Indicators of a universal process? Reconnection in the corona and magnetosphere

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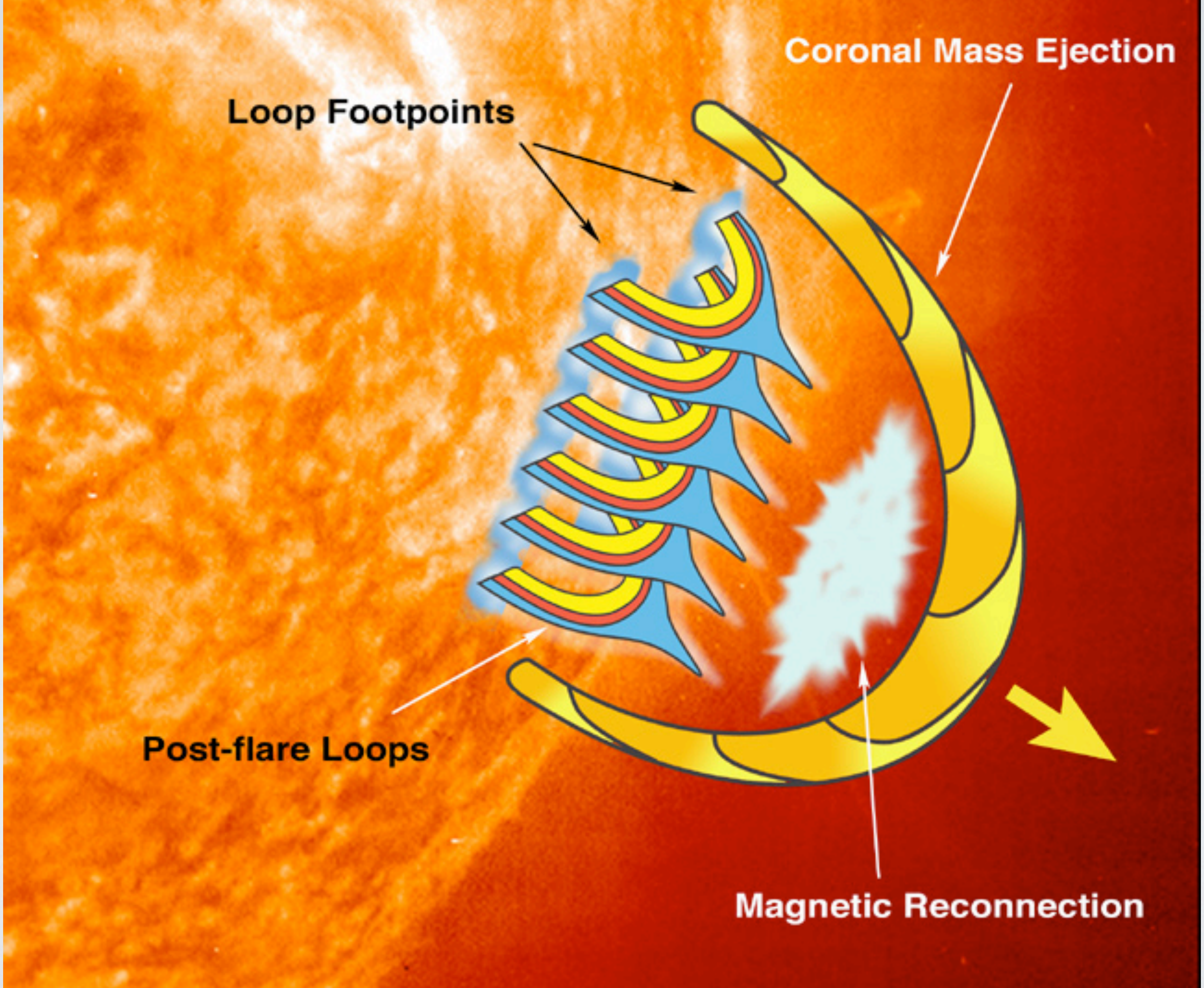
With thanks to Harlan Spence, Jeff Hughes, and the 2006-2007 New England Space Science Consortium Members
(see Reeves et al., JGR, 2008)

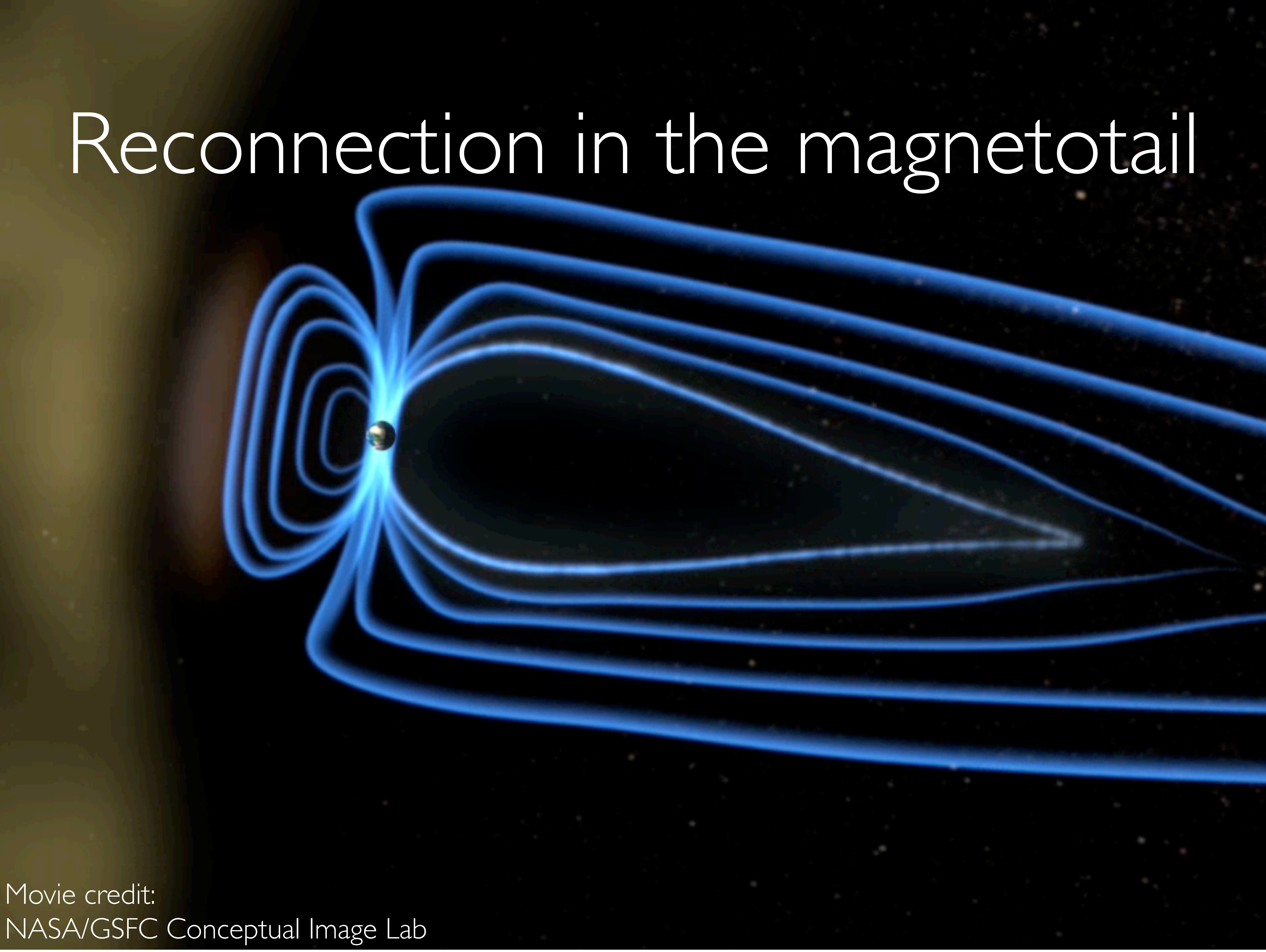
Reconnection in solar flares



"gaudiest cartoon" in Hugh Hudson's flare cartoon archive

The most spectacular example of reconnection in the corona is a solar flare. This cartoon (the gaudiest in Hugh Hudson's flare archive!) shows and erupting flux rope, and the phenomena we expect result from reconnection during a solar - flare loops that are aligned in an arcade and cusp shaped in hotter bandpasses, footpoints of loops.

Reconnection in the magnetotail



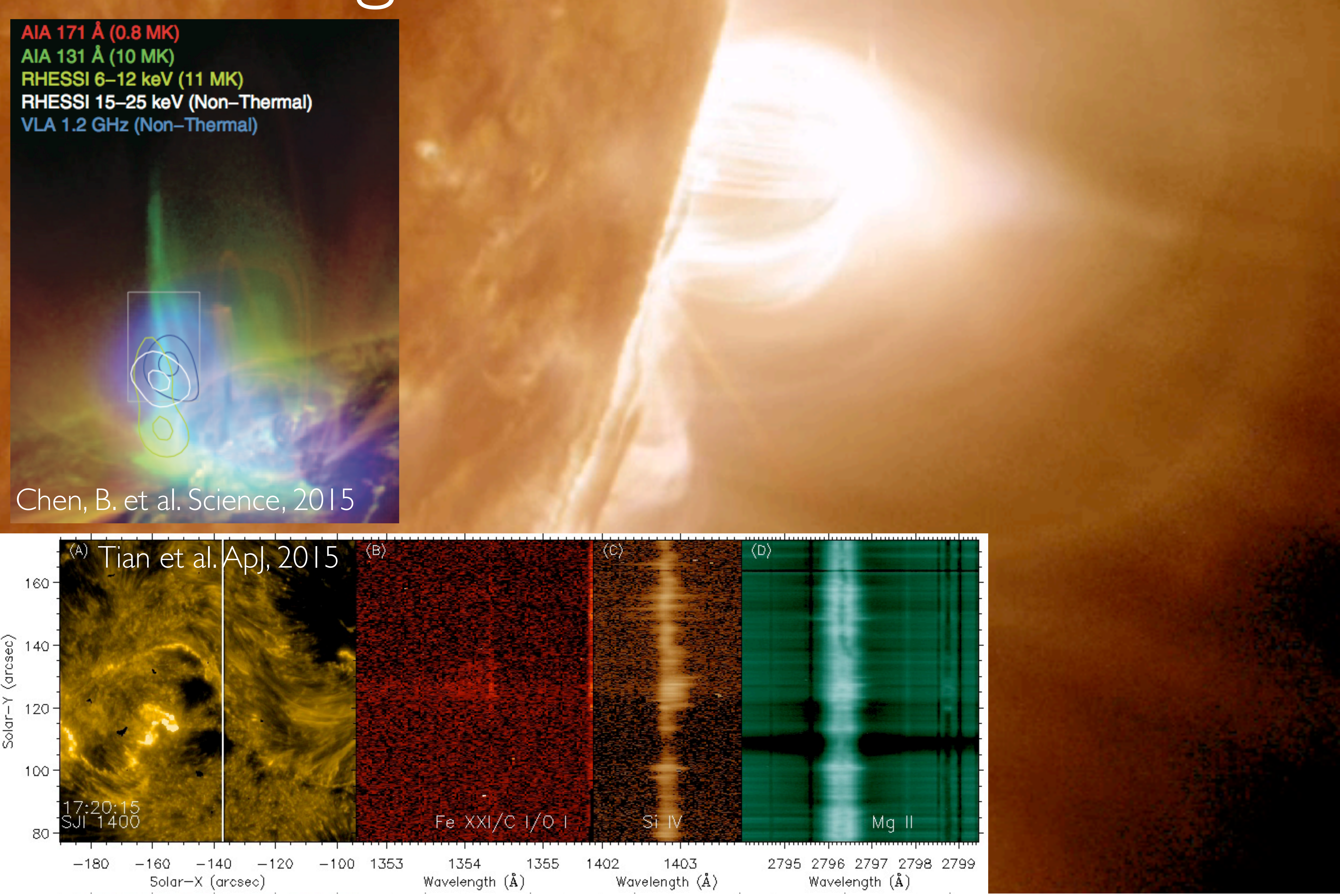
Reconnection also happens in the magnetosphere. When there is a southward turning interplanetary magnetic field, it reconnects with the field at Earth's bowshock, causing filed lines to flip around and initiate reconnection in the tail. particles straming down the field lines are responsible for activating the aurora.

Plasma parameters

	corona	magnetosphere
temperature	10^6 K	10^7 K
density	10^8 - 10^{10} cm^{-3}	1 cm^{-3}
magnetic field	10-1000 G	10^{-3} G
plasma β	0.001 - 0.01	1-10
length scale	10s Mm	10s Mm
Alfvén speed	100 - 1000 km/s	100 - 1000 km/s

The plasma environments in the corona and the magnetosphere are very different - densities and magnetic fields are much higher in the corona. However, characteristic length scales and the Alfven speed are very similar in the two regimes.

Observing the solar corona

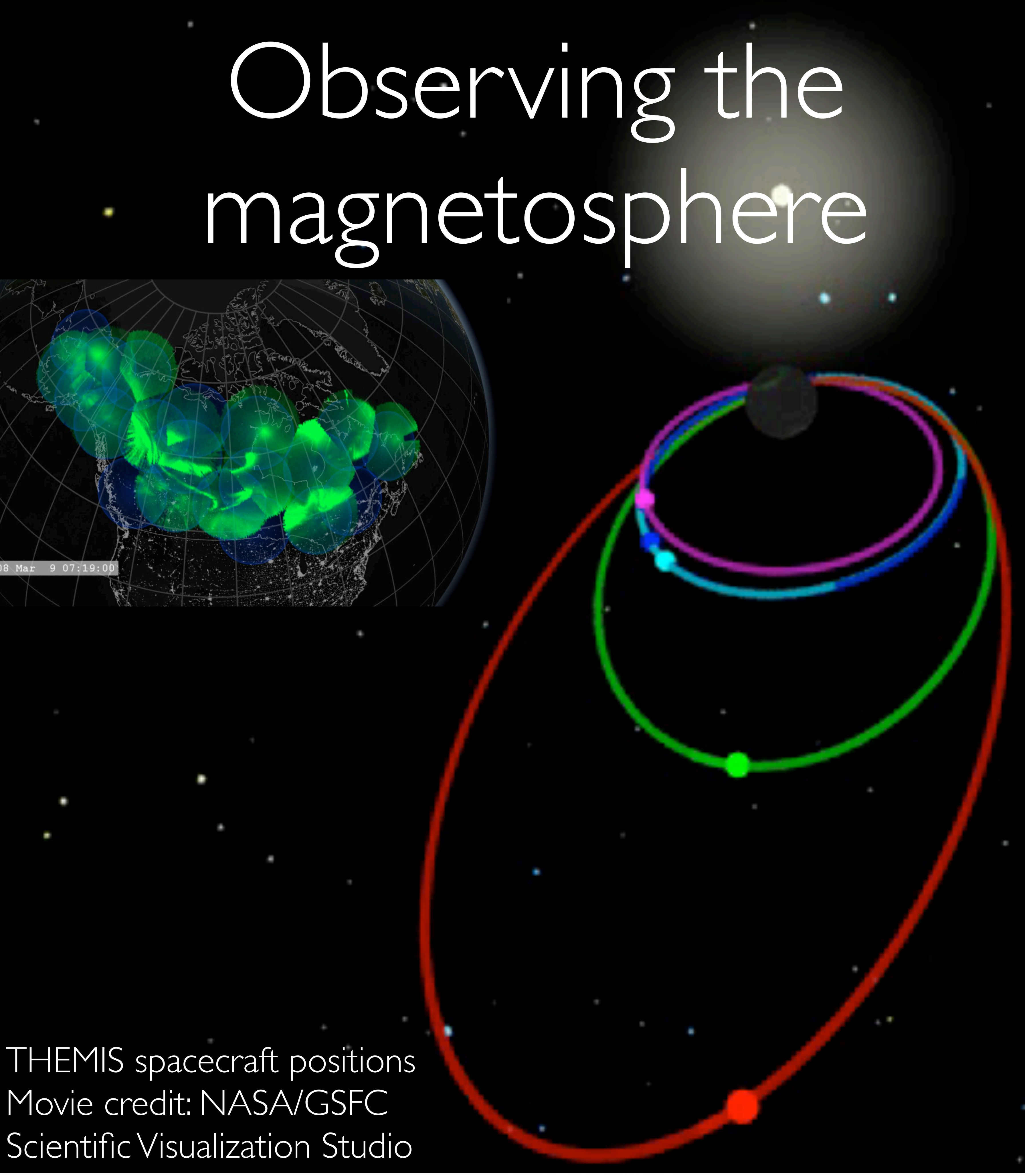


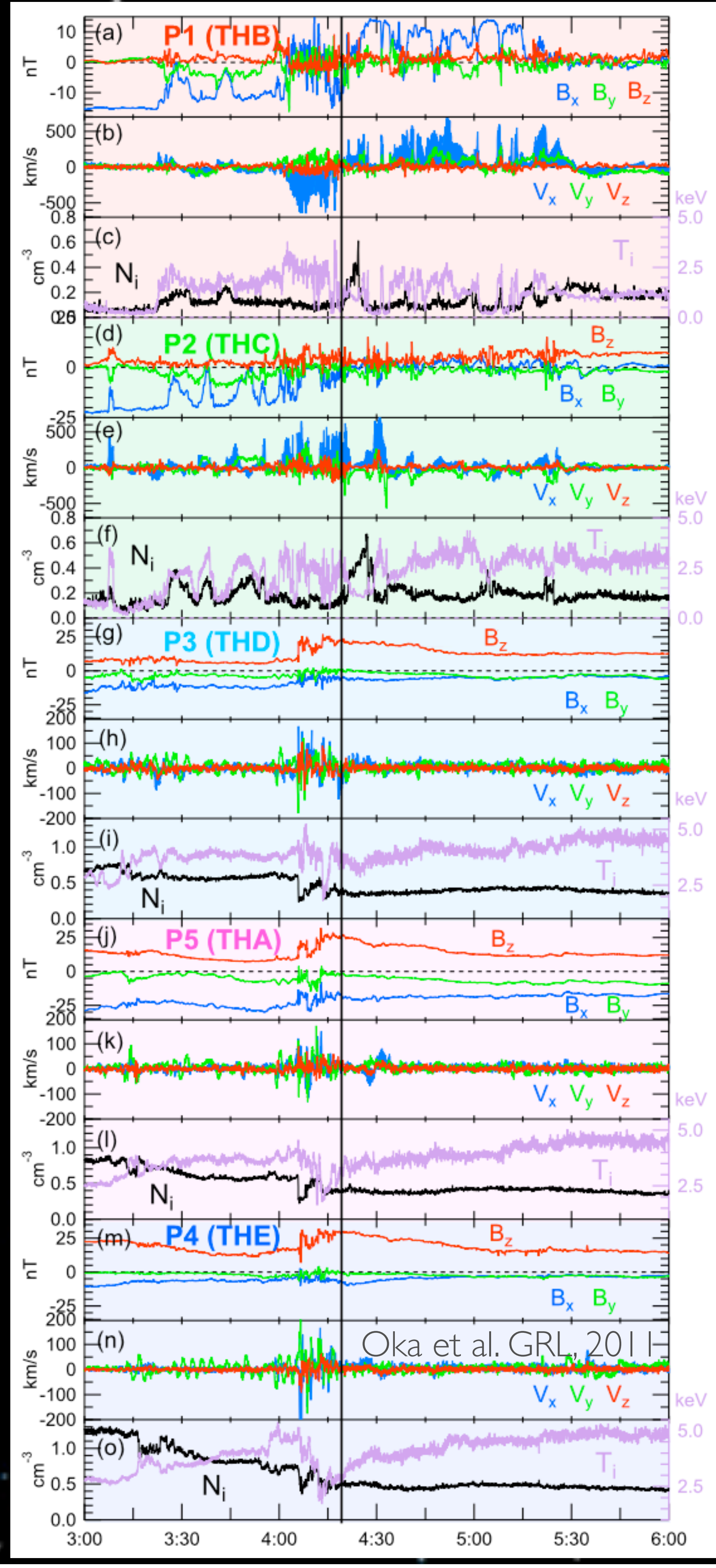
Chen, B. et al. Science, 2015

Tian et al. ApJ, 2015

The observations of the coronal are purely from the light that comes from the sun. We can infer magnetic field structure from the morphology of the plasma, but measuring it directly is difficult. Sometimes, we get lucky and there's a spectrometer slit in the right place, giving information about line-of-sight velocity and non-thermal broadening. X-rays and radio give us information about high energy processes.

Observing the magnetosphere





This movie shows the orbits of the five identical probes involved in the THEMIS mission. The measure several physical quantities of the plasma, including speed, density, and magnetic field. So in the magnetosphere, we get lots of physical information, but at only a few points in space. Additionally, all-sky imagers over the polar regions can give a global view of the aurora.

Reconnection signatures

- field line shrinkage (dipolarization)
- inflows and outflows
- energy deposition at footpoint of field line
- heating
- particle acceleration

These are signatures we might expect from reconnecting magnetic fields. I will mostly focus on the first three.

Field line shrinkage

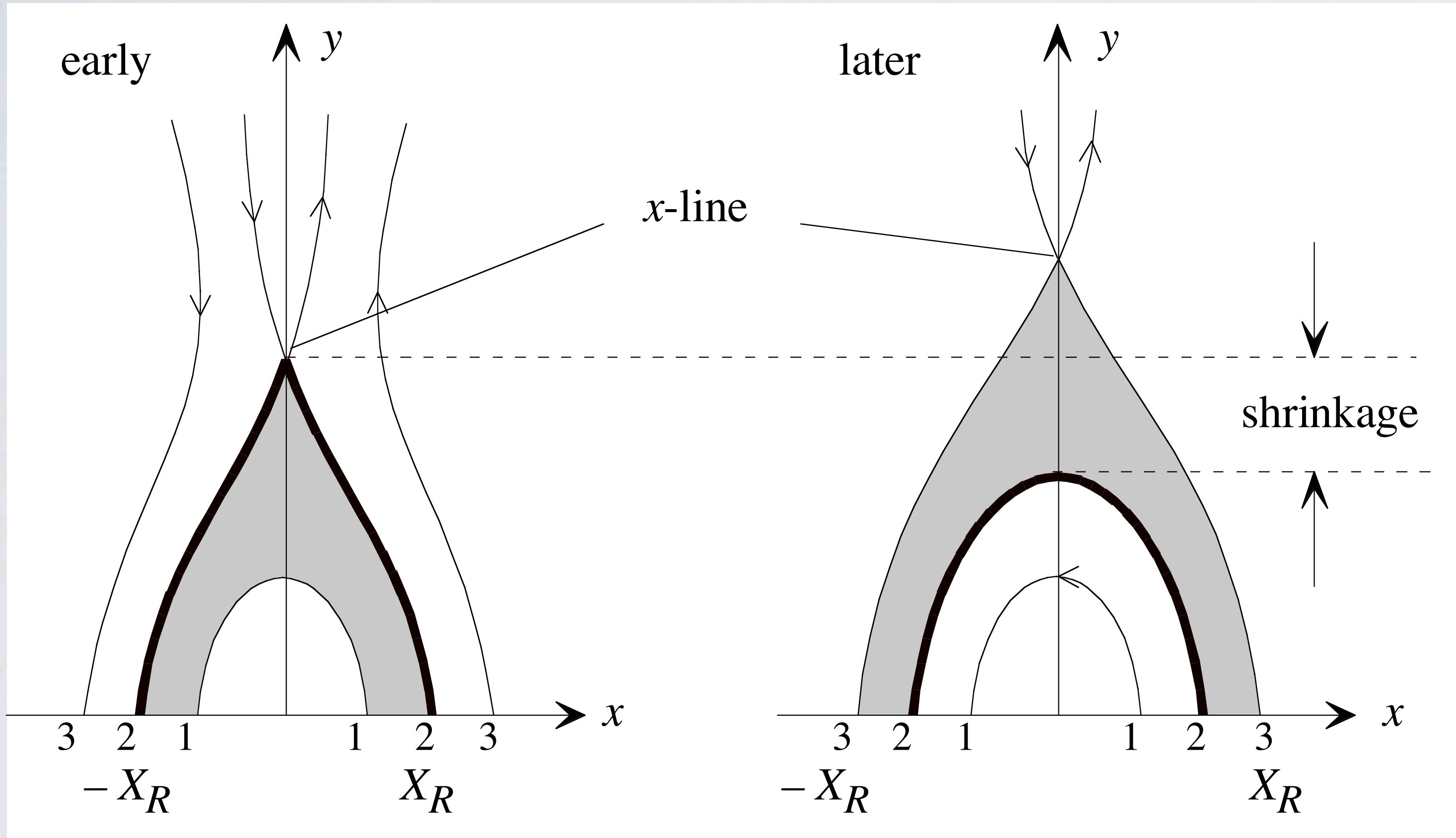
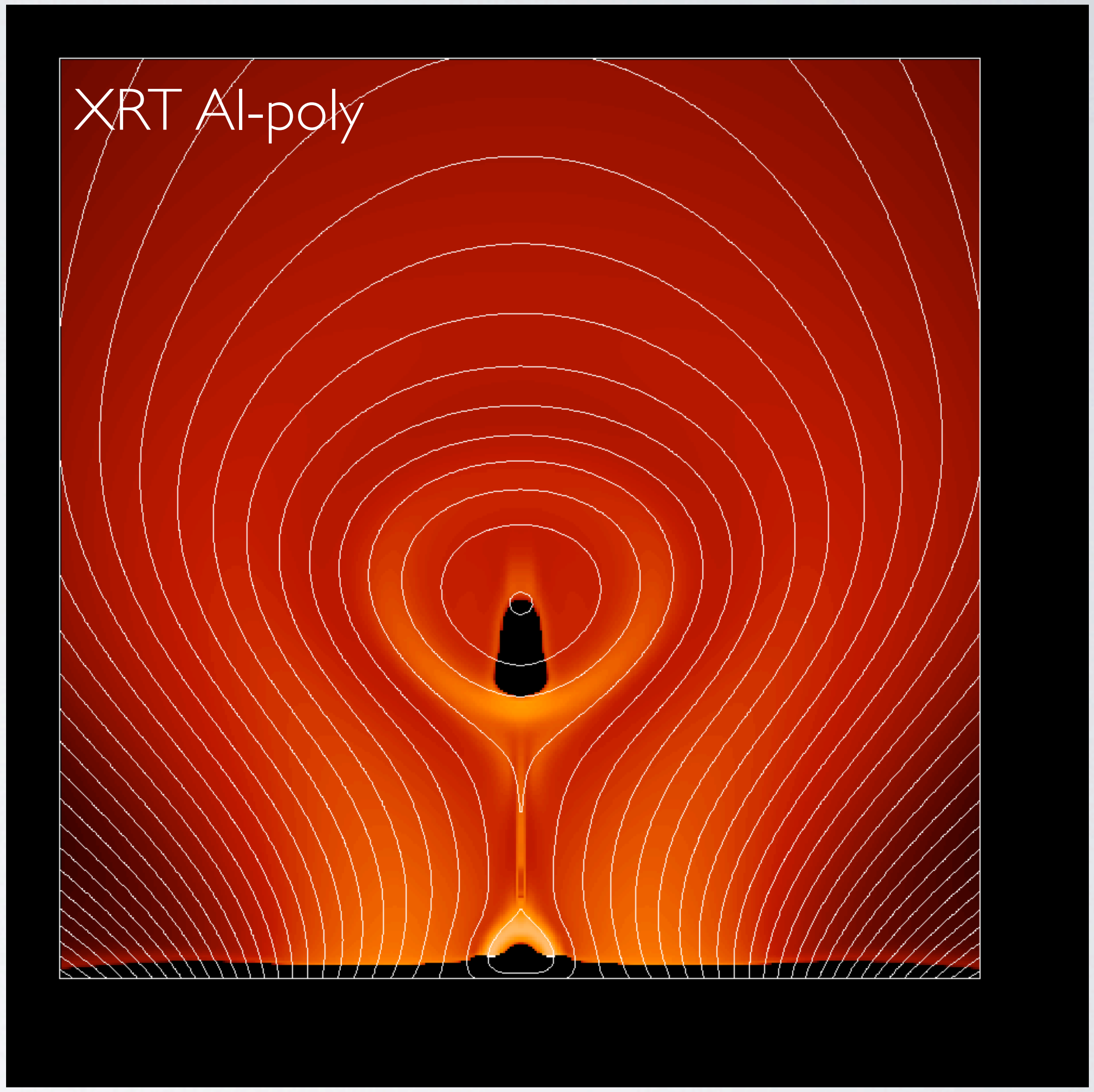


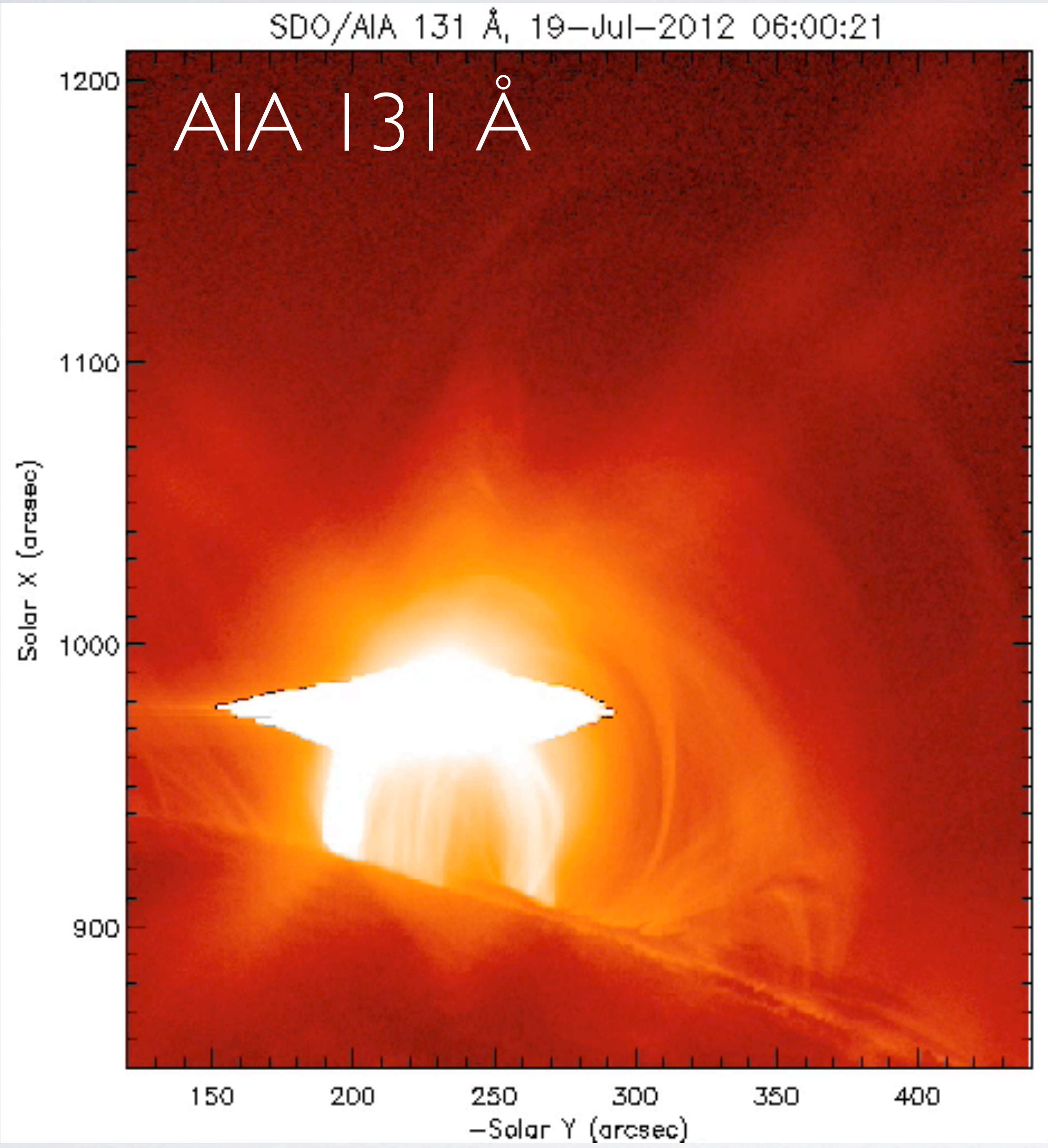
Figure courtesy T. Forbes



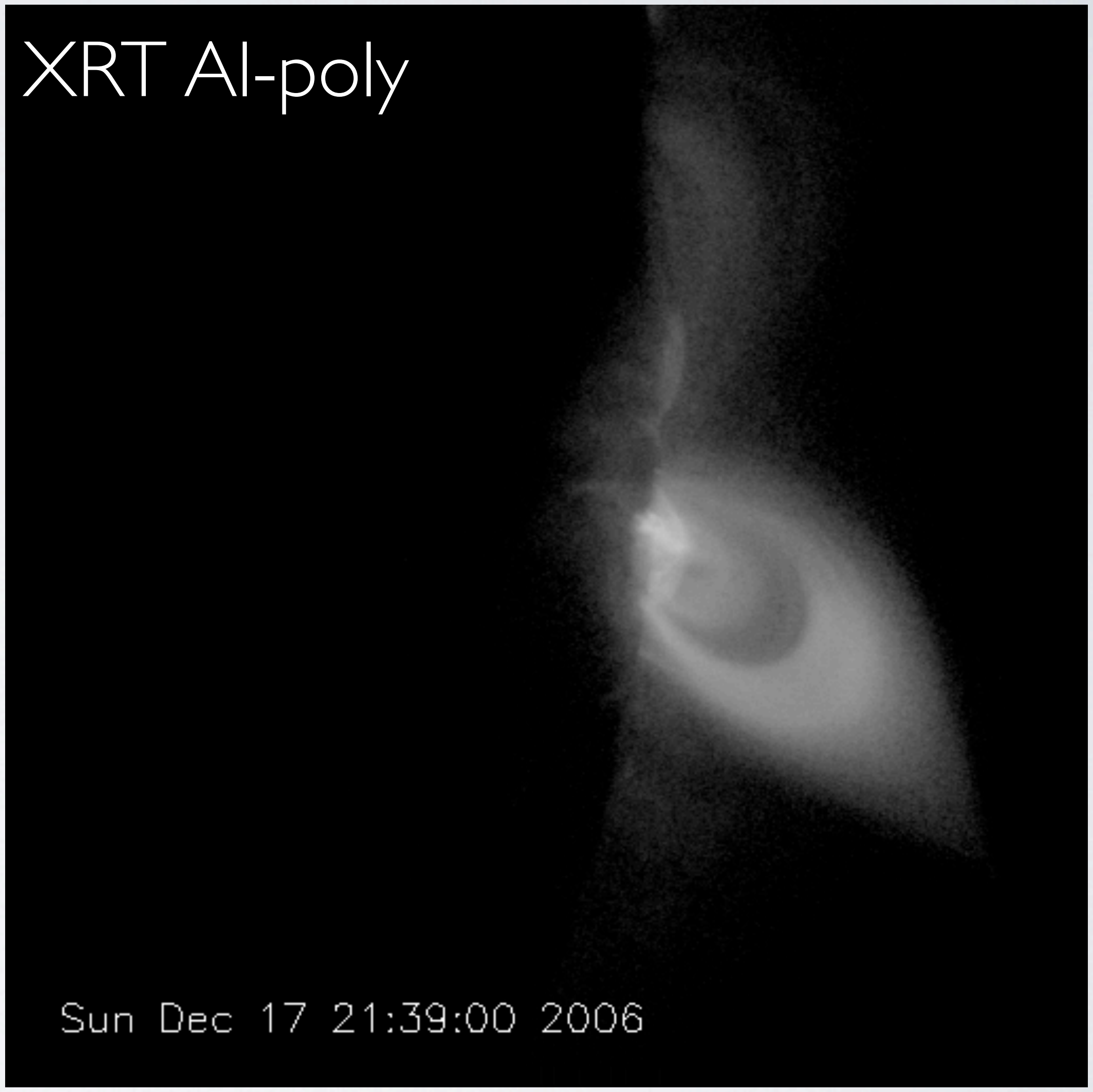
PSI MAS 2.5D simulation
(from Reeves et al. 2010)

As Terry mentioned in his talk, an expected outcome of reconnection is field line shrinkage, as shown in the figure. The movie is a 2.5D PSI simulated XRT movie, and shows the same thing.

Field line shrinkage



W. Liu et al., ApJ, 2013

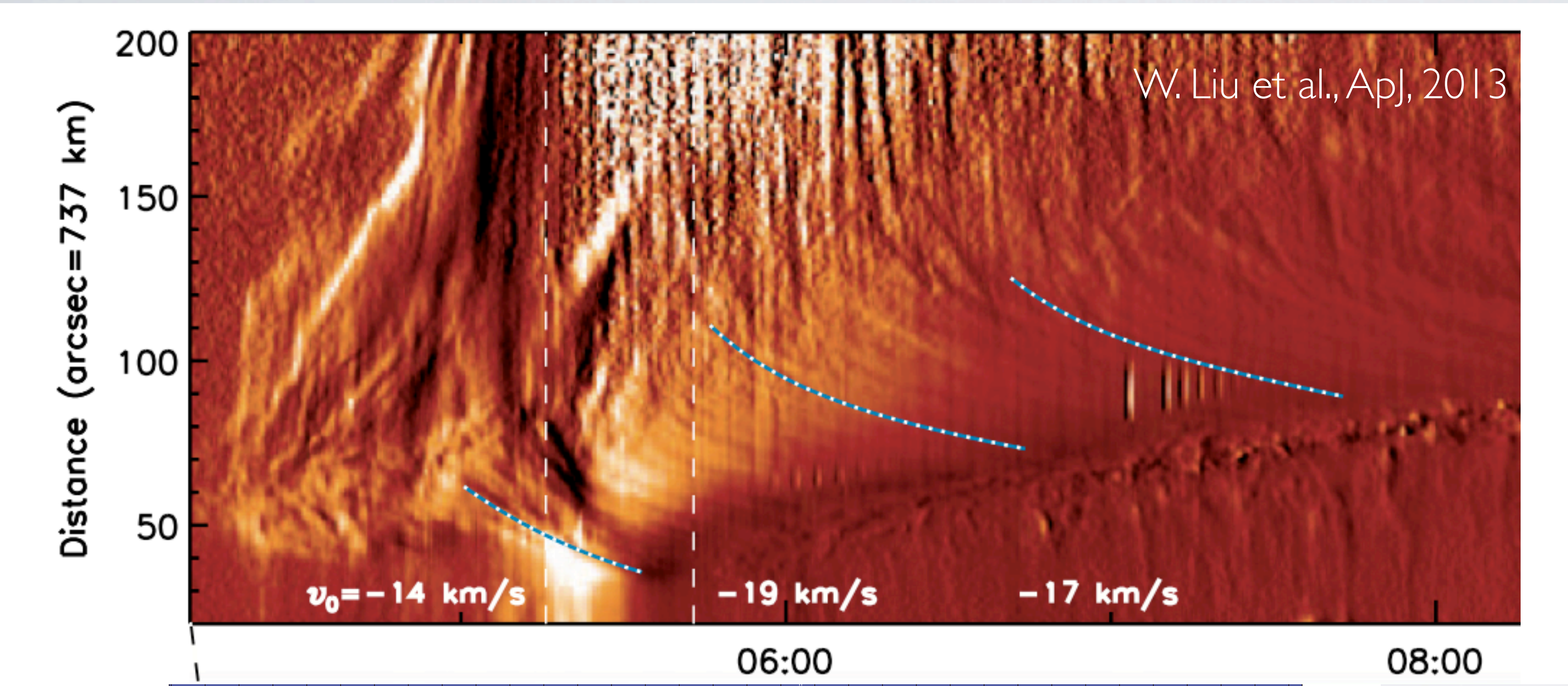


Reeves, Seaton & Forbes, ApJ, 2008
Reeves et al., JGR, 2008

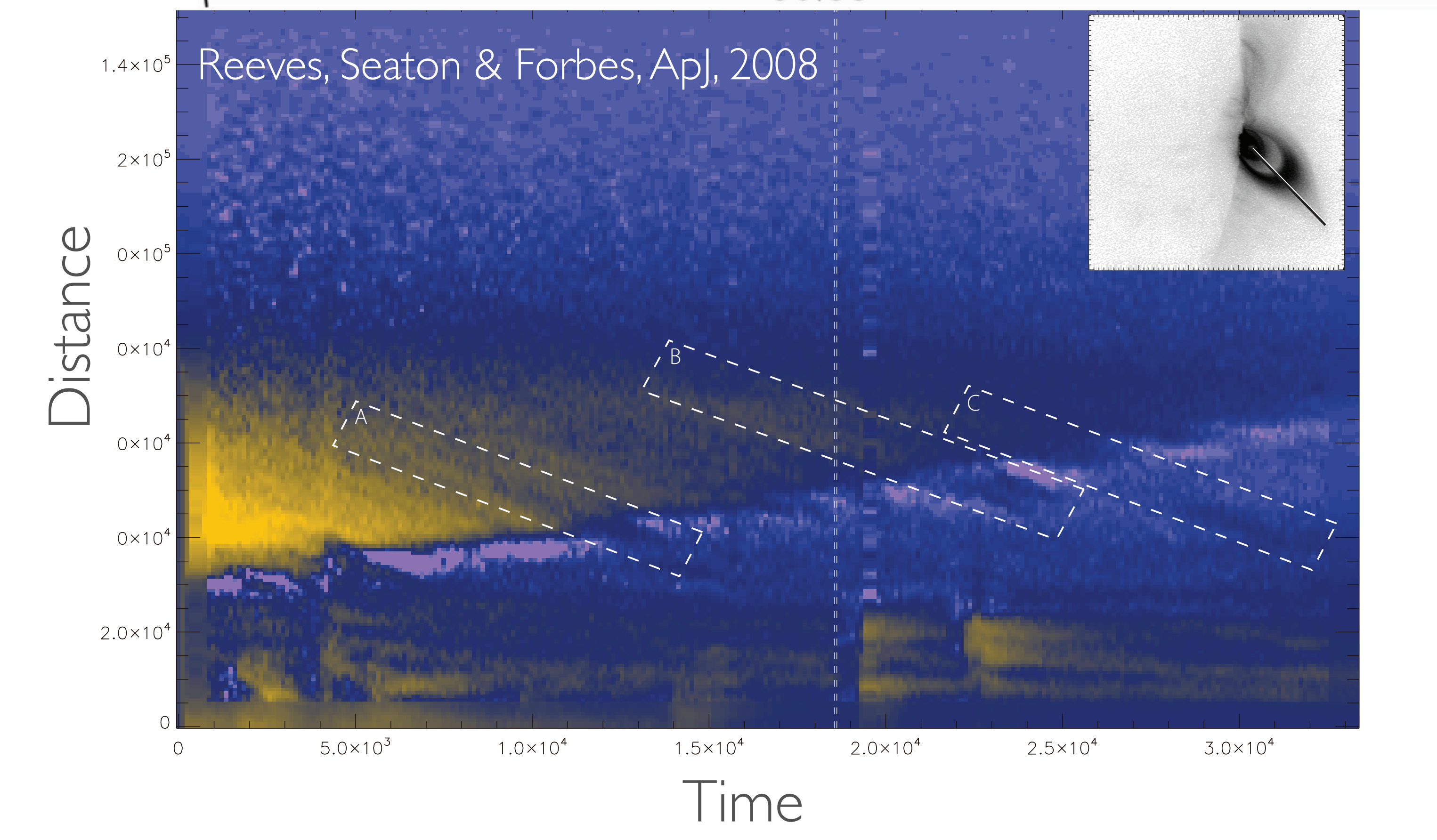
(see also Forbes & Acton 1996)

With high time-cadence imaging data, shrinkage has been observed in several flares, including this AIA 131 A observation by Wei Liu, and the XRT flare that Terry mentioned in his talk.

Shrinking velocities



v = 14-19 km/s



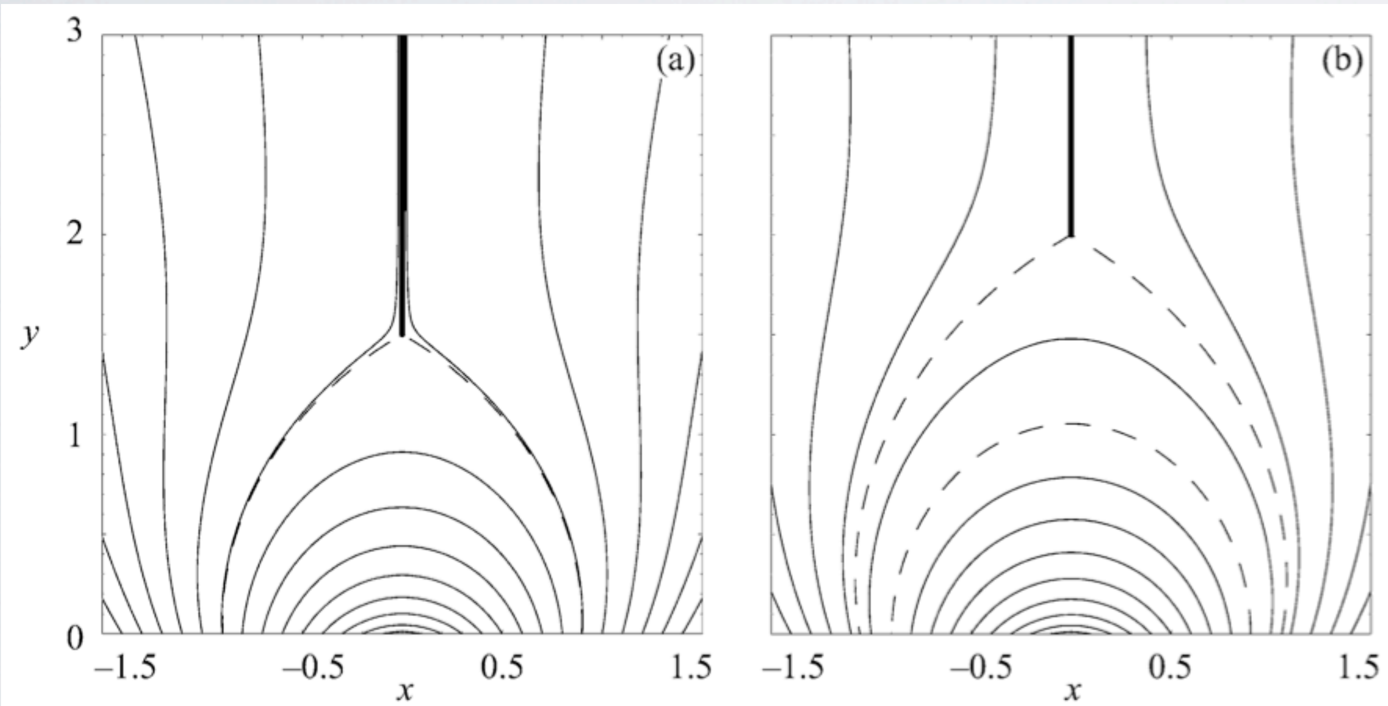
v = 5 km/s

Can be up to 50 km/s higher in the corona

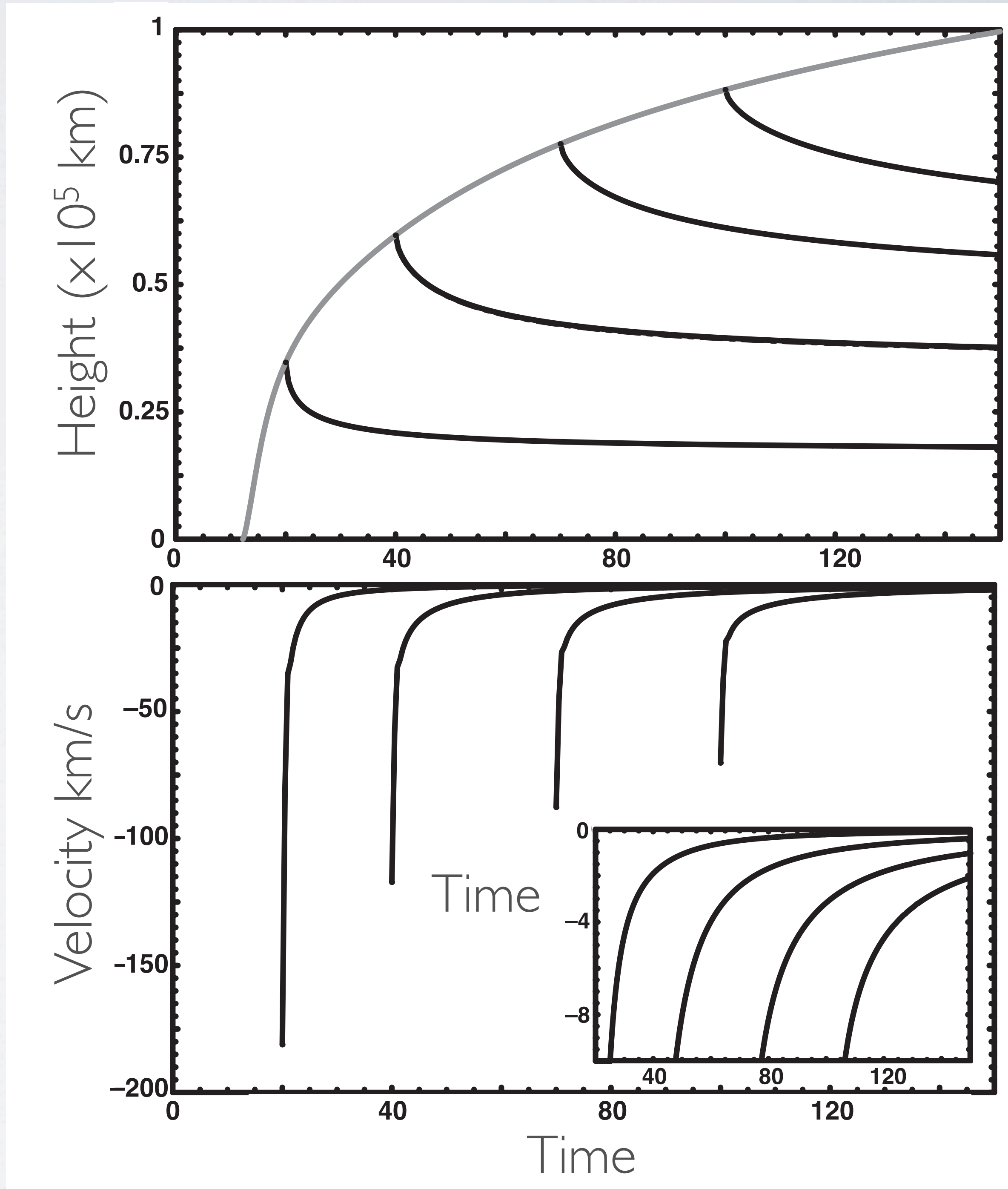
(e.g. 2007 May 2 event in Reeves, Seaton & Forbes, ApJ, 2008)

We can measure the speeds of the shrinking loops directly from the images, and they are on the order of 5-50 km/s

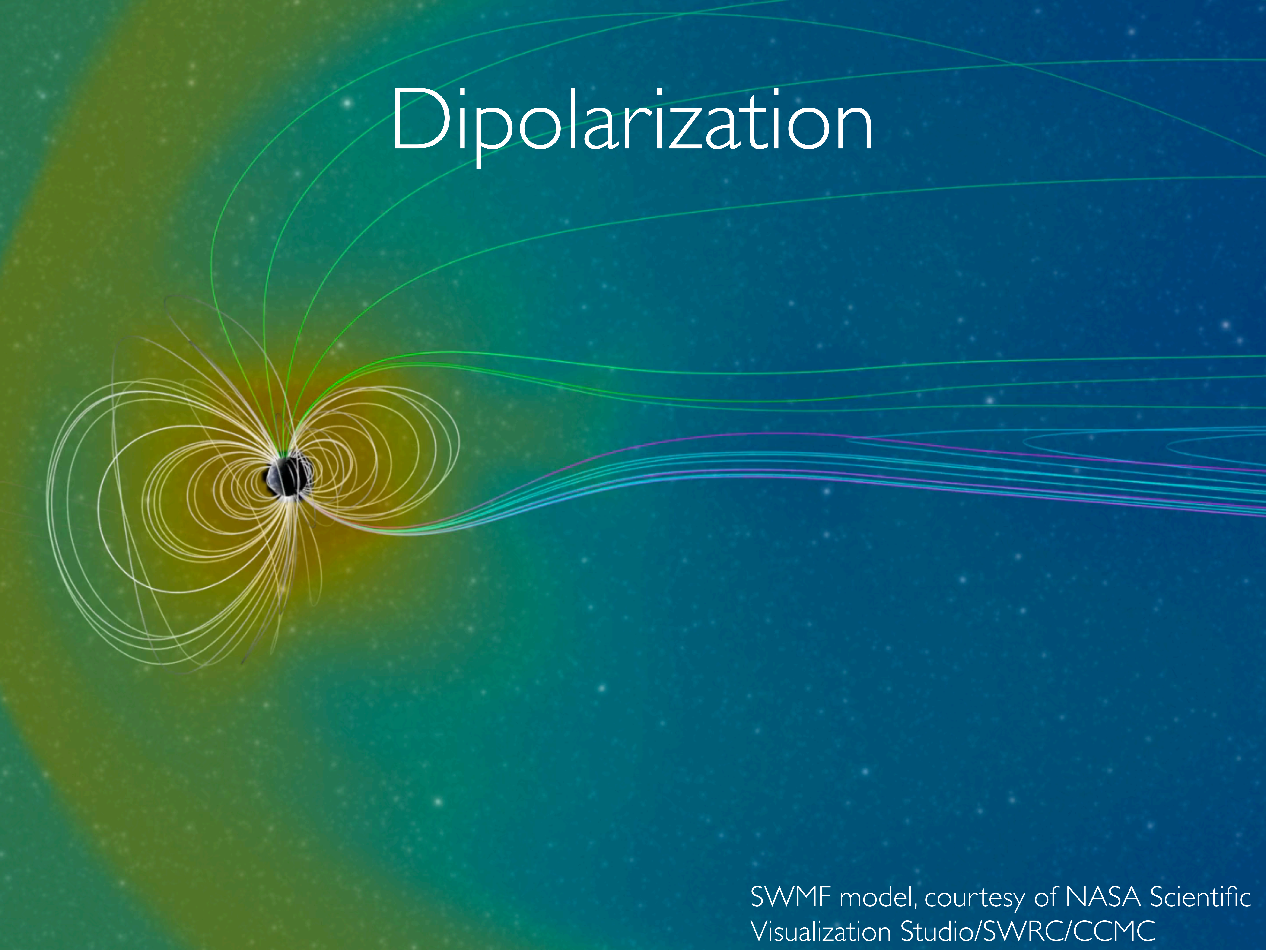
Theoretical calculations for shrinkage in flares



J. Lin, ApJ, 2004

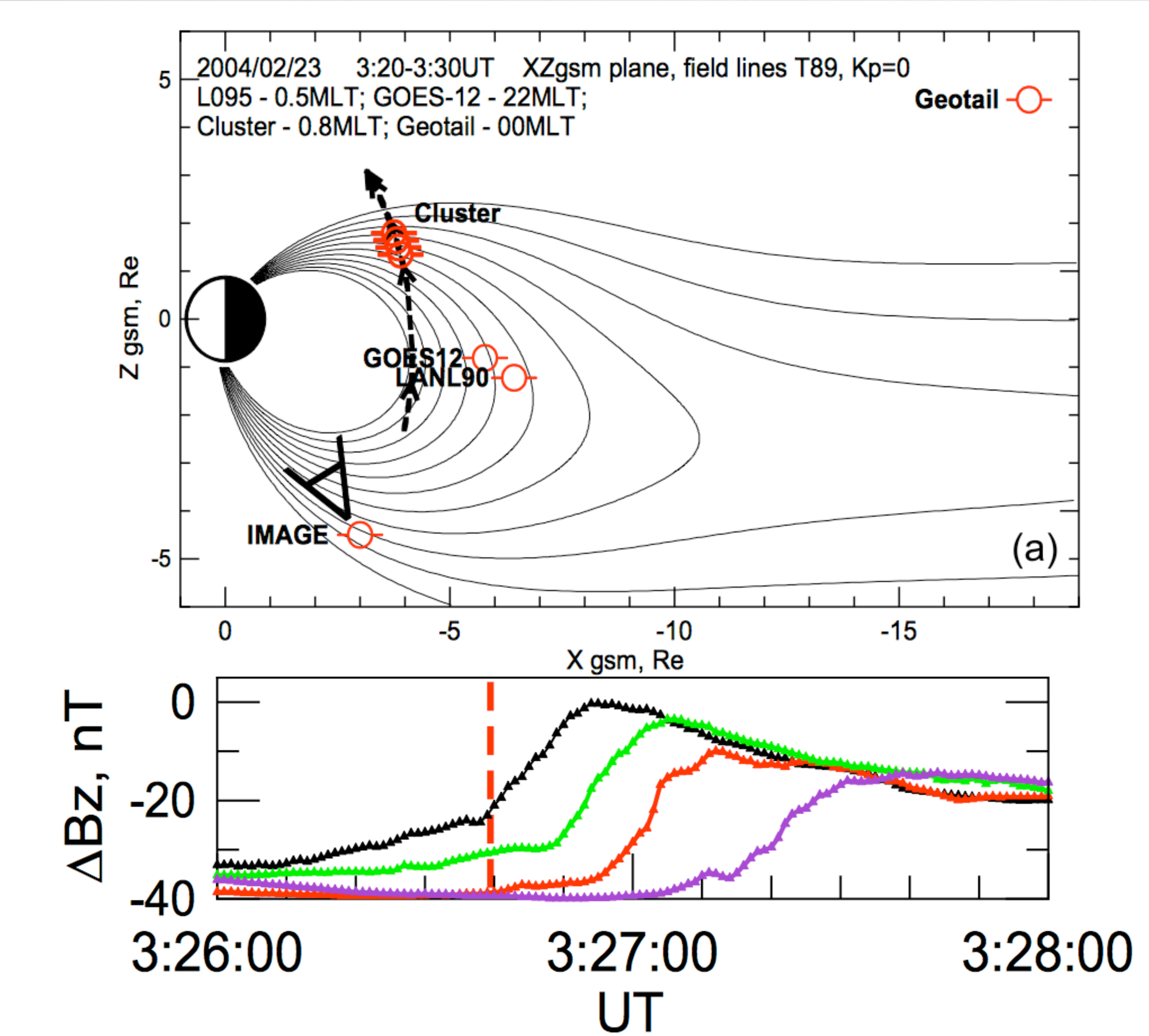


Using a 2D model, Lin (2004) calculated the trajectories of the loop tops and found that the loops shrink faster just after reconnection, and can have speeds of up to a couple hundred km/s high in the corona. As the loops encounter the newly reconnected loops below, they slow down to speeds of a few km/s.



In the magnetosphere, the same phenomenon is observed, but it is referred to as dipolarization because the field is becoming more dipolar, as shown in this simulation using the Space Weather Modeling Framework.

Multi spacecraft dipolarization



Apatenkov et al., AnnGeo, 2007

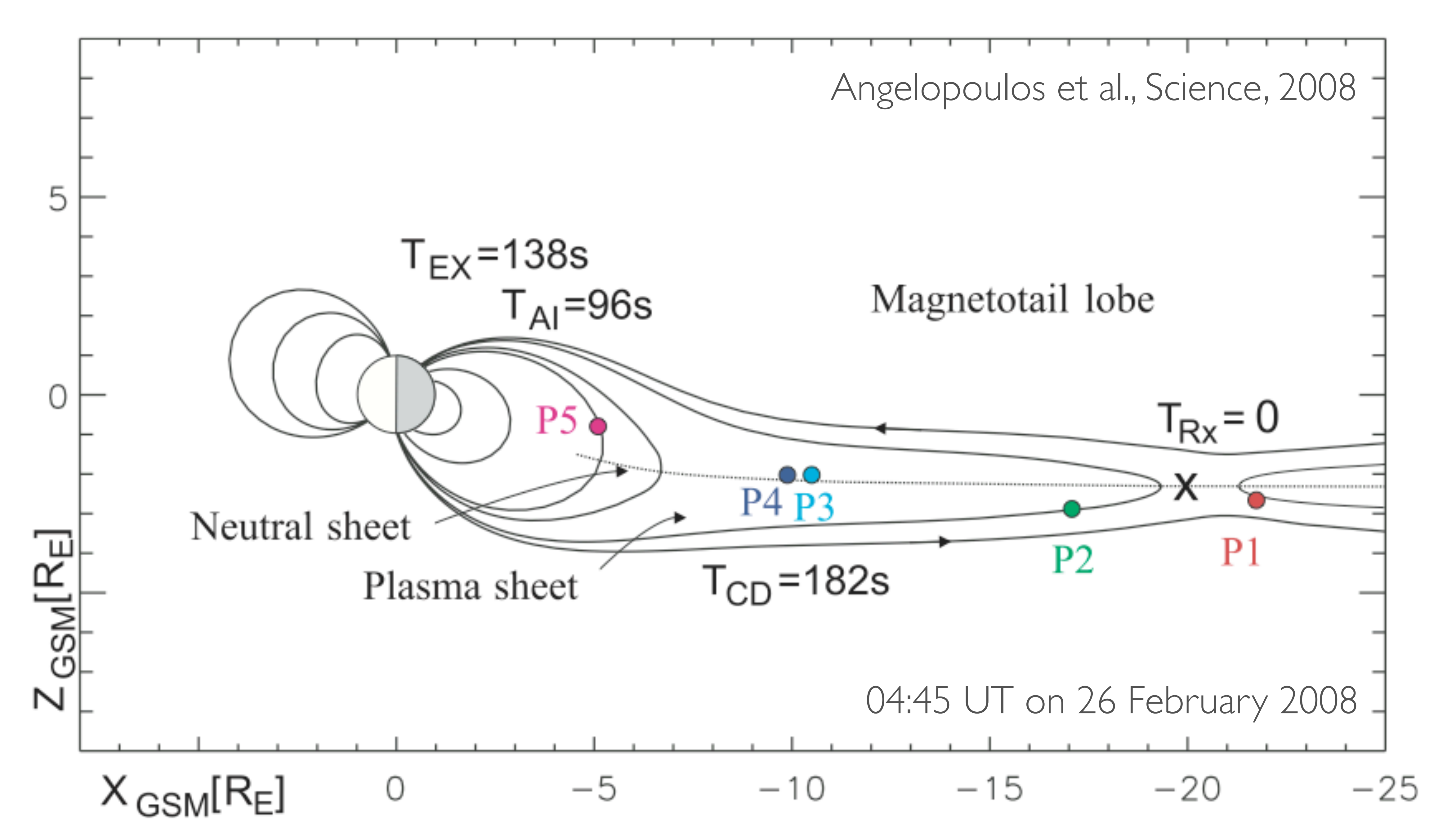
V=25 km/s at 5 R_E

V=200-400 km/s at 9-12 R_E

(see also Ohtani, JGR, 1998
Nakamura et al., JGR 2002)

Using the Cluster suite of spacecraft Apatenkov found dipolarization speeds of 25 km/s at 5 R_E by measuring the passage of the northward turning Bz as a function of time. Using other spacecraft in the vicinity, they found 200-400 km/s further out at 9-12 R_E.

Dipolarization at THEMIS

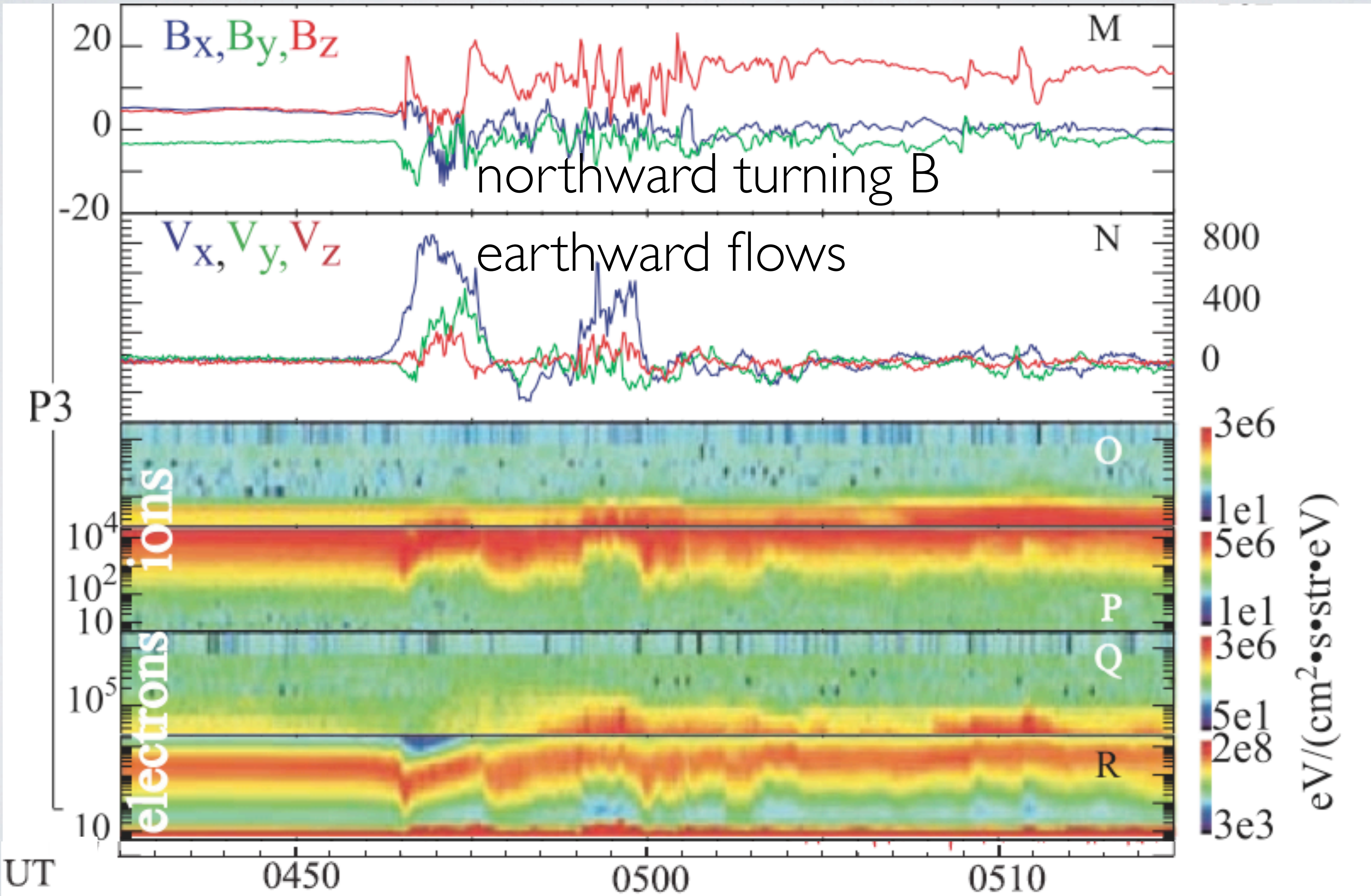


THEMIS-A THEMIS-E THEMIS-D THEMIS-C THEMIS-B

The P3 THEMIS spacecraft was well positioned on February 26 2008 to observe dipolarization during a substorm.

Dipolarization at THEMIS

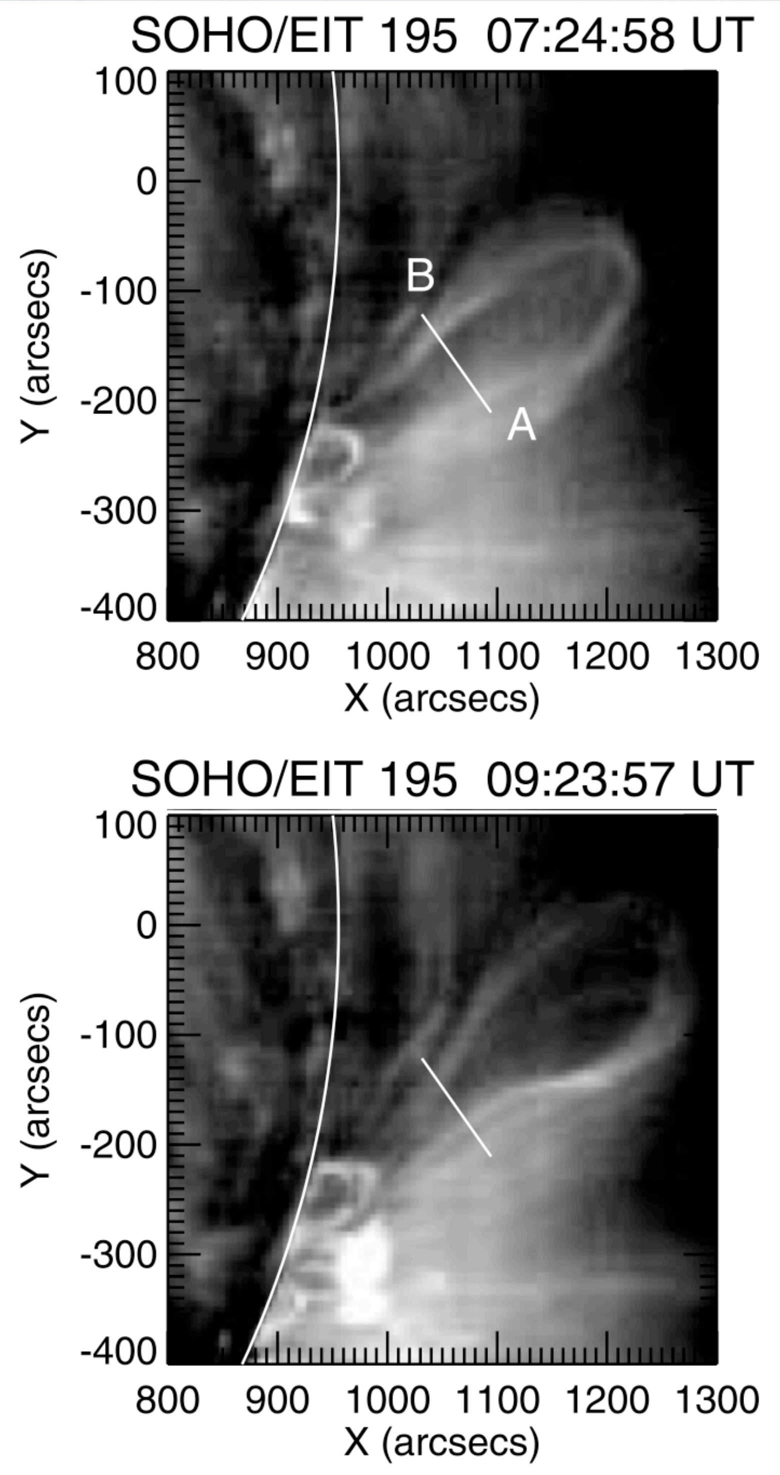
Angelopoulos et al., Science, 2008

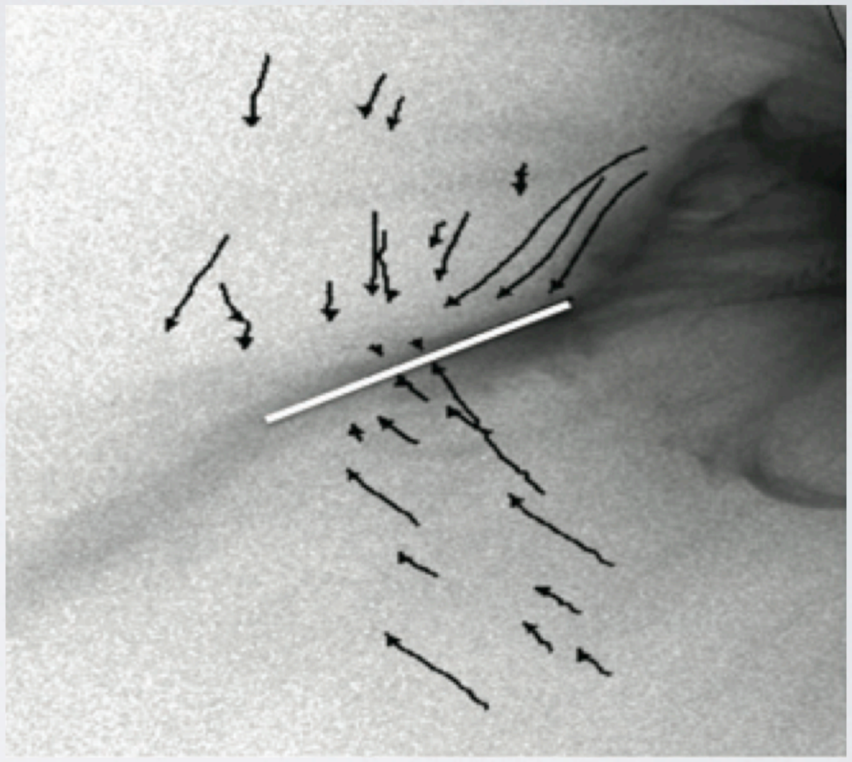


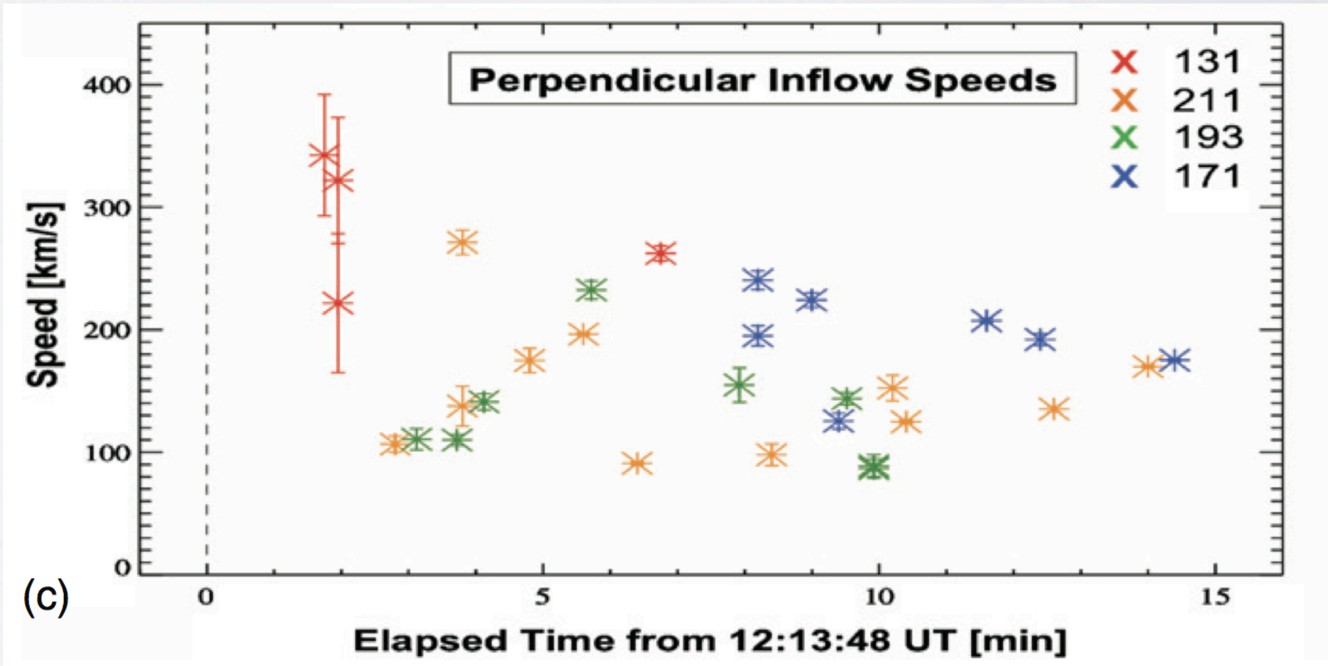
Northward turning Bz is indicative of dipolarization. Earthward flows of several hundred km/s were also observed.

Reconnection inflows

Narukage & Shibata, ApJ, 2006





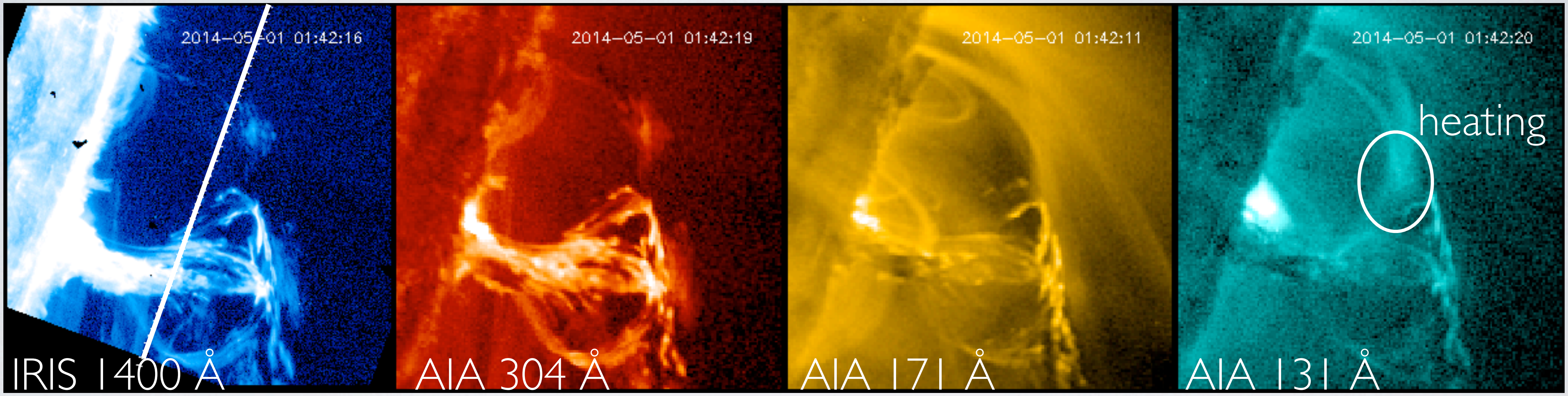


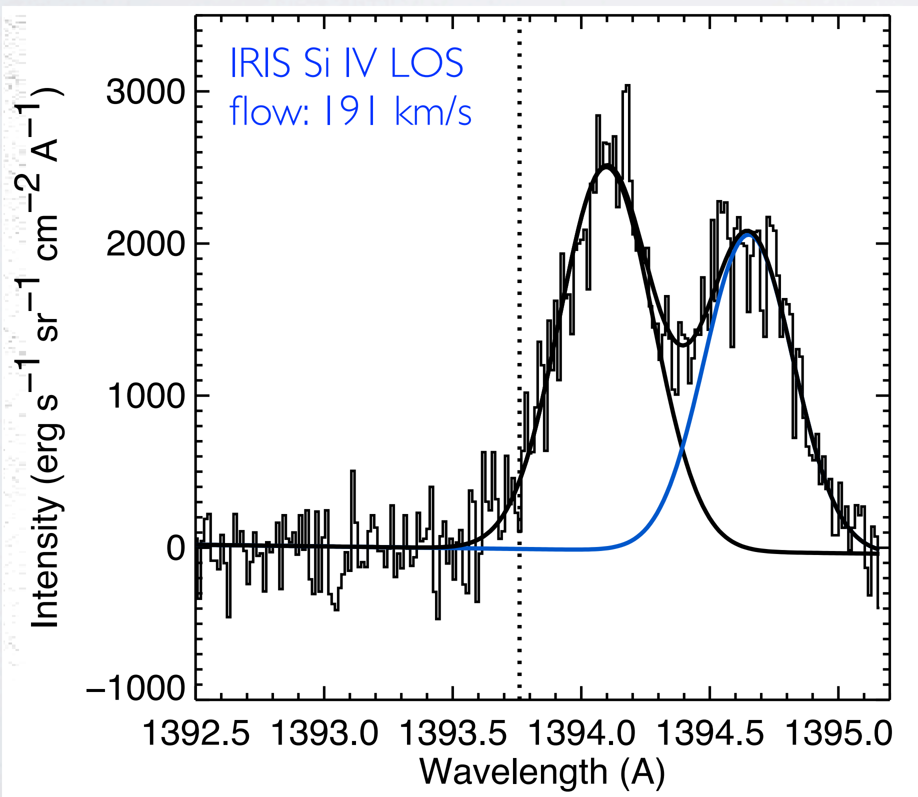
Savage et al., ApJ, 2012

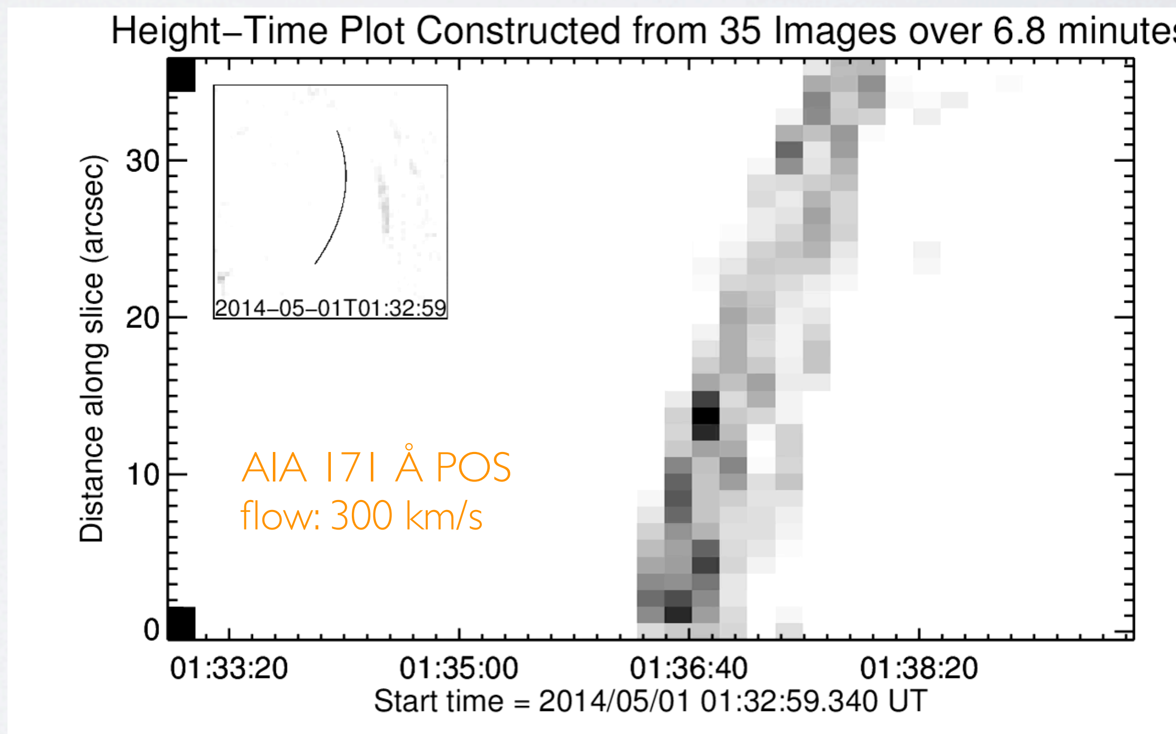
v_{inflow} = 2.6-38 km/s

Reconnection inflows have been observed, as in this observation by Narukage & Shibata, where they found inflows of about 3-38 km/s. Savage et al. also saw inflows with this observation using the AIA telescope, and they found faster speeds, on the order of several hundred km/s.

Reconnection outflows



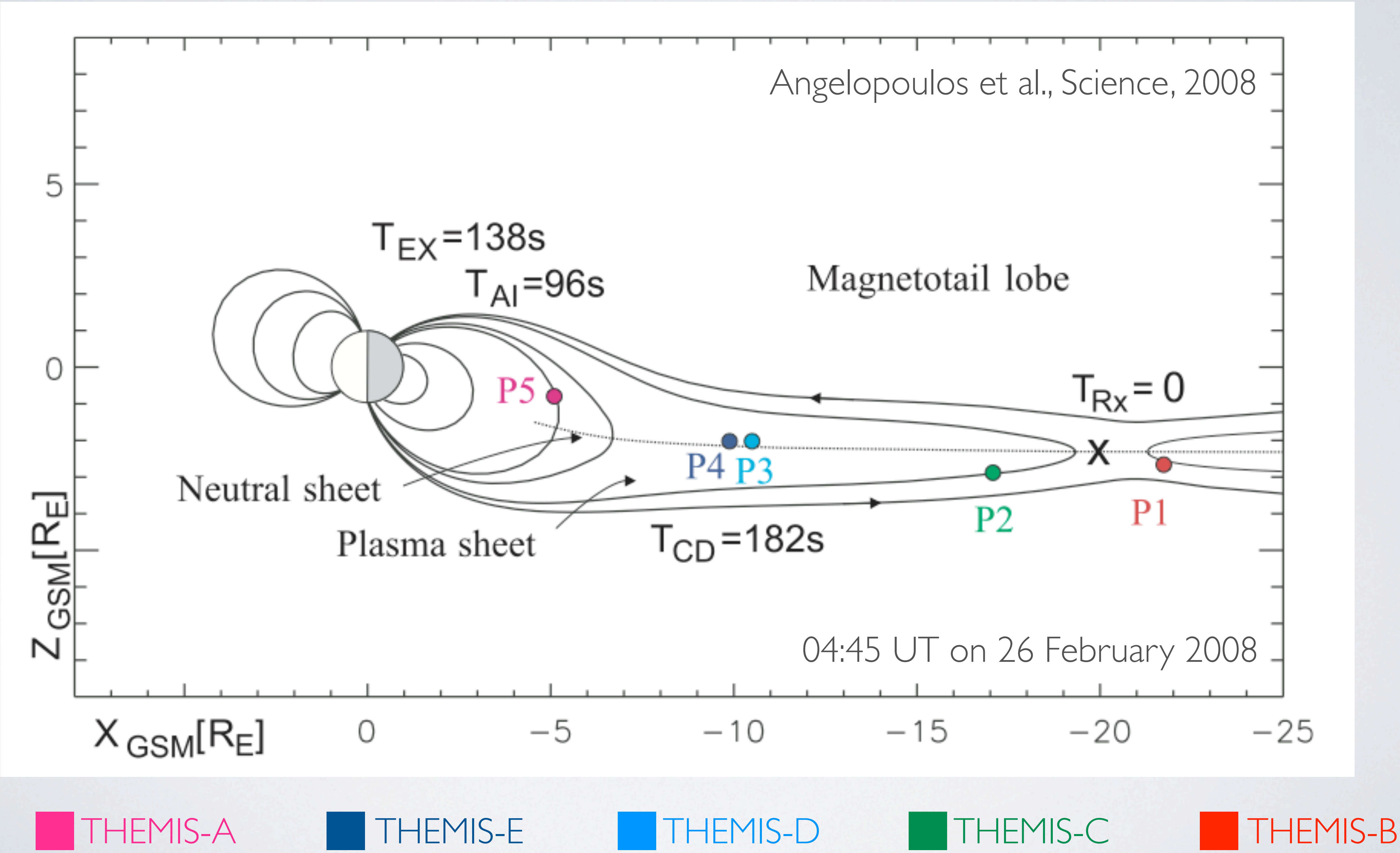




Reeves et al., ApJ, 2015

This observation of a small eruption at the limb with IRIS and AIA gives a good measurement of flows. There was an existing dome-like magnetic field, traced out by the coronal rain. A small filament eruption occurs, and the filament crashes into the overlying field. The IRIS slit location allows us to measure the redshifts of the moving plasma, giving line-of-sight flows of about 200 km/s. The motion in the plane of the sky can be traced in the AIA 171 Å channel, giving about 300 km/s, for a total velocity of about 400 km/s. Additionally, the brightening in the AIA 131 Å channel indicates that there is heating occurring at the reconnection site.

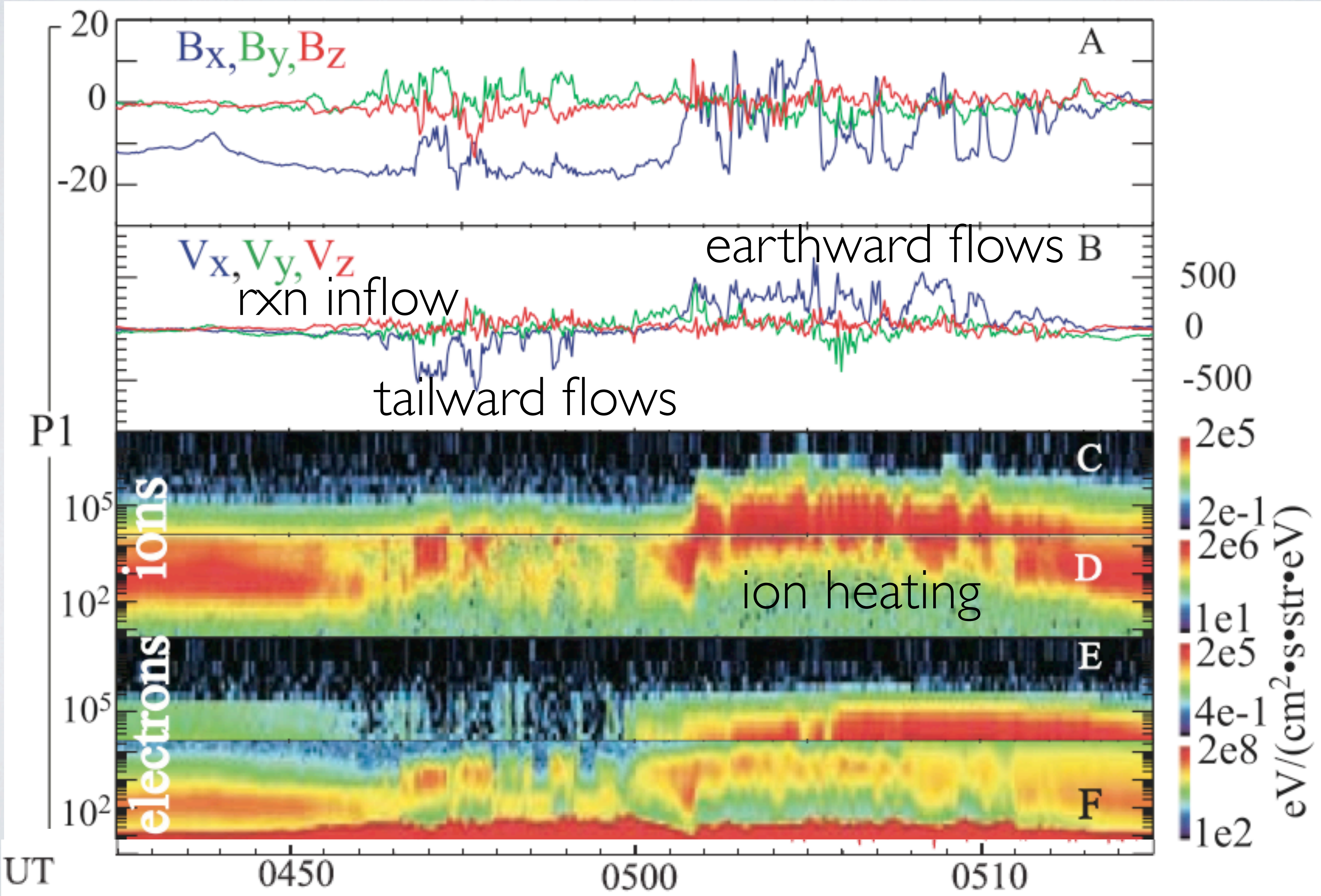
THEMIS positioned for flows



THEMIS P1 is very well positioned to see reconnection inflows and outflows in the 26 February 2008 event.

Reconnection flows

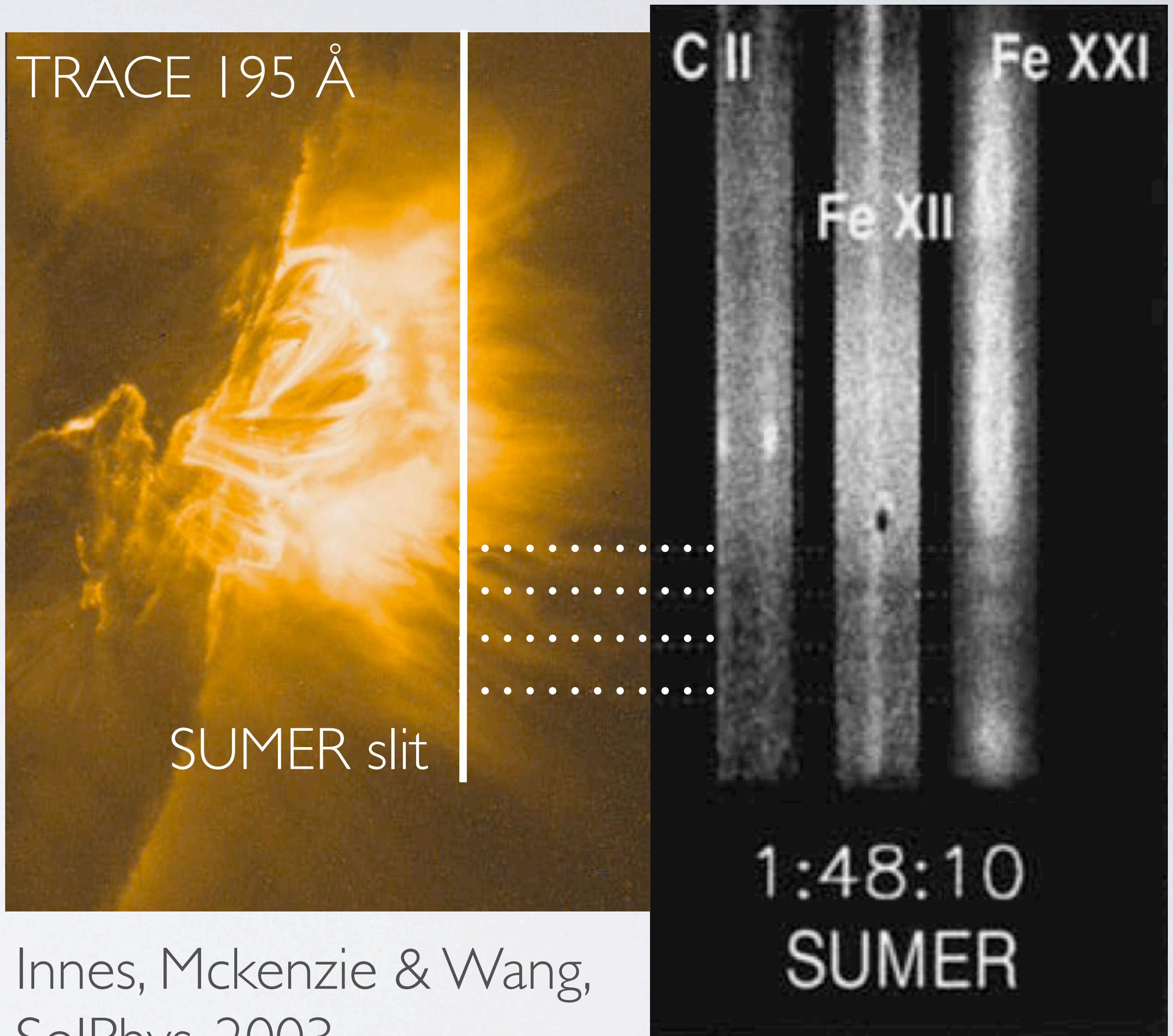
Angelopoulos et al., Science, 2008



The X-line moves tailward, crossing over P1. Thus the Vx flows switch direction, from tailward to earthward. Speeds of these flows are 400-500 km/s which is 67-90% of the Alven speed. Previous to these flows, small northward flow (Vz)(50-100 km/s) and southward turning B indicate flows into reconnection site, and reconnection onset. Ion heating is also observed.

Supra-arcade downflows

McKenzie & Hudson, ApJL, 1999

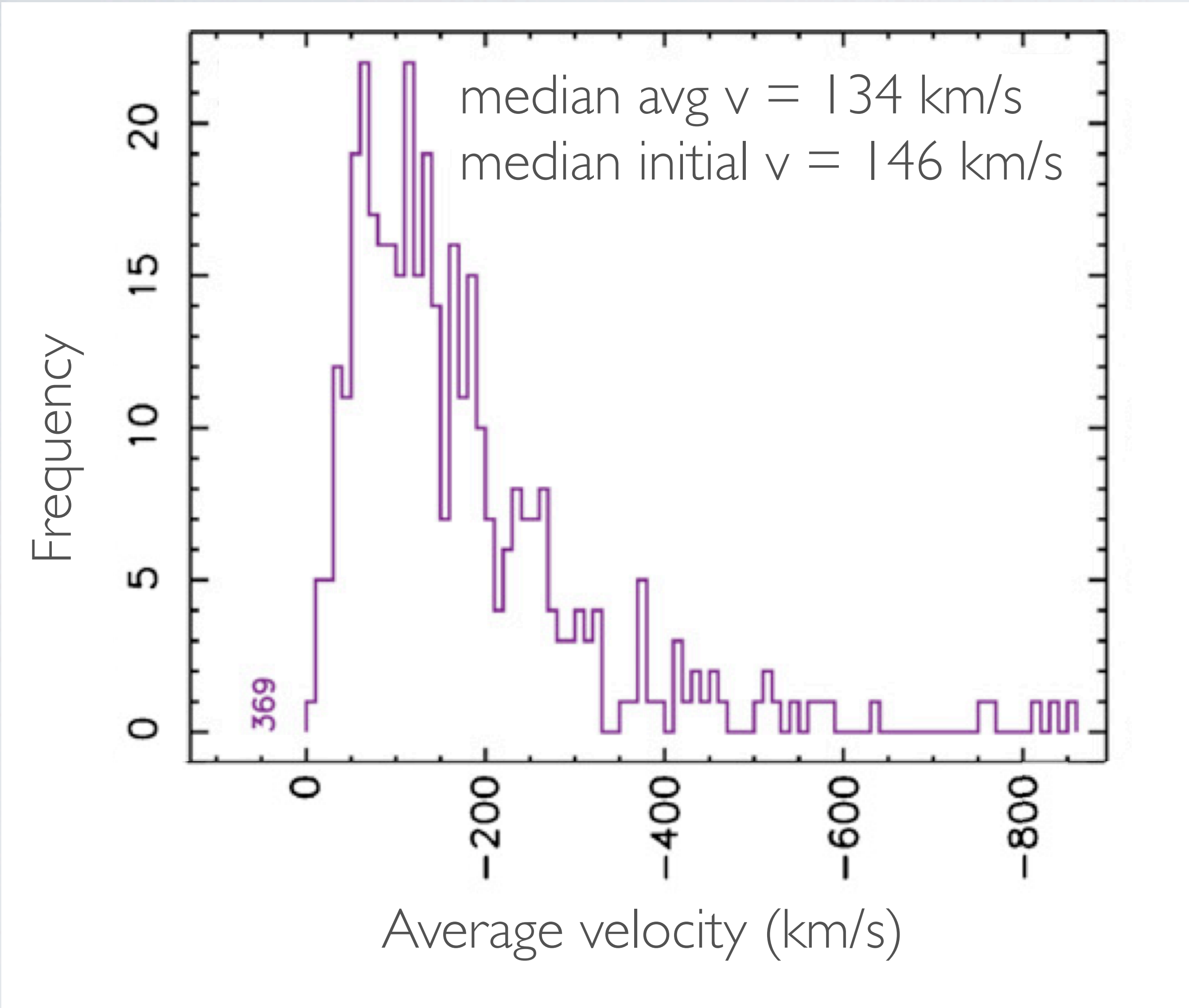


Innes, Mckenzie & Wang, SolPhys, 2003

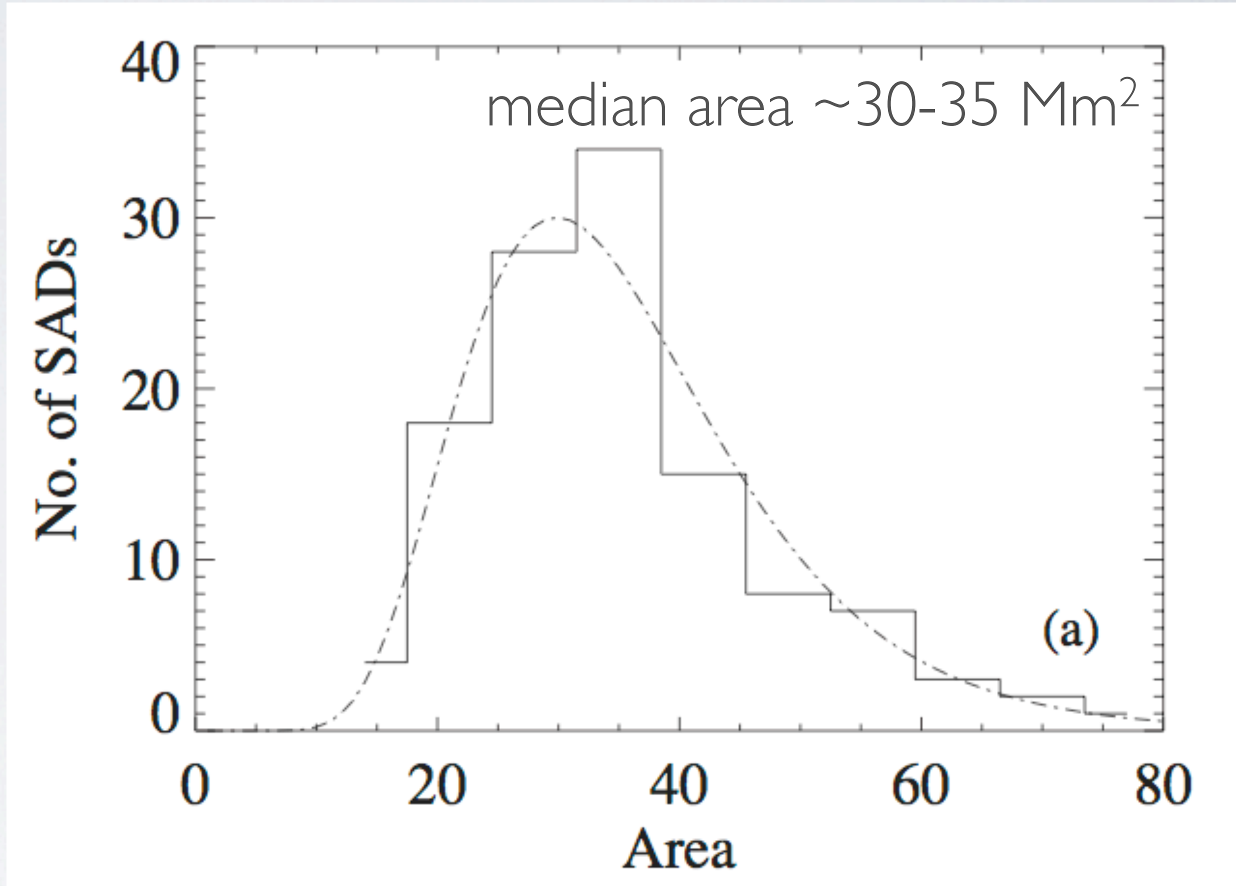
Downflows are not cool blobs, but density depleted regions

A particularly interesting kind of reconnection outflow that isn't predicted by 2D models is the supra-arcade downflow. These were discovered in 1999 by McKenzie and Hudson using Yohkoh SXT data, and they found dark features that flowed down above the flare arcade. A fortuitously placed SUMER slit showed that the downflowing features were not chunks of cooler material, but rather density depleted voids.

SAD characteristics



Savage & McKenzie, ApJ, 2011

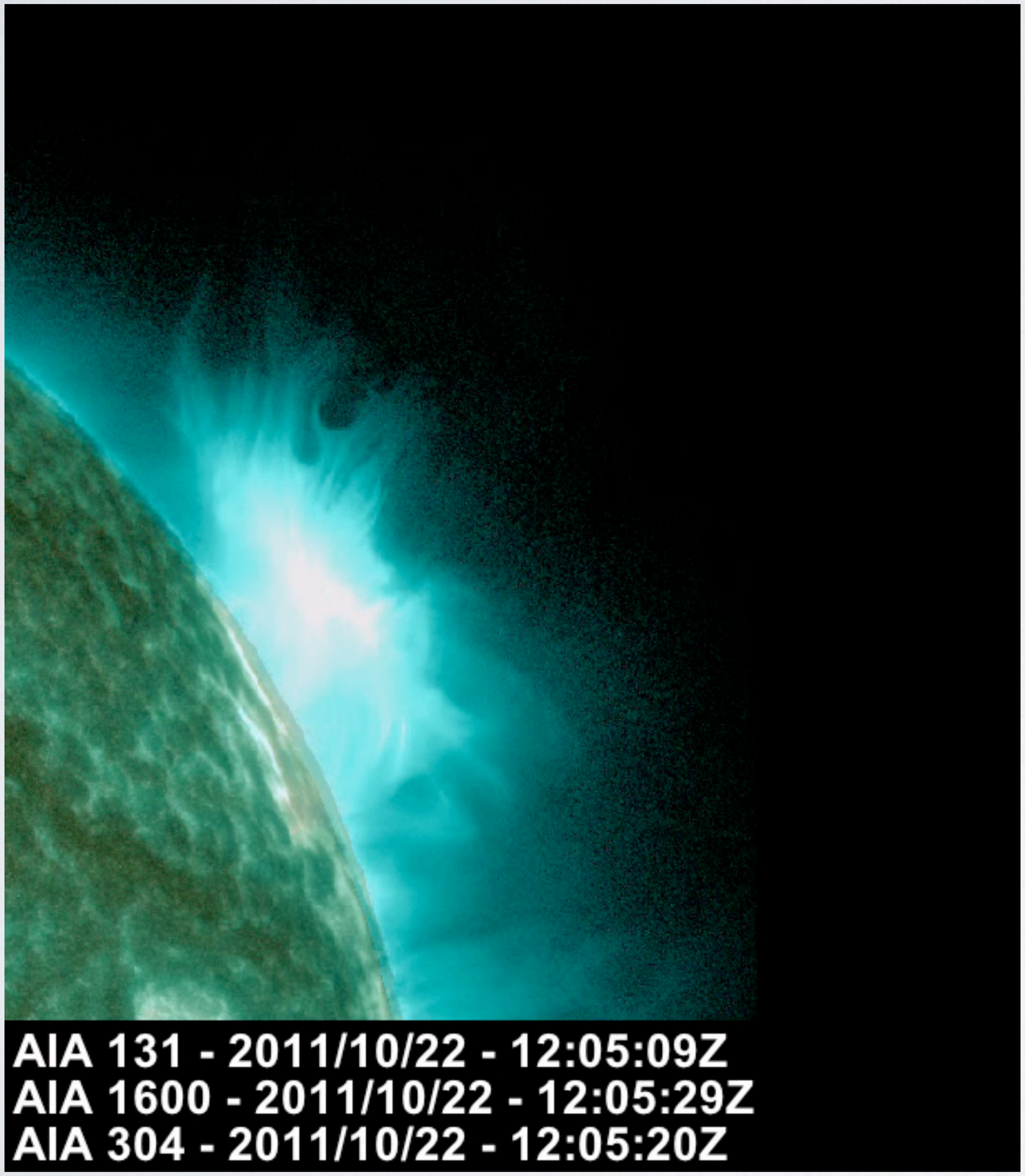


McKenzie & Savage, ApJL, 2011

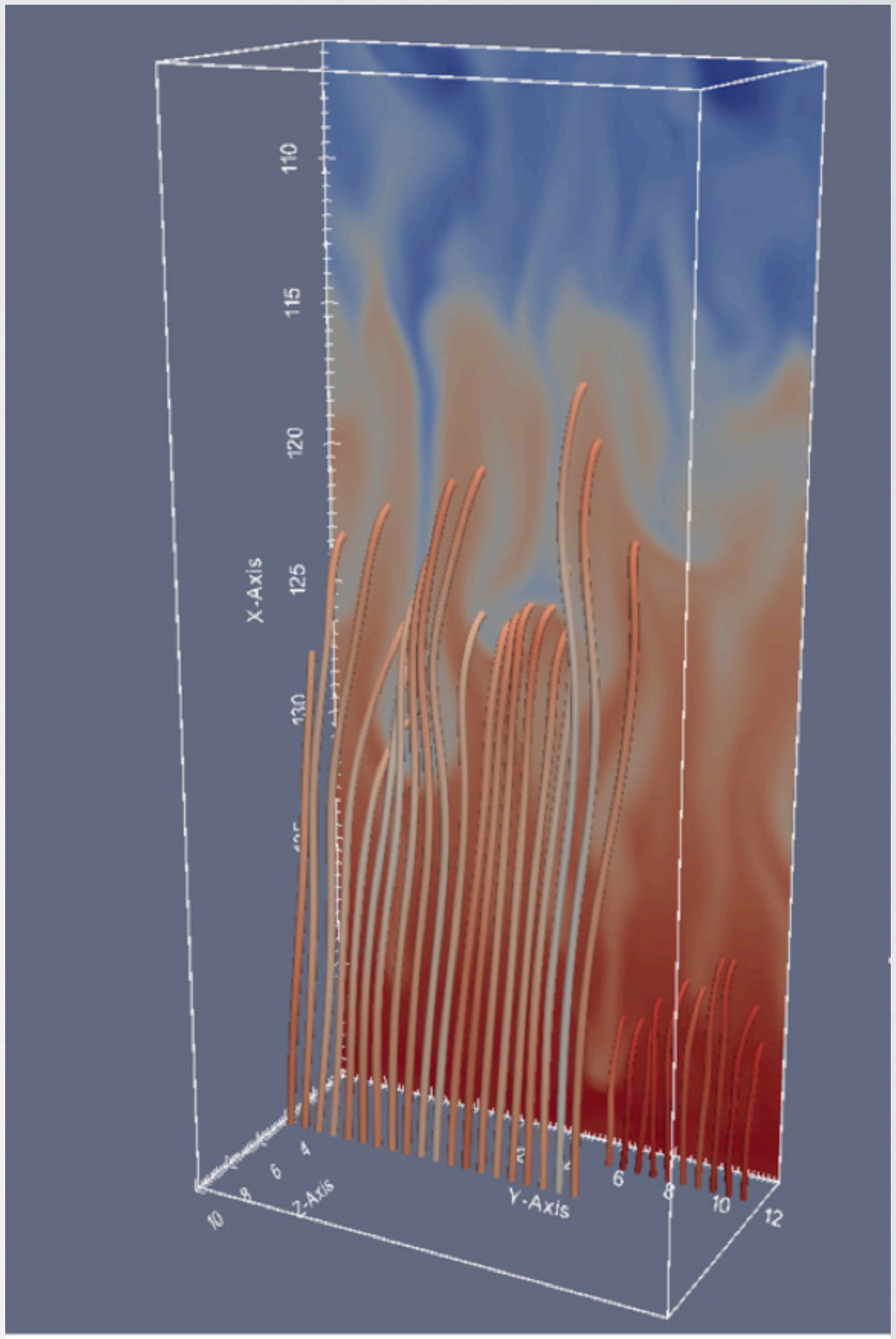
Note: This work done with TRACE, SXT, XRT. Should be redone with AIA!

SADs have characteristic speeds of a couple of hundred km/s. The median area of SADs has been found by McKenzie & Savage to be 30-35 Mm^2, with some events as high as 80 Mm^2. This work was done before AIA though, so it might bear a closer look!

SADs and loops



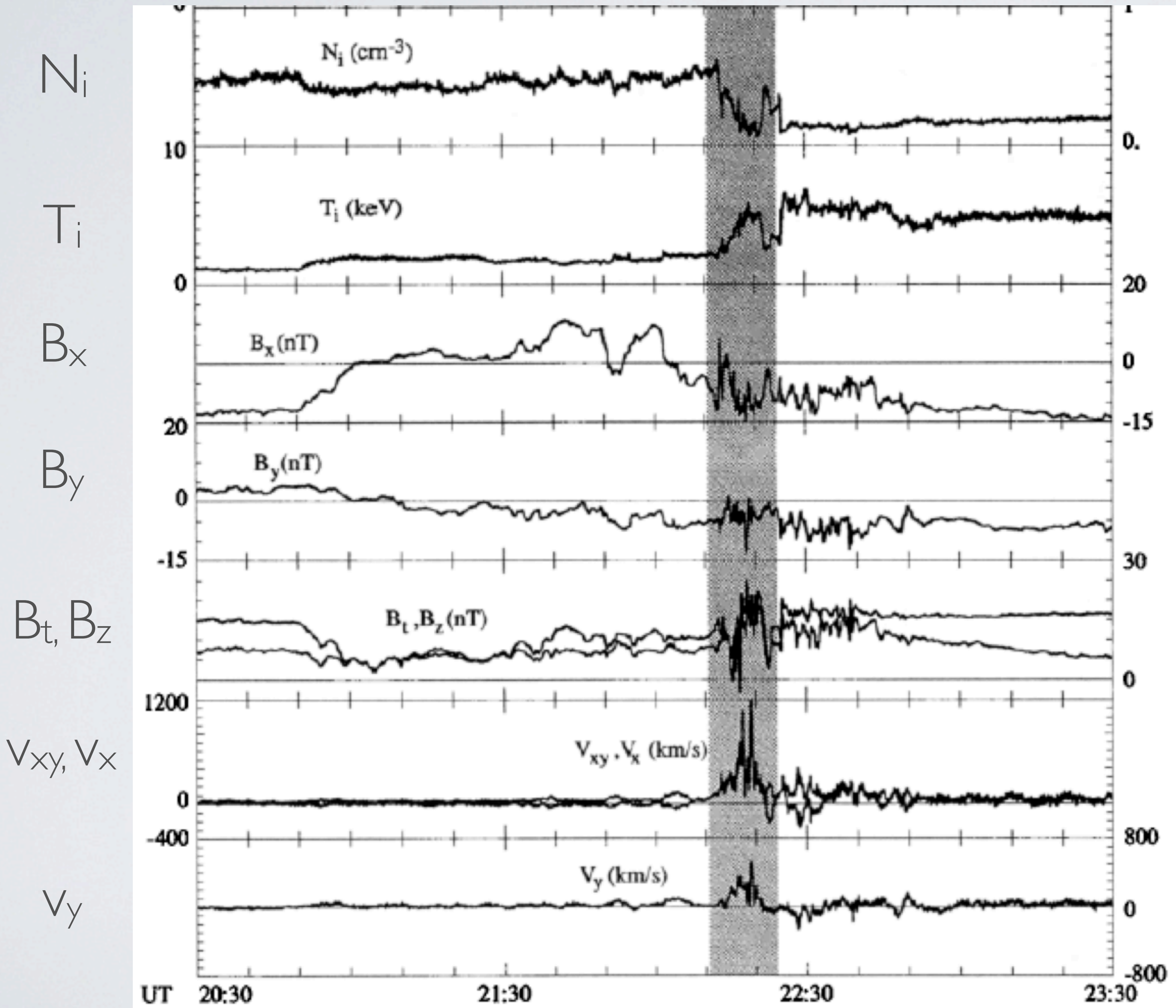
Savage, McKenzie & Reeves, ApJL, 2012



Guo et al., ApJL, 2014

SADS have a turbulent appearance, and were at first interpreted as depleted flux tubes shrinking through a dense plasma sheet. But recent AIA observations seem to show loops preceding the SADs, calling that interpretation into question. A model by Lija Guo posits that SADs are a result of a Rayleigh-Taylor like instability as reconnected flux tubes shrink through the plasma sheet.

Bursty Bulk Flows

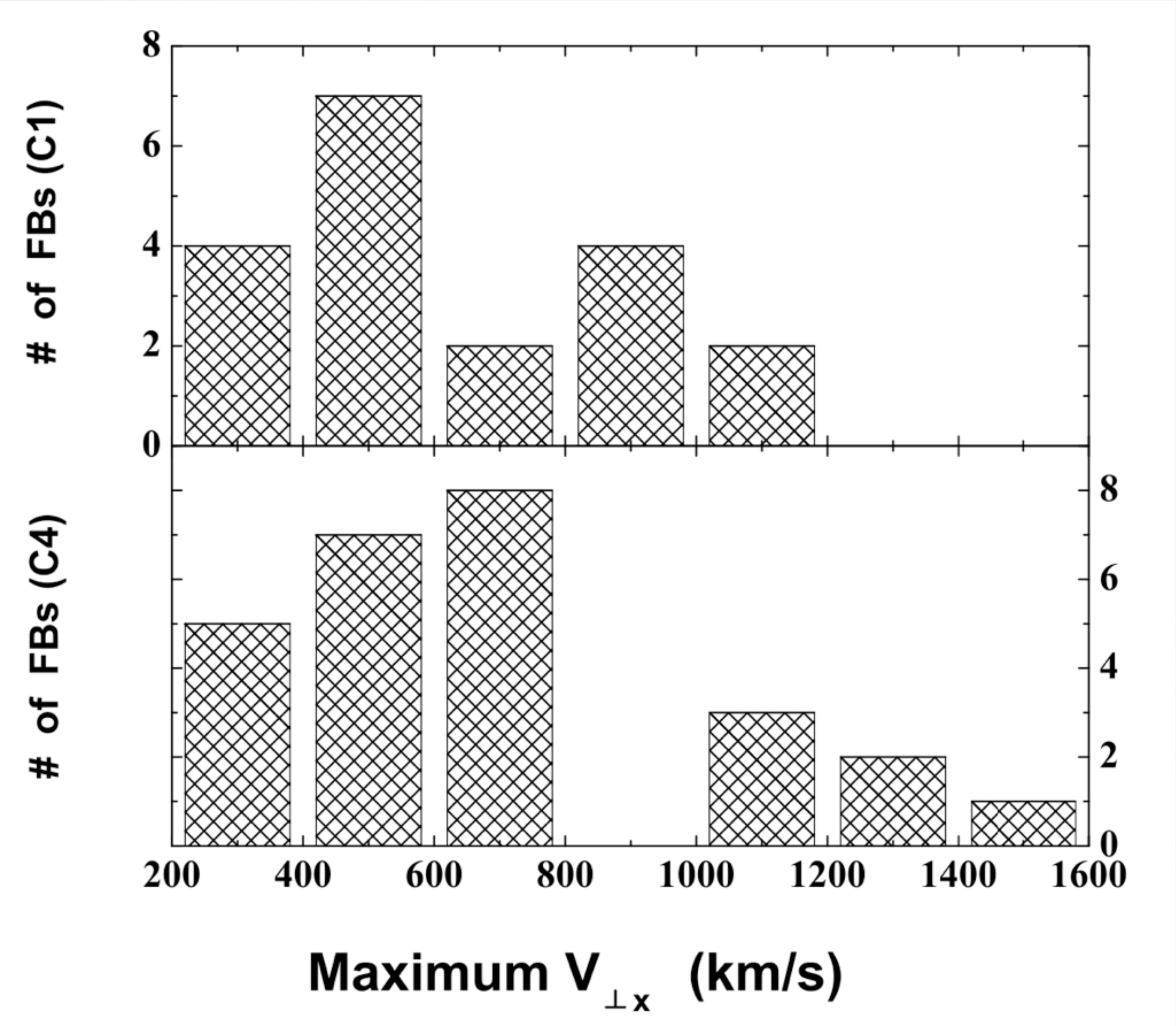


Angelopoulos et al., JGR, 1994

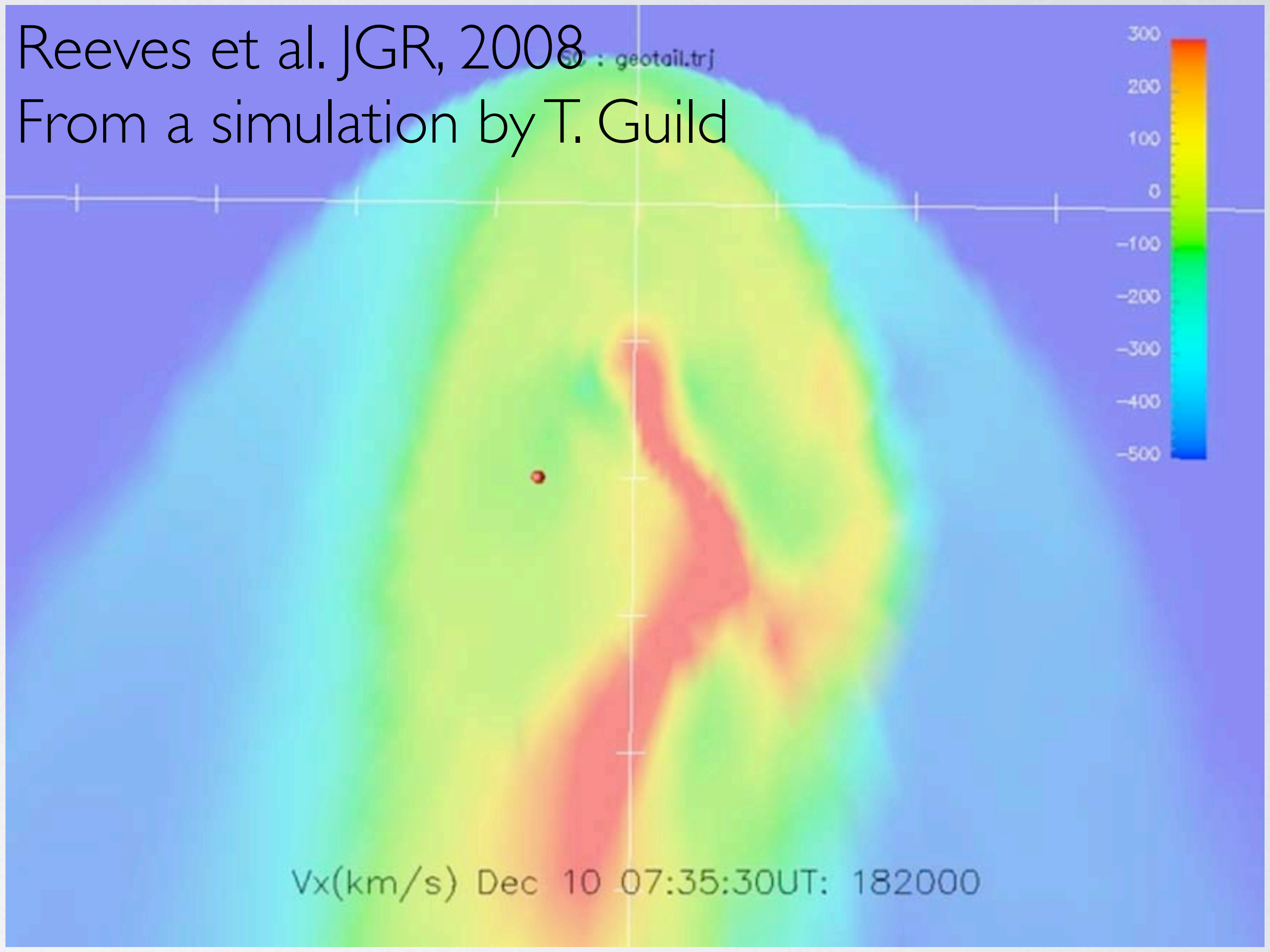
BBFs have depleted entropy ($PV^{5/3}$), which often translates to lower density than the surroundings

Bursty bulk flows are intermittent flow bursts in the magnetotail that reach speads of several hundred km/s. Their density is usually depleted. One model is that BBFs are (entropy) depleted flux tubes, shrinking towards earth, magnetic buoyancy force plays a role.

BBF Characteristics



H. Kim et al., JGR, 2010



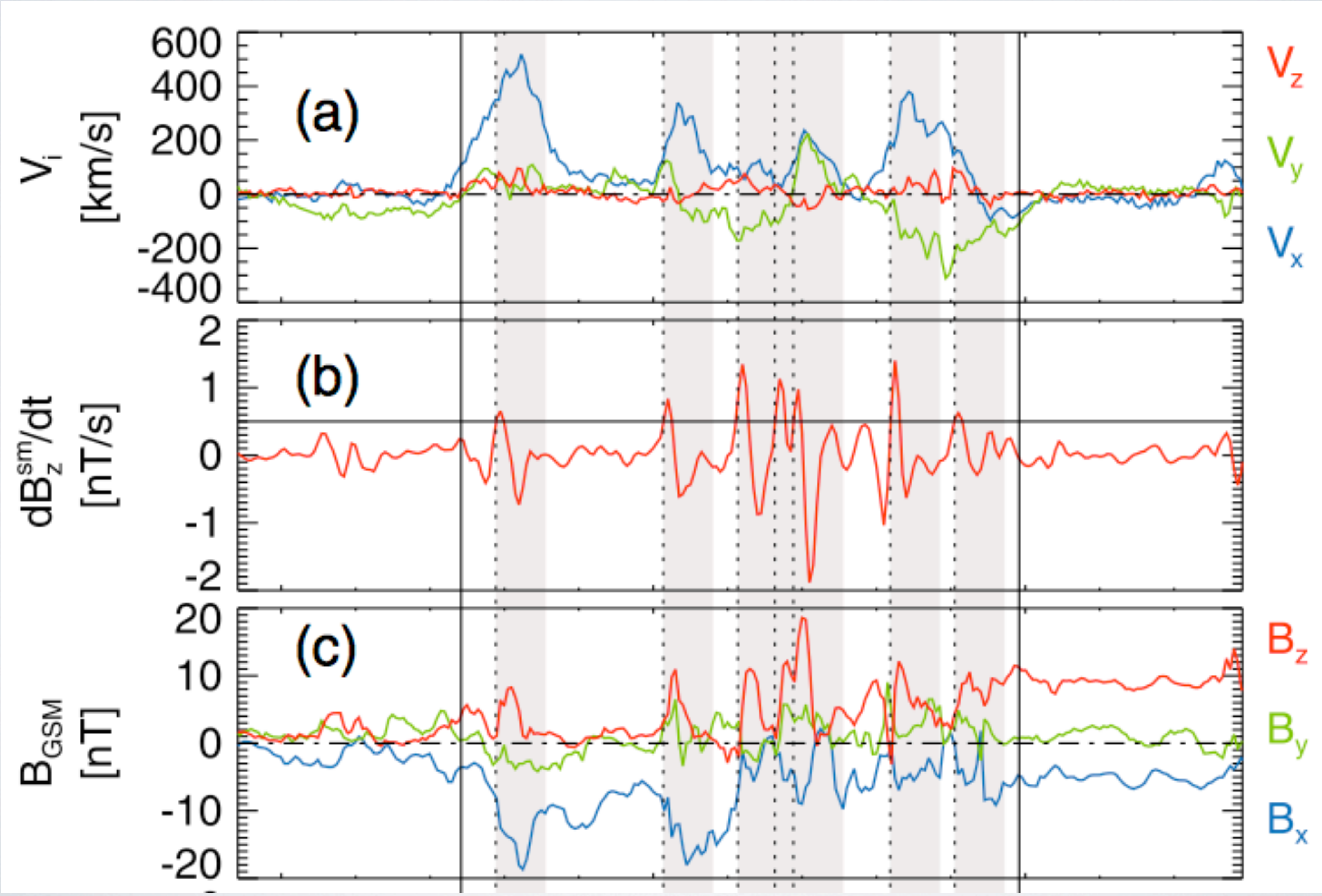
BBF flow sizes: 1-3 R_E
(areas of 30 -300 Mm^2)

(e.g. Sergeev et al, JGR, 1996; Angelopoulos et al, GRL 1997; Nakamura et al., GRL, 2004)

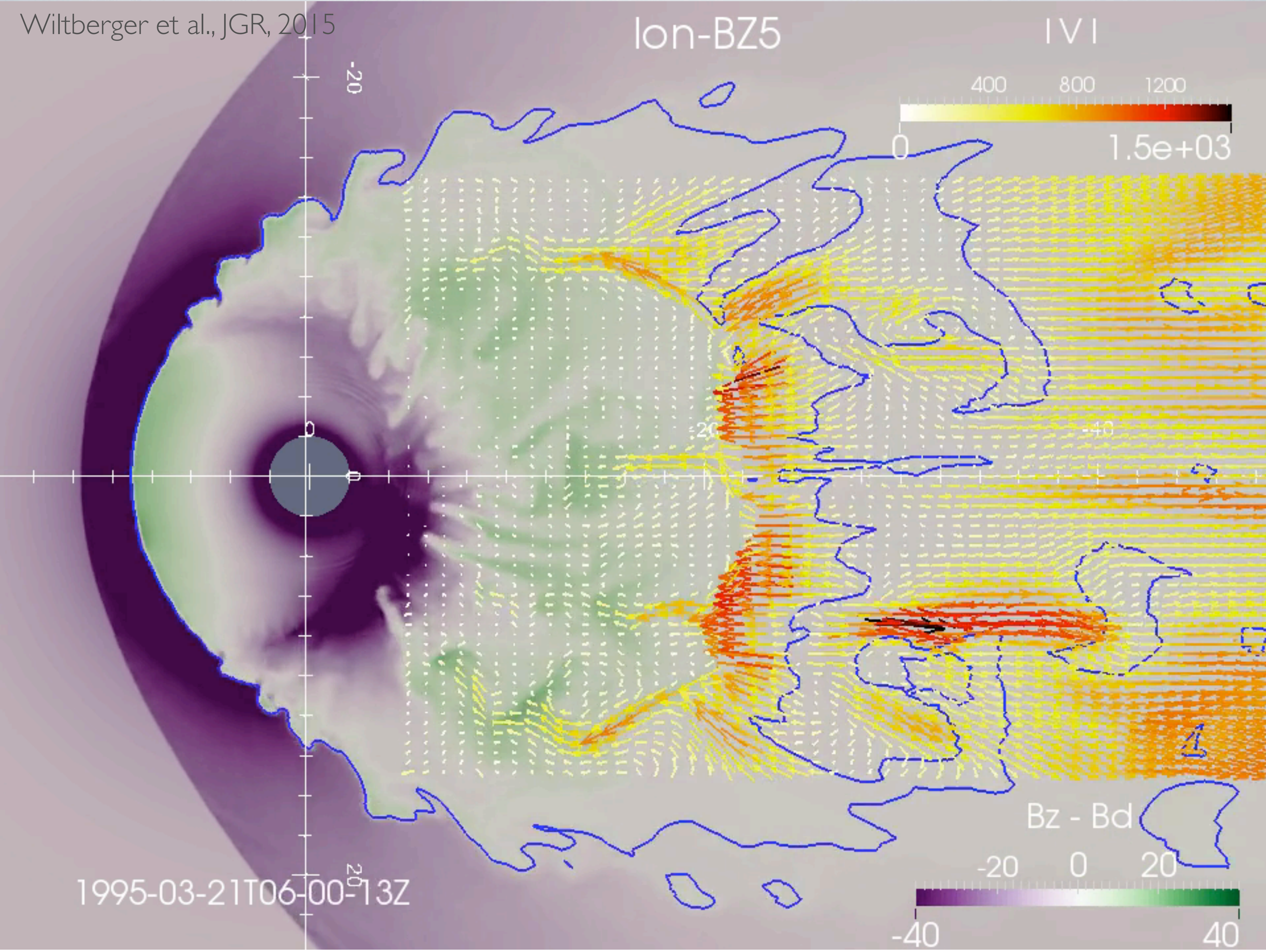
Speeds of BBFs are several hundred km/s, similar to SADs. The flow sizes of BBFs are 1-3 R_E as shown in this simulation by Tim Guild. Assuming a circular area, that translates to 30-300 Mm^2, very similar to SADs. The similarities between SADs and BBFs can inform the thinking about these phenomena - for example, one idea about BBFs was that their size is related to the ion-gyro radius. However, the ion-gyro radius is about a meter in the corona, so clearly that quantity is not governing the size of SADs.

BBFs and dipolarization

J. Liu et al., JGR, 2014

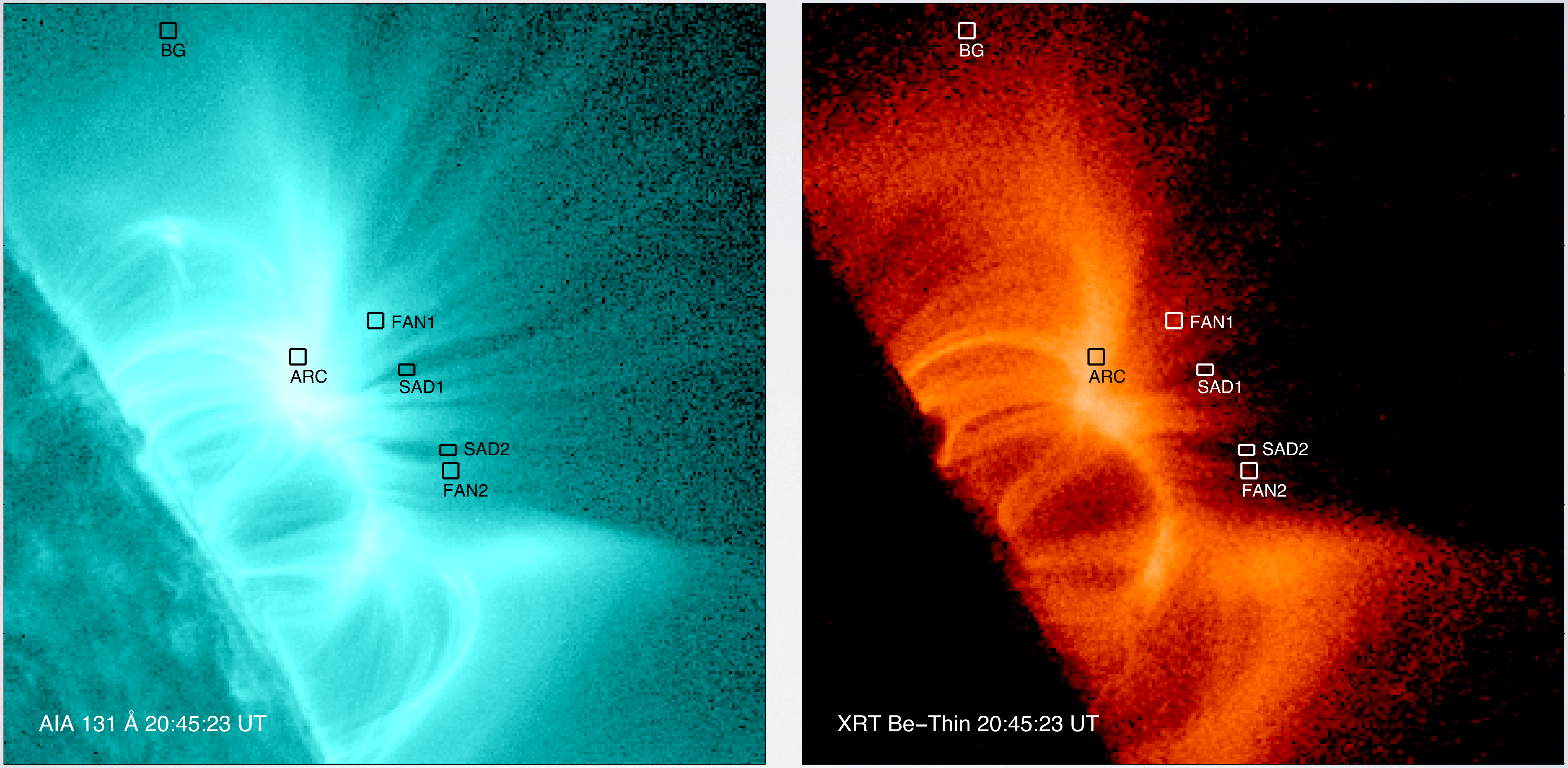


Bursty bulk flows are often correlated with northward turning magnetic field (Bz) as in this observation by Liu et al, which shows several flow bursts and the corresponding northward magnetic field.



This high resolution magnetosphere simulation by Mike Wiltberger shows the structure of the BBFs in the magnetotail. The purple/green color table shows the difference between the dipolar magnetic field and the magnetic field in the simulation. The red/yellow color table shows the speeds of the bursty bulk flows. The morphology is remarkably similar to the SADs in the corona.

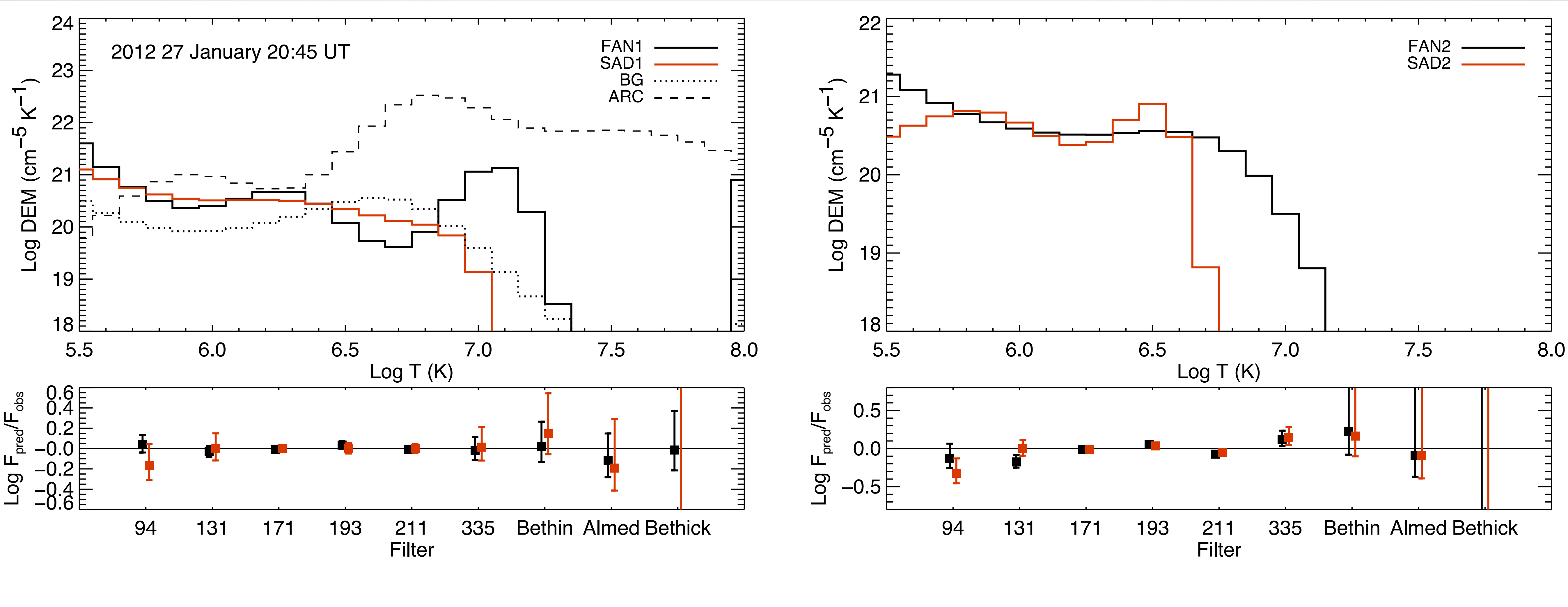
SAD temperatures



Hanneman & Reeves, ApJ, 2014

Supra-arcade downflow temperatures have also been measured. In this example by Hanneman & Reeves, we calculated the differential emission measures in each of the boxes labeled on the images.

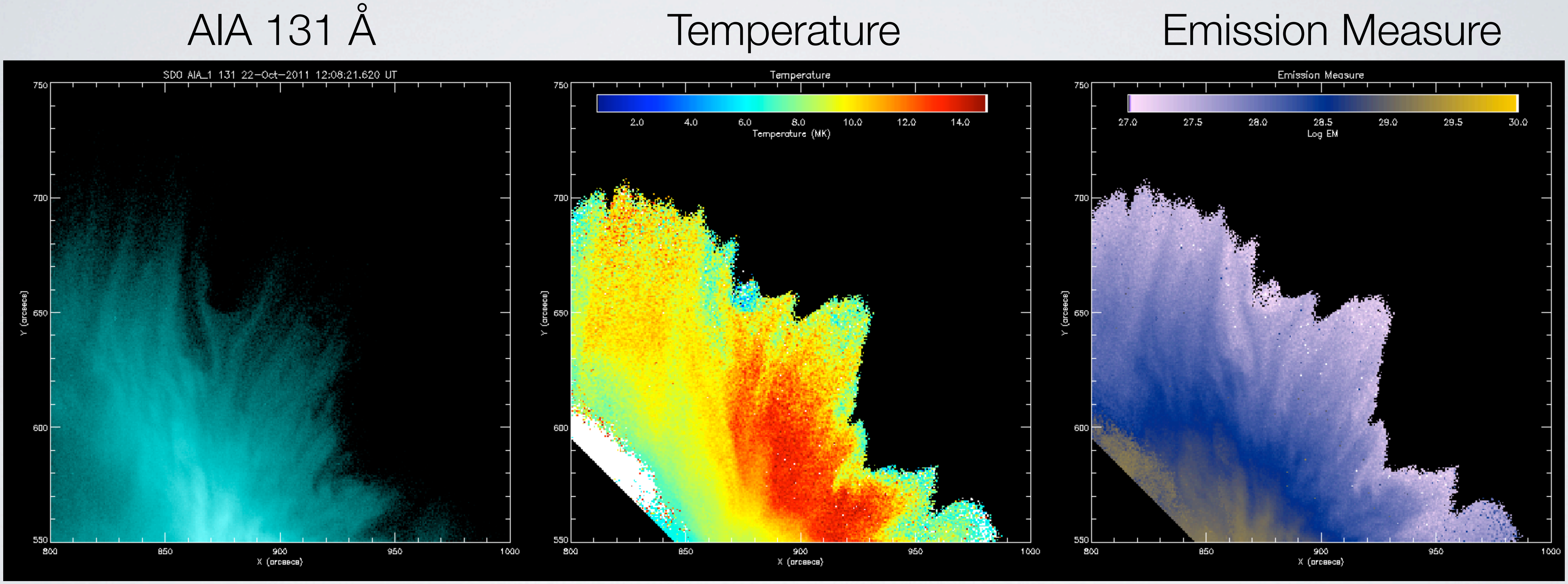
SAD temperatures



Hanneman & Reeves, ApJ, 2014

We found that, in general, the supra-arcade downflows were cooler than the surrounding plasma. Out of 11 cases studied, only one SAD shows a temperature increase.

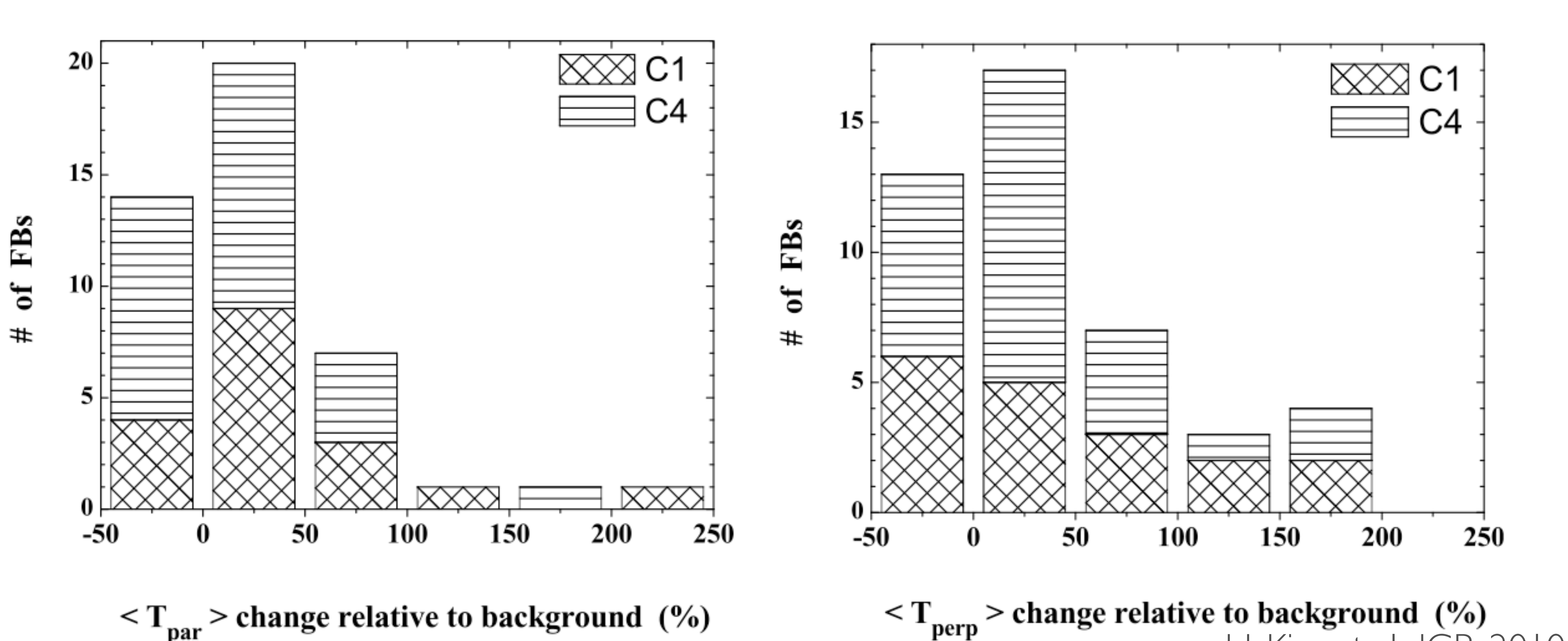
SAD temperatures



Reeves et al., in prep

This movie illustrates the point that the supra-arcade downflows are cooler (and less dense, i.e. there is less emission measure) that the surrounding plasma.

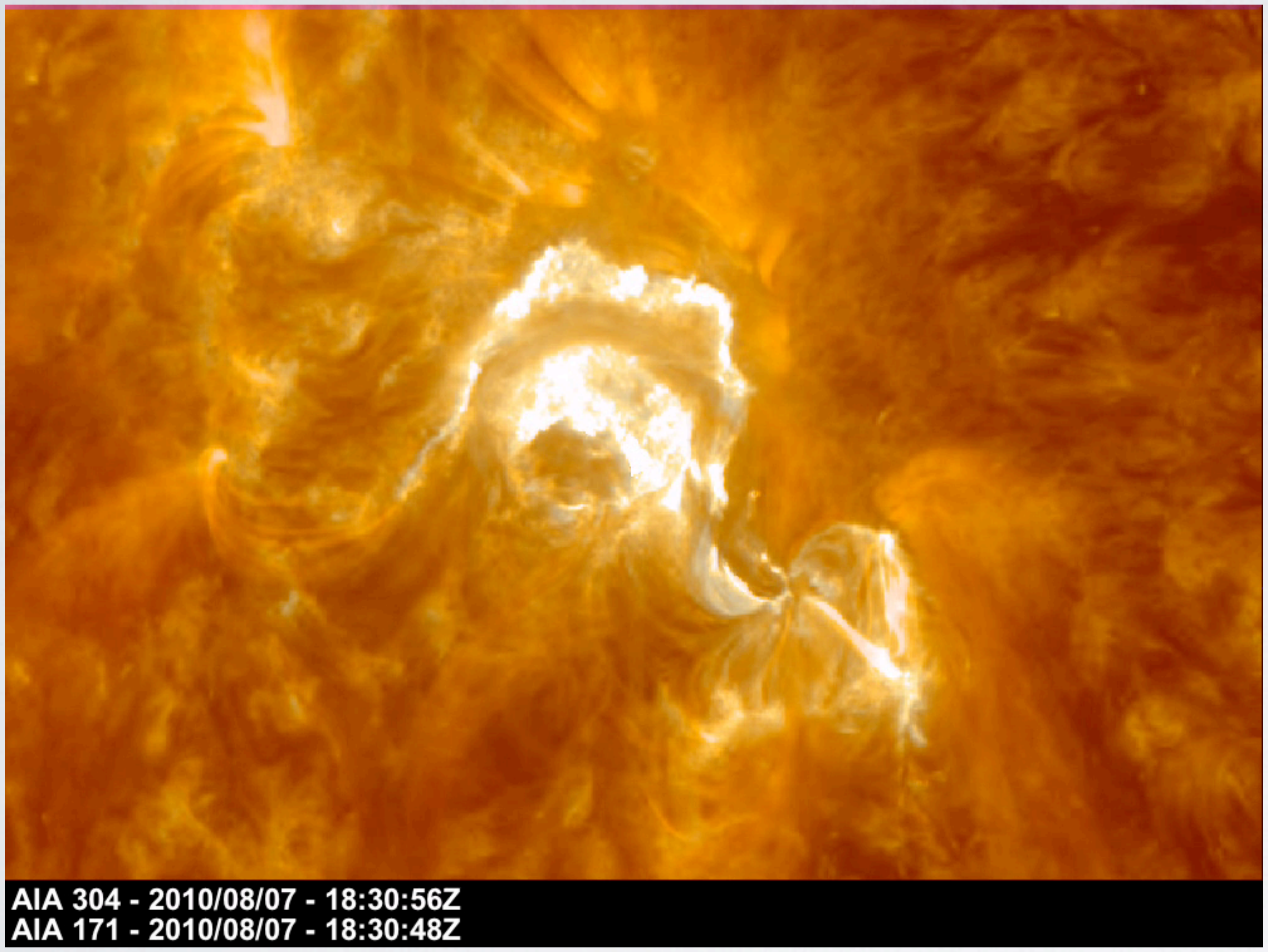
BBF temperatures

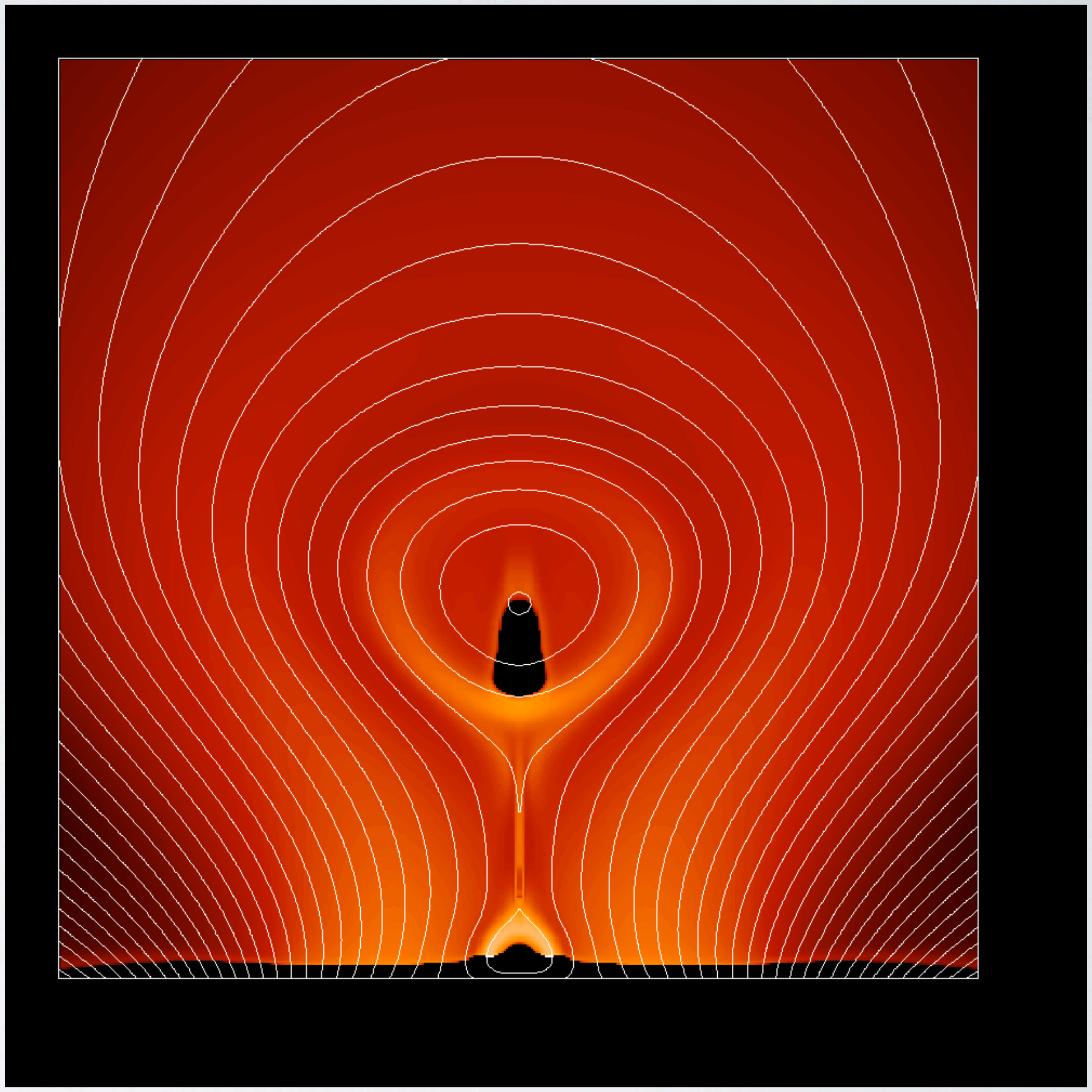


H. Kim et al., JGR, 2010

In bursty bulk flows, however, mostly the temperatures are *greater* that the surrounding plasma. A few cases have lower temperatures, but these BBFs still exhibit depleted entropy.

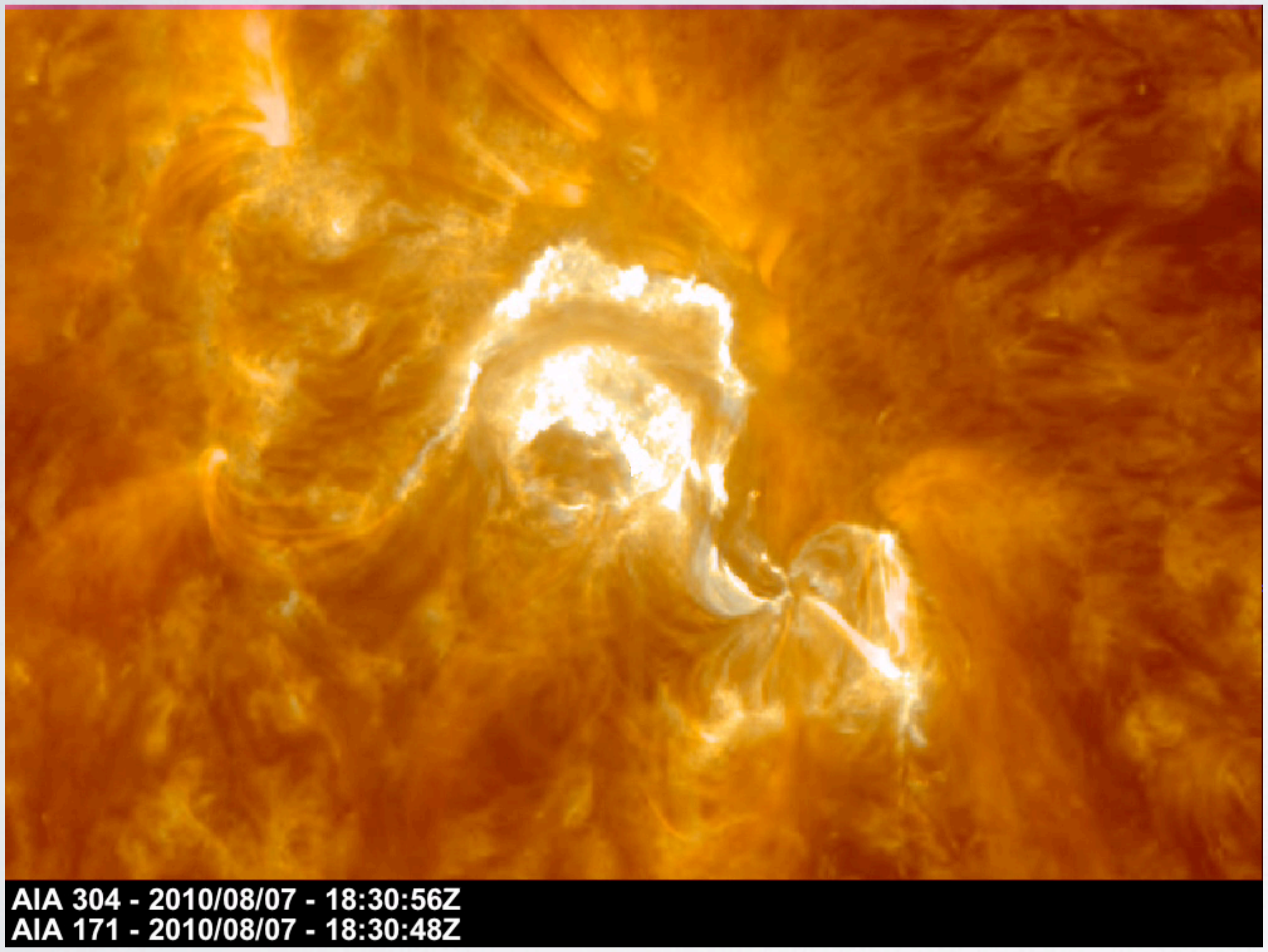
Flare ribbons

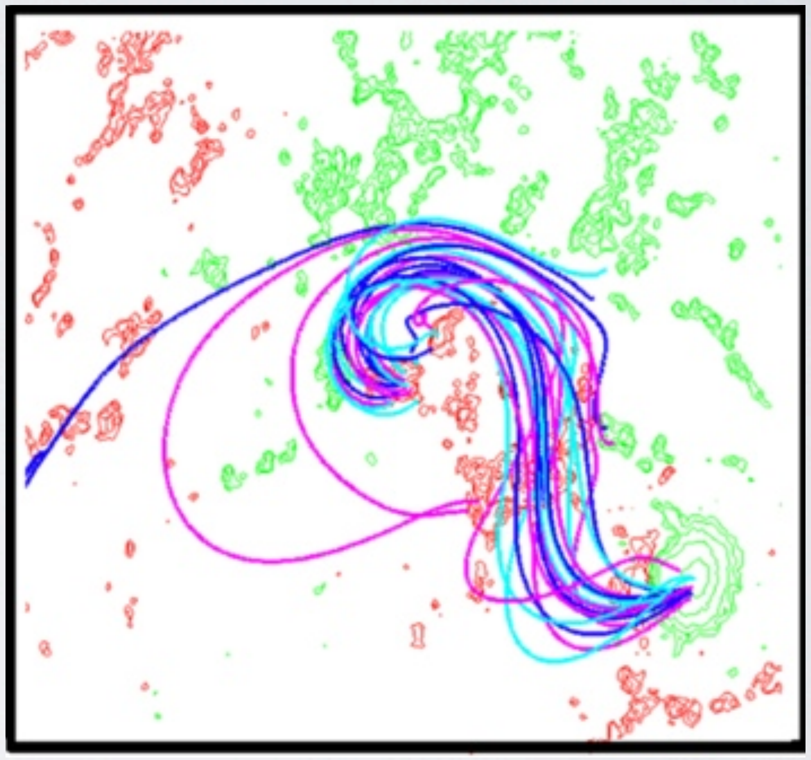




Flare ribbons are also an expected by product of reconnection. As reconnection happens, larger and larger loops are created, and their footpoints seem to spread away from each other.

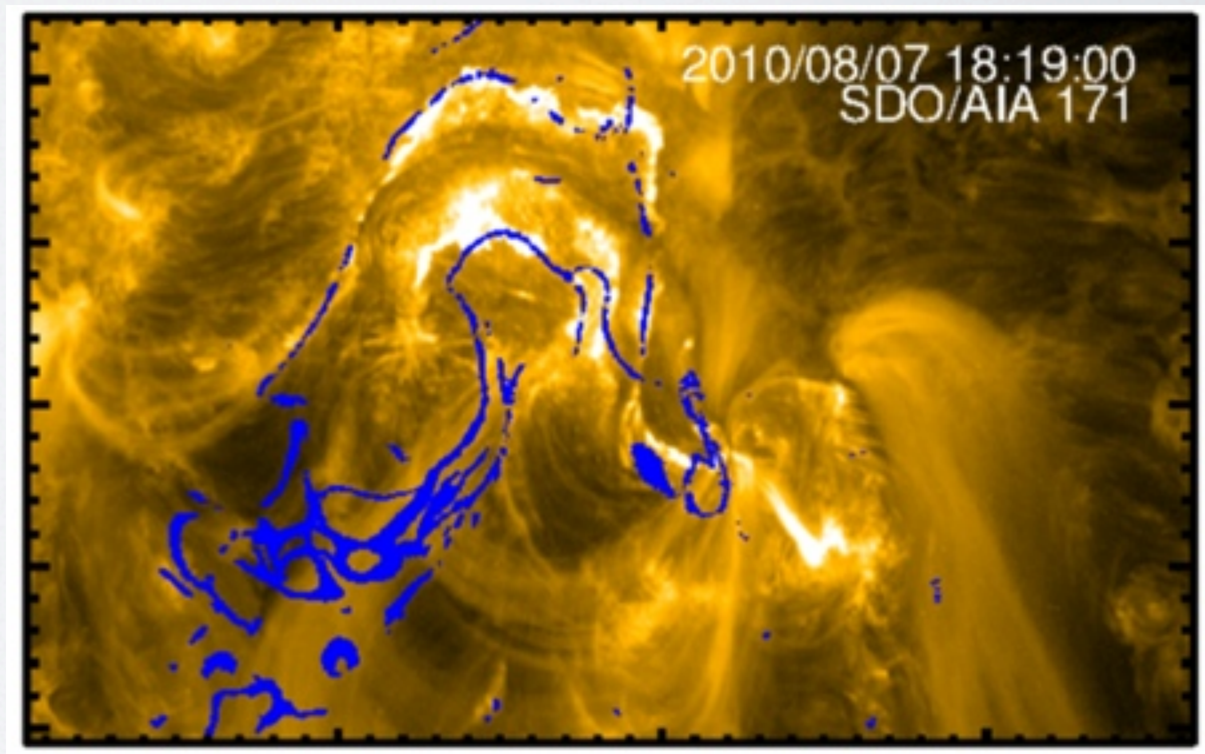
Flare ribbons





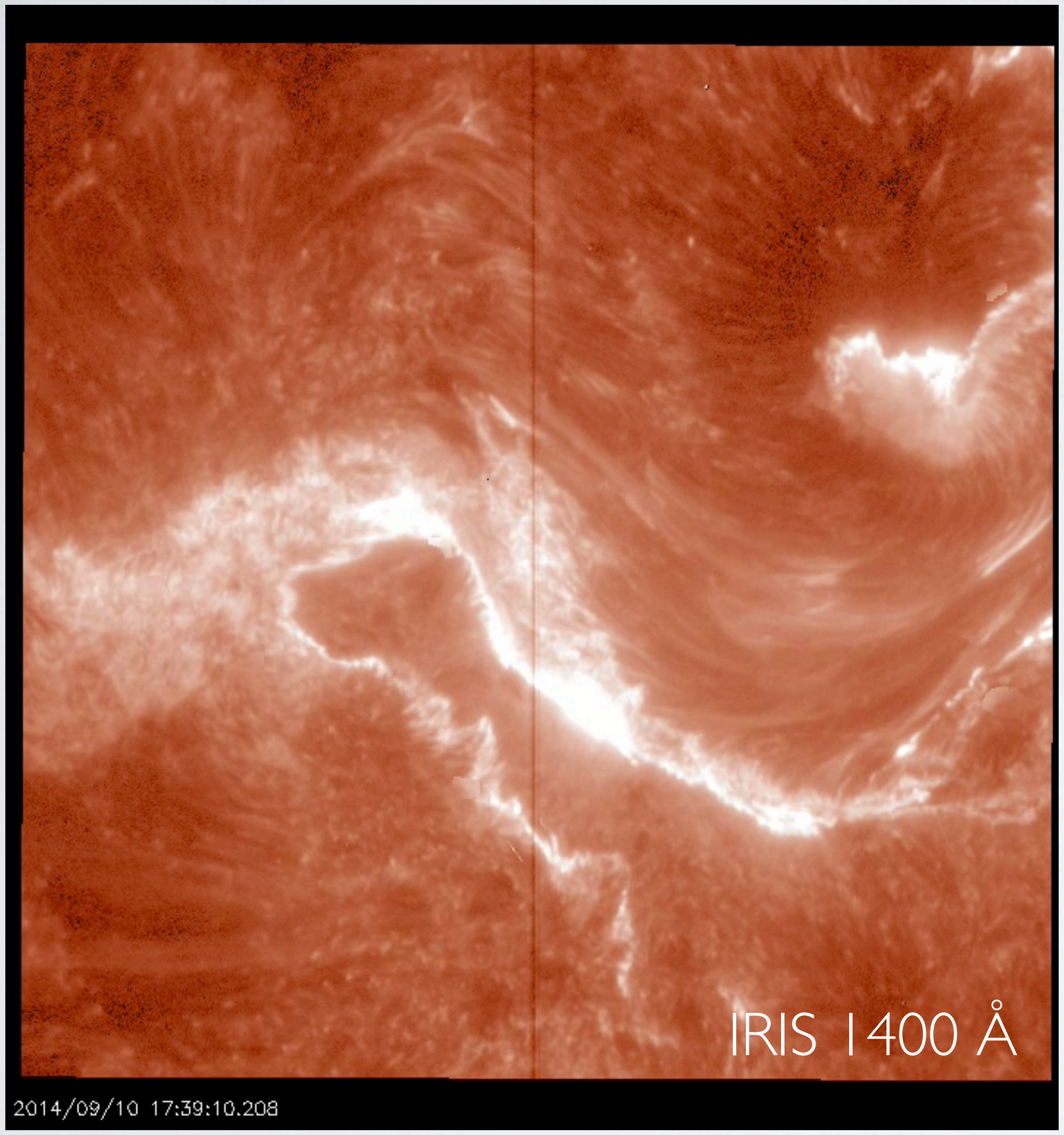
Savcheva et al., ApJ, 2016

Quasi-separatrix layers align with flare ribbons



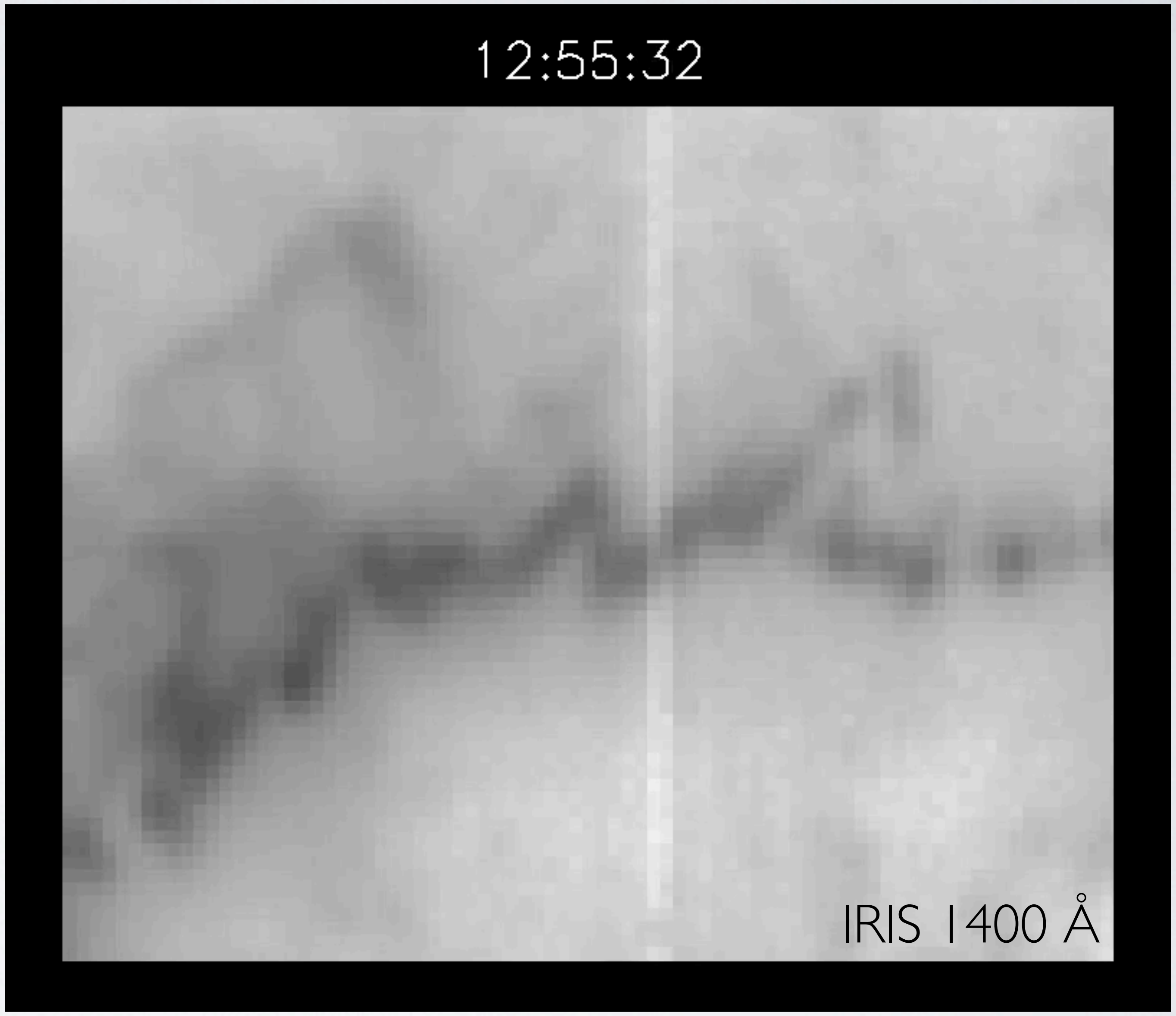
with 3D magnetic modeling, we can see that the footpoints align with the quasi-separatrix layers.

Flare ribbons



zipper motion

(see e.g. Tian et al., ApJ, 2015)



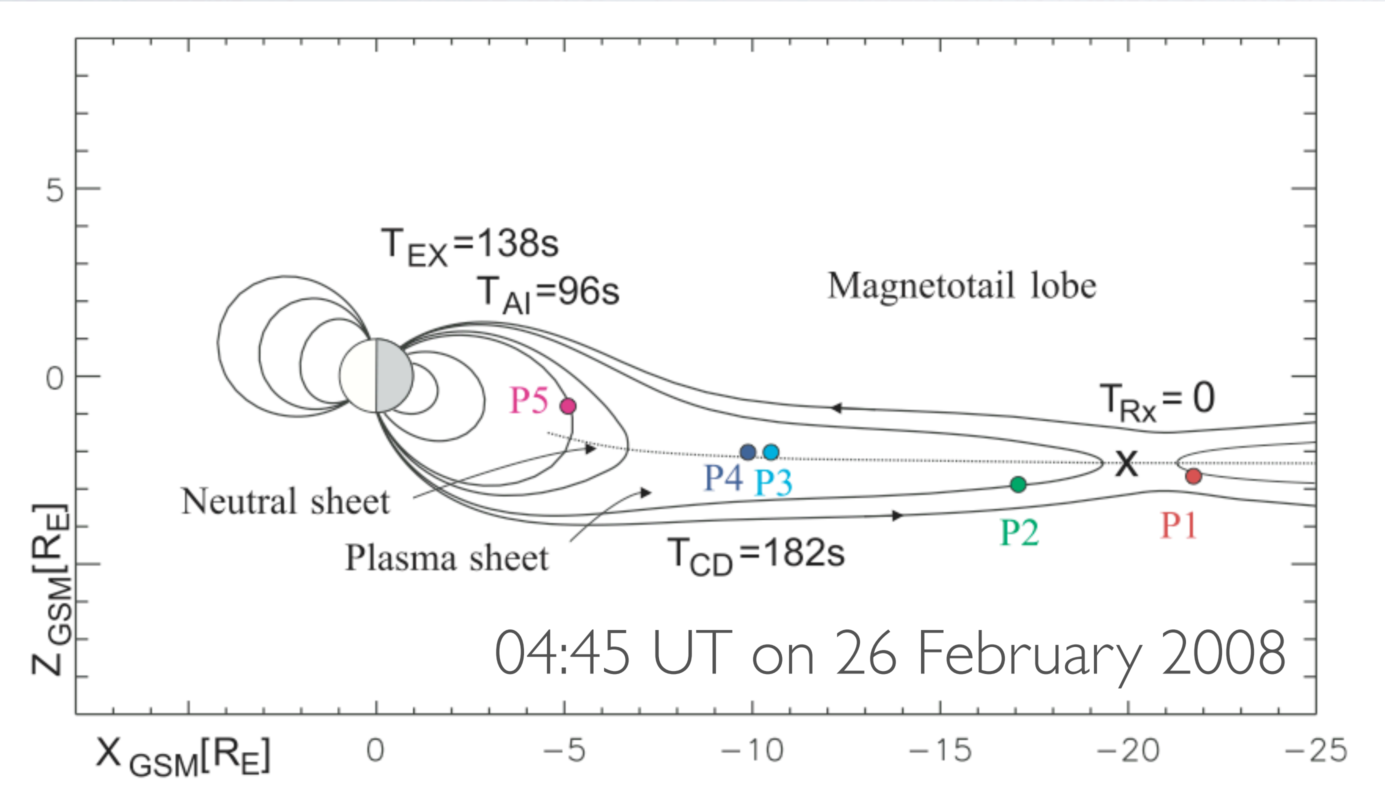
wave-like features

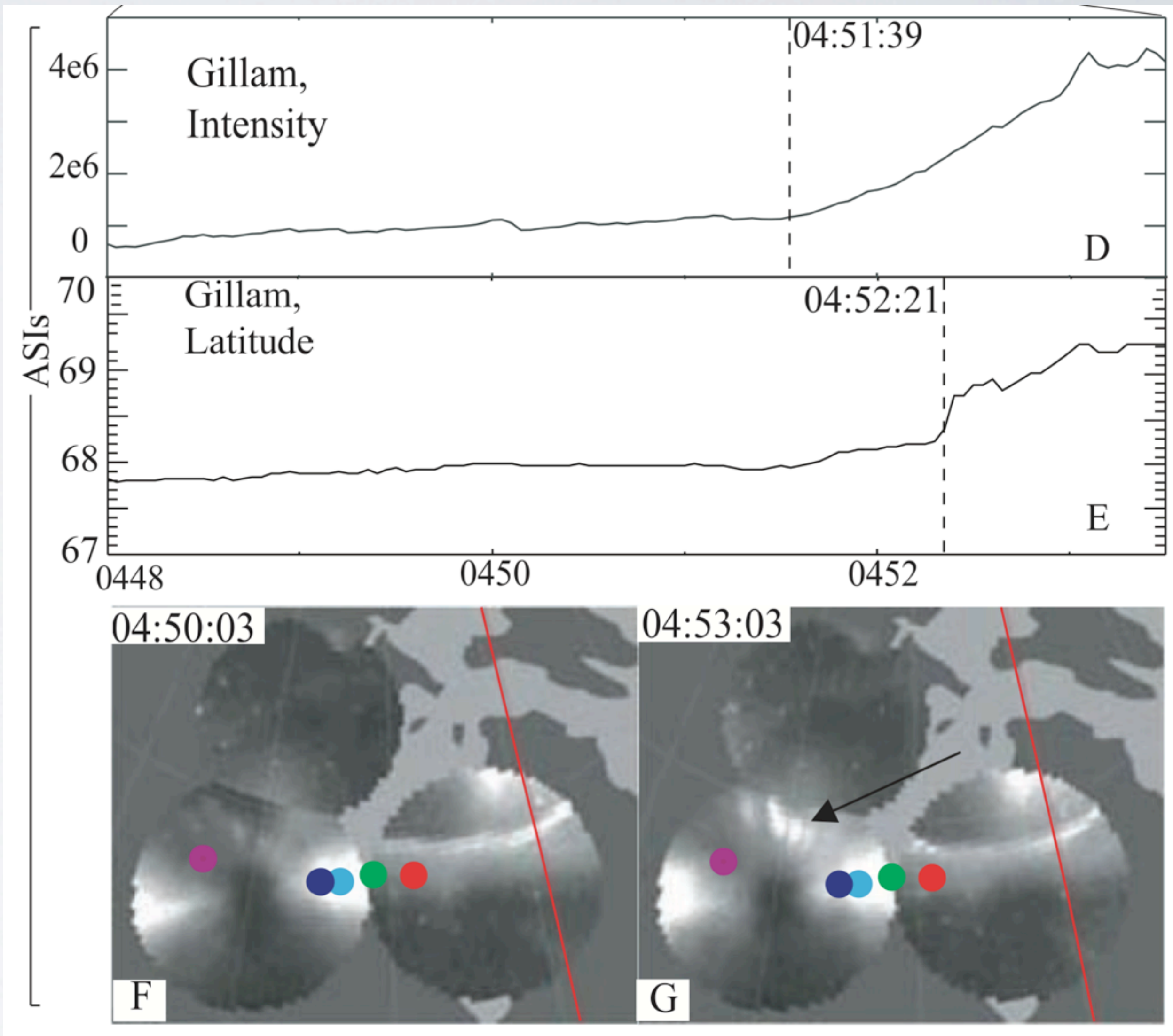
(Brannon et al., ApJ, 2015, Brosius & Daw, ApJ, 2015)

Footpoints can also show evidence of 3D effects. The observation on the left shows "zipper motion," which indicates that the reconnection is progressing from left to right. The observation on the right shows wave-like features in the flare footpoints.

Auroral response during substorms

Angelopoulos et al., Science, 2008

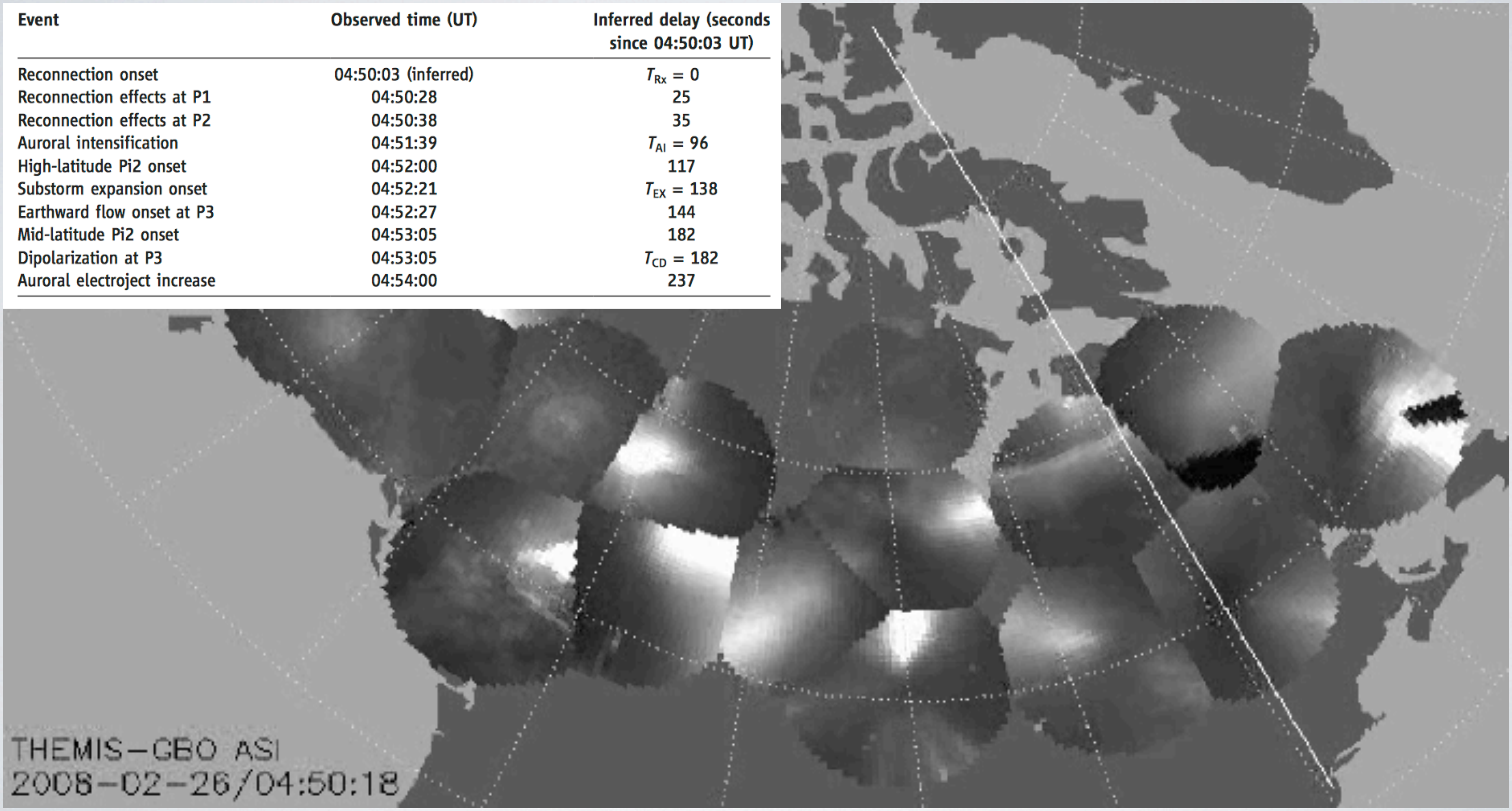




The aurora is the equivalent phenomena to flare ribbons in the magnetosphere. Substorm signatures include rapid auroral intensification, breakup of auroral structures into smaller filamentary structures, poleward expansion of auroral arcs. Observations of the aurora during the substorm from 26 February 2008 show these features. The colored dots on the auroral images are the projections of the THEMIS probes on to the Earth. Thea arrow indicates the first poleward expansion.

Reconnection and aurora

Event	Observed time (UT)	Inferred delay (seconds since 04:50:03 UT)
Reconnection onset	04:50:03 (inferred)	$T_{Rx} = 0$
Reconnection effects at P1	04:50:28	25
Reconnection effects at P2	04:50:38	35
Auroral intensification	04:51:39	$T_{AI} = 96$
High-latitude Pi2 onset	04:52:00	117
Substorm expansion onset	04:52:21	$T_{EX} = 138$
Earthward flow onset at P3	04:52:27	144
Mid-latitude Pi2 onset	04:53:05	182
Dipolarization at P3	04:53:05	$T_{CD} = 182$
Auroral electroject increase	04:54:00	237

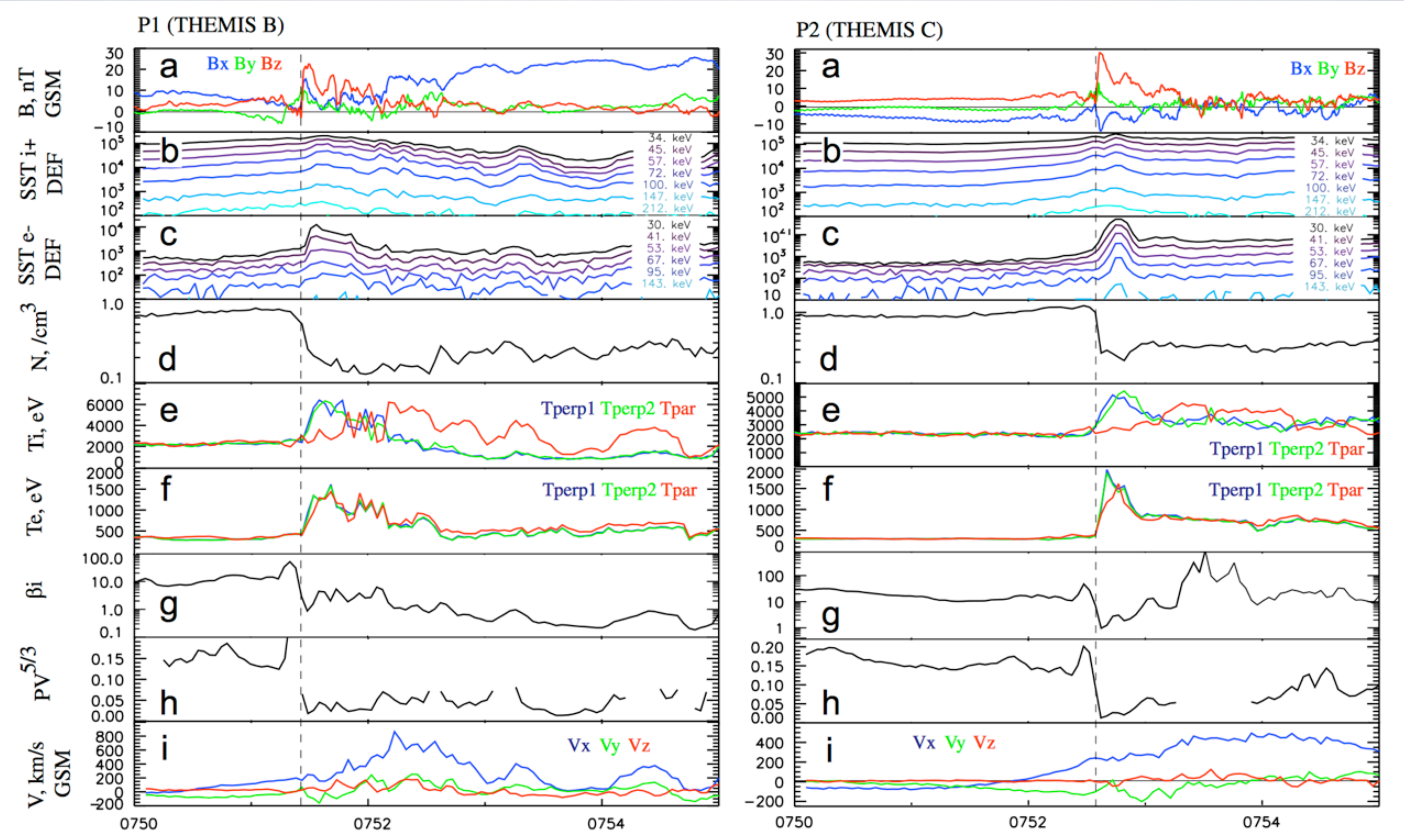


Angelopoulos et al., Science, 2008

Substorm onset is after reconnection onset, but before dipolarization, indicating that reconnection of more northerly field lines is the reason for poleward shift of aurora. Whether reconnection causes the poleward shift in the aurora had been a question up for debate in the magnetospheric community before this observation.

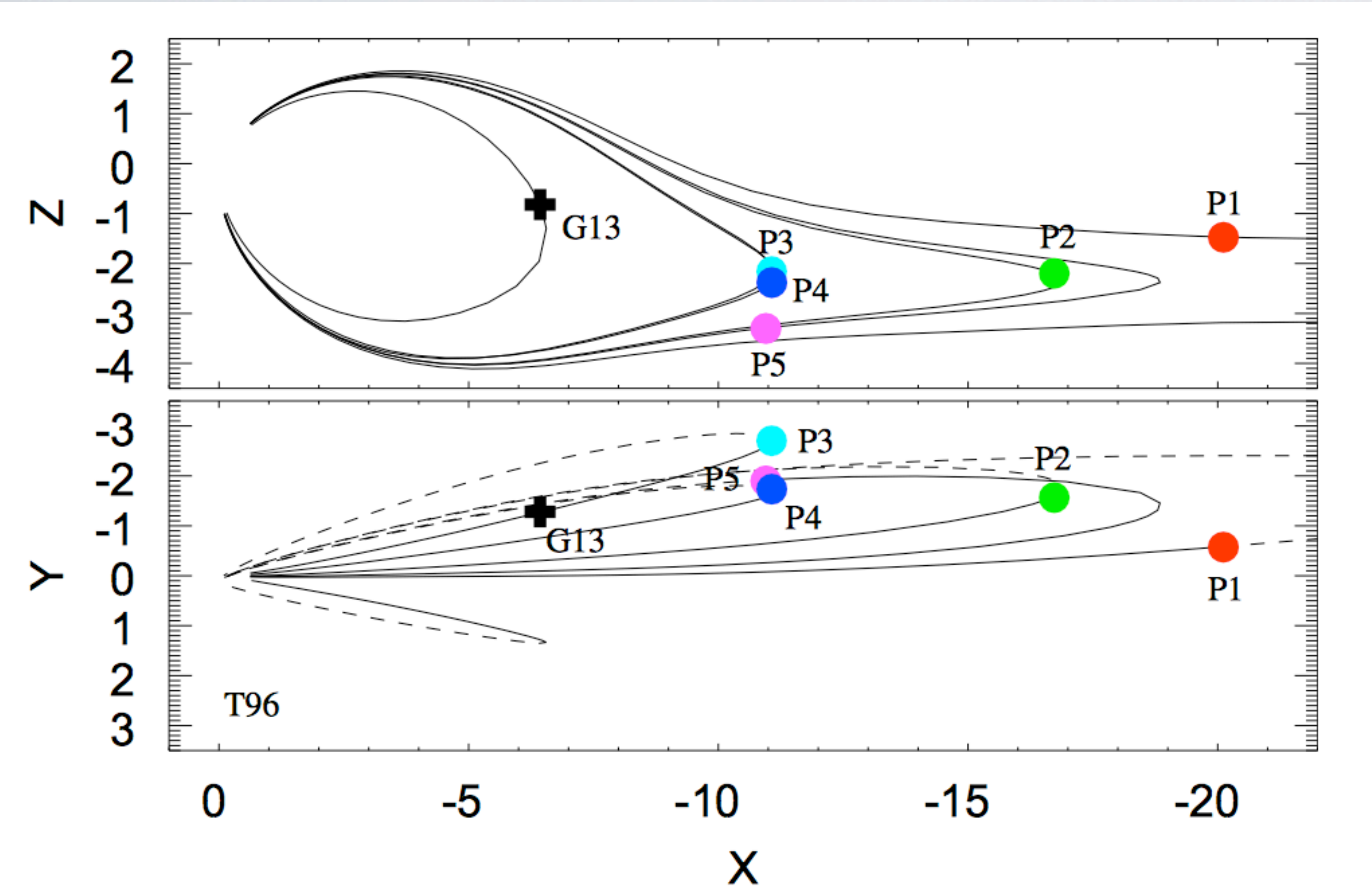
BBFs and aurora

Runov et al., P&SS, 2011

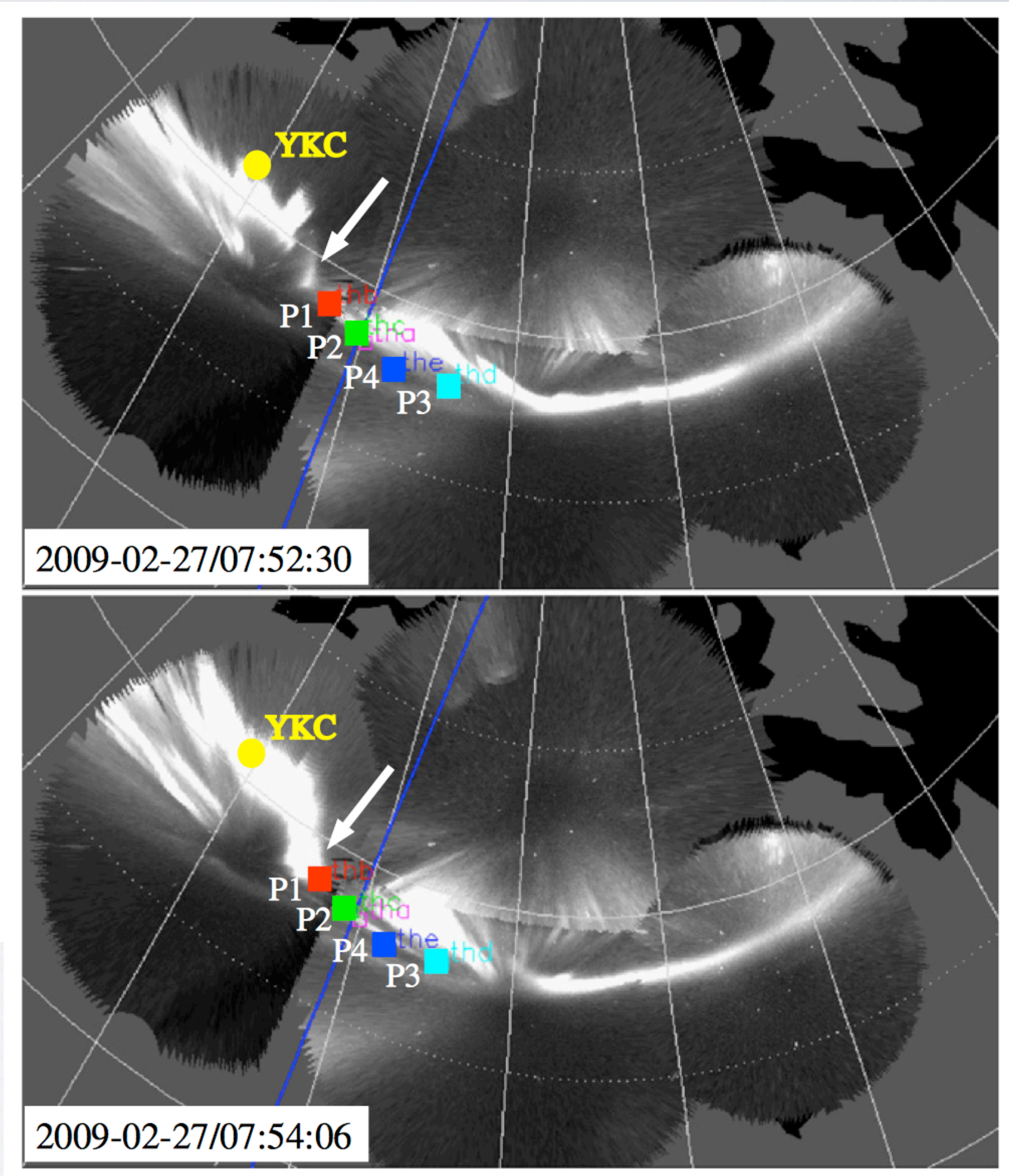


This is a typical bursty bulk flow, with an extended flow > 100 km/s depleted density, increased temperature (and decreased entropy)

BBFs and aurora

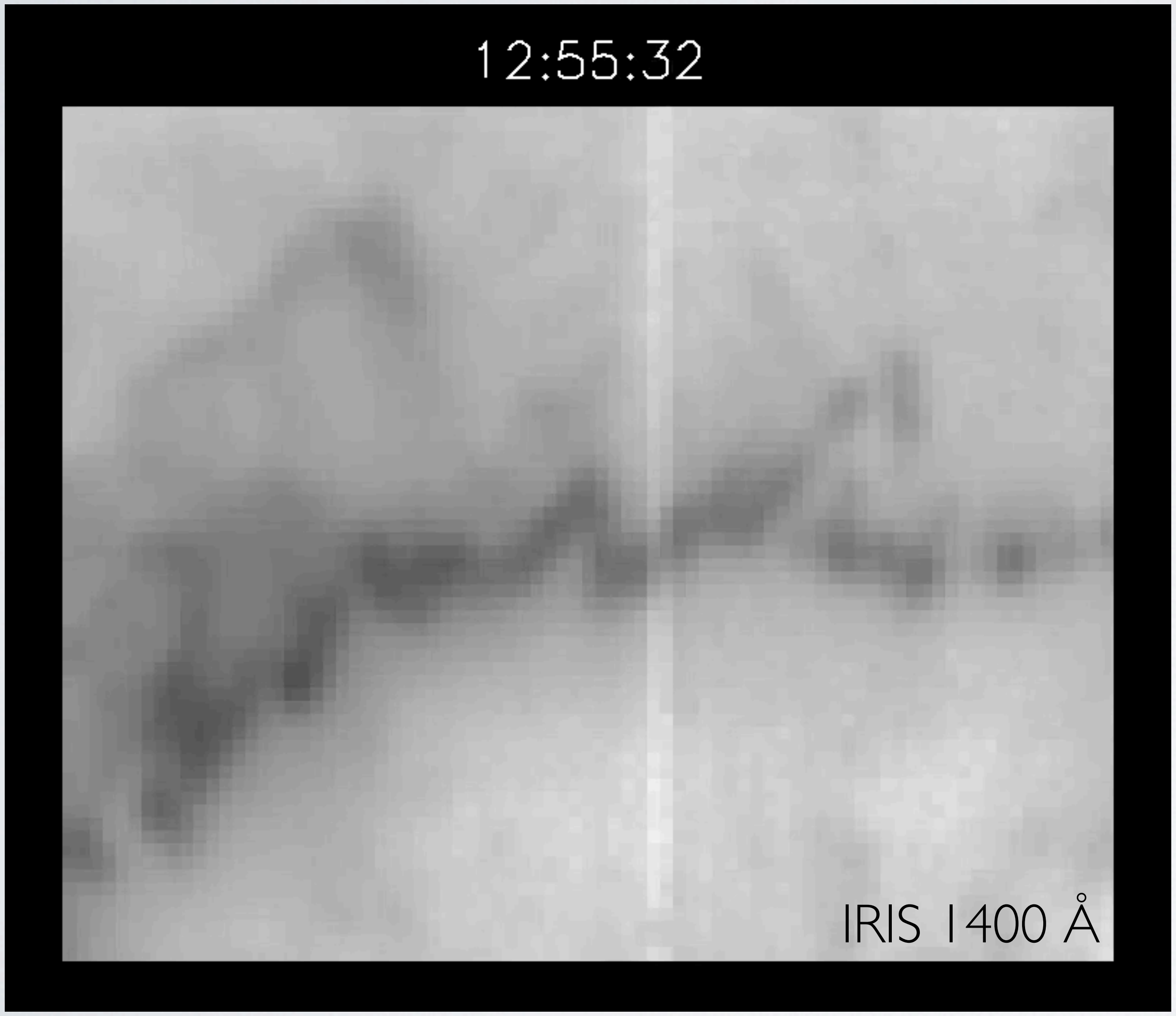


Runov et al., P&SS, 2011

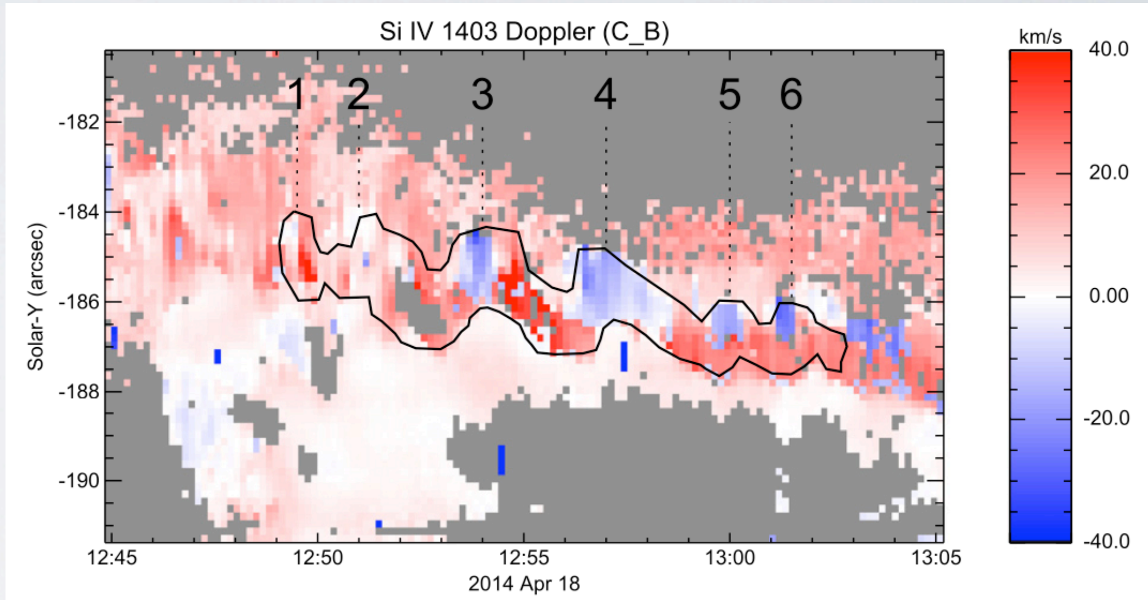


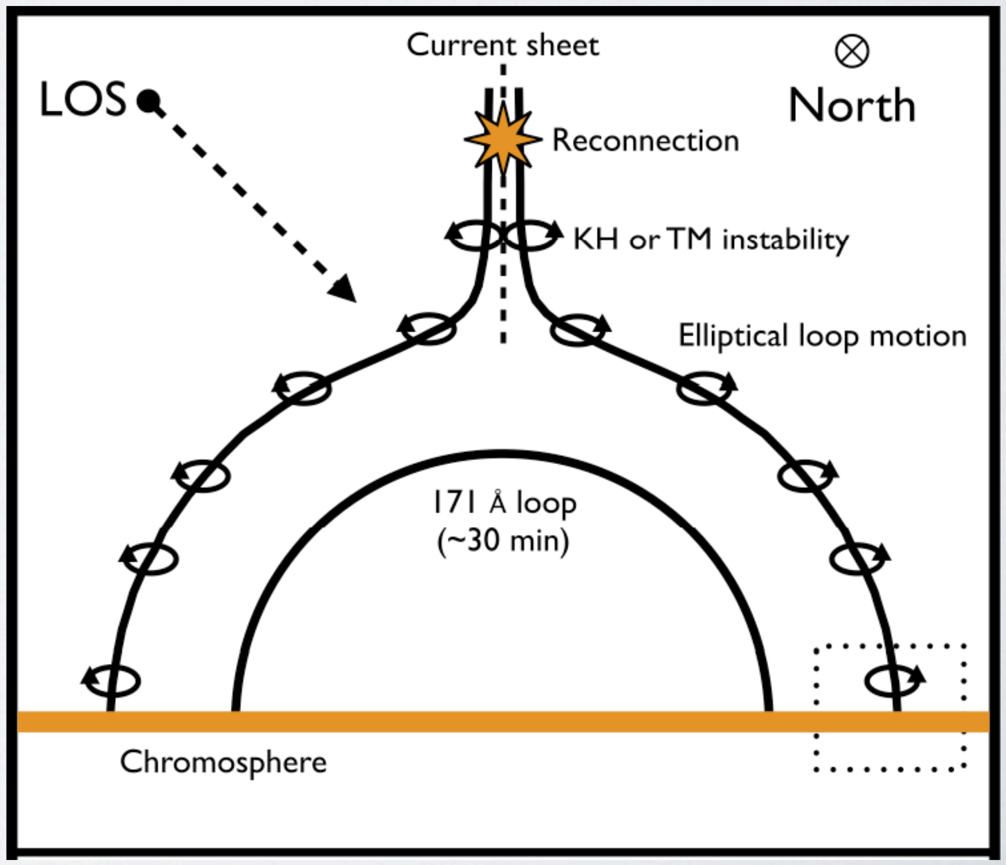
Mapping the THEMIS probes back to the Earth, the observations show that the bursty bulk flows are correlated with north/south oriented auroral arcs, indicated by the white arrows.

flare ribbons echoing current sheet instabilities?



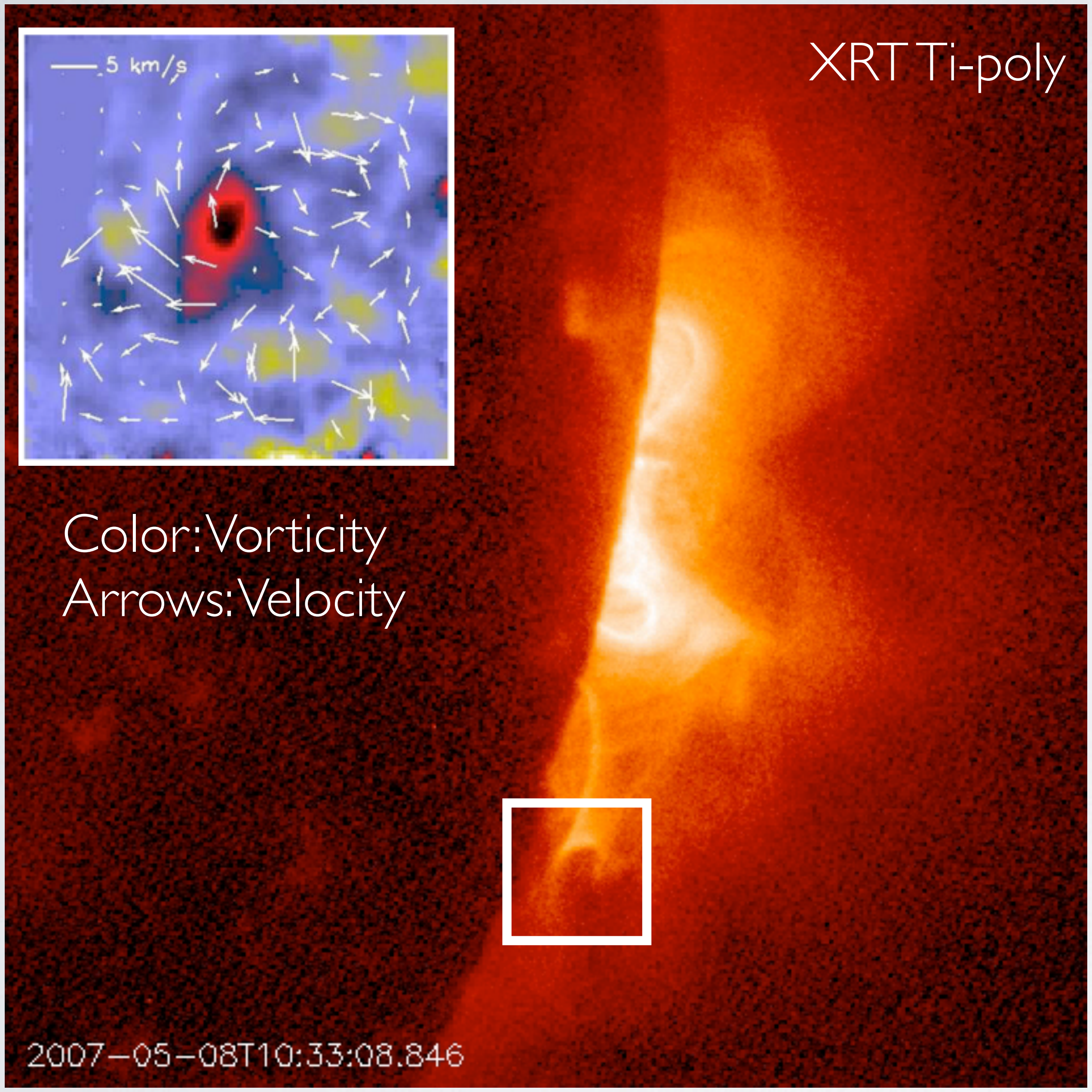
Brannon et al., ApJ, 2015
(but see Brosius & Daw, ApJ, 2015 for
an alternate interpretation)





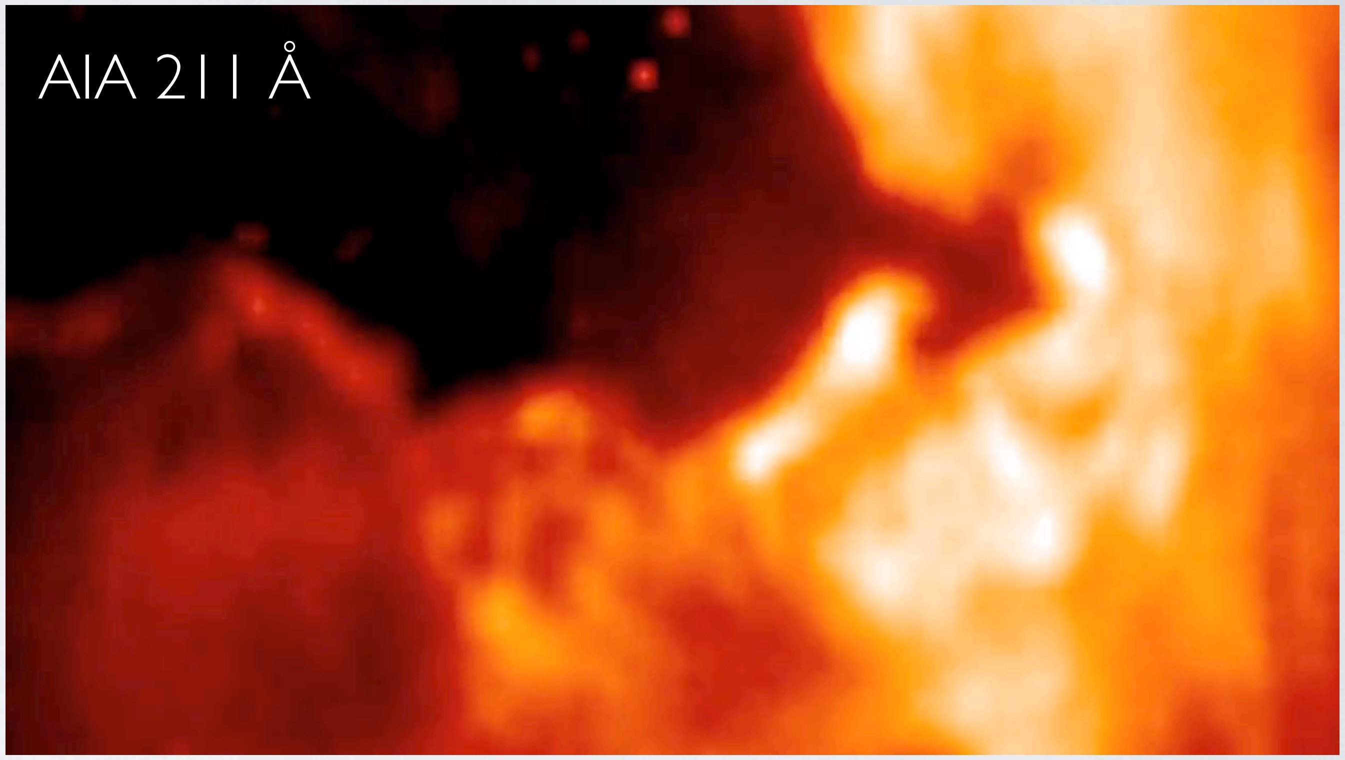
Interestingly, one interpretation of the wave-like features in the flare ribbons is that they are due to a Kelvin Helmholz or tearing mode instability in the current sheet region that is translated down to the footpoint of the loop. There is another interpretation by Brosius & Daw, though, that interprets the ribbon features as the result of particle acceleration due to patchy reconnection.

Post-CME Plasma Dynamics



Post-CME vortices

McKenzie, ApJ, 2013



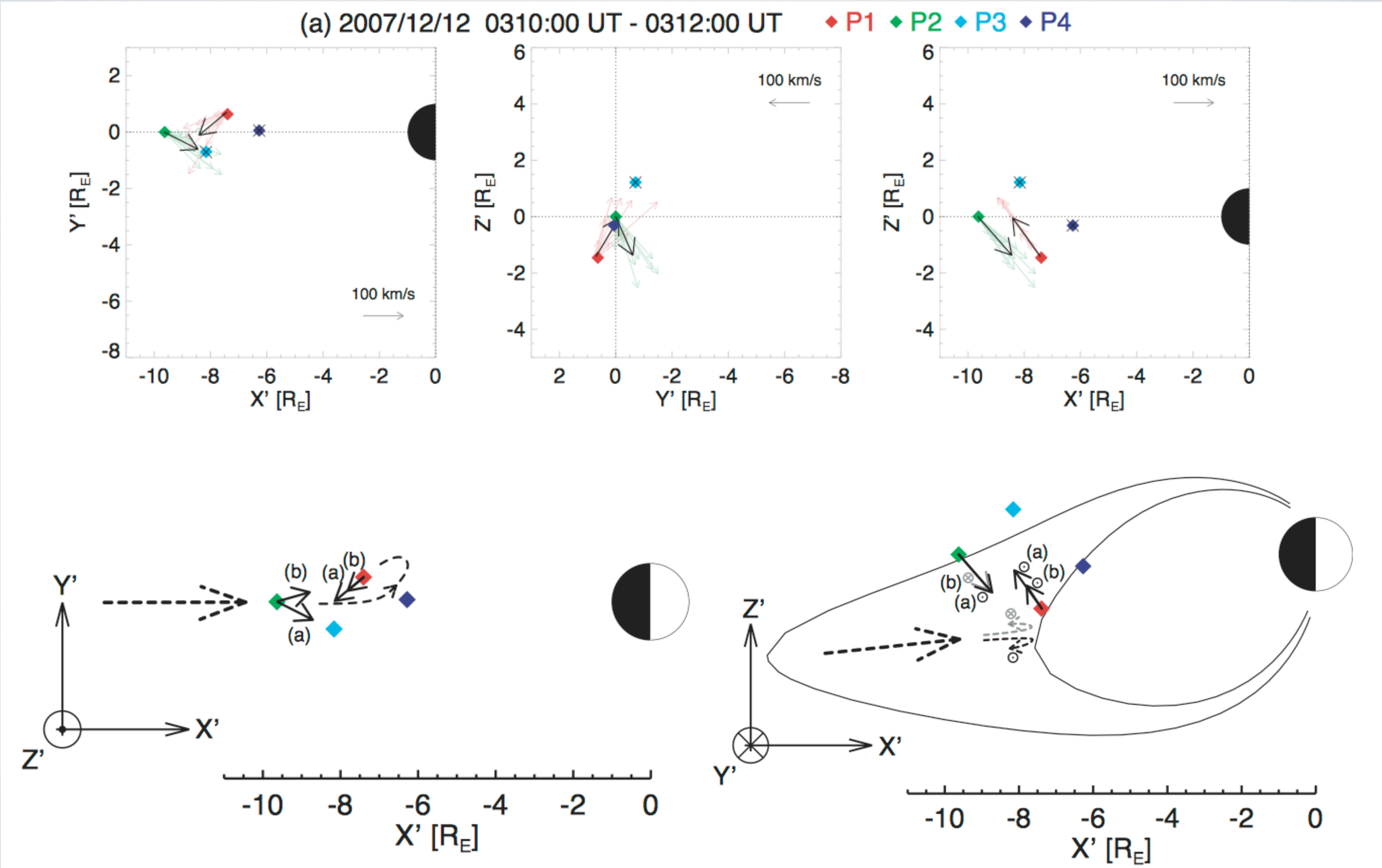
KHI Instabilities

Ofman & Thompson, ApJ, 2011
(see also Foullon et al., ApJL, 2011)

In addition to downflows, vortices are also observed in post-eruptive plasma sheets, as in this XRT data analyzed by David McKenzie, and this KHI instability following an eruption observed by Ofman & Thompson.

BBF vorticies

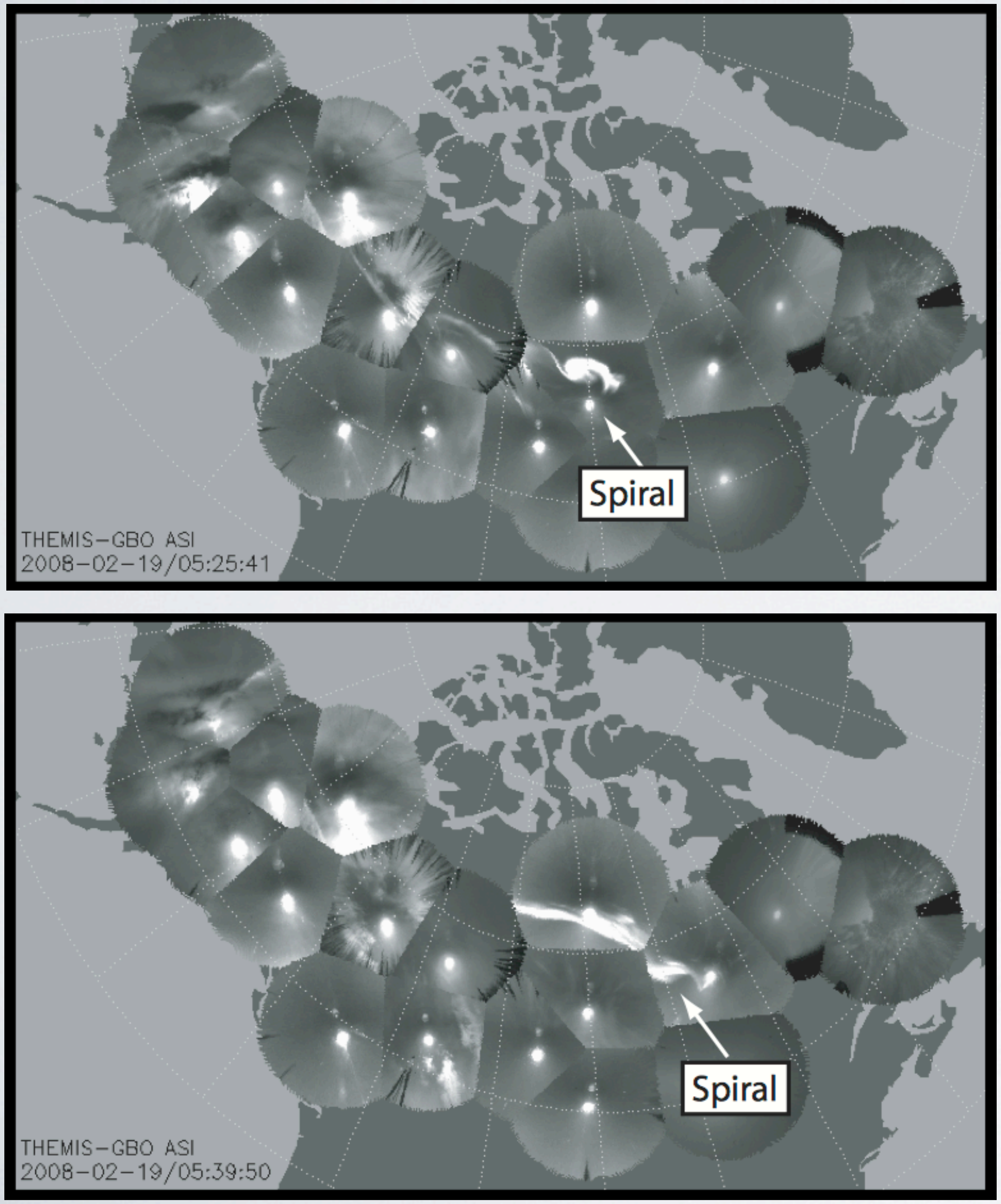
Keika et al., AnnGeo 2009

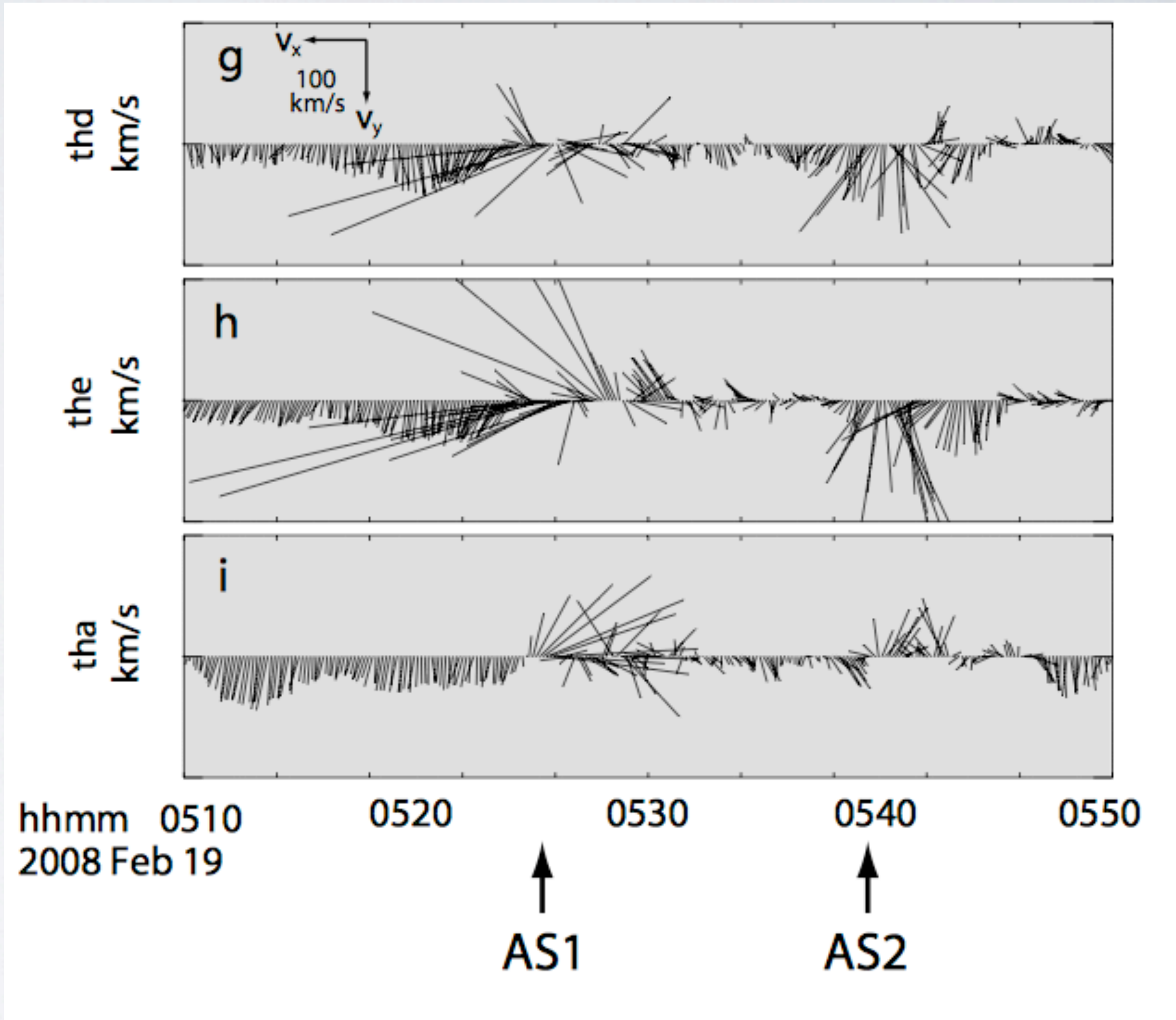


THEMIS data shows plasma vortices are formed in the vicinity of the flow braking region in the magnetosphere.

auroral spirals

Keiling et al., AnnGeo 2009





THEMIS flow vortices coincide with auroral spirals

Plasma vortices observed by THEMIS have been connected to spiral structures observed in the aurora.

Open Questions

- How can we use flare ribbon dynamics to tell us something about instabilities in the reconnection region?
- If SADs and BBFs are similar phenomena, why are SADs cool and BBFs (mostly) hot? Is "depleted entropy" a better measure?
- Do we have blind spots when observing reconnection in the corona that can illuminated by observations of reconnection in the magnetosphere?

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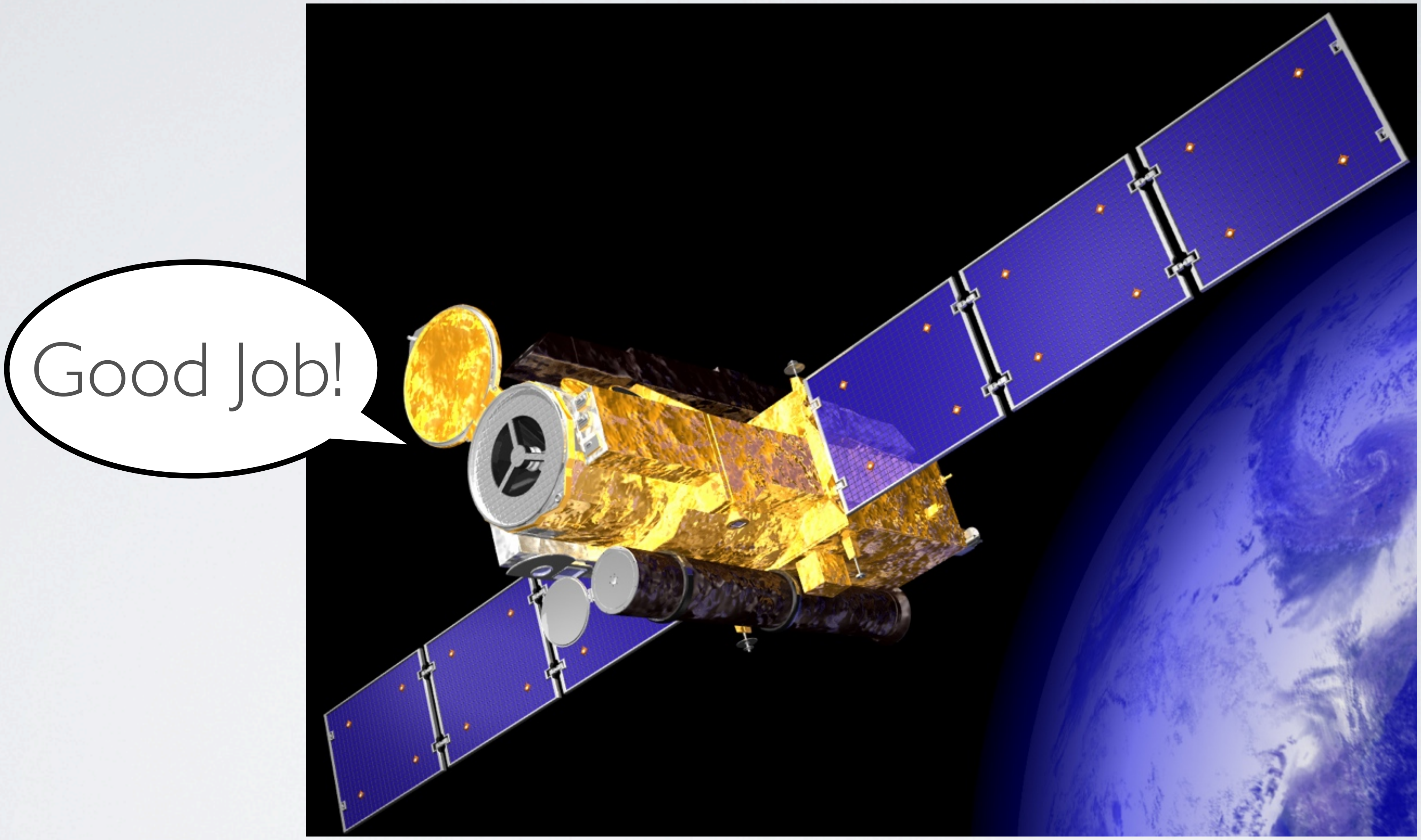

A great big THANK YOU to...

...students!!


Questions?
Aurora over Iceland
Photo credit: Karl Critz