ISSI Team - coronal rain 23-27 February 2015

The multi-thermal and multi-stranded nature of coronal rain

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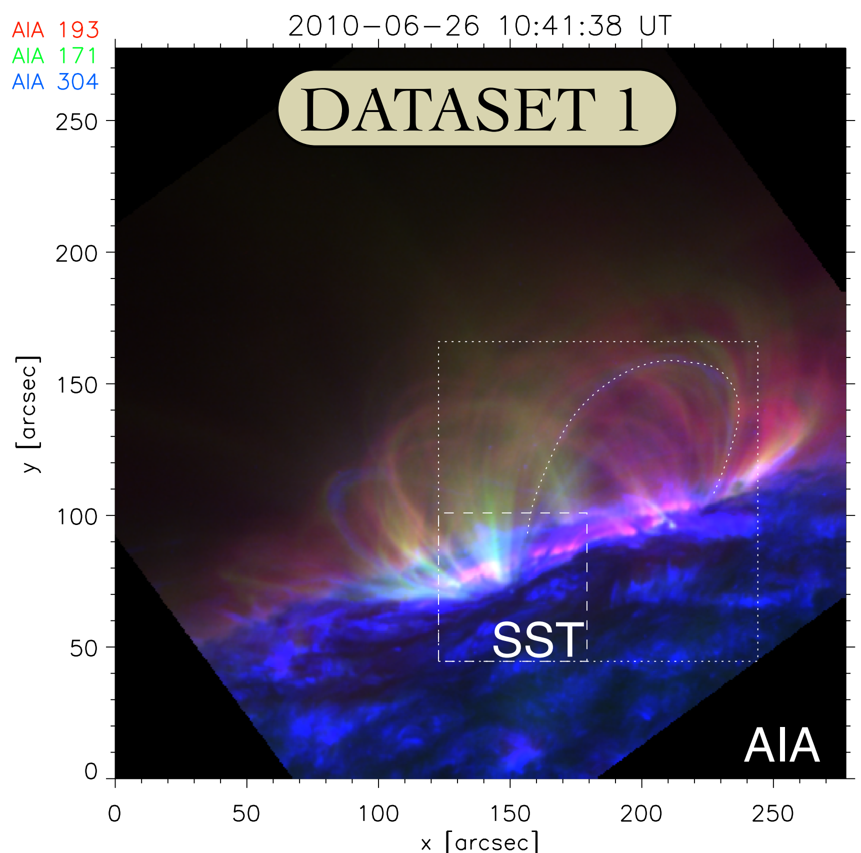
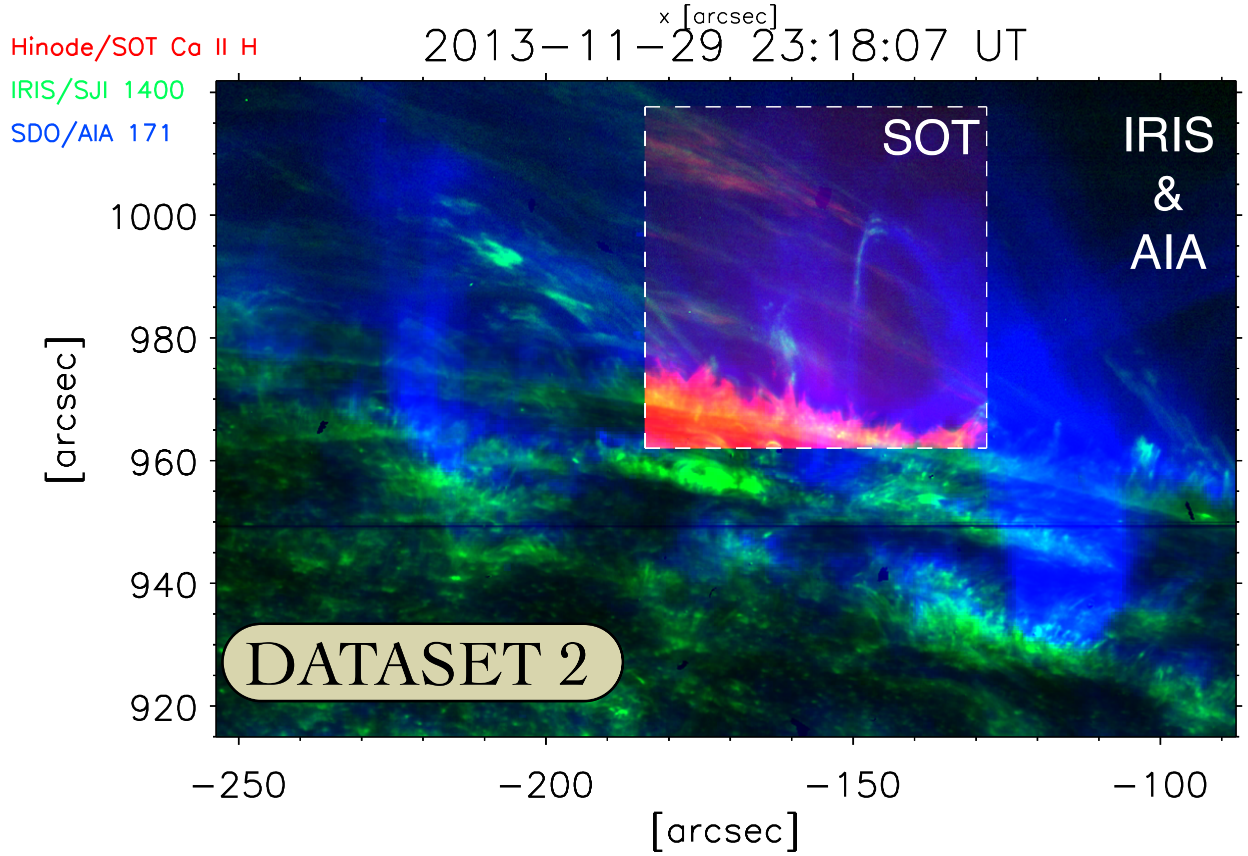
Submitted to ApJ

Multi-wavelength observations

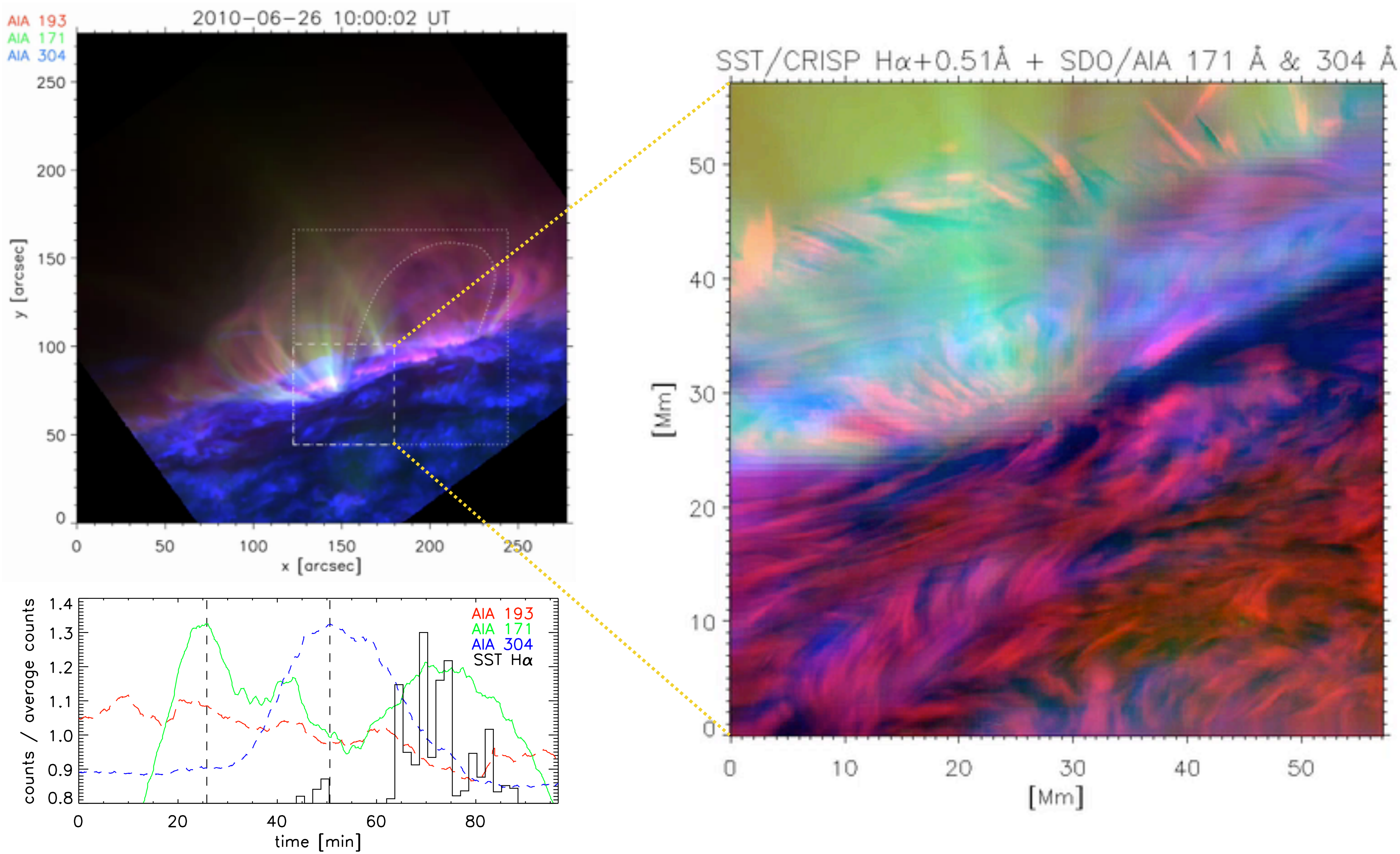




Instrument & Wavelengths	Dataset	Spatial (& spectral) resolution	Cadence [sec]	Formation temperature [log K]
SST/CRISP Hα	1	0.14” (0.085 Å)	9	3.3-4.2
Hinode/SOT Ca II H	2	0.2”	4.8	4-4.2
IRIS/SJI Mg II 2796 Å	2	0.4”	36.5	4-4.2
IRIS/SJI C II 1330 Å	2	0.33"	36.5	4.3
IRIS/SJI Si IV 1400 Å	2	0.33”	36.5	4.8
SDO/AIA He II 304 Å	1 & 2	1.2”	12	5
SDO/AIA Fe IX 171 Å	1 & 2	1.2”	12	5.9
SDO/AIA Fe XII 193 Å	1	1.2”	12	6.2

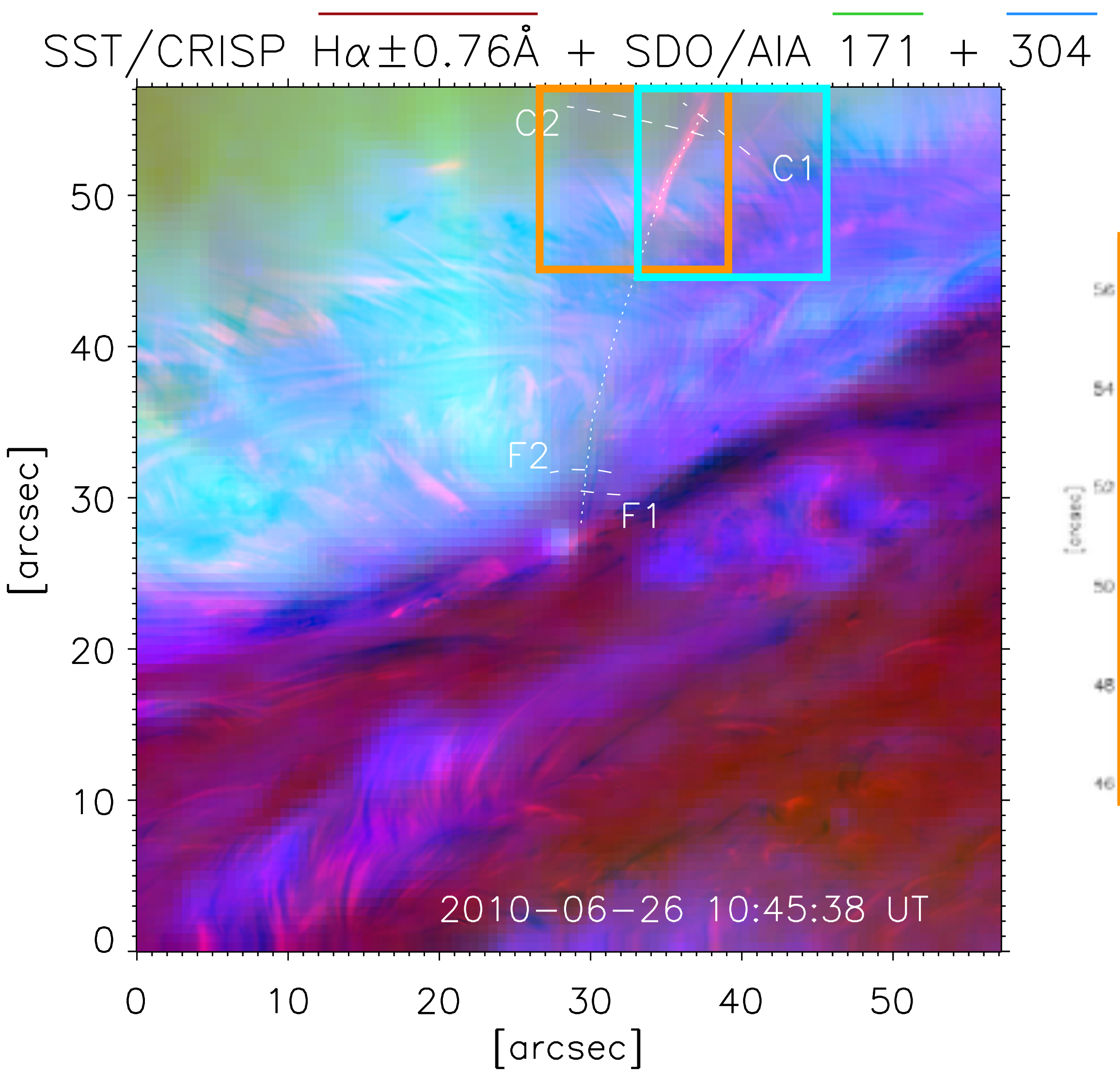
- Dataset 1: 26/06/2010, 10:03-11:40 UT, centred on AR 11084 at [-875”,-319"]
- Dataset 2: 29/11/2013, 22:30-23:30 UT, centred on AR 11903 at [944”,264”]

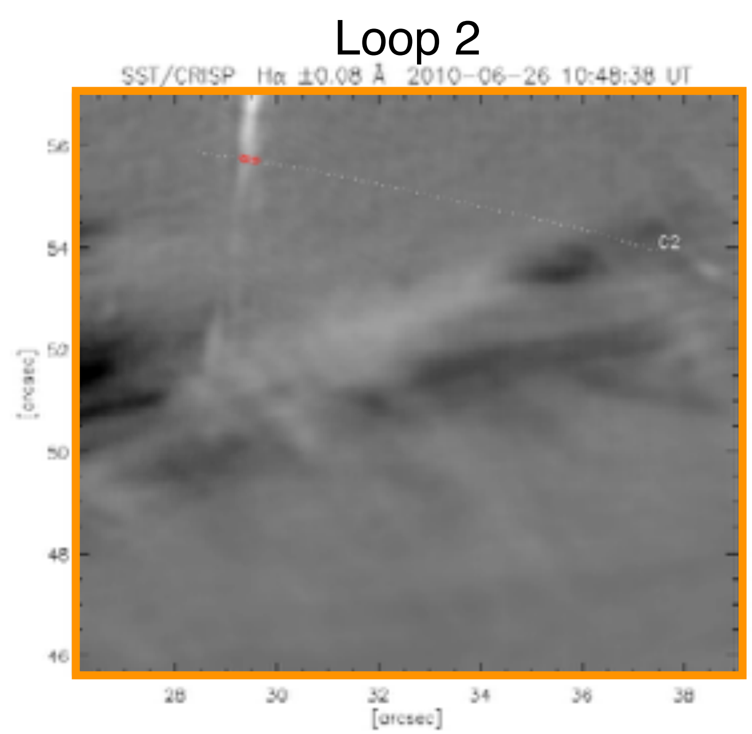
Progressive cooling

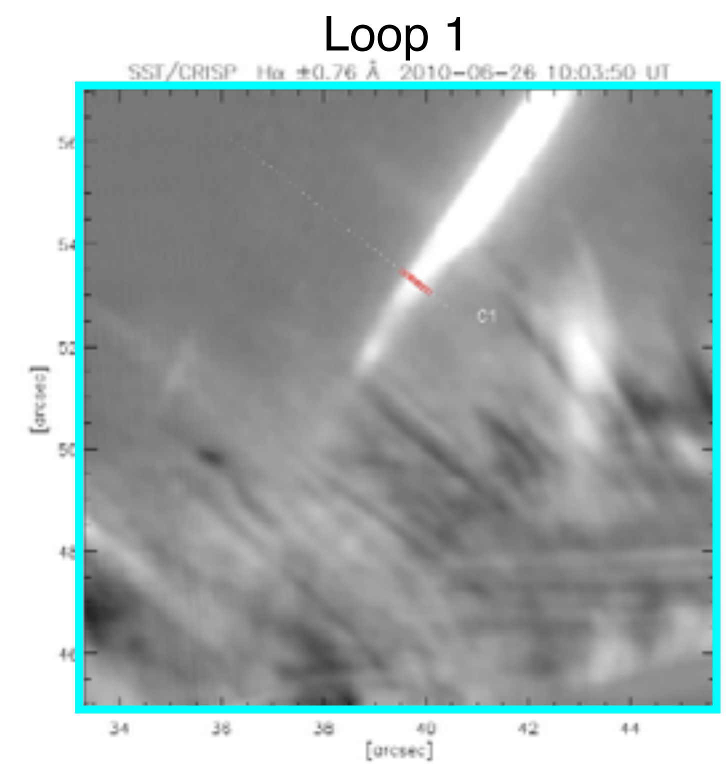


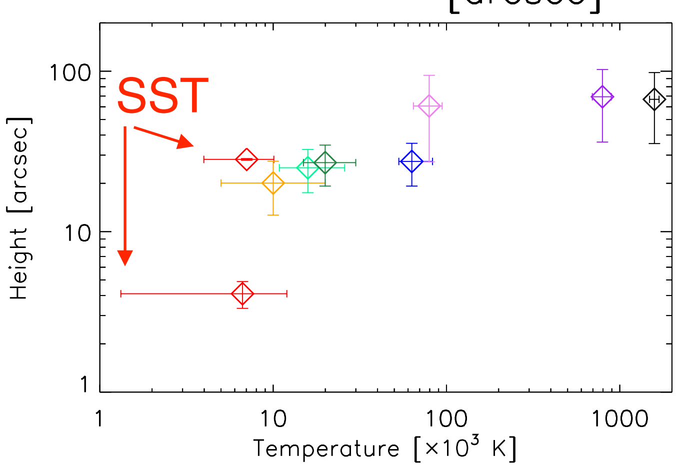
Progressive cooling from coronal to chromospheric temperatures is observed.
Thermal instability is at the origin of the intensity variability in these loops

Progressive cooling

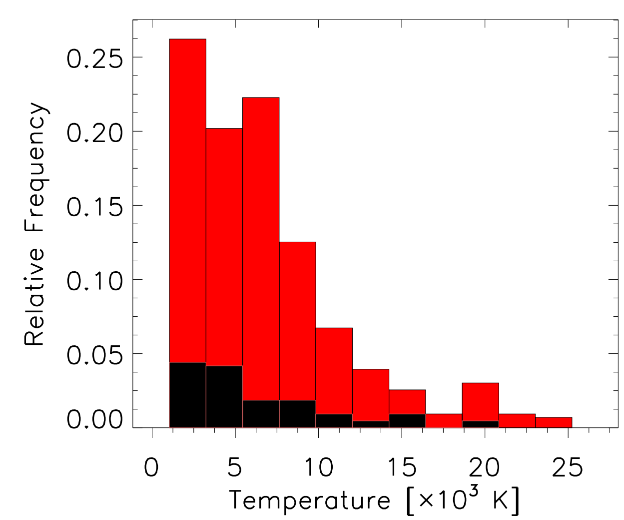


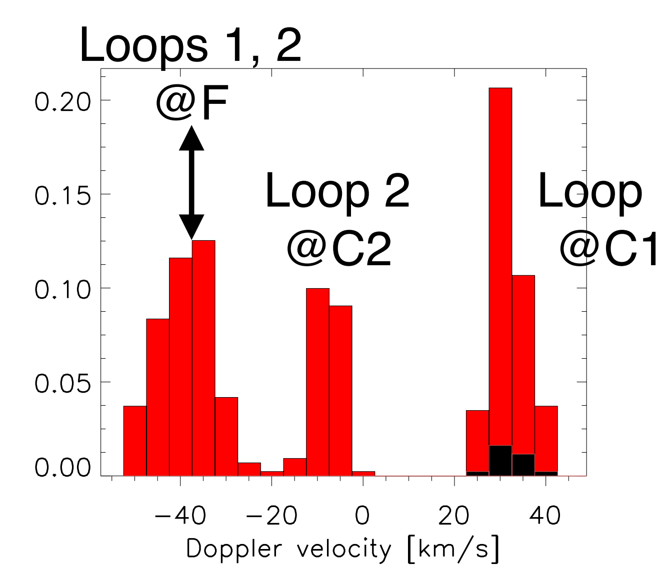




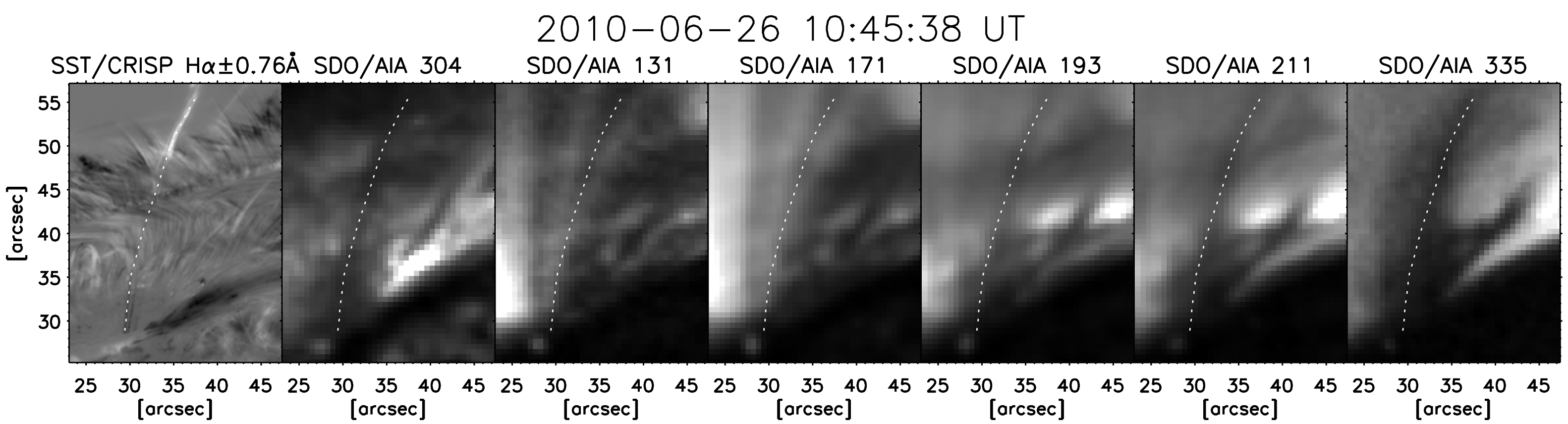


Very cool temperatures, preferentially at low heights

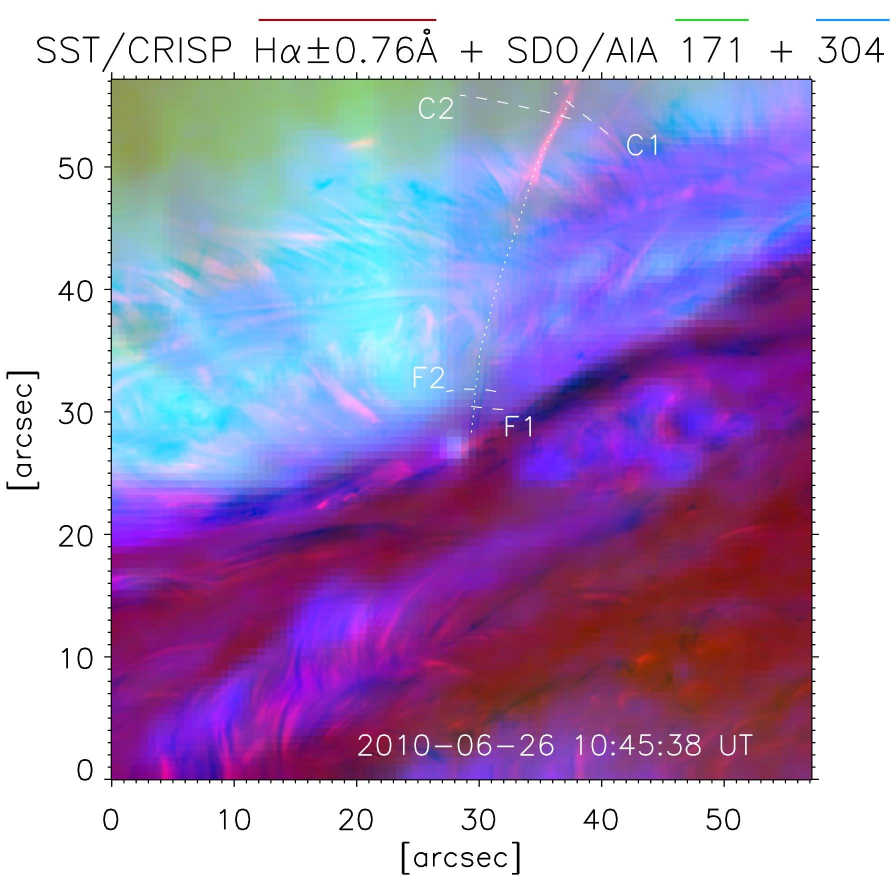


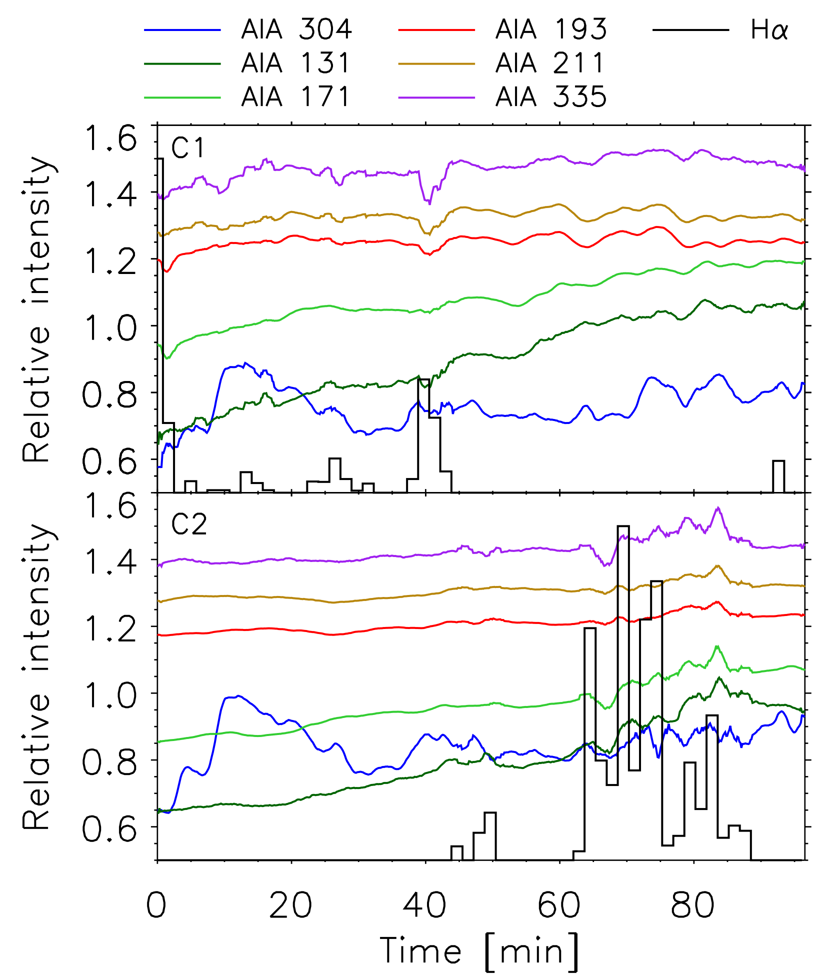


EUV variation associated with Hα rain emission



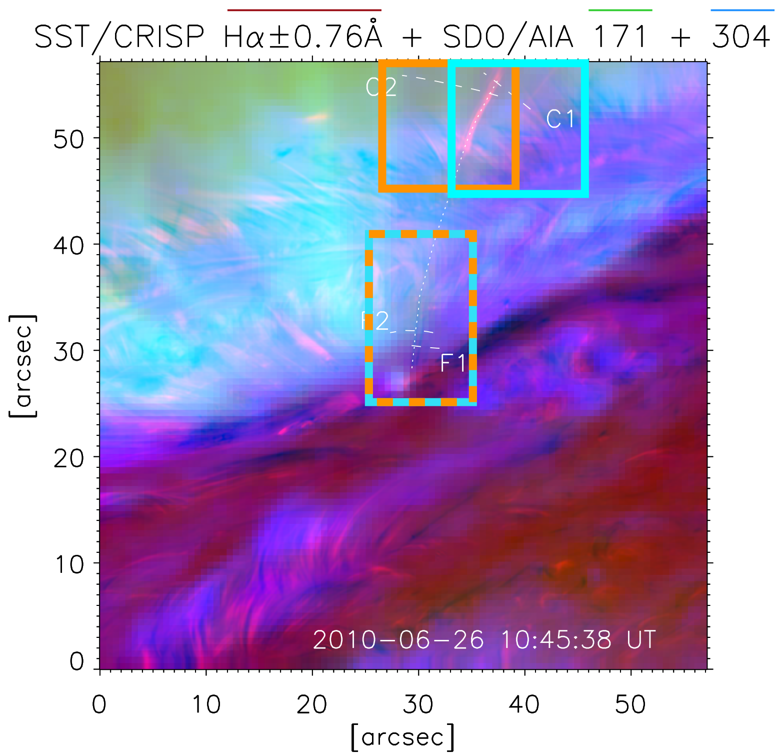
Hα rain is clumpy and surrounded by wider and continuous EUV absorption features.

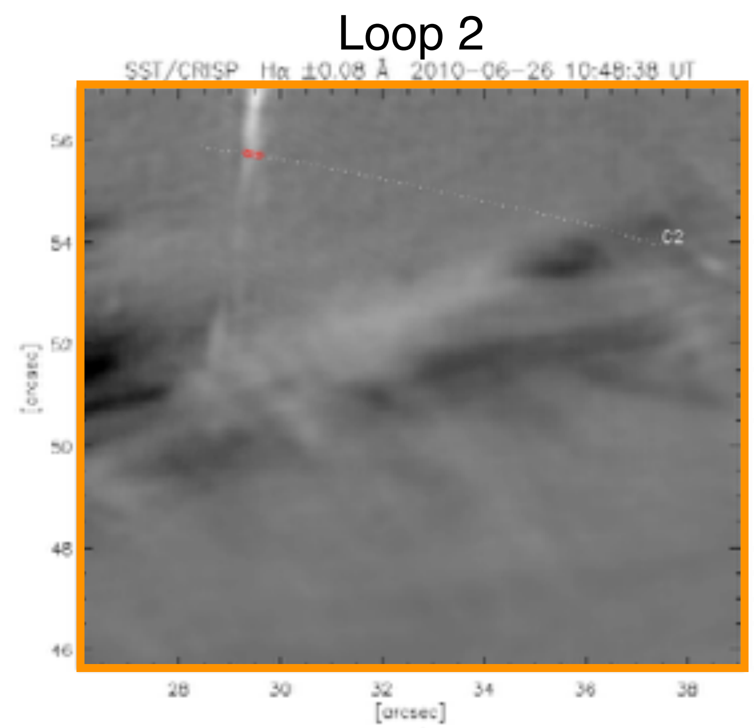


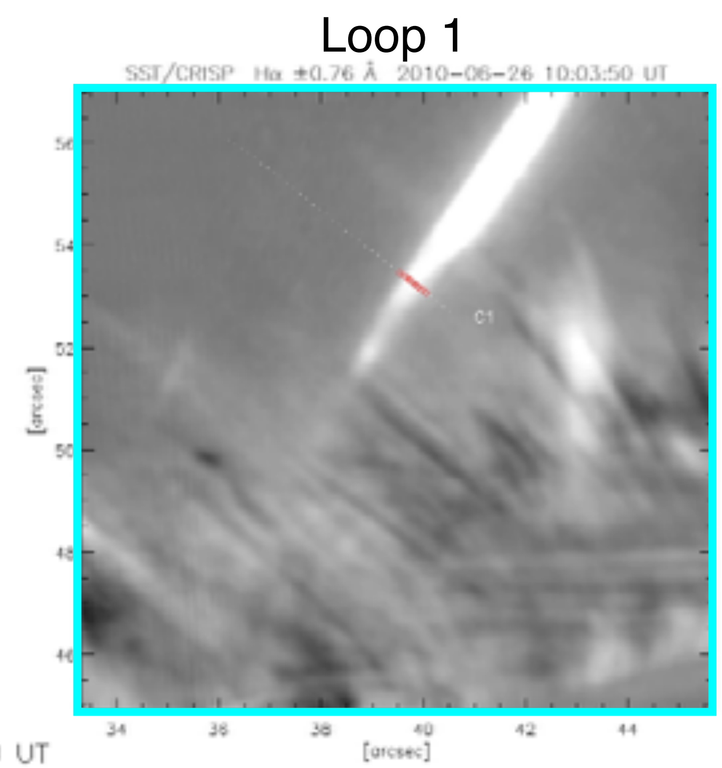


Large clumps and showers produce EUV variability: can lead to a quasi-periodic intensity variation

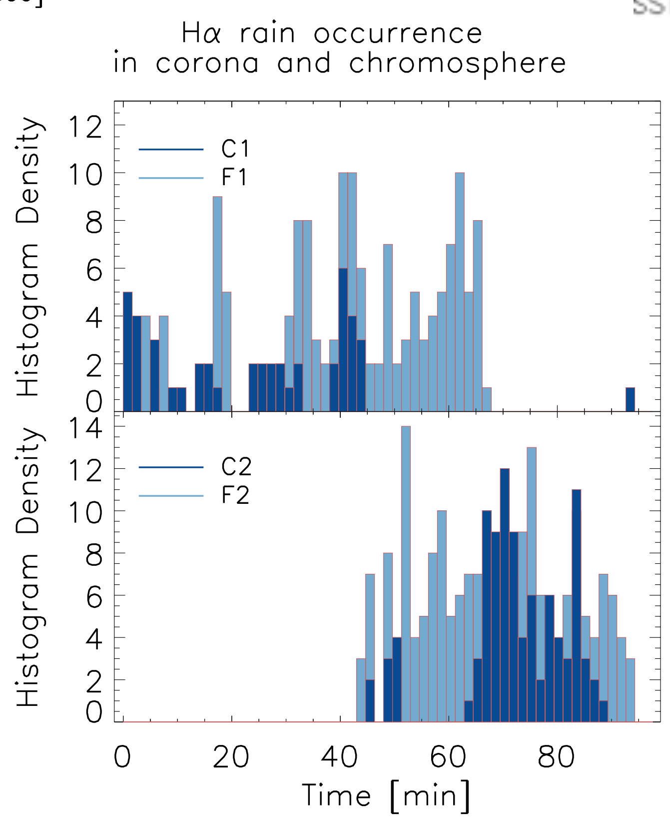
Clumpy vs. continuous

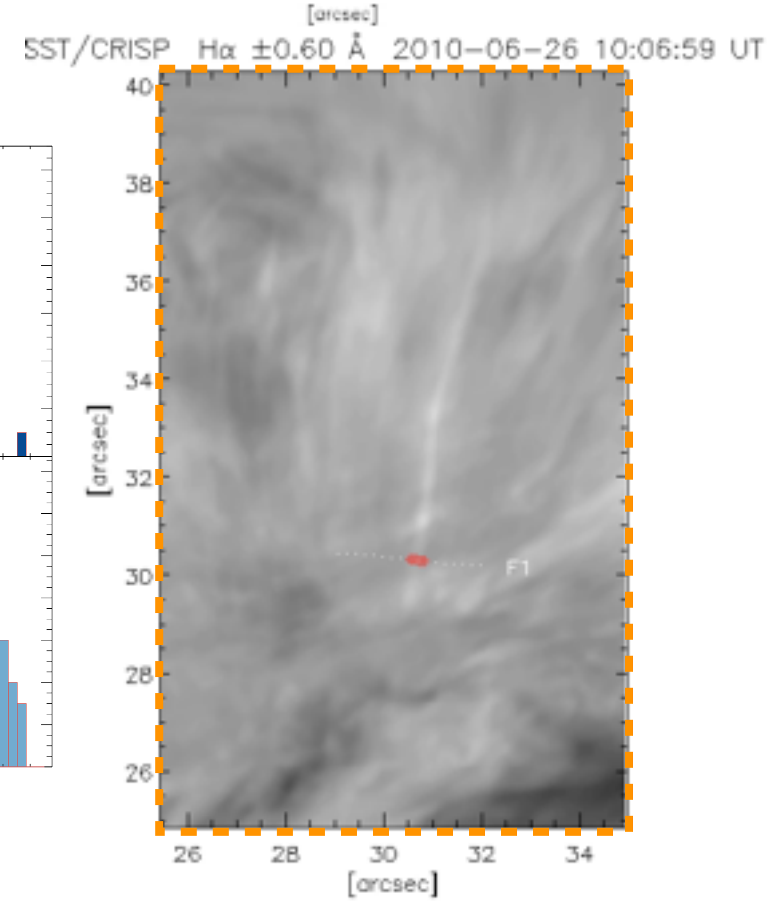


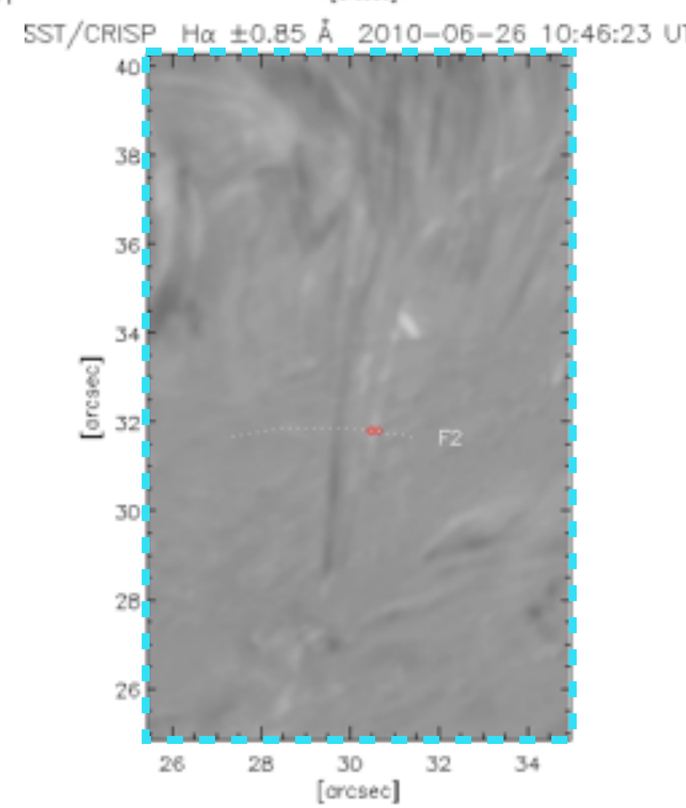




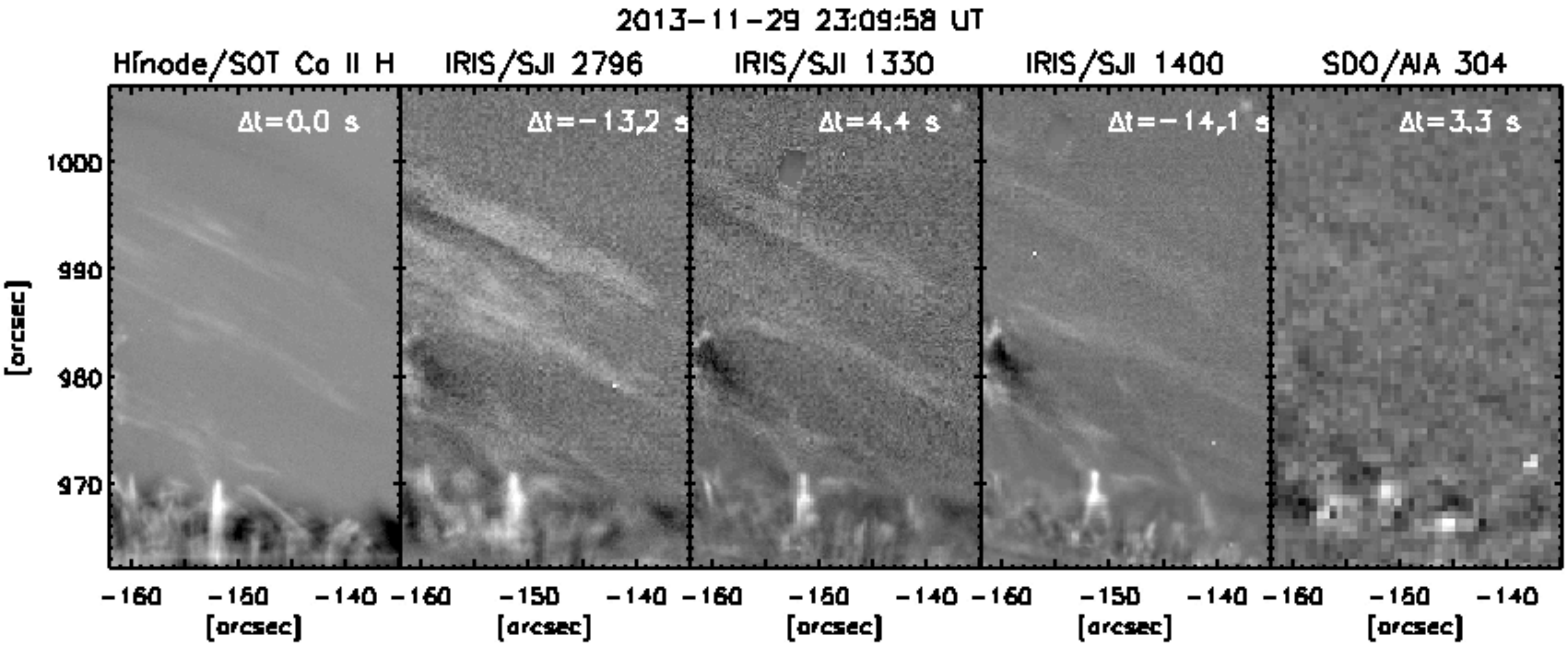
The clumpy and sporadic character of the rain at coronal heights (C1&C2) becomes persistent & continuous at chromospheric (F1&F2) heights

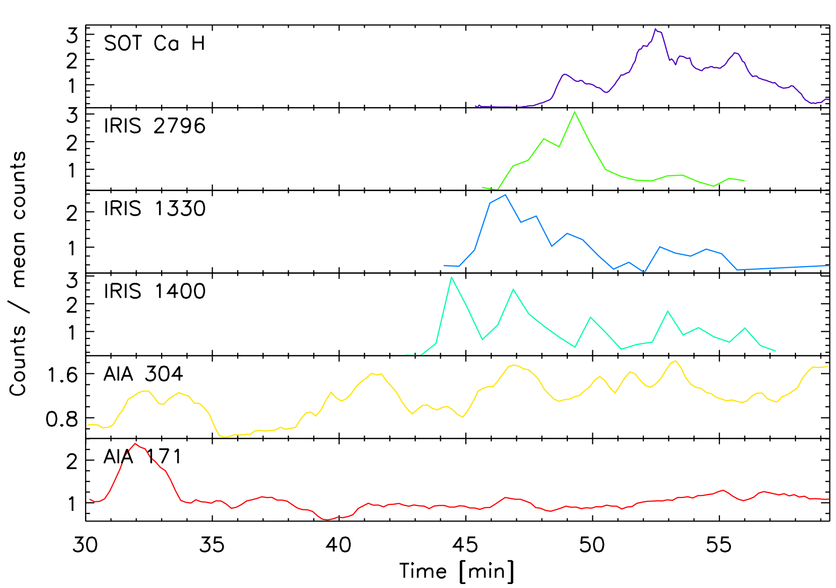




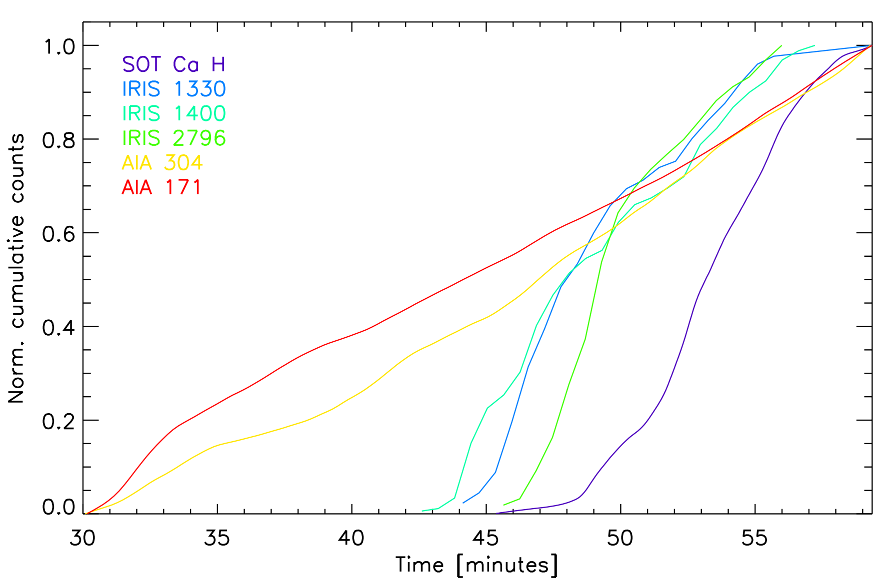


Cooling through TR lines

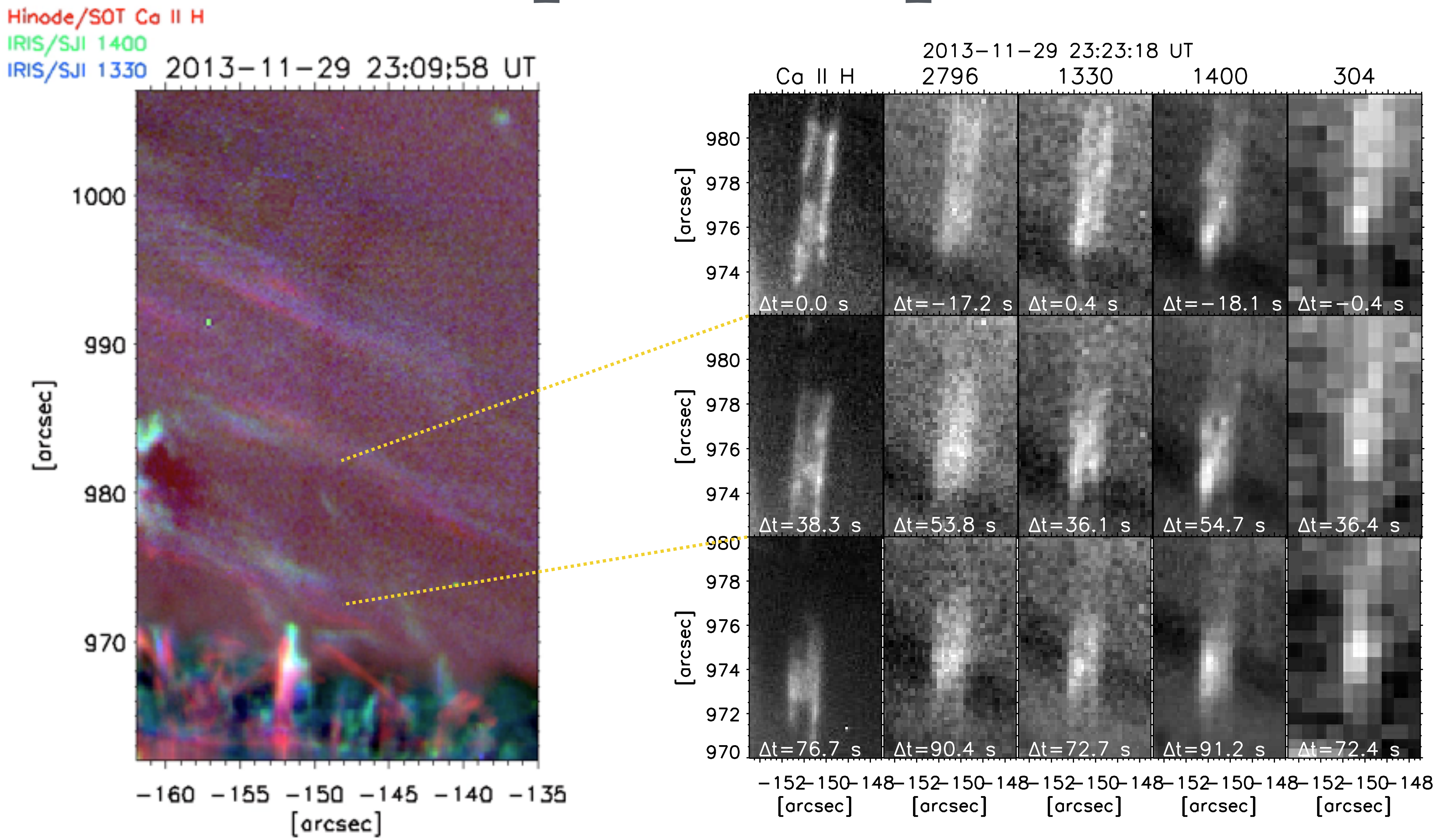




Progressive cooling from TR to chromospheric temperatures with a fast-slow two step behaviour

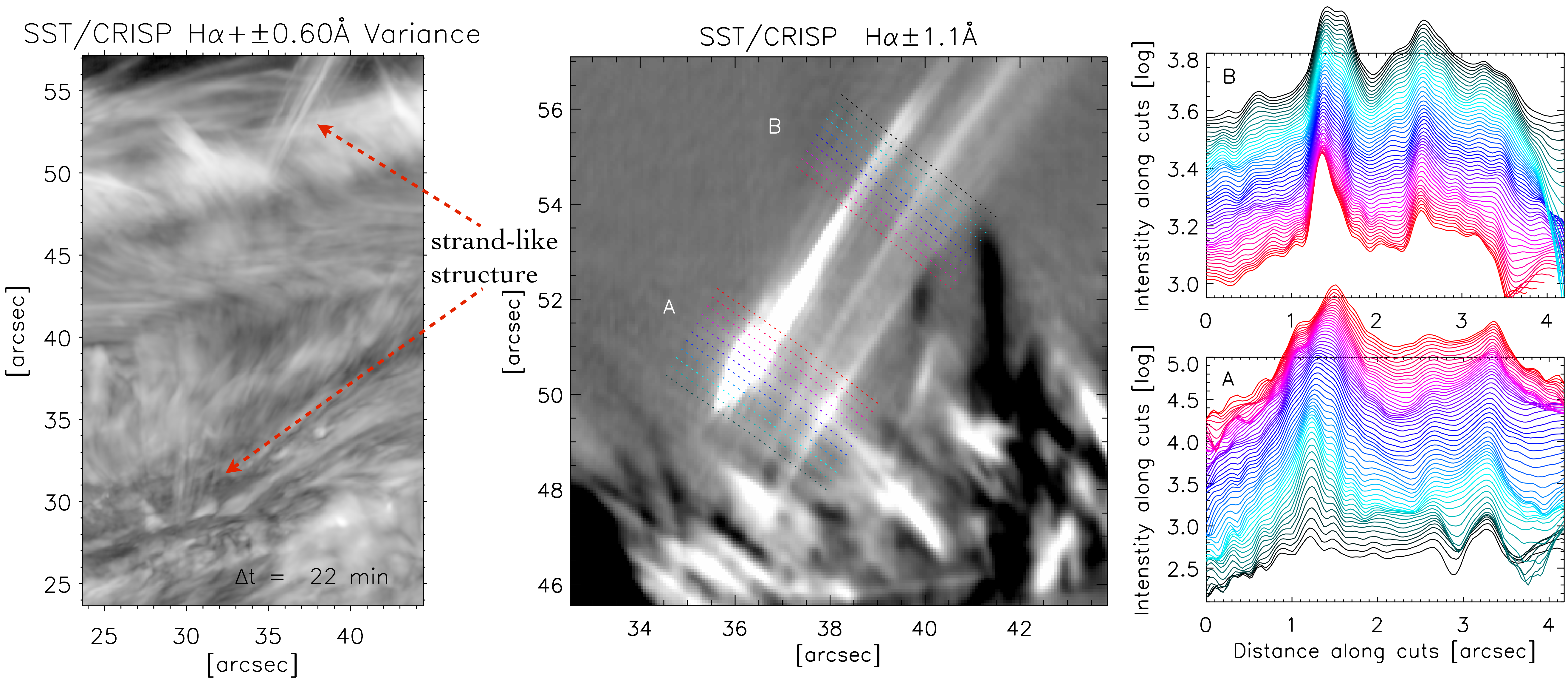


A multi-temperature phenomenon



- Strong co-spatial emission in TR and chromospheric lines
- Differences in structure appear at the smallest scales: chromospheric to TR temperature transition must exist at scales below Iris resolution (0.33")
- Strand-like structure extends to TR range

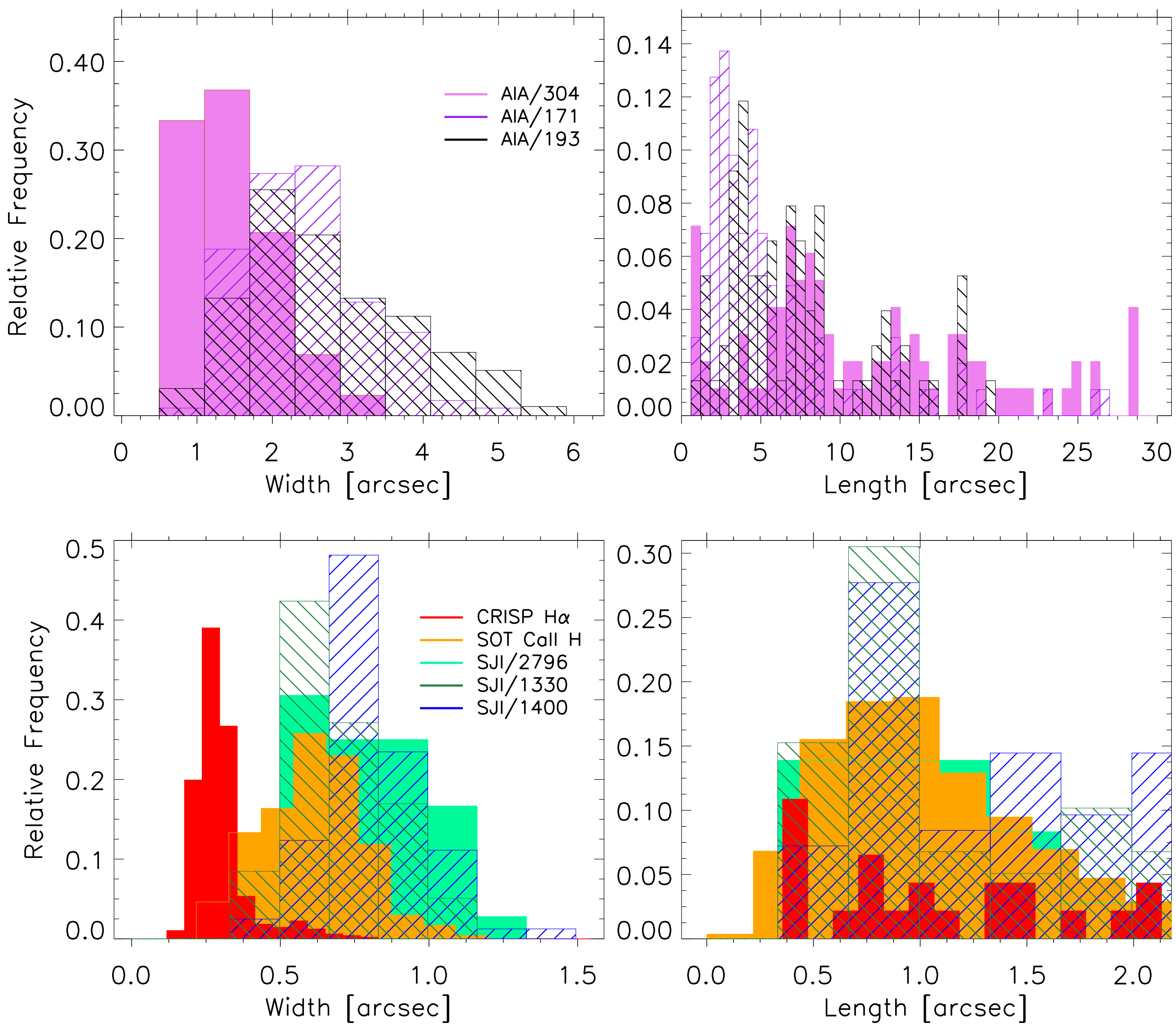
Multi-stranded structure



6-8 strands are visible in the projected plane of the sky, extending from coronal to chromospheric heights

Multiple ripples next to large clumps: highly reminiscent of the MHD thermal mode (Van der Linden & Goossens 1991)

Multi-stranded structure: tip of the iceberg?



- Significant difference in clump widths in AIA from TR to coronal temperatures (~0.5”) width of PCTR?
- Shape of width distribution is independent of temperature: sharp peak + long tail. Strong increase in clump numbers at lower temperatures but especially at higher resolution

➡Tip of the iceberg scenario?

- Lengths distribution is more random: reflects other factors at play (longitudinal)

Discussion - conclusions

EUV intensity variations as a signature of catastrophic cooling

- Thermal instability is the most general state of the plasma
  - Viall & Klimchuk 2012: most loops are in a cooling state.
  - Coronal loops in active regions often present intensity variations (out of hydrostatic equilibrium, Aschwanden et al. 2001; Reale 2010).
  - ➡Which fraction is in a state of thermal non-equilibrium?
- Is thermal instability generally complete? Does the instability often lead to catastrophic cooling (down to chromospheric temperatures)? Mikiç et al. (2013)
- Are common EUV intensity variations in AR loops a signature of thermal instability?

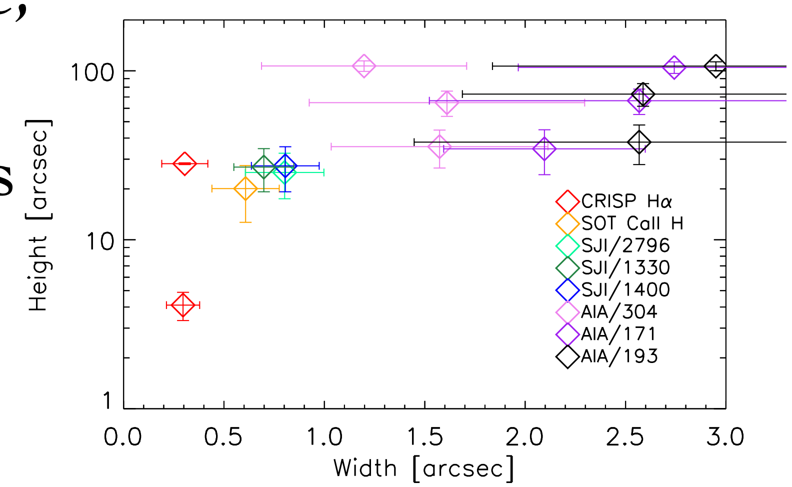
This study:

- Common EUV intensity variation in cooling loops are strongly correlated to coronal rain appearance (large clumps and showers) in TR and chromospheric lines (continuum absorption from H, He and He+: Heinzel & Anzer 2005, Labrosse+ 2010)
- Intensity variation can appear quasi-periodic

Discussion - conclusions

The problem of persistent red-shifts above sunspots

- Persistent red-shifts above sunspots, often associated to bright fan-shaped structures observed in EUV above the umbra, usually termed plumes (Brekke + 1990; Brueckner 1981; Dere 1982; Kjeldseth-Moe+ 1988, Foukal+ 1974; Brosius & White 2004; Brosius 2005…)
- Large range of downflow speeds: subsonic & supersonic, in both chromospheric and TR lines (Kleint+ 2014)
- Interpreted either as siphon flows or condensation flows (Reale+ 1996,1997, Mok+ 2008)
- Clumpy nature of coronal rain posed a problem of interpretation

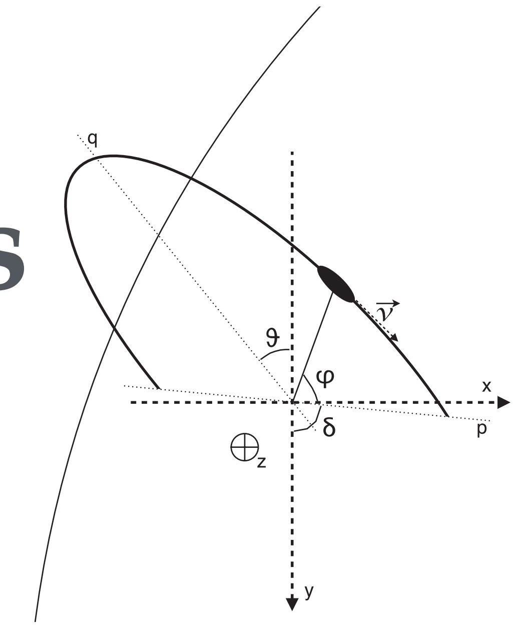


This study:

- Clumpy and sporadic character at coronal heights becomes persistent and continuous at low heights: offers explanation to this long standing problem
- Change of character is partly due to progressive cooling of the rain, but mostly to a funnel effect from the observed expansion of the magnetic field at low heights: From heights F to C (26”) the field expands by a factor of 2.

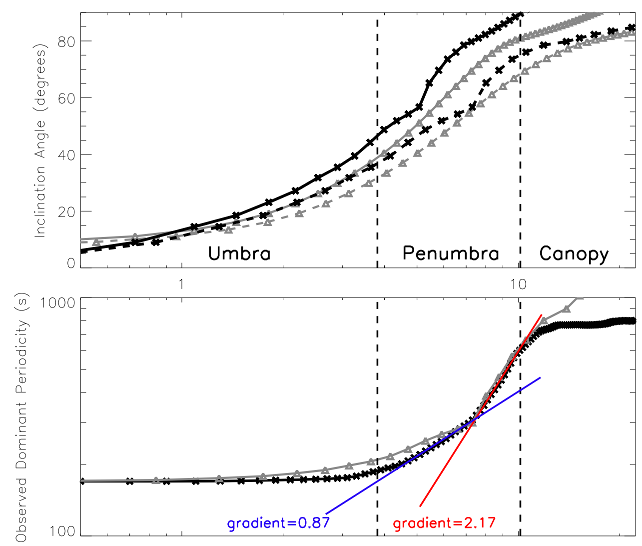
Discussion - conclusions

Global magnetic field tracer



- Full velocity vector from spectroscopic observations allows to infer the angle of fall of rain clumps with respect to the loop vertical (Antolin & Rouppe van der Voort 2012)

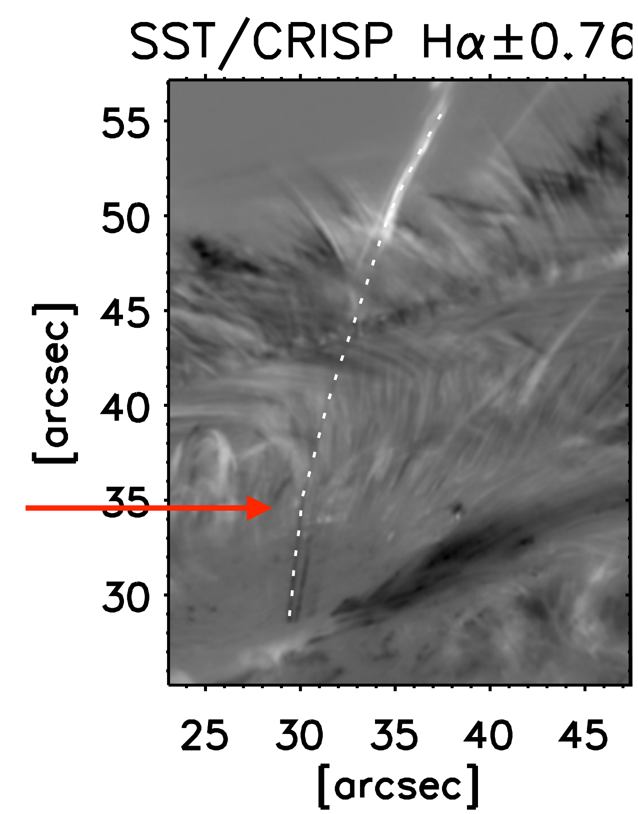
➡LOS projection effect can be eliminated to some extent



- Interesting applications as global magnetic field tracers
- Jess+ (2013): existence of a kink in the field above sunspot umbra leading to a characteristic change with height of the dominant periods of running penumbral waves from the photosphere into the chromosphere

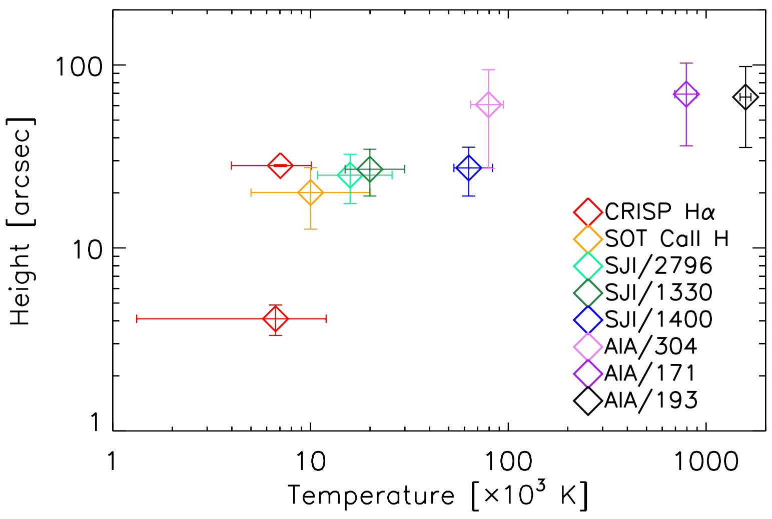
This study:

- Very long and thin rain clumps (>20 Mm long)
- Existence of a kink in the field, above which main expansion is observed



Discussion - conclusions

Multi-thermal character



- Progressive cooling: difference in emission with height?
- Fast-slow two-step cooling: transition to optically thick states?
- Loop stays bright in AIA 171. Usual sequential EUV intensity from hot to cool is not observed

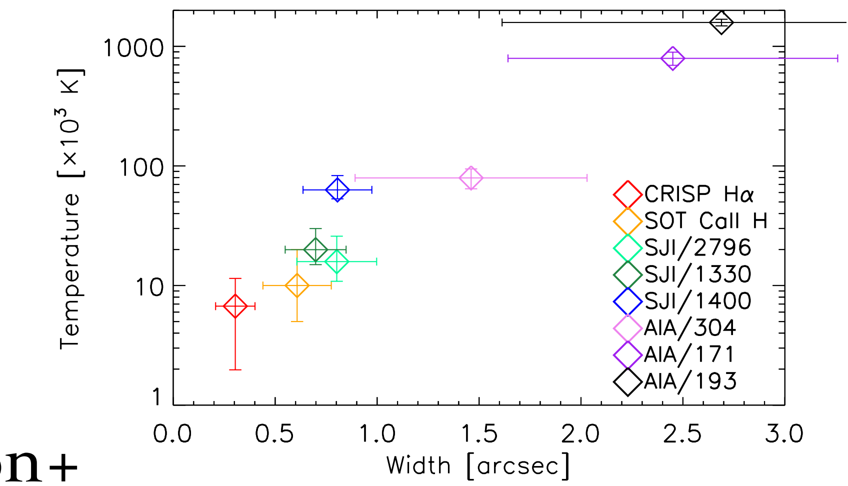
➡Not a necessary observational condition of thermally unstable loops

- High degree of co-spatiality in multi-wavelength emission (chromospheric and TR): large density inhomogeneity within thermally unstable loops. Thin transition from chromospheric to TR temperatures: < 0.33″. PCTR ~ 0.5”
- Thermal instability in low β plasmas is far more complex than the simple picture of a uniformly progressive cooling plasma with cool chromospheric cores surrounded by warmer diffuse material.
- How? Existence of tangential discontinuities in the field in which material can collapse (Low+ 2012a,b)

Discussion - conclusions

Elemental scales (1)

Instrument & filter	Dataset	Width [arcsec]	Length [arcsec]	Blobs / min
CRISP - Hα	1	0.3 ± 0.093	3.85 ± 5.77	5.
SOT - Ca II H	2	0.61 ± 0.17	1.05 ± 0.51	9.7
SJI - 2796	2	0.8 ± 0.19	2.49 ± 1.97	2.6
SJI - 1330	2	0.7 ± 0.15	1.75 ± 1.35	3.7
SJI - 1400	2	0.8 ± 0.17	1.76 ± 1.26	4.6
AIA - 304	2	1.56 ± 0.15	10.8 ± 6.5	2.2
AIA - 304	1	1.4 ± 0.7	12.7 ± 9.2	1.2
AIA - 171	1	2.45 ± 0.81	5.5 ± 5.2	1.2
AIA - 193	1	2.69 ± 1.07	7.4 ± 4.6	1.2



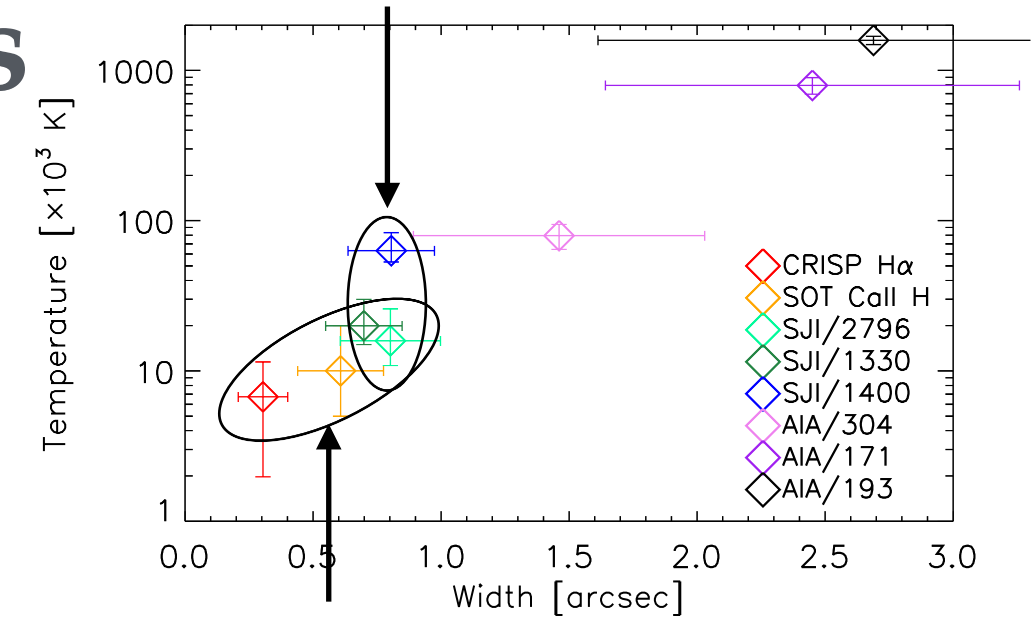
- Average standard deviation and widths (and the ratio) decreases at increasing resolution and decreasing temperature (AIA->SJI->SOT->CRISP)
- Number of clumps increases at higher resolution and decreasing temperature
- Bulk of the distribution undetected? (< 0.2″, also Scullion+ 2014): agreement with numerical simulations (Fang+ 2013)
- Lengths: much larger variable range. But generally clumpy at low temperatures. Big difference with prominences? Longitudinal effects: conduction, flows, instabilities…
- Agreement over several datasets (Antolin & Rouppe van der Voort 2012, Antolin+2012, Scullion+2014, Harra+2014). Similarity with widths of prominence threads.

➡Existence of elemental strand-like structures? Does thermal instability play a main role in the morphology, especially defining the widths? Is such substructure also expected in thermally stable loop? What is the influence of temperature?

Discussion - conclusions

Elemental scales (2)

insignificant width change, same resolution, drastic temperature change



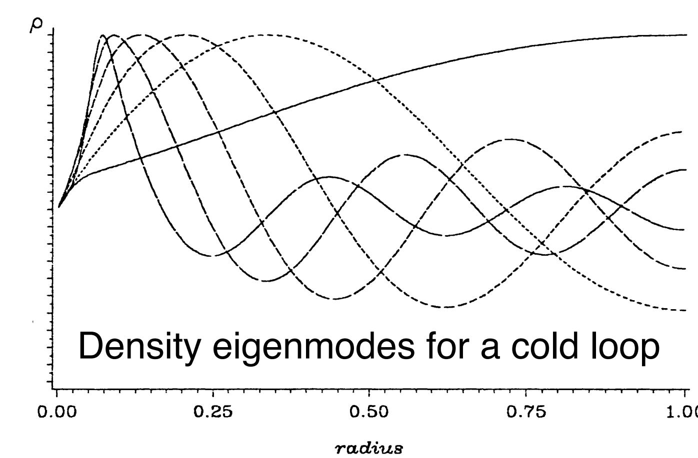
significant width change, significant improvement in resolution, no drastic temperature change

- Main role: resolution or temperature?

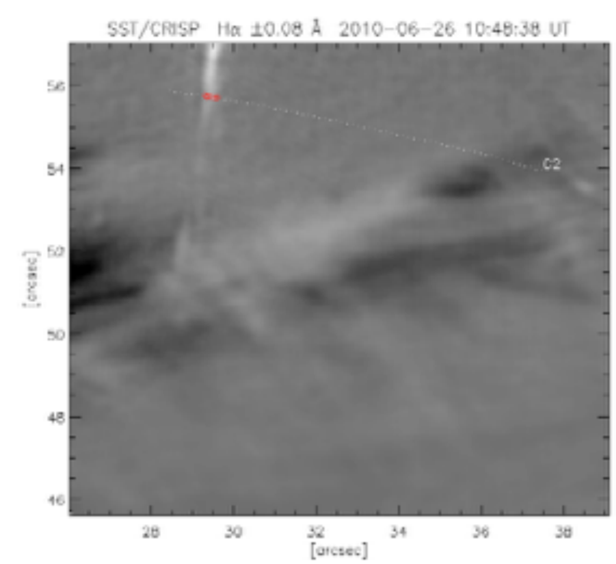
➡ Spatial resolution

- Strand-like structure extends into TR range
- Still, thermal instability can play a major role in defining the morphology

  How?



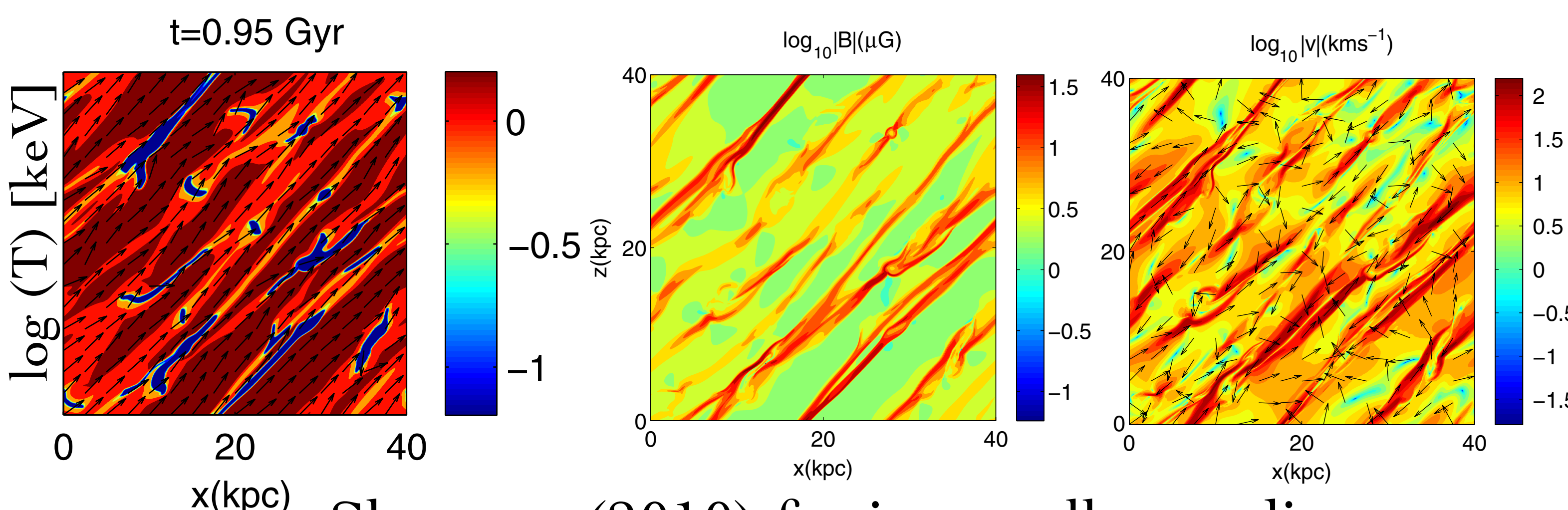
- MHD thermal mode (Field 1965, Van der Linden & Goossens 1991): small but non-zero perpendicular thermal conduction. Static MHD wave would move with the flow. Introduces density enhancements around clumps: further condensations in neighbouring loops?
- Other effect: large gas pressure variation across clumps introduces non-local enhancement of azimuthal magnetic field. Can affect plasma up- and downstream

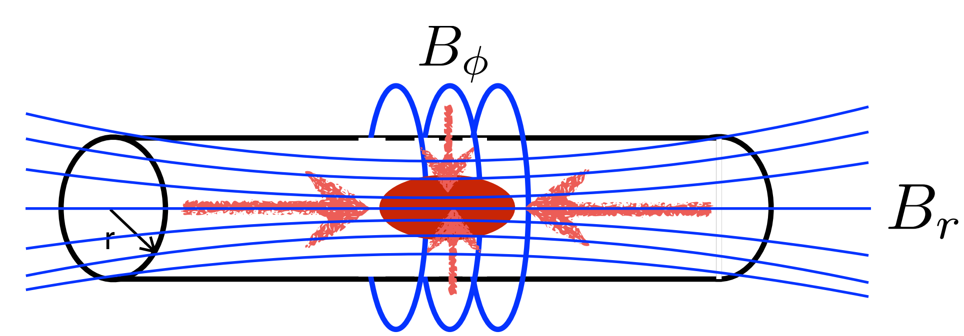


Discussion - conclusions

Elemental scales (3)

- Role of thermal instability in loop substructure. How?
- Other effect: large gas pressure variation across clumps introduces non-local enhancement of azimuthal magnetic field (~Bennett pinch effect). Can affect plasma up- and downstream due to flux freezing and high magnetic field tension.





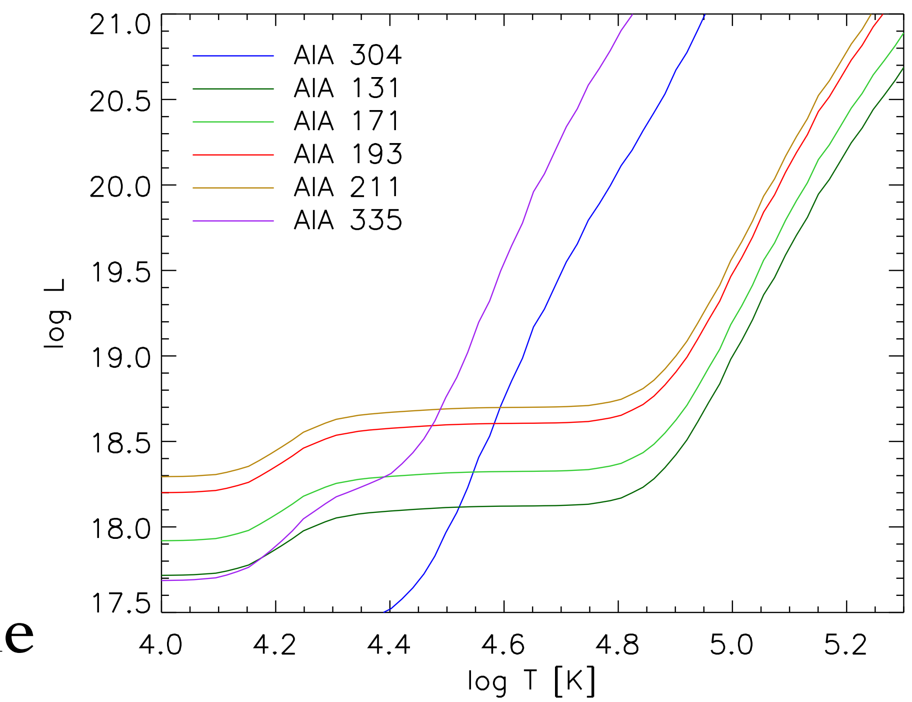
Sharma+ (2010) for interstellar medium

- May imply a relation between clumps' widths and the magnetic field at small scales: interesting MHD seismology applications
- Can it explain clumpy structure in longitudinal direction?
- Can it explain the lower downfall velocities? (higher magnetic pressure up-and downstream).

Discussion - conclusions

Densities

- Large clumps and showers produce detectable EUV darkening: we can estimate densities from continuum absorption (Landi & Reale 2013)



AIA: log T_{abs} ~ 4.4-4.6 for EUV width of 700 km
➡ n_e ~1.8–7.1×10^{10} cm^{-3}.
SST: T ~ 5500 K and a width of 400 km
➡ strong inhomogeneity. If constant pressure inside clump then core densities ~ 2.5 × 10^{11} cm^{-3}

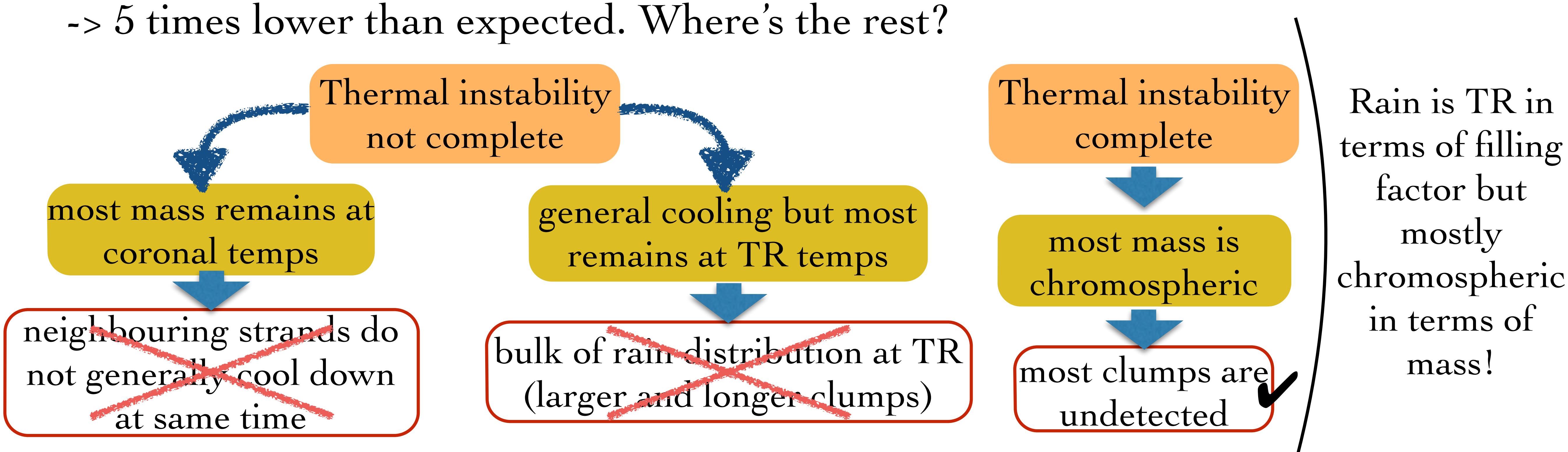
- Problem of low downward speeds:

v_{obs}~100 km/s. Assume <g_{eff}>=0.174 km s^{-2} (Antolin & Verwichte 2011)
-> v_{final}~150 km/s.
Bernouilli equation: increase of magnetic pressure downstream of 2.8-3.6 G would suffice to decelerate clump for downflows with average density 3–5×10^9 cm^{-3} and pressures 0.3 – 0.5 dyn cm^{-2}: consistent with estimated gas pressure from clump

Discussion - conclusions

Role in chromosphere-corona mass cycle

- Dataset 1: <density>= 1.4×10^{11} cm^{-3}, <width>=0.4", <length>=3.8"
  ➡ <downward mass flux per loop> = 1.23×10^{9} g s^{-1}
  Dataset 2: <mass flux> = 5.22×10^{9} g s^{-1}
- Agreement with Antolin & Rouppe van der Voort (2012), similar for prominences (Liu+ 2012) and comparable to estimated upload from spicules (Beckers 1972) -> important role in chromosphere-corona mass cycle
- Tip-of-the-iceberg scenario?
  Assuming that most of the rain is detected: <density in loop> = $6.2\text{-}7.3 \times 10^{8}$ cm^{-3}
  -> 5 times lower than expected. Where's the rest?



Thank you!

Conclusions

- Multi-temperature phenomenon: chromospheric & TR emission. Short time lags observed between TR and chromospheric lines (catastrophic cooling)
- Multi-strand nature: Significant increase of number at higher resolution. Tip of the iceberg scenario?
- Effect of temperature or resolution? Widths: 0.2″-0.3″($<10^4$ K), 0.6″-0.7″(10^{4-5} K), local effect on magnetic field? Strand-like structure in coronal lines?
- Possible influence of thermal mode at smallest scales.
- Less uniformity for lengths: many other agents at play (flows, thermal conduction, waves…)
- Mostly single emission peaks: optically thin?
- Non-thermal broadening < 10 km/s, small tail up to 25 km/s. Prominence-like material: extra component ~ 30-40 km/s. No height dependence. Slightly lower to previous results with coarser instruments. LOS effects?
- k/h ratio: 1.2 (prominence), 1.2-1.6 (coronal rain): moderately optically thick? Height dependent. Probably due to pressure changes within loop: probe of internal loop conditions. Turbulence?