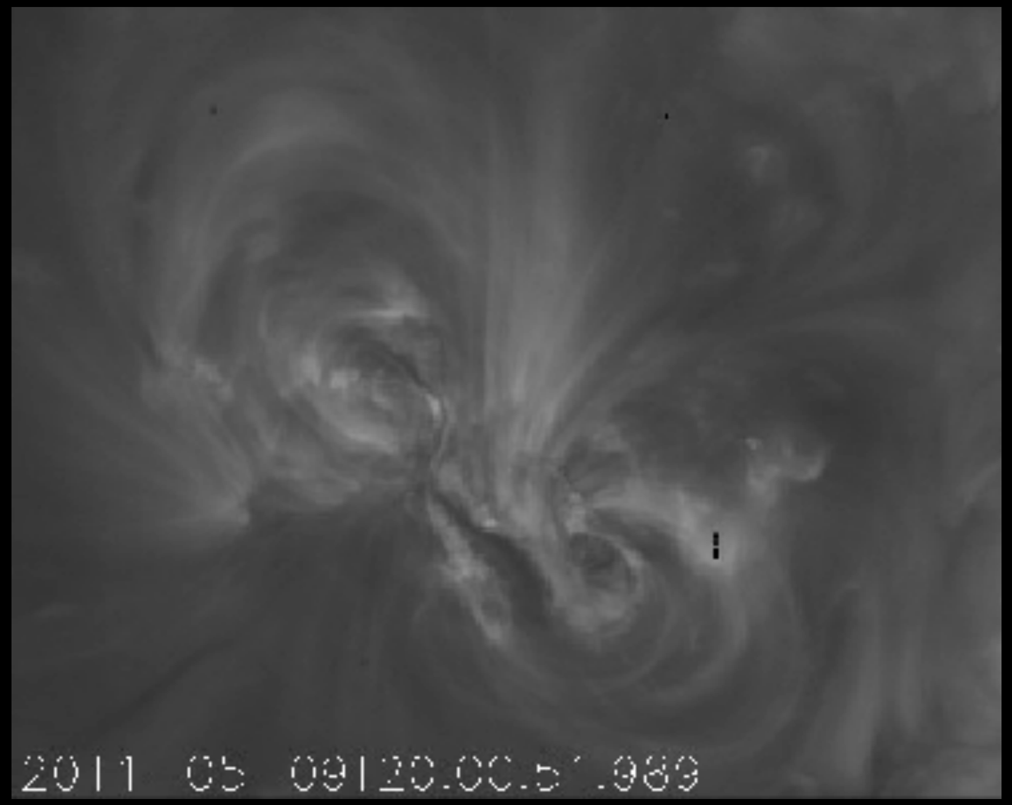
❖Highly structured coronal loops (dense and hot) appear during flares (EUV/X):
Flare Loops



❖Strong hard X-ray footpoints



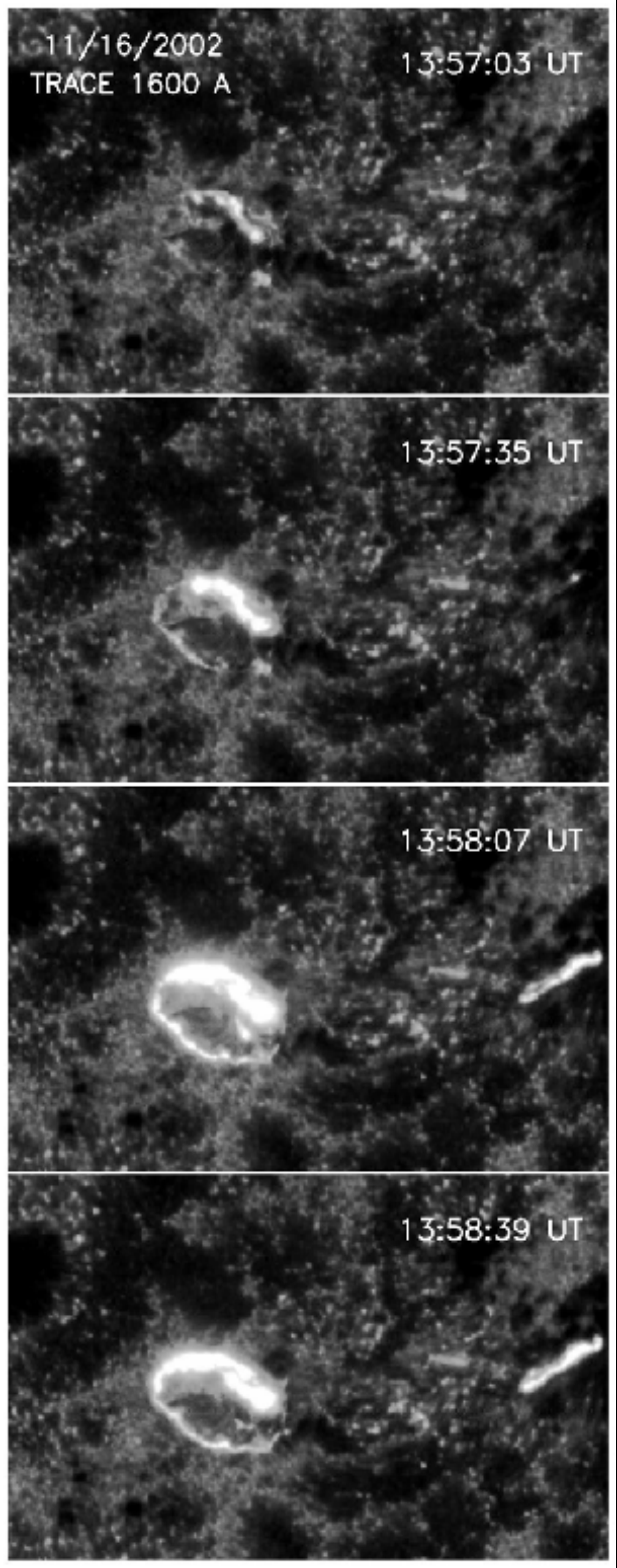
Krucker et al. (2008)



❖Highly structured "ribbons" develop at the bottom of loops
Flare ribbons

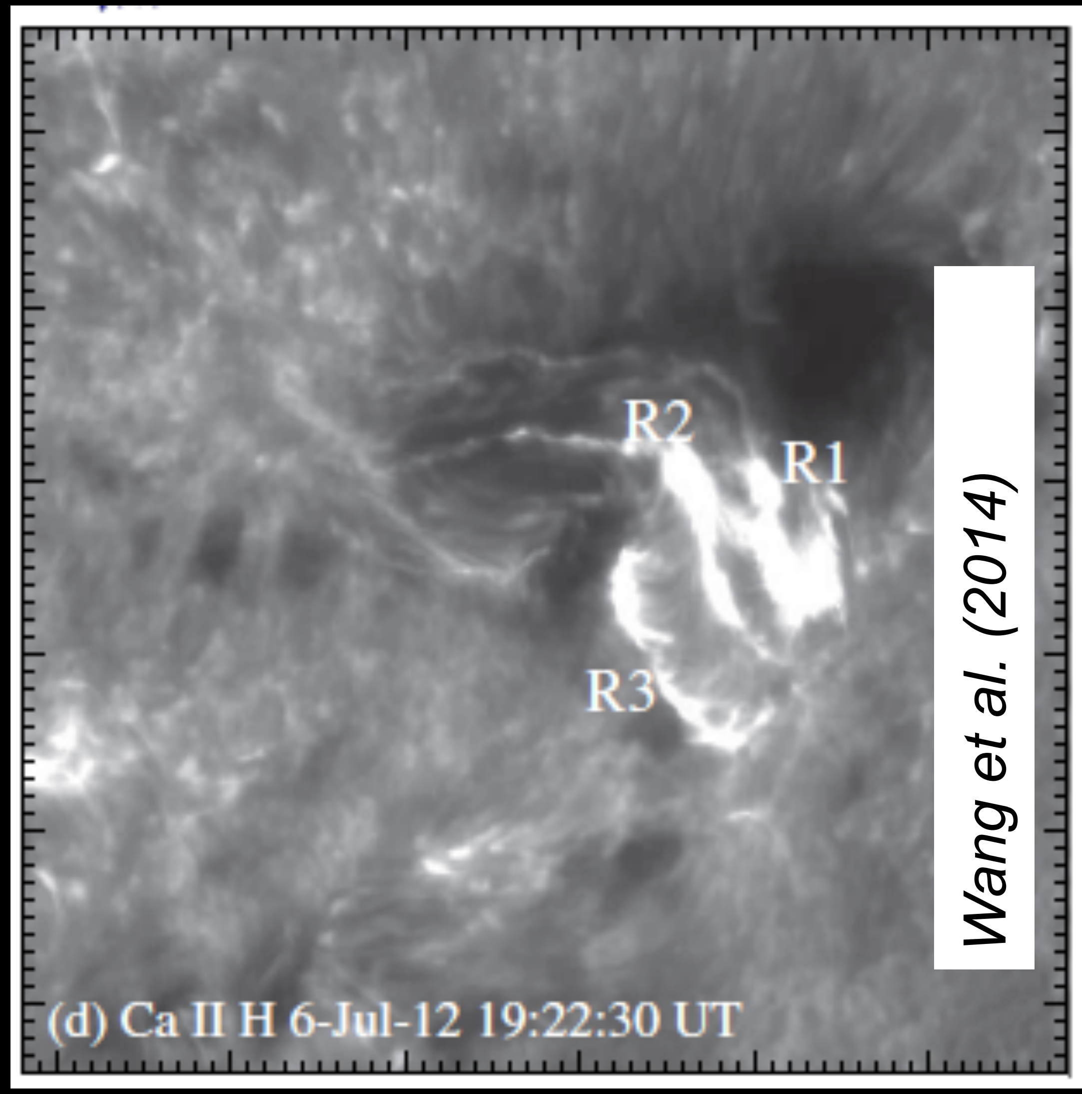
Schmieder et al. 1995, Moore et al. 1995, Asai et al. 2003, Fletcher et al. 2011, Zhang et al. 2011, Warren et al. 2011

C. Phenomenology, confined vs eruptive

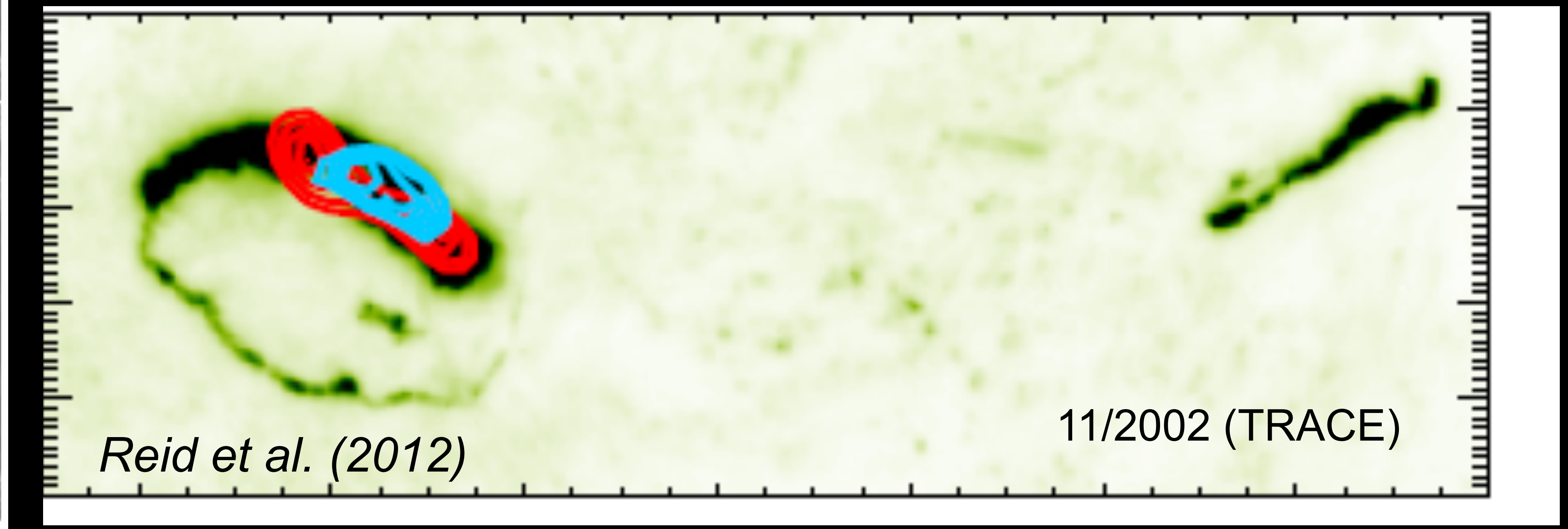


Masson et al. (2009)

- ❖ Circular ribbons
- ❖ (Ribbons can also be more complex)



Wang et al. (2014)



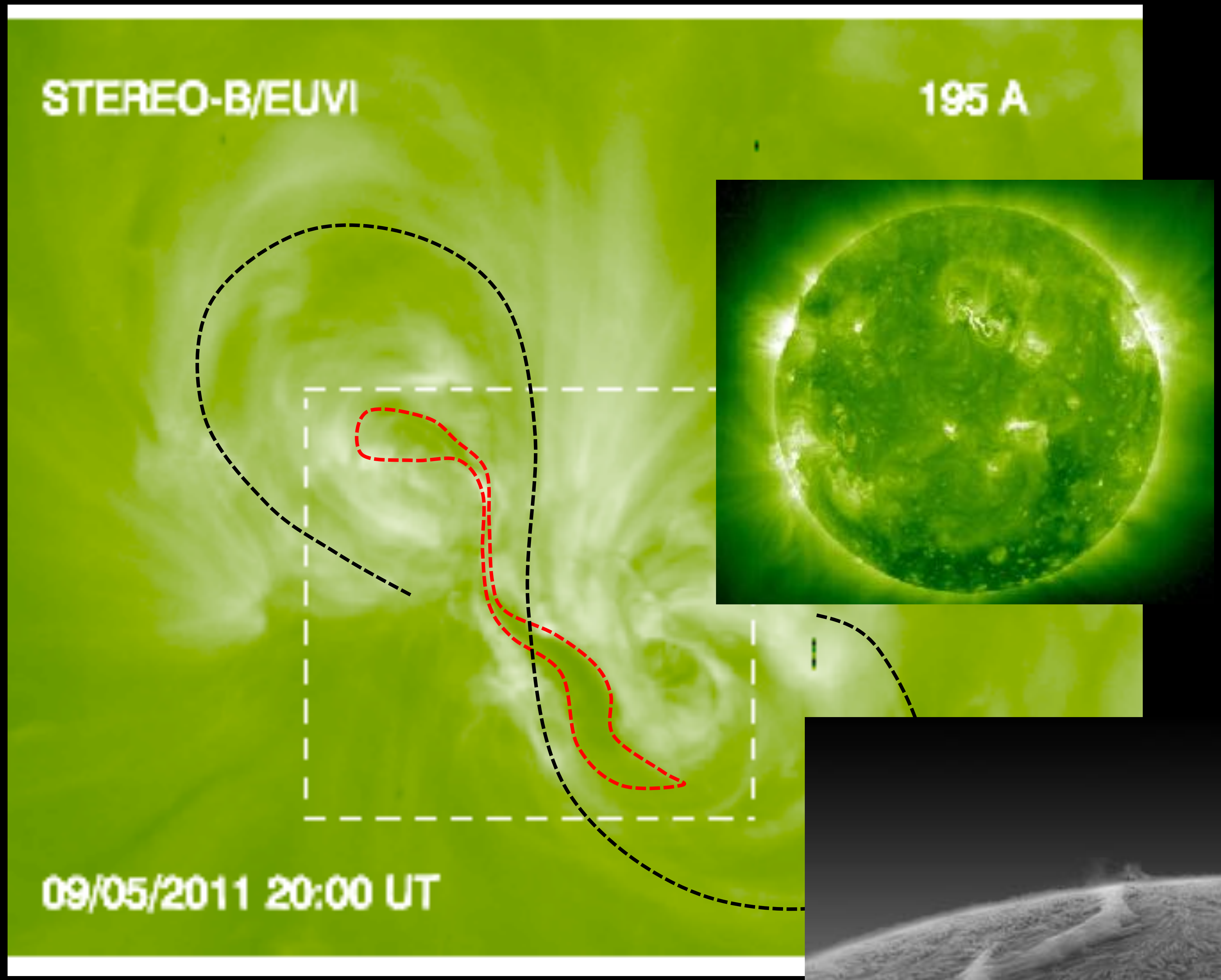
Reid et al. (2012)

11/2002 (TRACE)

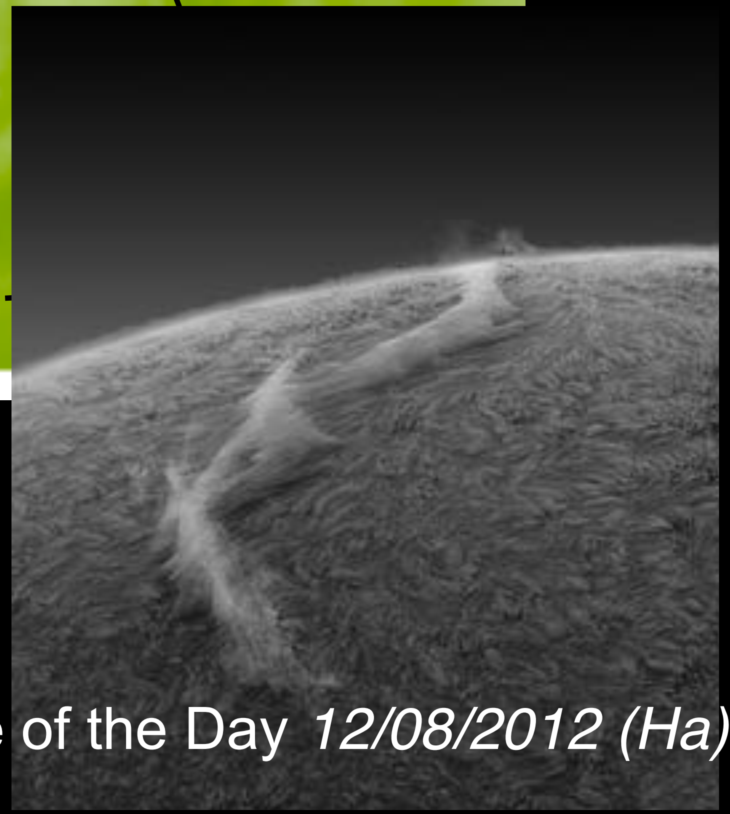
Pre-eruptive sigmoid & filament

(not always)

Rust & Kumar (1996),Green & Kliem (2009), Schmieder (2013)



Aulanier, Janvier & Schmieder (2012)



Astronomy Picture of the Day *12/08/2012 (Ha)*

Chap 2

D. Where does the flare energy come from?

Energy of a (solar) flare

$10^{28} \sim 10^{33}$ erg

Schrijver et al. (2012)

Magnetic field drives the coronal activity:

$\beta \sim E_{Th} / E_B \sim 2\mu P / B^2 < 1$

Where is the magnetic "free" energy stored?

We need:

- ☞A long duration energy storage phase

A few days (flares) to a few weeks (prominence eruptions)

- ☞A sudden energy release mechanism

Alfvénic timescales ≈ few minutes

- ☞A mechanism that can generate heat, kinetic energy, and non thermal (energetic) particles

How to release it?

D. Where does the flare energy come from?

Potential fields

MHD version of Ampère's law: $\mu \mathbf{J} = \nabla \times \mathbf{B}$

Simplest configuration = no currents: $\mathbf{J}_0 = \nabla \times \mathbf{B}_0 = 0$; $\nabla . \mathbf{B}_0 = 0$; $\mathbf{B}_0 = \nabla \Phi$

Mag. field expressed as a **potential** vector, minimum energy = $E_{B0} = \iiint \frac{1}{2} \mathbf{B}_0^2 \, dV$

D. Where does the flare energy come from?

Potential fields

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Mag. field expressed as a **potential** vector, minimum energy = $E_{B0} = \iiint \frac{1}{2} \mathbf{B}_0^2 \, dV$

Non-potential fields

$\mathbf{B} = \mathbf{B}_0 + \mathbf{B}_1$; $\nabla . \mathbf{B}_1 = 0$; $\iint \mathbf{B}_1 . d\mathbf{S} = 0$

$E_B = \iiint \frac{1}{2} \mathbf{B}_0^2 \, dV + \iiint \frac{1}{2} \mathbf{B}_1^2 \, dV + \iiint \mathbf{B}_0 . \mathbf{B}_1 \, dV$

D. Where does the flare energy come from?

Potential fields

MHD version of Ampère's law: $\mu \mathbf{J} = \nabla \times \mathbf{B}$

Simplest configuration = no currents: $\mathbf{J}_0 = \nabla \times \mathbf{B}_0 = 0$; $\nabla . \mathbf{B}_0 = 0$; $\mathbf{B}_0 = \nabla \Phi$

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Non-potential fields

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$$E_B = \iiint \tfrac{1}{2} \mathbf{B}_0^2 \, dV + \iiint \tfrac{1}{2} \mathbf{B}_1^2 \, dV + \iiint \mathbf{B}_0 . \mathbf{B}_1 \, dV$$

$$= E_{B0} + E_{B1} + \iiint (\nabla \Phi) . \mathbf{B}_1 \, dV$$

$$= E_{B0} + E_{B1} + \iiint [\nabla.(\Phi \mathbf{B}_1) - \Phi (\nabla . \mathbf{B}_1)] \, dV$$

▶ divergence-free

$$= E_{B0} + E_{B1} + \iiint \nabla.(\Phi \mathbf{B}_1) \, dV$$

▶Stoke's theorem

$$= E_{B0} + E_{B1} + \iint \Phi \mathbf{B}_1 . d\mathbf{S}$$

▶divergence-free (integral form)

$$= E_{B0} + E_{B1} > E_{B0}$$

Current-less **B**-field = lower bound of energy for a given B_z^{phot}

D. Where does the flare energy come from?

What kind of fields allow current storage?

MHD force balance equation: $\nabla p + \mathbf{J}\times\mathbf{B} + \rho\mathbf{g} = \rho D\mathbf{v}/Dt$

If we assume a steady state, with negligible gravitational forces and pressure gradients (low-β corona), we then obtain a force-free field, with $J \times B = 0$.

Force-free condition —> field and currents are aligned. Then, $\nabla\times\mathbf{B} = \alpha\mathbf{B}$. α *constant along field lines*

D. Where does the flare energy come from?

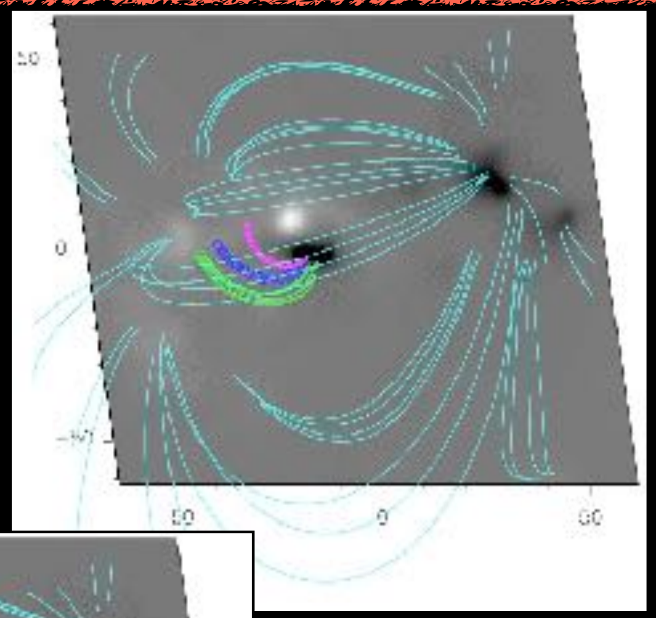
What kind of fields allow current storage?

MHD force balance equation: $\nabla p + \mathbf{J}\mathrm{x}\mathbf{B} + \rho\mathbf{g} = \rho D\mathbf{v}/Dt$

If we assume a steady state, with negligible gravitational forces and pressure gradients (low-β corona), we then obtain a force-free field, with J x B = 0.

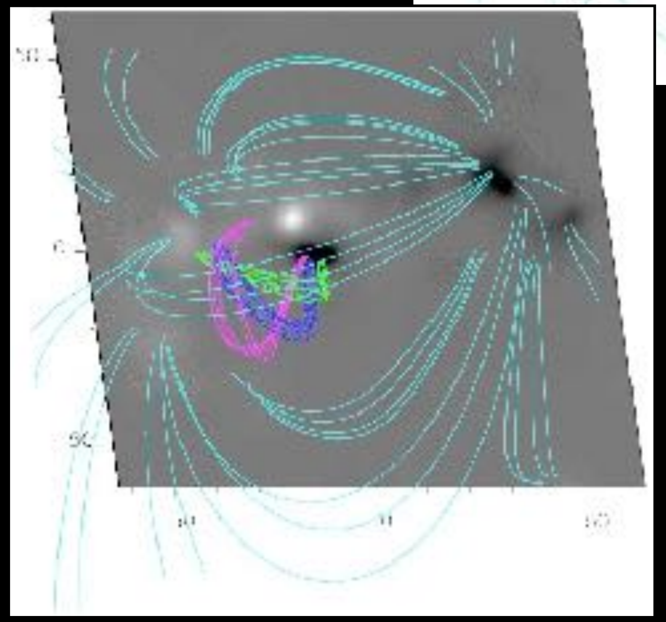
Force-free condition —> field and currents are aligned. Then, $\nabla\mathrm{x}\mathbf{B} = \alpha\mathbf{B}$. α *constant along field lines*

Potential fields $\alpha = 0$ $\nabla\mathrm{x}\,\mathbf{B} = 0$ ➔ $\mathbf{B} = \nabla\Phi$ B defined by a scalar potential



Linear force-free fields α = cst

Helmoltz equation has analytical solutions: $\nabla\mathrm{x}\,(\nabla\mathrm{x}\,\mathbf{B} = \alpha\,\mathbf{B}\,)$ ➔ $\nabla^2\,\mathbf{B} + \alpha^2\,\mathbf{B} = 0$

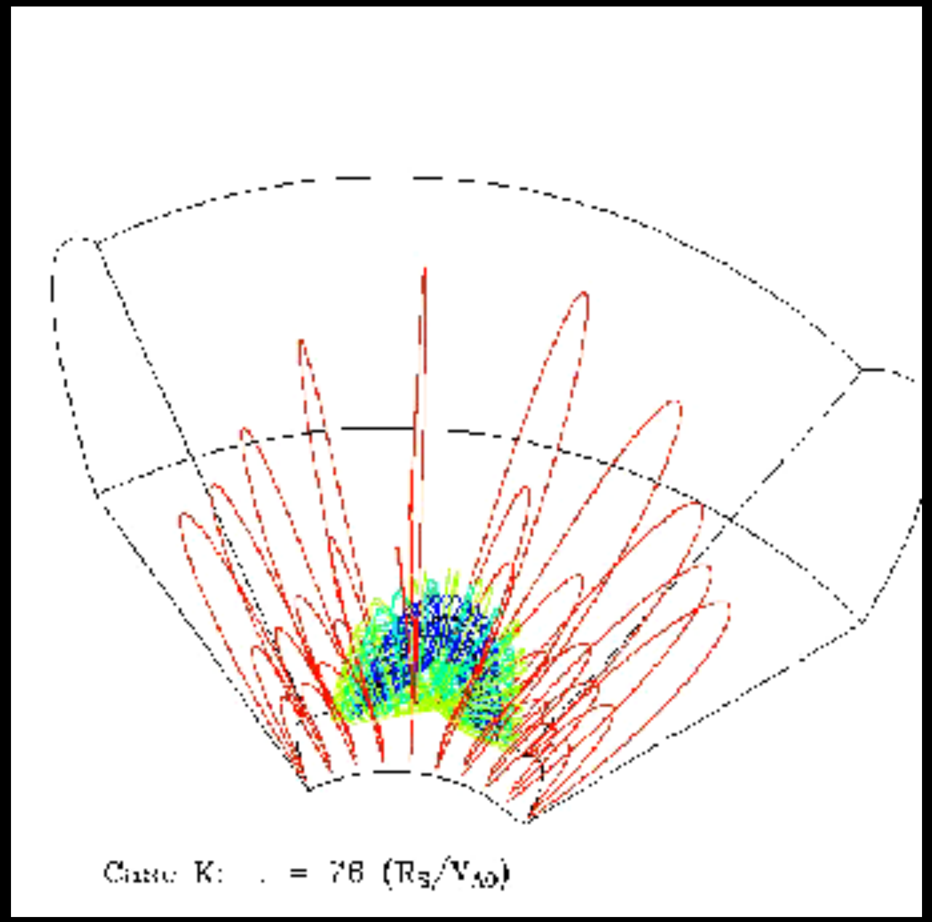


Non-linear force-free fields α = varying $\nabla.(\nabla\mathrm{x}\,\mathbf{B} = \alpha\,\mathbf{B}\,)$ ➔ $(\,\mathbf{B}\,.\nabla)\alpha = 0$

3 classes of force-free fields (2 are current-carrying)

D. Where does the flare energy come from?

<u>Building up the energy, two scenarios</u>



- ❖ Sub-photospheric emergence: Current carrying flux tube from convection zone

Pb: How are flux tubes traveling the whole convection zone?
How do they cross the photosphere/chromosphere? Only 25% of loops reach the chromosphere! *(see. L. Bellot-Rubio's lecture)*

- ❖ Slow photospheric motions

Twisting of 1 or 2 of the polarities

Shearing motions // inversion line

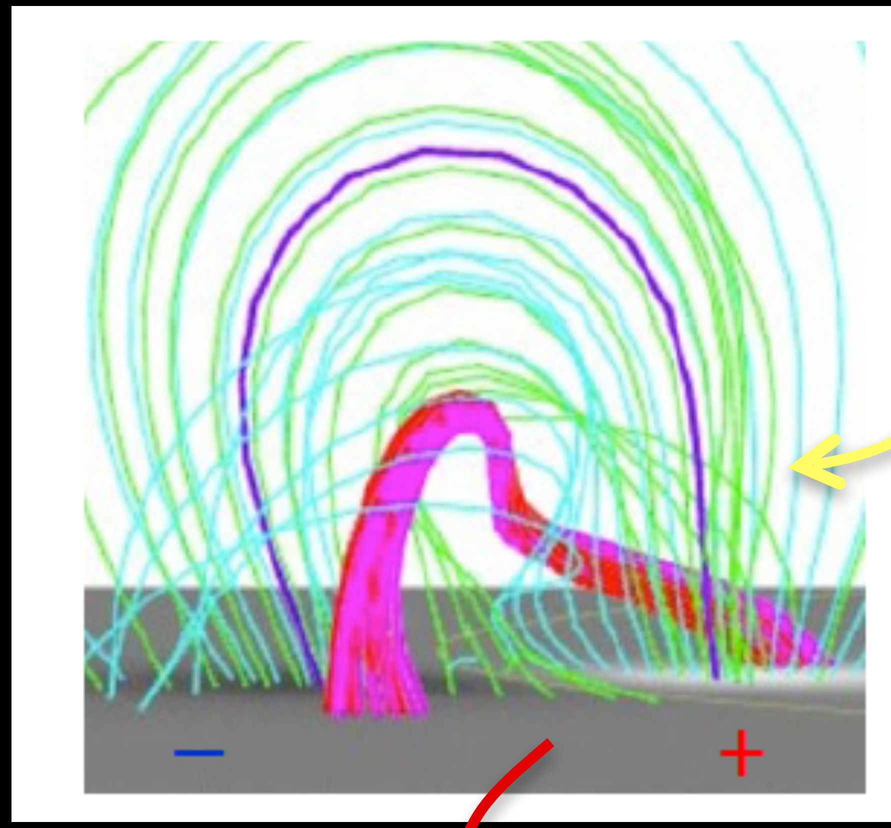
- ❖ Energy stored in closed field lines only

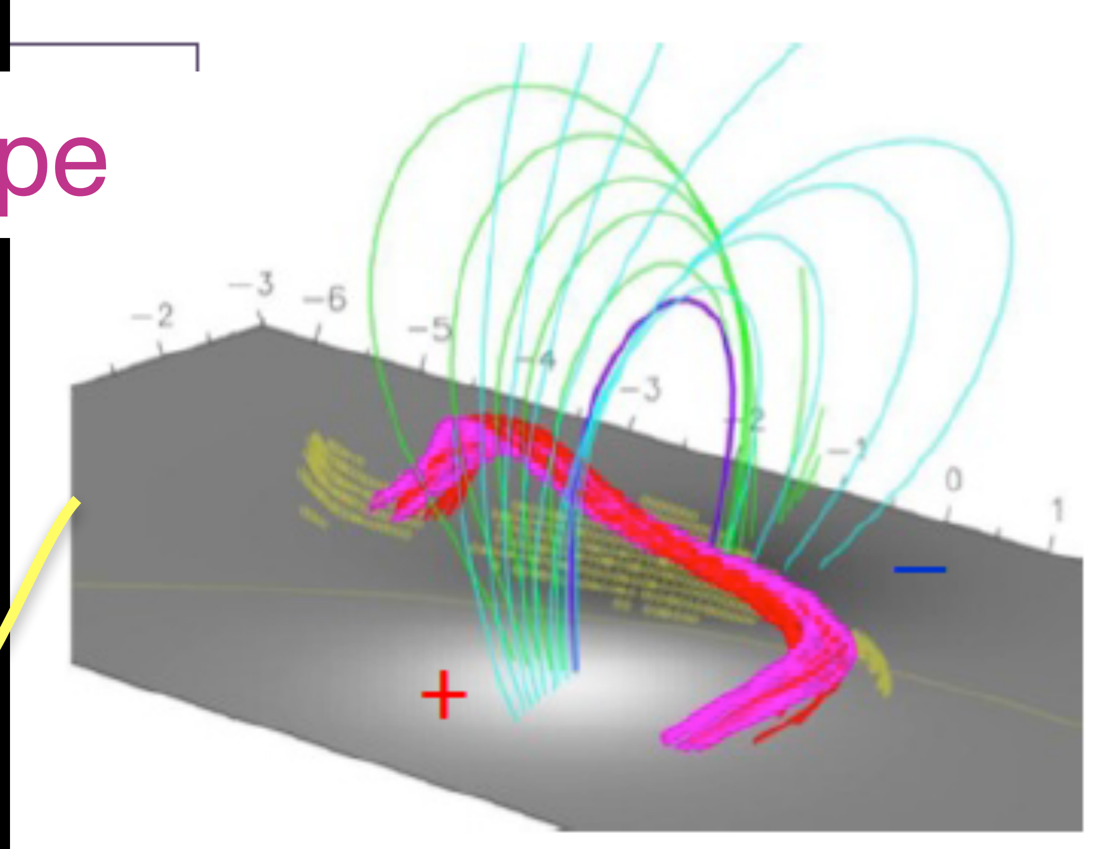
Evacuation of E_B at Alfvénic speeds in open fields

D. Where does the flare energy come from?

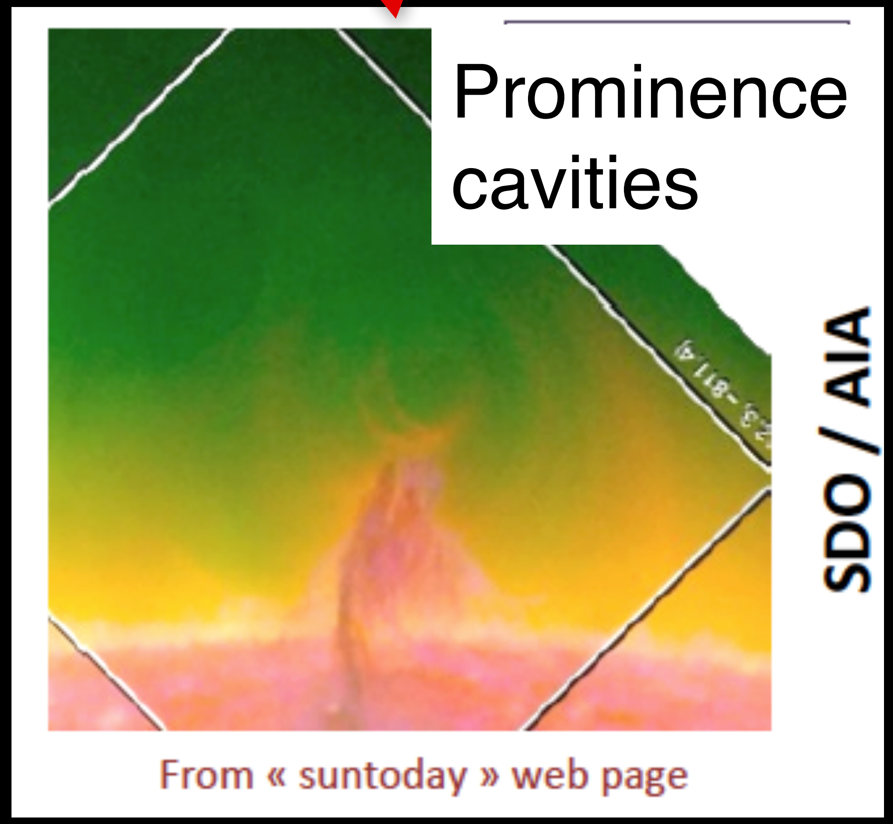
Clear evidences of J//B in different events, from different observations

Flux rope





MHD simulation (sheared bipole)
Aulanier et al. (2010)



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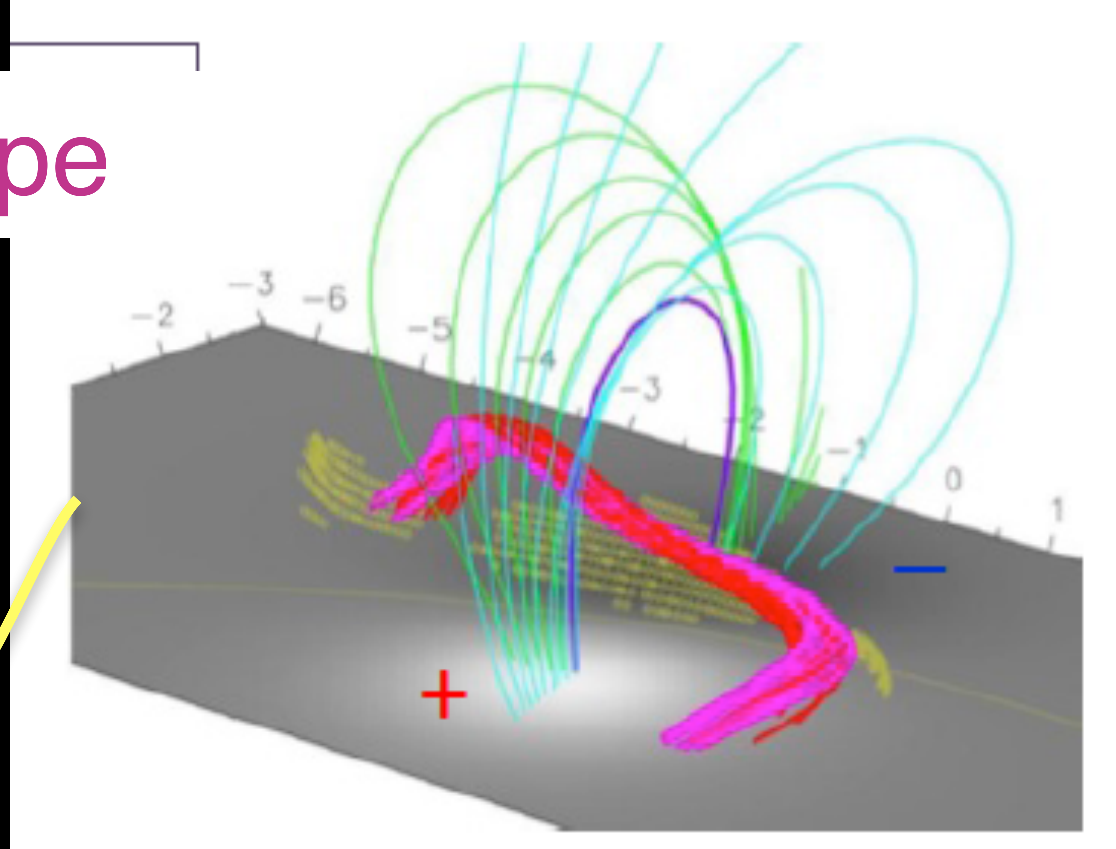

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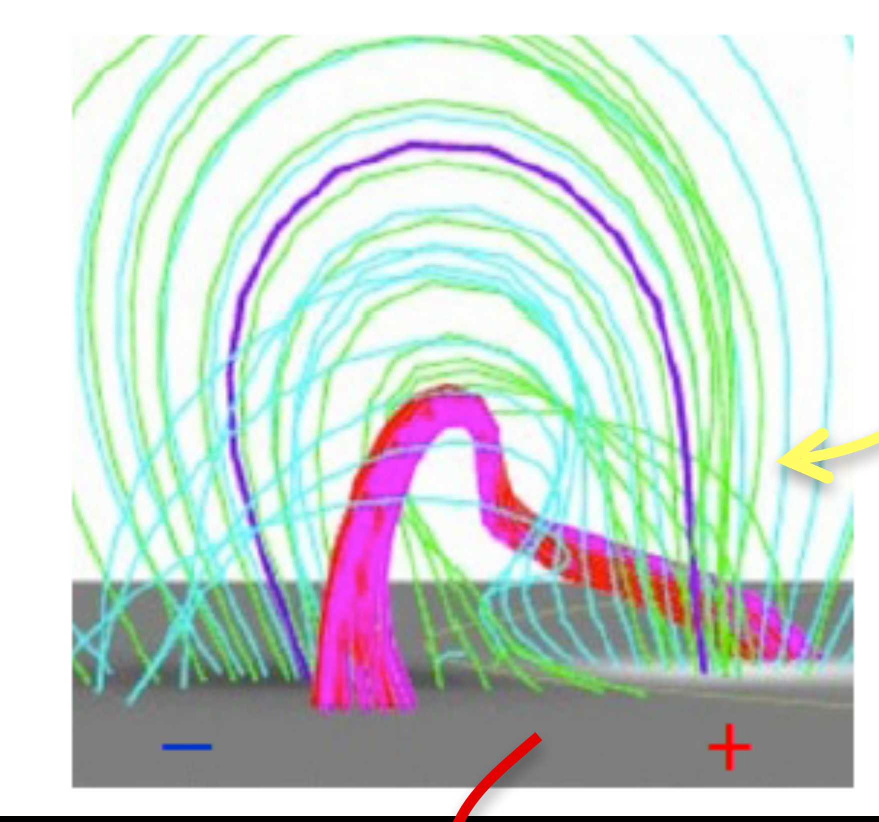
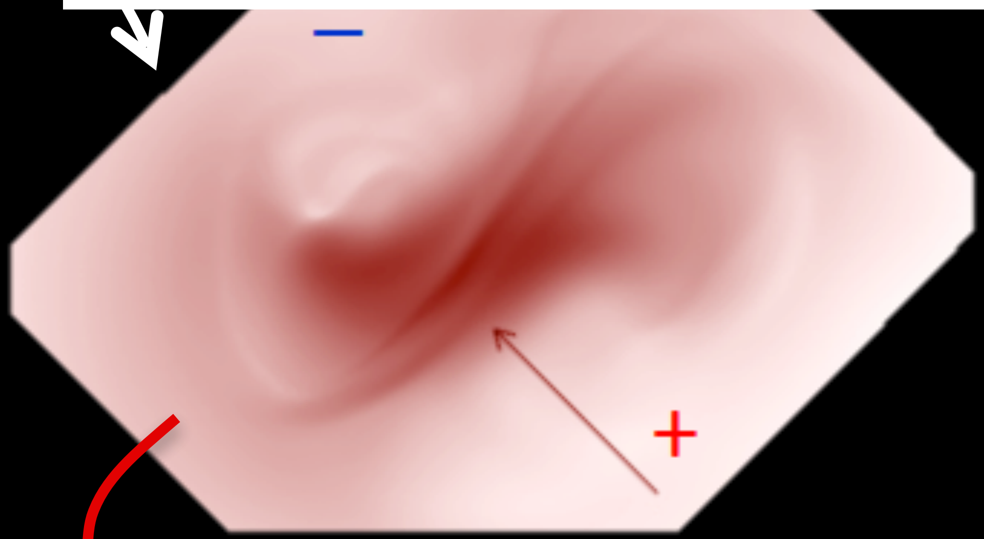
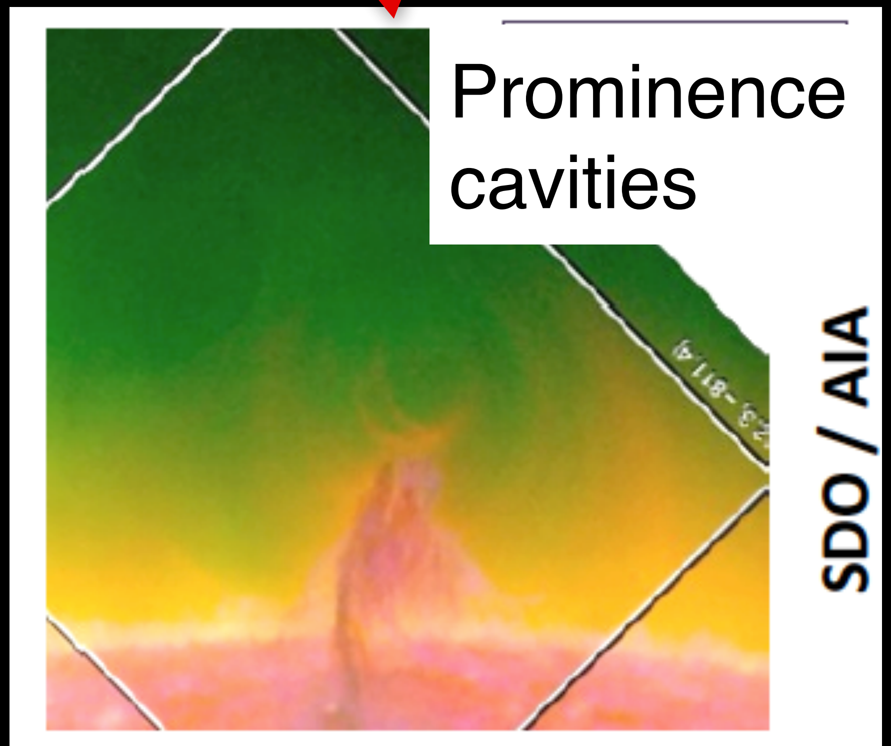
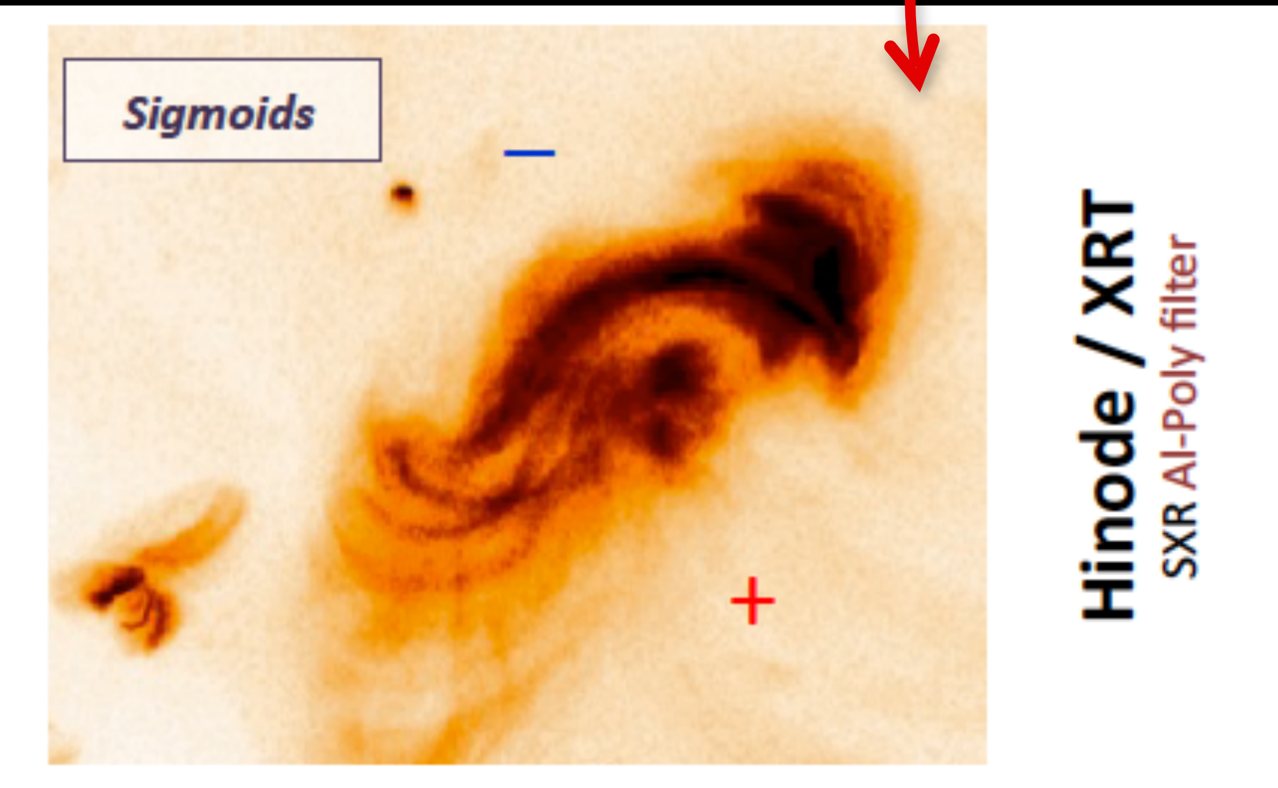


Vertically integrated current





From « suntoday » web page



McKenzie & Canfield (2008), Savcheva et al. (2009), Green & Kliem (2009)

D. Where does the flare energy come from?

Clear evidences of J//B in different events, from different observations

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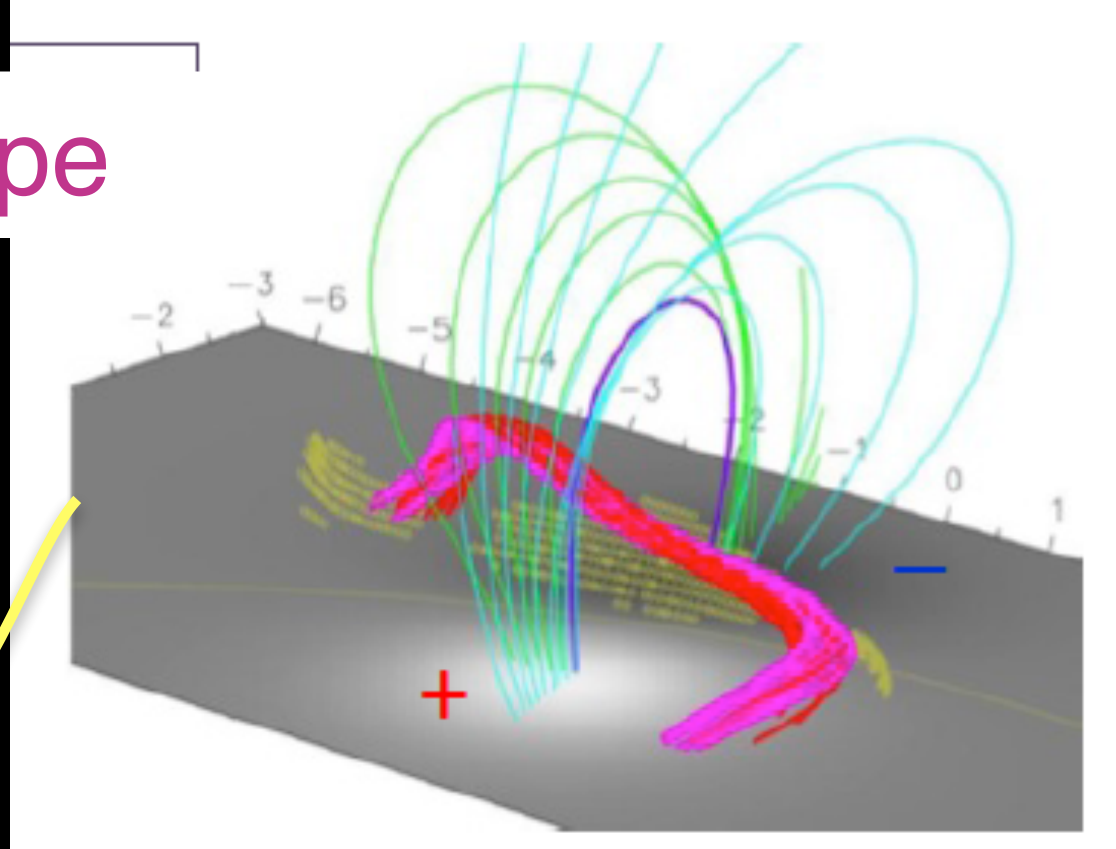

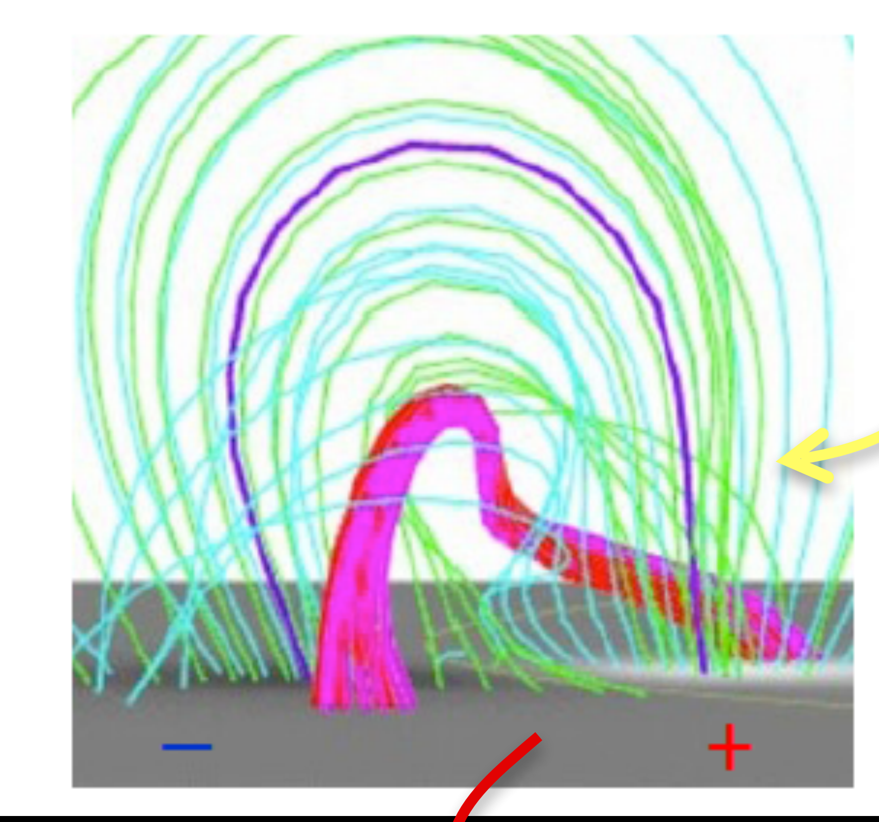

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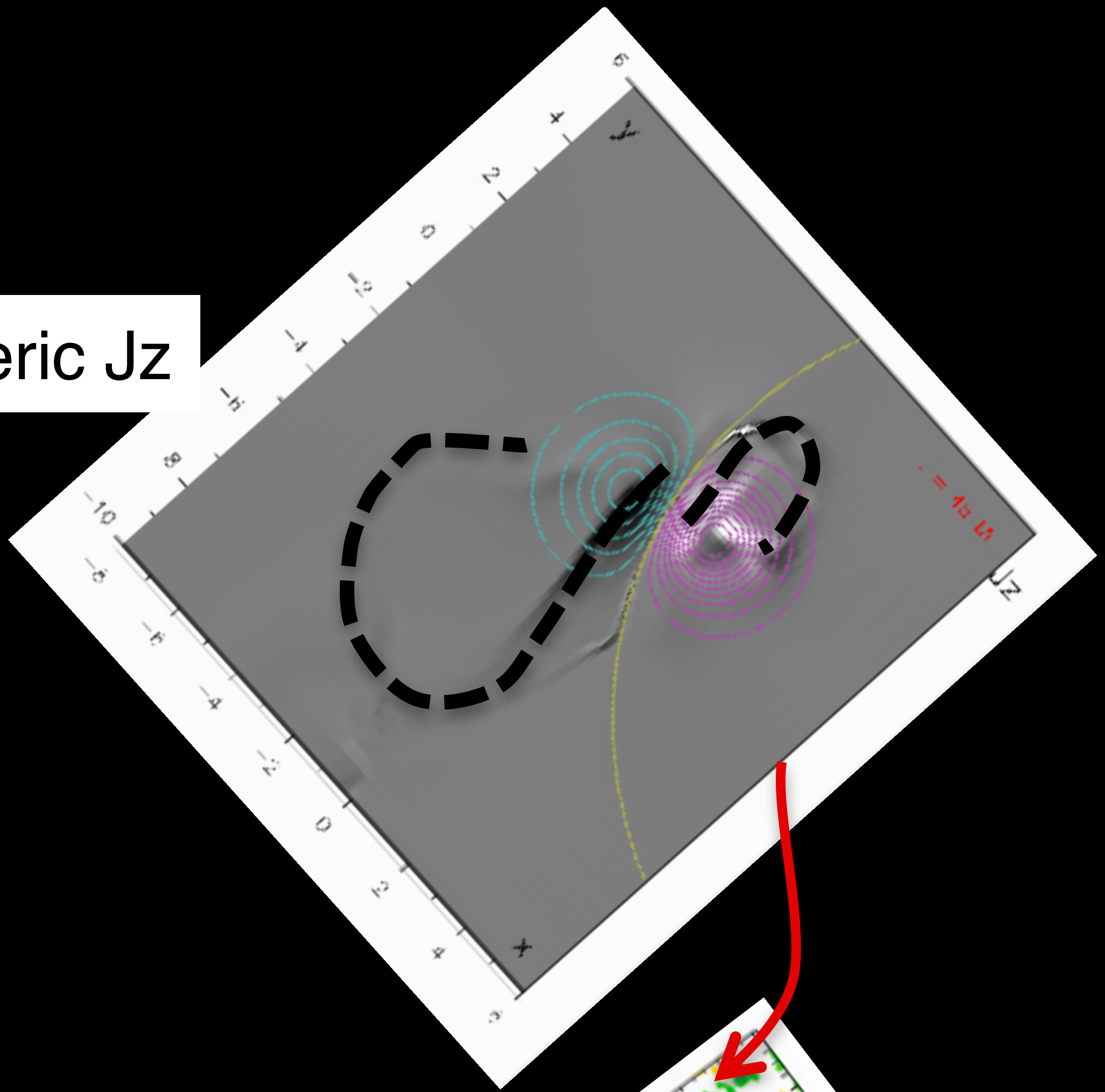
Photospheric Jz



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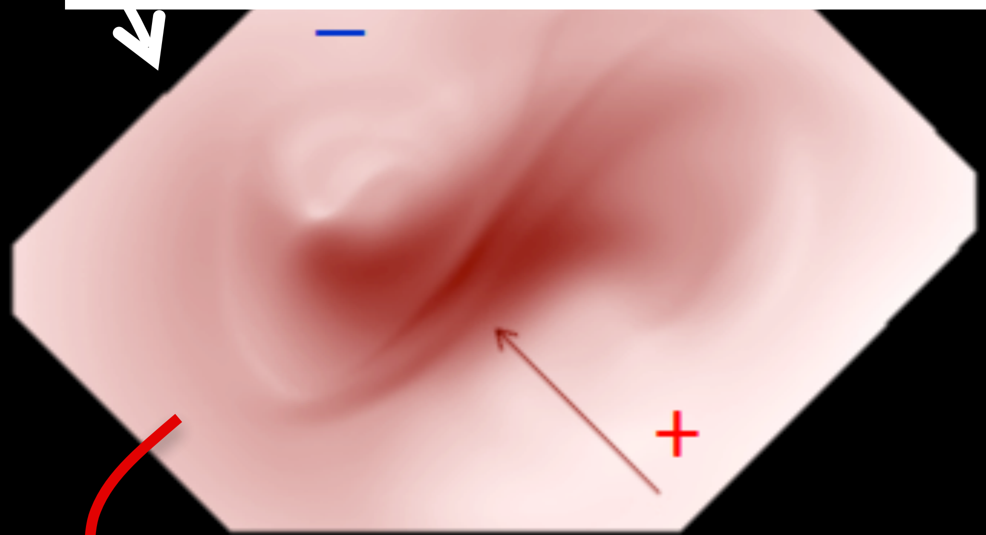
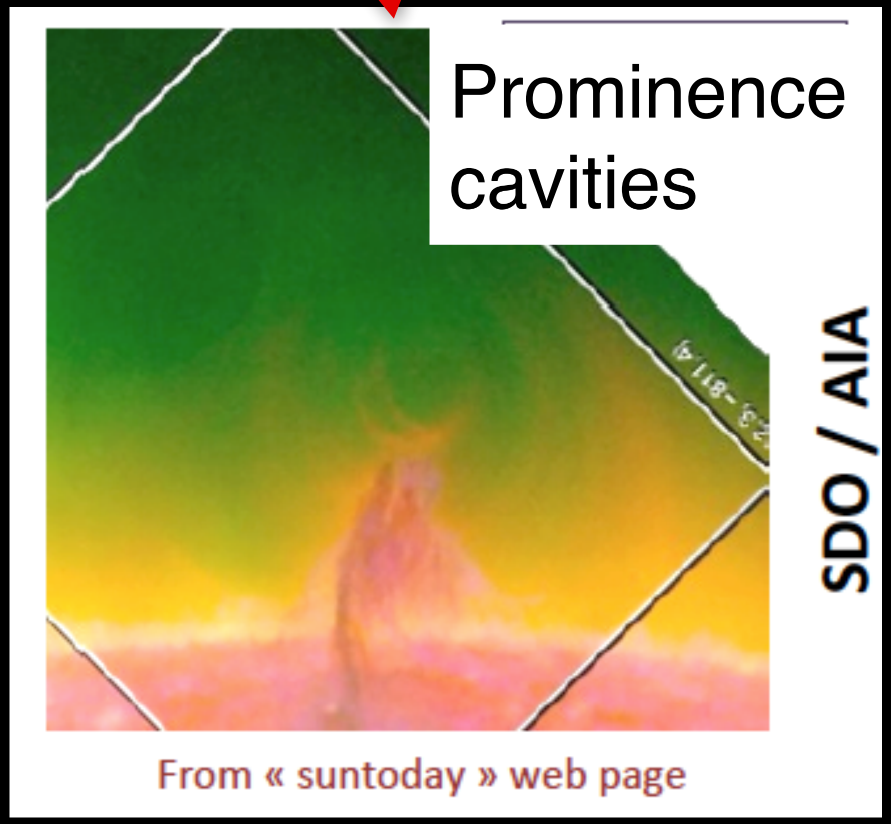
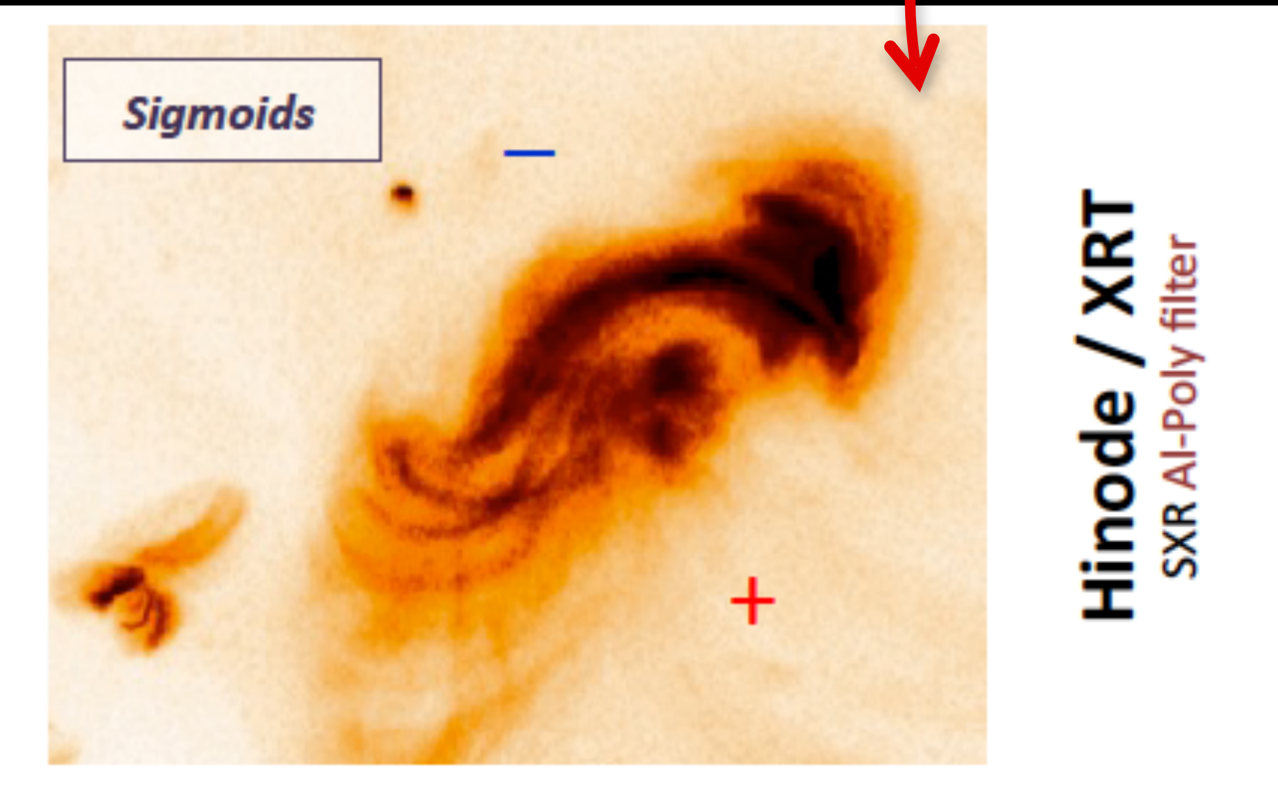
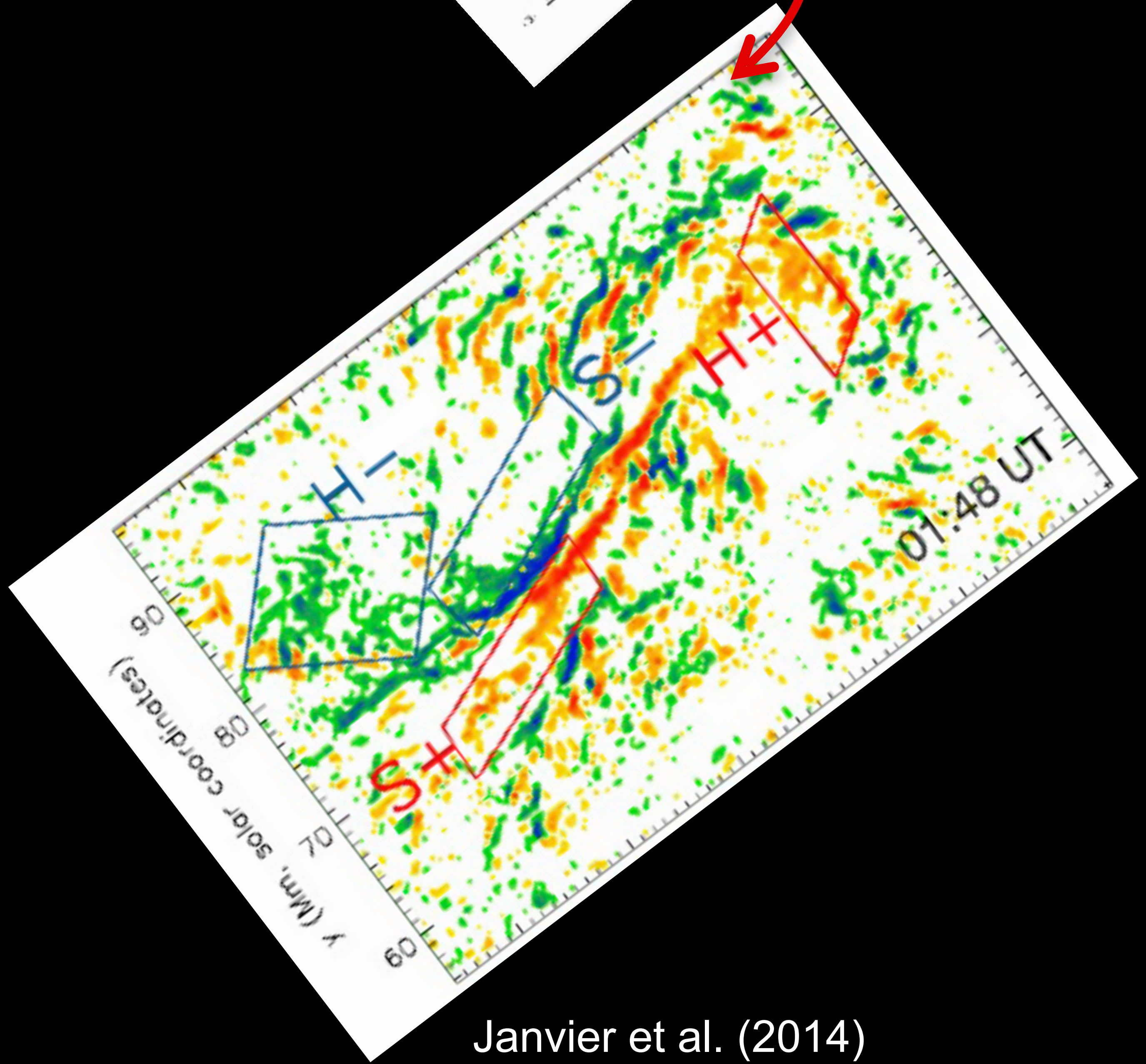






McKenzie & Canfield (2008), Savcheva et al. (2009), Green & Kliem (2009)



Janvier et al. (2014)

D. Where does the flare energy come from?

Flux ropes = current carrying structures

Flux ropes are expected to be at the heart of solar eruptions

(But little direct evidences, as only few magnetic field measurements in the corona.. DKIST?)

See reviews: Marubashi (2000), Watanabe et al. (2004), Chen (2017), Gopalswamy et al. (2018)

Chapter 3: Understanding magnetic reconnection from small scales to large scales

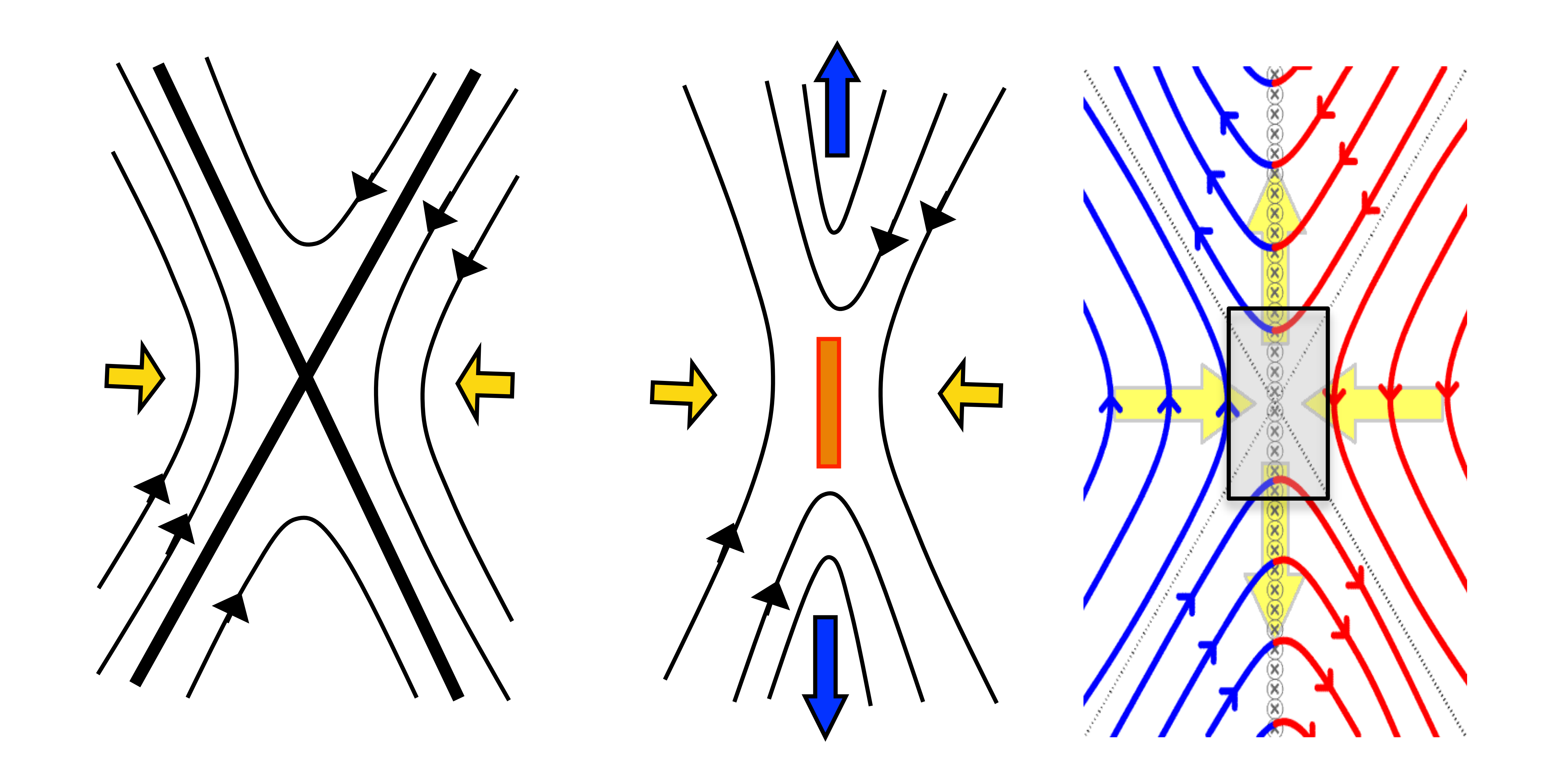
A. Magnetic reconnection as a core mechanism
B. Magnetic reconnection without null points
C. Testing the hypothesis w/ observations
D. 3D model and unsolved problems

Key idea: understand the development of the standard flare model, its 3D extension, comparisons between models and observations

A. Magnetic reconnection as a core mechanism

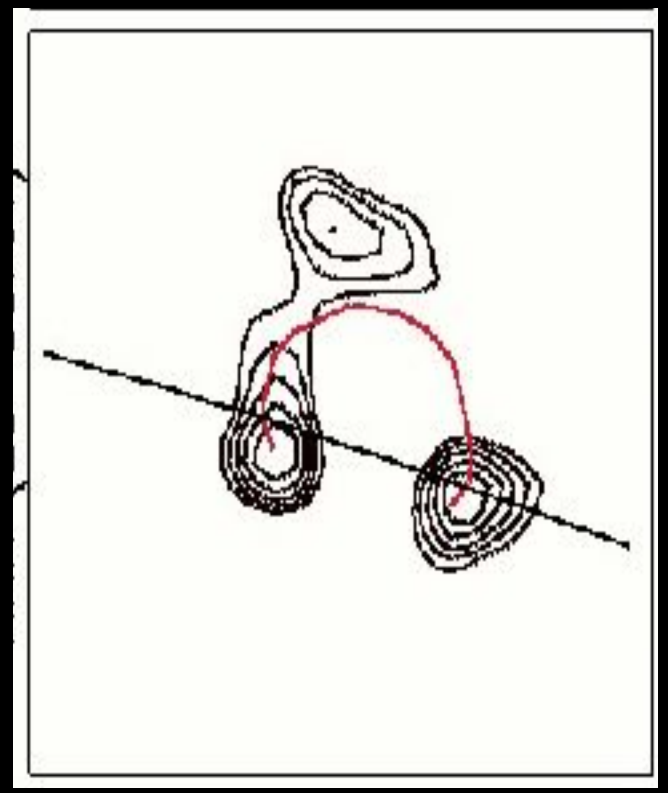
We needed a model for solar flares
(available energy is predominantly magnetic in the Sun's corona)

Early developments by:
Parker (1957, 1963), Sweet (1958), Syrovatskii (1981)
See reviews: Zweibel & Yamada 2009, Yamada 2010



Magnetic energy => heat (thermal) + non thermal energy + kinetic energy

Idea of **reconnection** (Dungey **1953**): Field near neutral point is unstable
→ Produce **current sheets (Energy storage!)**



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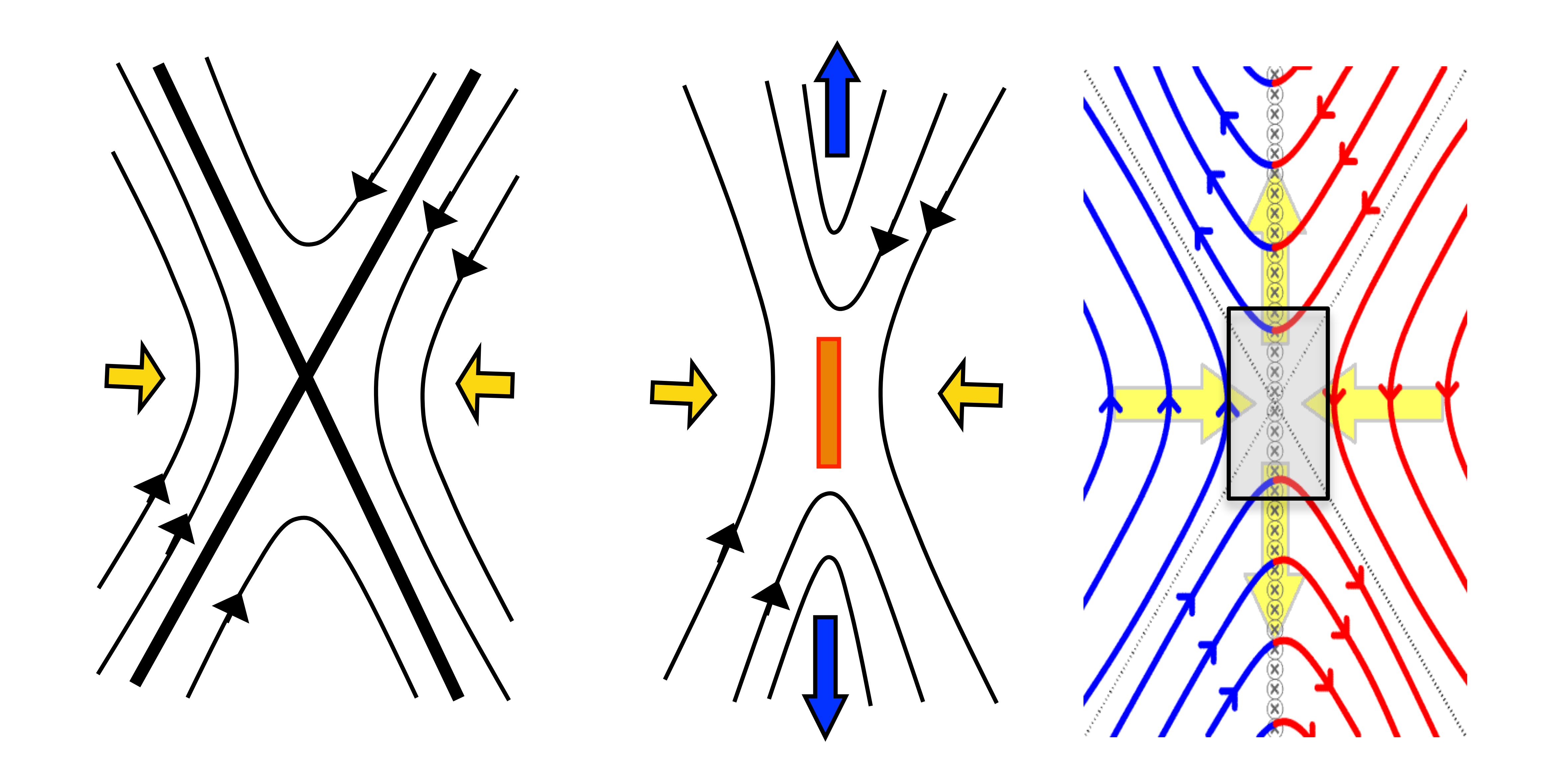
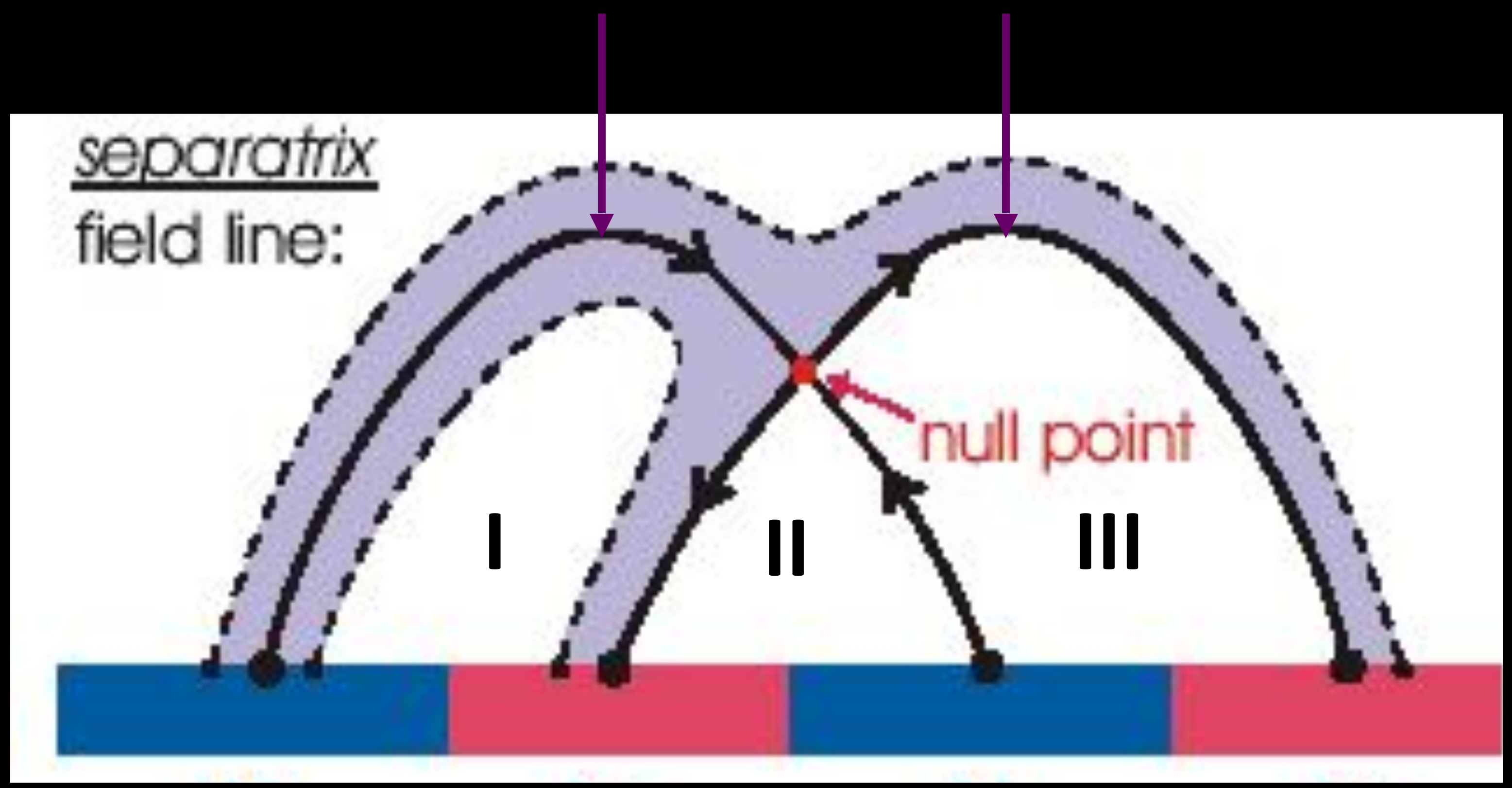


Magnetic energy => heat (thermal) + non thermal energy + kinetic energy

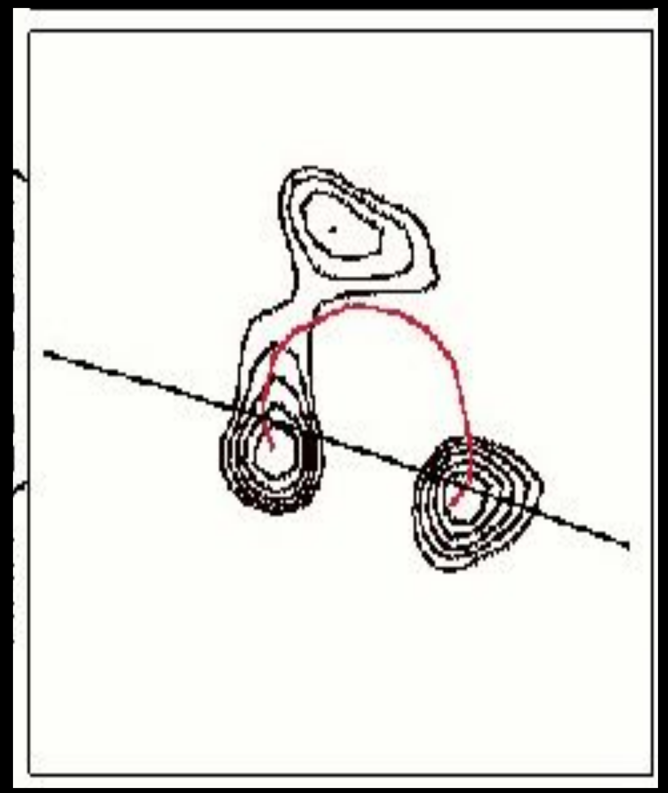
2D separatrices



4 connectivity domains

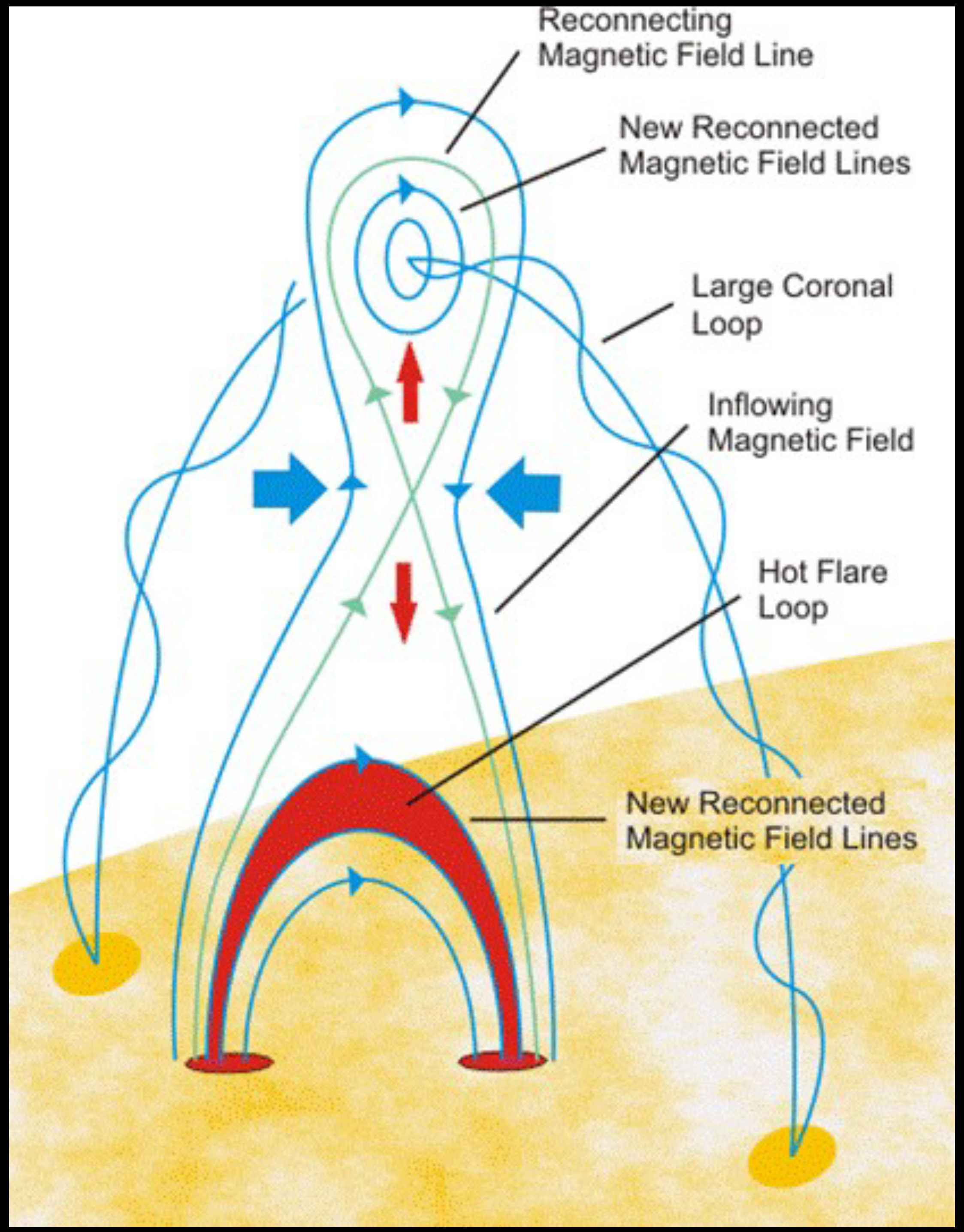
Idea of **reconnection** (Dungey **1953**): Field near neutral point is unstable
→ Produce **current sheets (Energy storage!)**

Sweet **1956 +** Parker **1957:** Magnetic energy conversion in current sheets **powers flares**



Chap 3

A. Magnetic reconnection as a core mechanism

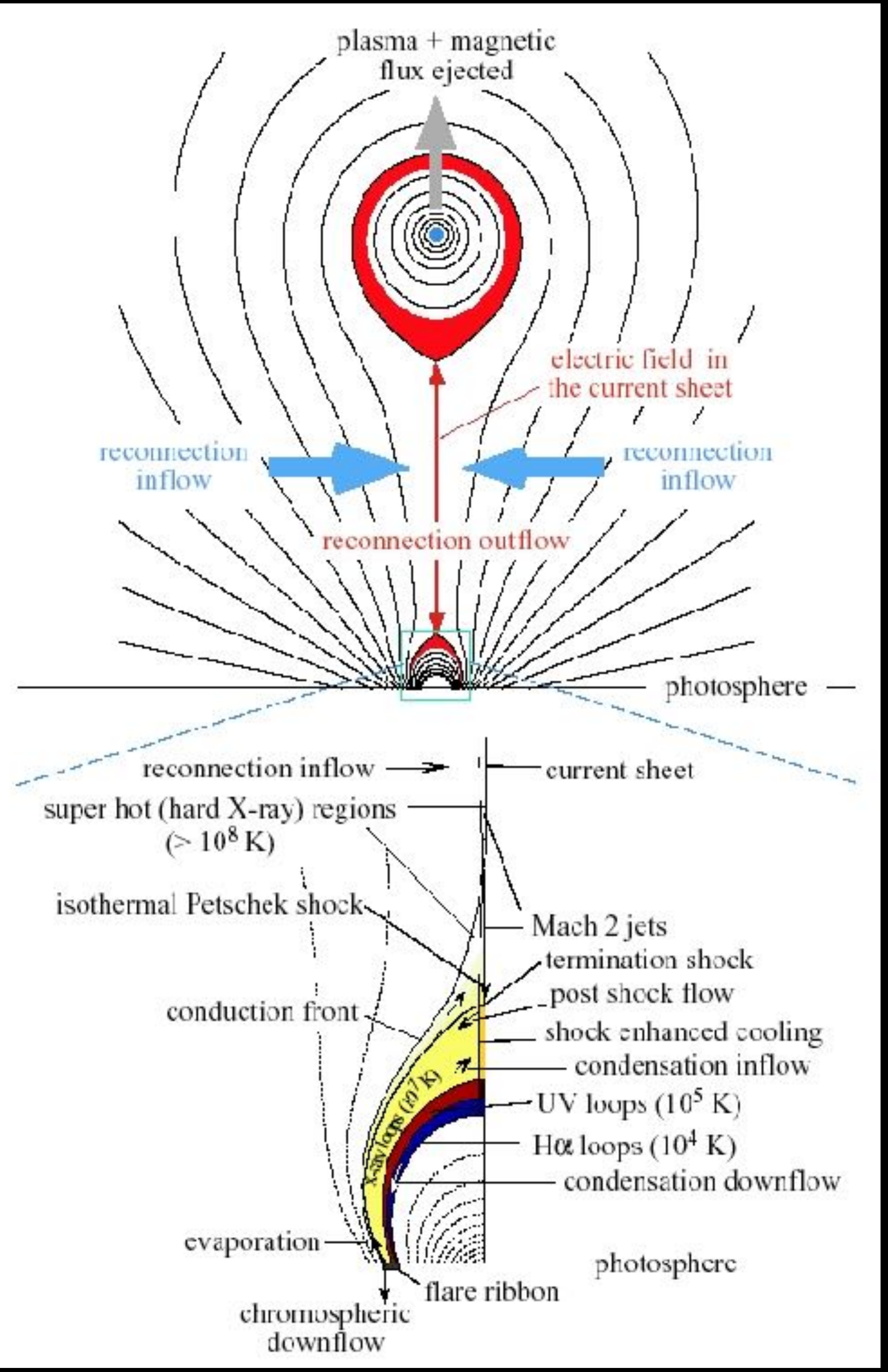


Magnetic reconnection leads to:

⇛ Flux rope + post-flare loops

⇛ Two flare ribbons

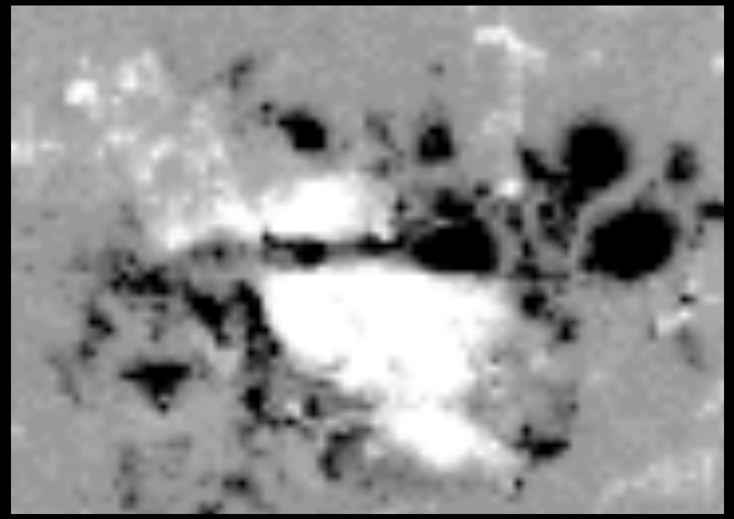
Carmichael (1964)
Sturrock (1966)
Hirayama (1974)
Kopp & Pneumann (1976)
Forbes & Malherbe (1986)



Standard flare model is developed and refined over the years

A. Magnetic reconnection as a core mechanism

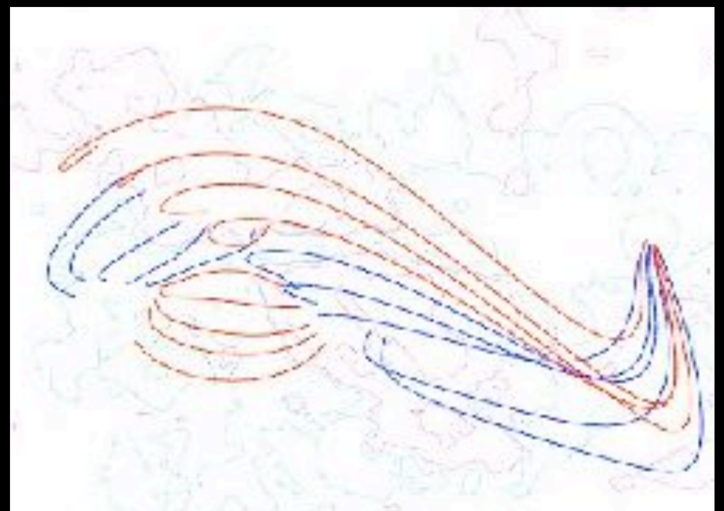
Flare model confirmed with computation of the magnetic field



Method:

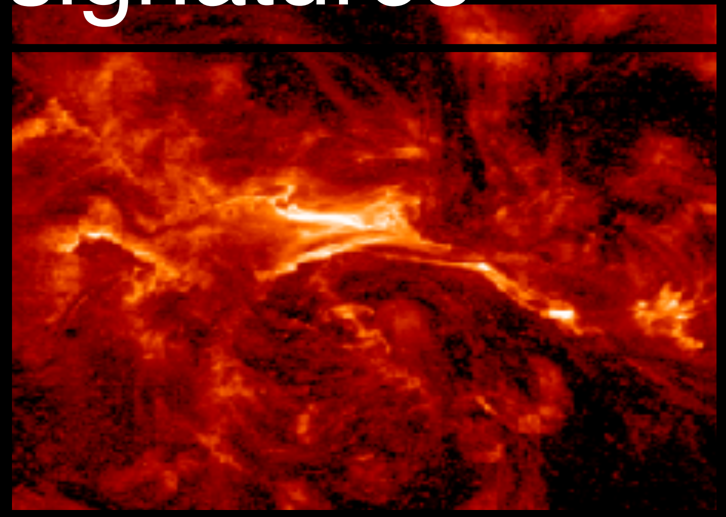
Input the photospheric magnetogram

Compute the coronal field

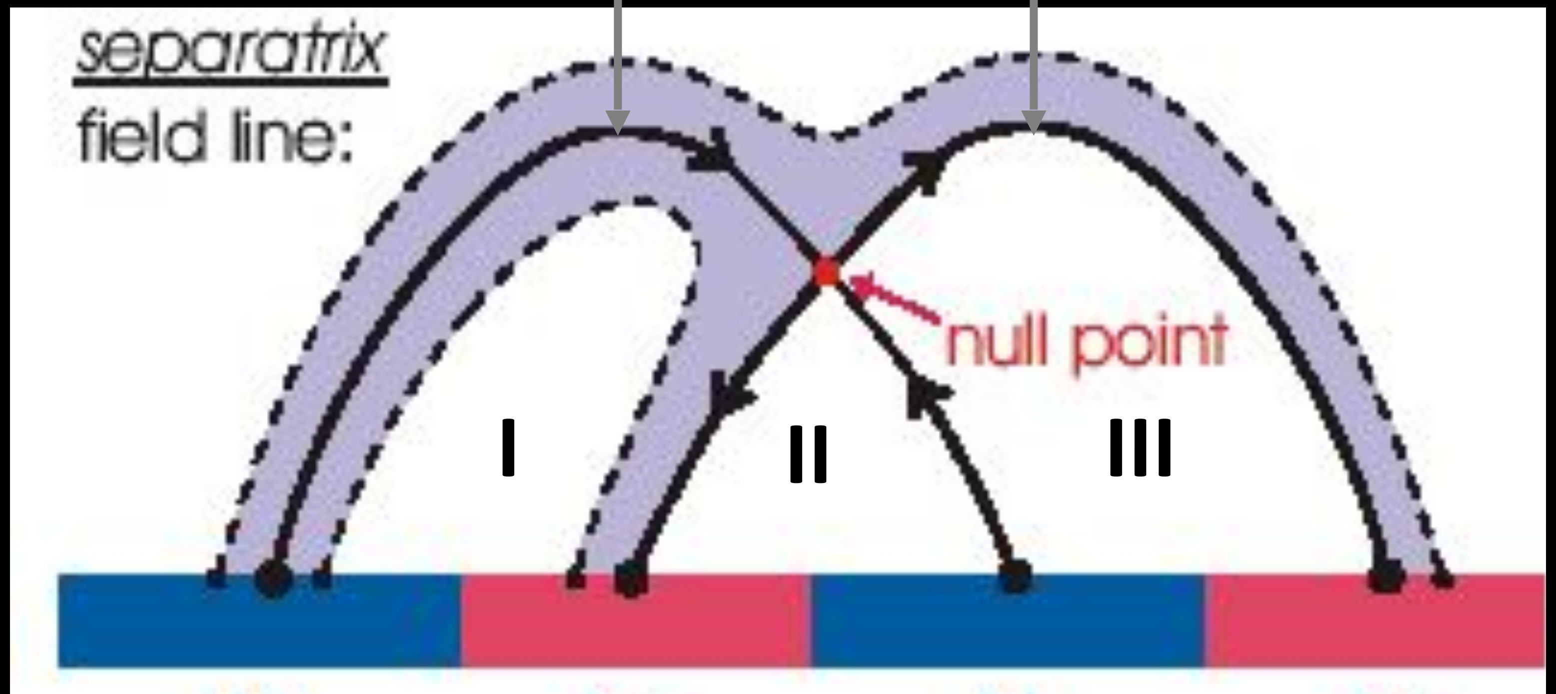


Compute magnetic null points & separatrices

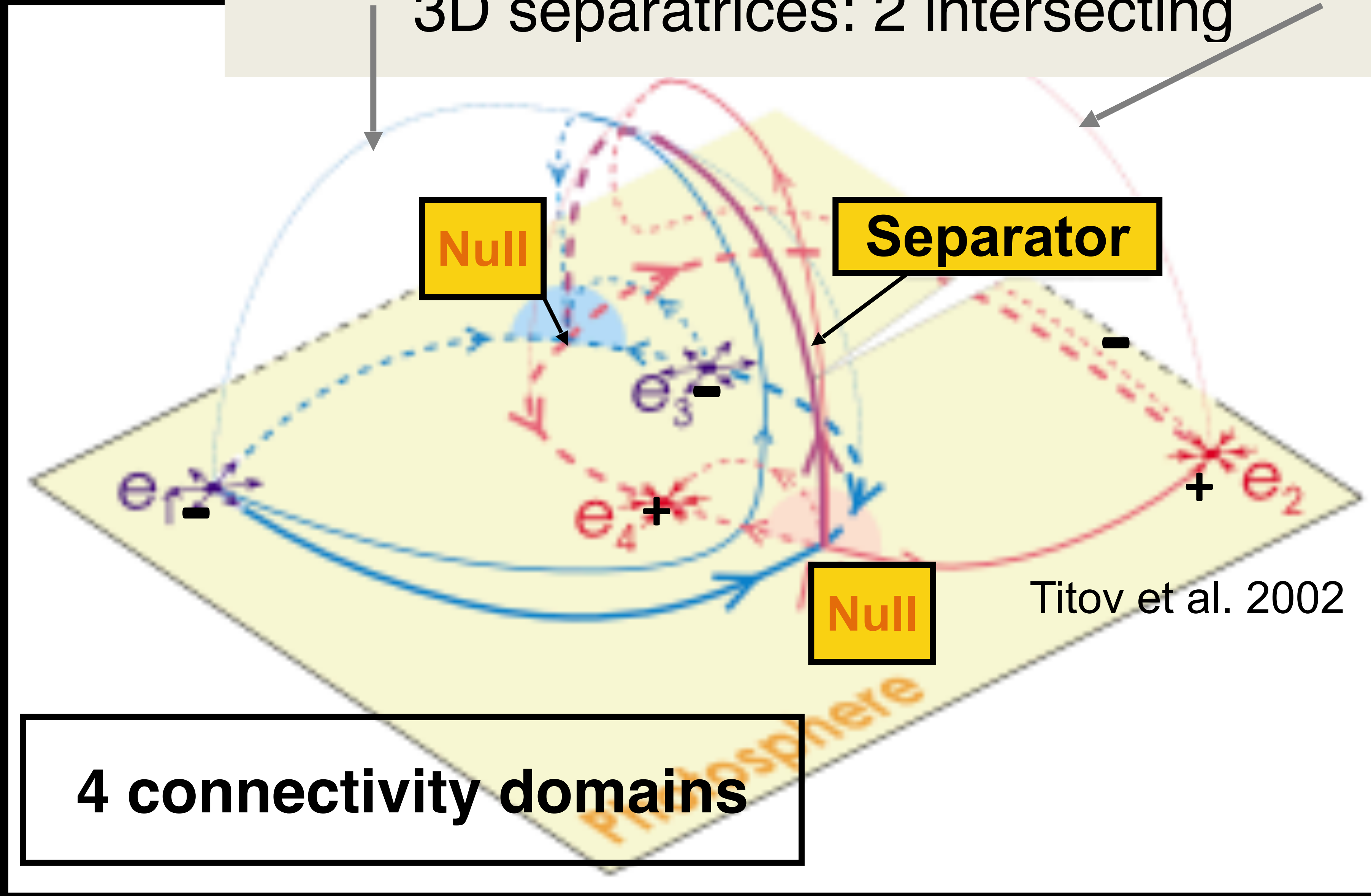
Comparison with observed energy release signatures



2D separatrices



3D separatrices: 2 intersecting



4 connectivity domains

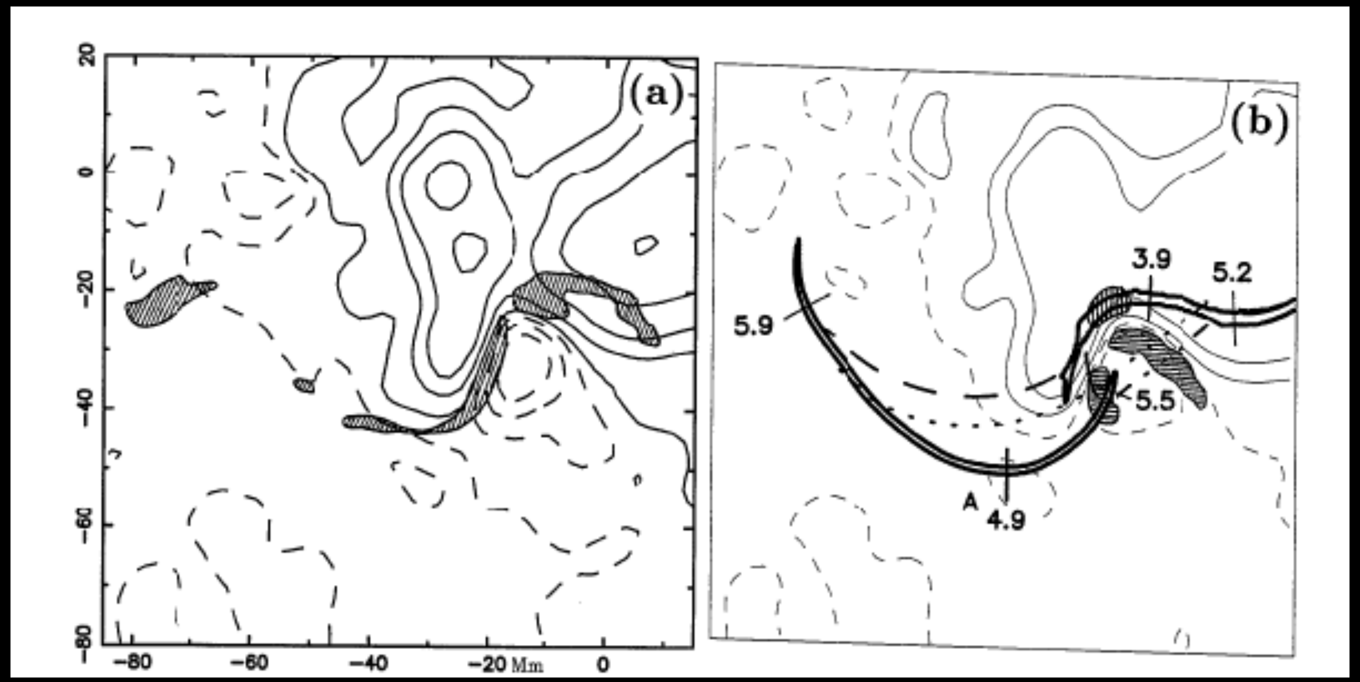
Titov et al. 2002

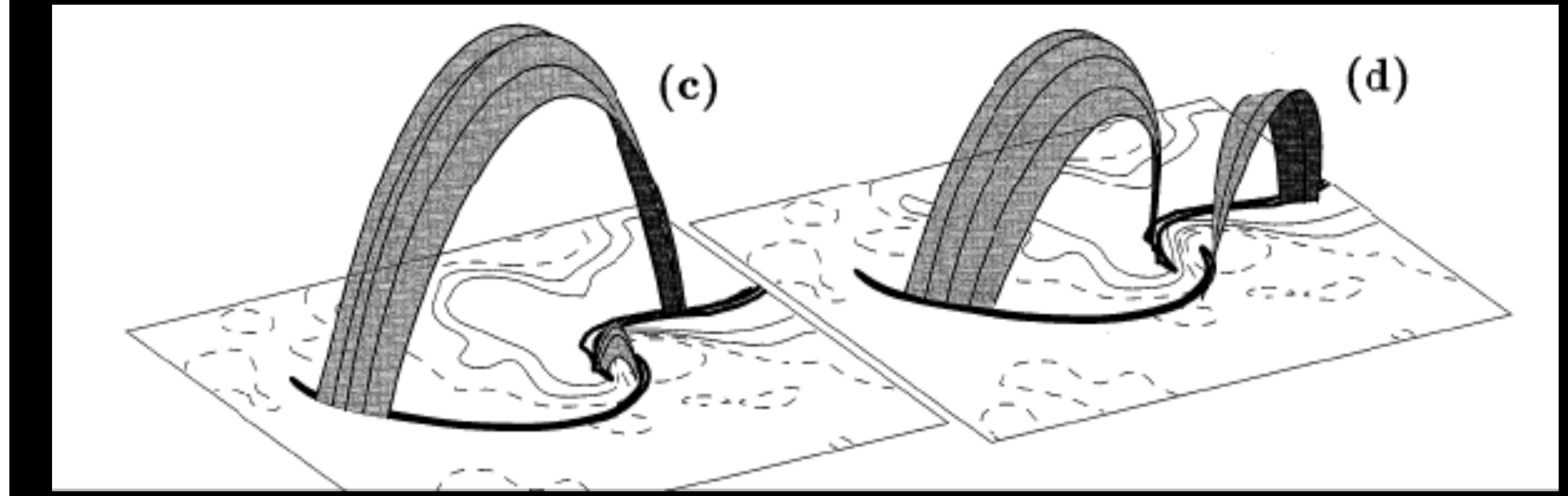
Chap 3

B. Magnetic reconnection without null points

Standard 2D model of flare relies on the concept of null points + separatrices

… but plenty of evidences that flaring happens w/o null points!





Priest & Démoulin **1995**
Démoulin et al. **1996-1997**

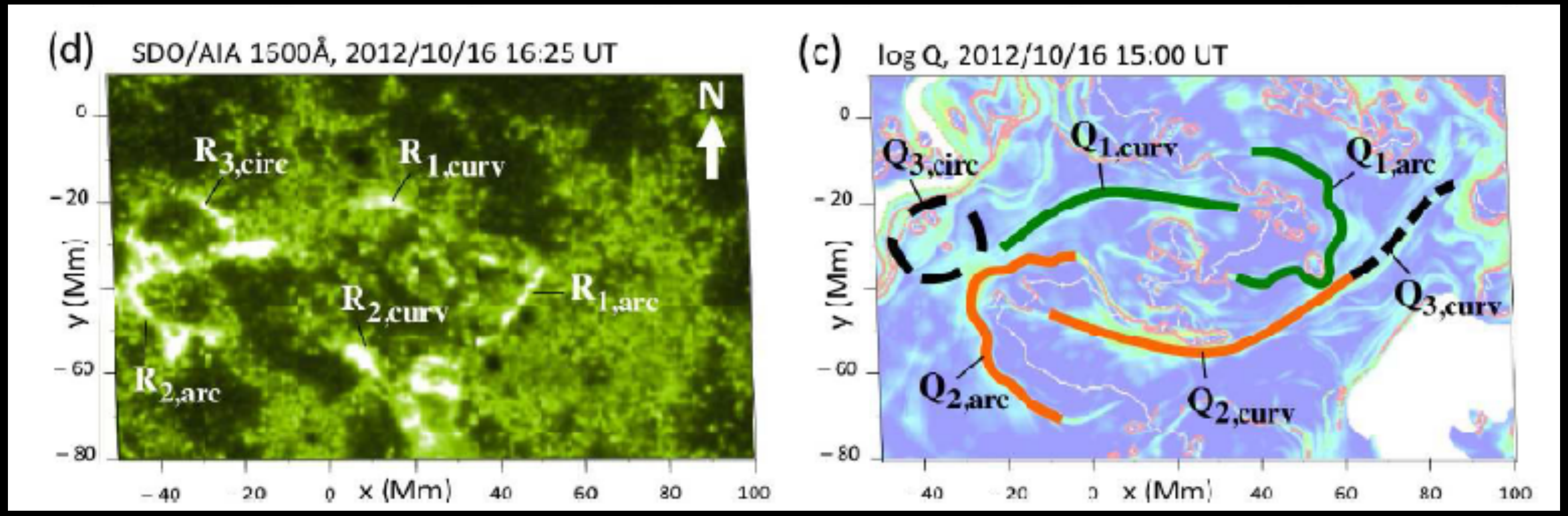
Idea of reconnection happening in regions of strong magnetic field distorsion:

« Quasi » separatrix layers

See: Démoulin et al. (1996), Titov et al. (2002), Pariat et al. (2012) for a mathematical definition of the "squashing factor" defining these QSLs

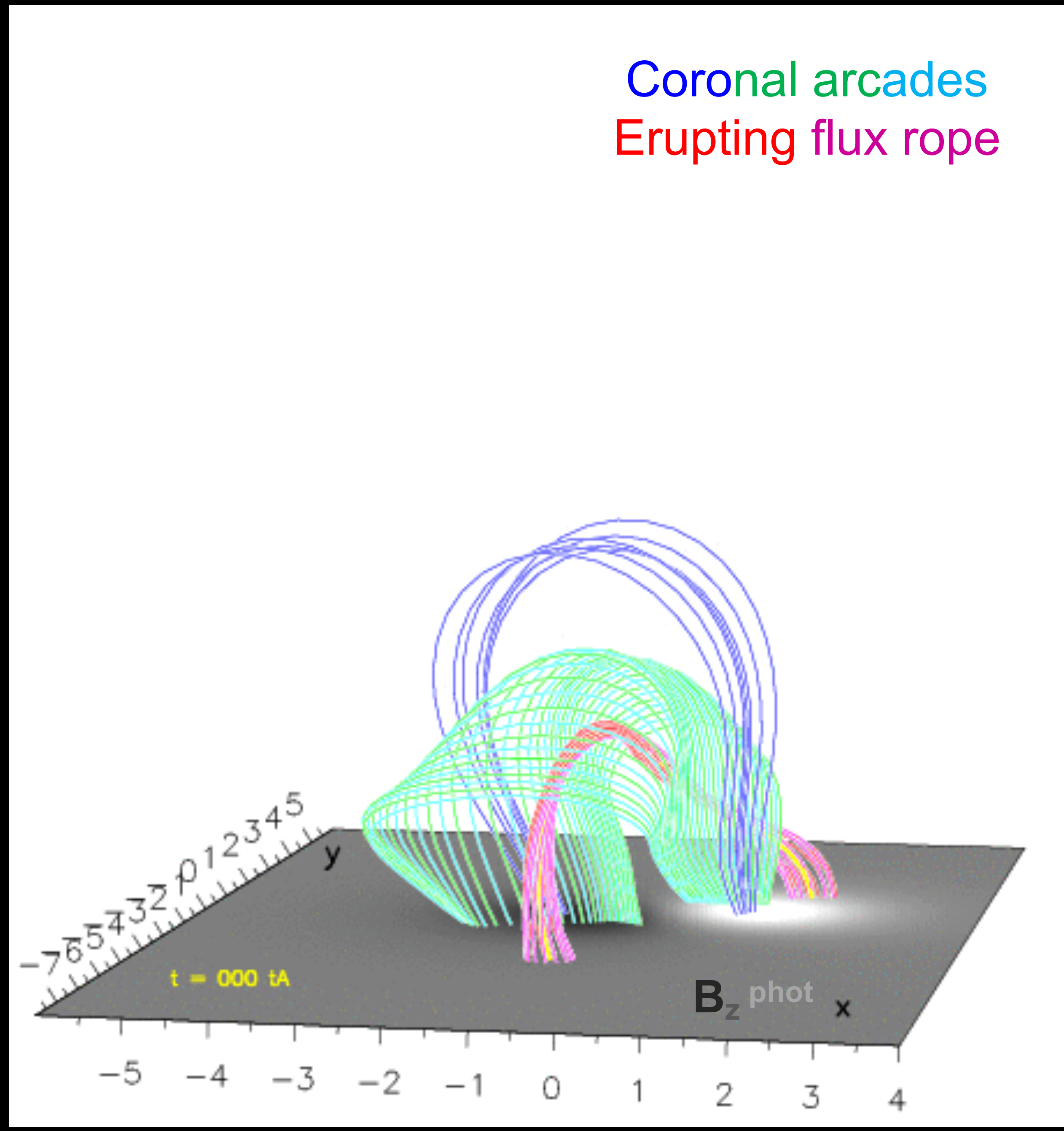
Reconnection can be (and is) defined **physically** as regions where ideal MHD breaks down (where B is distorted)

Since then: numerous evidences of flaring activity associated with quasi-separatrix layers:



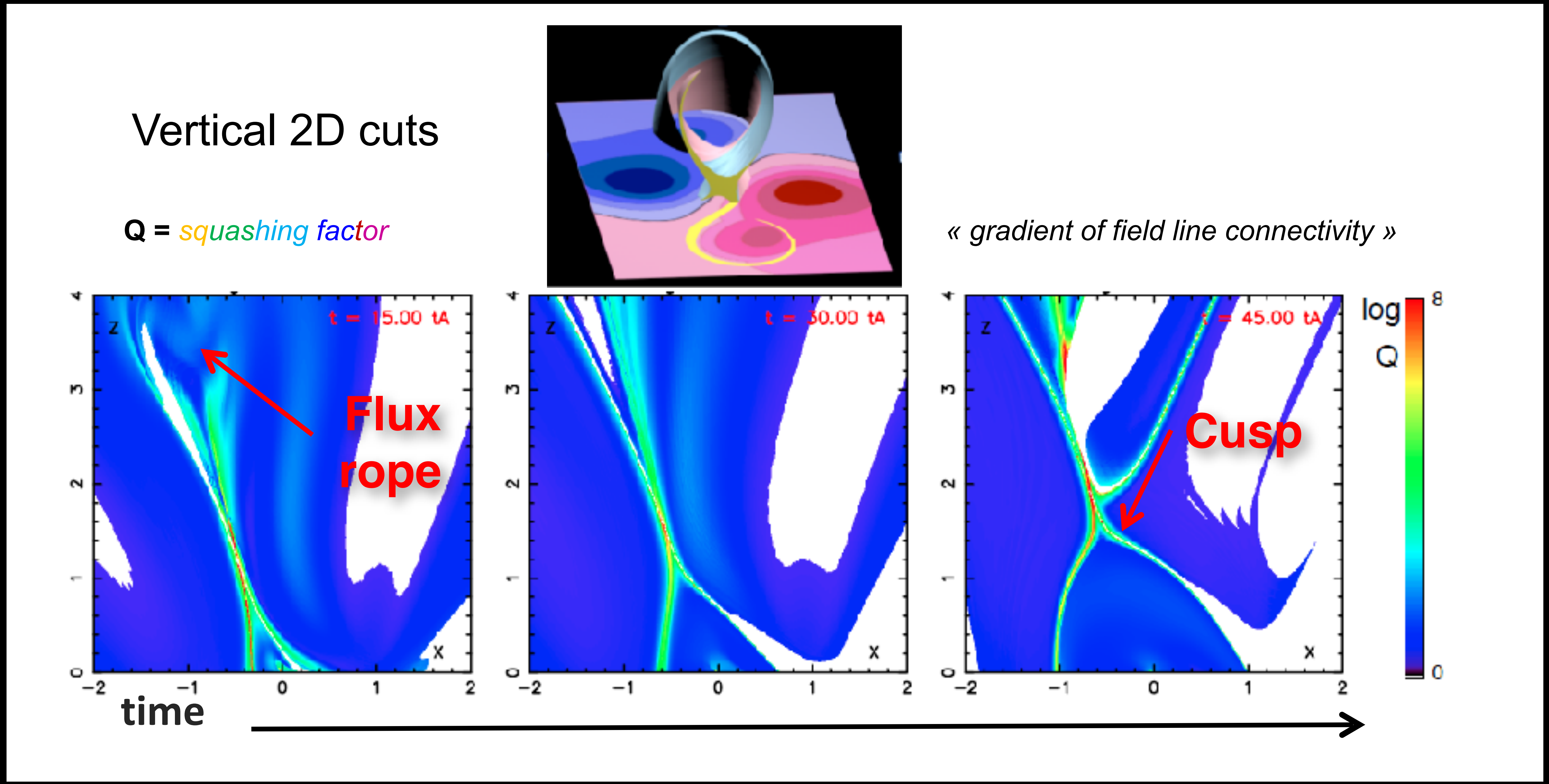
B. Magnetic reconnection without null points

Numerical simulation of a flux rope eruption



OHM code, β=0 simulation of eruptive flares

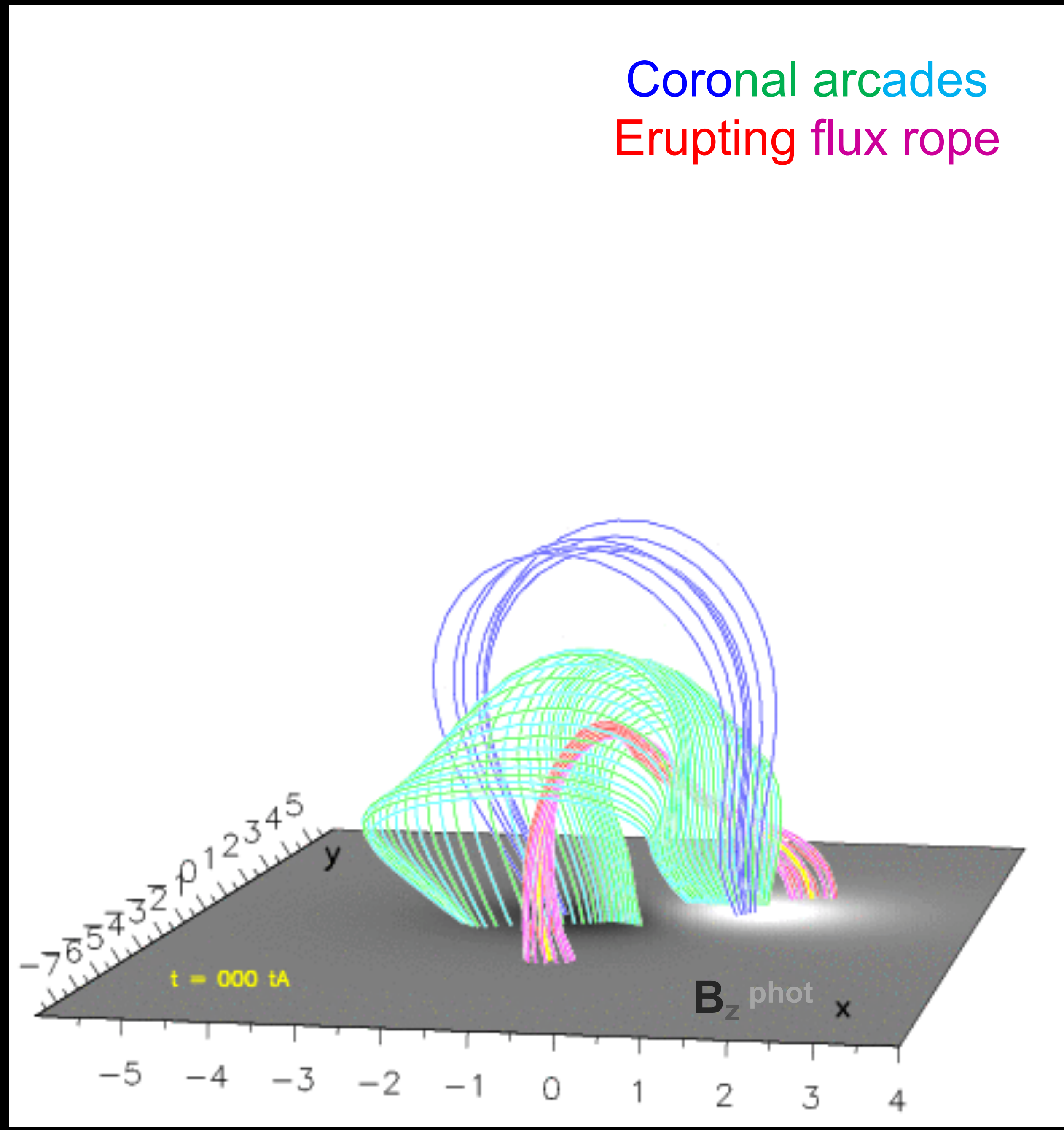
Janvier, Aulanier, Pariat & Démoulin (2013)



Reconnection takes place (but no null points)

B. Magnetic reconnection without null points

Numerical simulation of a flux rope eruption



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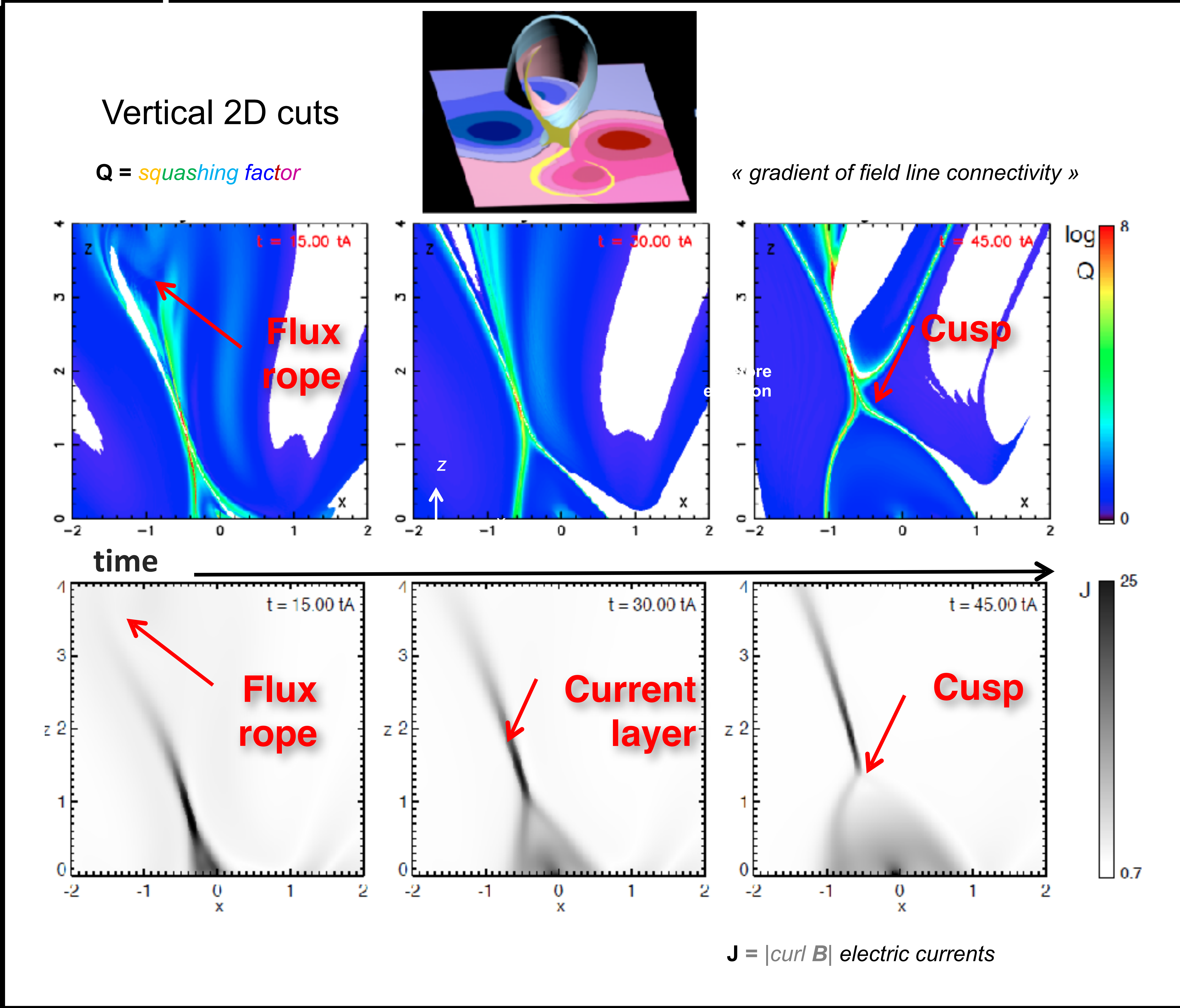
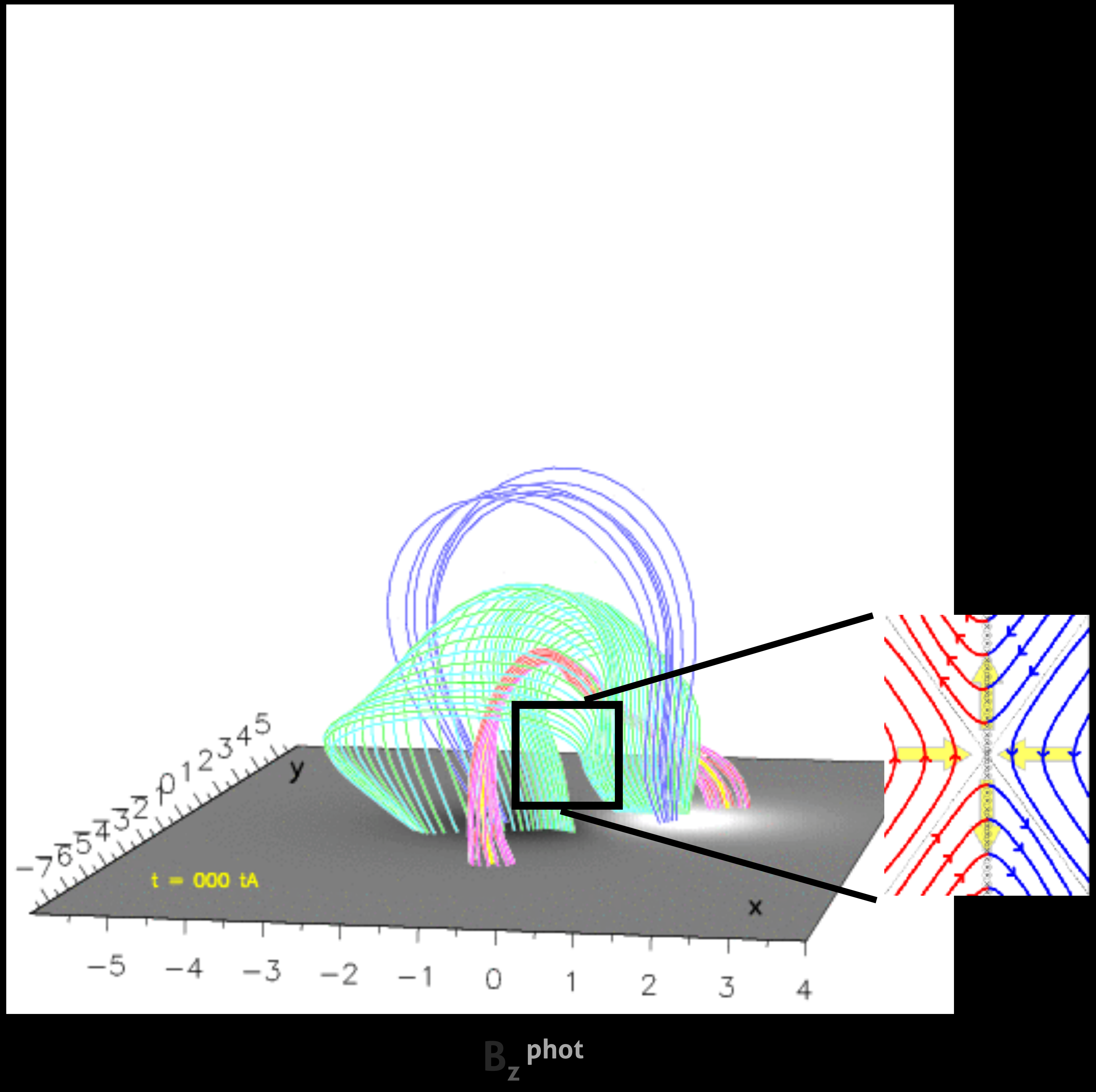
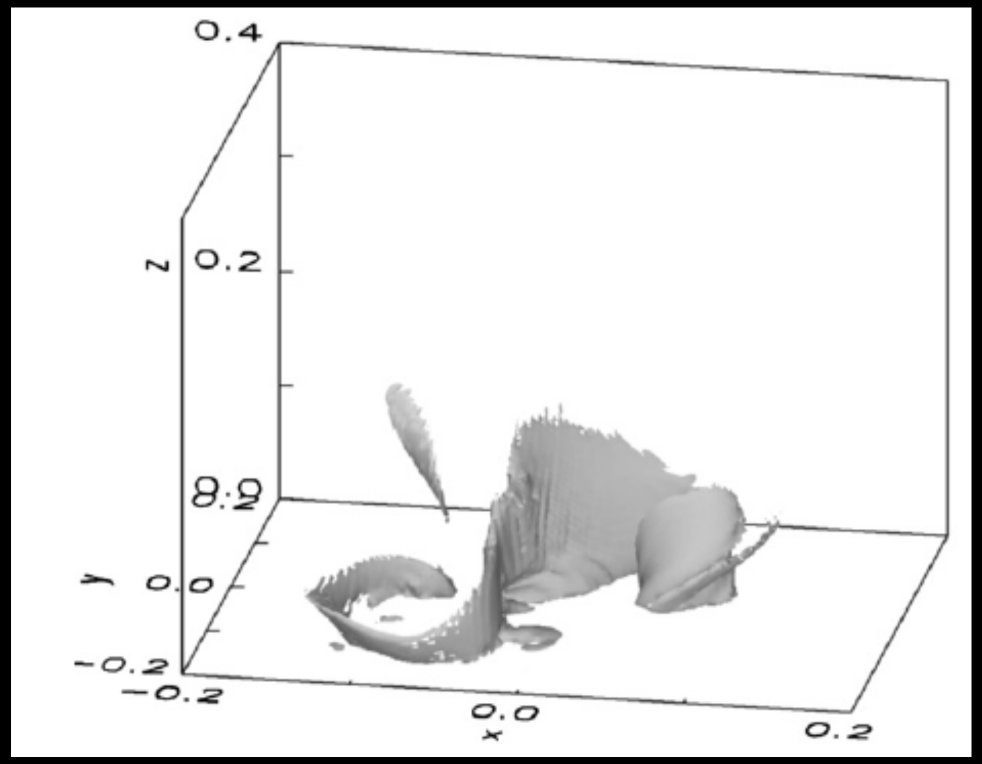


QSLs:
Preferential locations for electric current build-up

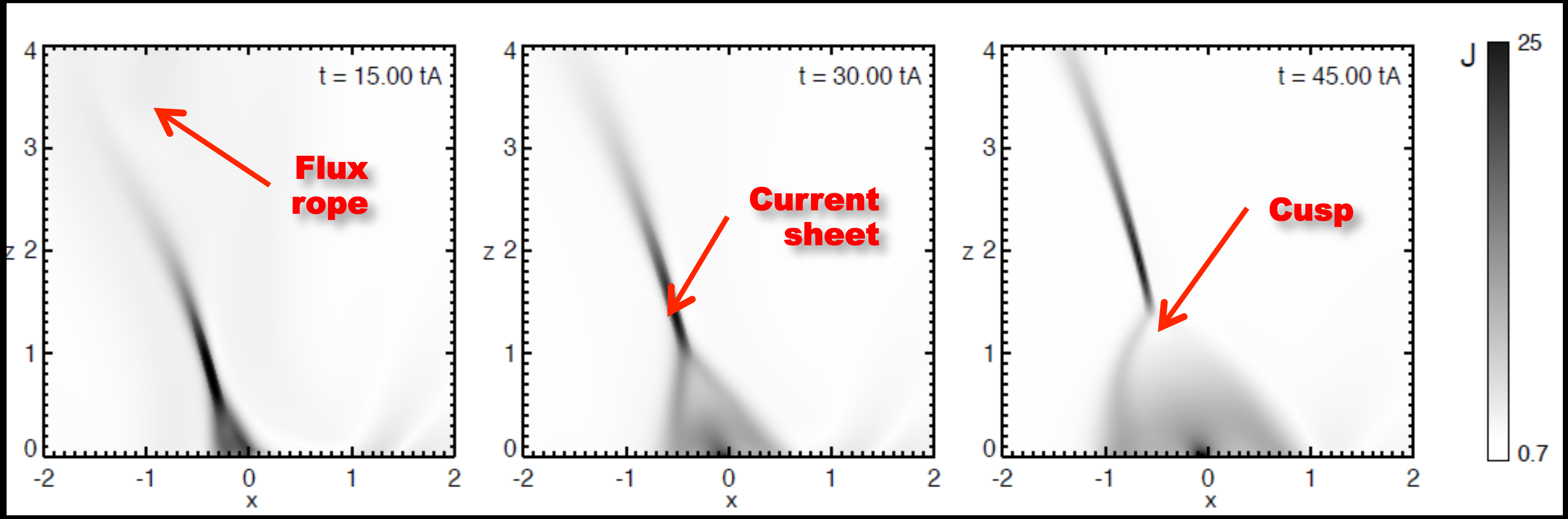
B. Magnetic reconnection without null points





Kliem et al. (2013)

Vertical cuts



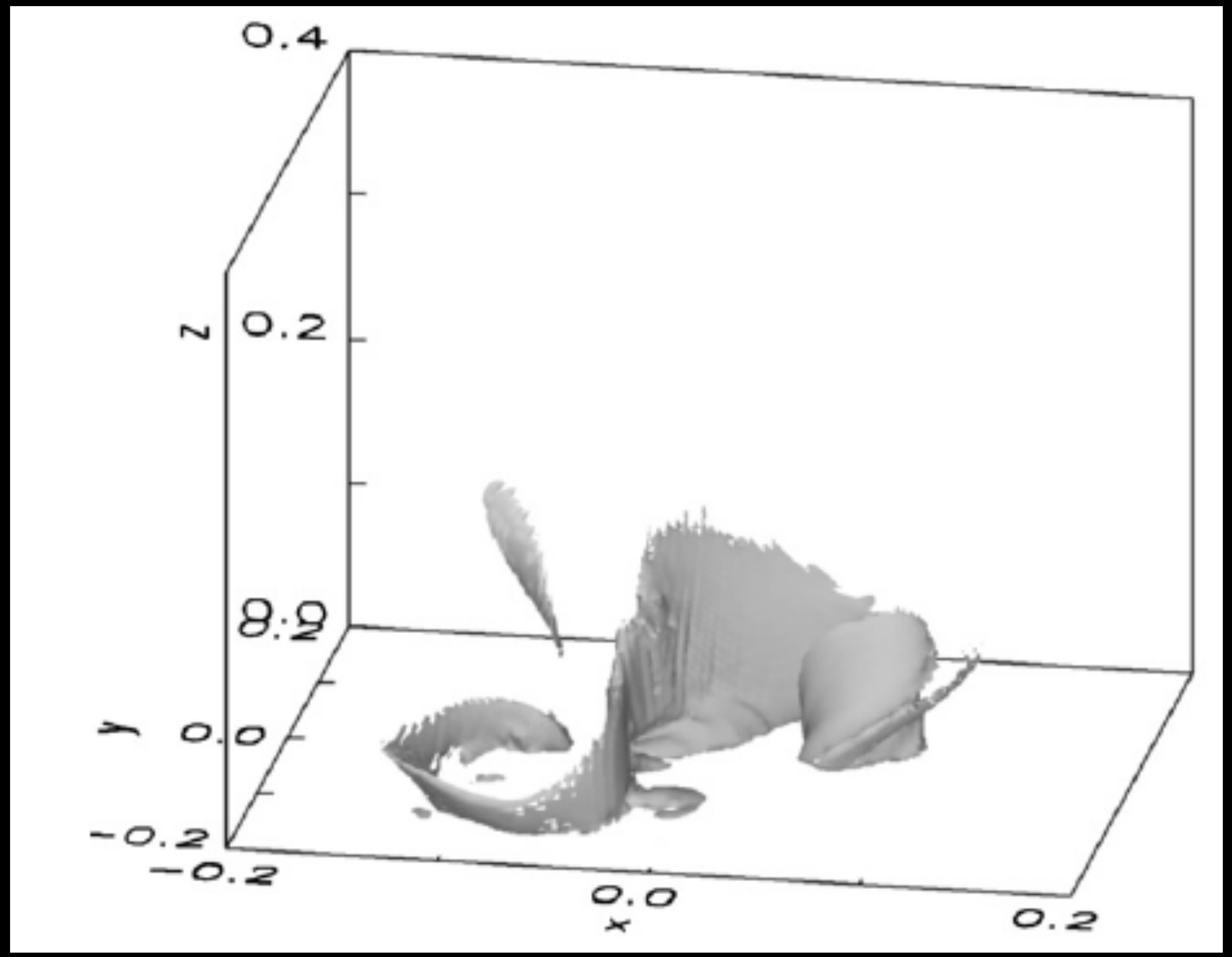
Janvier et al. (2013)

Collapse of the current layer (= thinning)

Prediction from the model (not yet observable!)

Chap 3

B. Magnetic reconnection without null points



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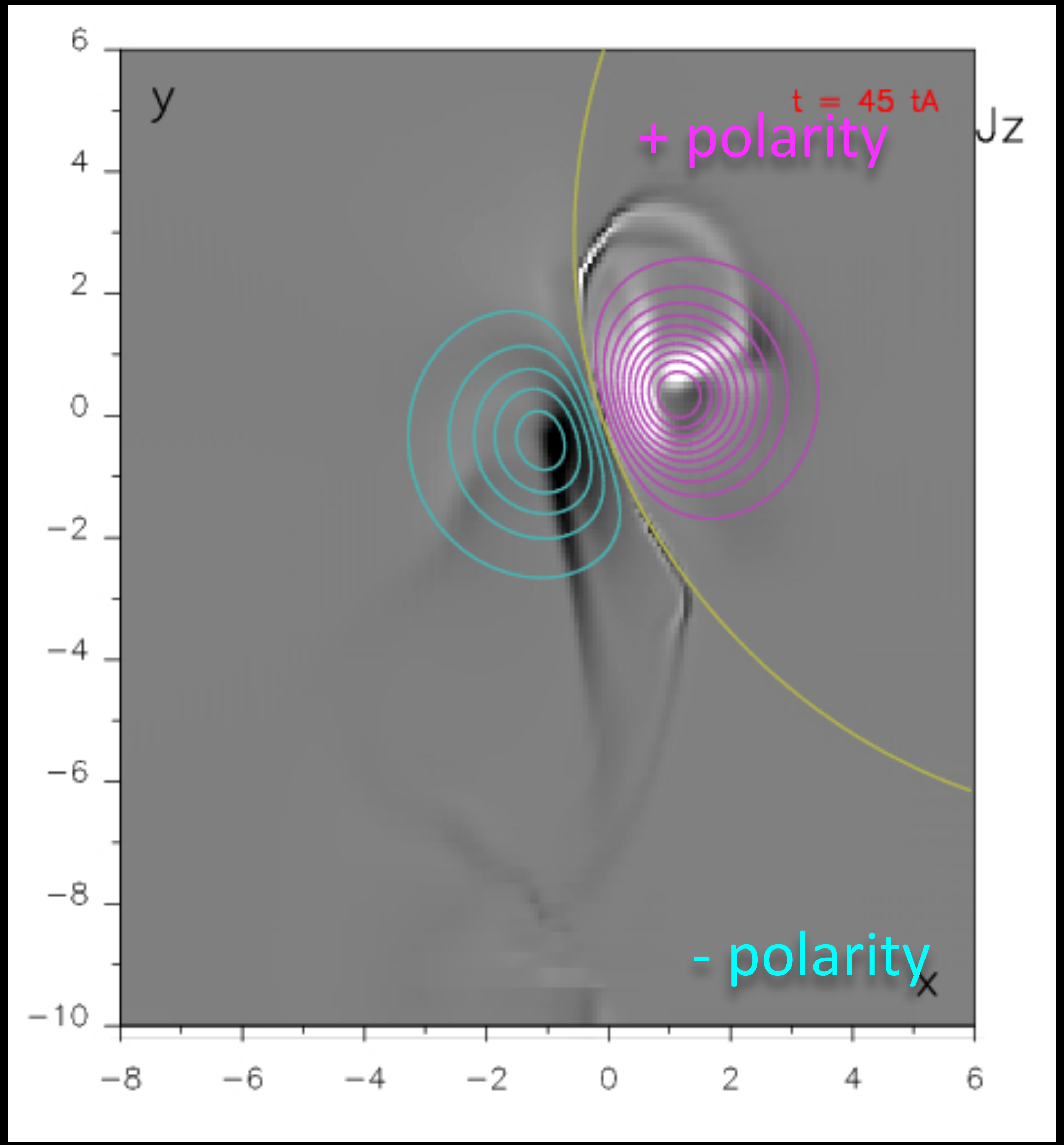

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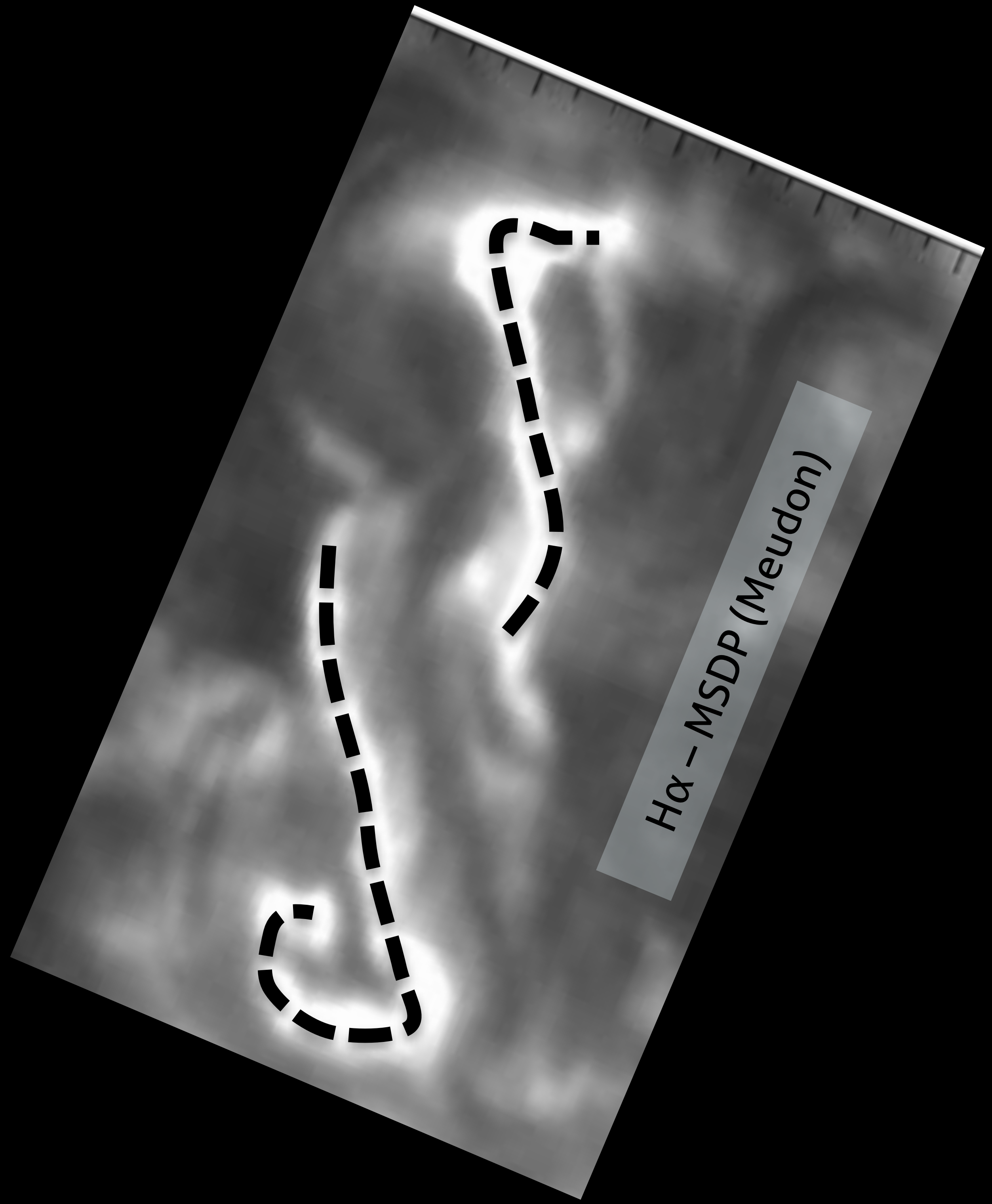
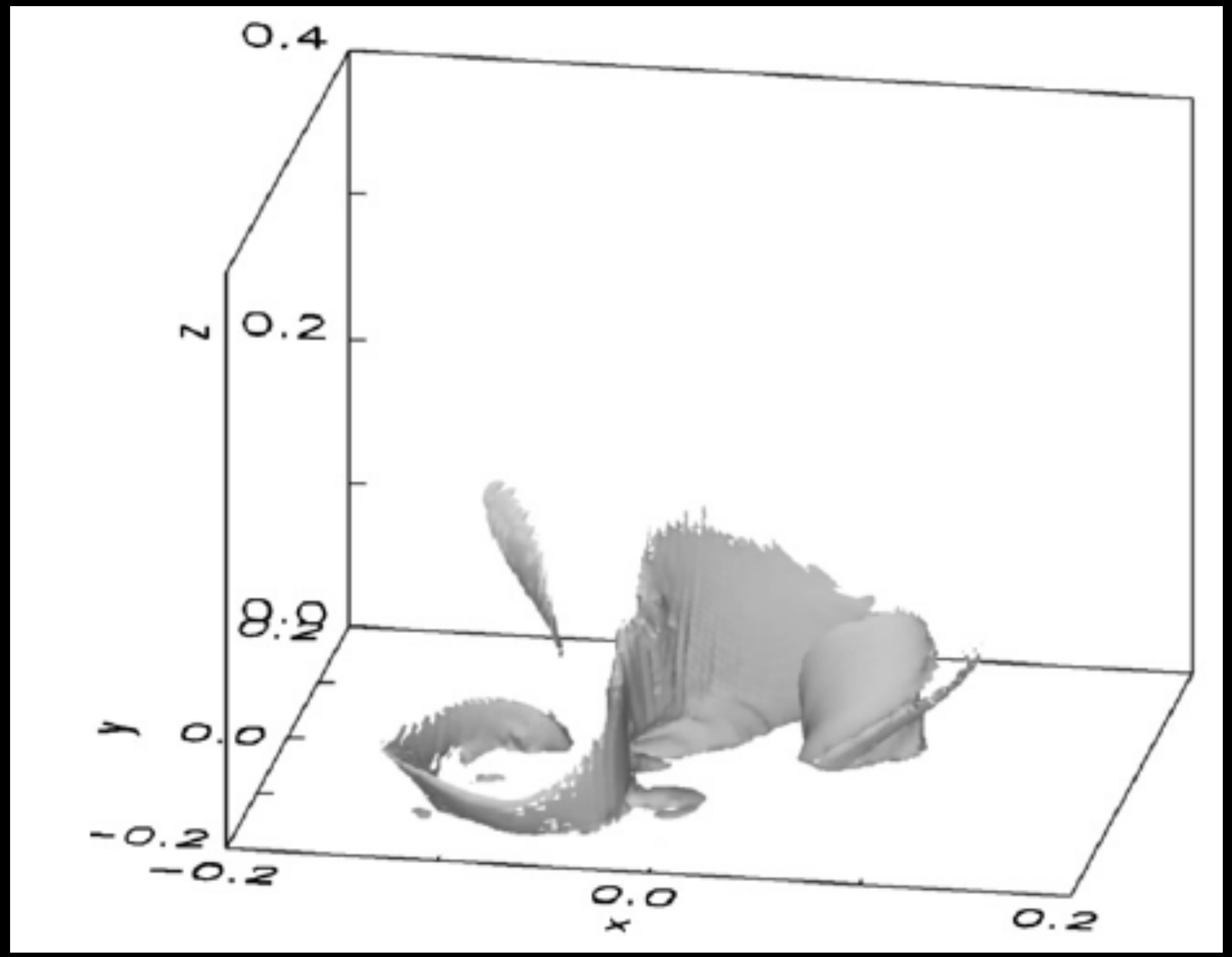


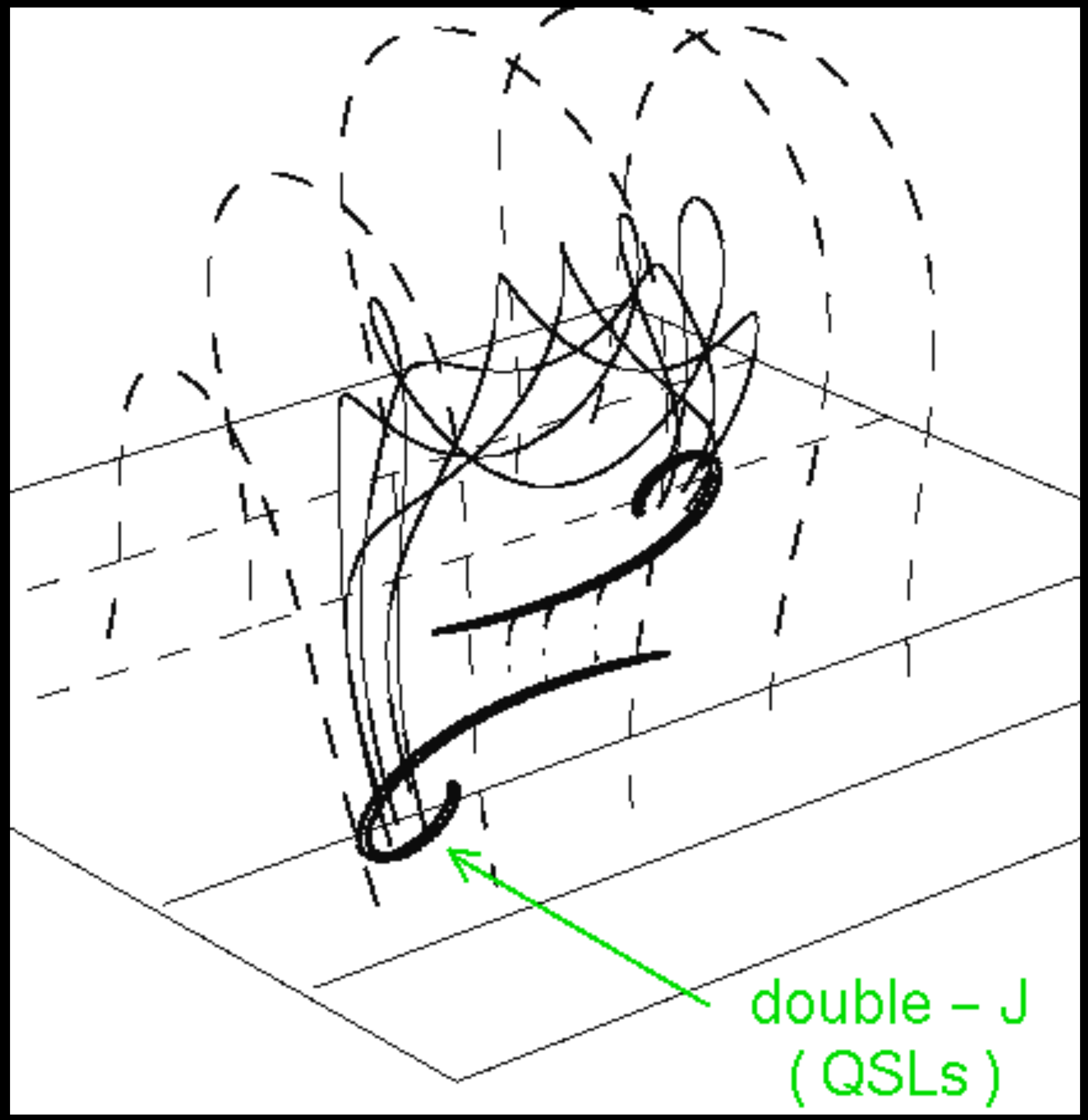
Chandra et al. (2009)

B. Magnetic reconnection without null points

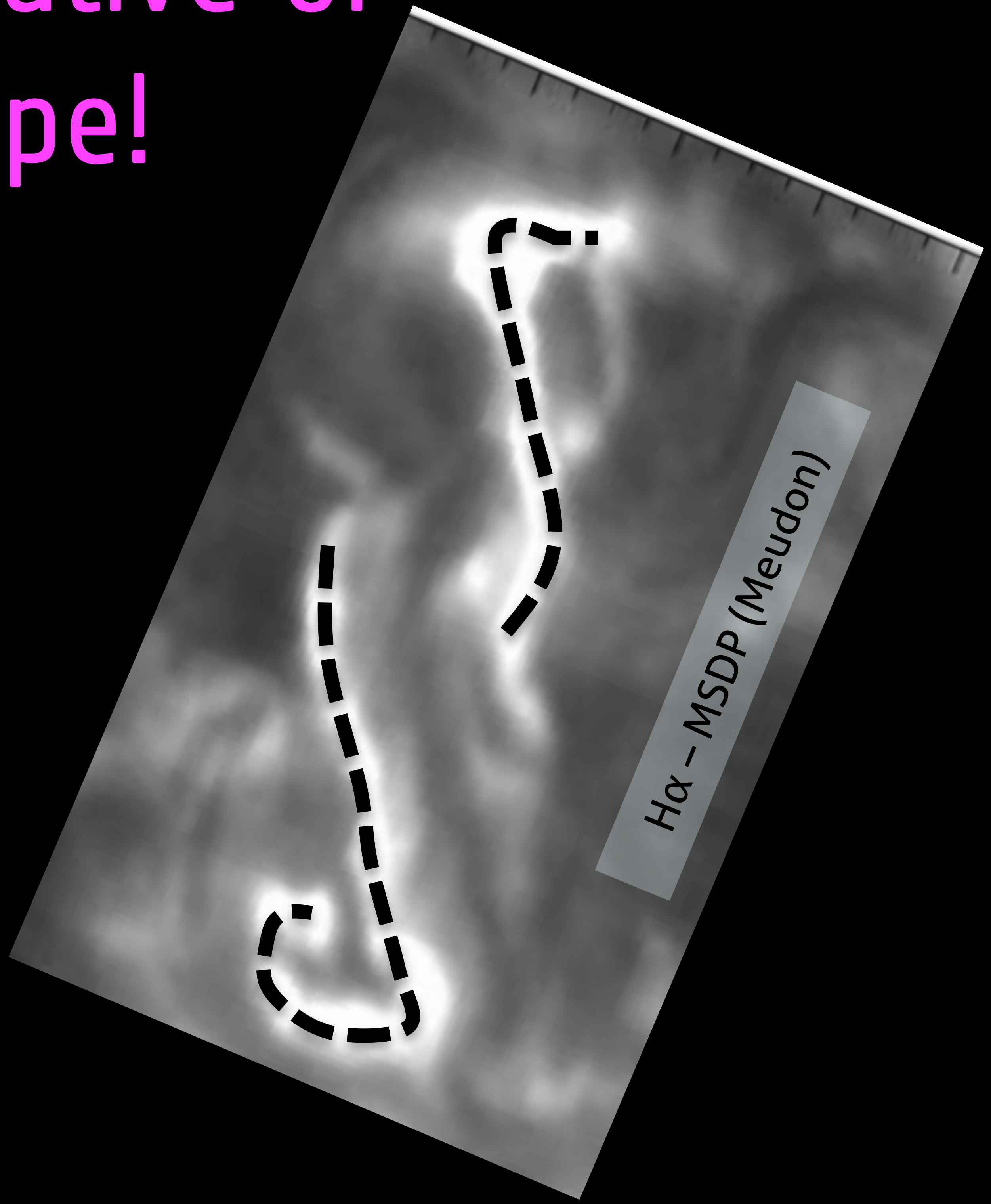
J-shape structure is indicative of the presence of a flux rope!



Kliem et al. (2013)



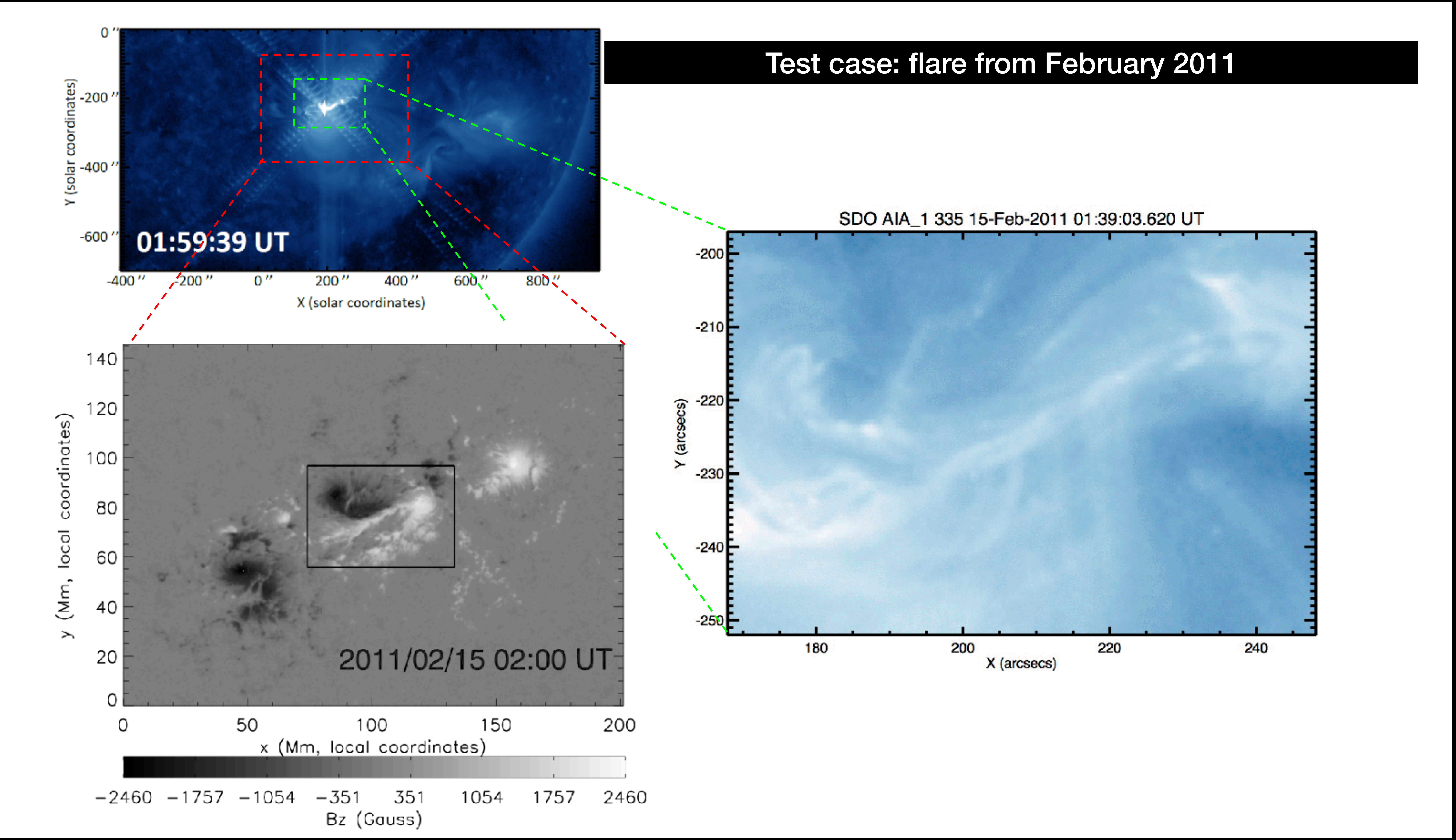
Démoulin, Priest & Lonie 1996



Chandra et al. (2009)

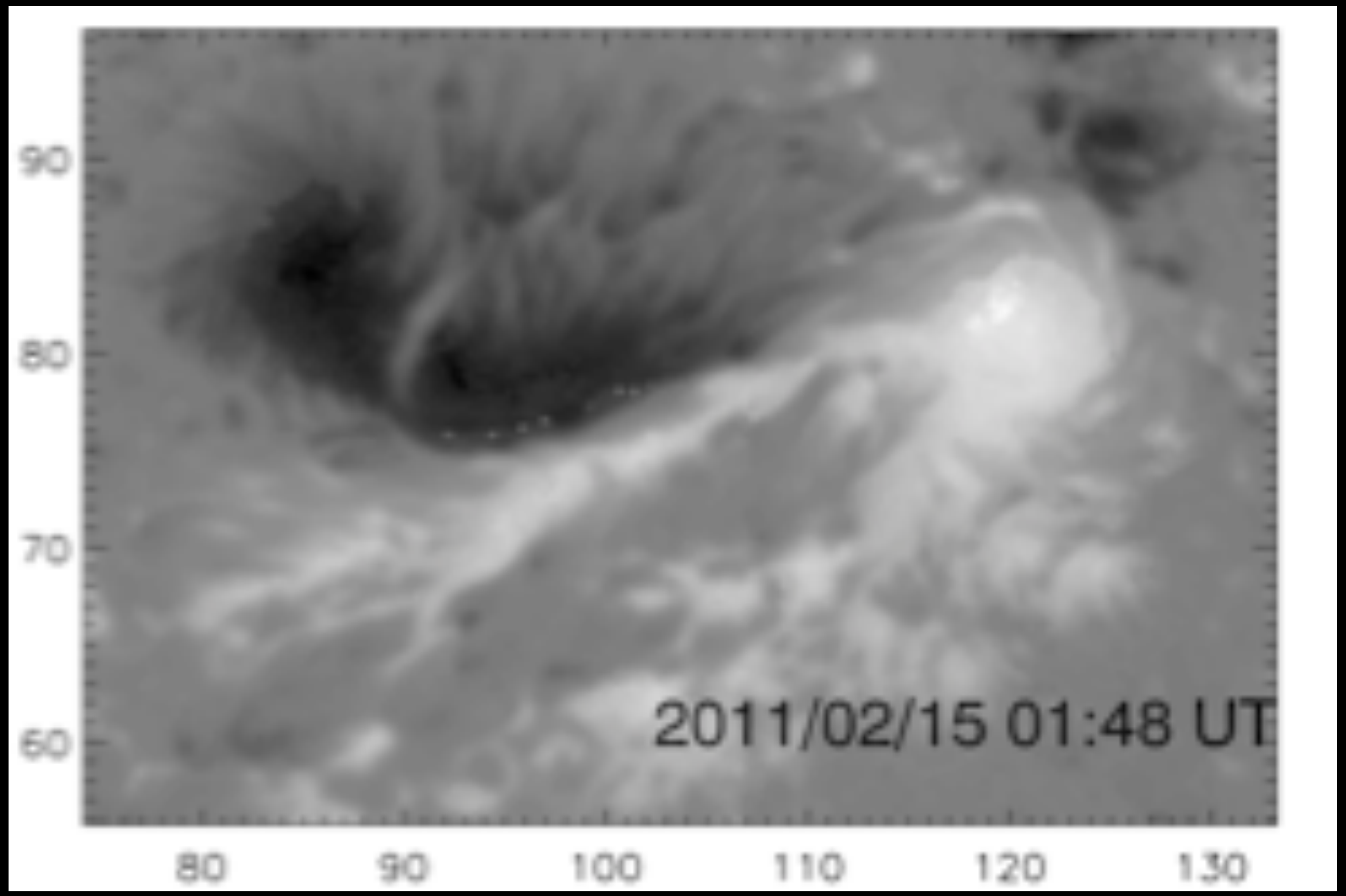
C. Testing the hypothesis w/ observations

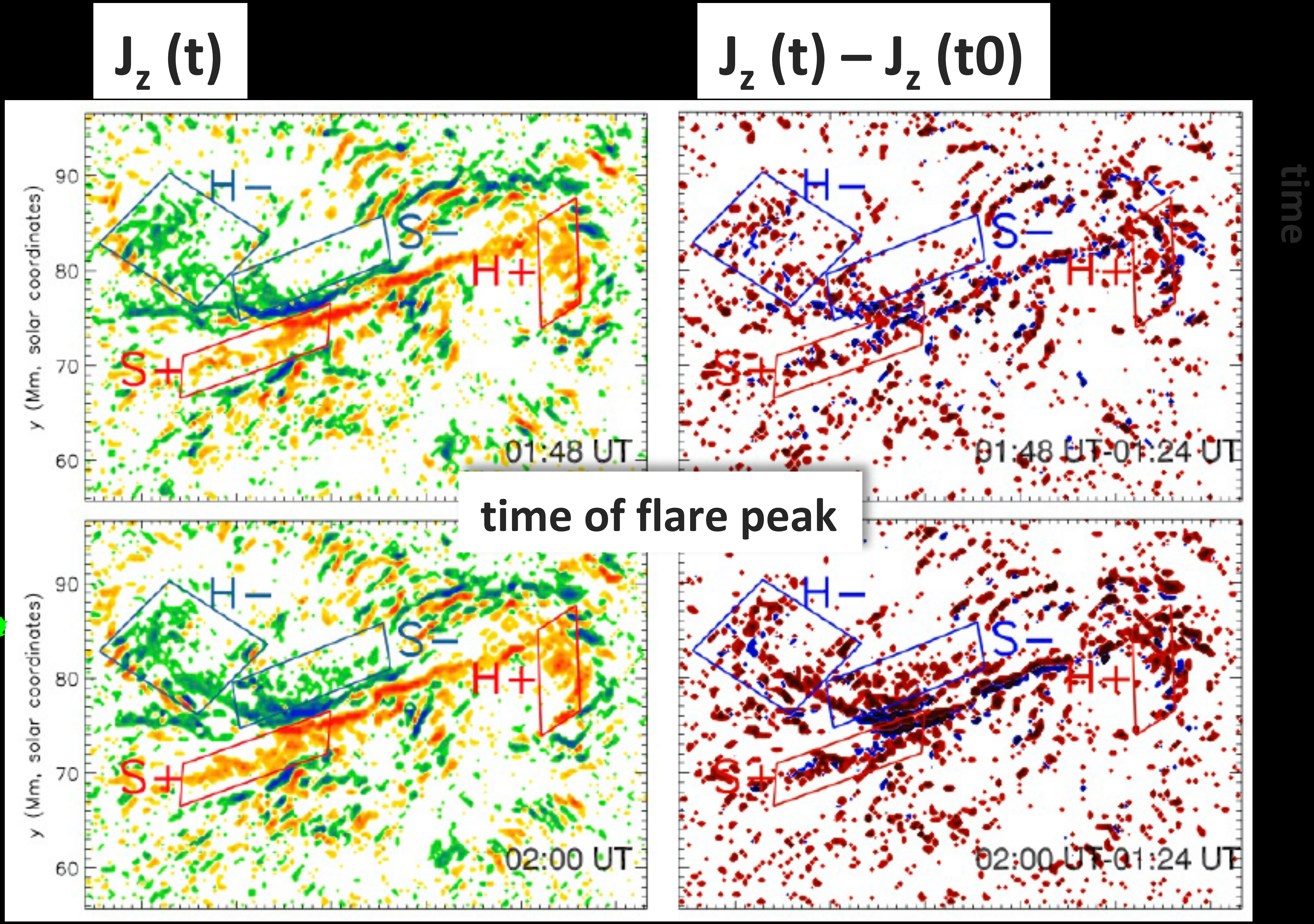
Test case: flare from February 2011



C. Testing the hypothesis w/ observations

B(x,y) ⇛ Current maps $J_z(x,y)$ ~ curl $|B|_z$
(12 min cadence w. HMI instrument aboard the NASA Solar Dynamics Observatory mission)

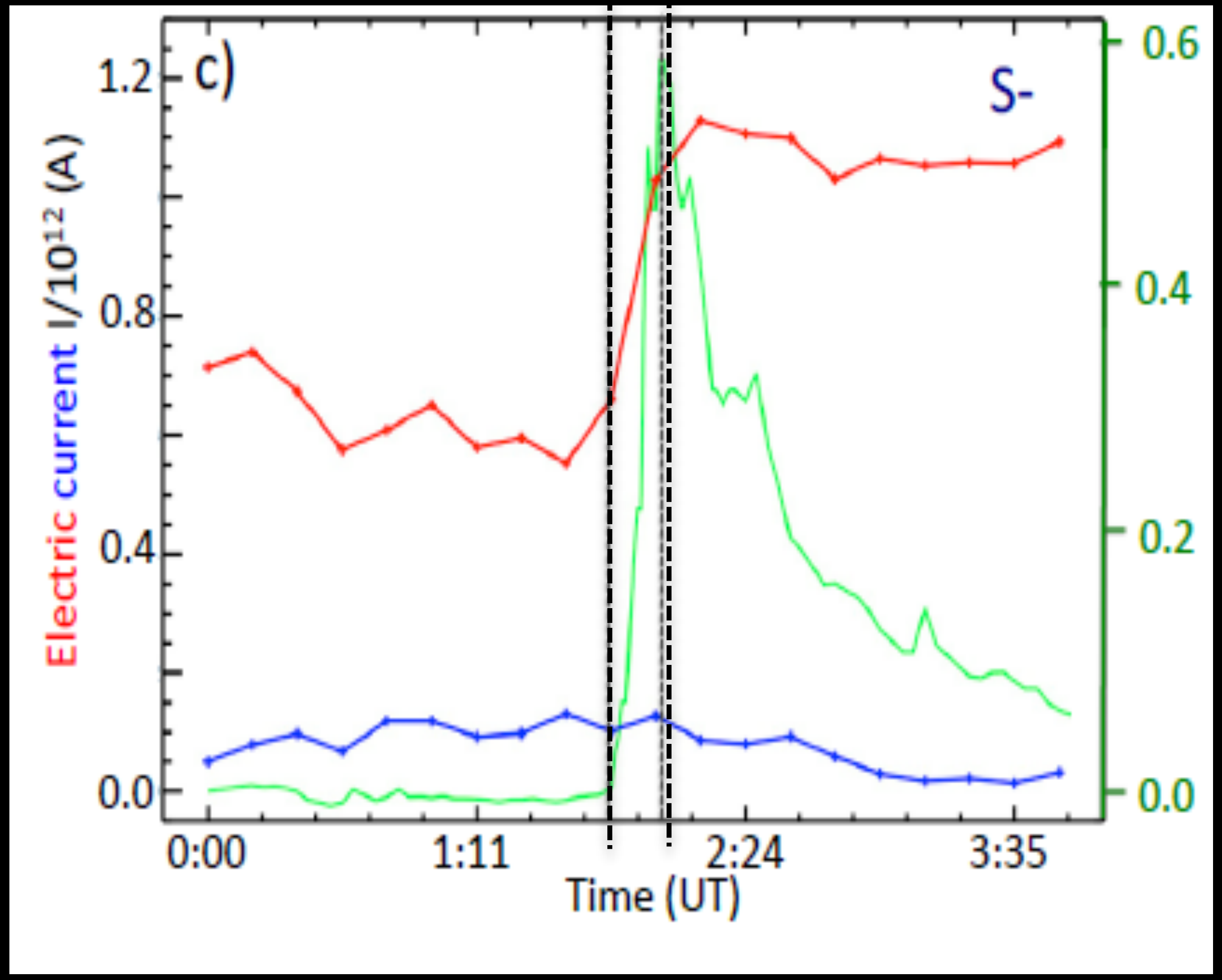


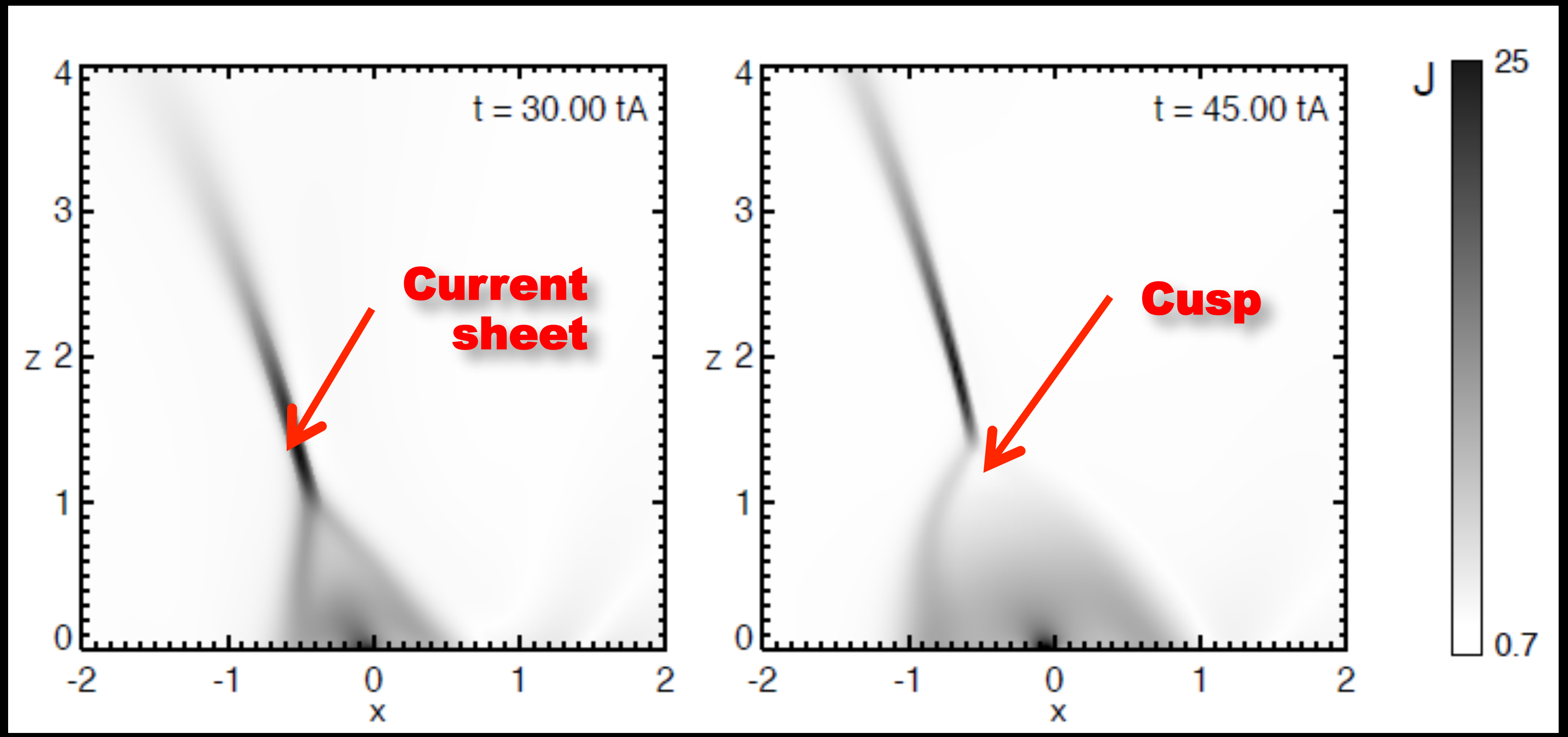


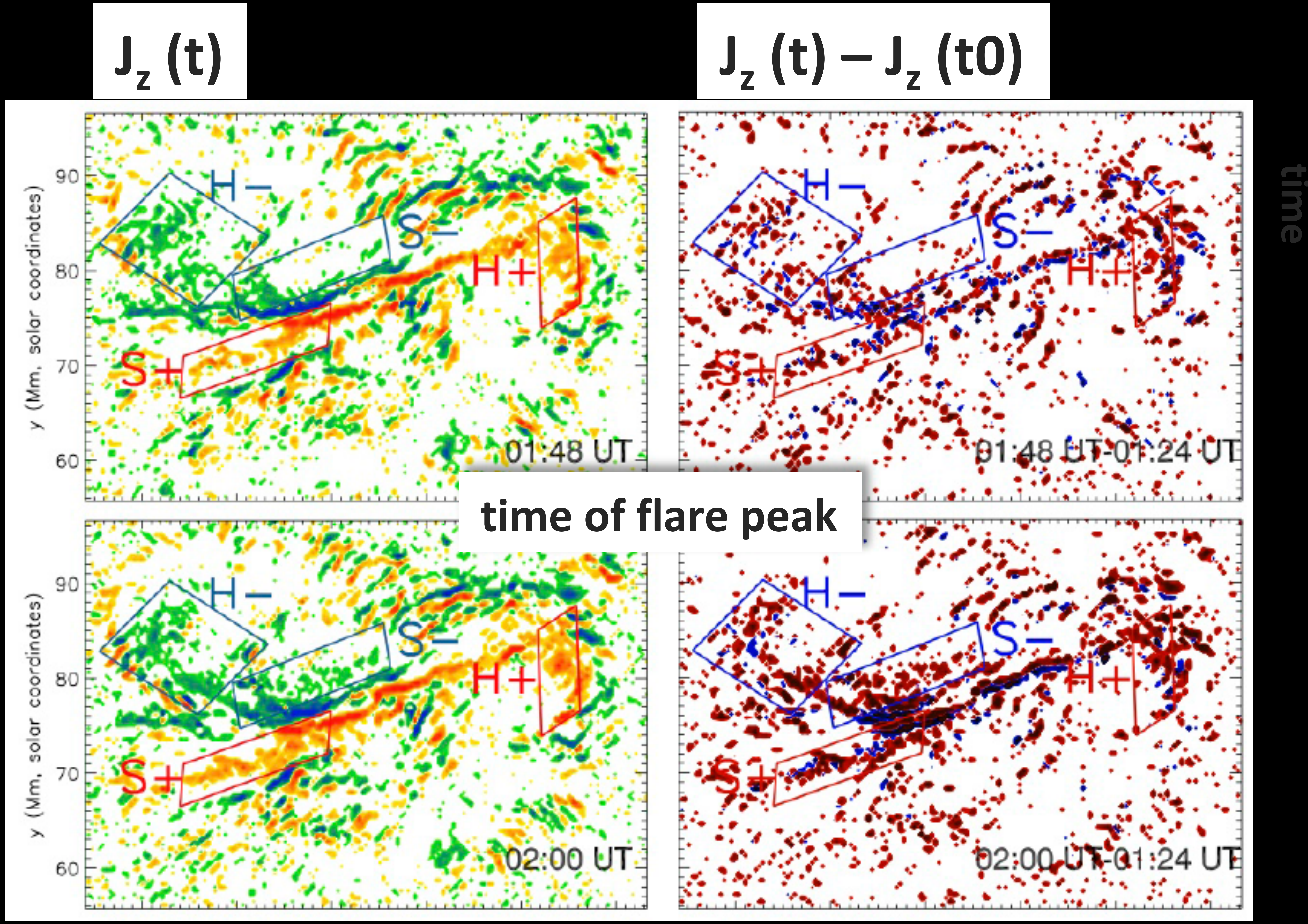
Photospheric vertical currents
=
traces (or "ribbons") of the 3D current "layer"

C. Testing the hypothesis w/ observations

Electric current I



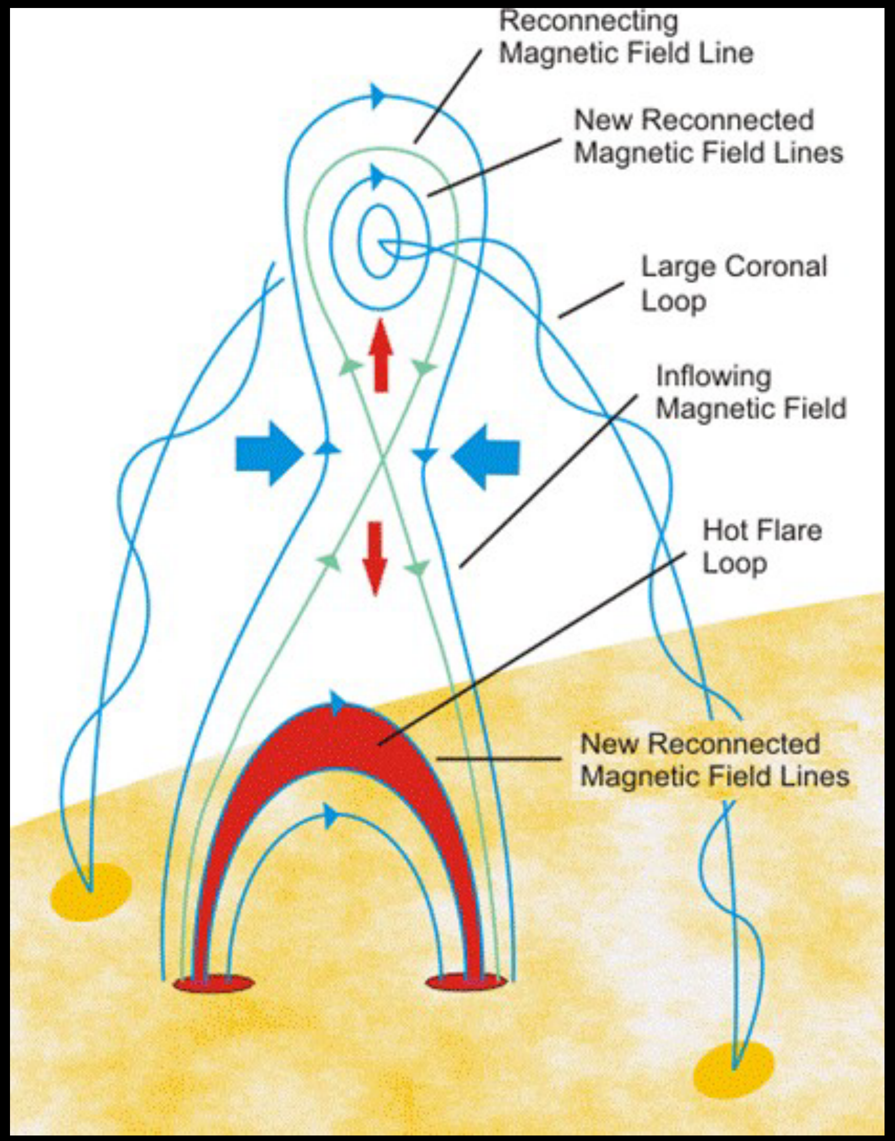


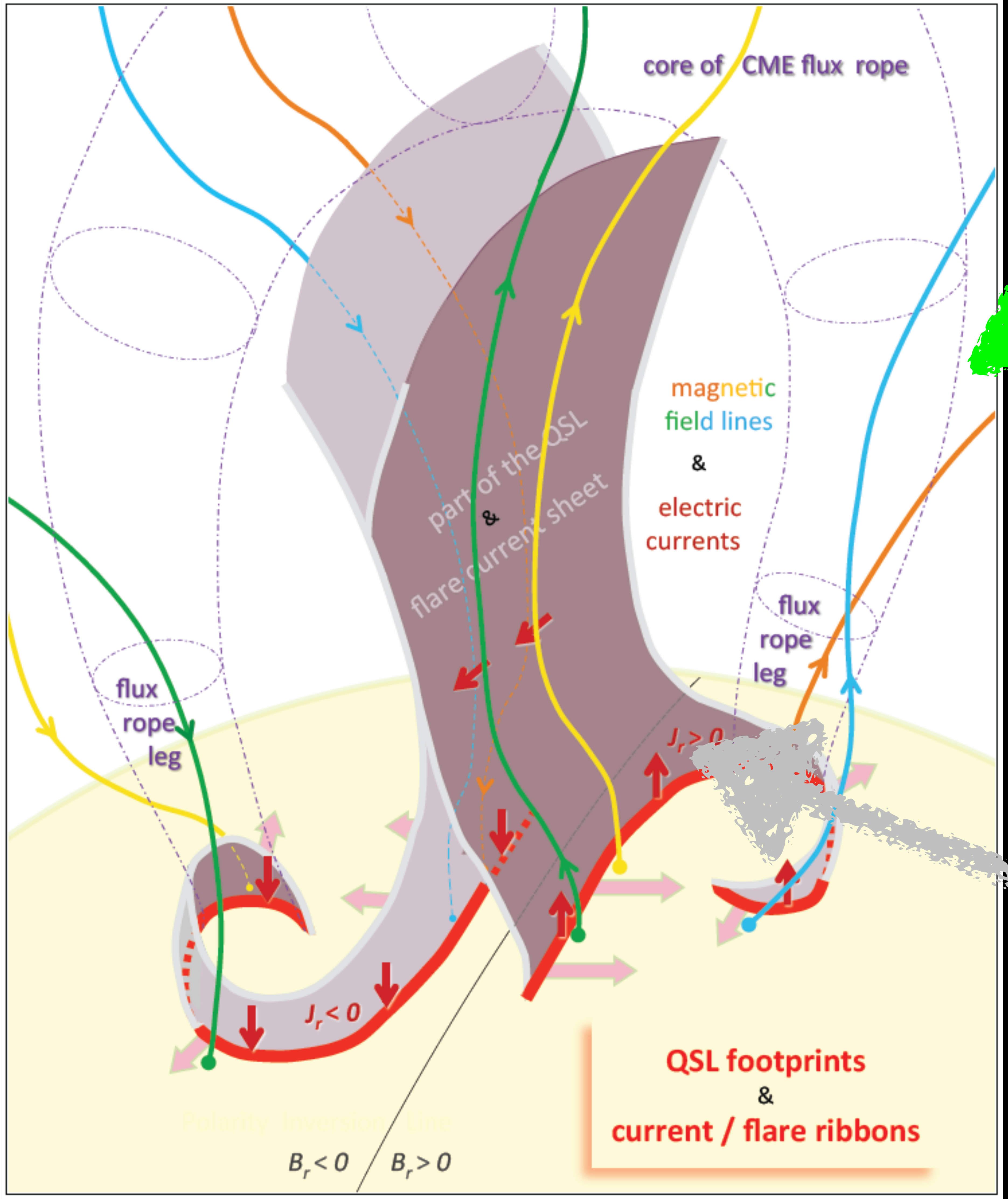


Increase of electric current
= collapse of the current layer

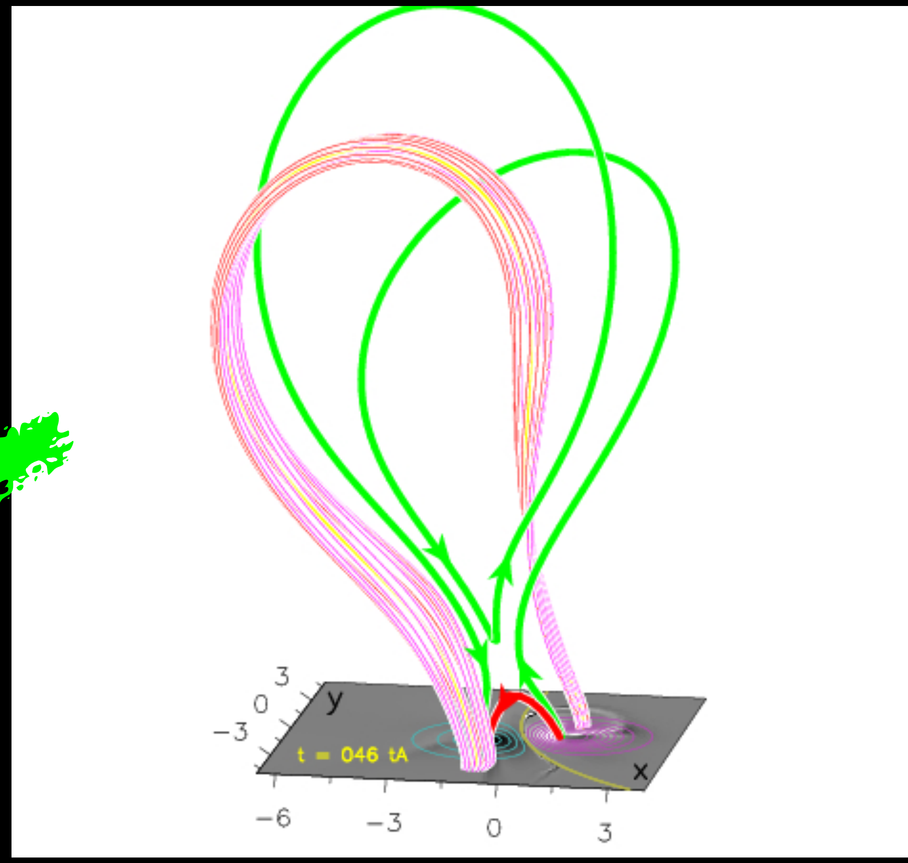
Janvier et al. (2014, 2016)

D. 3D model and unsolved problems

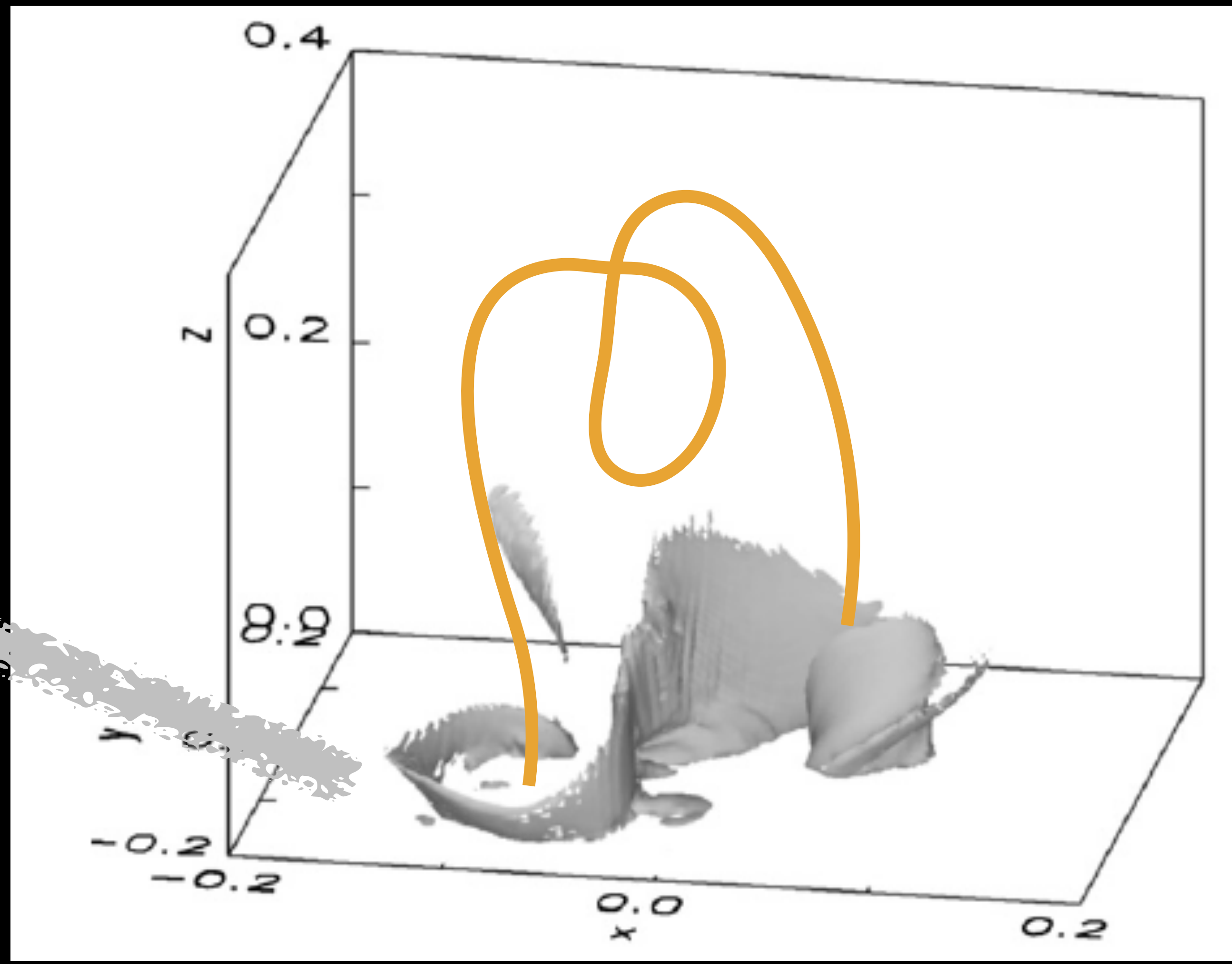




Janvier et al. (2014)



Flux rope + flare loops evolution



3D current "layer" (implication for reconnection + observed photospheric current evolution)

D. 3D model and unsolved problems

But...

There are still knowledge gaps

Pb: Details of energy transfer from global scale to small scale still not understood...
Current layer is given by the large-scale magnetic field (Mm) but dynamics happen at much smaller scales (m)

D. 3D model and unsolved problems

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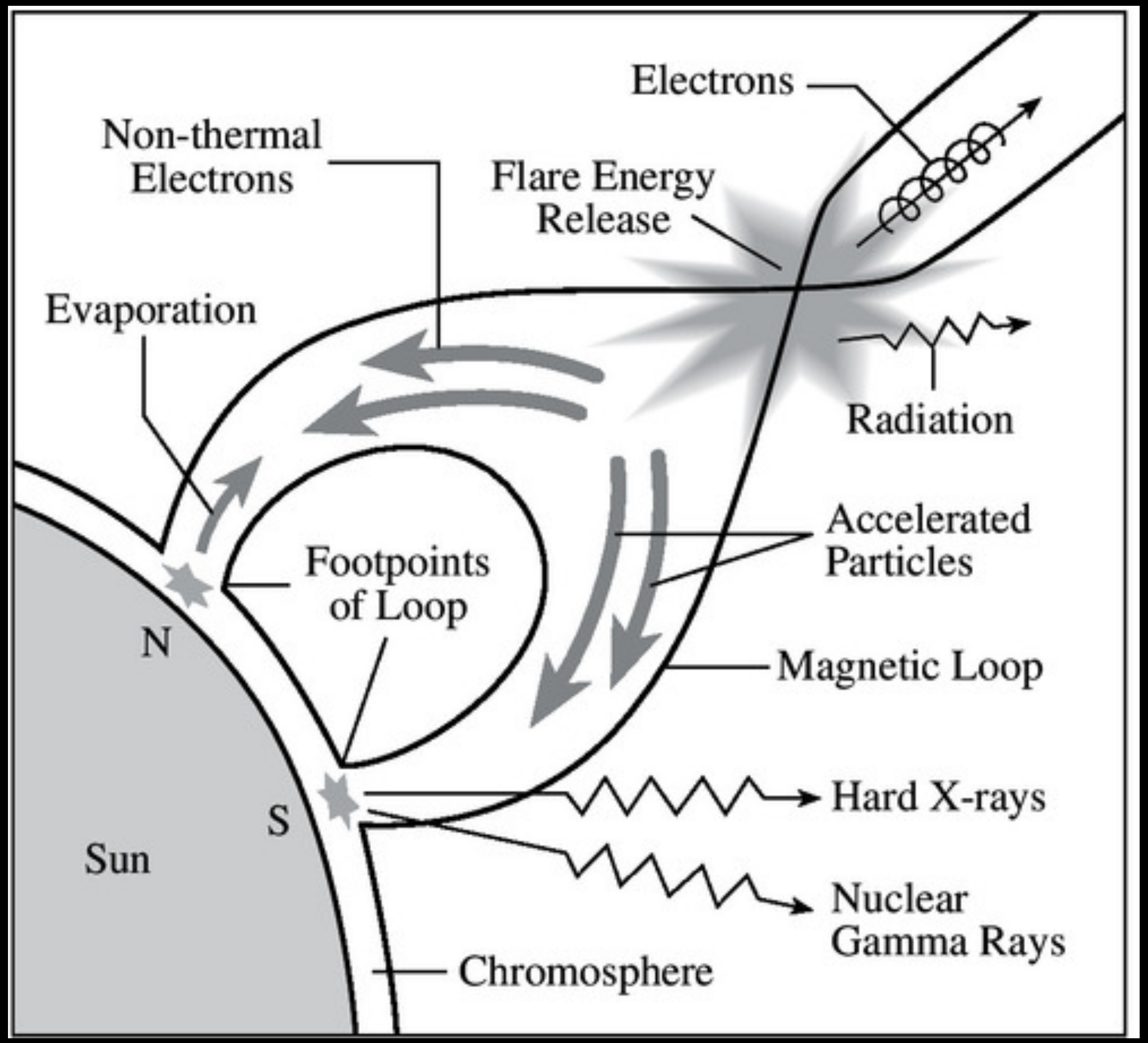
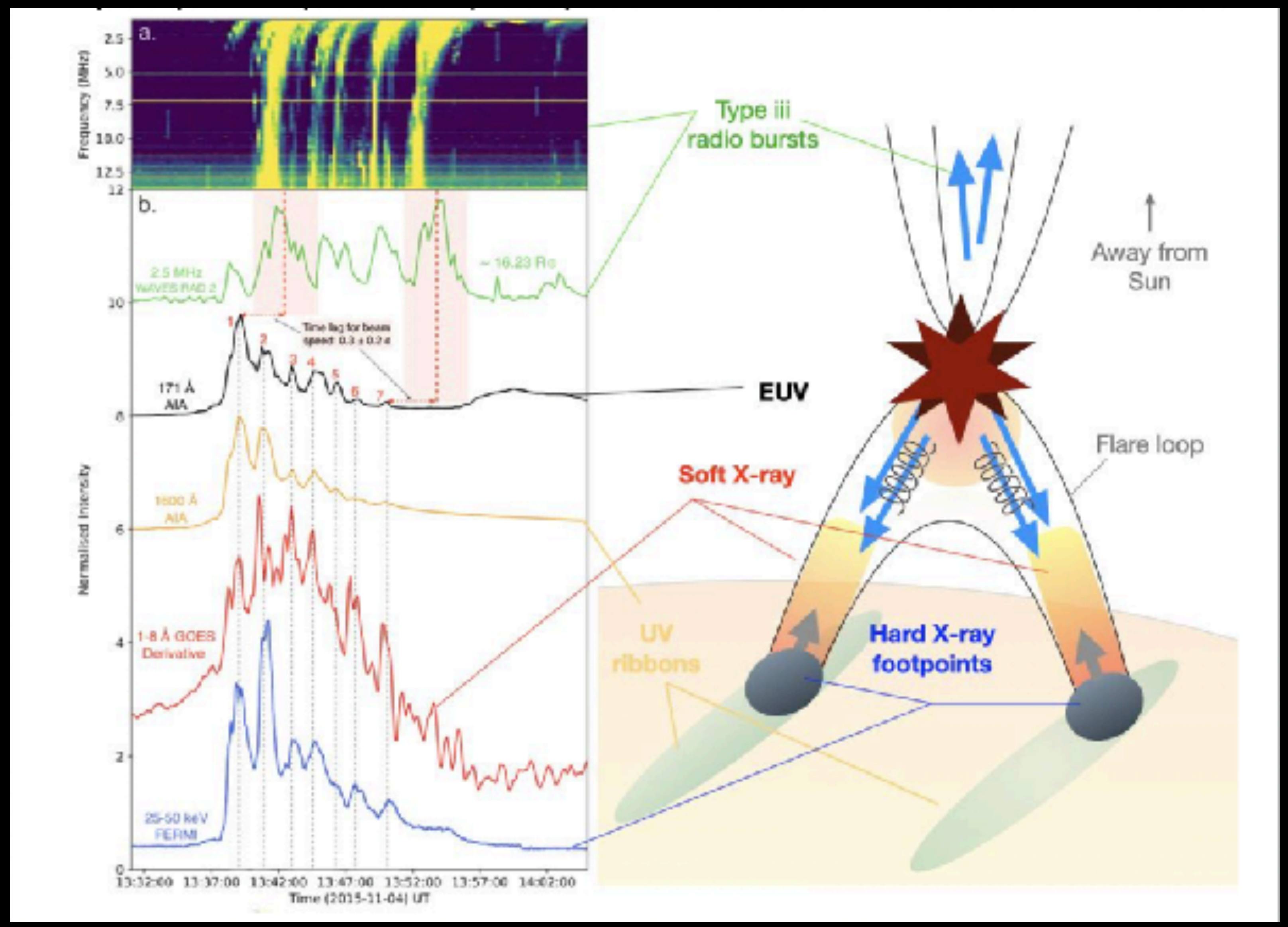


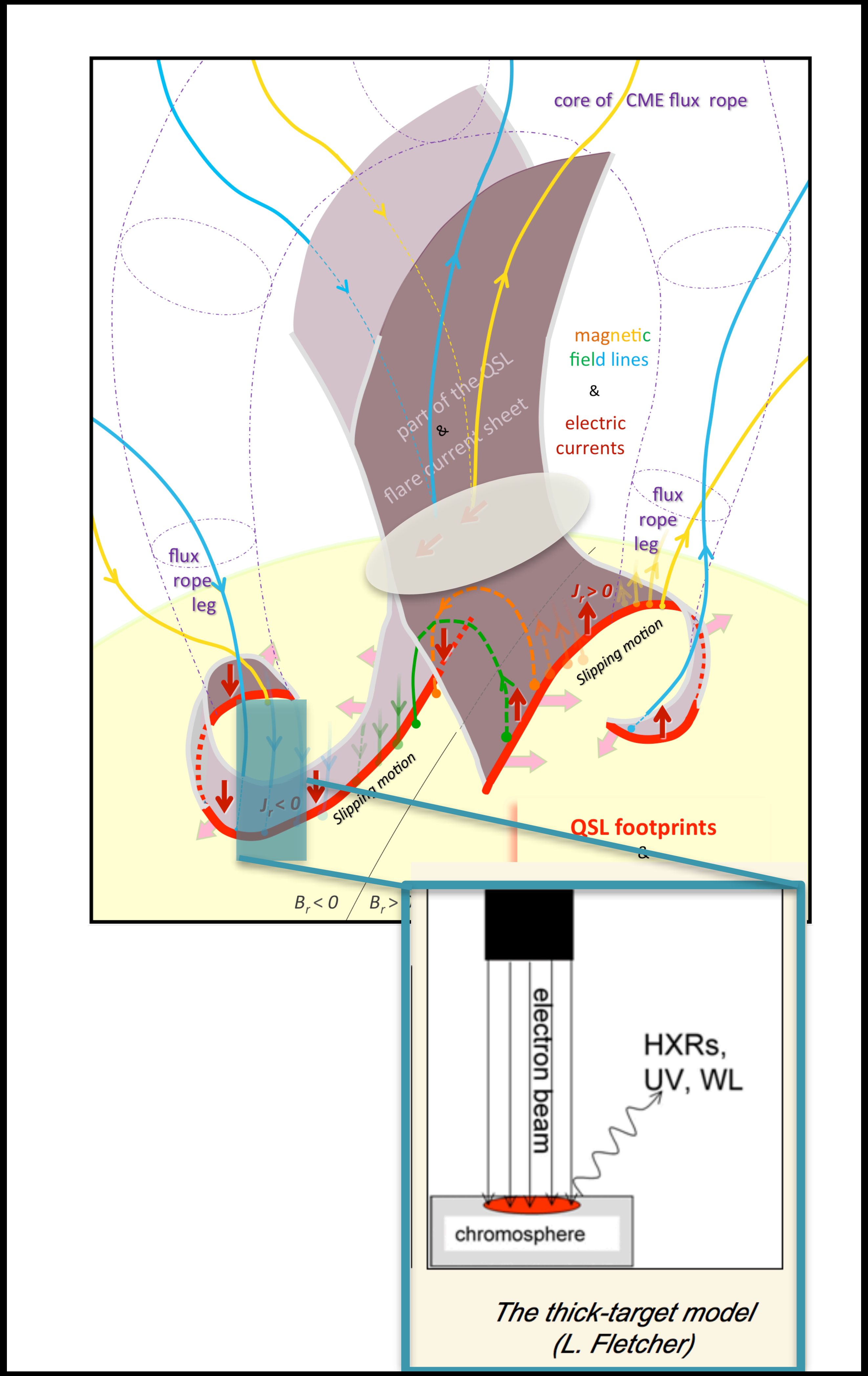
Quasi periodic pulsations



Inglis et al. 2023

Chap 3

D. 3D model and unsolved problems



Macroscopic dynamics of magnetic fields

Flux ropes, field distortion, current layers

+

Instabilities, forcing (e.g. photospheric motions)

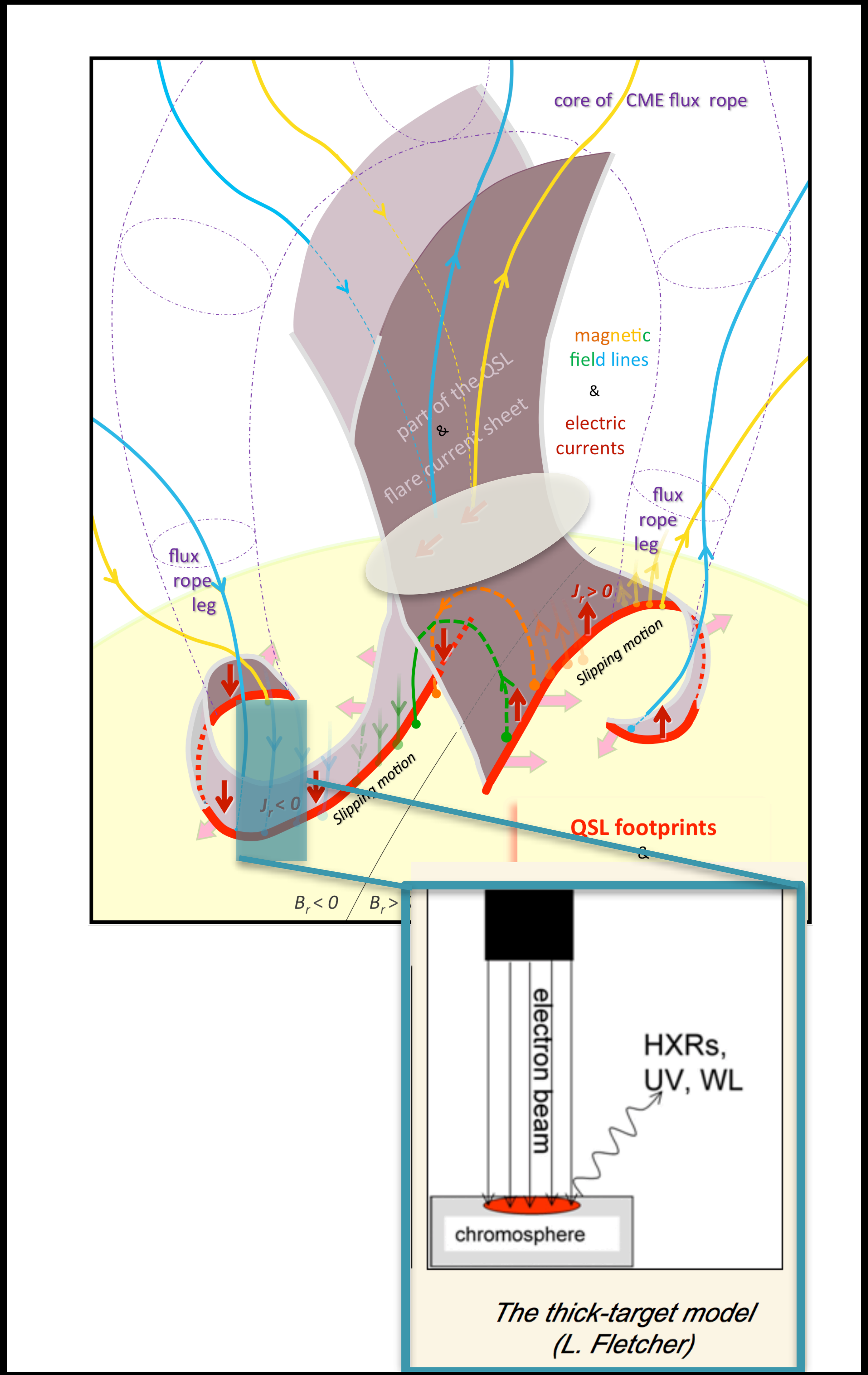
Current layer collapse, reconnection, large-scale morphology changes

Transport of Energy along new topology/morphology

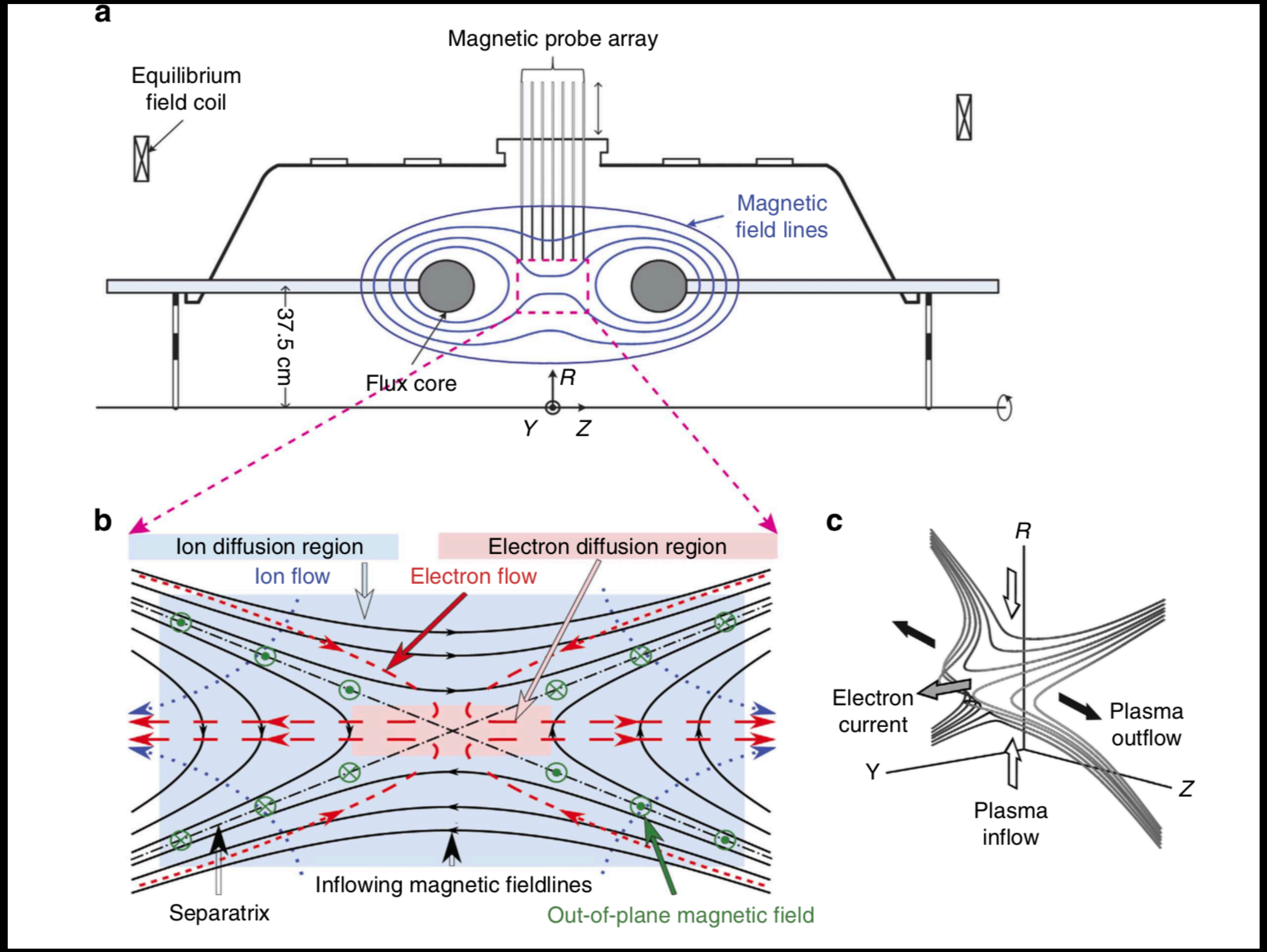
Particle acceleration, waves

Chap 3

D. 3D model and unsolved problems



Yamada et al. 2014, 2016, MRX experiment (Princeton)



Energy deposition is different for ions and electrons

« >50% of the magnetic energy is converted to particle energy, 2/3 of which transferred to ions and 1/3 to electrons. »

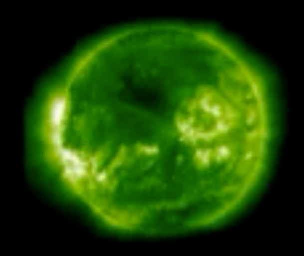
Also confirmed in MMS mission (see Toledo-Redondo et al. 2017)

But what about shocks, waves, magnetic islands, turbulence? (To be followed up on…)

Chapter 4: CMEs in the solar wind

A. CME - ICME link
B. Statistics on properties
C. Interplay with the solar wind (a multi spacecraft analysis)
D. Towards a CME model?
E. Multi-scale flux ropes… and reconnection problem again!

Key idea: long and spatially diverse surveys of CMEs help understand their properties, but we lack datapoints + the role of reconnection in forming heliospheric flux ropes



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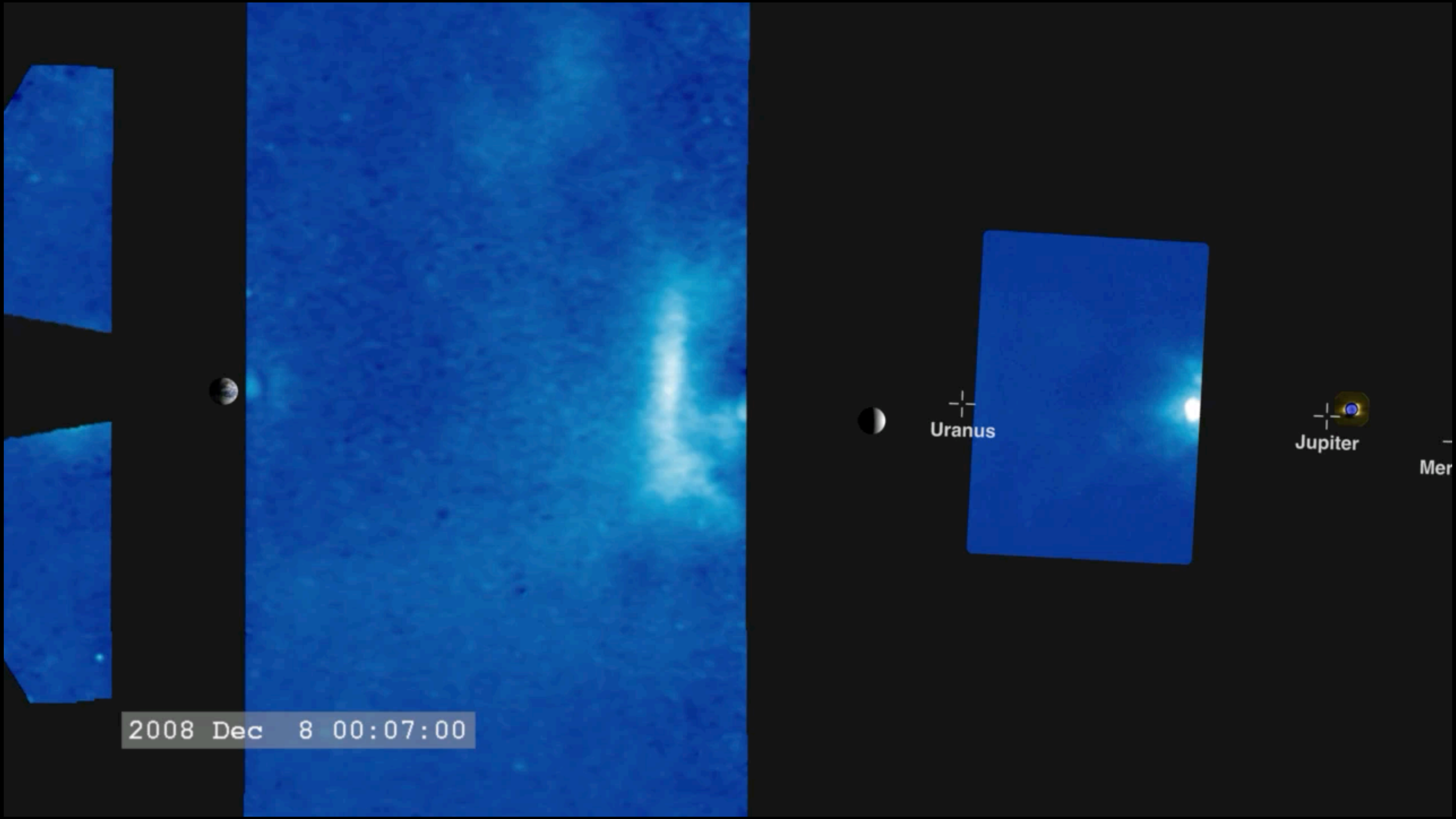
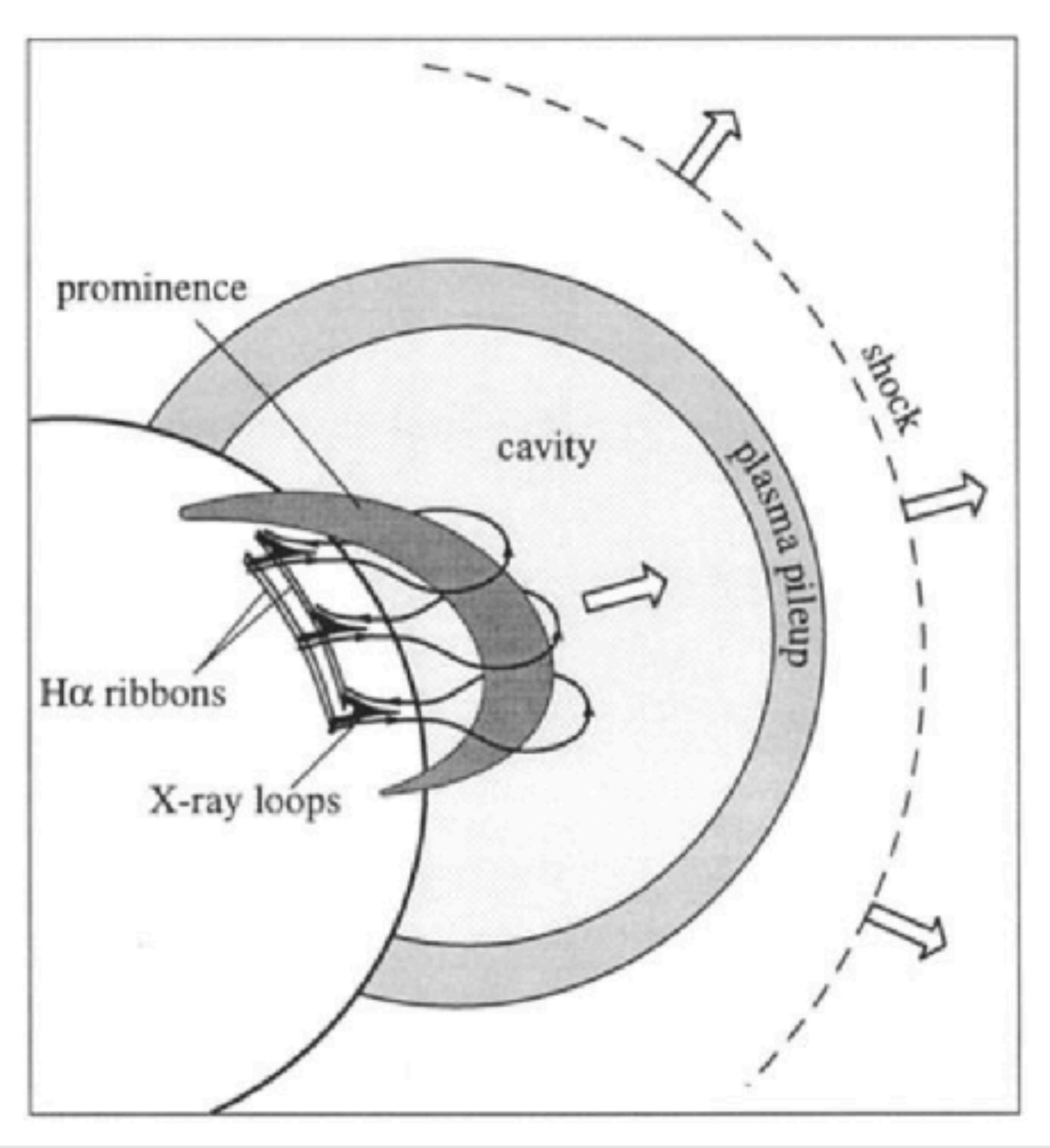


Heliospheric imagers

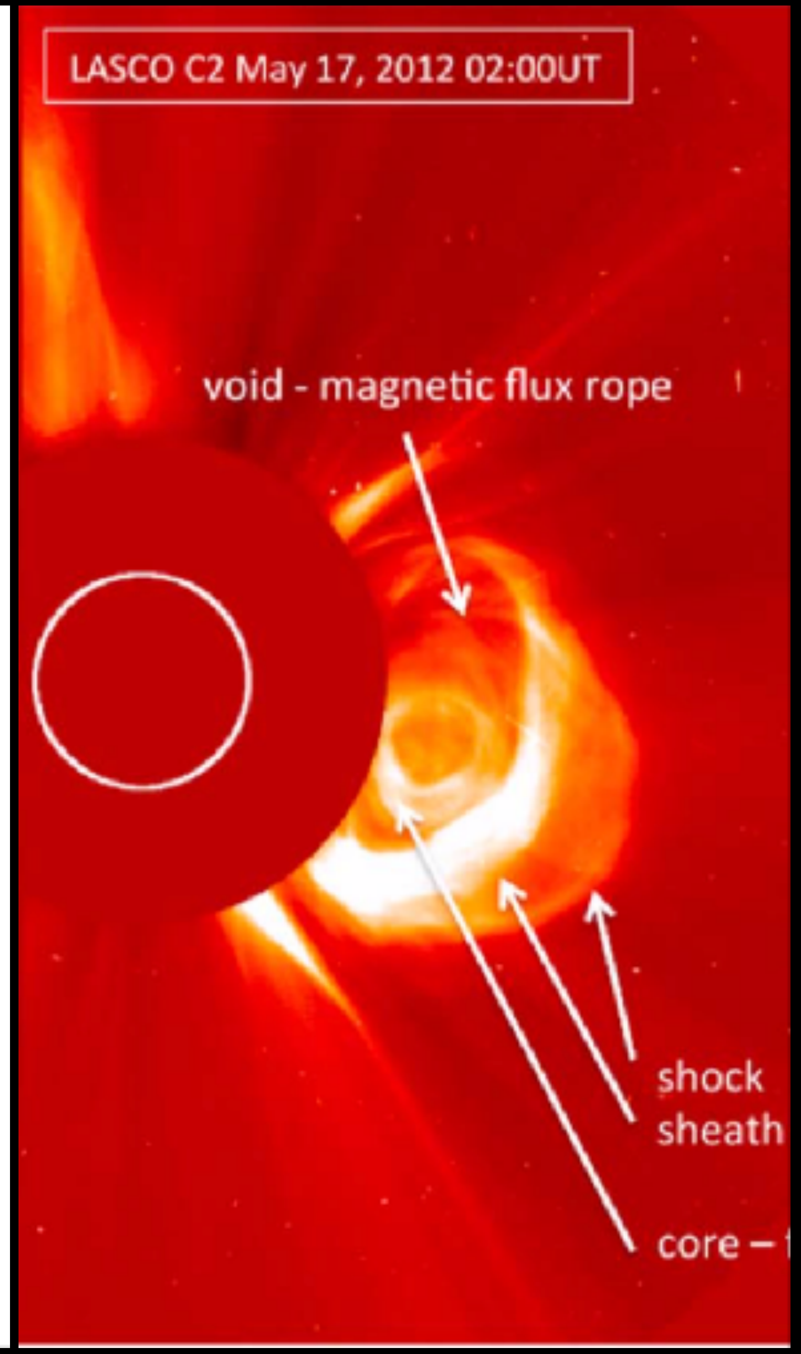
Chap 4

A. CME - ICME link

Remote-sensing



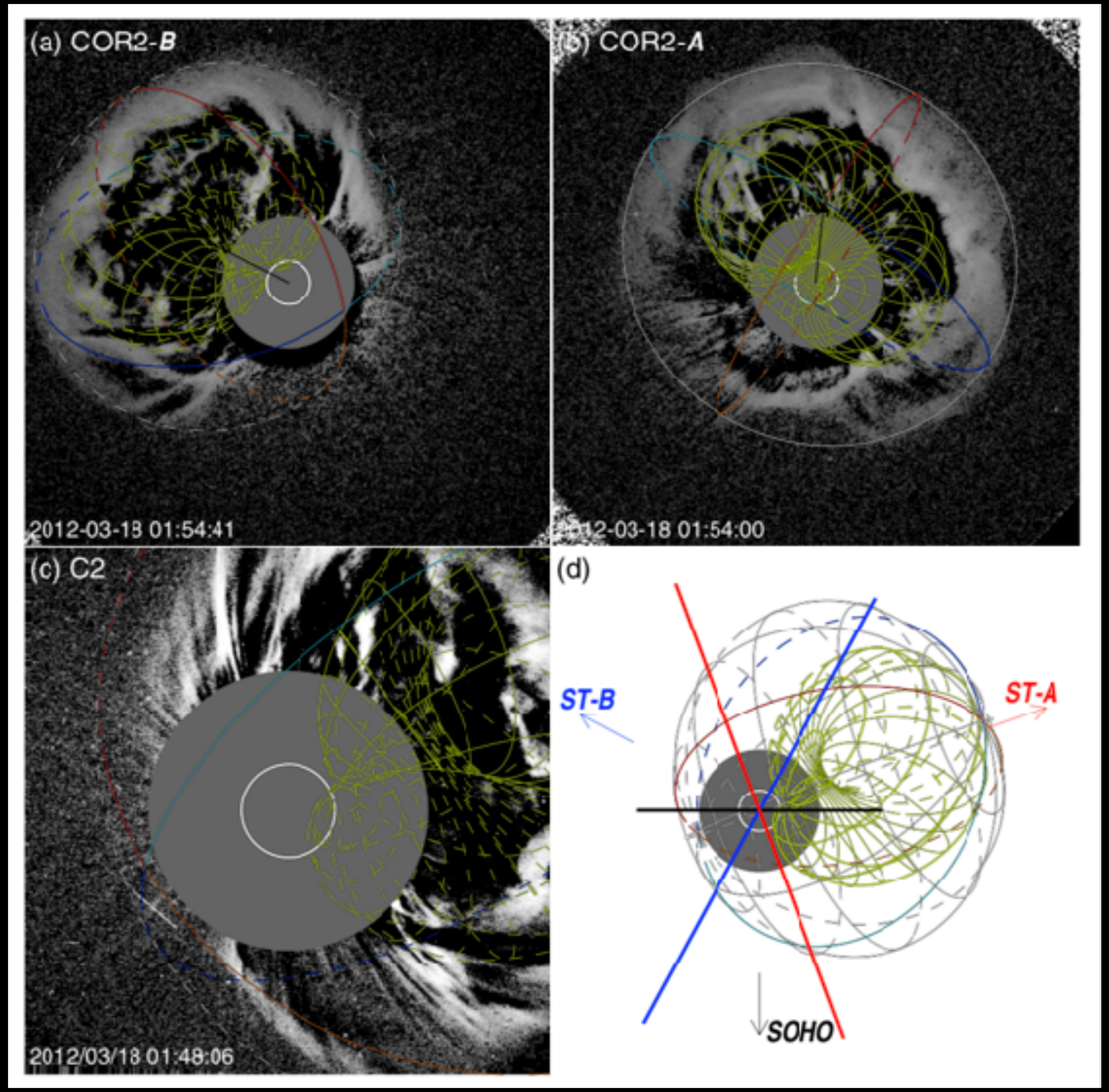
Forbes, 2000



Krauss et al. 2015

CME front formed due to plasma-pileup (snowplow effect) / shock compression

CMEs are low-density, difficult to track structures

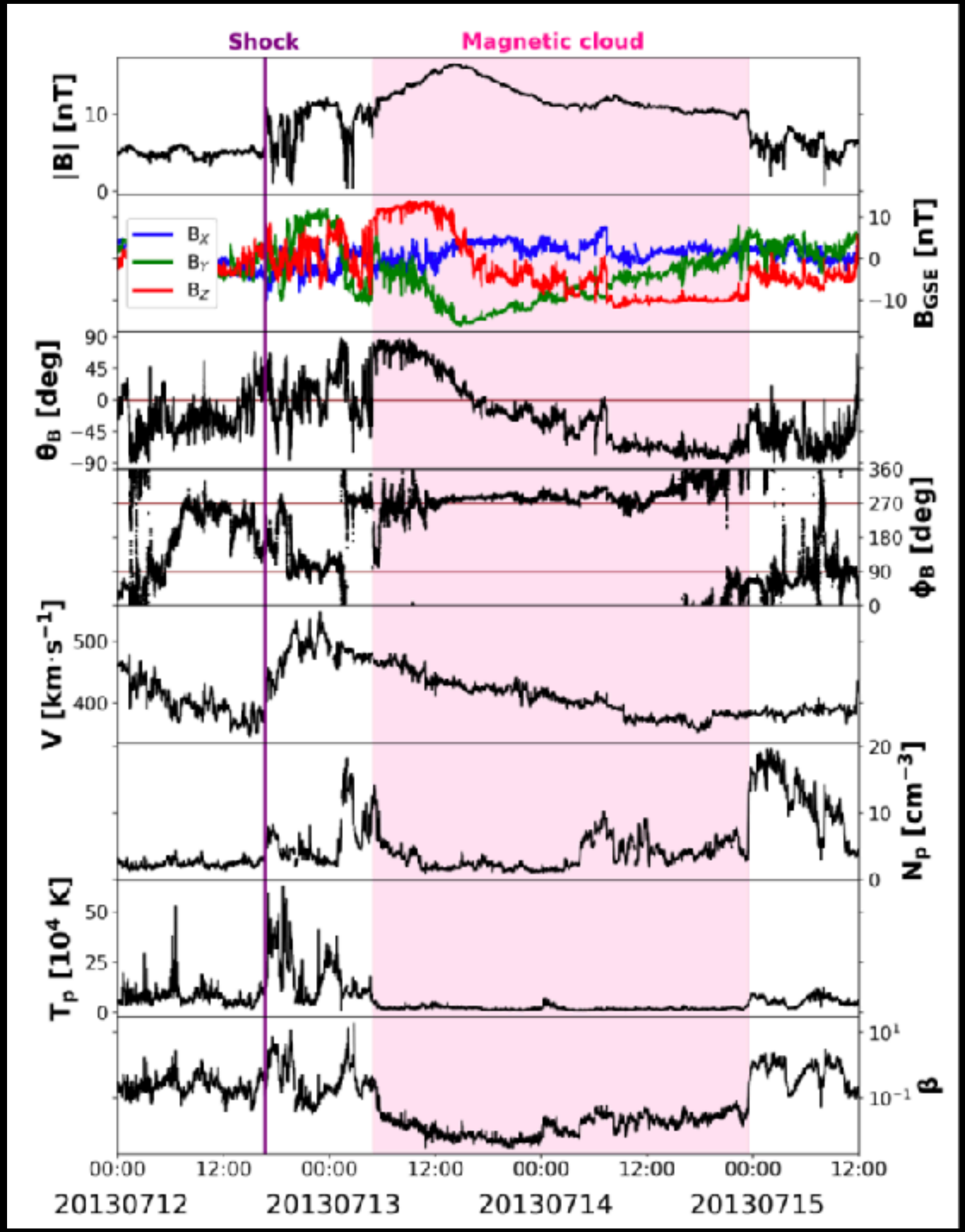


Derived parameters (i.e. speeds, widths, locations) measured from single v/p, with projection effects problems.

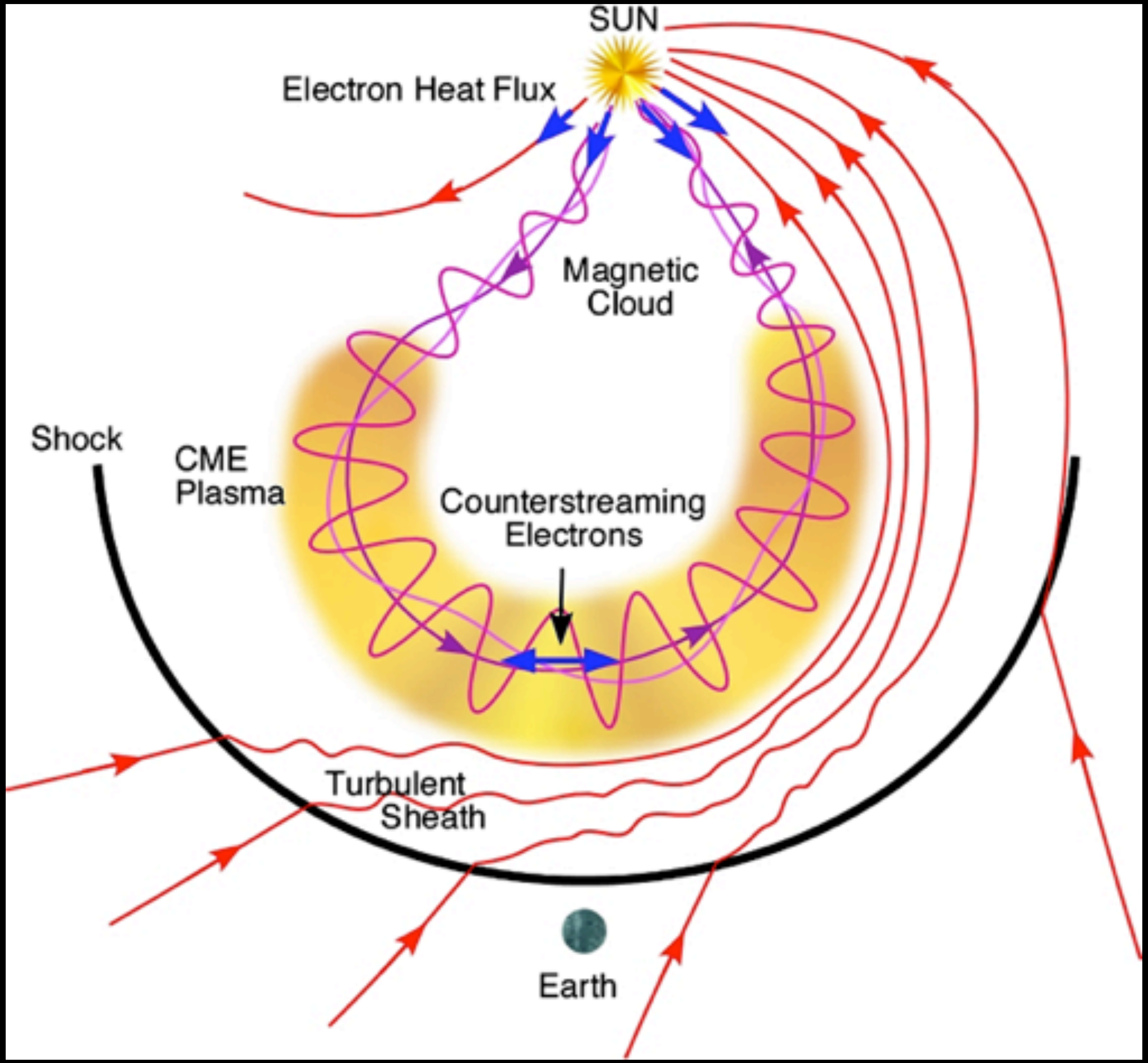
(Hundhausen, 1993, Burkepile et al. 2004, Cremades & Bothmer, 2004)

See reviews, e.g. Chen 2011, Kilpua et al. 2017

A. CME - ICME link In situ



Adapted from Palmerio et al.



Zurbuchen & Richardson 2006

A. CME - ICME link In situ

Interplanetary CMEs criteria:

See a summary of ICME in-situ signatures in:
Wimmer-Schweingruber et al. 2006; Zurbuchen & Richardson 2006

Enhanced ion charge states (e.g. Fenimore 1980)

Enhanced helium abundance (e.g. Borrini et al. 1982)
$N_{alpha}/N_p > 0.8$ (e.g. Liu et al. 2005)

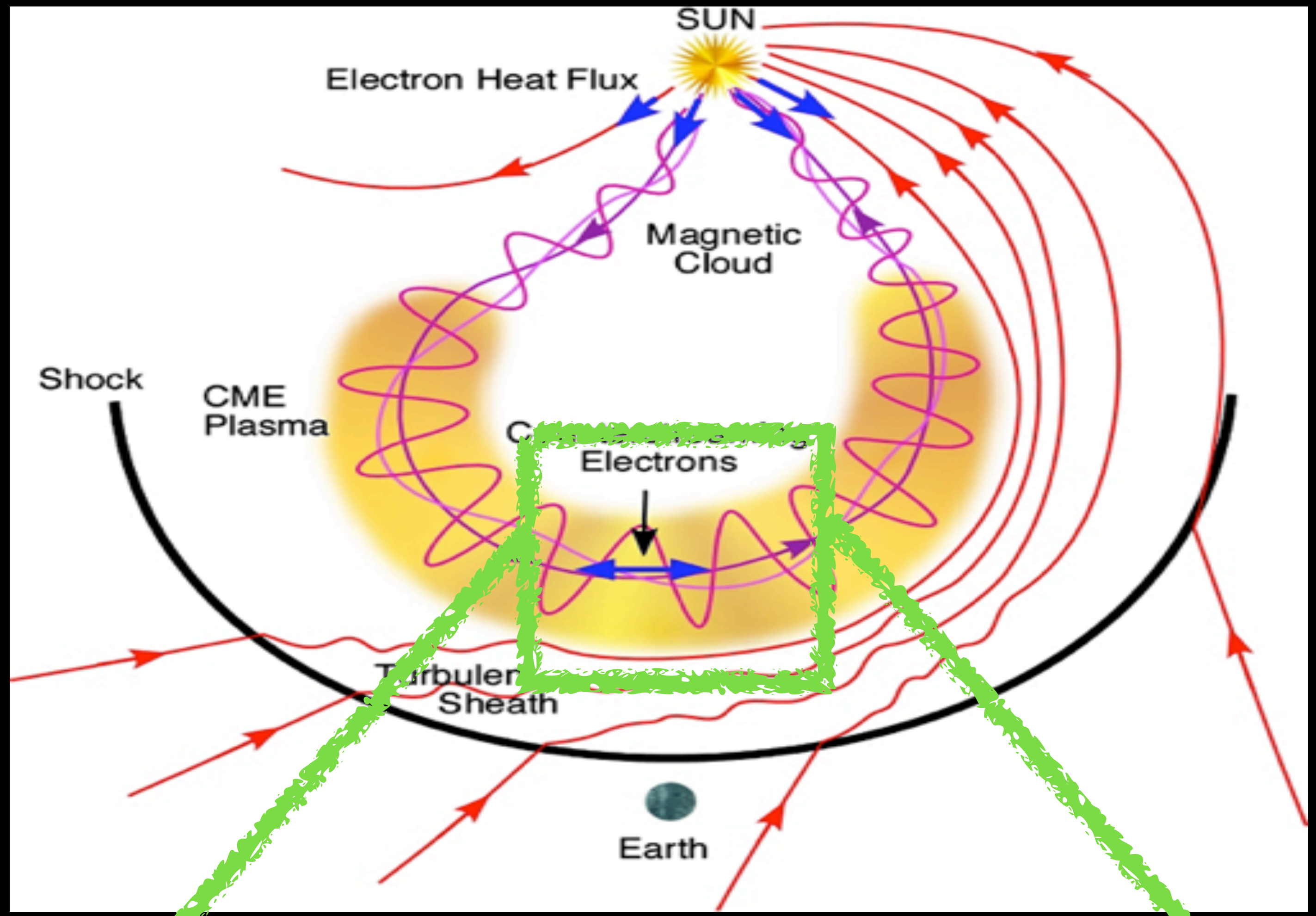
Counter-streaming suprathermal (>80 eV) electron beams (e.g. Gosling et al. 1987)

Proton temperature lower than SW (e.g. Gosling et al. 1973, Wang et al. 2005)
$T_P/T_{\text{expected in SW}} < 0.5$

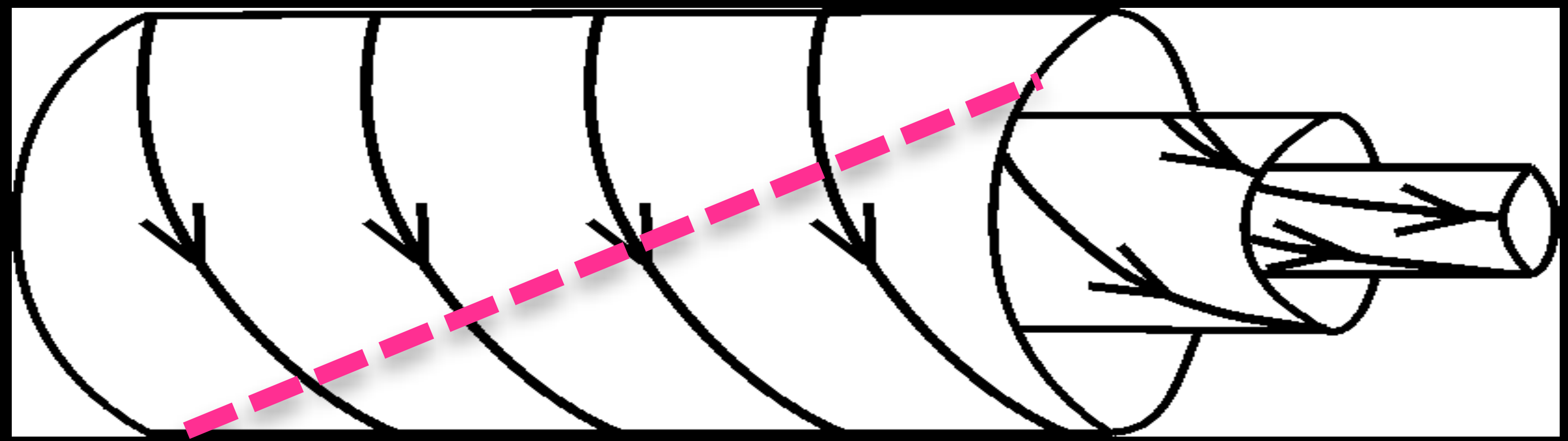
Low proton plasma beta

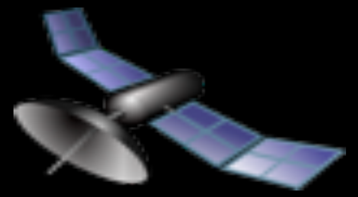
Stronger magnetic field than SW with low variance

Smooth and large rotation of MF



Flux rope = twisted magnetic structure



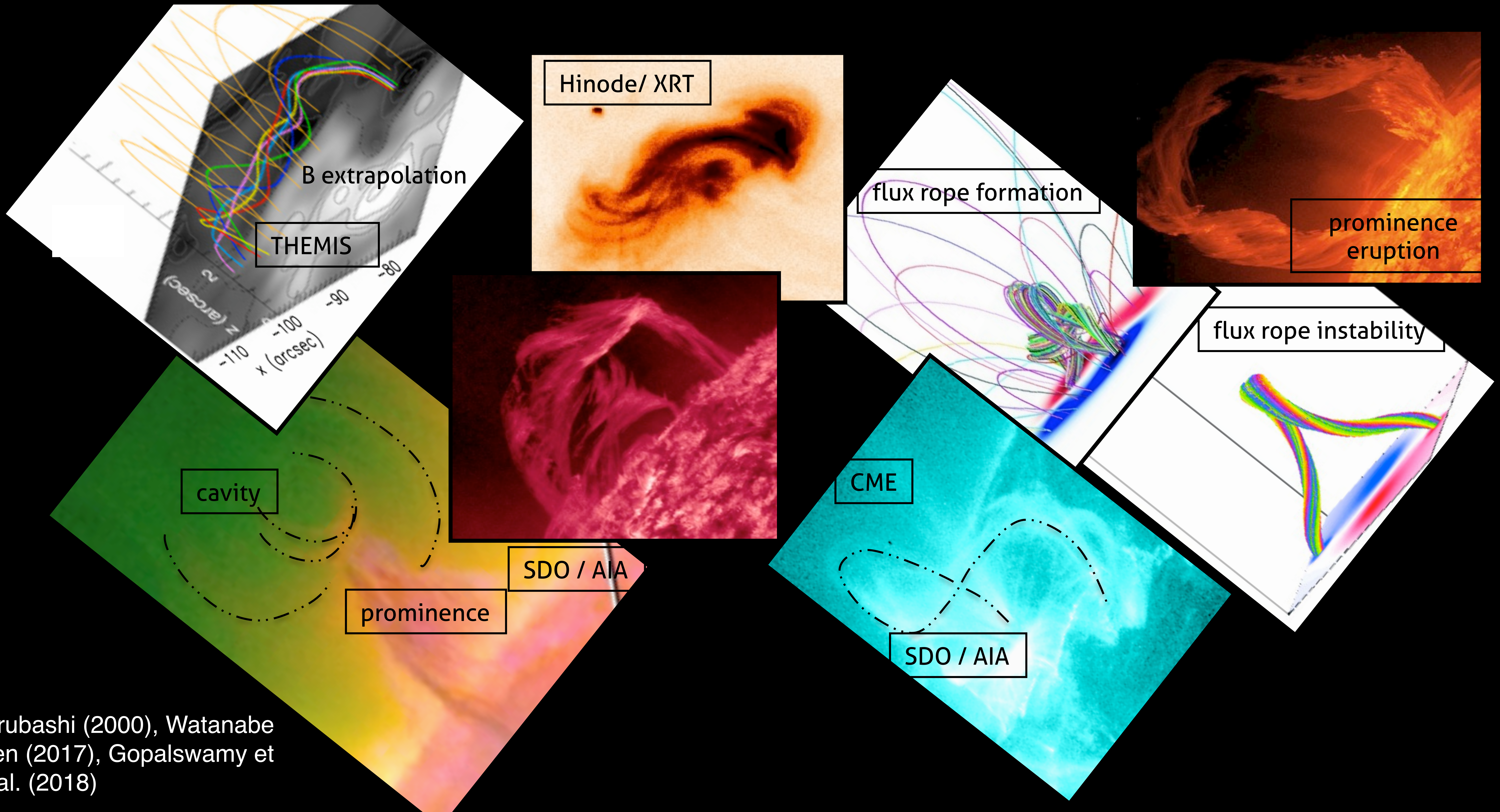


Magnetic clouds (MCs) criteria

Burlaga et al. 1981, Klein & Burlaga 1982, Lopez & Freeman 1986, Burlaga 1988, Lepping et al. 1990

A. CME - ICME link

Flux ropes are expected to be at the heart of solar eruptions



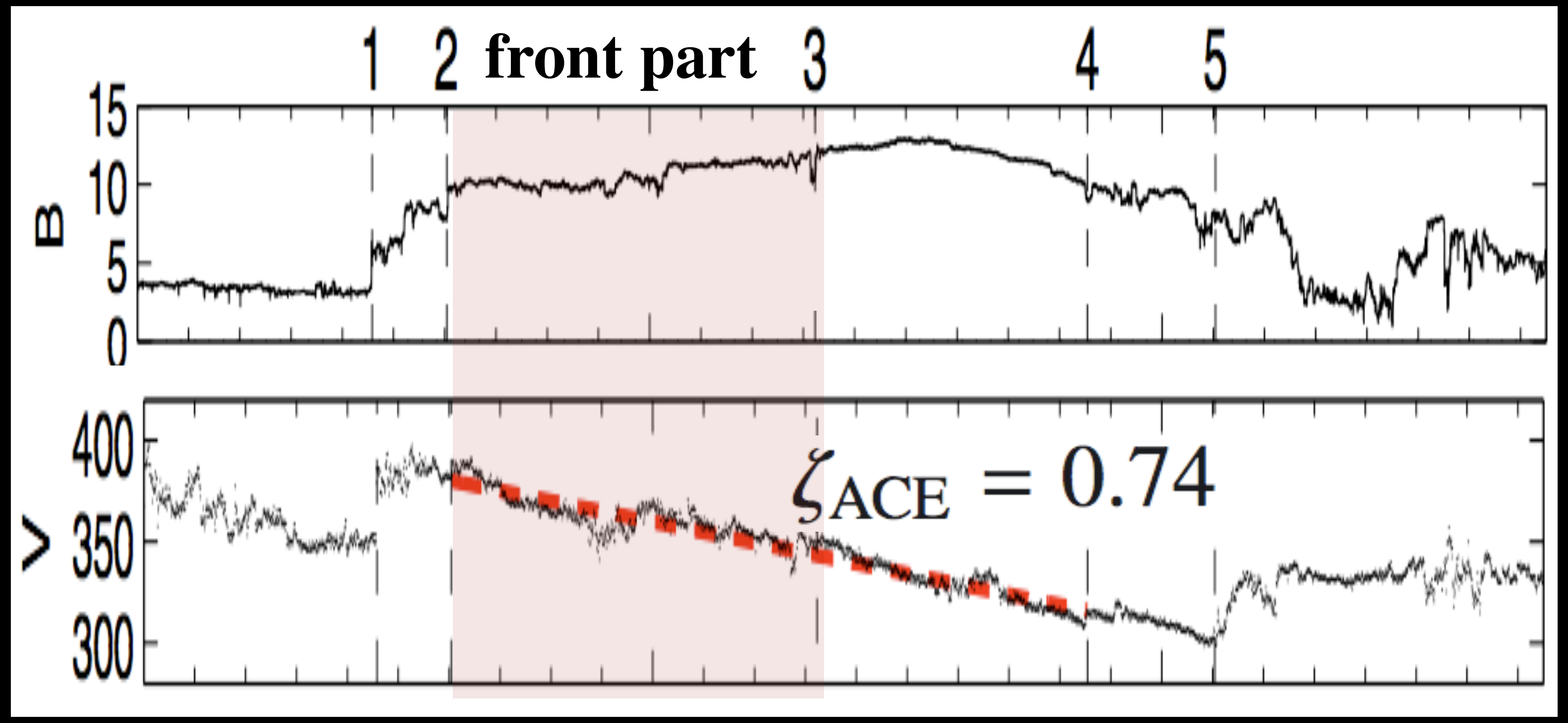
See reviews: Marubashi (2000), Watanabe et al. (2004), Chen (2017), Gopalswamy et al. (2018)

↳ B. Statistics on properties

Studies on: Expansion of the Magnetic Ejecta, profiles, statistics of mag. intensities

Multi-probes situated at different distances from the Sun allow looking at the evolution of ICMEs

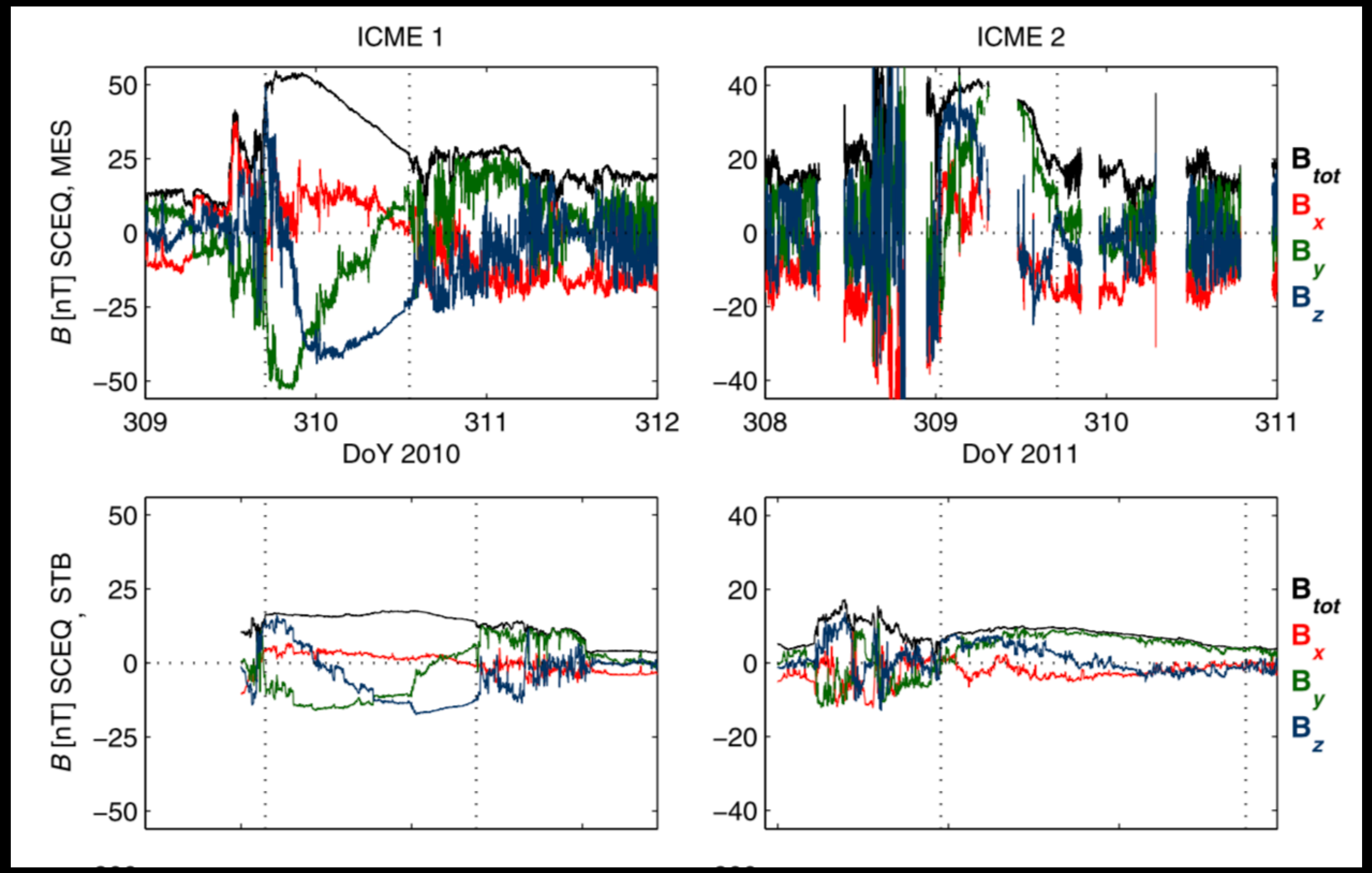
Case studies Sun - IP



Expansion rate, magnetic field budget, comparison of flux rope orientation, …

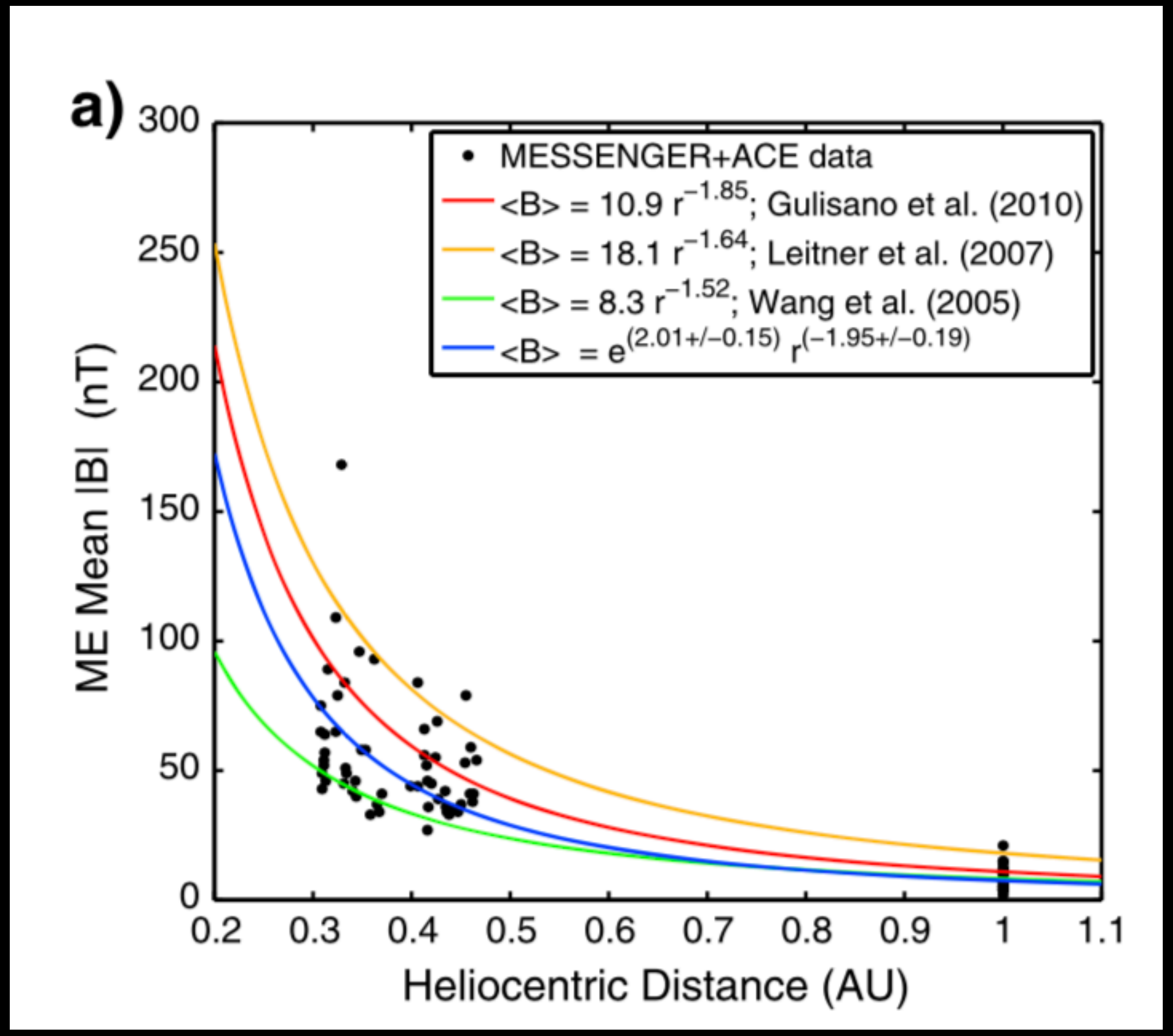
Nackwacki et al. 2011

Case studies IP-IP



Good et al. 2018: compare profiles of ICMEs seen at MESSENGER and STEREO B (applying models of expansion)

Statistics

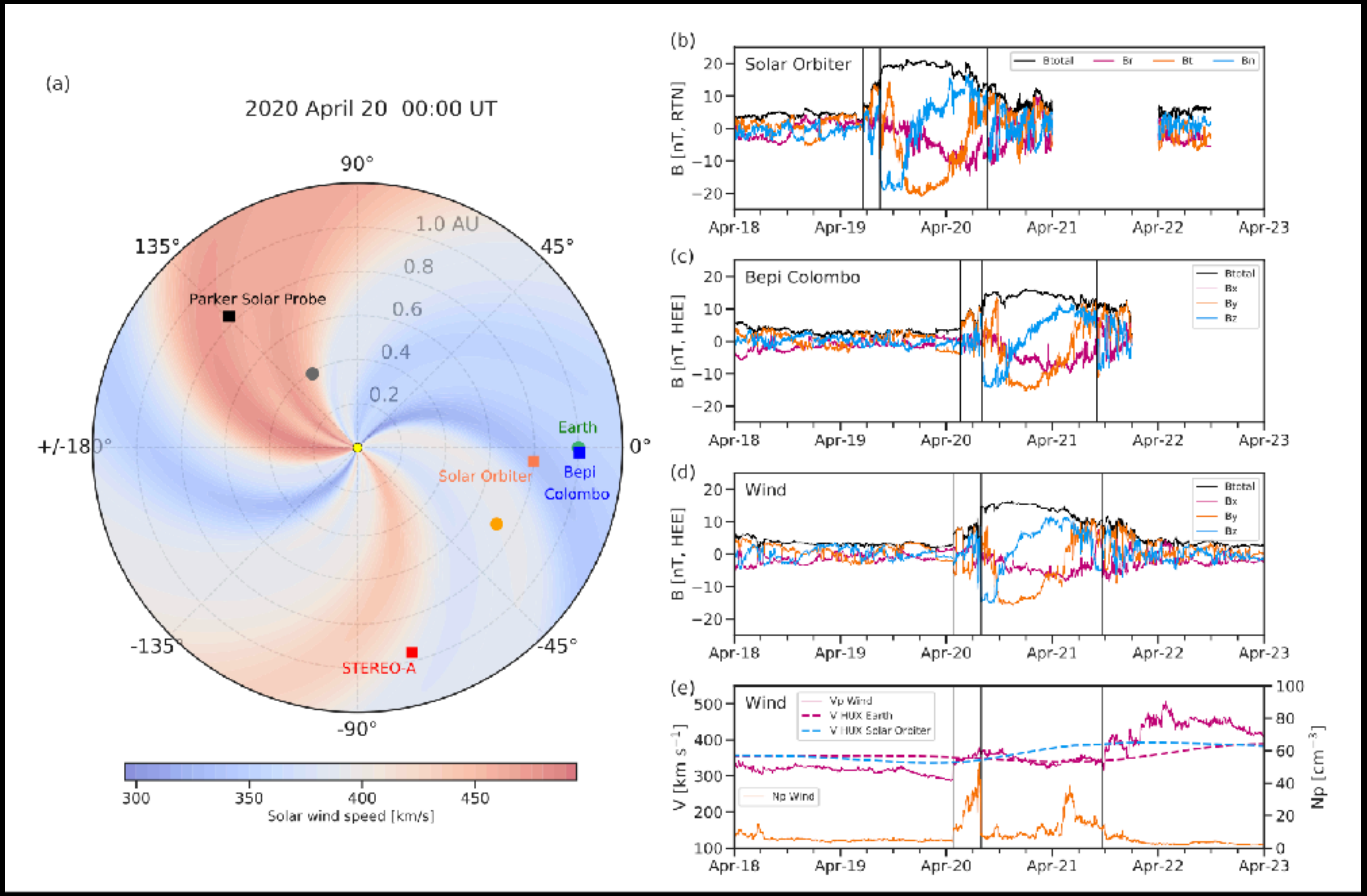


Winslow et al. 2015: statistical studies on magnetic field intensities
+ comparison with other scaling laws.

Chap 4

B. Statistics on properties

BUT: not coherent results are still found...



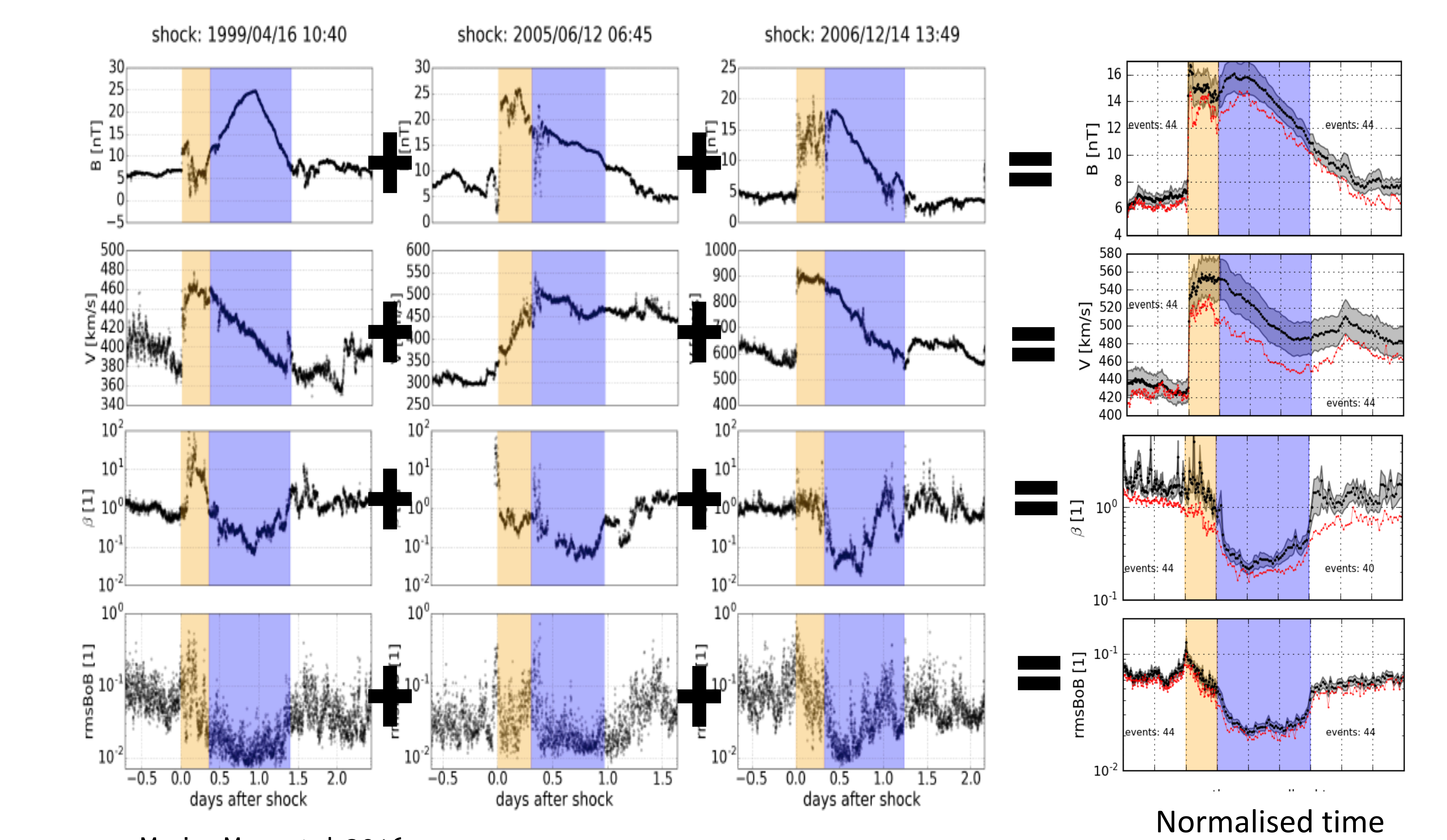
Dependence of the maximum (mean) magnetic field strength decreases with heliocentric distance as $r^{-1.24\pm0.50}$ ($r^{-1.12\pm0.14}$)

in disagreement with previous studies.

Expansion of the CME appears neither self-similar nor cylindrically symmetric (distortion due to solar wind?).

Davies et al. 2021

B. Statistics on properties

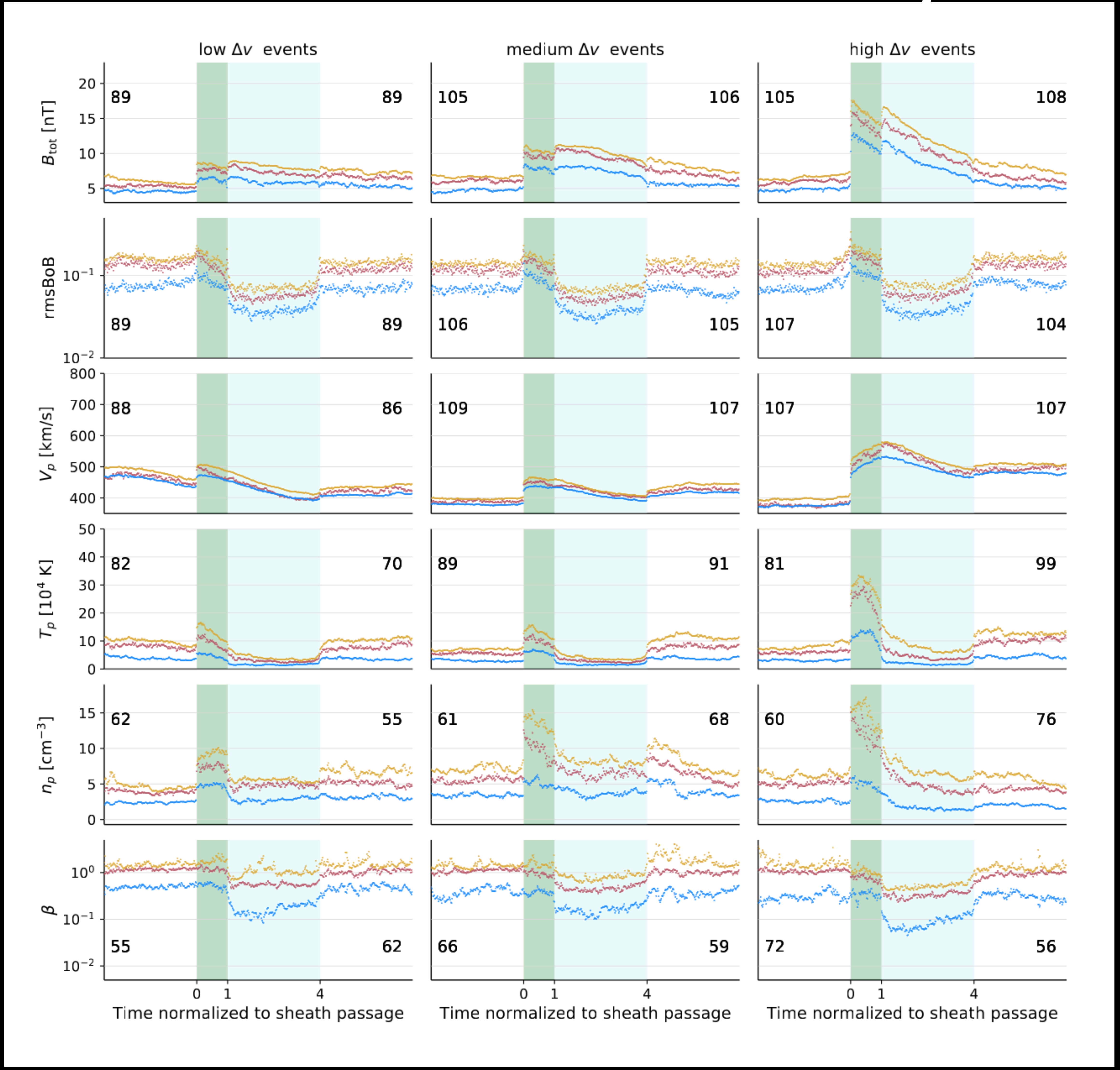


Masias-Meza et al. 2016 See also: Yermolaev 2012, Badruddin 2016, Rodriguez 2016

Superposing all ICMEs together underlines their **typical** features (known as the Superposed Epoch Analysis).

B. Statistics on properties

Statistics: ACE data (L1) over 20 years



Superposing all ICMEs together underlines their typical features

Shown here: the mean (yellow), median (red) and blue(most probable value) of the distributions in each time bins

-Different profiles depending on the relative speed o

-sheath region, ME magnetic field asymmetry different for relatively fast events

-sheath region compressed by both shock + ME in relatively fast events

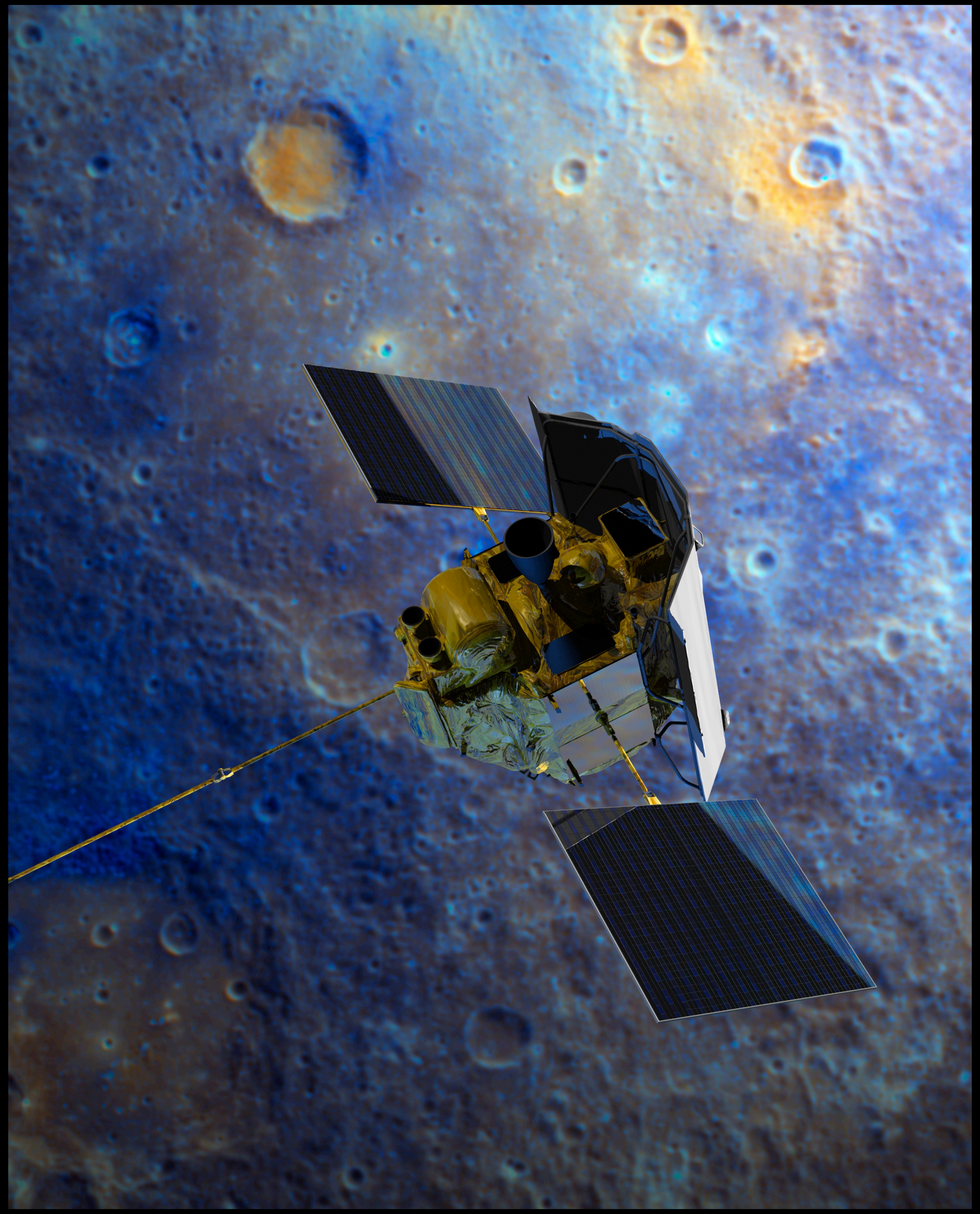
Shows the interaction between ICMEs and solar wind

Regnault et al. JGR (2020)

Chap 4

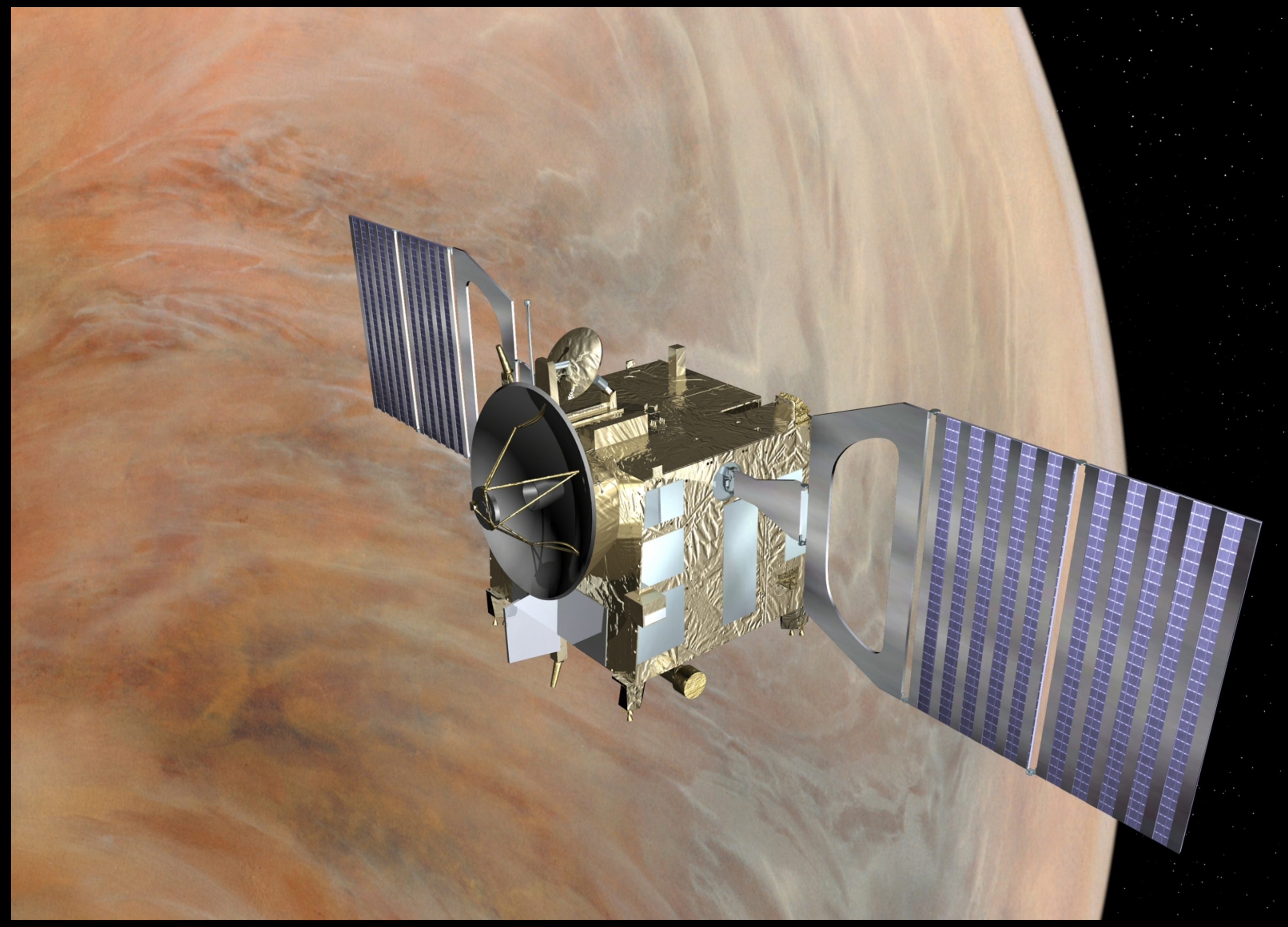
C. Interplay with the solar wind (a multi spacecraft analysis)

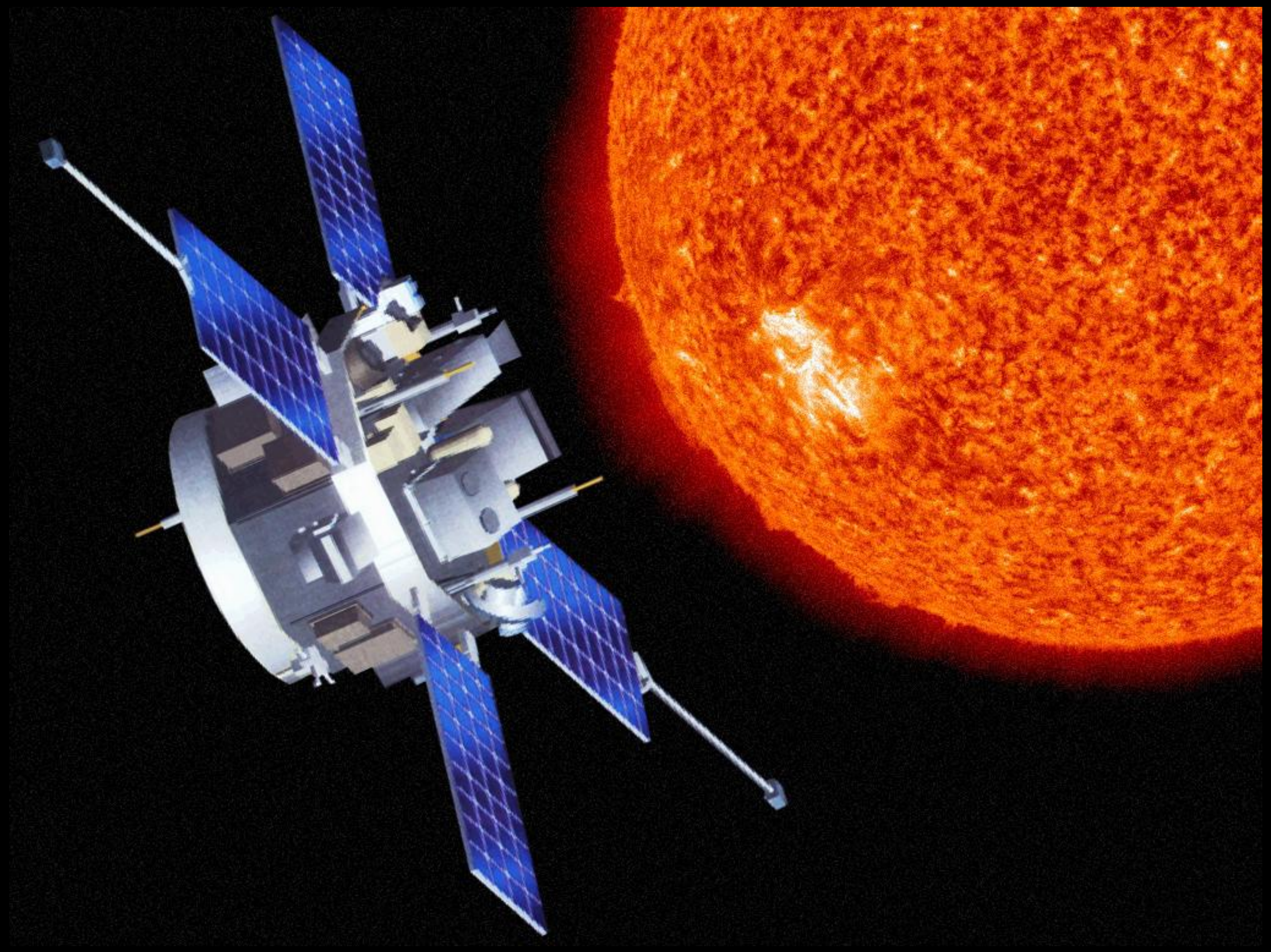
- Using planetary missions for multi-vantage point statistics



MESSENGER
ICME detections: from January 2009 till April 2015. 41 clean ICMEs

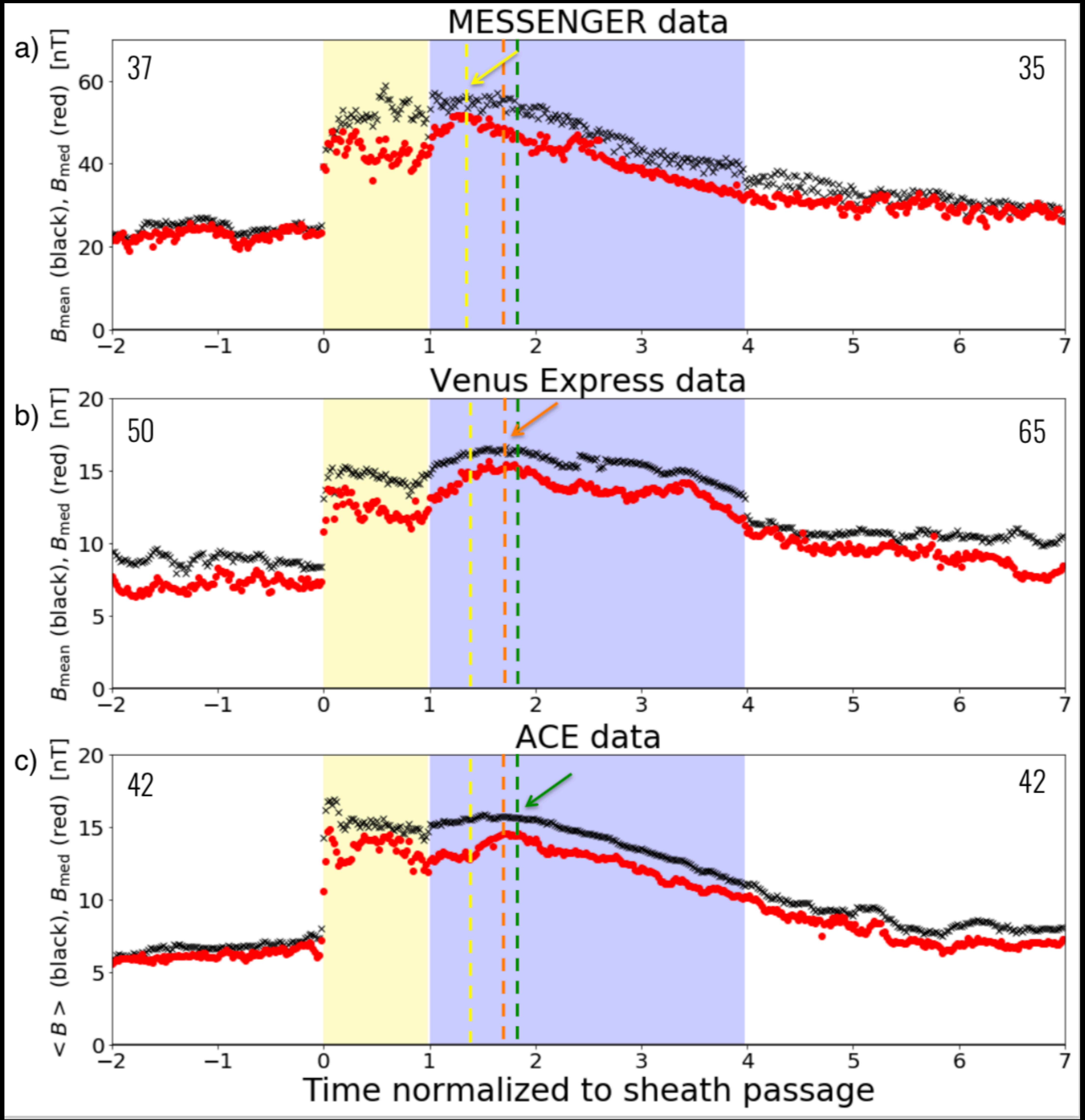
VENUS EXPRESS
ICME detections: from July 2006 till December 2014. 67 clean ICMEs



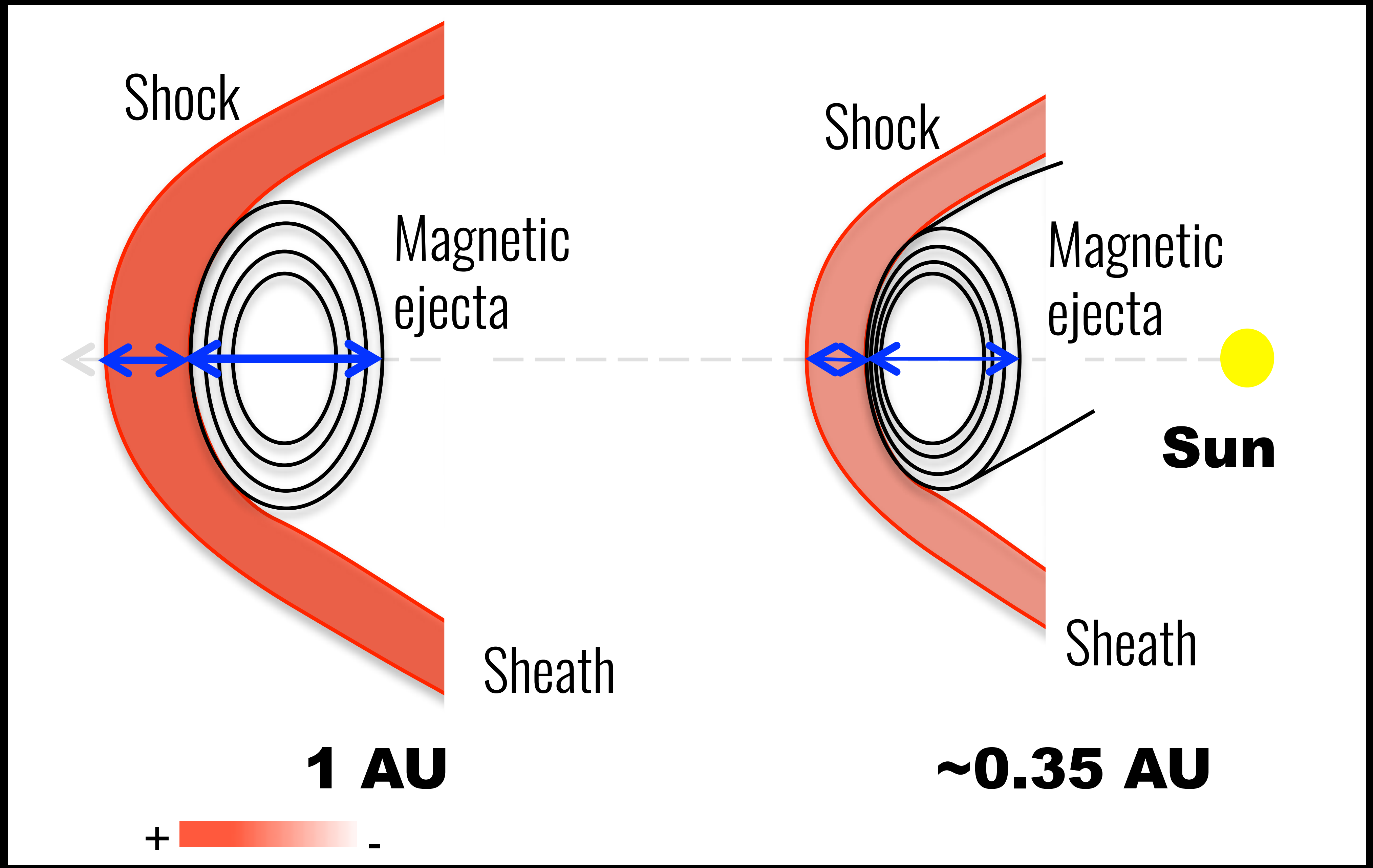


ACE
ICME detections: 20y of data. 44 clean ICMEs with a clear magnetic cloud.

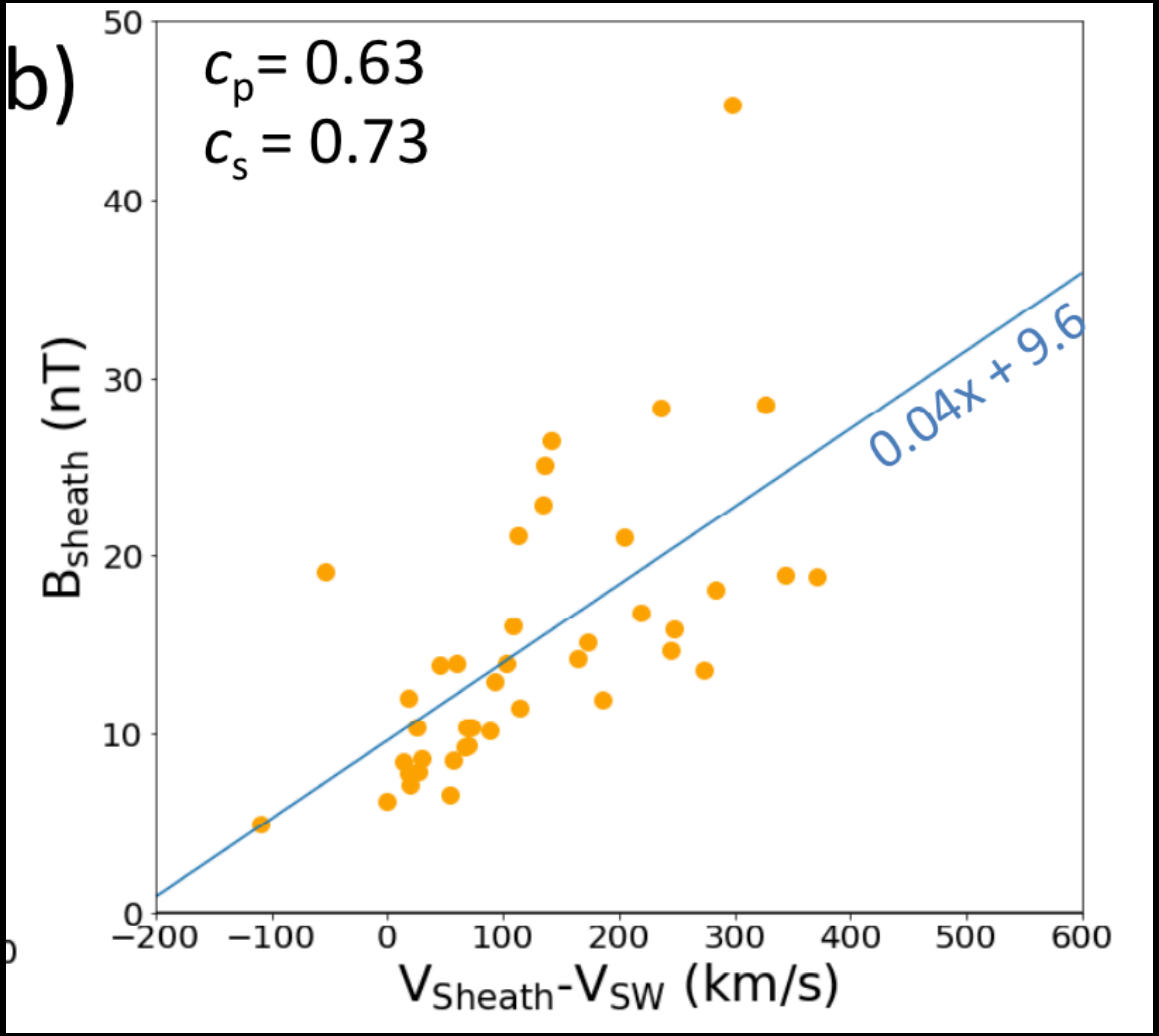
C. Interplay with the solar wind (a multi spacecraft analysis)



- Jump in sheath more important at 1 AU (sheath build-up)
- Thicker sheath + bigger ejecta at 1 AU (sheath build-up + expansion)
- Asymmetry more pronounced at Mercury



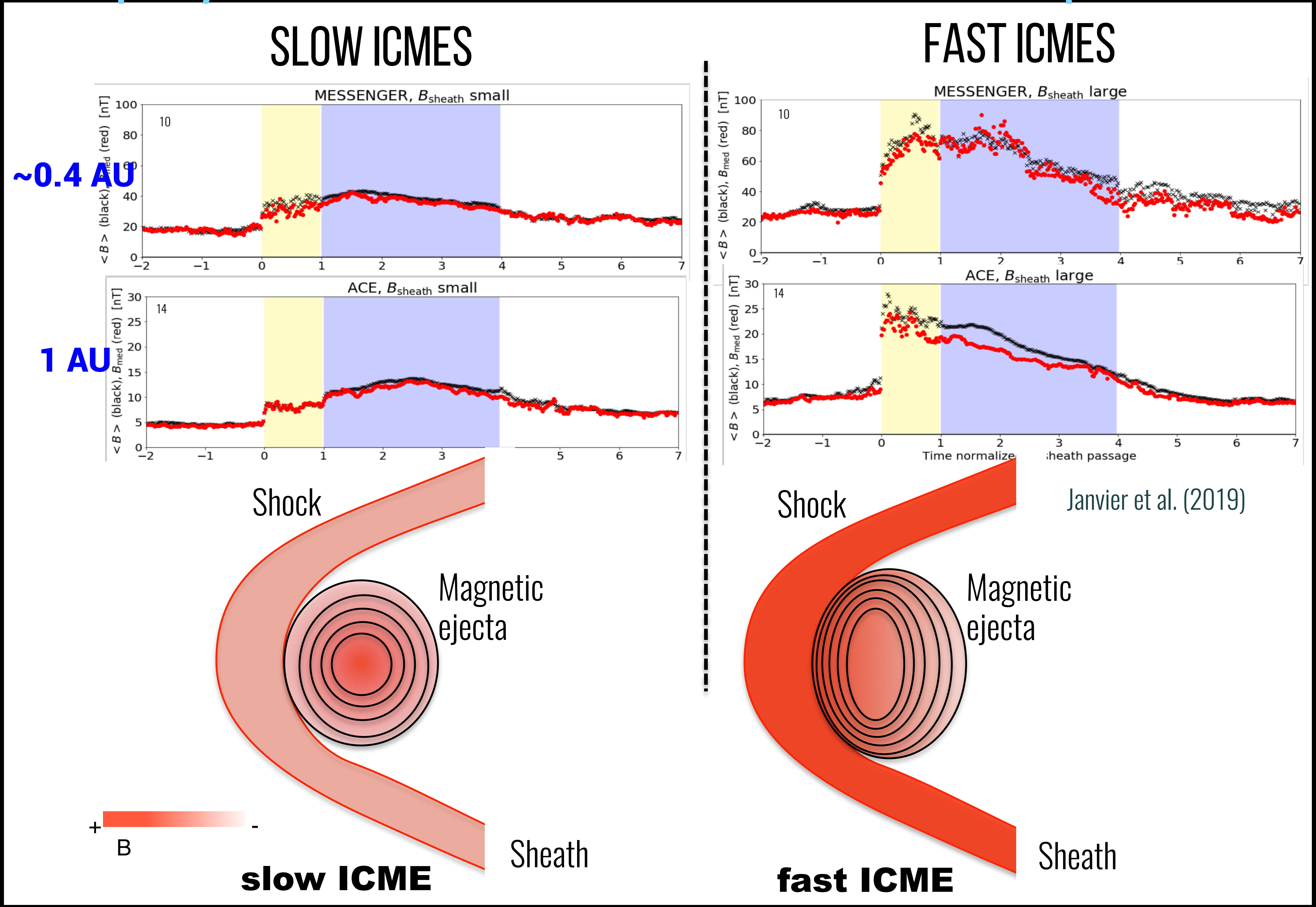
C. Interplay with the solar wind (a multi spacecraft analysis)



ACE data (at L1)
Found a correlation between magnetic field intensity in the sheath and the ICME speed

We can use the magnetic field as a proxy for the speed
(since we don't have the speed for MESSENGER and Venus Express)

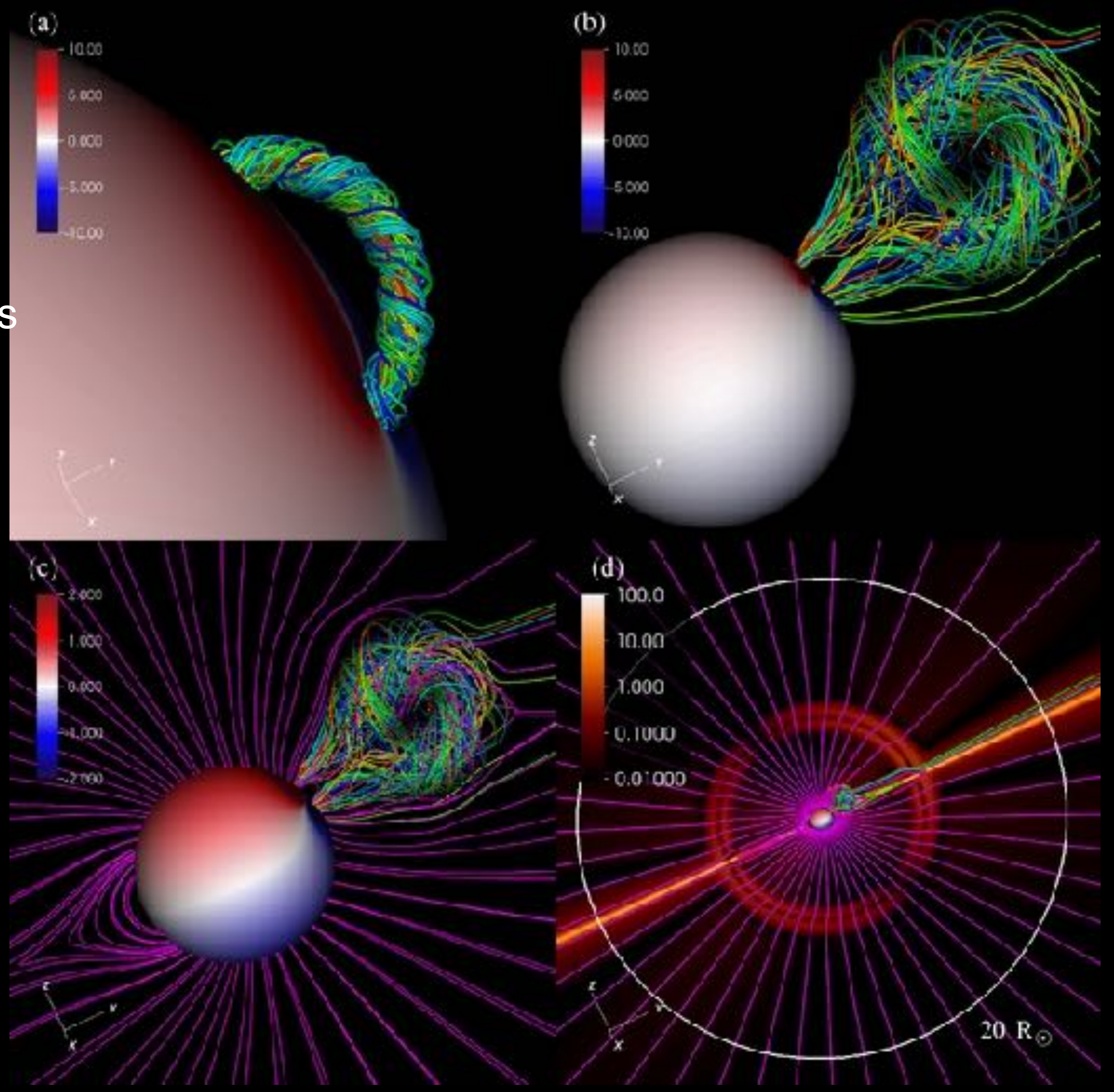
↳ C. Interplay with the solar wind (a multi spacecraft analysis)



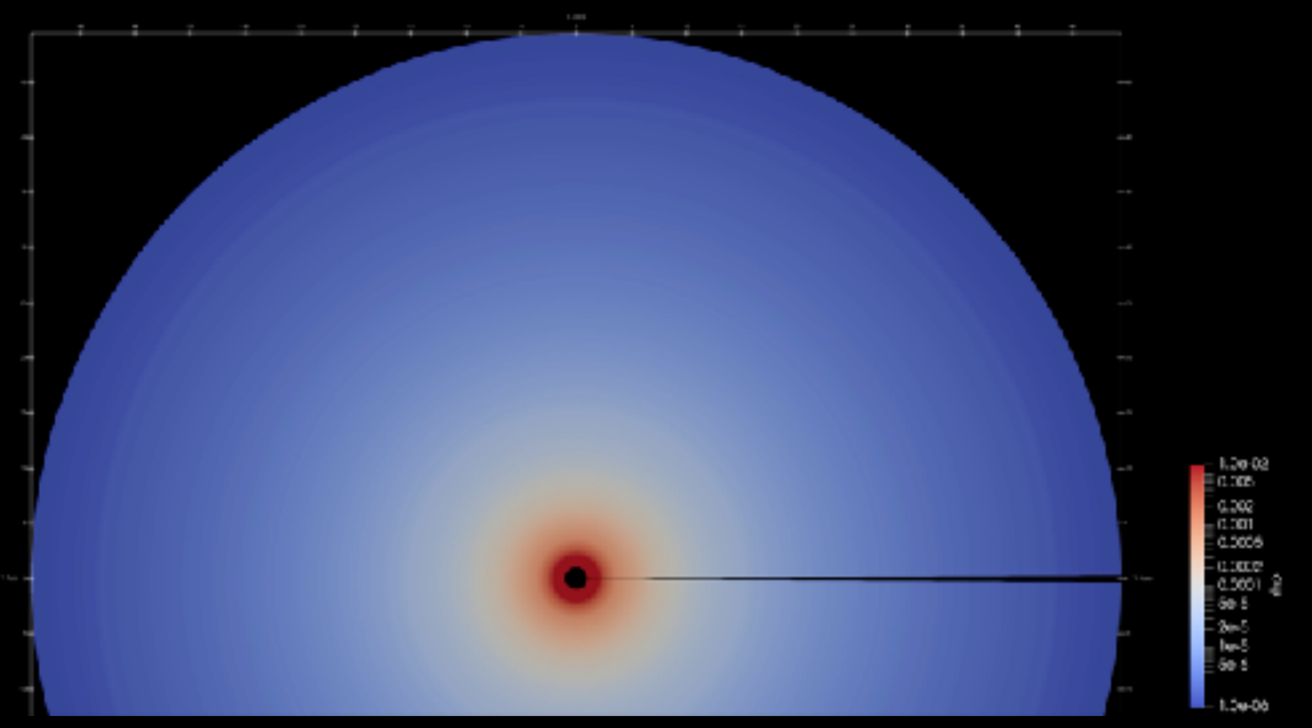
Janvier et al. (2019)

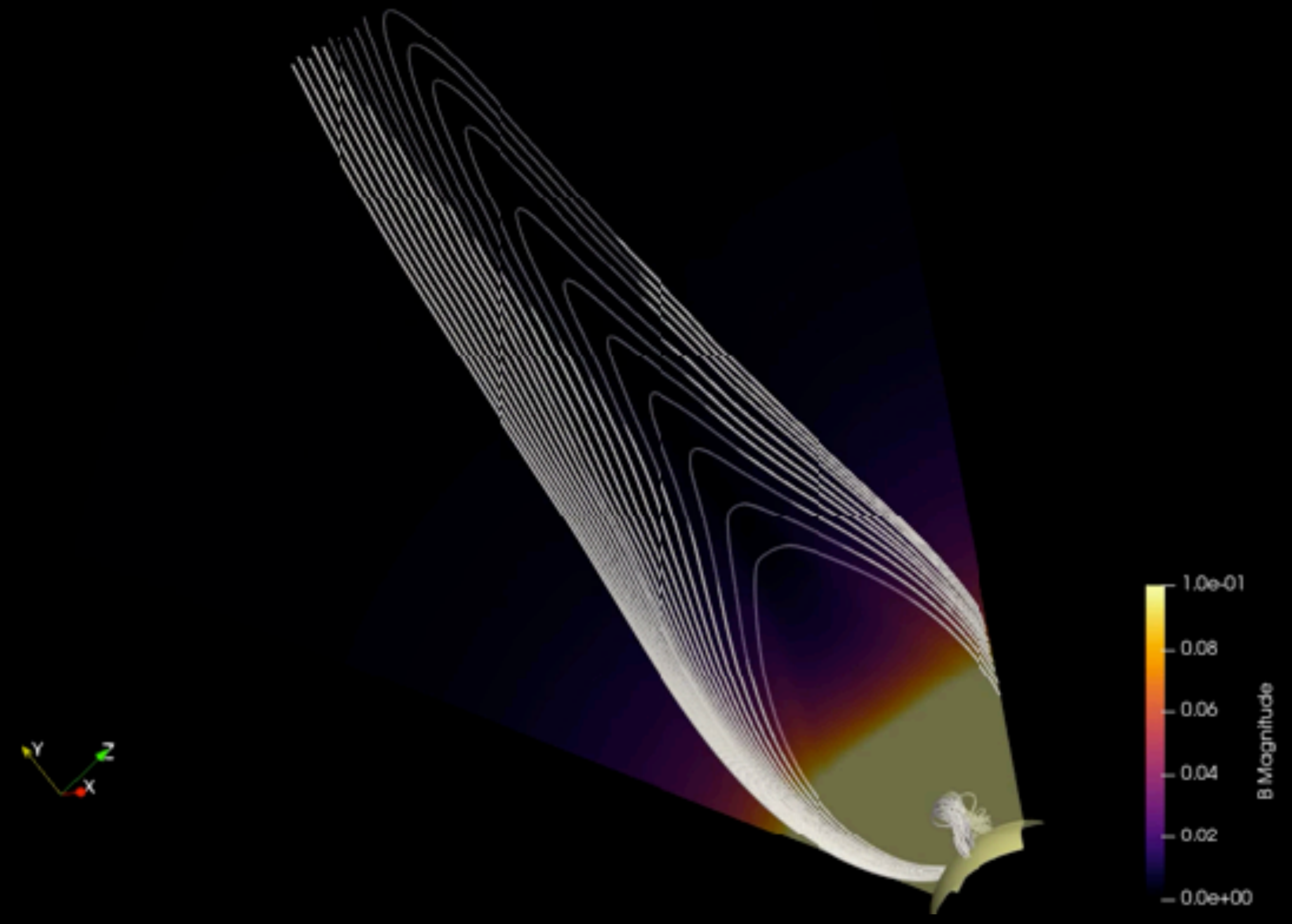
D. Towards a CME model?

PSI Group: Lionello et al, Downs et al, Torok et al, …
3D MHD model w/ Pluto
(Regnault 2022)



- Investigate interactions CME-Solar Wind (what mechanisms responsible for different profiles?)
- Cohesion of the magnetic field evolution
- Sheath + Shock evolution





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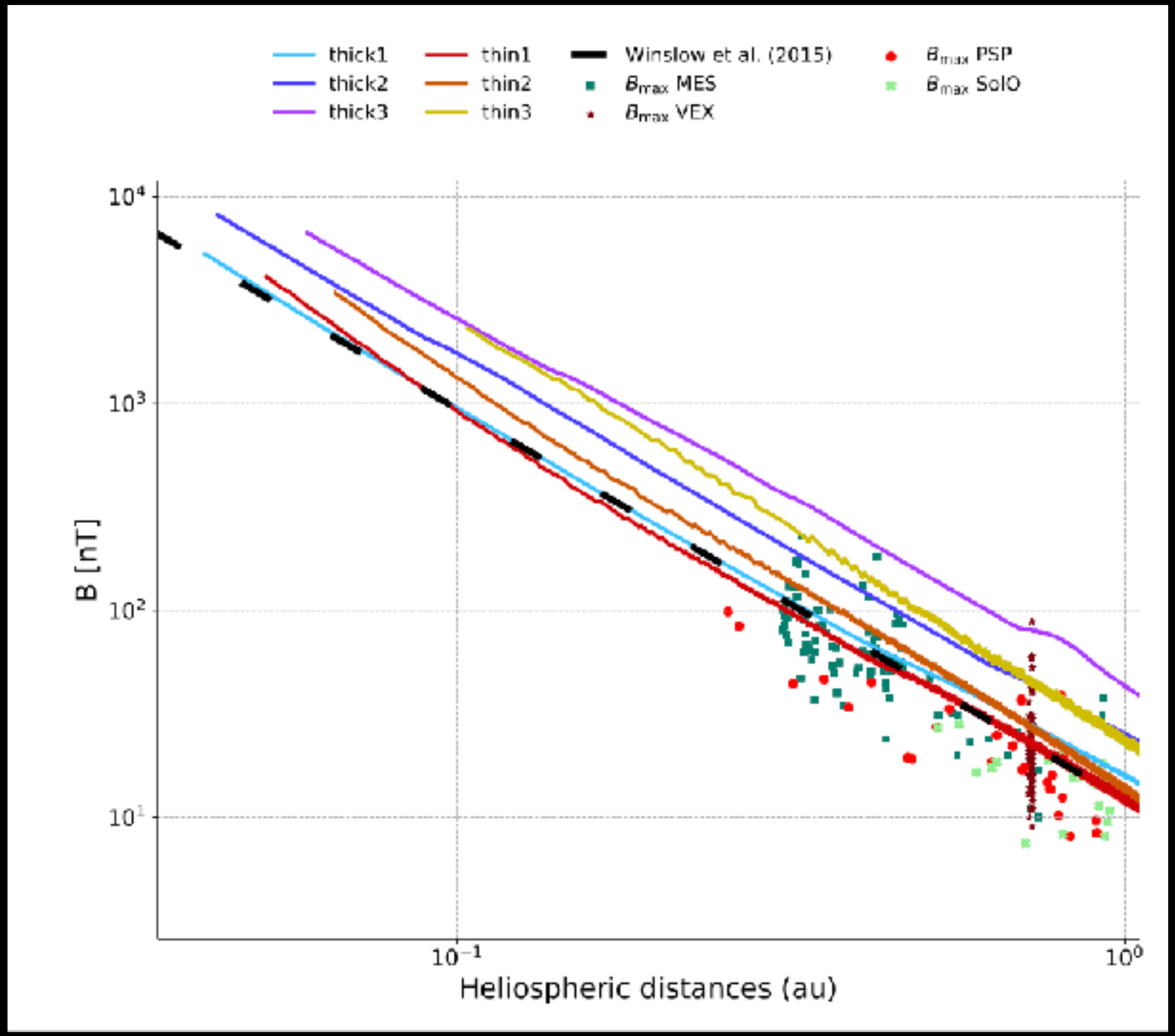
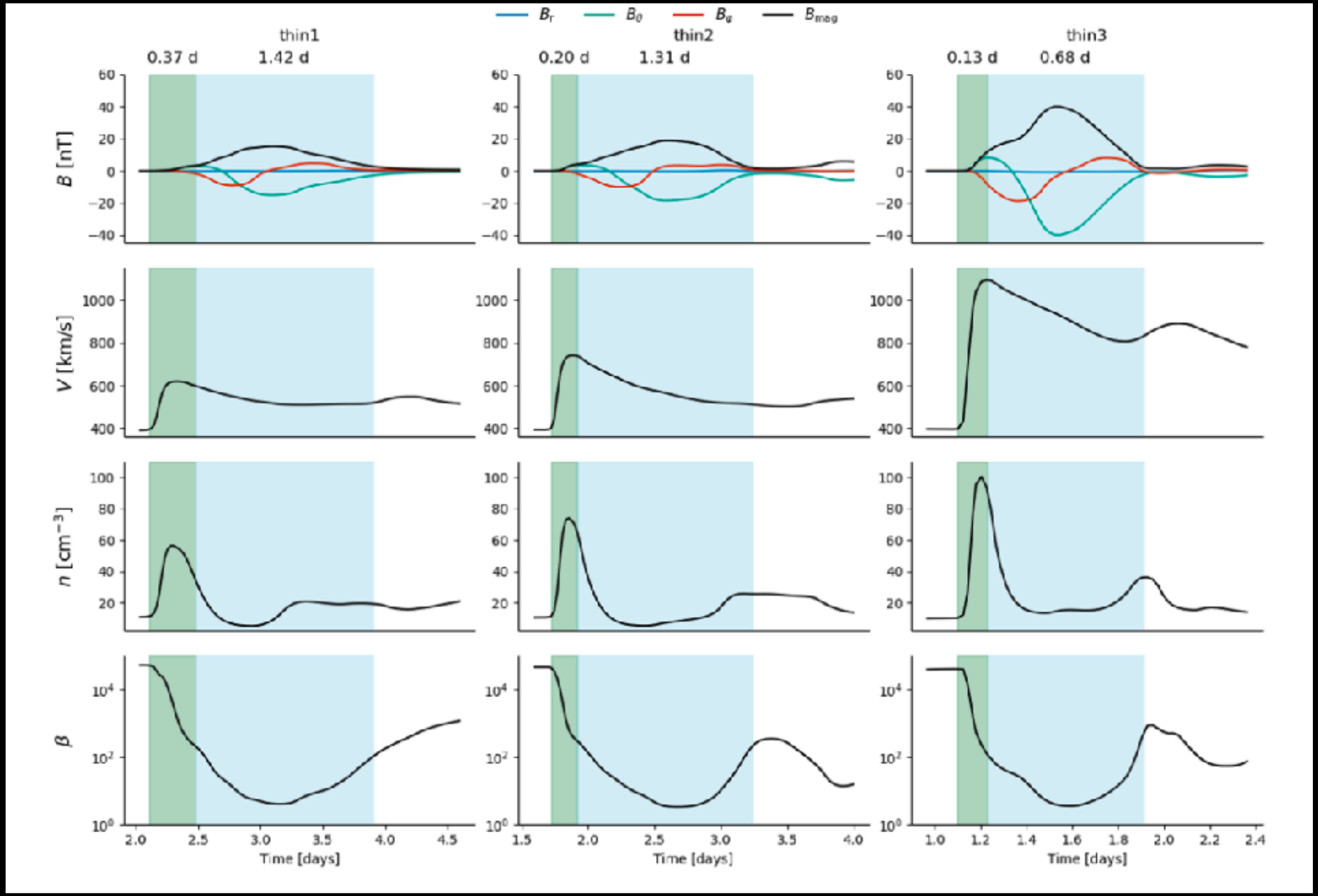
D. Towards a CME model?



Reproduces evolution of B field w/ distance

Different flux rope initiation configurations: different "strength" + speed



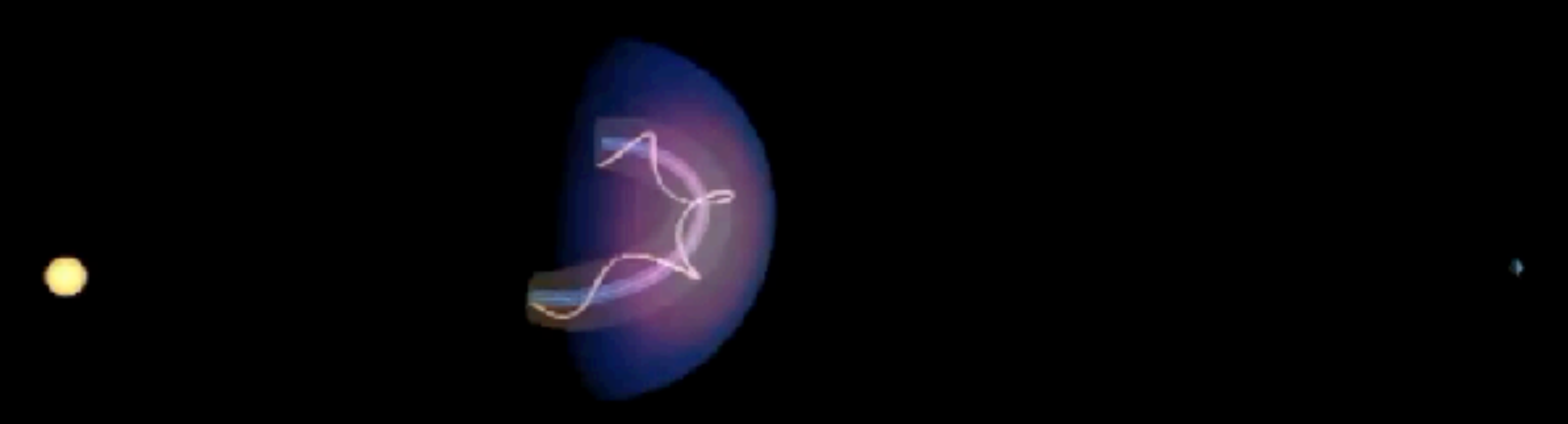
Synthetic observations: agreement w/ speed

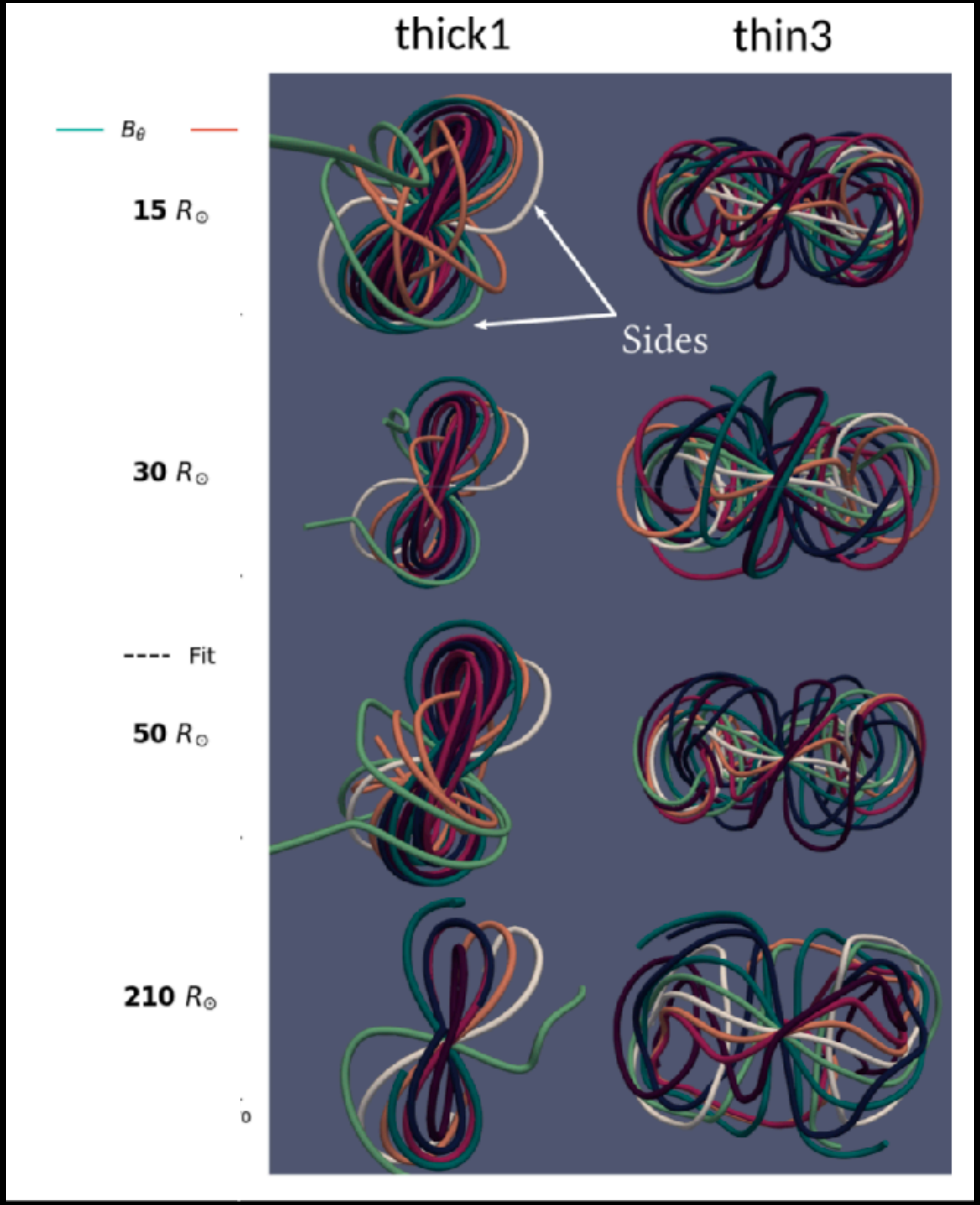
Chap 4

D. Towards a CME model?

But! All structures w/ small location angle (near the nose) + low impact parameter

Difficult to determine the 3D magnetic structure of an ICME because of the degeneracy of unique in situ profiles for each ICME.



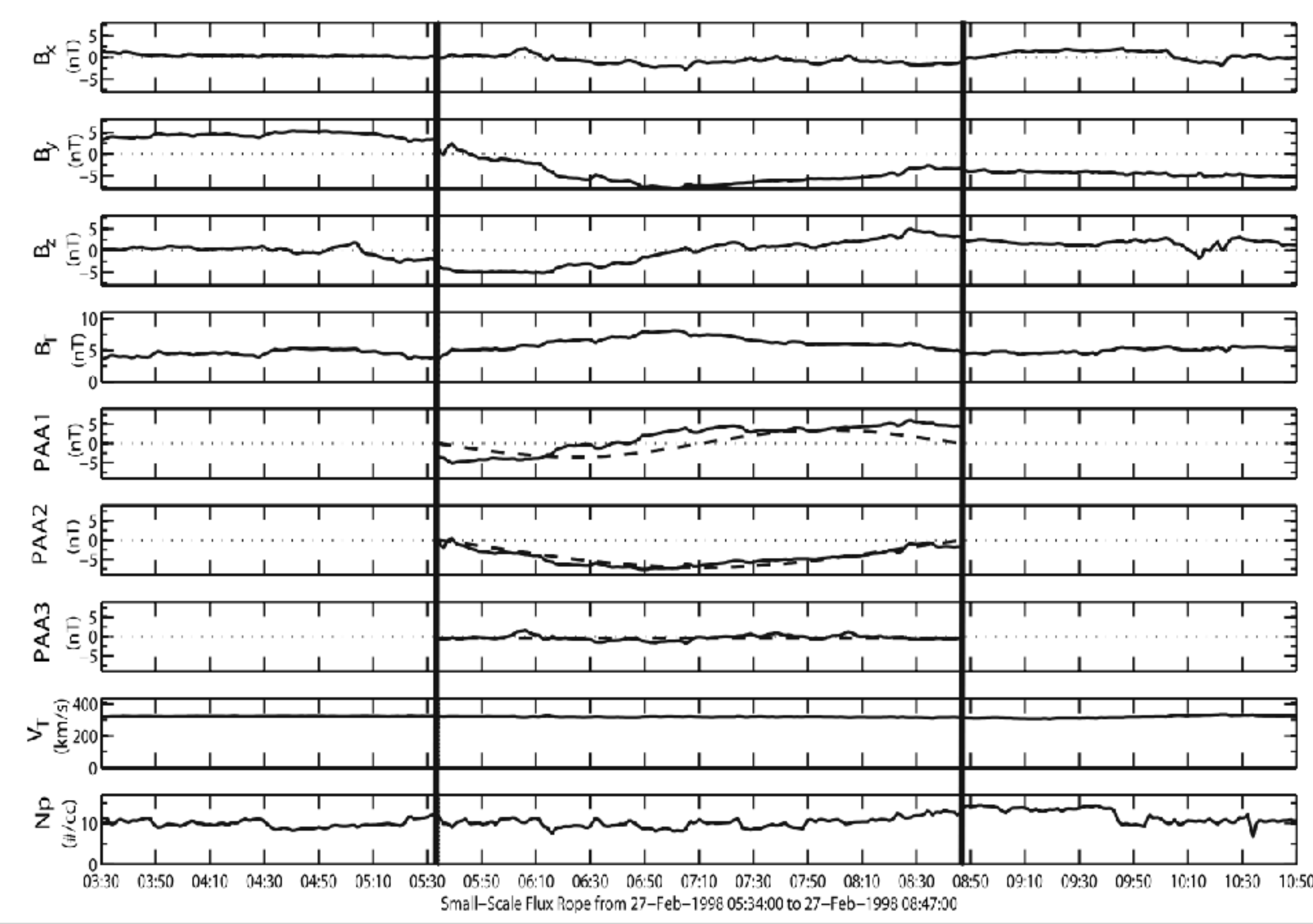


↳ E. Multi-scale flux ropes… and reconnection problem again!

Are small flux ropes (few minutes ~ few hours) = larger flux ropes (few hours ~ days, most generally ICME flux ropes) ?

- Similar speed (300 - 600 km/s)
- Sheath (not always)
- Signatures of magnetic reconnection (Tian et al. 2010, Lavraud et al. 2014)
- Same fitting models work (Feng et al. 2008, Lepping & Wu 2010)

Same same



Cartwright & Moldwin 2008: Example of a SFR of ~ a few hours

Chap 4

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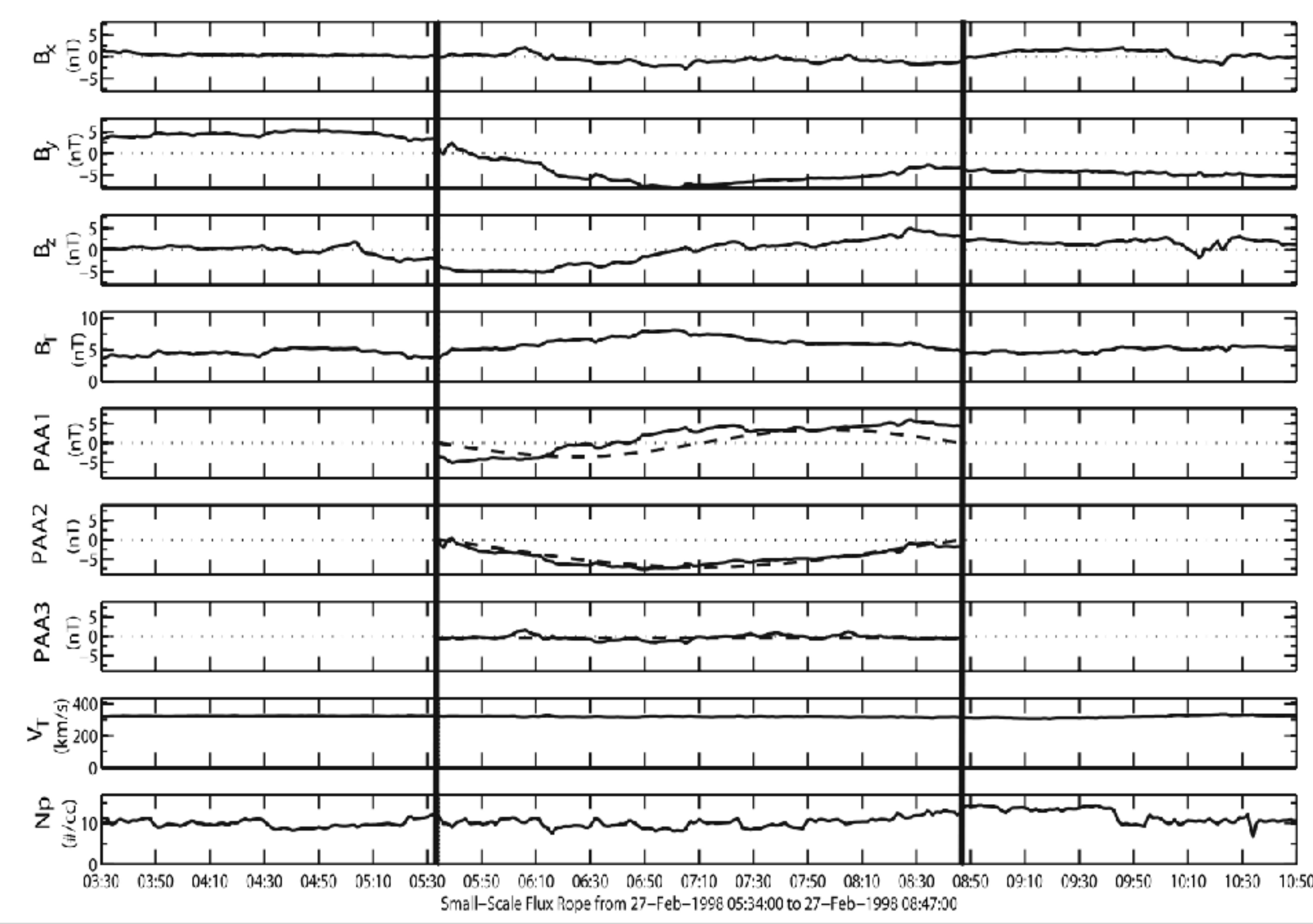
Same same

BUT

- Plasma beta (lower for MC)
- Proton temperature compared with the solar wind (lower for MC)
- Field strength (stronger for MC)
- Size distribution?

But different…



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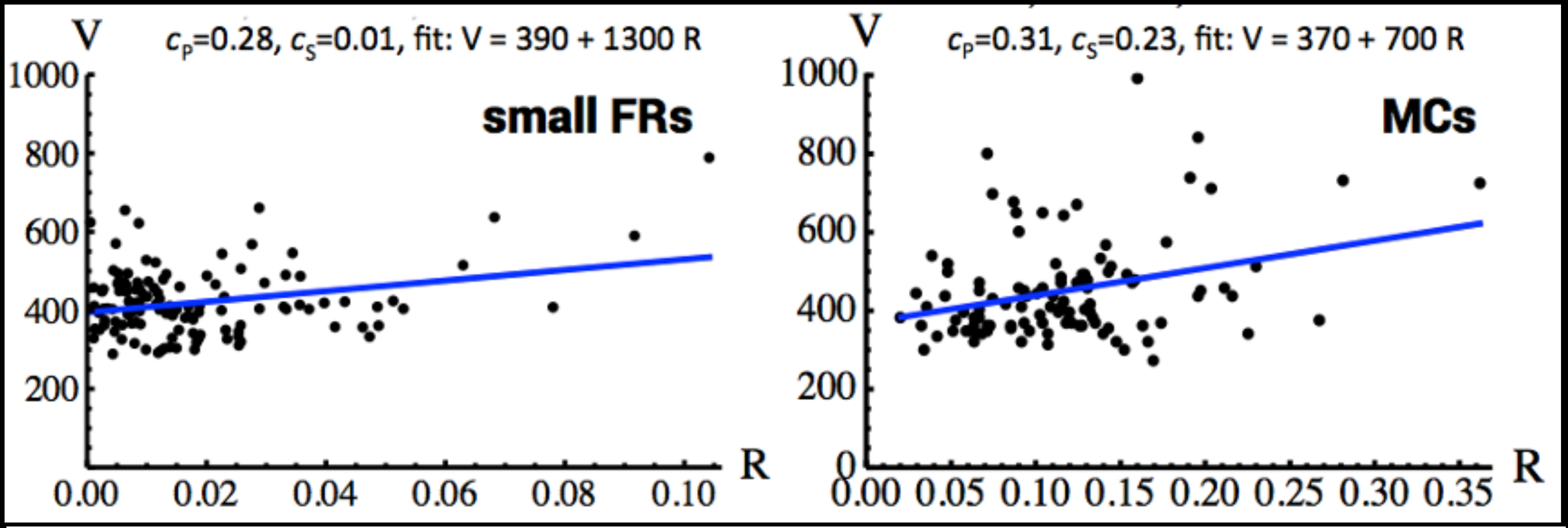
Results from a statistical analysis of several catalogues



Similar proportion of FRs with North-South or South-North B_Z

no cycle dependency

Similar correlations between flux rope parameters
(e.g. axial field strength w/ speed, radius)

Similar coronal ejection processes?

Similar distribution of location angle lambda = where we cross the FR

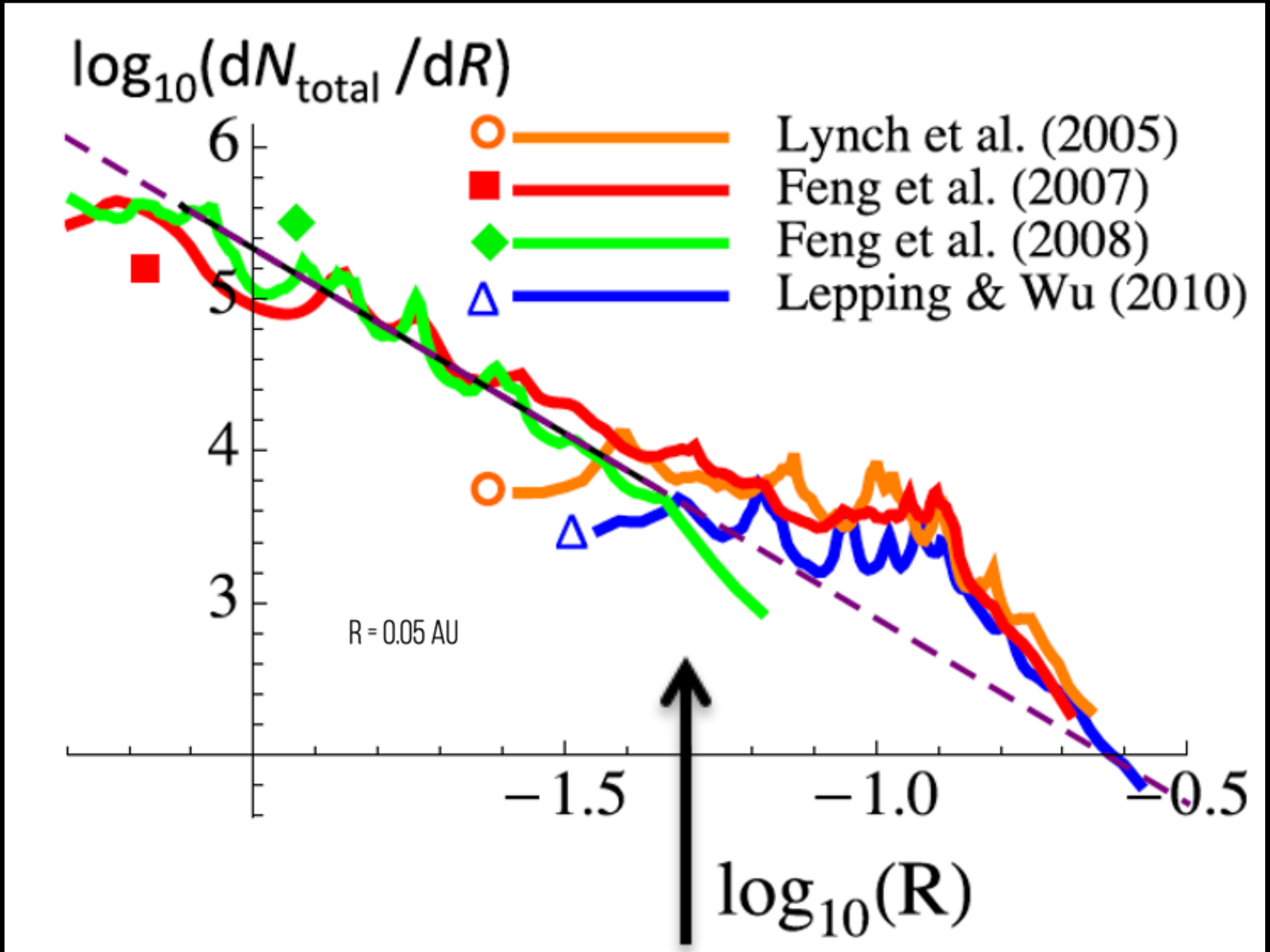
Janvier, Démoulin & Dasso (2014a, b)

E. Multi-scale flux ropes... and reconnection problem again!

Comparison of different flux ropes catalogues

Seems to be 2 interplanetary FR populations

But small flux ropes could come from the corona (e.g. blow-out jets? Reconnected flux leading to SFR?)



Small flux ropes with a power law

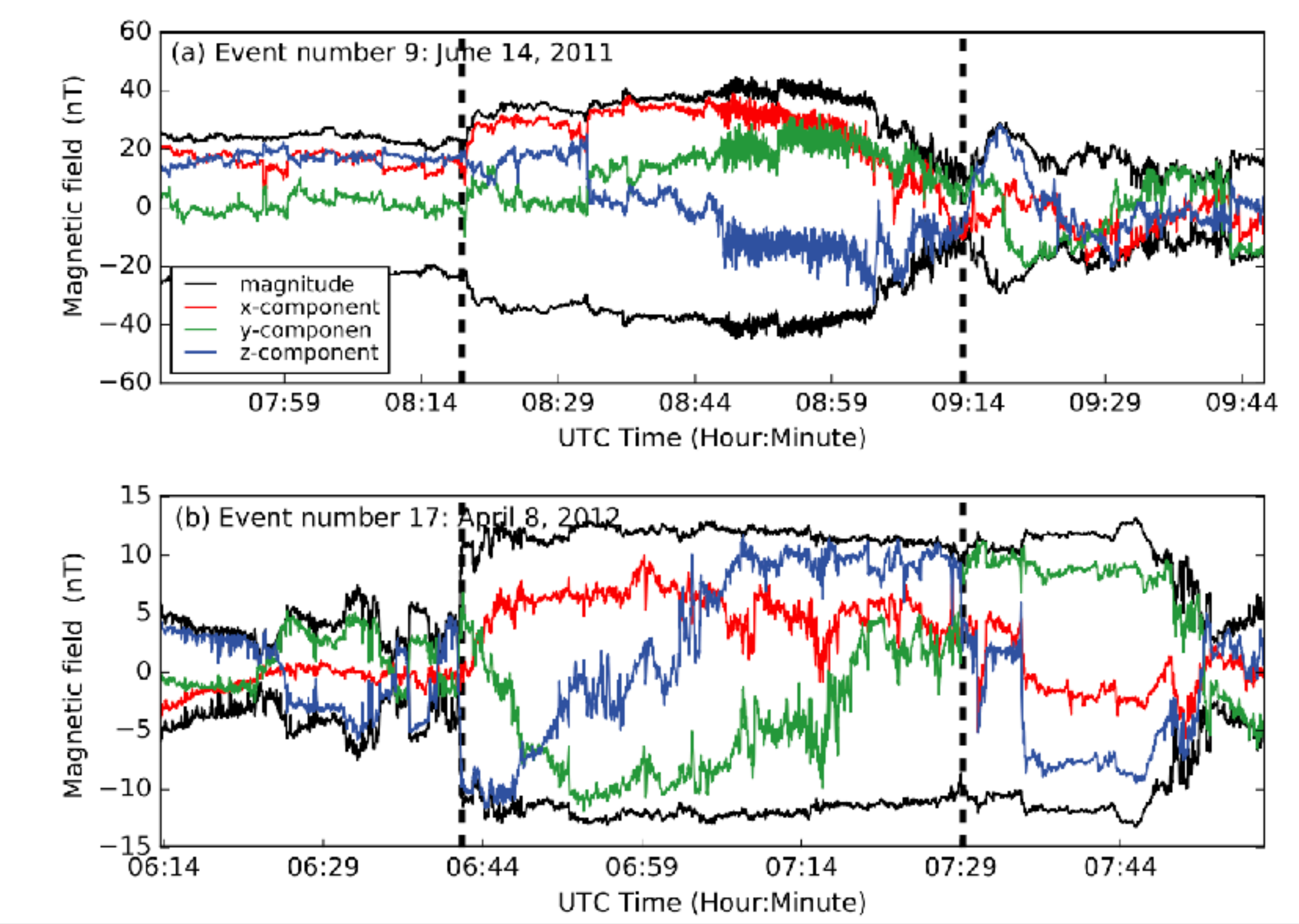
Magnetic clouds with a Gaussian distribution

Chap 4

↳ E. Multi-scale flux ropes… and reconnection problem again!

A Survey of Interplanetary Small Flux Ropes at Mercury

- SFRs observed at Mercury (MESSENGER data)
- SFR occurrence frequency is nearly 4x higher > 1au
- 2 SFR populations in data set:
  —> generation in a quasi-periodic formation process near the heliospheric current sheet (appear in clusters, short interval between them, near the HCS)
  —> the other formed away from the current sheet in isolated events (slightly bigger than the others)

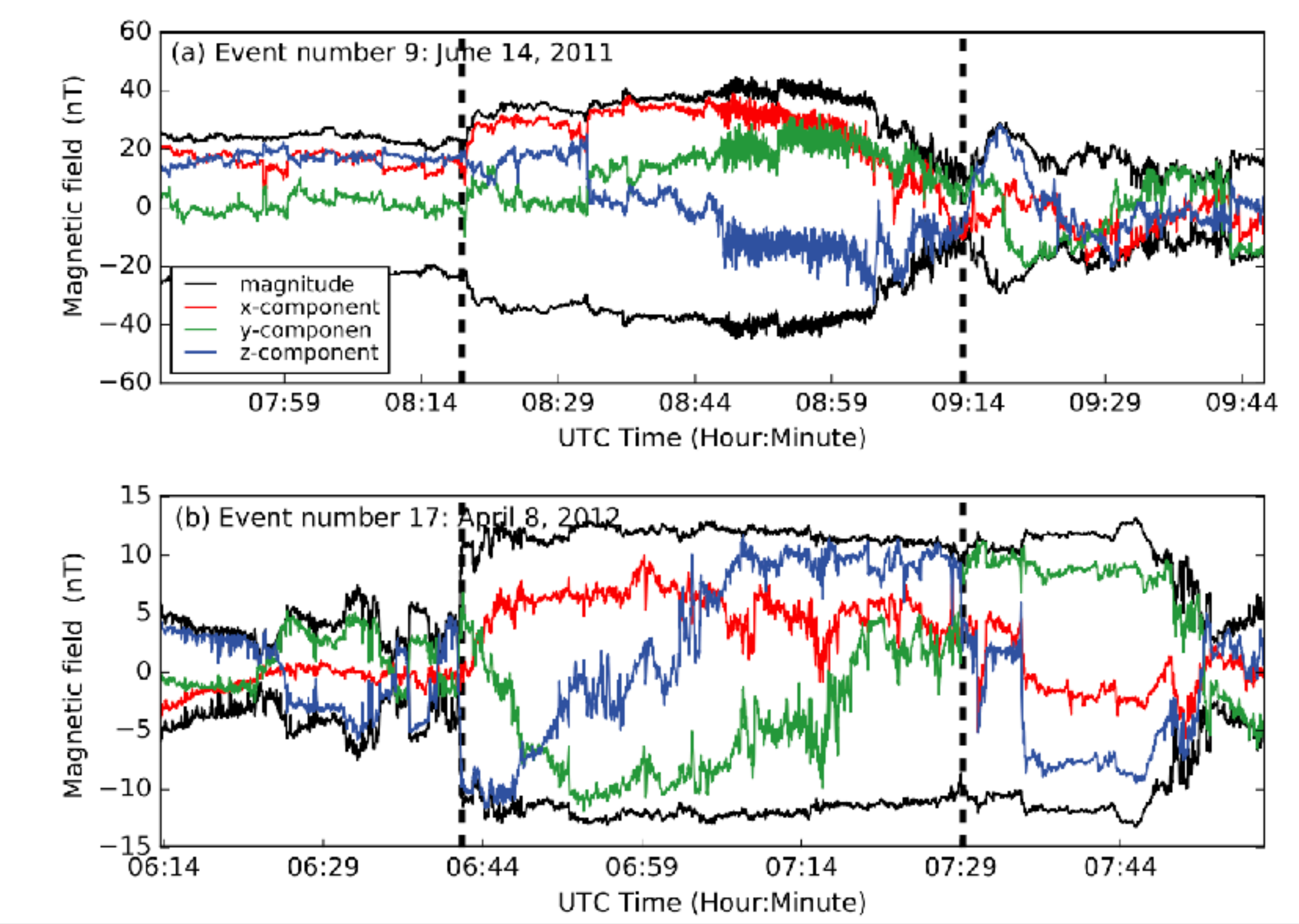


Murphy et al (2020)

↳ E. Multi-scale flux ropes... and reconnection problem again!

What are the possible formation processes?

- reconnection across the HCS (e.g. Moldwin et al. 2000)
- at the Sun w/ stream blobs (Sheeley et al. 2009)
- **periodic density structures (Viall et al. 2008)**



Murphy et al (2020)

Chap 4

↳ E. Multi-scale flux ropes… and reconnection problem again!

A possible connection to switchbacks?

Rapid polarity reversals of the radial heliospheric magnetic field, now routinely seen with Parker Solar Probe (but also Ulysses, Helios, ..)

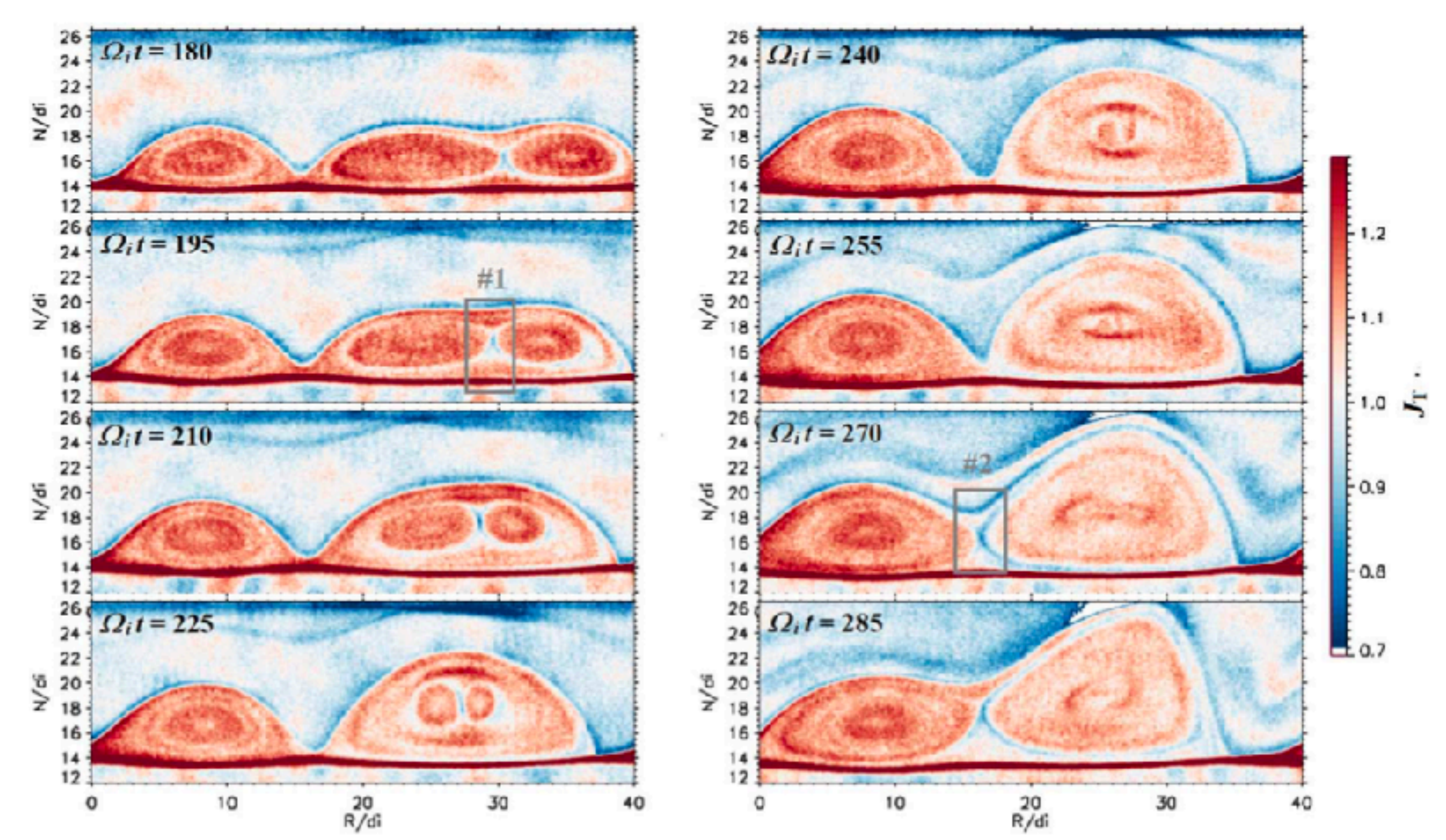


Figure 3. Dynamics of the FRs merging shown in the out-of-plane current J_T in the R–N plane.

Creation + merging of flux ropes at the (coronal base of the) HCS by interchange reconnection

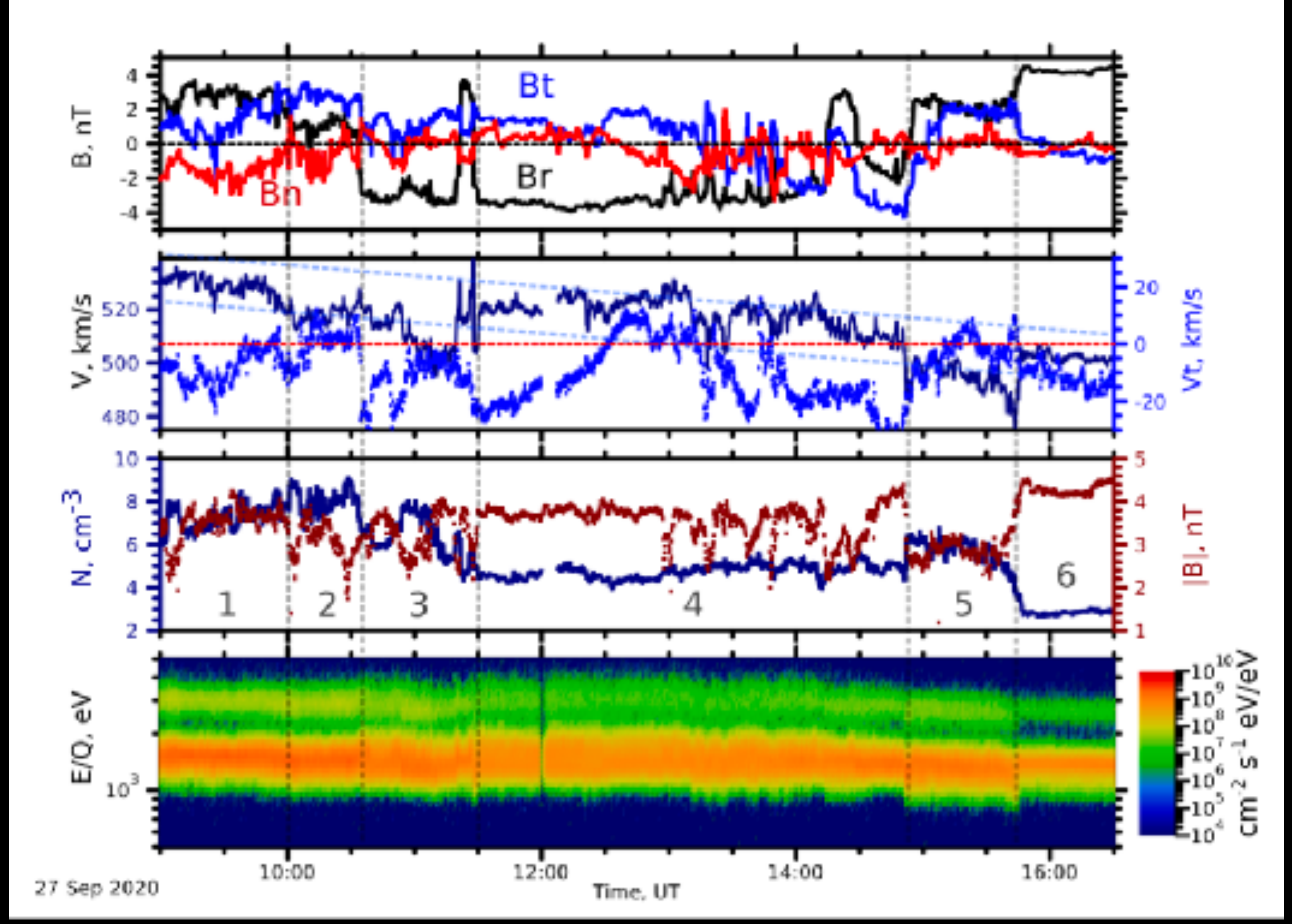
—> Would lead to coronal signatures of SFRs

See e.g. Réville et al. 2020, Drake et al. 2021, Agapitov et al. 2022,

Chap 4

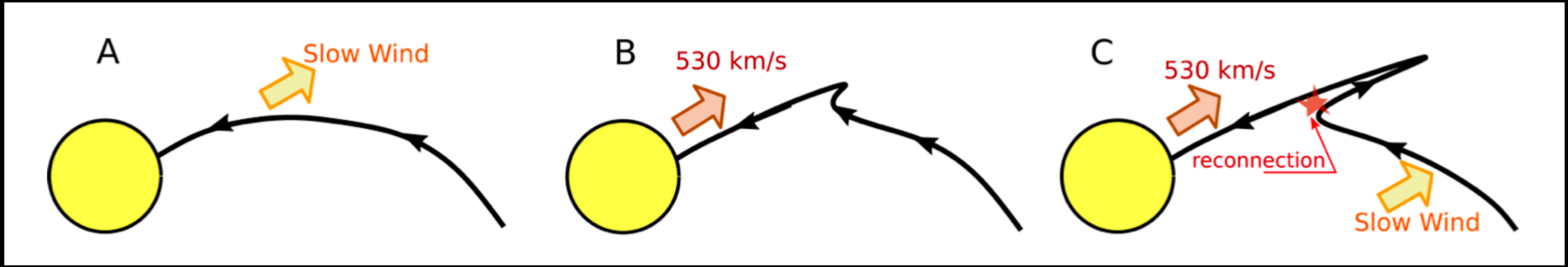
↳ E. Multi-scale flux ropes… and reconnection problem again!

A possible connection to switchbacks?



Rapid polarity reversals of the radial heliospheric magnetic field, now routinely seen with Parker Solar Probe (but also Ulysses, Helios, ..)

Structures seen in PSP as switchbacks most probably converted to a large flux rope and observed by Solar Orbiter

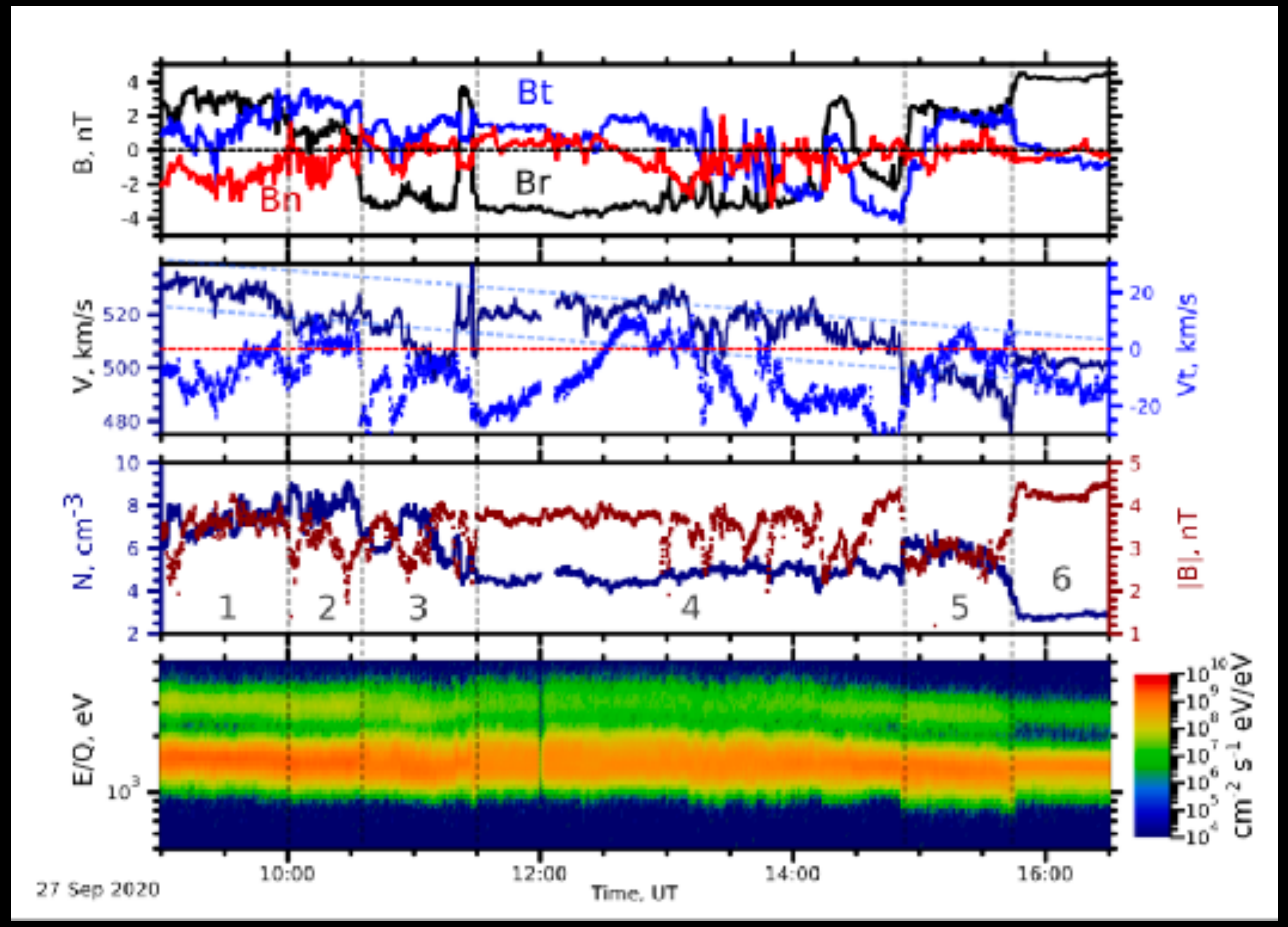


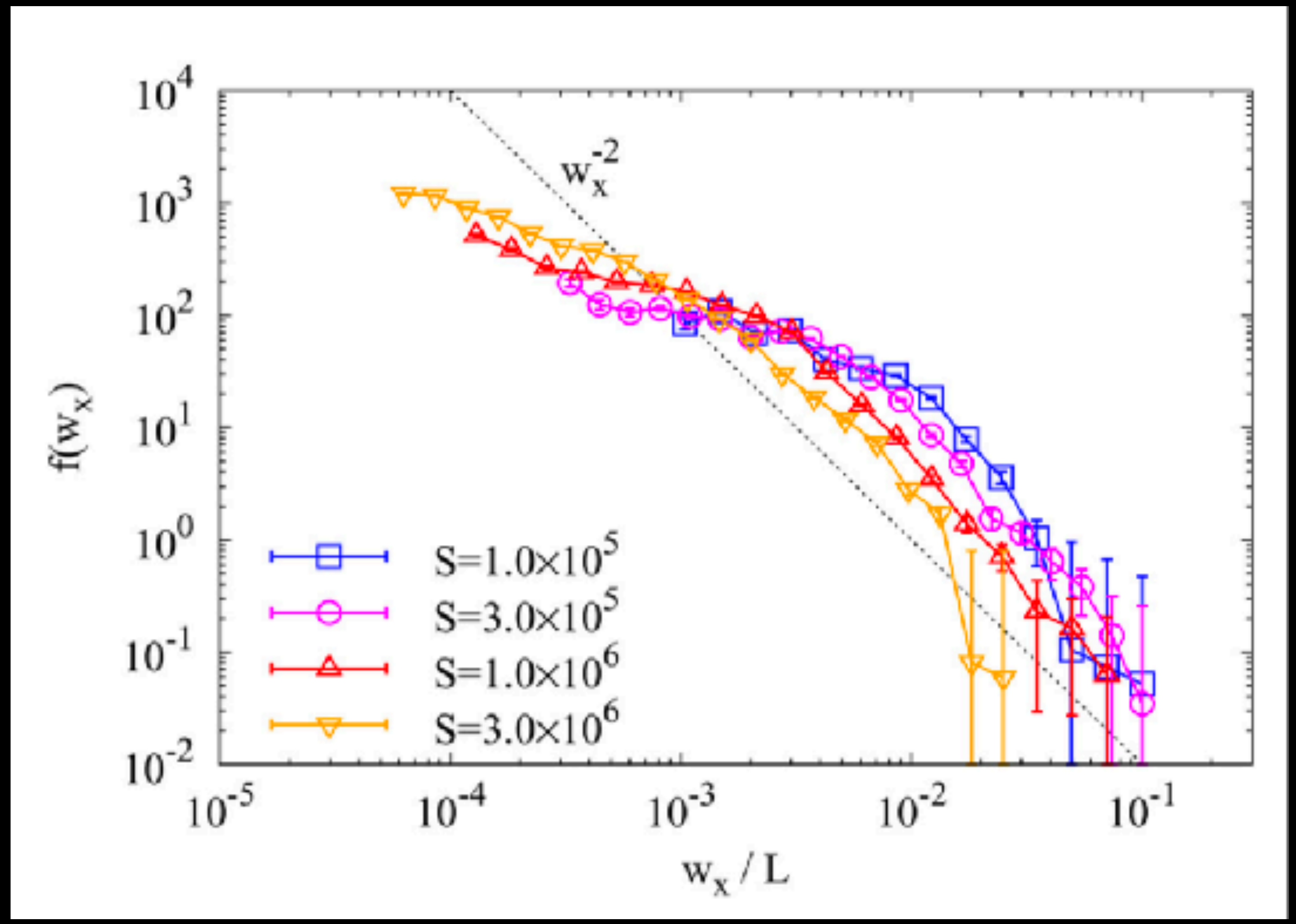
Fedorov et al (2021)

↳ E. Multi-scale flux ropes… and reconnection problem again!

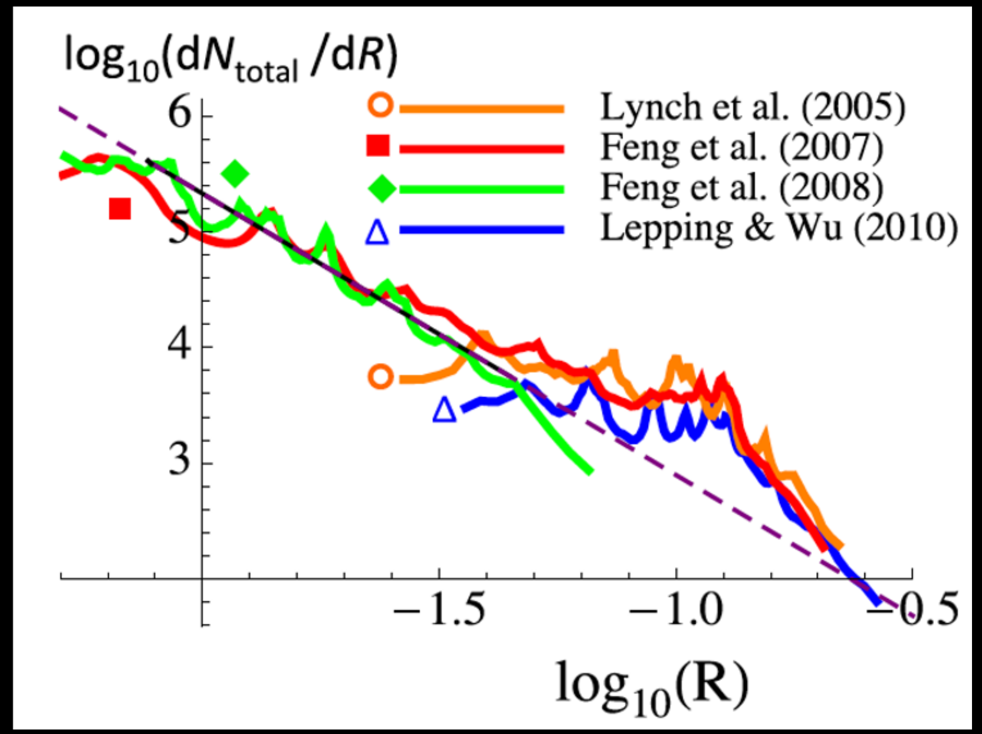
“Monster plasmoids” have been proposed in secondary tearing instability reconnection, with a power law…

Fedorov et al (2021)

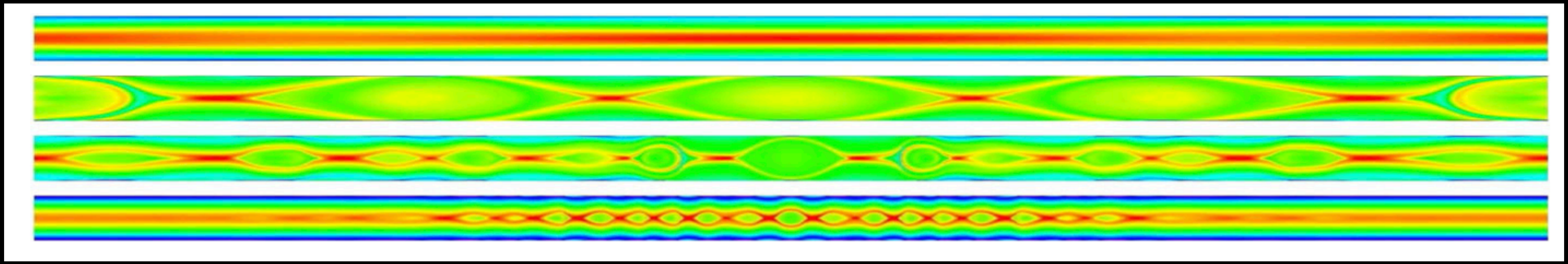




Loureiro et al (2012)



Janvier et al (2014)



Samtaney et al (2009)

Chapter 1: Observing the Sun's variability through the centuries

A. The Sun's variability through the naked eye
B. The Sun's variability through a (ground) telescope
C. The space telescopes era

Key idea: our understanding of the Sun has changed over time.. with variability since at every layer of the Sun's atmosphere.

Chapter 2: Flaring events, from observations to modelling

A. Anatomy of a flare
B. Eruptive vs confined flares
C. Phenomenology
D. Where does the flare energy come from?

Key idea: understanding the difference between flares and CMEs, and the fundamental structures where the flare energy is stored

Chapter 3: Understanding magnetic reconnection from small scales to large scales

A. Magnetic reconnection as a core mechanism
B. Magnetic reconnection without null points
C. Testing the hypothesis w/ observations
D. 3D model and unsolved problems

Key idea: understand the development of the standard flare model, its 3D extension, comparisons between models and observations

Chapter 4: CMEs in the solar wind

A. CME - ICME link
B. Statistics on properties
C. Interplay with the solar wind (a multi spacecraft analysis)
D. Towards a CME model?
E. Multi-scale flux ropes… and reconnection problem again!

Key idea: long and spatially diverse surveys of CMEs help understand their properties, but we lack datapoints + the role of reconnection in forming heliospheric flux ropes