Spectroscopic Observations of the Upper Solar Atmosphere

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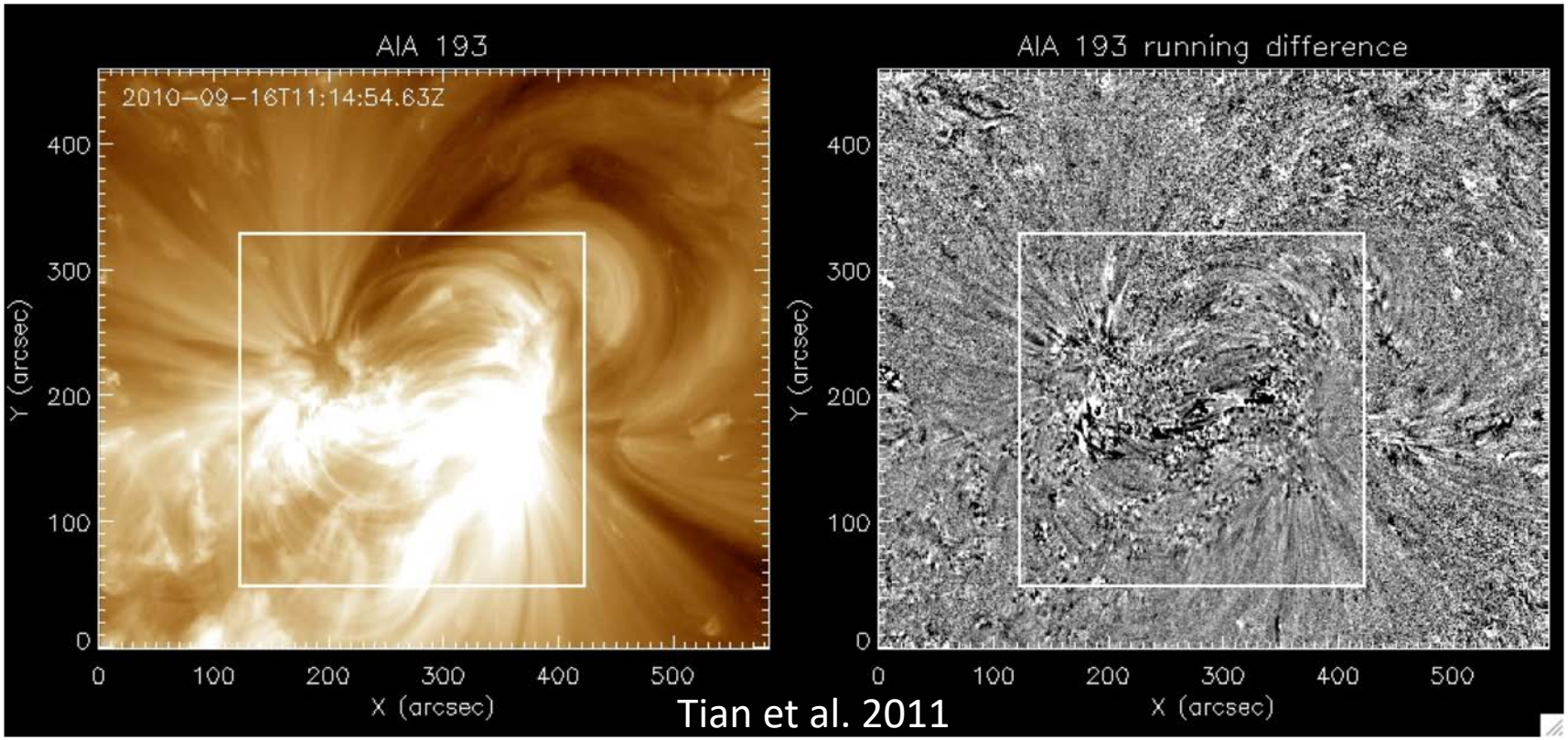
Outline

- Coronal upflows at AR boundaries
- CME-induced coronal dimmings
- Persistent coronal oscillations
- Quiet-Sun transition region
- Transition region above sunspots

Upward propagating disturbances (PDs) at AR boundaries



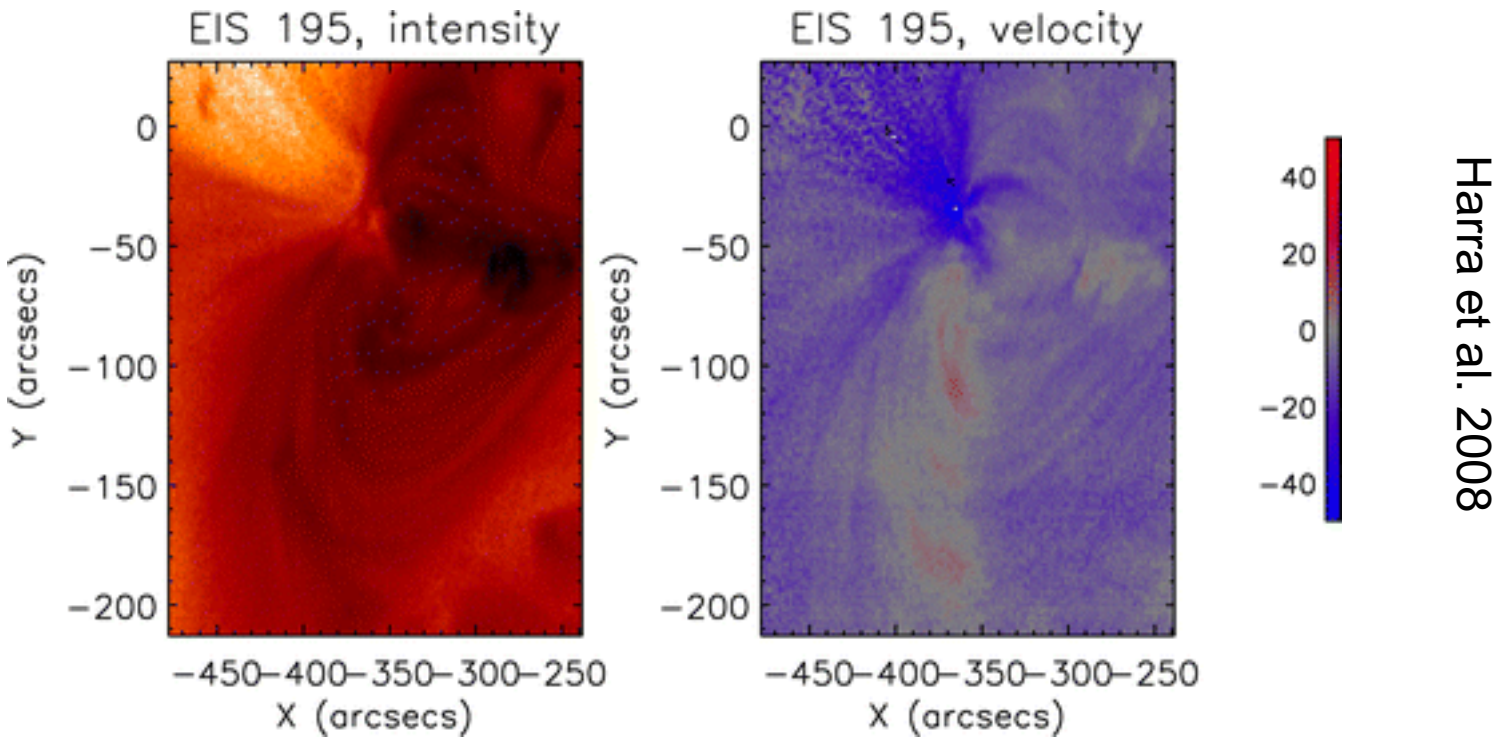
Tian et al. 2011

- PDs in EUV & X-Ray images: speed 50-200 km/s, period 3-15 min

➢ Slow waves: De Moortel+2002, Robbrecht+2001, King+2003, Marsh+2009, Wang+2009, Stenborg+2011, Yuan+Nakariakov 2012, Sharma+2020

➢ Mass flows: Sakao+2007, McIntosh+De Pontieu 2009, He+2010, Tian+2011

Blue shifts at AR boundaries



- SGF of coronal lines reveals ~20 km/s blue shift: Harra+2008; Marsch+2008; Doschek+2008; Del Zanna 2008; Tripathi+2009; Baker+2009; Murray+2010, Young+2011, Brooks+Warren 2011, van Driel-Gesztelyi+2012, Démoulin+2013, Brooks+2015
- Origin of the slow solar wind?

How are the Blueshifts and PDs connected

(1) Same locations:

AR boundaries

(2) Speeds

PDs: ~100 km/s

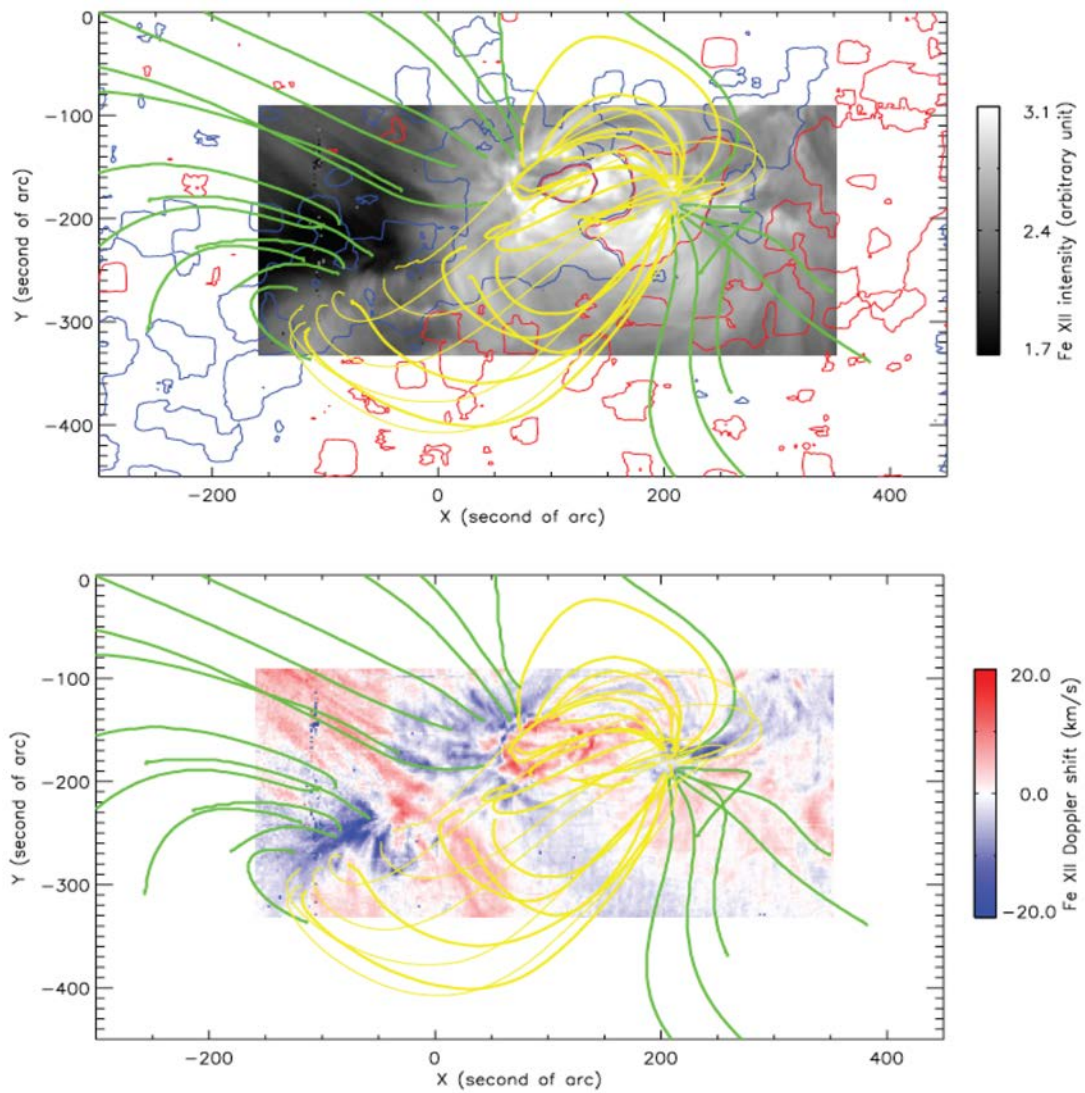
Blueshifts: ~20 km/s

(3) Periodicity

PDs: quasi-periodic

Blueshifts: unknown

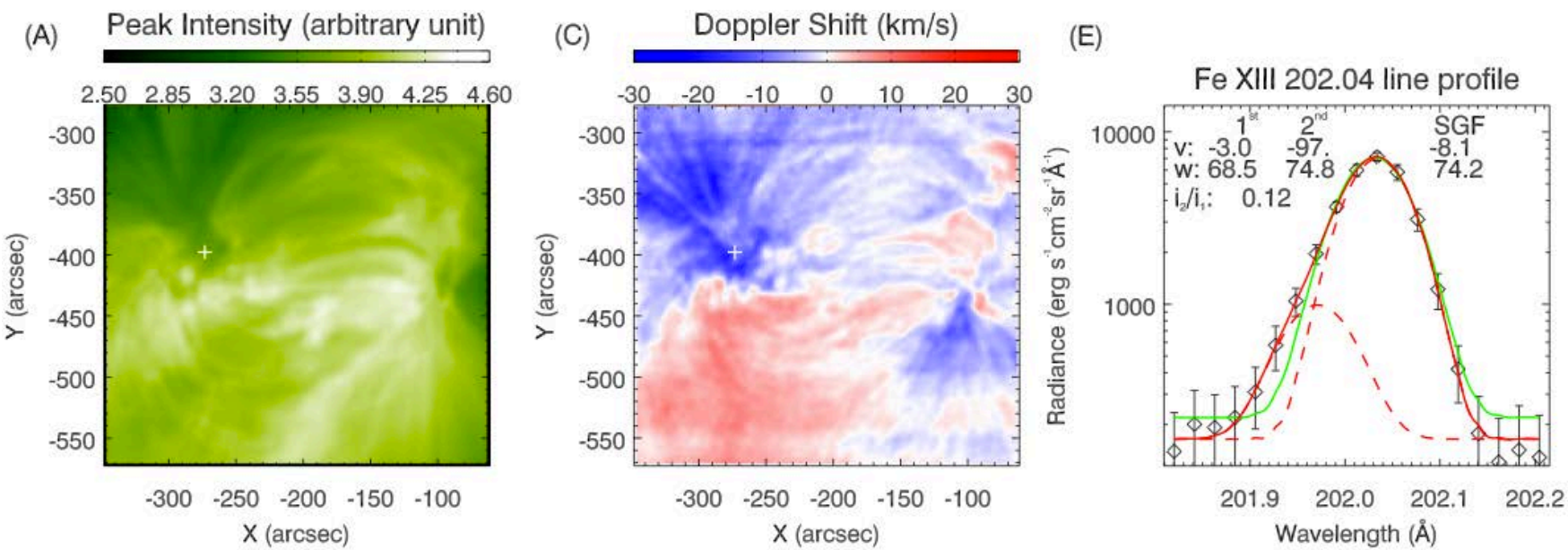
Fe XII 195.12 Å



Marsch, Tian, Sun, et al. 2008, ApJ

Two components of coronal emission

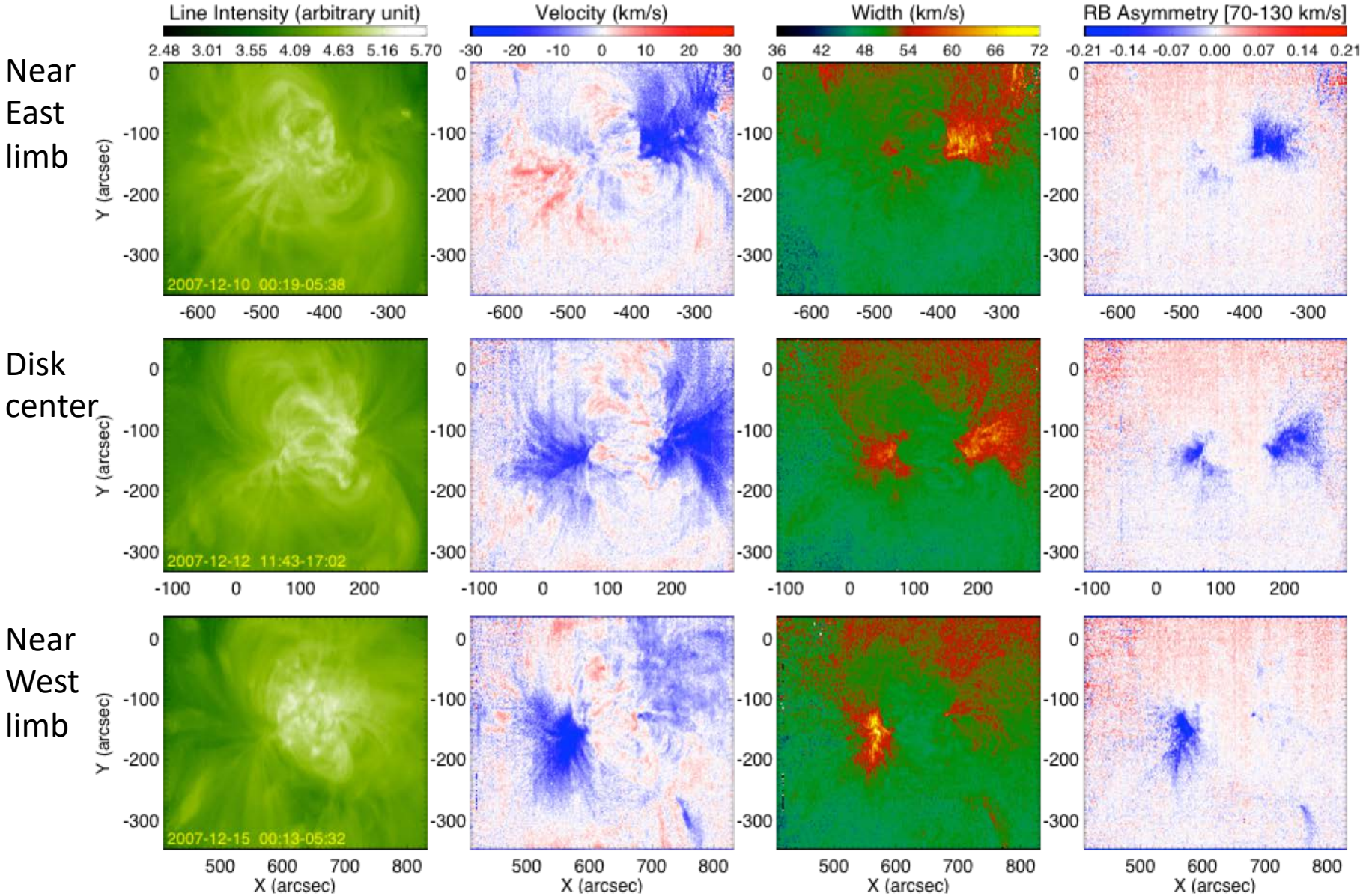
Enhanced blue wing in line profiles: an almost stationary primary component and a weak high-speed (~100 km/s) upflow component



Tian, McIntosh, De Pontieu, et al. 2011, ApJ

Also see: Hara+2008, De Pontieu+2009, McIntosh+De Pontieu 2009, Bryans+2010, Peter 2010, Nishizuka+Hara 2011, McIntosh+2012, Tripathi+Klimchuk 2013, Scott+2013, Patsourakos+2014, Klimchuk+2016

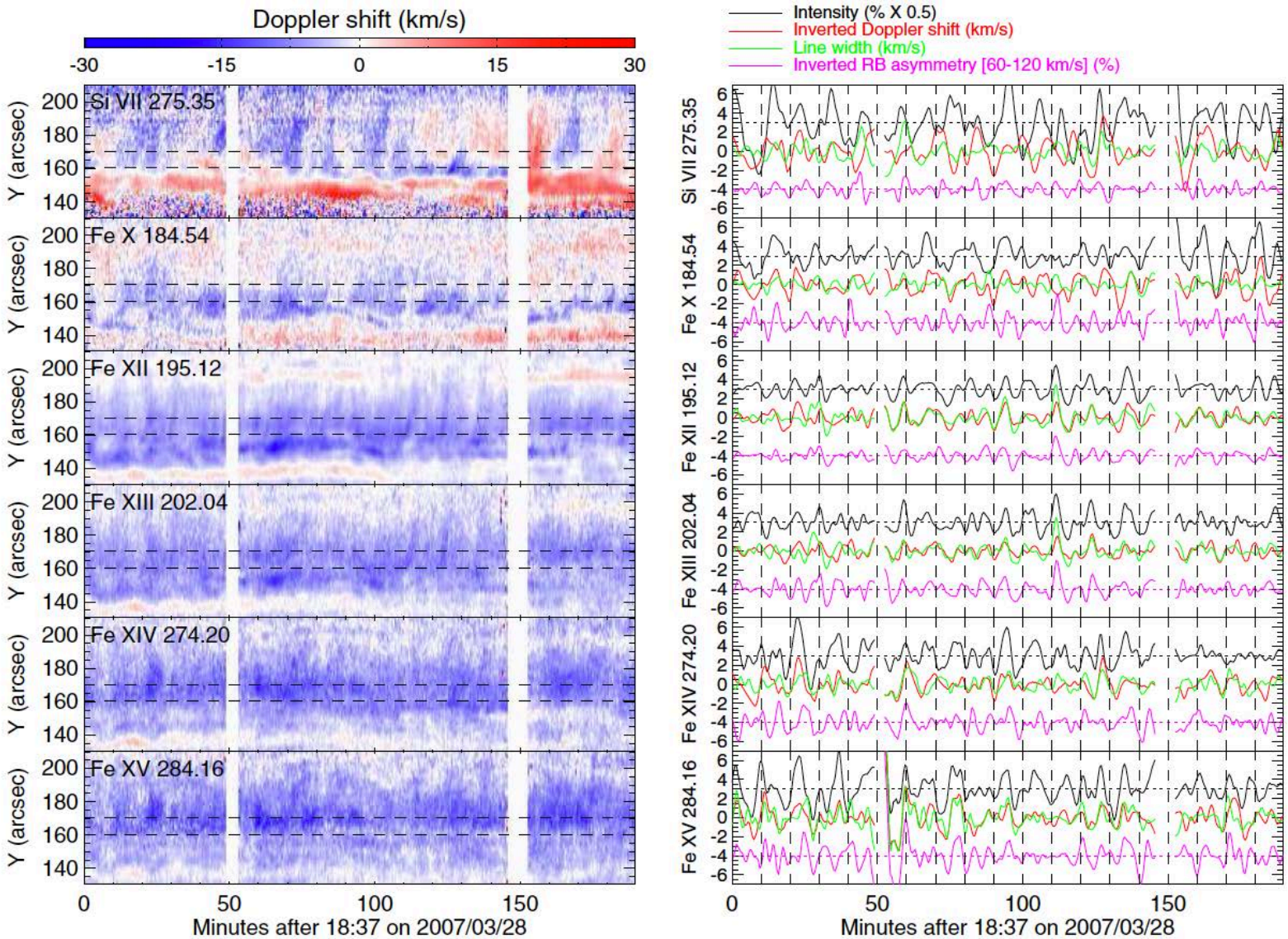
Profile asymmetry not caused by noise or blend



Tian et al. 2012, ApJ, 748, 106

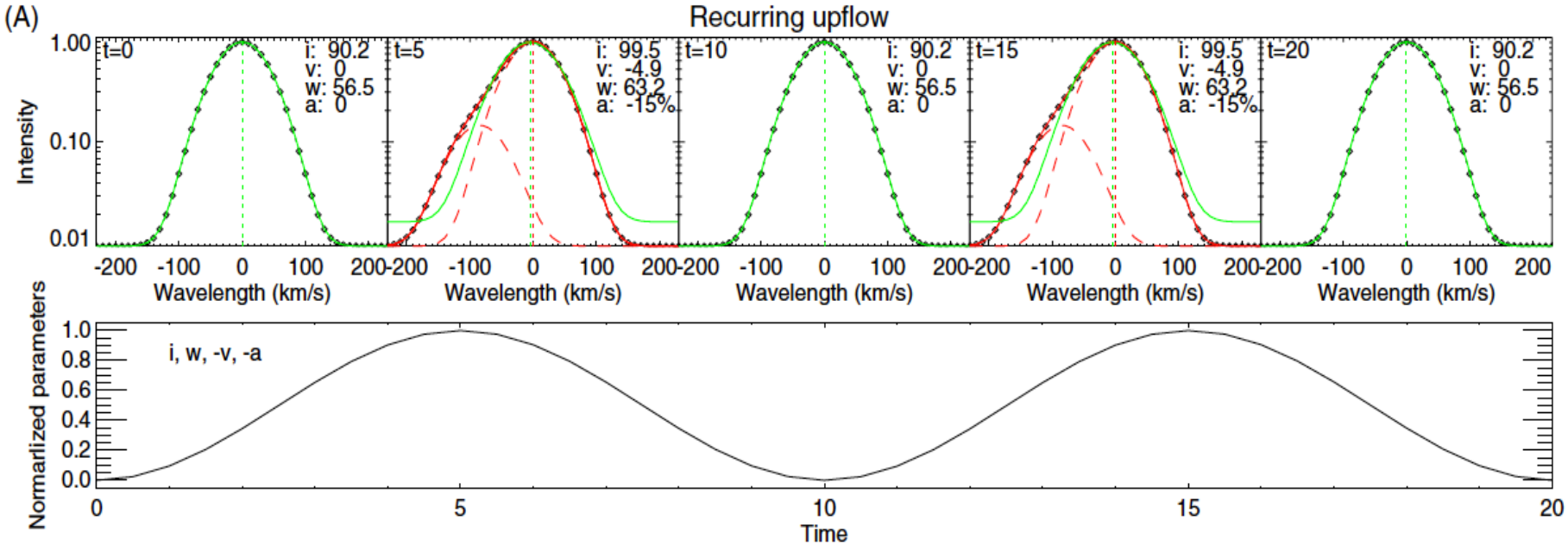
In-phase quasi-periodic variation of line parameters

Tian et al. 2012, ApJ, 759, 144



Often recur with periods of 3-15 min (De Pontieu & McIntosh 2010, ApJ; Tian et al. 2011, ApJL; Tian et al. 2012, ApJ)

Recurring upflow/jet scenario



- At t=0, 10, 20, there is no upflow and we only see the nearly stationary background emission component.
- At t=5, 15, we have both the background component and high-speed upflow component. The line intensity and line width both increase. The line profile reveals an enhancement at the blue wing and a SGF gives a small blue shift.

Connection between imaging and spectroscopic observations

Blueshifts & PDs

(1) Same locations:
AR boundaries

(2) Speeds
PDs: ~100 km/s
Blueshifts: ~20 km/s

(3) Periodicity
PDs: quasi-periodic
Blueshifts: unknown

2nd component & PDs

(1) Same locations:
AR boundaries

(2) Speeds: ~100 km/s

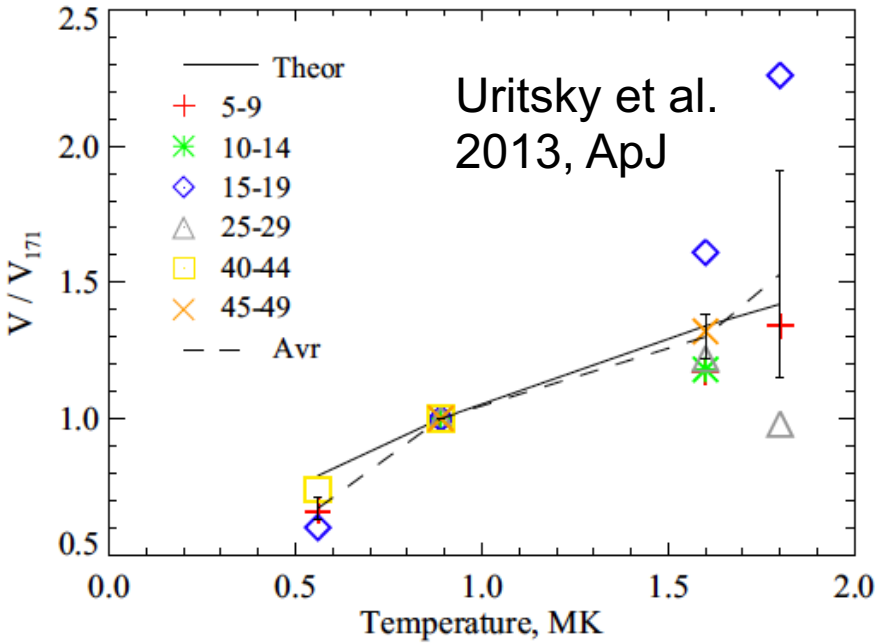
(3) Recurring time scale:
3-15 min

(4) Intensity change:
a few percent of the background intensity

It is the secondary upflow component that is associated with the PDs (Tian+2011)!

Waves or flows?

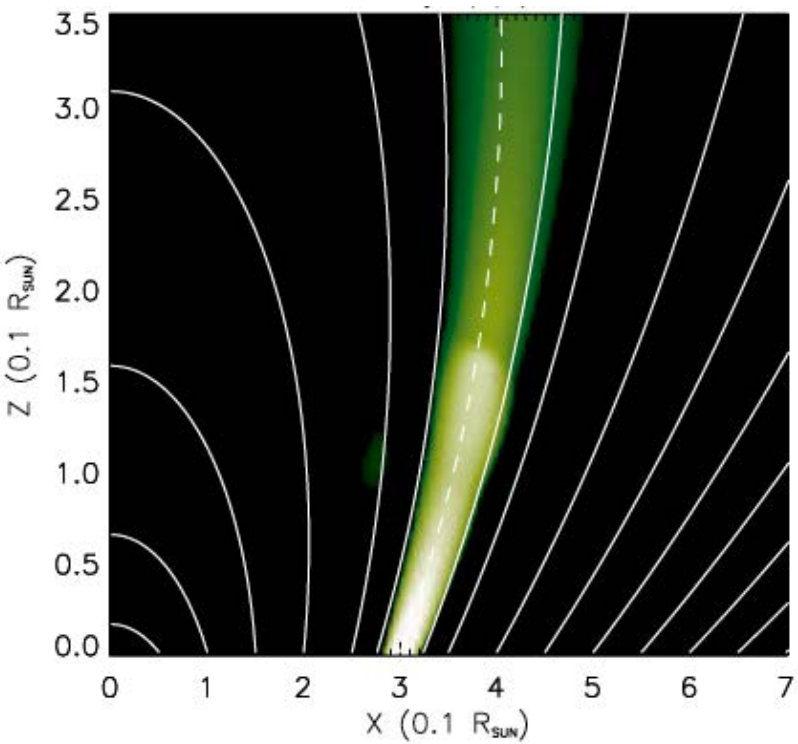
- The detailed analysis of EIS data strongly suggests that the PDs at AR boundaries are intermittent plasma jets.
- The scenario of slow waves with background upflows may also explain the blue shifts and correlated changes of different line parameters, though the predicted double frequency in the line width is not seen in EIS observations (Verwichte+2010).



- *T*-dependent PD velocity indicative of slow waves (Krishna Prasad+2012, Uritsky+2013).
- *T*-dependent velocity in sunspots, no clear dependence at non-sunspot locations (Kiddie+2012).

Both waves and flows!

- IRIS and AIA observations: both flows & shock waves contribute to PDs (Bryans+2016).
- 3D MHD modeling: upflow pulses inevitably excite slow waves propagating along the loop, flows & waves may both contribute to PDs at lower heights (Wang+2013). However, flow speeds (~40 km/s) are too small compared to those revealed from EIS observations.



Wang et al. 2013, ApJ

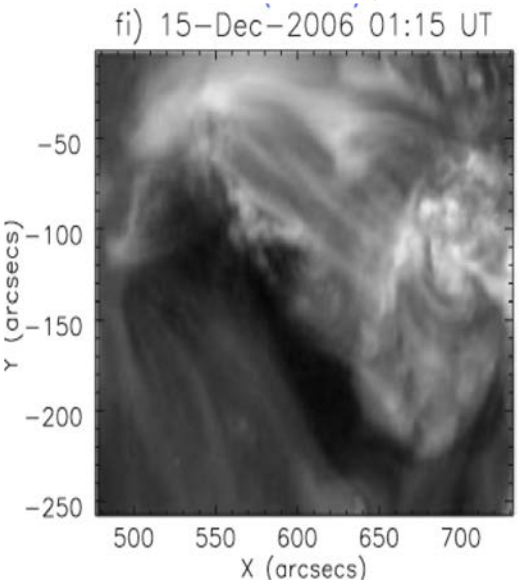
- How are the two related? Generation mechanisms? Still open questions! Requires multi-temperature and higher-resolution observations, and more realistic simulations.

Outline

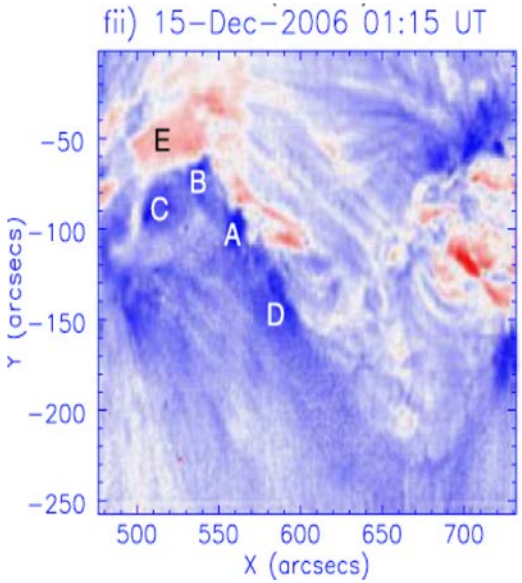
- Coronal upflows at AR boundaries
- CME-induced coronal dimmings
- Persistent coronal oscillations
- Quiet-Sun TR
- TR above sunspots

Spectroscopic observations of coronal dimmings

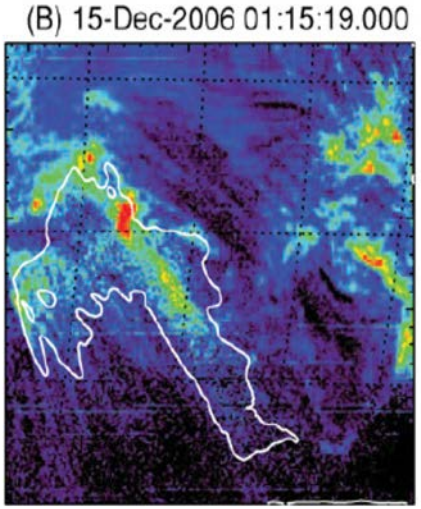
Intensity



Doppler shift



Line width



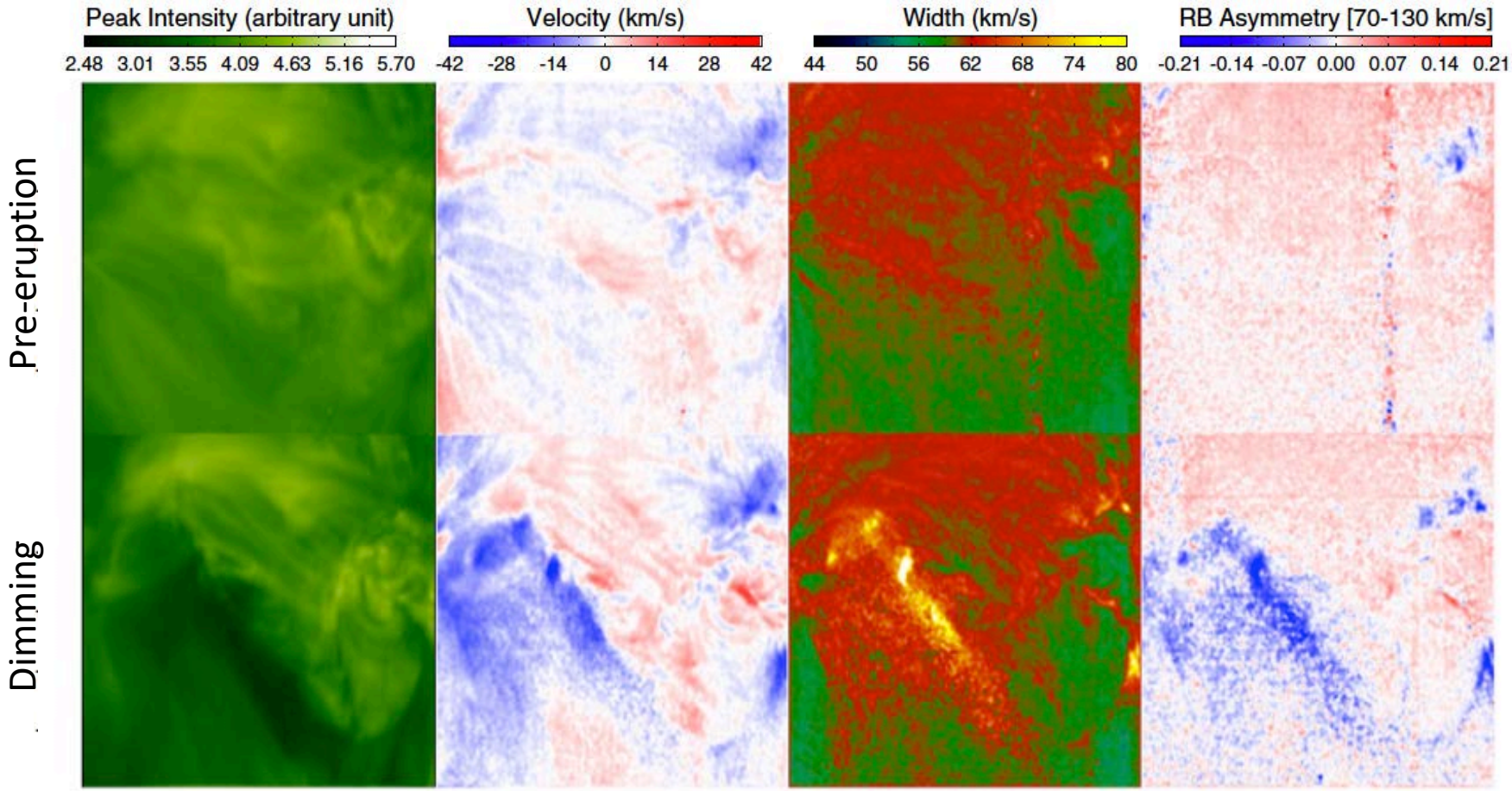
Attrill et al. 2010, Sol. Phys.

McIntosh 2009, ApJ

- ~20 km/s blue shift of coronal lines: outflows along opened field lines (Harra+2007, 2011; Jin+2009; Attrill+2010; Chen+2010; Tian+2012; Veronig+2019)
- Enhanced line broadening: growth of Alfven wave amplitude or inhomogeneity of flow velocities along LOS (McIntosh 2009; Chen+2010; Dolla+Zhukov 2011; Tian+2012)

Profile asymmetry in dimming regions

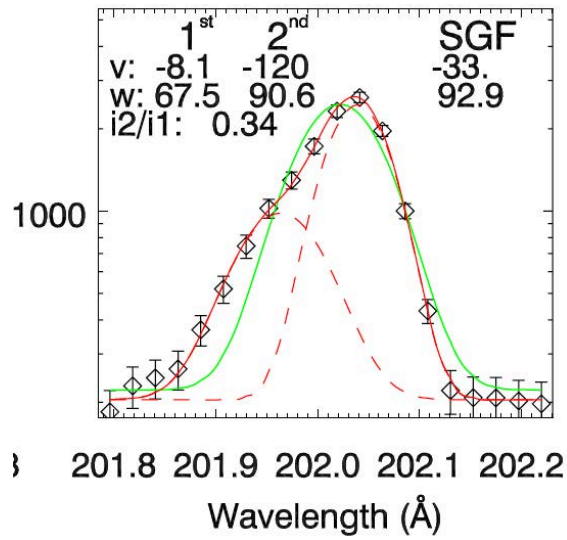
Fe XIII 202.04 Å



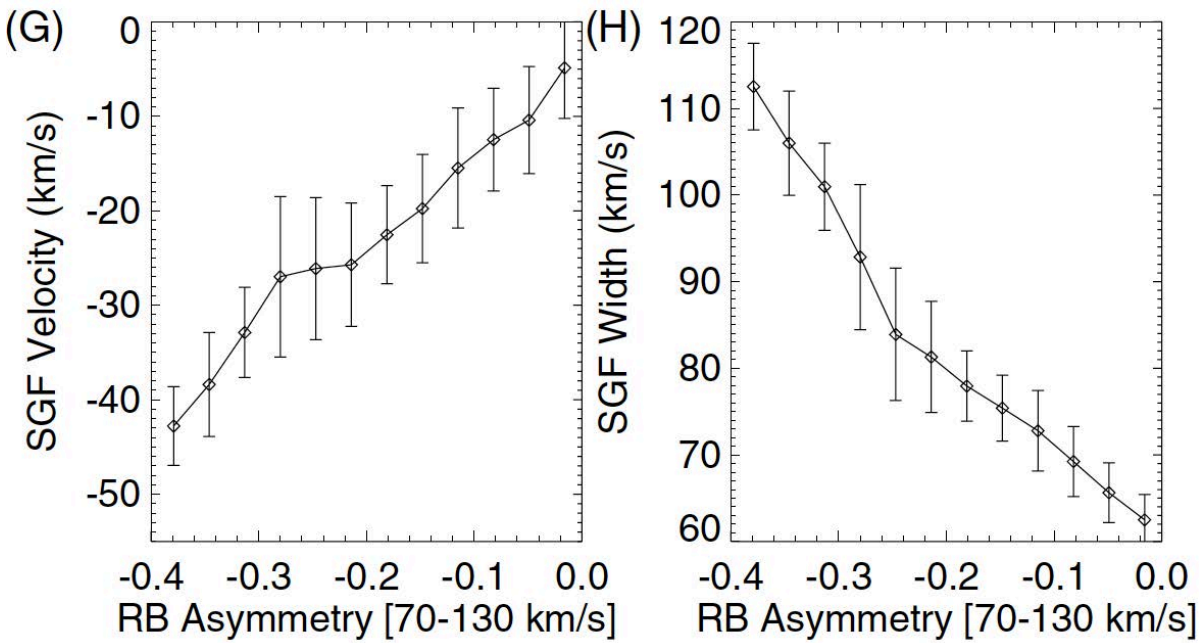
Dimming | SGF blue shift | Enhanced line broadening | Blue wing enhancement

Tian, McIntosh, Xia, et al. 2012, ApJ

Weak high-speed outflows from dimming regions

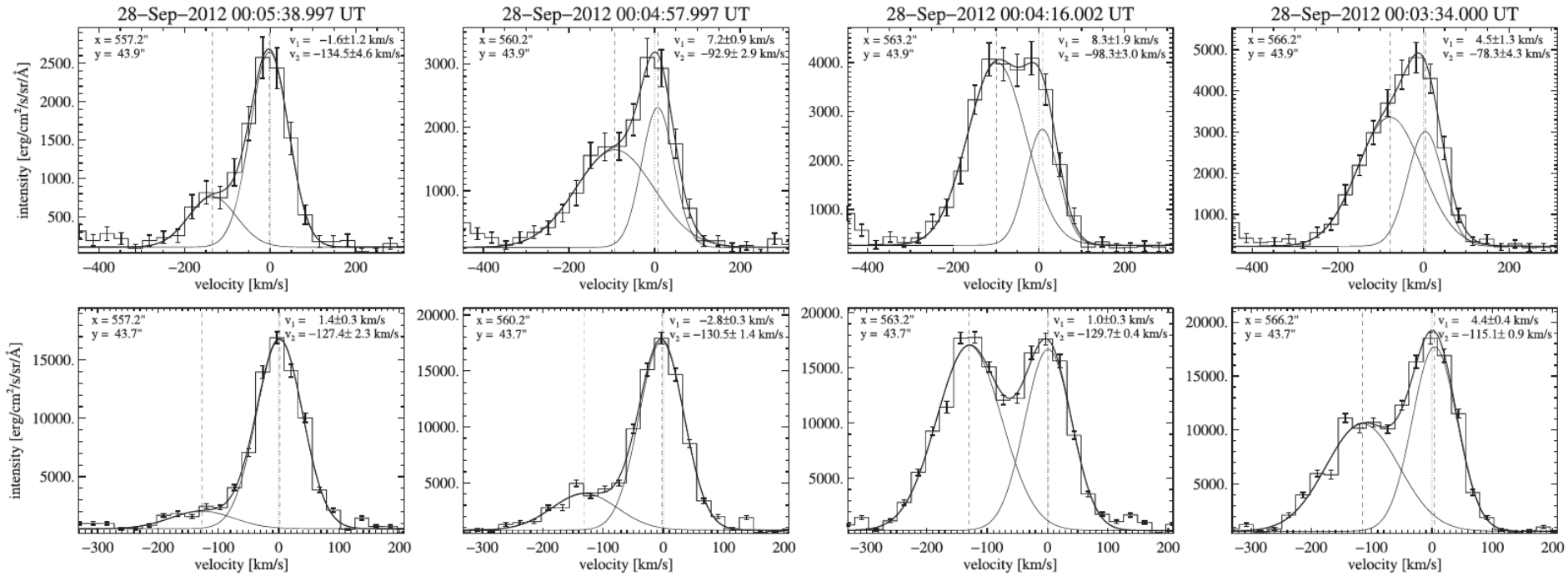


- Two emission components
  - A nearly stationary background
  - A weak high-speed (~100 km/s) component representing outflows
- Blue shift of ~20 km/s and enhanced line width are caused at least partly by the superposition of the two components



- SGF assumes everything moving at a uniform speed, thus can not reflect the real physics
- Only part of the coronal plasma in the dimming region flows outward at ~100 km/s

Some distinct double-component spectra

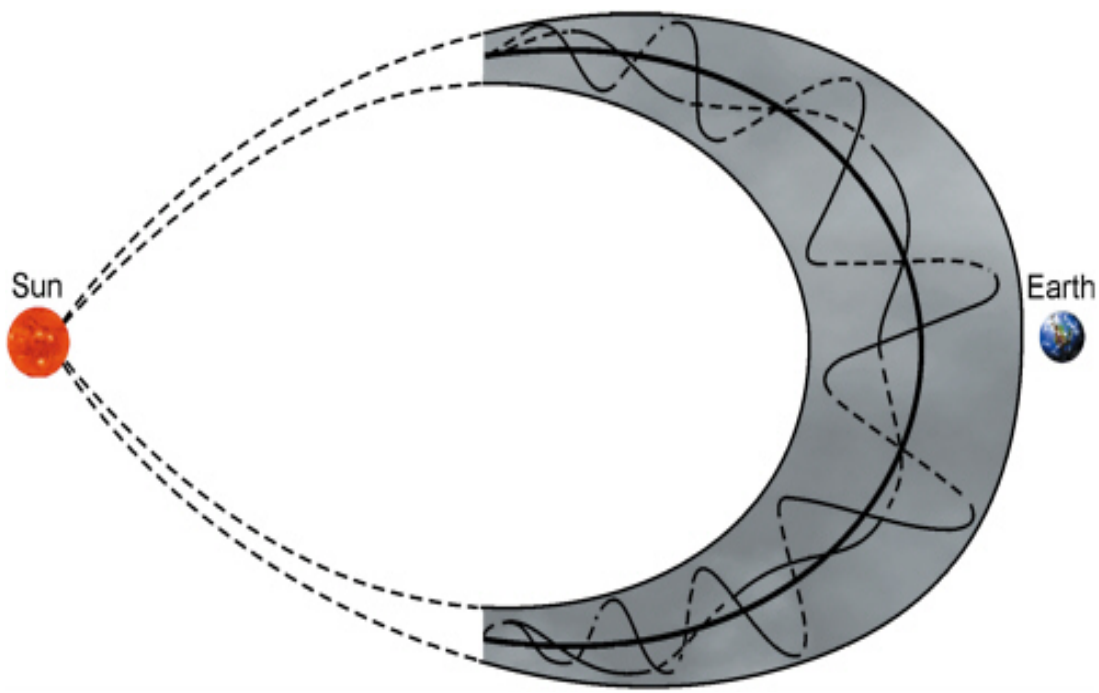


Distinct double-component spectra indicative of the superposition of a stationary and a fast upflowing plasma component are observed at the growing dimming border (Veronig+2019).

Dimming as a source of the solar wind

- Dimmings are transient CHs and are characterized by open field lines
- Similar high-speed outflows are also found at AR boundaries

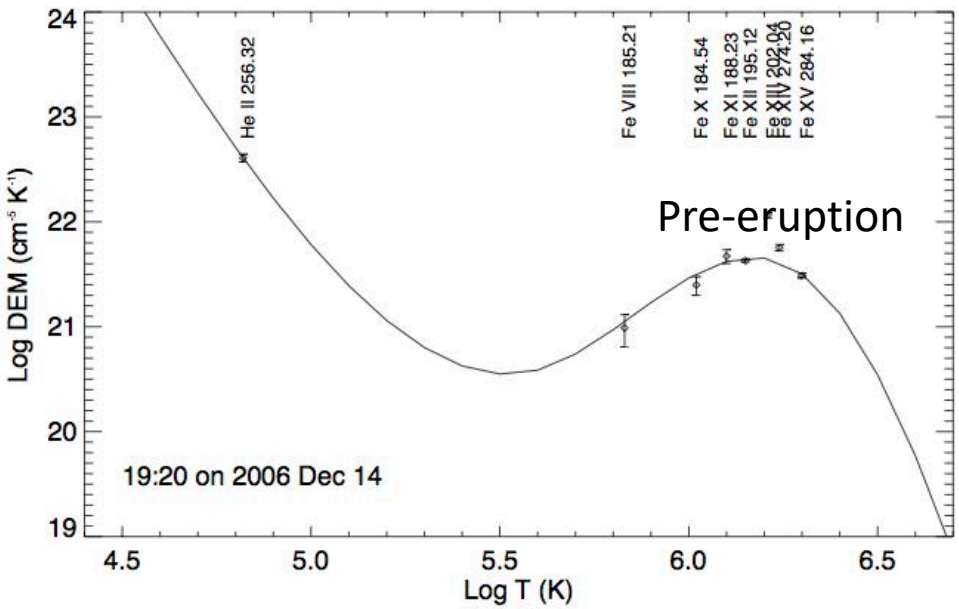
- Part of these weak, high-speed outflows may eventually become solar wind streams impacting the kinematics of CMEs
- The other part may provide mass to refill the corona after CME eruptions

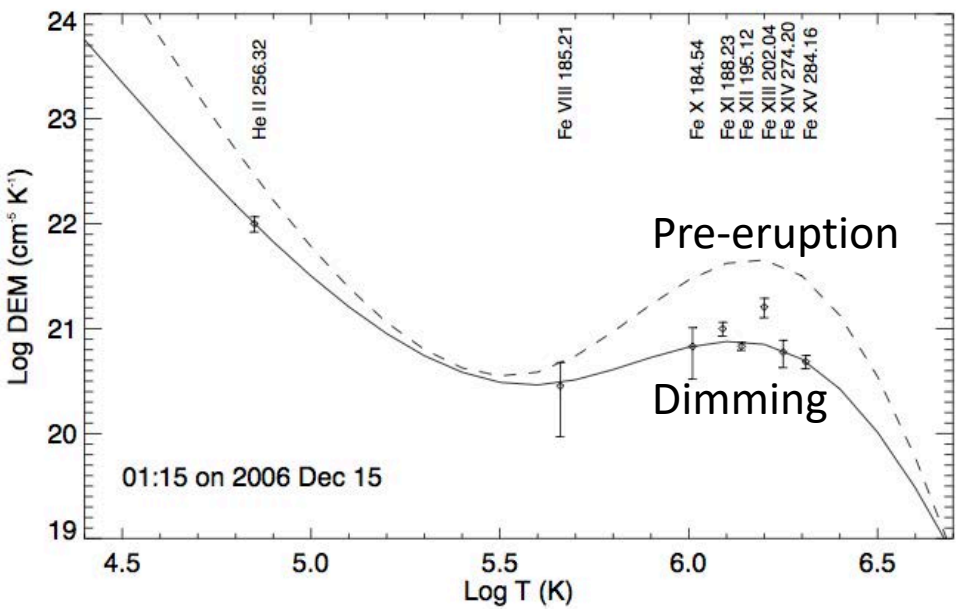


Lepping et al. 1990, JGR

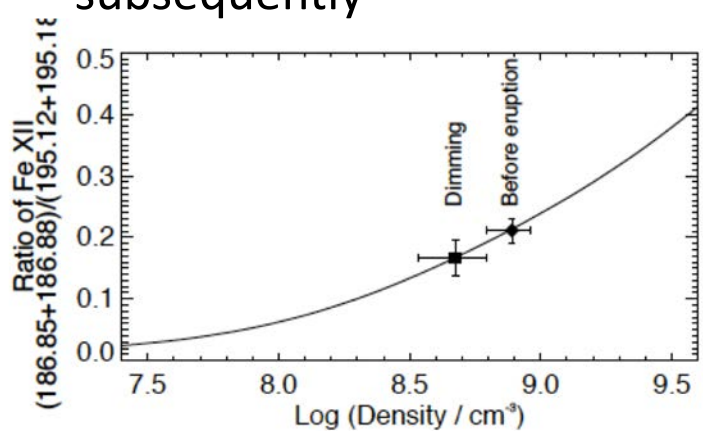
Density & Temperature diagnostics

Tian et al. 2012, ApJ

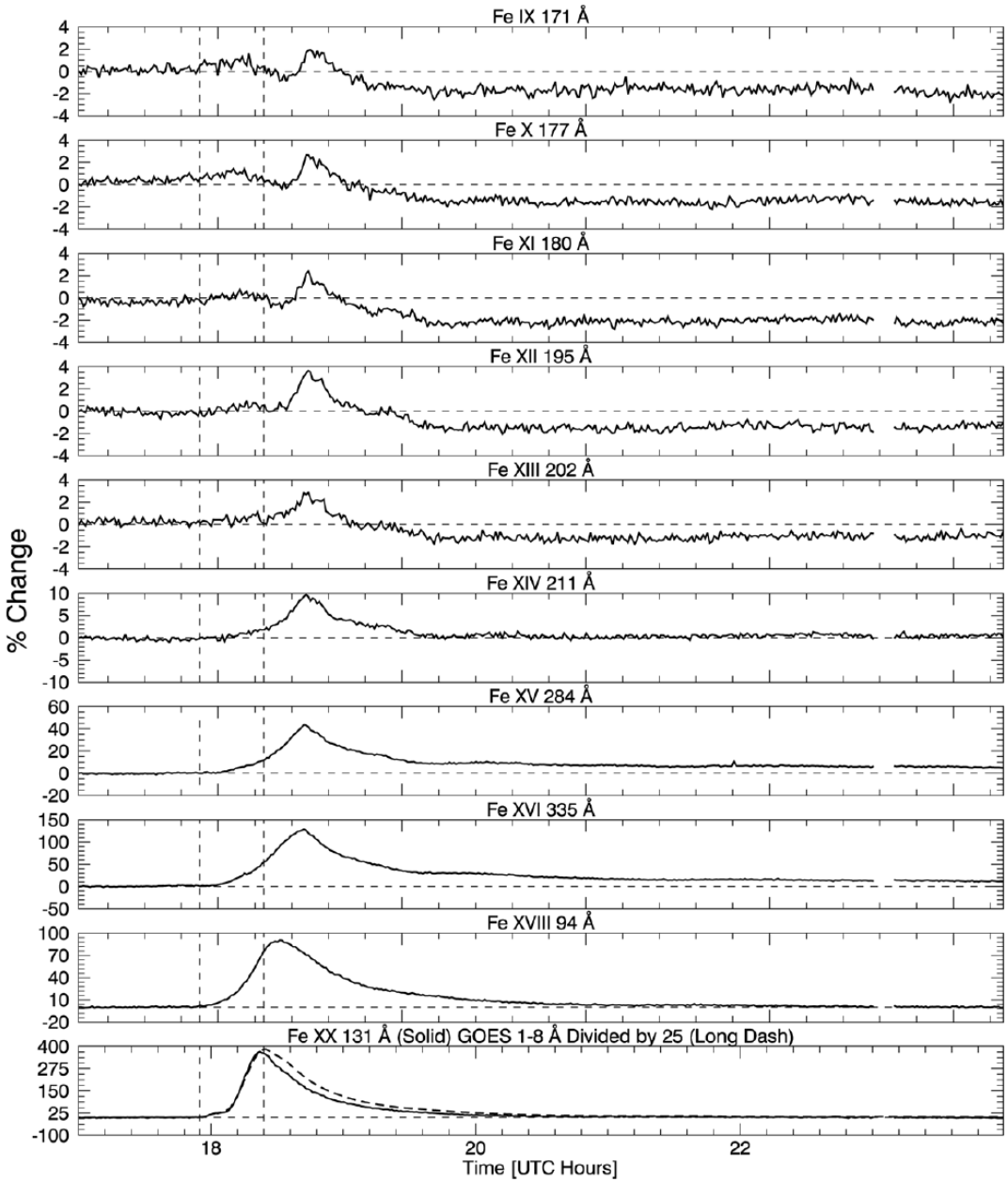




- Dimming due to escape of materials with log (T/ K) = 6.0–6.3.
- Dimming mainly due to mass loss rather than T change
  - ✓ No change in T_{peak} of DEM
  - ✓ Density decrease
- ✓ Estimated mass loss is 20-60% of the CME mass: A significant portion of the CME material comes from the region where dimming occurred subsequently



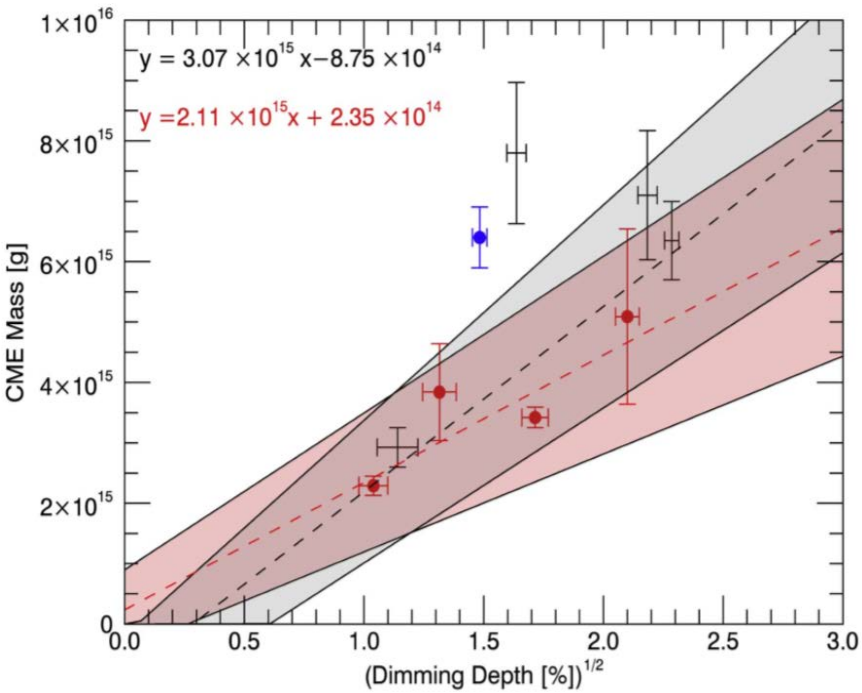
Dimming seen in Sun-as-a-star spectra

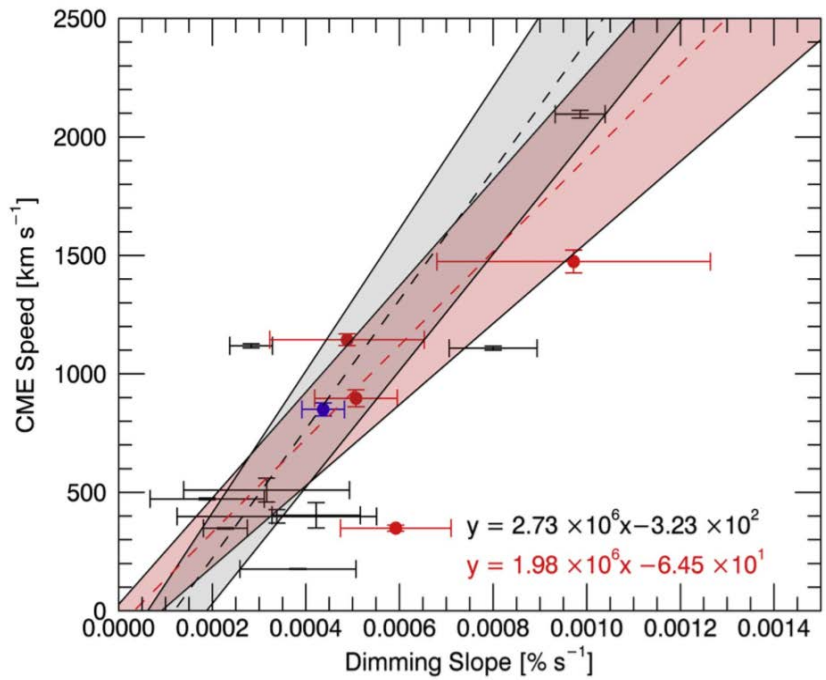


- The only characteristic that seems to show a consistent difference between flares with and without CMEs is that of dimming in lines characteristic of the quiet-Sun corona, i.e. 1-2 MK (Harra+2016)

Mason et al. 2014, ApJ

Inferring CME mass and speed from dimming





Mason et al. 2016, ApJ

- Correlation between CME mass and square root of dimming depth
- Correlation between CME speed and dimming slope

- A promising tool for stellar CME investigation

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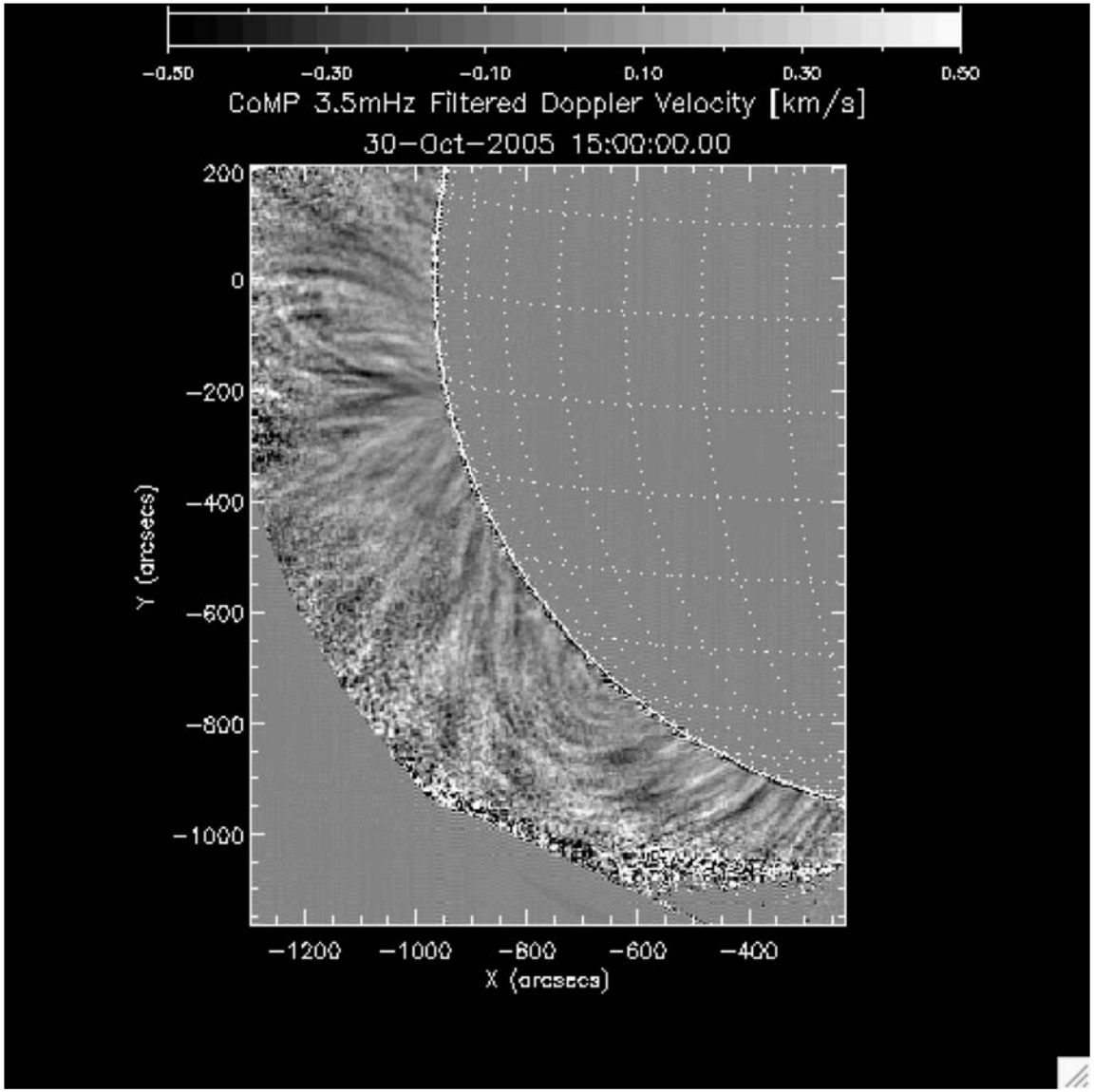
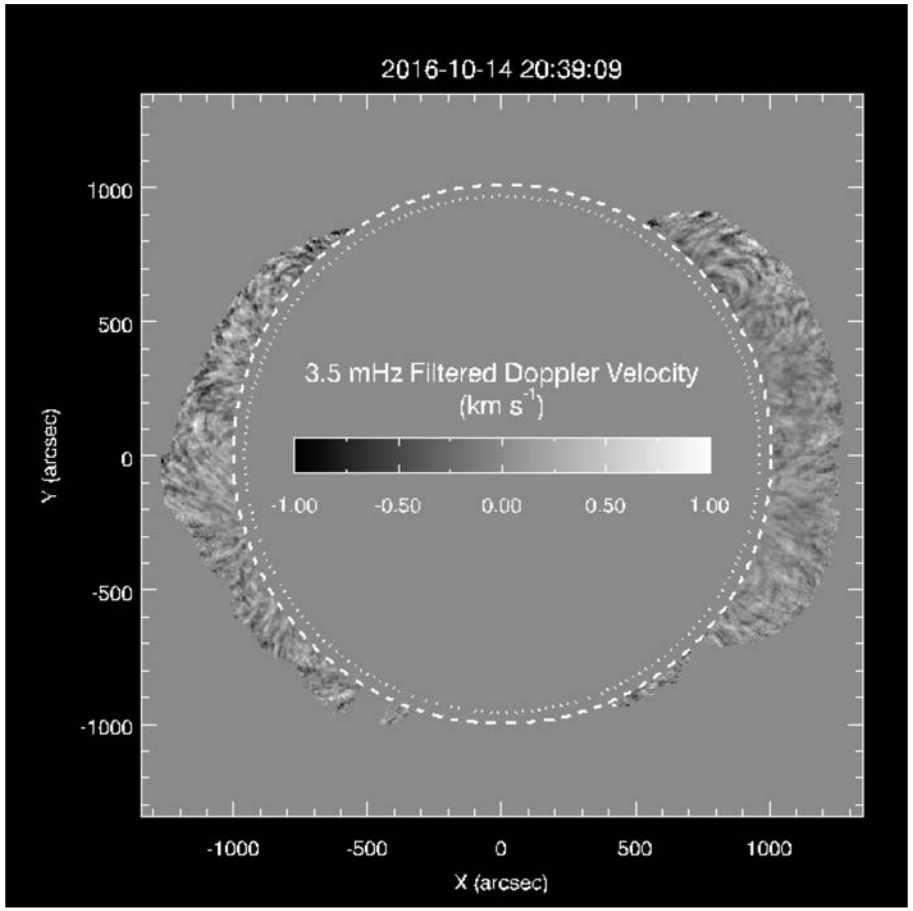
Propagating transverse waves in the corona

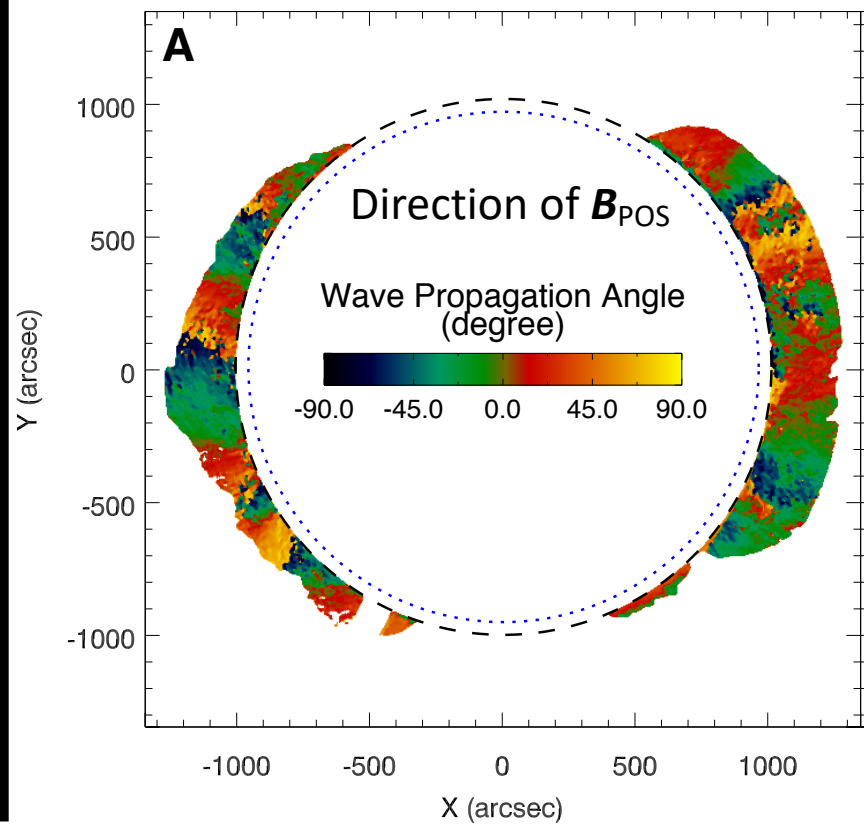


- Large-FOV spectroscopy with HAO's CoMP instrument using a tunable filter
- Pervasive propagating disturbances in the Doppler shift of Fe XIII 1074.7 nm: Alfvénic/kink waves

Tomczyk et al. 2007, Science
Tomczyk & McIntosh 2009, ApJ
Morton et al. 2015, Nat. Commun.

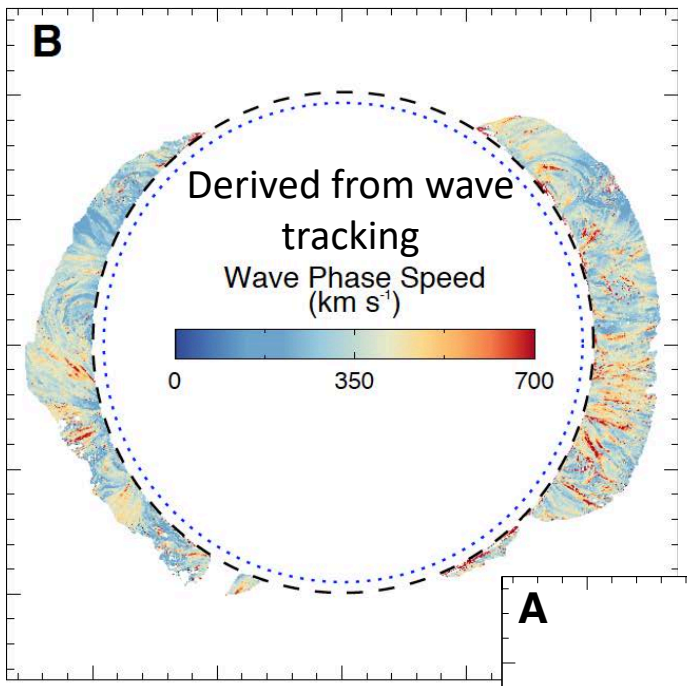
Prevalence of these waves in the global corona

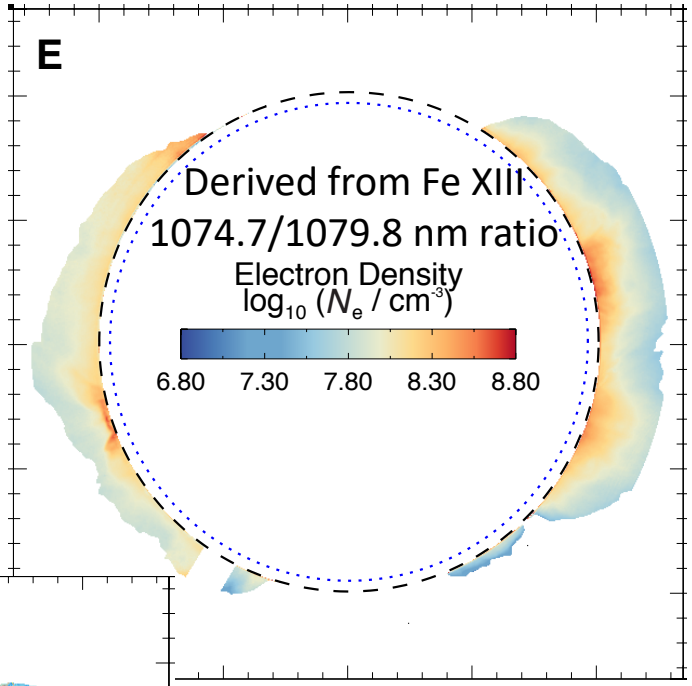


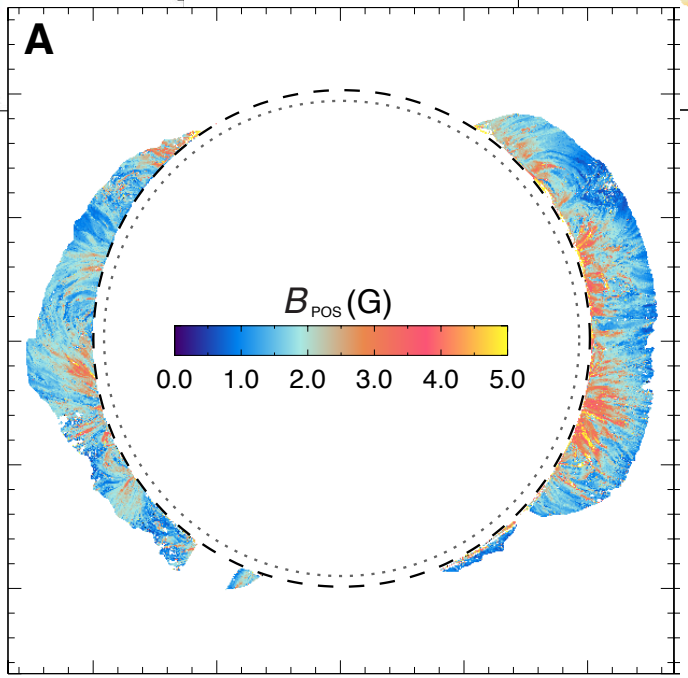


Z. Yang et al. 2020, Global maps of the magnetic field in the solar corona, *Science*, 369, 694
Z. Yang et al. 2020, Mapping the magnetic field in the solar corona through magnetoseismology, *Sci China Tech Sci*, DOI: https://doi.org/10.1007/s11431-020-1706-9

Mapping the magnetic field of the solar corona





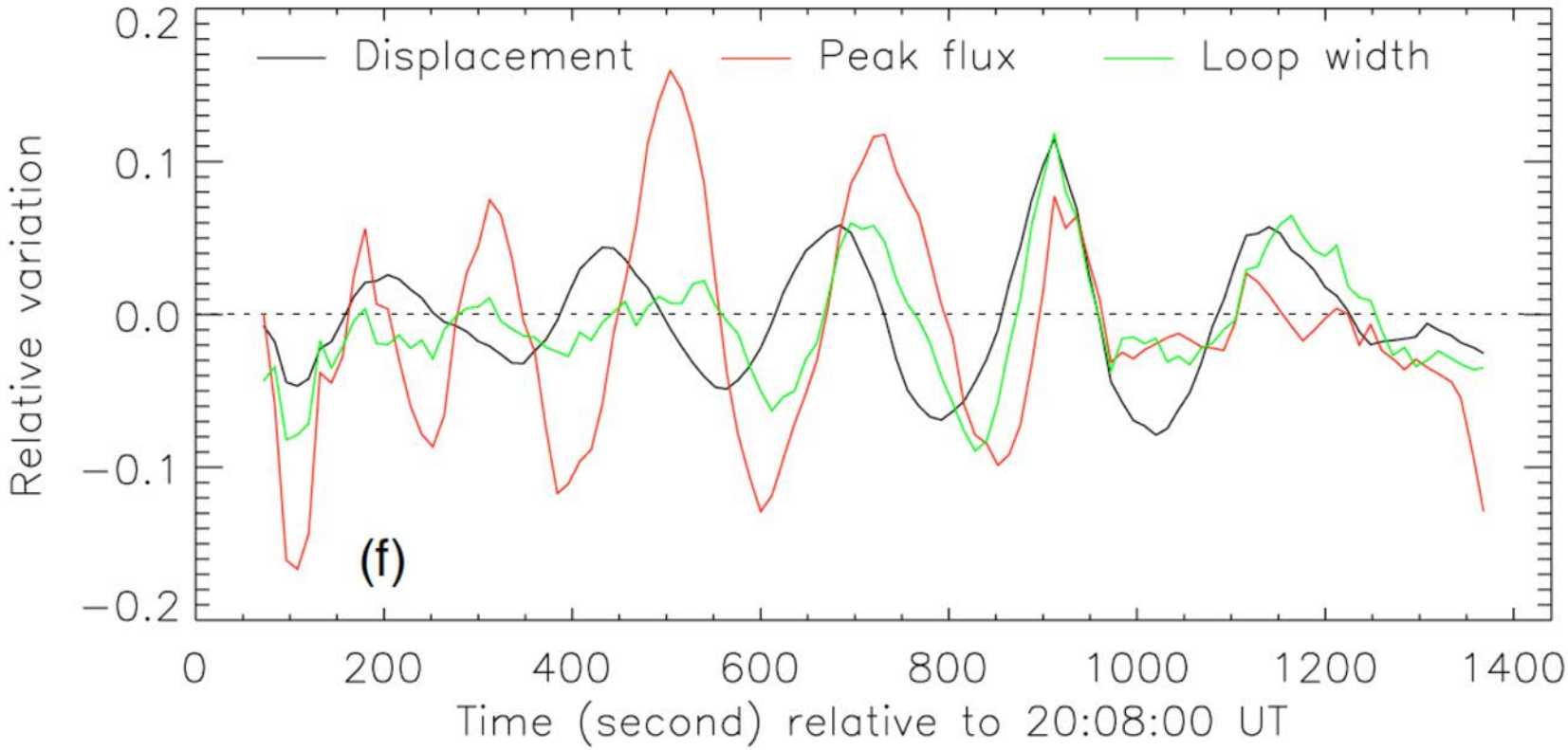


$$c_k^2 = \frac{B_i^2 + B_o^2}{\mu_0(\rho_i + \rho_o)}$$

$$c_k = \frac{B}{\sqrt{\mu_0 \langle \rho \rangle}}$$

Yang, Bethge, Tian, Tomczyk, Morton, et al. 2020, Science, 369, 694

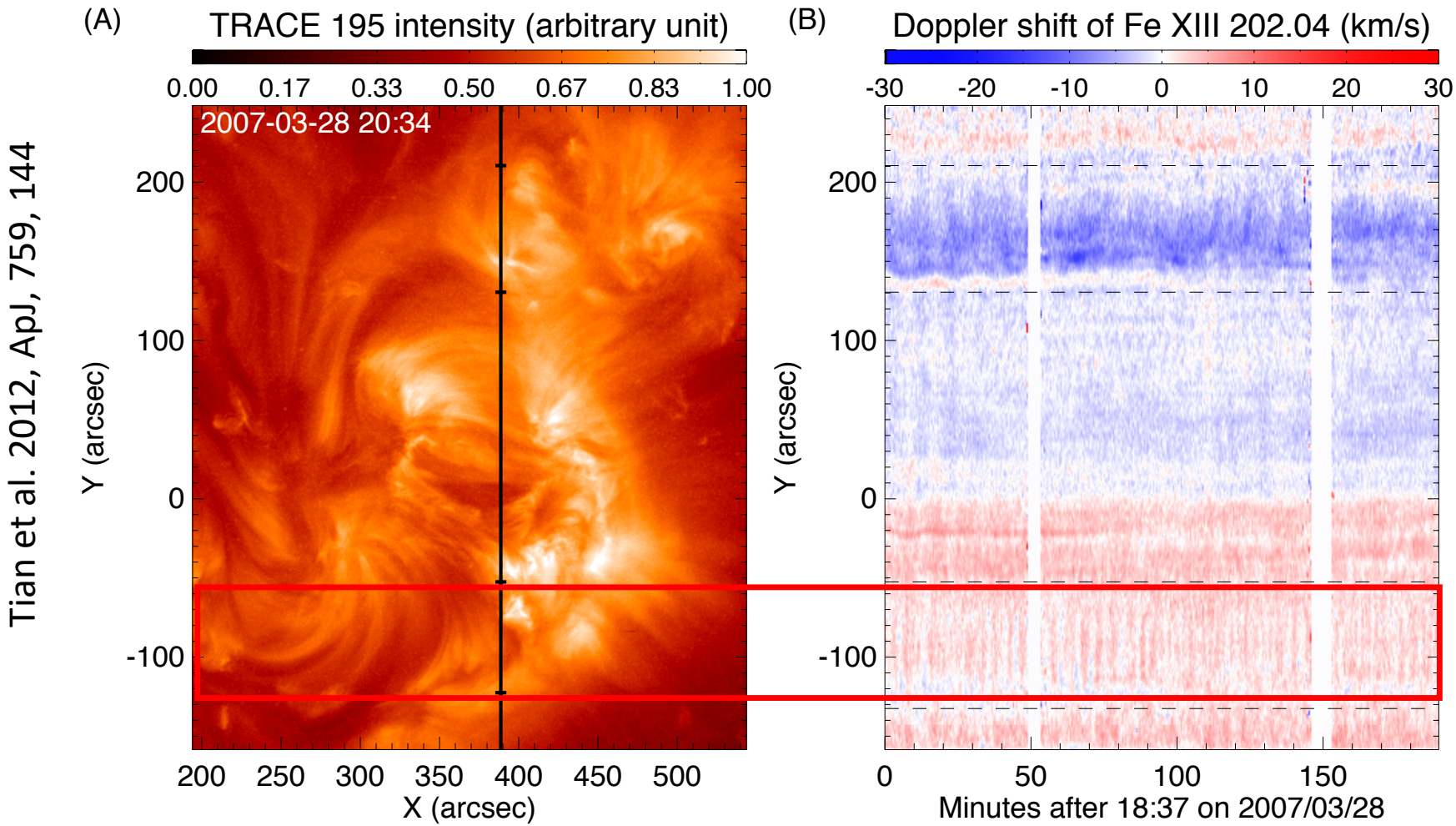
Decayless transverse oscillations in coronal loops



Wang et al. 2012, ApJ

- Periodic displacement of loops without obvious damping: first reported by Wang et al. (2012) and Tian et al. (2012) through imaging and spectroscopic observations, respectively
- Wang et al. (2012): triggered by a CME, lasting for more than ten cycles and even revealing growing amplitudes

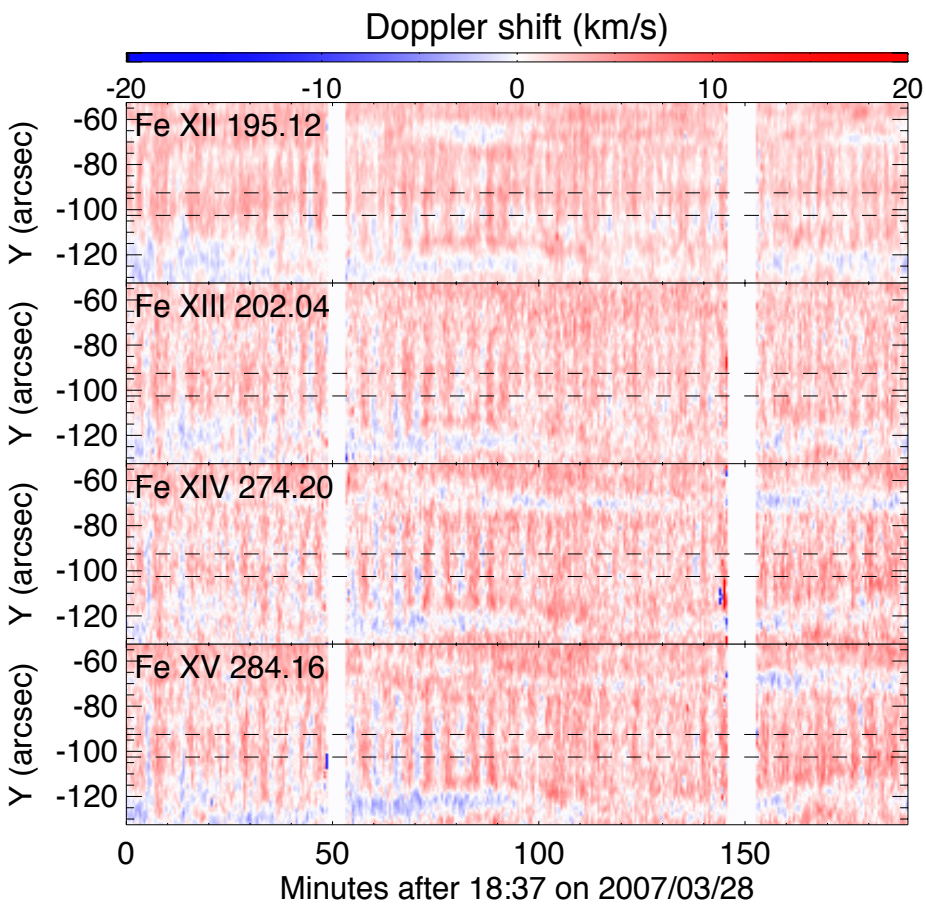
Spectroscopic observations of decayless transverse oscillations

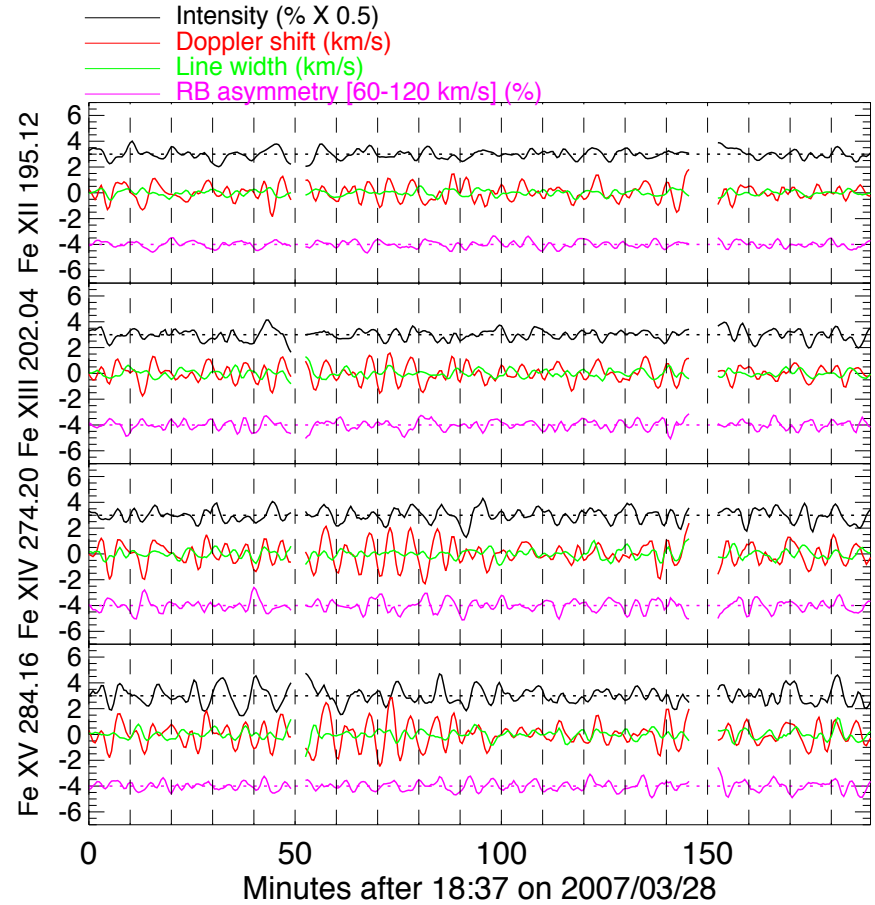


Tian et al. 2012, ApJ, 759, 144

- Examined all EIS sit-n-stare observations in ARs during Feb to April 2007
- Decayless/persistent Doppler shift oscillations are very common, no CMEs/flares
- Often observed when the slit is aligned with the upper part of loops

Low-amplitude decayless oscillations in quiet coronal loops

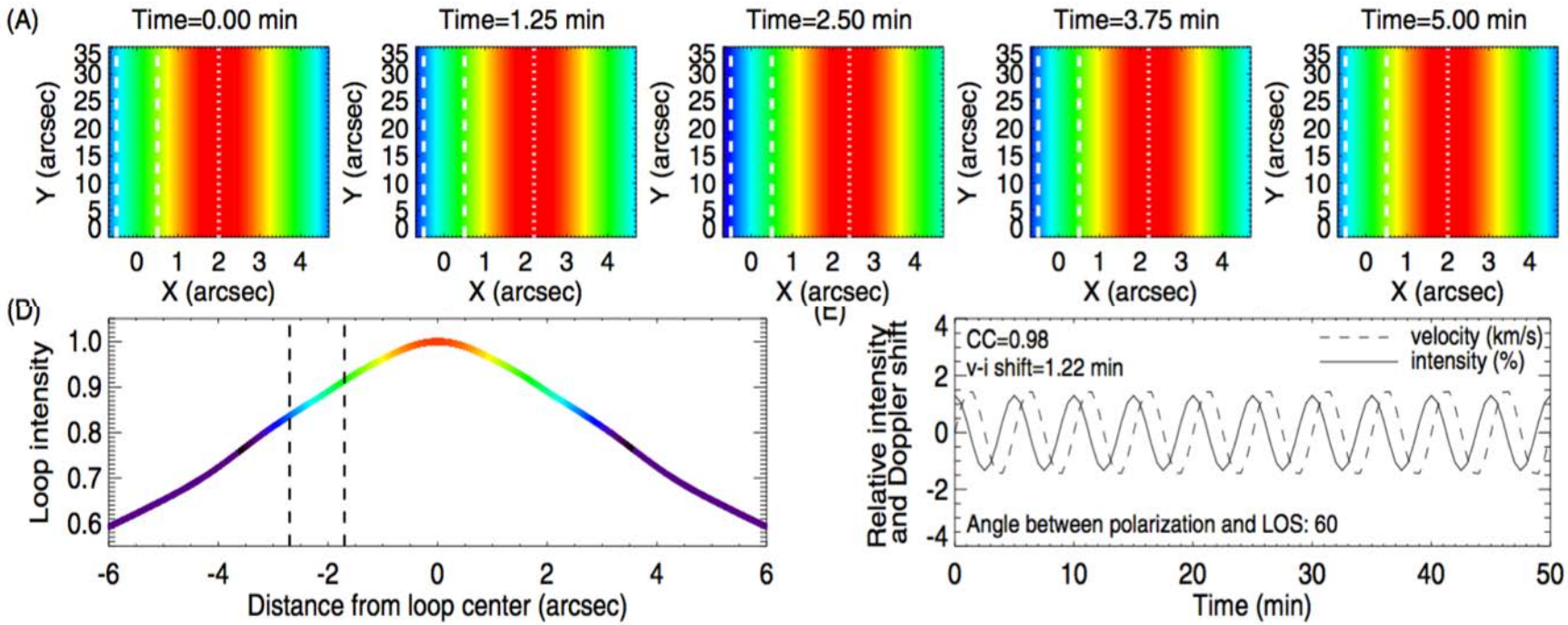




- Most prominent in Doppler shift of lines with T_f=1-2 MK, period 3-6 min
- Doppler shift amplitude ~2 km/s; Intensity variation ~2%
- Clearly decayless kink/Alfvénic oscillations, not related to eruptions

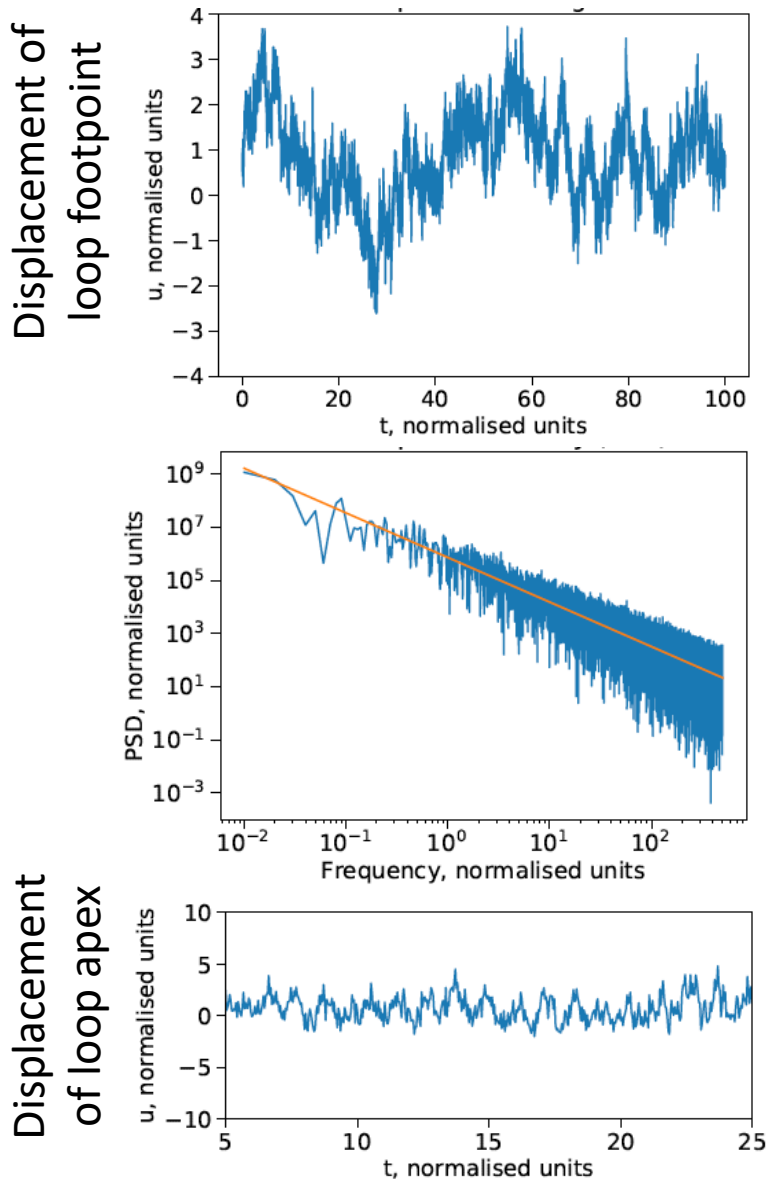
π/2 phase shift between intensity and Doppler shift

Slit location: between two dashed lines; Loop center: dotted line



- Intensity oscillations could also occur in observations of Alfvénic/kink waves, since periodic loop displacement could lead to the scenario that different parts (with different intensity) of a loop are sampled periodically.
- The phase shift is produced by loops moving into and out of a spatial pixel as a result of transverse oscillations.

How to produce decayless oscillations?



- The decayless behavior of these waves suggests a continuous supply of energy to the system.

- Afanasyev et al. (2020) developed a 1D time-dependent analytical model by considering kink oscillations of coronal loops driven by continuous random motions of loop footpoints.

$$\frac{\partial^2 u}{\partial t^2} + \alpha \frac{\partial u}{\partial t} = C_{\mathrm{k}}^2(x) \frac{\partial^2 u}{\partial x^2}$$

u: displacement
α: damping factor
C_k: kink speed

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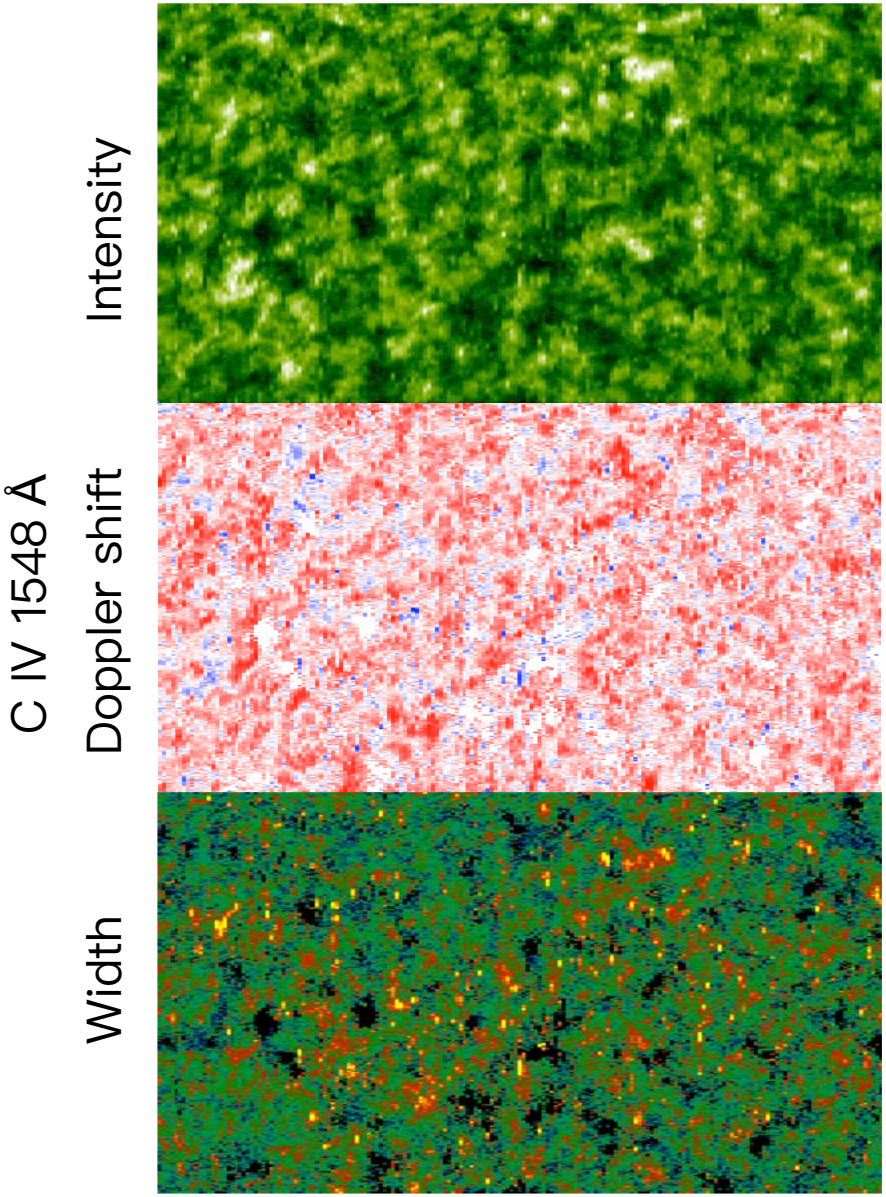
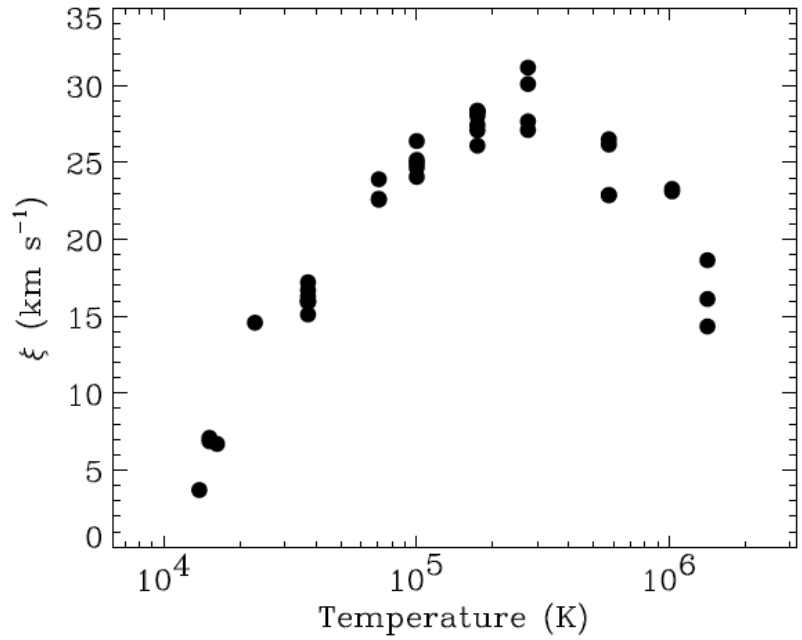
SUMER observations of the TR



- TR investigations largely based on spectroscopic observations.

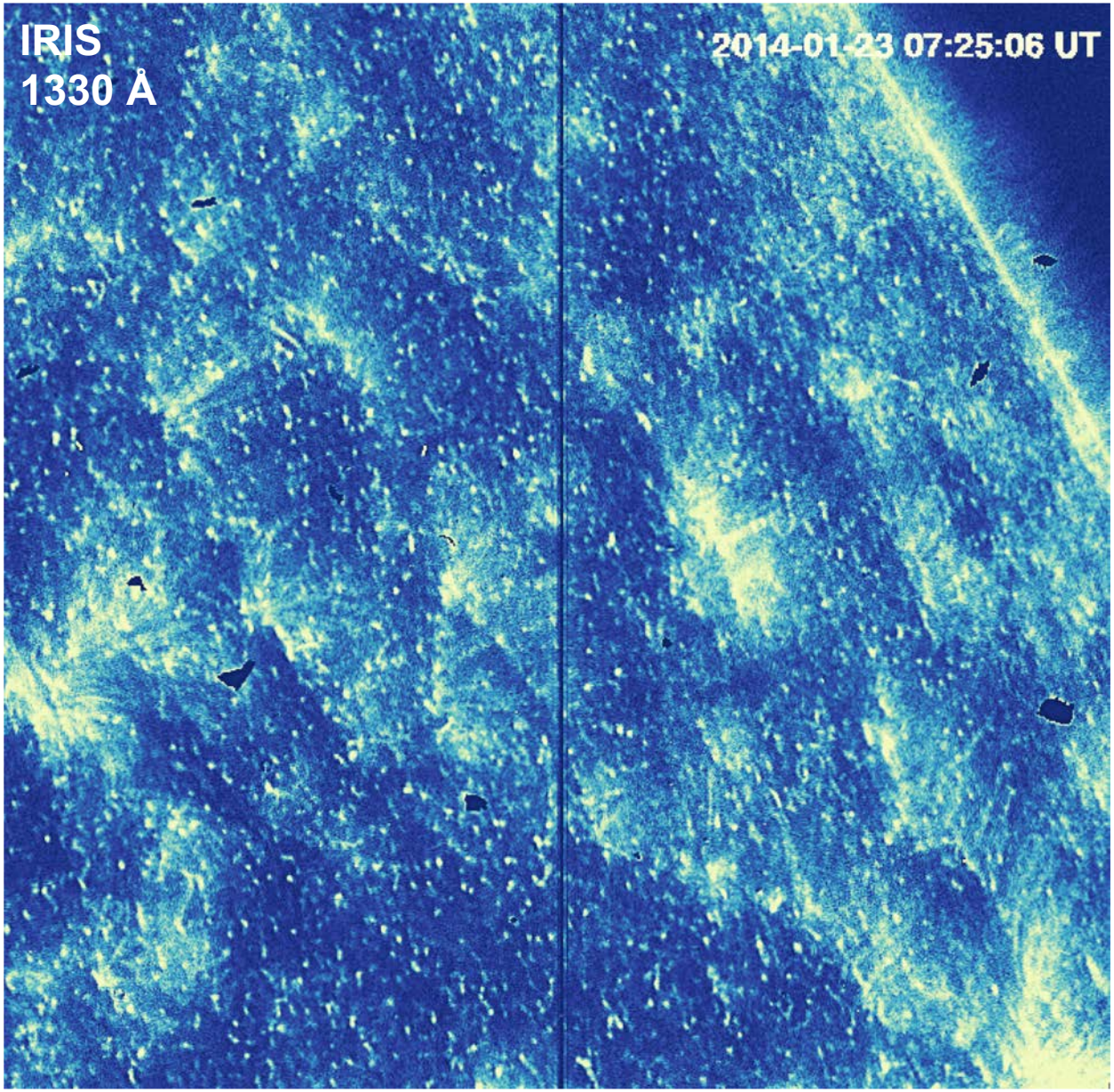


Chae et al. 1998, ApJ

- Temperature-dependent nonthermal broadening

Dammasch et al. 1999, A&A

Prevalent small-scale jets



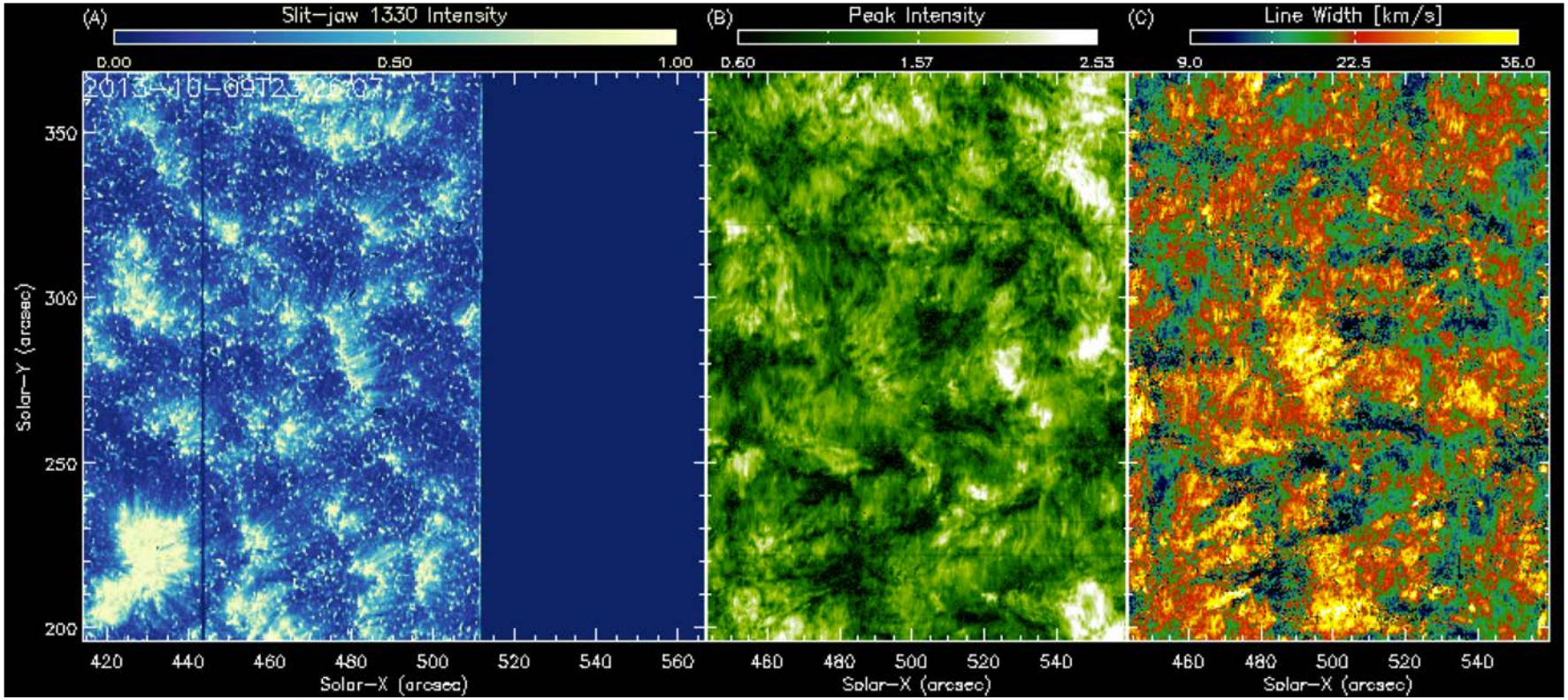
- Most prominent features in TR images

- *V*: 80-250 km/s
- *t*: <60 s
- *T*: 10^4 K - 10^5 K

- Some are likely
  - ➢ heating signatures of spicules (also see Pereira+2014, Rouppe van der Voort+2015, Narang+2016)
  - ➢ smallest jetlets (Raouafi+Stenborg 2014, Panesar+2018)

Tian, DeLuca, Cranmer, et al. 2014, Science

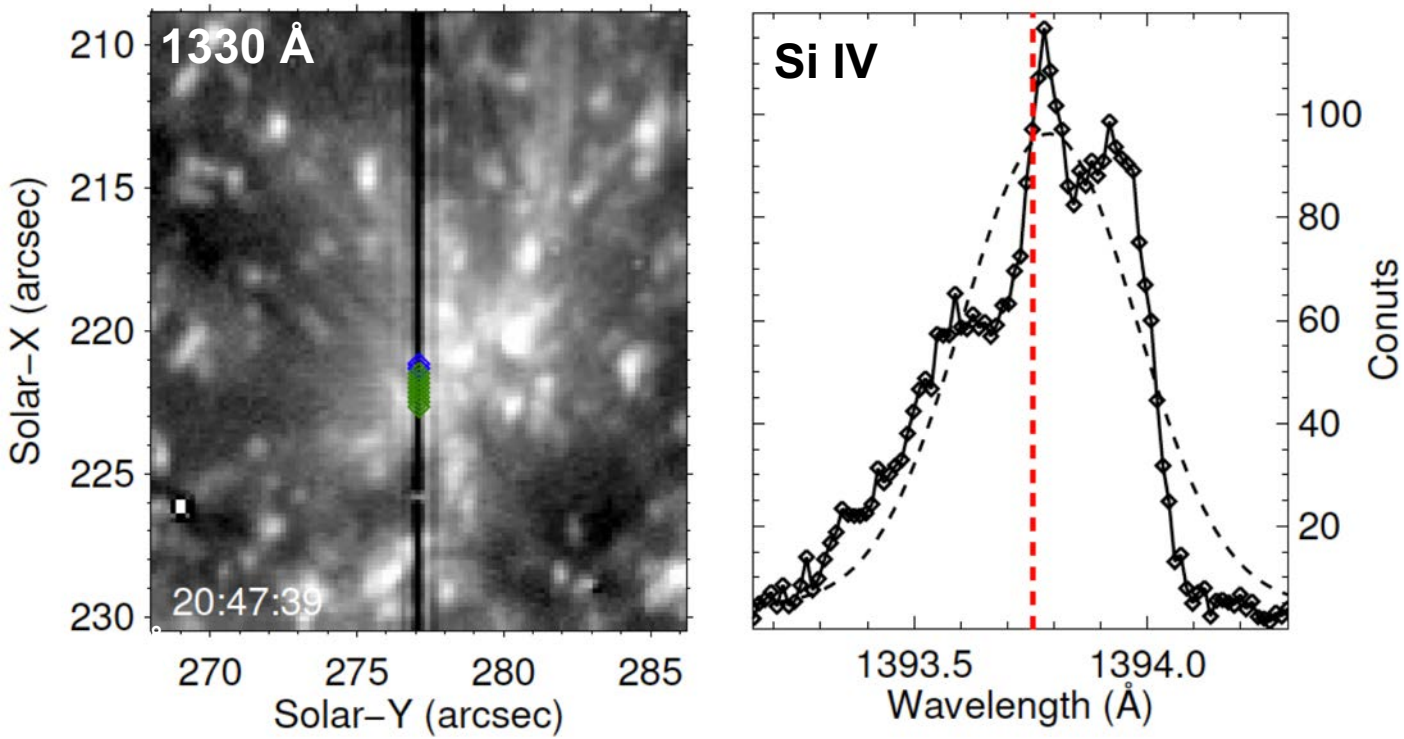
Nonthermal broadening associated with jets



- Many filamentary structures associated with the jets
- Large nonthermal widths of TR lines are associated with the jets (Tian+2014), caused by the accompanied unresolved transverse motions/waves or superposition of jets on background emission

Generation mechanism of these TR jets/spicules

Chen, Tian, Huang et al., 2019, ApJ



- Line profiles with enhanced wings or two peaks (TR EEs) at footpoints of some jets/spicules: superposition of bidirectional reconnection outflows on the background emission (Chae+1998; Chen+2019)
- Our recent observations of GST show some spicules driven by interaction of weak opposite-polarity internetwork field with the strong network field (Samanta+2019)

Heating of these TR jets/spicules to coronal temperatures?

Prevalent 0.1 MK jets imaged by IRIS (Tian et al. 2014, Science)

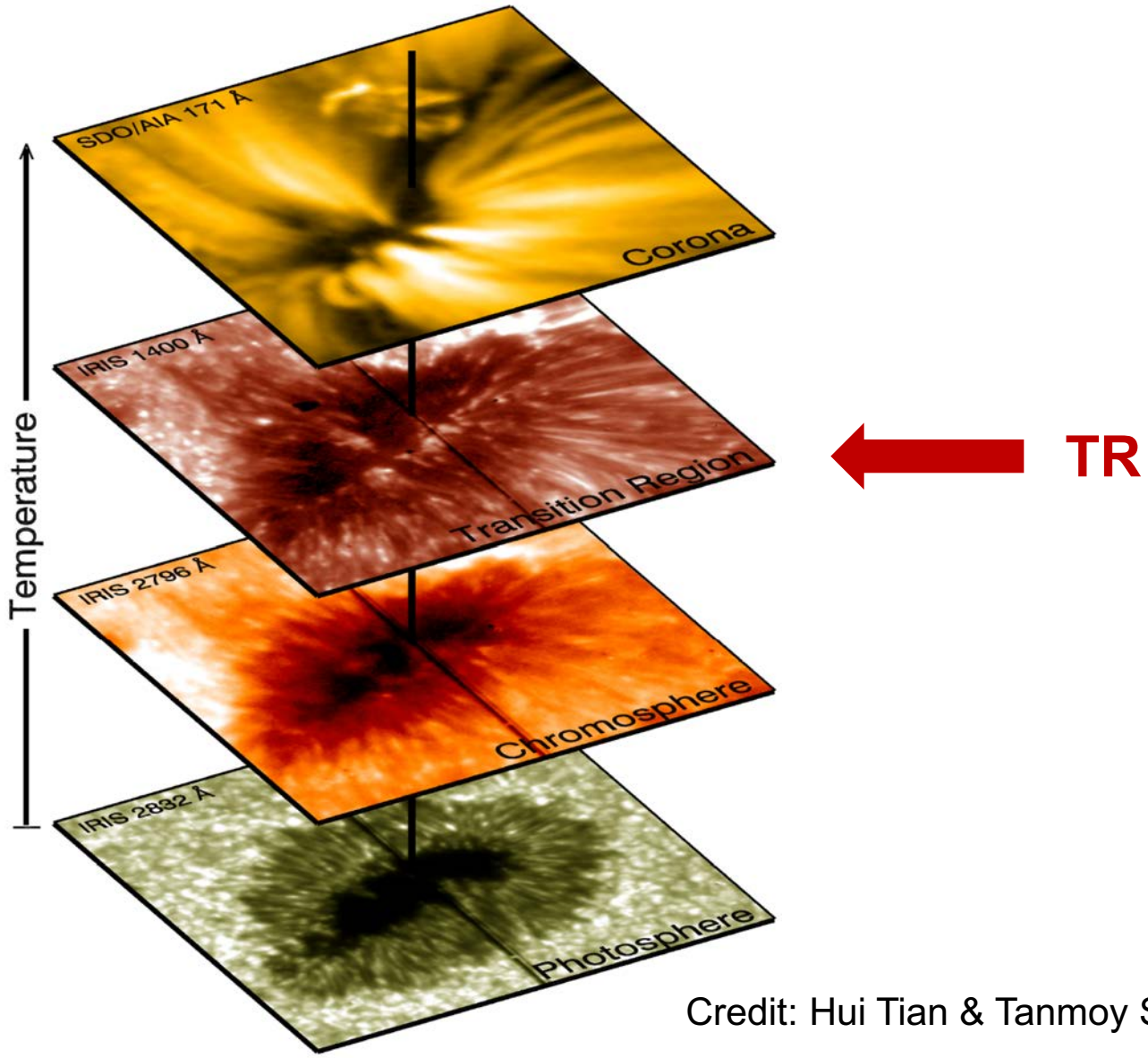
0.6 MK upflows indicated by Ne VIII blue shifts (Tian et al. 2009, ApJ)

- Some spicules can be traced to AIA EUV passbands, indicating possible heating to 10^6 K (De Pontieu+2011,Samanta+2019). But hard to exclude the possibility of TR contamination (Madjarska+2011).
- Are the Ne VIII blue shifts at network junctions caused by further heating of the prevalent TR network jets/spicules?

Outline

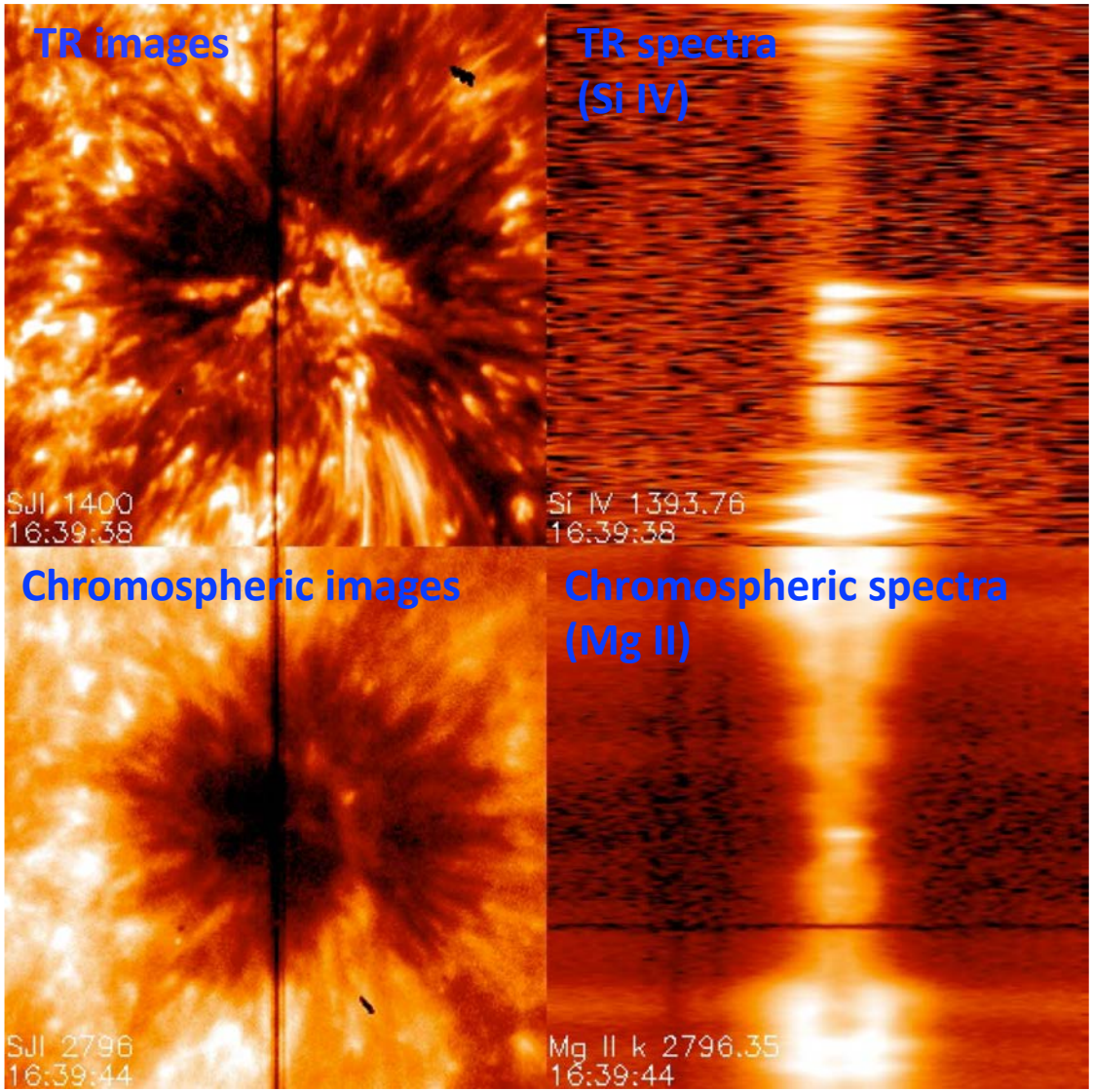
- Coronal upflows at AR boundaries
- CME-induced coronal dimmings
- Persistent coronal oscillations
- Quiet-Sun TR
- TR above sunspots

TR above sunspots



Credit: Hui Tian & Tanmoy Samanta

Sunspot oscillations in Chromosphere and TR



Slit/Solar-Y

Slit/Solar-Y

Solar-X

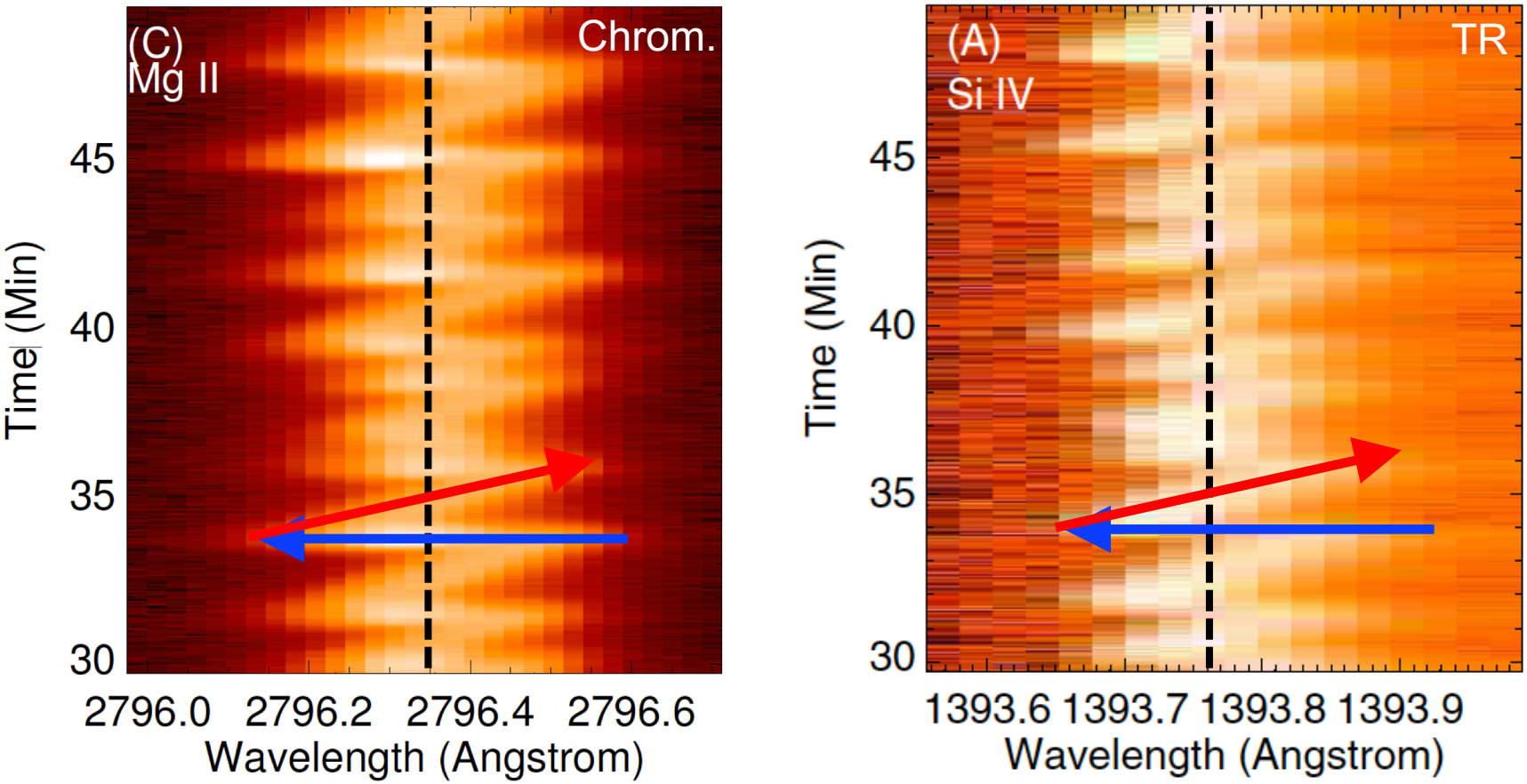
Blue ← Wavelength → Red

- TR (~10^5 K)
- Chromosphere (~10^4 K)

Tian, DeLuca, Reeves, et al. 2014, ApJ

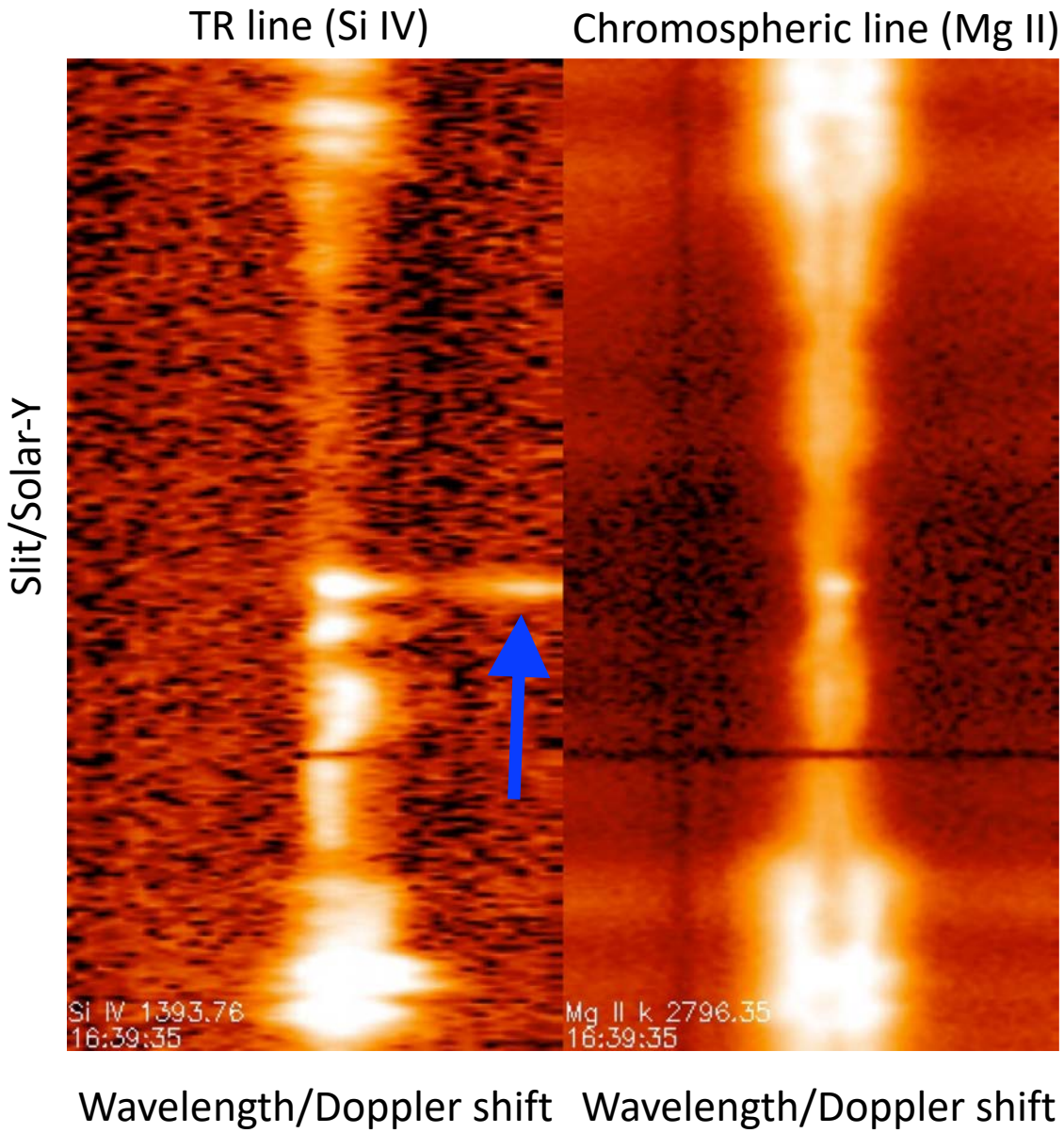
Also see
Madsen et al. 2015, ApJ
Yurchyshyn et al. 2015, ApJ
Ruan et al. 2018, ApJ

Shock wave nature of the oscillations



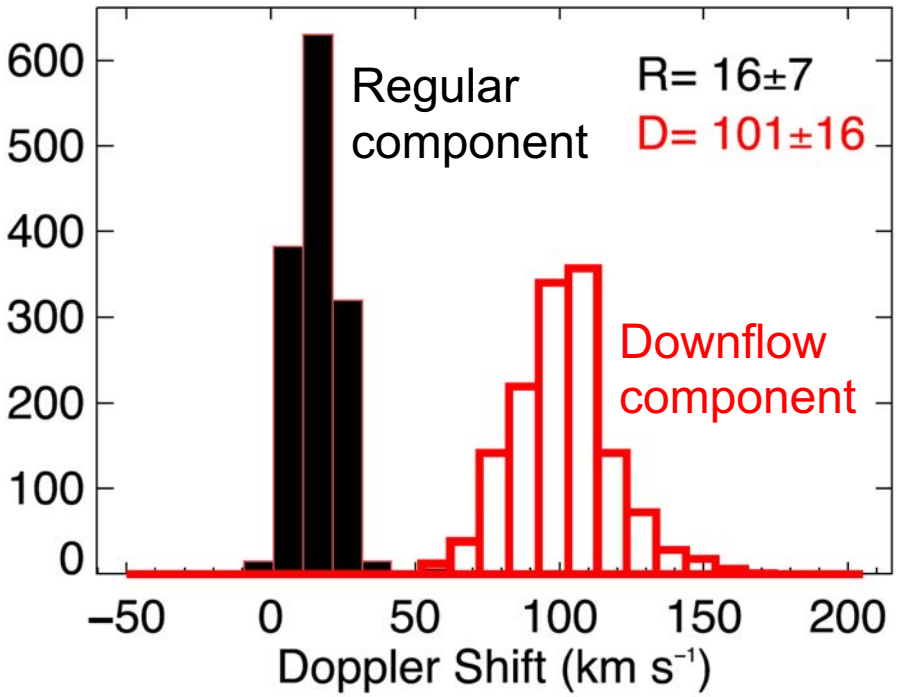
- MA waves generated by convective flows and global p-mode oscillations leak upward, steepen, and form shocks in the chromosphere and TR.
- A plasma parcel passing through a shock experience a sudden impulse ascending motion, followed by a gradual and constant deceleration.
- The Si IV oscillation lags that of Mg II by ~12 s: upward propagation.

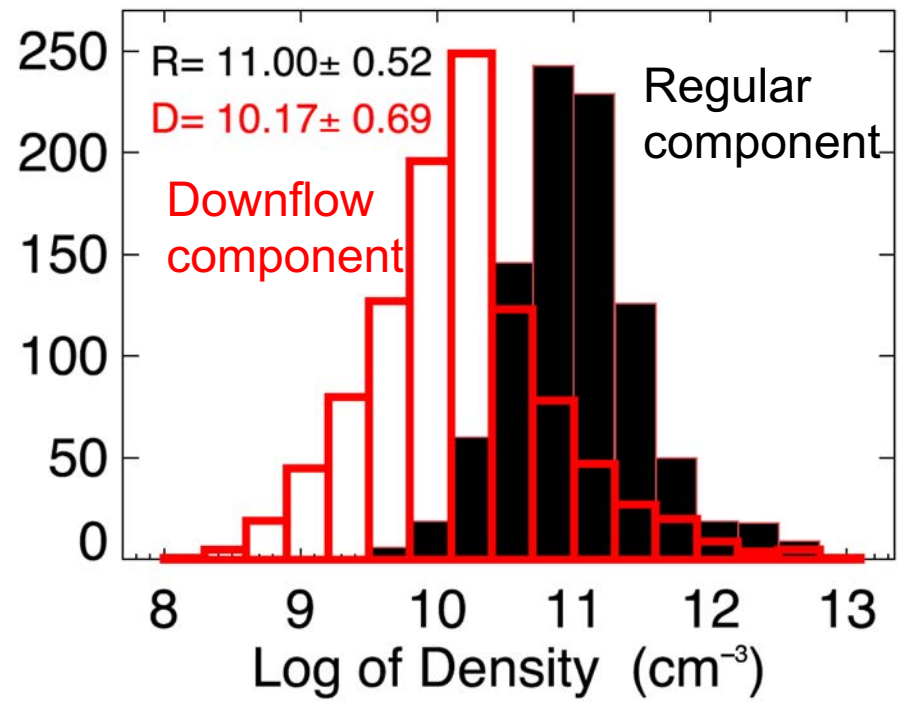
Persistent supersonic downflows to sunspots



- Two components in TR lines (e.g., Brynildsen+2001)
- No obvious oscillation
- IRIS observations allow for a statistical study of these downflows for the 1st time

Statistical properties of these downflows





Samanta, Tian, Choudhary, 2018, ApJ

- Identified in ~80% sunspots, with a velocity of ~100 km/s
- These downflows likely originate from the corona and are independent of the background TR plasma.
  - ✓ No oscillations
  - ✓ Downflow components are around one order of magnitude less dense than the regular components

Origin of these downflows

The mass ($m_{\rm cor}$) of plasma at coronal density $\rho_{\rm cor}$ supported by a loop of volume V is $m_{\rm cor} = \rho_{\rm cor} V$. Here $V = LA_{\rm cor}$, where L is the total length of the loop and $A_{\rm cor}$ is its cross-sectional area in the corona. The rate of mass loss ($\dot{m}_{\rm TR}$) from the loop at its base in the TR due to a downflow with speed v and density $\rho_{\rm TR}$ through a surface of cross-sectional area $A_{\rm TR}$ is $\dot{m}_{\rm TR} = v\rho_{\rm TR}A_{\rm TR}$. Then the timescale τ to completely drain the plasma from the loop in the form of downflows is given by

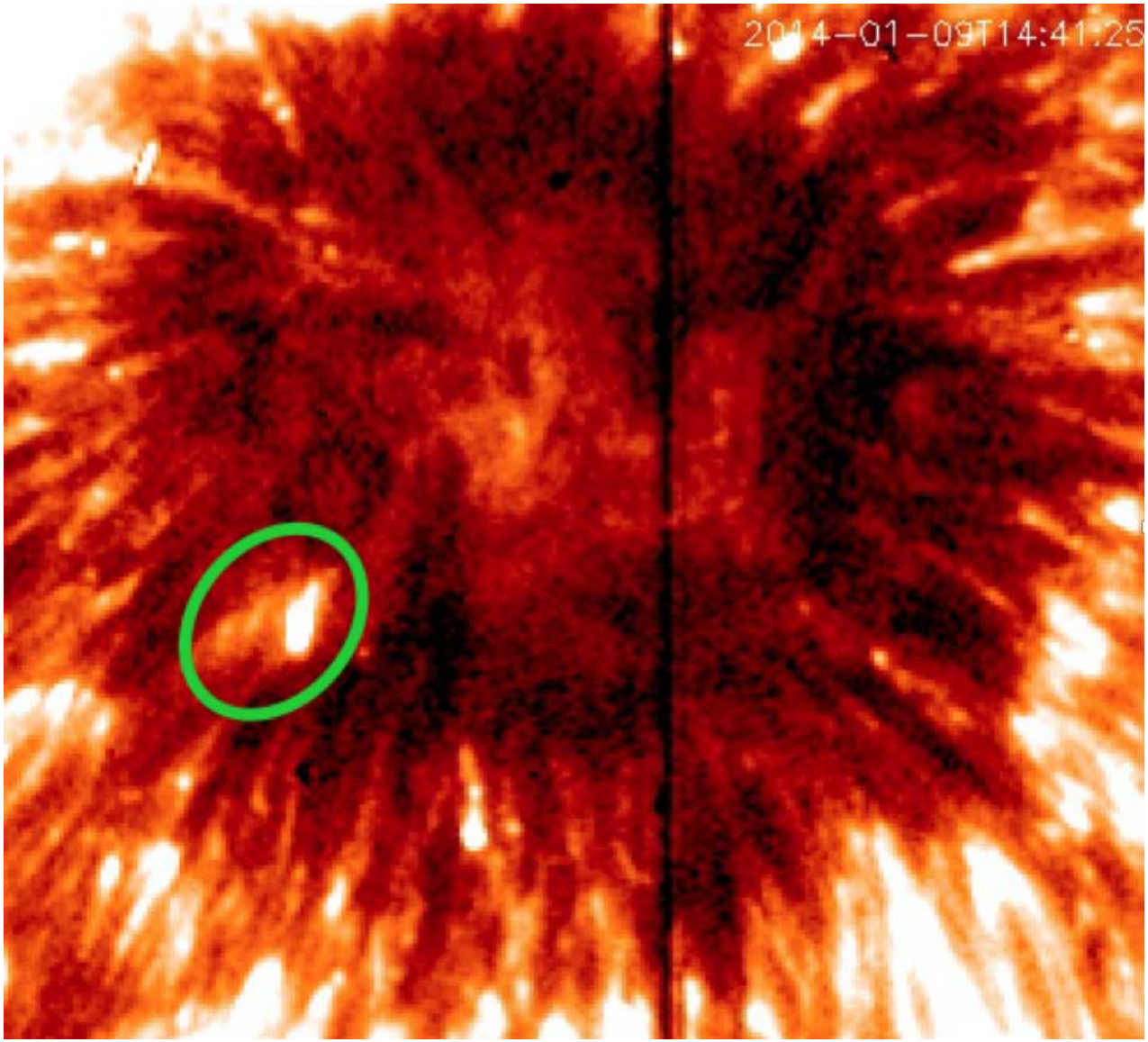
$$\begin{aligned} \tau &= m_{\rm cor}/\dot{m}_{\rm TR} \\ &= \frac{\rho_{\rm cor}}{\rho_{\rm TR}} \cdot \frac{A_{\rm cor}}{A_{\rm TR}} \cdot \frac{L}{v}. \end{aligned} \tag{2}$$

For a loop of 200–300 Mm long, hosting downflows of 100 km/s, the time it takes to drain the plasma is on the order of 100 s (Chitta+2016, Straus+2015).

Since these downflows last for hours or longer, there should be other sources of mass! Other footpoints? Prominences?

Also see Kleint et al. 2014, ApJL; Nelson et al. 2020, A&A

Penumbral bright dots in TR images



IRIS 1400 Å (~10^5 K)

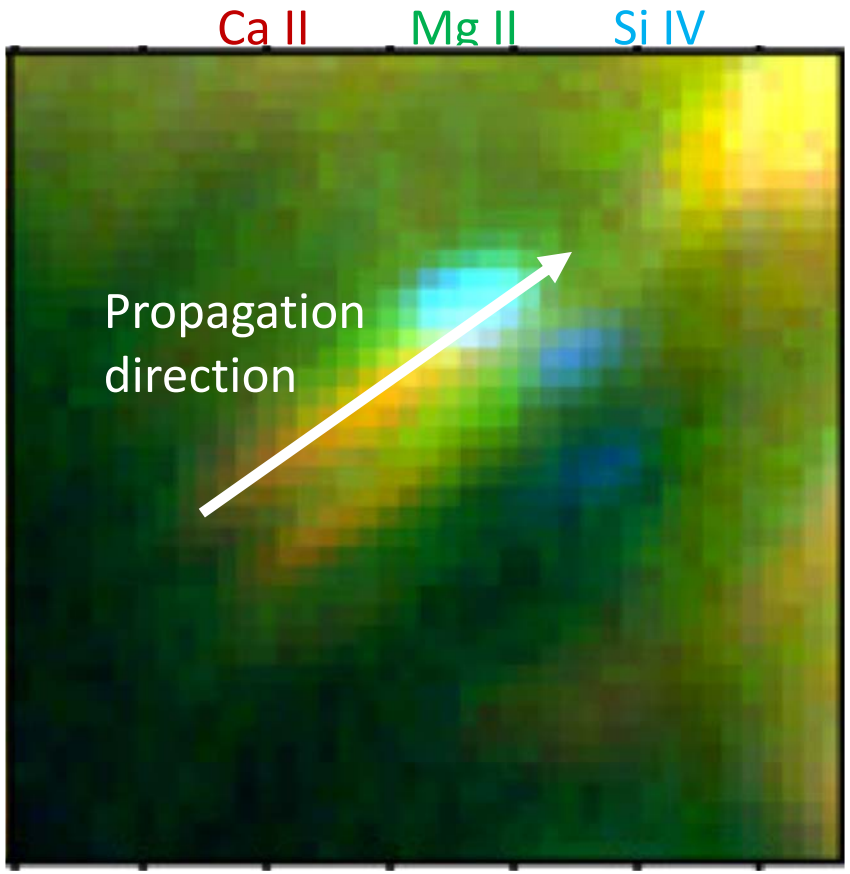
- Subarcsec transient brightenings
- Mostly <1 min
- Reach at least ~10^5 K (Si IV line emission)

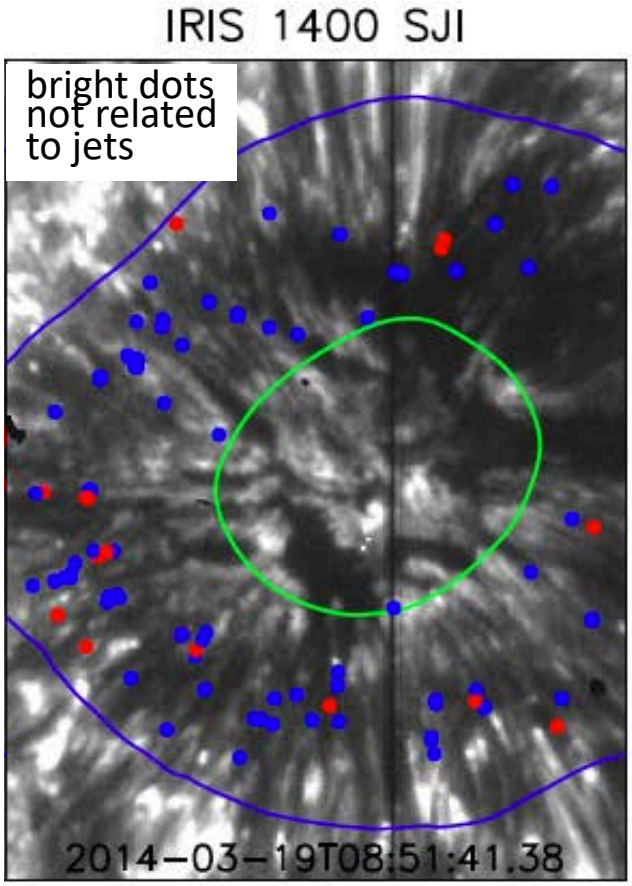
- Thermal energy same order of nanoflares

Tian, Kleint, Peter, et al. 2014, ApJL

Also see Alpert et al. 2016

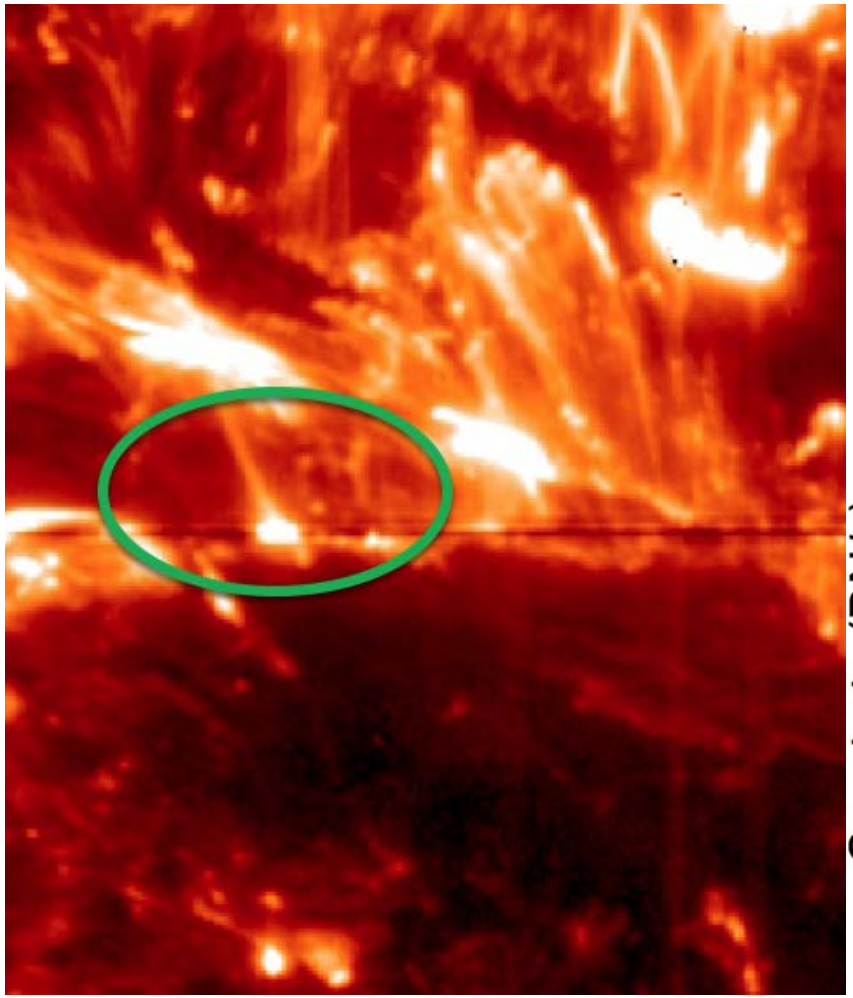
Heating of penumbral jets observed in chrom. passbands (Katsukawa+2007)?





- Heating at the front of some penumbral jets (Vissers+2015, Tiwari+2016)
- Some bright dots move inward, some are not associated with penumbral jets (Samanta+2017, Deng+2016)

Reconnection jets on LBs

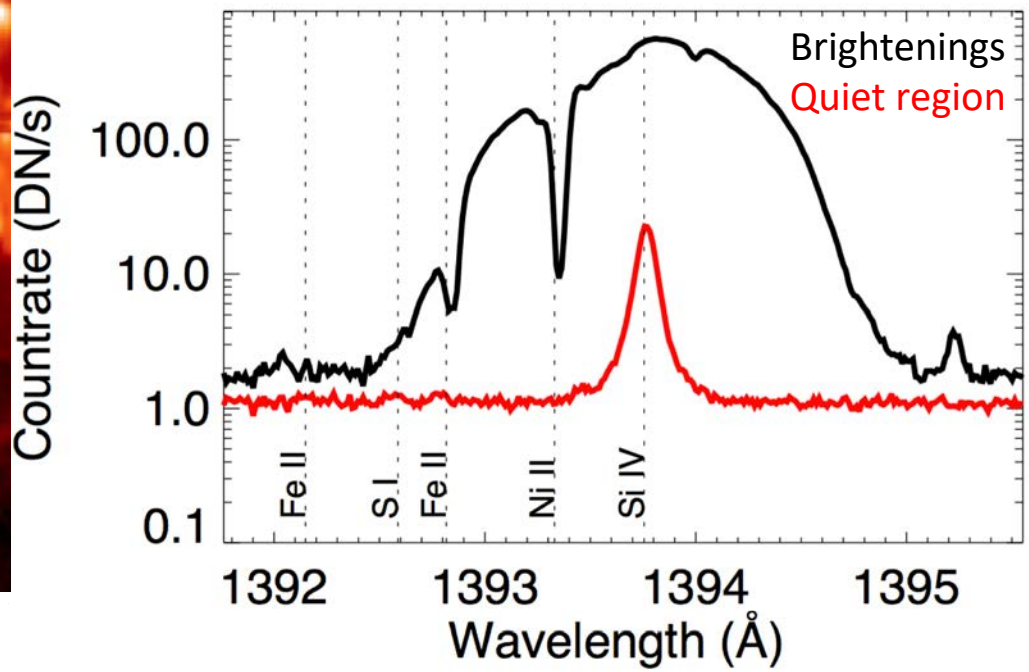


IRIS 1400 Å (~10^5 K)

Tian, Yurchyshyn, Peter, et al. 2018, ApJ

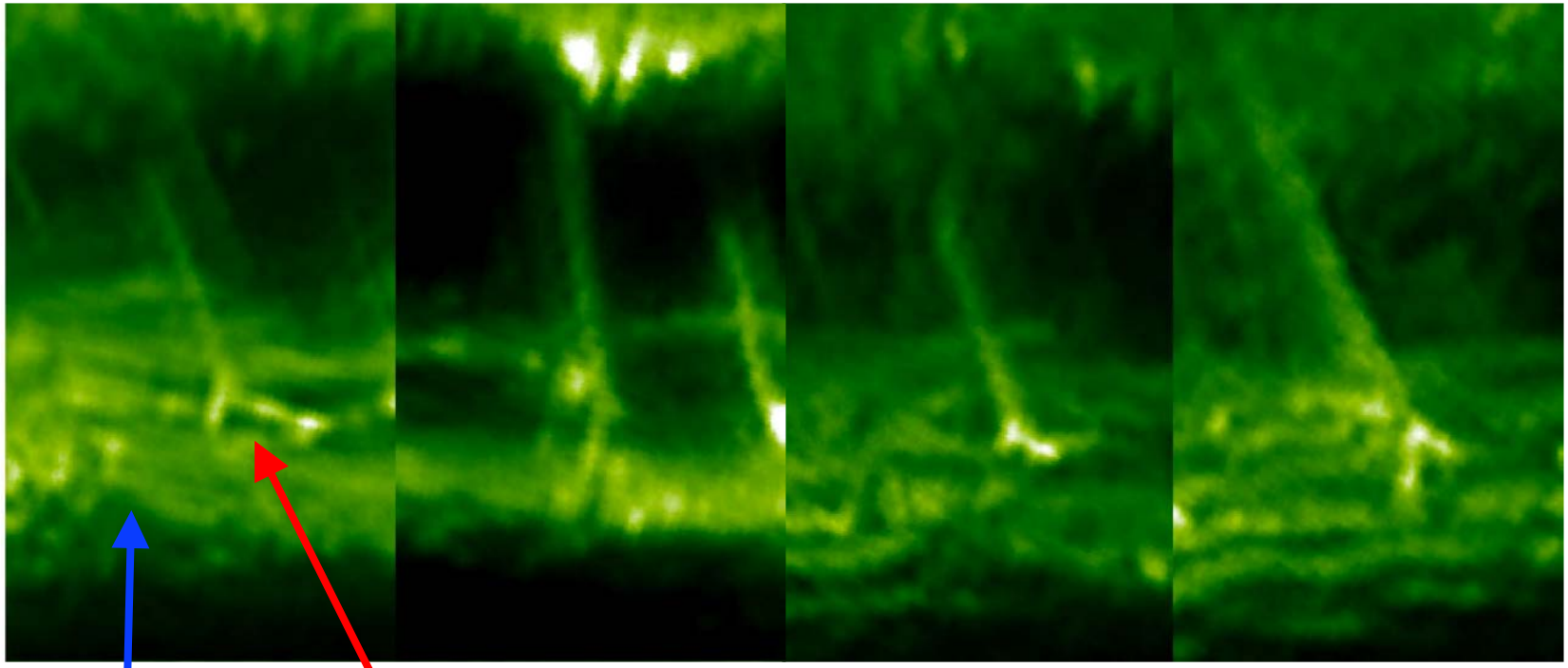
UV bursts (Peter+2014) at the footpoints of collimated jets

- Strong evidence of reconnection
- Significant heating



Similar profiles also reported by Toriumi et al. (2015) at LBs

Inverted Y-shaped structures in higher-resolution GST images



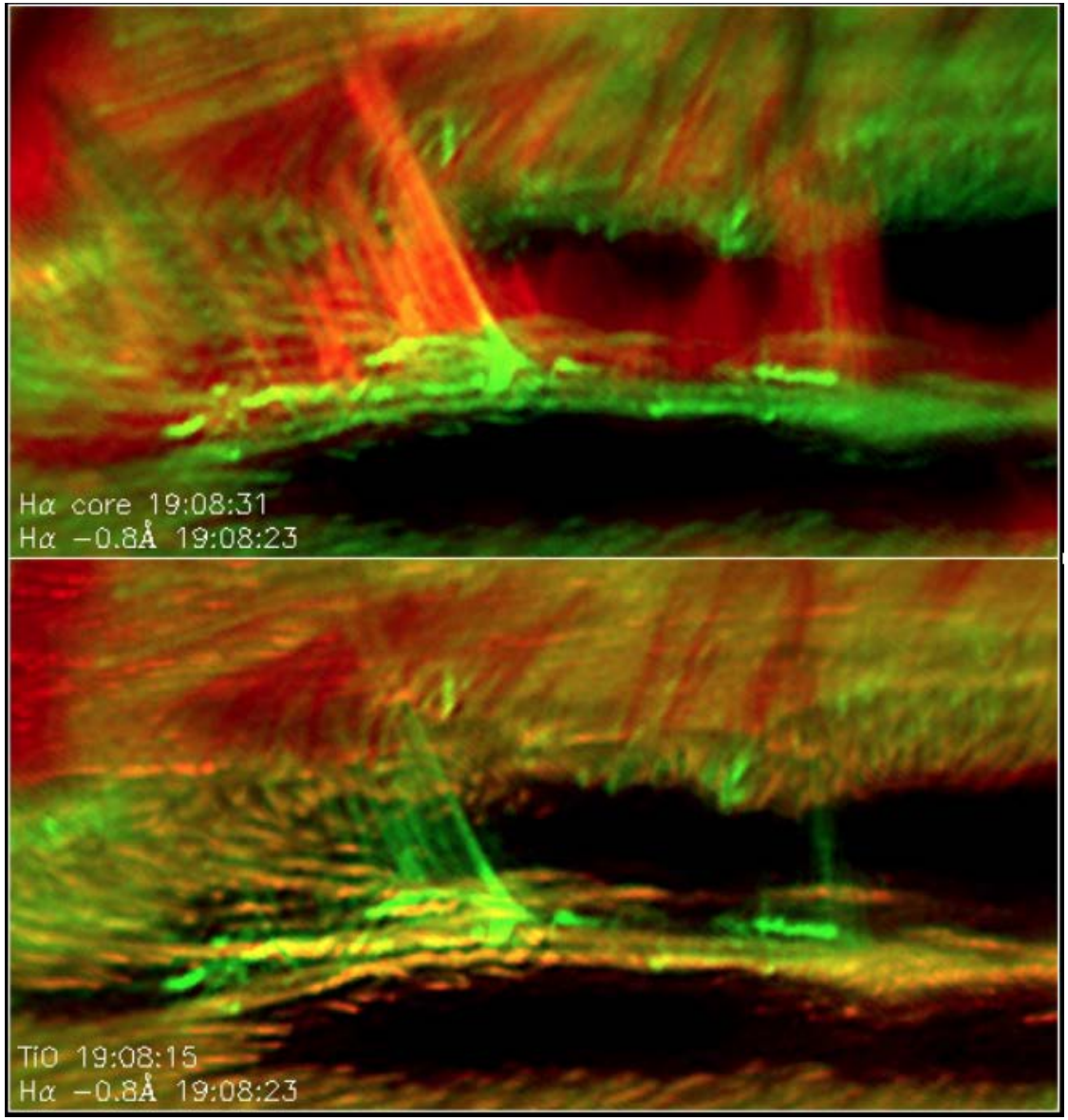
BBSO/GST Hα -0.8 Å

Light bridge

Jet

Inverted Y-shaped jets: Strong evidence of reconnection between magnetic bipoles and overlying unipolar fields (e.g., Shibata+2007)

Two types of activity on LBs



BBSO/GST

- Occasionally occurring long and fast reconnection jets
- Constant up-n-down motions along the entire LBs associated with upward propagating shock waves

Tian, Yurchyshyn, Peter, et al. 2018, ApJ
Zhang, Tian, He, Wang, 2017, ApJ

Also see Hou et al. 2017, ApJ

Summary

- Spectroscopy, especially UV and EUV spectroscopy, is an important tool to investigate the mass and energy transport processes in the upper solar atmosphere.

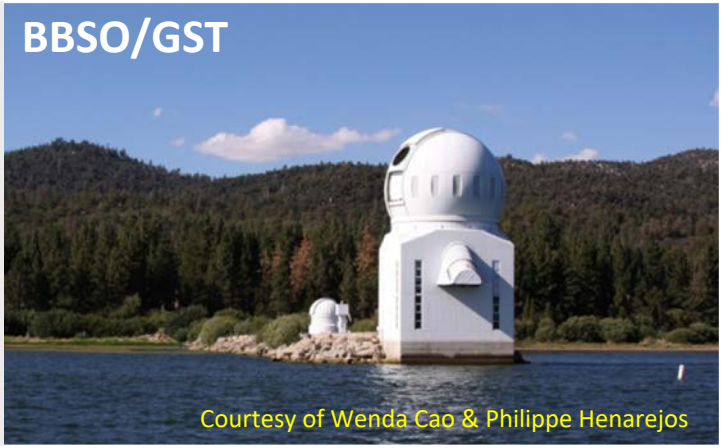
- Imaging spectroscopy could be used to produce maps of the coronal magnetic field.

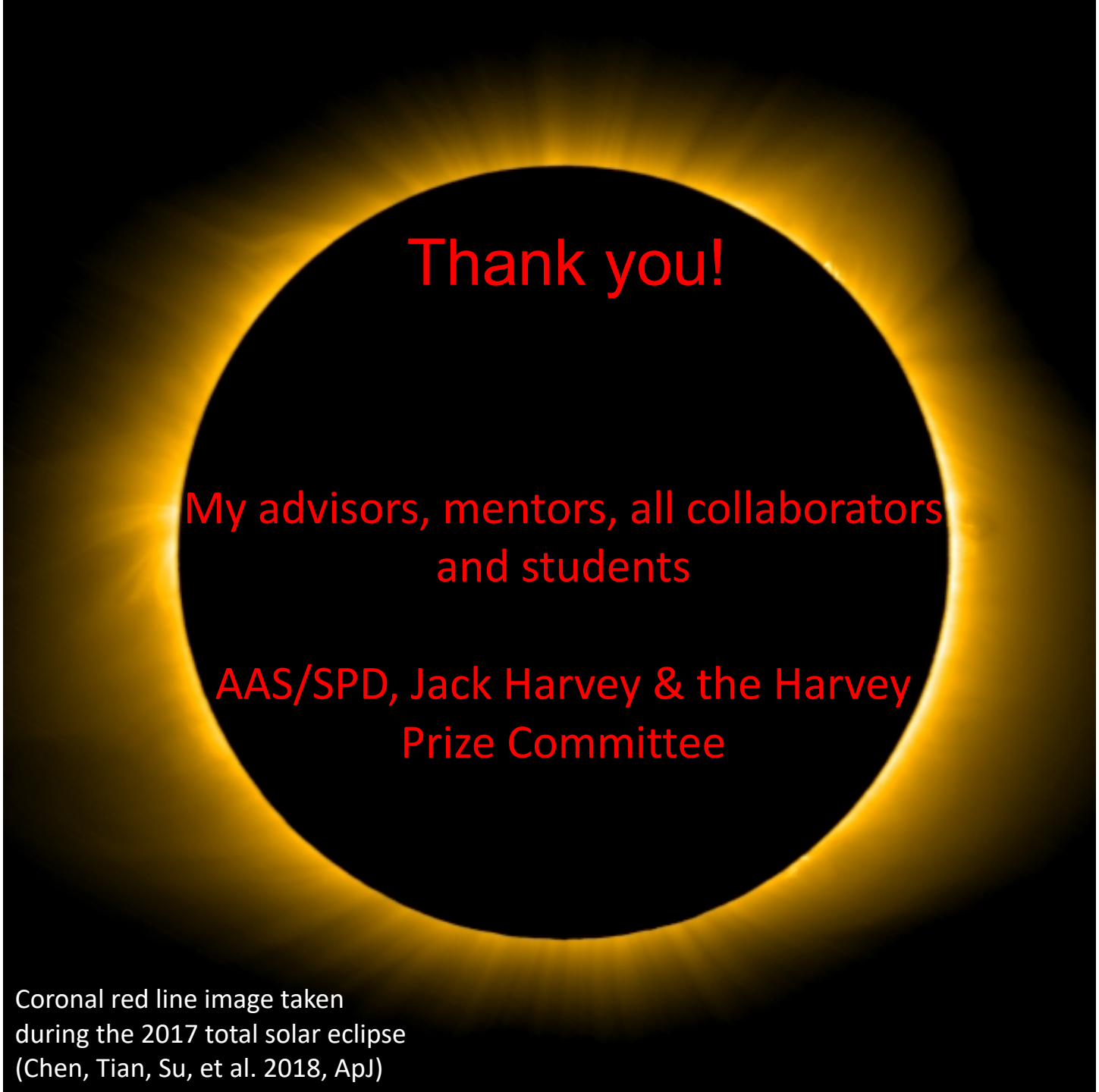
- Simultaneous imaging and spectroscopic observations are important for a complete understanding of various types of atmospheric dynamics.

Future perspectives on spectroscopy of the upper solar/stellar atmosphere

- Solar Orbiter/SPICE
  - ✓ Polar regions
  - ✓ Connect in-situ and remote-sensing measurements through FIP bias measurements
- UCoMP: global coronal spectroscopy through ground-based observations
- EUVST: sub-arcsec resolution for corona & TR
- Stellar EUV spectroscopy
  - ✓ No observations after EUVE (1992-2001)
  - ✓ Important for investigating impact of space weather on exoplanet habitability

Thank you! Wonderful instruments and groups





Thank you!

My advisors, mentors, all collaborators and students

AAS/SPD, Jack Harvey & the Harvey Prize Committee

Coronal red line image taken during the 2017 total solar eclipse (Chen, Tian, Su, et al. 2018, ApJ)