Unlocking the Secrets of the Sun

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Career Path

KING COLLEGE

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91-95 95-99 99-01

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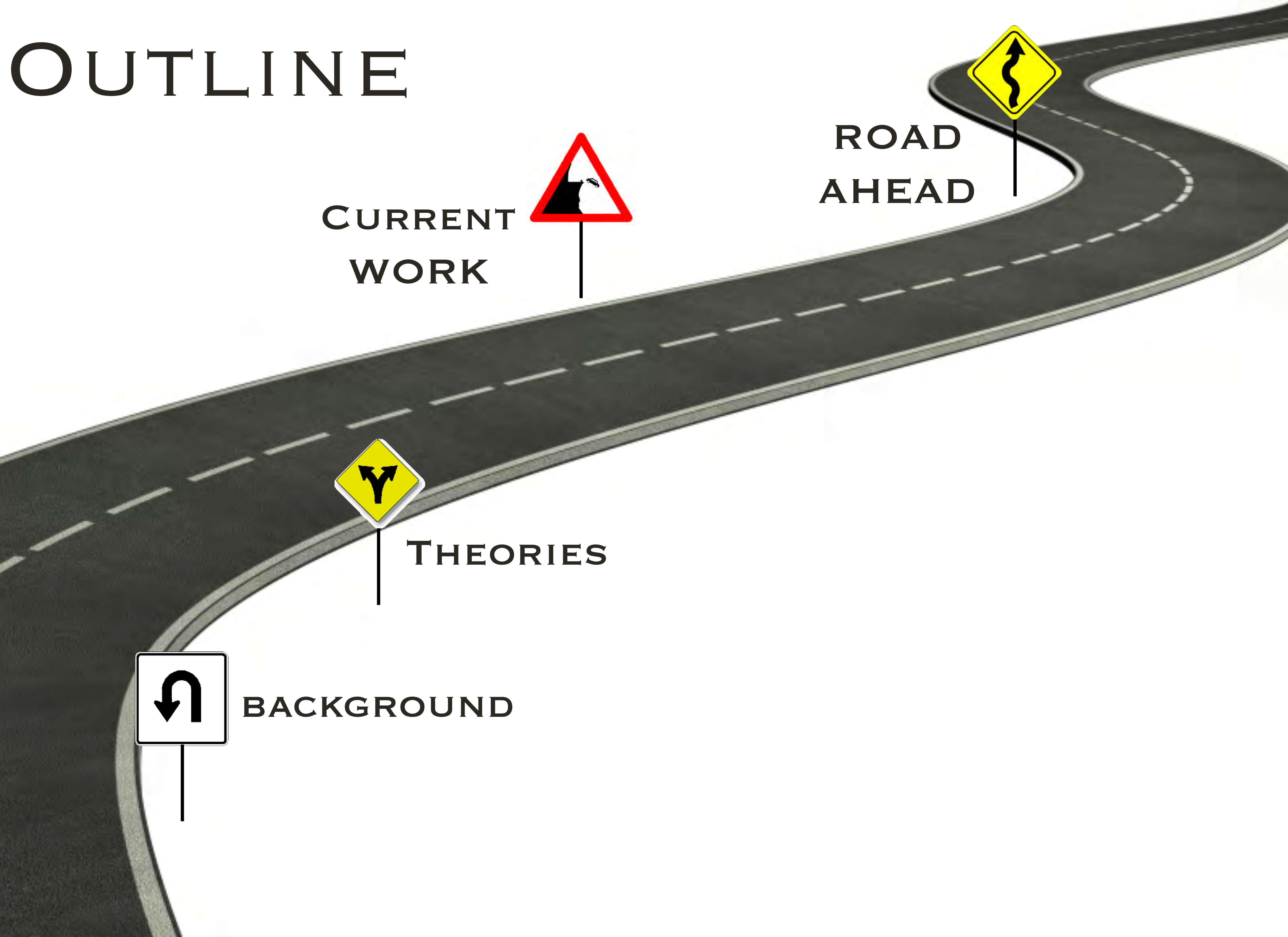
NASA

NAVAL RESEARCH LABORATORY WASHINGTON, DC

Outline

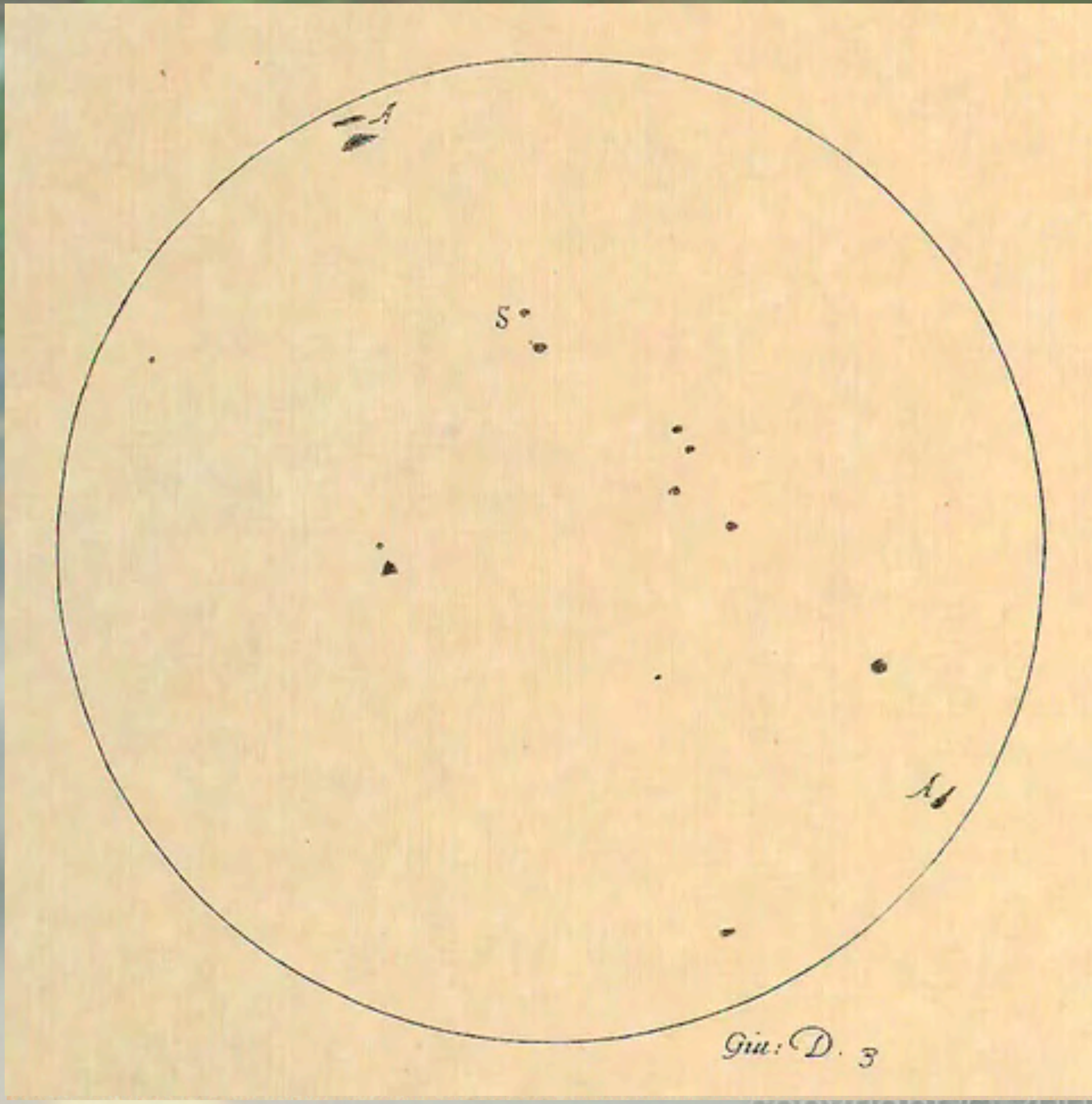


Background

What does the Sun look like?

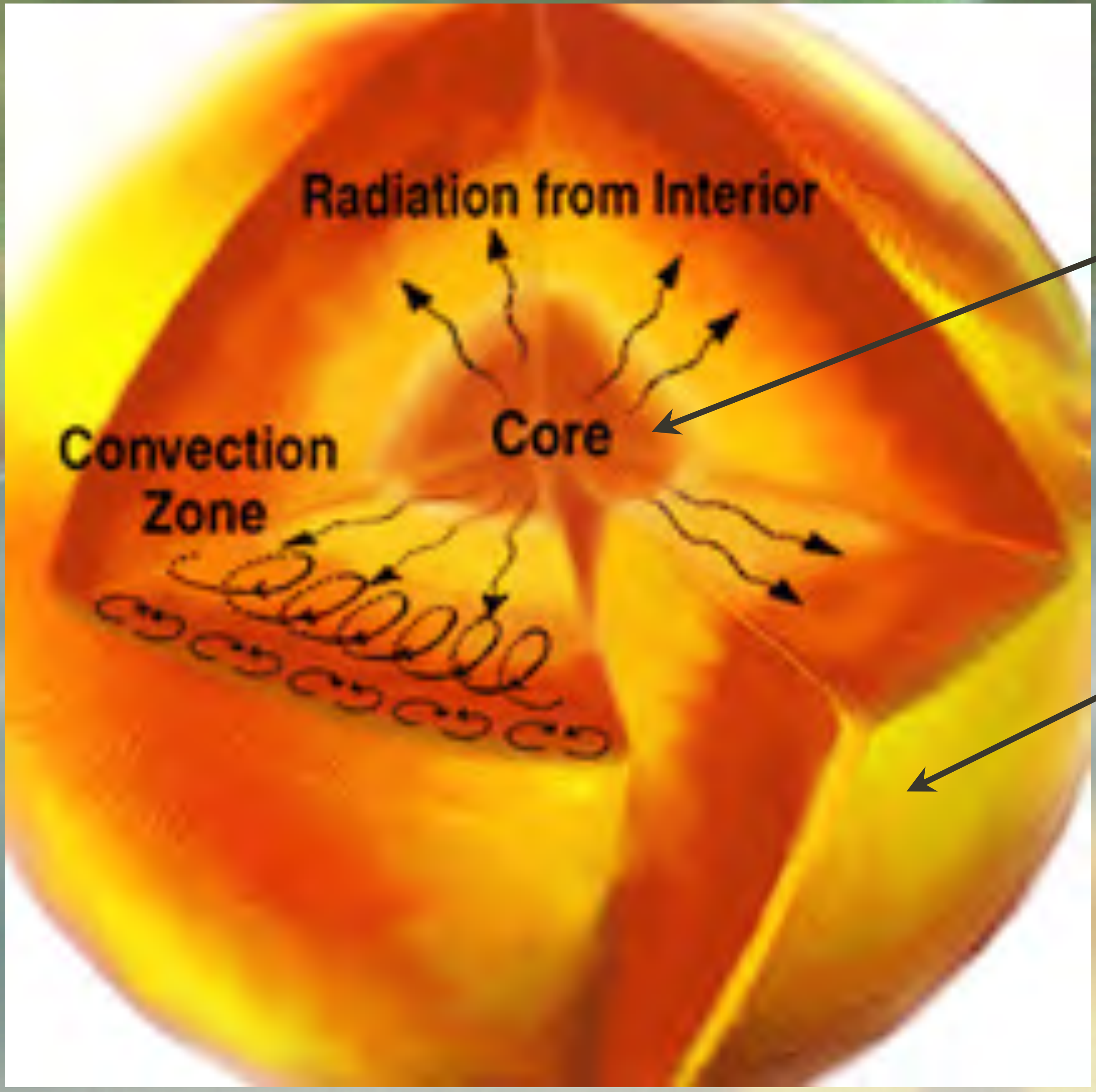
Galileo drew the Sun at the same time each day.
His drawings reveal "sunspots," dark areas on the Sun.

Now we know sunspots are strong magnets on the Sun.



Background

What is the temperature of the Sun?

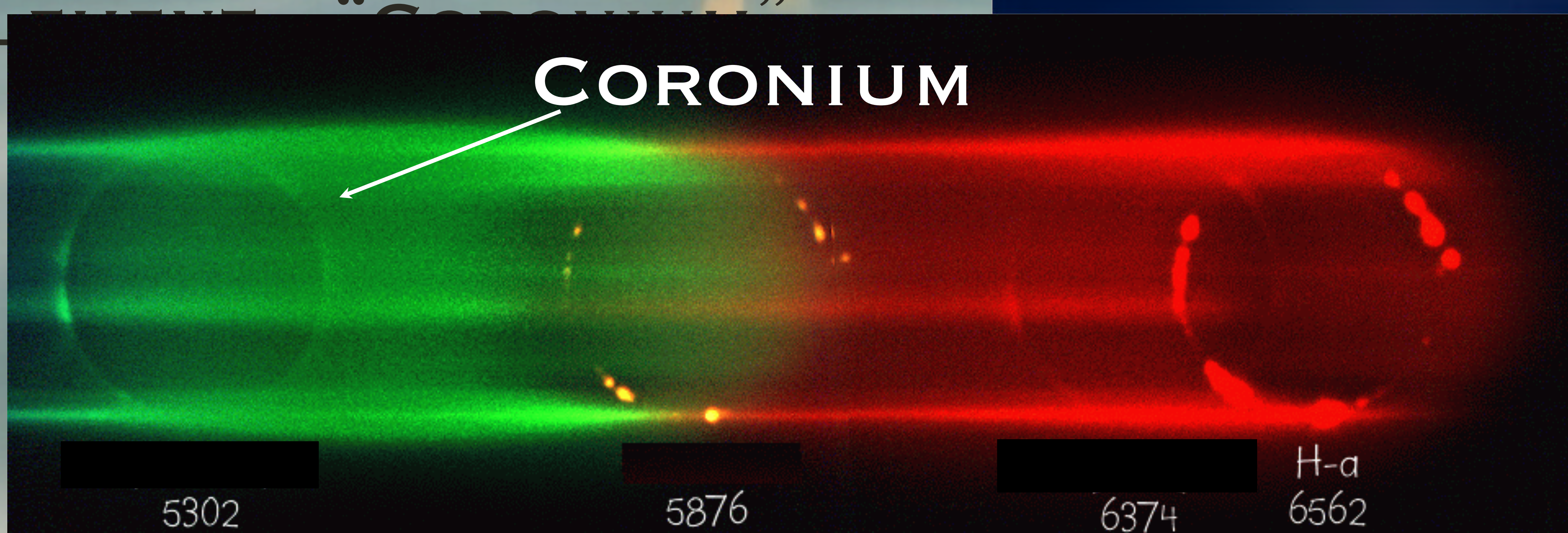


22 MK in core

5,000 K on Surface

Background

- In the mid-1800s, spectral observations of solar corona during eclipse discovered a spectral line from unknown element – “Coronium”



Background

- In the 1930s, Gotrian and Edlen discovered the 5303 line was from Fe XIV implying the solar corona contained million degree plasma.

- Originally, the atmosphere was treated as "plane parallel", meaning the temperature and density of the corona depend only on the distance from the solar surface

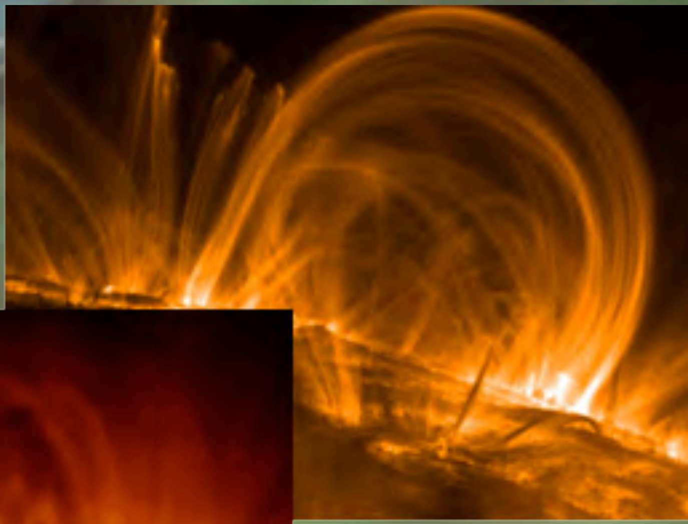
Background

First X-ray Image
of the Sun
April 19, 1960

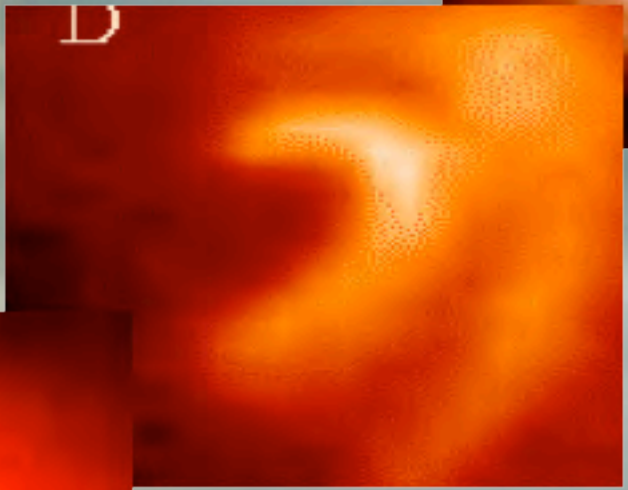
Background

Improvements in Spatial resolution led to finer and finer structures

Trace 1999



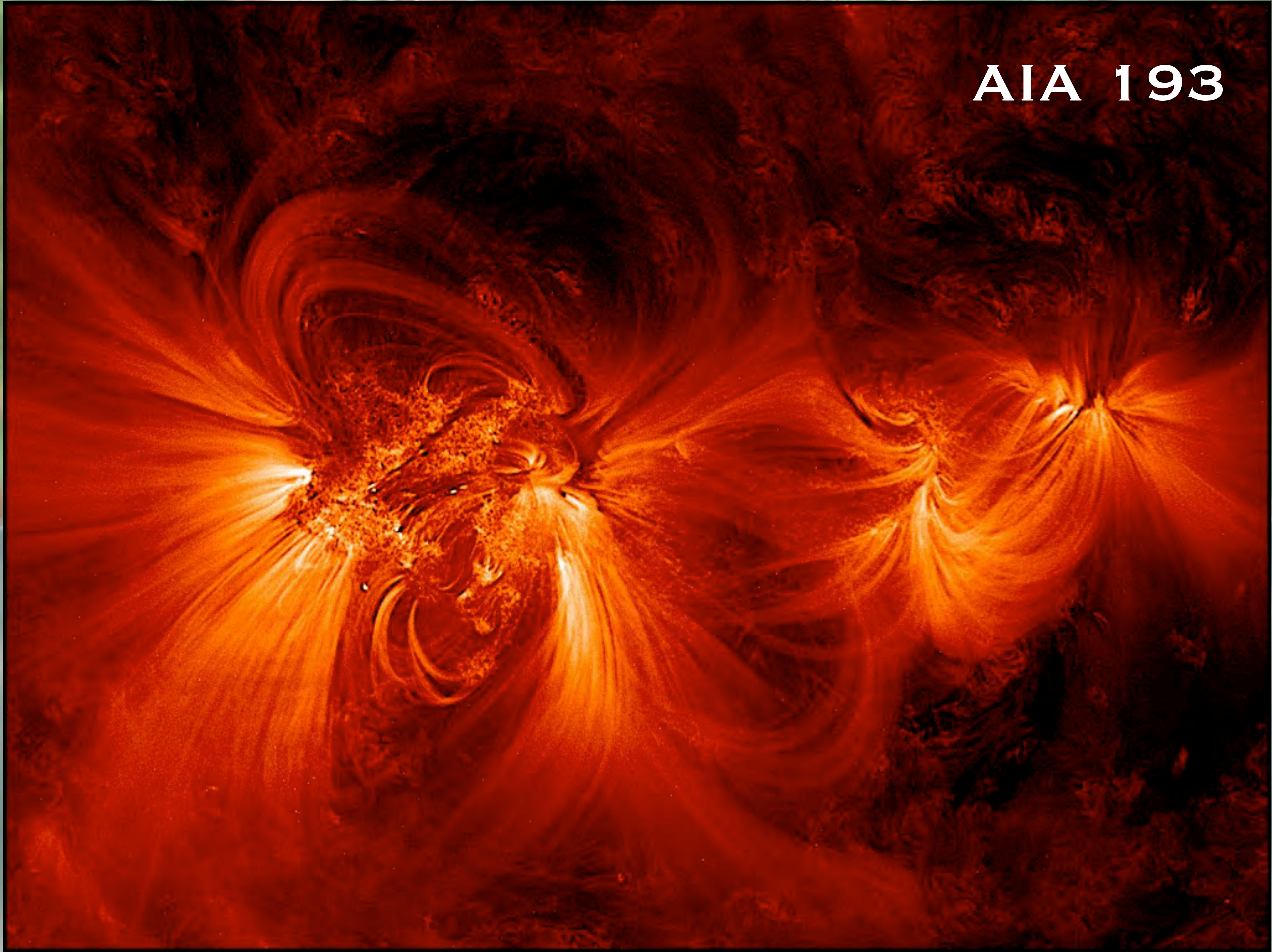
SOHO EIT 1996



Yohkoh 1982

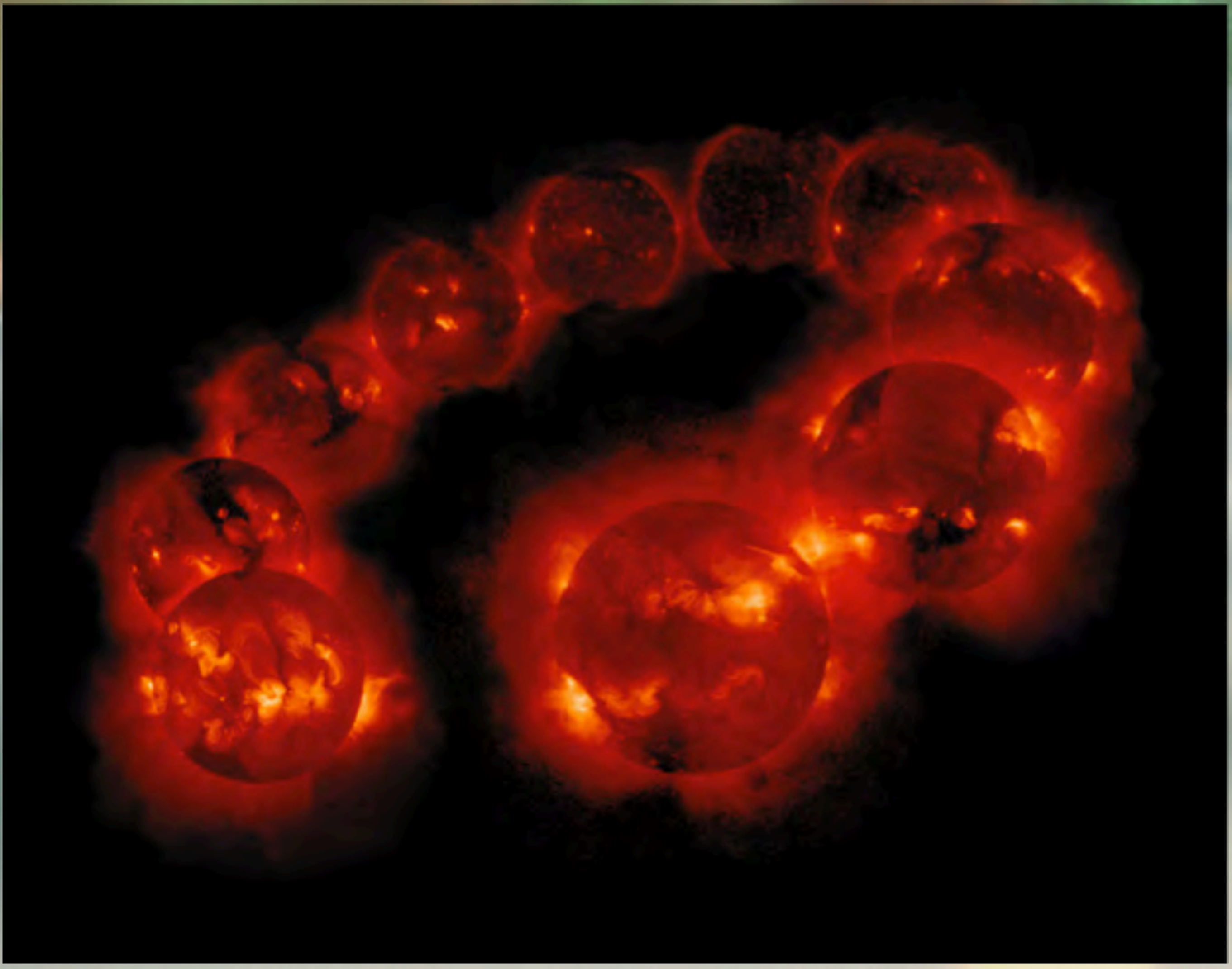
Skylab 1973

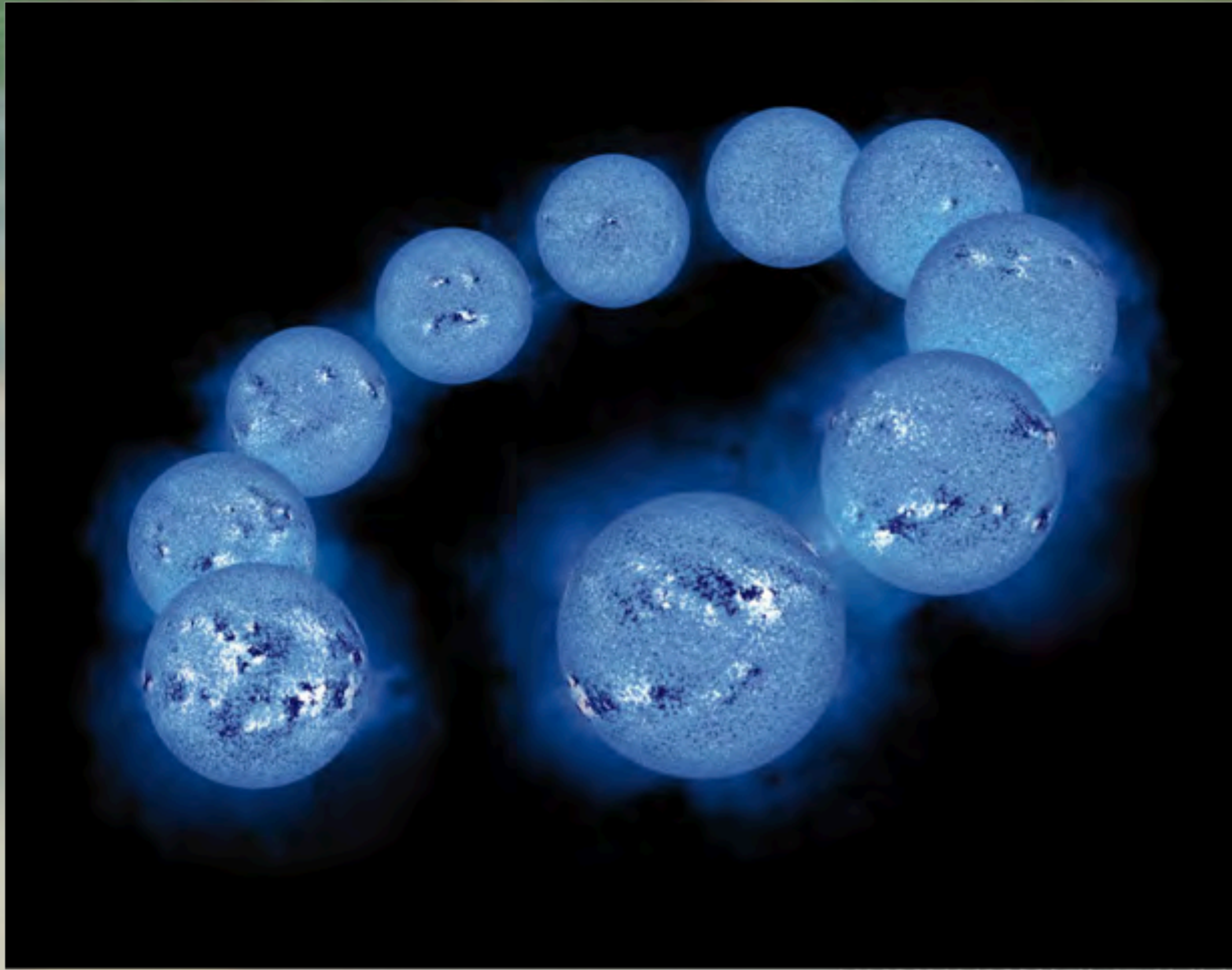
Background



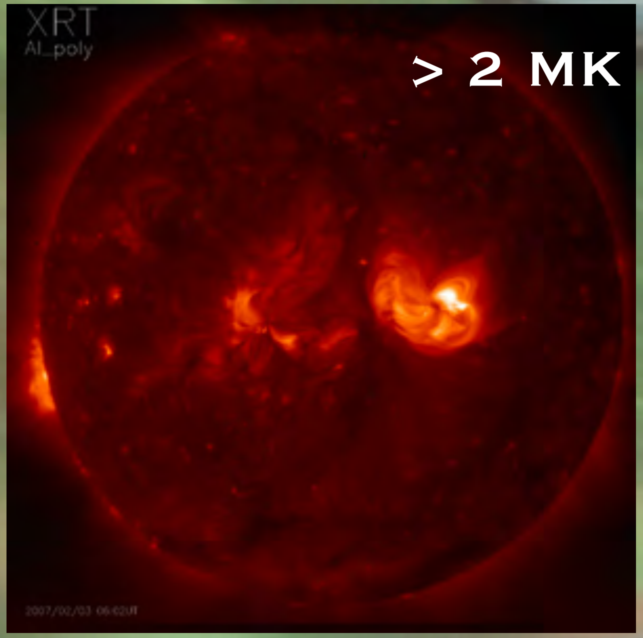
Background

There is more hot plasma in times of strong magnetic field.

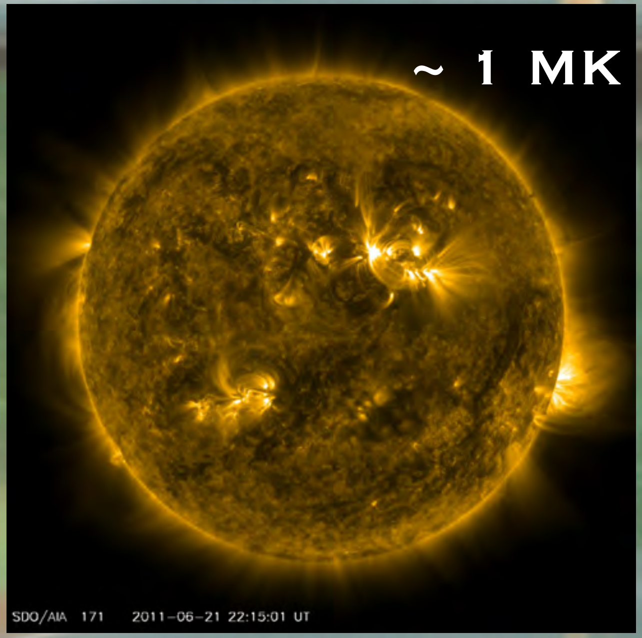




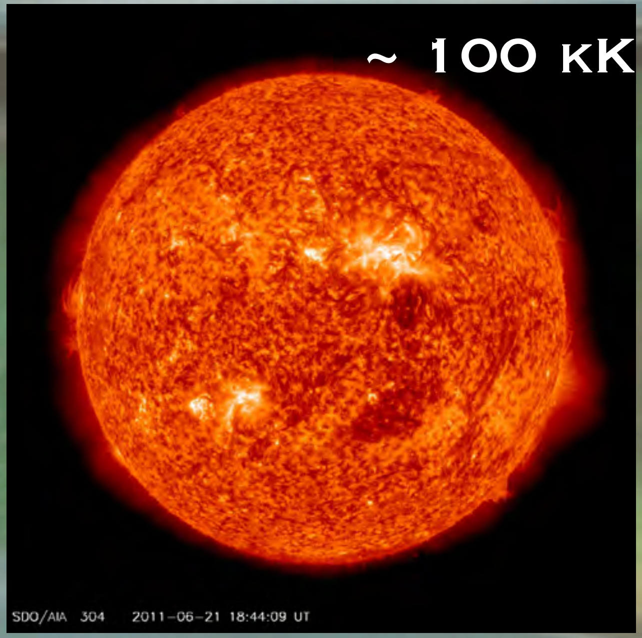
Background



X-ray



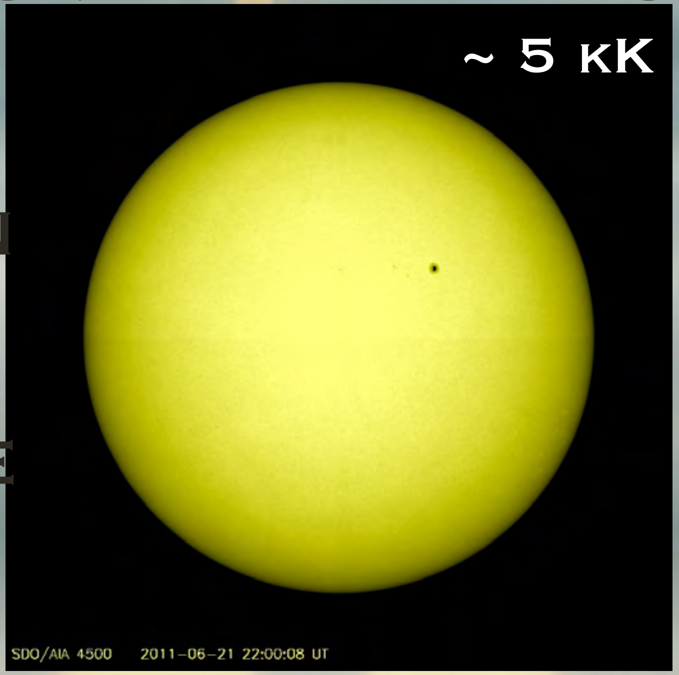
EUV



EUV

FUV

When we take images of the Sun in different wavelengths, we see different structures



White Light

Different wavelengths show different temperatures.

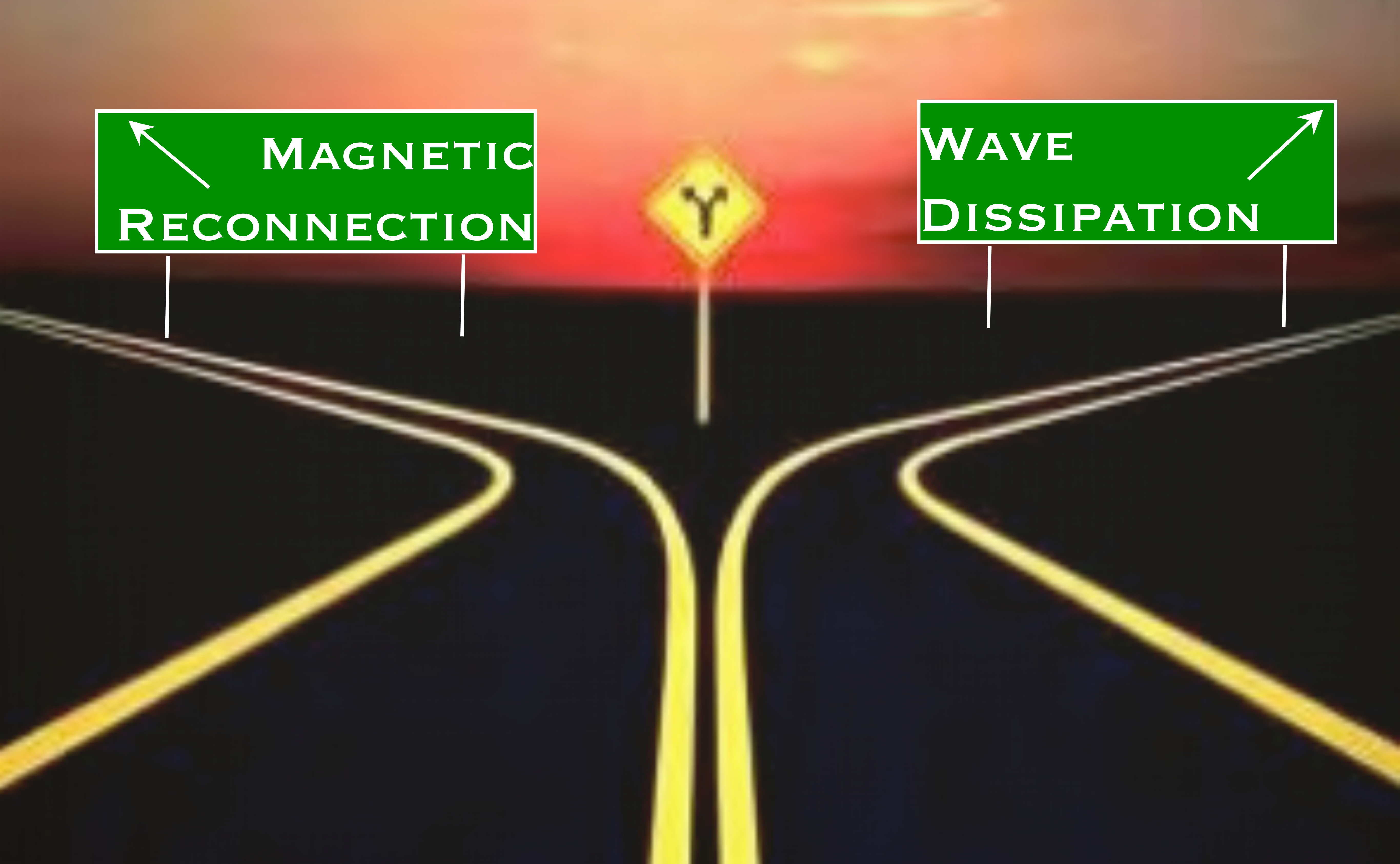
Background

Strand - Fundamental coronal structure

Loop - Observed coronal structure

If number of strands/loop = 1, we are resolving the corona.

Coronal Heating Theories



Heating and Dissipation mechanisms

Many different theories for carrying and dissipating energy in the corona

TABLE 5

Summary of the Scaling Law for Different Models of Coronal Heating

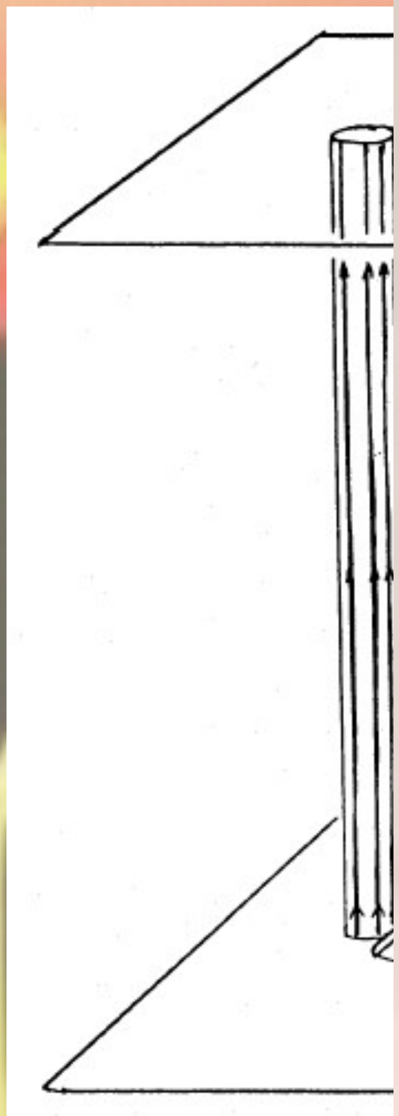
Model Characteristics	N^0	References	Scaling Law	Parameters
Stressing Models (DC)				
Stochastic buildup	1	1	$B^2L^{-2}V^2\tau$	
Critical angle	2	2	$B^2L^{-1}V \tan\theta$	
Critical twist	3	3	$B^2L^{-2}VR\phi$	
Reconnection $\propto v_A$	4	4	$BL^{-2}\rho^{1/2}V^2R$	
Reconnection $\propto v_{A\perp}$	5	5	$B^{3/2}L^{-3/2}\rho^{1/4}V^{3/2}R^{1/2}$	
Current layers	6	6	$B^2L^{-2}V^2\tau \log R_m$	
	7	7	$B^2L^{-2}V^2\tau S^{0.1}$	
	8	8	$B^2L^{-2}V^2\tau$	
Current sheets	9	9	$B^2L^{-1}R^{-1}V_{ph}^2\tau$	
Taylor relaxation	10	10	$B^2L^{-2}V_{ph}^2\tau$	
Turbulence with:				
Constant dissipation coefficients	11	11	$B^{3/2}L^{-3/2}\rho^{1/4}V^{3/2}R^{1/2}$	
Closure	12	12	$B^{5/3}L^{-4/3}\rho^{1/6}V^{4/3}R^{1/3}$	
Closure + spectrum	13	13	$B^{s+1}L^{-1-s}\rho^{(1-s)/2}V^{2-s}R^s$	$s = 0.7, m = -1$
	14			$s = 1.1, m = -2$
Wave Models (AC)				
Resonance	15	14	$B^{1+m}L^{-3-m}\rho^{-(1+m)/2}$	$m = -1.$
	16			$m = -2.$
Resonant absorption	17	15	$B^{1+m}L^{-1-m}\rho^{-(1+m)/2}$	$m = -1.$
	18			$m = -2.$
	19	16	$B^{1+m}L^{-m}\rho^{-(m-1)/2}$	$m = -1.$
	20			$m = -2.$
Current layers	21	17	$BL^{-1}\rho^{1/2}V^2$	
Turbulence	22	18	$B^{5/3}L^{-4/3}R^{1/3}$	

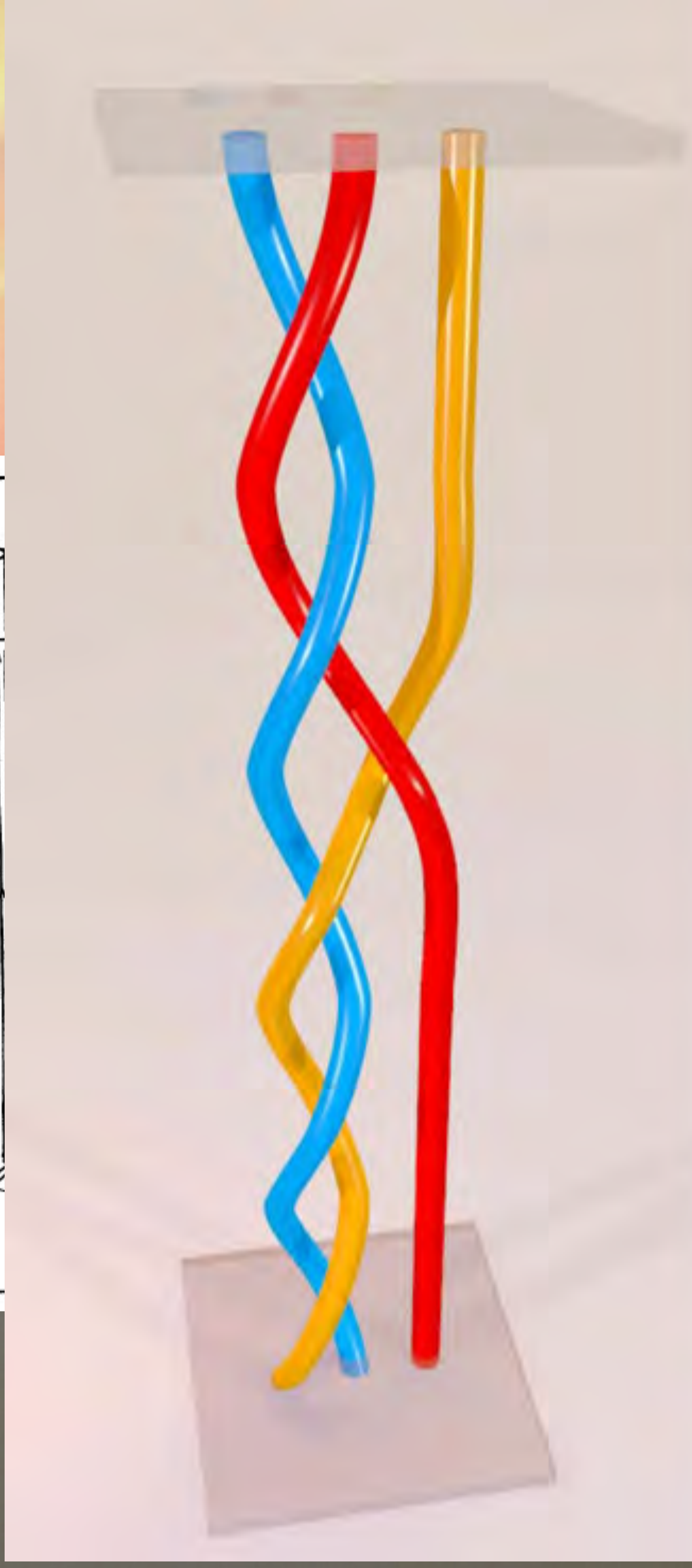
References.—(1) Sturrock & Uchida 1981, Berger 1991; (2) Parker 1988, Berger 1993; (3) Galsgaard & Nordlun 1997; (4) Parker 1983; (5) Parker 1983, modified; (6) van Ballegooijen 1986; (7) Hendrix et al. 1996; (8) Galsgaard & Nordlund 1996; (9) Aly & Amari 1997; (10) Heyvaerts & Priest 1984, Browning & Priest 1986, Vekstein et al. 1993; (1 Einaudi et al. 1996, Dmitruk & Gómez 1997; (12) Heyvaerts & Priest 1992, Inverarity et al. 1995, Inverarity & Prie 1995a; (13) Milano et al. 1997; (14) Hollweg 1985; (15) Ofman et al. 1995, Ruderman et al. 1997; (16) Halberstadt & Goedbloed 1995; (17) Galsgaard & Nordlund 1996; (18) Inverarity & Priest 1995b.

Mandrini et al, ApJ 2000

Nanoflare

- Parker suggested braiding of the magnetic field by photospheric motions would drive small-scale coronal reconnection
- Along individual strands, heating would be sporadic

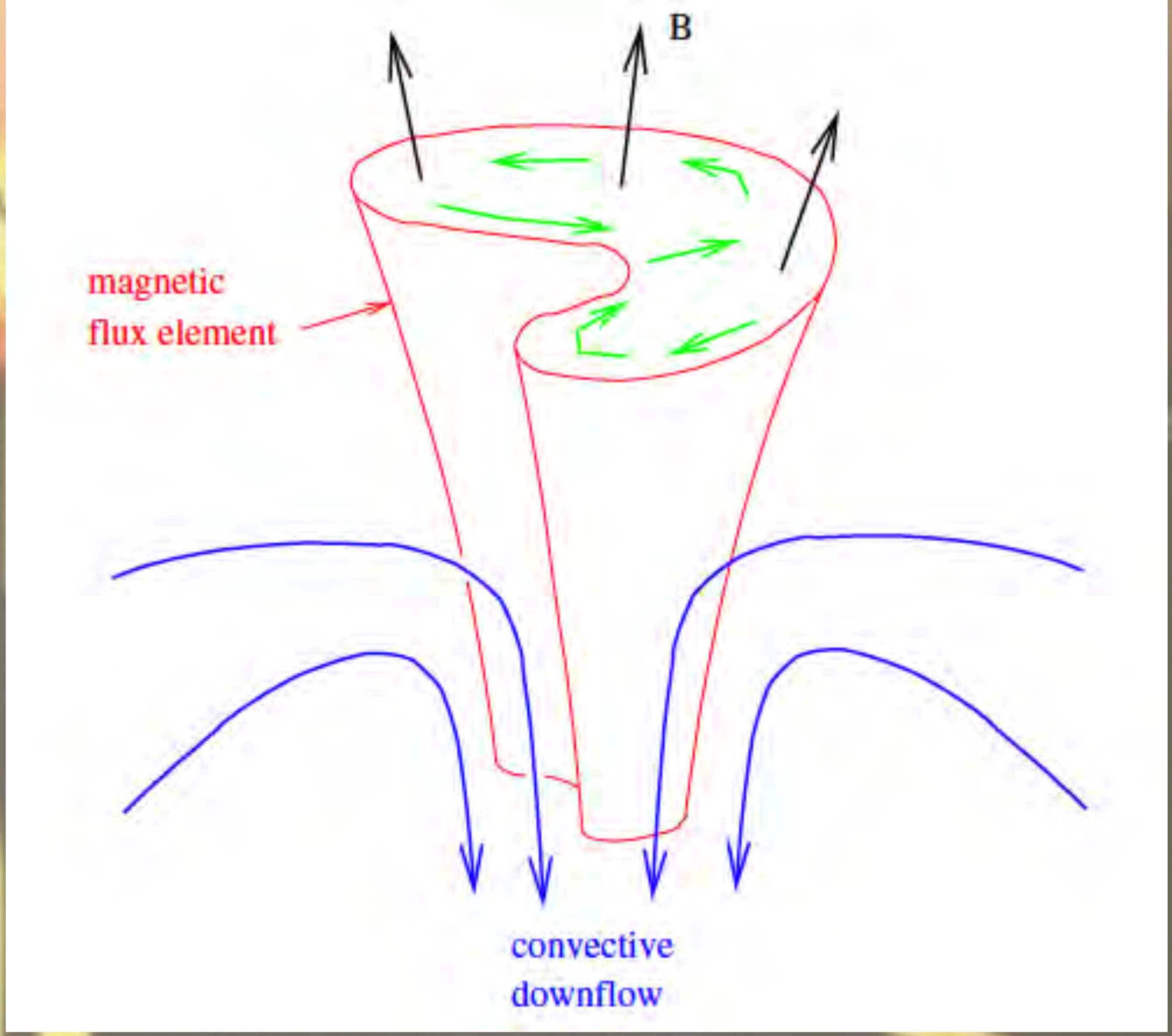





AIA 171
No evidence of
Coronal Braiding
AIA 171 15-Apr-2011 00:15:00

Waves

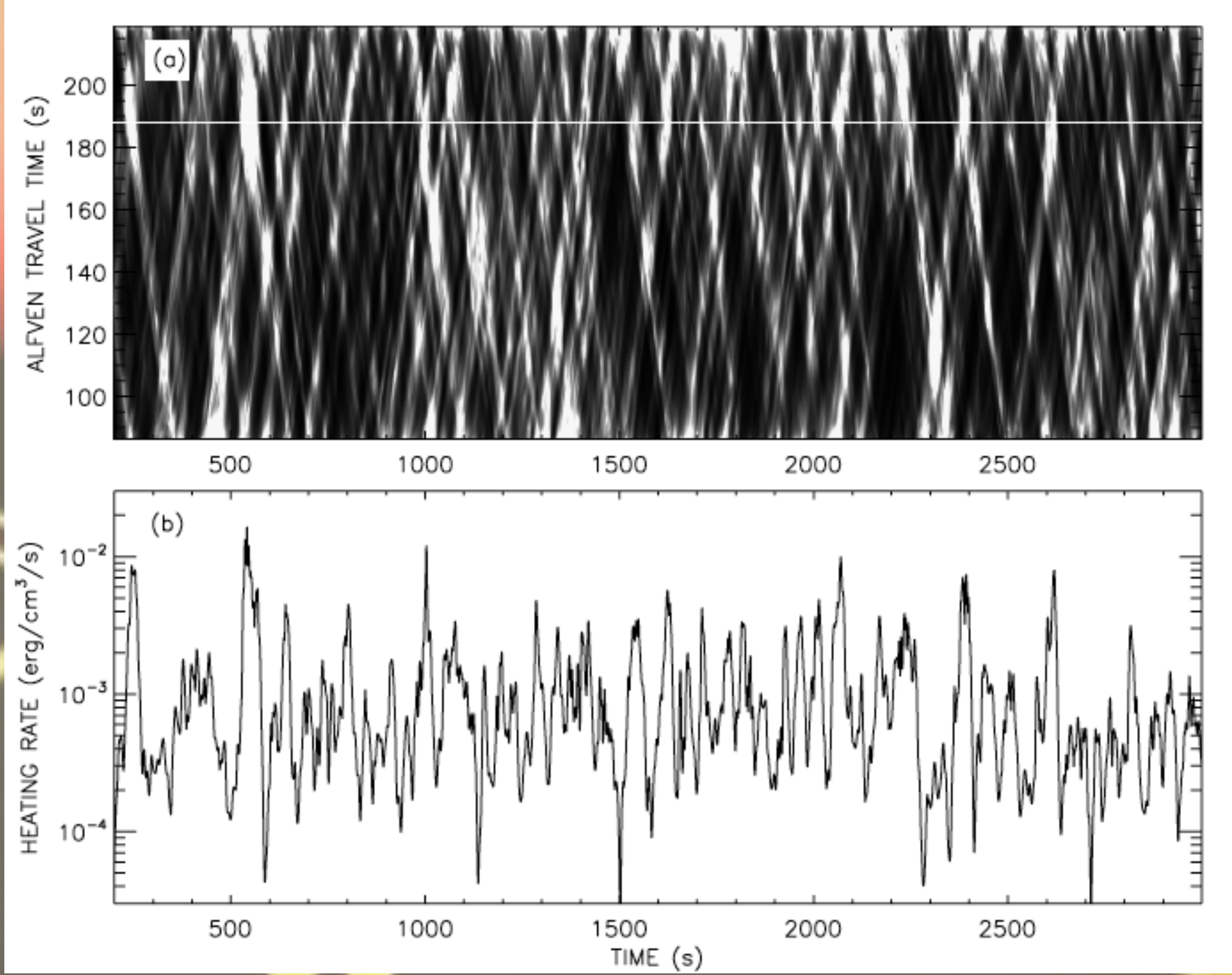
Alfven Waves dissipated by turbulence



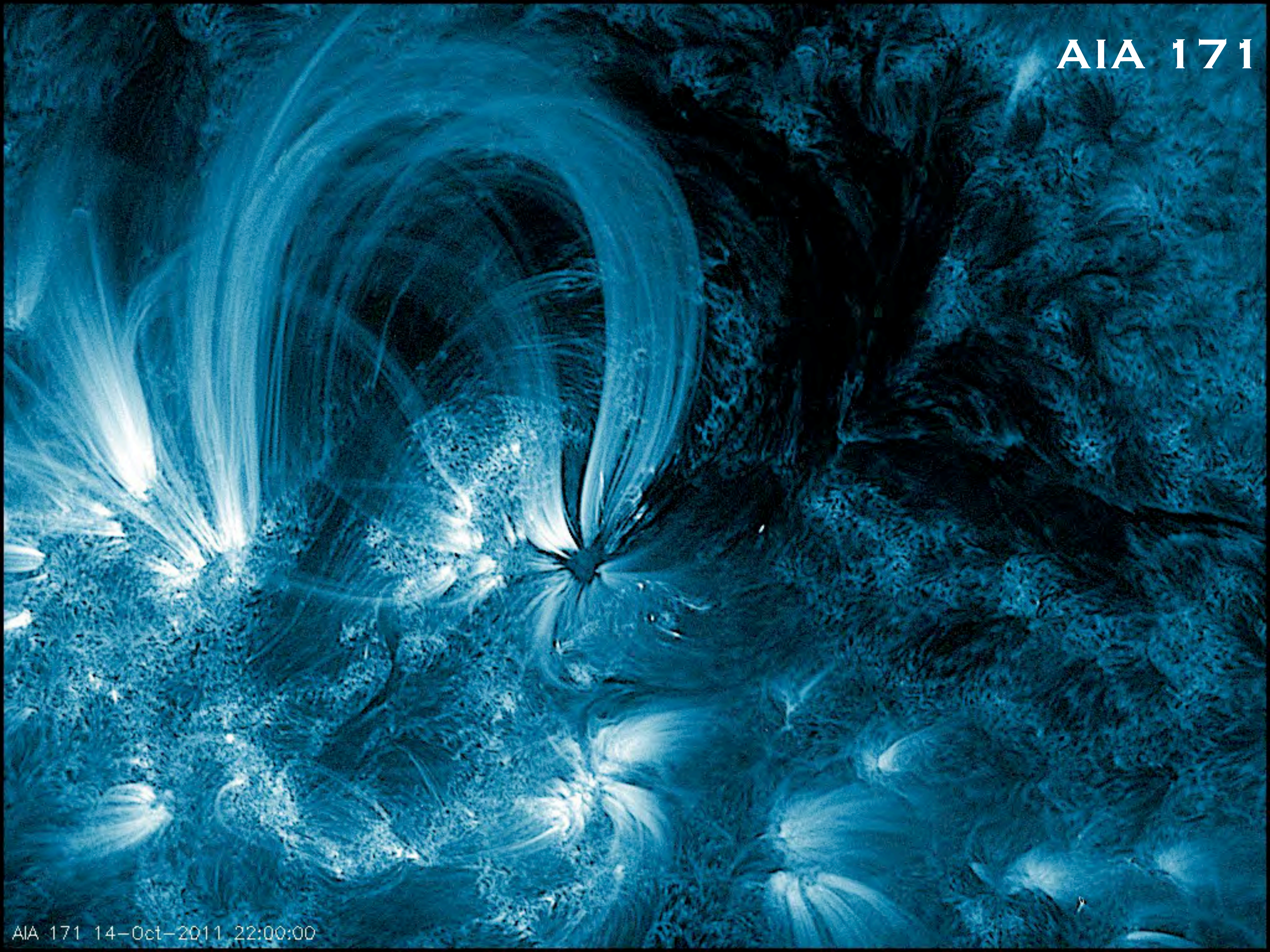
van Ballegooijen, et al. ApJ 2011

Waves

Heating along a single strand would be high-frequency (quasi-steady)

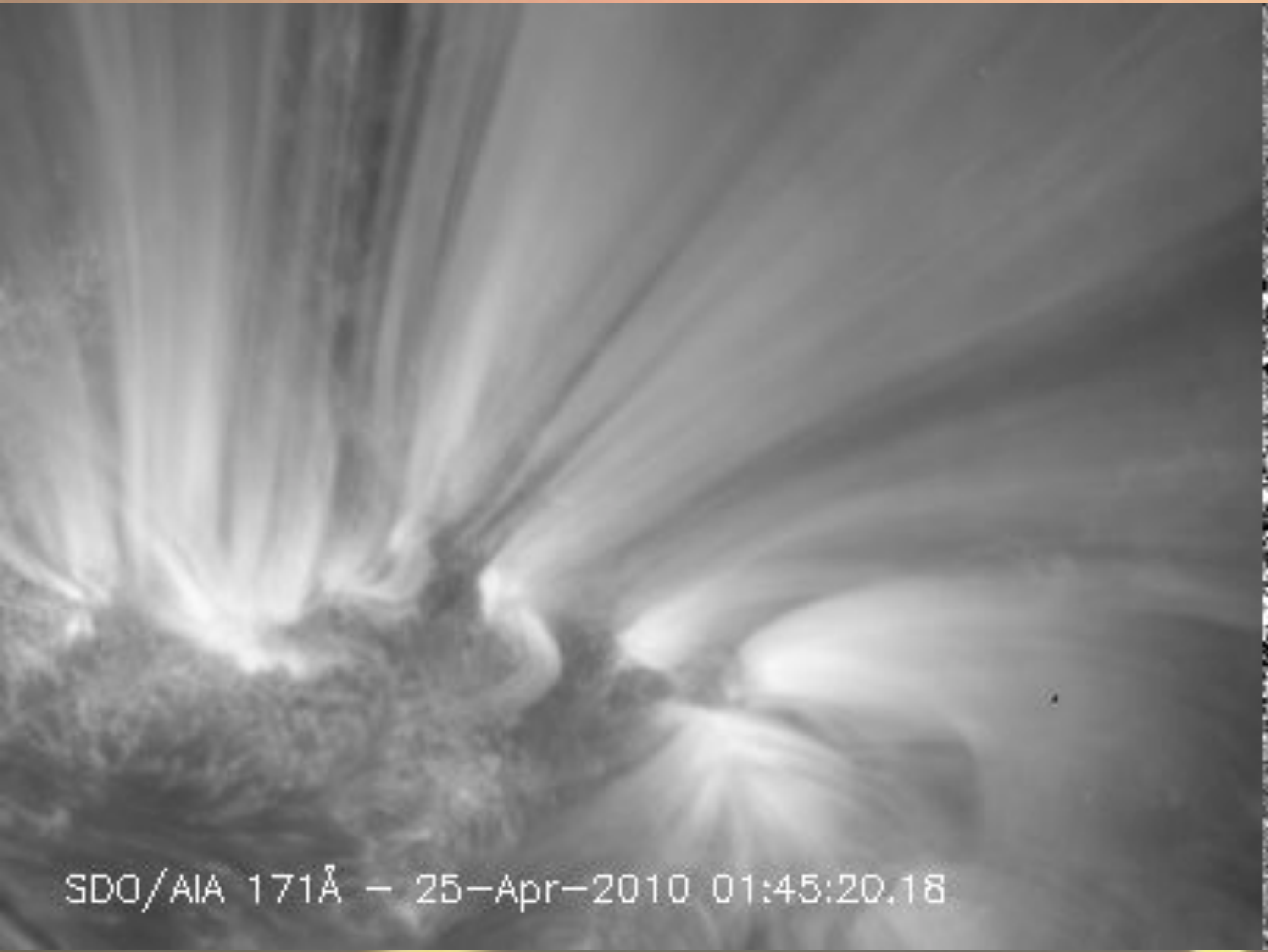


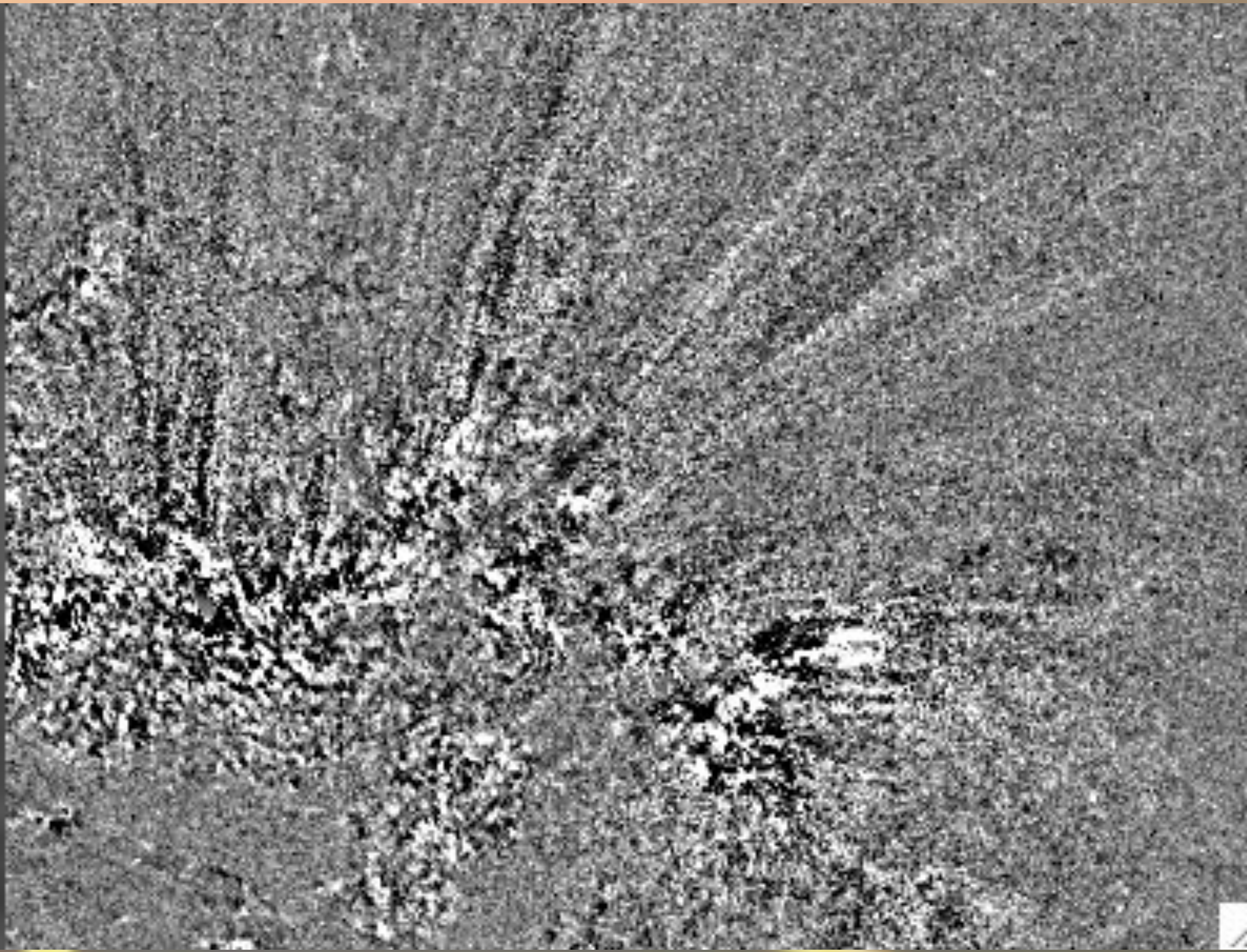
Asgari-Targhi & van Ballegooijen, ApJ 2012


AIA 171
AIA 171 14-Oct-2011 22:00:00

Waves are ubiquitous

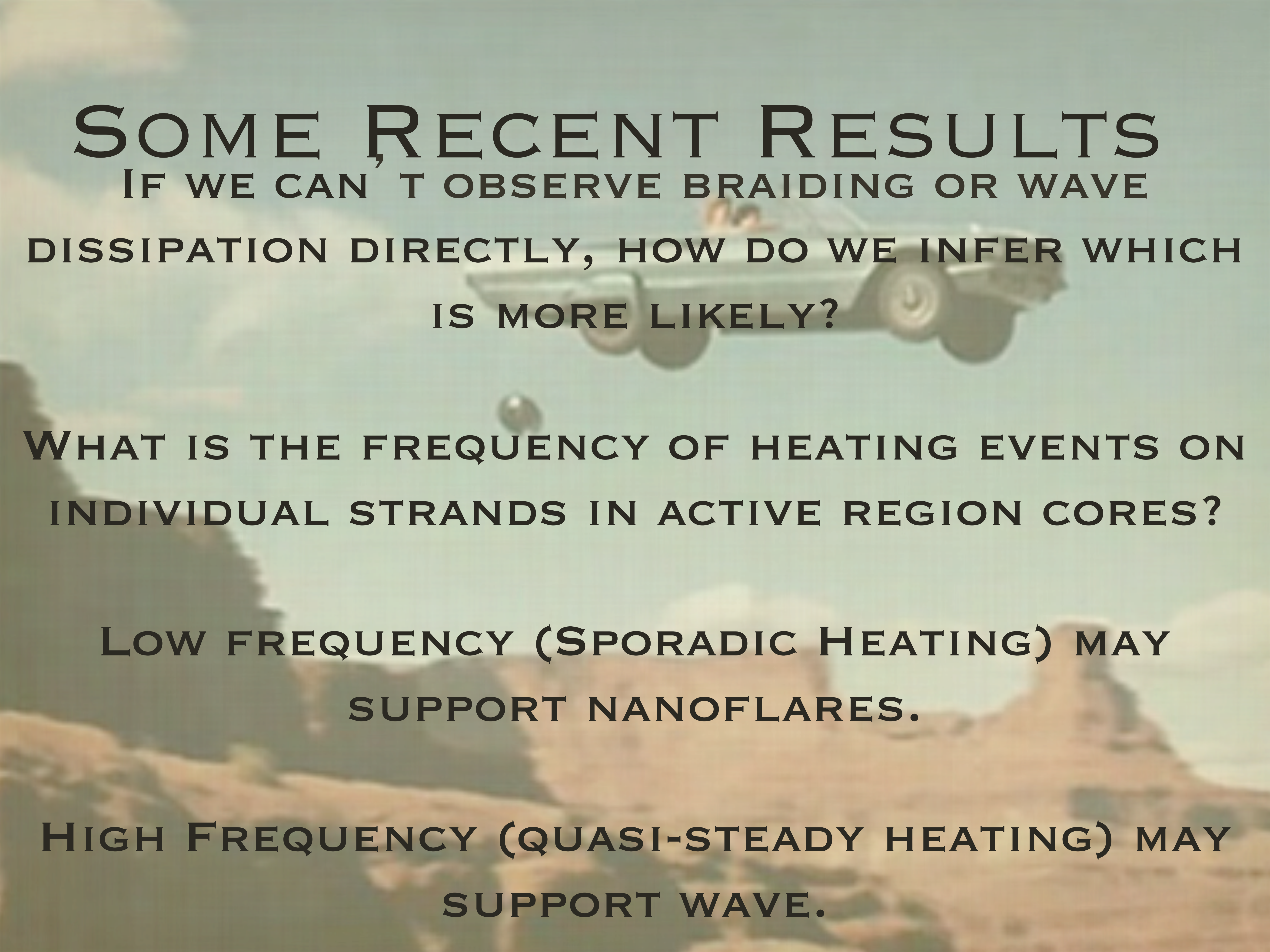
Waves are simply everywhere





Scott McIntosh

Some Recent Results



Some Recent Results

If we can't observe braiding or wave dissipation directly, how do we infer which is more likely?

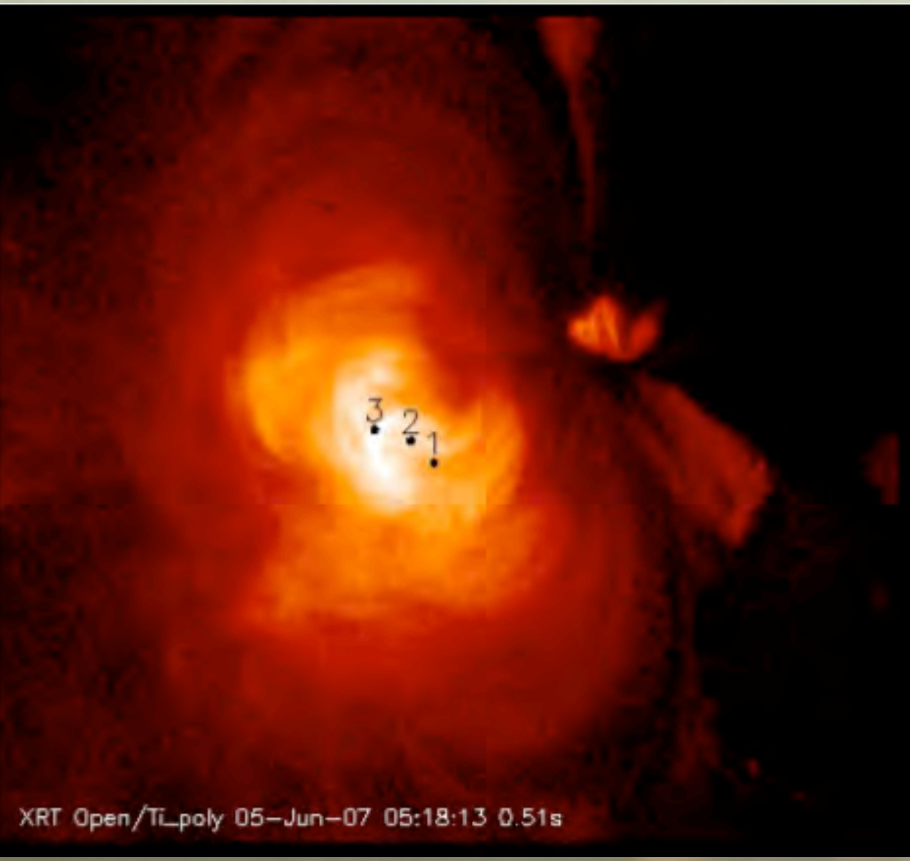
What is the frequency of heating events on individual strands in active region cores?

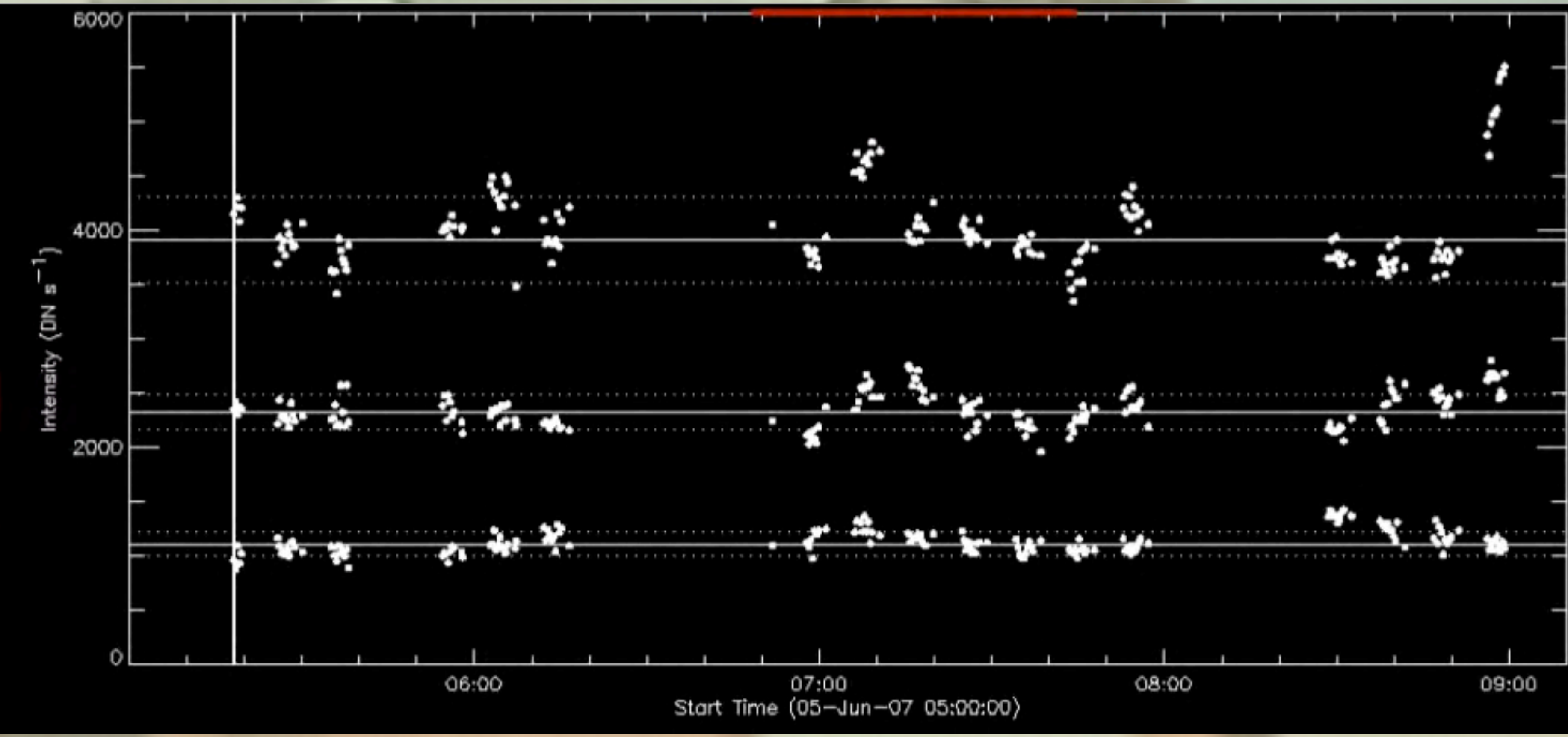
Low frequency (Sporadic Heating) may support nanoflares.

High Frequency (quasi-steady heating) may support wave.

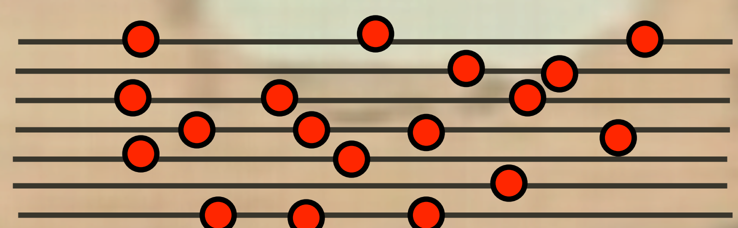
Active Region Core

- Steady, high temperature Intensity





Low Frequency Heating



High Frequency Heating

Modeling Frequency

- Solved the one-dimensional hydrodynamic equations for density, temperature, and velocity(s,t)

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial s}(\rho v) = 0$$

$$\frac{\partial}{\partial t}(\rho v) + \frac{\partial}{\partial s}\left(\rho v^2\right) = -\frac{\partial}{\partial s}(p) - \rho g_{\|}$$

$$\frac{\partial}{\partial t}\left(\frac{1}{2}\rho v^2 + \frac{p}{\gamma - 1}\right) +$$

$$\frac{\partial}{\partial s}\left(\frac{1}{2}\rho v^3 + \frac{\gamma p v}{\gamma - 1}\right) = -\rho v g_{\|} +$$

$$E_H - n_{\mathrm{e}}^2 P(T) + \frac{\partial}{\partial s}\left(\kappa \frac{\partial T}{\partial s}\right)$$

Unknown Energy Deposition.

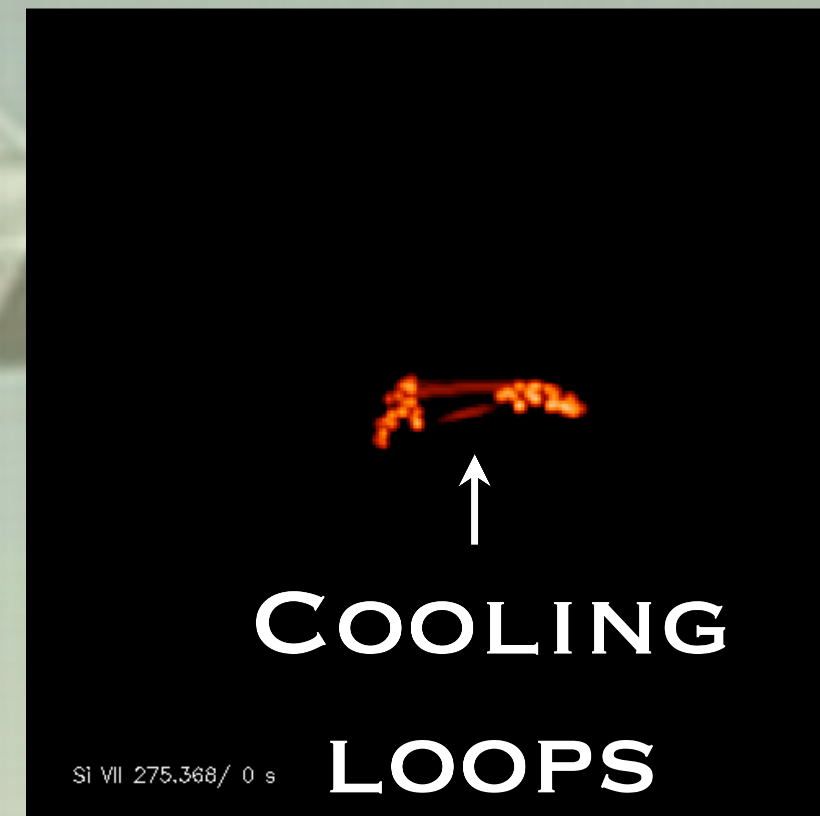
Choosing Energy Function

- assumed the heating of the strands was:

$$E_H(s,t) = E_0 + g(t)E_F \exp\left(\frac{(s-s_0)^2}{2\sigma_s^2}\right)$$

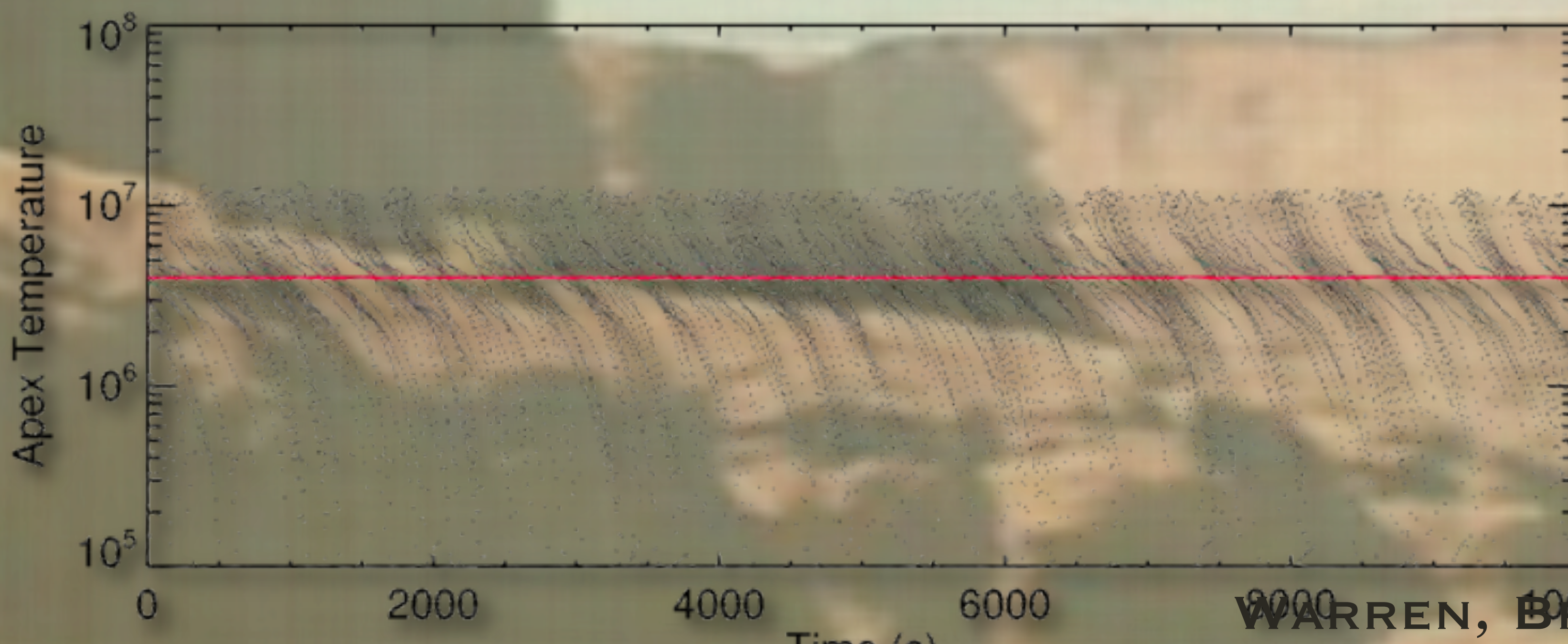
- where g(t) is a triangular pulse, E_F is the magnitude of the heating event and E_O is a small background heating
- The period of the heating = Tau

Low frequency heating



$\tau \sim \tau_{cool}$

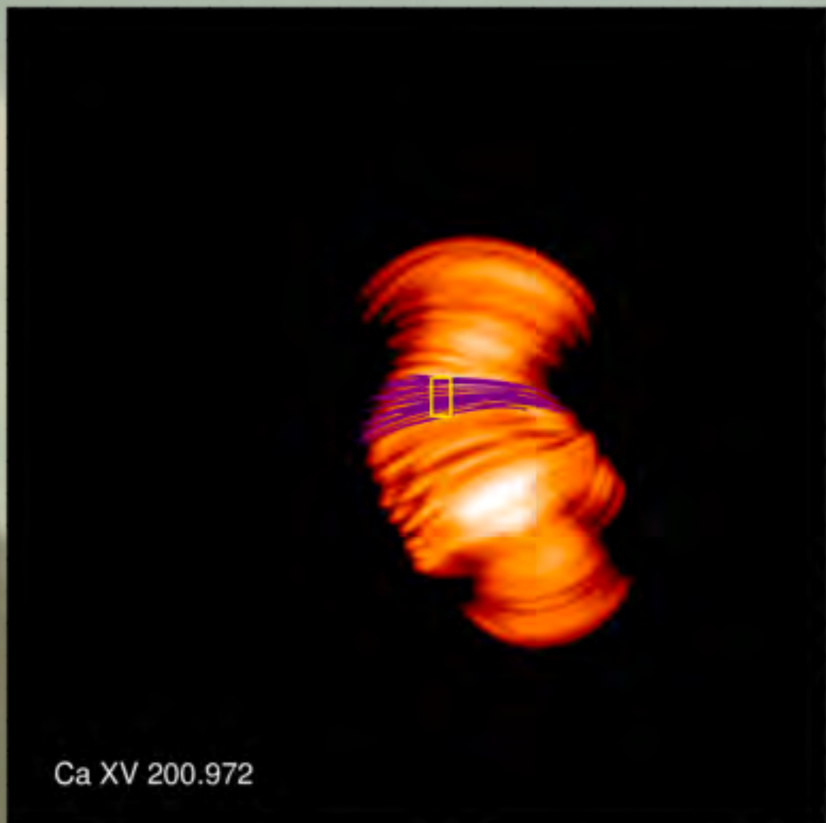
$\tau = 1200 \quad \delta = 67$



Excess high and low temperature emission

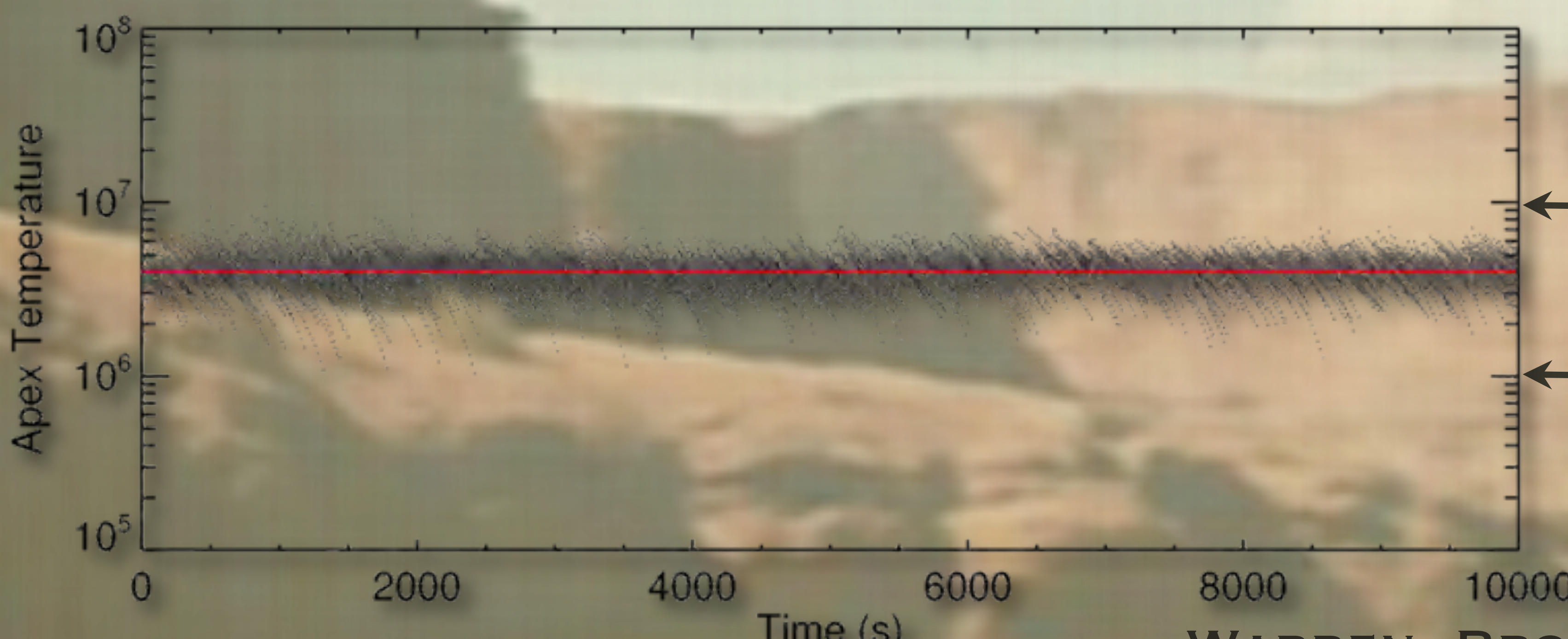
Warren, Brooks, & Winebarger, ApJ, 2011

High frequency heating



No Loops Cooling to 1 MK

$$\tau \ll \tau_{cool} \qquad \tau = 150 \quad \delta = 13$$



Almost no high or low temperature emission

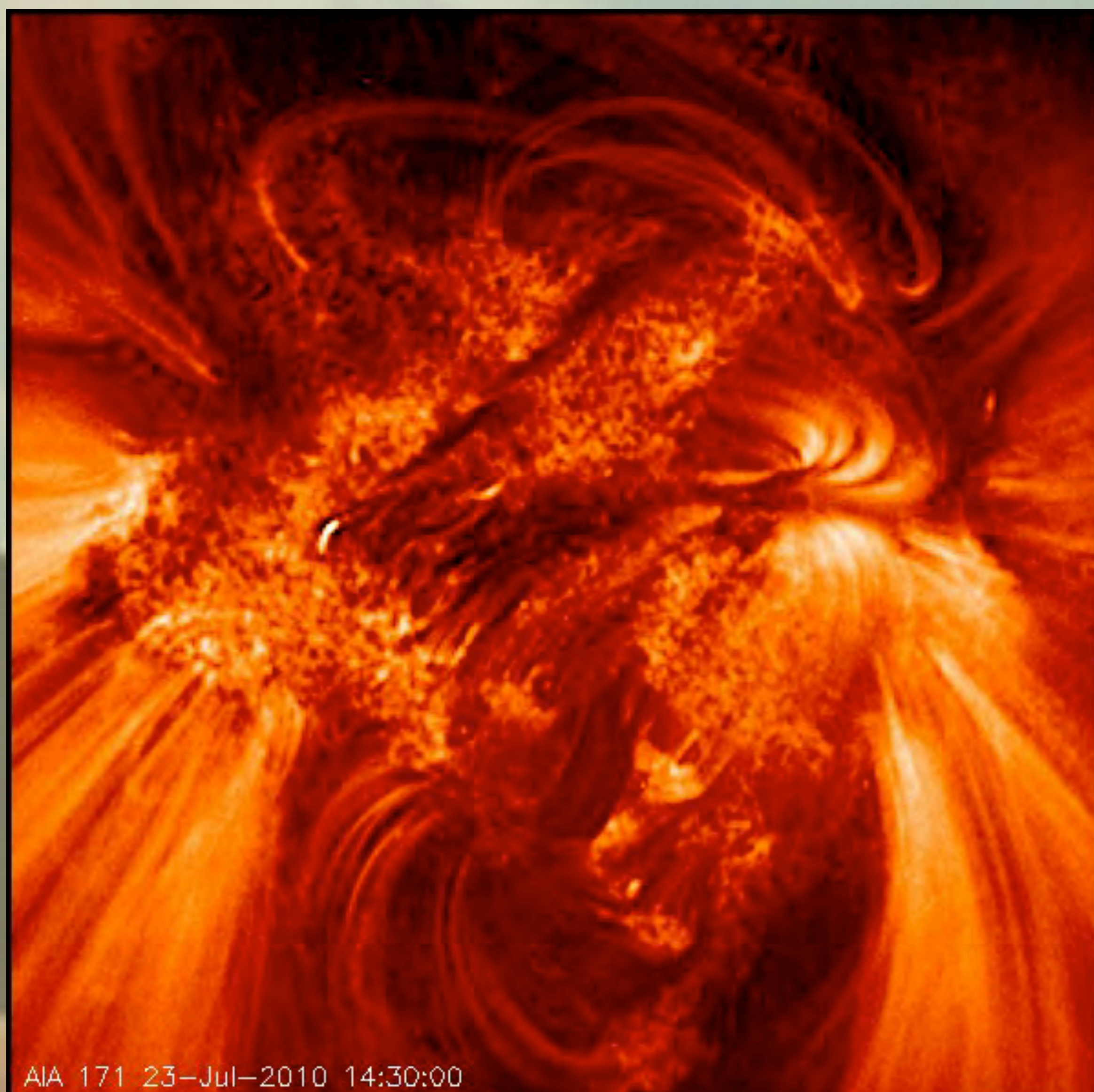
Warren, Brooks, & Winebarger, ApJ, 2011

What is the Frequency of Heating in the Core?

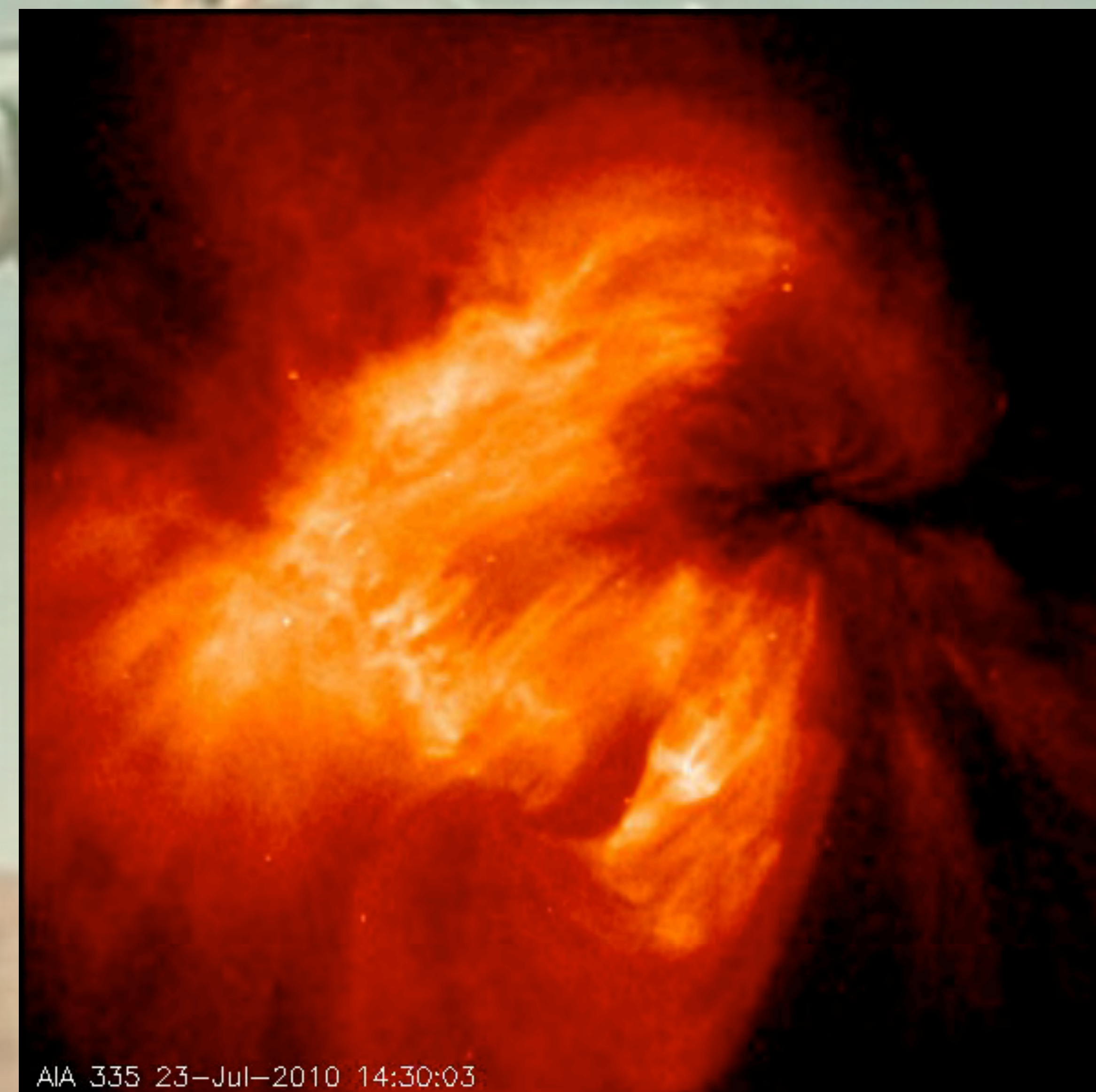
- Are there cooling Loops in the core?
- Is there enhanced warm (1 MK) emission?
- Does the core have a hot plasma Component?

	Cooling	Significant Warm Emission	Hot Plasma
high frequency (waves)	no	no	No
Low [illegible]	[illegible]	[illegible]	[illegible]

Not many cooling loops



AIA 171
Å

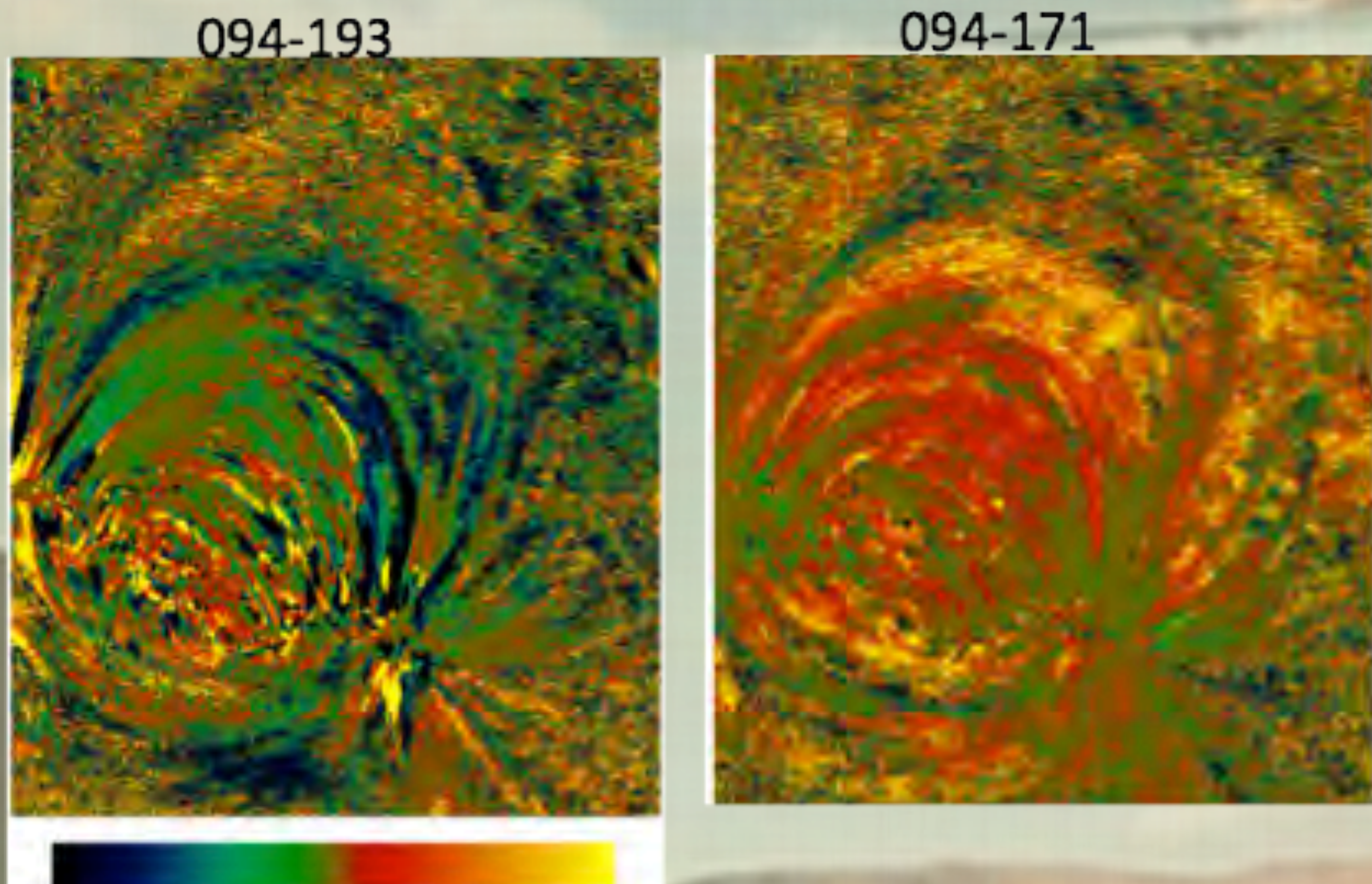


AIA 335
Å

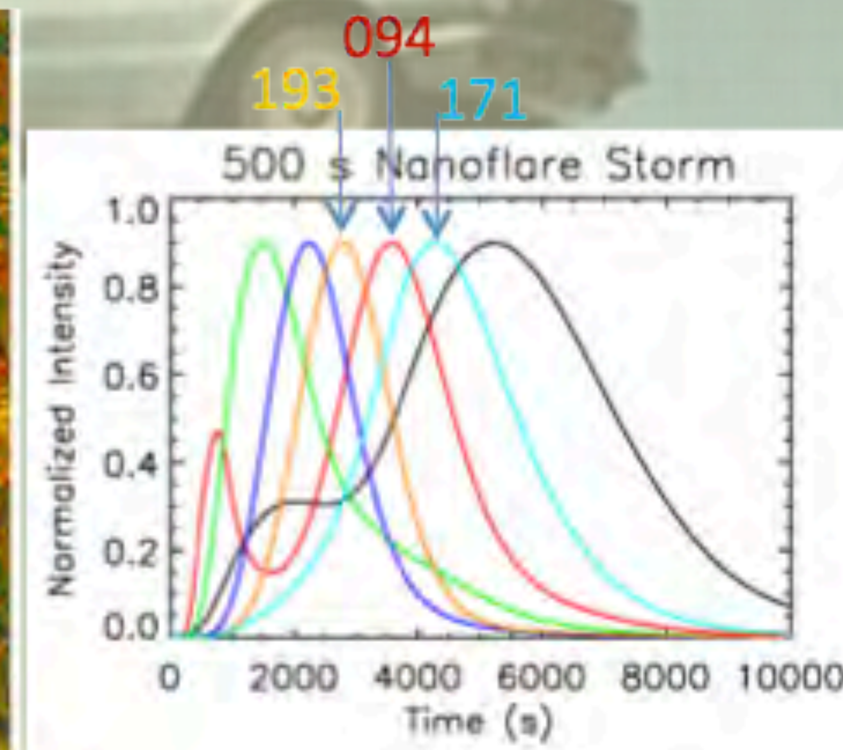
Warren, Brooks, & Winebarger, ApJ, 2011

Cooling everywhere!

Time-Lag Maps



Correlated backwards in time | zero time delay | Correlated forwards in time



- Based on this nanoflare storm model, we expect to see 193, then 094, then 171
- 094-193 should be backwards correlated (greens and blues)
- 094-171 should be forwards correlated (reds and oranges)
- What is going on in the active region core?

Majority of AR Structures are Cooling

Viall & Klimchuck, ApJ, 2012

What is the Frequency of Heating in the Core?

- Are there cooling Loops in the core?
- Is there enhanced warm (1 MK) emission?
- Does the core have a hot plasma Component?

	Cooling	Significant Warm Emission	Hot Plasma
high frequency (Waves)	**no**	no	No
Low			

Warm Emission

- Low frequency heating predicts additional warm (1 MK) emission.
- How much warm emission is required?

Mulu-Moore, Winebarger, & Warren, ApJ, 2011

Warm Emission

- Solved the one-dimensional hydrodynamic equations for density, temperature, and velocity(s,t)

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial s}(\rho v) = 0$$

$$\frac{\partial}{\partial t}(\rho v) + \frac{\partial}{\partial s}\left(\rho v^2\right) = -\frac{\partial}{\partial s}(p) - \rho g_{\|}$$

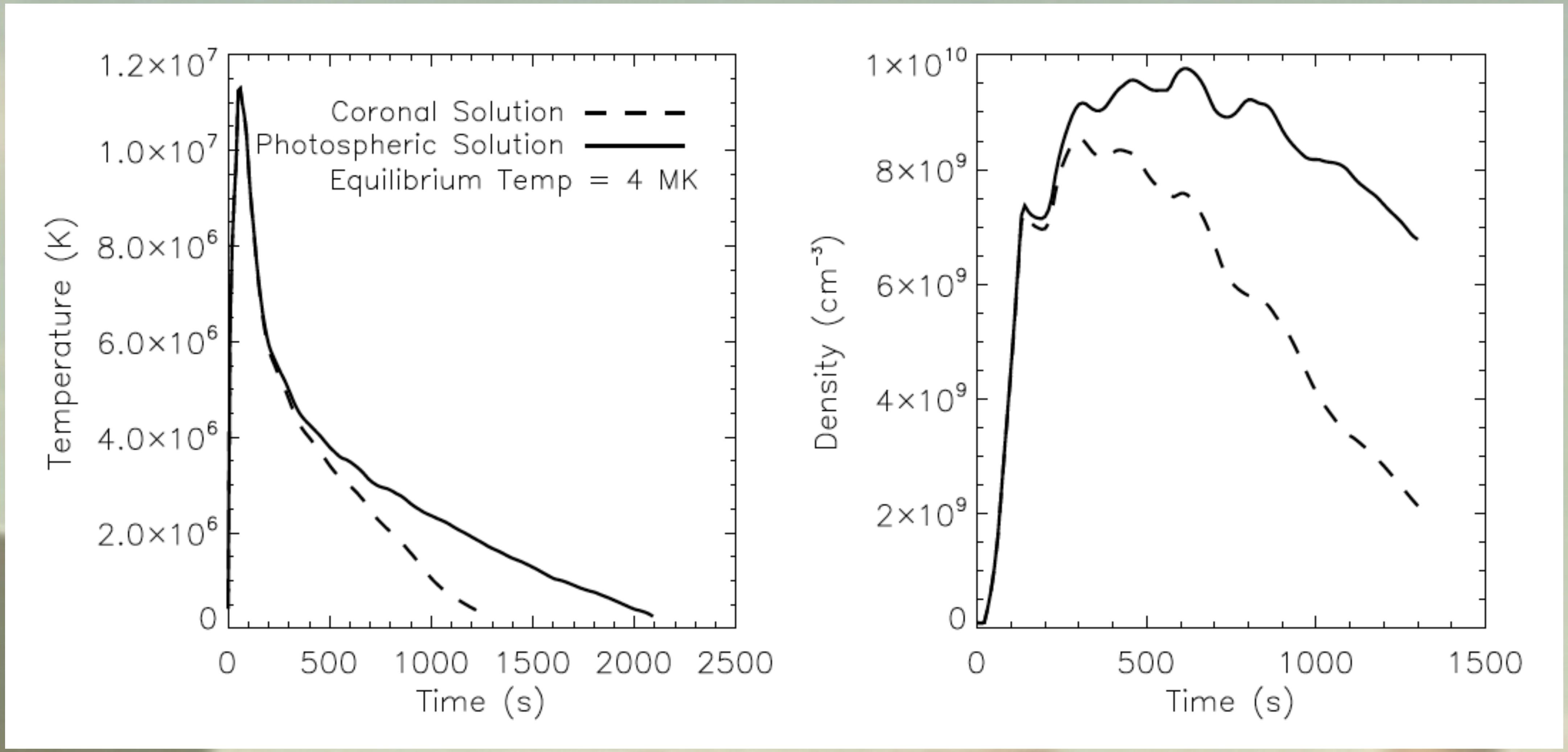
$$\frac{\partial}{\partial t}\left(\frac{1}{2}\rho v^2 + \frac{p}{\gamma - 1}\right) + \frac{\partial}{\partial s}\left(\frac{1}{2}\rho v^3 + \frac{\gamma p v}{\gamma - 1}\right) = -\rho v g_{\|} + E_H - n_{\mathrm{e}}^2 \boxed{P(T)} + \frac{\partial}{\partial s}\left(\kappa \frac{\partial T}{\partial s}\right)$$

The radiative losses depend on the composition of the plasma.

We run each simulation twice for coronal and photospheric abundances

Mulu-Moore, Winebarger, & Warren, ApJ, 2011

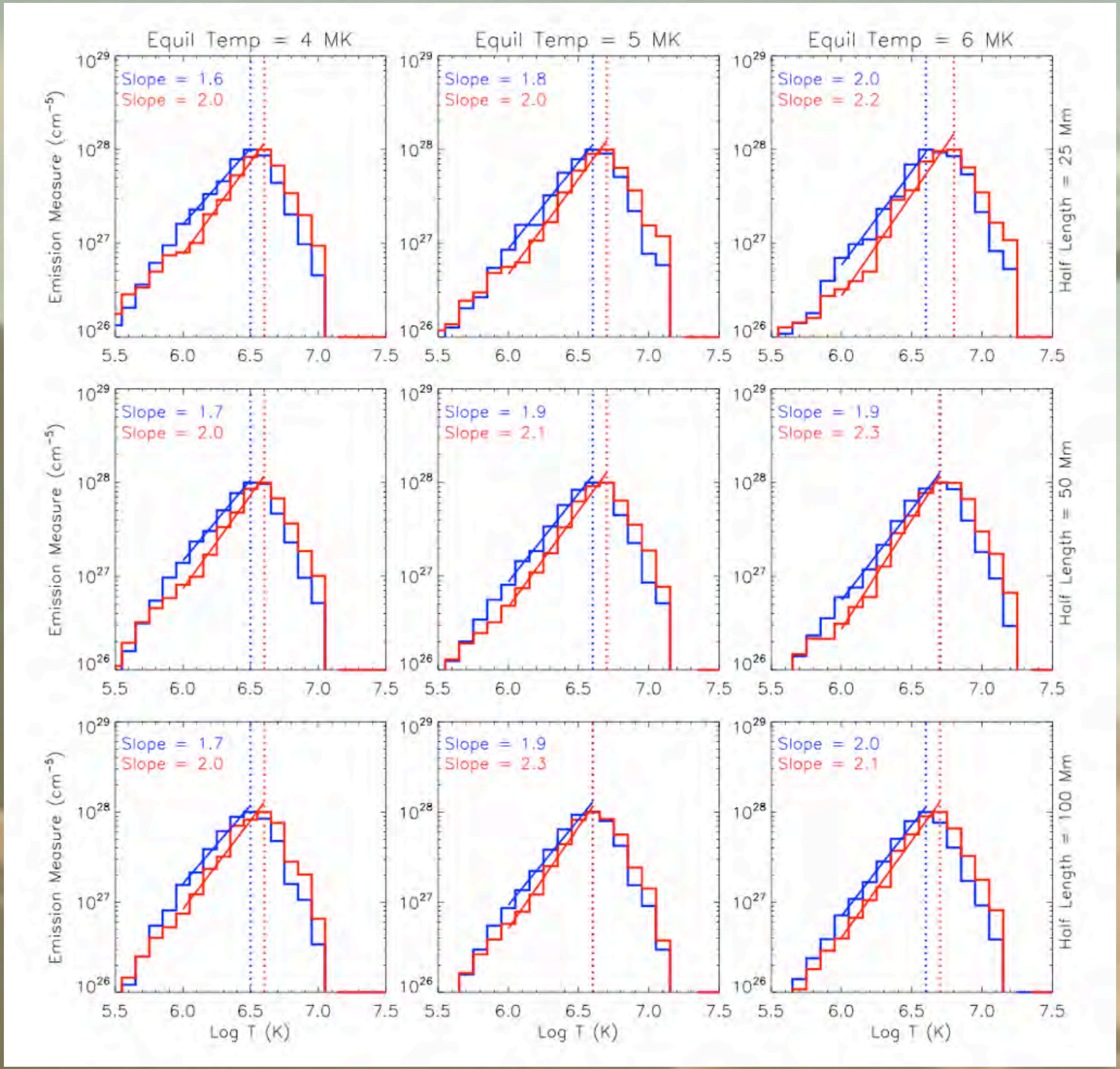
Warm Emission



- Example solution for each strand.
- We assume the loop is composed of a strand at each time step.

Mulu-Moore, Winebarger, & Warren, ApJ, 2011

Strong Warm Emission



Results from Low-Frequency "Nanoflare" Simulation

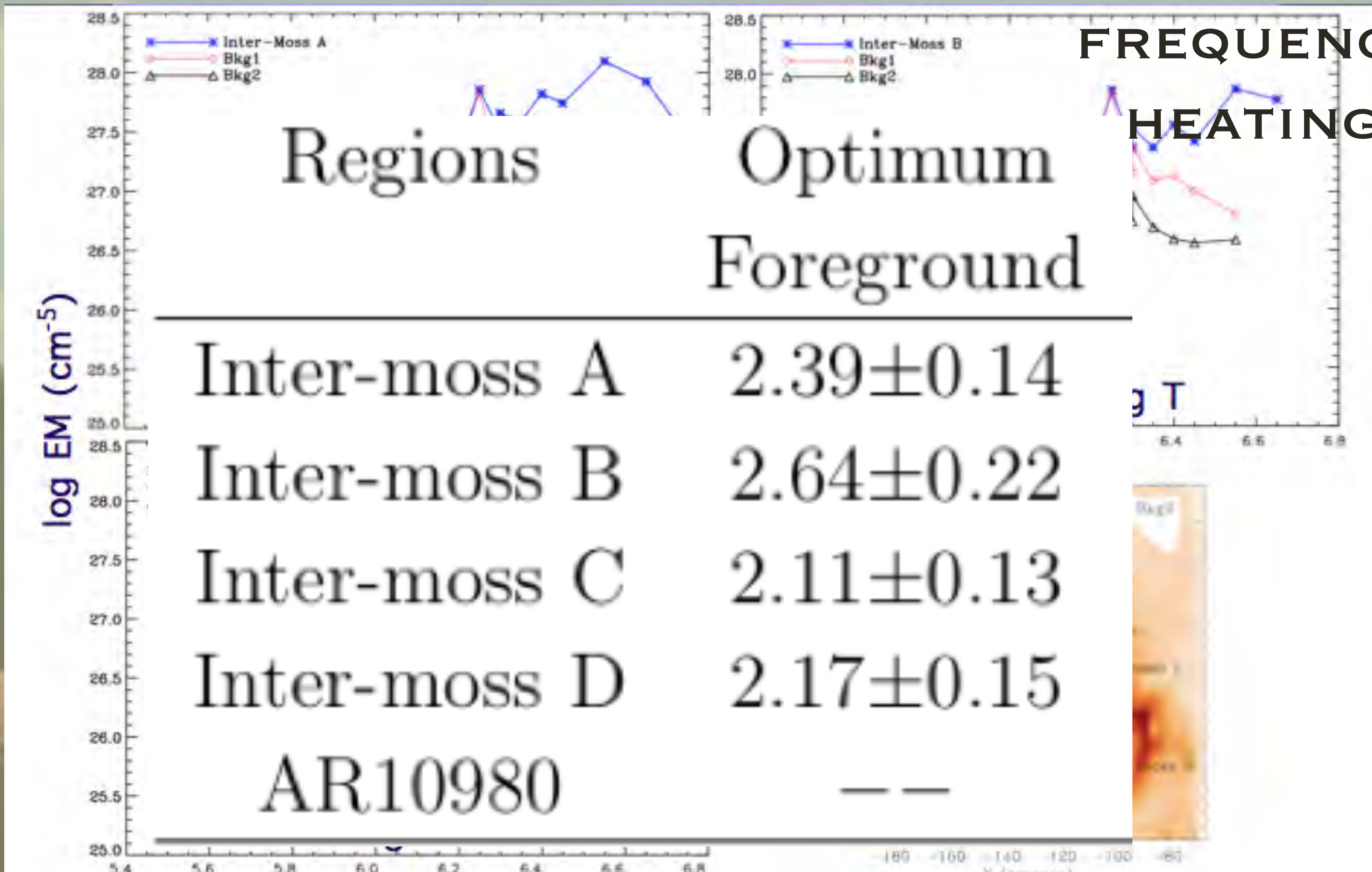
Slopes: 1.6-2.3

Average: ~2

Mulu-Moore, Winebarger, & Warren, ApJ, 2011

Warm Emission

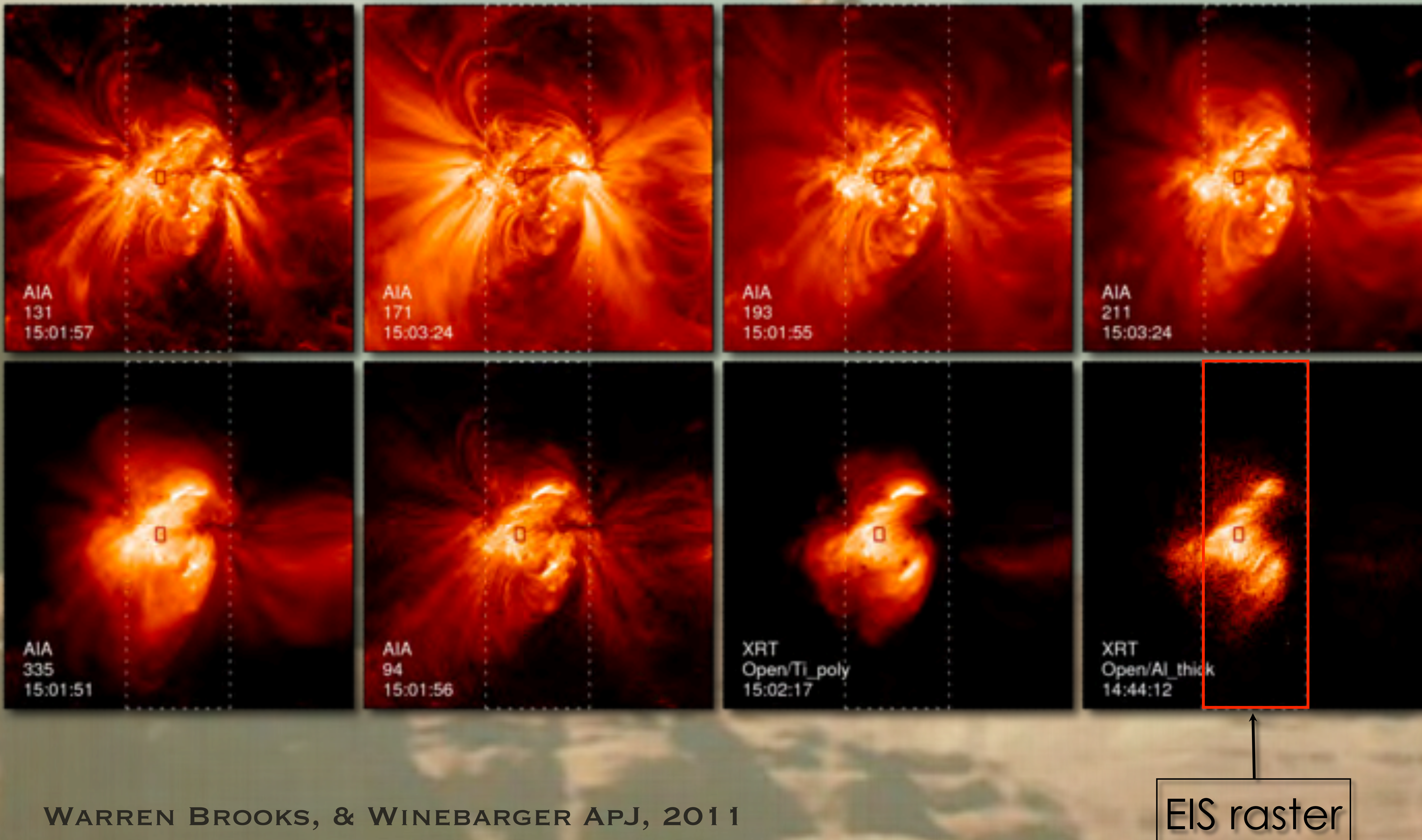
Consistent with low frequency heating



Regions	Optimum Foreground
Inter-moss A	2.39±0.14
Inter-moss B	2.64±0.22
Inter-moss C	2.11±0.13
Inter-moss D	2.17±0.15
AR10980	– –

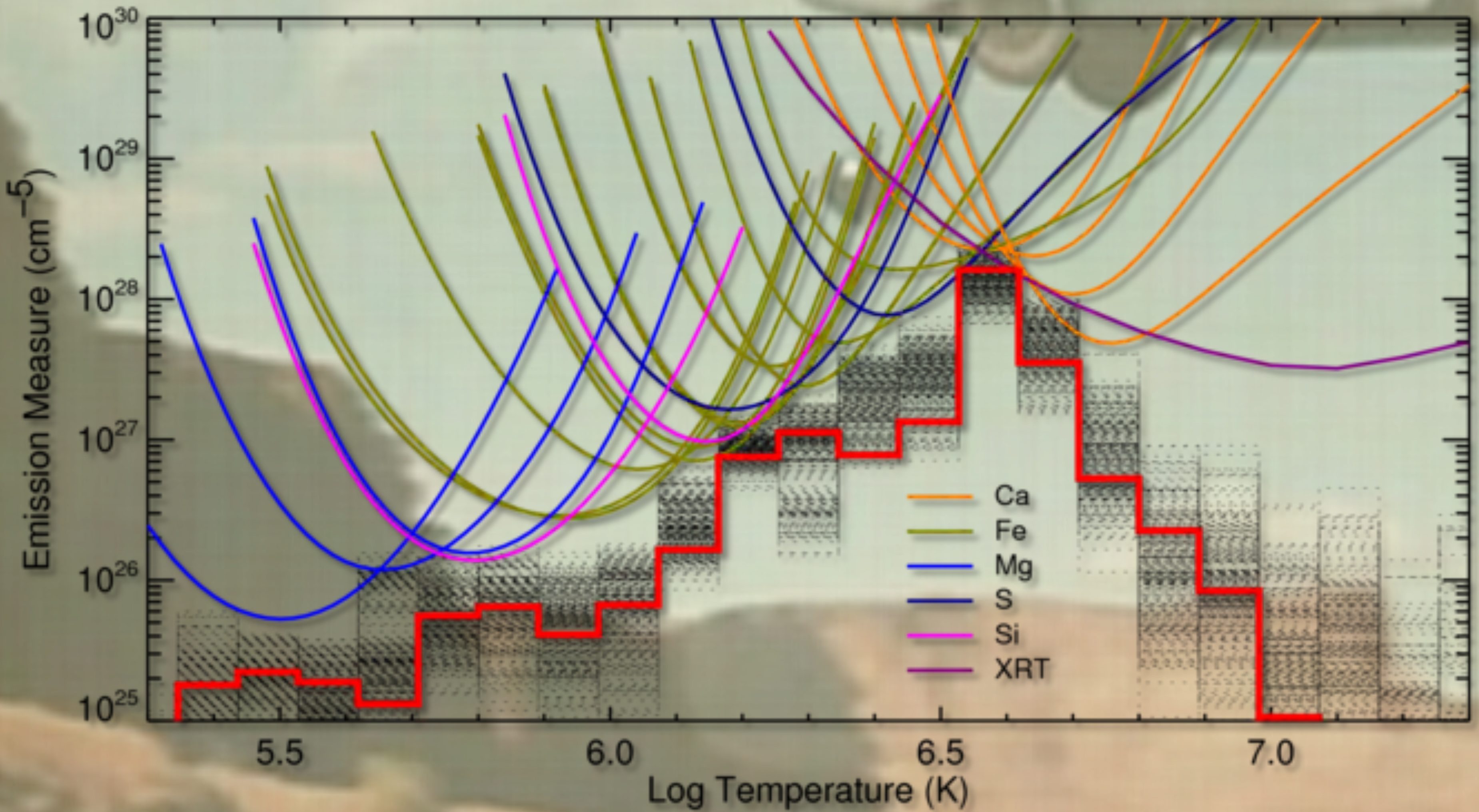
Tripathi, Mason, & Klimchuk, ApJ, 2011

Warm emission



Warren Brooks, & Winebarger ApJ, 2011

Warm Emission



Slope = 3.2

Not consistent with low frequency heating

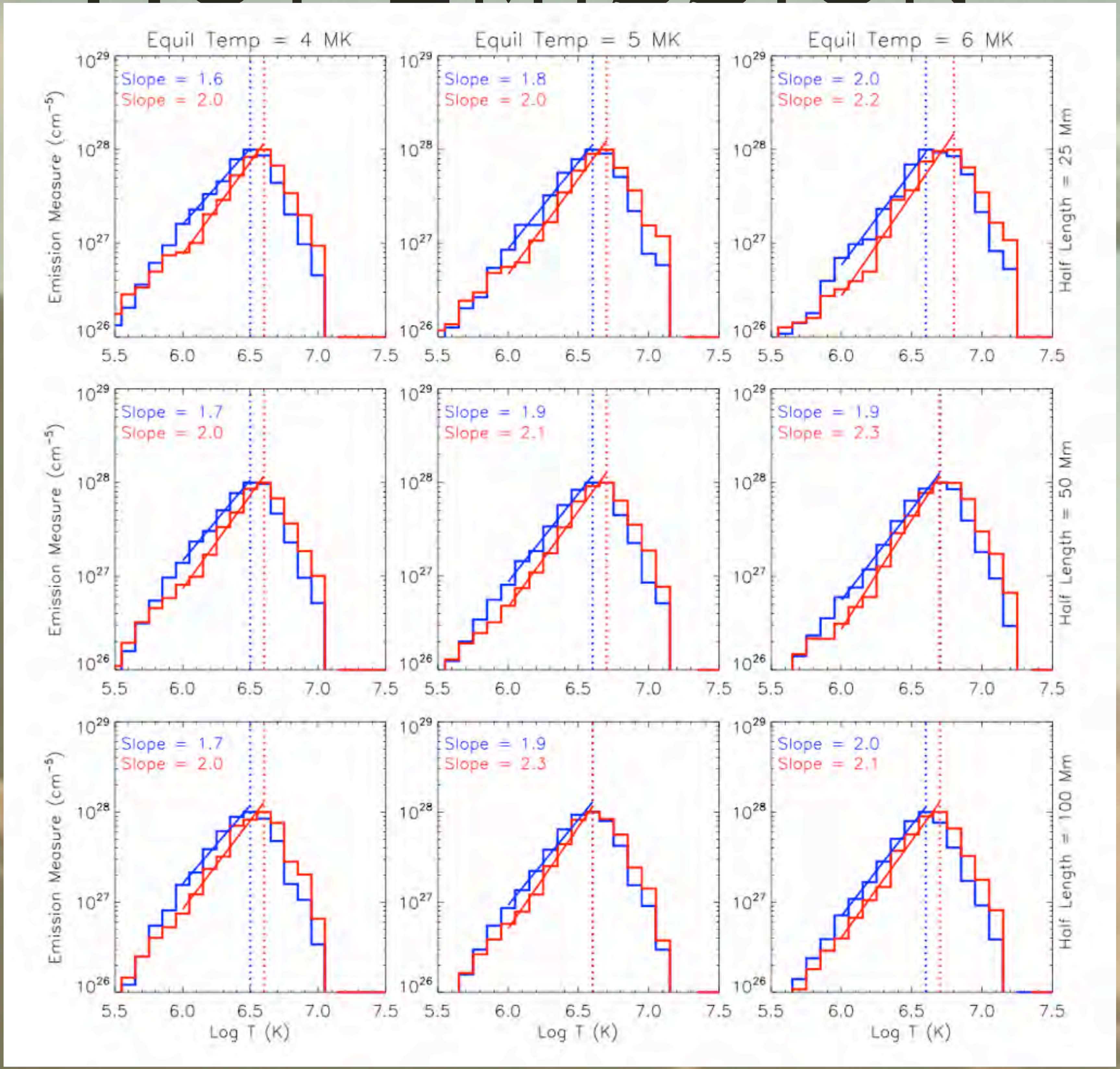
Warren Brooks, & Winebarger ApJ, 2011

What is the Frequency of Heating in the Core?

- Are there cooling Loops in the core?
- Is there enhanced warm (1 MK) emission?
- Does the core have a hot plasma Component?

	Cooling	Significant Warm Emission	Hot Plasma
high frequency (Waves)	NO	NO	No
Low			

Hot emission

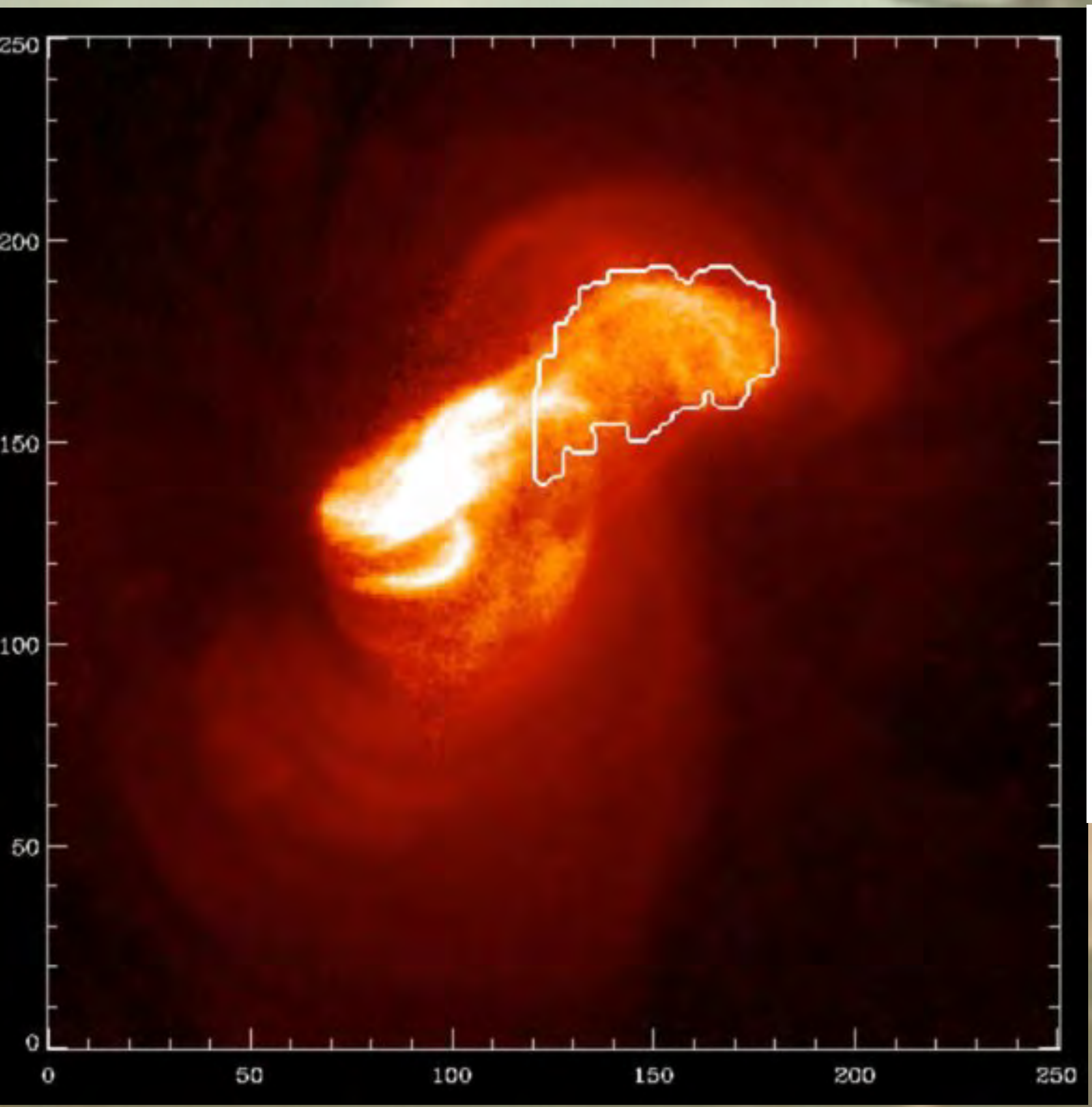


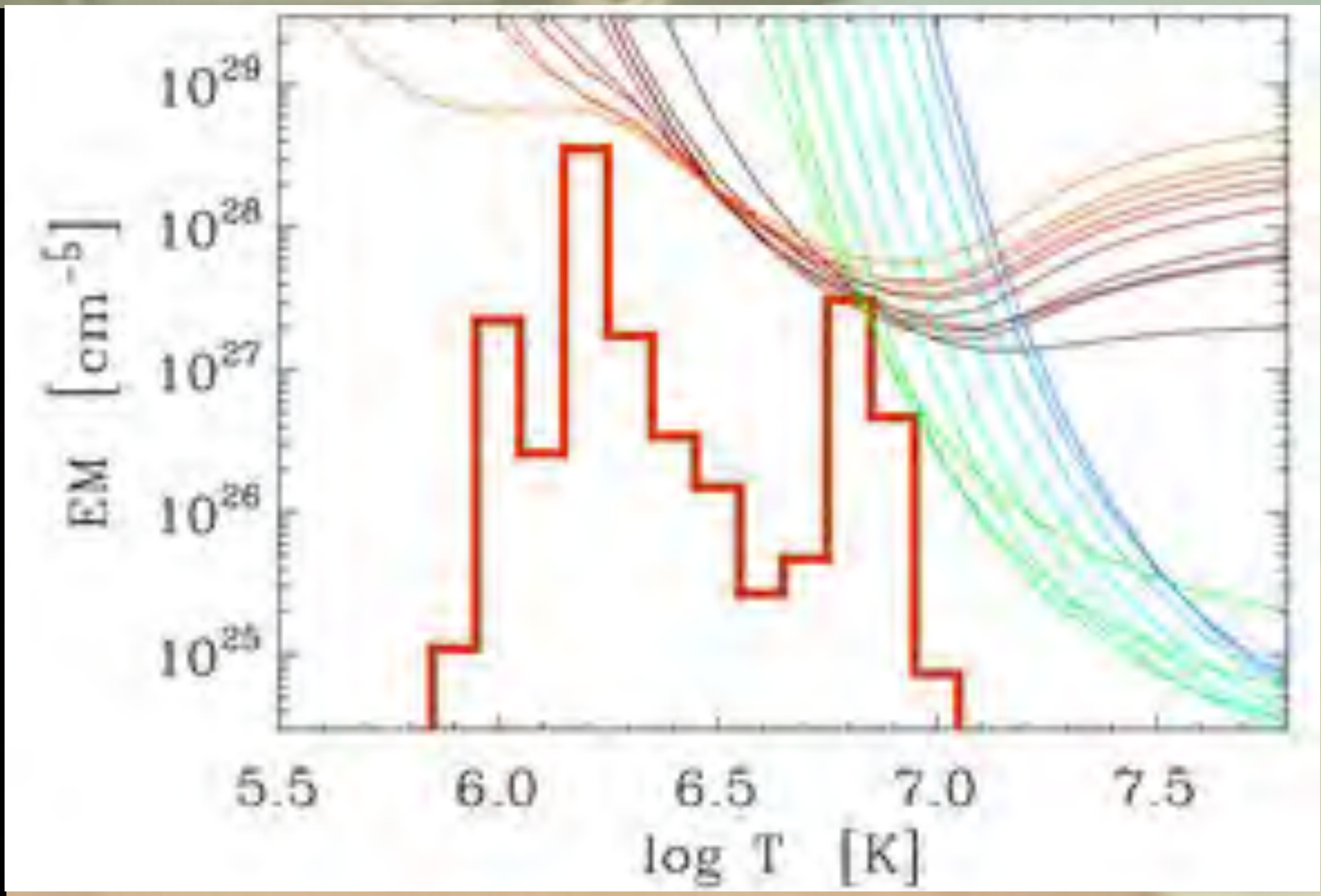
Enhanced High Temperature emission for low frequency heating is also predicted

Mulu-Moore, Winebarger, & Warren, ApJ, 2011

Hot emission

Several recent studies have found evidence of high temperature (8-10 MK) plasma

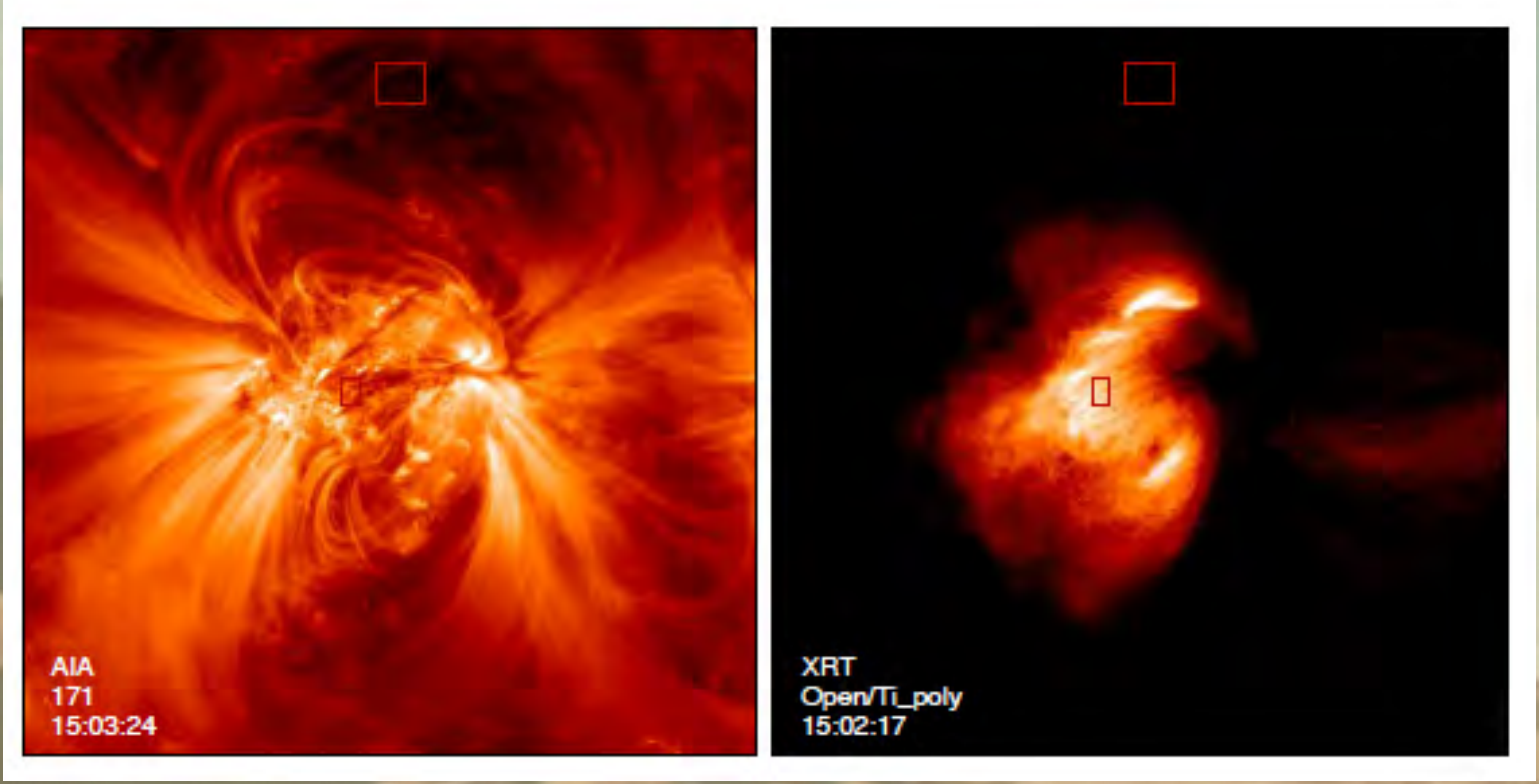




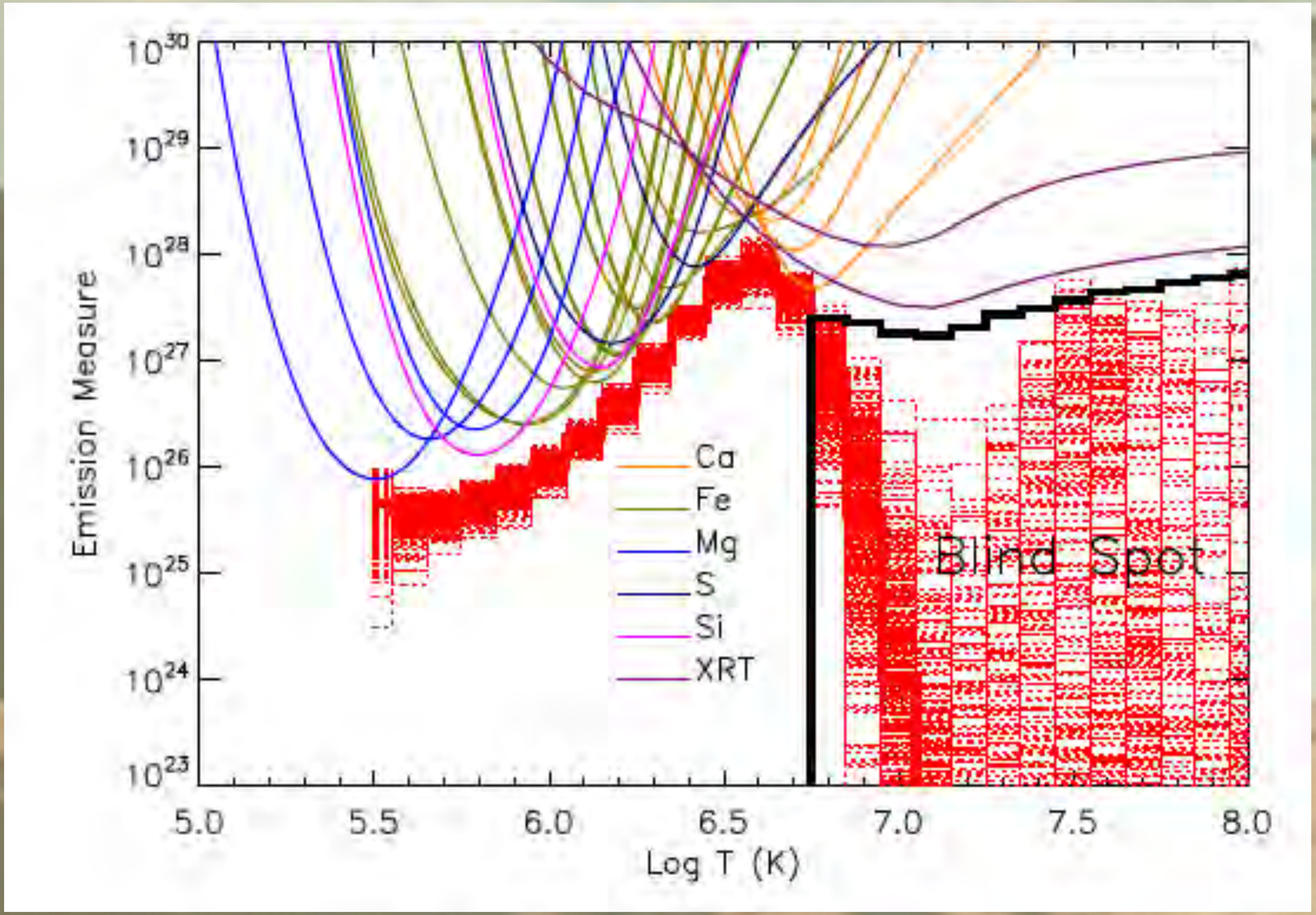
Schmelz et al. (2009)

also see Reale et al. (2009) and Shestov et al. (2010)

Hot emission



Hot emission



EIS & XRT cannot reliably detect high temperature plasma.

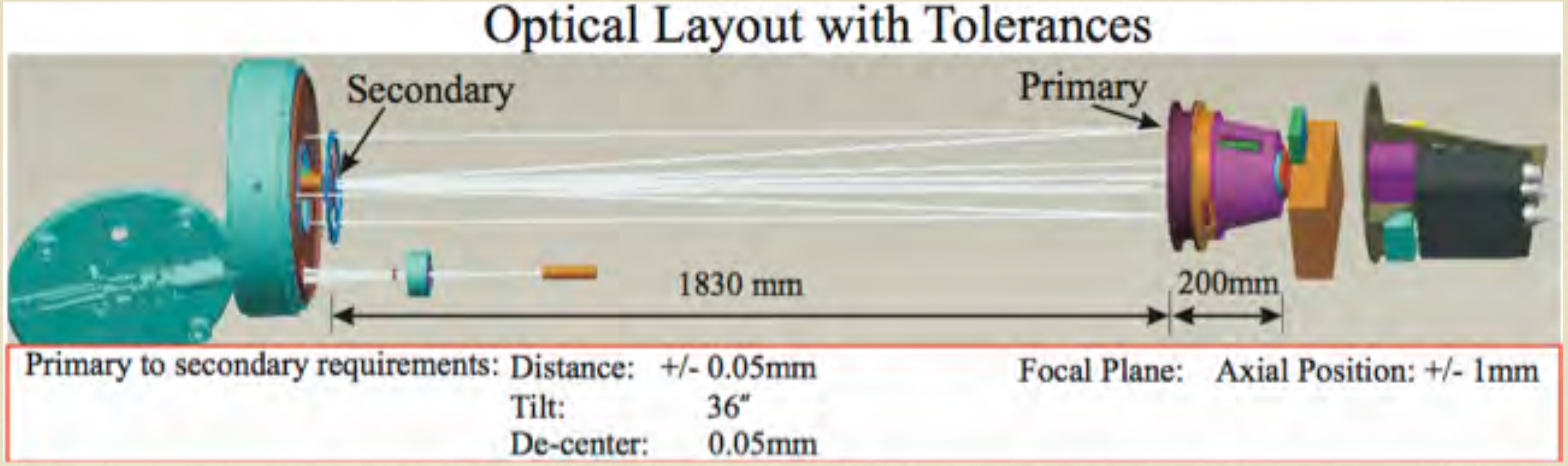
What is the Frequency of Heating in the Core?

- Are there cooling Loops in the core?
- Is there enhanced warm (1 MK) emission?
- Does the core have a hot plasma Component?

	Cooling	Significant Warm Emission	Hot Plasma
high frequency (Waves)	no	no	Wrong Instrument
Low			

The hunt for direct evidence of coronal braiding

High-resolution Coronal Imager (Hi-C)



- Images the sun in the 193 A passband (EUV, 1.5 MK)

- Spatial resolution is 36x that of other instruments

Hi-C Partner Institutions

NASA Marshall Space Flight Center (MSFC)
University of Alabama – Huntsville (UAH)
Smithsonian Astrophysical Observatory (SAO)
University of Central Lancashire, UK (UCLAN)
Lockheed Martin Solar and Astrophysical Laboratory (LMSAL)
Southwest Research Institute (SWRI)
Lebedev Institute (LI)

Hi-C Team Members

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Science Team:
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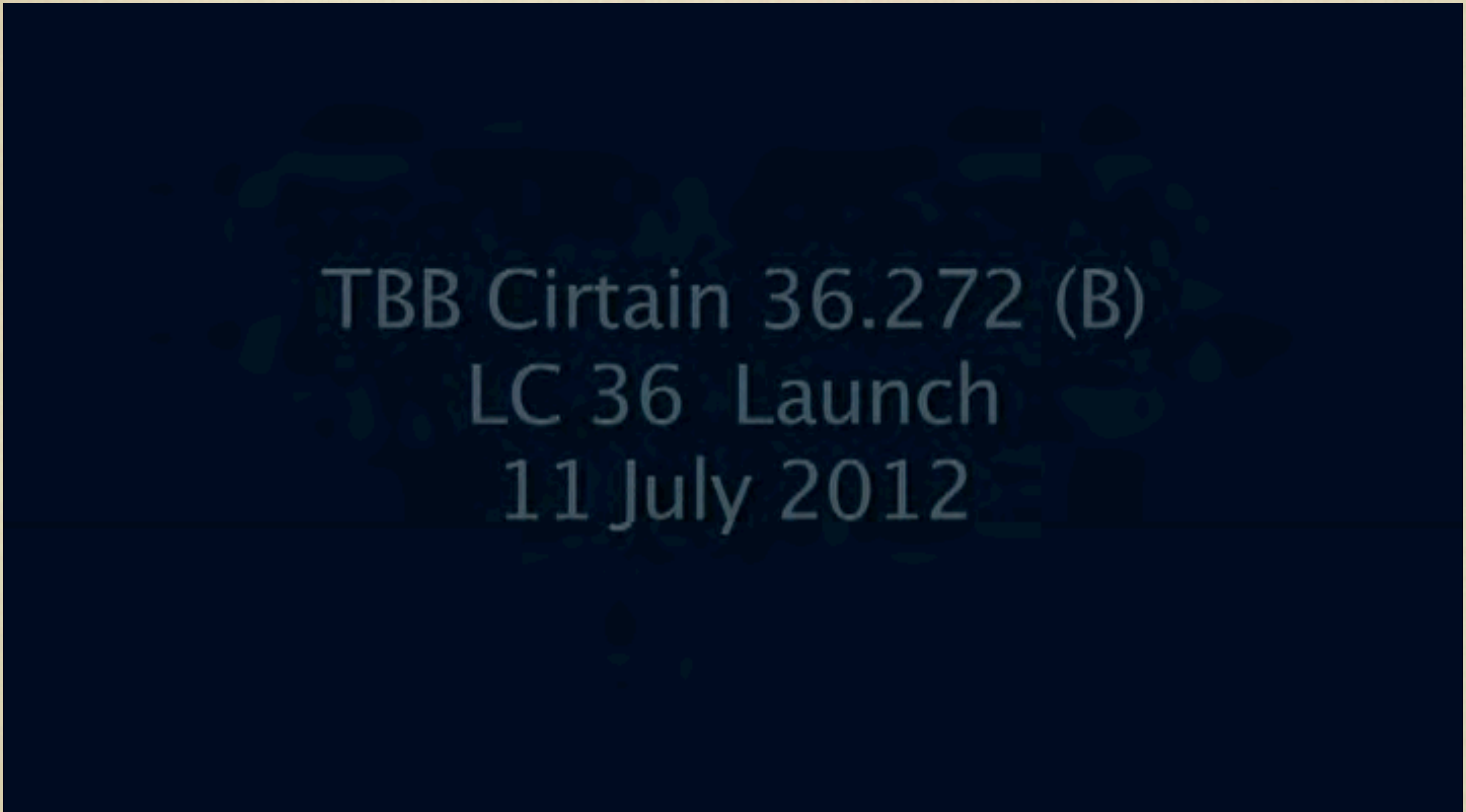
Ken Kobayashi (UAH)
Kelly Korreck (SAO)
Robert Walsh (UCLAN)
Amy Winebarger (MSFC)
Bart DePontieu (LMSAL)
Craig Deforest (SWRI)
Sergey Kuzin (LI)
Alan Title (LMSAL)
Mark Weber (SAO)

Engineering Team:
Peter Cheimets (SAO)
Dyana Beabout (MSFC)
Brent Beabout (MSFC)
William Podgorski (SAO)
Ken McKracken (SAO)
Mark Ordway (SAO)
David Caldwell (SAO)
Henry Berger (SAO)
Richard Gates (SAO)
Simon Platt (UCLAN)
Nick Mitchell (UCLAN)

Image above shows Hi-C launch team standing in front of the Hi-C rocket on the launcher at White Sands Missile Range.

Hi-C Launch



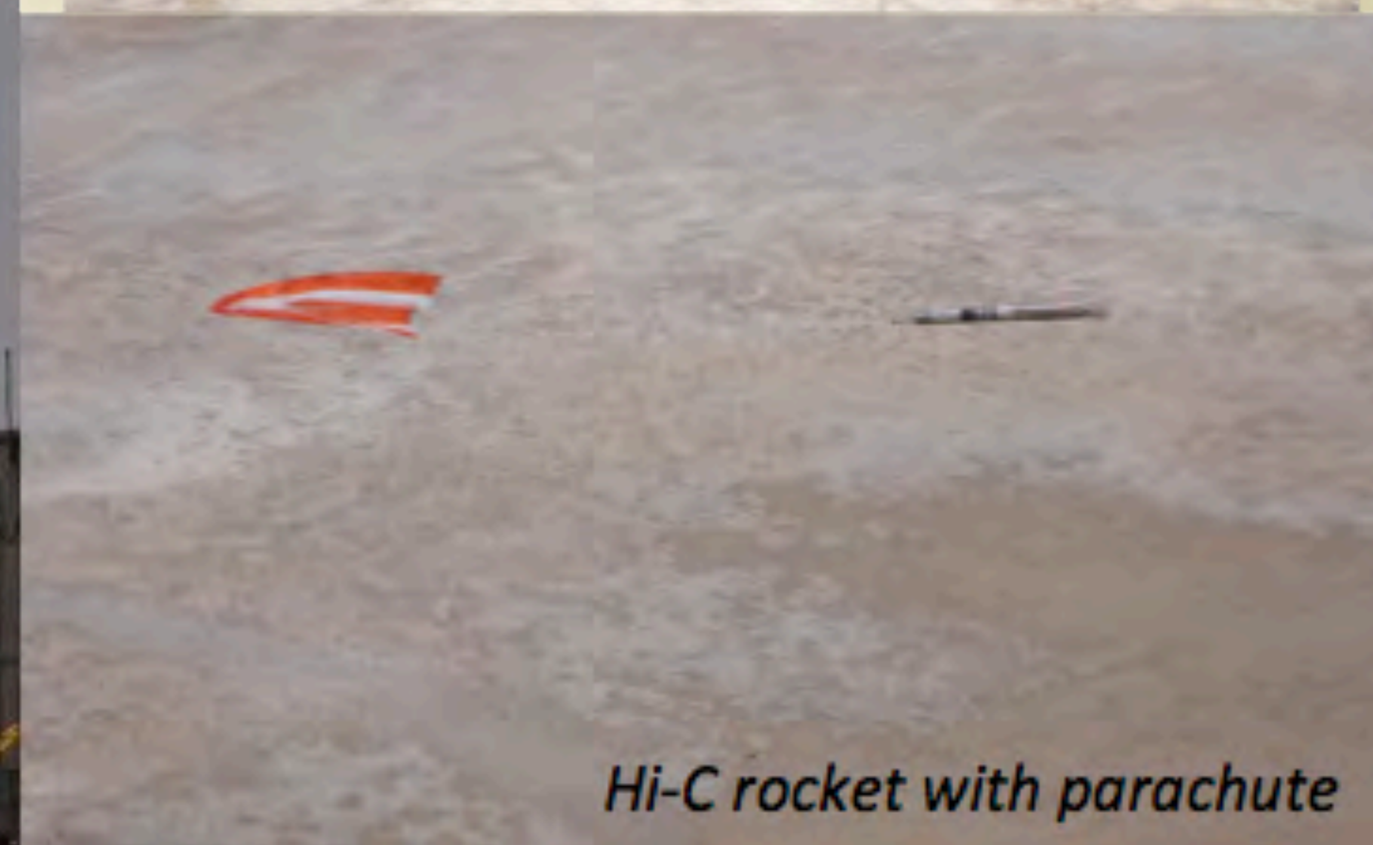
Hi-C was launched from White Sands Missile Range on 11 July 2012

Hi-C Launch

Hi-C was launched from White Sands Missile Range on 11 July 2012

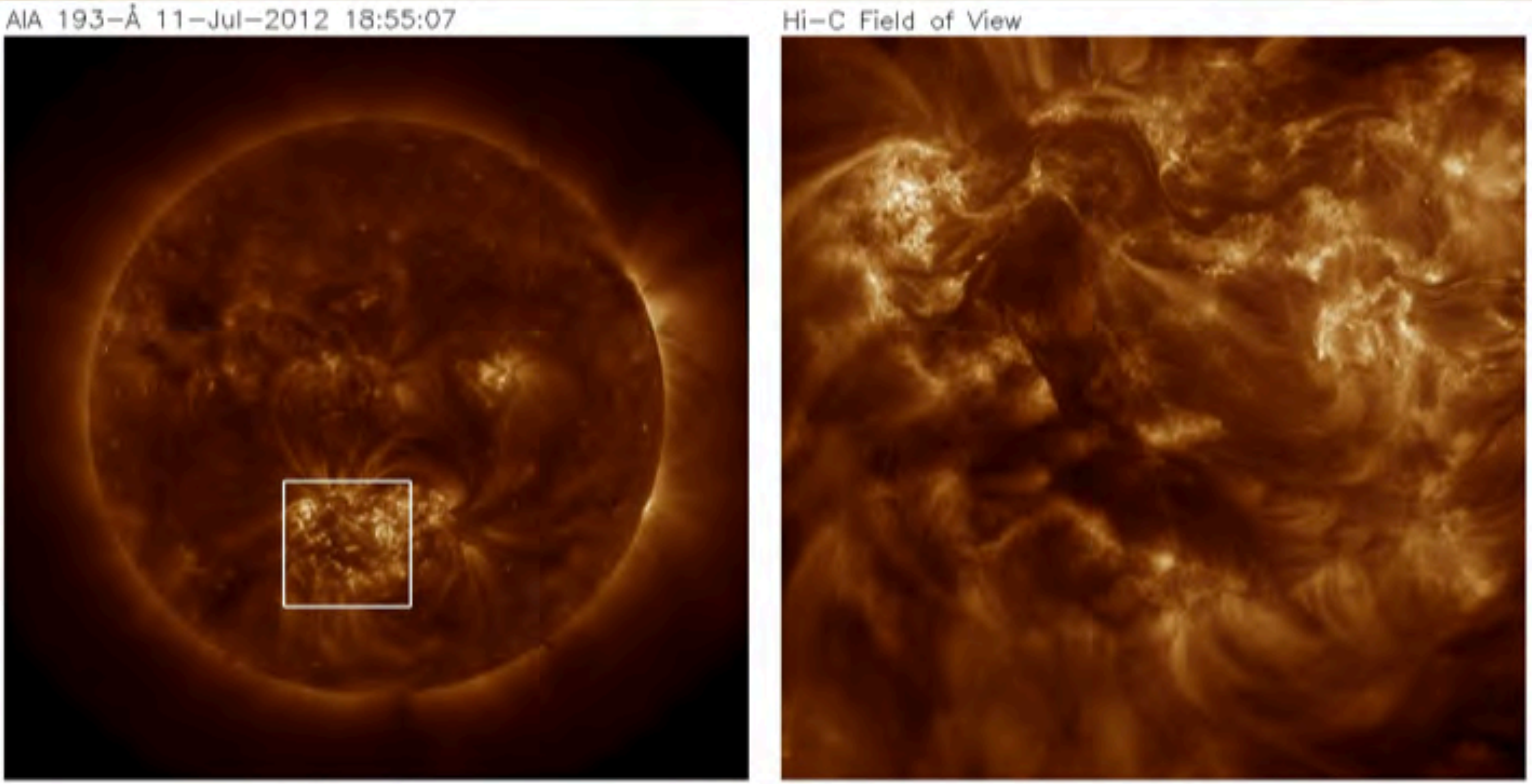
Hi-C Launch and Recovery

Hi-C recovery team



Hi-C rocket with parachute

Hi-C Target



The Hi-C target was Active Region 11520

Hi-C Data

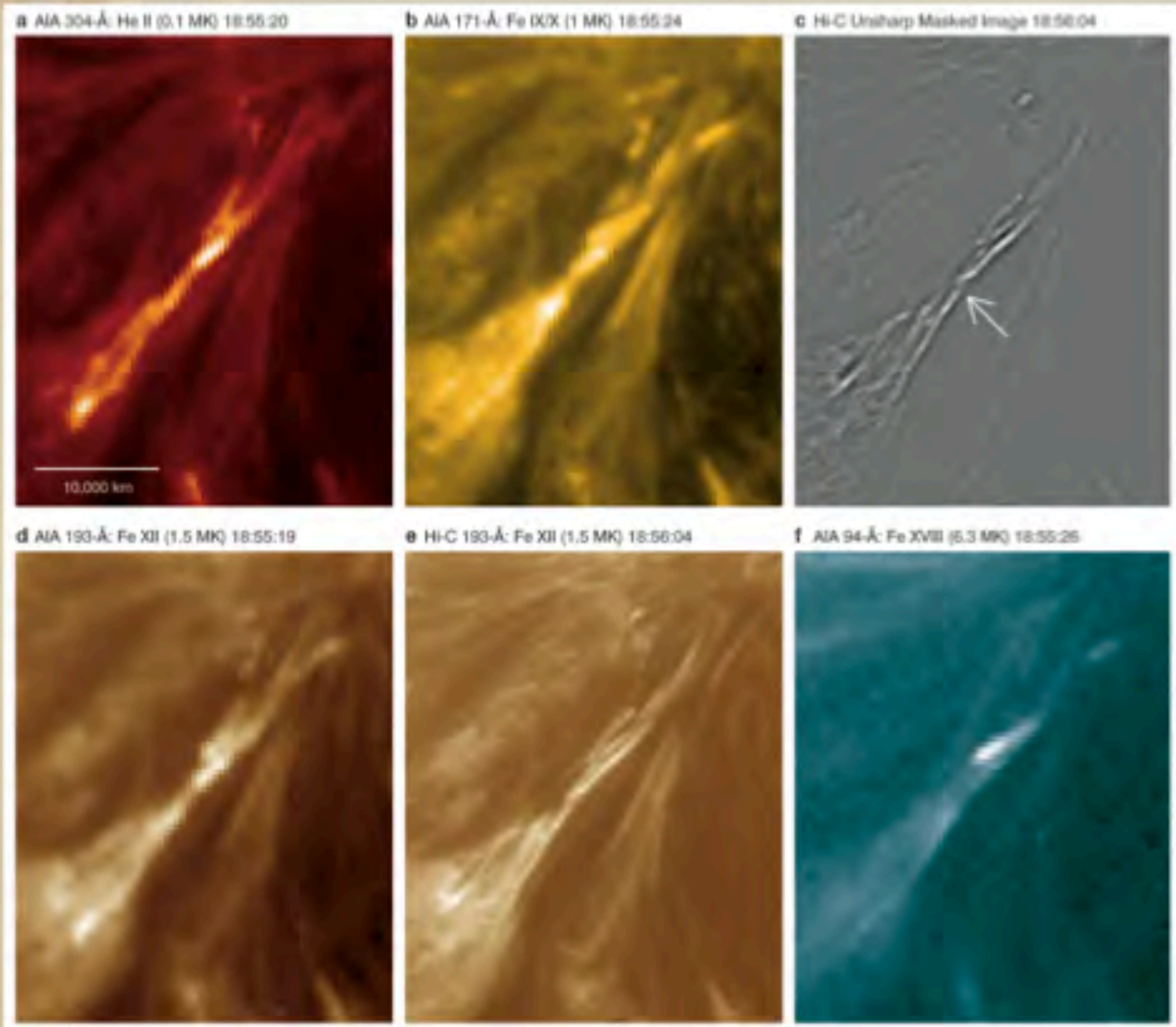
- Hi-C collected data for 345 s.
- Small shift in pointing during flight

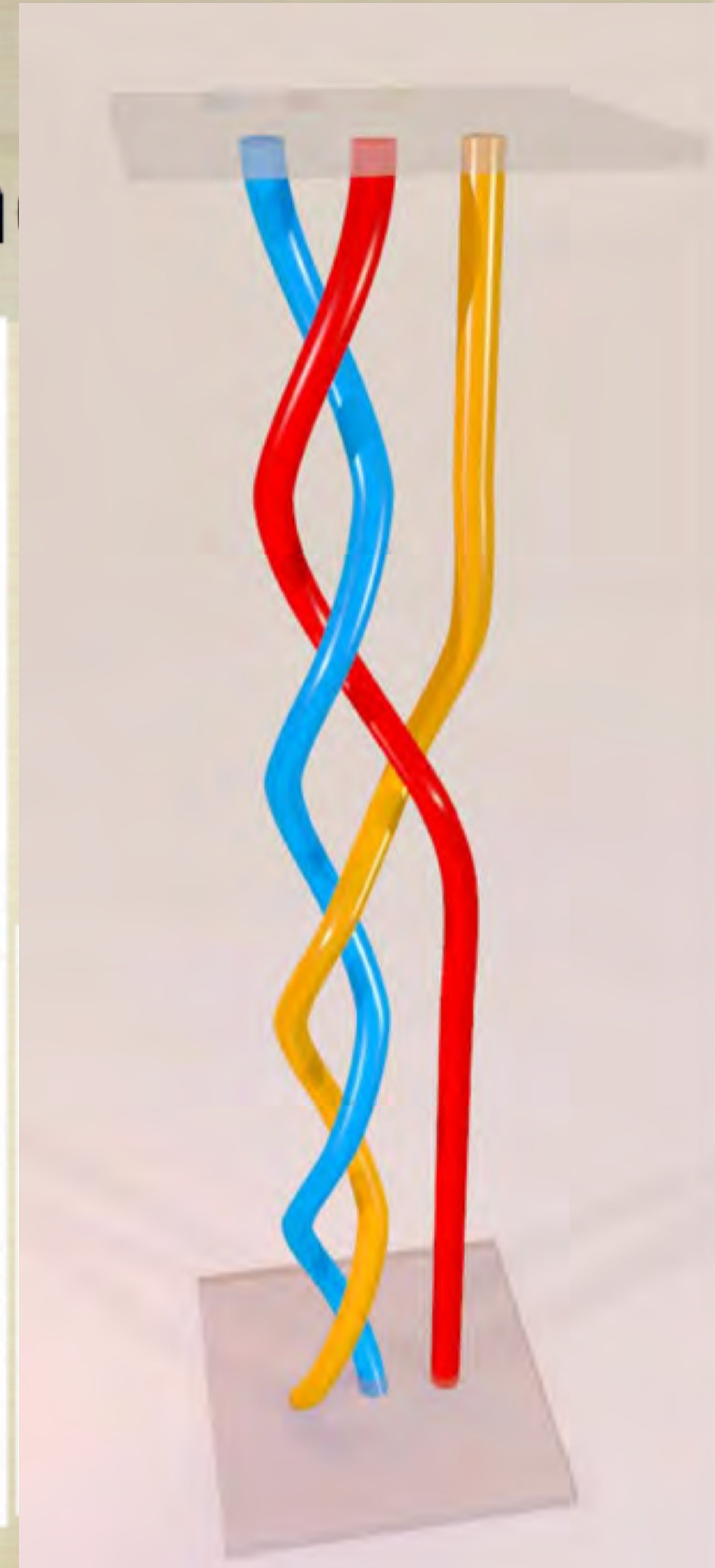
- Full frame (4kx4k) data
  - 30 full resolution images
  - 2 s exposures / 5 s cadence

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

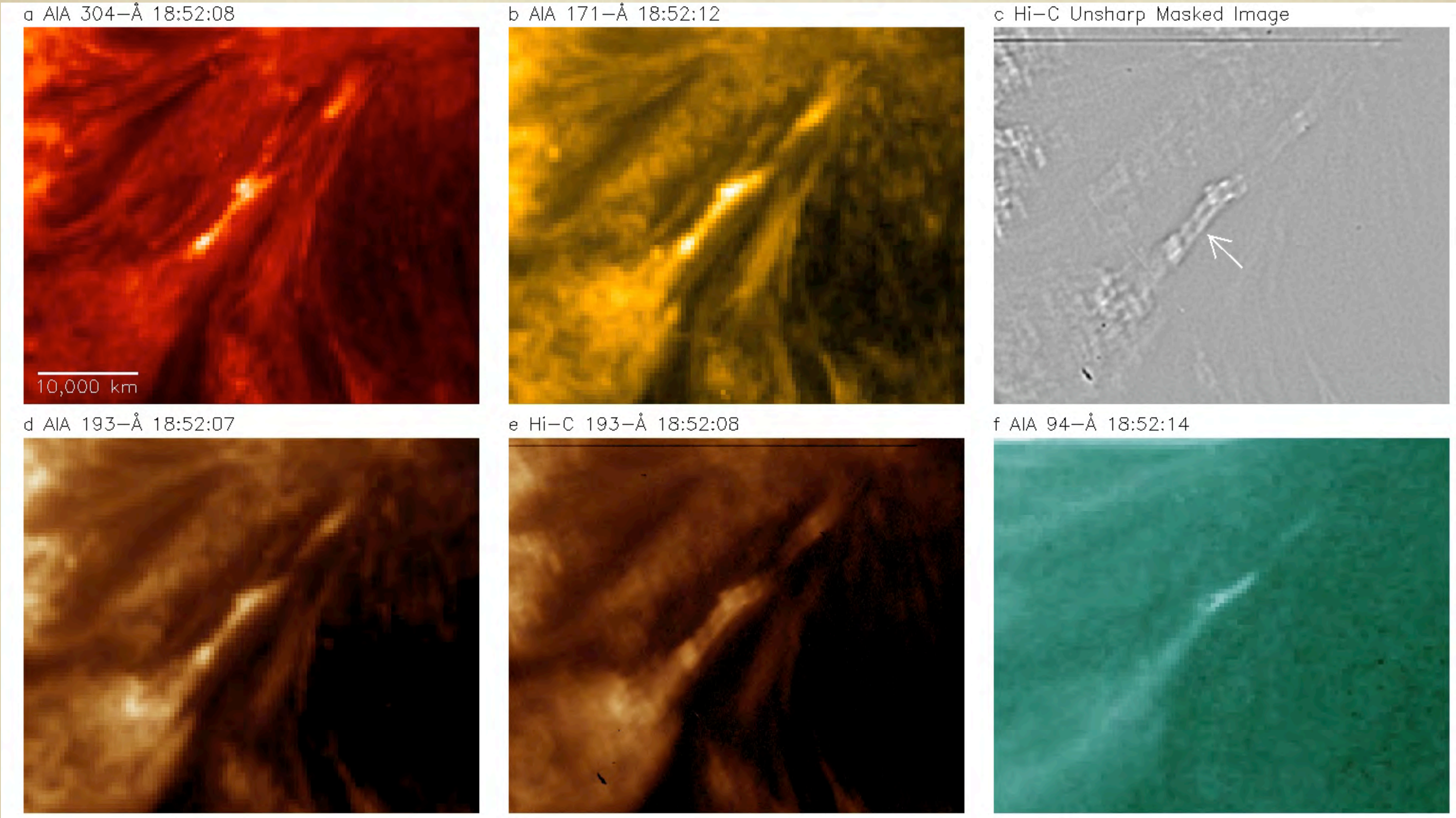
Hi-C First Results

Component Reconne





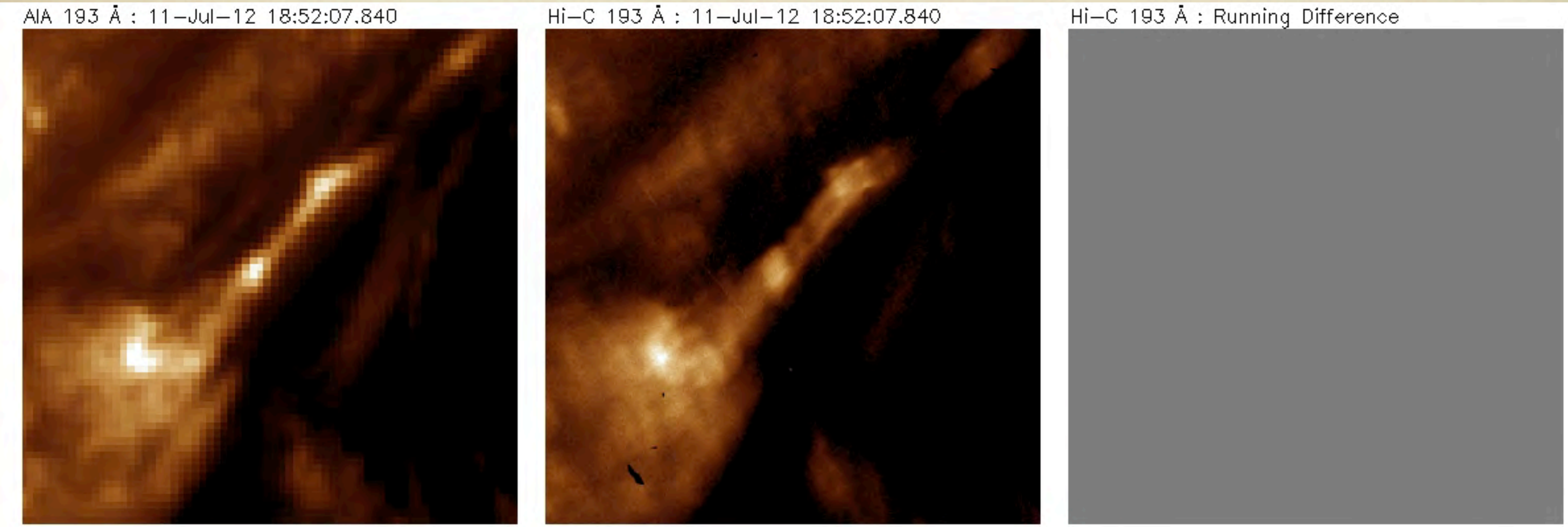
Component Reconnection



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

Cirtain et al, 2013, Nature

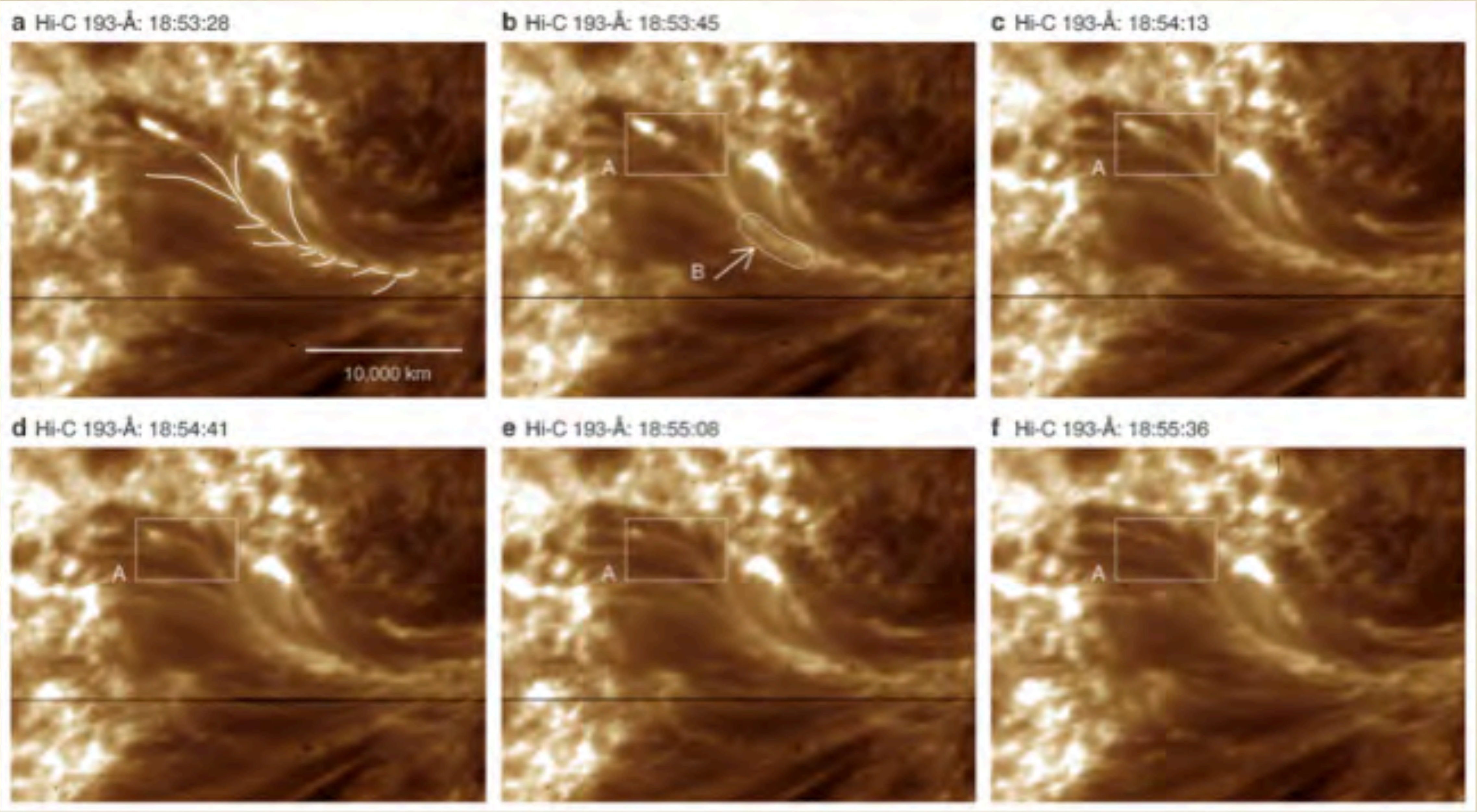
Component Reconnection



Velocities along structure estimated to be 150 km/s.

Cirtain et al, 2013, Nature

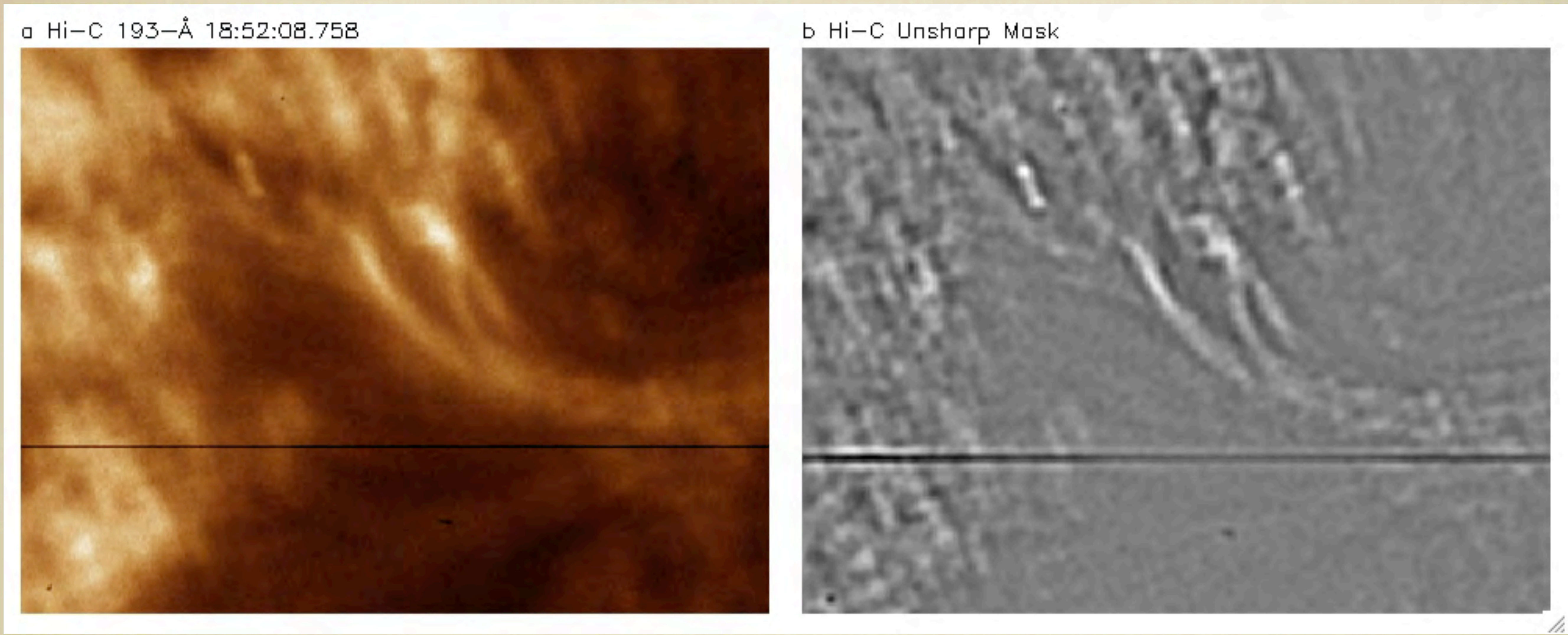
Braided Loop



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

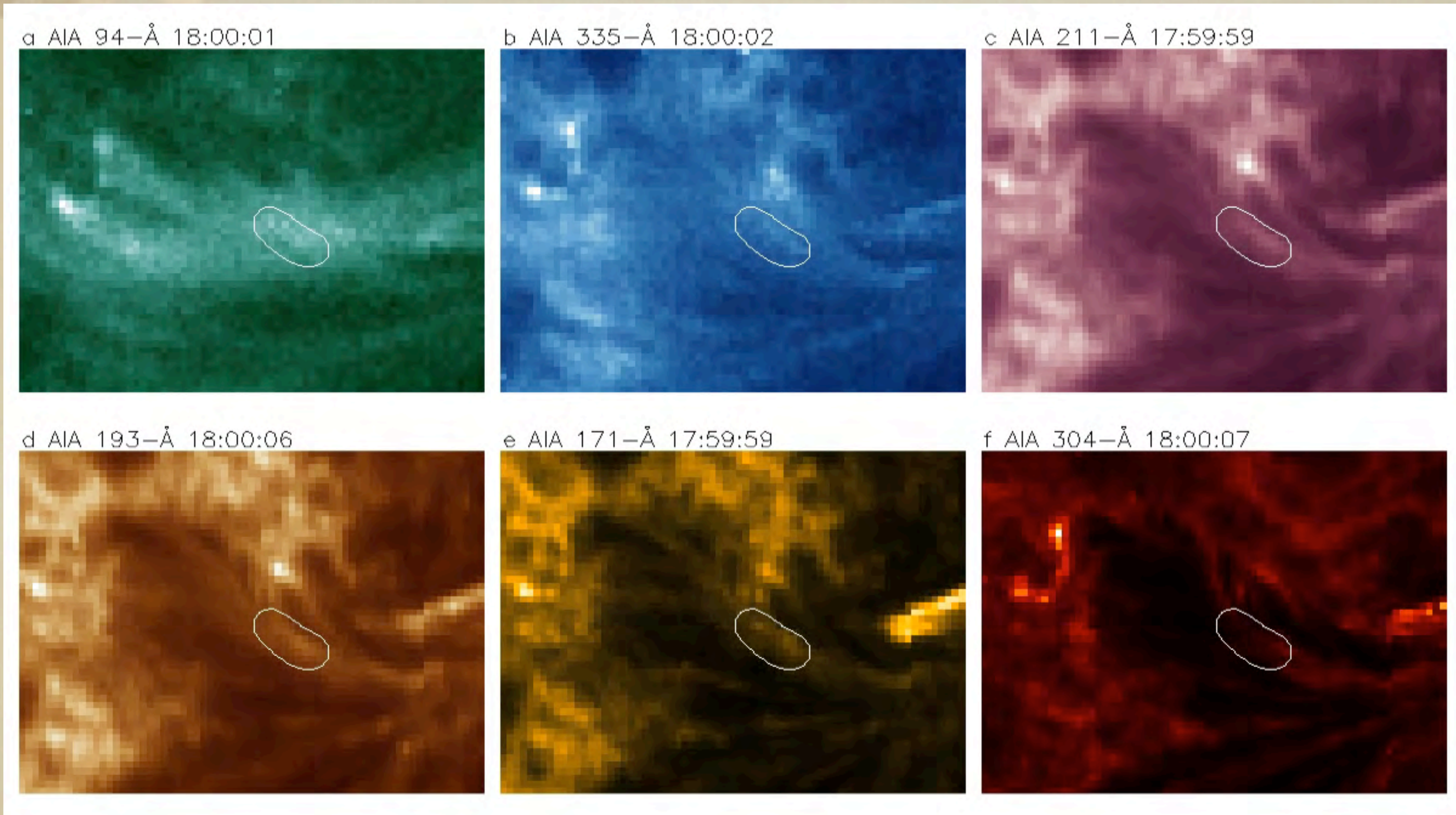
Cirtain et al, 2013, Nature

Braided Loop



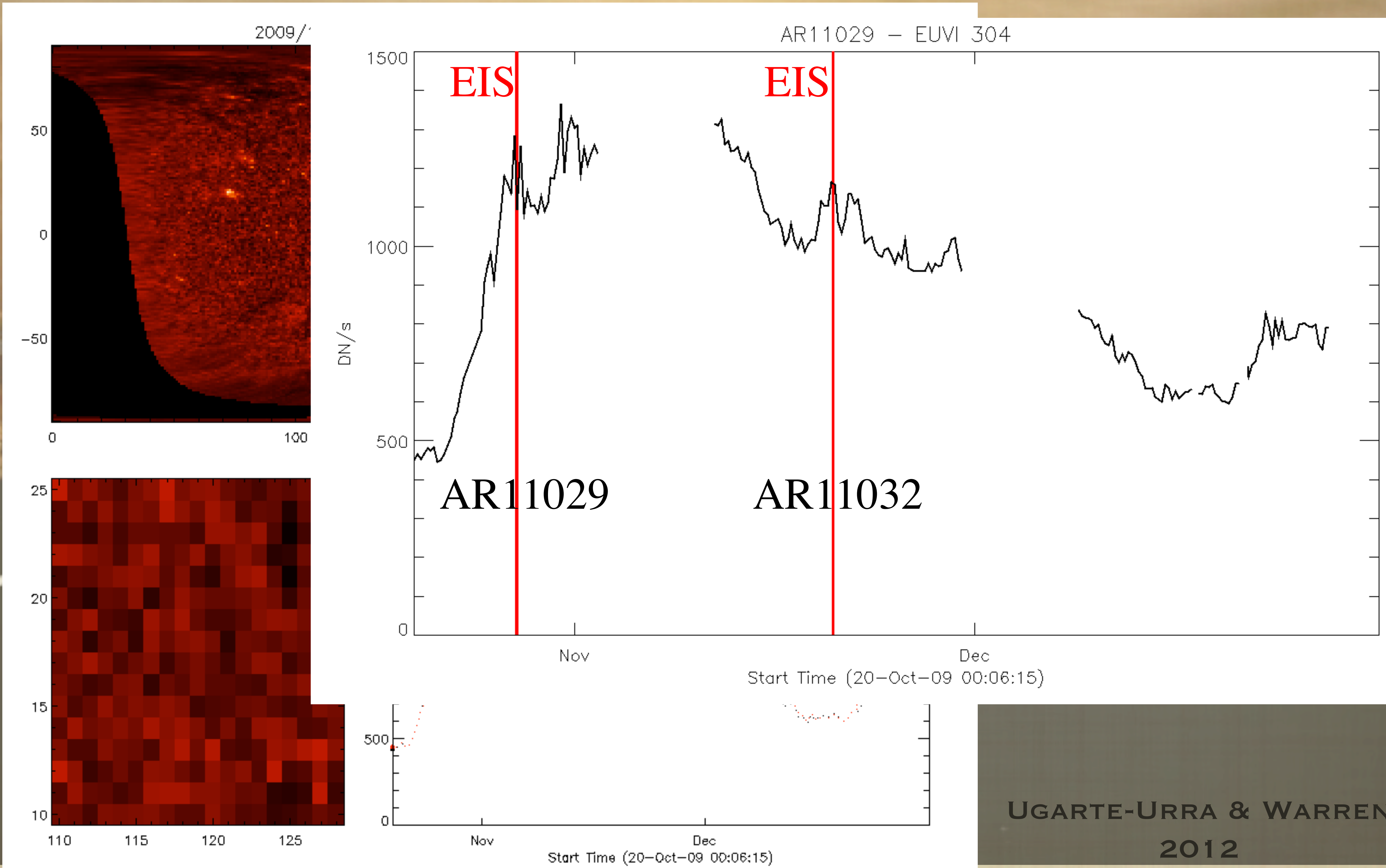
Cirtain et al, 2013, Nature

Braided Loop



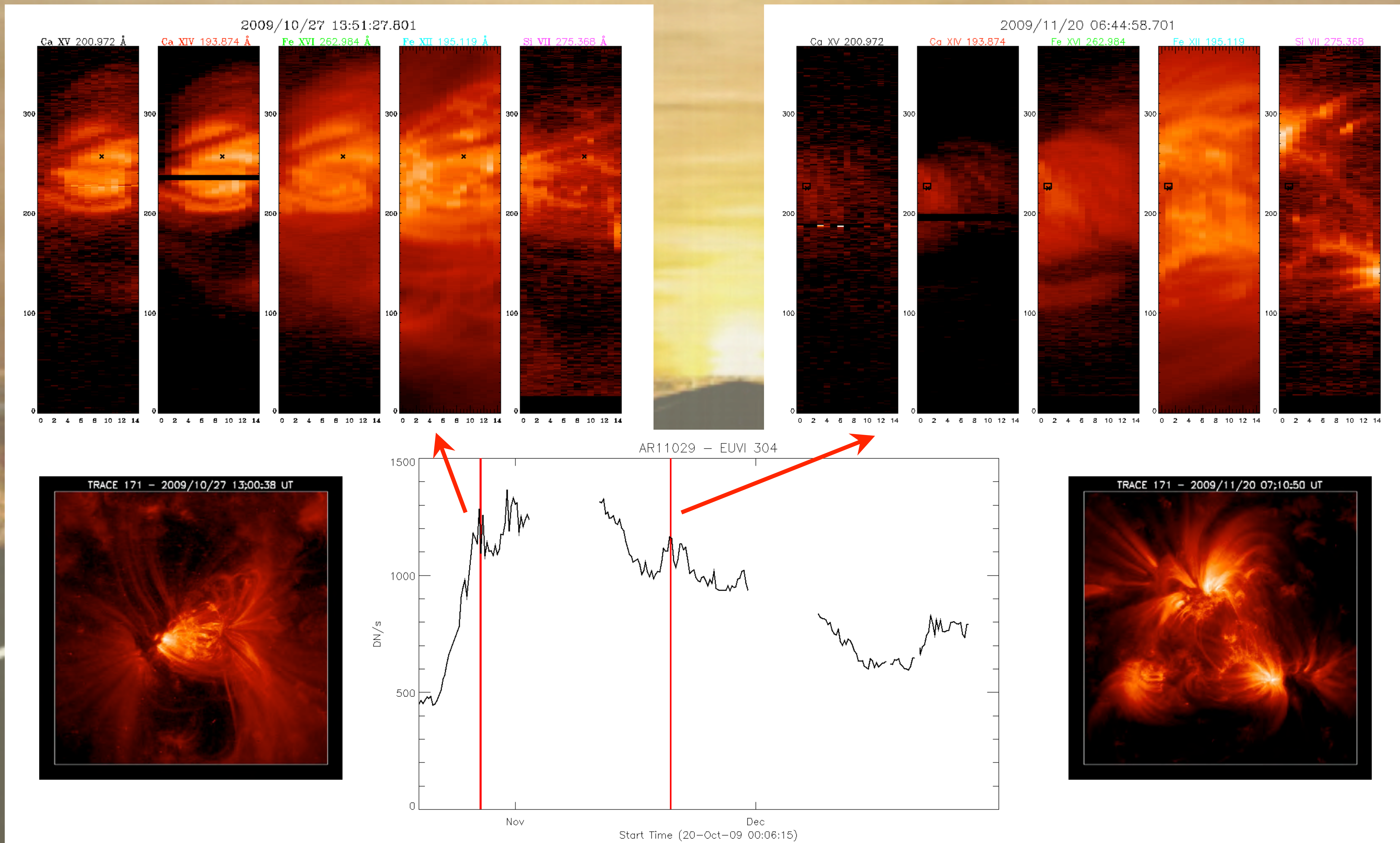
Loop involved in heating event prior to Hi-C flight. *Cirtain et al, 2013, Nature*

Active Region Evolution



Ugarte-Urra & Warren 2012

Active Region Evolution

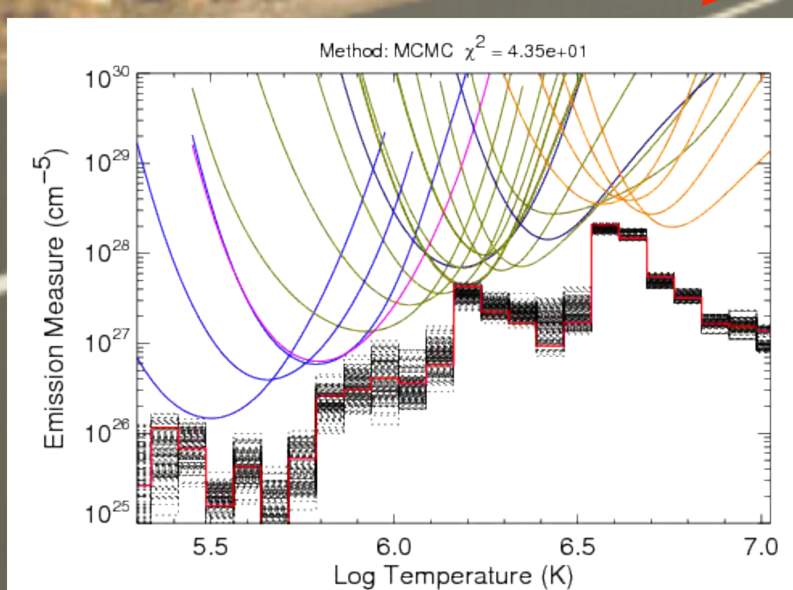


Ugarte-Urra & Warren 2012

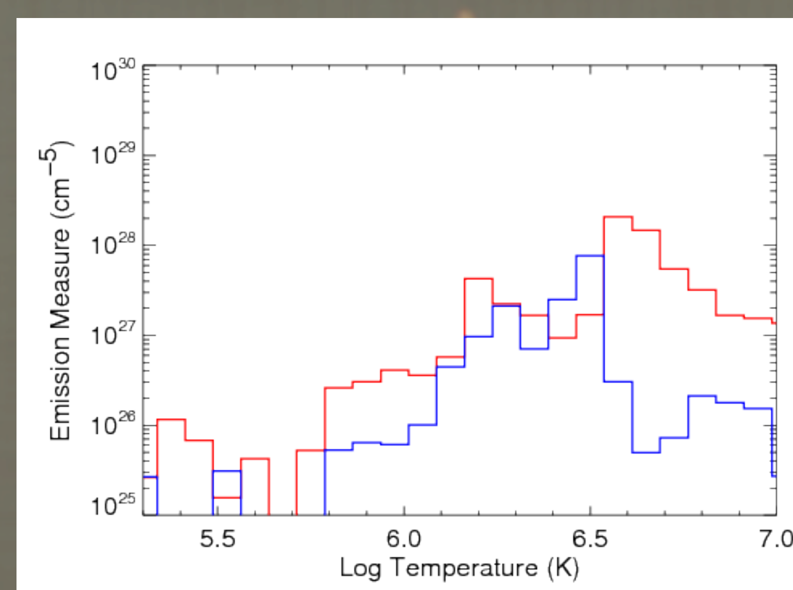
Active Region Evolution

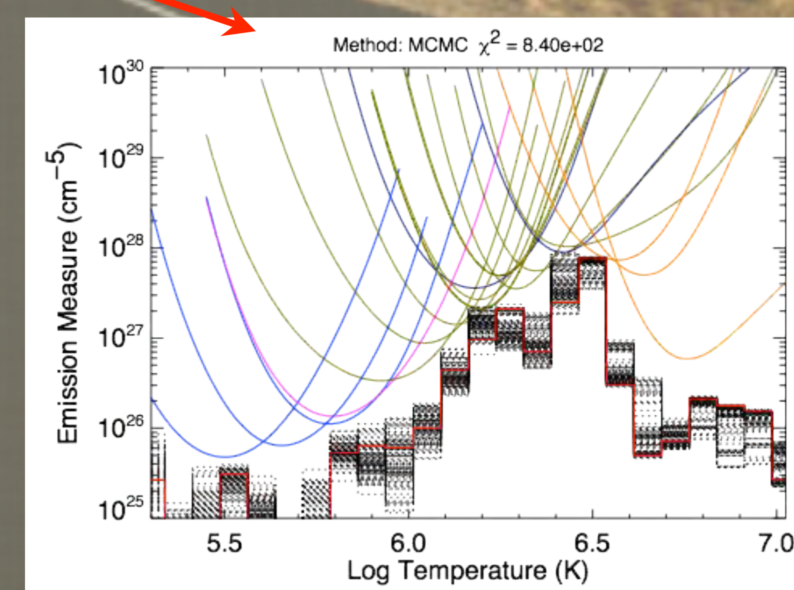
Young AR: evidence for cooling, enhanced hot and cool emission

Old AR: Steadier Emission, Less hot and cool emission



Emission Measure





Ugarte-Urra & Warren 2012

Final thoughts...

- Progress in understanding coronal heating continues.
- Two main camps on coronal heating - magnetic reconnection and wave dissipation.
- Observational evidence for BOTH.
- Hi-C, an instrument flown on a sounding rocket in 2012, took the highest resolution images of the solar corona.
- Images clearly show magnetic braiding and indicate magnetic reconnection