# The mass cycle between the chromosphere and the corona/solar wind

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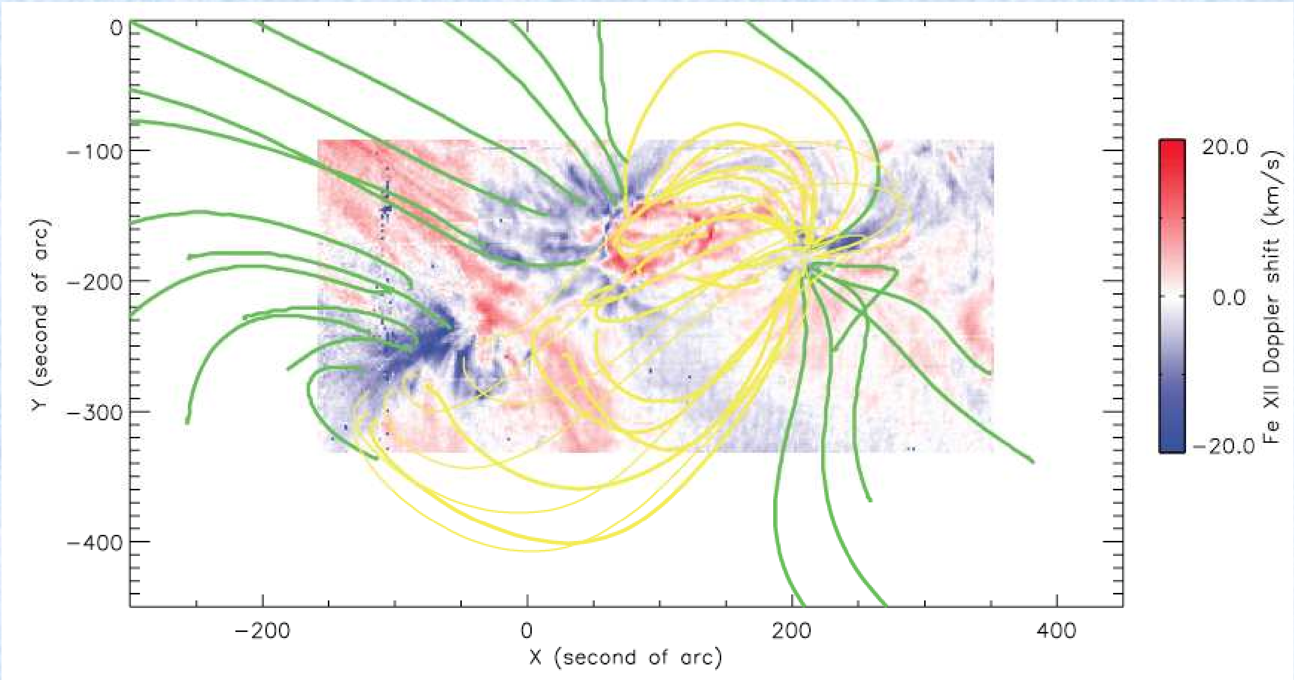
# Coronal circulation or mass cycling between the chromosphere and corona

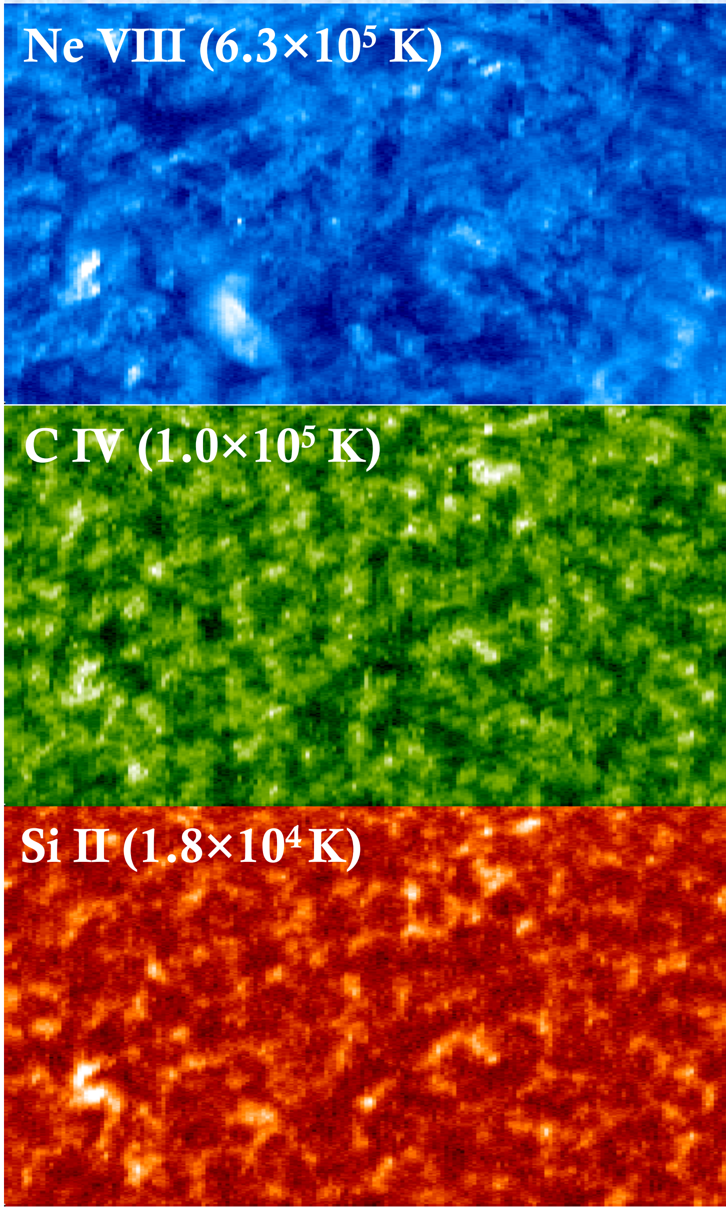



Marsch et al. 2008, ApJ, 685, 1262

▪ The plasma in the TR & corona is nowhere static but everywhere flowing, strongly guided by various magnetic channels. There is no static magnetically stratified plasma in the upper atmosphere, but rather a continuous global plasma circulation, being the natural perpetuation of photospheric convection which ultimately is the driver.

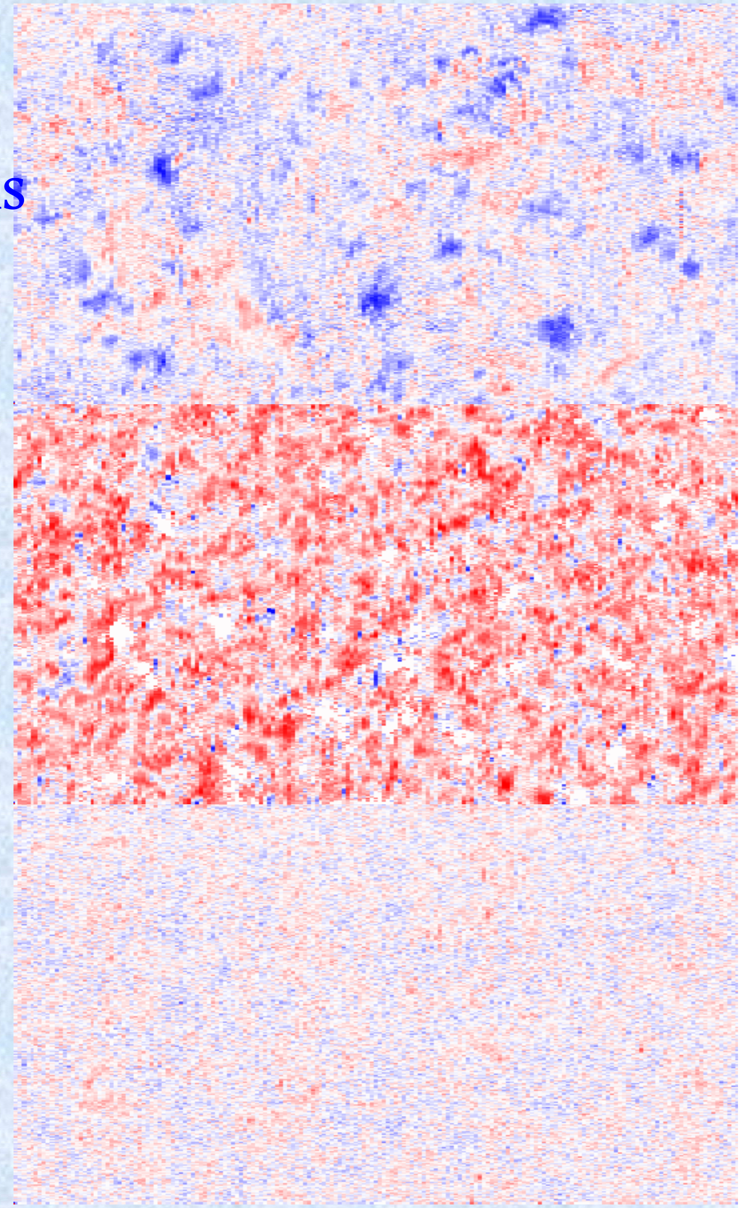
▪ Coronal circulation presumably extends to the corona's outer interface, which is assumed to be located near the so-called magnetic source surface (at 2.5-3 Rs), where the solar wind/heliospheric field actually begins.

# Plasma flows in QS

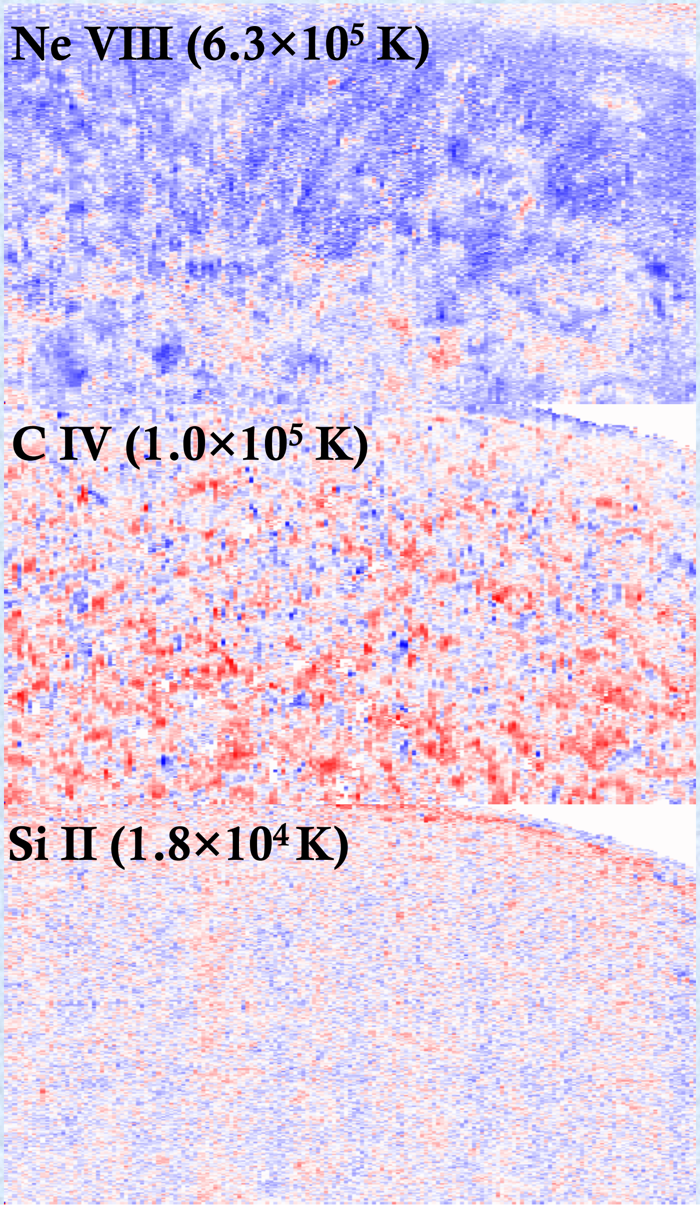



- Upper TR: blue shifts at network junctions
- Middle TR: red shift
- Lower TR: small shift

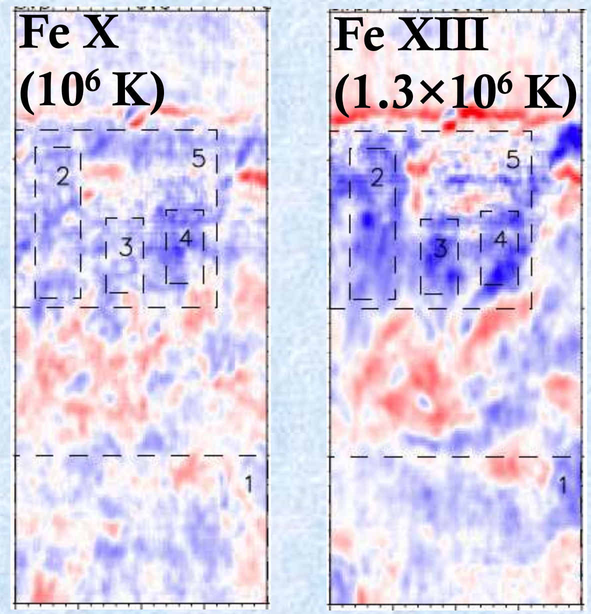
Dammasch et al. 1999, A&A, 346, 285
Hassler et al. 1999, Science, 283, 810



# Plasma flows in CH




- Upper TR: ubiquitous blue shifts (~5 km/s) interpreted as solar wind origin
- Middle TR: red shift
- Lower TR: small shift

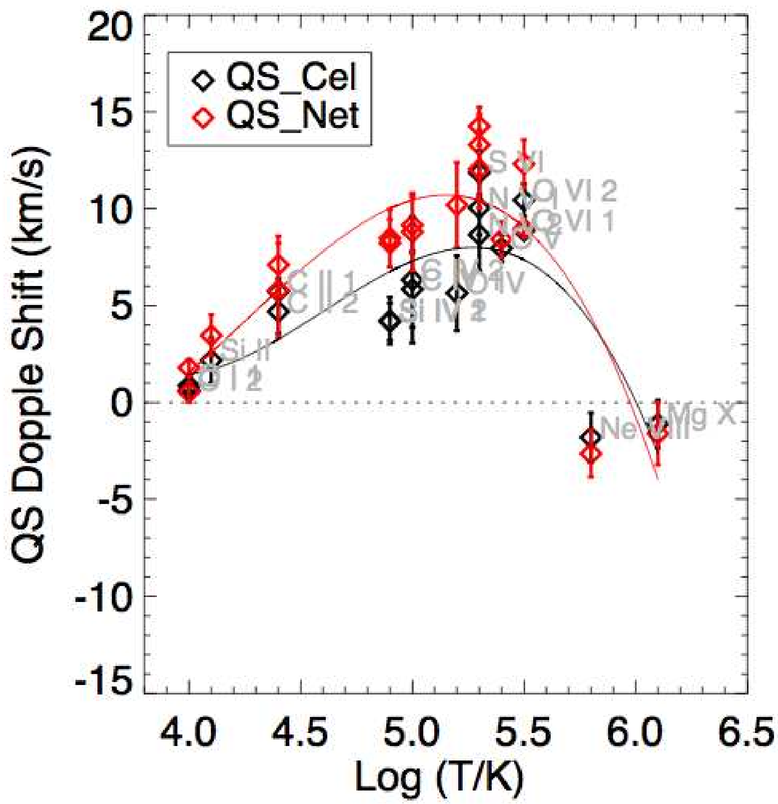


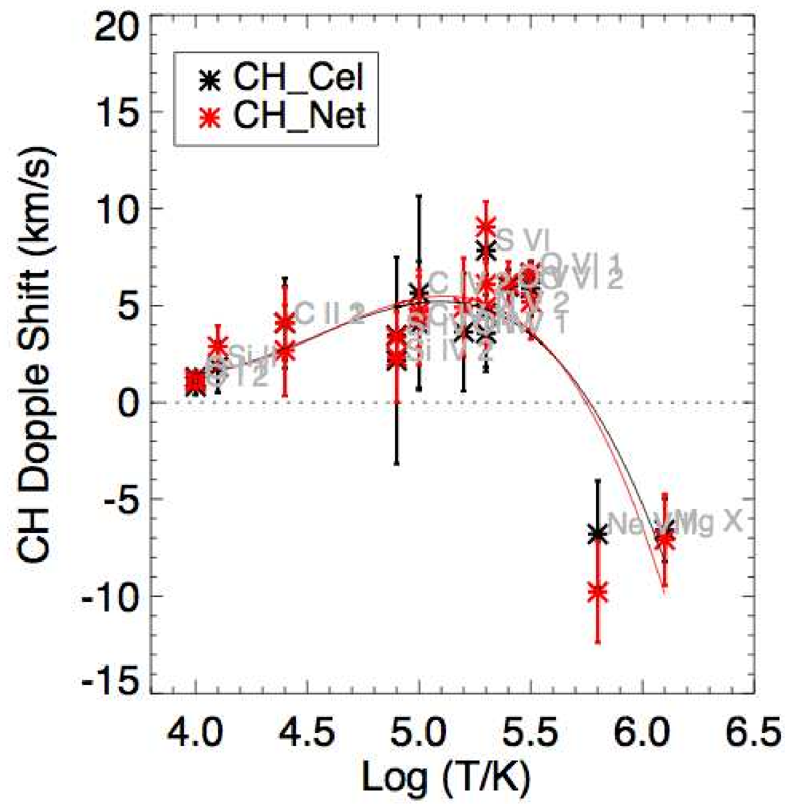

Tian et al. 2010, ApJ, 709, L88

- Corona: blue shift of 10-30 km/s, initial acceleration

Dammasch et al. 1999, A&A, 346, 285
Hassler et al. 1999, Science, 283, 810
Wilhelm et al. 2000, A&A, 353, 749
Aiouaz et al. 2005, A&A, 435, 713

# Temperature dependence of Doppler shift

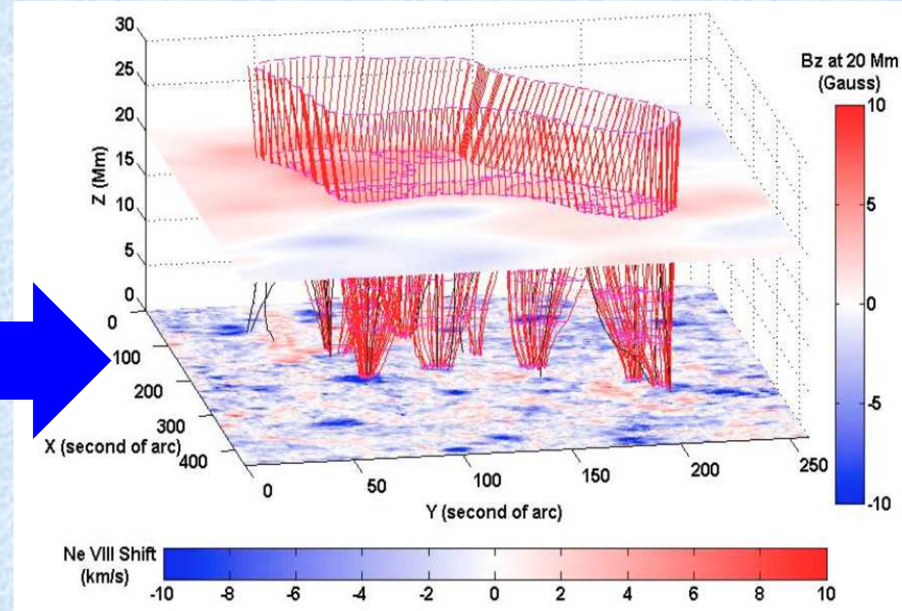


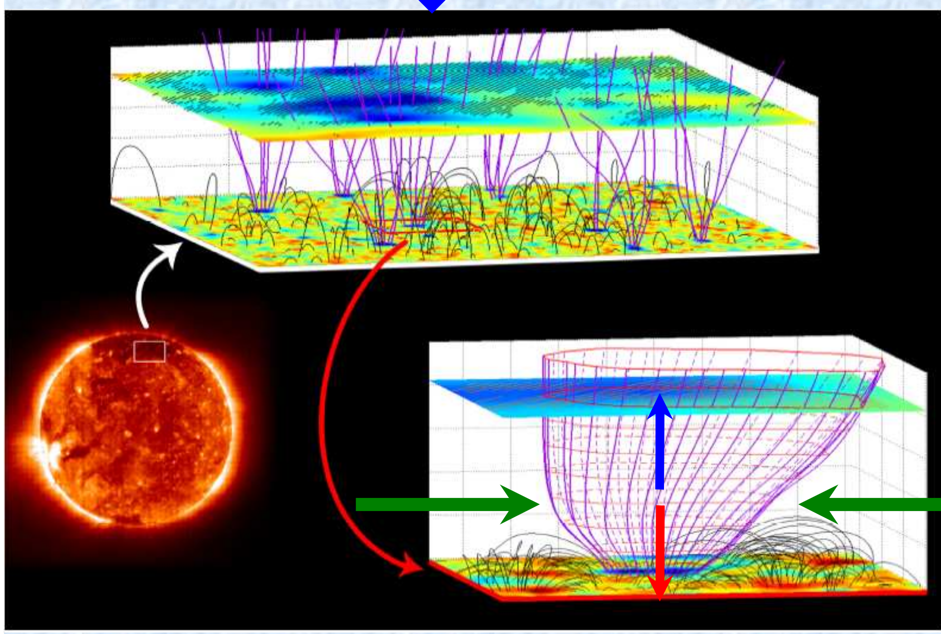


Wang et al. 2012, in preparation
Tian et al. 2010, ApJ, 709, L88
Xia et al. 2004, A&A, 424, 1025
Peter & Judge 1999, ApJ, 522, 1148
Dadashi et al. 2011, A&A, 534, A90
Teriaca et al. 1999, A&A, 349, 636
Brekke et al. 1997, Sol. Phys. 175, 349

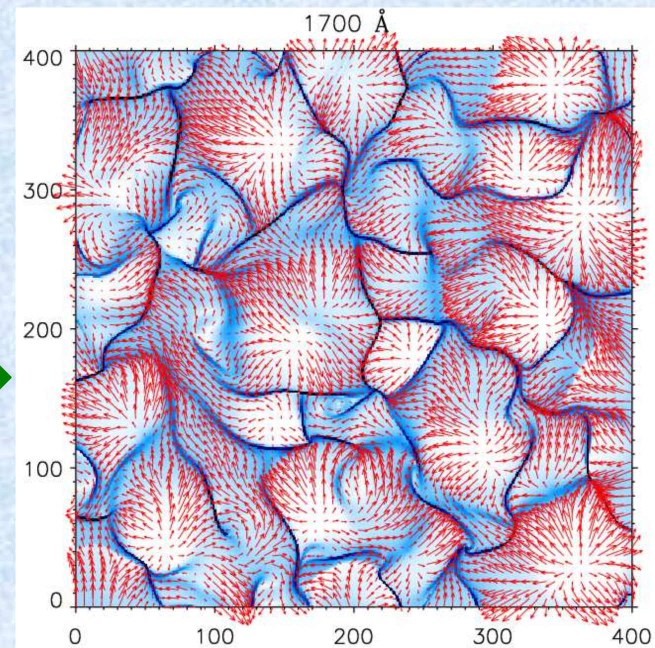
# Understanding solar wind mass supply and acceleration




Tian et al., A&A, 478, 915, 2008



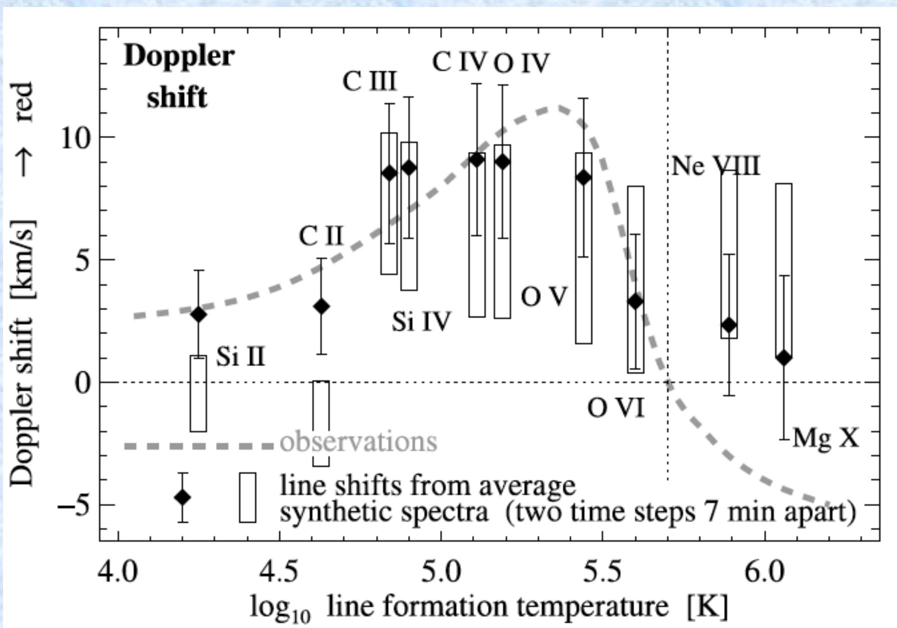
Tu et al. 2005, Science, 308, 519
Tu et al. 2005, Solar Wind 11



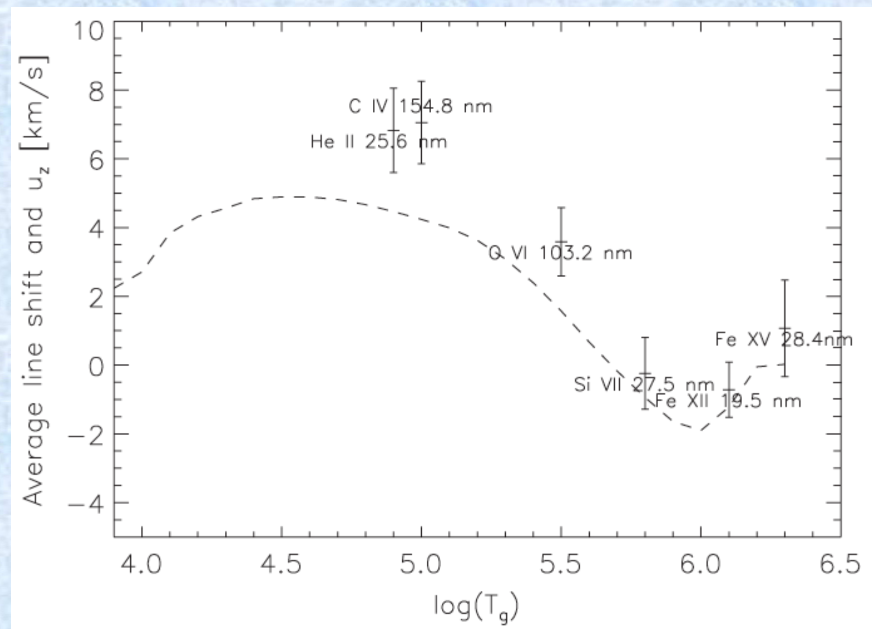

Tian et al., A&A, 519, A58, 2010

# Solving the coronal heating problem

- Braiding of magnetic field lines in the magnetically closed corona can produce the observed temperature dependence of TR Doppler shift
- Rapid episodic heating of the upper chromospheric plasma to coronal temperatures naturally produces downflows in TR lines, and slight upflows in coronal lines



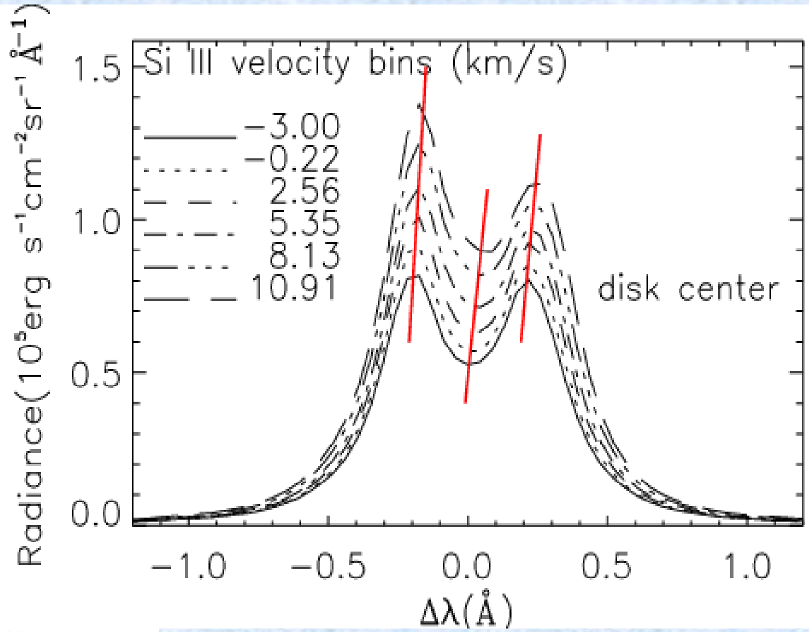

Peter et al. 2006, ApJ, 638,1086

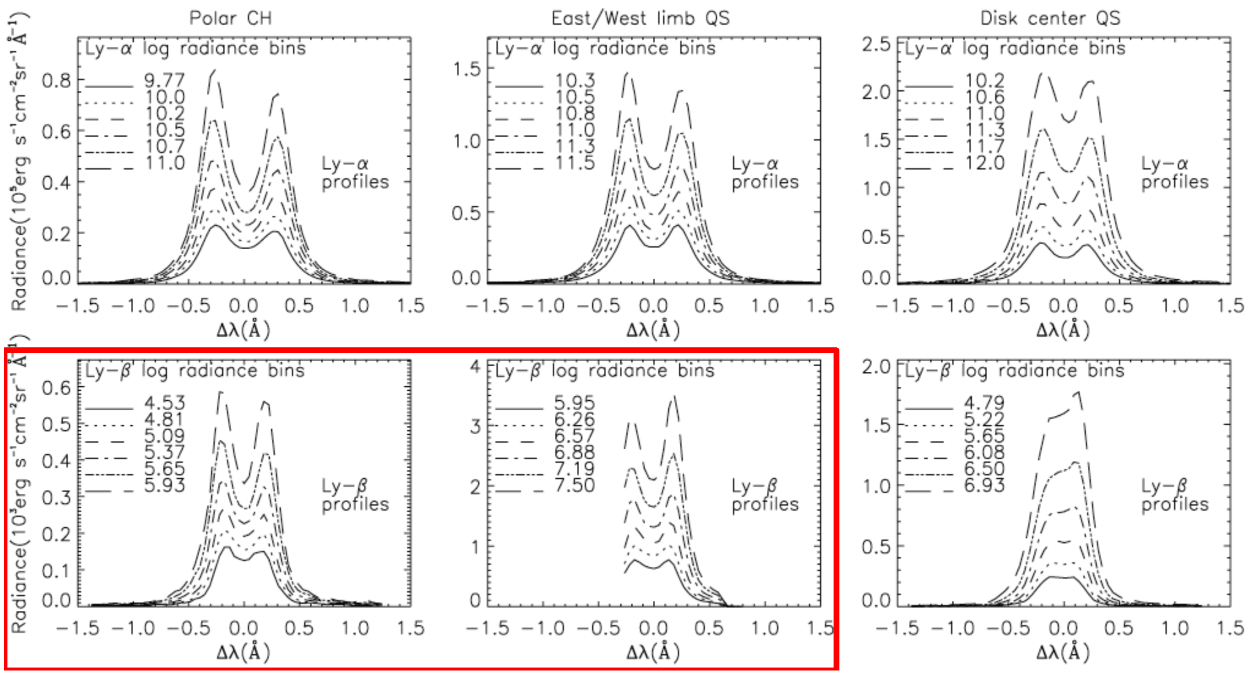



Hansteen et al. 2010, ApJ 718, 1070

# Improving solar atmosphere models

- Lyman line profile asymmetry closely related to TR and coronal flows:
  - Lyα asymmetry: more prominent as TR redshift increases
  - Lyβ asymmetry: reverse in CH, related to solar wind outflow?
- Conversion from Lyman line polarization to *B* depends on atmosphere models, which usually produce symmetric Ly line profiles. They can be improved by taking into account flows in the TR and corona.



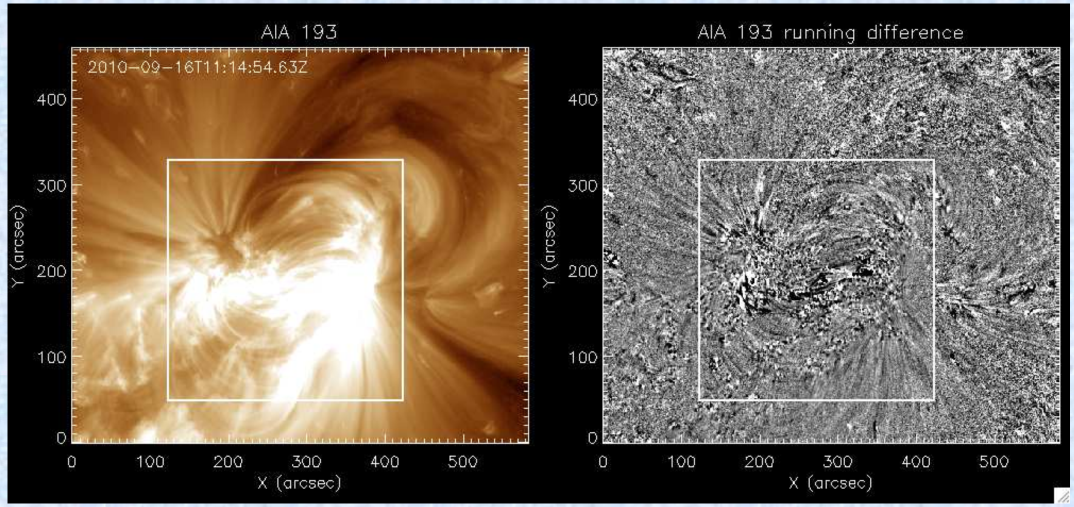



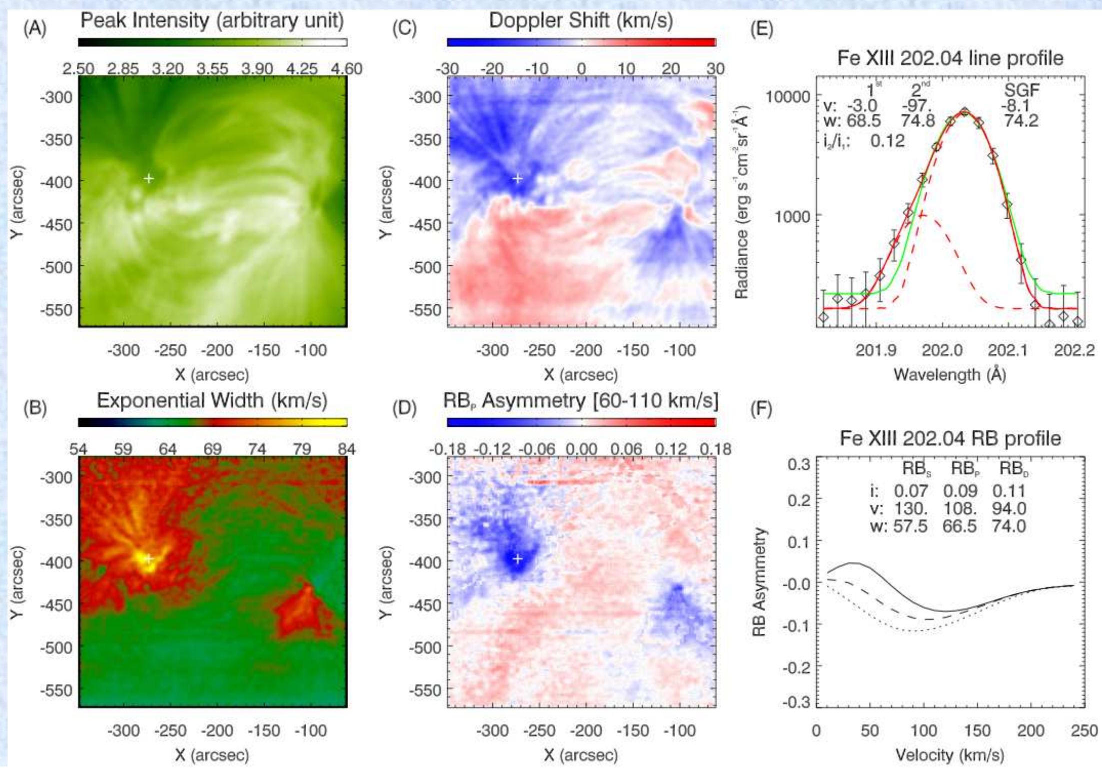

Curdt et al. 2008, A&A, 492, L9
Tian et al. 2009, A&A, 504, 239

Tian et al. 2009, ApJ, 703, L152

# High-speed upflows at AR edges

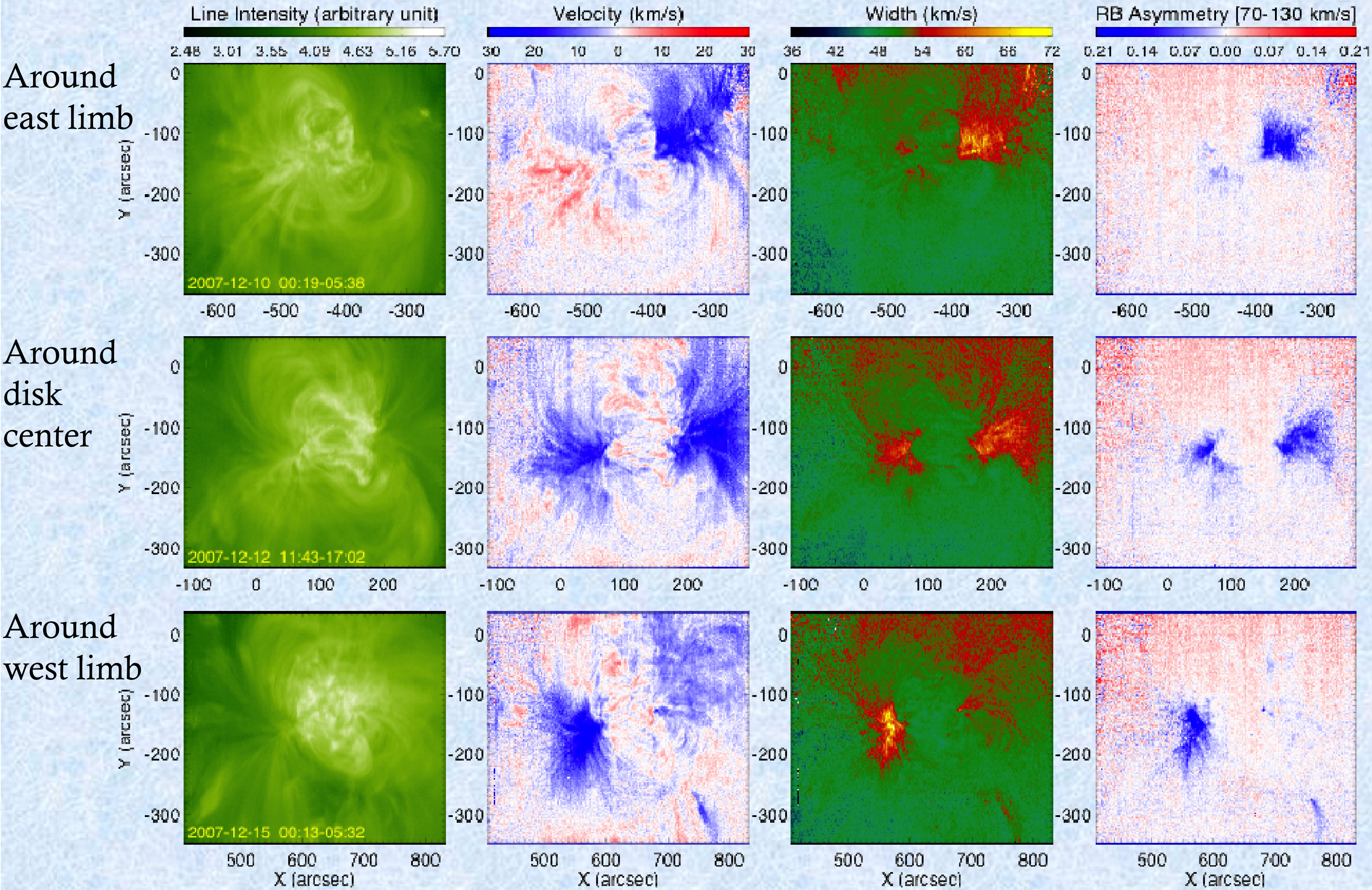
- PDs in EUV & X-Ray images: upflow speed ~100 km/s
- EUV spectroscopy:
  - ➢Blue shift of coronal lines: not the complete story
  - ➢Enhanced blue wing in line profiles: an almost stationary primary component and a weak high-speed secondary component
  - ➢RB analysis and DGF




Tian et al. 2011, ApJ, 738, 18
Dolla & Zhukov 2011, ApJ, 730, 113
Bryans et al. 2010, ApJ, 715, 1012
Peter 2010, A&A, 521, A51
McIntosh & De Pontieu 2009, ApJ, 706, L80
De Pontieu et al. 2009, ApJ, 701, L1
Hara et al. 2008, ApJ, 678, L67

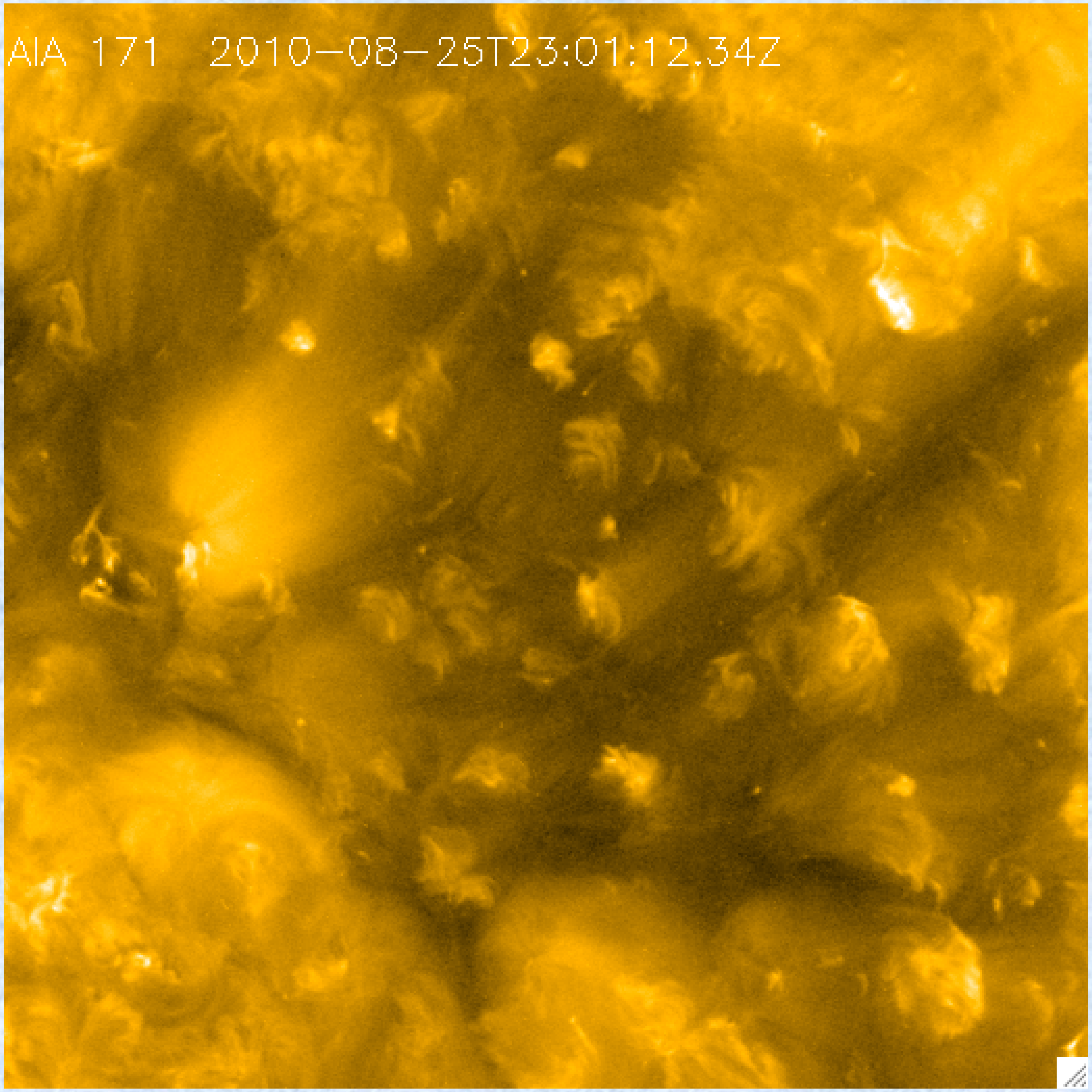
# Profile asymmetry not caused by noise or blend




Tian et al. 2012, ApJ, 748, 106

# Ubiquitous high-speed outflows in CHs

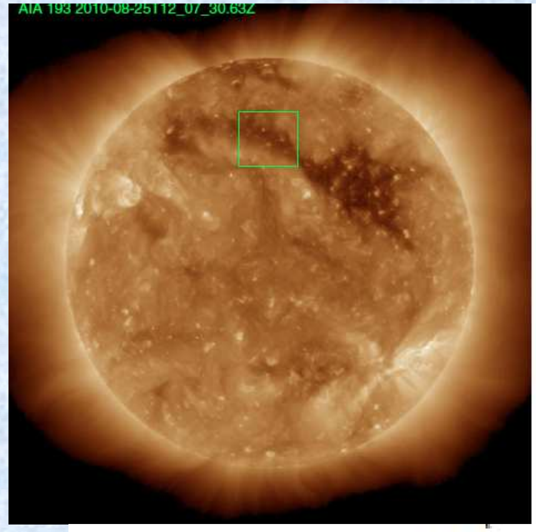
- AIA observations reveal unprecedented details inside CHs
- Plumes, PDs and Alfven waves are present in CHs
- Mass flux density: $1.67\mathrm{X}10^{-9}$ g cm$^{-2}$ s$^{-1}$ if using $\log(Ne/\mathrm{cm}^{-3})=8$ and $v=100$ km s$^{-1}$, mass flux two orders higher than that of solar wind
- Energy flux of coronal Alfvén wave ($f\rho<v^2>v_A$) is a significant portion of or comparable to that needed to power the solar wind (100 W m$^{-2}$)

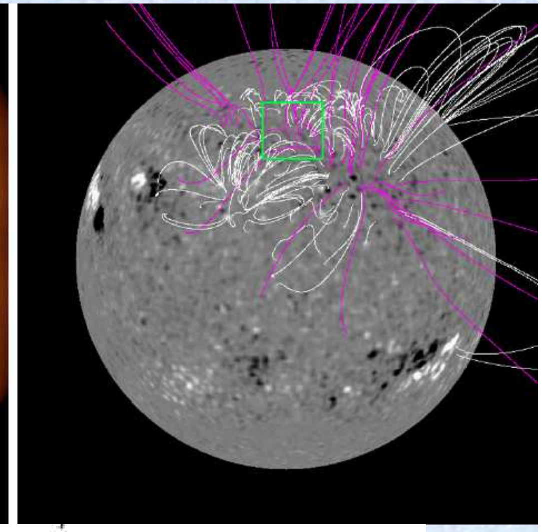


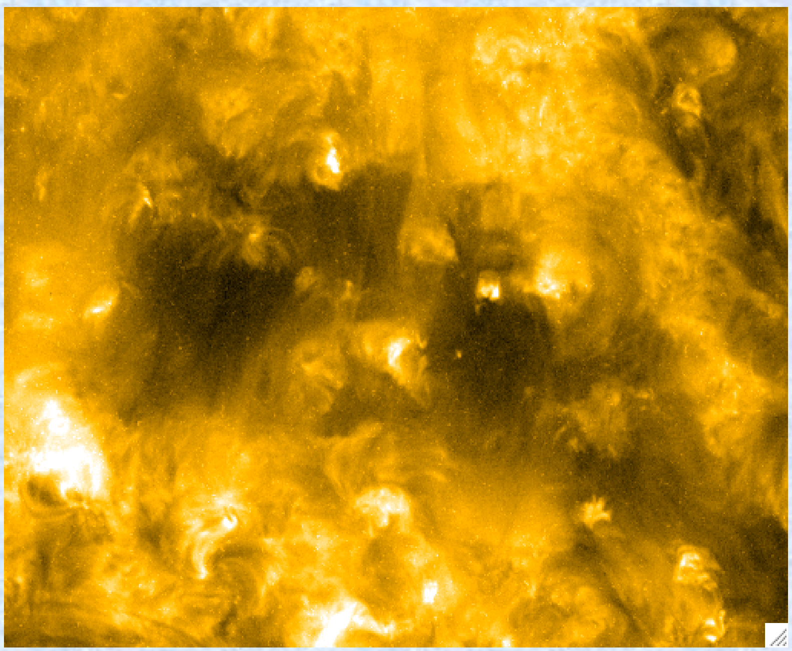

Tian et al. 2011, ApJ, 736, 130

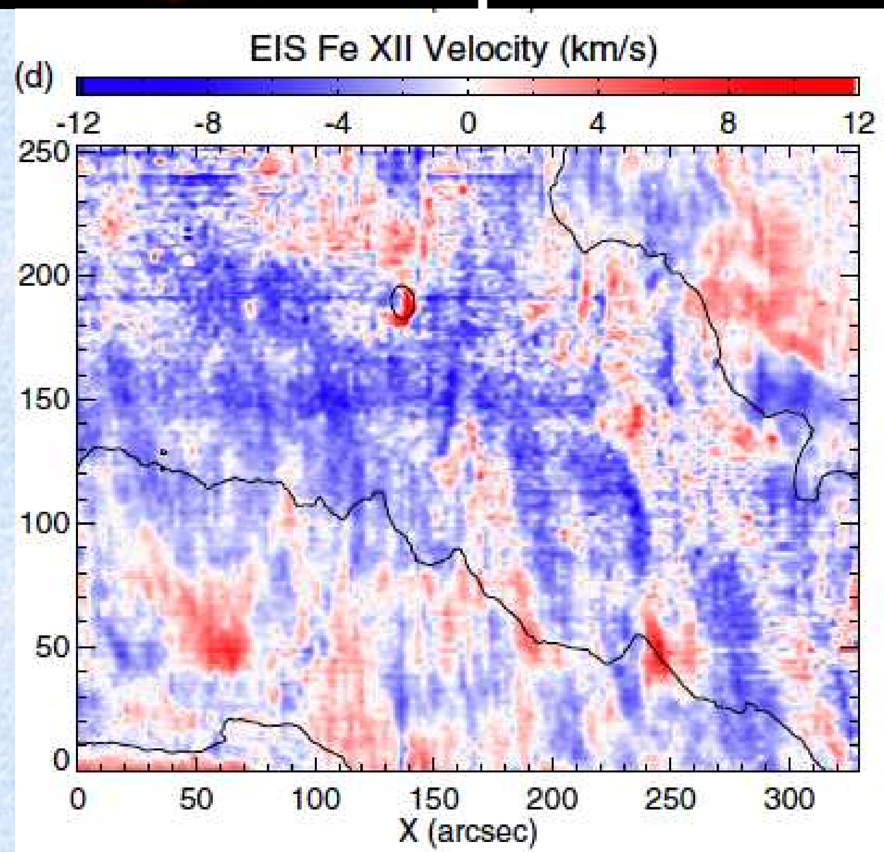
# High-speed outflows from QS

- QS outflows are discernible when projecting onto POS above surrounding CH
- Blue shifts in CH might be contaminated by QS outflows, not pure signatures of the fast solar wind



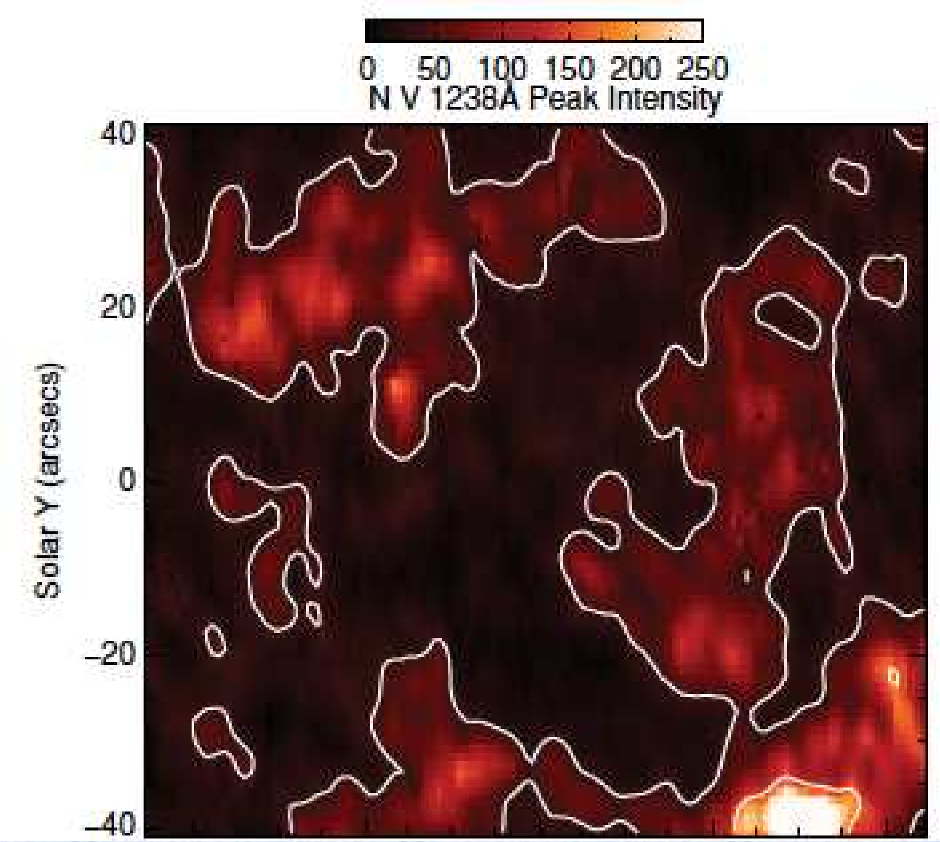




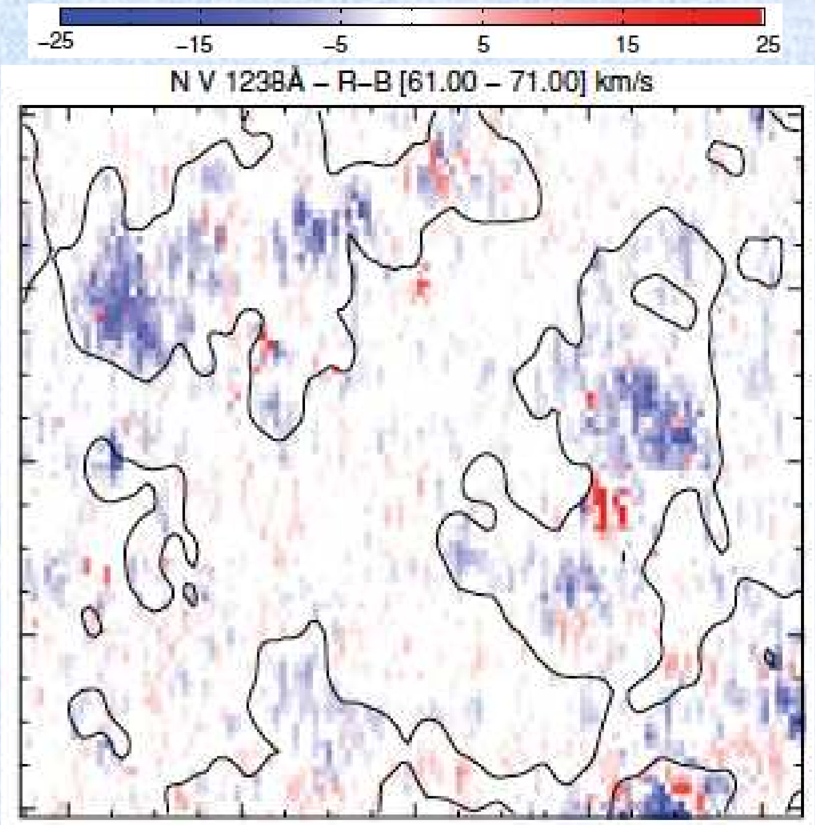

Tian et al. 2011, ApJ, 736, 130

# Blueward asymmetries in QS network

Intensity

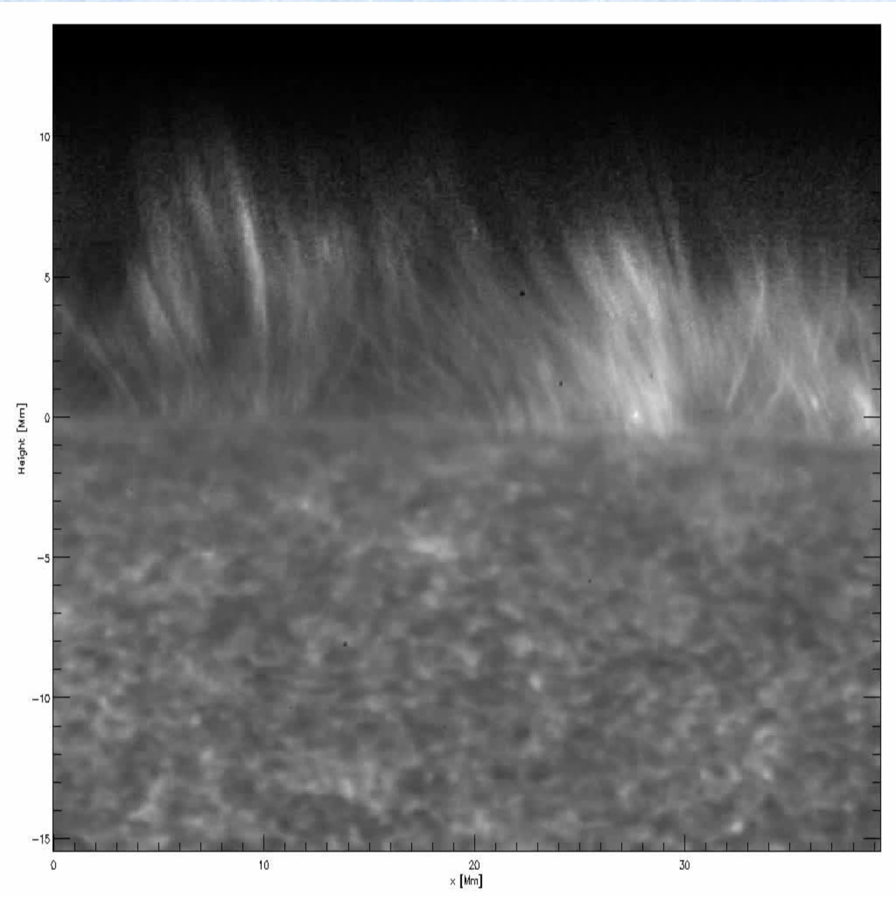



RB asymmetry

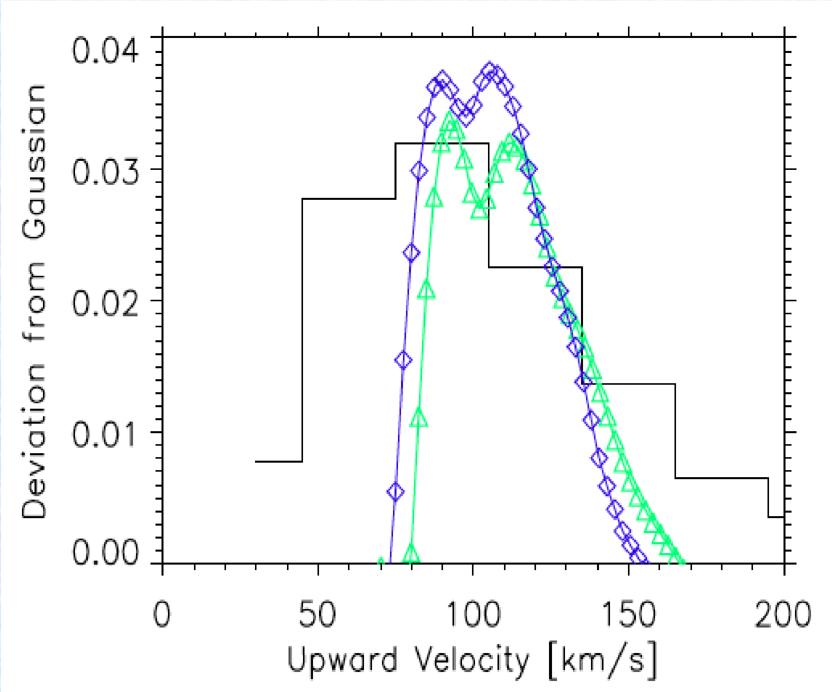



McIntosh & De Pontieu 2009, ApJ, 707, 524

# Connection between the secondary component in coronal line profiles & chromospheric type-II spicules




Black: tpye-II spicule in Ca II H 3968 Å
Blue: 2nd comp. in Fe XIV 264 Å profiles
Green: 2nd comp. in Fe XIV 274 Å profiles

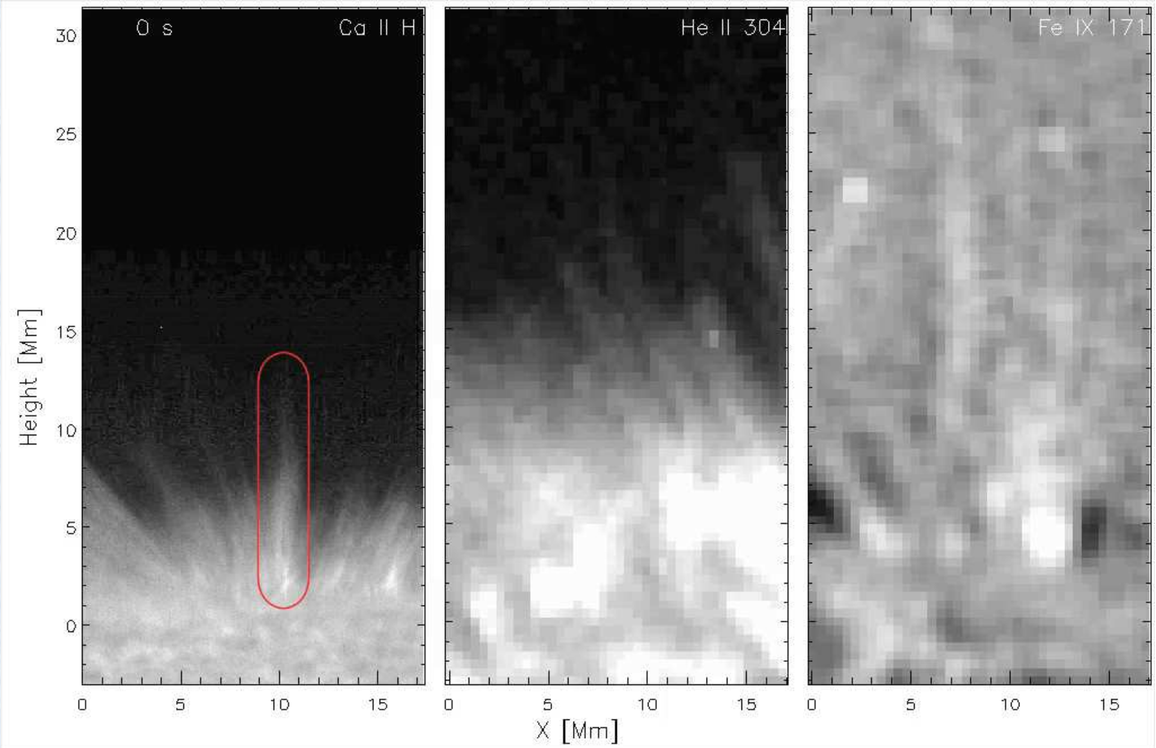



De Pontieu et al. 2007, PASJ, 59, S655

De Pontieu et al. 2009, ApJ, 701, L1

# Dispute I: Can spicules reach coronal temperature?

- De Pontieu et al. 2011, Science, 331, 55
  - TR spicules appear with a time delay of 10-20 s after the launch of chromospheric spicules. They reach much higher (~10 to 20 Mm).
  - Often also observe a coronal counterpart of the chromospheric/TR spicules
- Madjarska et al. 2011, A&A, 532, L1
  - Spicules are not present in spectral lines formed at T>300 000 K
  - The recent observation of spicules in the coronal 171 Å and 211 Å channels probably comes from the existence of TR emission

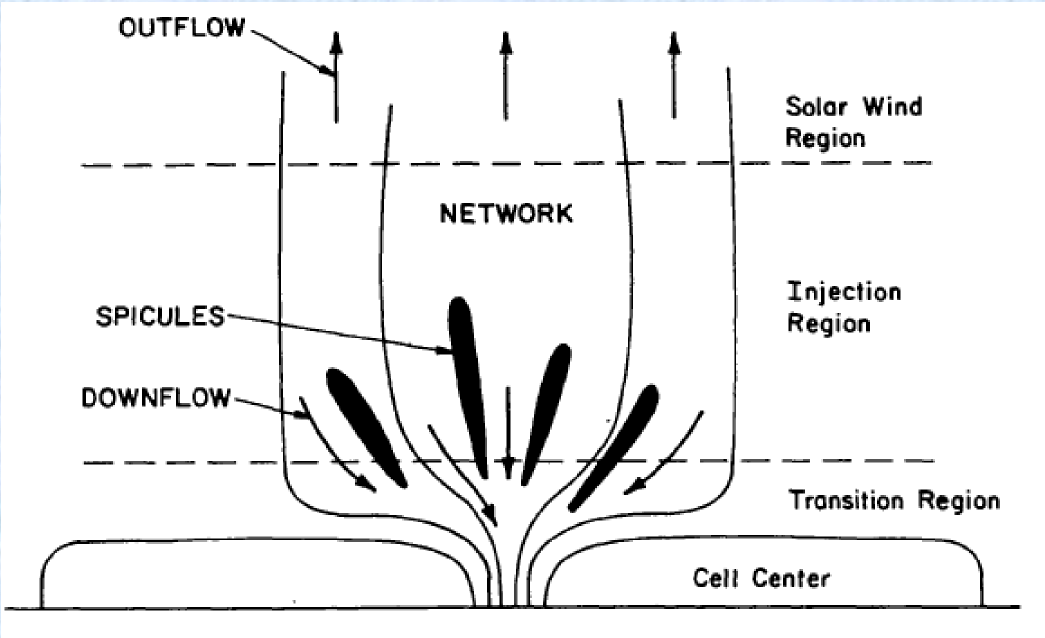



De Pontieu et al. 2011

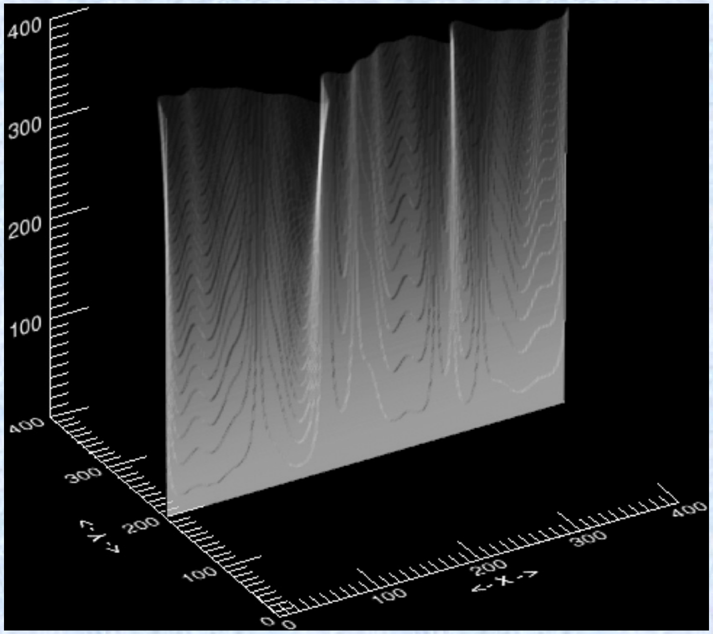
- Statistical studies are needed since only a small fraction of type-II spicules are heated to million degree (De Pontieu et al. 2011)
- Evaluate the contribution of non-dominant ions in AIA passbands, e.g., downflows in 131 but no downflows in 193 and 211

# Dispute II-spicules & PDs are current sheets?

- Spicules (perhaps also PDs) are flows guided by magnetic field lines.
- Judge et al. 2011: Some populations of spicules and fibrils correspond to warps in two-dimensional sheet-like structures rather than tube-like structures.
- Upward motions need to be explained by the sheet model

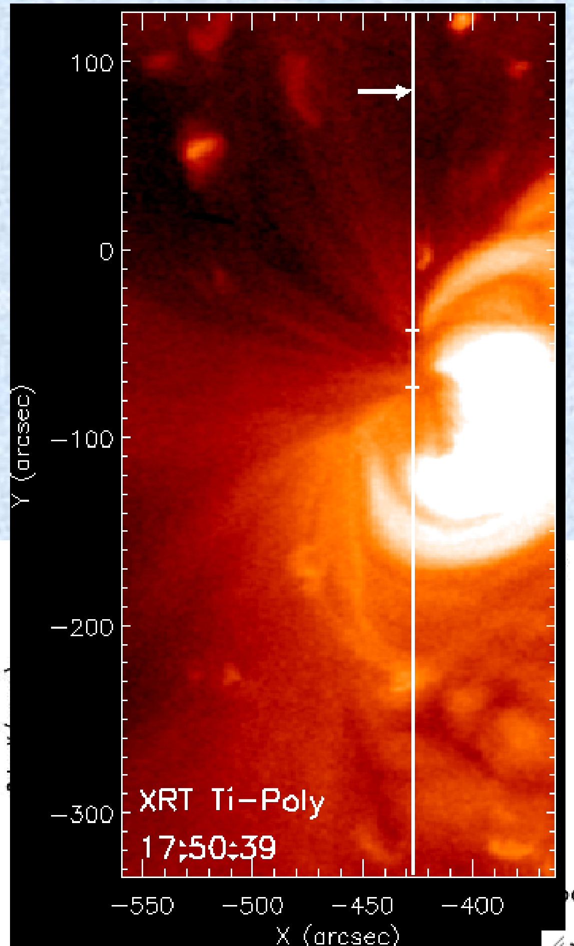


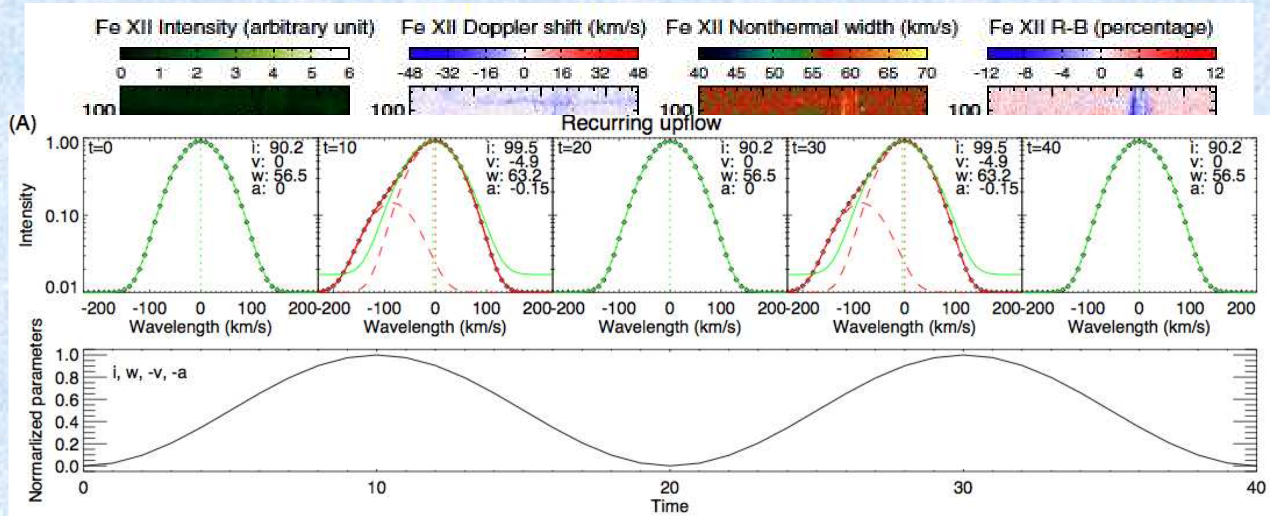

Pneuman & Kopp 1978, Sol. Phys., 57, 49

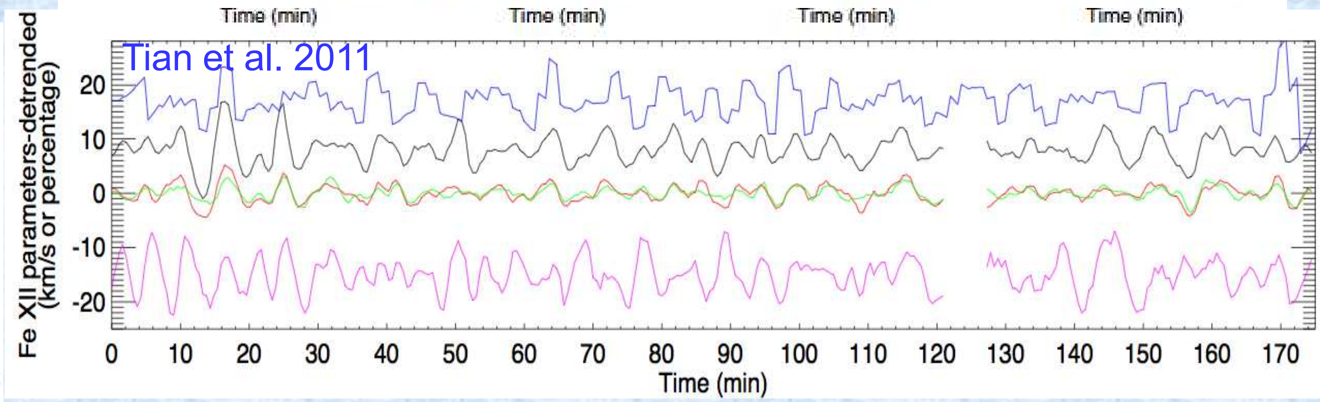


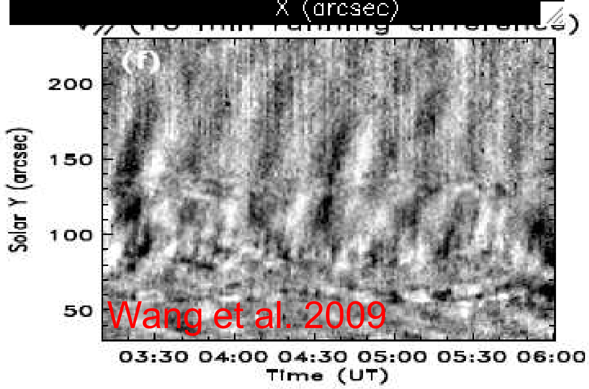

Judge et al. 2011, ApJ, 730, L4

# Dispute III-PDs are slow waves?



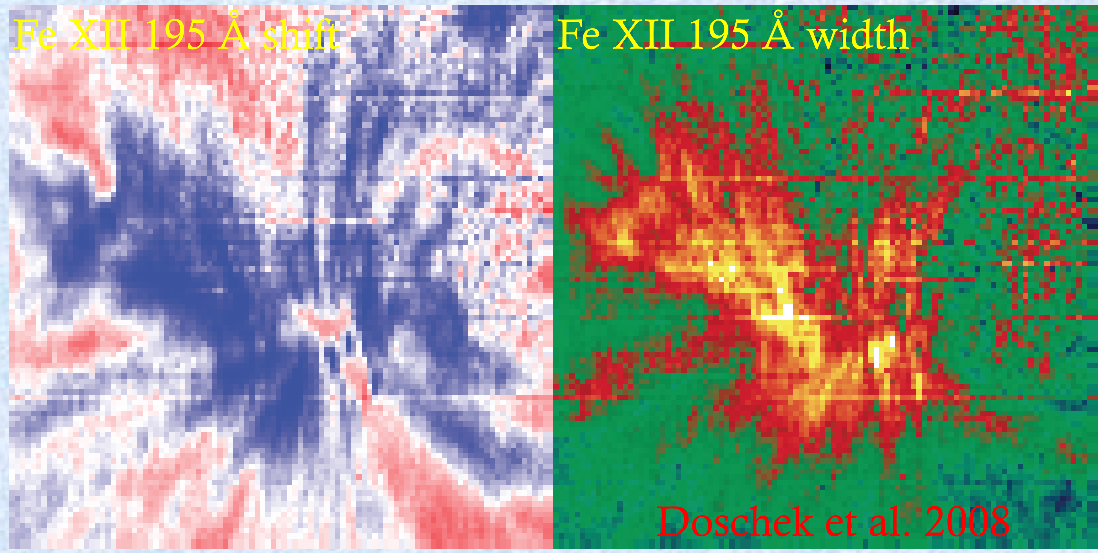



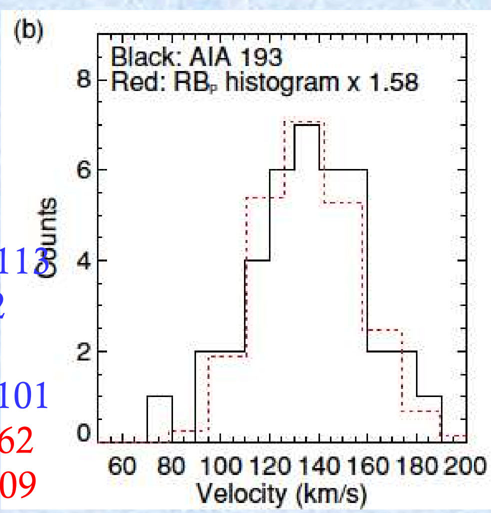

- Correlation between intensity and Doppler shift
- Blueshfit & blueward asymmetry all the time
- All line parameters show in-phase quasi-periodic variation, consistent with recurring upflow scenario

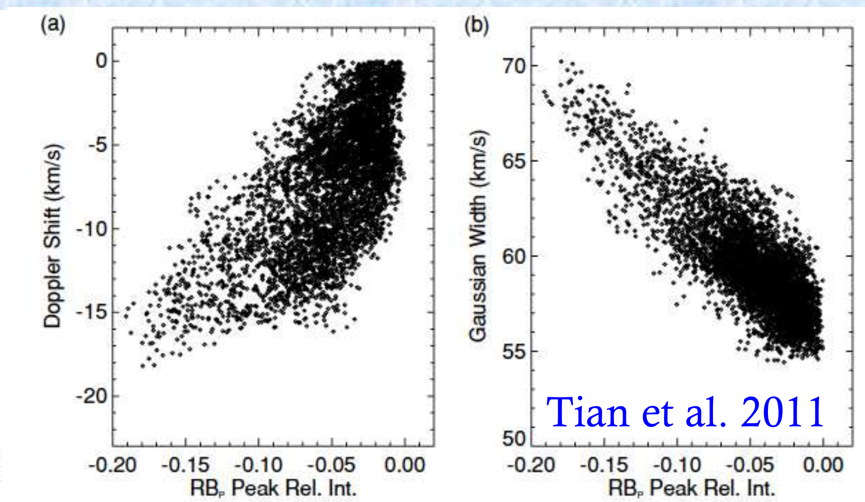
Verwichte et al. 2010, ApJ, 724, L194; Wang et al. 2009, A&A, 503, L25; et al.
De Pontieu & McIntosh, 2010, ApJ, 722, 1013; Tian et al. 2011, ApJ, 727, L37
Nishizuka & Hara 2011, ApJ, 737, L43

# Dispute IV-multiple components?

- Multiple comp. with each slightly Doppler-shifted with respect to each other
- Two distinct comp. in hot coronal lines
  - Correlation between blue shift/width and blueward asymmetry
  - Imaging observations: no continuous distribution of speed



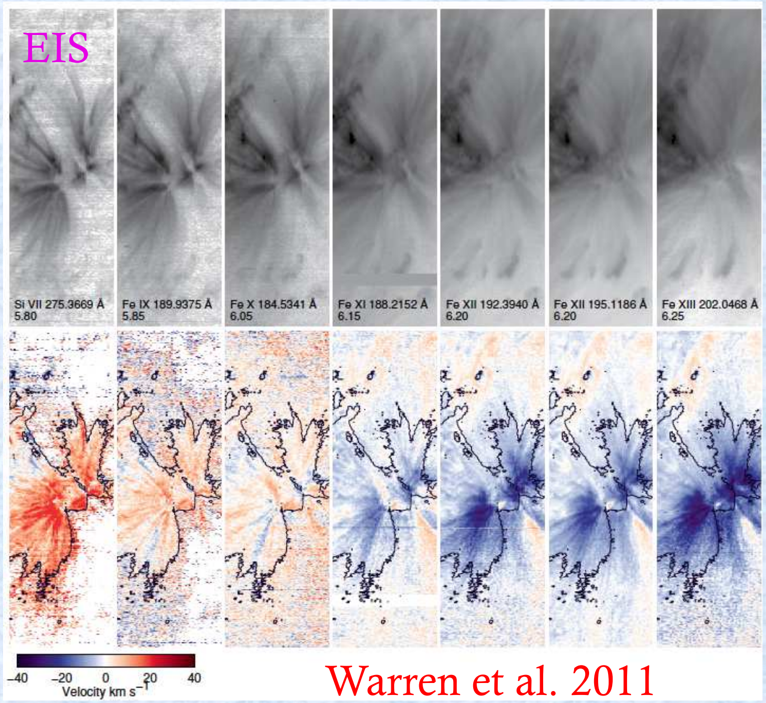



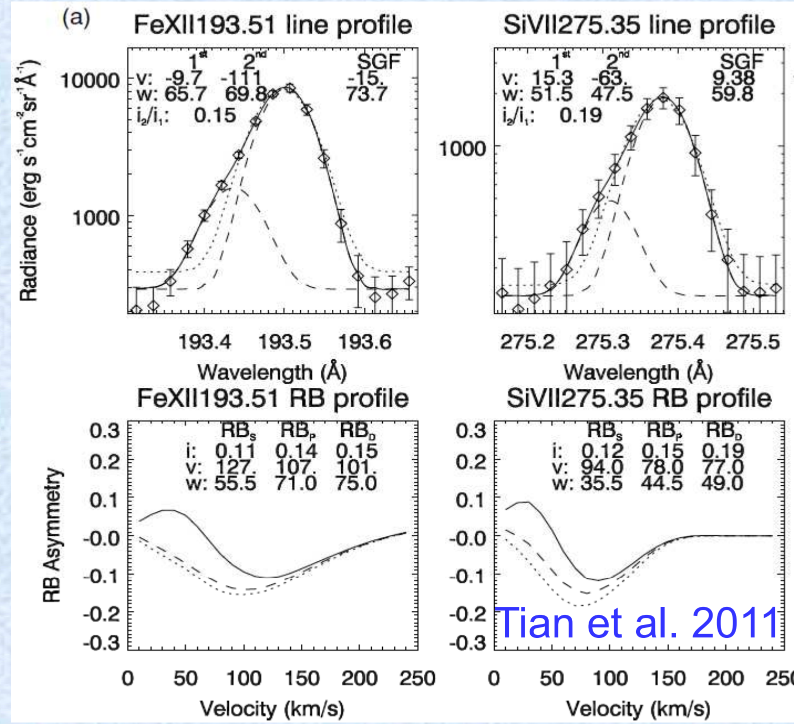



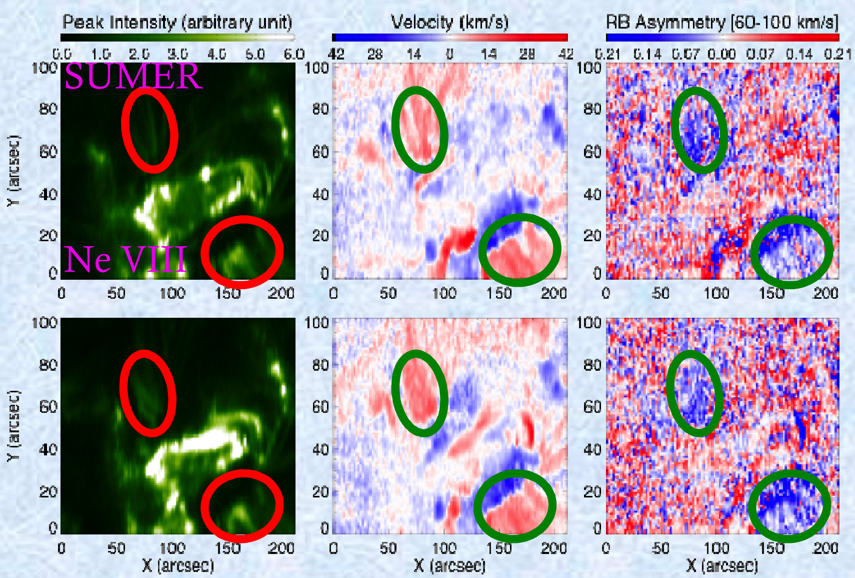


Tian et al. 2011, ApJ, 738, 18
Dolla & Zhukov 2011, ApJ, 730, 113
Bryans et al. 2010, ApJ, 715, 1012
Peter 2010, A&A, 521, A51
Scott & Martens 2011, ApJ, 742, 101
Doschek et al. 2008, ApJ, 686, 1362
Deschek et al. 2007, ApJ, 667, L109

# Dispute V-no upflows at TR temperatures?



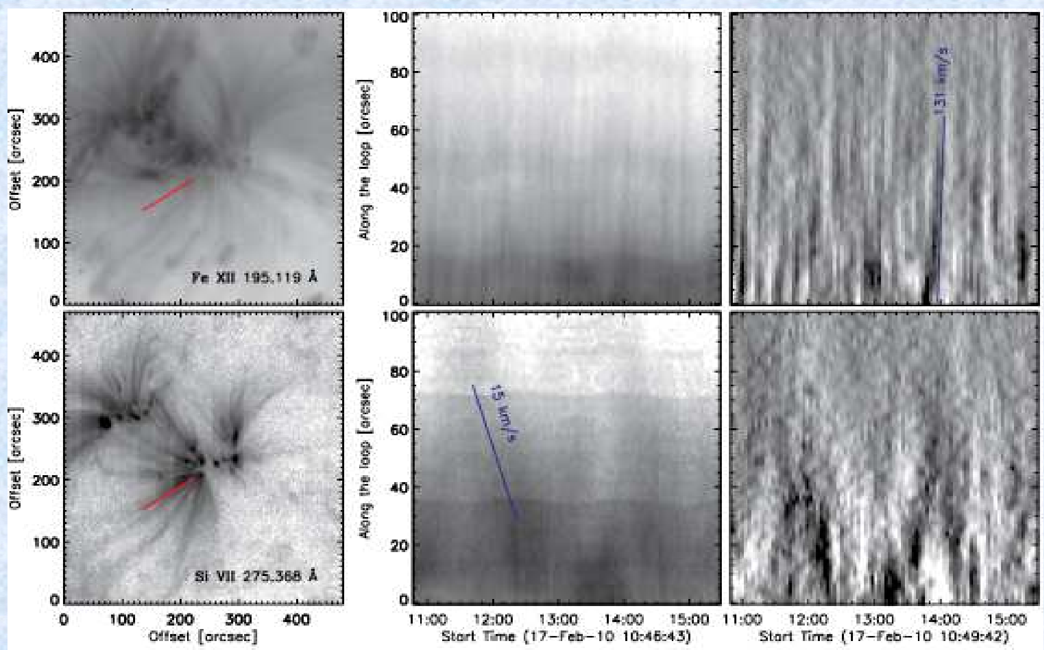



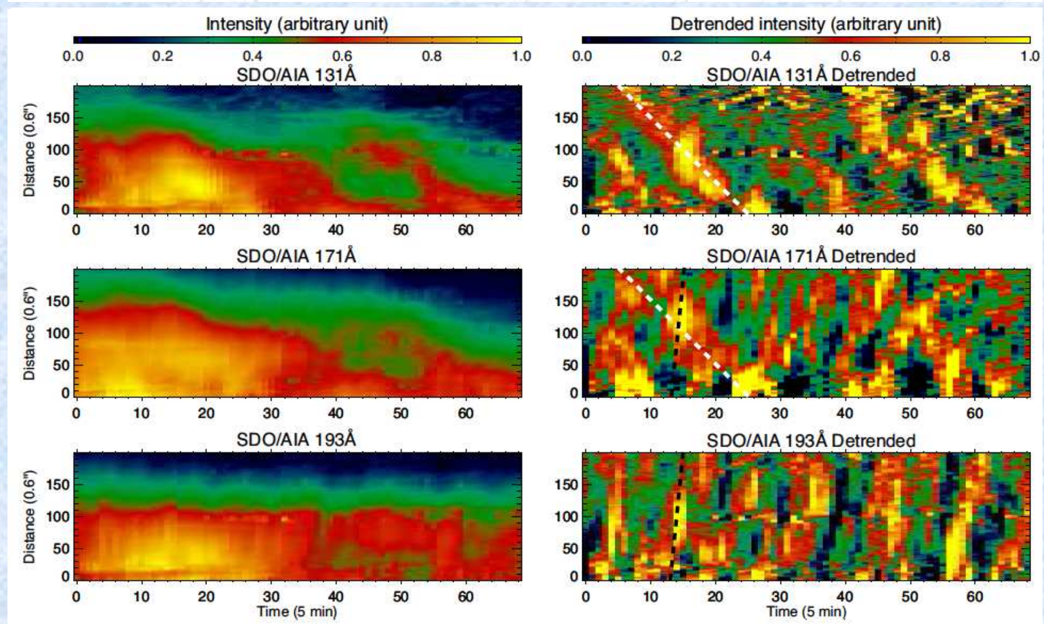

- Red shift at log T<6.0: fan loops and outflow regions are not the same
- Blueward asymmetry also clearly present at some locations, not everywhere because of the complication by cooling downflows

Tian et al. 2011, ApJ, 738, 18; McIntosh et al. 2012, ApJ, in press
Warren et al. 2011, ApJ, 727, 58; Young et al. 2012, ApJ, 744, 144
Ugarte-Urra & Warren 2011, ApJ, 730, 37

# Downflows in imaging observations

- Ugarte-Urra & Warren 2011, ApJ, 730, 37: 15-20 km/s in EIS slot images of Si VII
- Kamio et al. 2011, A&A, 532, A96: Quasi-periodic upward motions from loop footpoints in hot emission (AIA 193 Å), while sporadic downflows in cool emission (AIA 304, 131, 171 Å)
- McIntosh et al. 2012, ApJ, in press: Coexistence of downflows (~15 km/s) & upflows (~100 km/s) on the same structure in AIA 131 Å



# Causes of the flows

- Upflows
  - Chromospheric type-II spicules driven possibly by (component) reconnection, De Pontieu et al. 2007, PASJ, 59, S655
  - Outflows at AR boundaries: interchange reconnection between closed loops in the AR core and neighbouring open flux tubes, Del Zanna et al. 2011, A&A, 526, A137; Bradshaw et al. 2011, ApJ, 743, 66
  - Outflows from Chro. into corona: pressure gradient

    Hansteen et al. 2010, ApJ, 718, 107

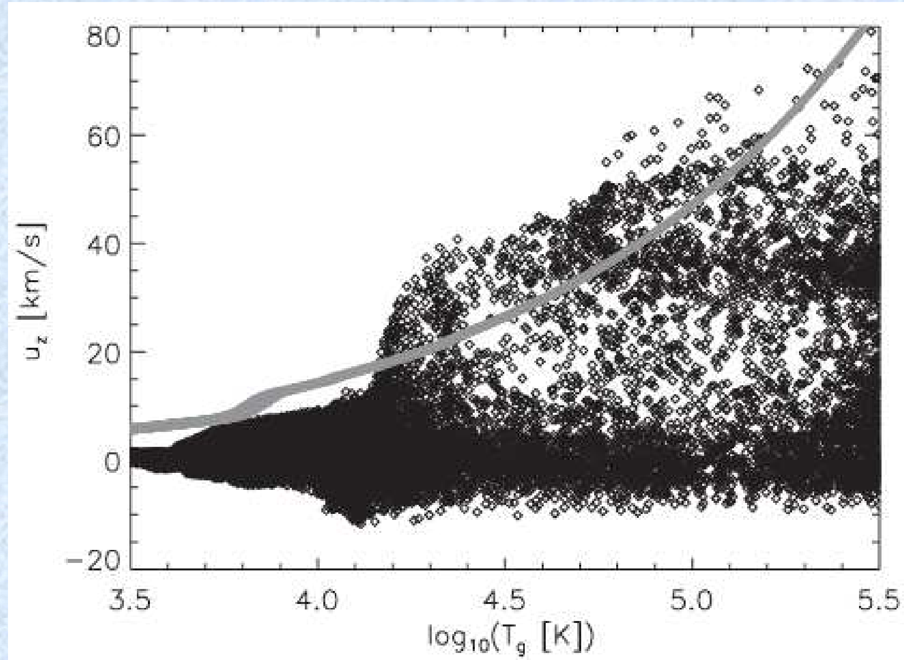
    Martínez-Sykora et al. 2011, ApJ, 732, 84

    Martínez-Sykora et al. 2011, ApJ, 736, 9

    Imada et al. 2011, ApJ, 743, 57

    Judge et al. 2012, ApJ, 746, 158

  Zacharias et al. 2011, 532, A112

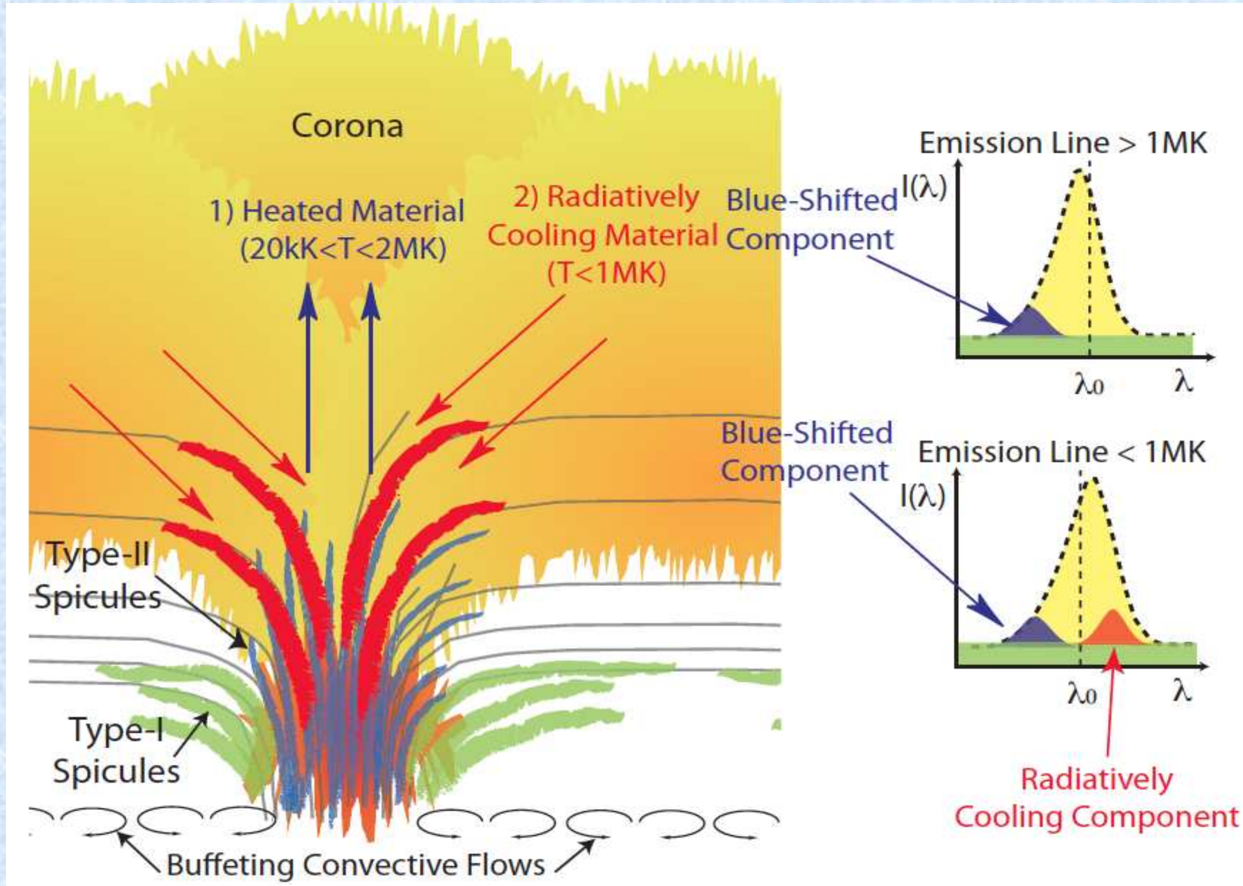



Martínez-Sykora et al. 2011

- Downflows
  - Plasma pushed downward by the downward pressure gradient, e.g., Hansteen et al. 2010
  - Catastrophic cooling followed by thermal non-equilibrium, e.g., Peter et al. 2012, A&A, in press

# Mass circulation-three emission components

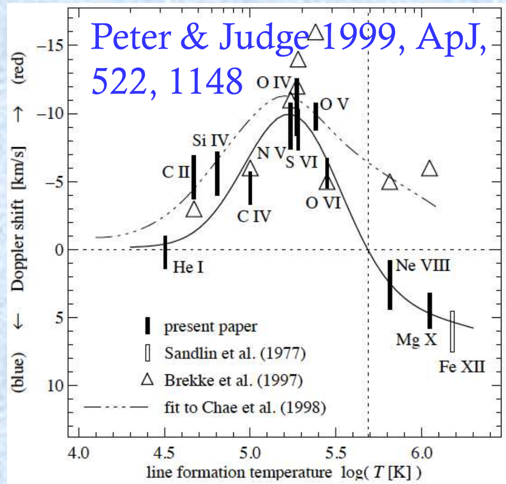
- A nearly static background
- A high-speed (~100 km/s) outflow resulting from impulsive heating in the chromosphere: type-II, PDs
- A downflow (~20 km/s) corresponding to the cooling of previously heated plasma: downflows in TR passbands

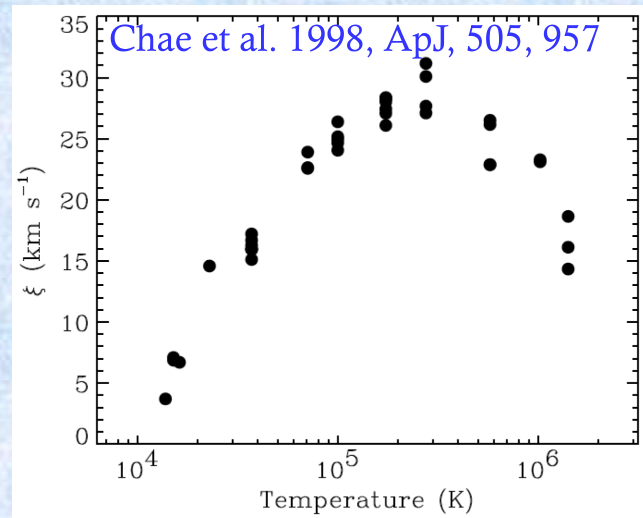


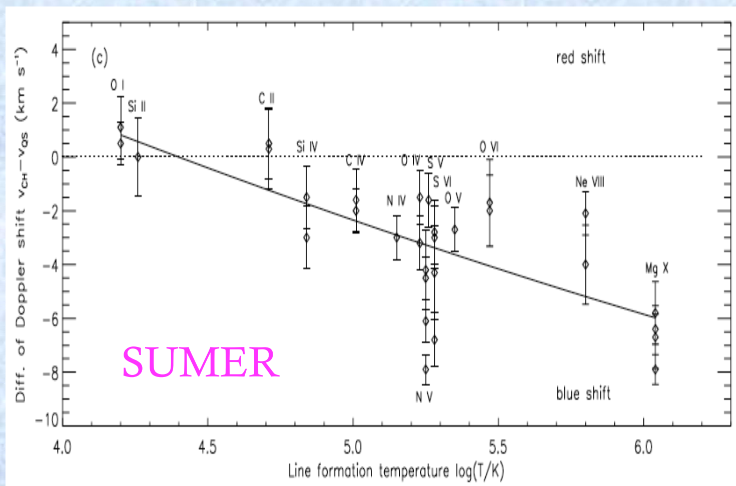

McIntosh et al. 2012, ApJ, in press

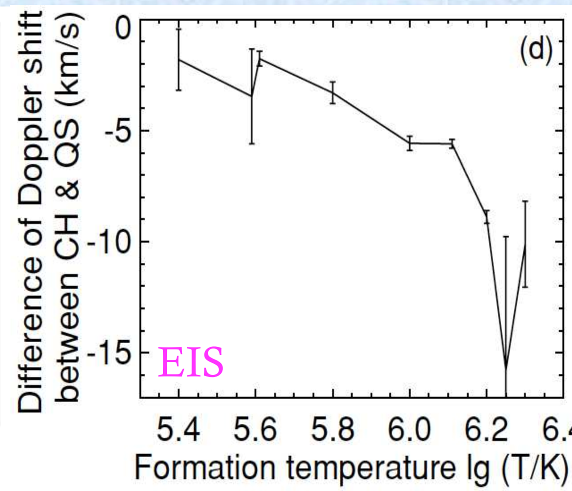
# Understanding the temperature dependence of TR Doppler shift and non-thermal width

- It is probably the relative contributions of the three components that produce these magic curves!
- More blueshifted in CH than in QS: less return of outflowing plasma
- See poster #



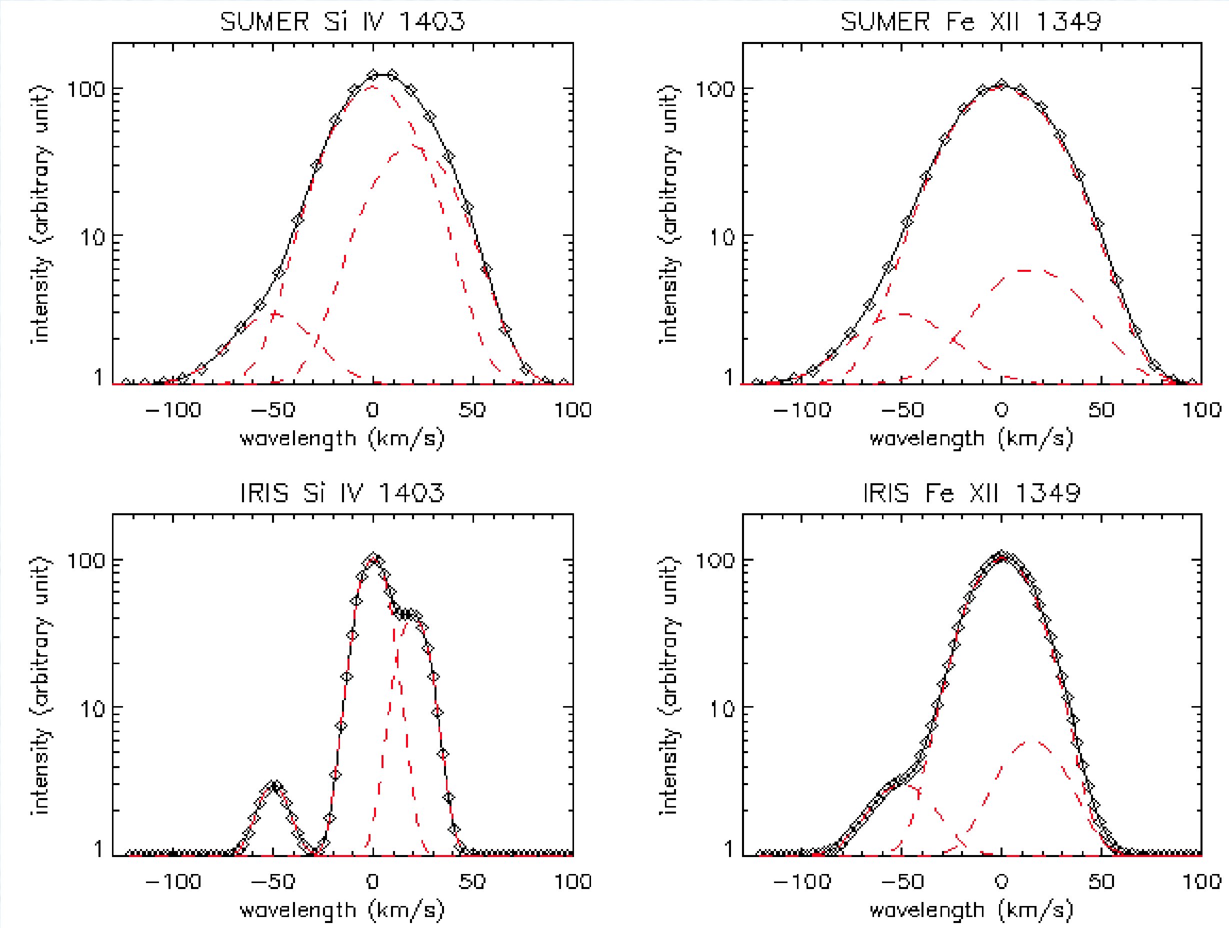




Xia et al. 2004, A&A, 424, 1025

Tian et al. 2010, ApJ, 709, L88

# What IRIS can do

- Unambiguous decomposition of different components are not possible with present instruments
- IRIS, with a very small instrumental width, very high spectral, temporal and spatial resolutions, may be able to accurately resolve different components



# Summary

- There is no static magnetically stratified plasma, but rather a continuous mass cycling/circulation between the chromosphere and corona/solar wind.
- Signatures of high-speed upflows and slow downflows have been observed by both imaging and spectroscopic observations in various regions of the Sun. They are natural results of the mass cycling between the chromosphere and corona/solar wind.
- IRIS may be able to unambiguously resolve different components in the mass cycling process.