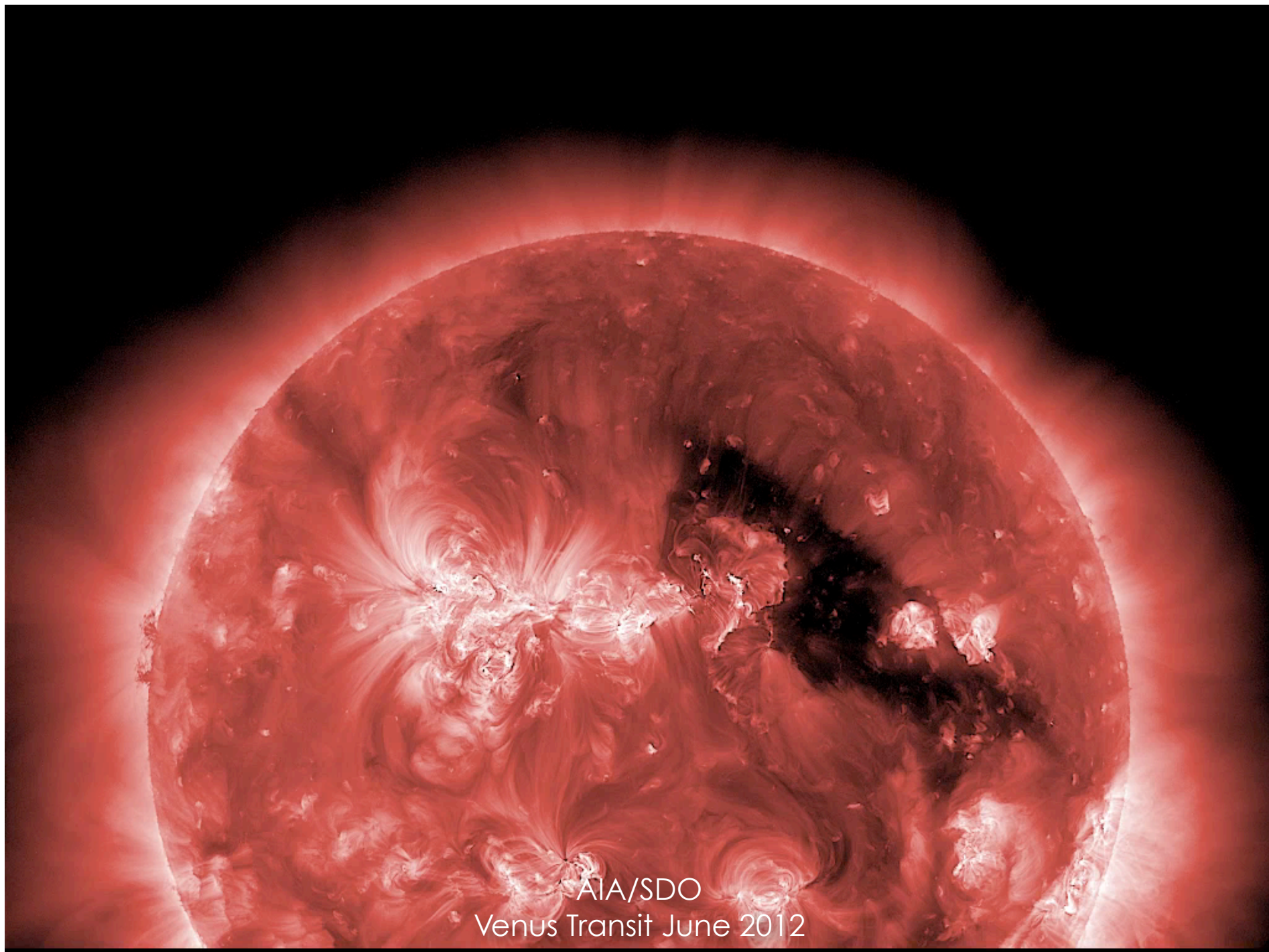


# Supra Arcade Downflows and Evidence for Magnetic Reconnection in Solar Flares

Harry Warren  
Naval Research Laboratory

Geospace Environment Modeling 2012 Summer Workshop  
June 18, 2012



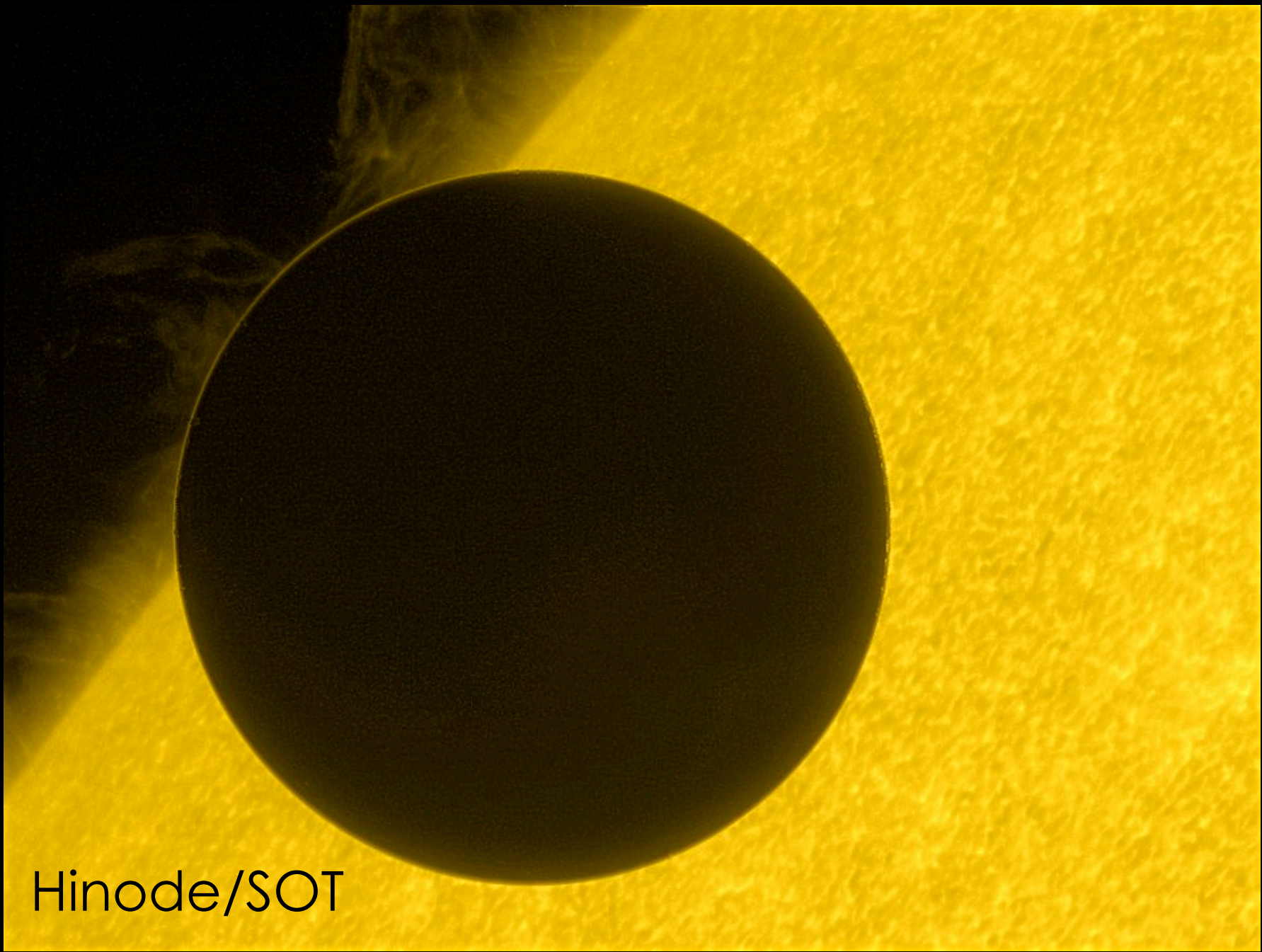
AIA/SDO  
Venus Transit June 2012





AIA/SDO 131 Å  
January 27, 2012





Hinode/SOT





## Summary

Background:  
What am I looking at?

Hinode/SOT



## Summary

Background:  
What am I looking at?

Reconnection in Flares:  
Cusps  
Downflows

Hinode/SOT





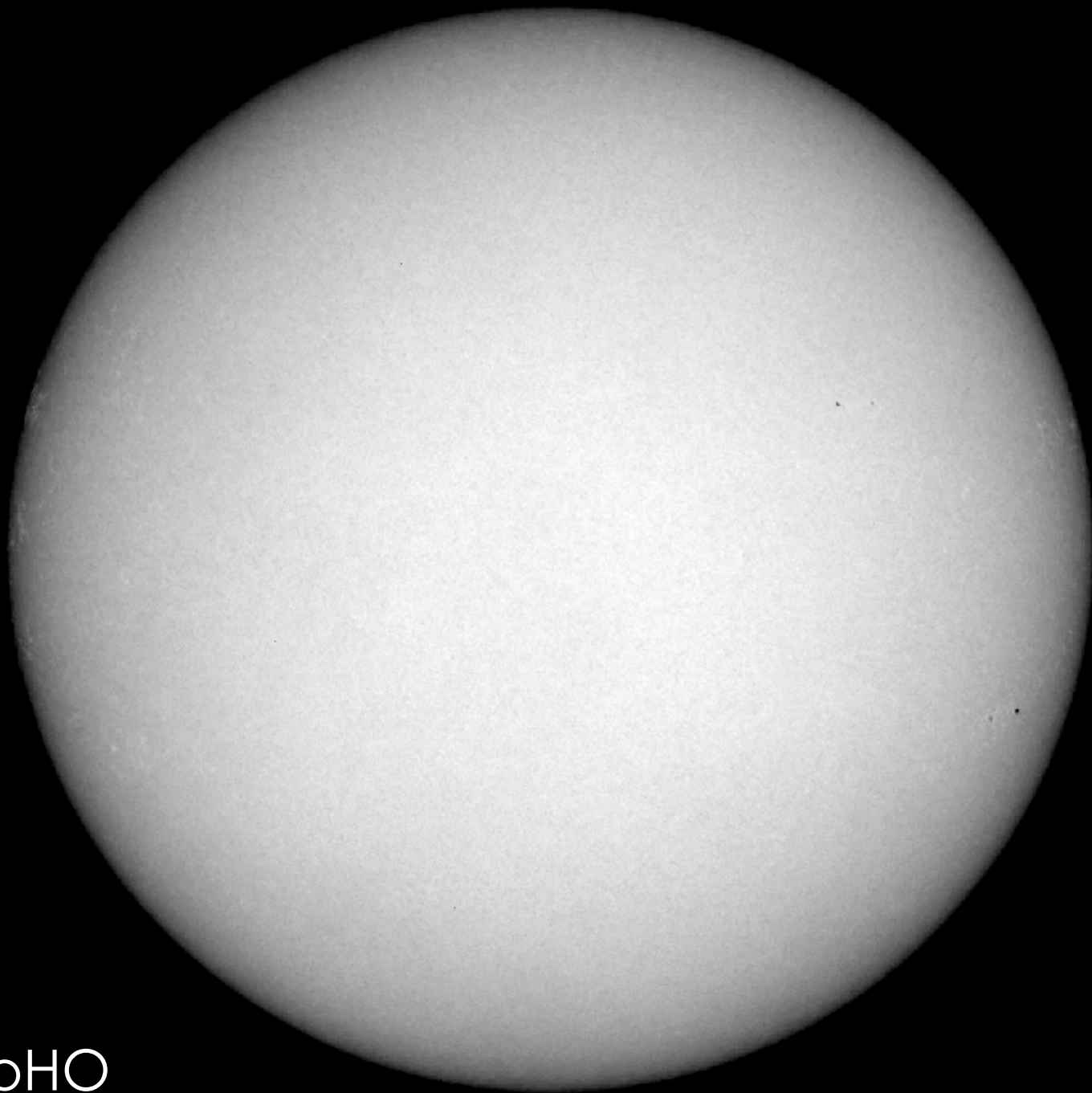
## Summary

Background:  
What am I looking at?

Reconnection in Flares:  
Cusps  
Downflows

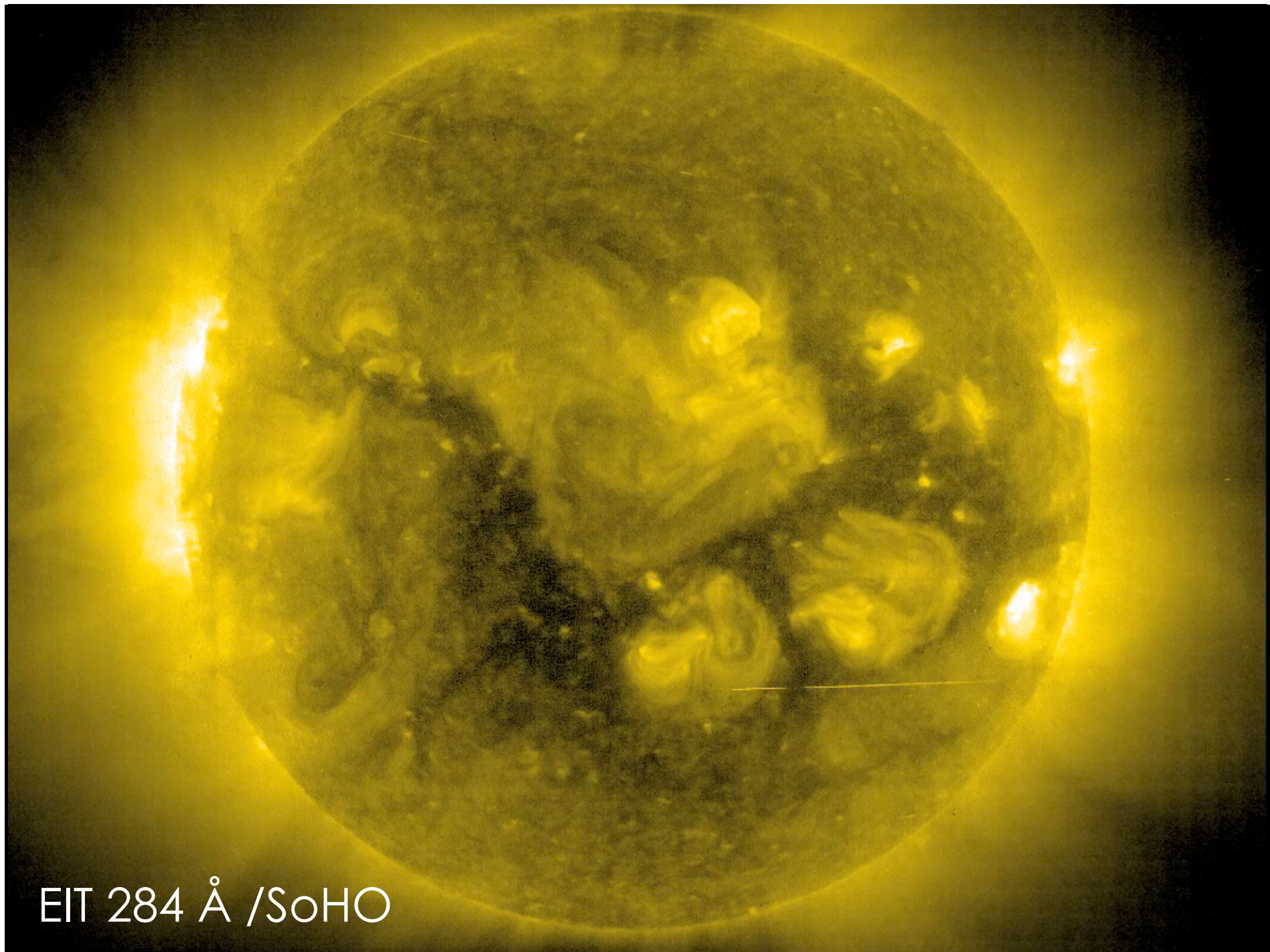
Downflows in the  
outer corona

Hinode/SOT

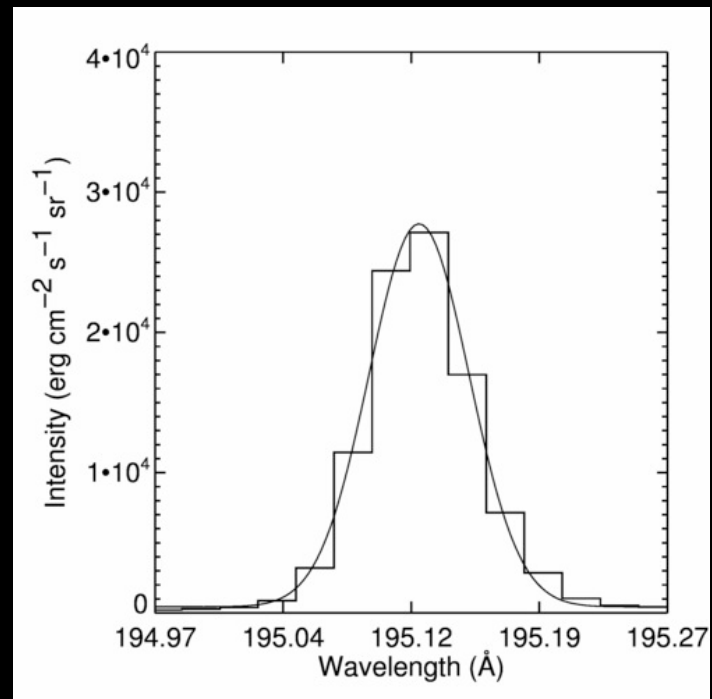
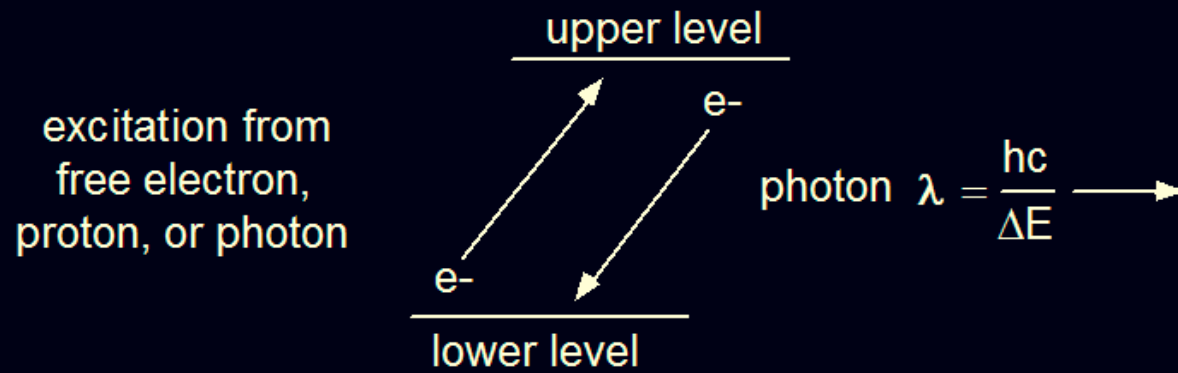


MDI/SoHO



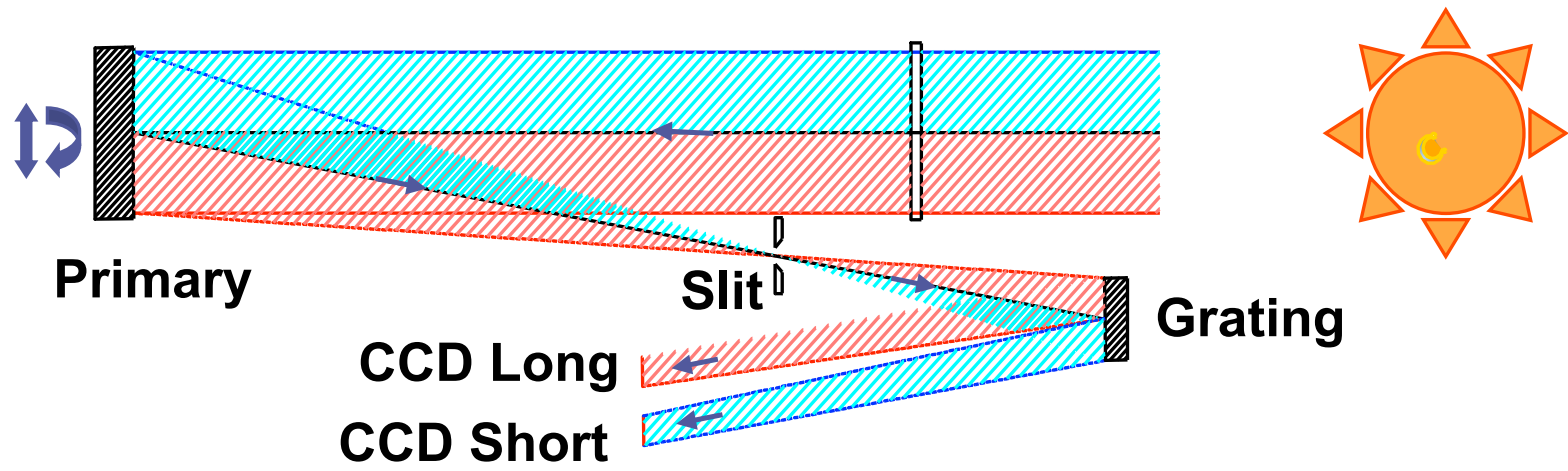


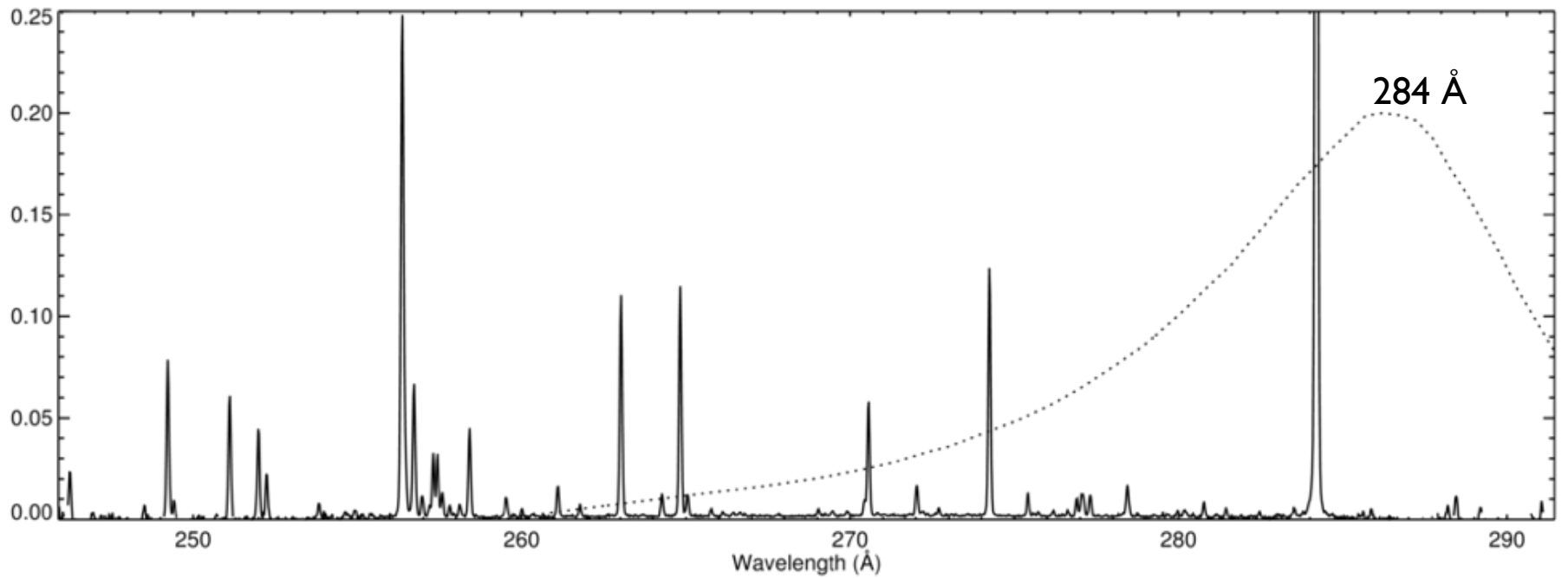
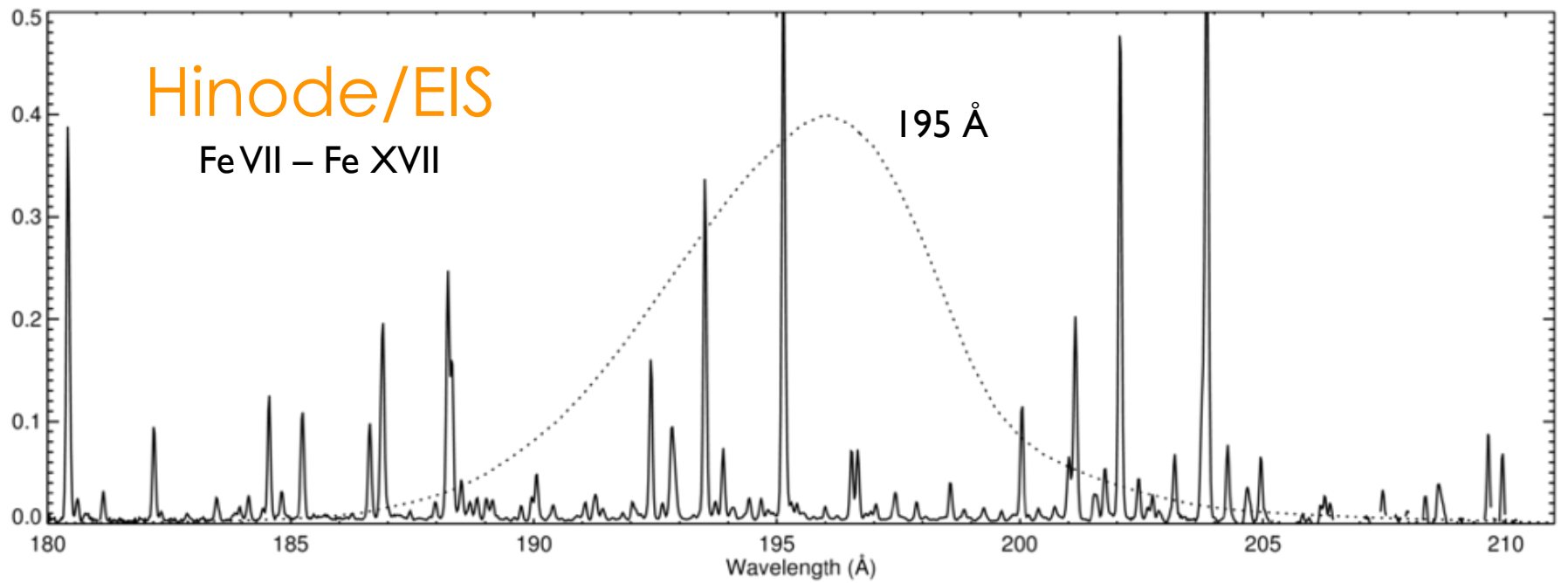
EIT 284 Å /SoHO



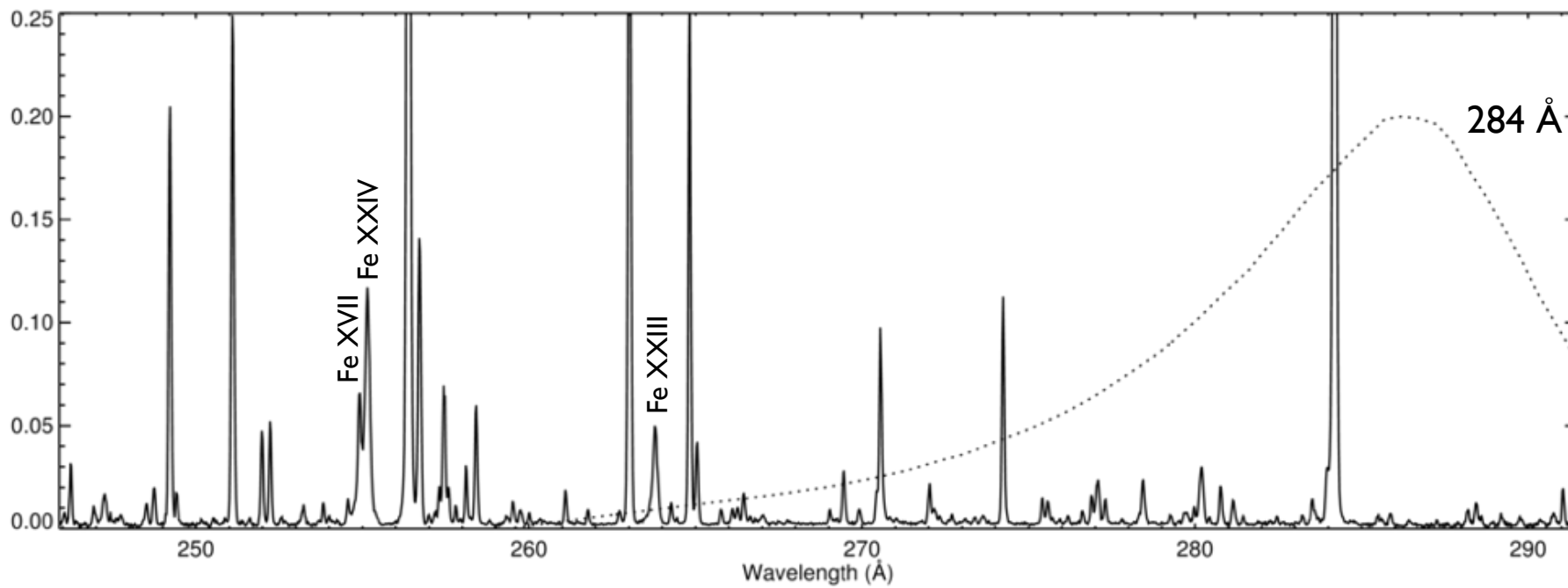
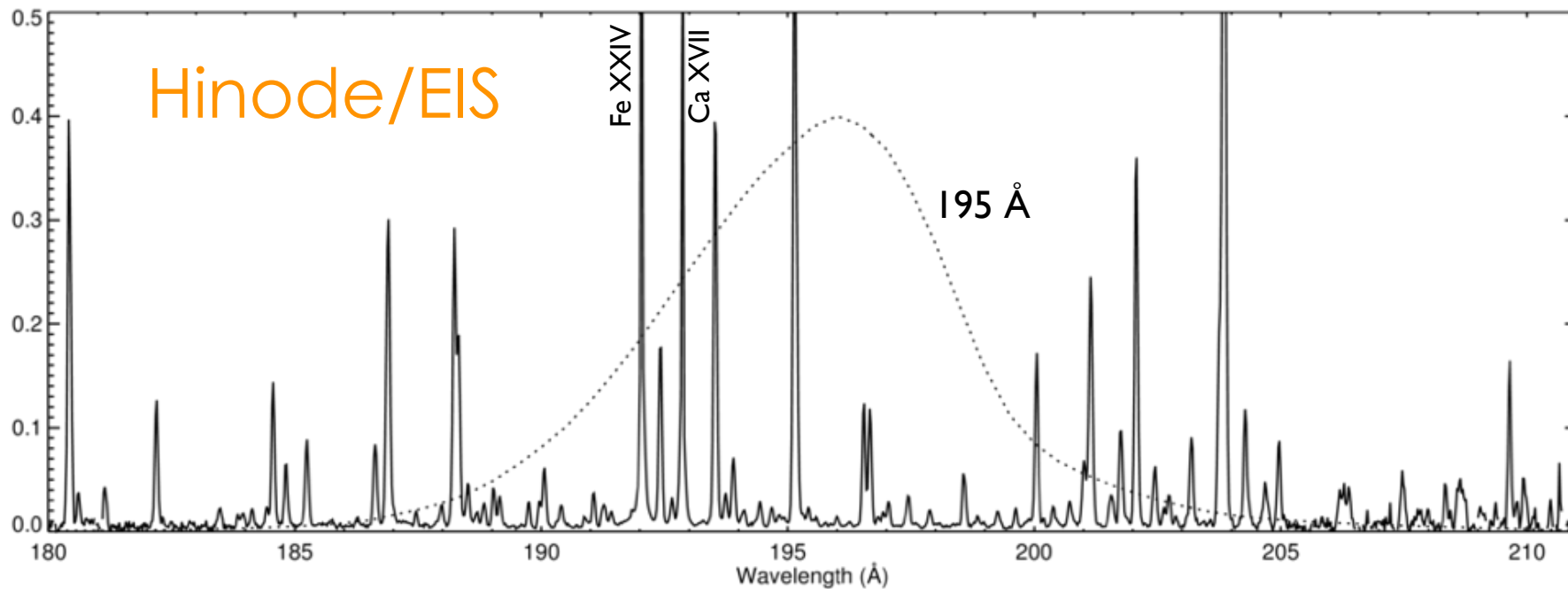
Fe XII 195.119  $\text{\AA}$





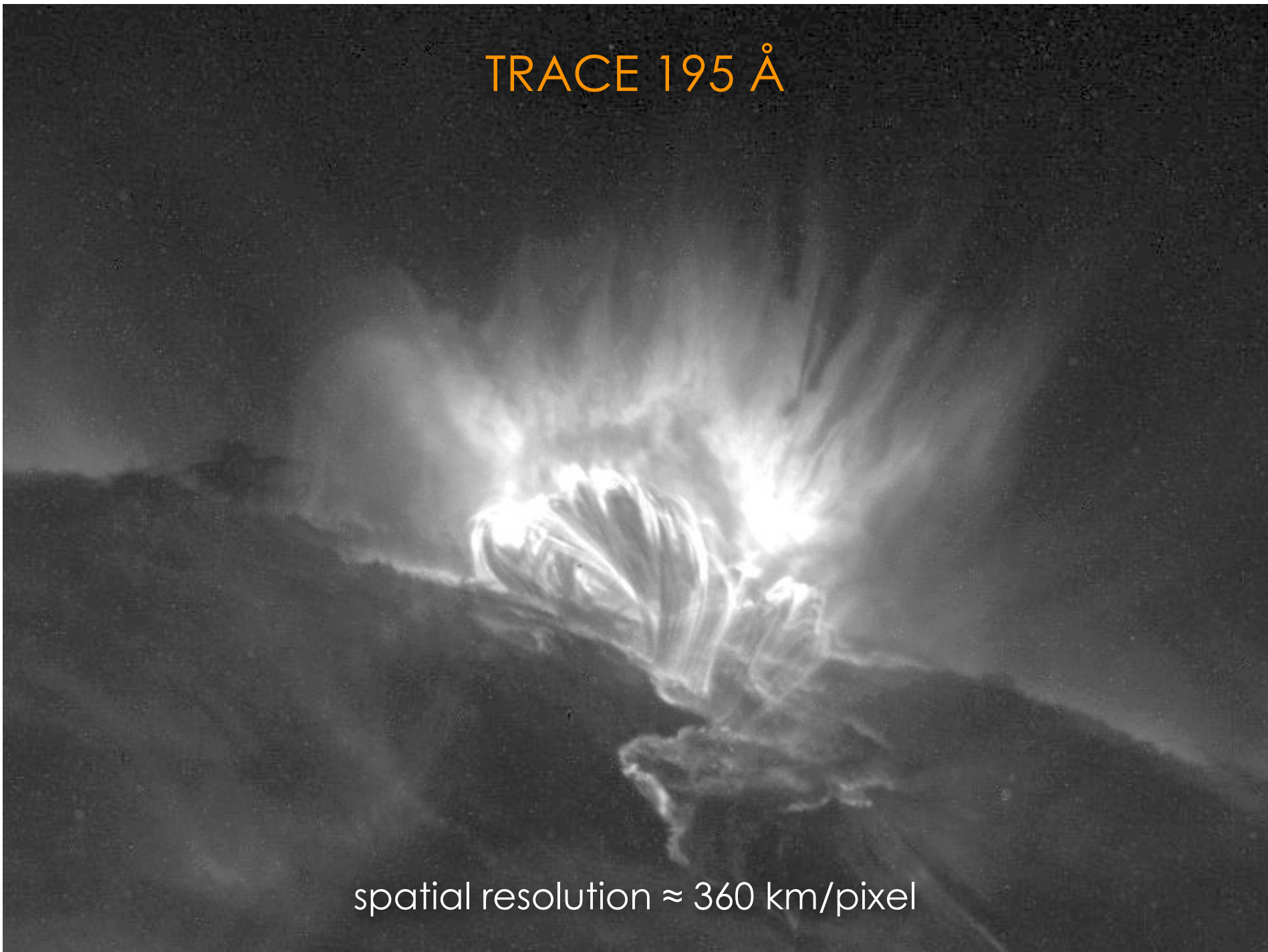






TRACE 195 Å

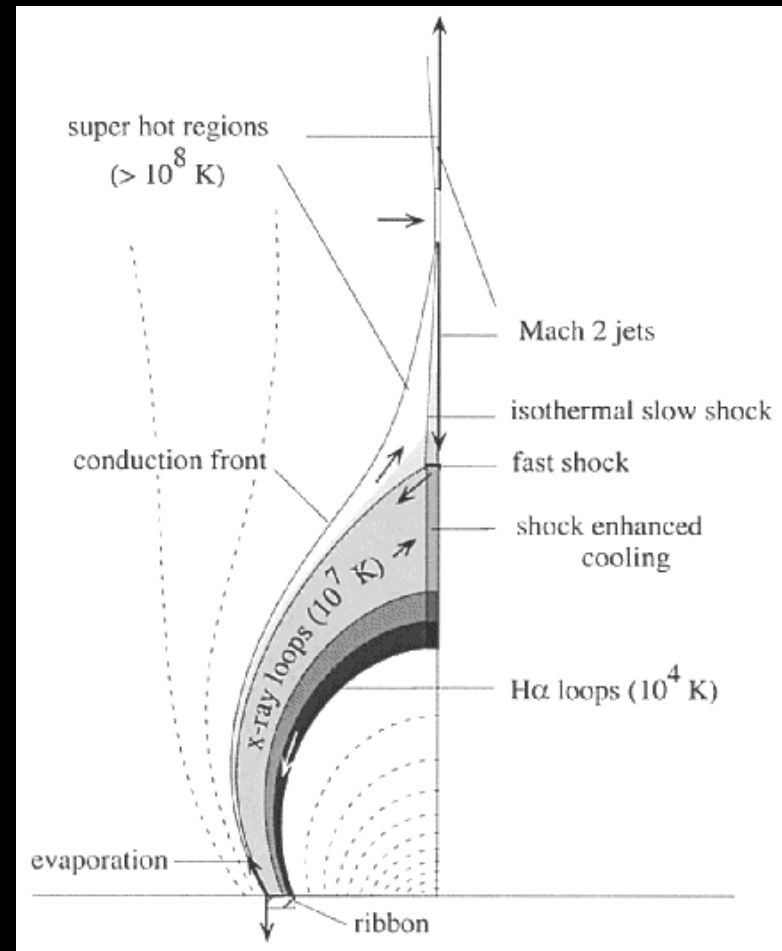
spatial resolution  $\approx 360$  km/pixel





# The Cusp as “Visual Proof”

# The Cusp as “Visual Proof”

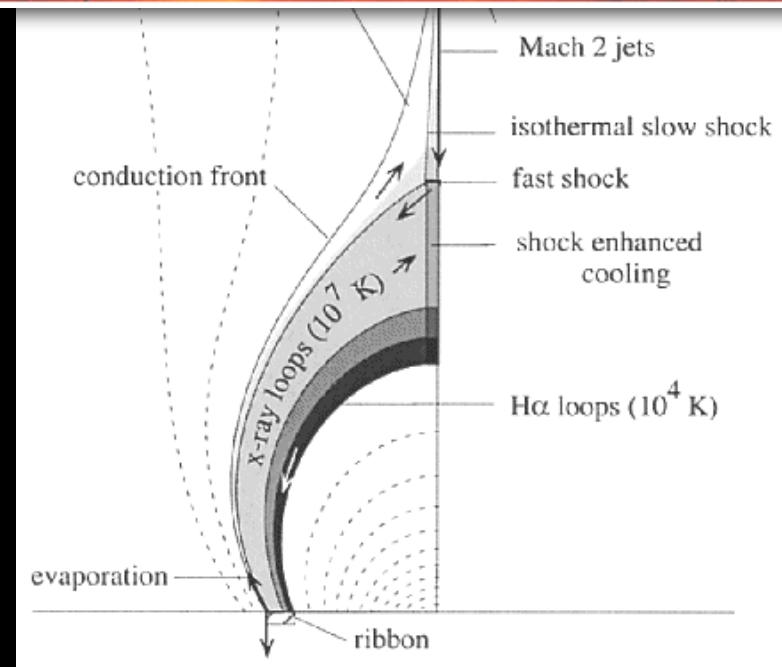
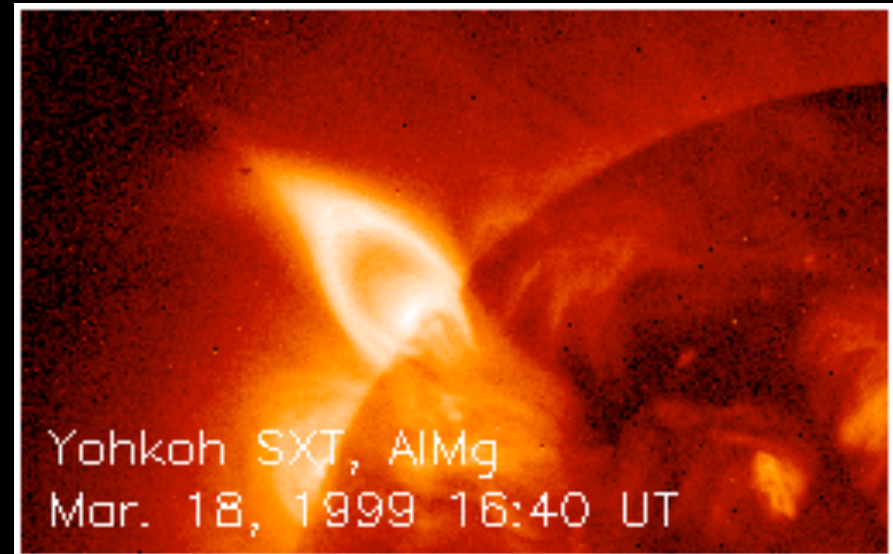


Forbes & Acton, ApJ, 1996



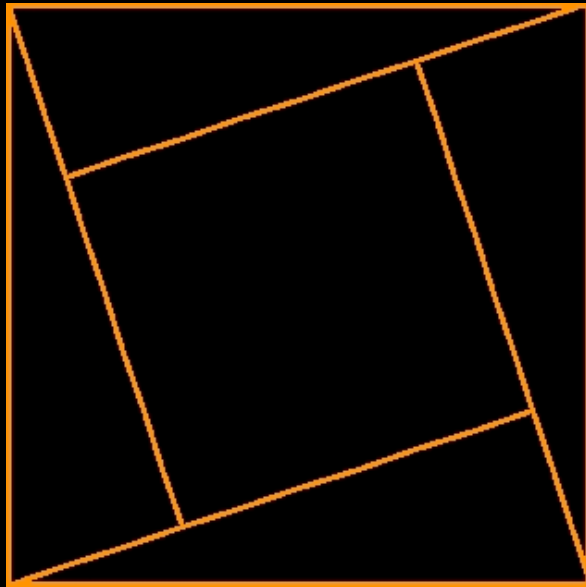
# The Cusp as “Visual Proof”

“A Magnificent Cusp”  
Hugh Hudson/Yohkoh Science Nugget



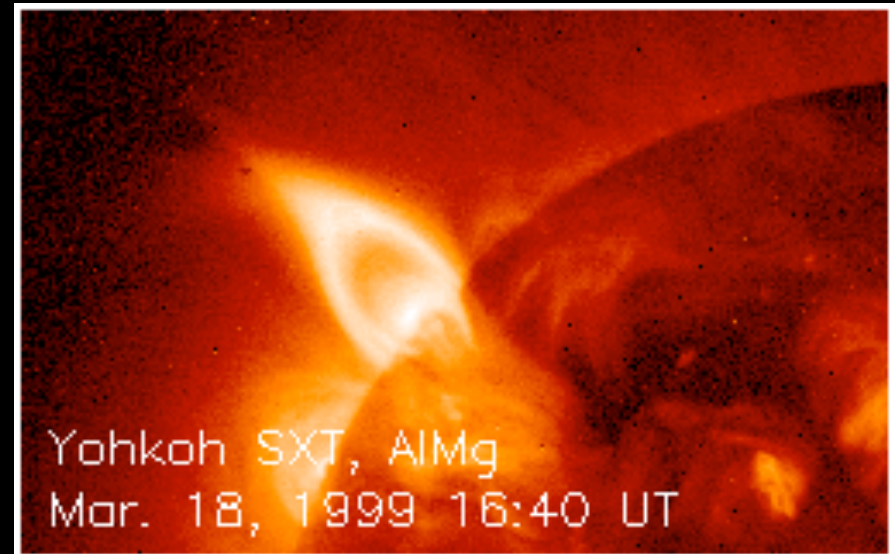
Forbes & Acton, ApJ, 1996

# The Cusp as "Visual Proof"

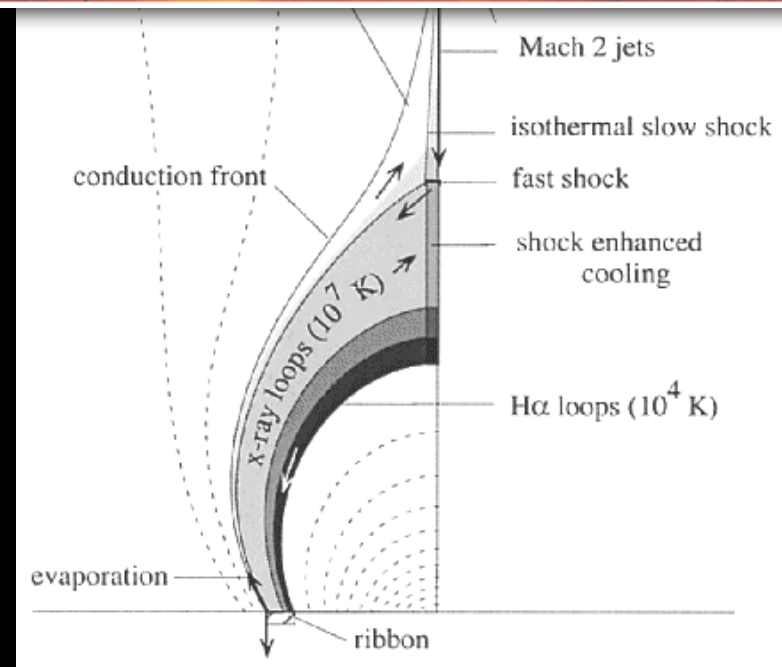


"Behold!"  
proof of the Pythagorean Theorem  
Bhaskara II (1114-1185)

## "A Magnificent Cusp" Hugh Hudson/Yohkoh Science Nugget



Yohkoh SXT, AlMg  
Mar. 18, 1999 16:40 UT



Forbes & Acton, ApJ, 1996



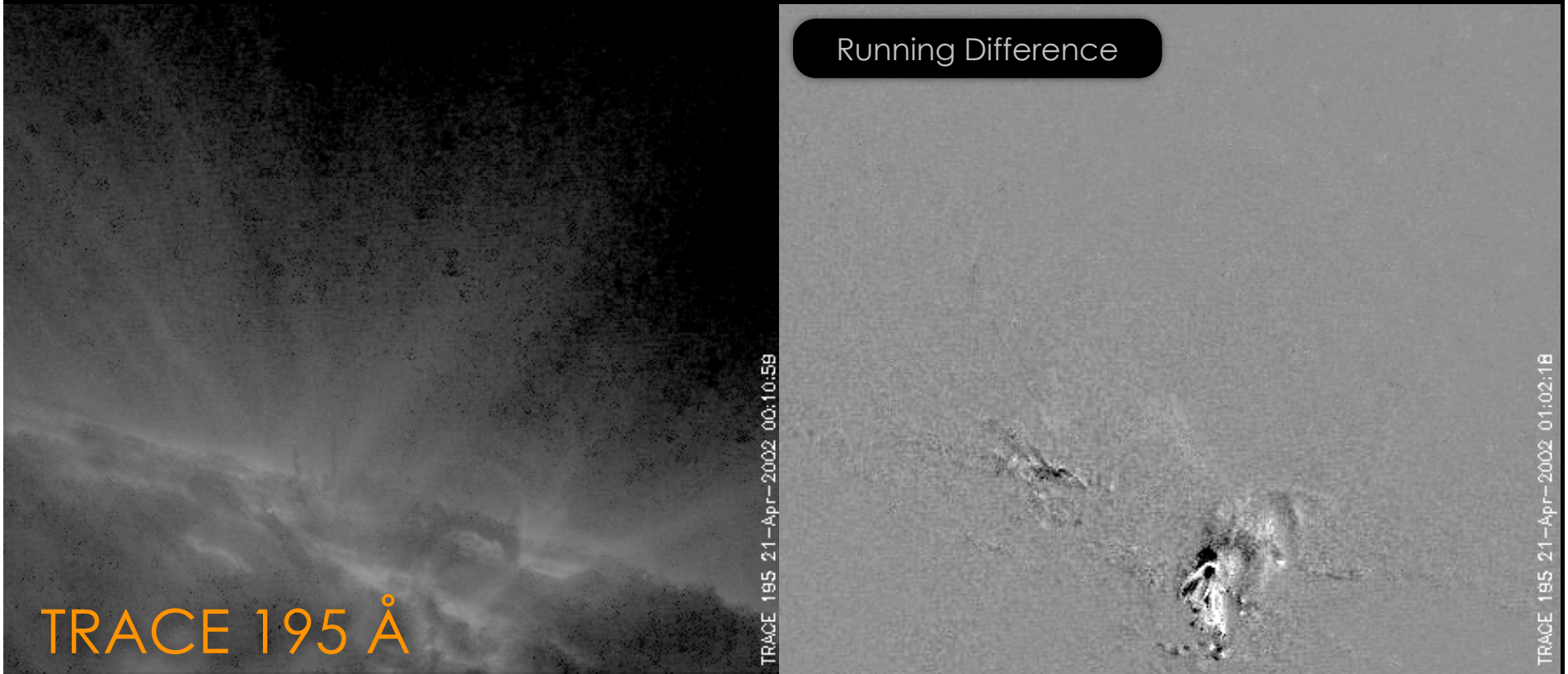
# Supra-Arcade Downflows

TRACE 195 Å

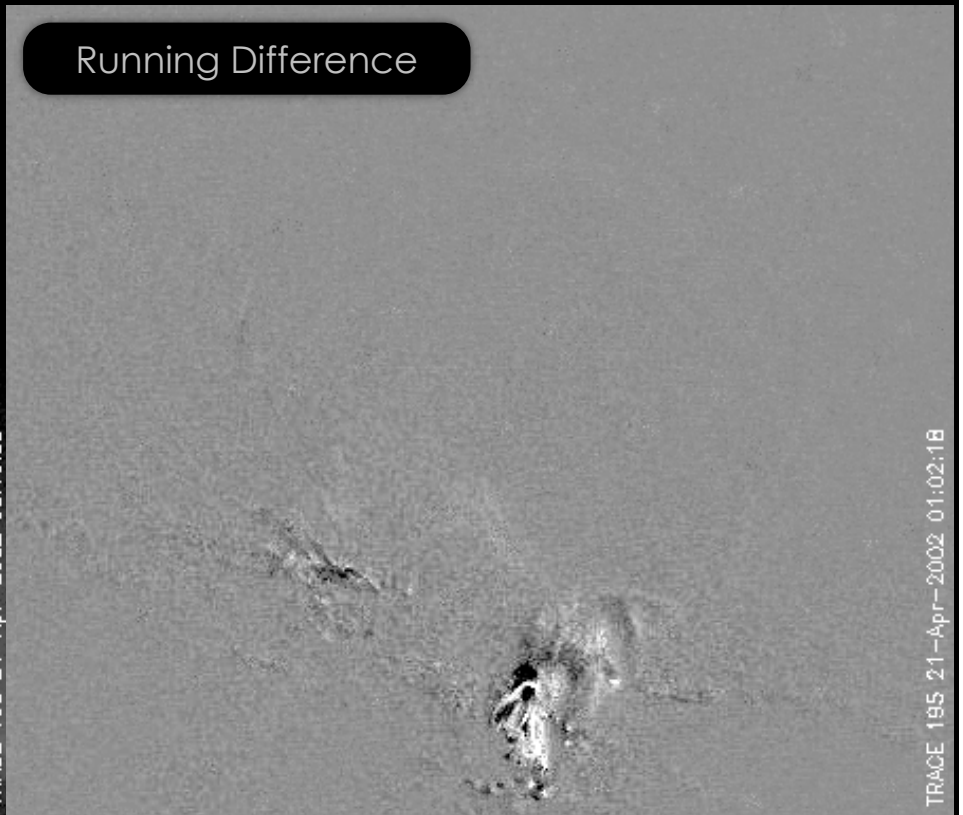
TRACE 195 21-Apr-2002 00:10:59

Running Difference

TRACE 195 21-Apr-2002 01:02:18



# Supra-Arcade Downflows



- McKenzie & Hudson, ApJ, 1999
- McKenzie, Solar Physics, 2000
- Innes et al., Solar Physics, 2003
- Asai et al., ApJ, 2004
- Sheeley, Warren, & Wang, ApJ, 2004

- Reeves et al., JGRA, 2008
- Warren et al., ApJ, 2011
- **Savage & McKenzie, ApJ, 2011**
- Takasao et al., ApJ, 2012
- Savage et al., ApJ, 2012



# Supra-Arcade Downflows

TRACE 195 Å

TRACE 195 21-Apr-2002 00:10:59

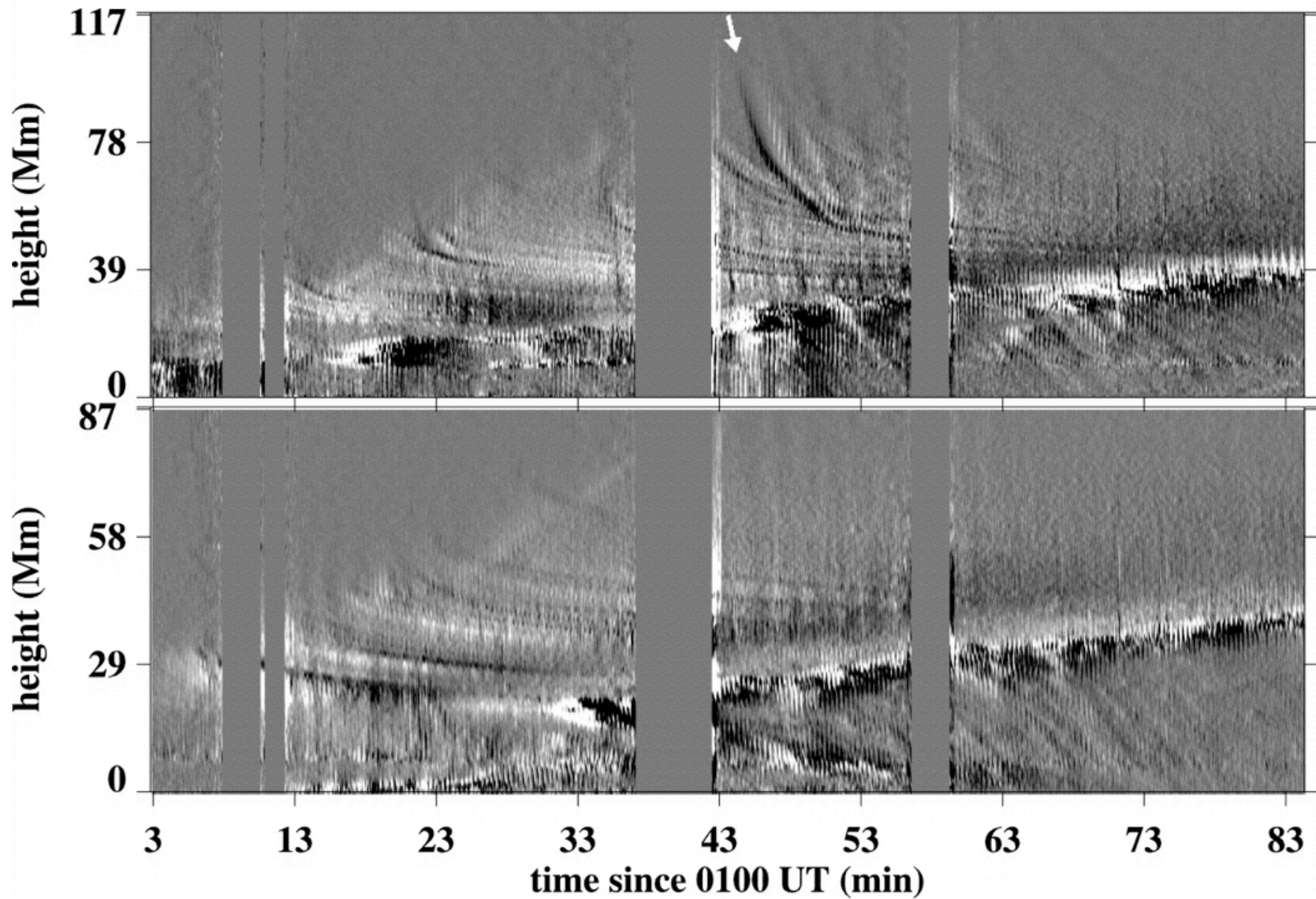
Running Difference

TRACE 195 21-Apr-2002 01:02:18

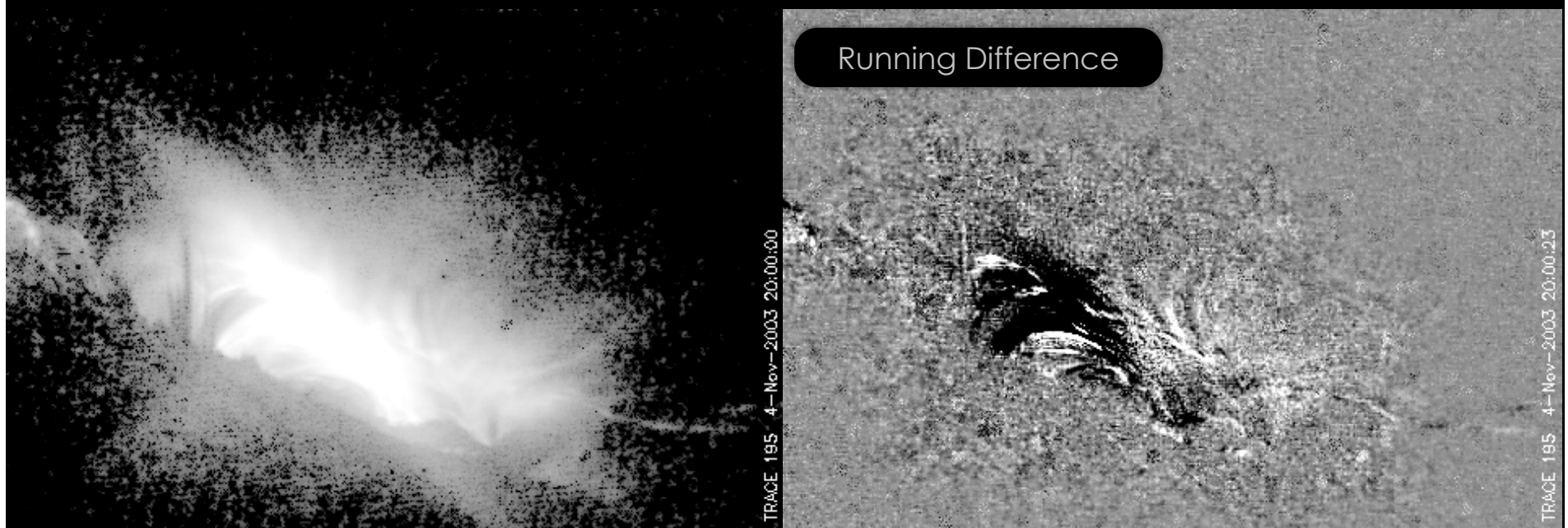
- McKenzie & Hudson, ApJ, 1999
- McKenzie, Solar Physics, 2000
- Innes et al., Solar Physics, 2003
- Asai et al., ApJ, 2004
- Sheeley, Warren, & Wang, ApJ, 2004

- Reeves et al., JGRA, 2008
- Warren et al., ApJ, 2011
- **Savage & McKenzie, ApJ, 2011**
- Takasao et al., ApJ, 2012
- Savage et al., ApJ, 2012

## Height-Time Plot for Measuring Kinematics



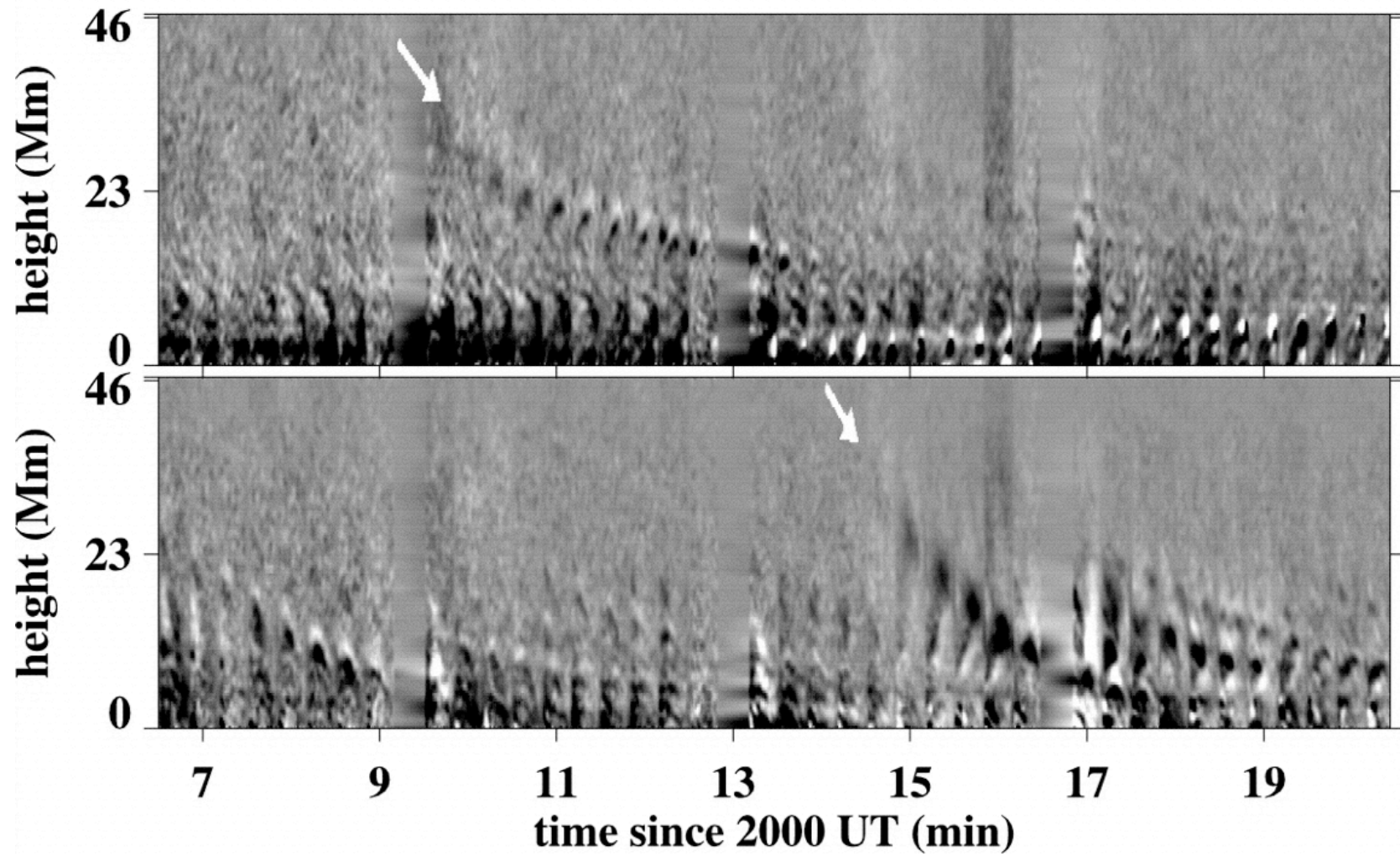
# Supra-Arcade Downflows: Another Example



TRACE 195 Å



## Height-Time Plot



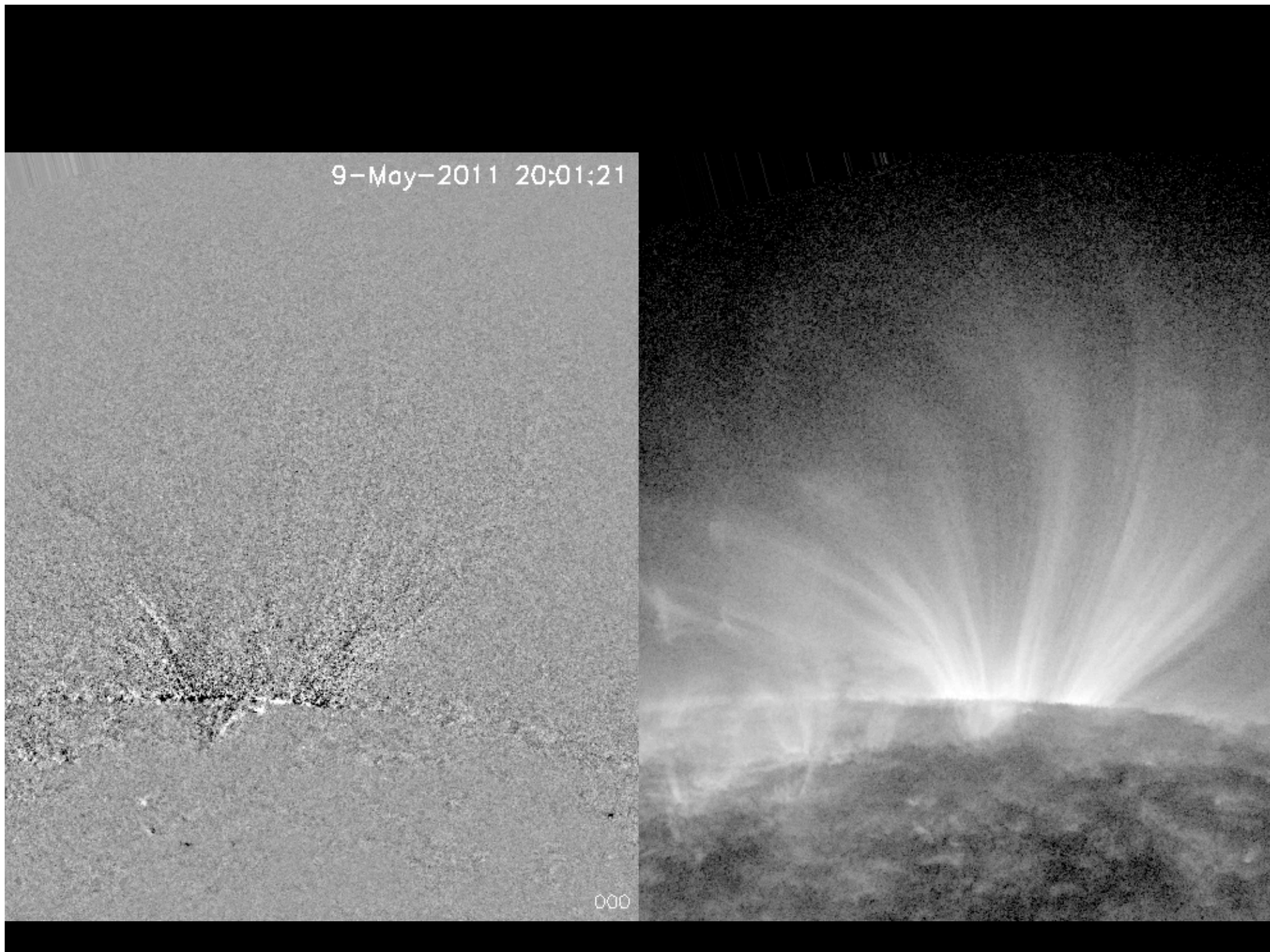
This image shows a solar flare captured by the AIA/SDO instrument at a wavelength of 131 Å. The flare is visible as a bright, white, and blueish-white structure in the lower-left quadrant of the image, extending upwards and to the right. The background is a dark, grainy blue, representing the solar corona. The text "AIA/SDO 131 Å" is overlaid in the bottom-left corner in a yellow-orange color.

AIA/SDO 131 Å

May 8, 2011

9-May-2011 20:01:21

000





9-May-2011 20:01:21

09-May-11 21:28:33



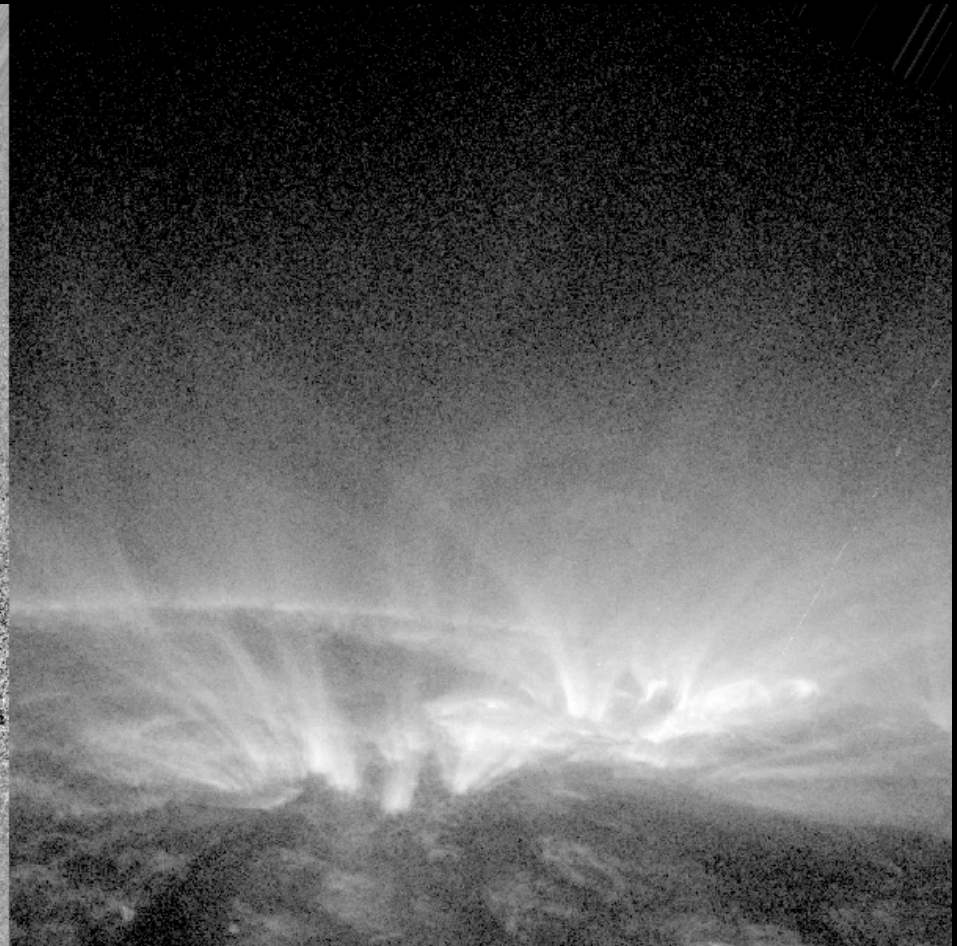
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0131

16-Mar-2011 17:31:57



001





0131

16-Mar-2011 17:31:57

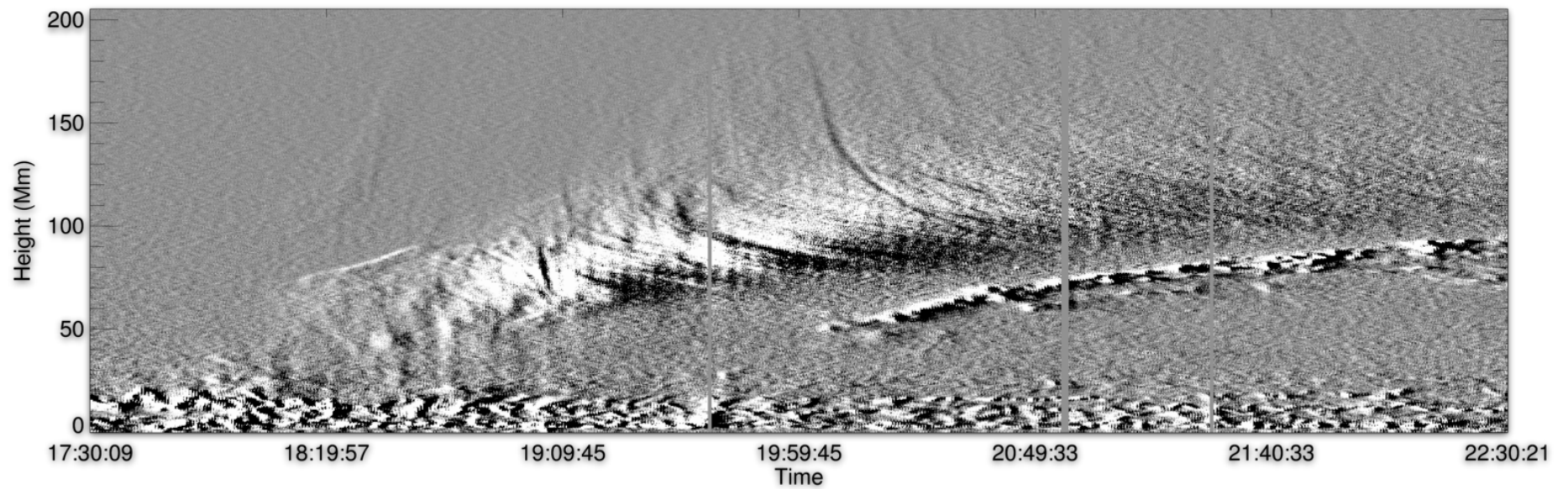
16-Mar-11 20:02:09

001

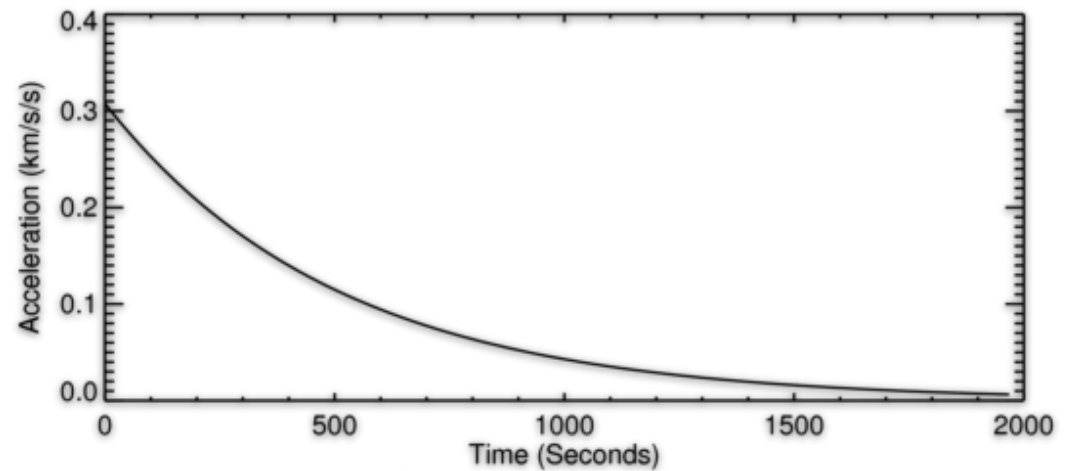
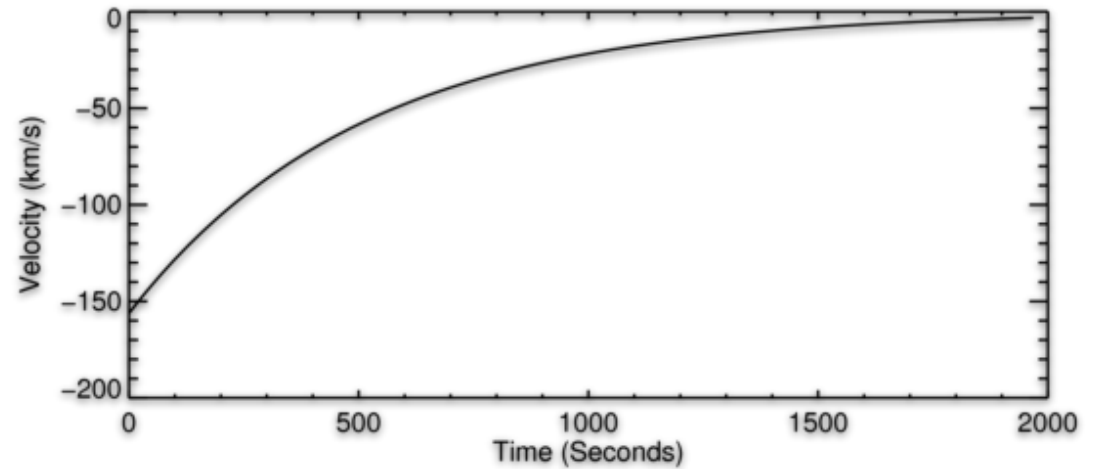
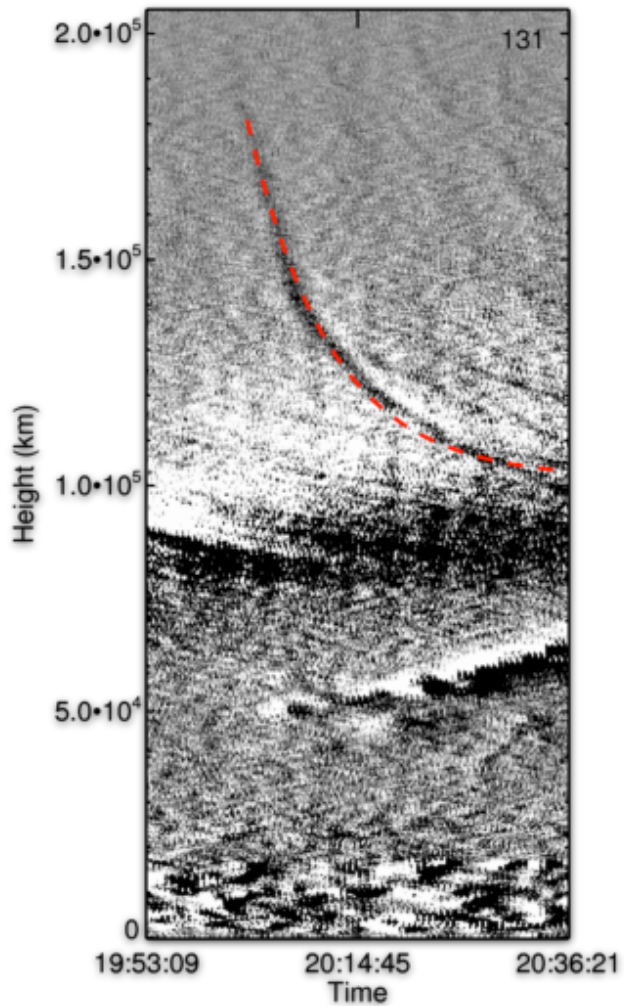


# Height-Time Plot: March 16, 2011

SDO/AIA 131 Å



# Example Height Time Track: March 16, 2011



$$h(t) = h_0 + v_T t + a_0 \tau^2 (e^{-t/\tau} - 1)$$

$$v(t) = v_T - a_0 \tau e^{-t/\tau}$$

$$a(t) = a_0 e^{-t/\tau}$$

TABLE 1  
INFLOW PROPERTIES

Track	$h_0$ (Mm)	$a_0$ ( $\text{km s}^{-2}$ )	$\tau$ (s)	$v_0$ ( $\text{km s}^{-1}$ )	$v_T$ ( $\text{km s}^{-1}$ )
16 March 2011					
00	132.6	0.039	831.7	-32.1	0.0
01	149.0	2.282	119.0	-271.6	0.0
02	178.6	0.274	454.1	-124.5	0.0
03	196.6	0.492	290.6	-143.0	0.0
04	204.3	0.857	226.7	-194.2	0.0
05	136.5	0.619	261.2	-161.7	0.0
06	188.9	0.271	500.6	-135.8	0.0
07	180.9	0.308	507.7	-156.2	0.0
08	225.6	0.089	1031.3	-91.7	0.0
09	250.4	0.044	1938.6	-84.6	0.0
9 May 2011					
00	113.6	2.185	128.1	-279.9	0.0
01	118.9	1.043	212.5	-221.7	0.0
02	131.1	1.506	166.6	-250.9	0.0
03	117.6	0.581	231.3	-134.3	0.0
04	128.2	0.440	345.3	-152.1	0.0
05	110.8	0.161	406.1	-65.3	0.0
06	63.8	0.087	659.1	-57.1	0.0
07	82.0	0.237	363.8	-86.1	0.0
08	80.4	1.050	115.6	-121.3	0.0
09	103.7	0.786	192.2	-151.1	0.0
10	73.8	0.306	245.1	-75.1	0.0
11	90.9	0.375	270.7	-101.7	0.0
18 May 2011					
00	75.2	2.687	102.1	-274.4	0.0
01	84.7	2.726	97.1	-264.8	0.0
02	83.3	0.451	274.1	-123.7	0.0
03	70.5	3.407	77.7	-264.8	0.0
04	61.7	1.190	120.0	-142.8	0.0
05	75.1	0.867	165.8	-143.7	0.0
06	88.3	0.473	316.6	-149.9	0.0
07	70.7	1.059	155.9	-165.0	0.0
08	76.7	0.438	243.4	-106.5	0.0
09	83.1	0.403	440.2	-177.5	0.0



TABLE 1  
INFLOW PROPERTIES

Track	$h_0$ (Mm)	$a_0$ ( $\text{km s}^{-2}$ )	$\tau$ (s)	$v_0$ ( $\text{km s}^{-1}$ )	$v_T$ ( $\text{km s}^{-1}$ )
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00	132.6	0.039	831.7	-32.1	0.0
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03	196.6	0.492	290.6	-143.0	0.0
04	204.3	0.857	226.7	-194.2	0.0
05	136.5	0.619	261.2	-161.7	0.0
06	188.9	0.271	500.6	-135.8	0.0
07	180.9	0.308	507.7	-156.2	0.0
08	225.6				
09	250.4				
9 May 2011					
00	113.6				
01	118.9				
02	131.1				
03	117.6				
04	128.2				
05	110.8				
06	63.8				
07	82.0				
08	80.4				
09	103.7				
10	73.8				
11	90.9				
18 May 2011					
00	75.2				
01	84.7				
02	83.3				
03	70.5				
04	61.7				
05	75.1	0.867	165.8	-143.7	0.0
06	88.3	0.473	316.6	-149.9	0.0
07	70.7	1.059	155.9	-165.0	0.0
08	76.7	0.438	243.4	-106.5	0.0
09	83.1	0.403	440.2	-177.5	0.0

## Median Initial Height

ALA: 111 km/s

Savage & McKenzie 2011: 83 km/s

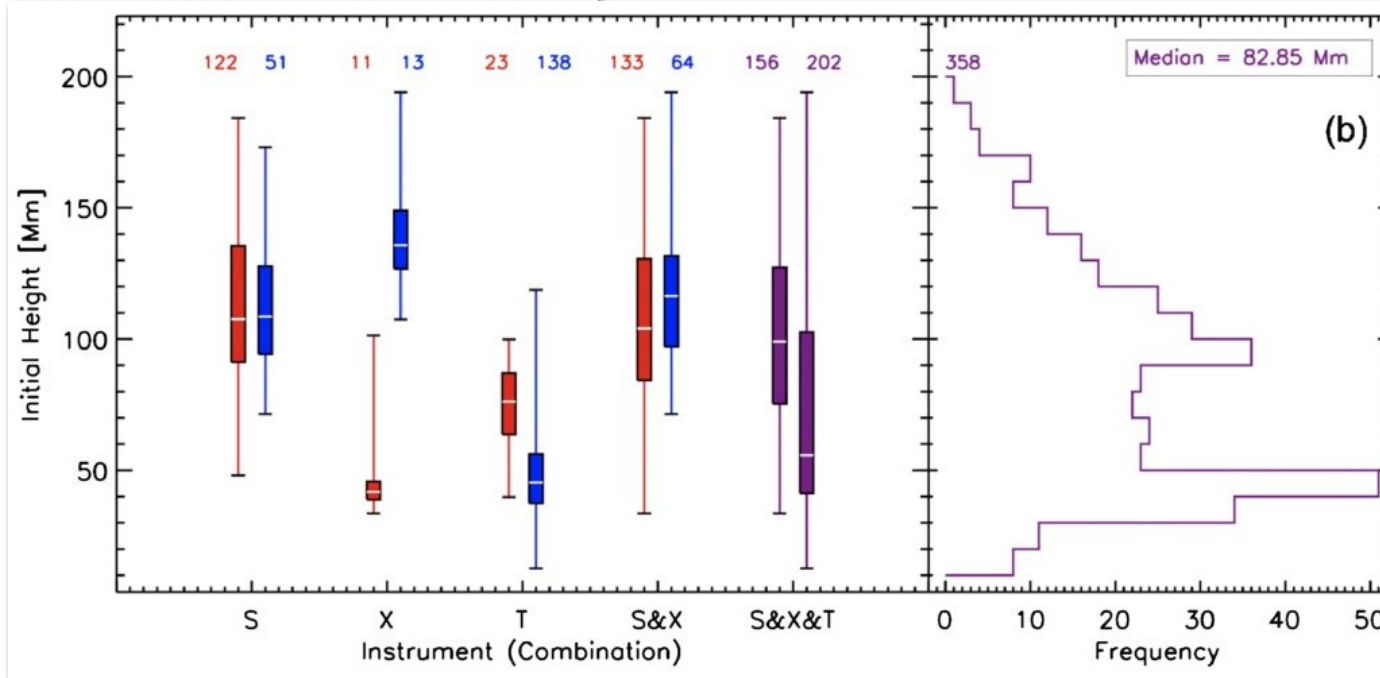


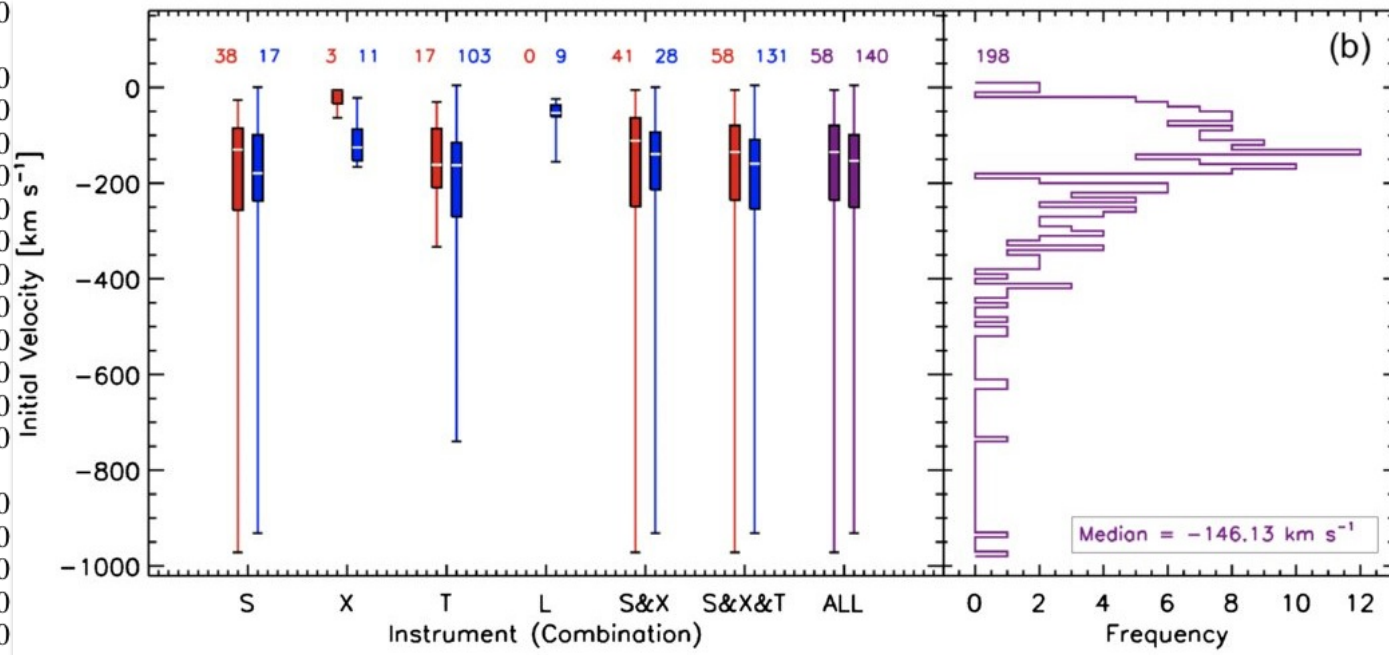
TABLE 1  
INFLOW PROPERTIES

Track	$h_0$ (Mm)	$a_0$ ( $\text{km s}^{-2}$ )	$\tau$ (s)	$v_0$ ( $\text{km s}^{-1}$ )	$v_T$ ( $\text{km s}^{-1}$ )
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07	180.9	0.308	507.7	-156.2	0.0
08	225.6	0.089	1031.3	-91.7	0.0
09	250.4	0.044	1938.6	-84.6	0.0
9 May 2011					
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01	118.9	1.043	212.5	-221.7	0.0
02	131.1	1.506	166.6	-250.9	0.0
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06	63.8	0.087	659.1	-57.1	0.0
07	82.0	0.237	363.8	-86.1	0.0
08	80.4	1.050	115.6	-121.3	0.0
09	103.7	0.786	192.2	-151.1	0.0
10	73.8	0.306	245.1	-75.1	0.0
11	90.9	0.375	270.7	-101.7	0.0
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08	76.7	0.438	243.4	-106.5	0.0
09	83.1	0.403	440.2	-177.5	0.0

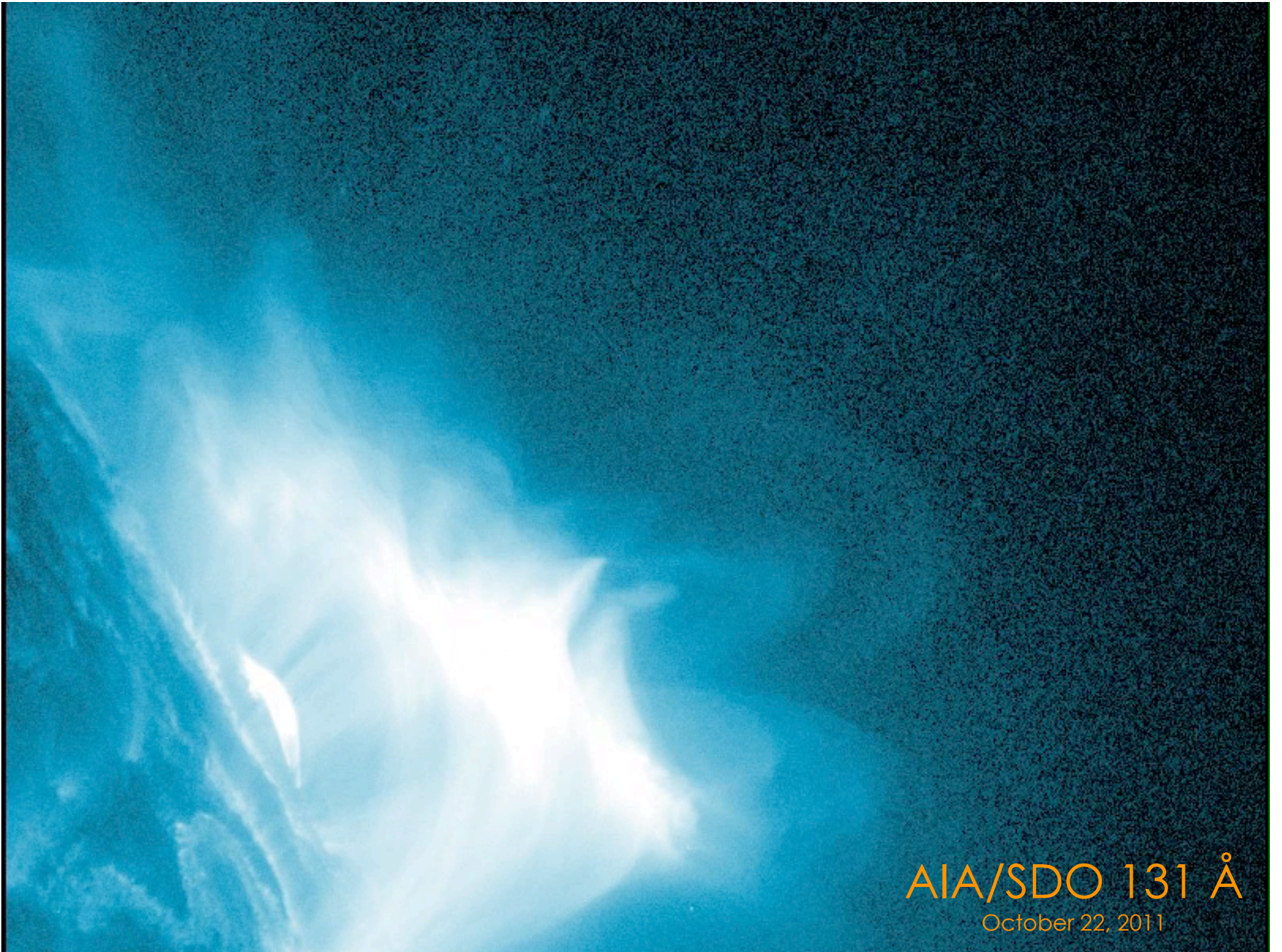
TABLE 1  
 W PROPERTIES

$\tau$ (s)	$v_0$ (km s <sup>-1</sup> )	$v_T$ (km s <sup>-1</sup> )
831.7	-32.1	0.0
119.0	-271.6	0.0
454.1	-124.5	0.0
290.6	-143.0	0.0
226.7	-194.2	0.0
261.2	-161.7	0.0
500.6	-135.8	0.0
507.7	-156.2	0.0
1031.3	-91.7	0.0
1938.6	-84.6	0.0
128.1	-279.9	0.0
212.5	-221.7	0.0
166.6	-250.9	0.0
231.3	-134.3	0.0
345.3	-152.1	0.0
406.1	-65.3	0.0
659.1	-57.1	0.0
363.8	-86.1	0.0
115.6	-121.3	0.0
192.2	-151.1	0.0
245.1	-75.1	0.0
270.7	-101.7	0.0
102.1	-274.4	0.0
97.1	-264.8	0.0
274.1	-123.7	0.0
77.7	-264.8	0.0
120.0	-142.8	0.0
165.8	-143.7	0.0
316.6	-149.9	0.0
155.9	-165.0	0.0
243.4	-106.5	0.0
440.2	-177.5	0.0

**Median Initial Velocity**  
 AIA: -144 km/s  
 Savage & McKenzie 2011: -146 km/s







AIA/SDO 131 Å  
October 22, 2011



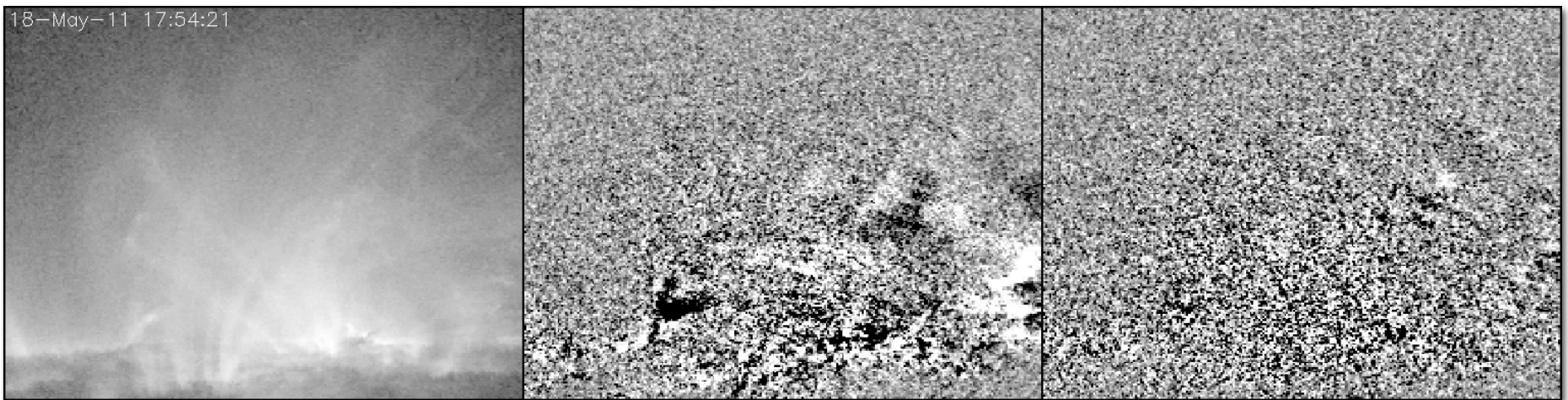
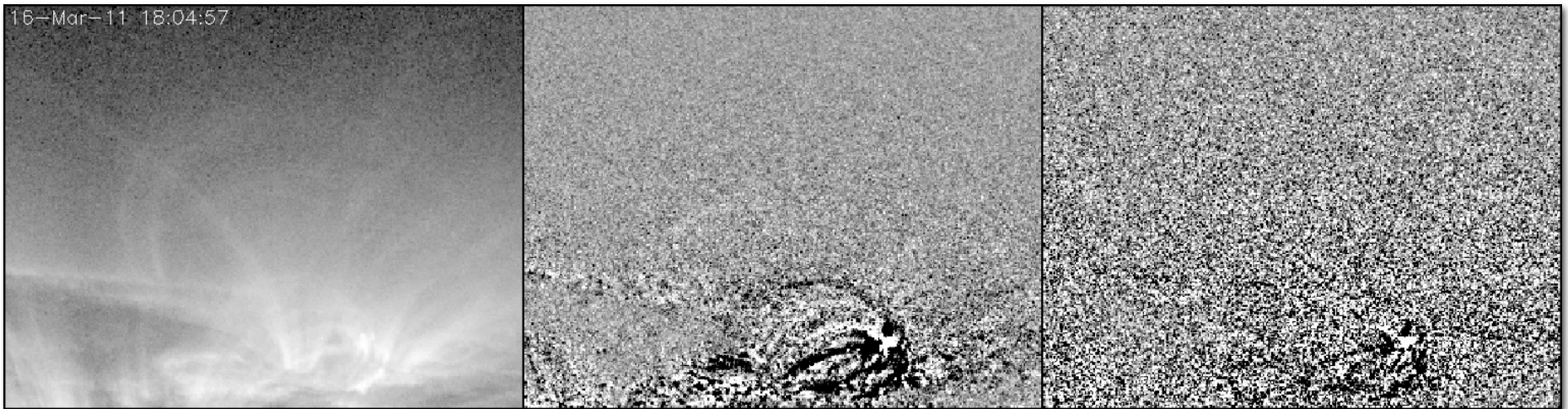
Evidence for "patchy" reconnection?

AIA/SDO 131 Å  
October 22, 2011



# Initial Formation of High Temperature Flare Loops

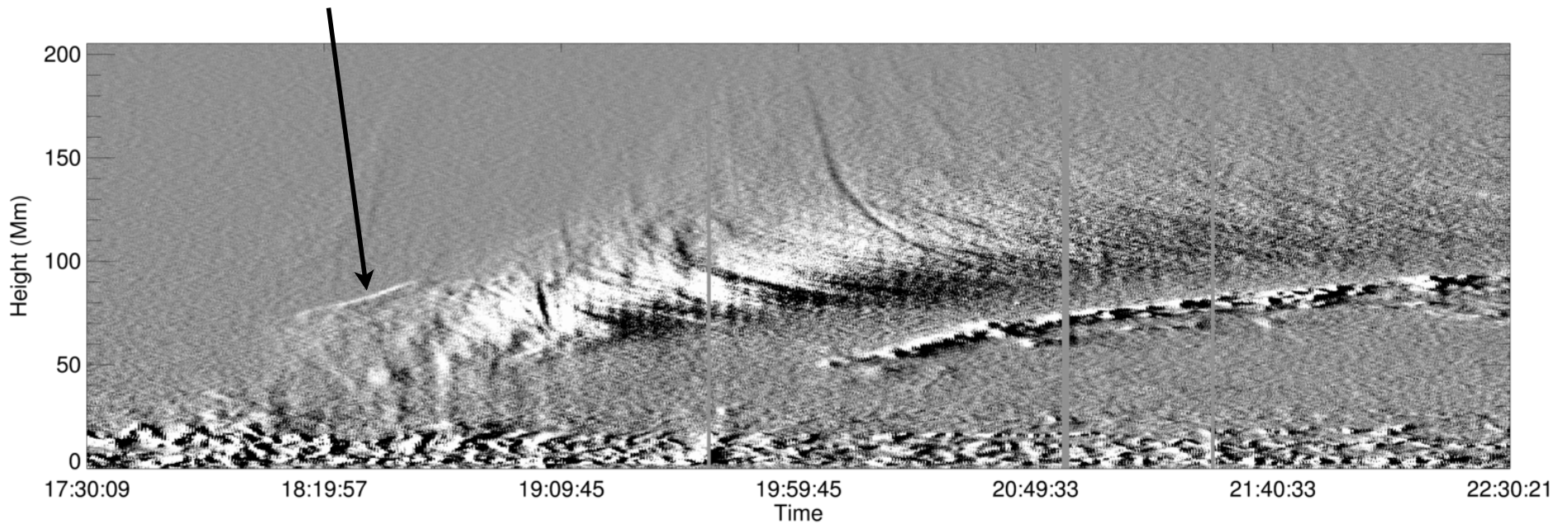
first hot loops form "in place" - no initial downward motion



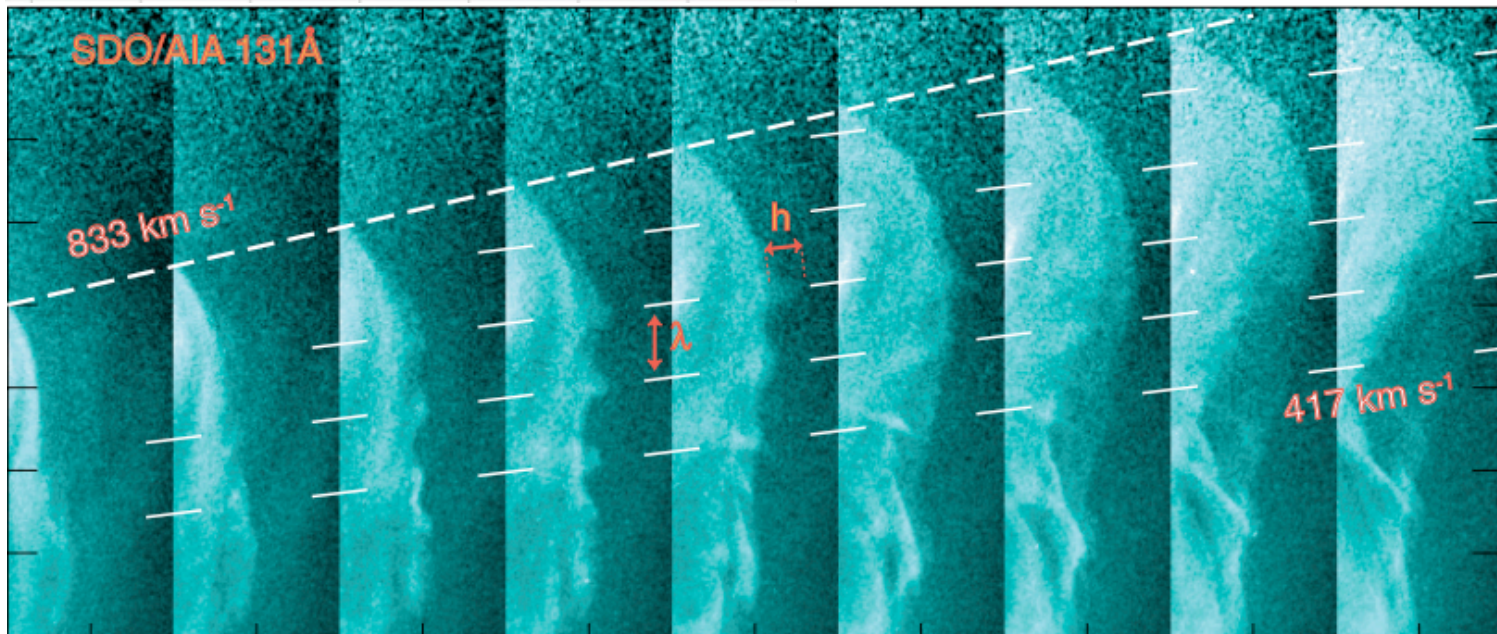
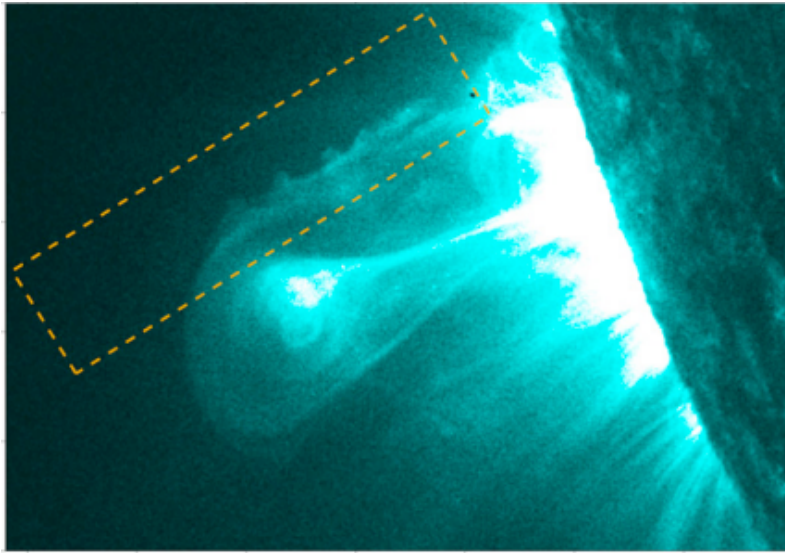


# Height-Time Plot: March 16, 2011

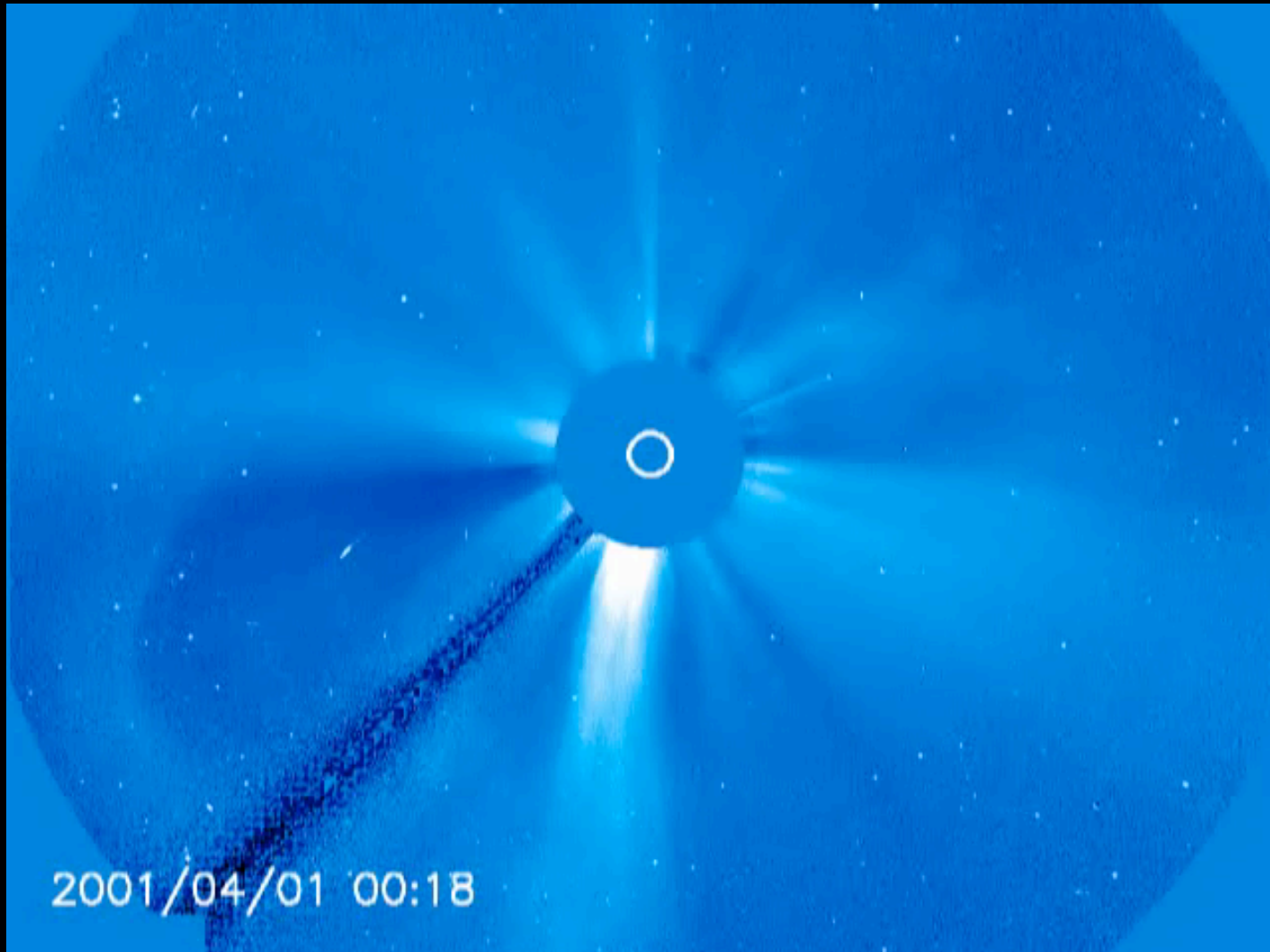
first hot loops form  
“in place” - no initial  
downward motion



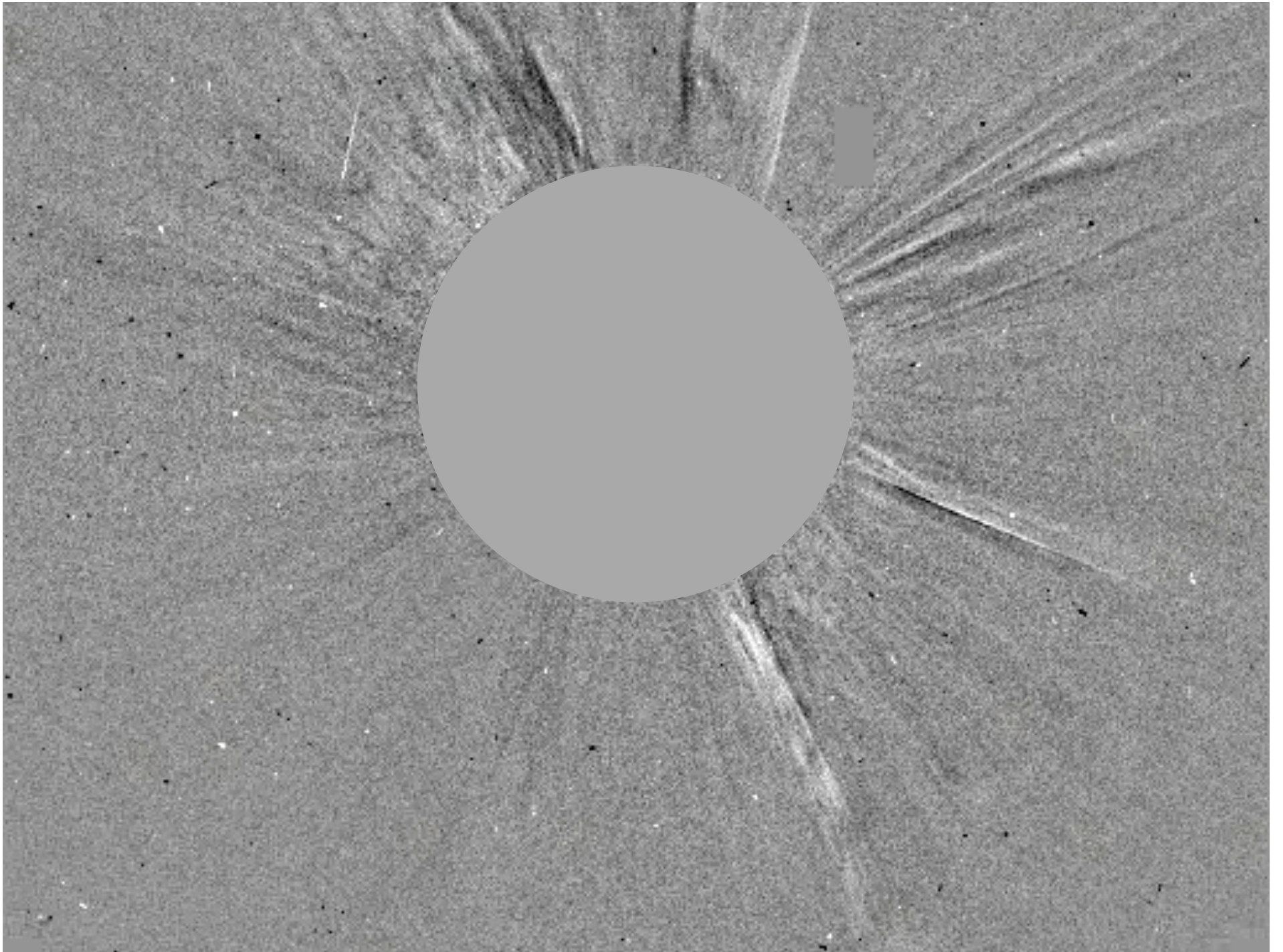
# Kelvin-Helmholtz Instability?



# Inflows in the Outer Corona



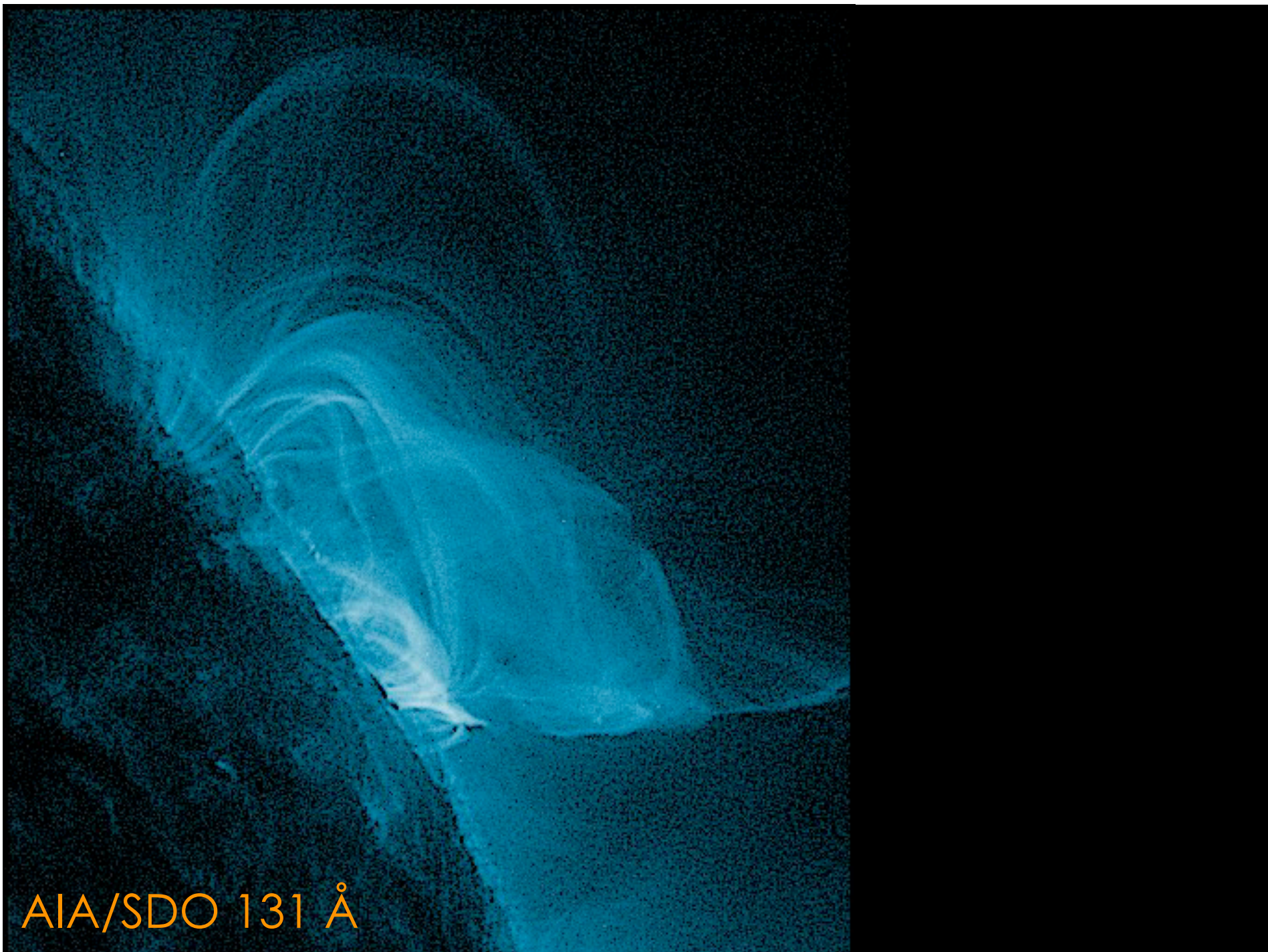






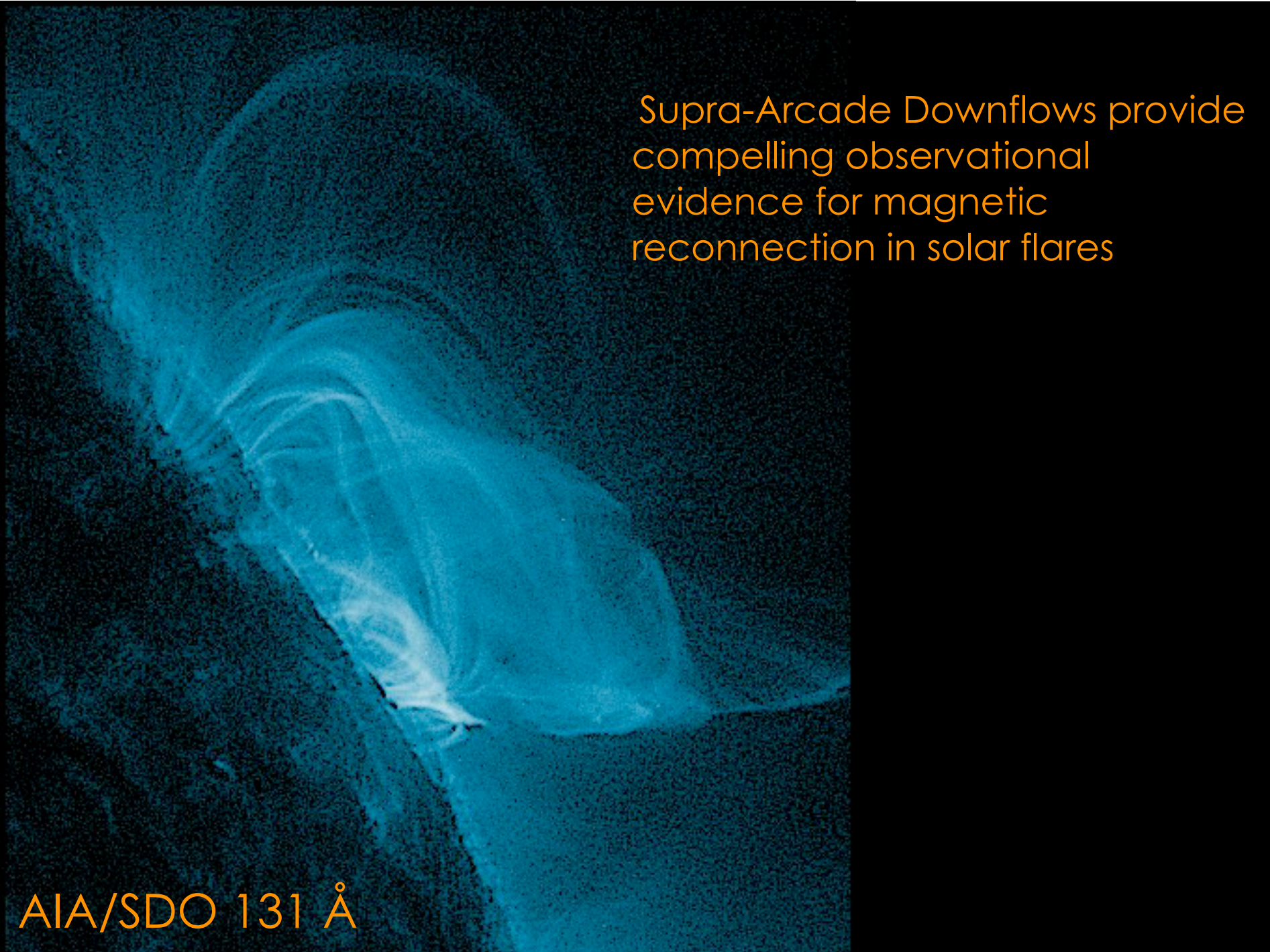
C2 2005/10/03 00:06





AIA/SDO 131 Å

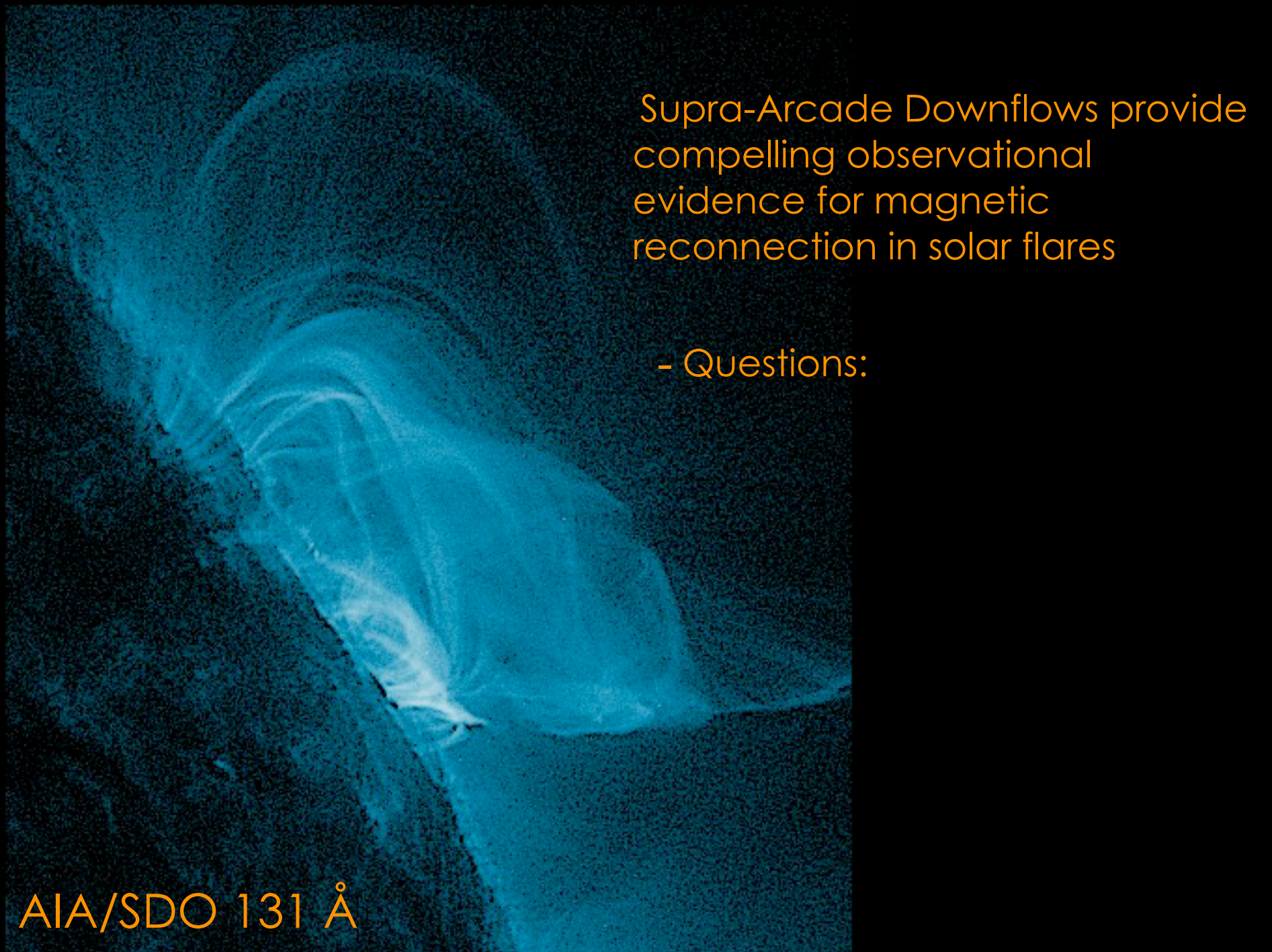


A solar flare image captured by the AIA/SDO instrument at 131 Å. The image shows a bright, curved structure on the left side, likely an arcade of magnetic flux ropes. To the right of this structure, there are several distinct, downward-pointing features known as supra-arcade downflows. These downflows appear as bright, elongated structures extending from the top of the arcade towards the bottom of the frame. The background is dark, highlighting the bright emission from the solar plasma.

Supra-Arcade Downflows provide compelling observational evidence for magnetic reconnection in solar flares

AIA/SDO 131 Å



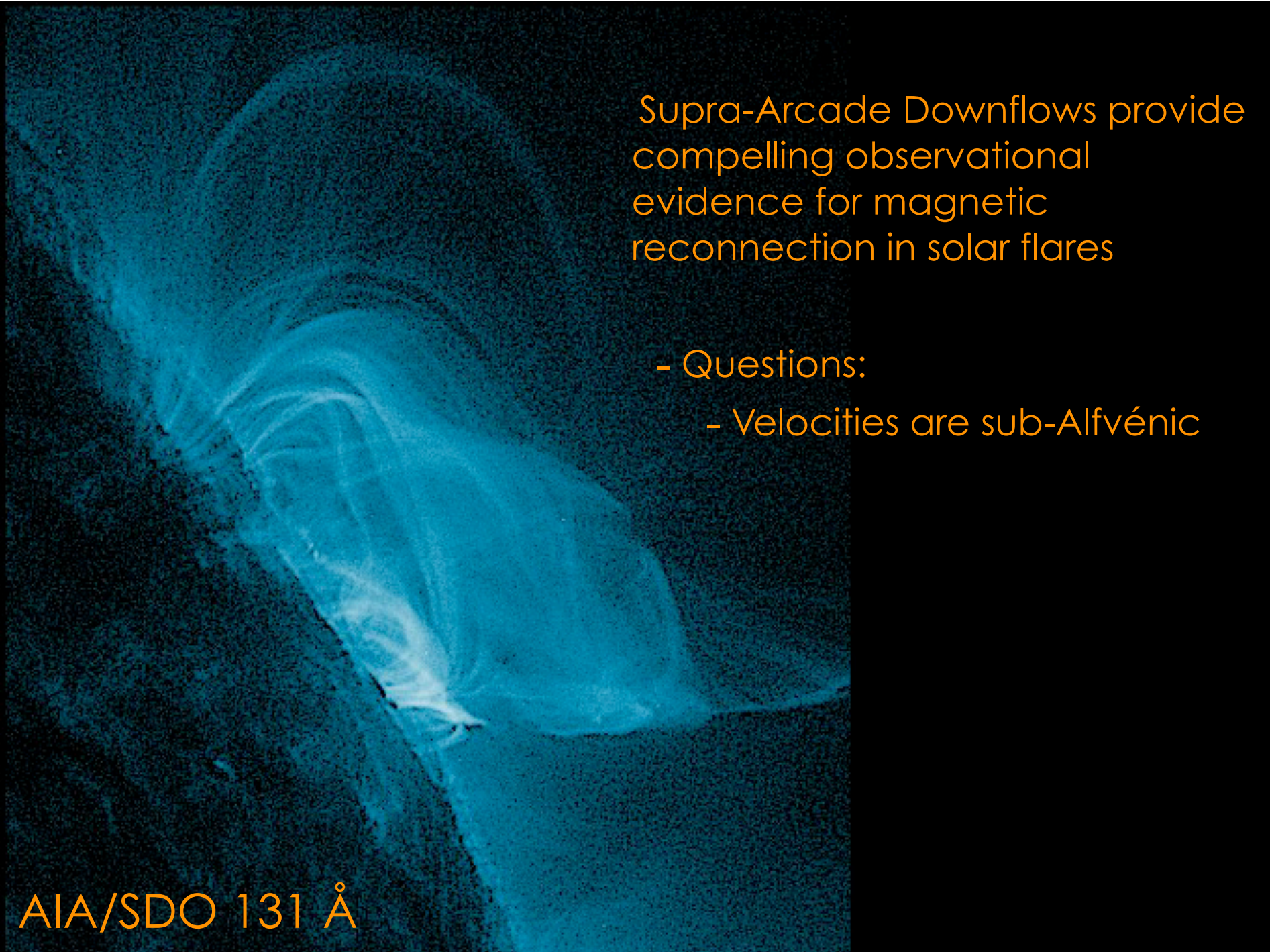
A high-resolution solar image in the 131 Å wavelength, showing a bright, curved structure in the upper left quadrant, likely a solar flare or coronal mass ejection. The structure is composed of multiple parallel, slightly curved filaments that appear to be moving or expanding. The background is dark with some faint, diffuse emission.

Supra-Arcade Downflows provide compelling observational evidence for magnetic reconnection in solar flares

- Questions:

AIA/SDO 131 Å



A high-resolution solar image in the 131 Å wavelength, showing a bright, curved structure in the solar corona. The structure appears to be a magnetic flux rope or a similar configuration, with a bright, curved filamentary structure. The background is dark, and the structure is illuminated from the left, creating a bright, curved shape that extends across the frame. The image is a high-resolution view of the solar corona, showing the intricate details of the magnetic field and the plasma structure.

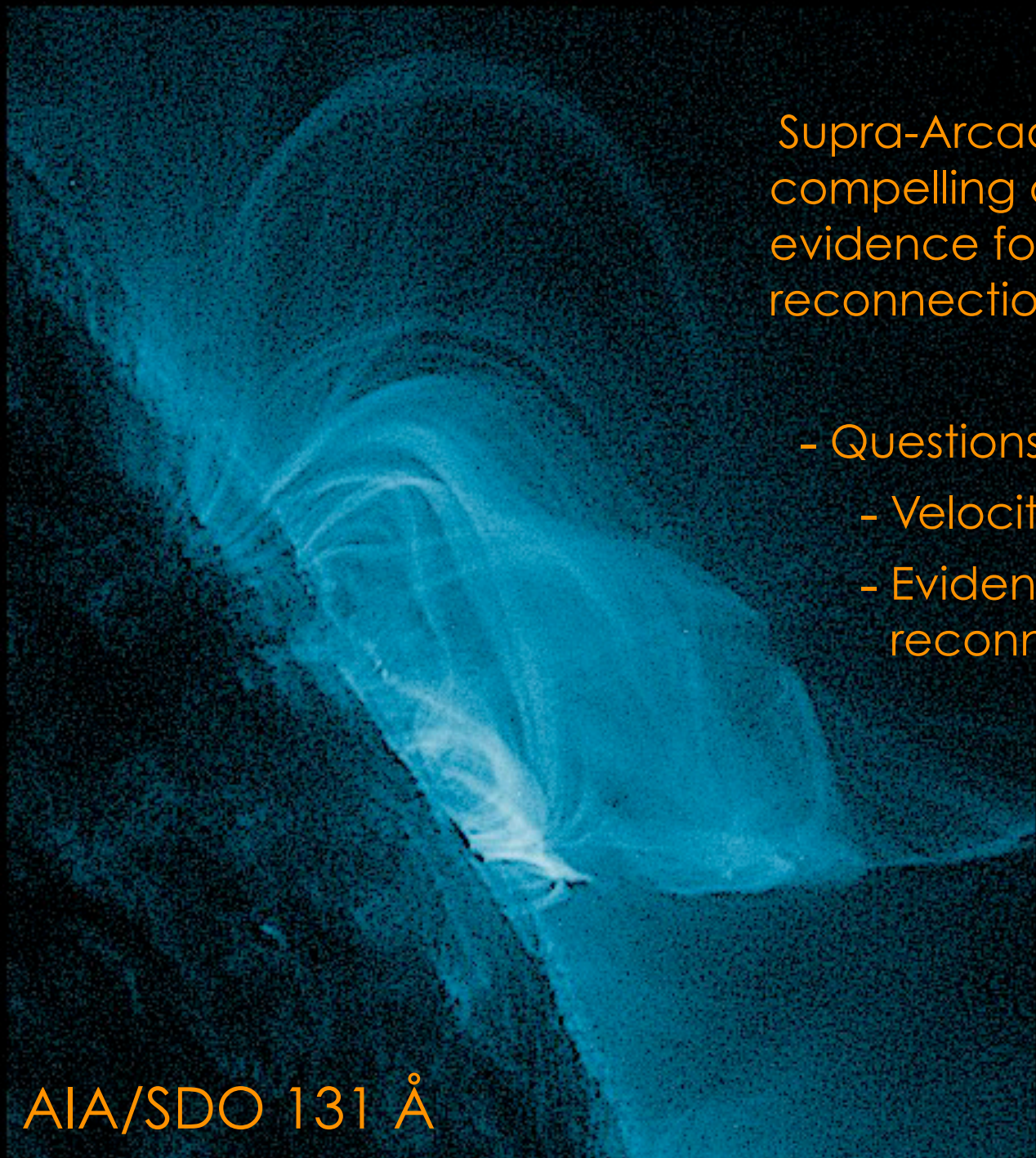
Supra-Arcade Downflows provide compelling observational evidence for magnetic reconnection in solar flares

- Questions:

- Velocities are sub-Alfvénic

AIA/SDO 131 Å



A high-resolution solar image in the 131 Å band from the AIA/SDO instrument. The image shows a complex solar flare structure with bright, curved features and a prominent region of supra-arcade downflows. The background is dark, and the flare structures are highlighted in bright yellow and white. The text is overlaid on the right side of the image.

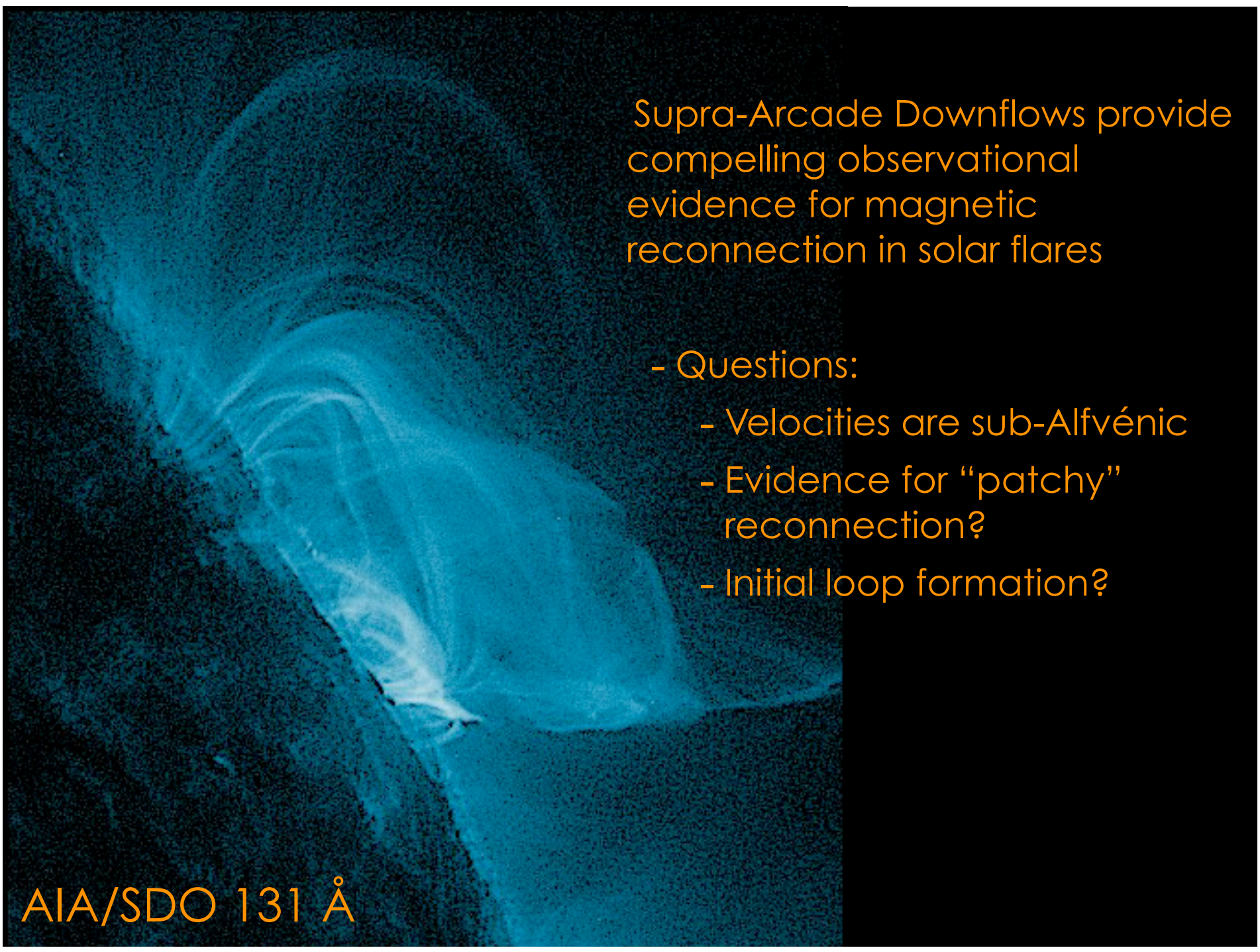
Supra-Arcade Downflows provide compelling observational evidence for magnetic reconnection in solar flares

- Questions:

- Velocities are sub-Alfvénic
- Evidence for “patchy” reconnection?

AIA/SDO 131 Å



A high-resolution solar image in the 131 Å wavelength, showing a bright, curved structure in the solar corona. The structure appears to be a magnetic loop or arcade, with a bright, narrow channel of plasma flowing downwards from the top of the loop, characteristic of a supra-arcade downflow. The background is dark, with some faint, diffuse emission.

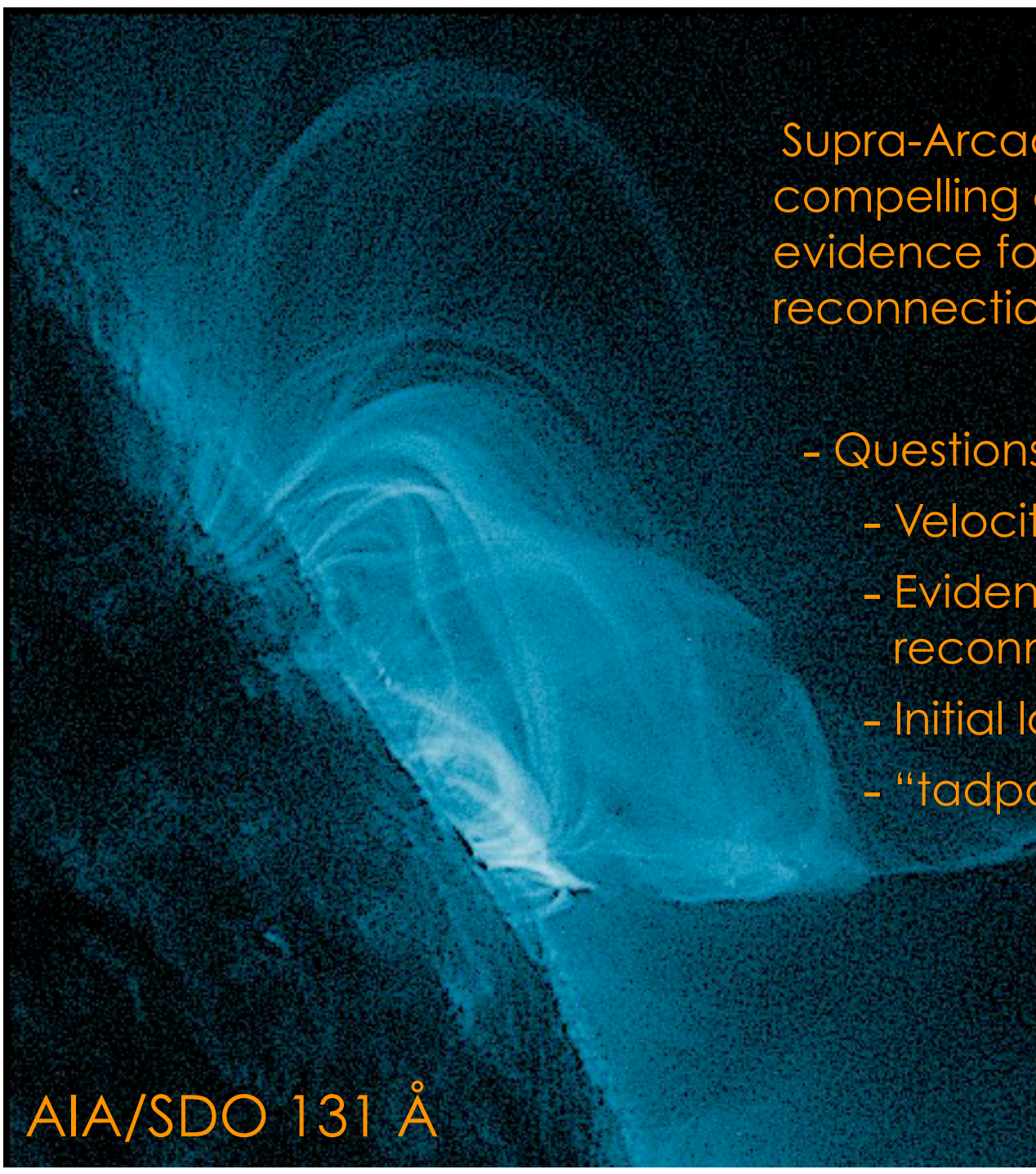
Supra-Arcade Downflows provide compelling observational evidence for magnetic reconnection in solar flares

- Questions:

- Velocities are sub-Alfvénic
- Evidence for “patchy” reconnection?
- Initial loop formation?

AIA/SDO 131 Å



A blue-tinted image of a solar flare captured by the AIA/SDO 131 Å instrument. The image shows a bright, curved structure with a central loop and a series of parallel, downward-pointing features known as supra-arcade downflows. The background is dark, highlighting the intense light of the flare.

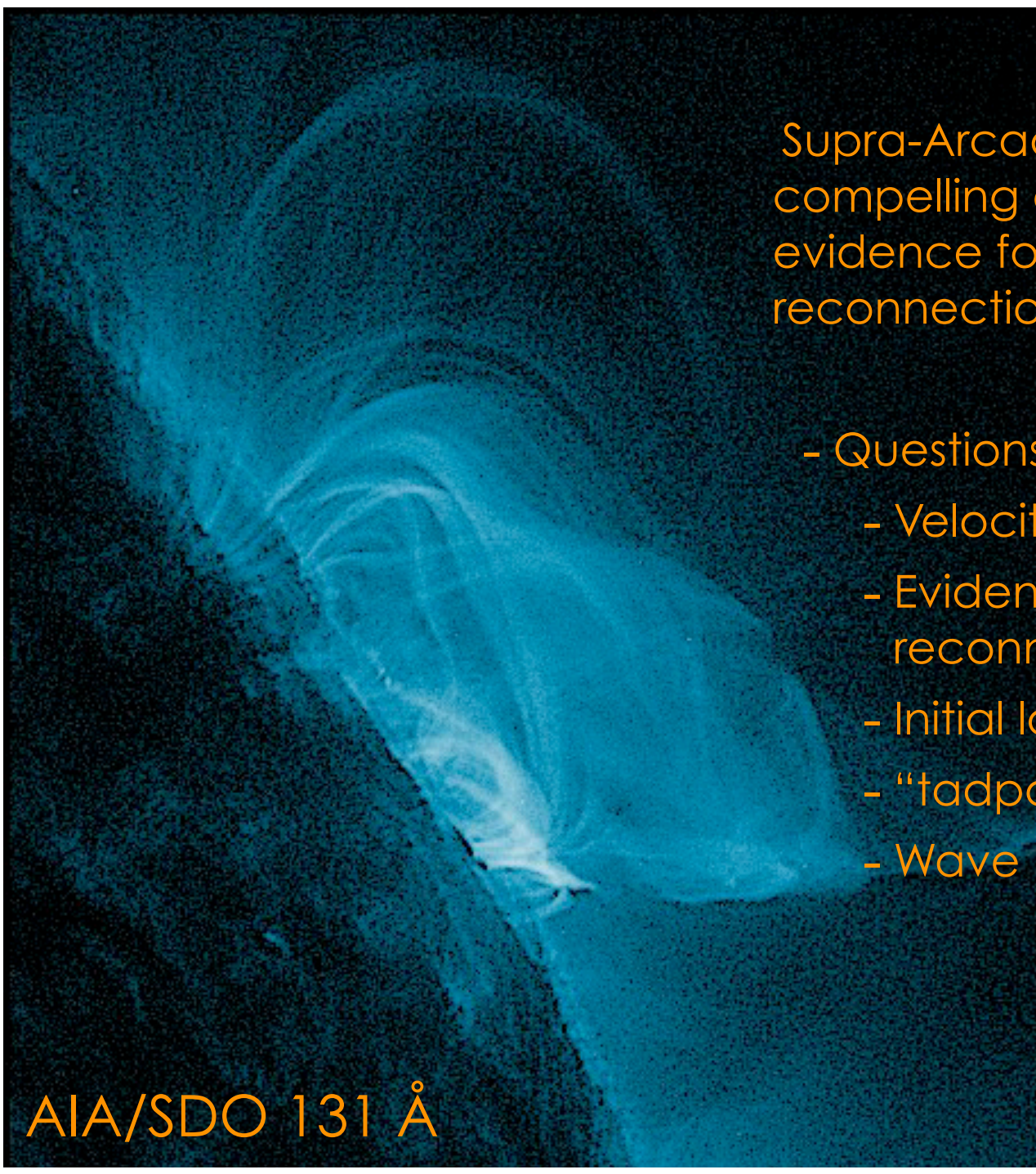
Supra-Arcade Downflows provide compelling observational evidence for magnetic reconnection in solar flares

- Questions:

- Velocities are sub-Alfvénic
- Evidence for “patchy” reconnection?
- Initial loop formation?
- “tadpoles” vs “loops”

AIA/SDO 131 Å



A solar flare image captured in the 131 Å wavelength by the AIA instrument on the SDO satellite. The image shows a bright, curved structure, likely a magnetic arcade, with a distinct region of bright emission. The background is dark, highlighting the structure. The text on the right side of the image discusses supra-arcade downflows and their implications for magnetic reconnection.

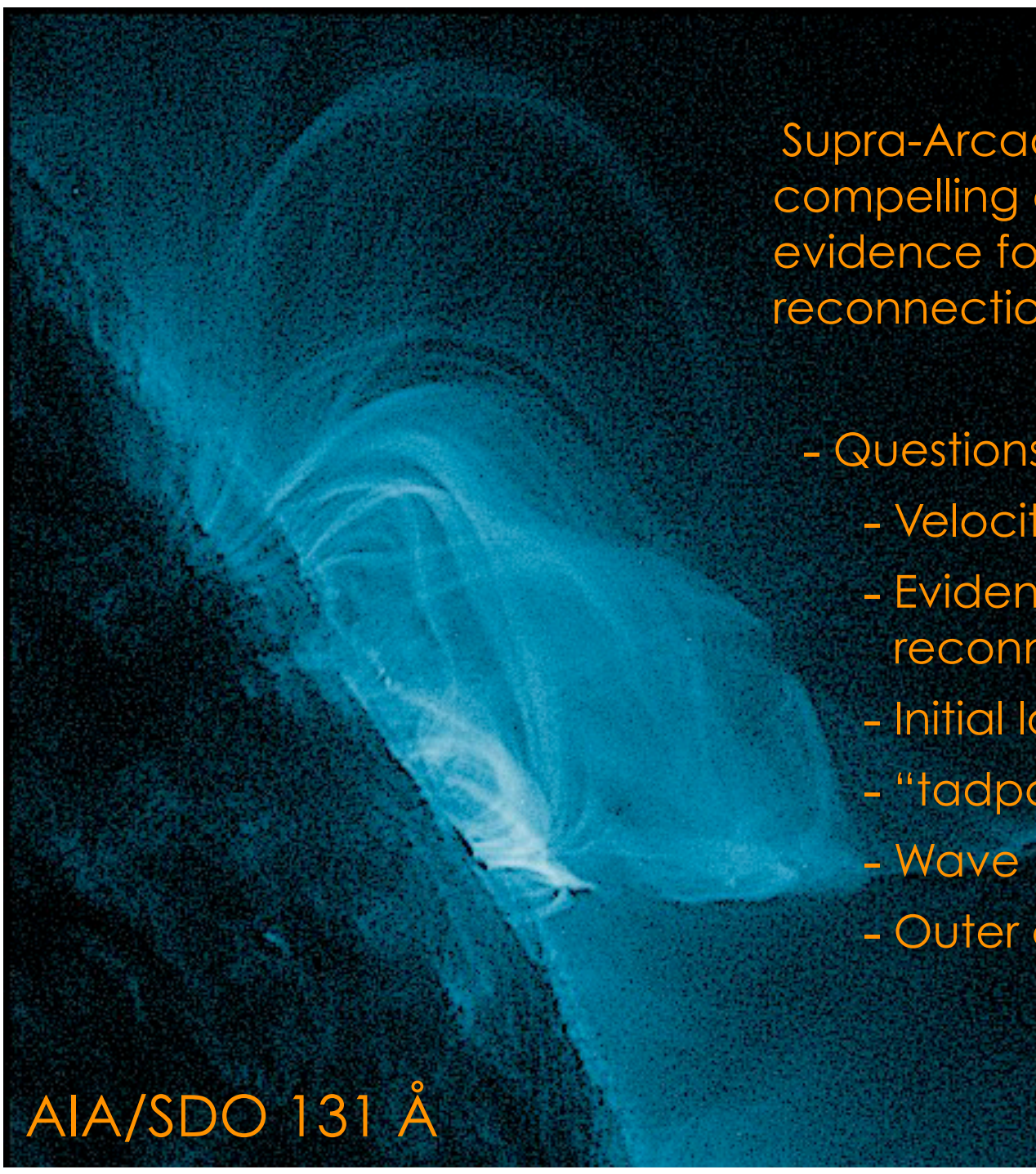
Supra-Arcade Downflows provide compelling observational evidence for magnetic reconnection in solar flares

- Questions:

- Velocities are sub-Alfvénic
- Evidence for “patchy” reconnection?
- Initial loop formation?
- “tadpoles” vs “loops”
- Wave motions?

AIA/SDO 131 Å



A blue-tinted image of a solar flare captured by the AIA/SDO instrument at 131 Å. The image shows a bright, curved structure with a central loop and a bright, downward-pointing flow of plasma, characteristic of supra-arcade downflows. The background is dark, highlighting the intense emission from the flare.

Supra-Arcade Downflows provide compelling observational evidence for magnetic reconnection in solar flares

- Questions:

- Velocities are sub-Alfvénic
- Evidence for “patchy” reconnection?
- Initial loop formation?
- “tadpoles” vs “loops”
- Wave motions?
- Outer corona?

AIA/SDO 131 Å