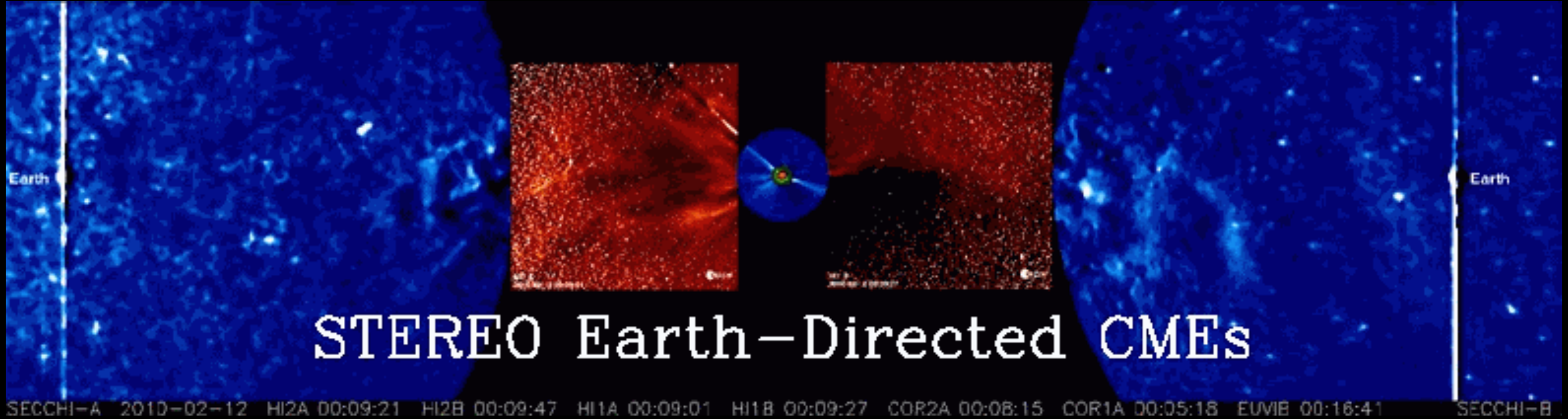




# 磁绳子和磁重联

— 日冕物质抛射的起源和早期演化

程鑫

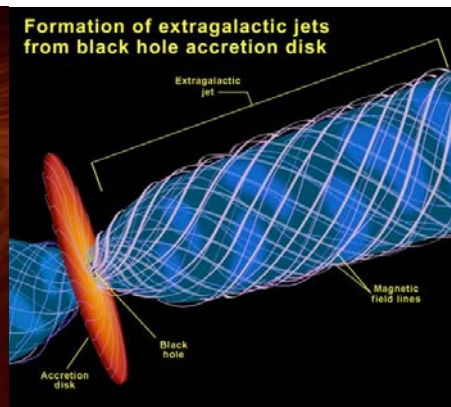
南京大学 天文与空间科学学院



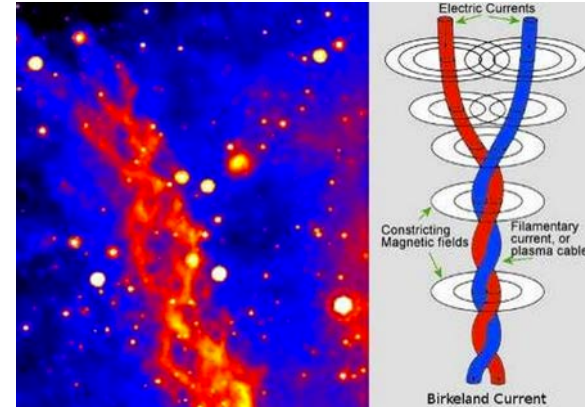


## 螺旋结构

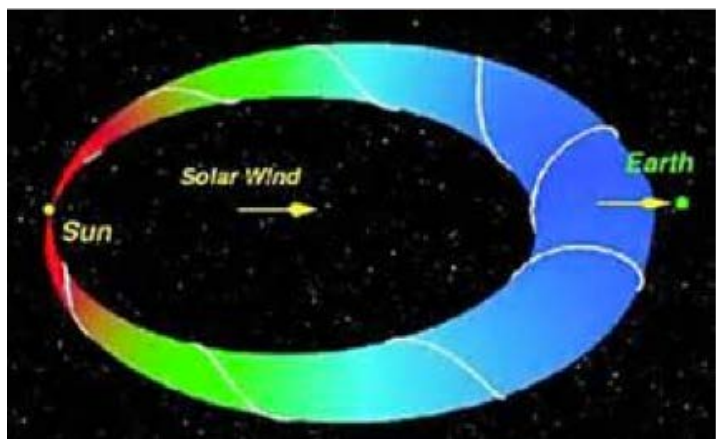
**磁绳：** 磁螺旋结构，其内部所以磁力线相互缠绕。  
普遍存在于我们宇宙空间!!



**Black hole**  
(Meier et al. 2001)



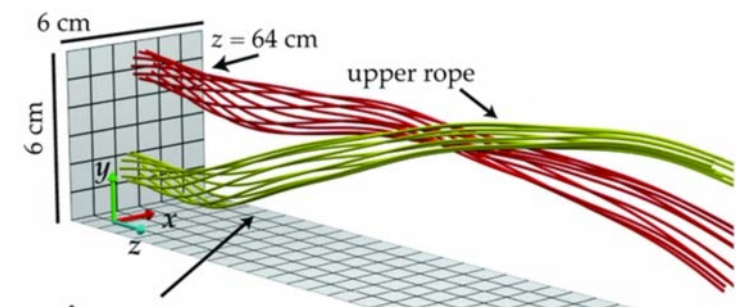
**Nebula**  
(Morris et al. 2006)

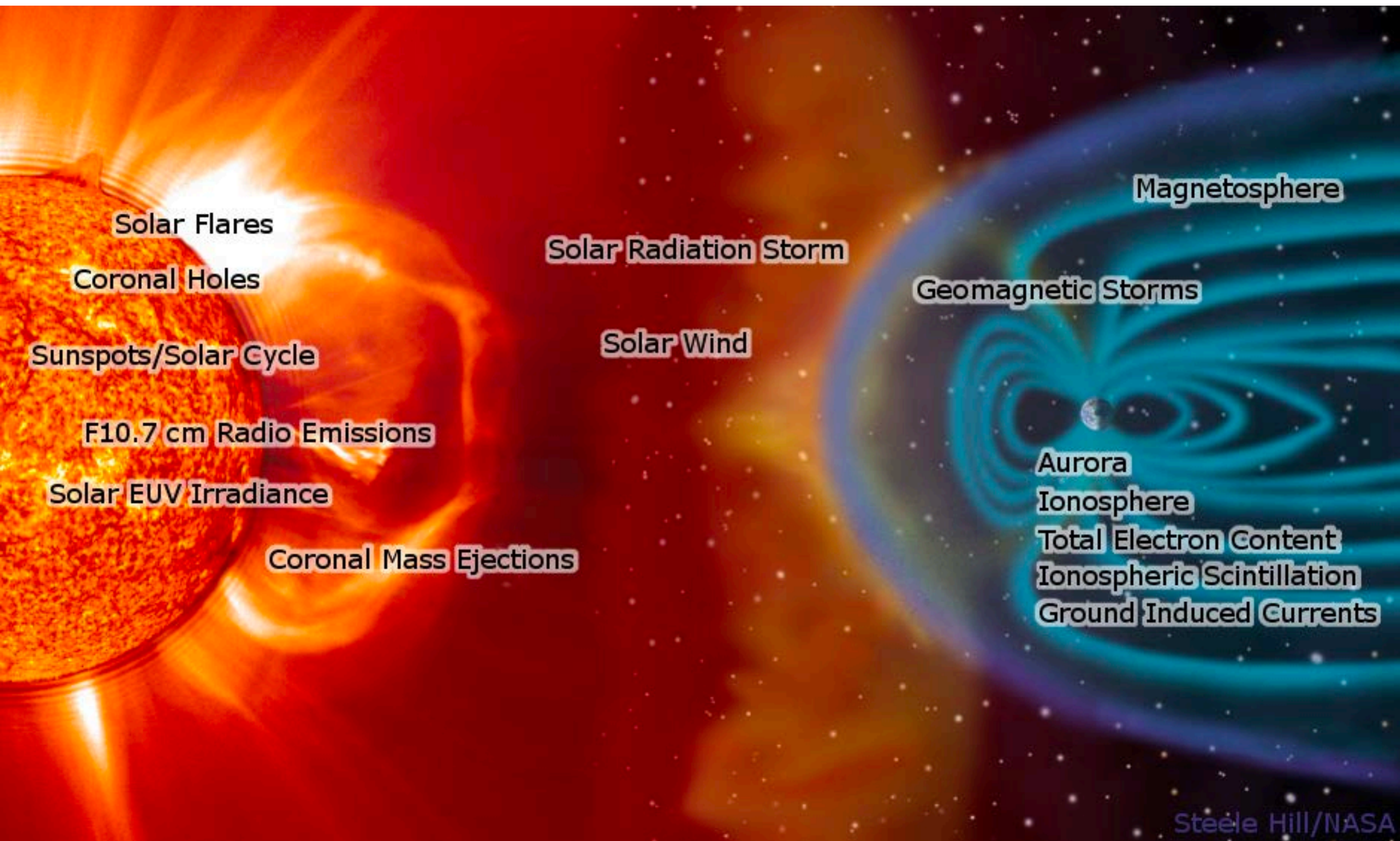


**Magnetopause**  
(Burlaga 1988)



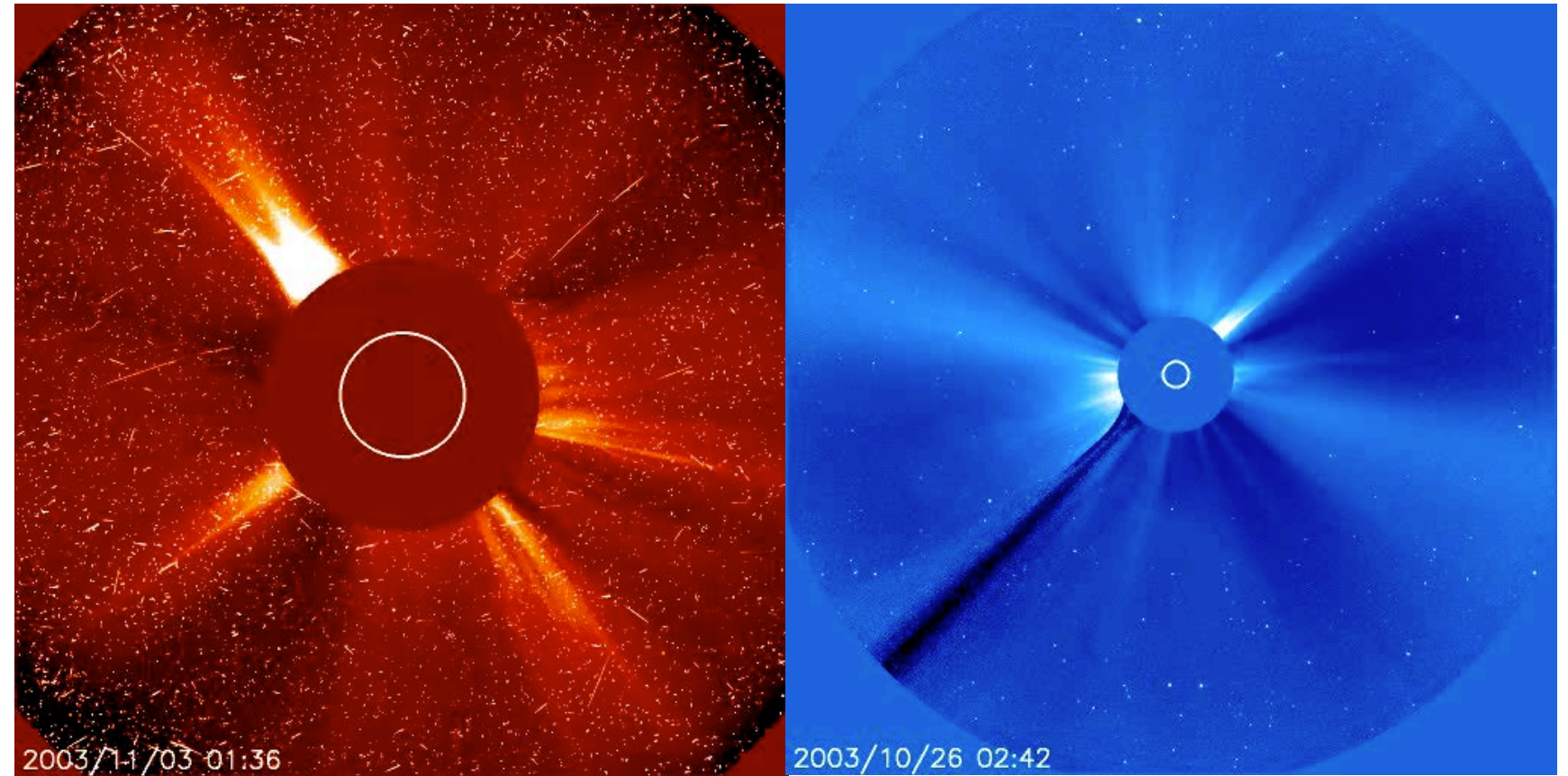
**Laboratory experiment** (Gekelman et al. 2012)



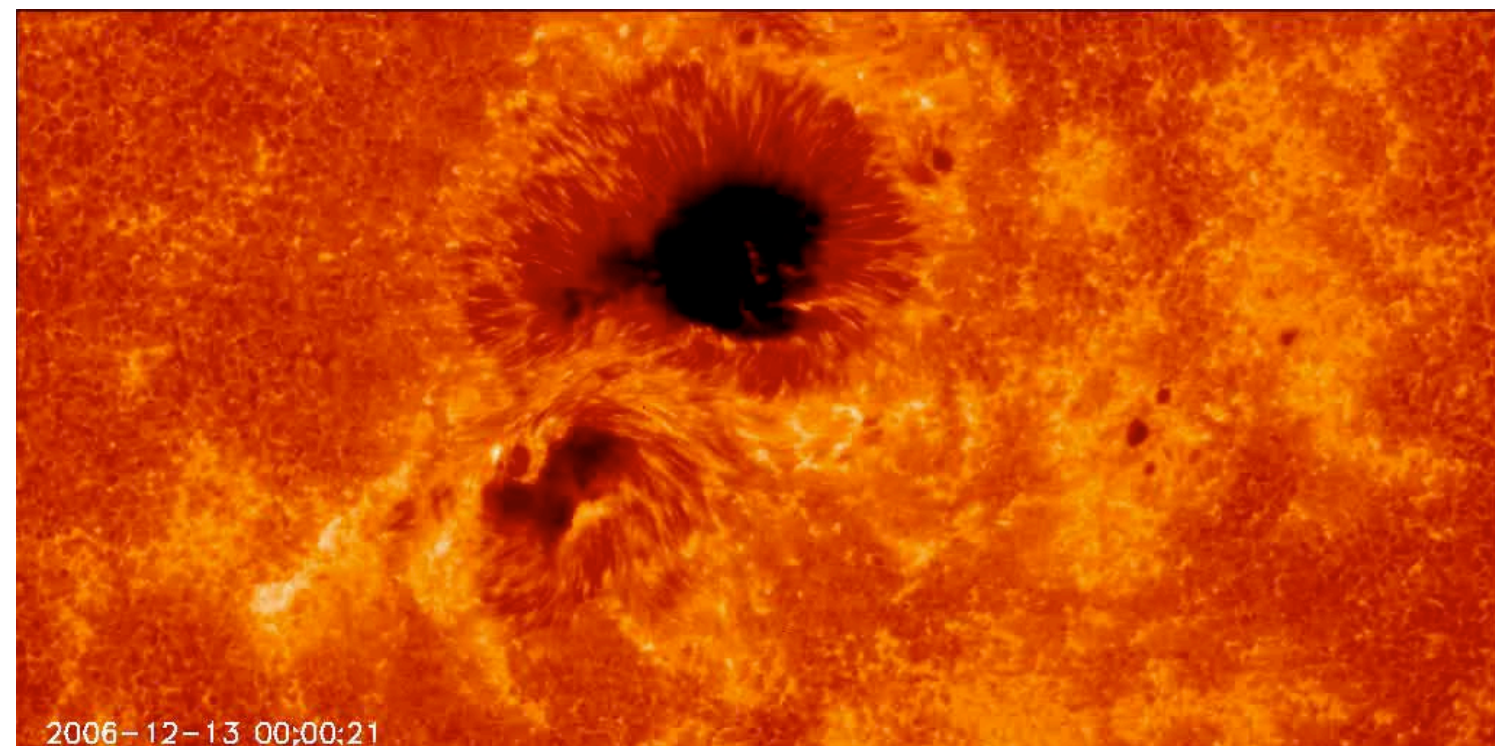


# 太阳系中两种最剧烈的爆发

日冕物质抛射  
Coronal Mass Ejections



太阳耀斑  
Solar Flares

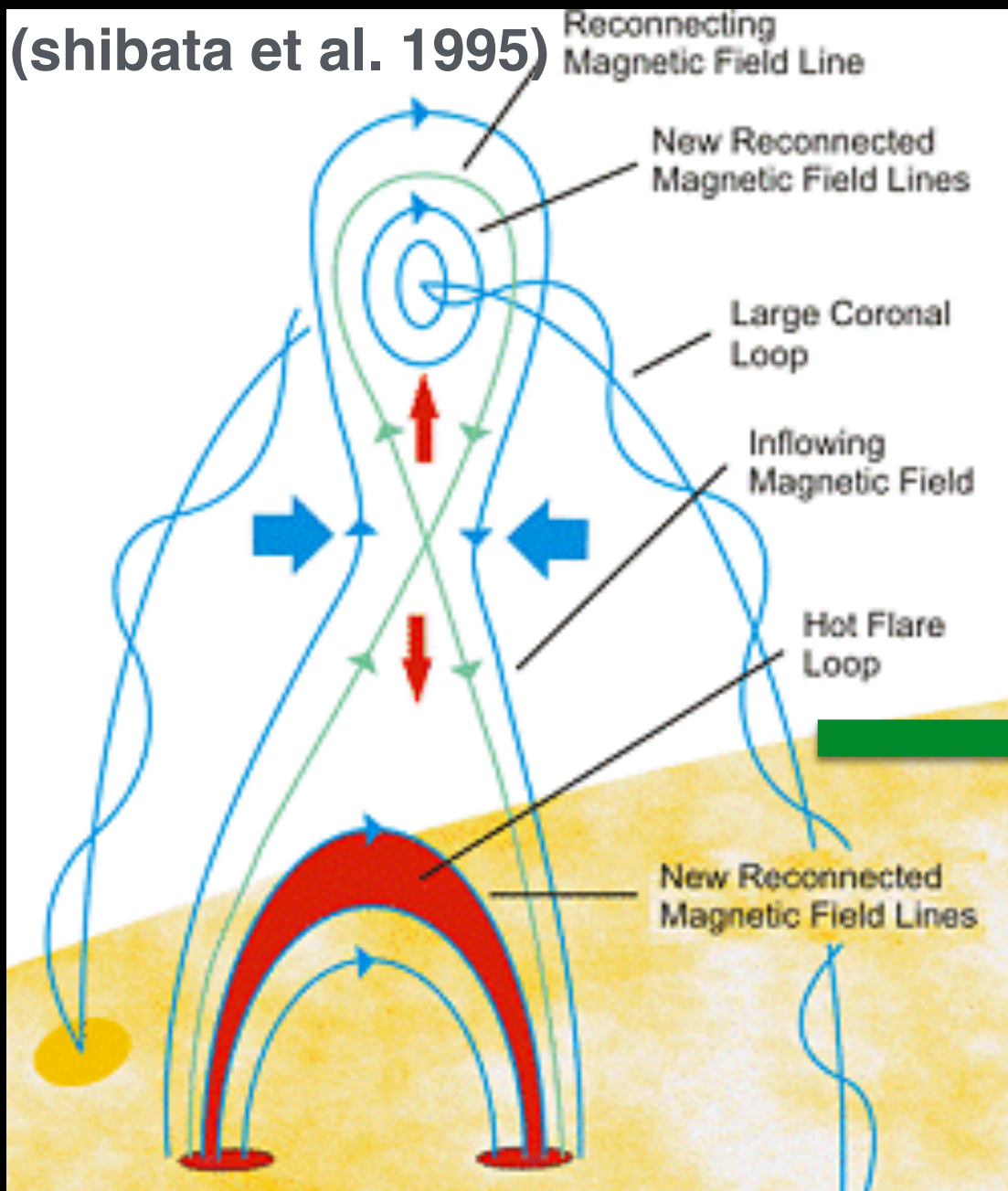


# 主要内容:

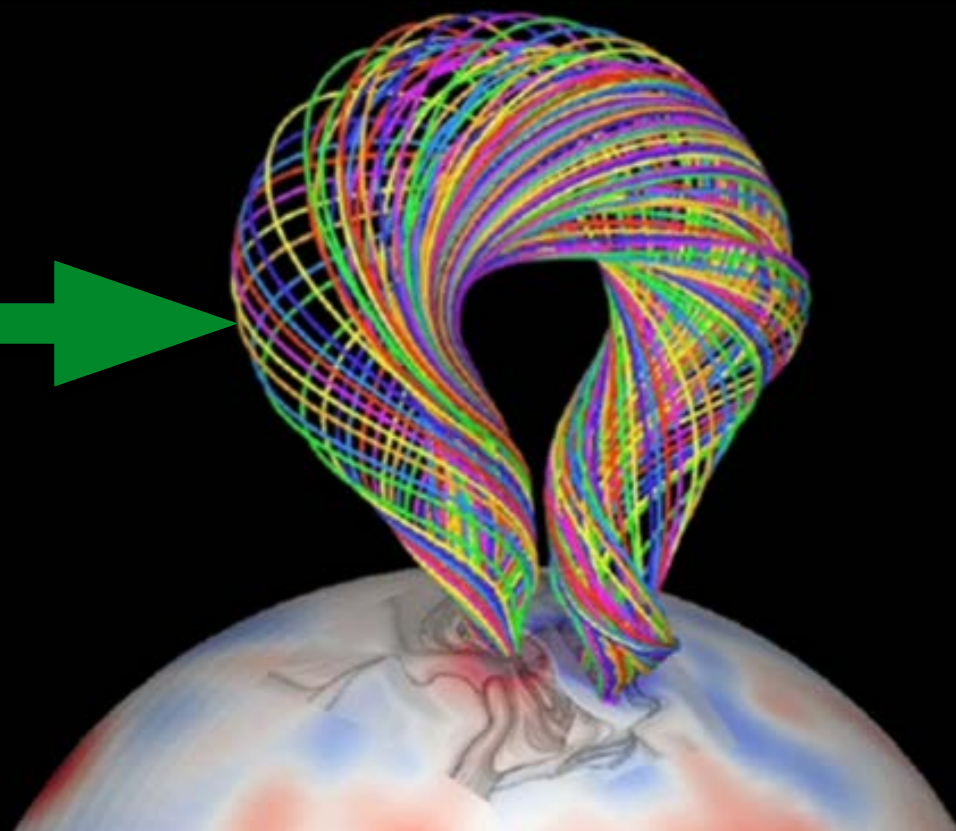
- Evidence and formation of pre-existing MFRs,
- Early evolution of CMEs,
- Magnetic reconnection during CME/flares

# 磁绳子的特征和形成机制

# CME/flare模型



**磁绳**被认为是太阳大气中的基本磁场结构，其向上抛射引起CME，同时在其下方形成耀斑 (Forbes & Isenberg 1991; Chen 1996; Titov &

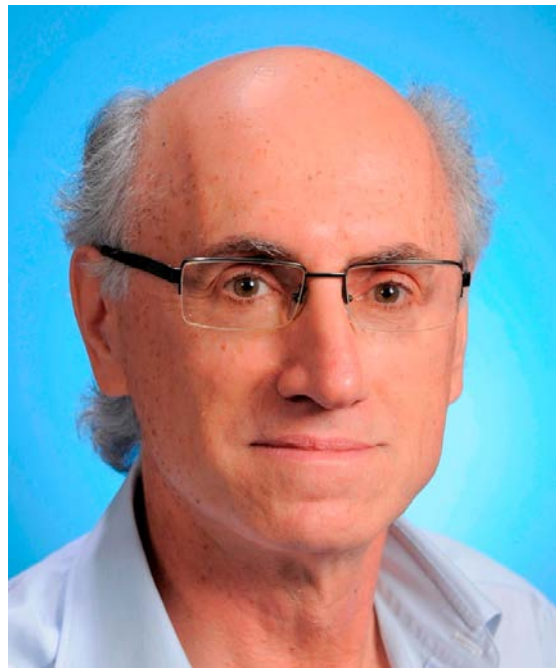


# 太阳爆发前身结构本质之争

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## 剪切磁拱

## 磁绳



**S. K. Antiochos**

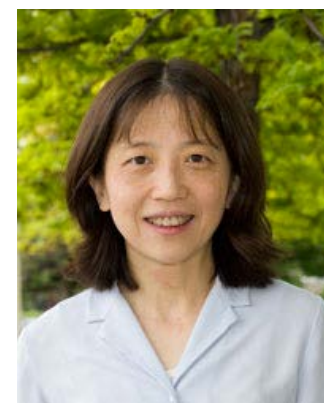
# VS



**B. Kliem**



**V. Vourlidas**



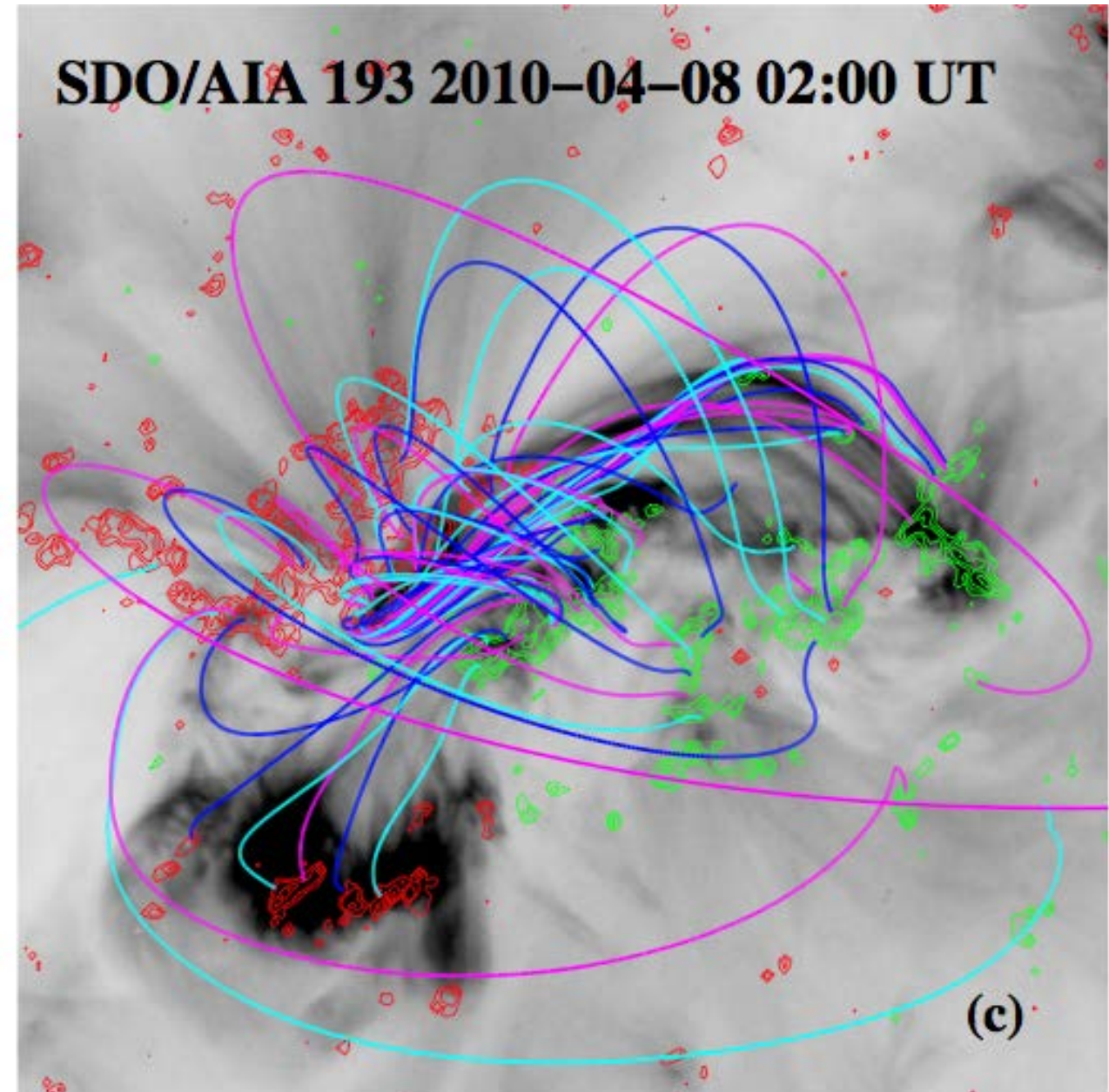
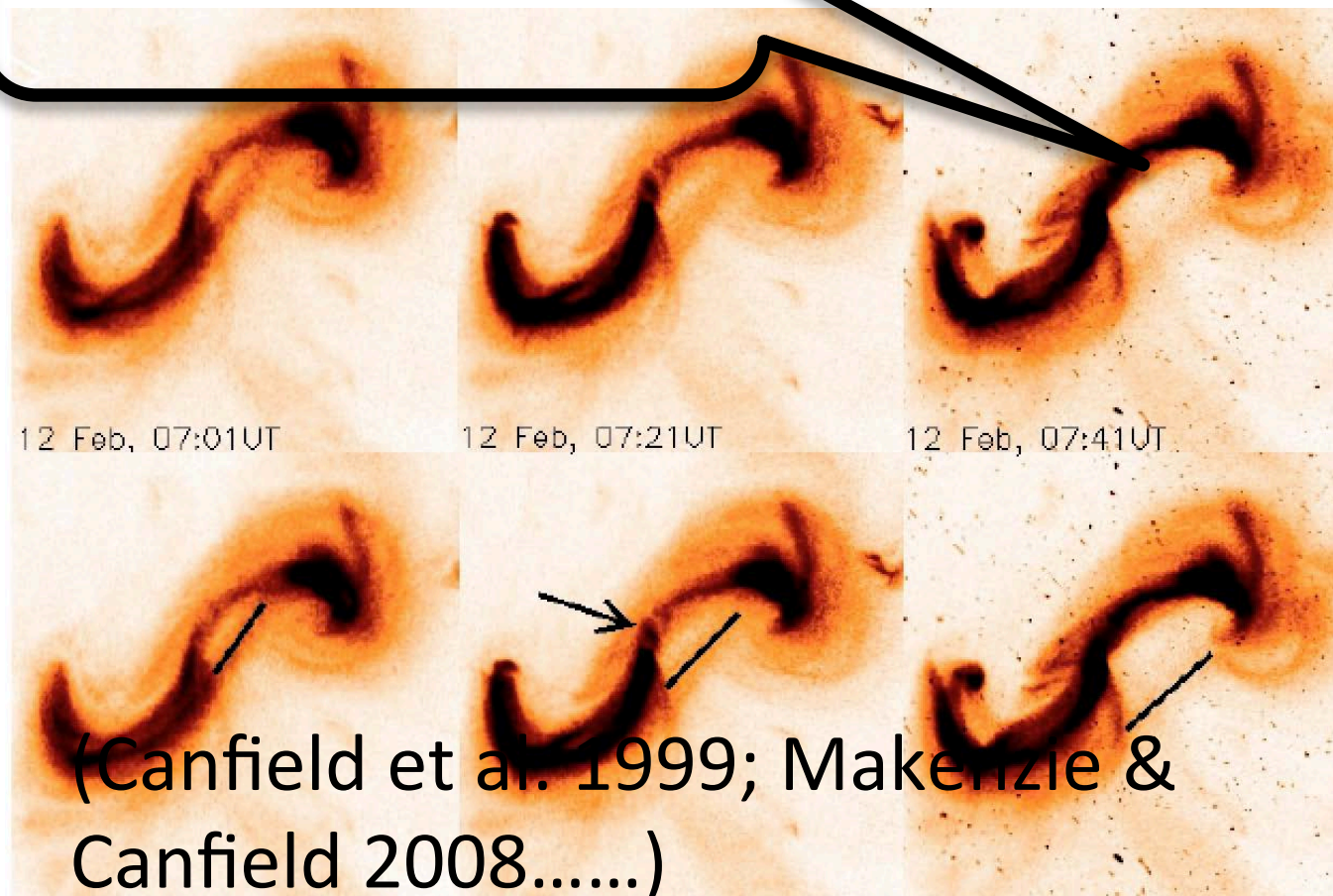
**Y. Fan**



**G. Aulanier**

# 磁绳在日冕中存在的间接证据

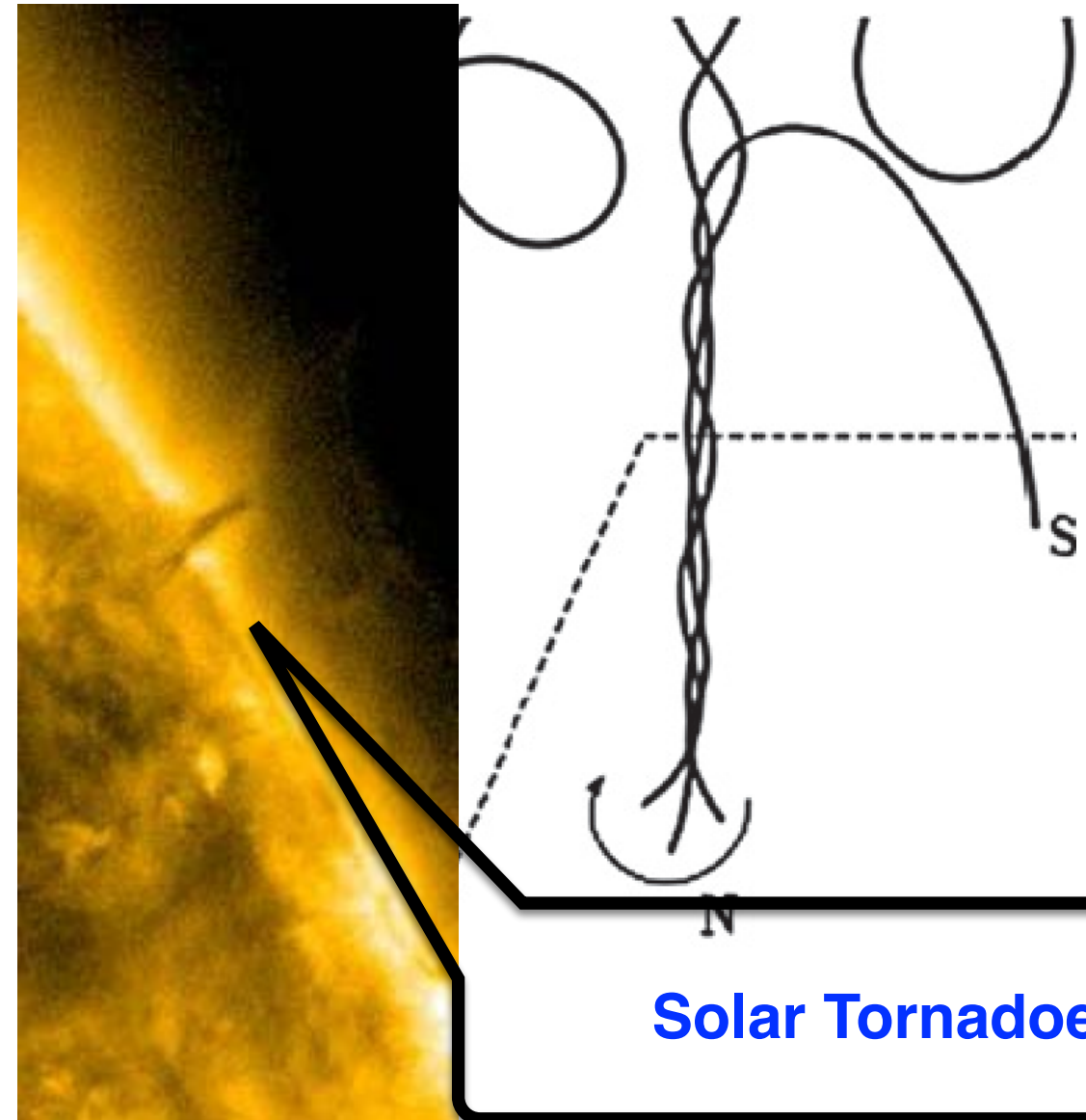
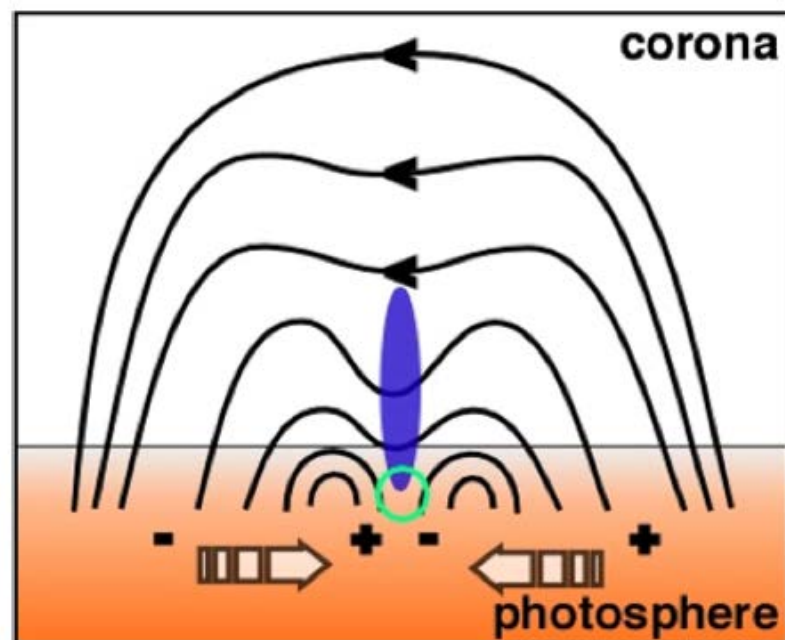
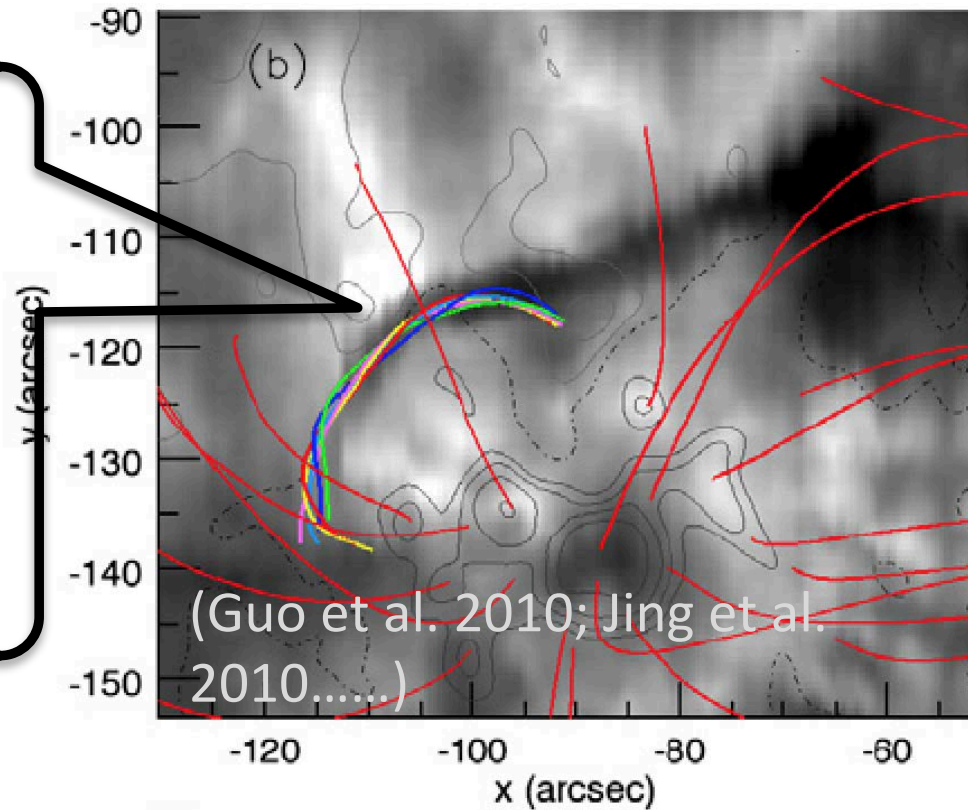
## Sigmoids:



(Su et al. 2011)

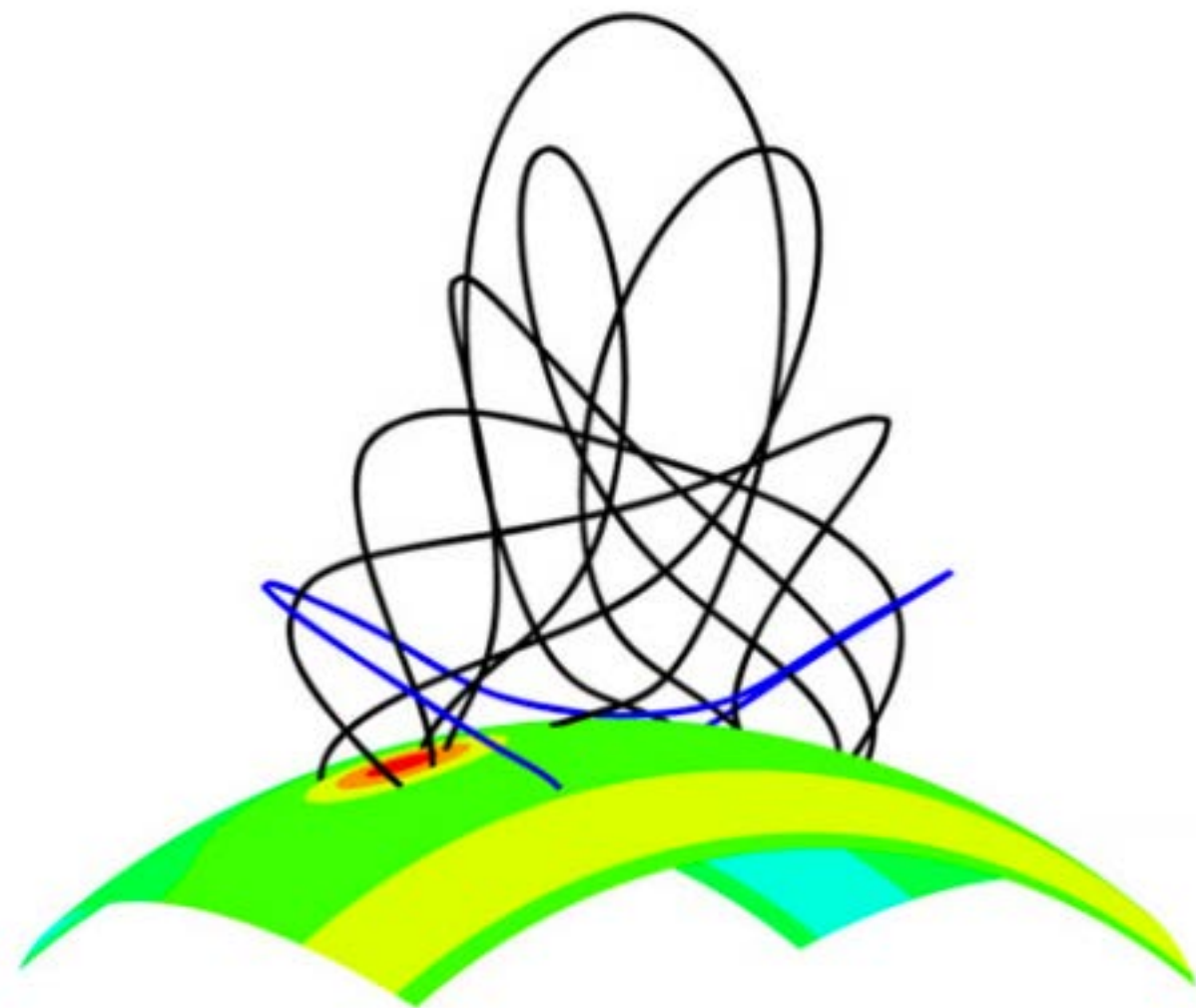
# 暗条/日珥

Filaments:

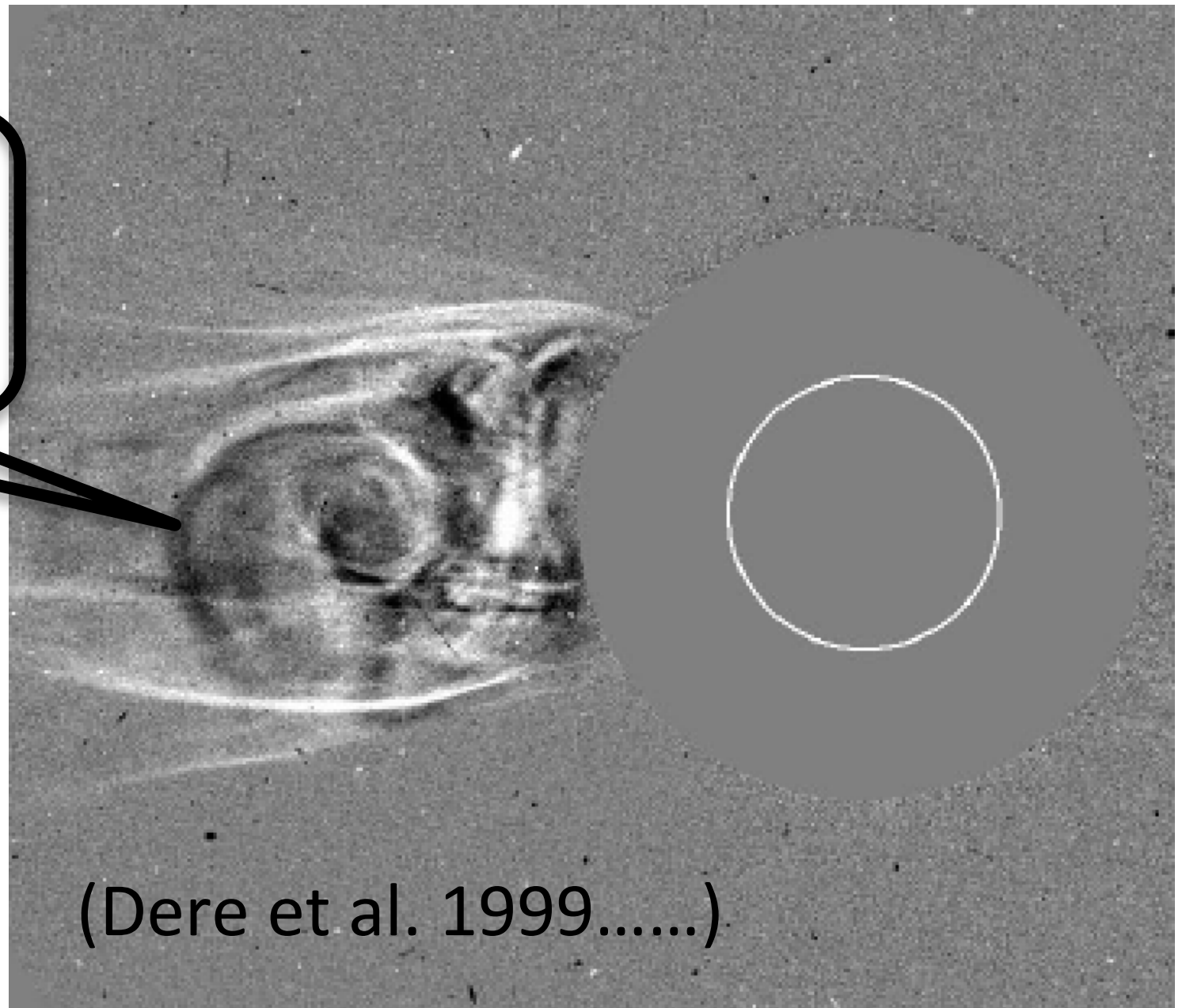


(Zhang et al. 2011; Li et al. 2012; Su et al. 2012; Wedemeyer et al. 2012)

# 暗腔



**Helical  
brightening:**



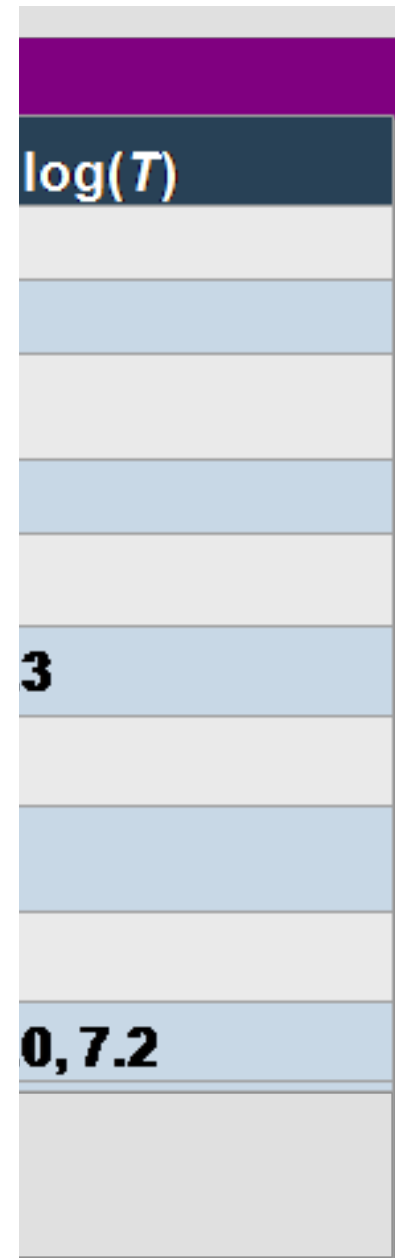
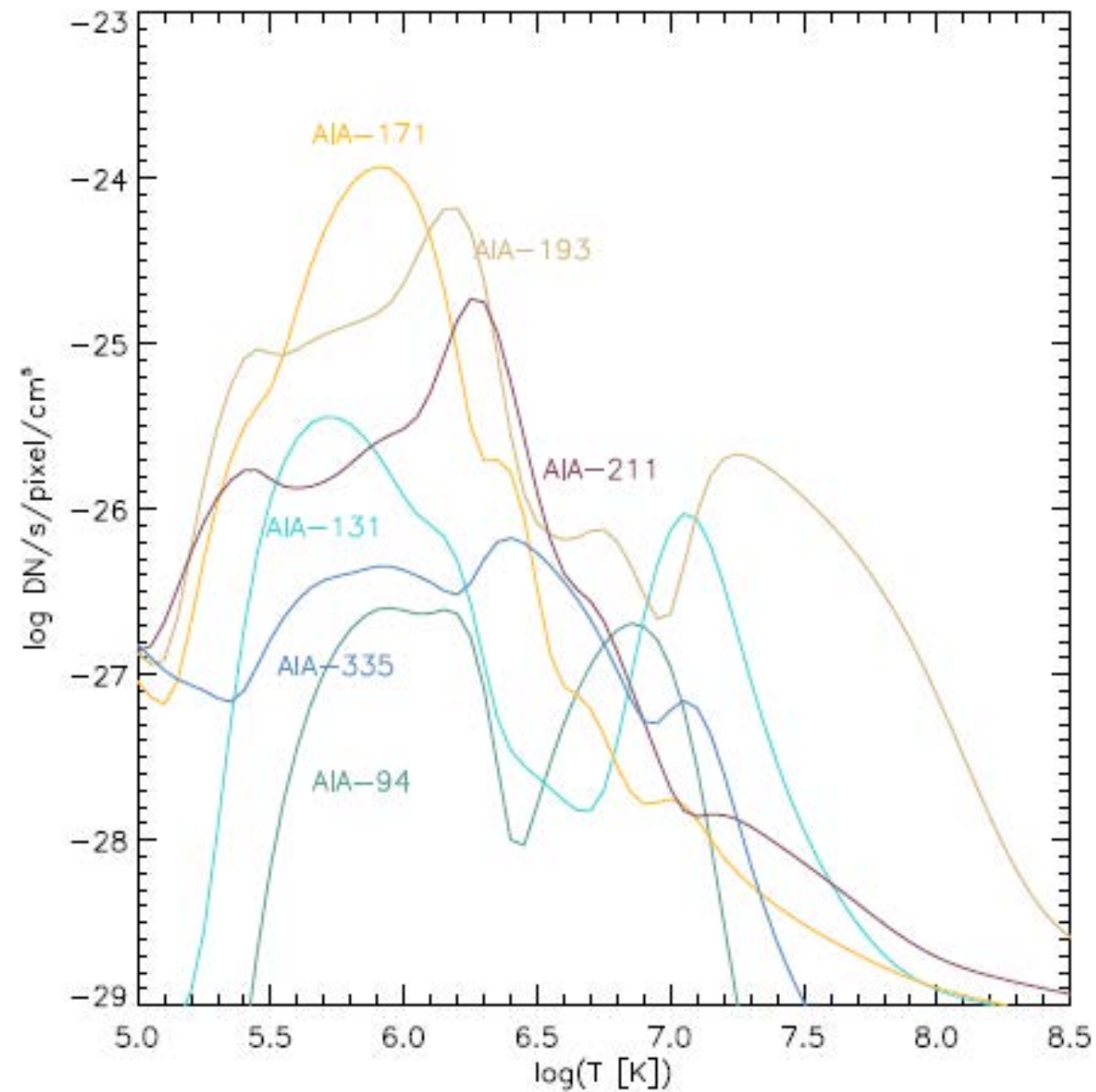
(Dere et al. 1999.....)

# AIA

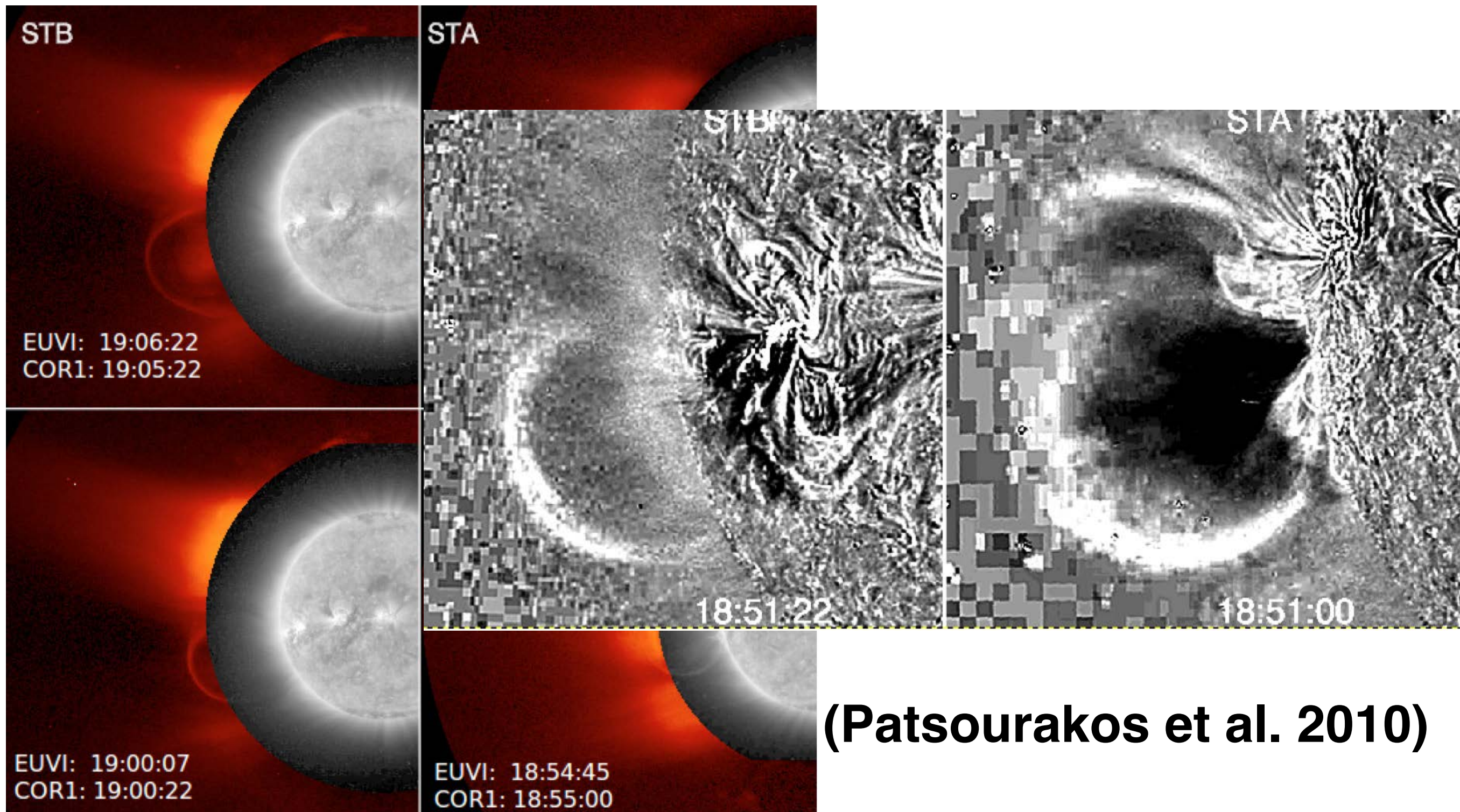
## AIA wavelength bands

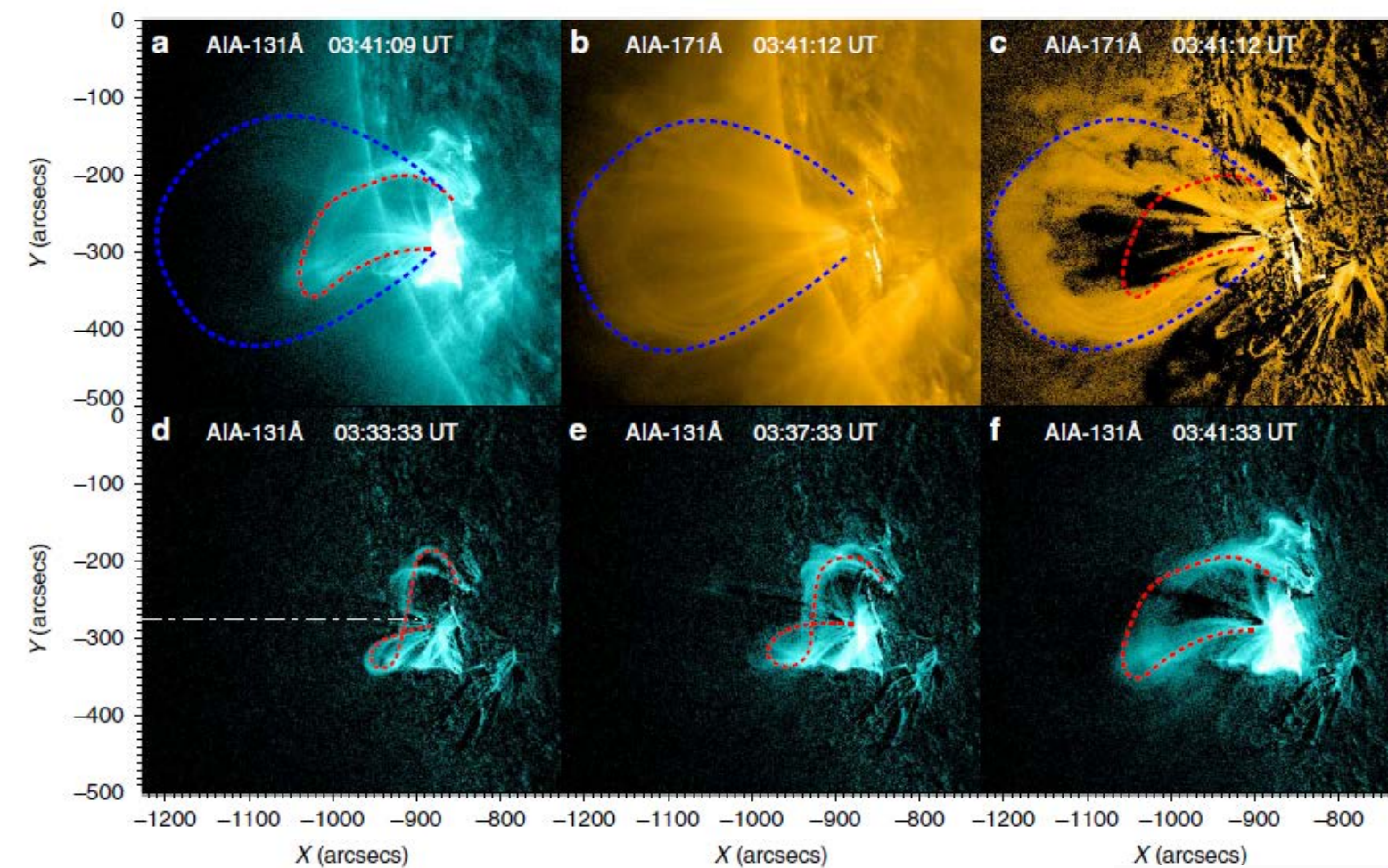
| Channel | $\Delta\lambda^{\dagger\dagger}$ | Ion(s)       |
|---------|----------------------------------|--------------|
| Visible | -                                | Continuum    |
| 1700Å   | -                                | Continuum    |
| 304Å    | 12.7                             | He II        |
| 1600Å   | -                                | C IV+cont.   |
| 171Å    | 4.7                              | Fe IX        |
| 193Å    | 6.0                              | Fe XII, XXIV |
| 211Å    | 7.0                              | Fe XIV       |
| 335Å    | 16.5                             | Fe XVI       |
| 94Å     | 0.9                              | Fe XVIII     |
| 131Å    | 4.4                              | Fe VIII, XX+ |

\*Absorption allows imaging of  
 $\dagger\dagger$ FWHM, in Å



# CME in the inner corona

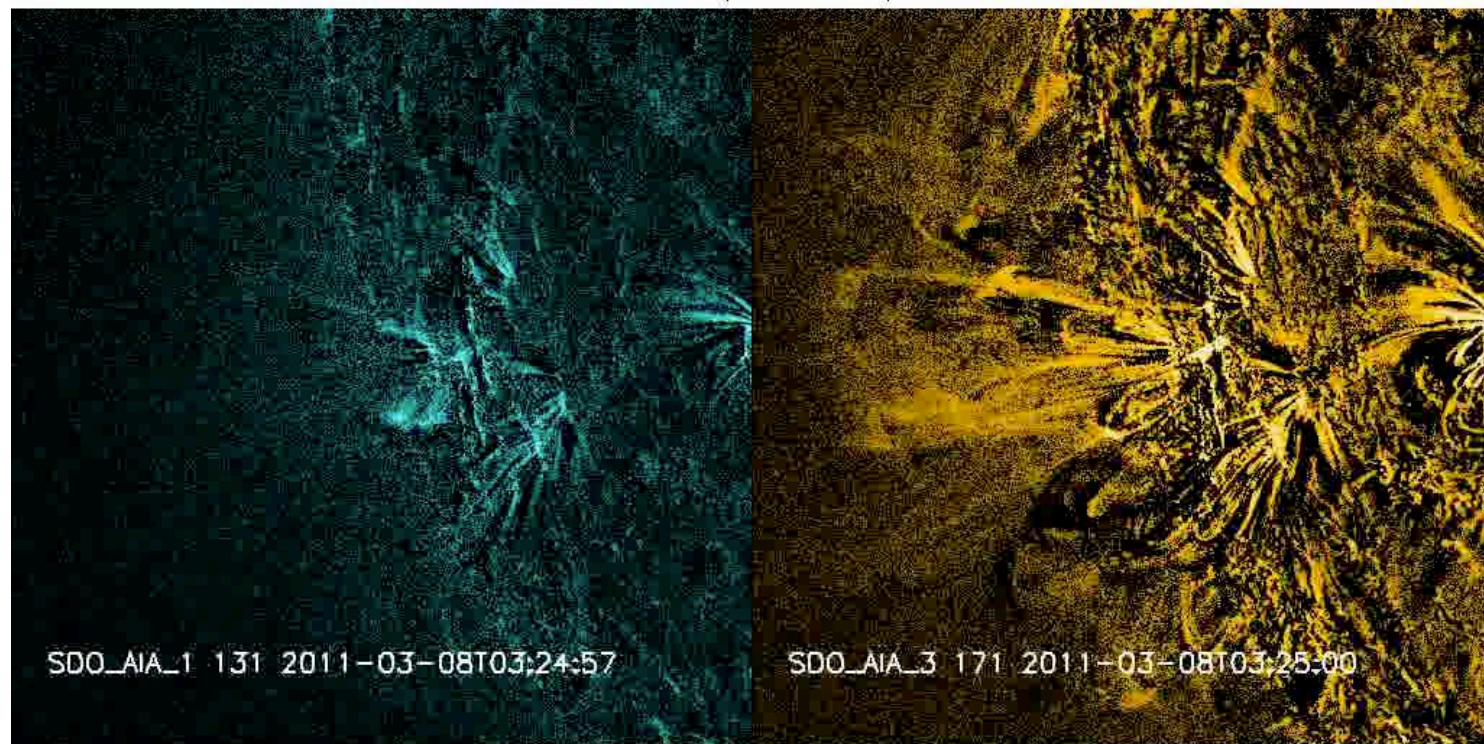
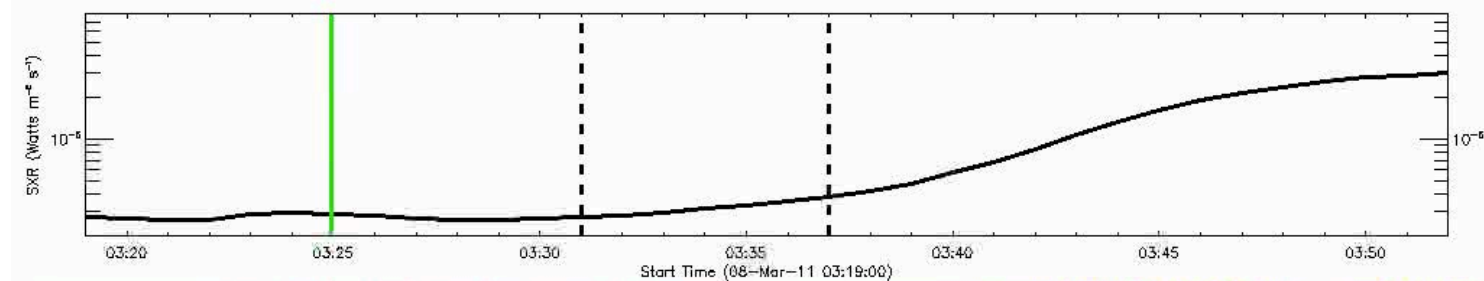




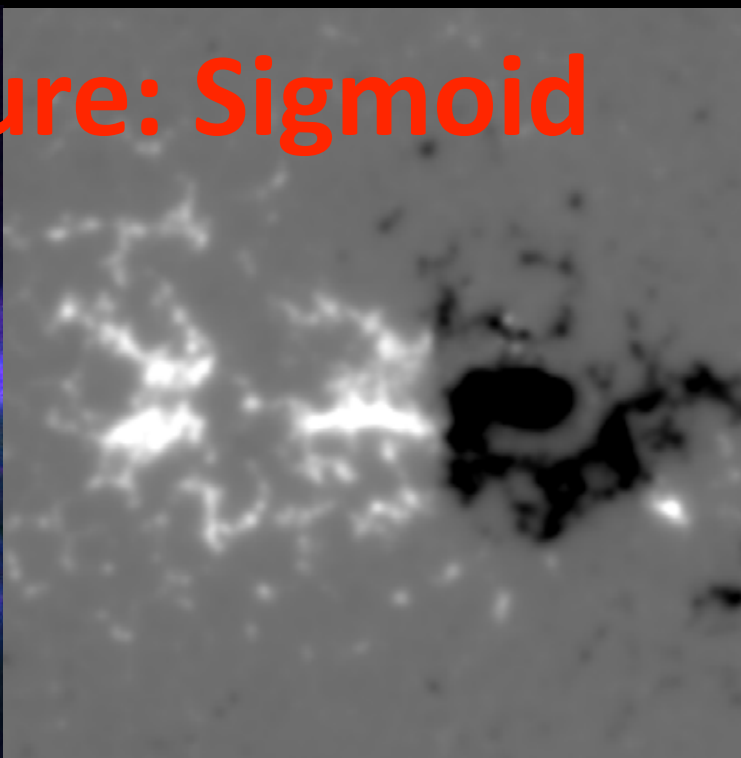
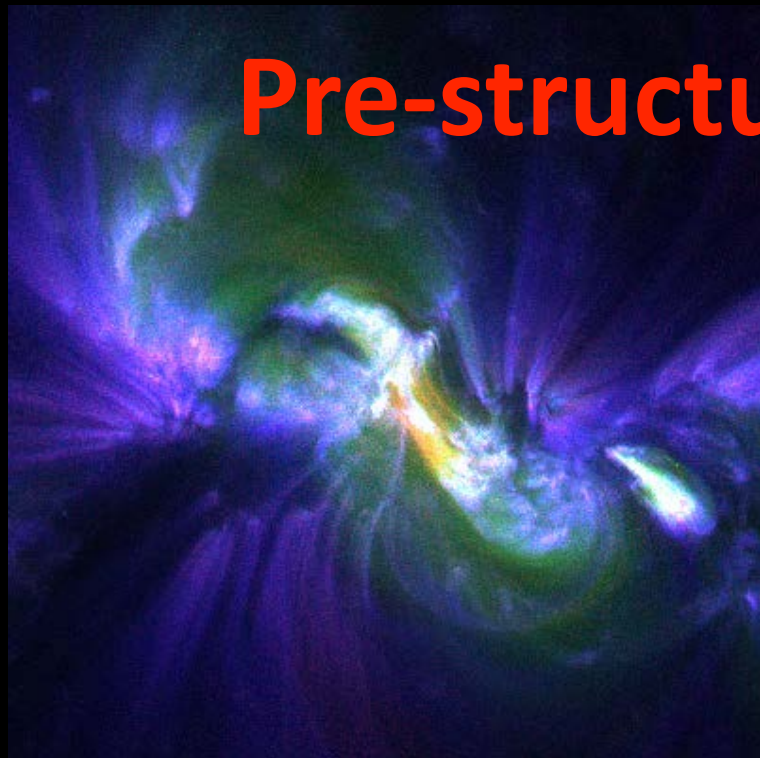
1. Appearing as a **channel-like structure** with a high temperature of  $>7\text{MK}$ ,
2. Appearing **in the dark cavity**, following a bright front,
3. Existing **prior to the first appearance** of the CME,
4. Evolving from **S-shape to semicircle**,
5. With **fixed footpoints**.

“Direct” evidence of the existence of MFRs:  
EUV Hot Channel

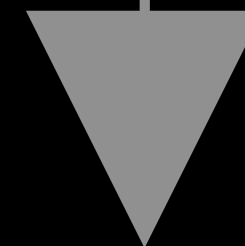
(Zhang, Cheng & Ding 2012)



**Pre-structure: Sigmoid**

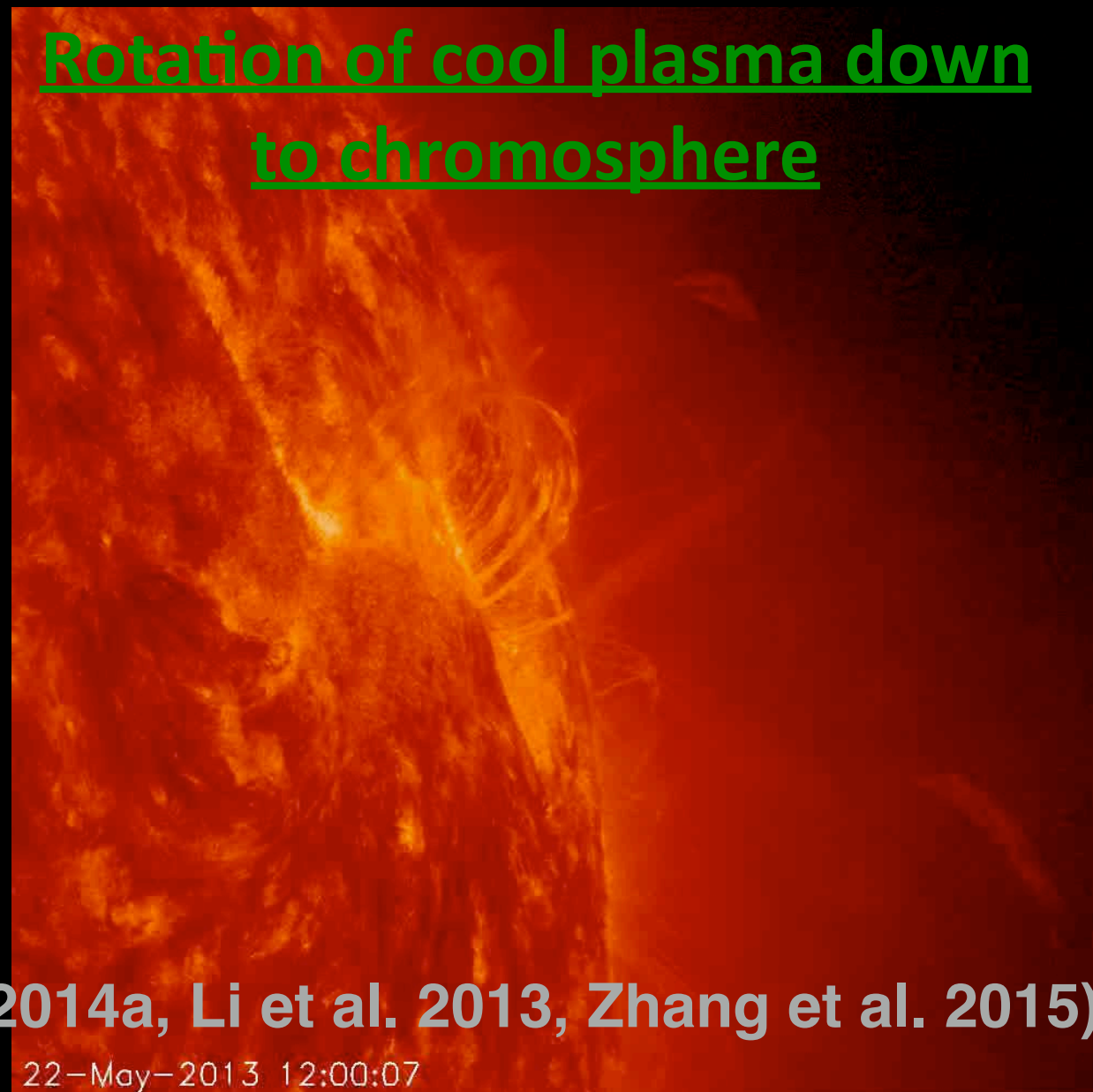


**Four days**



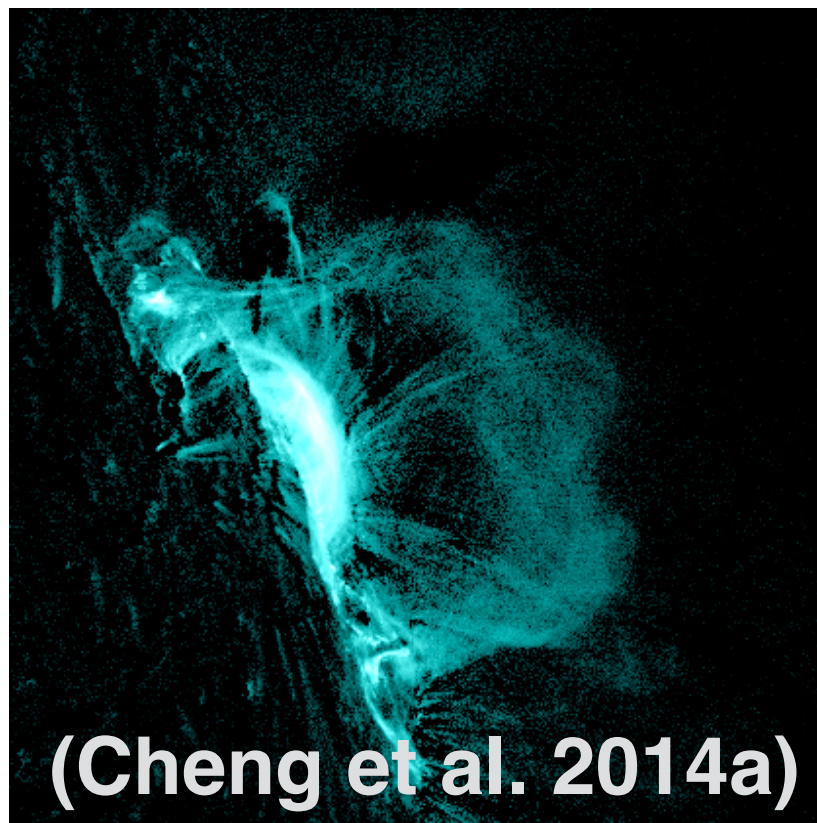
**Helical threads inside MFR**

**Rotation of cool plasma down  
to chromosphere**

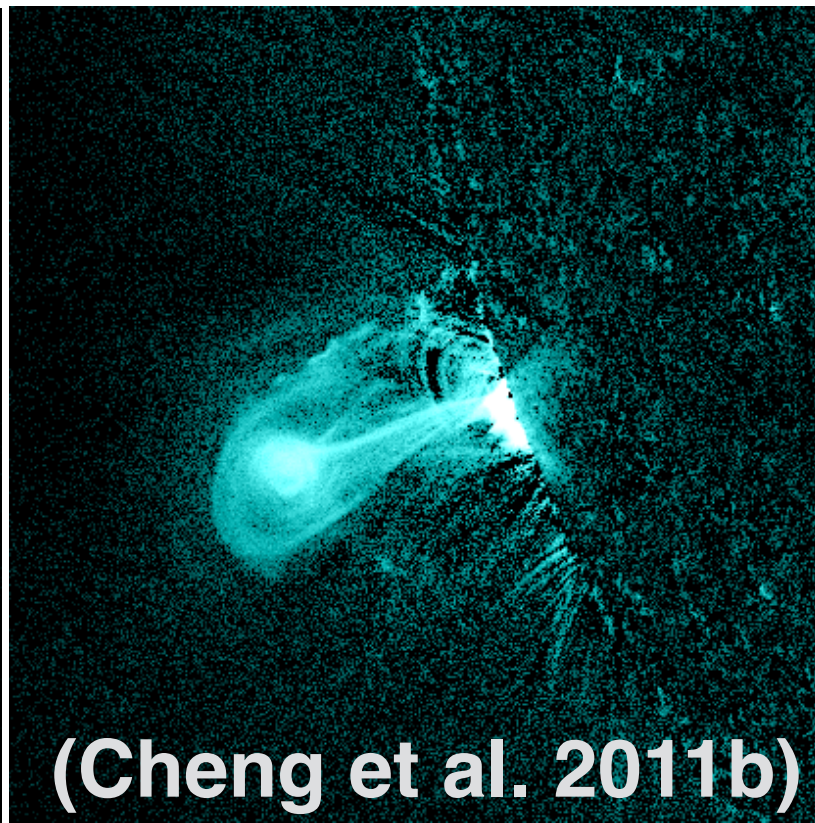


**(Cheng et al. 2014a, Li et al. 2013, Zhang et al. 2015)**

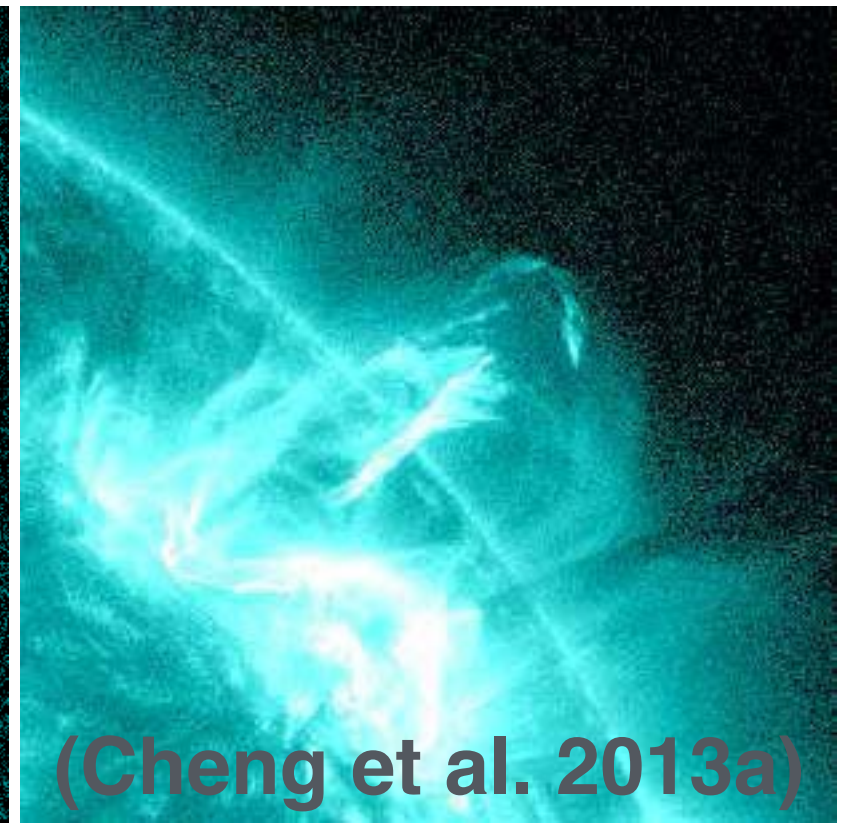
# Different Orientations:



(Cheng et al. 2014a)

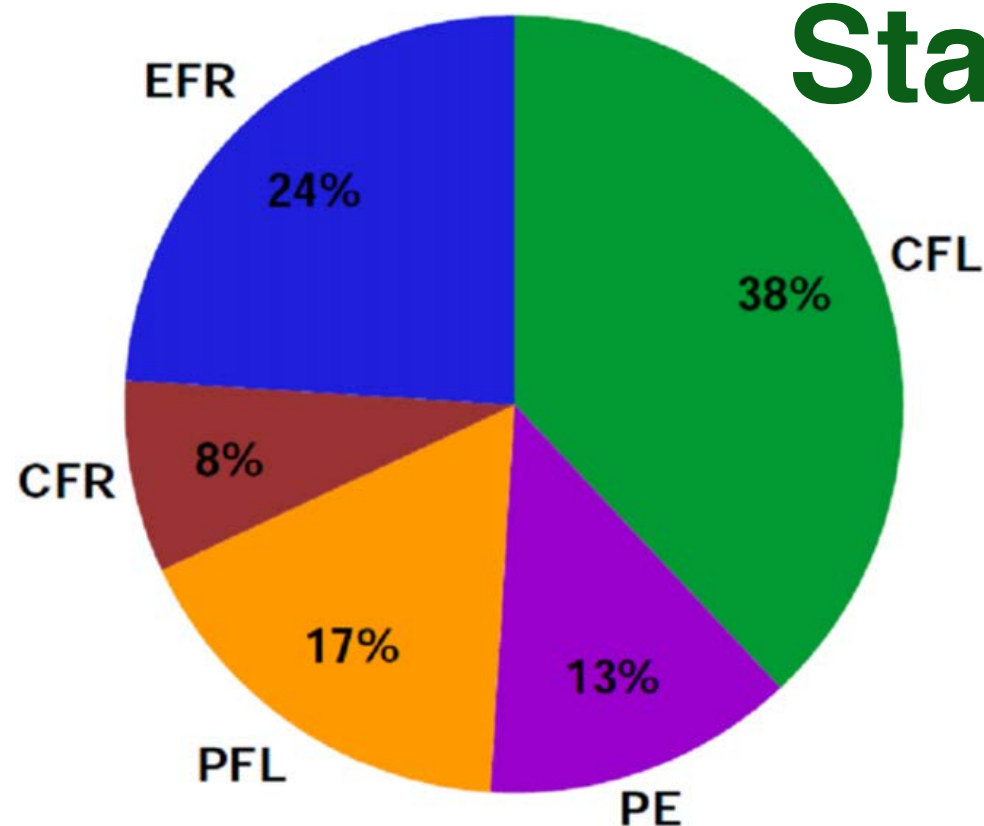


(Cheng et al. 2011b)



(Cheng et al. 2013a)

## Statistical results:



1. Confined flare events with hot FRs (CFR)
2. Eruptions with hot FRs (EFR)
3. Prominence eruption events without hot FRs (PE)
4. Eruptions without hot FRs or prominences (PFL)
5. Confined flare events without hot FRs (CFL)

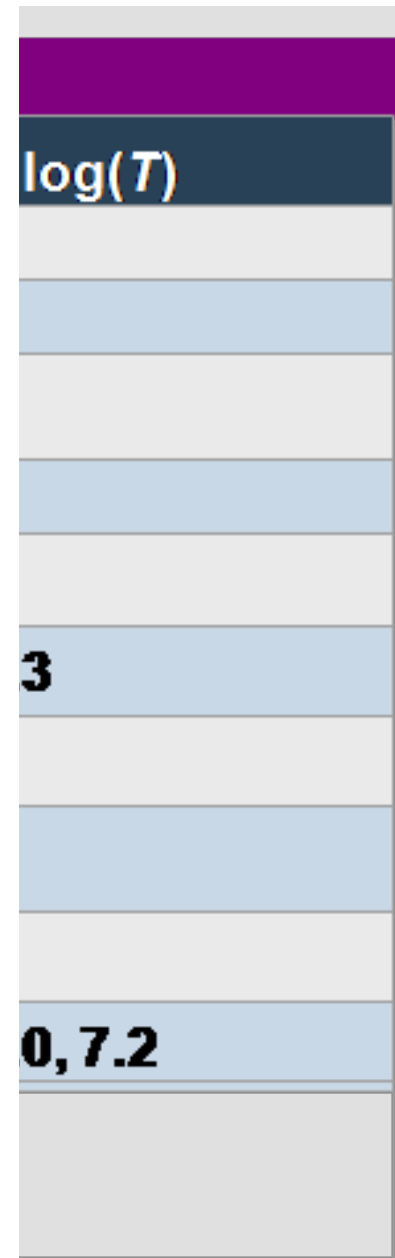
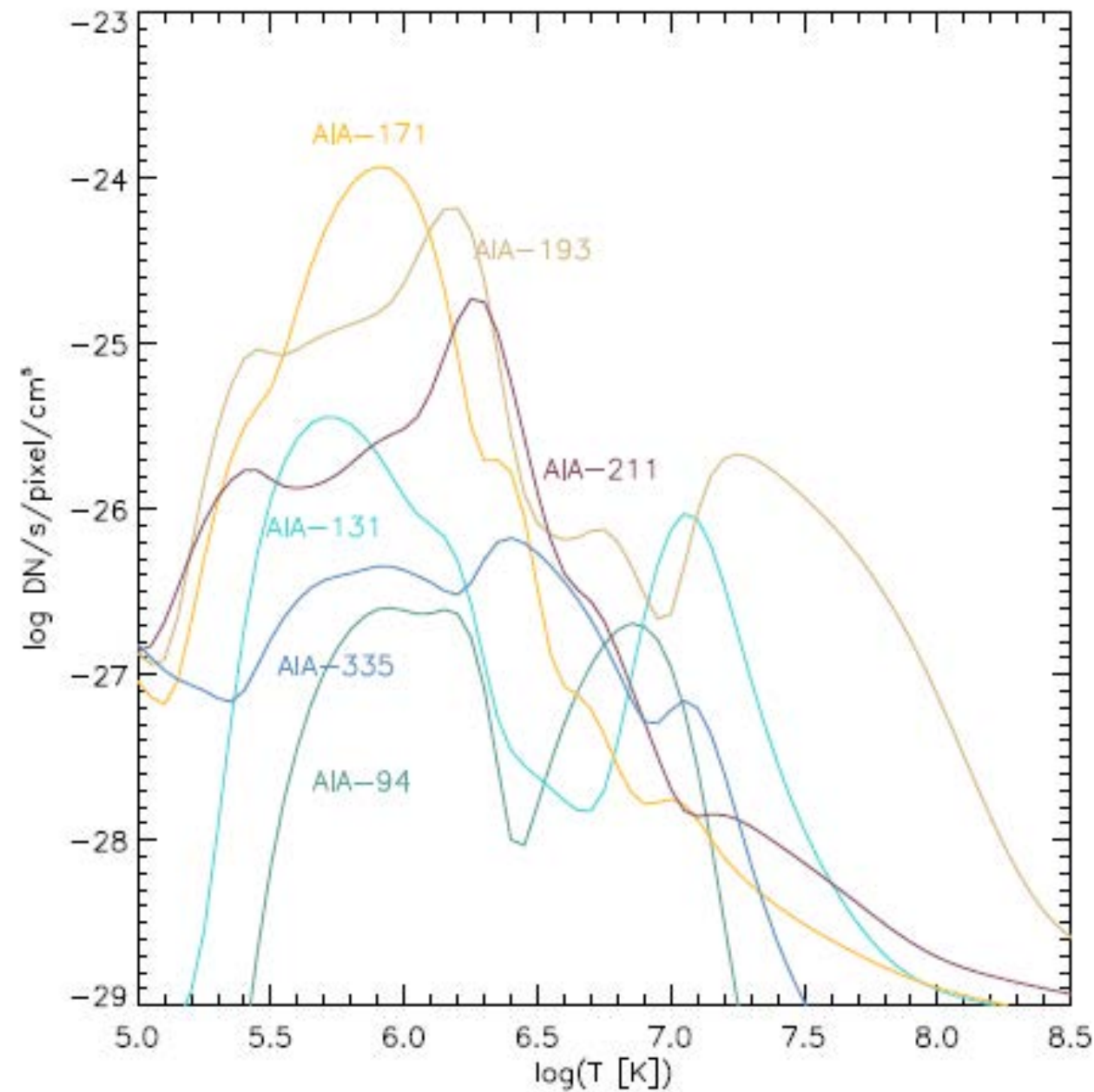
(Nindos et al. 2015)

# DEM反演

## AIA wavelength bands

| Channel | $\Delta\lambda^{\dagger\dagger}$ | Ion(s)       |
|---------|----------------------------------|--------------|
| Visible | -                                | Continuum    |
| 1700Å   | -                                | Continuum    |
| 304Å    | 12.7                             | He II        |
| 1600Å   | -                                | C IV+cont.   |
| 171Å    | 4.7                              | Fe IX        |
| 193Å    | 6.0                              | Fe XII, XXIV |
| 211Å    | 7.0                              | Fe XIV       |
| 335Å    | 16.5                             | Fe XVI       |
| 94Å     | 0.9                              | Fe XVIII     |
| 131Å    | 4.4                              | Fe VIII, XX+ |

\*Absorption allows imaging of  
 $\dagger\dagger$ FWHM, in Å



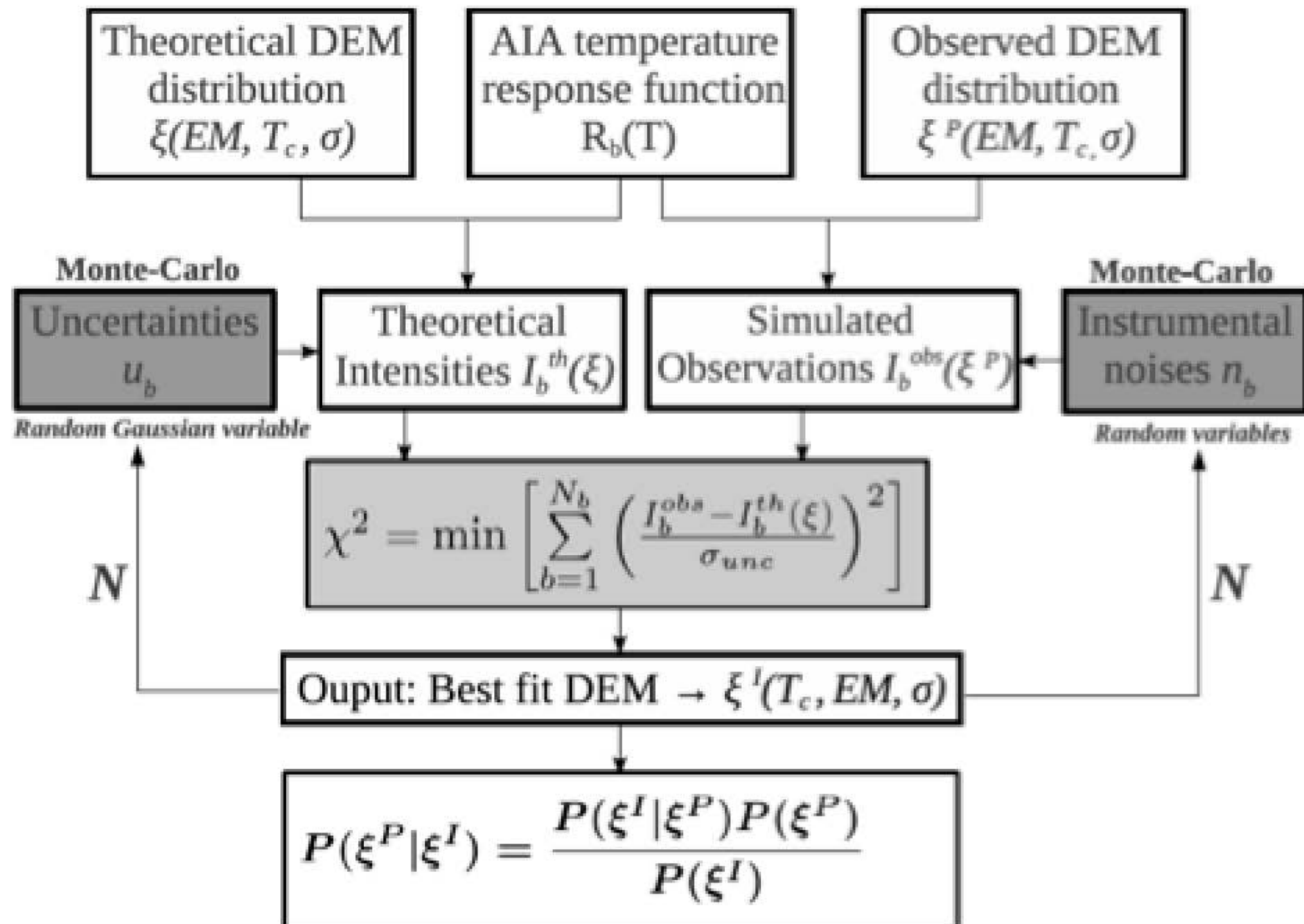
## ***Method: Iterative***

$$F_i = \int R_i(T) \times \text{DEM}(T) dT,$$

**We assume a starting DEM that apply for above function, and compare the predicted observations with the real observations for each filter.**

**The optimal DEM spline is found using IDL mpfit routines, which search towards a minimum  $\chi^2$**

## Method: Iterative



(Guennou et al, 2012, ApJS)

**Therefore, the reverse method is good enough somehow to recover the temperature and density in various corona structures**

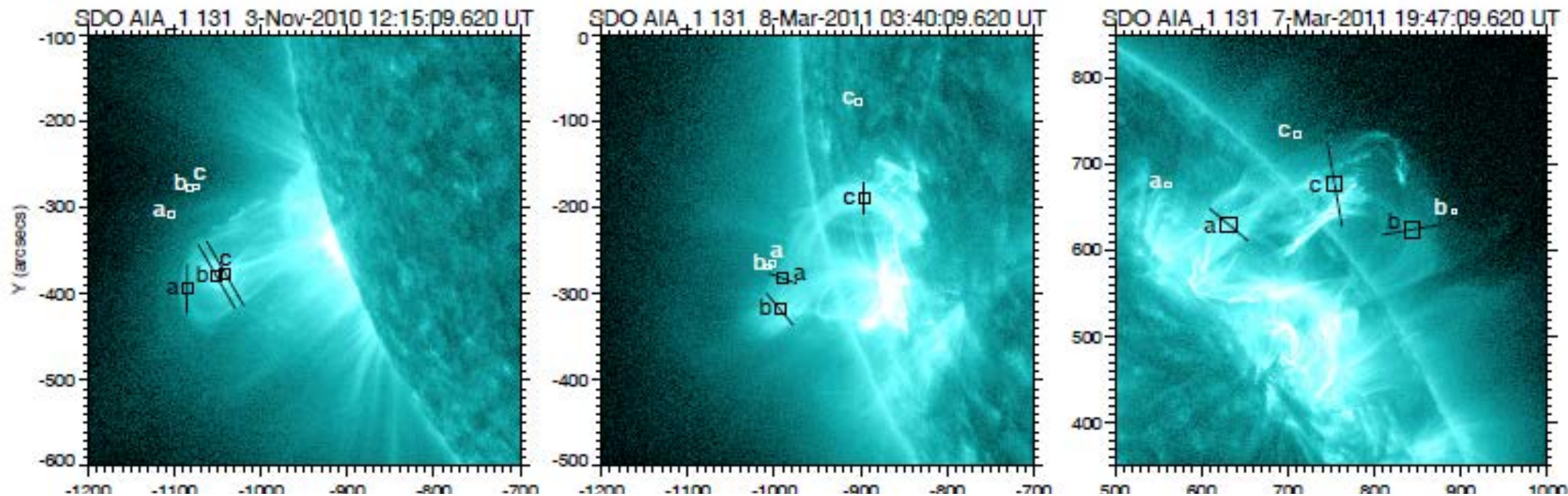
**After knowing DEM, we can obtain emission measure (EM) , average temperature (T) , and density (n).**

$$EM = \int DEM(T) dT = \int n^2 dl$$

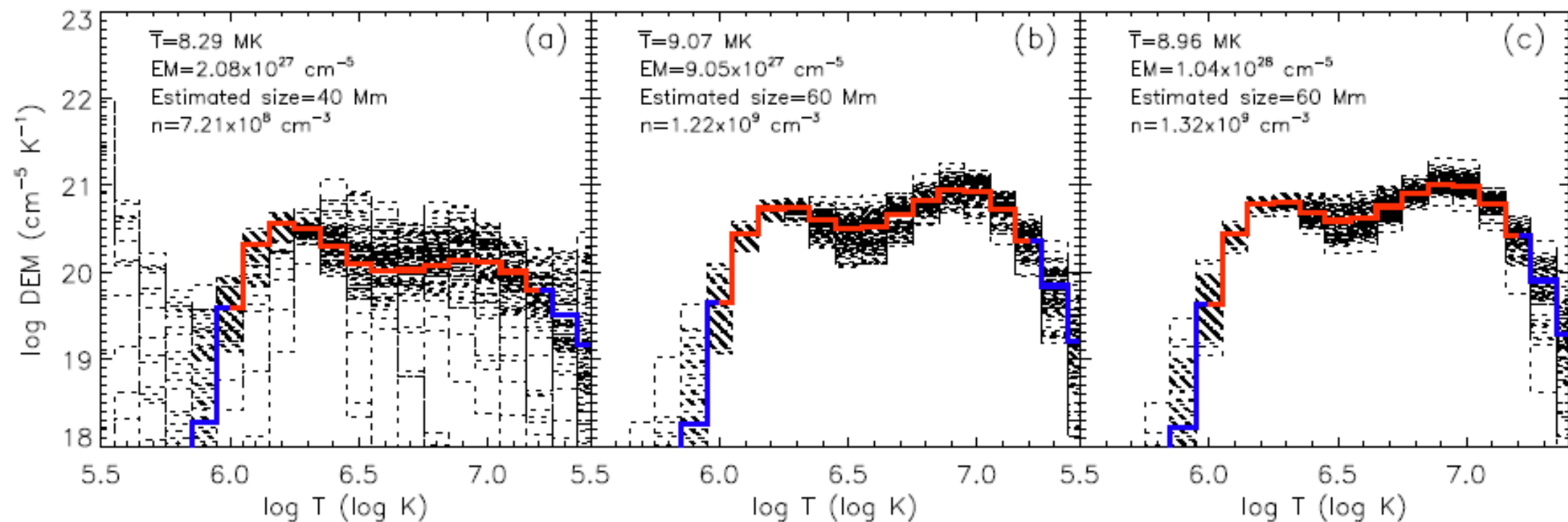
$$\bar{T} = \frac{\int DEM(T) * T dT}{\int DEM(T) dT},$$

$$n = \sqrt{\frac{EM}{l}}.$$

# DEM structure of MFR



2010-11-03 Event



# 磁绳如何形成， 那里形成？

July 7 00:00 UT:

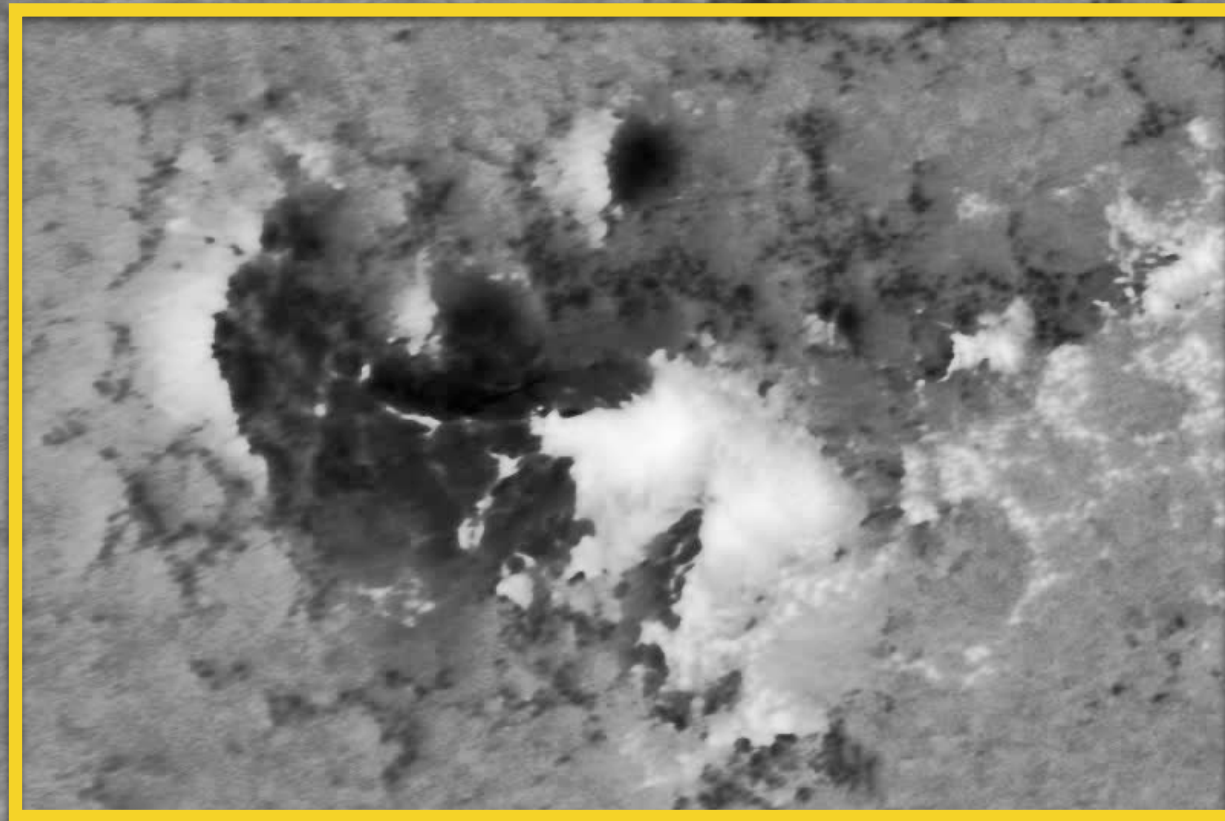
July 11 00:00–July 12 03:00 UT:

July 12 16:10 UT:

活动区出现于太阳东边缘

剪切核心磁场转化为强缠绕性磁场

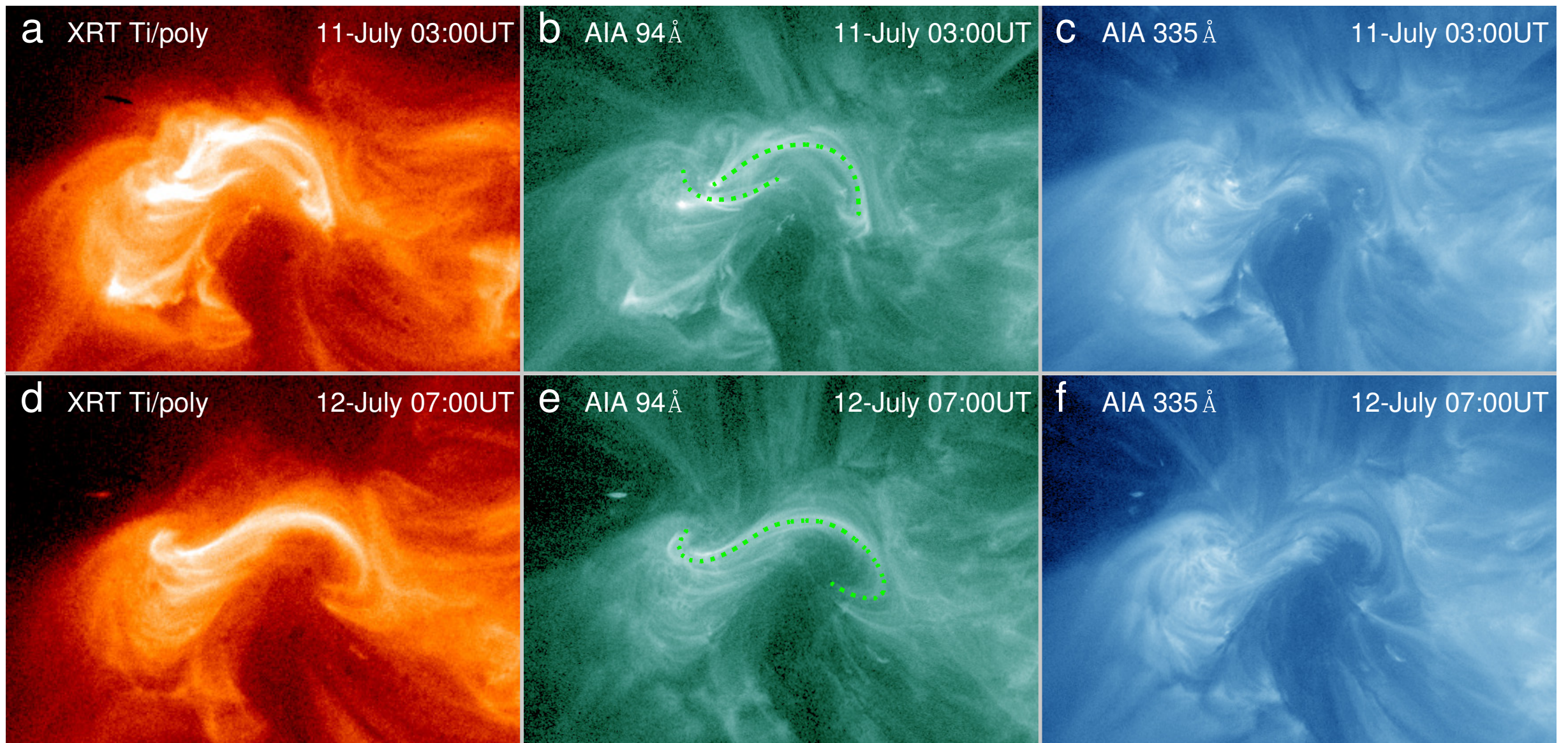
热磁绳爆发, 产生X1.3级耀斑和快速CME



**NOAA 11520**

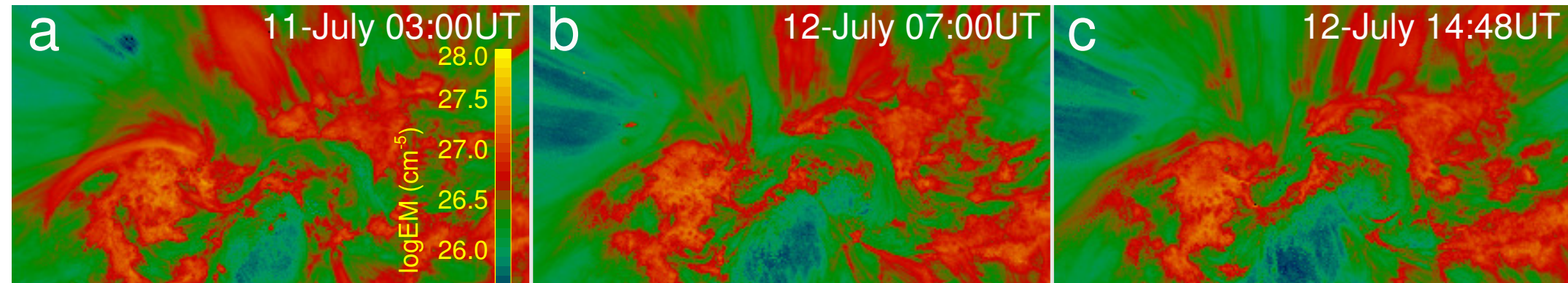
# Formation of MFRs

## An MFR formation in sigmoidal AR 11520

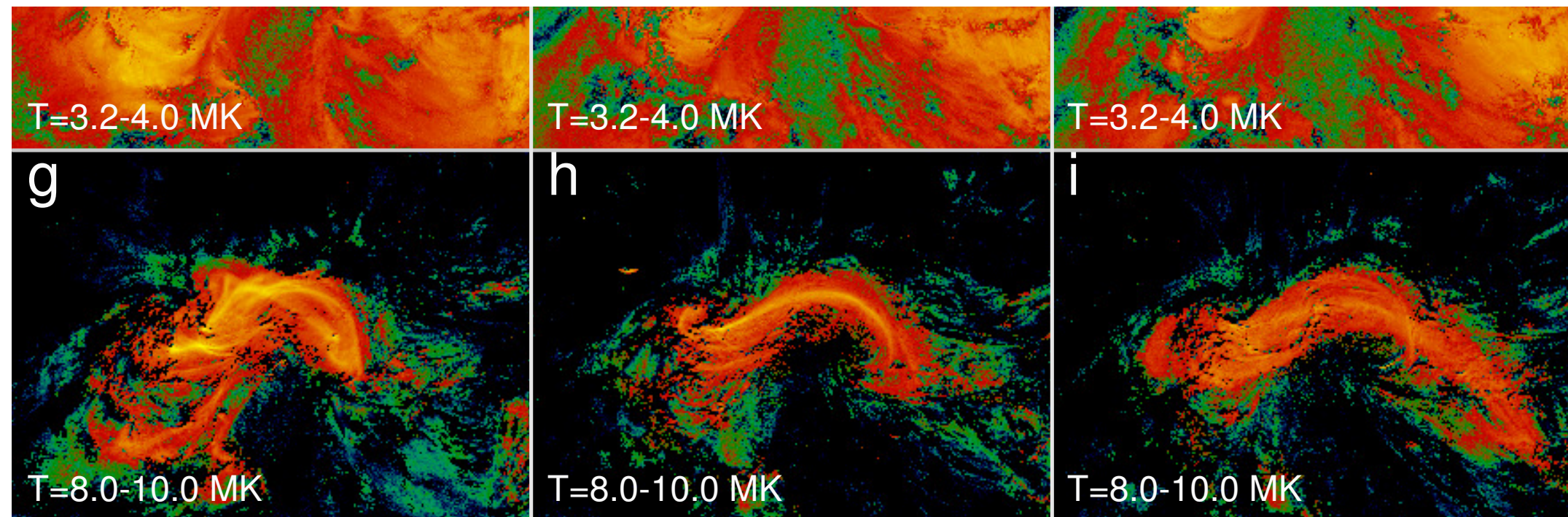


Sheared arcades ---> continuous sigmoidal/twist lines

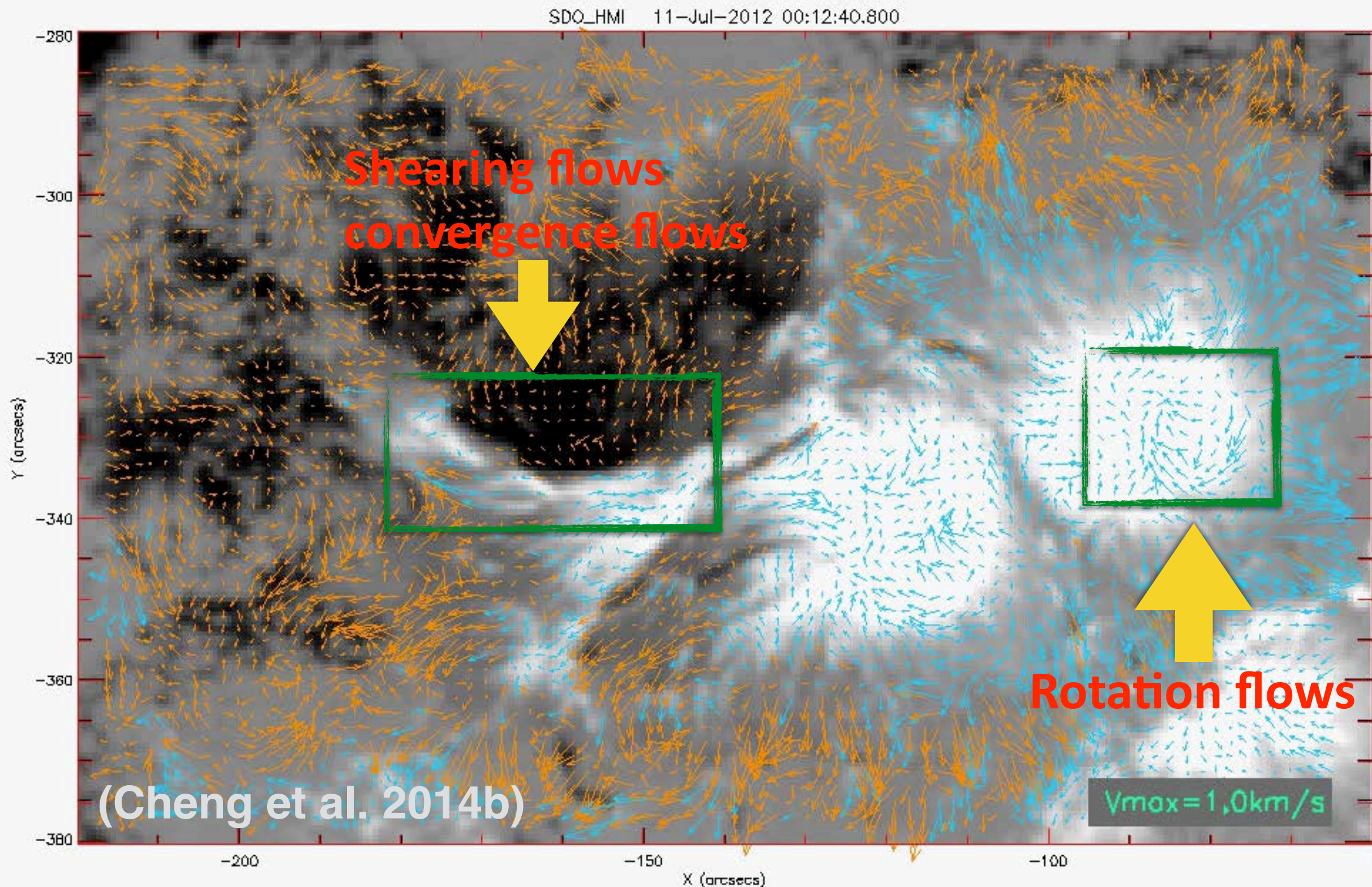
# Temperature Structures of MFR



1. High temperature of the core field shows that the reconnection takes place there.
2. The formation of MFR could be from the reconnection between sheared arcades.

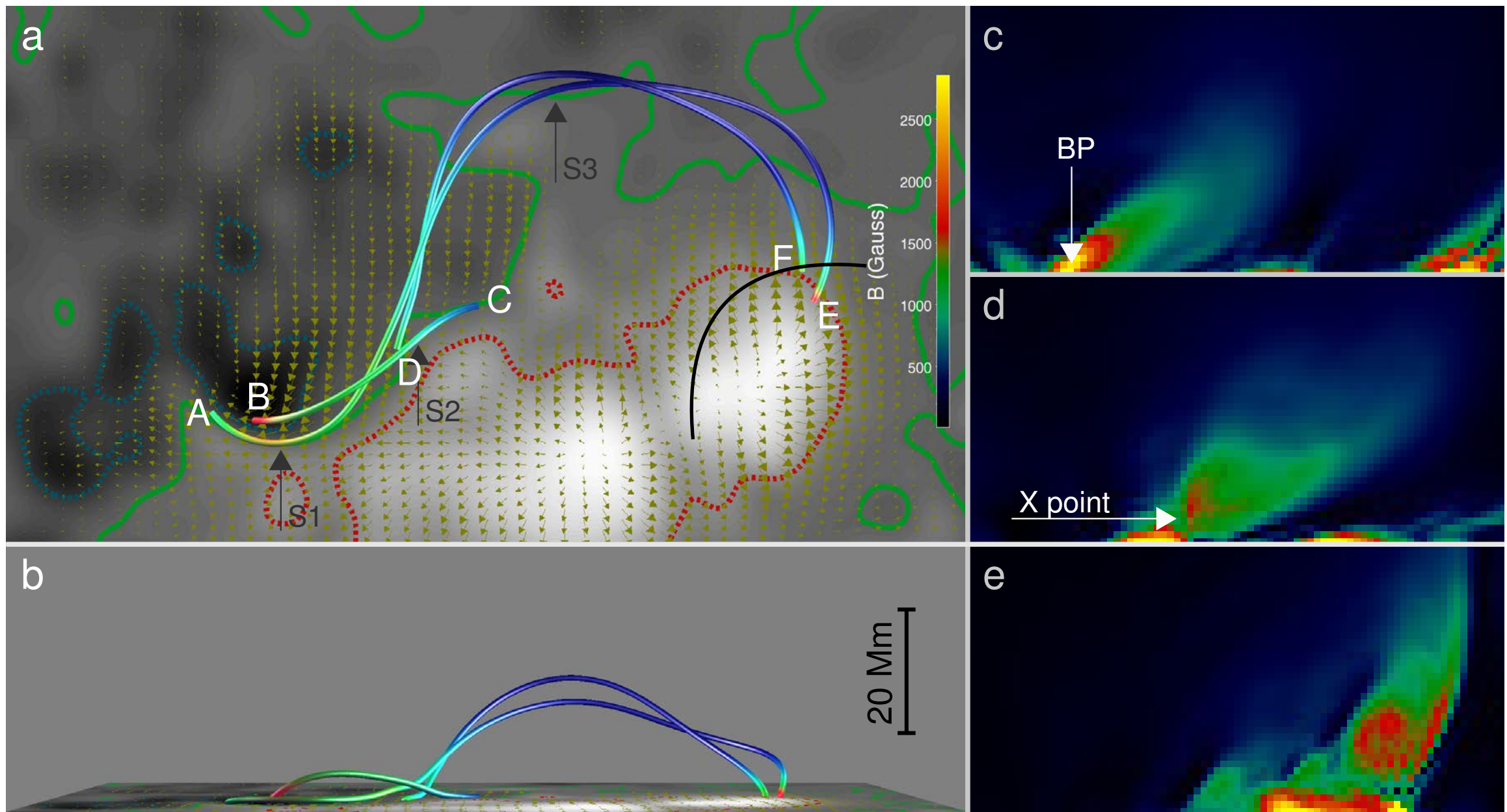


# Photosphere flows:



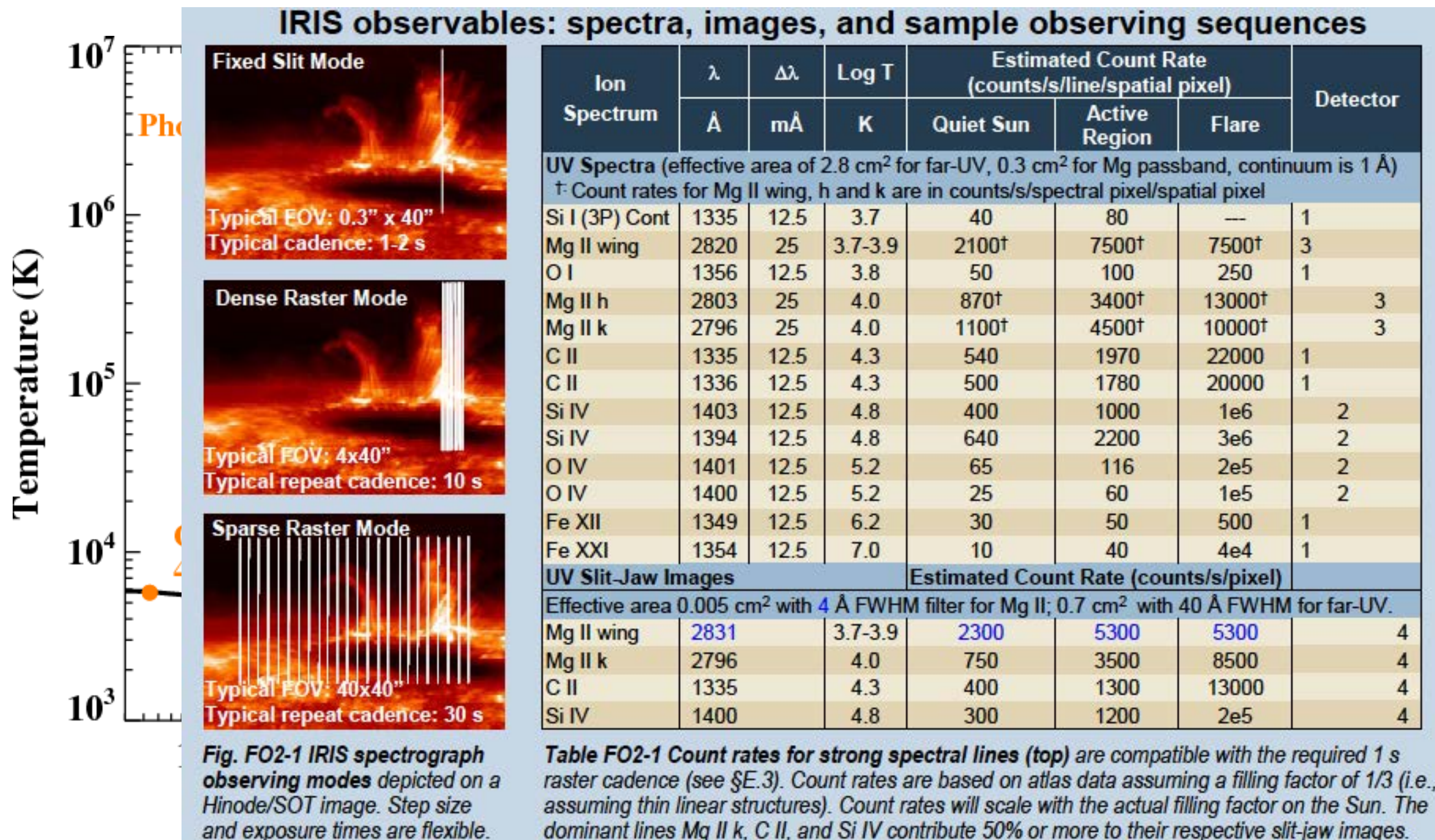
# NLFFF structures of MFR

$$\nabla \times \mathbf{B} = \alpha \mathbf{B},$$
$$\nabla \cdot \mathbf{B} = 0,$$

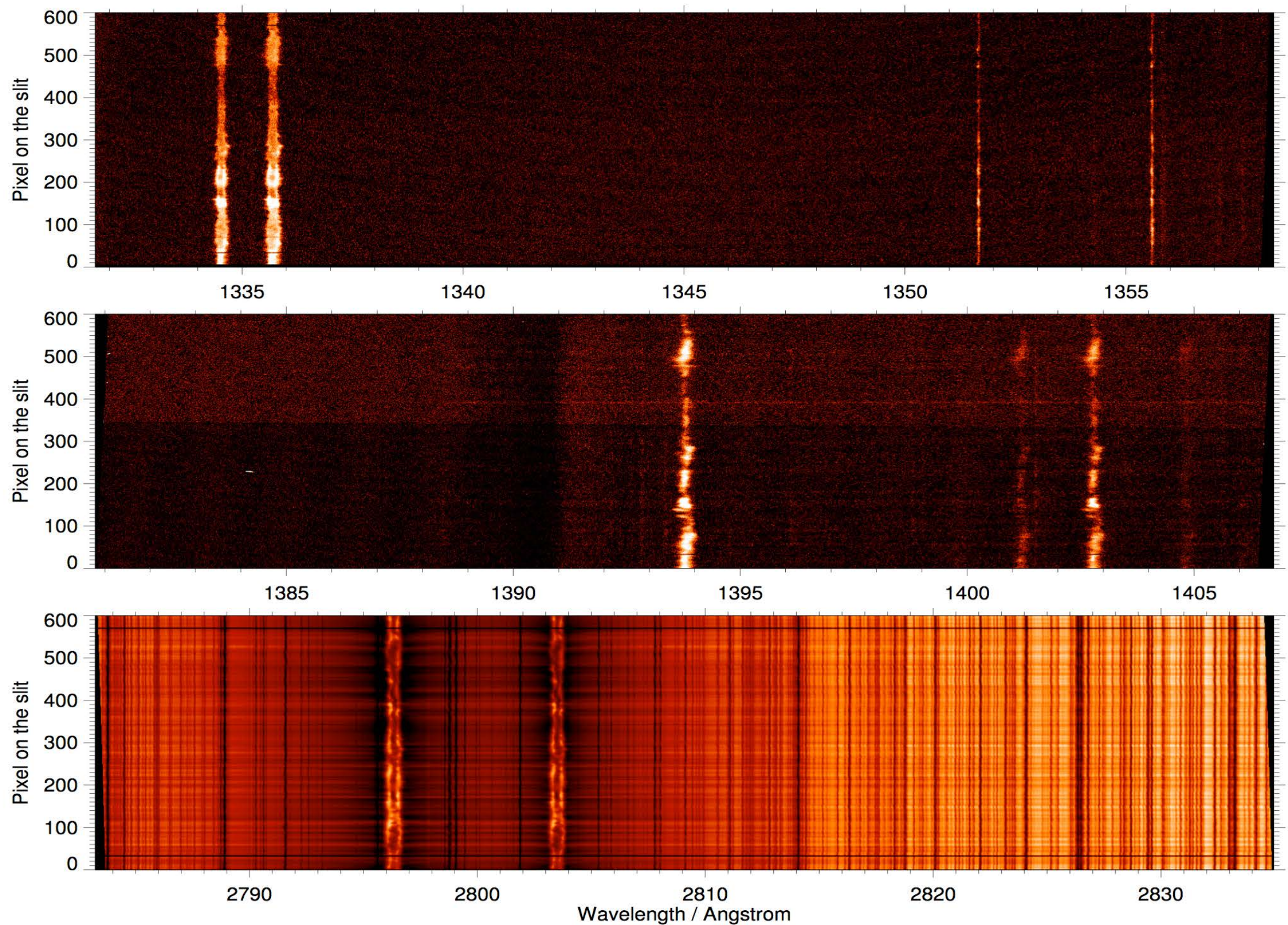


The reconnection pattern varies spatially from **bald-patches** to **hyperbolic flux tube** along the direction of the MFR axis.

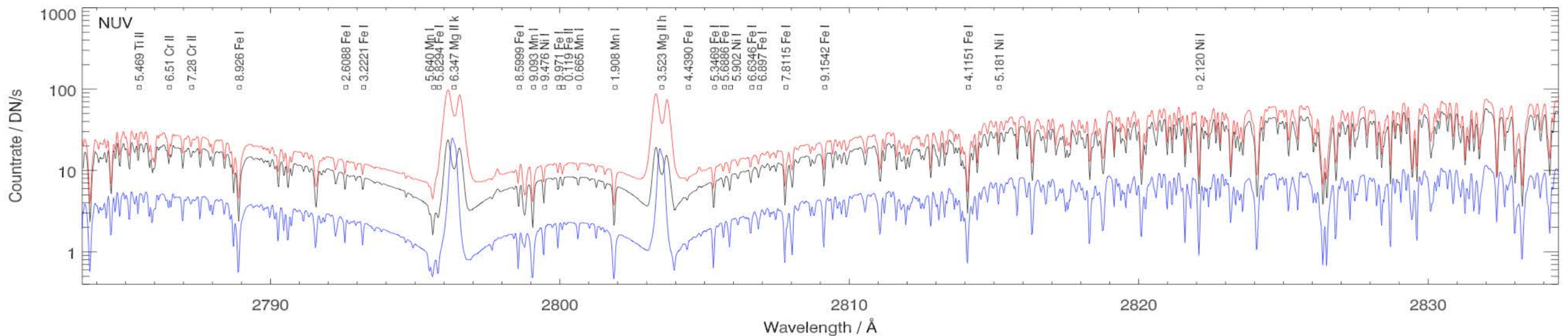
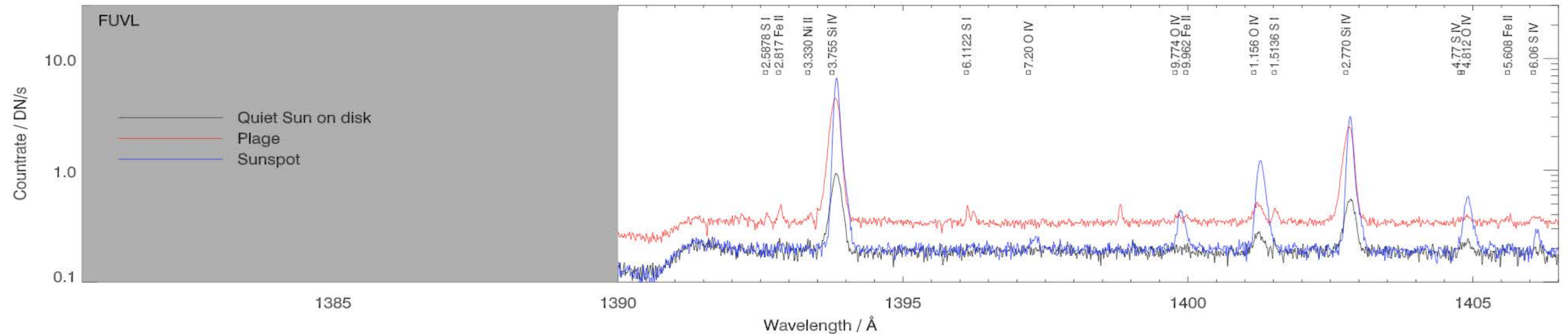
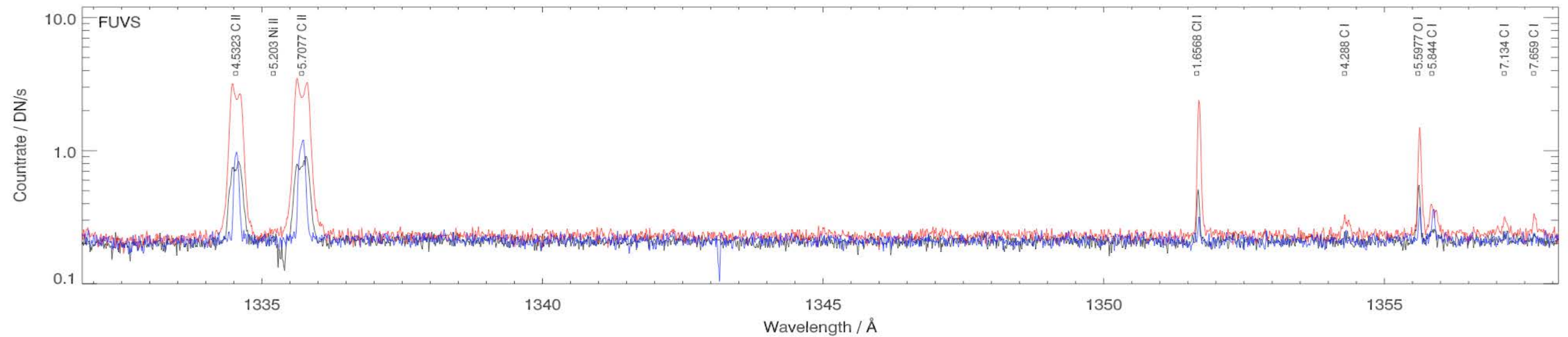
# IRIS observables: spectra, images, and sample observing sequences

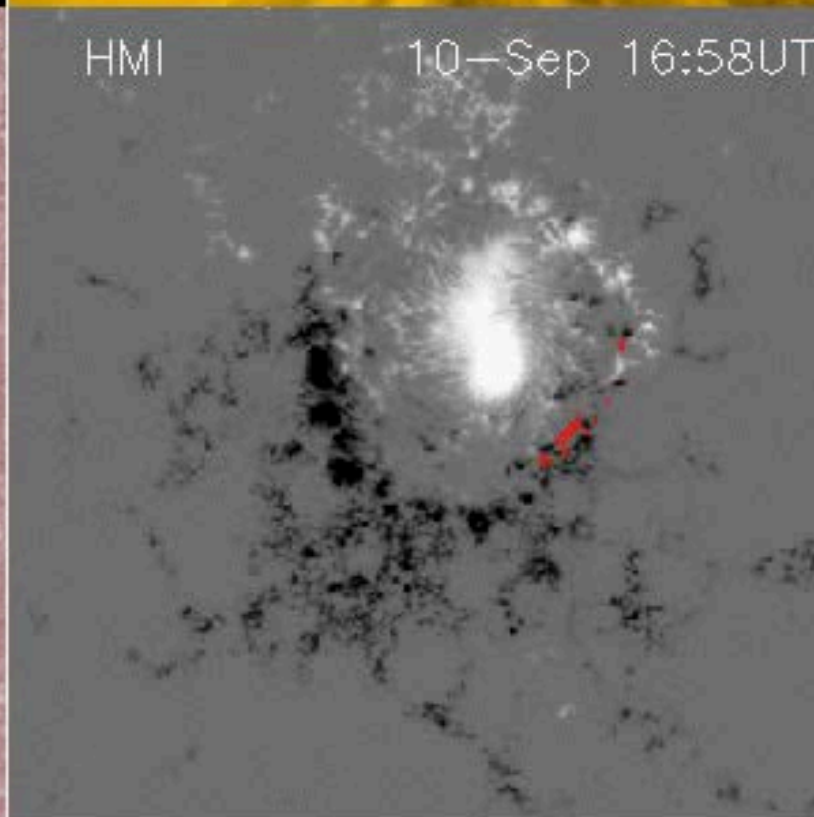
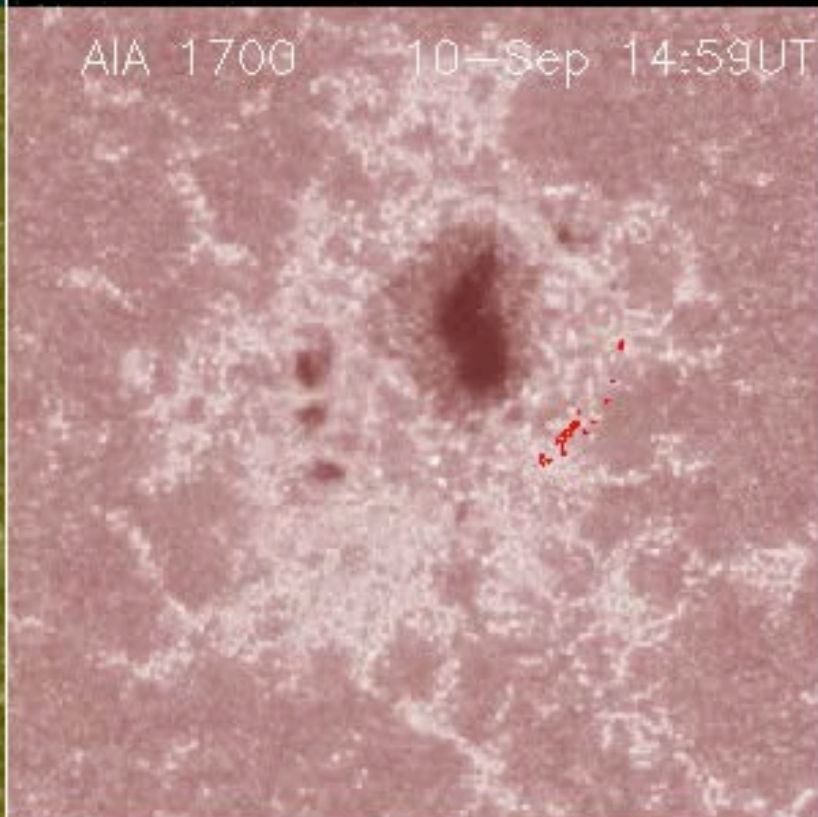
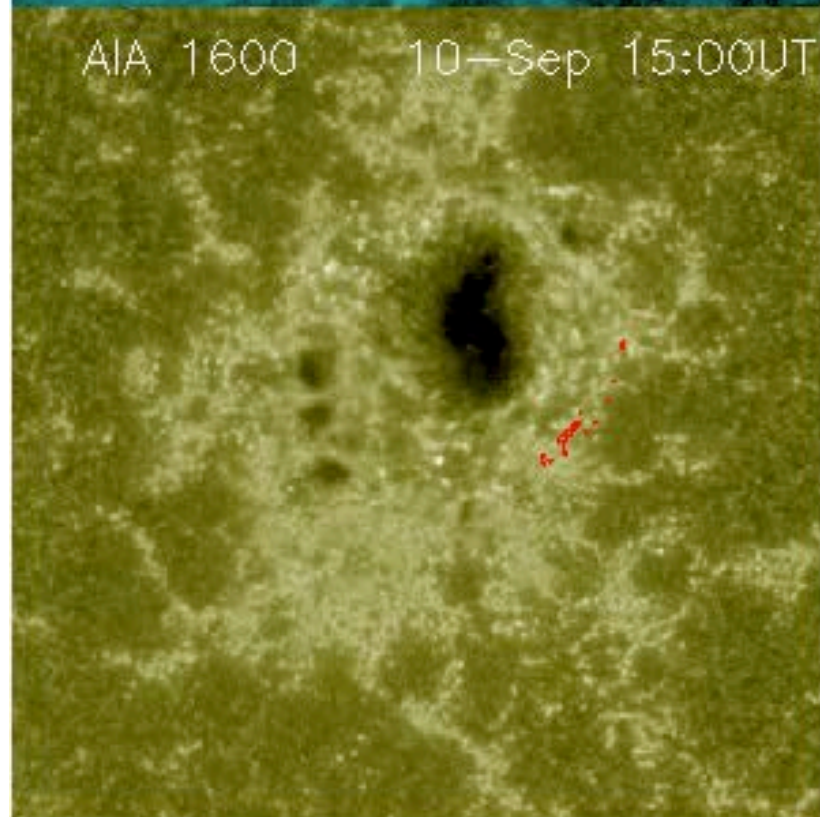
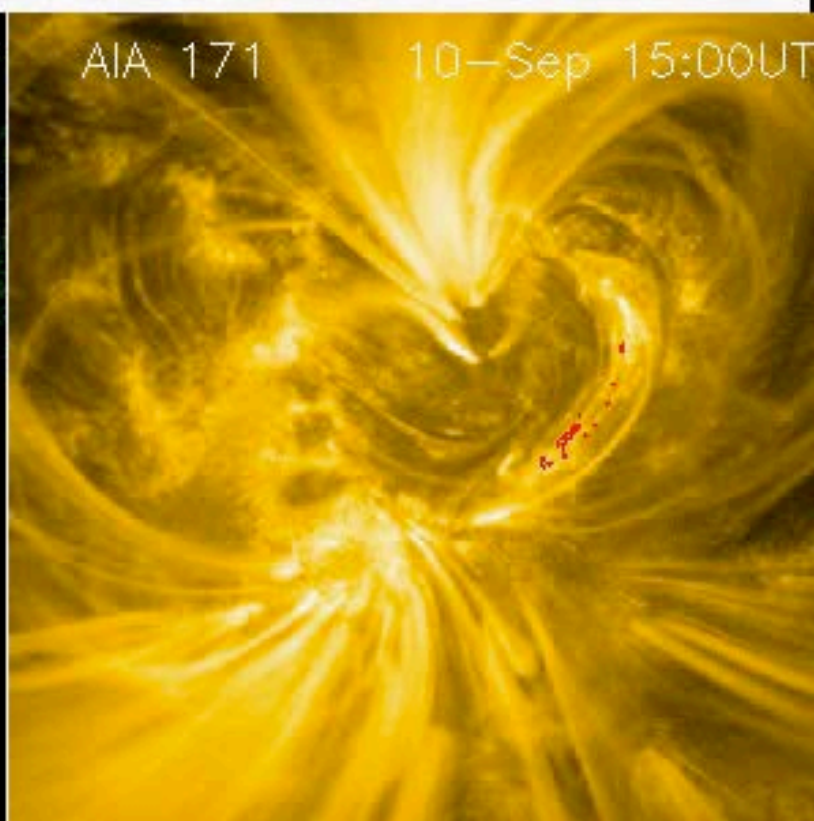
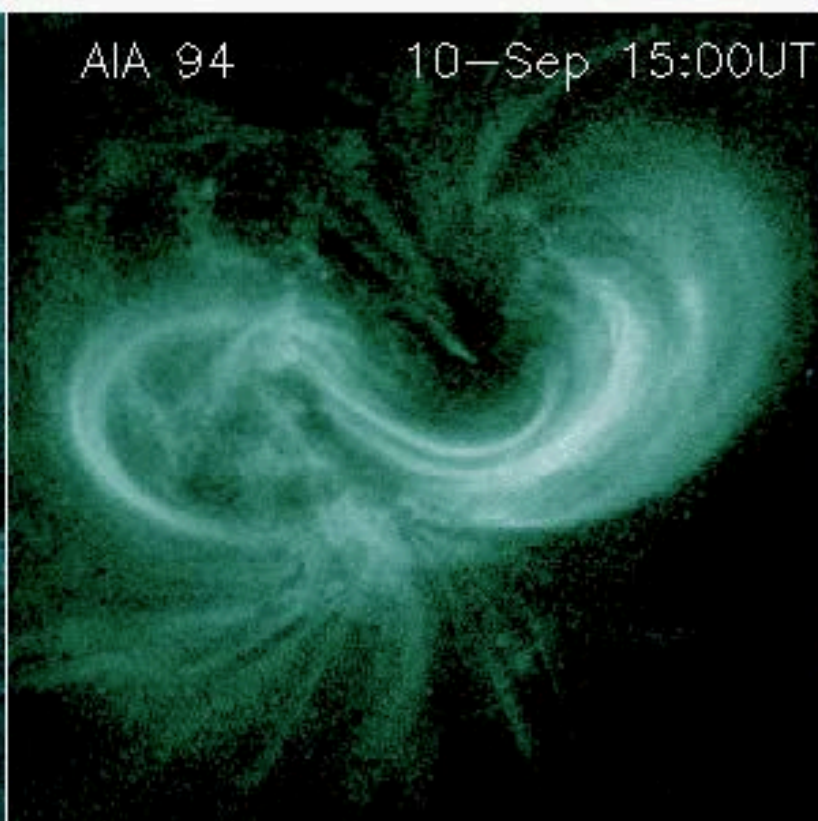
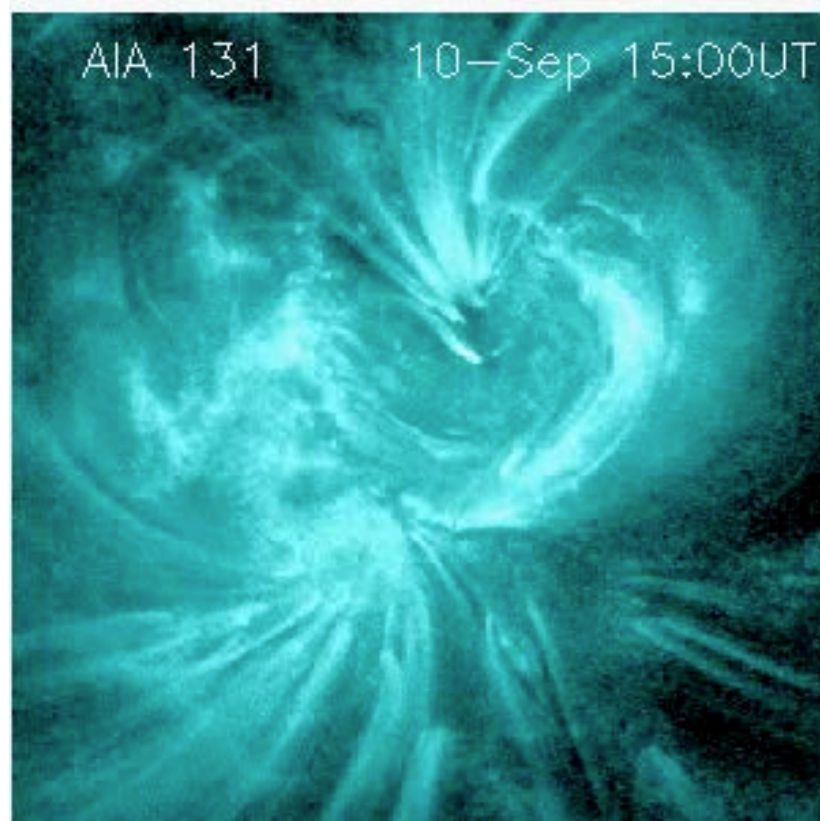
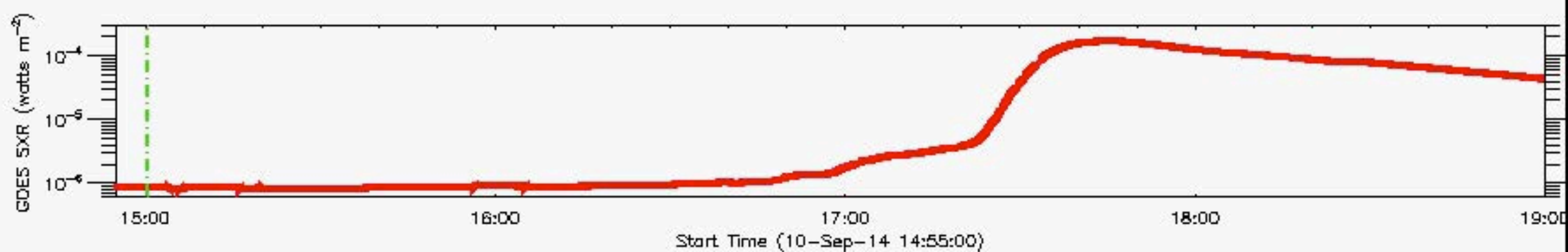


# Spectral Images

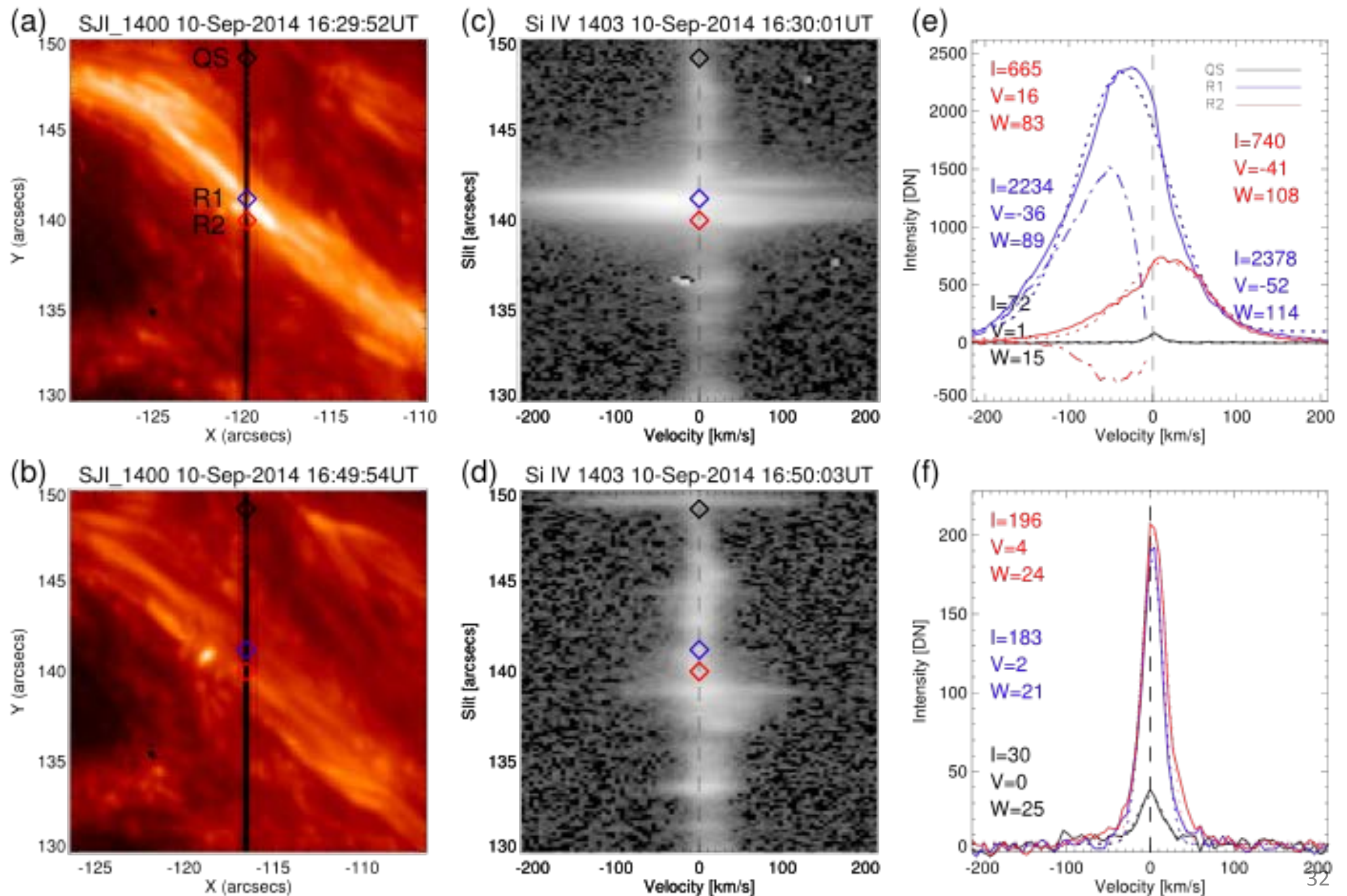


# Profiles of Spectra

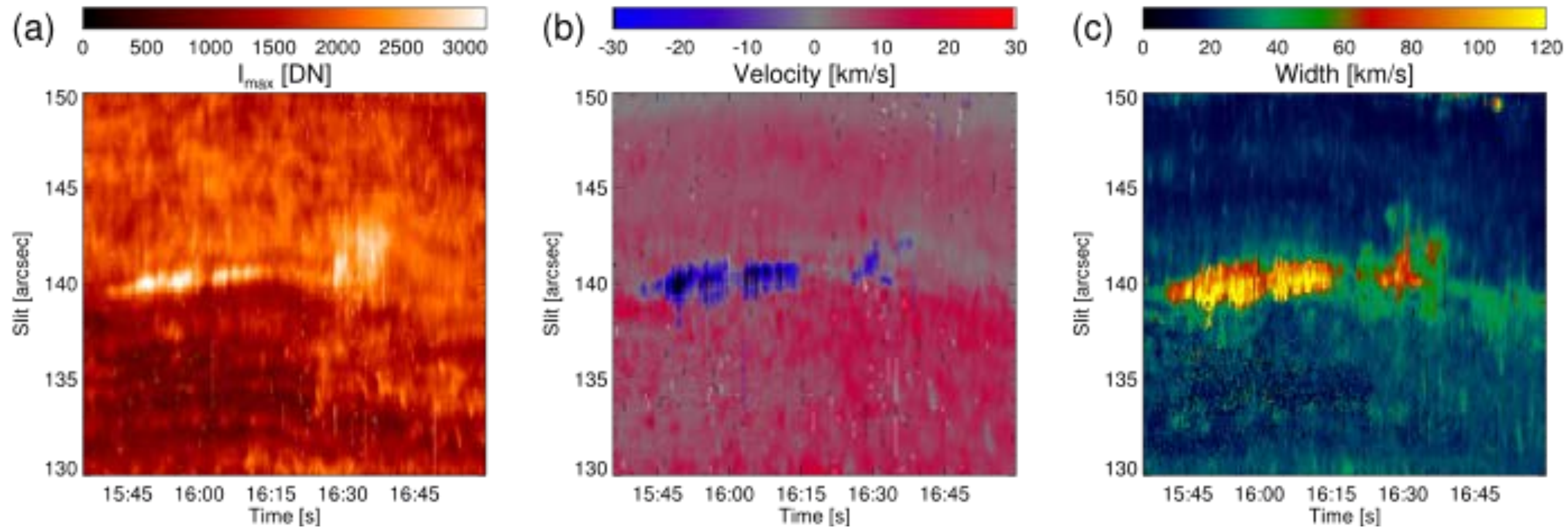




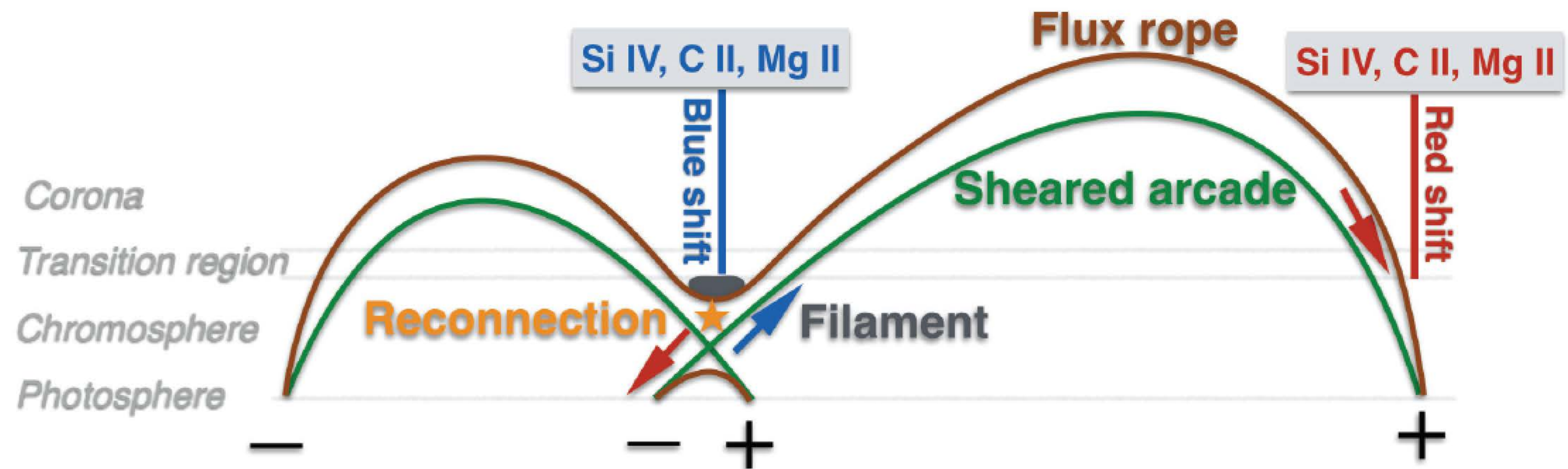
# 2014-September-10: Si IV



# 2014-September-10: Si IV



# 可能的形成机制



# 日冕物质抛射的开始和早期演化

# Initiation mechanisms

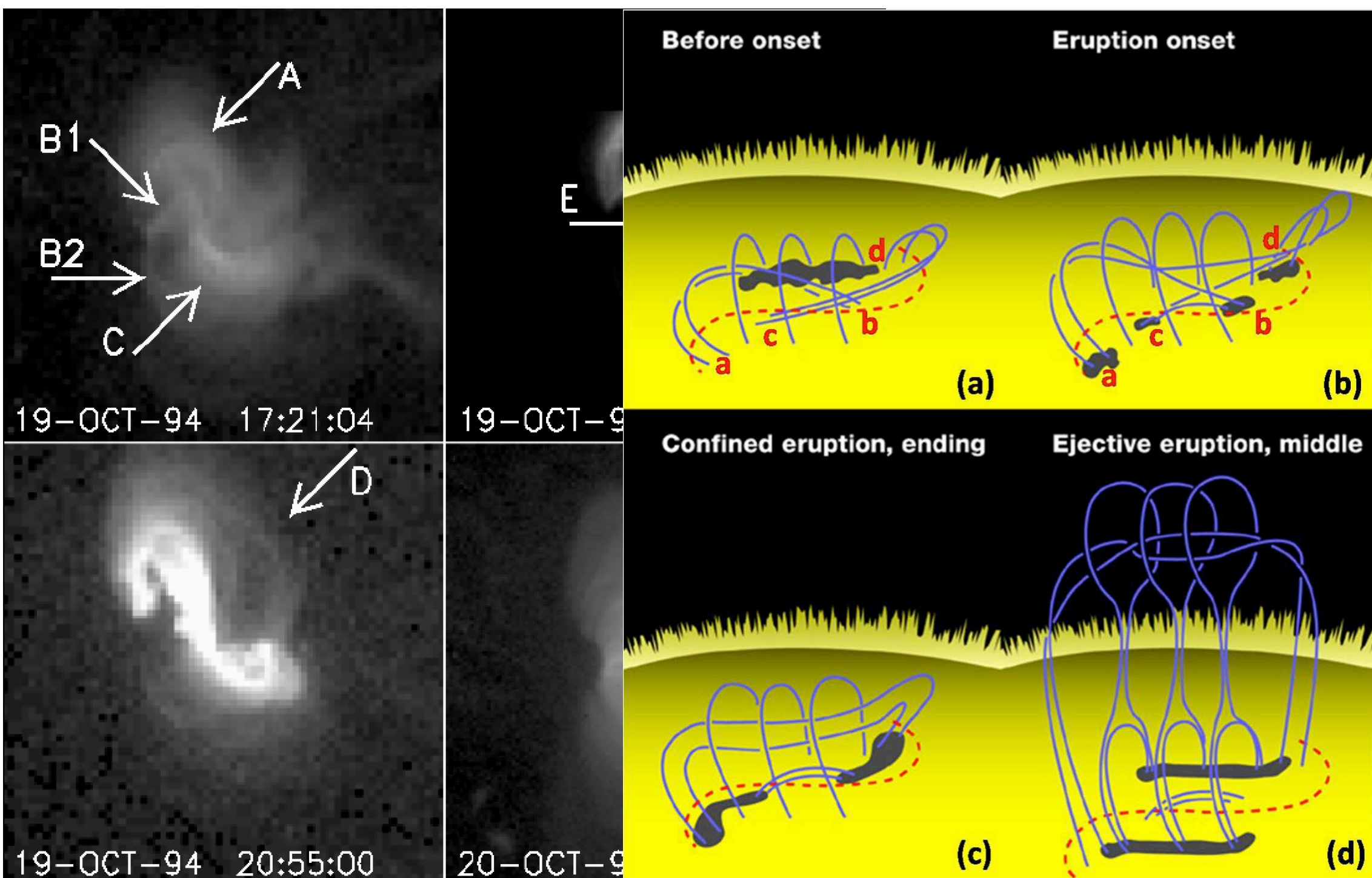
## Reconnection type

1. Tether-Cutting (Moore & Labonte 1980...)
2. Breakout (Antiochos et al. 1999)
3. Flux Emergence (Chen & Shibata 2000)

## Ideal MHD type

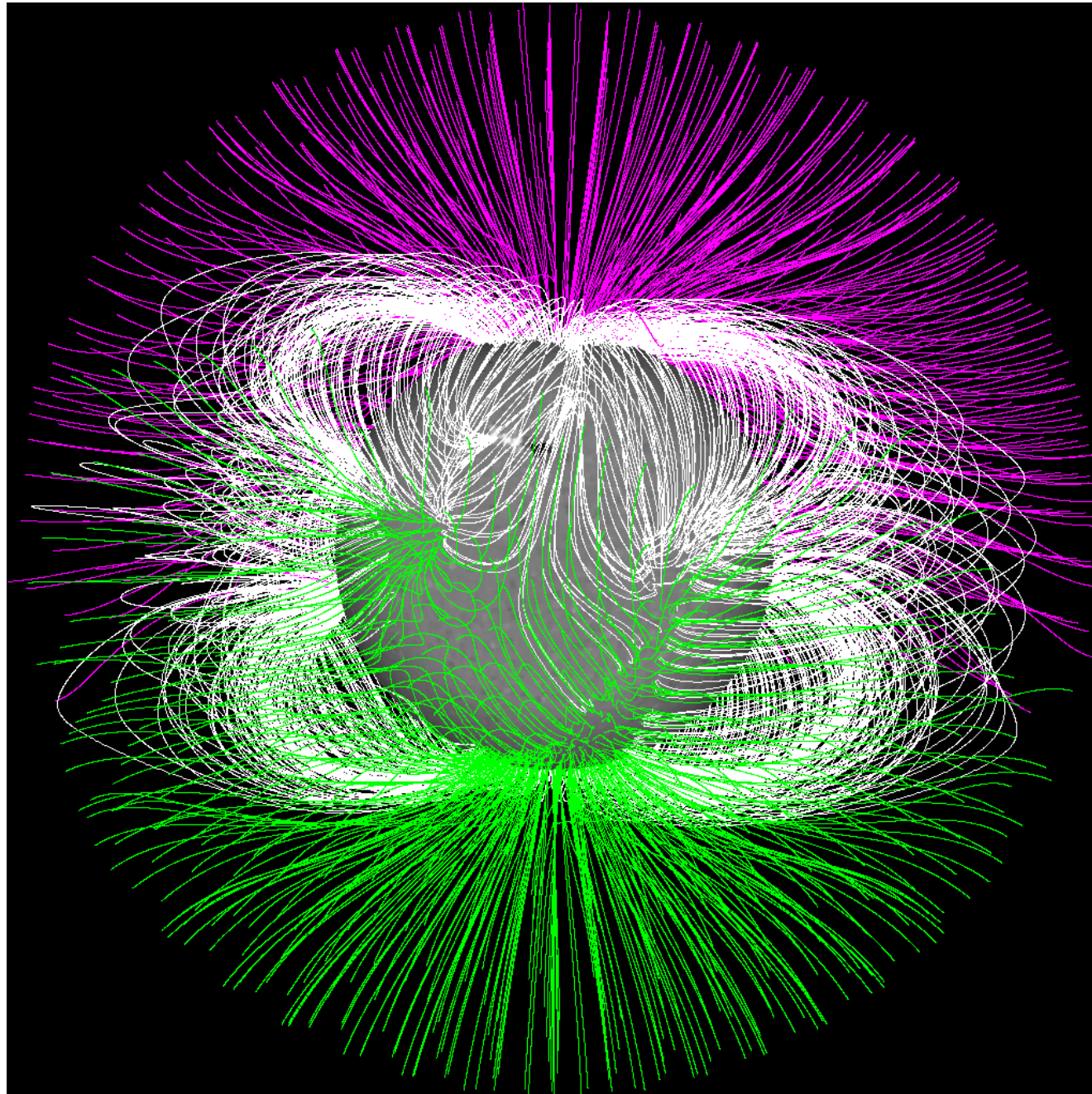
1. Partial Torus Instability (Olmedo & Zhang 2010...)
2. Kink Instability (Hood & Priest 1981...)
3. Loss of equilibrium (Forbes & Isenberg 1991...)

# Tether-Cutting

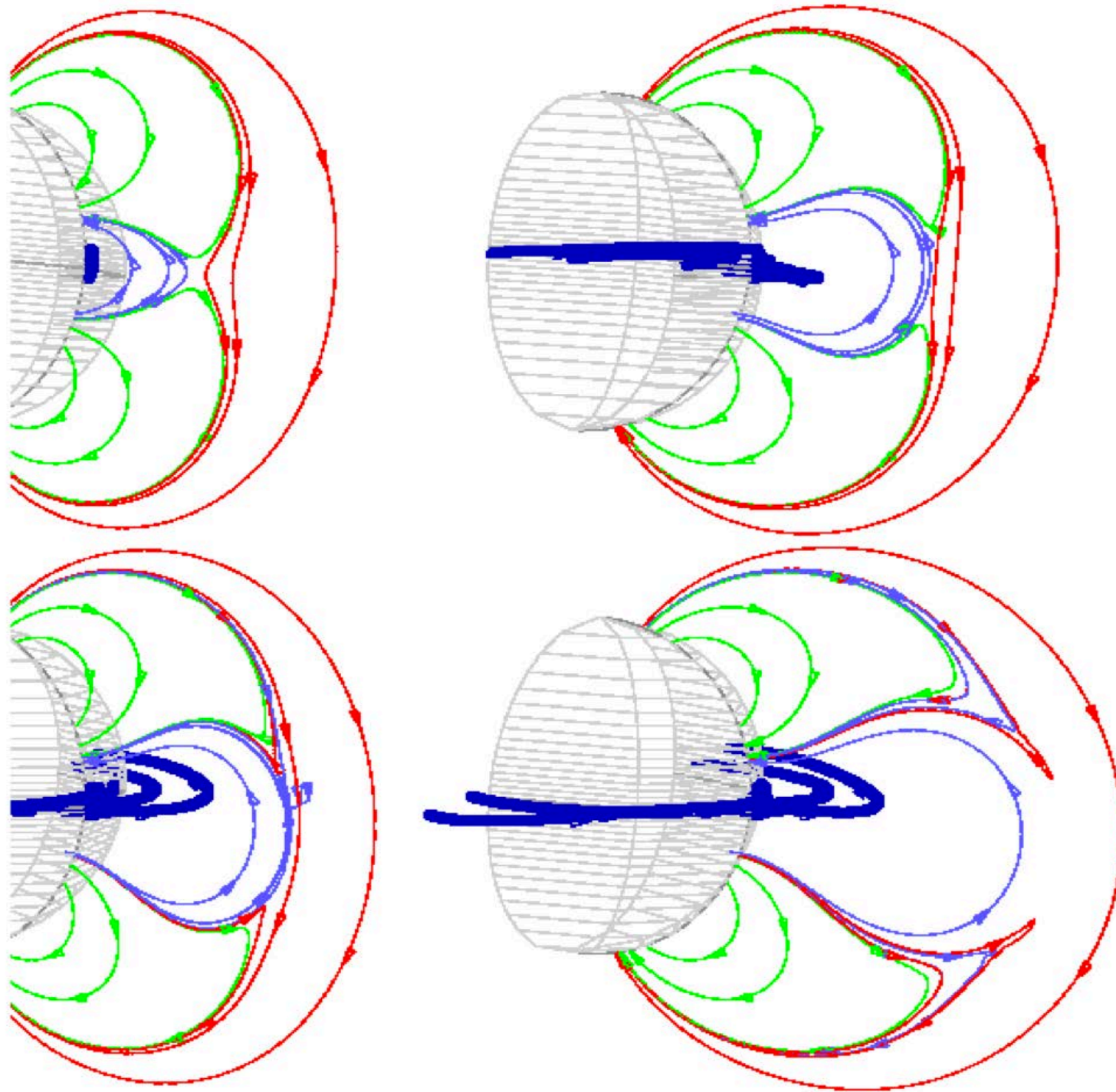


# Aly-Sturrock 限制

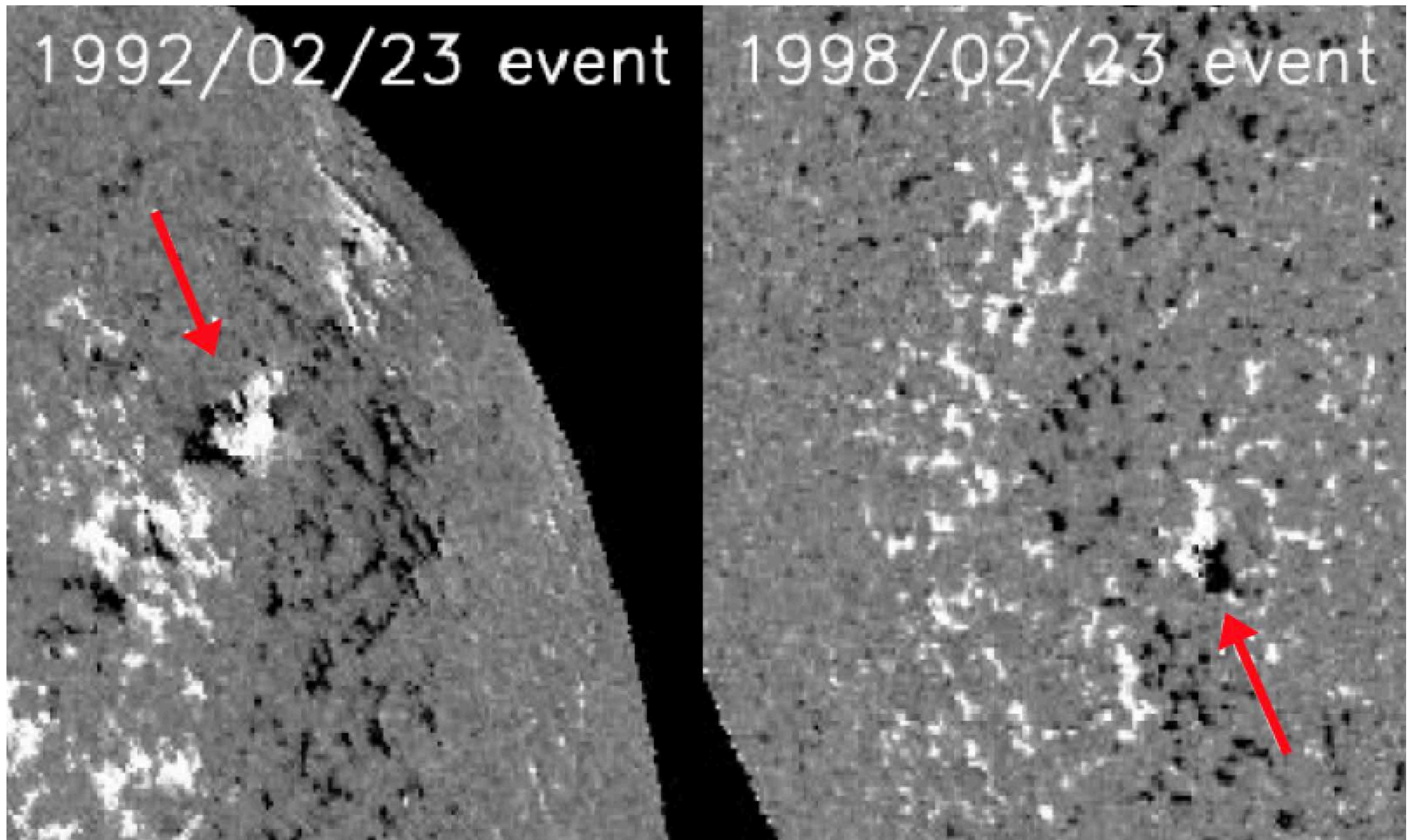
完全打开的磁场总是比对应的无力场拥有更多的磁能。



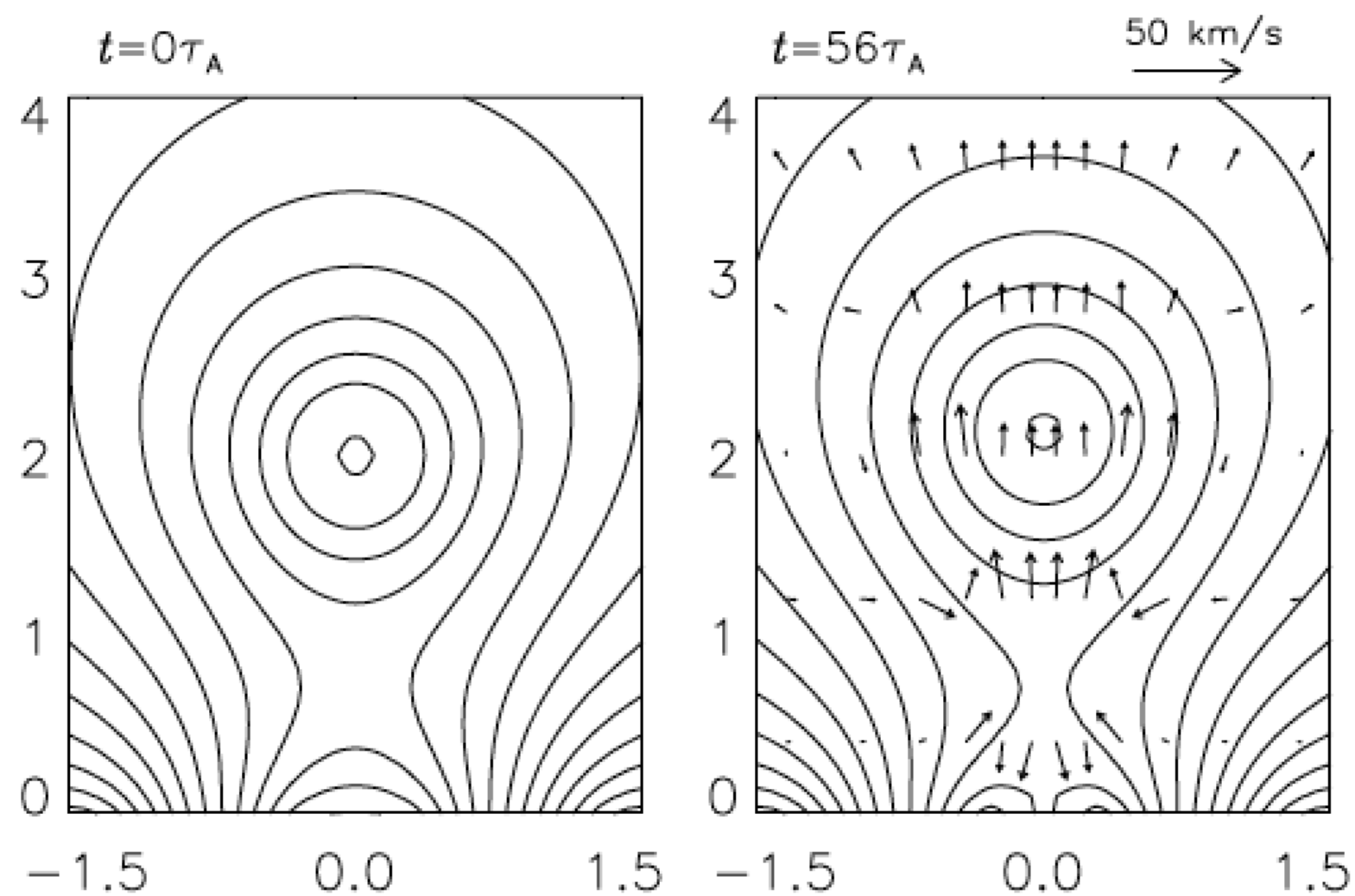
# Breakout model



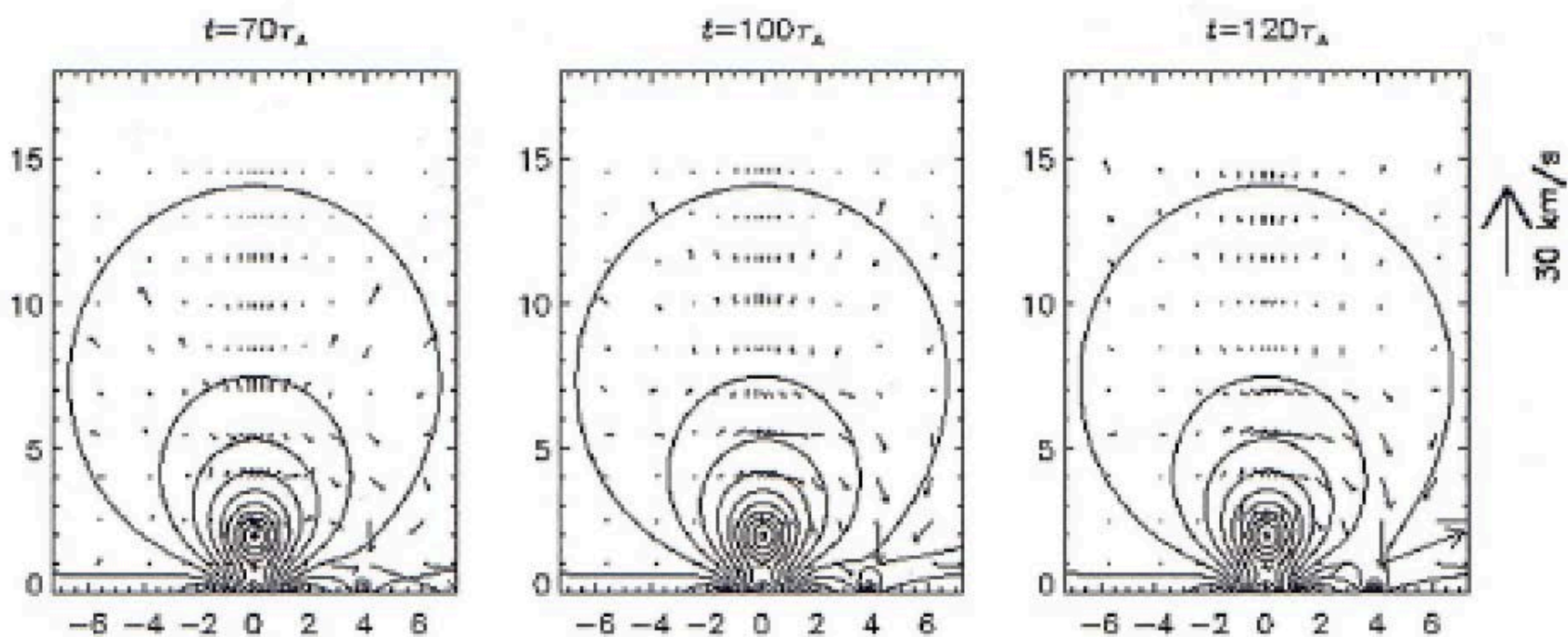
# Flux Emergence



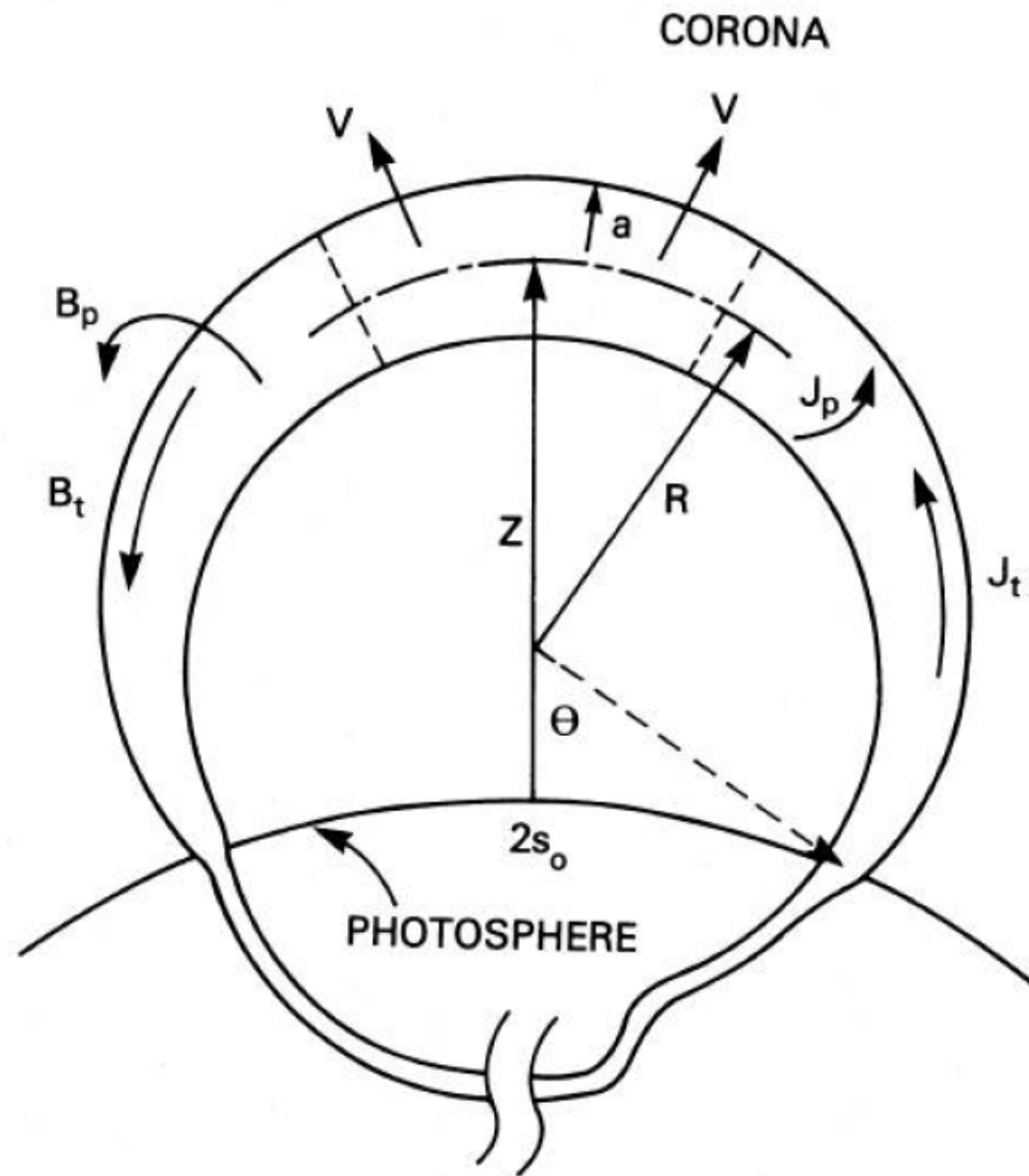
磁绳正下方浮现



磁绳侧下方浮现



# Ideal MHD instability: **Torus Instability**



(Shafranov 1966; Chen 1989;  
Kliem & Torok 2006)

那么磁绳顶点截面处的力密度可以写为:

$$f = \frac{1}{c} \mathbf{J} \times \mathbf{B}.$$

对整个截面积分得到顶点处等离子体元的运动方程:

$$M \frac{d^2 Z}{dt^2} = \frac{I_t^2}{c^2 R} \left[ \left( \ln \left( \frac{8R}{a} \right) - 2 + \frac{\xi_i}{2} \right) - \frac{1}{2} \frac{B_t^2 - B_{et}^2}{B_p^2} + 2 \frac{R}{a} \frac{B_s}{B_p} + 1 \right],$$

**轴向电流产生  
的自身电感**

$$M \frac{d^2 a}{dt^2} = \frac{I_t^2}{c^2 a} \left[ \frac{B_t^2 - B_{et}^2}{B_p^2} - 1 \right],$$

电流环的轴向电流为 $\mathbf{J}_t$ 、环向电流为 $\mathbf{J}_p$ 、轴向磁场为 $\mathbf{B}_t$ 、环向磁场为 $\mathbf{B}_p$ 、背景的轴向磁场为 $\mathbf{B}_{et}$ 、环向磁场为 $\mathbf{B}_s$ 、电流环的大半径为 $R$ 、小半径为 $a$ 、顶点高度为 $Z$ 、足点分离距离为 $2S_0$

$$\frac{d^2 \delta Z}{dt^2} = \Gamma^2 \delta Z.$$

$$\Gamma^2 = \frac{I_t^2}{c^2 R M} \frac{\Delta}{Z} \left[ \frac{2Z}{R} \frac{dR}{dZ} + \left( \frac{Z}{\Theta} \frac{d\Theta}{dZ} + \frac{Z}{c L_p I_t} \frac{d\Phi_s}{dZ} \right) \frac{1 - 1/\Delta}{1 + 1/\hat{L}} - n \right].$$

$$n \equiv - \frac{Z}{B_s} \frac{dB_s}{dZ}.$$

$n$ 表示磁场的高度衰减,  $\Theta$ 表示部分电流环在光球以上的弧长占相同半径电流环总周长的比。

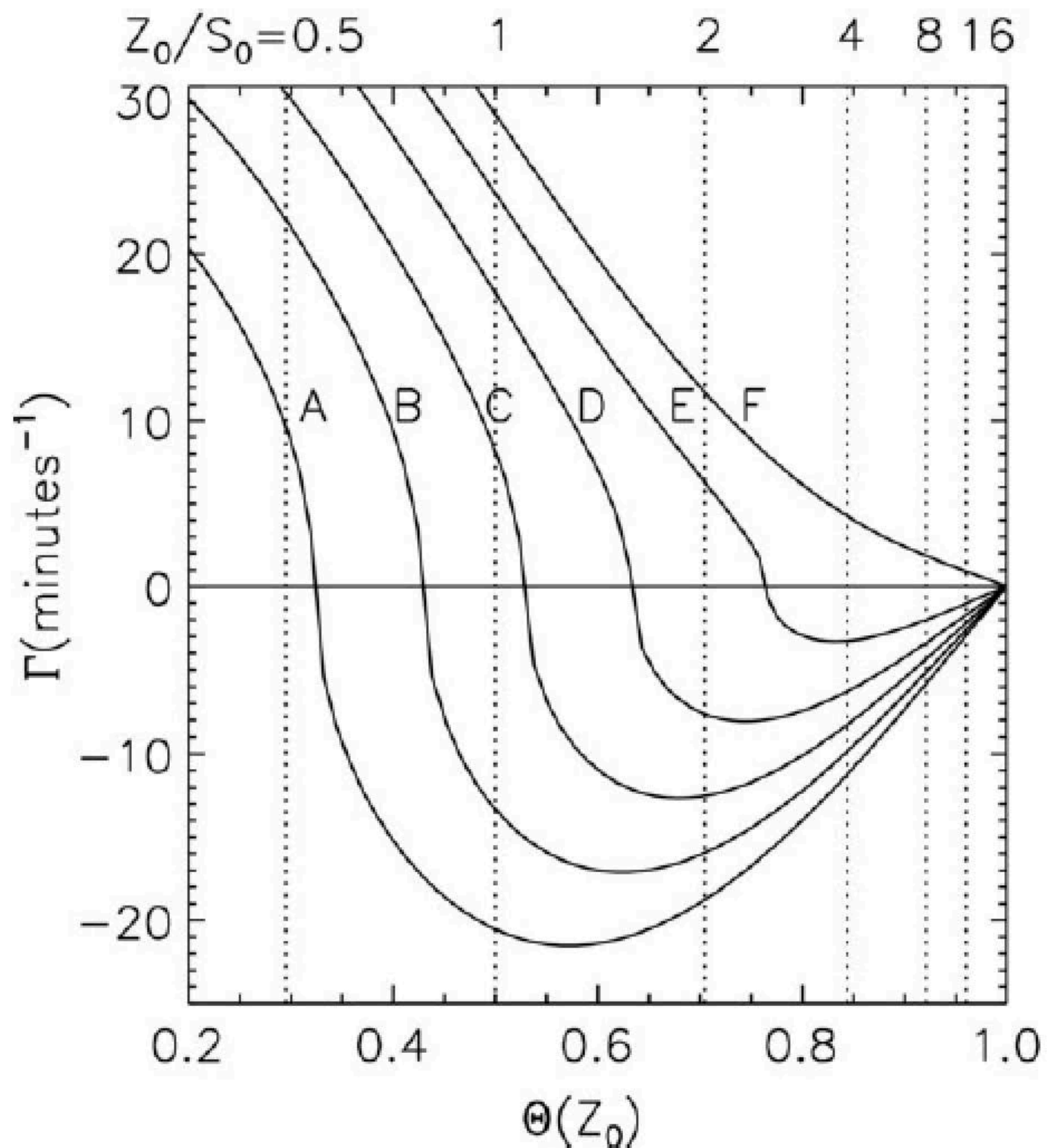
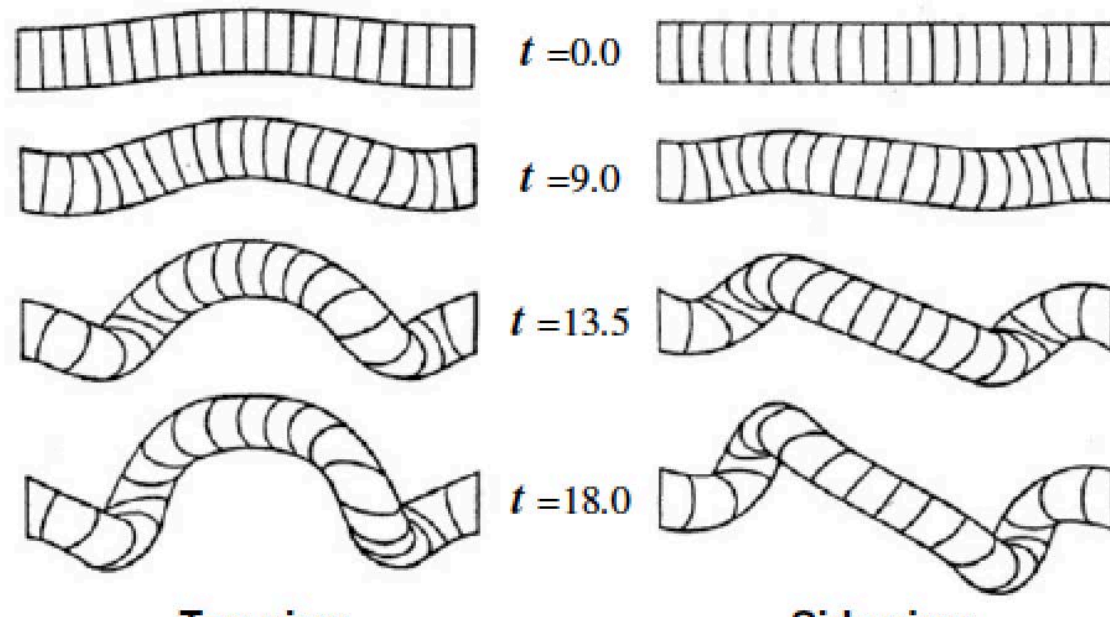


图 2.5 部分电流环不稳定性模型中磁绳扰动方程的解，实线A–F表示背景环向磁场强度的衰减指数 $n$ 从-0.25变化到2.25。其中，正的 $\Gamma$ 值表示磁绳不稳定性的指数增长，而负的 $\Gamma$ 值表示不稳定性的振荡频率 (Olmedo & Zhang, 2010)。

# Ideal MHD instability: Kink **Instability**



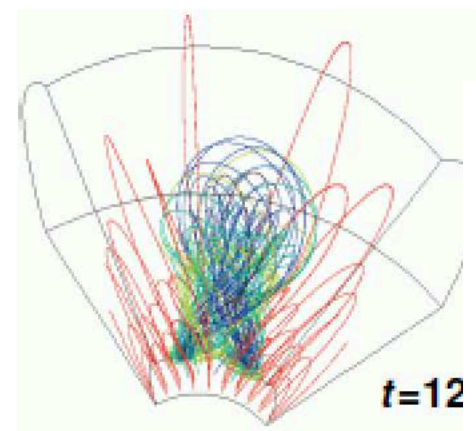
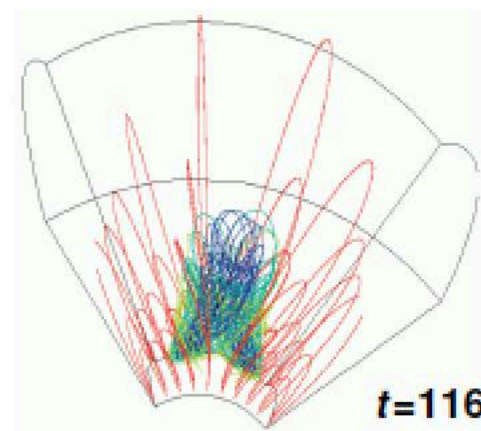
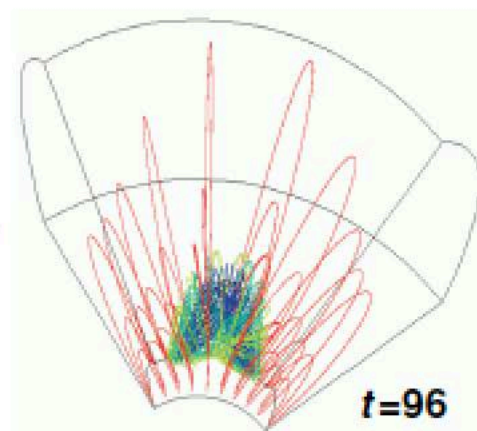
Controlled by the **total twist**:

$$\Phi = \frac{lB_{\phi}(r)}{rB_z(r)},$$

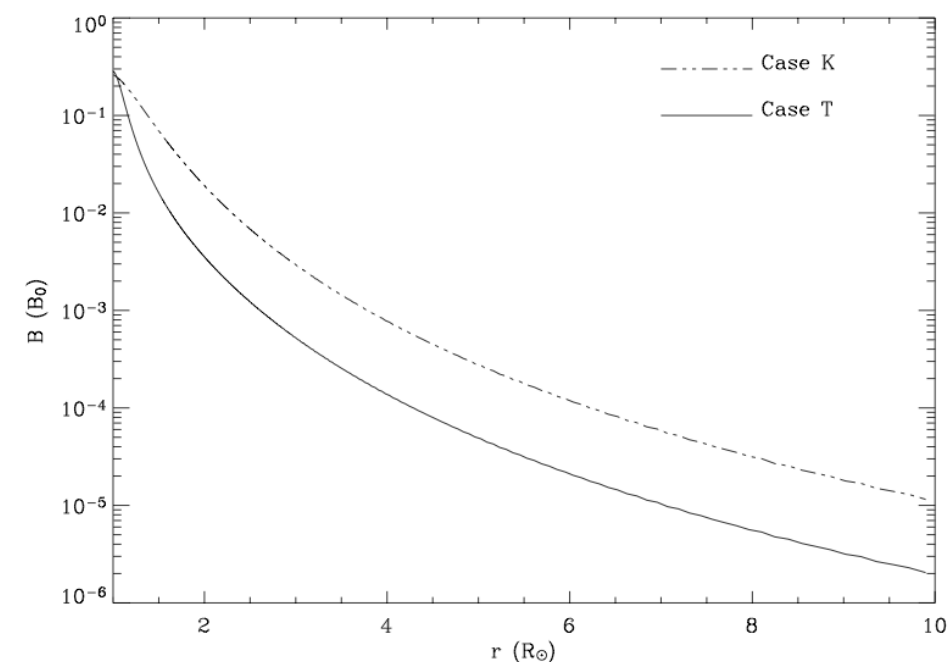
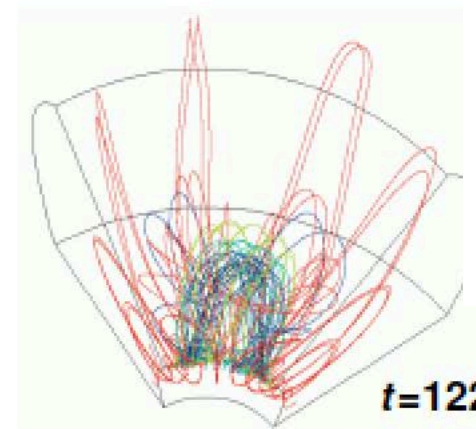
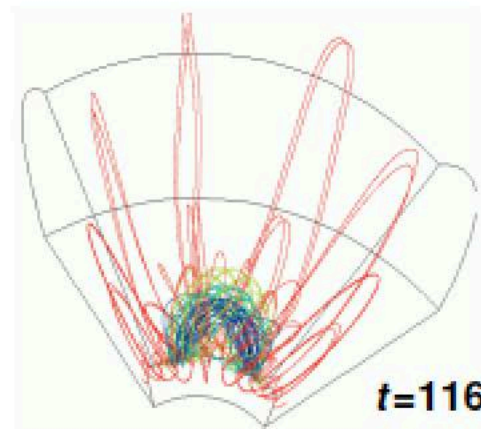
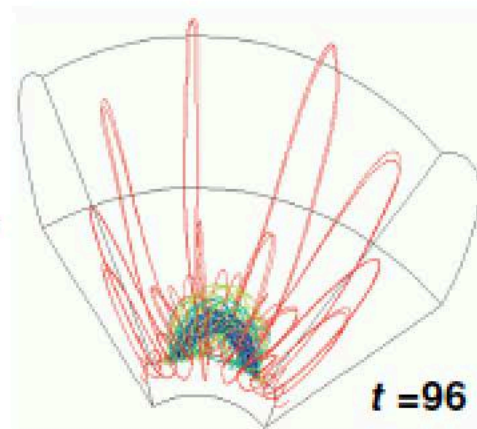
where  $l$  is the length of the current-carrying flux system,  $r$  is the (minor) radius, and  $B_z$  and  $B_{\phi}$  are the axial and azimuthal field components, respectively.

(Hood & Priest 1981; Torok & Kliem. 2003)

Kink  
Instability



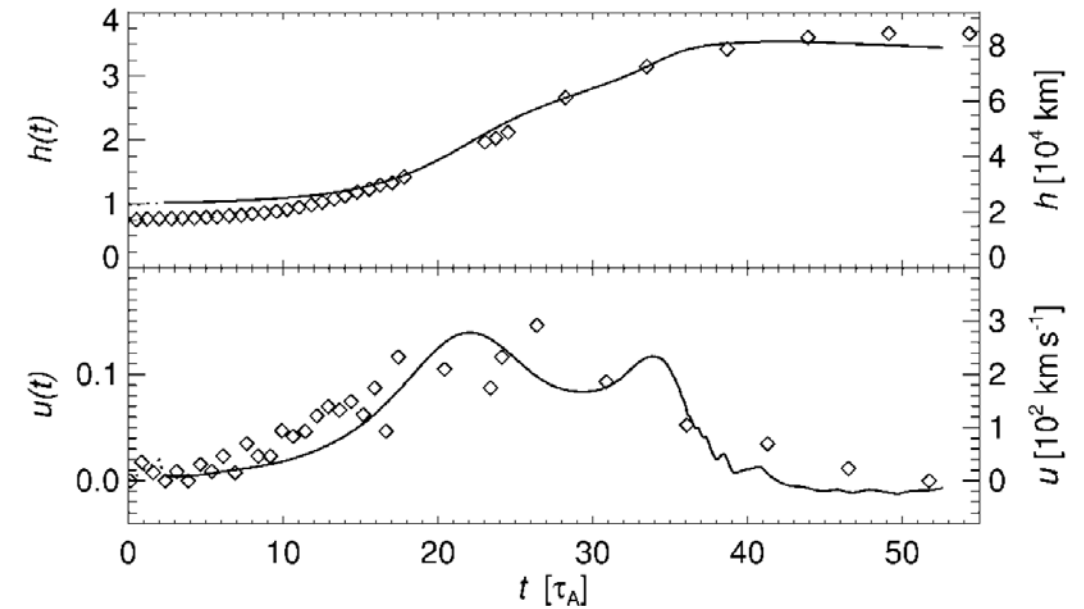
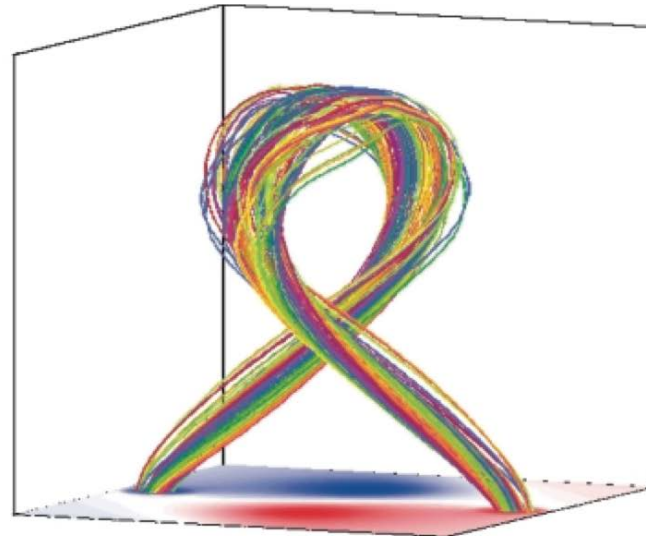
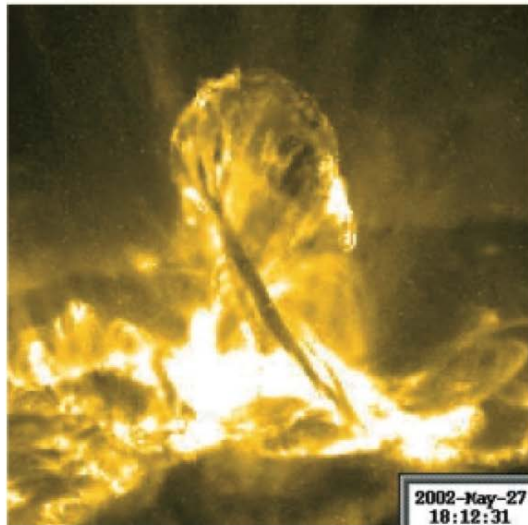
Torus  
Instability



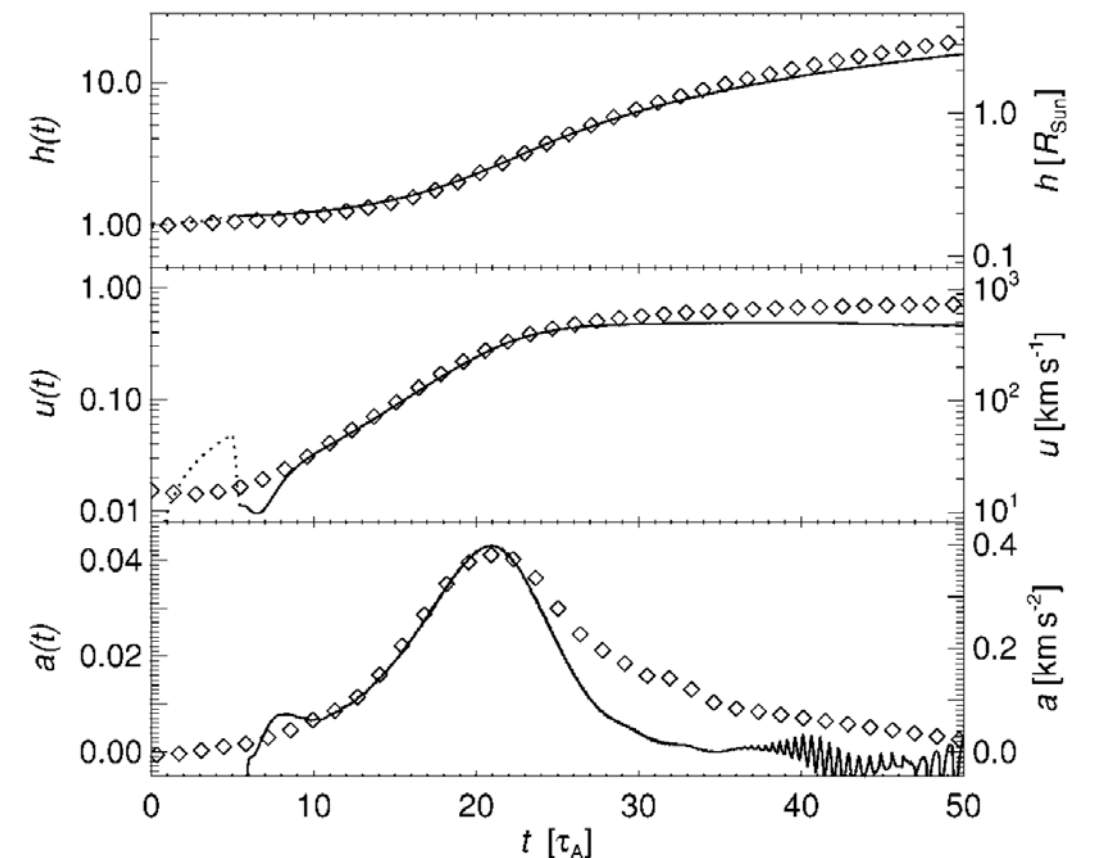
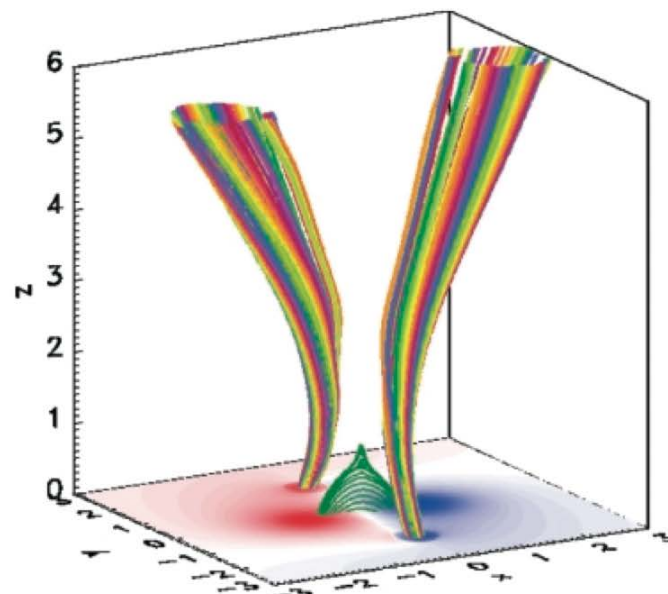
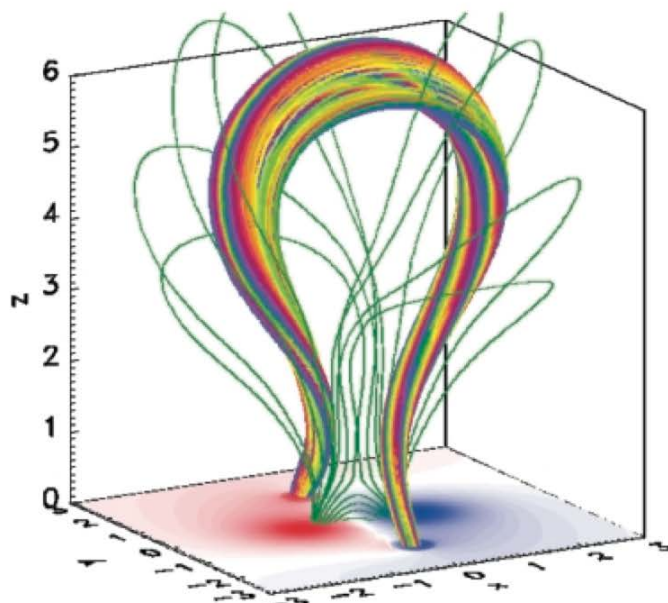
(Fan et al. 2014)

# Confined and Eruptive Eruption

$n=0.83$

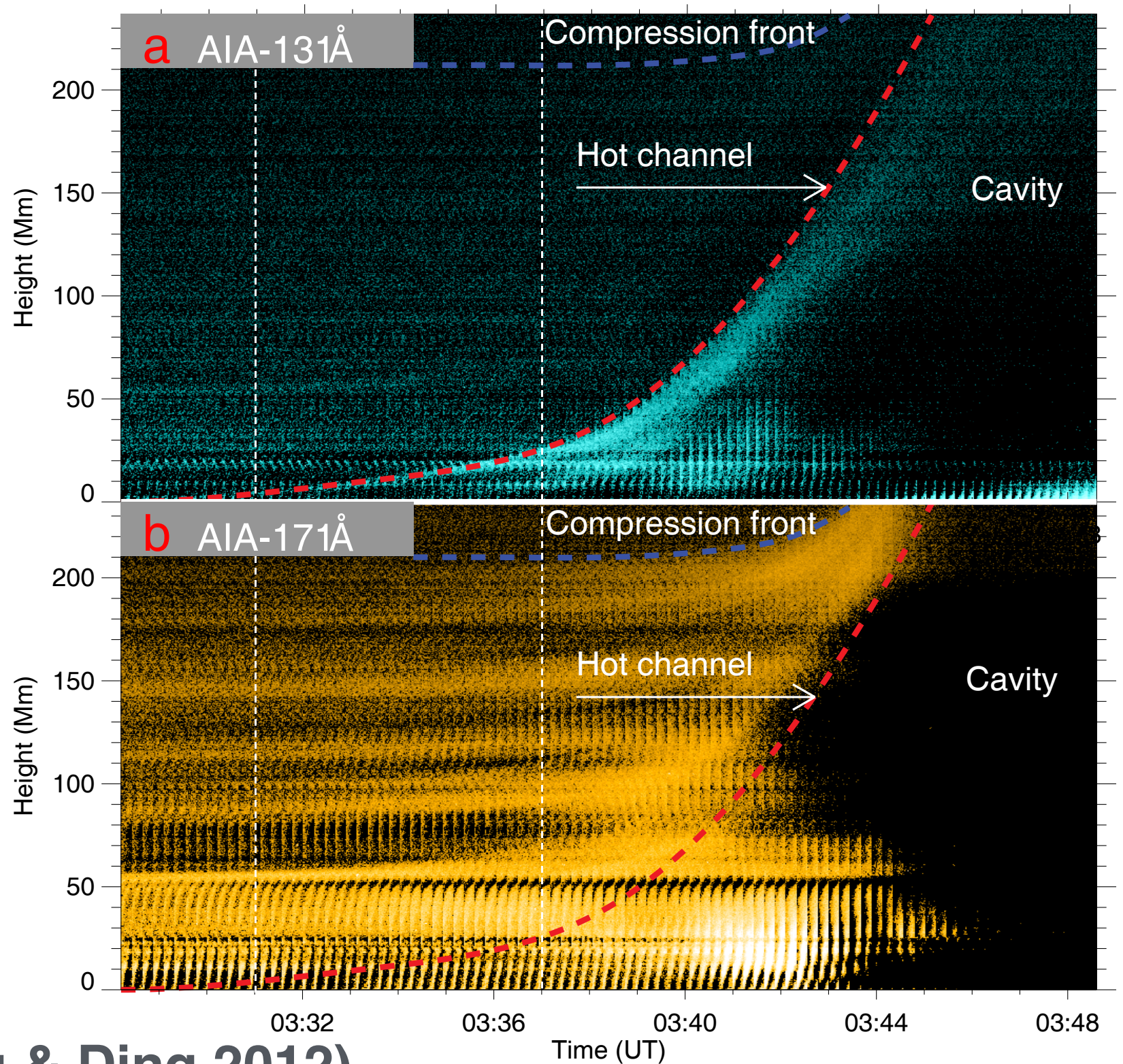
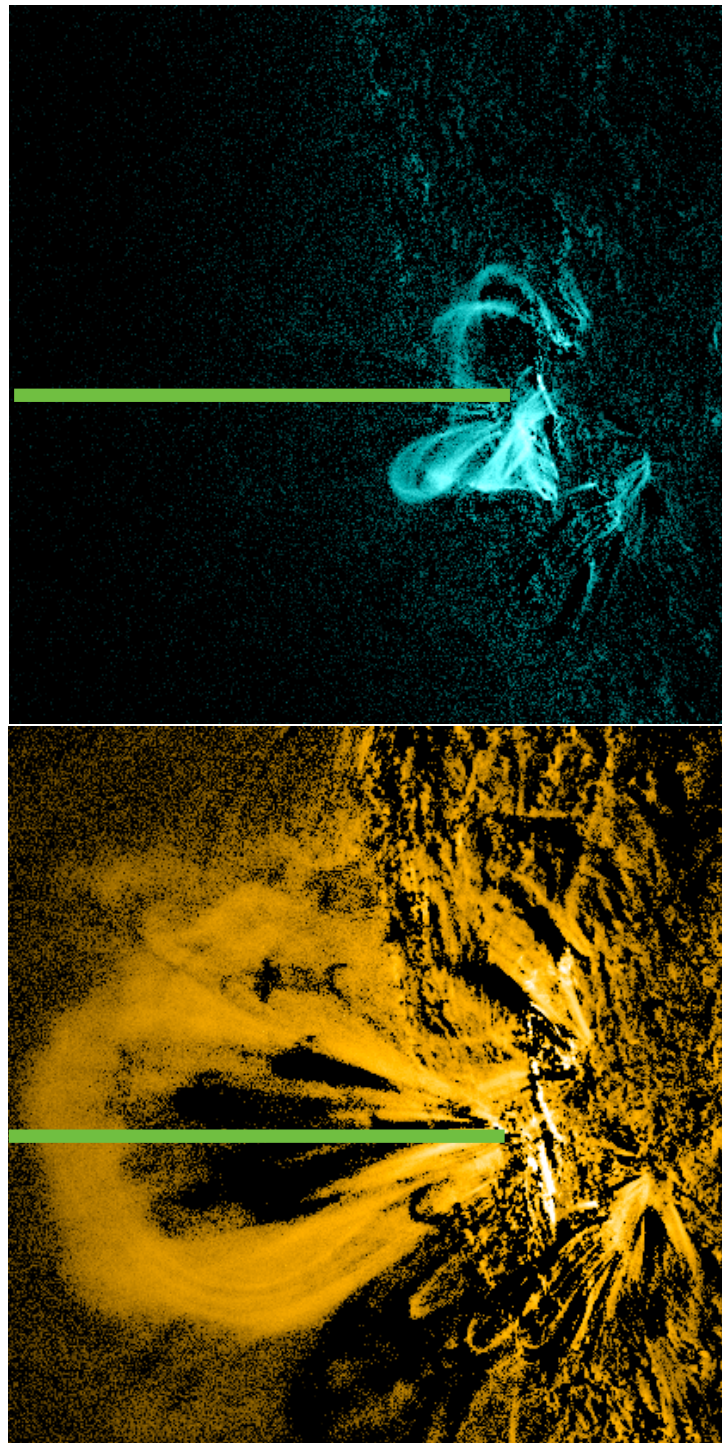


$n=1.54$



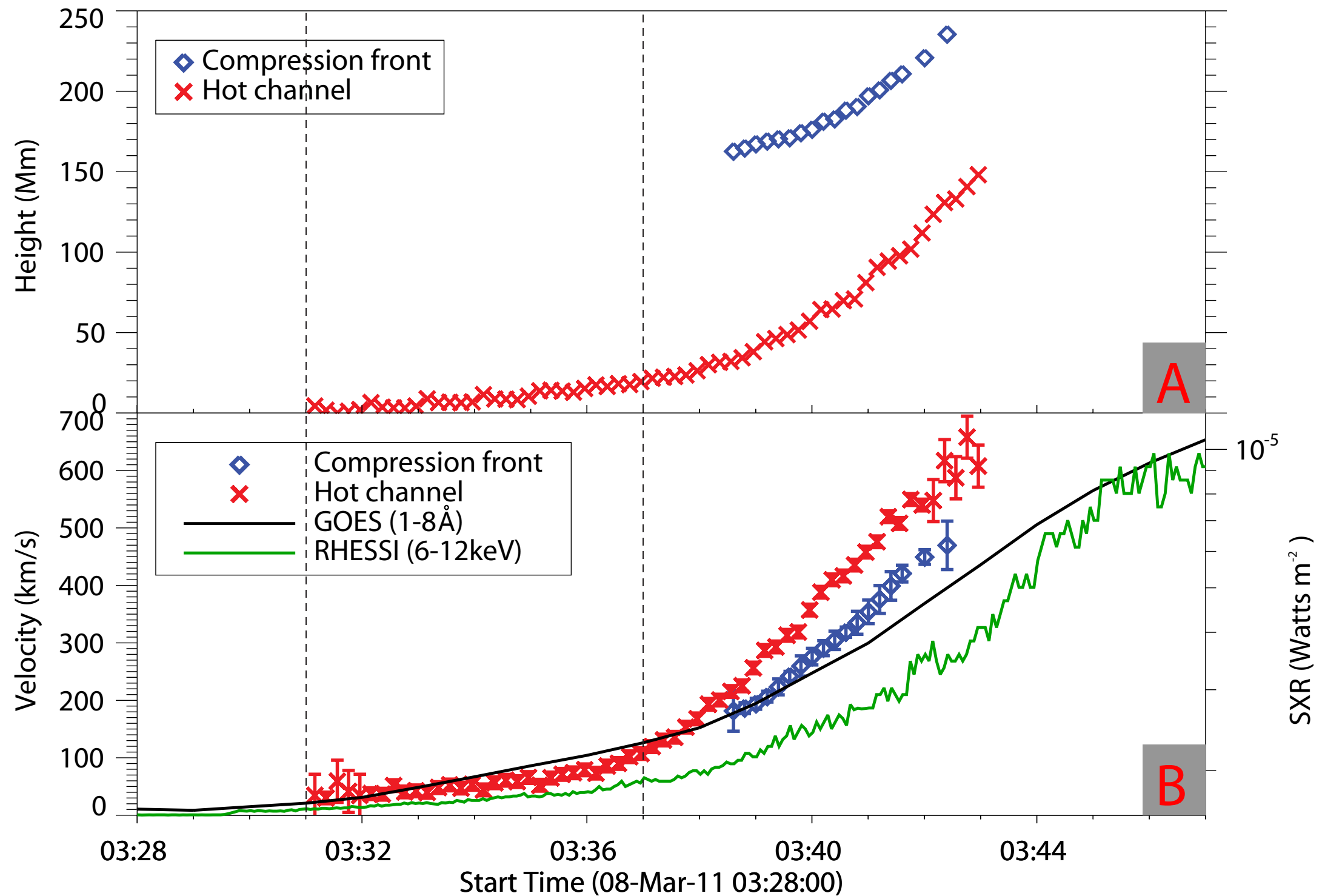
(Ji et al. 2003; Torok & Kliem 2005)

# 磁绳在CME早期演化中的作用



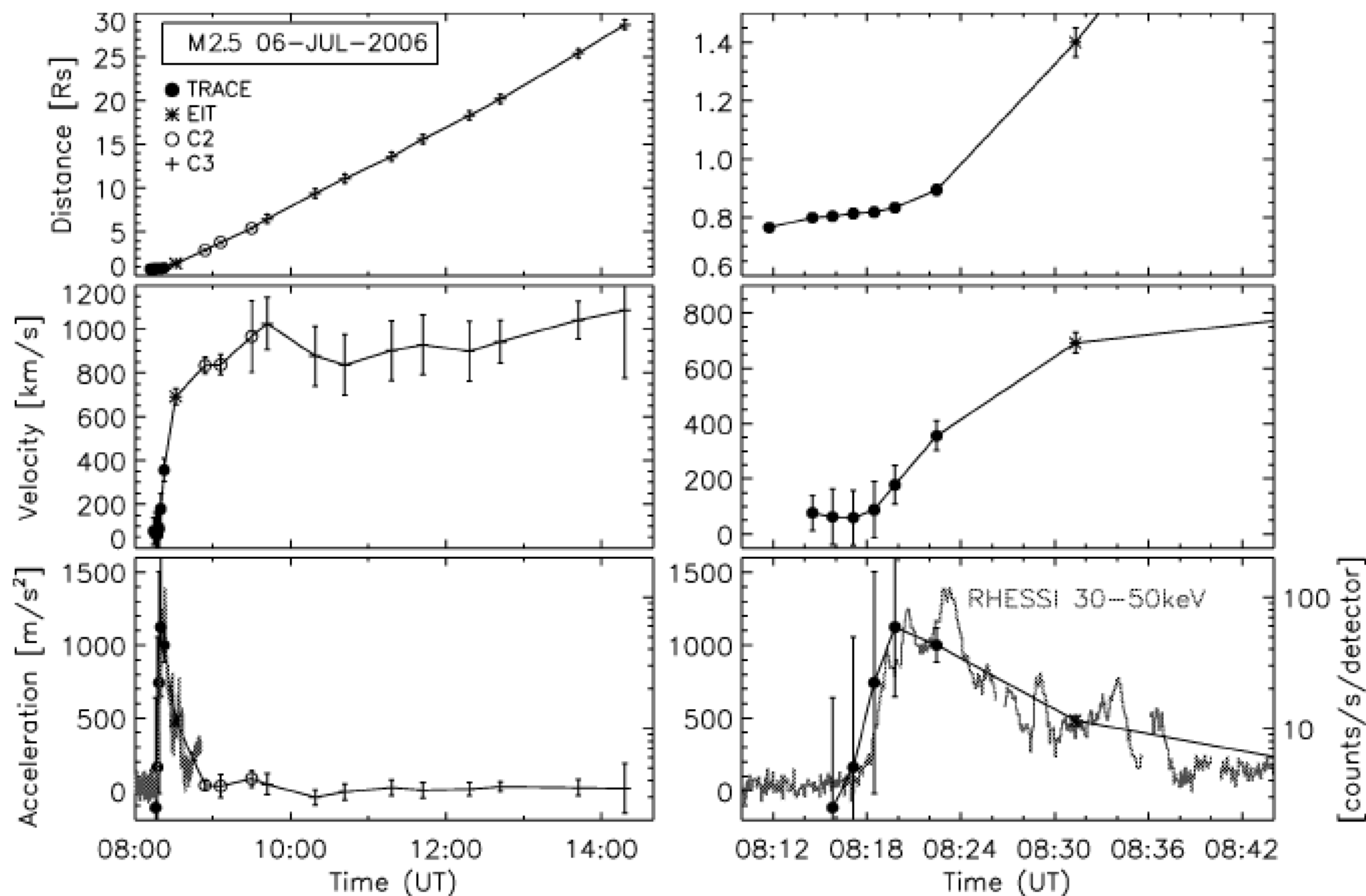
(Zhang, Cheng & Ding 2012)

# Role of MFR in forming and accelerating CME



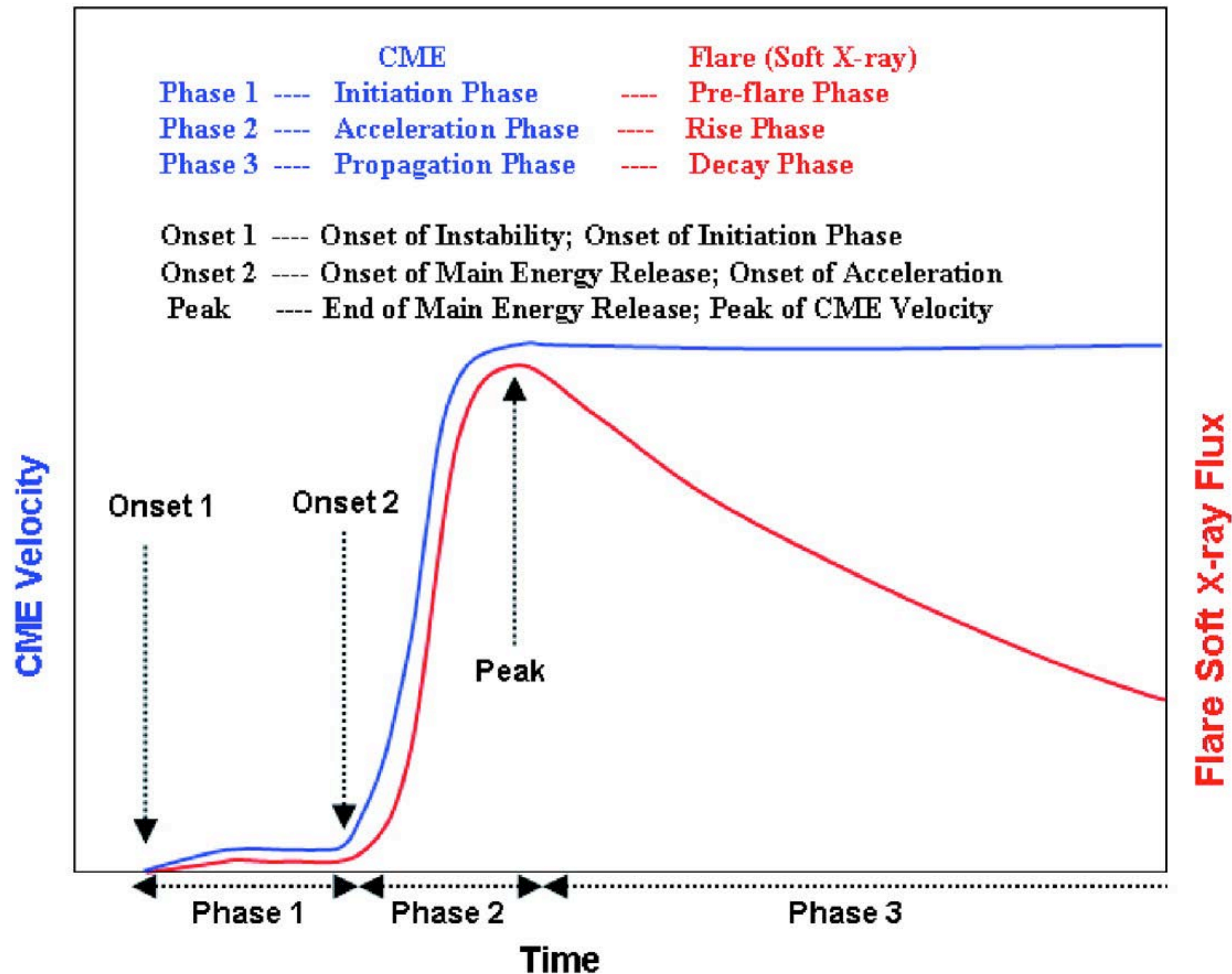
(Zhang, Cheng & Ding 2012; Cheng et al. 2013a, 2014a)

# 耀斑硬X射线和CME加速的关系



# CME理论模型

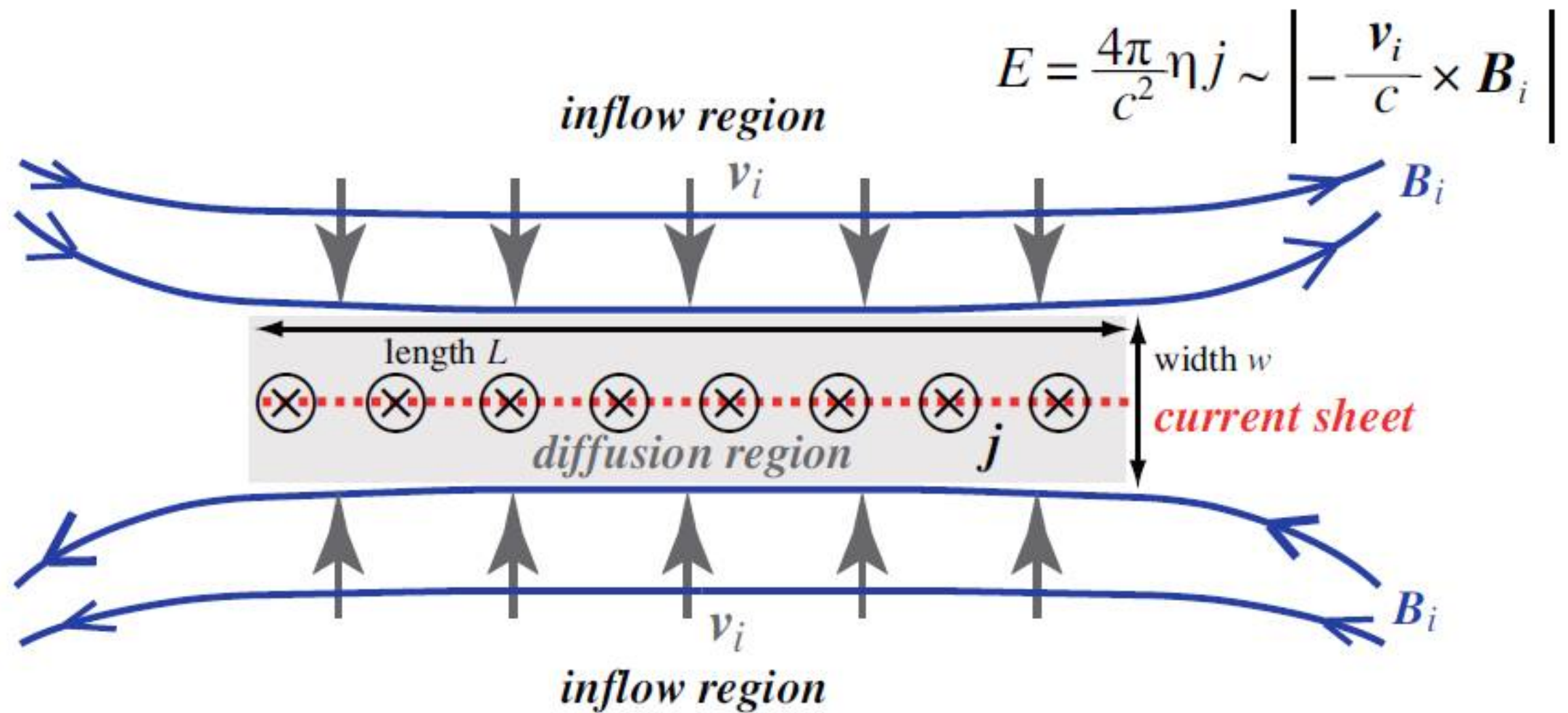
CME Kinematic Evolution and Timing with Associated Flare



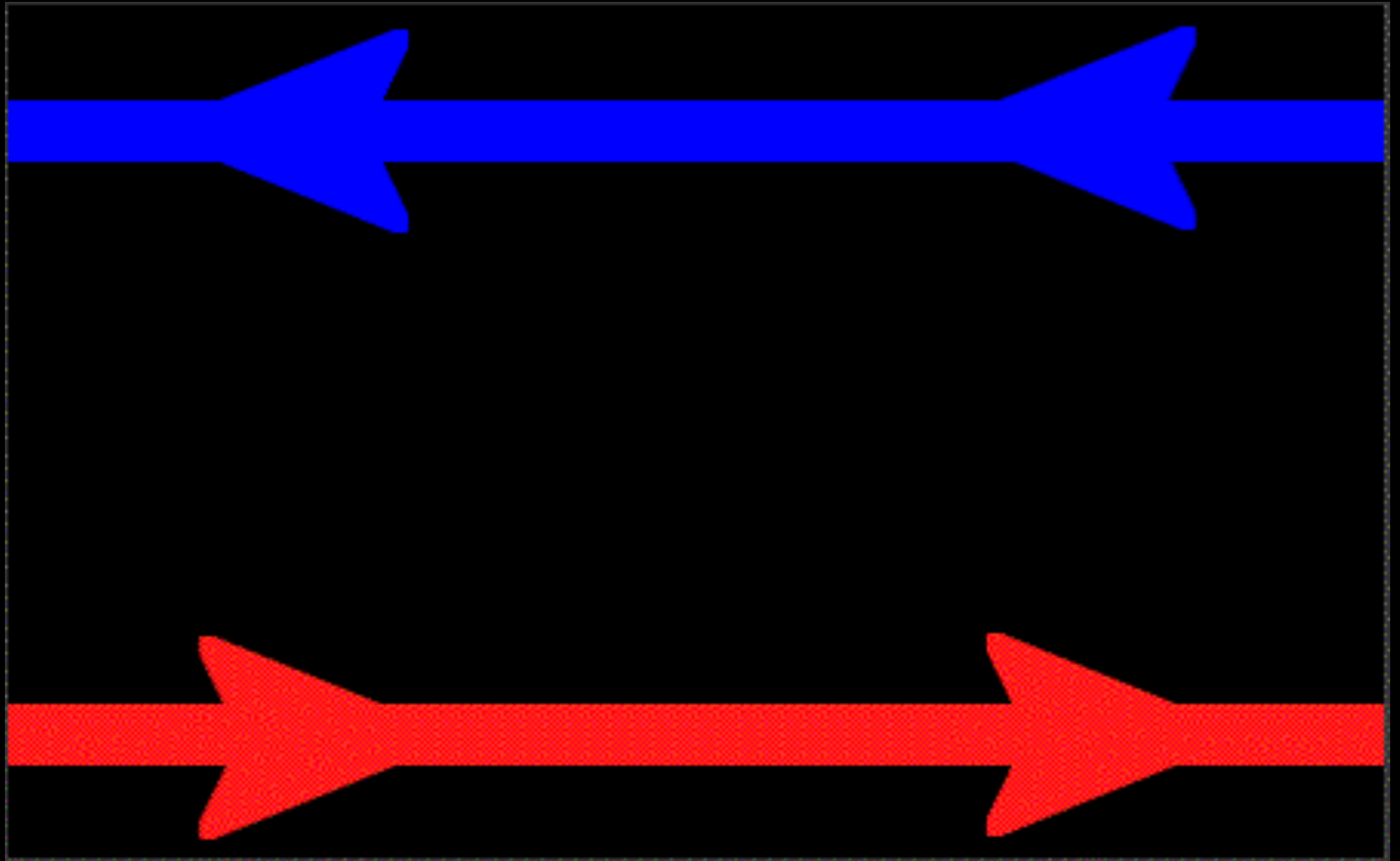
# 日冕物质抛射中的磁场重联

# CME 加速模型

## 磁重联



# Reconnection in 2D



# 重联机制

$$d\phi / dt = cE = 4\pi c^{-1} \eta j = v_i B_i = \text{constant}$$

$$\frac{d\phi / dt}{v_A B_i} = \frac{v_i B_i}{v_A B_i} = M_A$$

For Sweet-parker model

$$M_A = R_m^{-1/2}$$

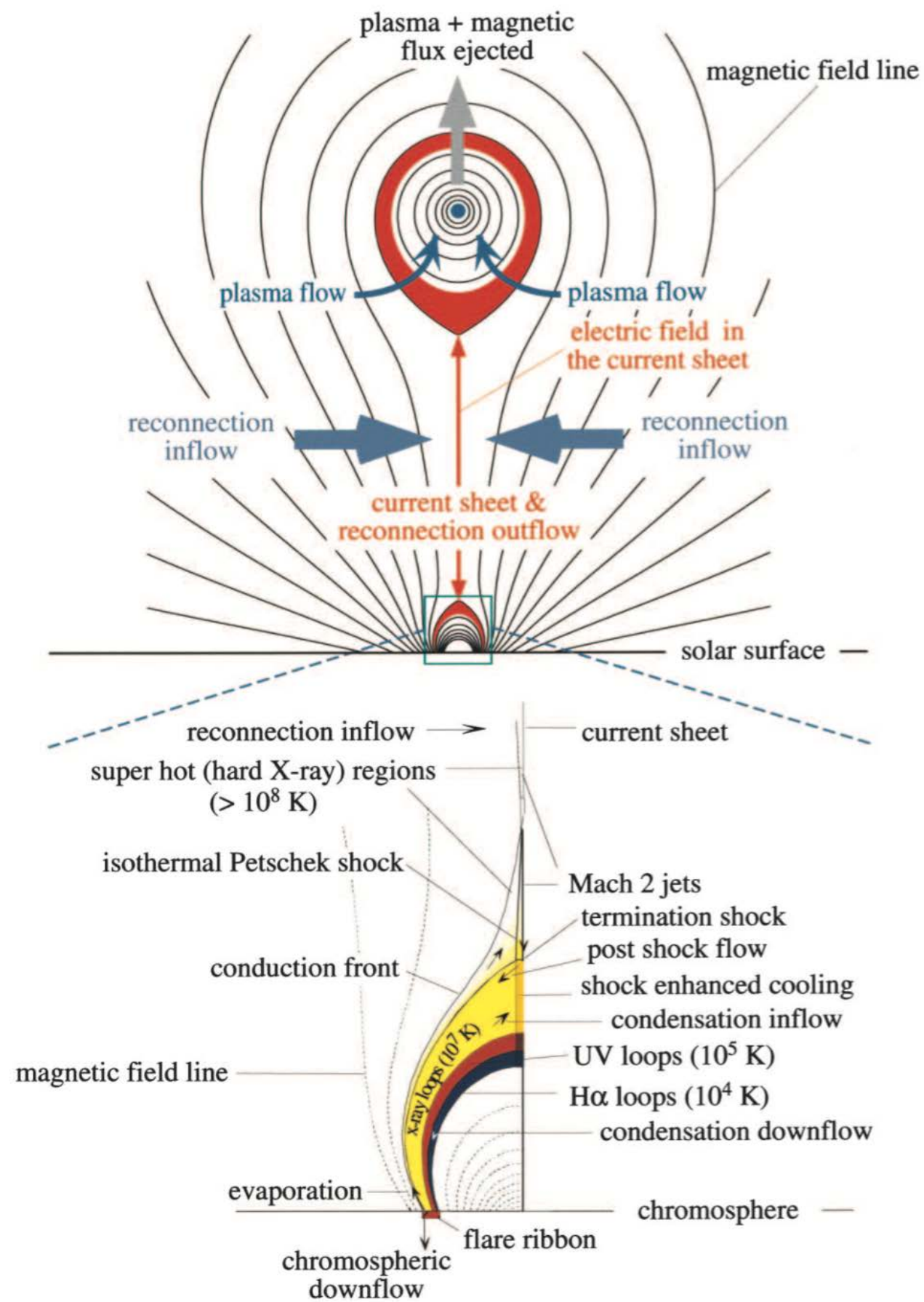
日冕磁雷诺数一般为 $10^{14}$

For Petschek model

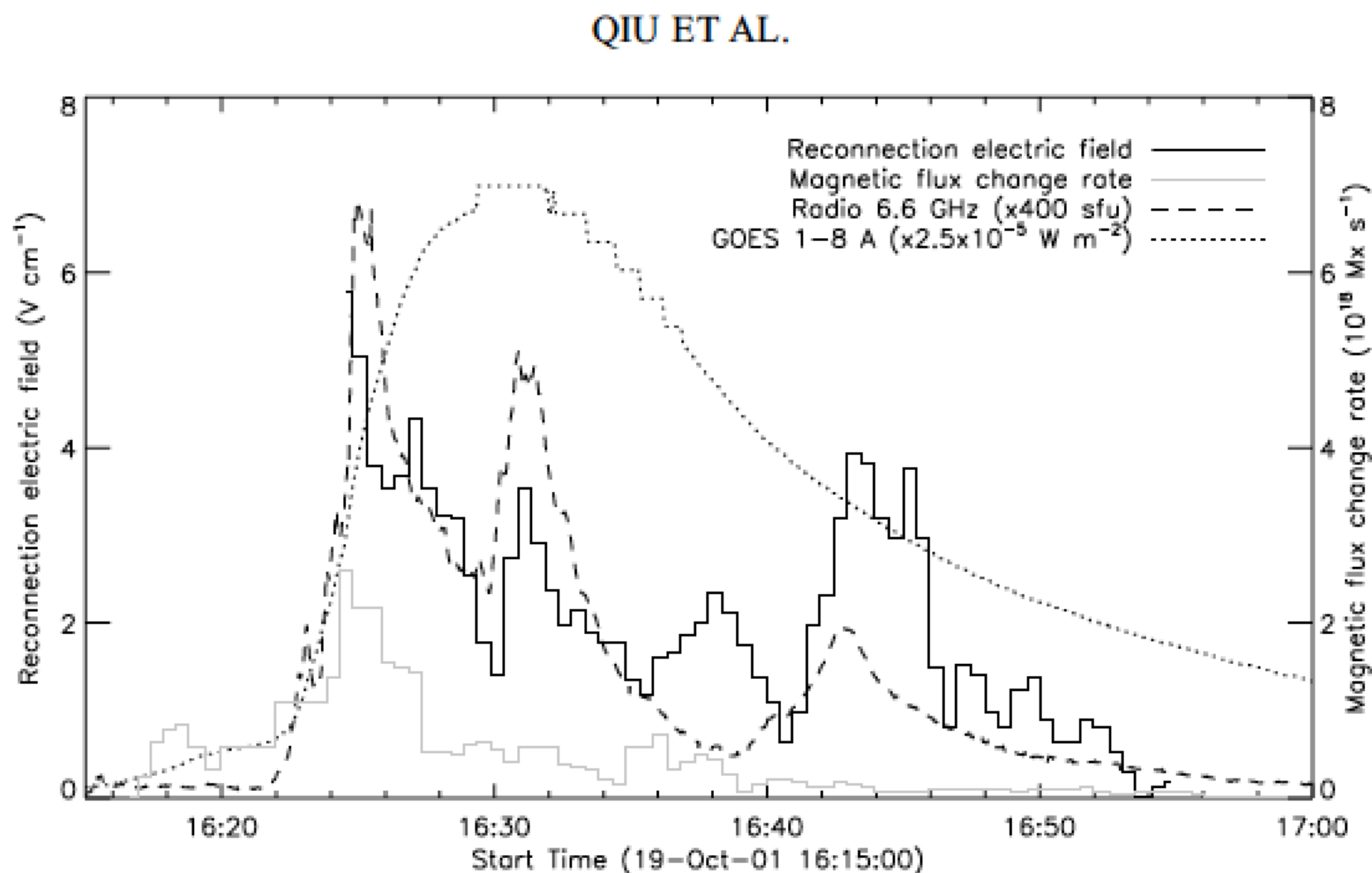
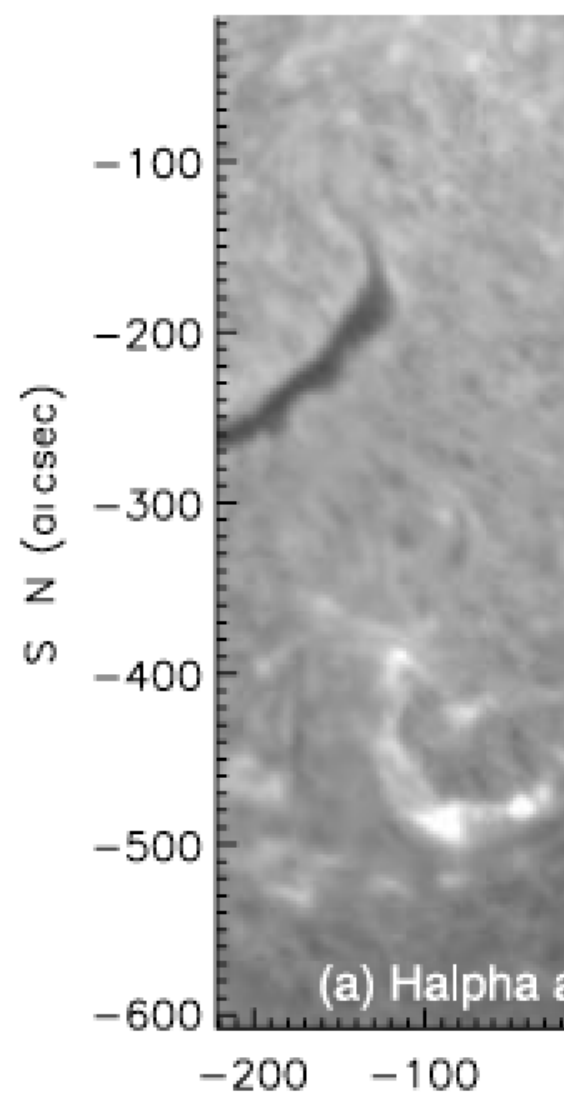
$$t_{rec} = L / v_i = t_A / M_A$$

$$M_A = \pi / 8 \ln R_m$$

$$dE / dt = L^2 B_i^2 v_i / 4\pi$$



# 重联电场和耀斑的关系

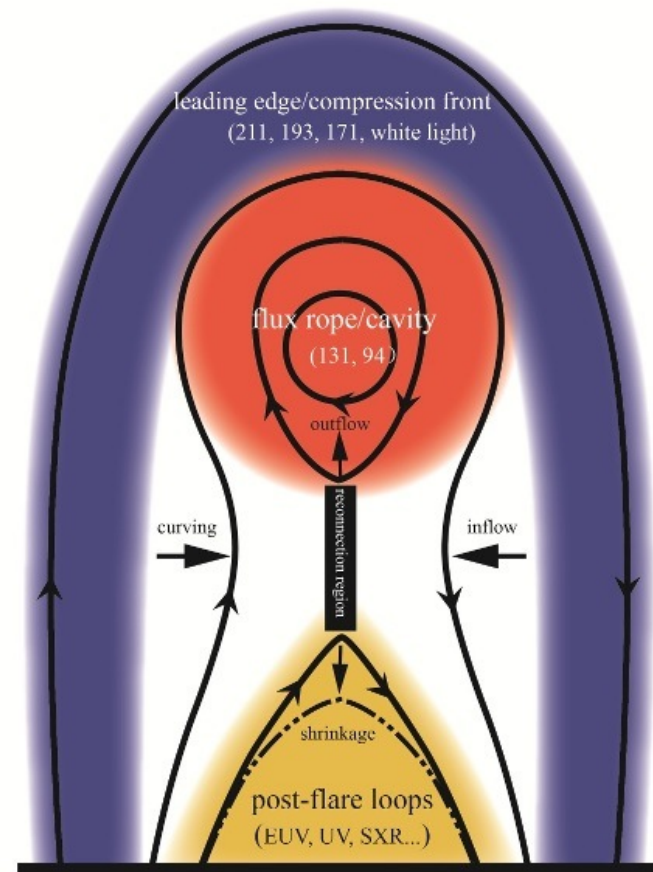
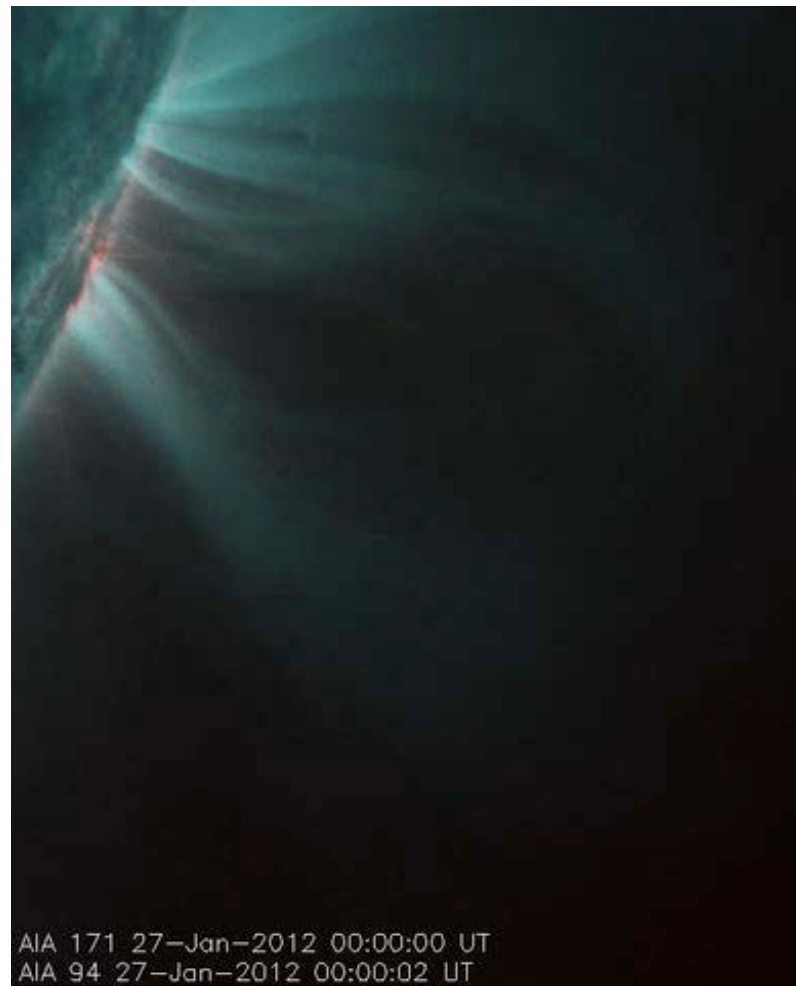
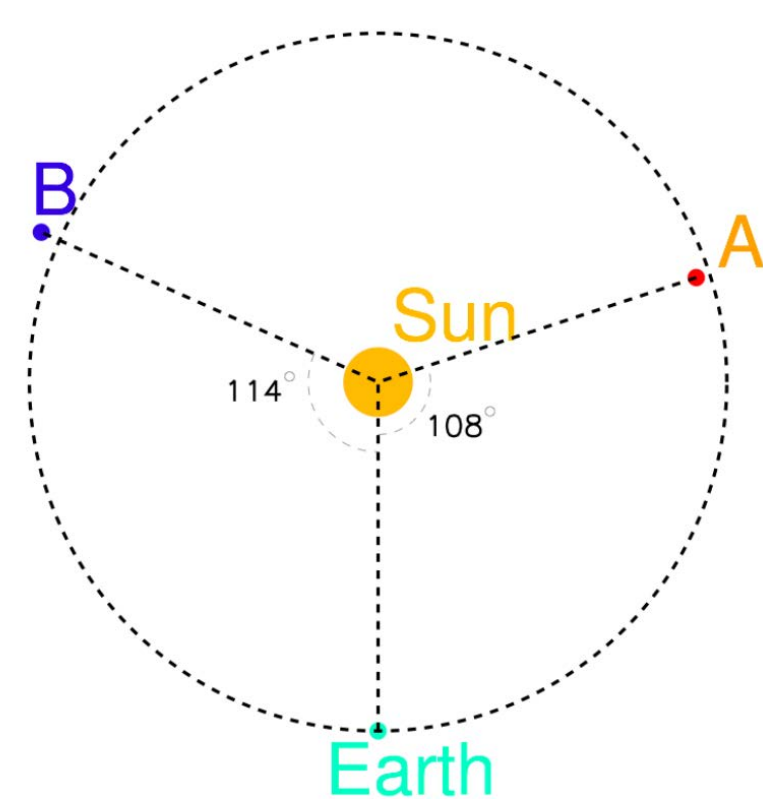


# 磁绳下方三维磁重联的EUV成像

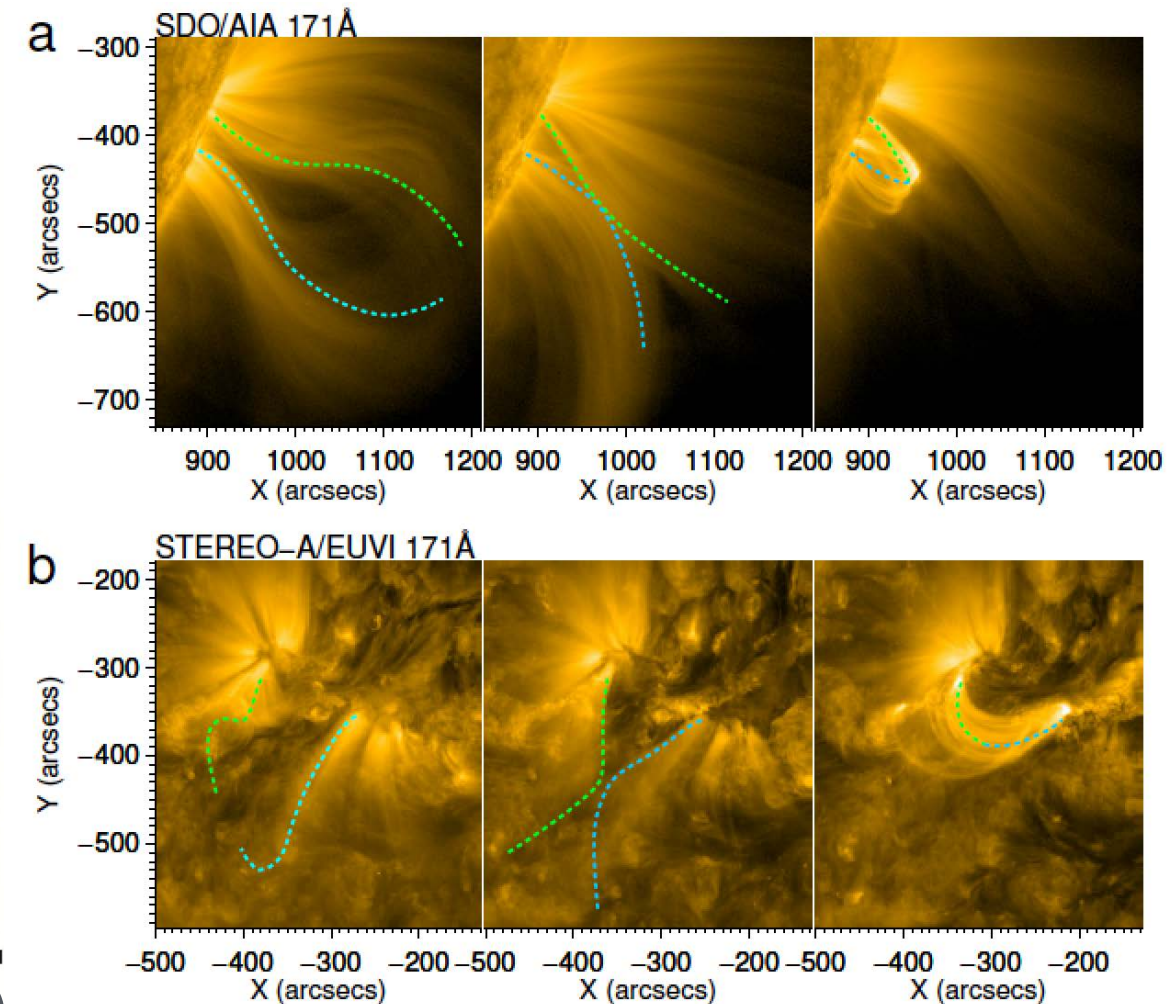
J. Q. Sun, **X. Cheng\***, M. D. Ding et al. 2015

Received 15 Jan 2015 | Accepted 22 May 2015 | Published 26 Jun 2015

DOI: 10.10

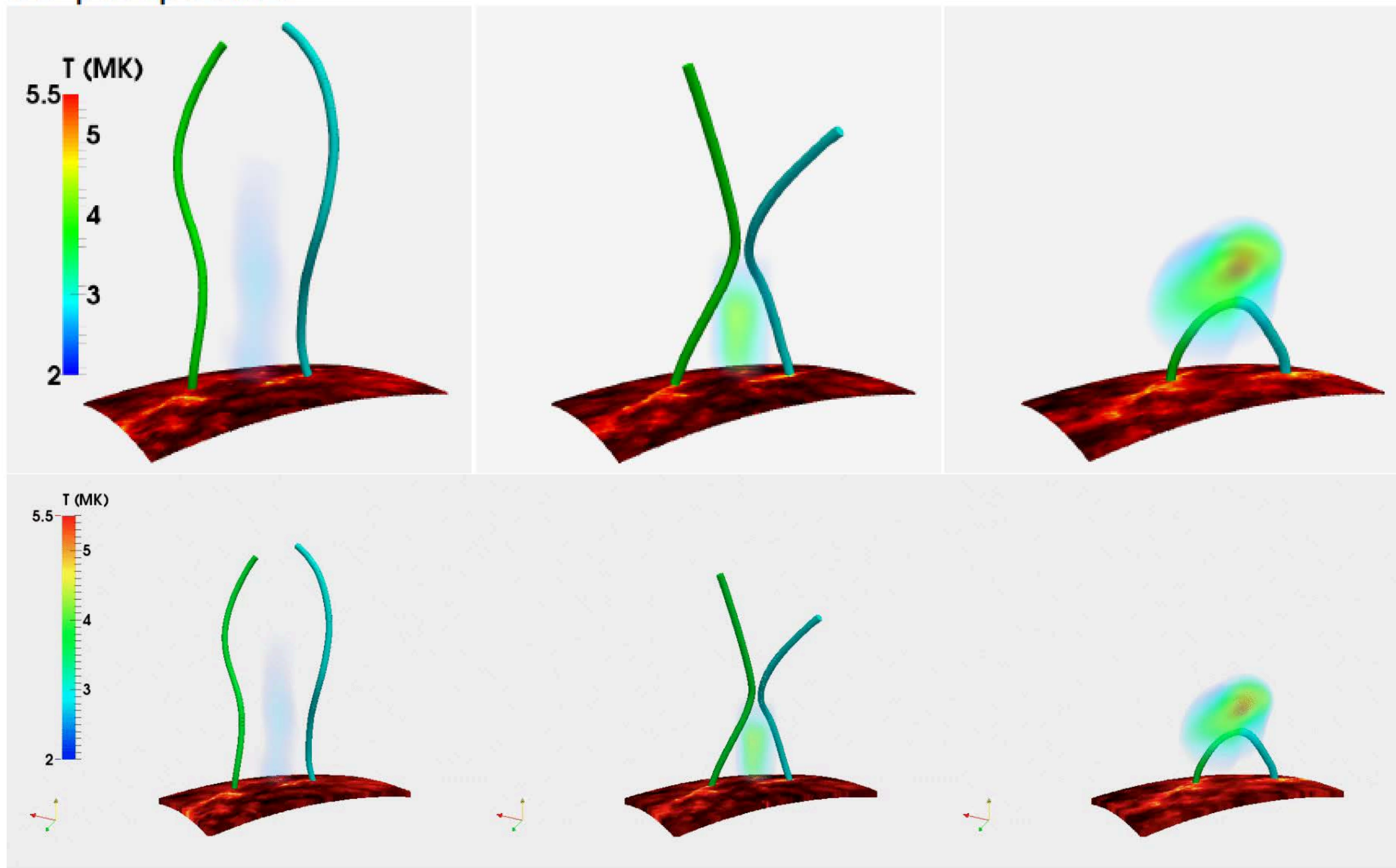


(Cheng et al. 2011b)



# 磁重联过程的3D磁拓扑演化

3D perspective



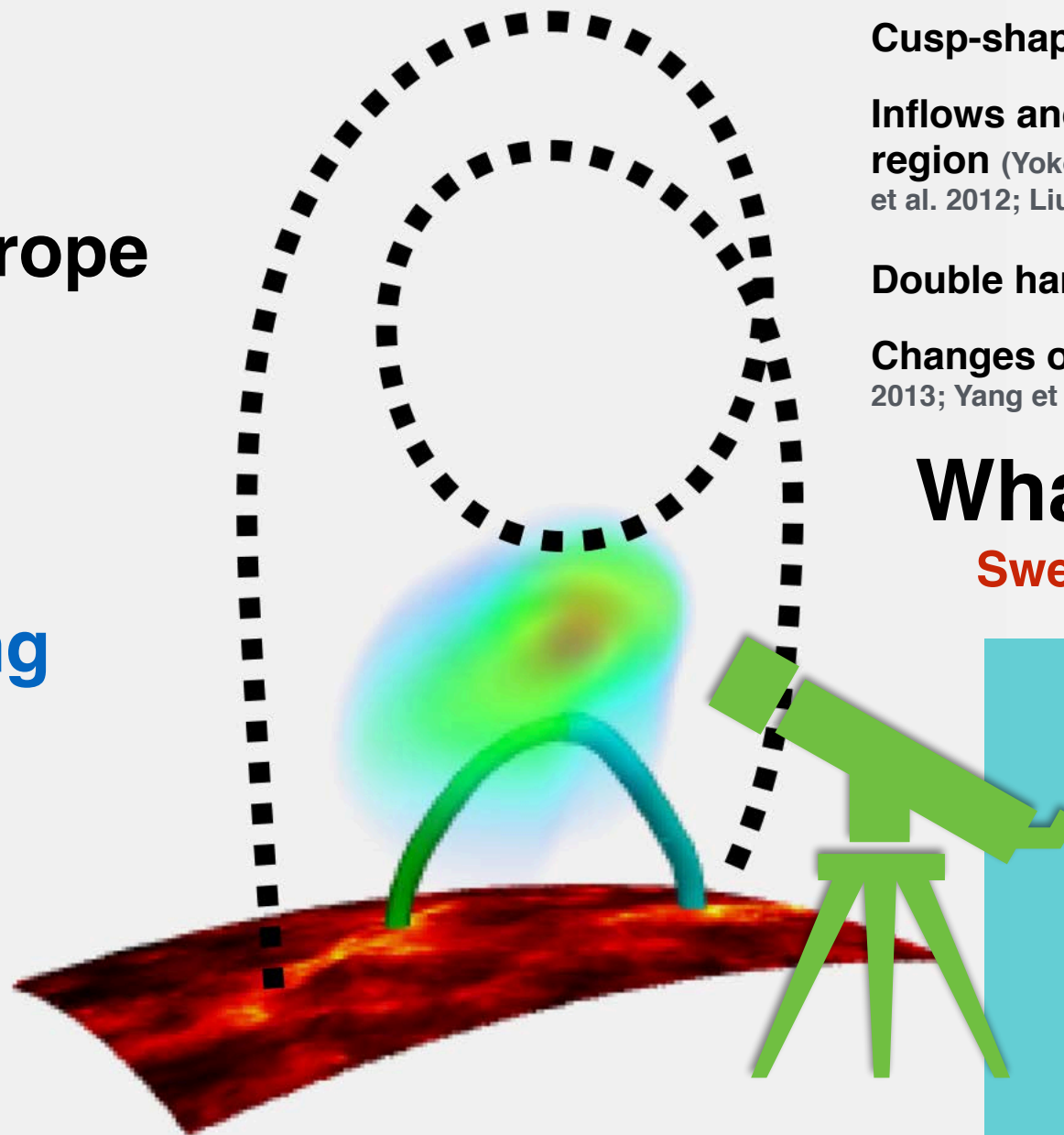
# 3D structure of Solar Eruption

Erupting flux rope

Reconnection  
Plasma heating

Flare loops

Flare ribbons



Cusp-shaped flare loops (Masuda et al. 1994);

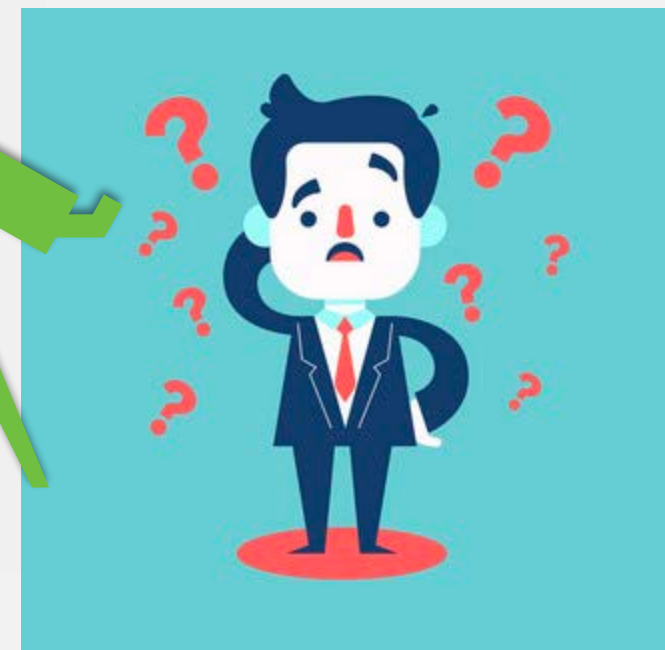
Inflows and downflows near the reconnection region (Yokoyama et al. 2001; Savage & McKenzie 2011; Takasao et al. 2012; Liu et al. 2013; Xue et al. 2016)

Double hard X-ray coronal sources (Su et al. 2003);

Changes of connectivity of coronal loops (Su et al. 2013; Yang et al. 2015; Li et al. 2016).

## What happens here

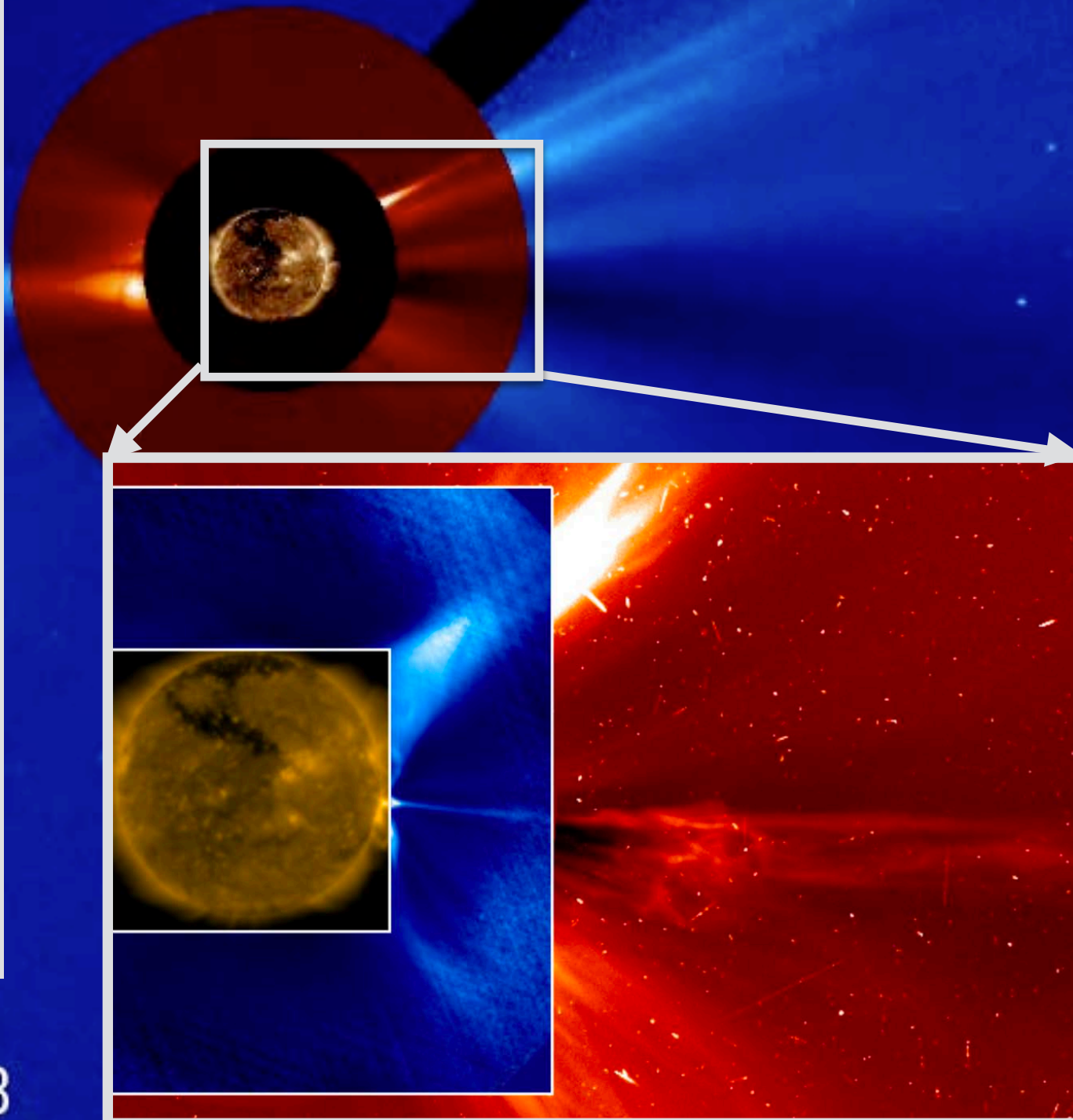
Sweet-Parker and Petschek?



(Sun, Cheng et al. 2015)

# A tale told by 2017-09-10 CME eruption

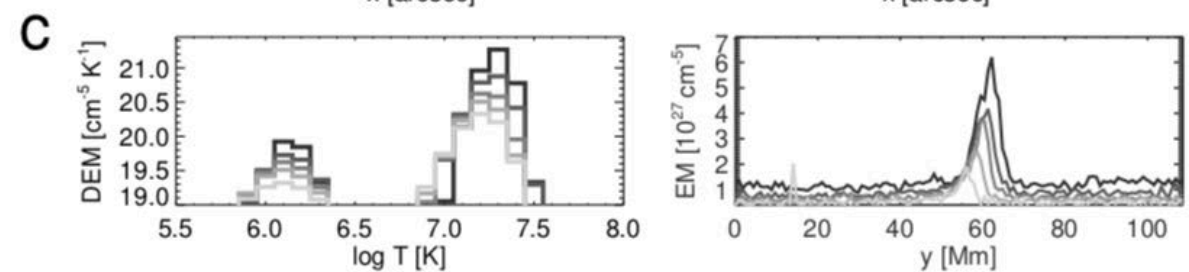
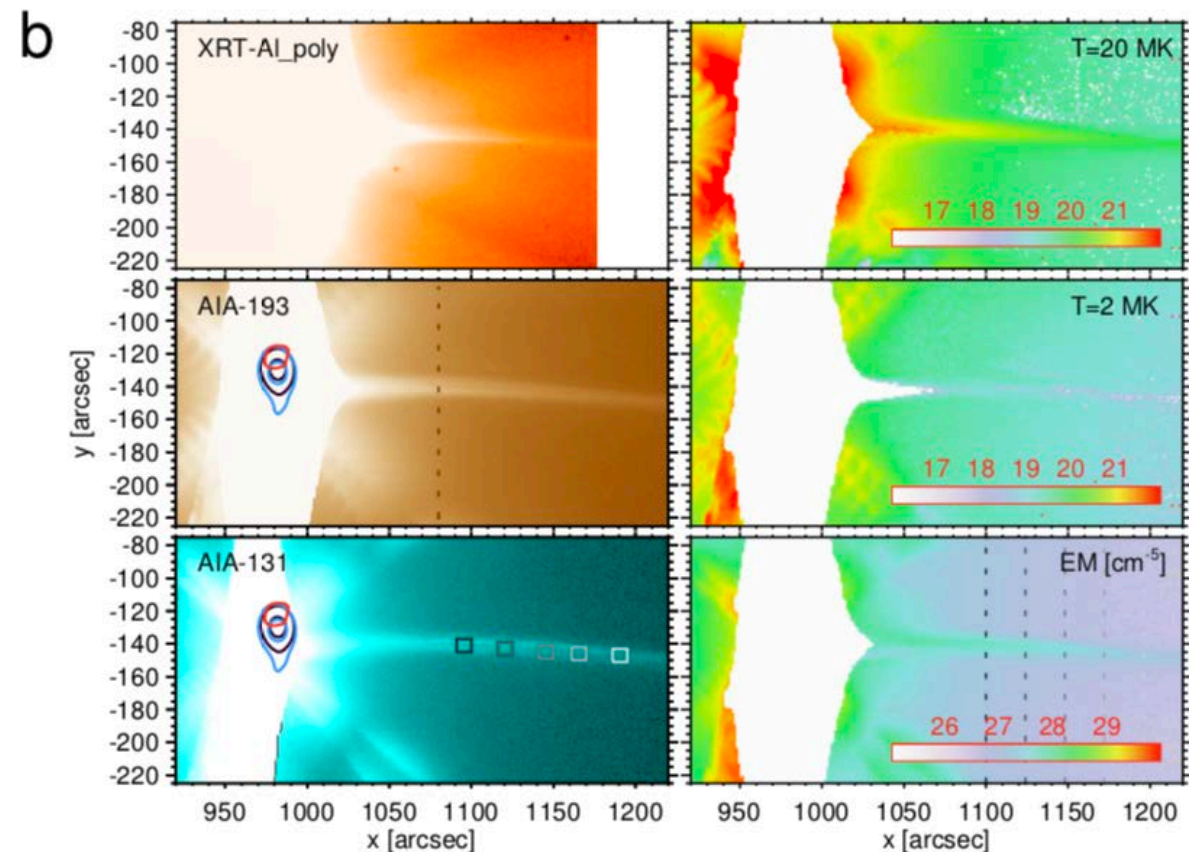
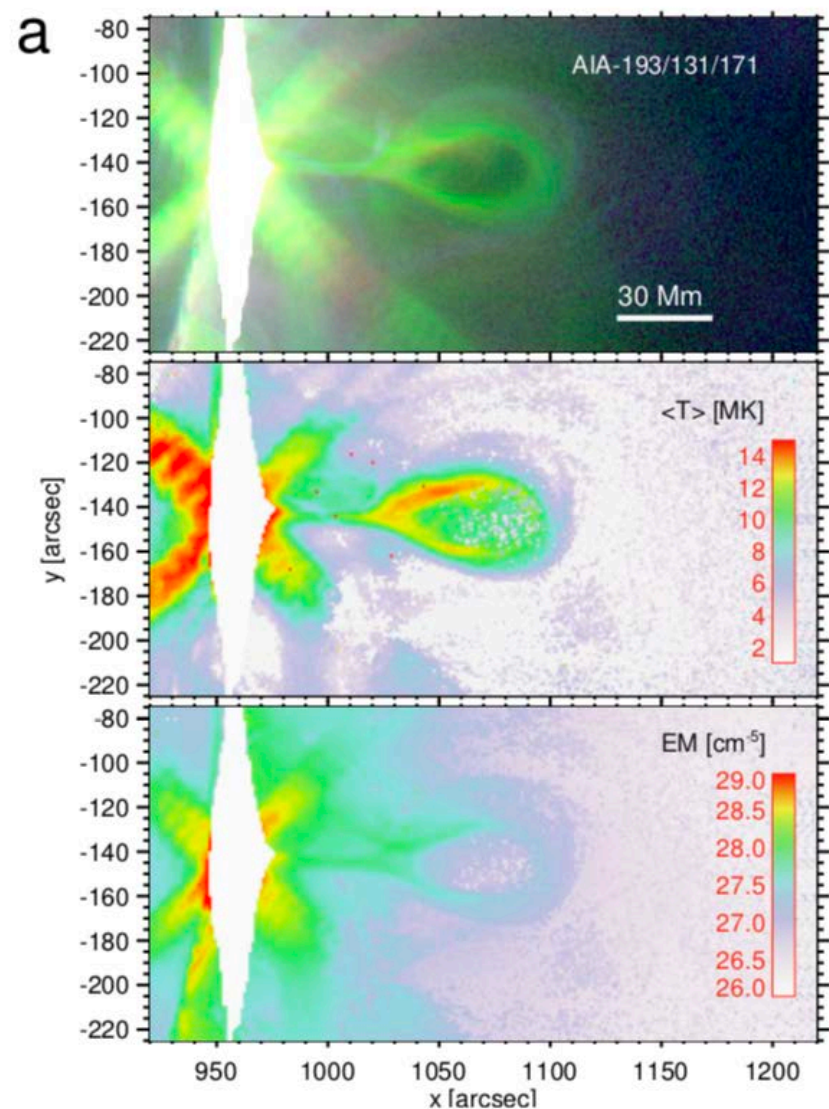
- **Very fast CME** with a speed of 3000 km/s and the second largest flare in the past ten years
- **The linear structure** connecting the CME bottom and flare top is clearly observed and that appears to be very dynamic.
- **Similar to 2D picture of solar eruption by Lin & Forbes (2000).**



2017-09-10T15:06:08

# What happens in current sheet?

told by 2017-09-10 limb eruption

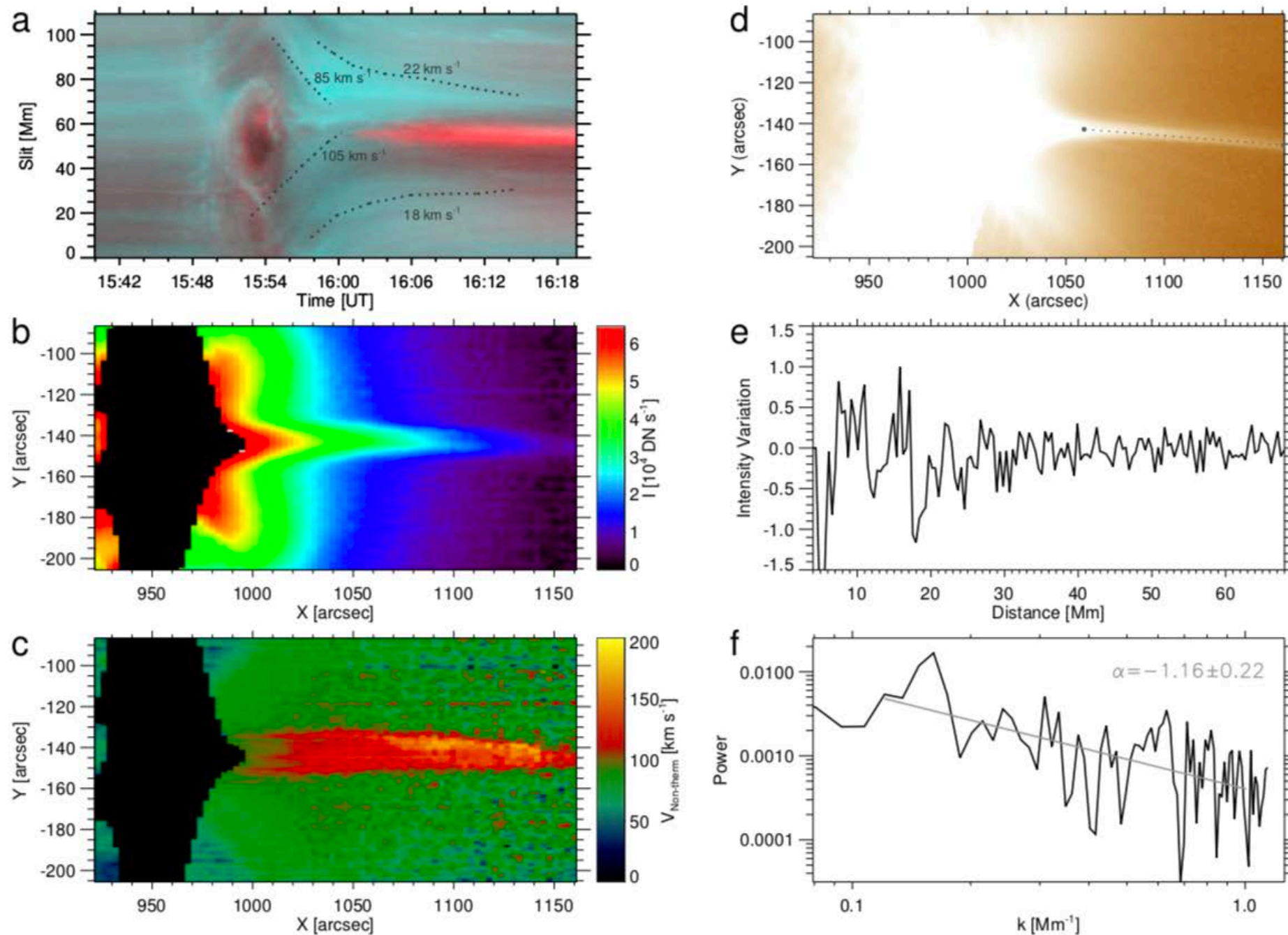


hot blob  $\rightarrow$  flux rope?

20 MK; significant heating!!

(Cheng et al. 2018 ApJ)

# Turbulence and fragmented current sheet

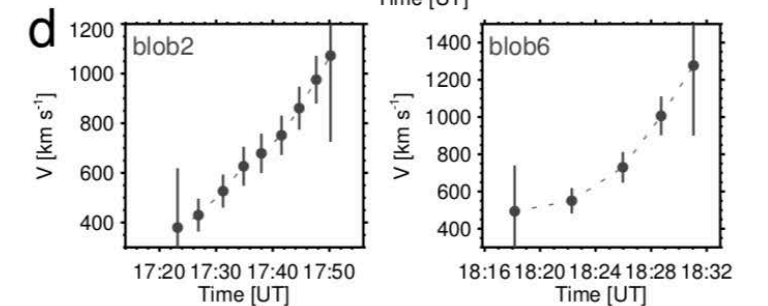
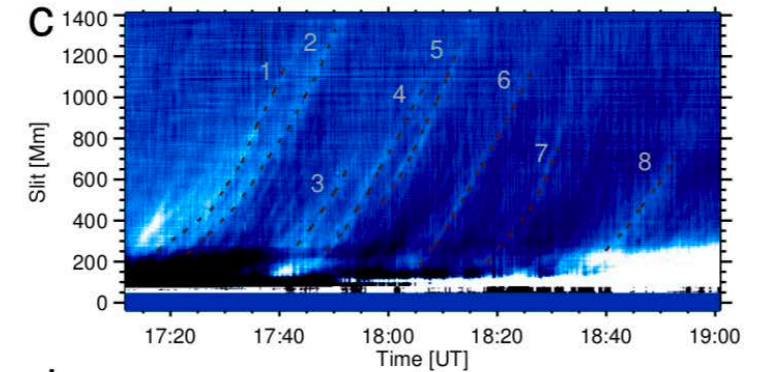
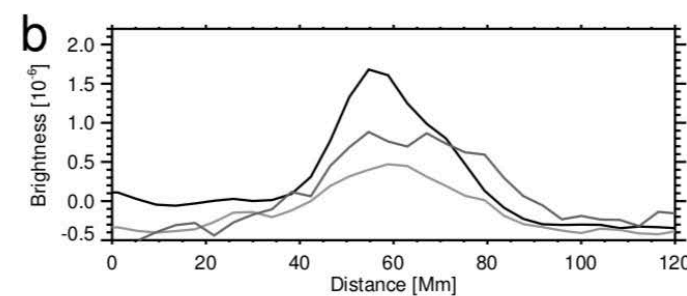
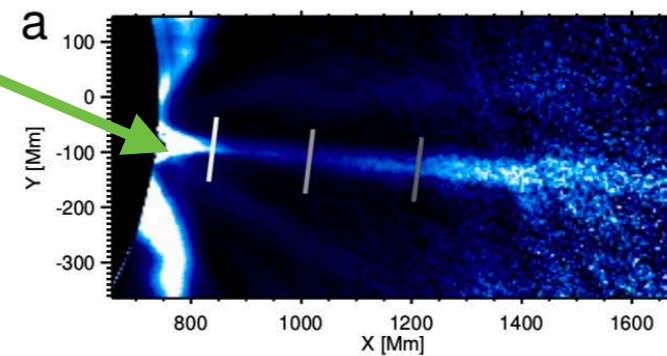
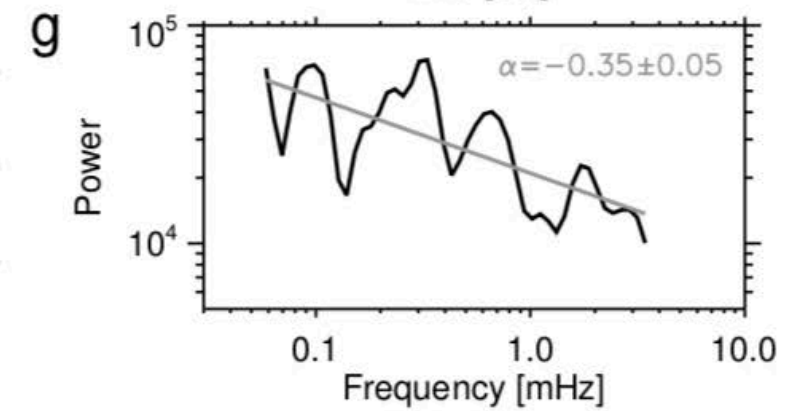
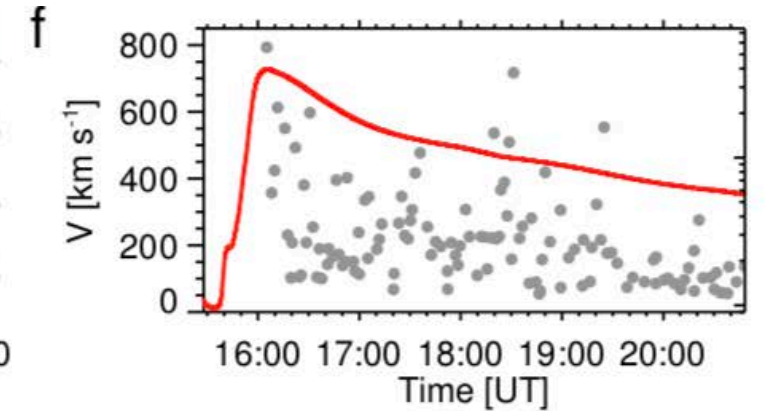
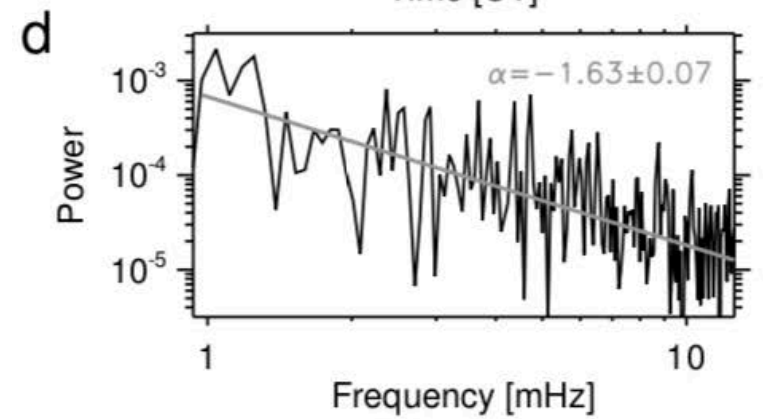
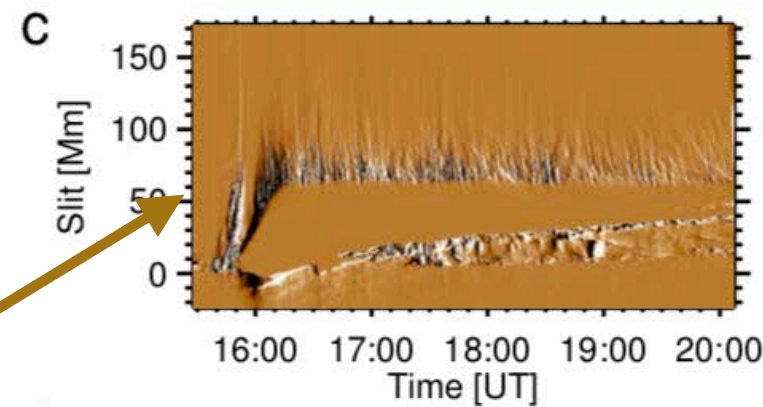
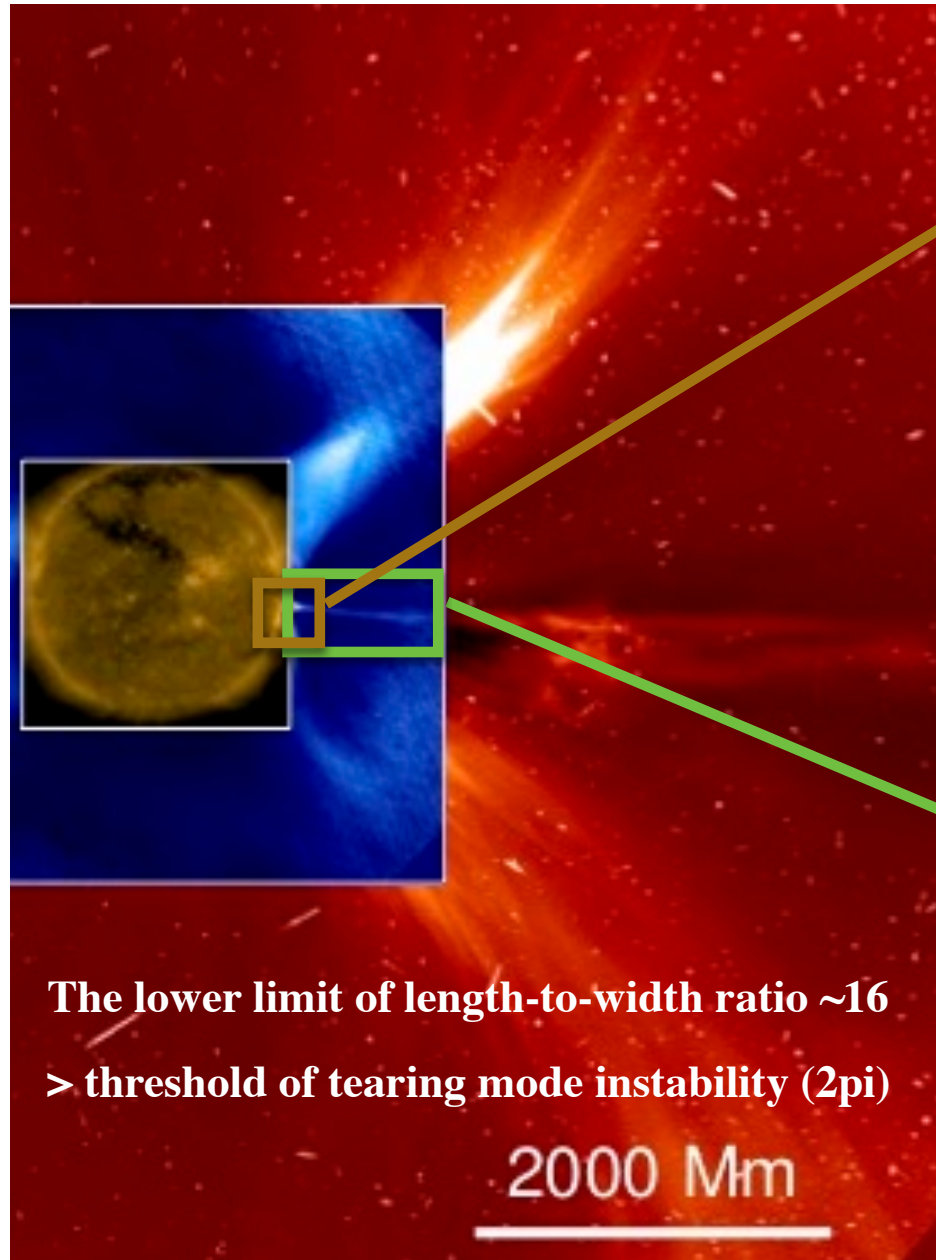


**significant non-thermal  
—> turbulence?**

**fragmented current sheet  
—> plasmoids**

(Li et al. 2018, ApJL; Cheng et al. 2018 ApJ)

# Intermittent outflows: **Fragmented**



(Cheng et al. 2018 ApJ)

# 总结：

1. 日冕中存在**磁螺旋结构 (磁绳)**，其在太阳爆发之前就已经存在，观测特征为千万度的**极紫外通道结构**。
2. 磁绳子可能是在光球剪切、汇聚运动下、通过在**低层大气中的磁重联形成**，持续时间从几个小时到几天不等。
3. 日冕物质抛射的早期动力学过程（形成和加速）和相关耀斑辐射的变化**由磁绳的动力学过程决定**。磁绳抛射导致磁重联，快速释放磁能加速日冕物质抛射和增强耀斑辐射。
4. 重构的磁重联三维磁拓扑结构**表明磁重联位置具有三维属性**，支持磁绳导致CME/flare爆发模型。
5. 磁重联发生在电流片中，其中的等离子体被**直接加热**。大的电流片长宽比说明撕裂膜不稳定性的发生，**它能够产生磁岛和湍流，保证高重联率**。**磁重联在太阳爆发过程中以撕裂和湍流的方式进行**。

