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Multi-scale observations of thermal nonequilibrium cycles in coronal loops

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9th Coronal Loops Workshop

Long-period intensity pulsations & Coronal rain

Quasi-steady heating
mainly **concentrated at the loop footpoints** ➡ **Evaporation-condensation cycles**

No possible thermal equilibrium

Both phenomena reflect the spatio-temporal characteristics of the heating in coronal structures

- Long-period intensity pulsations: **Coronal counterpart of thermal nonequilibrium cycles**

Auchère et al, 2014, Froment et al. 2015, 2017, Pelouze et al. 2019b, submitted

✔ **Thermal phenomenon** ✘ **Not triggered by an other event, Not a mechanical oscillation**

- Coronal rain: **TR/chromospheric counterpart of thermal nonequilibrium cycles**

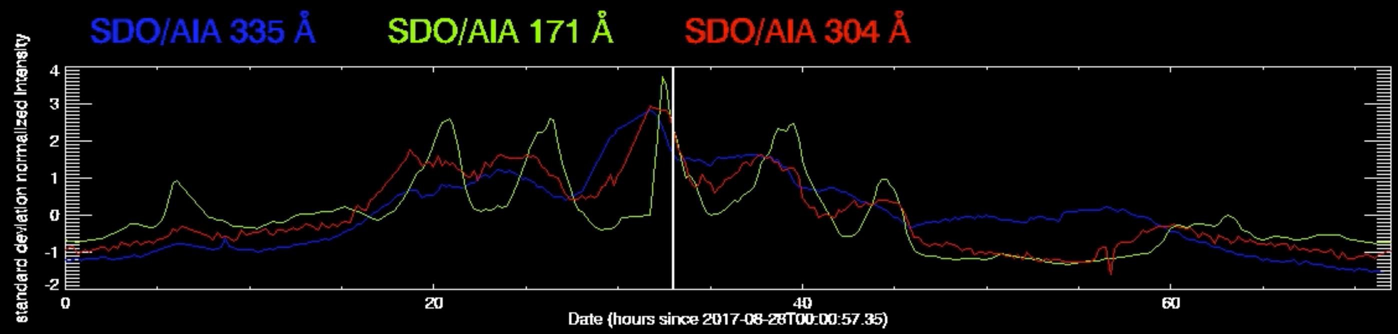
e.g. *Antolin et al, 2015*

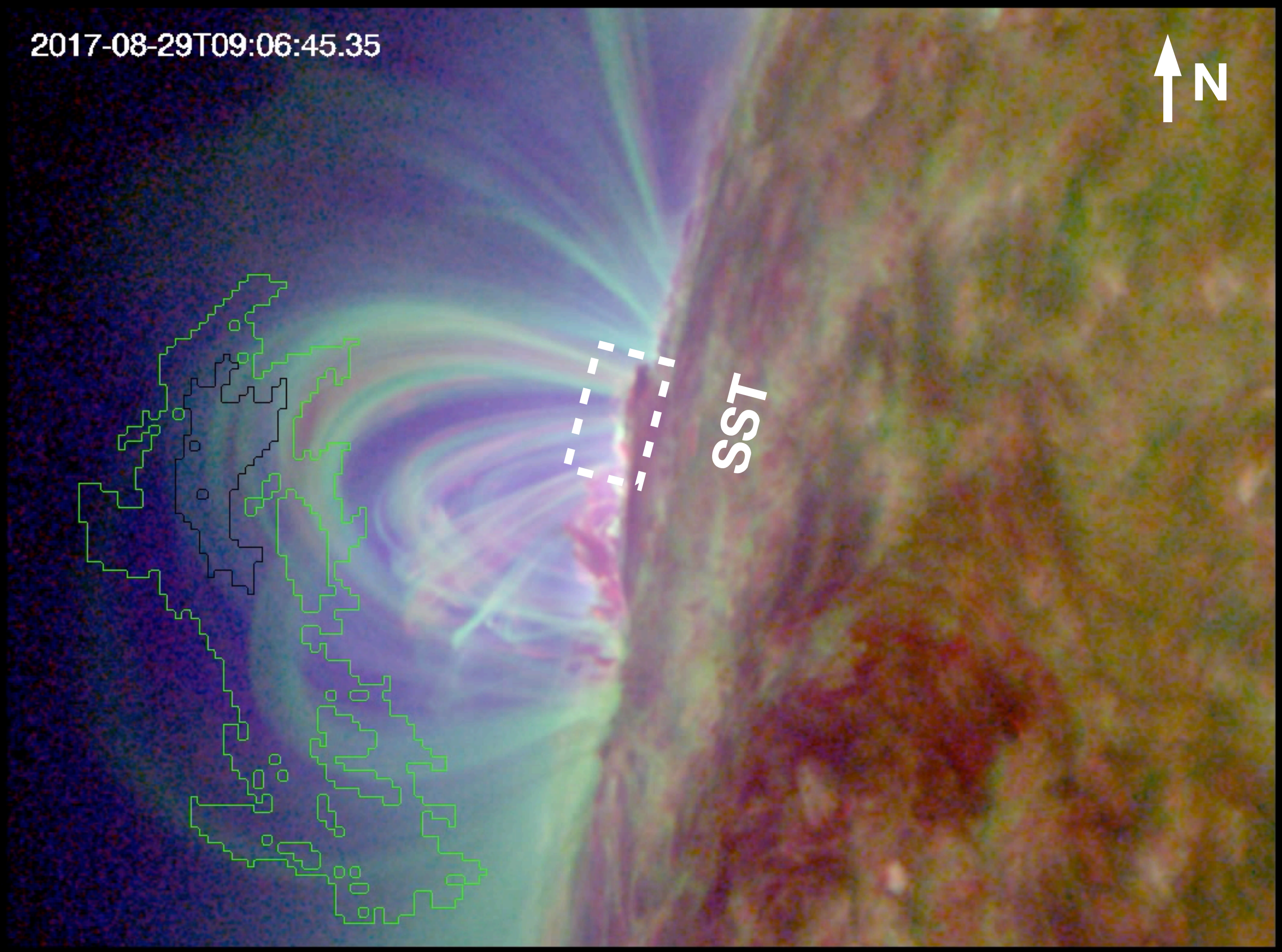
Produced by a local thermal instability : thermal runaway acting in TNE

Periodic rain event observed for the first time with SDO/AIA in *Auchère et al. 2018*
➡ **How cold can it get?**

Multi-thermal analysis off-limb

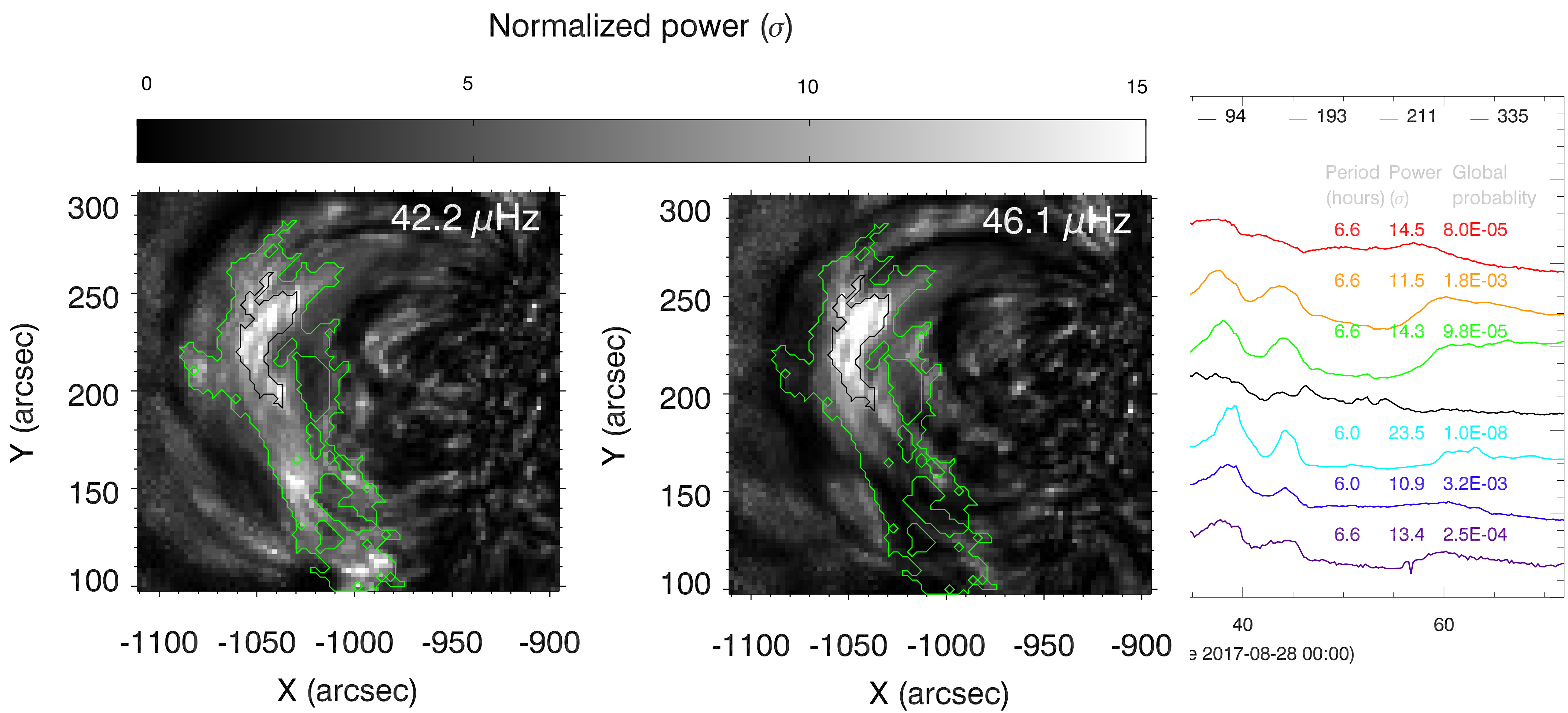
Combination of SDO and SST observations to capture the extreme spatial scales covered by the TNE processes





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

Long-period intensity pulsations



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

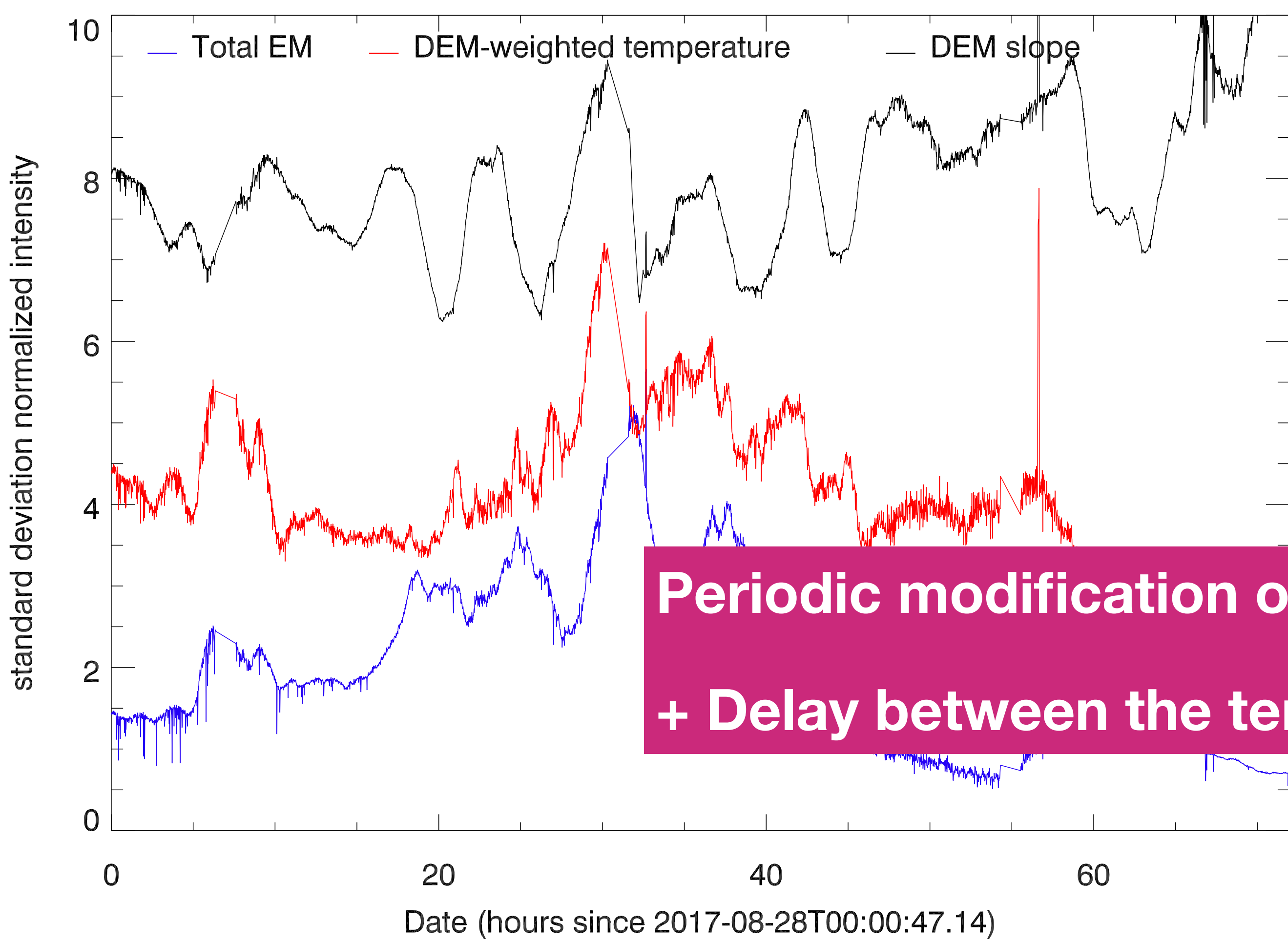
➡ Period of ~ 6.h in almost all the channels

➡ Very clear event

Thermal cycles from DEM analysis

Analysis of the thermal structure of the pulsating loops

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



➡ **Cycles (~6h)**

➡ **The temperature increases before the total EM ($\propto n_e^2$)**

➡ **The slope evolution is showing the heating and cooling phases**

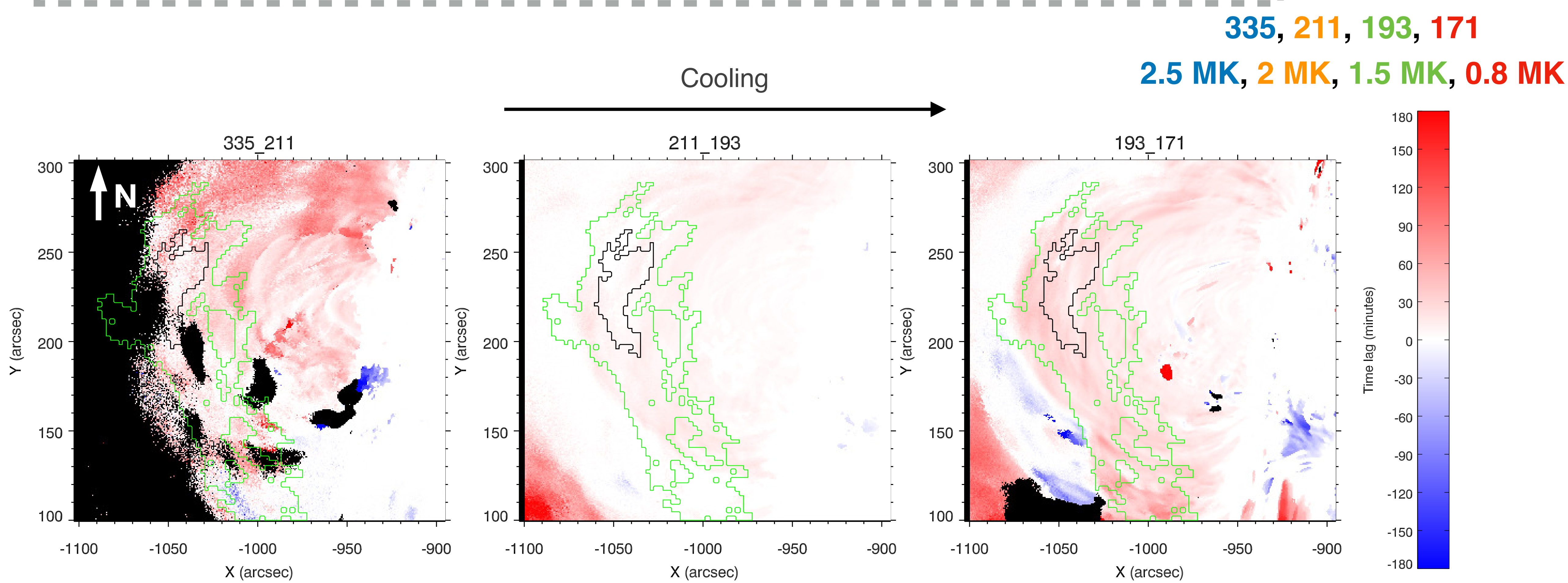
Periodic modification of the thermal structure

+ Delay between the temperature and the density

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

Cooling signatures from AIA time-lag maps

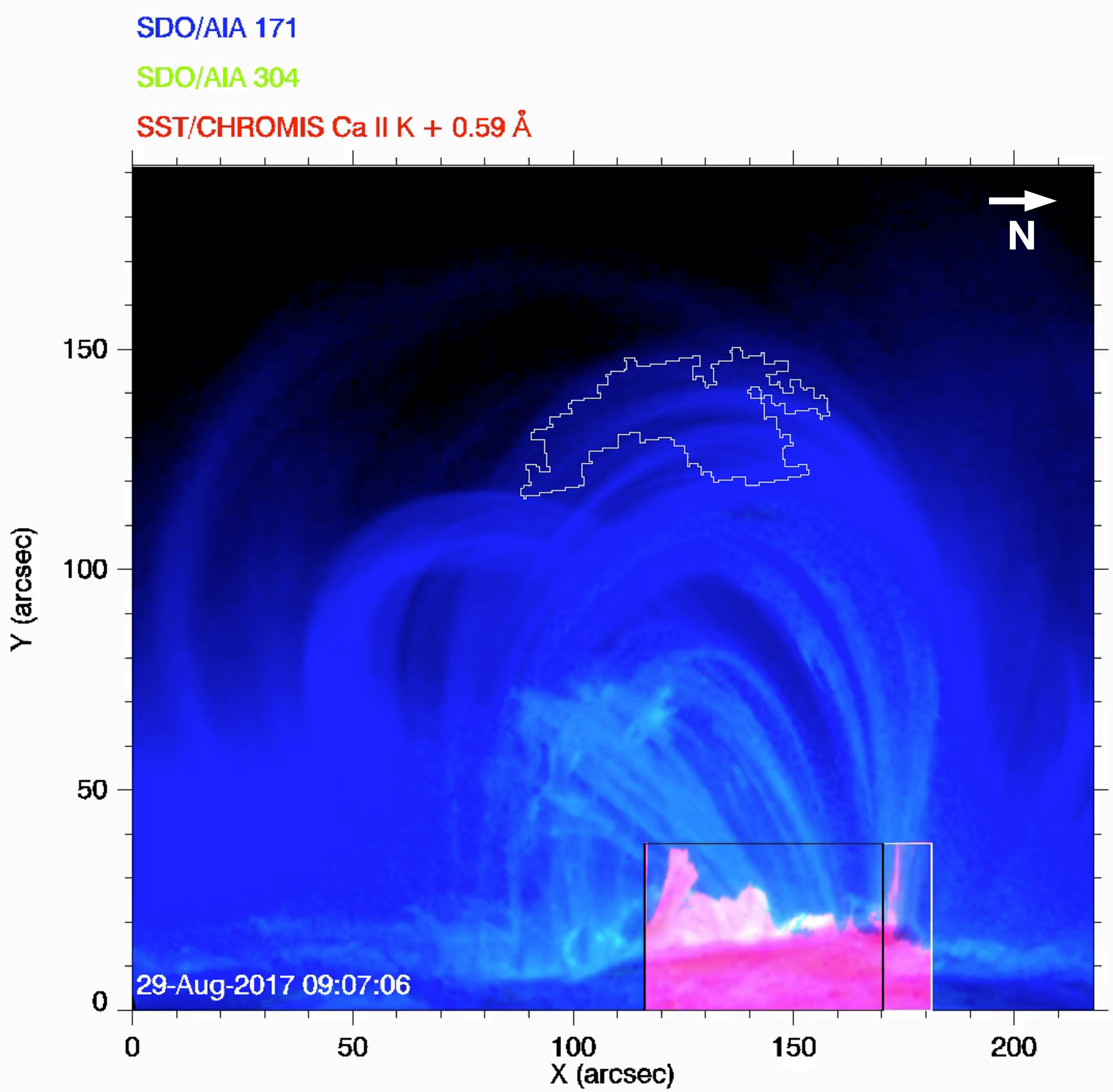
Time lags (same technique as in *Viall & Klimchuk, 2012*):
- peak **cross-correlation** values (pairs of channels)
- to **reconstruct the order of the channels** and thus **the temperatures**



➡ **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**

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”

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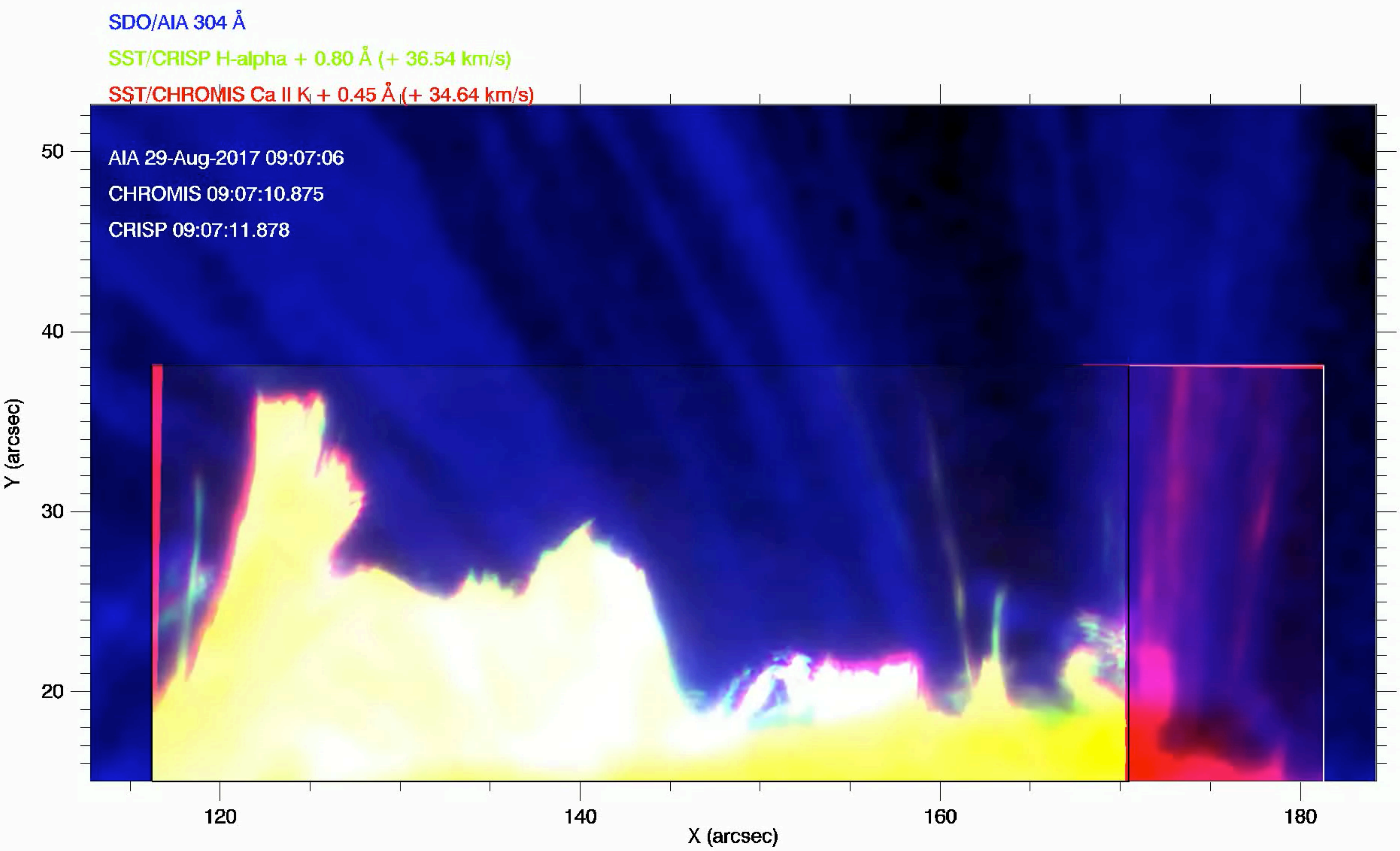
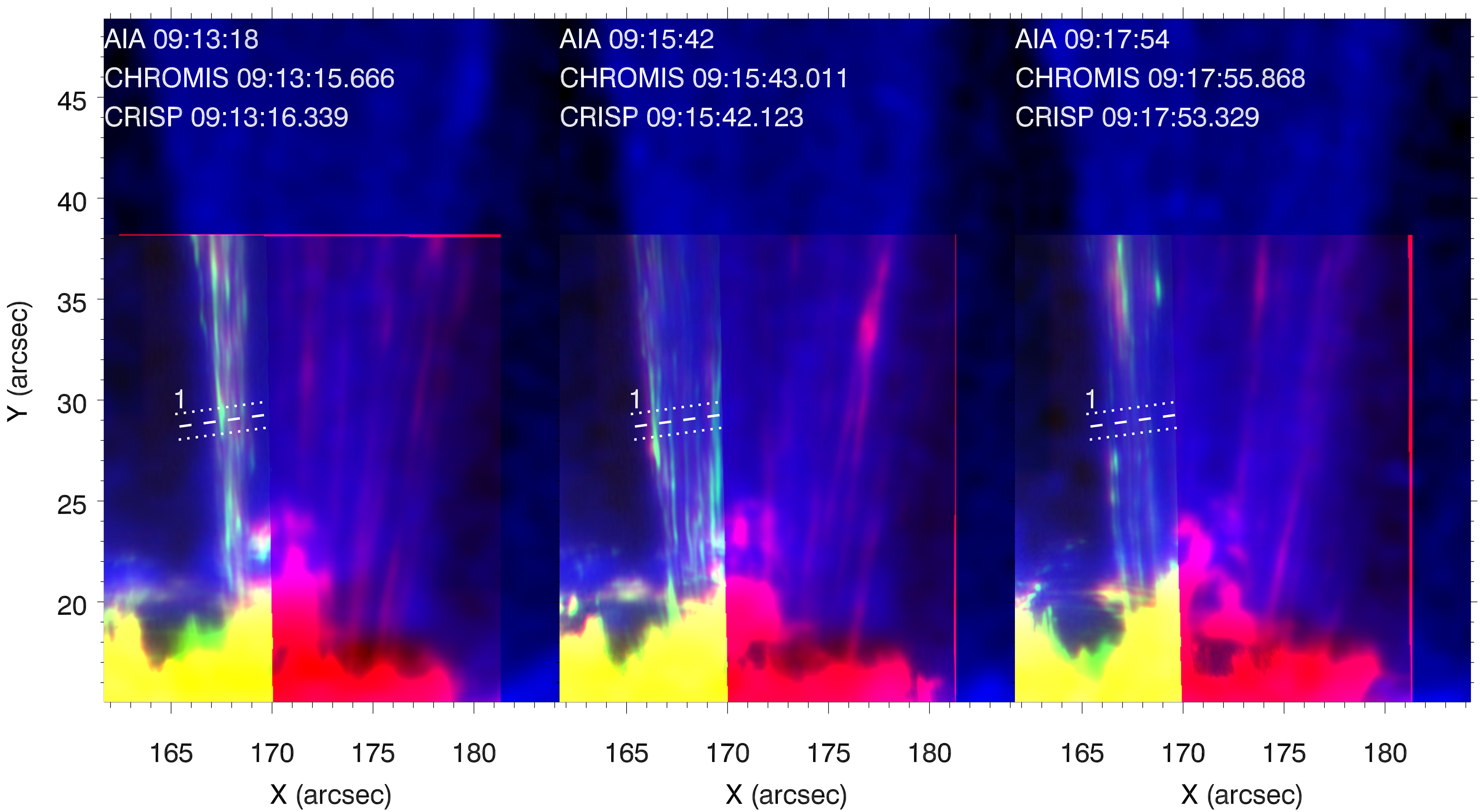
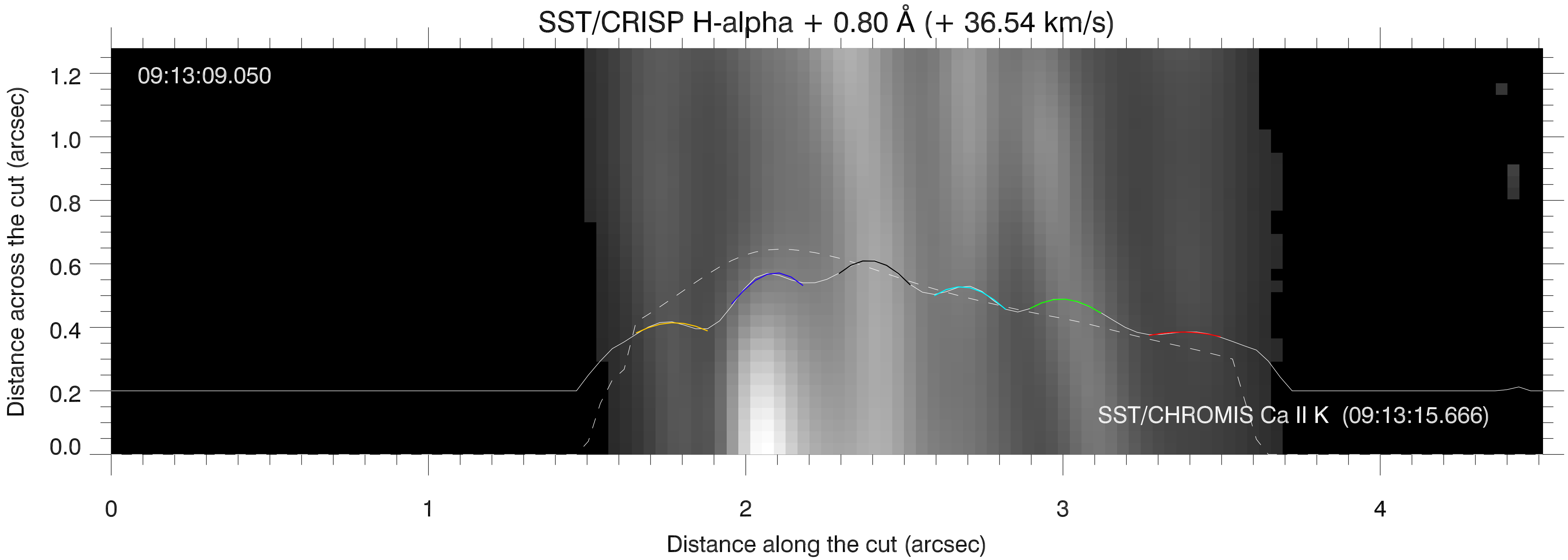


Morphology and temporal evolution of the rain

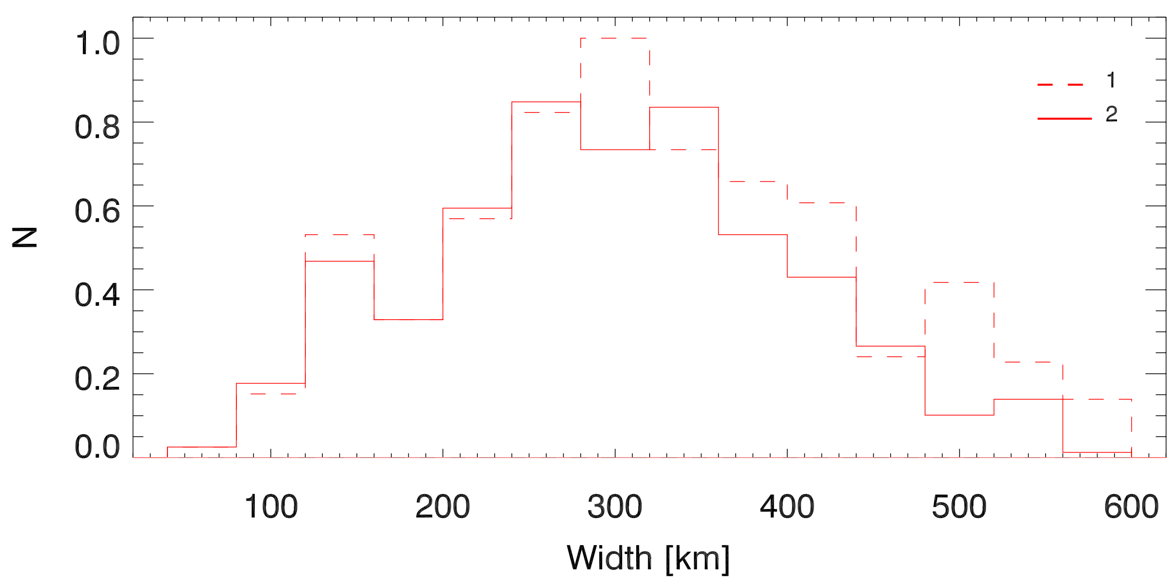
SDO/AIA 304 Å
SST/CRISP H-alpha + 0.80 Å (+ 36.54 km/s)
SST/CHROMIS Ca II K + 0.45 Å (+ 34.64 km/s)



Morphology and temporal evolution of the rain

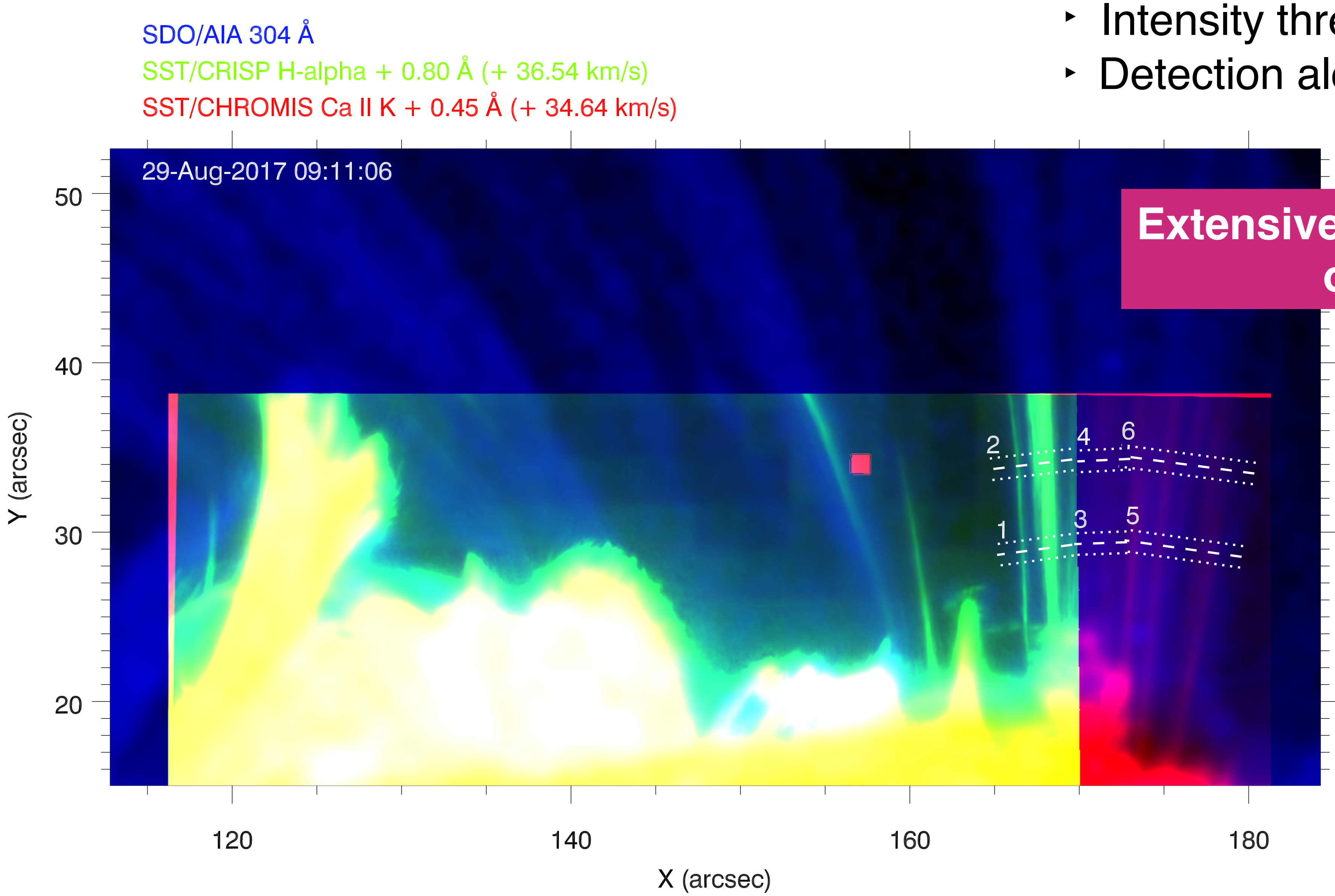


➡ Strand-like structures



Width typical of rain studies (e.g. Antolin et al. 2015)

Thermodynamic of the rain



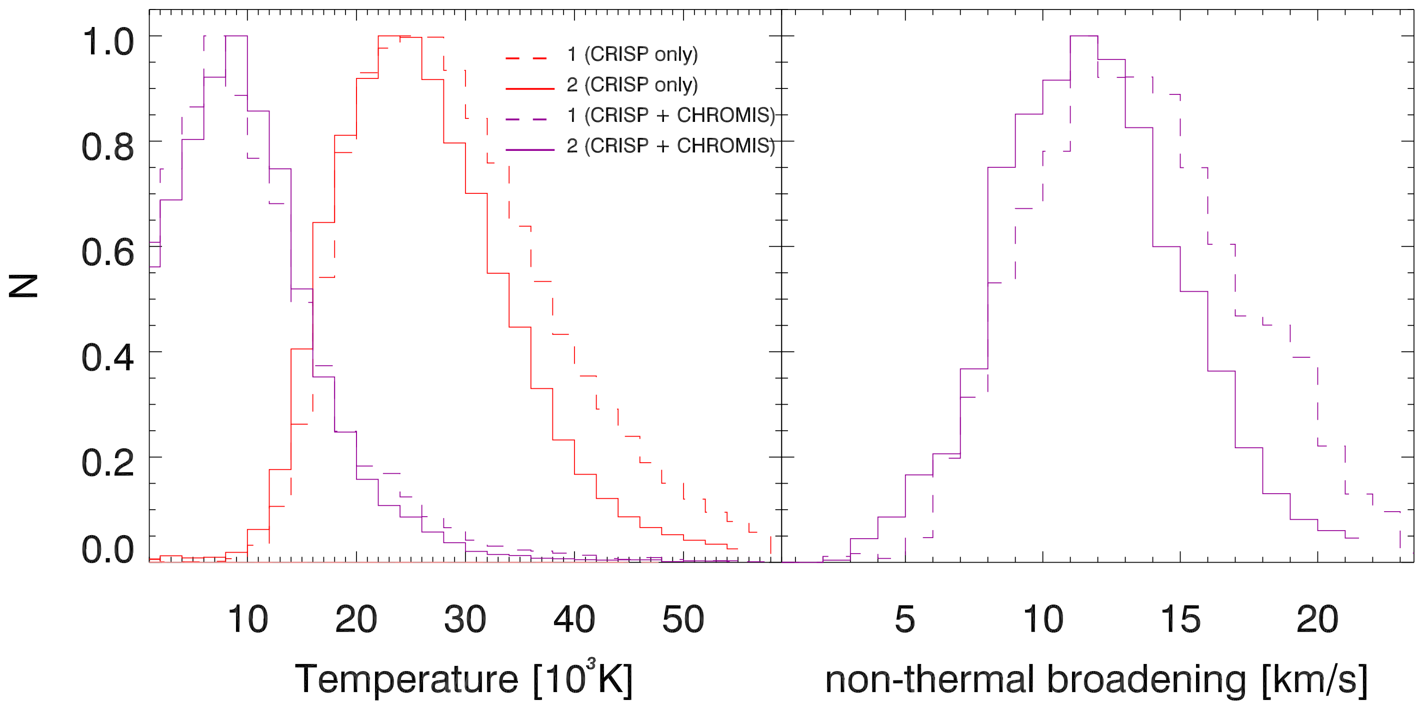
- Intensity threshold to detect rain pixels
- Detection along different paths

Extensive spectral characterisation of the rain clumps

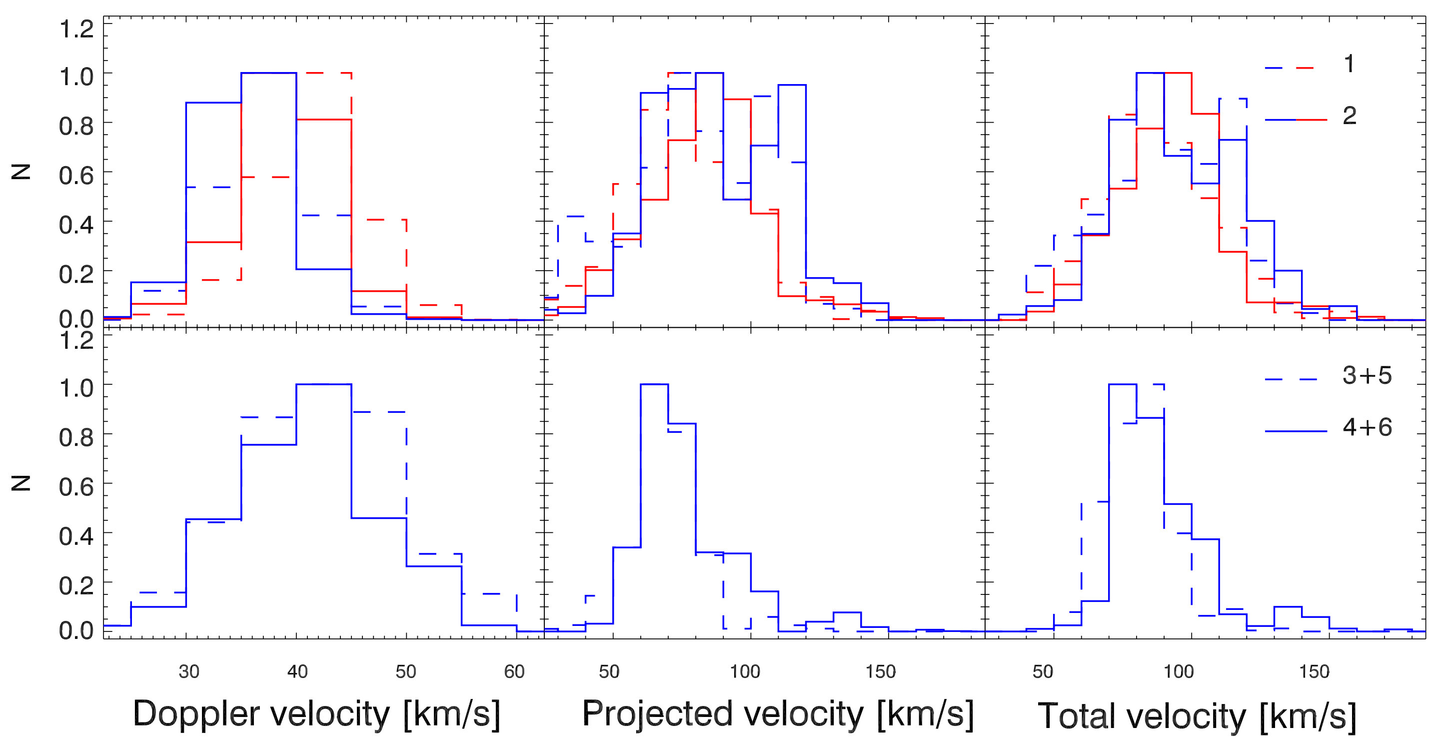
- Gaussian fit on the Hα and Ca II K condensation profiles

➡ Temperature, velocity, density measurements
➡ Can combine both lines to compute temperatures more accurately

Thermodynamic of the rain



Full catastrophic cooling to chromospheric temperatures

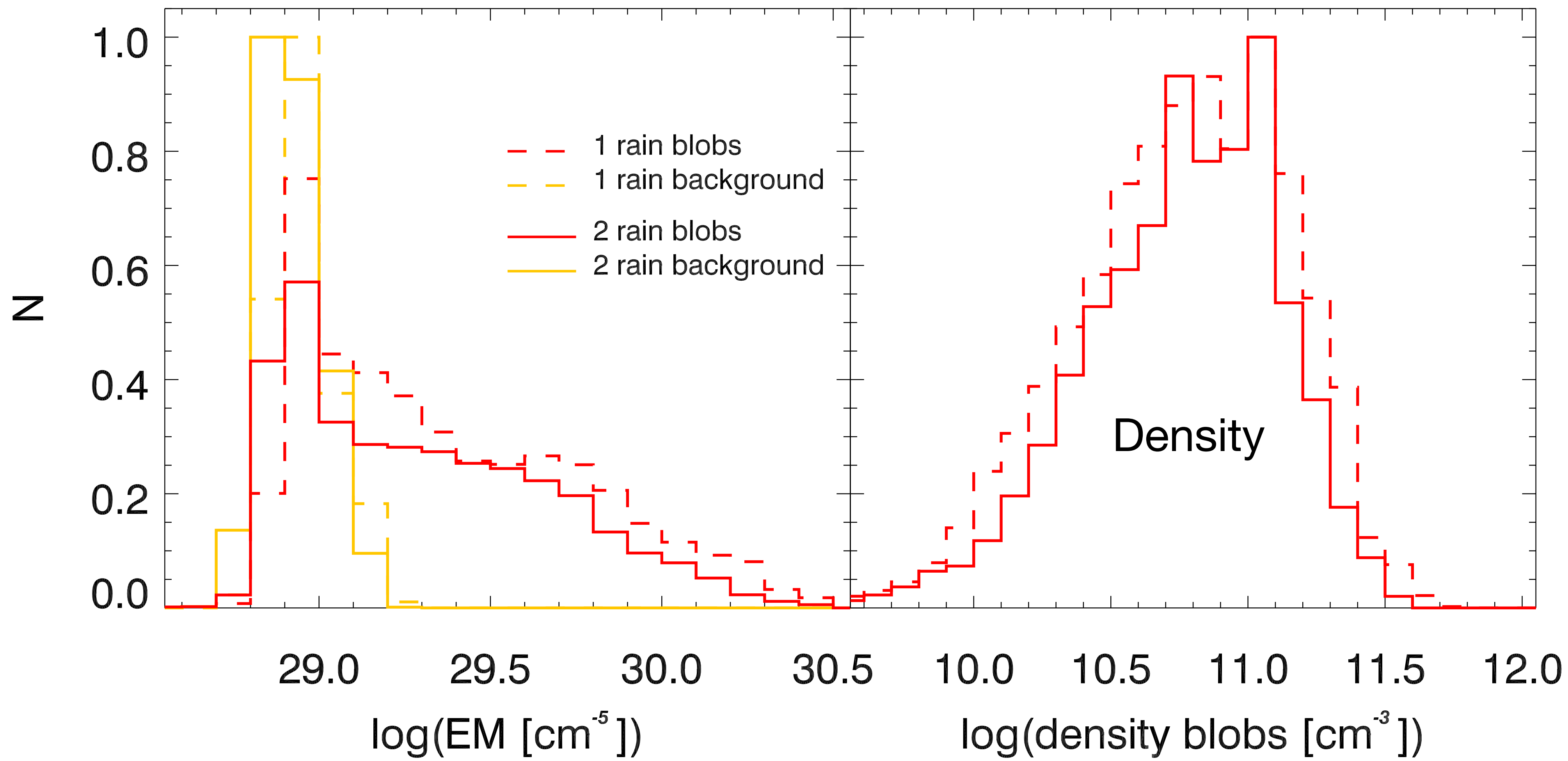


➡ Temperature and velocity consistent with other rain studies (*Antolin & Rouppe Van der Voort 2012, Ahn et al. 2014, Antolin et al. 2015)*

Chromosphere-corona mass cycle

Emission measure in H_α strongly correlated to the absolute H_α intensity (Gouttebroze et al. 1993)

$$n_{e,c} = \sqrt{\frac{1}{w}\left(EM_{\mathrm{H},bg+c} - \langle EM_{\mathrm{H},bg}\rangle\right)}$$



Mass drain rate on the order of 3×10^9 g s^{-1}

Conclusions

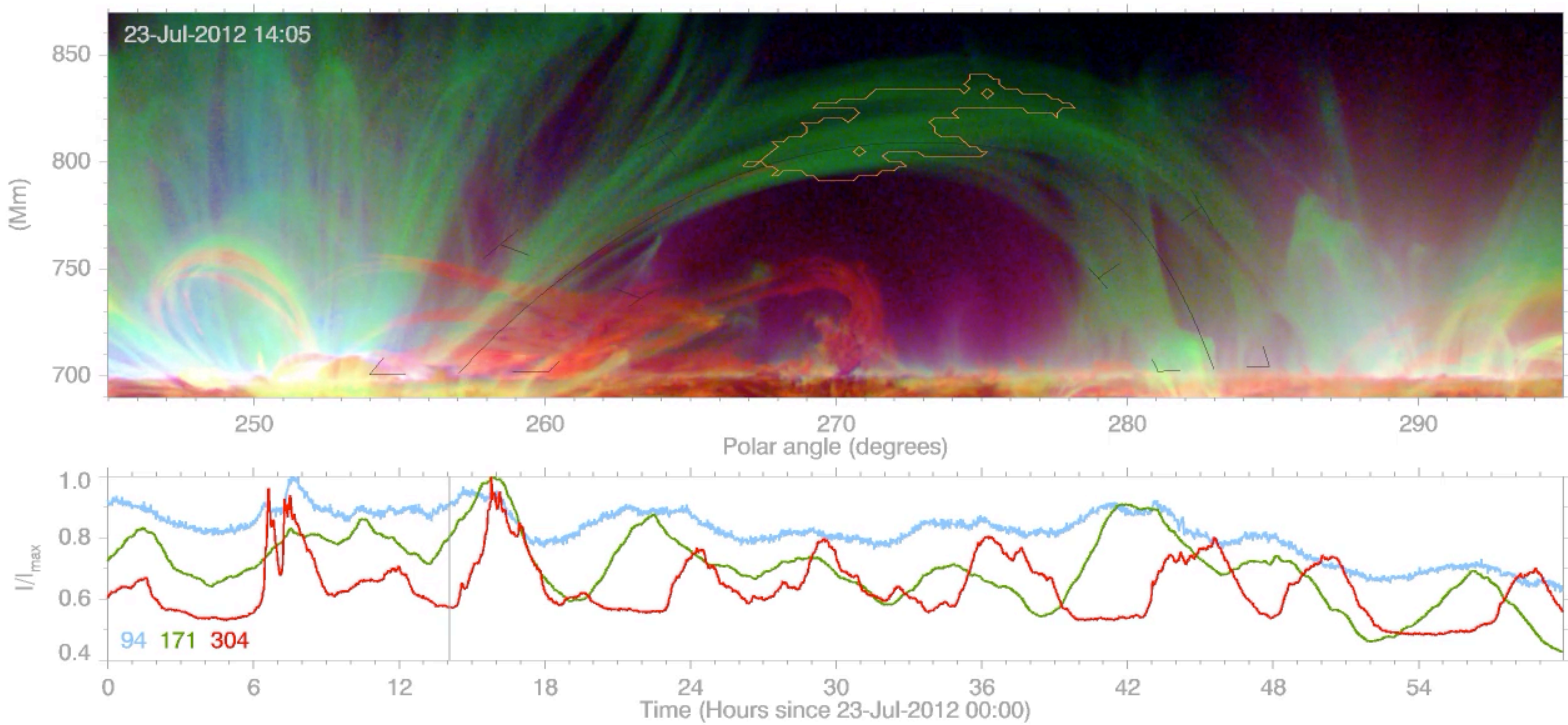
- Global behaviour that connect many different scales (temporal, spatial, temperature and density conditions), from the corona to the chromosphere
- These observations reinforce the link between both phenomena
- Coronal rain observed everywhere in the AR, not only in the pulsating loops
- Long-period intensity pulsations and coronal rain in every AR
- Stratified and high frequency heating can be present beyond structures that are experiencing TNE, as shown in e.g. Froment et al. 2018
- Any model of AR should take these phenomena into account
- Implication for circulation of mass and energy in the solar corona

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

$$\sigma_{\rm H} = \frac{\lambda_{0,\rm H}}{c}\sqrt{\frac{k_{\rm B}T_{\rm H}}{m_{\rm H}} + \xi^2_{nth,\rm H}}$$

$$T = \frac{m_{\rm H} * m_{\rm Ca}}{m_{\rm Ca} - m_{\rm H}}\frac{c^2}{k_B}\left[\left(\frac{\sigma_{\rm H}}{\lambda_{0,\rm H}}\right)^2 - \left(\frac{\sigma_{\rm Ca}}{\lambda_{0,\rm Ca}}\right)^2\right],$$

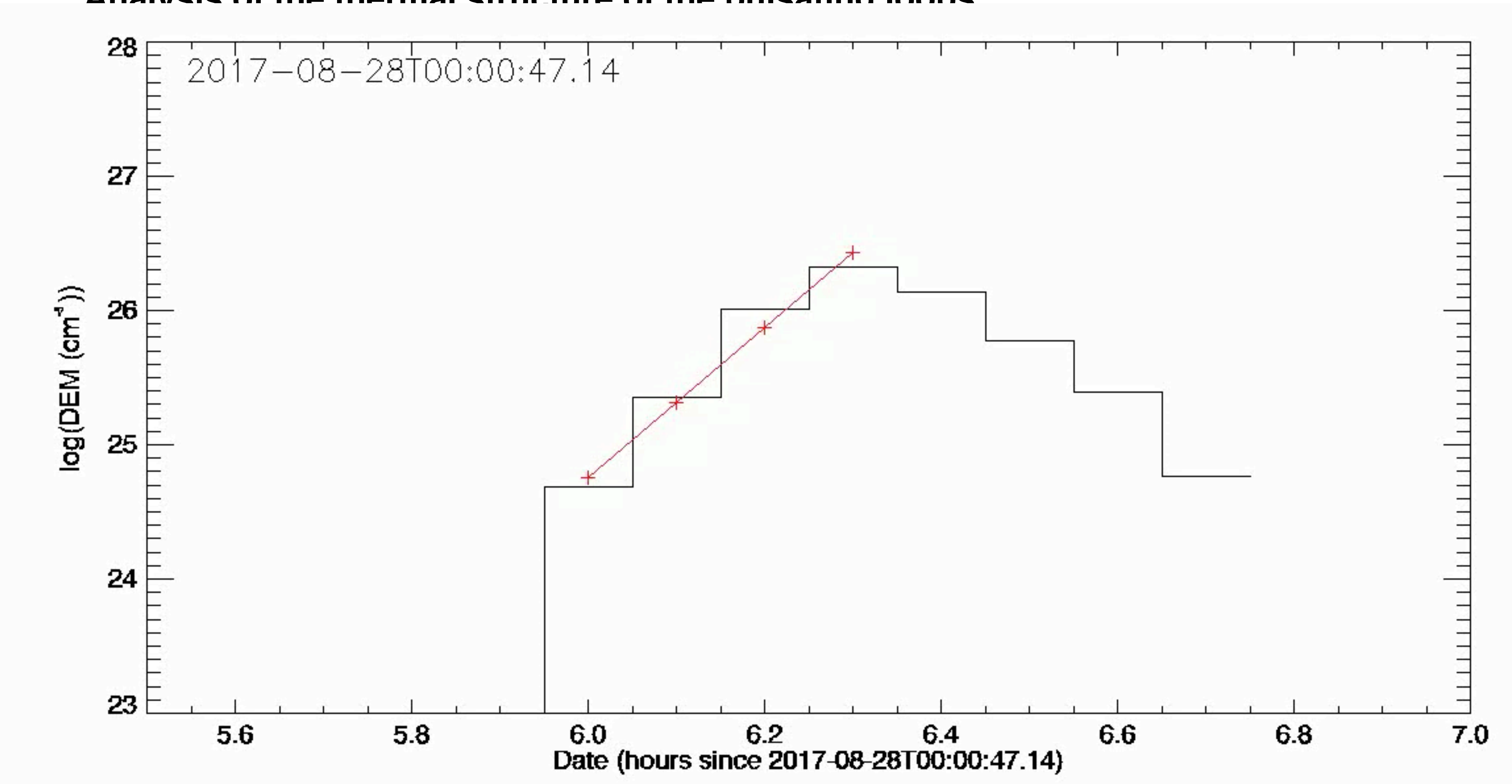
$$\xi_{nth} = c\sqrt{\frac{m_{\rm Ca} * \left(\frac{\sigma_{\rm Ca}}{\lambda_{0,\rm Ca}}\right)^2 - m_{\rm H} * \left(\frac{\sigma_{\rm H}}{\lambda_{0,\rm H}}\right)^2}{m_{\rm Ca} - m_{\rm H}}}.$$



23-Jul-2012 14:05
850
800
750
700
(Mm)
250
260
270
280
290
Polar angle (degrees)
1.0
0.8
0.6
0.4
I/I$_{max}$
94 171 304
0
6
12
18
24
30
36
42
48
54
Time (Hours since 23-Jul-2012 00:00)

Thermal cycles from DEM analysis

Analysis of the thermal structure of the pulsating loops



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

➡ **Strong evidence of TNE**