AST5770

Solar and stellar physics

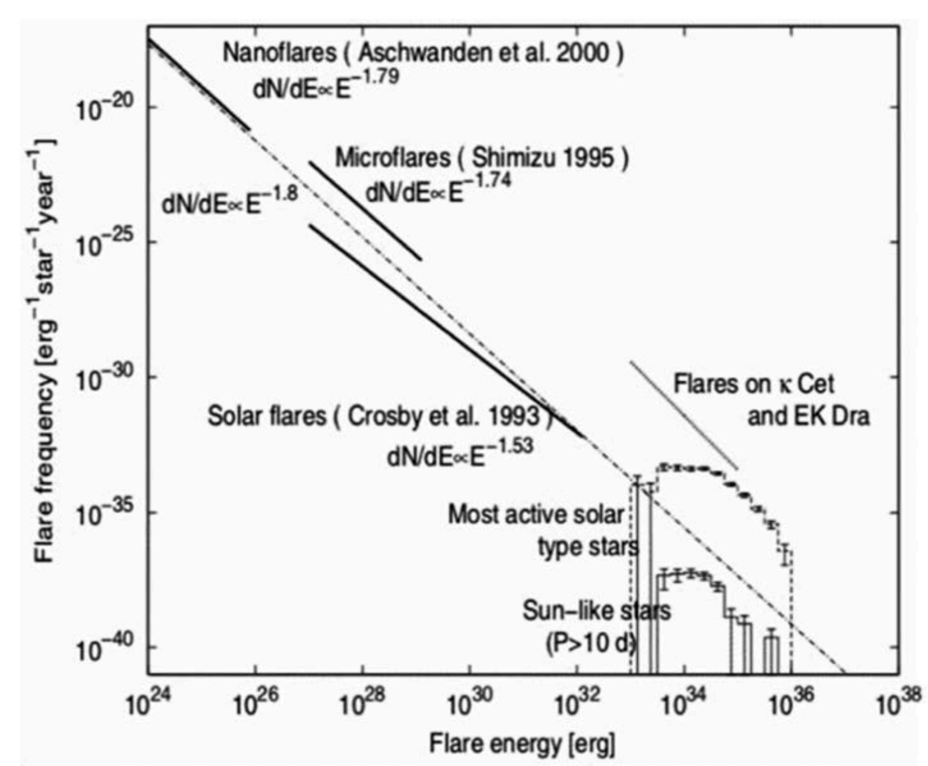
Sven Wedemeyer, University of Oslo, 2023

Solar/Stellar flares

Recap

Credits: NASA's Goddard Space Flight Center/S. Wiessinger

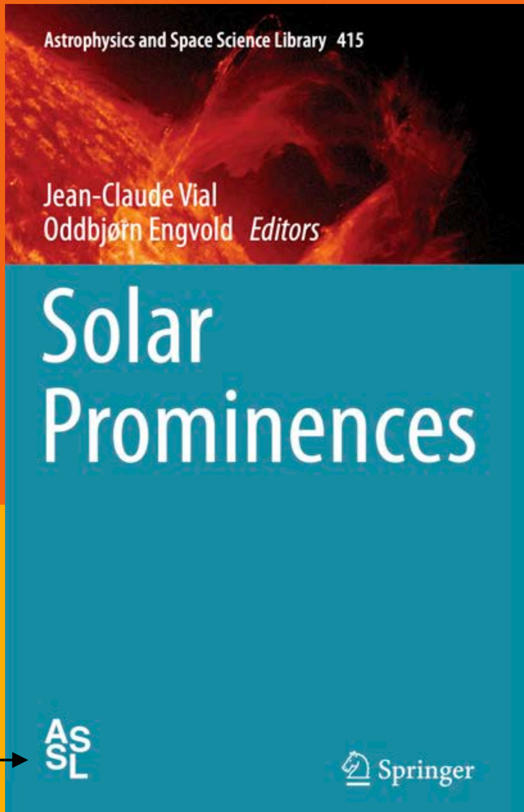
1. The occurrence rate of solar flares seems to vary in line with the solar cycle. Why is that?
2. A flare as a result of magnetic reconnection is a scalable phenomenon. What are the smallest flares called and where do they occur?
3. Why are these tiny flares of particular interest?
4. We observe superflares on other stars. How often do we expect to see such a Carrington-event-like flare to occur on the Sun?
5. Which stars are particularly known for megaflares?
6. On these stars, how much does the brightness of the whole star change during a megaflare?
7. Do you remember the flare class for this extreme flare on DG CVn (the red dwarf star shown in one of the movies last time)? How much stronger is that compared to strong flares observed on the Sun?



Aschwanden & Parnell (2002)

Filaments
Prominences
CMEs

Further reading:
Gibson (2018)
Parenti (2014)
Vial & Engvold (2015)

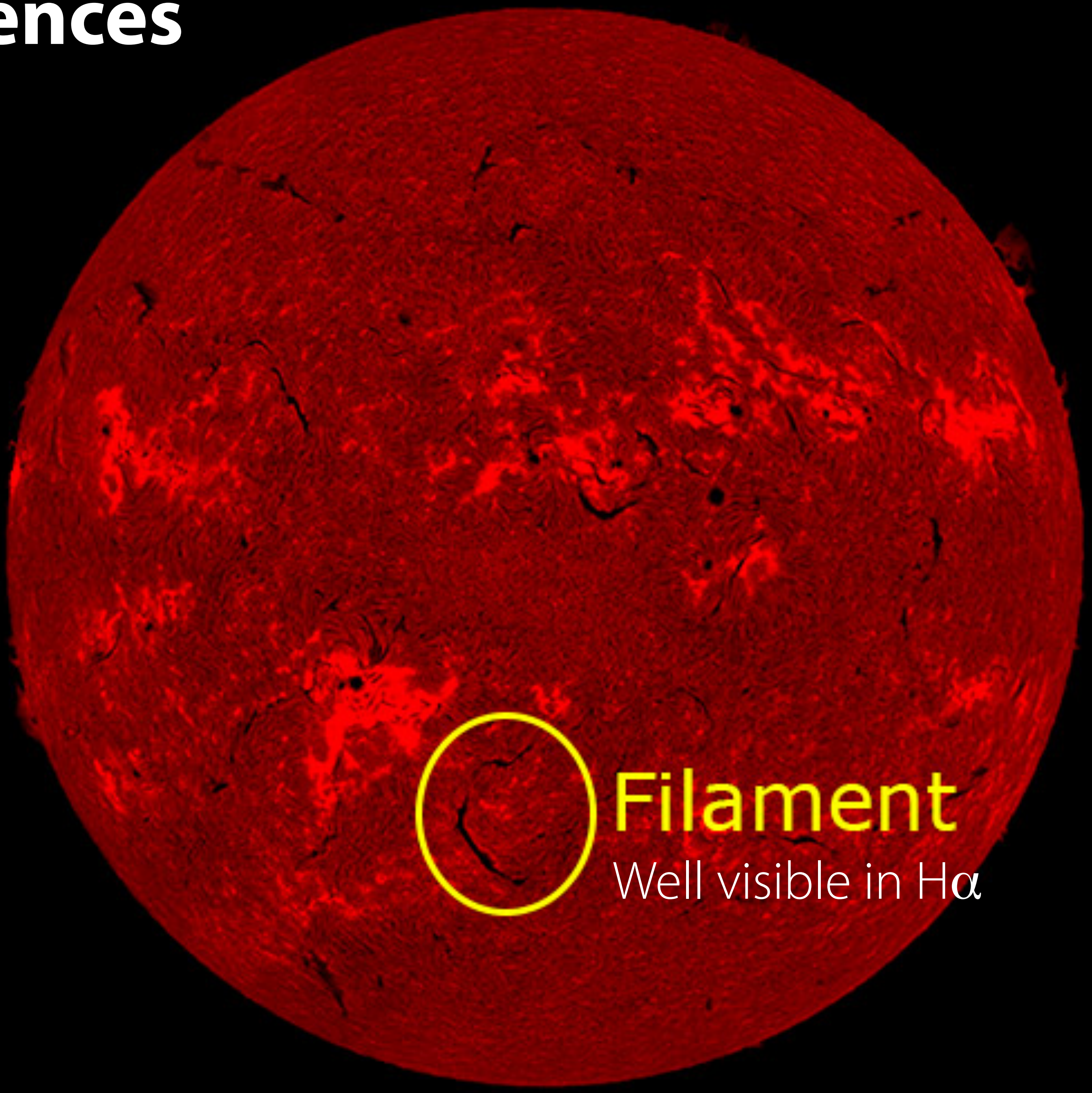


Filaments and prominences

Solar filaments vs. Prominences

Filament:

- Known since systematic H-alpha observations started over a century ago.
- Huge arcs of plasma appear dark against bright background on solar disk
- Cooler and denser than surroundings and atmosphere below
- Filaments held in place by magnetic fields
- Filaments can last for several days - or sometimes up to months!
- Most common around solar maximum

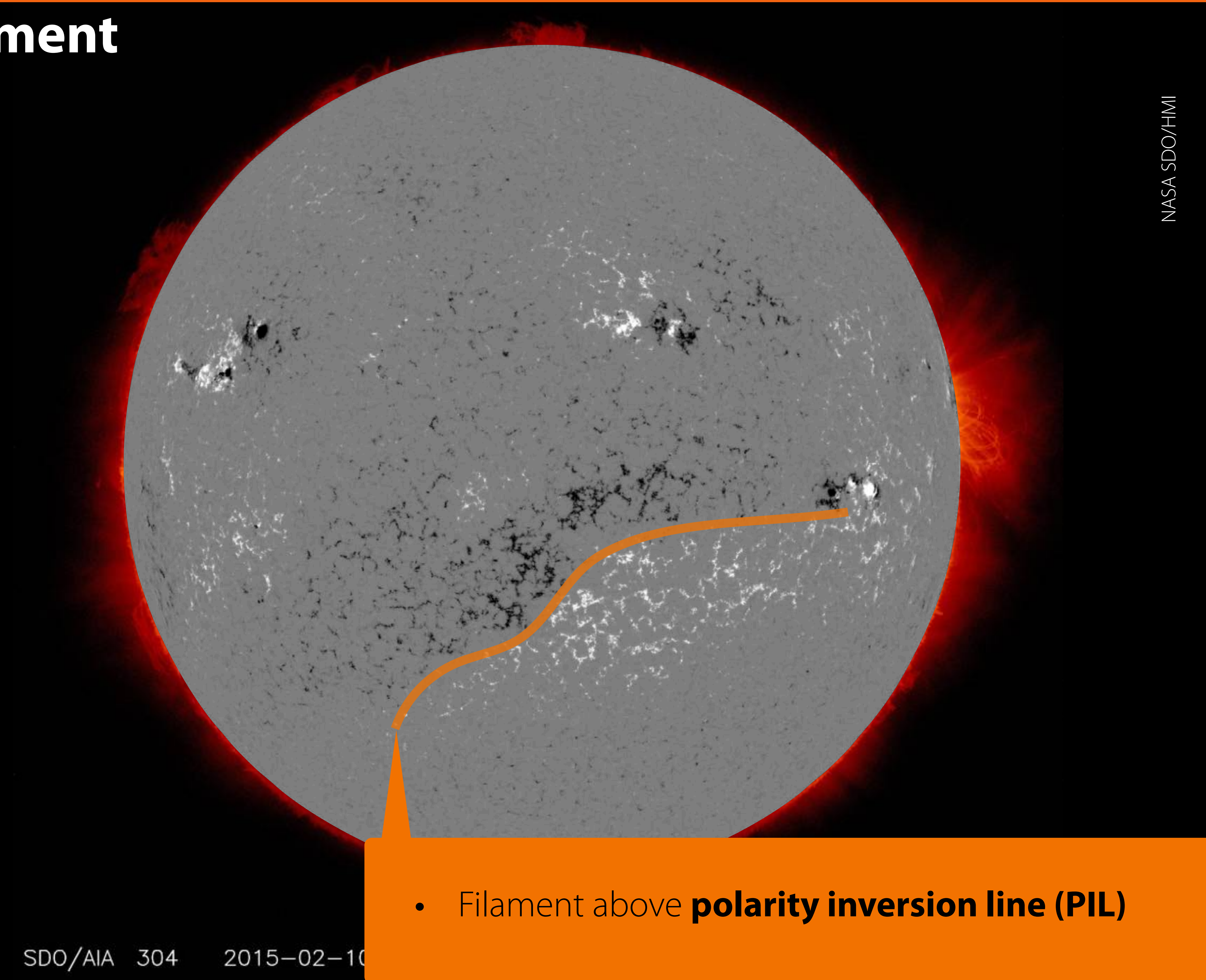


Big Bear Solar Observatory

- **Types:**
  - **Active Region Filament**: in / near an active region (multiple bipolar pairs of sunspots, neutural line filaments).
  - **Intermediate filaments** (at the border of active regions)
  - **Quiet Region Filament** (polar crown, hedgerow, curtains, floating arches, arcs, fans, etc.)

Filaments and prominences

Giant filament

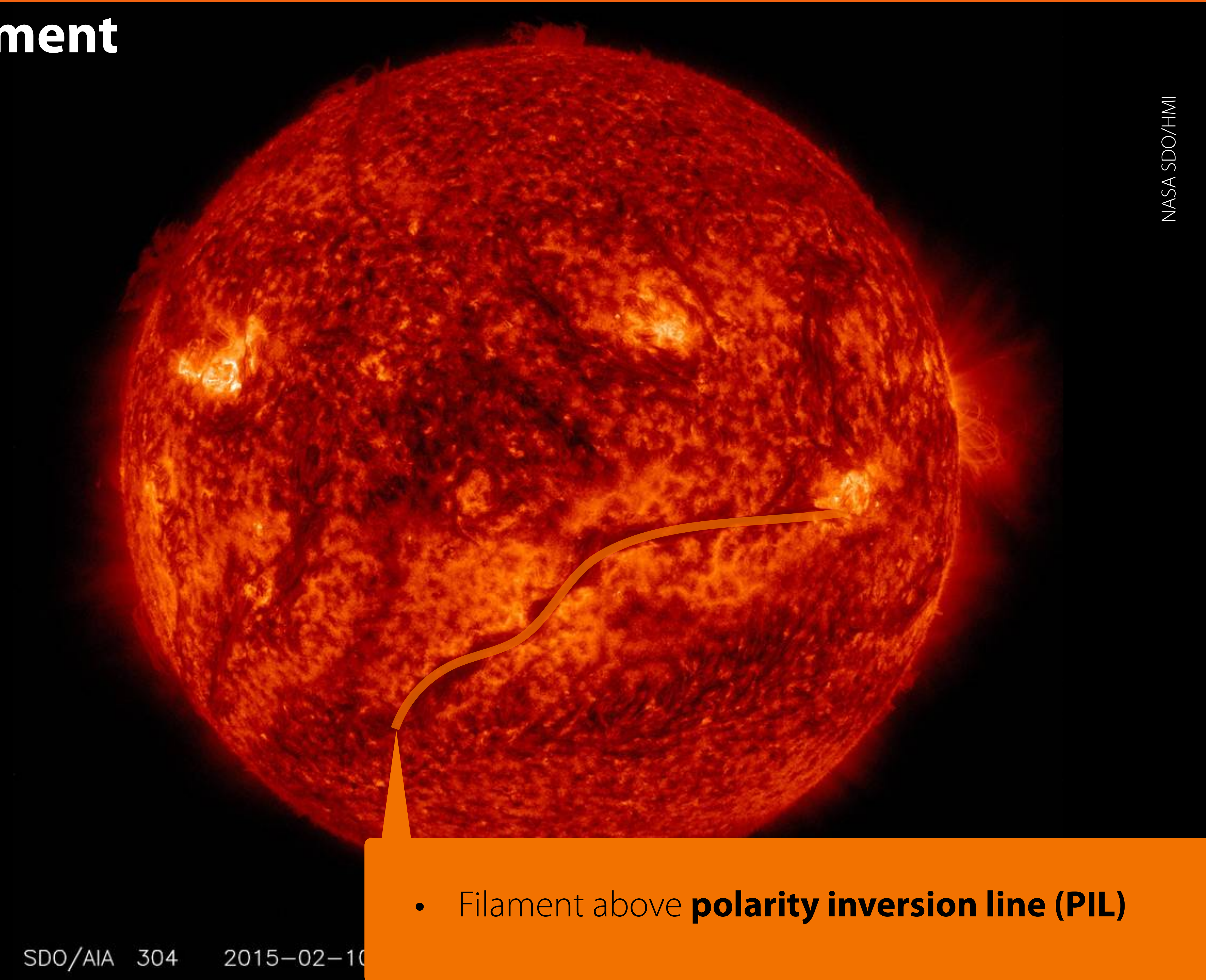


NASA SDO/HMI

- Filament above **polarity inversion line (PIL)**

Filaments and prominences

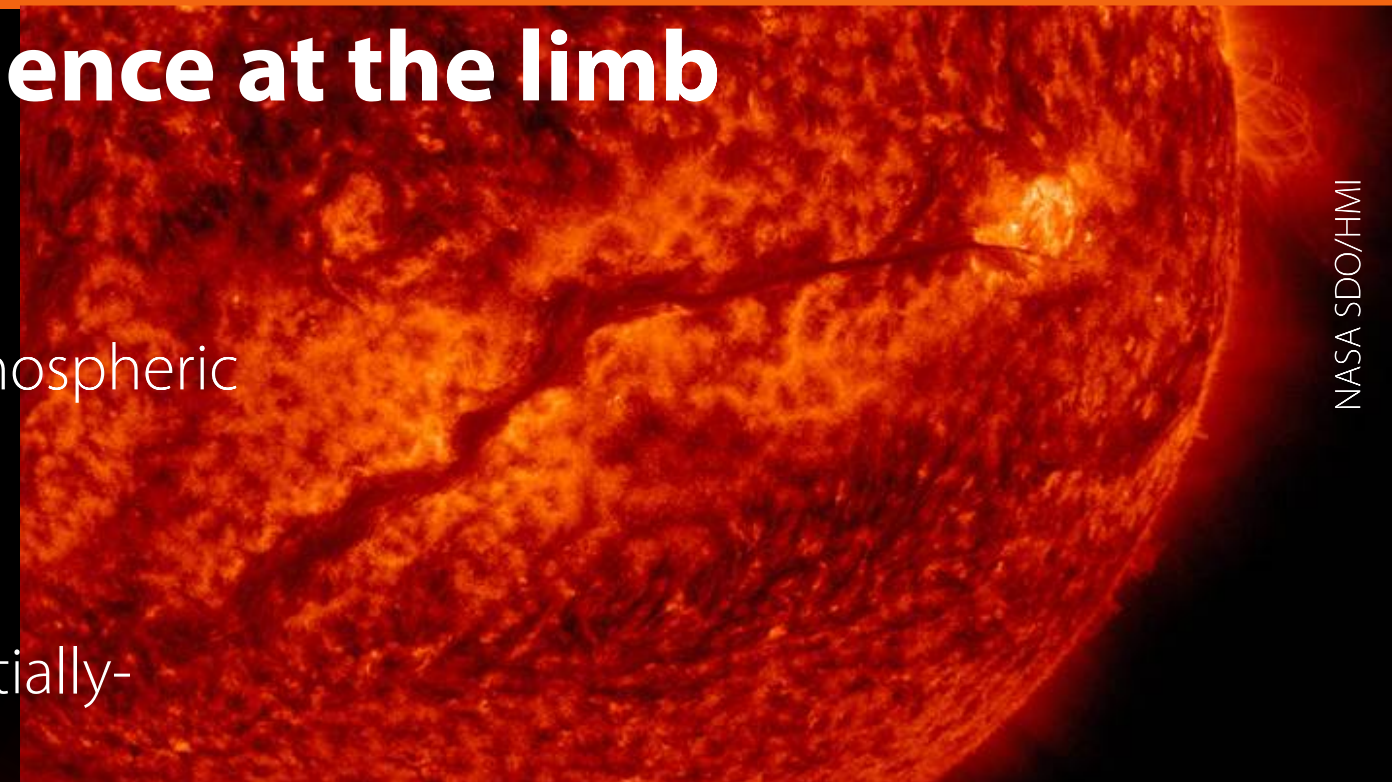
Giant filament



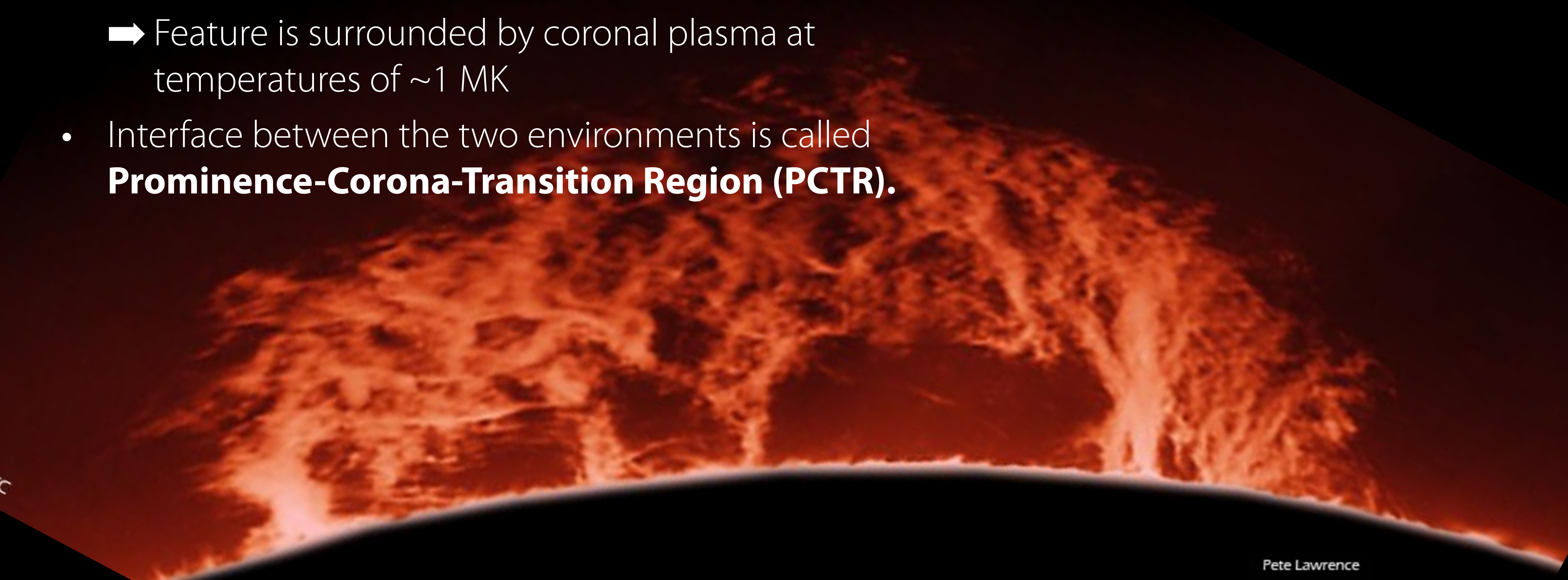
- Filament above **polarity inversion line (PIL)**

Filaments and prominences

Filament on disk — prominence at the limb



- **Prominences:** Same as filaments but seen sideways above the limb of the Sun
- Plasma in prominences/filaments at chromospheric temperatures ($7000 \leq T \leq 20\,000$ K).
- Denser than surrounding atmosphere.
  ➡ prominence/filament core made of partially-ionized plasma,
  ➡ Feature is surrounded by coronal plasma at temperatures of ~1 MK
- Interface between the two environments is called **Prominence-Corona-Transition Region (PCTR).**



Filaments and prominences

Prominences

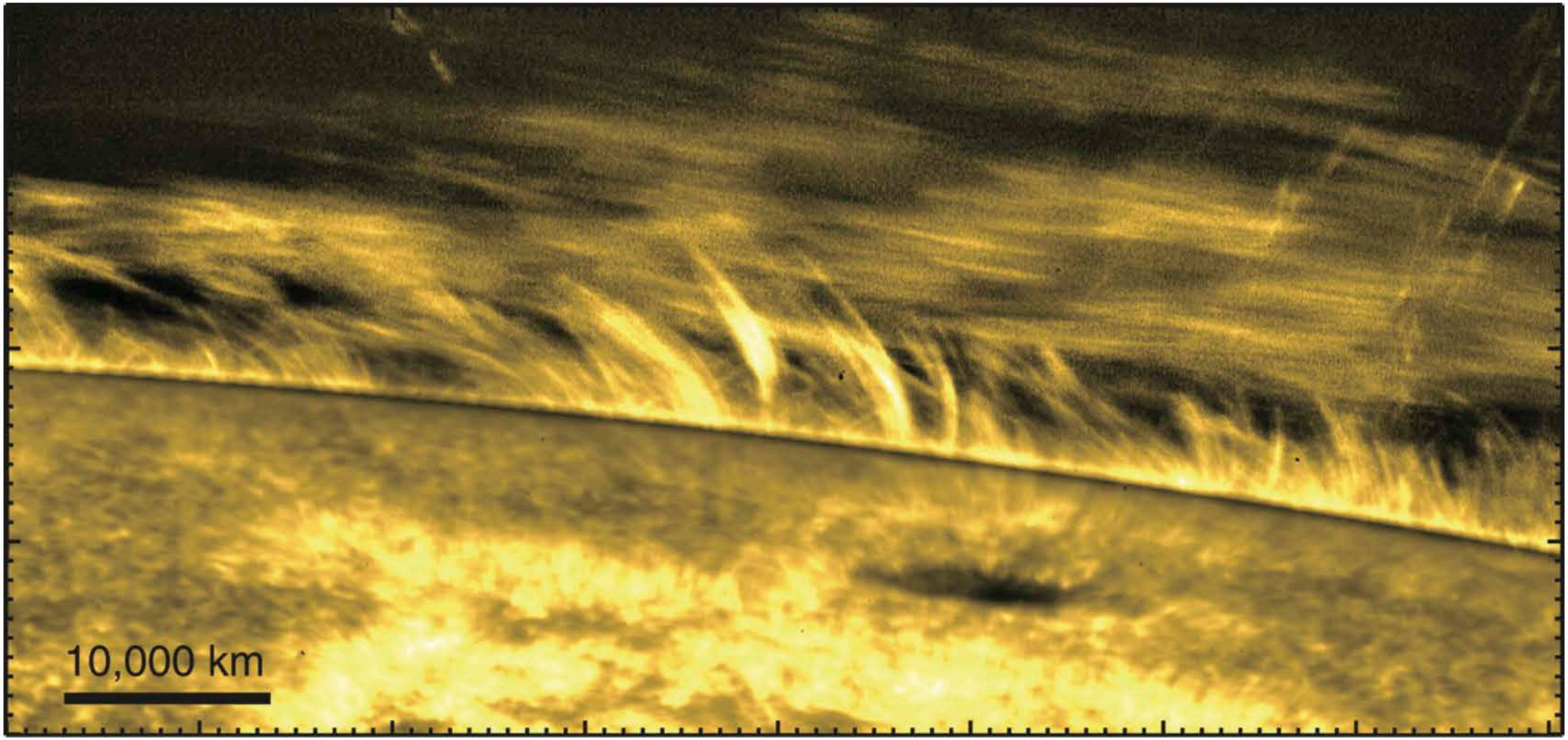
- Filament: Visible (not always) in absorption when observed in surroundings at coronal temperatures
- High density + low temperature:
  ➡ Plasma optically thick at certain wavelengths (e.g., most of the hydrogen and helium resonance lines and continua).
  ➡ Filaments appear darker than the surrounding quiet Sun when observed on disk, e.g. in Hα 6562.8 A or in He II 304 A
- Prominence: Plasma seen against dark and cold space in background
  ➡ Prominence appears in emission

Filaments and prominences

Prominences

Prominences: Same as filaments but seen sideways above the limb of the Sun

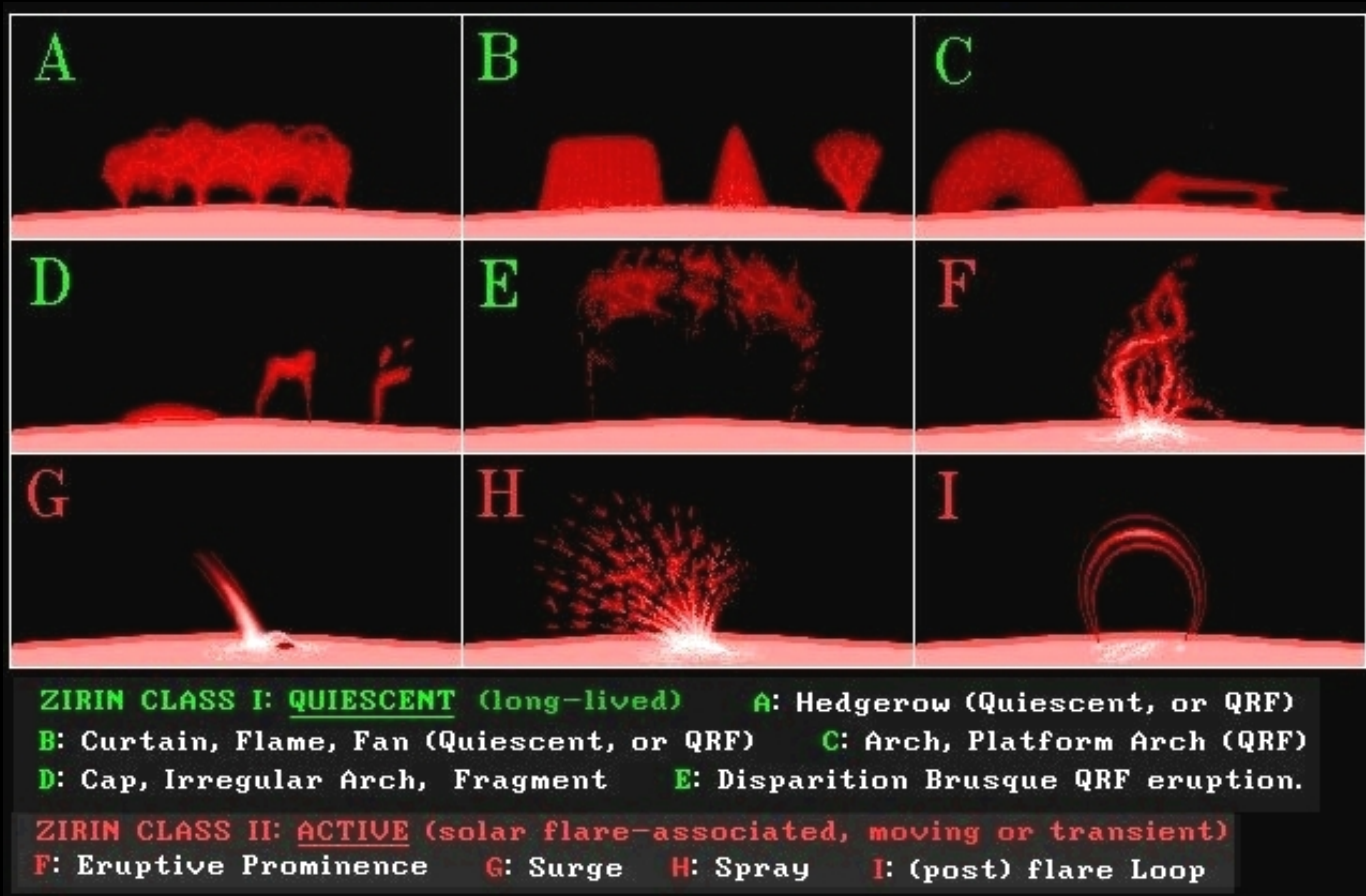
- Appear bright as they are hotter than the cool background (space)



High-resolution image on the solar limb obtained with Hinode/SOT Ca II H-line 3968 Å. Image reproduced by permission from Okamoto *et al.* (2007); copyright by AAAS.

Filaments and prominences

Prominences

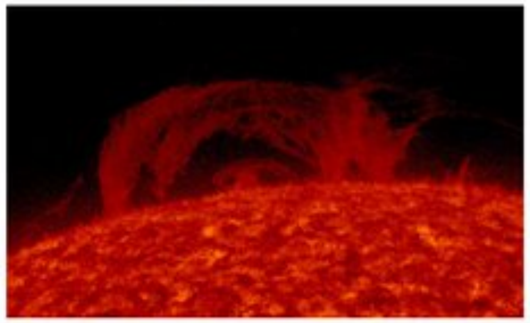


Zirin

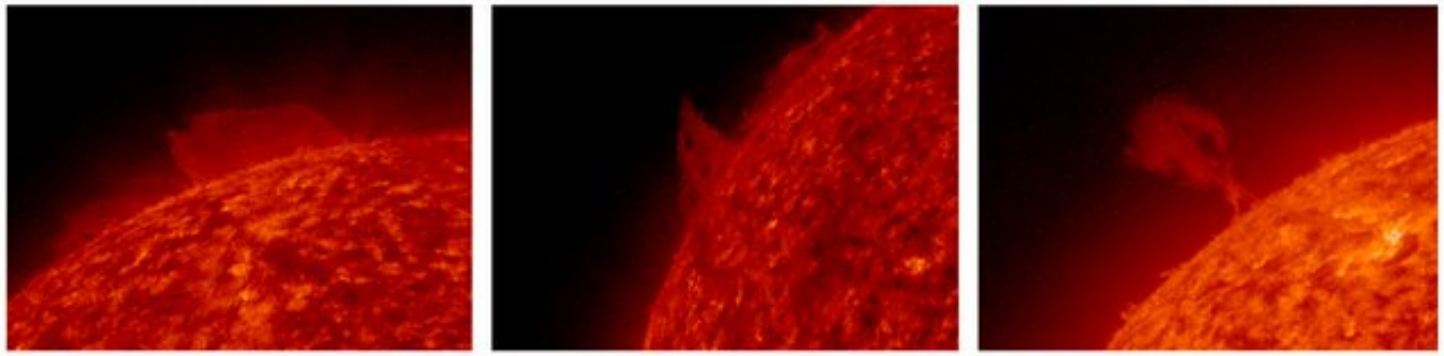
Filaments and prominences

Class I (quiescent, long lived)

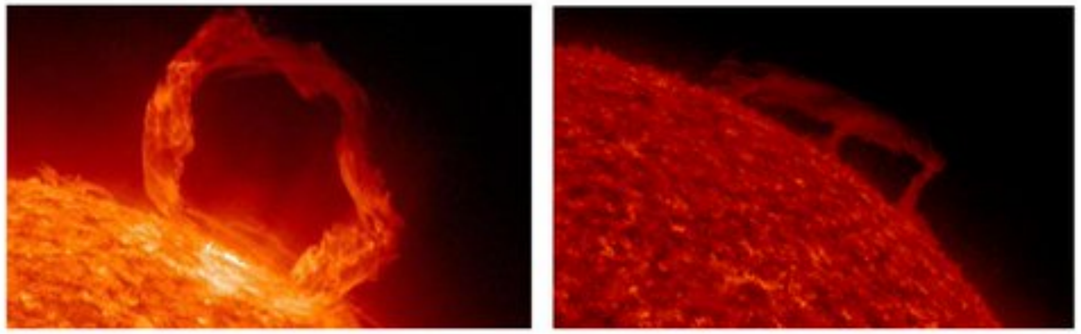
A: hedgerow



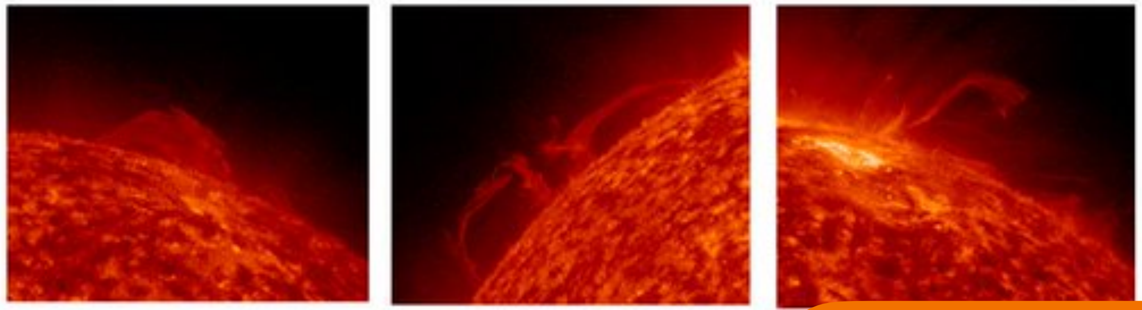
B: curtain, flame, fan



C: arch, platform arch

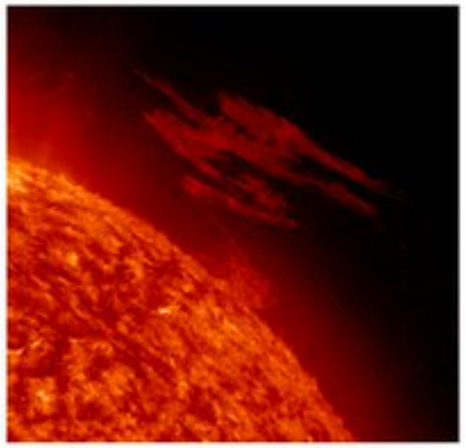


D: cap, irregular arch, fragment



Ascending prominence (end of the quiescent phase), “Disparition Brusque”: (“lifting off”) eruption.

E: detached disparition brusque

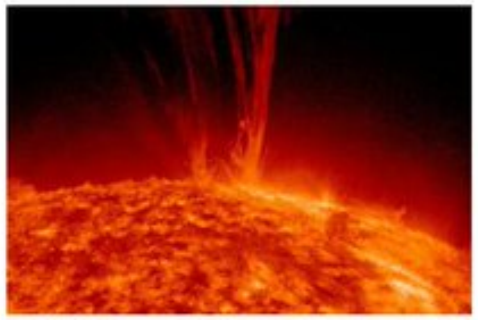


Class II (active, moving or transient)

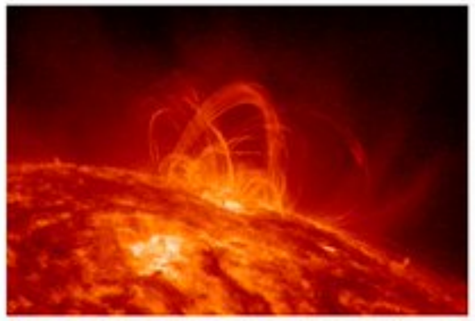
F: eruptive prominence

G: surge

H: spray



I: flare loop



Filaments and prominences

Dimensions and properties

- Typical dimensions:
  - thickness: ~5 Mm
  - height: ~26 Mm (up to 50 Mm)
  - length: ~50 Mm (up to 200 Mm, especially quiescent filaments)

- Long and thin

- Temperature in a prominence ≈ 10^4 K = 1/100 than in the surrounding corona,
  ➡ Lateral pressure equilibrium
  ➡ Density in prominence ~100 times the coronal density!
  - Transition from coronal background to prominence material under research
- Most prominences occur below a latitude of 60°
- 80% show no obvious motion (Wang et al. 2010).
- Many quiescent filaments exhibit morphological asymmetry
- Quiescent filaments can become very long and last for one or more solar rotation!

- How to explain the observed structures so that they obey MHD force balance? (Needed for keeping the structure stable for so long!)

Filaments and prominences

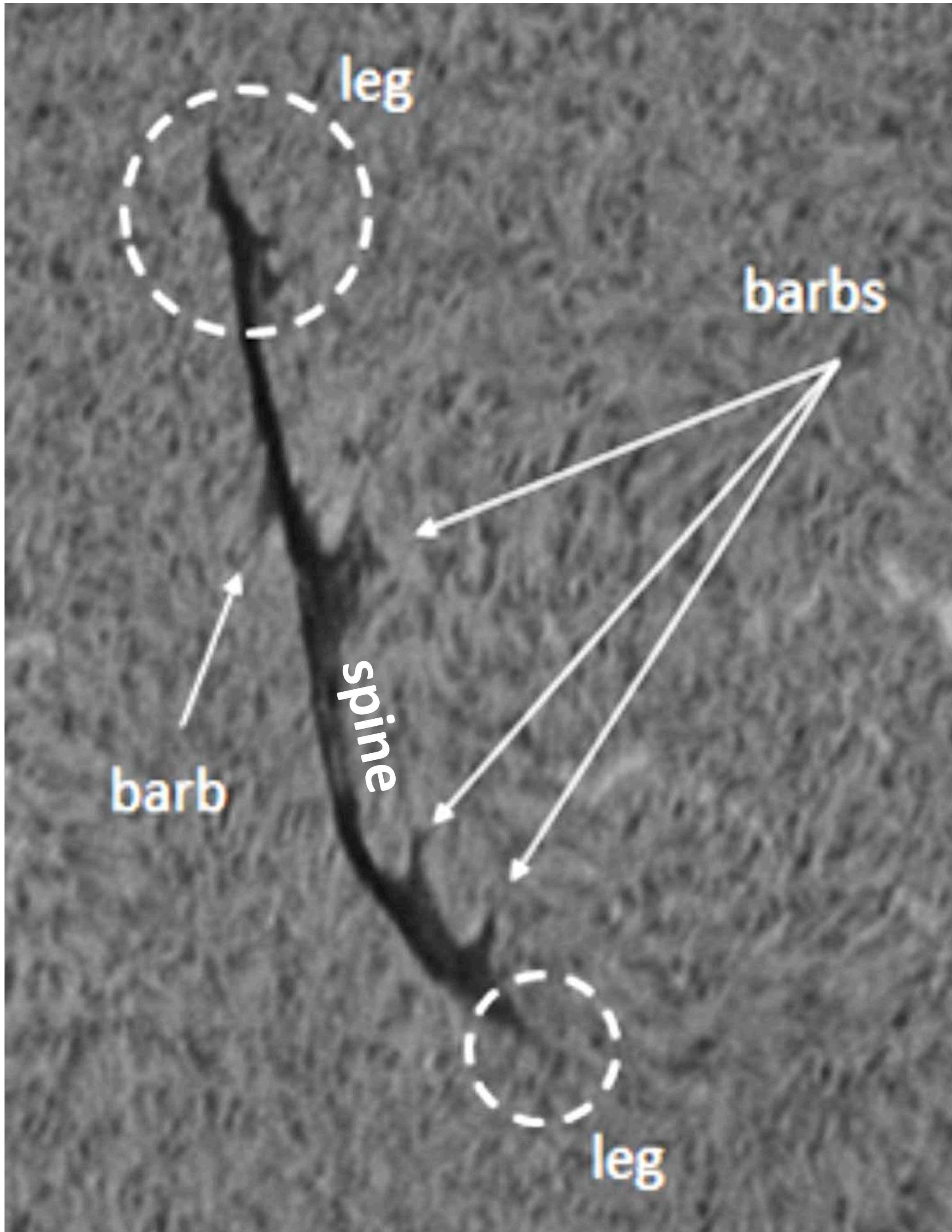
“Anatomy” of filaments and prominences

- Filament consists of a spine, legs, and barbs
  (names given a long time ago…)

- **Spine**: long, very thin, darkish filament feature.
  - Long and thin (in models sometimes referred to as "slab".

- **Legs:** Ends of the spine, can be one or multiple end points

- **Barbs:** Lateral extensions from spine



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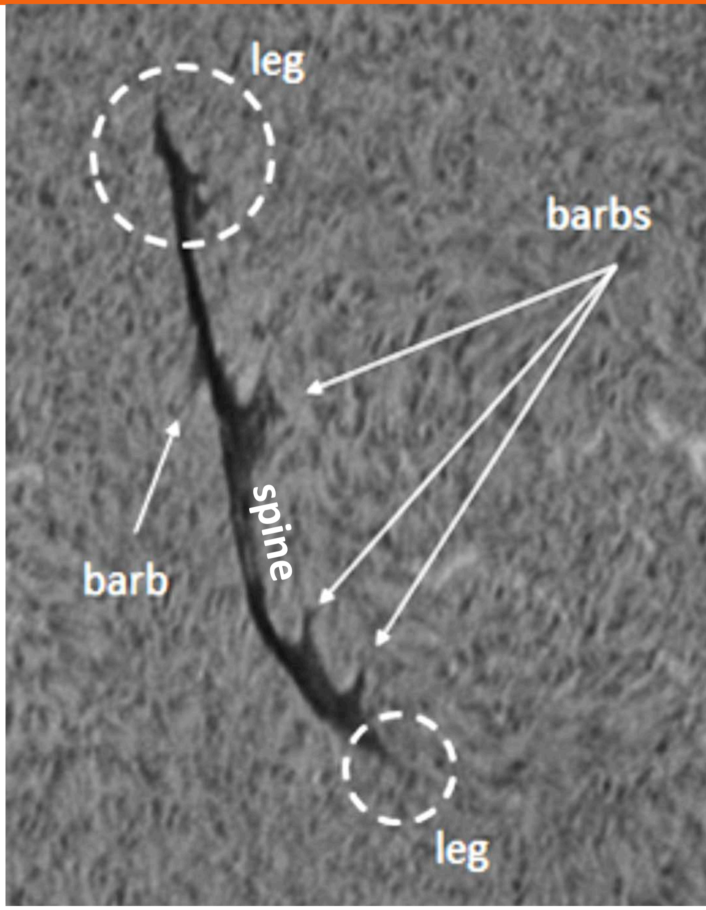

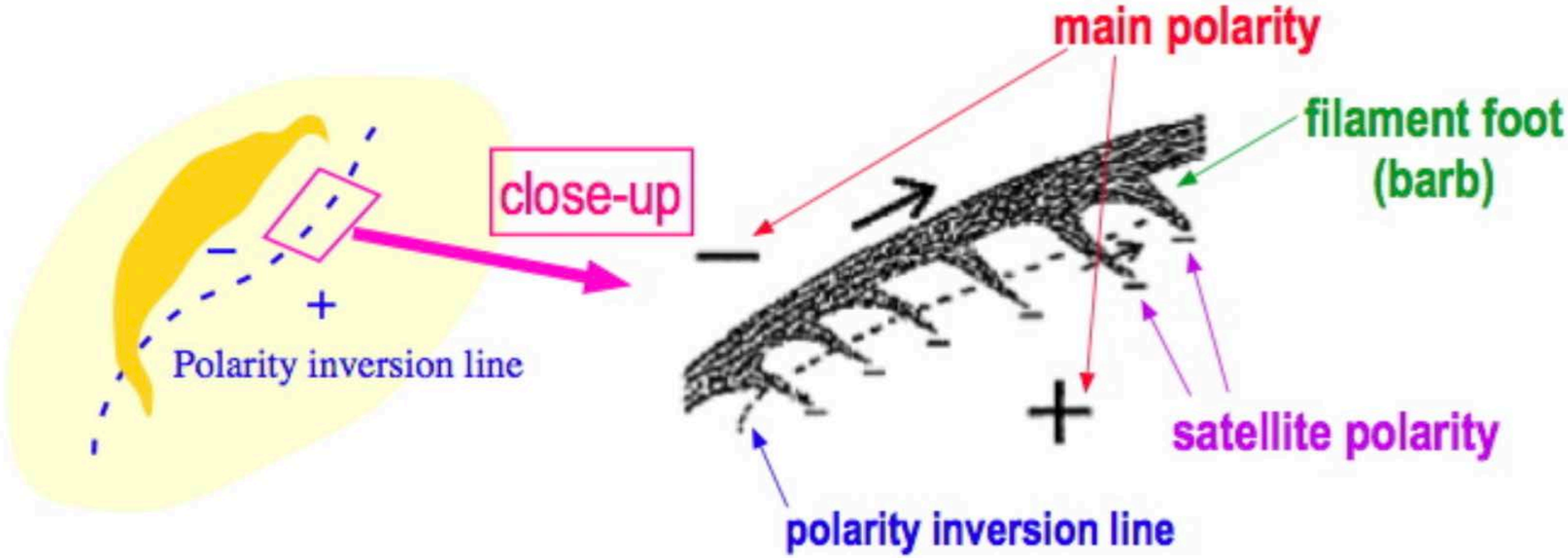

Martin (1998), Chae et al. (2001)

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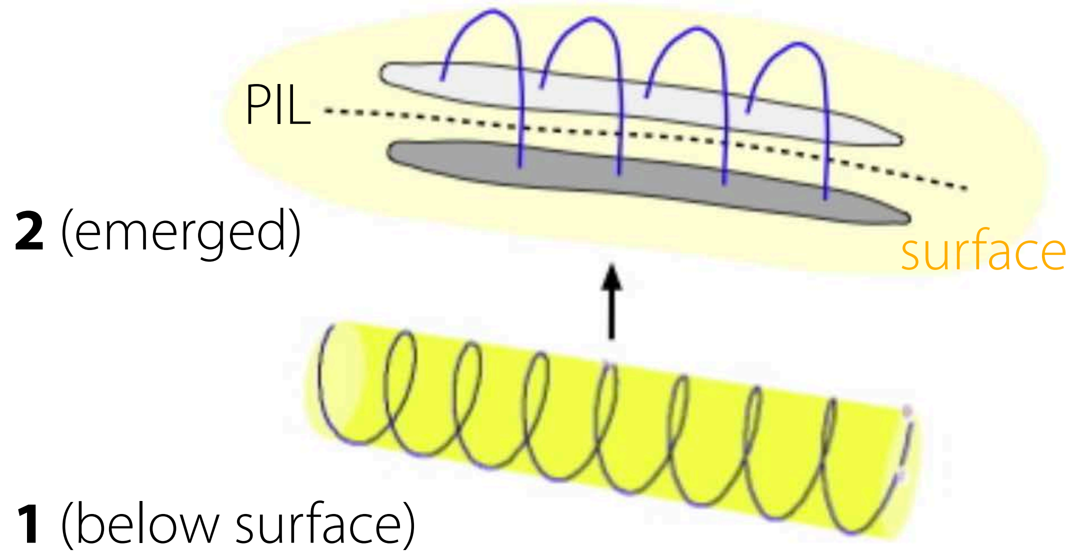
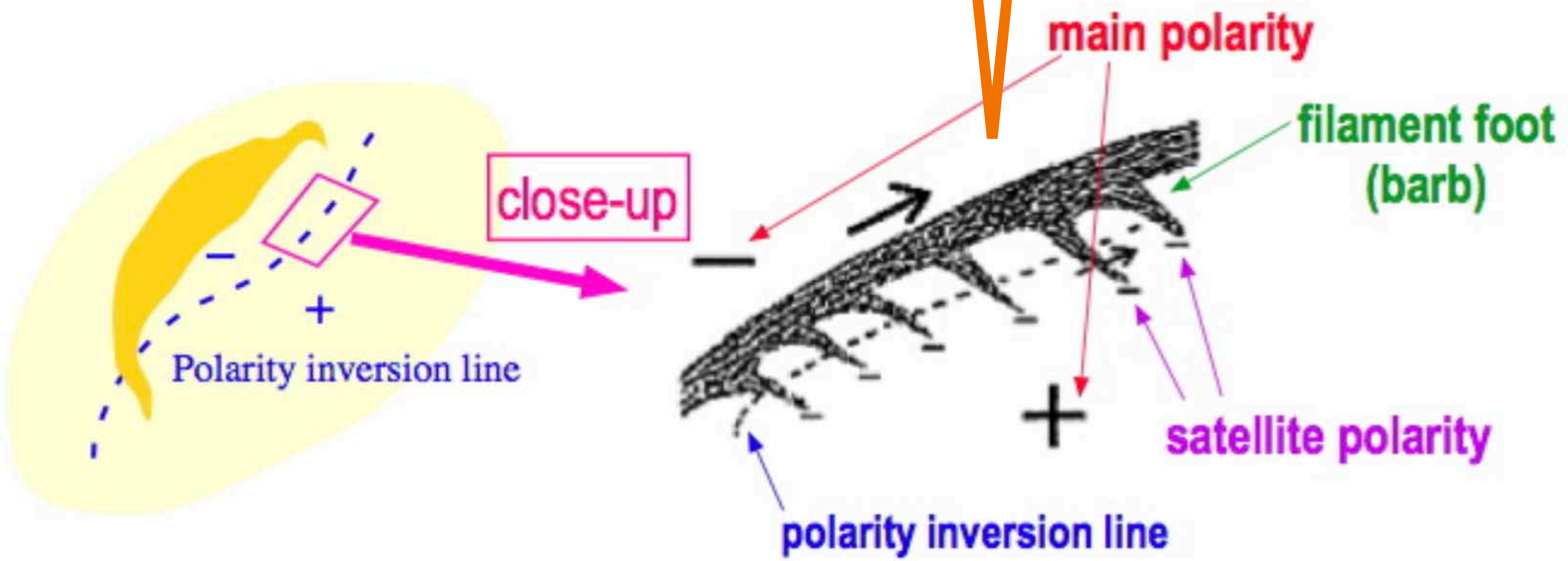
Formed by emergence of a twisted flux structure through "solar surface"



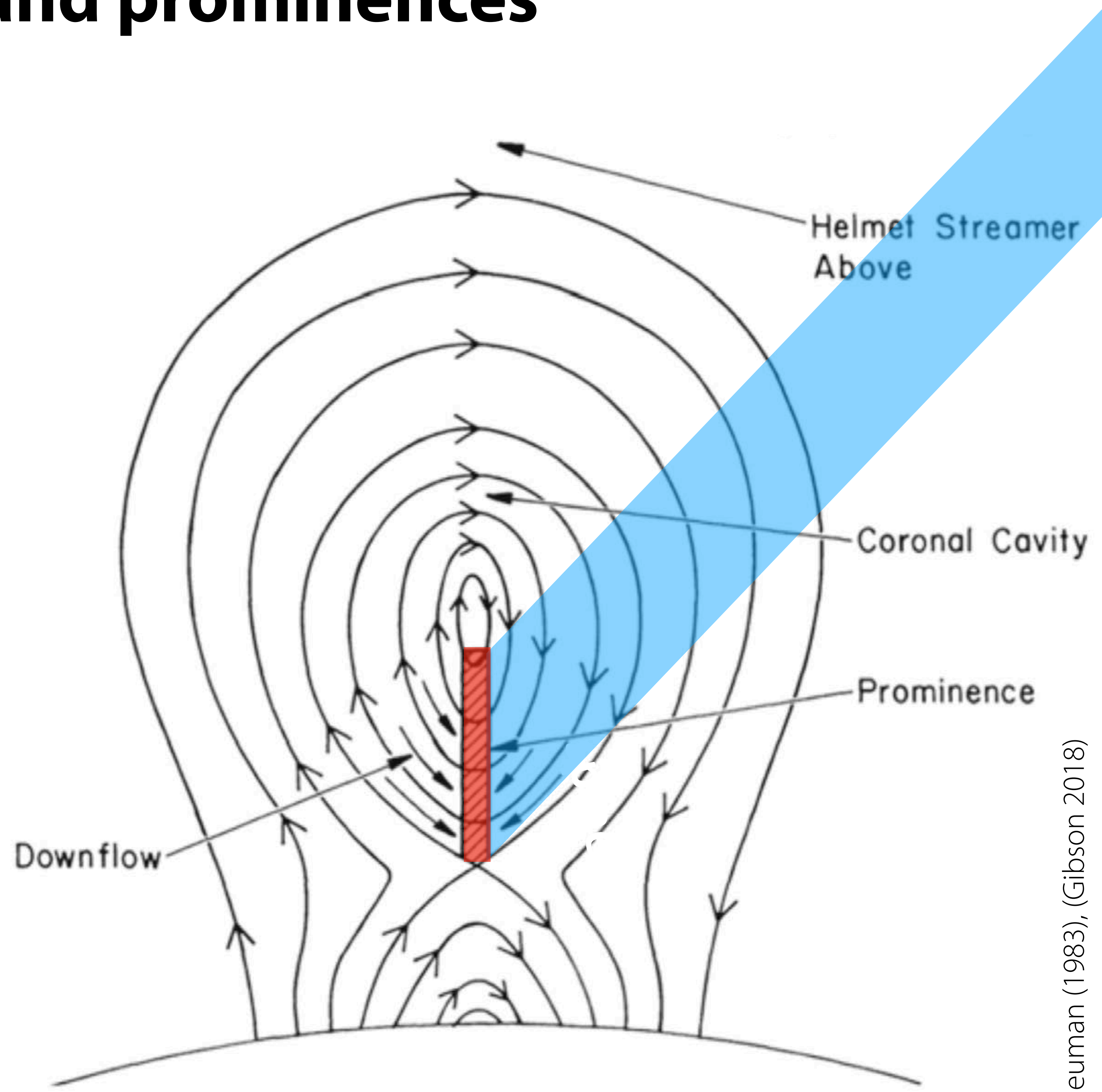


Martin (1998), Chae et al. (2001)

Filaments and prominences

"Anatomy" of filaments and prominences

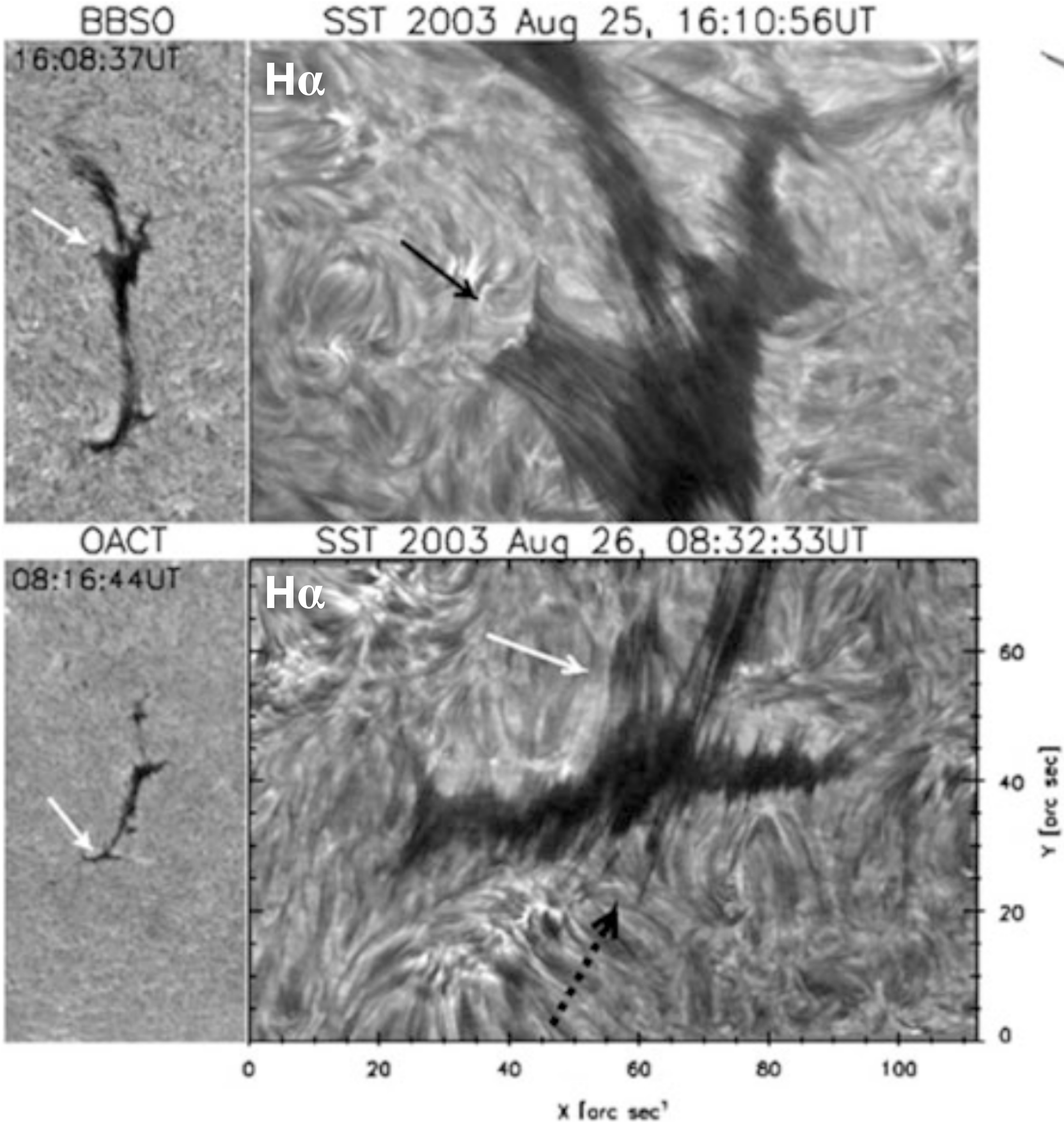
- Note: Width of filament spine may appear wider than actually true due to perspective effects.

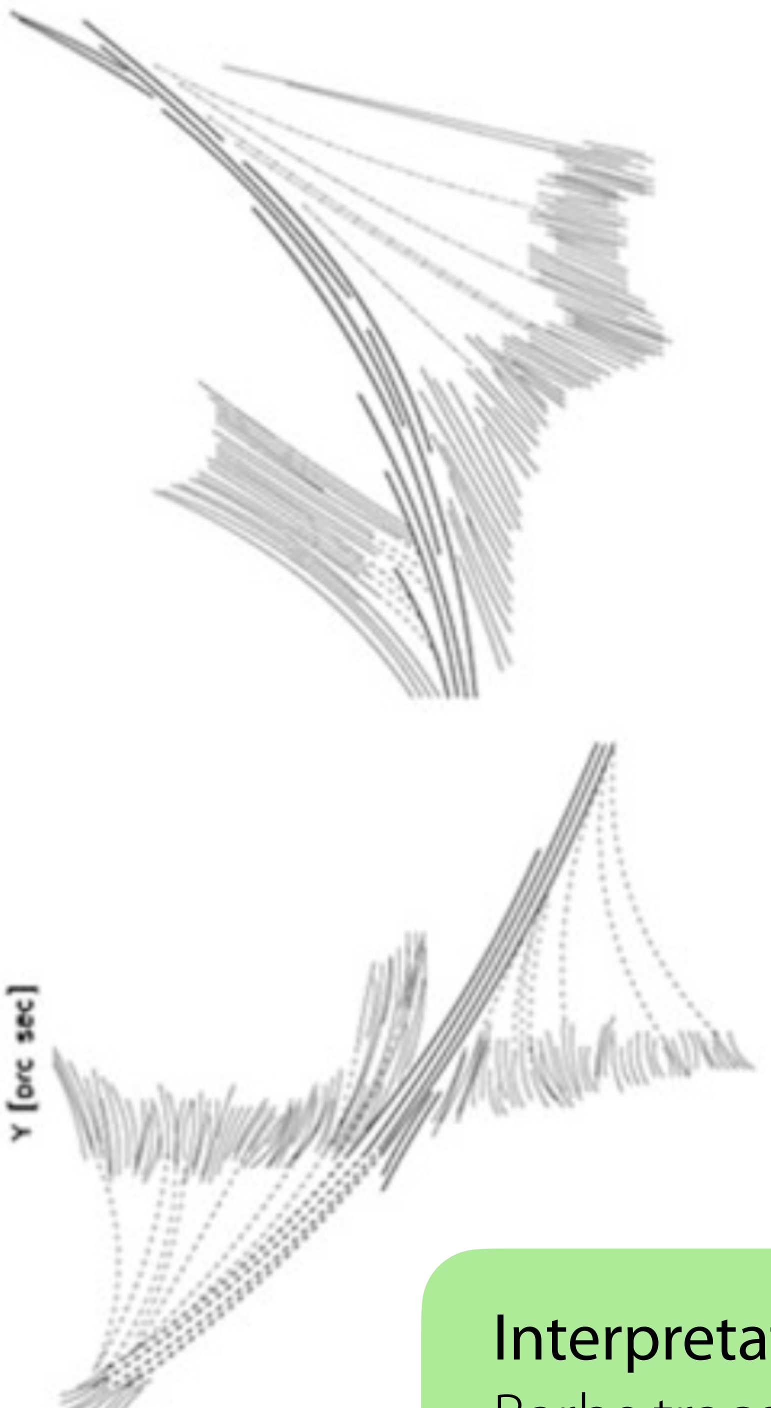


Pneuman (1983), (Gibson 2018)

Filaments and prominences

Barbs and magnetic field





Solid lines:
Observed barbs

Dashed lines:
From tracing flows in the image time series

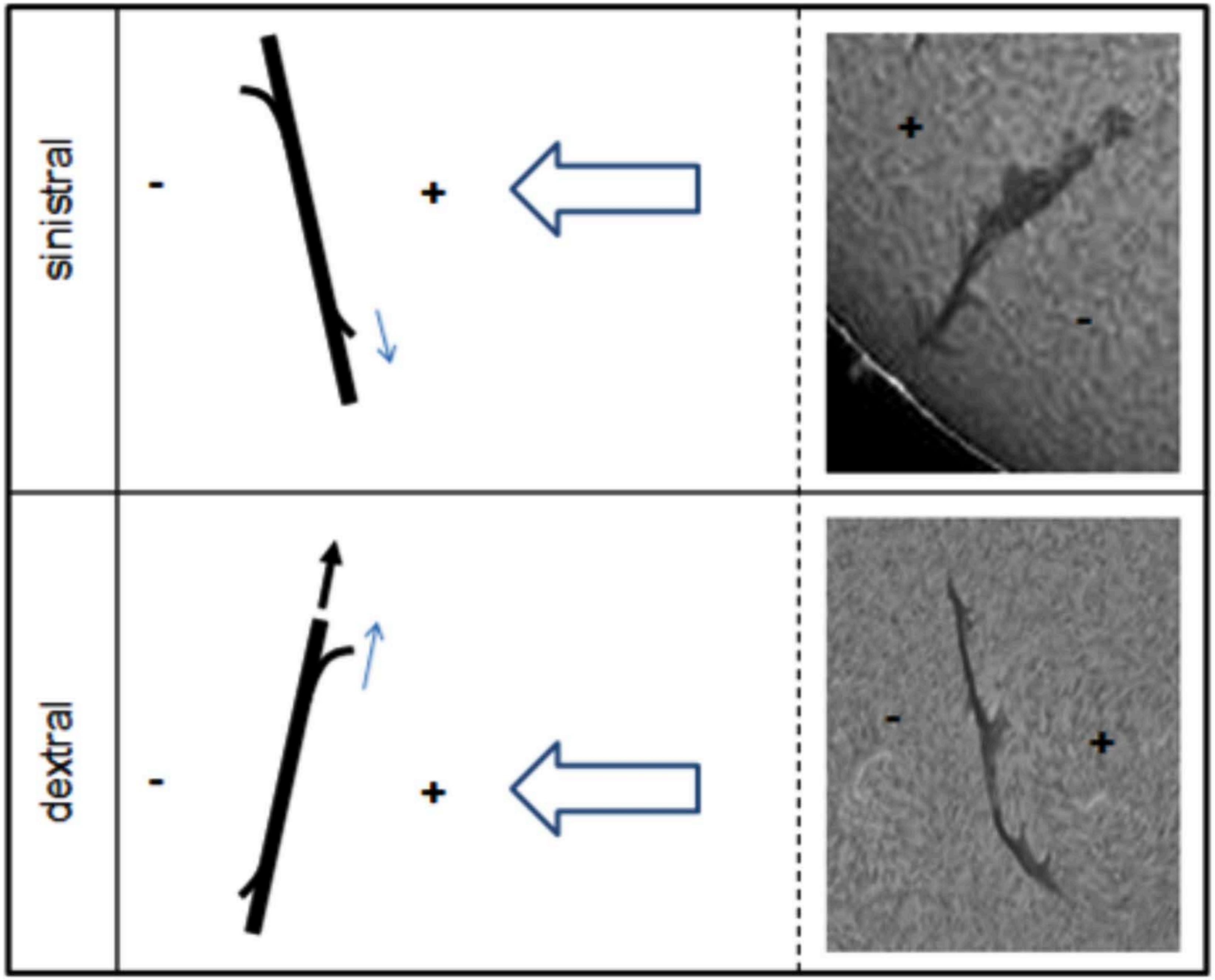
Interpretation:
Barbs trace magnetic field, connecting to the spine

Lin & Engvold

Filaments and prominences

Chirality (Handedness)

- Magnetic fields get twisted
- Can you have opposite handedness:
  - Sinistral (left)
  - Dextral (right)



Filaments and p

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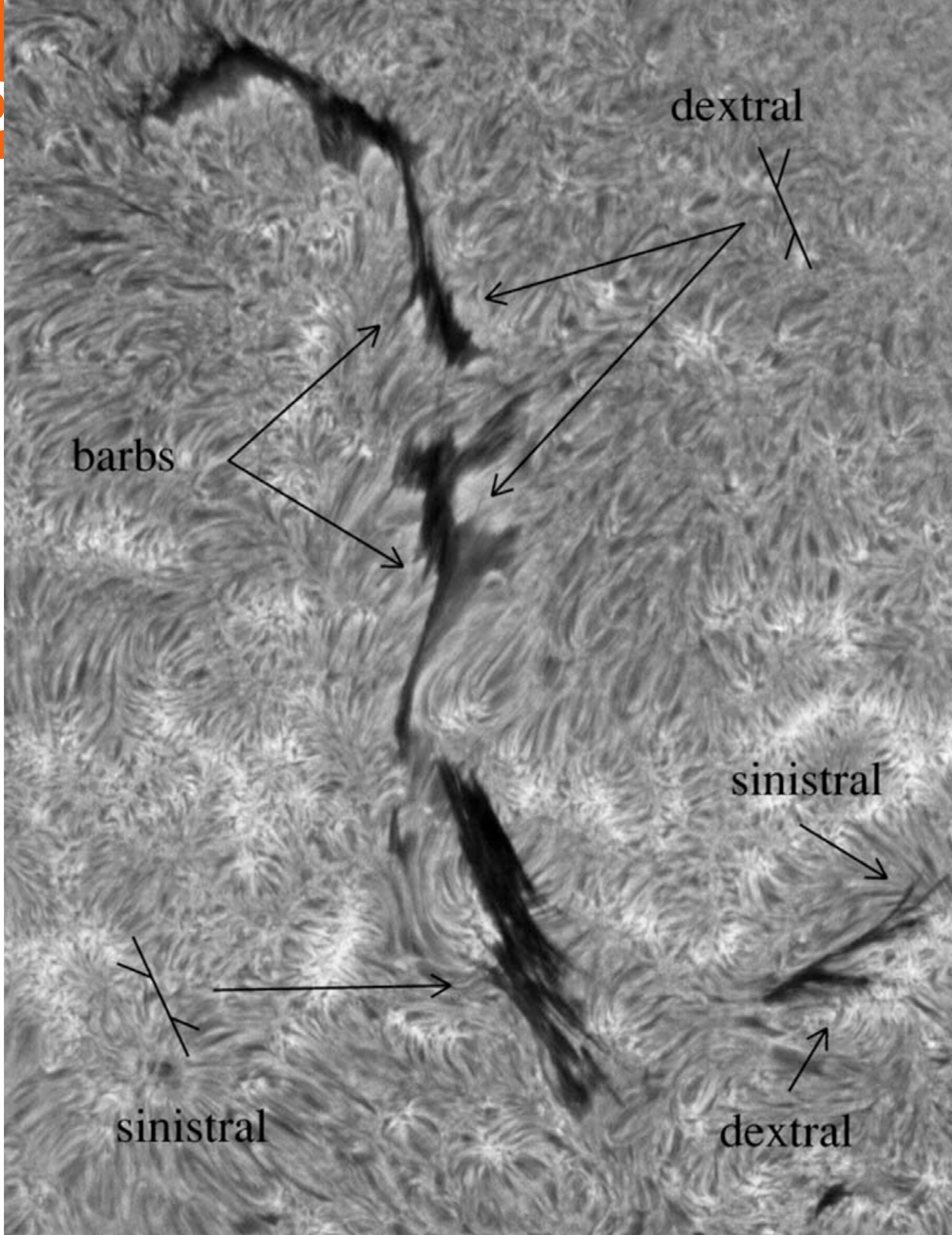


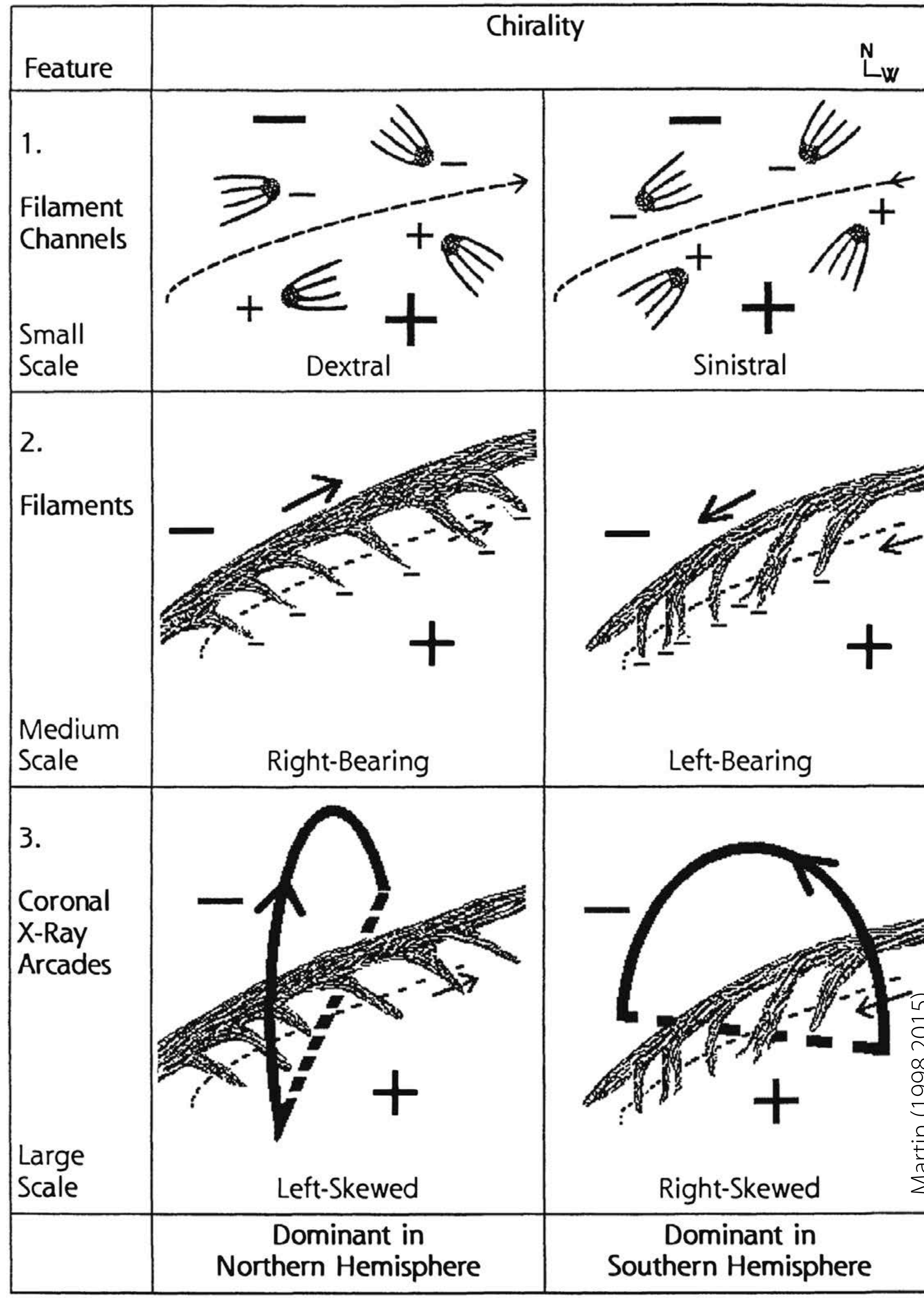
Parenti (2014) — USAF, ISOON image courtesy D. Neidig; from work of A.A. Pevtsov

Filaments

Chirality

- Chirality relations between prominence (filament) and surrounding environment:
  1. Chromospheric fibrils observed in filament channels;
  2. filament extensions (barbs) from central spine; and
  3. Overlying coronal loops.

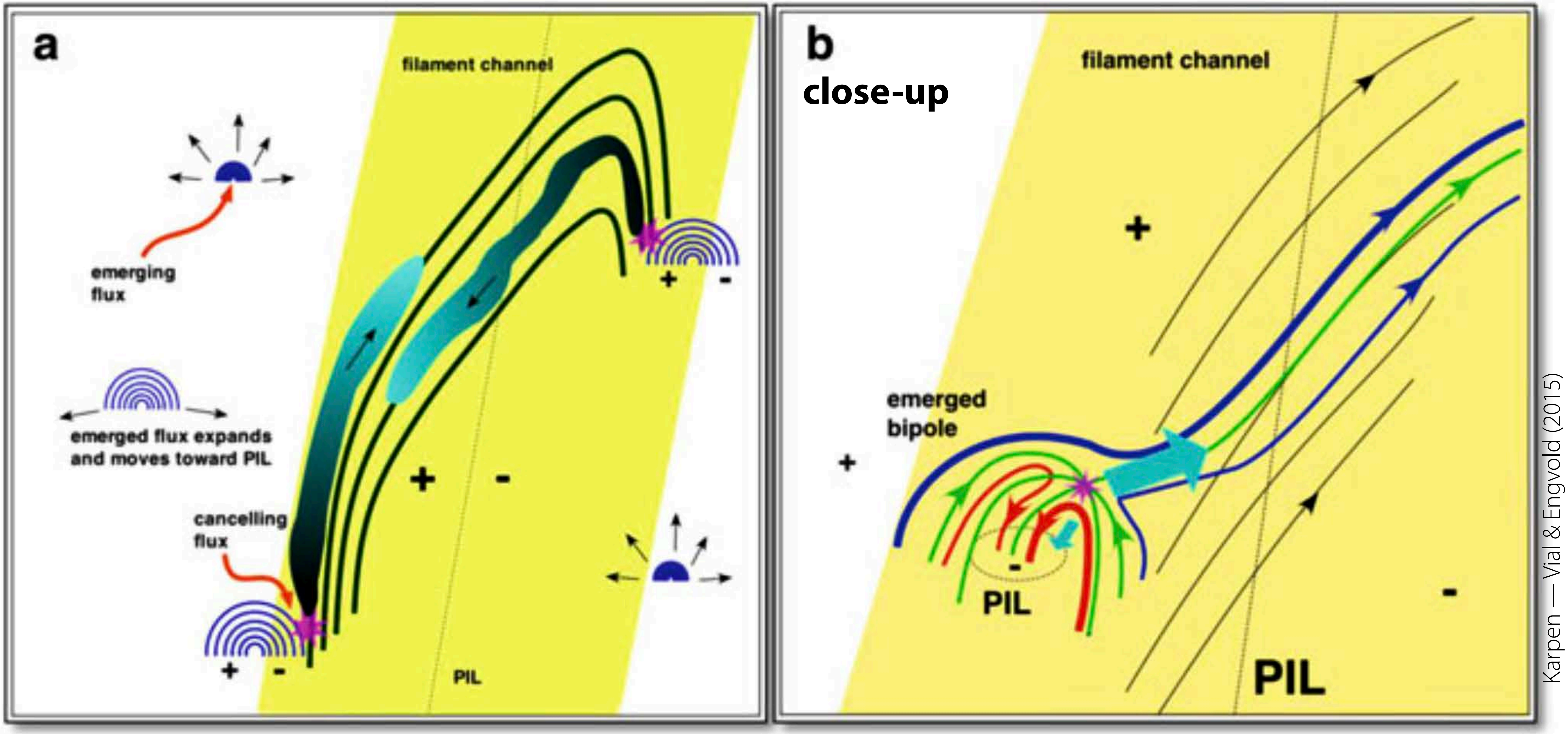
- Note: adequate spatial resolution needed for a proper determination of chirality determinations, directions and flow patterns
- Projection effects can complicate/limit such studies!



Filaments and prominences

Injection of plasma into prominence/filament

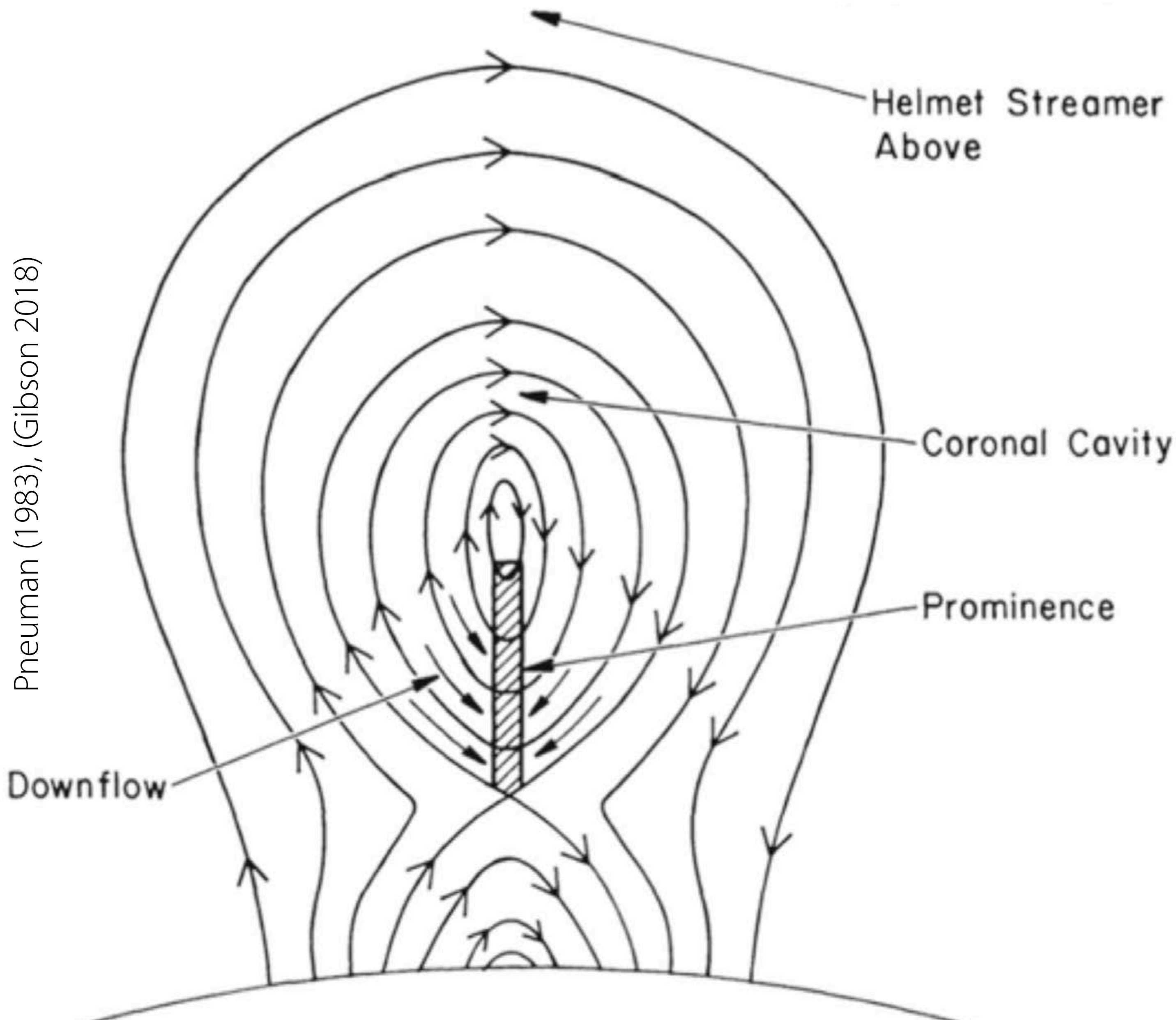
- Reconnection events between emerged bipolar at end points (legs)
- Injects plasma into pre-existing filament channel (magnetic field structure)



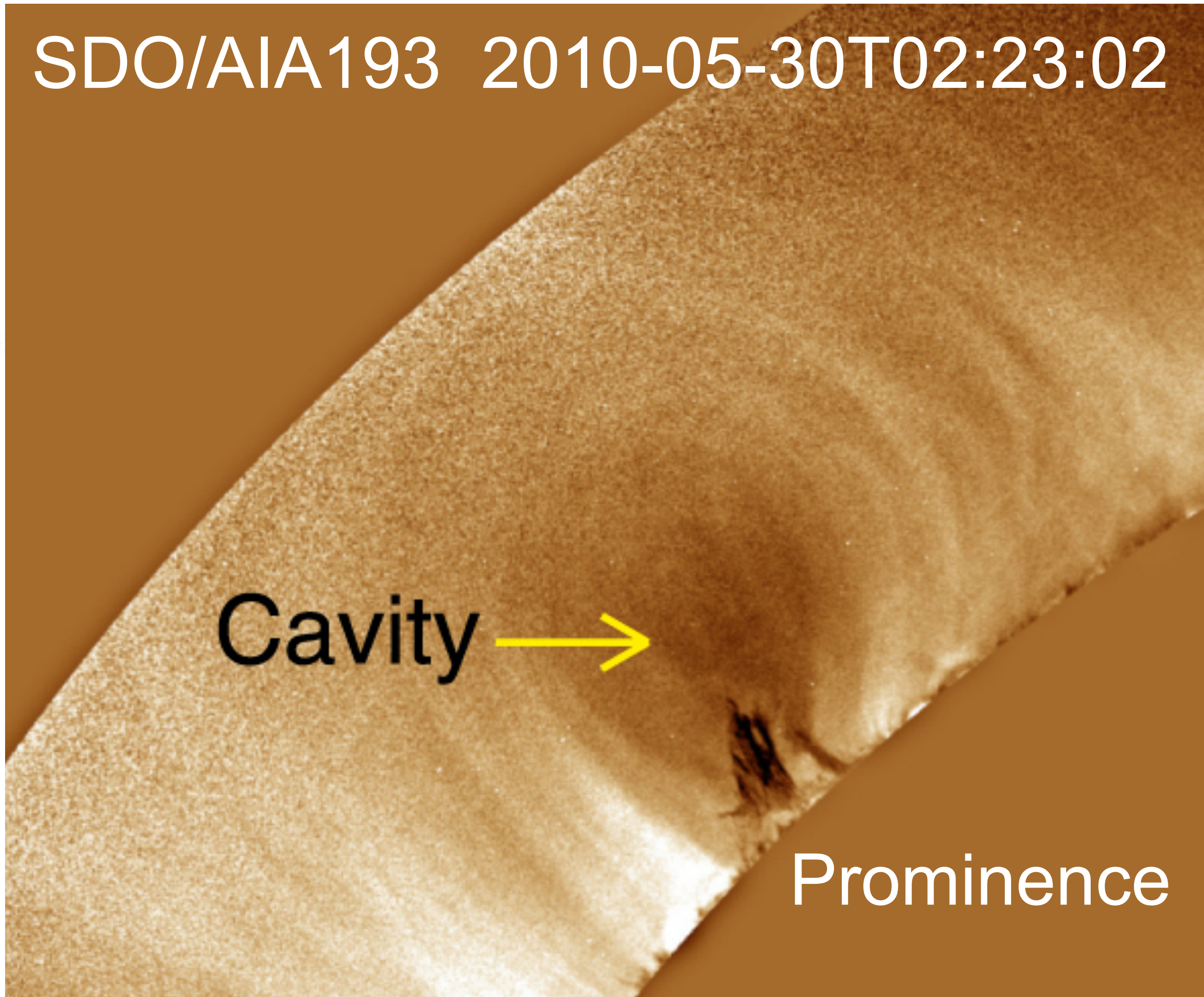
Filaments and prominences

Cavity

- Space below coronal loops appears to be "void" or at least plasma with much lower density than compared to prominence below
- Prominence: higher density (surrounding corona has low density) — Plasma beta!
- Magnetic field lines frozen into plasma, move along with it



Pneuman (1983), (Gibson 2018)

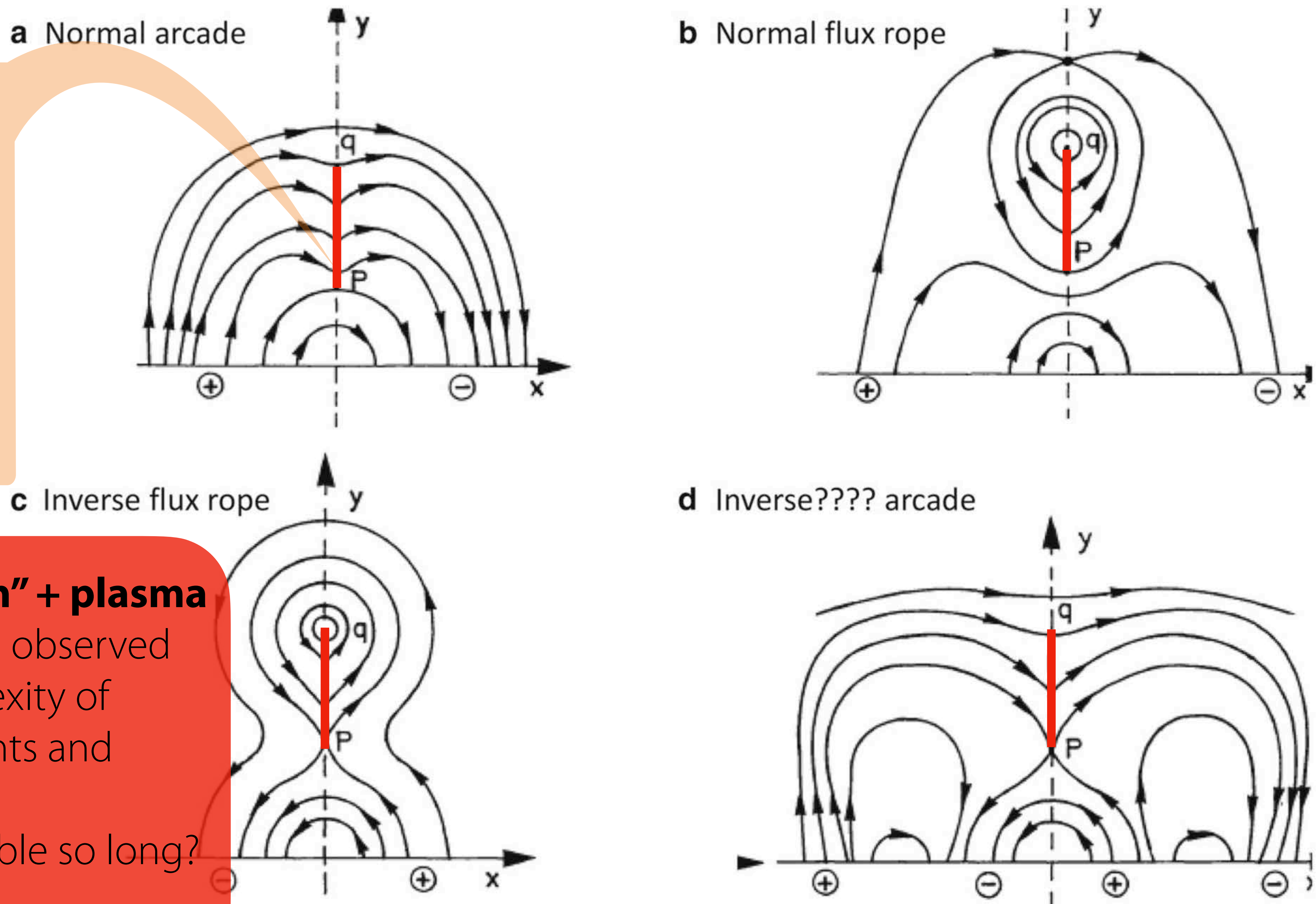


Filaments and prominences

Possible models

- Different models suggested that explain different aspects
- How to get the magnetic field configuration to match the observations!?

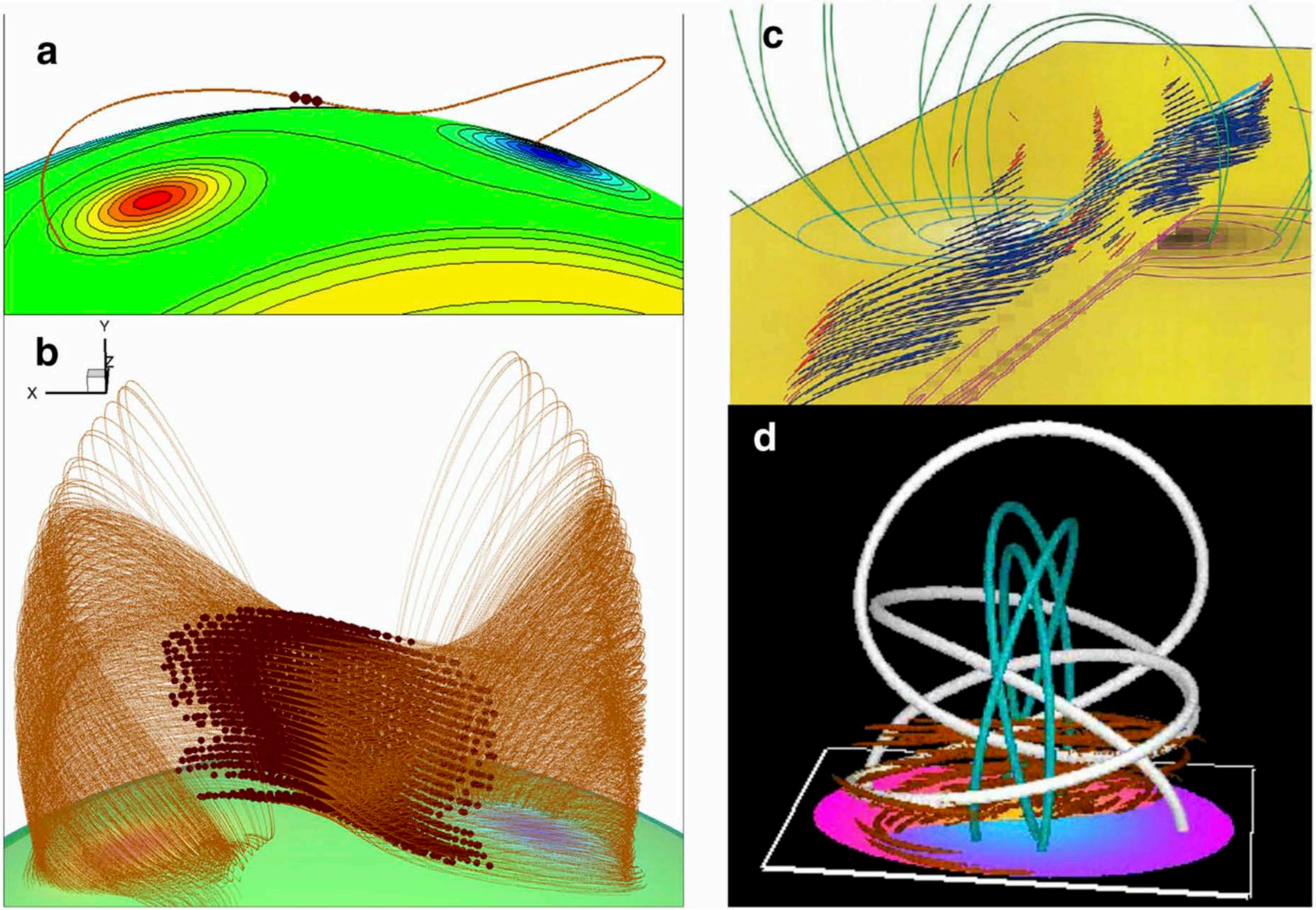
Magnetic dip
Plasma "trapped" / supported by magnetic field but "pulling it down" due to gravity; (partially) outlining the magnetic field



Gibson 2018, adapted from Malherbe & Priest (1983)

Magnetic "skeleton" + plasma
- How to explain the observed variety and complexity of structure in filaments and prominences?
- How can it stay stable so long?

3D models



Gibson 2018

Fig. 6 "Painting the dips" of a magnetic skeleton results in sheet-like prominences, independent of magnetic topology. **a** Demonstration of the small region this would represent for a sample, dipped field line within a flux rope field model, and **b** demonstration for many field lines within the rope (after Gibson and Fan 2006a). **c** Painted dips within 3D sheared-arcade model. Image reproduced with permission from Aulanier et al. (2002), copyright by AAS. **d** Painted dips within 3D analytic model of spheromak-type magnetic flux rope. Image reproduced with permission from Lites and Low (1997), copyright by Springer

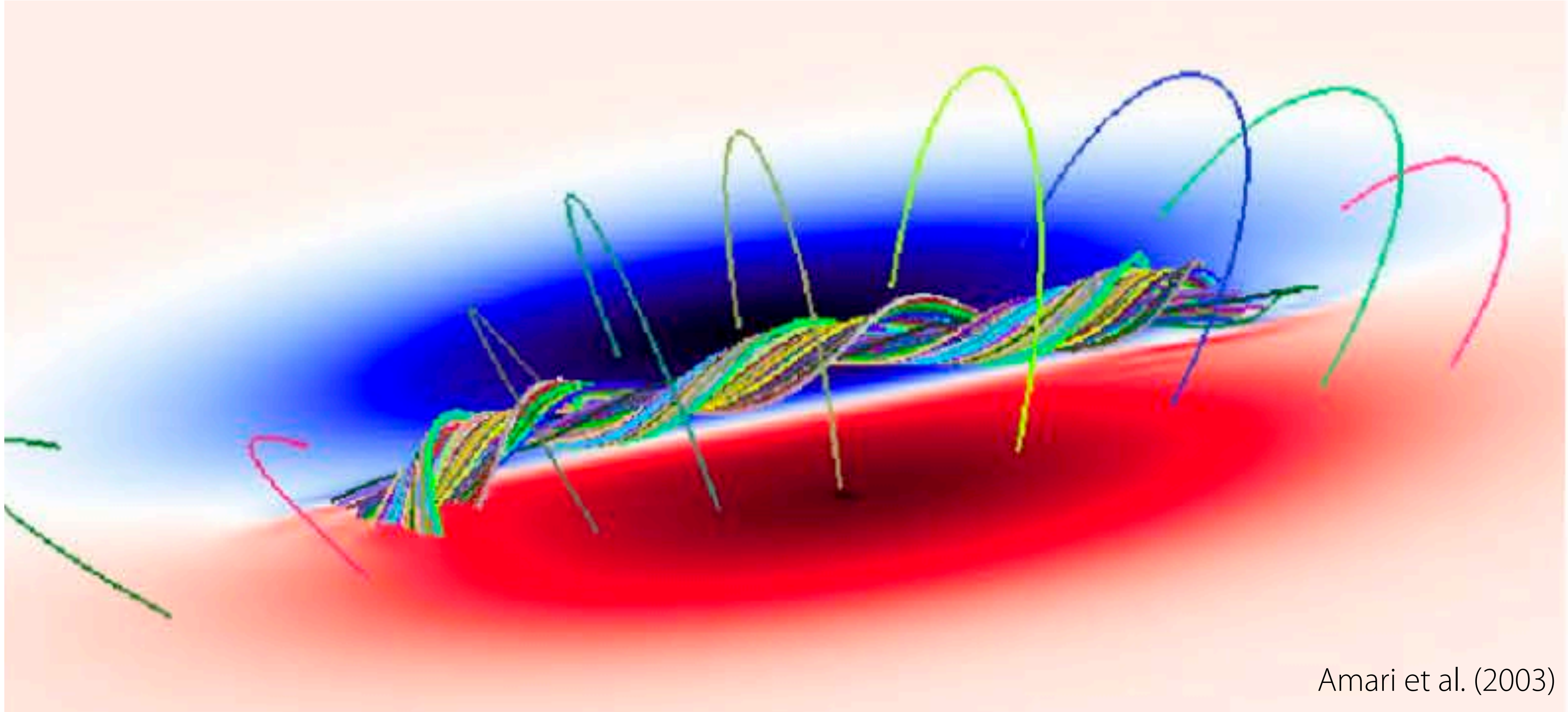
Example for how to acknowledge reproduced figures

Filaments and prominences

Magnetic field topology

- Magnetic field in filament channel has a strong axial component, carries electric currents
- **Twisted** filament strands helically wrapped around the axial field.
- Helical flux rope held down by overlying arcade that is anchored in the neighboring network elements
- “This magnetic configuration cannot accurately be modeled with a potential field or a linear force-free field, but rather needs a nonlinear force-free field (NLFFF) model.” (Aschwanden 2019)

Note:
Magnetic helicity is a measure of the helical twist



Amari et al. (2003)

3D models

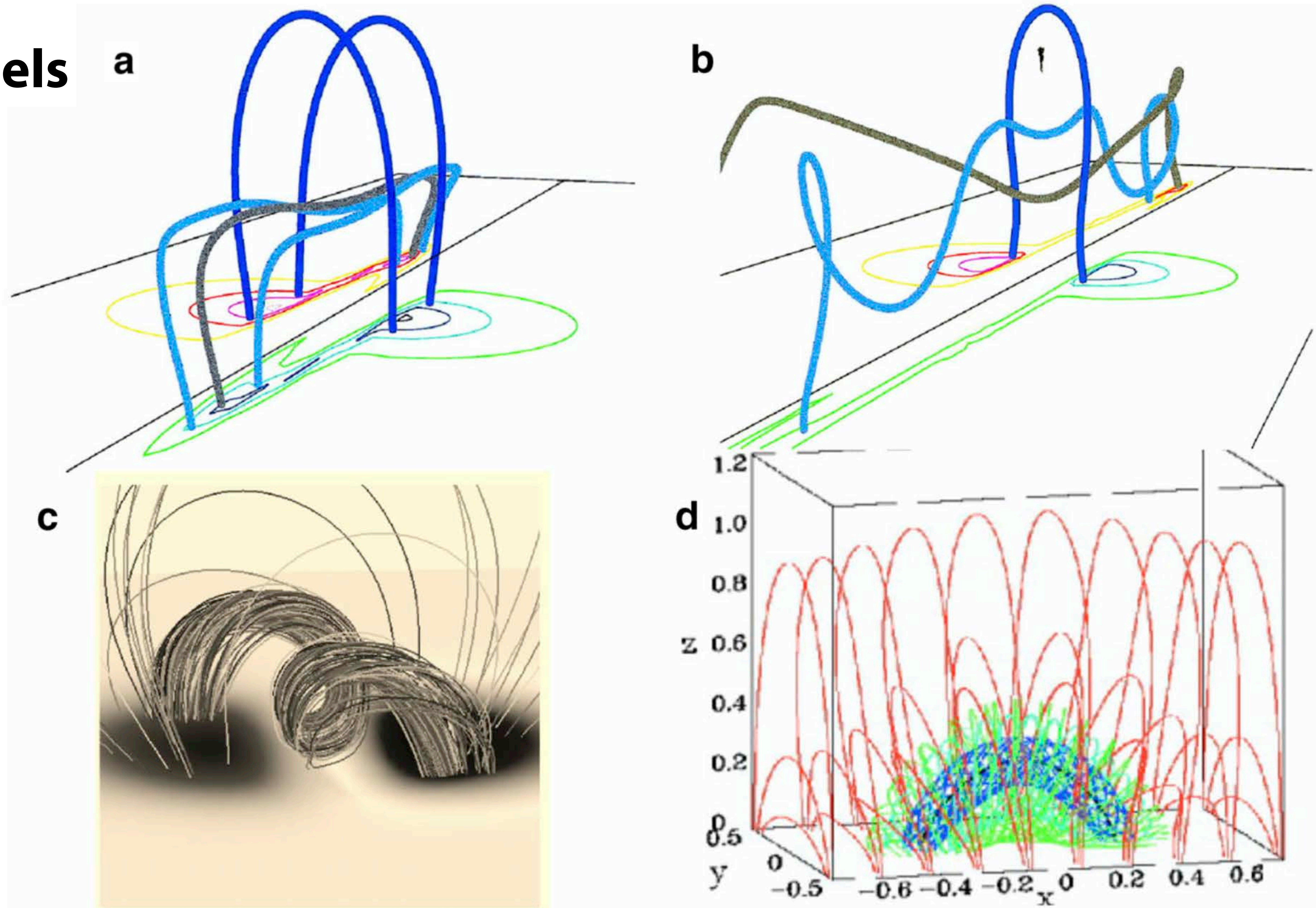


Fig. 5 3D magnetic configurations with dipped field capable of supporting prominences. Field lines from DeVore and Antiochos (2000) **a** sheared arcade and **b** flux rope; **c** Amari et al. (1999) and **d** Fan and Gibson (2004) flux ropes. Images reproduced with permission, copyright by AAS

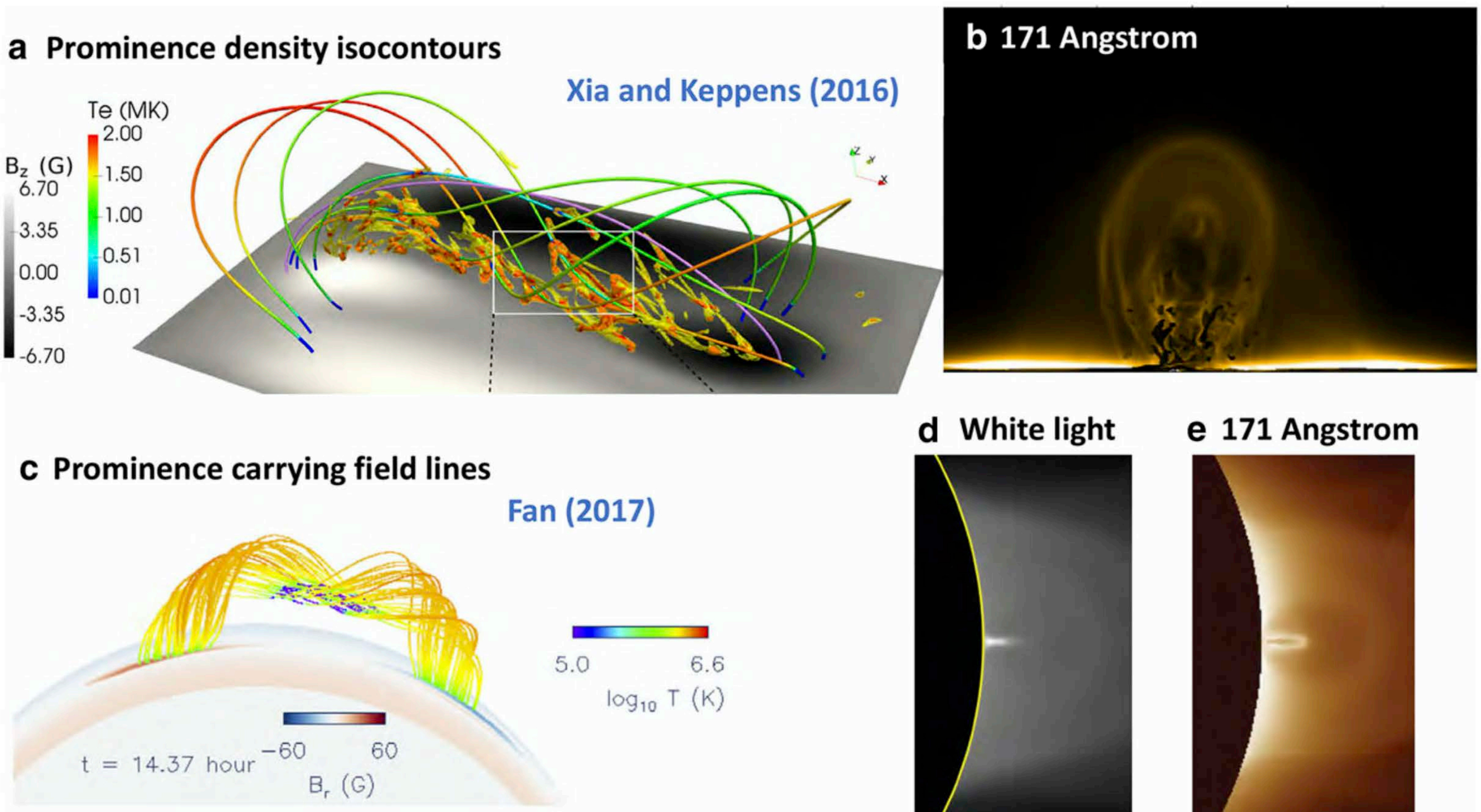
Gibson 2018

Filaments and prominences

Need for simulations

- Different models explain different aspects but difficult to find a comprehensive model that explains all observations

➡ **MHD simulations** may also yield the answer here (but challenging as usual)

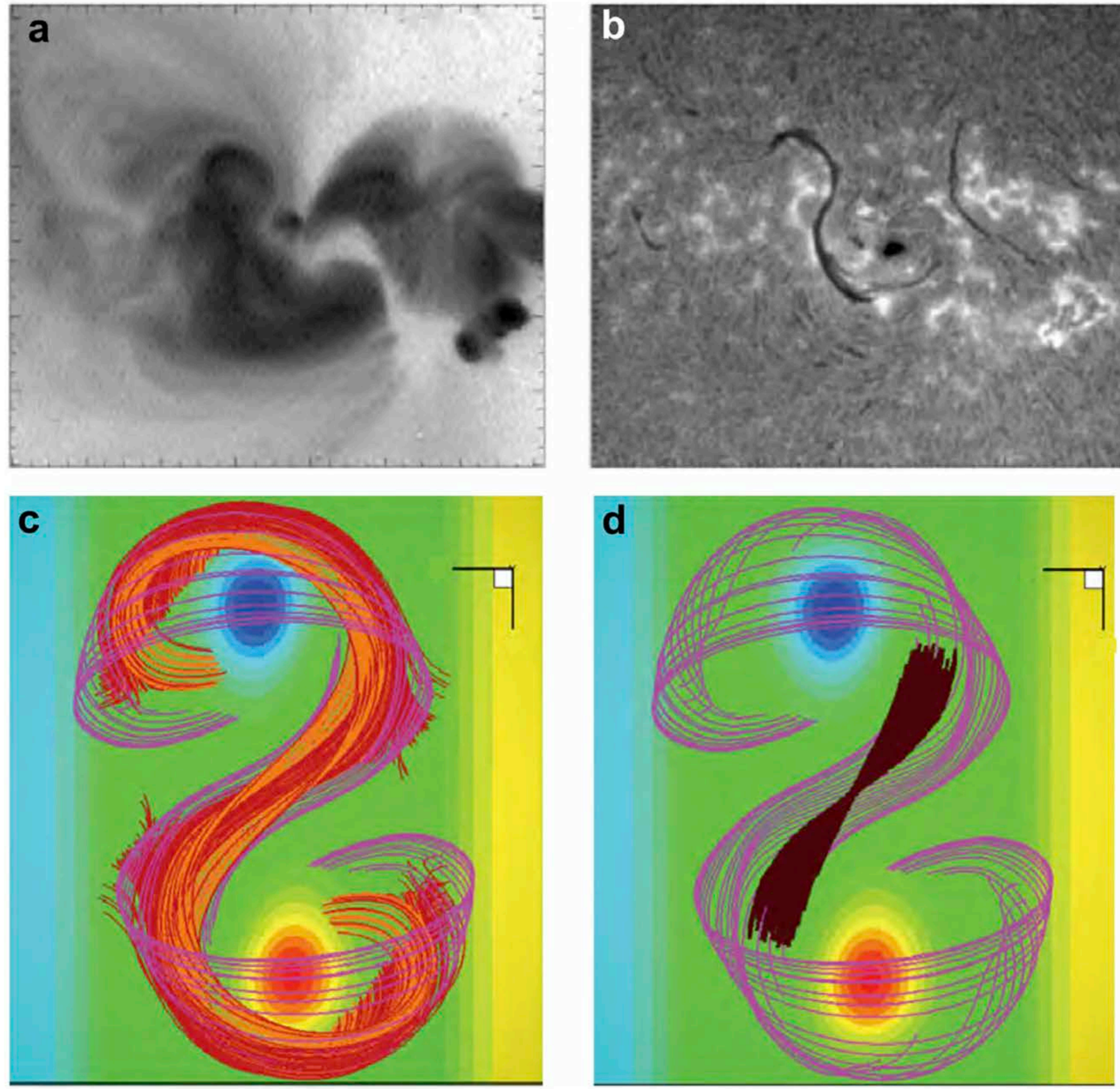


Filaments and prominences

Sigmoids

- Soft-Xray (SXR) "sigmoids": active regions with characteristic S or inverse-S shape
- Large range in size:
  - Regions of sheared loops forming (inverse) S-shape together, persist for several days
  - Sharply defined individual sigmoidal loop, short-lived/ transient (several hours)
- Sigmoids may appear and disappear without eruption (within several days)
- Magnetic field twisted and stressed

➡ Prone to eruption



Gibson et al. (2002), Gibson & Fan (2006)

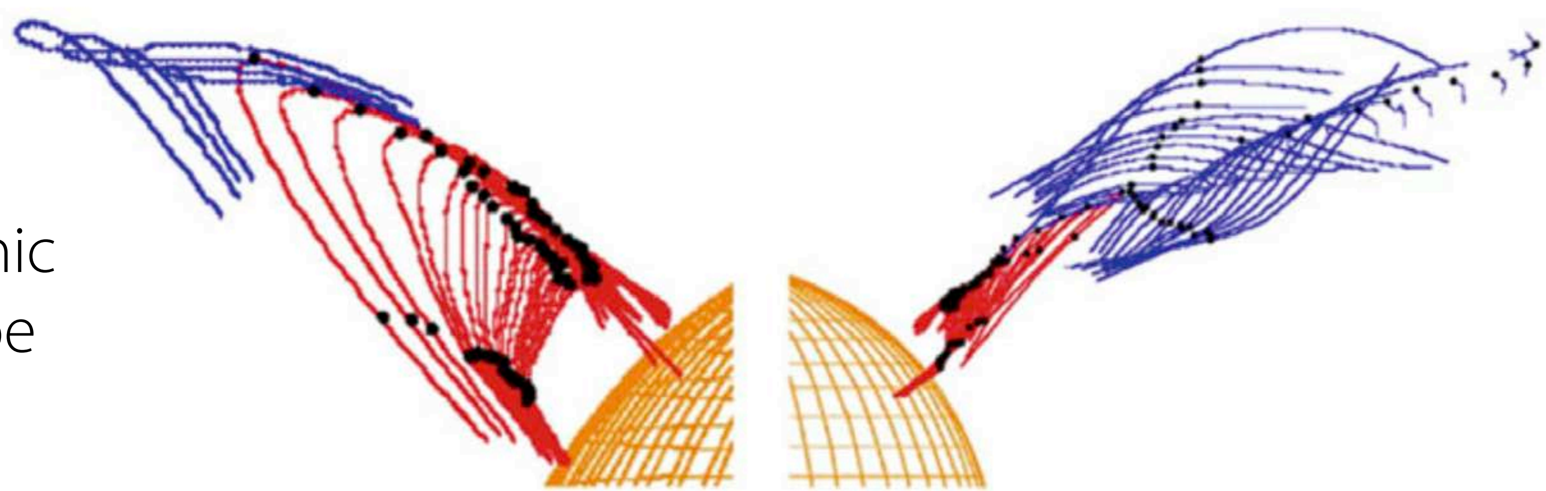
Filaments and prominences

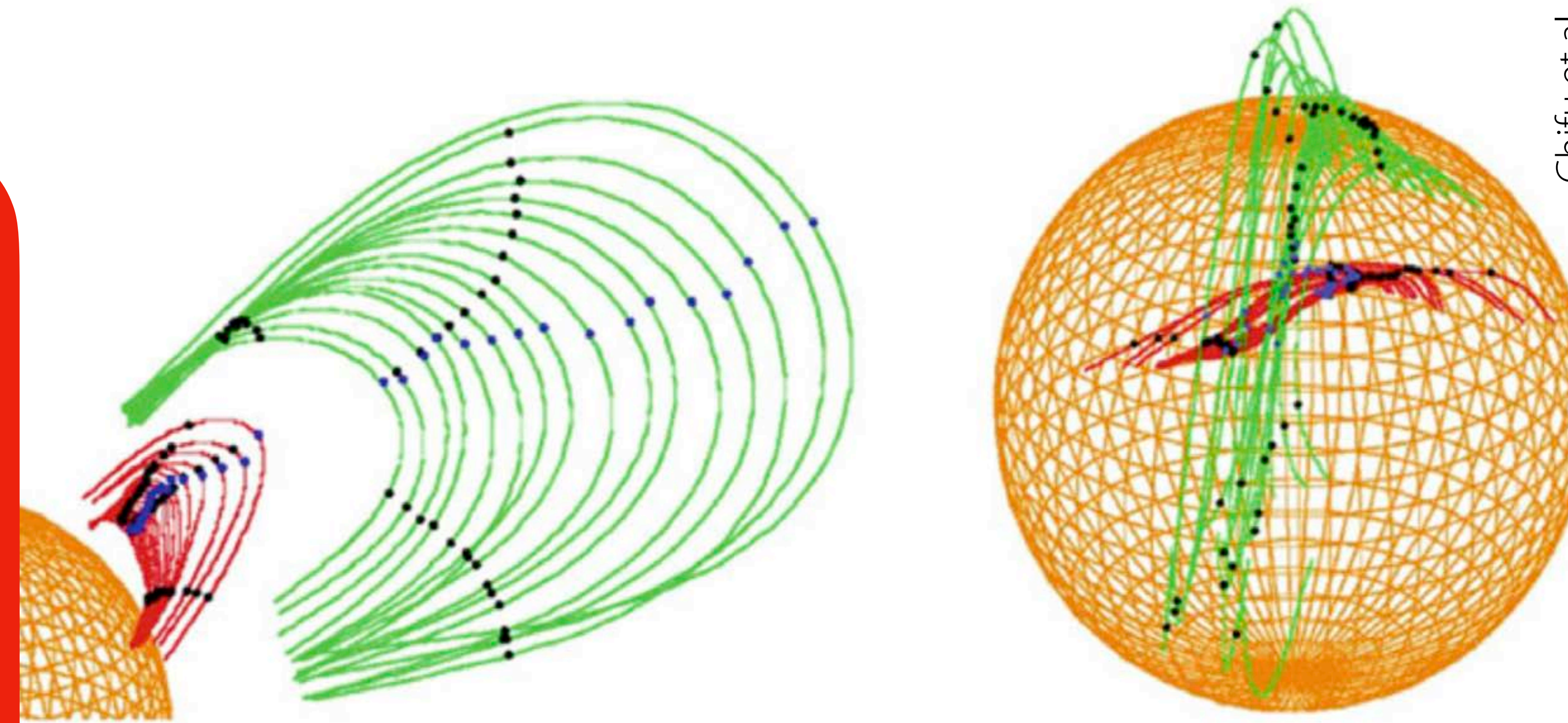
Eruptive filaments

- Eruption can be triggered at instabilities at filament legs
- Stereoscopic triangulation: true 3D velocity and acceleration of rising filaments
- Gradual filament eruption as "slow" as $v = 10^2$ km/s, $a = dv/dt = 3$ m s^{-2}, over 17hours, followed by a gradual CME

- Other stereoscopic observations imply initial mass off-loading
  - May trigger rise and catastrophic loss of equilibrium of a flux rope

- Rotating erupting prominence: Untwisting of magnetic field





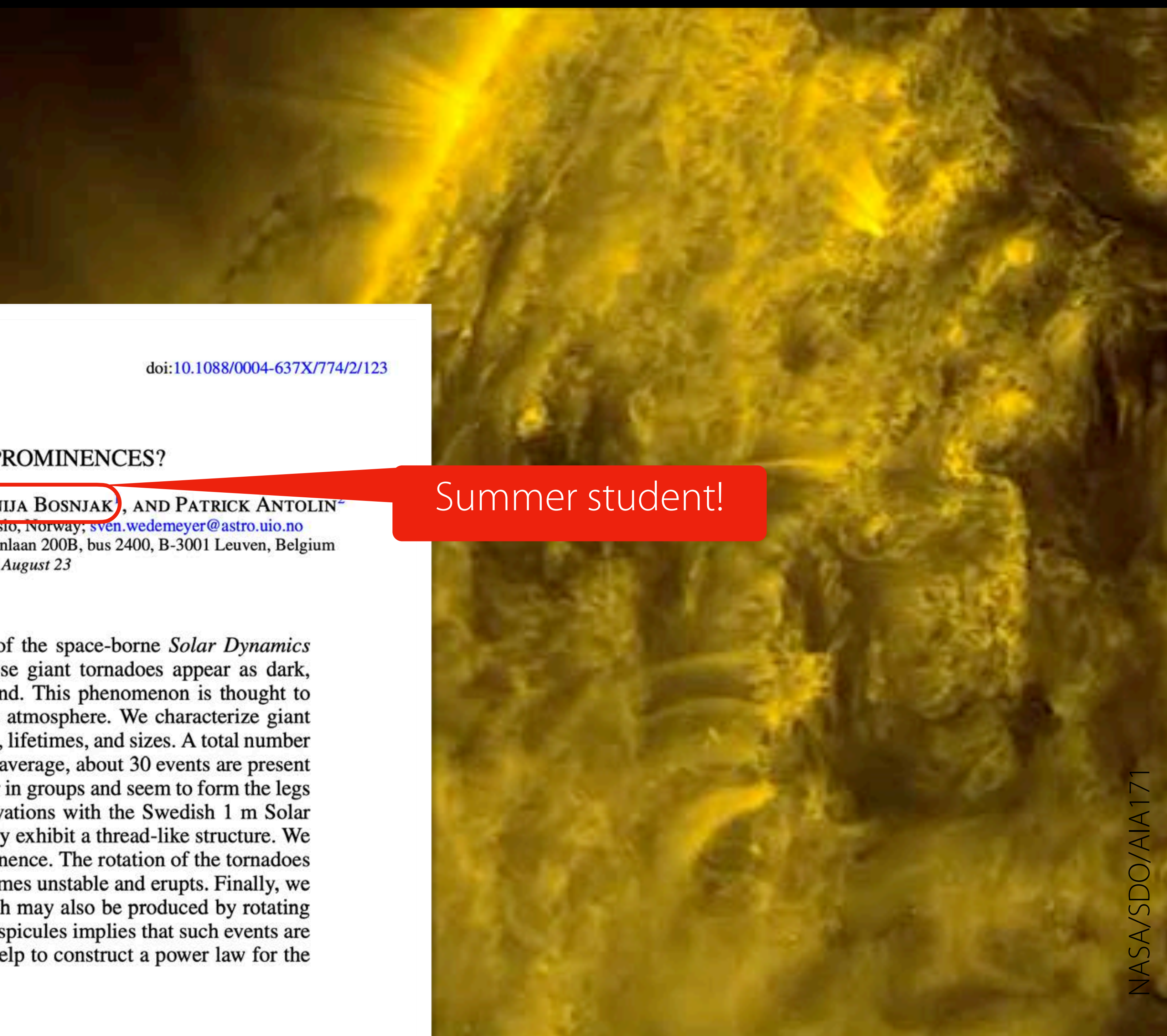
Chifu et al. (2012)

Still many aspects regarding the triggering of filament/ prominence eruptions and Coronal Mass Ejections under investigation

Filaments and prominences

Giant "tornadoes"

- True or apparent rotation — debated



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ARE GIANT TORNADOES THE LEGS OF SOLAR PROMINENCES?

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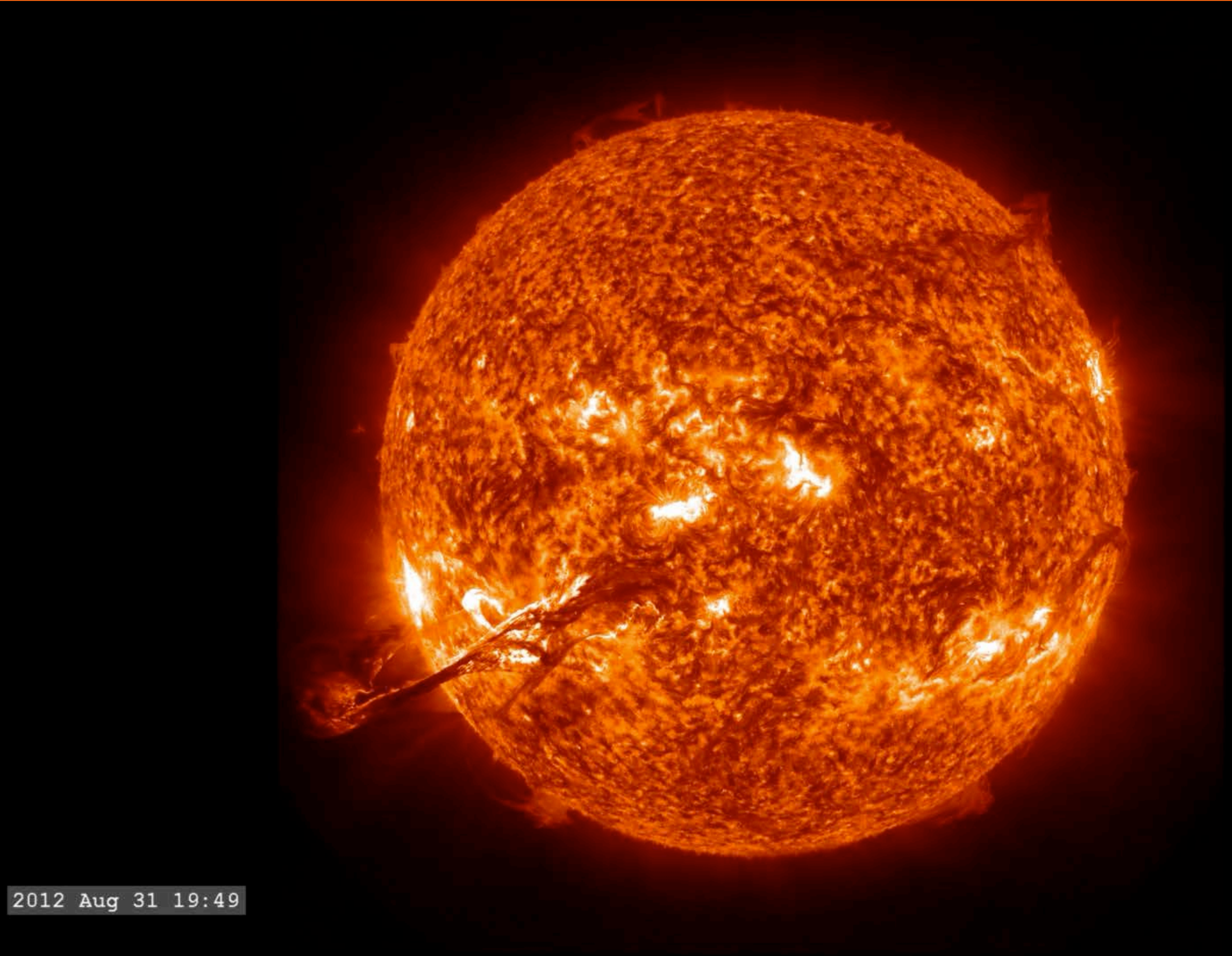
ABSTRACT

Observations in the 171 Å channel of the Atmospheric Imaging Assembly of the space-borne *Solar Dynamics Observatory* show tornado-like features in the atmosphere of the Sun. These giant tornadoes appear as dark, elongated, and apparently rotating structures in front of a brighter background. This phenomenon is thought to be produced by rotating magnetic field structures that extend throughout the atmosphere. We characterize giant tornadoes through a statistical analysis of properties such as spatial distribution, lifetimes, and sizes. A total number of 201 giant tornadoes are detected in a period of 25 days, suggesting that, on average, about 30 events are present across the whole Sun at a time close to solar maximum. Most tornadoes appear in groups and seem to form the legs of prominences, thus serving as plasma sources/sinks. Additional Hα observations with the Swedish 1 m Solar Telescope imply that giant tornadoes rotate as a structure, although they clearly exhibit a thread-like structure. We observe tornado groups that grow prior to the eruption of the connected prominence. The rotation of the tornadoes may progressively twist the magnetic structure of the prominence until it becomes unstable and erupts. Finally, we investigate the potential relation of giant tornadoes to other phenomena, which may also be produced by rotating magnetic field structures. A comparison to cyclones, magnetic tornadoes, and spicules implies that such events are more abundant and short-lived the smaller they are. This comparison might help to construct a power law for the effective atmospheric heating contribution as a function of spatial scale.

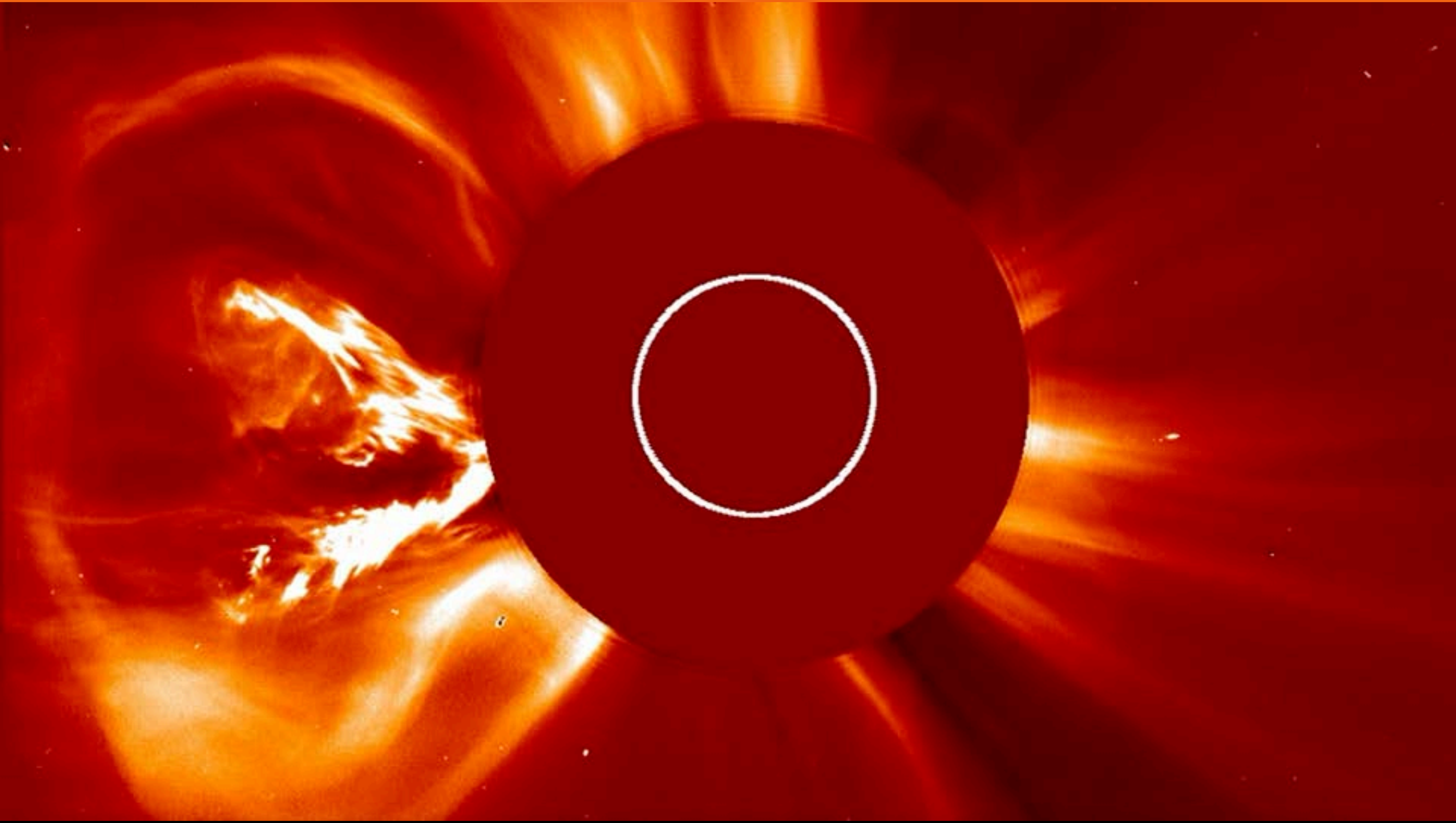
Key words: Sun: atmosphere – Sun: filaments, prominences

Prominence eruption



- August 31, 2012 — Eruption of a long filament, producing a CME
- CME speed > 5 10^6 km/s, not directed to Earth (but disturbed magnetosphere, caused aurora)
- Ejection from different viewpoints: SDO, STEREO, SOHO

Prominence eruption



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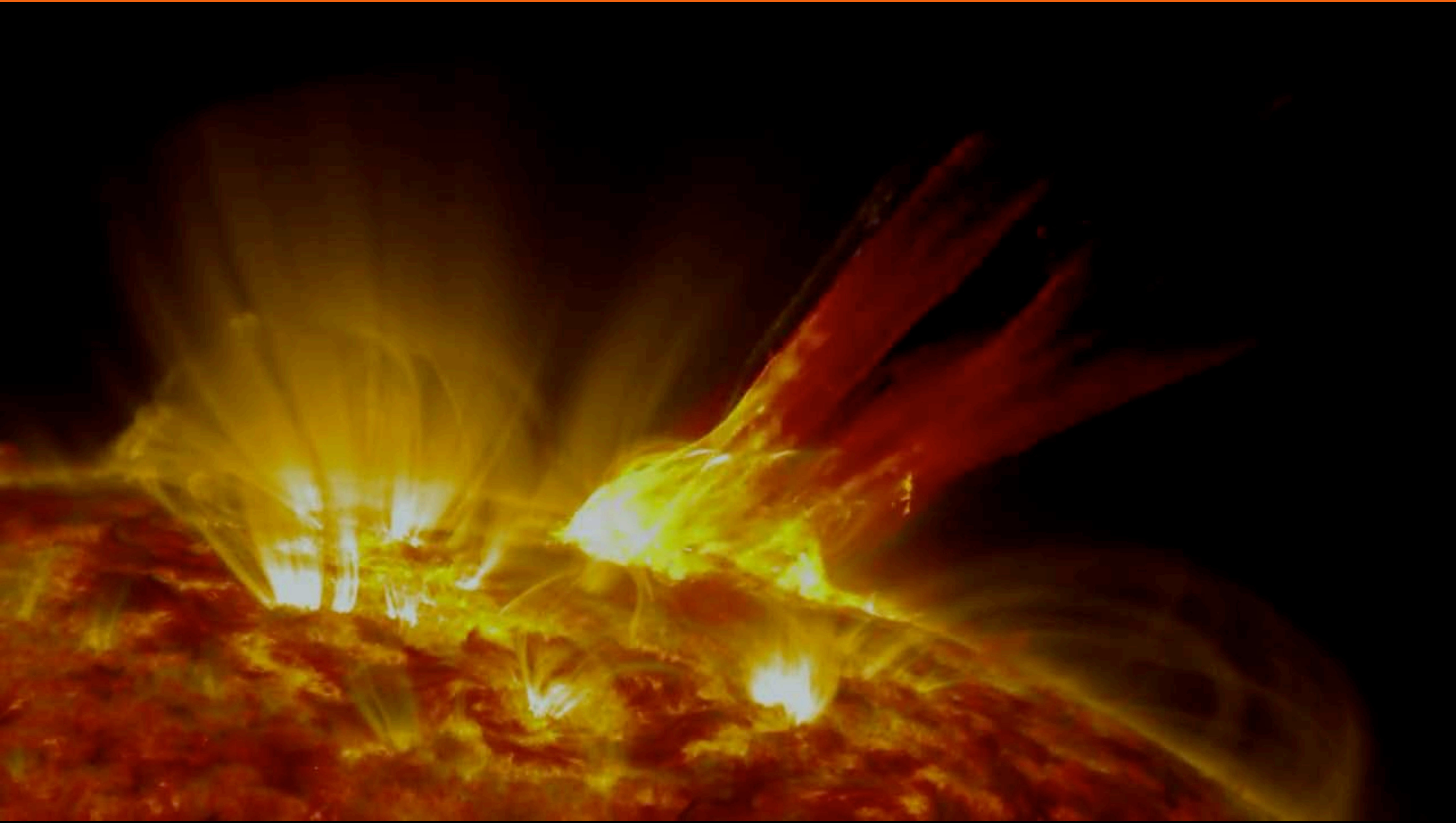
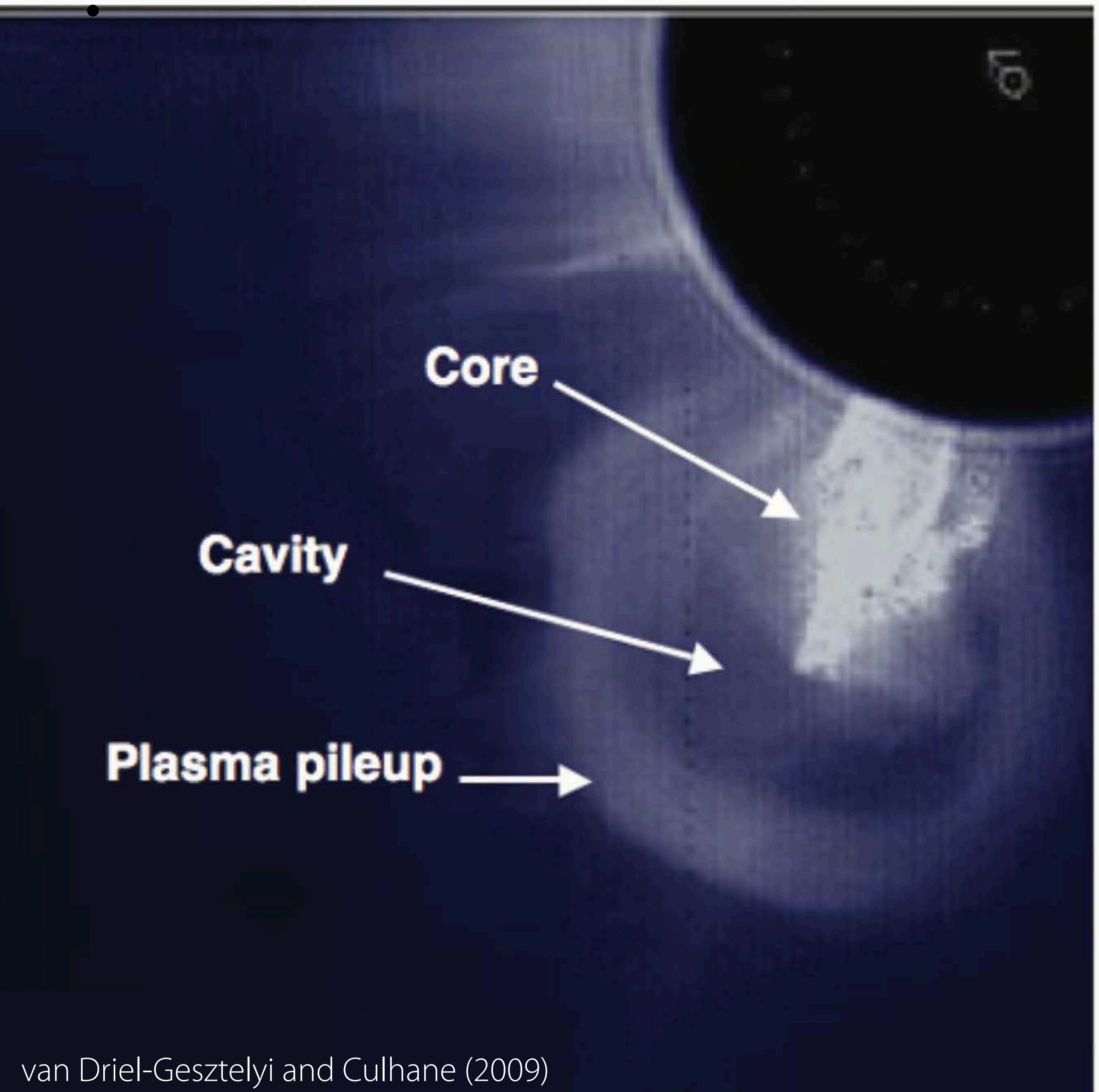


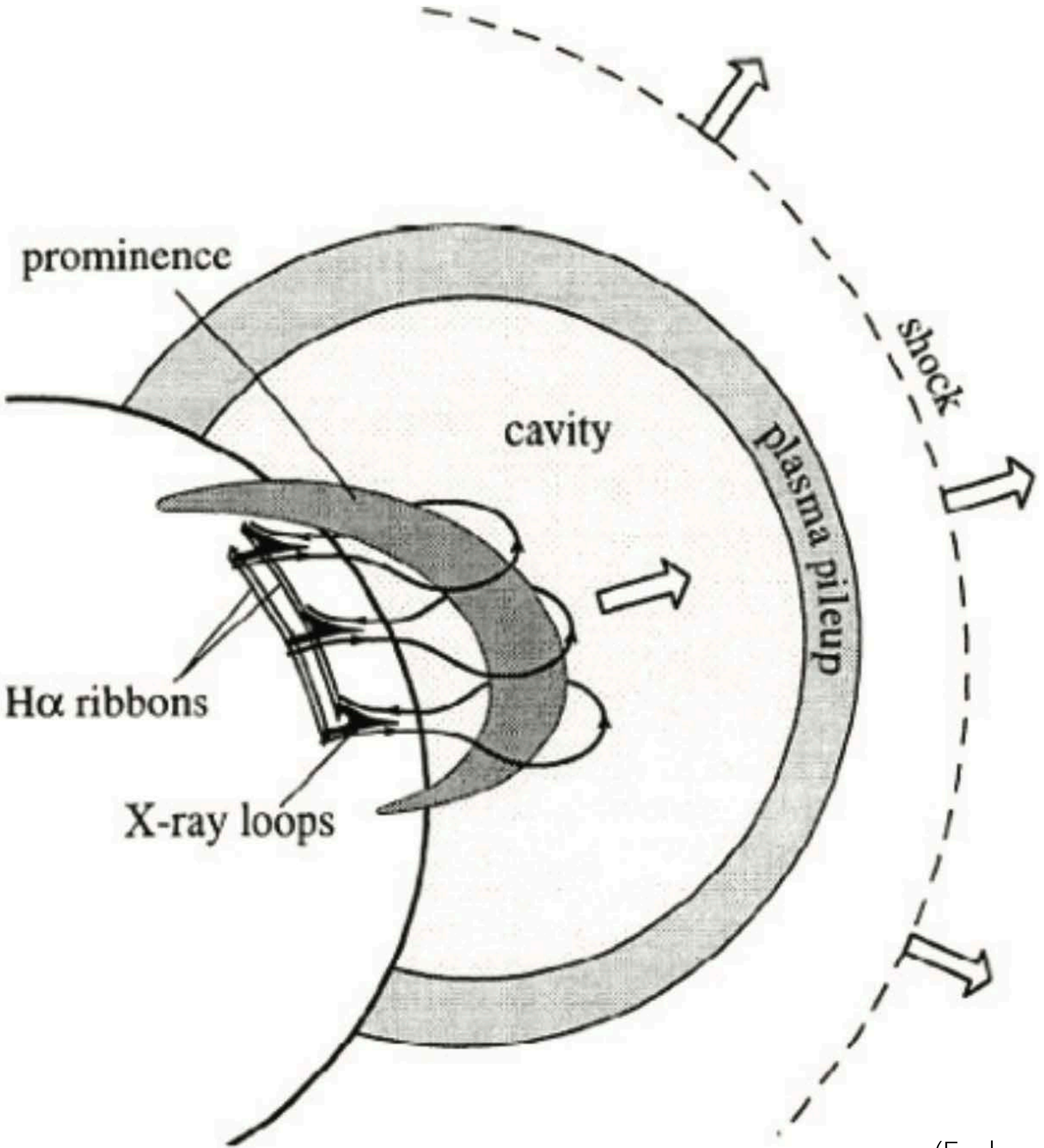
SDO/AIA — April 21, 2015, prominence eruption, 6 hour time lapse
yellowish: AIA171, orange: AIA304

Coronal Mass Ejection

- In most cases associated with an eruptive prominence or/and a flare BUT CME and flare not always seen together!
- Often bubble-shaped, bright filaments with a helical structure
- Naming: It is rather prominence mass than mass from the corona itself that is ejected.
-



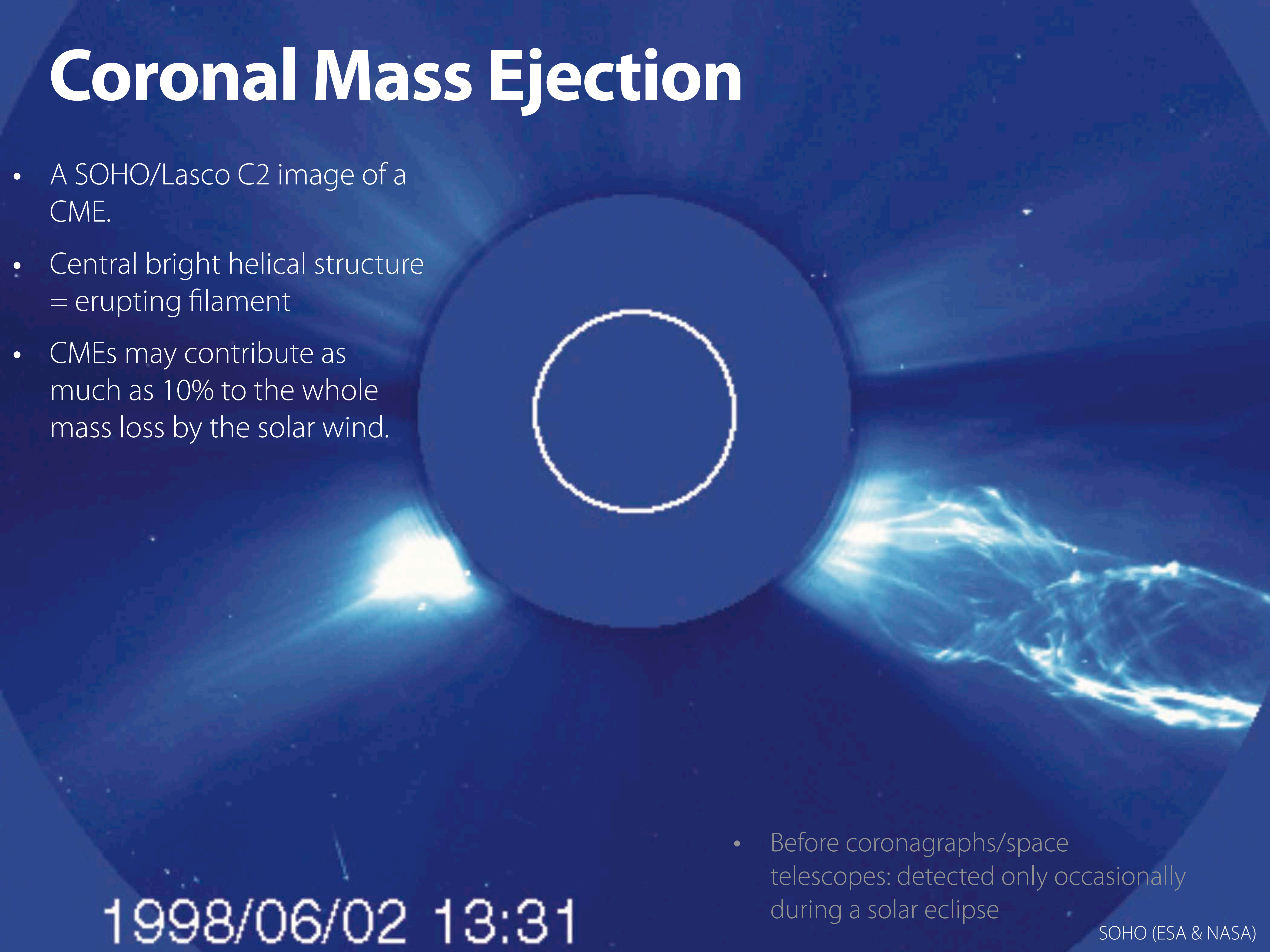
van Driel-Gesztelyi and Culhane (2009)



(Forbes, 2000)

Coronal Mass Ejection

- A SOHO/Lasco C2 image of a CME.
- Central bright helical structure = erupting filament
- CMEs may contribute as much as 10% to the whole mass loss by the solar wind.



- Before coronagraphs/space telescopes: detected only occasionally during a solar eclipse

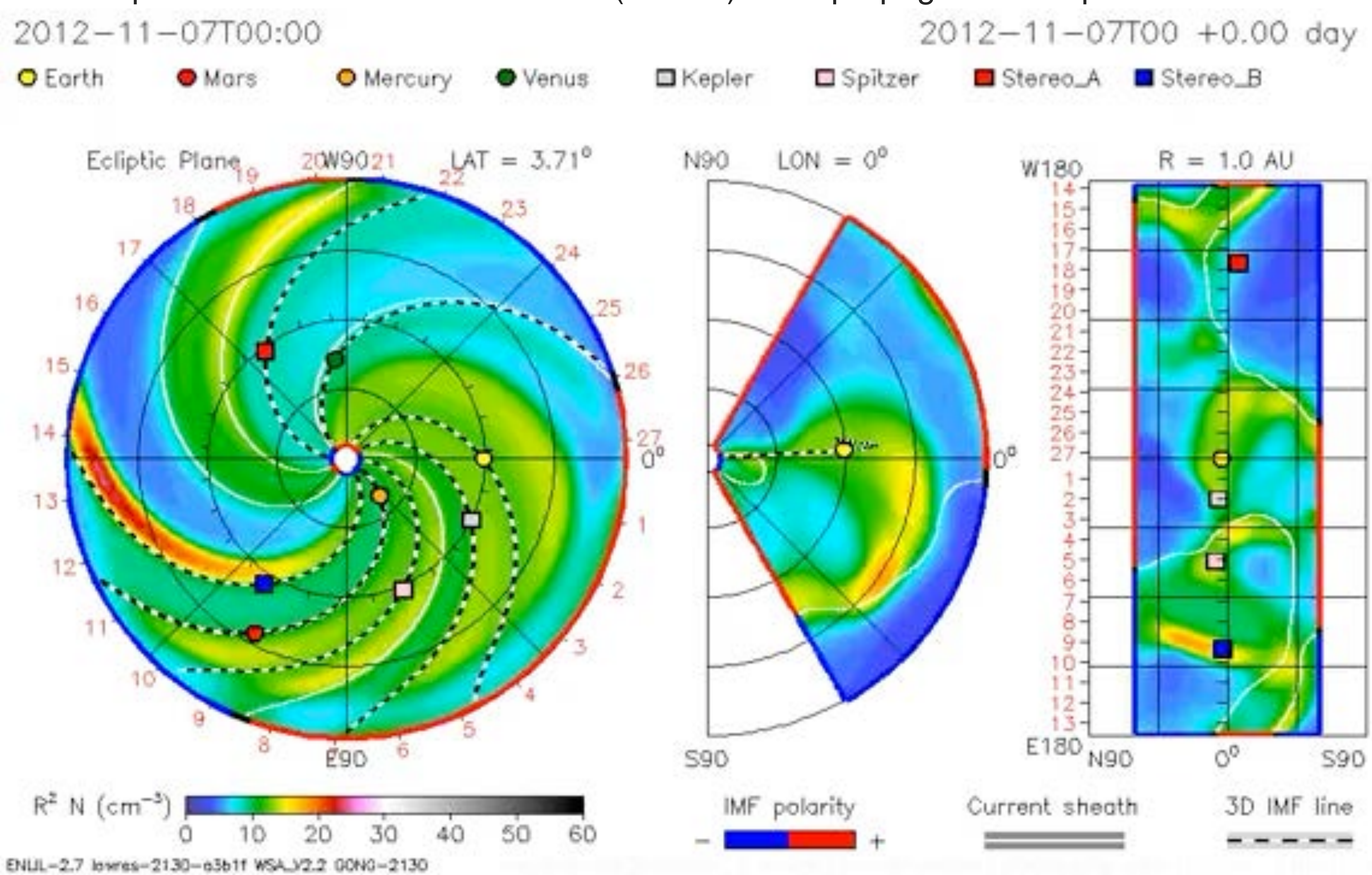
SOHO (ESA & NASA)

Coronal Mass Ejection

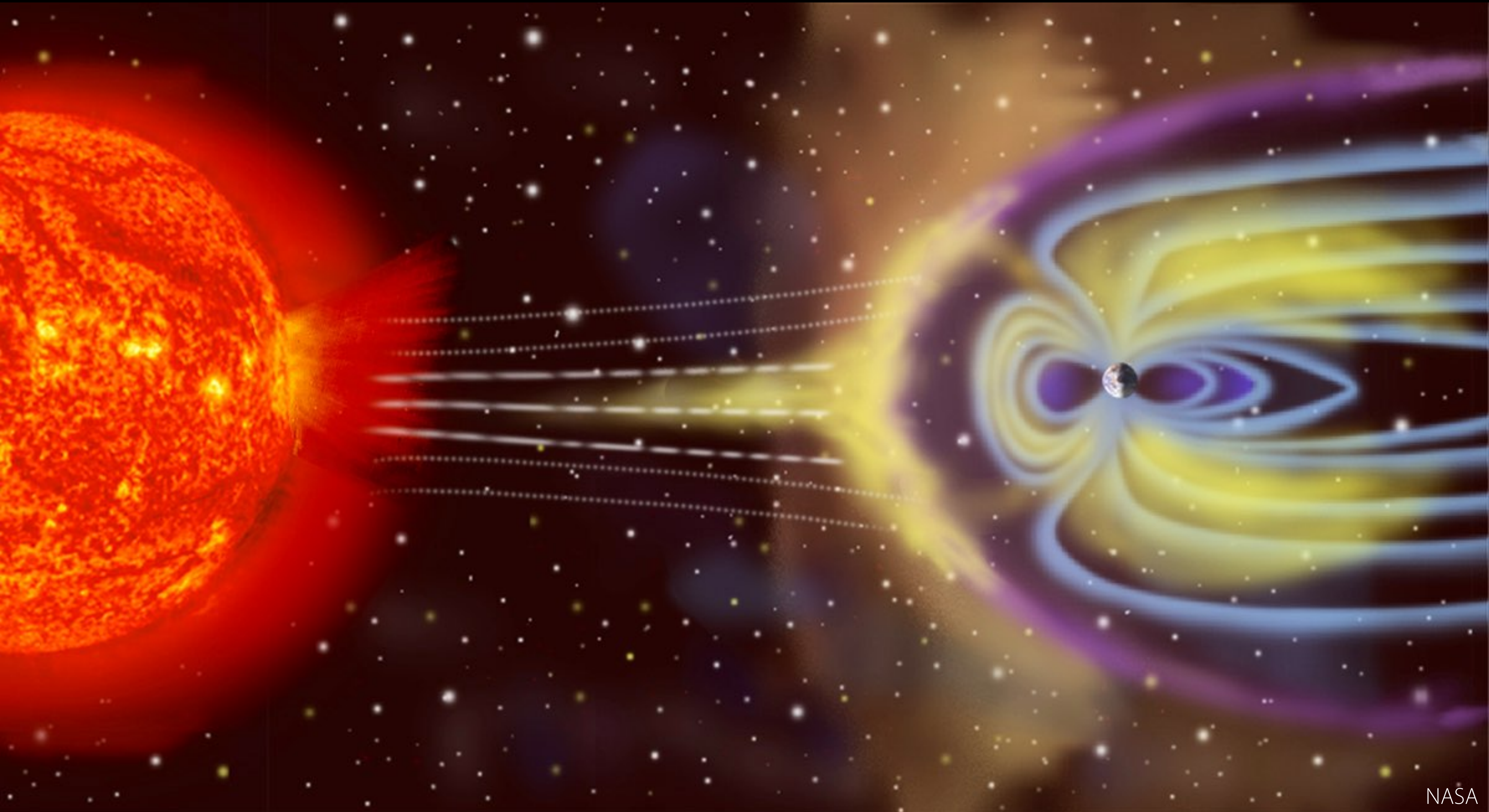
CME propagation

- Depending on initial speed, several days until reaching Earth's orbit (or Earth itself)

NASA Space Weather Research Center (SWRC) CME propagation computer model.

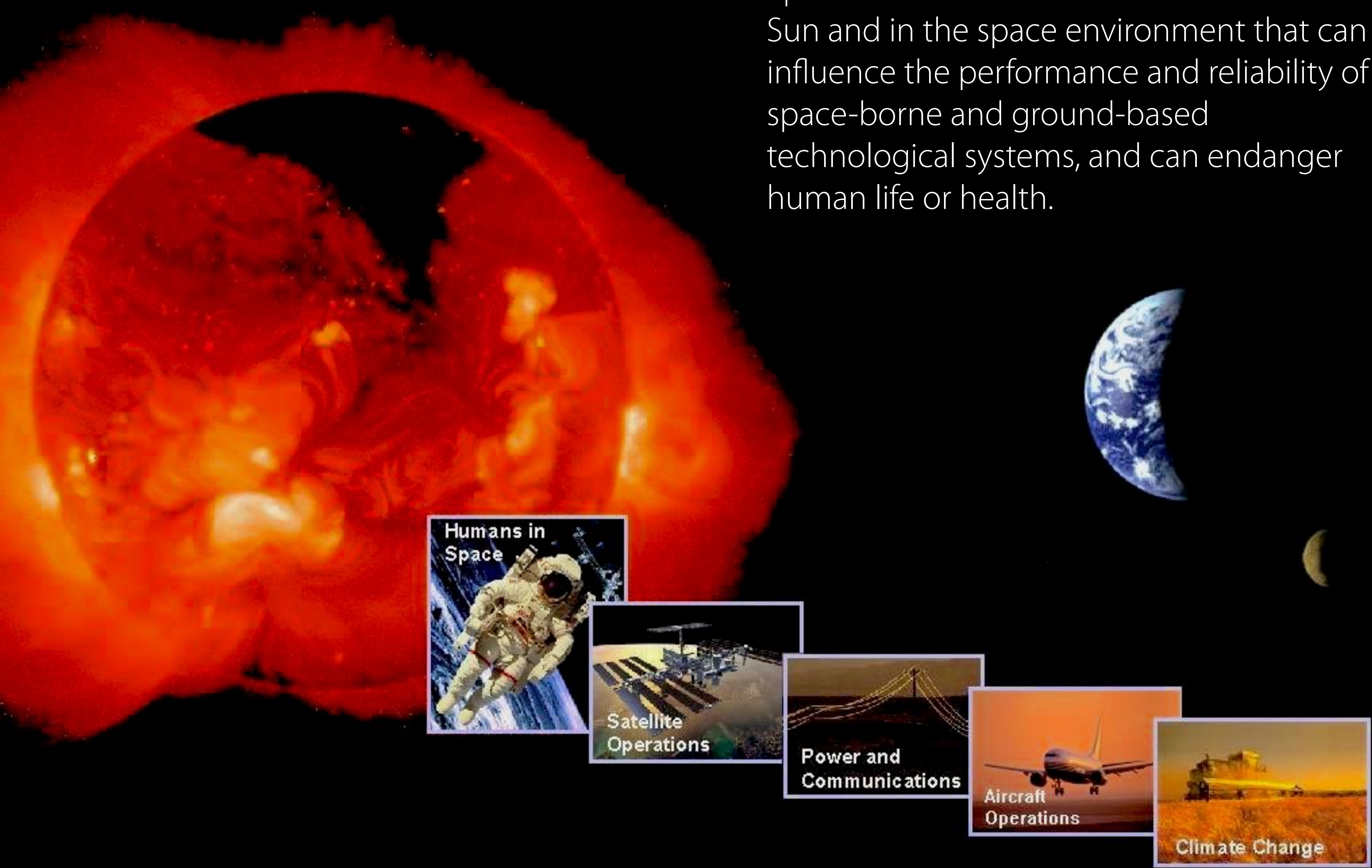


Space Weather



Space Weather

Space weather refers to conditions on the Sun and in the space environment that can influence the performance and reliability of space-borne and ground-based technological systems, and can endanger human life or health.



Space Weather

Solar flare classification	Associated X-ray flux - I (W/m^2)	Possible effects on Earth
B	$I < 1E\text{-}06$	none
C	$1E\text{-}06 \leq I < 1E\text{-}05$	Possible effects on space missions.
M	$1E\text{-}05 \leq I < 1E\text{-}04$	Blackout in radio transmissions and possible damages in astronauts outside spacecraft.
X	$I \geq 1E\text{-}04$	Damage to satellites, communication systems, power distribution stations and electronic equipment

Table 1.1: Description of solar flare classes (TANDBERG-HANSSEN; EMSLIE, 2009)

- **Example: March 1989** - X15 flare + 2 CMEs leading to a geomagnetic storm
  - Some satellites lost control for several hours.
  - GOES satellite communications interrupted, weather images lost.
  - Sensor malfunction on Space Shuttle Discovery
  - Currents induced in power lines in **Quebec**, Canada, leading to **power outage** for 9 hrs.