Observing the internal dynamics of a solar filament eruption

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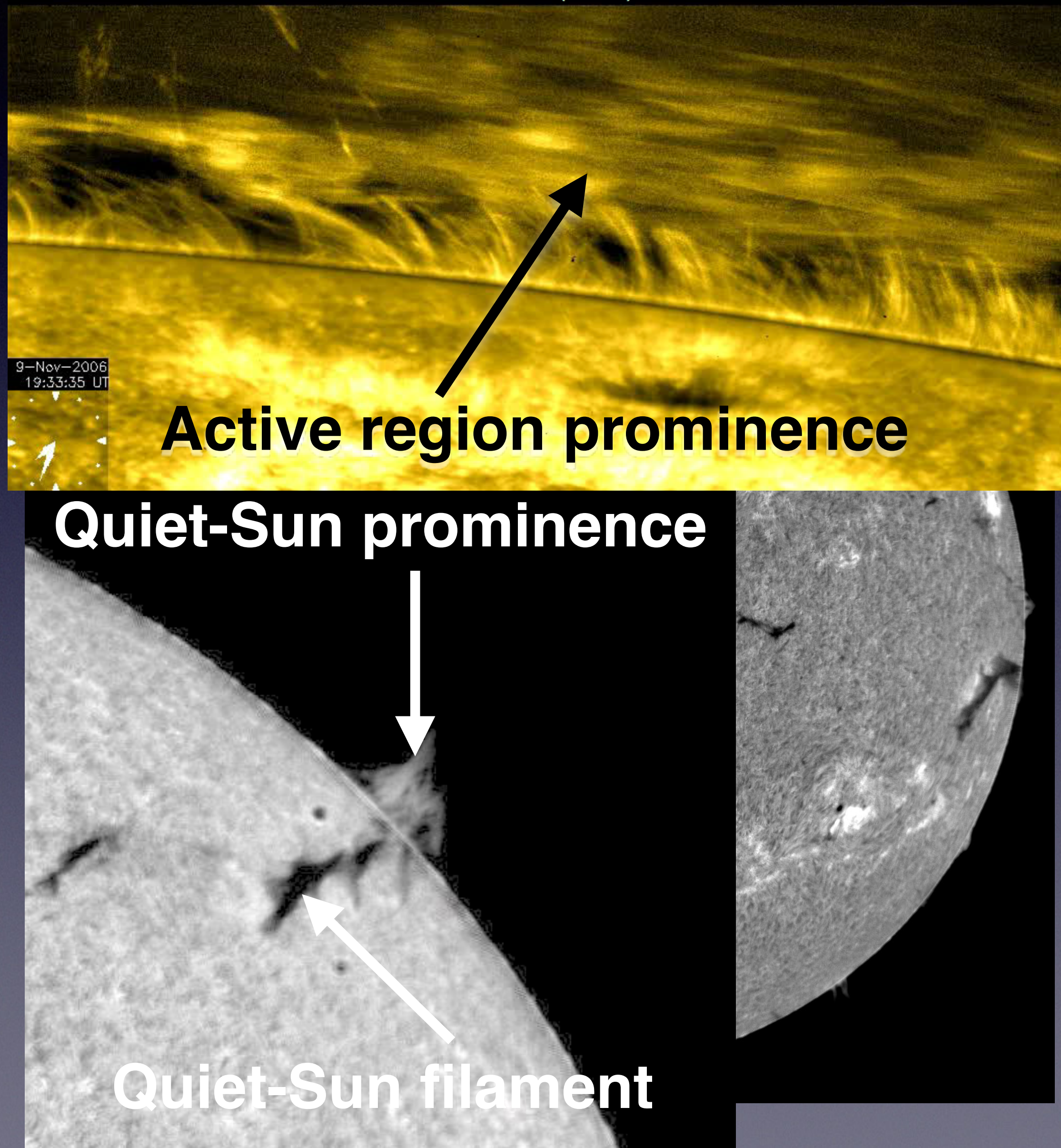
Overview

- What are solar filaments?
- Why do we care about them?
- What new perspectives does our study reveal?

Solar filaments: observation

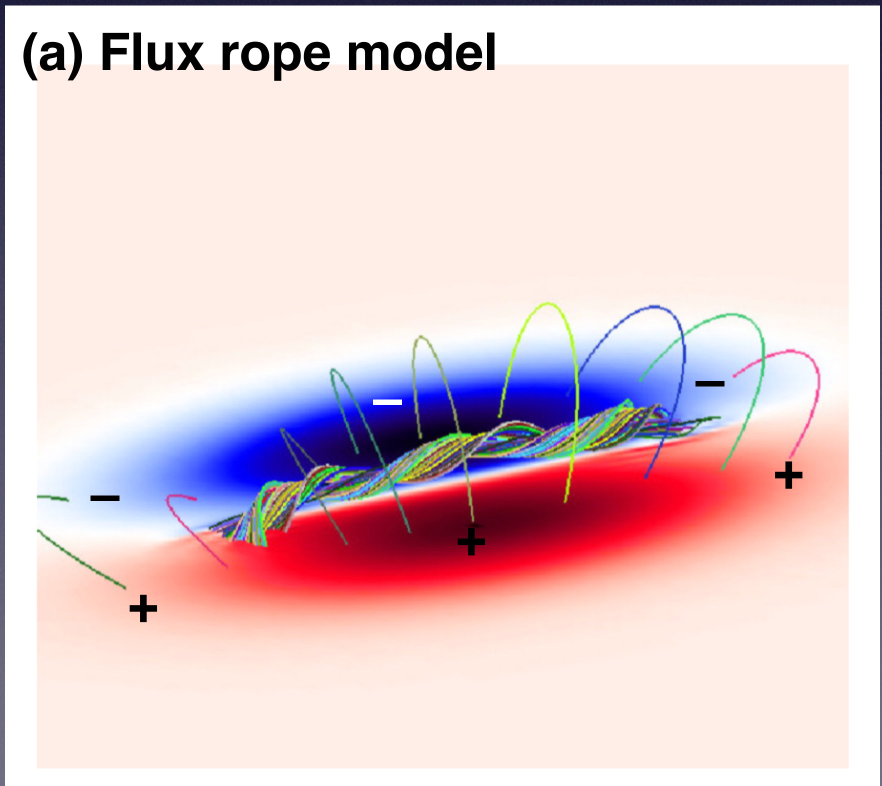
- A ***filament*** is a suspension of dense, partially-ionised plasma in the solar atmosphere…
  - … surrounded by much hotter, fully-ionised (but lower density) corona
- They cross the star's surface on scales from a few 100 Mm (in active regions) to several $R_\odot$ (quiet Sun)
- Viewed above the limb (edge) of the Sun, against the blackness of space, filaments are known as a ***prominences***.

Hinode/SOT Ca II H; Okamoto *et al*. (2008) 10.1126/science.1145447

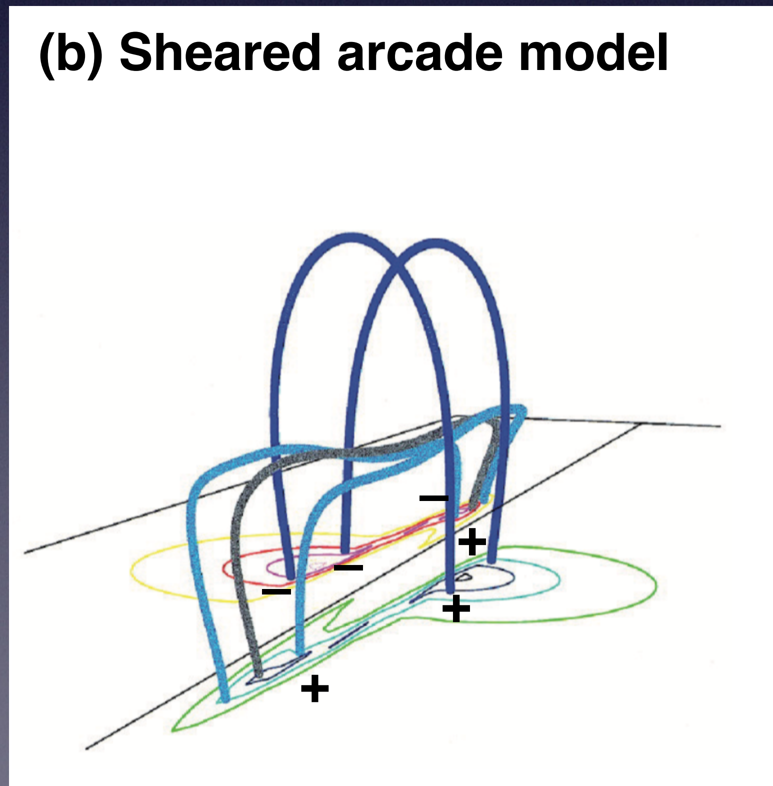


Solar filaments: model

- Filaments closely follow magnetic polarity inversion lines.
- Their suspension can be understood in terms of concave-up sections in the magnetic field that are:
- (a) within the bottom half of a magnetic flux rope
- *or* (b) dips in some other magnetic configuration, thought to be formed by the shearing of magnetic arcades



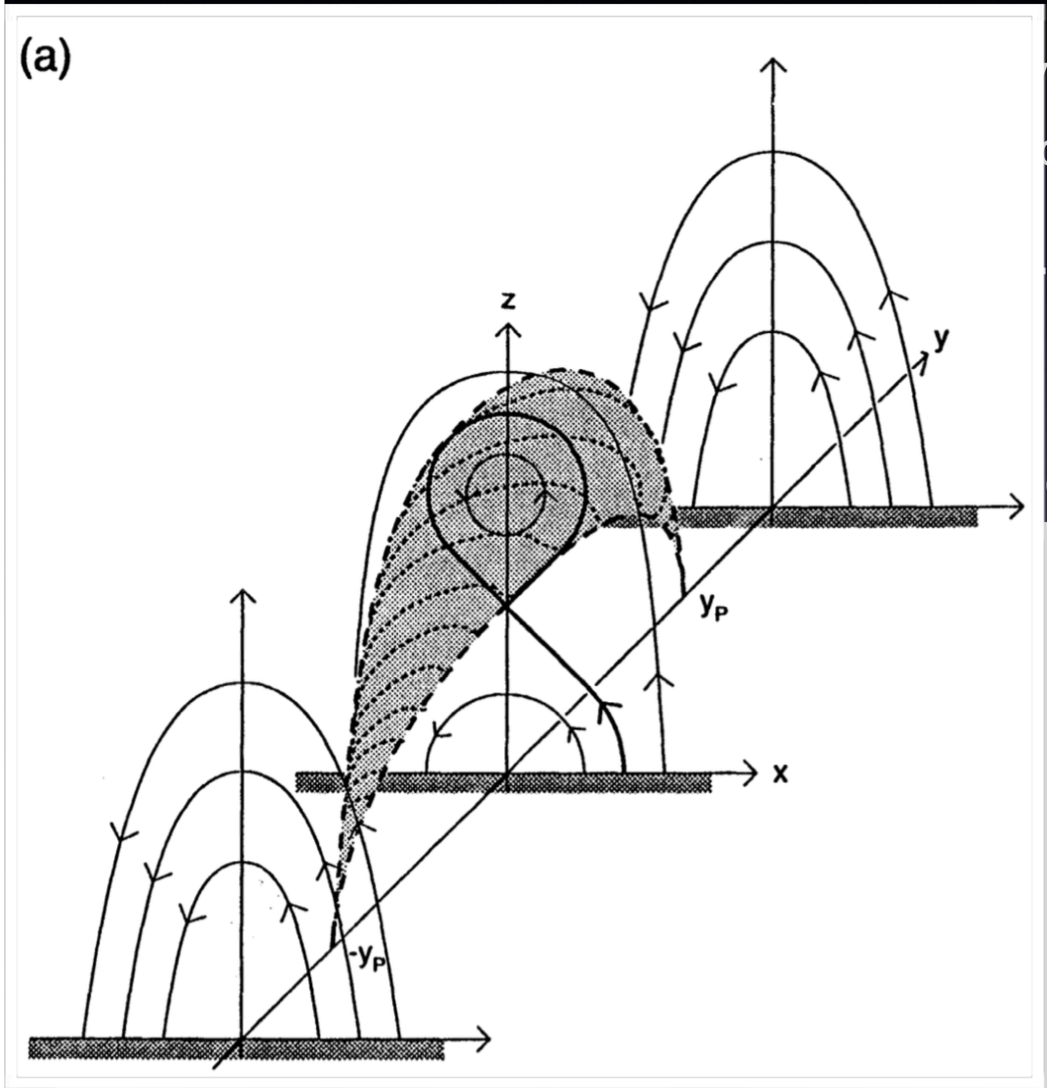
(a) Flux rope model



(b) Sheared arcade model

Parenti (2014), *Living Rev. Solar Phys.*, 11; DeVore & Antiochos (2000), *ApJ*, 539, 954; Amari *et al.* (2003) ApJ, 595, 1231

Building a flux-rope topology

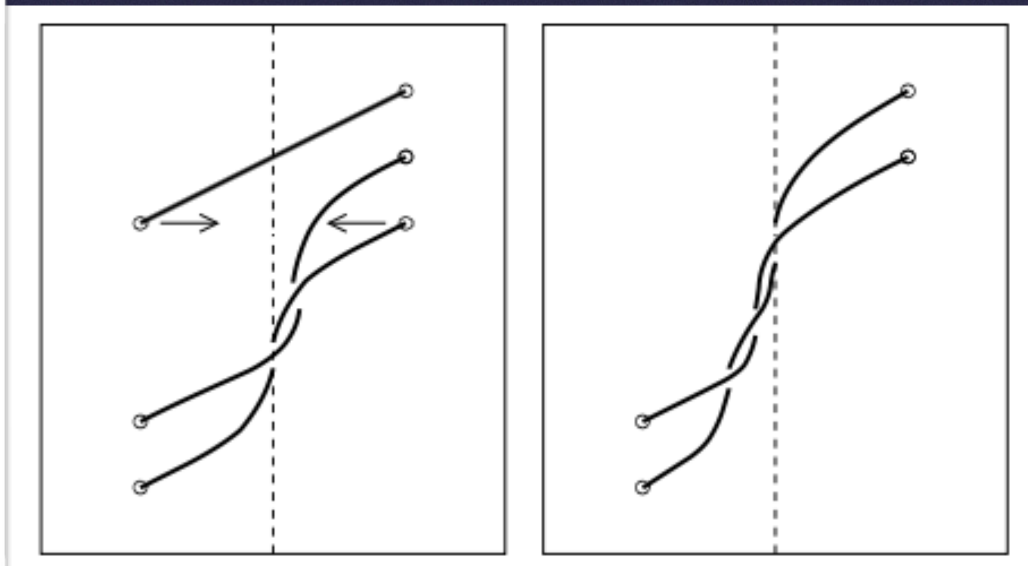


ity photosphere (lots of photo-electrons)

on downdrafts) at the surface of the Sun bring field

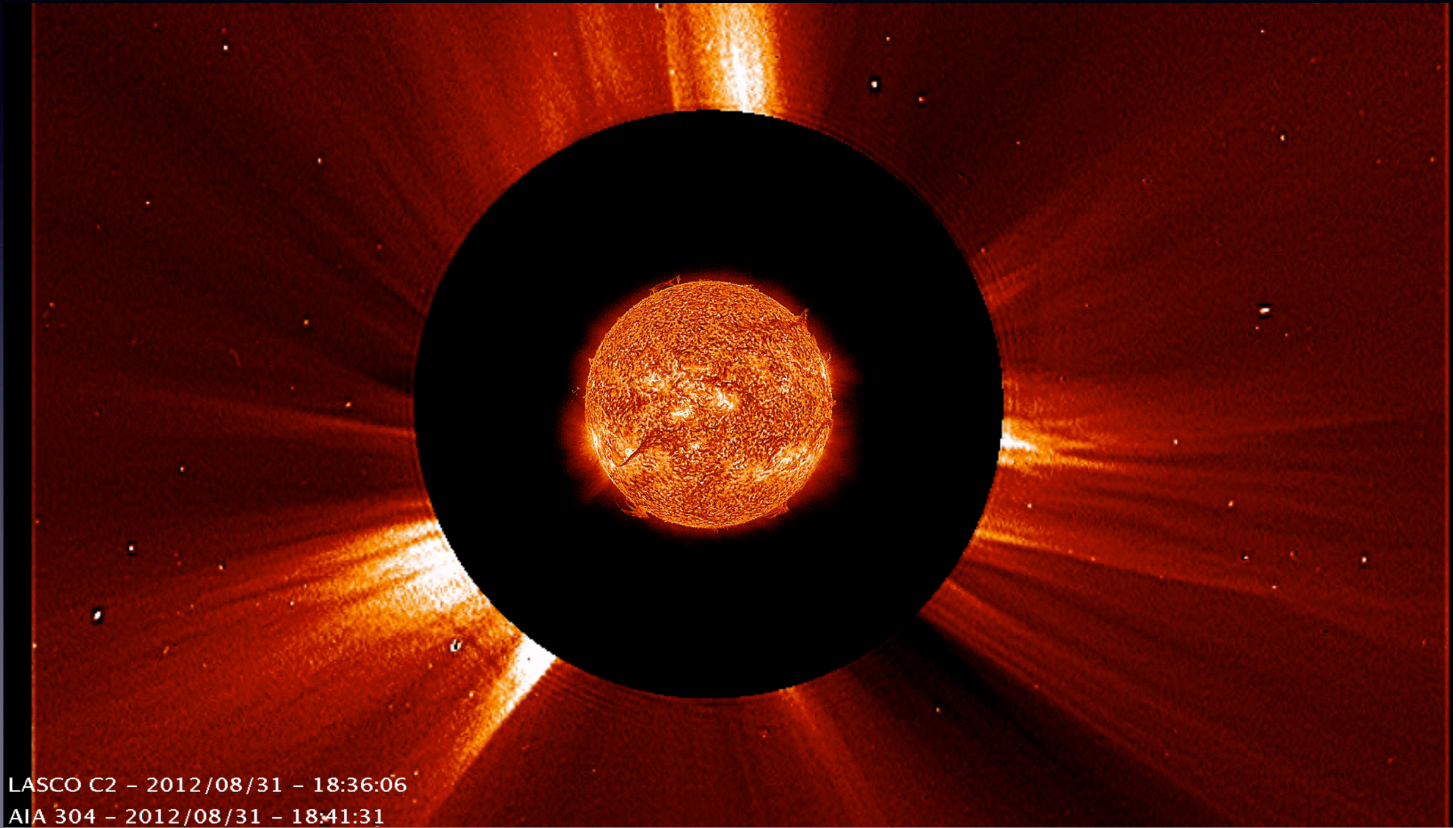
estraining (overlying) **field**

ecome… **… a flux rope**

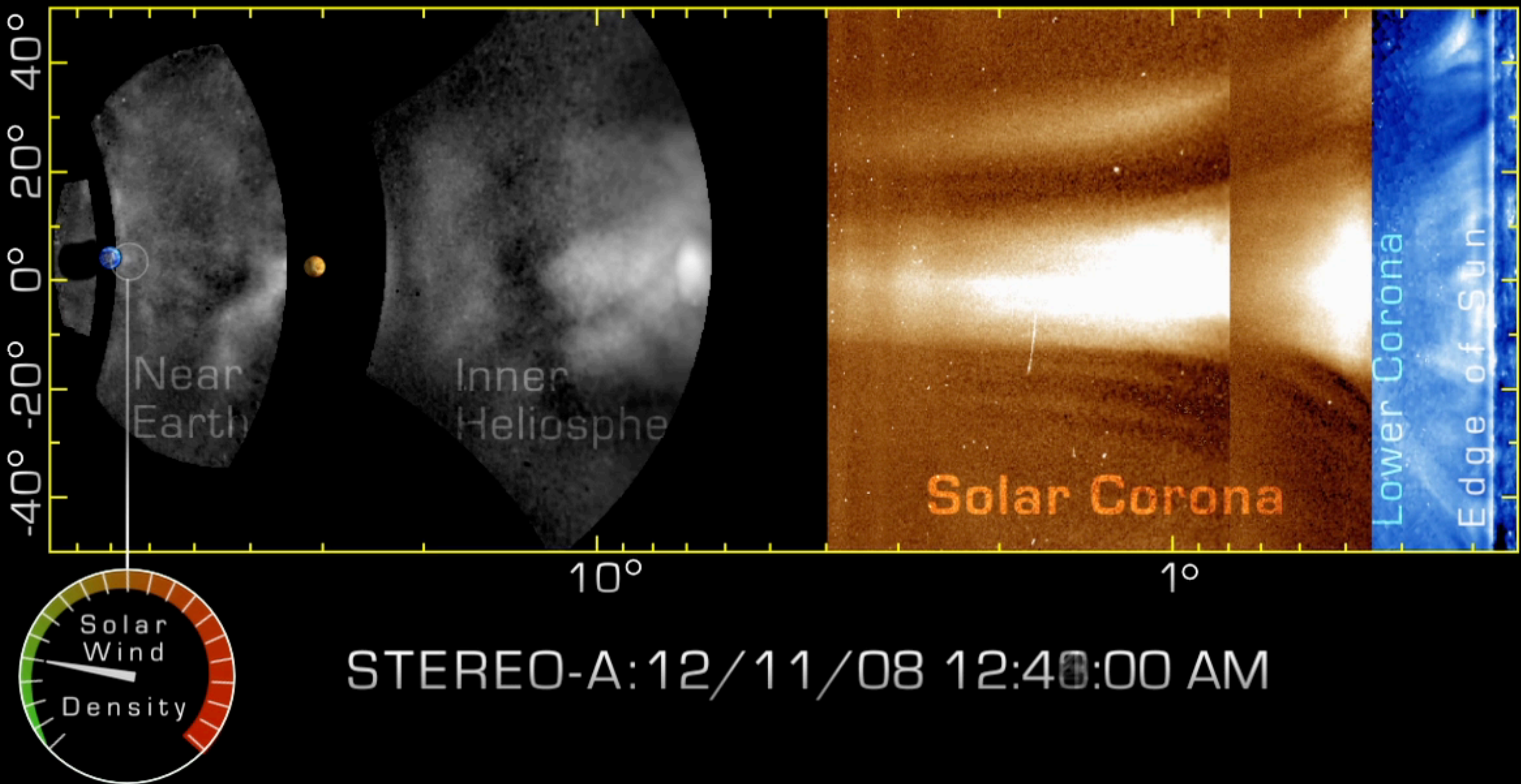


Green, Kliem & Wallace (2011), *A&A*, **526**, A2

Why do we care about filaments?

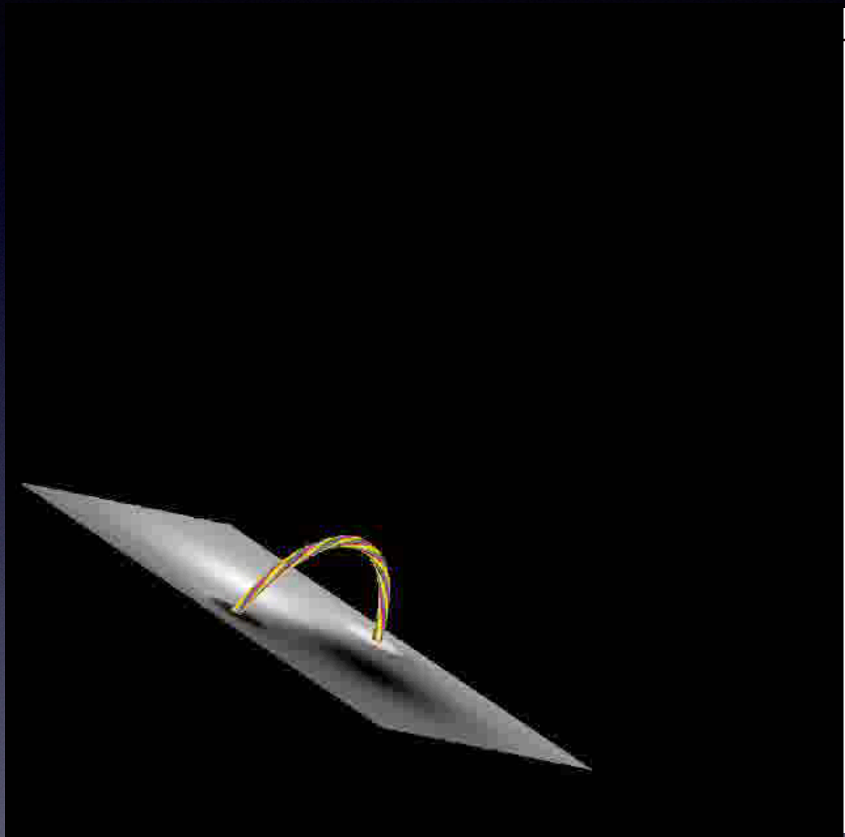


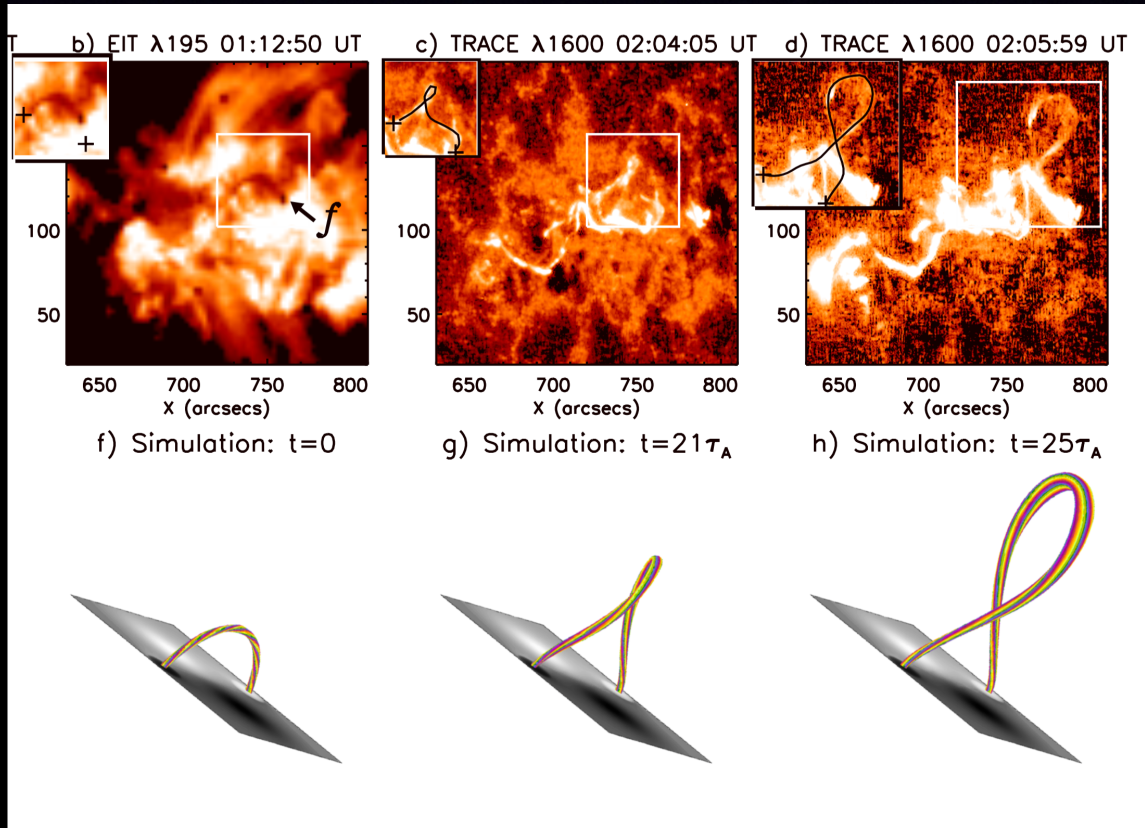
CMEs disrupt the heliosphere



Courtesy: Craig DeForest (SWRI) / NASA *STEREO*

<u>One</u> illustration of flux-rope eruption

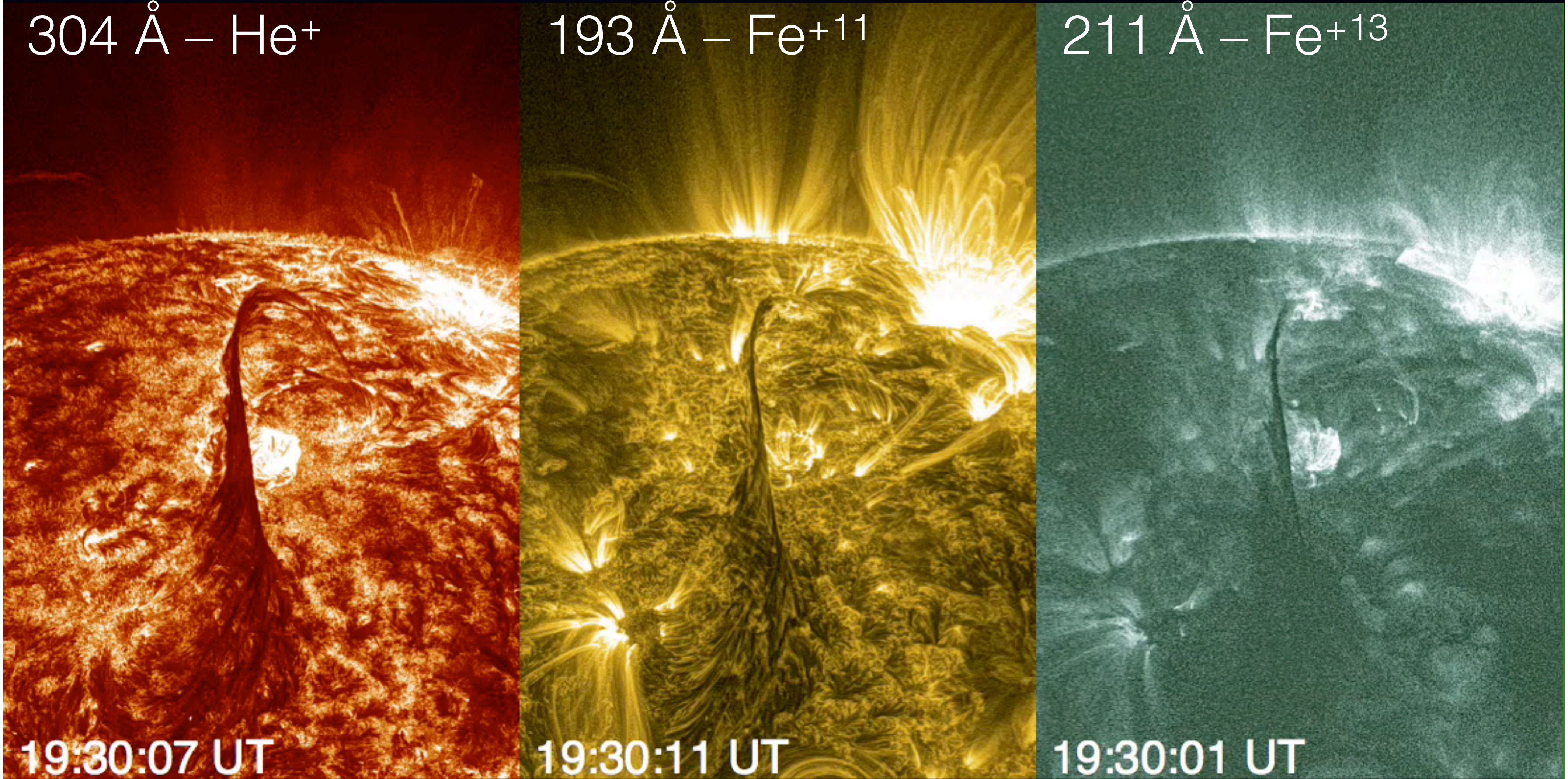




- Helical kink instability kicks in when gradient in $|B|$ exceeds some critical value for a given number of windings of the field
- Now thought to be less important than the **torus instability.**

Williams *et al. (2005)*, *ApJ*, **628**, L163

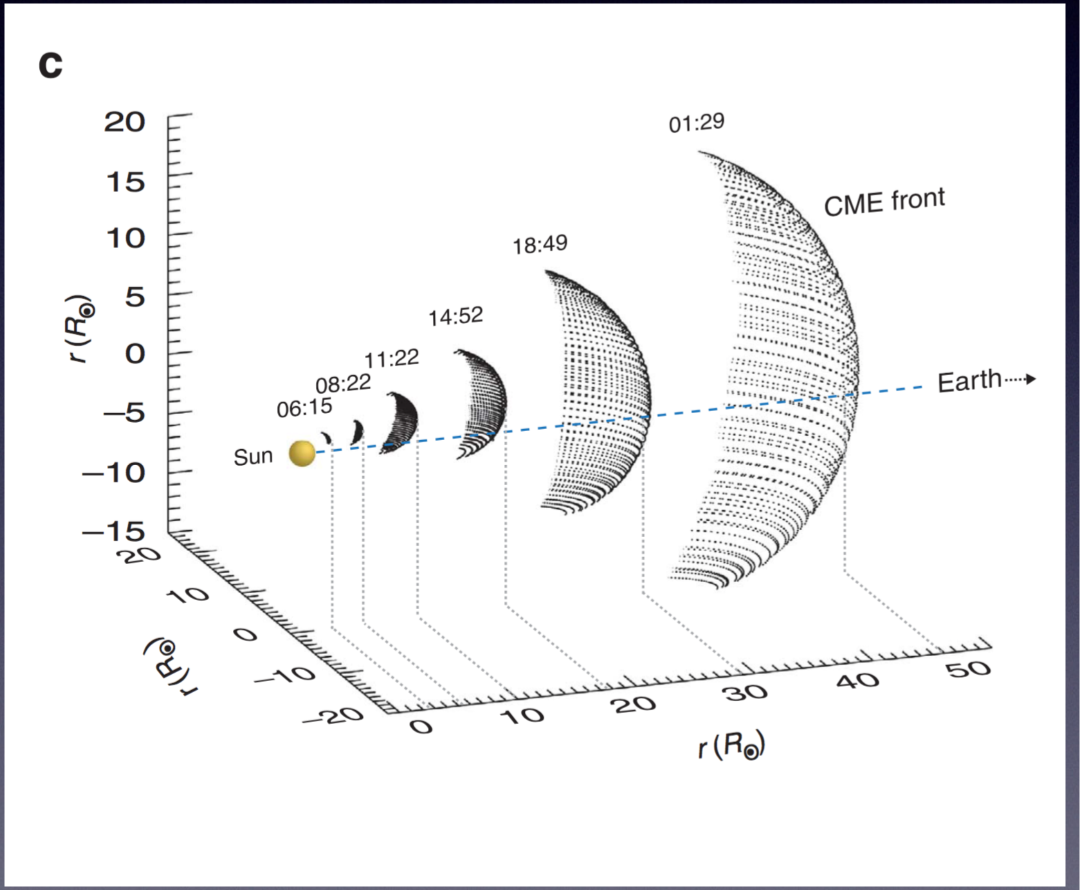
Flux-rope morphology is often revealed by the filament plasma



data from **Solar Dynamics Observatory**/Atmospheric Imaging Assembly

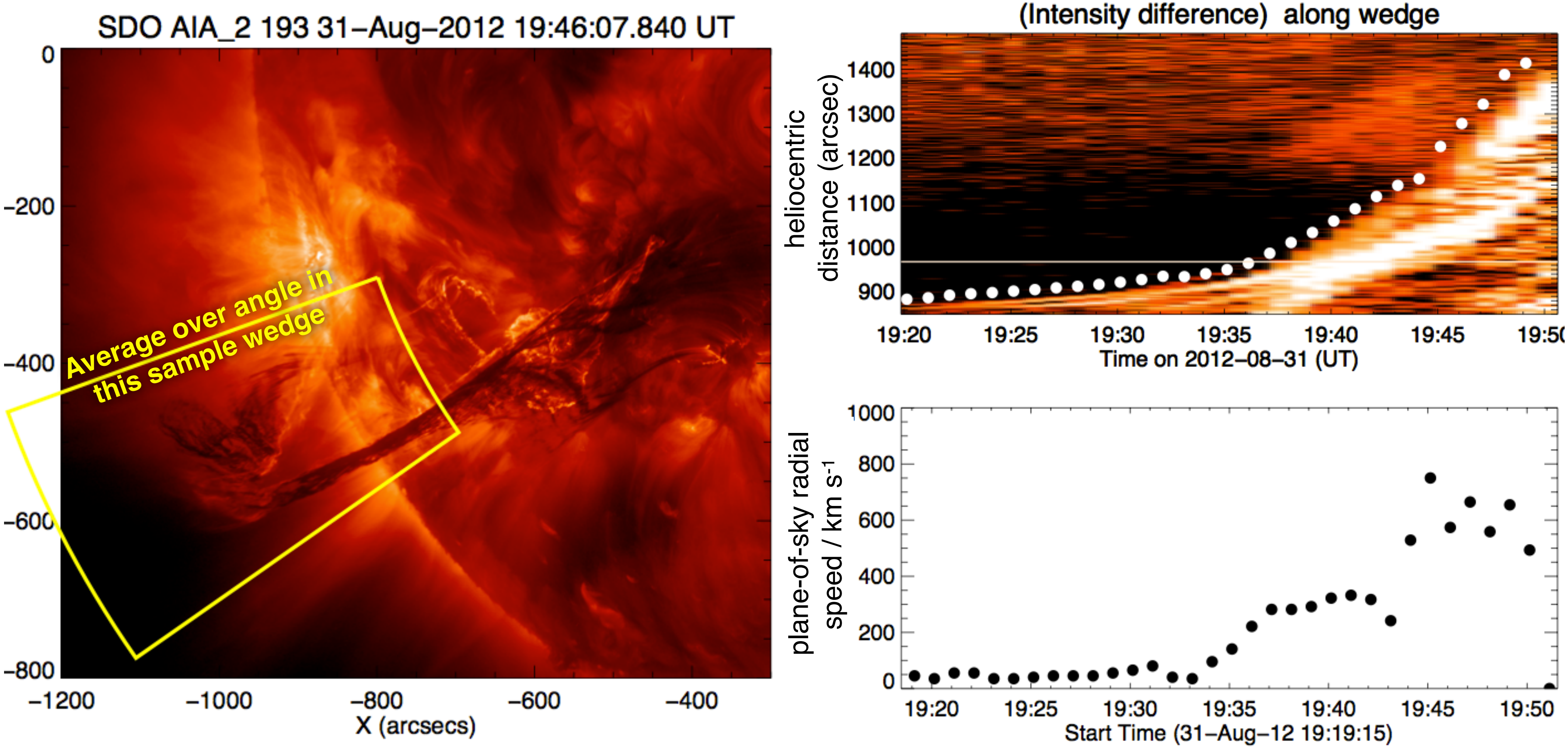
Problem: which direction is the CME headed in?

- **CMEs** have already been shown to not necessarily propagate radially
- Drag forces when interacting with solar wind may be the reason for deflection (Byrne et al. 2010)
- How does this compare with ***filament*** eruption direction?
    - How would we know? We can't easily do stereoscopic observations as we did with CME front (over many dozen $R_\odot$)



Byrne et al. (2010) *Nature Communications*, **1**, 74

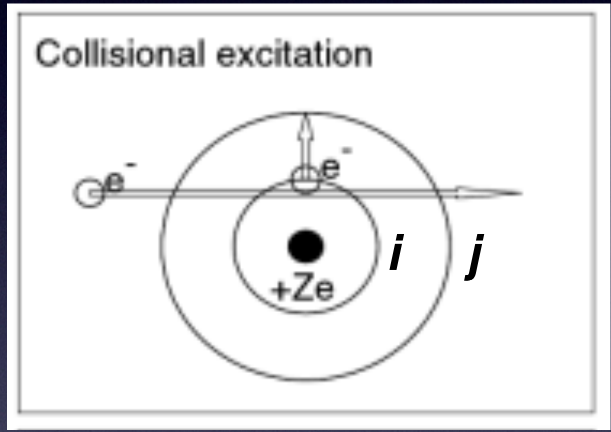
Plane-of-sky velocity is easy

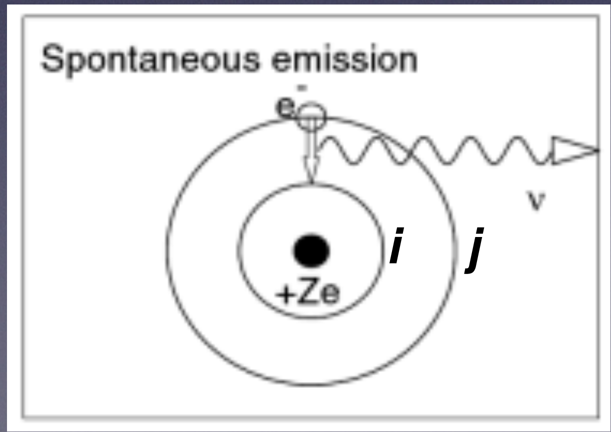


For the line-of-sight velocity component,
we could really do with **Doppler shift**: spectrally resolved data!

Emission-line spectra

- Vast majority of what you see in a solar EUV is due to emission "lines"
- Bound electron (in an ion) is excited from a lower energy state ($n=i$) to a higher energy state ($n=j$) by a collision C_{ij}
- Later decays back from $n=j$ to $n=i$
- Energy gap between levels is fixed so wavelength is fixed (in the frame of the atom/ion)
    - Can be changed by Doppler-shifts (moving frame with respect to observer)

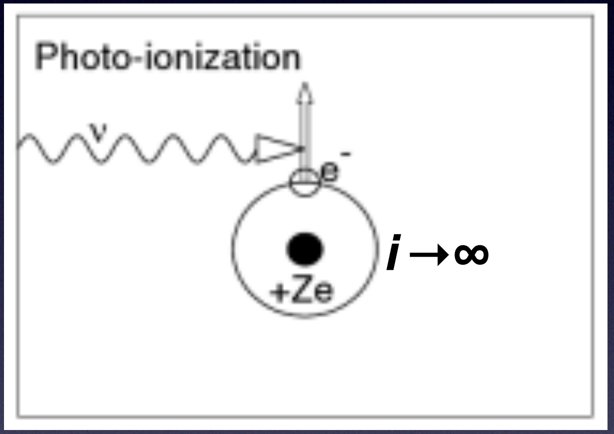


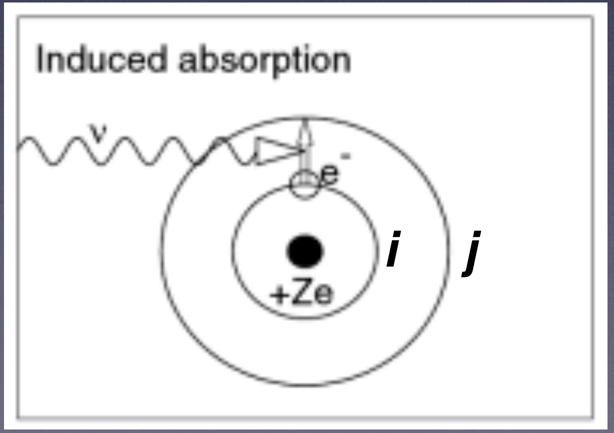


Physics of the Solar Corona: An Introduction, Aschwanden

But filaments mostly *absorb* EUV radiation

- They are too cold to excite EUV transitions by electron collisions ($\log_{10} T \sim 4$).
  - so they mostly just destroy EUV photons
- Two processes are important for this **absorption**:
  - **Photoionisation**
    - continuum with an edge (and peak) at $\lambda = hc/\varepsilon_{i\infty}$
  - **Resonant** (“induced”/“bound-bound”/“**line**”) **absorption**, B_{ij}
    - a narrow-band effect, strongly peaked
    - Resonant absorption is several orders of magnitude **stronger than photoionisation** at its peak wavelength.

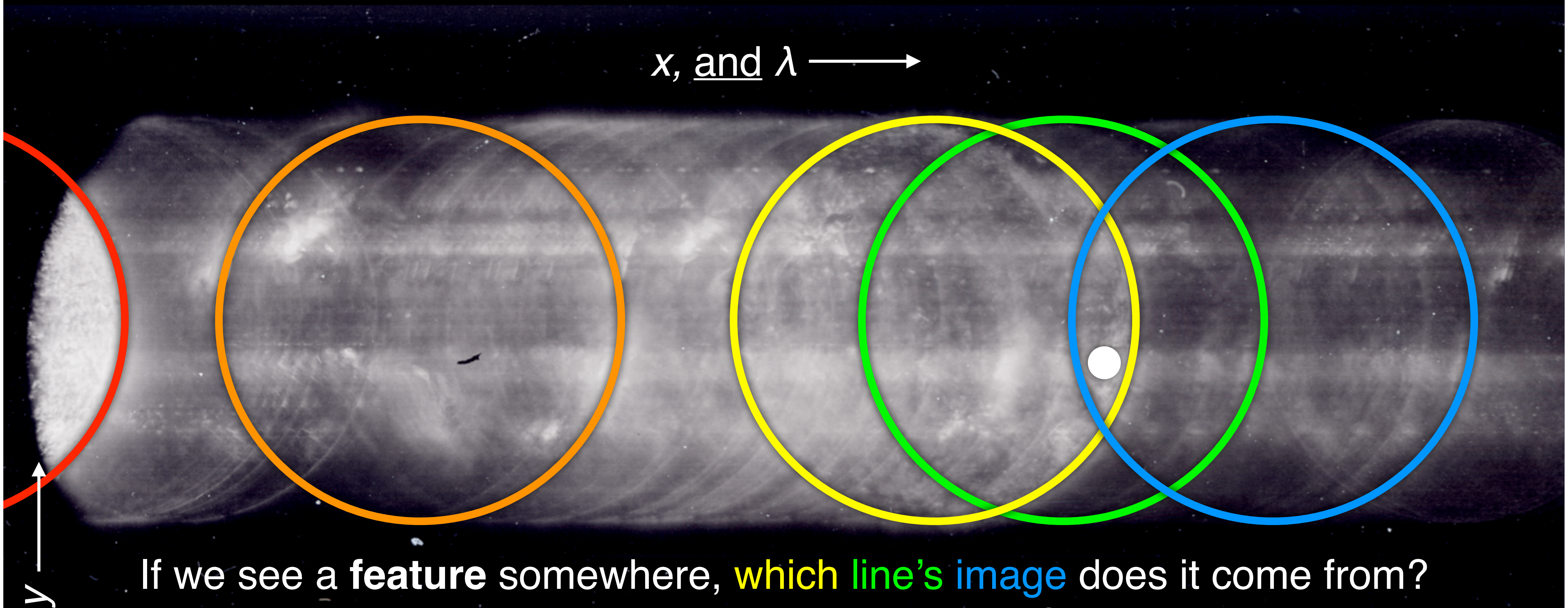




Physics of the Solar Corona: An Introduction, Aschwanden

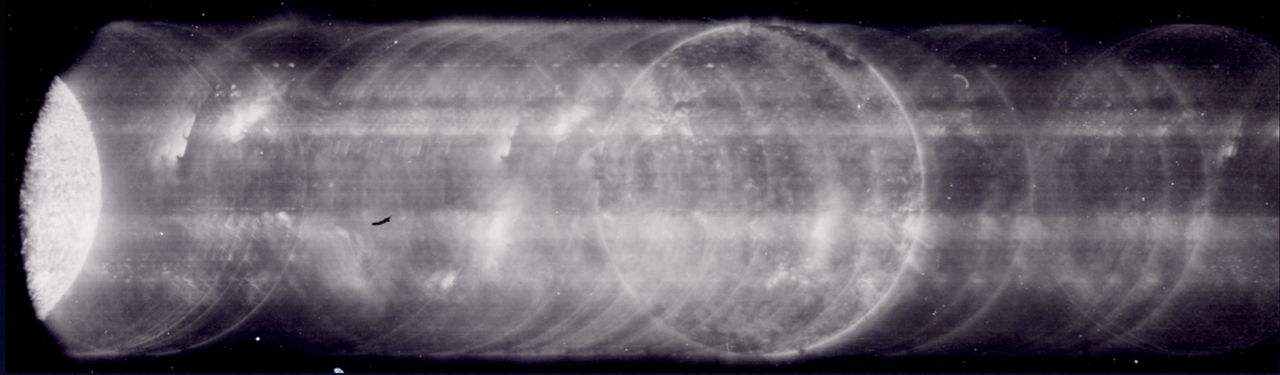
Spectrally dispersed image of the Sun on a 2D detector

Each circle represents the Sun's limb at a particular emission-line wavelength



If we see a **feature** somewhere, which line's image does it come from?
And, therefore, which part of the Sun?

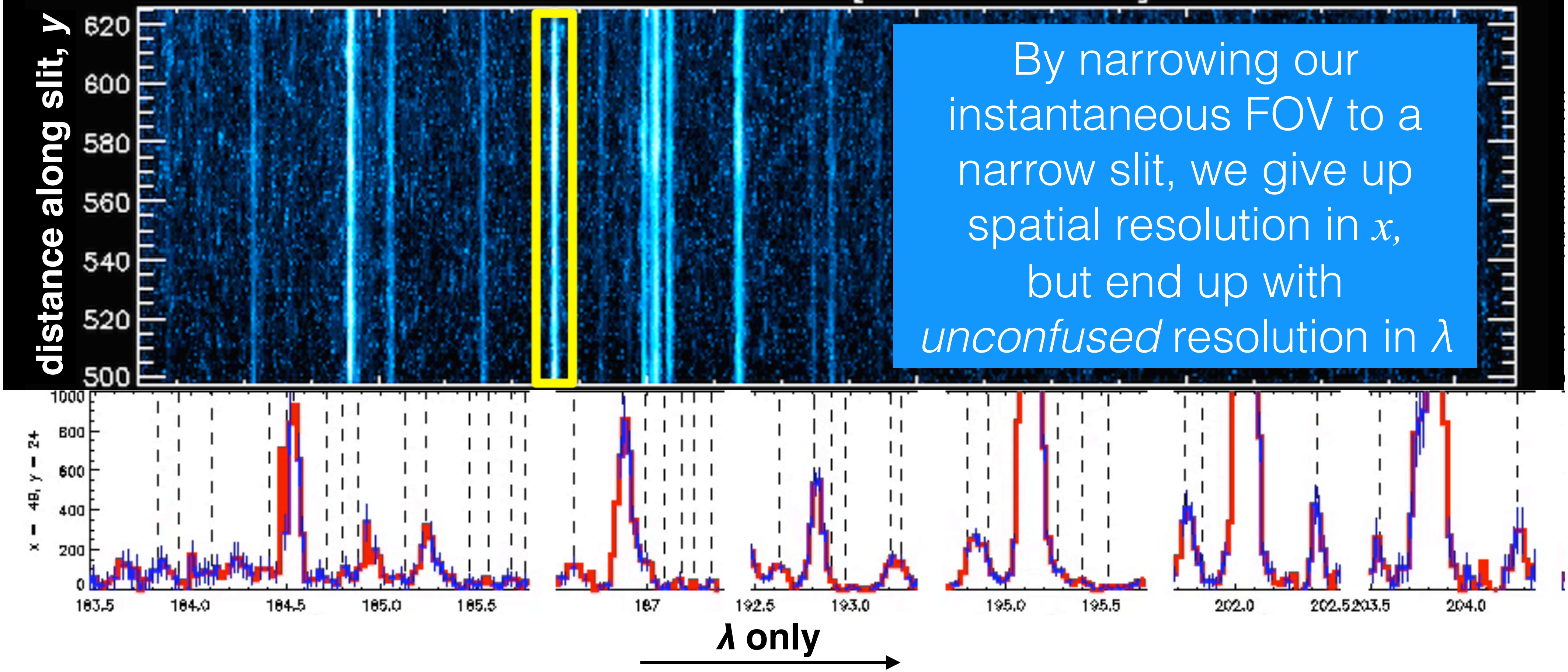
Overlappograms *vs* Slit Spectrograms



- Just spreading wavelengths out means that spatial position gets confused with λ.
- Detectors are still largely ≤ 2-dimensional
    - CCD, CMOS/APS, pen & paper…
- So if you want to de-confuse these...

- Take a 1D column (slit) of a focused image
- Disperse *that* in the direction perpendicular to slit length
- Removes confusion with space in direction of dispersion
- But there are disadvantages (of course… this *is* experiment)

Skylab S082A slitless spectrograph

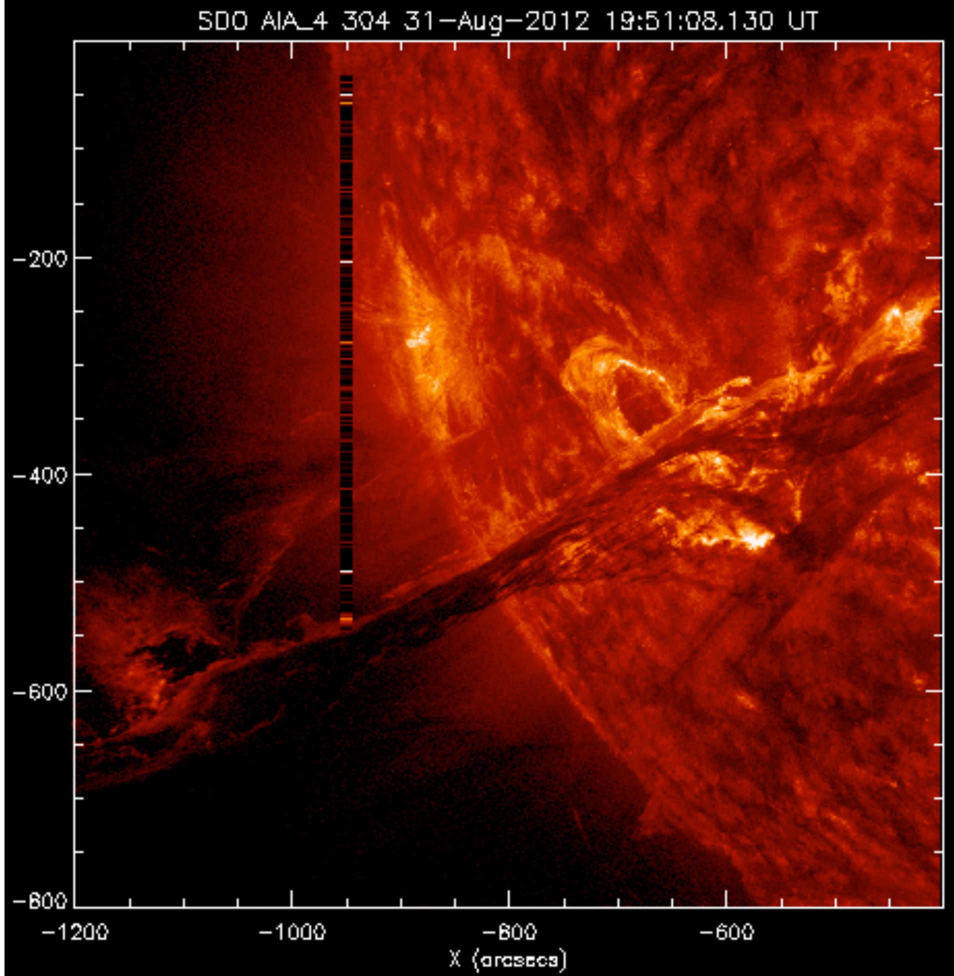


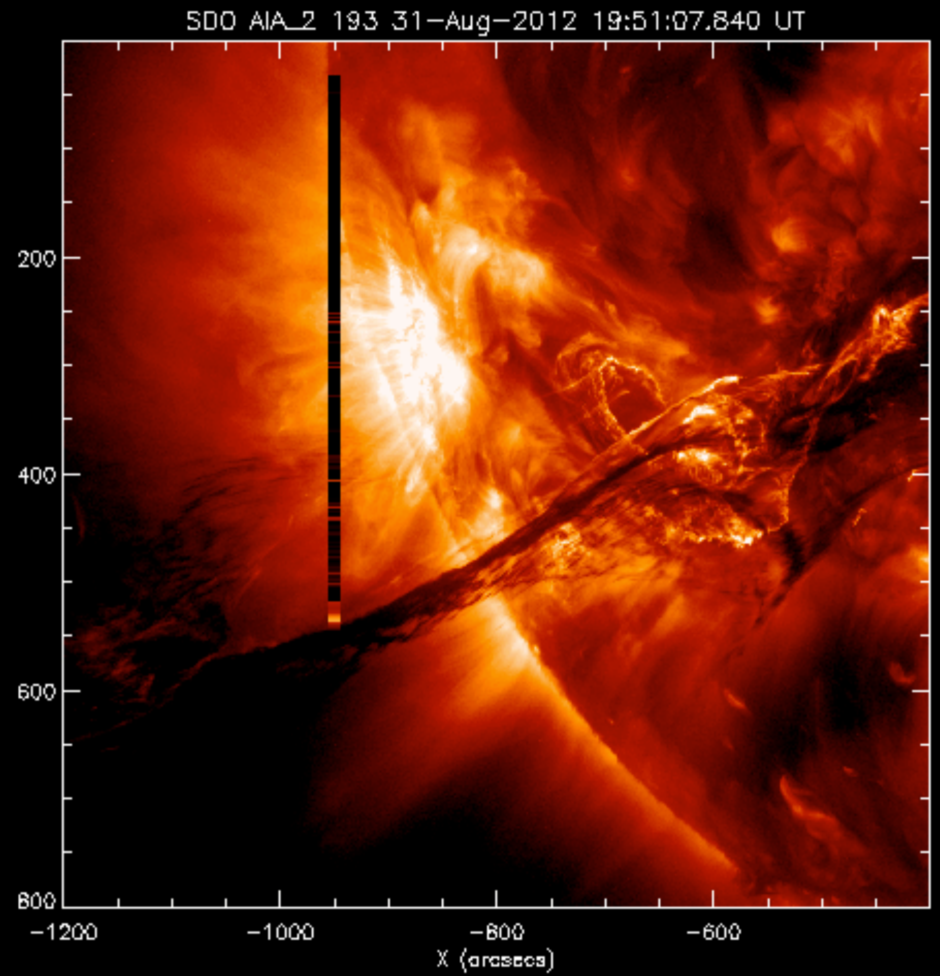
- One of these dispersed slit images ends up on our detector as brightness in (λ, y)
- Each horizontal slice is therefore **the spectrum** $\boldsymbol{I(\lambda; x,y)}$ at position (x,y)
- In the animation, we take slices at a fixed slit (*x*) position, so a fixed time, but at **changing values of *y*** – for illustration only.

Filament eruptions & *Hinode*'s EUV Imaging Spectrometer (EIS)

- Normally we hunt and measure CMEs with **large angle** imaging instruments
  - especially useful are coronagraphs (fields typically several solar radii wide)
- Tricky for a slit spectrometer like EIS to observe a filament eruption because of the small instantaneous FOV.
- But we got lucky in August 2012 – when we were helping to *calibrate* a large-angle coronagraph

Filaments are dark, so not much signal for getting an emission Doppler velocity 😕

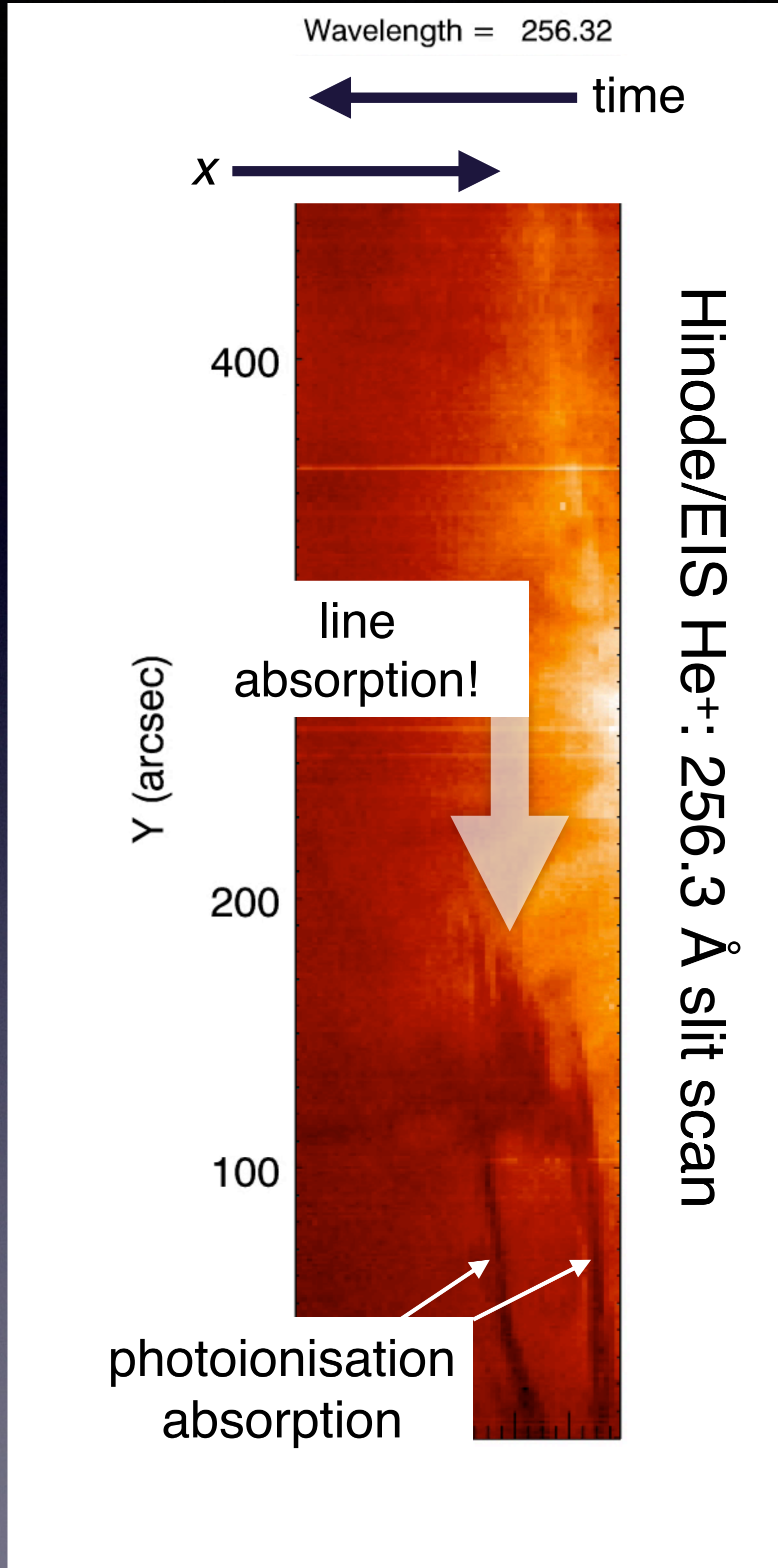




Is there anything we can use to constrain the LOS velocity?

Doppler-shifted resonant absorption by He+ (n = 1→3)

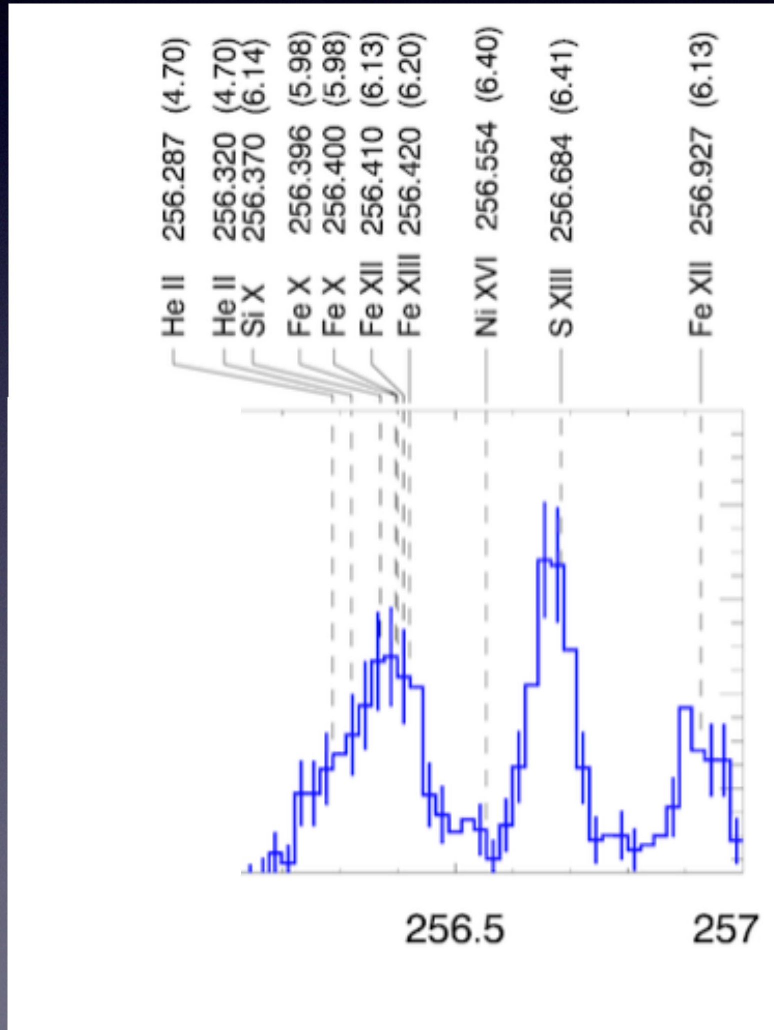
- Animation tunes through wavelengths around the He+ line (256.32 Å), in a scanning slit raster
(x/t, y)
  - Background is off-limb solar corona (some He+, mostly coronal Fe lines)
  - **Dark feature is filament** (absorbing)
- In principle, if He II has a line-of-sight velocity, its absorption should have 2 characteristics:
  - a) a specific wavelength
  - b) this wavelength will be Doppler shifted if the material is moving along our line-of-sight



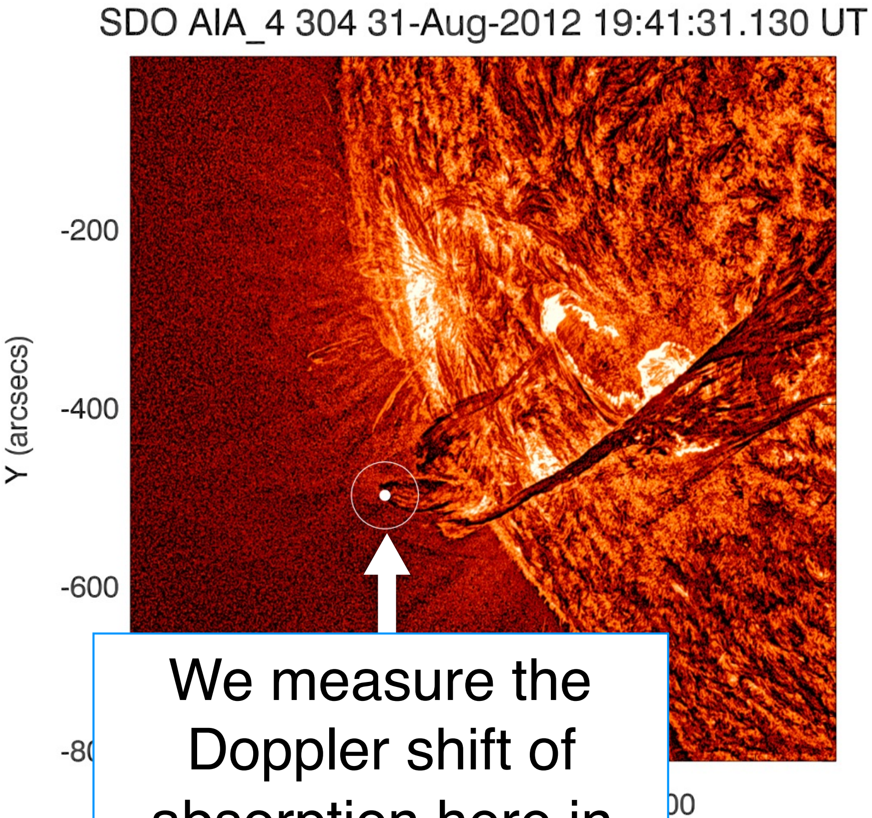
Penn (2000), *Solar Physics*, **197**, 313

So how do we know how much absorption there is?

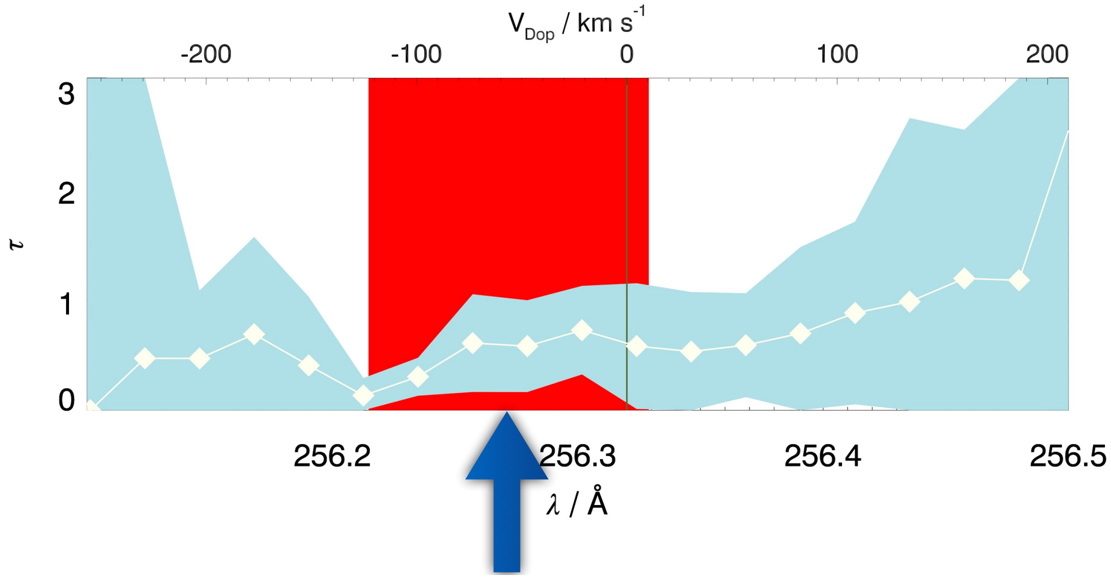
- Tricky thing with measuring the strength of the absorption ("sillhouetting") effect…
  - You need to know what you're sillhouetting!
  - Otherwise there's no way to tell whether you're absorbing more light, or if the background light is just darker at that point.
- We model a background spectrum using lines of Fe X, XII and XIII which are:
  - a) not near the He^+ line, but still in the EIS spectrum
  - b) in the same ratios as in another point in the EIS raster, well away from the filament.



Doppler-shifted resonant absorption by He^{+} ($n = 1 \rightarrow 3$)



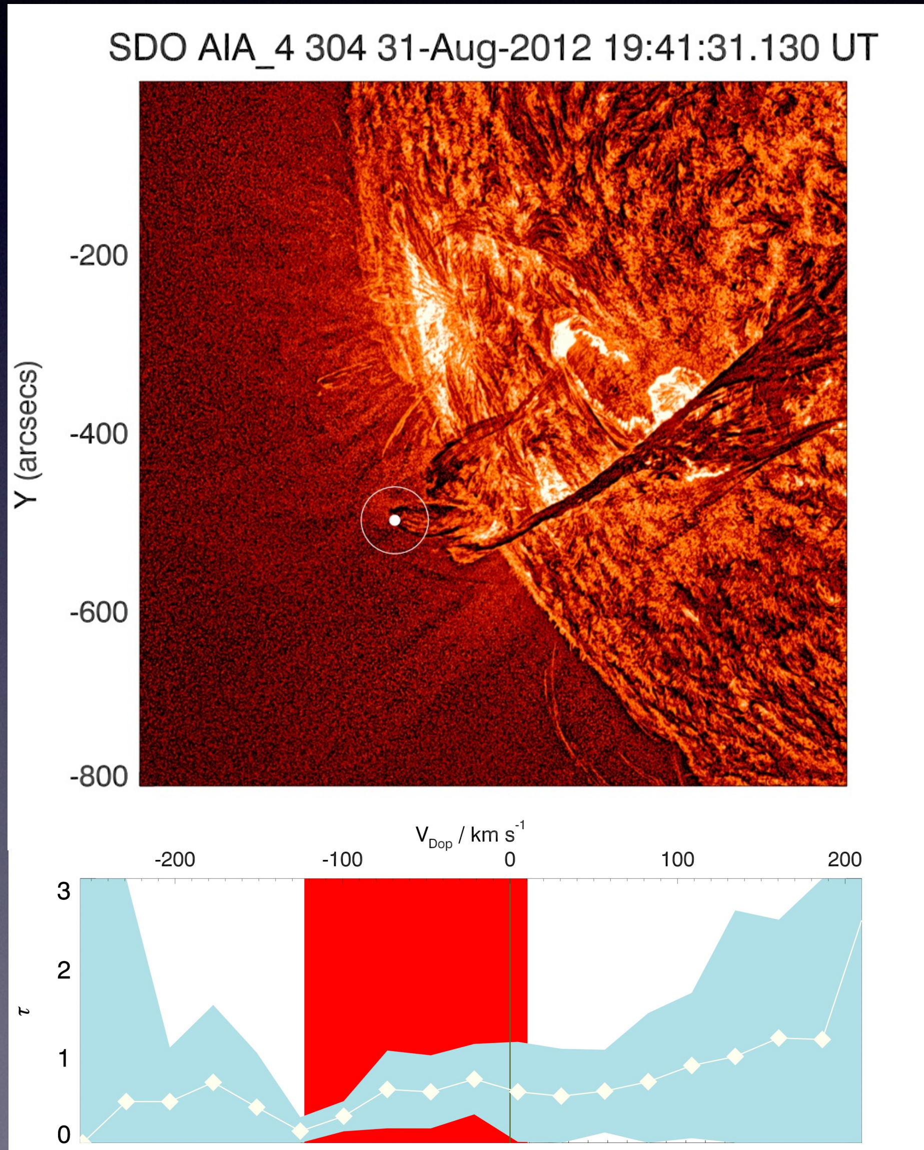
We measure the Doppler shift of absorption here in apex



- Wavelength/velocity region where resonant absorption is above measurement noise.
- This is the range of Doppler speeds that the absorbing material is at.
- We assume that helium will move with the rest of the plasma & thus the bottom of the flux rope.

Comparison of POS and LOS velocities

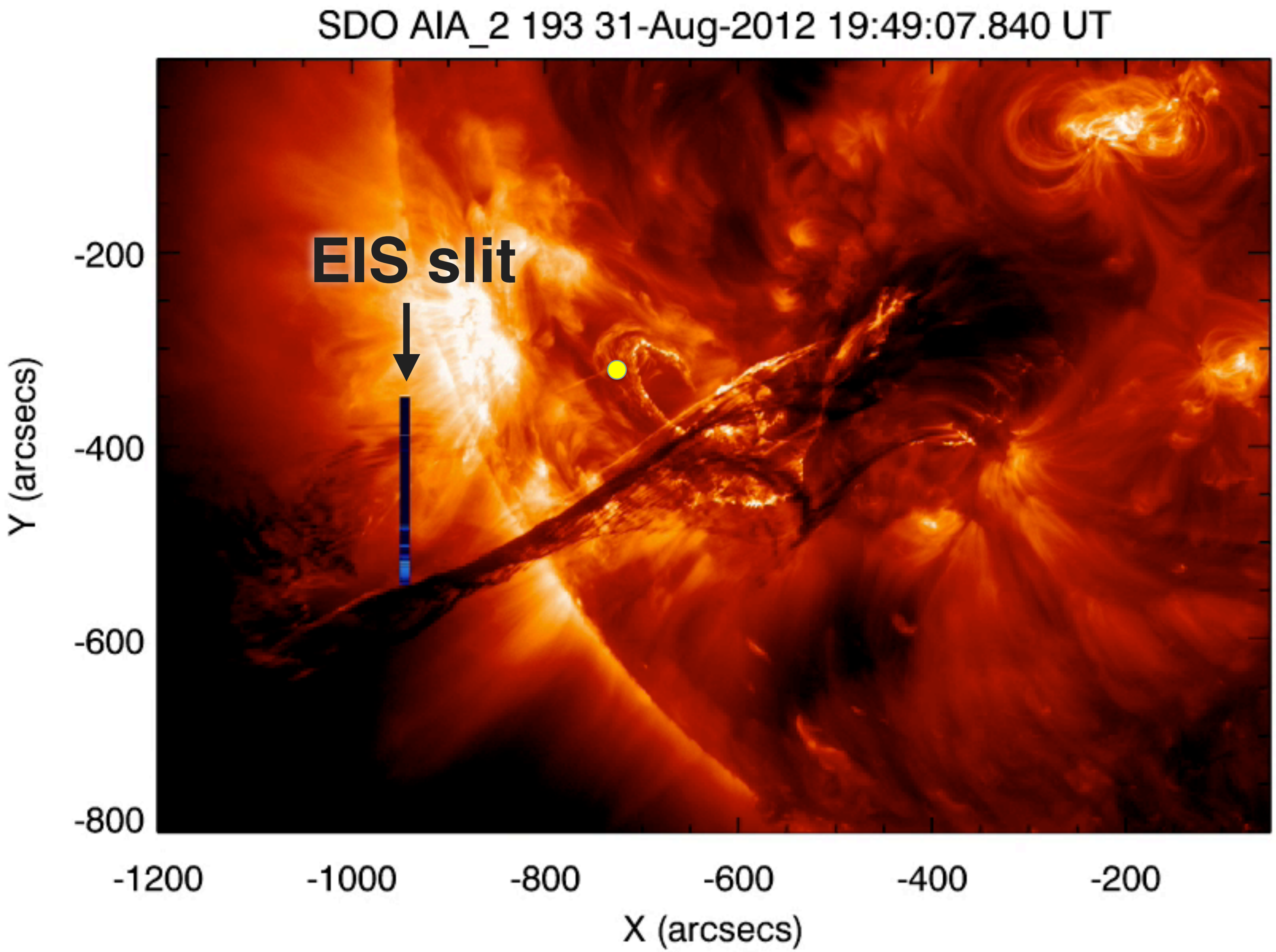
- We know latitude & longitude of source active region
- We also know the plane-of-sky and Doppler velocities… So is it a radial eruption?
- **No!** Blue-shift is too small for this (by about 50%)



Remarks & direction

- Combination of filtergraph images and line spectra from two different observatories – but of the same ion: He^{+}
- Using this unusual (absorbing) line in the EUV spectrum, we've been able to use a spectrometer, designed for coronal-temperature physics, to look at the 3D dynamics of very cool material.
    - Beyond just a single Doppler shift, we also get a *distribution* of LOS velocities, which we can use to probe the dynamics of what passes through our spectrometer slit.
- Erupting flux ropes are widely studied structures at the Sun on the macro scale.
- With this technique the Doppler distributions, mean velocity, and mass (column density) contained in each pixel can be mapped see how the plasma "swirls" on the internal *local* scale

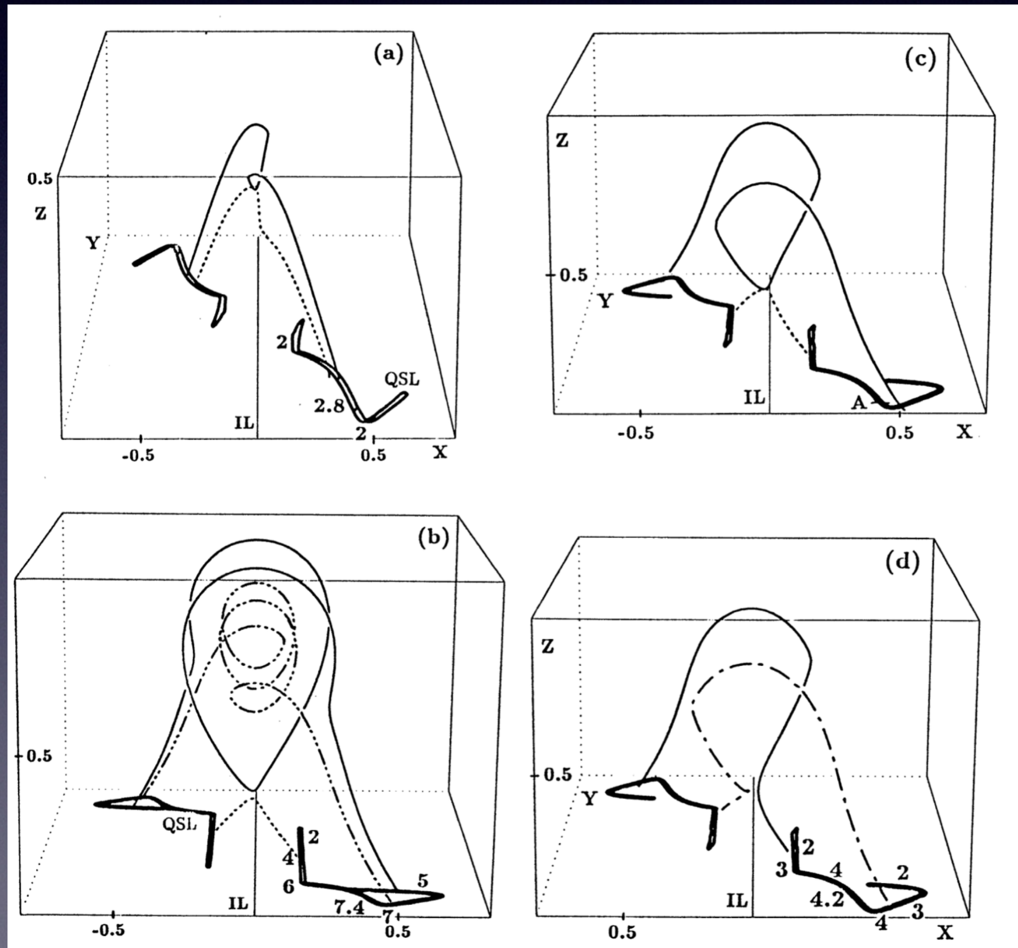
Curious, bright,thread-like structure beside the erupting filament



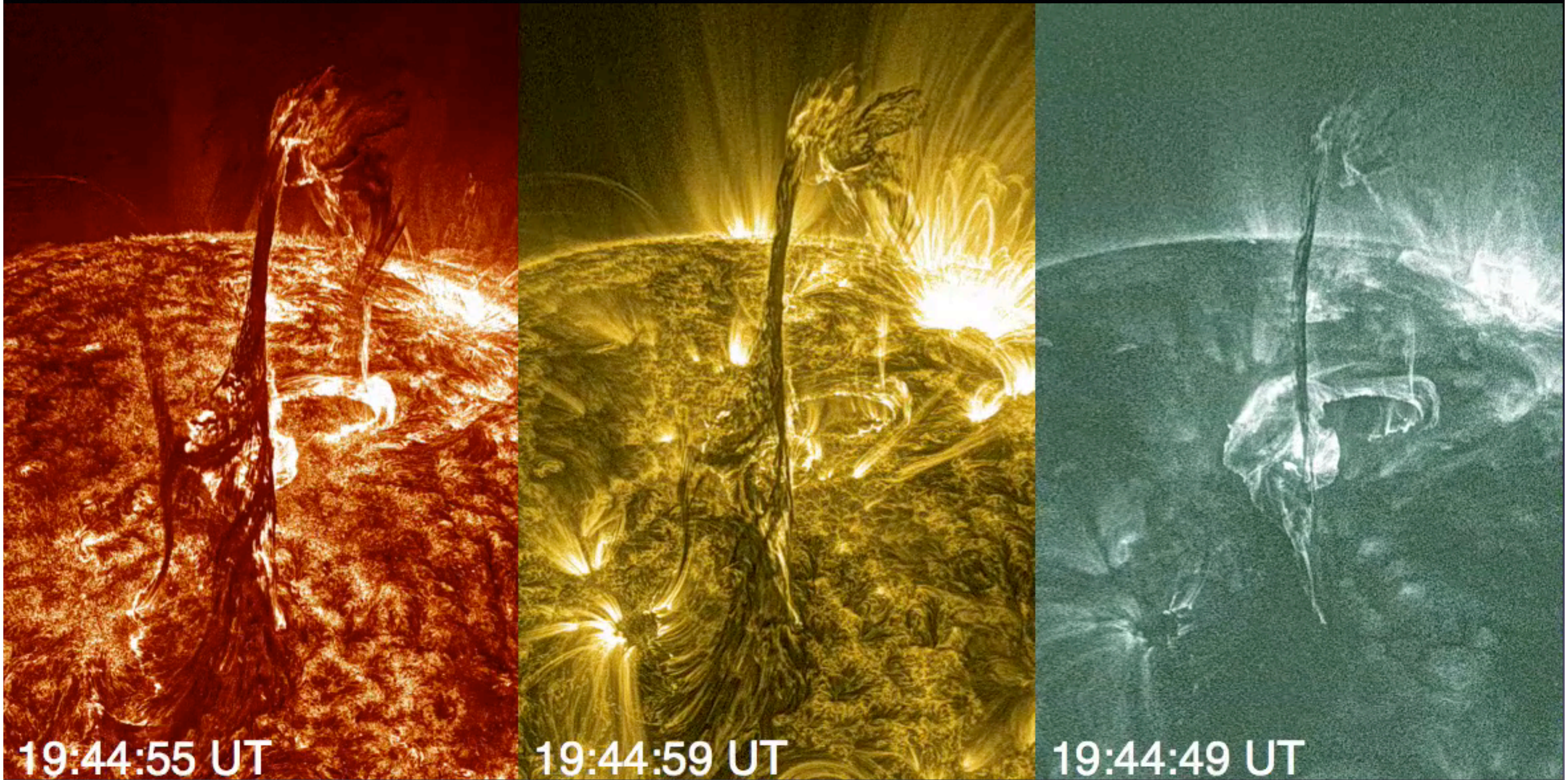
Quasi-separatrix layers

Field lines in QSLs

- These are the continuous extension of the separatrix surface concept
- And are regions where “neighbouring” field footpoints map to radically different places at the opposite footpoint.
- These layers are **prime surfaces** across which **reconnection** can take place

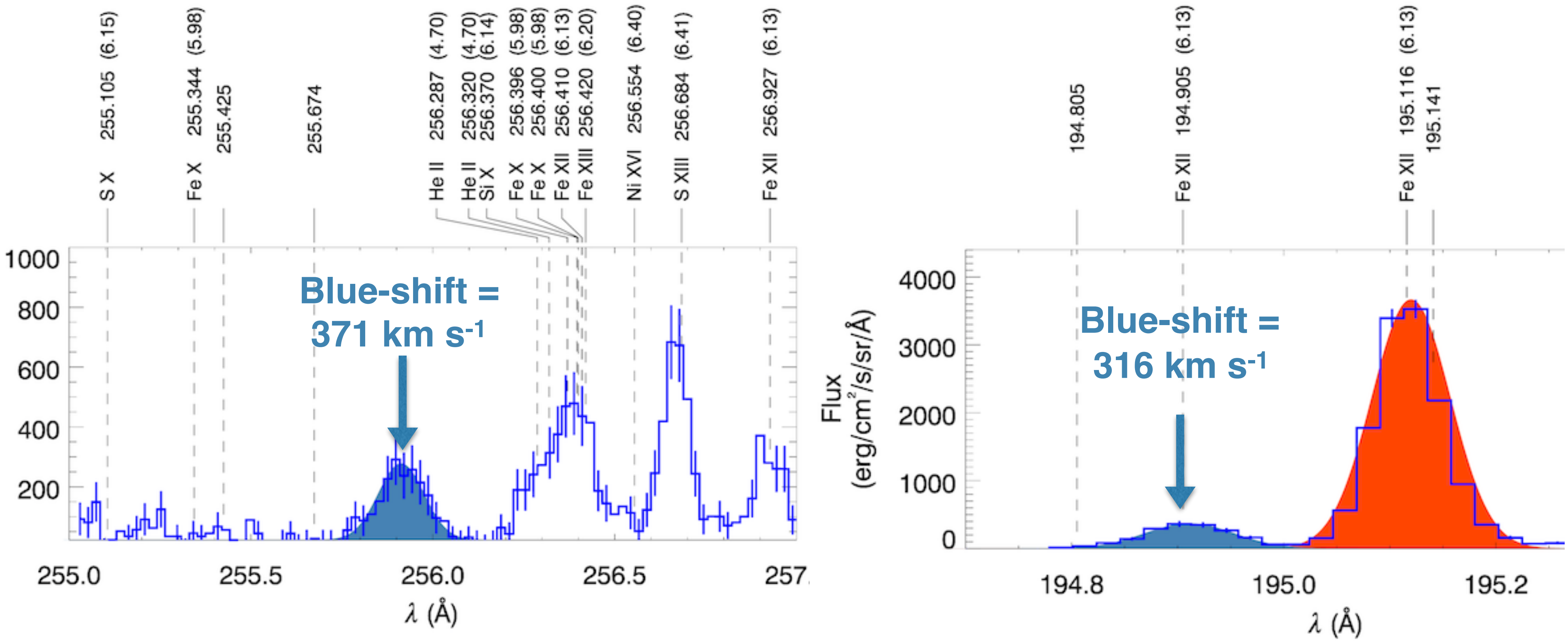


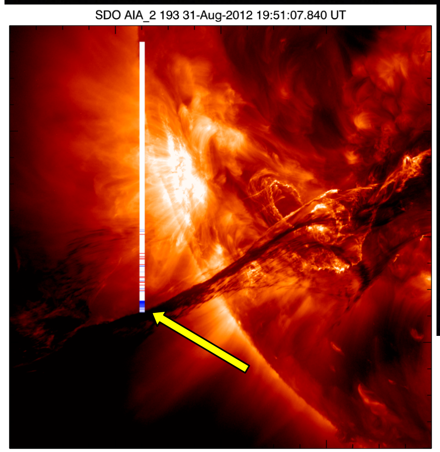
Aulanier *et al.* (2006), *Solar Physics,* **238**, 347; Démoulin et al. (1996), JGR, 101, 7631



The thread appears to be rooted in, or very close to, the flare ribbons.
Fast, subsonic upflows (~150 km/s)

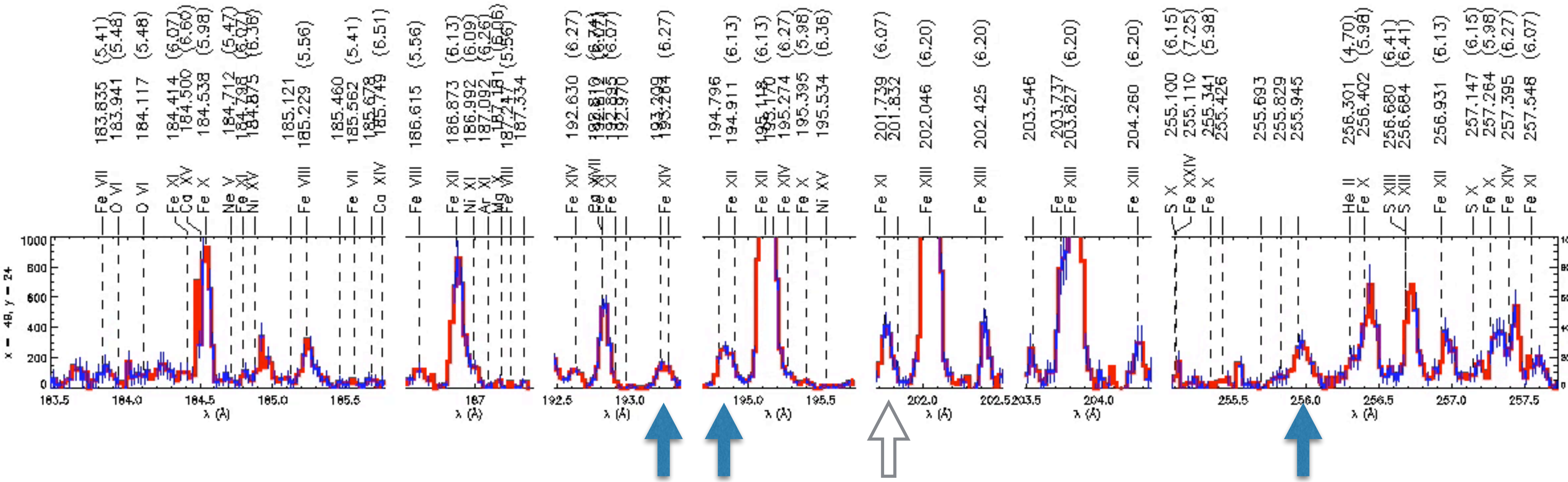
Obvious blue-shifted components





Multiple lines show blue-shift in the thread

Here we freeze time, with the scanning slit in a single position, but change our *y* co-ordinate along the slit, showing change in Doppler shift of certain, cooler lines (log $T < 6.2$)



Fe^{+11}

193.51 Å

195.12 Å

He^{+}

256.32 Å

"Ly_β"

($n = 3 \rightarrow 1$)

§

- EIS reveals some surprisingly strong Doppler flows *along* the inside edge of a filament as it's erupting almost perpendicular to the LOS
  - They appear to be connected to, or just inside, the flare ribbons at the photosphere
  - These flows are supersonic in the higher parts, and so must be somehow driven by the magnetic field
  - They are <u>much</u> faster than the structure's overall motion.
- Crucially, this structure is so far **unexplained**!
- To get a full picture of erupting filaments/ CMEs we need spectroscopic as well as imaging information!