# Initiation and Energy Release of Solar Coronal Mass Ejections (CMEs)
# ~~& Relevant Solar Radio Bursts~~


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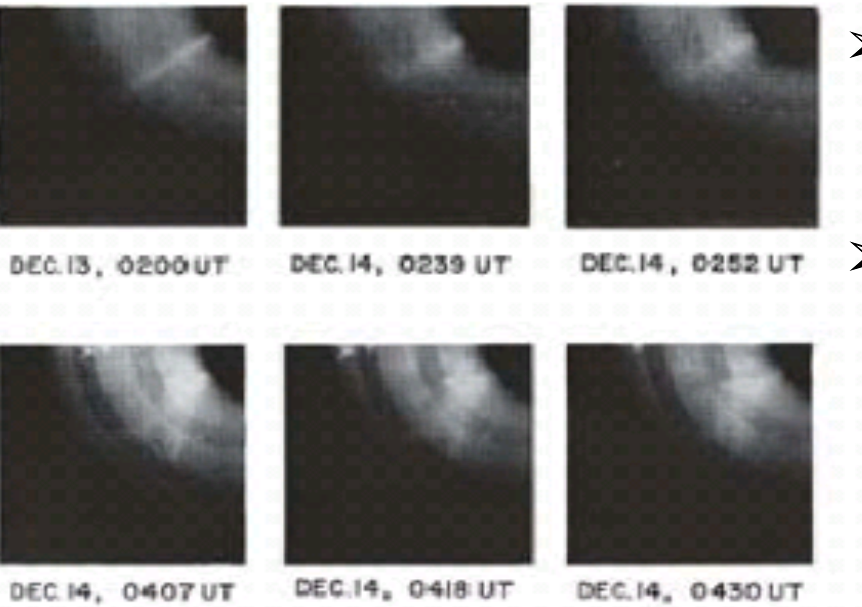
# Initiation and Energy Release of CMEs

## Outline

1. General Observations of Solar Eruptions
2. Energy Budget, Big Picture, and Questions
3. What to ERUPT?(what structure carries the free energy: a twisted flux rope)
4. Flux Rope Formation (and Enhancement)
5. Flux Rope Instab. & Forces Acting on the Rope
6. Triggering/Initiation Processes of CMEs
7. Energy Release Mechanisms: Instability VS REC.
8. Failed Eruptions

Summary

# 0. The First CME was detected by OSO-7 in 1971




. CME Observed on 13-14 Dec 1971

Howard, 06

- 1971.12.14: US-Navy OSO-7 (Orbiting Solar Obs., ~110 ys later than the flare discovery, Carrington 1859)
- Drawing of the total solar eclipse (1 July 1860) by Italian astronomer G. Tempel with an isolated structure, with supporting evidence from others (Eddy 1974; Alexander, 06)


The delay in CME discovery is due to the fact that the corona brightness is extremely weak, much weaker than the disk!

To observe the corona:

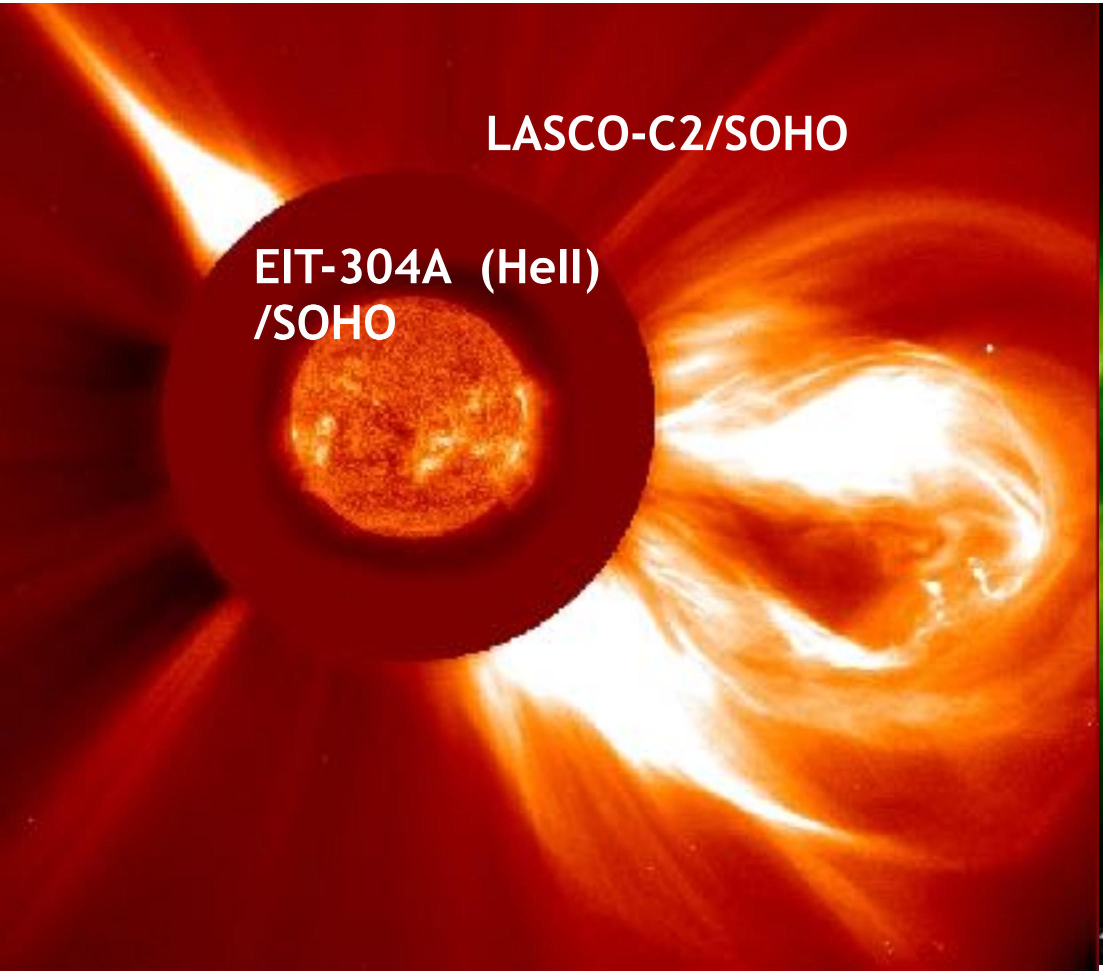
a total solar eclipse or a coronagra

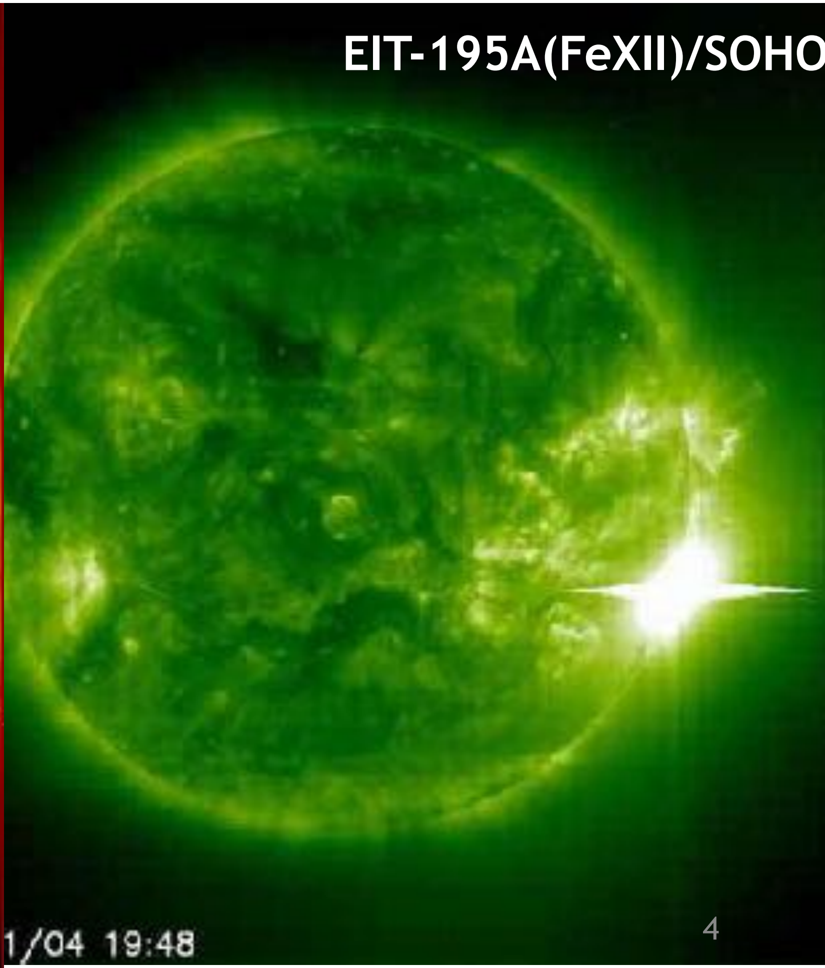
# 1. General Observations of Solar Eruptions

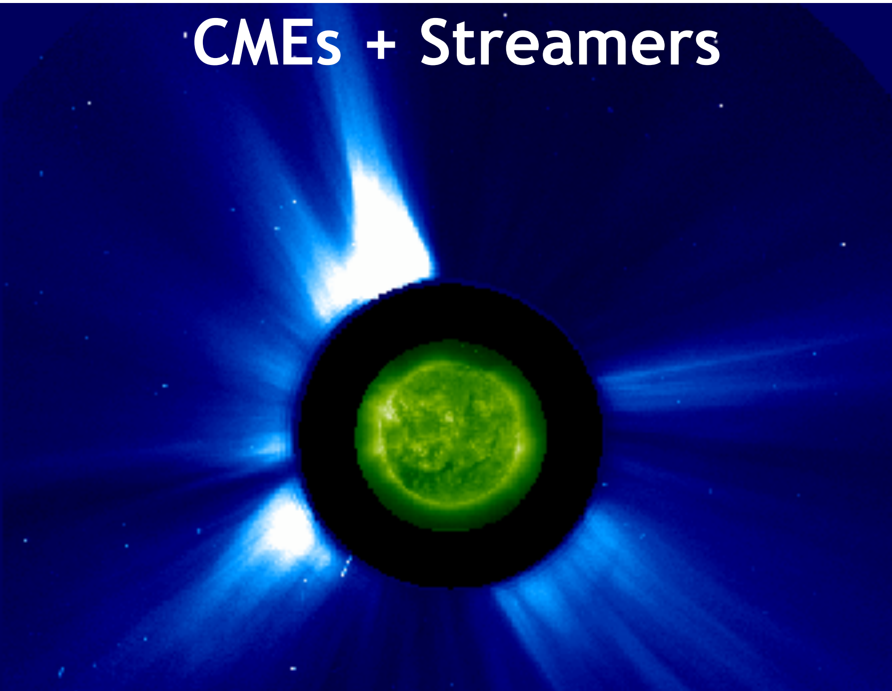
## Coronal Mass Ejections and Solar Flares

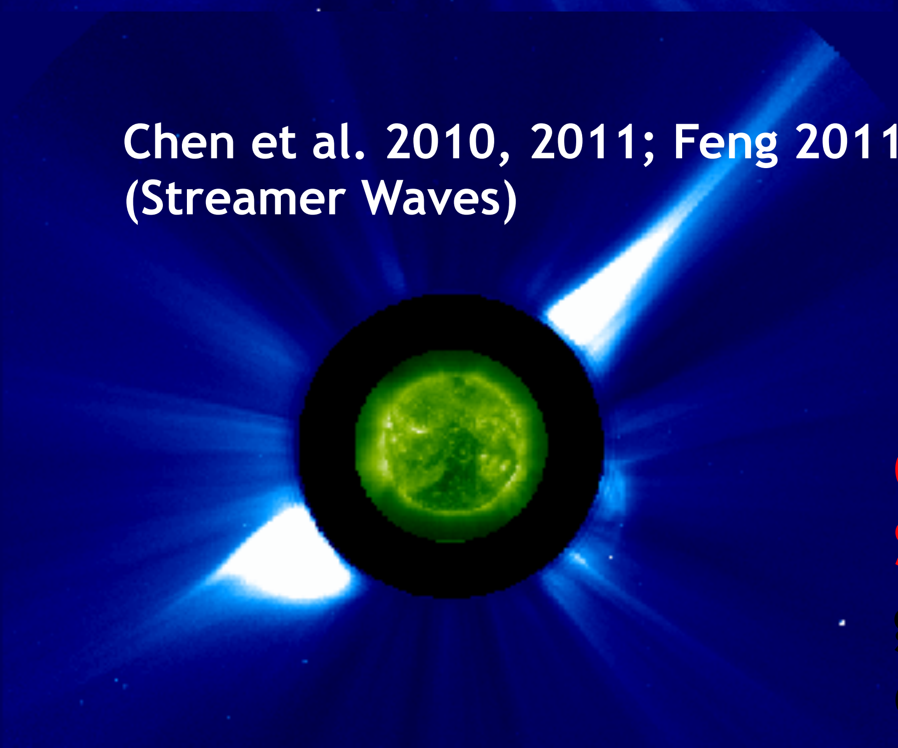
CME:   Ejection of Mass（Magnetized Plasmas）

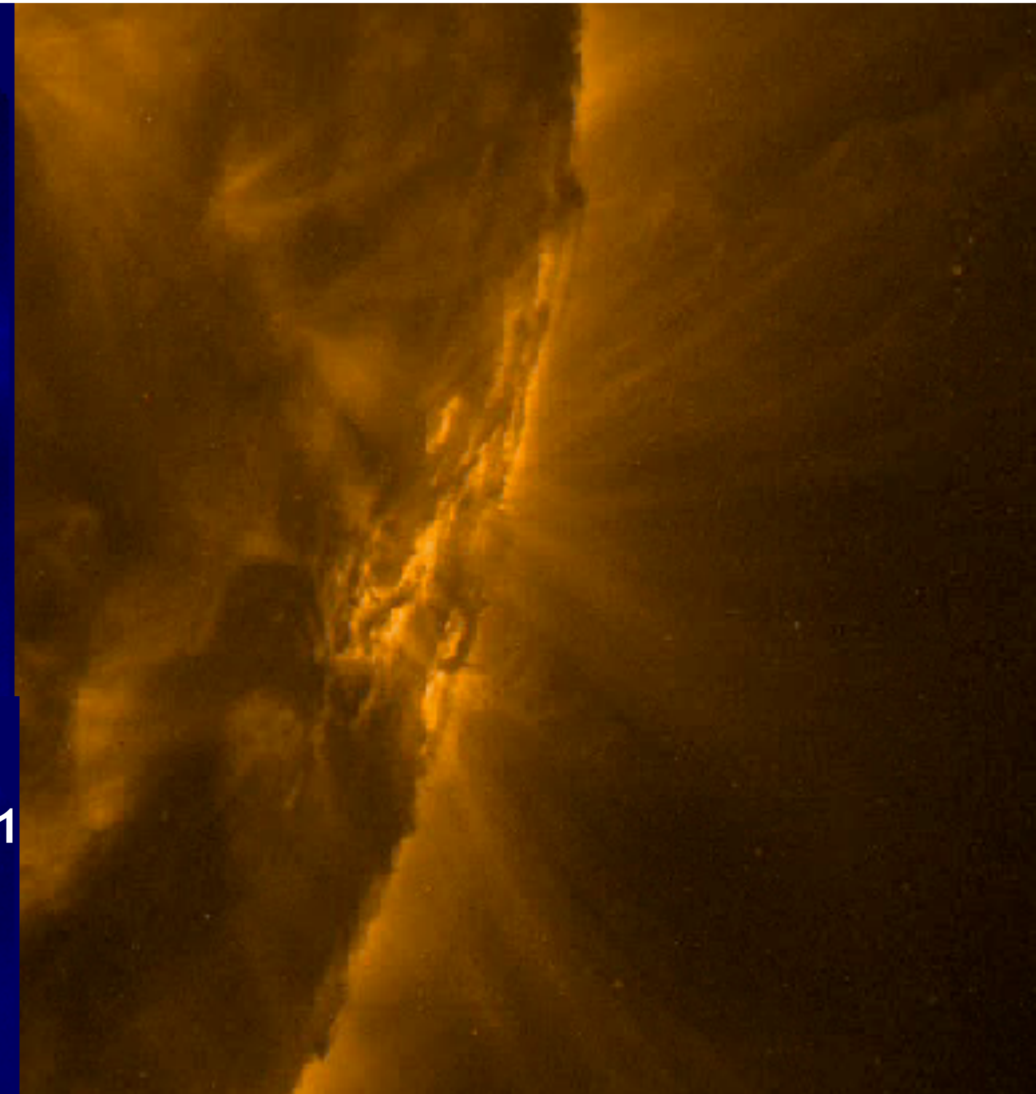
Flare: Burst of EM Radiations(From Radio to Gamma-Rays)





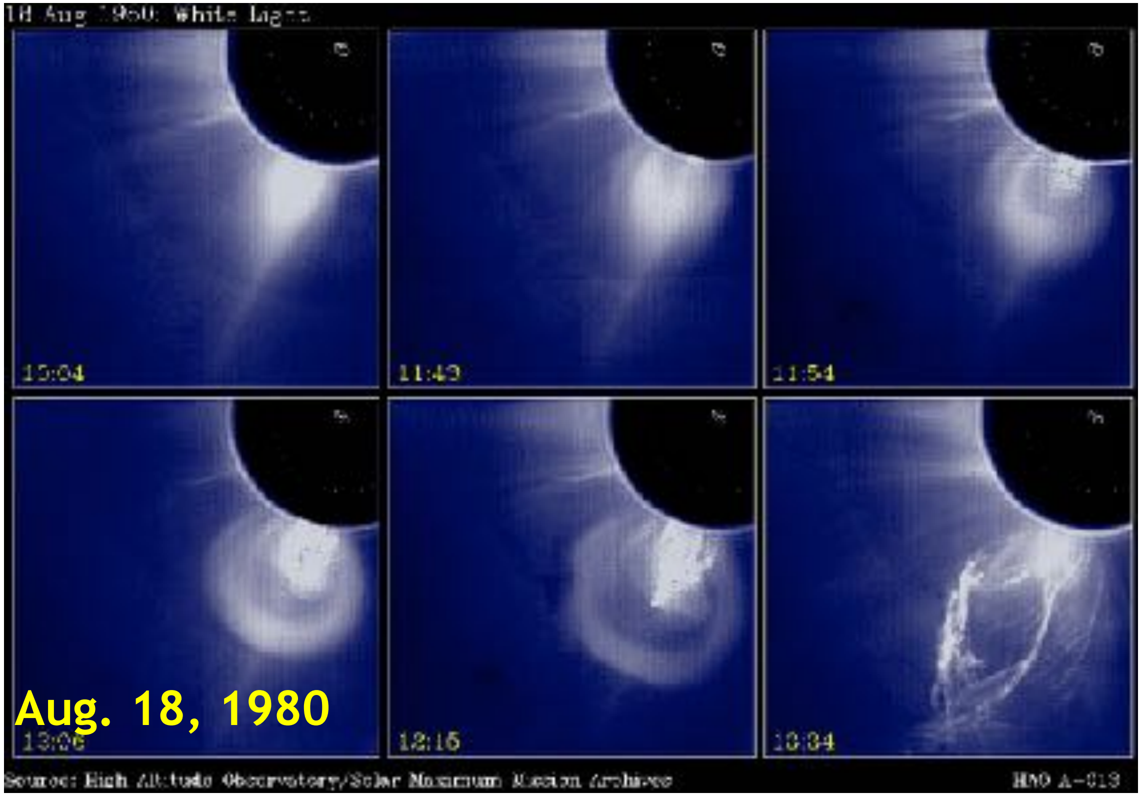



CMEs, interacting with streamers
Solar flare: sudden brightening
growing post-f. loops with bright t
downflowing structures

# 1. General Observations of Solar Eruptions

## ➢ Basic Numbers




**Occurrence Rate:**

Solar Max.:
3 - 5 per day
Solar Min.:
1 per days (or longer)

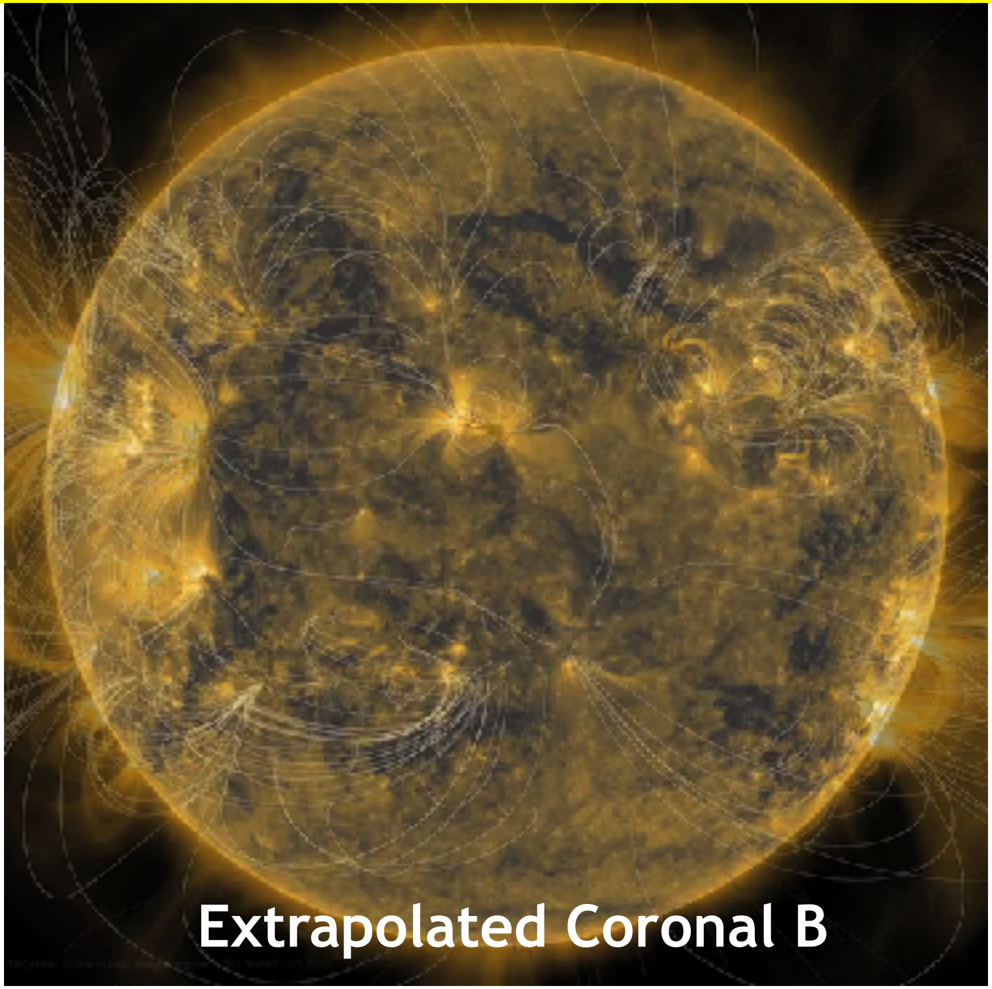
**Speed:**
20 - 4000 km/s,
450 km/s (median)

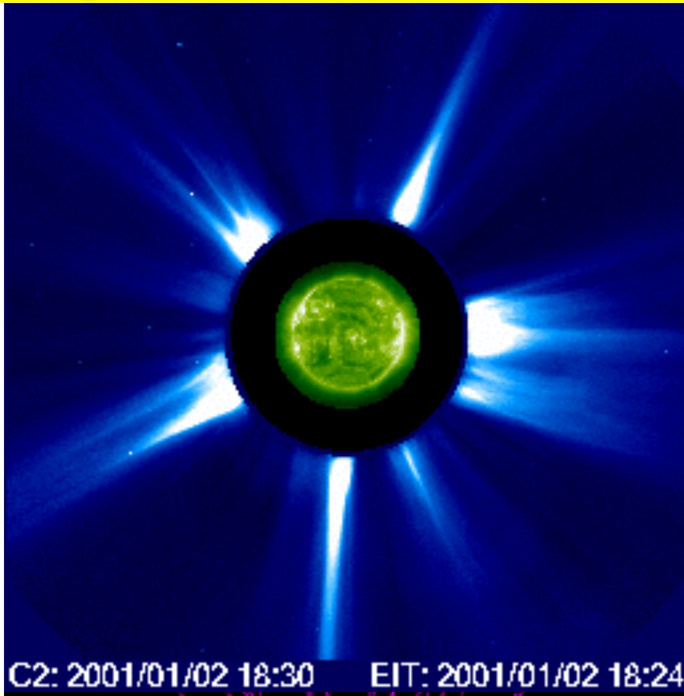
**Mass:**
$10^{15\text{-}16}$ g per CME

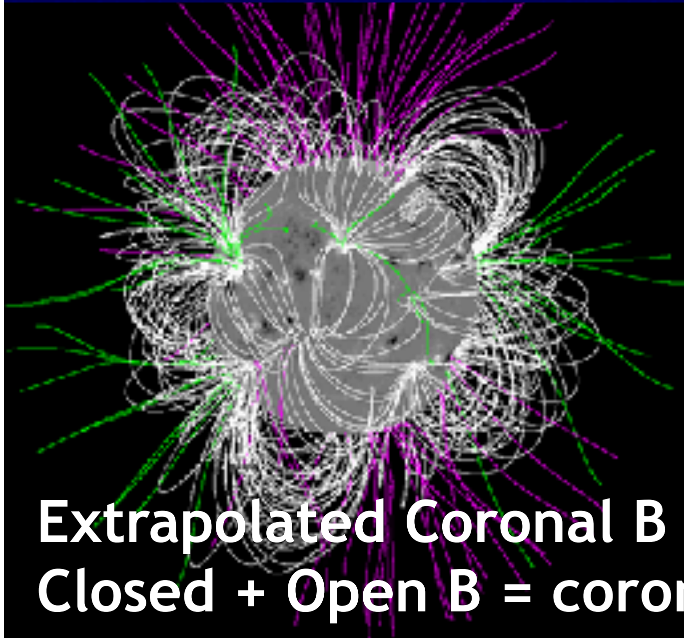
**Energy:**
$10^{30\text{-}32}$ ergs per CME

One Atomic Bomb: 2. $\times 10^8$kg TNT~ $10^{22}$ erg
One average CME ~ $10^{8\text{-}10}$ (~billion) Atomic Bombs
A tiny amount of energy will impact the earth if the CME prop. towards Earth , this may cause catastrophic effects→ Space Weather Applications

# 1. General Observations of Solar Eruptions



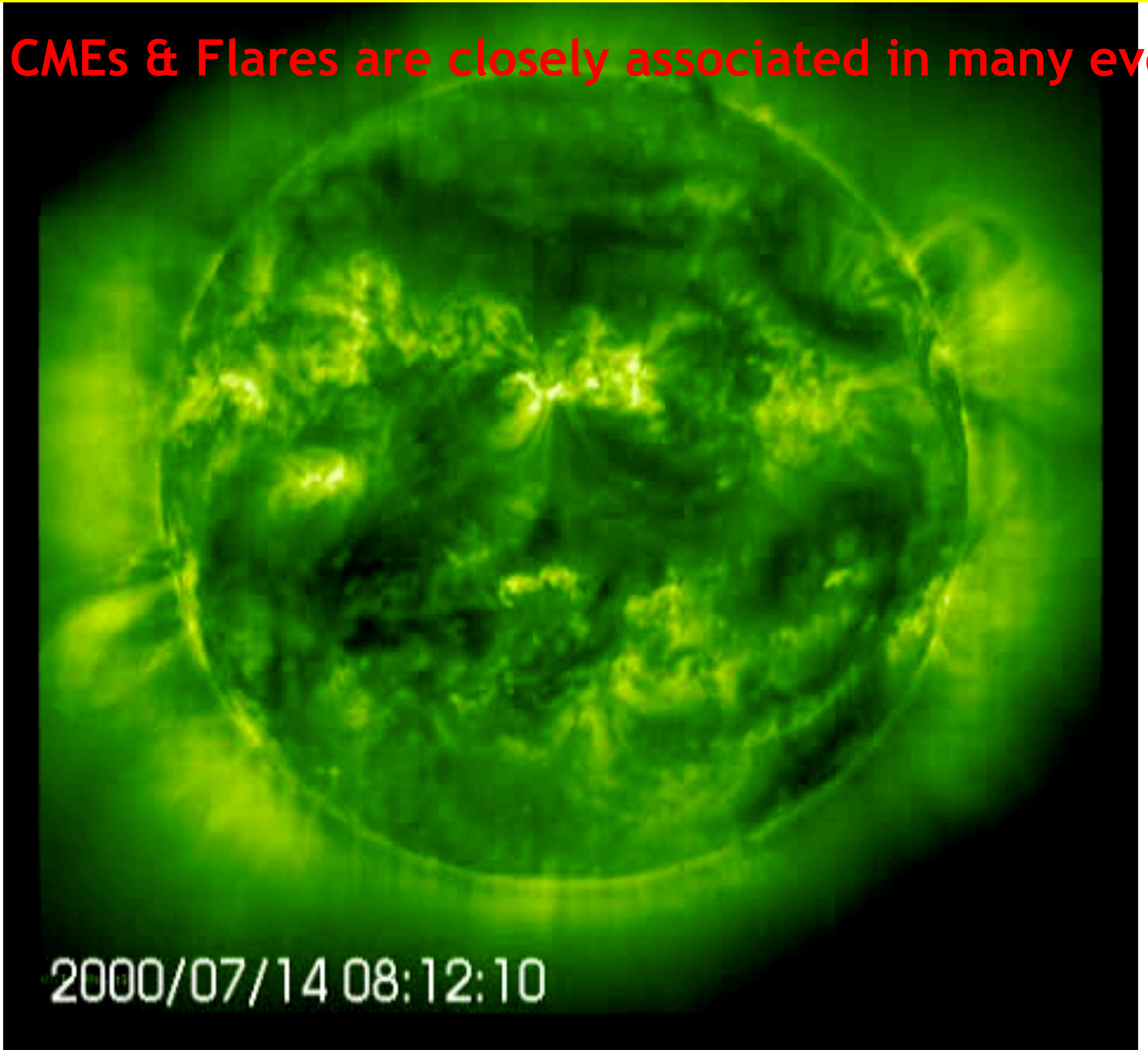



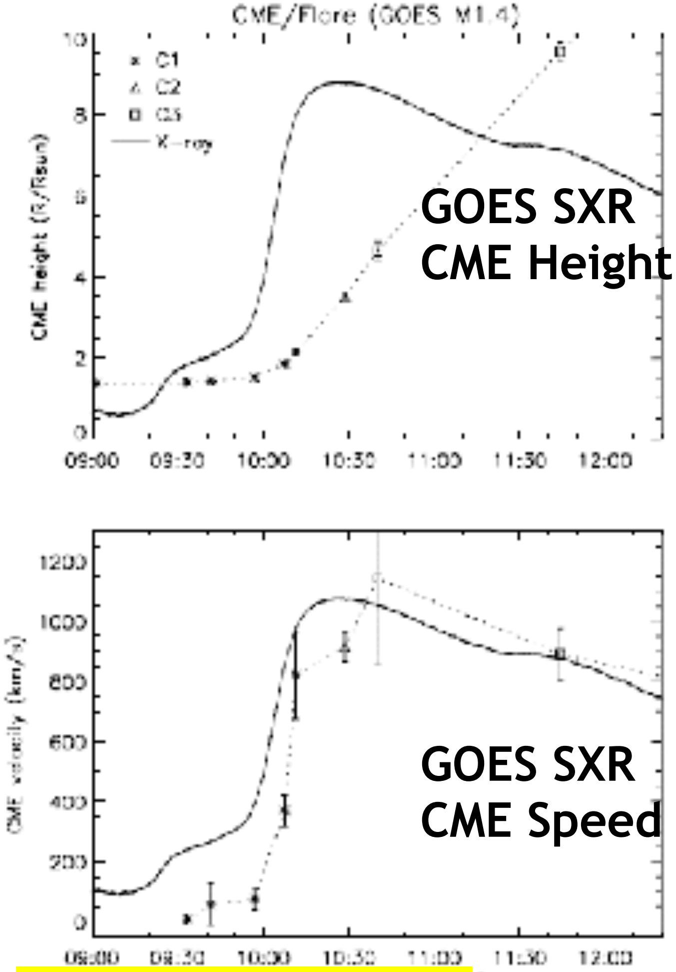

**MOVIE-2: the magnetically-dominated solar atmosphere with closed loops, bright AR, mostly above sunspots with strong B**

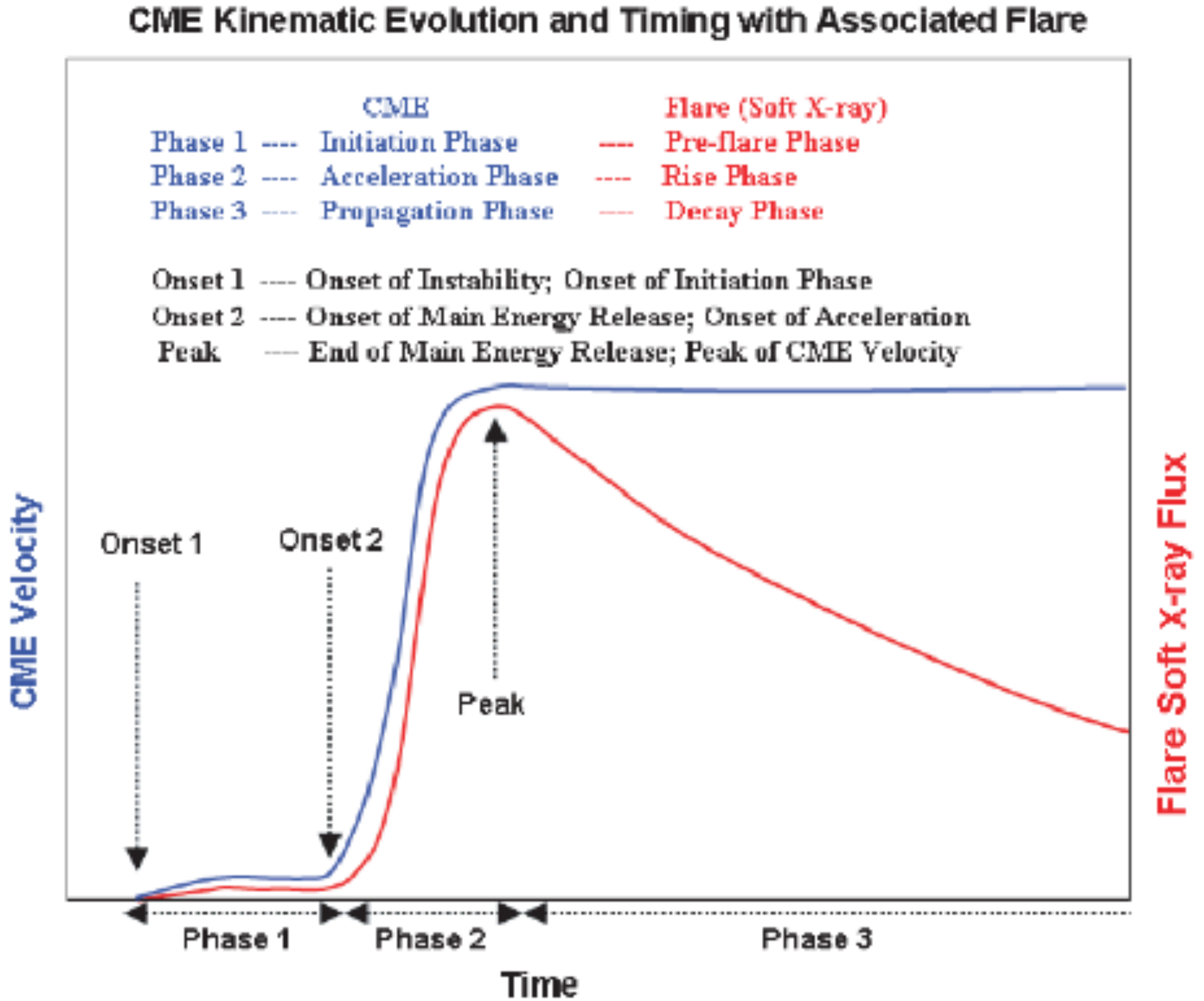
# 1. General Observations: CME-flare association

**CMEs & Flares are closely associated in many events**



# 1. General Observations: CME-flare association



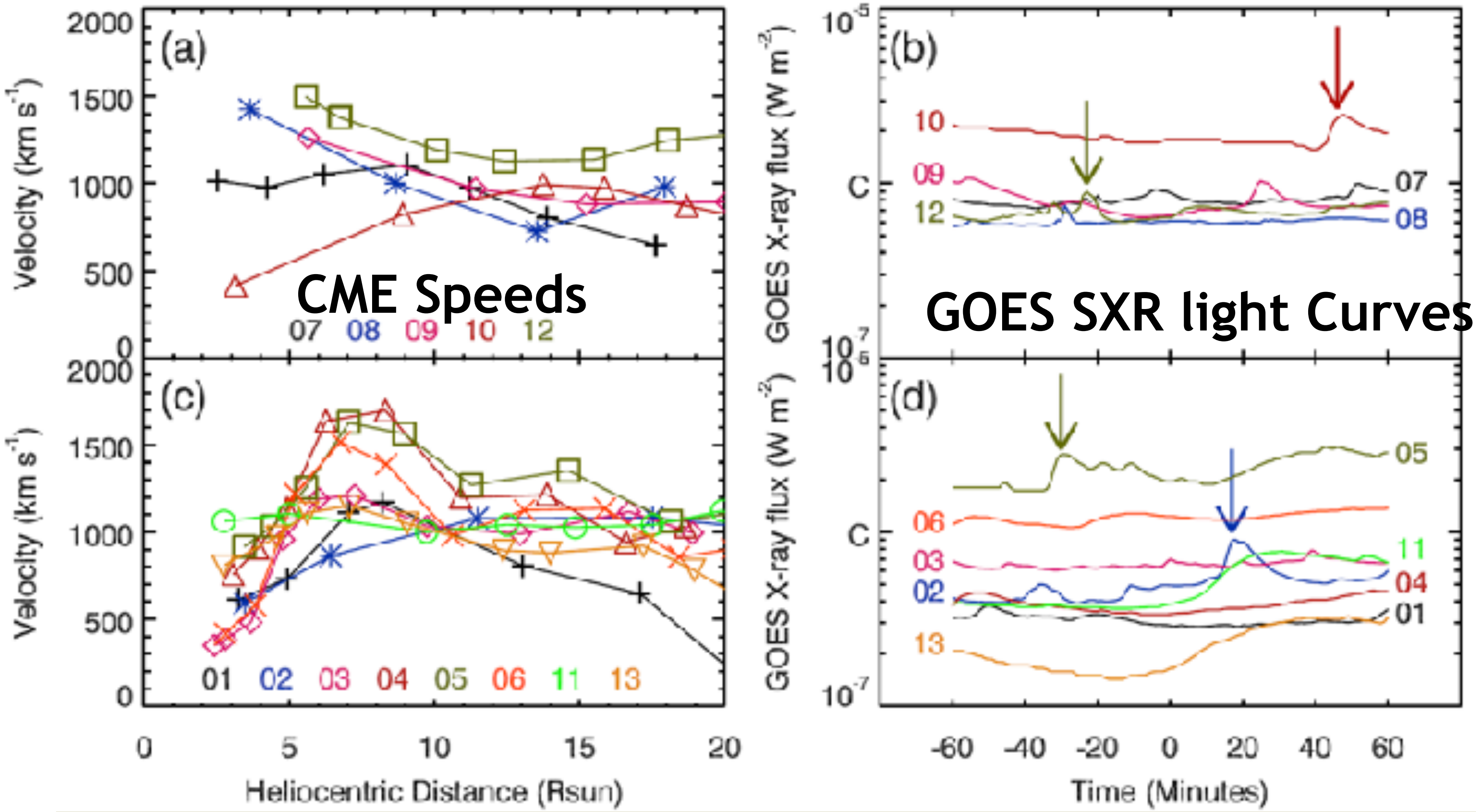




**Zhang et al. 2001, 2004**
**Zhang & Dere, 2006**
**Qiu et al. 04;Kundu etal 04**
**Sterling & Moor 2005**

**CME acc. closely associated with flare SXR pr**

# 1. General Observations: CME-flare NON Associat.

**Examples of non-association (Song et al. 2013):**
**Even fast CMEs may not be associated with any flares**

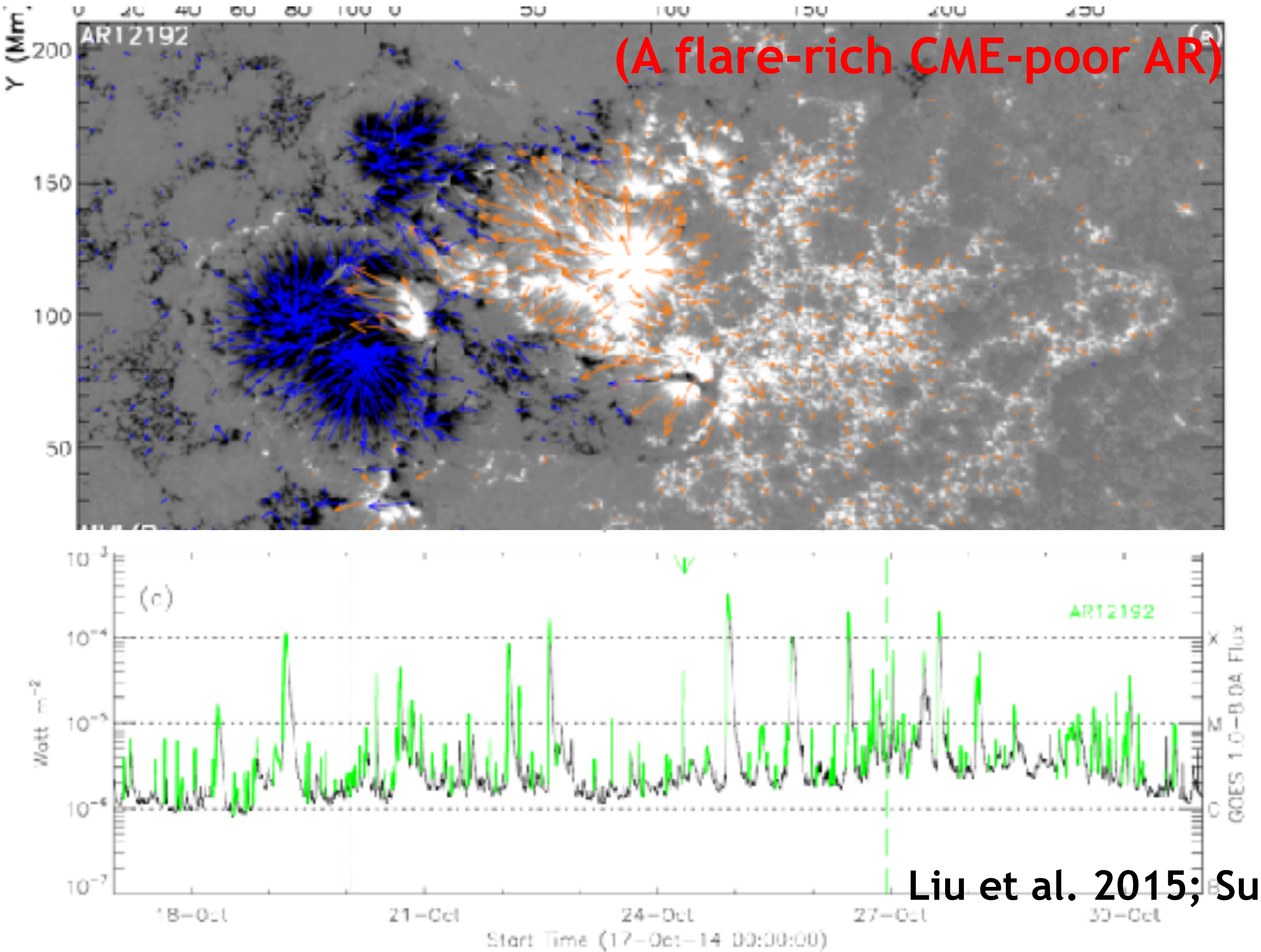



**Fast (>1000 km/s) \ front-side \ wide (>20°) \ No X-ray flares**

**→13 events in solar cycle 23! No observable flares (GOES-X**

# 1. General Observations: CME-flare NON Associat.

**The largest AR (since Sept. 1990) NOAA 12192 (Oct. 2014) releases 127 C + 32 M + 6 X flares, yet with only one small jet-like CME.**




Liu et al. 2015; Sun et al. 20

# 1. General Observations: CME-flare association

**Association studies show:**

**1. close CME-flare association :**

→Many CMEs are accompanied by flares (Harrison 95);

→CME parameters closely associated with flare properties (Zhang J. et al.,01; Qiu J. et al, 04, 07; Maricic et al. 07 …)

→Reconnections may play an important role in energizing CMEs

**2. not-very close CME-flare association:**

According to some large-sample statistical studies/case studies

→CME-flares are only loosely associated (Gosling 76, Sheeley 99; Hundhausen97, Yashiro etal.05, Vrsank etal.05..)

70% of C-, 44% of M-, 10% of X-flares are not accompanied by CMEs

# 2. Energy Budget, Big Picture, and Questions

## Strongest energy release in the solar

**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$^{-3}$ |

(Forbes, 2000)

**Energy Requirements**

**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 ($m_p ngh$) | $h = 10^5$ km | 0.5 |
| Magnetic ($B^2/8\pi$) | $B = 100$ G | 400 |

**Energy Sources**

**Kinetic + Thermal + Radiation + Potential + Magnetic = CONST**

**→B is dominant in sources!**

# 2. Energy Budget, Big Picture, and Questions

**Two Basic Observations:**
**mass ejection/acceleration, no rapid change before eruption.**

- ➢ Solar eruptions involve processes with SLOW and FAST t-scales:

**GRADUAL energy storage process and FAST energy release process!**

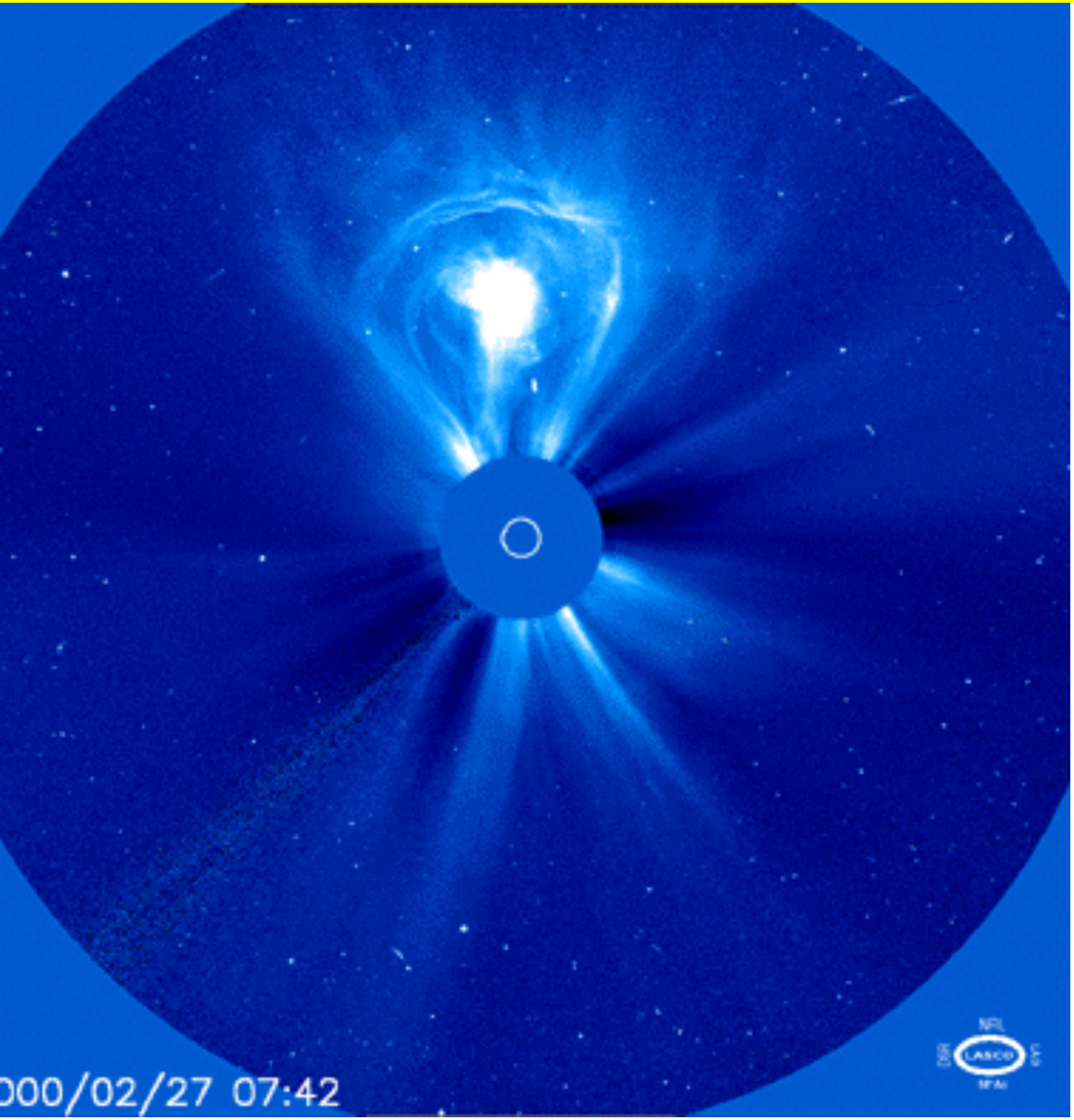
- ➢ The pre-eruption corona is of high B-energy (non-potential, a magnetic structure with a significant amount of current)

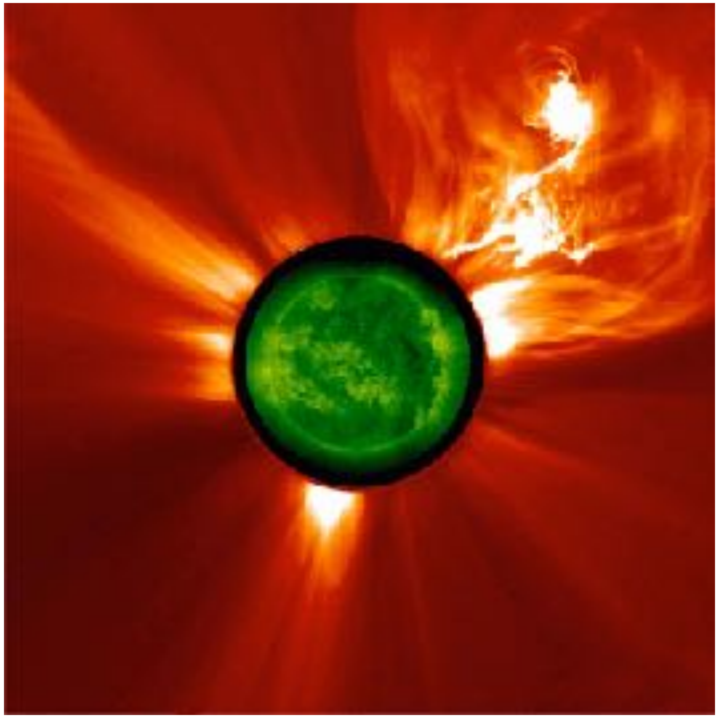
**Major Q: How is the energy stored and released for CMEs?**

- ➢ WHAT structure carry the "FREE" energy, powering the CME?
- ➢ CMEs are from conversion of B to mechanical energy, work done by (magnetic) FORCES!?
- ➢ Any specific triggers of the sudden energy release?
- ➢ How energy converted, through Ideal instability, resistive instability (rec.)? Which one dominates?

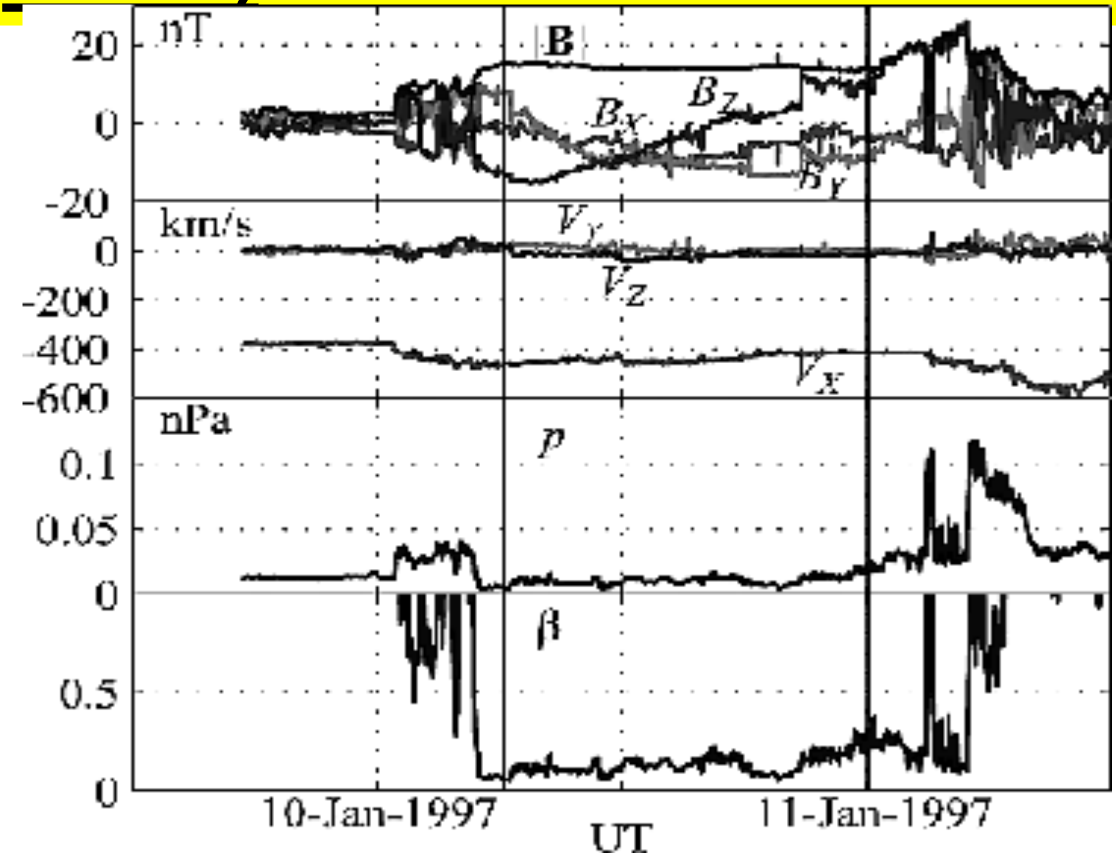
# 3. What to ERUPT?(What structure carries the free E)

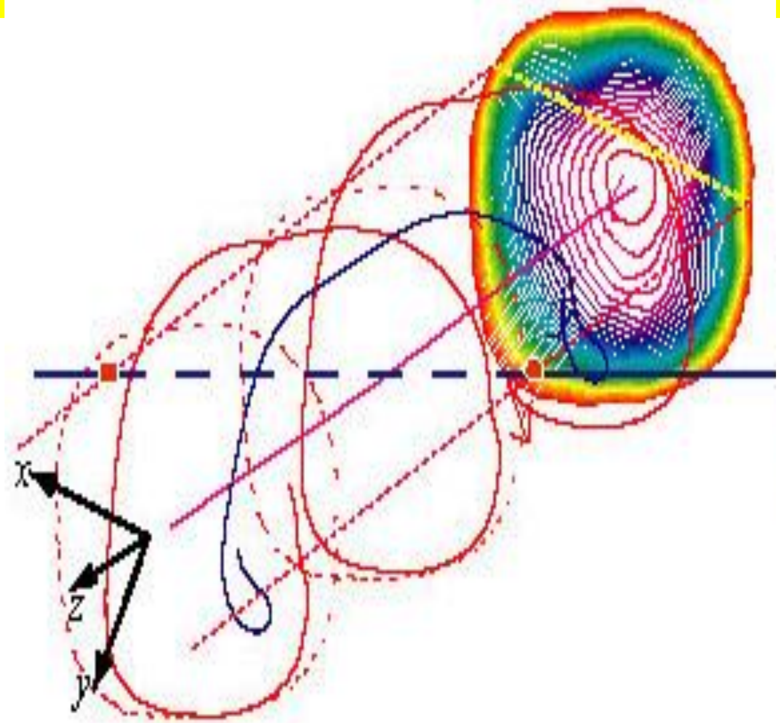
Typical 3-component ejecta: 1) bright front
2) dark cavity
3) bright core
Hard to tell, need to go lower!



# 3. What to ERUPT?(twisted structure in many ICMEs)

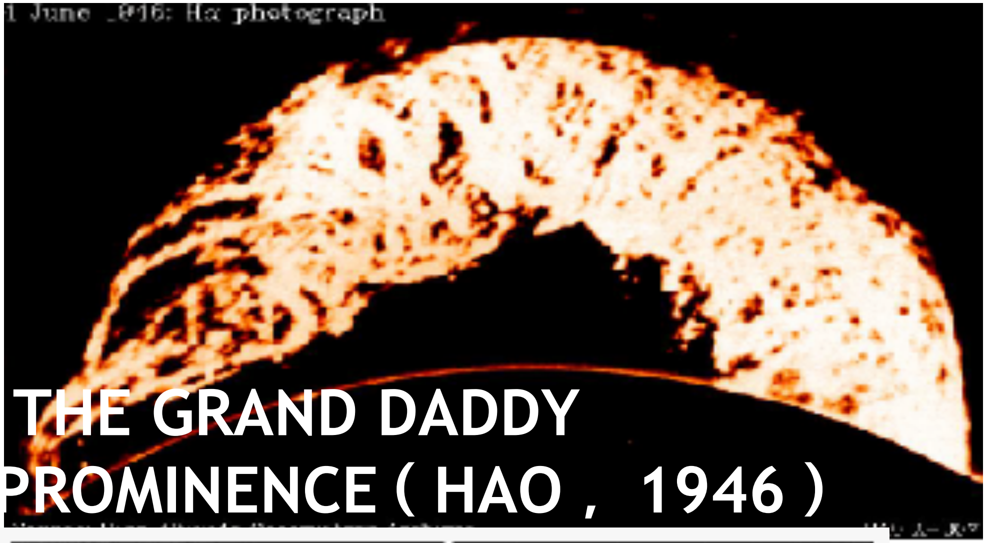



x: projected s/c path

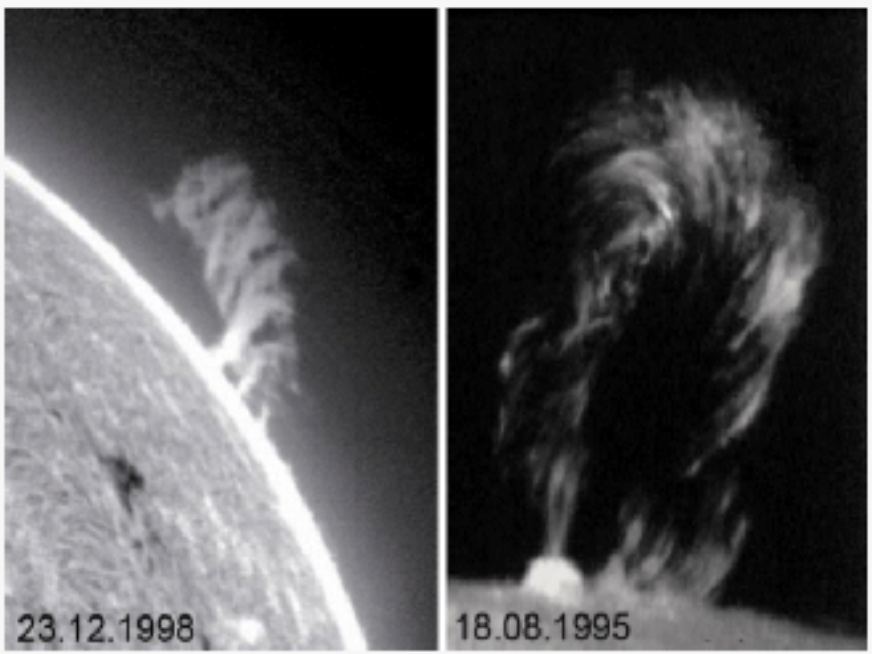
**In-situ data and the 2D Reconstruction of B reveals magnetically-twisted structure (flux rope)**

# 3. What to ERUPT? (twisted structure of prom.)



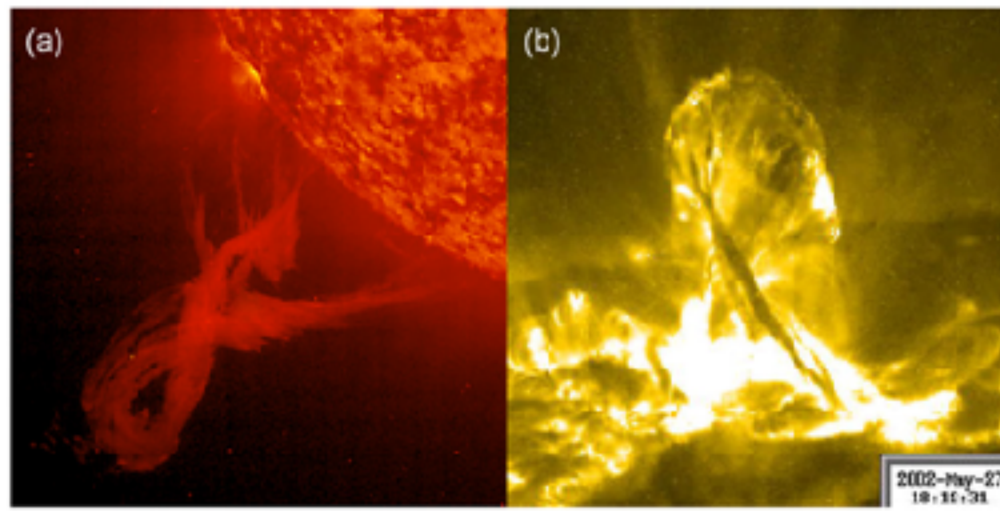

3 types of pre-CME structure
(according to T):

1). Low-temperature prom.:
Twisted structures are seen in
many eruptive prominences




Flippov et al., 2015

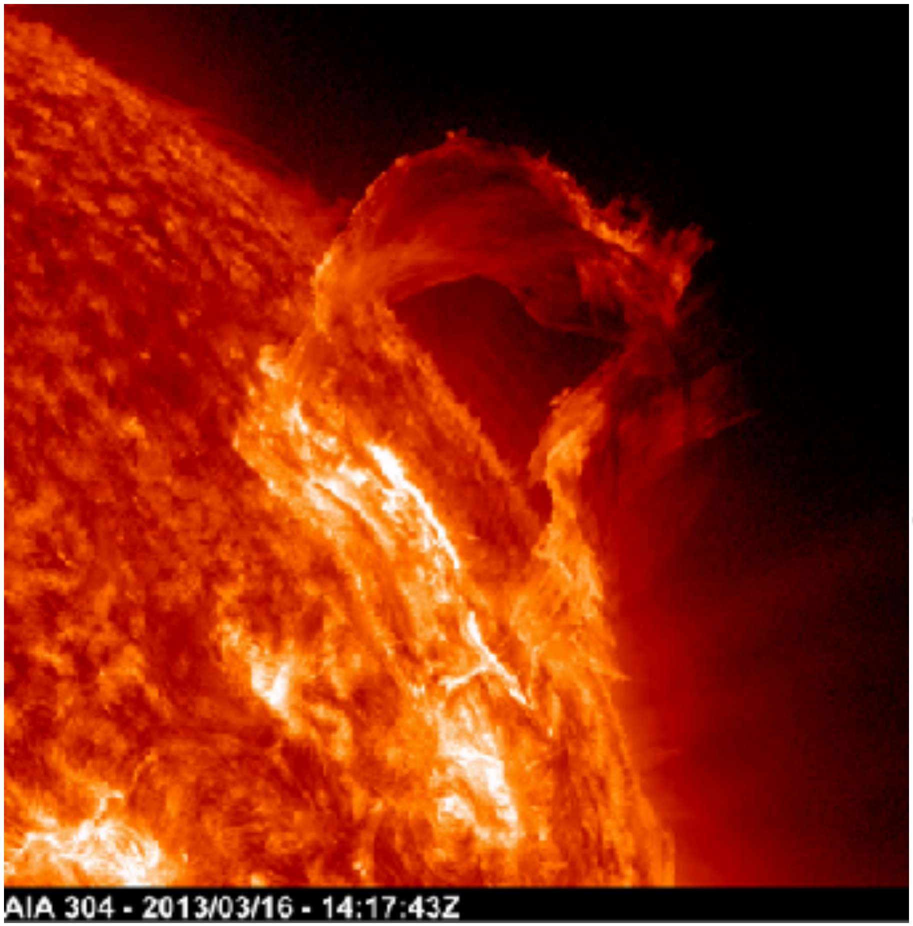
Figure 3
Twisted prominences (courtesy: Big Bear Solar Observatory).

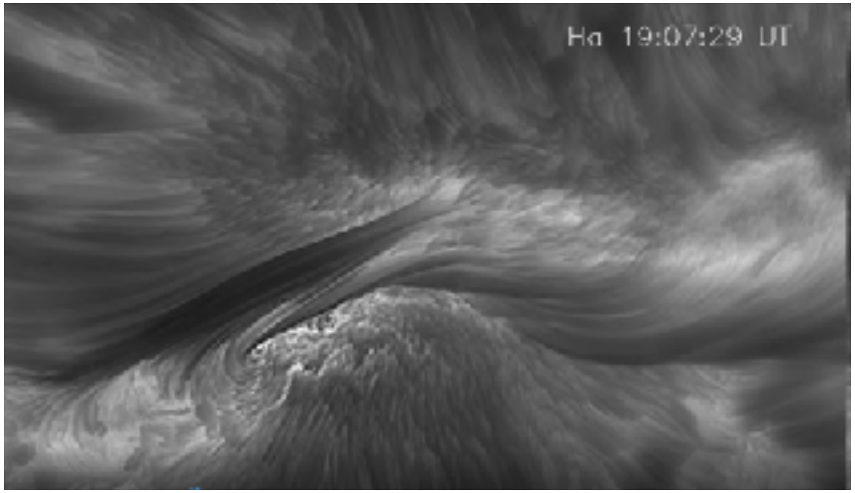



Torok et al., 2014

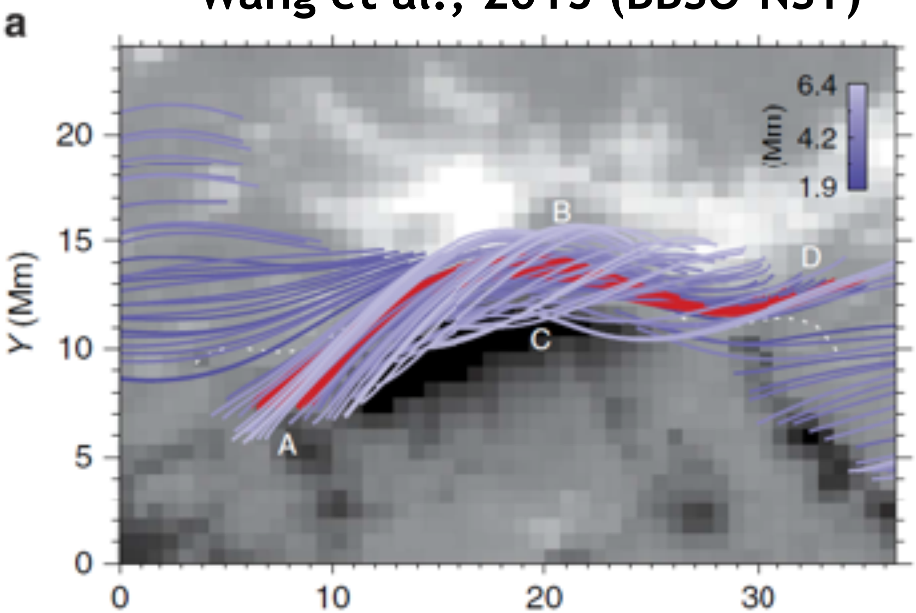
# 3. What to ERUPT?(twisted structure of prom.)

(Movie 3- Prominence Erupt.) (Movie 4- Prominence Erup




Wang et al., 2015 (BBSO-NST)

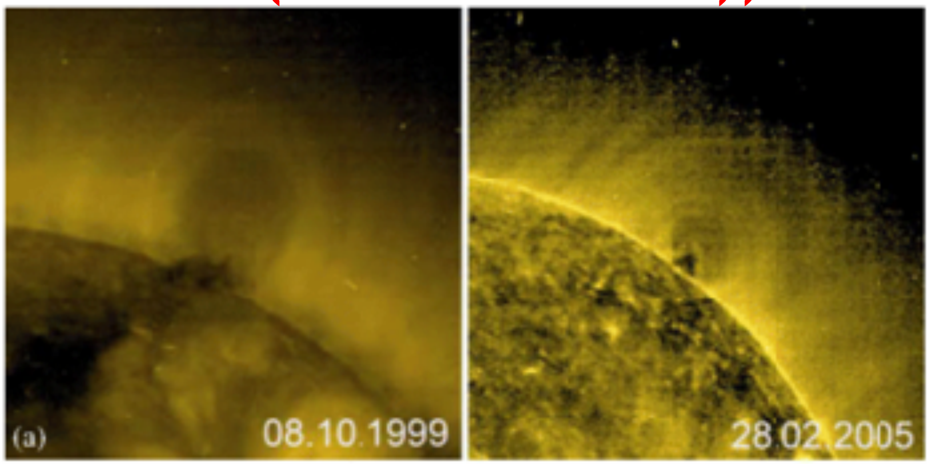


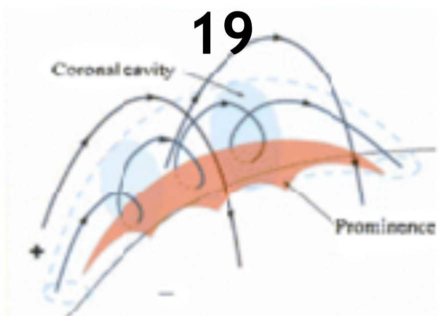
## 3. What to ERUPT?(twisted structure in cavities)

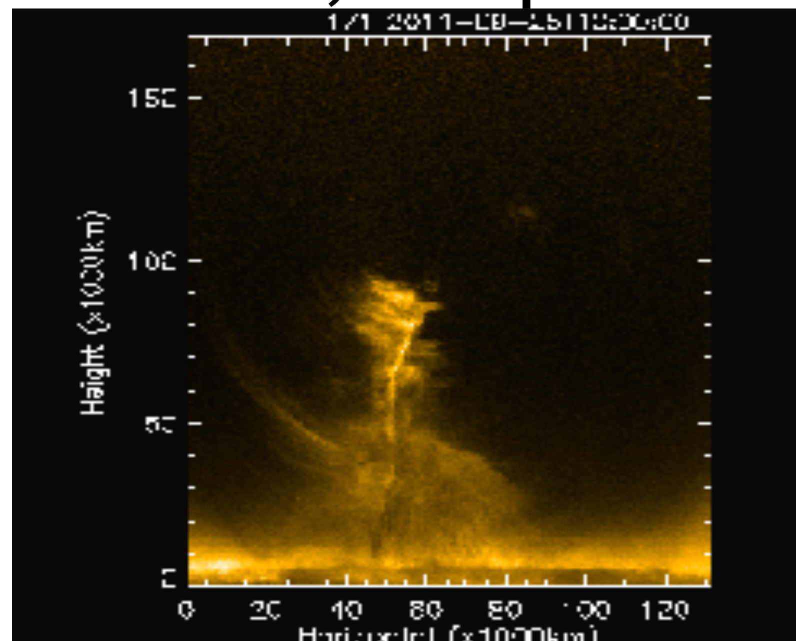
3 types of pre-CME structure (according to T):

**2). Coronal cavity (Normal T) (show internal rotating motion (solar tornado))**

Cavity: dark, circular area obser in EUV and WL, with prominence



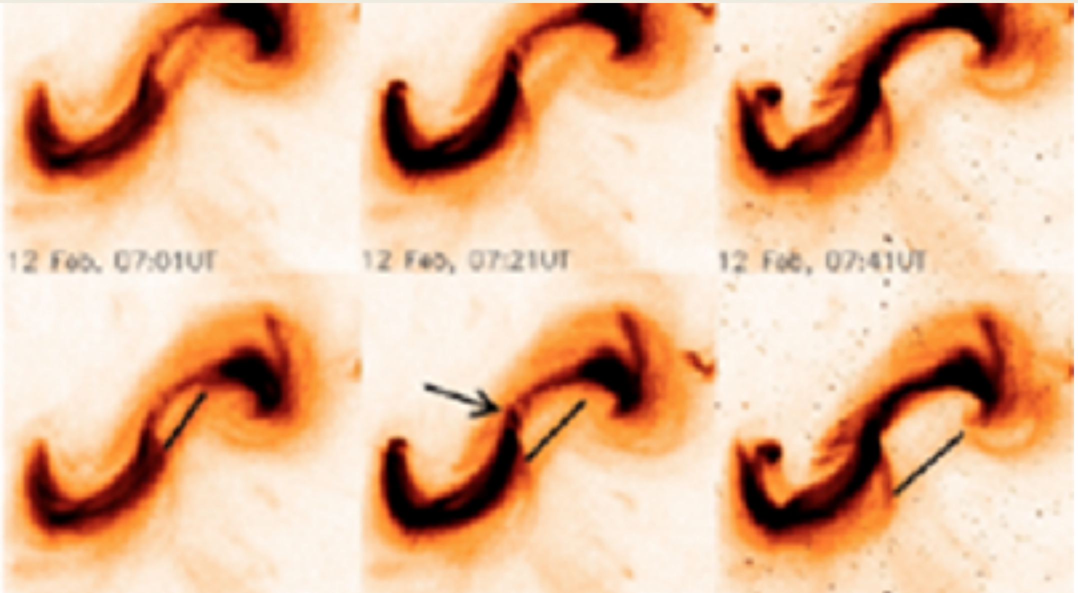



(b)

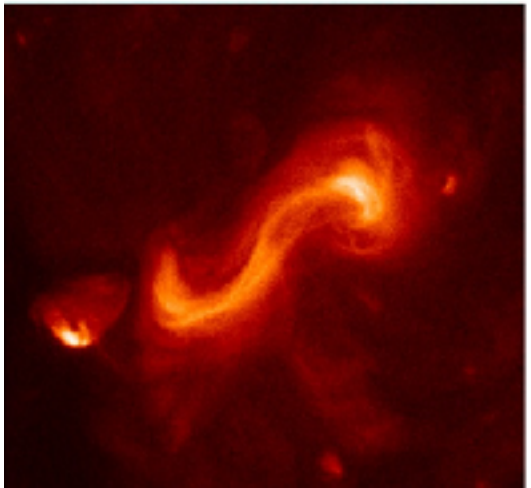
(Zhang & Liu 2011; Li et al. 2012)

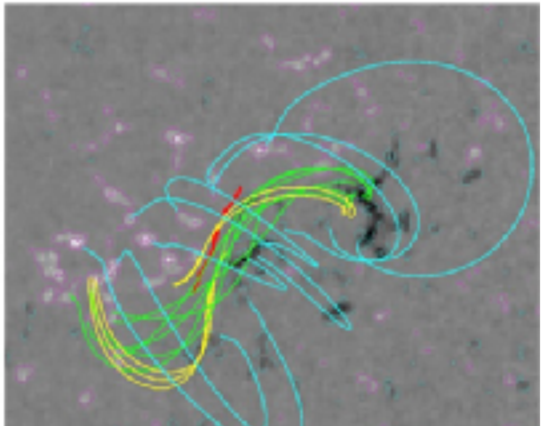
# 3. What to ERUPT?(twisted structure of sigmoids)

extrapolation




(Canfield et al. 1999; Makenzie & Canfield 2008……)

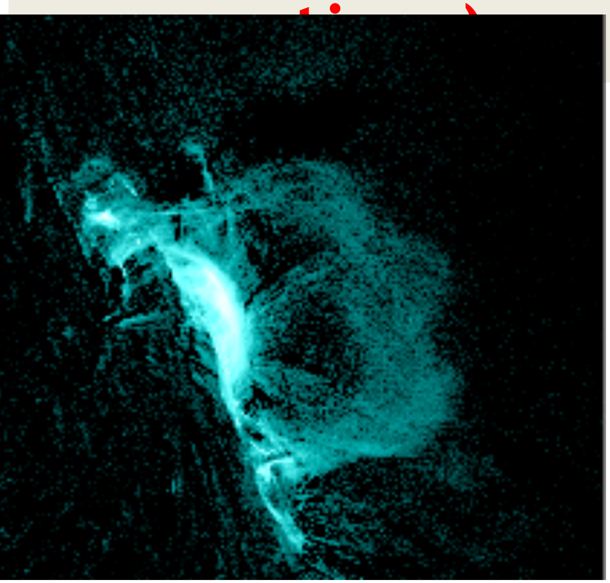




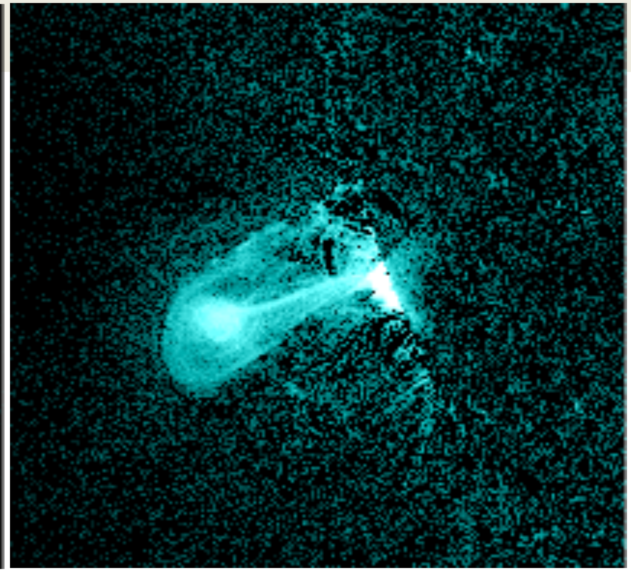
(Savcheva et al. 2012)

# 3. What to ERUPT?(twisted structure of Hot Channels)

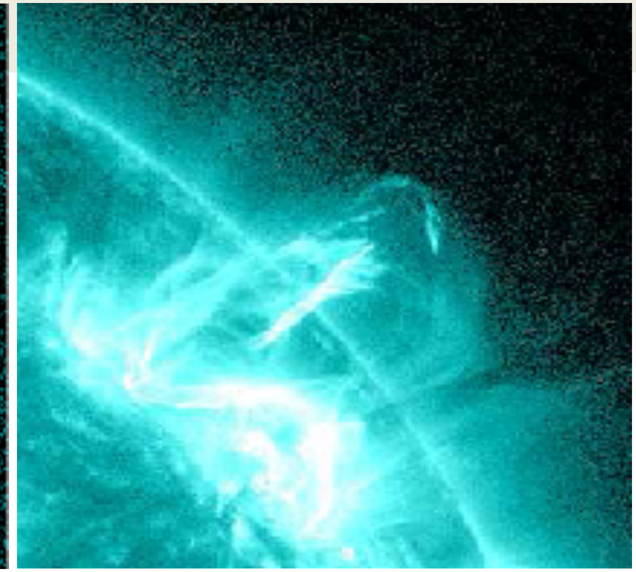
(observed by AIA/SDO at 94/131A from diff.



(Cheng et al. 2014a; Li et al. 2013)



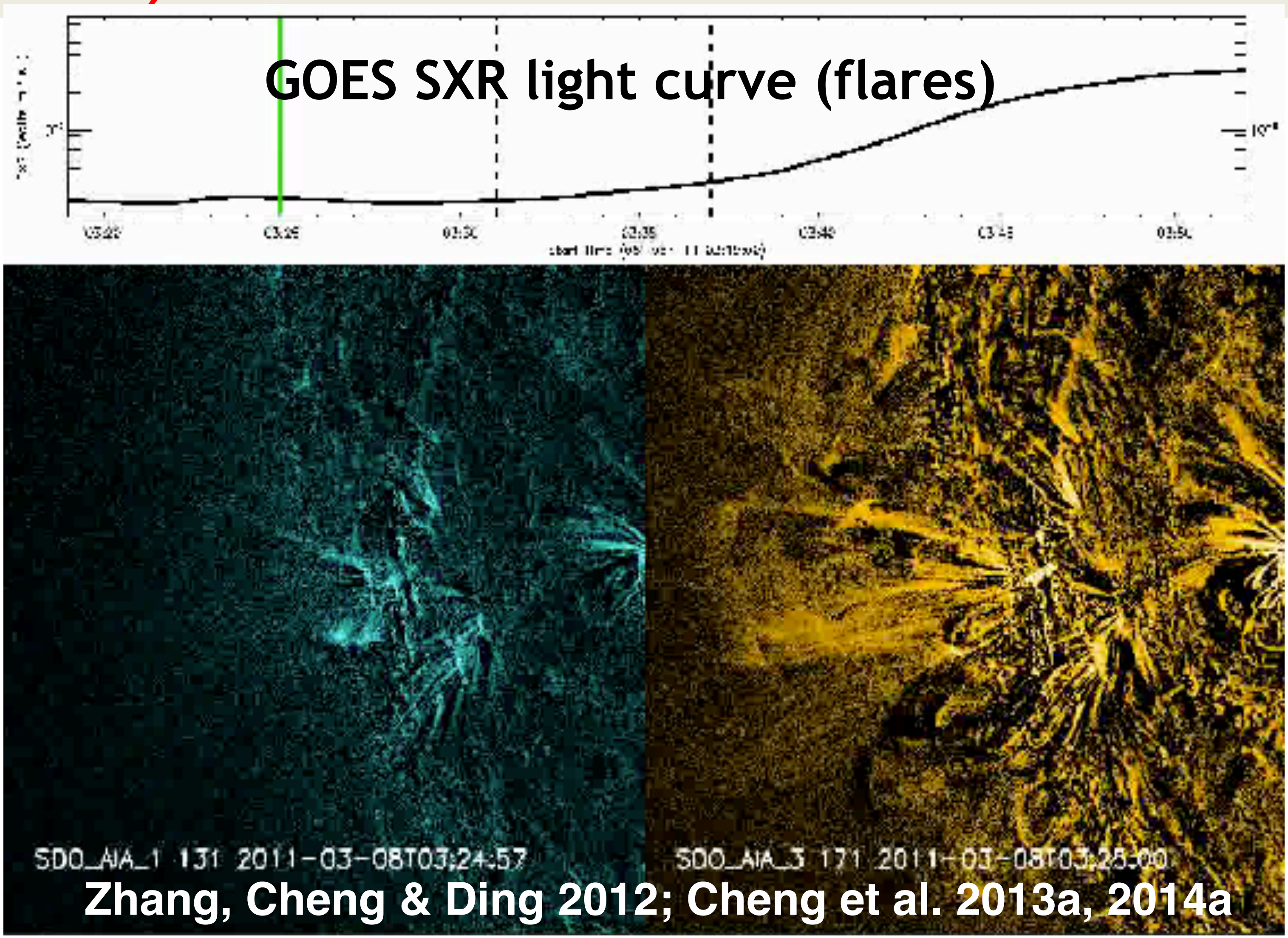
(Cheng et al. 2011b; Song et al. 2014)



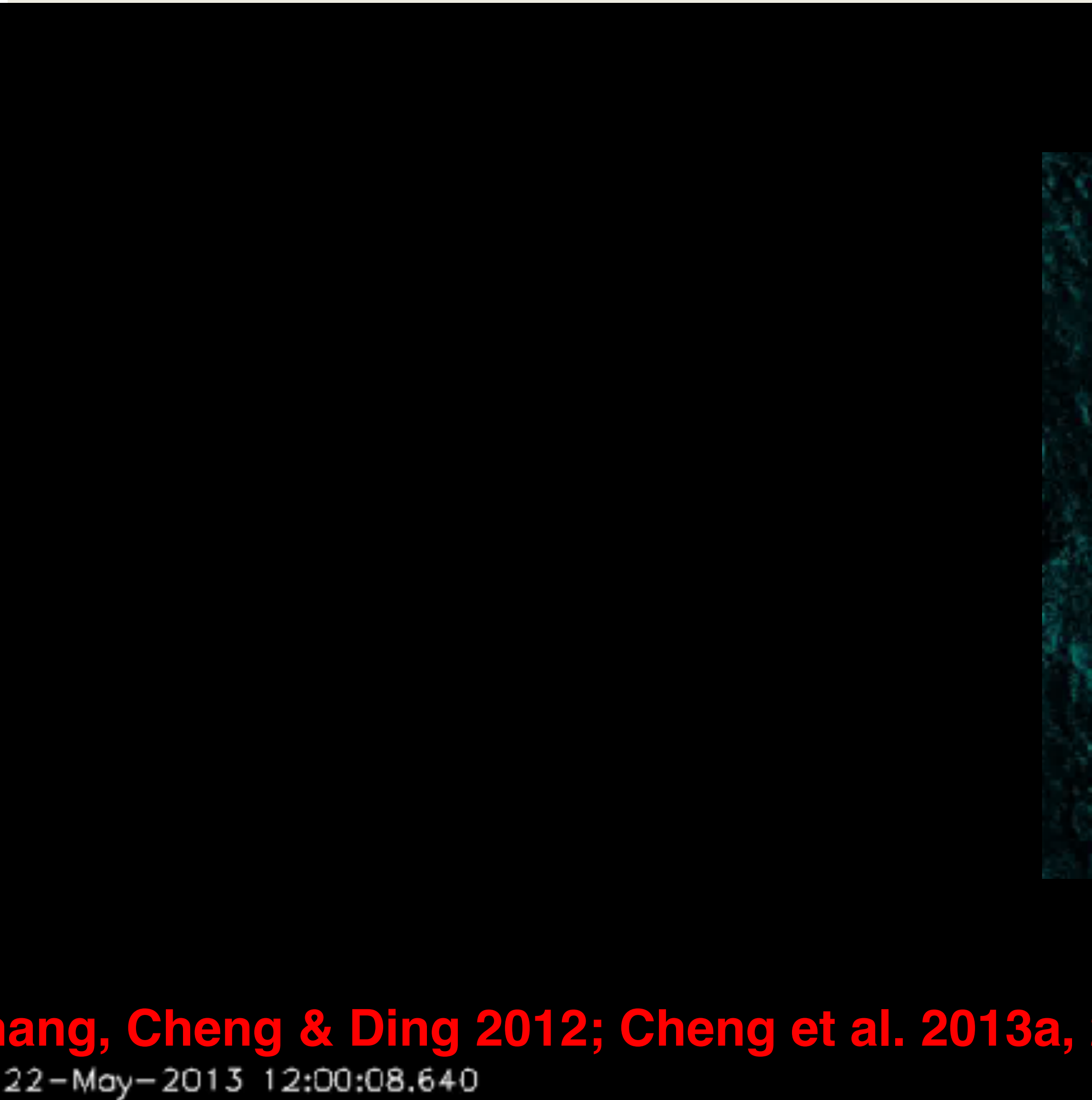
(Cheng et al. 2013a; Patsourakos et al. 2013)

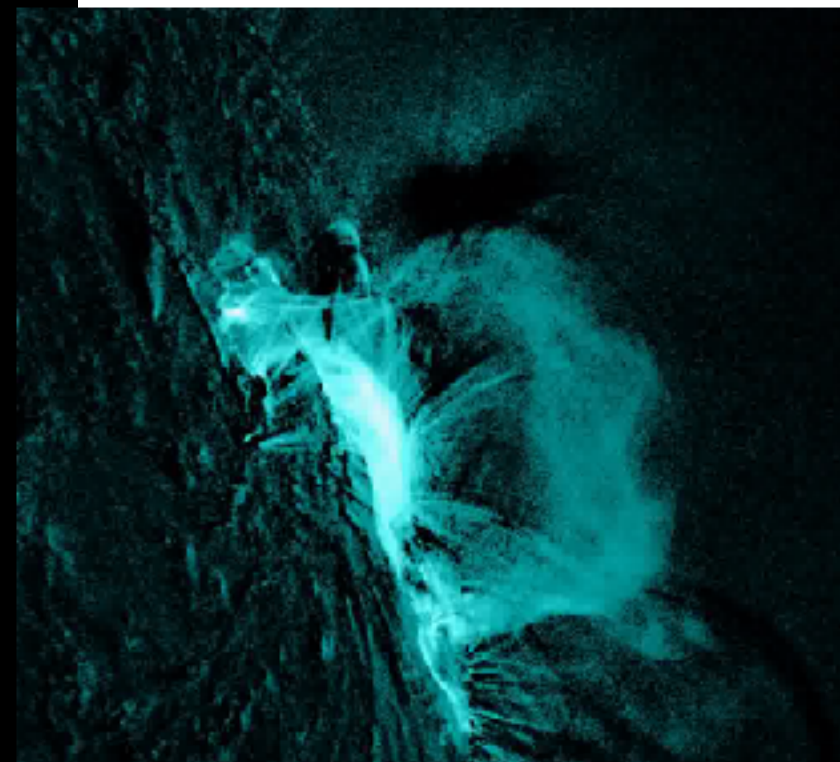
# 3. What to ERUPT?(twisted structure of Hot-Channels)

## 3.2) Hot Channel structure (seen by AIA SDO at 94/131A)



# 3. What to ERUPT?(twisted structure of Hot-Channels)

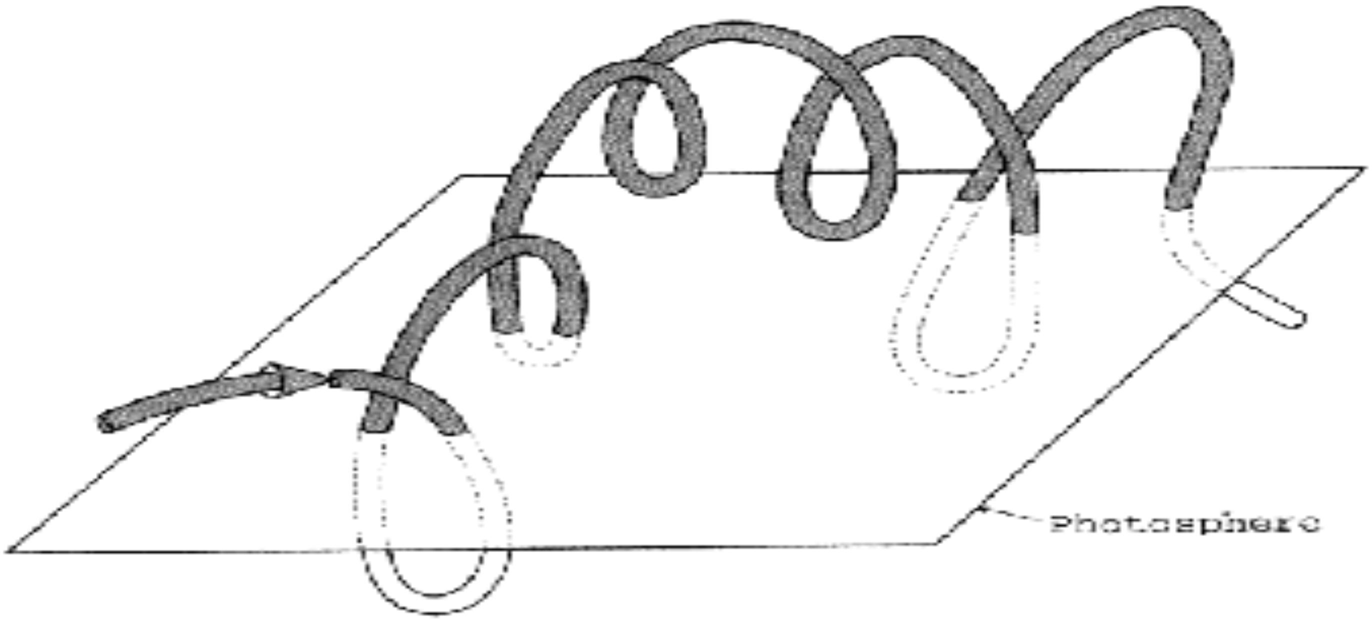


TWISTED STRUCTURE

ang, Cheng & Ding 2012; Cheng et al. 2013a, 2014a

# 3. What to erupt? A flux rope (in many cases)!




A 3-D flux rope scketch (Low, B. C., 2000)

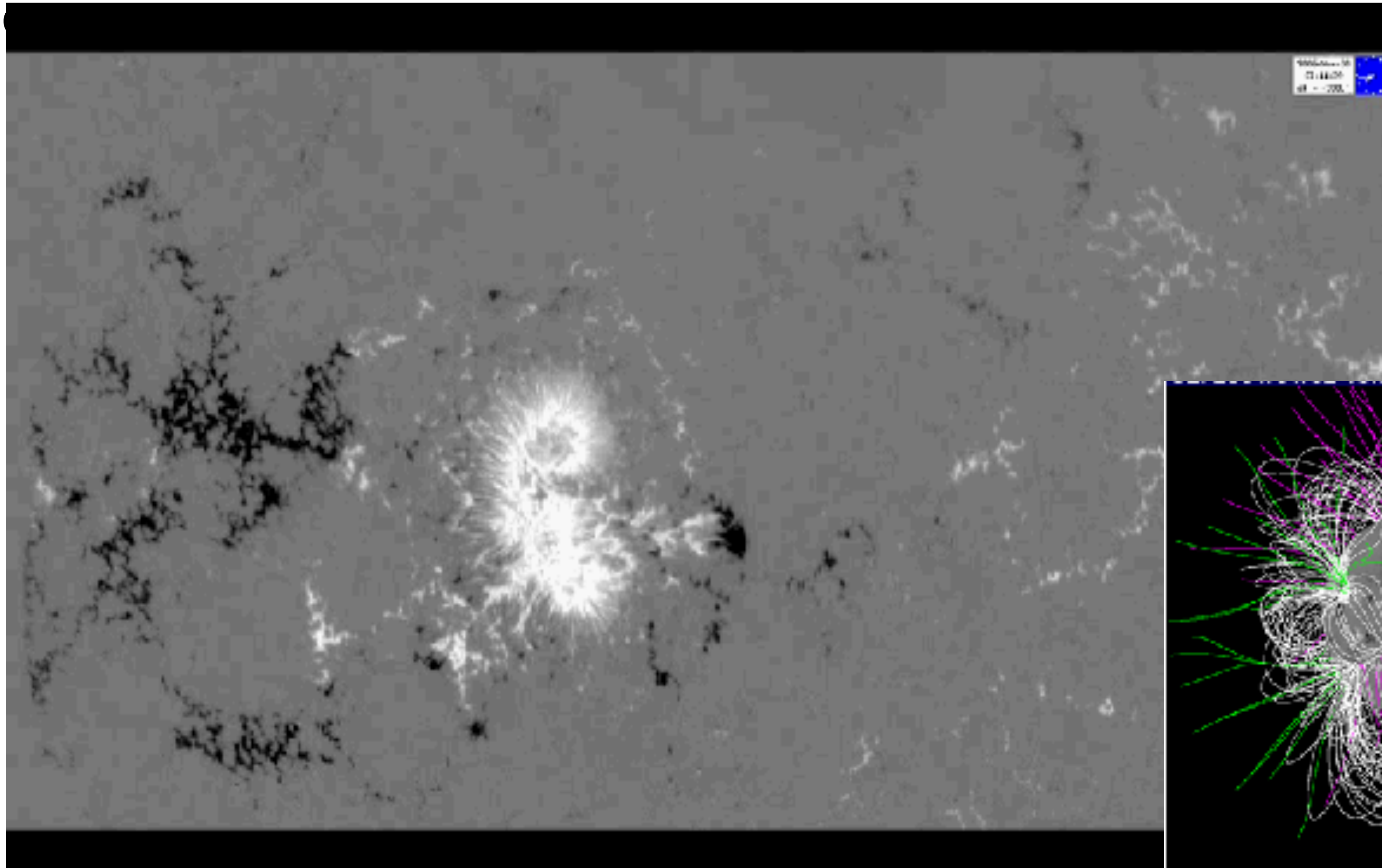
Common characteristics: the twisted structure (flux rope)

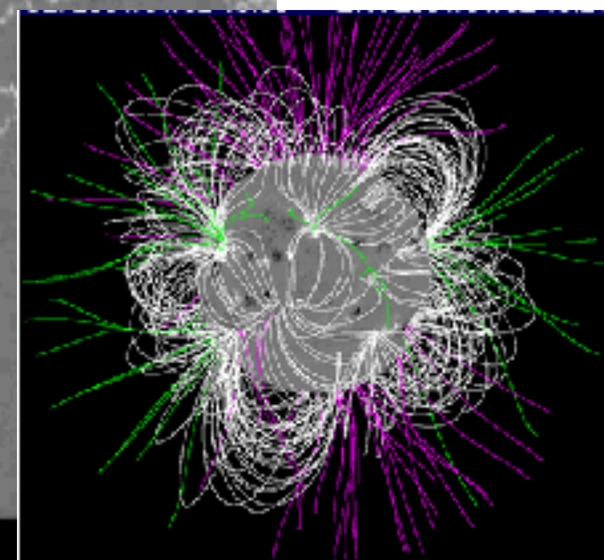
→ALL present CME models involve a flux rope structure!
(different in how and when the flux rope are formed, e.g., before or during the eruption)

# 4. Flux Rope Formation (and enhancement)

**Conceptual Illustrations (like many concepts discussed here):**

**Photospheric footpoint motions and the driven rec. in the**

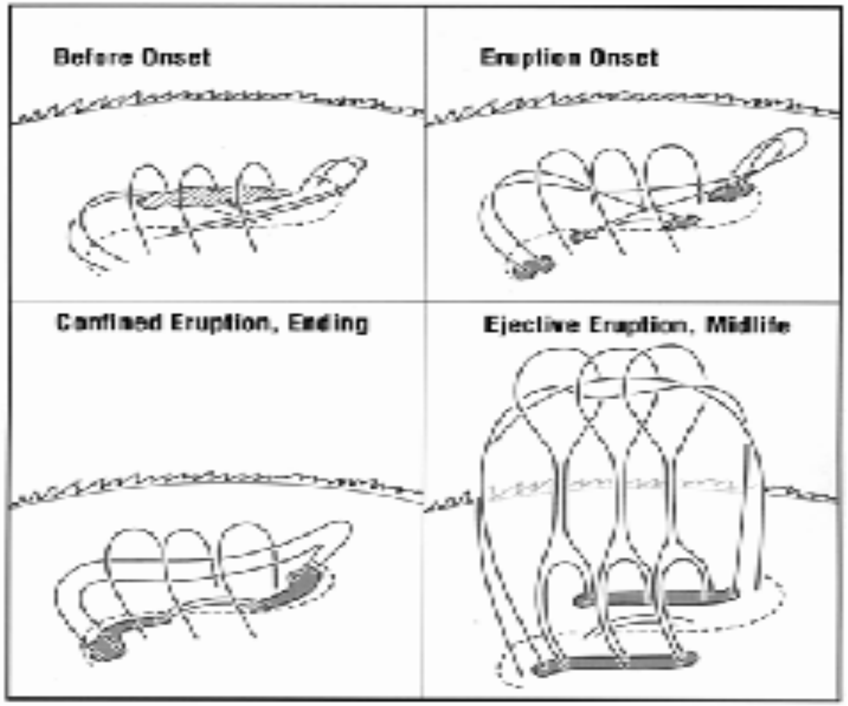




**Footpoint motions: shear\converge\twist (rotate)\emerge\cancellation**

# 4. Flux Rope Formation (and Enhancement)

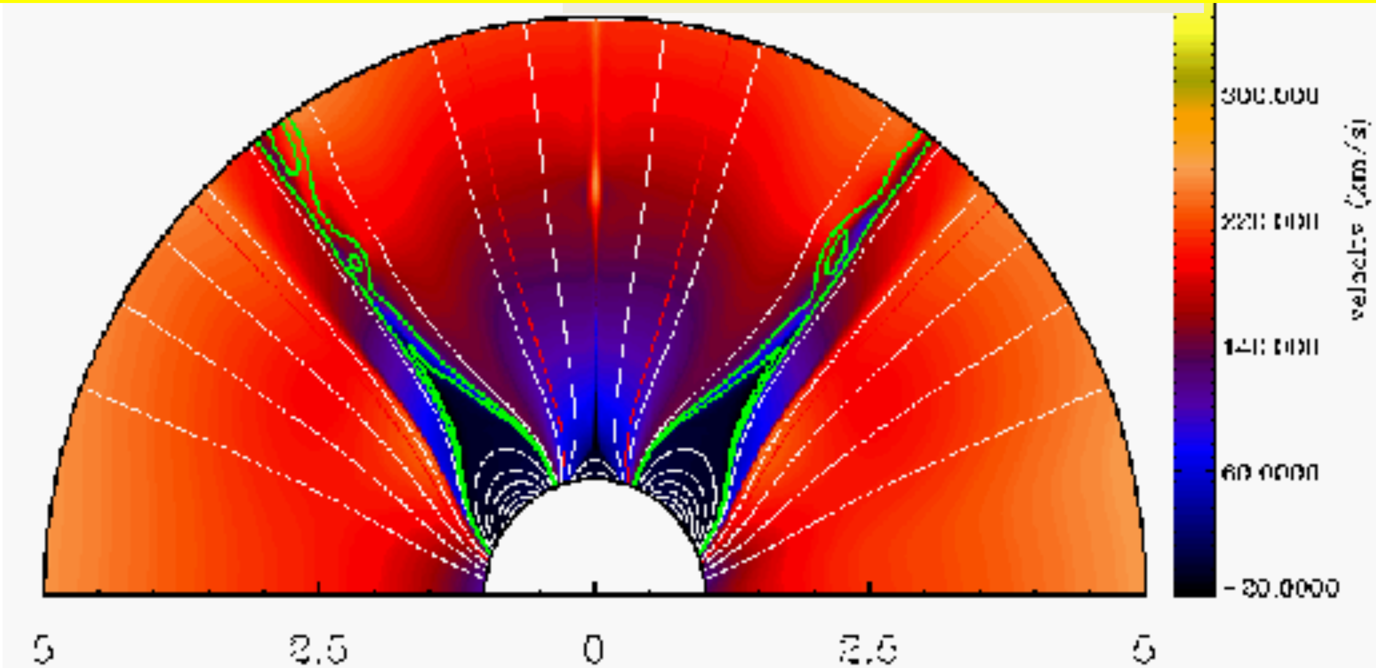
- **Magnetic Shear →current build-up in highly-conductive corona→rec.→partially release energy, tranport helicity→ flux rope**




**Tether-cutting reconnection**(Moore et al., 1980, 2001; van Ballegooijen et al. 1989)

- **Flux emergence (Fan et al. 2001; Gibson et al. 2004)**
- **Sunspot rotation/twist (Evershed,1910;…Yan&Qu2007;Ruan2014)**

# 5. Flux Rope Instability, & Forces Acting on the Rope



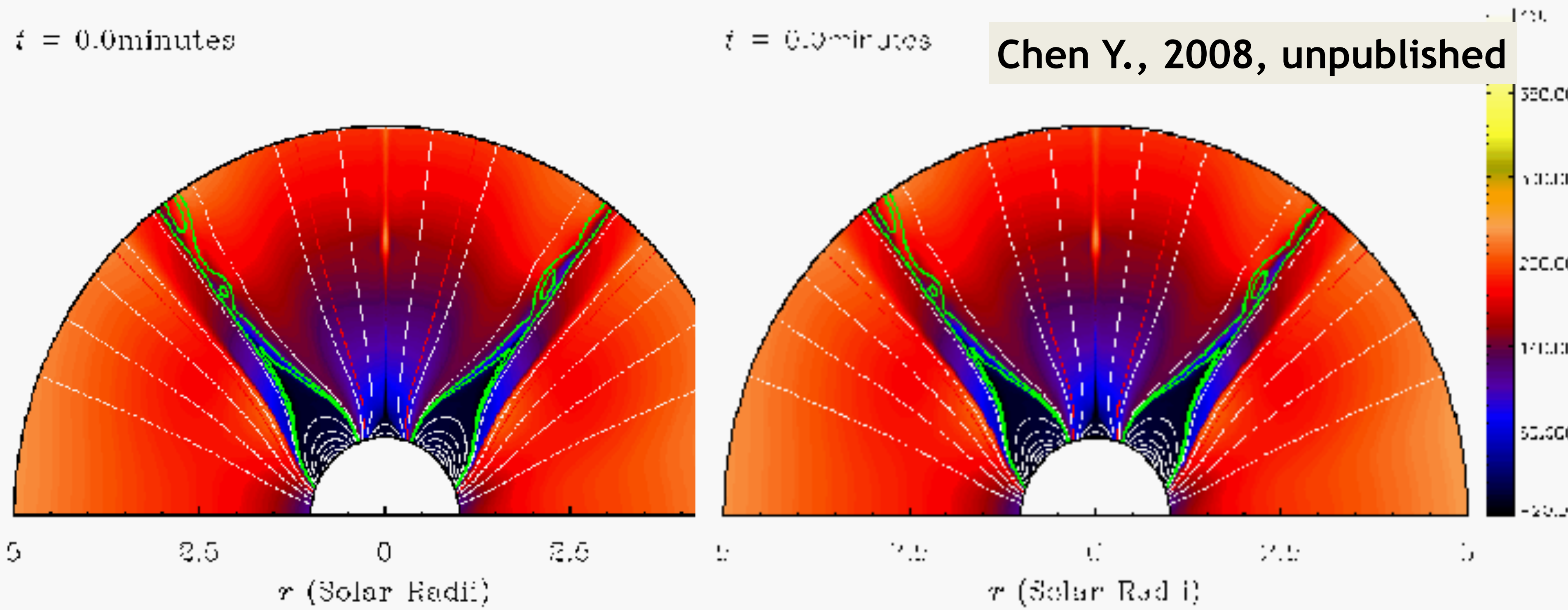

Initial External B: mostly potential, without any free energy to erupt

Flux rope : the Engine (driver, energy carrier) of Eruption

External B: the container/trap/cage of the flux rope (External B ~~ large-scale closed-loop systems, well observed)

Interplays between the two central components : rope B and the external B are critical to determine 'ERUPT OR NOT (Equilibrium)'

# 5. Flux Rope Instability, & Forces Acting on the Rope



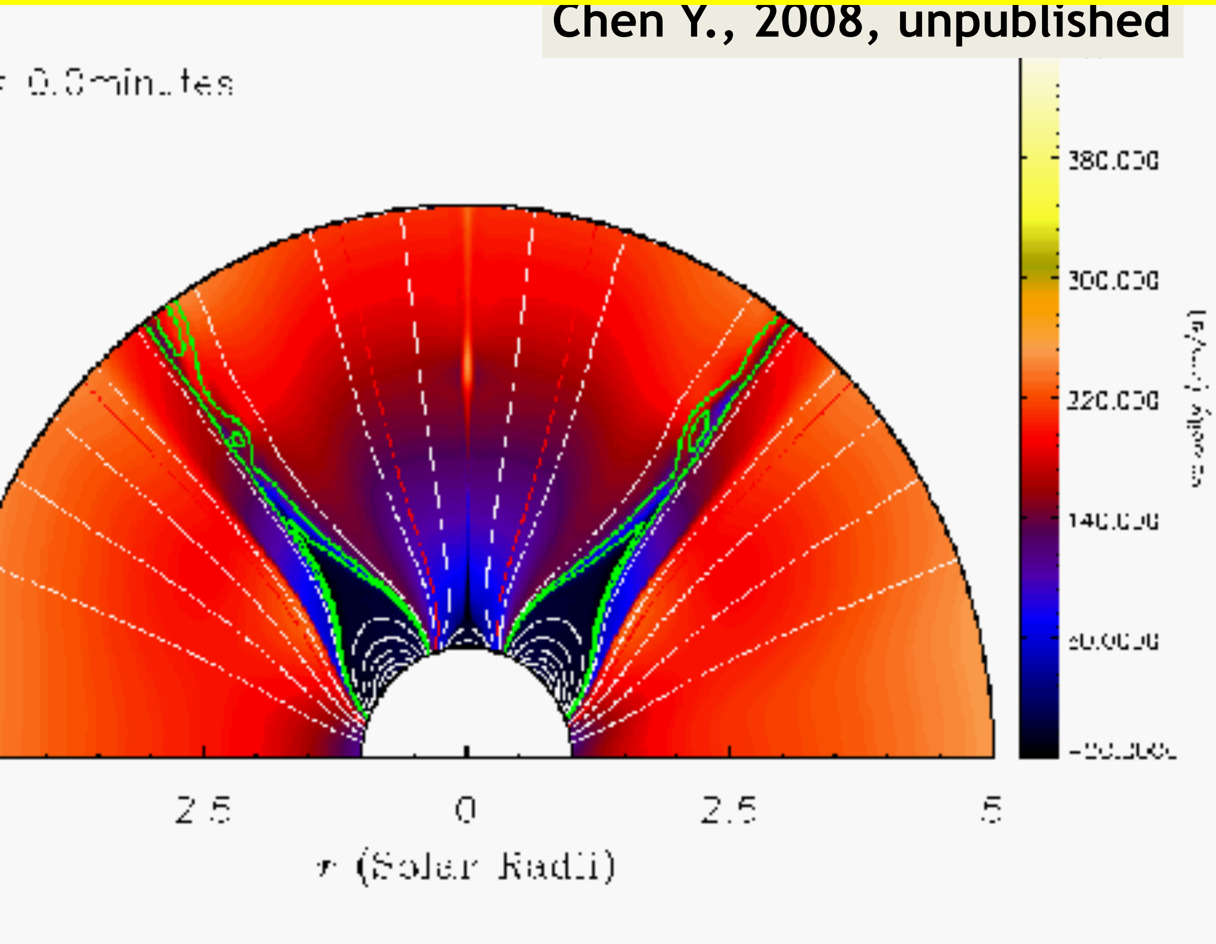

**Major Components of the model: b.g. field + emerging rope**

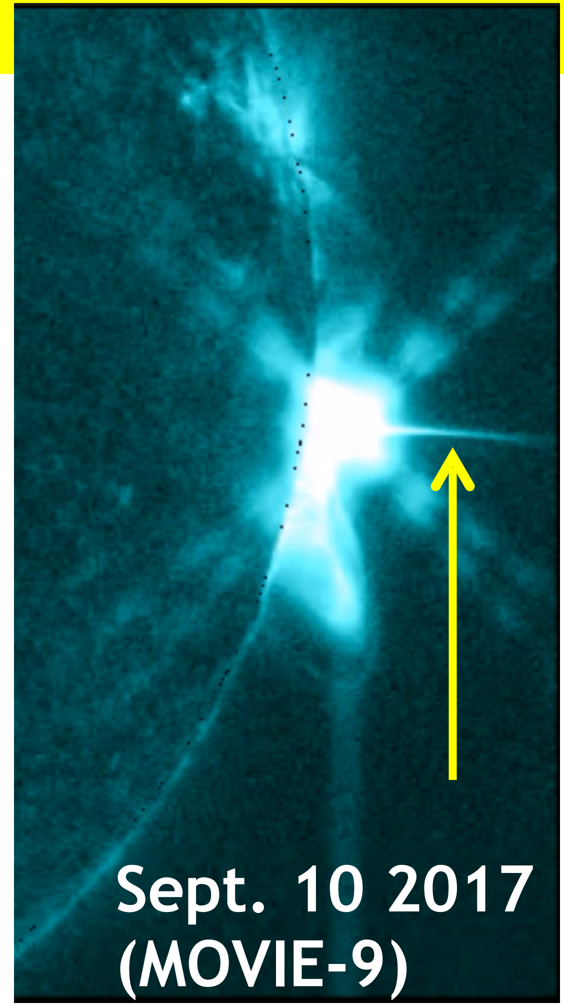
**If the rope flux < a threshold → stable, equilibrium**

**> the threshold → unstable, eruption**

**Terms used in literature** (Van Tend & Kuperus, 1978; Isenberg, Forbes, Lin…; Hu, Chen…; Torok & Kliem…):

# 5. Flux Rope Instability, & Forces Acting on the Rope




**An important (3rd) mag. component appears during eruption:**

**the current sheet behind the ejecta**

# 5. Flux Rope Instability, & Forces Acting on the Rope

2007)


$$n = -\,\mathrm{dlog}(B)/\mathrm{dlog}(h)$$

**Torus I.**: Rising (as a whole), **Instab. criterion:** decay index (n>1.5-2)

**Kink I.**: Writhing (Rotating), **Instab. criterion:** total twist

**NOTE:** these criteria are given under very-simplified conditions, keep this in mind when use!

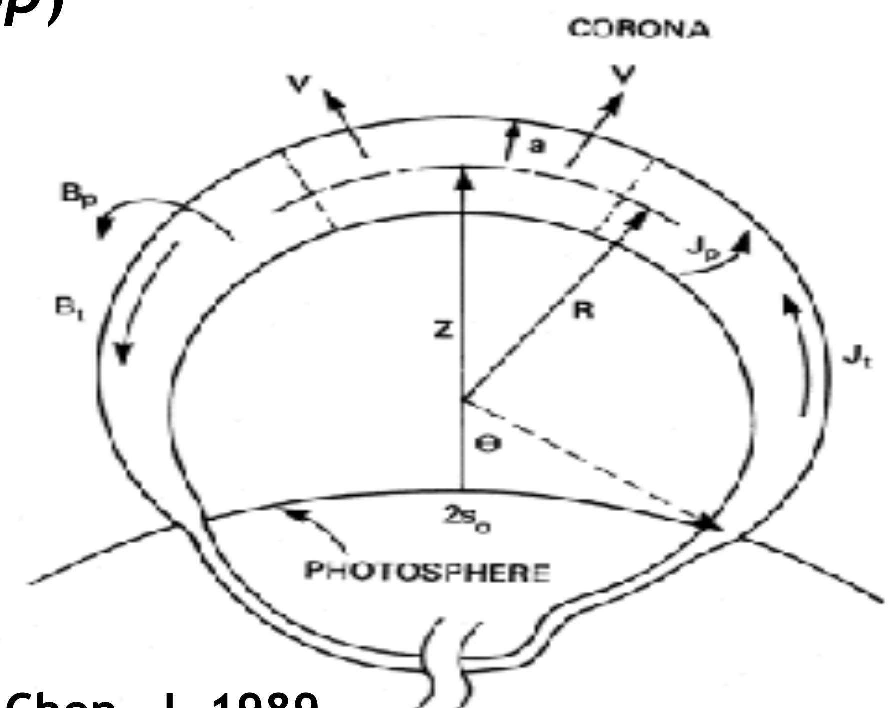
(NOT fully-considering the rope properties for TI and b.g. properties for KI)

# 5. Flux Rope Instability, & Forces Acting on the Rope

Poloidal J ←→Toroidal B & Toroidal J ←→Poloidal B

→Self Force: the rope field exerts forces on the rope current (itself)

(Upward: *Jt X Bt (dominant driving force)*, downward: *Jp X Bp*)




Chen, J. 1989

$$\rho \frac{d\vec{v}}{dt} = -\nabla p + \rho \vec{g} + \vec{J} \times \vec{B}$$

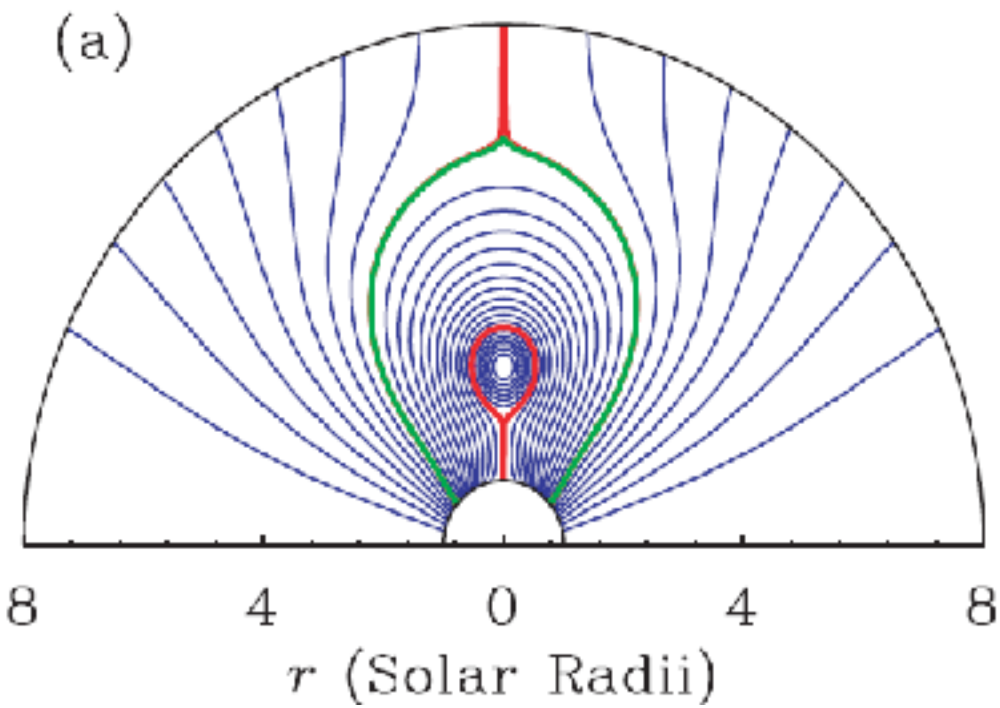
$$\mu_0 \vec{J} = \nabla \times \vec{B}$$

# 5. Flux Rope Instability, & Forces Acting on the Rope

*Jt_rope X Bt_rope*

**(from the toroidal current & its image)**

- **Dominant downward (confining) forces:**
  ***Jrope X Bbg*** **(from the b.g. or external field) (in equilibrium)**
  ***Jrope X Bbg + Jrope X Bcs*** **(in equilibrium and eruption)**
  **(from the bg and the cs)**



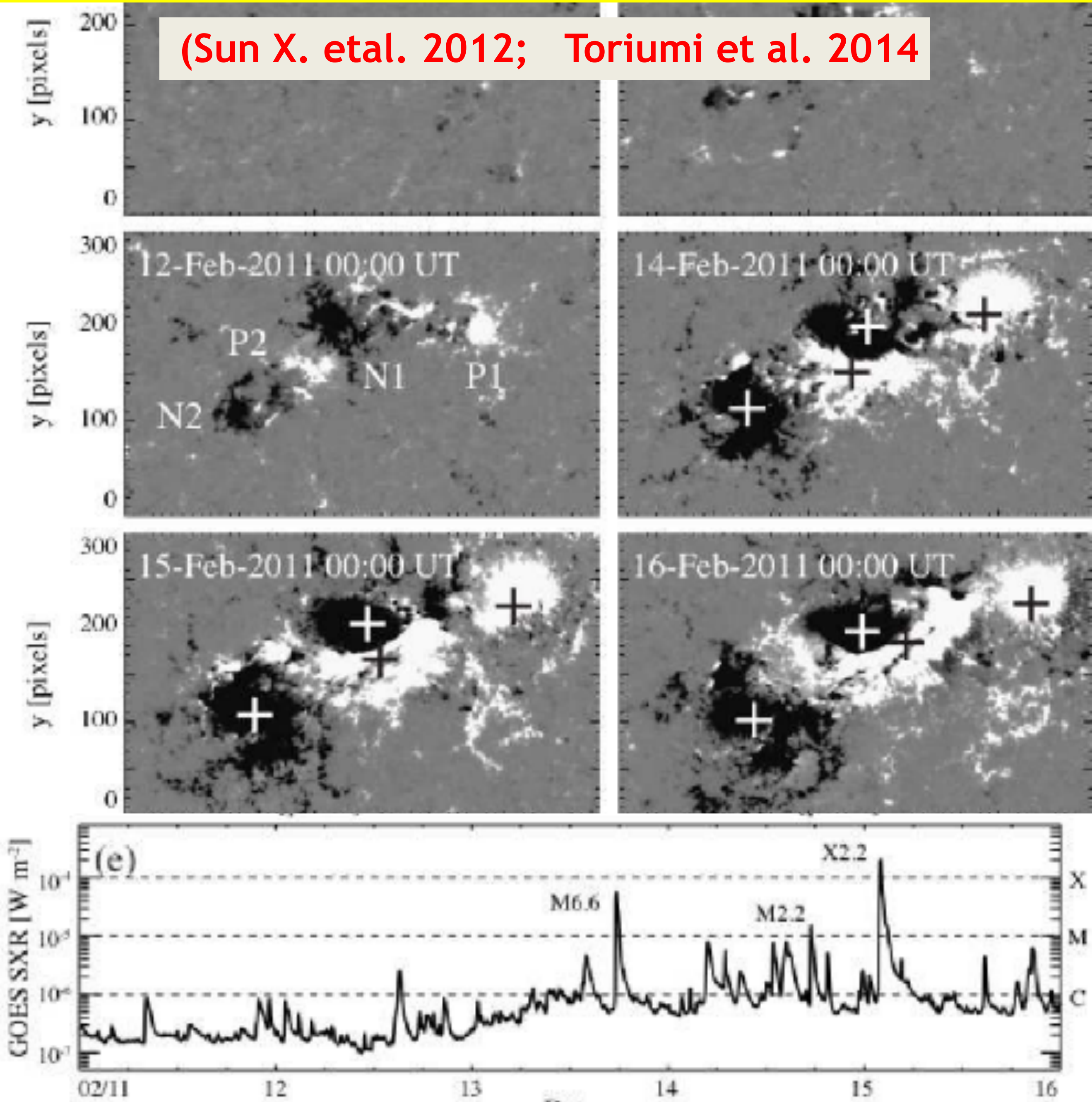

**Chen et al. 2006**

# 6. Triggering/Initiation Processes of CMEs

Both bipolar & multi-polar ARs can be CME sources.

Q: Is this source diff. important?
Many major erupt. from multi-polar ARs.
(COMPLEXITY MAY BE ESSENTIAL)
Antiochos (99, 98) developed a CME-initiation model that relies on the multi-polar configuration.

(Sun X. etal. 2012;   Toriumi et al. 2014



# 6. Triggering/Initiation Processes of CMEs

**'ERUPT OR NOT' determined by the rope-Bext interplay!**

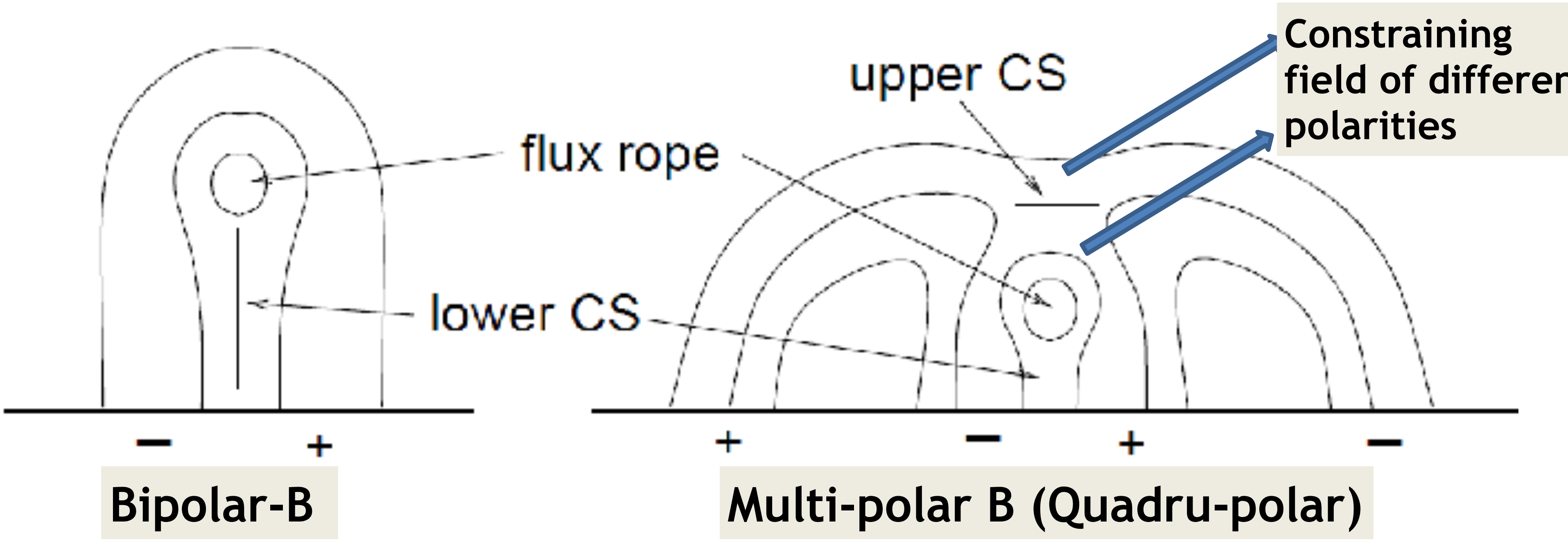
**Processes (acting on a marginal-stable system) that can enhance the flux rope or weaken the constraint of the b.g. B can be a trigger.**

**Such as, photosphere-footpoint & overlying-arcade motions: more twist, shear, arcade expansion** (Moore; Antiochos; Isenberg-Forbes-Lin; Torok-Kliem……)

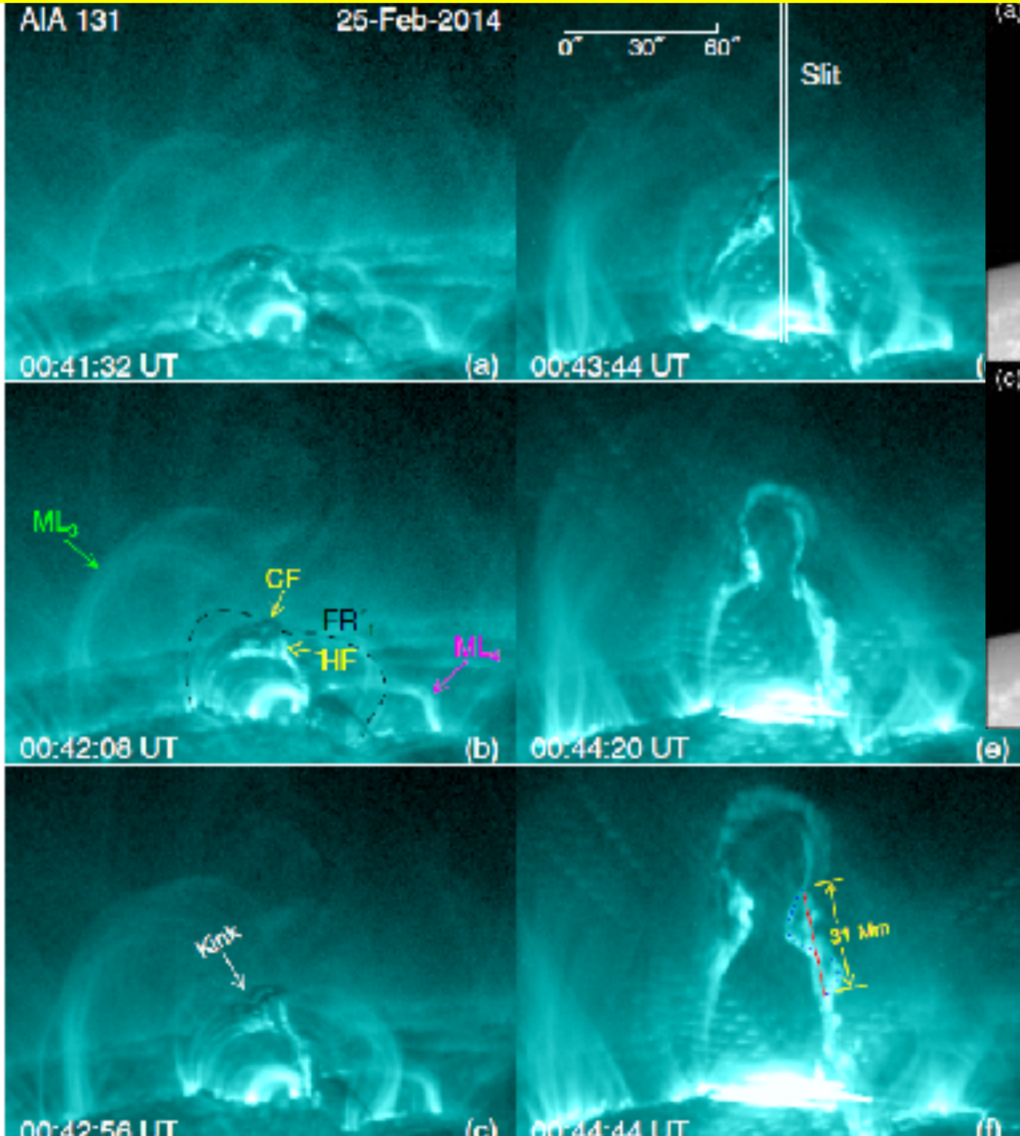
**+ various forms of RECs：**

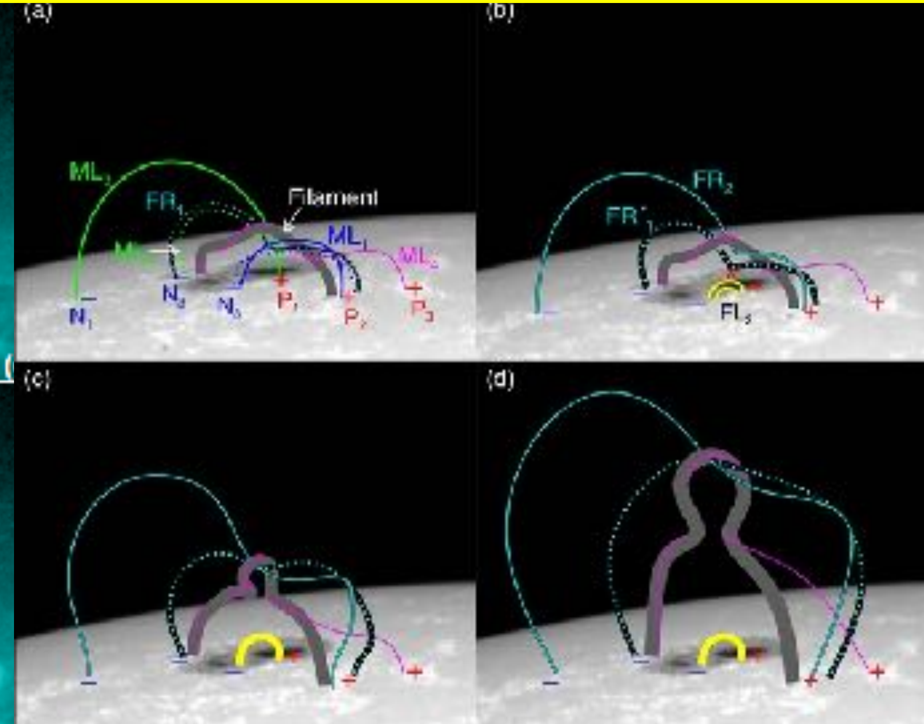
**Internal or tether-cutting reconnection (at Lower CS)**

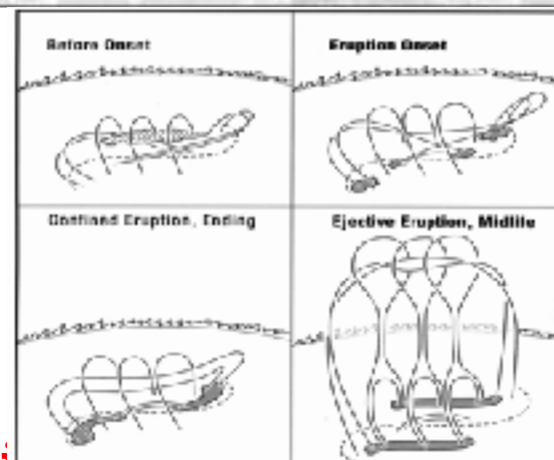
**External reconnection or magnetic break-out (at Upper CS)**



# 6. Triggering/Initiation Processes of CMEs



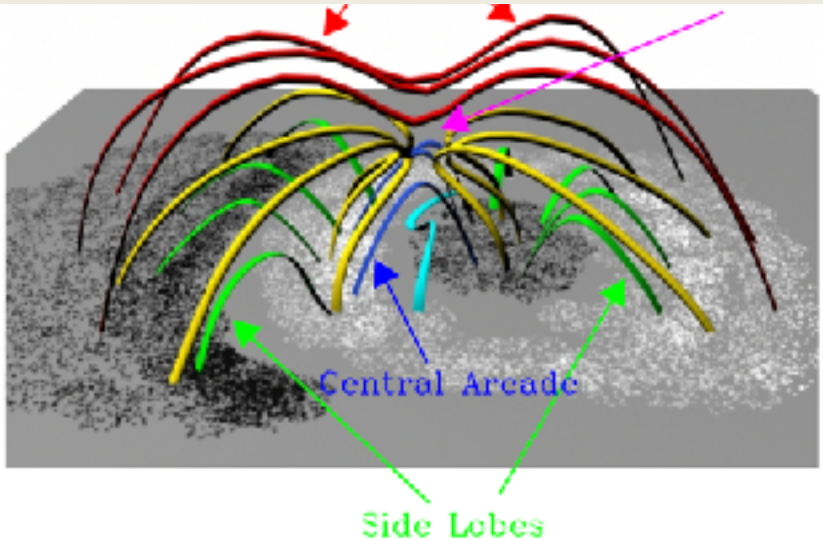

**Case 1 : Internal Tether-cutting reconnection**

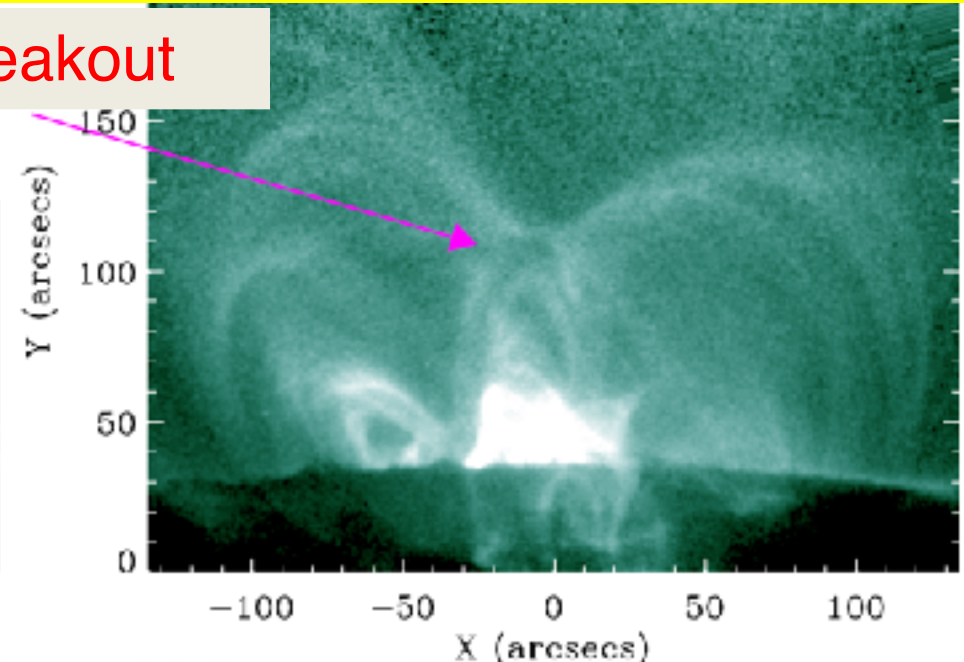
**→flux rope kink instab.**(ChenHD etal, 14, MOVIE 6)

Moore & Labonte 1980
van Ballegooijen et al. 1989
Moore et al., 2001

# 6. Triggering/Initiation Processes of CMEs

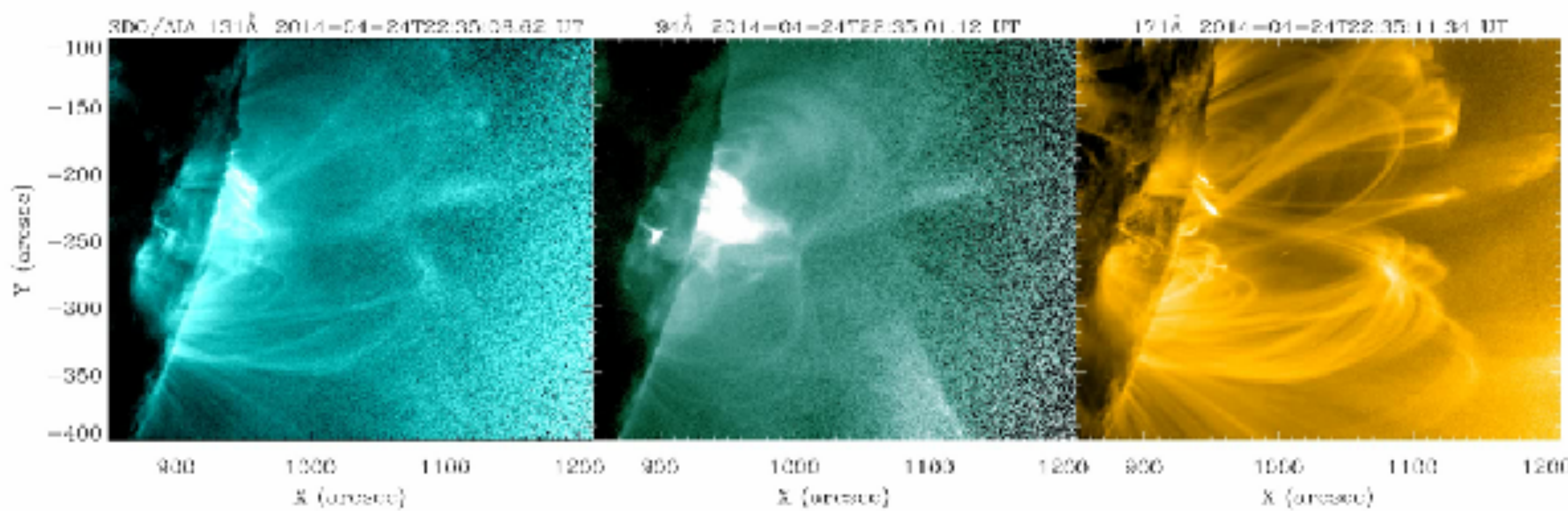
## Case 2 : External Magnetic Breakout



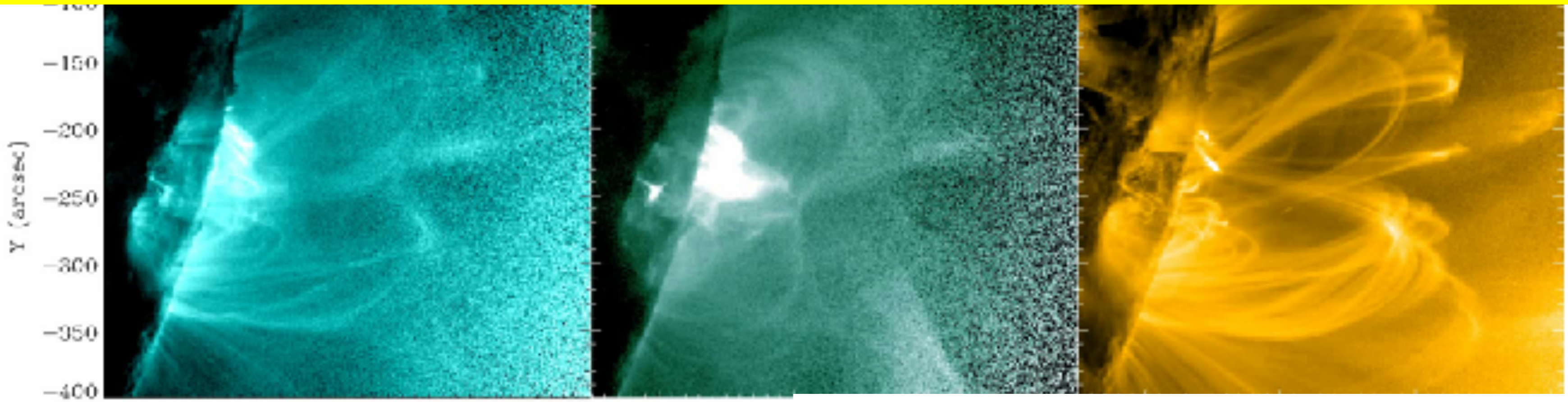



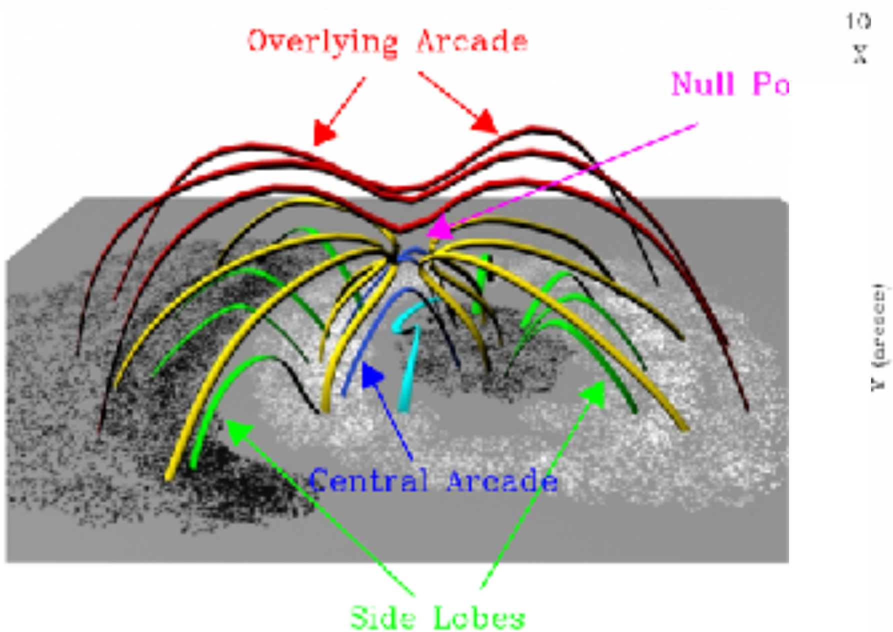

40 min of breakout reconnection➔X-flare + CMEs

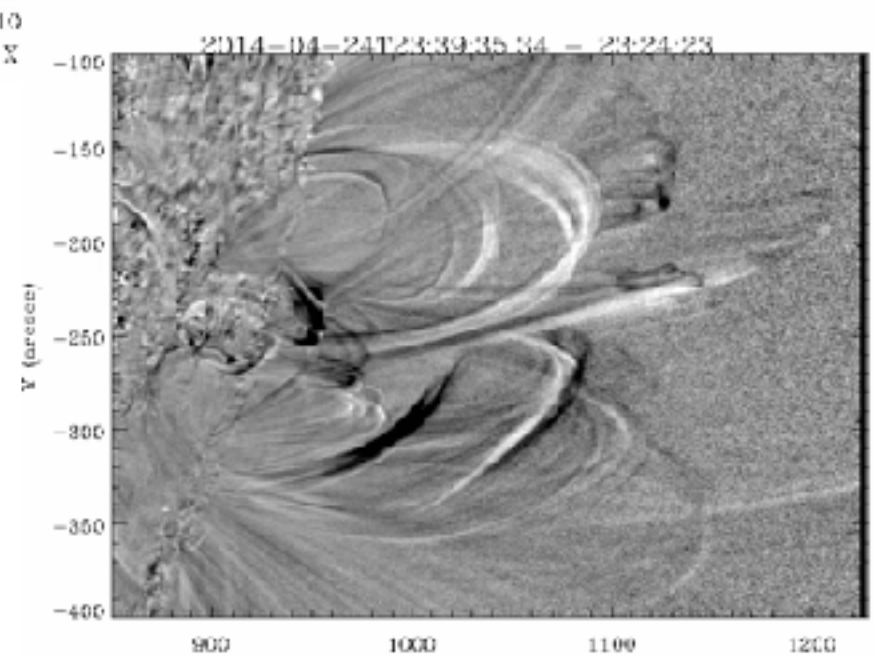
**Chen et al., 2016, 2017**



# 6. Triggering/Initiation Processes of CMEs



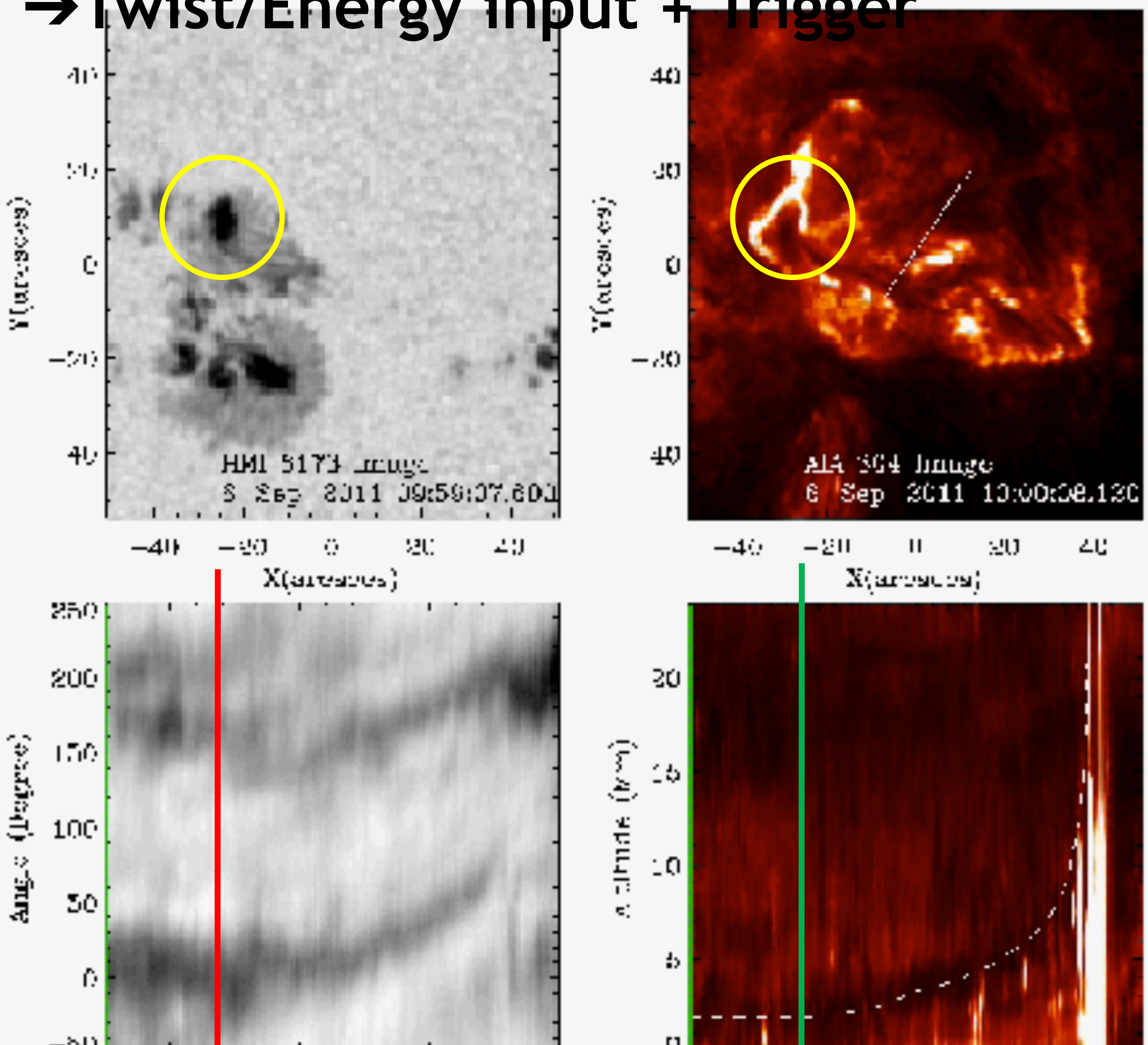



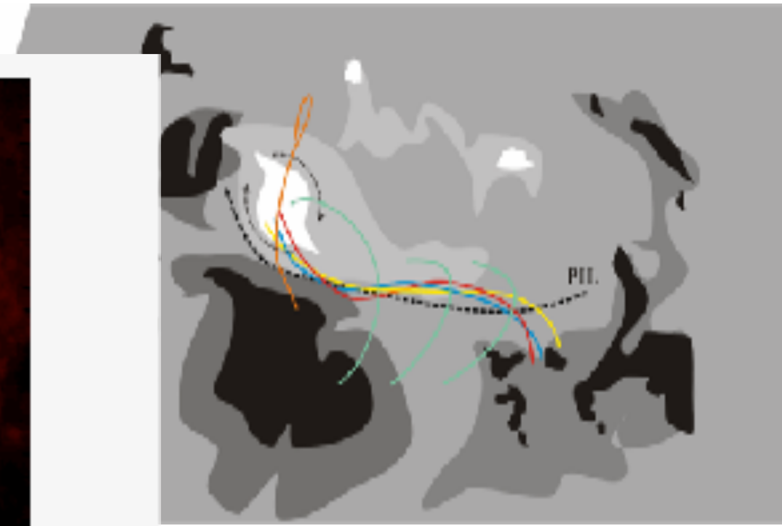

**High-temperature X-cusp pairs (40 min), some loops moving aside, both lower central arcade & upper big arcade approach X-cusps**
**➔breakout reconnection**

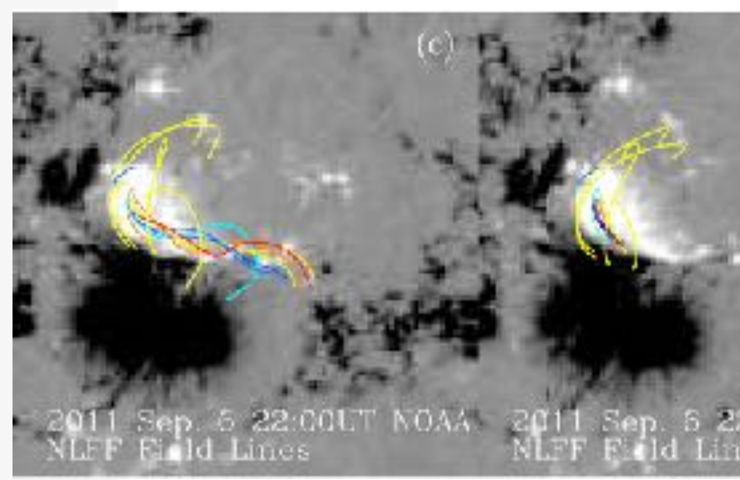
# 6. Triggering/Initiation Processes of CMEs

**Case 3 (non-reconnection, sunspot rotation triggered, Ruan et al. 14)** Rotating for 6 hrs pre-eruption, twisted filament rises accordingly.

→Twist/Energy input + Trigger



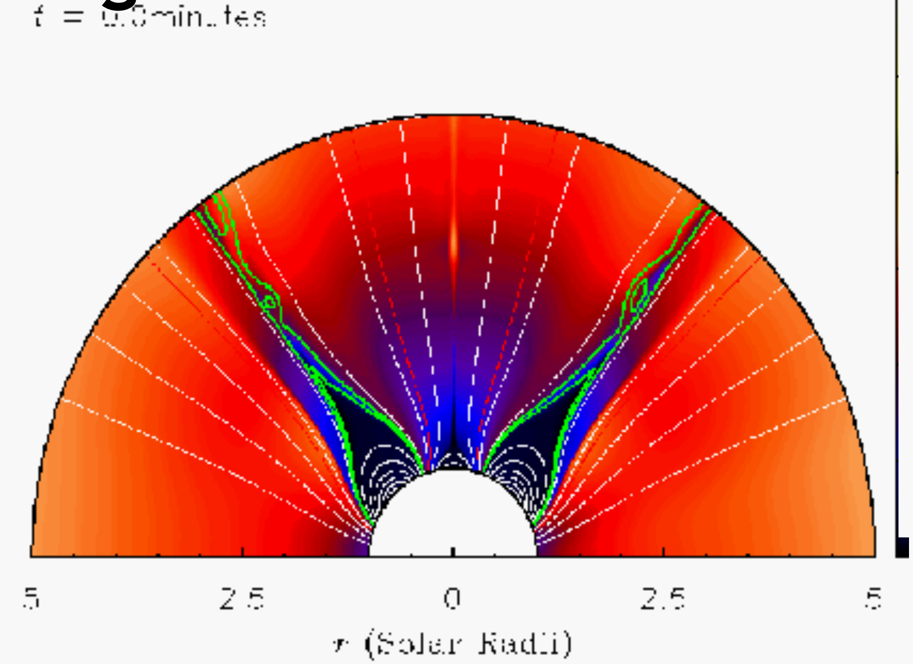



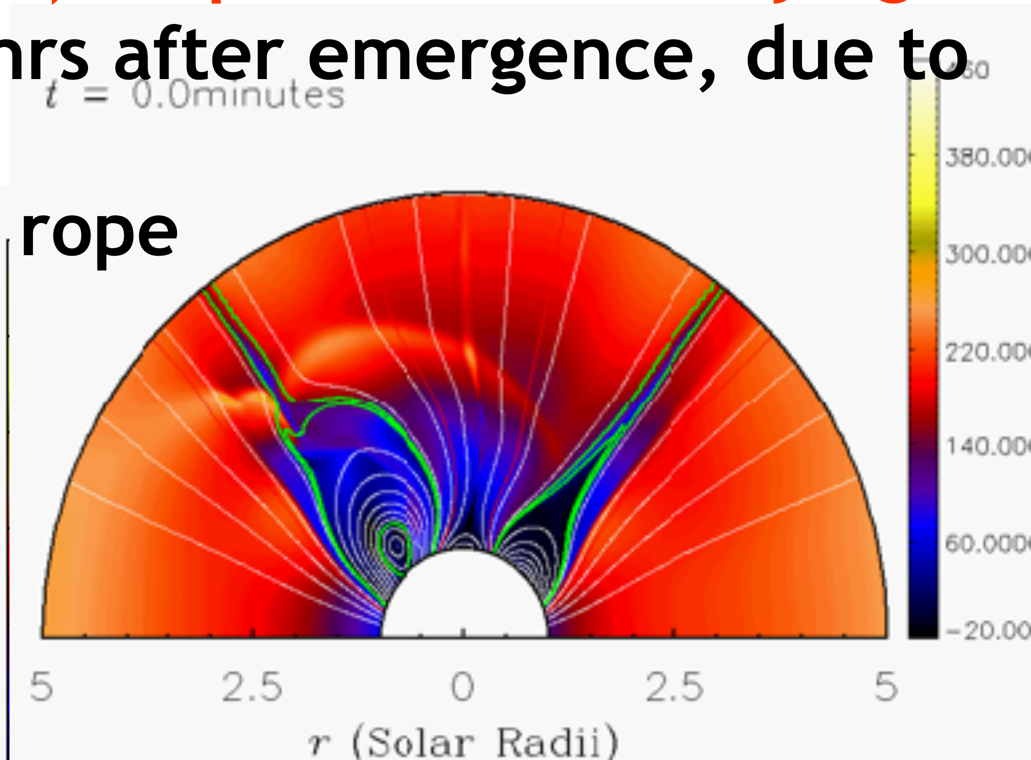



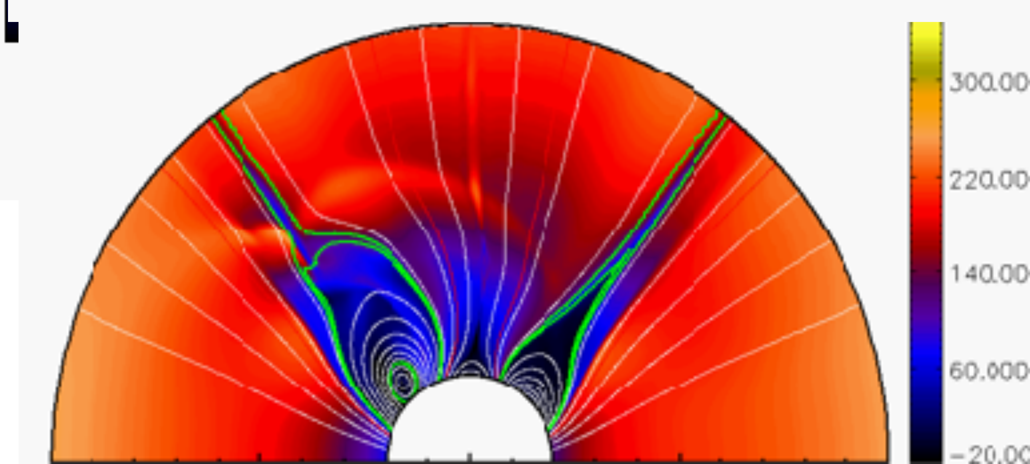
# 6. Triggering/Initiation Processes of CMEs

**Case 4 (Non-reconnection): expansion of overlying arcade** Left : Erupts 8 hrs after emergence, due to expansion

Right : with another flux rope




Streamer blow-outs

Chen 2008, not-published

# 7. Energy Release Mechanisms: Instability VS Rec.

**B Energy (in the corona) can be released by:**

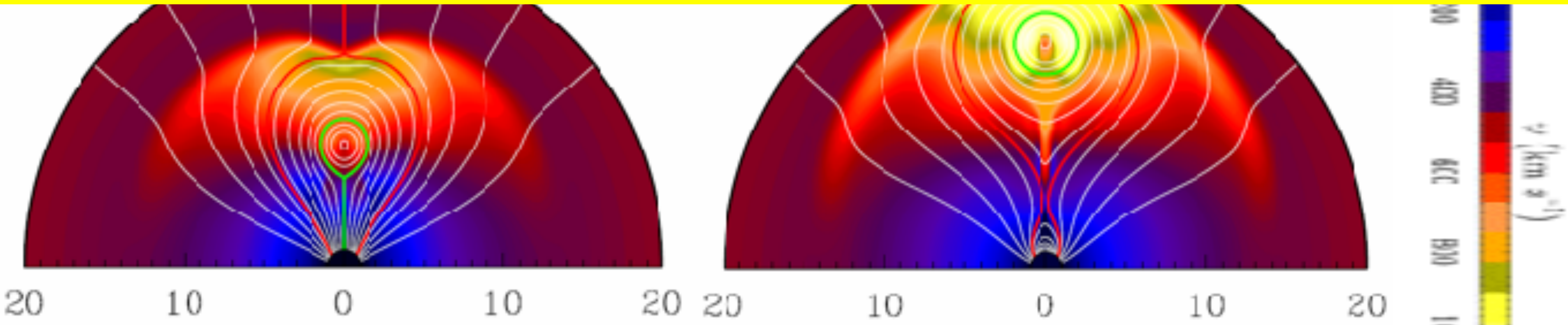
1) **Ideal MHD instability, whose development results in unbalanced force driving the flux rope to erupt, and contribute to the energy conversion**

Energy conversion rate (from B to mechanic): $\langle \vec{B} \cdot \vec{v}$

**2) Resistive reconnection→a widely-accepeted process to convert mangetic energy into thermal, partial, and wave energies (more details on next slide)**

**Misunderstanding regarding the role of rec. in CME dynamics:** **(mainly accelerated by rec. (jets?), dominant in CME energetics )**

# 7. Energy Release Mechanisms: Instability VS Rec.

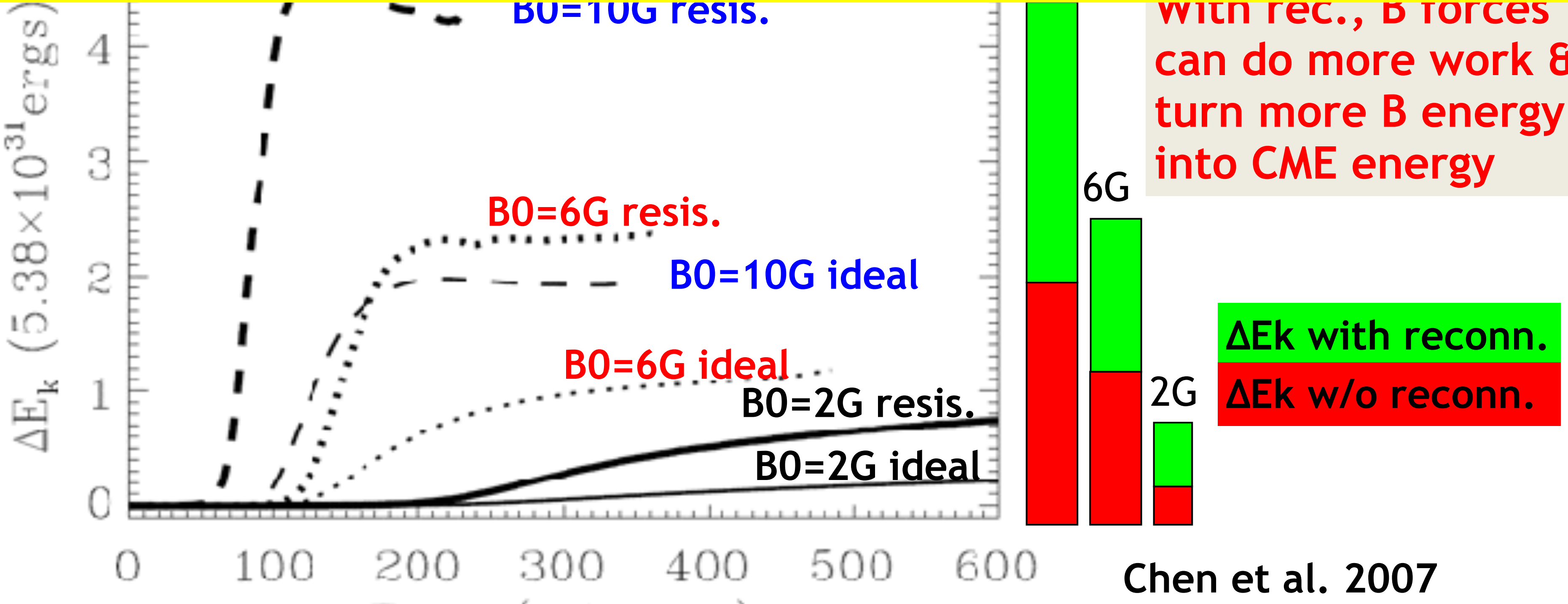



**Flux rope eruption with and w/o reconnection, Chen et al., 2007**
**→With rec., the CME moves faster with a growing flux rope.**

Reconnections can release the coronal B energy in three ways:
1) energetic particles, heated plasmas (flares & loops)
2) fast jets, ejected plasmoids, may help CME acceleration
3) change topology, current distribution, and forces on the rope:

reduce confining force by the c.s. formed during the

# 7. Energy Release Mechanisms: Instability VS Rec.




Chen et al. 2007

- Reconnections result in faster CMEs through weakening constraining forces and enhancing driving forces
- A positive feedback between CME speed & rec. rate
- No REC. still CMEs

→Is REC. necessary/dominant to CMEs acc.?

# 7. Energy Release Mechanisms: Instability VS Rec.

**How to resolve this (role of rec.) observationally?**

**Non-trivial, since:**

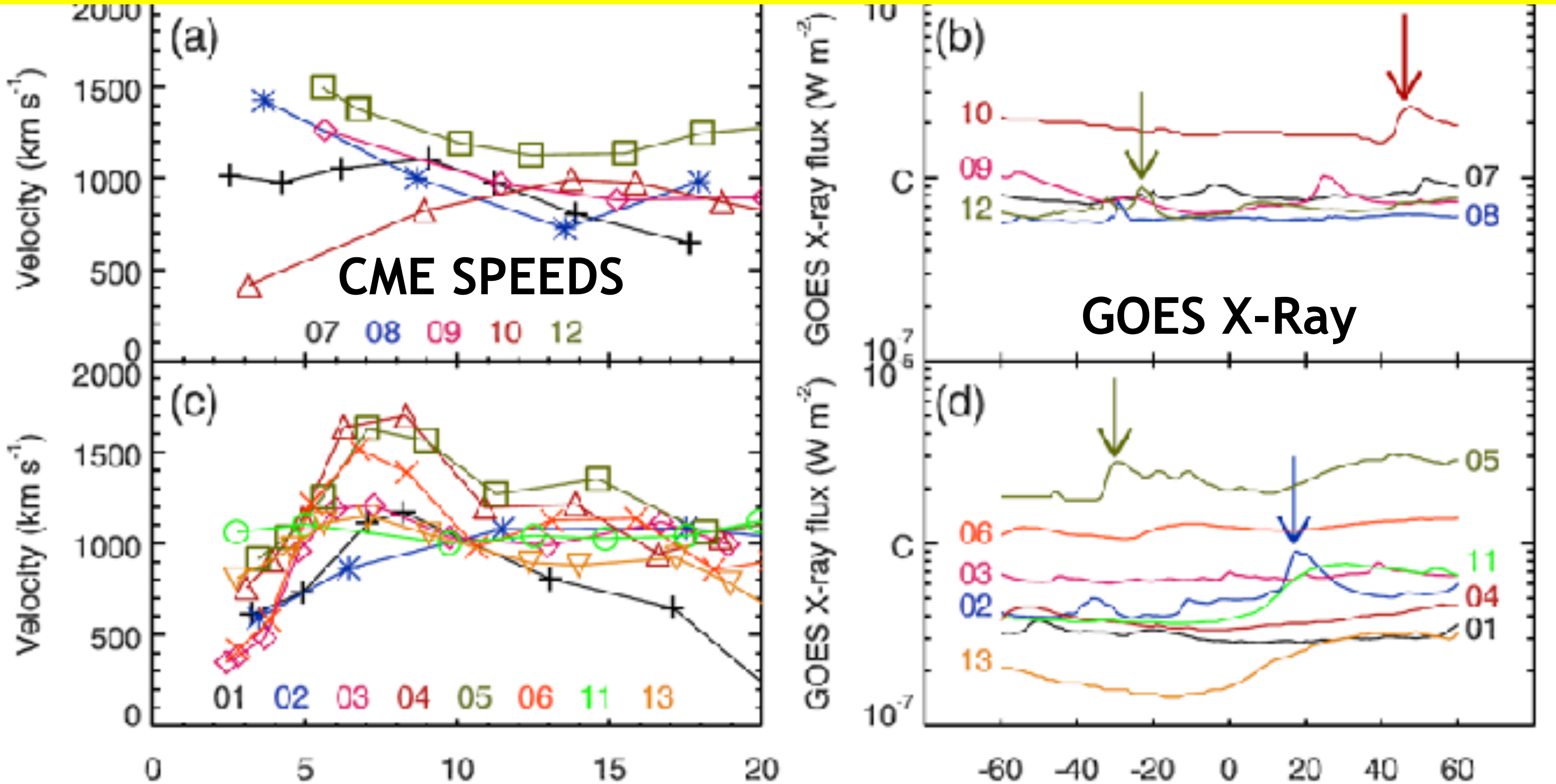
**Coronal B not measurable with present tech.**

**Flare-CME appear often synchronously, sometimes highly correlated!**

**Our efforts:**

- **Searching Fast CMEs without X-ray Flares (Song etal. 2013)**
- **Two-stage acceleration of eruptive filament (Song etal. 15,18)**

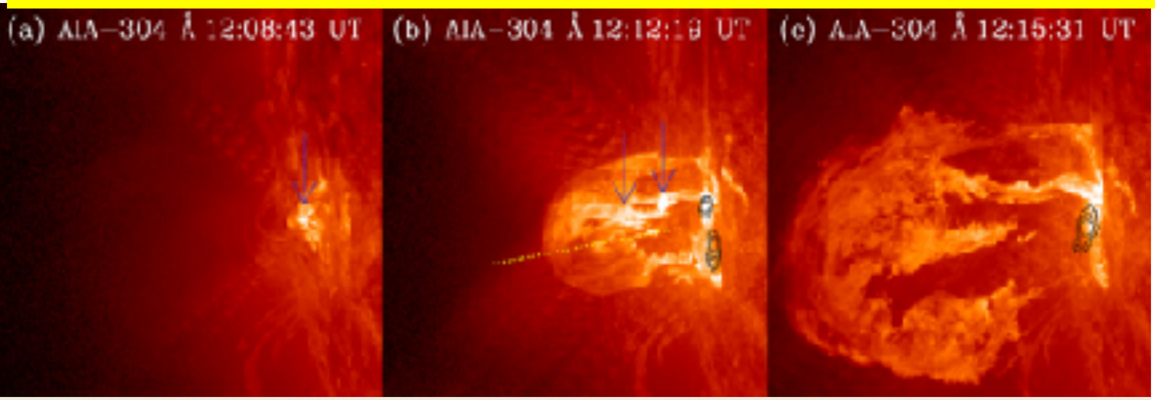
# 7. Energy Release Mechanisms: Instability VS Rec.

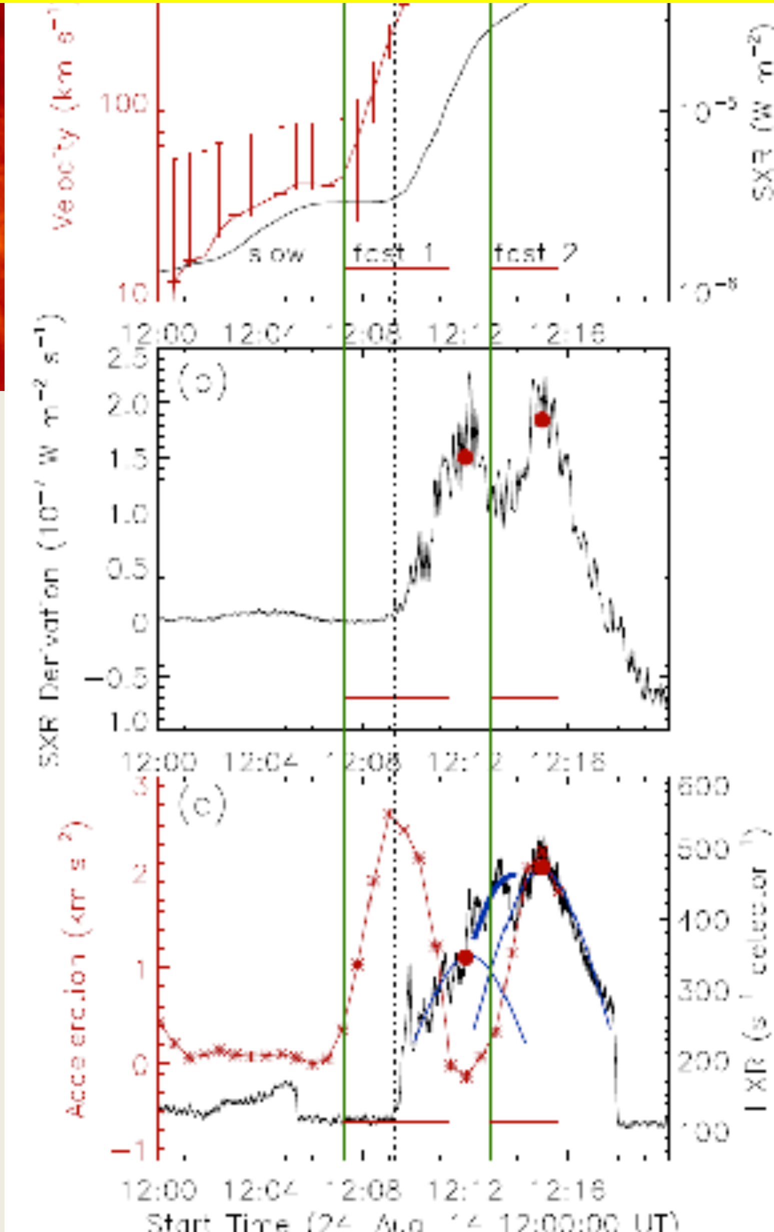



**Fast (>1000 km/s) \ front-side \ wide (>20°) \ No X-ray flares**

**→13 events in solar cycle 23! All are long filament eruptions from**

# 7. Energy Release Mechanisms: Instability VS Rec.




Movie-7 (Song et al. 2015)

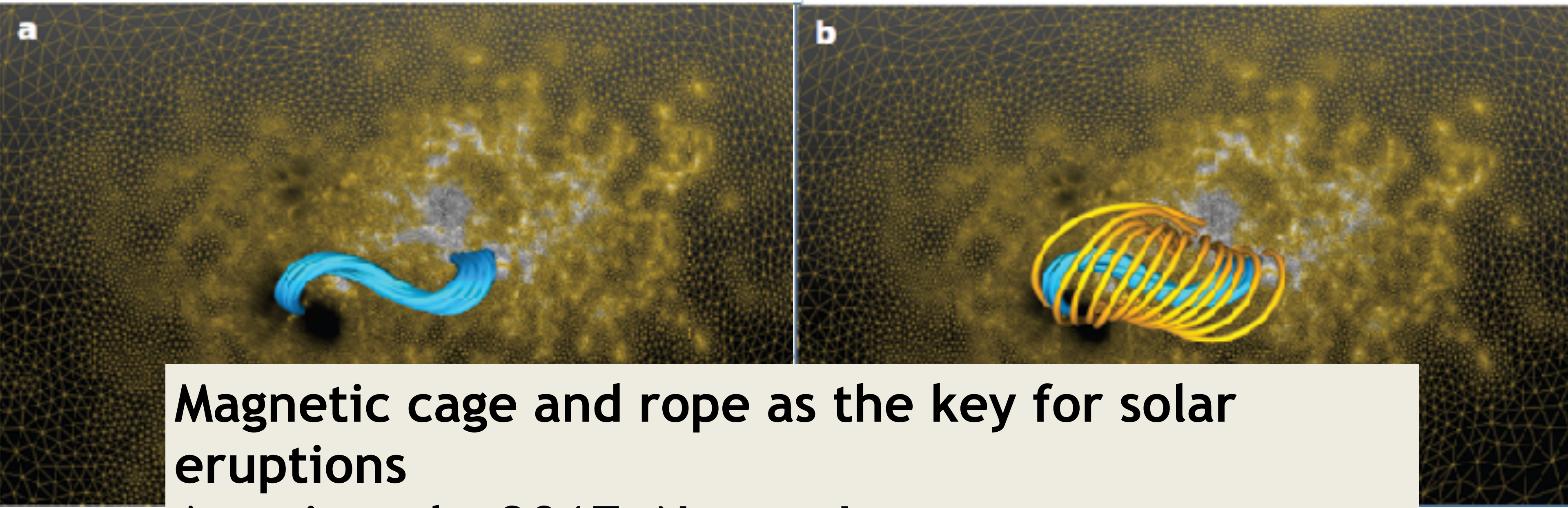
Acceleration at both stages: ~ 1600 m $s^{-2}$

Stage I is earlier than the flare rise (II),

so in Stage I, CME is acc. by instab.-related energy release, not by rec..

If assuming Stage 2 is mainly

# 8. Failed Eruptions (Ji et al. 2013)




Magnetic cage and rope as the key for solar eruptions
Amari et al., 2017, Nature Letter

Song et al. 2018, to be submitted
Movie-8

Interplays between the rope and the external field

1) The flux rope is kink-instable
2) Strapping/constraining effect
   external field is strong enou

# Summary on CME Initiation and Energy Release

work done by $\vec{J} \times \vec{B}$ )

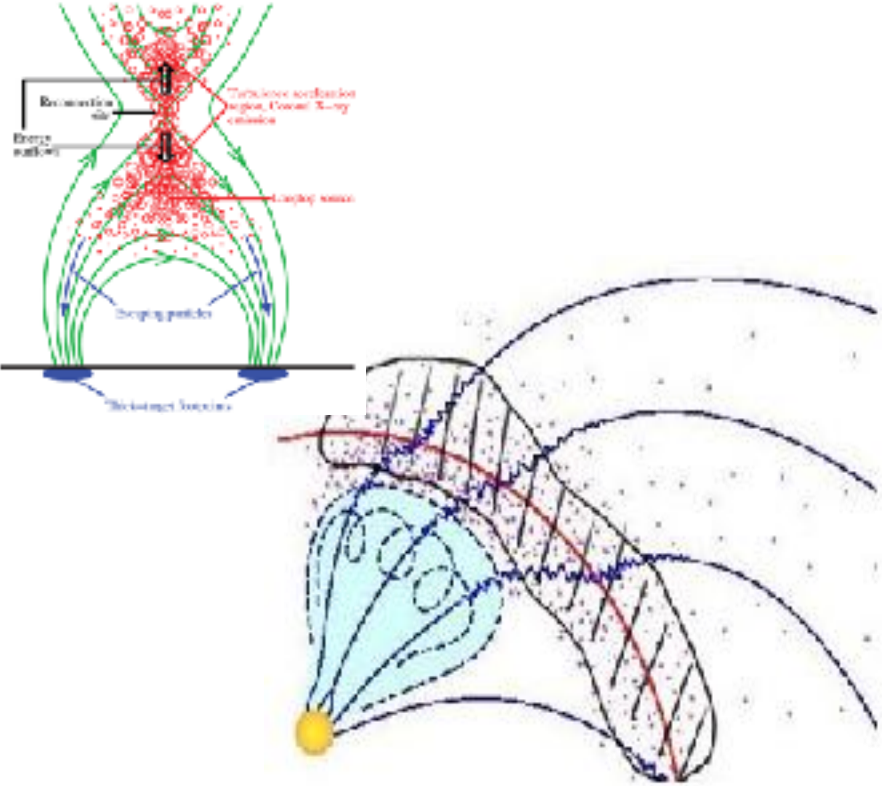
2) Pre-eruptive structure: non-potential, twisted flux rope or strongly sheared arcade (rope forms after getting reconnected)

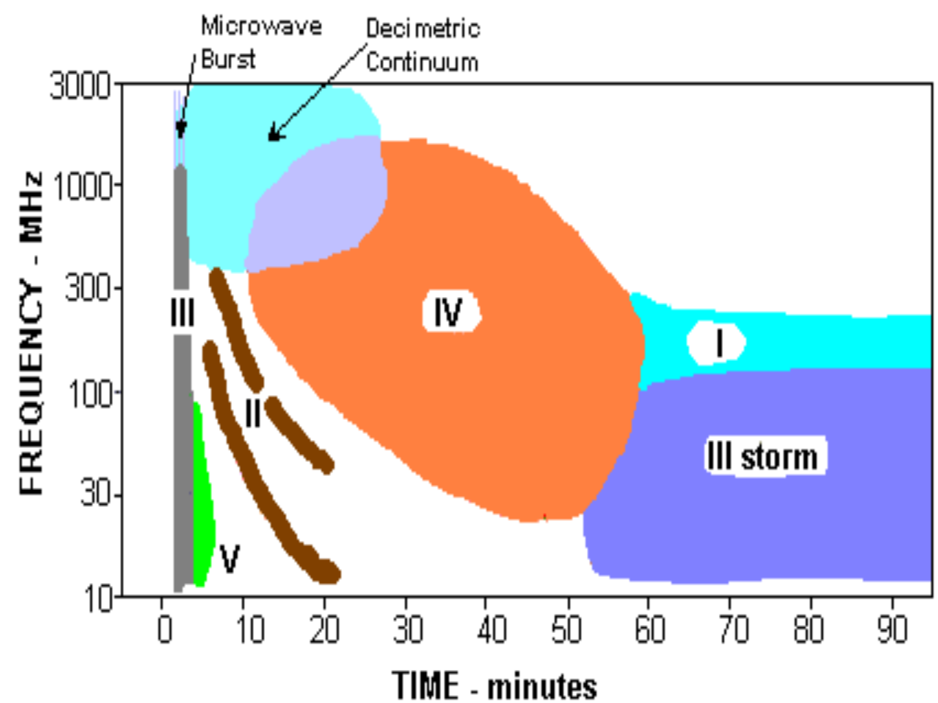
3) CMEs may be caused by the onset and development of flux rope instability, the major driving force is the self force of the rope
4) Interplays between the flux rope and the external field are critical to determine "Erupt or NOT"

5) Triggering process (reduce constrain, enhance flux rope): internal and external recon., non-rec. process, sometimes not separable from usual energy storage process
6) REC. acc. CMEs mainly through weakening constraining forces and enhancing driving forces (by dissipating current and changing B topology

# Part II: Solar Radio Bursts Relevant to CMEs

## Particles can be accelerated by CME shocks, rec.

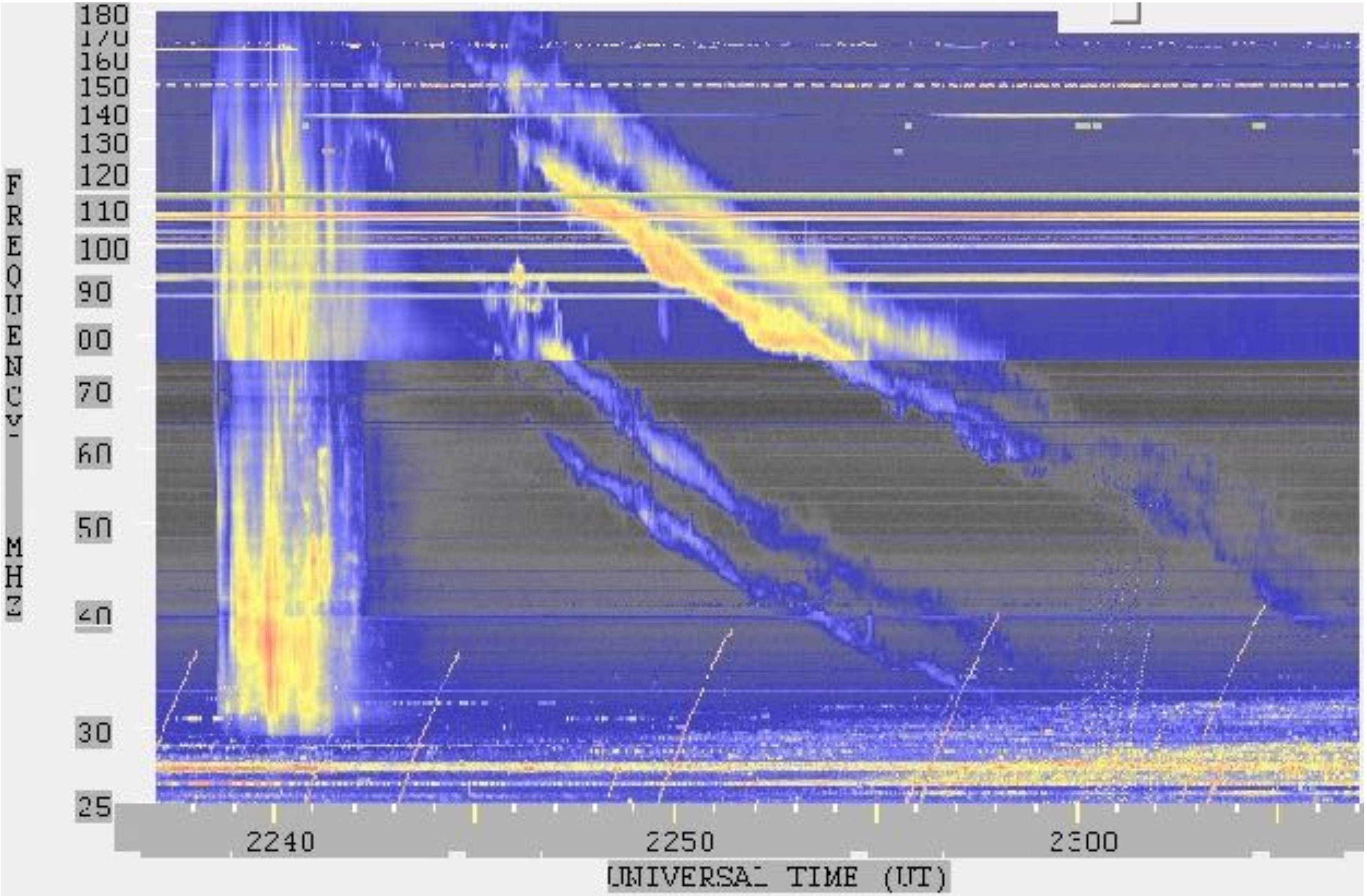




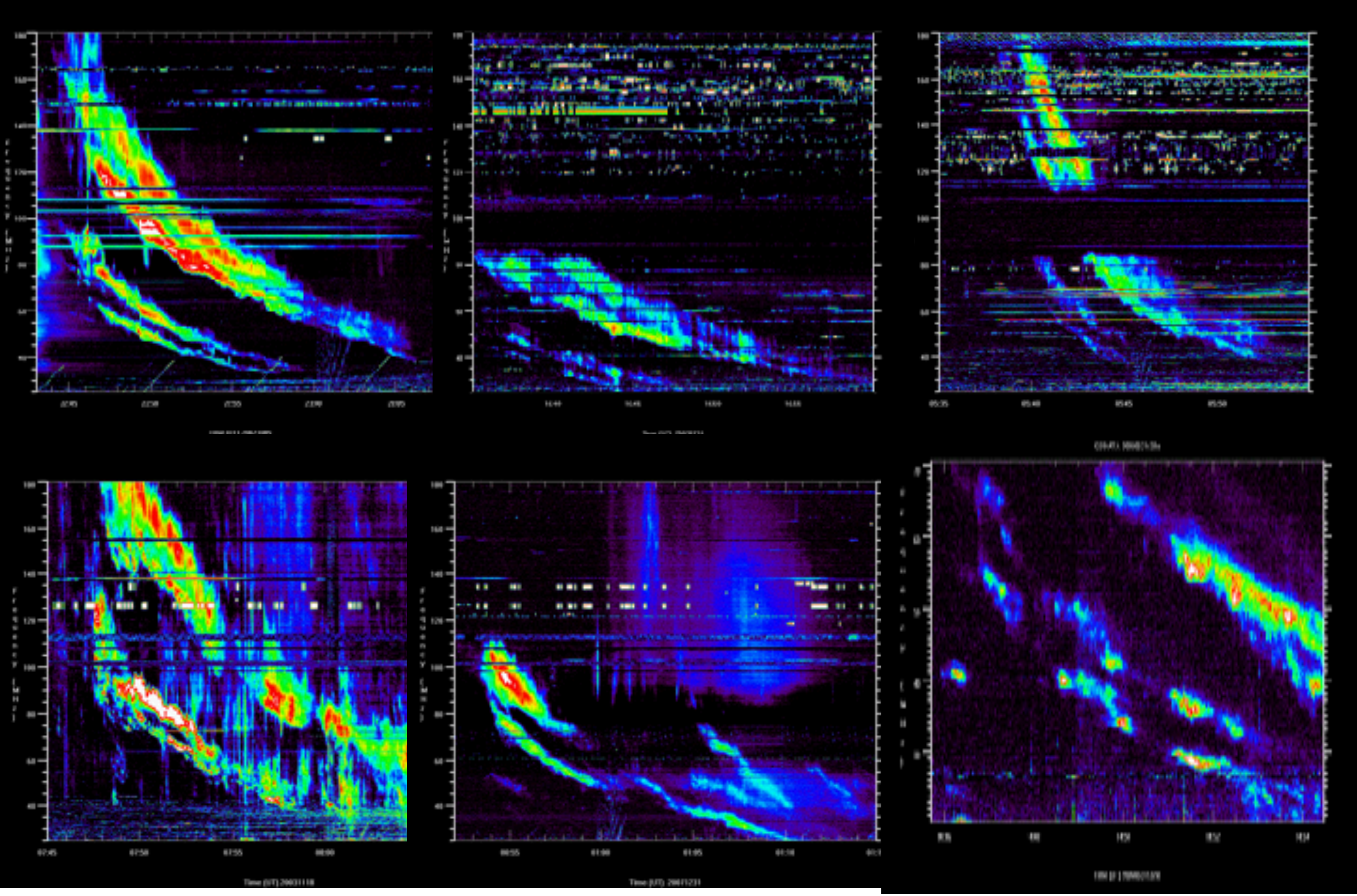

Energetic e- → solar Radio bursts→energy release, e- acc., heating &
kinetic instabilities, etc. (Payne-Scott, 1946; Wild & McCready 1950; Melrose 1980; ....)

CME-relevant:

Type II: slow + narrow (shock-acce. Electrons), ~mins




**A classical Type-II burst with F-H and band splits**



**Type-II band splits (Du et al., 2014, 2015). Type-II emission mechanism:**

A moving type-IV burst (Vasanth et al., 2018)

Coherent or incoherent?
If coherent, what mechanis