ASTR-6000 Seminar
COLLAGE: Coronal Heating, Solar Wind, & Space Weather

March 10, 2022

Coronal Mass Ejections (CMEs): a whirlwind tour

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Dr. Thomas Berger

Outline

1. CME Characteristics

- CMEs vs. solar wind properties at the Sun and at L1
- Three-part structure of CMEs
- Coronal signatures associated with CMEs: flares, filament eruptions, sigmoids, “EIT waves”, etc.
- The CACTUS catalog

2. Solar Magnetic Eruptions: the unifying concept

- The eruptive flux rope model: all the “coronal signatures” explained in one model
- “Stealth CMEs” de-mystified

3. CME propagation through interplanetary space

- Charged particle acceleration and radiation storms
- CME scale and structure relative to the planets: lead in to space weather lectures

Review: solar wind characteristics

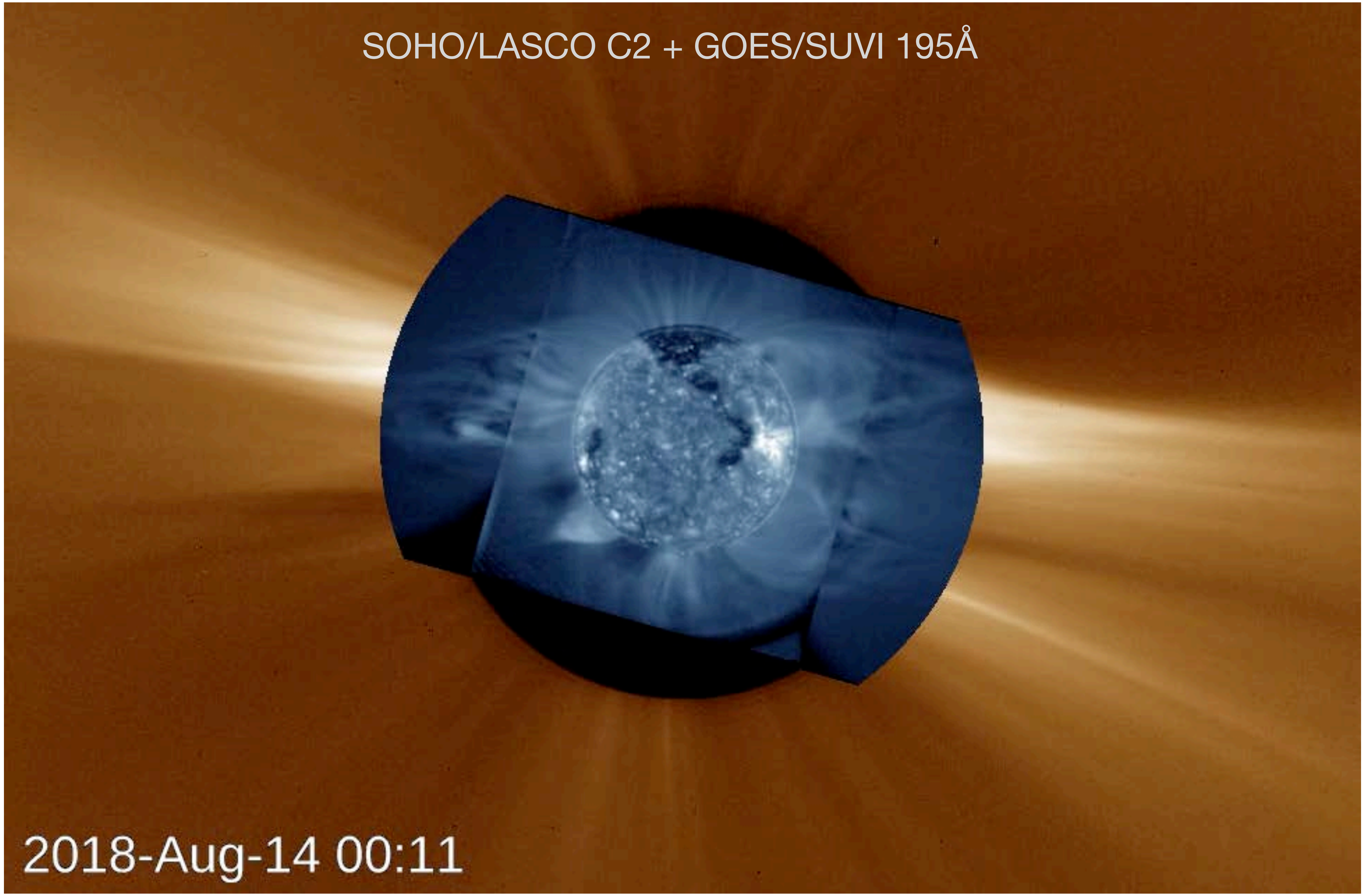
The solar wind is a constant outflow of ~10^6 K plasma from the Sun

Basic solar wind properties:

“Slow solar wind”:
300–500 km/sec

“Fast solar wind”:
600—800 km/sec
Coronal holes

27-day recurrence



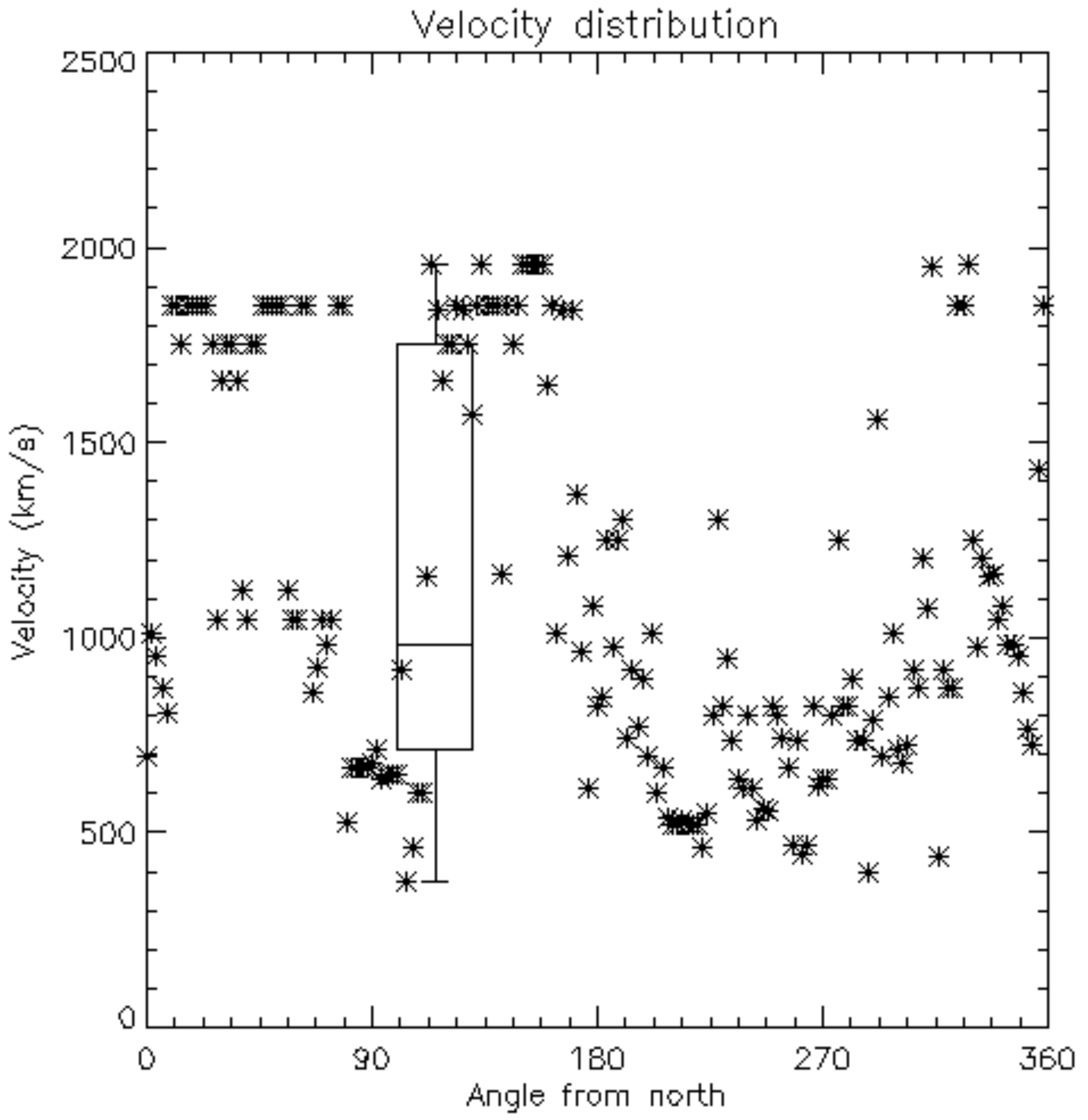
Seaton et al., Nature Astronomy, 2021, https://doi.org/10.1038/s41550-021-01427-8

CMEs are clearly different than the solar wind

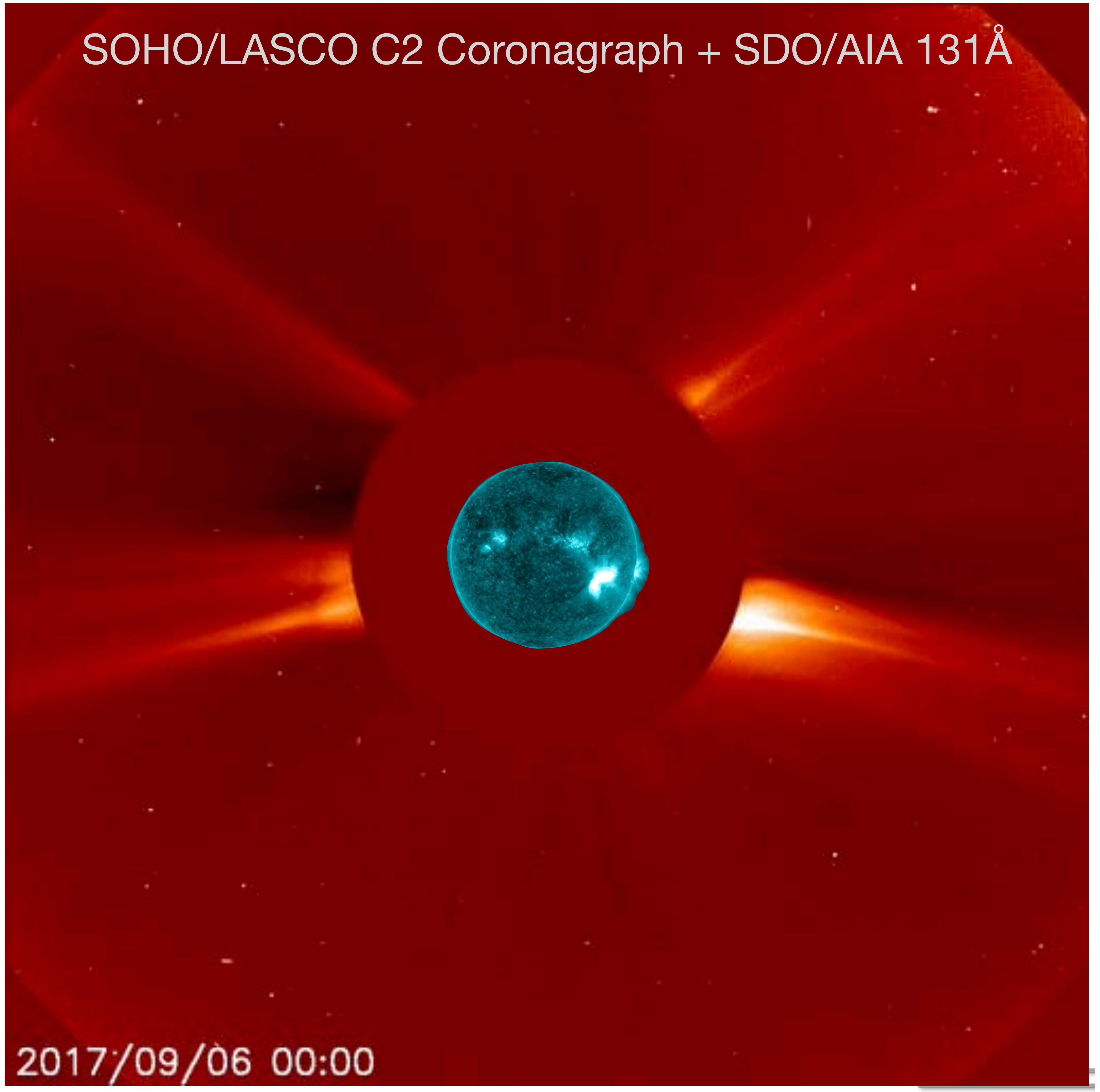
CMEs are impulsive, episodic, events, typically much faster than solar wind

06-Sep-2017 CME properties:

Max speed: ~1950 km/s



https://wwwbis.sidc.be/cactus/catalog/LASCO/2_5_0/qkl/2017/09/CME0017/CME.html



CMEs are sometimes called "solar wind structures" or "solar wind transients", particularly in the magnetospheric research community.

While there are "transient" effects in the solar wind (e.g. CIRs), avoid using this term when talking about CMEs:

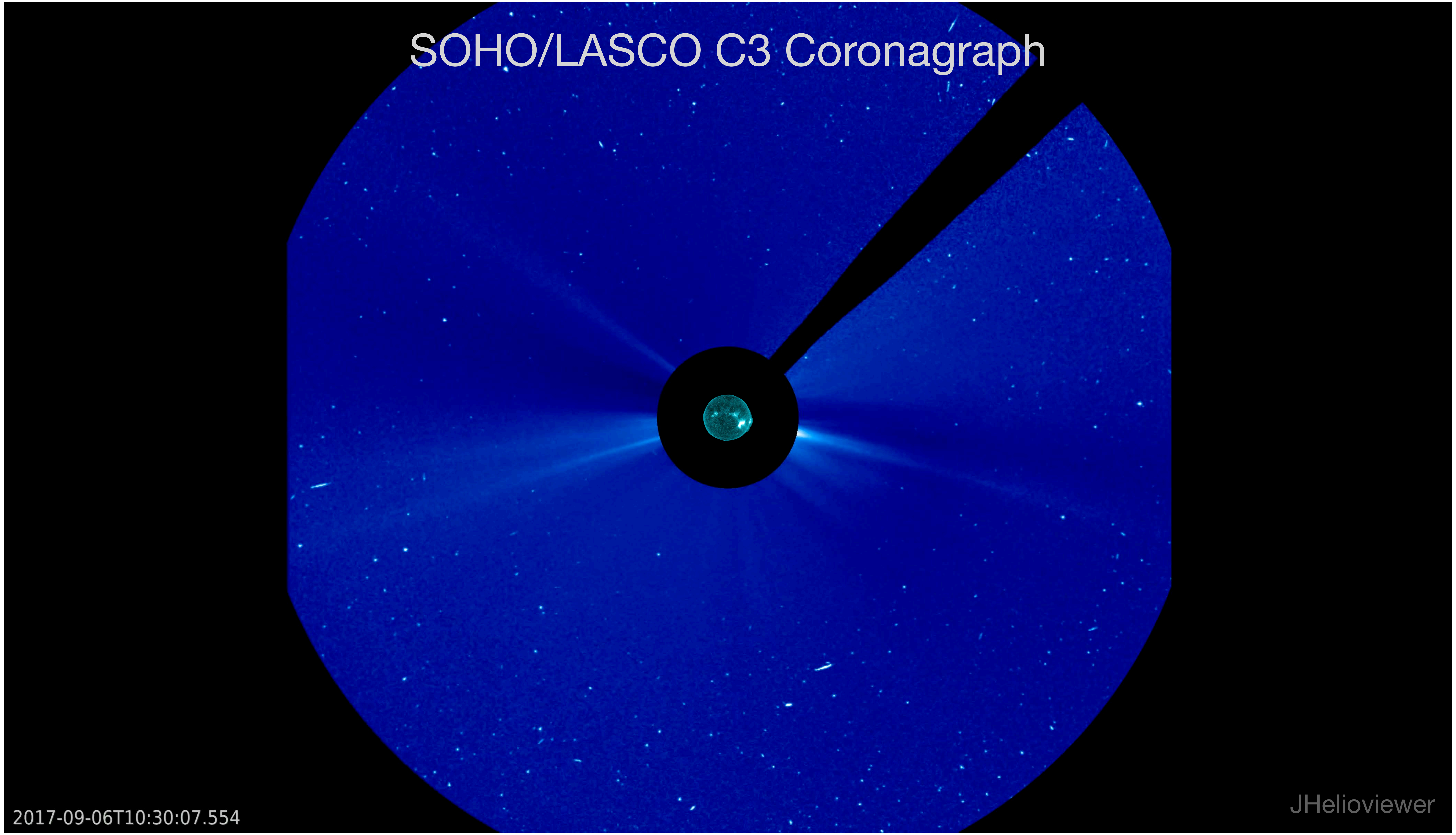
CMES are not solar wind.

CMEs are clearly different than the solar wind

CMEs are impulsive, episodic, events, typically much faster than solar wind

06-Sep-2017 CME properties:

Max speed: ~1950 km/s



Average CME properties:

Speed: 489 km/s
Max speed: 3000 km/s (4-Aug-1972)

Angular width: 47°

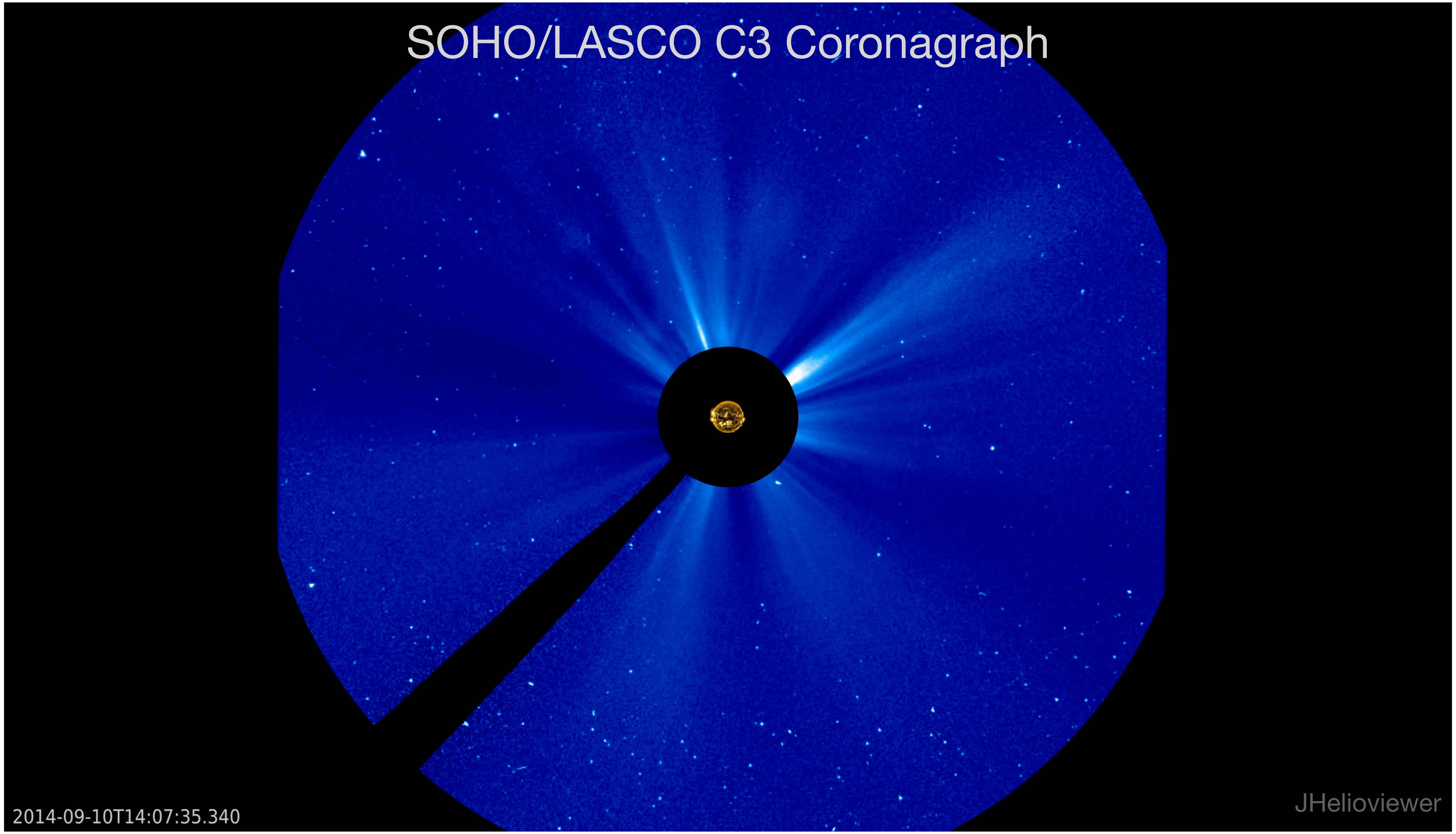
Mass: 1.3×10^{12} kg

KE: 2.0×10^{23} J

Avg. speed < solar escape velocity. What's going on?

Earth-directed CMEs are called "Halo" CMEs

Note that non-halo CMEs can still impact Earth



Interplanetary Measurements confirm differences

CME vs. solar wind Co-rotating Interaction Region in measurements at L1

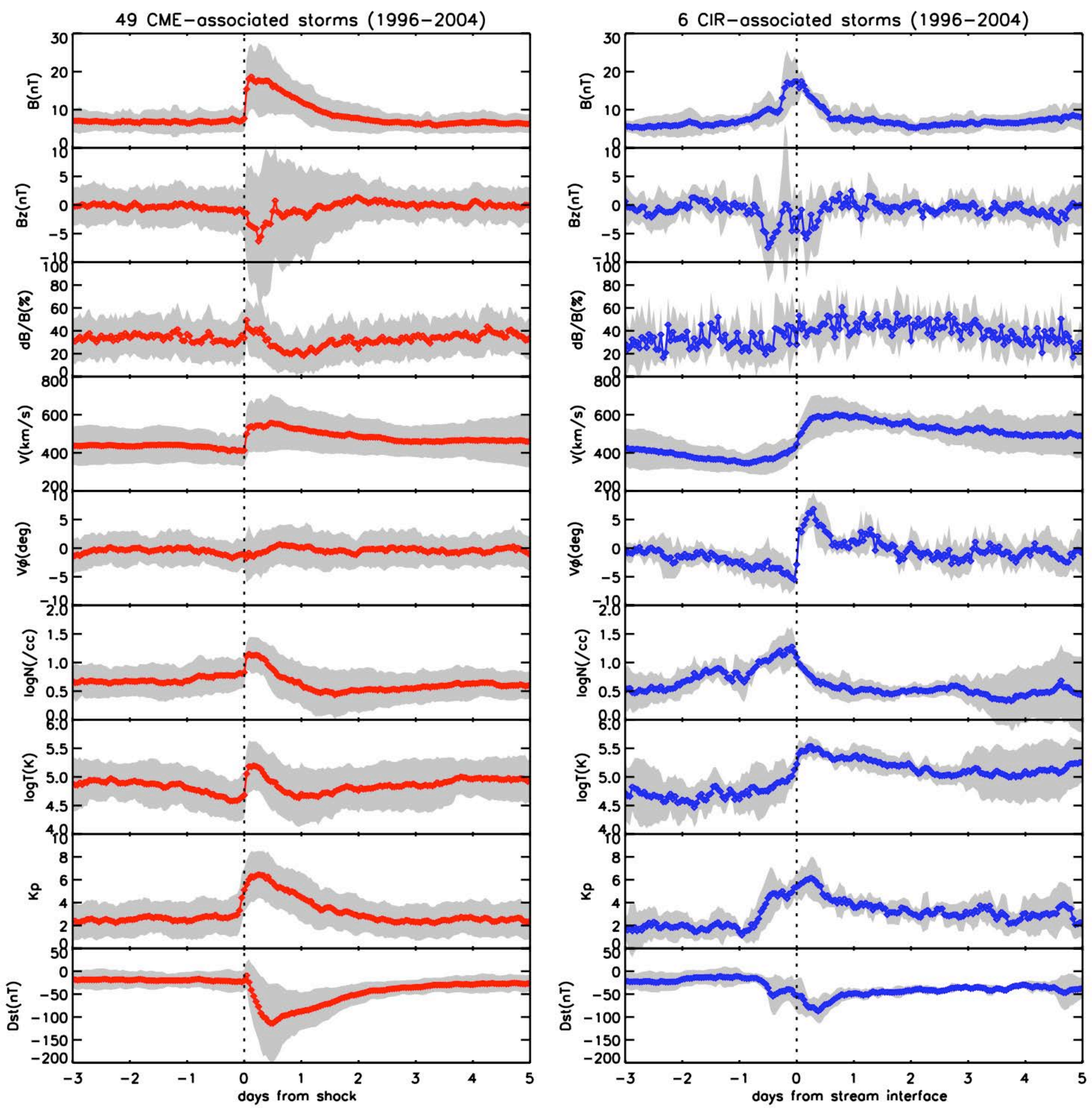
Steep shock in magnetic field and proton velocity.

CME arrival defined by shock

Temperature rises rapidly and declines

In general, steeper and deeper decline in Dst

CMEs | CIRs



In general, no shocks (although some CIRs can produce fairly steep shocks in N and V)

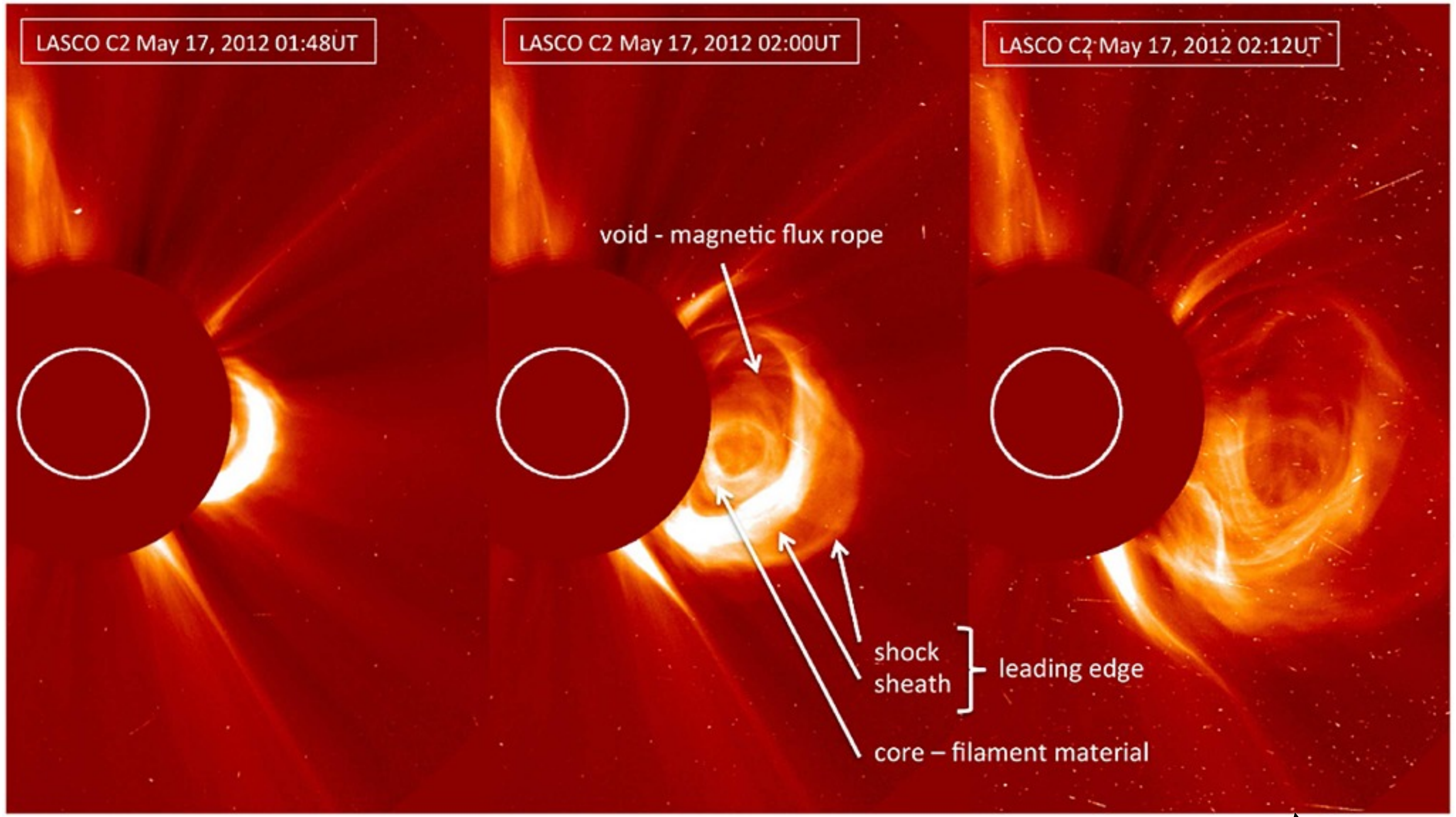
CIR arrival defined by sudden change in $V\phi$

Temperature rises more gradually and stays high

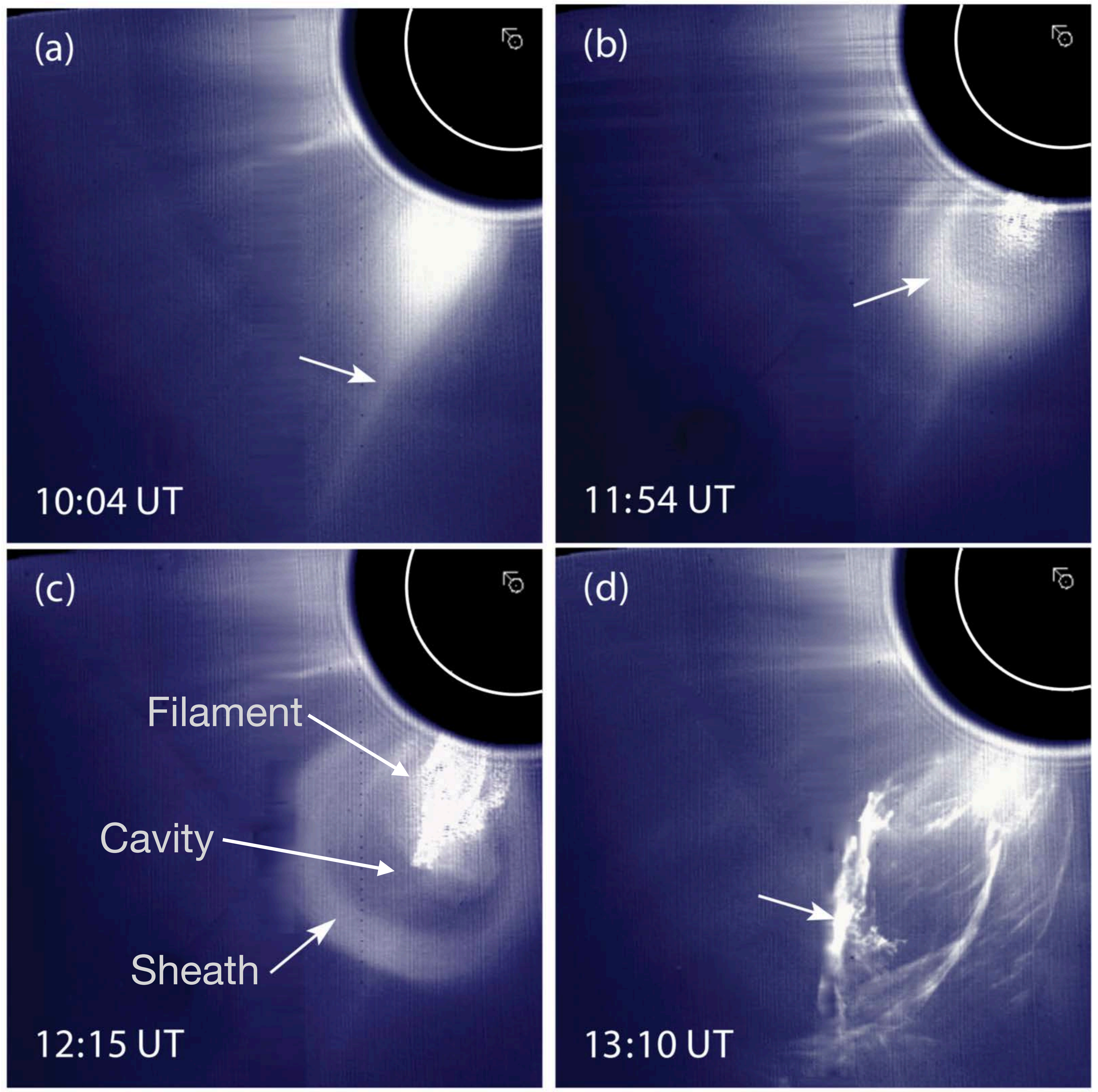
Kataoka & Miyoshi, Sp. Weath. Journ., 2006, https://doi.org/10.1029/2005SW000211

Three-part structure of CMEs

Shock/sheath, cavity, and filament/driver plasma



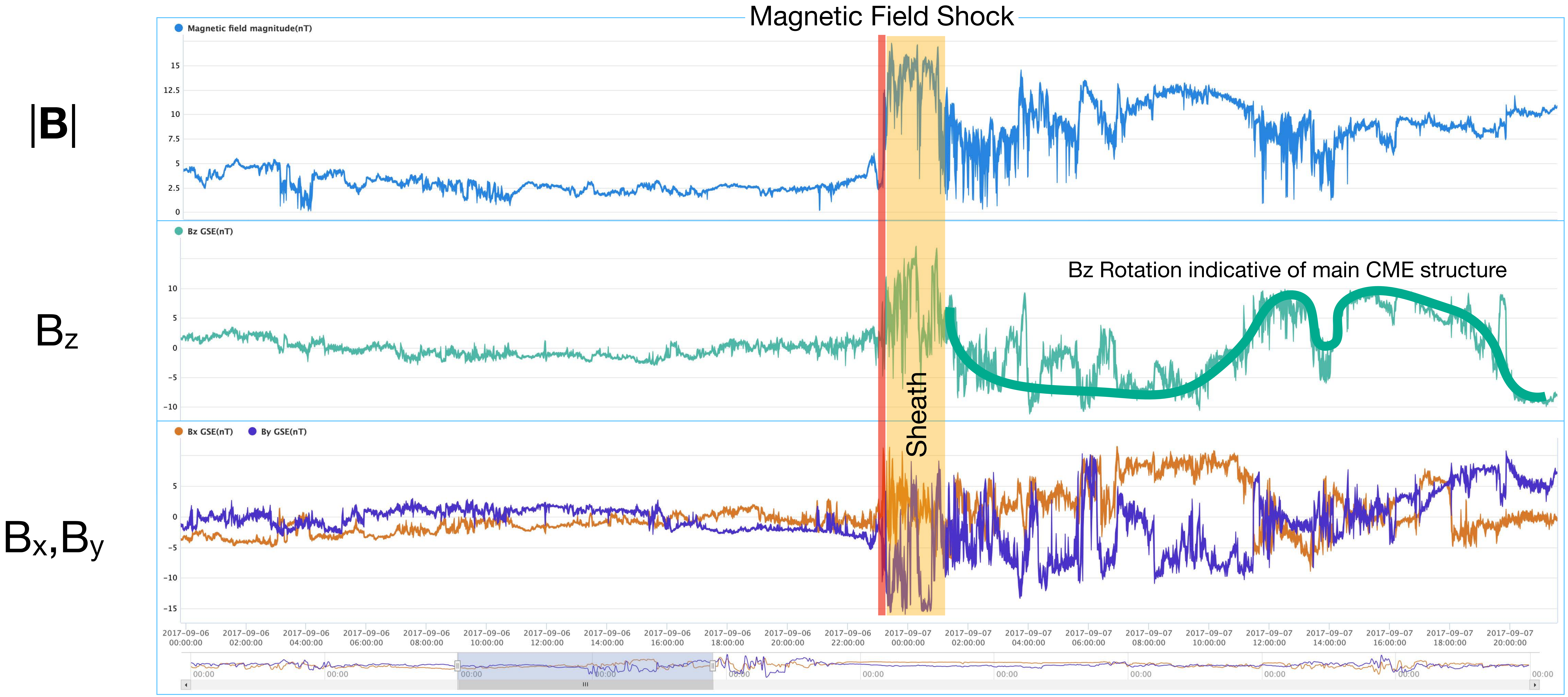
Solar Max Mission (SMM)
Coronagraph/Polarimeter Instrument, 1980



Later phases don't look so orderly…

08-Sep-2017 CME measured at L1

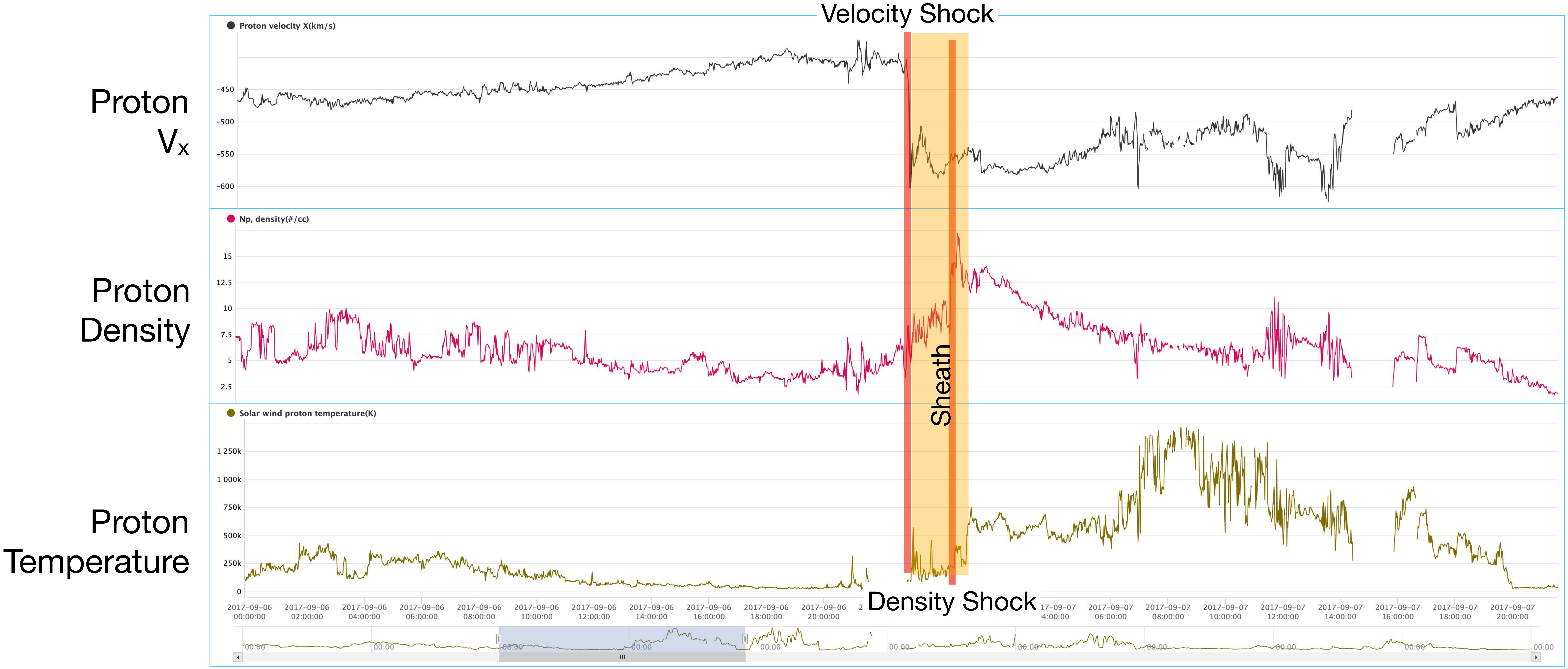
DSCOVR satellite Interplanetary Magnetic Field (IMF) data



Space Weather Data Portal: https://lasp.colorado.edu/space-weather-portal/home

08-Sep-2017 CME measured at L1

DSCOVR satellite solar wind plasma data



Space Weather Data Portal: https://lasp.colorado.edu/space-weather-portal/home

CMEs vs. ICMEs

You will sometimes hear it insisted that an event is not a CME until it's been detected in interplanetary space, either *in situ* or in large angle coronagraphs.

People call these "**Interplanetary CMEs**" or ICMEs.

These same people will sometimes insist that images of eruptions into space from EUV telescopes cannot be called CMEs.

I.e., if it is not detected as having escaped the Sun, you can't assume that it has.

Coronal signatures associated with CMEs

Note that not all CMEs have all of these characteristics

1. Flares

- Electromagnetic radiation (photons) emitted during and following solar eruptions.

2. Filament eruptions

3. Sigmoid eruptions

These two really the same thing:

- A “filament” is plasma trapped in a twisted magnetic flux rope, typically outside of the core of an AR.
- A “sigmoid” is the X-ray signature of a highly twisted magnetic flux rope in the core of an AR.

4. “EIT waves” or EUV waves

- Blast wave from large magnetic eruptions propagating through the corona and chromosphere.
- When seen in the chromosphere in Hα, called “Morton waves”. Discovered long before EIT mission.

5. Coronal dimmings

- Removal of coronal material by a CME leading to formation of dark regions in EUV images.

6. Post-eruptive arcades or brightening

- Also called “Post-flare loops”.
- Indicative of magnetic field returning to more “potential-like” topology after eruption.

From Ma et al., ApJ, 722, 2010, https://doi.org/110.1088/0004-637X/722/1/289

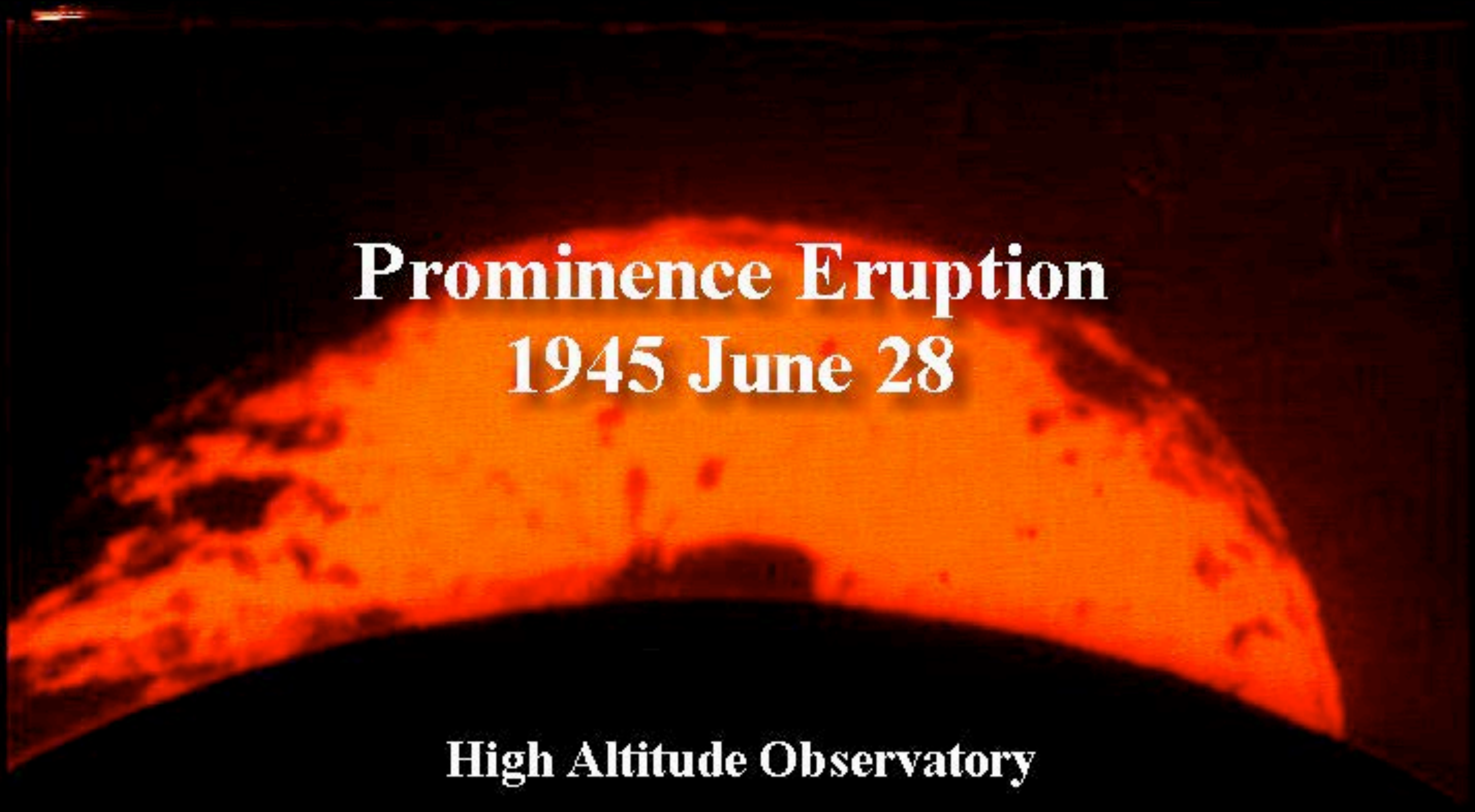
Coronal signatures associated with CMEs

Flares: the most visible signature of Active Region eruptions

NOAA AR 12673

Coronal signatures associated with CMEs

Filament eruptions: “Grandpa” the largest filament eruption observed to date

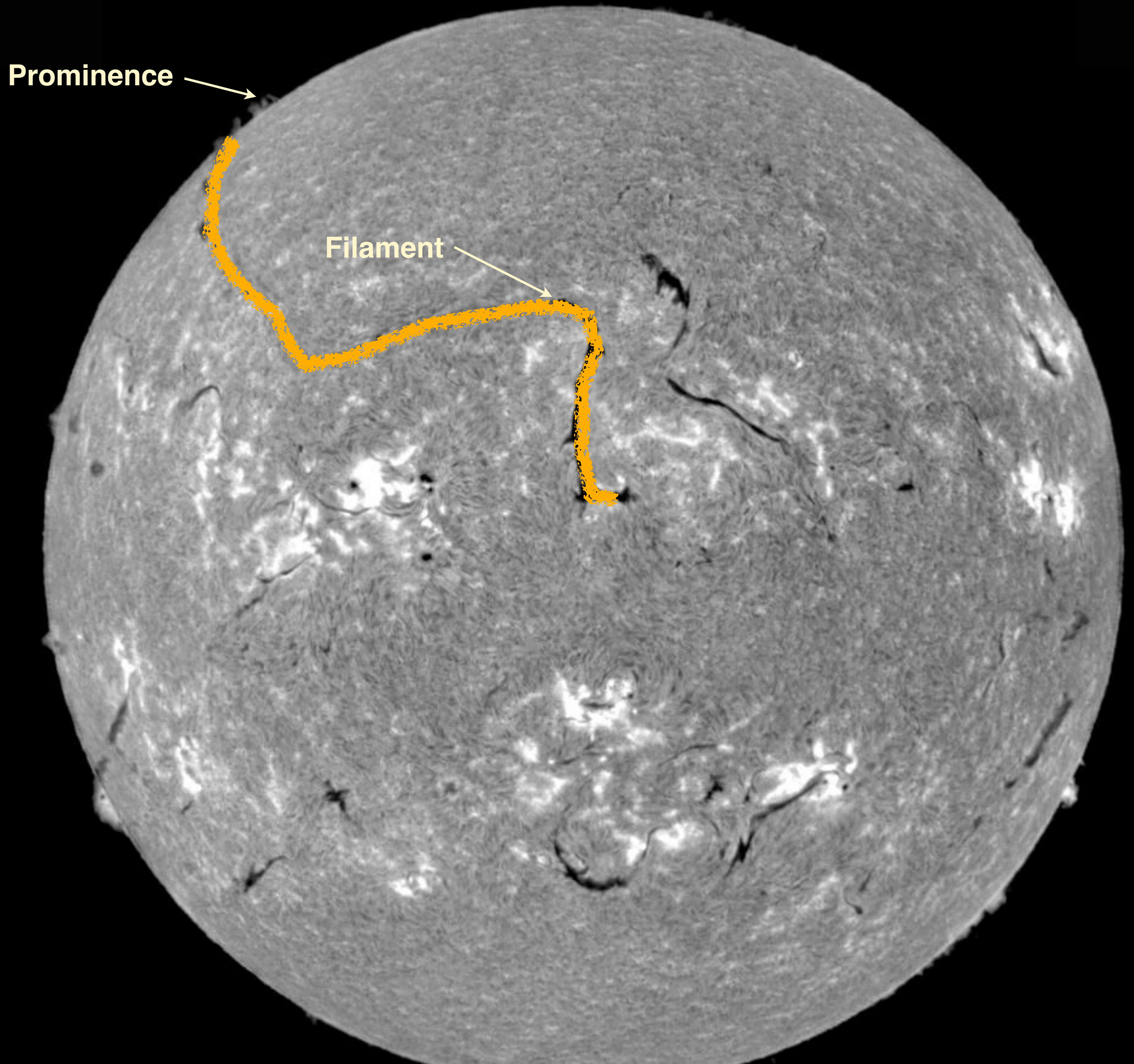


Climax Mine Observatory, Colorado

Walter Roberts using the first Lyot coronagraph in the US

Filaments = Prominences = flux ropes in the corona

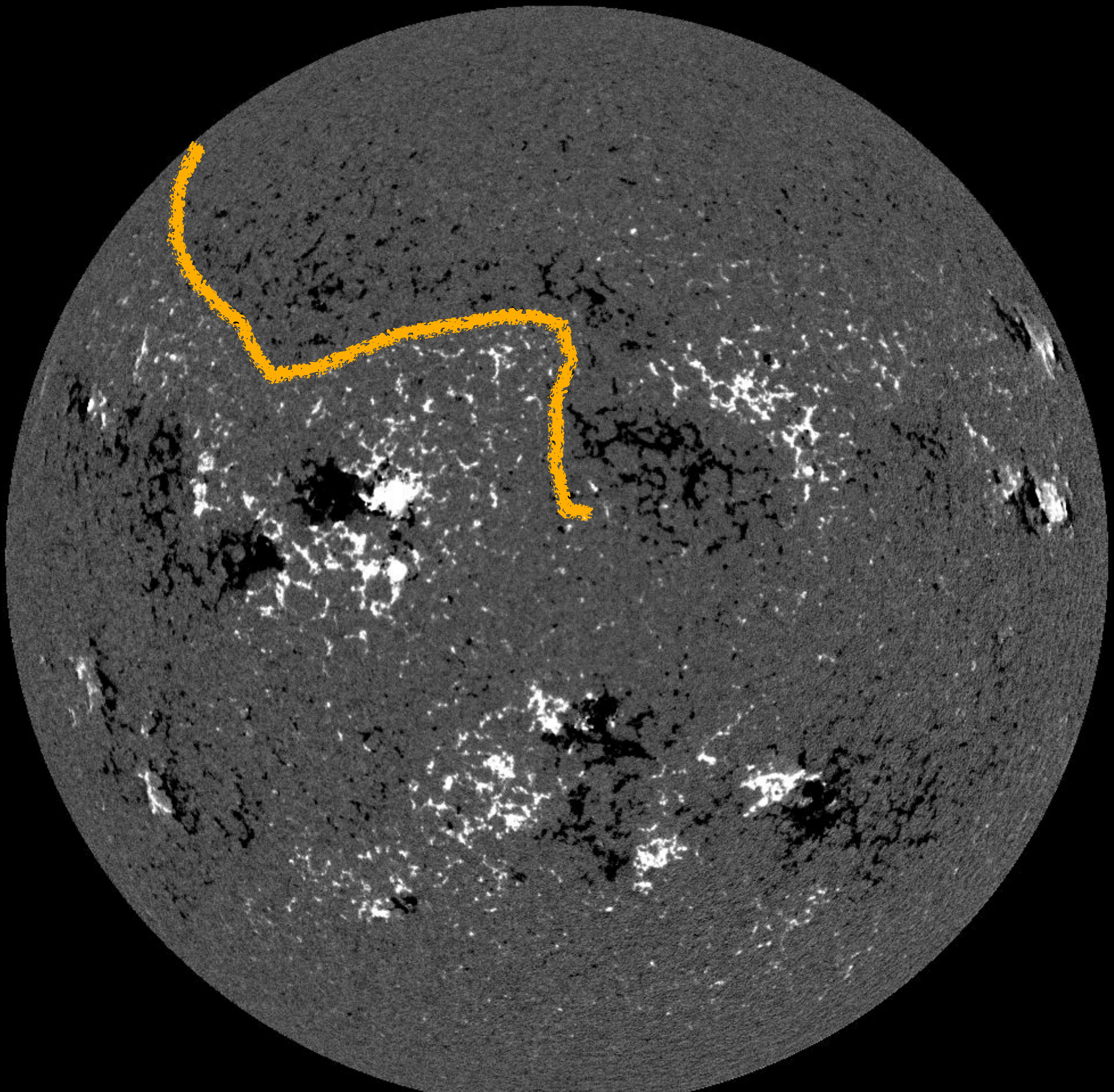
Filament: absorption on the disk, Prominence: emission off the limb



BBSO Hα
2000-09-01

Filaments = Prominences = flux ropes in the corona

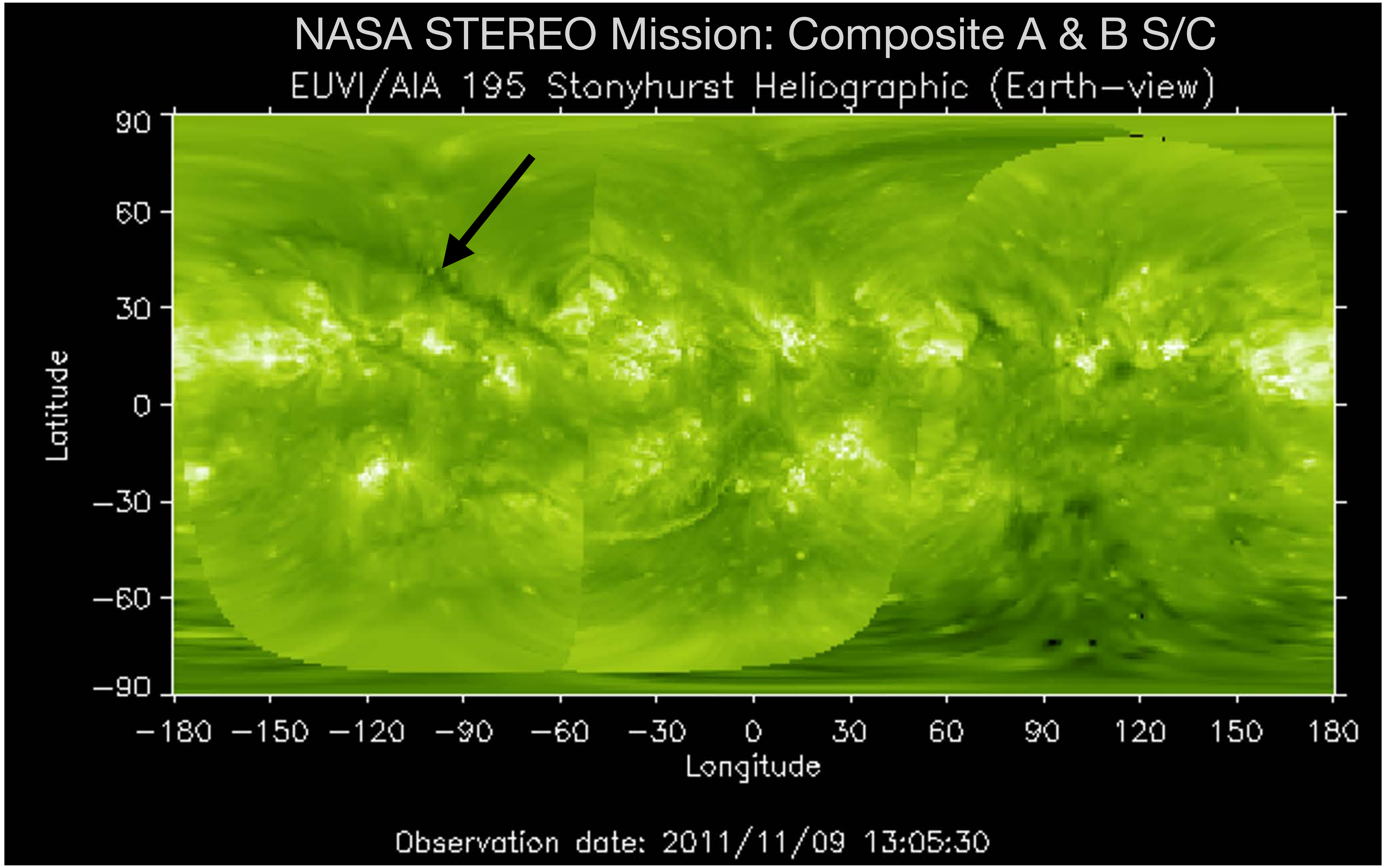
As in active regions, flux ropes form over polarity inversion lines



MDI Magnetogram
2000-09-01

Filament flux ropes are the largest magnetic structures on the Sun

Lengths up to 600 Mm (~1Rs) are not uncommon

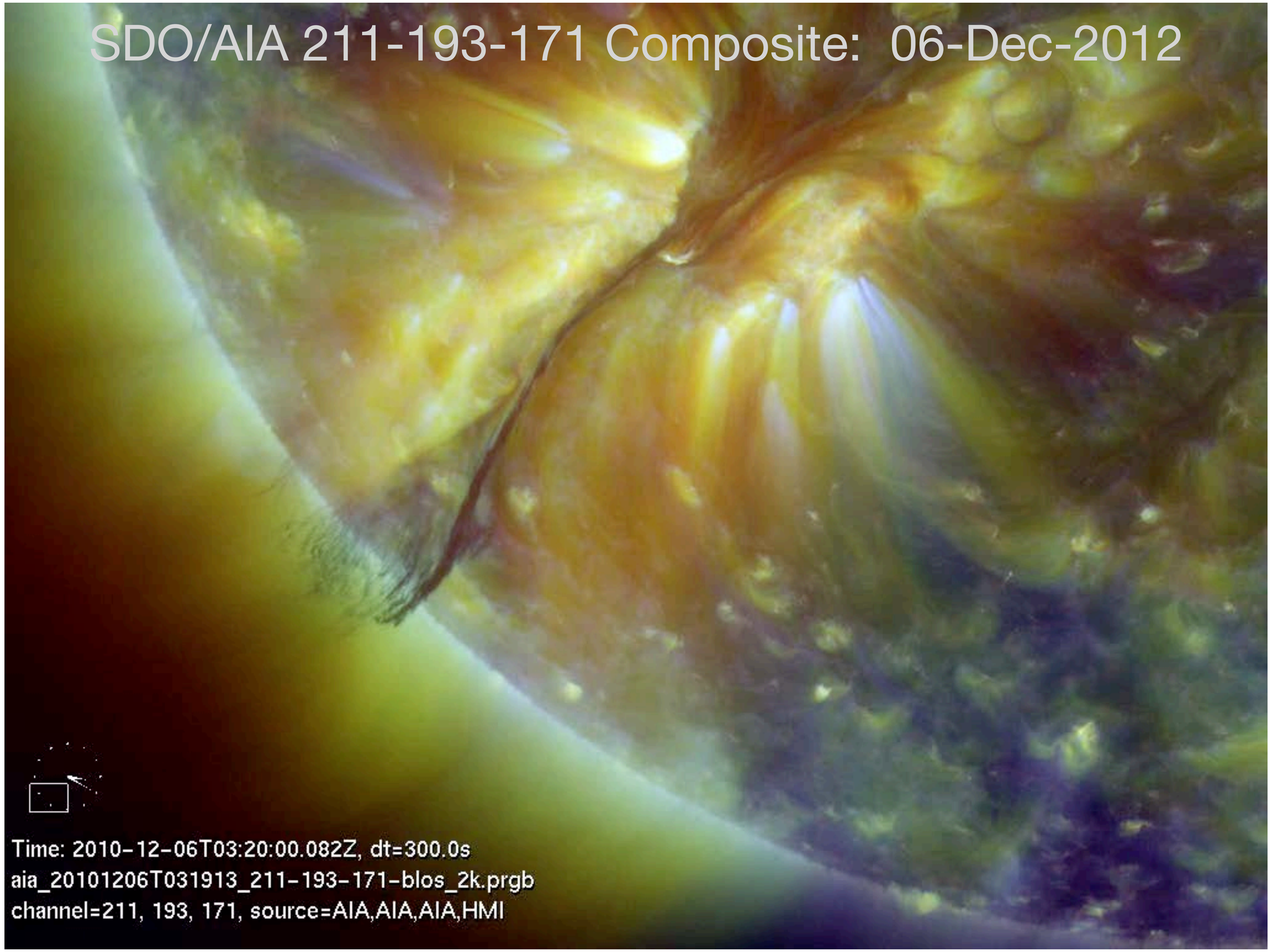


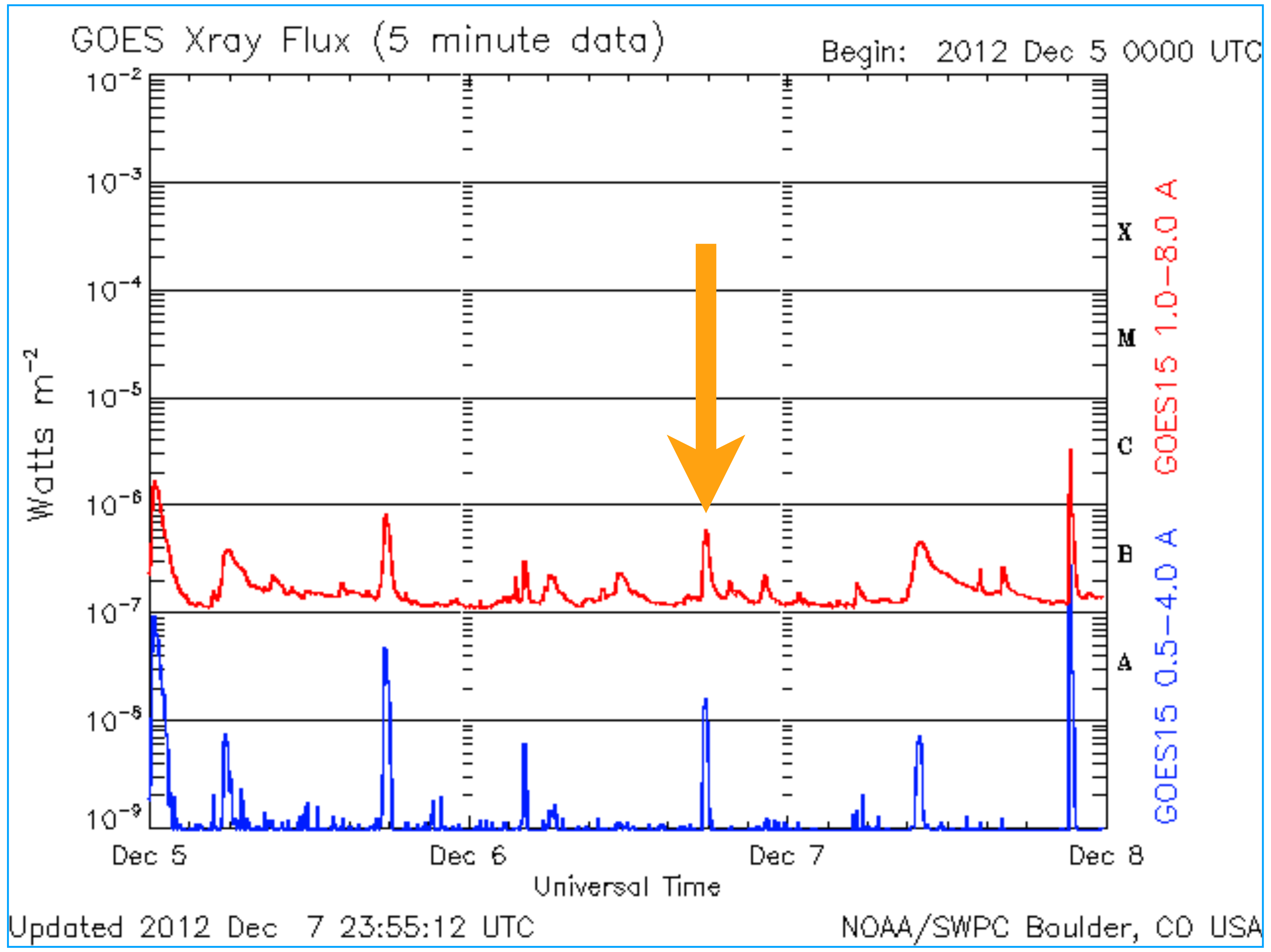
Longitude: -60° to -150°
Latitude: 15° to 55°

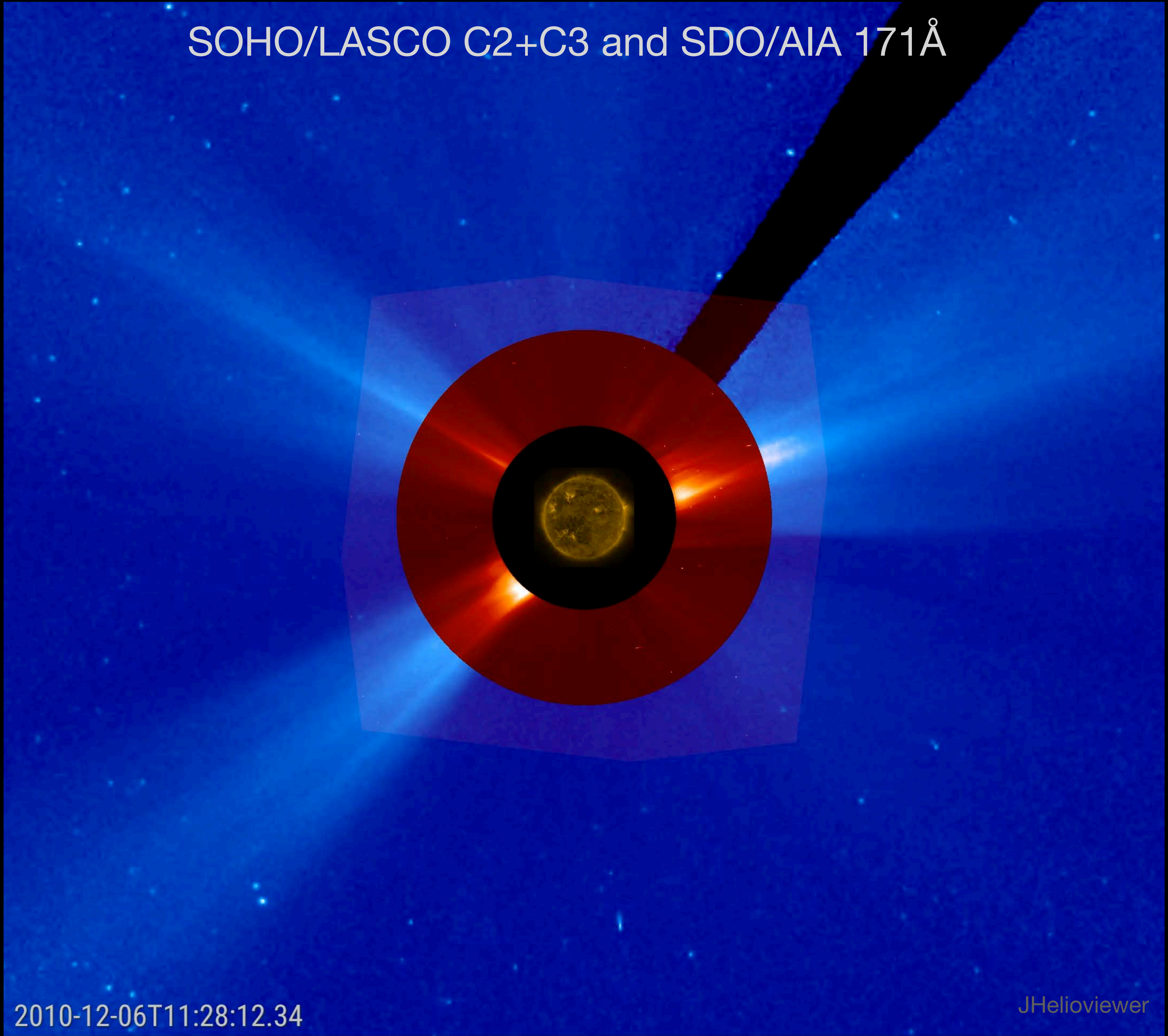
Length = ~600 Mm

Coronal signatures associated with CMEs

Filament eruptions: EUV filament seen in absorption






SOHO/LASCO C2+C3 and SDO/AIA 171Å
2010-12-06T11:28:12.34
JHelioviewer

Left off of the list: “Coronal cavities”

Coronal cavities occur above quiet Sun filament/prominence structures

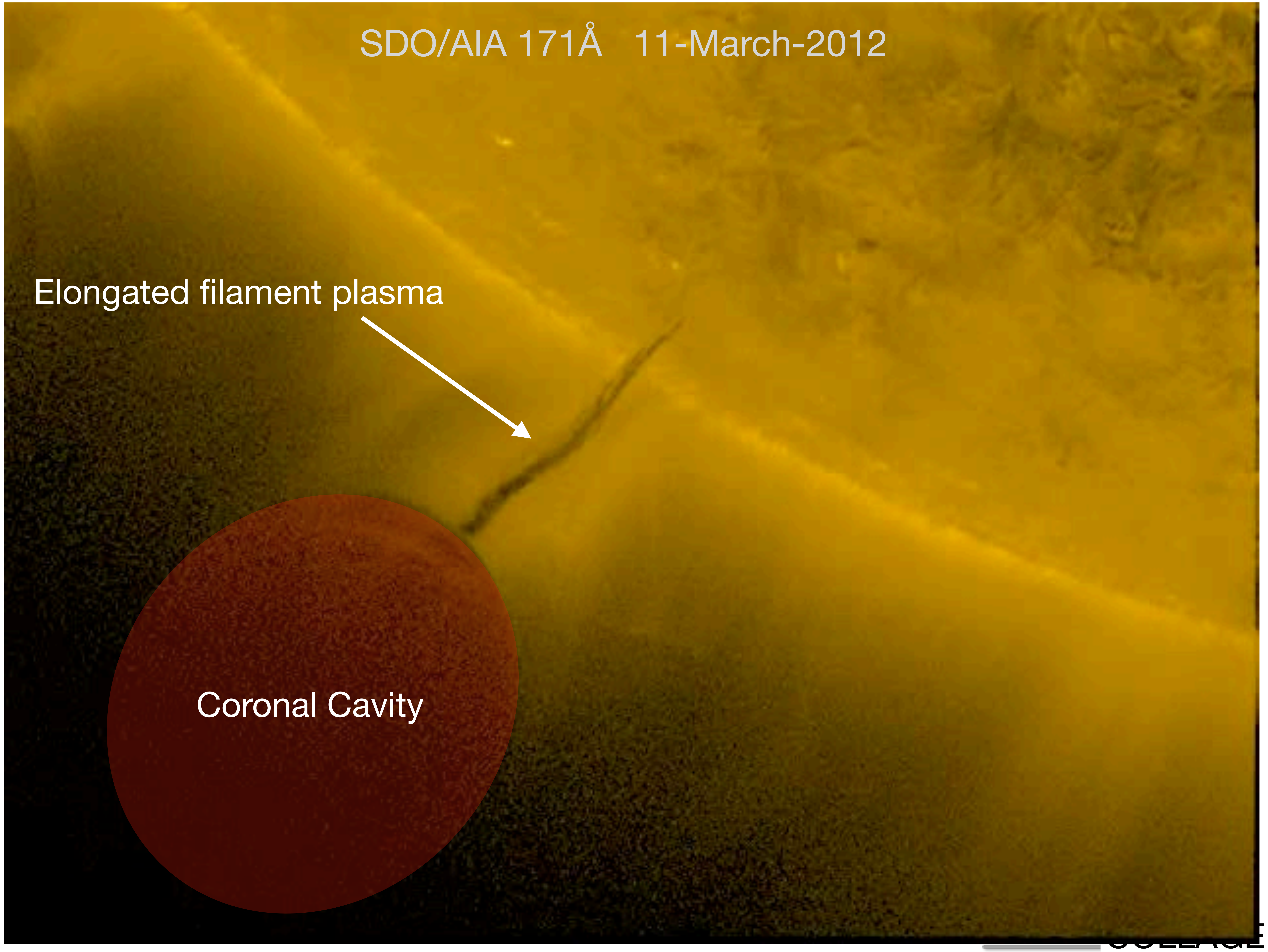
Coronal cavities are the signatures of large twisted flux ropes in the high corona.

They form the bulk of the magnetic structure of the CME after eruption.

Prominences are coronal plasma that has cooled, condensed, and is draining out of the flux rope.

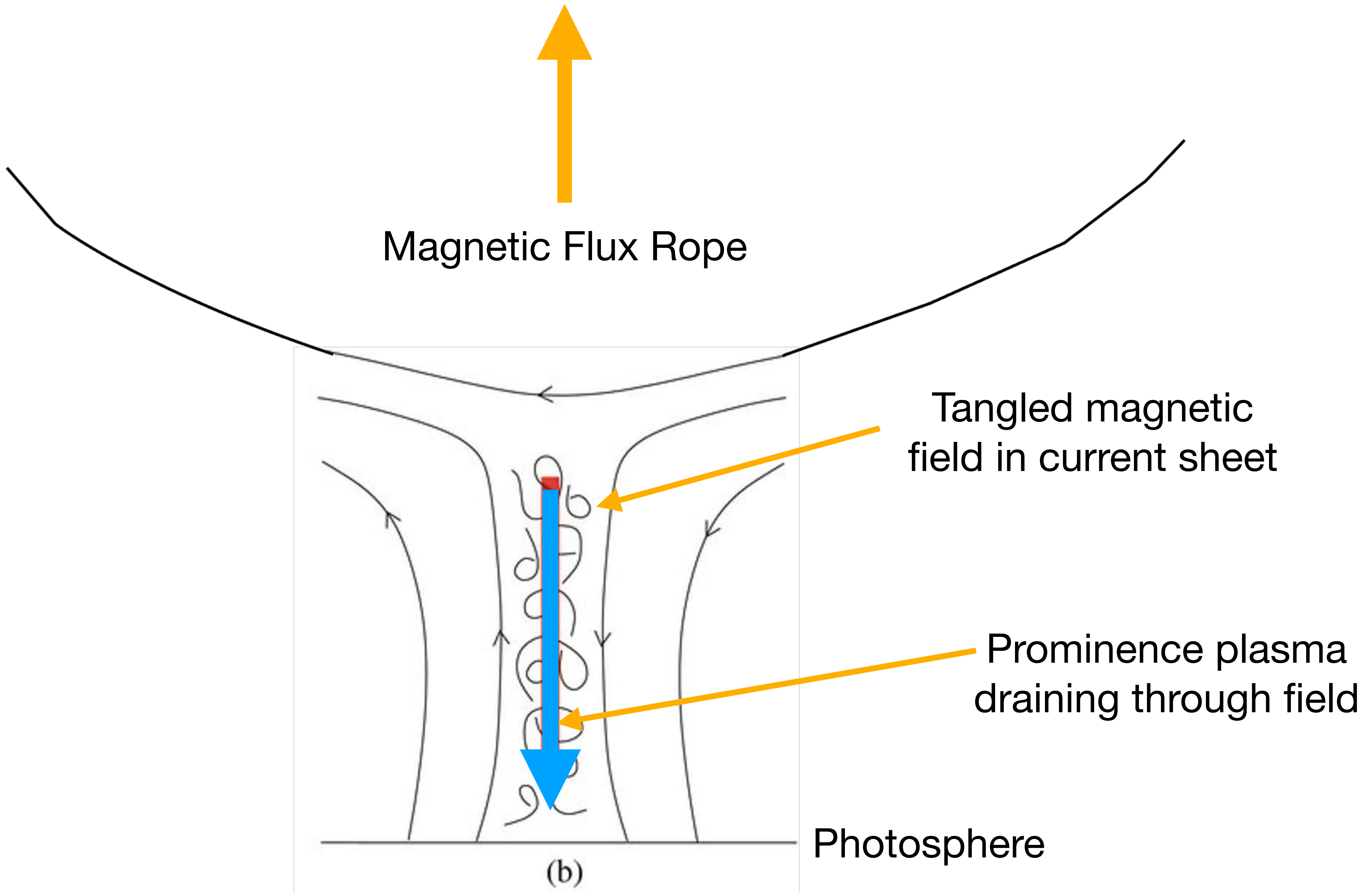
Coronal cavities all eventually erupt to form CMEs

Coronal cavity demarcates the magnetic flux rope



Flux Rope - Prominence Model

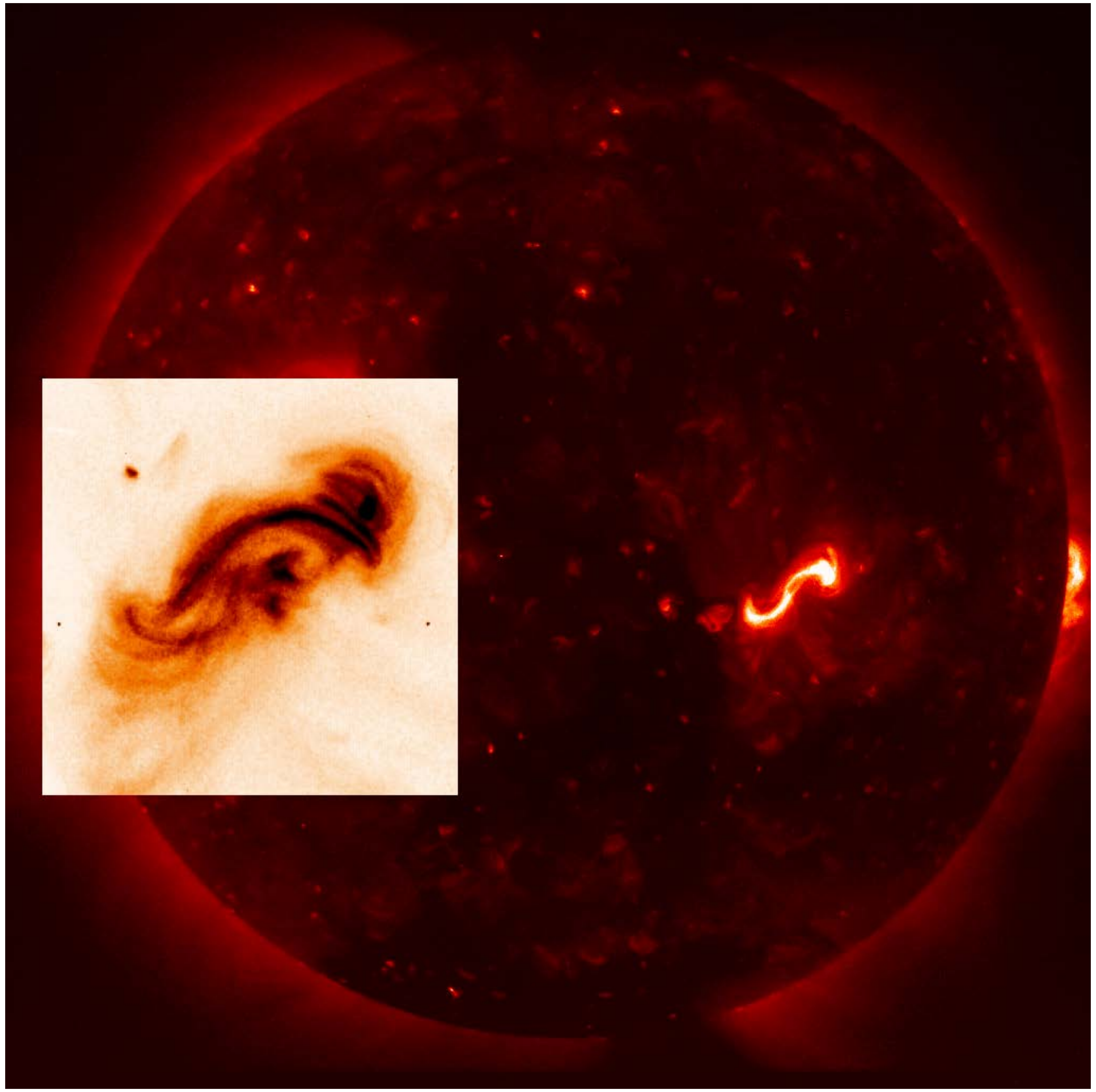
Prominence plasma drainage slowed by twisted/tangled magnetic field



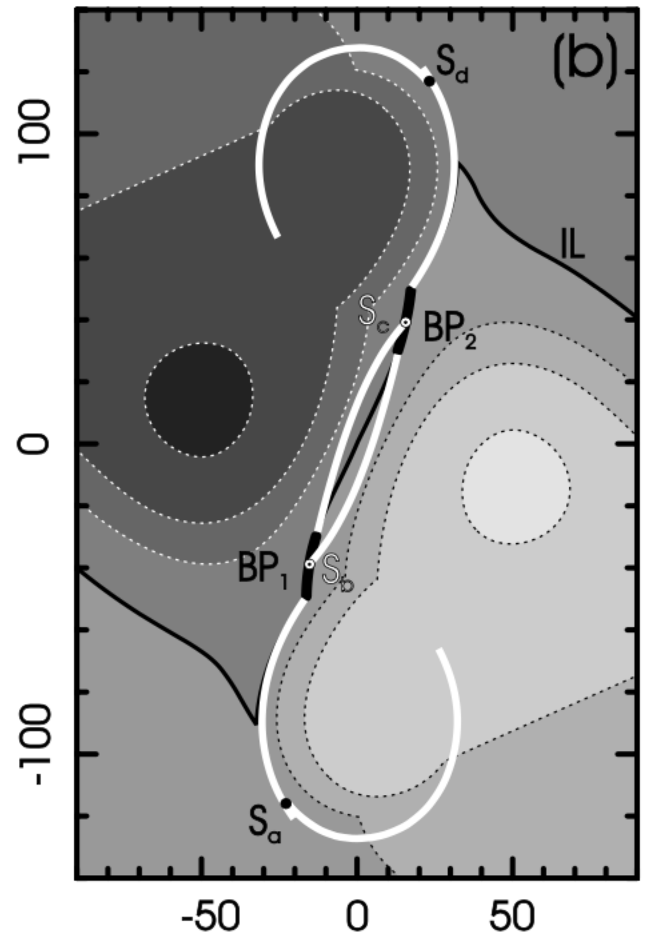
Van Ballegooijen & Cranmer, ApJ, 711, 164, 2010, https://doi.org/10.1088/0004-637X/711/1/164

Coronal signatures associated with CMEs

X-ray sigmoids: evidence of twisted magnetic fields in the corona



http://solar.physics.montana.edu/press/XRT_Sigmoid.html



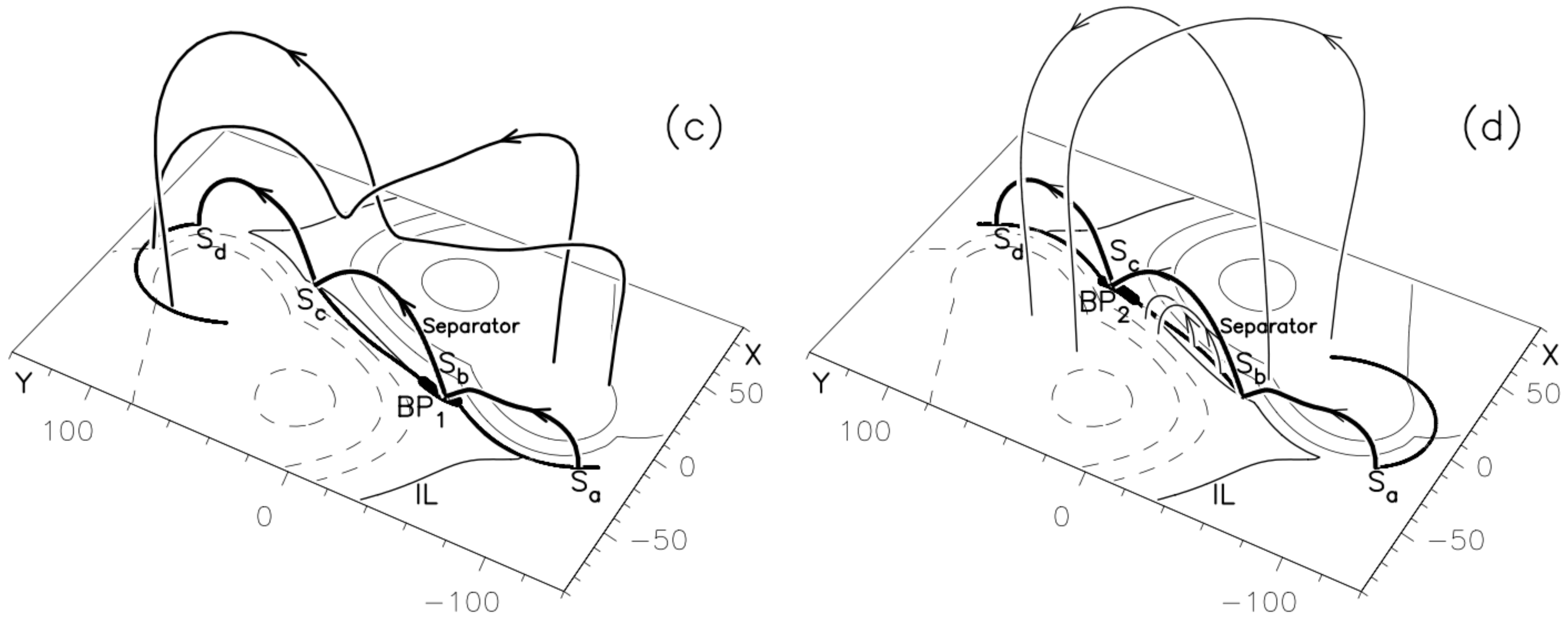
Photospheric magnetic field configuration

BP = “bald patch”
S = separator anchor points

Coronal magnetic loop topology

(c) twisted flux tube field lines

(d) untwisted field lines above and below the flux rope



Titov & Démoulin, Astron. & Astrophys., **351**, 707, 1999

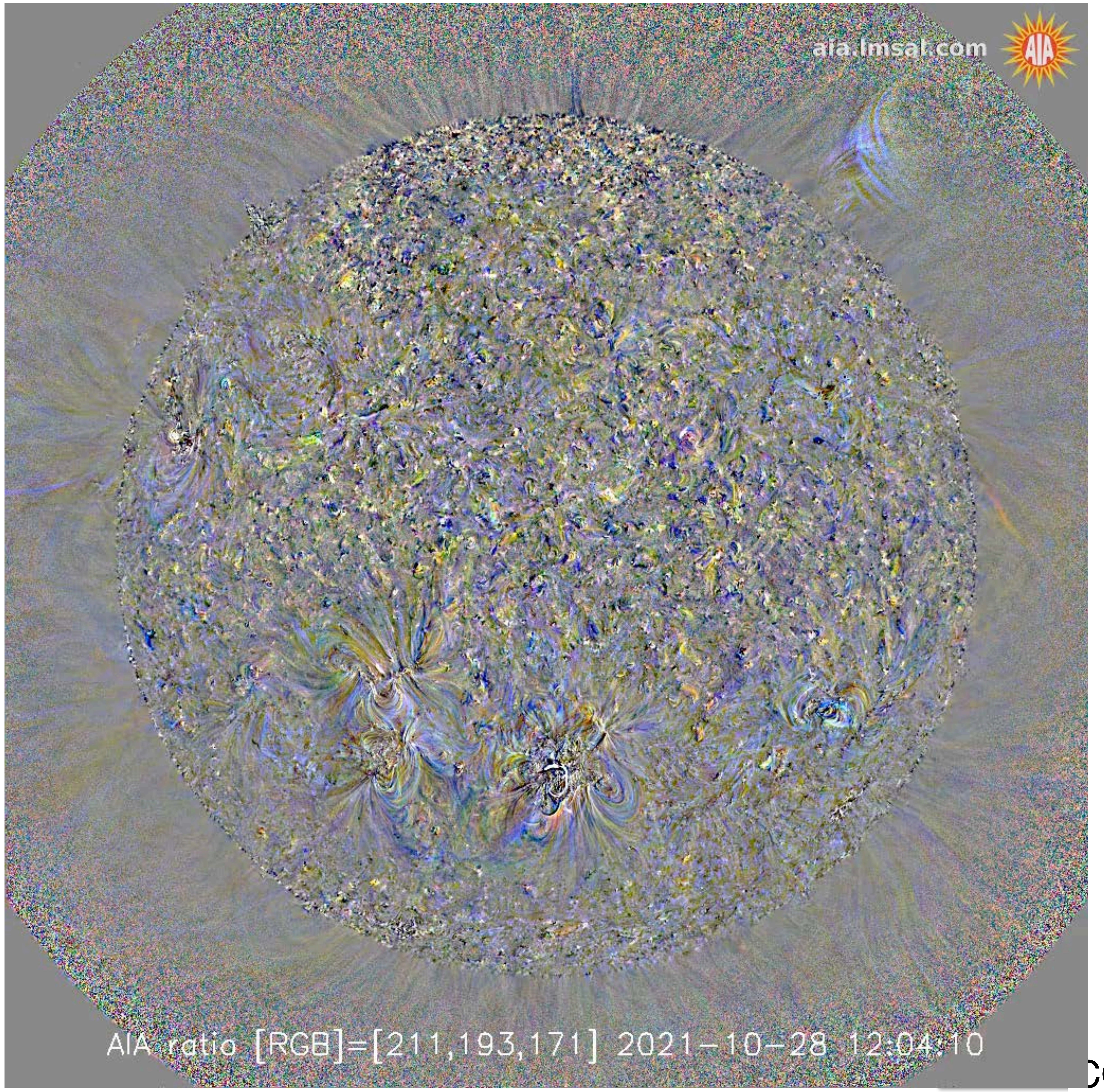
Coronal signatures associated with CMEs

“EIT waves”

Named after the SOHO Extreme ultraviolet Imaging Telescope (EIT) since they were (re)discovered in those data.

Also called “EUV” waves these days.

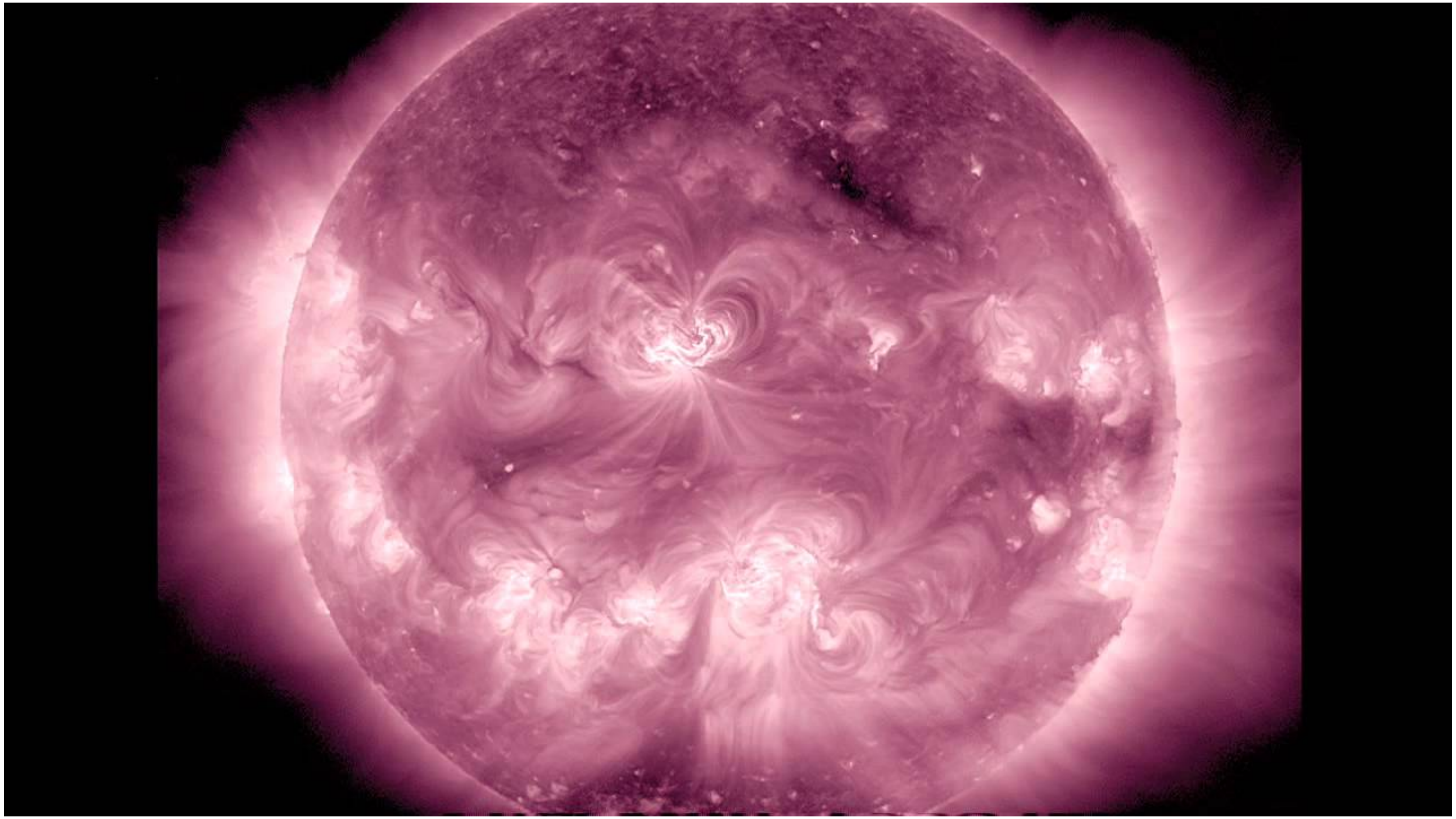
Originally discovered in Hα movies by Morton in the 1960s.



Coronal signatures associated with CMEs

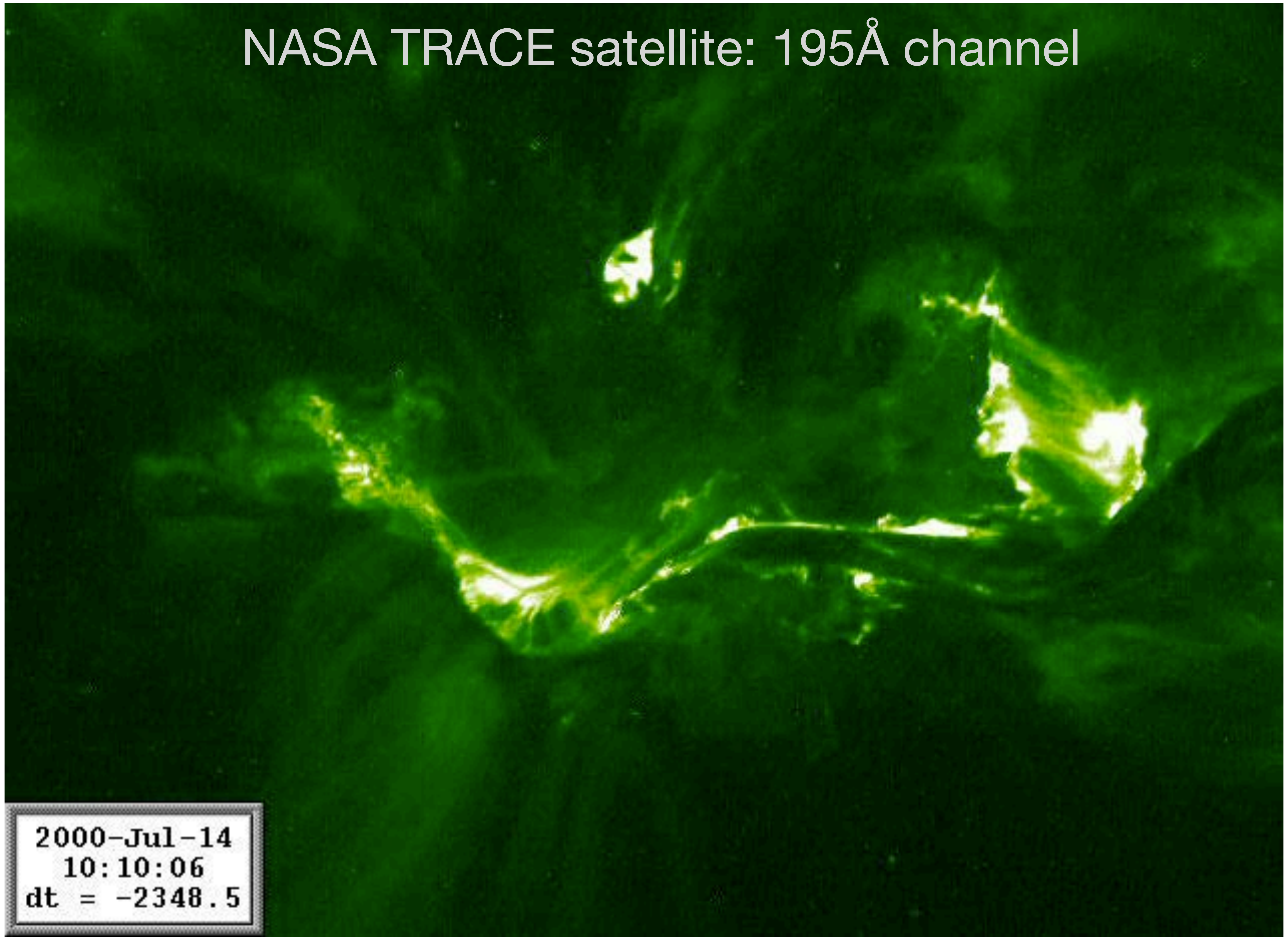
Coronal dimming (and EIT wave)

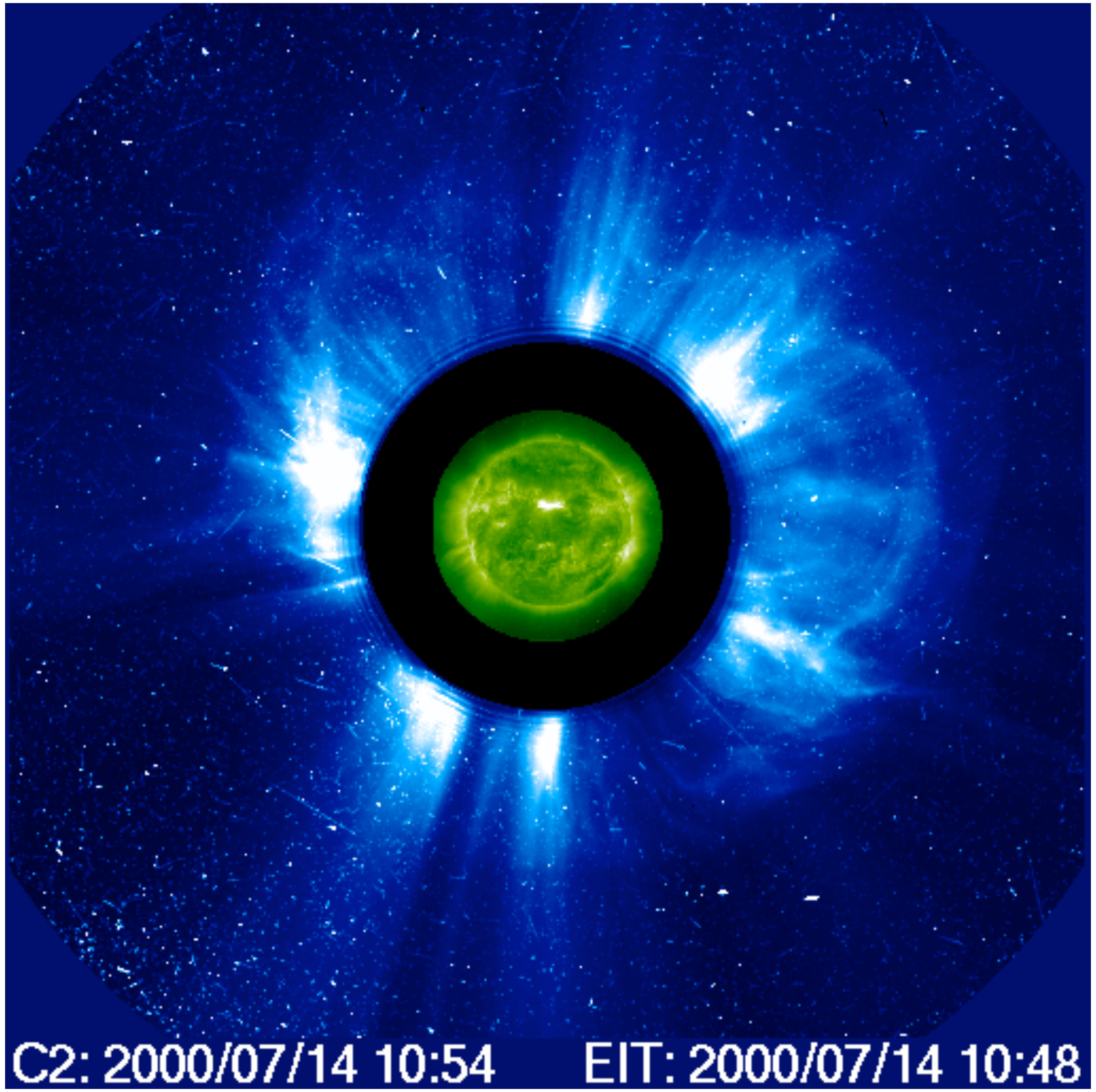
SDO/AIA coronal dimming: 10-Sep-2014 17:00 UT



Coronal signatures associated with CMEs

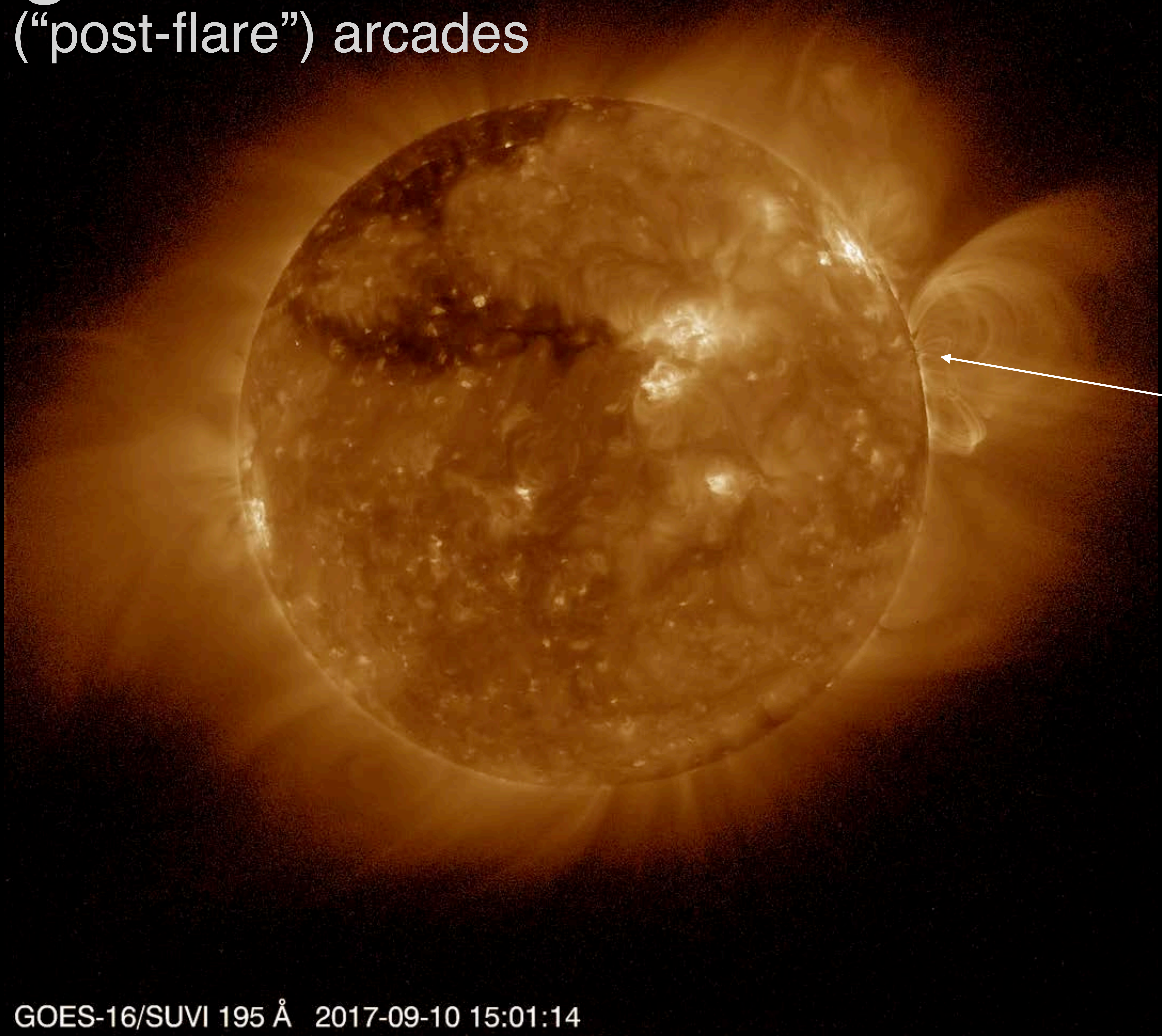
Post-eruptive ("post-flare") arcades





Coronal signatures associated with CMEs

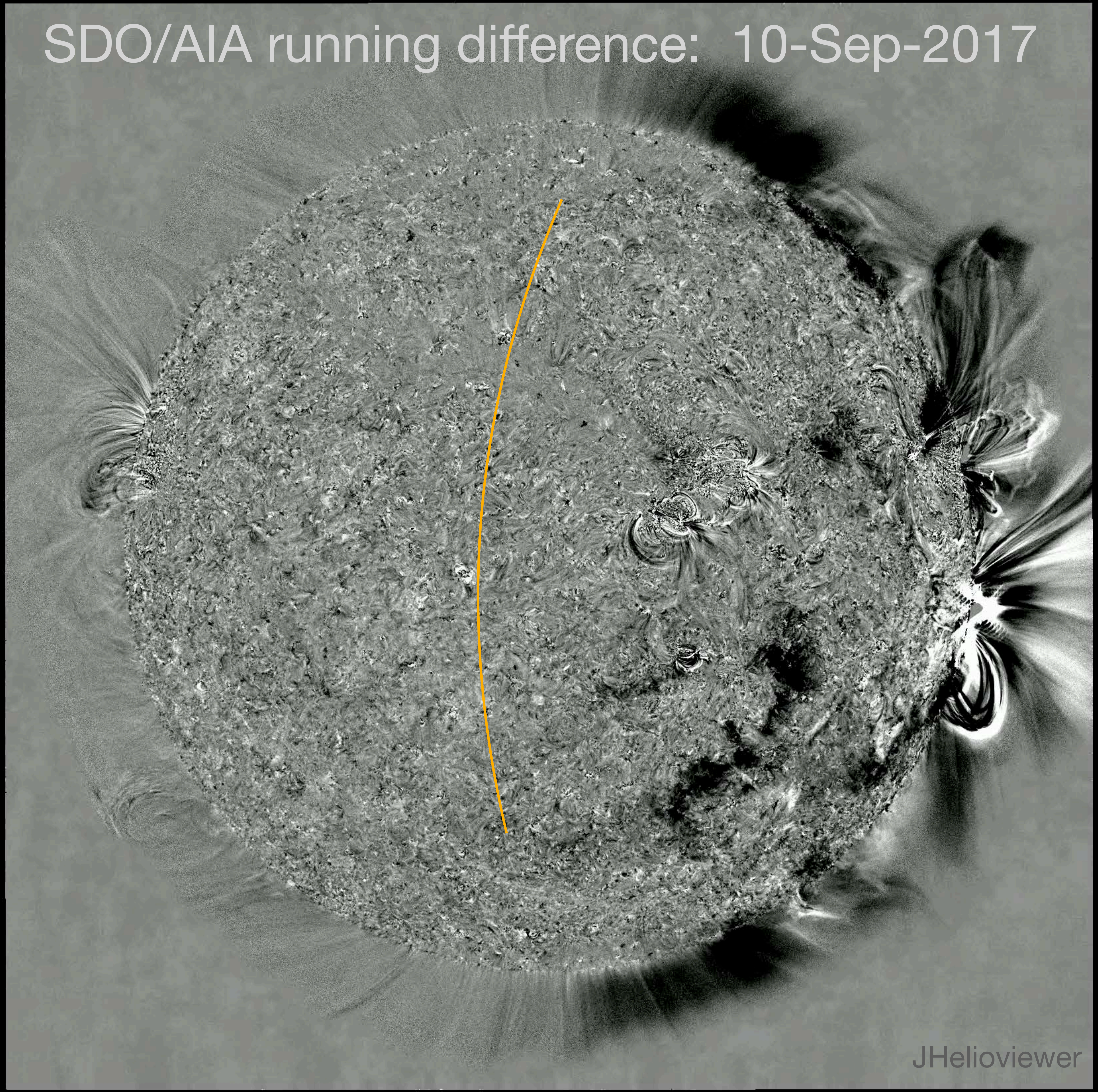
Post-eruptive (“post-flare”) arcades



11th Brightest X-ray flare on record
X8.2

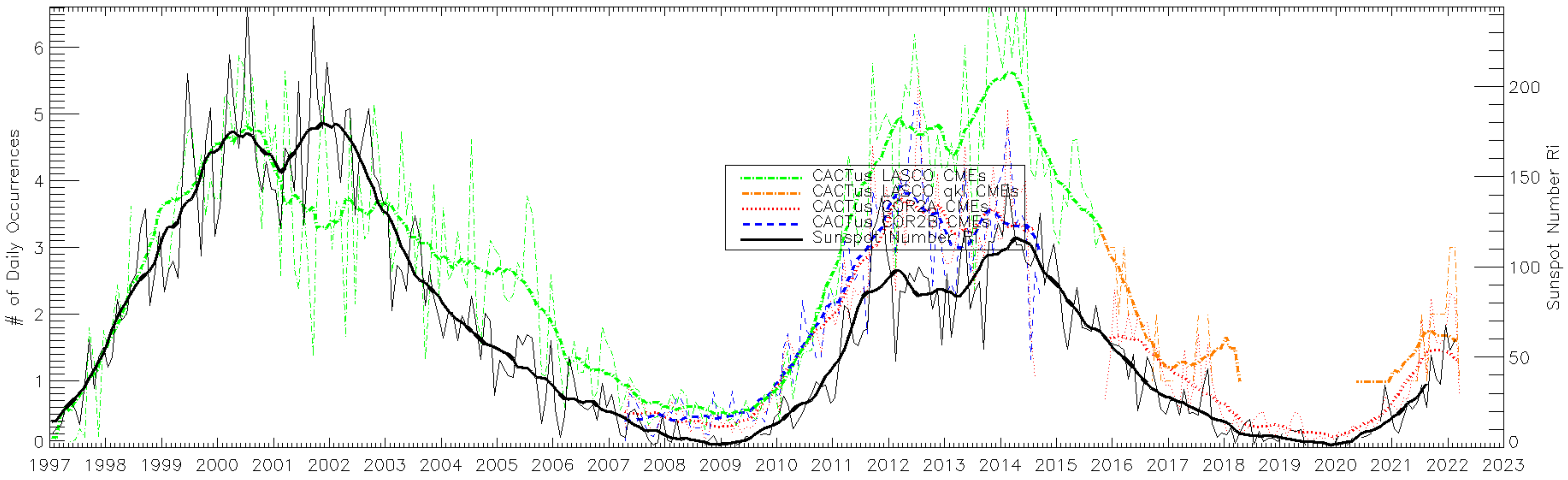
Coronal signatures associated with CMEs

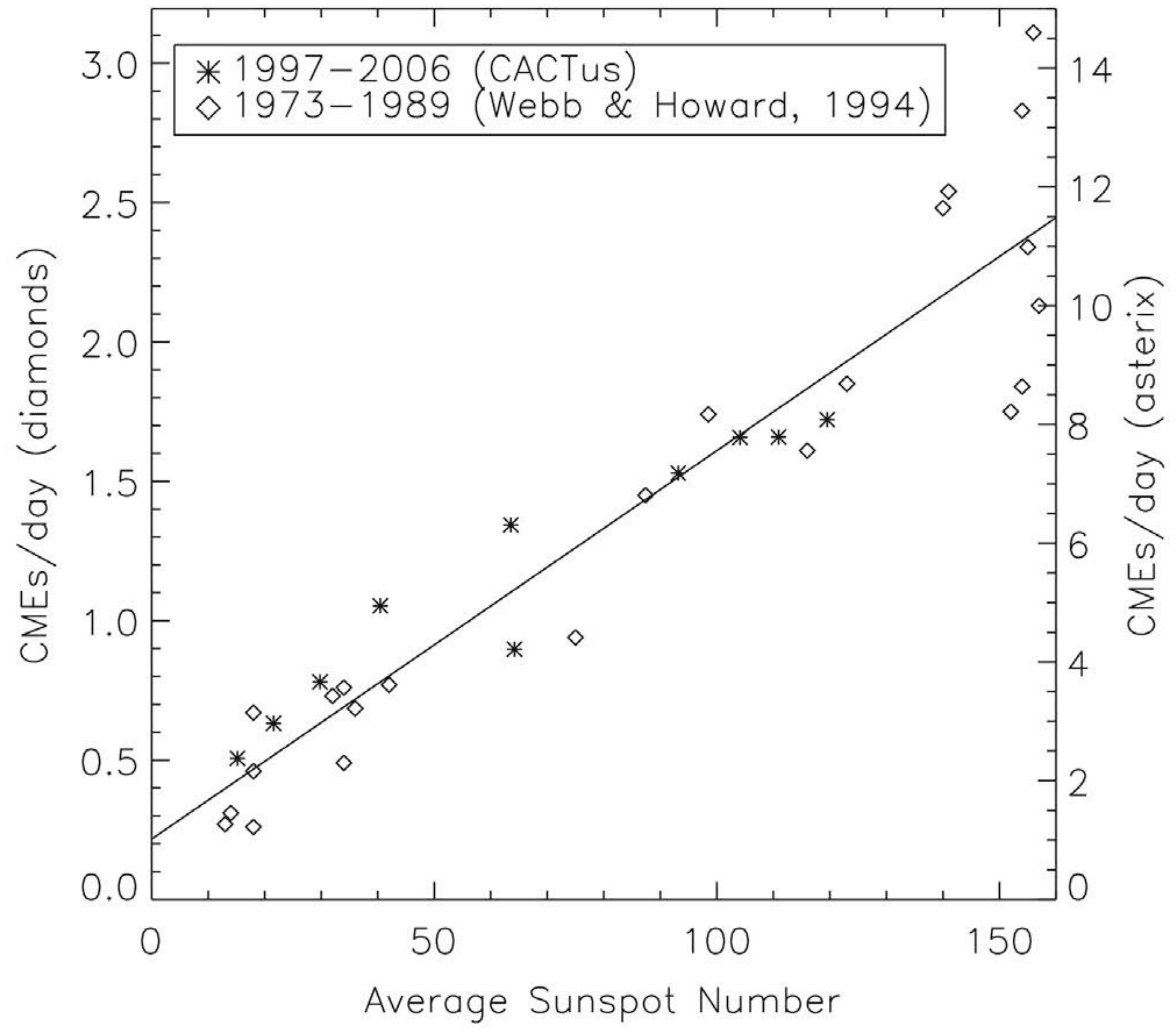
Very large eruptions: “EIT waves” and post-flare loop arcade



The CACTUS CME catalog

Automatic CME detection using SOHO/LASCO and STEREO/COR2





Robbrecht et al., ApJ, 2009, https://doi.org/10.1088/0004-637X/691/2/1222

https://wwwbis.sidc.be/cactus/

Issue: Solar Cycle 24 was more CME active than Cycle 23?

Solar Magnetic Eruptions

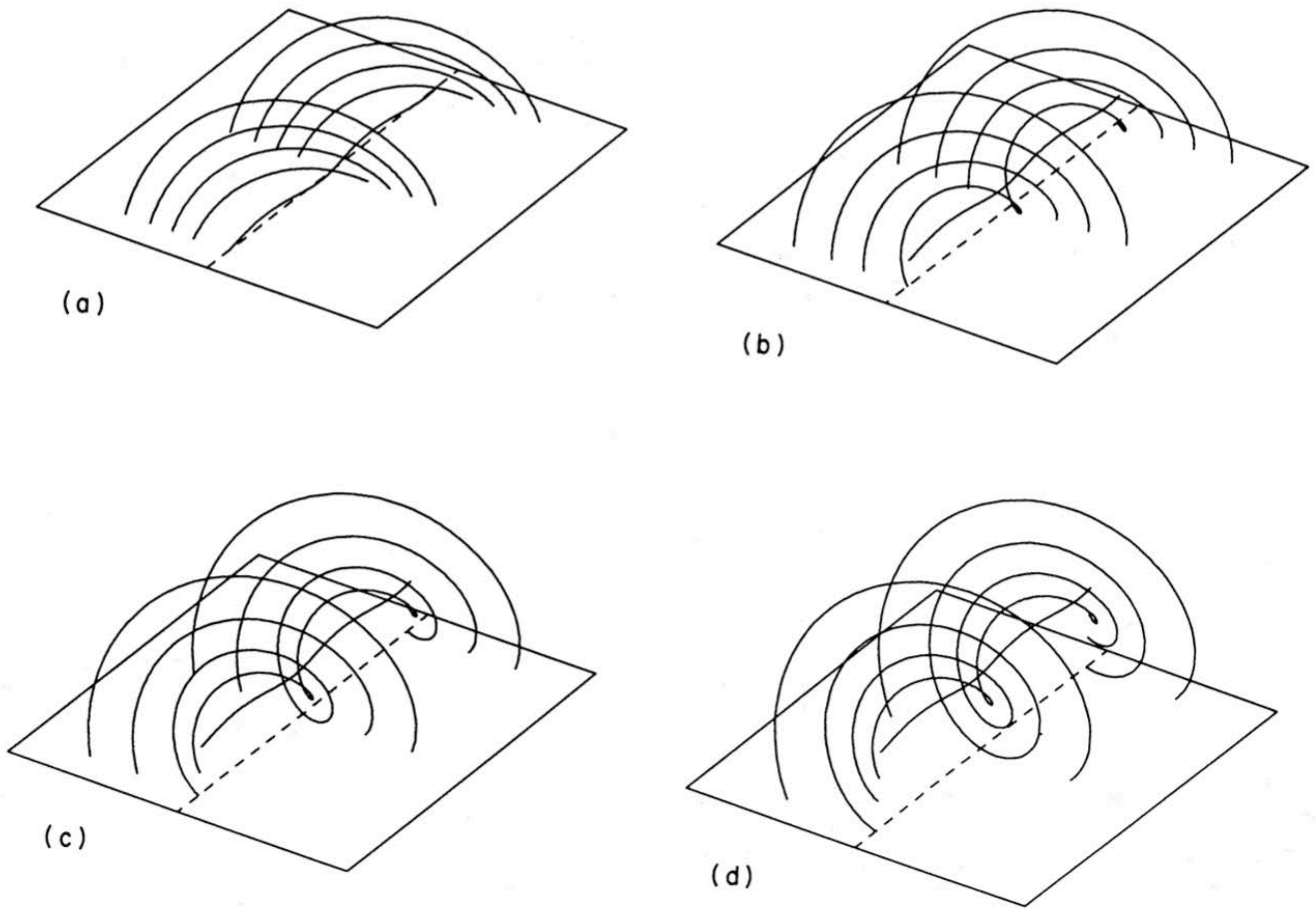
A unifying concept rooted in magnetic reconnection that explains flares, CMEs, and their quixotic relationship

- Basic elements of the concept:
  - Hypothesis: the necessary prerequisite for a magnetic eruption is a "**magnetic flux rope**" (MFR).
  - MFRs are formed when the convective motions in the photosphere (and possibly pressure-driven flows in the chromosphere) twist magnetic field lines into "**non-potential**" configurations.
  - Non-potential magnetic field configurations can store "**Free Energy**" that can be converted to kinetic energy of the coronal plasma to accelerate particles and drive CMEs.
  - **Magnetic reconnection** triggers the eruption, releasing the twist in the field and converting the magnetic free energy.

Magnetic Flux Rope Formation

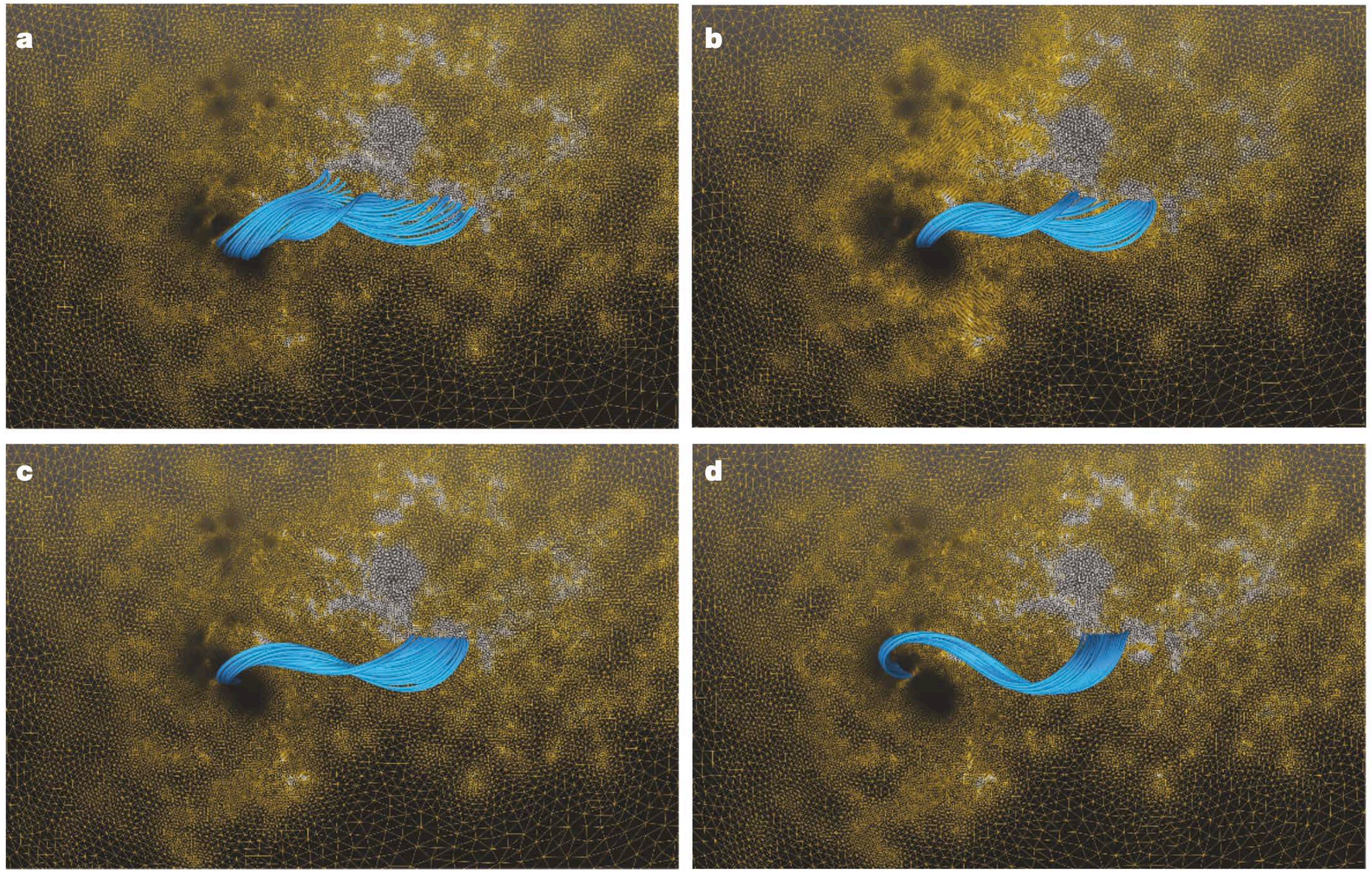
Analytic and Ideal MHD simulations

Analytical model of shearing and cancellation of field lines across a Polarity Inversion Line (PIL)



van Ballegooijen & Martens, ApJ, **343**, 971,1989

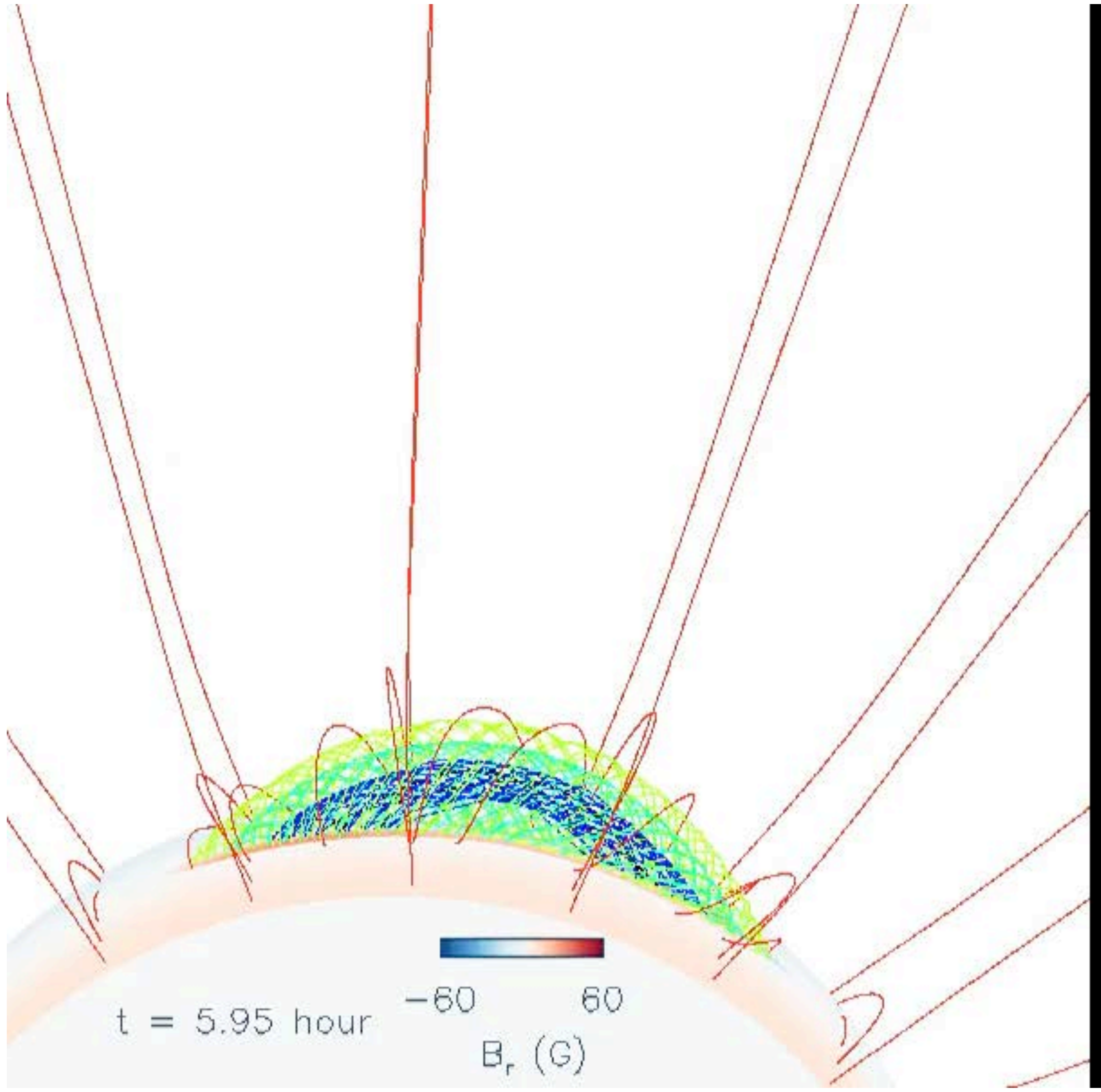
Ideal MHD model of MFR formation on actual magnetic field data from October 2014



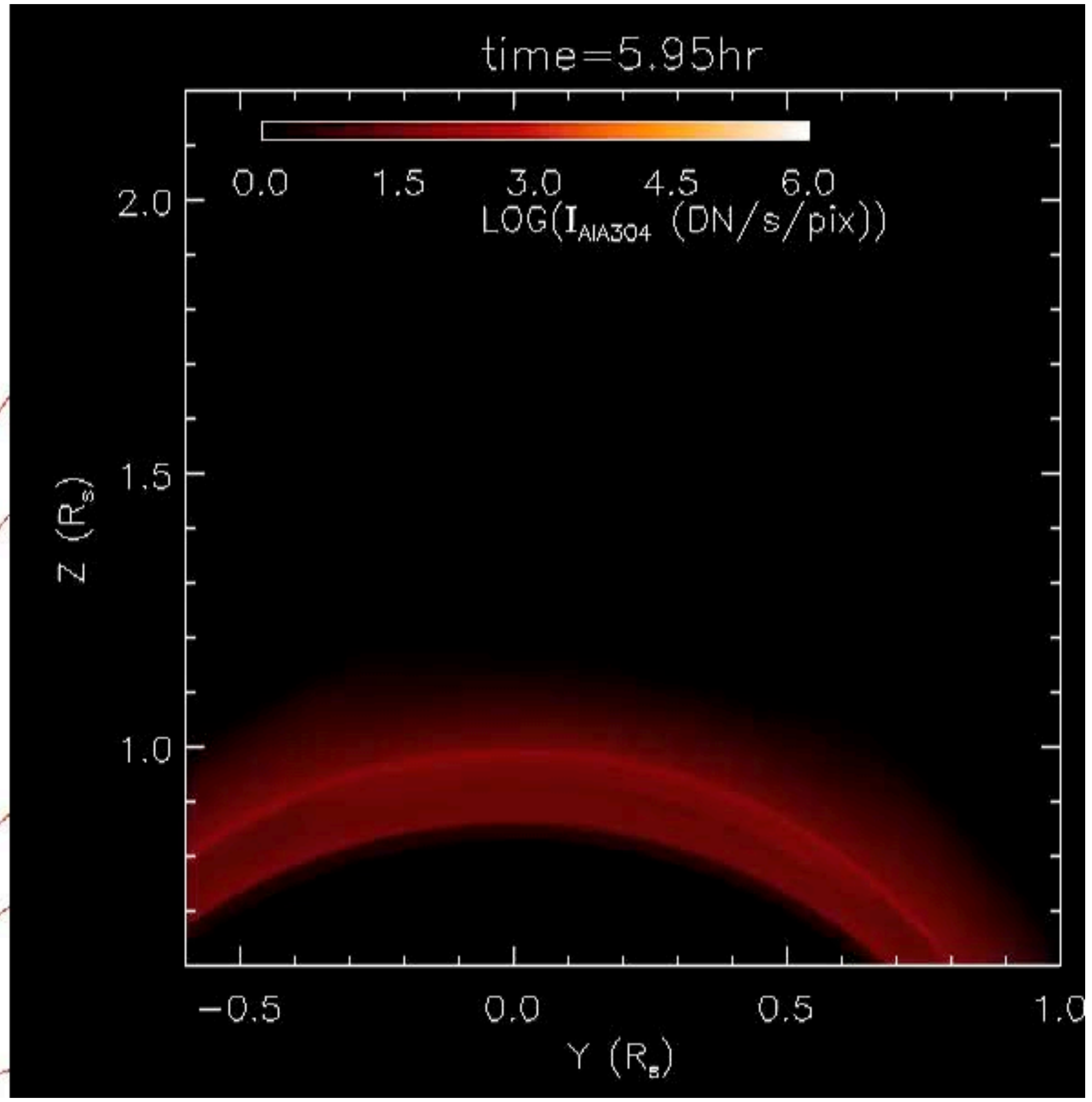
Amari et al., Nature, 2018, https://doi.org/10.1038/nature24671

Magnetic Flux Rope Eruption

Energy buildup, buoyancy, reconnection, and eruption



Ideal MHD driven flux rope model

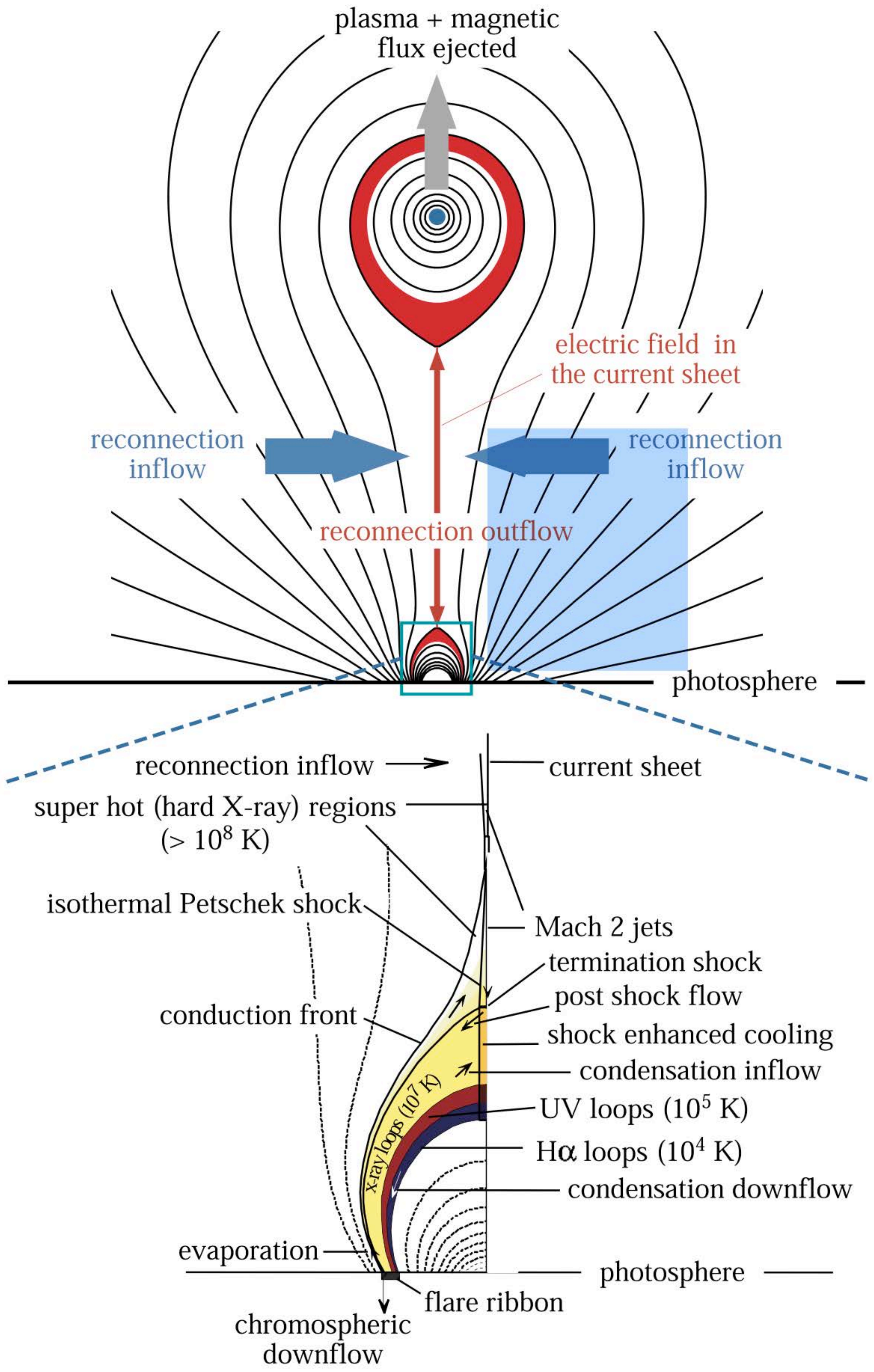


Simulated SDO/AIA 304Å intensity

Fan, ApJ, **862**, 2018, https://doi.org/10.3847/1538-4357/aaccee

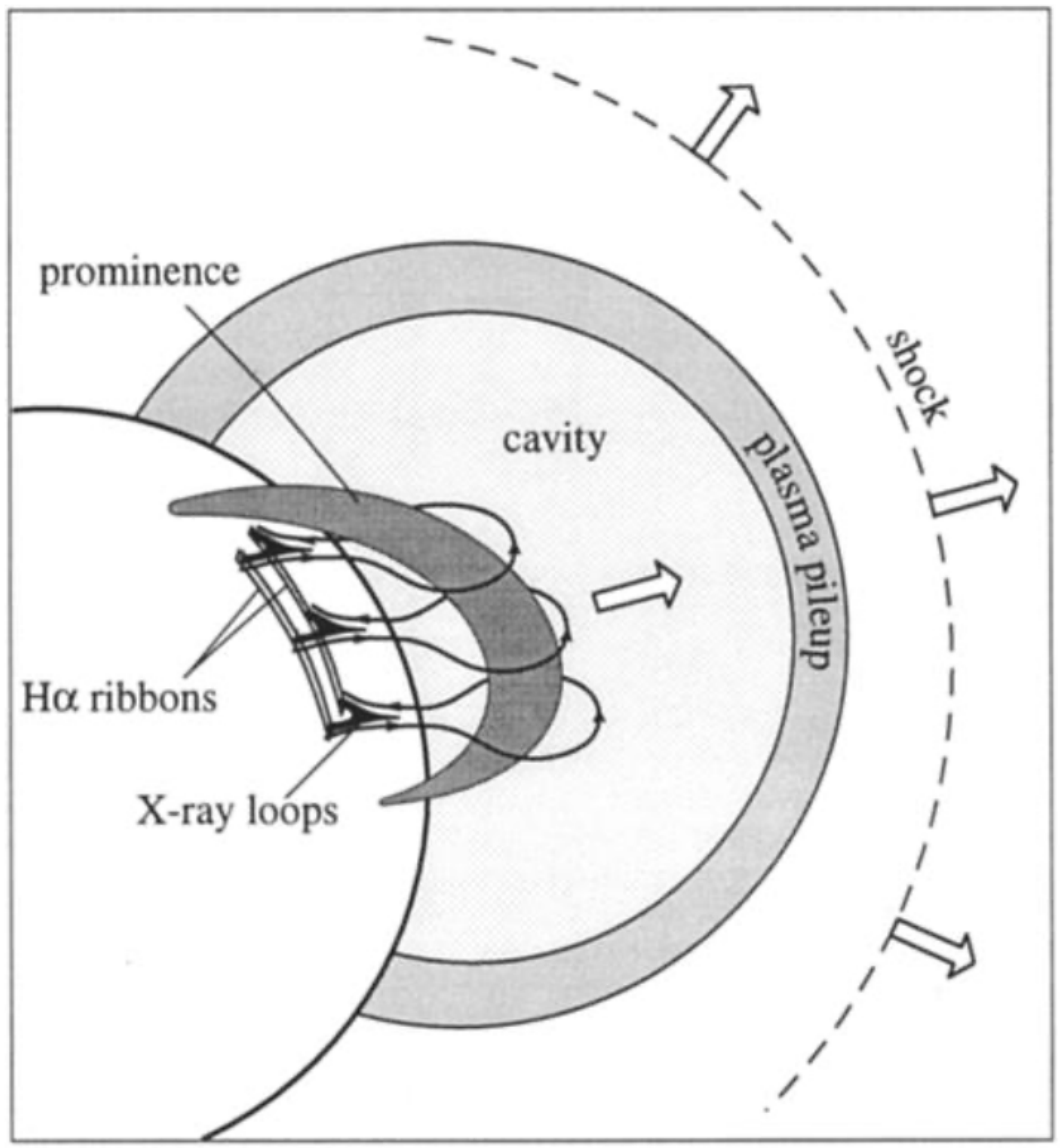
Solar Magnetic Eruptions

Cartoon representations



Ko et al., ApJ, **594**, 2003, https://doi.org/10.1086/376982

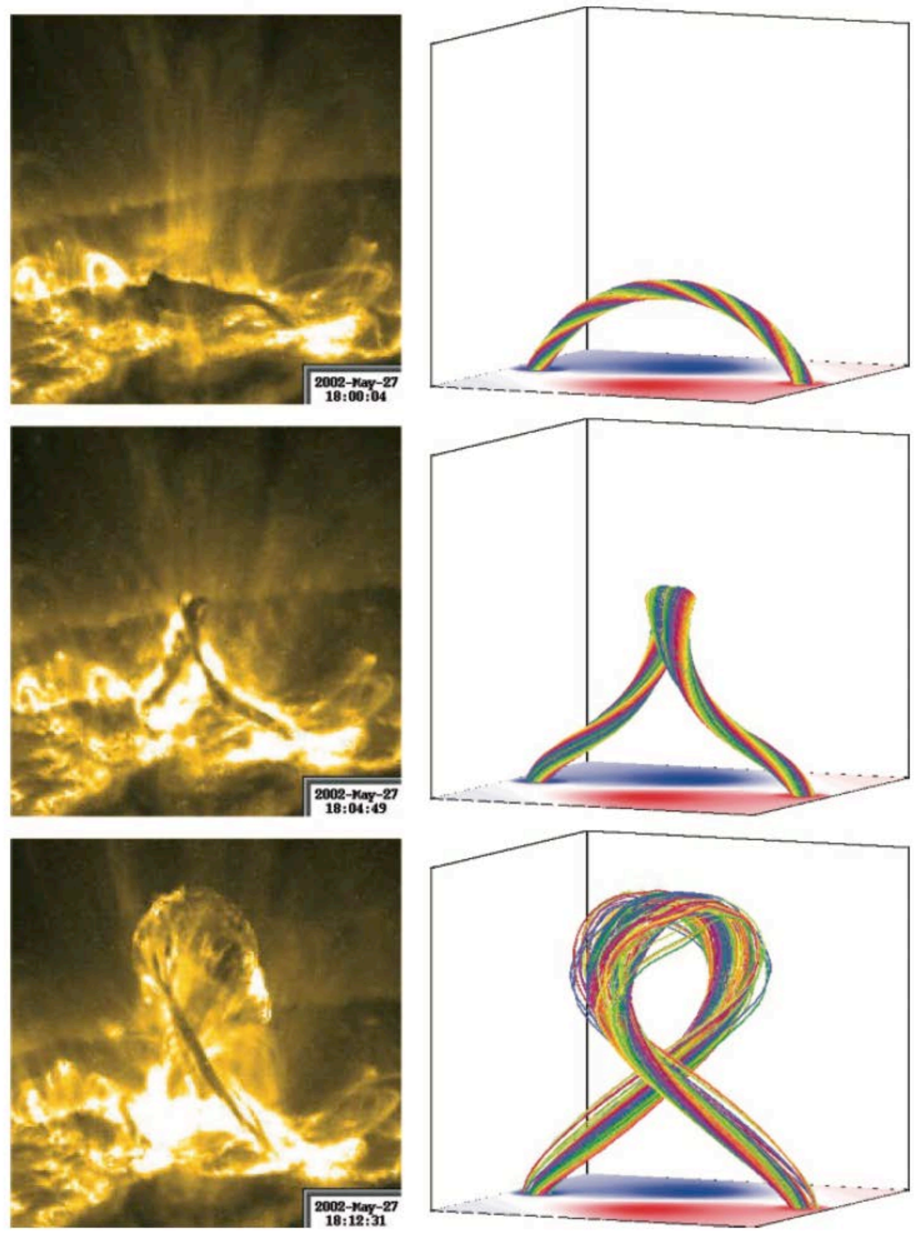
Active Region eruption with X-ray flare



Forbes, JGR, 2000, https://doi.org/https://doi.org/10.1029/2000JA000005

SME concept explains CME-flare relationships

- **Large flare without CME**:
    - e.g., 24-October-2014 X3.1 flare, or 27-May-2002 M2 flare
    - Confined eruption: overlying field prevents CME escape (Amari et al., 2018) or kink instability insufficient to drive eruption (Torok & Kliem, 2005).
    - Erupted plasma channeled back to surface.

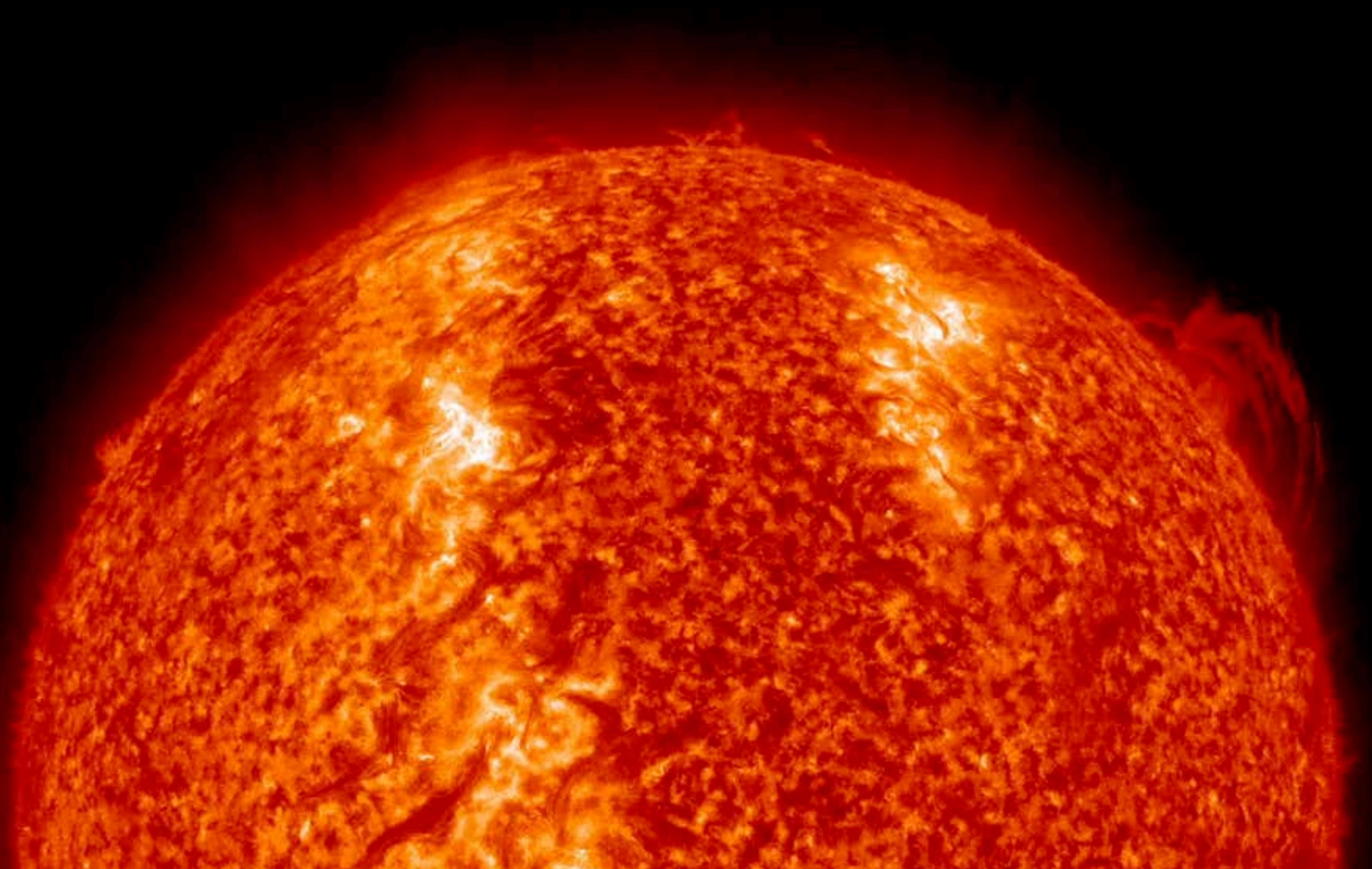


Torok & Kliem, ApJ, **630**, 2005, https://doi.org/10.1086/462412

- **Large CME without flare**:
    - e.g., 06-Dec-2012 filament eruption.
    - Large-scale filament flux rope eruption.
    - Reconnection energy insufficient to drive flare-producing plasma or particle acceleration.

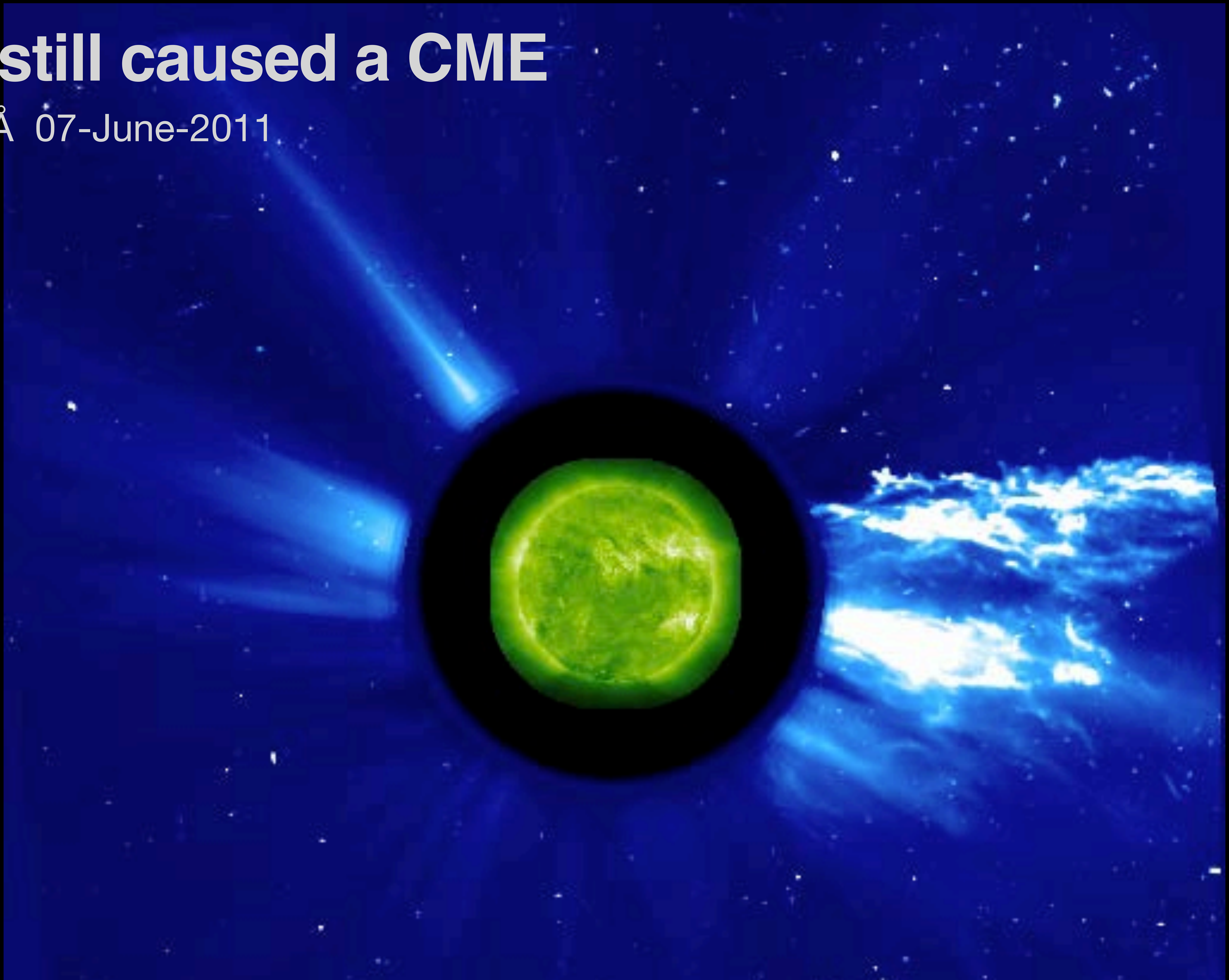
Escape velocity for the prominence plasma is not guaranteed…

SDO/AIA 304Å 07-June-2011



…but it still caused a CME

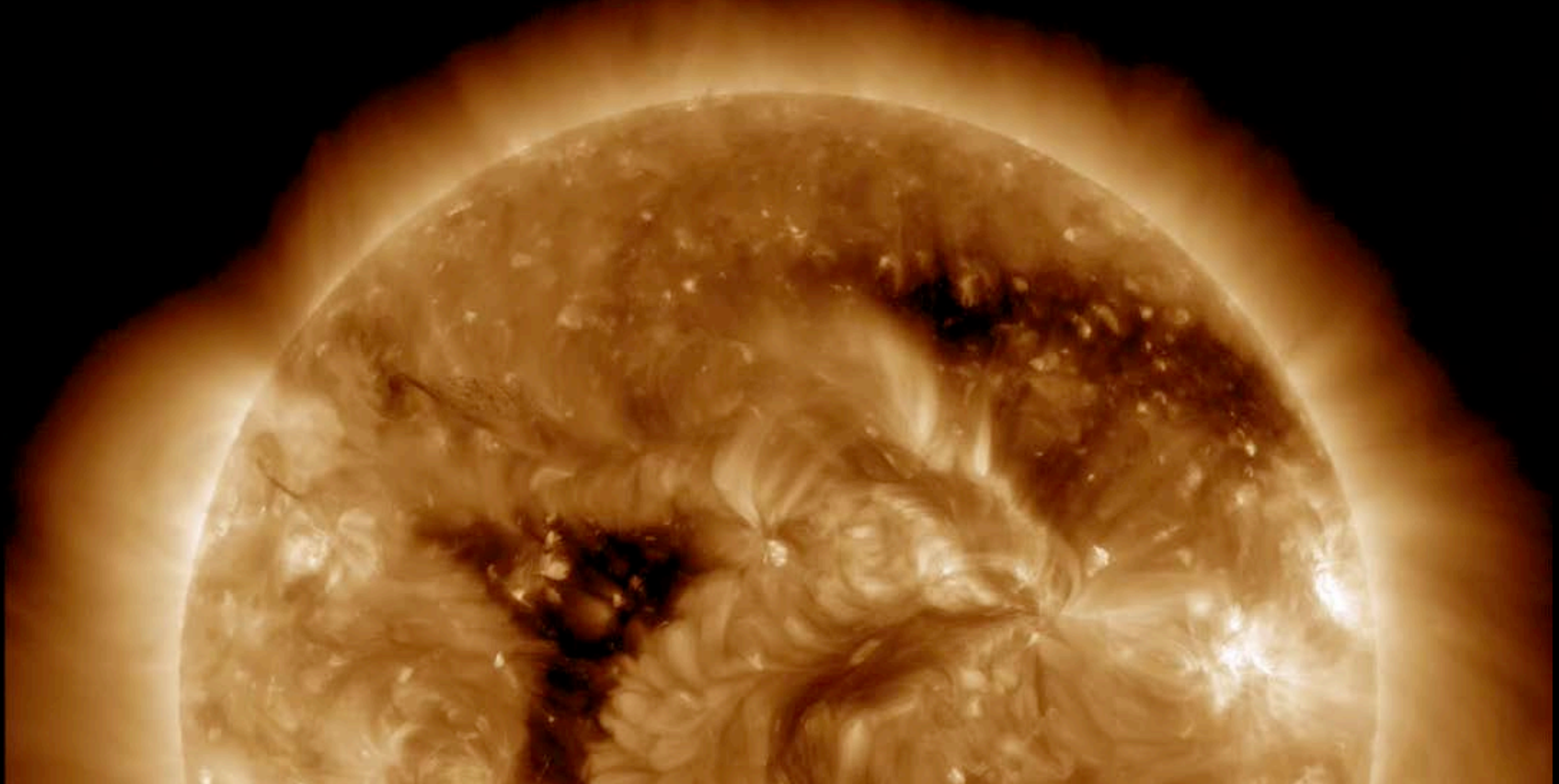
SDO/AIA 304Å 07-June-2011



Stealth CMEs occur with no associated flare

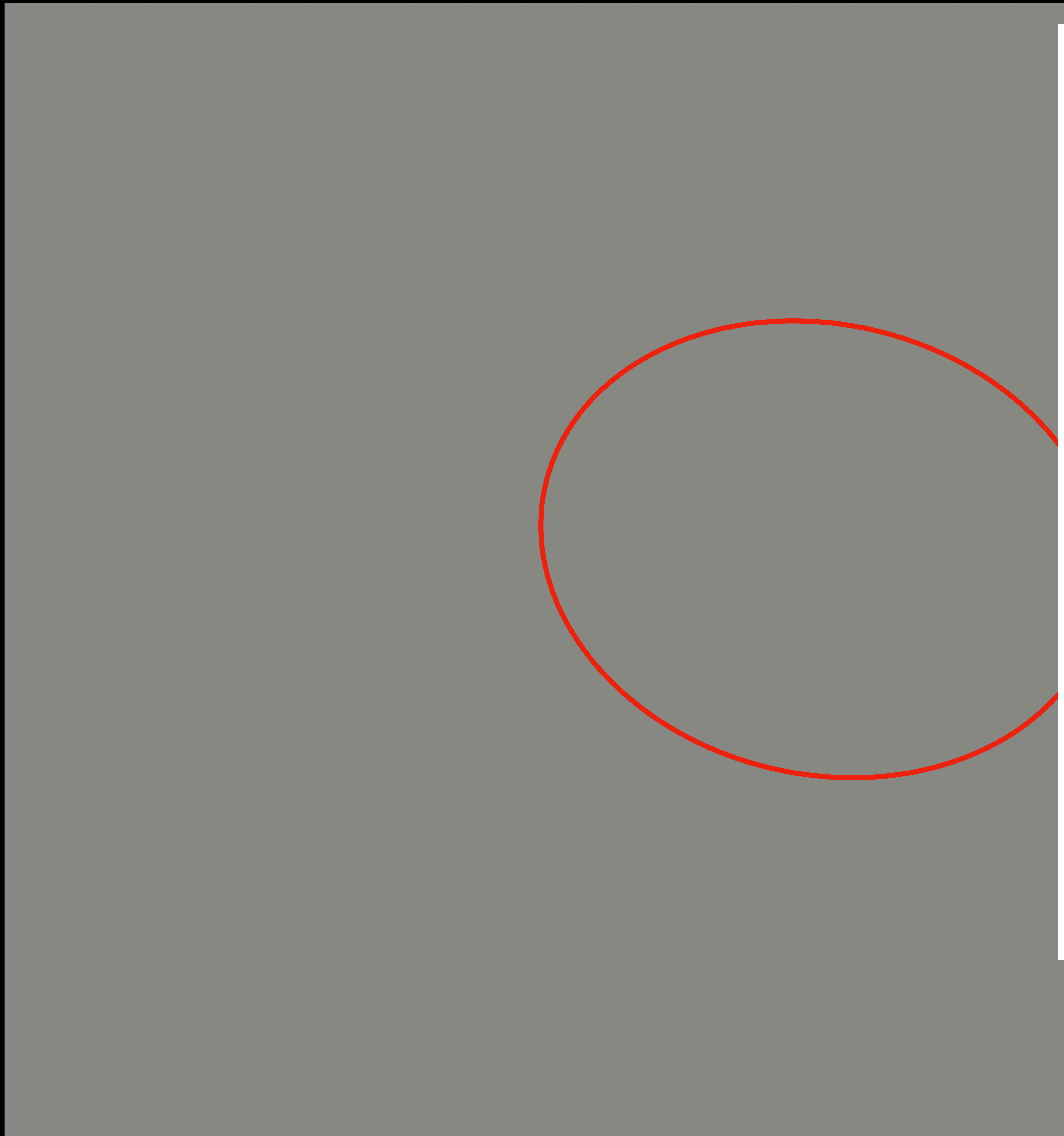
But often there are other coronal signatures

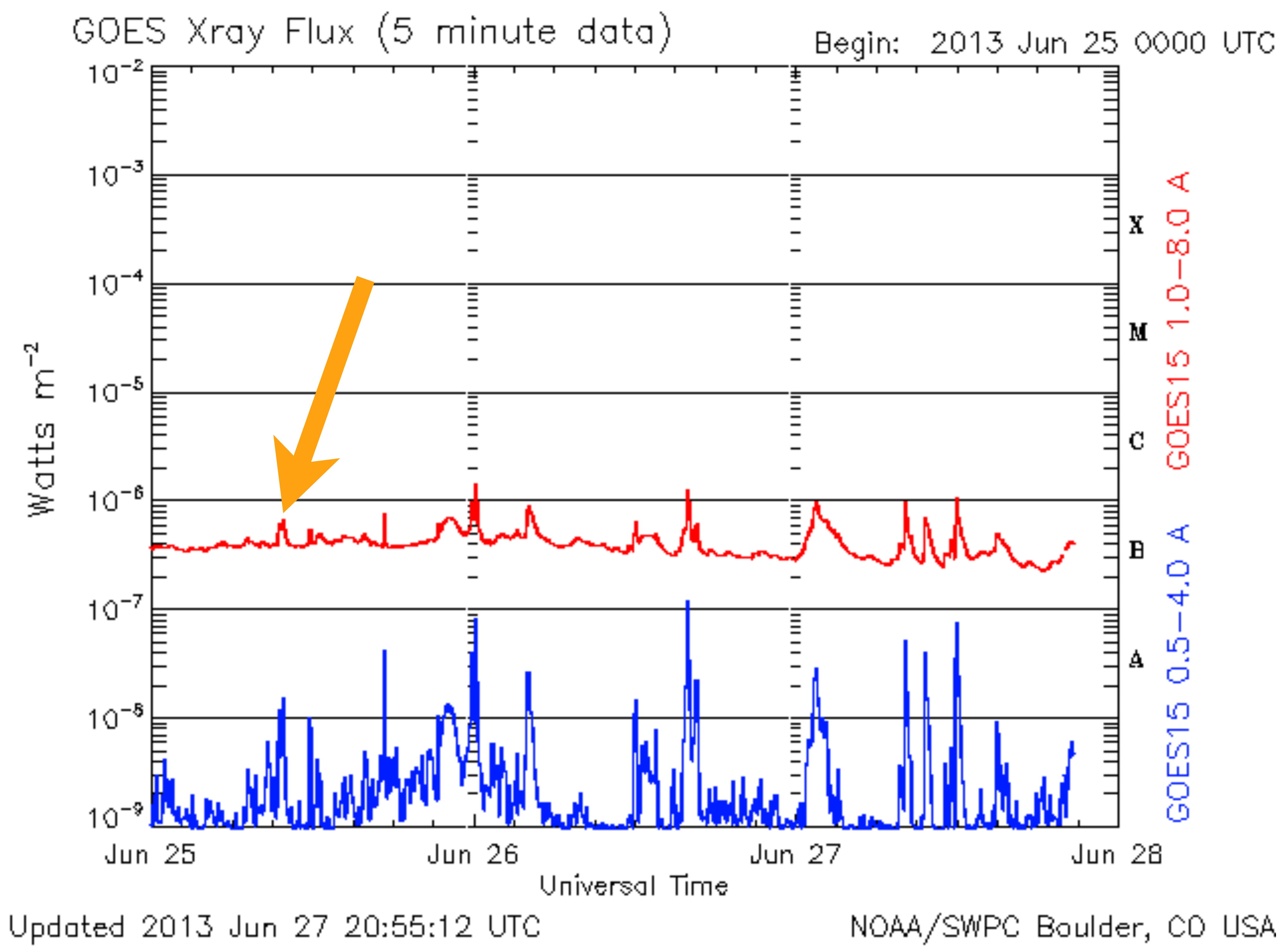
SDO/AIA 193Å 25-June-2013



Stealth CMEs occur with no associated flare

SDO/AIA 193Å Base difference movie 25-June-2013

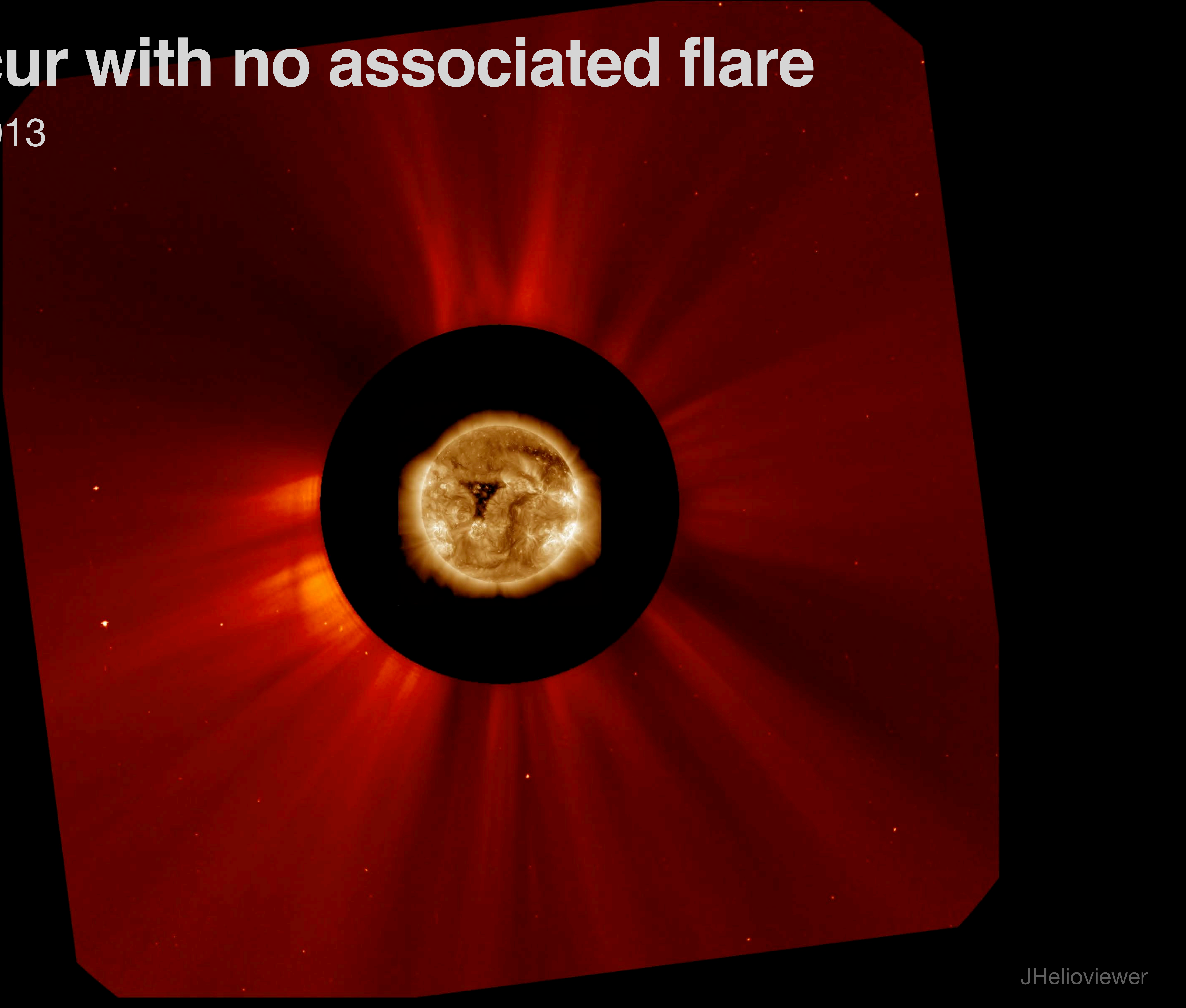




Stricter definition: CME detected *in-situ* with no solar coronal signature at all

Stealth CMEs occur with no associated flare

SOHO/LASCO C2 25-June-2013

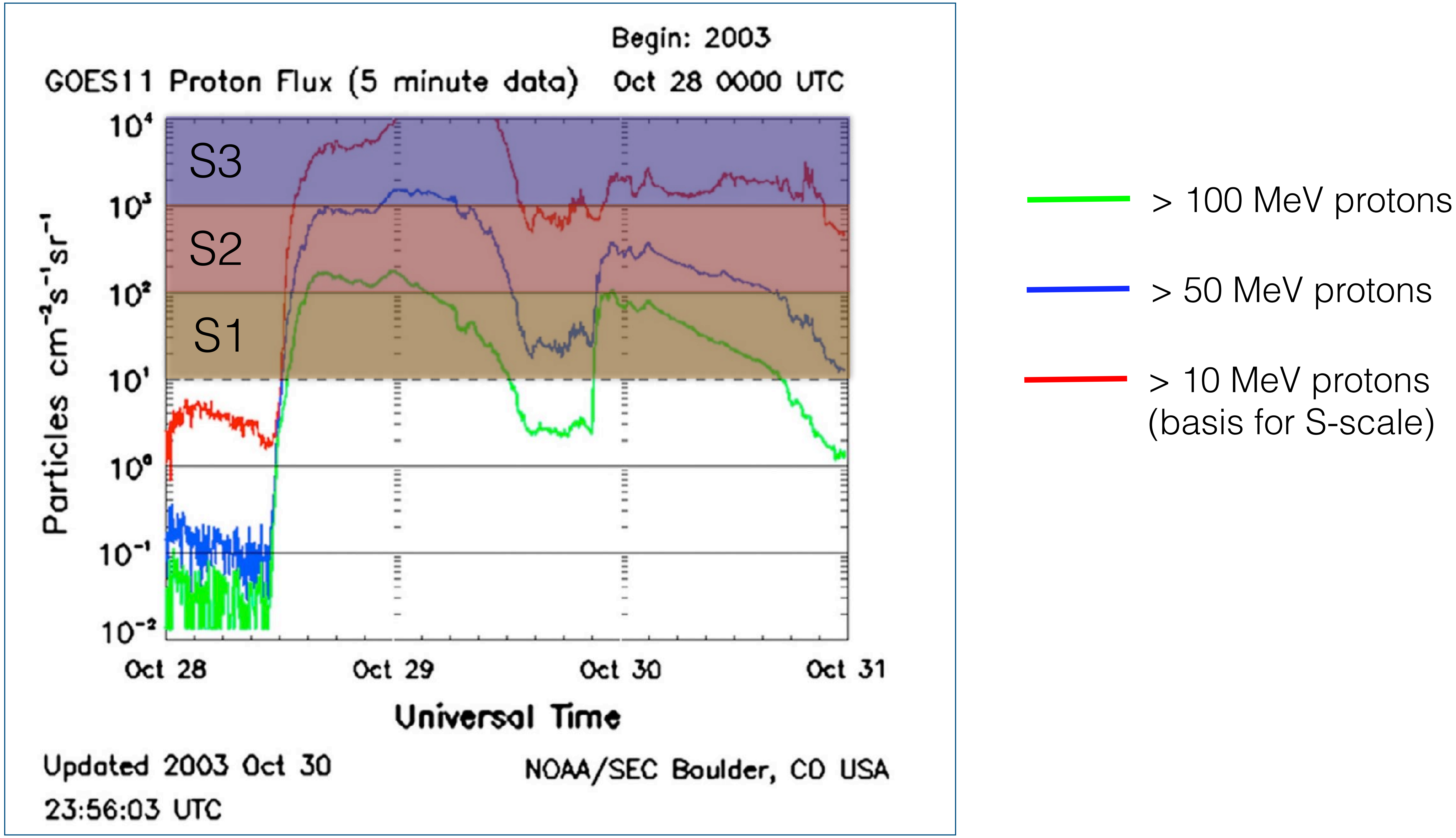


Solar Eruptions Cause “Solar Energetic Particle” (SEP) events

Also called “Radiation Storms” in operational forecasting

Radiation Storms are classified by their >10 MeV proton flux

Classified by the NOAA GOES/SEISS instrument suite

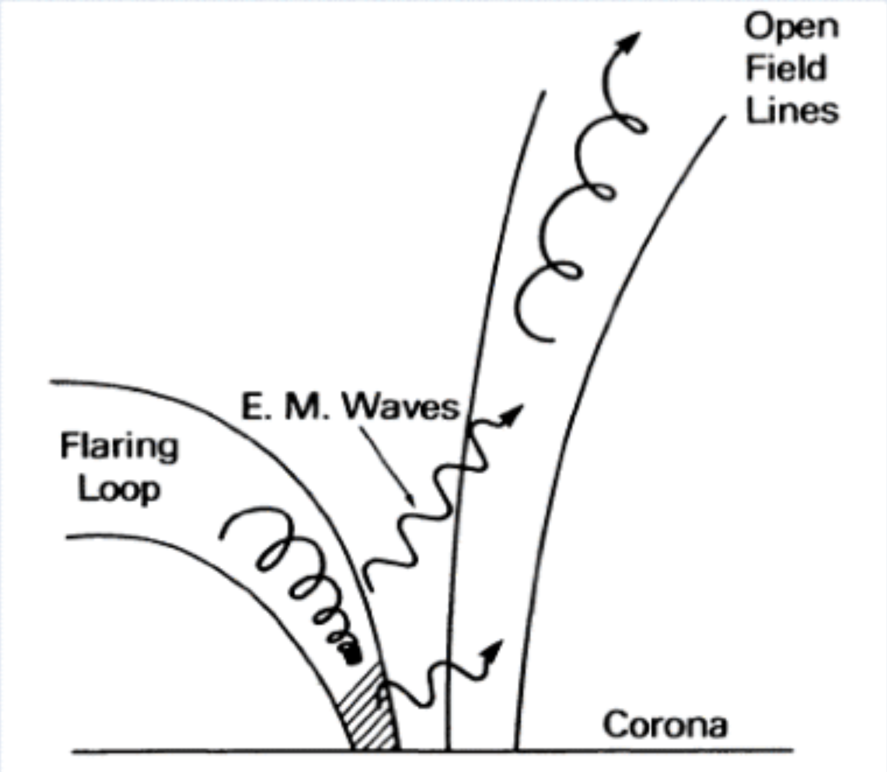


The 29-Oct-2003 **S4** storm is the largest radiation storm in the 21st century

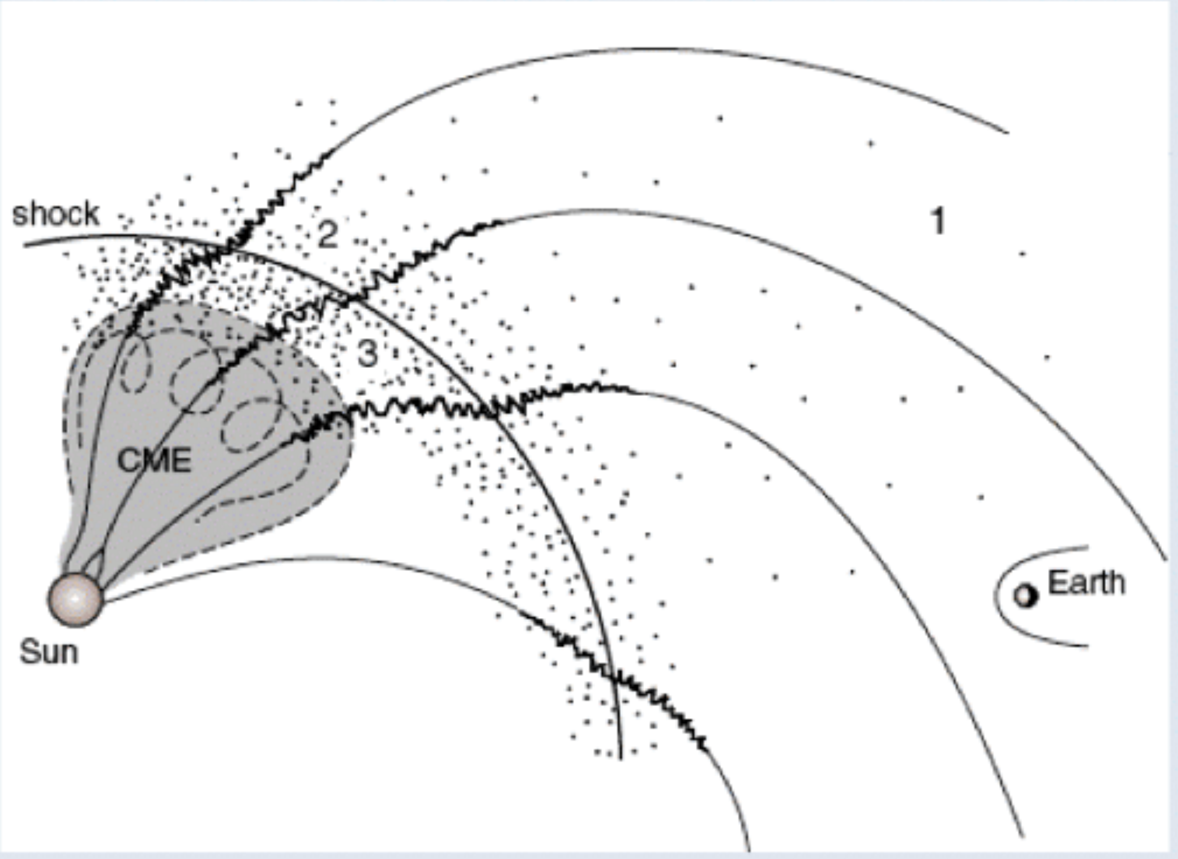
Two sources of SEP events

"Flare site" and CME acceleration

<table>
<tr><th></th><th>Impulsive SEPs</th><th>Gradual SEPs</th></tr>
<tr><td>Duration</td><td>minutes – hours</td><td>hours – days</td></tr>
<tr><td>Connection to Sun?</td><td>B-field connected
to flare site ± 10-20º</td><td>subtends > 180º of longitude!</td></tr>
<tr><td>Physics</td><td>connected to flares, jets, or "narrow" CMEs



</td><td>due to shocks ahead of large CMEs



</td></tr>
<tr><td>Element abundances</td><td>weird: lots of heavy metals;
$^3He > {^4He}$?!</td><td>similar to surrounding corona</td></tr>
<tr><td>Prefers to accelerate:</td><td>electrons</td><td>protons & ions</td></tr>
</table>

Can also create solar
neutrons and gamma rays

CME shock fronts accelerate charged particles

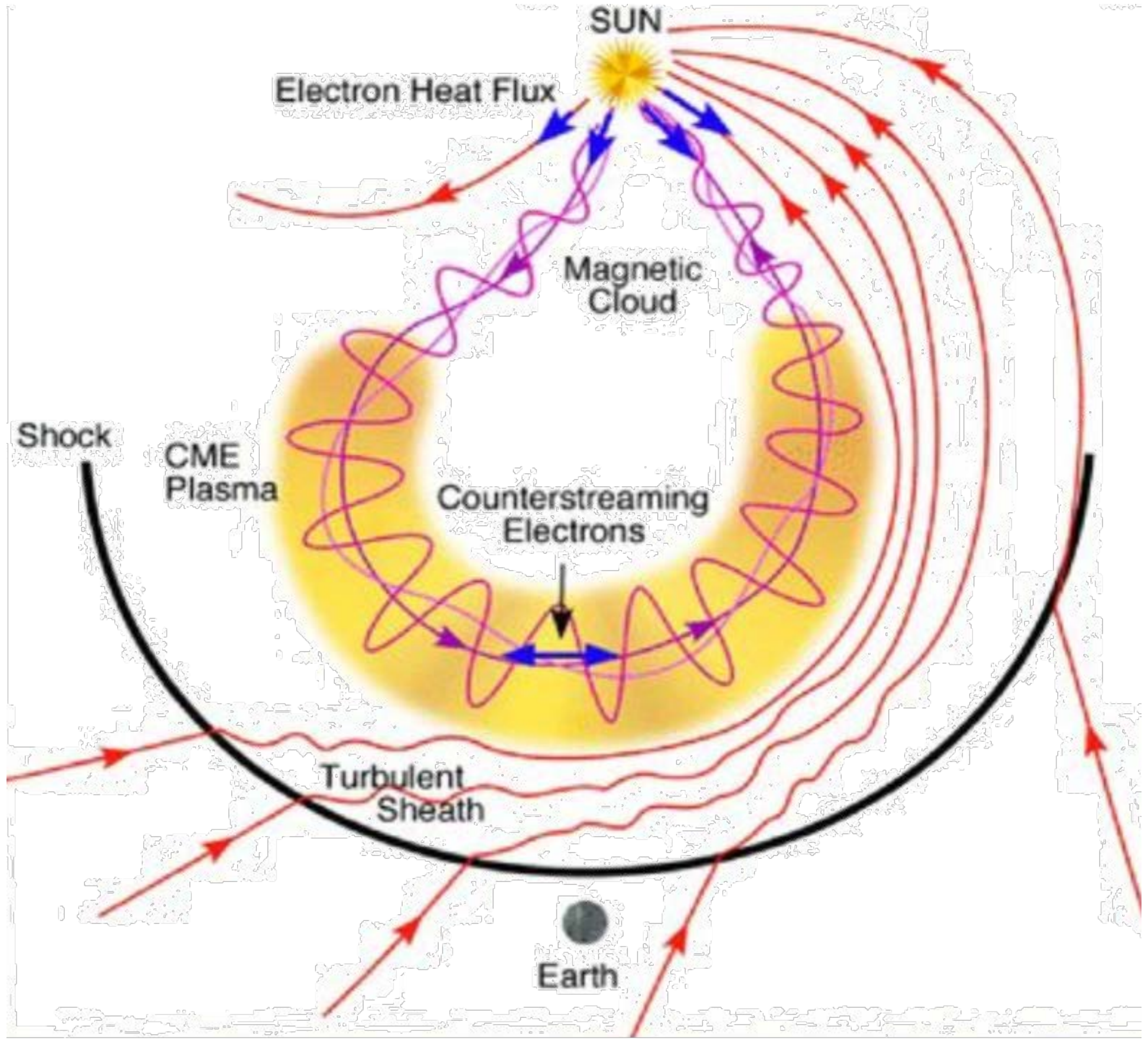
Fermi acceleration mechanism causes gradual SEP

- Many CMEs are accelerated sufficiently so they propagate out super-Alfvénically (more specifically, faster than the fast-mode wave speed).

- Thus, they eventually must form an **MHD shock** out in front of the flux rope.

- Typical shock-formation distances are around 5 to 10 solar radii, which agrees with the timing of when gradual SEP events seem to begin.

- But **how** do shocks accelerate particles up to MeV → GeV energies?

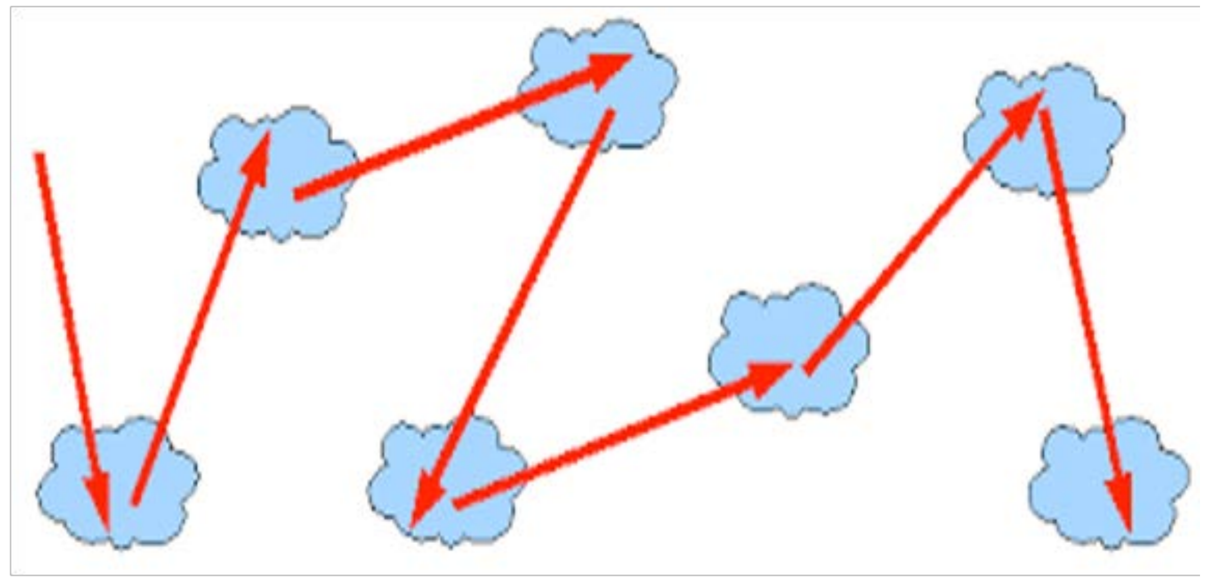


Several proposed mechanisms for particle acceleration

Shock-based and E field-based

- Fermi (1949) proposed a stochastic multiple-scattering effect in which particles are reflected from strong-B regions (like in a magnetic bottle).

  They gain energy in head-on collisions, and lose energy in trailing collisions, but there's a slight preponderance for the head-on ones (highway analogy: more oncoming cars pass by you every minute than you see pass you on your side). It's **too weak** an effect to really matter.



- Litvinenko (1996) proposed that the **E**-field at coronal reconnection sites (current sheets) can do the job straightforwardly:

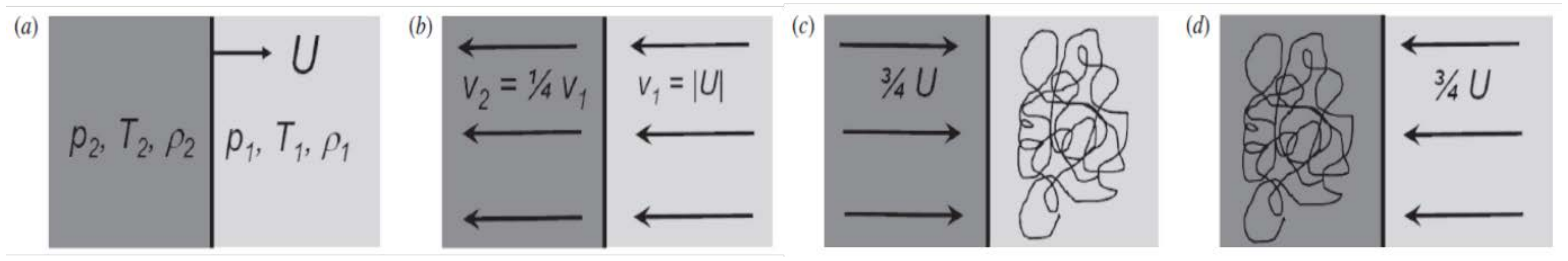
$$\frac{d}{dt}(\gamma m \mathbf{v}) = q\left(\mathbf{E} + \frac{\mathbf{v}\times\mathbf{B}}{c}\right)$$

- Bell (1978), Lee (2005), and many others proposed a more efficient version of **"diffusive" Fermi acceleration** that is efficient when near an MHD shock.

Diffusive Fermi Acceleration

Bell(1978), Lee(2005), and others

- Shocks are defined by there being mass that flows through them.
- Consider a shock that propagates out from the Sun with velocity *U:*



- (a) Sun's inertial frame, (b) reference frame of the shock, (c) frame of upstream (light gray) gas, (d) frame of downstream (dark gray) gas.
- When crossing the shock from **either** side, a particle sees the plasma moving toward it at a velocity of 0.75*U.*
- If the **B**-field is *oblique* to the shock normal, a particle's gyro-orbit can take it back and forth across the shock many times. **It gains energy after every crossing.**

Diffusive Fermi Acceleration

Details leading to SEP events

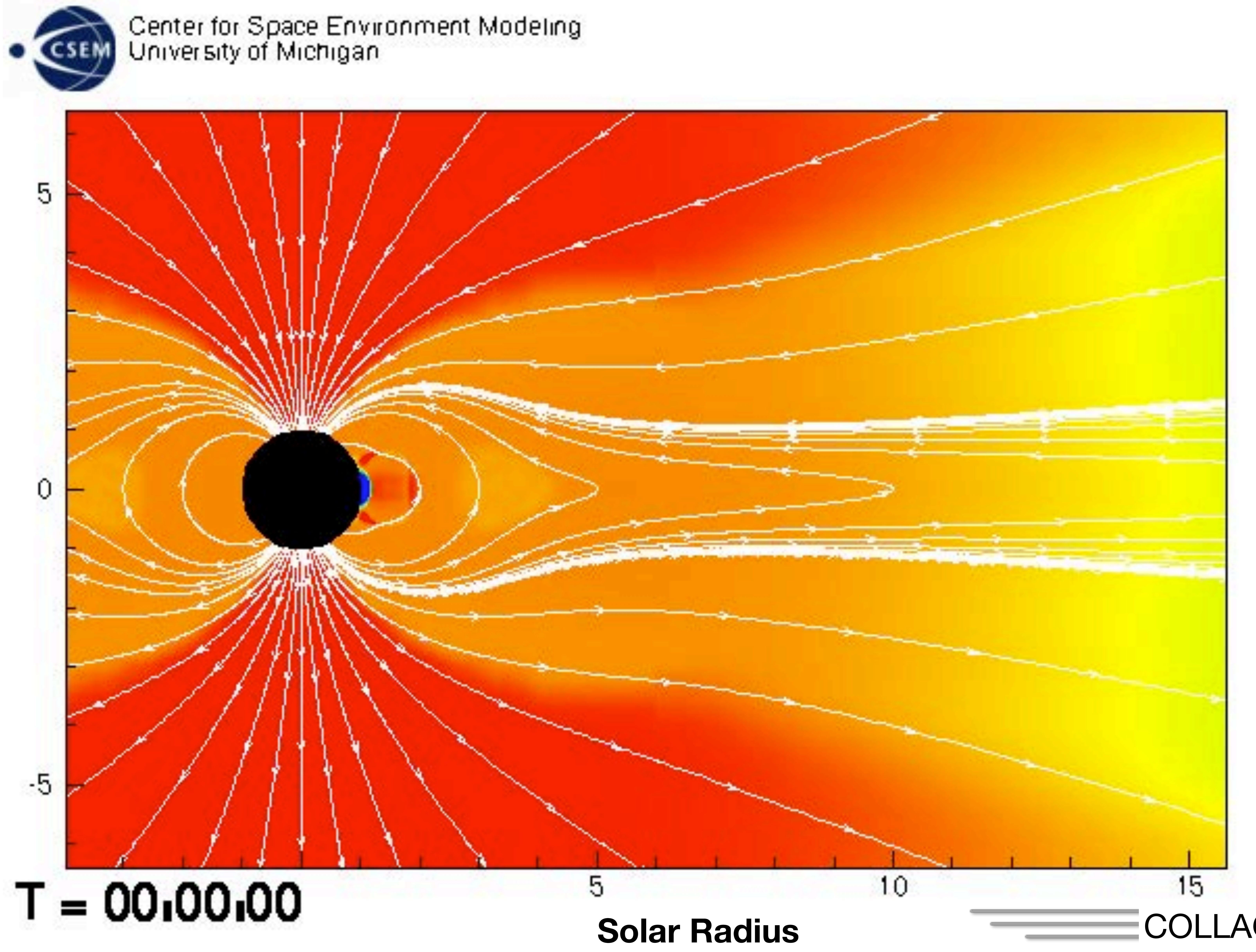
- Some particles end up escaping the shock to propagate ahead of it.
- The observed energy spectrum & absolute number of **escaping SEPs** depend on many details of the shock:
  - Where it forms in the corona.
  - Speed, shock strength, and Mach number:

$$r = \frac{\rho_2}{\rho_1} \quad \Rightarrow \quad \alpha = \frac{r+2}{2r-2} \quad \Rightarrow \quad P(E) \propto E^{-\alpha}$$

  - Its finite spatial extent in other directions.
  - The presence of waves/turbulence in the vicinity of the shock.
  - Properties of the low-energy (thermal & slightly supra-thermal) part of the particle distribution function.
    - This last issue is key: there must be enough "**seed particles**" to bootstrap the process. This may be why "one-two-punch" CMEs can make so many SEPs.

CME propagation through interplanetary space

Ideal MHD model of large CME propagation to Earth



CME propagation through IP space: complexity reigns

STEREO-A HI instrument 22—25 June 2013

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Reading for next week

Koskinen et al., “Achievements and Challenges in the Science of Space Weather”, Space Sci. Review, **212**, 1137, 2017

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