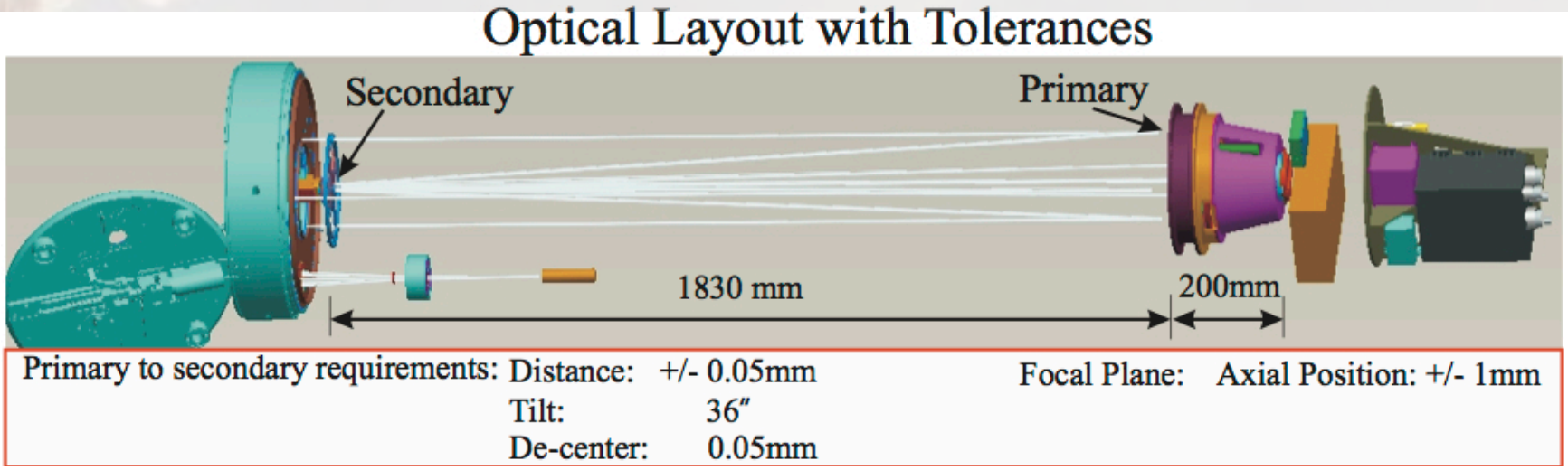
The High Resolution Coronal Explorer

Dr. Jonathan Cirtain

Dr. Amy Winebarger

High-resolution Coronal Imager (Hi-C)



Hi-C is a narrowband EUV imager. The wavelength band is centered on 193 Å.

Multilayer coatings by David Windt, RXO LLC.

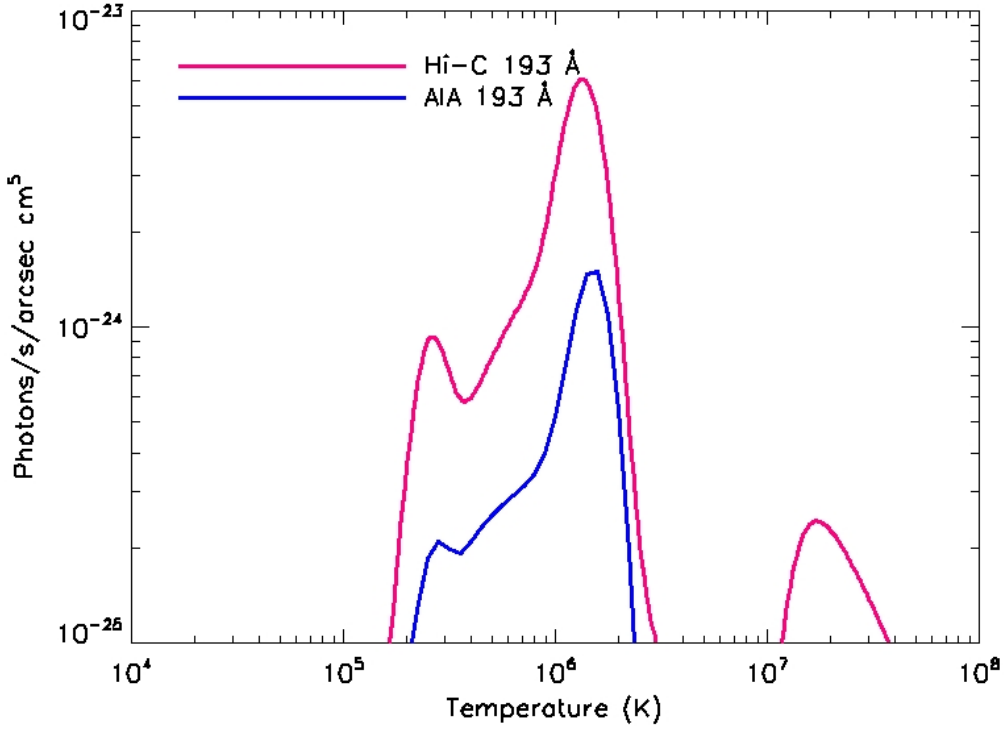
Hi-C Telescope Optical Design

Telescope Properties:	
Focal Length	23.9 m
Plate Scale	114 µm/arcsec
Focal Ratio	f/109
Field of View	6.8x6.8 arcmin
RMS Spot Diameter (averaged over f.o.v.)	0.08 arcsec
CCD Camera:	
Size	49.1 mm^2
Scale	0.1 arcsec/pixel

Primary Mirror:	
Radius of Curvature	4000±4.0 mm
Diameter	240 mm
RMS slope error	0.4 µrad
Secondary Mirror:	
Radius of Curvature	370±0.5 mm
Conic	-1.14±0.10
Diameter	30 mm
RMS slope error	0.1 µrad

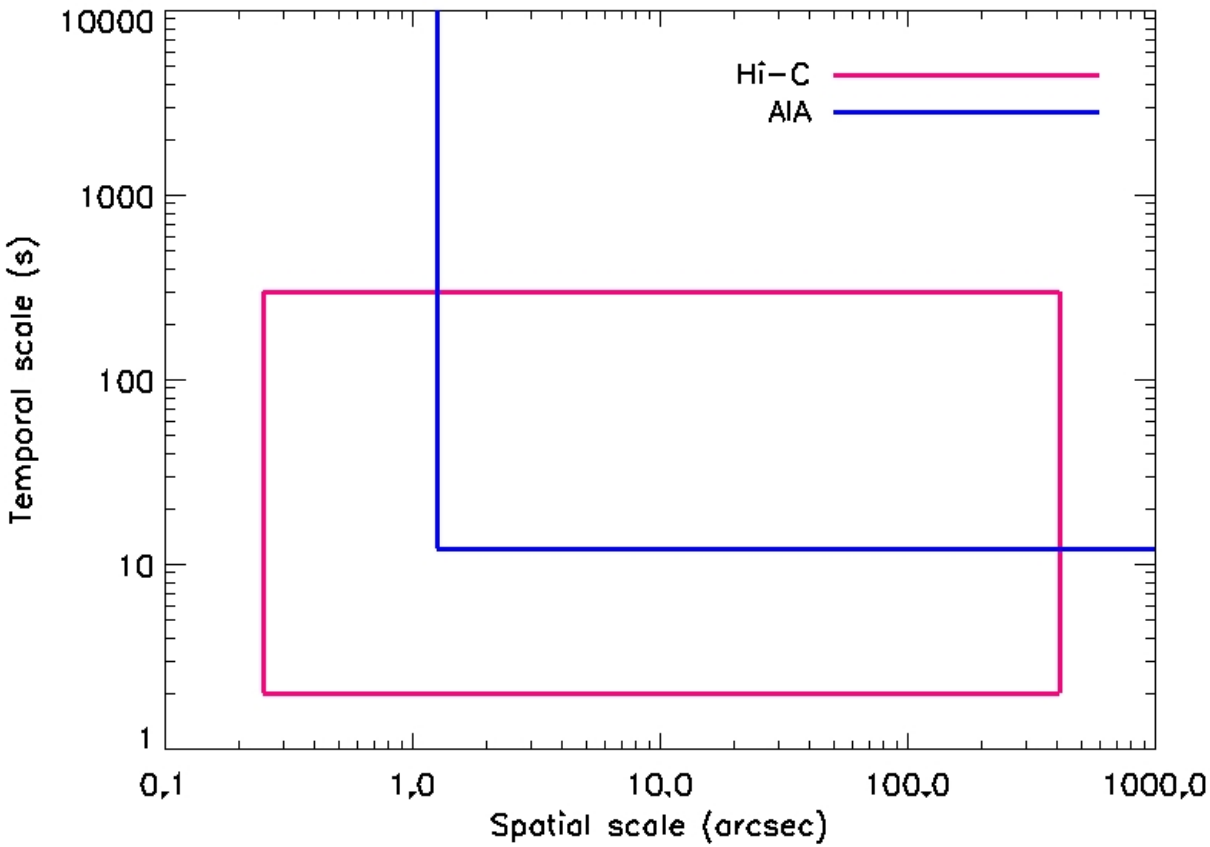
Hi-C Passband

- The Hi-C 193 Å passband is similar to the 193 Å passband on the Solar Dynamics Observatory (SDO) Atmospheric Imaging Assembly (AIA).
- Hi-C has roughly 5 times the effective area of AIA.

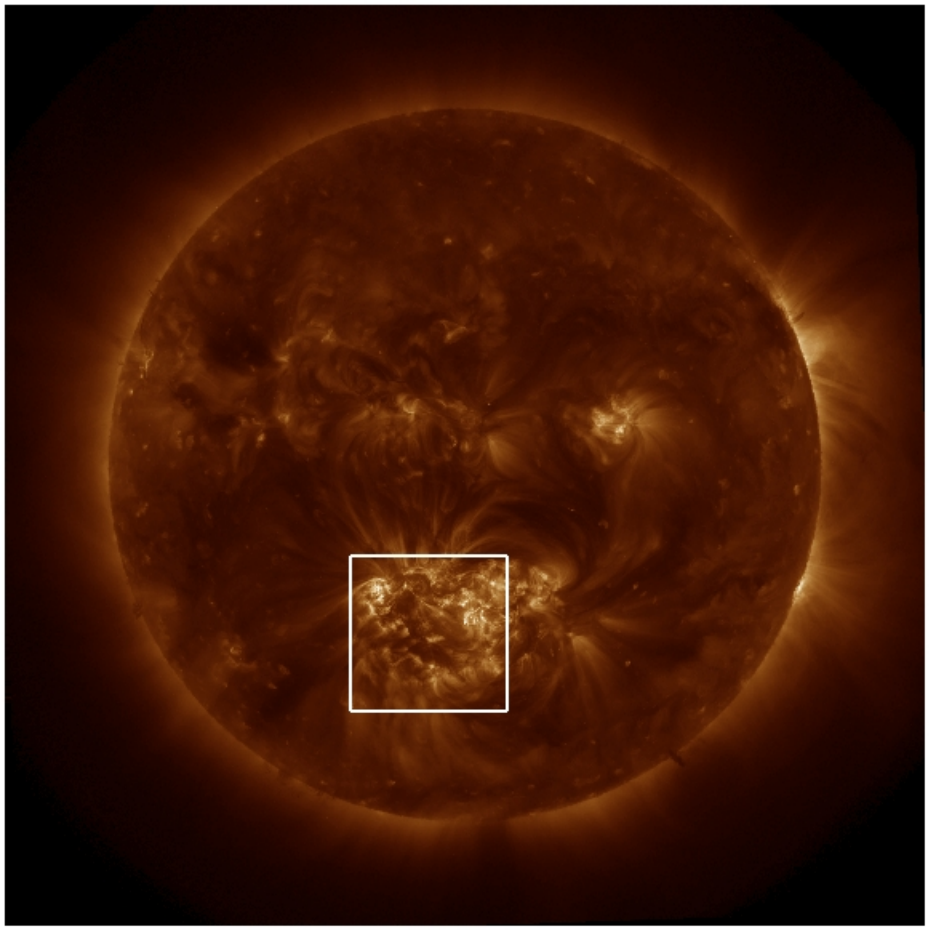


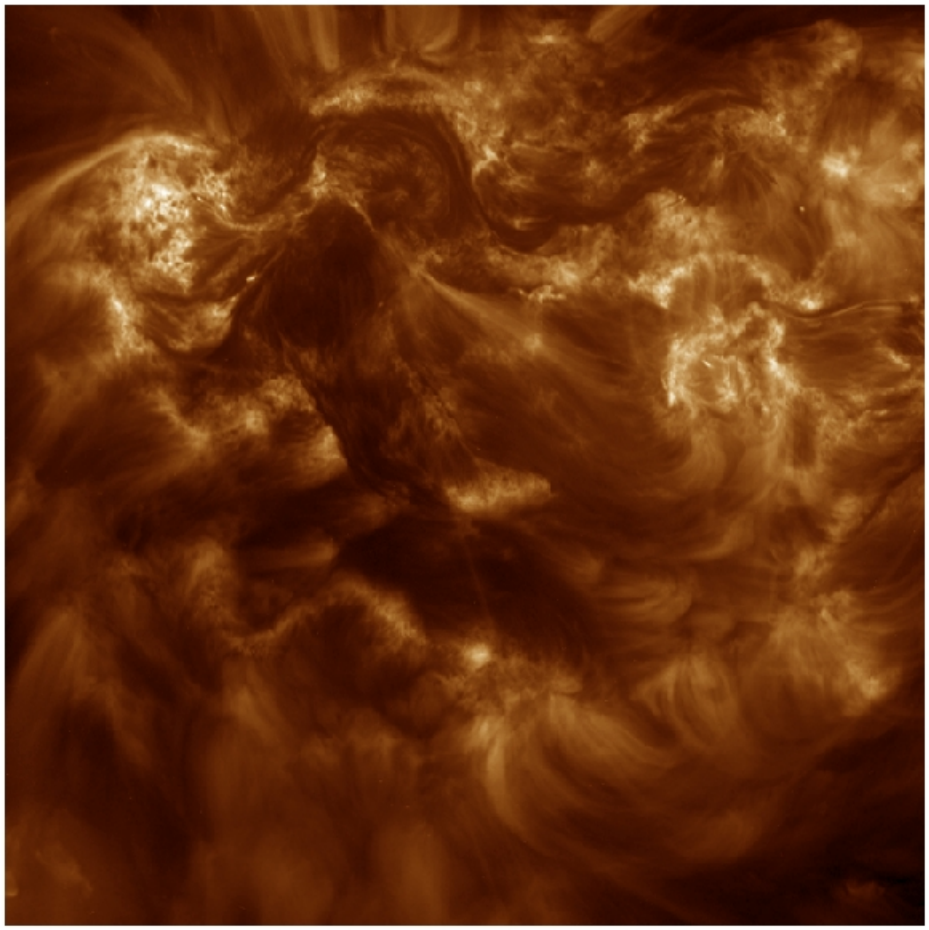
Hi-C Discovery Space

- The spatial resolution of Hi-C is five times better than AIA .
- The cadence of Hi-C is 2.5 – 6 times better than AIA.



Hi-C Target





The Hi-C target was Active Region 11520

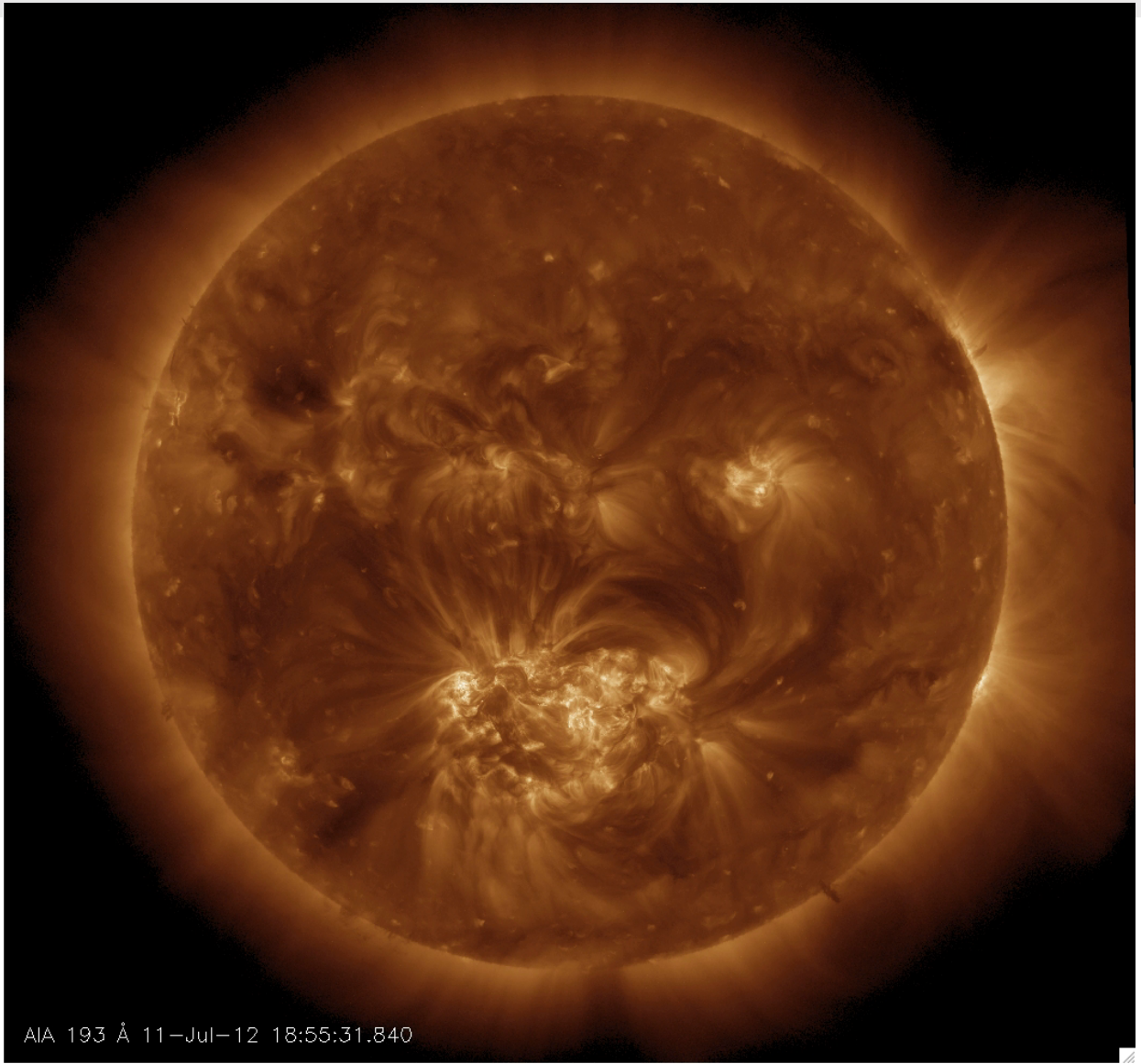
Hi-C Data

- Hi-C collected data for 345 s.
- Small shift in pointing during flight

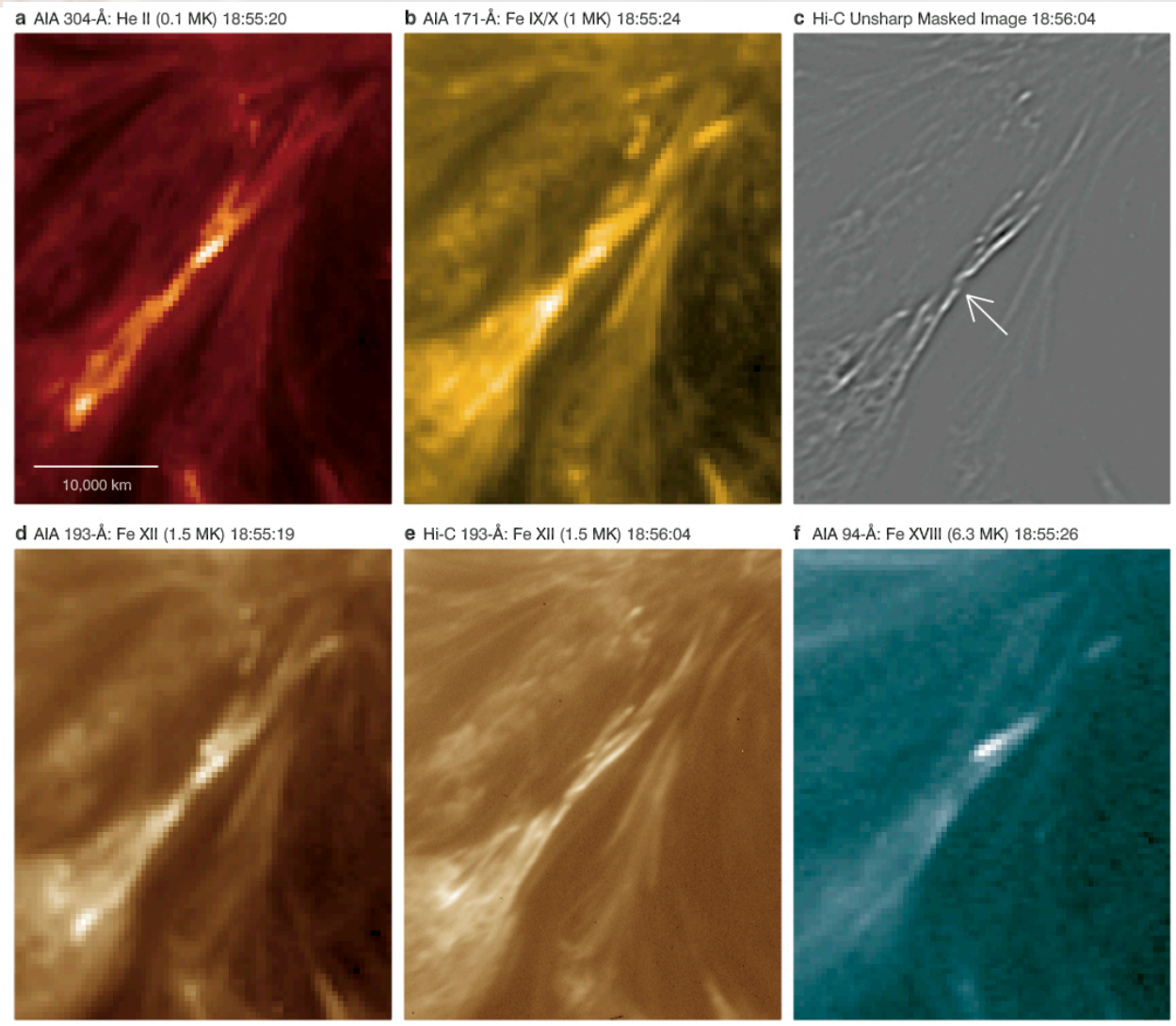
- Full frame (4kx4k) data
  - 30 full resolution images
  - 2 s exposures / 5 s cadence

- Partial frame (1kx1k) data
  - 86 full resolution image
  - 0.5 s exposures / 1.4 s cadence

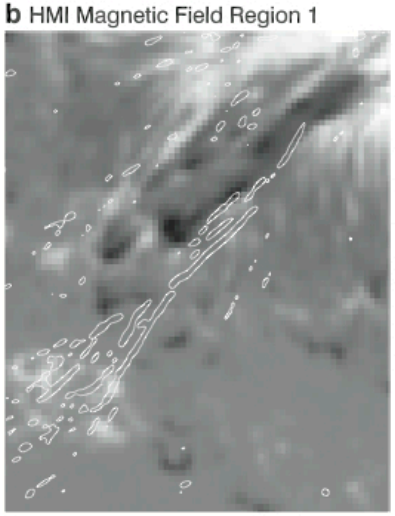
Hi-C First Results



Component Reconnection

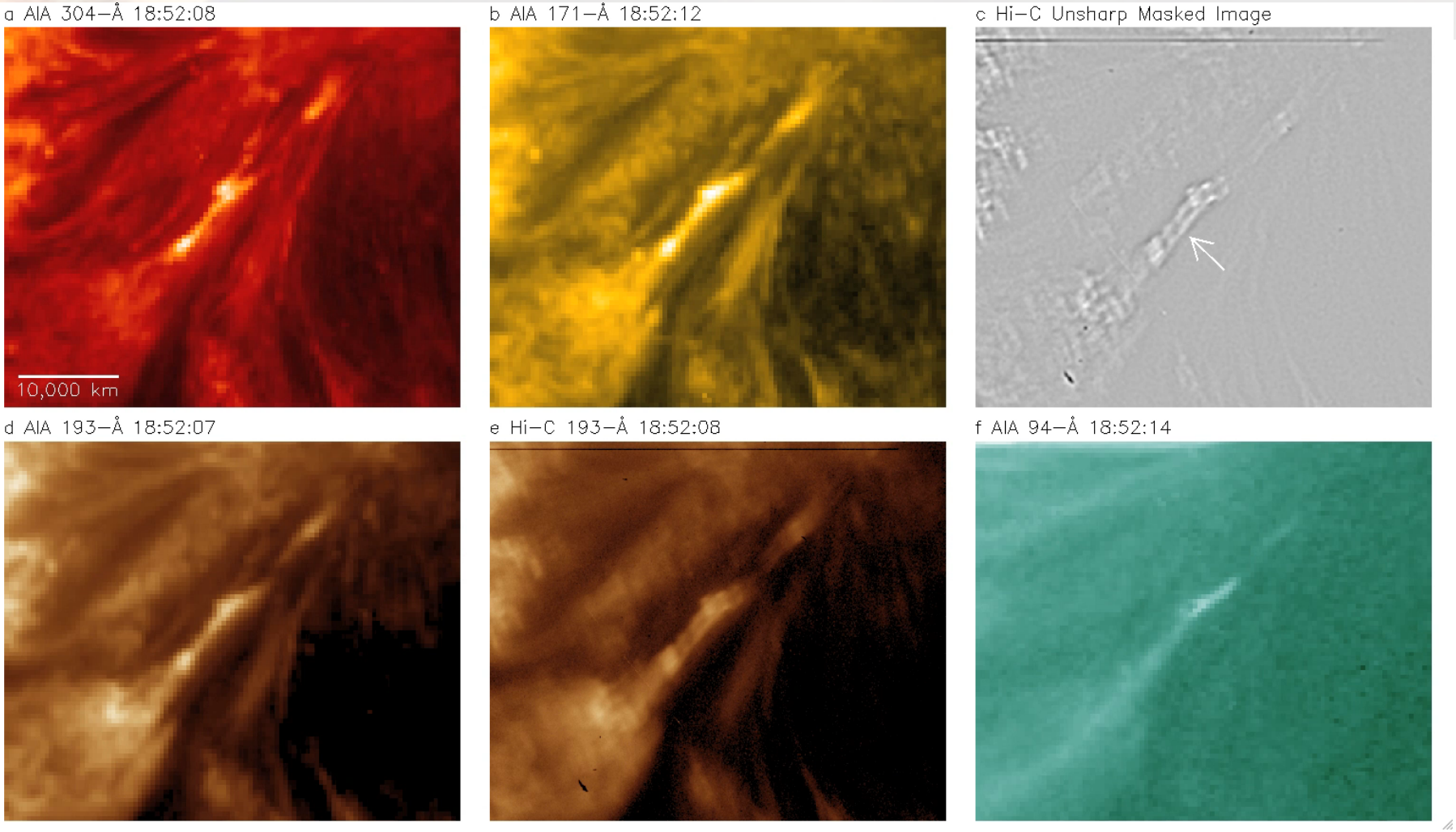


- Magnetic field braiding has been suggested as a energy storage mechanism in the solar corona.
- Hi-C observed braided magnetic field.



Cirtain et al, 2013, Nature

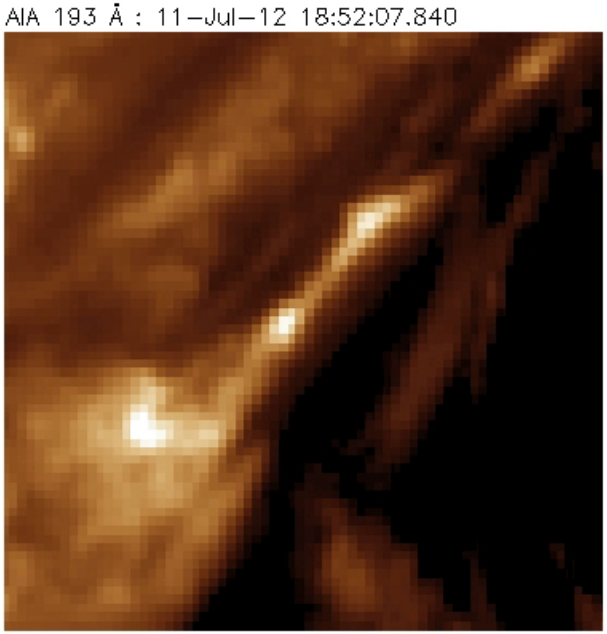
Component Reconnection

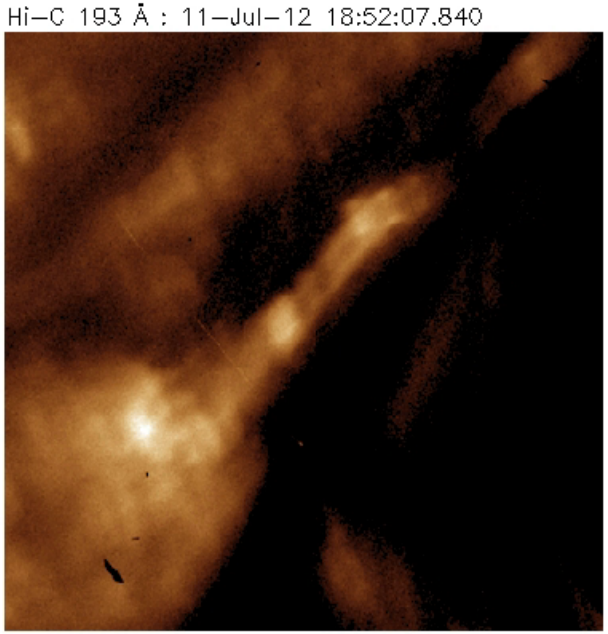


Shortly after the Hi-C flight, a small flare was observed at the field line crossing.

Cirtain et al, 2013, Nature

Component Reconnection

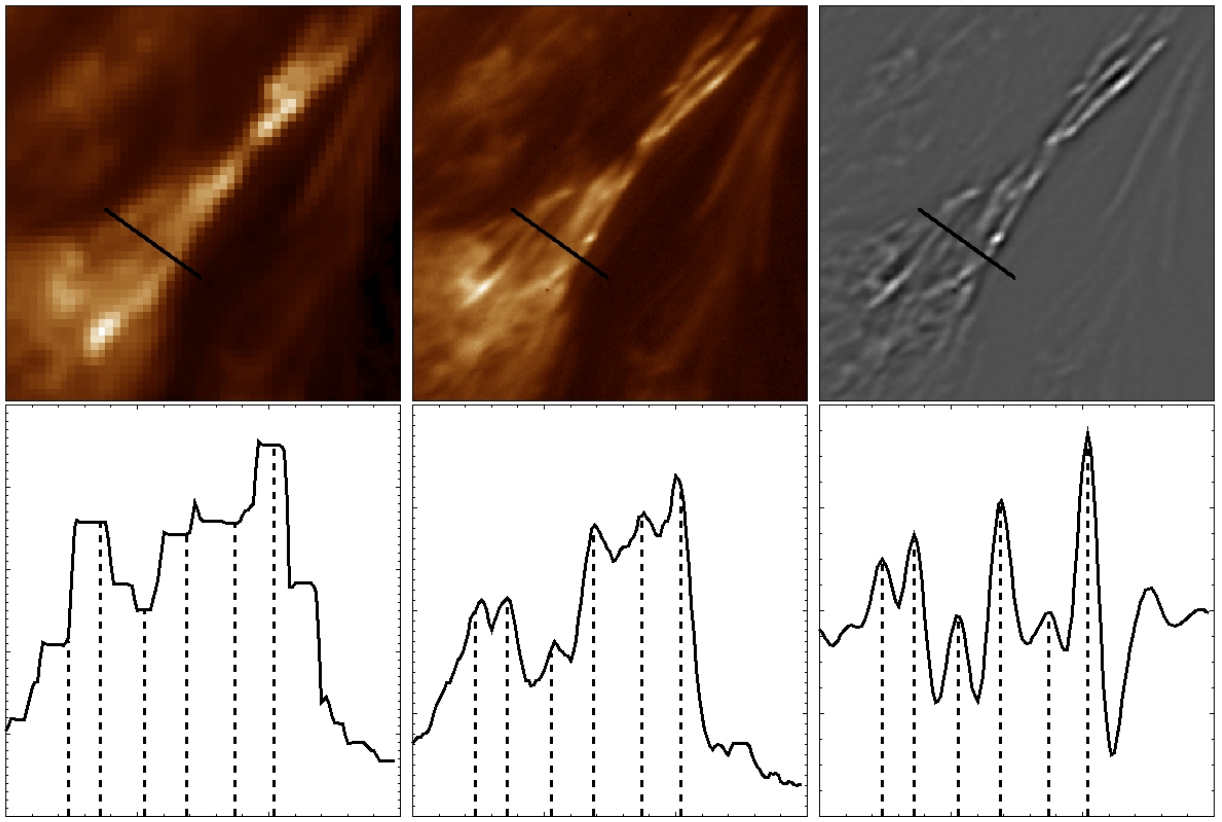




Velocities along structure estimated to be 150 km/s.

Cirtain et al, 2013, Nature

Component Reconnection

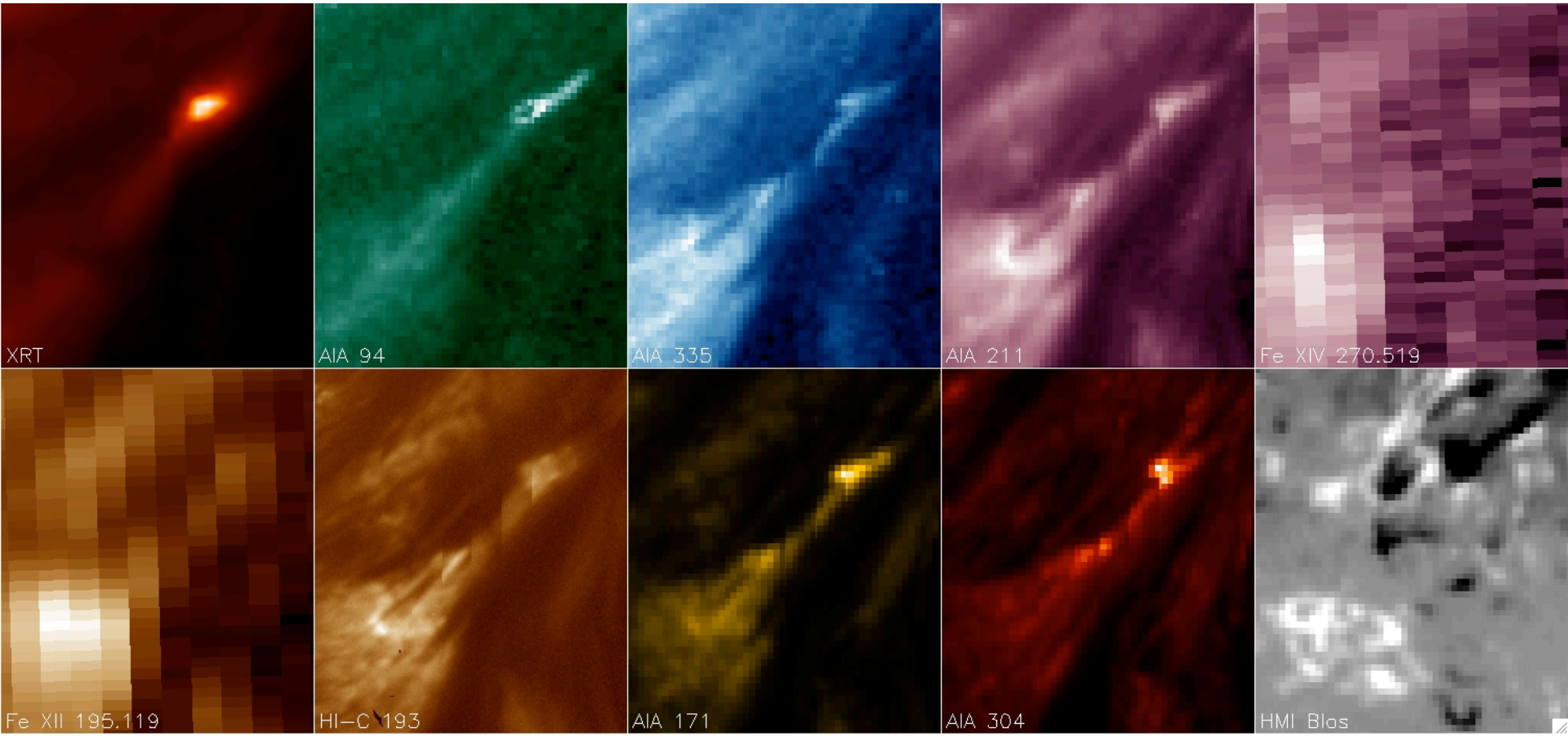


- Cuts across the braided loop show that the loop is composed of at least 6 strands.

Winebarger et al, in prep.

Component Reconnection

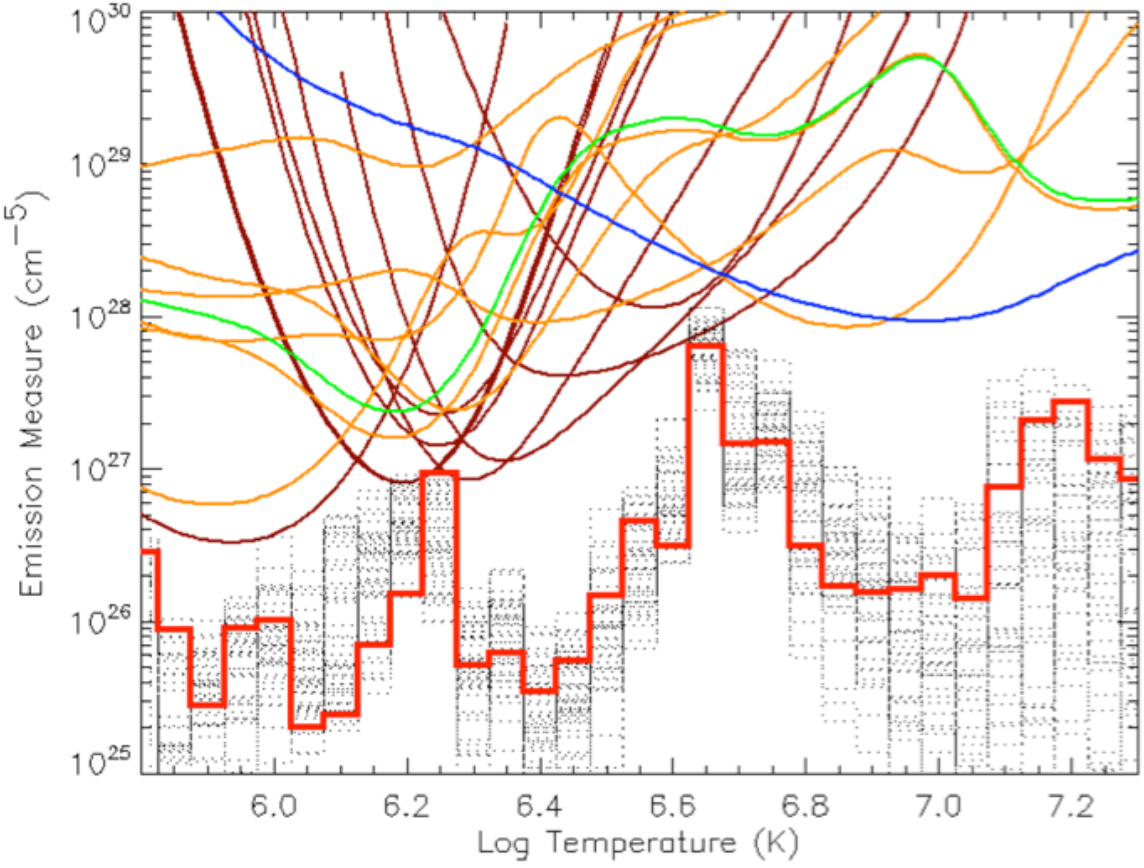
time ←



- EIS rastered over the loop with density-sensitive spectral lines in Fe XII and Fe XIII in addition to several high temperatures lines.

Winebarger et al, in prep.

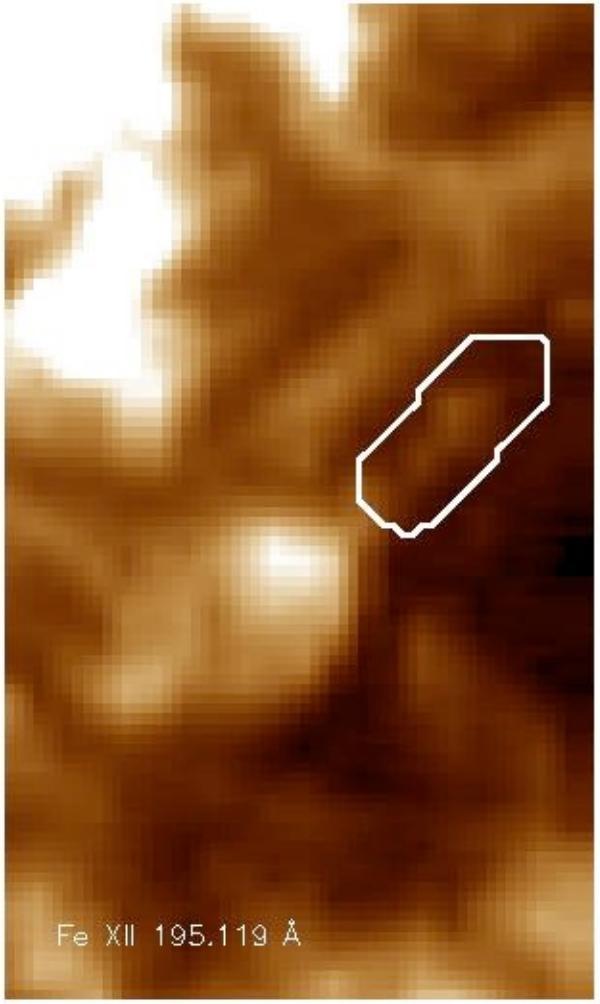
Component Reconnection

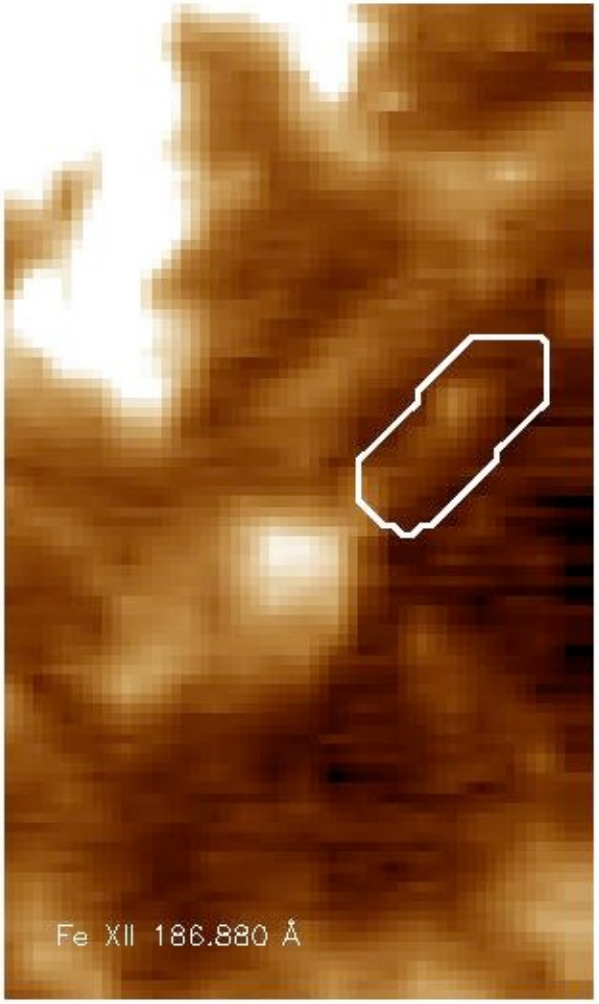


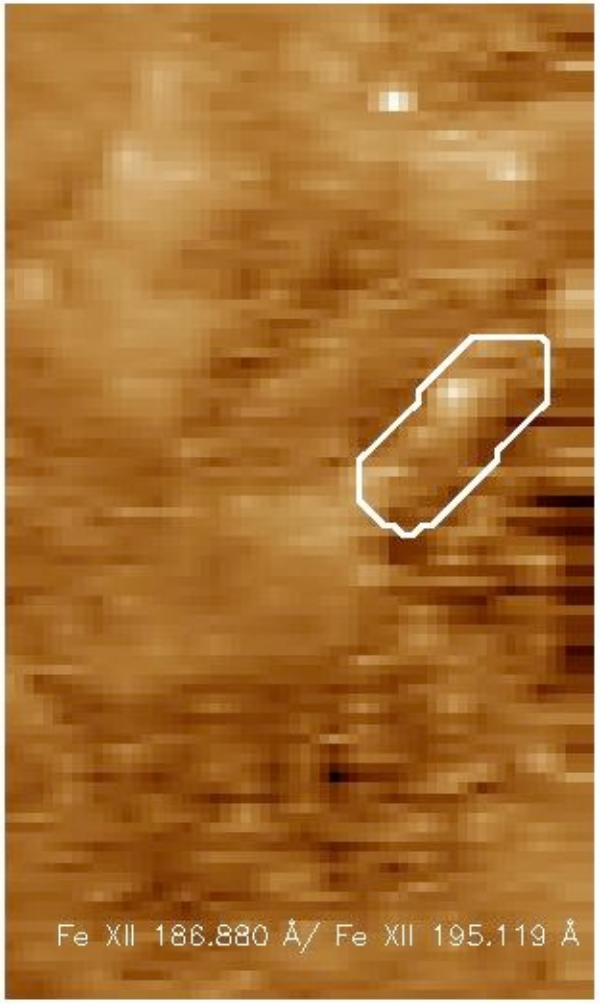
DEM is a mess.

Winebarger et al, in prep.

Component Reconnection

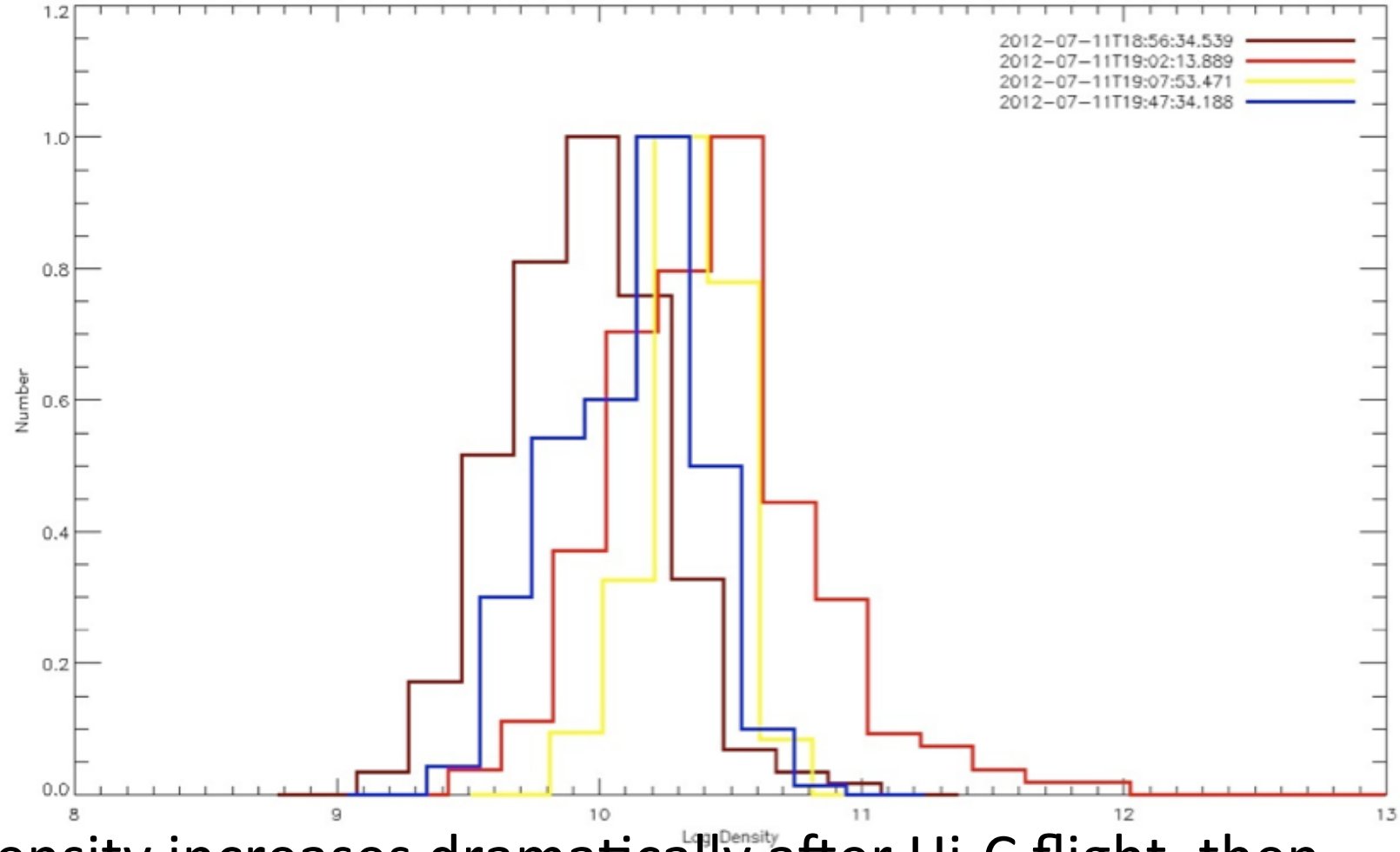






EIS rastered over the loop with density-sensitive spectral lines in Fe XII and Fe XIII in addition to several high temperatures lines.

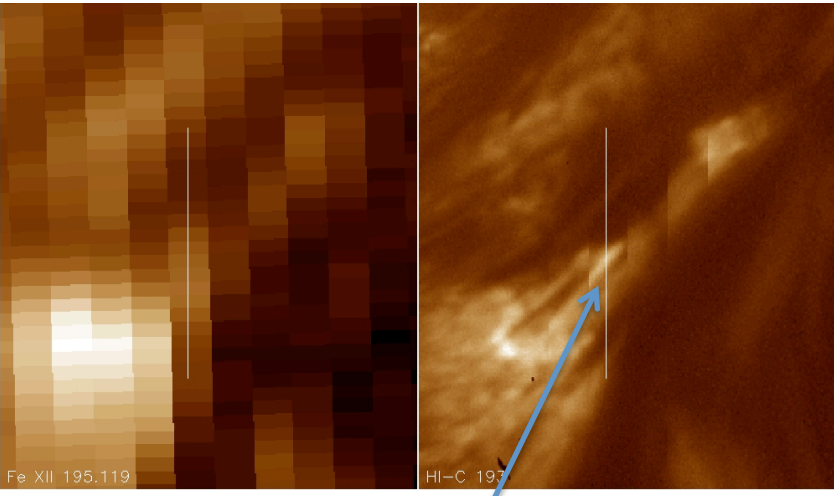
Component Reconnection

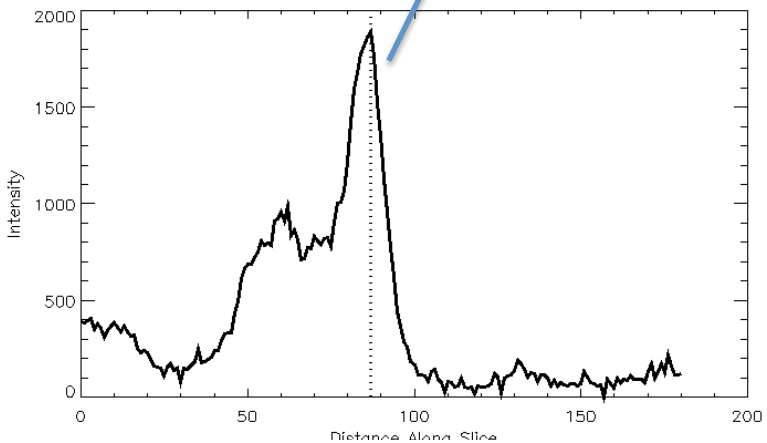


Density increases dramatically after Hi-C flight, then decreases.

Winebarger et al, in prep.

Component Reconnection





From EIS, we determine:

- Temperature = 1.8 MK
- Densities = 0.5-7 x 10^{10} cm^{-3}

From Hi-C, we determine:

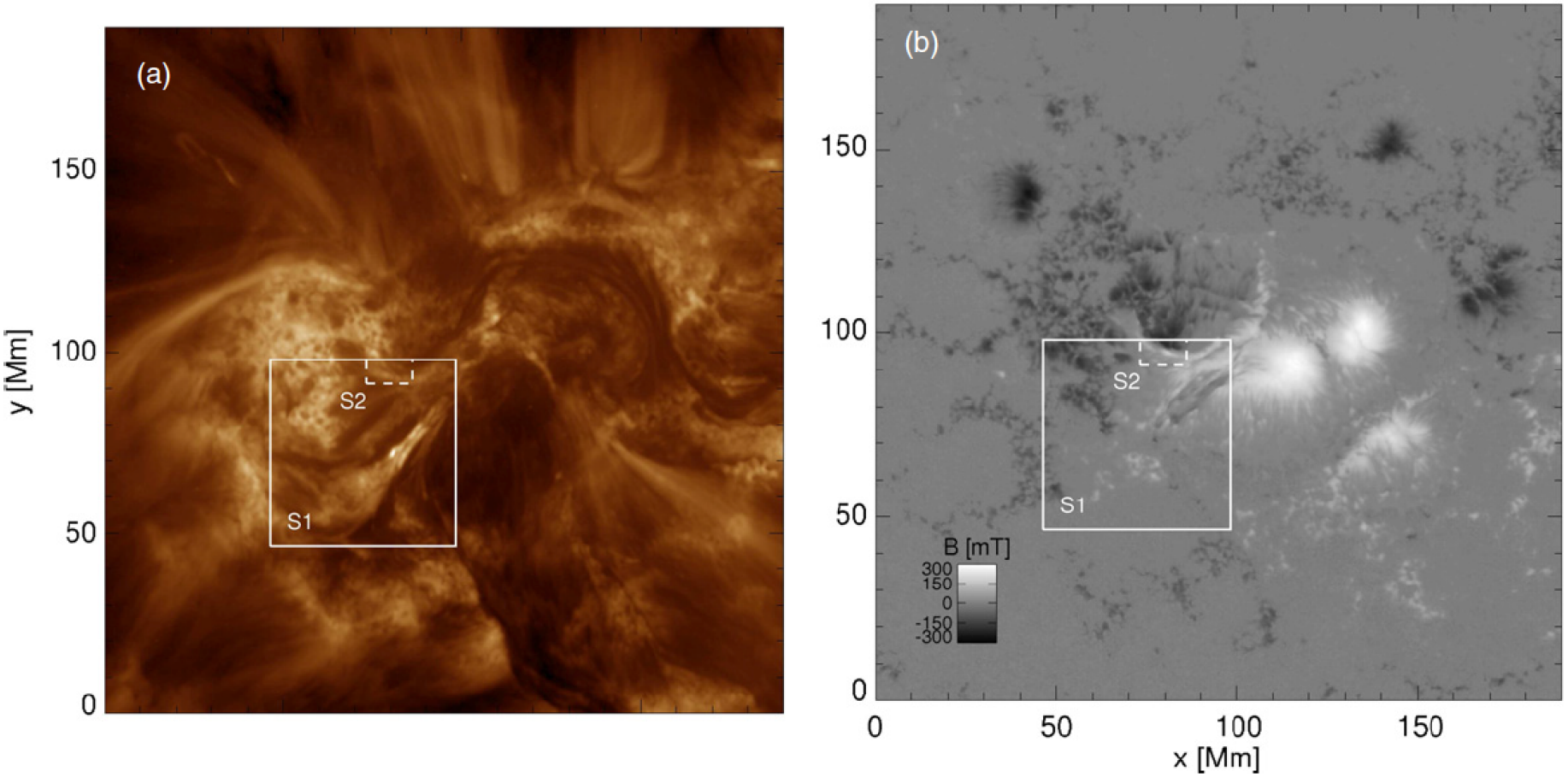
- radius of structure = 435 km.

To obtain observed Hi-C intensity, we need:

- Density = 1.15 x 10^{10} cm^{-3}

Additional analysis is being completed by Brooks and collaborators.

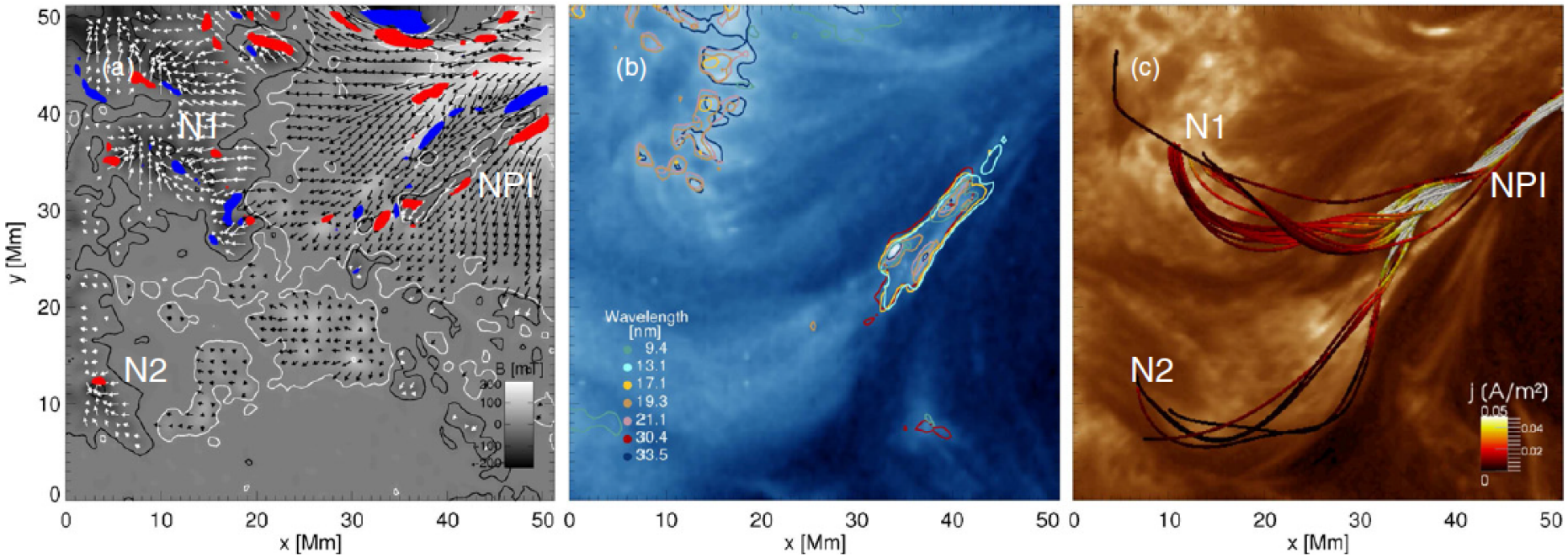
Component Reconnection



Thalmann et al (2014) have looked at the magnetic field in the vicinity of this region.

Thalmann et al, ApJ, 2014

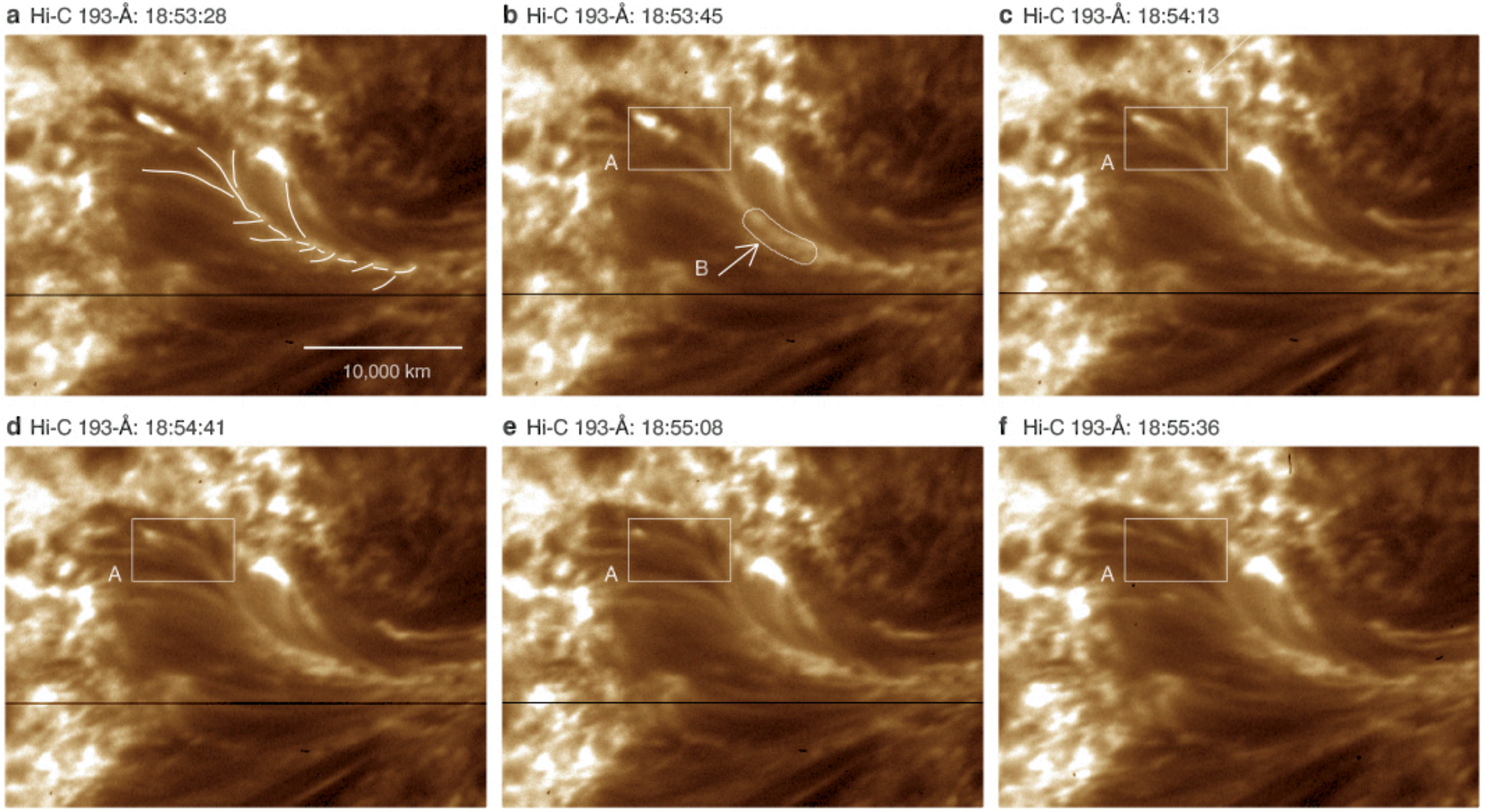
Component Reconnection



They use the HMI vector field map to extrapolate the NLFF field. They find evidence for braiding of the field.

Thalmann et al, ApJ, 2014

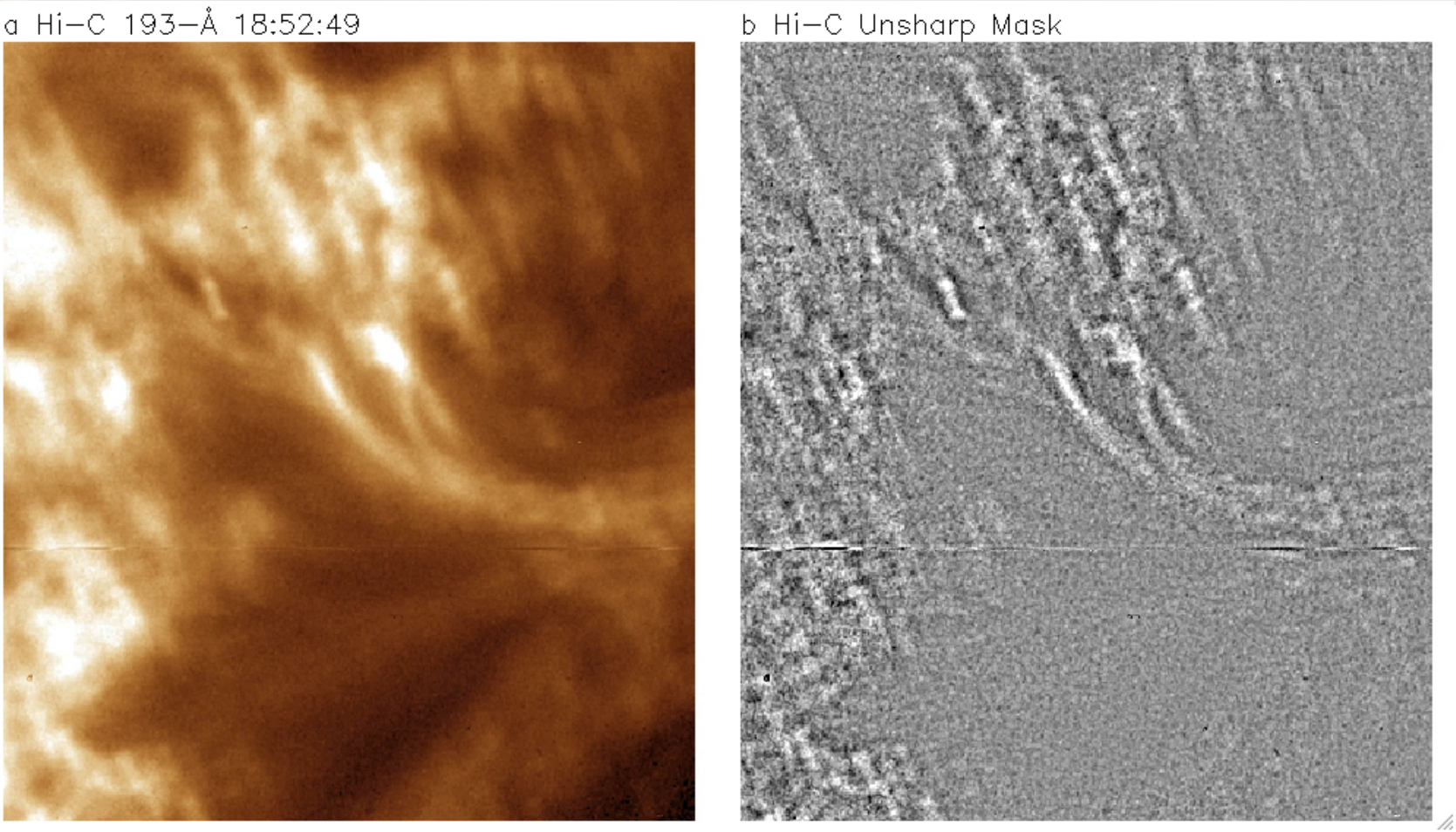
Braided Loop



Multiple strands join into this structure. It appears to unwind during Hi-C observations.

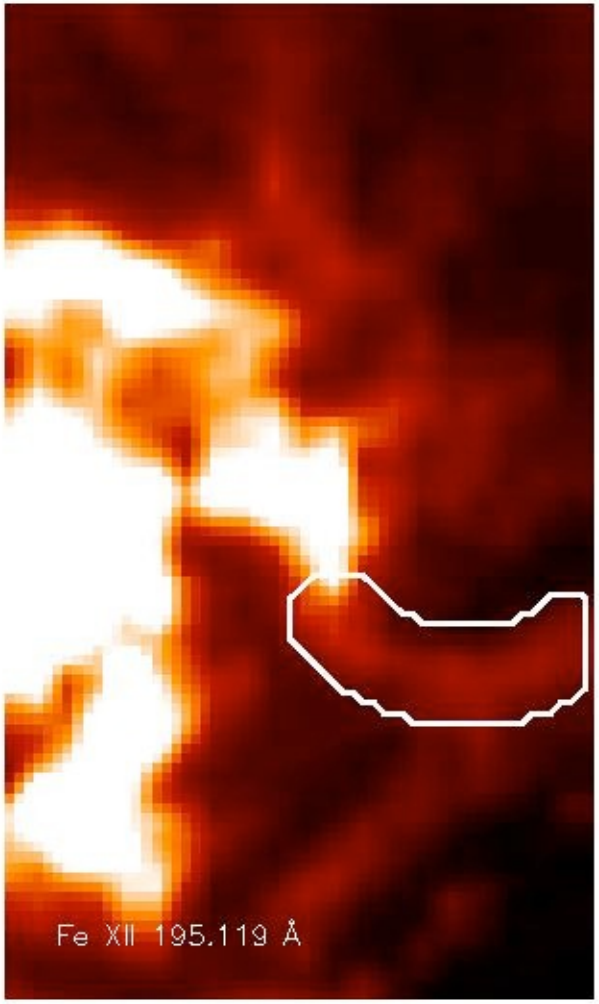
Cirtain et al, 2013, Nature

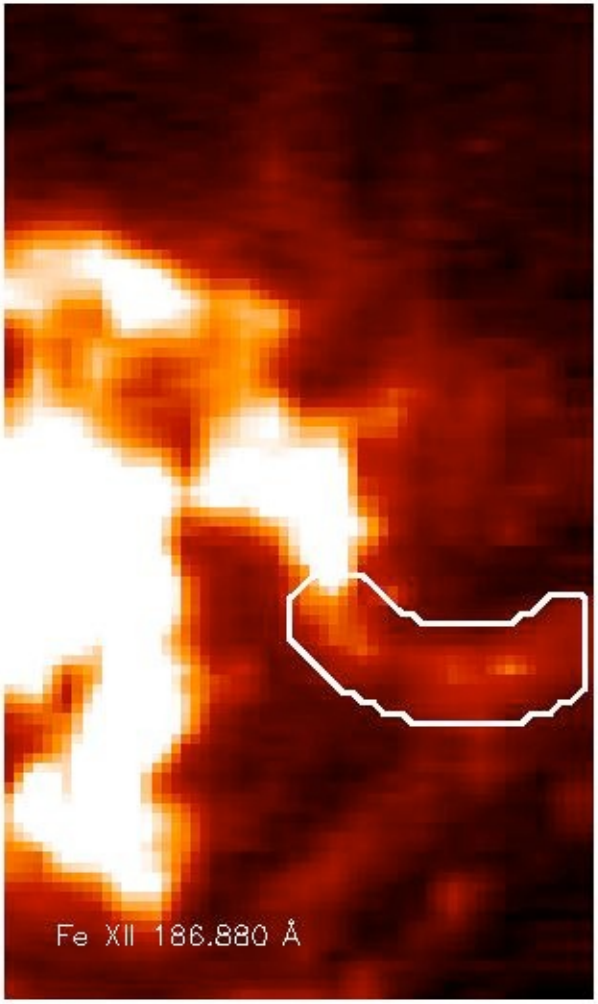
Braided Loop

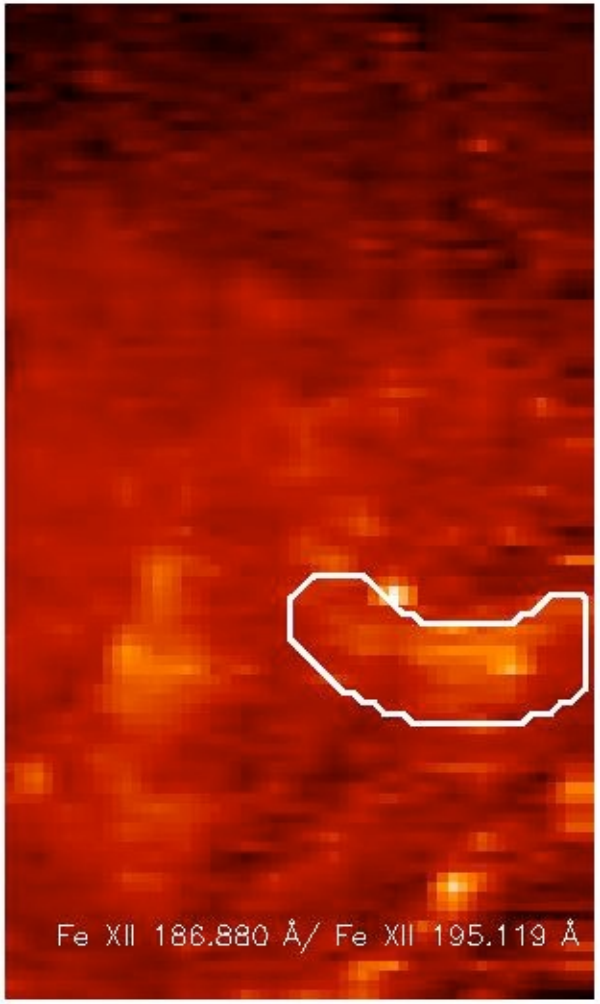


Cirtain et al, 2013, Nature

Braided Loop

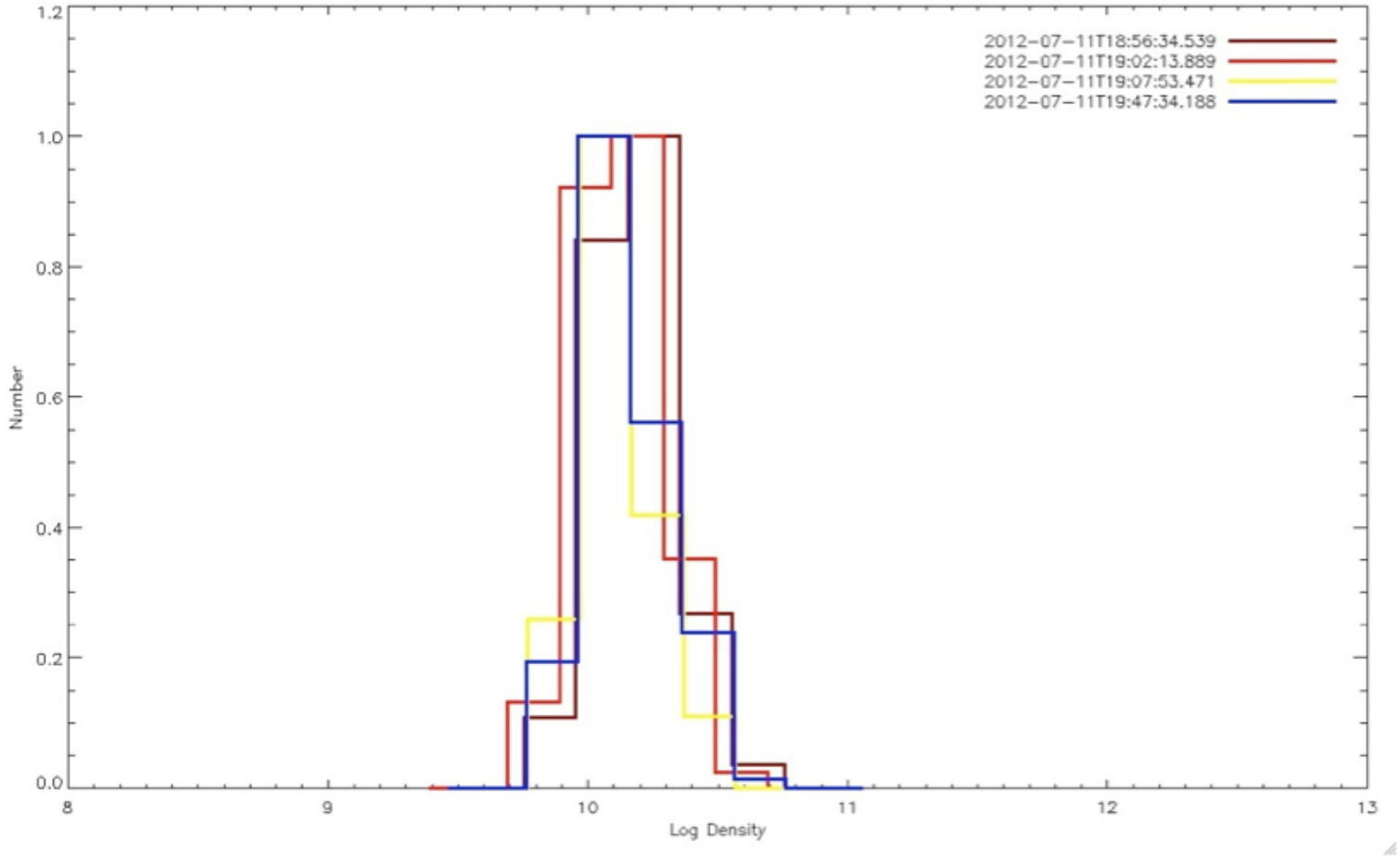






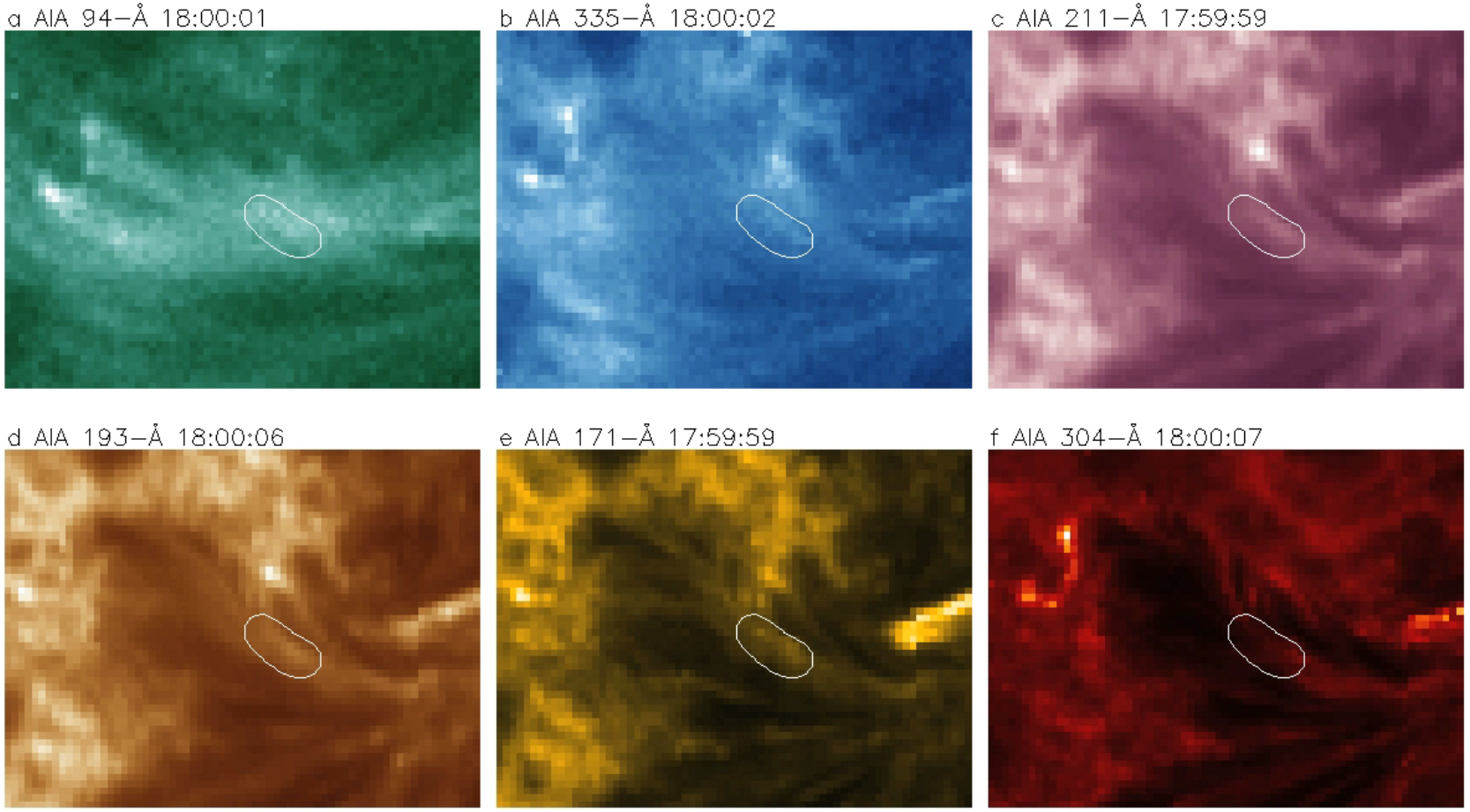
Intensities + ratios suggests small filling factor.

Braided Loop



Unlike other loop, densities remain constant over time.

Braided Loop



Loop involved in heating event prior to Hi-C flight.

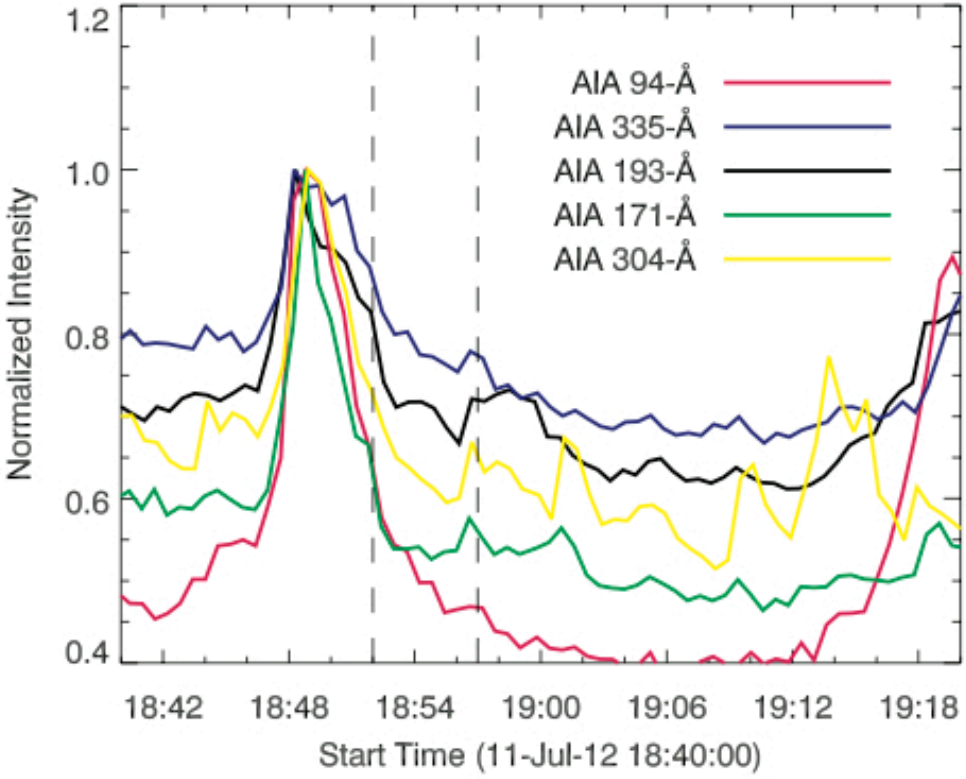
Cirtain et al, 2013, Nature

Braided Loop

Hi-C observed the loop in decline after heating event.

B_ϕ ~ *100G*
V ~ 10^{11} km^3
$(B_\phi)^2 V/8\pi = 10^{29}$ ergs

Note: From EIS and AIA data an estimate of the radiated power loss is ~ 10^{26} ergs sec^{-1}



Cirtain et al, 2013, Nature

Braided Loop

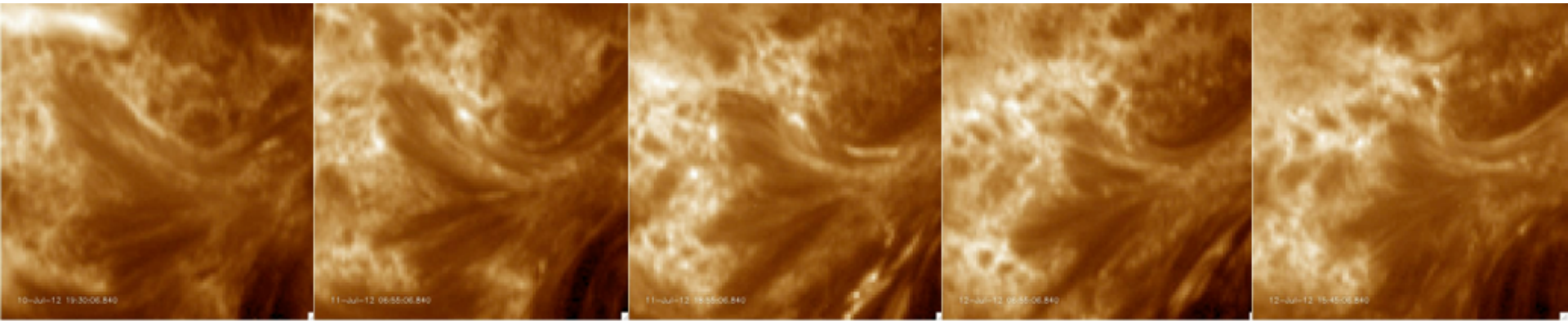
Physical Measurement	Cirtain et al 2013	Wilmot-Smith et al 2011
Event duration	~730 sec	~500 sec
Peak temperature	~5 MK	2.5-4 MK
Flow velocity	~150 km sec^{-1}	~600 km sec^{-1}
Axial Field strength	~100G	~10 G
Plasma density	~10^{10} cm^{-3}	~10^{10} cm^{-3}
Energy release	10^{26} ergs	10^{25} ergs

Braided Loop

- 1 day

Hi-C Flight Time

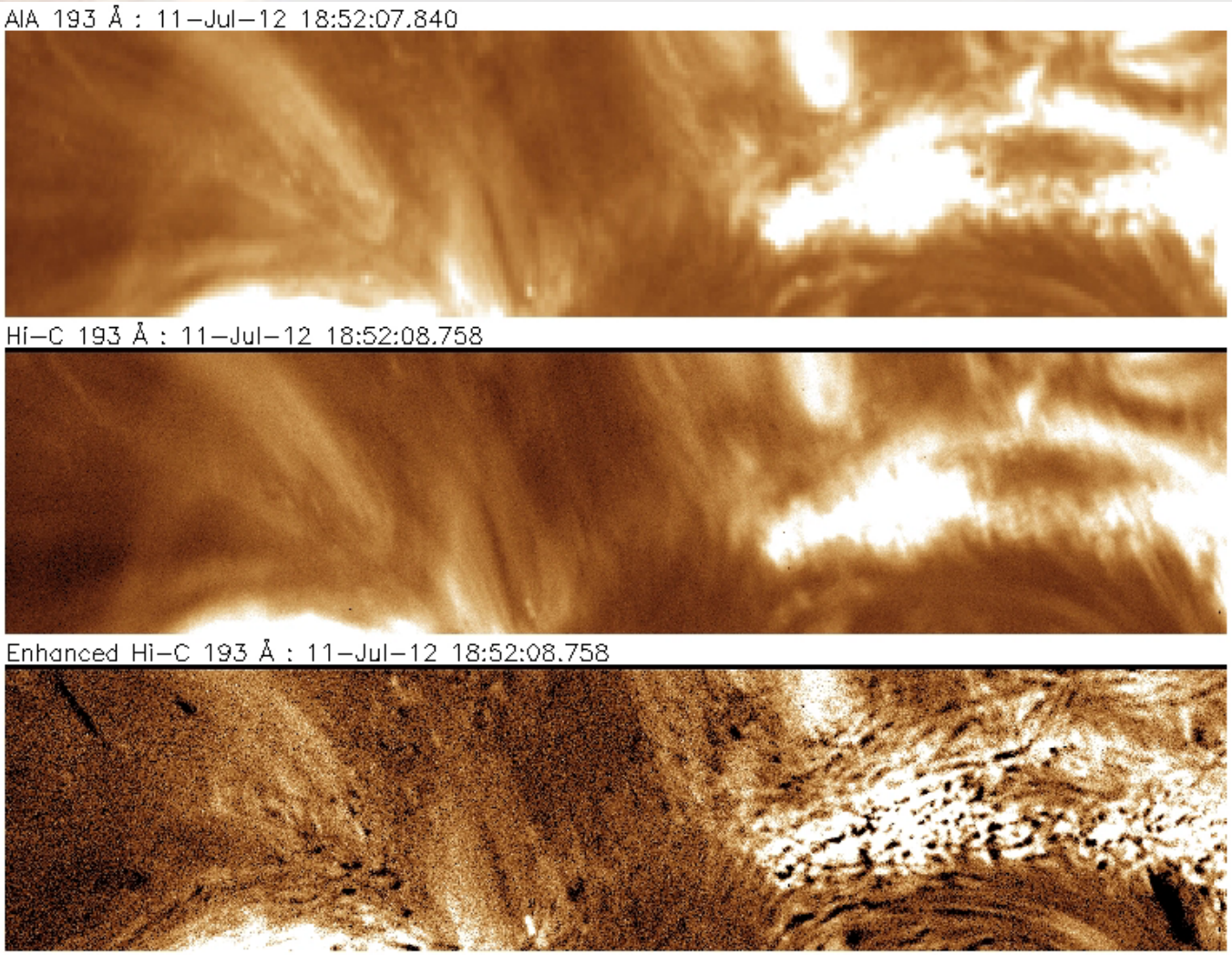
+ 1 day



This is a long lived structure and is evident +- 24 hours from the Hi-C flight.

We are now looking at the evolution of the structure in AIA and HMI to understand better its evolution.

“Dots”

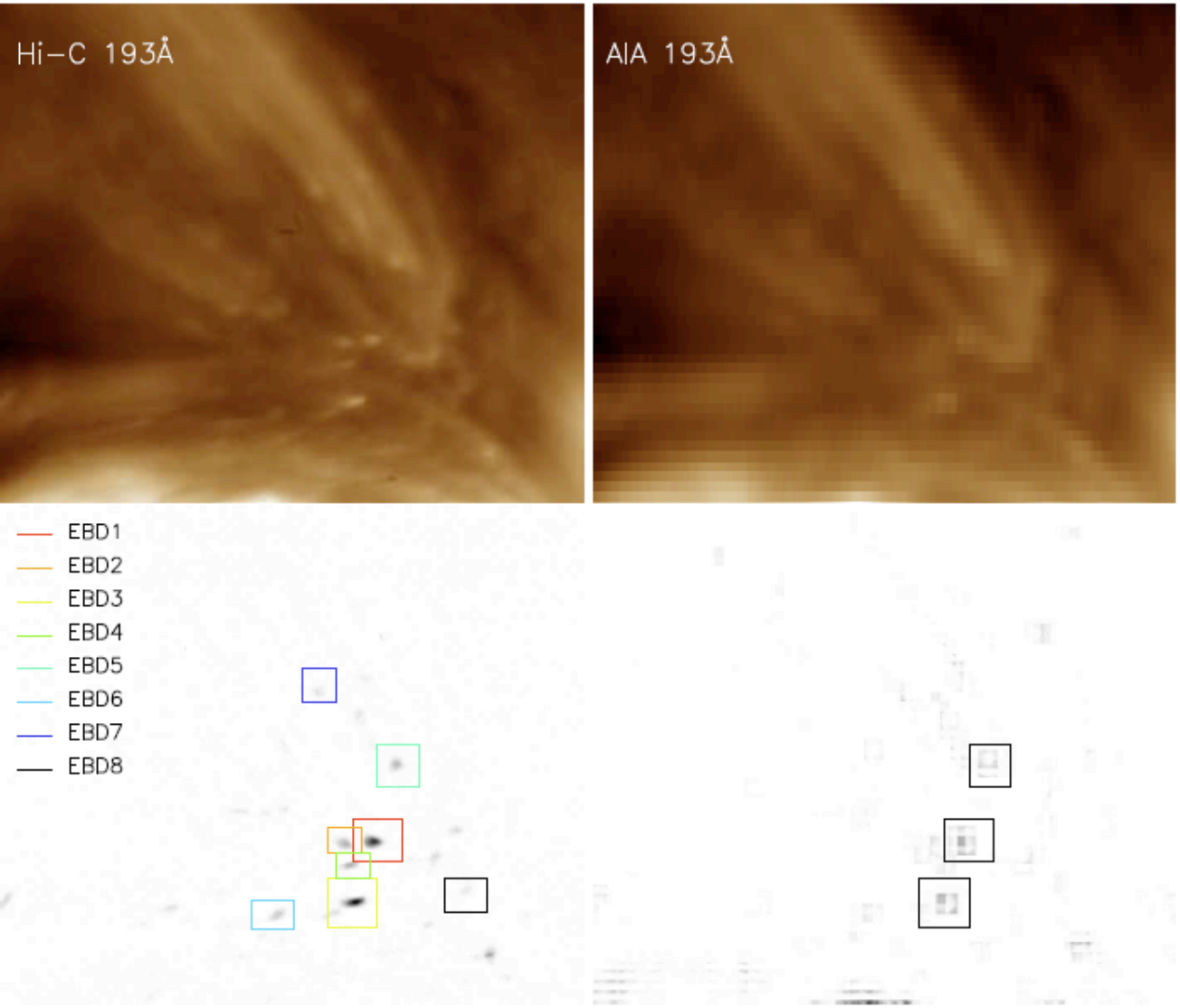


``Dots'' are small-scale, short-lived brightenings that occur at the periphery of the active region.

They may be associated with open fields.

Regnier, et al. (2014) ApJ

“Dots”



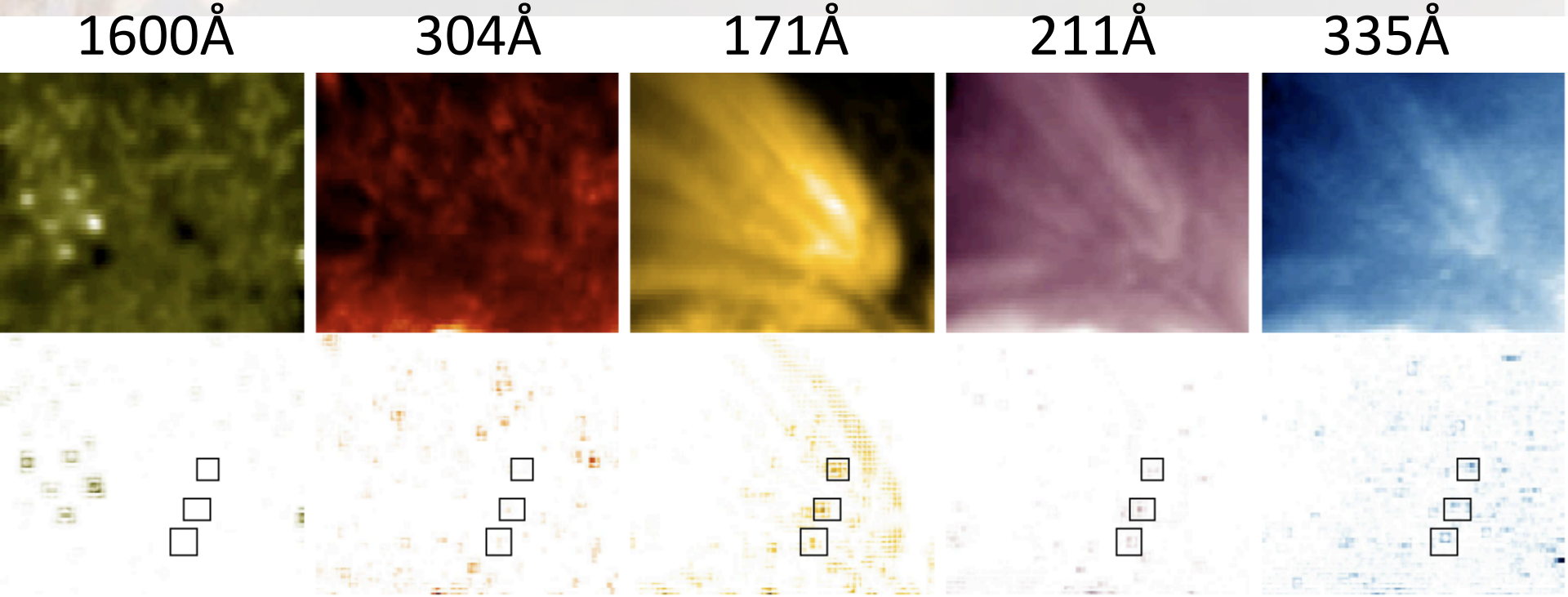
A filtering technique is used to determine locations of dots.

8 dots are identified in Hi-C data with this method.

3 dots are found in AIA 193 data.

Regnier, et al. (2014) ApJ

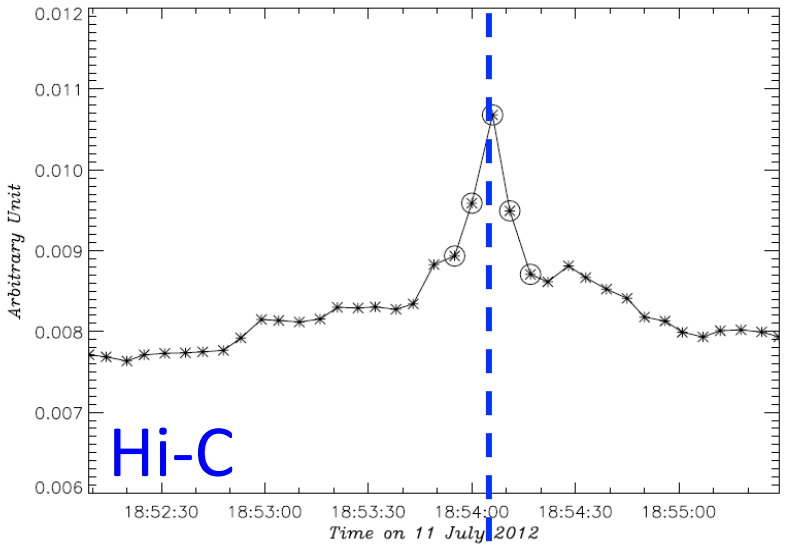
“Dots”

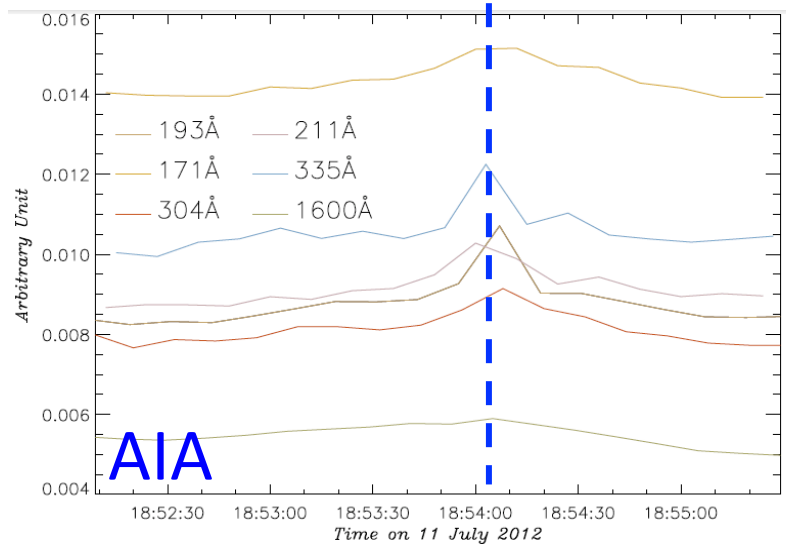


Some of these dots are observed in other AIA passbands.

Regnier, et al. (2014) ApJ

“Dots”

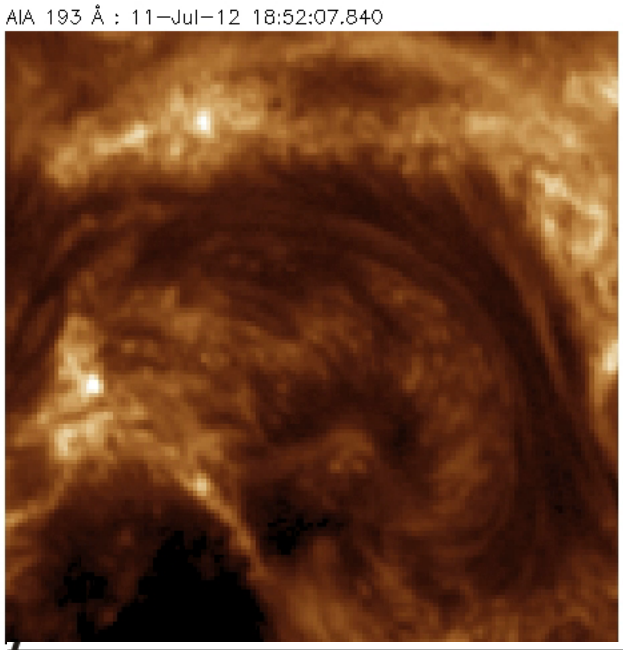


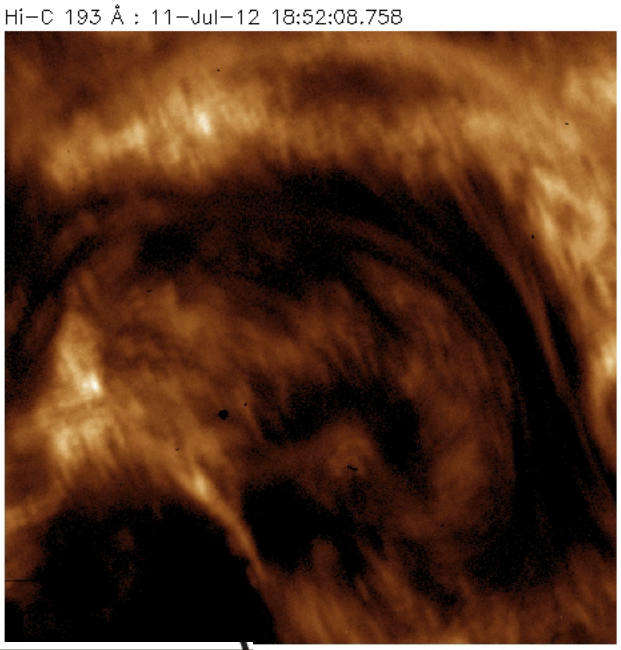


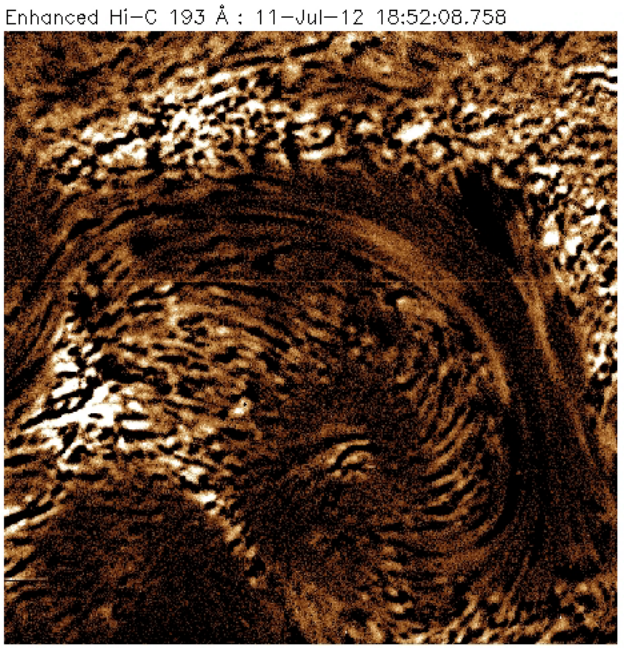
- Dots generally appear in only one AIA image, but several Hi-C images.
- Characteristic duration of 25s
- Characteristic length of 680 km (<1’’)
- Not fully spatially or temporally resolved in SDO/AIA

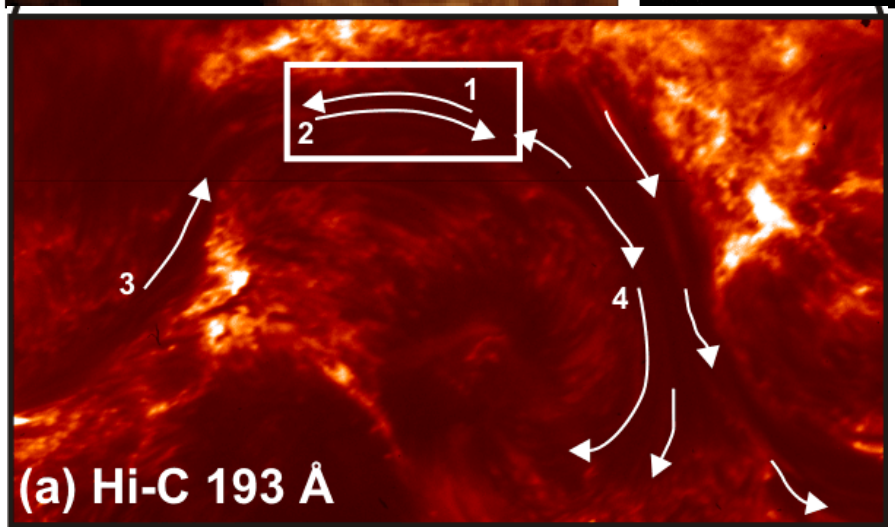
Regnier, et al. (2014) ApJ

Bi-directional Flows in Filaments





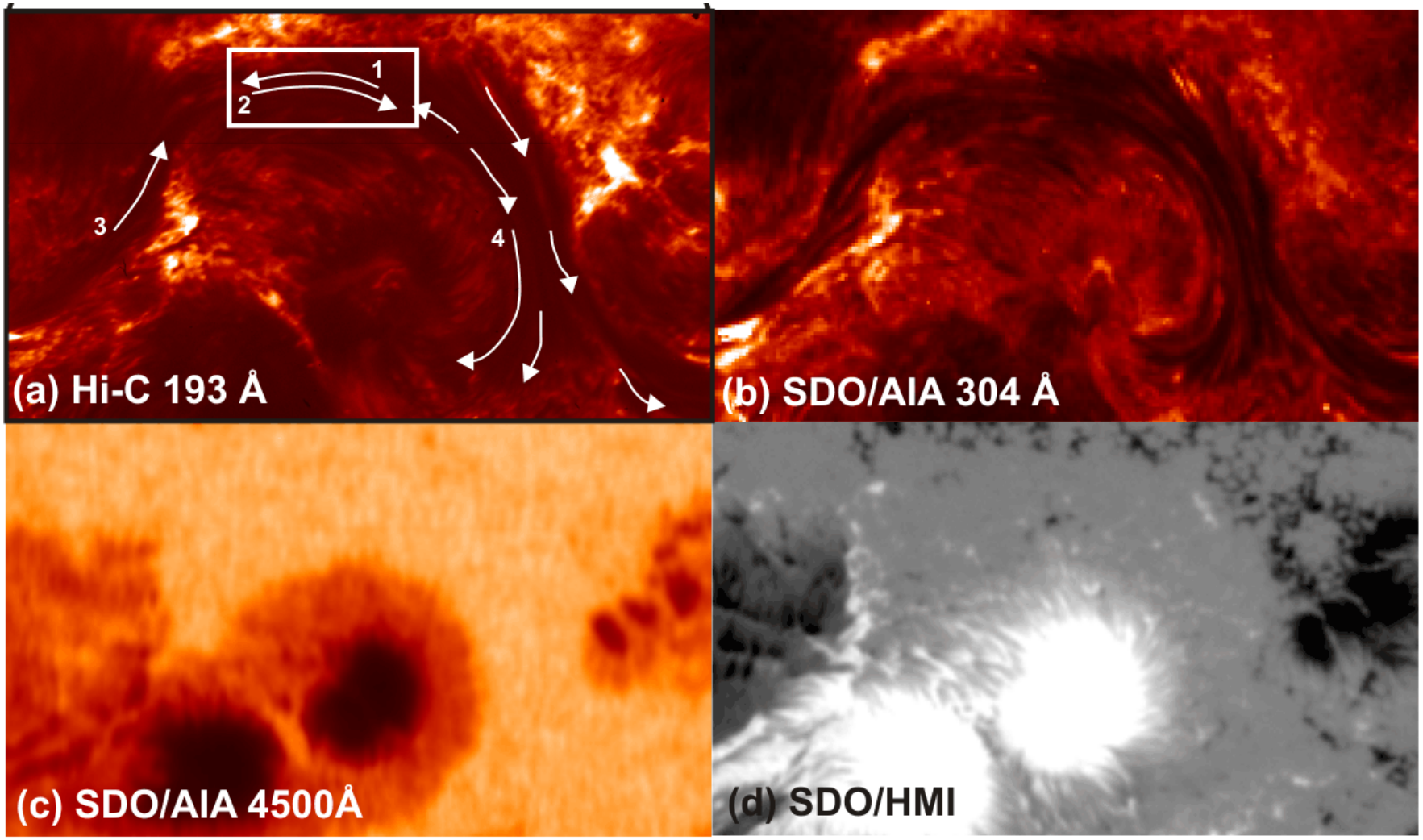




Hi-C observed bi-directional flows in a filament. This is the first observations of such flows in the EUV channel.

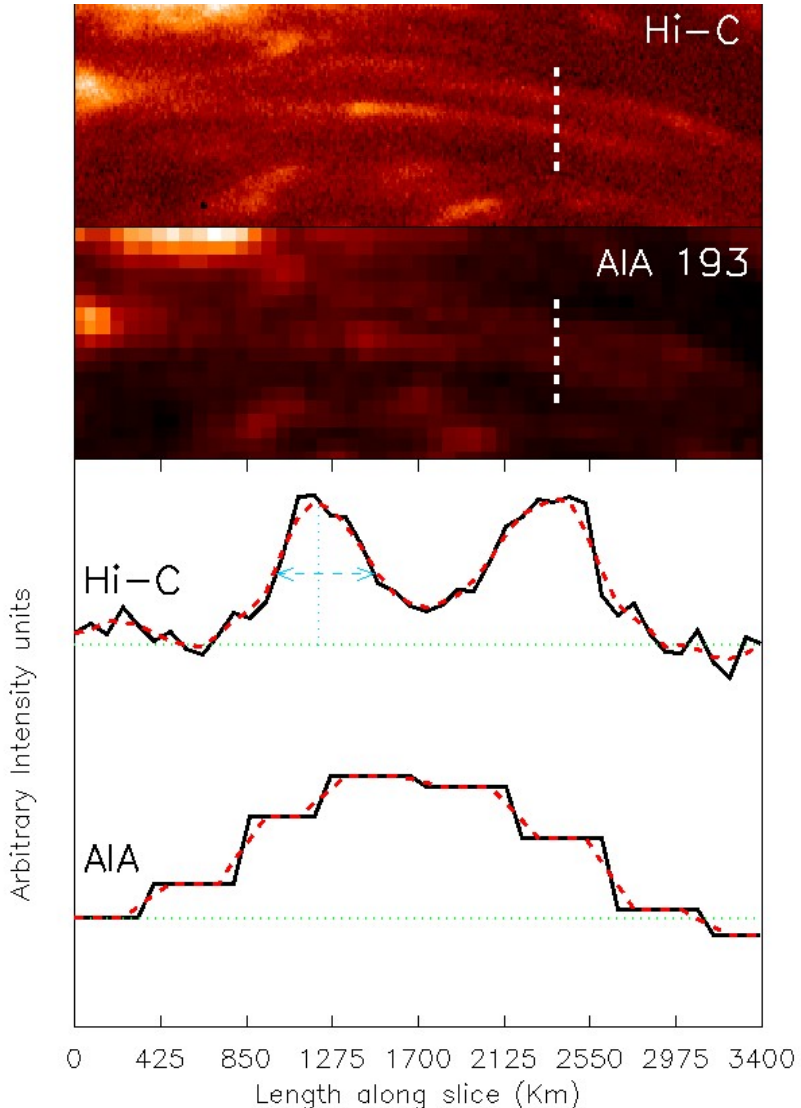
Alexander, et al. 2013, ApJ

Bi-directional Flows in Filaments



Alexander, et al. 2013, ApJ

Bi-directional Flows in Filaments

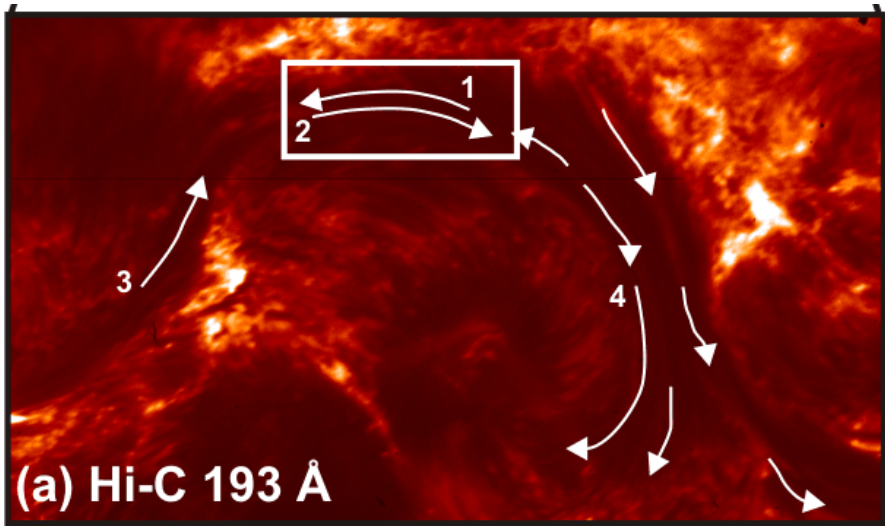


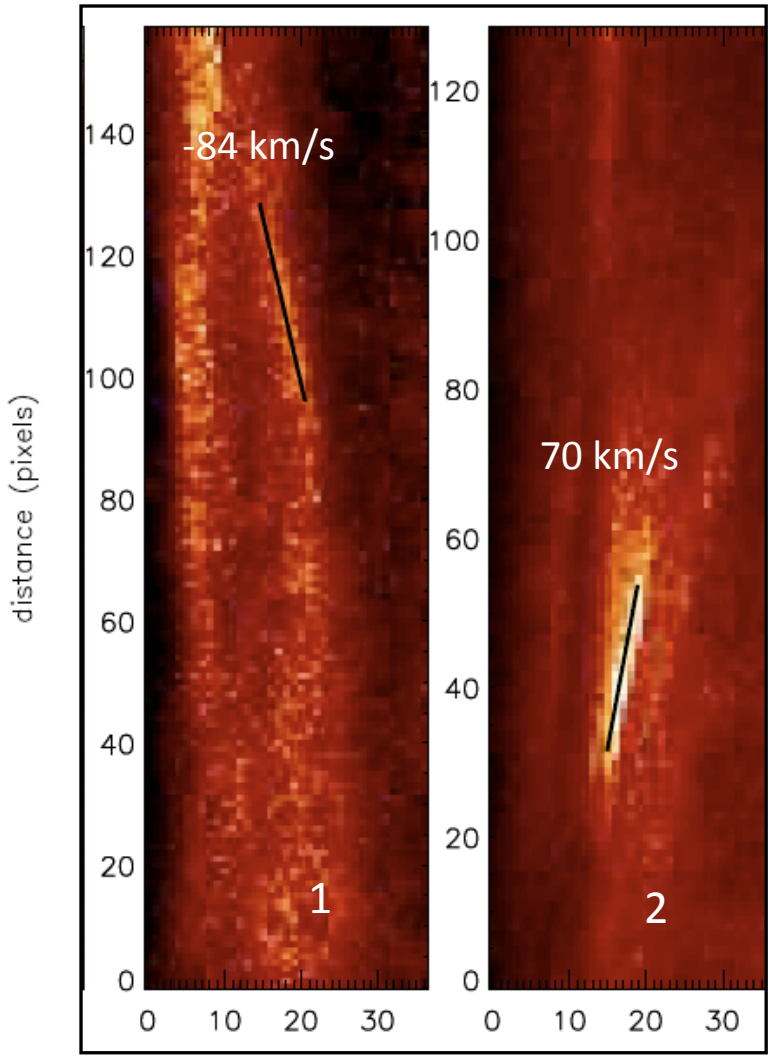
- Hi-C resolves two structures roughly 0.8” wide
- AIA sees only a single structure.

Alexander, et al. 2013, ApJ

Bi-directional Flows in Filaments

Velocities of Flows 1 and 2 are roughly equal and in opposite directions.

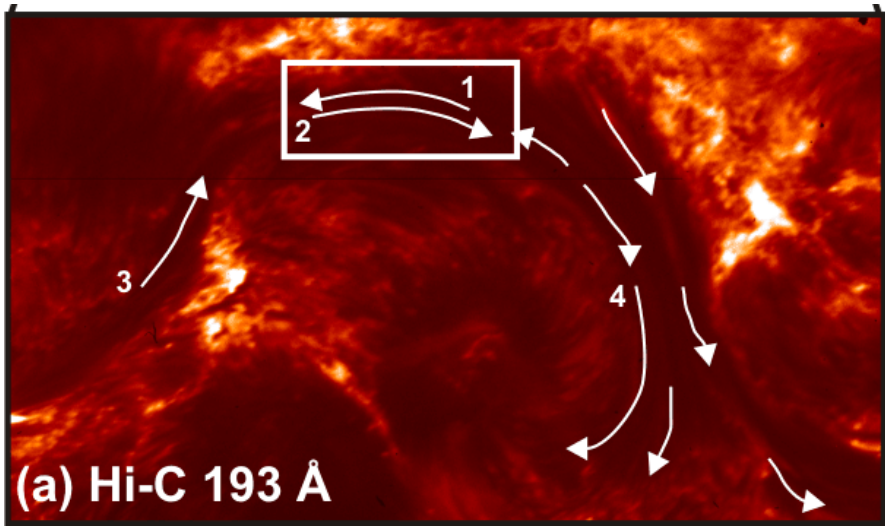


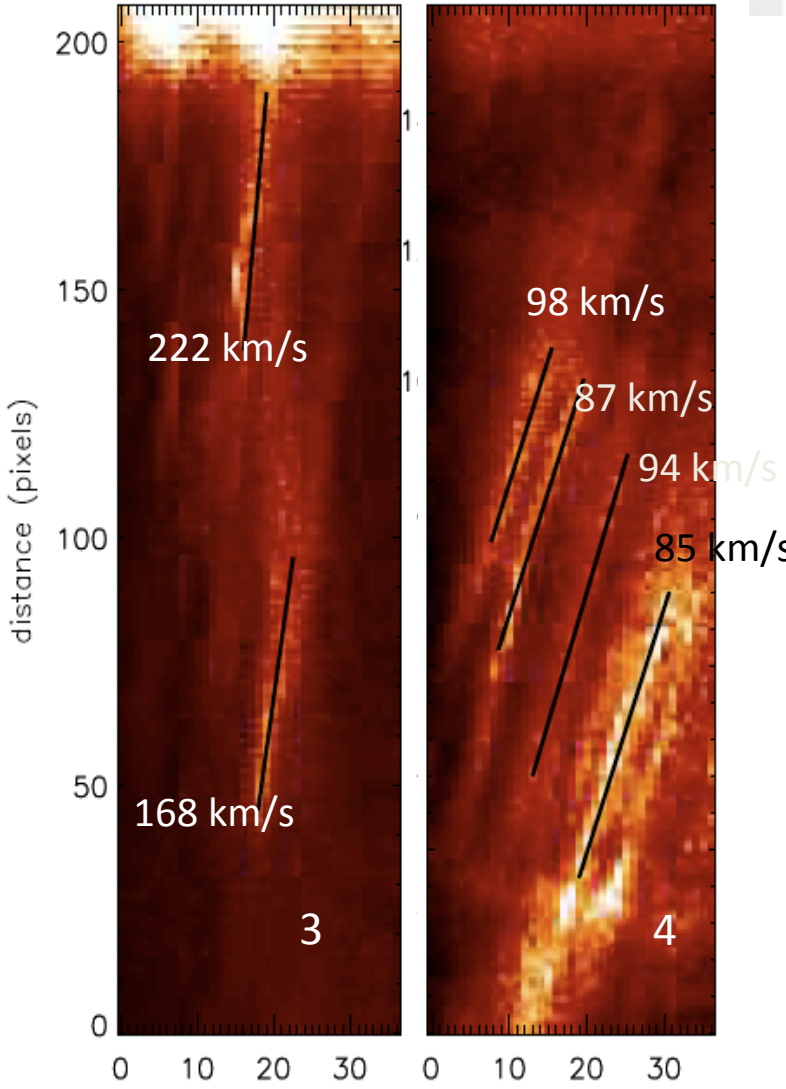


Alexander, et al. 2013, ApJ

Bi-directional Flows in Filaments

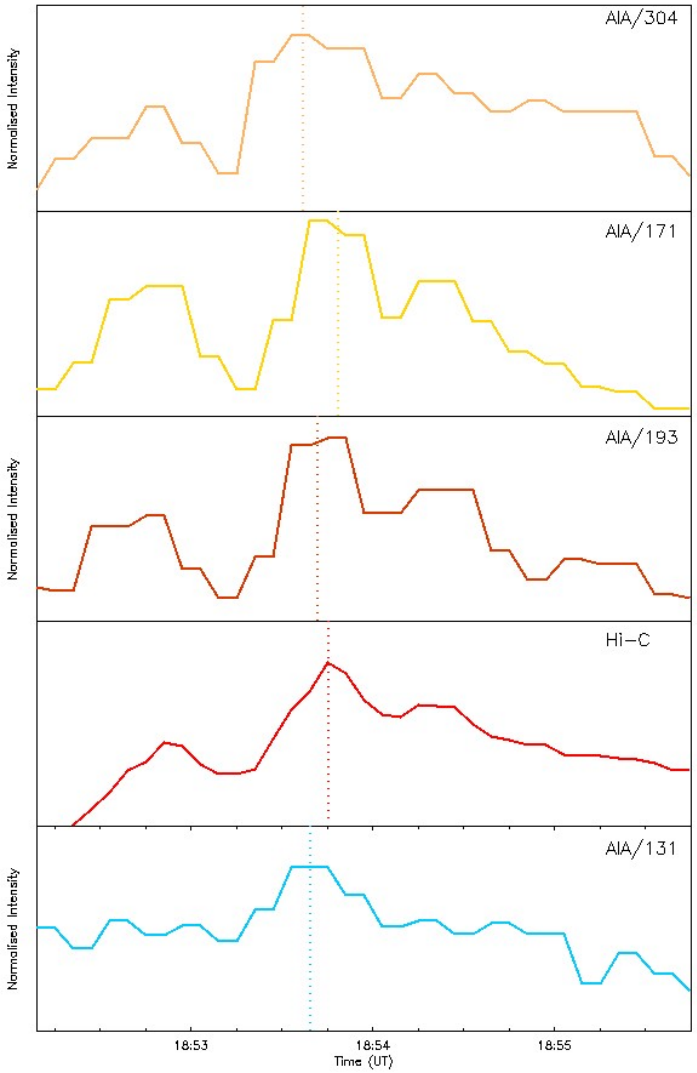
Velocities of Flows 3 is > 150 km/s and Region 4 shows period flows of ~100 km/s.



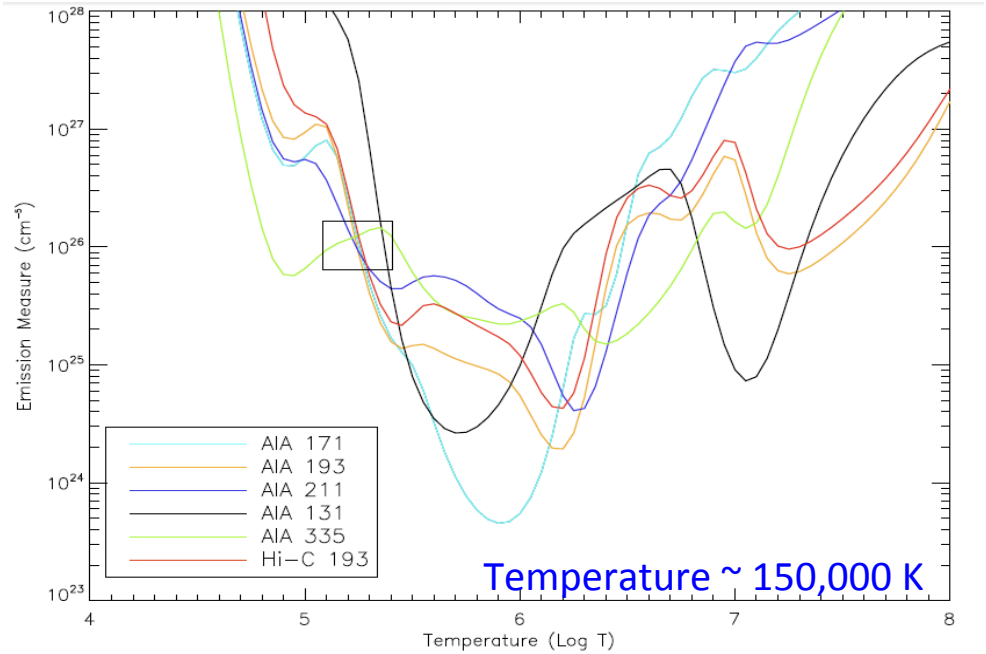


Alexander, et al. 2013, ApJ

Bi-directional Flows in Filaments

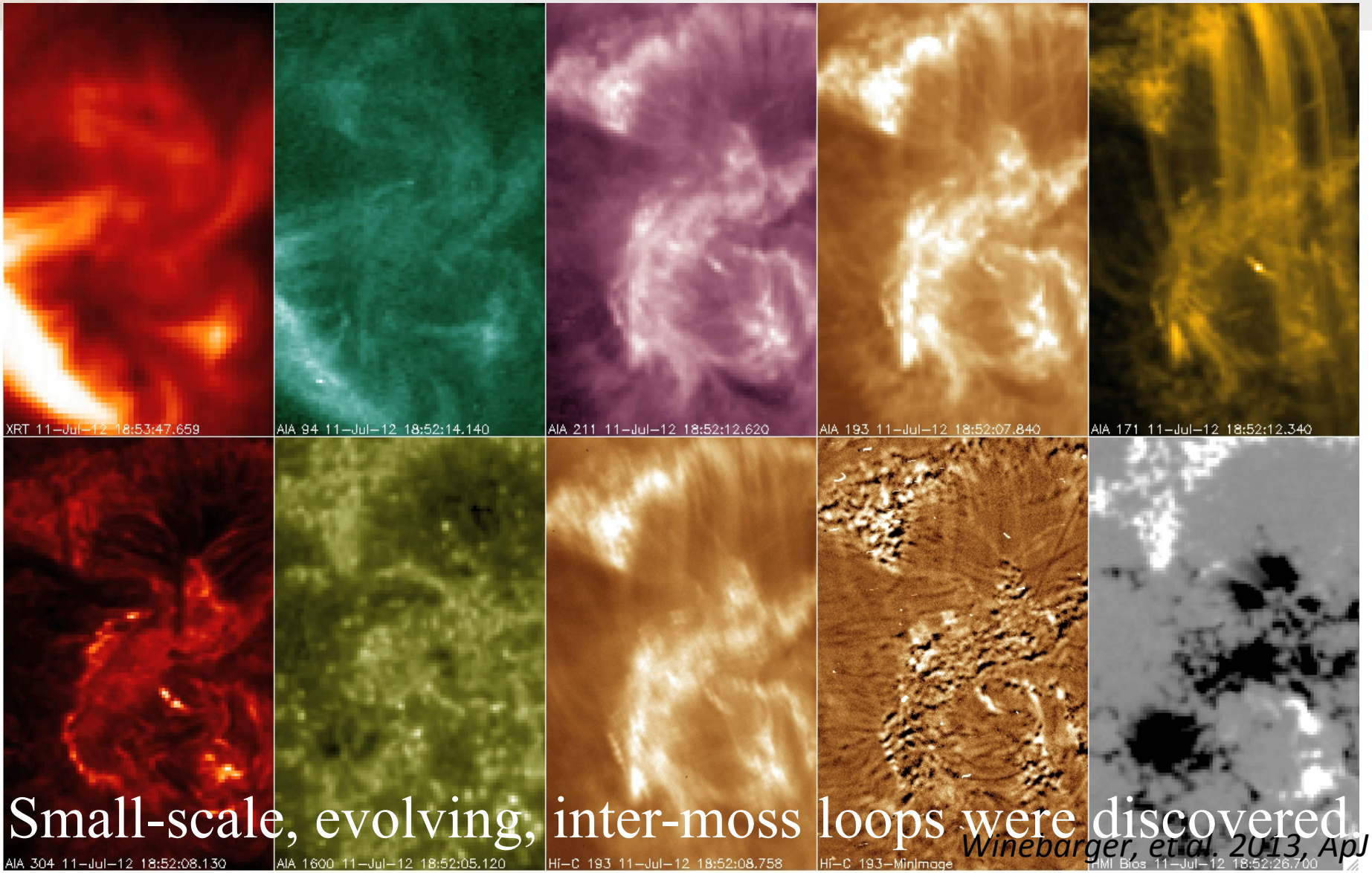


Light curves and EM Loci plots indicate the plasma is at an isothermal, cool temperature.



Alexander, et al. 2013, ApJ

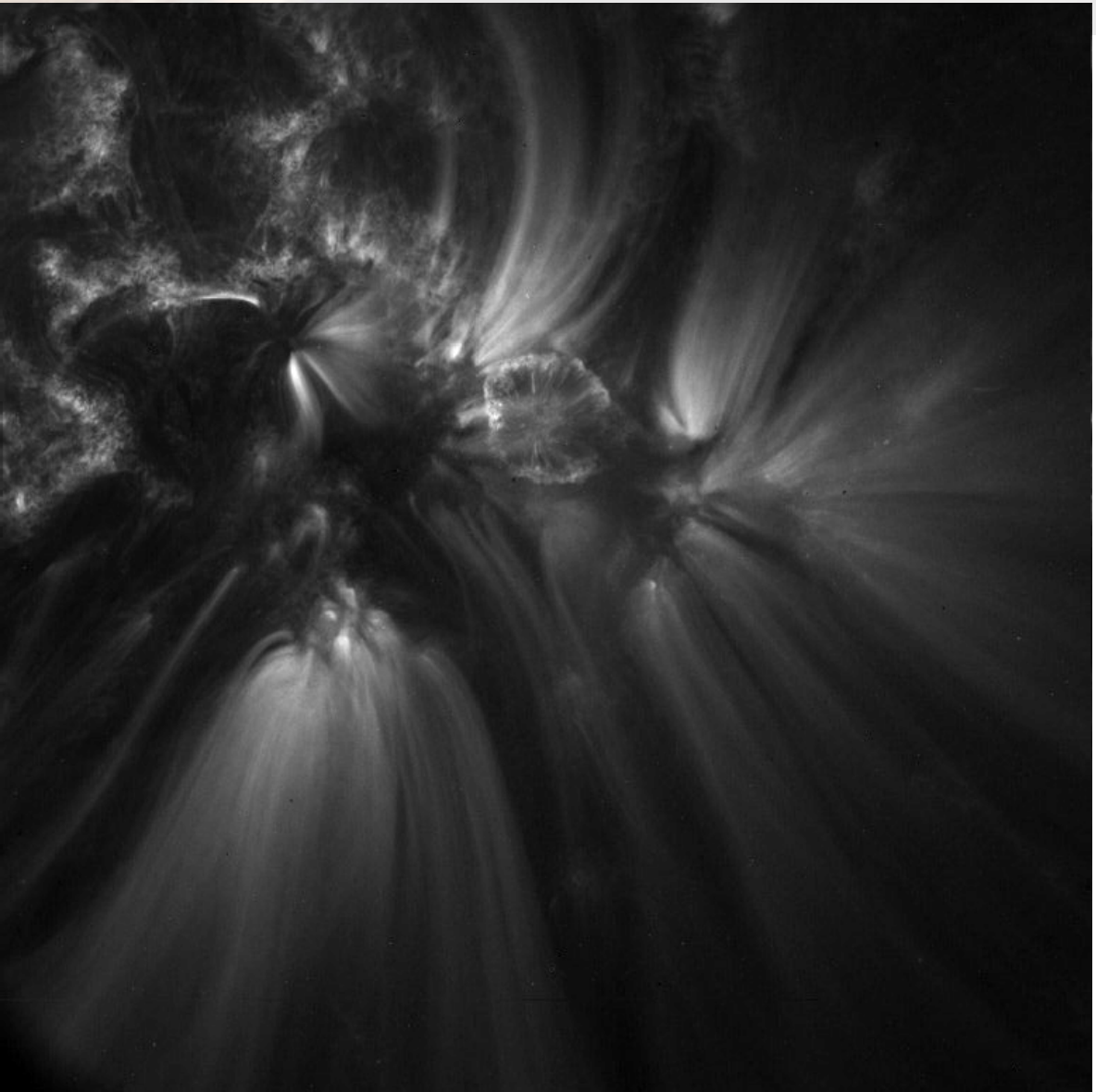
Transition Region Loops



Small-scale, evolving, inter-moss loops were discovered.

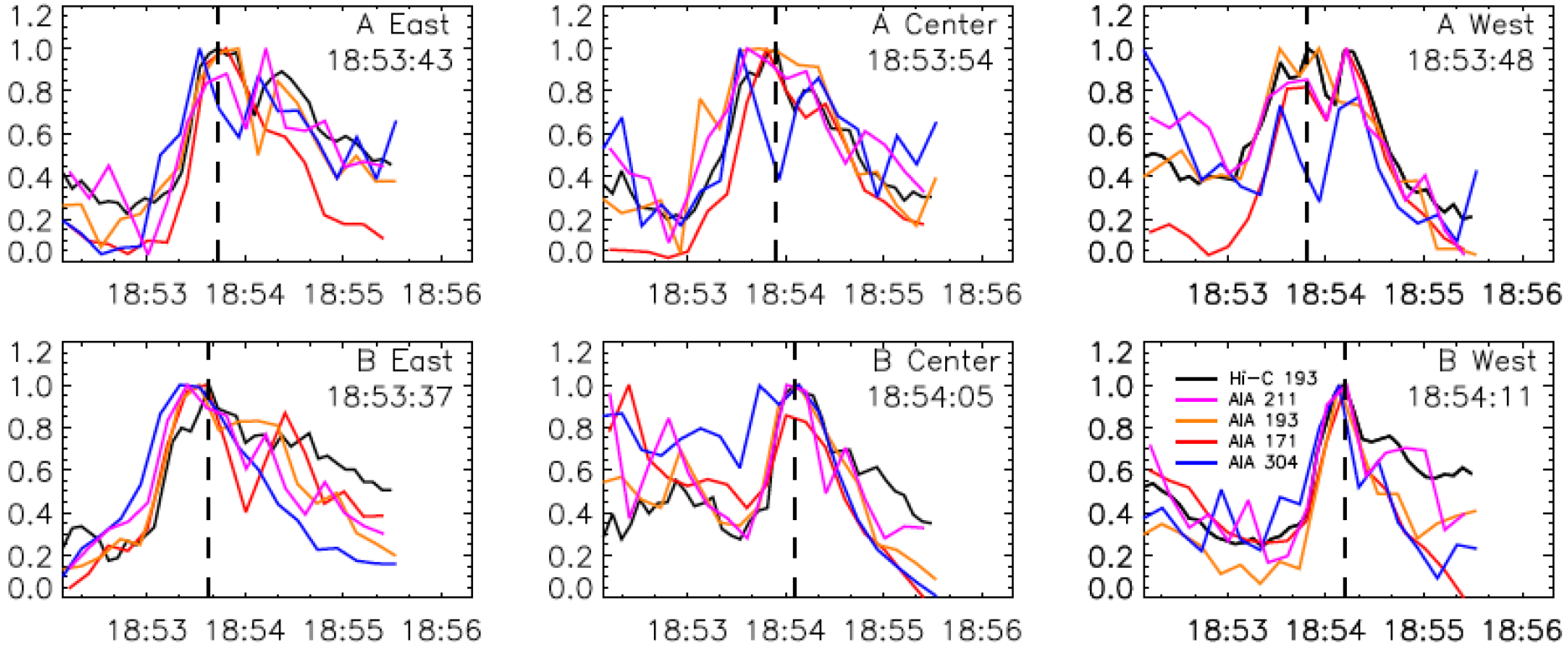
Winebarger, et al. 2013, ApJ

Transition Region Loops



TRACE saw "flashes" between moss regions. Due to low cadence, these would sometimes show up in a single frame.

Transition Region Loops



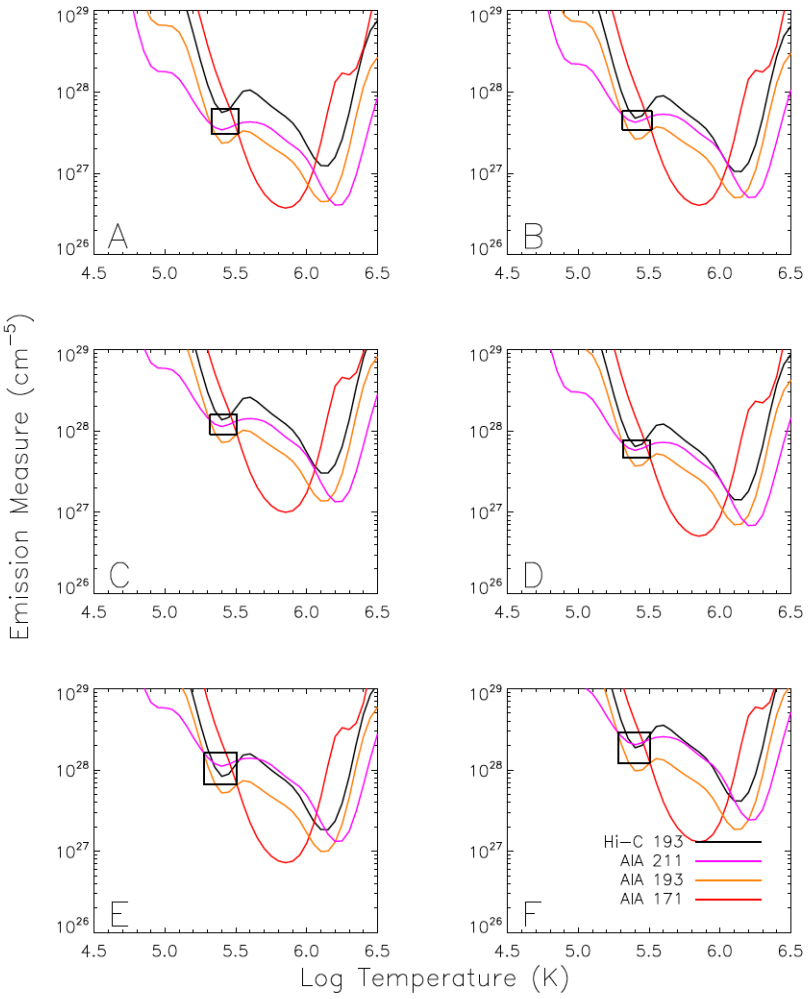
Loops appear simultaneously in all AIA channels, not sequentially like cooling loops. Loop lifetimes are ~60s.

Winebarger, et al. 2013, ApJ

Transition Region Loops

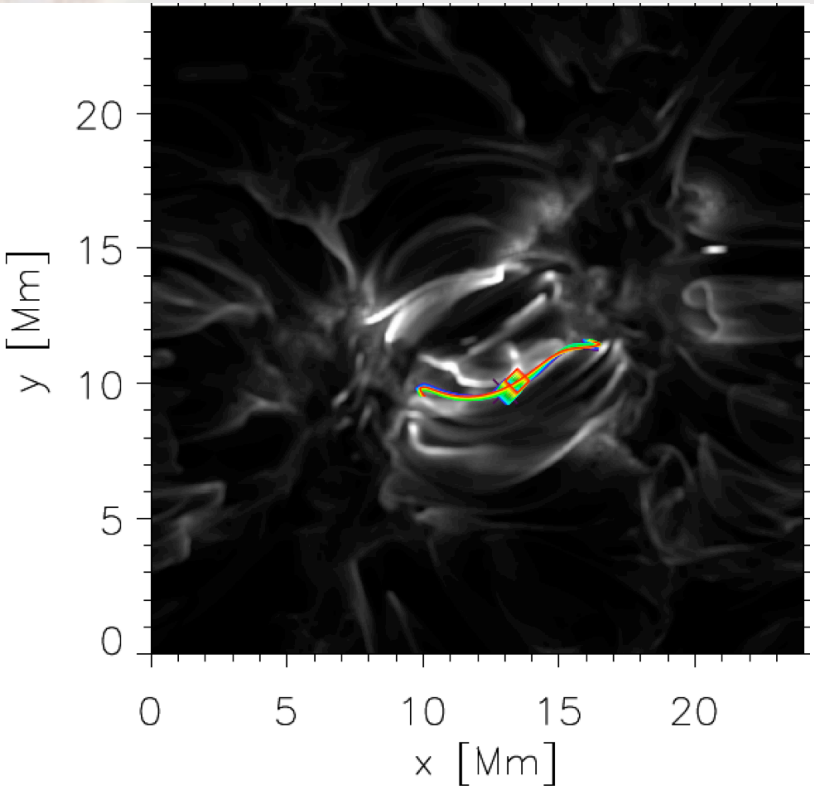
Loop	Log T	Log EM	Log n_e	Log Energy (ergs)
A	5.42± 0.10	27.64± 0.16	9.94± 0.08	24.3
B	5.41± 0.10	27.65± 0.12	9.90± 0.06	24.6
C	5.41± 0.10	28.08± 0.12	10.11± 0.06	24.7
D	5.41± 0.10	27.78± 0.11	9.94± 0.06	24.7
E	5.39± 0.12	28.01± 0.19	10.06± 0.10	24.8
F	5.39± 0.11	28.28± 0.19	10.21± 0.10	24.8

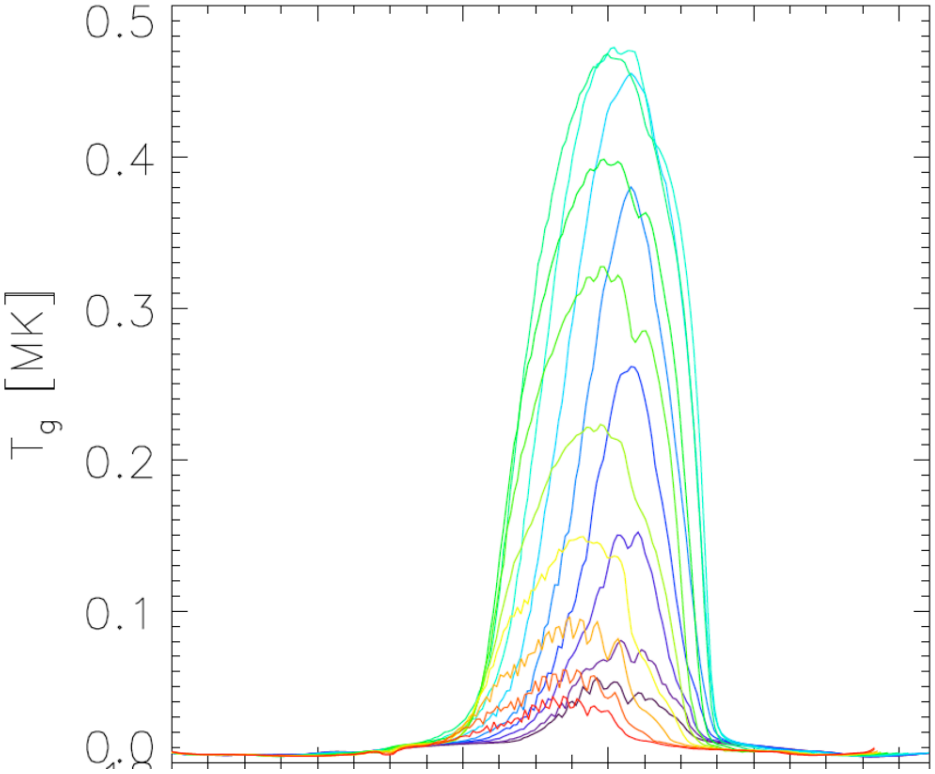
- Because loops evolve identically in multiple AIA filters, we conclude the loops are isothermal.
- EM Loci analysis indicate a cool (300,000 K) temperature.
- Density estimates are 7-10 x 10^9 cm^{-3}.
- Energy estimates are ~10^{24} ergs.



Winebarger, et al. 2013, ApJ

Transition Region Loops



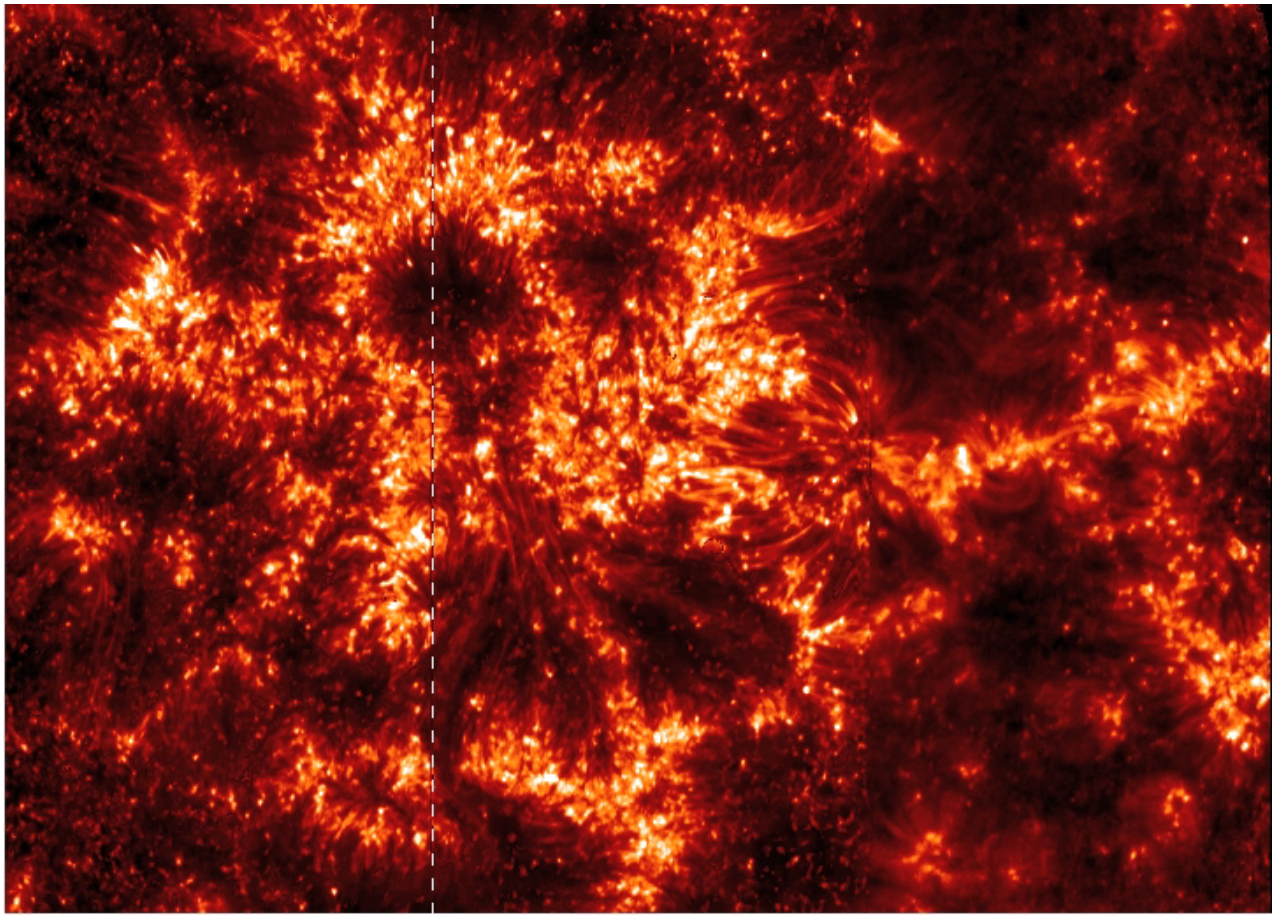


Common in Bifrost simulations.
Occur because of low-lying braided field.

Winebarger, et al. 2013, ApJ

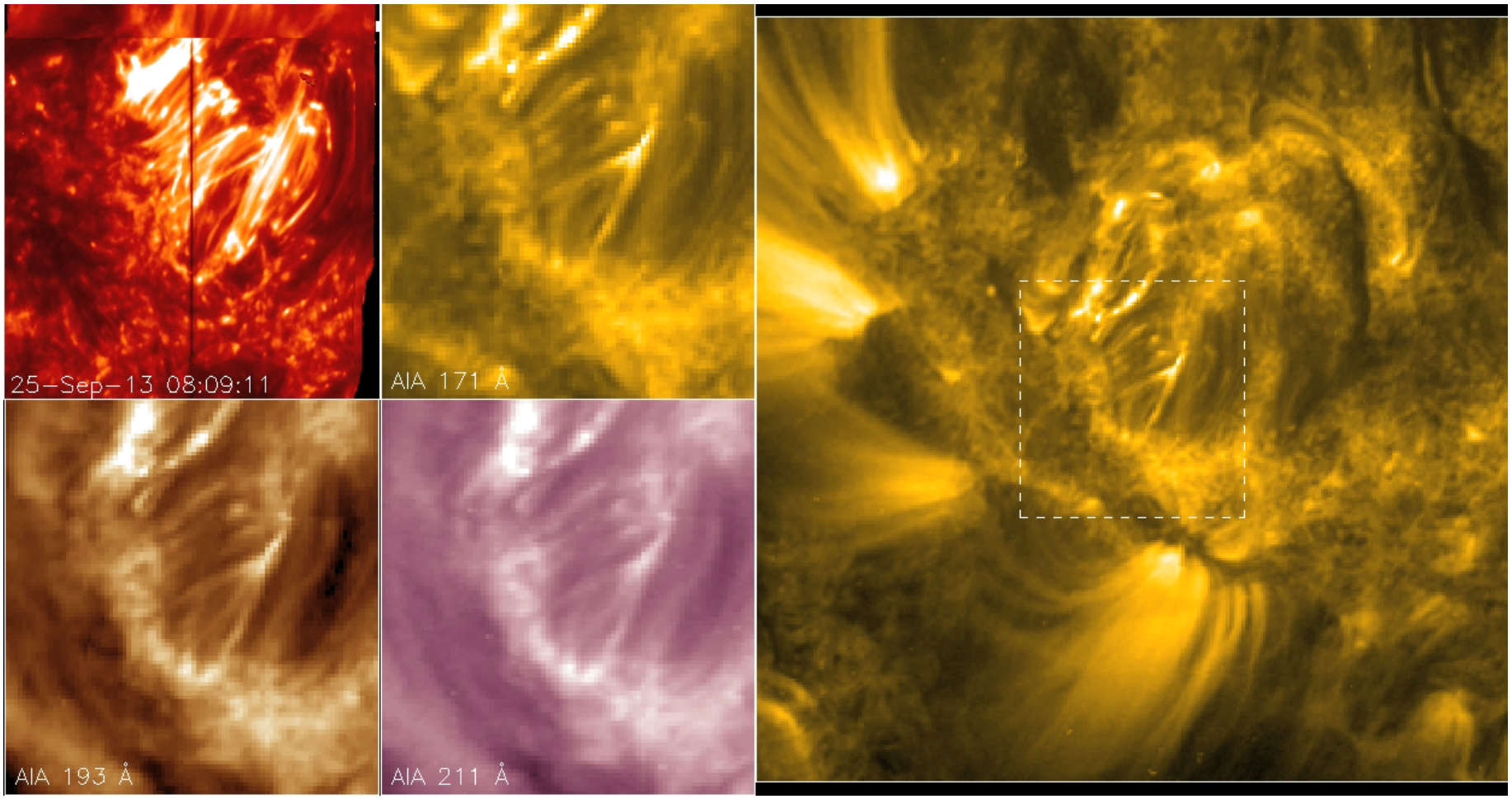
Transition Region Loops

If these are TR phenomenon, we should see them in IRIS.



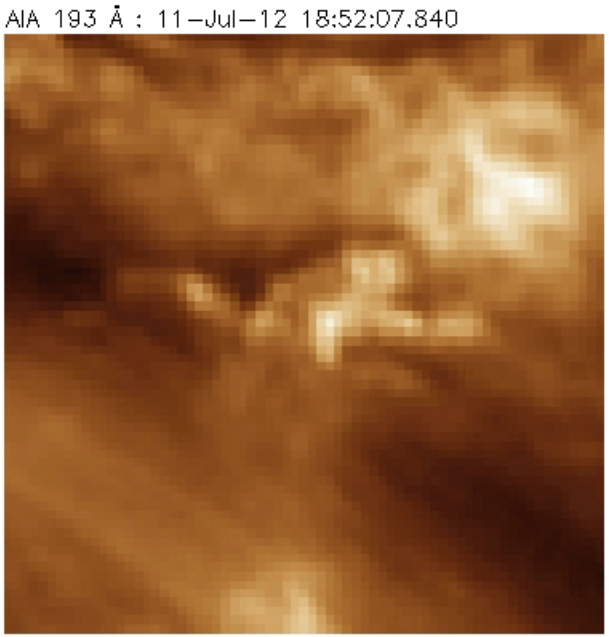
Winebarger, et al. in prep

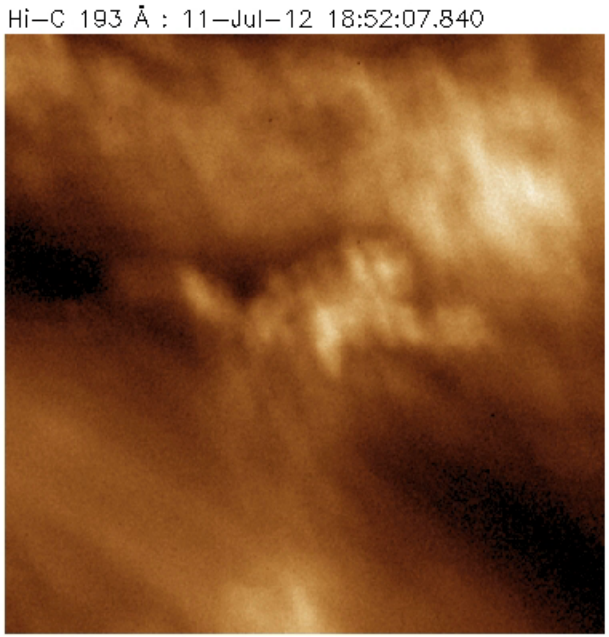
Transition Region Loops

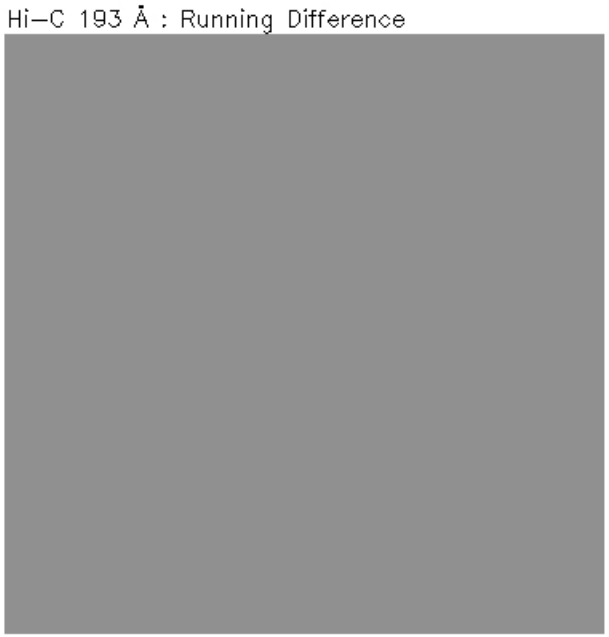


Winebarger, et al., in prep

Dynamic Moss



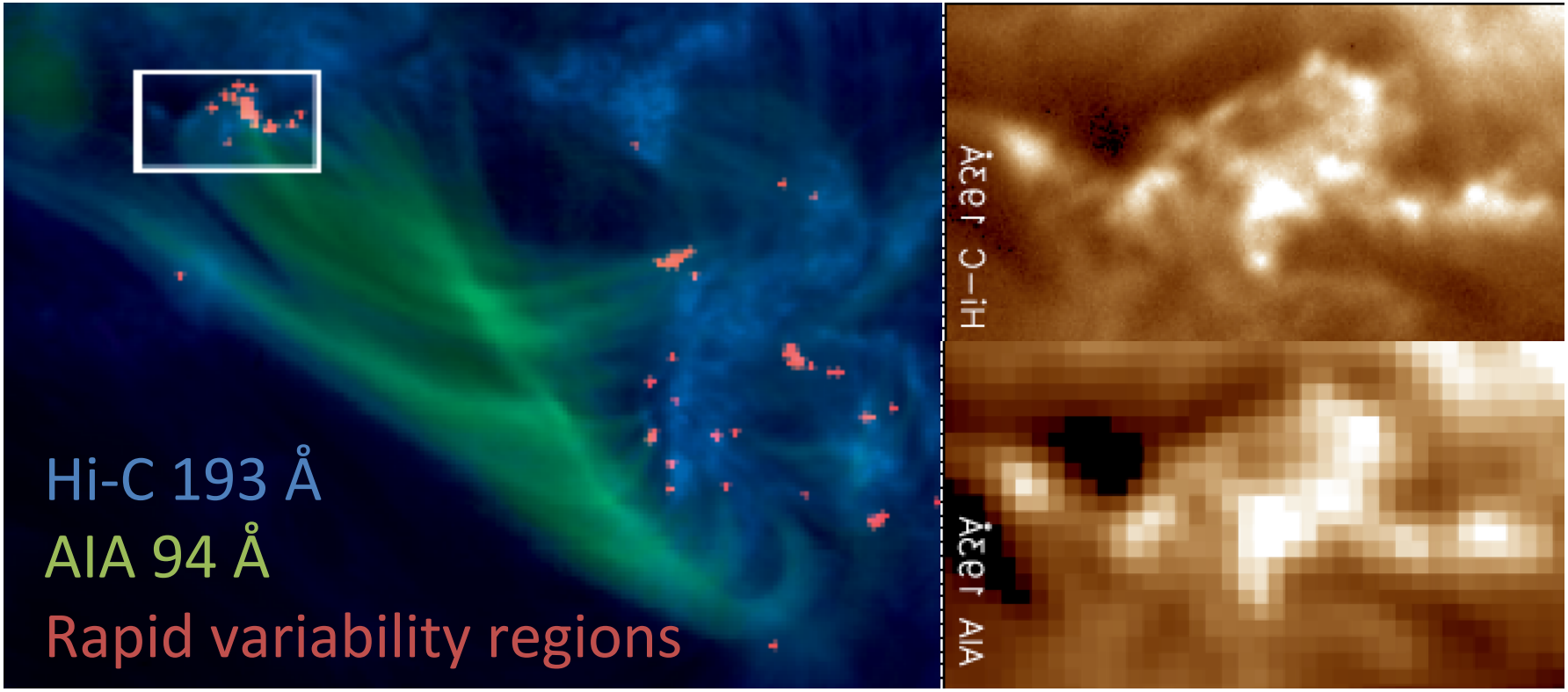




- Hi-C observed a location of highly dynamic moss.

Testa, et al., 2013, ApJ

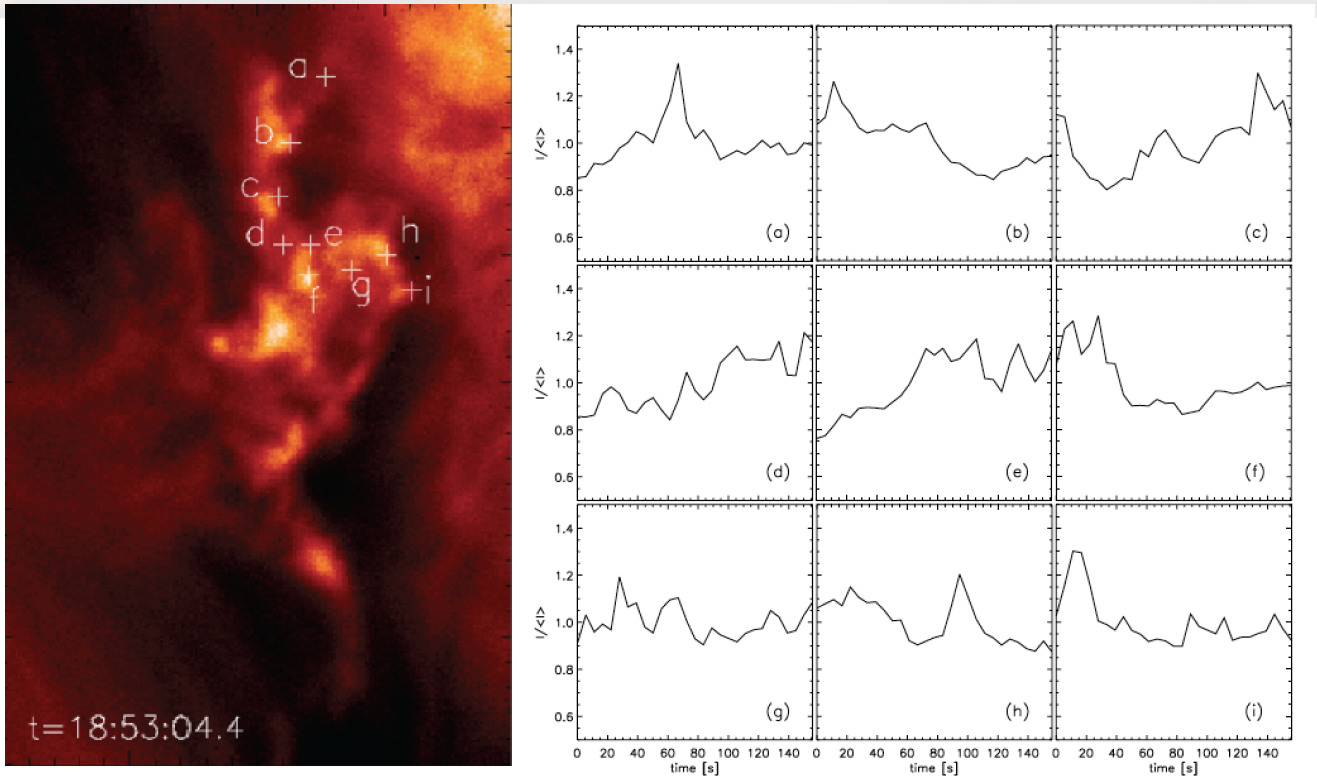
Dynamic Moss



- Dynamic moss occurs at footpoint of high temperature loops.

Testa, et al. 2013, ApJ

Dynamic Moss

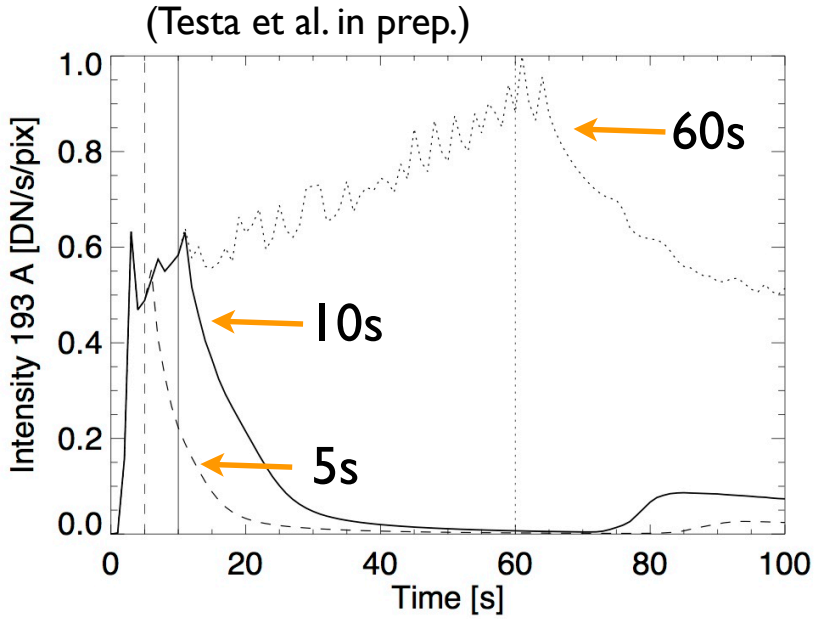


- Events as short as 15 s with increase in intensity on the order of 20-30%.
- Suggestive of footpoint response to coronal reconnection.

Testa, et al. 2013, ApJ

Dynamic Moss

Transition region (moss) emission can be used as a diagnostic of coronal heating. Specifically, it might be able to limit the duration of the heating event.



1D HD loop models for impulsive heating with different durations τ_{heat} = 60s, 10s, 5s

193Å intensity integrated at loop footpoints (<3x10^{8}cm) shows short duration brightenings at the 'footpoint' for short lived heating events

Testa, et al., in prep

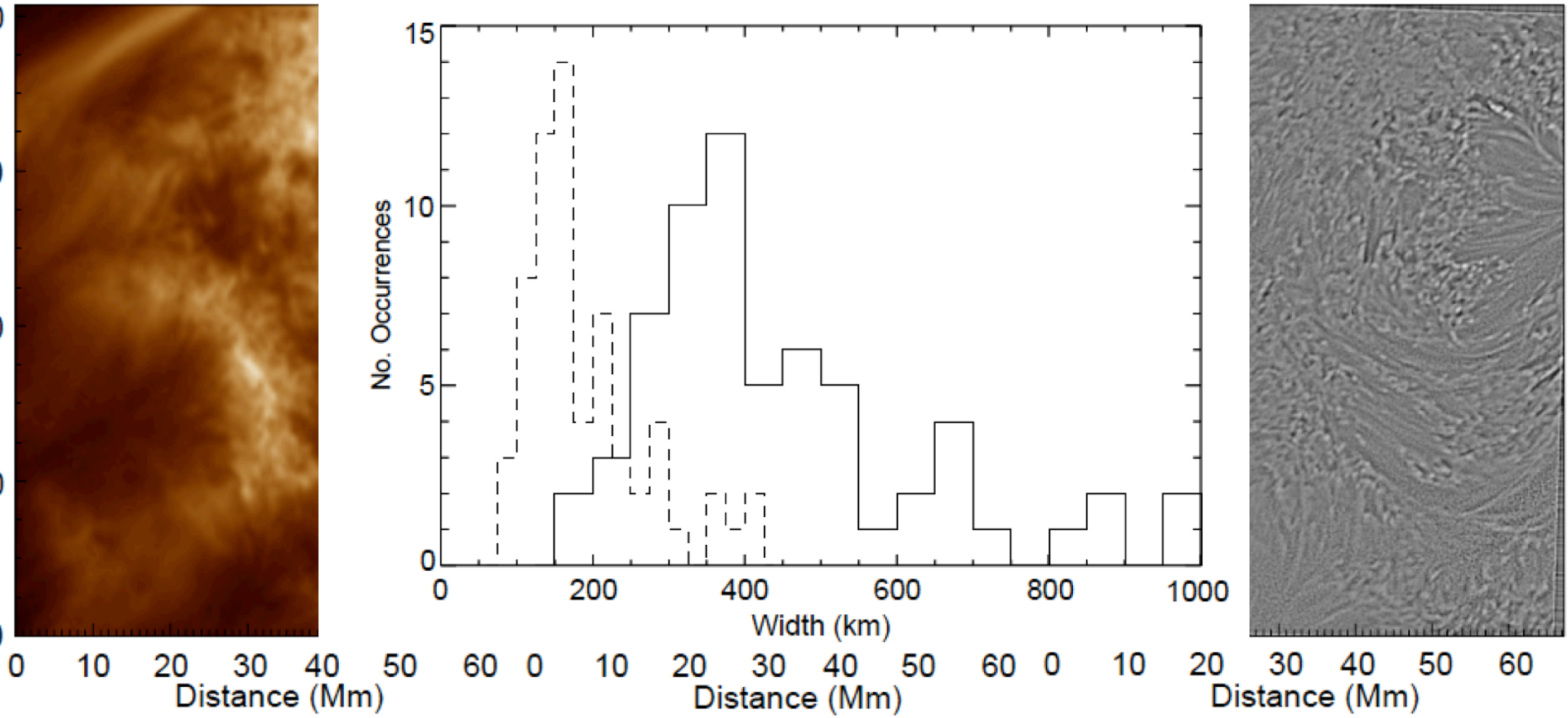
Substructure

One of the goals of Hi-C was to characterize the substructure in the corona.

Is AIA resolving structures?

If not, what are typical structure sizes?

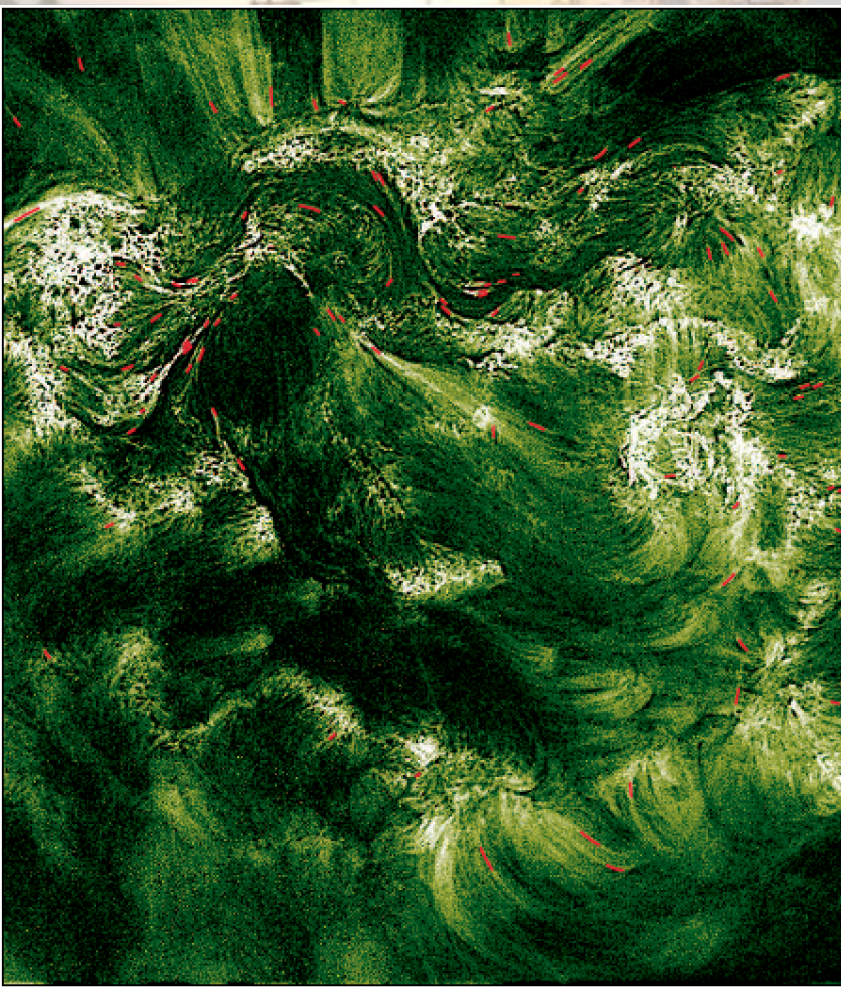
Moss Substructure

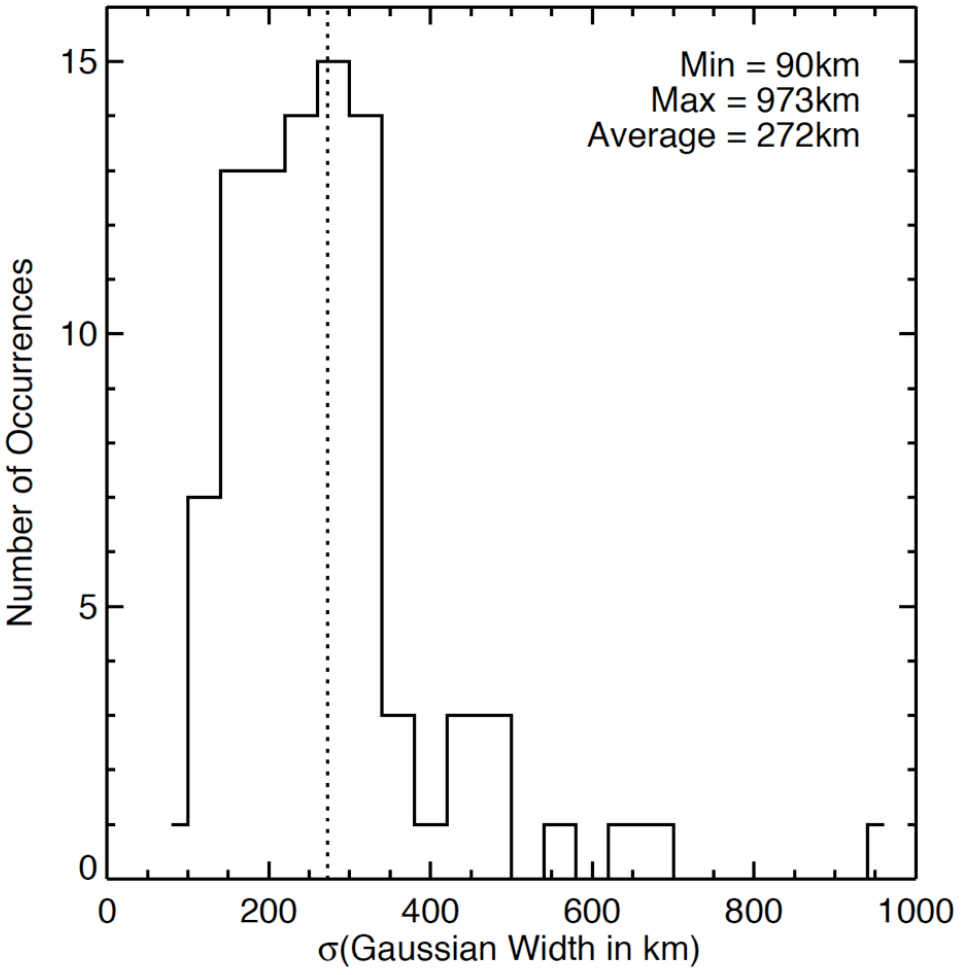


The widths of moss elements were measured.
Average Gaussian width was 188 km.

Morton & McLaughlin, 2013, A&A, in press

Loop Substructure



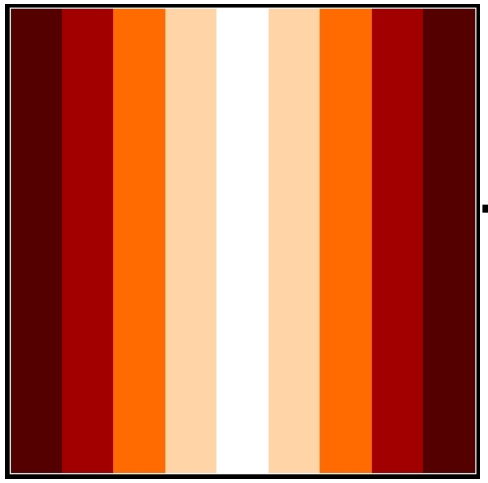


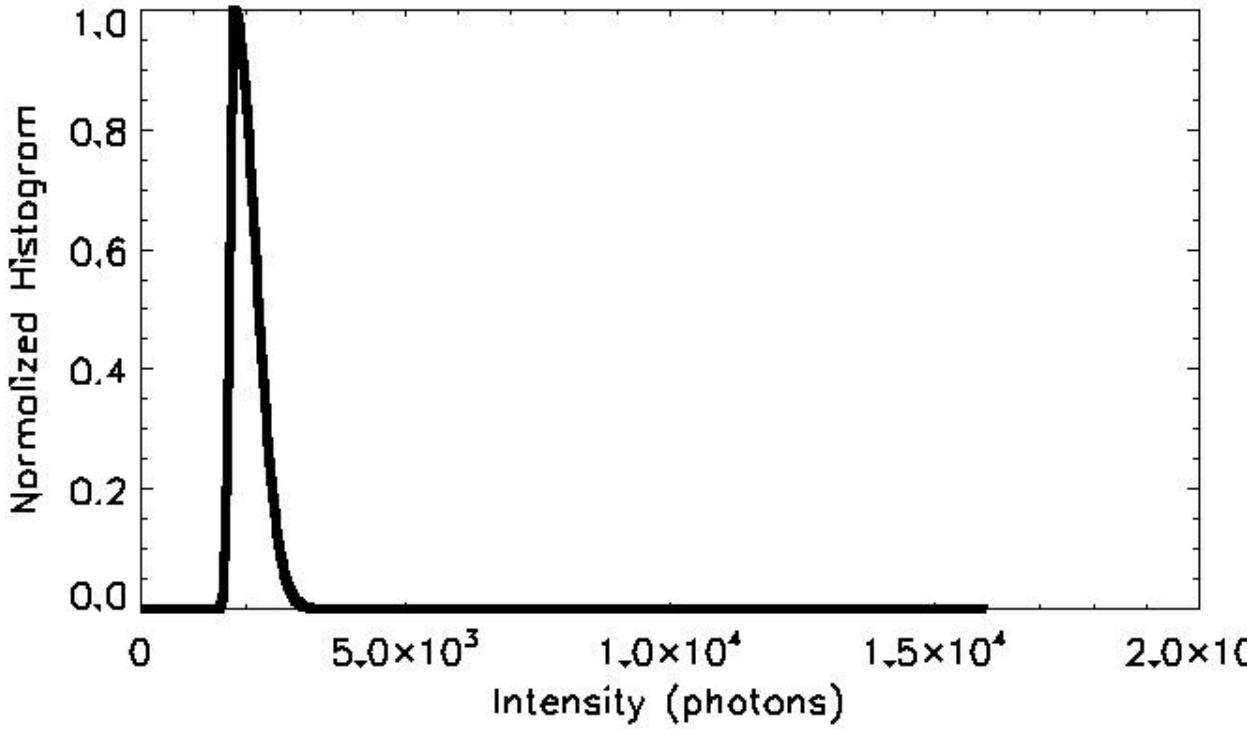
The widths of 91 loop segments were measured.
The most typical width with 270 km.

Brooks et al., 2013, ApJ, 772, 18

Substructure Consequences

Current Resolution Instrument (e.g., AIA)

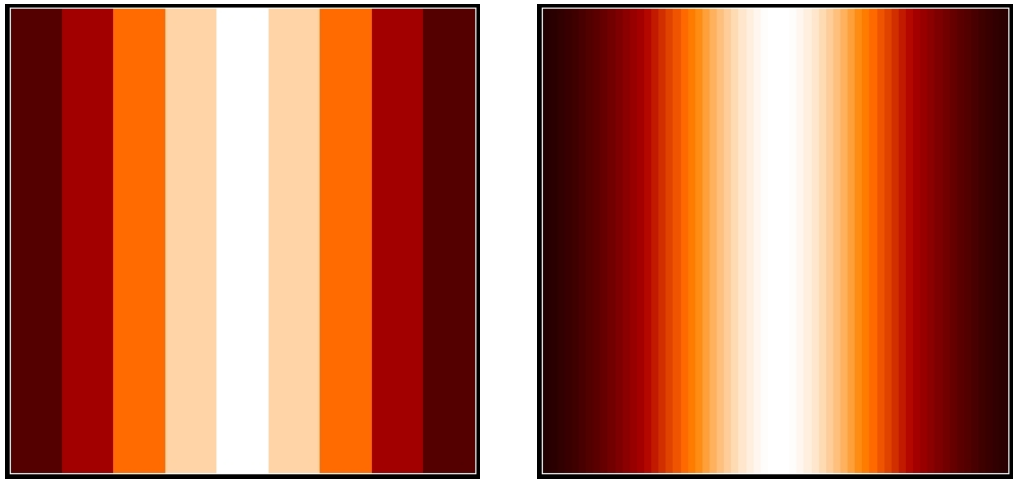




Substructure Consequences

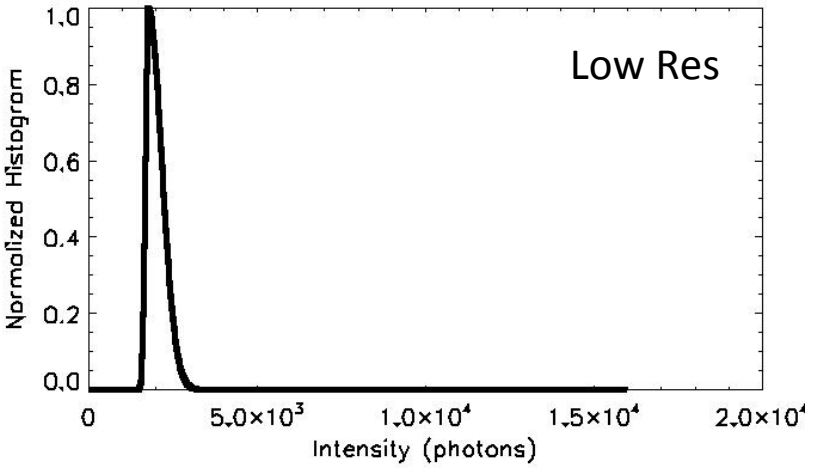
Current Resolution Instrument (e.g., AIA)

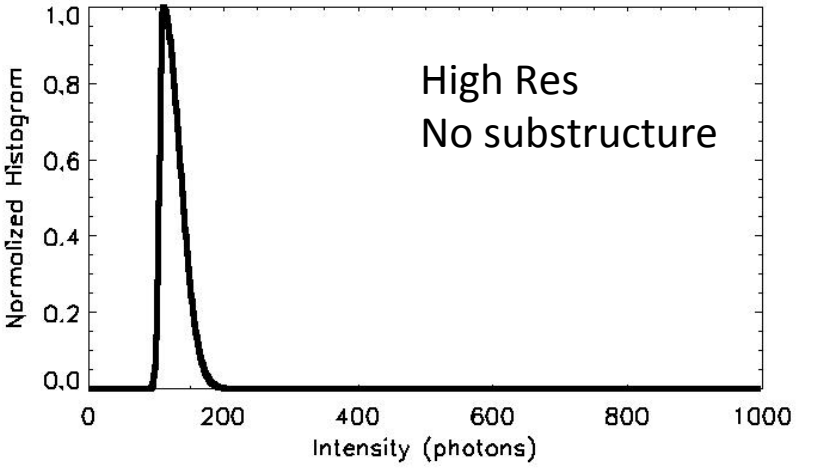
High Resolution Instrument (e.g., Hi-C), no substructure



Improve Resolution by 16x

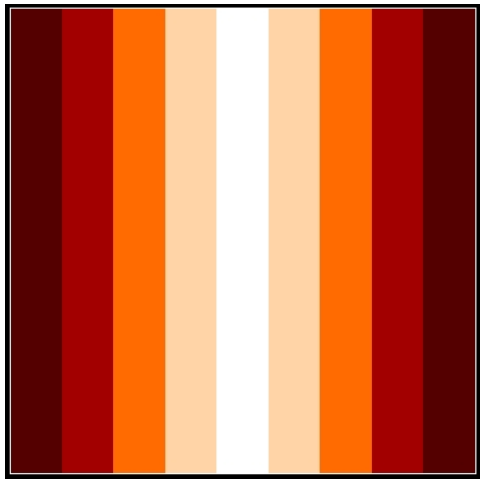
We can always predict the no substructure distribution from the low resolution distribution.



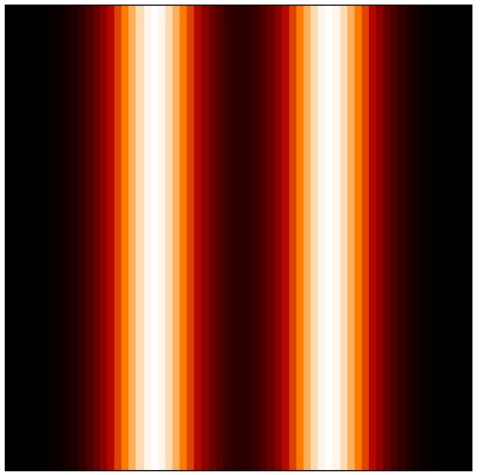


Substructure Consequences

Current Resolution Instrument (e.g., AIA)

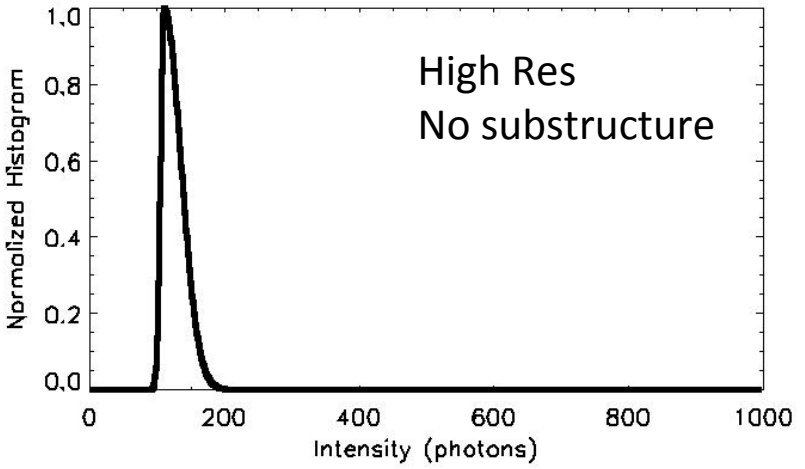


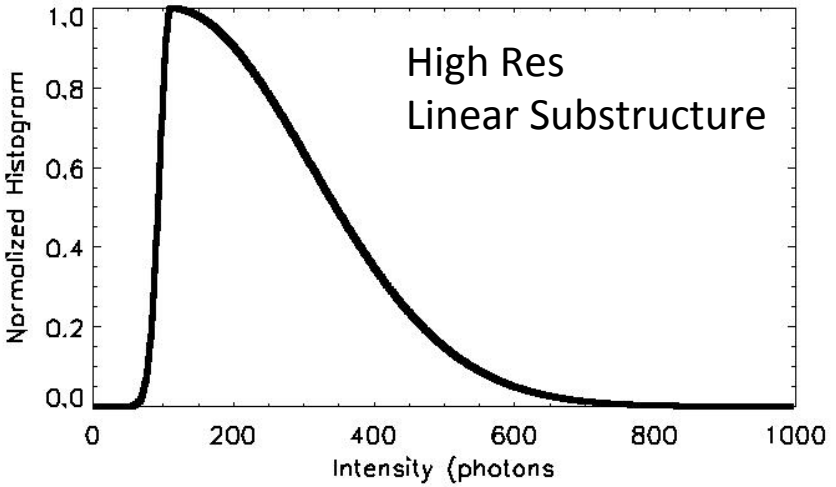
High Resolution Instrument (e.g., Hi-C), linear substructure



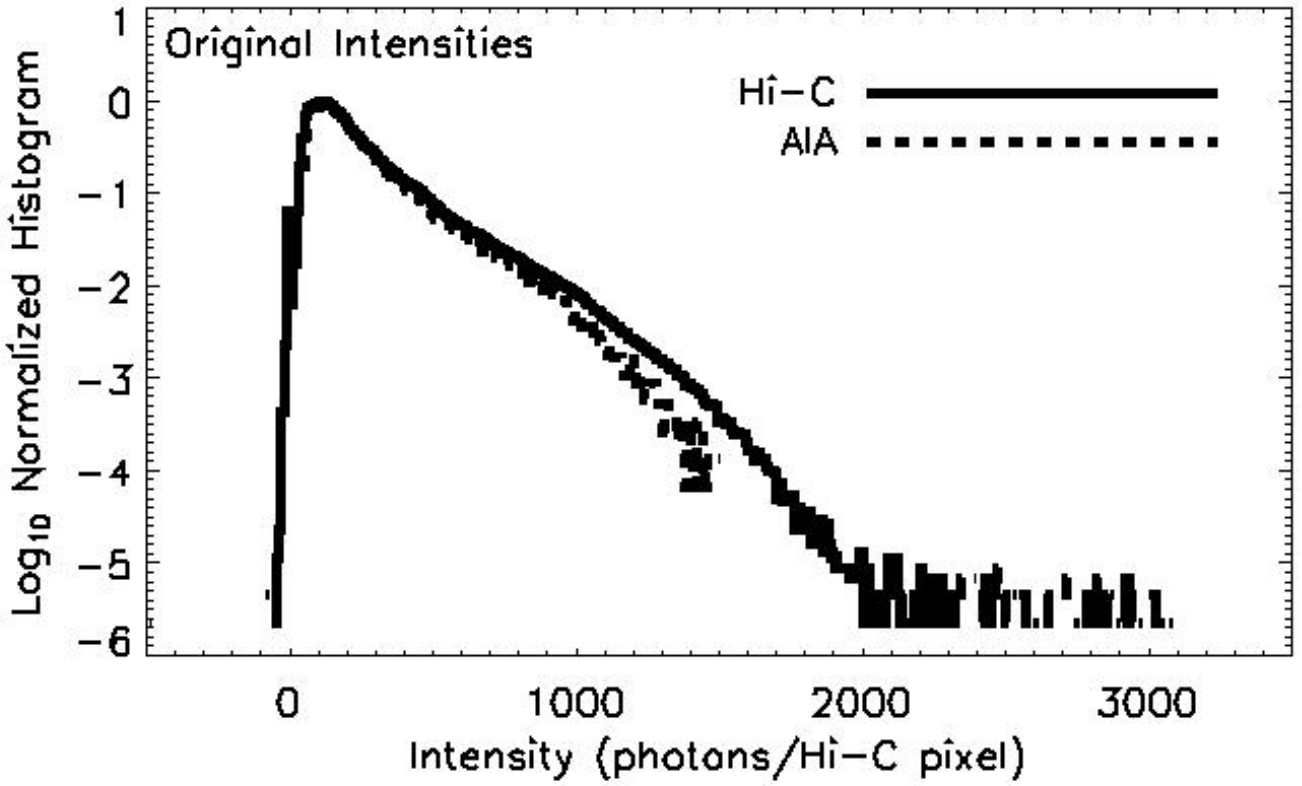
Improve Resolution by 16x

For linear substructure, we expect brights to be brighter, darks to be darker.





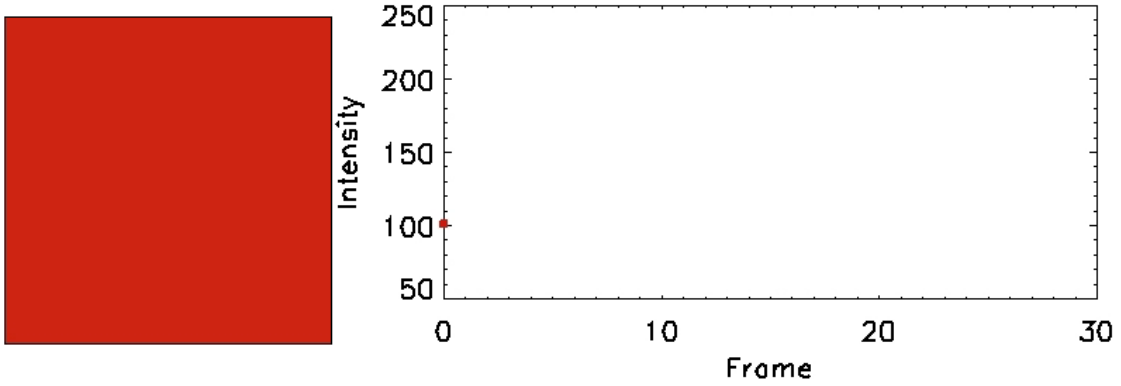
Observed by Hi-C



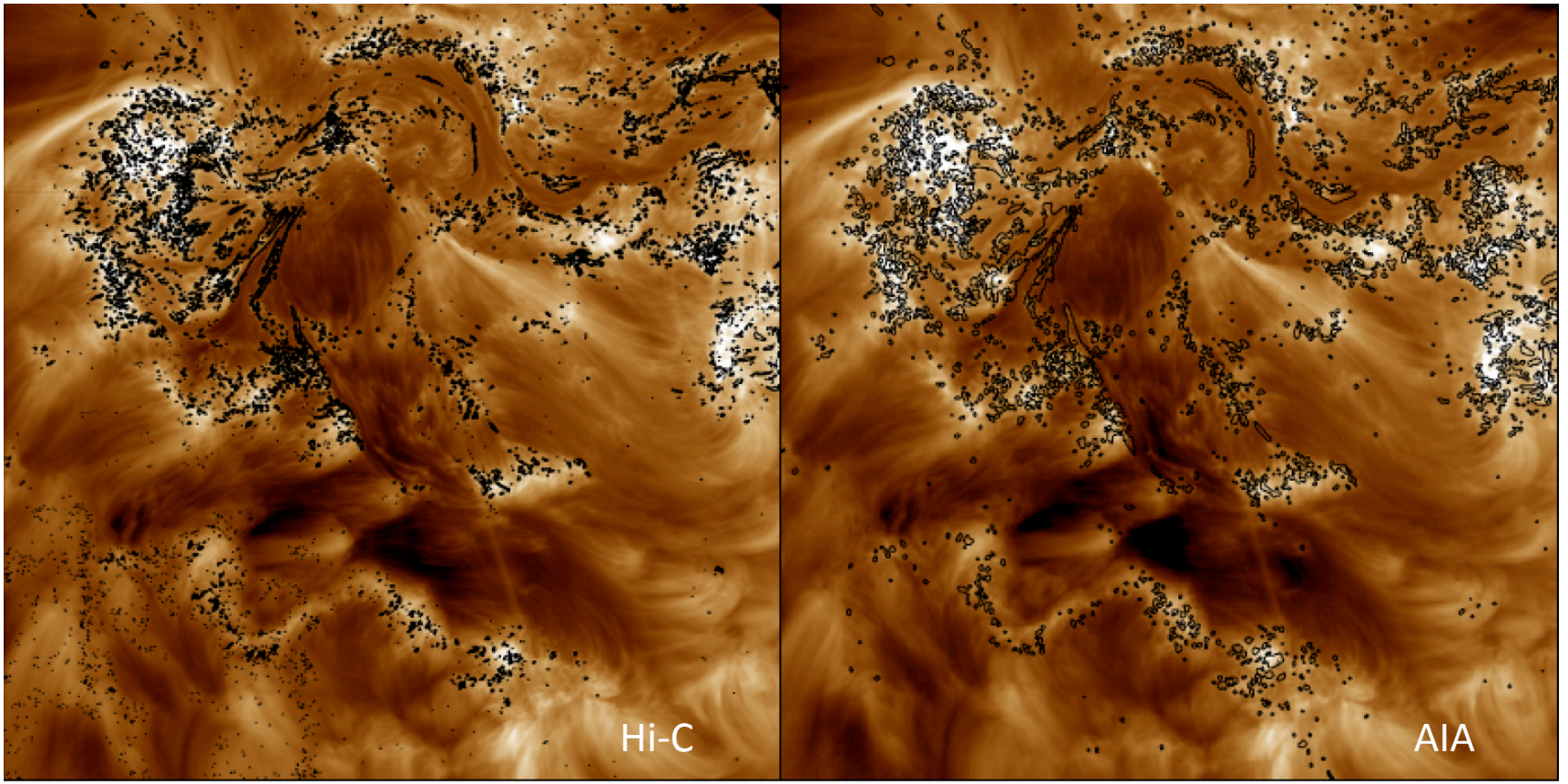
Hi-C initially did not appear to demonstrate the ~3-4 increase in intensity expected for linear substructure.

Winebarger et al., 2013, in prep

Transient Events



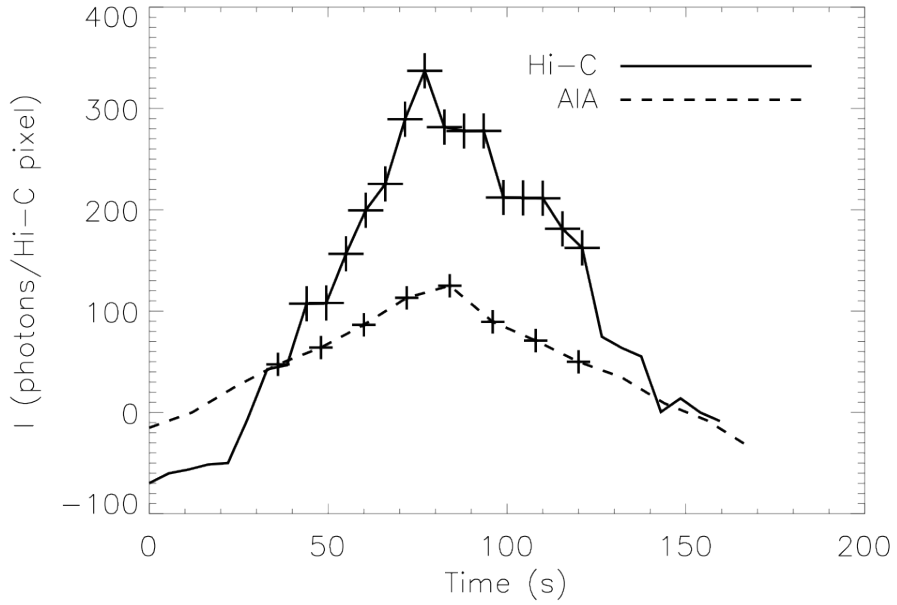
Transient Events

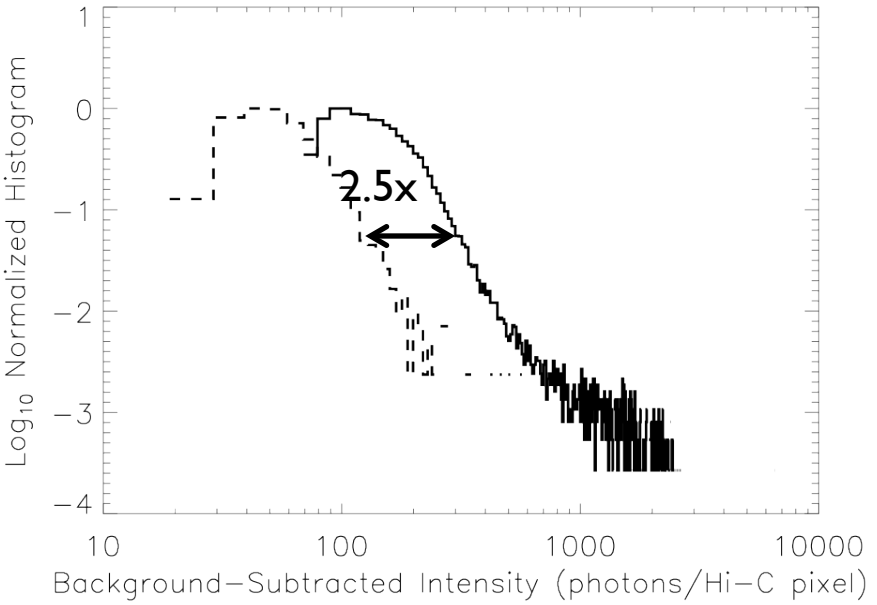


Found locations of transient events in the Hi-C and AIA data.

Winebarger et al., 2013, in prep

Transient Events

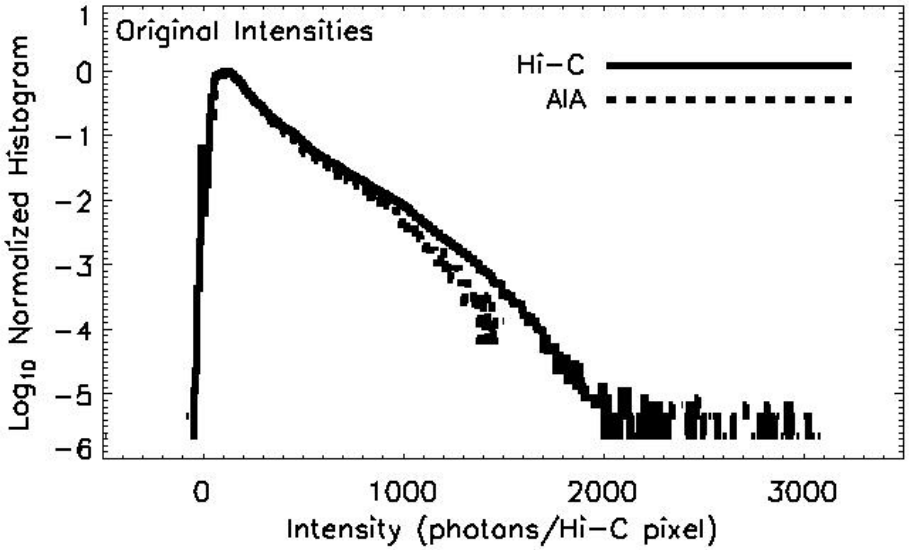


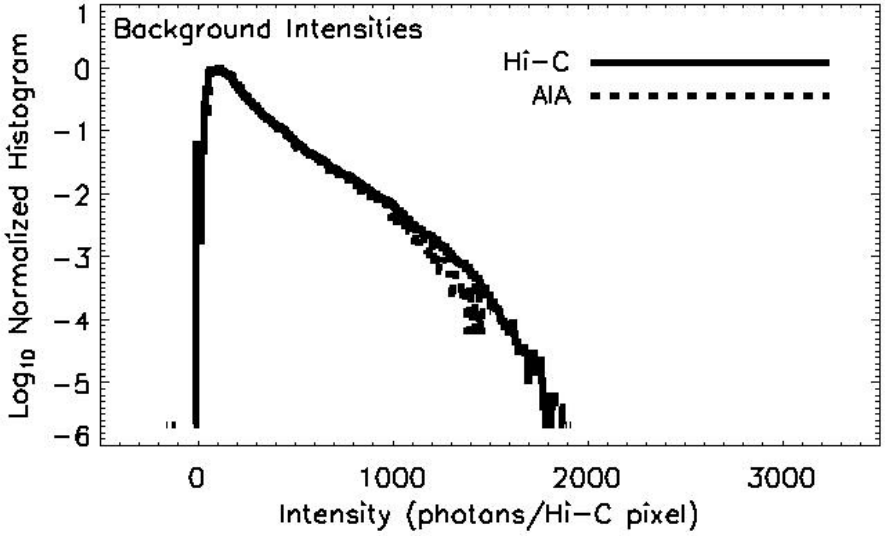


We found that transient events in Hi-C were 2.5 times brighter than transient events in AIA. We conclude this is due to linear substructure, unresolved by AIA.

Winebarger et al., 2013, in prep

Background





Hi-C reveals that the background varies smoothly, i.e., has little substructure.

Winebarger et al., 2013, in prep

Summary

- Hi-C obtained the highest spatial and temporal resolution observations ever taken in the solar corona.
- Hi-C reveals dynamics and structure at the limit of its temporal and spatial resolution.
- Hi-C observed ubiquitous fine-scale flows consistent with the local sound speed.

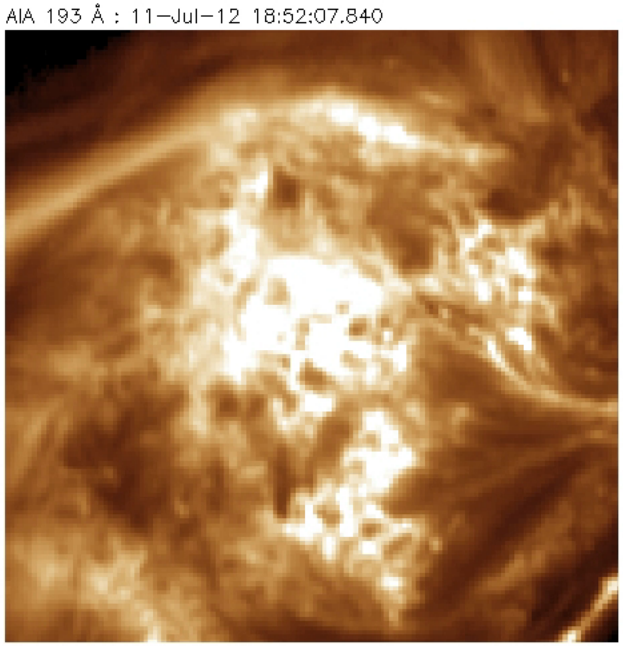
Summary

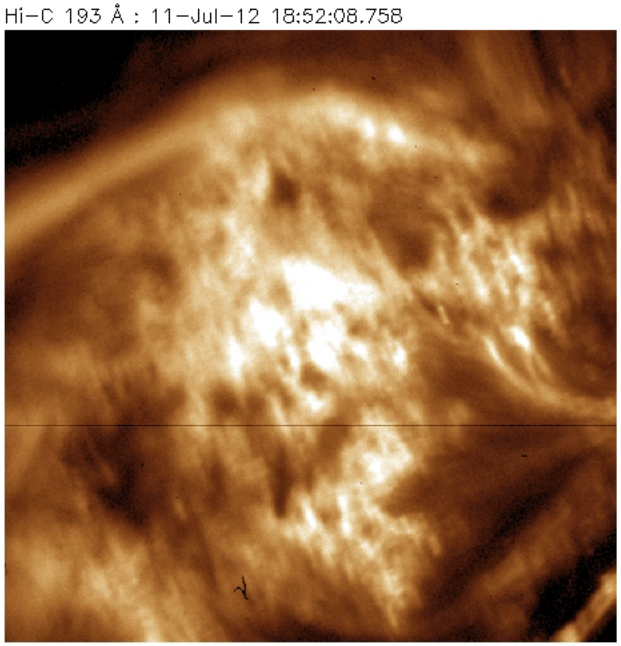
- For the first time in the corona, Hi-C revealed magnetic braiding and component reconnection consistent with coronal heating.

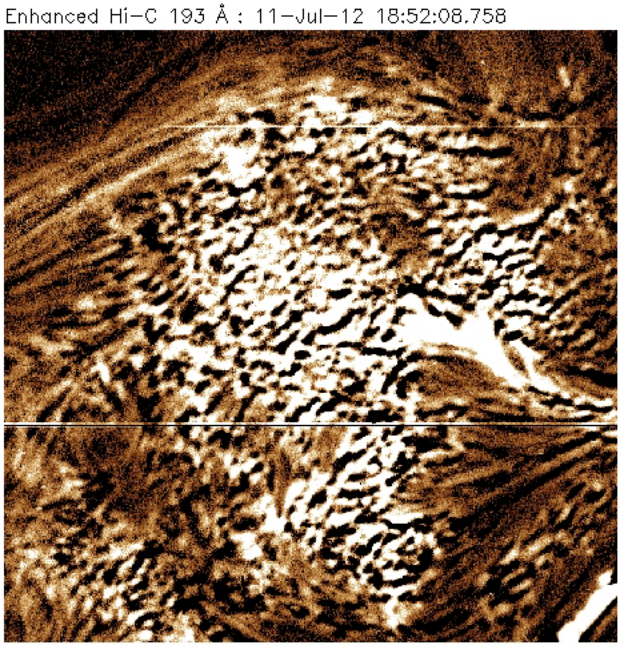
- Hi-C shows evidence of reconnection and heating in several different regions and magnetic configurations with plasma being heated to $0.3 – 8 \times 10^6$ K temperatures.

- Surprisingly, many of the first results highlight plasma at temperatures that are not at the peak of the response functions.

Spicules in Moss



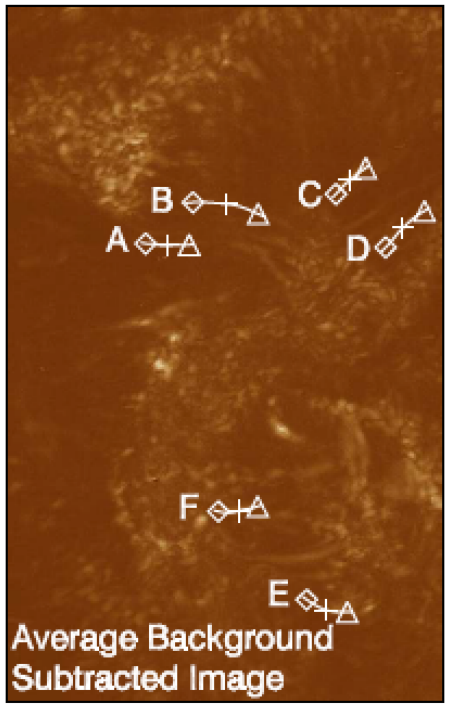


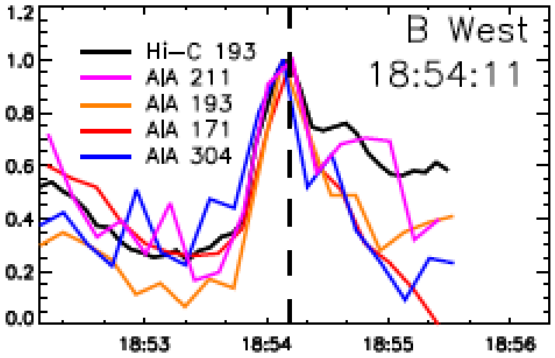


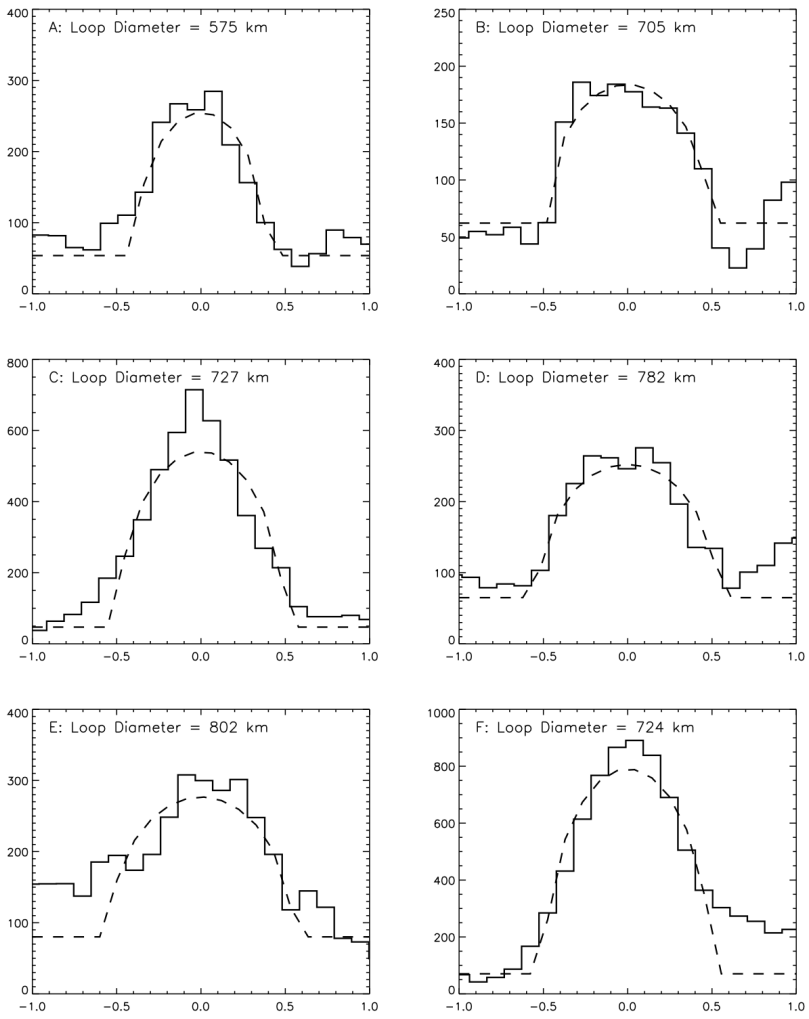
Hi-C reveals many short-lived absorption features in the moss.
These features are likely spicules – dense plasma at chromospheric temperatures.
Currently studying the lifetime and evolutions of these features.

Winebarger, in prep.

Transition Region Loops







- Six loops were identified.
- Diameter of loops 575-800 km
- Lifetime of loops < 60 s.

Winebarger, Walsh, in prep.