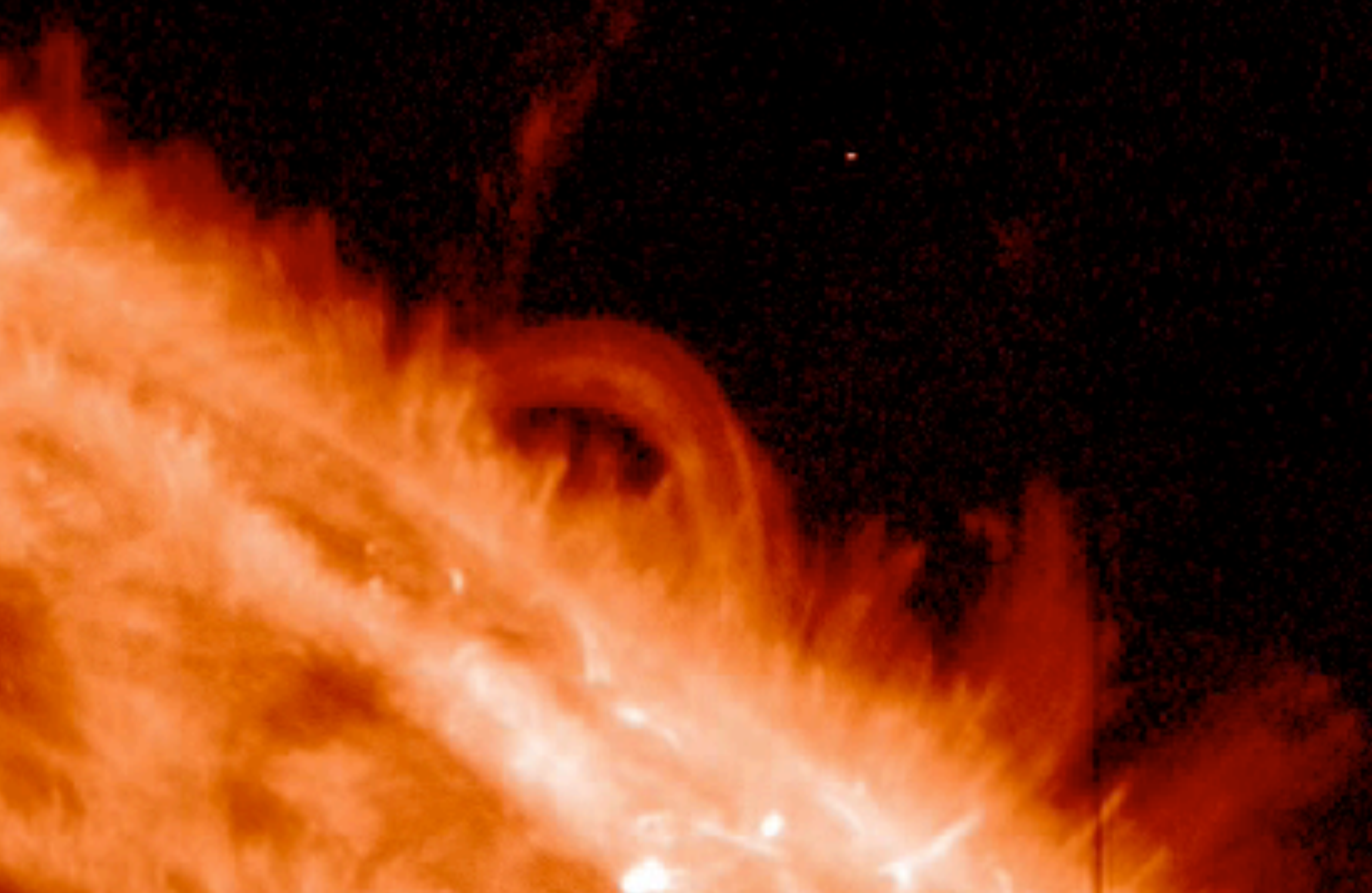
Interface Region Imaging Spectrograph (IRIS)

What have we learned and which exciting discoveries await us?

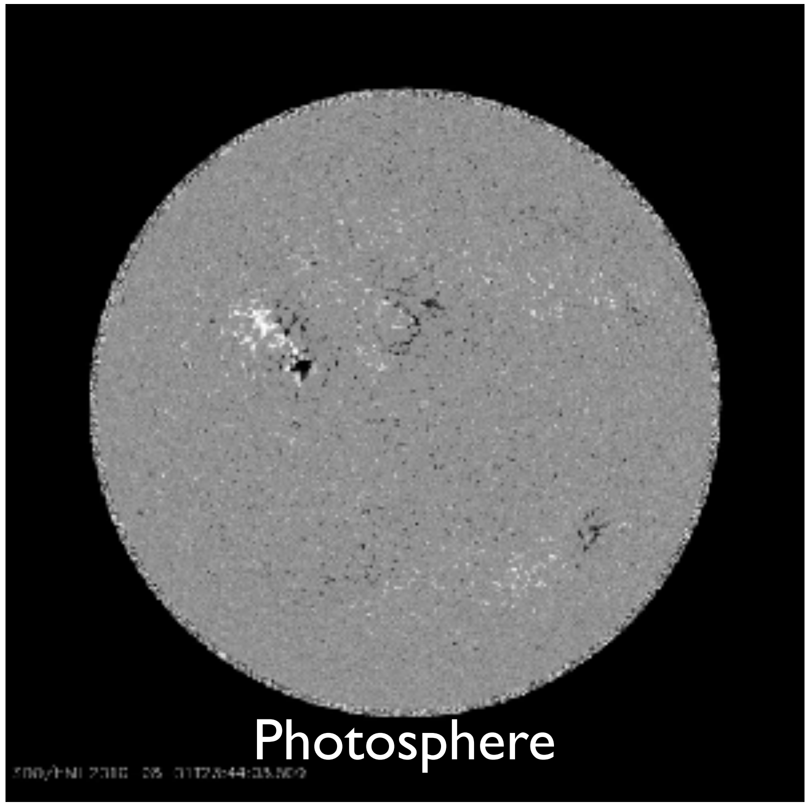
Bart De Pontieu

IRIS Principal Investigator, LMSAL

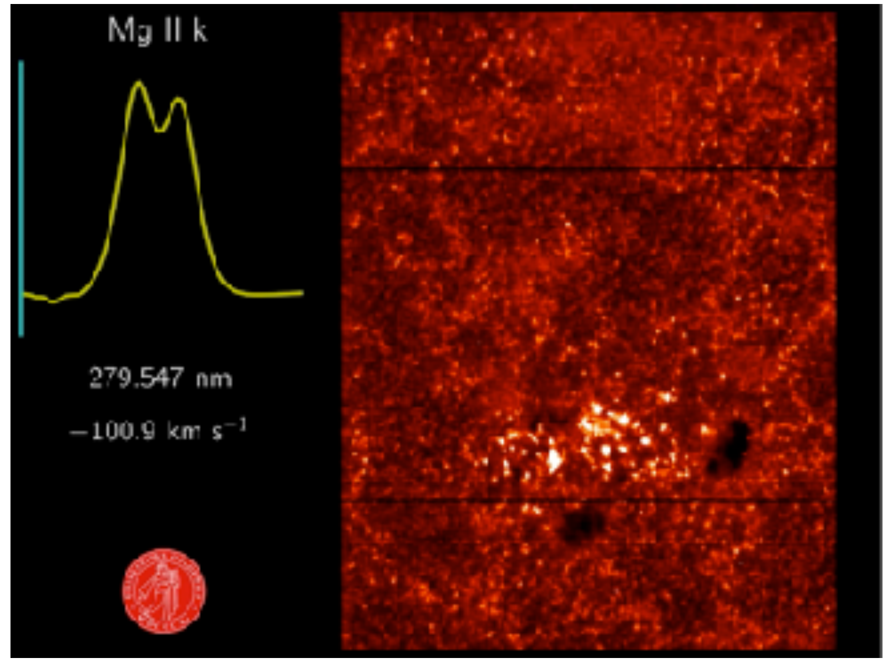


IRIS focuses on the chromosphere and transition region

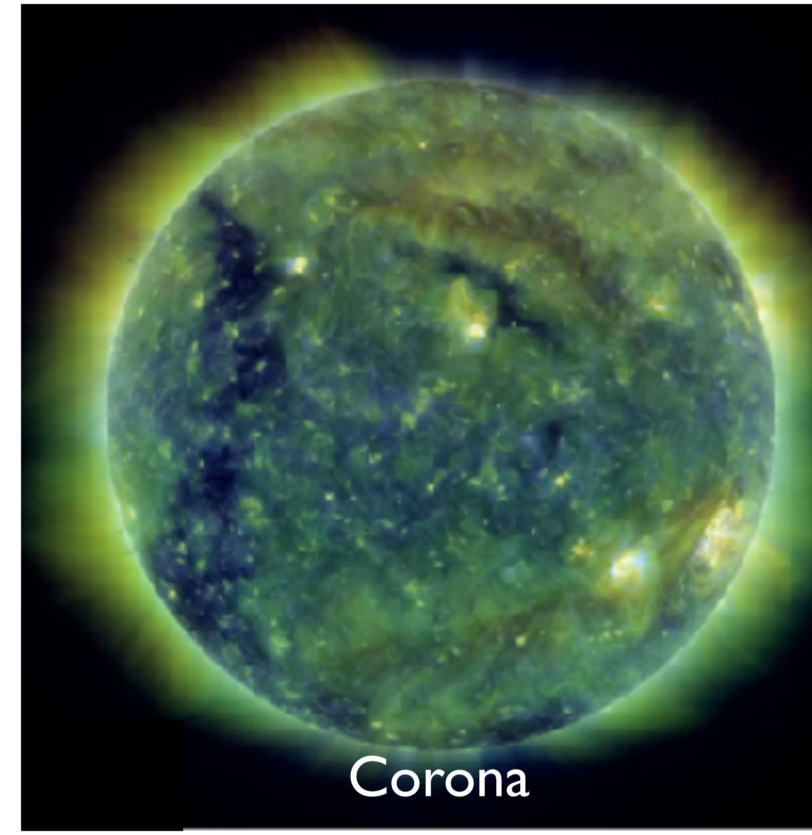
Source of magneto-convective energy



Most mechanical energy deposited in chromosphere

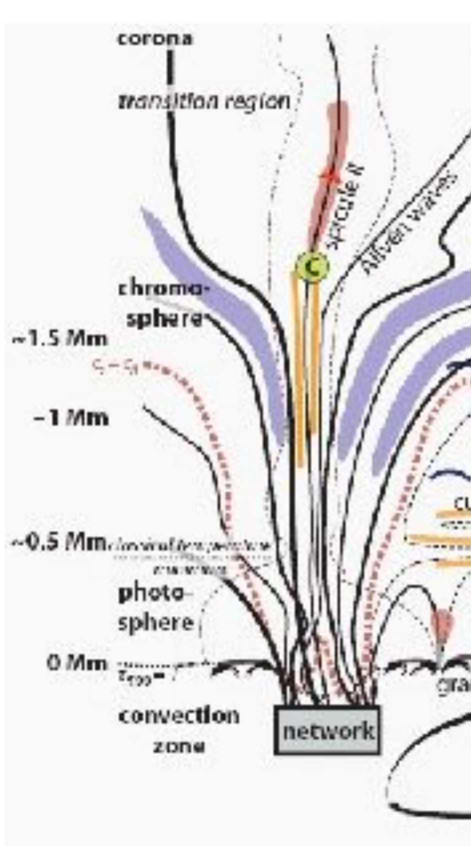


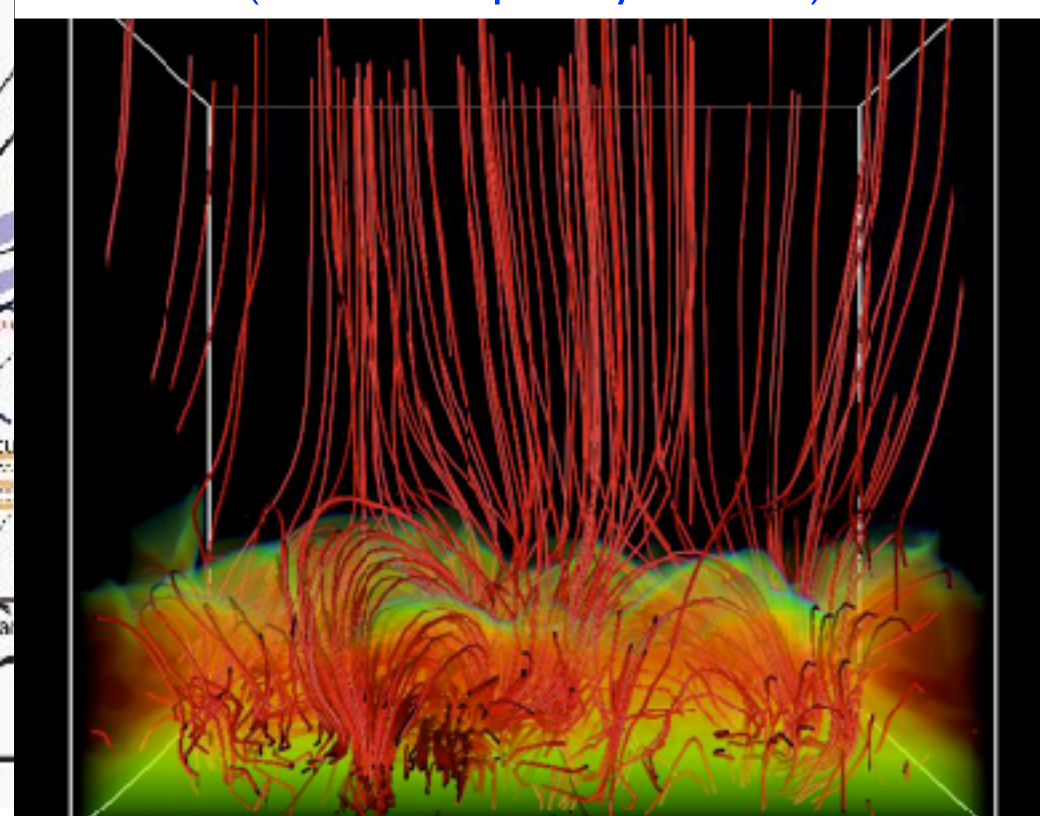
1-10% of mechanical energy deposited in corona



Advanced numerical simulations to guide IRIS observations

(4 sims now publicly available)





IRIS Prioritized Science Goals (PSGs)

PSG 1: Study fundamental physical processes in the solar atmosphere

PSG 2: Investigate the (in)stability of the magnetized atmosphere

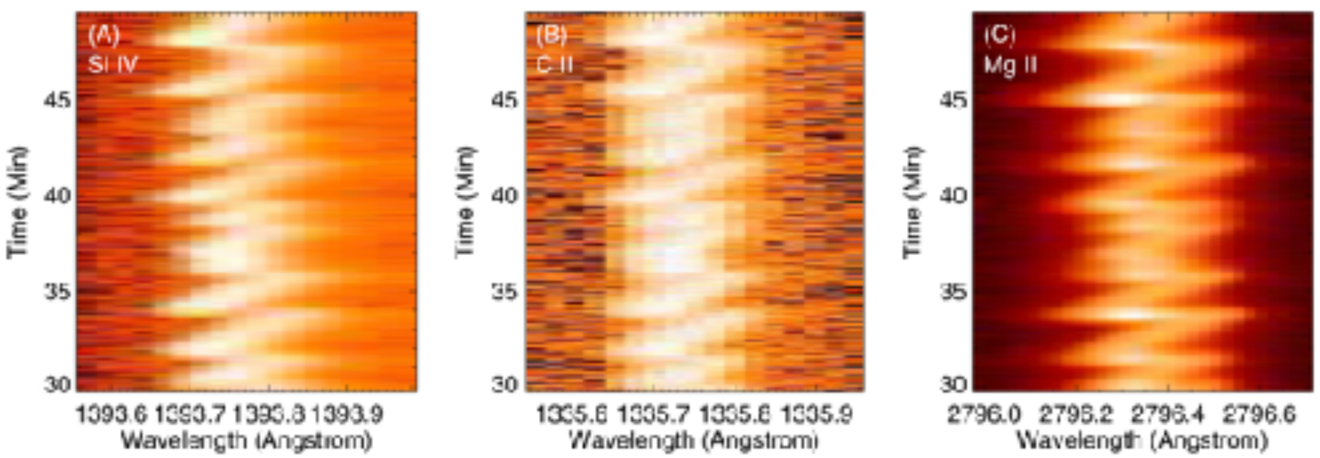
PSG 3: Analyze energy and mass transfer between photosphere, chromosphere and corona

PSG 4: Quantify variations of far and near ultraviolet solar radiation over the solar cycle

PSG 5: Explore the solar-stellar connection

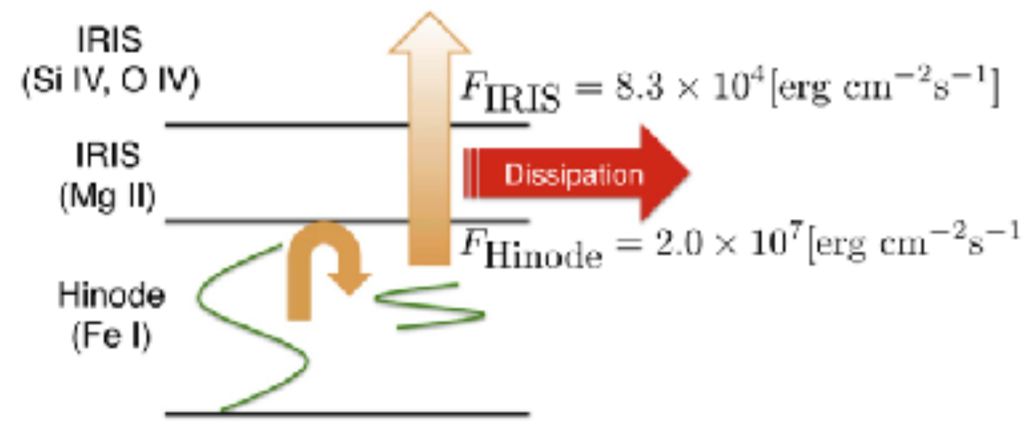
Heating of the quiet and active region (but quiescent) chromosphere: shocks

Tian et al., 2014

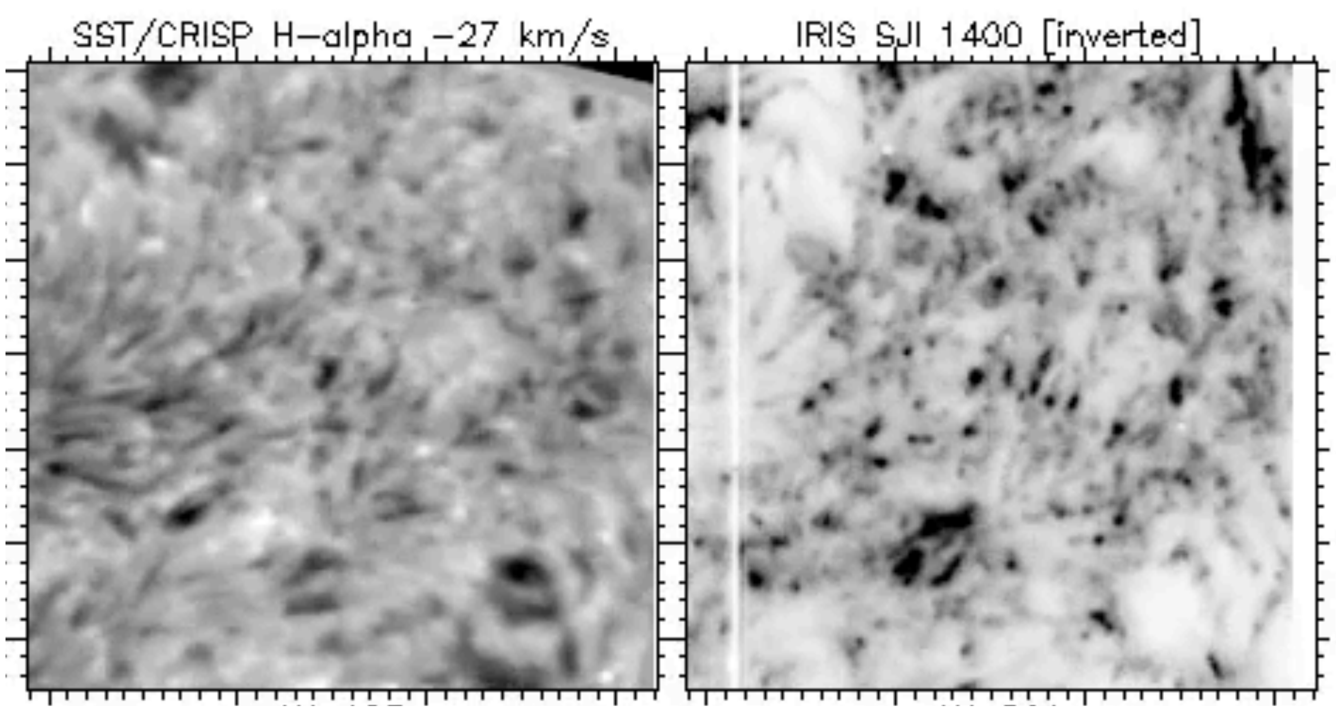


Magneto-acoustic shocks dominate the chromosphere in quiet Sun network and internetwork, active region plage and sunspots

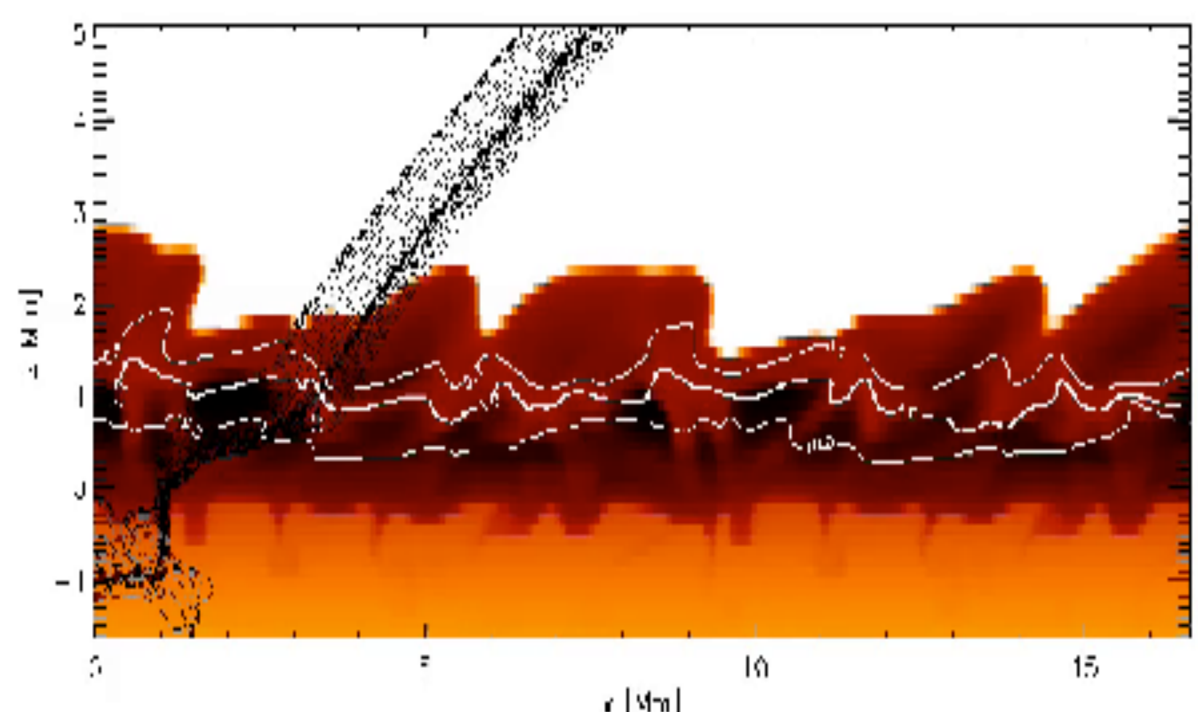
Kanoh et al., 2016



Hinode/IRIS observations suggest shock waves in sunspots carry a large energy flux into the chromosphere, while Zhao et al., (2016) use SDO/IRIS/BBSO observations to trace these waves to sub-surface source



Skogsrud et al., 2016



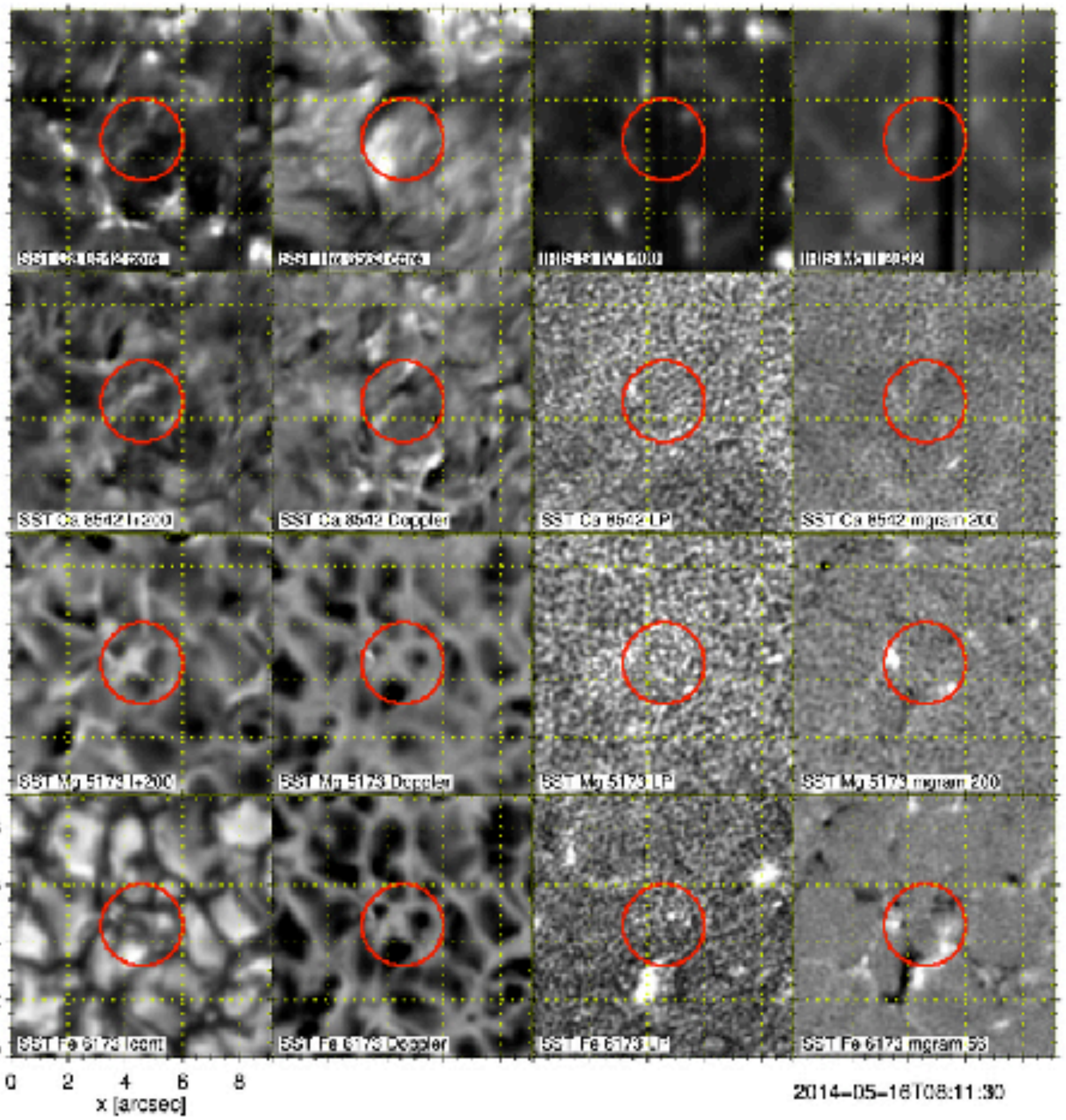
Hansteen et al., 2006

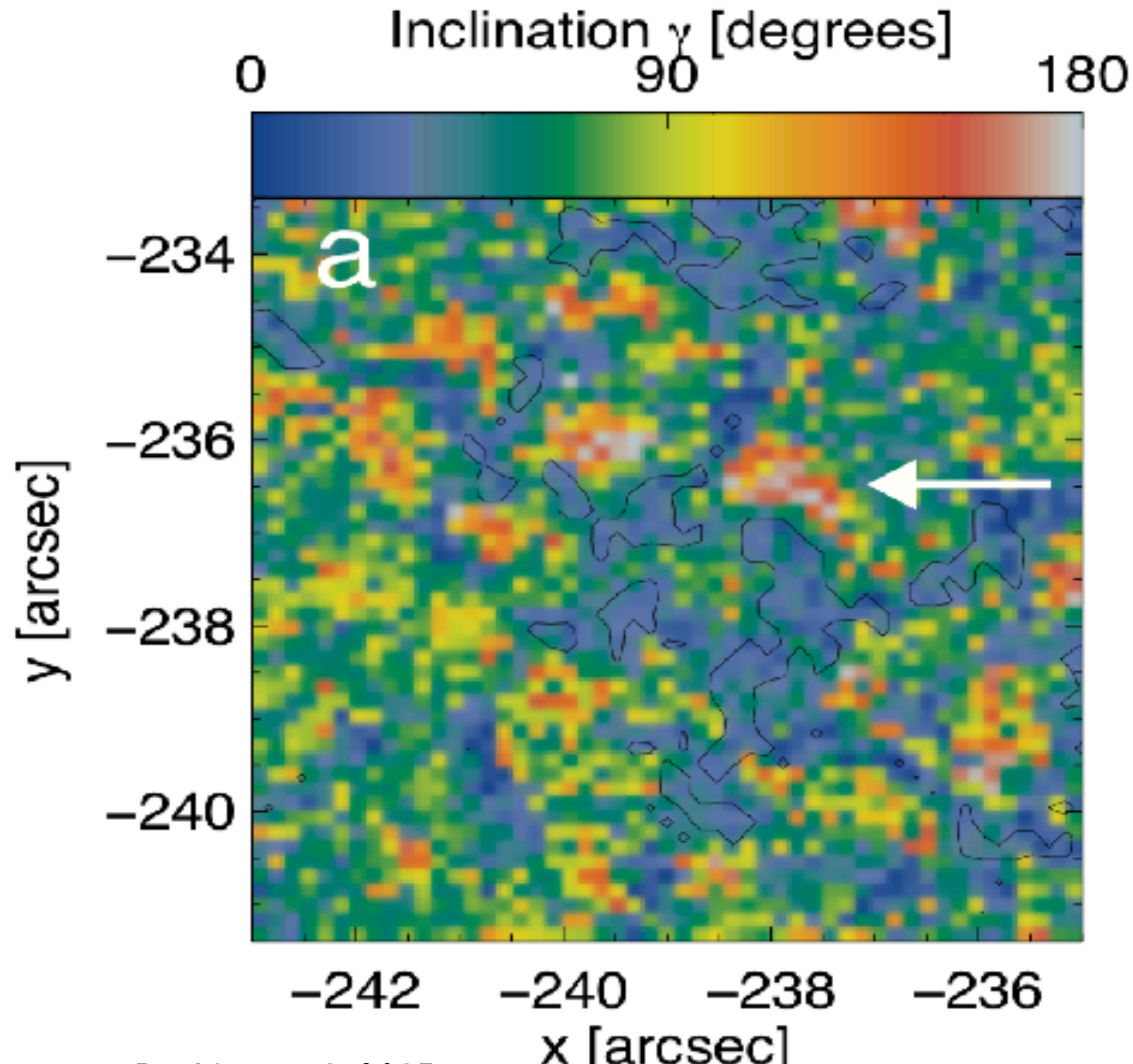
These magneto-acoustic shocks lead to small-scale jets or dynamic fibrils in plage, and cause brightenings in the low transition region (TR)

Formation of shocks well understood, but how important are they for the local energy balance in the plage, sunspot and network atmosphere?

Heating of the quiet and active region (but quiescent) chromosphere: small-scale magnetic fields

Gosic et al., 2017





Buehler et al., 2015

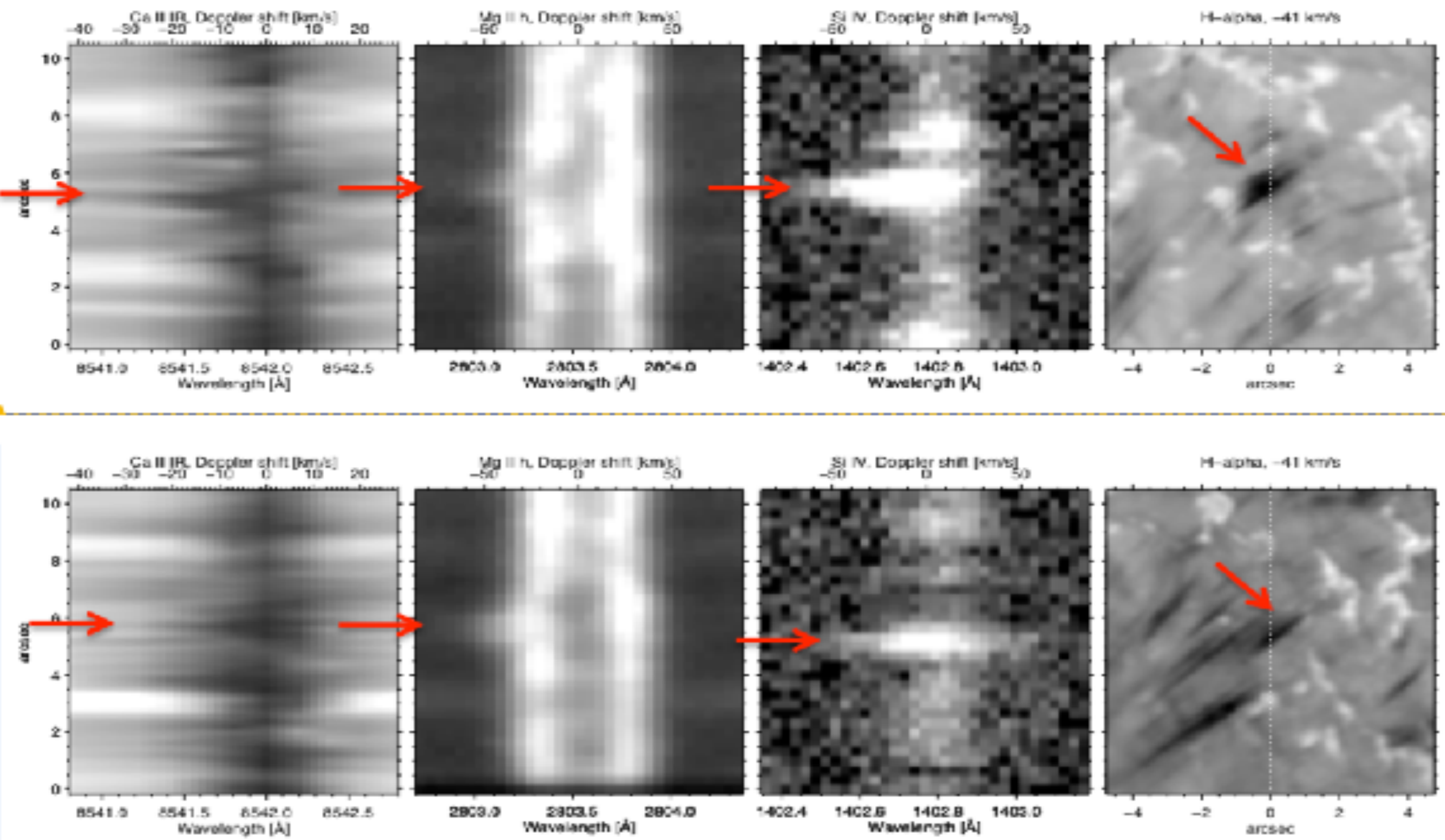
Ubiquitous granular-scale magnetic fields have enormous potential for impacting the energy balance of the low solar atmosphere

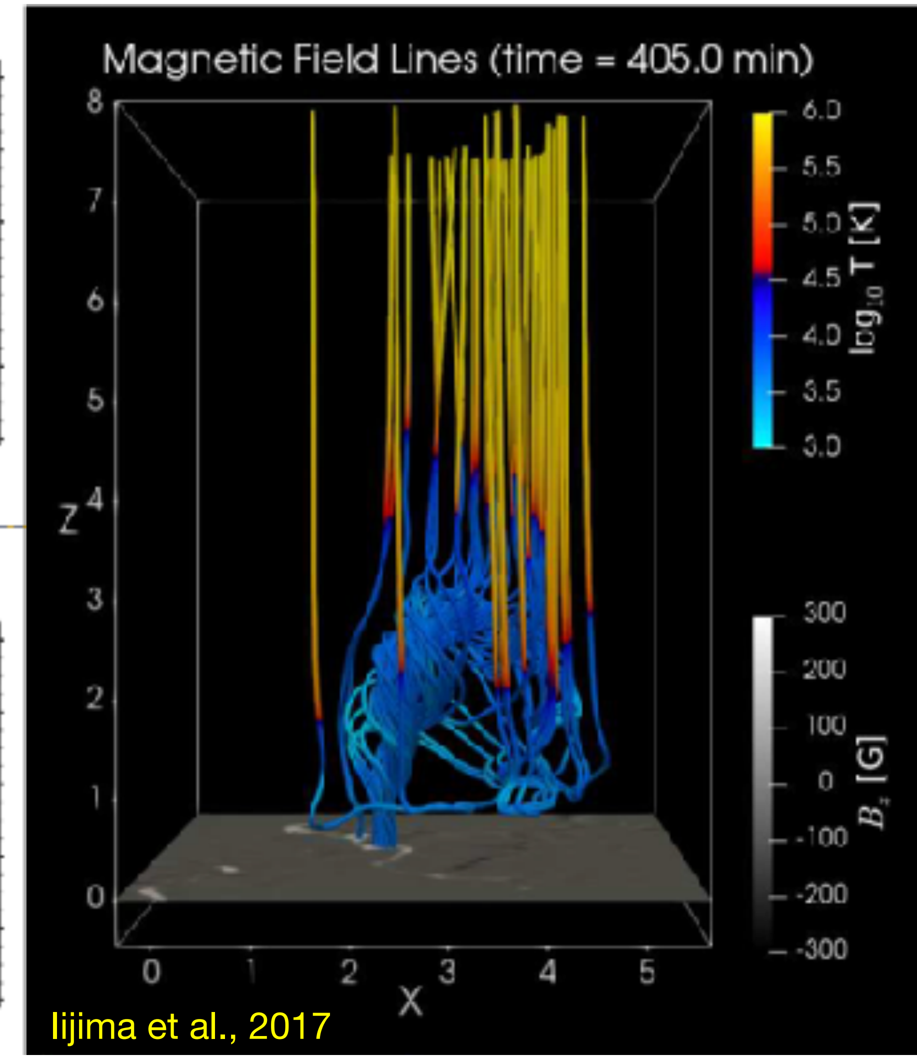
Hinode/Swedish Solar Telescope/IRIS observations reveal effects of cancellations of currently observable fields on chromospheric heating negligible

What about effects of emergence of granular-scale fields?

What about effects of weak fields in and around plage?

Chromospheric dynamics: the formation of spicules





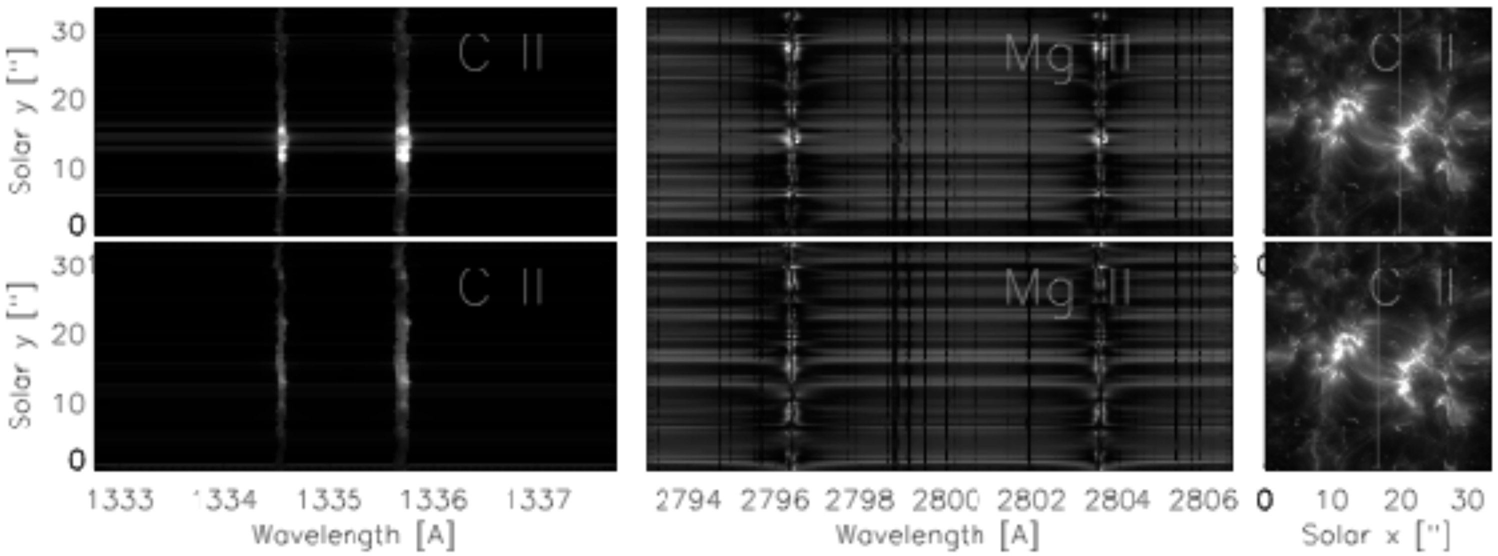
- Spicules are jets at the interface of chromosphere and corona
- New numerical simulations shows how they are generated through the interaction between strong and weak magnetic fields when strong magnetic tension is released in the chromosphere
- Neutral particles in the partially ionized chromosphere play a key role: allow tangled magnetic fields to penetrate into the atmosphere
- Comparison with IRIS and Swedish Solar Telescope observations show very good match

Advances in numerical models required: 3D models, more realistic radiative treatment in alternative models (Iijima et al., 2017, Yang et al., 2018) and detailed comparisons with observations and observational constraints (e.g., Alissandrakis et al., 2018)

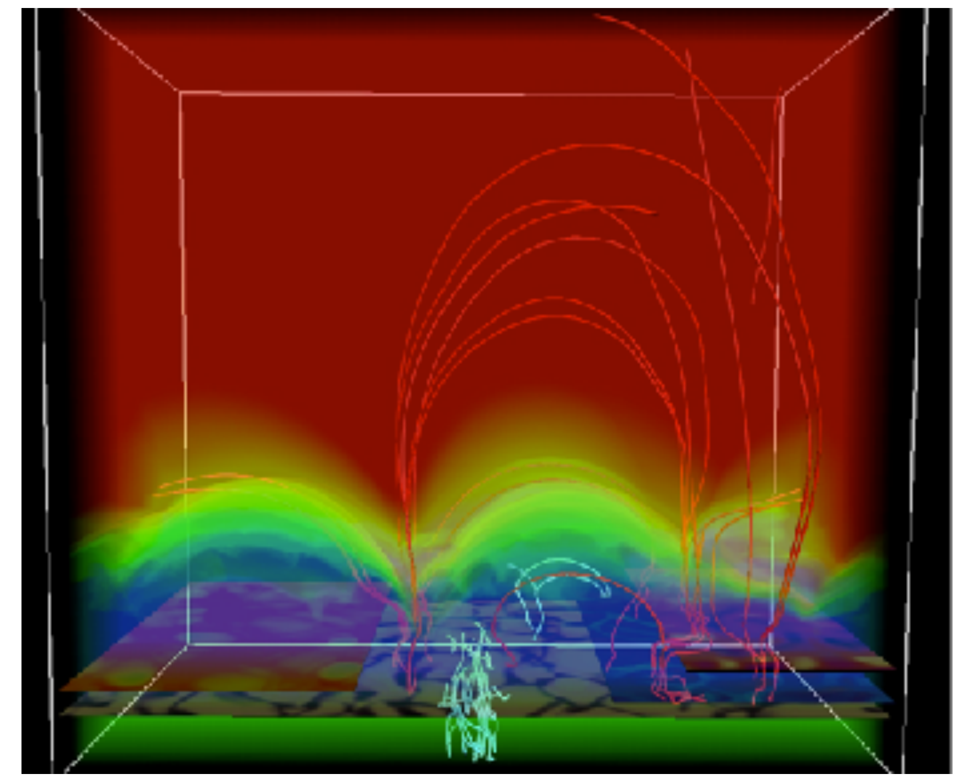
Observational studies linking photospheric activity with launch of spicules (magnetic field, vorticity,…)

Public release of numerical models should be encouraged (e.g., iris.lmsal.com/modeling.html)

Chromospheric heating in strong magnetic field regions (plage, network)



Carlsson et al., 2016

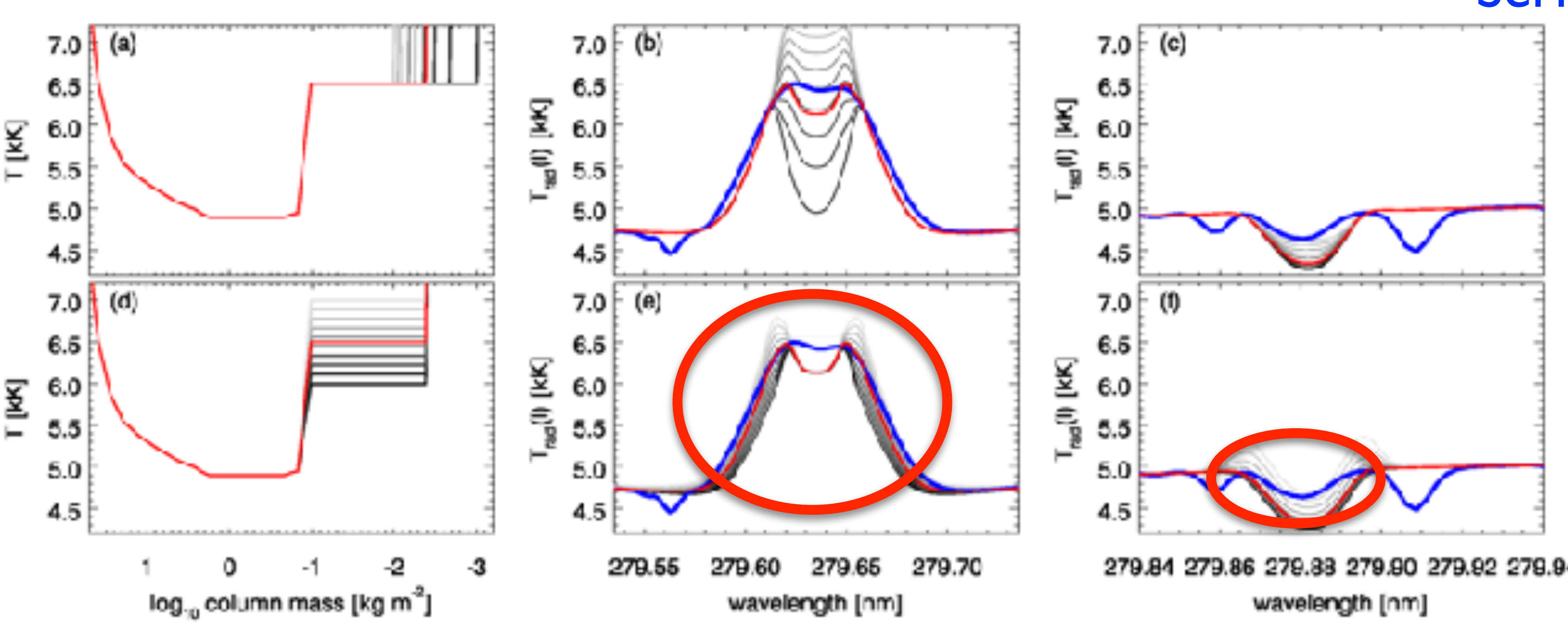


Bifrost numerical models are heated by braiding/current dissipation but show Mg II h/k profiles that are too narrow and not bright enough?

Which physical processes are missing? Ion-neutral interactions? Plasma physics processes? Requires advances in numerical modeling and better constraints

Bifrost numerical models publicly available for analysis: enhanced network, coronal hole, active region

Series of IRIS diagnostics papers

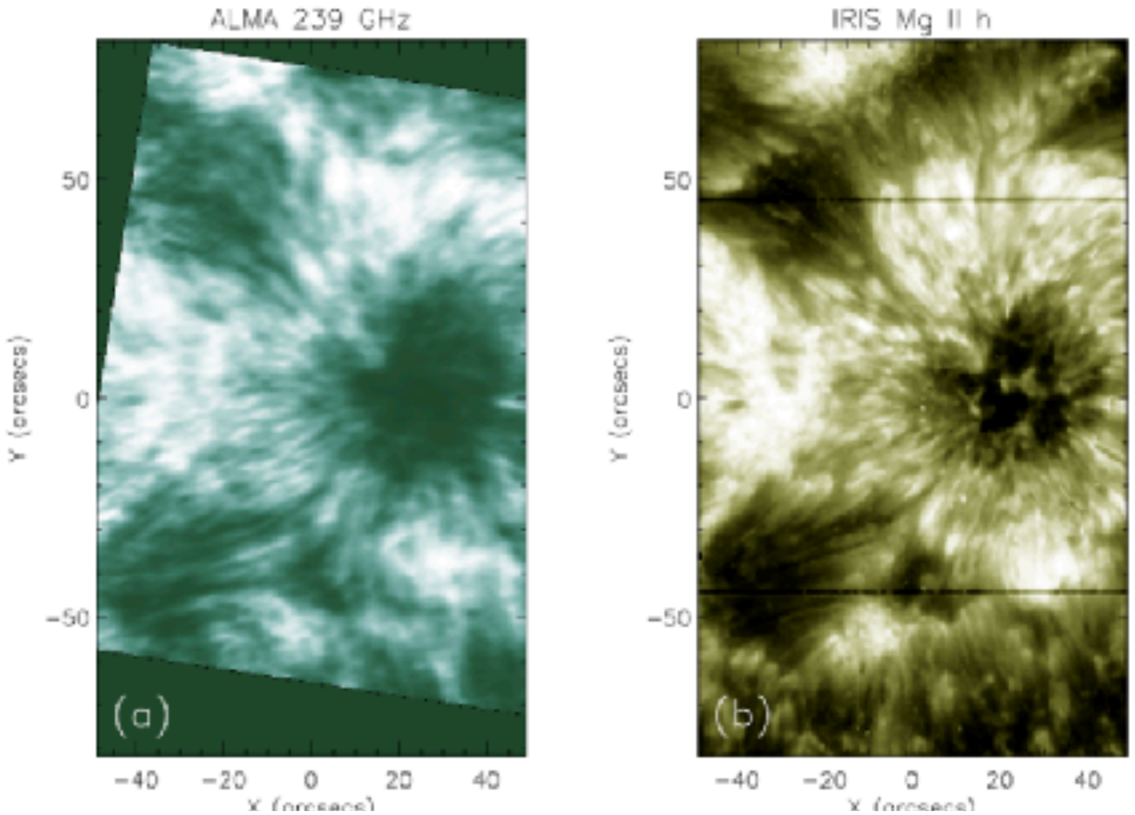


Carlsson et al., 2015

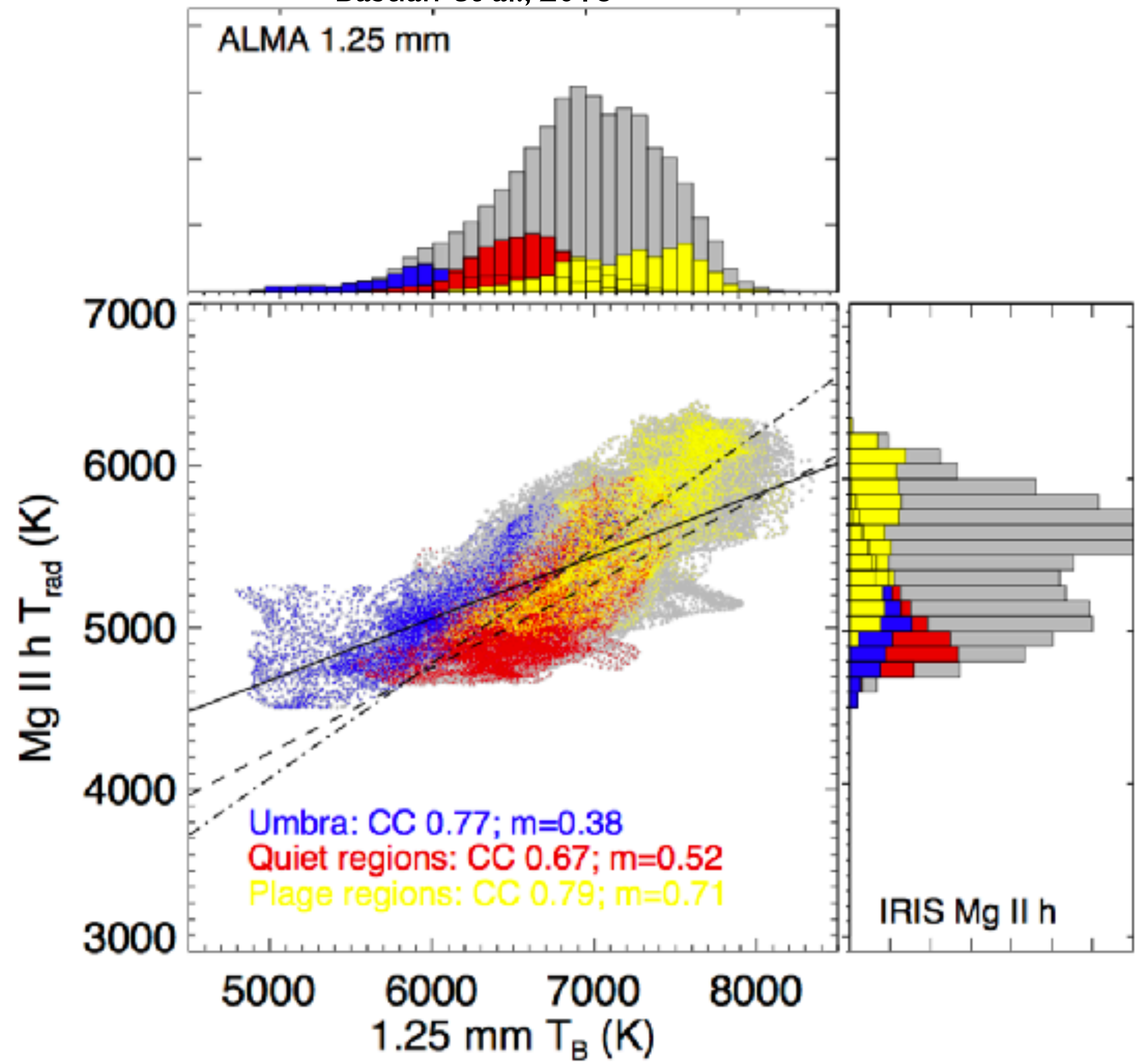
Toy models suggest single peak profiles in plage are caused by dense, hot plasma in middle chromosphere, constrained by Mg II h/k and Mg II triplet

Heating constraints from ALMA observations

Bastian et al., 2017



Bastian et al., 2018



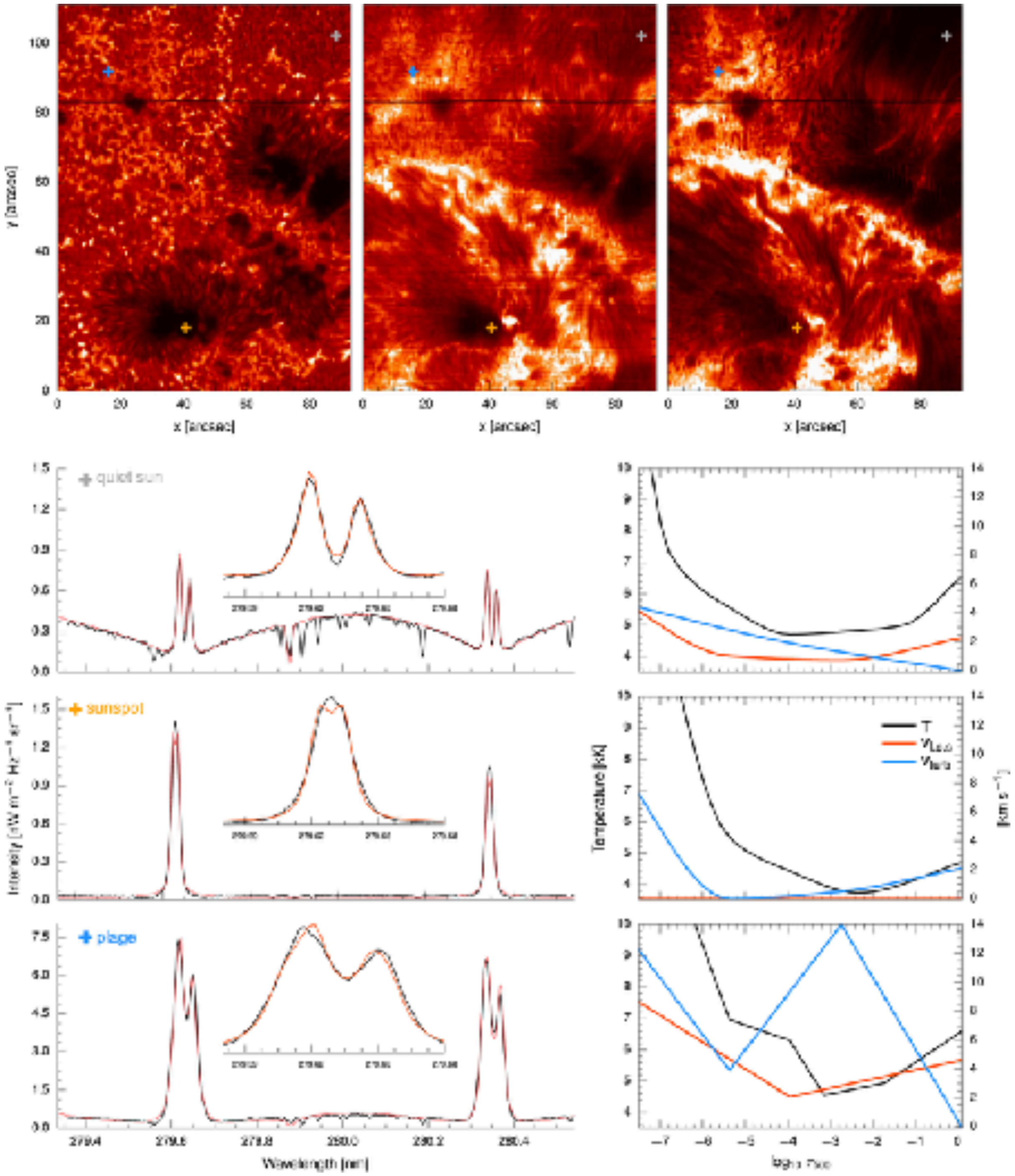
IRIS is prioritizing coordination with ALMA observing programs

First ALMA measurements reveal higher temperatures and broader range of temperatures than IRIS and than current numerical models

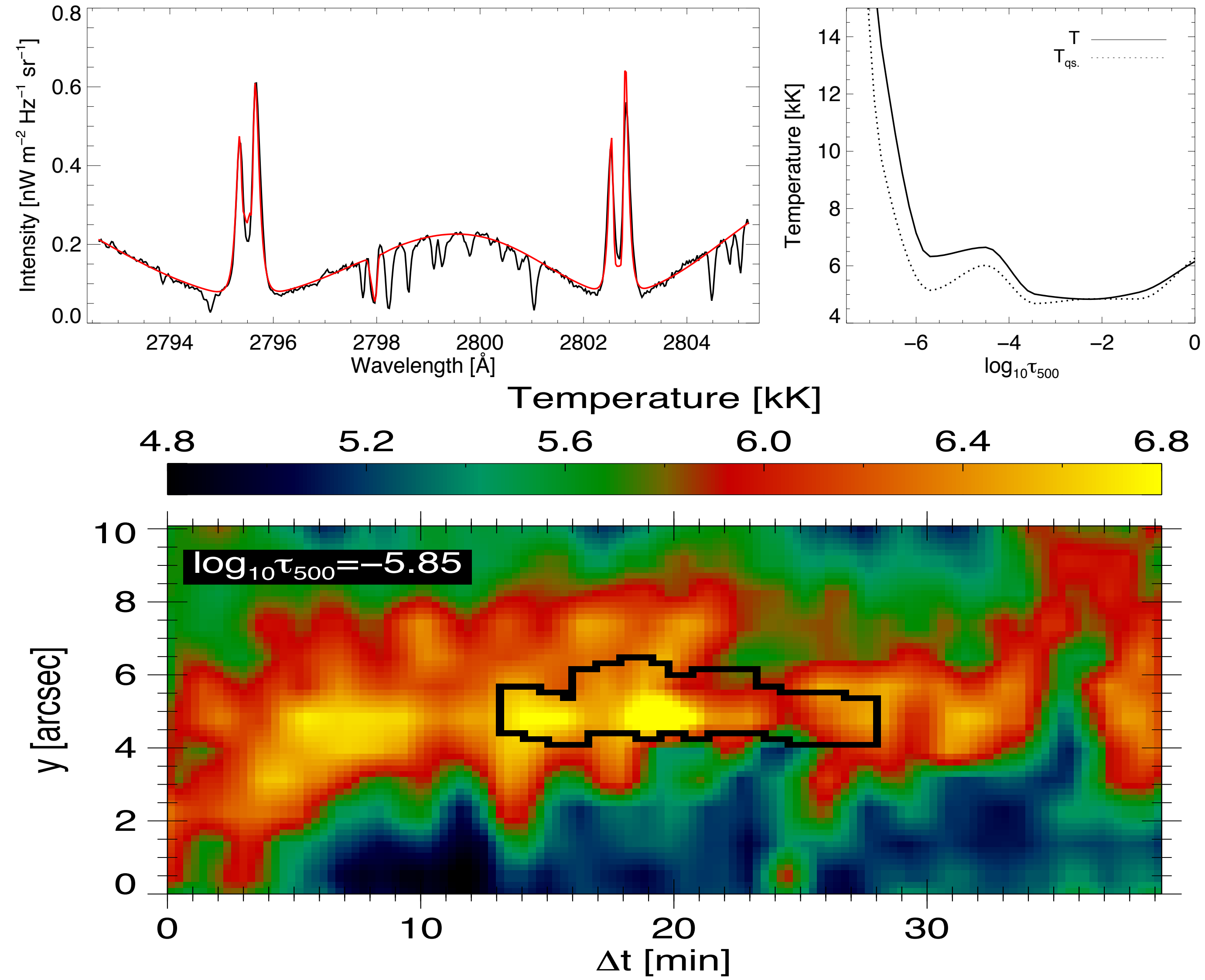
Preliminary results challenge our understanding of both ALMA and IRIS observables and of chromospheric heating constraints

Heating constraints from inversions of chromospheric lines

De la Cruz Rodriguez et al., 2016



Gosic et al., 2018



Novel inversion technique (STiC) for chromospheric lines (including PRD) can provide estimates for temperature, density, velocity, turbulence as a function of height in low solar atmosphere

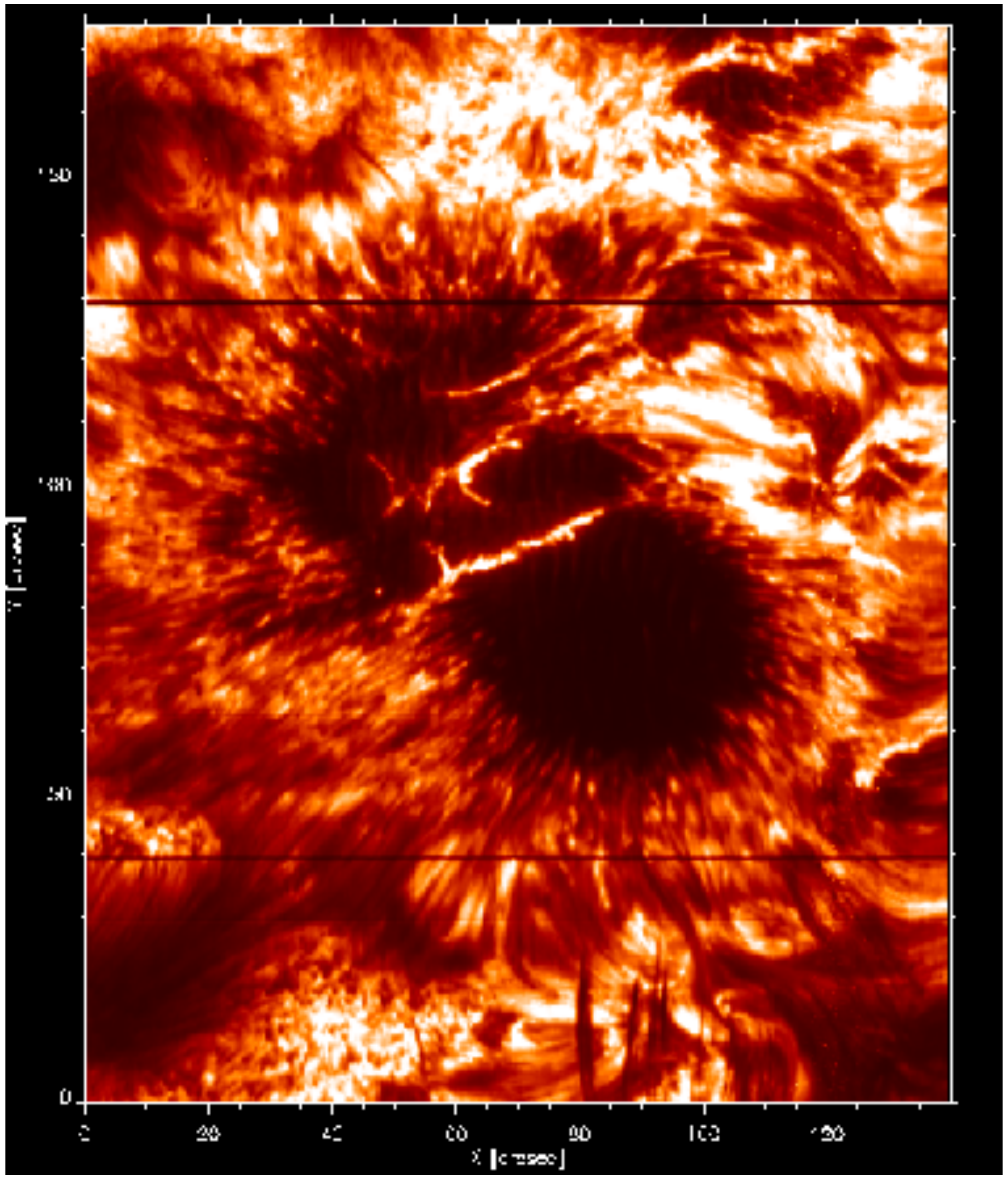
IRIS Mg II h & k spectra allow reconstructing a model atmosphere from the middle photosphere up to transition region

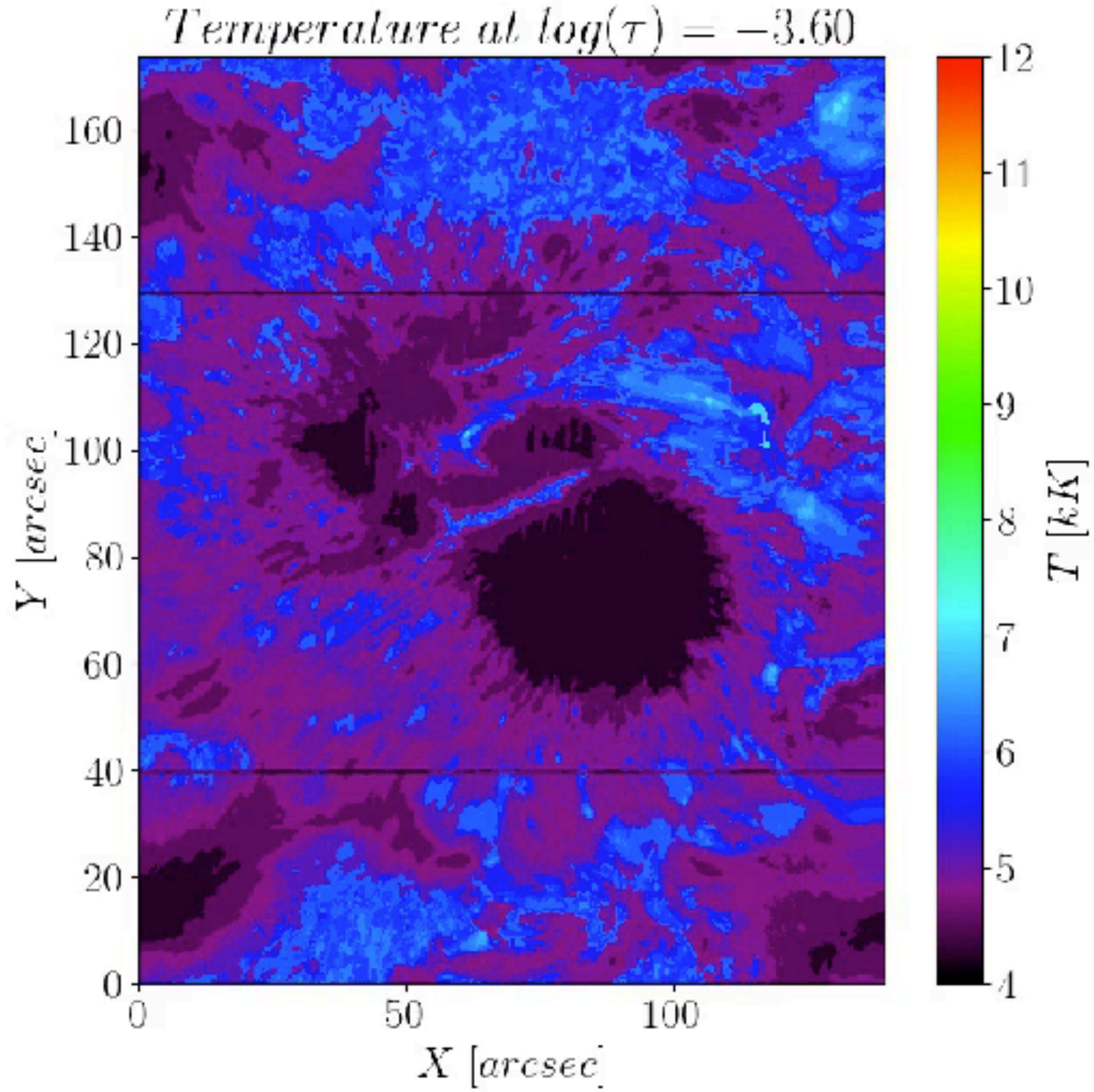
Inversions with STiC code for the first time allow quantification of impact of internetwork cancellations and emergence on energy balance

Many other possible applications if computational limitations can be overcome

Heating constraints from inversions of chromospheric lines

Sainz Dalda et al., 2018



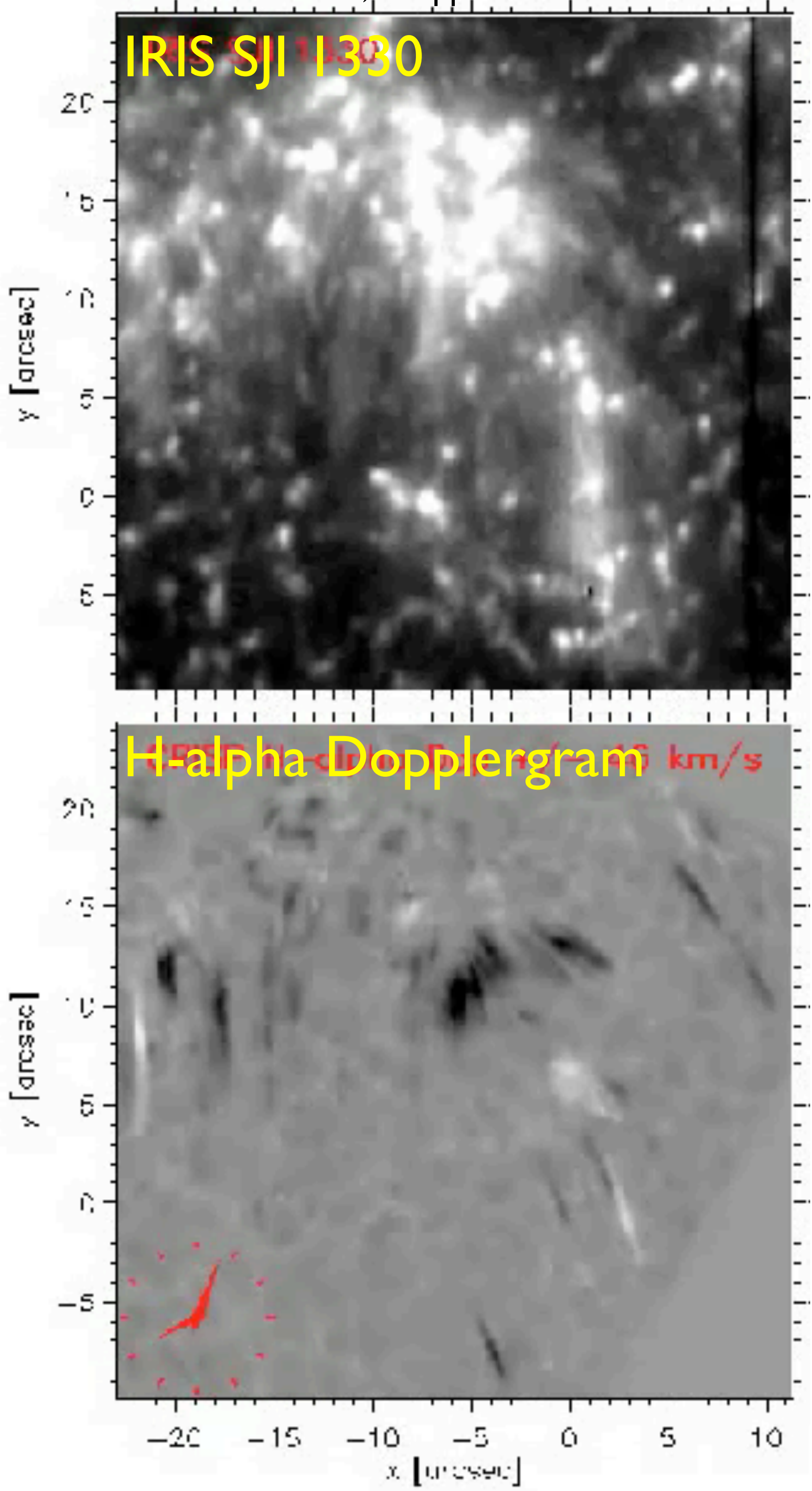


Preliminary results show that combination of cluster analysis (k-means method) and inversion code can lead to computationally efficient means of diagnosing chromospheric conditions (a few minutes instead of a few months)

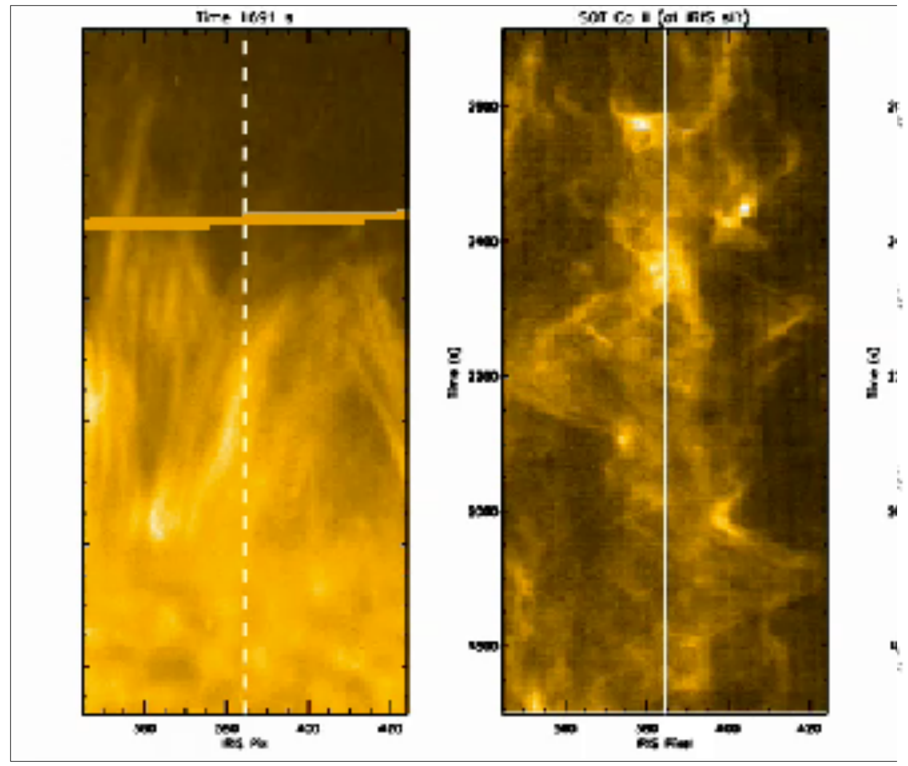
Will become available in solarsoft/irispy later this year

Alfvén waves and heating of the solar atmosphere

De Pontieu et al. 2014, Rouppe van der Voort et al. 2015

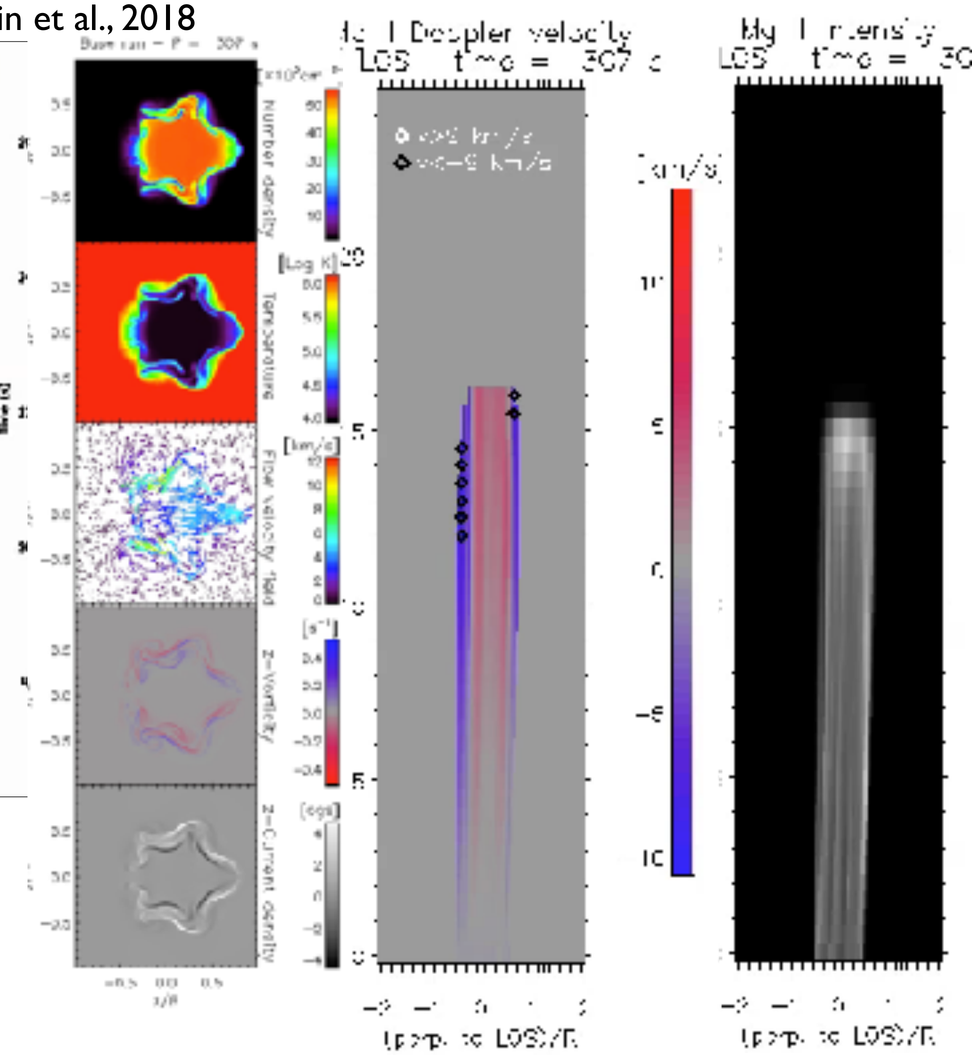


IRIS/SST observations reveal Alfvén waves often associated with heating



IRIS observations show evidence for a variety of wave modes

Antolin et al., 2018



Including resonant absorption and Kelvin Helmholtz instability

Evidence for resonant absorption first reported in prominences (Okamoto et al., 2015, Antolin et al., 2015)

How common is this dissipation process?

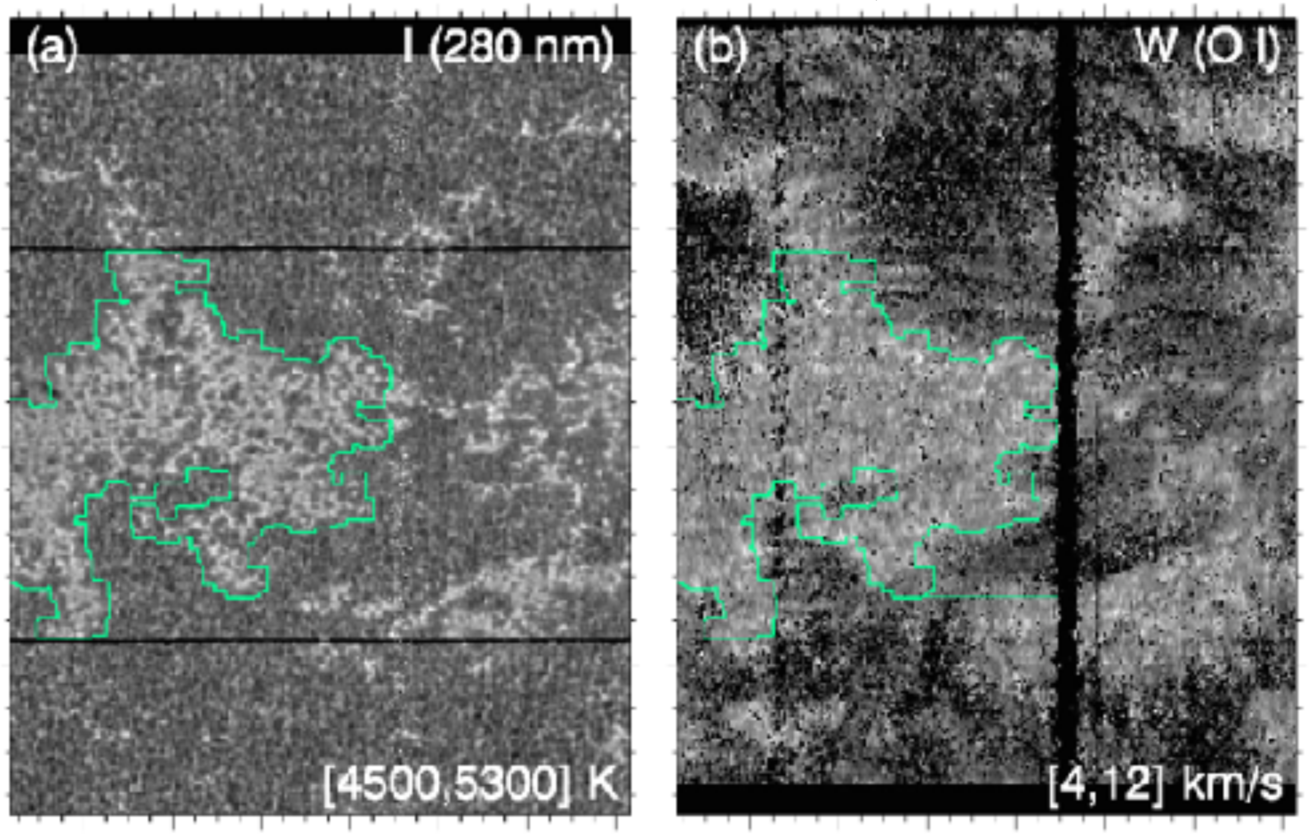
How much energy is dissipated in the chromosphere & TR?

How common are these waves and how are they generated?

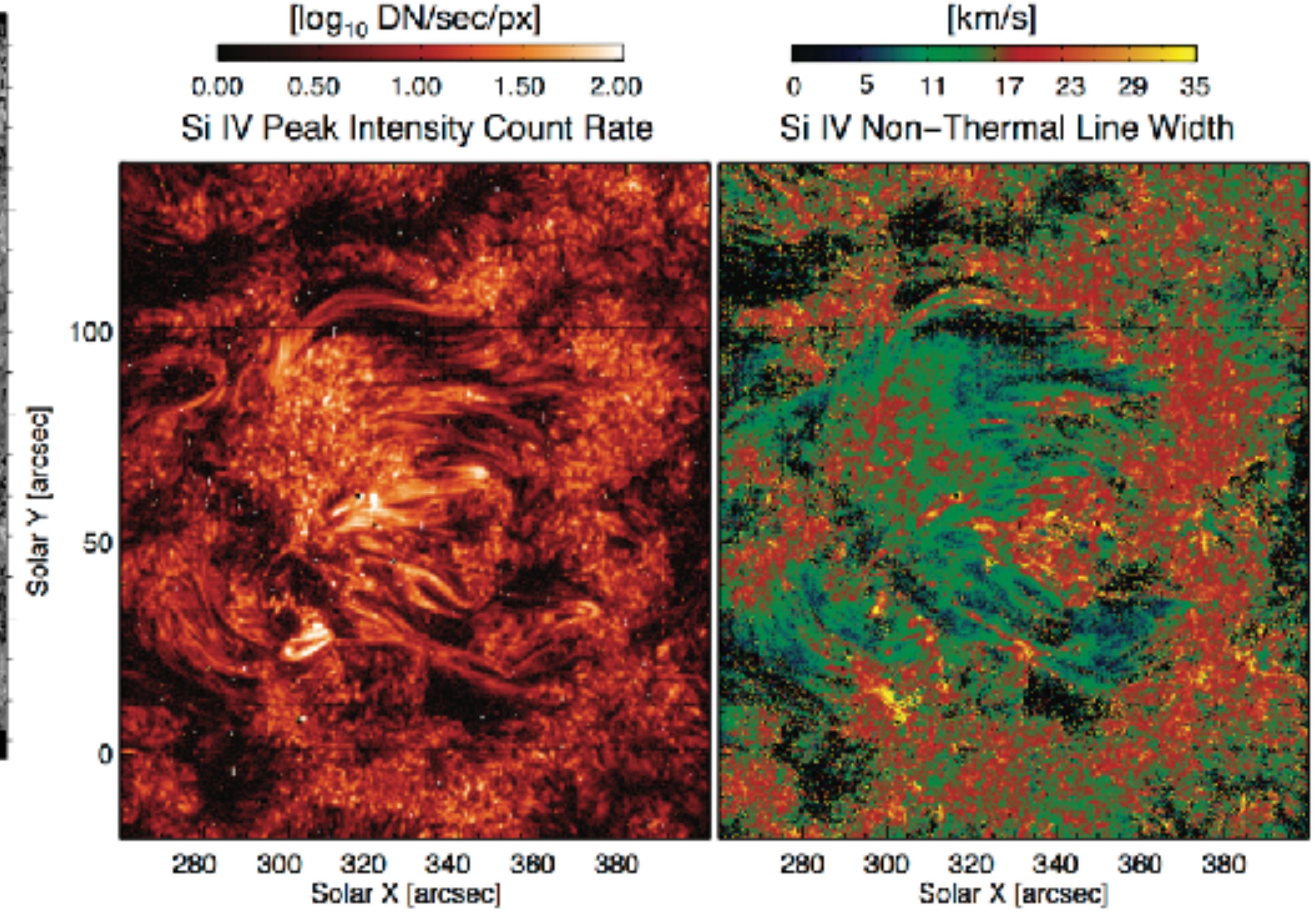
Spicules (Martinez-Sykora et al., 2017, Iijima et al., 2018)? Or more general process (photospheric vorticity, Alfvenic turbulence?)

Observational evidence for Alfvenic waves/turbulence in chromosphere?

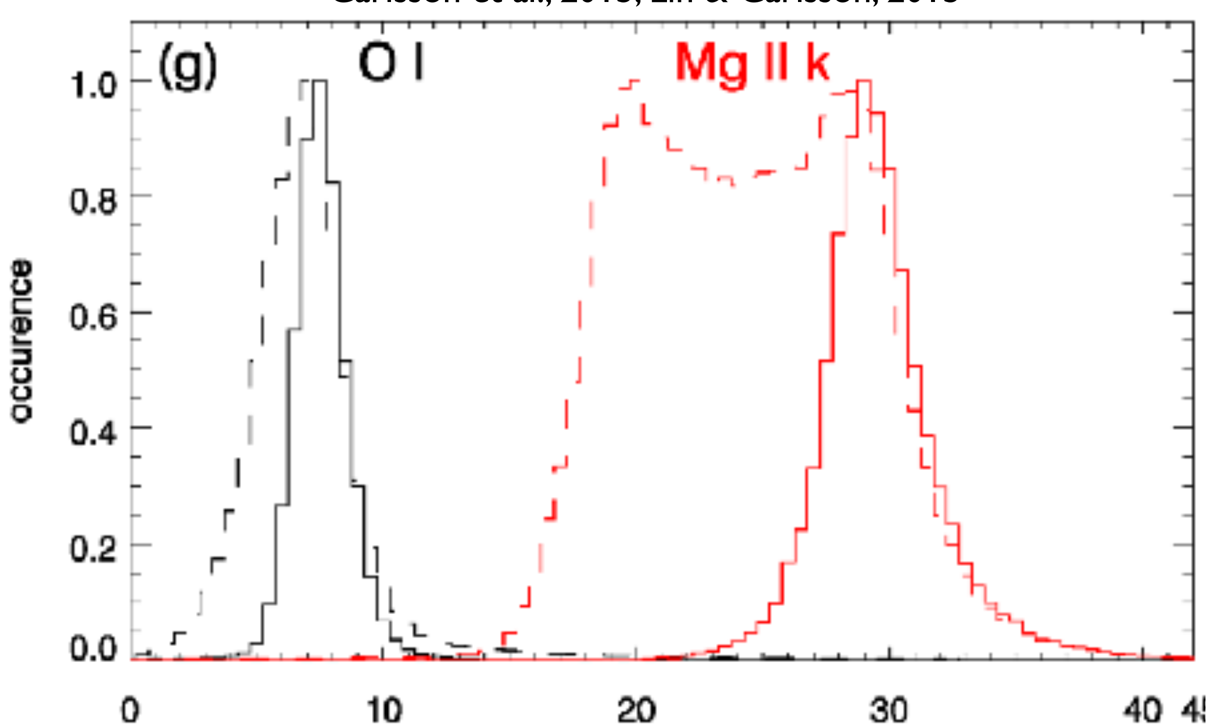
Carlsson et al., 2015



De Pontieu et al., 2015



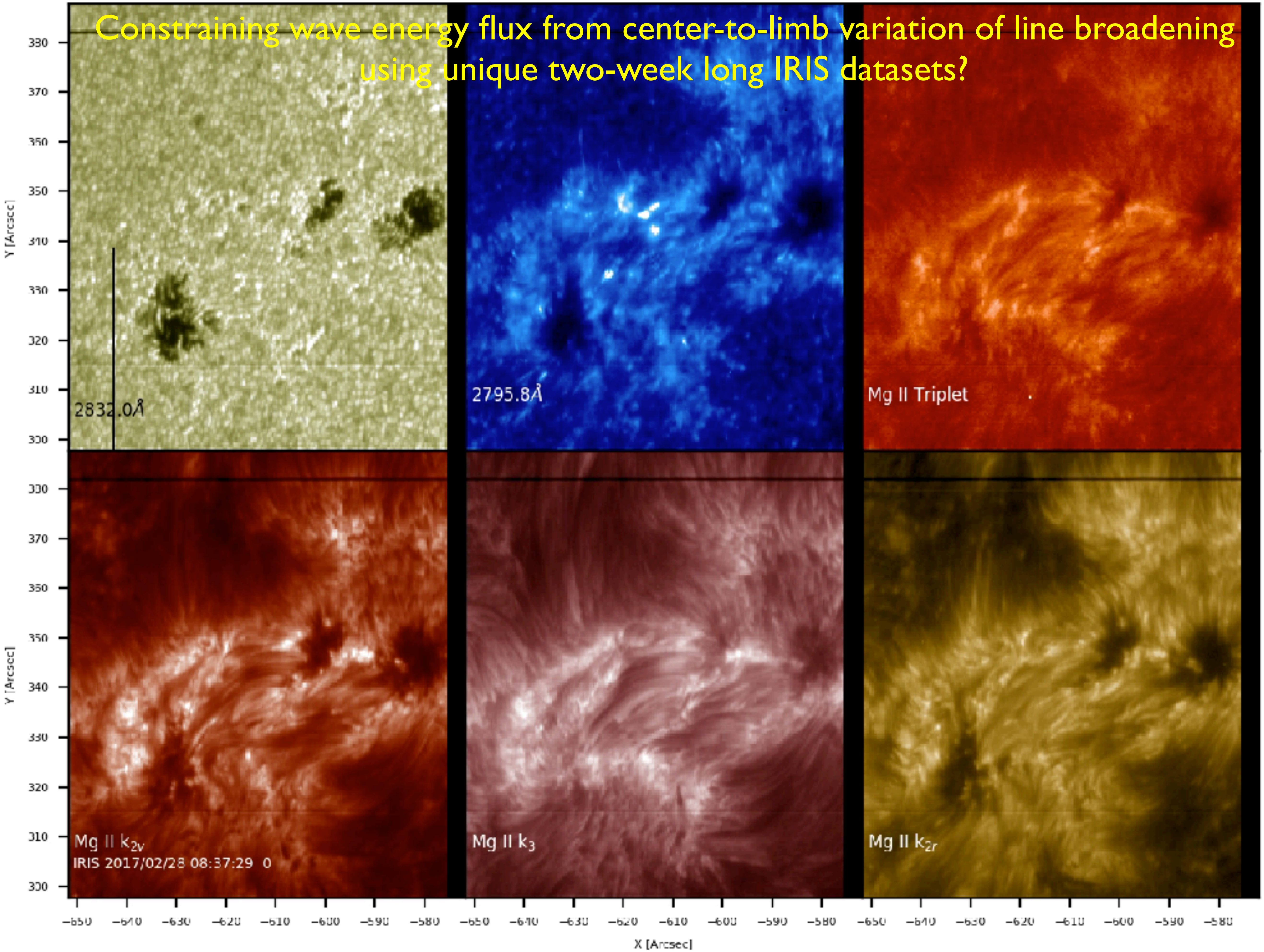
Carlsson et al., 2015, Lin & Carlsson, 2015



Alfvenic turbulence may also help explain apparent invariance of broadening of Si IV to high spatial resolution of IRIS

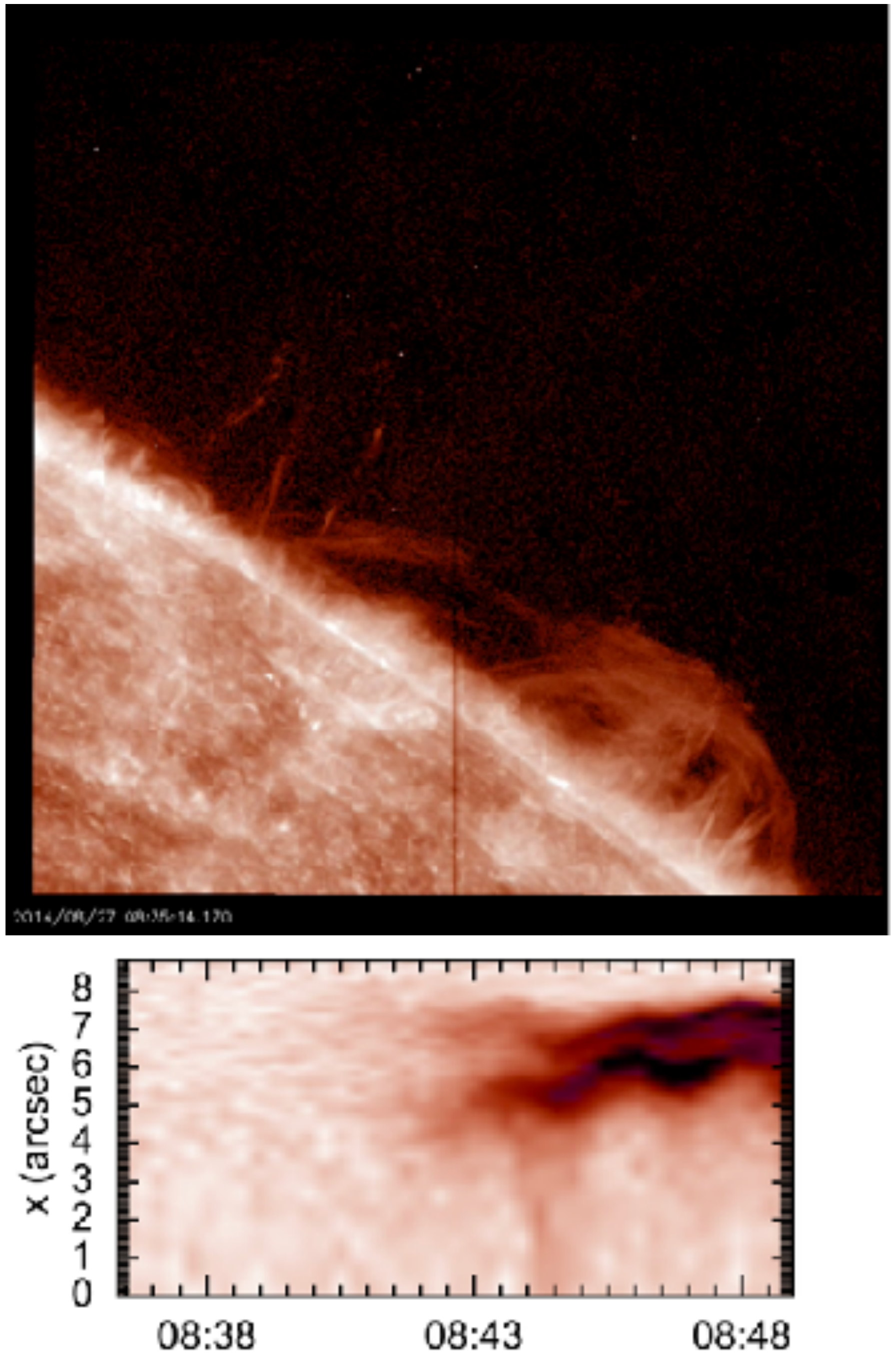
Significant non-thermal broadening in plage regions
Chromosphere: ~ 7 km/s (from Mg II inversions & O I line)

Constraining wave energy flux from center-to-limb variation of line broadening using unique two-week long IRIS datasets?



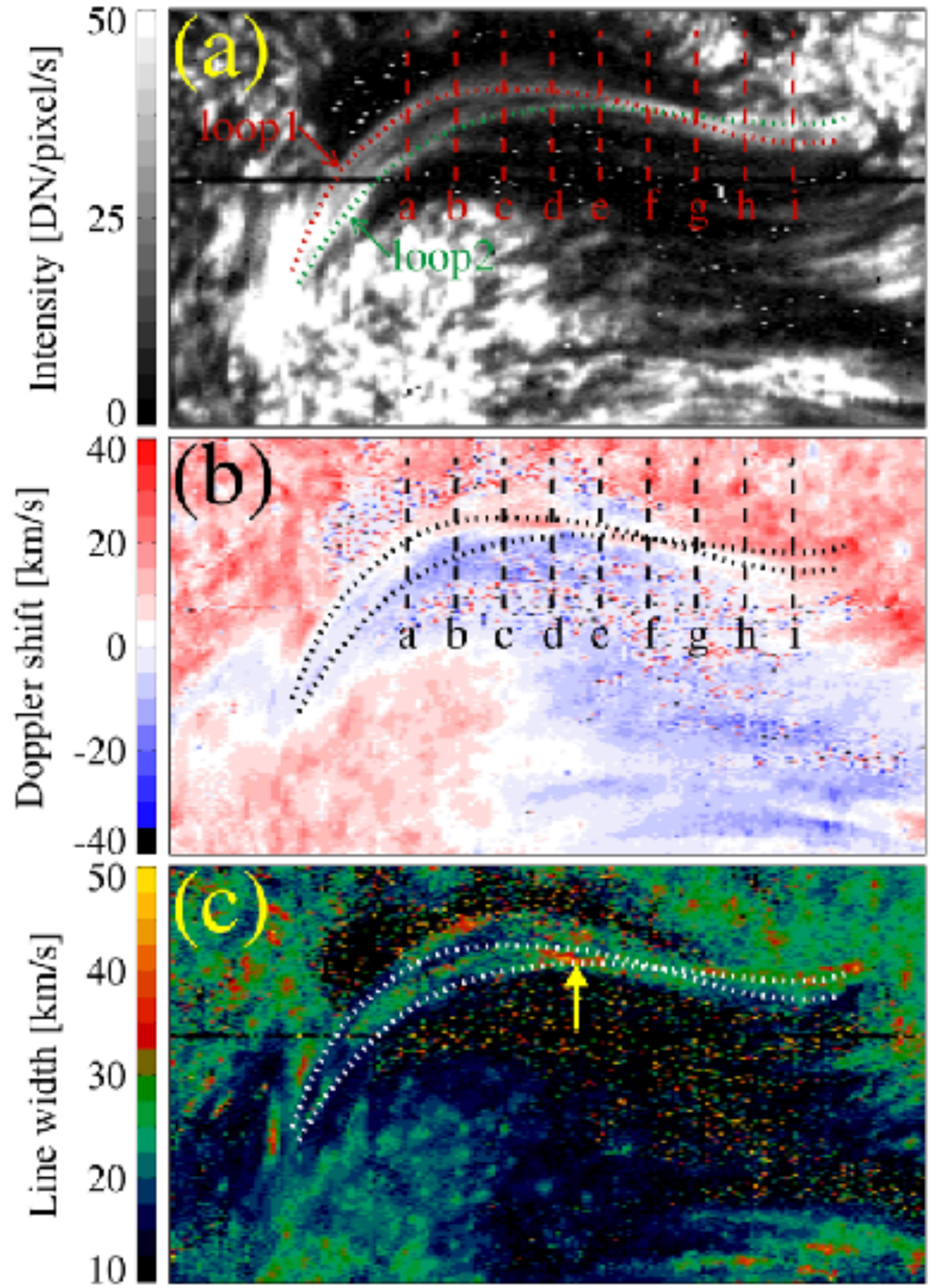
Generation of Alfvenic waves?

Verwichte & Kohutova , 2018
Kohutova et al., 2017



Alfven waves triggered by sudden condensation in loops suffering from coronal rain?

Li et al., 2014

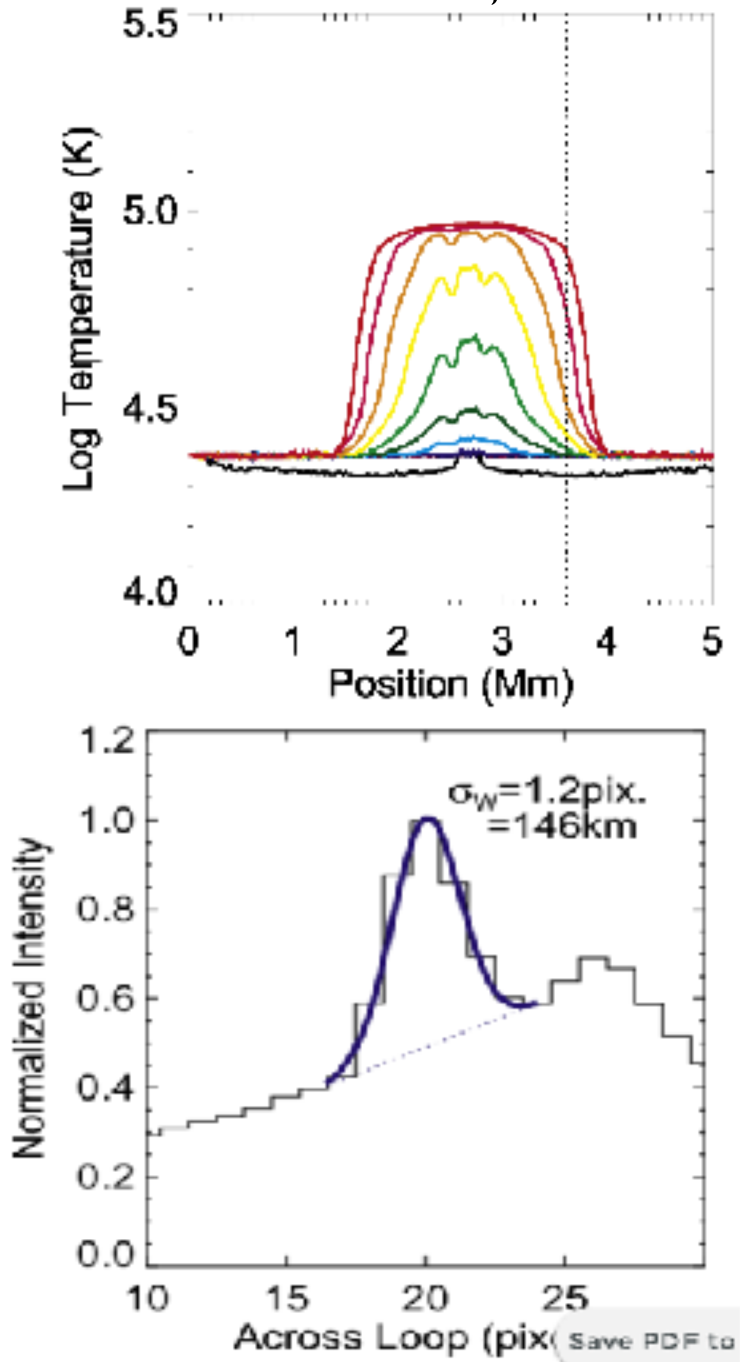


Broadening/twist generated through interchange reconnection of crossing loops?

How common are these processes?

Braiding and heating of the low solar atmosphere

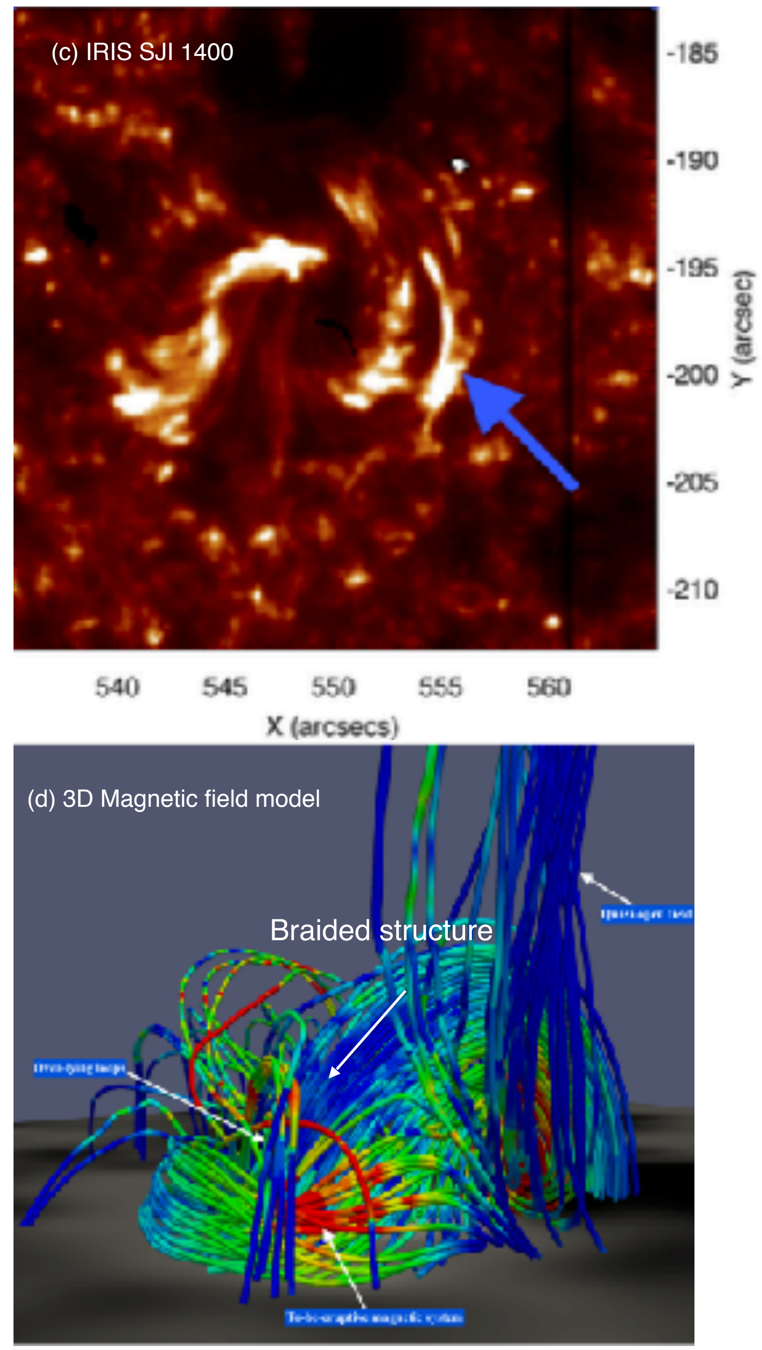
Brooks et al., 2016



Small-scale loops in transition region (“unresolved fine-scale structure” or UFS, Hansteen et al., 2014) resolved by IRIS & compatible with single-strand heating

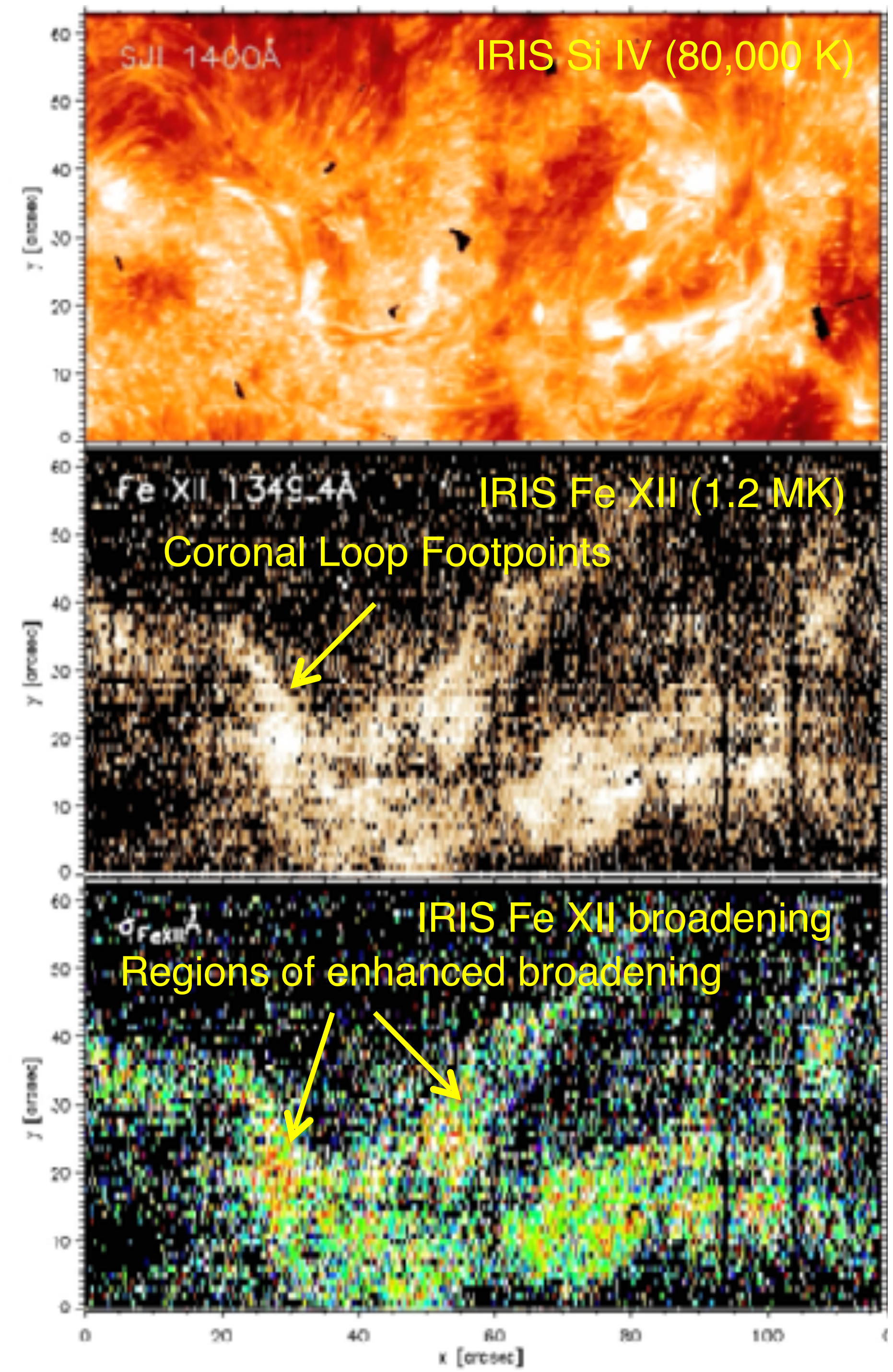
Spatial scale set by switch-on nature of secondary instability?

Huang et al., 2018



Braiding and resulting jets, heating and explosive events revealed during eruption?

Testa et al., 2016

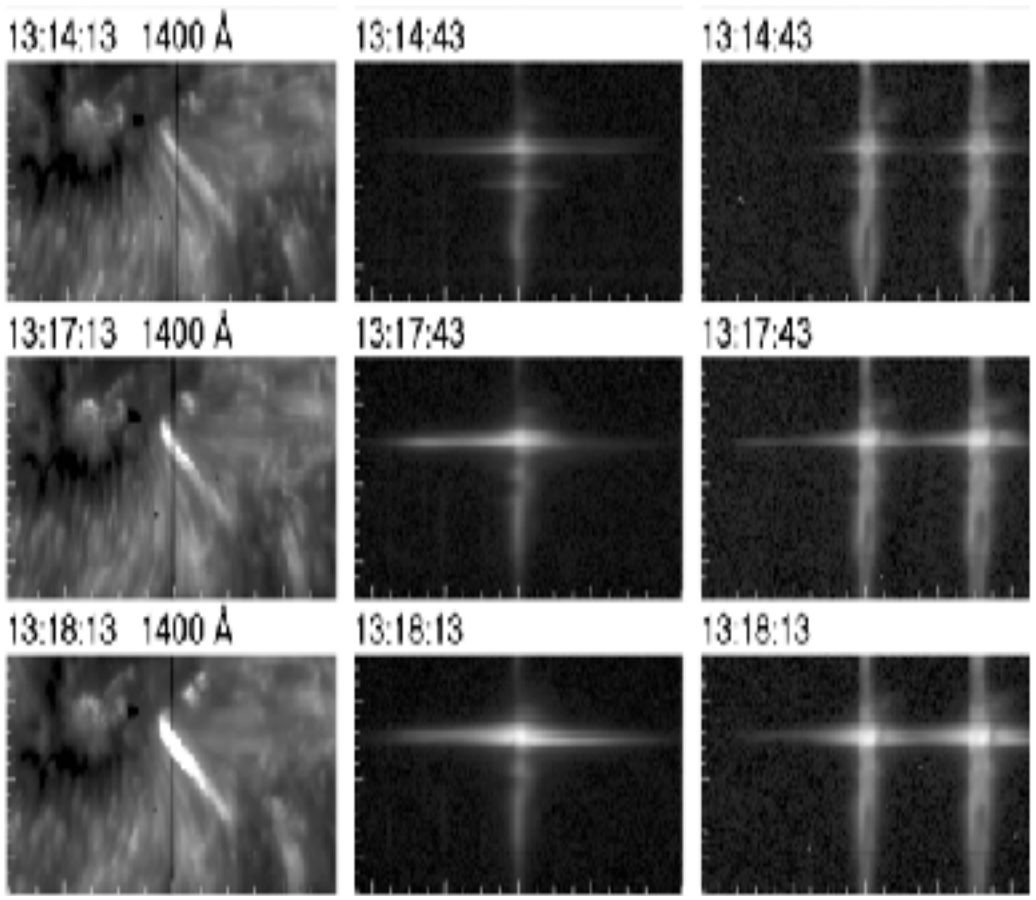


Enhanced non-thermal broadening at loop footpoints signature of braiding? Compatible with 3D radiative MHD simulations

How common are these processes?

Braiding and heating of the low solar atmosphere

Alissandrakis et al., 2017

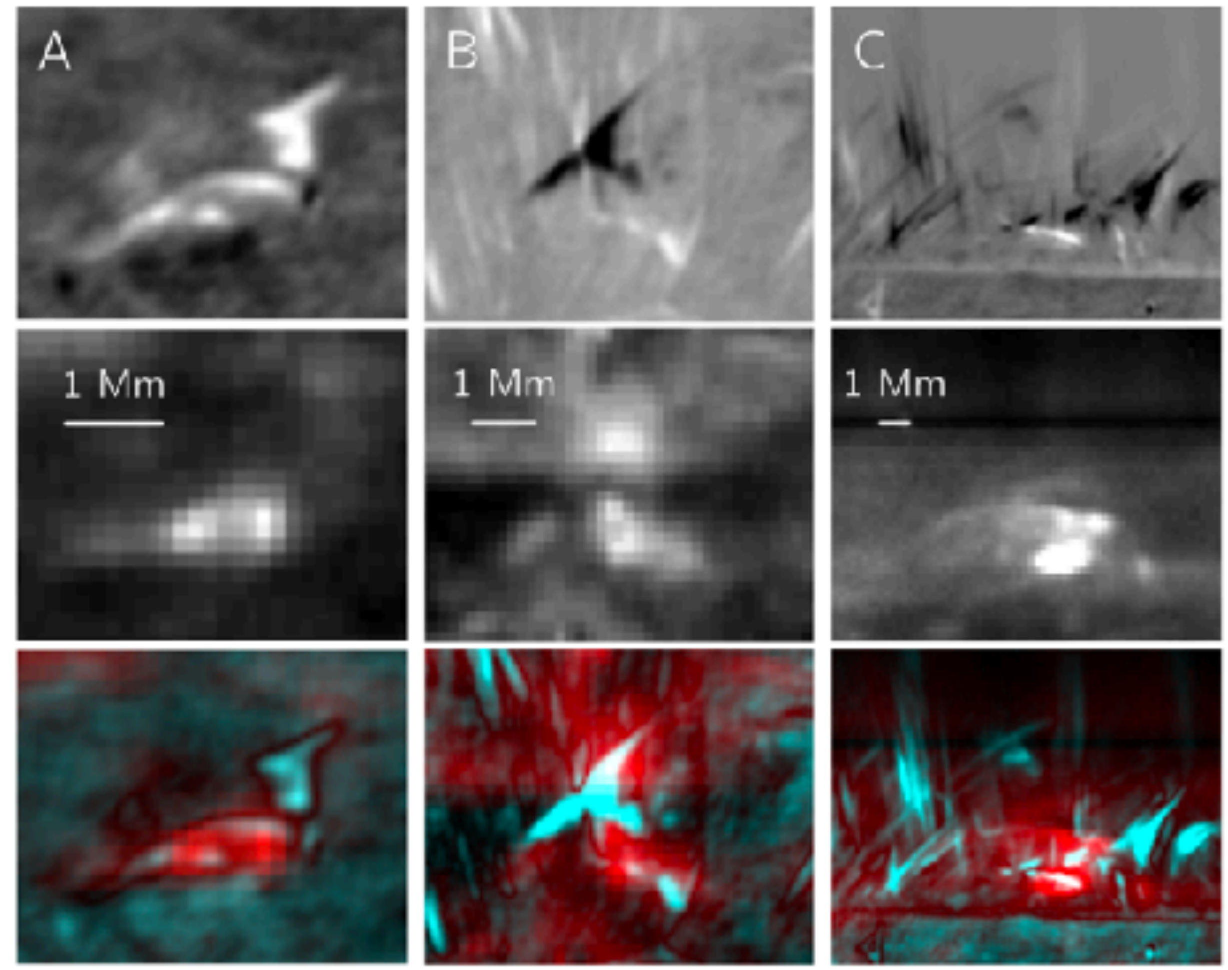


Reconnection resulting from interaction between two loop strands at shallow angles, similar to what is expected from braiding

Leads to strong brightening, heating and non-thermal broadening

See also recent study by Yan et al., 2018

Pereira et al., 2018

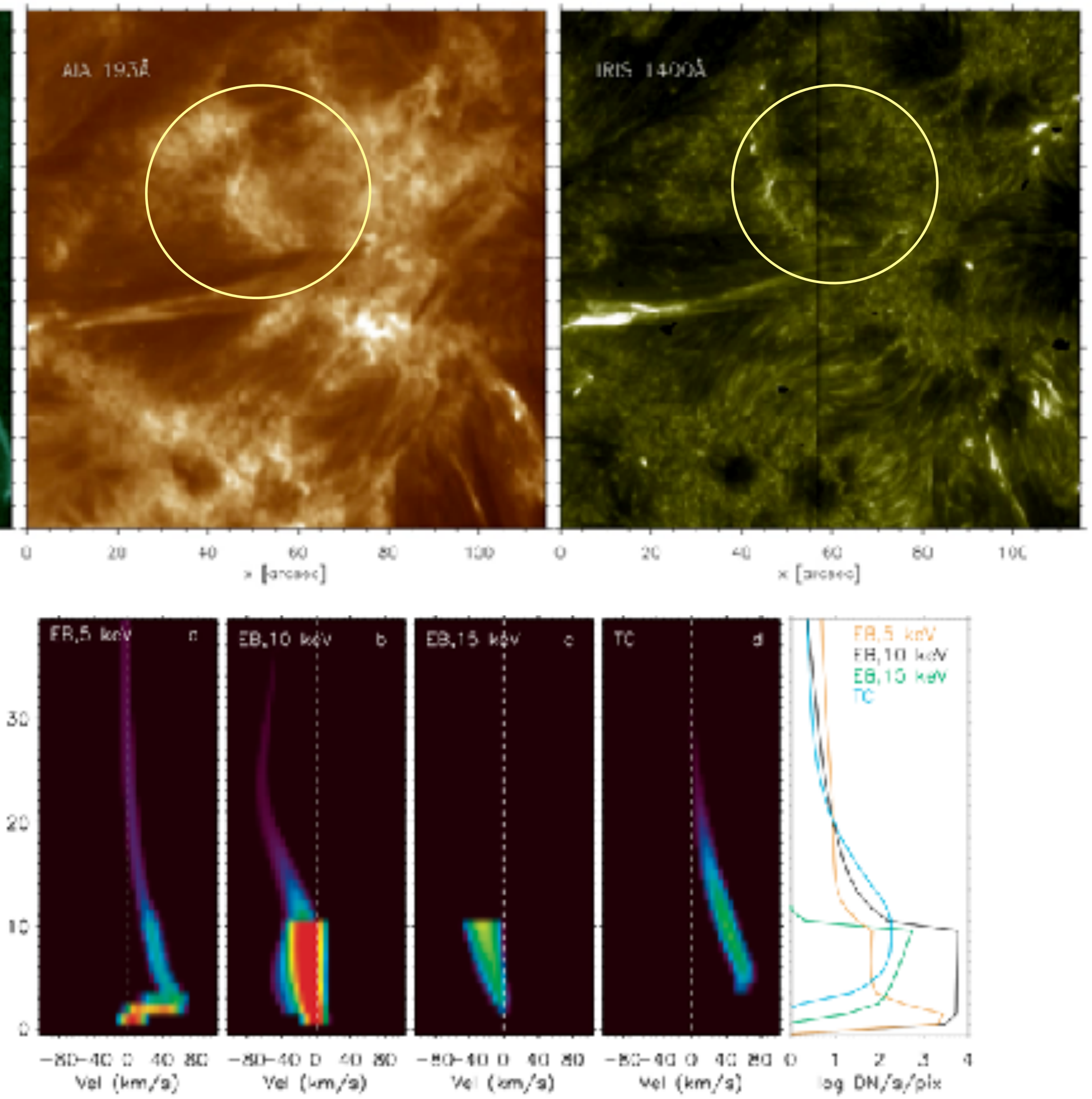


Subset of UFS loops appear to be associated with chromospheric counterparts and flux emergence-related phenomena

More statistical studies of small-scale loops
Connection with flux emergence?

Non-thermal particle acceleration and chromospheric heating

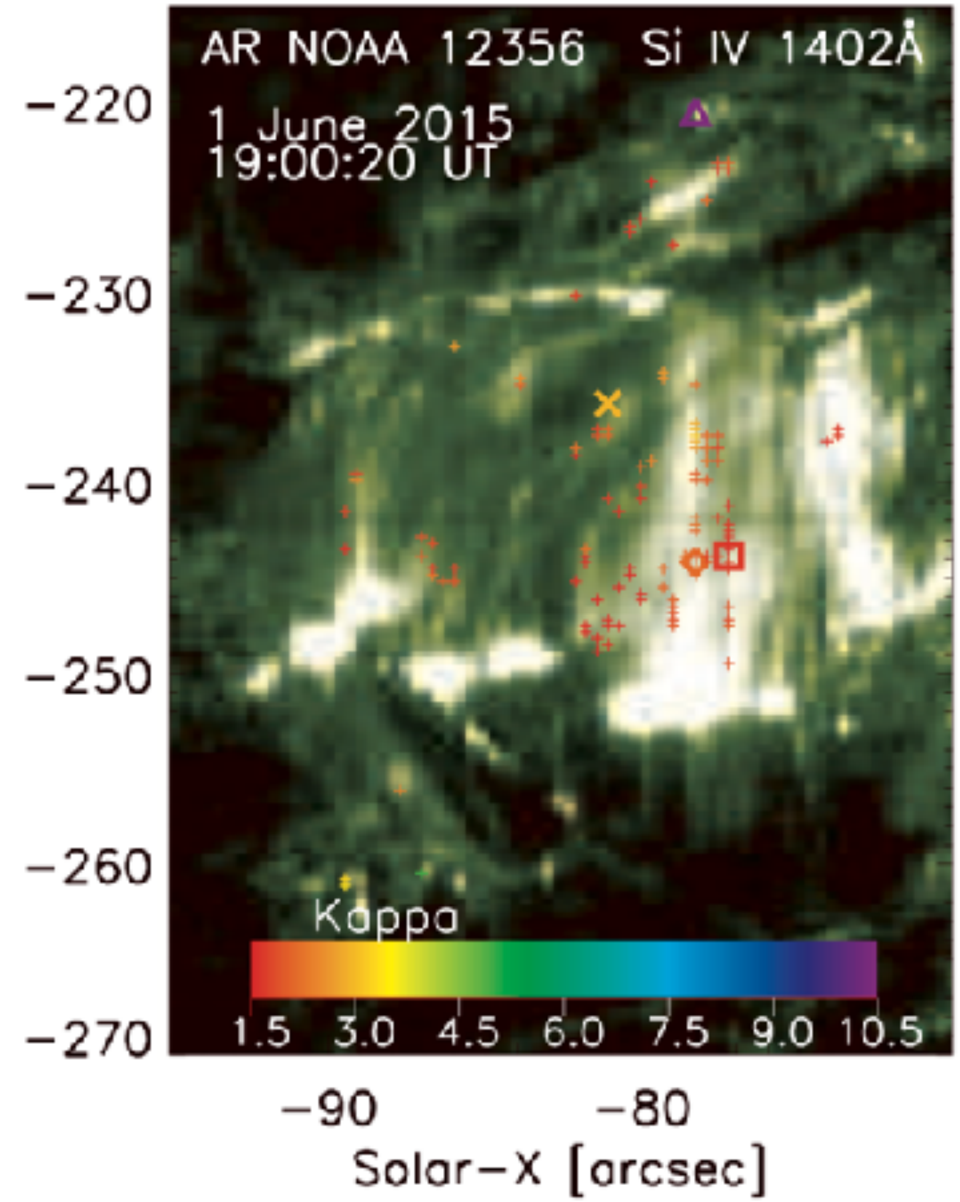
Testa et al., 2014; Polito et al., 2018



Short-lived brightenings in chromosphere and TR of hot loops indicative of energy deposition by non-thermal particles generated by (large-angle?) reconnection in the corona

Recent numerical simulations suggest these will only be visible in empty loops, i.e., before the loops are filled

Dudik et al., 2017, Dzifcakova et al., 2017



Discovery of non-Maxwellian κ-distributions in Si IV profiles in active regions

Could help explain why Si IV is brighter than O IV (although non-equilibrium ionization may also play a role, Martinez-Sykora et al., 2016)

Indicative of reconnection or turbulence ?

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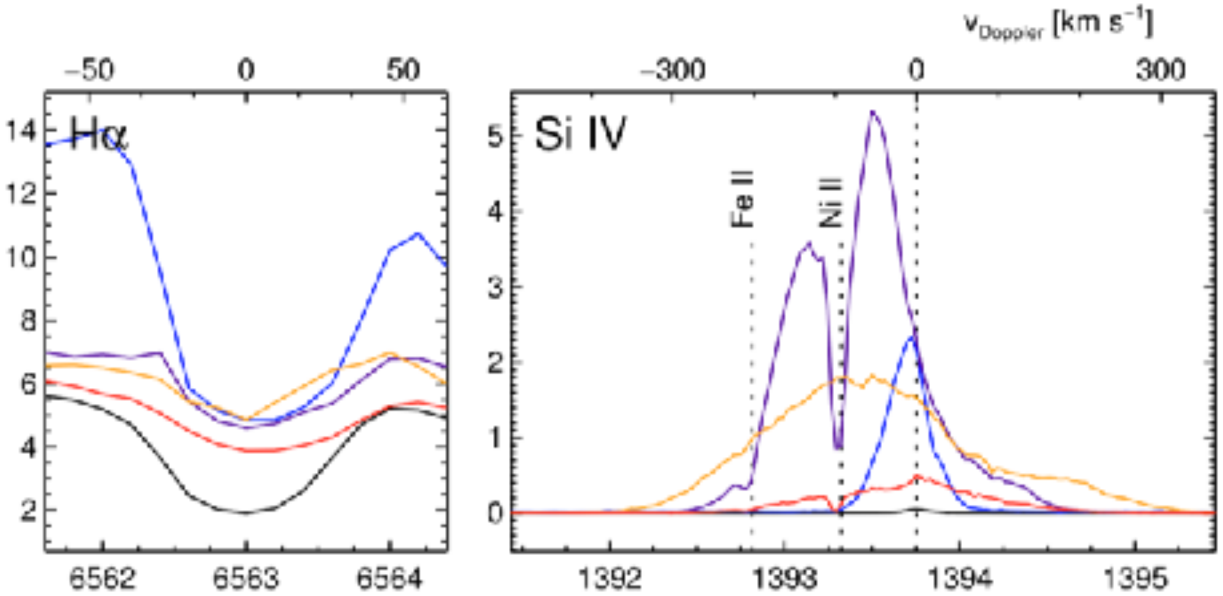
Magnetic reconnection in the low solar atmosphere: UV bursts

Peter et al., 2014; Vissers et al., 2015; Gupta & Tripathi, 2015
and many other papers



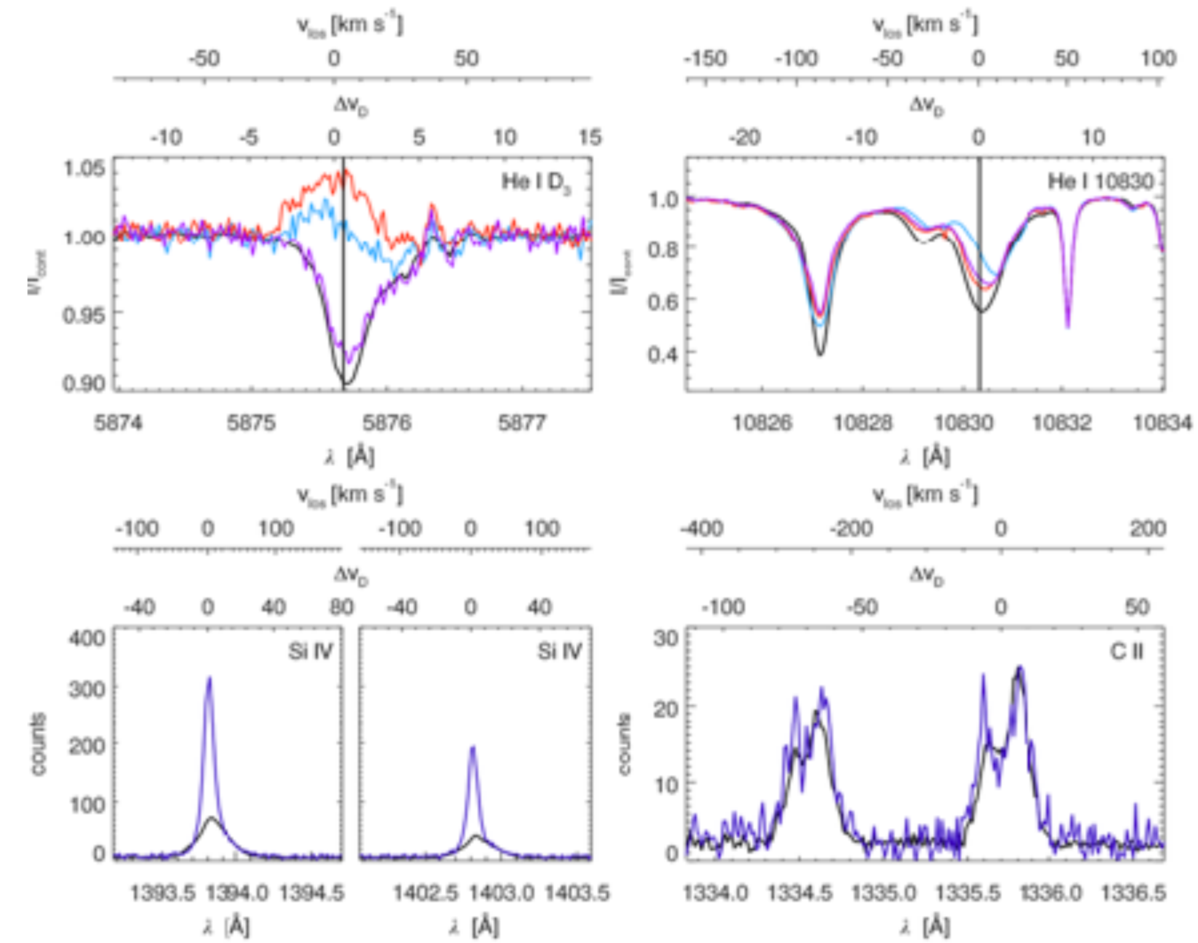
IRIS bombs, now called "UV bursts" are short-lived energetic events in which:
- plasma is heated to high T at upper photosphere/ low chromospheric heights
- plasma is accelerated to Alfvenic speeds

Signature of magnetic reconnection as deduced from event properties and magnetic field configuration

Overlying canopy (partially) obscures signals (e.g., H-alpha line center), but various IRIS diagnostics reveal direct views of reconnection site

Studies of UV bursts interesting laboratory to study reconnection

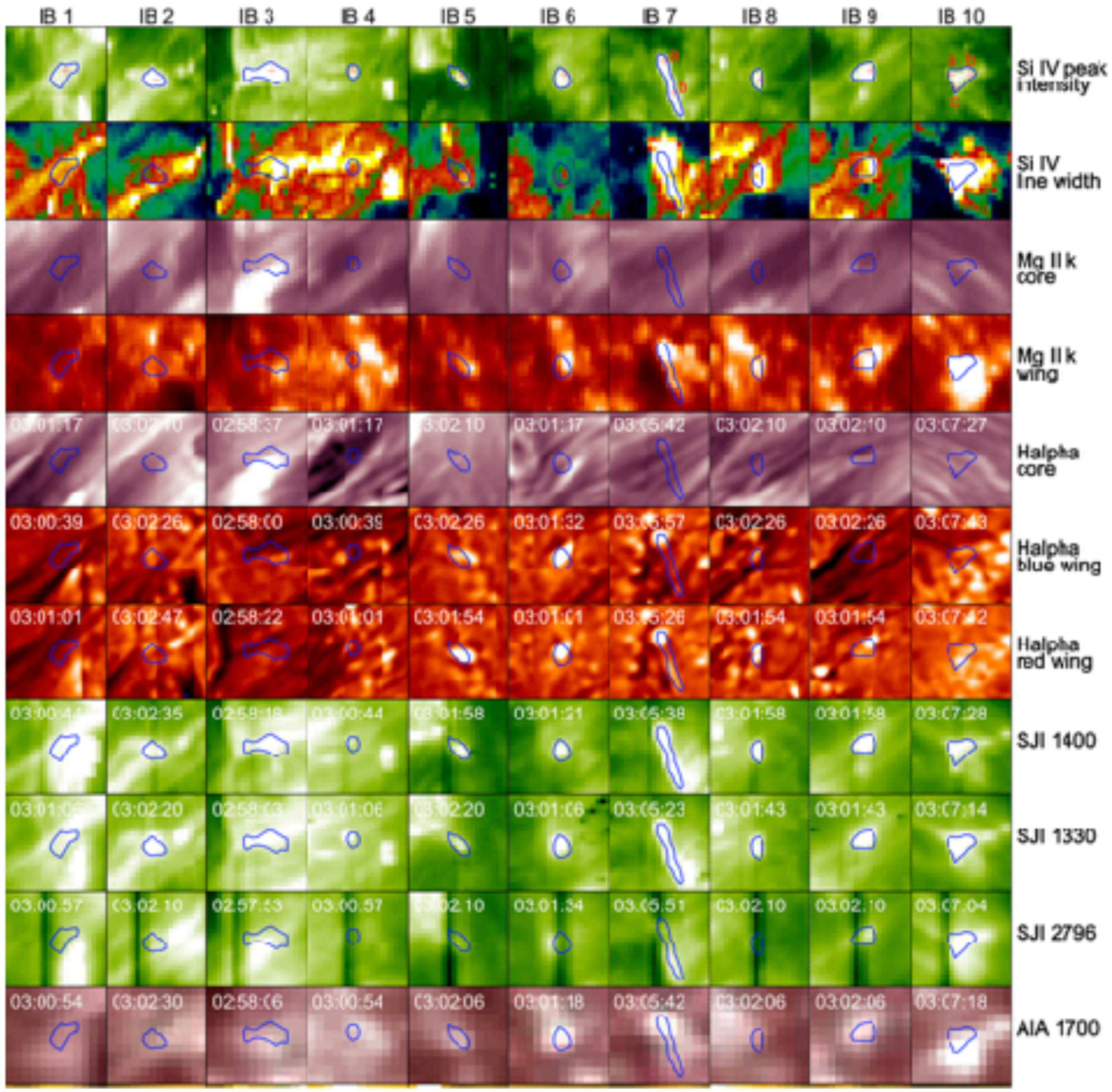
Peter et al., 2014; Grubecka et al., 2016;
Judge , 2015; Rutten, 2016; Hong et al., 2017; Libbrecht et al., 2017



Temperature reached in UV bursts?
- Not necessarily as high as equilibrium ionization predicts (80,000 K, Peter et al., 2014, Judge, 2015)
- Higher than 1D models can reproduce (Grubecka et al., 2016)
- Maybe formed in LTE ionization (15,000 K, Rutten 2016)?
- Combination of He II lines (SST) and IRIS suggests in some events T~50,000 K (Libbrecht et al., 2017)

UV bursts & Ellerman bombs?

Vissers et al., 2015, Kim et al., 2015, Tian et al., 2016
and many other papers



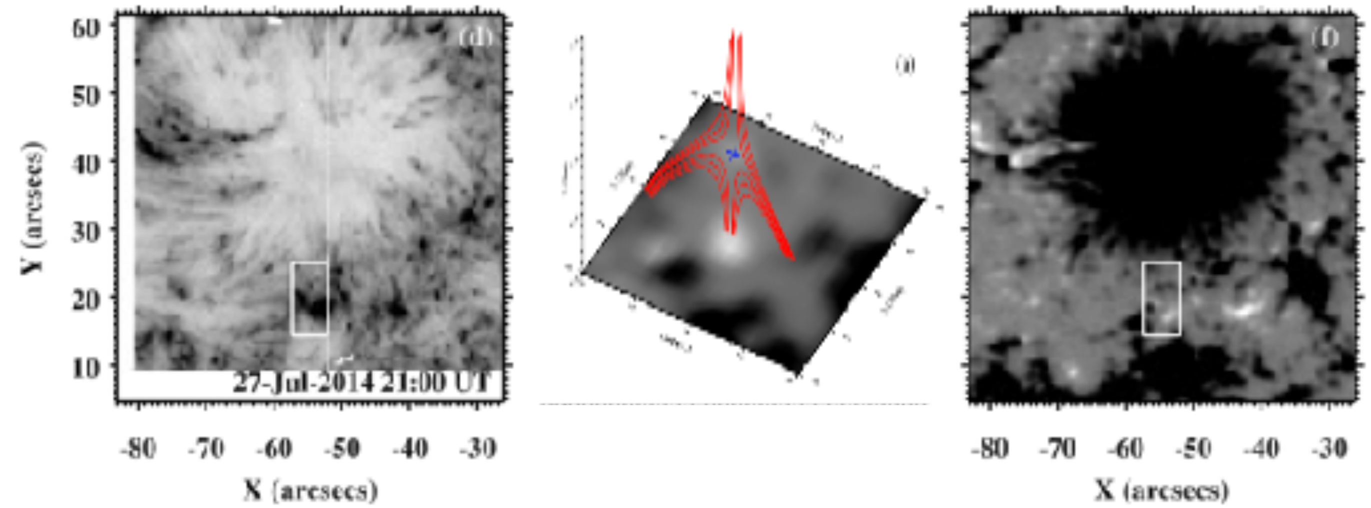
Coordinated observations with ground-based telescopes (H-alpha) show that a subset of IRIS bombs are related to Ellerman bombs (visible in H-alpha wing)

Height of reconnection site plays key role in making IRIS or Ellerman bomb?

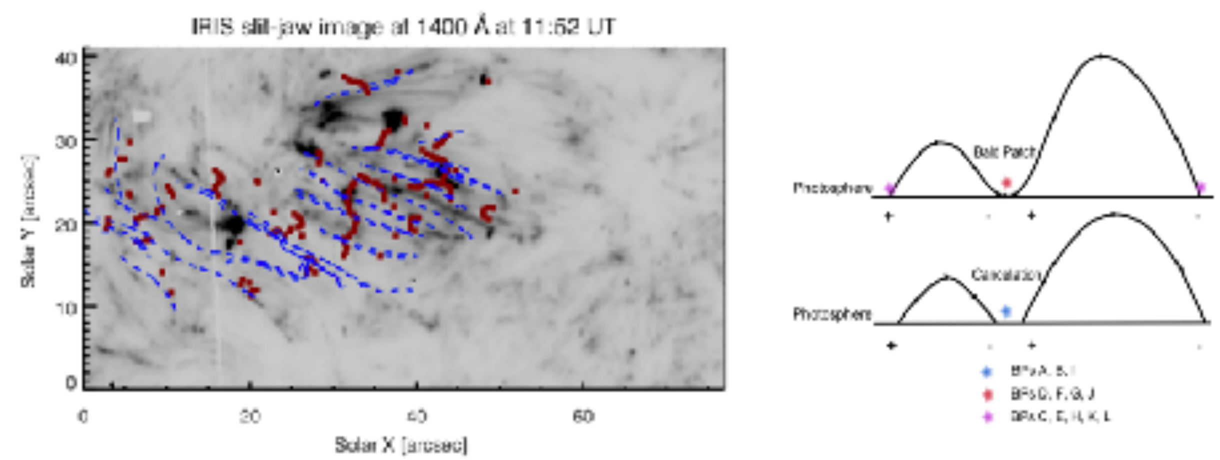
More coordinated IRIS-GBO observations needed

Magnetic field conditions?

Chitta et al., 2017



Zhao et al., 2017



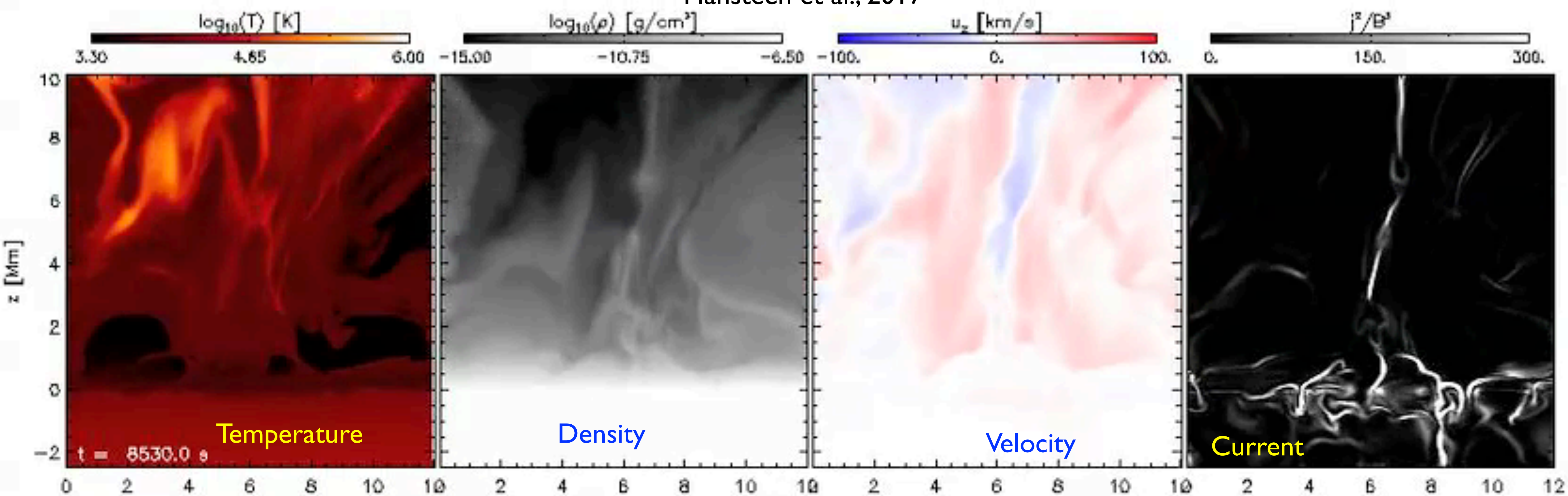
Magnetic field extrapolations and magneto-frictional calculations provide insight into the height of the reconnection site

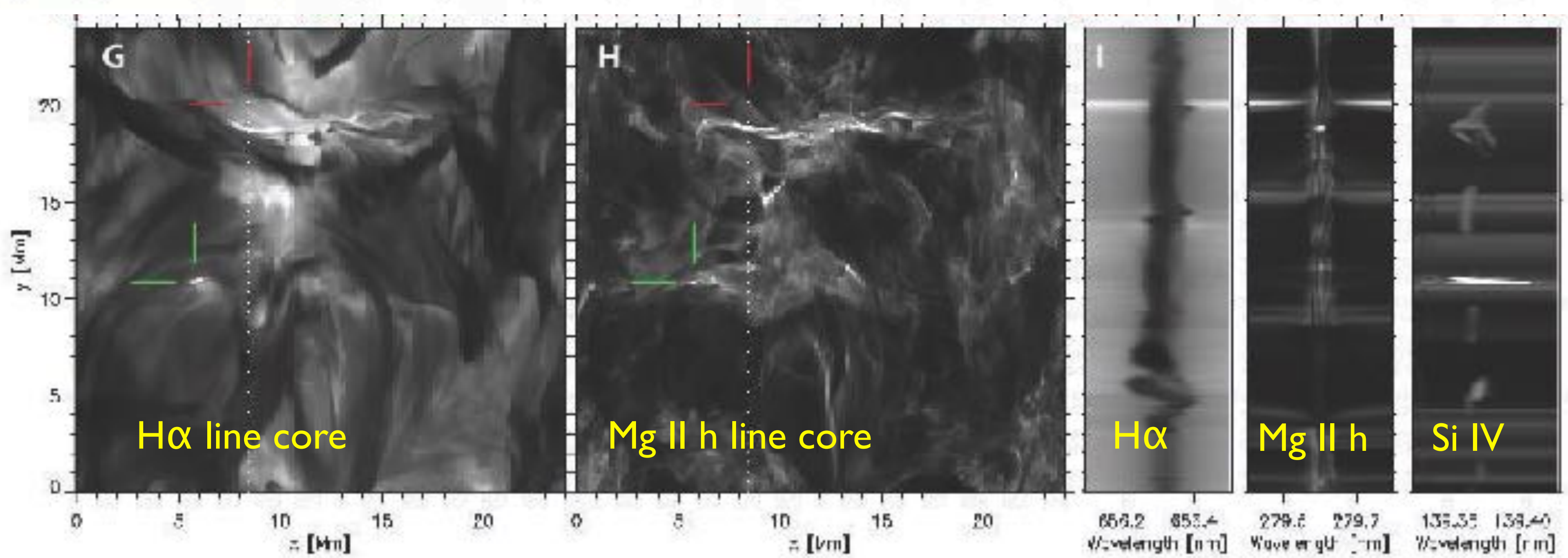
Relative importance of QSLs, null points, cancellation unclear

Need more statistical approaches to understand differences between various "bombs"

Magnetic reconnection in the low solar atmosphere: UV burst modeling

Hansteen et al., 2017





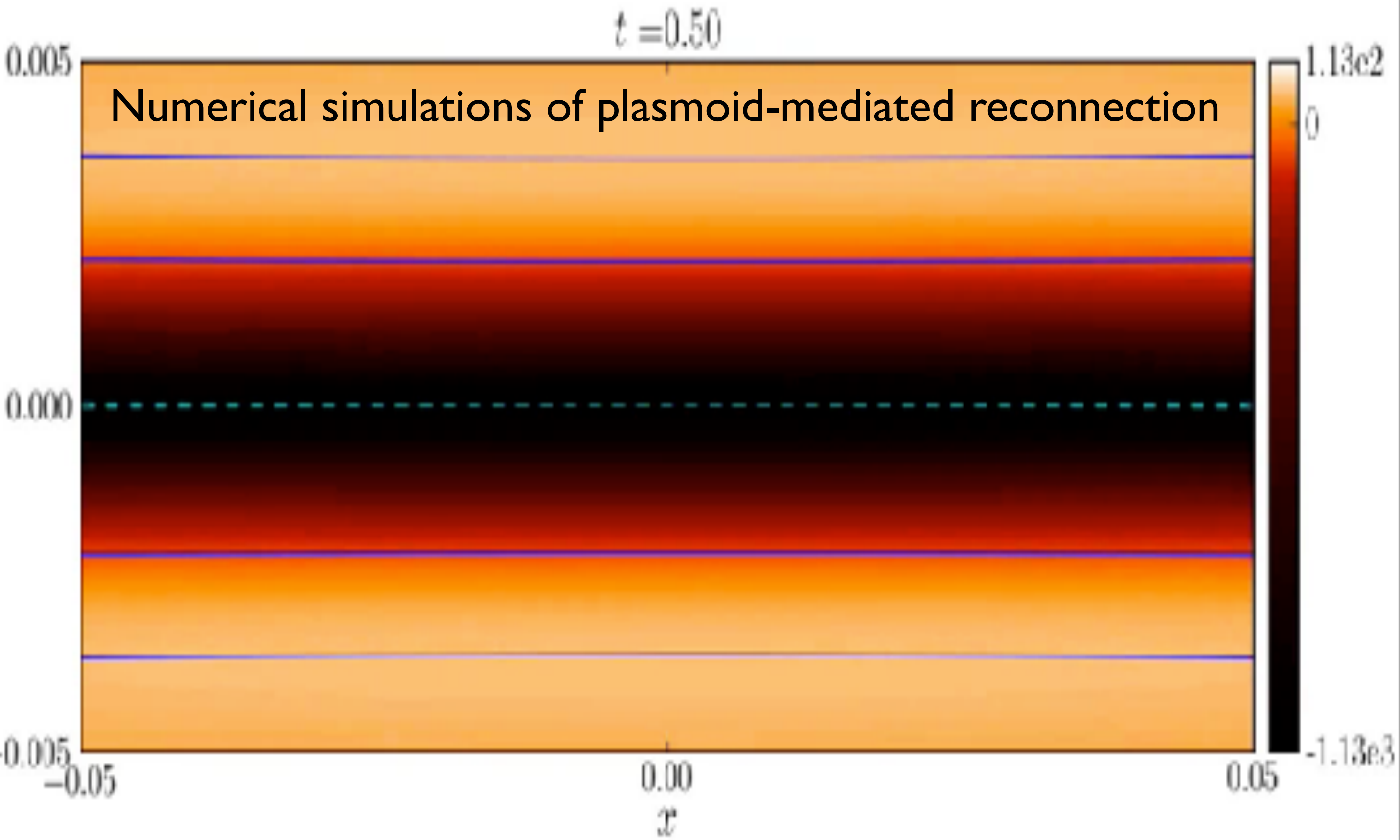
- Radiative MHD modeling (using Bifrost) shows very good similarities with Swedish Solar Telescope and IRIS observations

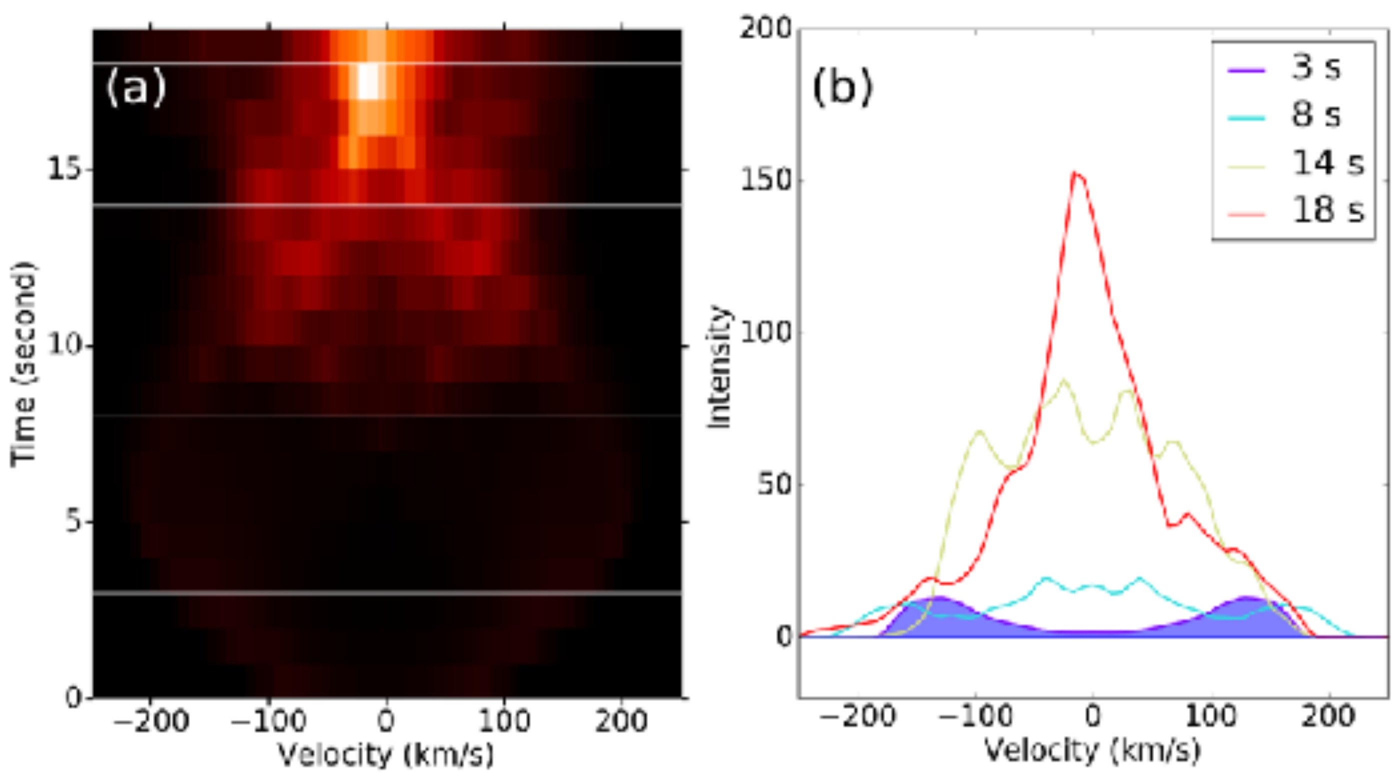
- Discrepancies remain, including the very high T at low heights, challenging current models of reconnection in the partially ionized chromosphere

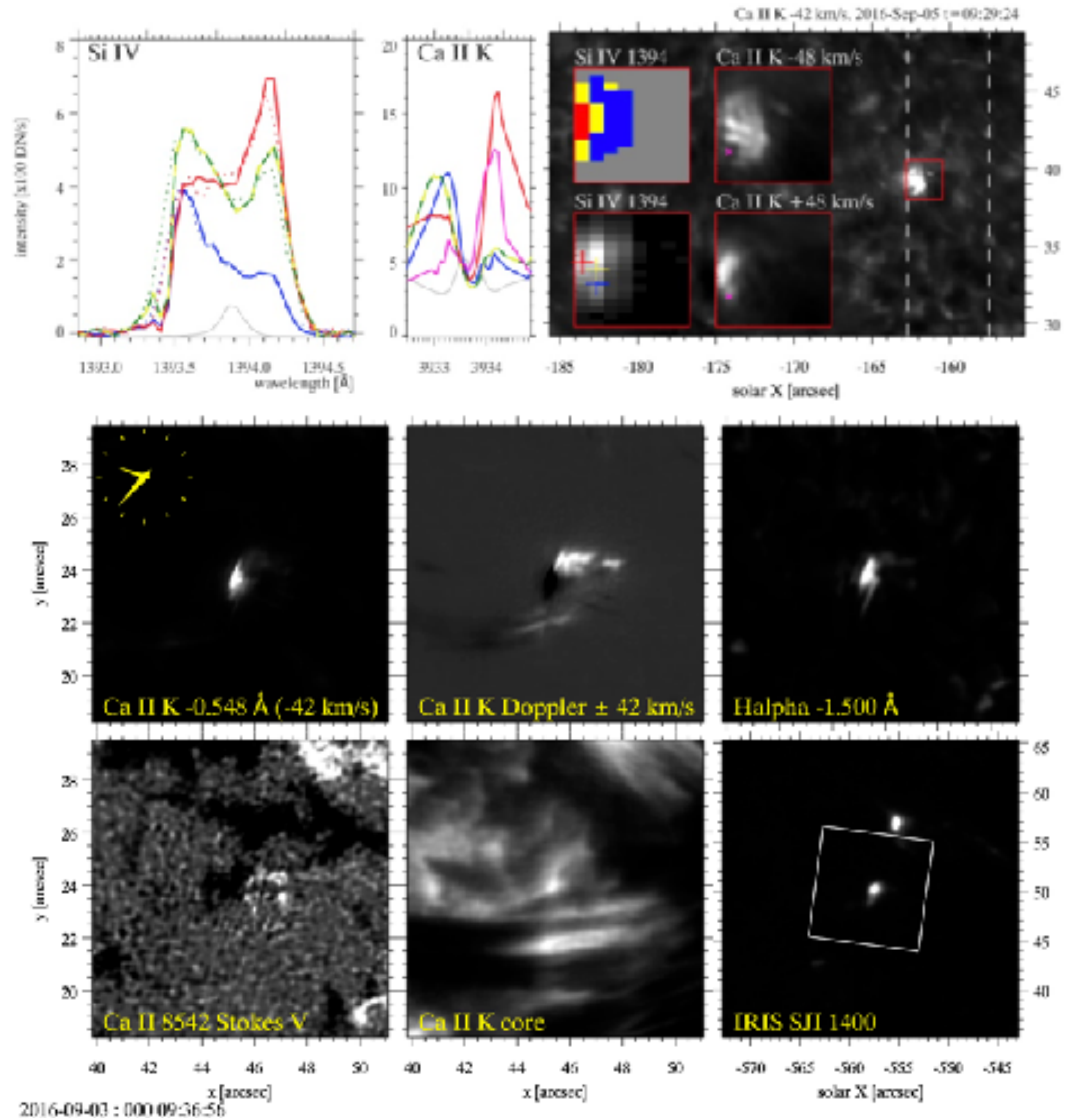
Magnetic reconnection mediated by plasmoid instability

Innes et al., 2015, Guo et al., 2017, 2018

Rouppe van der Voort et al., 2017







IRIS spectra at high temporal and spatial resolution reveal details of transition from slow to fast reconnection, constraining theoretical models of magnetic reconnection

Very high resolution CHROMIS observations (SST) reveal plasmoids in IRIS bombs, providing support for the indirect inference of plasmid-mediated reconnection

Indirect evidence for plasmoid-mediated reconnection in micro flares from Warren et al., 2016, Reep et al., 2016

Need more statistics on properties of bursts observed and more realistic numerical modeling

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Energy deposition during flares

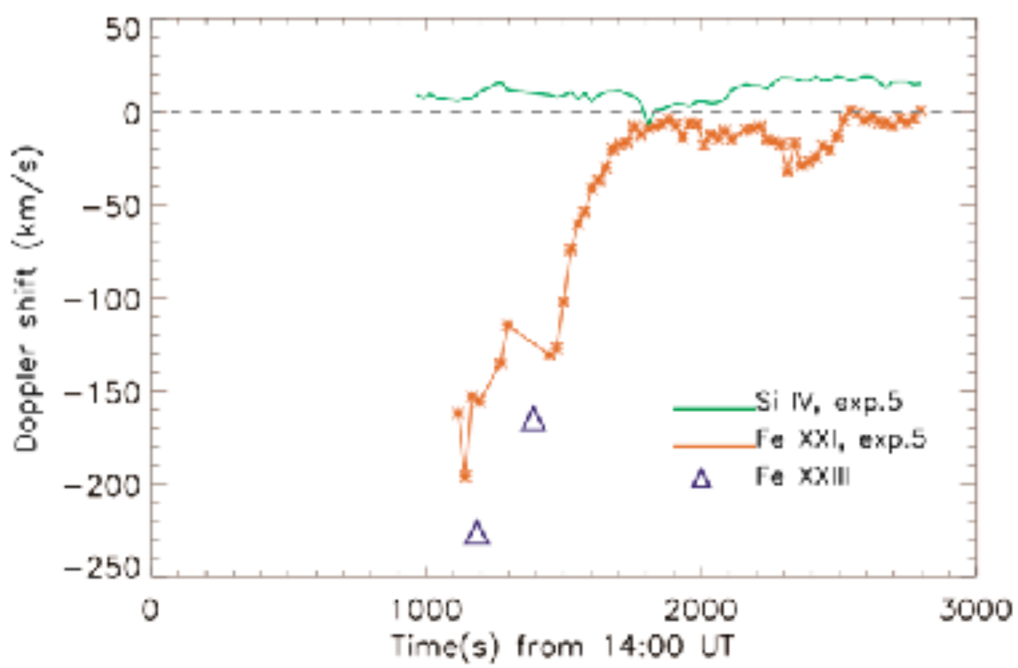
PSG 3: Analyze energy and mass transfer between photosphere, chromosphere and corona

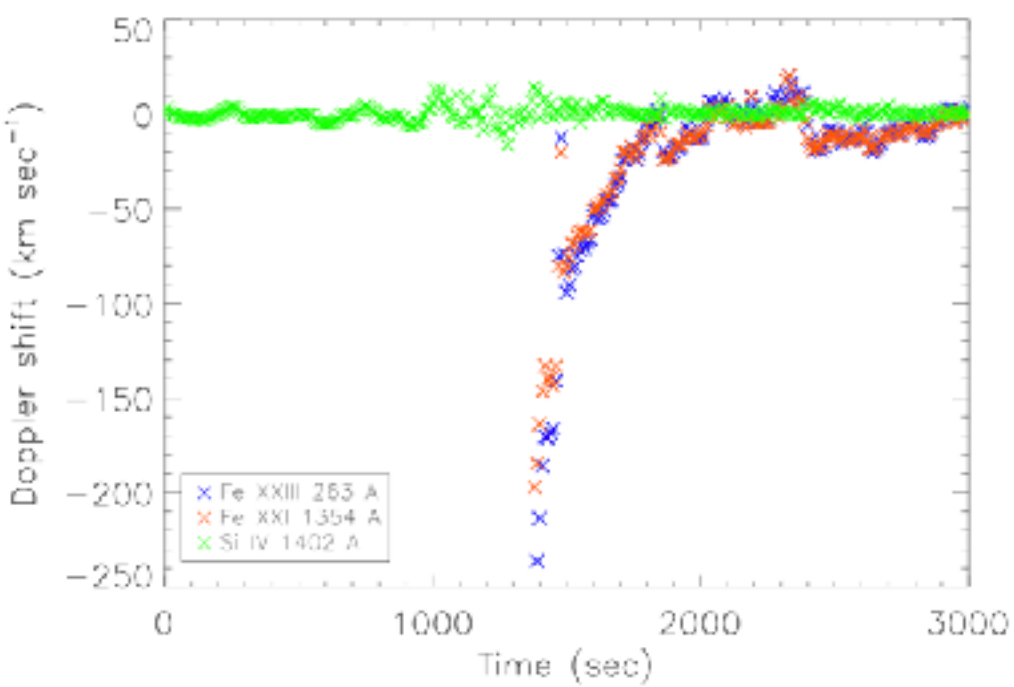
PSG 4: Quantify variations of far and near ultraviolet solar radiation over the solar cycle

PSG 5: Explore the solar-stellar connection

Non-thermal energy deposition in the low solar atmosphere of flares

Polito et al., 2016

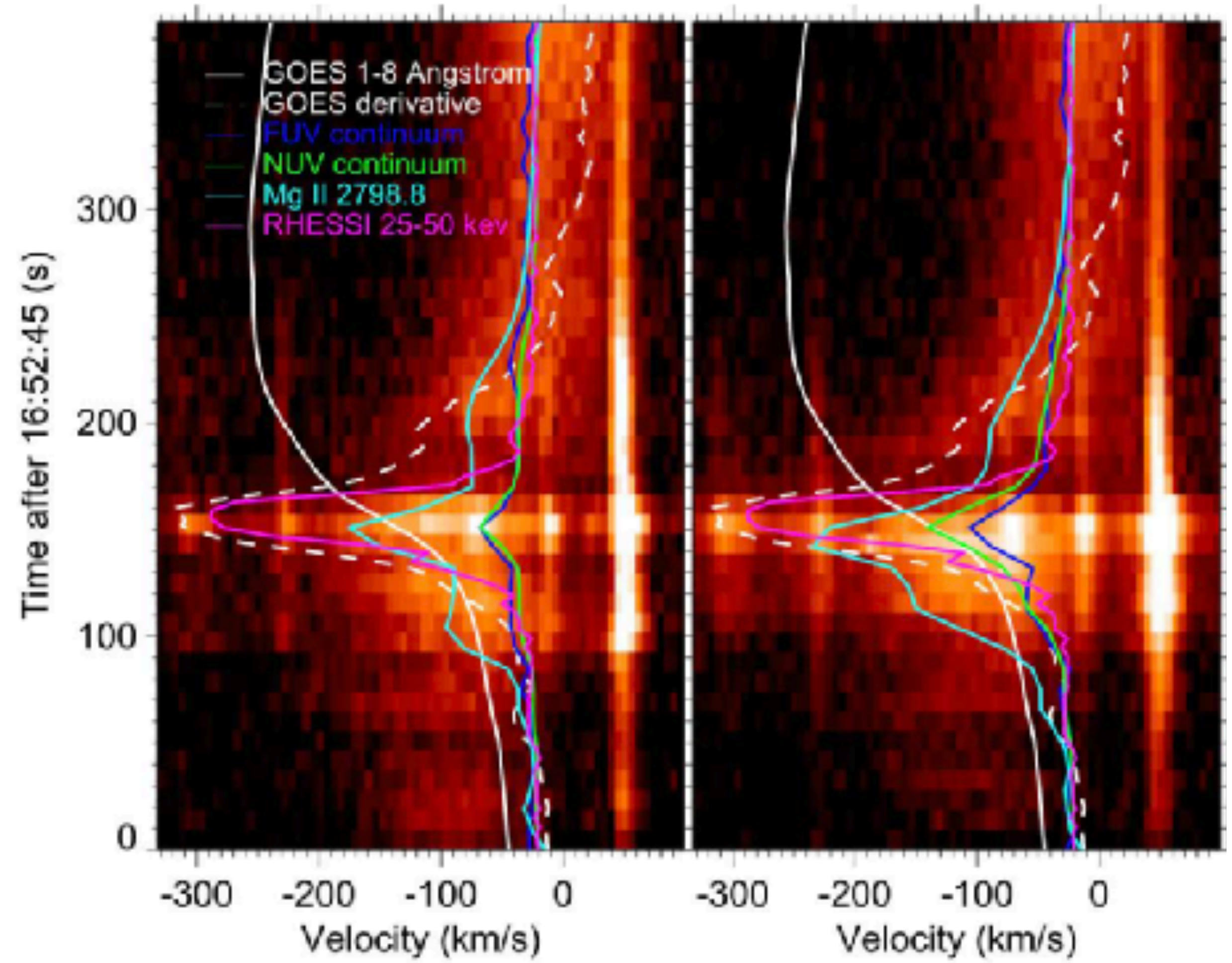




Numerical models show support for scenario in which non-thermal electrons generated in the coronal current sheet/reconnection site propagate towards loop footpoints where they are thermalized and cause evaporation

(but in some flares, thermal conduction plays significant role too, Battaglia et al., 2015)

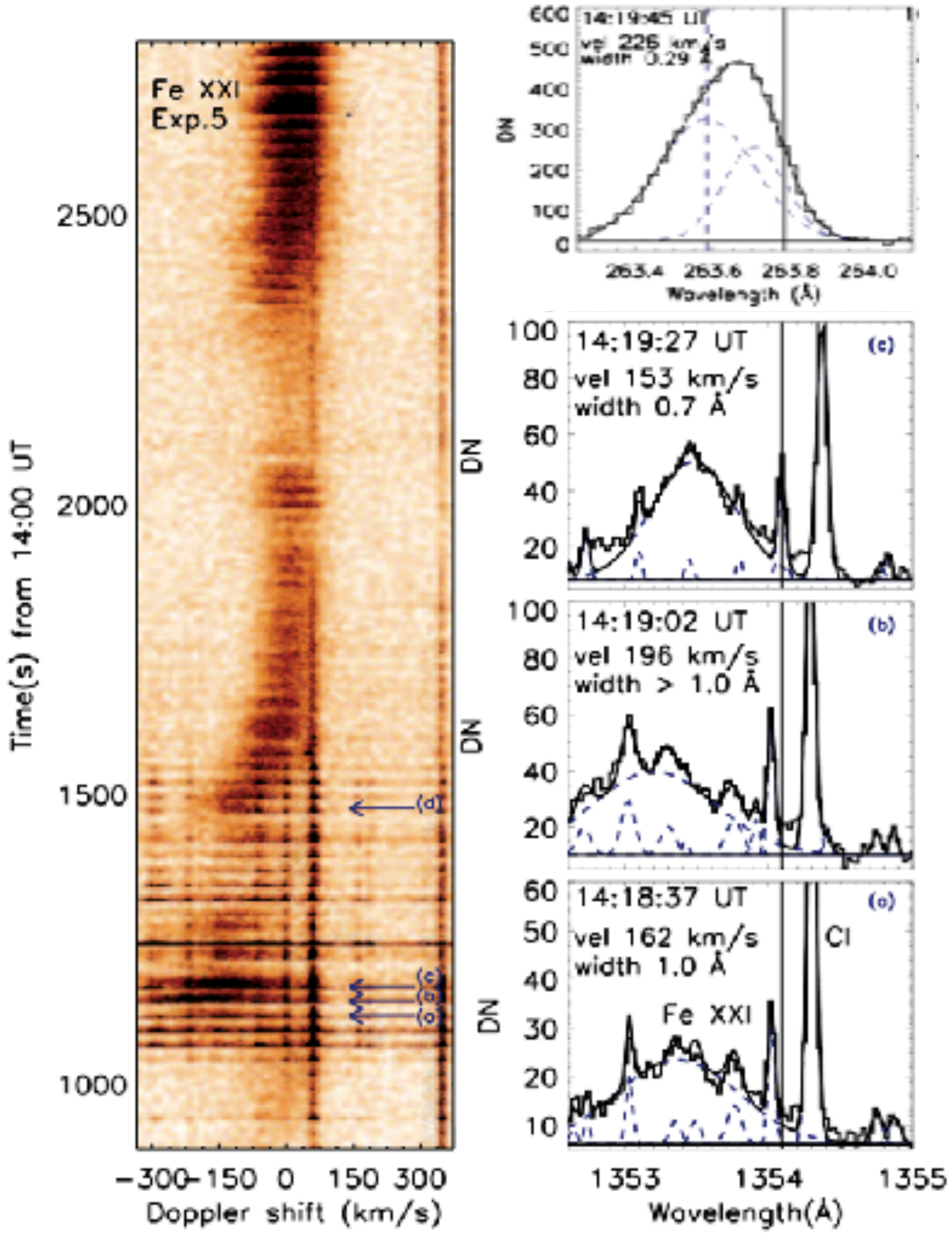
Tian et al., 2015



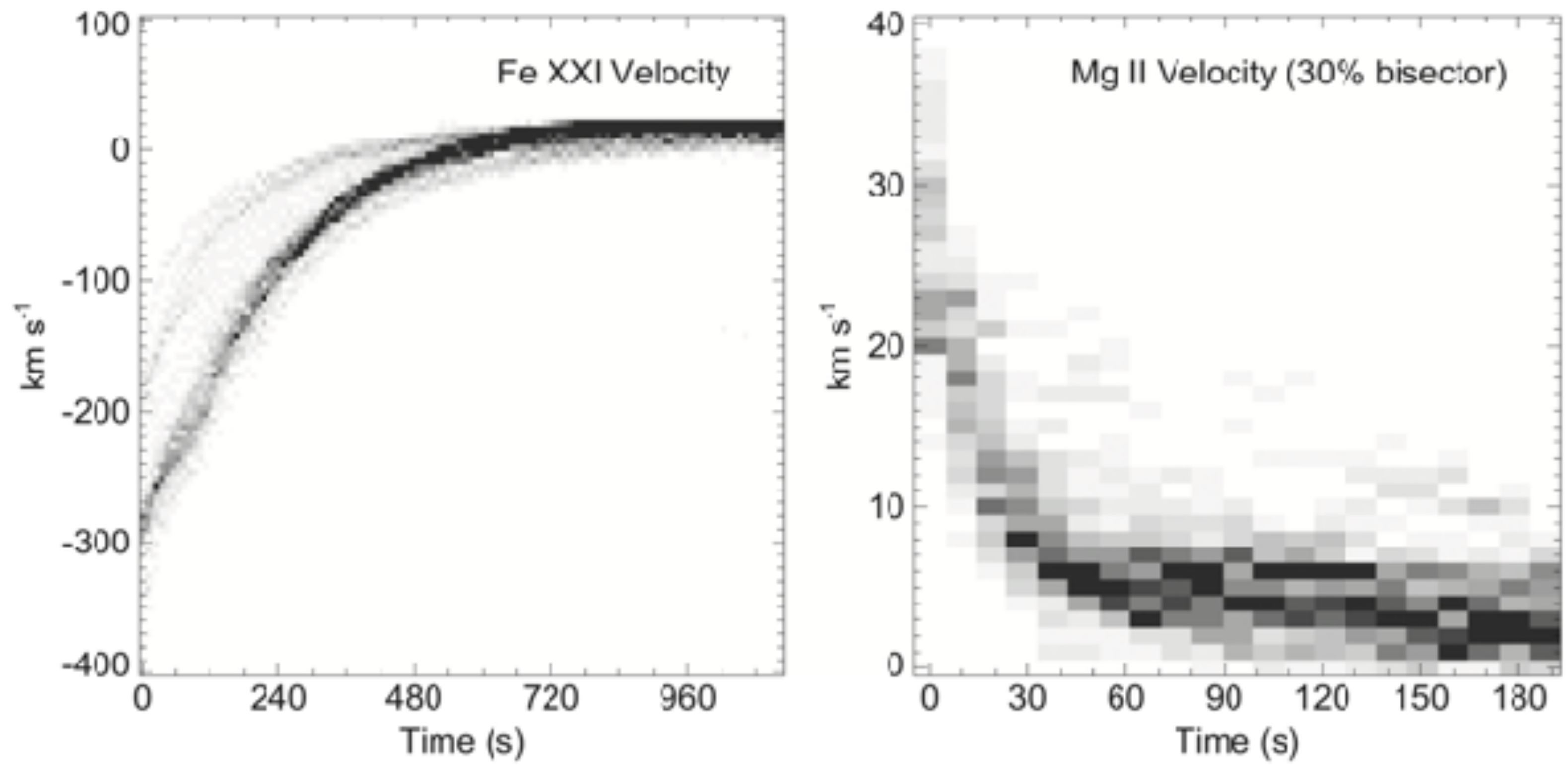
This scenario is also supported by observed correlations between IRIS observations of up flows of hot plasma and hard X-ray flux from RHESSI and GOES (see also Li et al., 2017 for a correlation with radio emission and IRIS Doppler shifts)

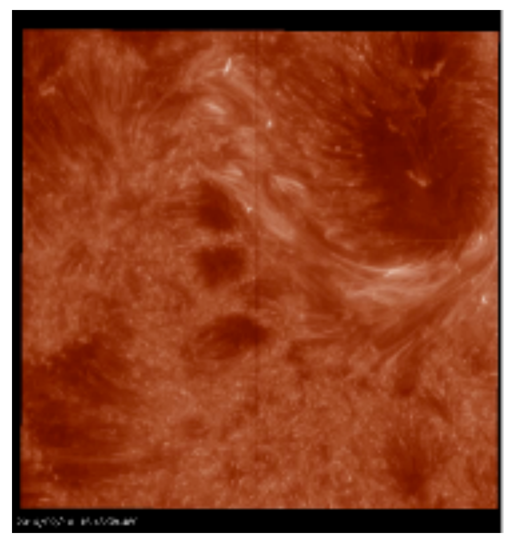
Hot plasma evolution during flares

Polito et al., 2016



Graham & Cauzzi, 2015





IRIS for the first time resolves hot upflows (fully blue-shifted Fe XXI 1354Å) in flare ribbons from stationary components in loops (unresolved w/EIS)

Resolves long-standing discrepancy and provides support for evaporative flows (both explosive, Brosius et al., 2016, and gentle, Li et al., 2015)

Puzzling initial increase of up flow speed, followed by decrease

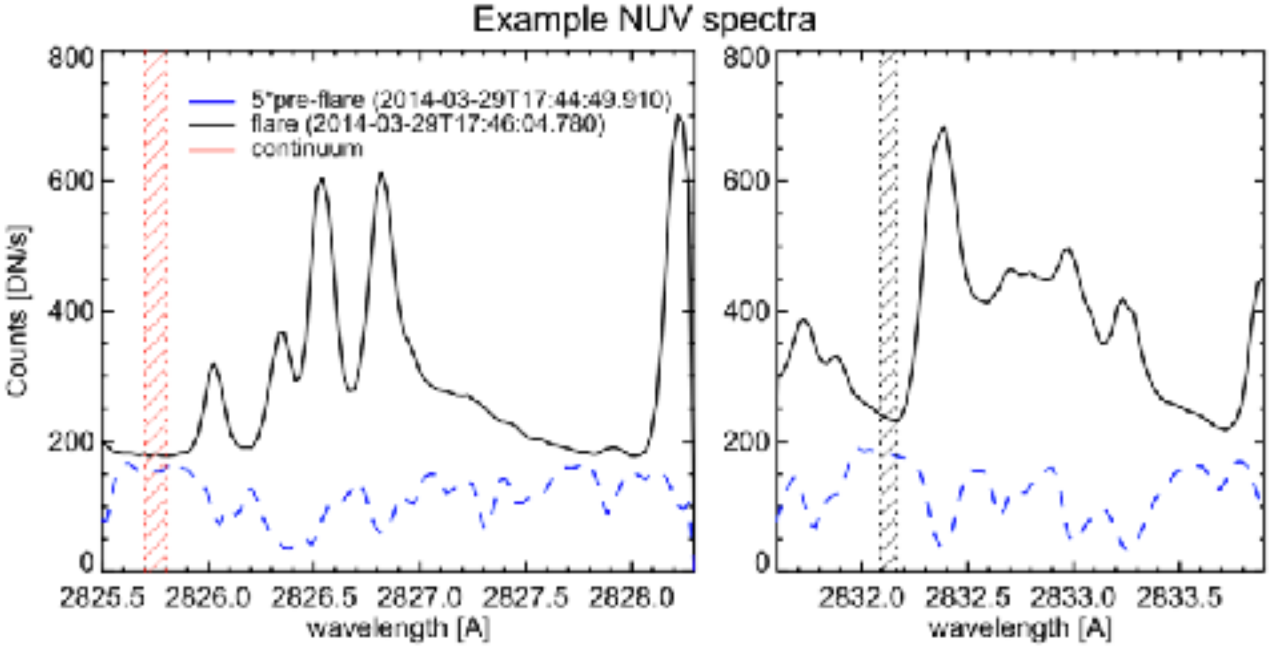
Dozens of flare ribbon pixels show very similar evolution of Fe XXI upflows and Mg II downflows

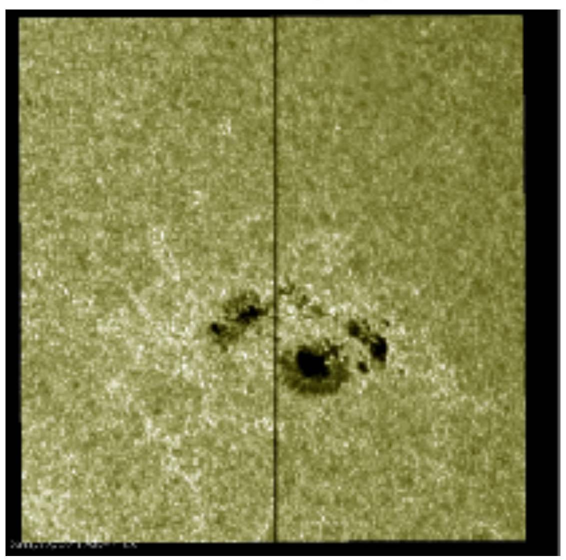
Is energy input per “field line” uniform, or is evaporation governed by local conditions rather than initial energy input?

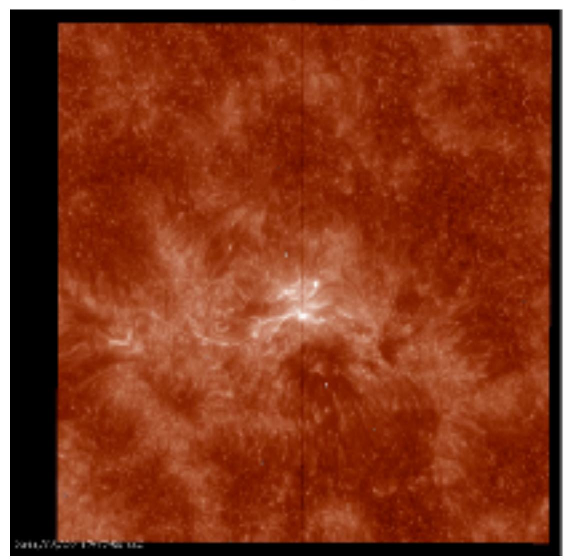
Puzzling delays between coronal upflows and chromospheric downflows not compatible with evaporation? (see also Sadykov et al., 2016)

Constraints from white-light flares

Kleint et al., 2016







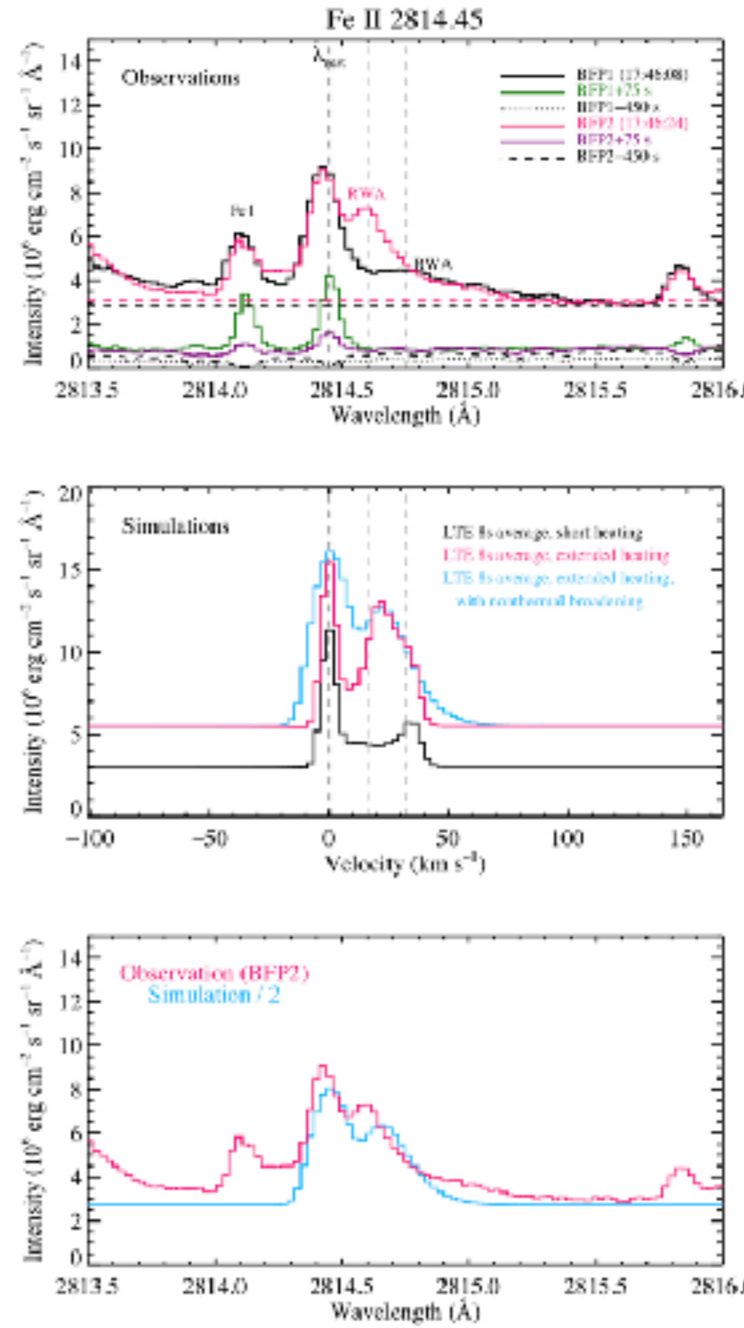
Flares often show significant emission in white light, the nature of which has been unknown (black-body, Balmer continuum, etc)

Implications for commonly assumed scenario of non-thermal electrons thermalizing in the low atmosphere

IRIS observations and modeling help constrain the processes involved, suggesting Balmer continuum in the chromosphere and H- continuum in the photosphere play a role (see also Heinzel & Kleint, 2015, Kowalski et al., 2017)

Role of non-thermal electrons supported by RHESSI/IRIS observations (Lee et al., 2017), suggesting 6-22% of non-thermal electron energy dissipated in chromosphere

Kowalski & Allred, 2017

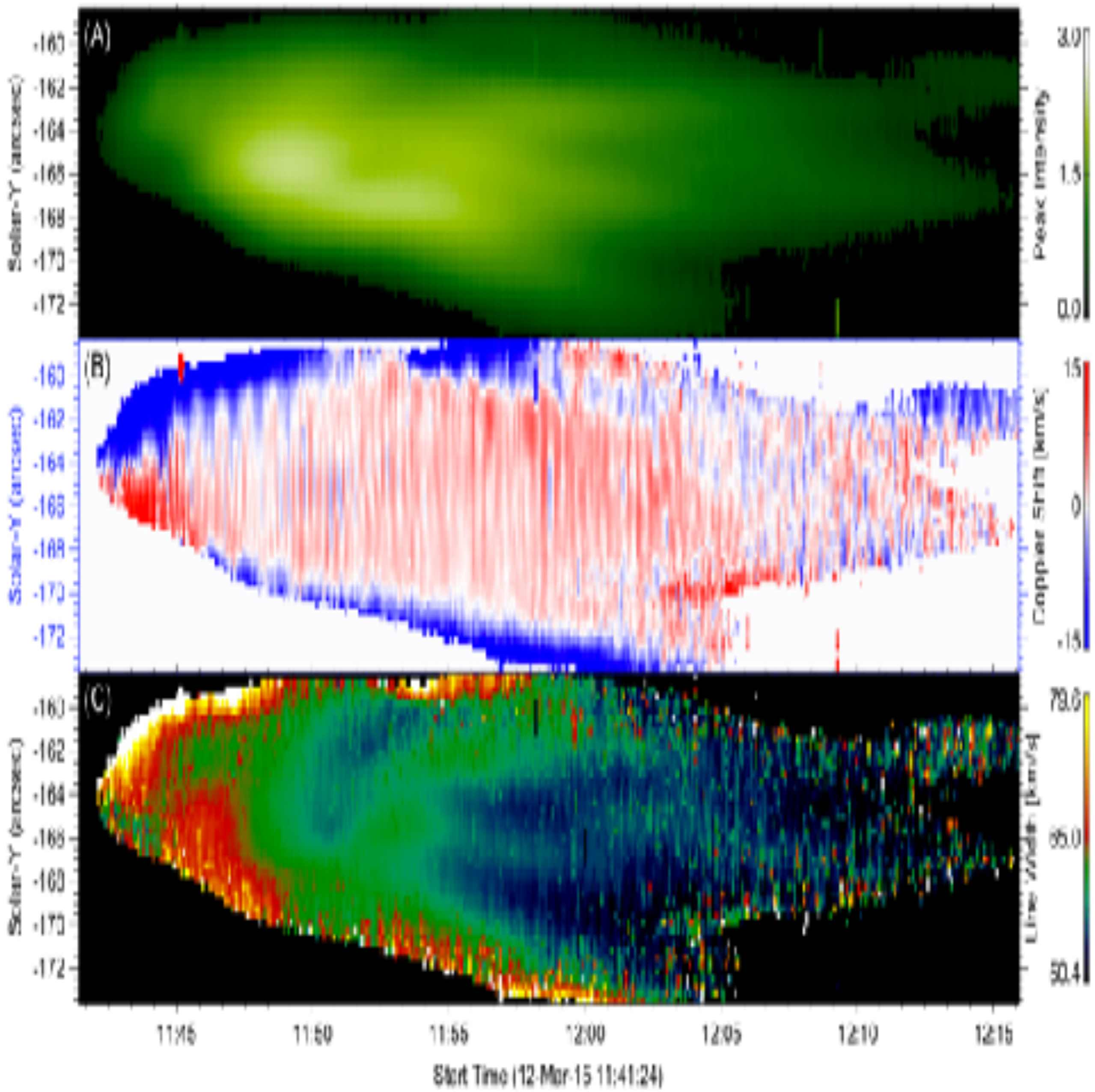


Numerical simulations of very high electron beam fluxes and thick target model can explain NUV continuum enhancements during flare (Balmer continuum)

Can also explain puzzling asymmetric profiles of chromospheric Fe II: two flaring regions: down flowing chromospheric condensation and stationary layer below, both heated by electron beams

Diagnosing flare processes and conditions

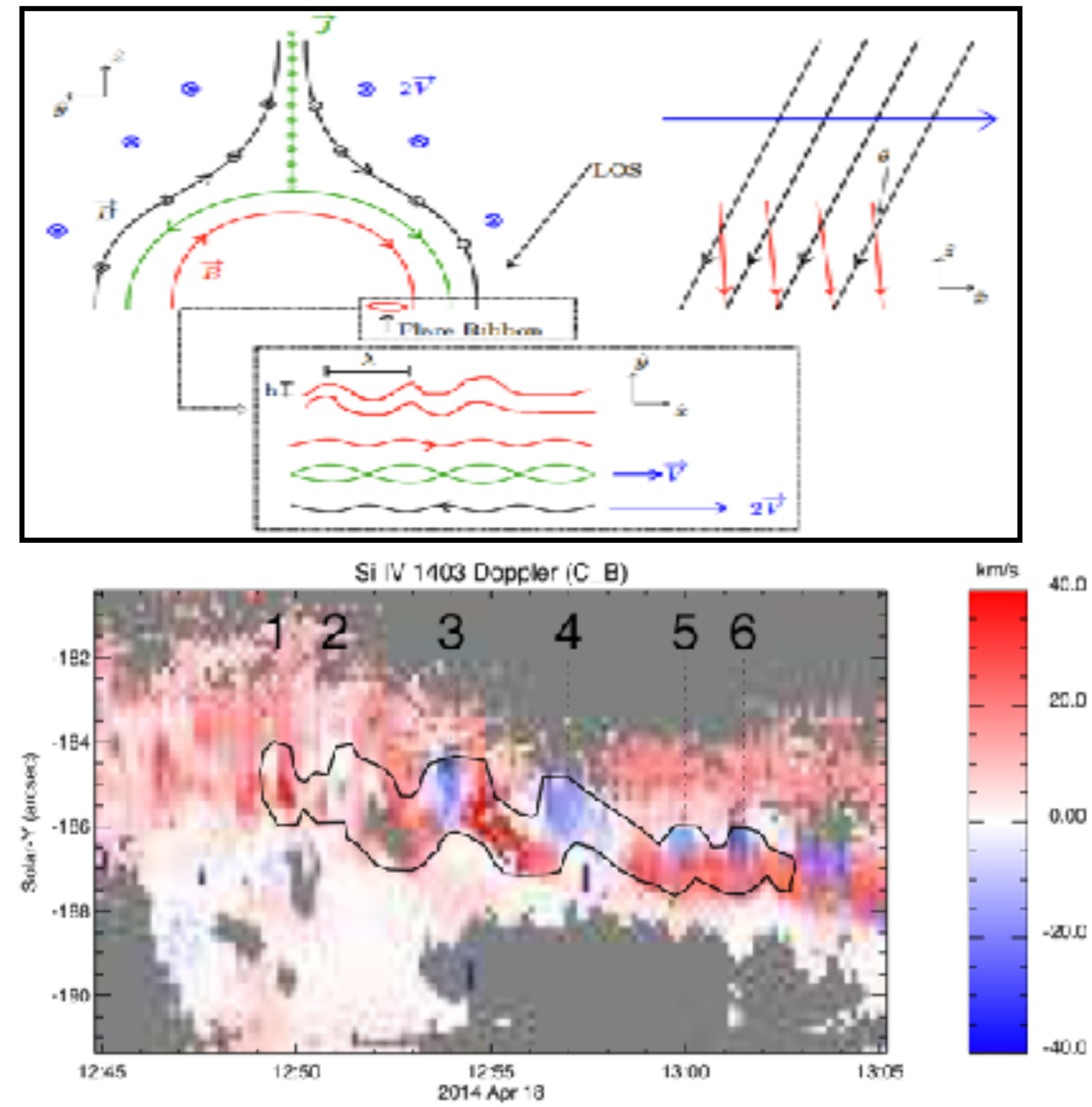
Tian et al., 2017



Short-period velocity and intensity oscillations in Fe XXI emission during aftermath of flare suggests presence of global fast sausage mode, providing constraints on flare loop density contrast and lower limit to Alfven speed outside flare loop

See also Li et al., 2017 for kink-mode oscillation detection

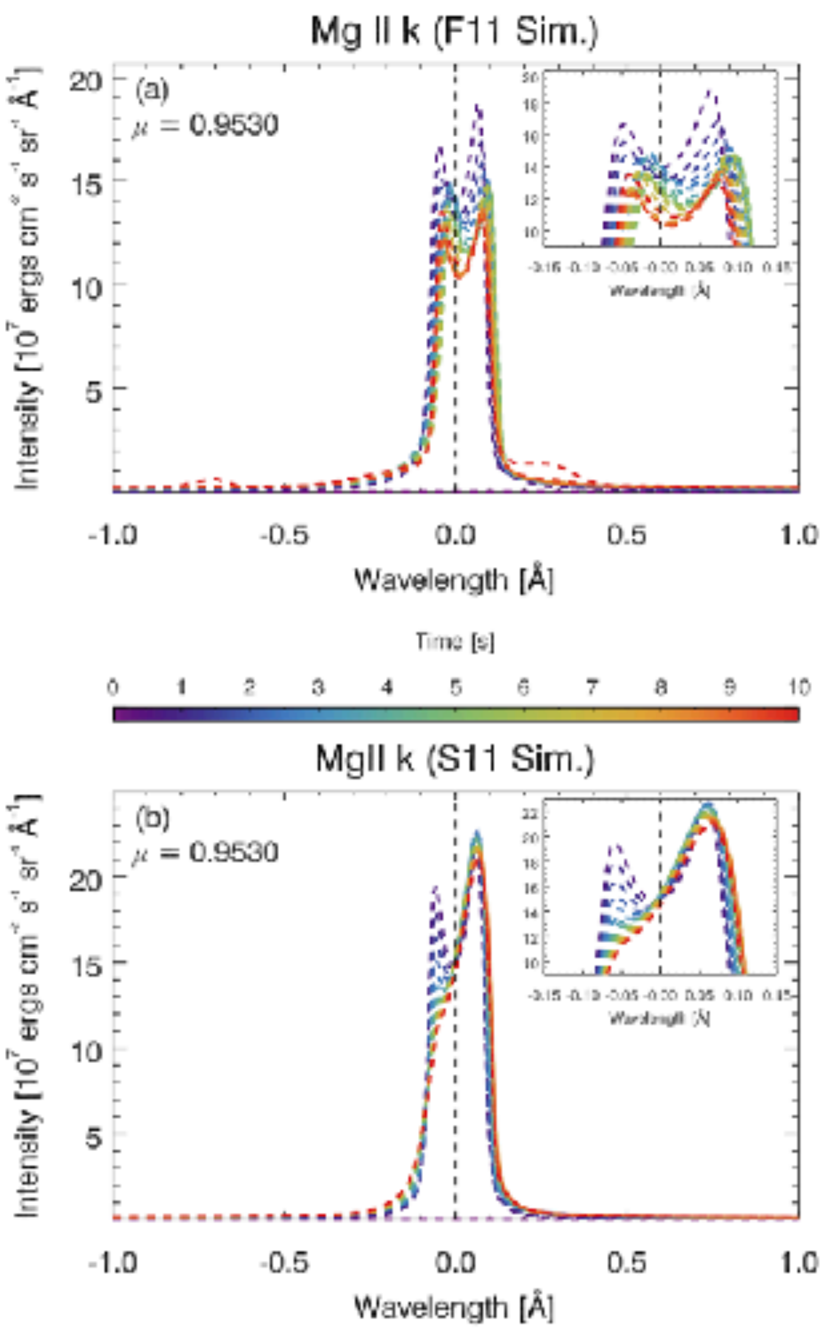
Brannon et al., 2015; Parker & Longcope, 2017



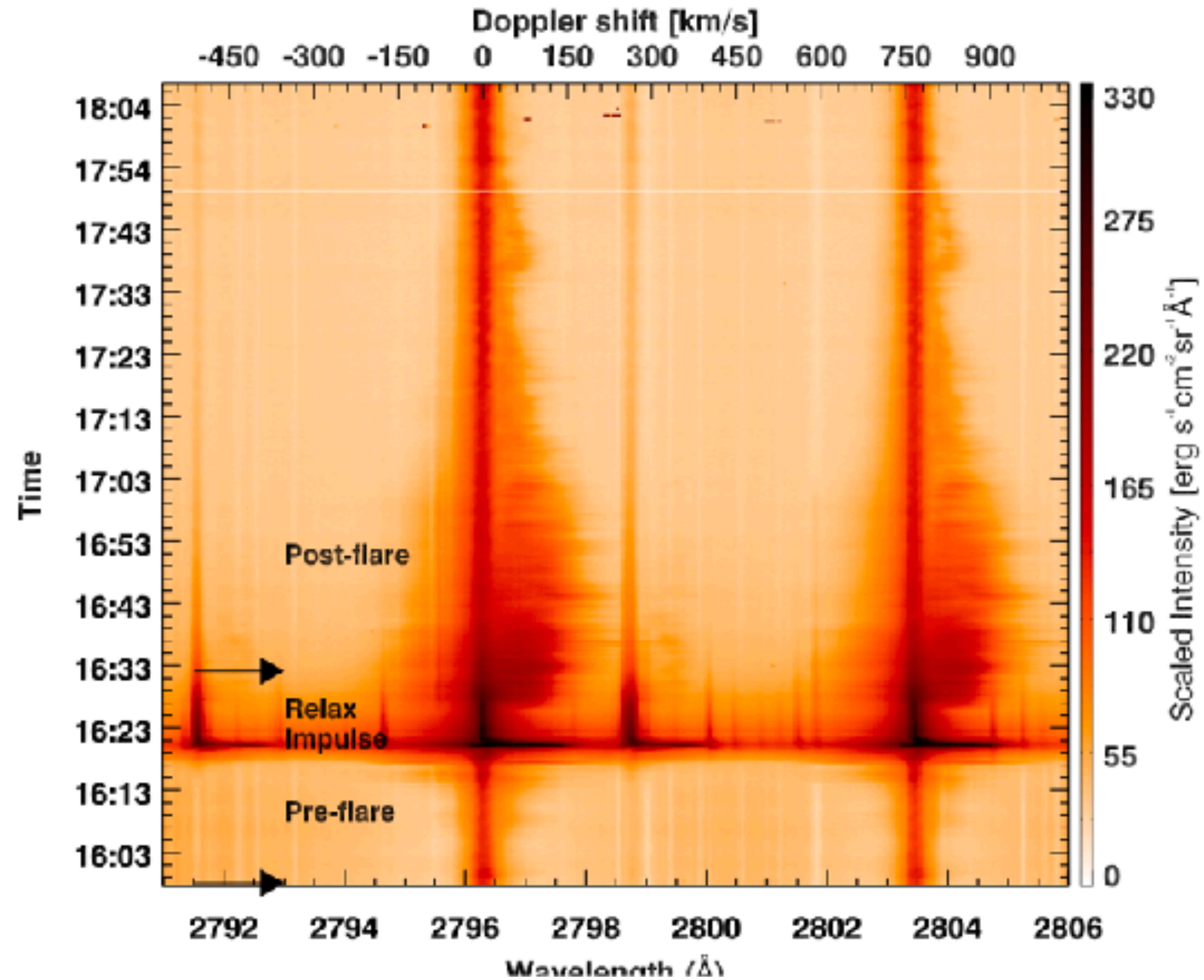
Puzzling quasi-periodic sawtooth pattern with alternating up- and downflows in flare ribbons with differing interpretations: bursty reconnection (Brosius et al., 2016), slip-running reconnection (Li et al., 2017) or tearing mode instability (Parker & Longcope, 2017)

The role of Alfvén waves in flares

Kerr et al., 2016



Lacatus et al., 2017

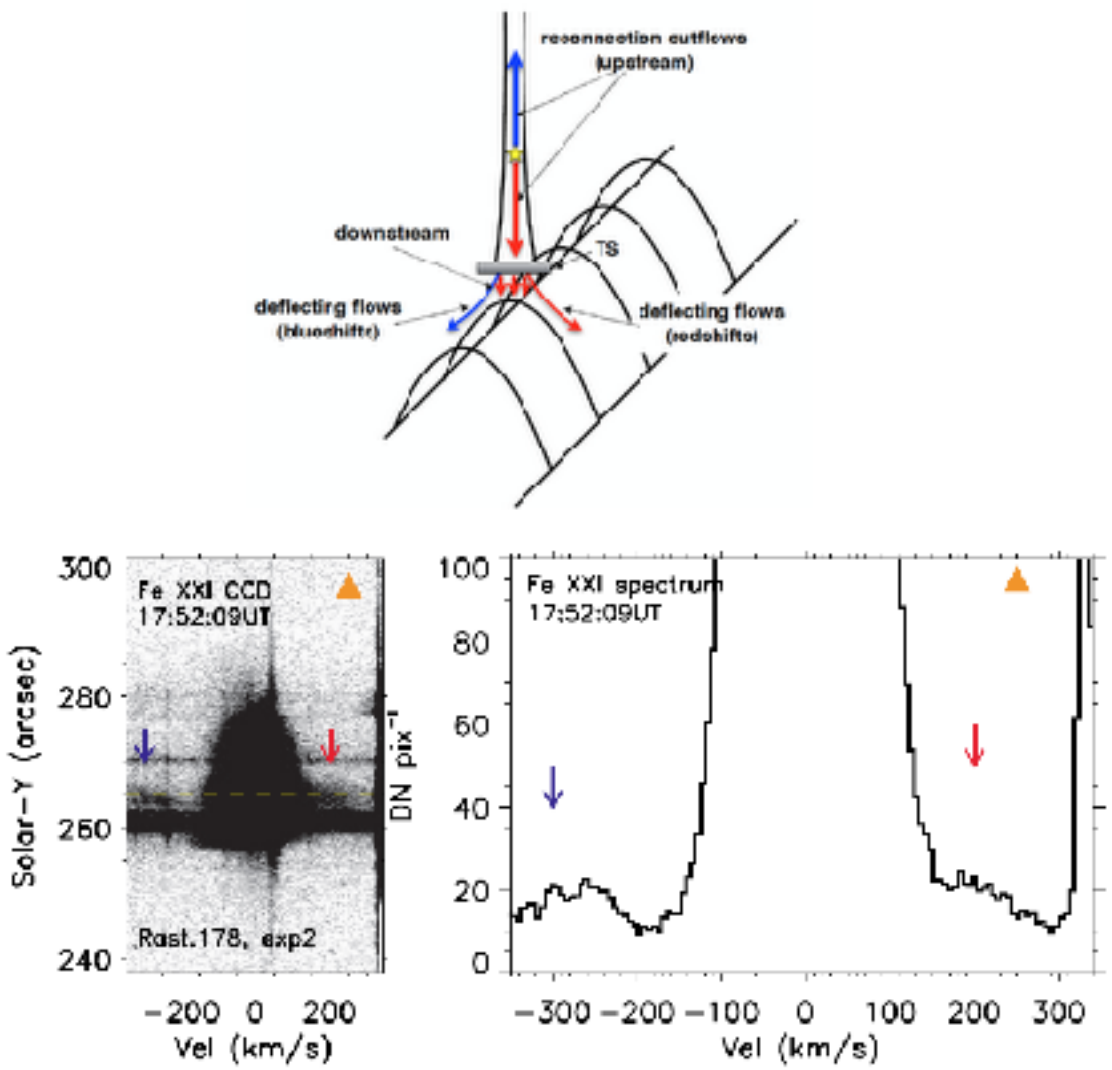


Detailed comparisons between electron beam driven model and Alfven wave driven model and IRIS observations provides support for Alfven wave model (asymmetric, single peak, broader)

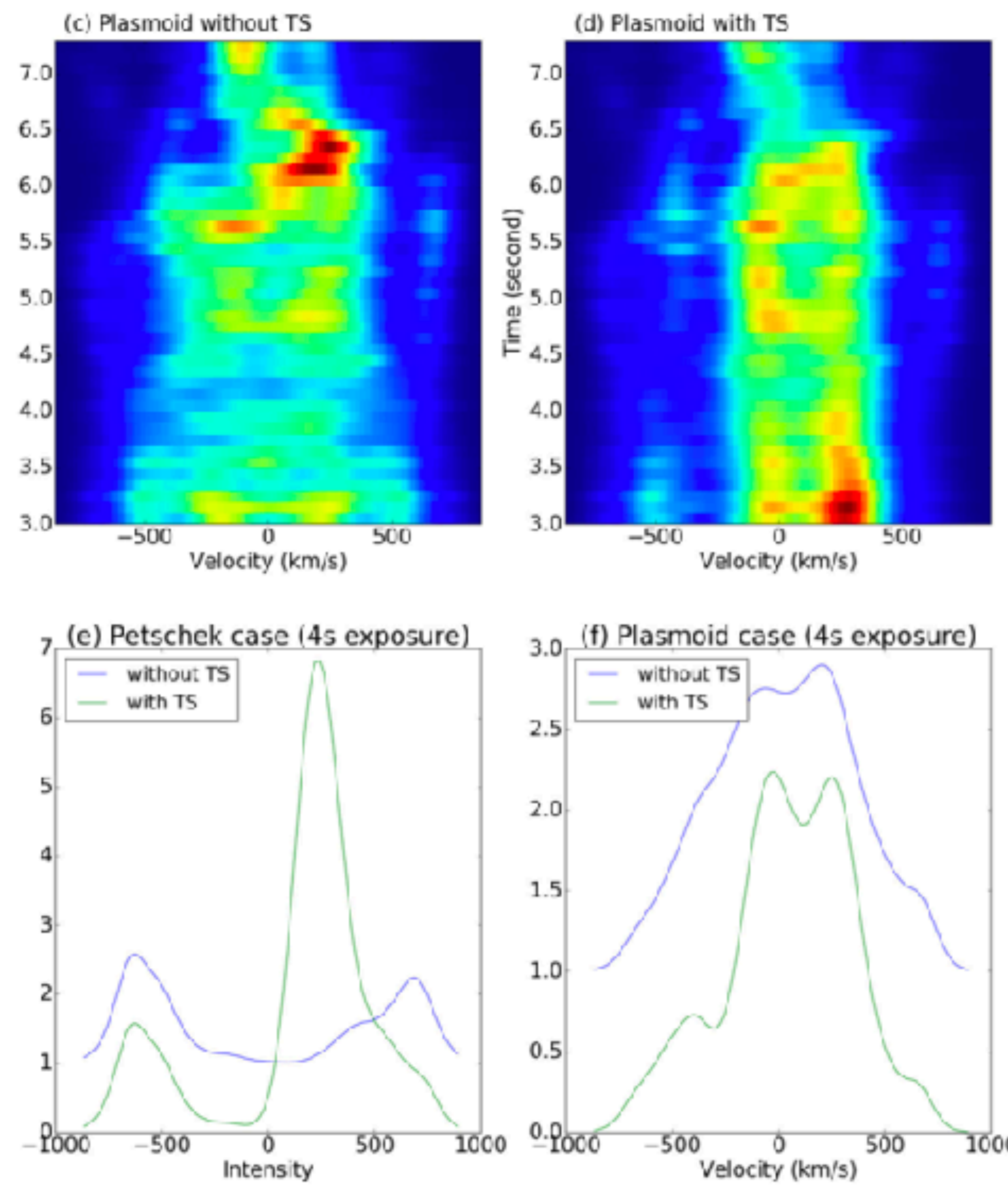
IRIS observations suggest a link between heating in post-flare loops and non-thermal broadening, suggesting a role for Alfven waves or turbulence

Termination shock?

Polito et al., 2018



Guo et al., 2017

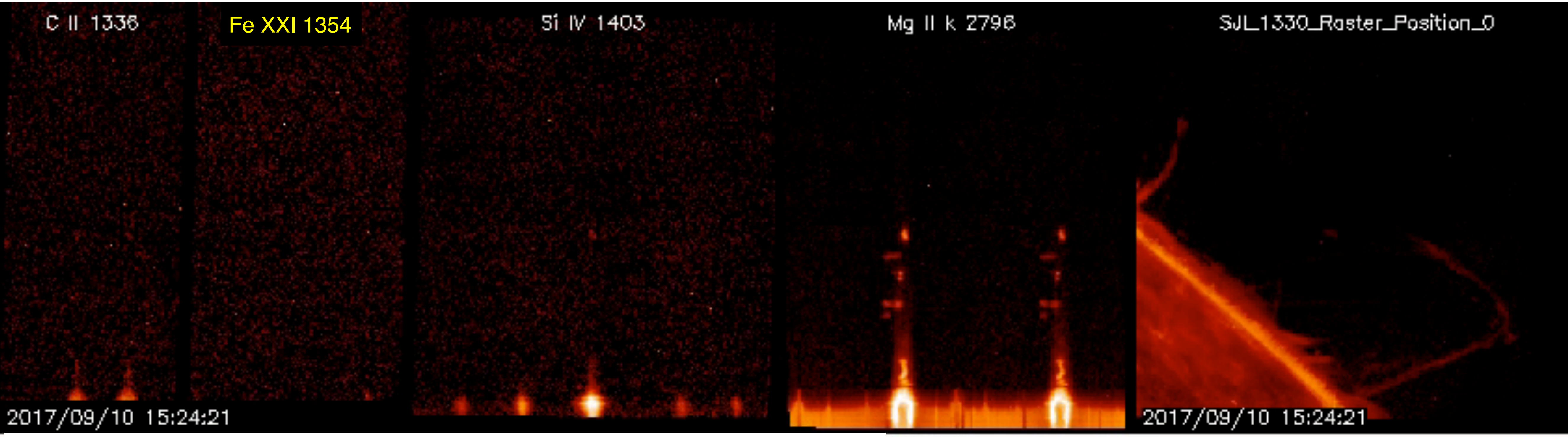


Termination shocks predicted by standard flare model, but have not been clearly observed

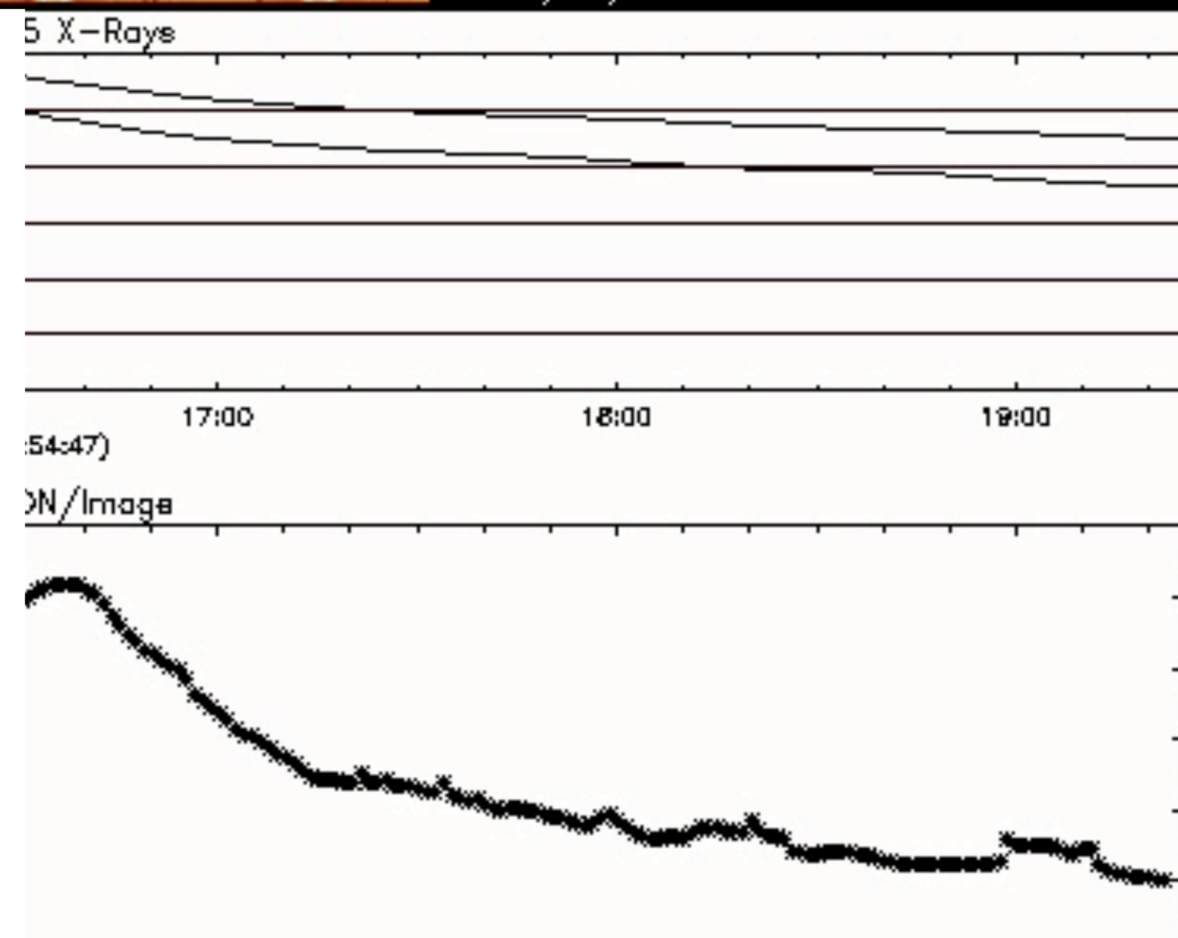
IRIS observations show faint redshifts and blueshifts in Fe XXI emission at 200 km/s close to flare loop tops and where RHESSI shows strong non-thermal electror fluxes

Particle acceleration in a shock near the lop tops could explain the presence of coronal hard X-ray sources in flares without resorting to unphysically high densities.

Statistical studies of flares?



IRIS has caught 10 X-class flares, 72 M-class flares and 500 C-class flares since launch in 2013 (flare list on http://iris.lmsal.com)



Most flare-related IRIS papers focus on a single flare, so not always clear how common processes are

Some flare aspects have not yet been studied (e.g., supra-arcade downflows)

IRIS Prioritized Science Goals (PSGs)

PSG 1: Study fundamental physical processes in the solar atmosphere

PSG 2: Investigate the (in)stability of the magnetized atmosphere

Initiation of CMEs and flares

PSG 3: Analyze energy and mass transfer between photosphere, chromosphere and corona

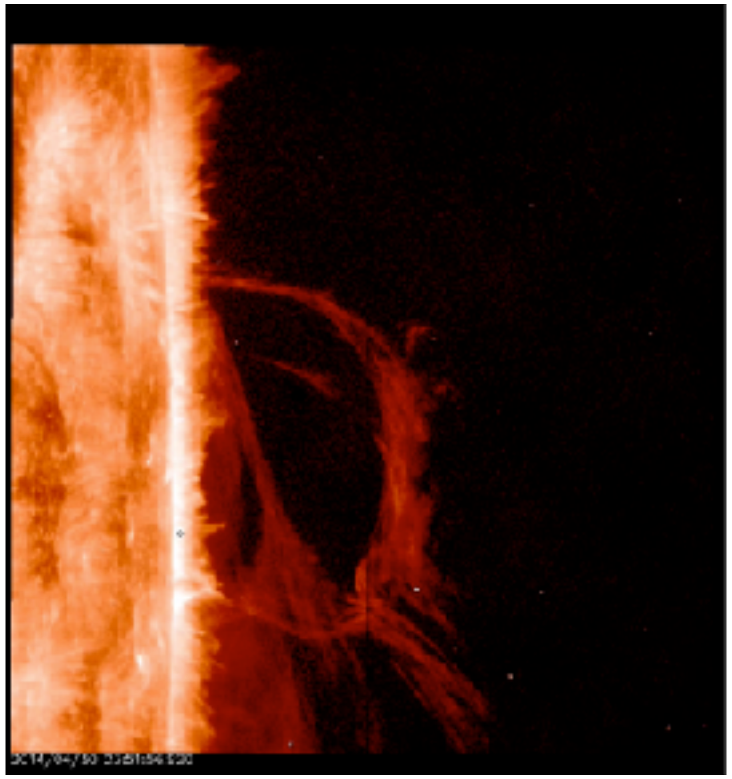
PSG 4: Quantify variations of far and near ultraviolet solar radiation over the solar cycle

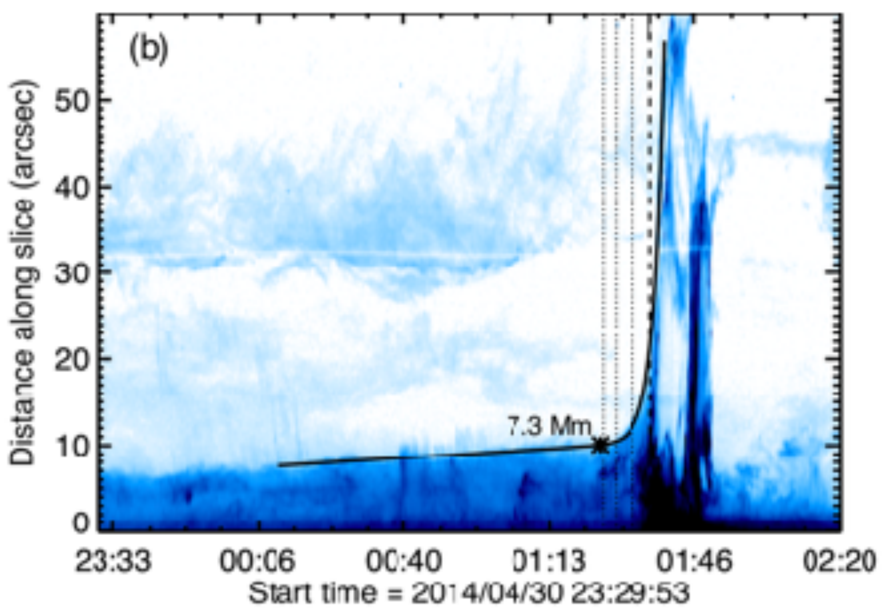
PSG 5: Explore the solar-stellar connection

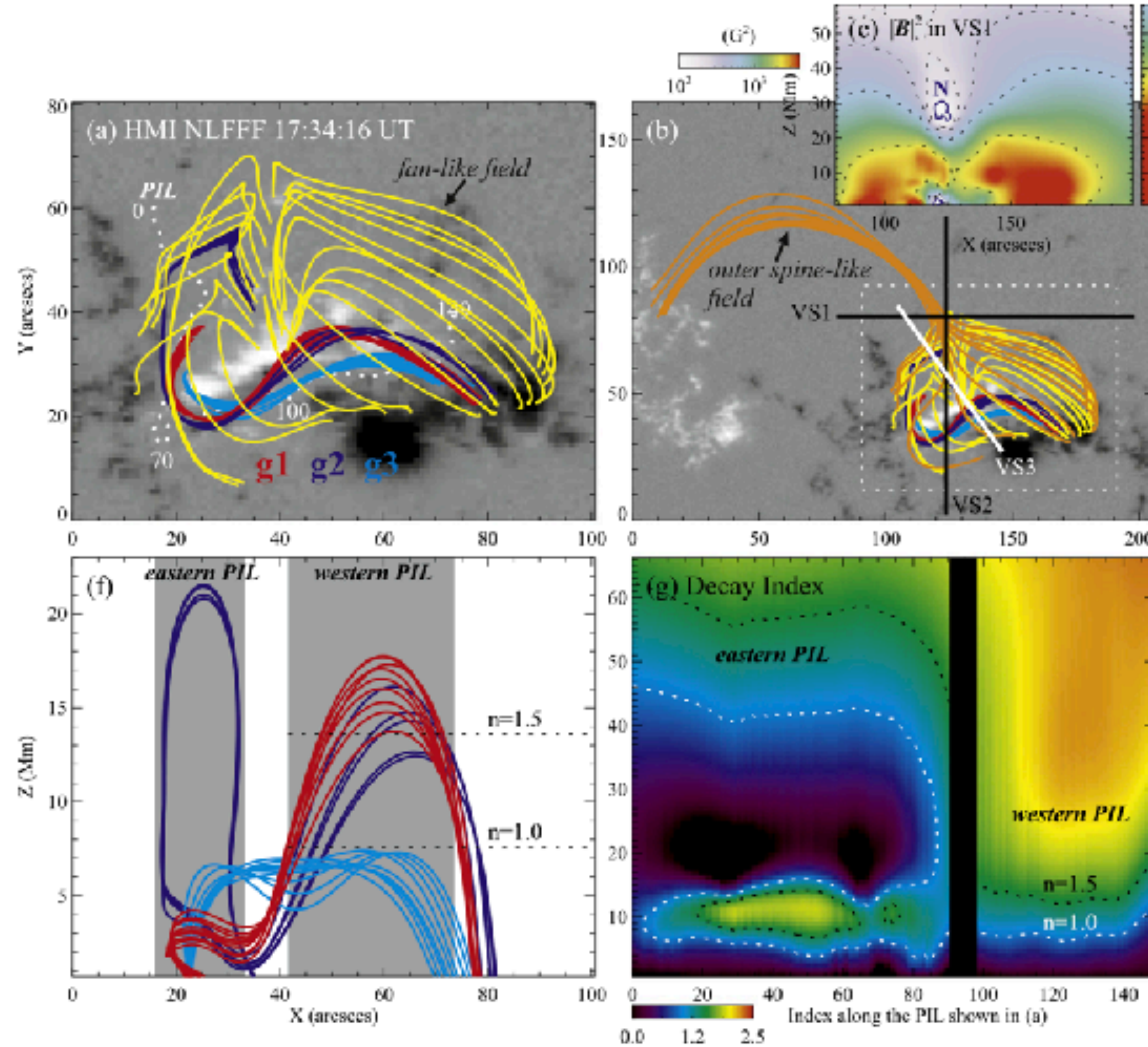
CME initiation

Reeves et al., 2015, Kumar et al., 2015, Dudik et al., 2016

Liu et al., 2015







Reconnection triggers prominence eruption

Small-scale brightenings support tether-cutting instead of break-out model

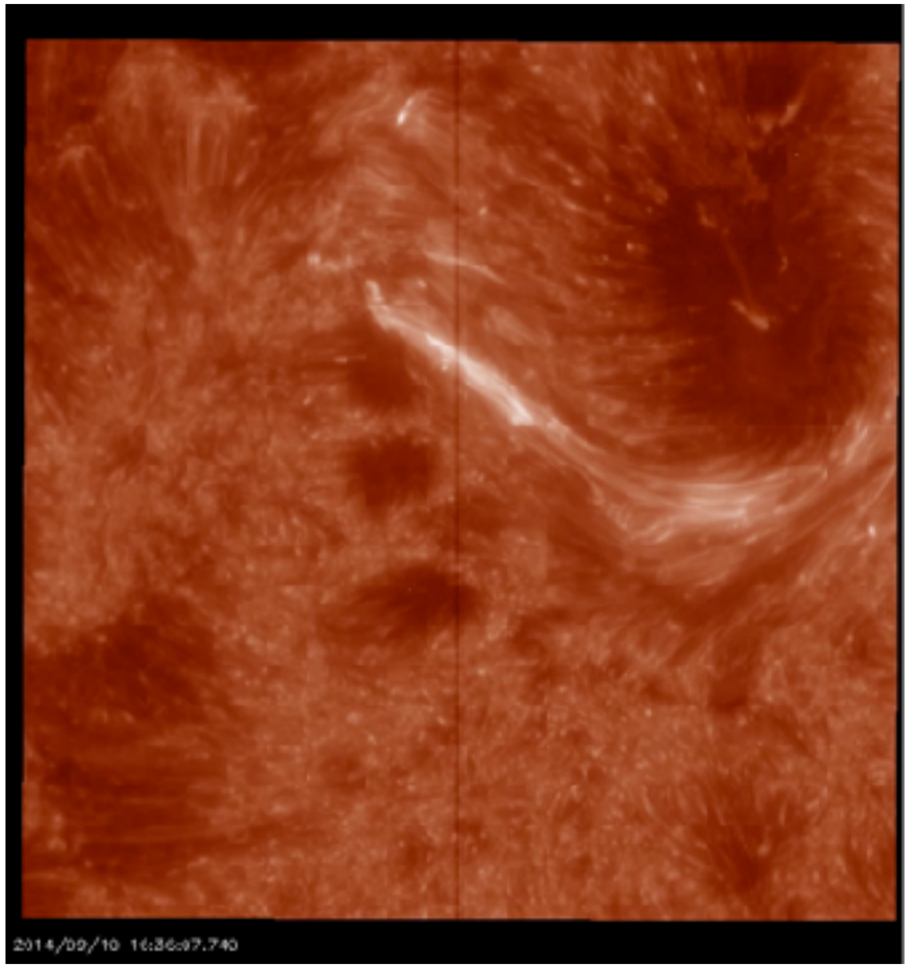
Tether cutting driven by slipping reconnection (Dudik et al., 2016)

Evidence for breakout-type reconnection at a coronal quasi-null region (leading to circular flare ribbons), followed by filament eruption

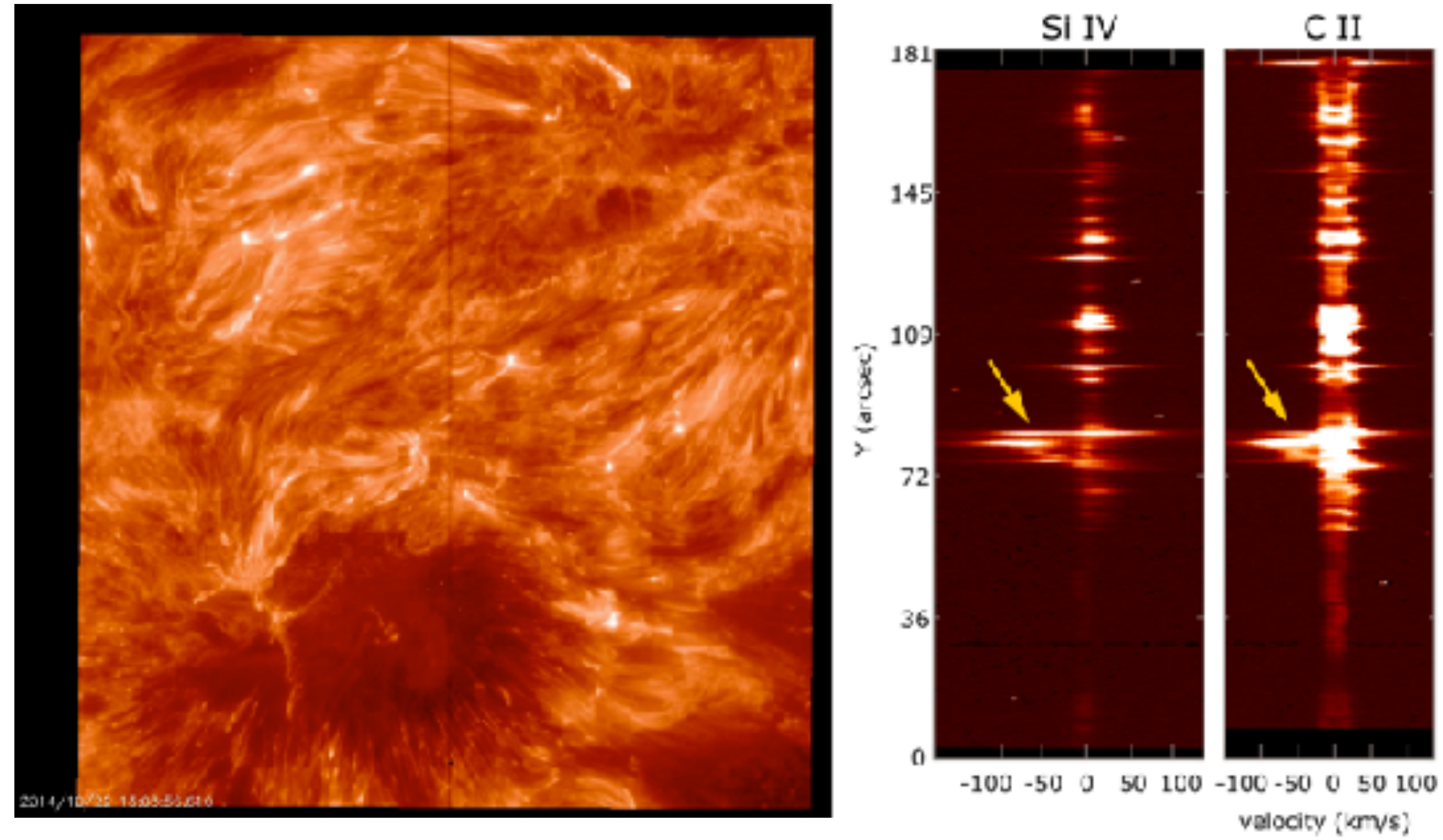
More statistics needed to understand the dominant mechanism(s)

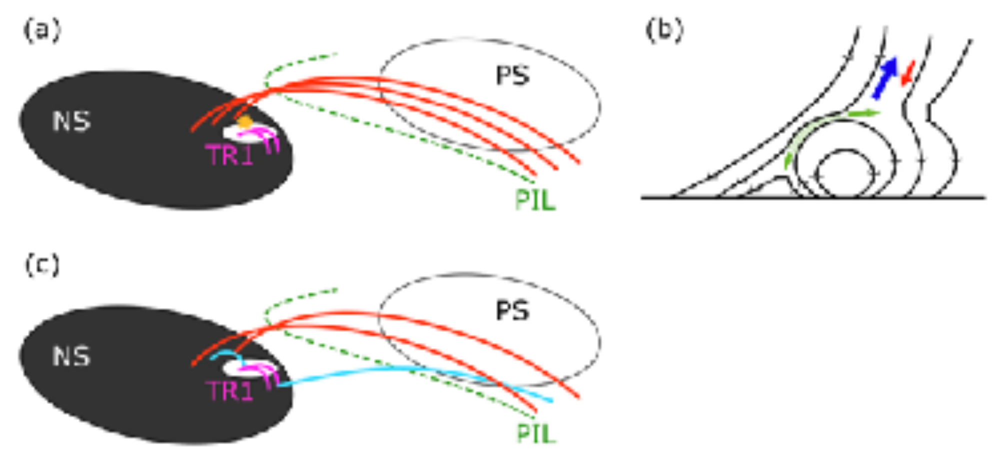
Precursors to CMEs

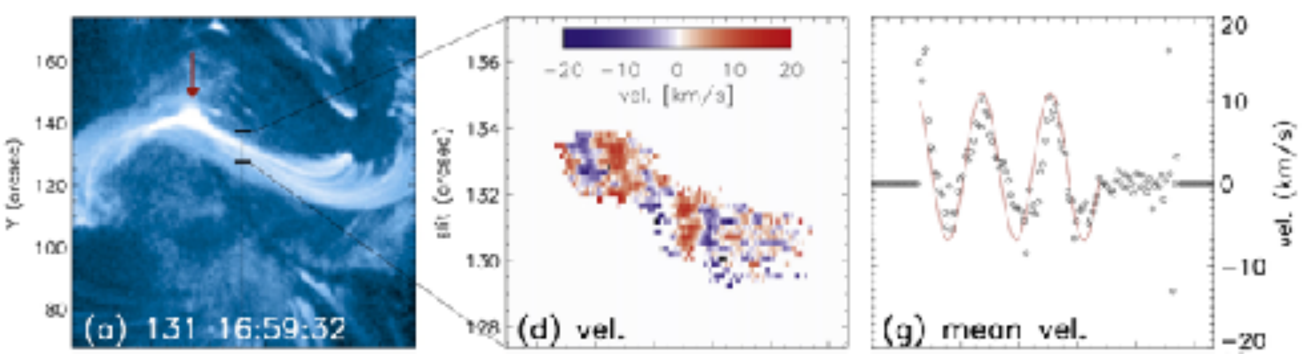
Zhou et al., 2016



Bamba et al., 2017; Woods et al., 2017







Oscillations observed in IRIS Fe XXI 1354Å spectra of sigmoid before eruption

Suggests magnetic flux rope energized by external reconnection with ambient field

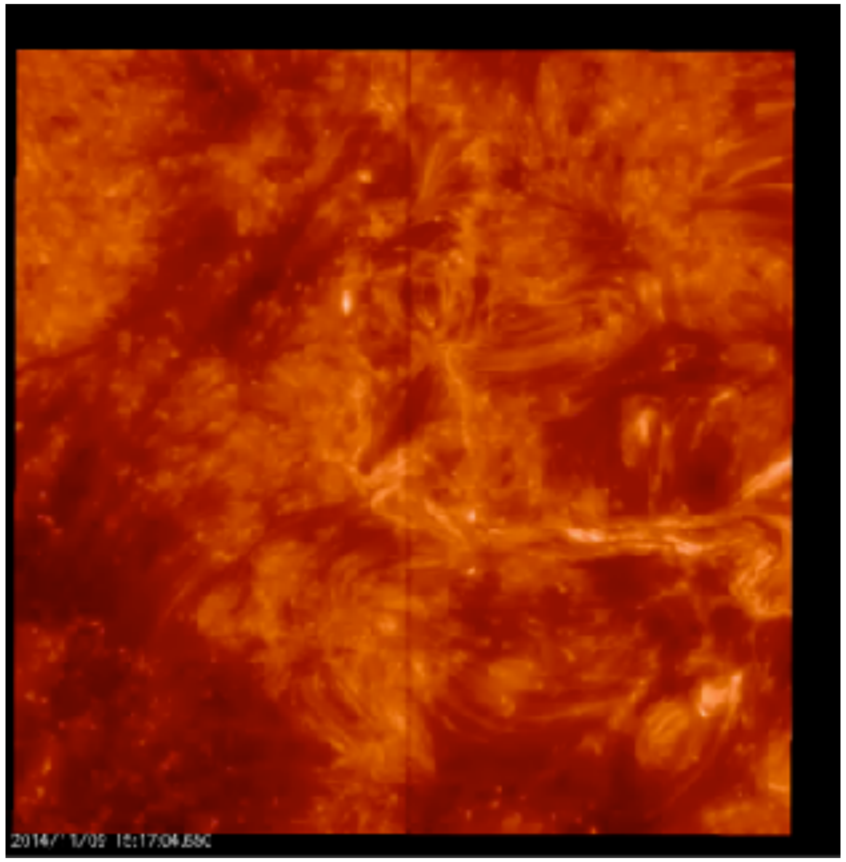
Underscores diagnostic potential of pre-cursor phase

Chromospheric jet plays role in triggering of X-class flare: small bipole field can trigger flare via magnetic shear cancellation with highly sheared AR field

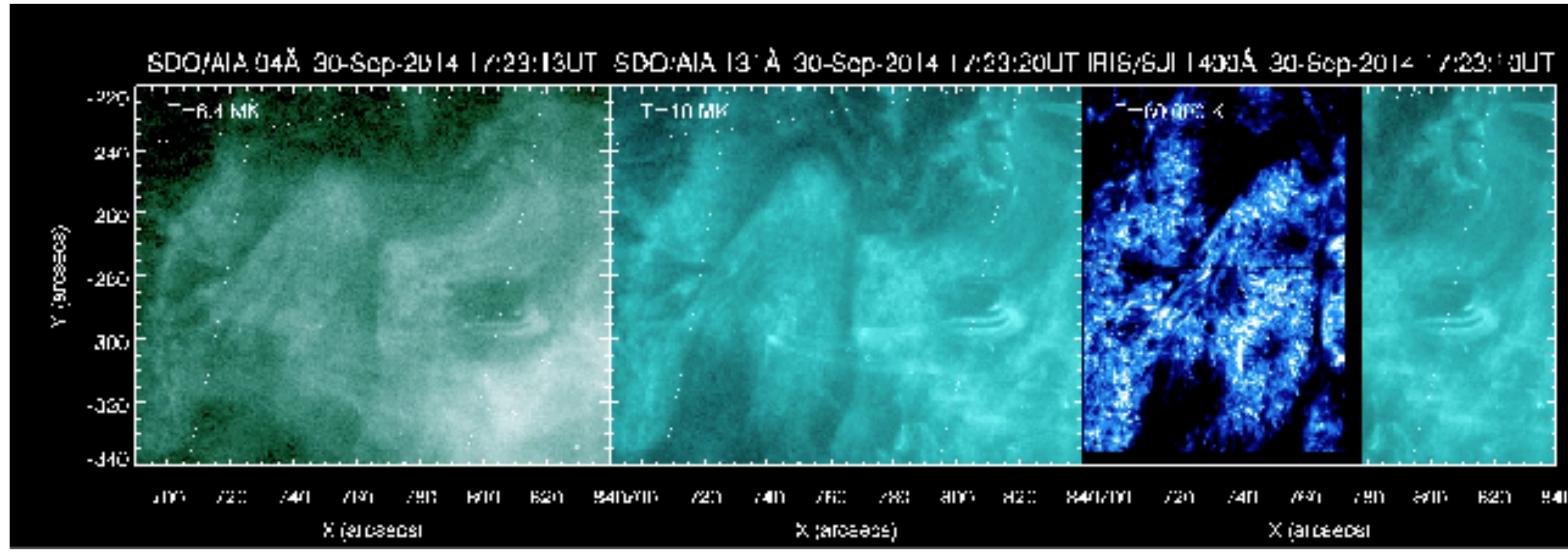
Analysis such as this requires detailed photospheric field modeling and inclusion of spectroscopy and imaging data from photosphere to corona

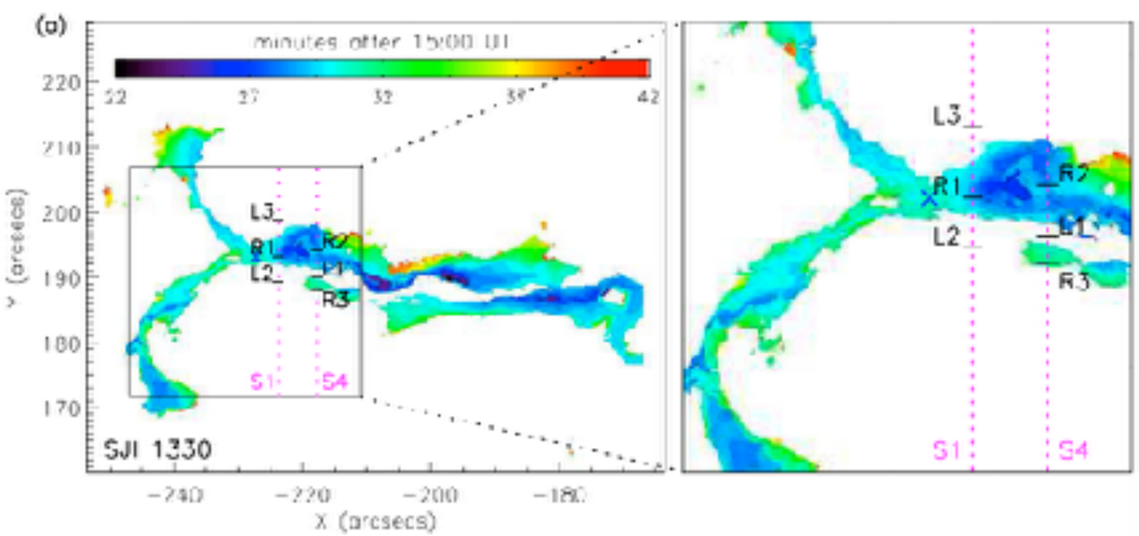
Initiation or prevention of flares/CMEs

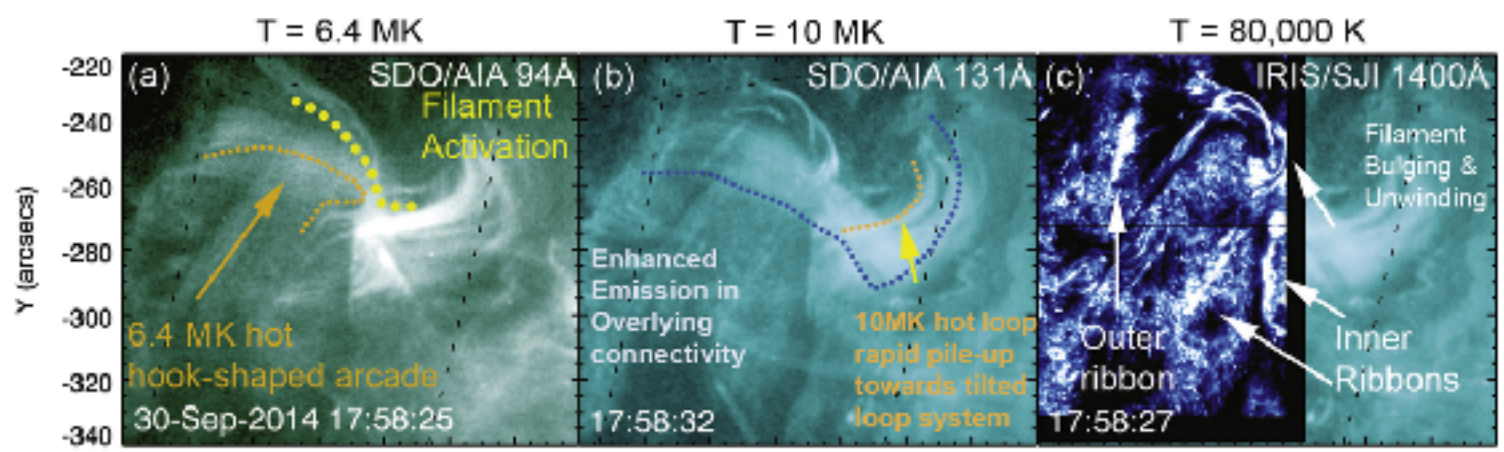
Li et al., 2017



Chintzoglou et al., 2017







Strong bidirectional flows seen in Si IV during X-class flare with converging ribbons towards X-point: suggestive of separator reconnection, occurring very low in the atmosphere

Failed filament eruption study shows rising flux rope destroyed during interaction with ambient magnetic field

Topology of surrounding magnetic field critical in prevention of eruption

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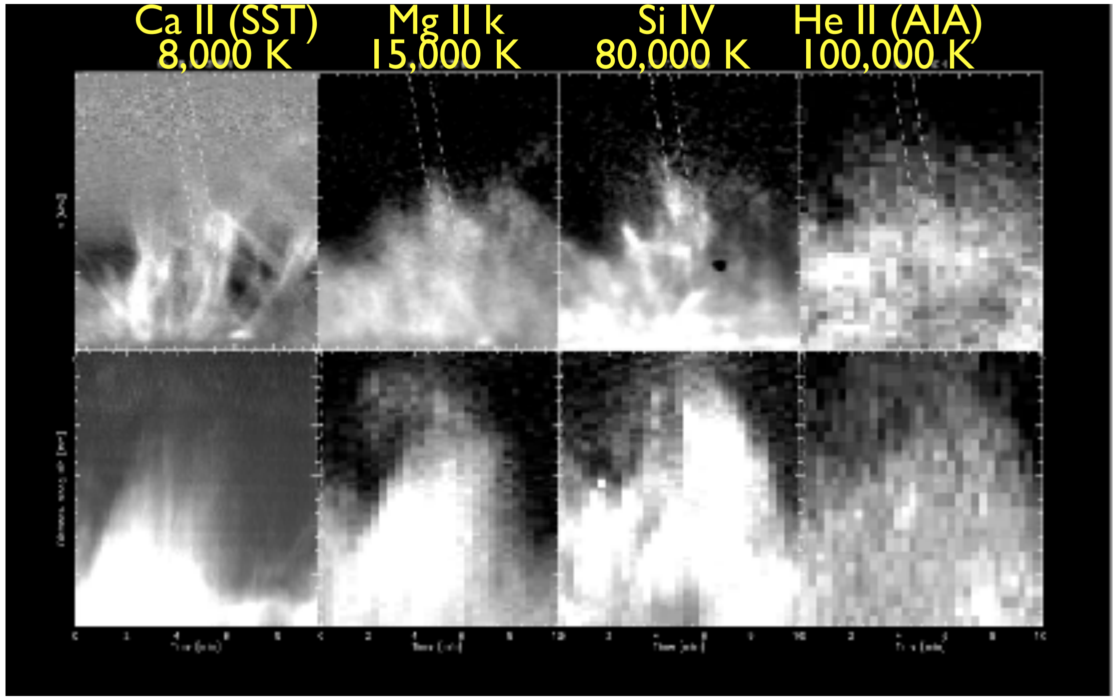
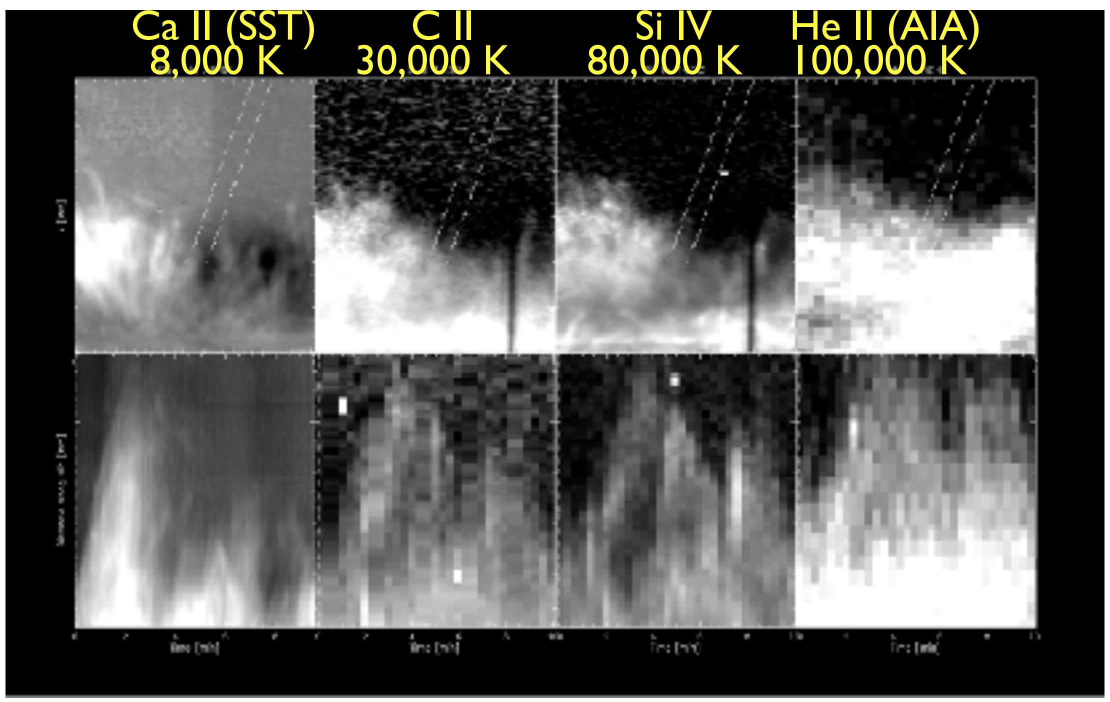
The impact of spicules on the outer atmosphere

Pereira et al., 2014, Skogsrud et al., 2015

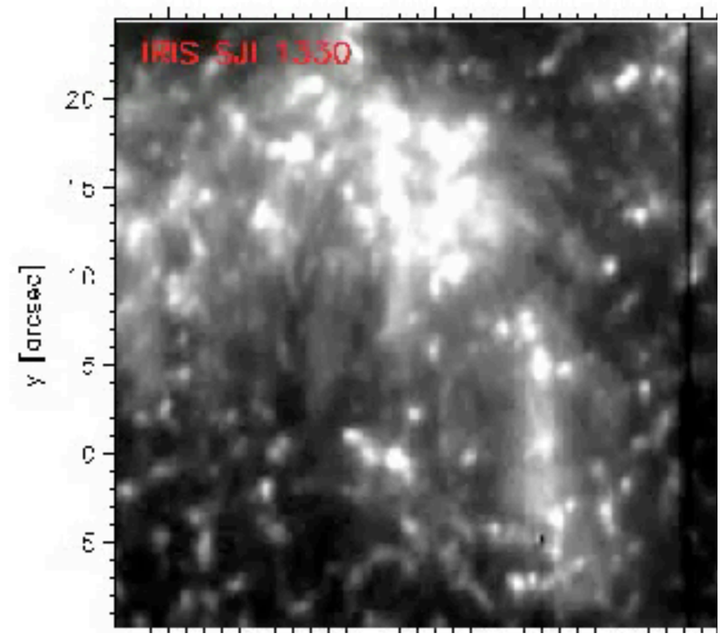


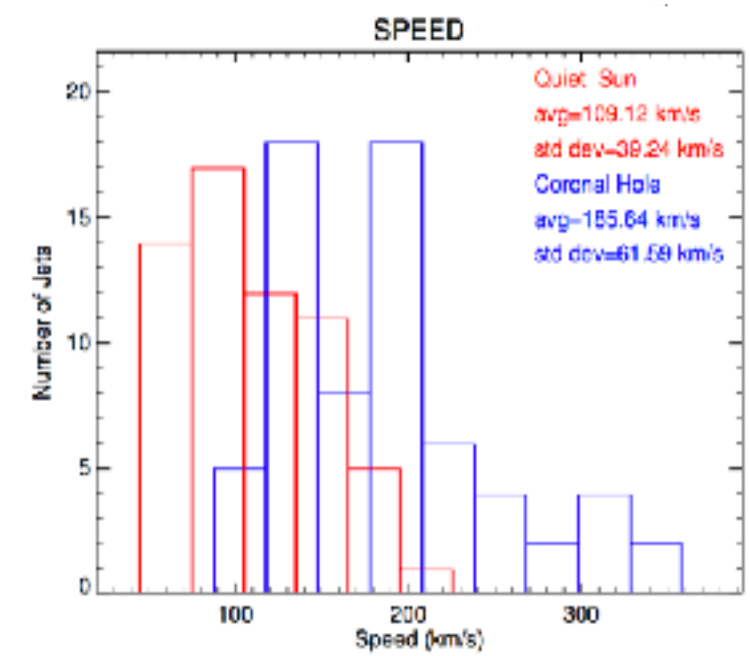


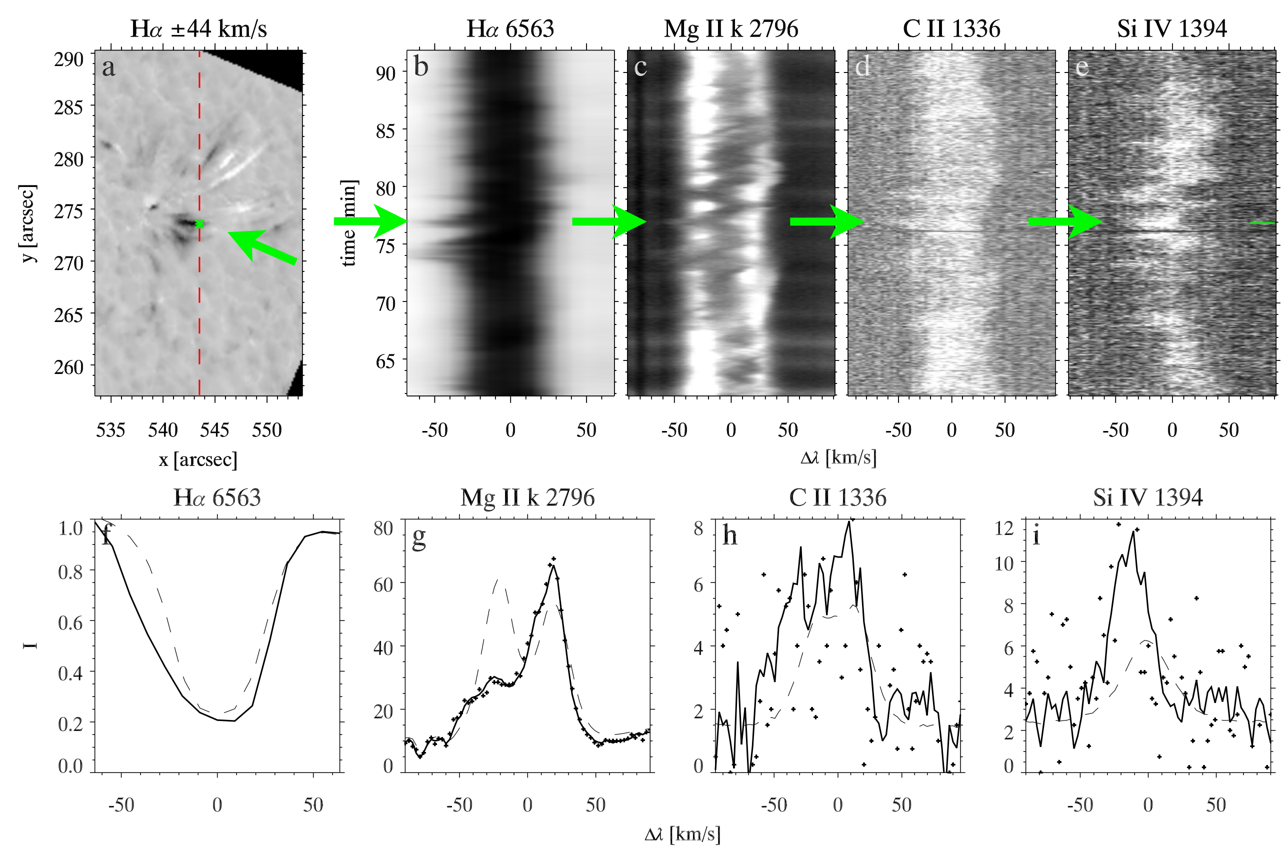
Spicules are multi-threaded with different threads at different temperatures

Some threads appear to show rapid heating over the whole length to TR temperatures (Si IV, C II)

Tian et al., 2014, Rouppe van der Voort et al., 2015, Narang et al., 2016



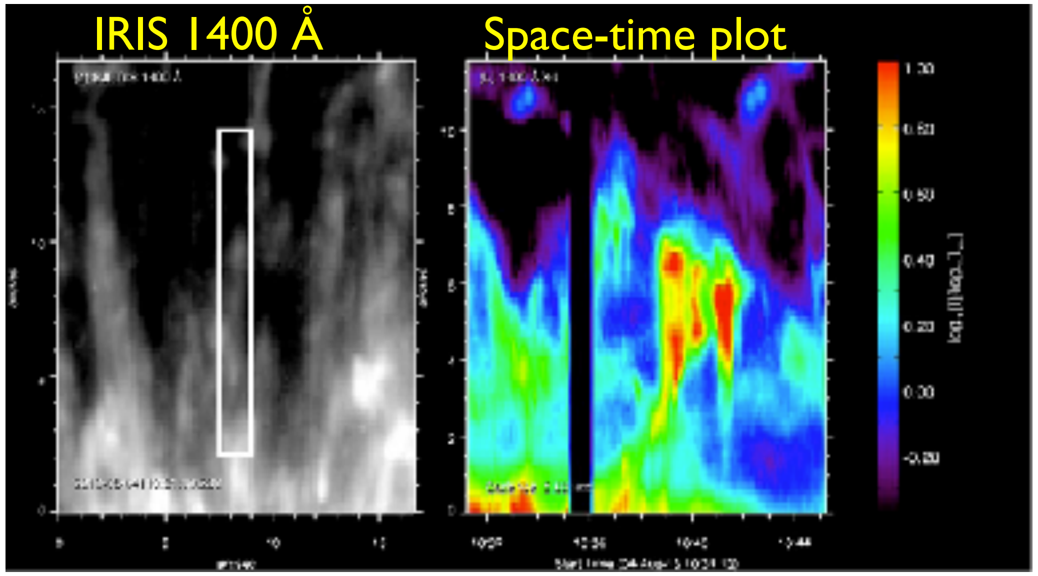


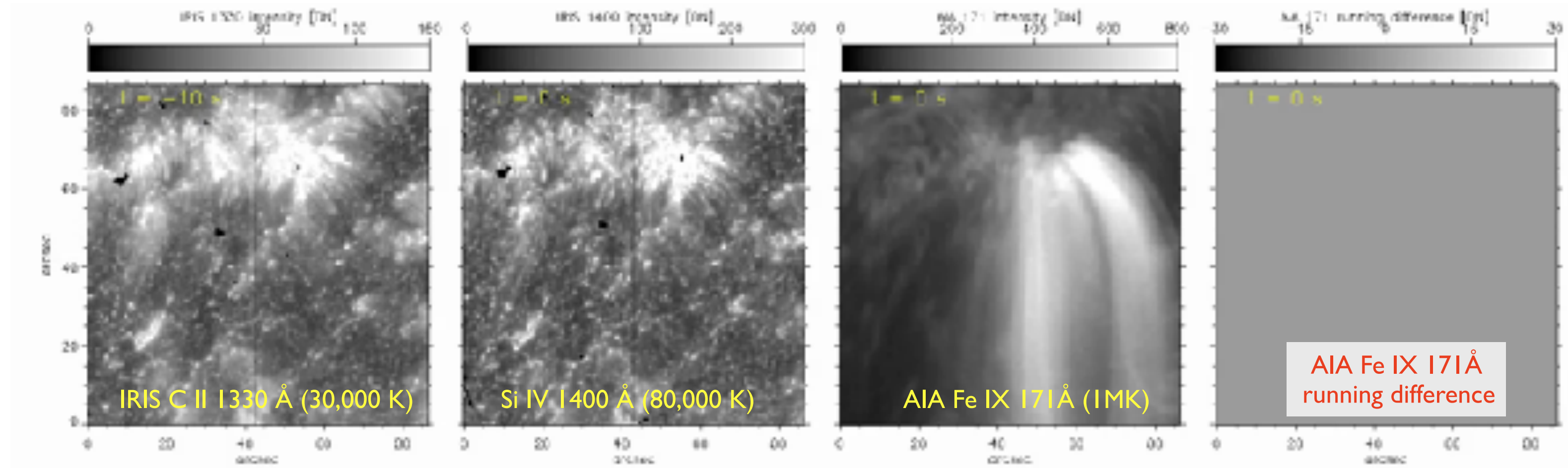


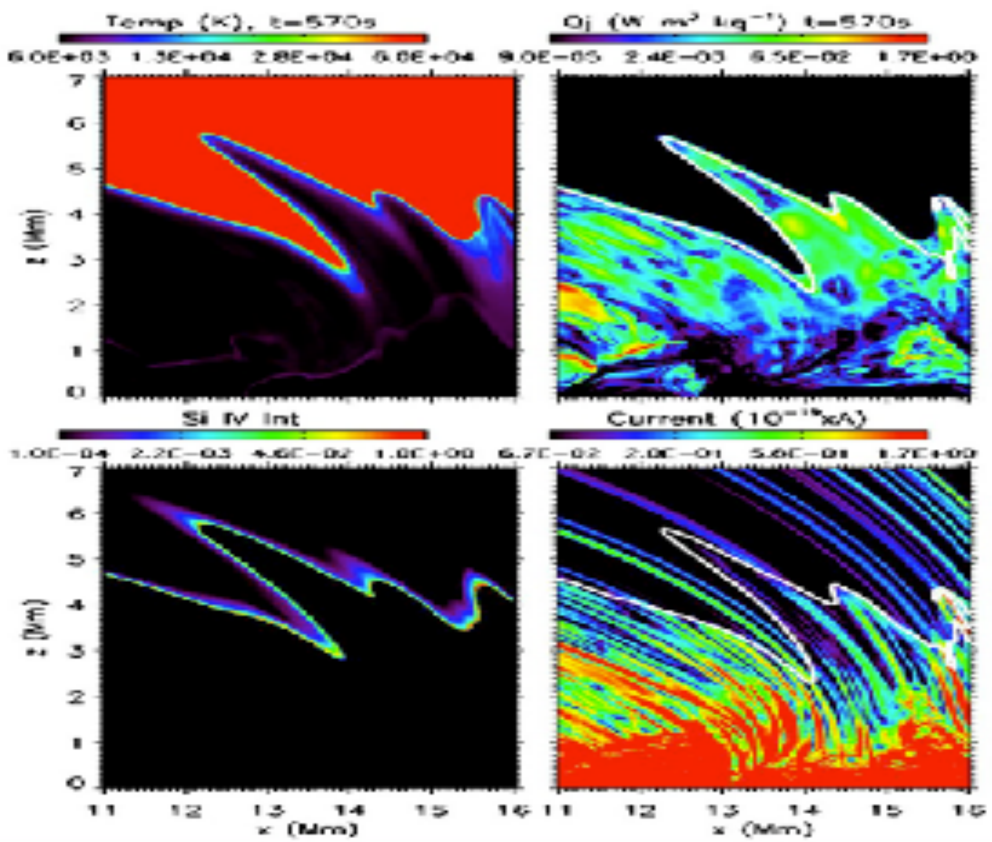
"Network jets" associated with spicules, but appear to have much higher apparent speeds (100-300 km/s) than Doppler shifts (50-70 km/s)

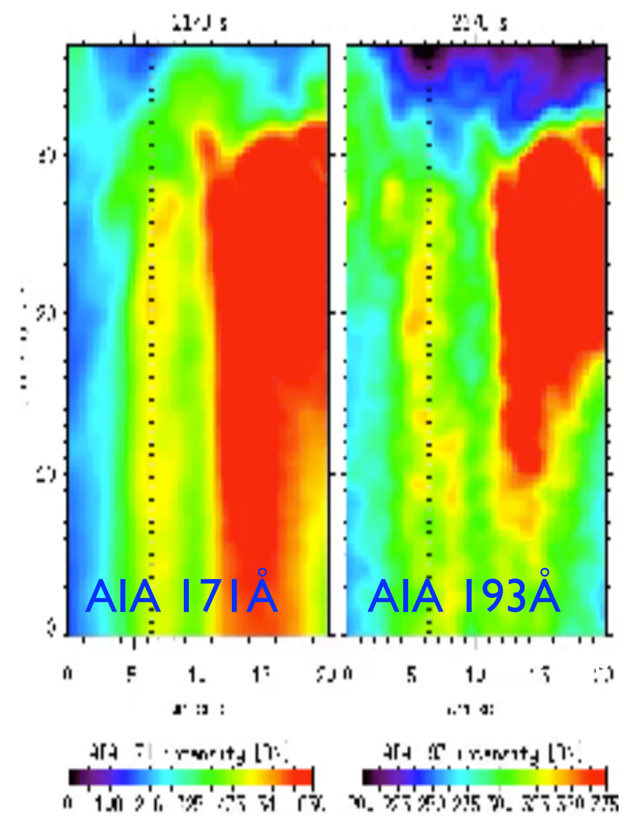
The impact of spicules on the outer atmosphere

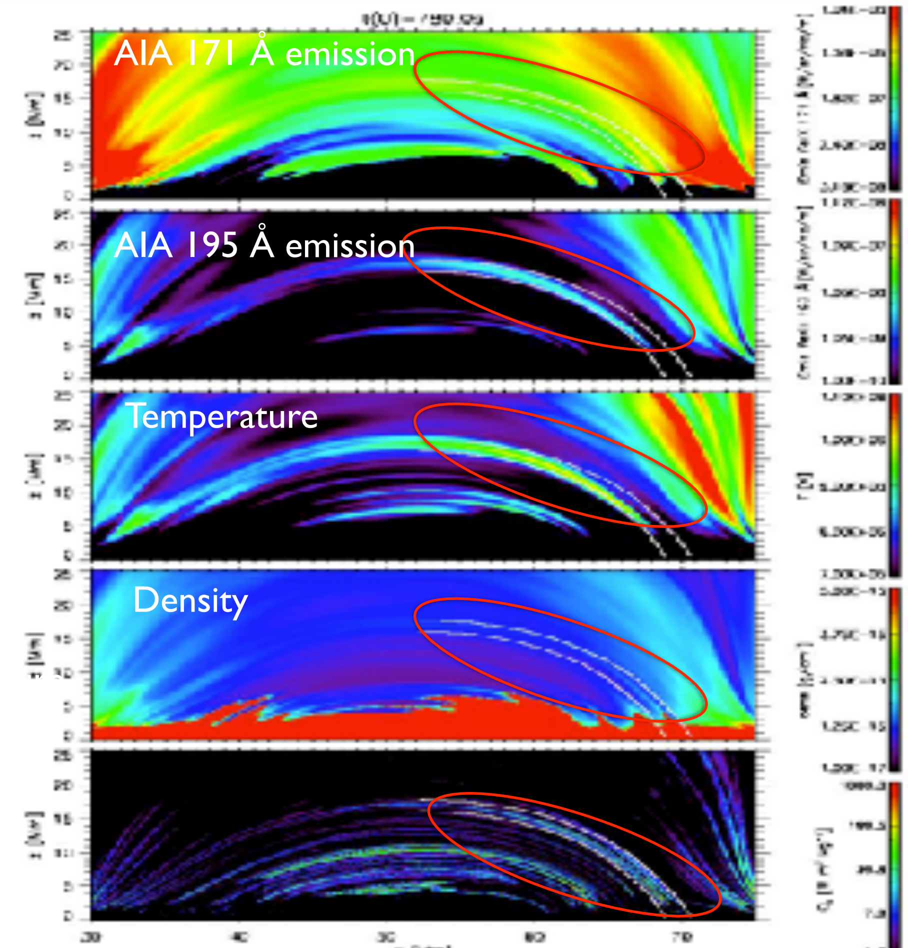
De Pontieu, et al., 2017a, Chintzoglou et al., 2018 De Pontieu, et al., 2017b, see also Samanta et al., 2015, Pant et al., 2015, Bryans et al., 2016











Comparison with numerical model of spicule formation shows that these "TR spicules" appear to be caused by heating fronts associated with dissipation of currents propagating at Alfvenic speeds

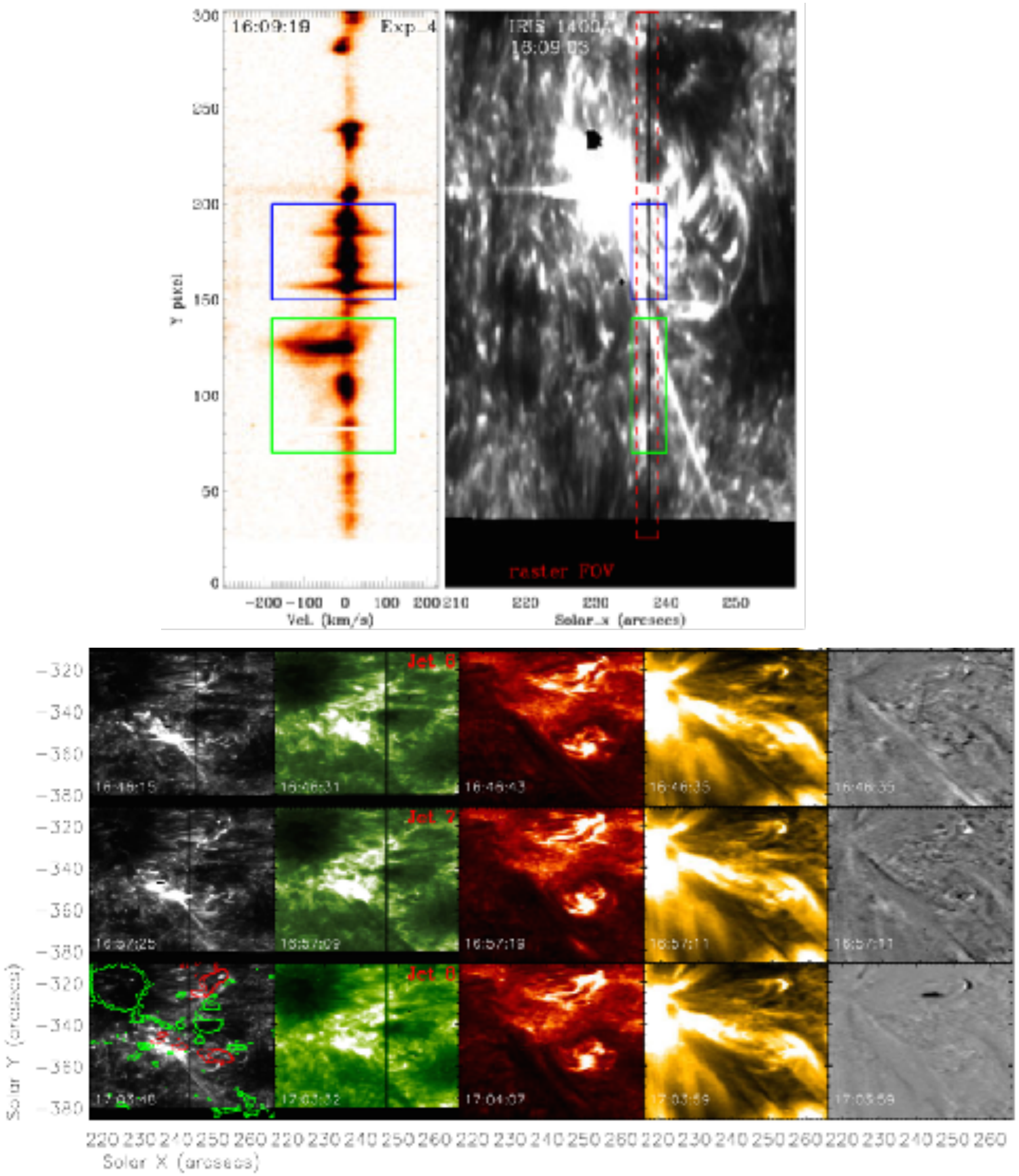
This impacts estimates of contribution to coronal and solar wind and helps quantify TR energy balance

Observations and numerical modeling provide evidence for substantial coronal heating associated with spicules, possibly driven by electrical currents associated with Alfven waves and spicule formation

Unclear which role heating associated with spicules plays in coronal energy balance in various regions

Mass balance of the outer atmosphere: jets and CMEs

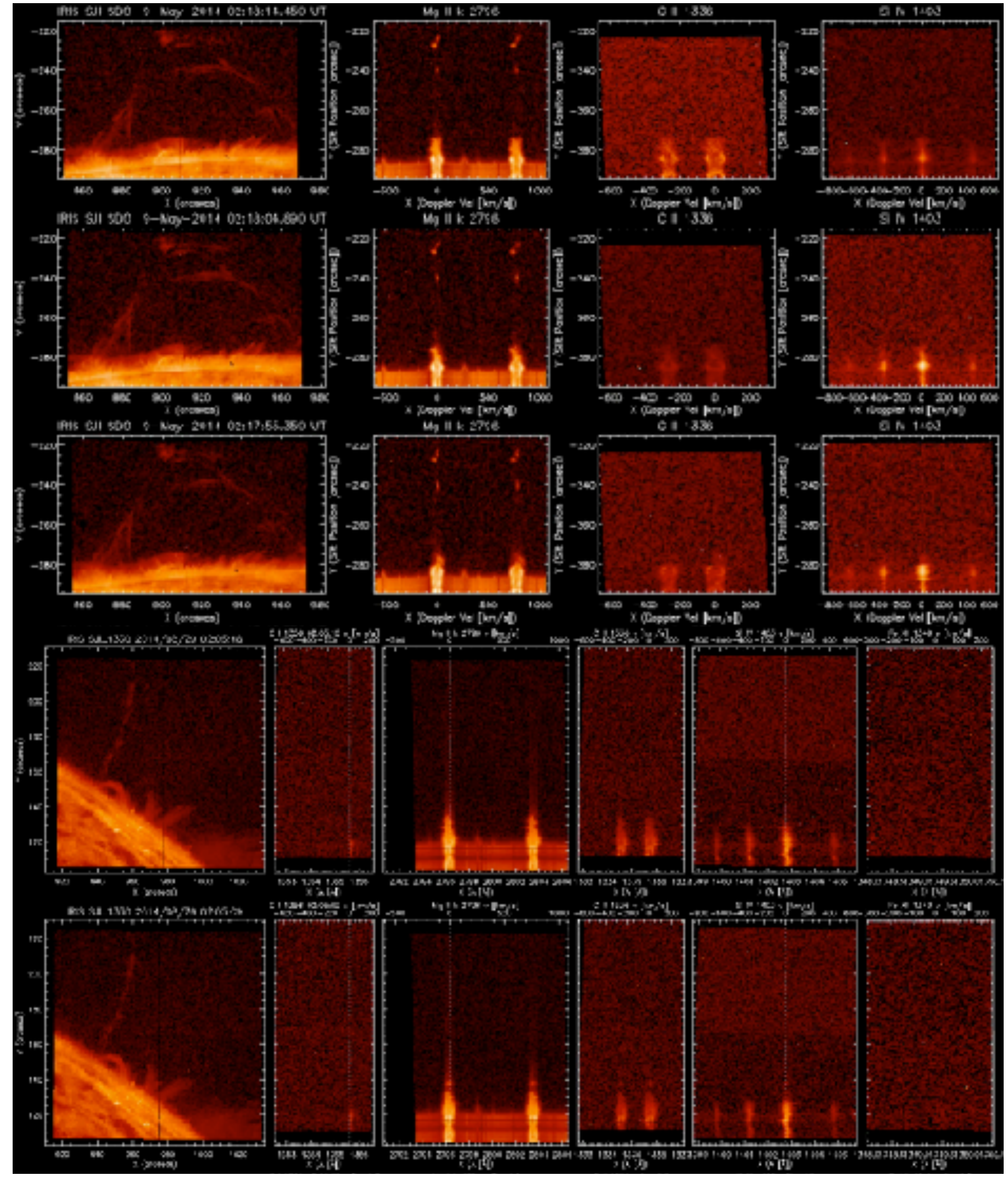
Chen & Innes, 2016



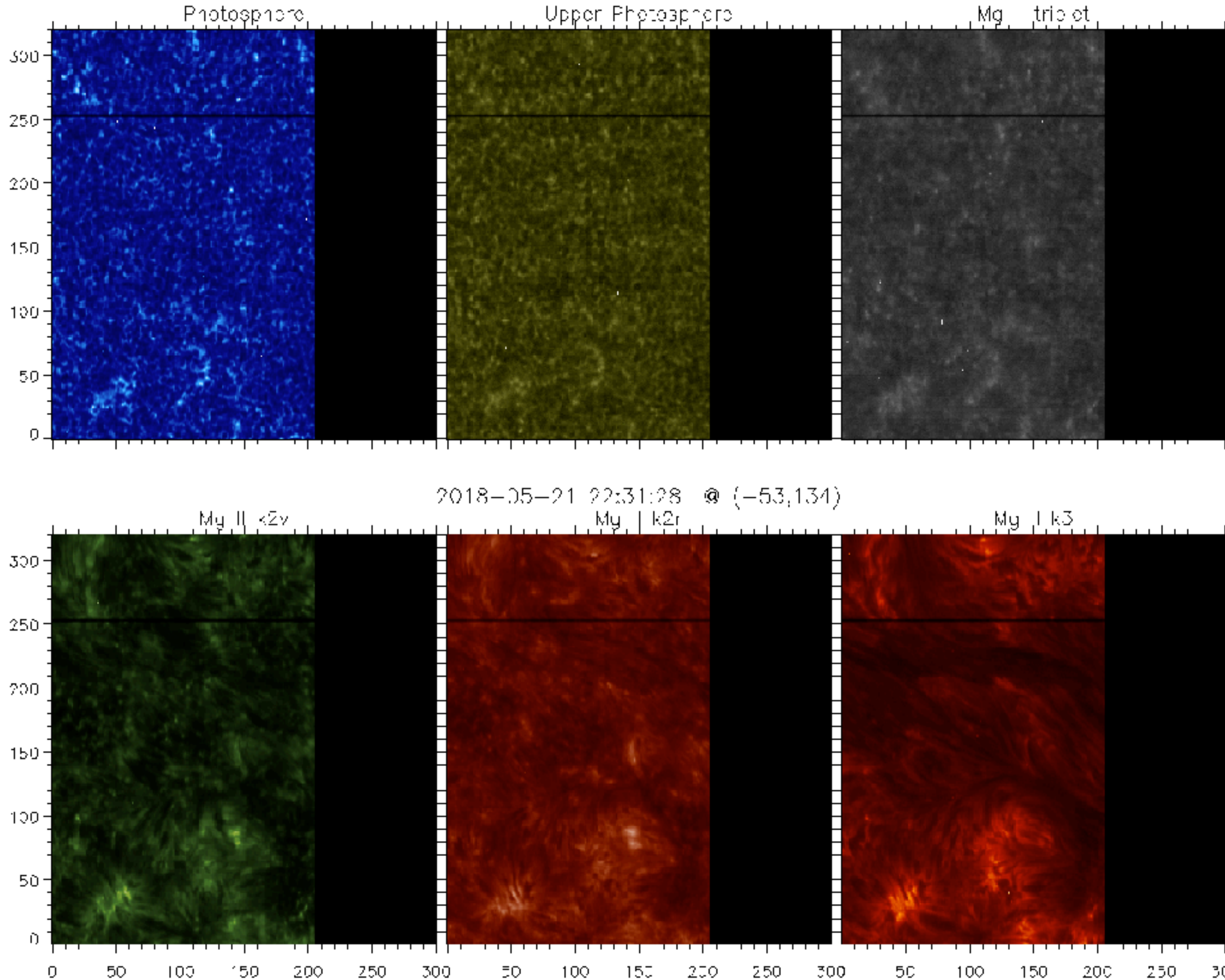
"Undercover" EUV jets (invisible to SDO/AIA) discovered with IRIS — might significantly increase contribution to mass balance of corona

Unclear how common these jets are

Liu et al., 2015



IRIS observations of CMEs provide insight into the velocity vector (e.g., Doppler dimming) and their contribution to solar wind mass flux


Photosphere
Upper Photosphere
Mg triplet
2018-05-21 22:31:28 @ (-53,134)
Mg II k2v
Mg II k2r
Mg II k3

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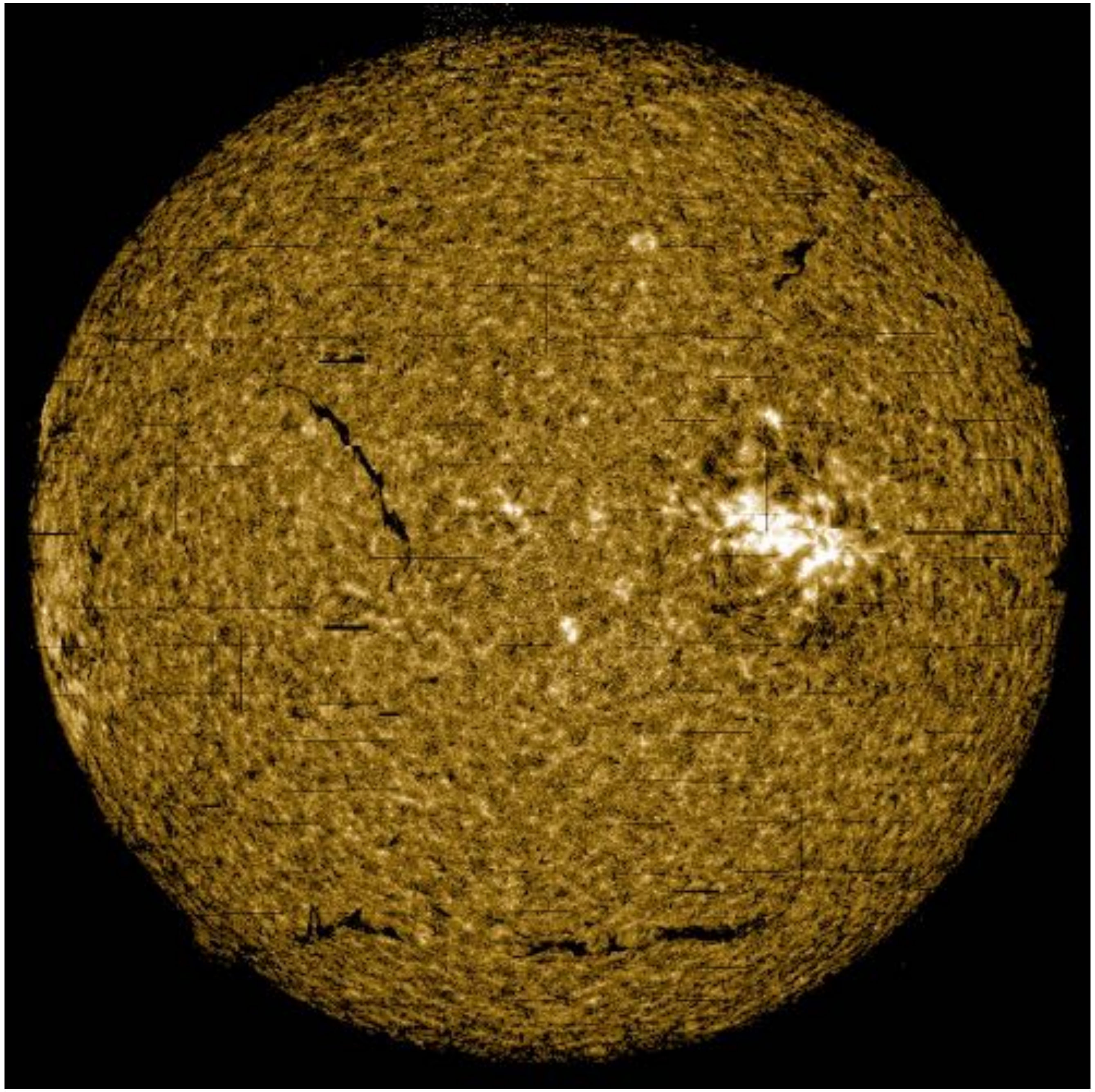
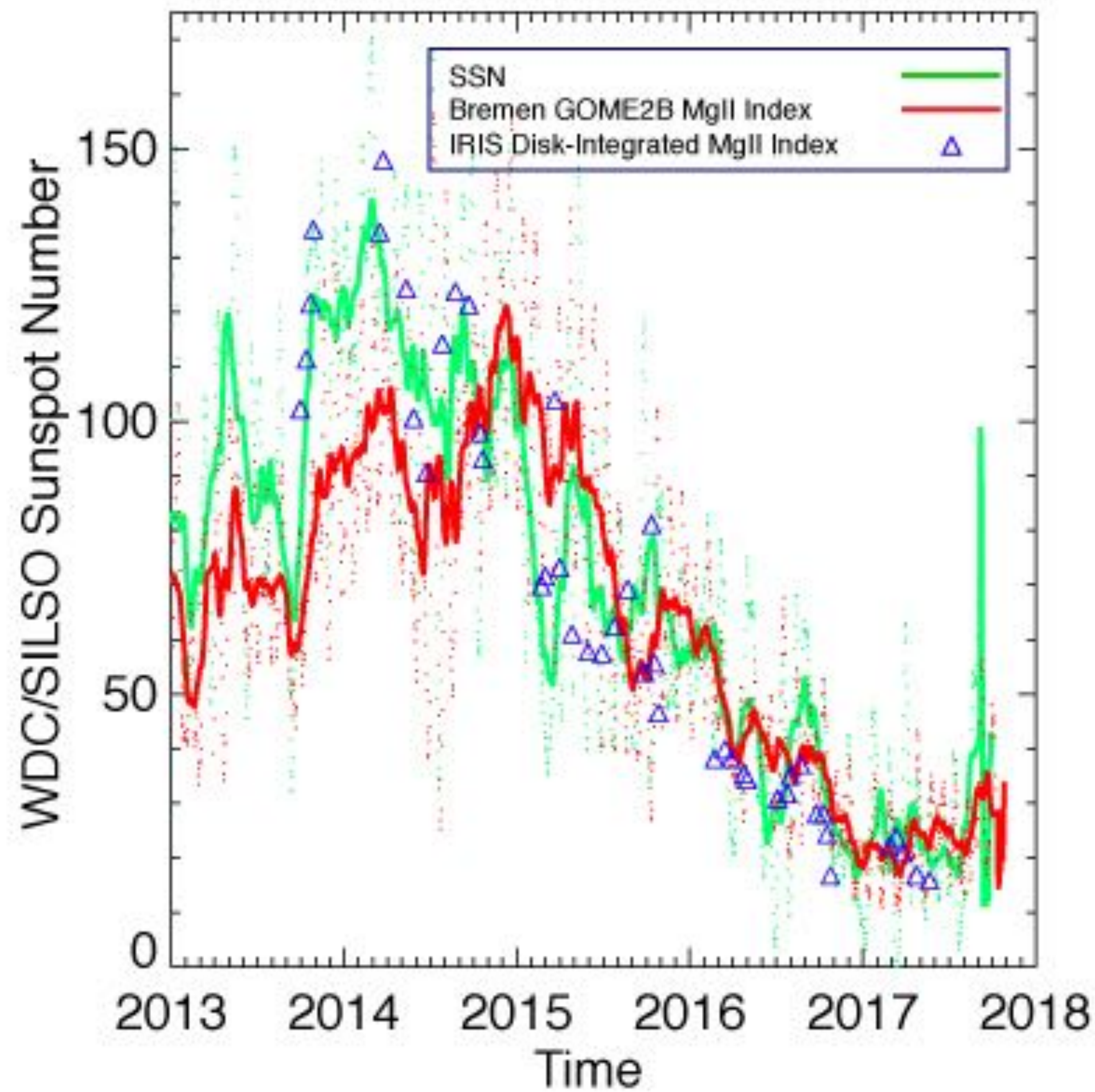
Physical origins and cyclical variations of Mg II index

PSG 5: Explore the solar-stellar connection

PSG 4: Cyclical variability of NUV irradiance



IRIS full-disk scan
Mg II h3 intensity



McIntosh & Bryans, 2018

Monthly IRIS full-disk mosaics (coordinated with Hinode/SOT-EIS, SDO/AIA-HMI, SOLSTICE) allow unprecedented study of physical origins of Mg II index, a key proxy for the effects of the solar UV radiation on the Earth's atmosphere

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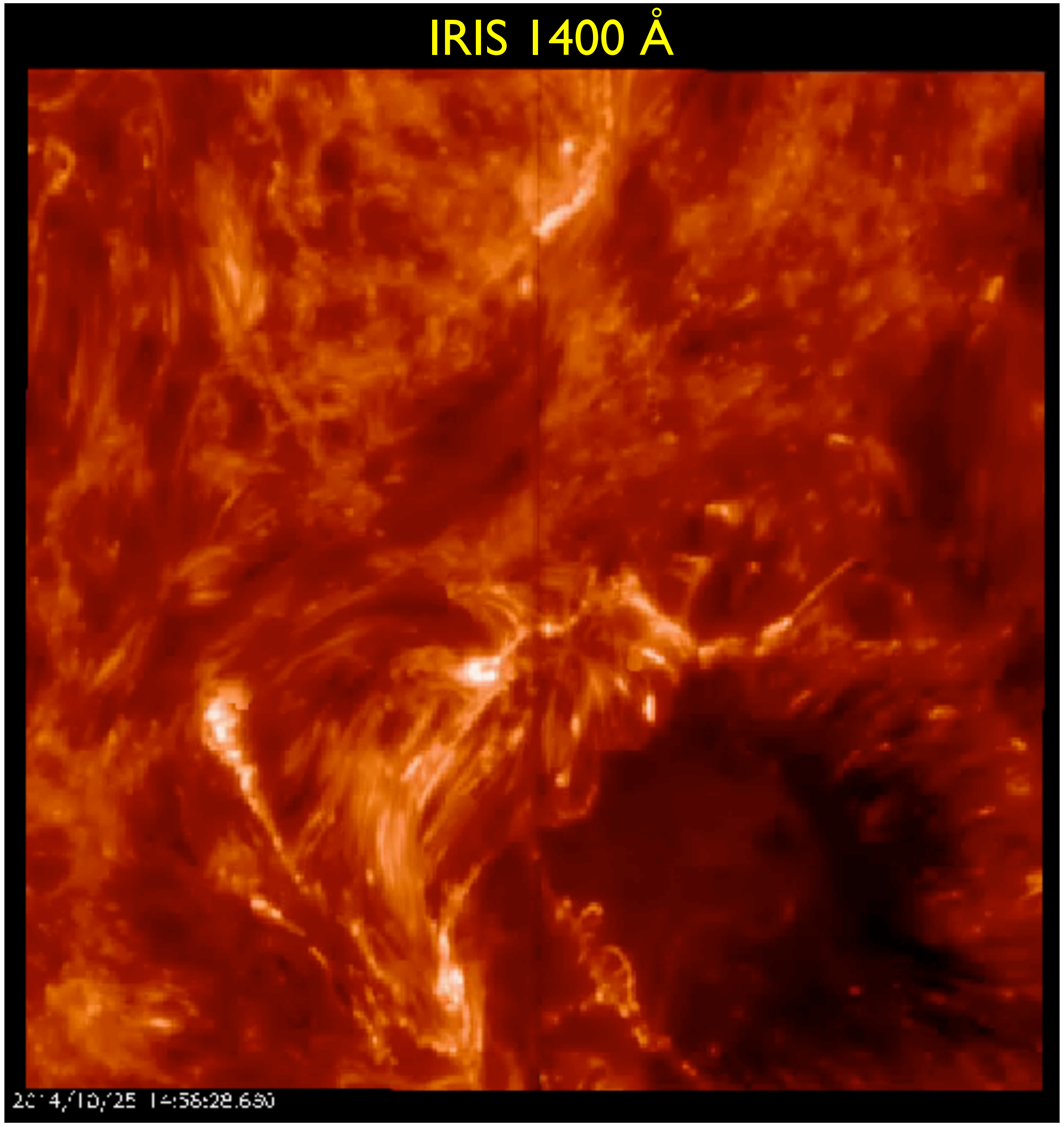
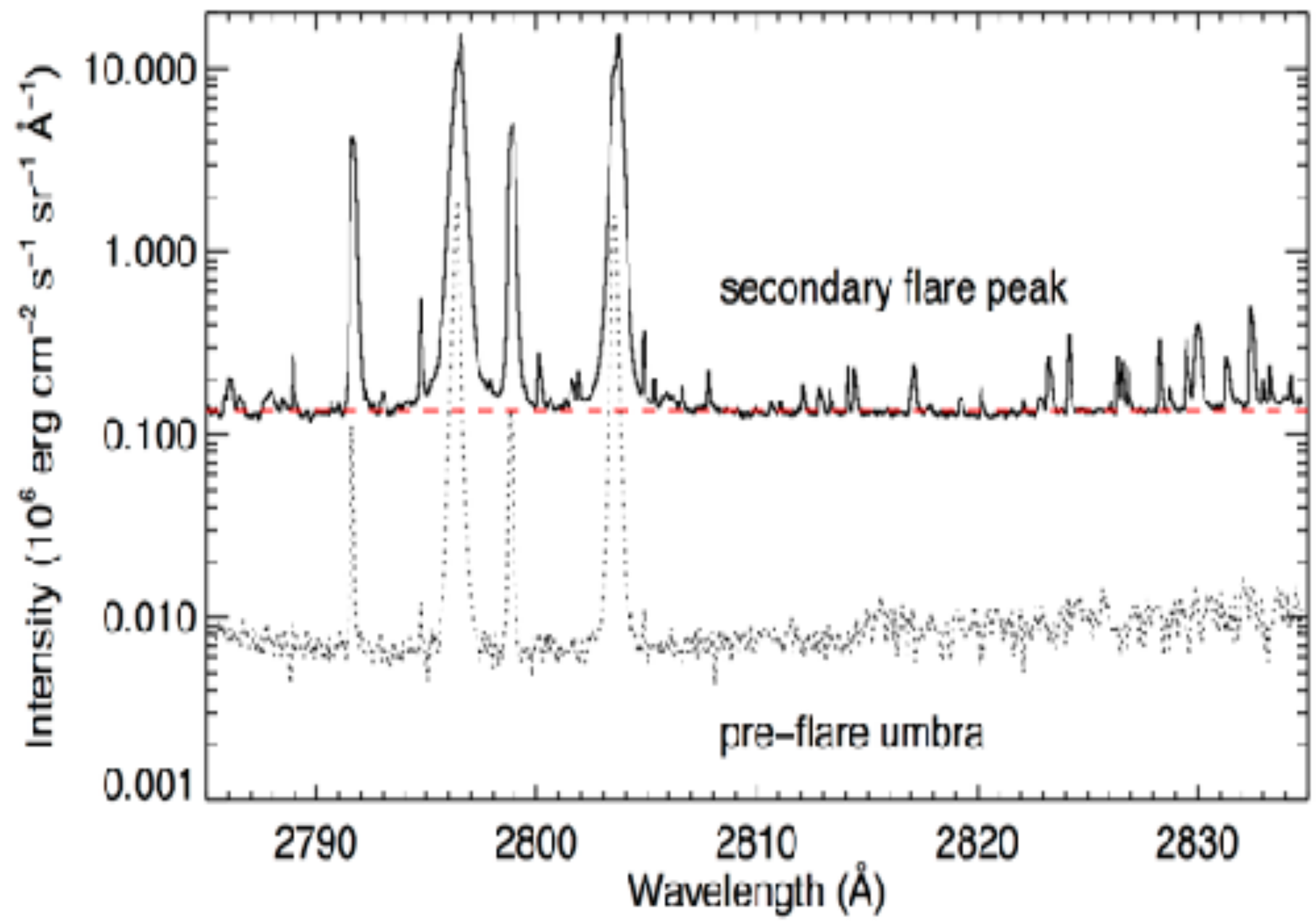
Non-thermal electrons in flares on giants

PSG 5: Non-thermal electrons and white light emission in secondary flares





Kowalski et al., submitted to ApJ, 2018

Special observing mode (full read-out) observations of flare ribbons, combined with Fermi measurements of hard X-rays, have provided evidence for white-light emission during a secondary flare event caused by the impact of a very high flux of non-thermal electrons

Provides insight into asymmetric spectra in flares on active M-dwarf stars

Unique opportunities for IRIS during the next few years

- Exciting developments in numerical modeling:
  - inversion techniques to determine chromospheric conditions using Mg II line
  - multi-fluid numerical simulations coming online

- Solar cycle heading towards minimum (~2019/2020):
  - solar cycle variability of UV emission and its impact on Earth's atmosphere
  - IRIS directly images and obtains spectra of the footpoints of the solar wind

- Synergies with new ground-based facilities:
  - ALMA: large mm radio telescope array now available for solar studies (ESO/Chile)
    - first regular solar observations with ALMA have finished (cycle 4/5, 2017-2018)
    - IRIS will prioritize coordination with successful ALMA solar proposals in future cycles (added interferometric capabilities).
  - DKIST: largest (4m) solar telescope in world, first light in 2019,
    IRIS will prioritize coordination with DKIST as it comes online

  - new post-focal instrumentation has come online at Swedish Solar Telescope, GREGOR, Spain, Goode Solar Telescope at BBSO, etc.

All of these facilities complement IRIS observations - particularly measuring chromospheric magnetic fields in the regions IRIS observes.

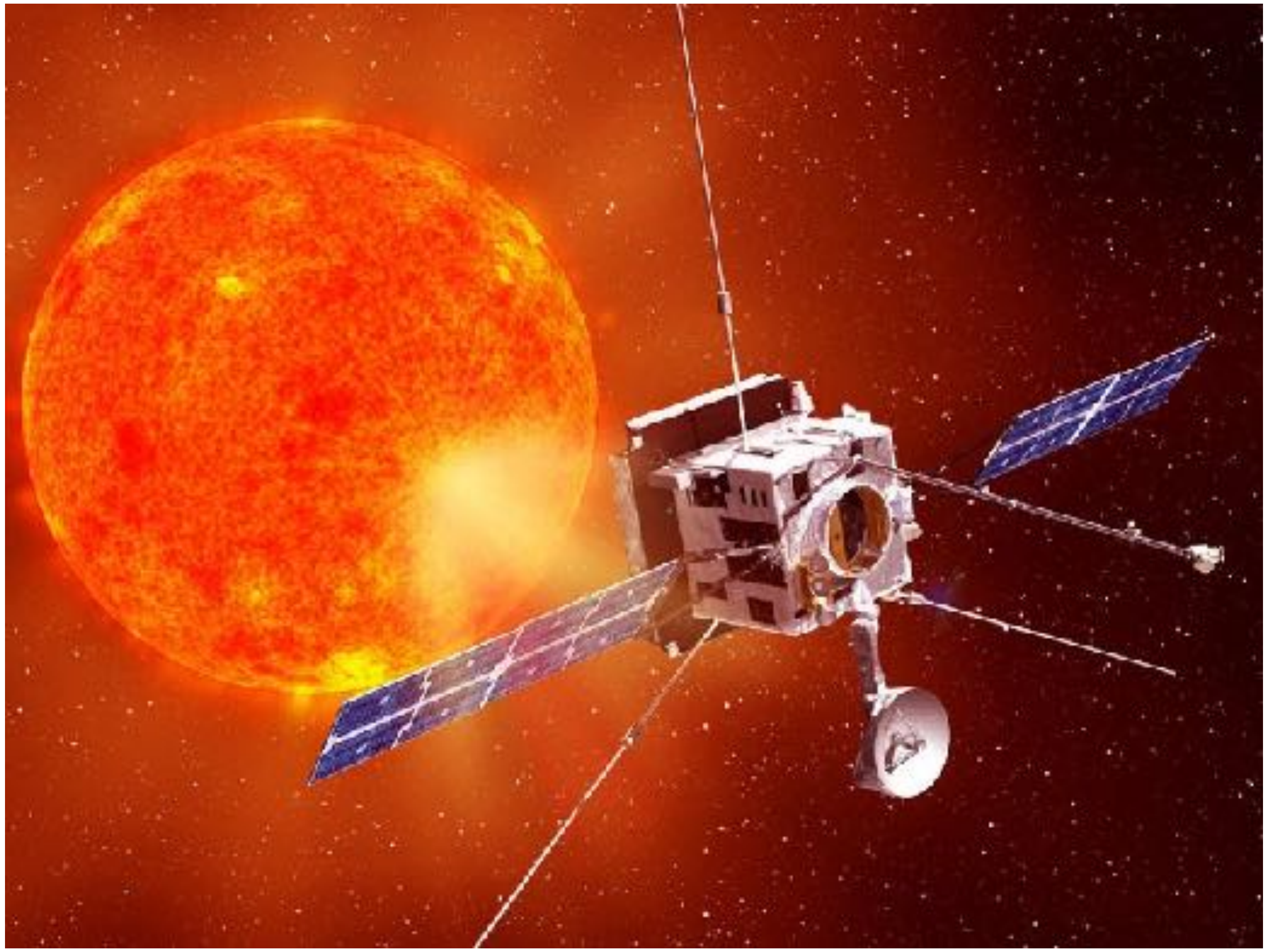
Unique opportunities for IRIS during the next three years

- IRIS is highly complementary with new space-based facilities and will provide key data that enhances the science investigation for both:

Parker Solar Probe

- Parker Solar Probe does not have remote sensing instruments directly looking at the Sun
- IRIS will obtain context for PSP with images and spectra of the footpoint regions of the field lines that PSP "corotates" with for weeks on end, starting in Fall 2018

Solar Orbiter



IRIS will provide invaluable data in a solar region (chromosphere, transition region) that is not well covered by any instrument on Solar Orbiter, and at higher spatial resolution (0.33 arcsec vs. 1 arcsec) and with 2 orders of magnitude more telemetry, i.e., at a cadence that enhances the SOLO data