Crossing the Transition Region

Hui Tian

High Altitude Observatory,
National Center for Atmospheric Research, U.S.

Collaborators: C.-Y. Tu, E. Marsch, W. Curdt, L. Teriaca, U. Schühle, S. W. McIntosh, B. De Pontieu, J.-S. He, L.-D. Xia, S. R. Habbal, H. E. Potts, R. Attie, J.-C. Vial, S. Kamio, et al.

02/02/2012 Bad Honnef

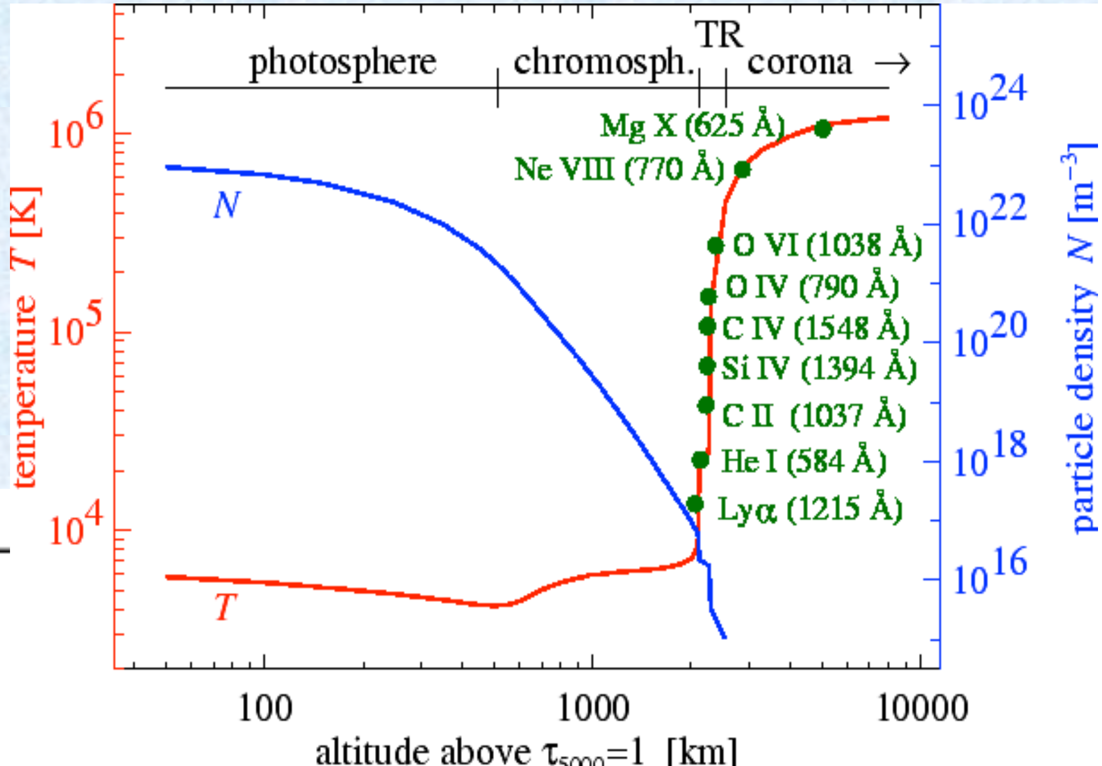
Outline

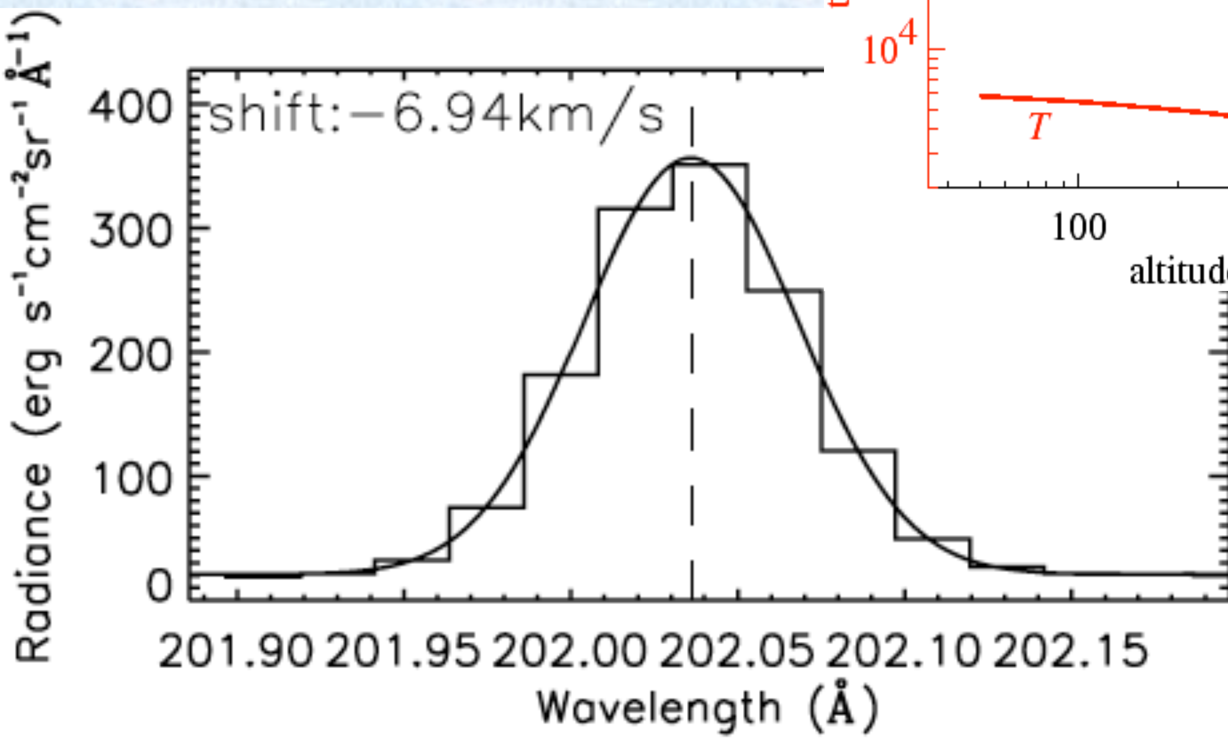
- Recent observations of TR structures and emission
- Formation of the solar wind in TR/chromosphere
- Mass cycling between the chromosphere and corona/solar wind

Optically thin emission

Spectroscopic observation

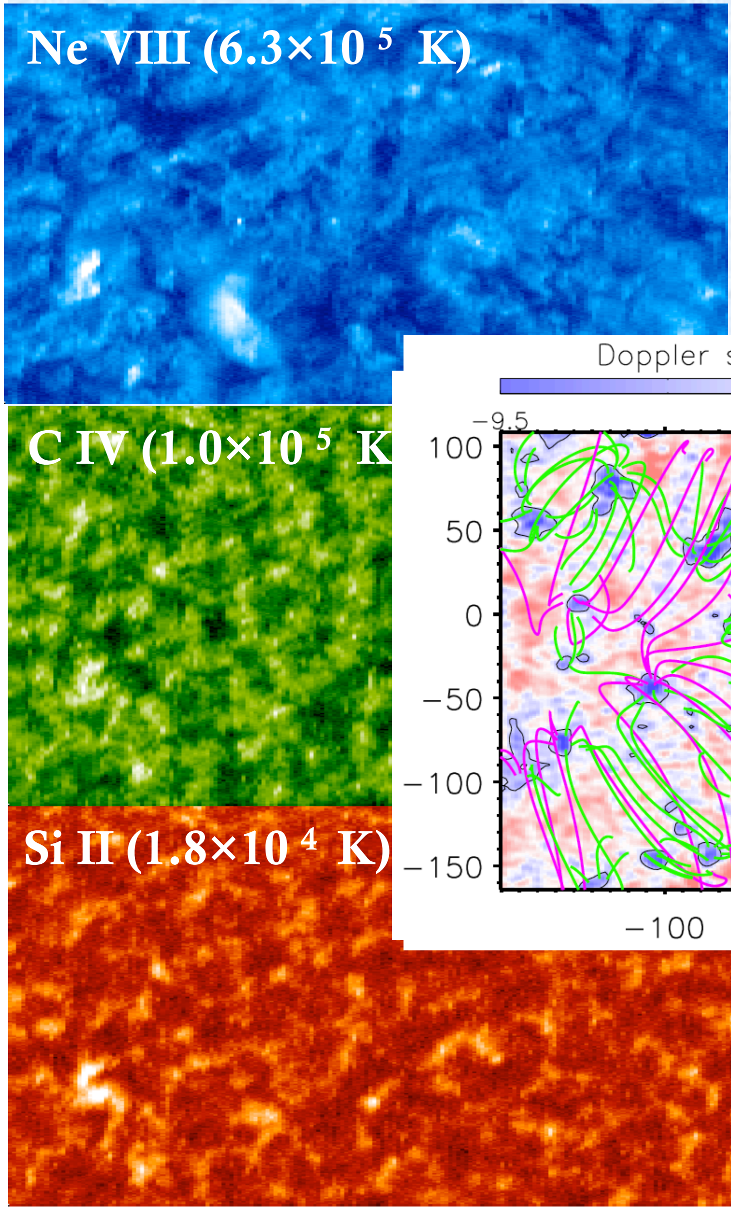
- Radiance
- Doppler shift
- Line width



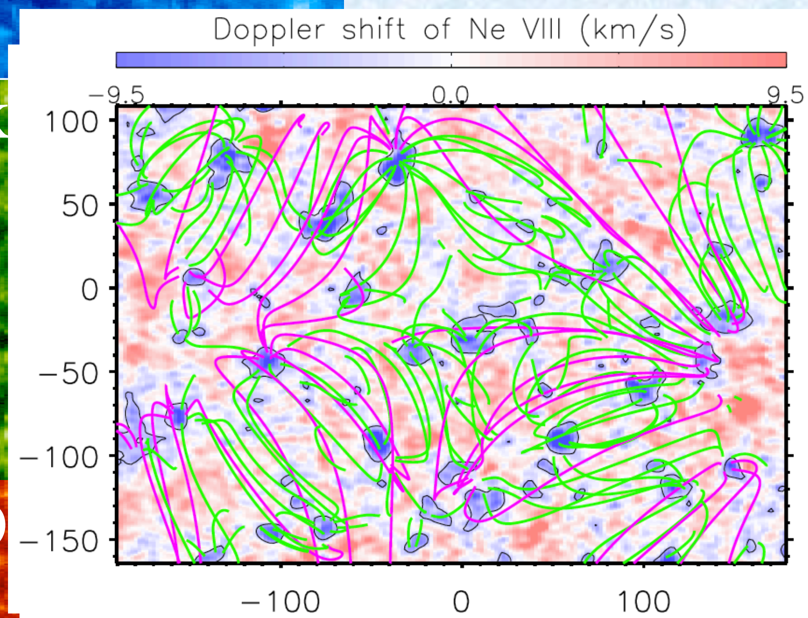


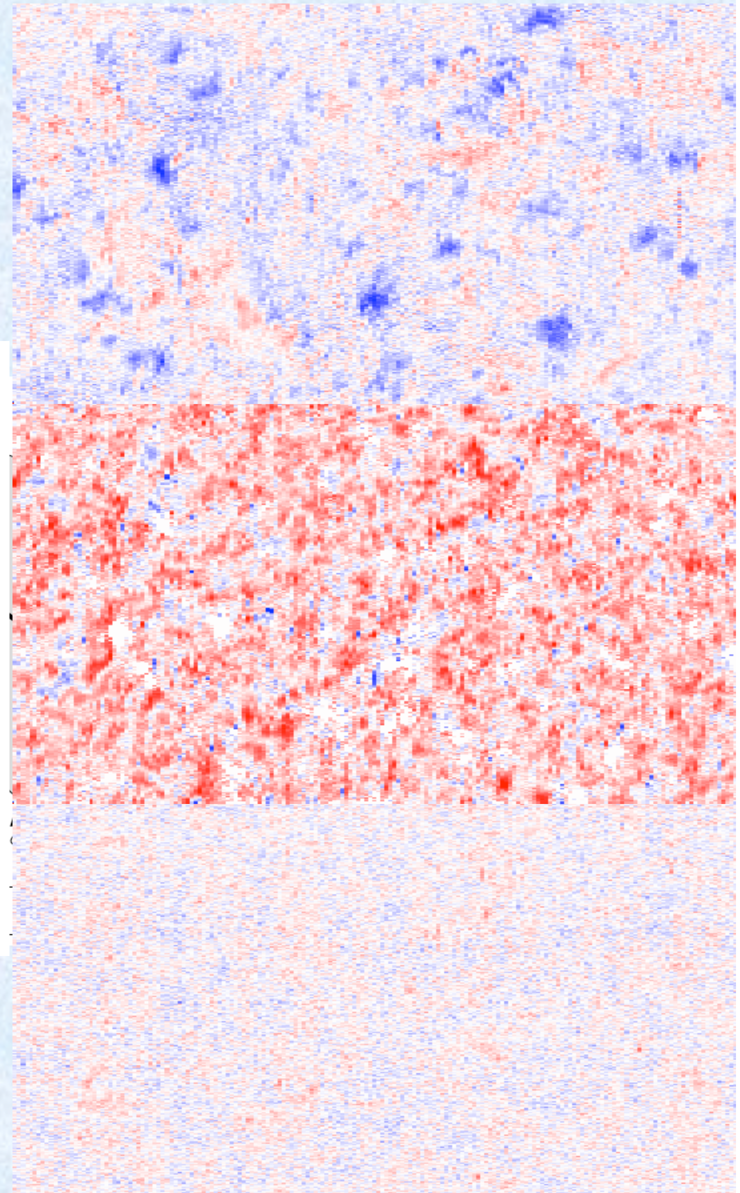
Vernazza, Avrett, & Loeser, 1981, ApJS, 45, 635
Peter 2004, Reviews in Modern Astronomy, 17, 87

Pattern of TR network and flows



Tian et al. 2008, ApJ, 704, 883





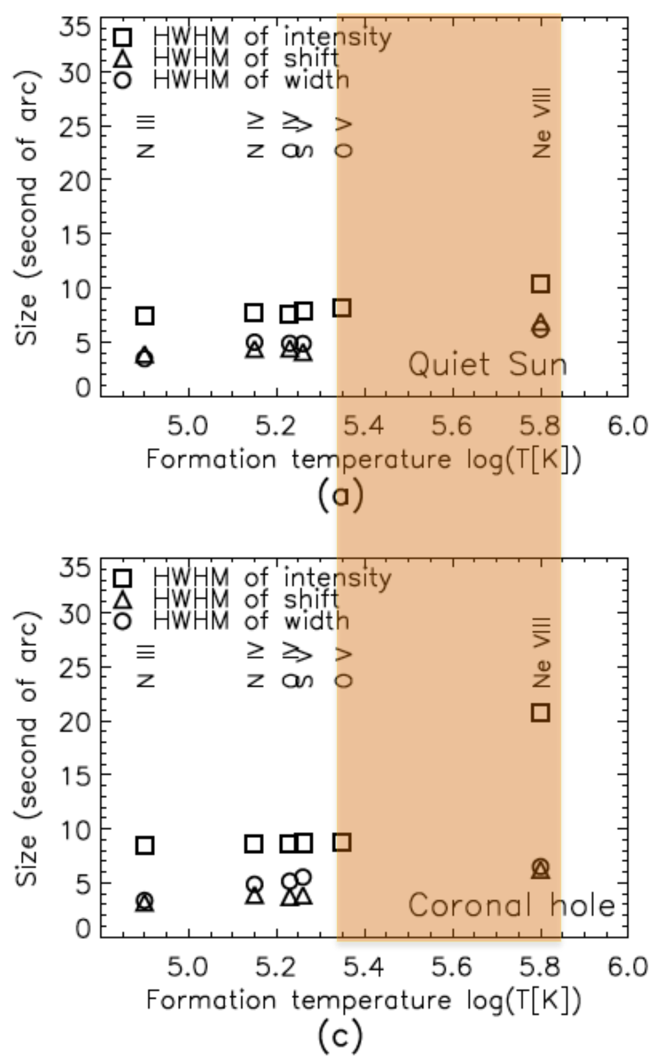
Peter 2001, A&A, 374, 1108

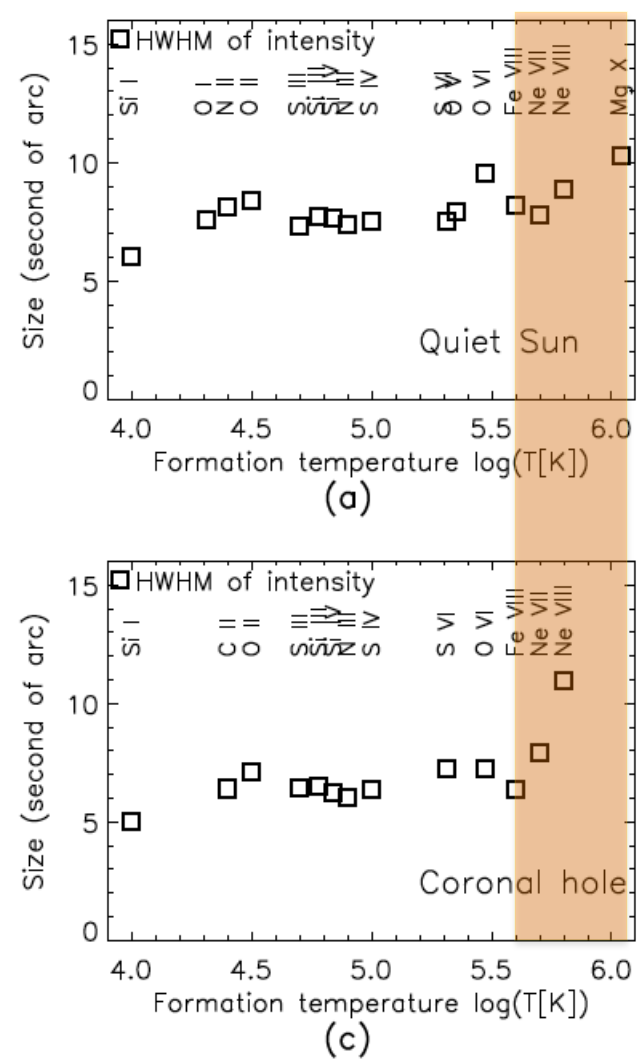
Dammasch et al. 1999, A&A, 346, 285

Network size

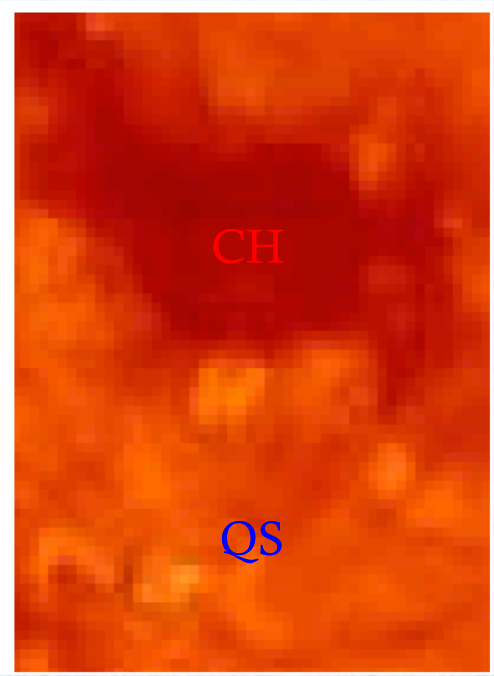
- Network size (characteristic size of the bright emission feature in intensity images):
  - Stable across a very wide T range
  - Increases from middle TR to upper TR more dramatically in CH than in QS

Tian et al. 2008, A&A, 482, 267



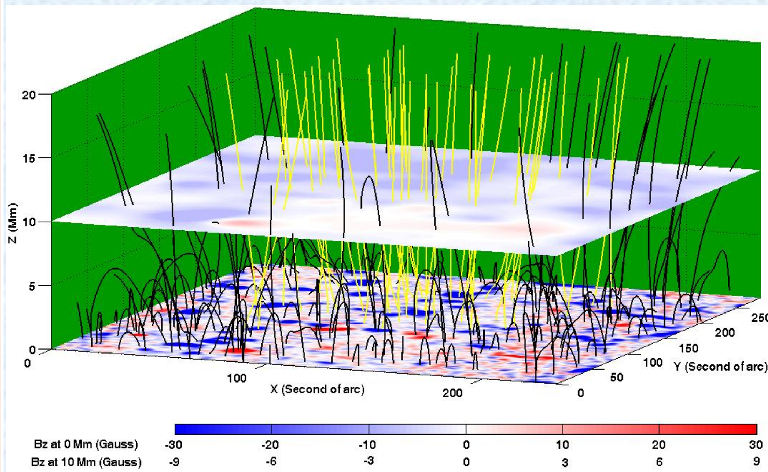


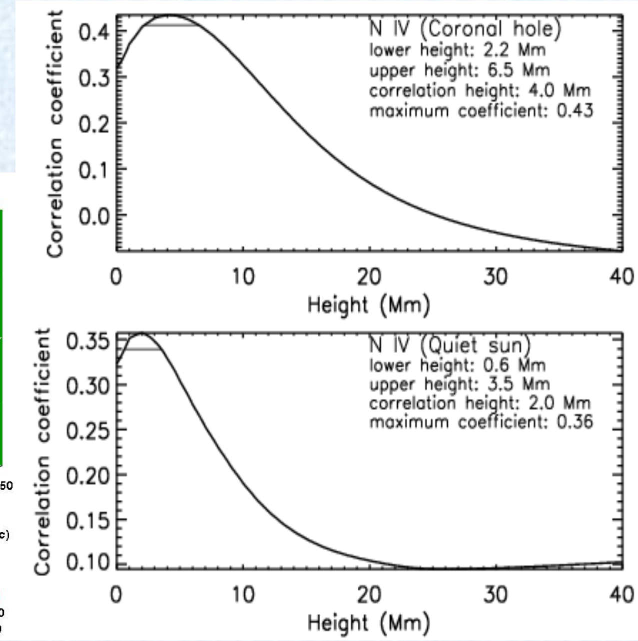
Height of TR in CH and QS



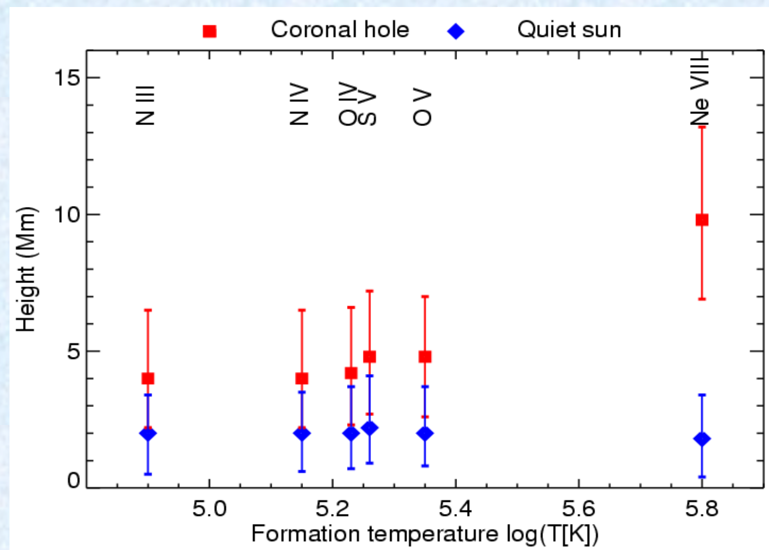
Black : closed field lines

Yellow : open field lines



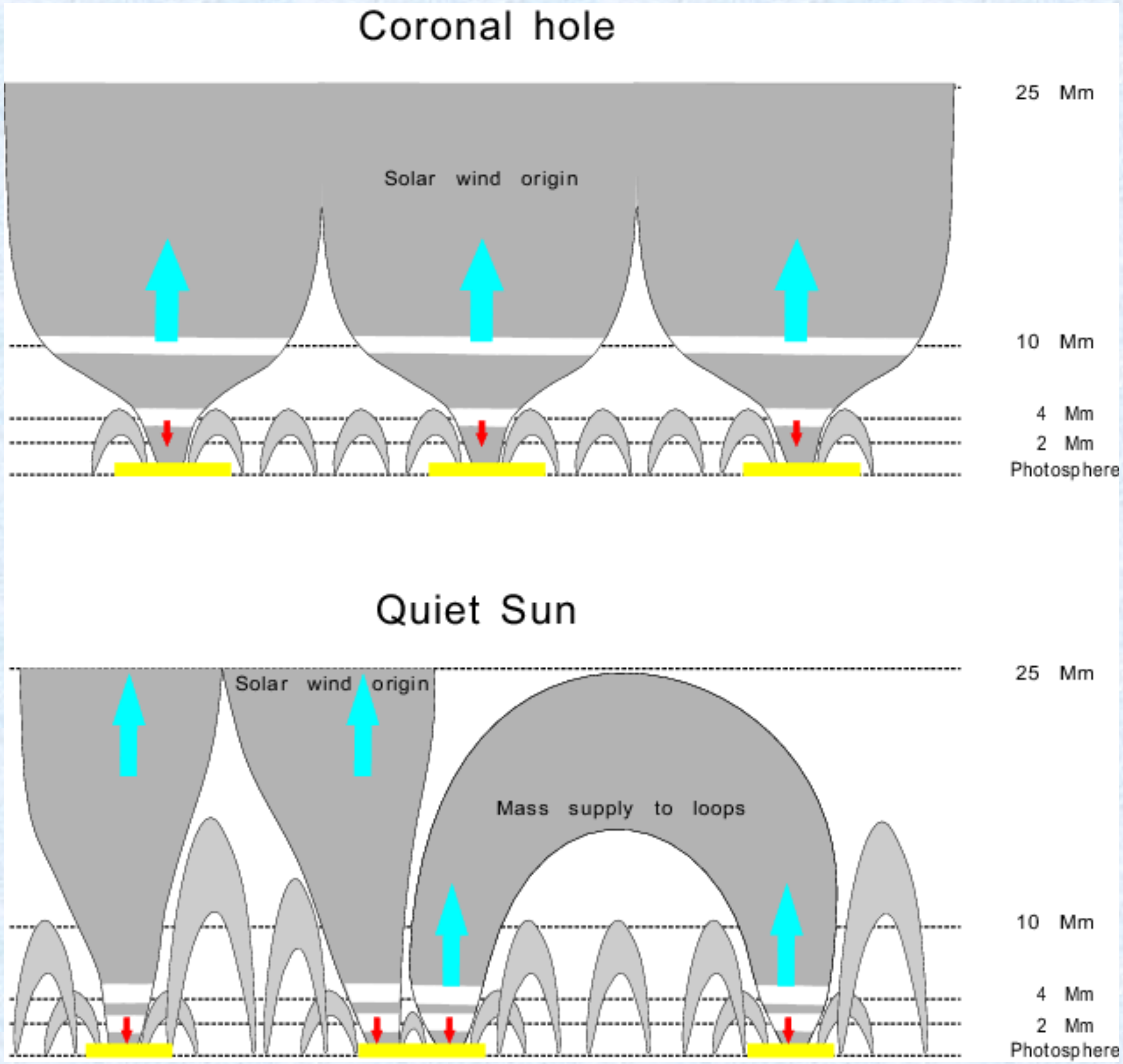


- TR height : CH>QS
- TR thickness : CH>QS



Tu et al. 2005, ApJ, 624, L133
Tian et al. 2008, ChJAA, 8, 732

TR structures in CH & QS

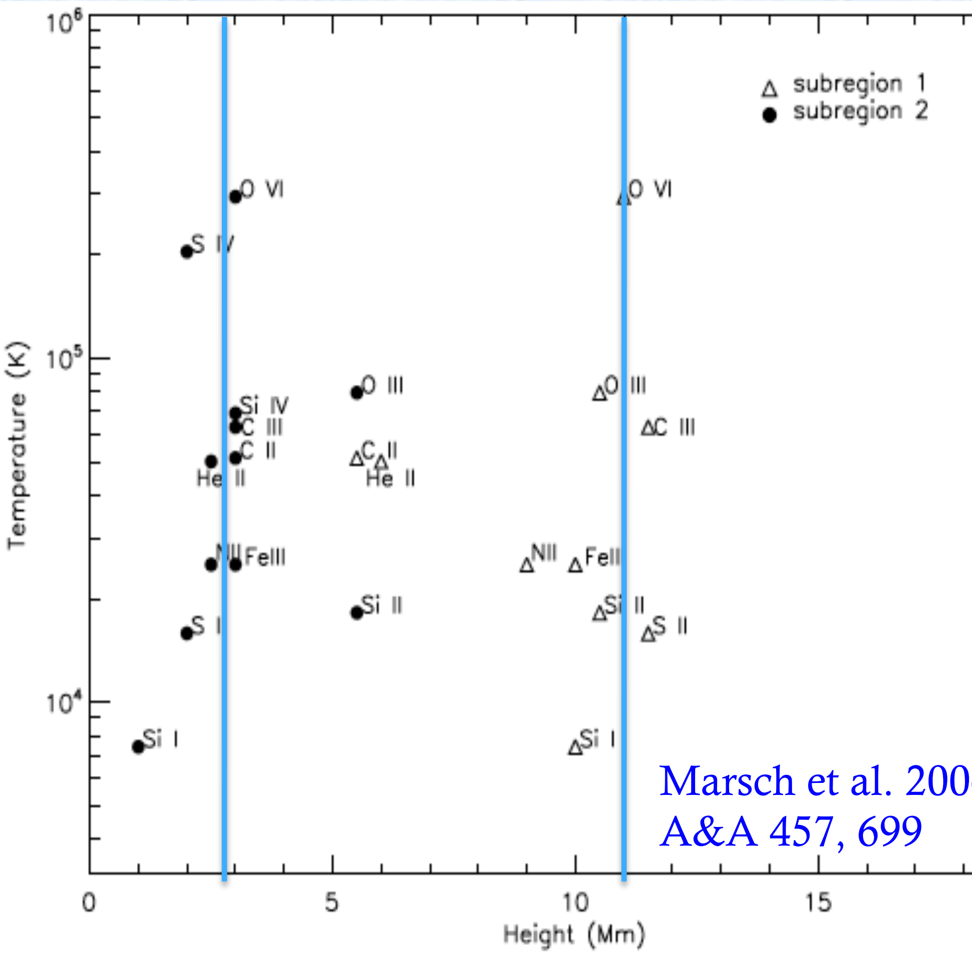


Tian et al. 2010, New Astron. Rev., 54, 13

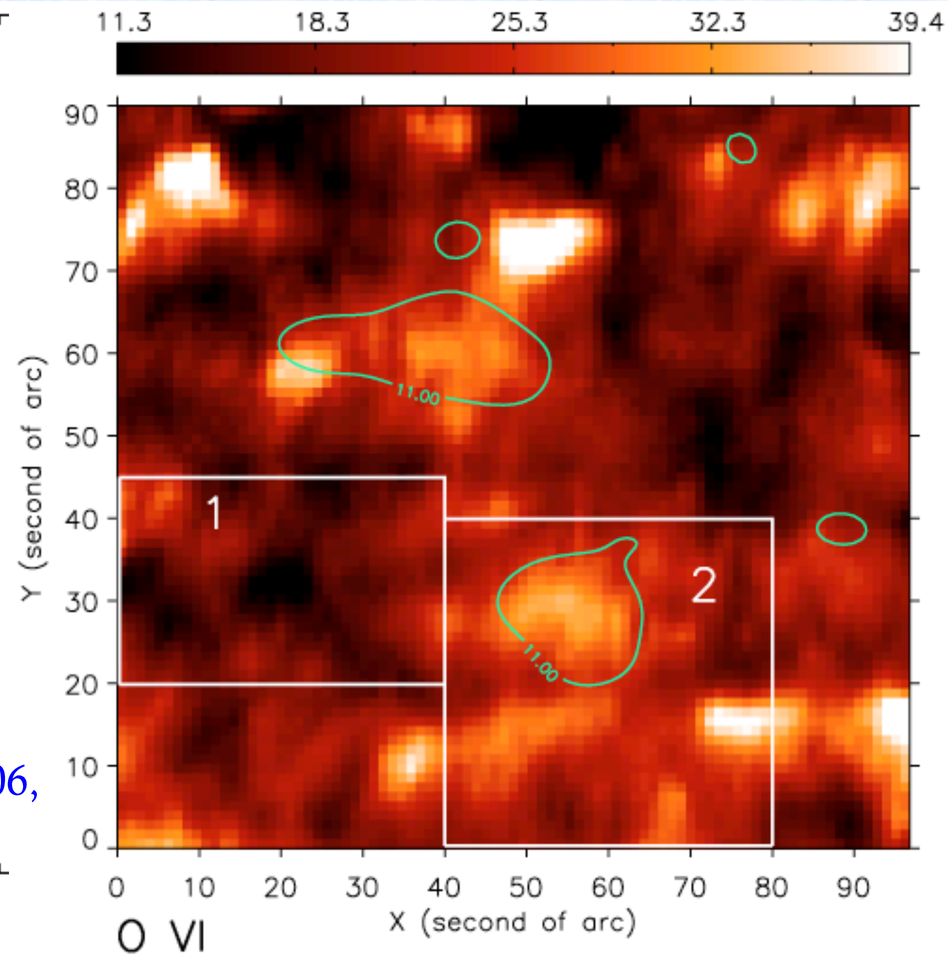
He et al. 2010, Adv. Space Res., 45, 303

TR region: a thin layer?

- Locally thin: coexistence of ions with different formation temperatures at about the same height in TR loops, and similarly in open fields.
- But highly nonuniform: TR height varies a lot at different locations

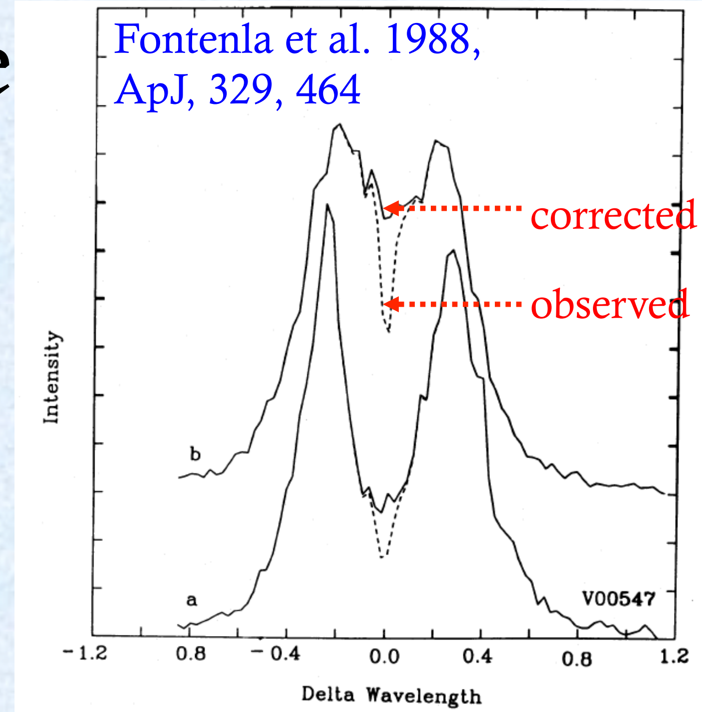


Marsch et al. 2006, A&A 457, 699

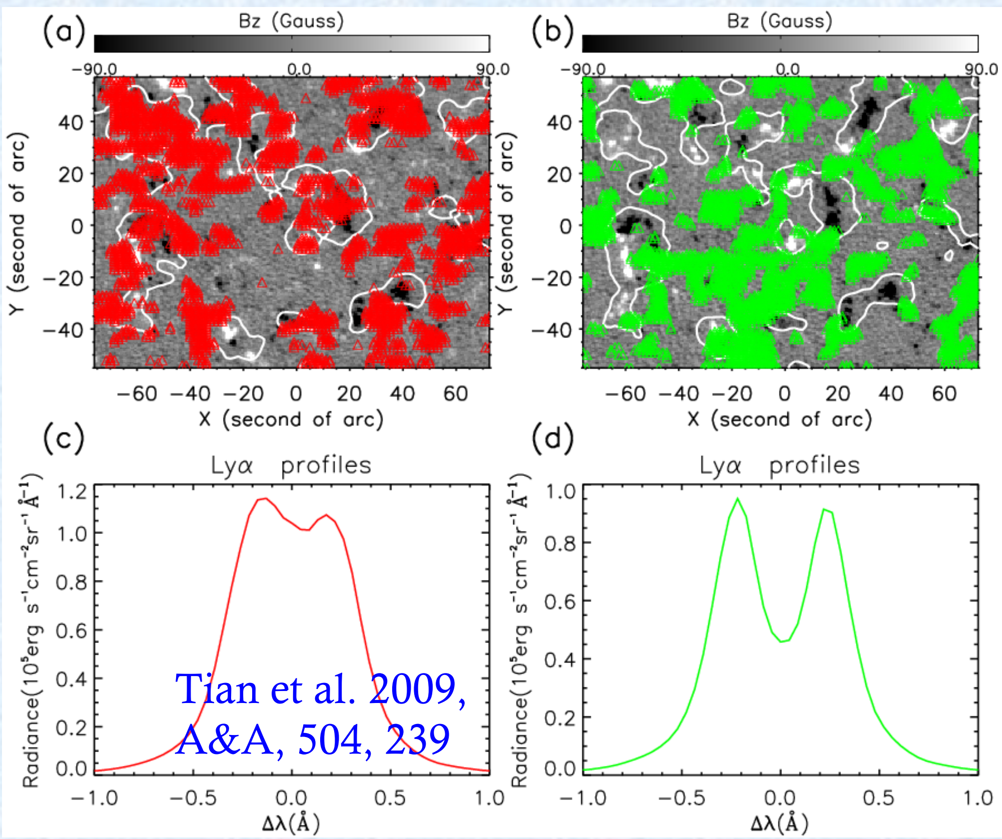


Lower TR: clean Ly α profile

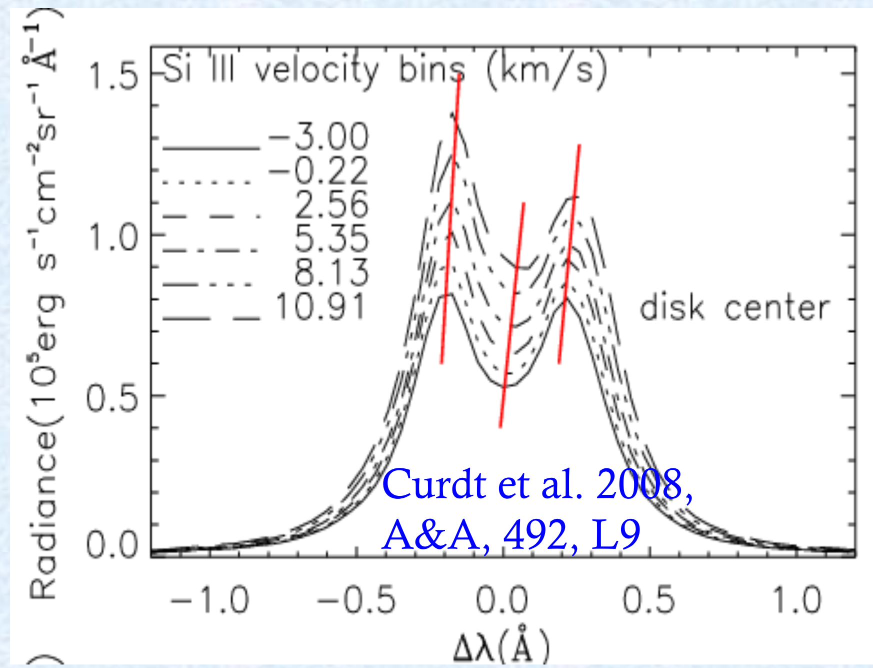
- Asymmetry
  - Stronger blue peak
  - More prominent as TR redshift increases
- Network profiles tend to be less reversed



Fontenla et al. 1988, ApJ, 329, 464

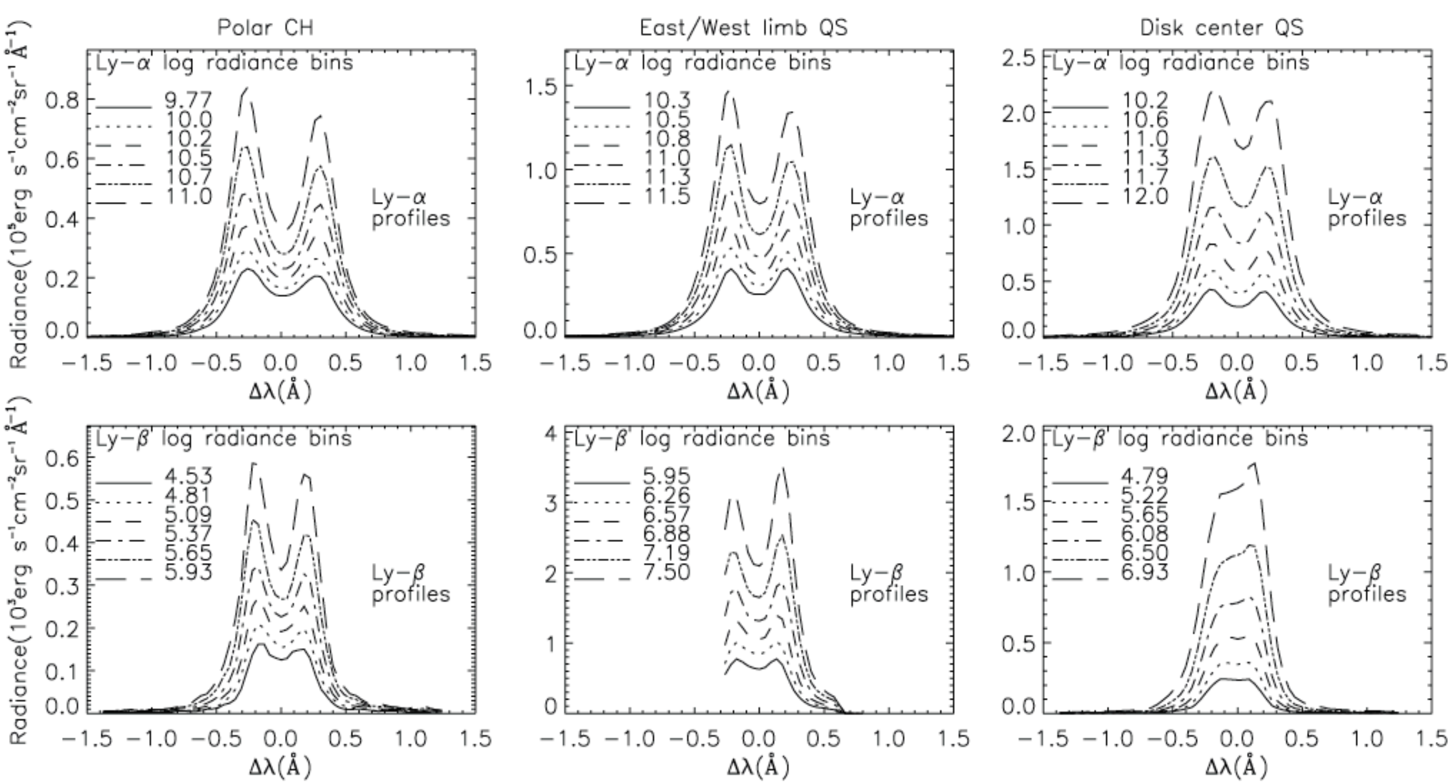


Tian et al. 2009, A&A, 504, 239

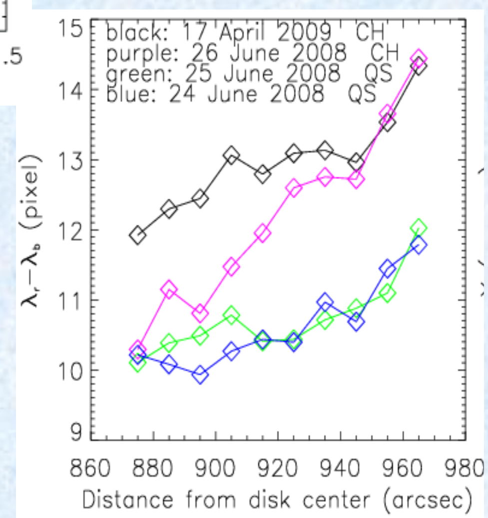


Curdt et al. 2008, A&A, 492, L9

Lower TR: Ly α & Ly β profiles in CH

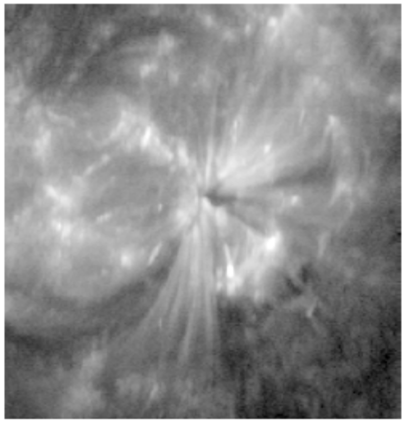


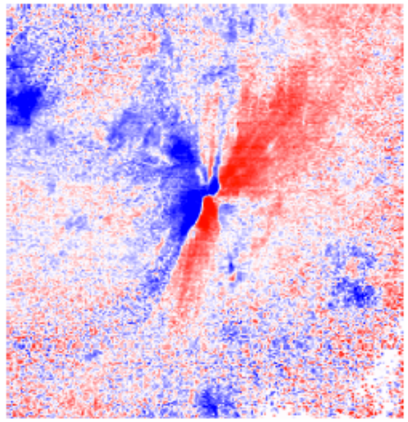
- Ly β asymmetry reverses in CH
  - Solar wind outflows?
  - Magnetic field line orientation



- Ly α peak separation
  - Larger in CH: more atomic hydrogen in higher layer?
  - Increases towards the limb

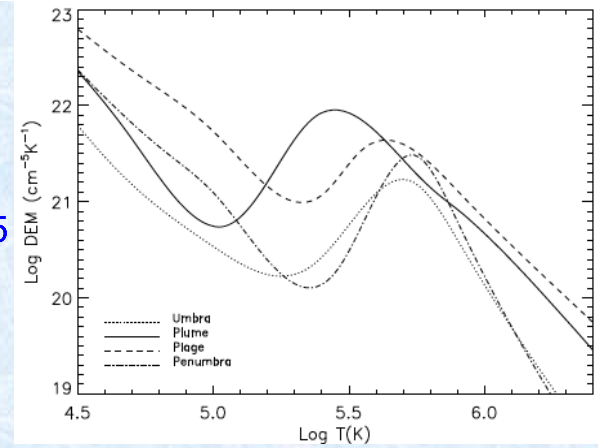
Tian et al. 2009, ApJ, 703, L152



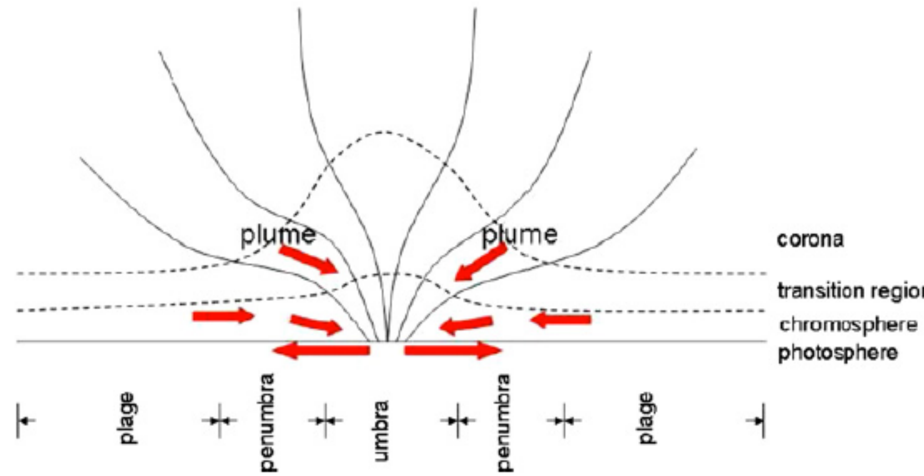


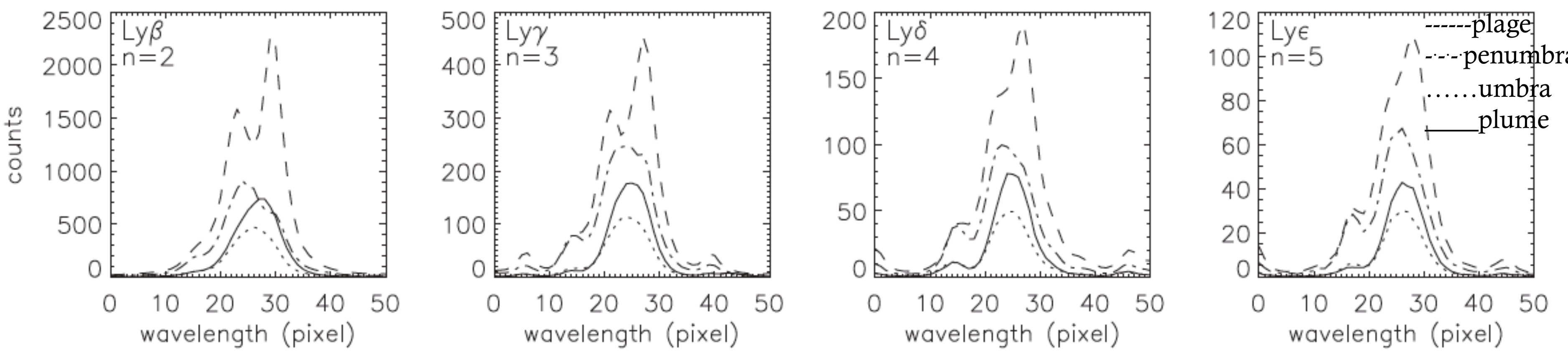
TR in ARs

Dammasch et al. 2008, Ann. Geophys., 26, 2955
Nicolas et al. 1982, Sol. Phys., 81, 253
Tian et al. 2009, A&A, 505, 307



- Sunspot plumes: enhanced emission at TR temperatures
- Much lower density in umbra and plume: $(\log(Ne/\mathrm{cm}^{-3})=10$
- Lyman line profiles not reversed in umbra and plume
- TR above sunspots is higher and probably more extended than in the surrounding plage region





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- Recent observations of TR structures and emission
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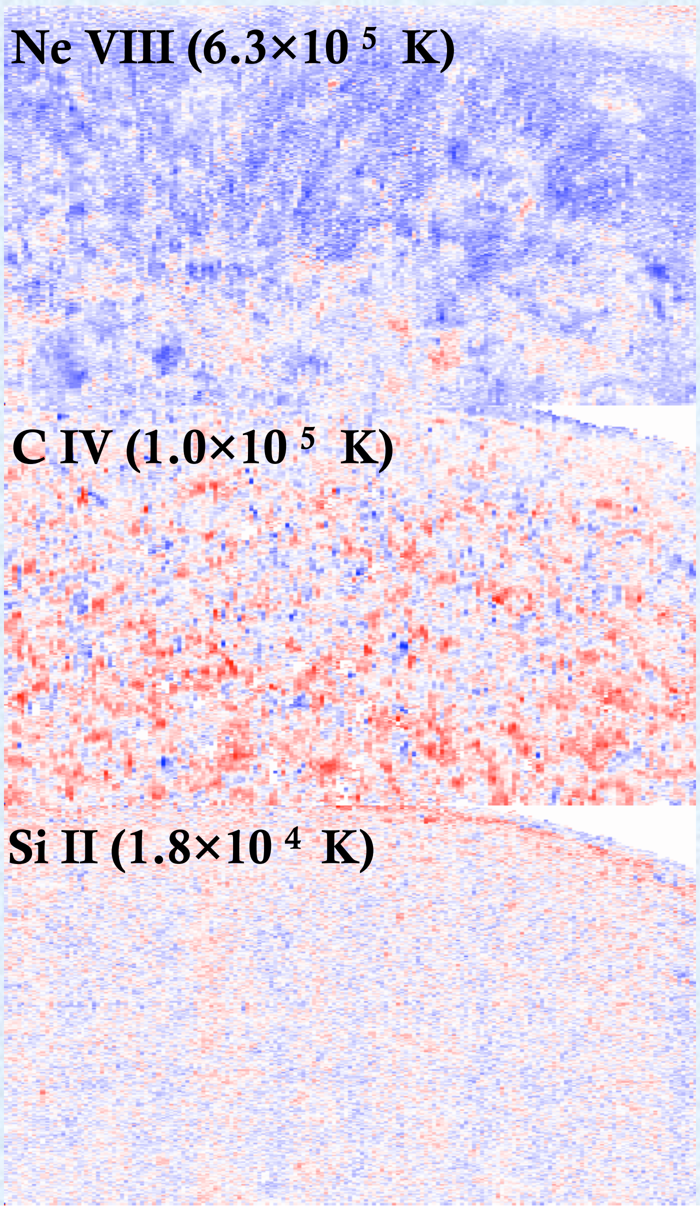
- Mass cycling between the chromosphere and corona/solar wind

Doppler shift in CHs

Polar CH

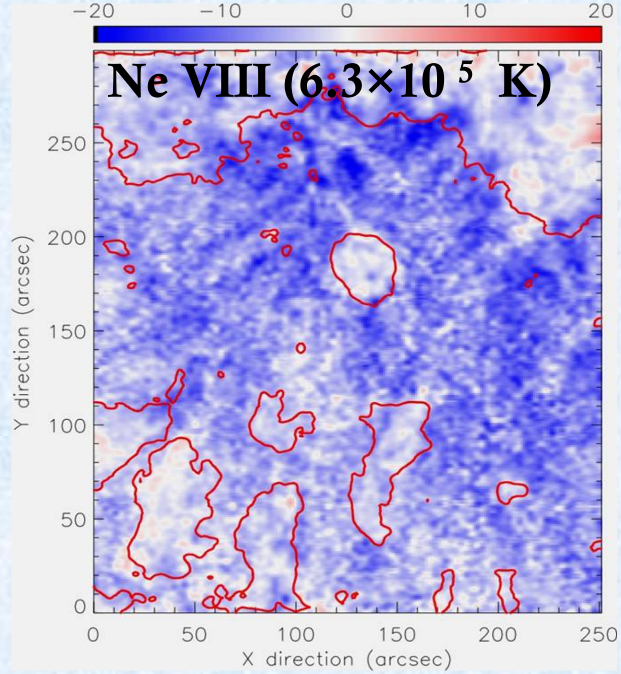


- Upper TR: ubiquitous blue shifts widely interpreted as solar wind origin

- Middle TR: red shift

- Lower TR: small shift

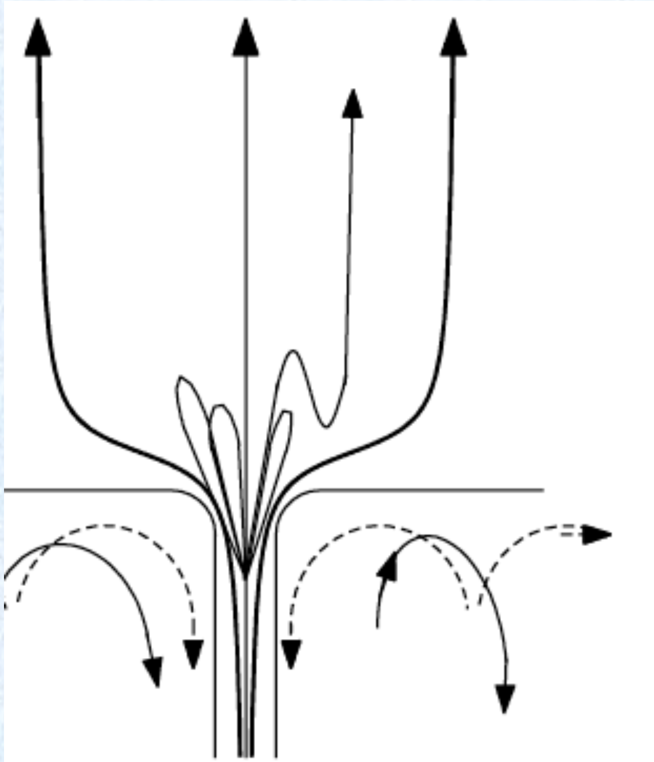
Equatorial CH



Xia et al. 2003, A&A, 399, L5

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

Reconnection driven solar wind model



(c) AXFORD & McKENZIE (1993)

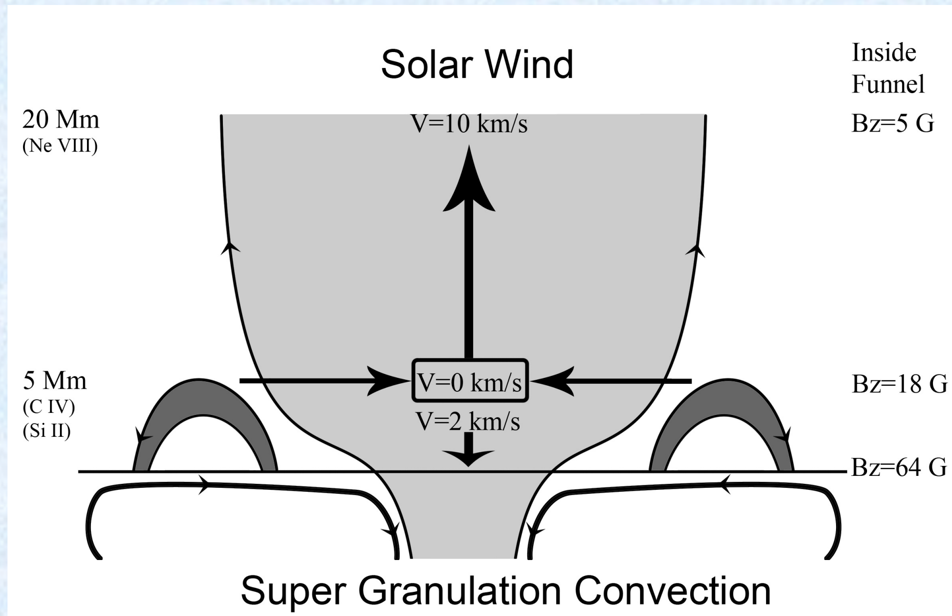
"Junkyard" – dynamic

Reconnection – microflares

Waves → out

Loops → down

New flux fed in at sides

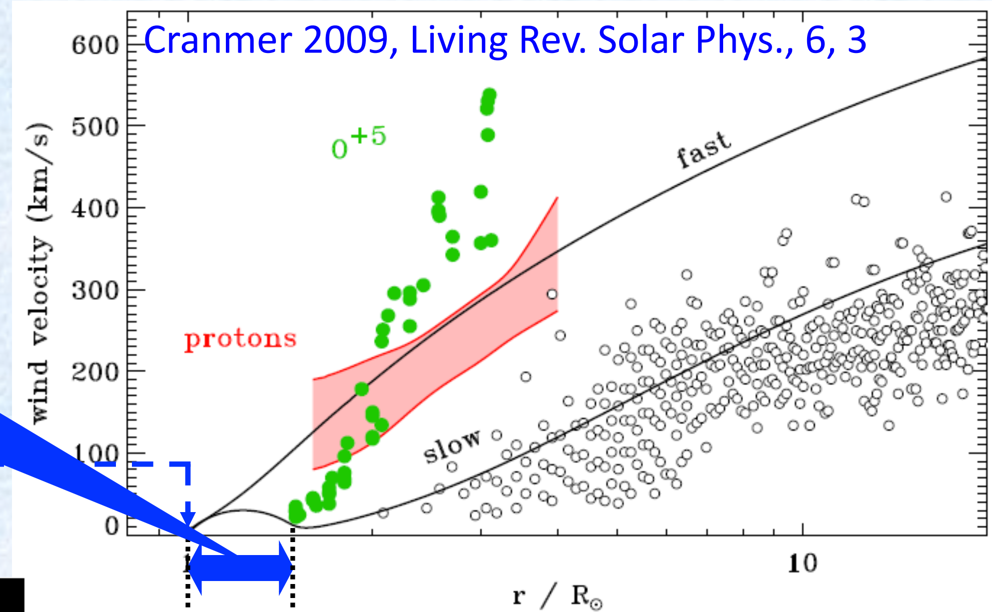


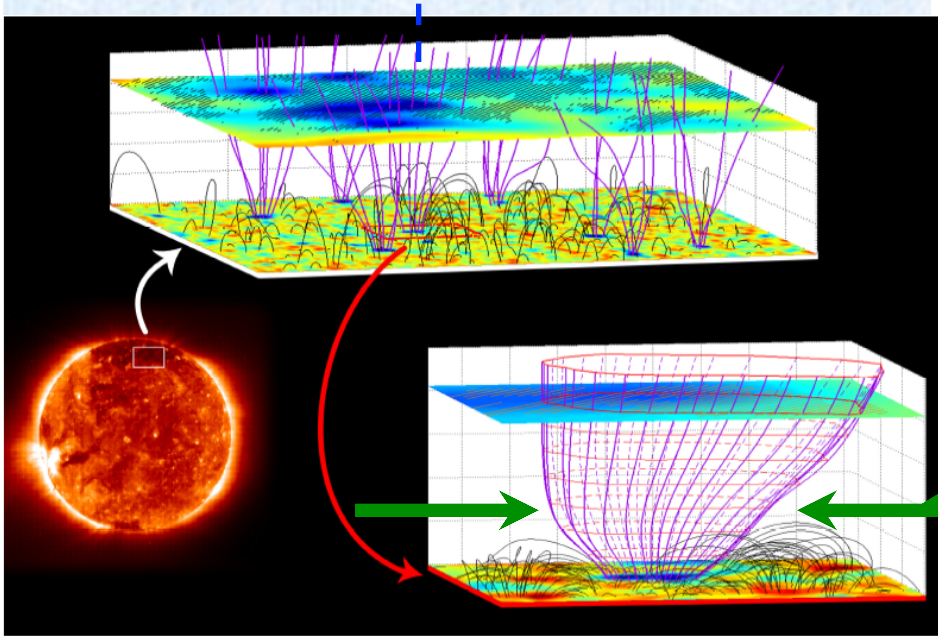
Tu et al. 2005, Science, 308, 519

Tu et al. 2005, Solar Wind 11

Fast wind from magnetic funnels

Initial acceleration (from ~5 km/s to ~100 km/s)



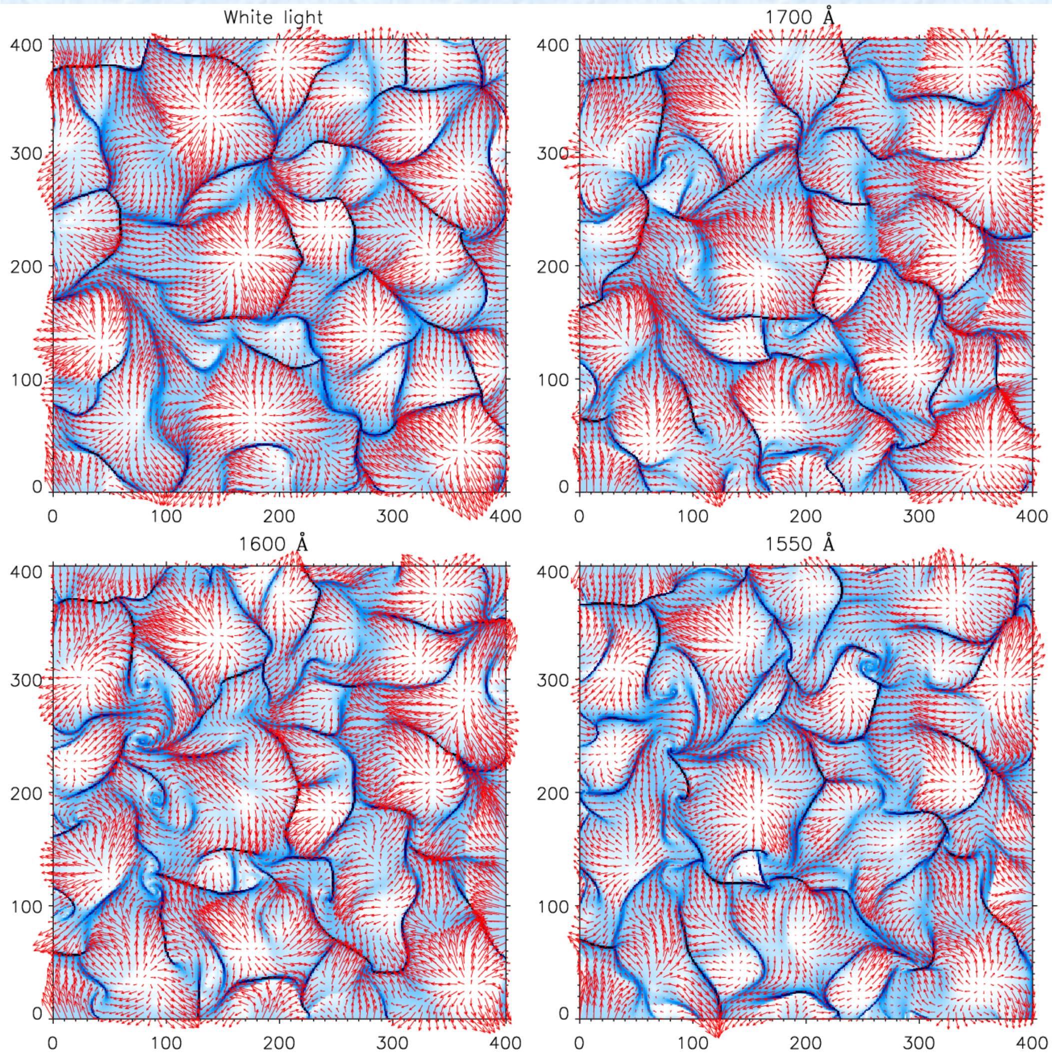


Solar wind mass supply through supergranule-scale magnetoconvection in the chromosphere & TR

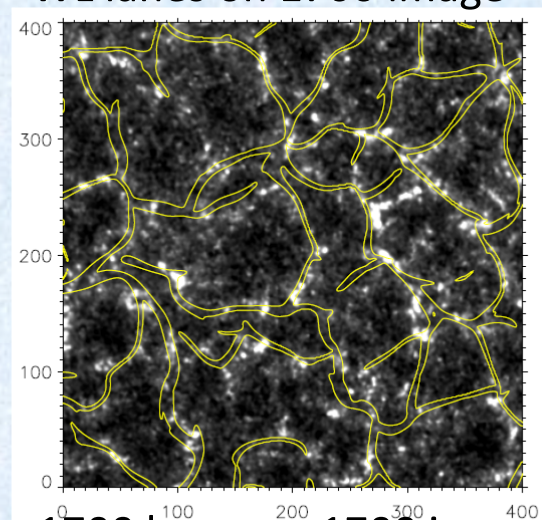
Tu et al. 2005, Science, 308, 519

Tu et al. 2005, Solar Wind 11

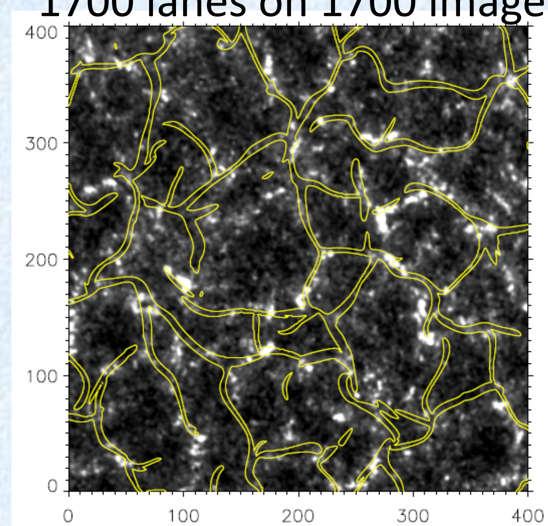
Signature of supergranule-scale magnetoconvection in the chromosphere



WL lanes on 1700 image



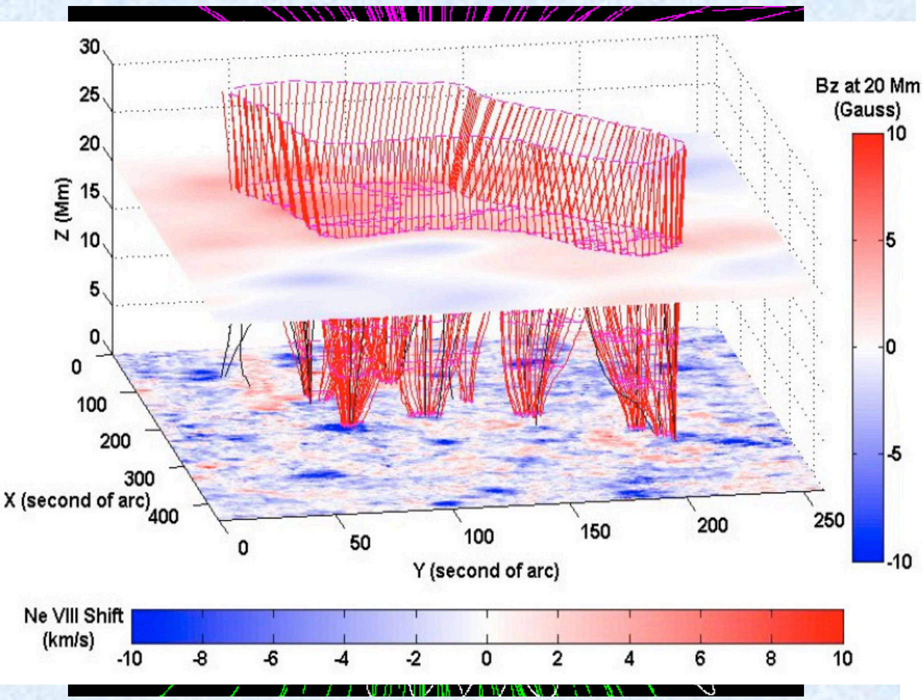
1700 lanes on 1700 image



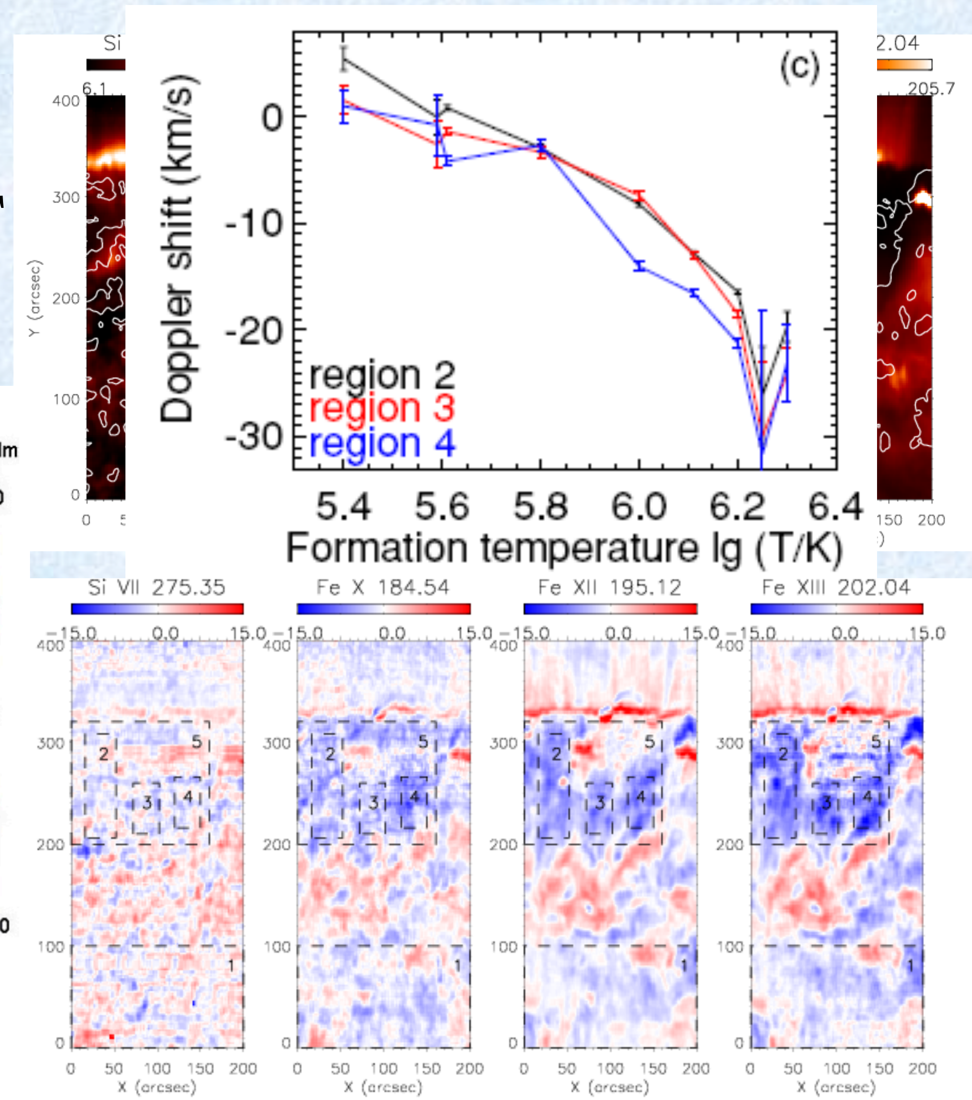
Tian et al., A&A, 519, A58, 2010

Initial acceleration of the fast solar wind (I)

- Blueshift in TR and coronal lines, increases with T
- Blueshift patches converge as T increases

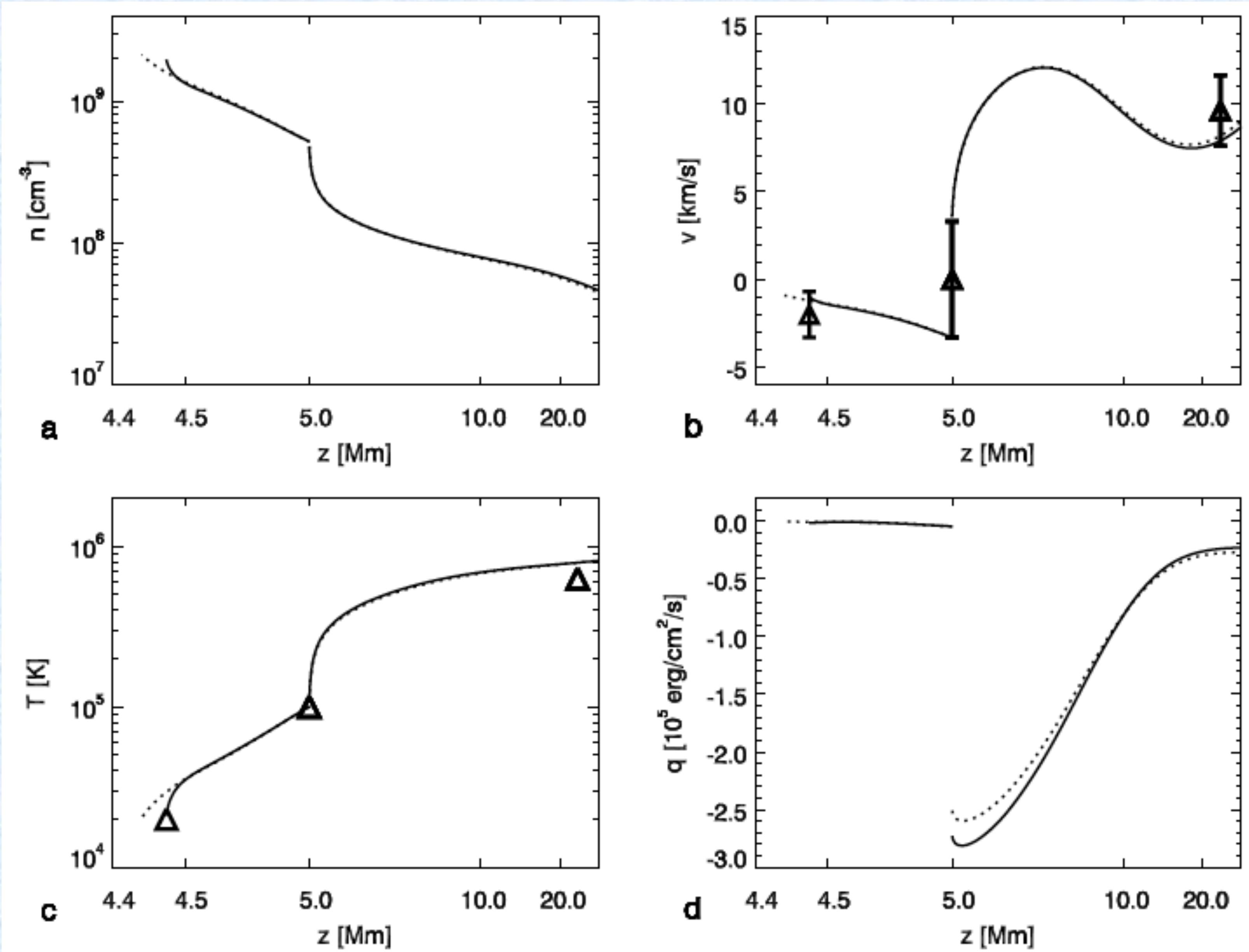


Tian et al., A&A, 478, 915, 2008



Tian et al., ApJ, 709, L88, 2010

1-D model



He et al. 2008, Sol. Phys., 250, 147

Outline

- Recent observations of TR structures and emission
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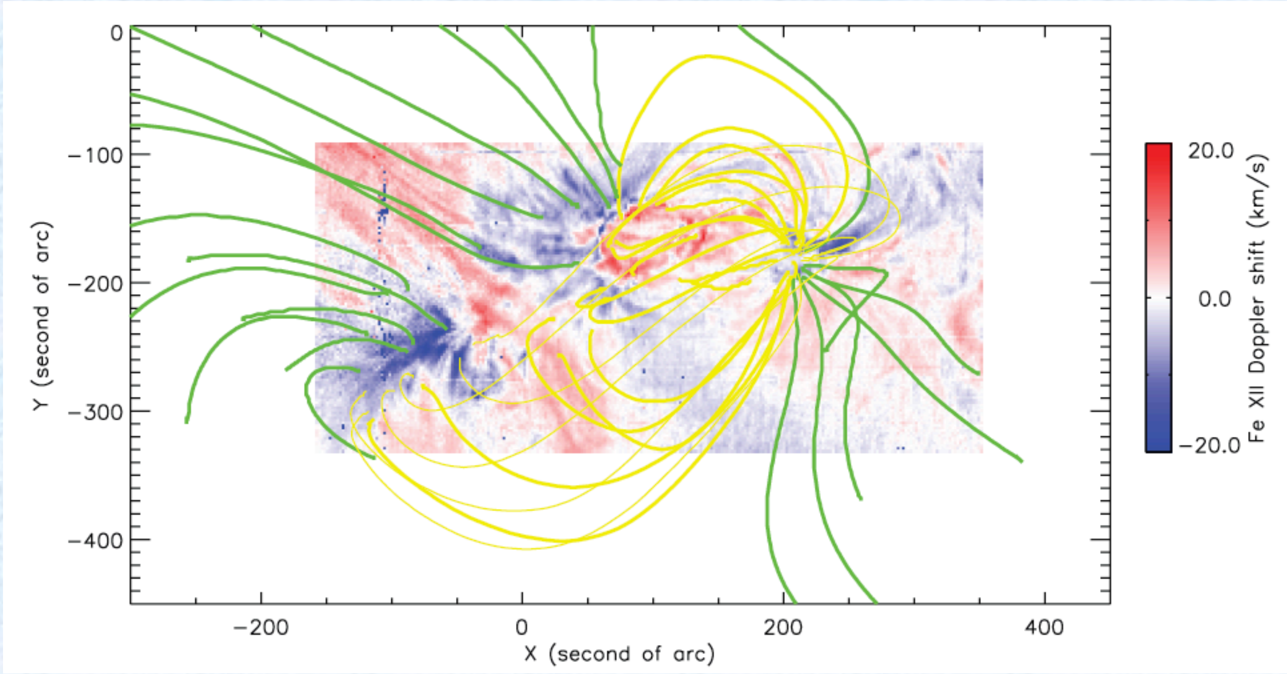
Coronal circulation



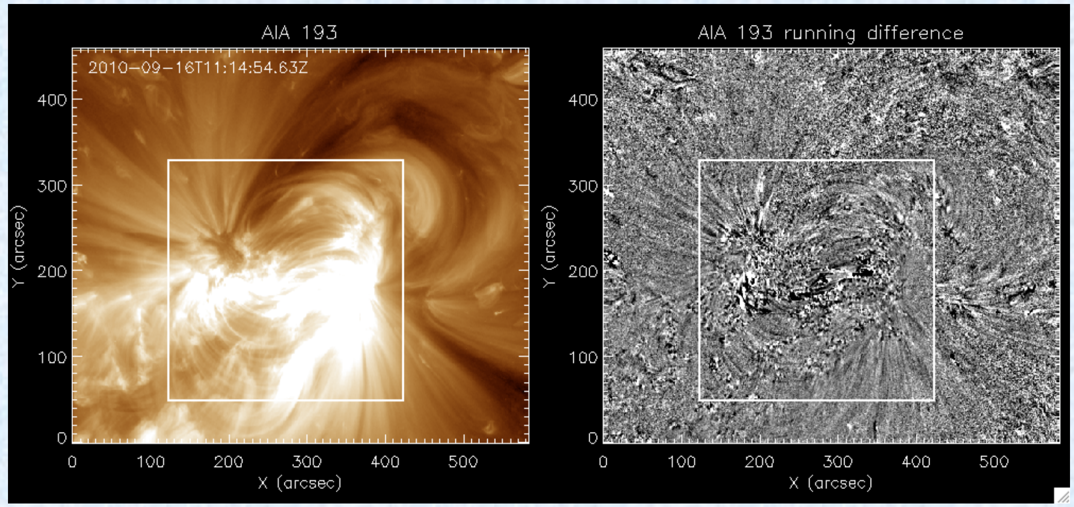
Marsch et al. 2008, ApJ, 685, 1262

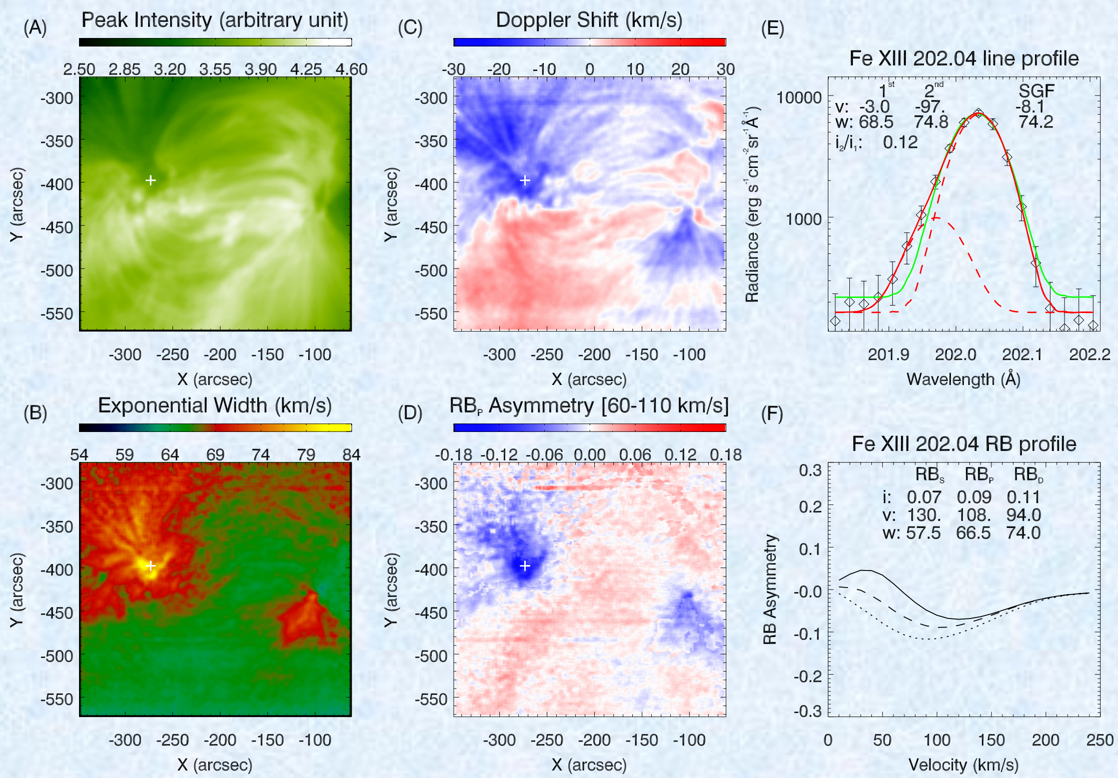
▪ To emphasize that the plasma in the TR & corona is nowhere static but everywhere flowing, strongly guided by various magnetic channels. Evidence for these processes exists in the ubiquitous redshifts mostly seen at both legs of loops on all scales, and the sporadic blueshifts occurring in strong funnels. 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.

High-speed upflows at AR edges

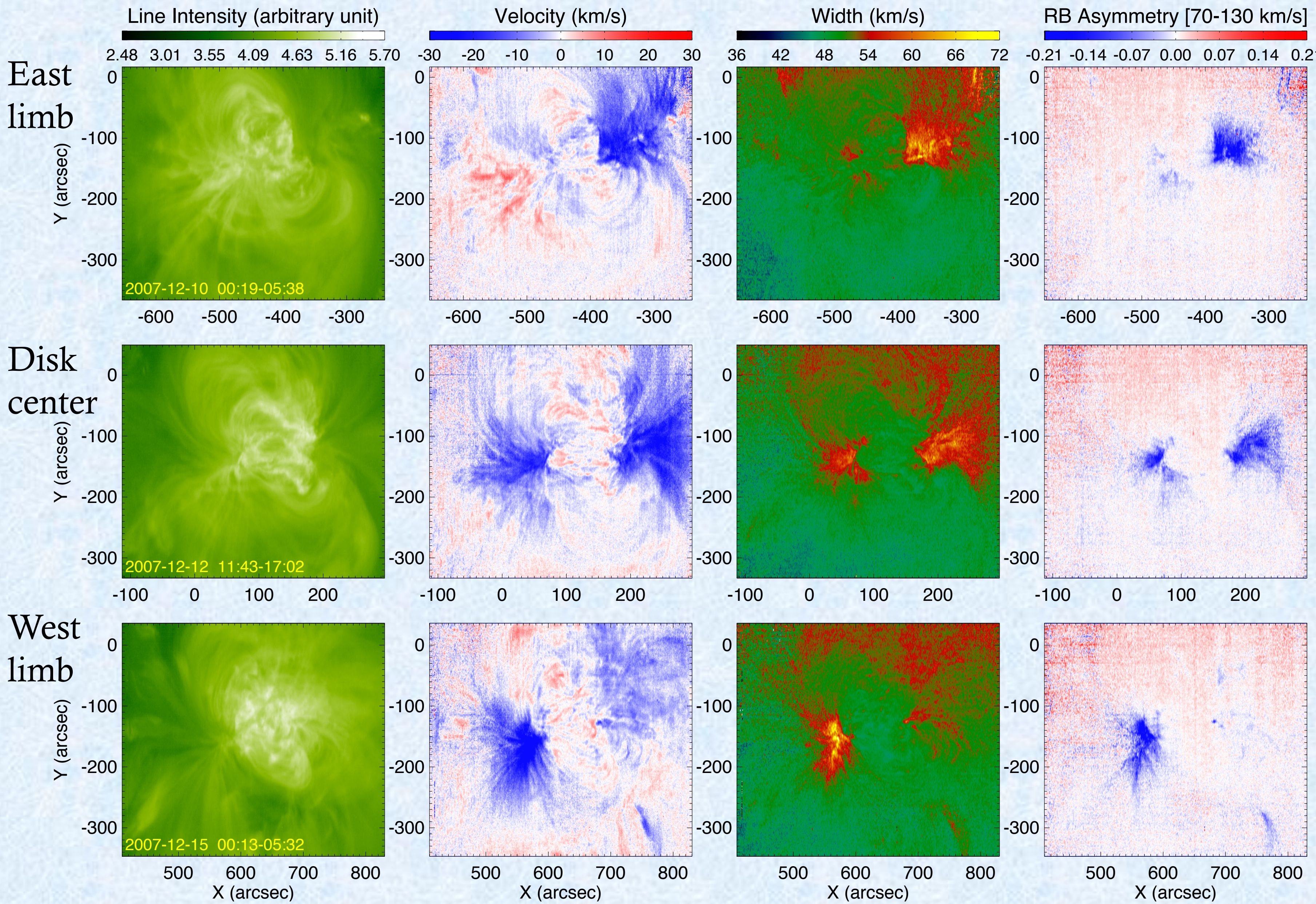
- PDs in EUV & X-Ray images: upflow speed ~100 km/s
- EUV spectroscopy:
  - ➢Blue shift of coronal lines 20km/s: not true!
  - ➢Enhanced blue wing in line profiles: an almost stationary primary component and a high-speed secondary component
  - ➢We use both double Gaussian fit and profile asymmetry analysis





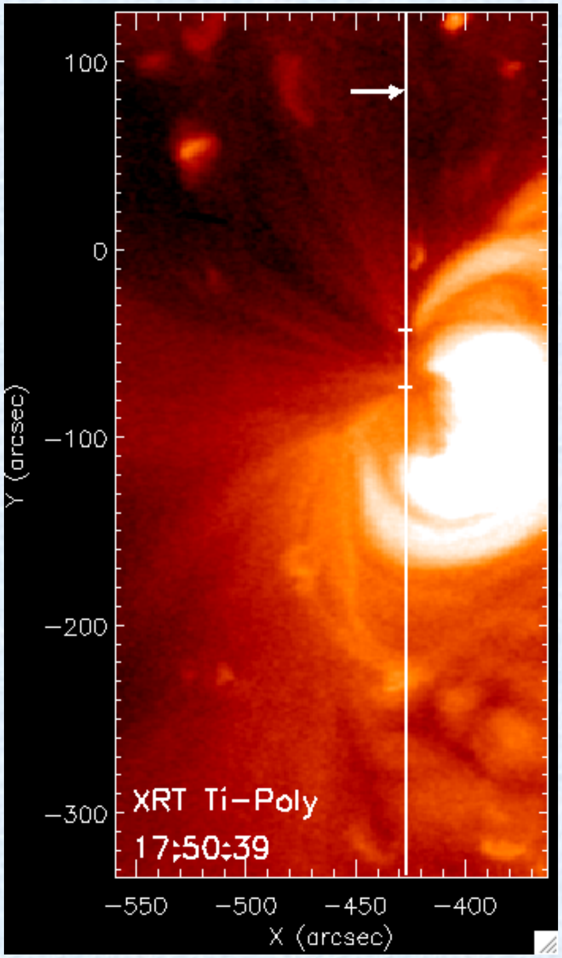
Tian et al. 2011, ApJ, 738, 18
Dolla & Zhukov 2011, ApJ, 730, 113
Bryans et al. 2010, ApJ, 715, 1012
Peter 2010, A&A, 521, A51
McIntosh & De Pontieu 2009, ApJ, 706, L80
De Pontieu et al. 2009, ApJ, 701, L1
Hara et al. 2008, ApJ, 678, L67

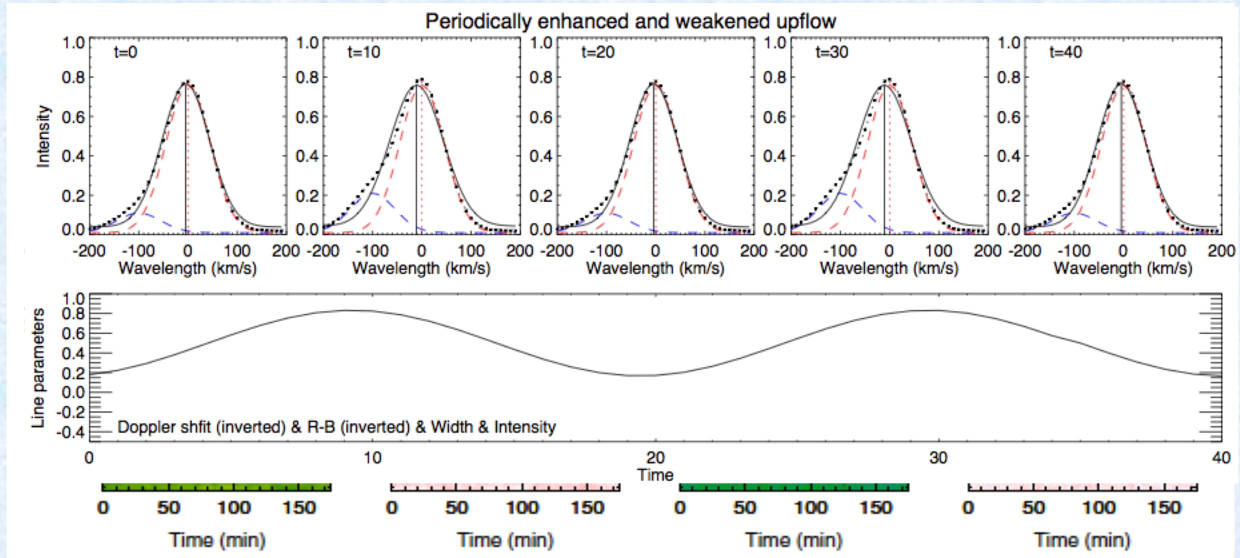
Profile asymmetry not caused by noise or blend

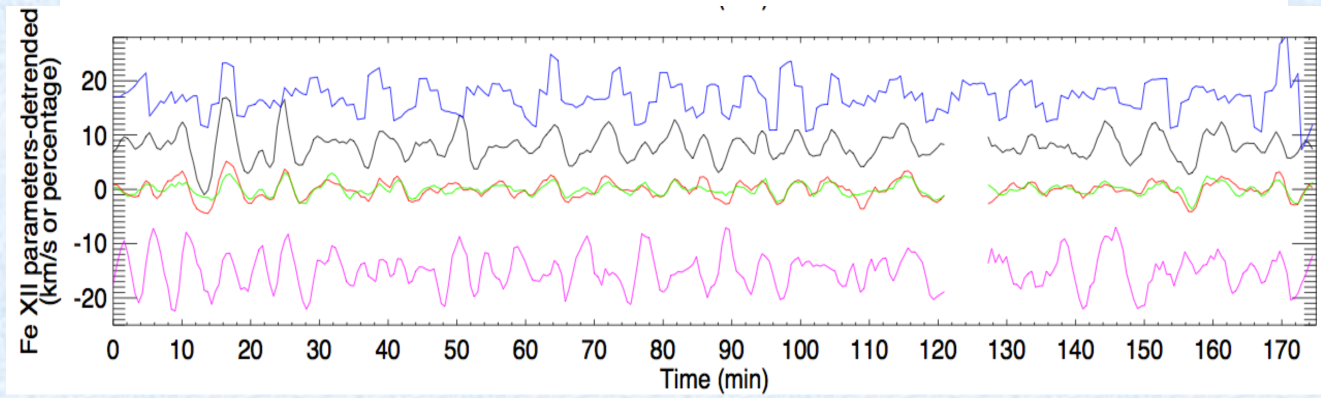


Tian et al. 2012, ApJ, 748, 106

Periodicity of the high-speed outflow





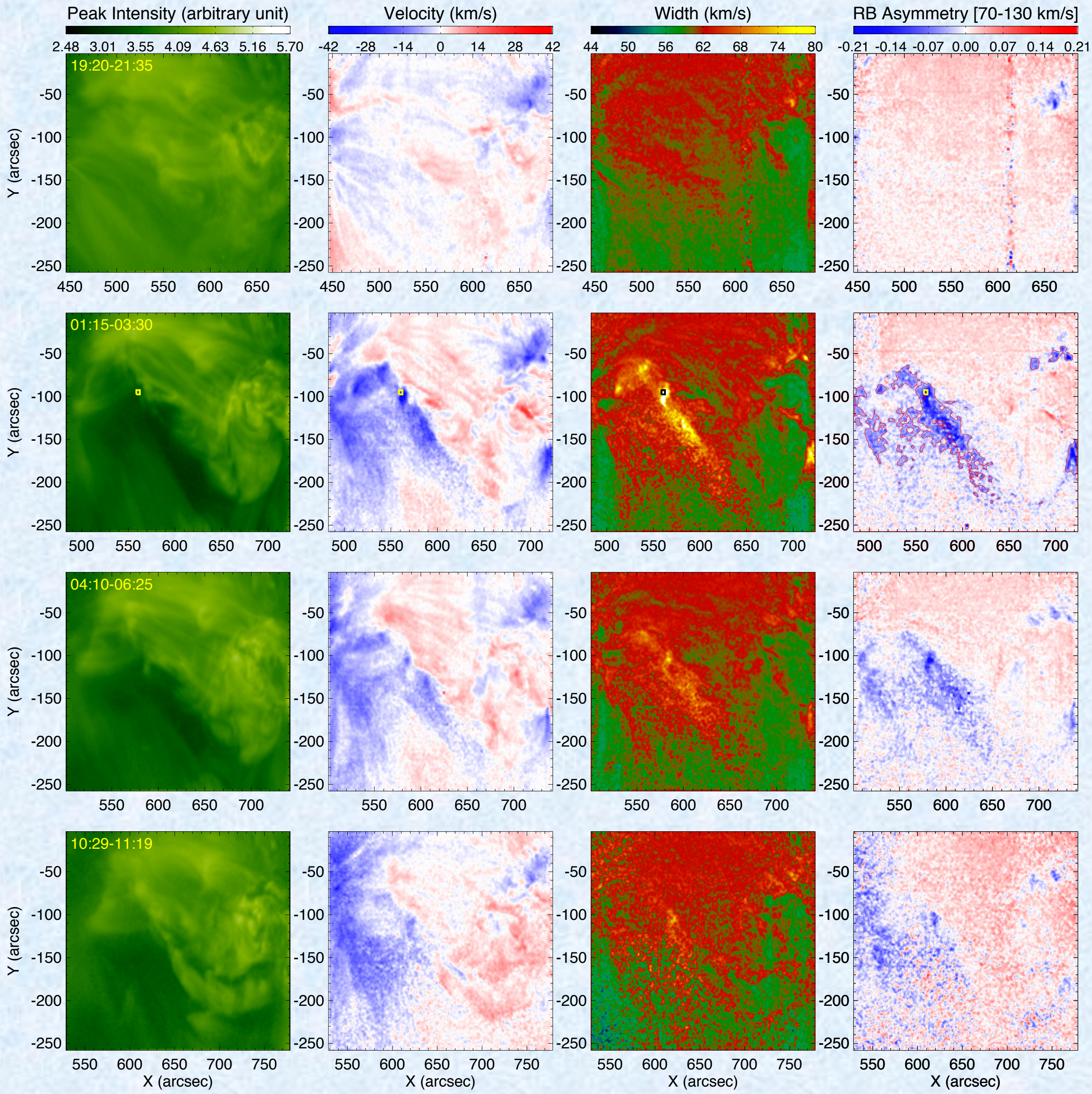


Tian et al., ApJ, 727, L37, 2011
De Pontieu & McIntosh, ApJ, 722, 1013, 2010

- Blueshfit & blueward asymmetry all the time
- All line parameters show in-phase quasi-periodic variation, consistent with the scenario of recurring upflow
- XRT intensity and EIS line parameters show similar oscillatory behavior, suggesting that PDs are responsible for the 2nd component
- solar wind is not continuous but intermittent?

black: intensity
red: Doppler shift (inverted)
green: line width
purple: R-B (inverted)
blue: XRT intensity

Outflows in CME-related dimming region

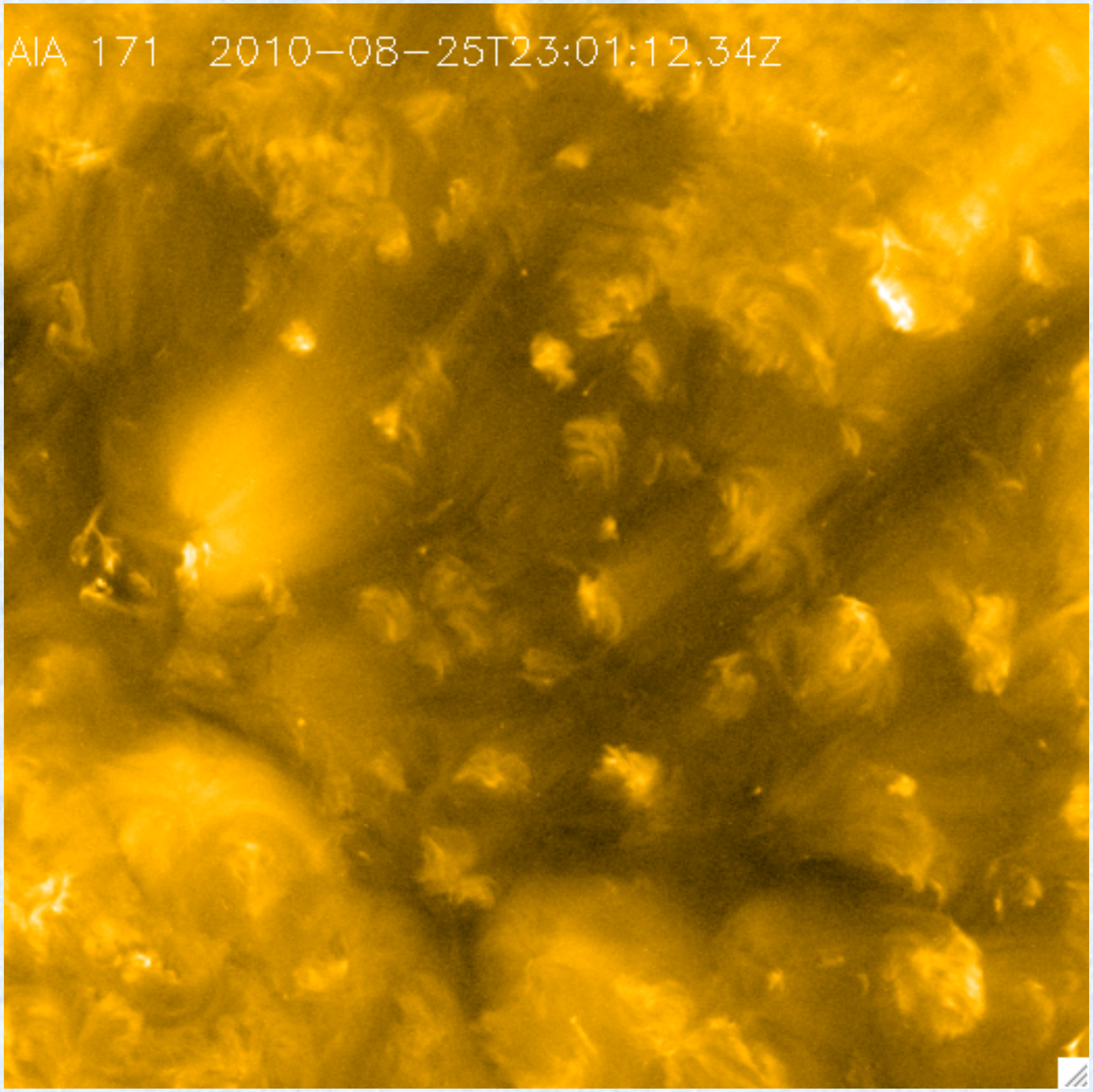


Solar wind outflows and Alfven waves along the field lines opened by CME eruption?

Tian et al. 2012, ApJ, 748, 106

Ubiquitous high-speed outflows in CHs

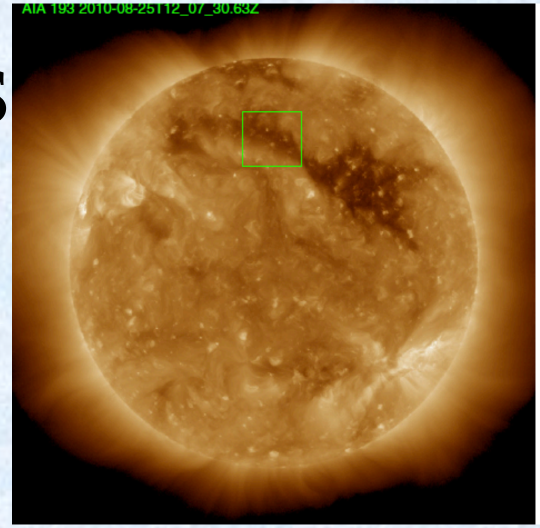
- AIA observations reveal unprecedented details inside CHs
- Plumes, PDs and Alfven waves are present in CHs
- Mass flux density: $1.67\text{X}10^{-9}$ g cm^{-2} s^{-1} if using $\log(N\text{e}/\text{cm}^{-3})=8$ and v=100 km s^{-1}, mass flux two orders higher than that of solar wind
- Energy flux of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

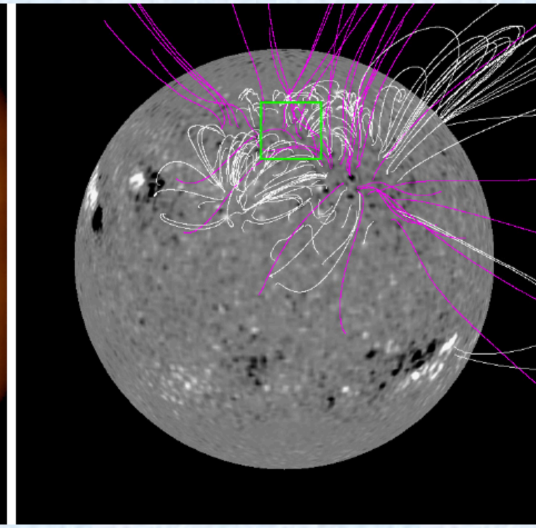


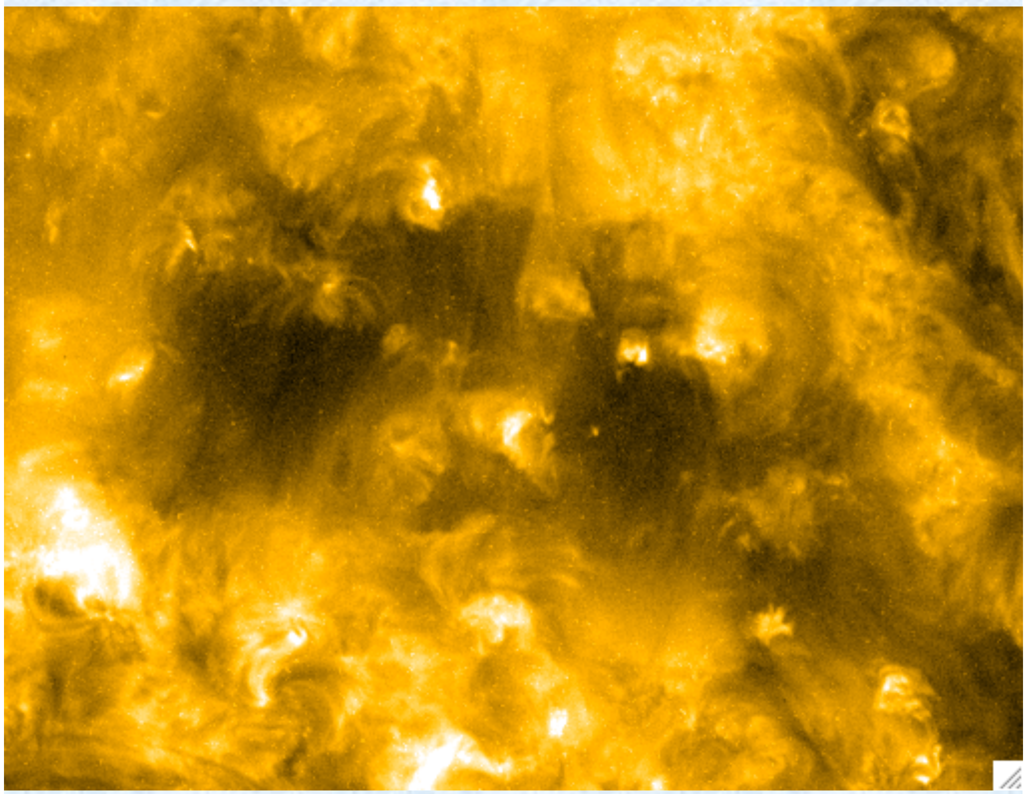
Tian et al. 2011, ApJ, 736, 130

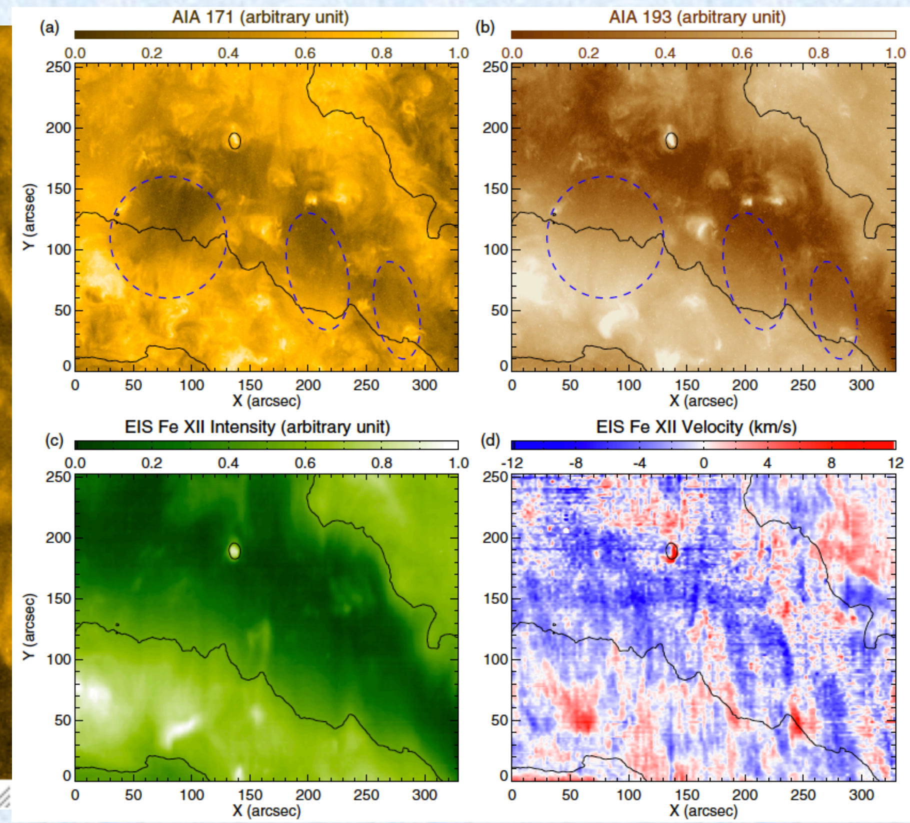
High-speed outflows in QS

- QS plumes often project onto the plane of the sky above surrounding CH
- Blue shifts in CH might be contaminated by QS outflows, not pure signatures of the fast solar wind





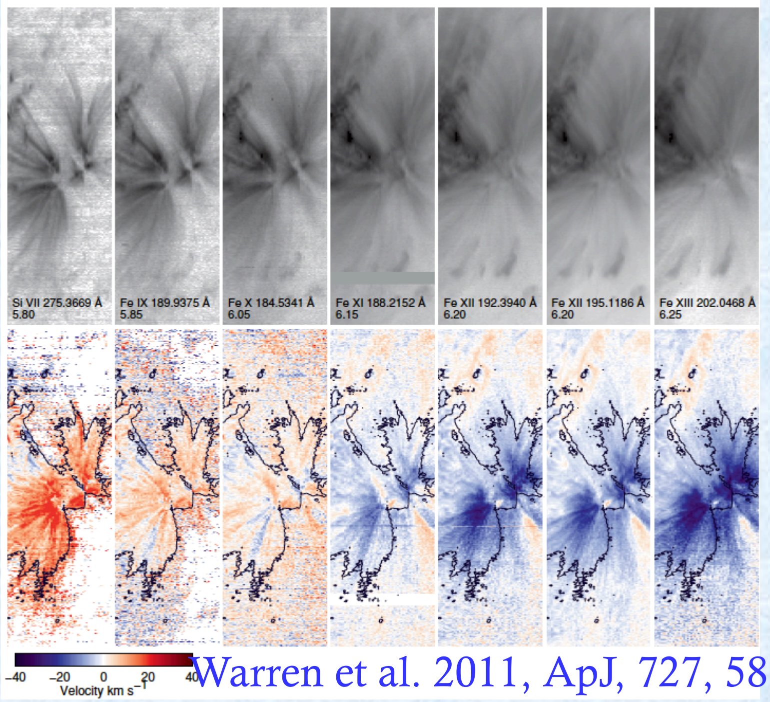




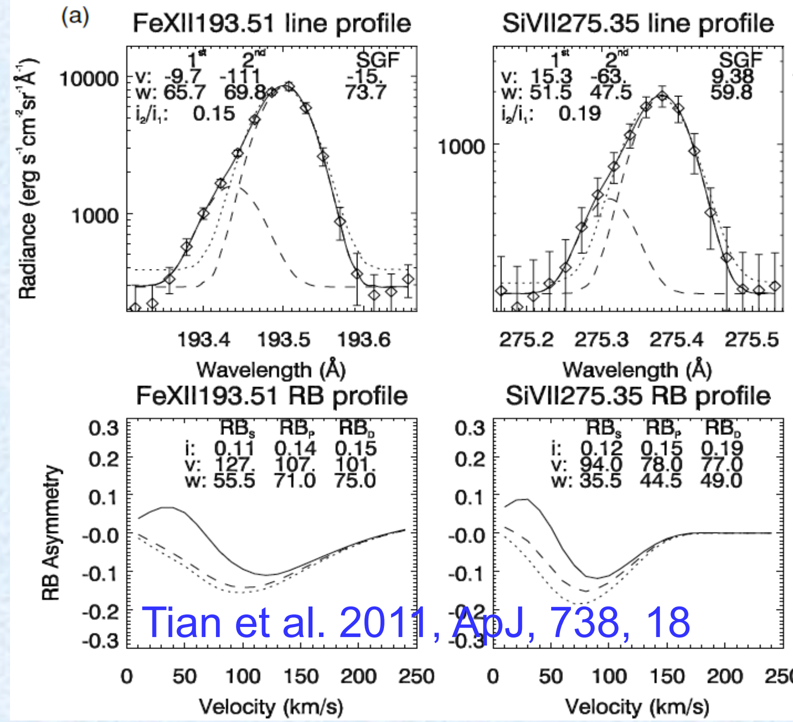
Tian et al. 2011, ApJ, 736, 130

Profile asymmetry of TR lines

EIS

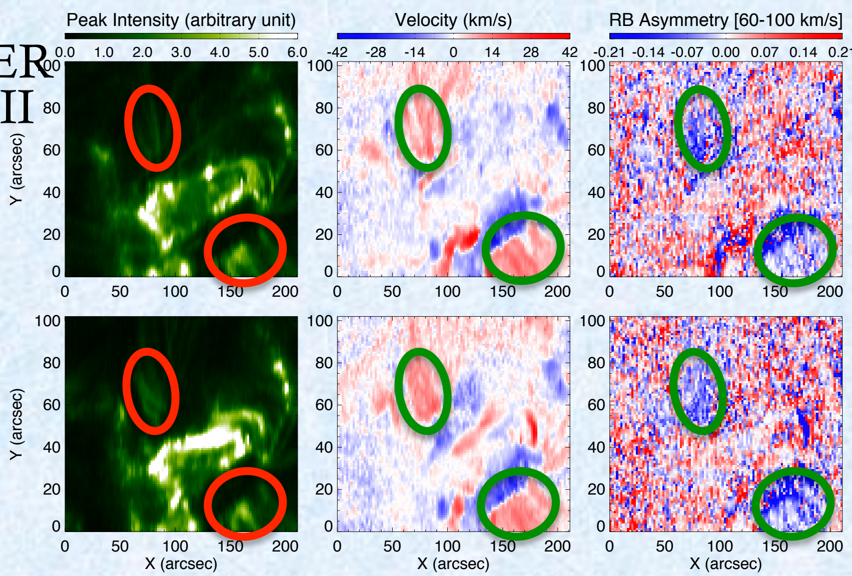


Warren et al. 2011, ApJ, 727, 58



Tian et al. 2011, ApJ, 738, 18

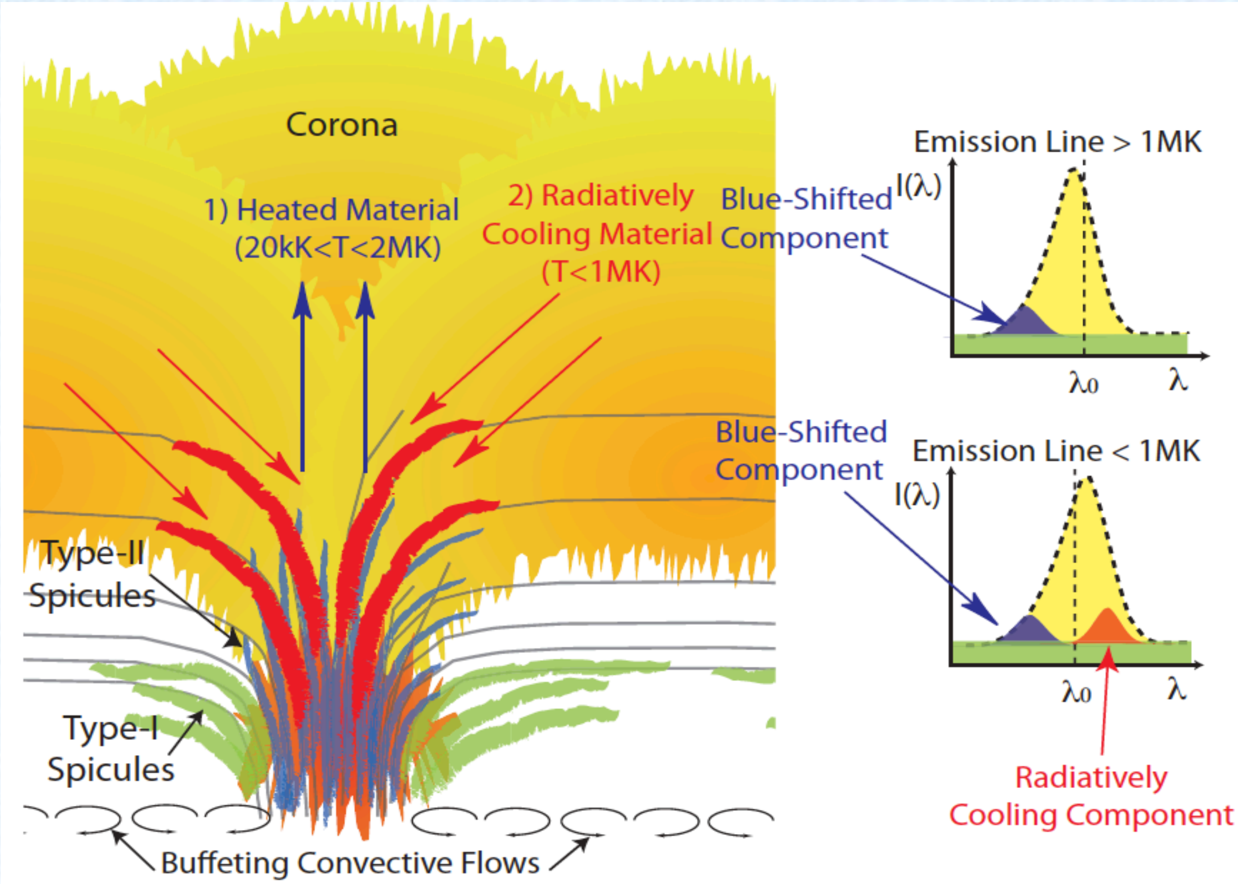
SUMER
Ne VIII



- From red shift at log T<6.0 to blue shift at log T>6.0
- Blueward asymmetry also clearly present in some locations
- Derived velocity of the 2nd comp. is smaller
- Cool lines are complicated by cooling downflows!

Mass circulation-three emission components

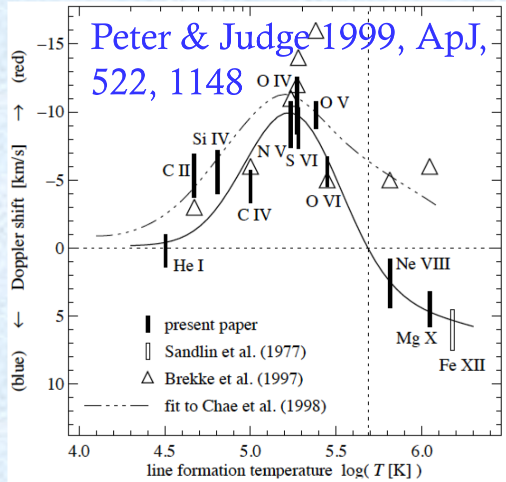
- A nearly static background
- A high-speed (~100 km/s) outflow resulting from impulsive heating in the chromosphere: type-II, PDs
- A downflow (~20 km/s) corresponding to the cooling of previously heated plasma: downflows in TR passbands

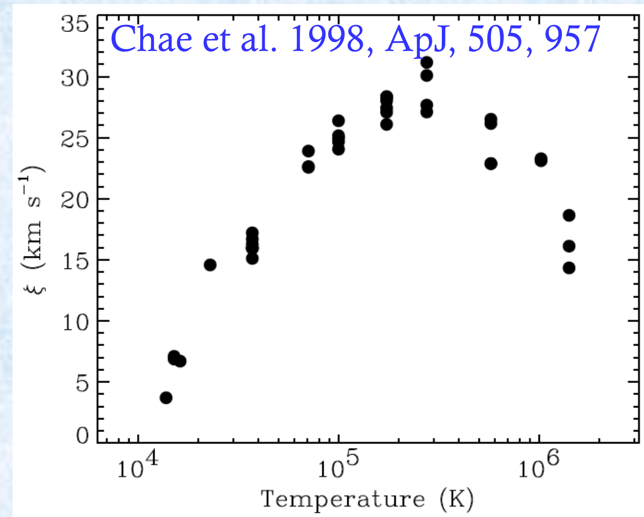


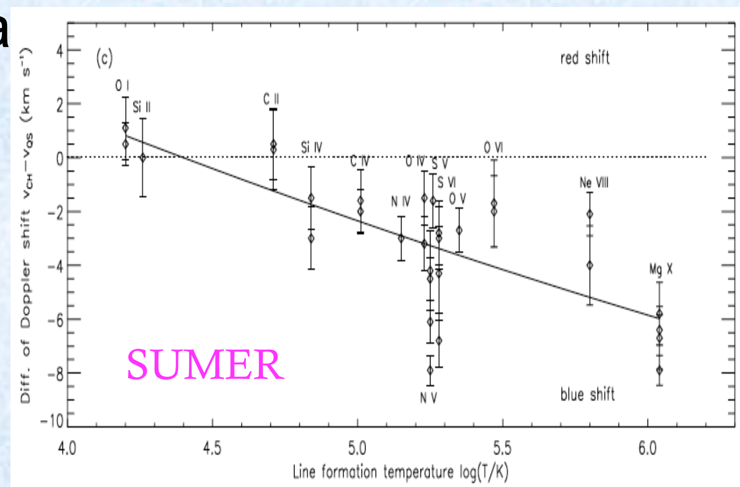
McIntosh et al. 2012, ApJ, 749, 60

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

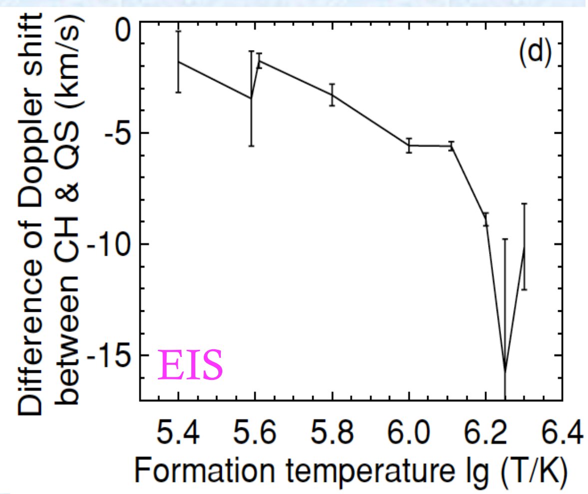
- It is probably the different relative contributions of the three components that produce these magic curves!
- More blueshifted in CH than in QS: less return of outflowing plasma
- Next step: unambiguously resolve the three components at different temperatures







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



Tian et al. 2010, ApJ, 709, L88

Summary

- TR structures
  - TR might be locally thin, but are highly nonuniform.
  - TR is higher and more extended in CH than in QS. Magnetic structures expand through TR more strongly in CH than in QS.
  - Clean solar Ly α profiles have been obtained in different regions, to be reproduced and explained by solar atmosphere models
  - TR above sunspots is higher and probably more extended than in the surrounding plage region
- Reconnection driven solar wind model
  - supergranule-scale convection in the chromosphere
  - Initial acceleration
  - 1-D model
- Mass circulation in TR and corona
  - High-speed upflows have been observed by both imaging and spectroscopic observations in various regions on the Sun, mass supply to the corona and solar wind at a speed of the order of 100 km/s, not ~10 km/s; is intermittent, not continuous
  - Two components in coronal lines and three components in TR lines