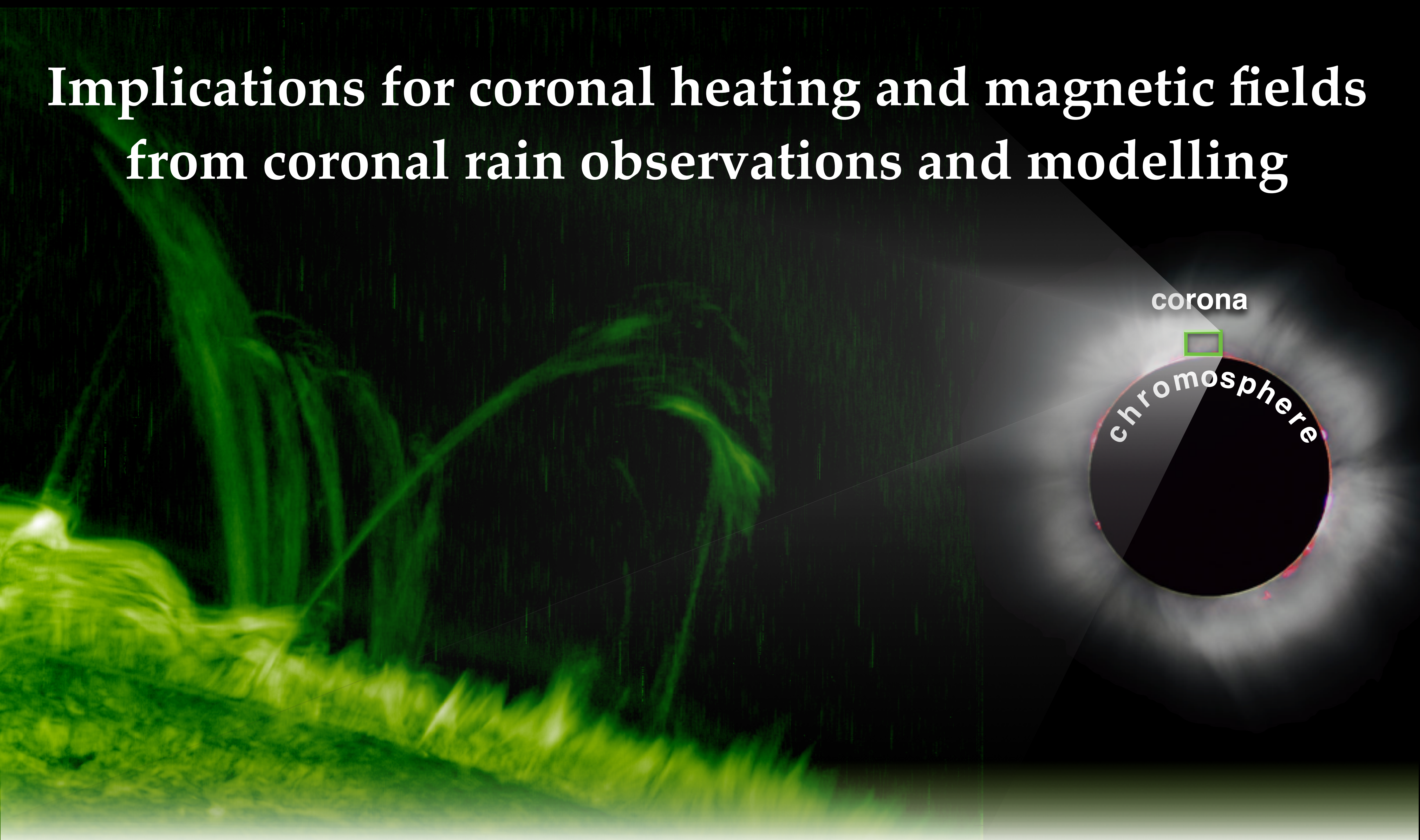
Implications for coronal heating and magnetic fields from coronal rain observations and modelling



2nd Meeting - ISSI Team in Space Sciences

ISSI Team - coronal rain

11-15 July 2016

The team

19 members - 14 institutions - 9 countries

Core members	Institute / University	Country
Patrick Antolin (coordinator)	University of St Andrews	UK
Philip Judge	HAO	USA
Lucia Kleint	FHNW	Switzerland
Wei Liu	Stanford-LMSAL	USA
Juan Carlos Martinez Oliveros	Berkeley	USA
Ramon Oliver	UIB	Spain
Luc Rouppe van der Voort	UIO	Norway
Tom Van Doorsselaere	KU Leuven	Belgium
Erwin Verwichte	Warwick	UK
Gregal Vissers	UIO	Norway
Kyoko Watanabe	NDA	Japan
Teimuraz Zaqarashvili	SRI	Austria
Young participants	**Institute**	**Country**
Xia Fang	KU Leuven	Belgium
Petra Kohutova	Warwick	UK
Tom Schad	IFA	USA
Self-supported external members	**Institute**	**Country**
Eamon Scullion	Northumbria	UK
Fabio Reale	Palermo	Italy
Roberto Soler	UIB	Spain
Sven Wedemeyer	UIO	Norway

Updates - 1st ISSI Meeting

1st Meeting: 23-27 February 2015

- 14 (+3) participants, 29 talks

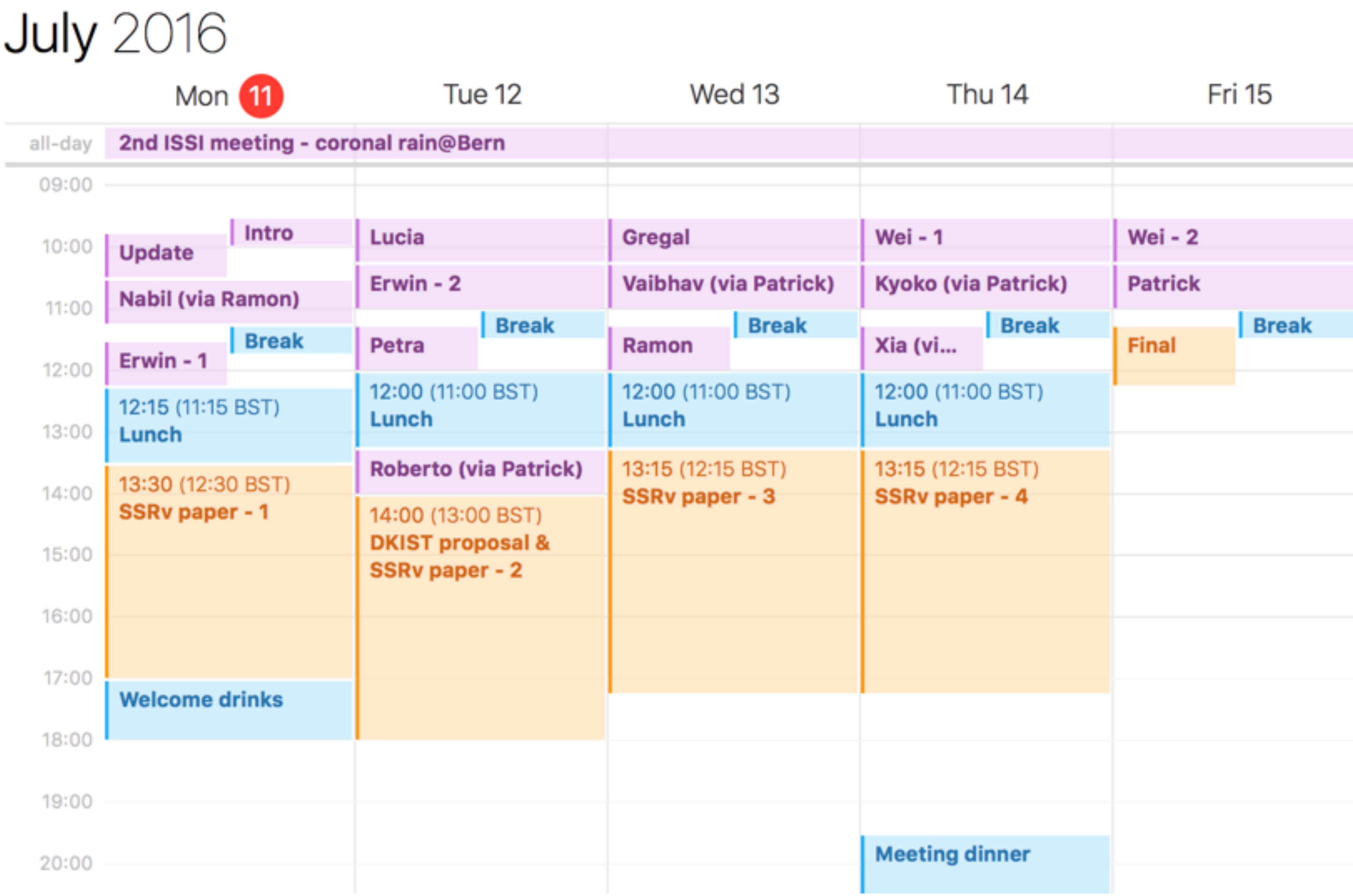
1. Observations of coronal rain in the solar atmosphere
   - The “standard model” of coronal rain (non-flaring regions)
     (Petra, Luc, Gregal, Teimuraz, Tom S., Lucia, Patrick)
   - Observations: Associated phenomena (return flows from prominence eruptions, flocculent flows)
     (Wei, Gregal, Fabio)
   - Observations: Coronal rain in post-flare loops
     (Fabio, Kyoko, Juan C.)

2. Physics of coronal rain
   - Instabilities & waves (2 sessions)
     (Xia, Ramón, Patrick, Fabio, Erwin, Phil, Tom V., Roberto)

3. Workshop – tools for rain analysis
   - IRIS, CRISPEX *(Lucia, Gregal)*

4. Future prospects
   - DKIST, ALMA, SOLAR-C *(Tom S., Sven, Kyoko)*

Calendar



- Talks
- Discussion sessions

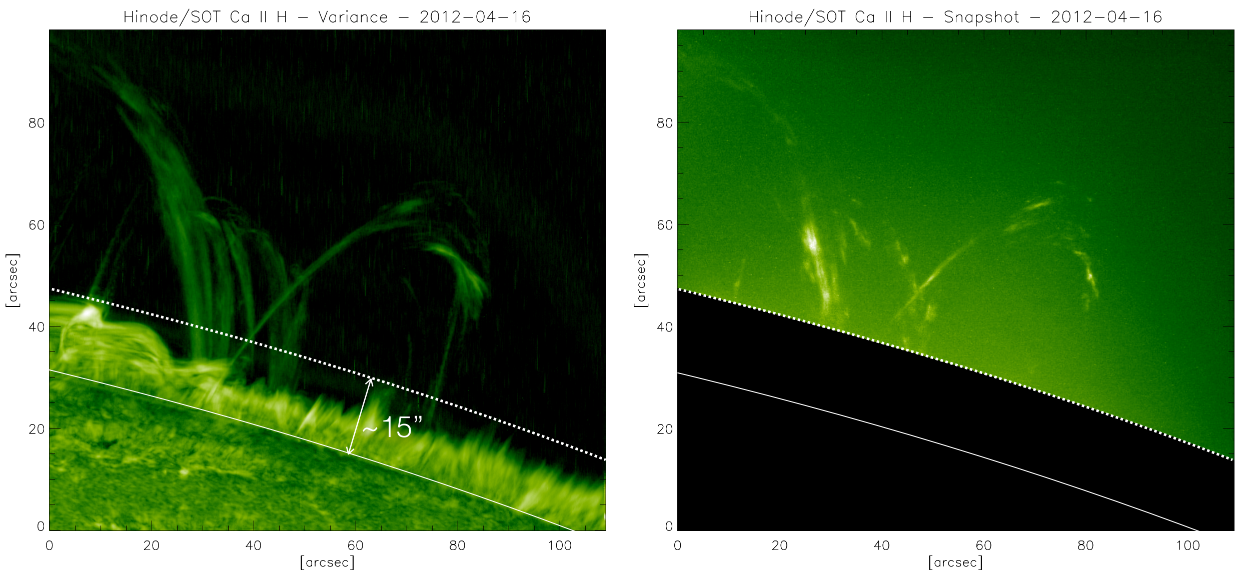
Talks: 45 min (30+15)

Selected recent work in the field

1. ALMA Proposal
2. Selected papers:
    1. Froment C. et al., ApJ. 807 (2015)
    2. Straus et al., A&A 582 (2015)
    3. Jing J. et al. Nat. Phys., 6:2319 (2016)
    4. Scullion E. et al. ApJ (accepted)
    5. Soler R. et al. (in prep) -> Tuesday afternoon

ALMA proposal
- The Cool Alter-Ego of the Solar Corona -

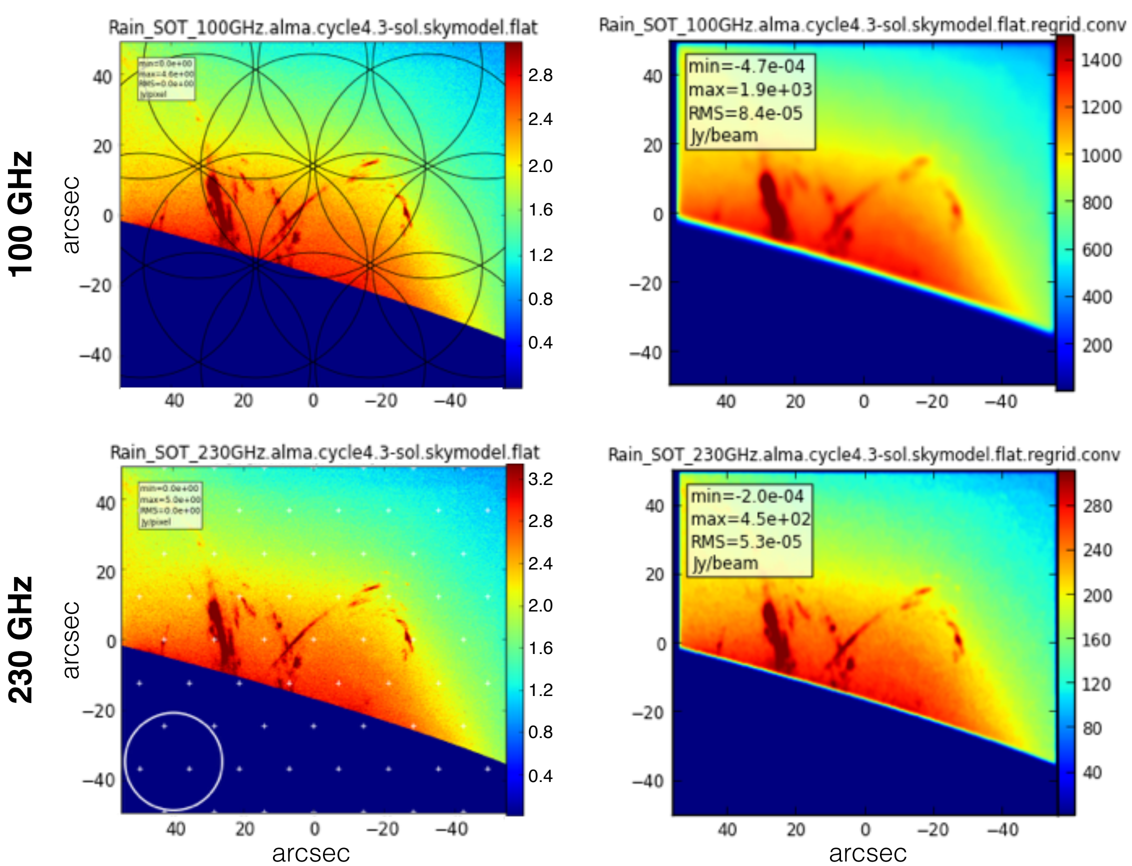
Submitted April 20, 2016



Measure thermal inhomogeneity of the solar corona:
→ characterise thermodynamic state and amount of coronal rain

Table 1: *Summary of requirements*

	Large FOV mode	High Cadence Mode
pointing	mosaic	single
FOV for band 3	60×120 arcsec^2	60×60 arcsec^2
FOV for band 6	60×120 arcsec^2	25×25 arcsec^2
# of C40 pointings in band 3	11	1
# of C40 pointings in band 6	57	1
cadence	<15 min	2 sec
duration	2 hrs×2	2 hrs×2



- ALMA Cycle 4: band 3 & 6
- 2 obs modes: Large FOV & High cadence
- Target: off-limb AR, Rain showers
- T_b: 5000 K (100 GHz), 2200 K (230 GHz), Opt. thick.: 0.6 (100 GHz) and 0.3 (230 GHz)

Evidence for evaporation-incomplete condensation cycles in warm solar coronal loops

Froment C. et al., ApJ. 807 (2015)

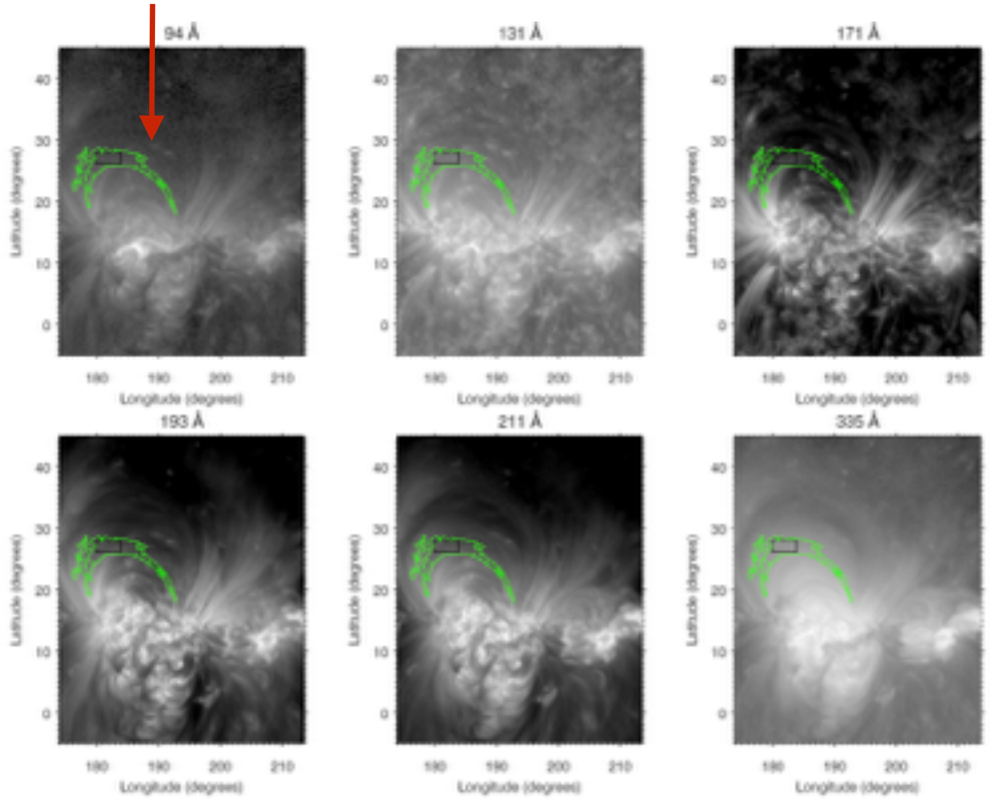
- **Context / Motivation**
  - Spatial and temporal distribution of heating of coronal loops: **impulsive heating scenarios** ("nanoflare" heating, uniform or footpoint) vs. **quasi-continuous heating at footpoints**
  - Quasi-continuous heating easily leads to thermal instability (thermal non-equilibrium) -> prominences & coronal rain, evaporation-condensation cycles
  - Cycles have a complete or incomplete character (*Mikic+ 2013*). Simulations show that such solutions match well the observations.
- **Results**

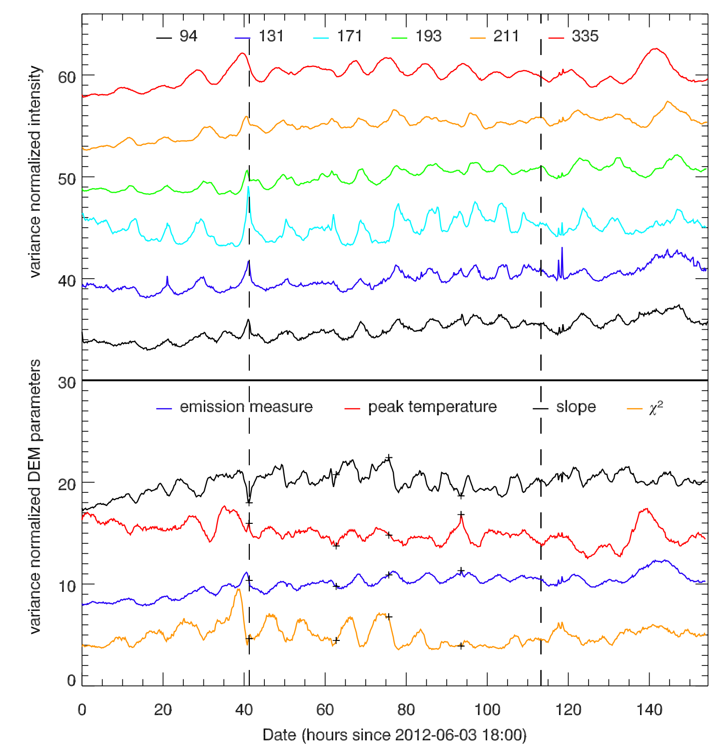
  Evidence for widespread cooling & evaporation-condensation cycles (long period pulsations in intensity & DEM: thermal cycles), some incomplete?
- **Method**

  DEM analysis + time-lag analysis + Fourier analysis. Automatic detection (*Auchère+2014*) for 6 days of AIA data (13 min cadence). 3 AR analysed in detail: >50% of detections are in AR, of which 50% are associated with loops

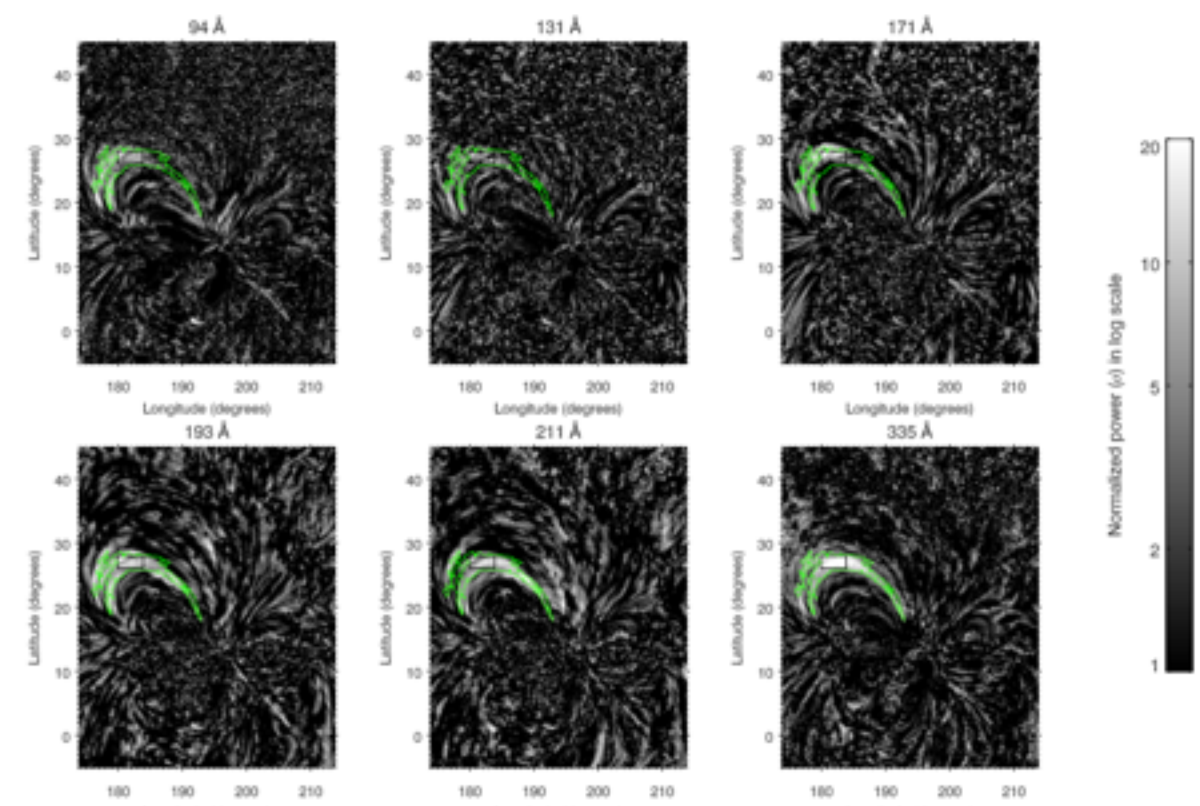
Evidence for evaporation-incomplete condensation cycles in warm solar coronal loops

location of 335 pulsations





power maps at 9 hr period:



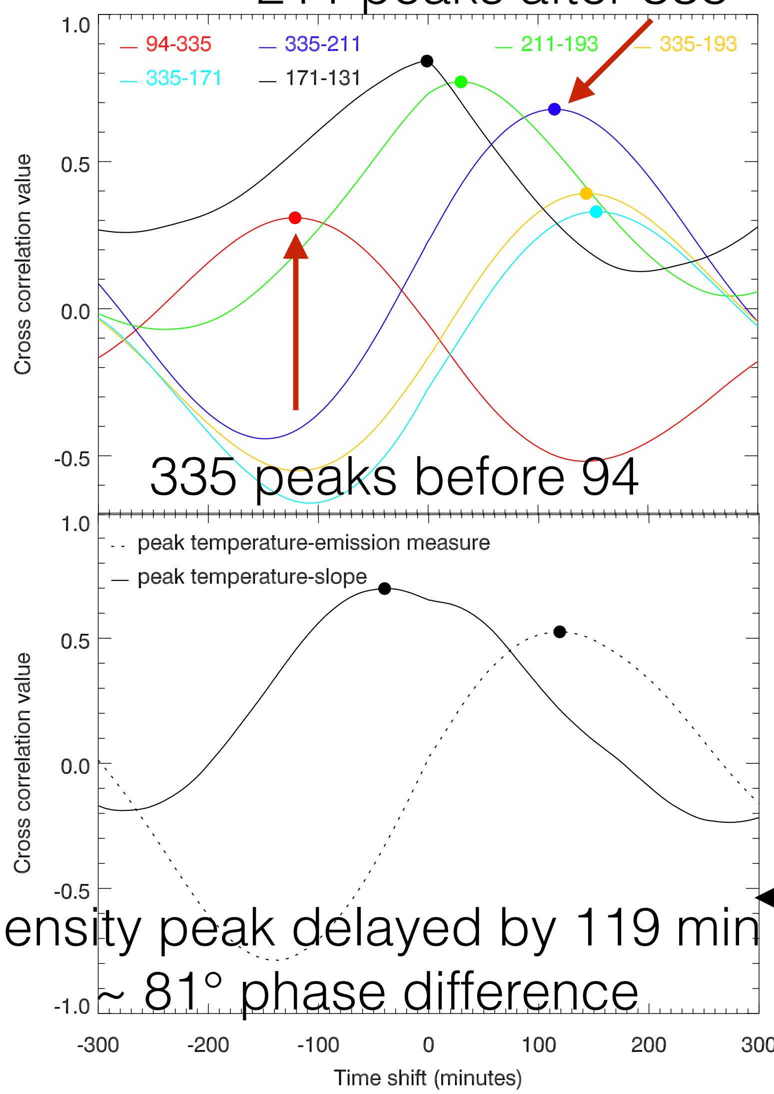
- Power peak at 9 hrs (other 2 ARs: 5.6 hrs & 3.8 hrs)
- Present in intensity, DEM, peak temperature & X^2
- -> periodical changes in thermal structure

Froment C. et al. (2015)

Observations - cooling

Pairs of channels	Time lag (min) from cross-correlations (Fig. 9)	Time lag (min) from differences of phase Fig .(11)
335-211	113	122
211-193	26	20
335-193	145	142
94-335	-115	-114
335-171	142	155
171-131	-1	-51

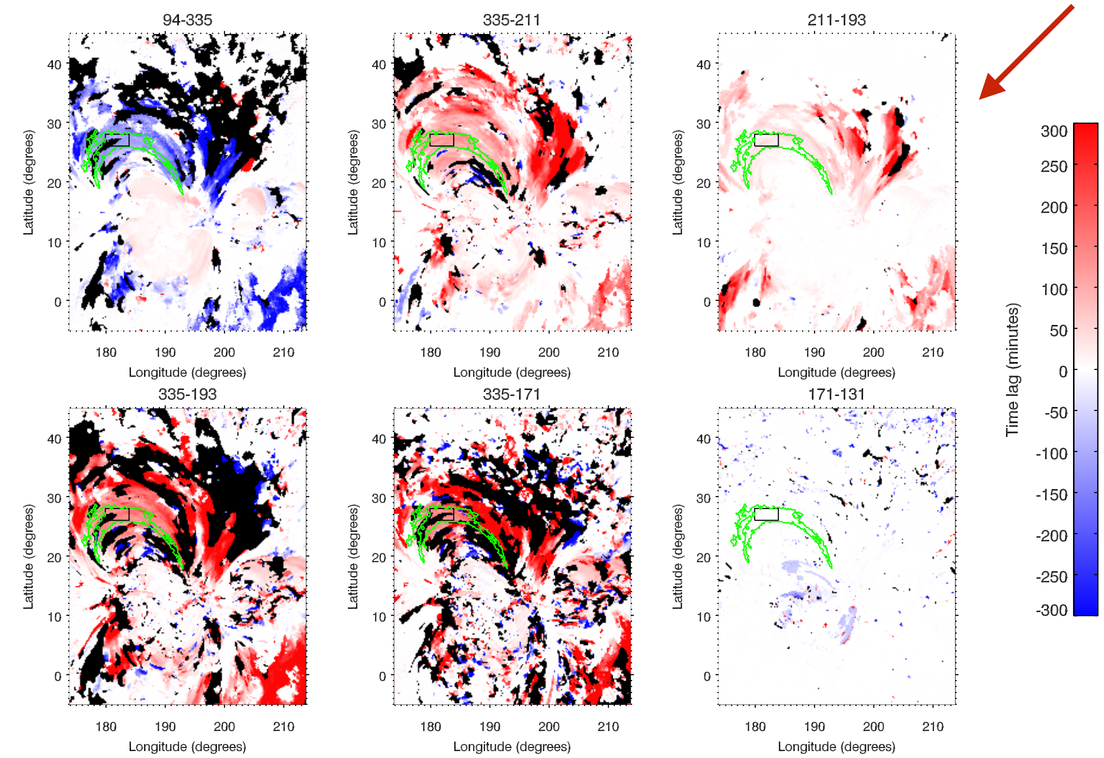
211 peaks after 335

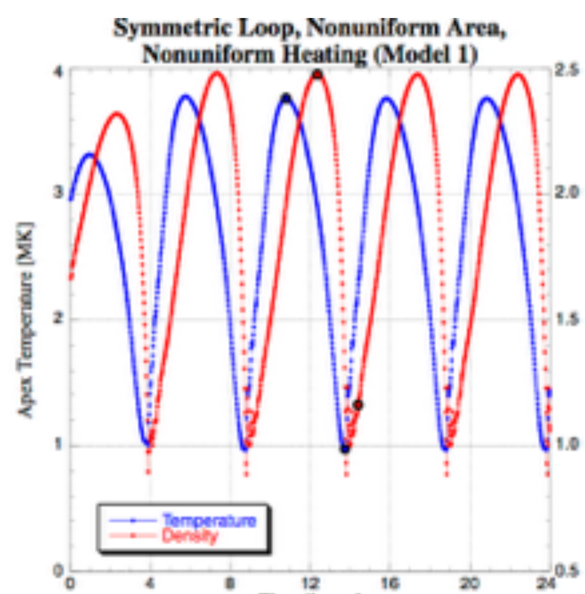


Froment C. et al. (2015)

335: 2.5 MK,
211: 2 MK,
193: 1.5 MK,
94: 1 & 7 MK,
171: 0.8 MK,
131: 0.5 MK

similar result as in Viall & Klimchuk 2012





Mikic et al. 2013

- Time-lag results confirmed by phase method (Auchère + 2014, isolates pulsating structure in Fourier space)
- TNE with incomplete condensations may provide best match

Observations - cooling

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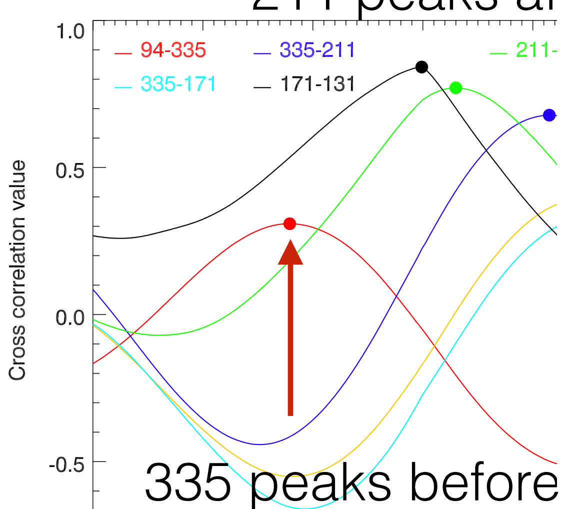
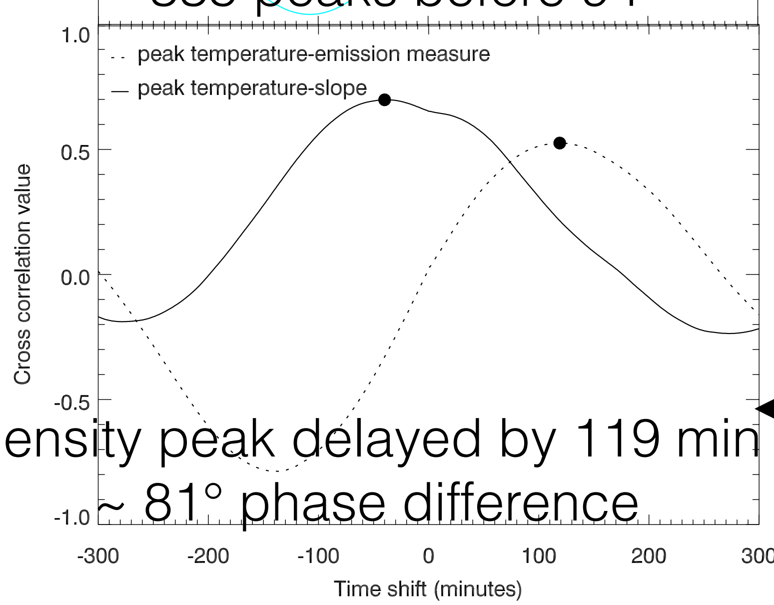
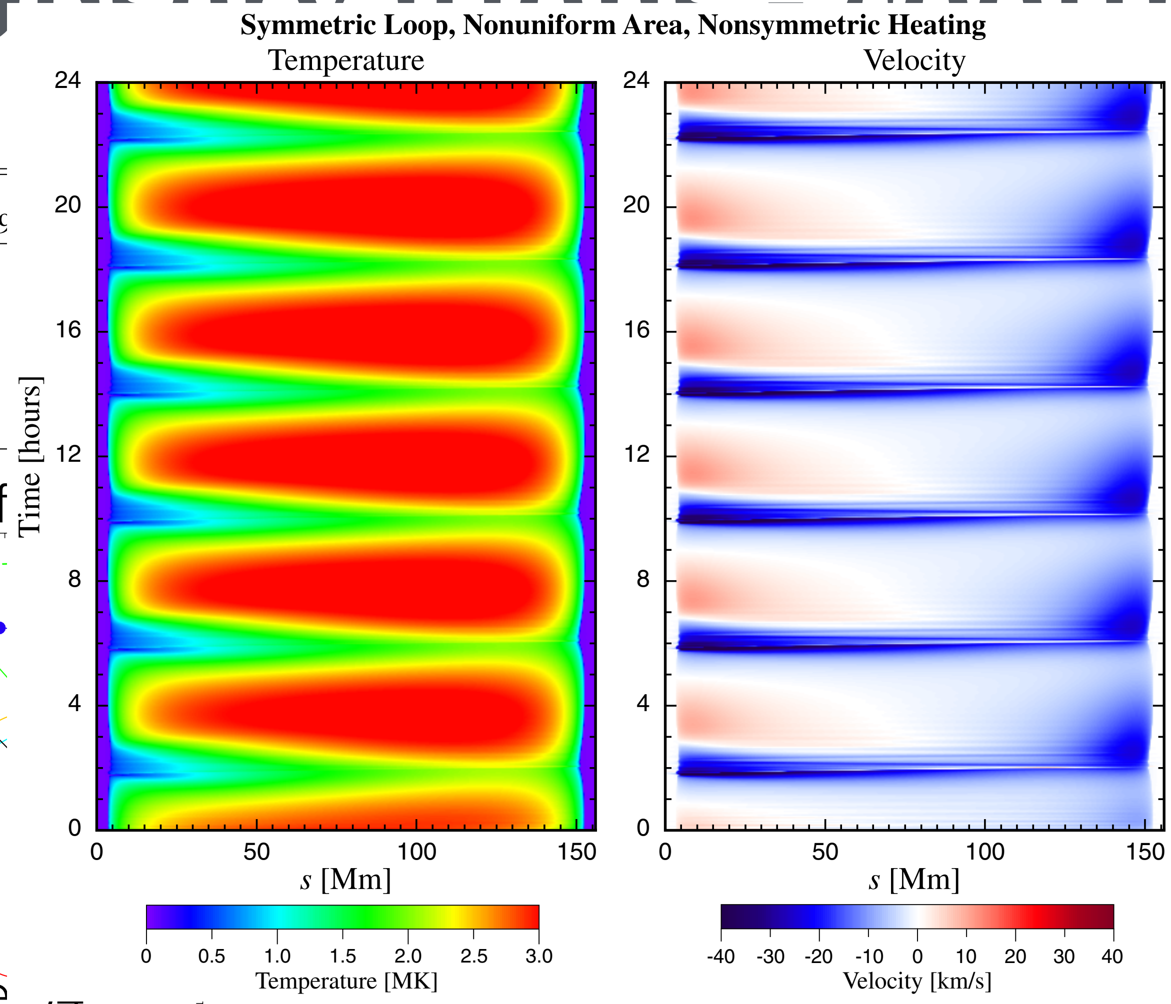


335 peaks before 94

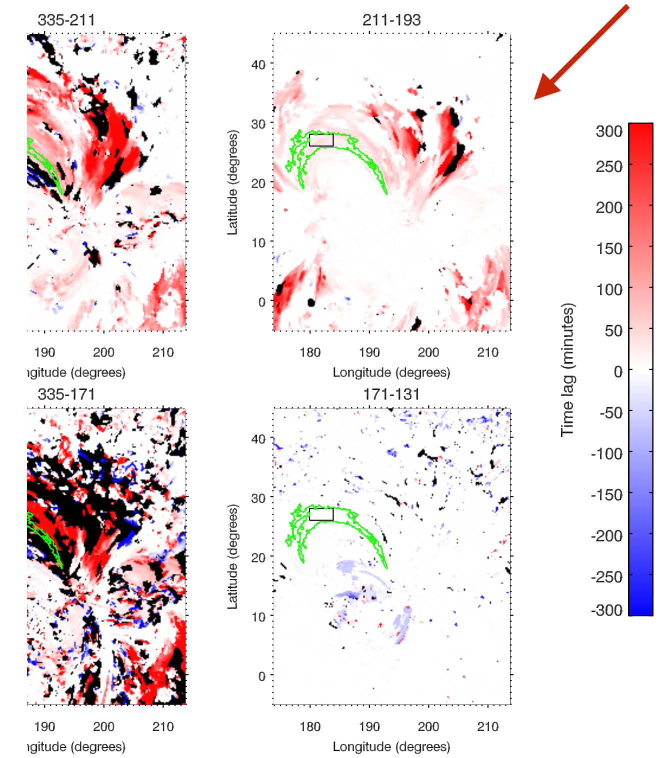


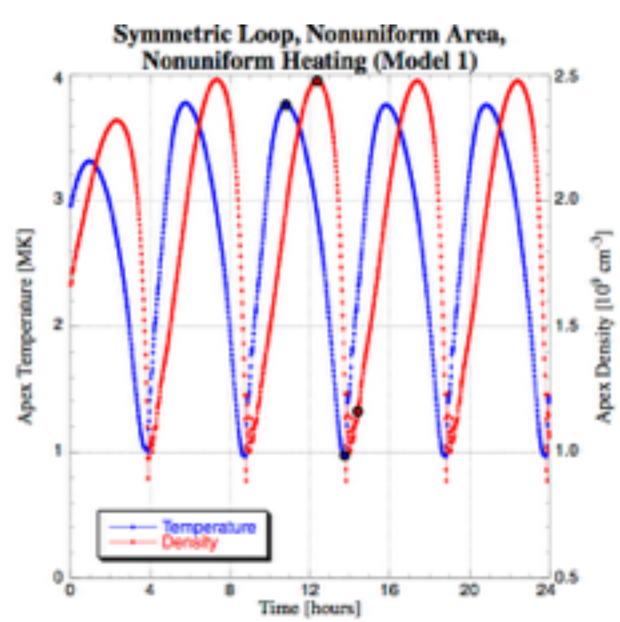
density peak delayed by 119 min
~ 81° phase difference

Froment C. et al. (2015)



as in Viall & Klimchuk 2012





Mikic et al. 2013

- Time-lag results confirmed by phase method (Auchère + 2014, isolates pulsating structure in Fourier space)
- TNE with incomplete condensations may provide best match

A steady-state supersonic downflow in the transition region above a sunspot umbra

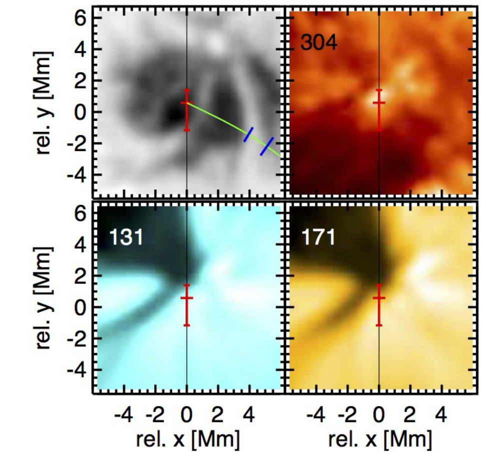
Straus T. et al., A&A 582 (2015)

- **Context / Motivation**
  - Sunspot upflows/downflows linked to heating activity
  - High-speed downflows (~80 km/s) often observed in TR lines (HRTS: Dere'82; Nicolas+'82; UVSP: Gurman'93; SUMER: Brynildsen+'01,'04)
  - IRIS: Kleint+'14 -> broad lines, no distinct 2nd component, intermittent (~20s bursts)
- **Results**

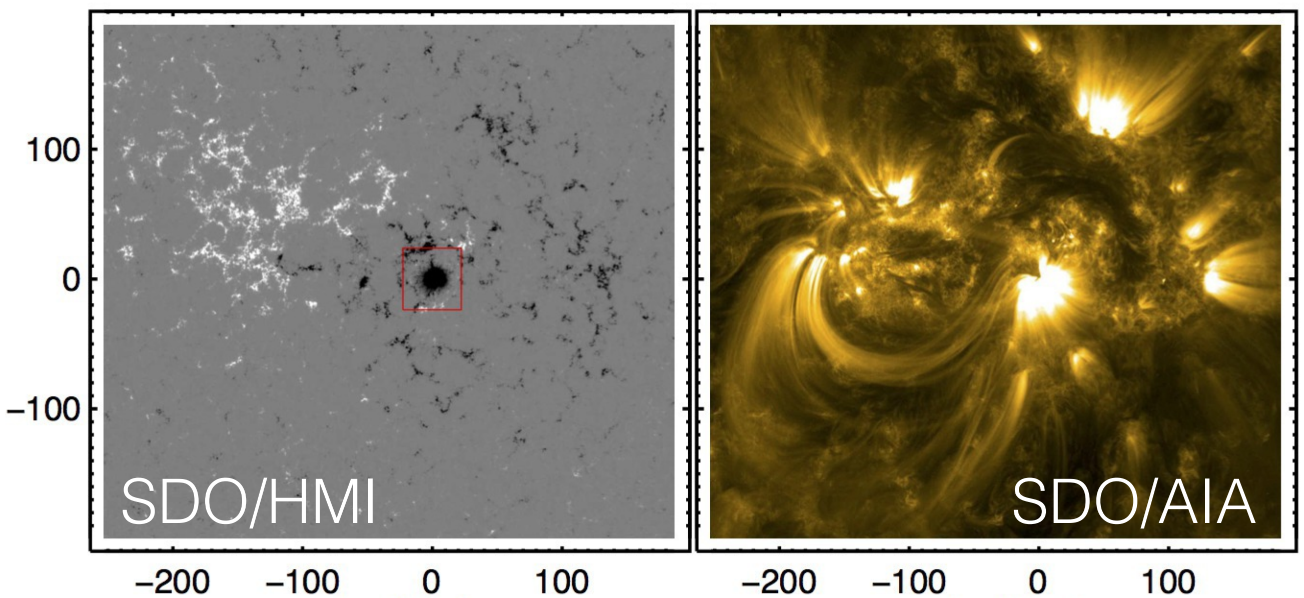
  IRIS obs in Si IV & O IV of a high-speed (~90 km/s), steady (~80 min), dense ($10^{10.6}$ cm^{-3} -> $5x10^{-7}$ g cm^{-2} s^{-1}) downflow into sunspot umbra. Interpreted as stationary termination shock of siphon flow in cool loop
- **Method**

  IRIS SJI & SG 80 min obs; density estimates: Si IV & O IV. Also co-alignment with AIA.

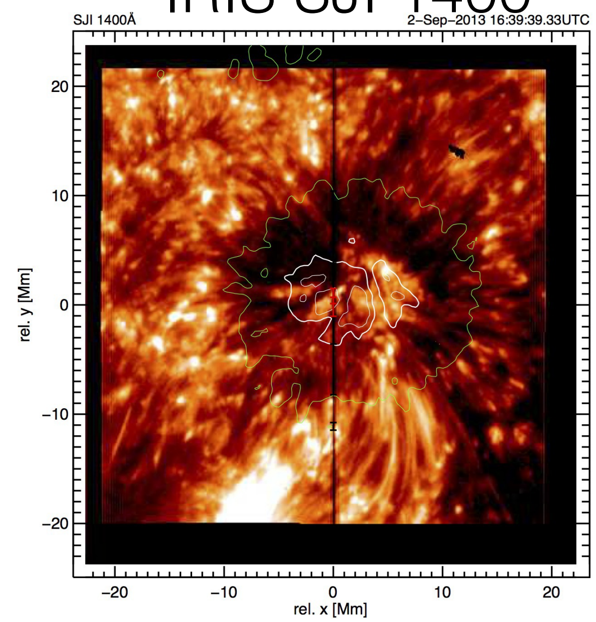
A steady-state supersonic downflow in the transition region above a sunspot umbra



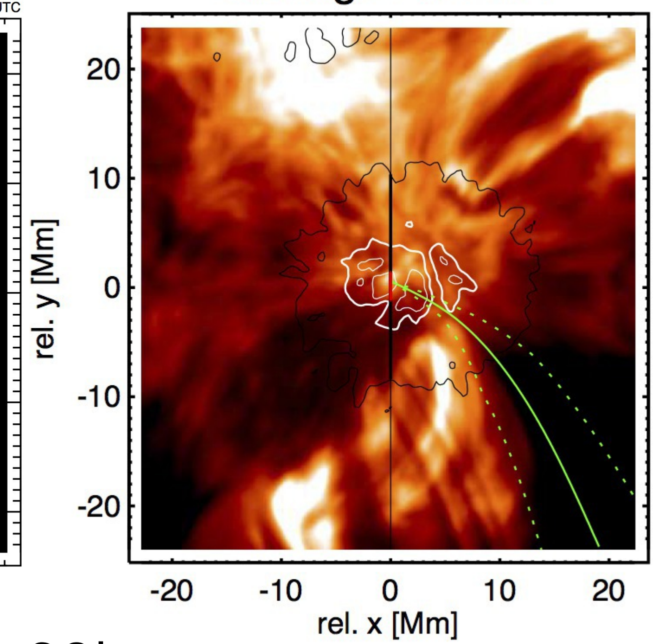
Straus T. et al., A&A 582 (2015)



IRIS SJI 1400

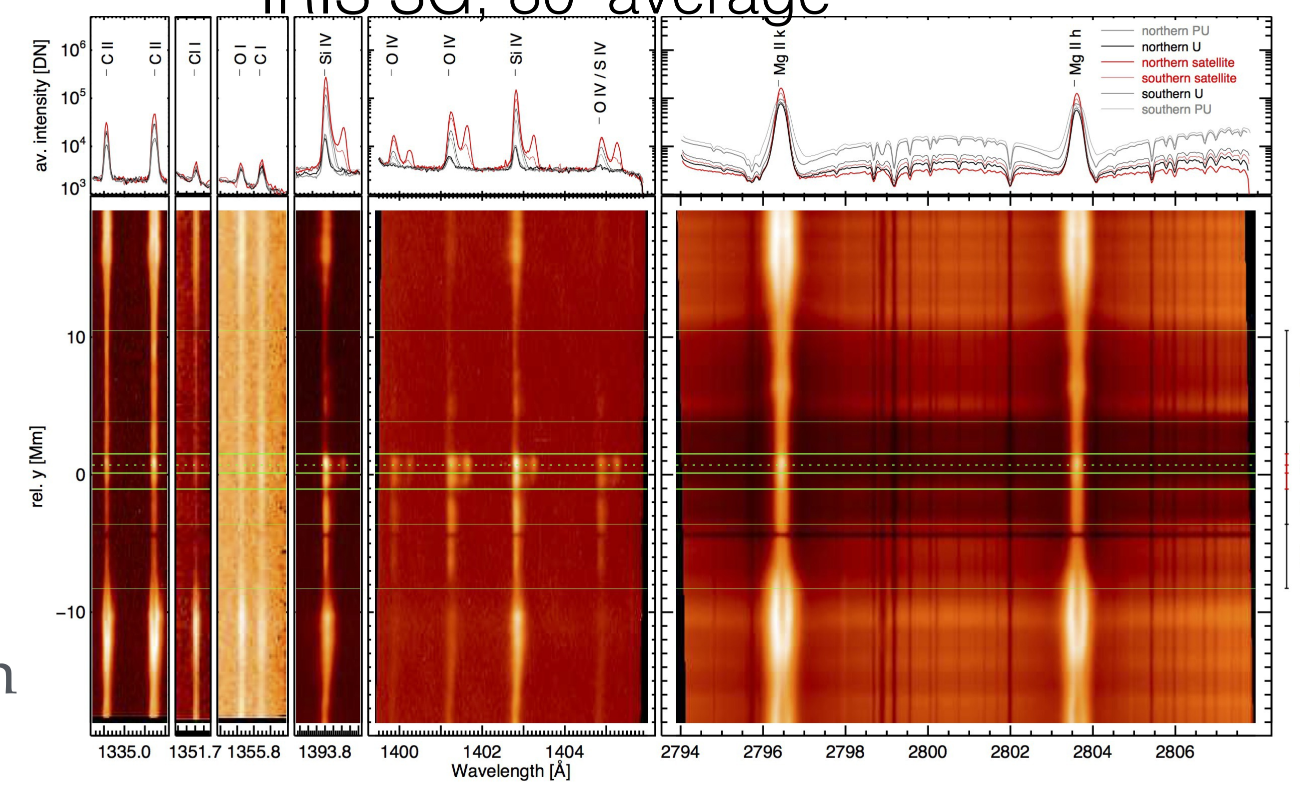


average AIA 304



OIV: 0.15 MK, **SiIV**: 0.07 MK, **no redshift in chromospheric lines**

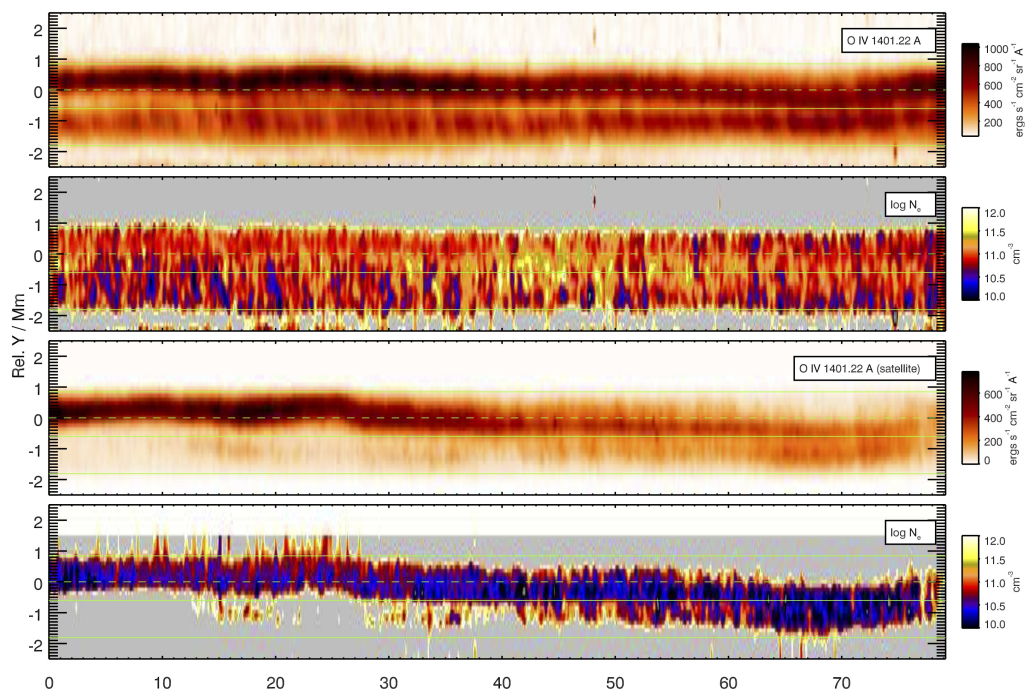
IRIS SG, 80' average



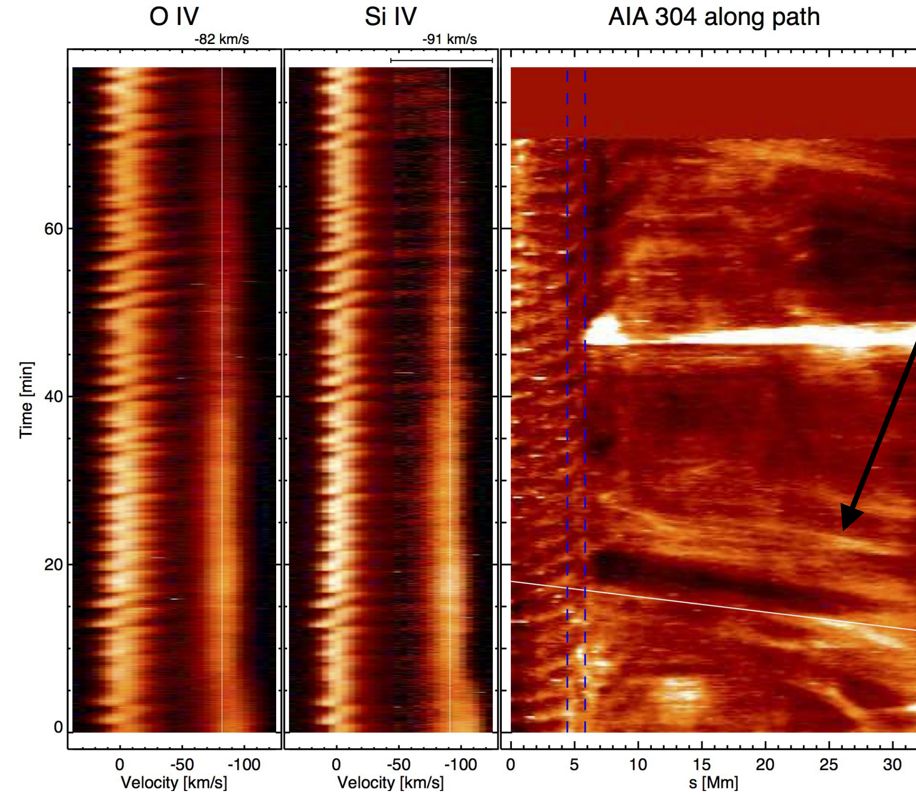
- Downflow location coincides with source of umbral running waves *(Yurchyshyn+'15)* and location of strongest field
- stable over 80", most pronounced in O IV, 70-90 km/s, Gaussian profiles, C II & O IV optically thin line ratios (~2) but moderately thick in Si IV for satellites, broader than main components

Straus T. et al., A&A 582 (2015)

- Ratio: OIV 1399.77 / 1401.16
- Mean main: log Ne~10.95±0.2, satellite: 10.6±0.25



- Anti-correlation between satellite and main intensities
- Satellite component shows less pronounced shock pattern, opposite behaviour: slow rise followed by faster decrease -> downward shock?
- supersonic -> subsonic siphon flow: shock & modulation by 3-min wave

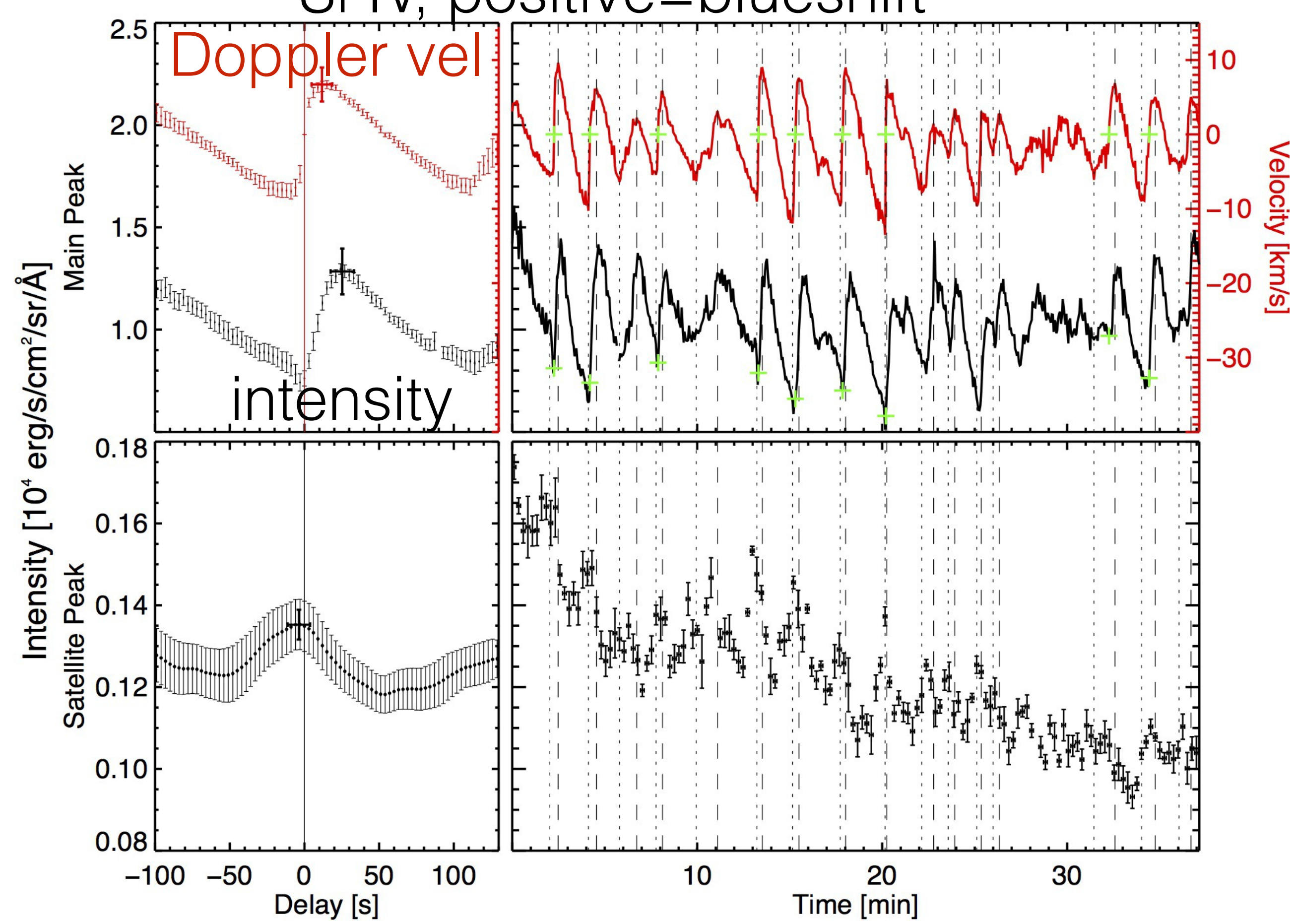


coronal rain

clumpy, intermittent, usually T~10^4 K, "may not be the cause"

- Brighter satellite when main component passes through 0 (redshift to blueshift)

Si IV, positive=blueshift



Unprecedented Fine Structure of a Solar Flare Revealed by the 1.6 m New Solar Telescope

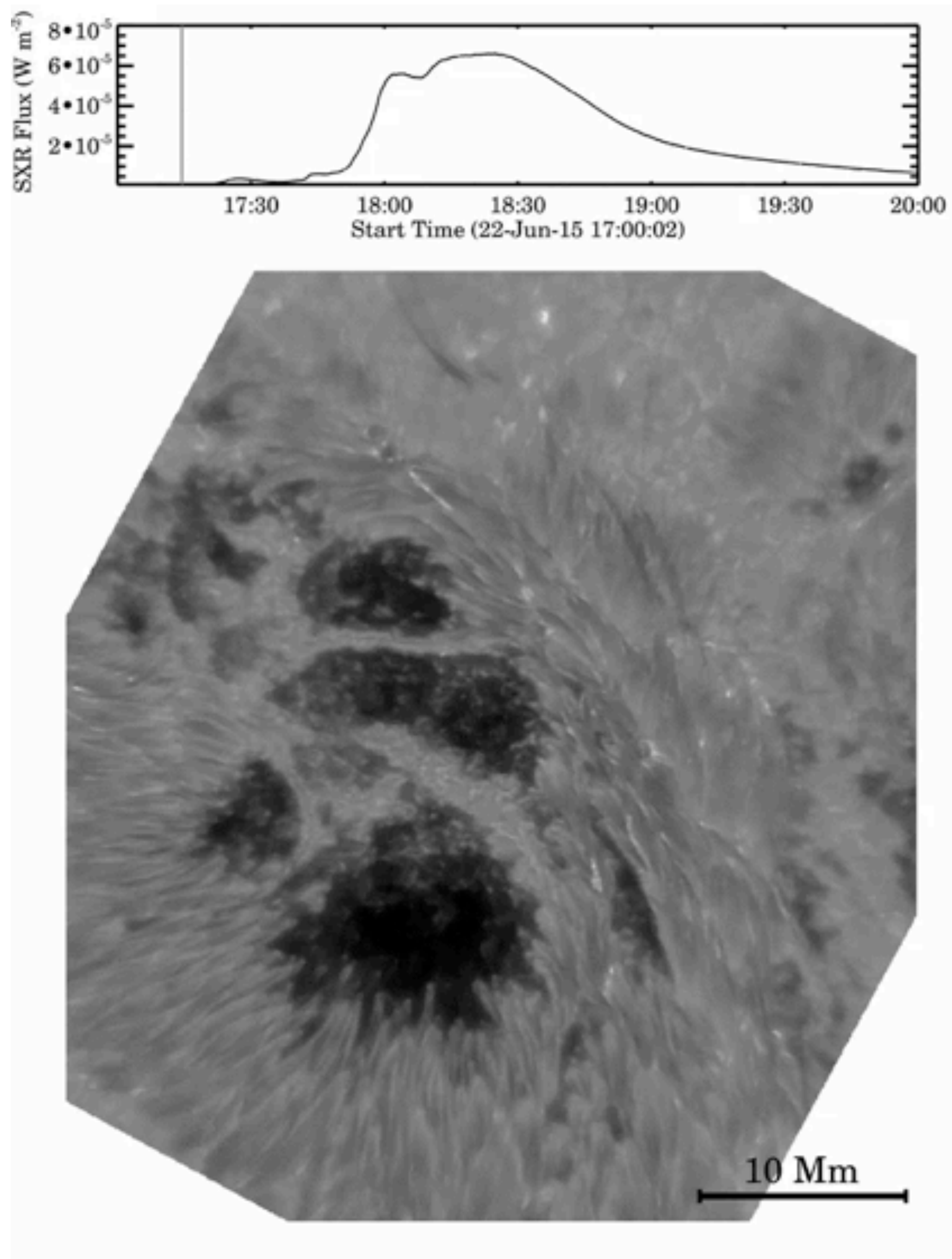
Jing J. et al. (2016)

- **Context / Motivation**
  - Fine-structure of flare ribbon, post-flare loops (rain) & associated energy transport in flares not well constrained.
- **Results**

  Similar cross-sectional widths of are ribbons, post-flare loops and footpoint brighenings, (80–200) km. Emission area strongly constrained: influence for non-thermal electron estimation
- **Method**

  Observation of a M-class flare with VIS/NST (1.6 m), Hα @ BBSO + IRIS

Unprecedented Fine Structure of a Solar Flare Revealed by the 1.6 m New Solar Telescope

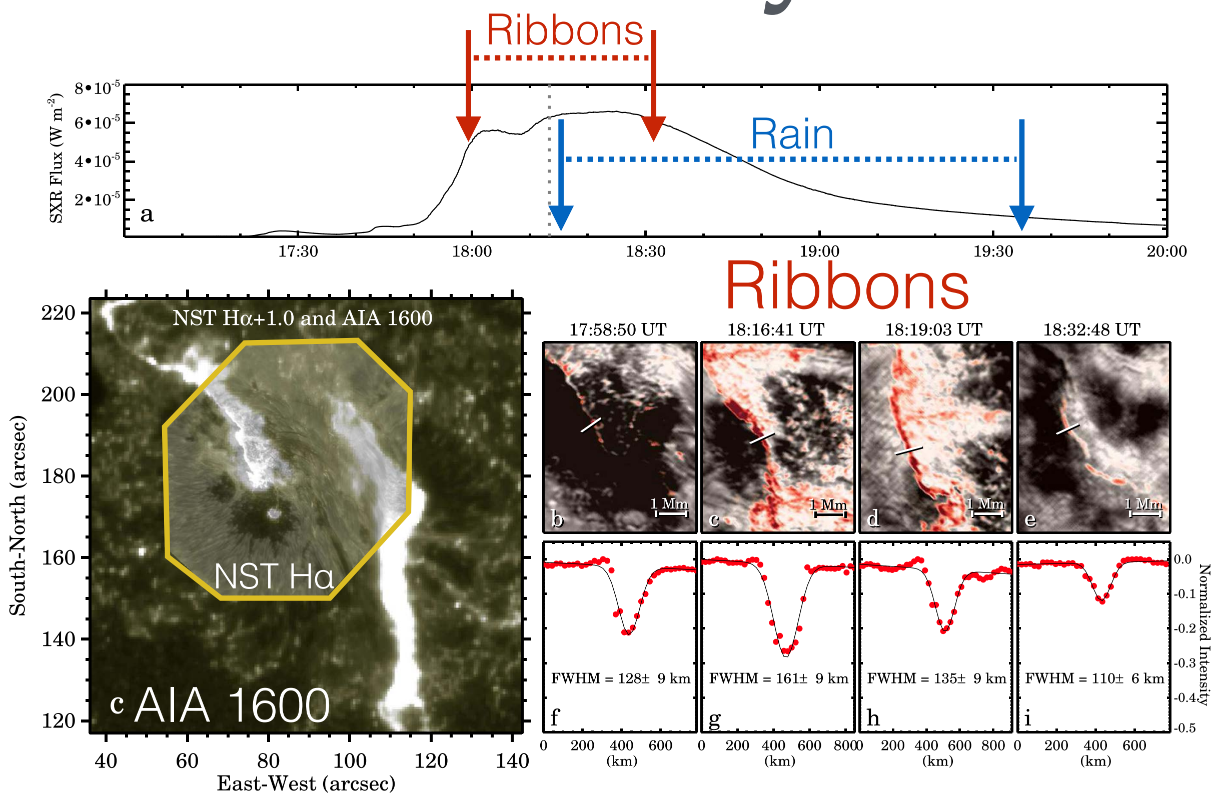


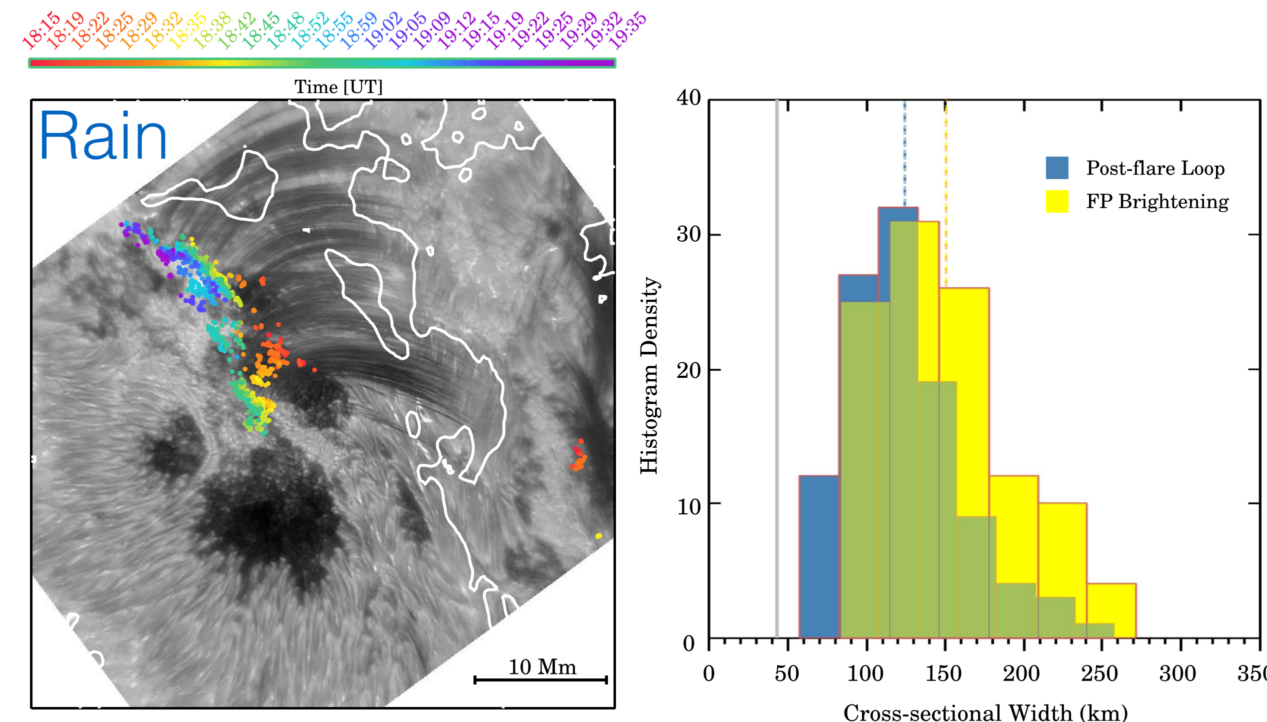
GOES X-ray 1-8 Å

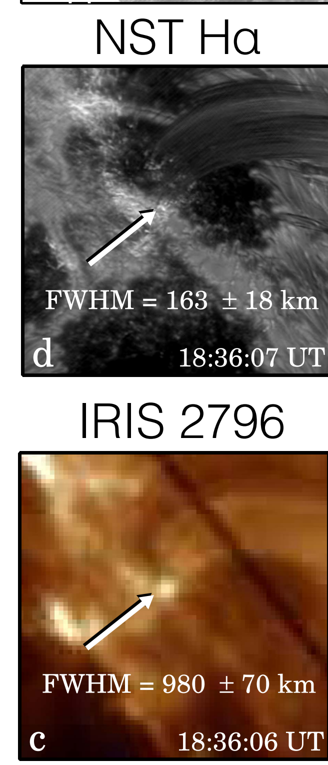
NST Hα

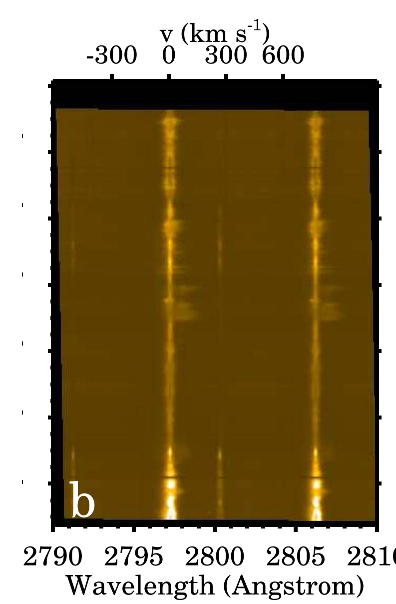
Jing J. et al. (2016)

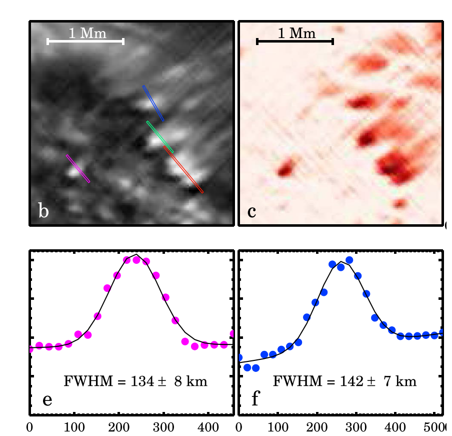
Unprecedented Fine Structure of a Solar Flare Revealed by the 1.6 m New Solar Telescope











- Path of ribbons re-traced by rain
- Visible & UV brightening at FP from rain (post-flare loops) ≠ SCBs
- Energy budget? Collision or shock wave?
- Size of ribbons, rain blobs and FP brightening very similar
- -> true spatial scale of energy transport mechanism?

Jing J. et al. (2016)

Observing the formation of flare-driven coronal rain

Scullion E. et al., ApJ (Accepted)

- **Context / Motivation**
  - Rapid cooling and fine-scale structure of plasmas in post-flare loops
- **Results**

  - Detail investigation of coronal rain formation in post-flare loops. 4 phases: conduction to radiation dominated

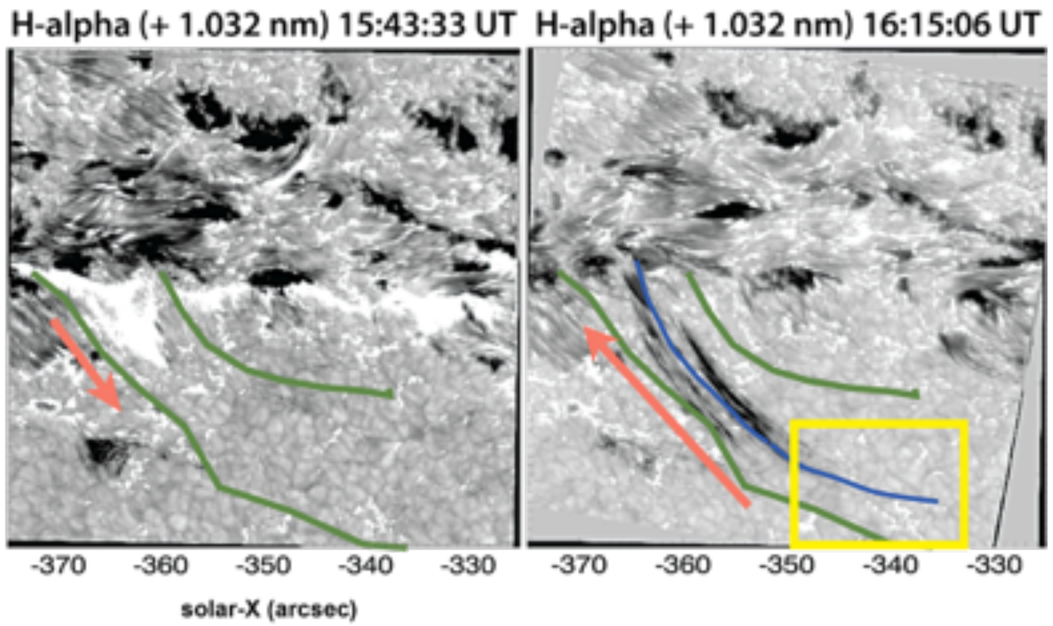
  - Acceleration of cooling at final stage in chromospheric coronal rain formation (7300 K/s -> 22700 K/s).
- **Method**

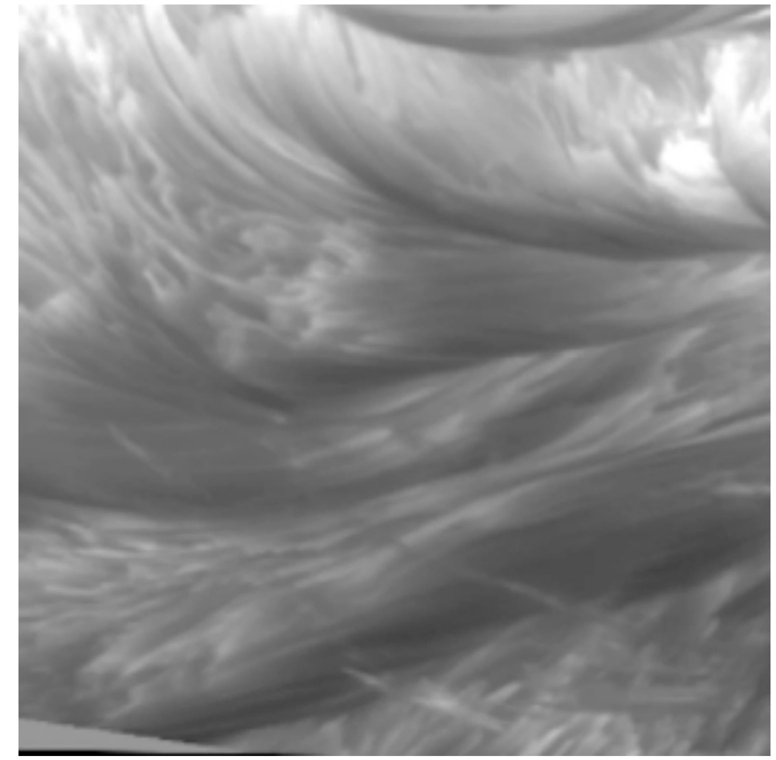
  SST/CRISP + SDO/AIA

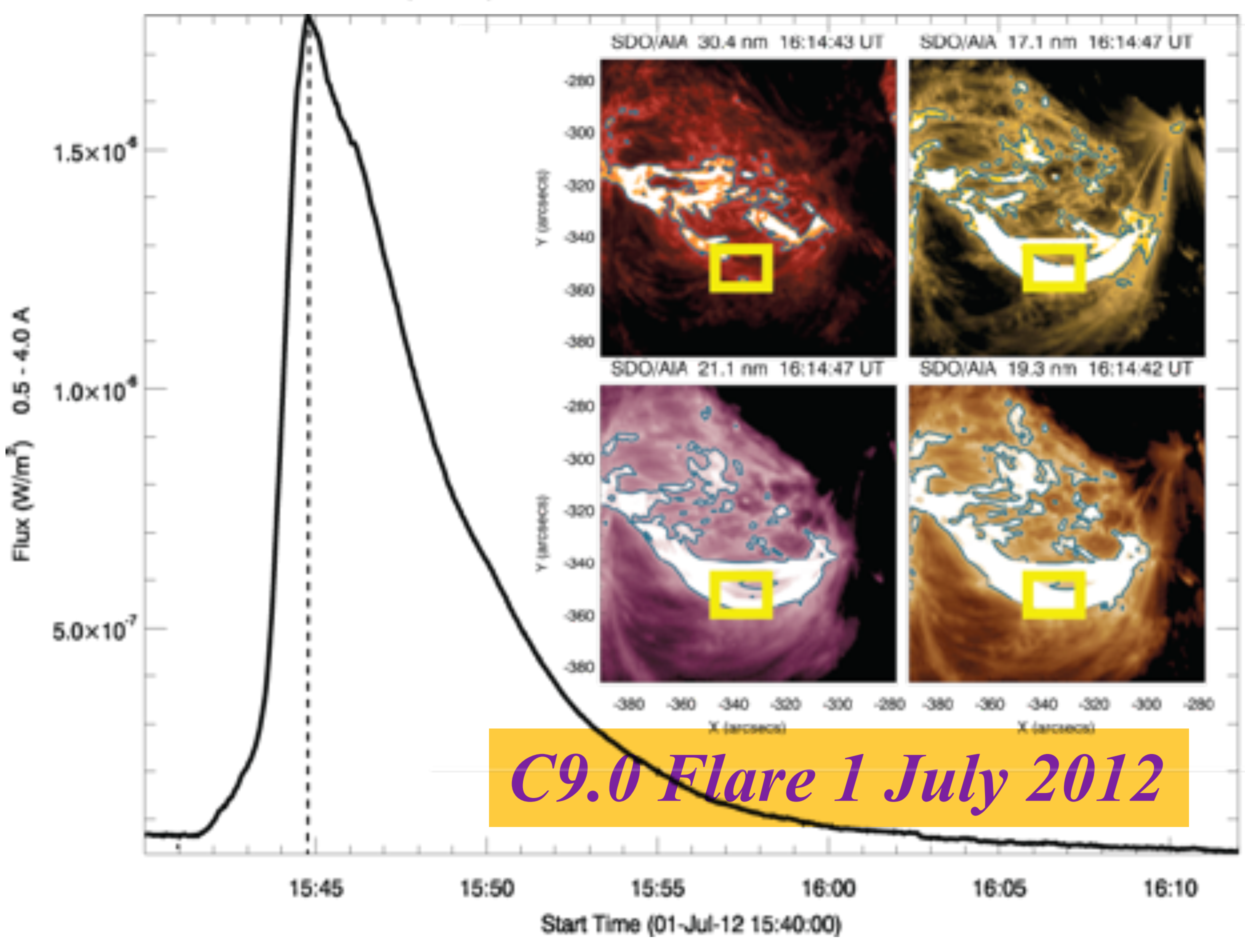
  DEM inversion

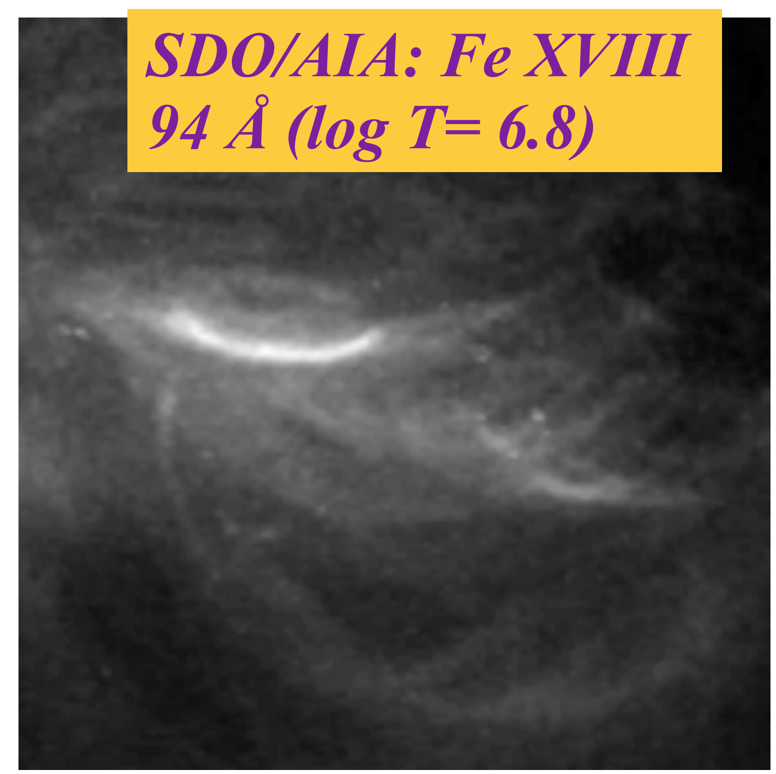
Observing the formation of flare-driven coronal rain

Source and sink of coronal rain

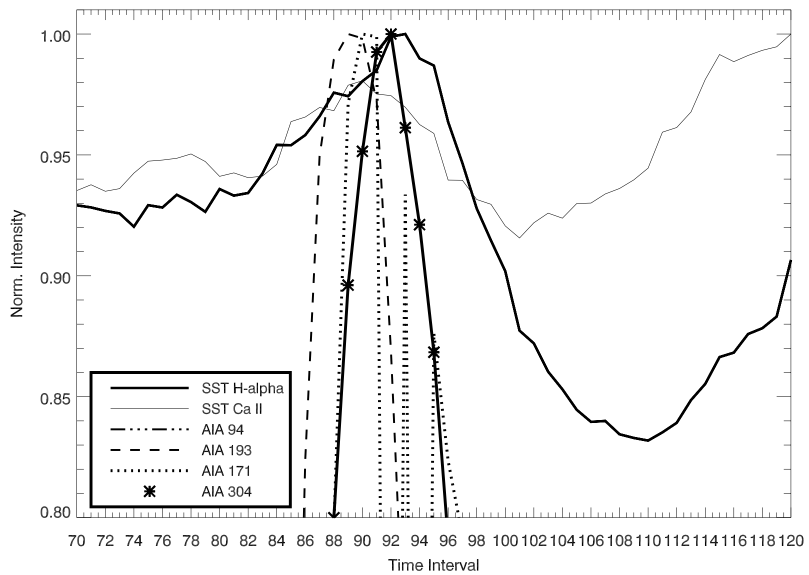


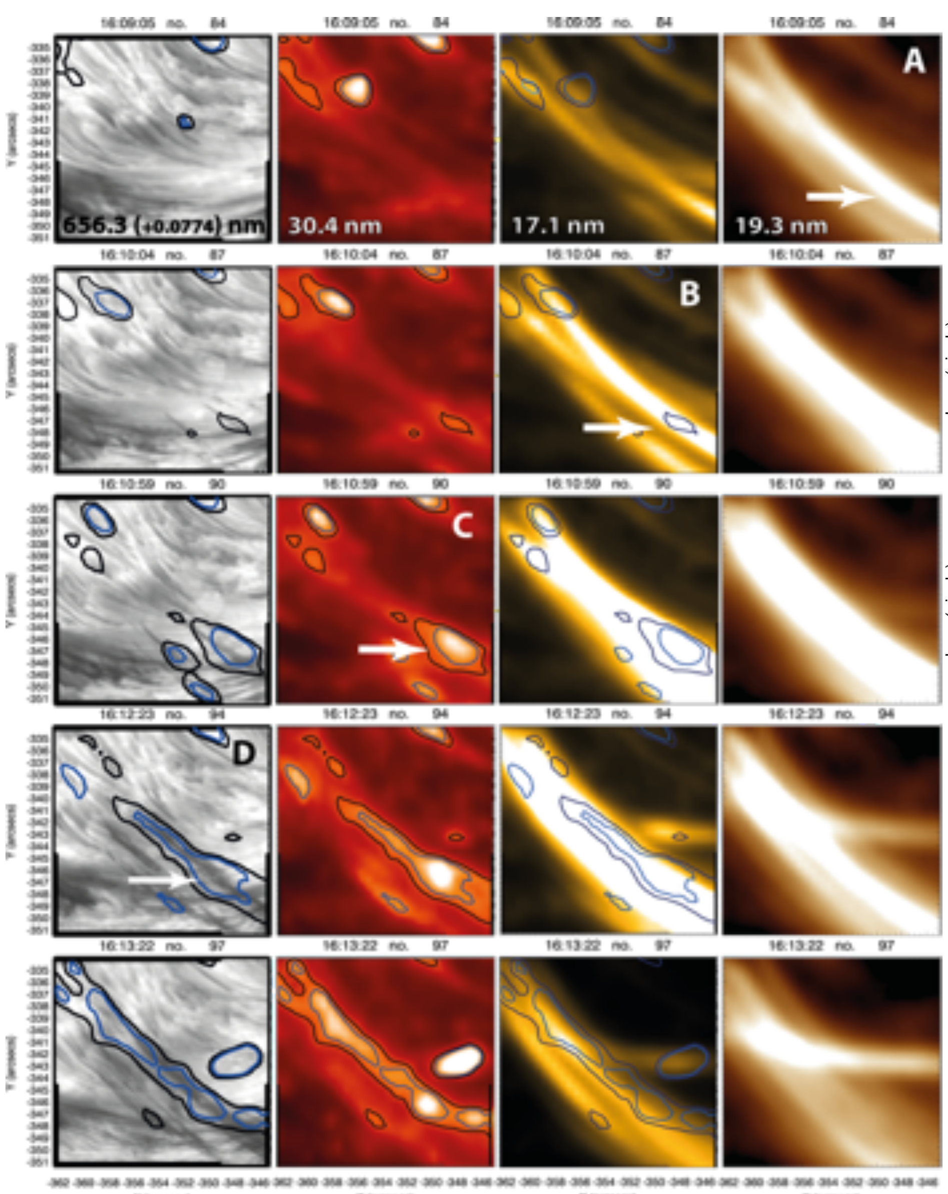


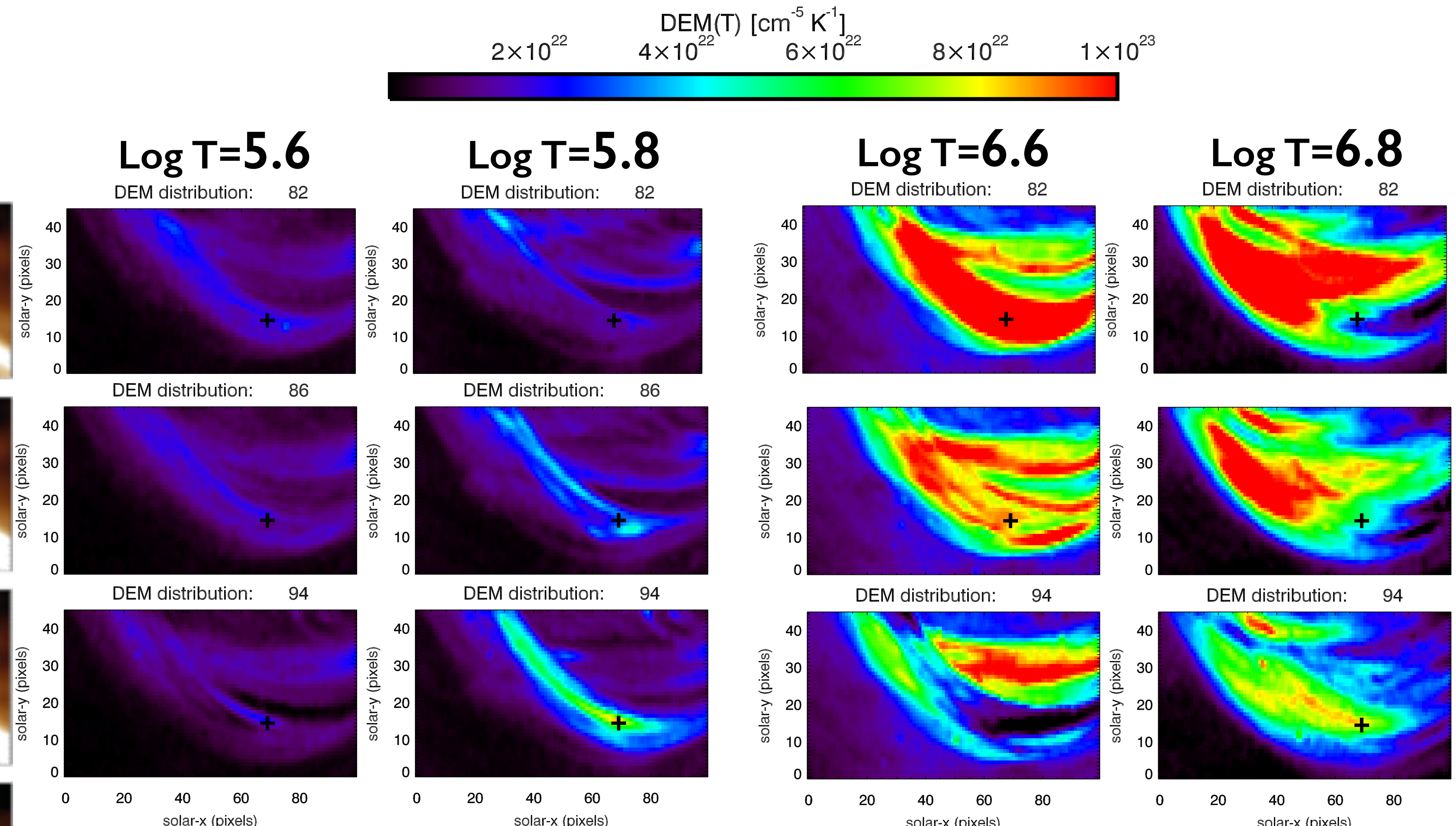


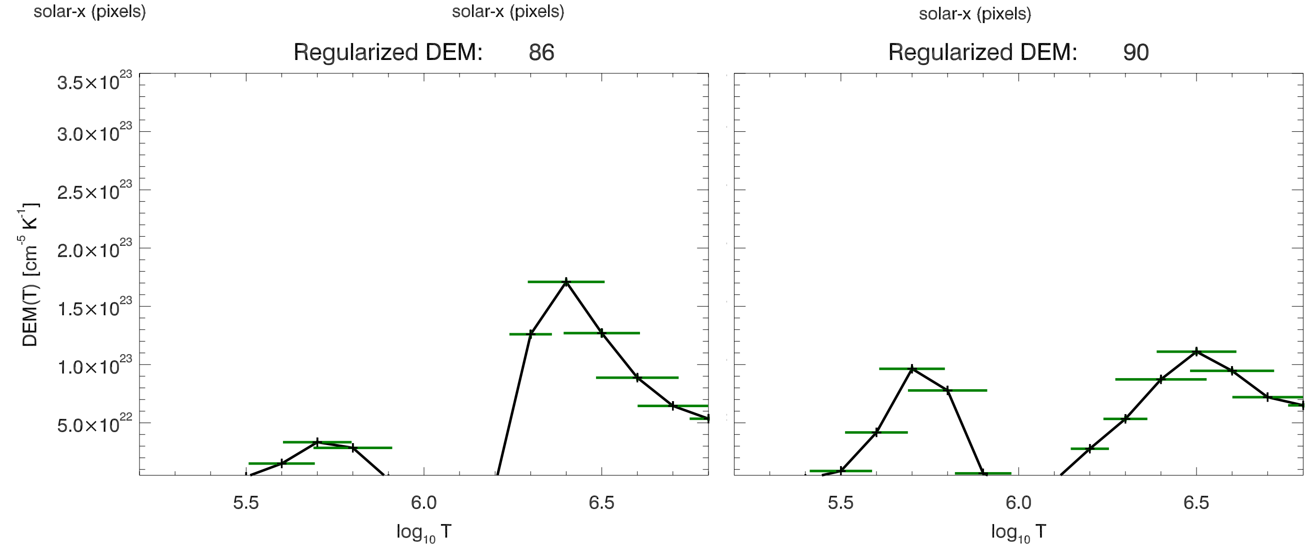


Observing the formation of flare-driven coronal rain



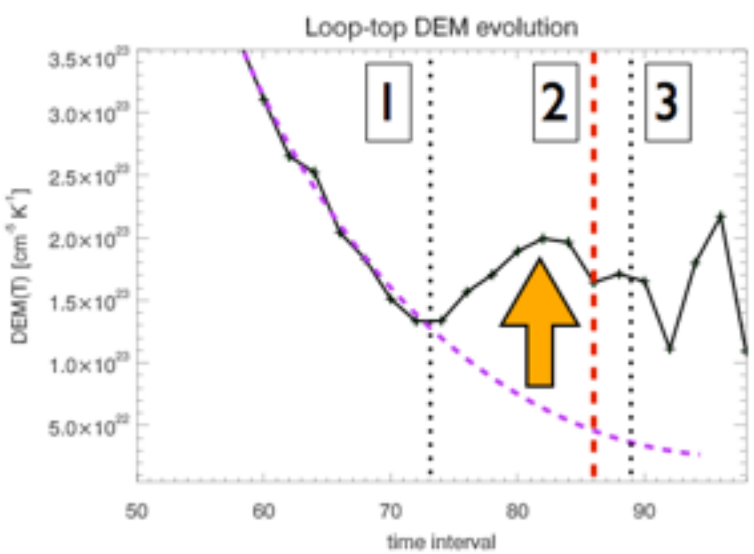


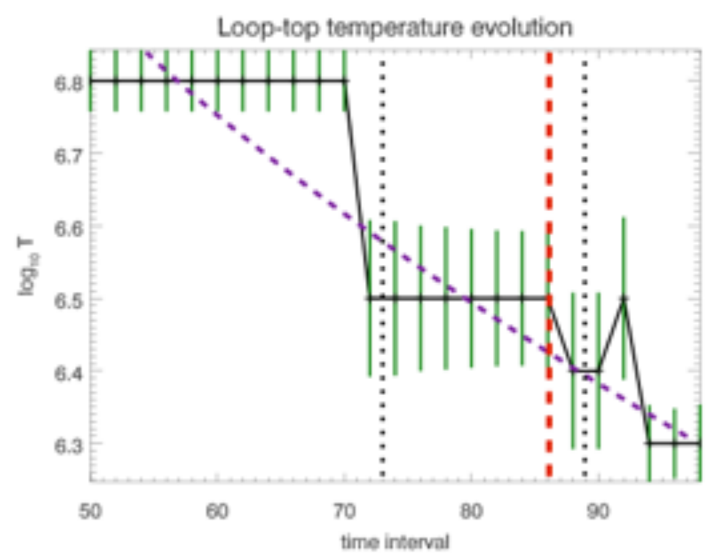


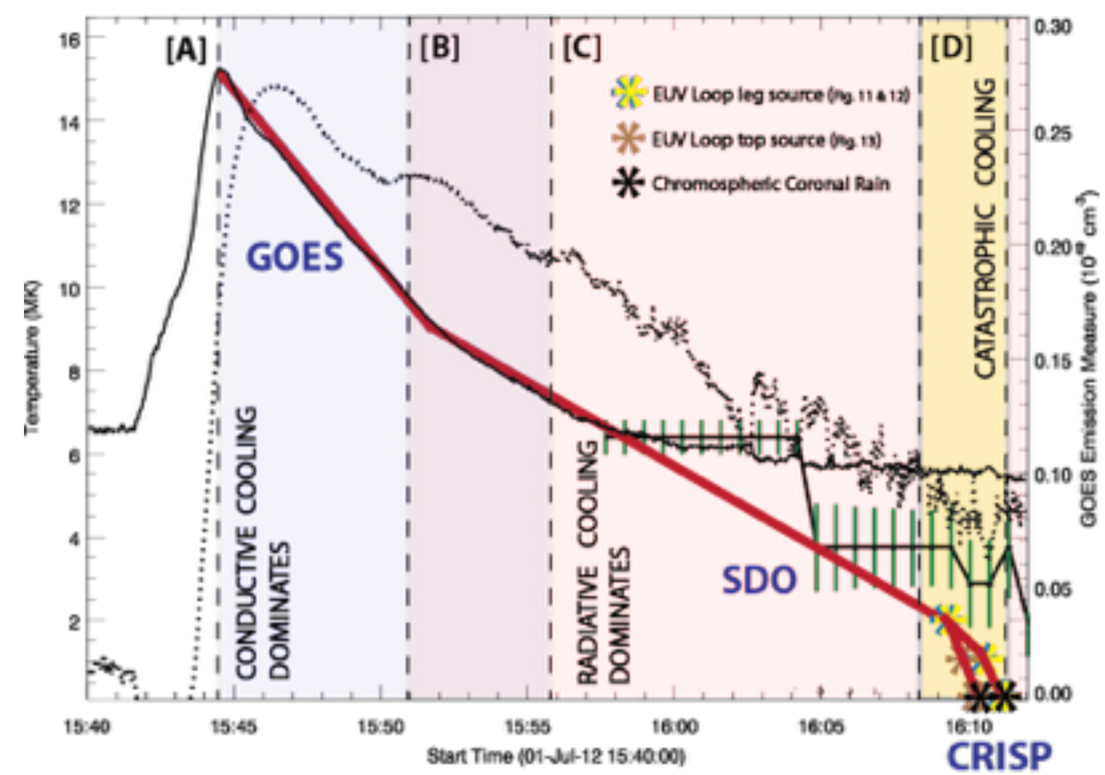


Observing the formation of flare-driven coronal rain

Scullion et al., 2016







rate of cooling = 7,300 K / sec

Detecting the onset of the loop-top thermal instability [1] leading to mass condensations [2] and at last catastrophic cooling with detectible chromospheric coronal rain [3]

Space Science Review on Coronal Rain

Major deliverable of ISSI Team in Space Sciences

Space Science Review on Coronal Rain

Structure - main topics

- Definition: thermal instability
- Kinds (quiescent & flare-driven), visibility across spectrum
- Methods: Observations & Simulations
- Relation with similar phenomena (prominences & flocculent flows)
- Interdisciplinary (Solar & Stellar)
- Main target problems