Review of coronal jets, and the Jet-Heliosphere Connection

Alphonse C. Sterling[1]

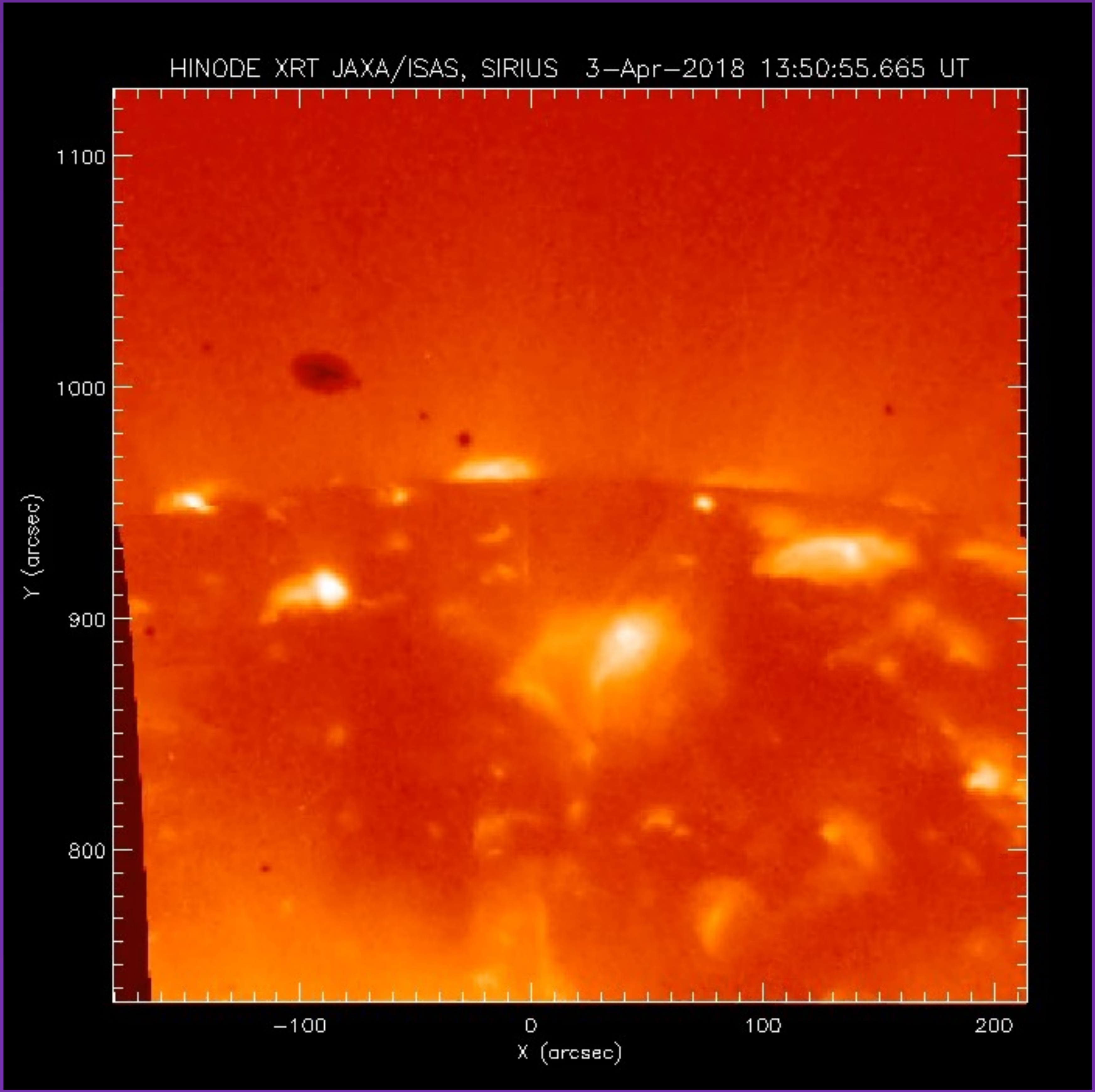
1. NASA/MSFC, Huntsville, AL, USA

Supported by NASA's HSR and HSOC programs, and the MSFC/Hinode project.

Solar Coronal Jets

- Solar coronal jets have been regularly observed since the Yohkoh days (Shibata et al. 1992; Yokohama & Shibata 1995 & 1996; Shimojo et al. 1996; Nisticò et al. 2009, 2015; Cirtain et al. 2007; Savcheva et al. 2007; Moore et al. 2010; etc). For reviews see Shibata & Magara (2011), Raouafi et al. (2016), Hinode Review Team et al. (2019, section by Sterling), Shen (2021).
- In polar coronal holes: size ~50,000 km x 8000 km; rate ~60/day (Savcheva et al. 2007).
- Often have a "hot loop" at the jet's base, located asymmetrically off to one side of the base.
- Many jets show twisting motions during their growth phase (e.g., Pike & Mason 1998, Kamio et al. 2010, Moore et al. 2015).
- Sterling et al. (2015) argued that they form from "minifilament eruptions"; small-scale versions of large-scale filament eruptions.

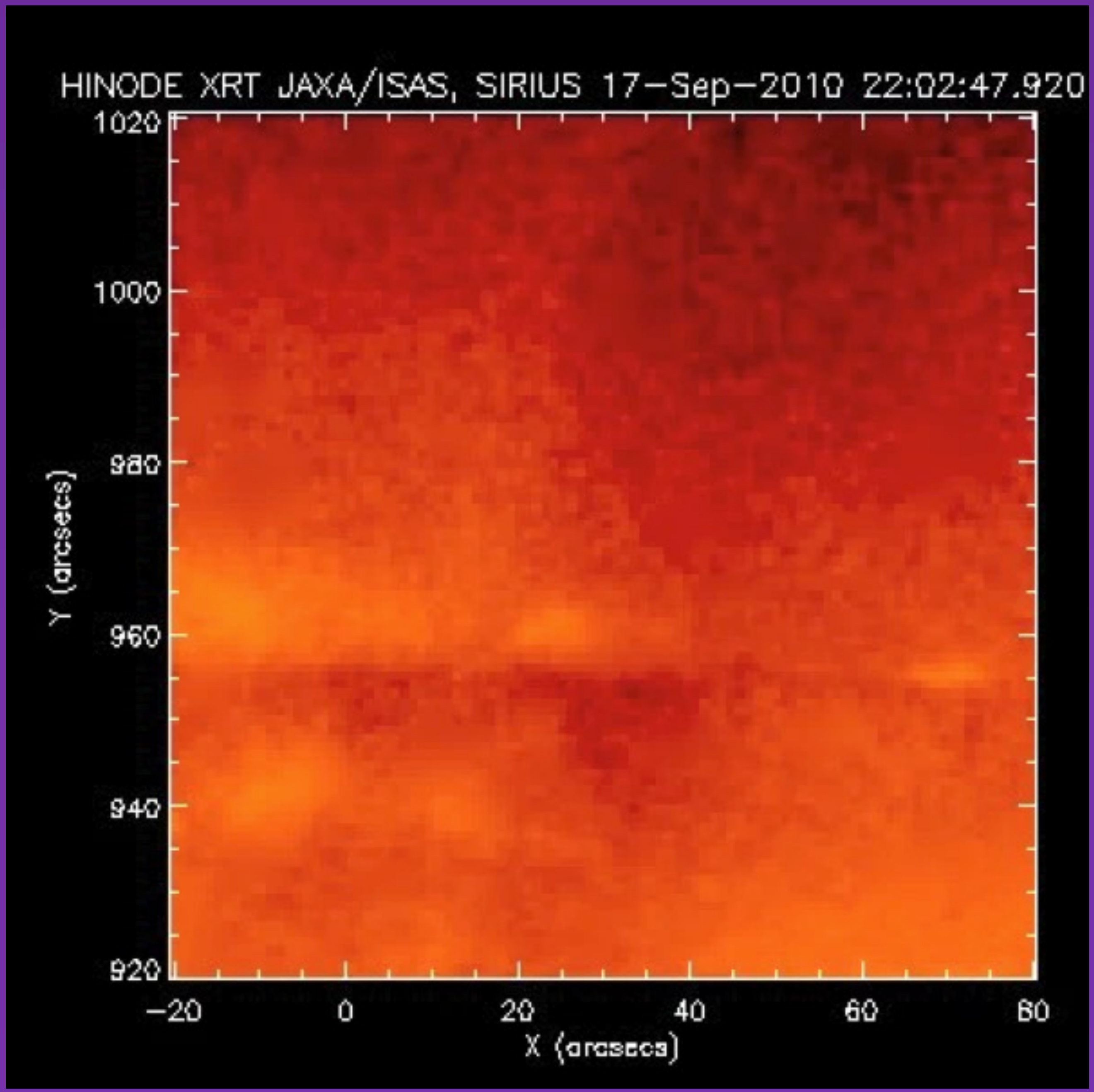
Hinode XRT



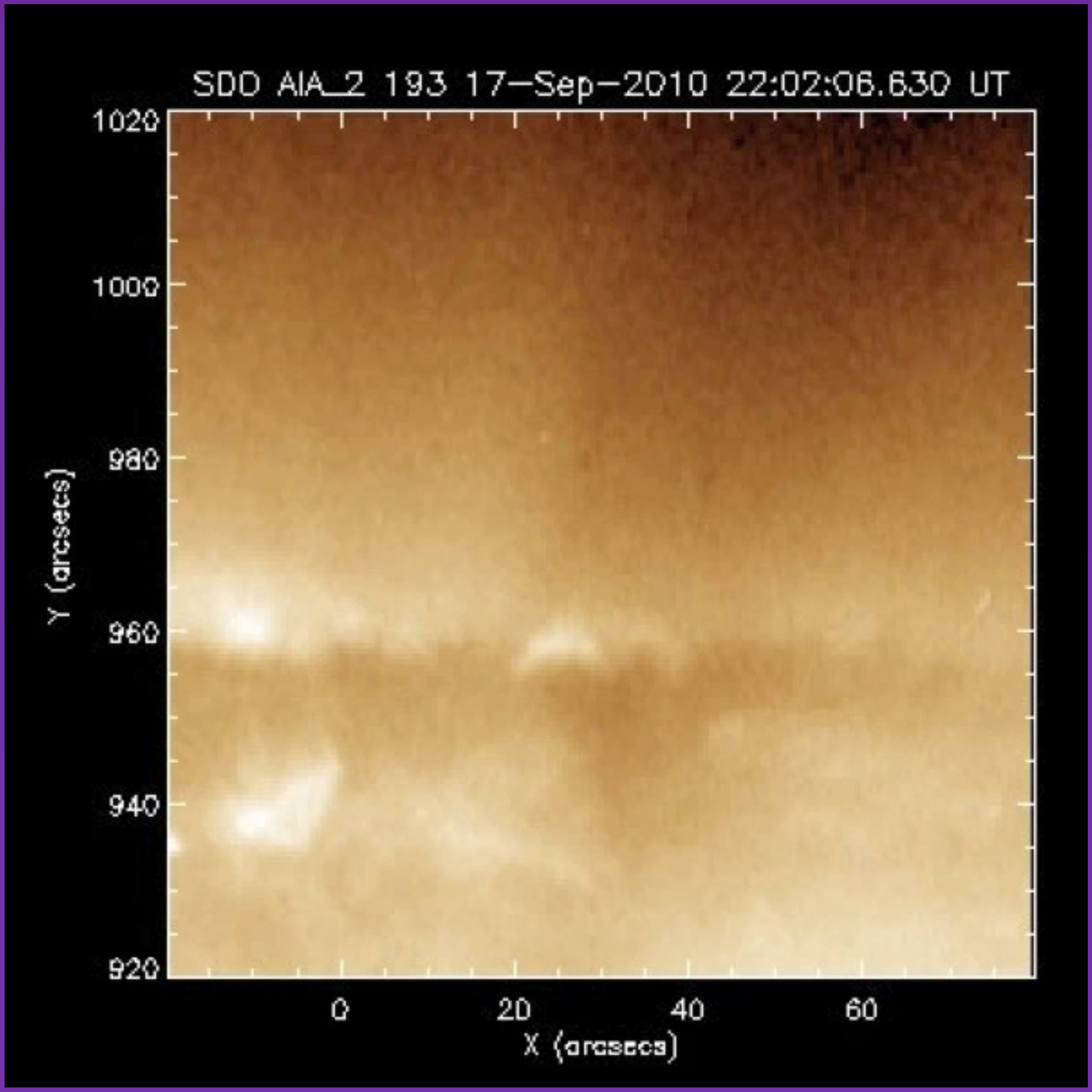
Sterling et al. (2022)

Coronal Hole Jets: “Minifilament eruptions”

XRT

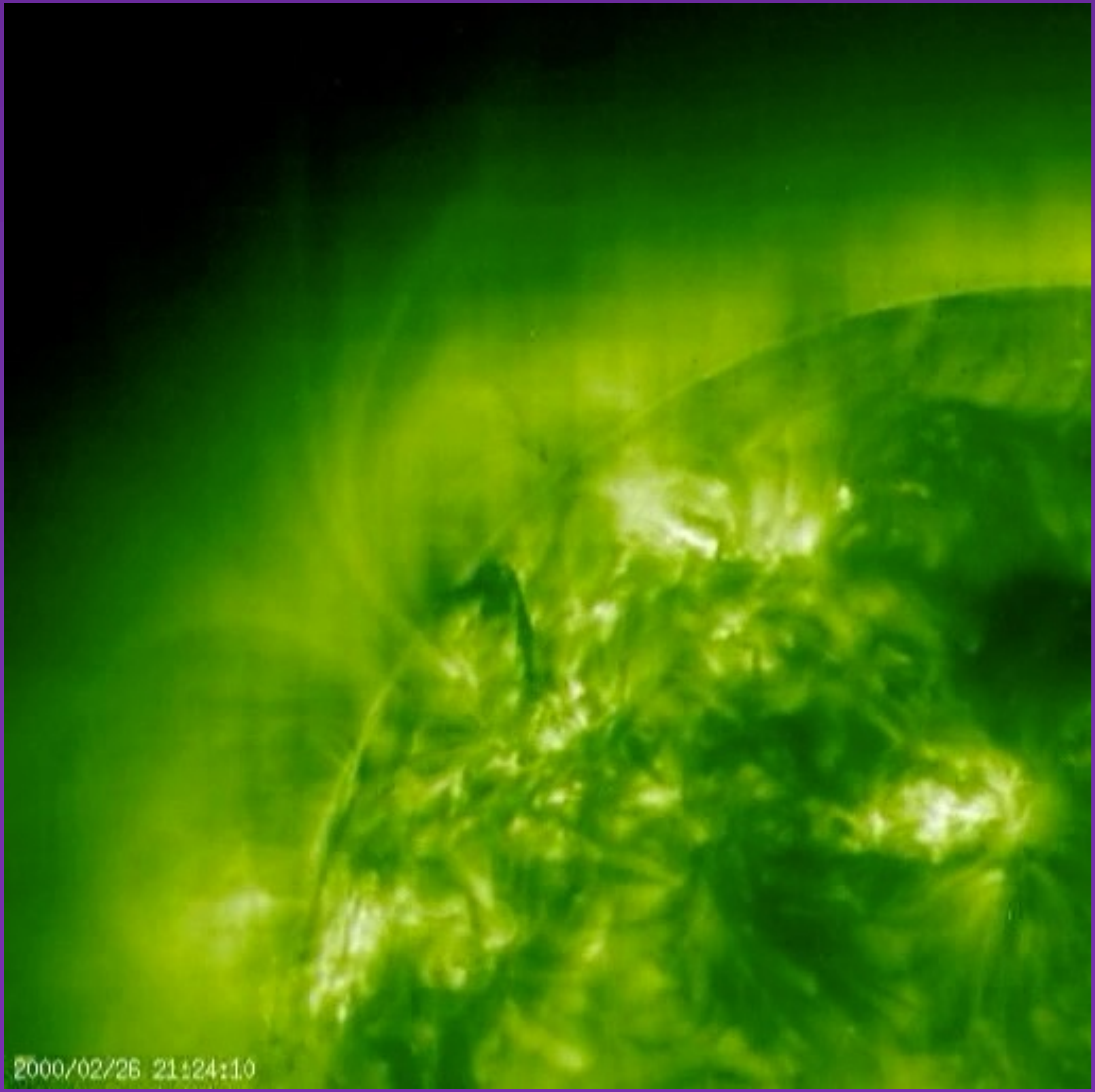


AIA 193



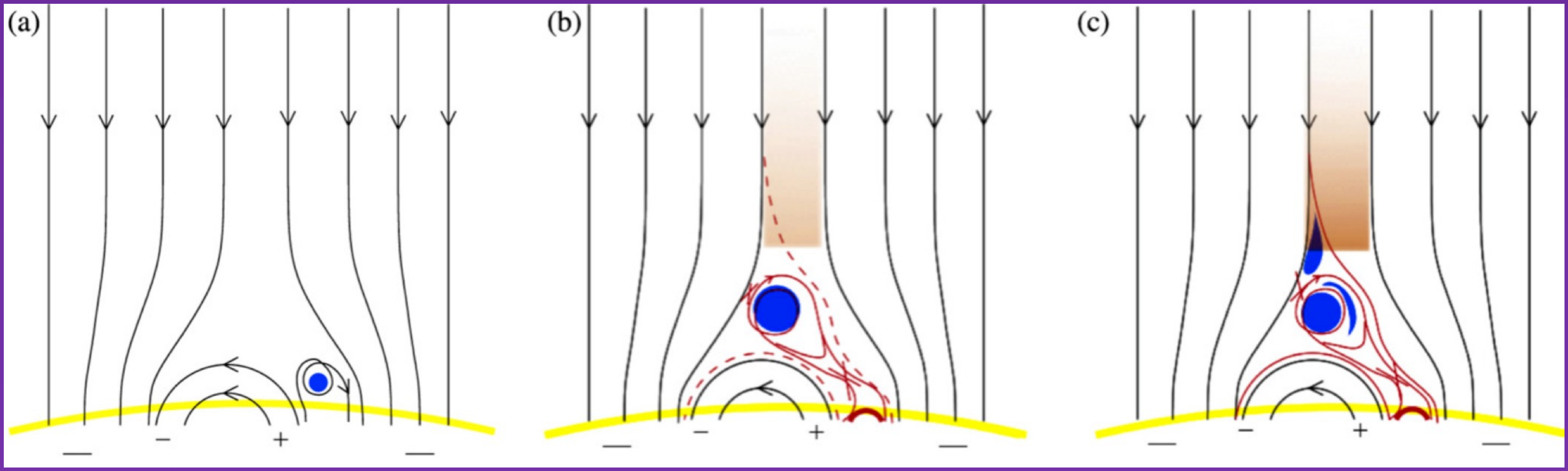
Sterling et al. (Nature, 2015): 20 Polar CH jets.

“Normal” Filament Eruption (SoHO/EIT)

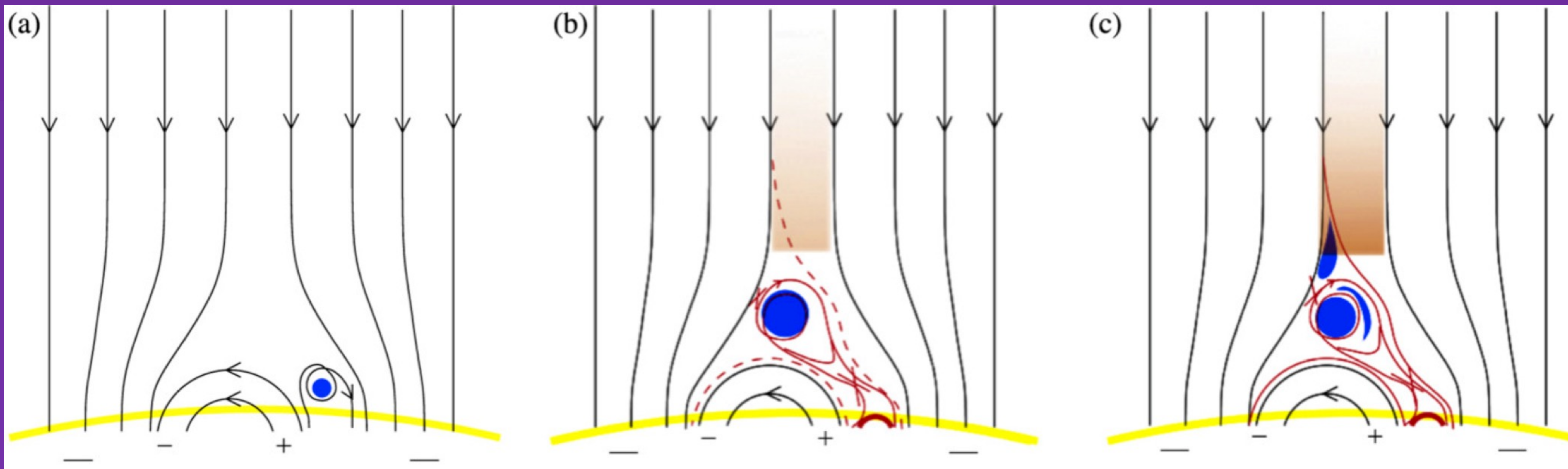


A. Sterling

(Sterling & Moore 2004)



(Sterling et al. 2015)



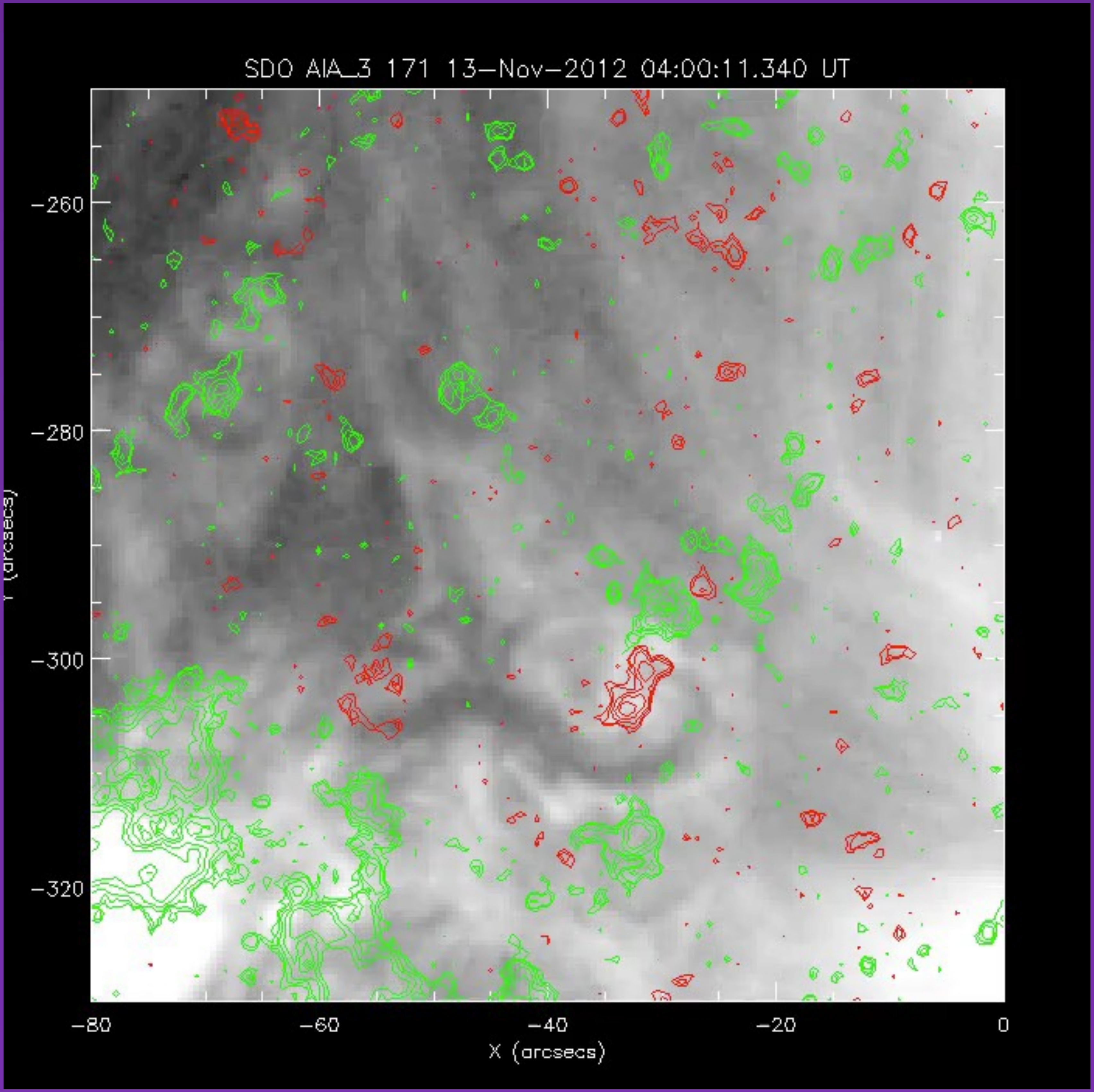
(Sterling et al. 2015)

(Numerical simulations/modeling: Wyper et al. 2017, Farid et al. 2022.)

What Causes Miniature-Filament Eruptions?

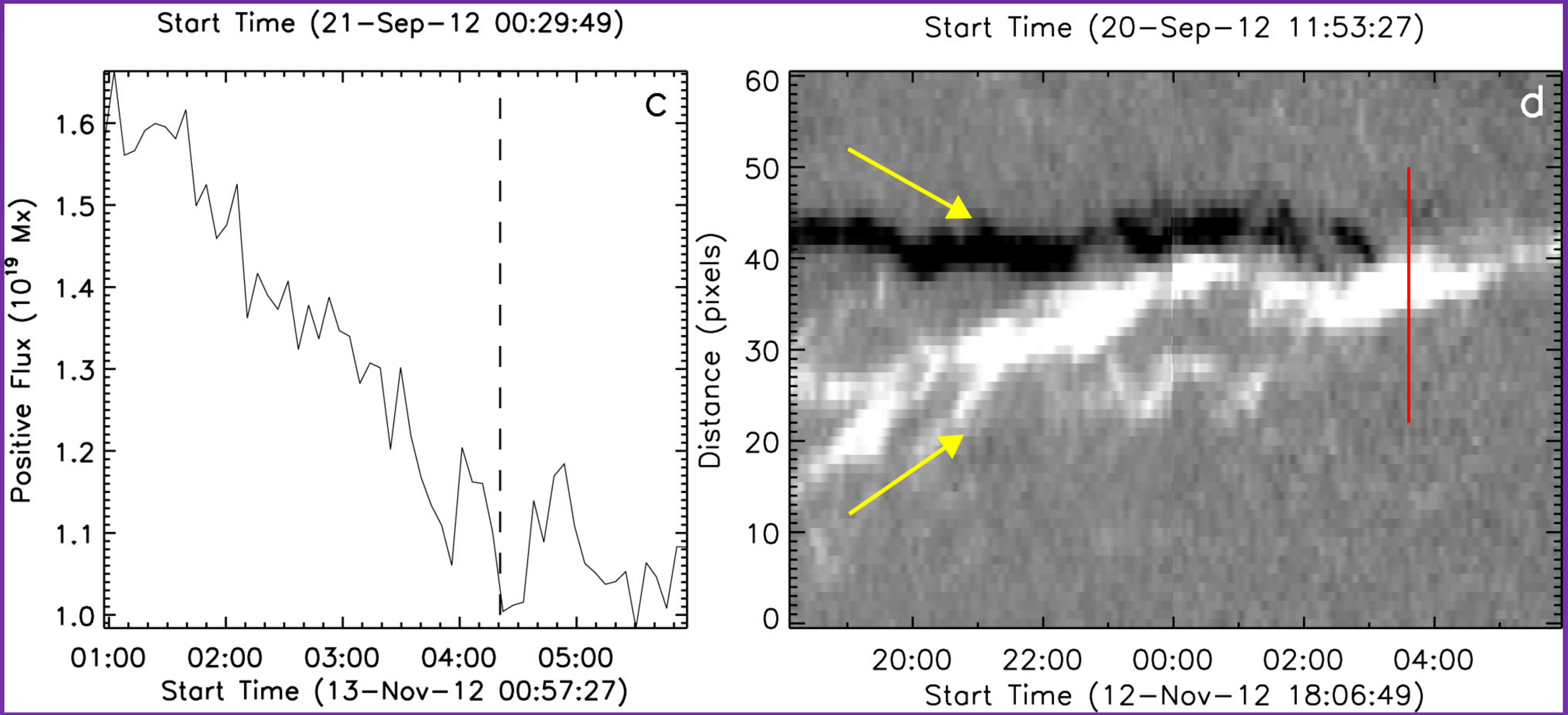
- Several studies found flux cancelation leading to jets (e.g., Hong et al. 2011, 2014; Huang et al. 2012; Young & Muglach 2014a,b; Adams et al. 2014; Muglach 2021).

- Some other studies found jets from location of emerging flux+flux cancelation (e.g., Liu et al. 2011; Shen et al. 2012, 2017; Hong et al. 2012; Li et al. 2015), or perhaps strong convergence and shearing (Kumar et al. 2018).



(cf. Panesar et al. 2016)

Same for QS jets: Occur at cancelation sites.



(Ave. Cancelation rate: ~10^{18} Mx/hr.)

Panesar, Sterling, & Moore (2016b)

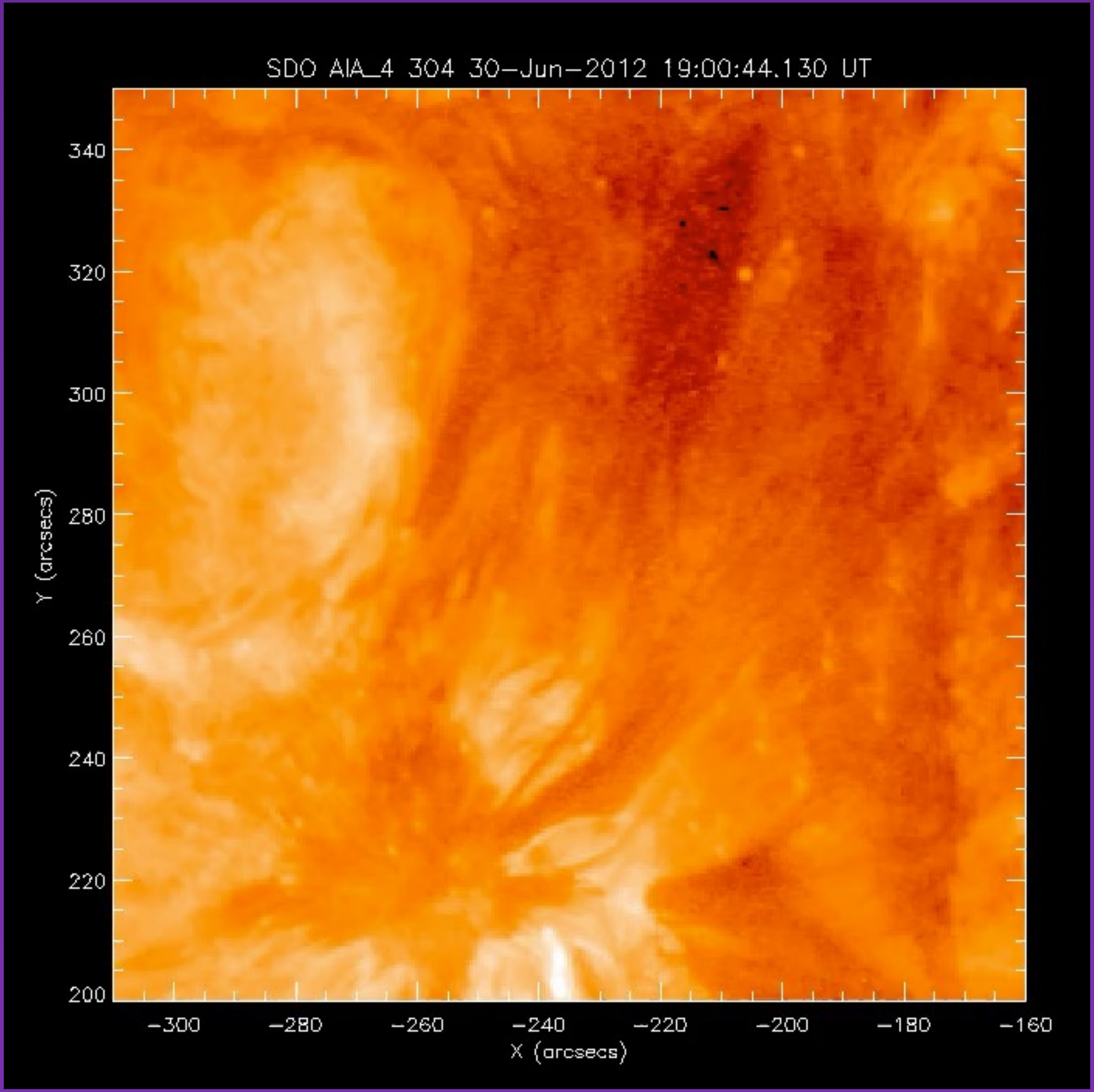
Heliospheric Connection

- CMEs/outflows: Some coronal jets make "white-light jets," aka "narrow CMEs" (width $\lesssim 10^{o} - 15^{o}$; Wang et al. 1998, Moore et al. 2015). And some ARs jets make broad CMEs (e.g., Panesar et al. 2016b). Far-away blobs: Yu et al. (2014, 2016).

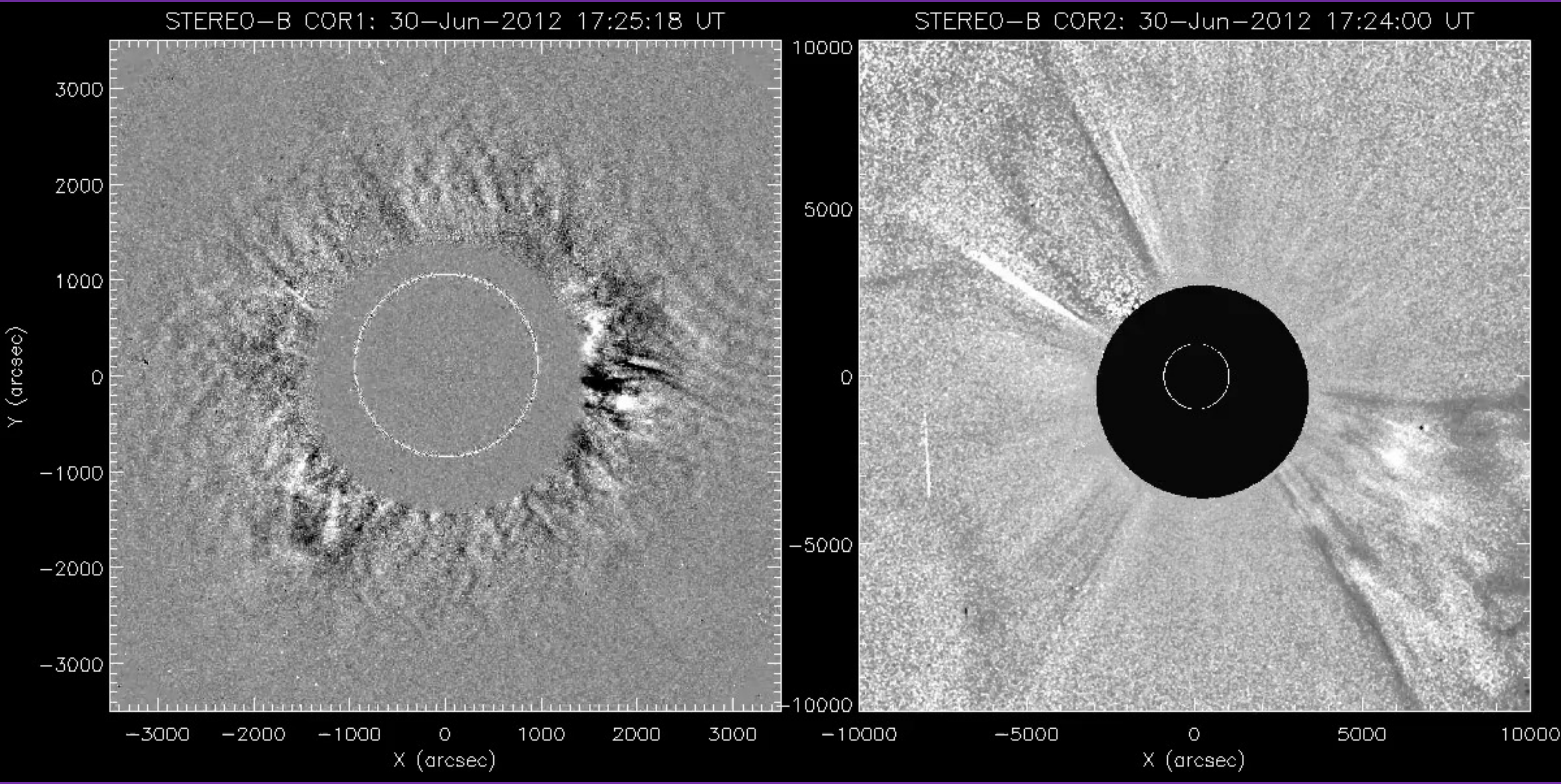
- Plumes: Small-scale jets occur both inside of and outside plumes (Raouafi et al. 2023). Some jets may start plumes (Raouafi et al. 2008, Pucci et al. 2014).

- Recent ideas: Jet-like features might be the source of PSP-observed magnetic switchbacks (Sterling & Moore 2020). Jet-like features might contribute to the solar wind (Moore et al. 2011, Raouafi et al. 2023).

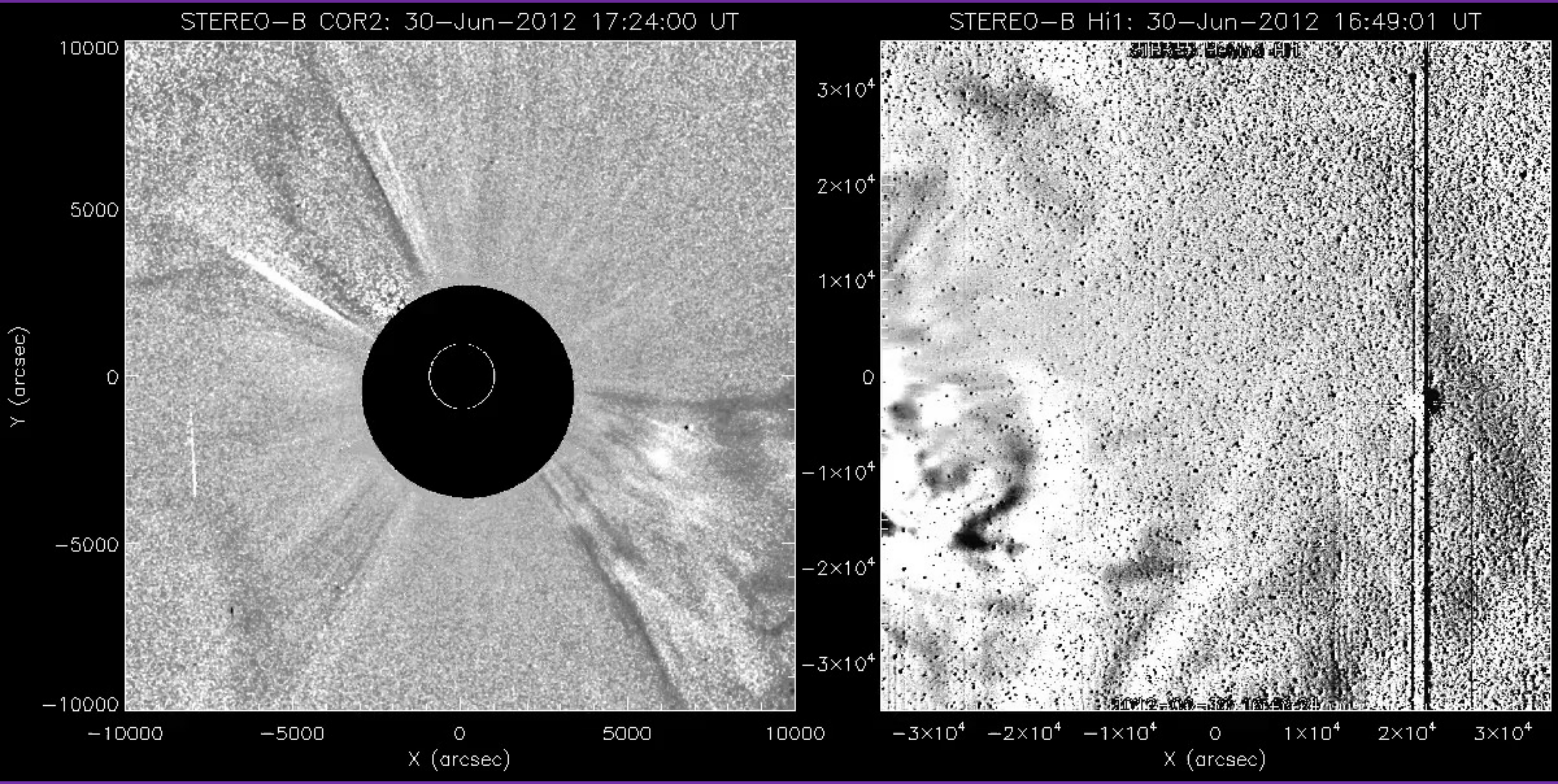
Jet/Narrow-CME Connection



Sterling & Moore (2020)

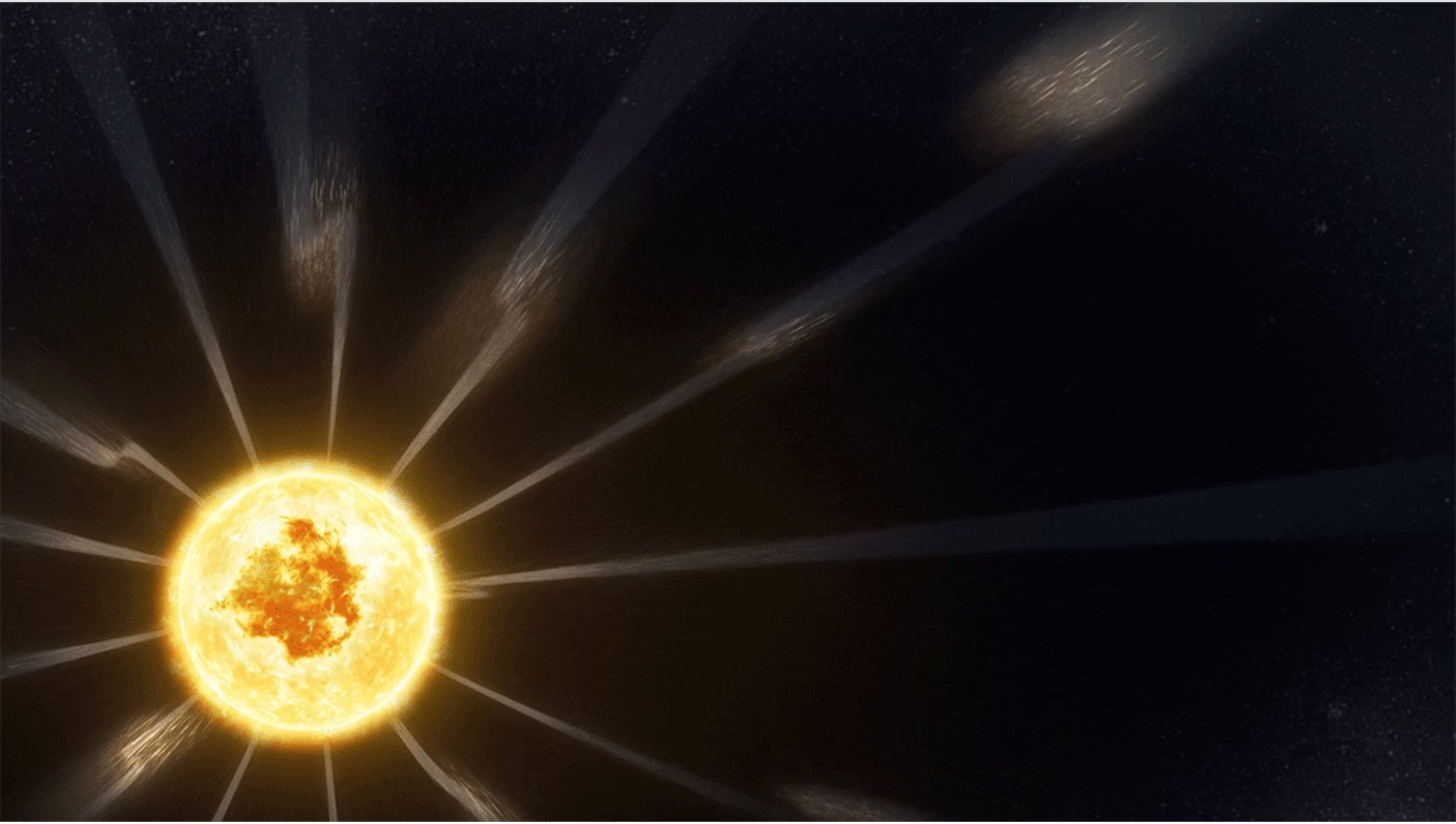


Sterling & Moore (2020)



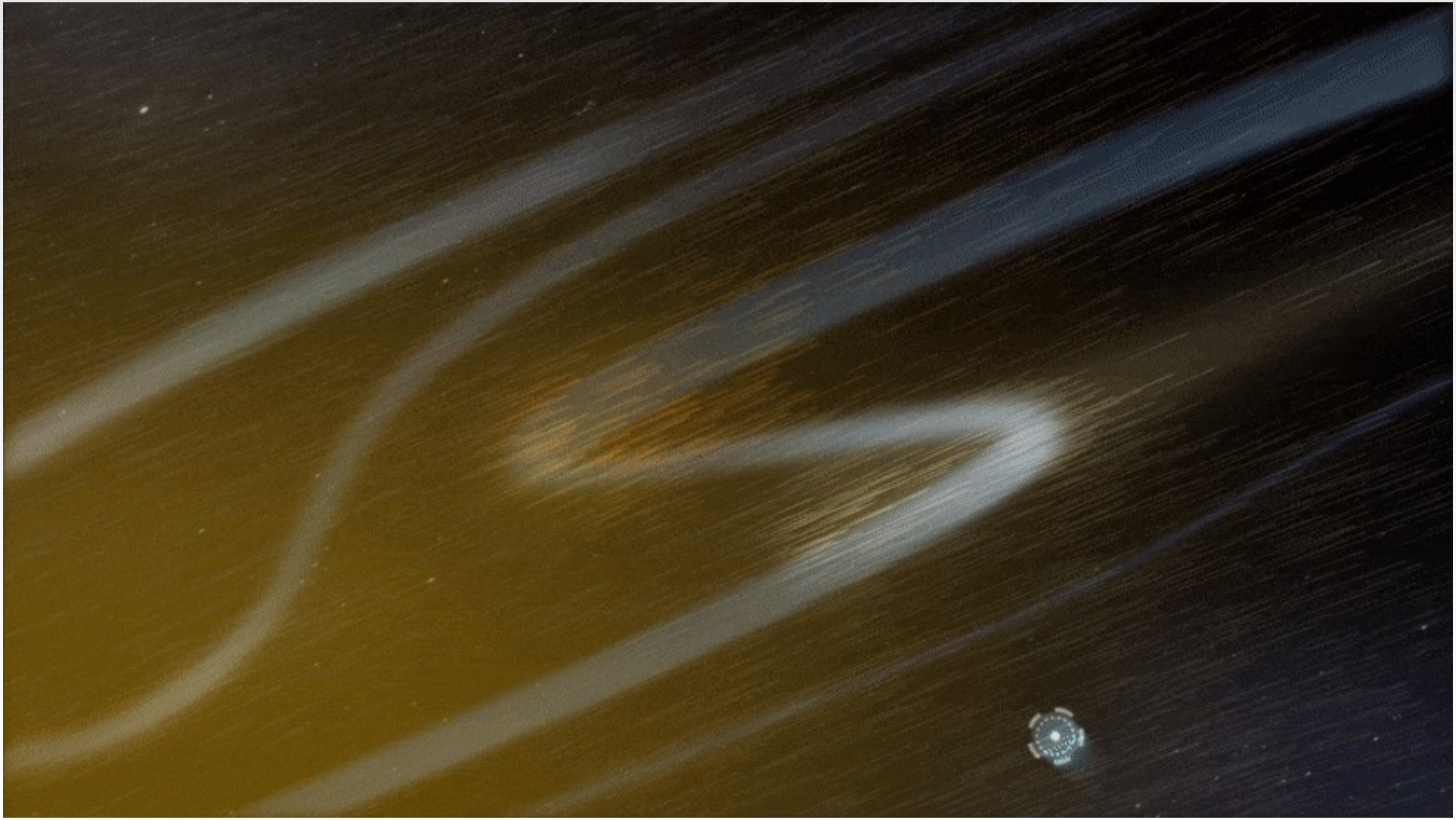
Sterling & Moore (2020)

Possible Switchback Connection



GSFC/Adriana Marique Gutierrez

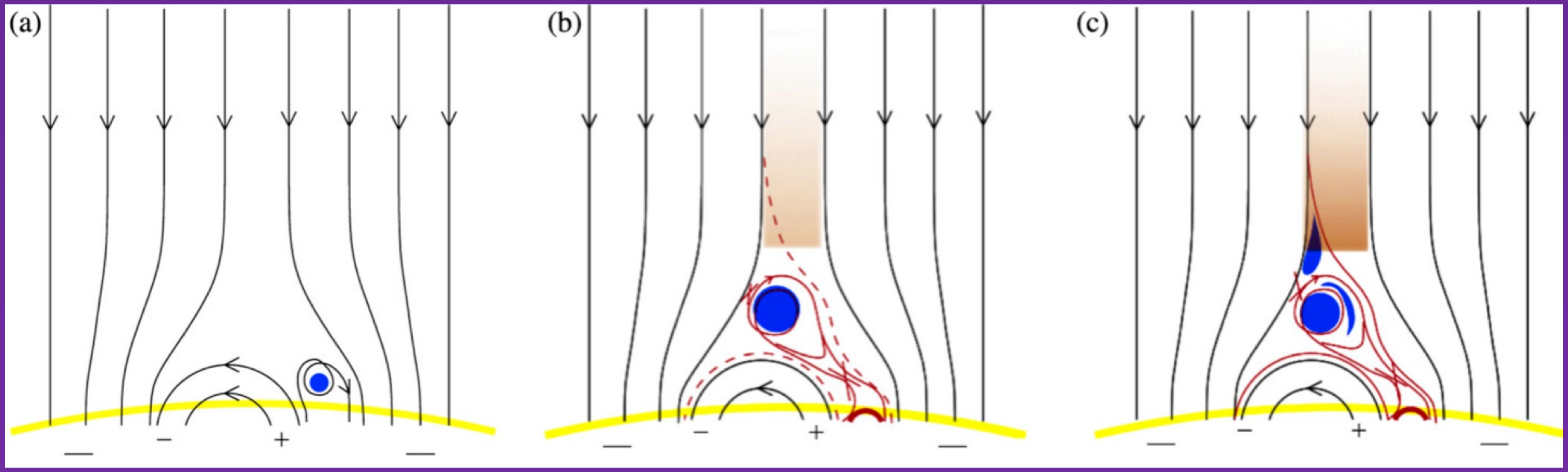
https://www.nasa.gov/feature/goddard/2021/switchbacks-science-explaining-parker-solar-probe-s-magnetic-puzzle



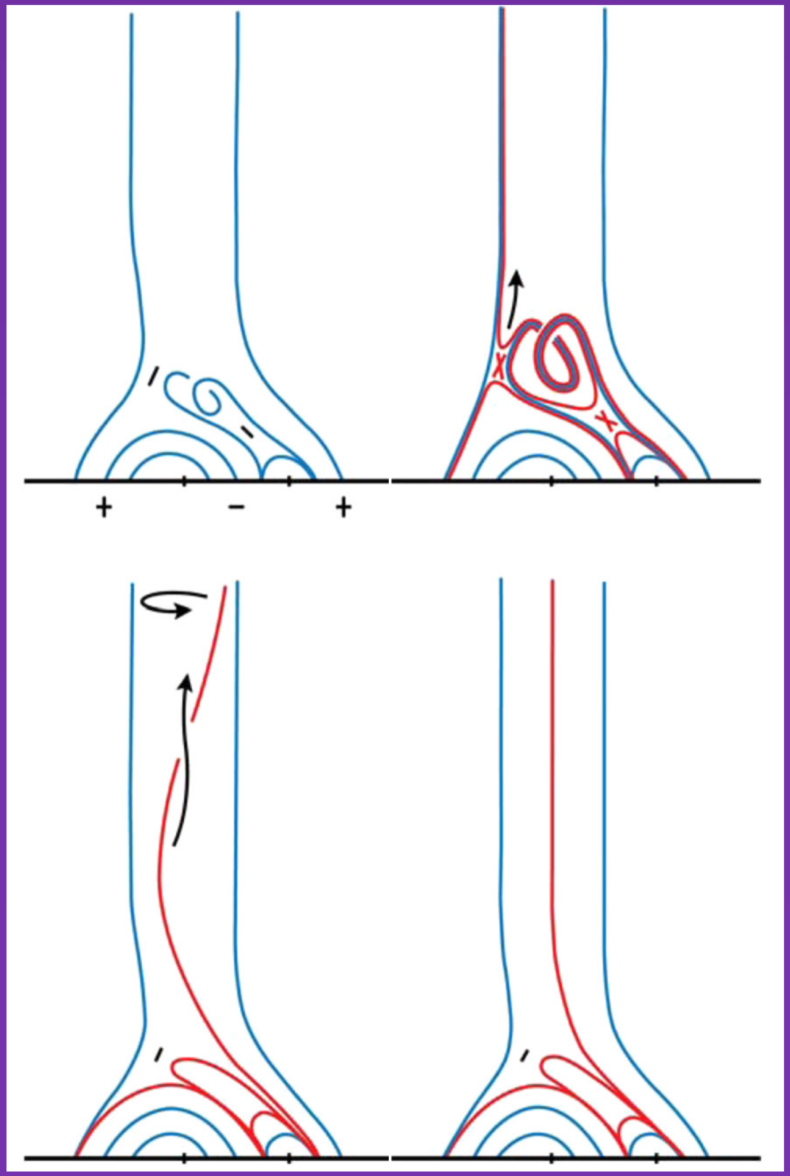
GSFC/Adriana Marique Gutierrez

https://www.nasa.gov/feature/goddard/2021/switchbacks-science-explaining-parker-solar-probe-s-magnetic-puzzle

- A jet could launch a magnetic twist onto open field.
- The resulting magnetic packet would propagate out along the field at the Alfvén speed.
- That speed varies with distance from the Sun: ~1000 km/s in the corona, and ~100 km/s at 35 R_sun.
- The wave packet, initially of size ~R_sun (Moore et al. 2015, Sterling & Moore 2020), will feel different Alfvén speeds at its front and near-Sun sides; this Alfvén-speed gradient will result in the wave packet becoming more compact with distance from the Sun.
- The result will be a feature that PSP could detect as a switchback.

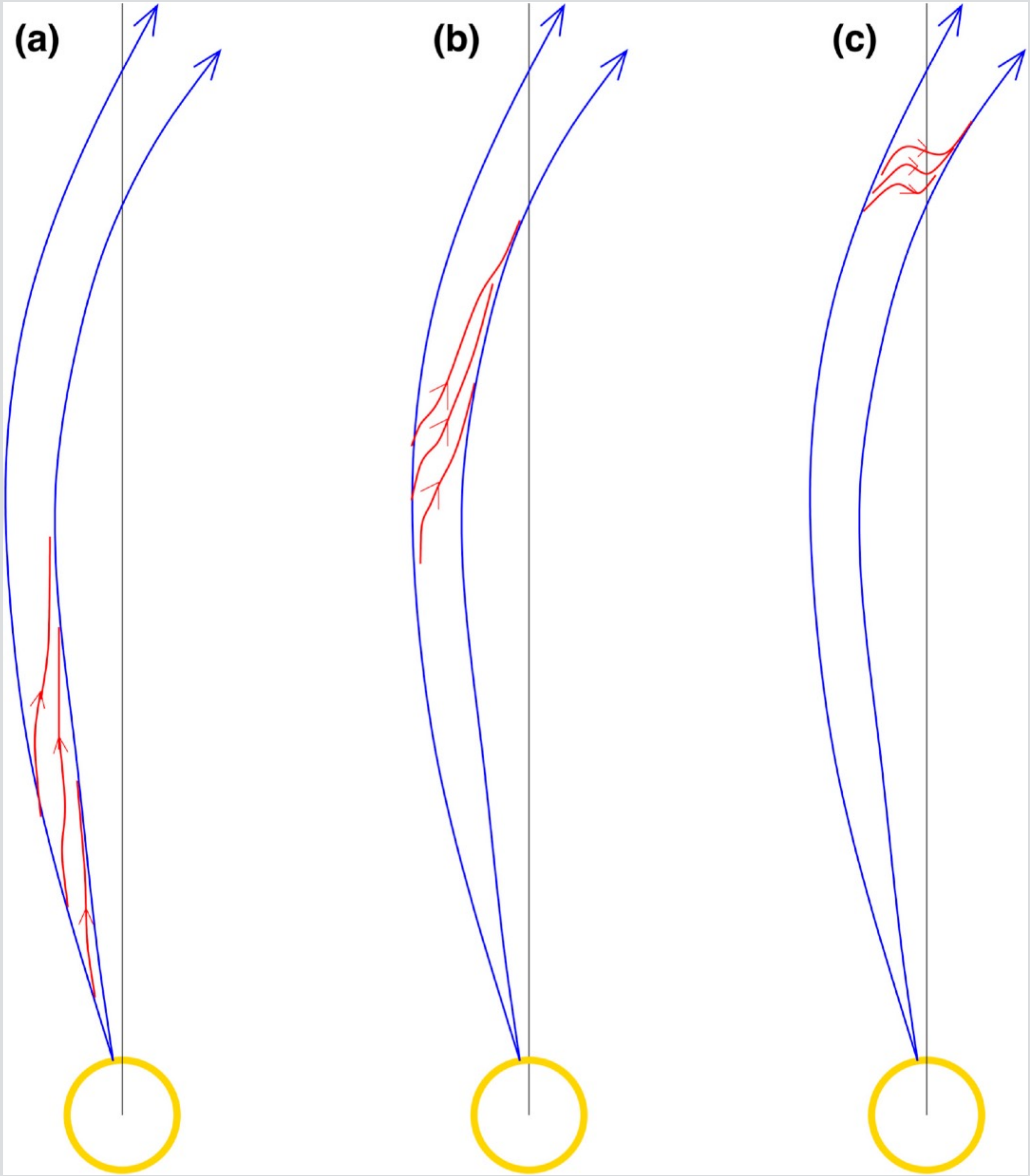


(Sterling et al. 2015)



(Moore et al. 2015)

(Cf. Shibata & Uchida 1986)

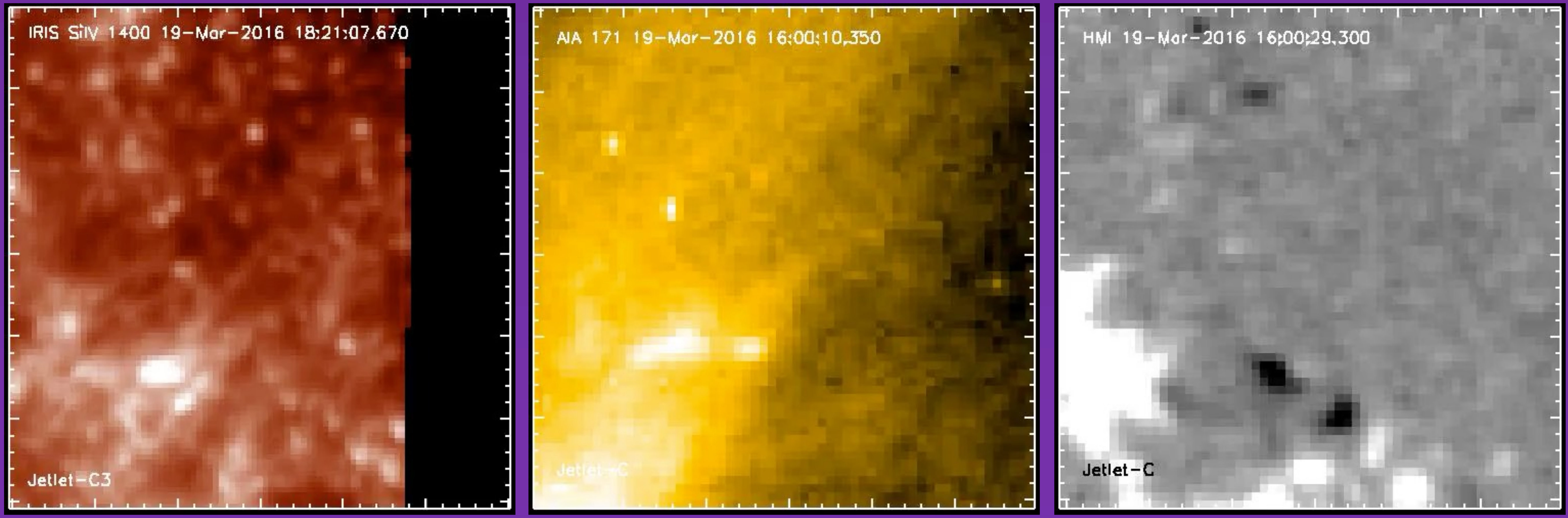


Sterling & Moore (2020)

“Jets” on Smaller Size Scales

Jetlets

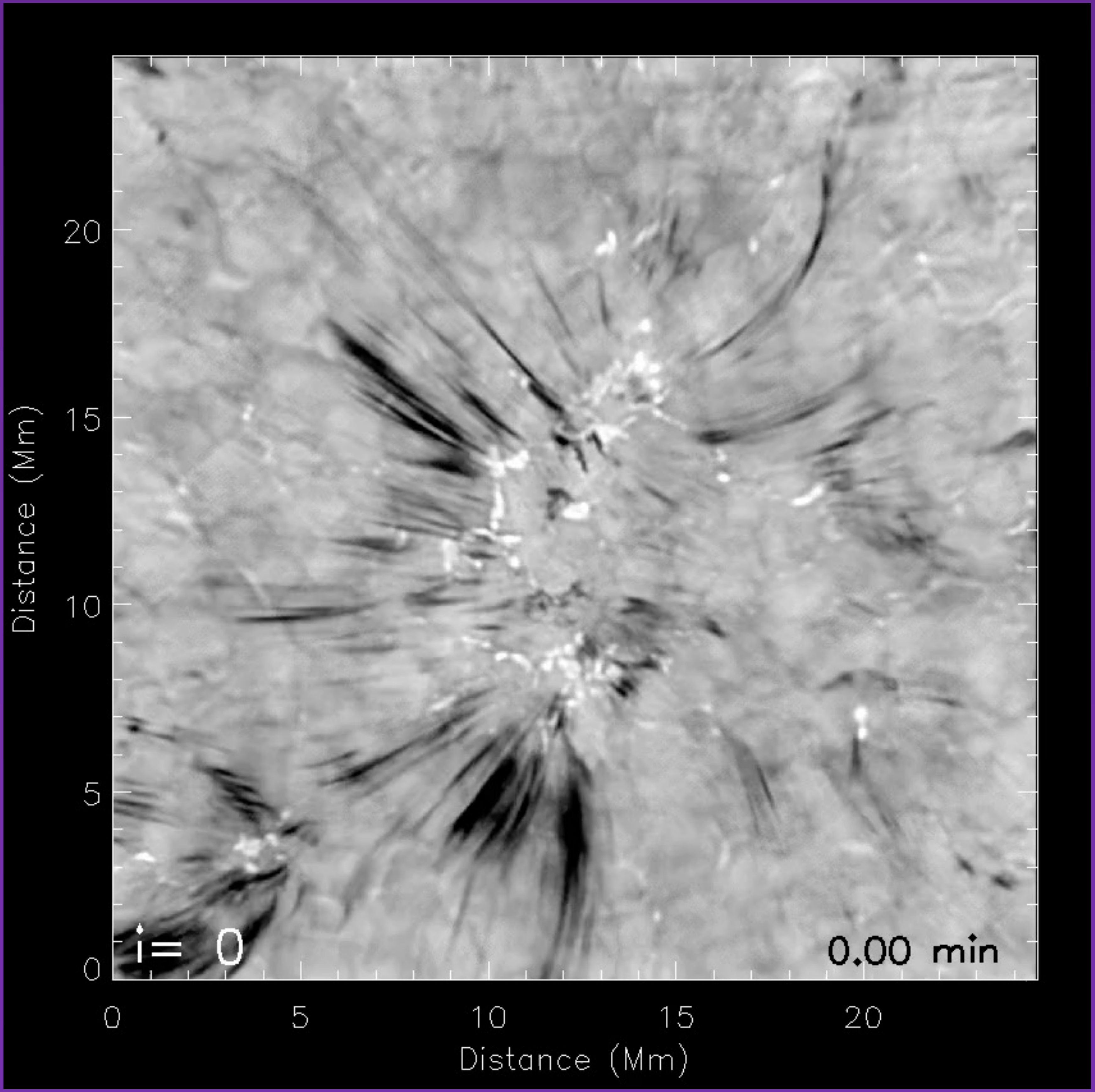
- Smaller than jets, larger than spicules.
- Seen in EUV, and in UV (IRIS).
- First identified at plume bases (Raouafi & Stenborg 2014).
- Also occur in more general network locations (Panesar et al. 2018).



Panesar et al. (2018)

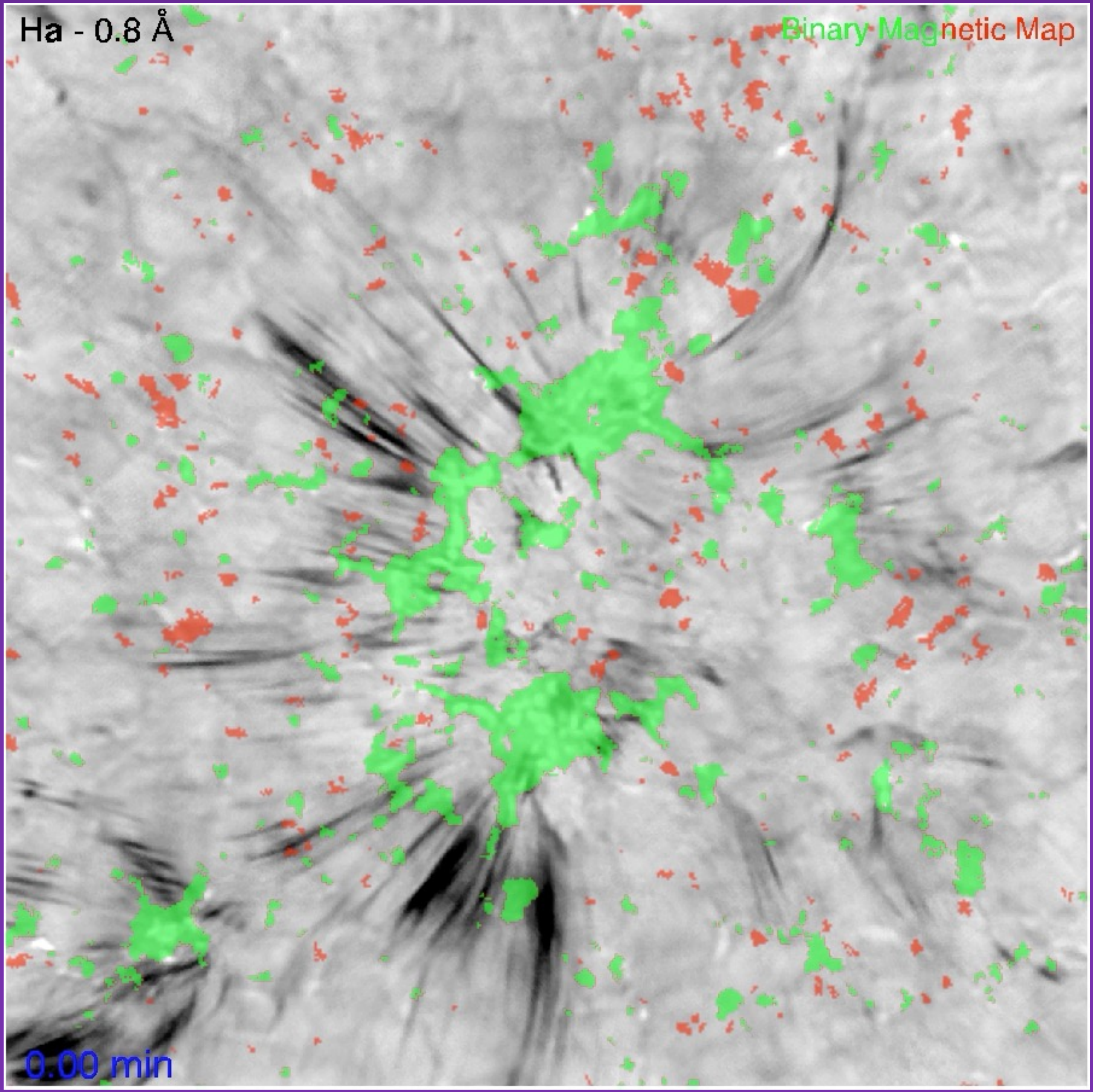
Spicules

- Chromospheric features, observed for well over 100 years.
- Share *some* properties with jets (Sterling & Moore 2016, Sterling et al. 2020a).
  - Jet-like appearance and dynamics.
  - Often spin.
  - Magnetic bases (Samanta et al. 2019).
- Comparison lacks in other ways:
  - No clear evidence for erupting microfilament.
  - No confirmed base brightenings.



Samanta et al. (2019, Science); Sterling et al. (2020a)

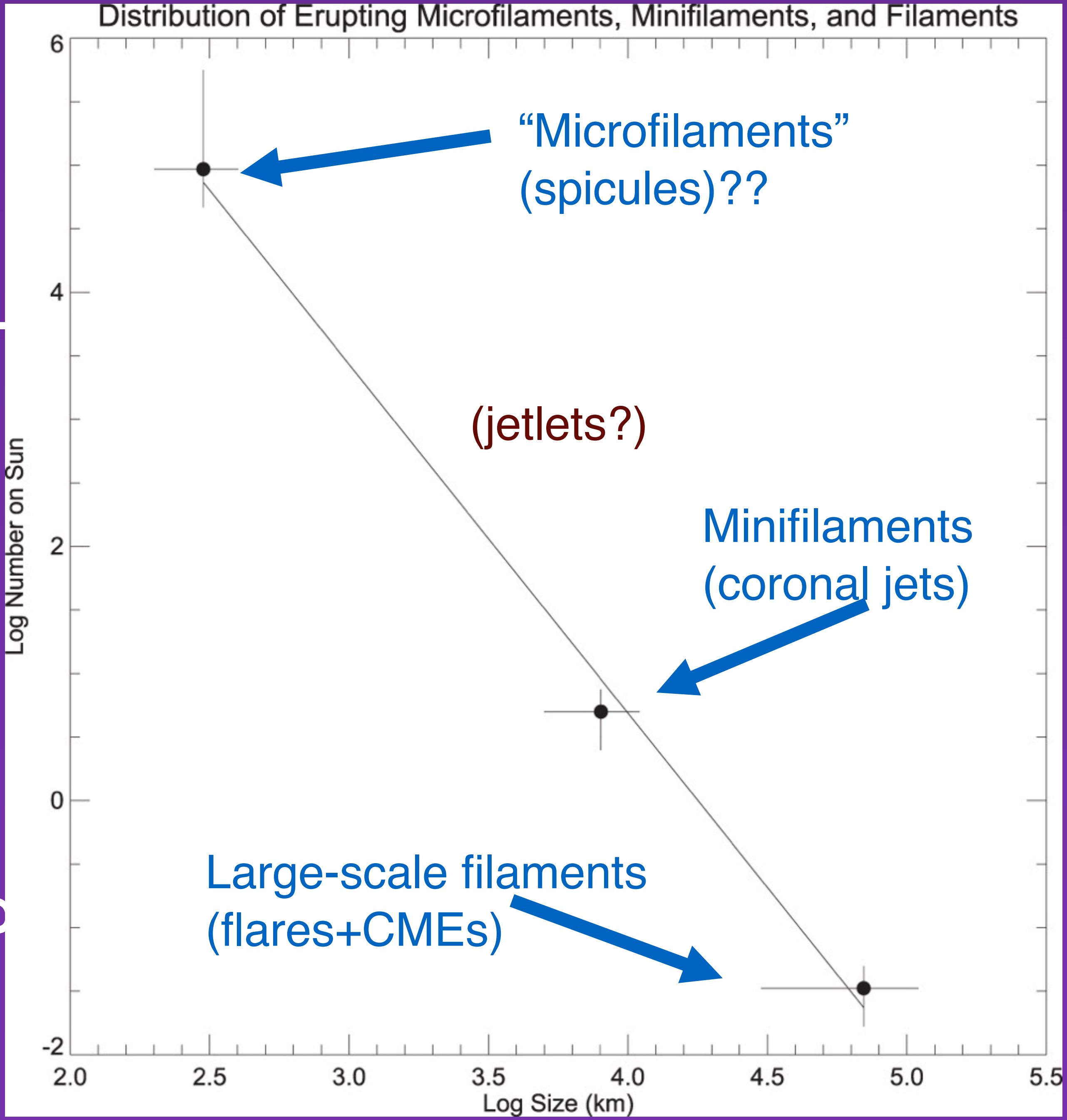
A. Sterling



A. Sterling

Samanta et al. (2019, Science)

Filament-Like Feature Eruptions on Smaller Scales??

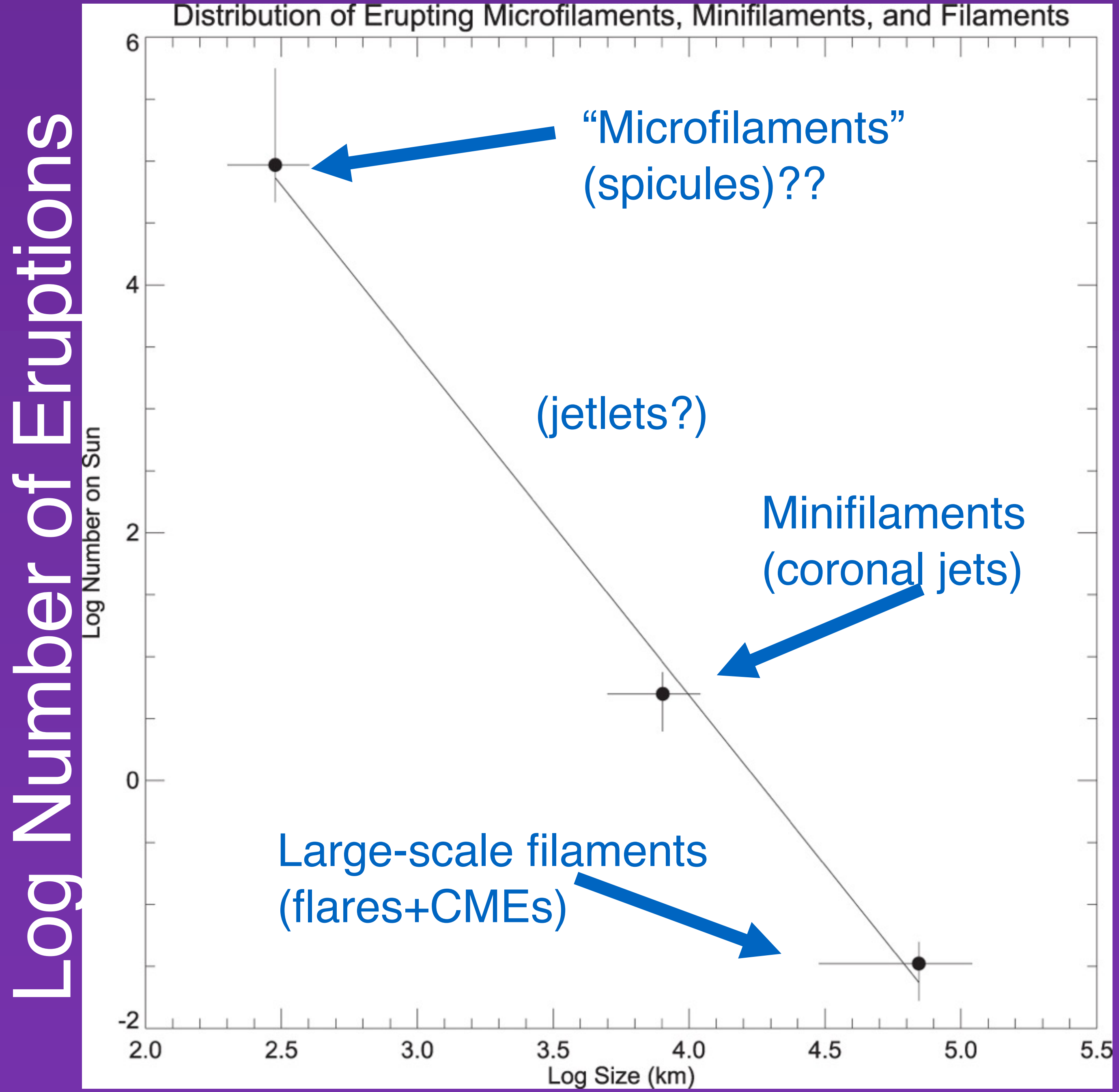


Log Number of Eruptions

Log "Filament" Size

Sterling & Moore (2016)

Filament-Like Feature Eruptions on Smaller Scales??



Log “Filament” Size

Sterling & Moore (2016)

If all size-scale jets contribute, they might cotribute to many switchbacks and much of the solar wind.

Summary

- Approaching a good understand of coronal jets: At least many jets are miniature filament eruptions triggered by flux cancelation. AR jets are likely similar, but altered due to the more-complex AR field.

- Jets reach into the heliosphere, with white-light jets/narrow CMEs, and plasma outflows.

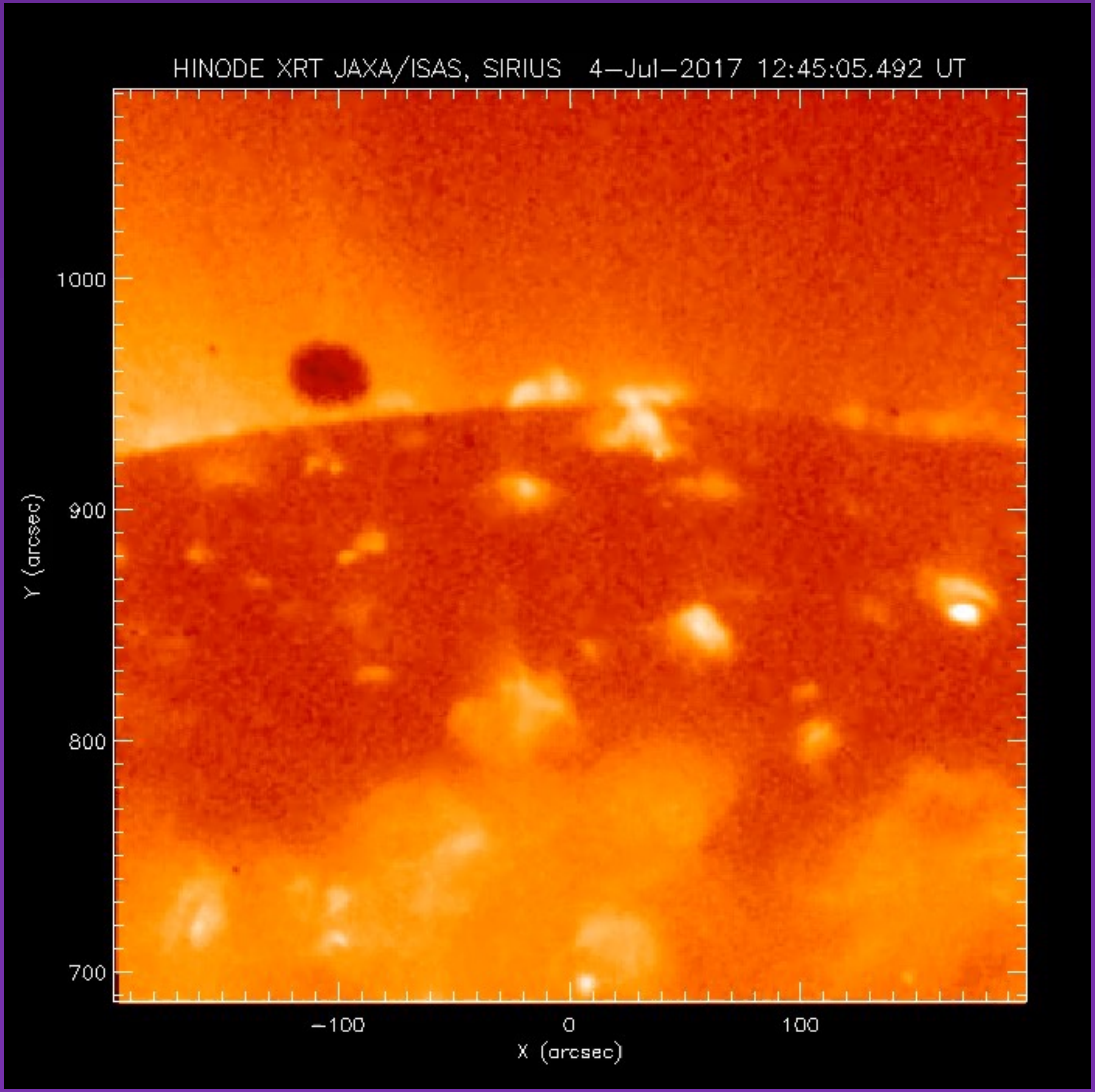
- How does jet physics scale to different sizes? (Large eruptions? ``Jetlets''? Spicules??)

- Might jets (and/or jet-like features) be the source of the PSP-observed switchbacks?

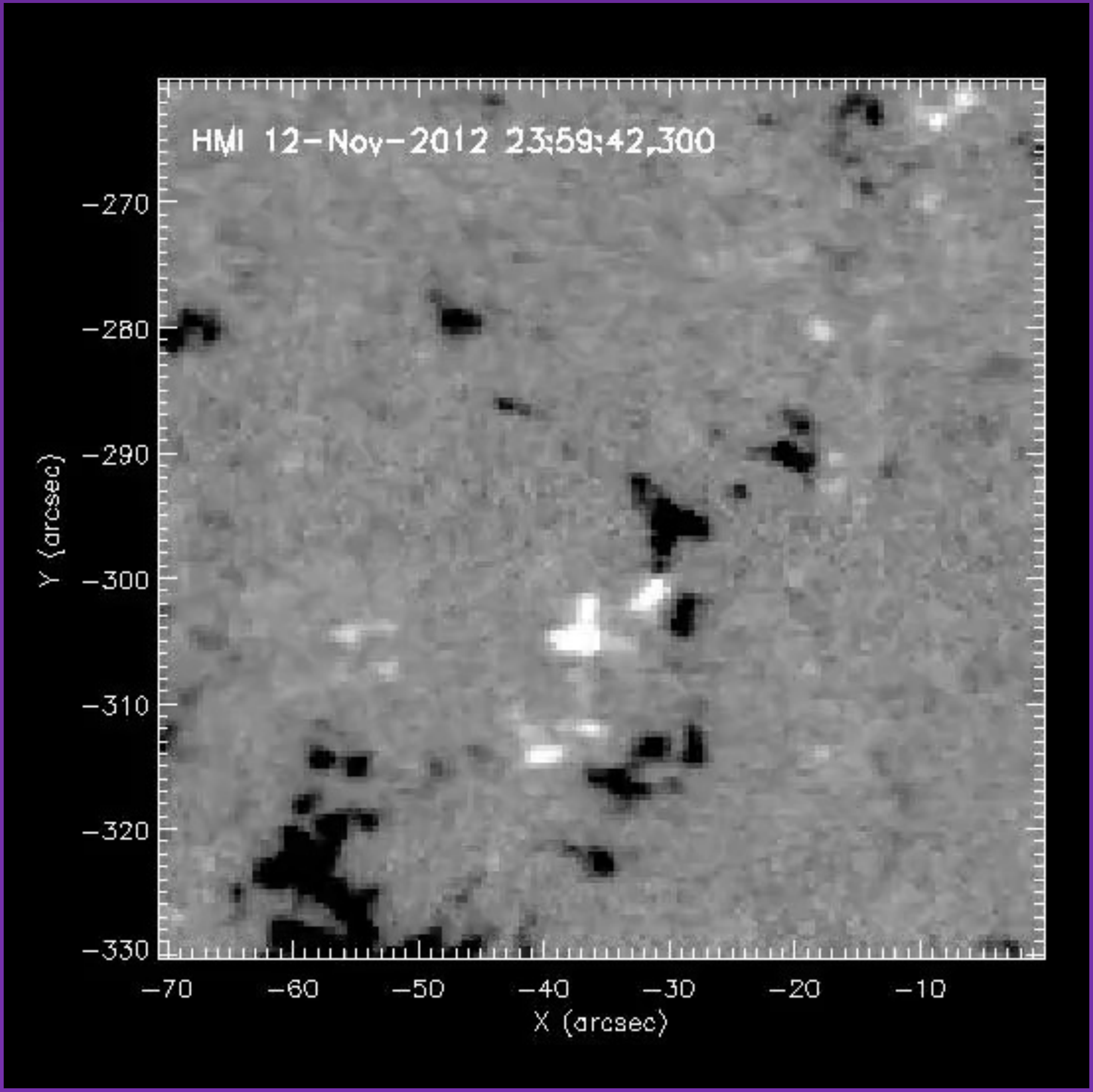
Image:
Alphonse Sterling
21 August 2017,
Lewisville, Idaho

(Backup Slides)

Hinode XRT



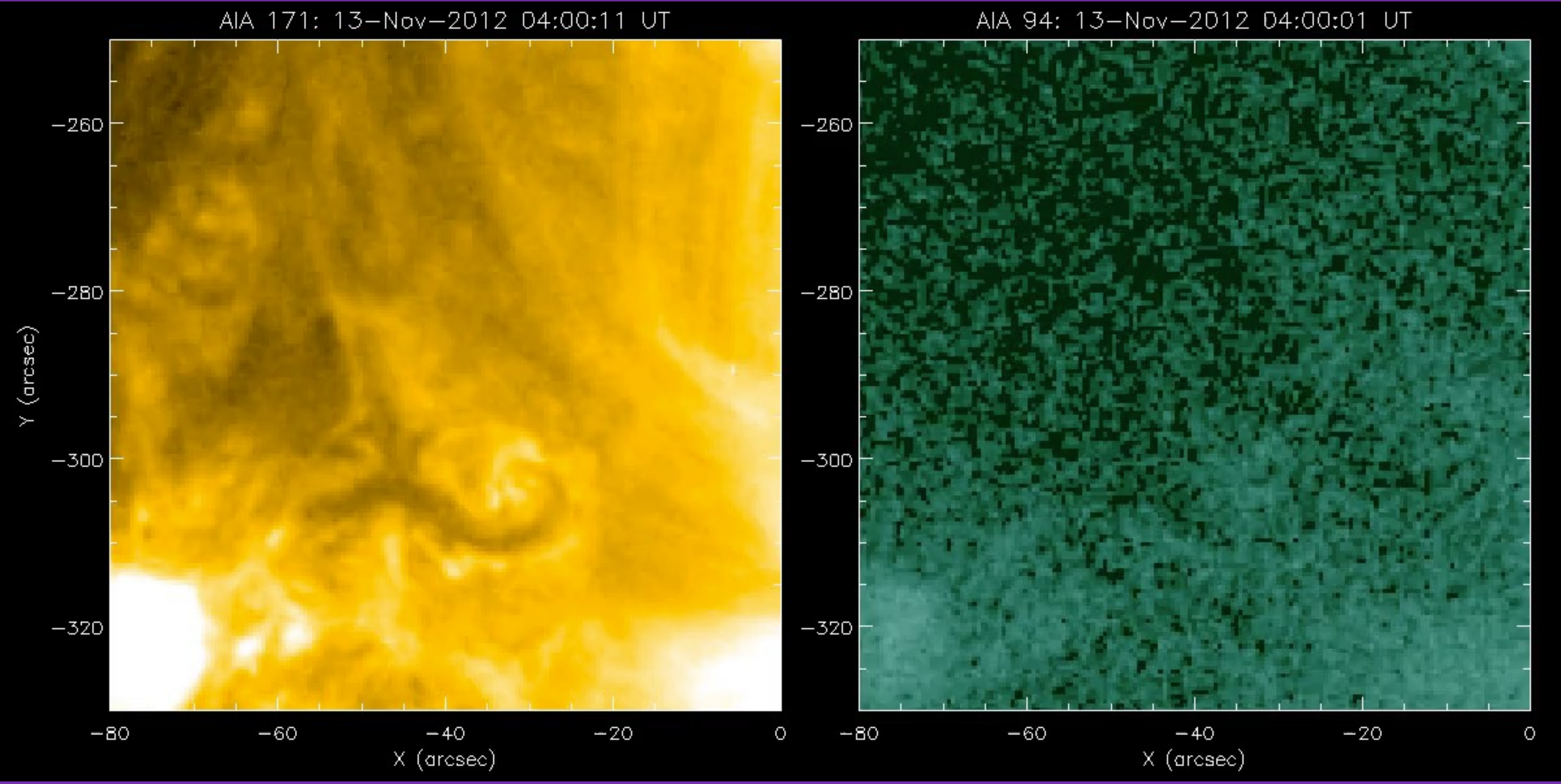
Sterling et al. (2022)



Panesar et al. (2016)

Quiet Sun Jets — Similar to PCH jets

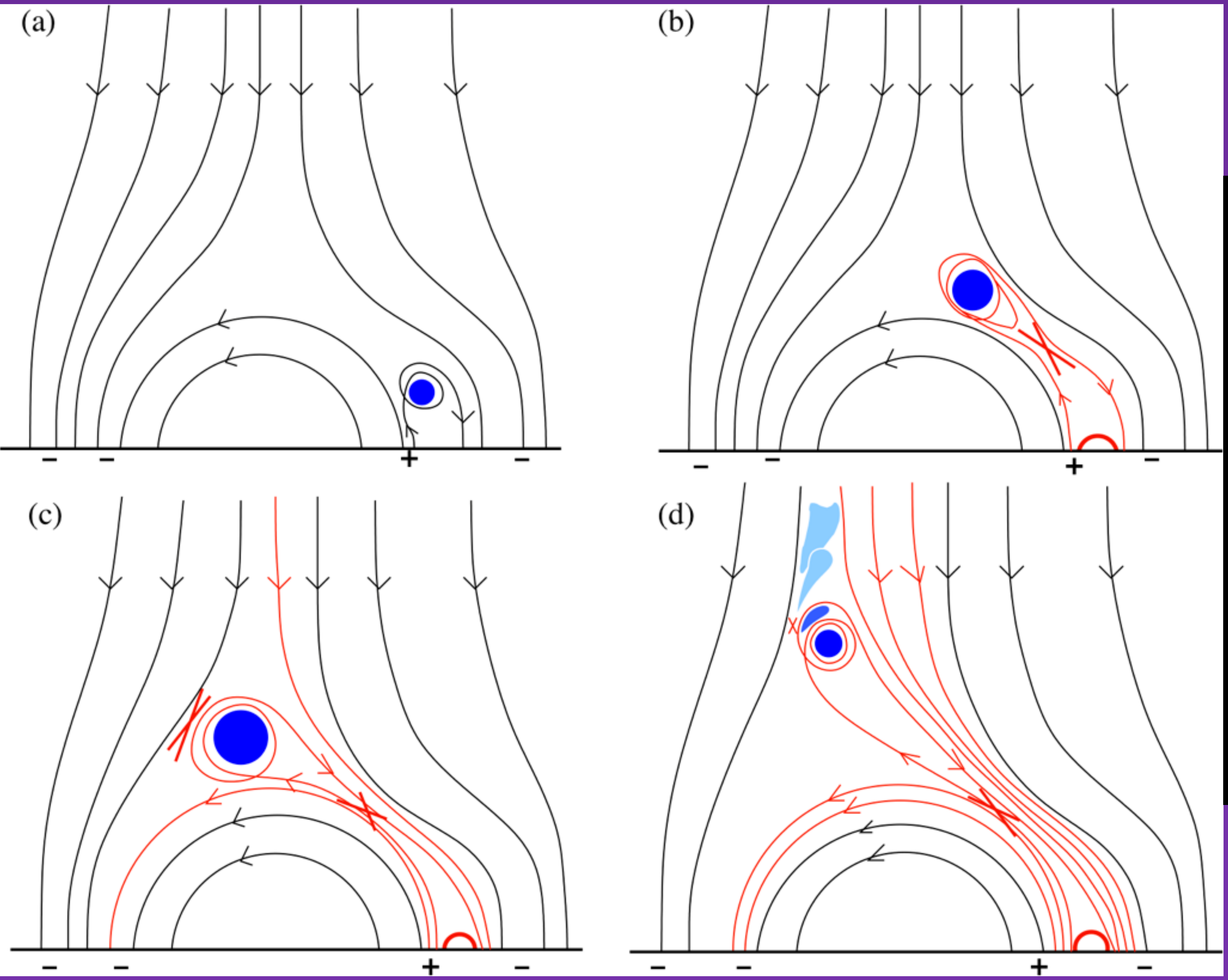
AIA 171 AIA 94

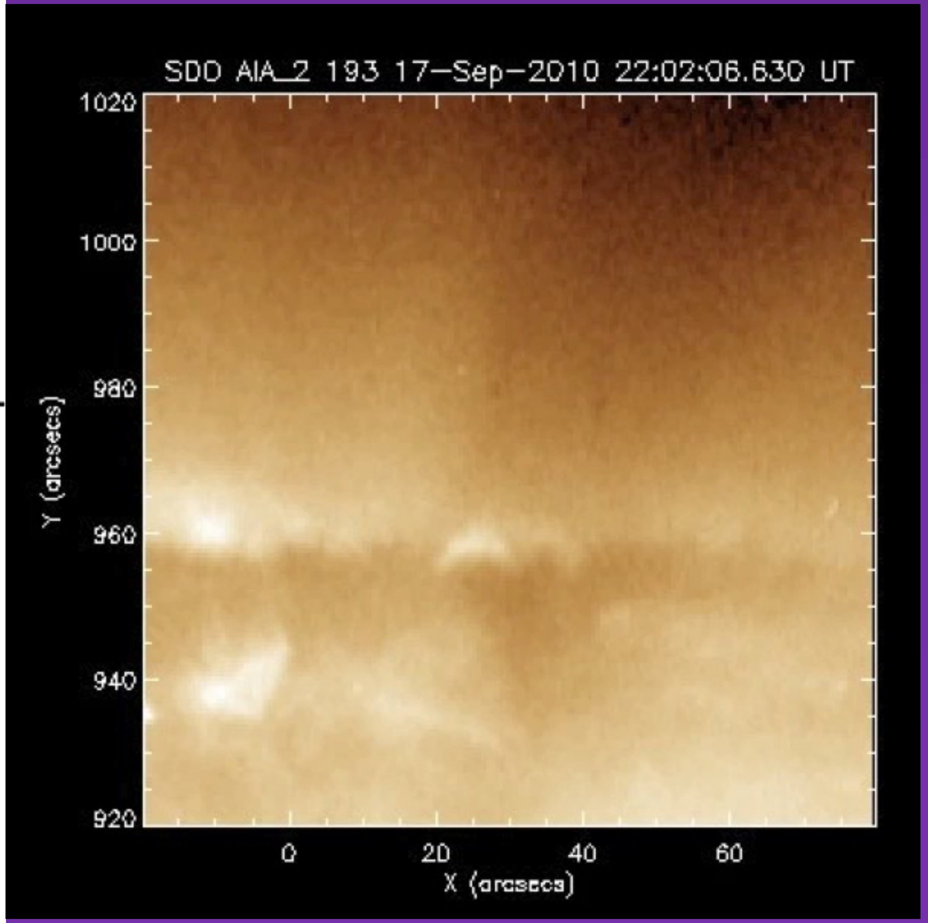


(Panesar et al. 2016b)

A. Sterling

Minifilament-Eruption Model for (X-Ray) Jets





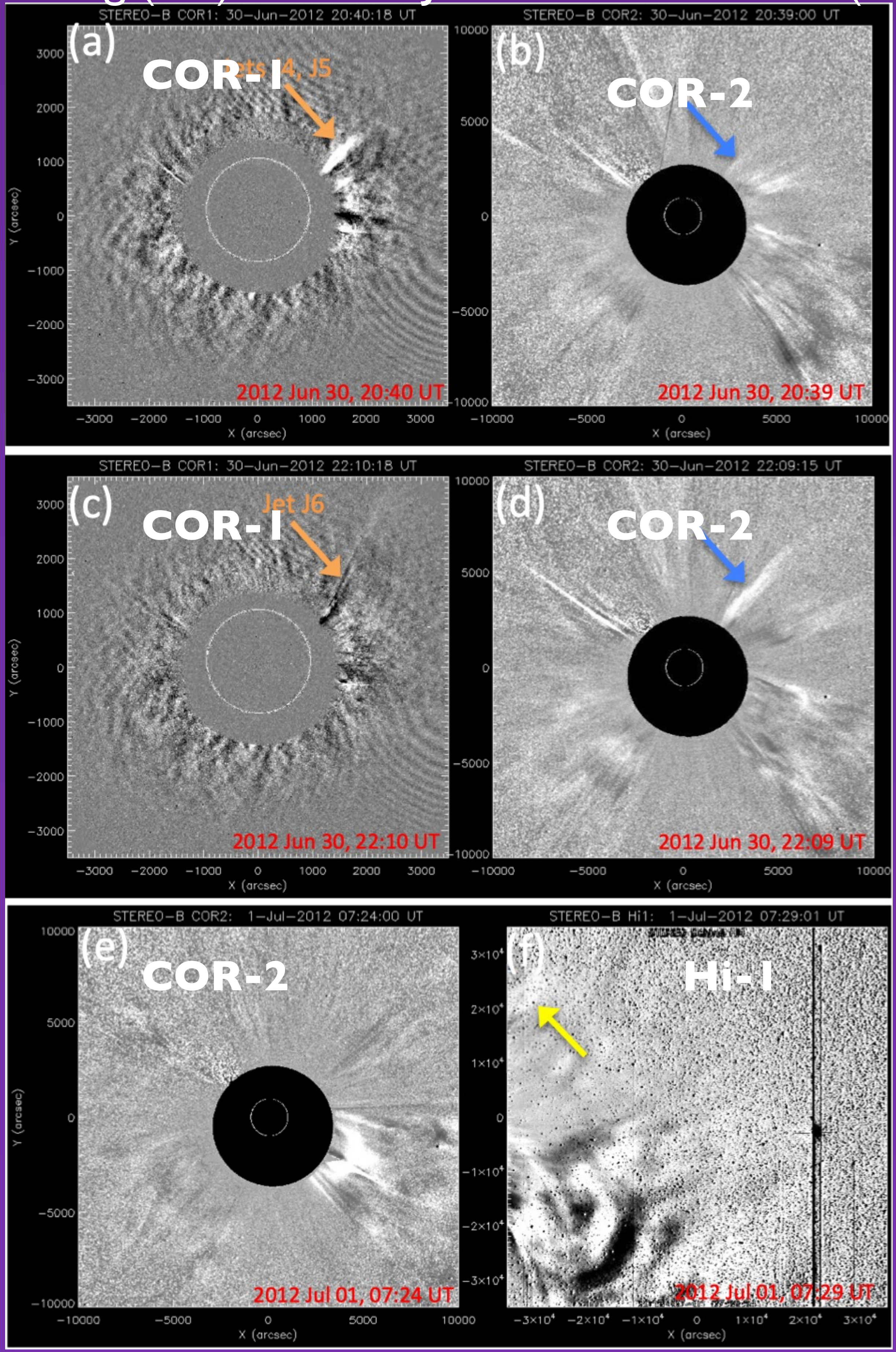
Sterling et al. (2015, 2016, 2017)

Quiet Sun jets work the same way (Panesar et al. 2016)

Modeled by Wyper et al. (2017, 2018)

A. Sterling

Far-Reaching (AR) Coronal Jets from STEREO-B (and AIA)

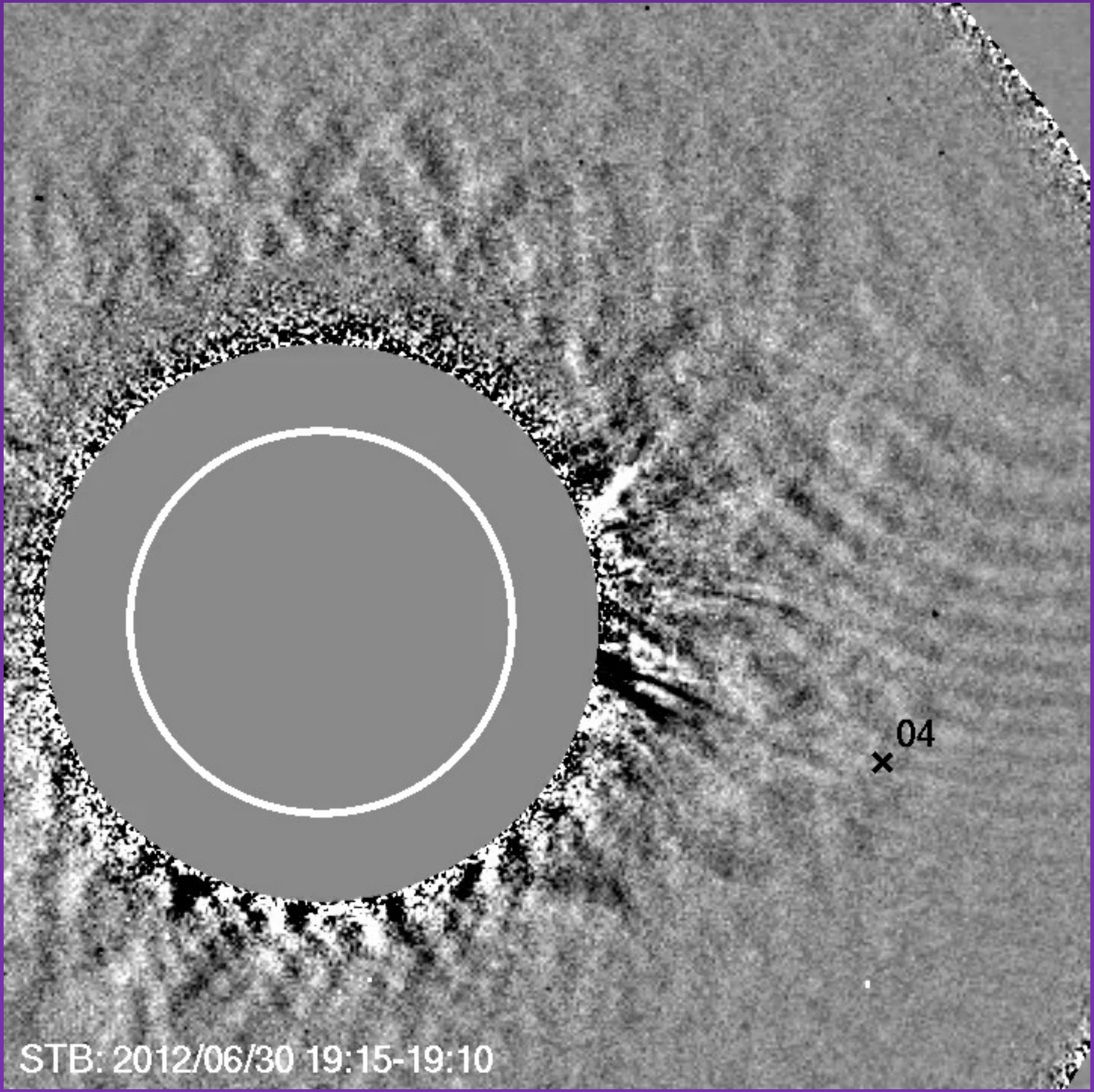


A. Sterling

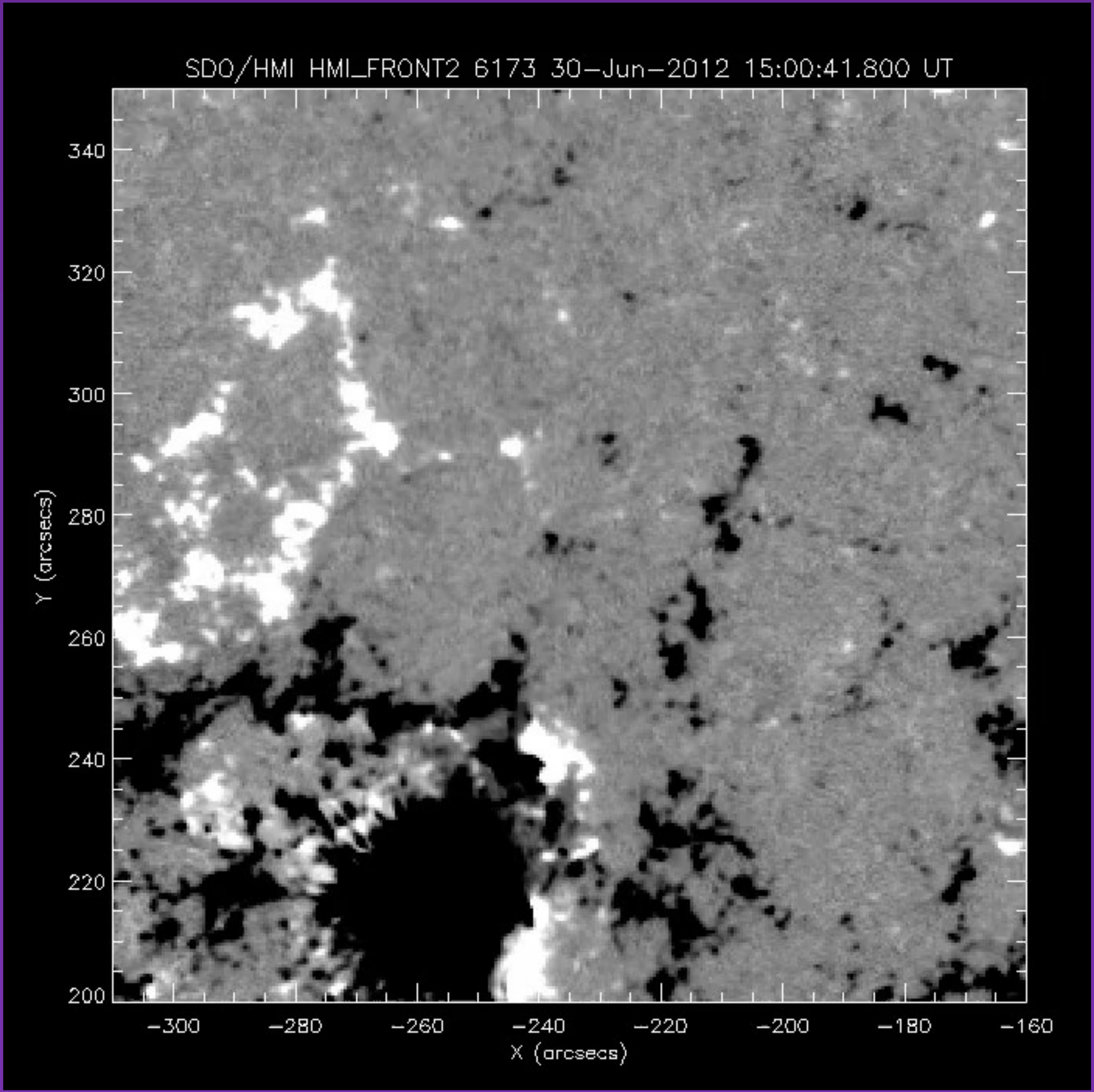
(Sterling & Moore 2020; also see, e.g., Yu et al. 2014, 2016)

PSP observations of switchbacks suggests that they are generated on preferred size scales, that of supergranules (Bale et al. 2021, Fargette et al. 2021), and on the size scale of granules (Fargette et al. 2021).

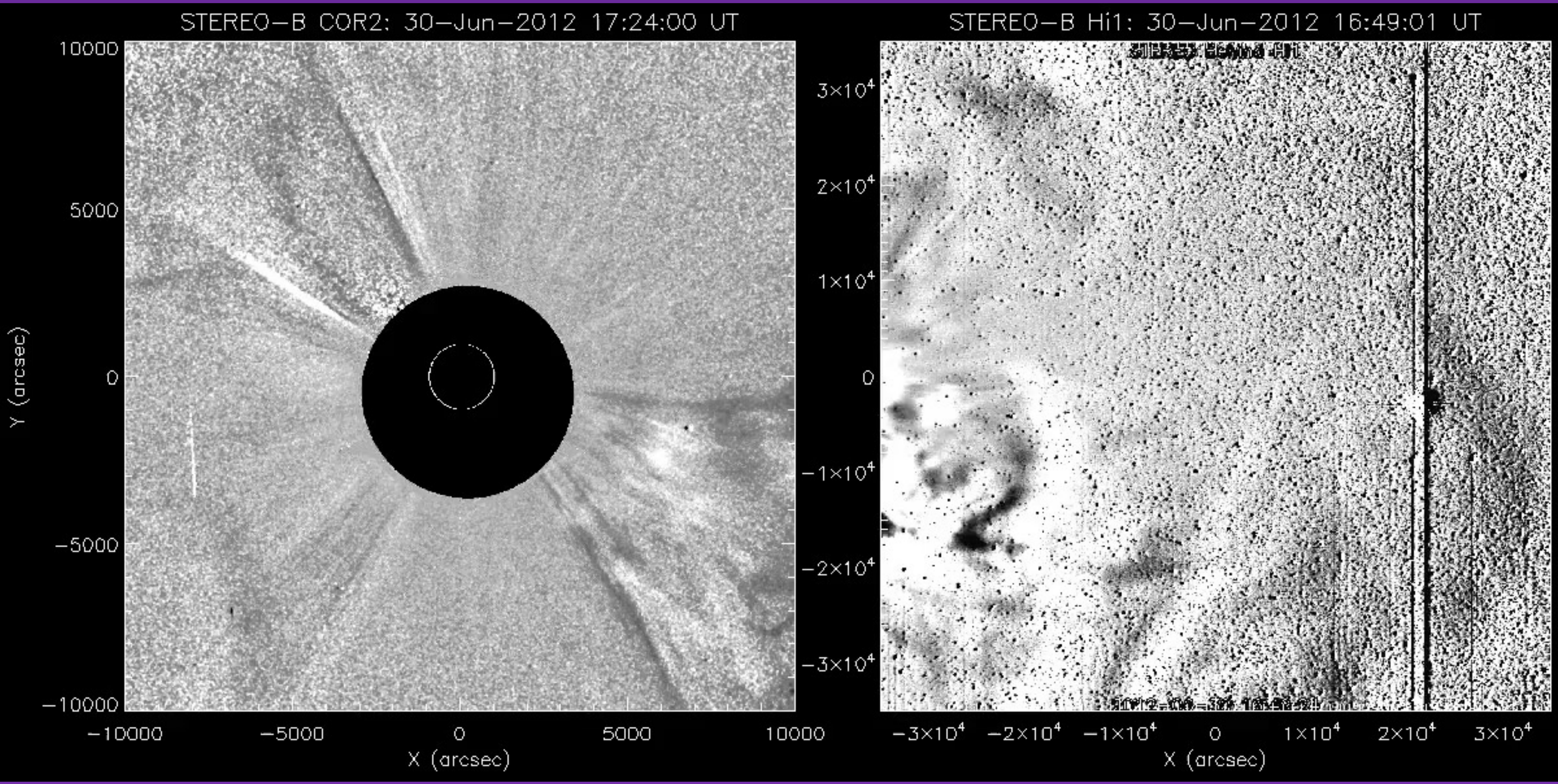
The three size scales for large-scale filament eruptions, jet-producing minifilament eruptions, and possible spicules produced from microfilament eruptions, reflect three natural magnetic size-scales on the Sun: active regions, supergranules, and granules. (Sterling et al. 2020.)



(Sterling & Moore 2020)



Sterling & Moore (2020)



(Sterling & Moore 2020)

Large-scale eruptions are like jet-producing eruptions, but on a larger scale (filaments ~30,000 — 10^5 km).

Jets occur from erupting minifilaments of size ~8000 km —18,000 km (Sterling et al. 2015, Panesar et al. 2016, McGlasson et al. 2019).

It is plausible that the jet mechanism occurs on smaller size scales, with increasing frequency, with “jetlets” (widths ~4000 km, Raouafi & Stenborg 2014; Panesar et al. 2018), and maybe even some spicules (widths ~ few x10^2 km; Sterling & Moore 2016).

If all can become switchbacks, the rates would be much larger than then the few x 100/day from canonical coronal jets.

Such jets might also contribute to the solar wind (Moore et al. 2011, Raouafi et al. 2023).

- Some coronal jets make “white-light jets,” aka “narrow CMEs” (width $\lesssim 10^{o}-15^{o}$; Wang et al. 1998, Moore et al. 2015). And some ARs jets make broad CMEs (e.g., Panesar et al. 2016b).

- Recent ideas: Jet-like features might be the source of PSP-observed magnetic switchbacks (Sterling & Moore 2020). Jet-like featuresmight contribute to the solar wind (Moore et al. 2011, Raouafi et al. 2023).

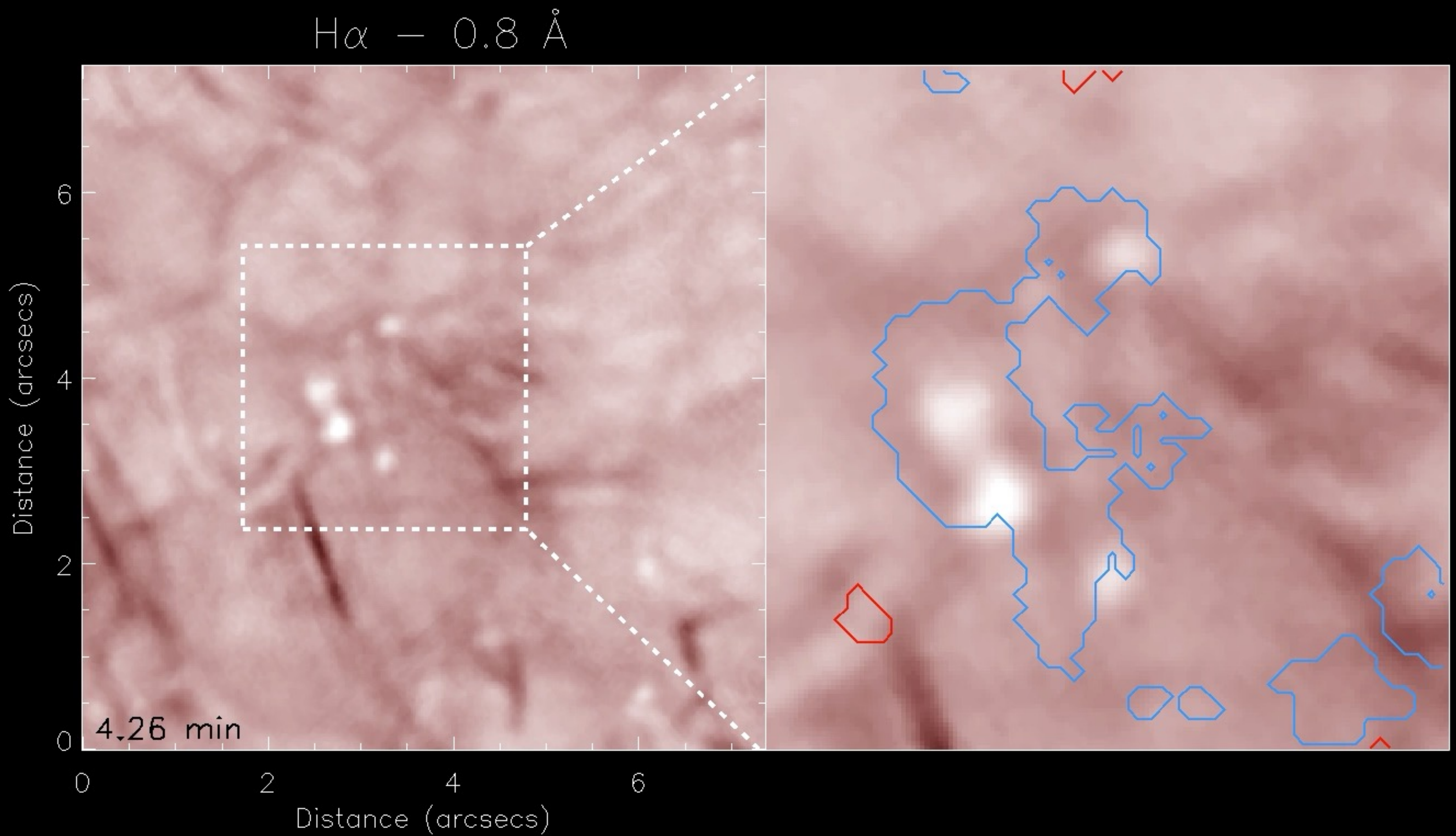
- Some coronal jets make “white-light jets,” aka “narrow CMEs” (width $\lesssim 10^o - 15^o$; Wang et al. 1998, Moore et al. 2015). And some ARs jets make broad CMEs (e.g., Panesar et al. 2016b).

- A recent idea is that jets or jet-like features might be the source of PSP-observed magnetic switchbacks (Sterling & Moore 2020).

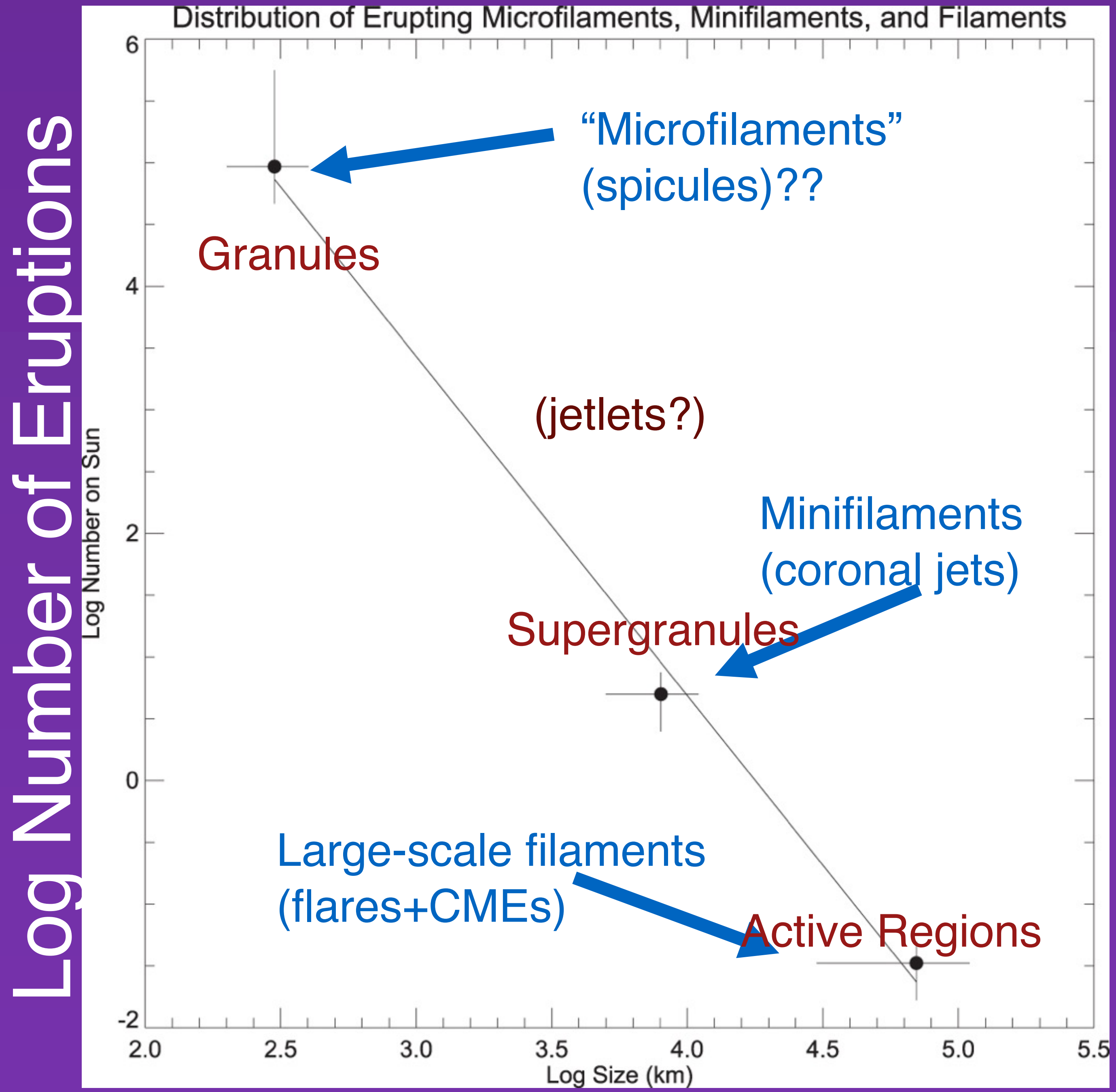
- Another recent idea is that jet-like features can contribute to the solar wind (Moore et al. 2011, Raouafi et al. 2023).

- It is plausible that the jet mechanism occurs on smaller size scales, with increasing frequency, with “jetlets” (widths ~4000 km, Raouafi & Stenborg 2014; Panesar et al. 2018), and maybe even some spicules (widths ~ few $x10^2$ km; Sterling & Moore 2016).

- If all size-scale jets contribute, the rates would be much larger than then the few x 100/day from canonical coronal jets. This would be needed to explain switchbacks/solar wind.



Samanta et al. (2019, Science); Sterling et al. (2020a)



Log “Filament” Size

Sterling & Moore (2016)