Multi-scale observations of thermal nonequilibrium cycles in coronal loops

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http://www.issibern.ch/teams/observecoronloop/

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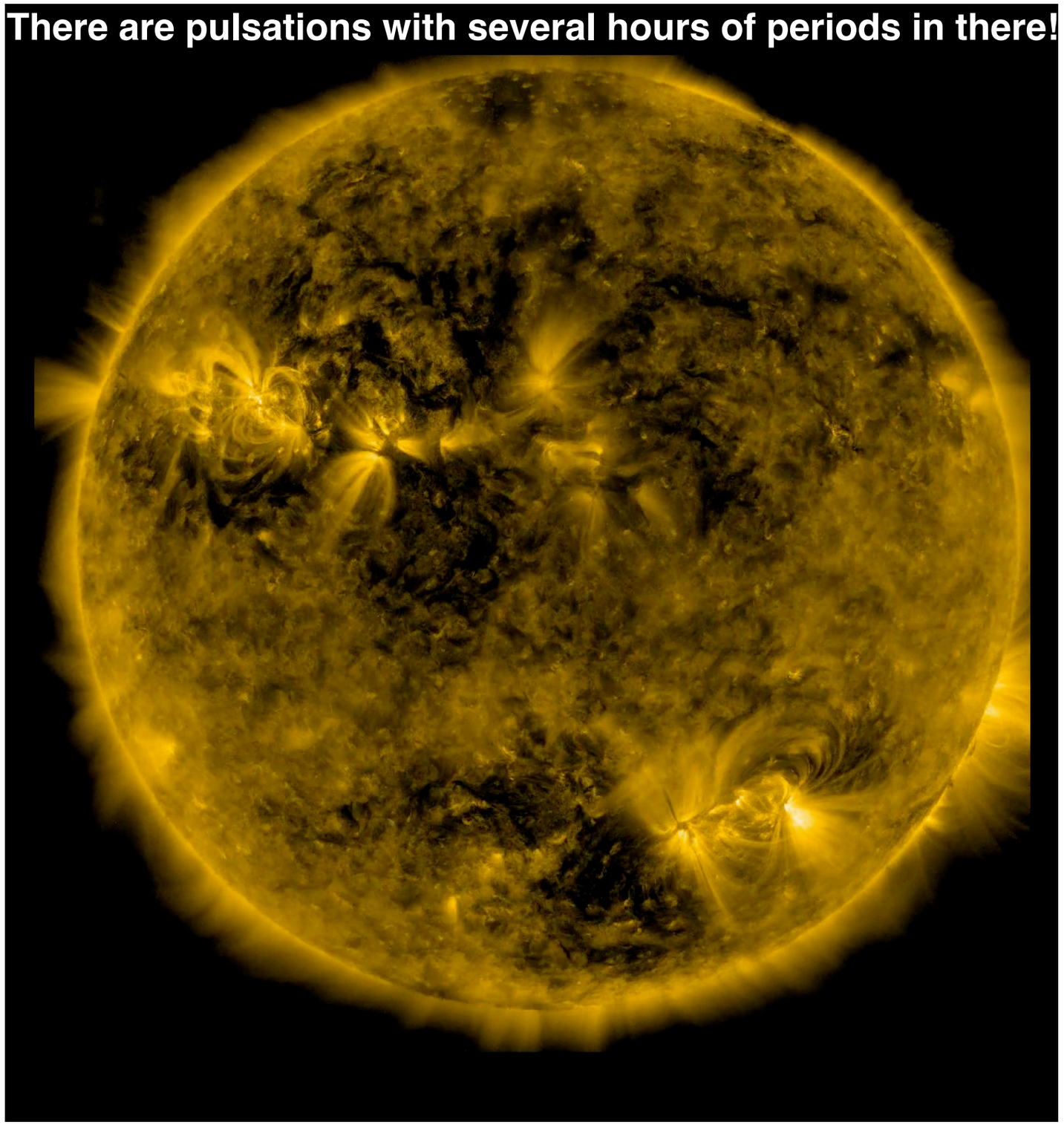
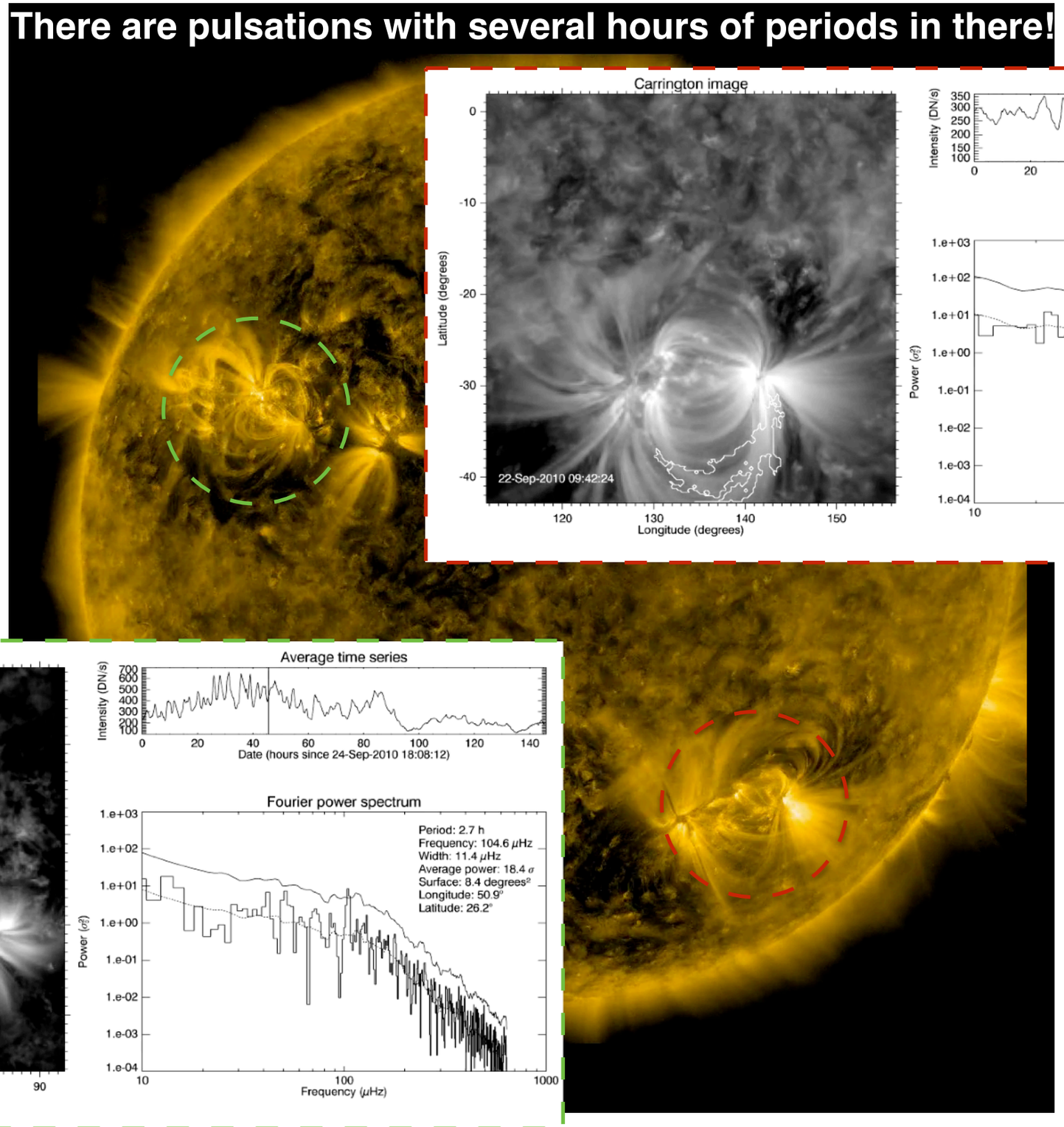
Long-period EUV pulsations are very common



Long-period EUV pulsations are very common

There are pulsations with several hours of periods in there!



Pulsating loops in almost every active region

➡ **Intensity pulsations** (2 - 16 hrs) in coronal EUV channels

On-disk detections:

- **917 events found in 13 yrs of EIT (195 Å)**
Auchère et al. 2014

54% AR, 45% QS

- **3181 events found in 6 yrs of AIA**
Froment 2016, PhD thesis

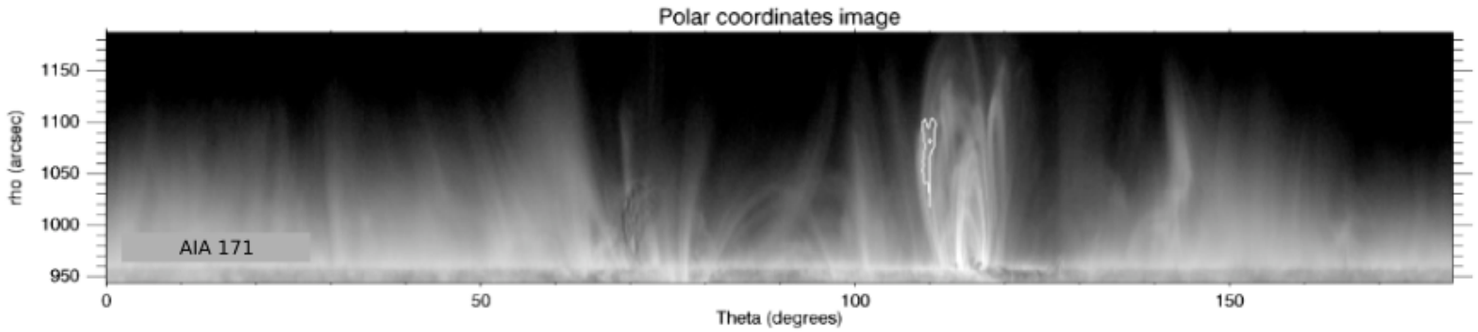
67% AR, 33% QS

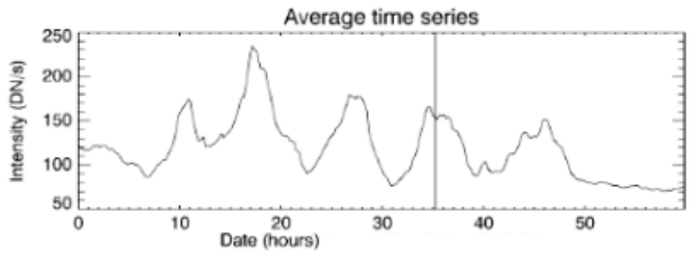
Database and full statistics soon publicly available
Froment et al., in prep

Off-limb detections:

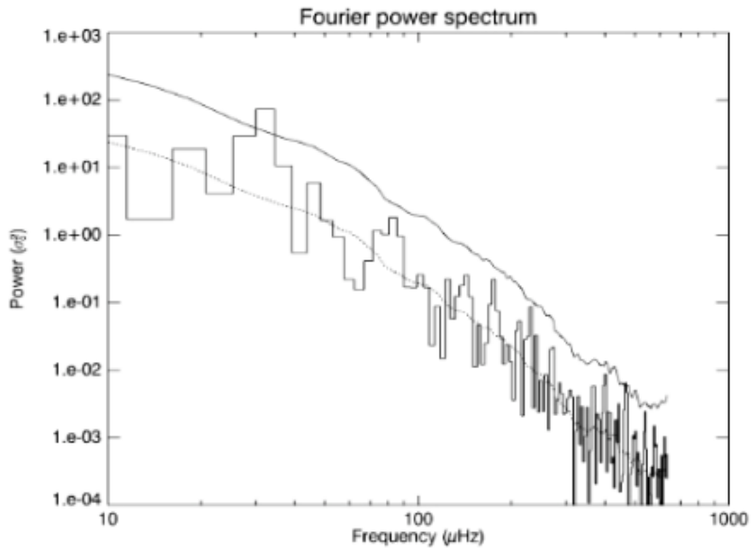
- **2981 events found in 7 yrs of AIA off-limb**

62% AR, 38% QS





Frequency: 31.3 μHz
Frequency width: 9.2 μHz
Frequency resolution: 4.6 μHz
Period: 8.9 h
Maximum power: 37.6 σ
Average power: 21.7 σ
Average intensity: 118.4
Relative amplitude: 0.196
Threshold: 10.0 σ
Theta: 109.8°
Rho: 1070.5 arsec
Surface: 188.0 pixels

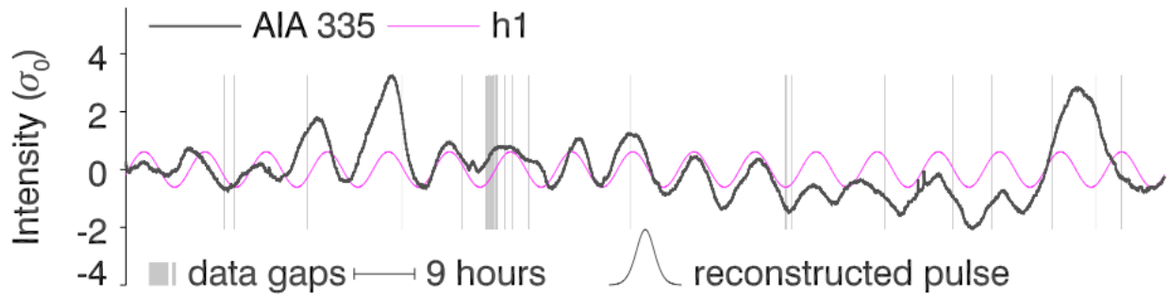


What are these pulsations?

✗ Not triggered by an other event, Not a mechanical oscillation

➡ Not connected to late phase of flare or CMEs

➡ Not the signature of vibration mode but a periodic train of pulses of random amplitudes (*Auchère et al. 2016*)



✓ Thermal phenomenon

➡ Current explanation for these pulsations:
Coronal counterpart of thermal nonequilibrium cycles

➡ **Implications for coronal heating: spatial location and timescale**

Thermal nonequilibrium (TNE)

➡ TNE processes are known to play an important role for **prominences**
(e.g. *Antiochos & Klimchuk 1991,* Luna *et al.* 2012; Xia *et al.* 2014)
and **coronal rain** (e.g *Müller et al. 2005*)

Quasi-steady heating
mainly **concentrated at the loop footpoints**

Unstable loops, no possible thermal equilibrium

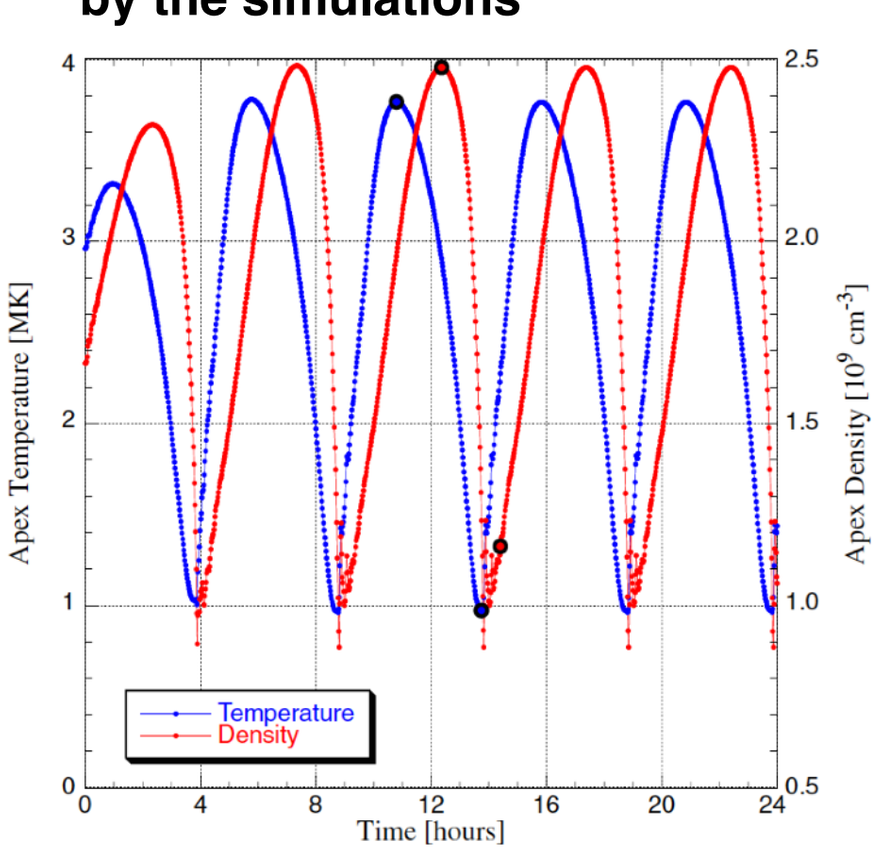
Evaporation of chromospheric plasma
Temperature ↗ → Density ↗

« **Catastrophic cooling** », thermal instability
Thermal runaway & recombination

Condensation
the plasma falls toward the loop legs

pulsations in the temperature and the density

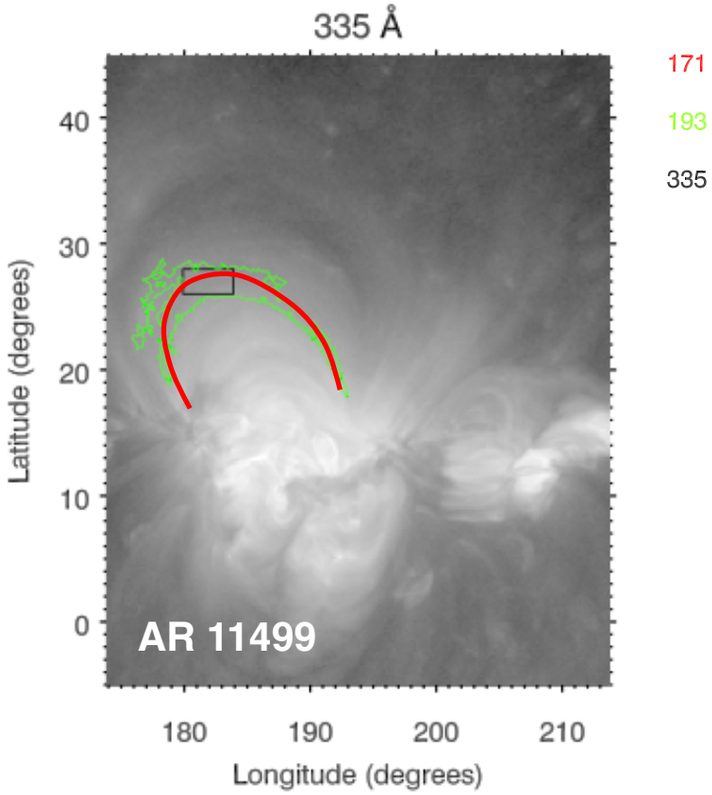
A periodic evolution predicted by the simulations



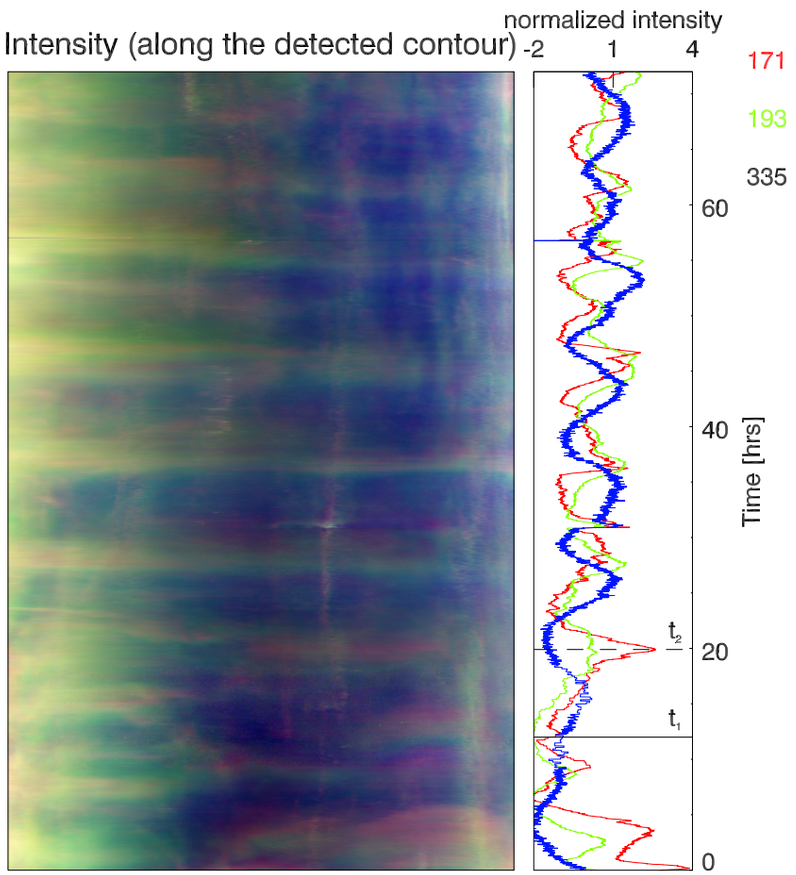
Mikić et al, 2013

Evaporation/condensation cycles in loops

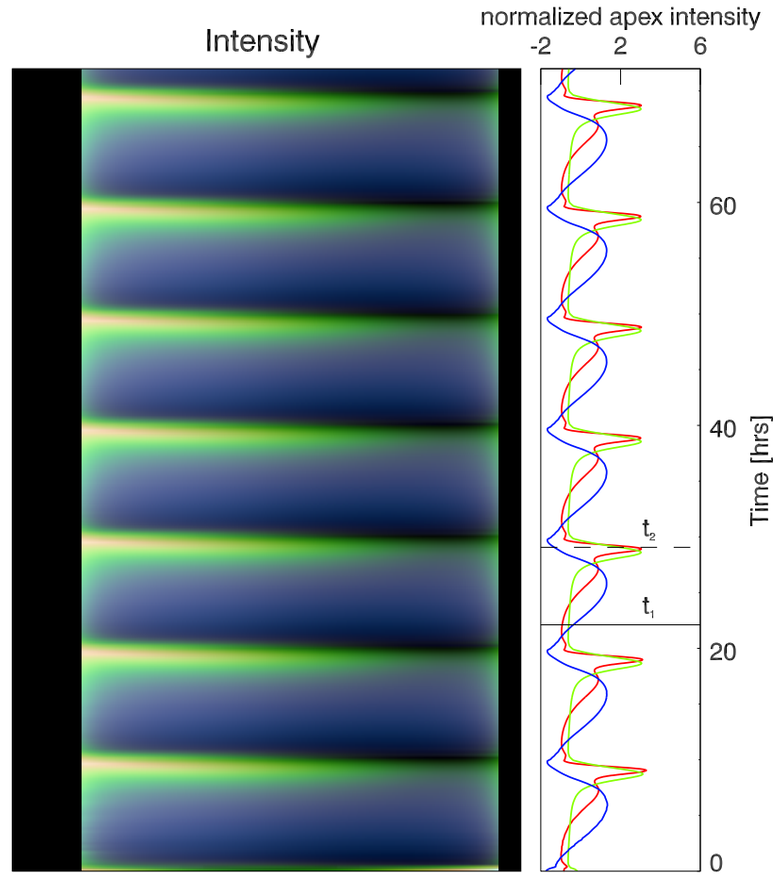
Detection with AIA
9 hr pulsations in AR 11499



AIA observations
Froment et al. 2015



Synthetic intensities from a 1D hydrodynamic simulation
Froment et al. 2017 & 2018

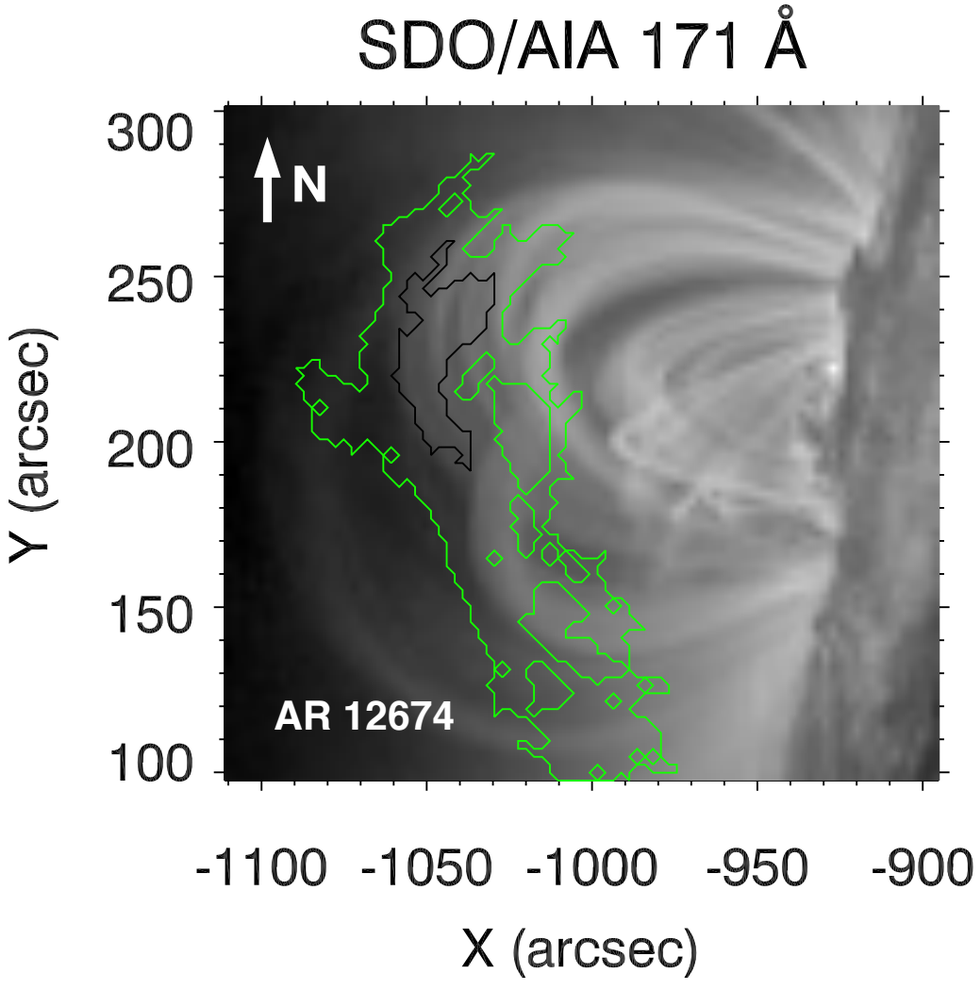


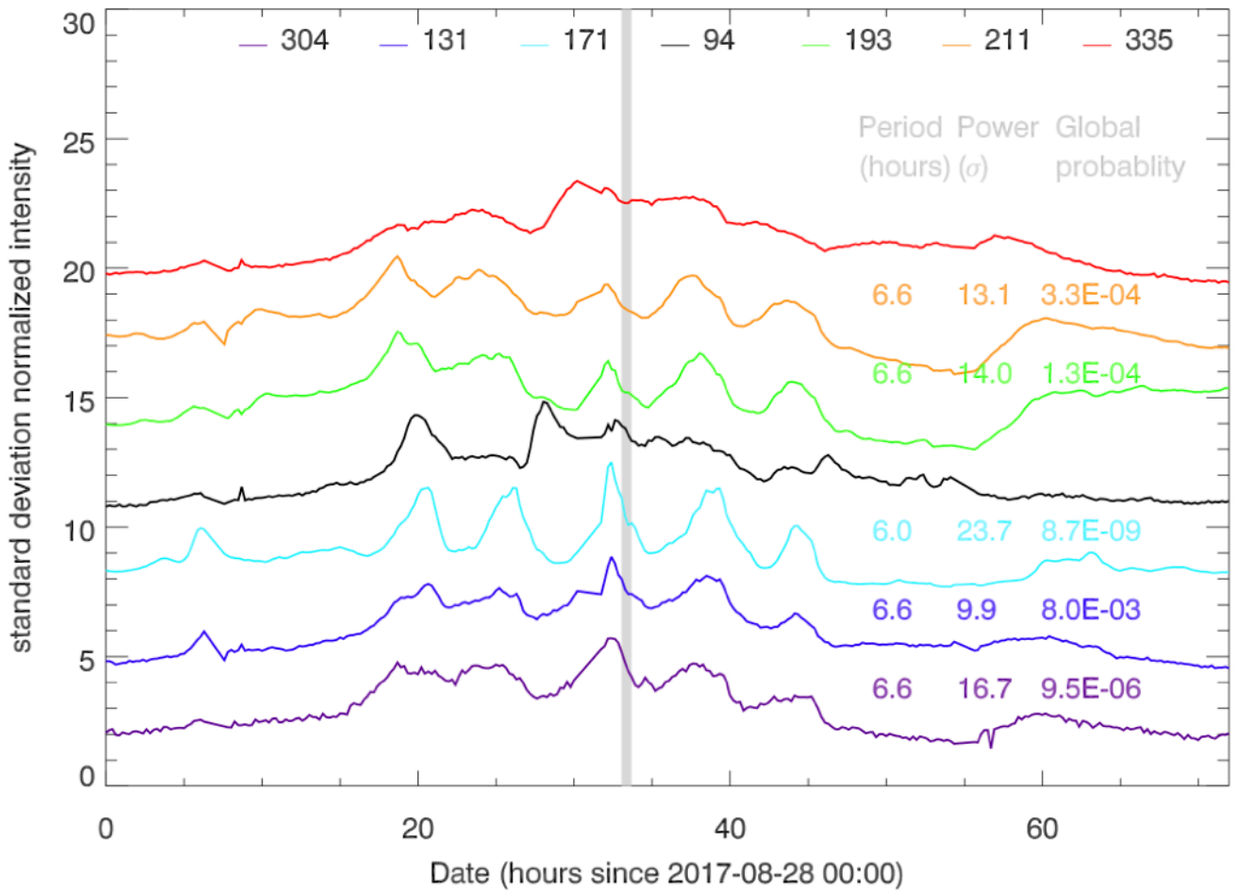
➡ **Periodic rain event observed for the first time (with SDO/AIA, *Auchère et al. 2018*)**

➡ **How cold can it get?**

➡ At least some events should show **coronal rain down to chromospheric temperatures**

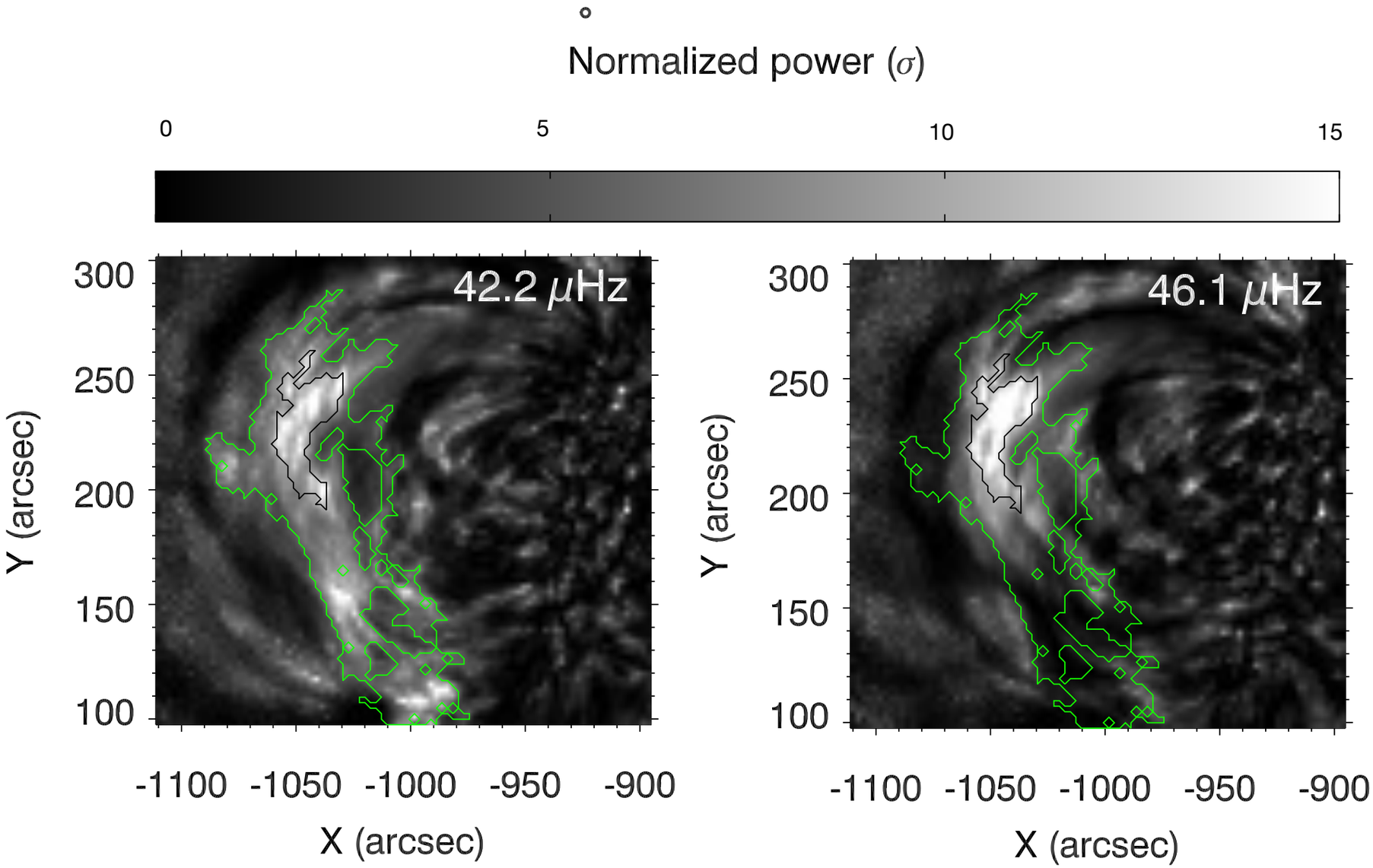
Multi-thermal analysis off-limb with SDO and SST

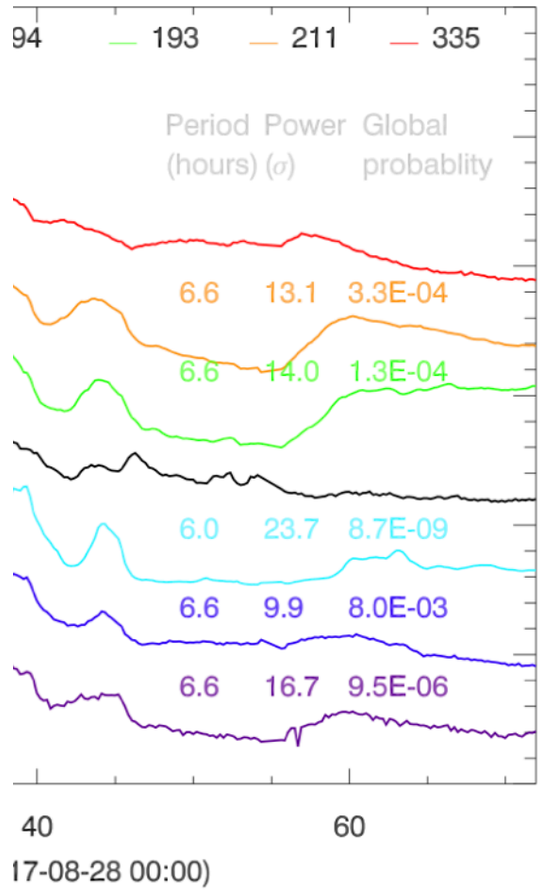




Froment, Antolin, Henriques & Rouppe van der Voort, in prep

Multi-thermal analysis off-limb with SDO and SST

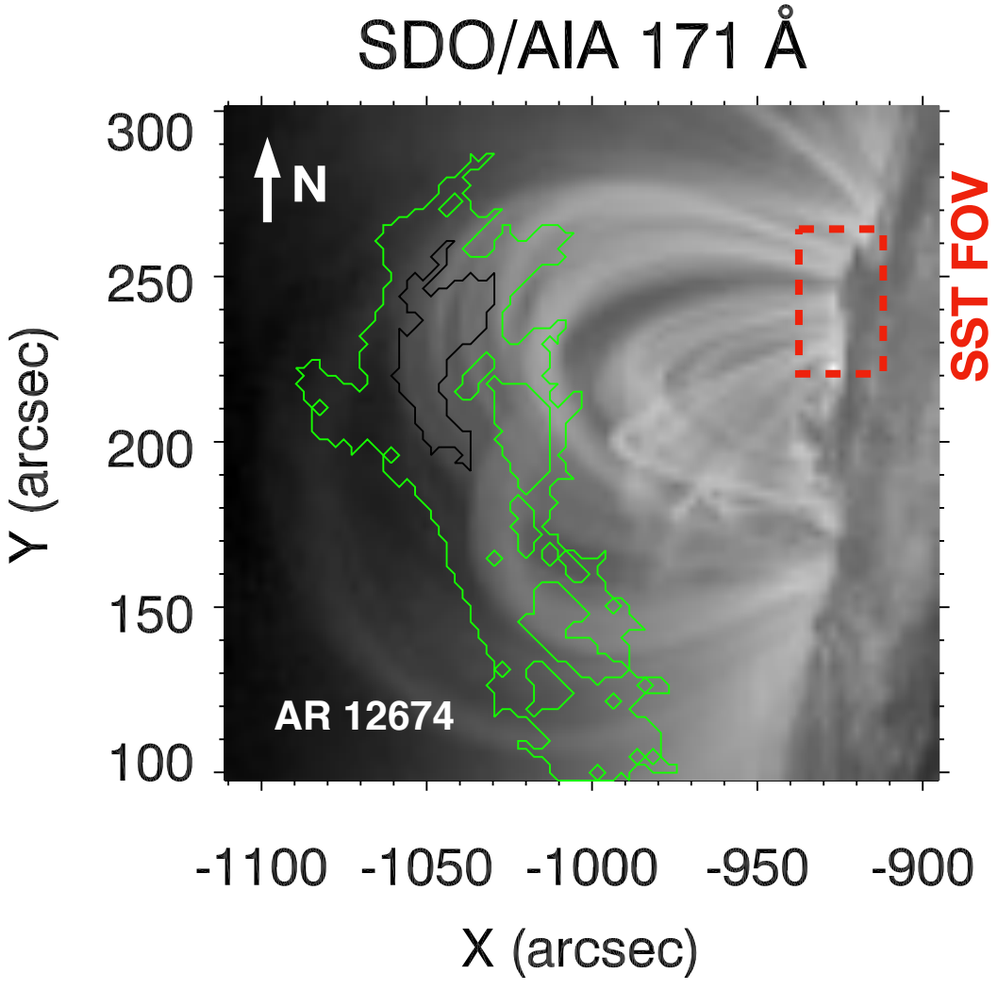


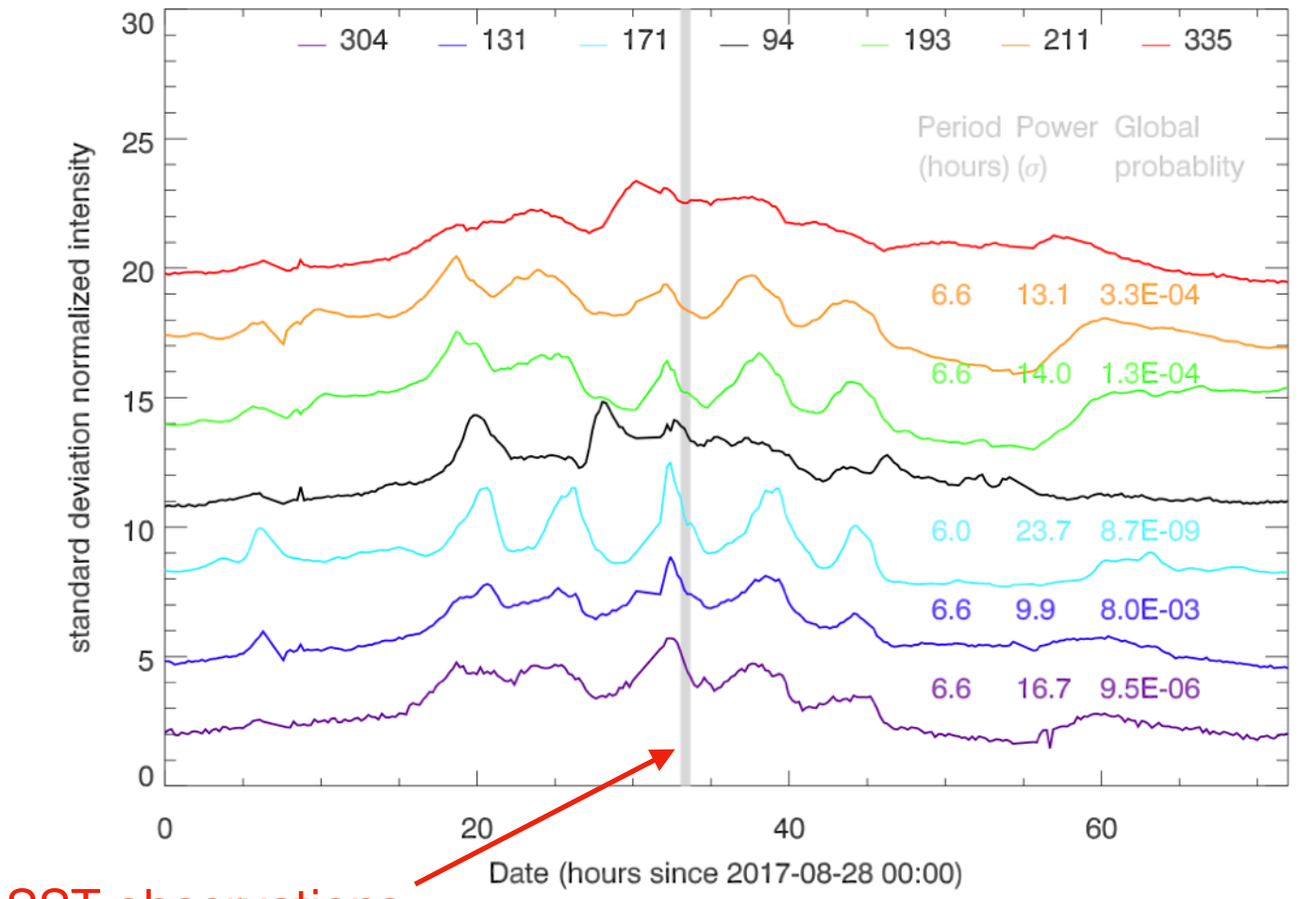


Normalized power at ~6.0h
more than 10σ: confidence level of 99%

ent, Antolin, Henriques
ope van der Voort, in prep

Multi-thermal analysis off-limb with SDO and SST





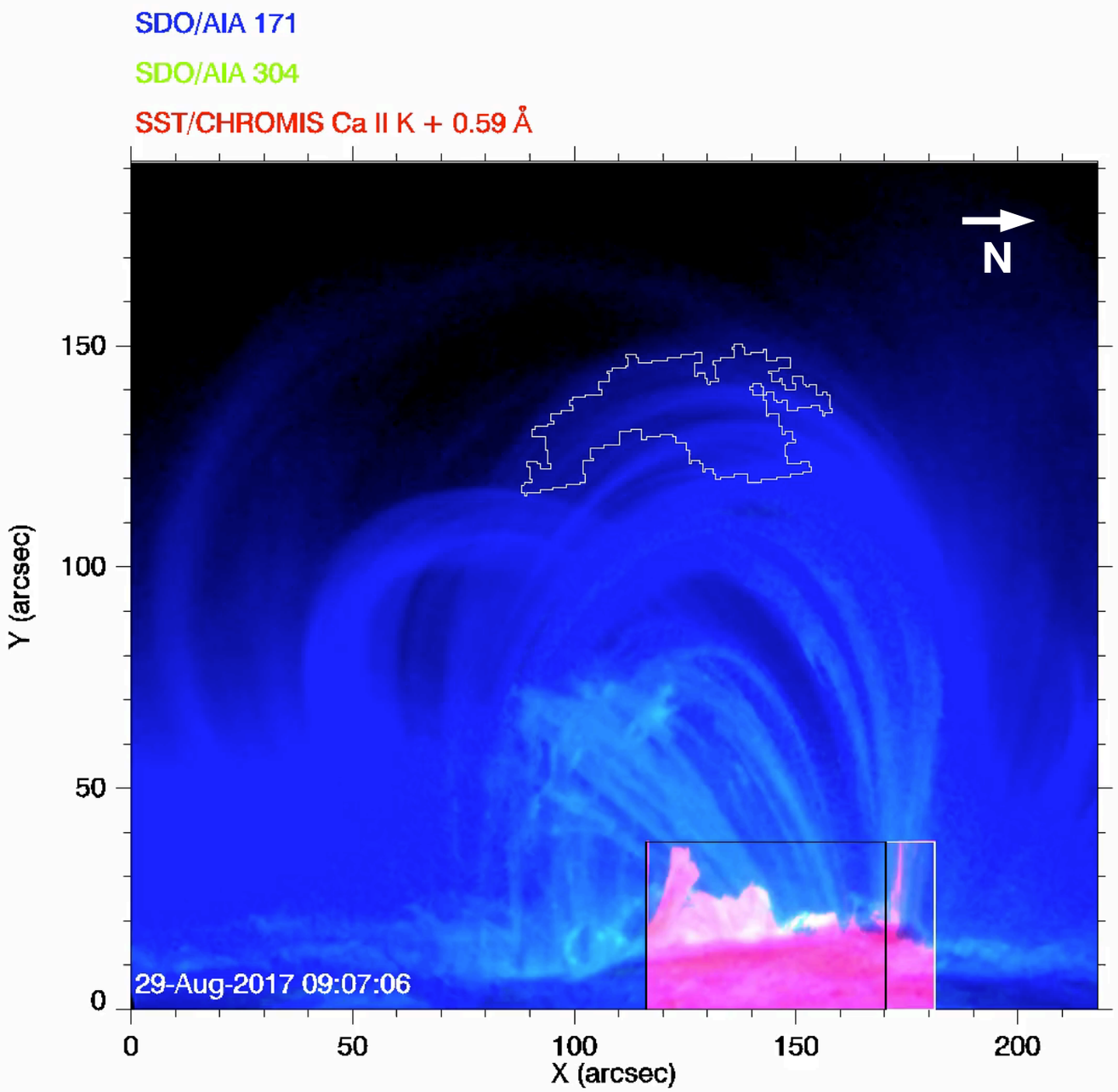
Froment, Antolin, Henriques & Rouppe van der Voort, in prep

➡ Period of ~6.h in almost all the channels

➡ Swedish 1-m Solar Telescope (SST) observations at **one footpoint** during the **cooling phase of one of the cycles**

SST observations for one cooling phase

- ➡ Observation of the cycle from coronal to **chromospheric temperature**
- ➡ High-resolution coronal rain observations



SST data:

~30 min during of the cooling phase
At the middle of the AIA sequence

- **CRISP: Hα (6563 Å)**
  pixel size: 0.06”
- **CHROMIS: Ca II K (3934 Å)**
  pixel size: 0.04”

SST observations for one cooling phase

- ➡ Observation of the cycle from coronal to **chromospheric temperature**
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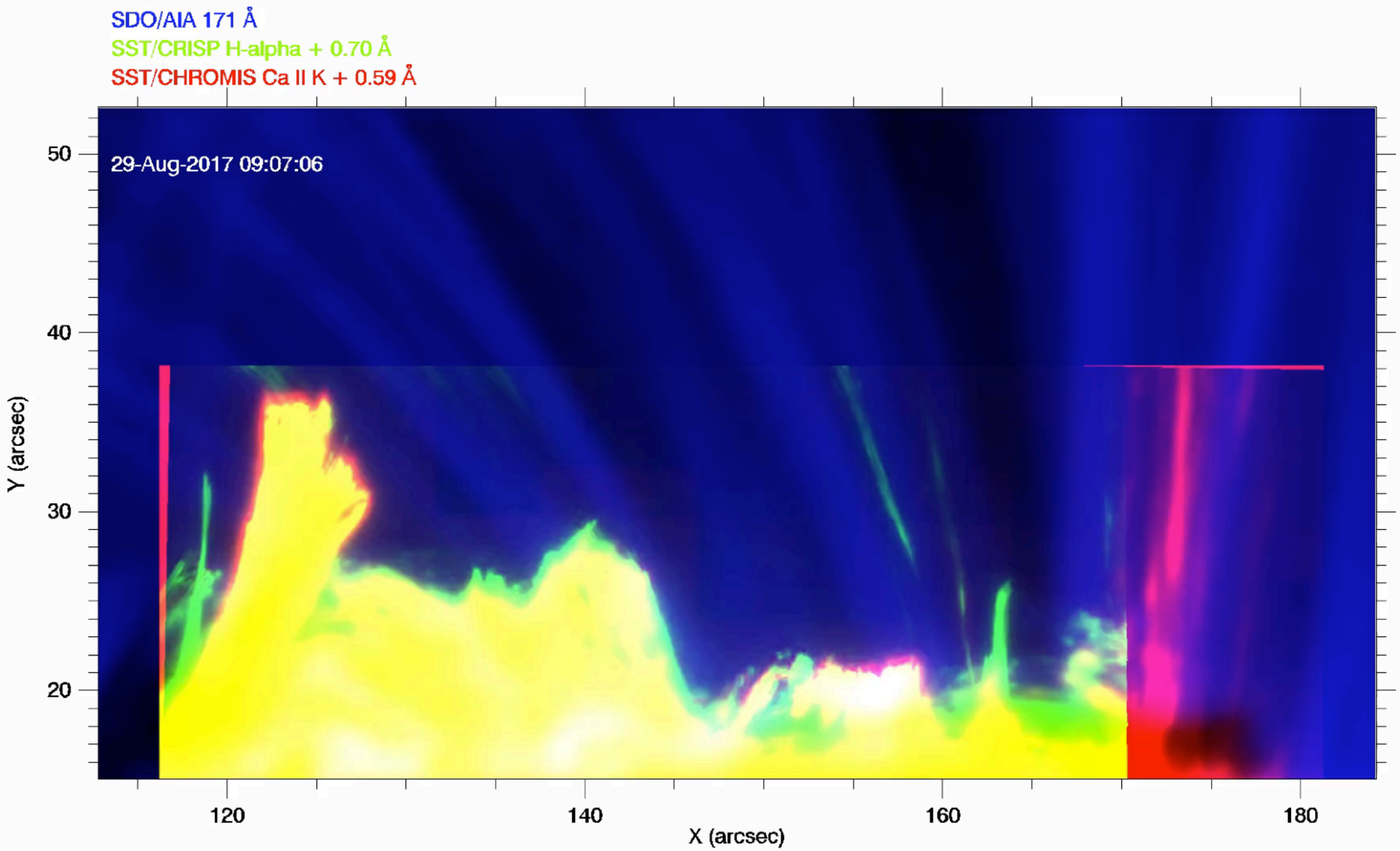
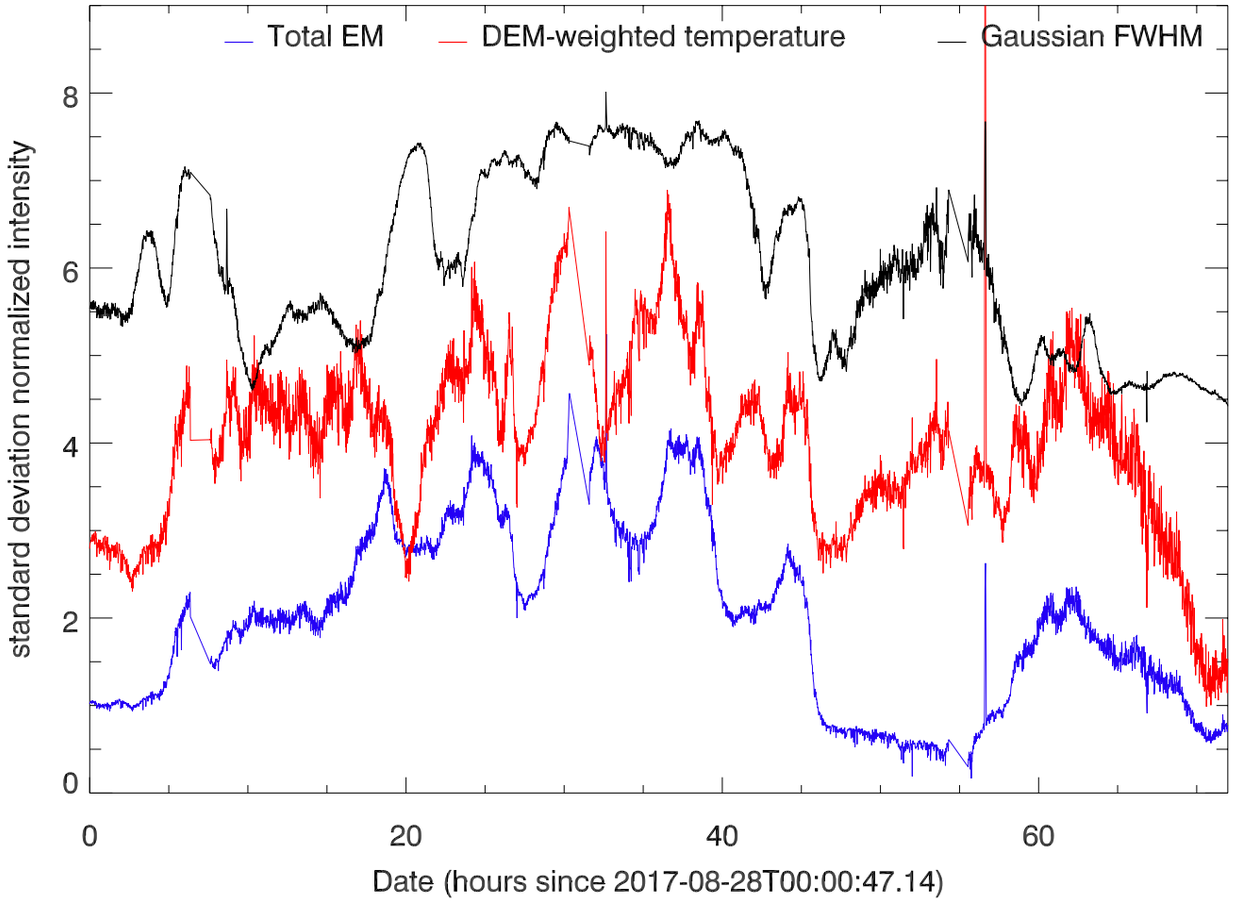


Evolution of the temperature and the density

Analysis of the thermal structure

➡ **Reconstruction of the Differential Emission Measure (DEM) -** code from *Cheung et al, 2015*



➡ **Cycles** (~6h) in the DEM-weighted temperature and the total EM ($\propto n_e^2$)

➡ **The temperature increases always before the total EM**

➡ Temperature and width anti-correlated
Thermal width increase
⟶ cooling phases

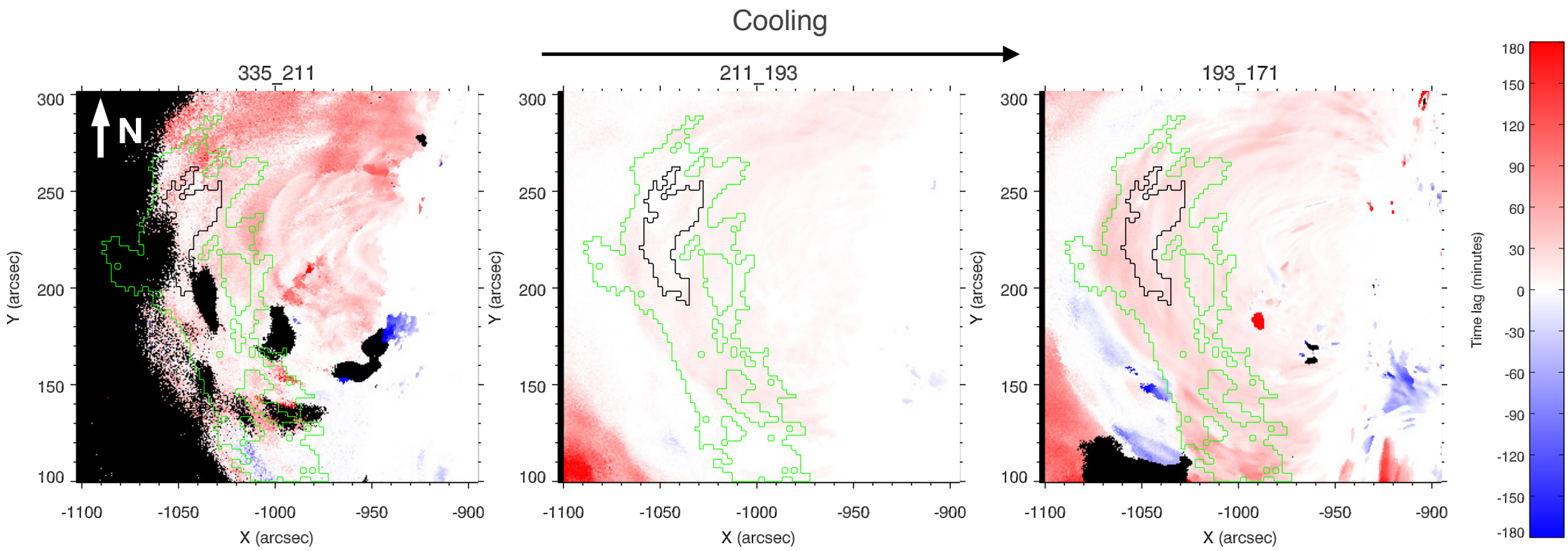
➡ **Same conclusions as for on-disk observations of pulsating loops**

➡ **Strong evidence of TNE**

Observation of cooling with SDO/AIA

Time lags (same technique as in *Viall & Klimchuk, 2012*):

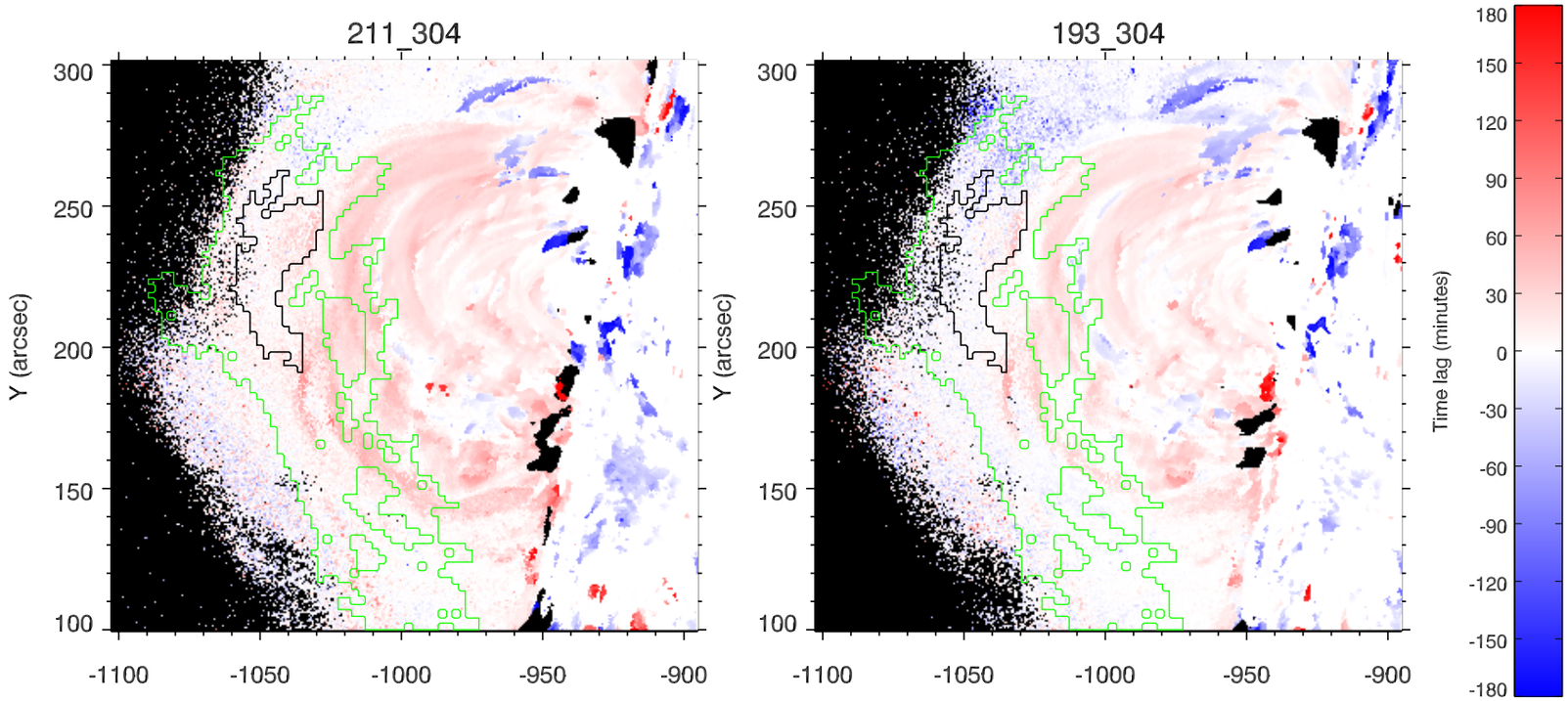
- peak **cross-correlation** values (pairs of channels)
- to **reconstruct the order of the channels** and thus **the temperatures**

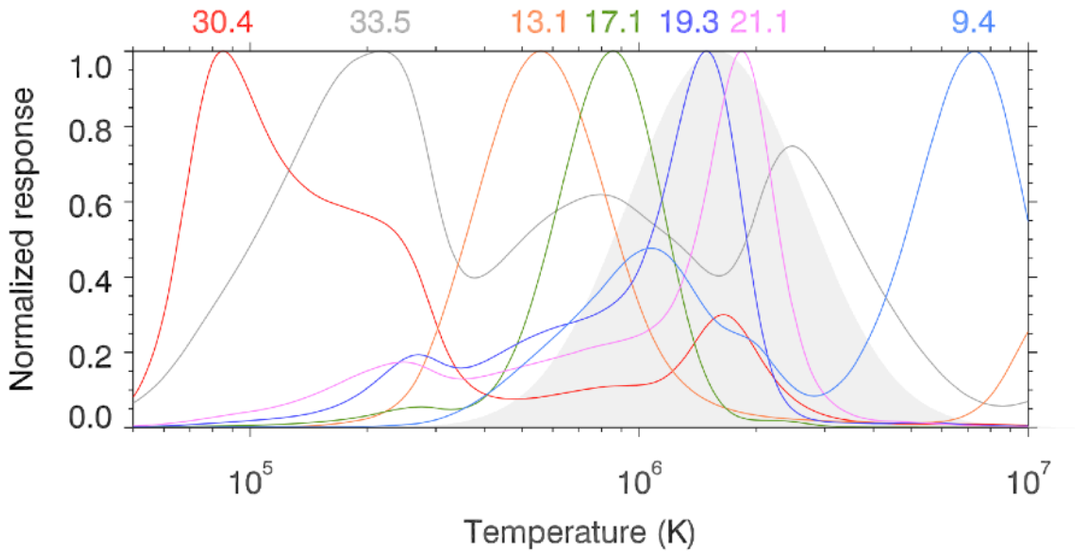


➡ **Widespread cooling, same patterns of time lags as on-disk observations**

➡ **The pulsating loops have the same cooling behavior as the rest of the active region**

Observation of cooling with SDO/AIA



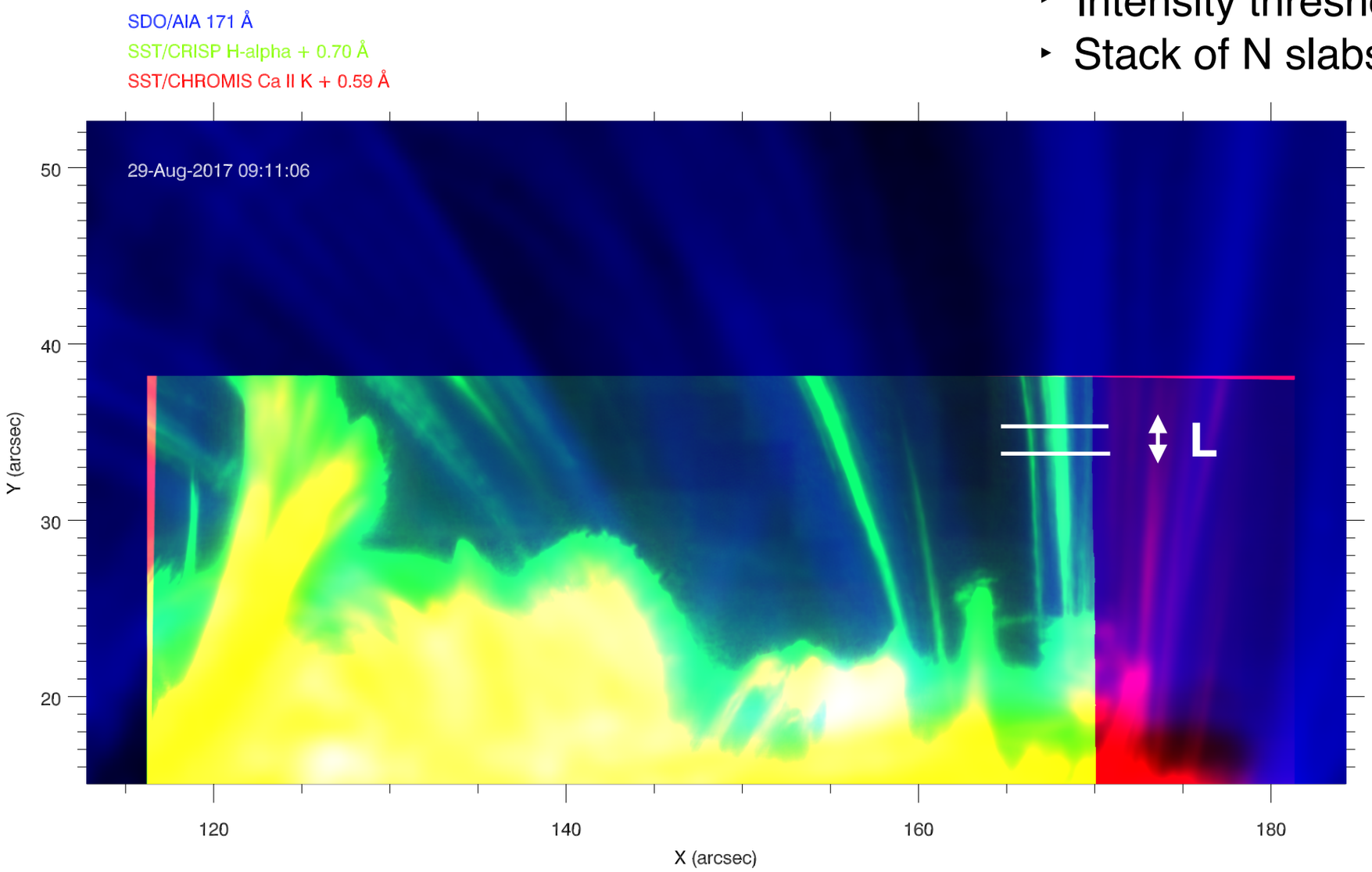


From Auchère et al. 2018

- **Observations of the two components of 304?**
- **Condensations not starting at the loop apex?**

Thermodynamic of the rain

- Intensity threshold to detect rain pixels
- Stack of N slabs in time

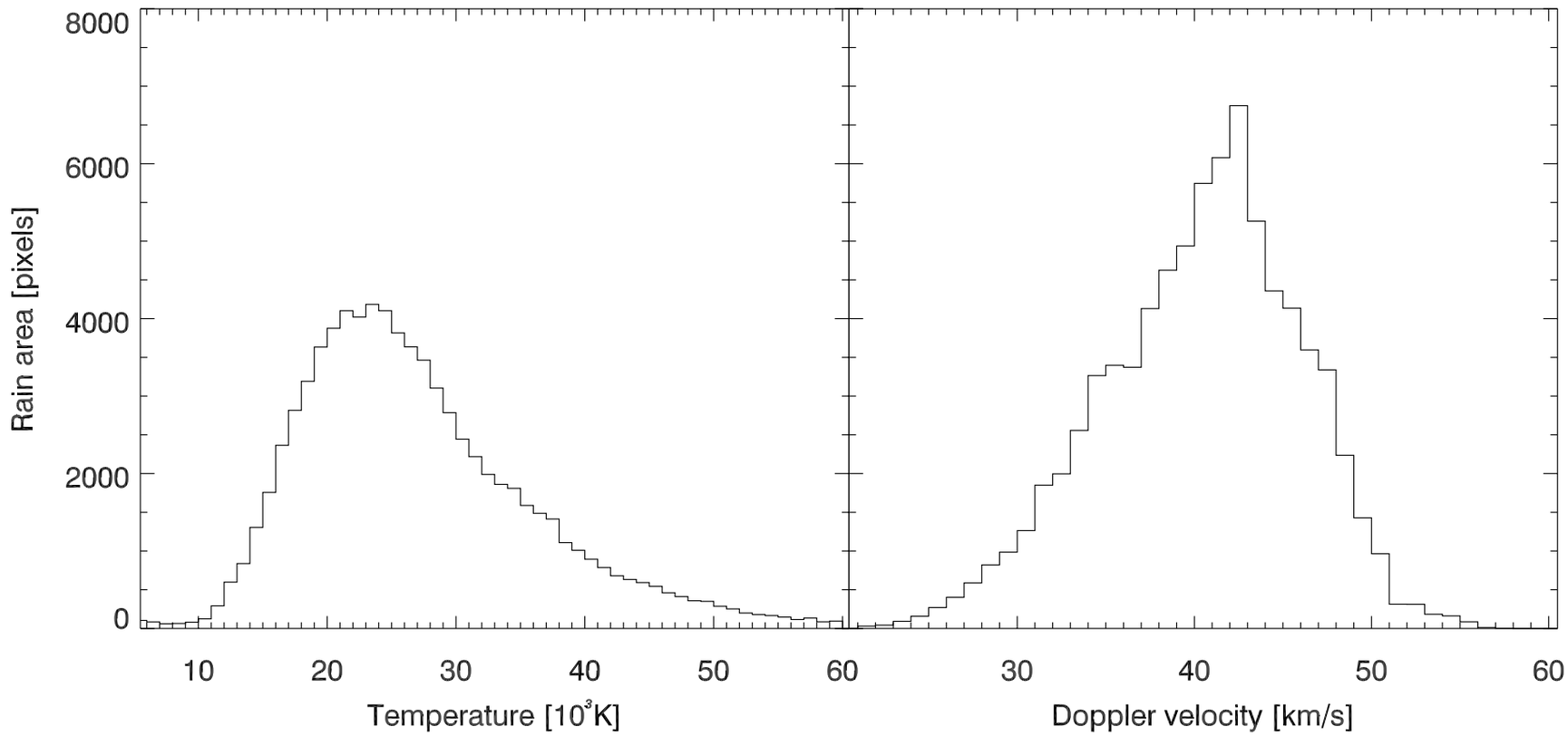


- Gaussian fit of the Hα condensation profiles

$$FWHM = 2\sqrt{2\ ln2}\ \frac{\lambda_0}{c}\sqrt{\frac{2k_BT}{m_H} + \cancel{\nu_{mic}^2}}$$

➡ upper bounds for the plasma temperature

Thermodynamic of the rain



➡ Preliminary results:

Average temperature: ~25 000 K
Average Doppler velocity: ~39 km/s

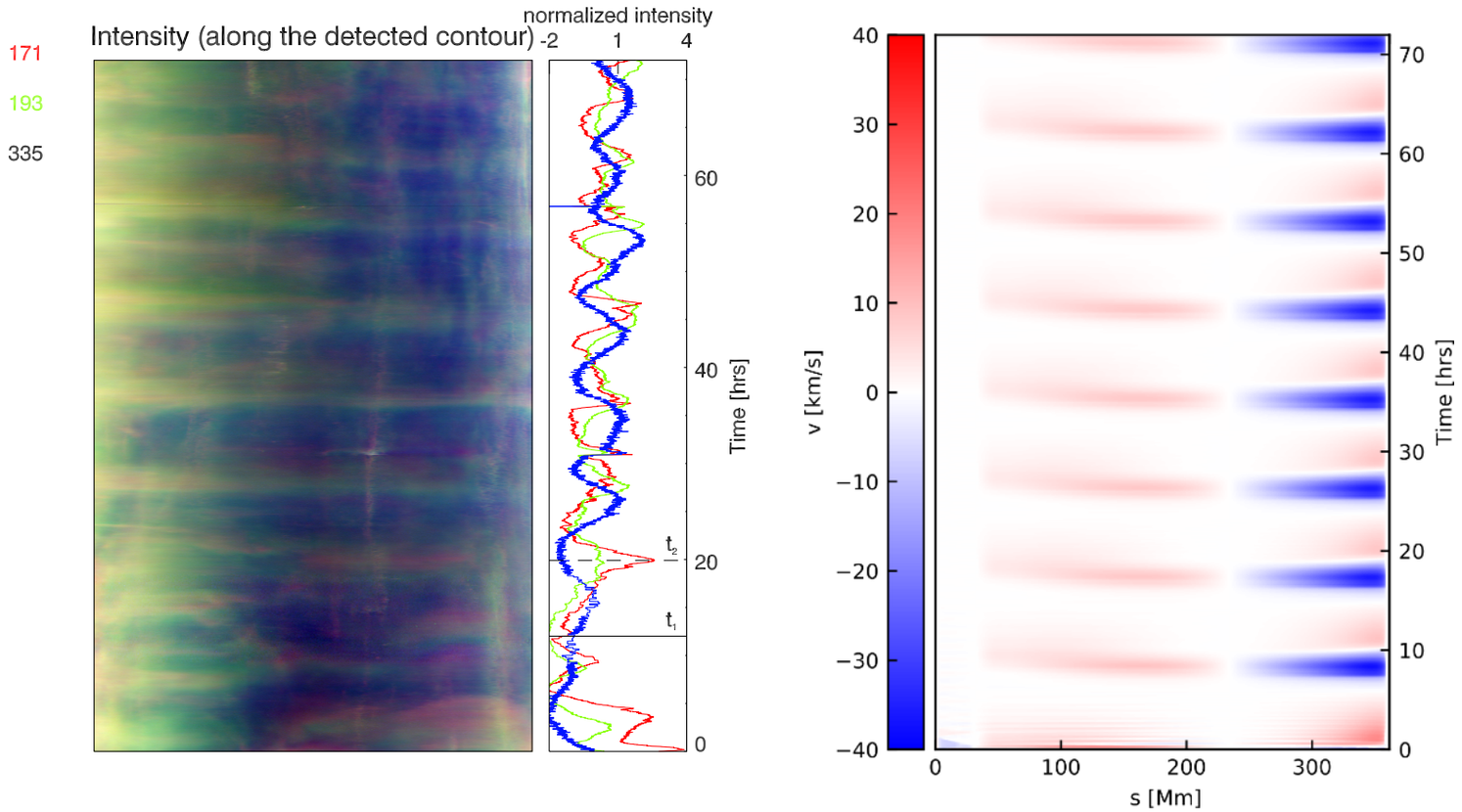
Projected velocities ~70 km/s
Total velocity ~80 km/s

➡ Temperature and velocities consistent with other rain studies
(*Antolin & Rouppe Van der Voort 2011, Ahn et al. 2014, Antolin et al. 2015)*

Periodic flows?

Missing observables:

- **Periodic upflows and downflows should be detectable** even when no coronal rain is visible



➡ Existing **Hinode/EIS datasets** have either **high SNR** or **high cadence**.
But both are needed to detected these flows

➡ See Gabriel Pelouze's poster (paper in prep.)

Conclusions

- **Long-period intensity pulsations** (several hours) are **very common in coronal loops**
- **Long-period intensity pulsations** are **the coronal counterpart** of **thermal nonequilibrium cycles** and thus of **quasi-constant** and **highly stratified heating**
- The pulsating loops studied with AIA off-limb show the same thermal behaviour as for on-disk pulsating loops
- These observations allow us to **probe the bulk of the cooling phases** and emphasise that these **pulsations and coronal rain are two aspects of the same phenomenon**
- **Implication for circulation of mass and energy in the solar corona**

To go further

Some open questions:

- What fraction of the coronal volume experiences TNE?
- Are the non-pulsating loops and diffuse emission produced by a completely different heating deposition in time and space?
- What determines whether a condensation forms or the thermal collapse is aborted before reaching chromospheric temperatures?

ISSI team selected in 2017:
Observed Multi-Scale Variability of Coronal Loops as a Probe of Coronal Heating
http://www.issibern.ch/teams/observecoronloop/

Thank you !