Evidence for a highly-stratified heating in coronal loops

Evidence for cycles of evaporation and incomplete condensation in warm solar coronal loops C. Froment et al. 2015 ApJ 807 158

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Coronal Loop Workshop VII - 21-23 July 2015

Thermal non-equilibrium (TNE)

Heating localized near the footpoints

↓

TNE
Evaporation / Condensation cycles
pulsations in the temperature and density

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Temperature ↗ → Density ↗

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the plasma falls toward the loop legs

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TNE is widely accepted to play a key role in the formation of prominences and coronal rain (*Antiochos et al, 1999,2000, Müller et al, 2003,2004, Antolin et al, 2010*)

TNE is often discarded to happen in warm loops (*Klimchuk et al, 2010*), BUT:

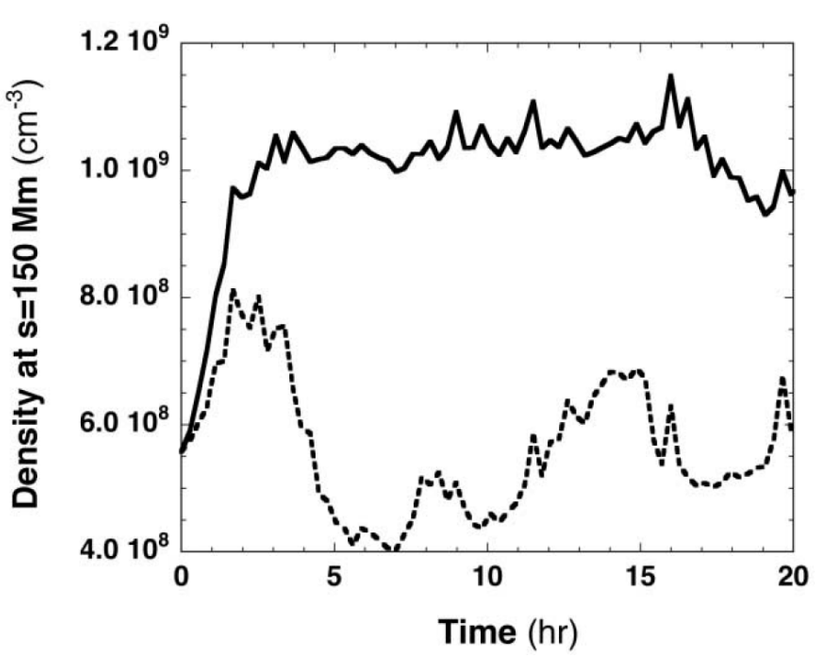
➡ Recent simulations (*Lionello et al, 2013; Mikić et al, 2013; Winebarger et al, 2014*) show that it can not be ruled out

➡ **Inconsistencies with observations may be due to oversimplification of the geometry**

Thermal non-equilibrium (TNE)

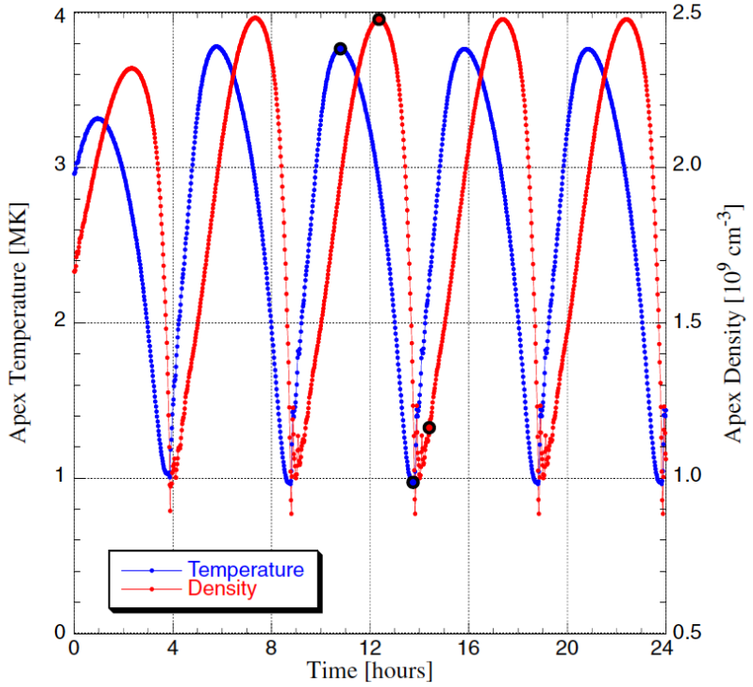
Heating localized near the footpoints can produce TNE **for both impulsive** (with a high repetition) **and steady heating**

Nanoflare heating highly localized at the footpoints



Karpen & Antiochos, 2008

Steady heating highly localized at the footpoints



Mikić et al, 2013

Thermal non-equilibrium (TNE)

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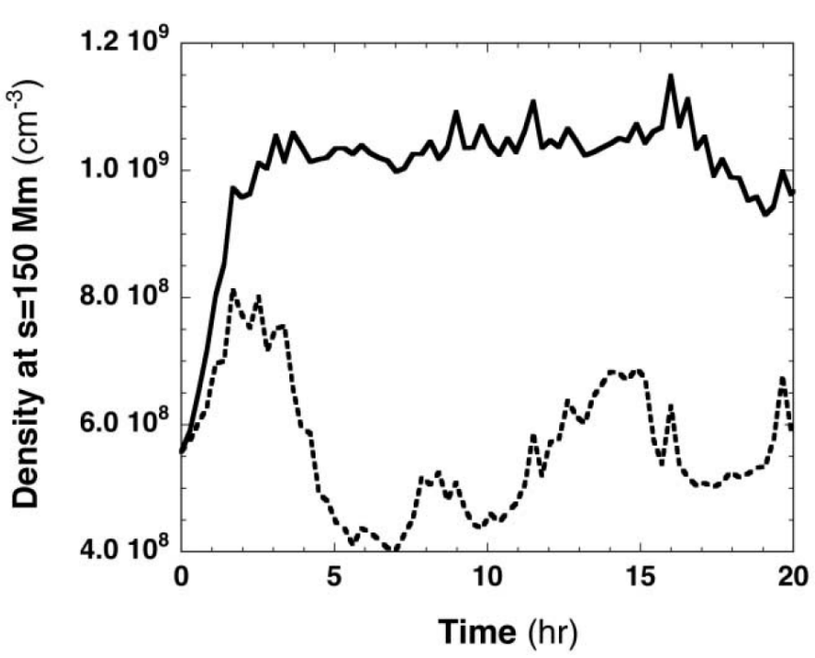
Until now no direct observational evidence of TNE in loops



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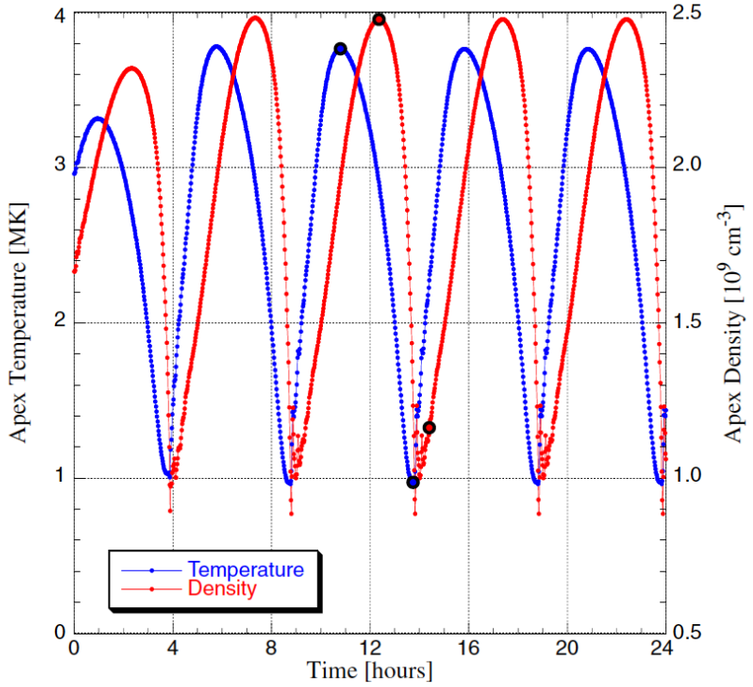


Mikić et al, 2013

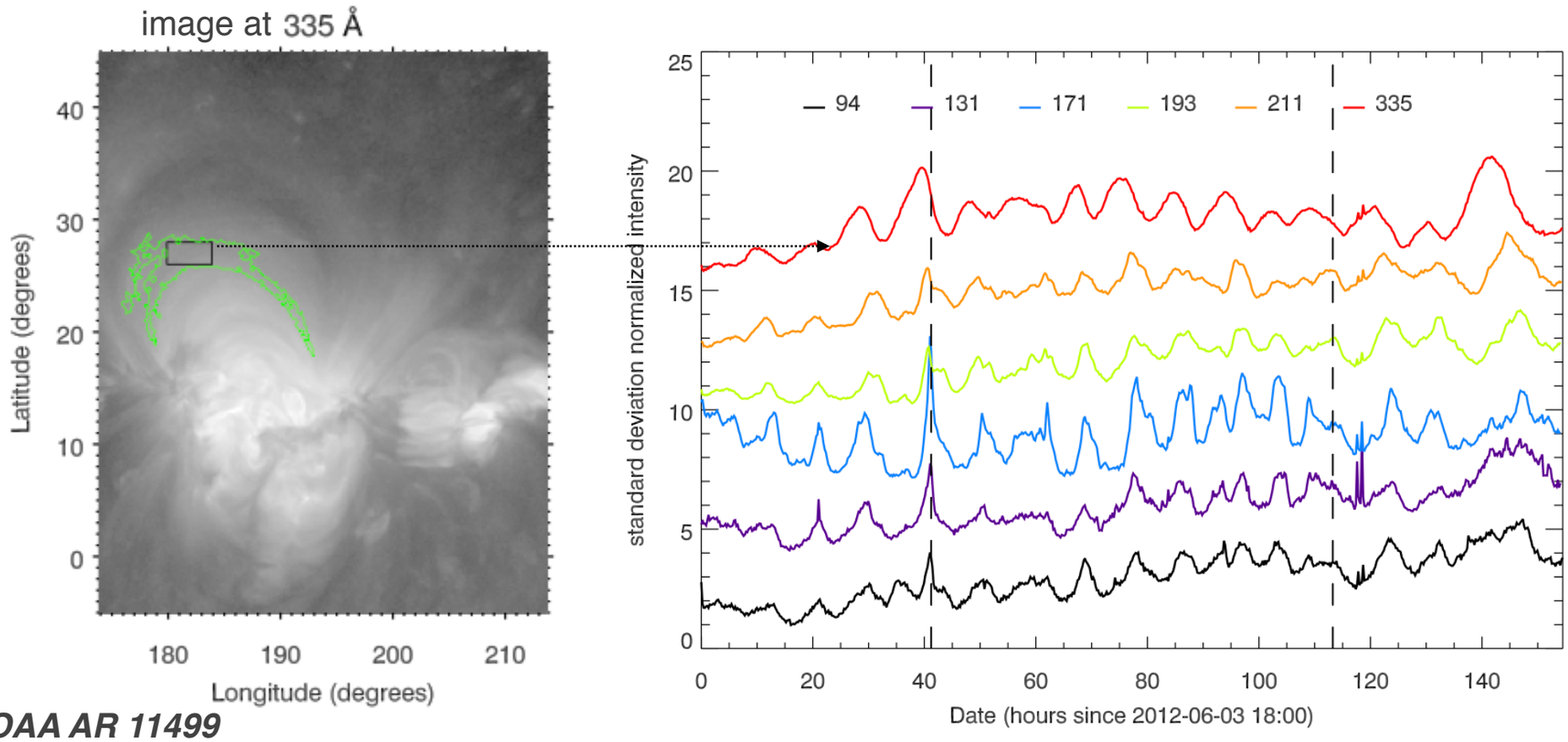
Long-period intensity pulsations in loops

Recently discovered in the corona, periods from 2 to 16 hours

Very common: in ~1/2 of the active regions (estimated for the year 2000) (*Auchère et al, 2014*)

One typical event studied with AIA (*Froment et al, 2015*)

➡ pulsations with a **period of 9.0 h**



NOAA AR 11499

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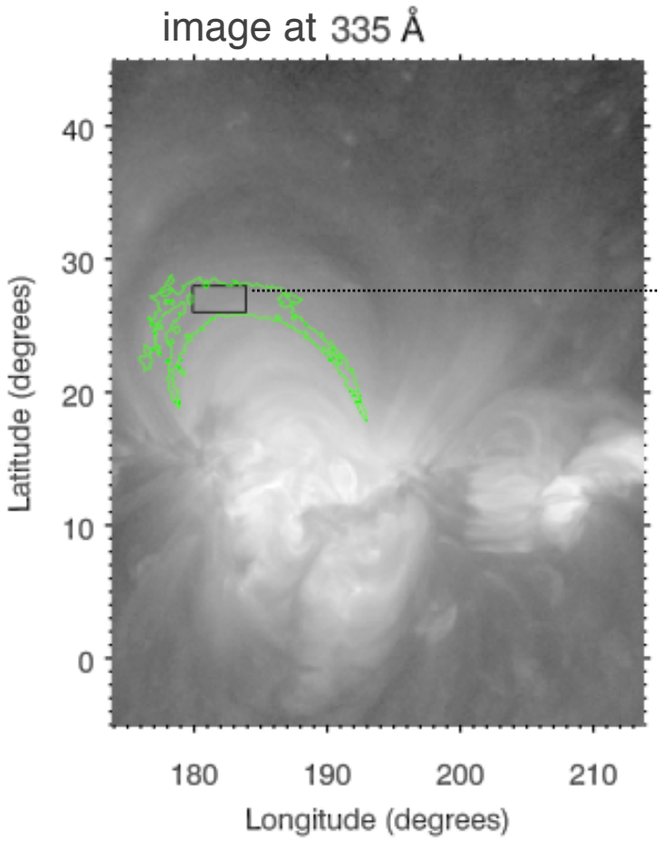
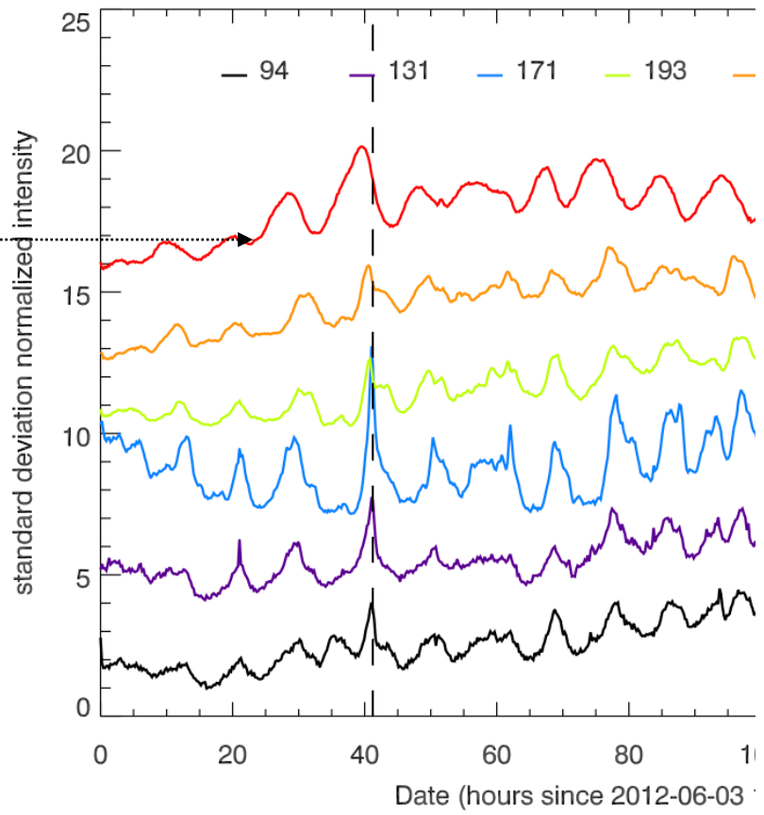
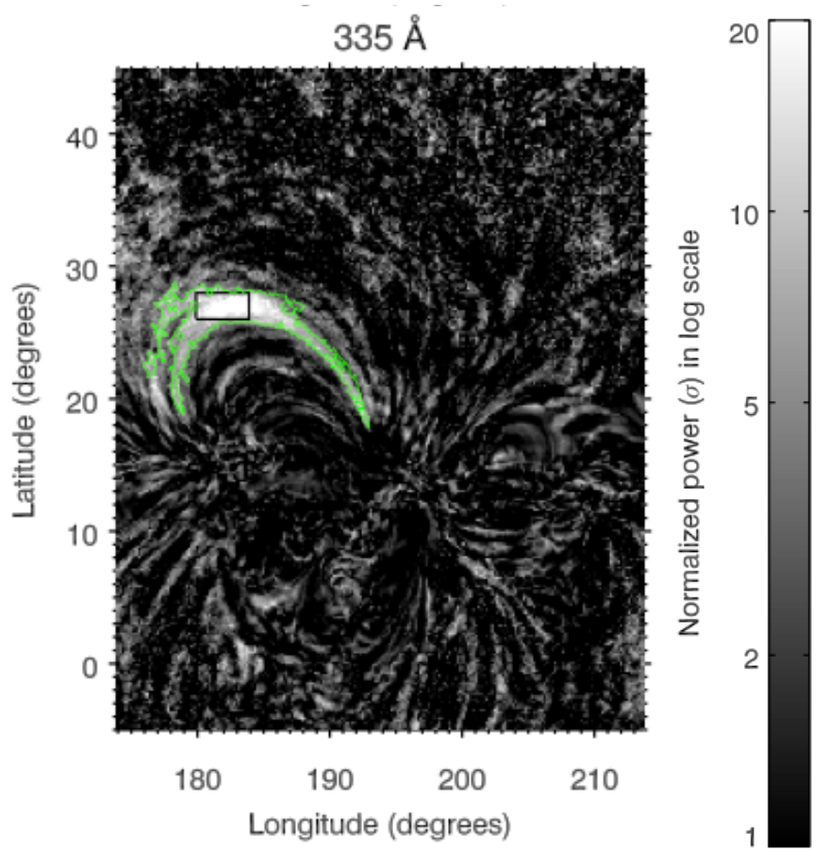




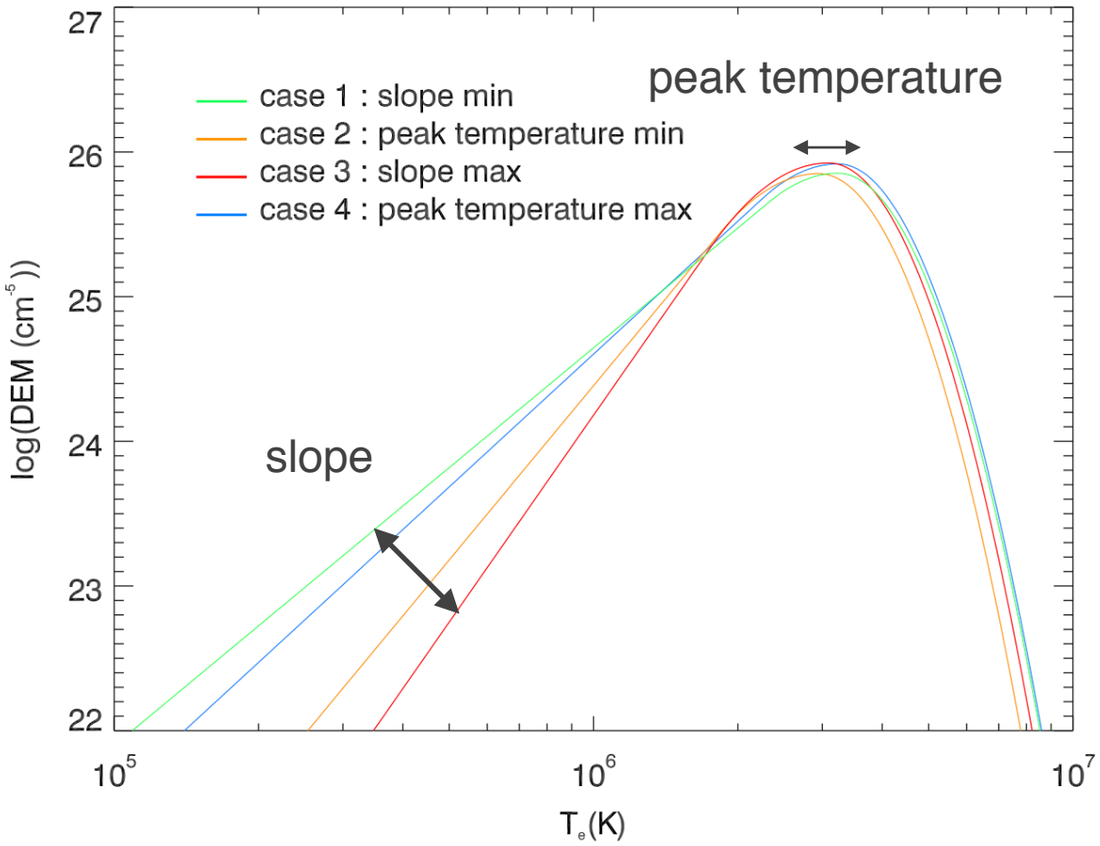


NOAA AR 11499

Normalized power at 9.0h

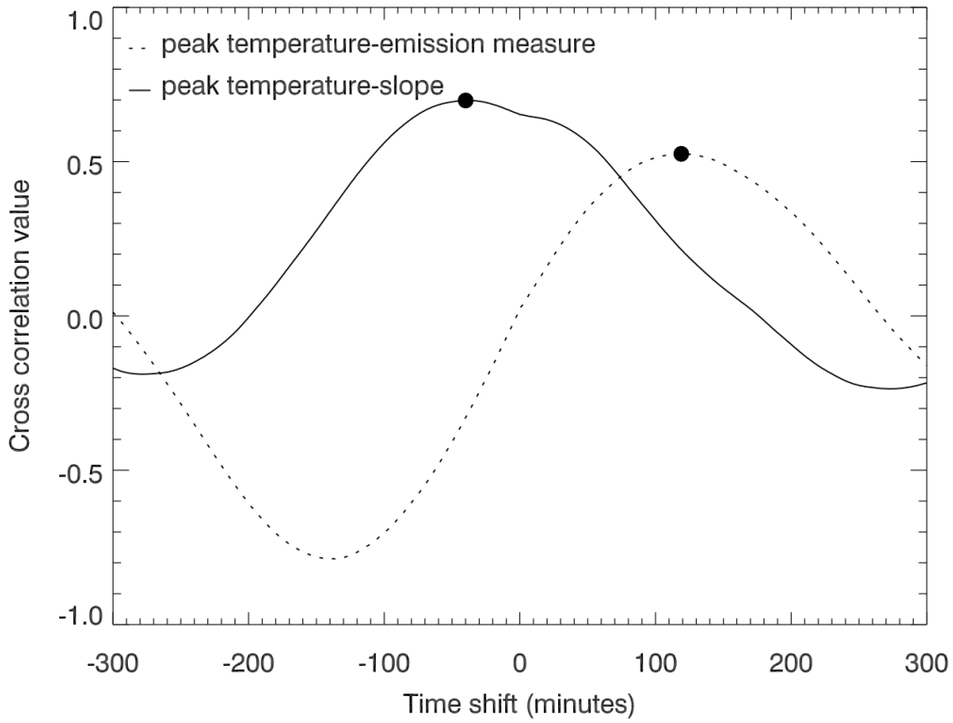
more than 10σ: confidence level of 99%

Intensity pulsations linked to loop heating



Active Region DEM model (*Guennou et al, 2013)*

Typical shape in AR (*Warren et al. 2011, Winebarger et al. 2011,…*)



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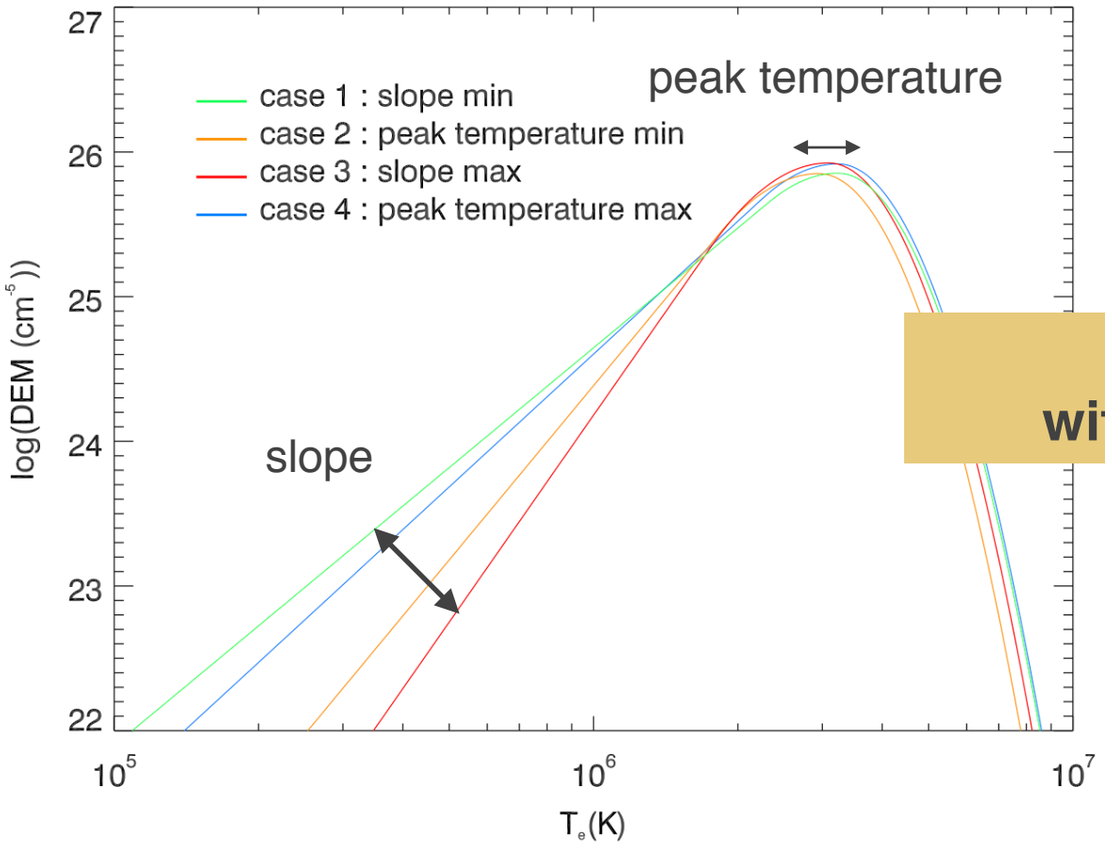

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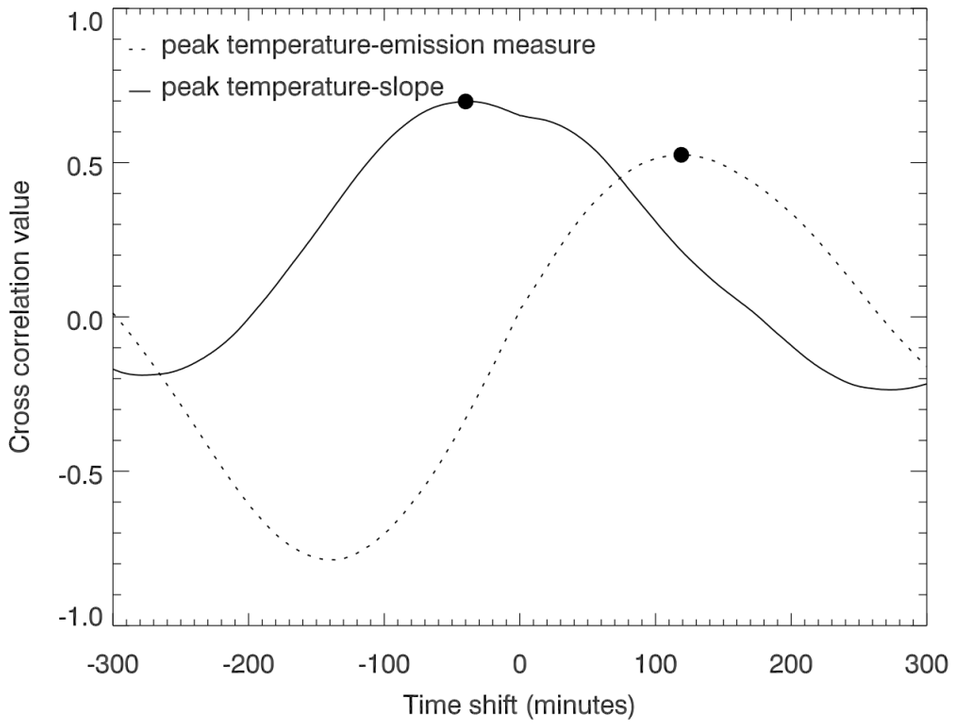
Pulsations in the thermal structure of loops with a high amplitude in the slope and the total EM



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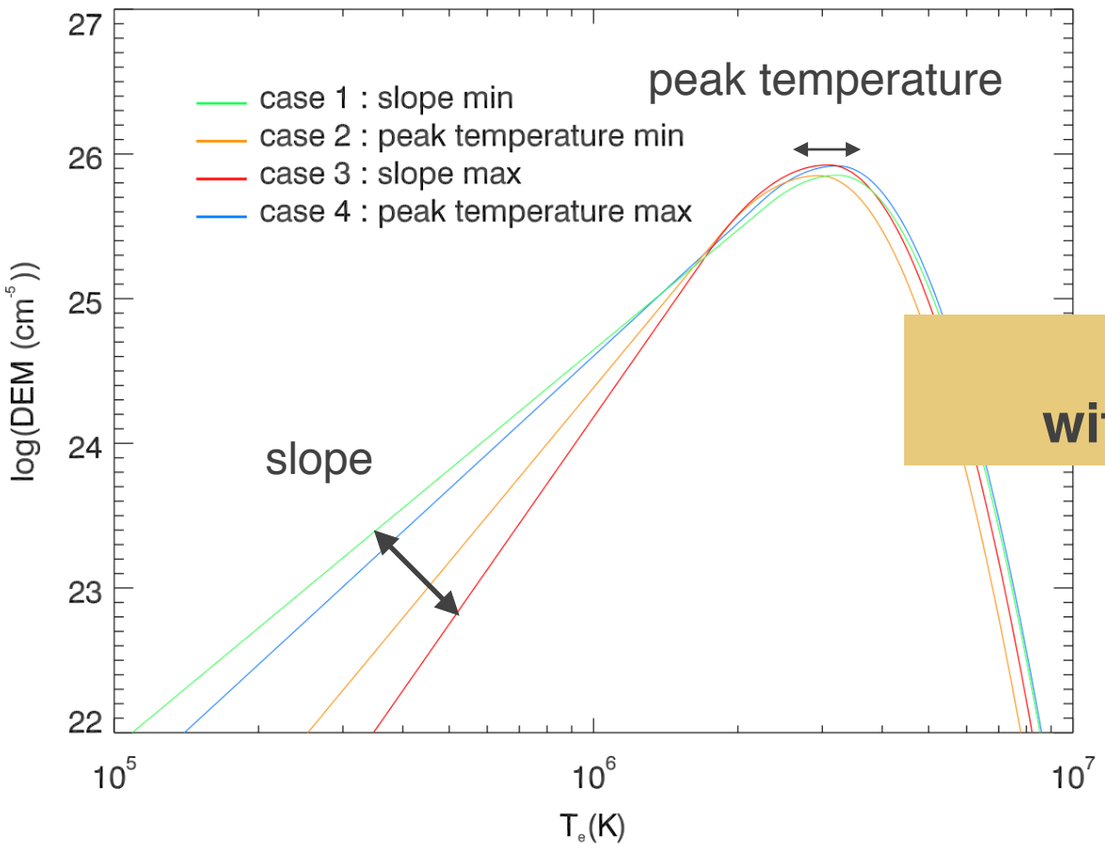

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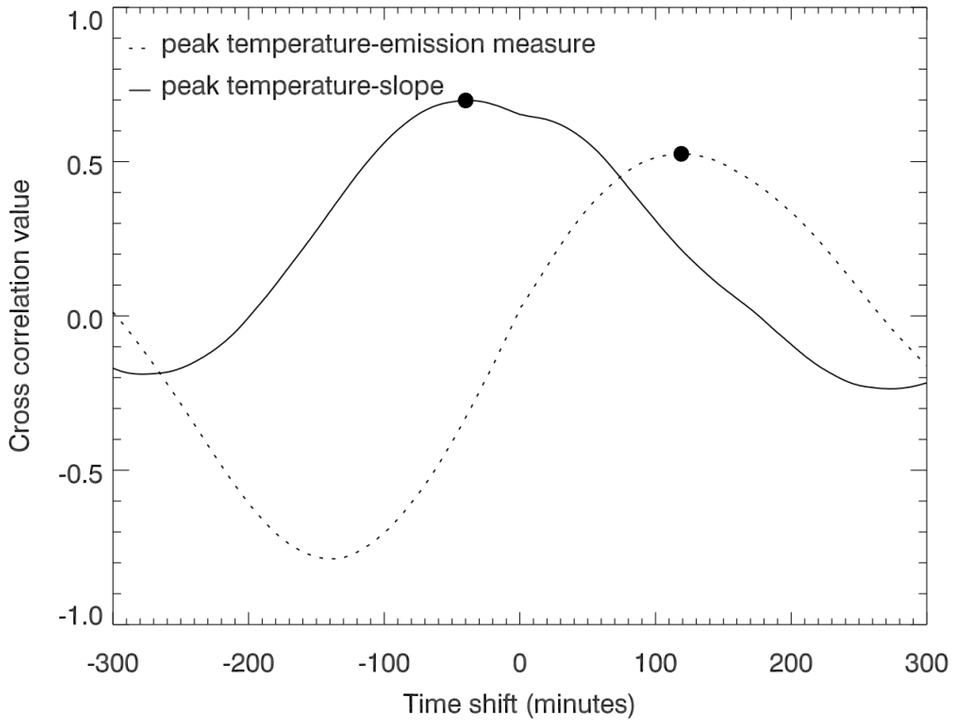

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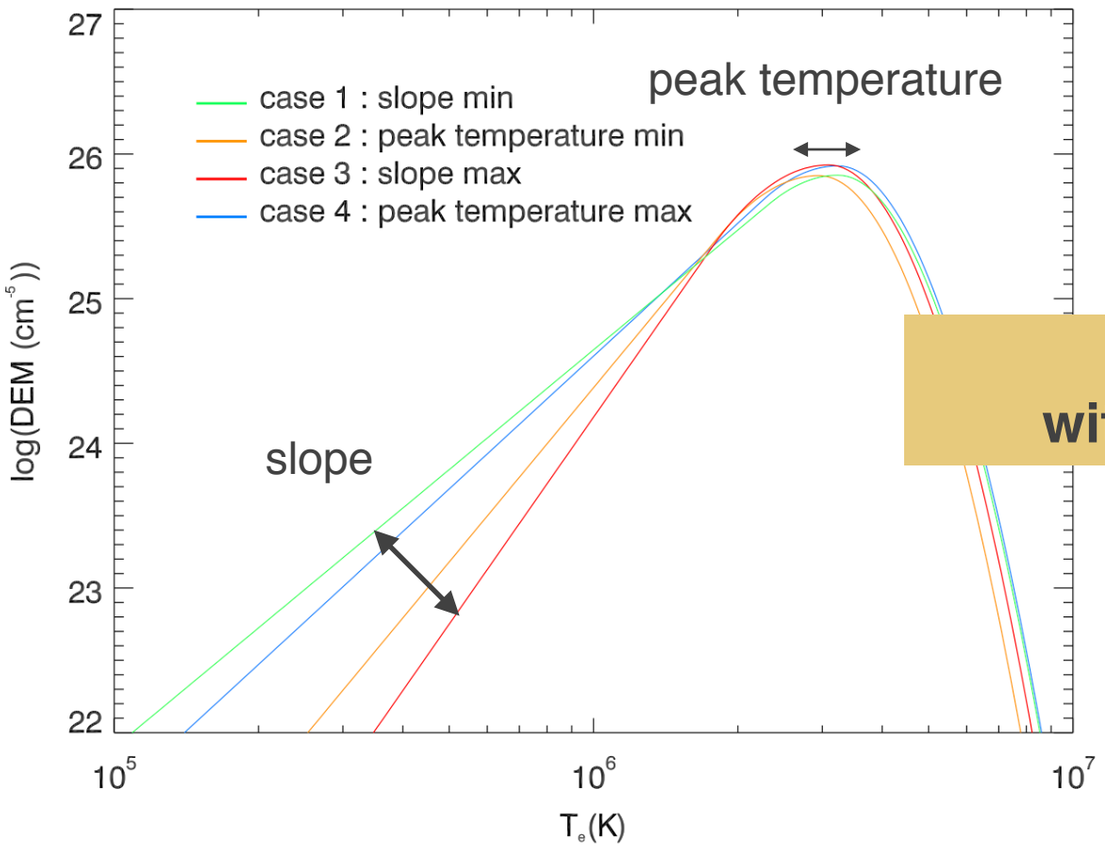

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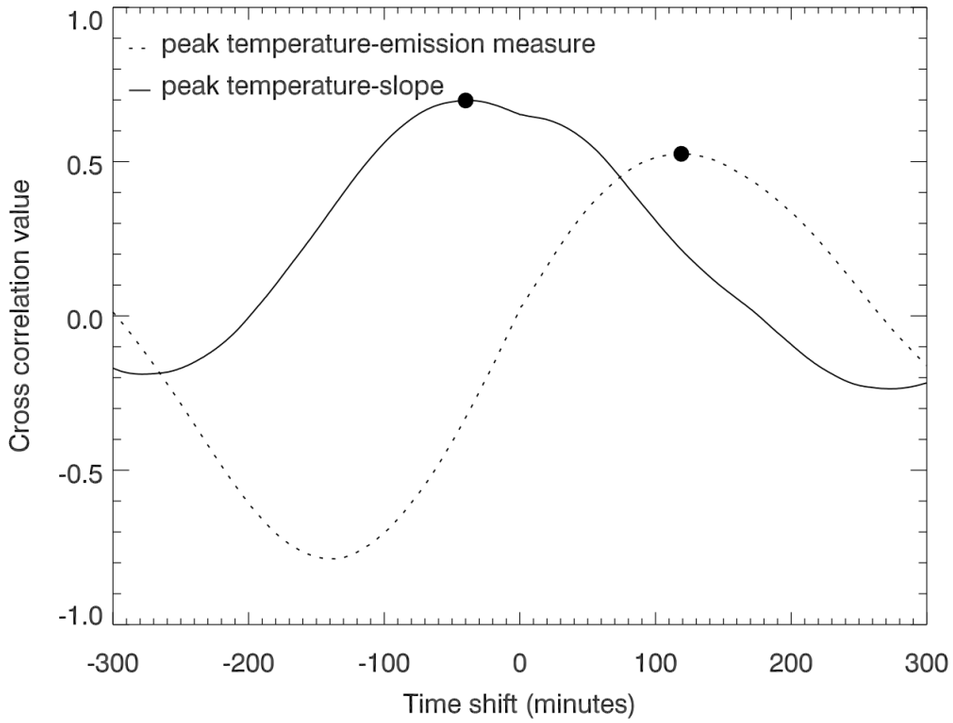
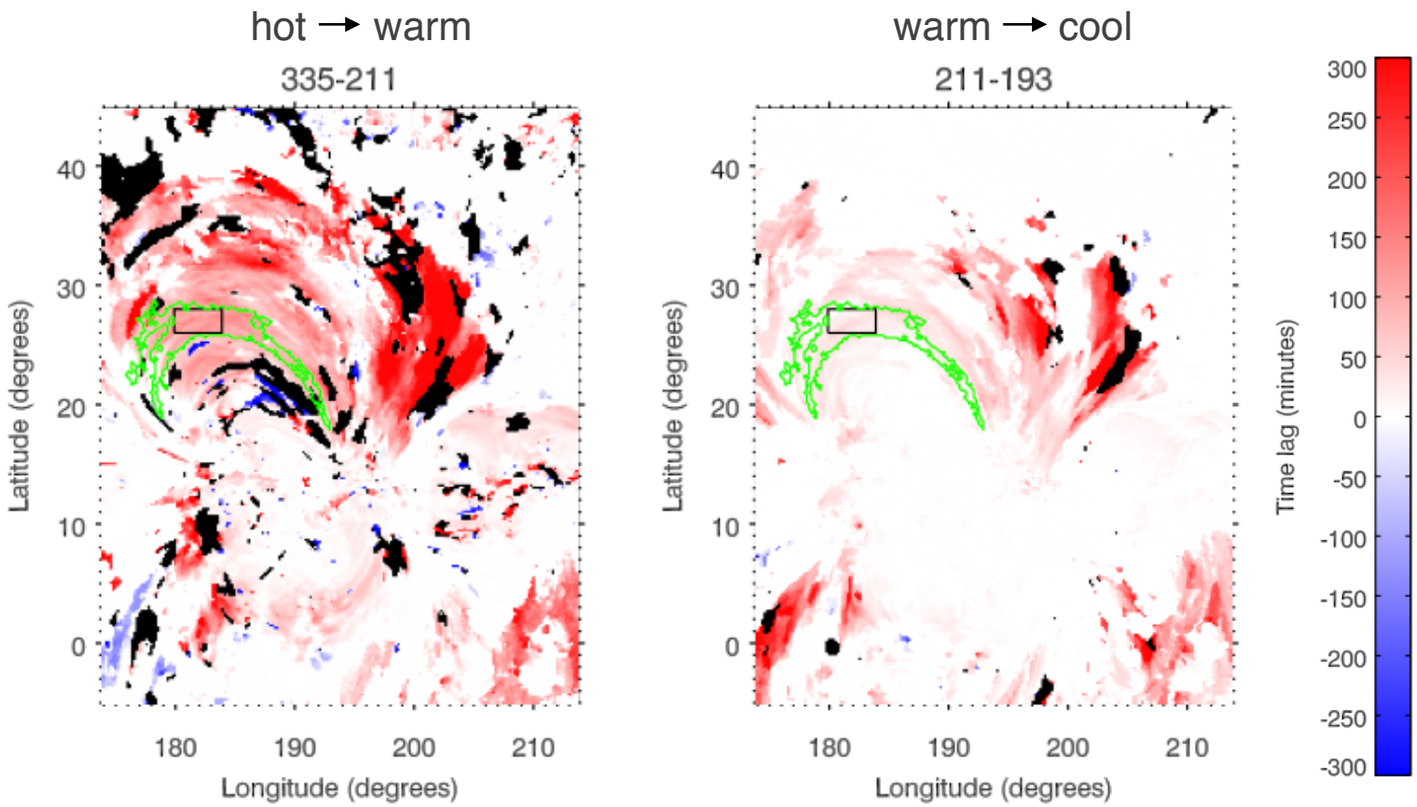
➡ **Strong evidence of TNE**



Are these loops different ?

Time lag maps (peak cross correlation values)



same method as in Viall & Klimchuk, 2012

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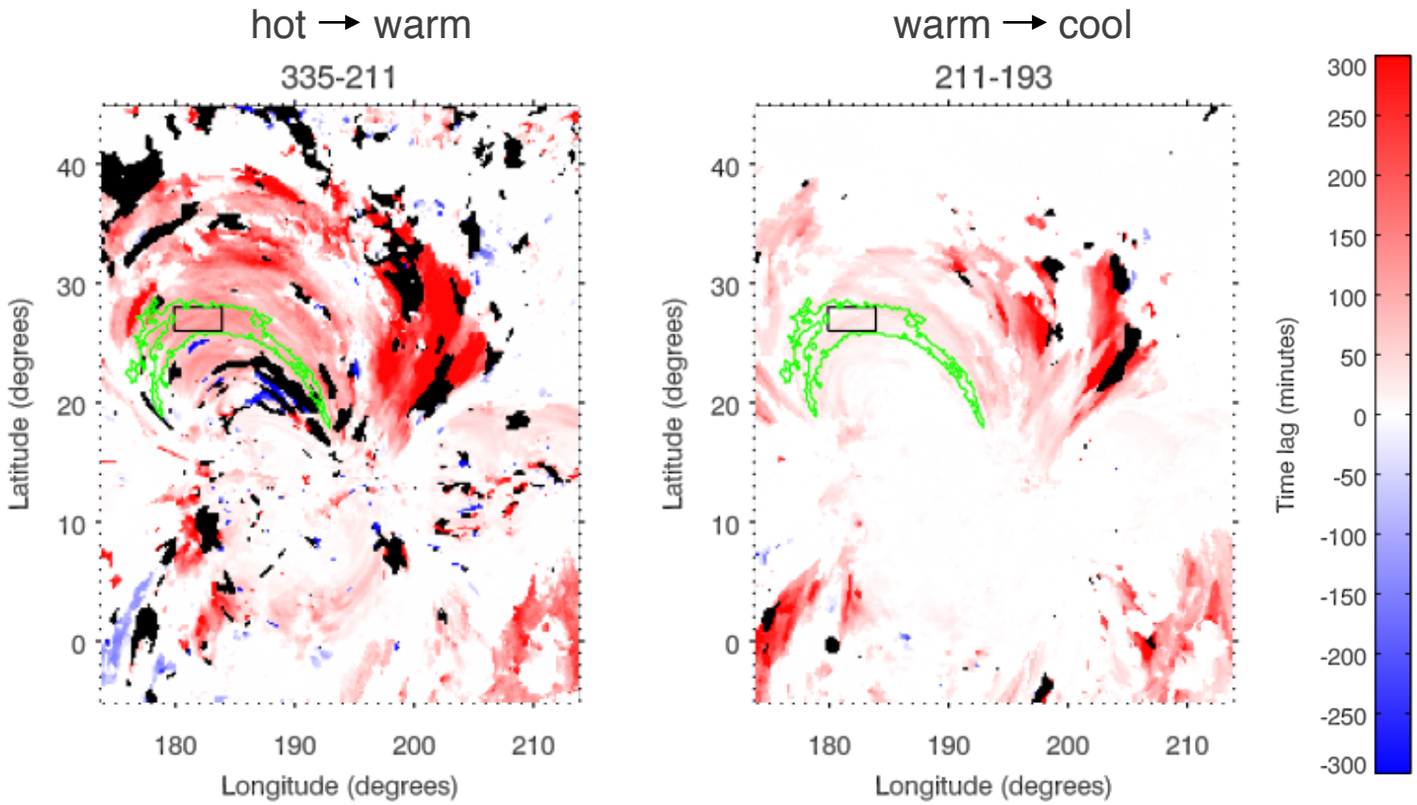

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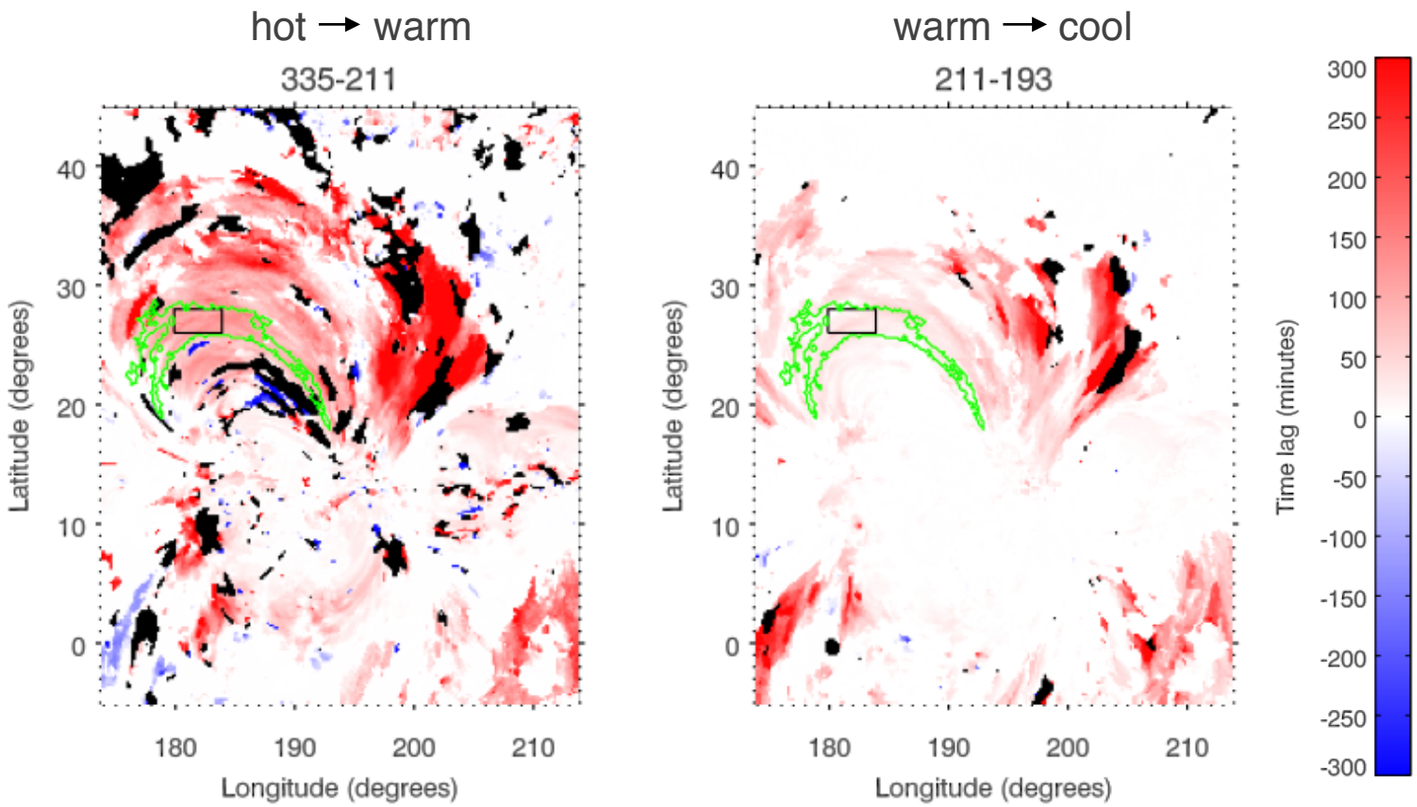

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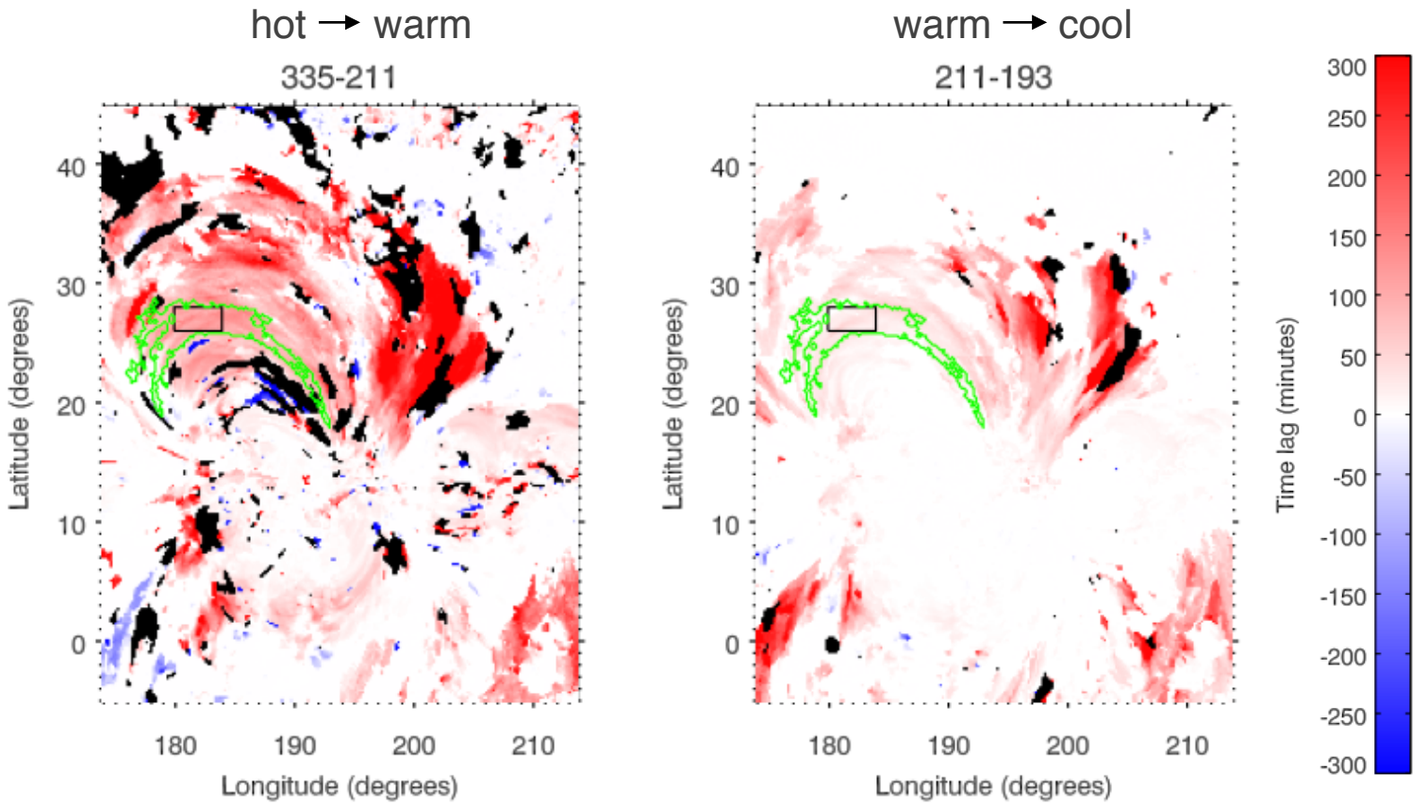

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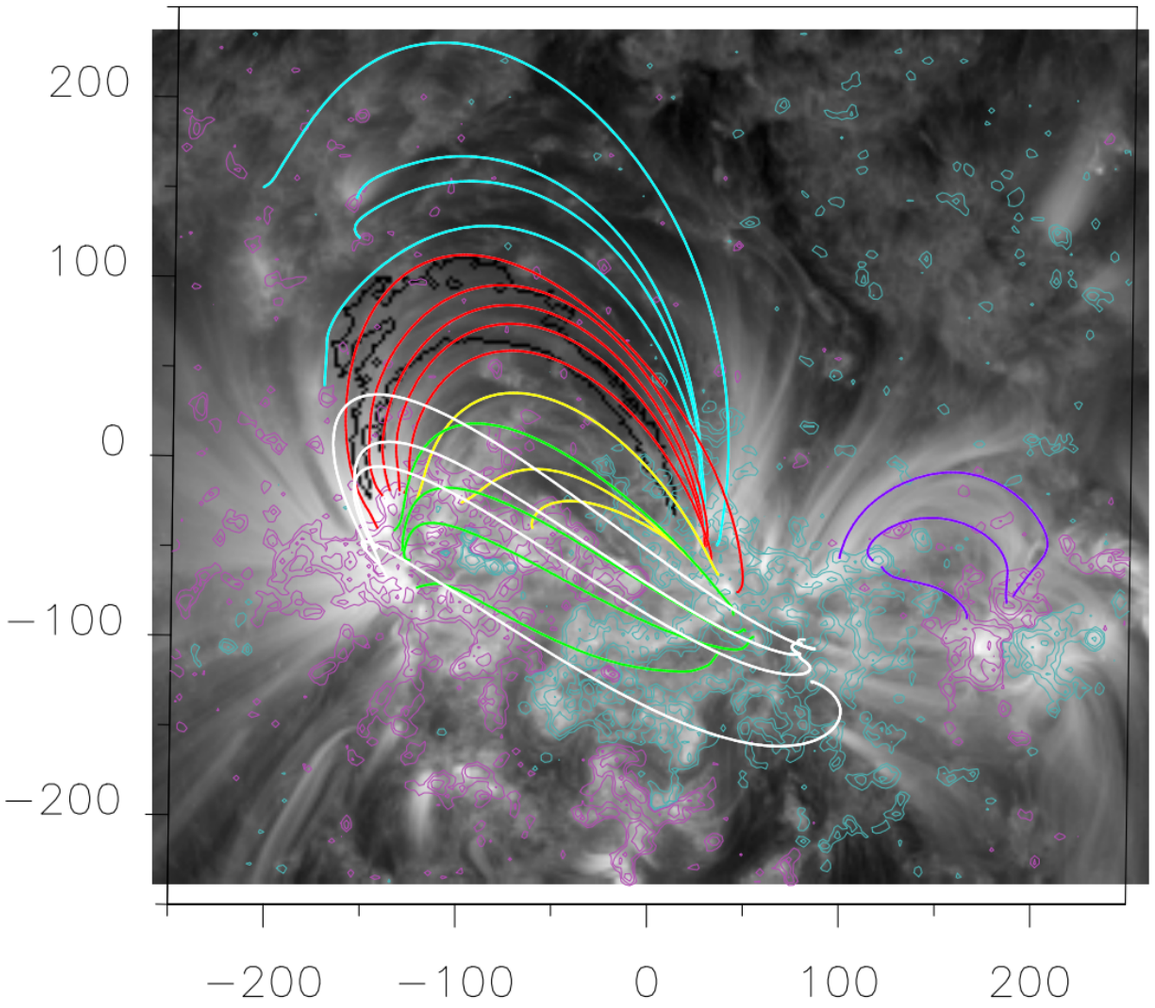
The pulsating loops have the same cooling/heating behavior as the rest of the active region

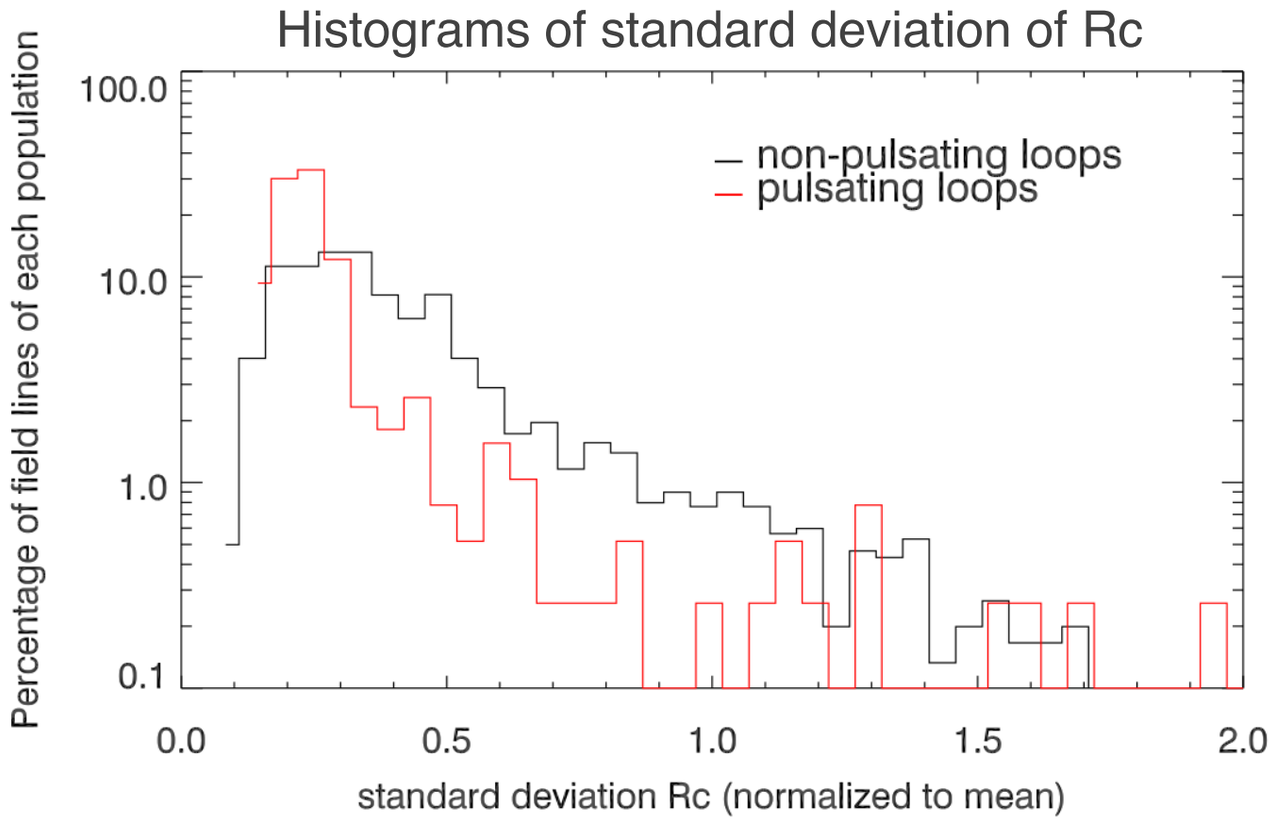
But a different response of the plasma for these loops

Loops geometry from a LFFF extrapolation

Have the field lines a different geometry in the pulsating area?

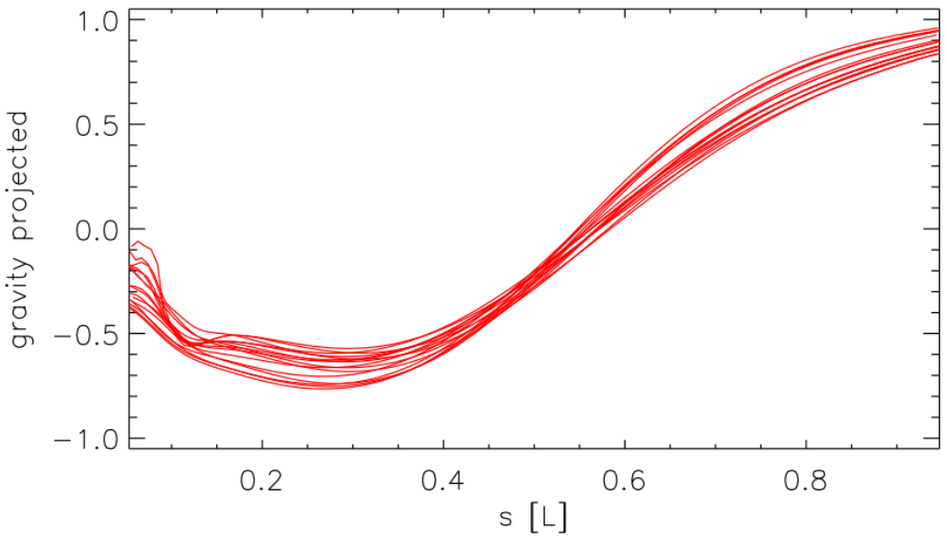


Extrapolations made in collaboration with G. Aulanier
(LFFF code courtesy G. Aulanier)



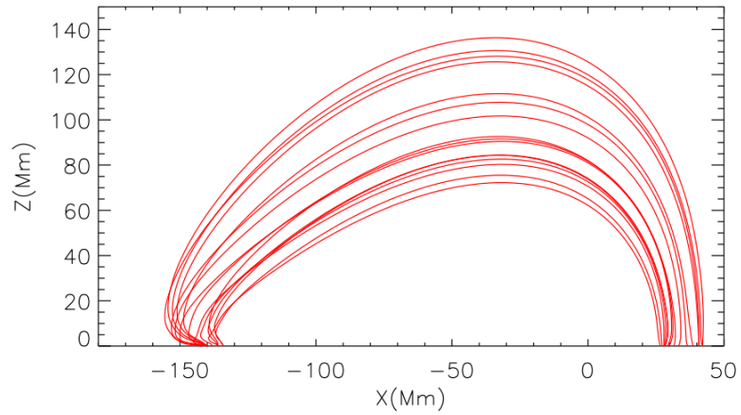
Estimate the general degree of asymmetry

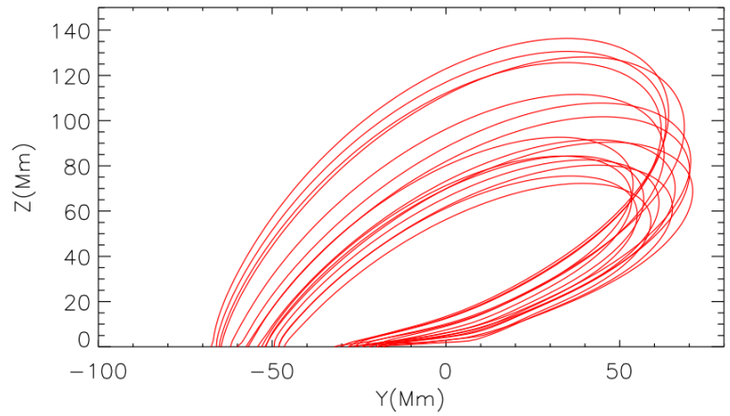
Loops geometry from a LFFF extrapolation

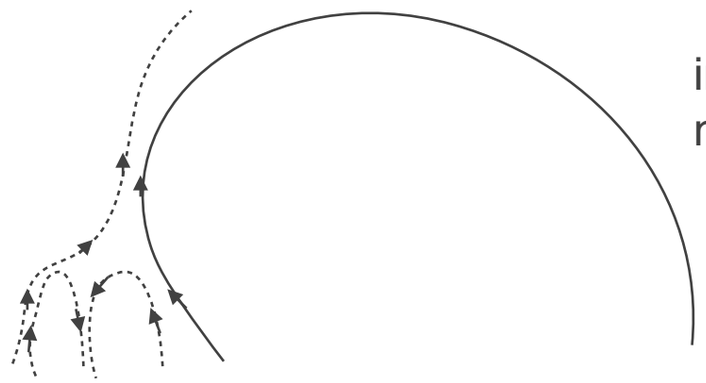


45% of the lines matching pulsating loops have this characteristic deviation against 12% for the others

A particular magnetic field topology:
Null point? To be confirmed







in case of null point near one footpoint

This asymmetric magnetic field topology favoured reconnections at one footpoint
→ strong asymmetric heating, a key ingredient to produce TNE !

Conclusions

- Our recent observations reveal that **long-period intensity pulsations** (several hours) are **very common in coronal loops**

- **Long-period intensity pulsations** are likely to be **observational signatures** of **TNE** in loops and thus of **highly stratified heating**

- **Magnetic topology** can explain emergence of these cycles for only some loop bundles

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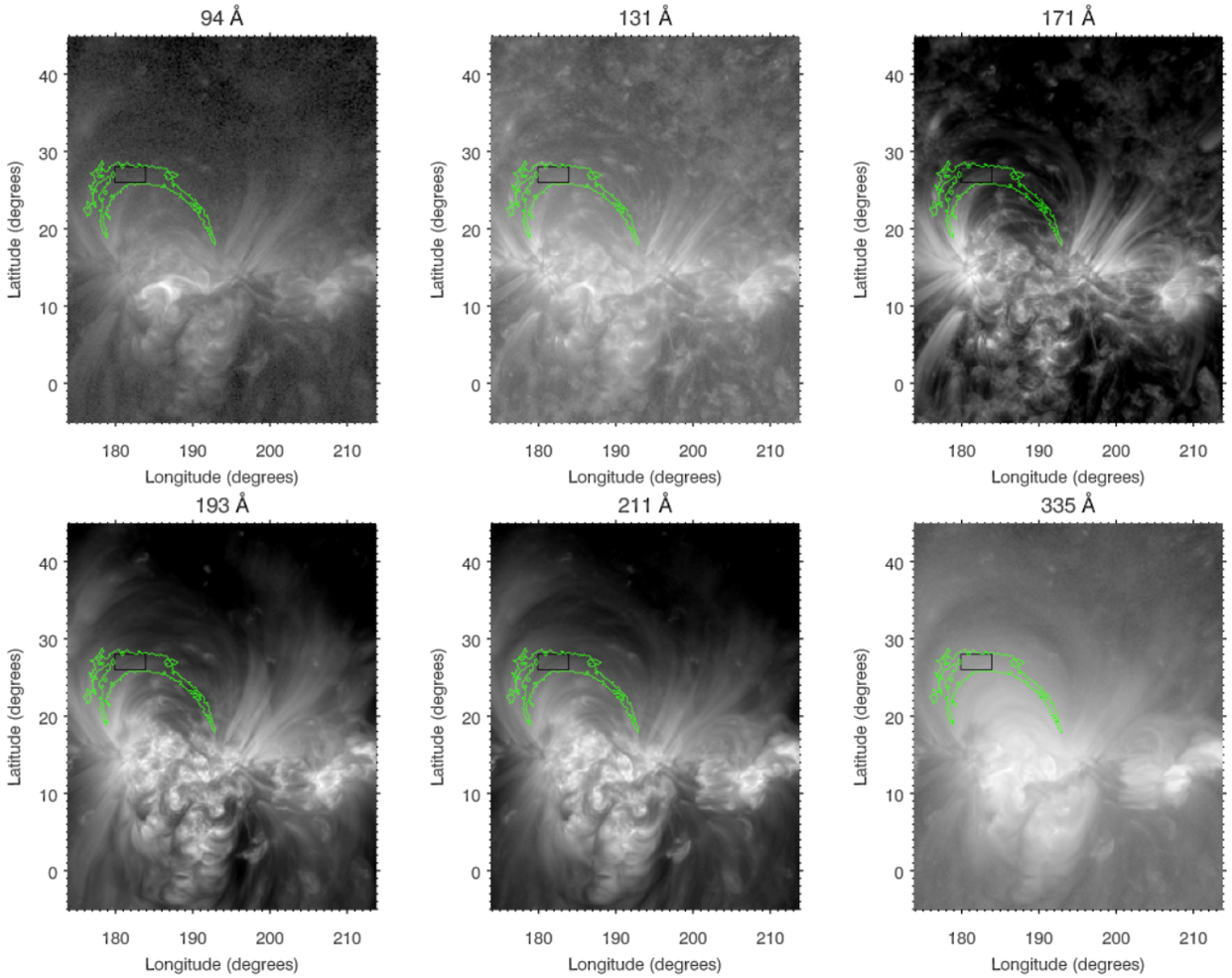
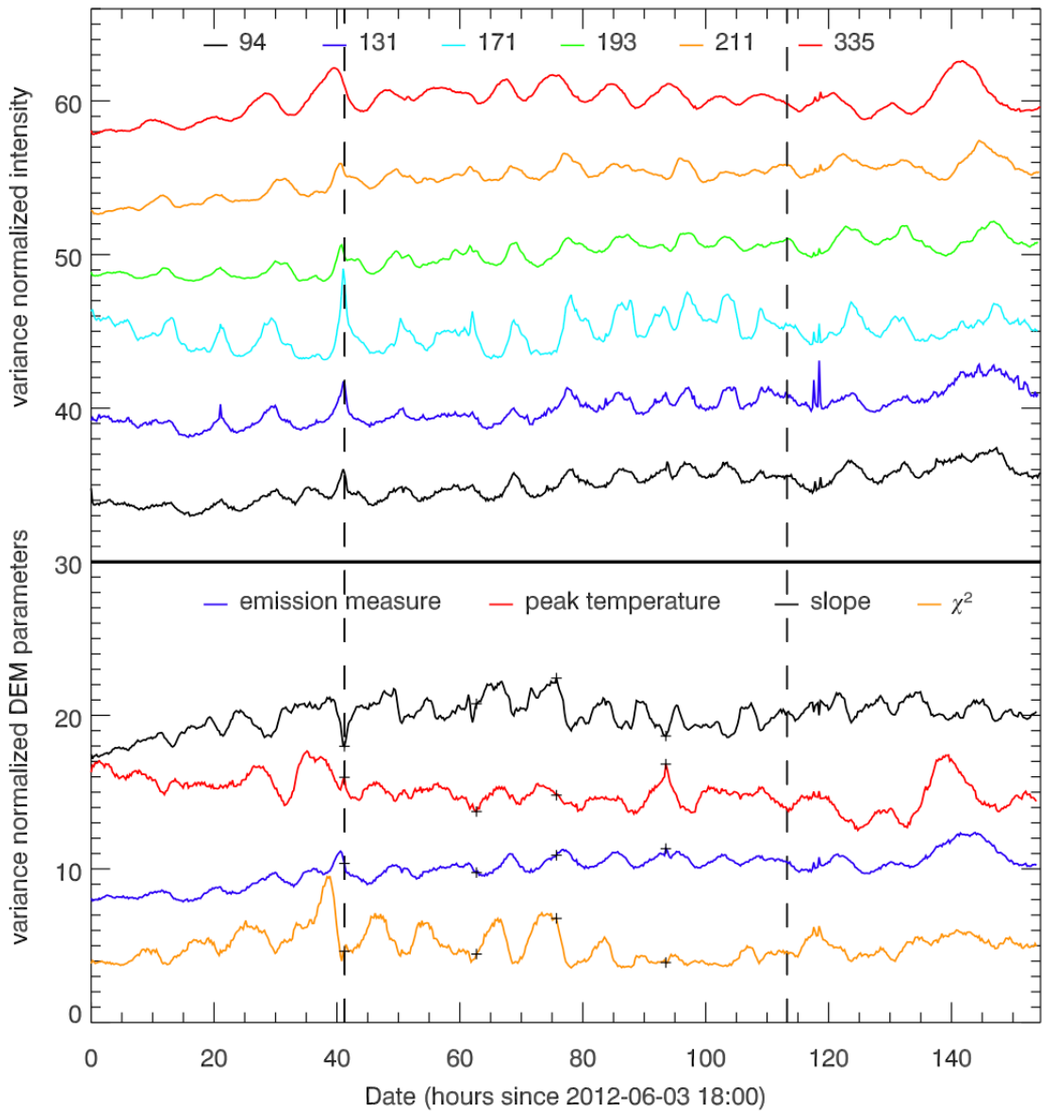
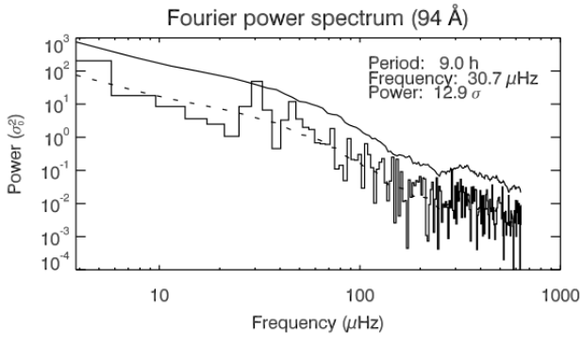
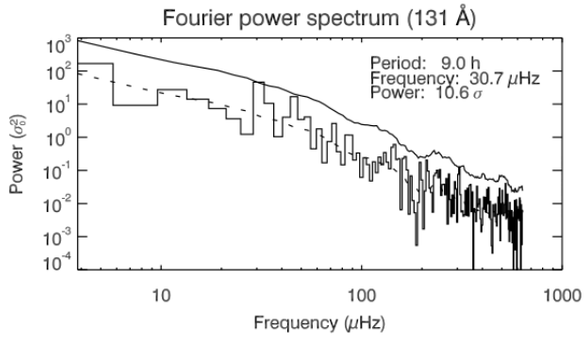
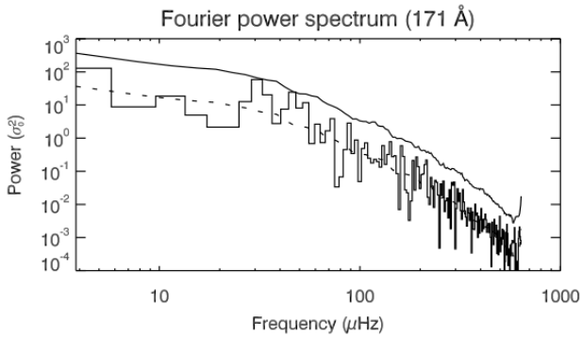
Thank you !

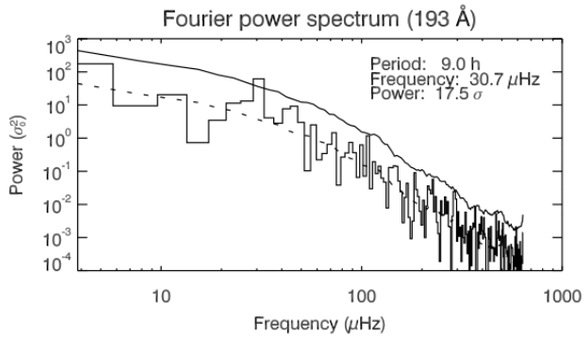

94 Å
131 Å
171 Å
193 Å
211 Å
335 Å
Latitude (degrees)
Longitude (degrees)
0
10
20
30
40
180
190
200
210

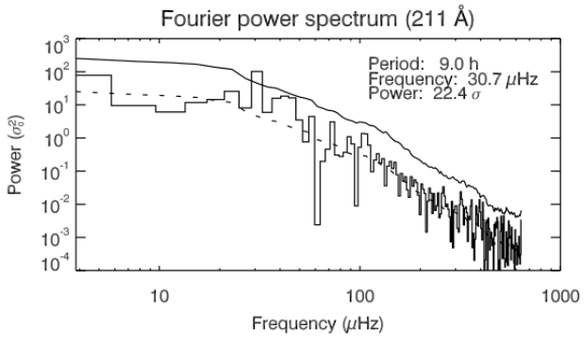

94
131
171
193
211
335
variance normalized intensity
emission measure
peak temperature
slope
χ^2
ce normalized DEM parameters
Date (hours since 2012-06-03 18:00)
0
20
40
60
80
100
120
140

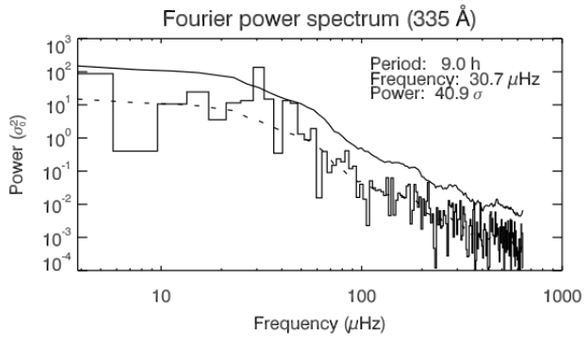

Fourier power spectrum (94 Å)
Period: 9.0 h
Frequency: 30.7 μHz
Power: 12.9 σ
Power (σ_0^2)
Frequency (μHz)

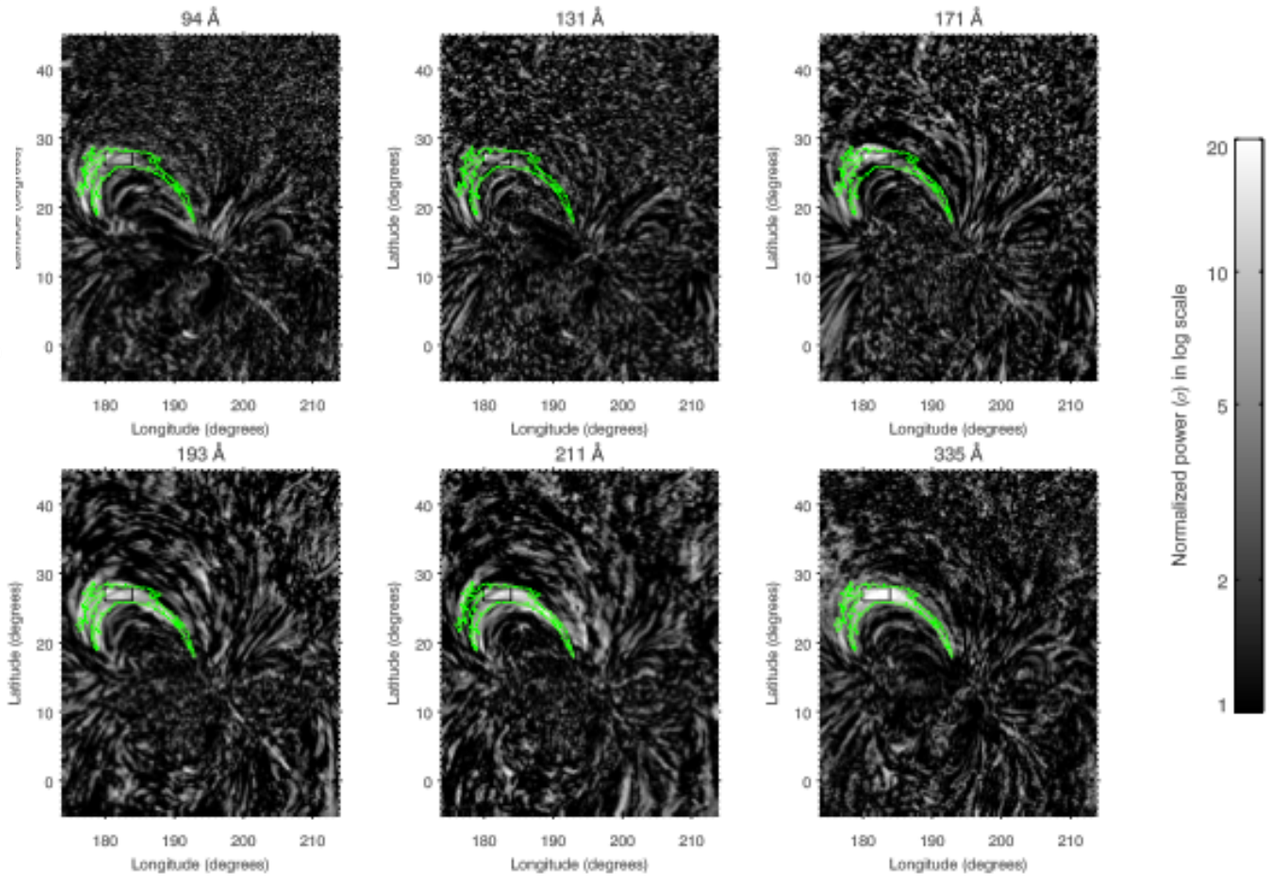

Fourier power spectrum (131 Å)
Period: 9.0 h
Frequency: 30.7 μHz
Power: 10.6 σ
Power (σ_0^2)
Frequency (μHz)

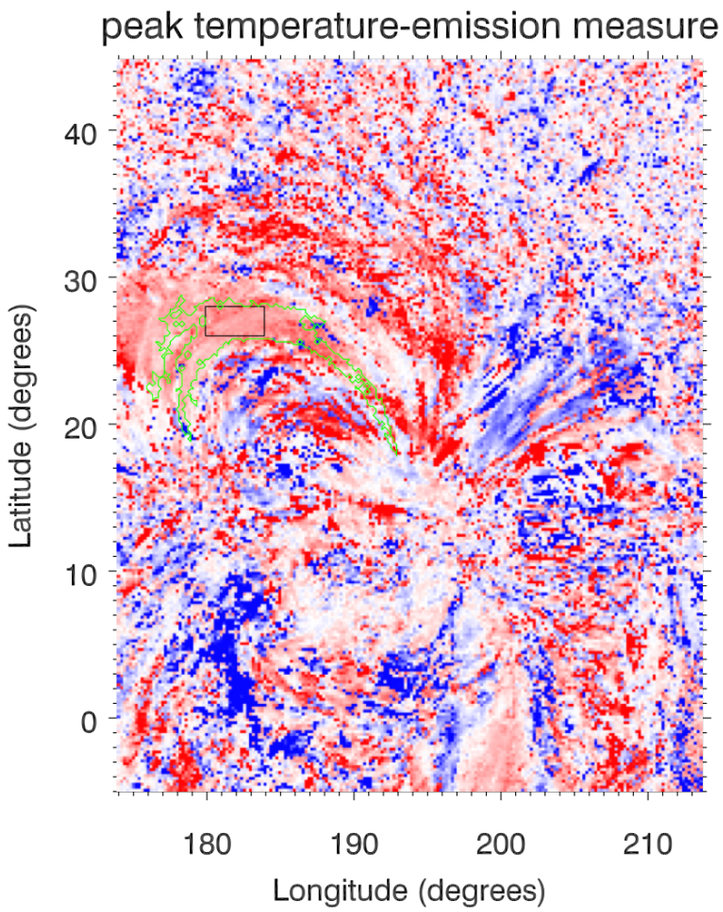

Fourier power spectrum (171 Å)
Power (σ_0^2)
Frequency (μHz)

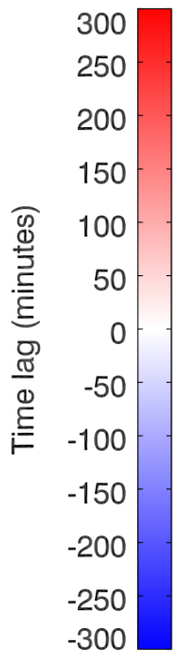

Fourier power spectrum (193 Å)
Period: 9.0 h
Frequency: 30.7 μHz
Power: 17.5 σ
Power (σ_0^2)
Frequency (μHz)

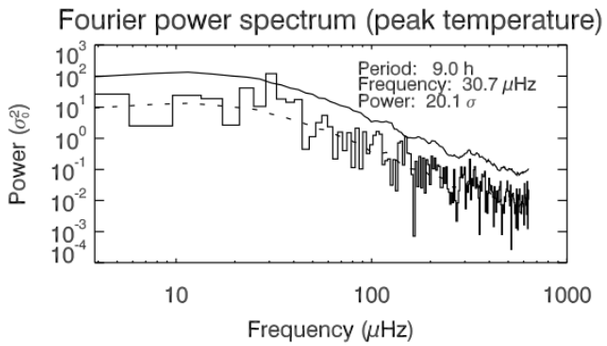

Fourier power spectrum (211 Å)
Period: 9.0 h
Frequency: 30.7 μHz
Power: 22.4 σ
Power (σ_0^2)
Frequency (μHz)

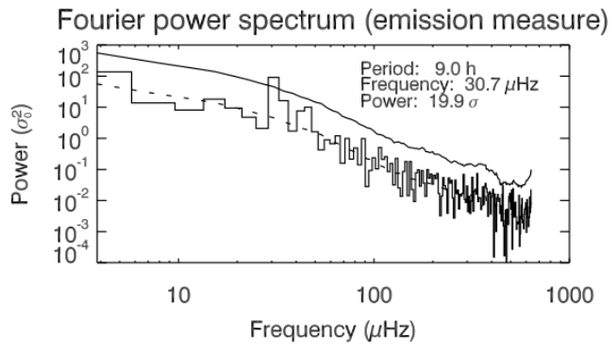

Fourier power spectrum (335 Å)
Period: 9.0 h
Frequency: 30.7 μHz
Power: 40.9 σ
Power (σ_0^2)
Frequency (μHz)

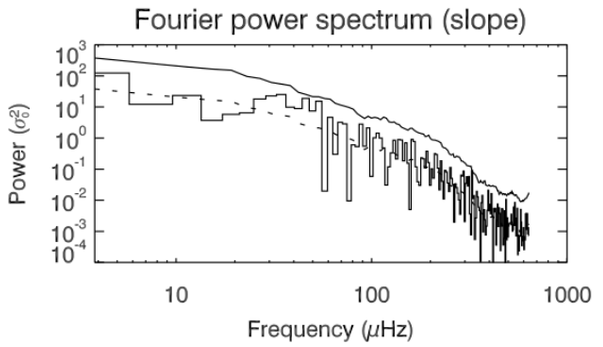

94 Å
131 Å
171 Å
193 Å
211 Å
335 Å
Latitude (degrees)
Longitude (degrees)
Normalized power (σ) in log scale

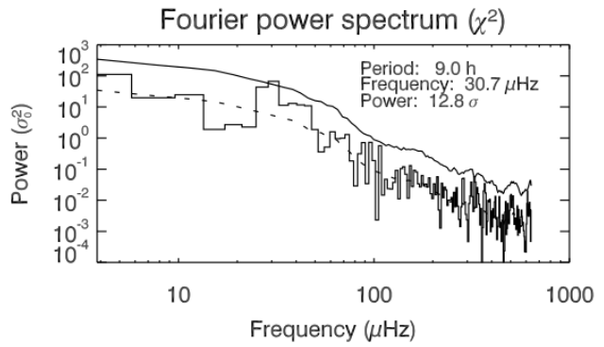

peak temperature-emission measure
Latitude (degrees)
40
30
20
10
0
180
190
200
210
Longitude (degrees)

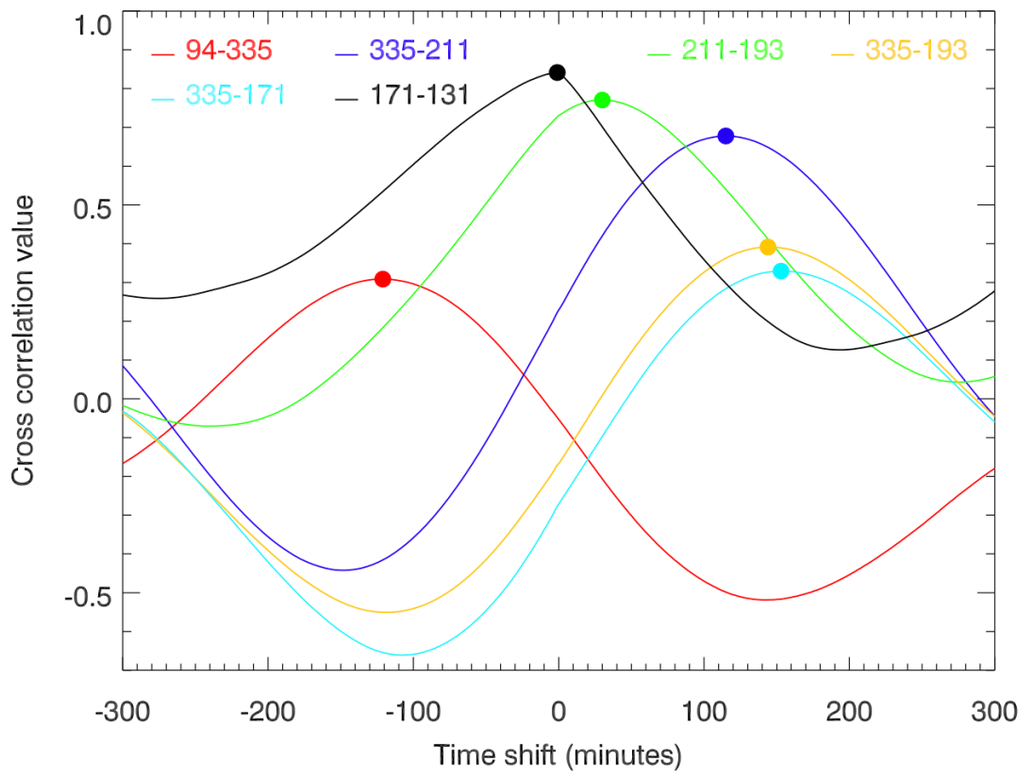

Time lag (minutes)
300
250
200
150
100
50
0
-50
-100
-150
-200
-250
-300

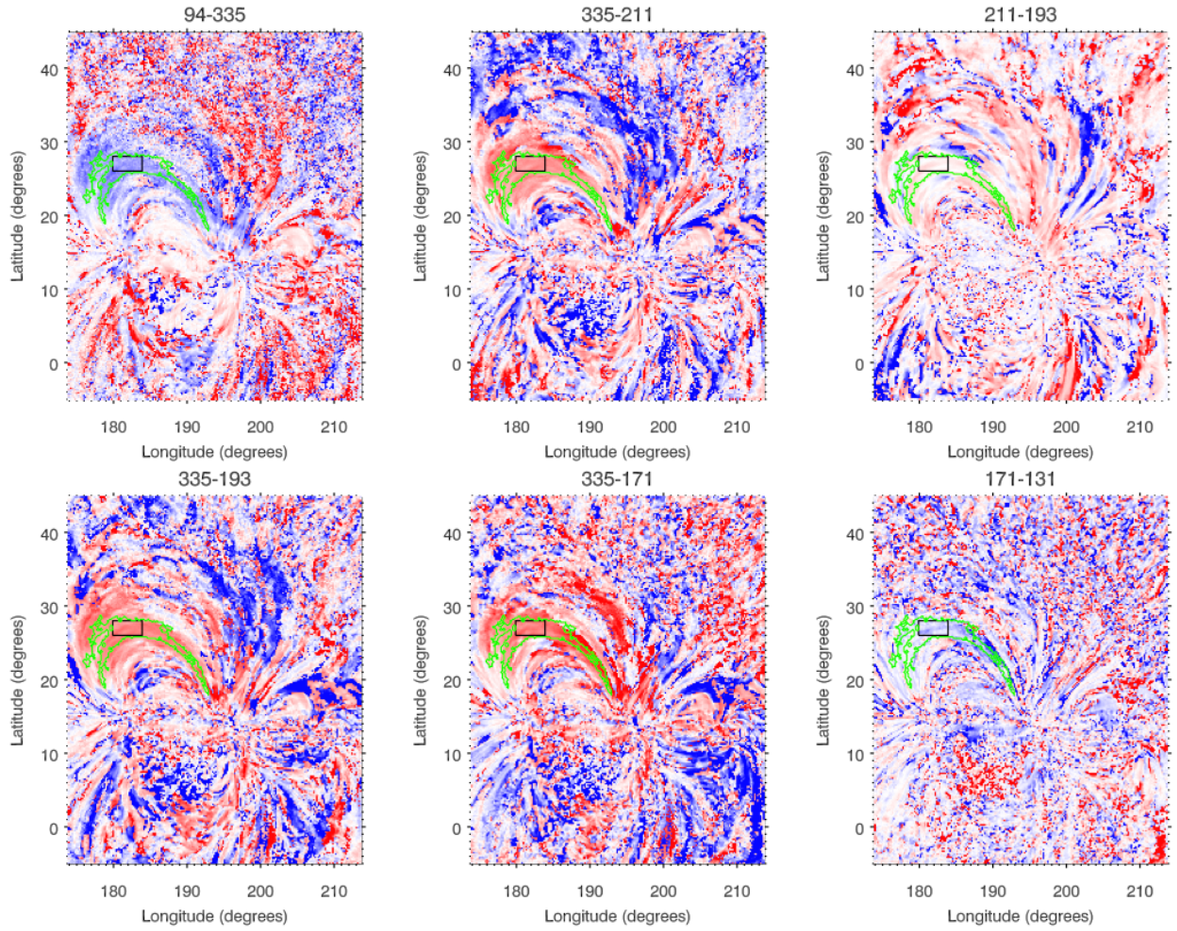

Fourier power spectrum (peak temperature)
Period: 9.0 h
Frequency: 30.7 μHz
Power: 20.1 σ
Power (σ_0^2)
Frequency (μHz)

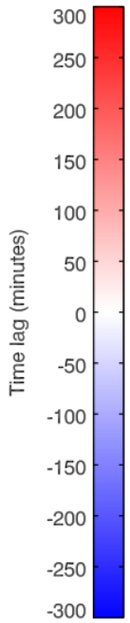

Fourier power spectrum (emission measure)
Period: 9.0 h
Frequency: 30.7 μHz
Power: 19.9 σ
Power (σ_0^2)
Frequency (μHz)

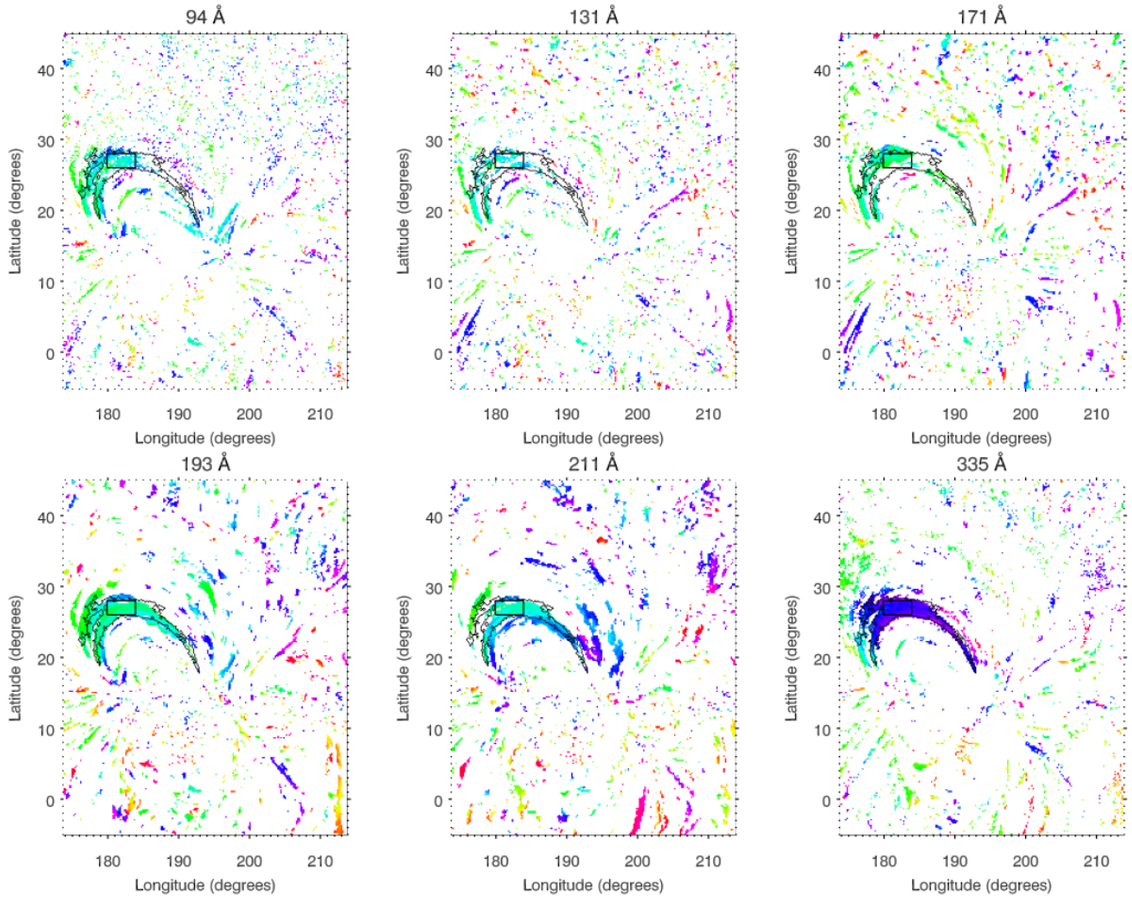

Fourier power spectrum (slope)
Power (σ_0^2)
Frequency (μHz)


Fourier power spectrum (χ^2)
Period: 9.0 h
Frequency: 30.7 μHz
Power: 12.8 σ
Power (σ_0^2)
Frequency (μHz)

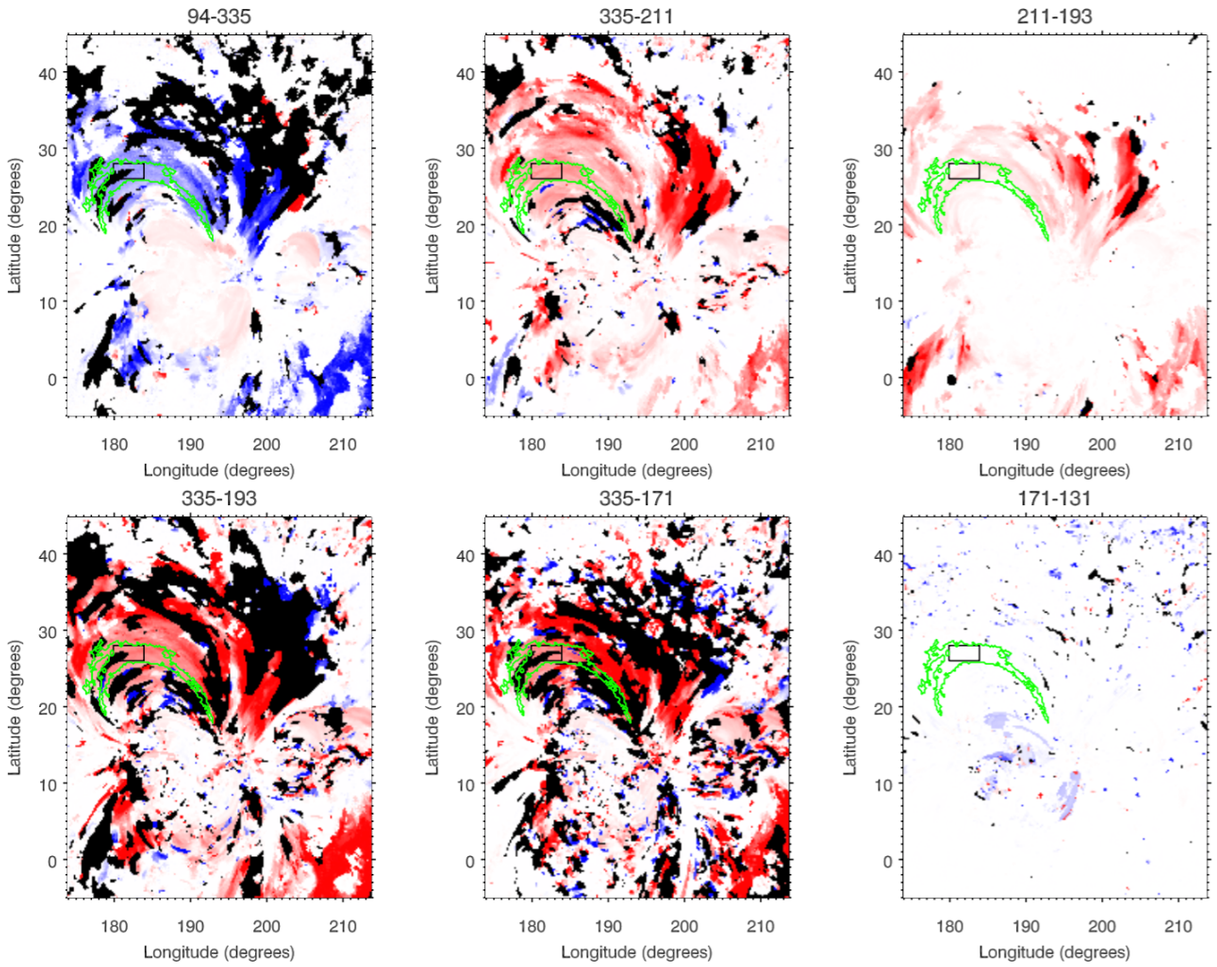

94-335
335-211
211-193
335-193
335-171
171-131
Cross correlation value
Time shift (minutes)

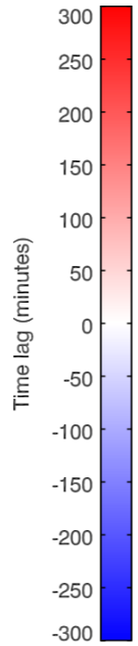

94-335
335-211
211-193
335-193
335-171
171-131
Latitude (degrees)
Longitude (degrees)
180
190
200
210
0
10
20
30
40

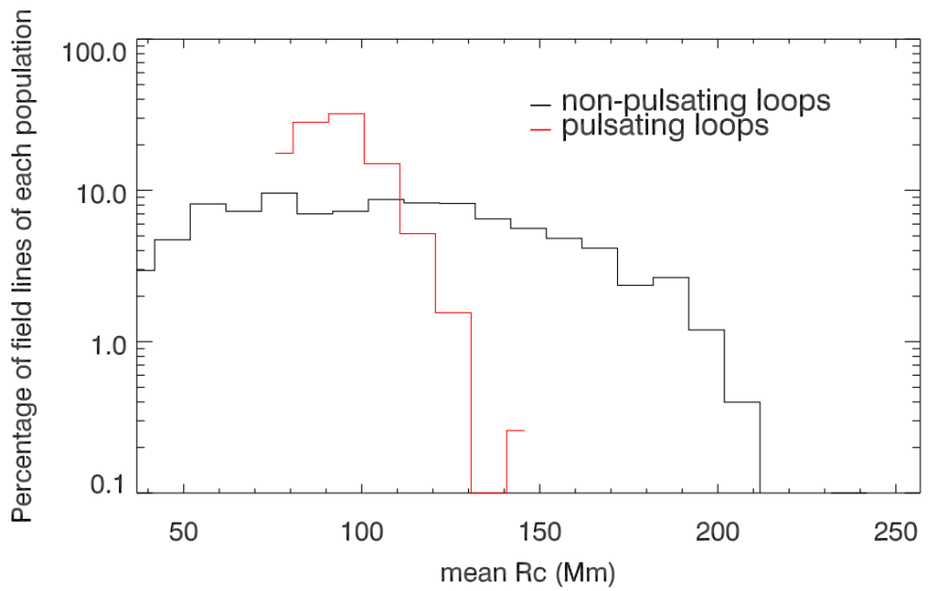

Time lag (minutes)
300
250
200
150
100
50
0
-50
-100
-150
-200
-250
-300

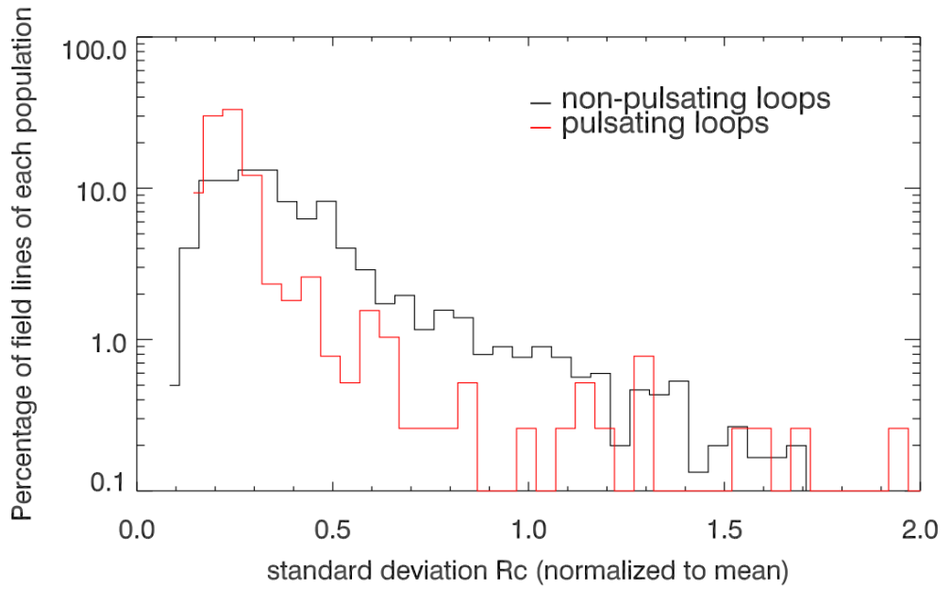

94 Å
131 Å
171 Å
193 Å
211 Å
335 Å
Latitude (degrees)
Longitude (degrees)
180
190
200
210
0
10
20
30
40

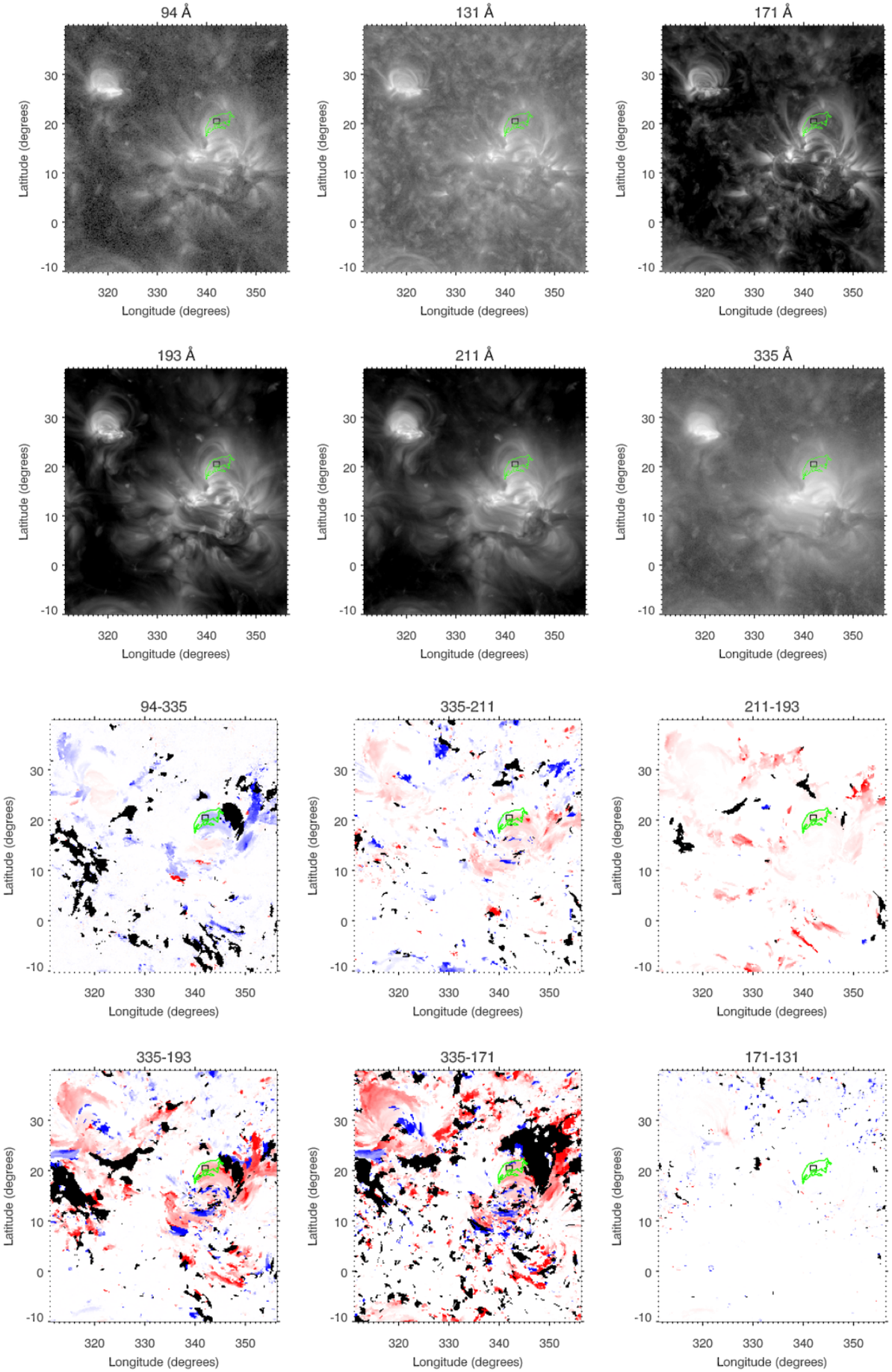
Phase (hours)
4.52
3.39
2.26
1.13
0.00
-1.13
-2.26
-3.39
-4.52

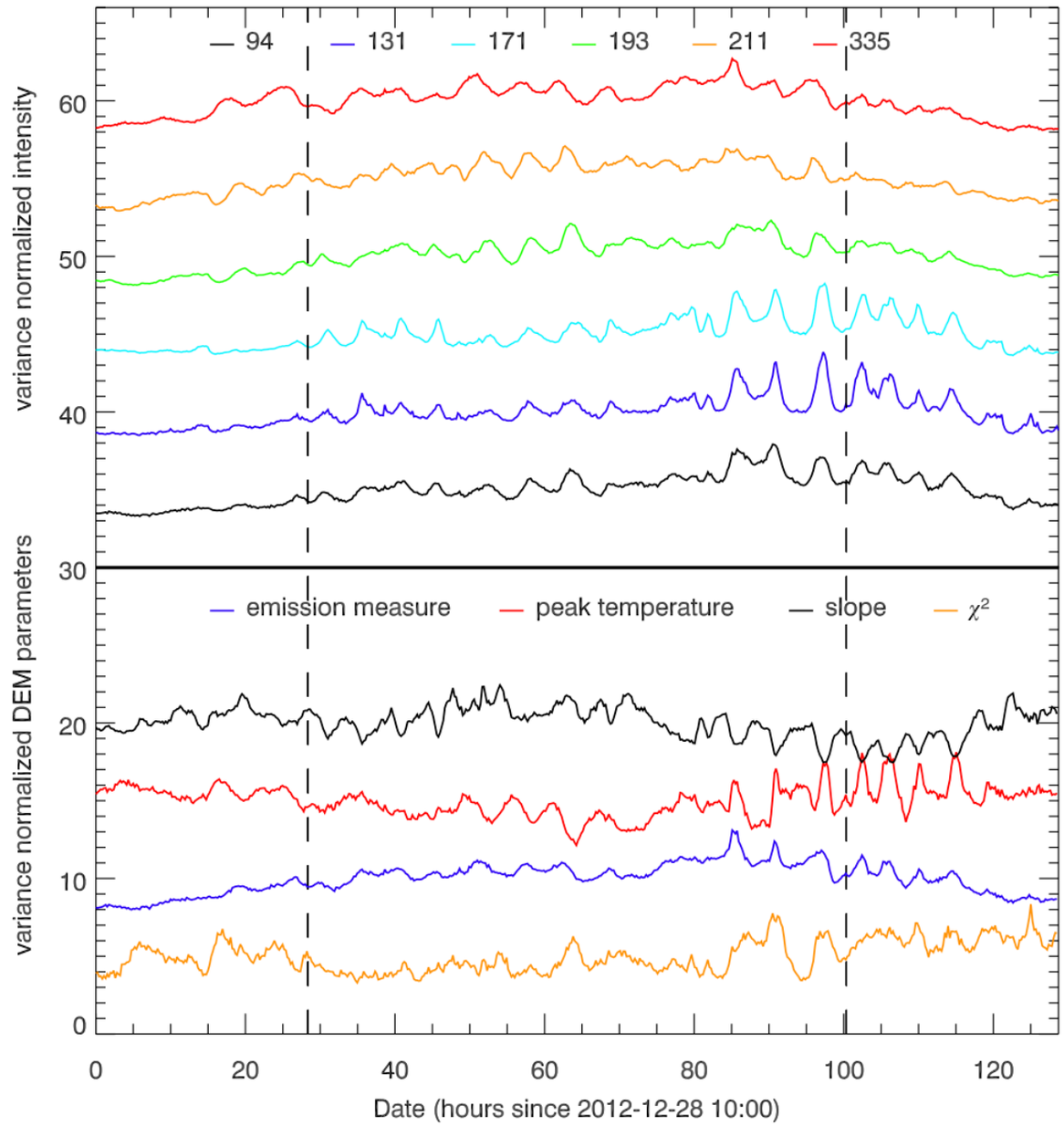

94-335
335-211
211-193
335-193
335-171
171-131
Latitude (degrees)
Longitude (degrees)
180
190
200
210
0
10
20
30
40

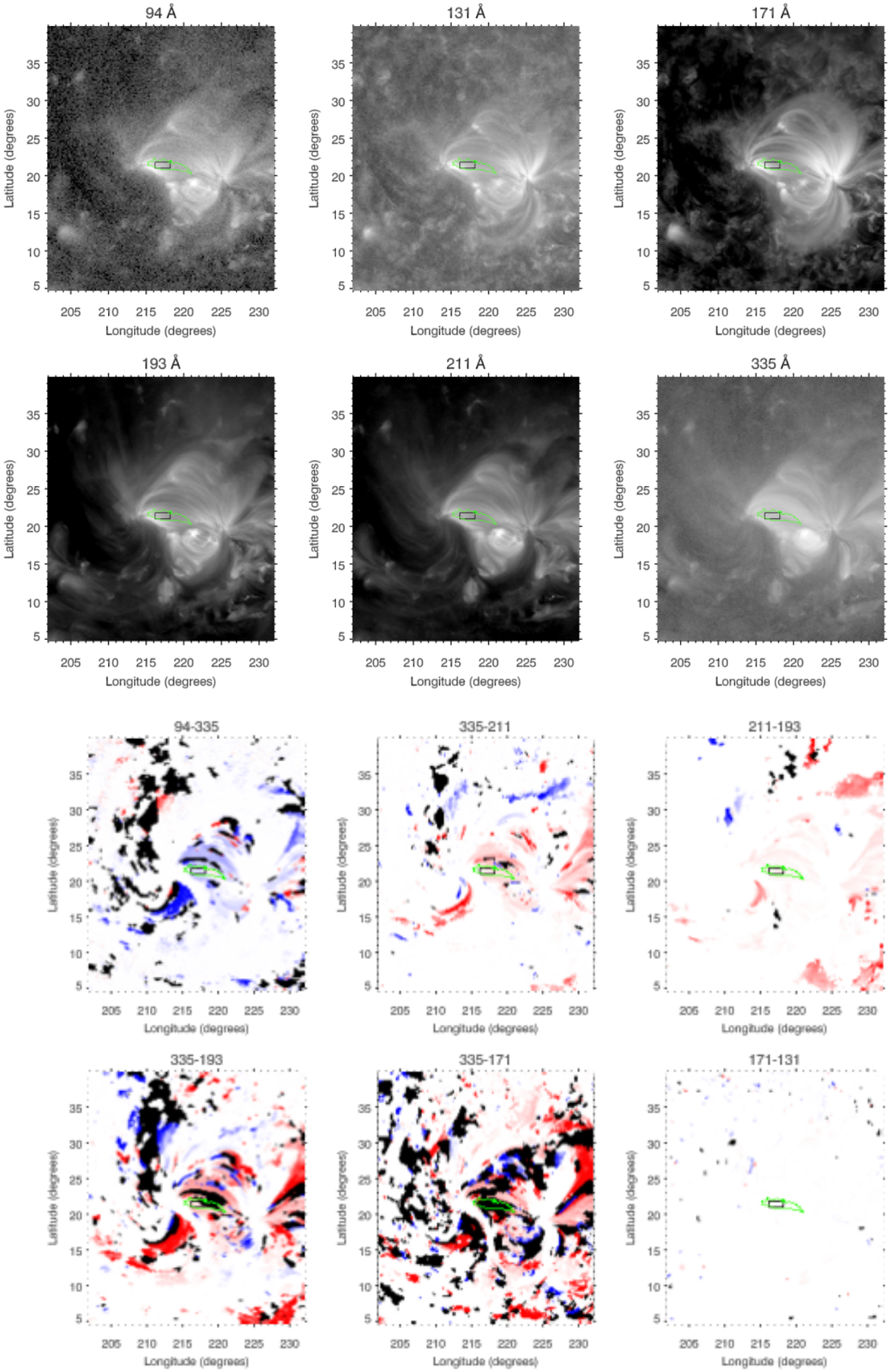

Time lag (minutes)
300
250
200
150
100
50
0
-50
-100
-150
-200
-250
-300

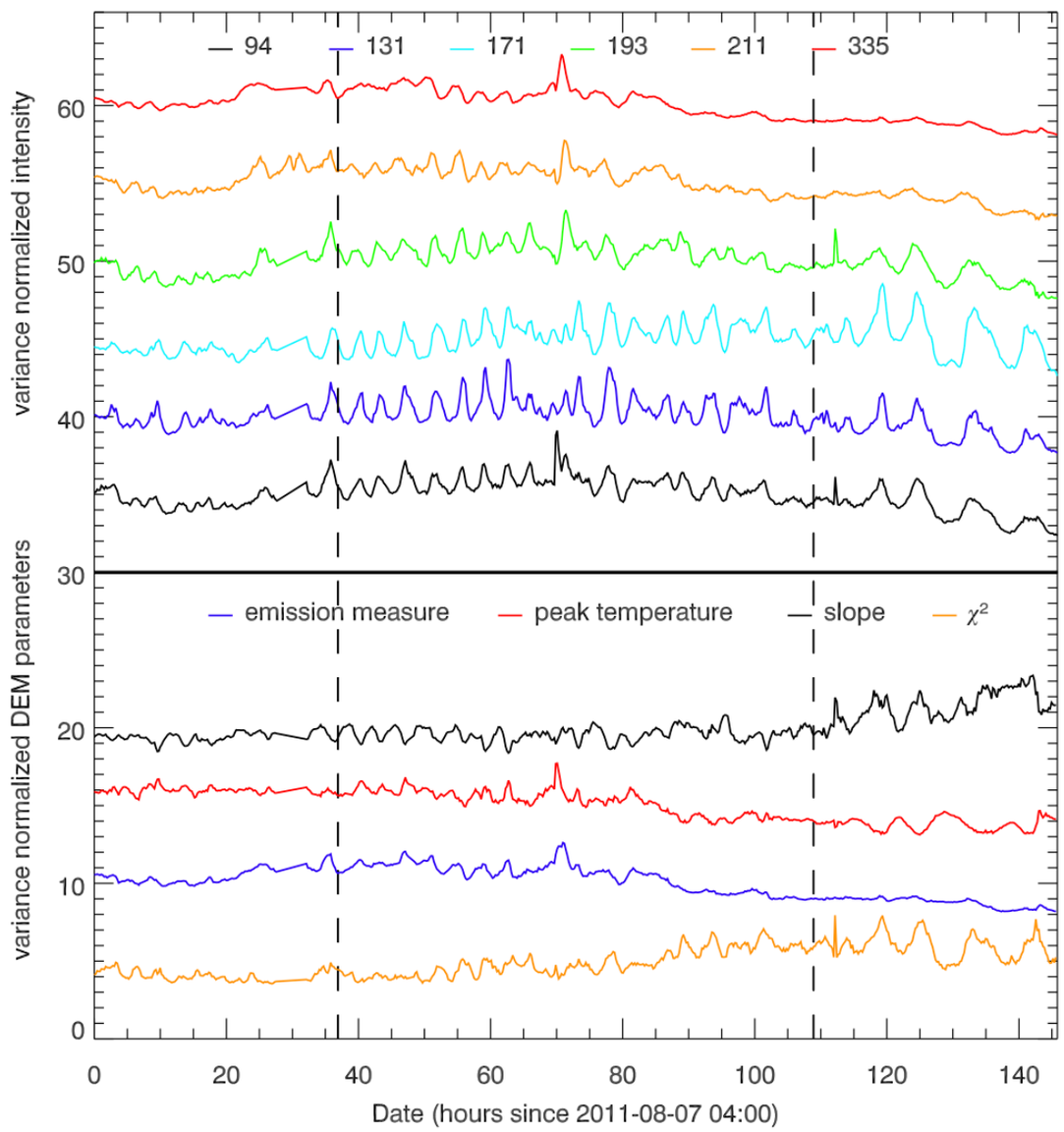

non-pulsating loops
pulsating loops
Percentage of field lines of each population
100.0
10.0
1.0
0.1
50
100
150
200
250
mean Rc (Mm)

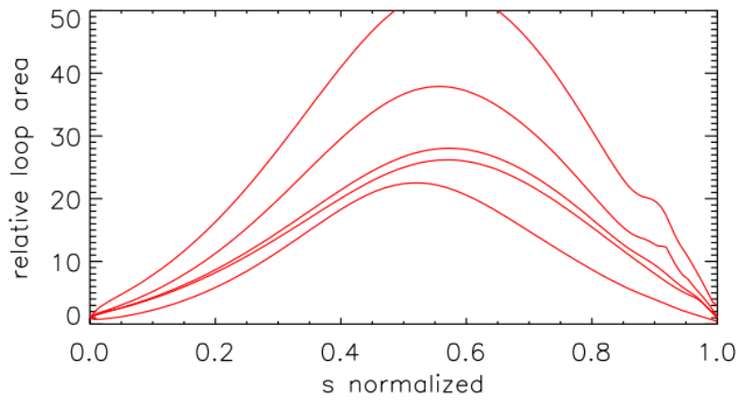

non-pulsating loops
pulsating loops
Percentage of field lines of each population
100.0
10.0
1.0
0.1
0.0
0.5
1.0
1.5
2.0
standard deviation Rc (normalized to mean)

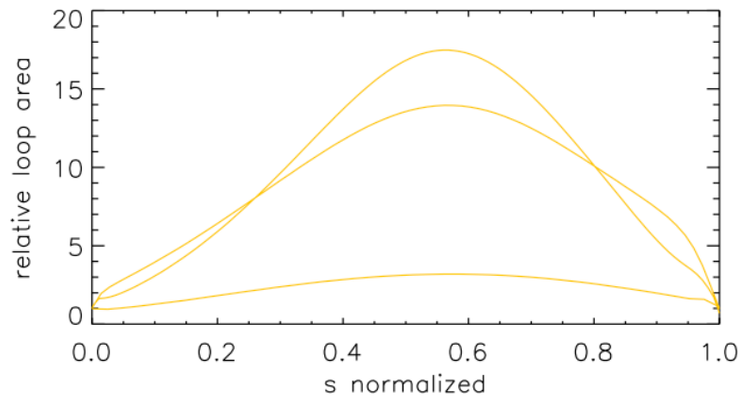

94 Å
131 Å
171 Å
193 Å
211 Å
335 Å
94-335
335-211
211-193
335-193
335-171
171-131
Latitude (degrees)
Longitude (degrees)
Time lag (minutes)

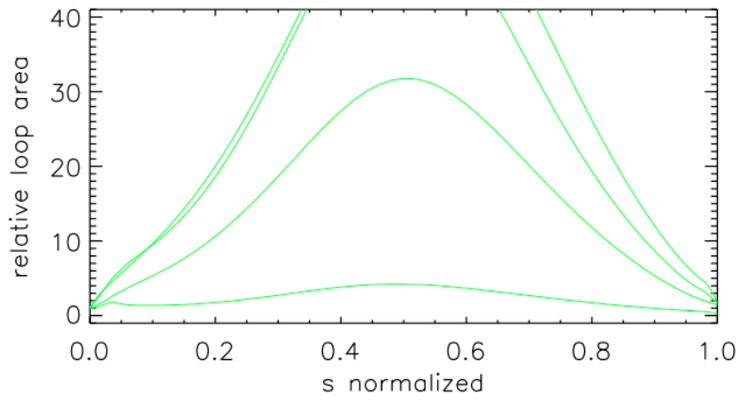

94
131
171
193
211
335
variance normalized intensity
emission measure
peak temperature
slope
χ^2
variance normalized DEM parameters
Date (hours since 2012-12-28 10:00)

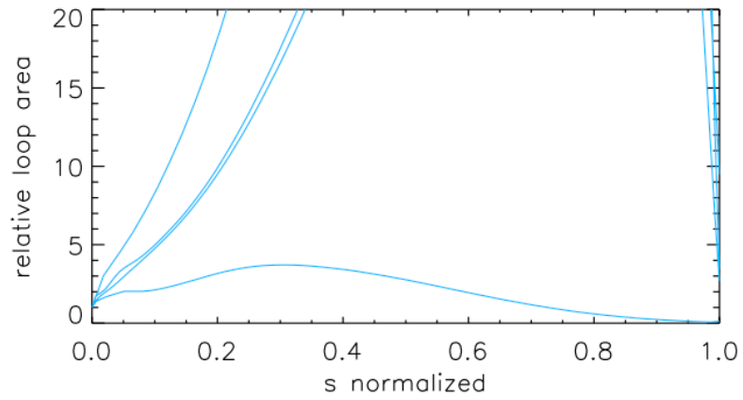

94 Å
131 Å
171 Å
193 Å
211 Å
335 Å
Latitude (degrees)
Longitude (degrees)
94-335
335-211
211-193
335-193
335-171
171-131
Time lag (minutes)

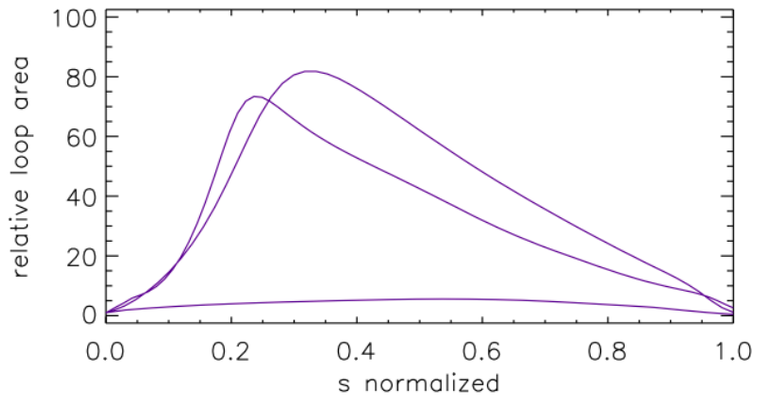

94
131
171
193
211
335
variance normalized intensity
emission measure
peak temperature
slope
χ^2
normalized DEM parameters
Date (hours since 2011-08-07 04:00)

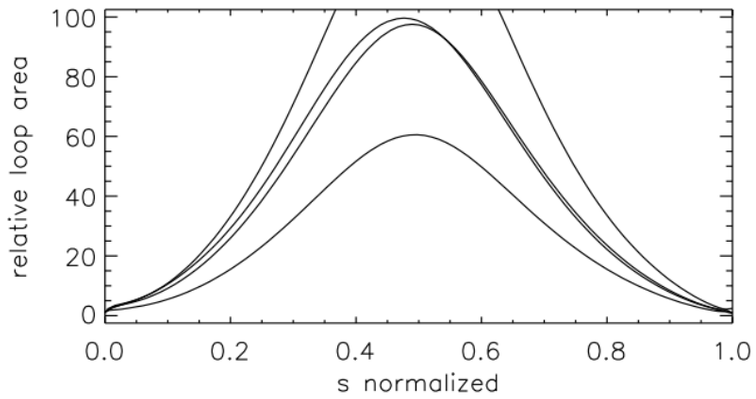

relative loop area
s normalized


relative loop area
s normalized


relative loop area
s normalized


relative loop area
s normalized


relative loop area
s normalized


relative loop area
s normalized

1D hydrodynamic simulation

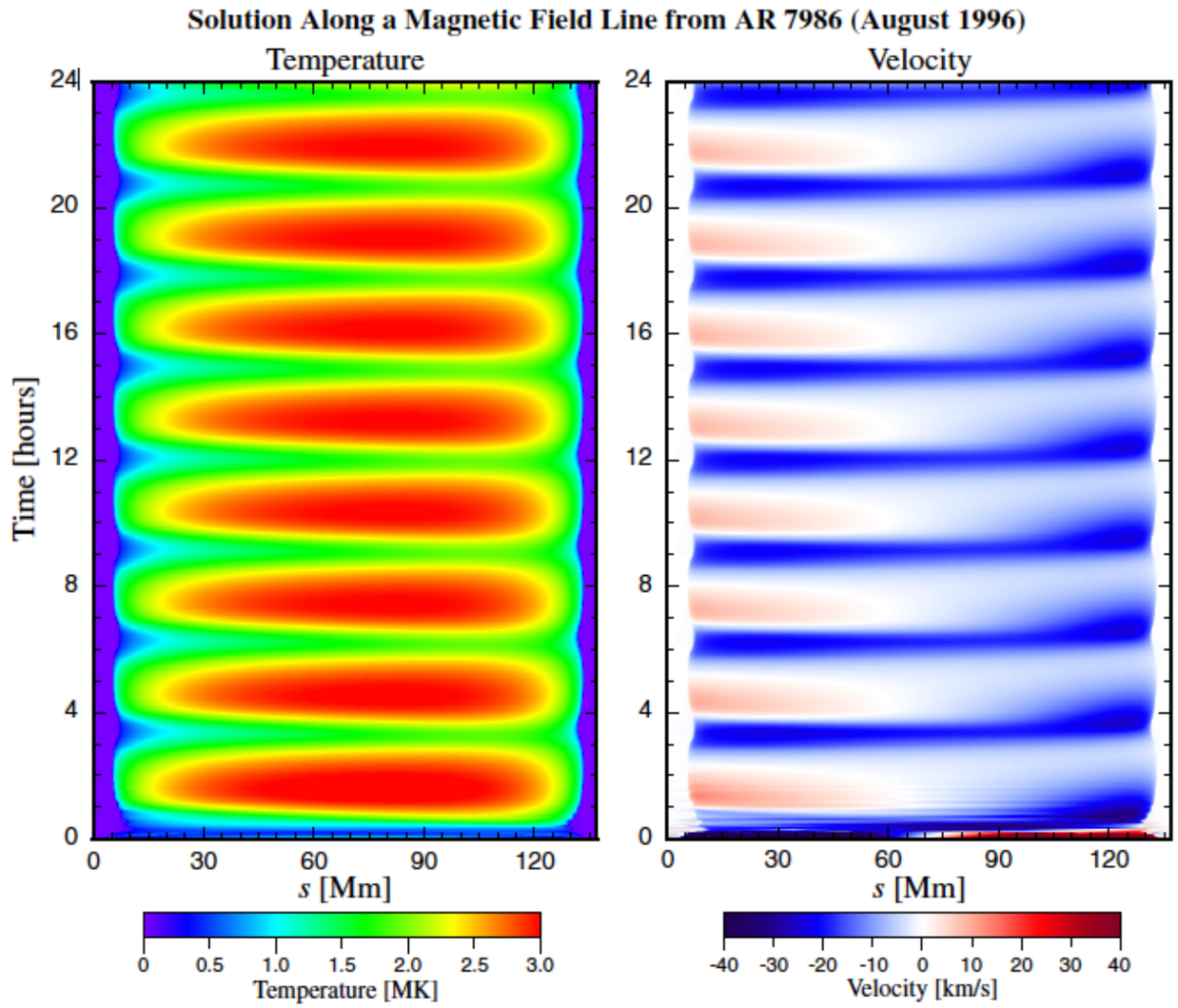
Tests with the lines extrapolated with LFFF code for different populations of loops (pulsating and not pulsating)

Are the pulsating loops different by:

- ➡ a particular magnetic field topology
- ➡ a high reconnection layer at one footpoint? i.e. heating strongly asymmetric

1D hydro code courtesy Z. Mikić

test with the simulated intensities with the output temperatures, densities: reproduce the observed long-period pulsations?



Mikić et al, 2013