The Heating of the Solar Atmosphere: From the bottom up?

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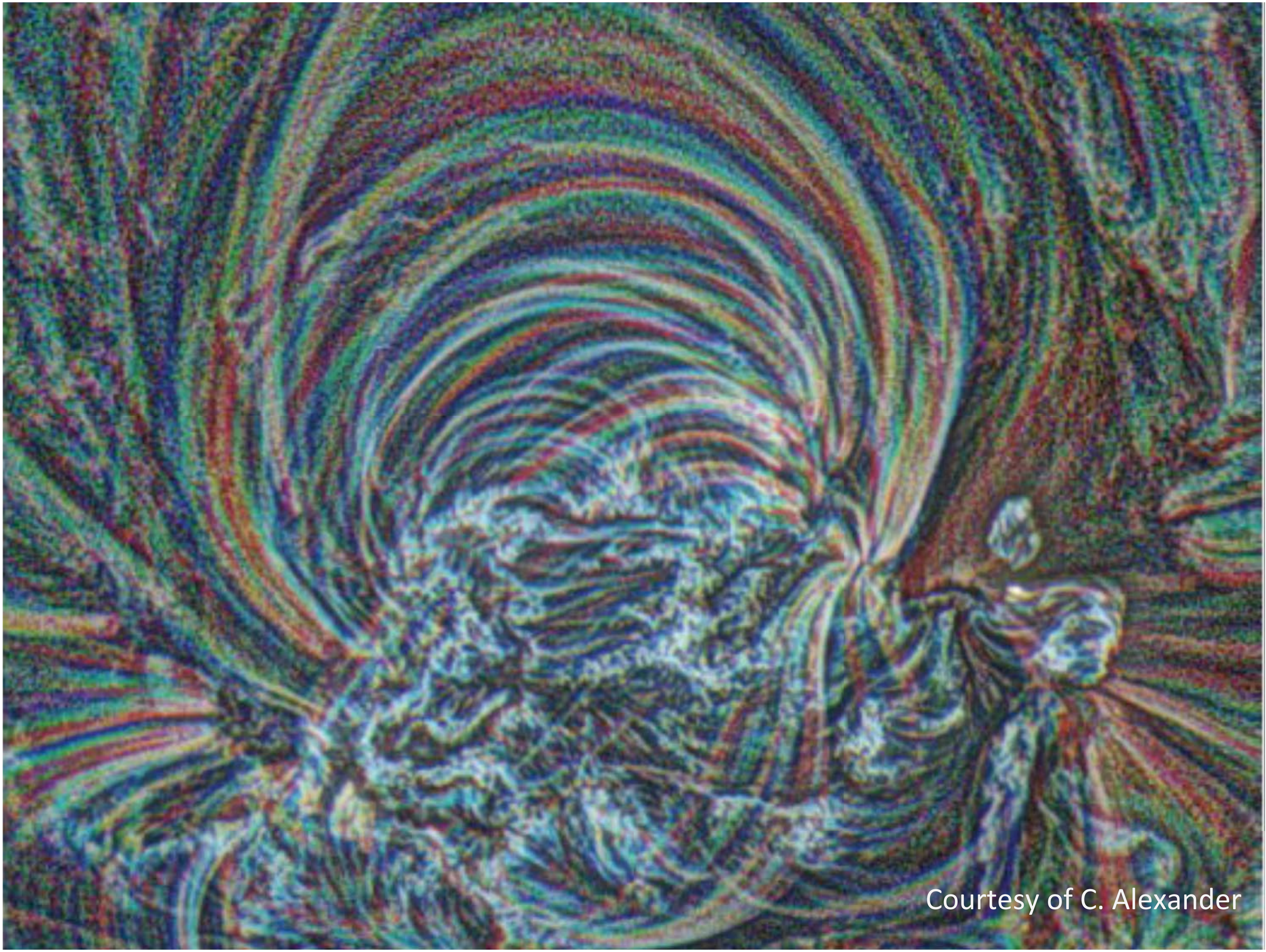
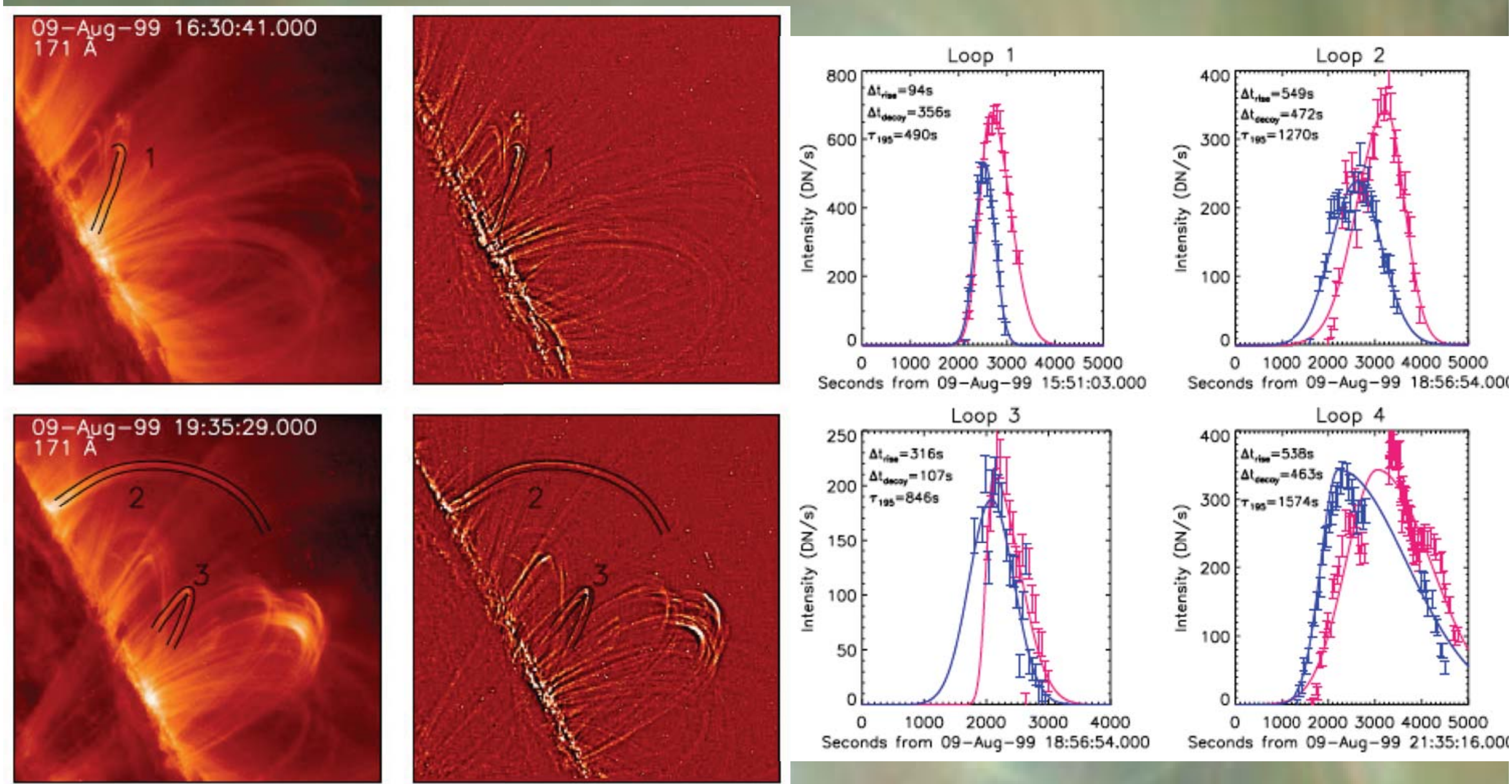
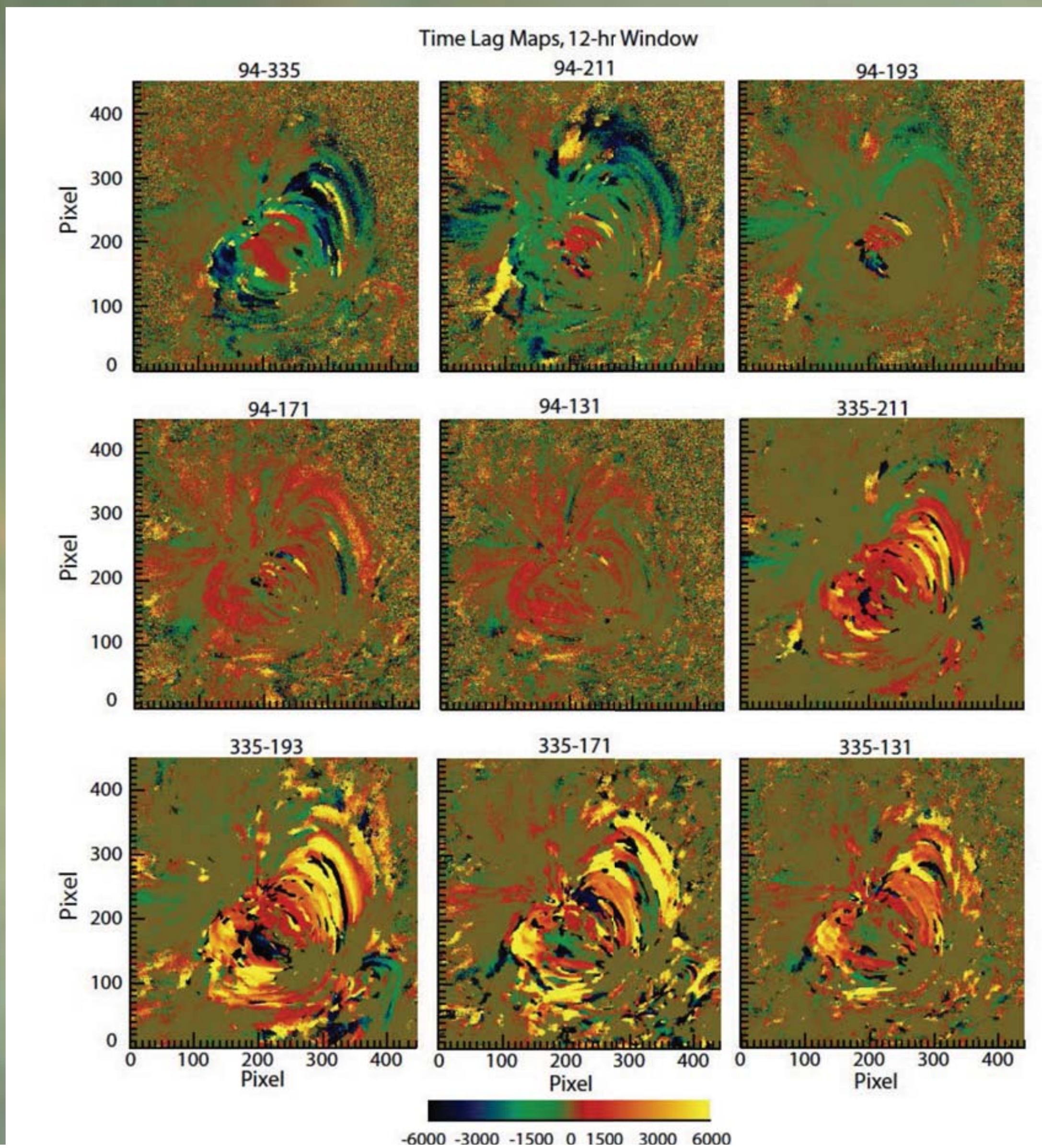

Courtesy of C. Alexander

EUV Loop Evolution

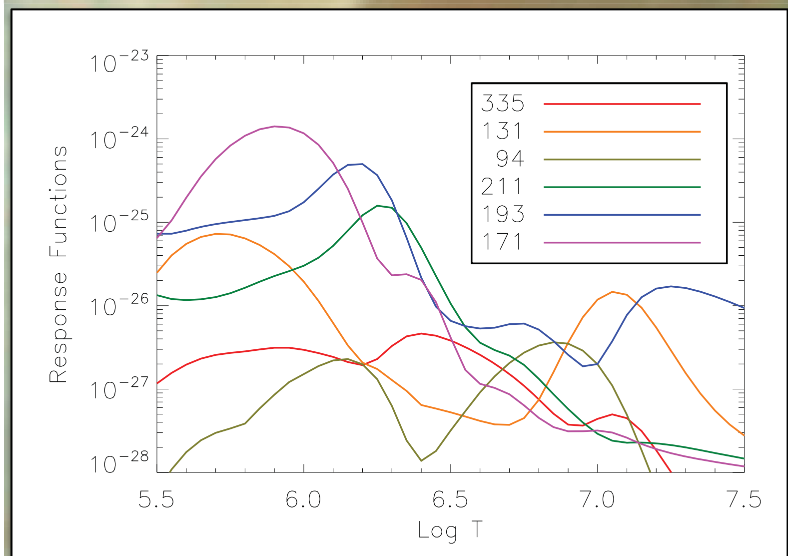


Mulu-Moore et al., ApJ, 742, 6

Timelag maps

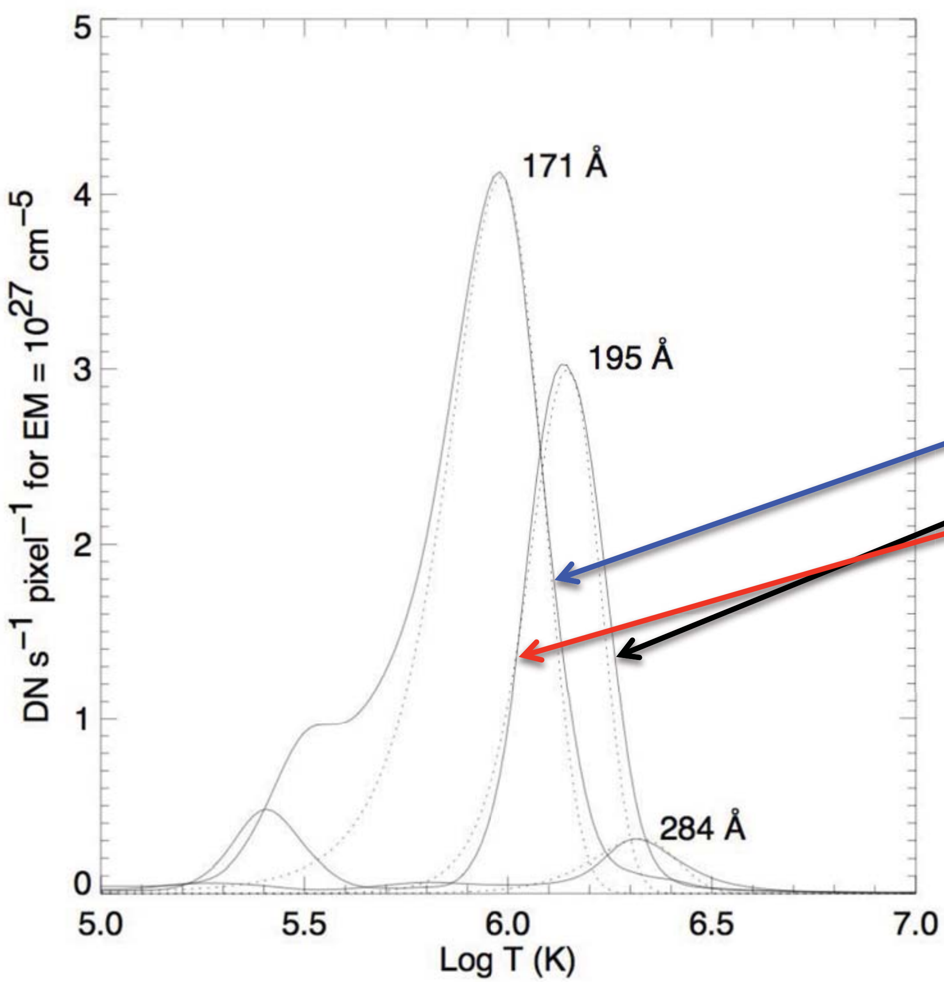


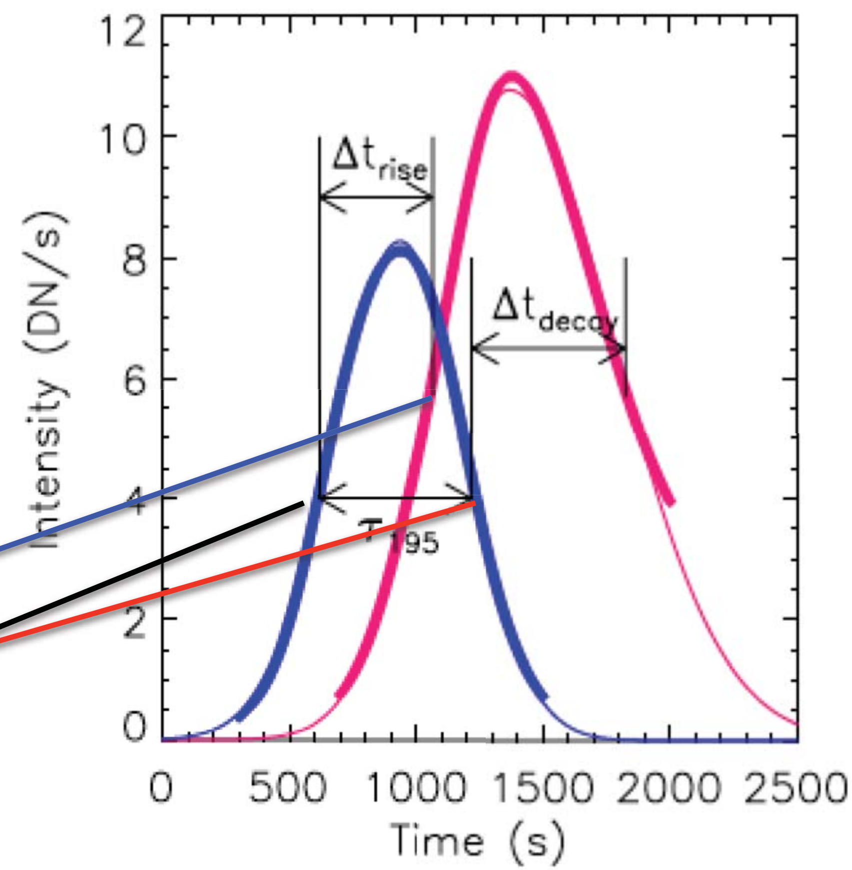
Method developed by Viall et al. finds evidence for widespread cooling in AIA channels.



Viall & Klimchuk, 2012, ApJ, 753, 35

Using lightcurves to calculate cooling time





Lightcurves provide fundamental information on the evolution of the plasma.

Using lightcurves to calculate cooling time

Table 2

Measured Rise Delays, Cooling Times, Measured and Calculated Lifetimes of the Selected Loops

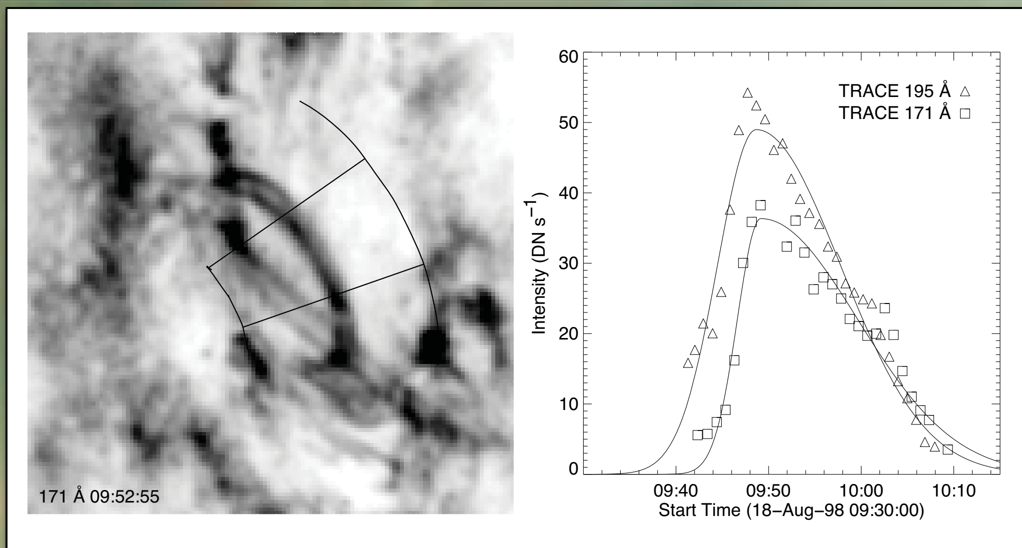
Loop	$\Delta t_{\rm rise}$ (s)	γ_T (s)	$\tau^{195}_{\rm meas}$ (s)	$\tau^{195}_{\rm calc}$ (s)	Ratio	Single or Multi
1	94 ± 17	291 ± 52	490 ± 83	143 ± 26	3.4 ± 0.2	M
2	549 ± 36	1702 ± 113	1270 ± 87	834 ± 55	1.5 ± 0.1	M
3	316 ± 74	977 ± 231	846 ± 59	480 ± 113	1.8 ± 0.2	M
4	538 ± 51	1668 ± 158	1574 ± 72	817 ± 78	1.9 ± 0.1	M
5	571 ± 47	1770 ± 146	946 ± 49	867 ± 72	1.1 ± 0.1	S
6	618 ± 112	1916 ± 347	968 ± 57	1034 ± 170	0.9 ± 0.2	S
7	149 ± 78	462 ± 158	1450 ± 82	226 ± 119	6.4 ± 0.5	M
8	650 ± 47	2015 ± 146	1857 ± 69	987 ± 126	1.9 ± 0.1	M

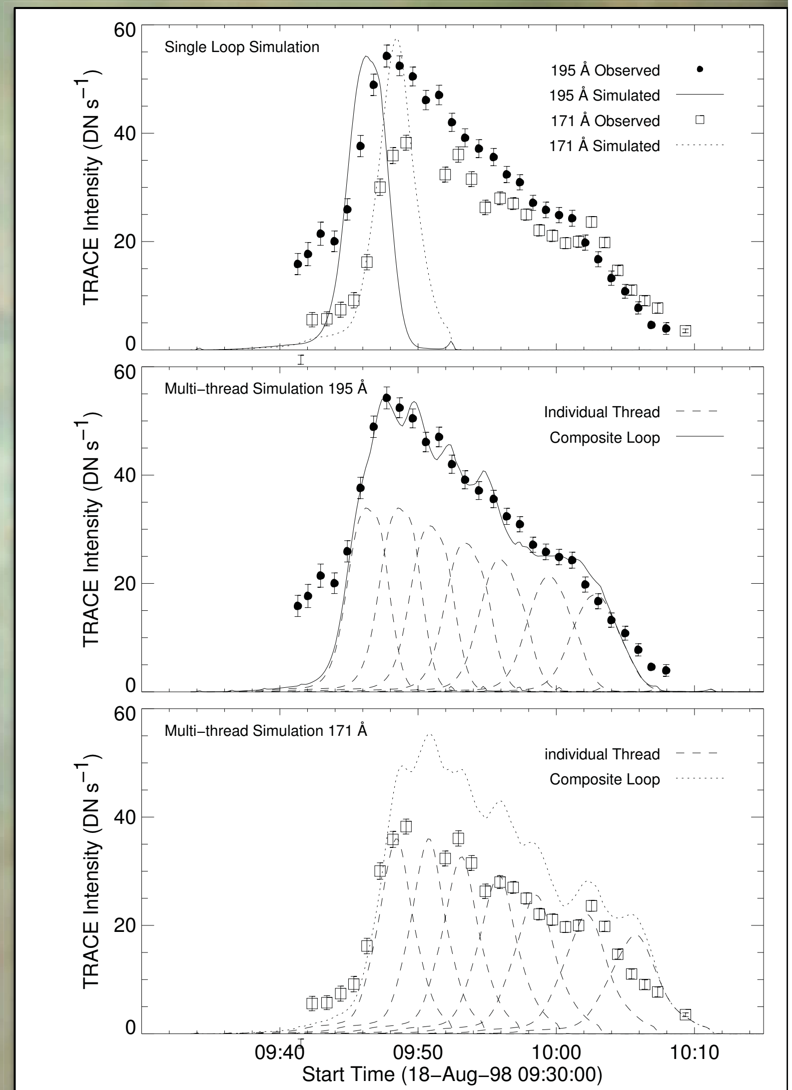
The majority of loops cannot be explained by single cooling loops.

One way of overcoming this is to introduce multiple strands.

Mulu-Moore et al., ApJ, 742, 6

Single vs multi-strand model

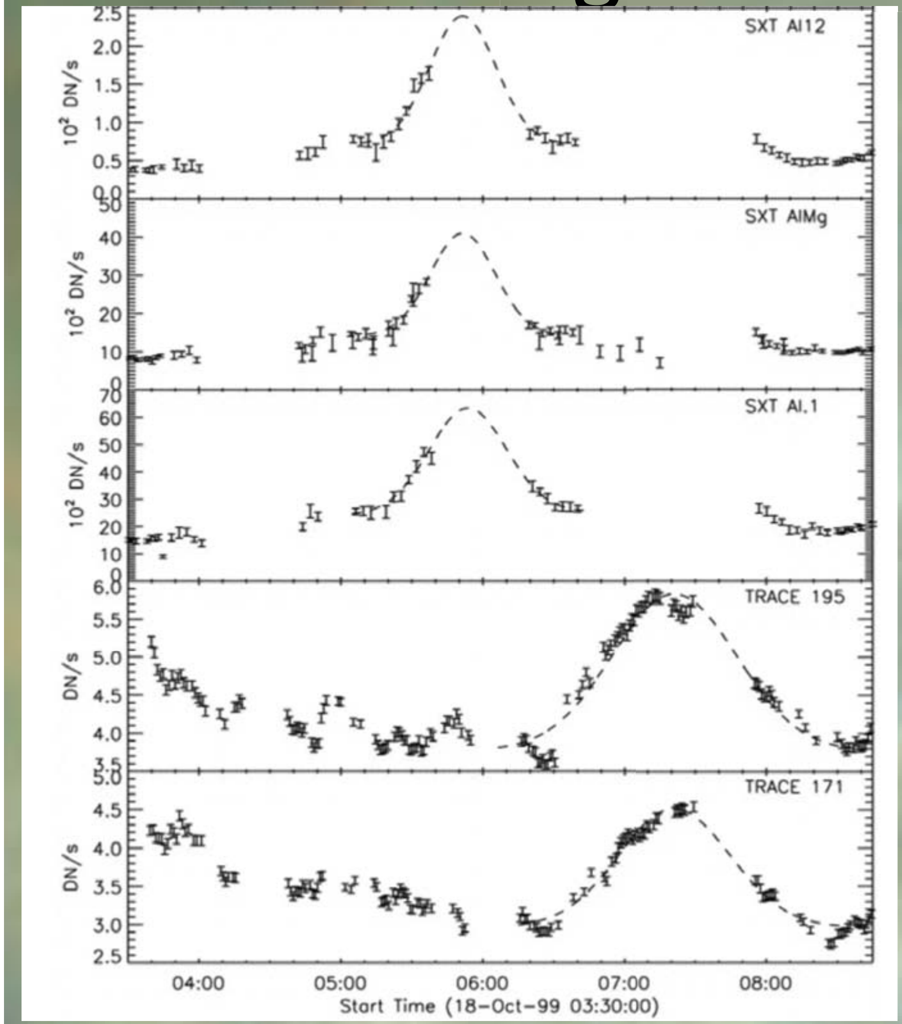


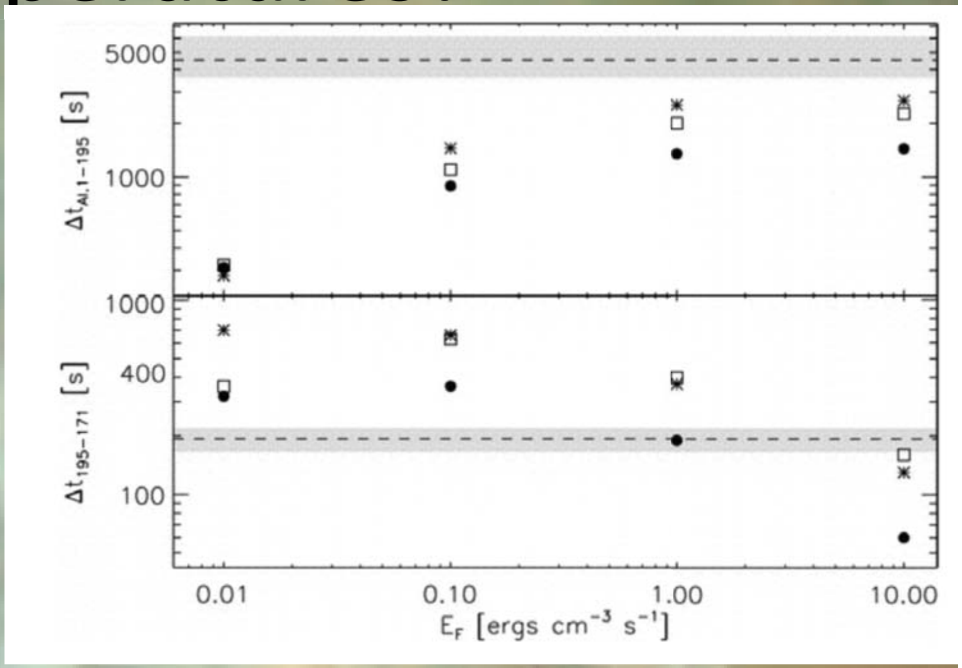


"Short nanoflare storm" appears to well match the observed loop evolution from 195 to 171.

Warren et al., 2003, ApJ, 593, 1174

What about when loops cool from higher temperatures?





A loop is observed to cool from SXT to TRACE.

Multiple attempts to model the loop with many different parameters failed to match time scales.

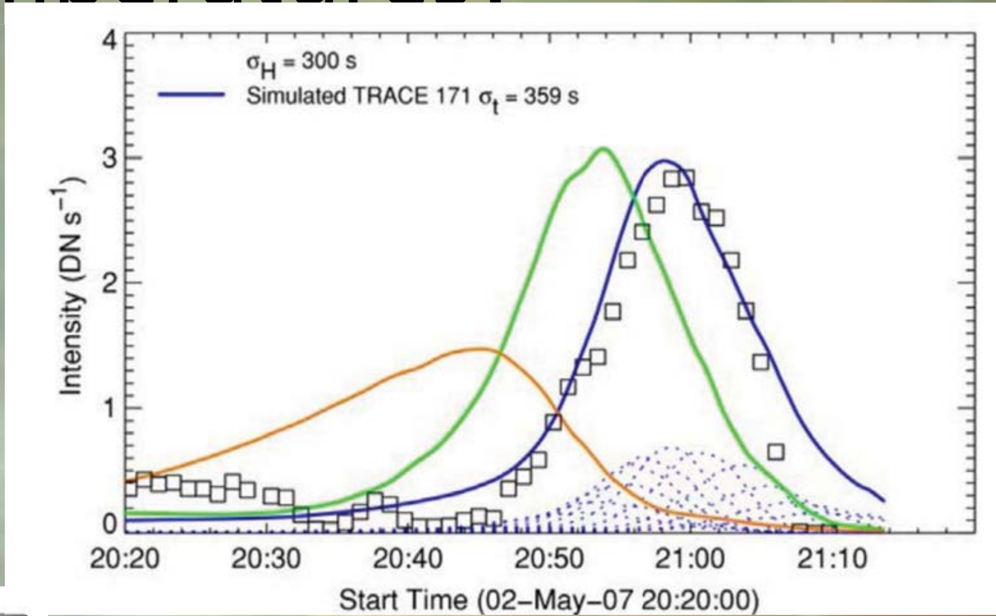
The observations evolve ***more slowly*** than predicted by the model.

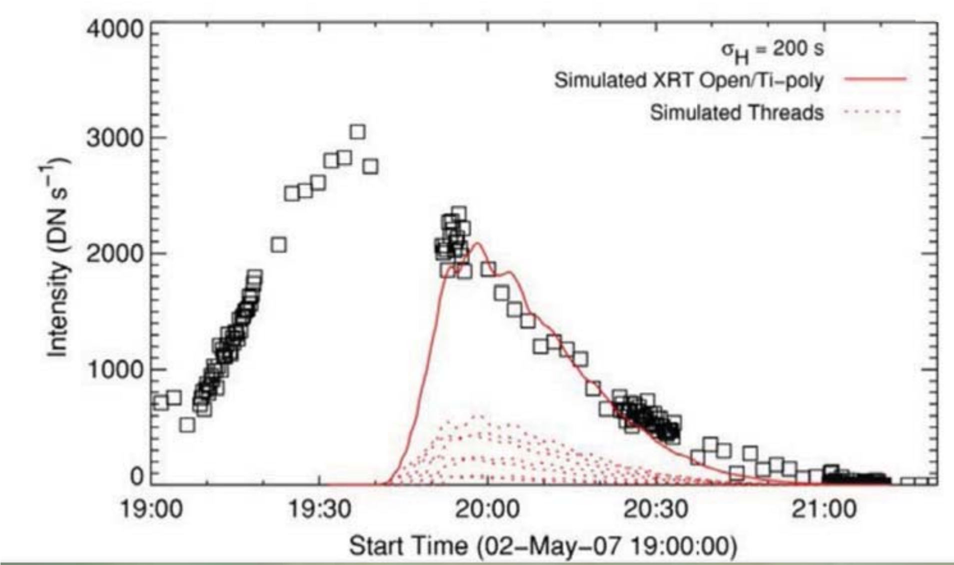
Ugarte-Urra et al., 2006, 643, 1245

What about when loops cool from higher temperatures?

Warren et al (2010) followed a TRACE loop in 171.

The modeled loop using the short nanoflare storm model.





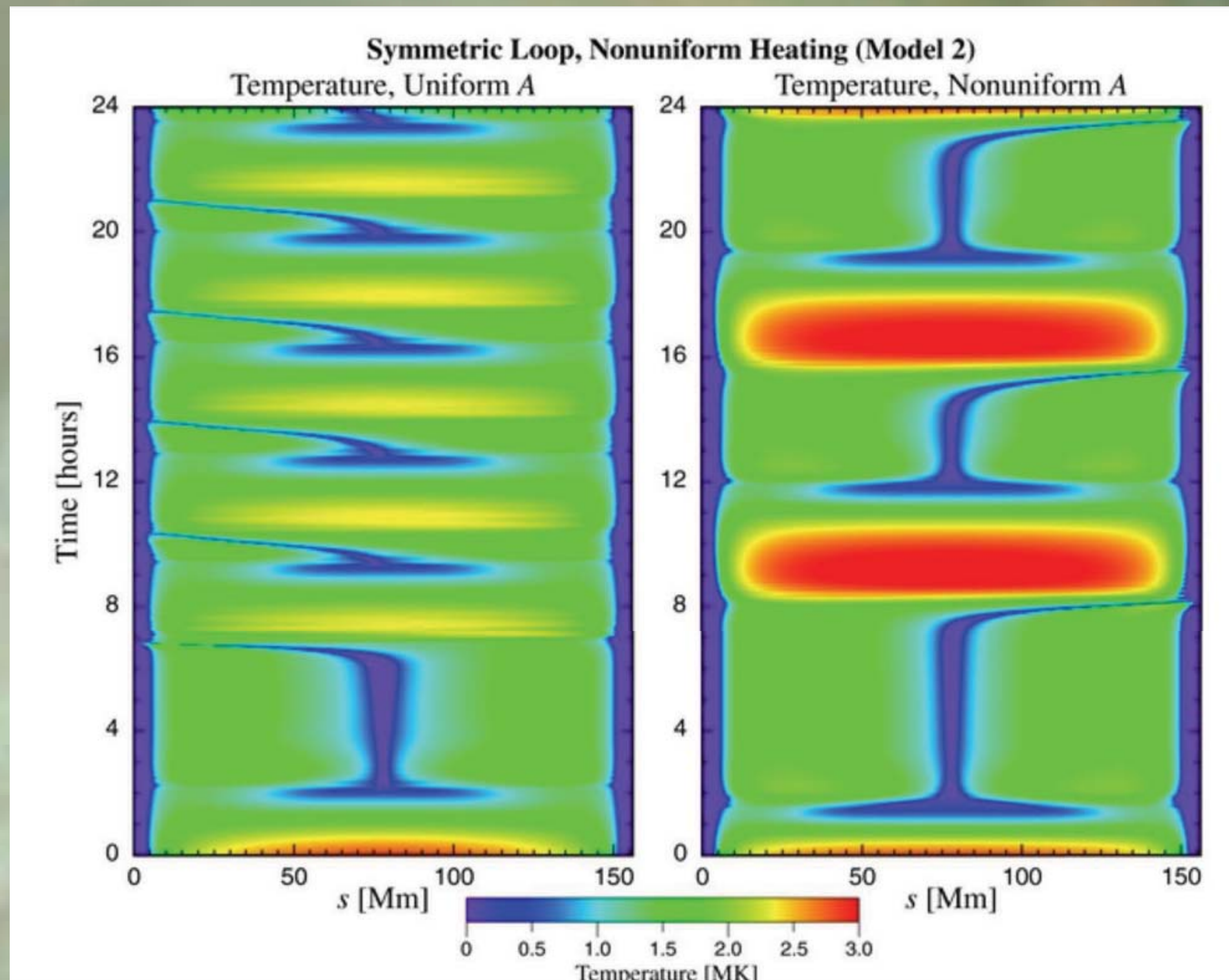
The strands that match the TRACE 171 data do not match the XRT lightcurve.

The observations evolve ***more slowly*** than predicted by the model.

Warren et al., 2010, ApJ, 713, 1095

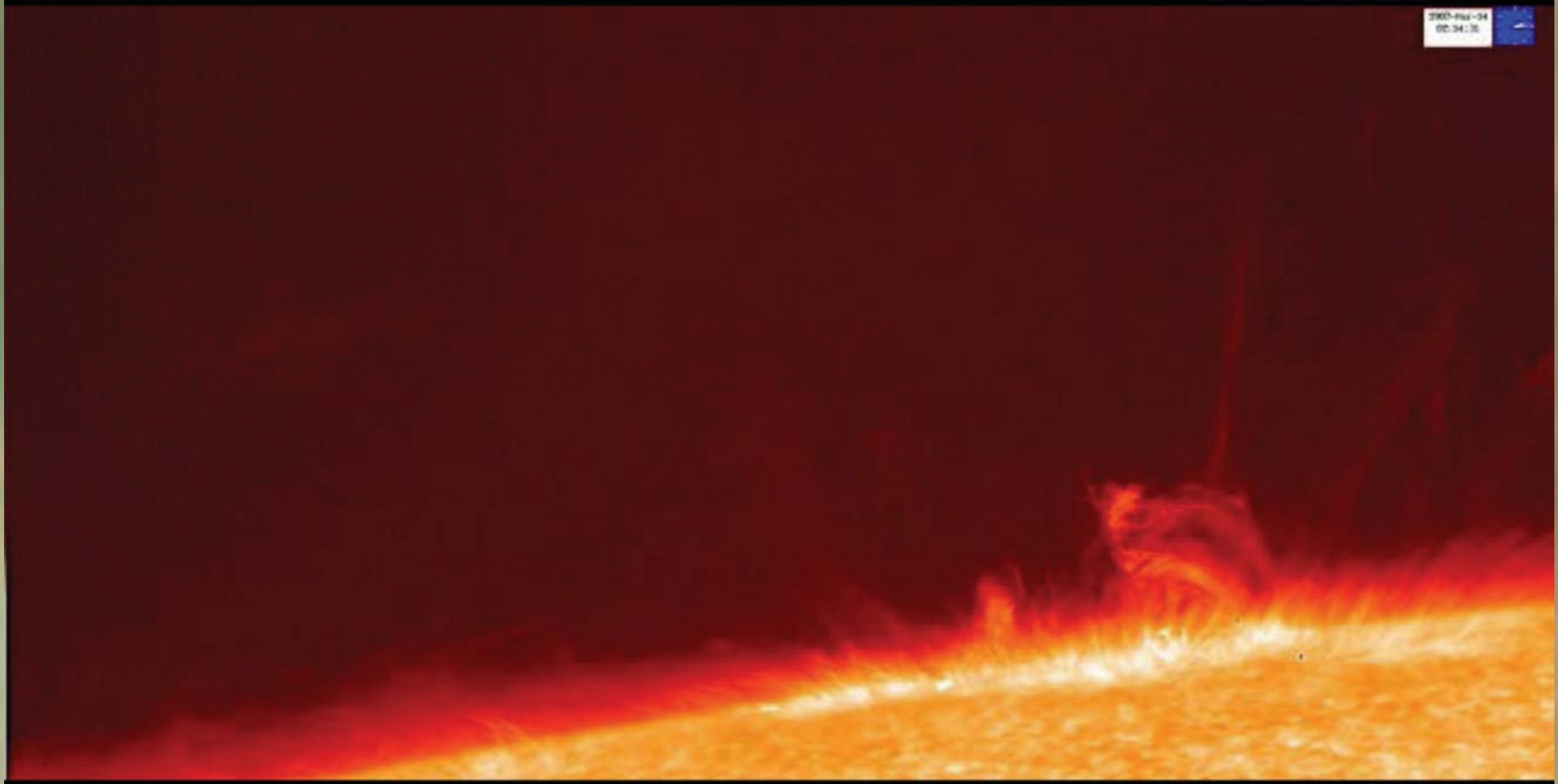
Could footpoint heating be an answer?

Highly stratified (footpoint) heating has been studied for many years in relation to filament formation and corona rain.



Mikic et al., 2013, ApJ, 773, 94

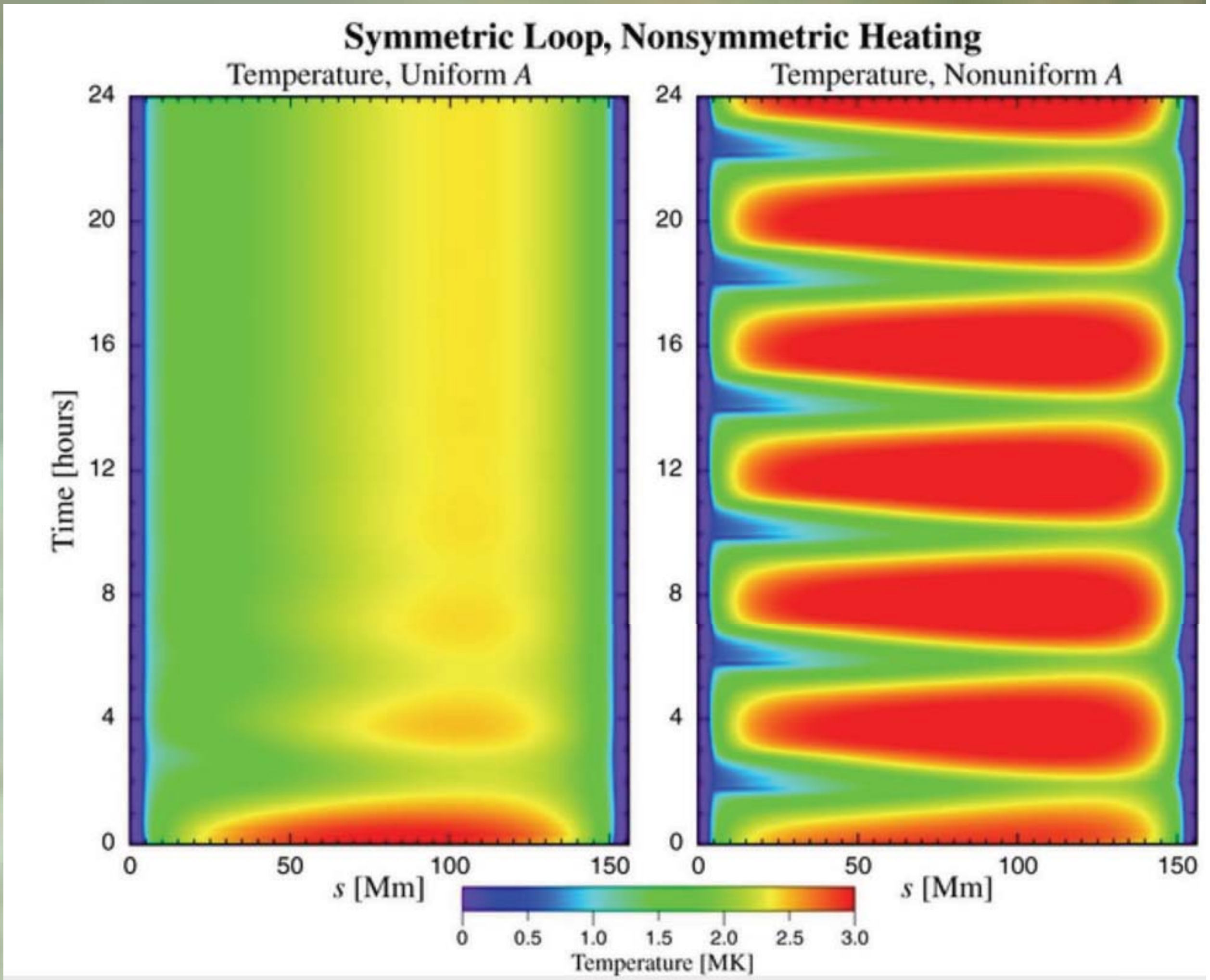
Coronal Rain



Could footpoint heating be an answer?

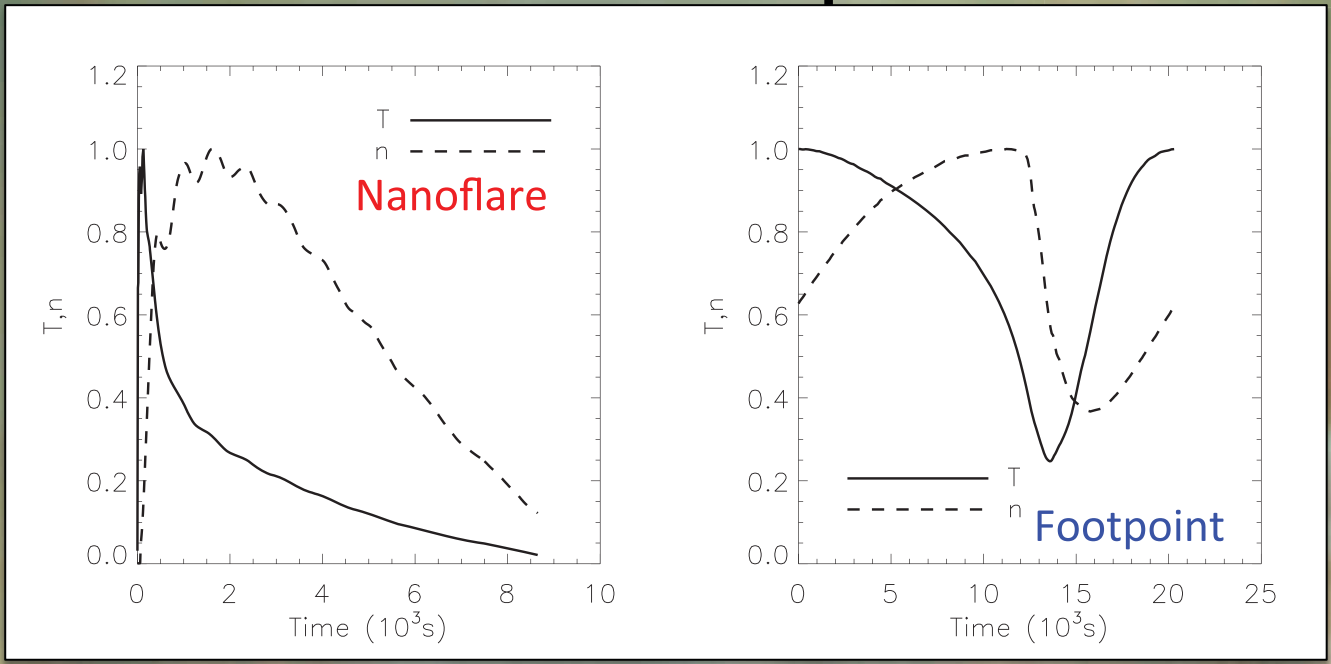
Klimchuk et al. (2010) found that footpoint heating could not reproduced observational signatures of EUV loops.

Mikic et al. (2013) found that footpoint heating in asymmetric, nonuniform loops form “incomplete” condensations.



Mikic et al., 2013, ApJ, 773, 94

Comparison of T,n evolution between nanoflare and footpoint heating



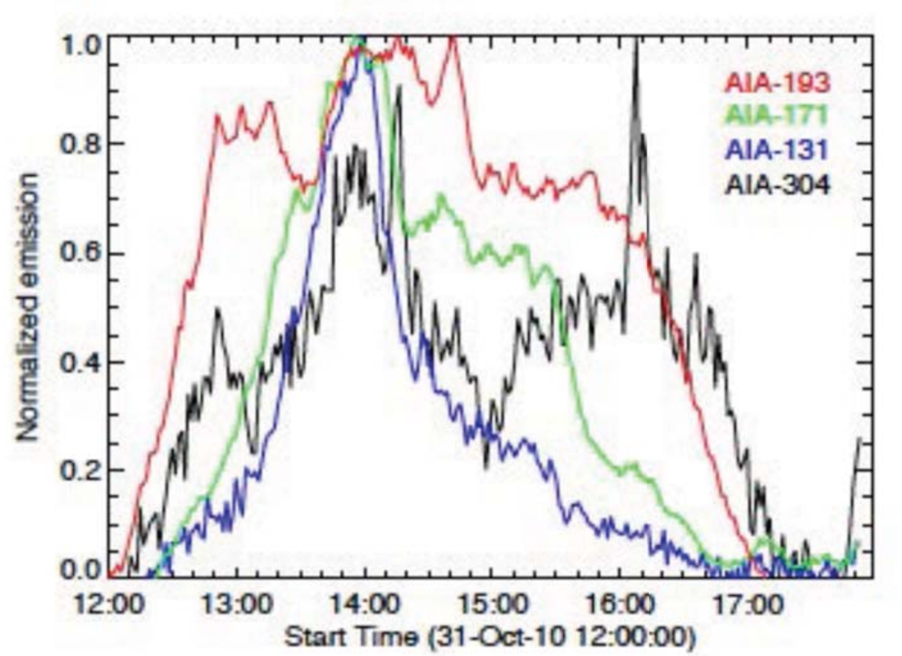
In naoflare heating, temperature and density peak early. Temperature drops quickly at first, then slower.

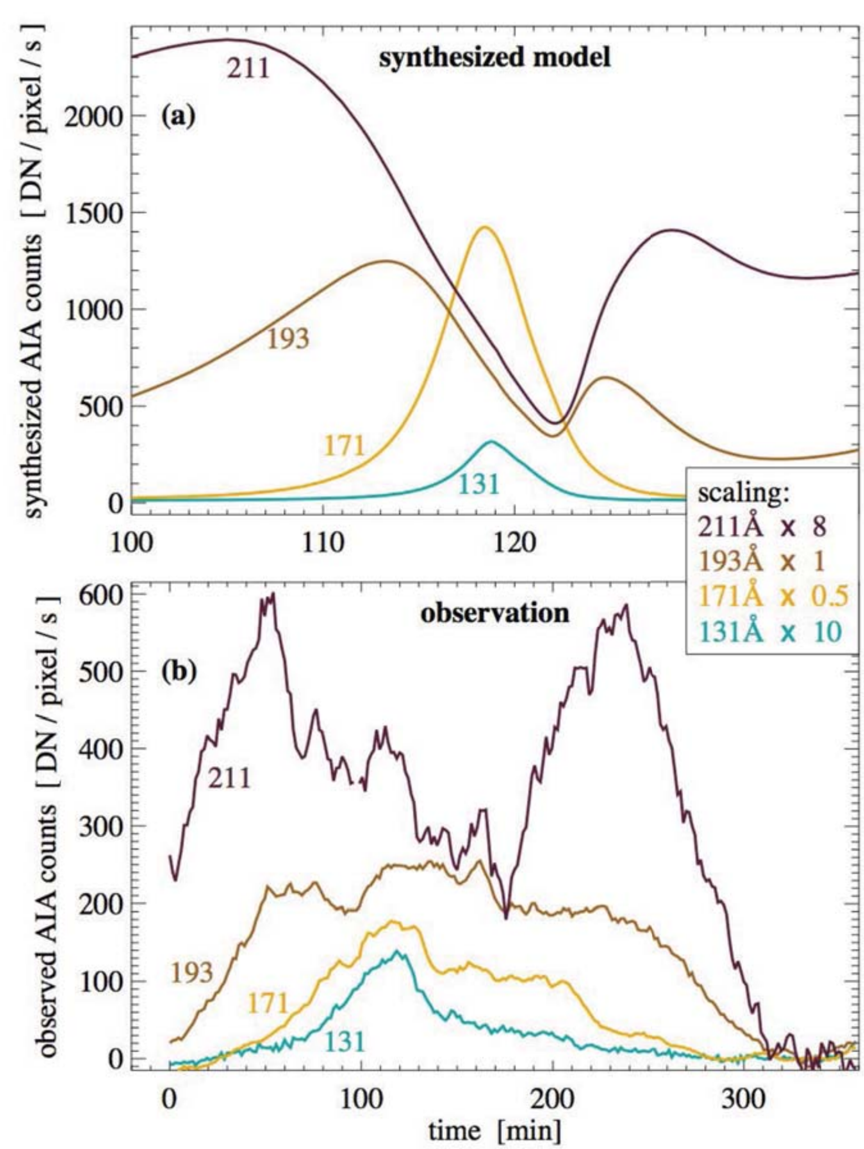
In footpoint heating, temperature peaks early then declines while density increases until condensation. Cooling is slow at first, then more rapid. If heating continues, temperature will turn around.

Time scales are longer for footpoint heating.

Winebarger et al (in prep)

Additional evidence for footpoint heating

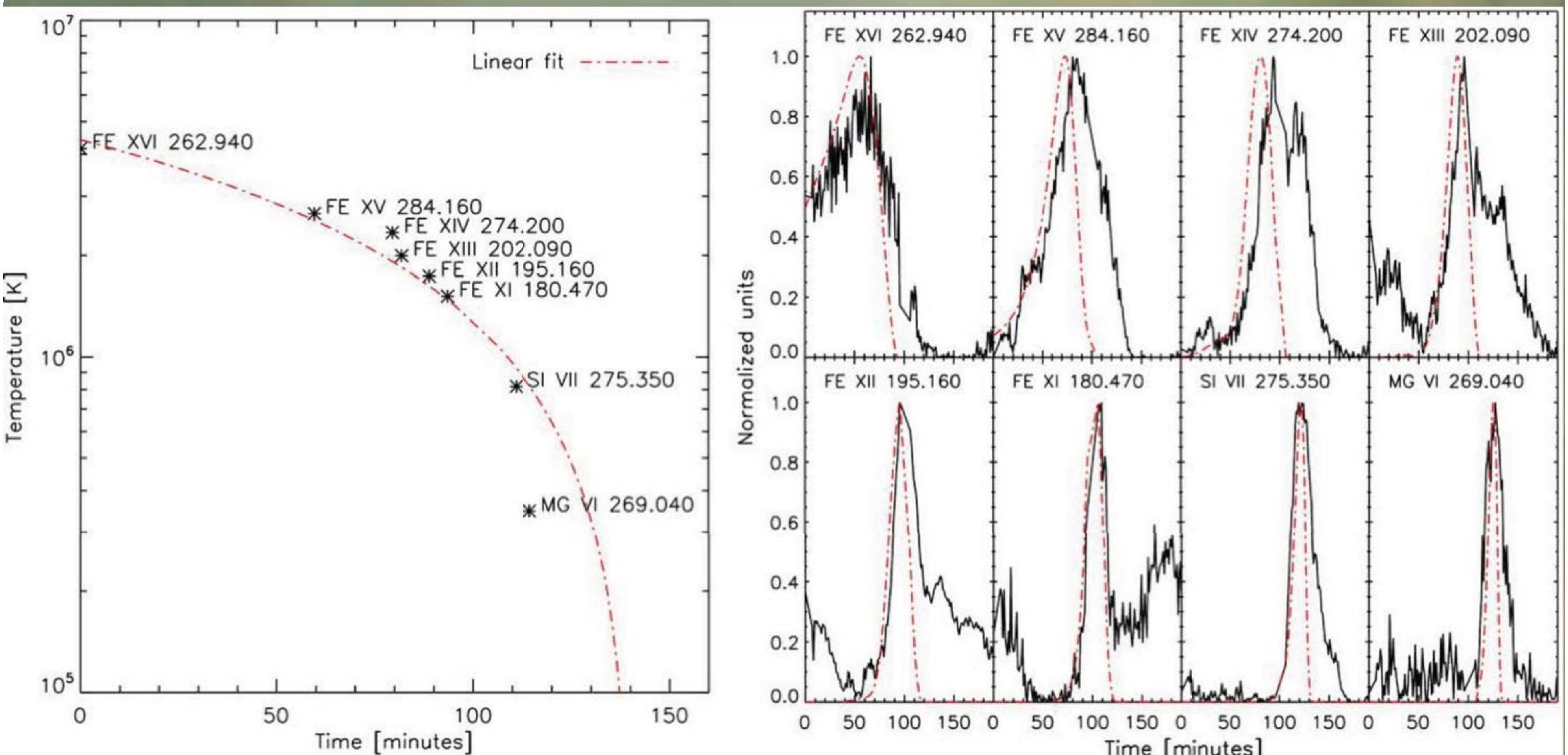




Kamio et al (2011) observed a lightcurve in AIA that Peter et al (2012) modeled using footpoint heating.

Kamio et al., 2011, A&A, 532, 96
Peter et al., 2012, A&A, 537, 152

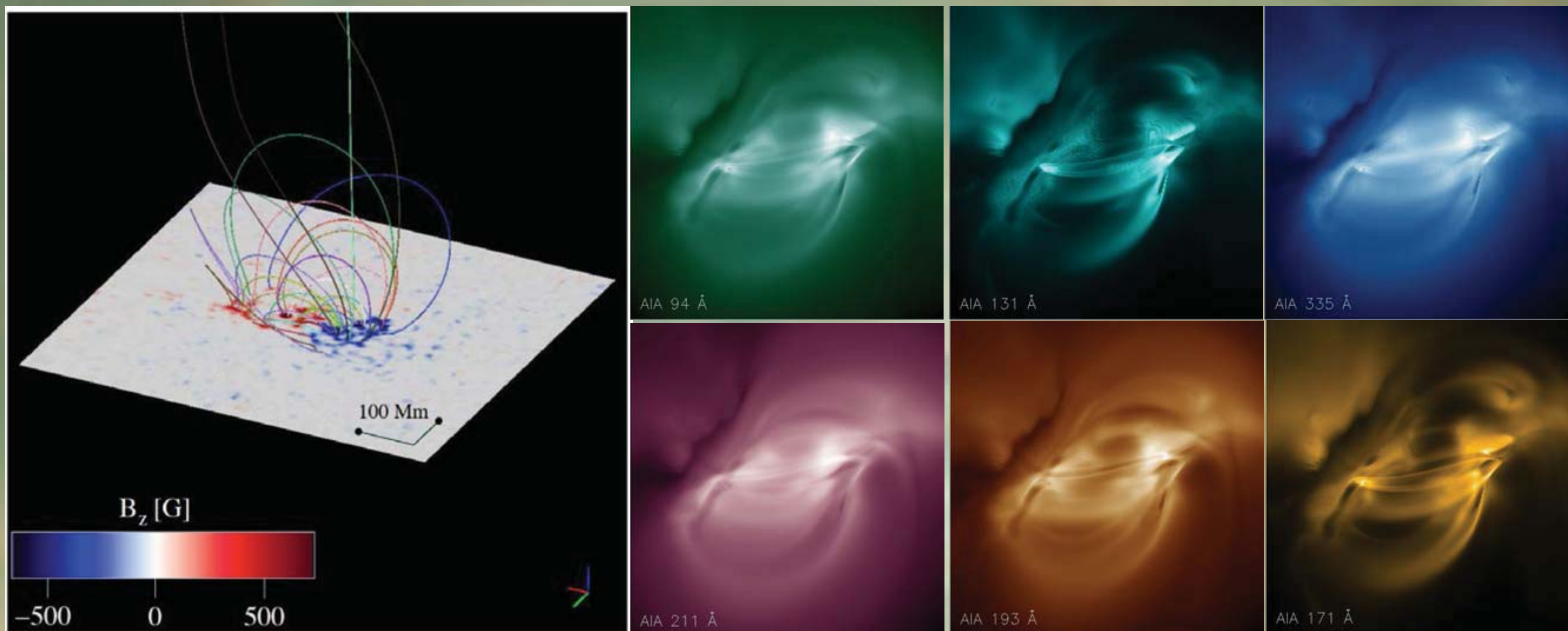
Additional evidence for footpoint heating



Evolution of EIS loop shows slow, then fast temperature evolution.

Ugarte-Urra et al. 2009, ApJ, 695, 642

Study of footpoint heated loops

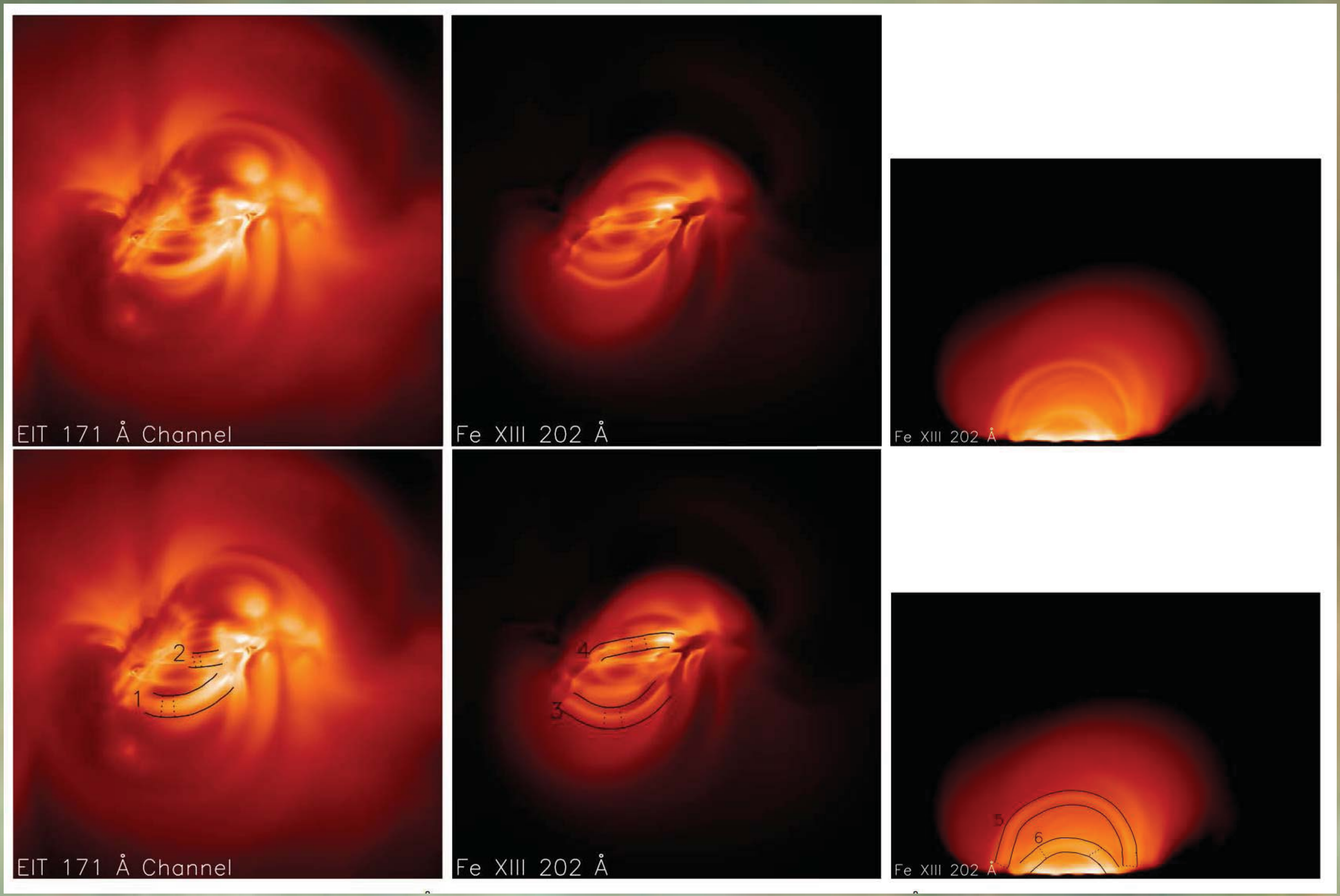


Start with photospheric magnetic field measurements of AR 7986 from August 30, 1996.

Apply the heating rate $H = h_0 B^{7/4} n_e^{1/8} L^{-3/4}$ (Rappazzo et al. 2008, ApJ, 667, 1348)

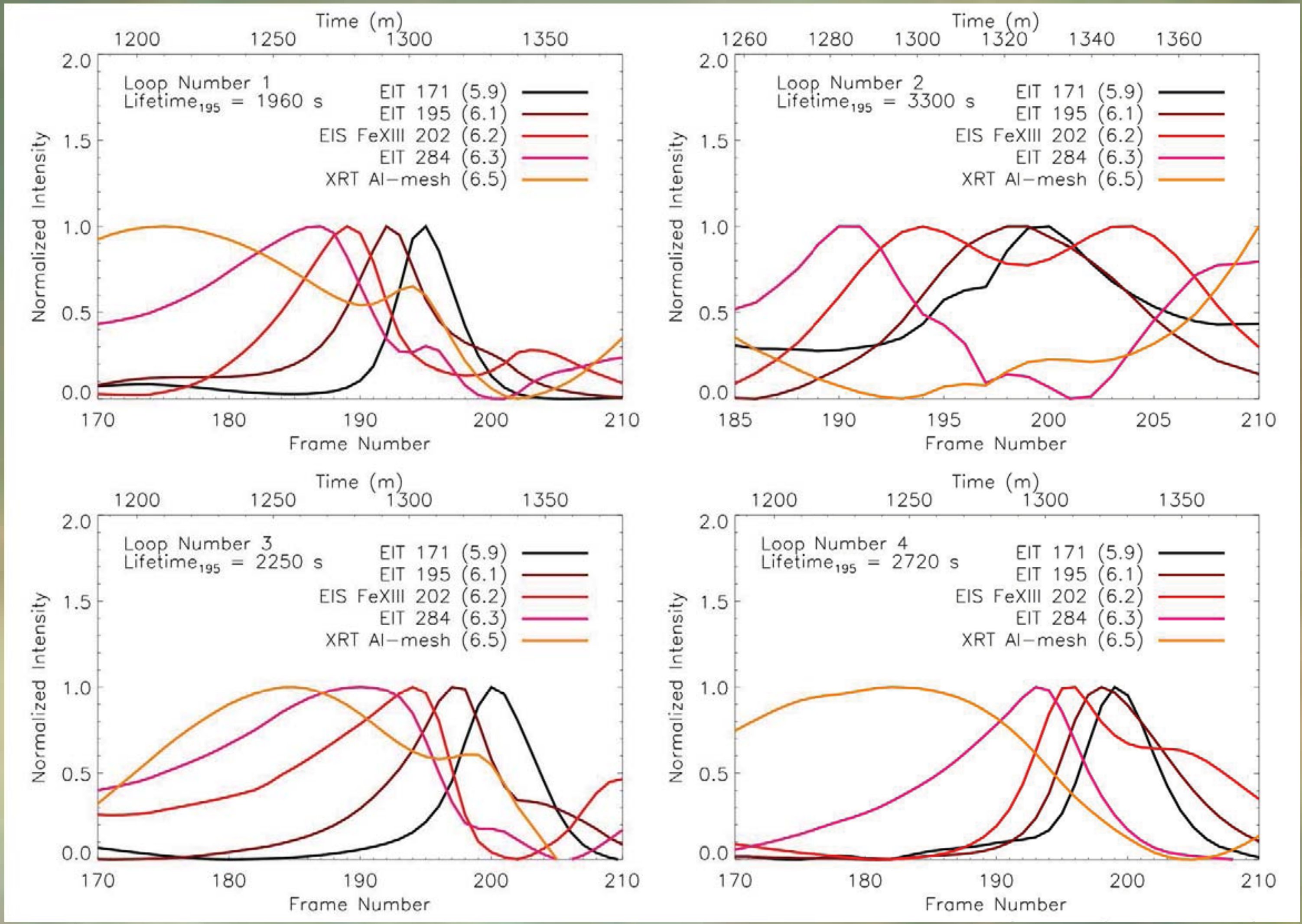
Mok, Y. et al. 2008, ApJ, 679, 161

Study of footpoint heated loops



Lionello et al. 2013, ApJ, 773, 134

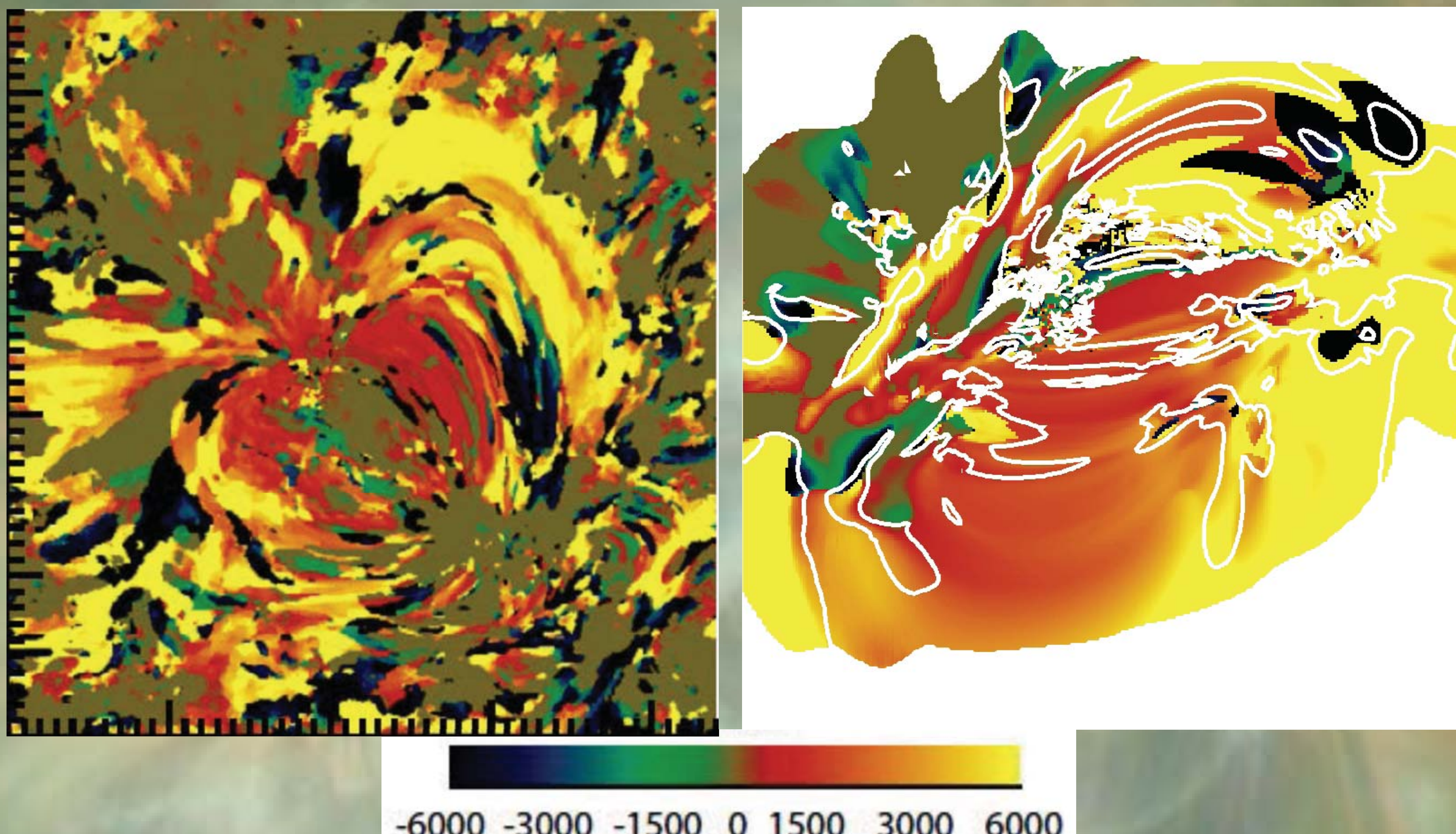
Study of footpoint heated loops



Lionello et al. 2013, ApJ, 773, 134

Study of footpoint heated loops

AIA 211 - AIA 171

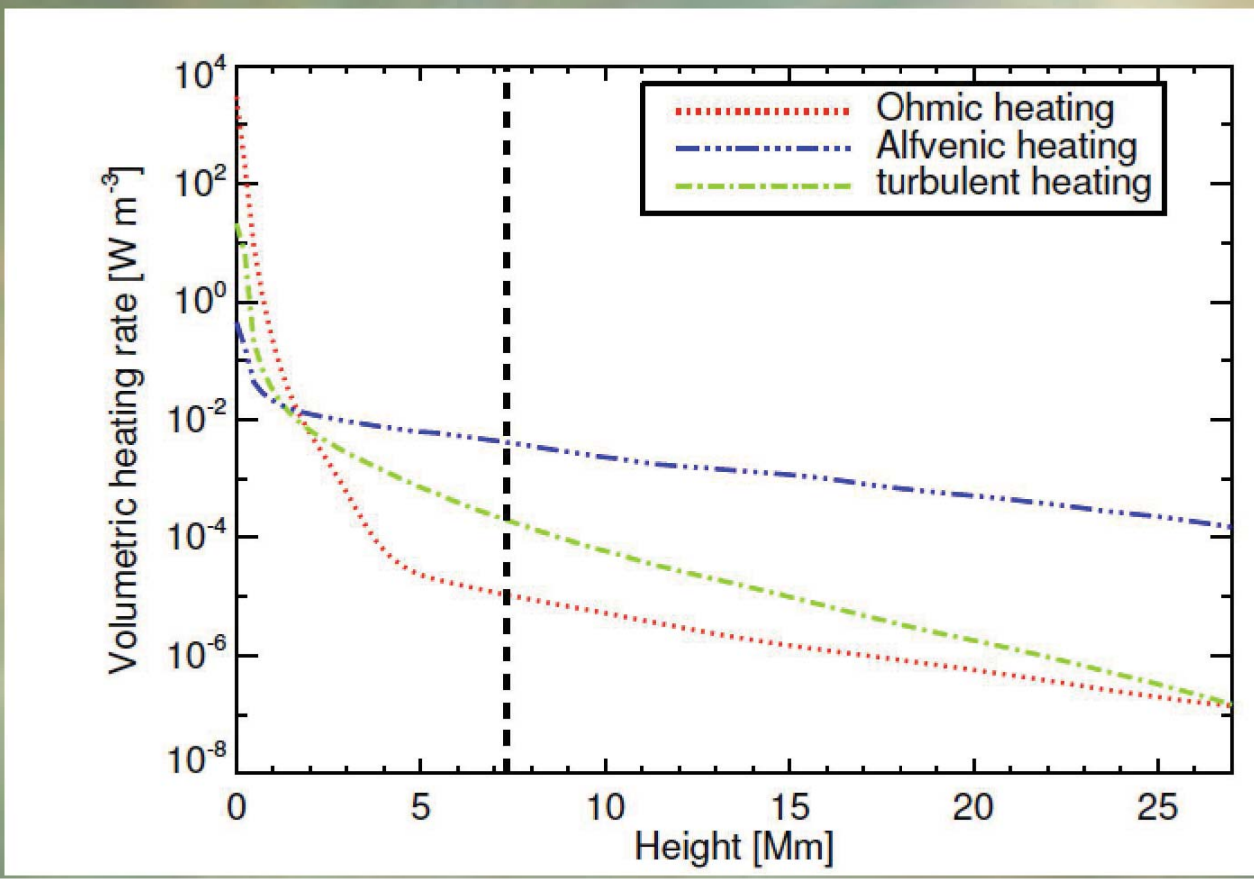


Not the same active region, but similar time lags.

Winebarger et al. in prep

What does that tell us about the mechanism?

$Q_{Ohm} = \eta\mu j^2$ (Bingert & Peter, 2011,A&A, 530, 112)
$Q_{Alf} \sim B^{0.55}$ (van Ballegooijen et al. 2011, ApJ, 736, 3)
$Q_{turb} \sim B^{1.75}$(Rappazzo et al. 2008, ApJ, 667, 1348)



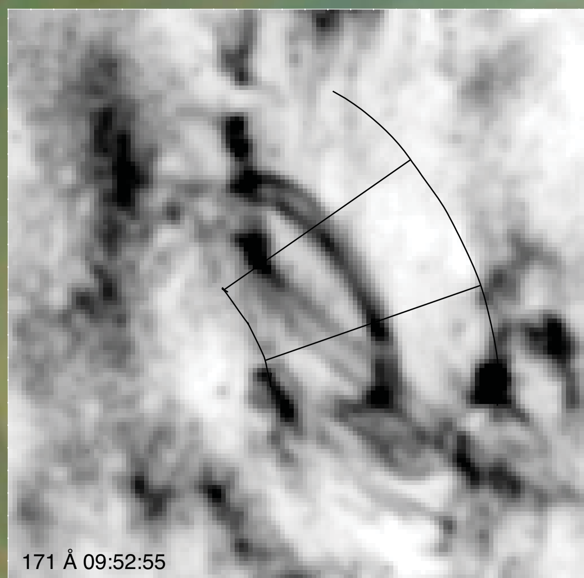
Van Wettum et al., 2013, A&A, 554, 39

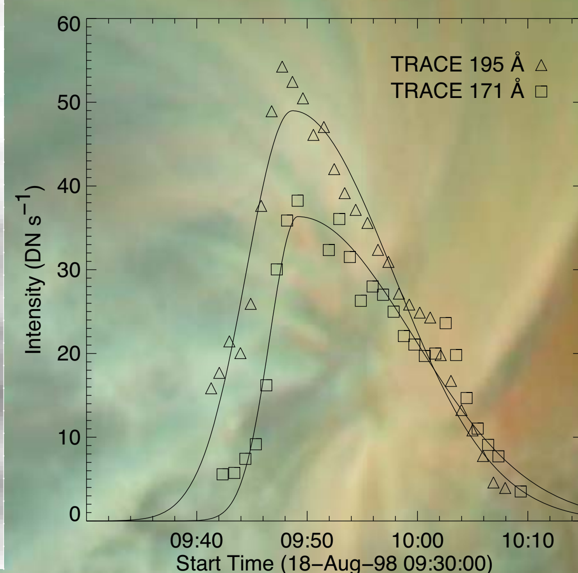
Is the corona heated from the bottom up?

- Time scales are important!
- There is some qualitative agreement between footpoint heating and EUV observations.
- There are significant enough observational differences between nanoflare and footpoint heating that should be investigated with a combination of AIA and XRT.
- The biggest hindrance in completing a quantitative comparison is lack of knowledge of the geometry and loop length.

Thank you for your attention!

EUV Loop Evolution



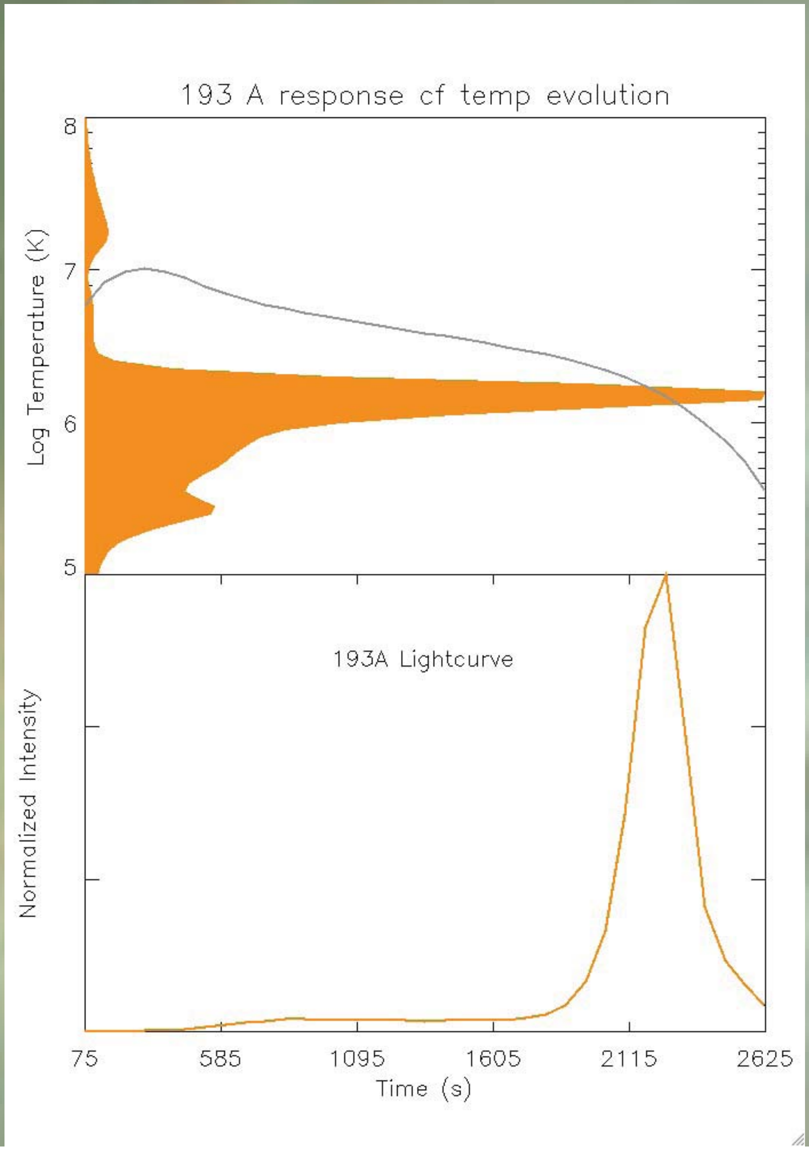


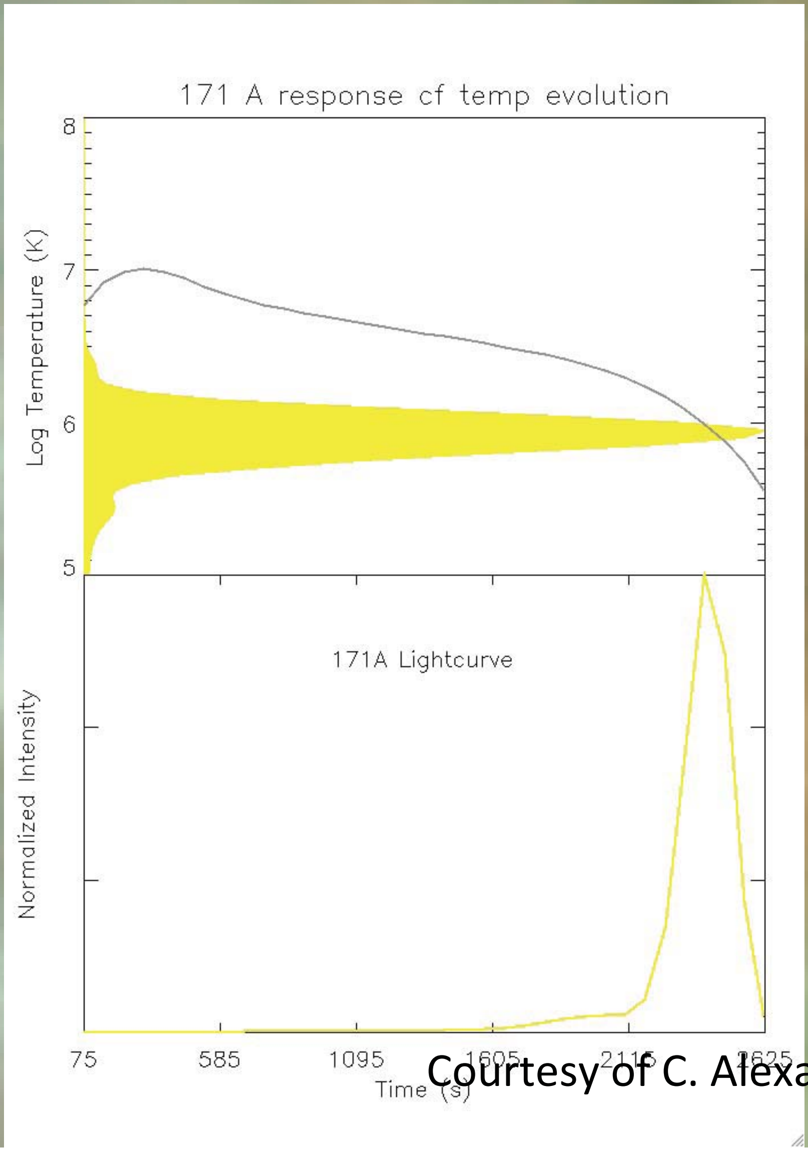
A fundamental property of EUV loops is that they "cool," meaning they appear in higher temperature channels before they appear in lower temperature channels.

Review of observations

- Loops appear in higher temperature channels before cooler temperature channels
- The lifetime of a loop is longer than expected based on the cooling time
- Loops cooling from two similar-temperature channels have been modeled as short nanoflare storm
- Loops cooling from two very hot to very cool channels have not been modeled as short nanoflare storm.
- The observations evolve ***more slowly*** than predicted.

Cooling loops





Courtesy of C. Alexander