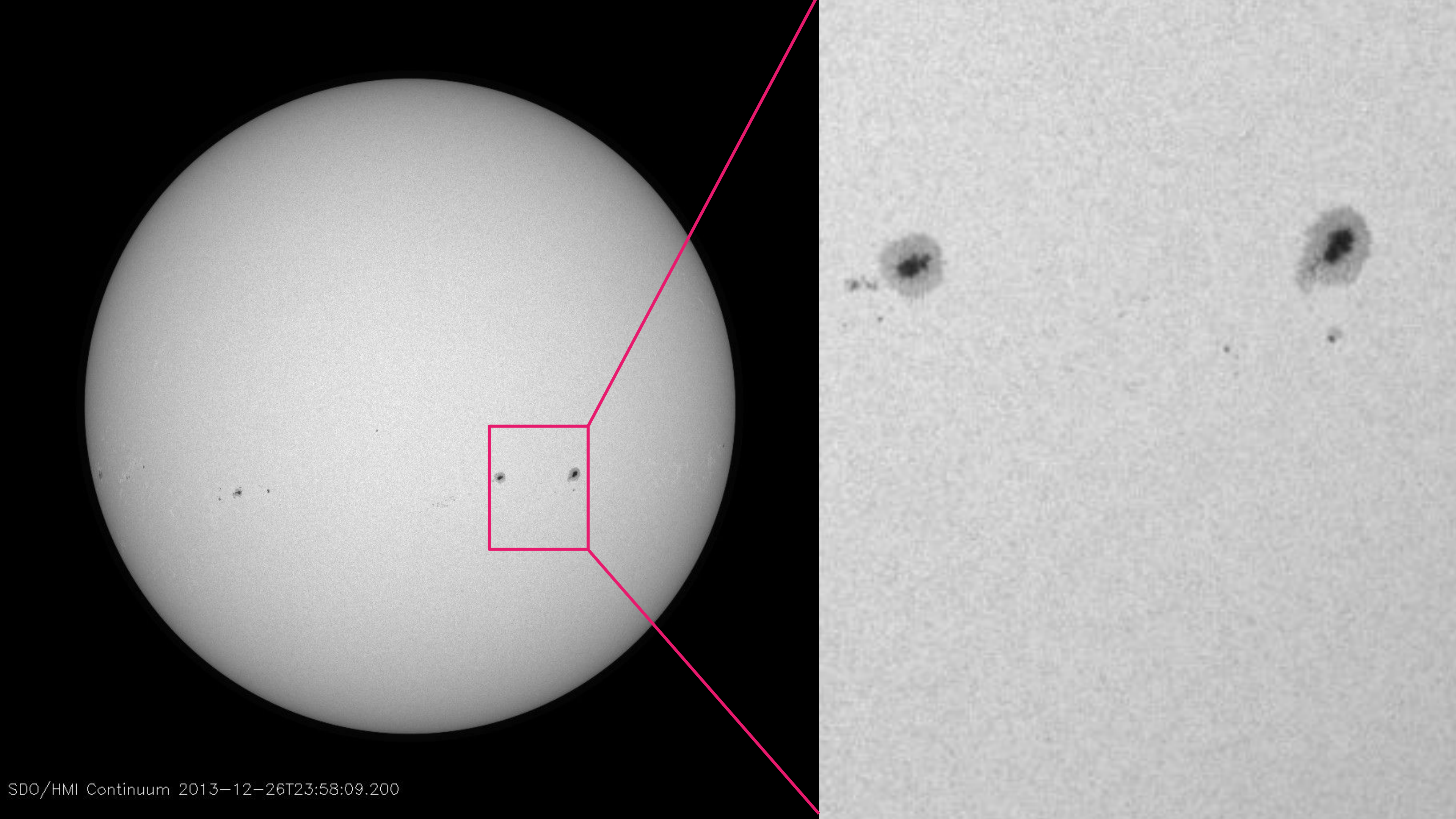
On the origin of solar wind and solar coronal heating

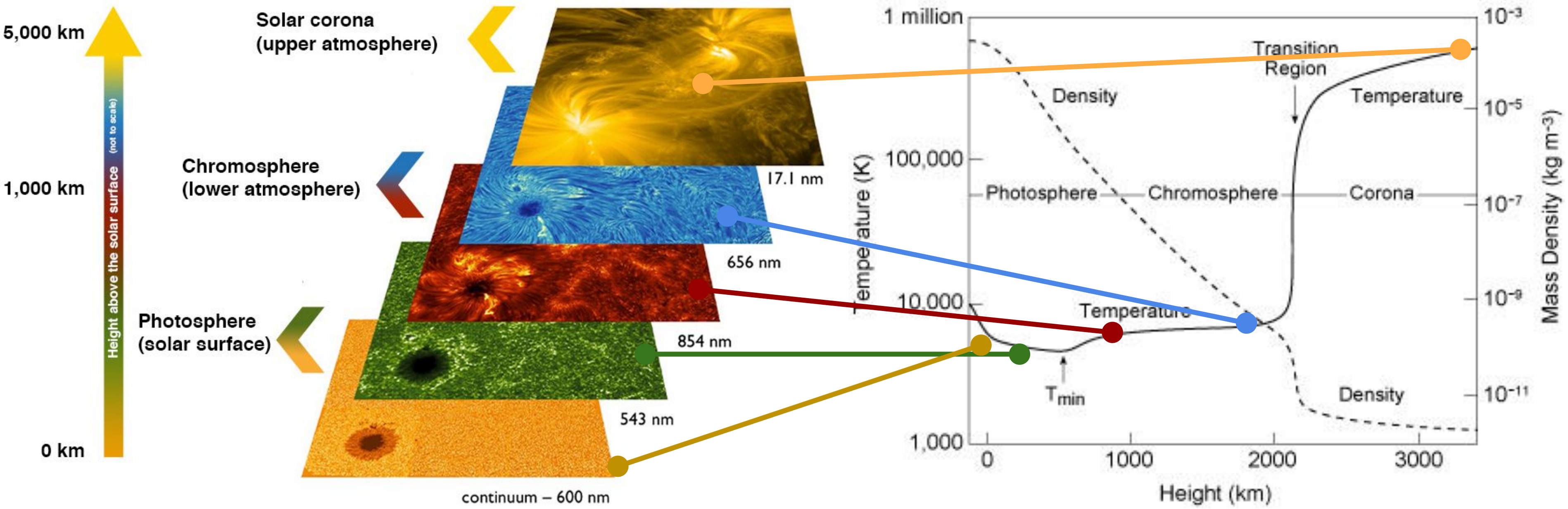
Vishal Upendran[1], Durgesh Tripathi[1]
Inter University Centre for Astronomy and Astrophysics, Pune

Credit: u/HTPRockets on Reddit: Eruptive solar prominence and fine spicules along the limb


One fine day at IUCAA 🖤


SDO/HMI Continuum 2013-12-26T23:58:09.200

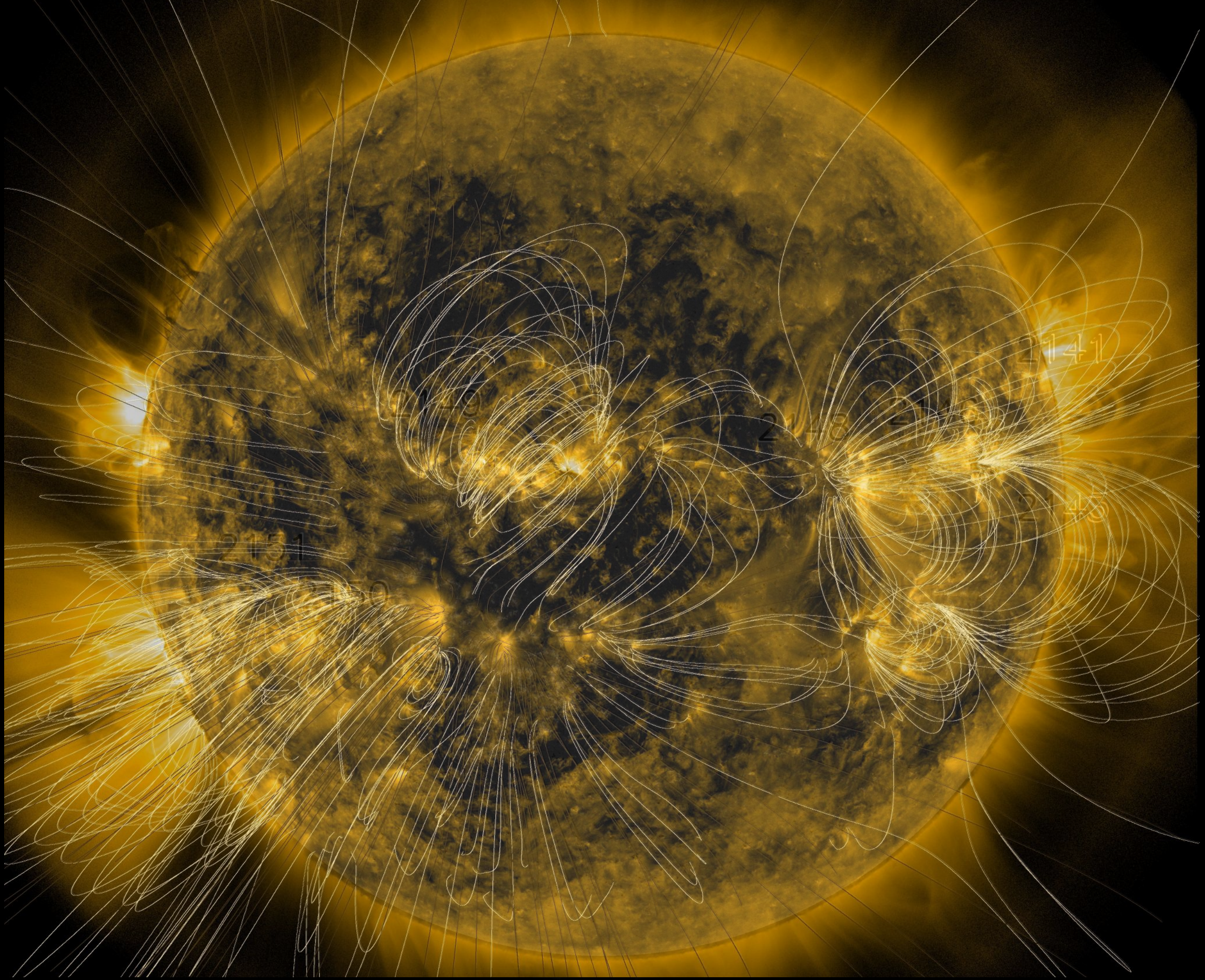
The solar atmosphere



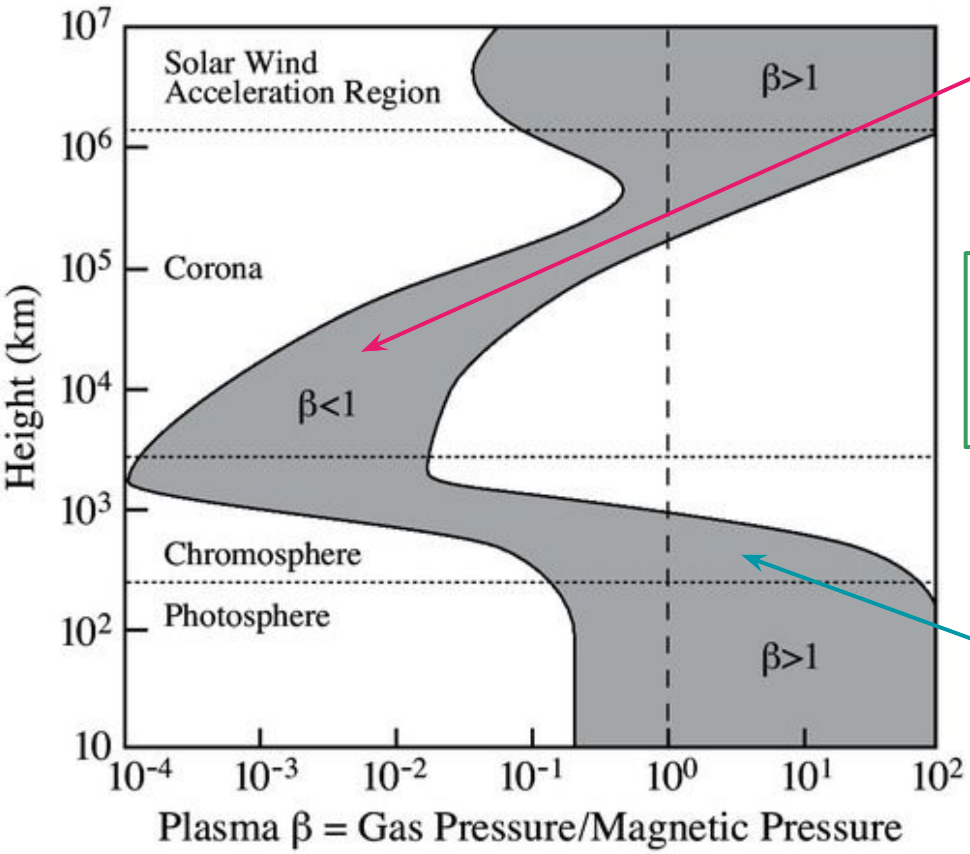
Credit: NSO/AURA/NSF & NASA/SDO;

Credit: NASA's Cosmos

The Magnetic Sun



What dictates the dynamics?



Magnetic field dictates dynamics.

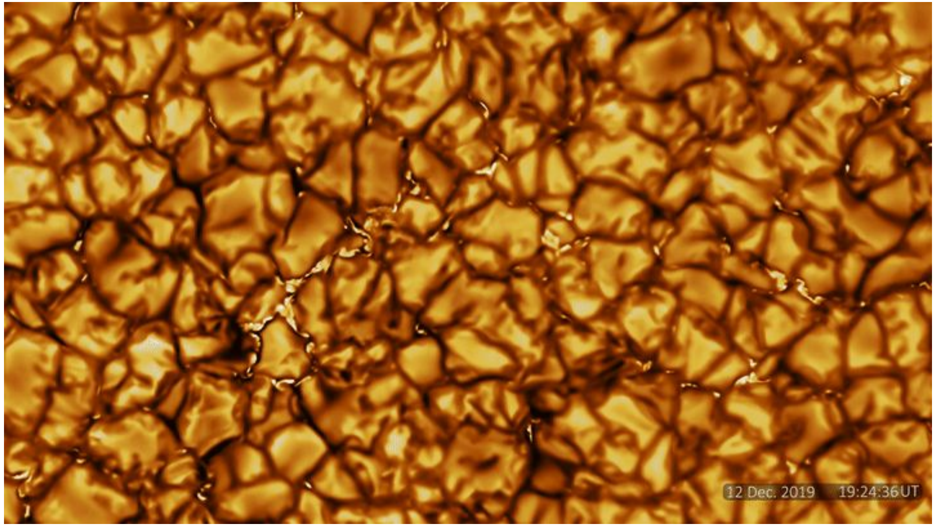
From G. Allen Gary, Plasma beta above a solar active region: Rethinking the paradigm, Solar Physics 203, 71-86 (2001).

Gas pressure or velocity dictates dynamics.

Let’s embark on a journey of plasma, starting from the photosphere!

T ≈ 5500 K, $\beta > 1$

Photosphere: The churning of plasma

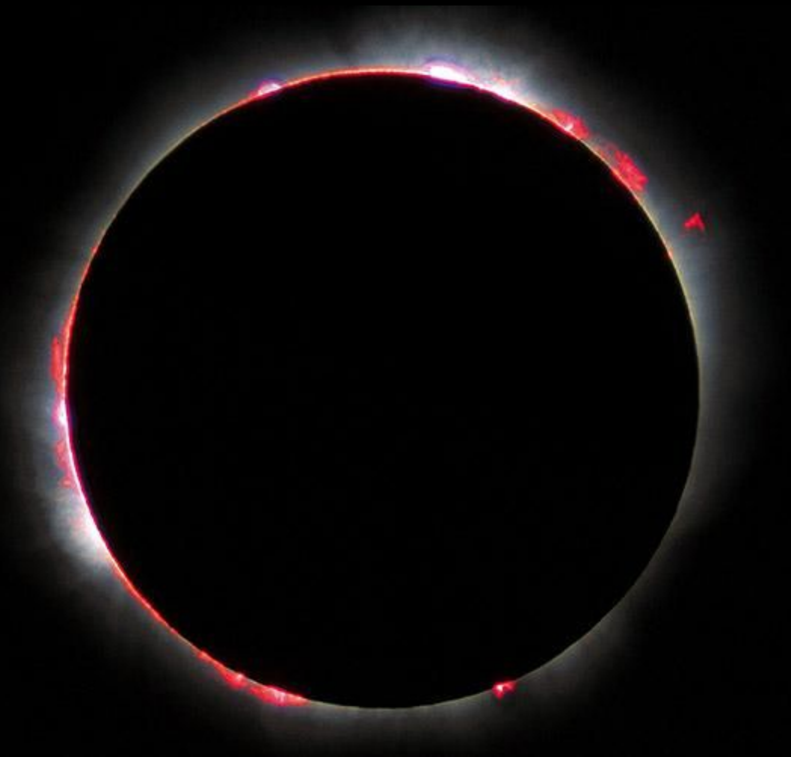


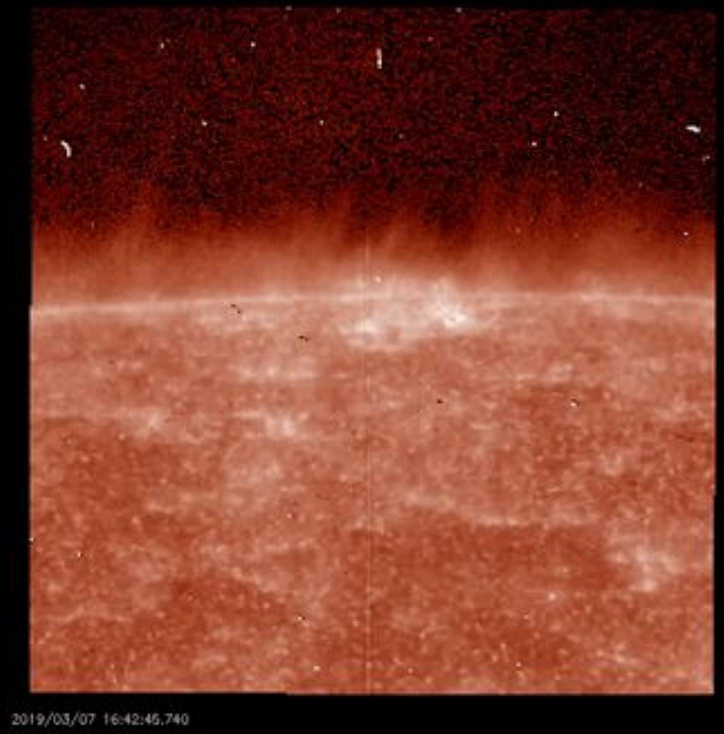
Convection: Sun. Credit: DKIST/NSO/NSF/AURA

Convection: On a stove

Chromosphere: The ring of colours!

$T \approx 10^4 - 8x10^4$ K, $\beta \approx 1$



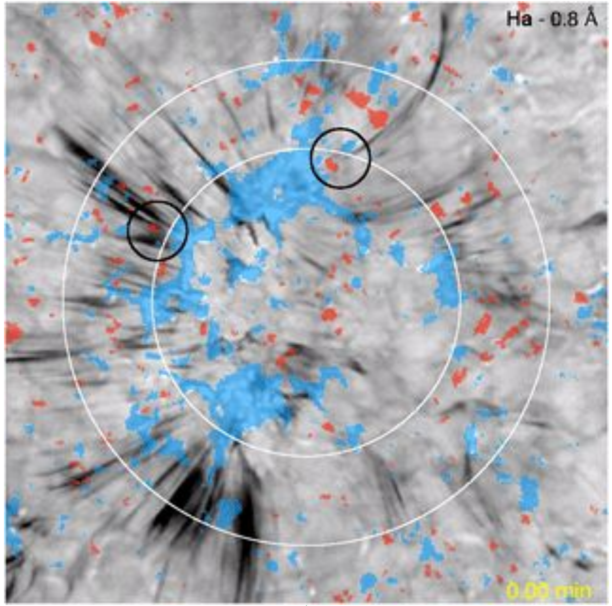


Chromosphere: Credit: Luc Viatour; UCAR

Plumes: IRIS, LMSAL/NASA, Krzysztof Barczynski

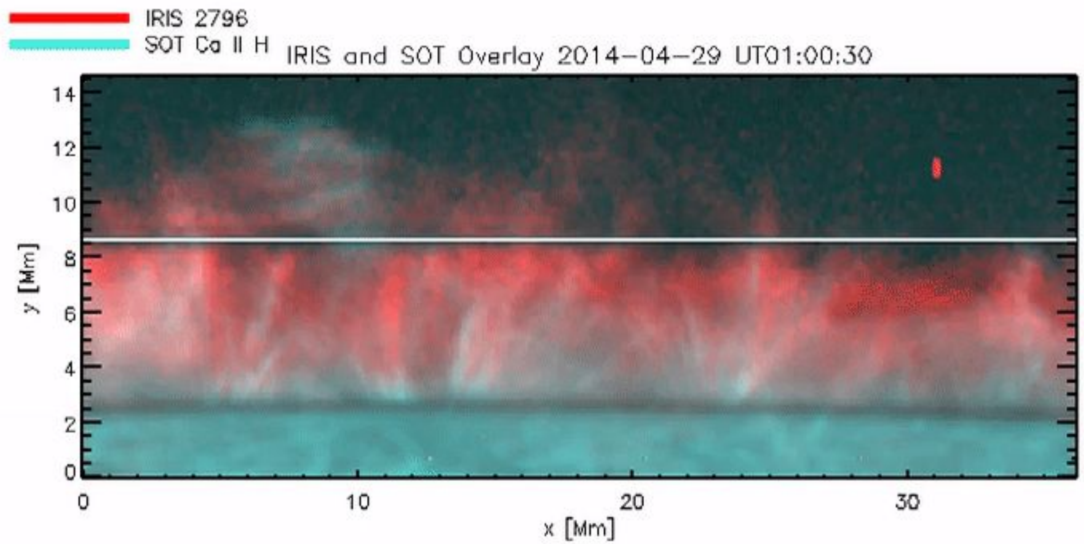
Some form of Jets?

T ≈ 10^4 - $8x10^4$ K, $\beta \approx 1$



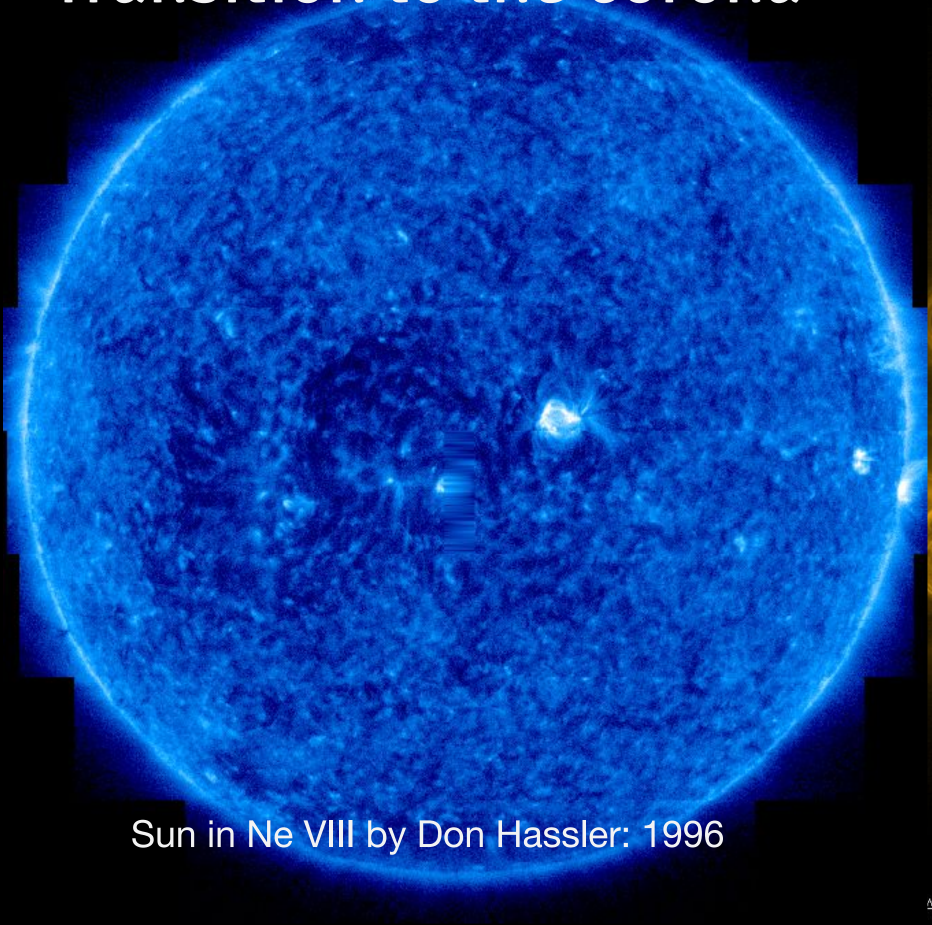
Spicules and magnetic field: From Samanta et al 2019 Science 366, 6467

Spicular motion: From P. Antolin et al 2018 ApJ 856 44

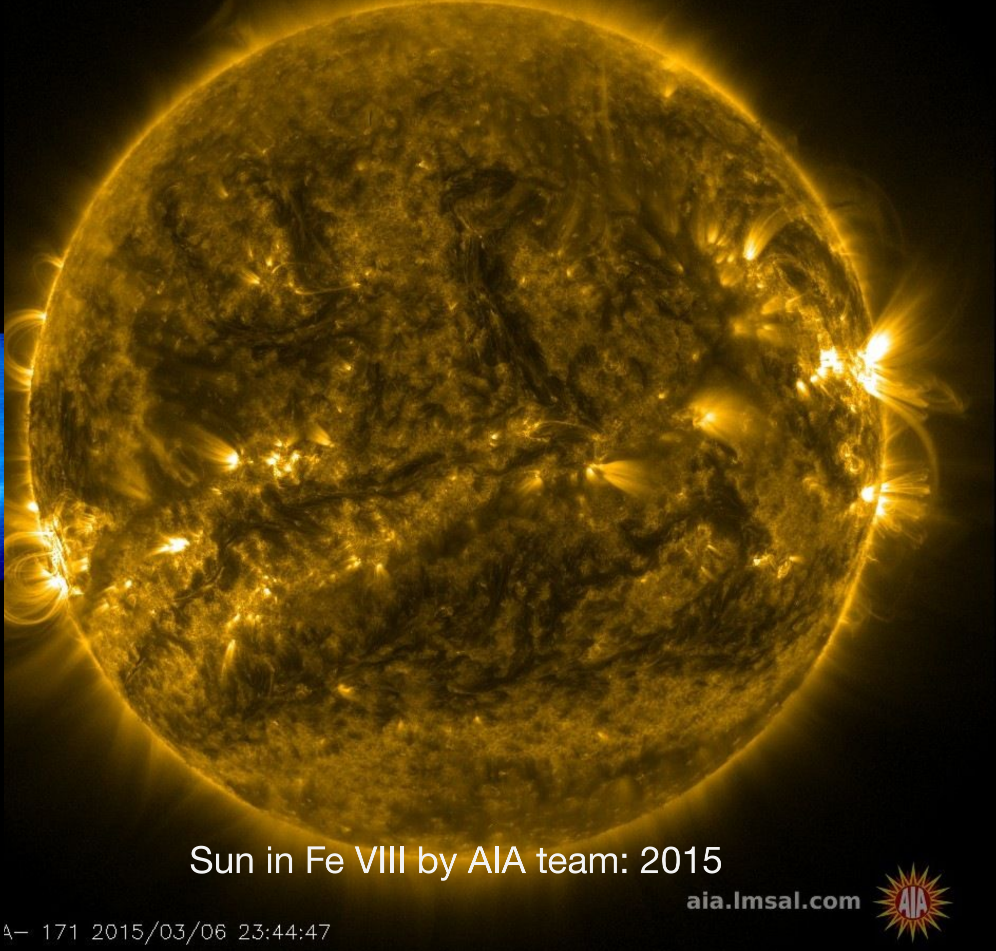


Transition to the corona

$T \approx 10^5$ K, $\beta \leq 1$



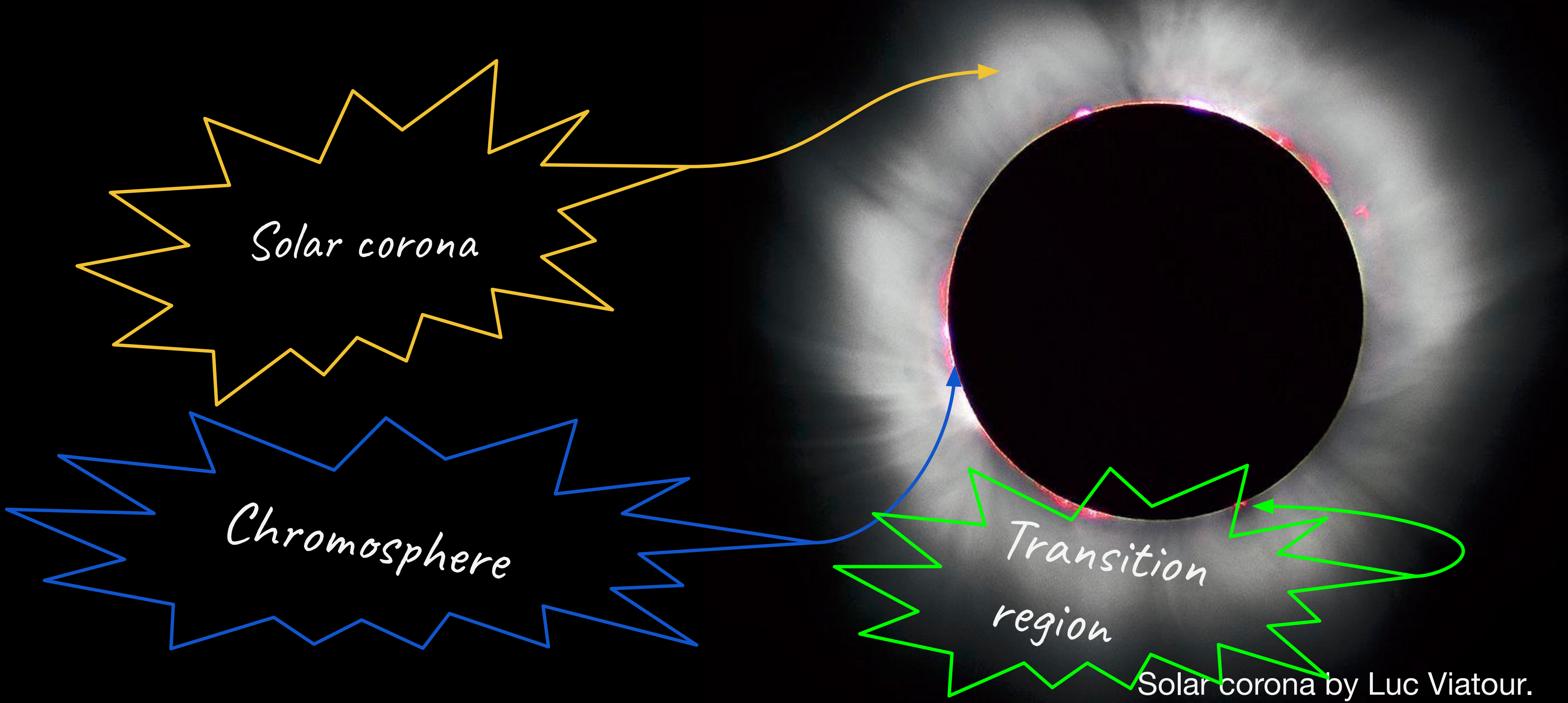
Sun in Ne VIII by Don Hassler: 1996



Sun in Fe VIII by AIA team: 2015

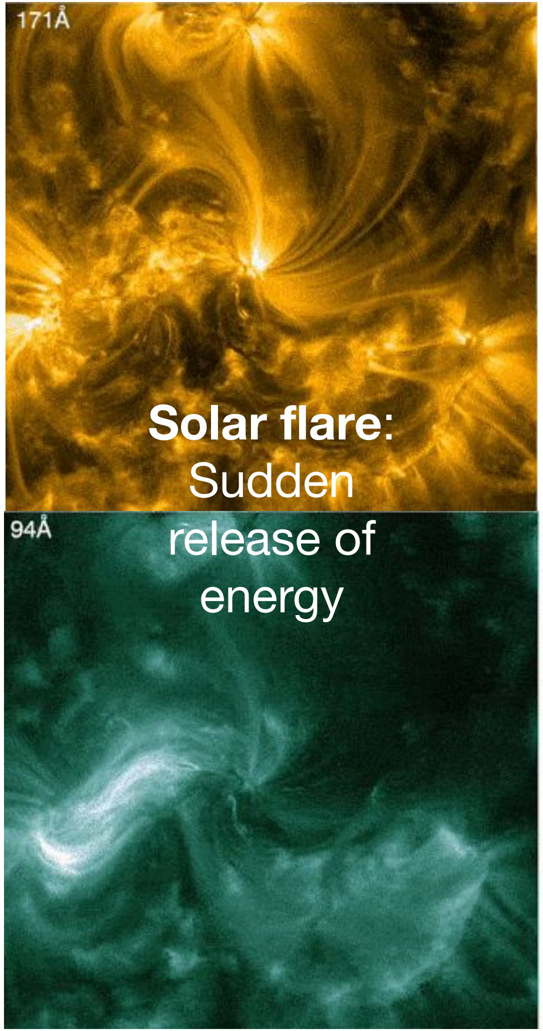
Solar corona: The crown of gas!

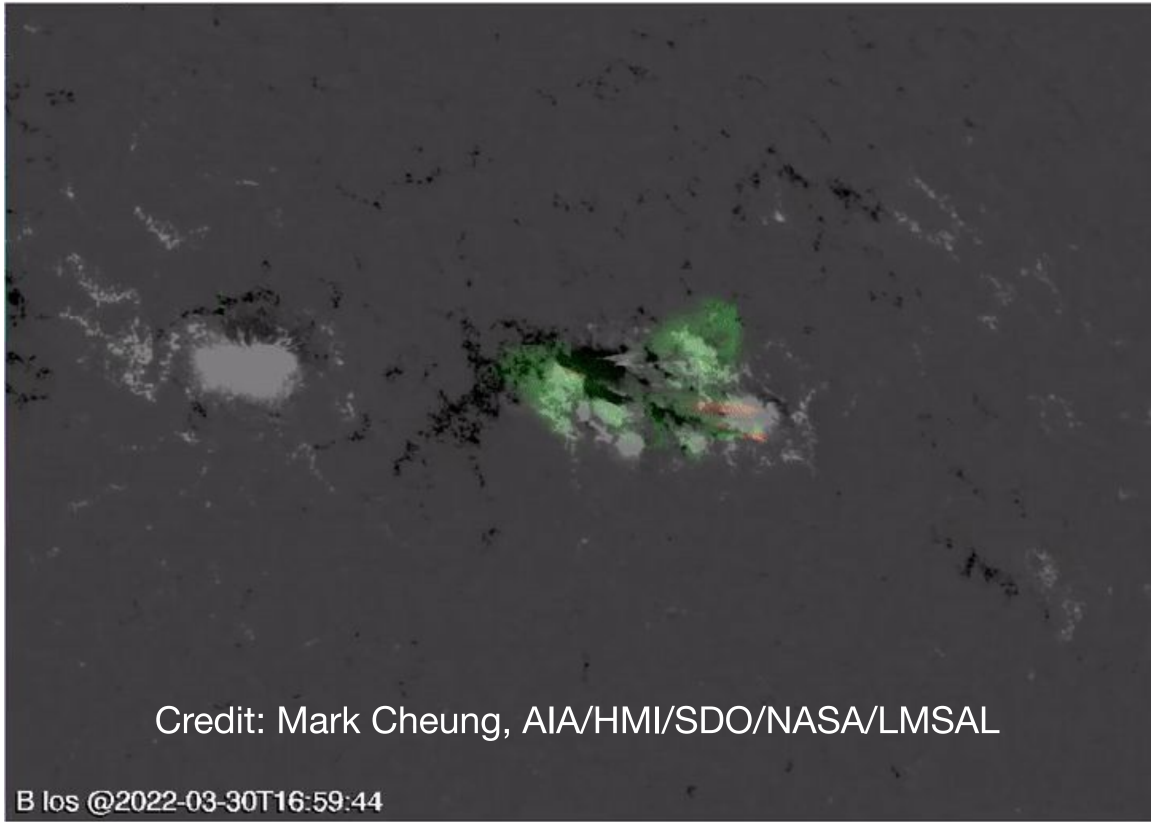
$T \gtrsim 10^6$ K, $\beta << 1$



Solar corona by Luc Viatour.

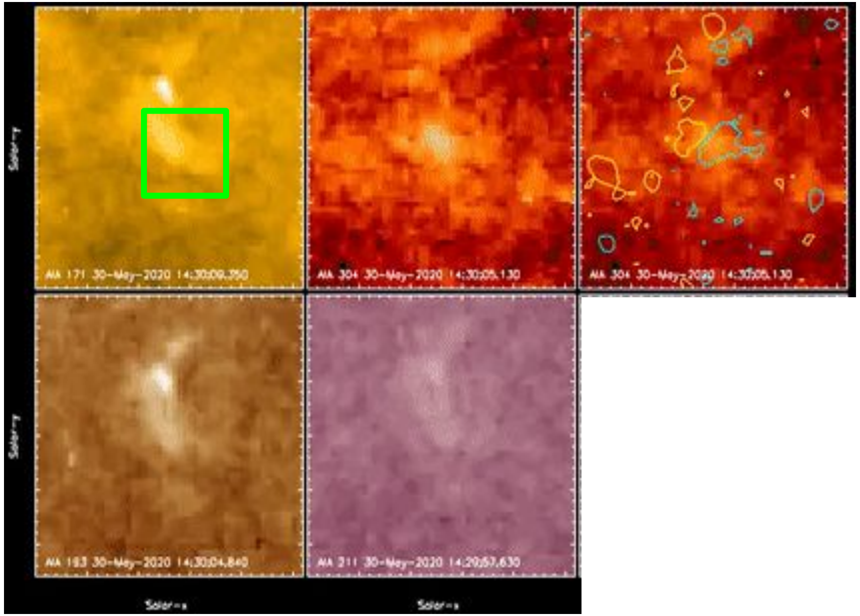
Energy transfer in the Active regions!





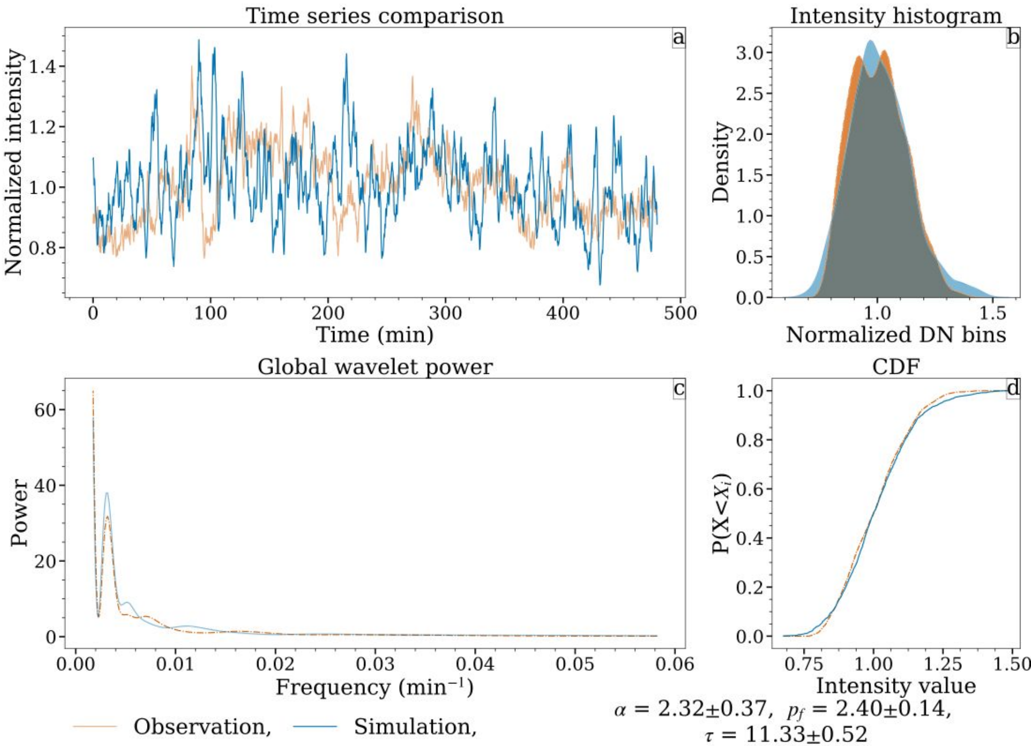
Flares: Convert magnetic energy to thermal energy.

Energy transfer in the Quiet regions!



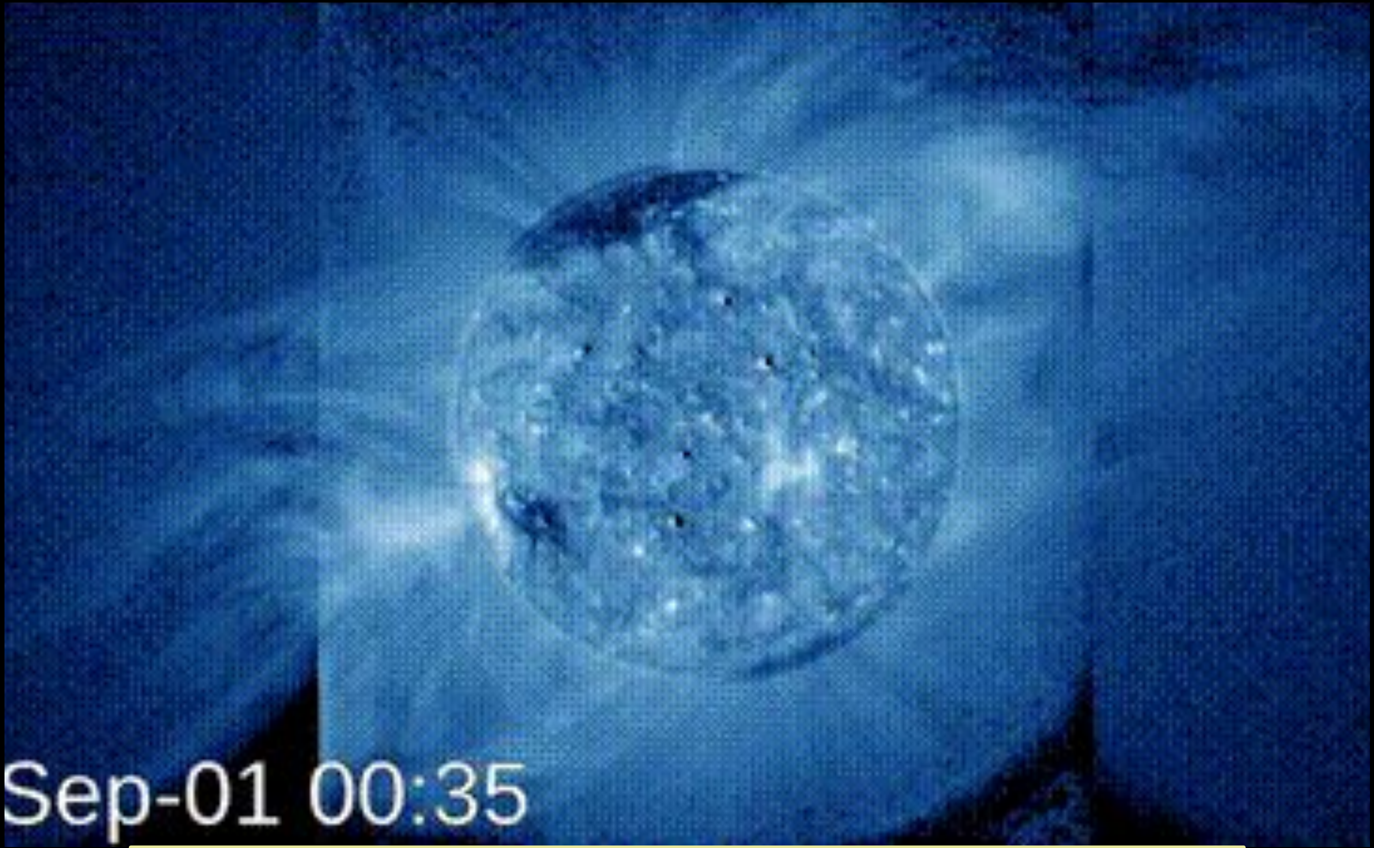
Small scale brightenings: From Navdeep K. Panesar et al 2021 ApJL 921 L20

Pixel-scale impulsive events: From **Vishal Upendran** and Durgesh Tripathi 2021 ApJ 916 59



Larger scale: Middle corona

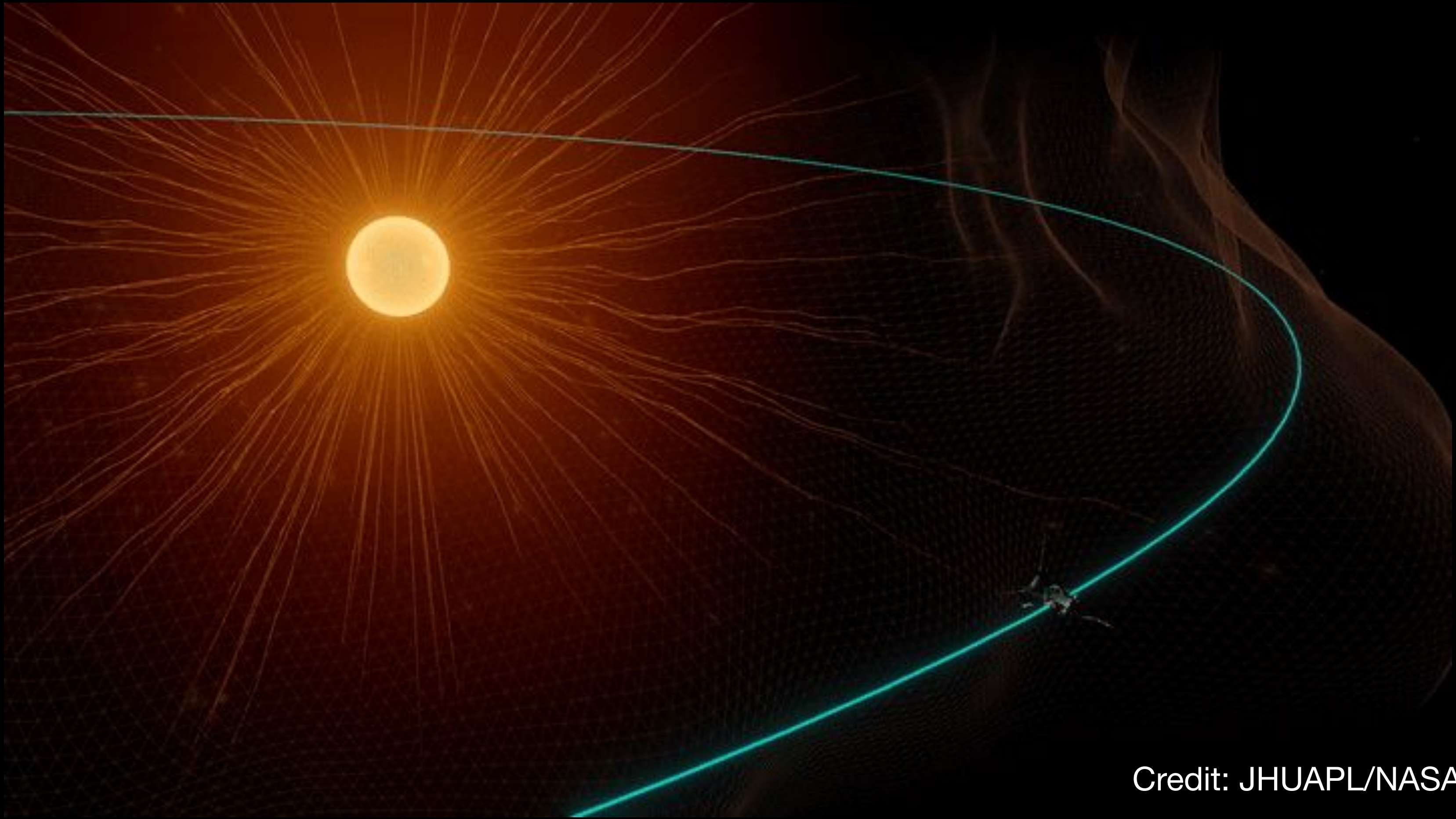
$T \gtrsim 10^6$ K, $\beta << 1$



Seaton D.B. et. al, Nat Astron 5, 1029–1035 (2021)

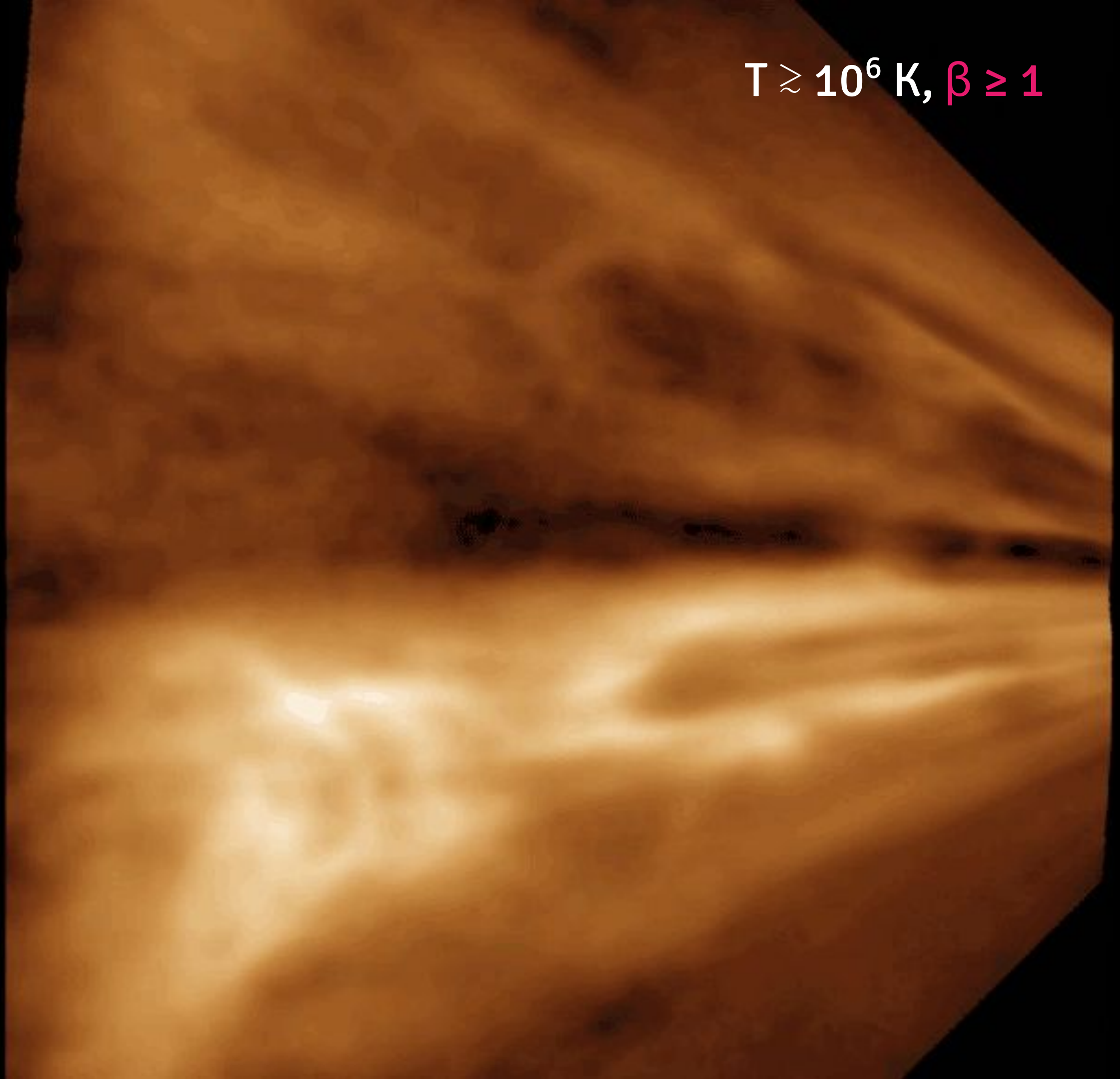
Corona to solar wind

$T \gtrsim 10^6$ K, $\beta \approx 1$



Credit: JHUAPL/NASA Ben Smith

Plasma flowing out!



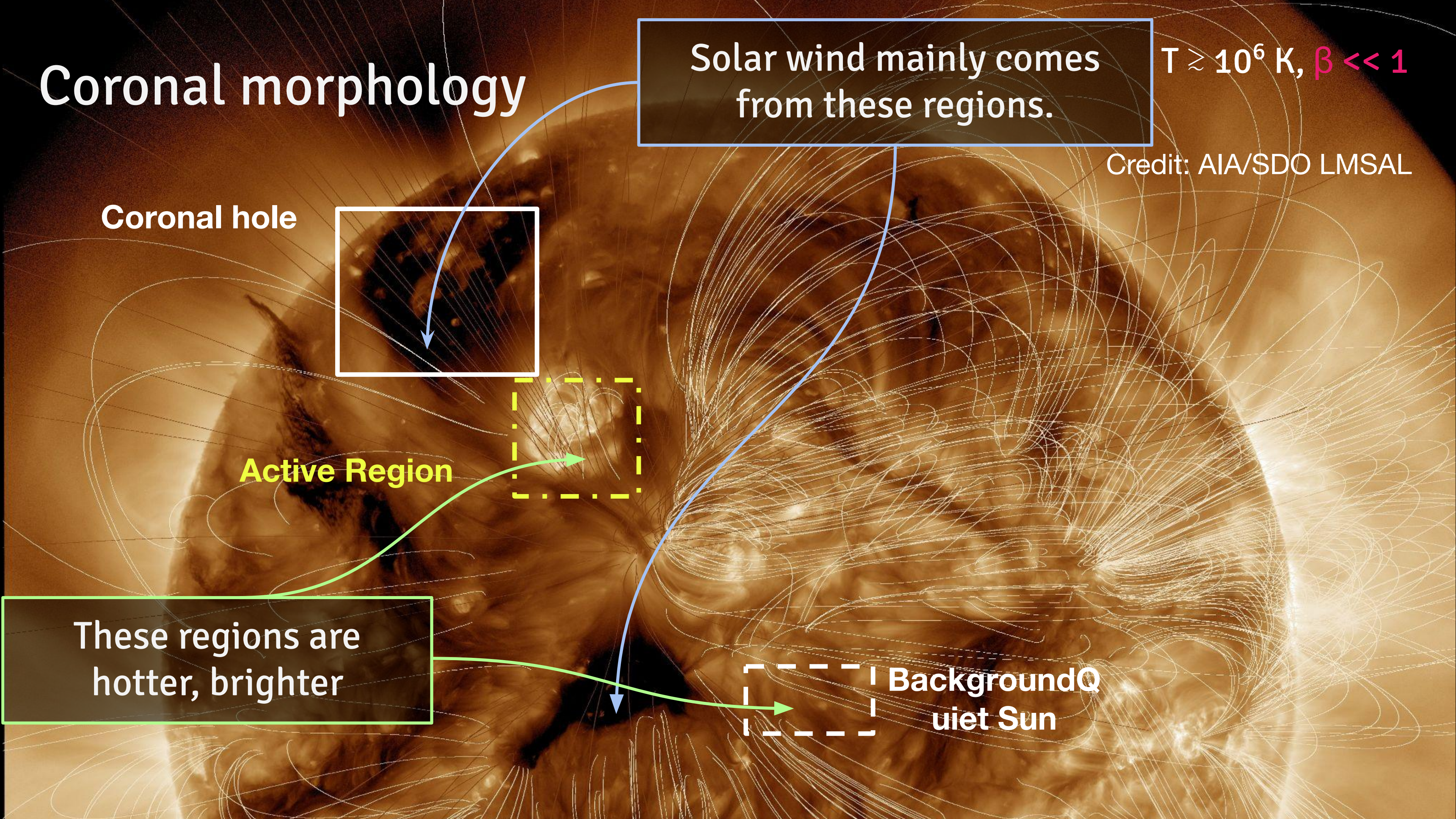
Credits: NASA SVS; data from Craig DeForest, SwRI

Sweeping past the Earth

$T \gtrsim 10^6$ K, $\beta \geq 1$

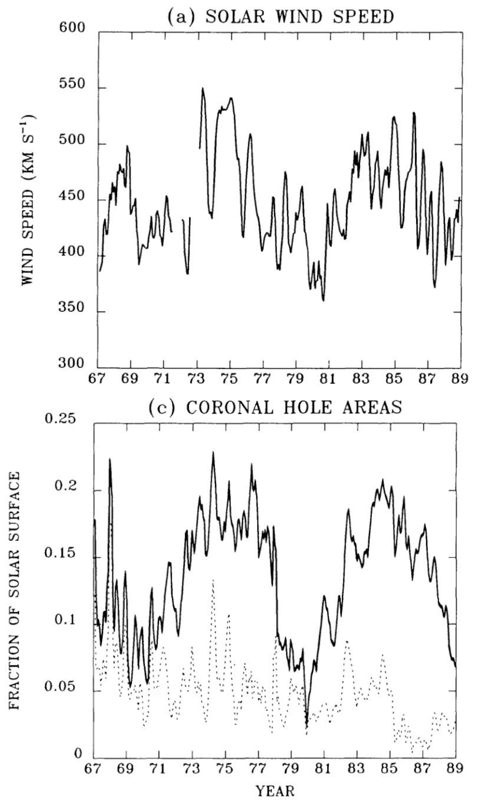
Credits: NASA's Goddard Space Flight Center/Scientific Visualization Studio/Greg Shirah: https://svs.gsfc.nasa.gov/3902

Coronal morphology

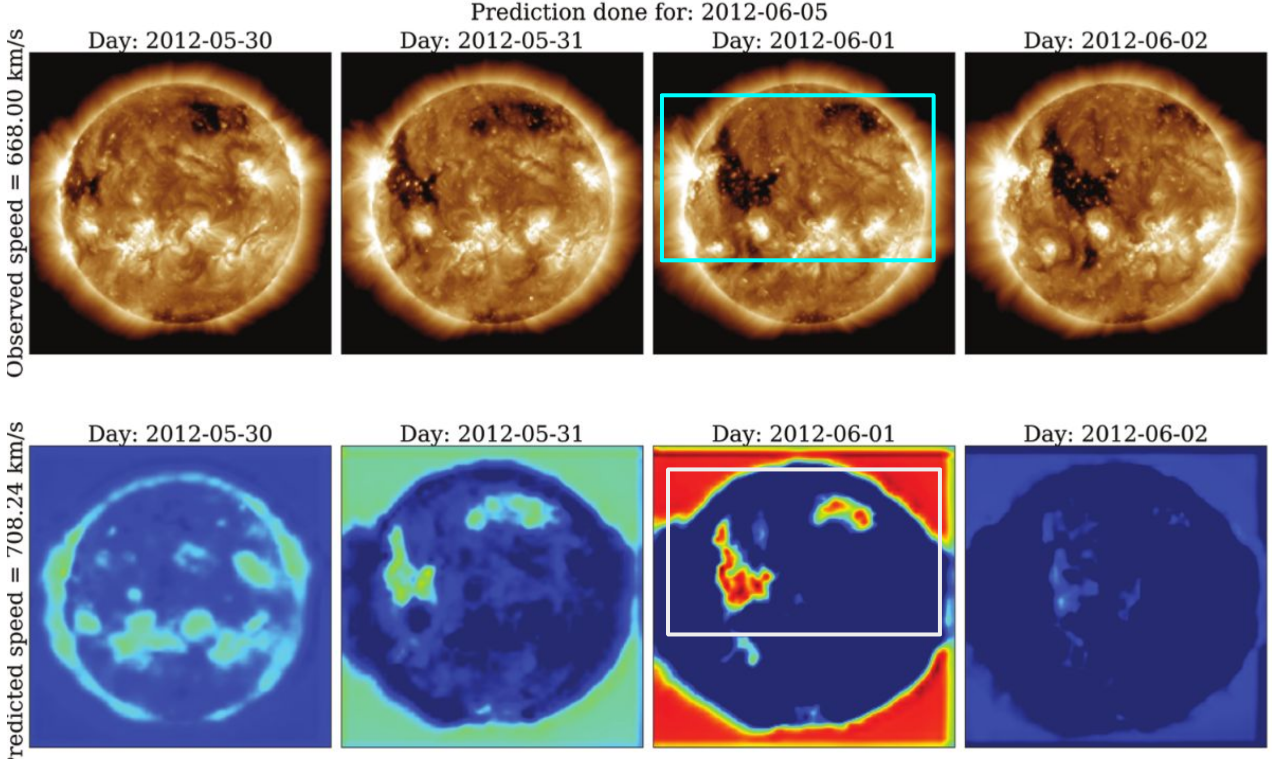


Origins of the solar wind?

Check out my talk at Robert Bosch Centre for Data Science and Artificial Intelligence on Wednesday! 👇



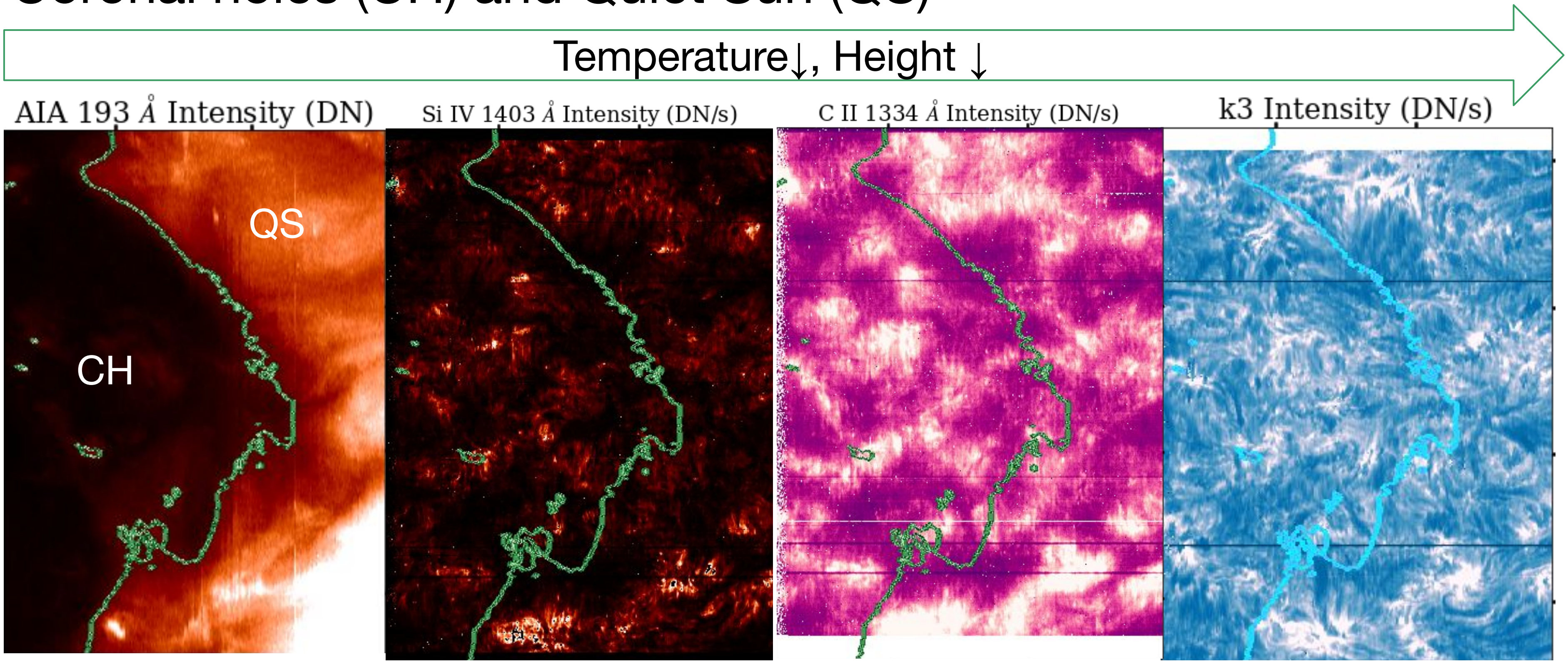
Solar wind speed and Coronal hole area. From: Wang & Sheeley, ApJ 355:726-732,1990 June 1



Solar wind sources from Deep learning, from:

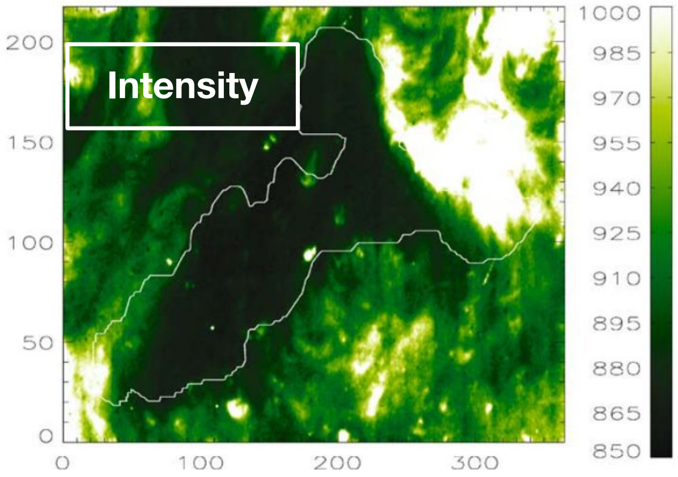
Vishal Upendran et. al (2020). Solar wind prediction using deep learning. Space Weather, 18, e2020SW002478

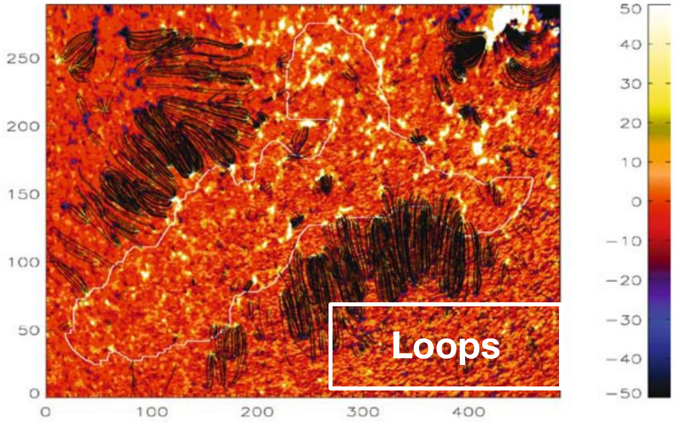
Coronal holes (CH) and Quiet Sun (QS)

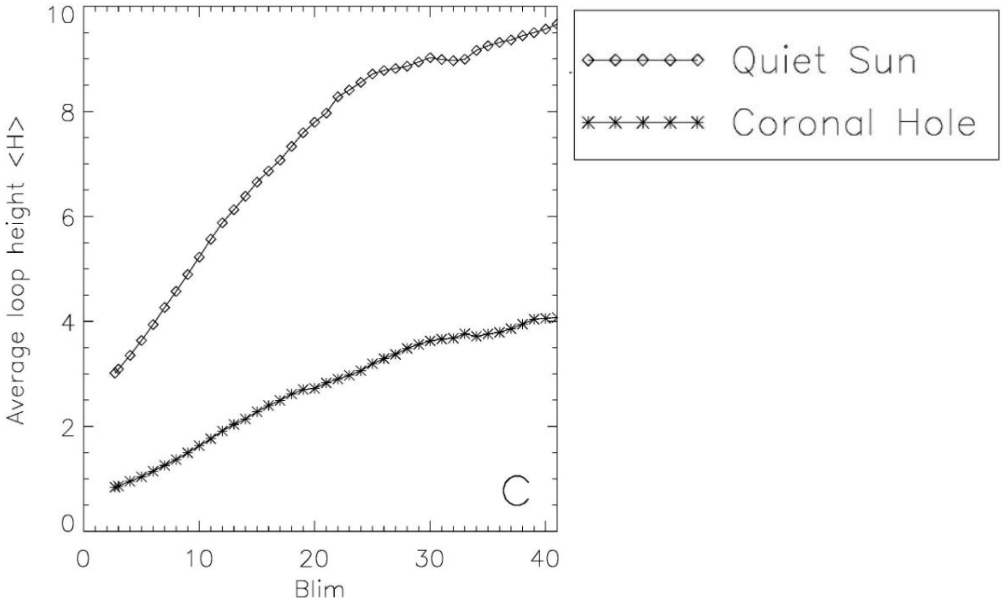


Visually, CHs seem similar to QS at lower temperatures → **Differentiation** key to understanding Coronal heating and solar wind emergence!

Differentiation: Gross properties with Magnetic fields







Figures from Wiegelmann & Solanki (2004).

Typical loop height is less in CHs → large differences seen as intensity in the corona?

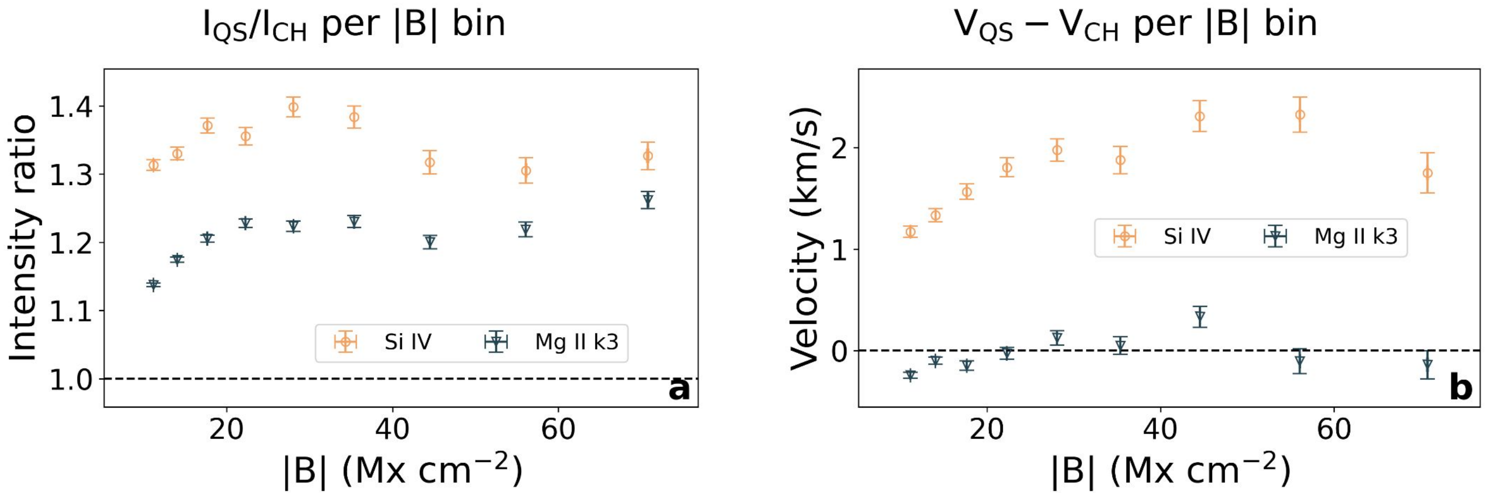
Science question: How do local plasma conditions vary in CHs and QS with (i). Height, and (ii). Magnetic flux density?

Main paper: **Vishal Upendran** & Durgesh Tripathi 2022, "On the formation of solar wind & switchbacks, and quiet Sun heating", ApJ 926 138

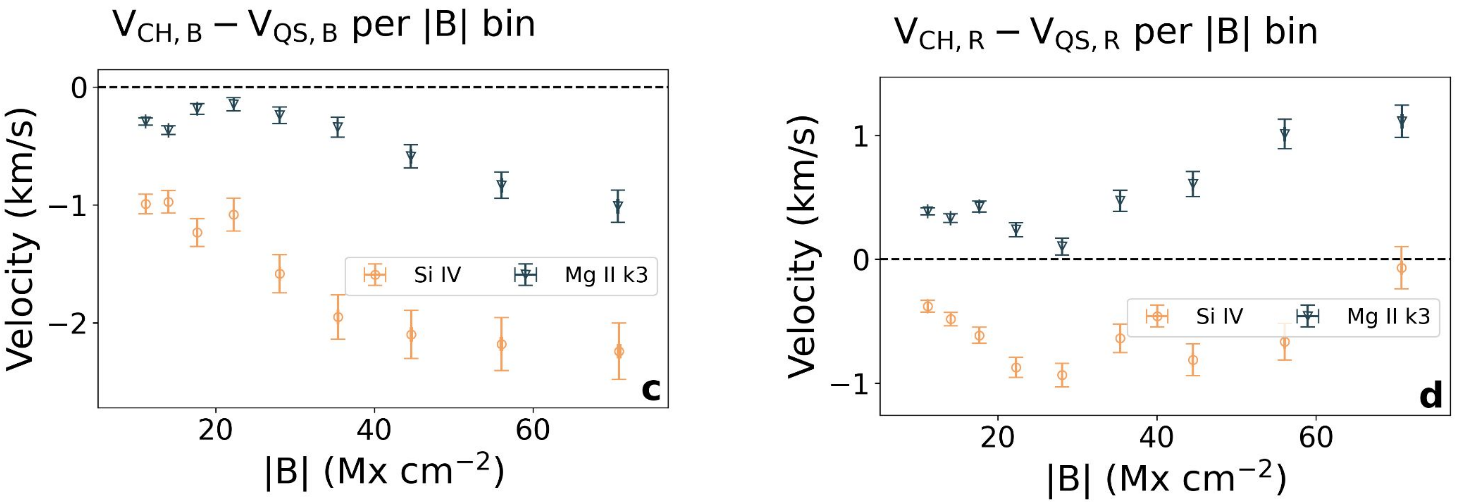
Paper on C II: **Vishal Upendran** & Durgesh Tripathi 2021, "Properties of the C II 1334 Å Line in Coronal Hole and Quiet Sun as Observed by IRIS", ApJ 922 112

Study line intensity and velocity as a function of |B|:
Mg II h & k, C II 1334 Å (chromosphere) and Si IV 1394 Å (transition region).
≈ 1,000,000 spectra analyzed!

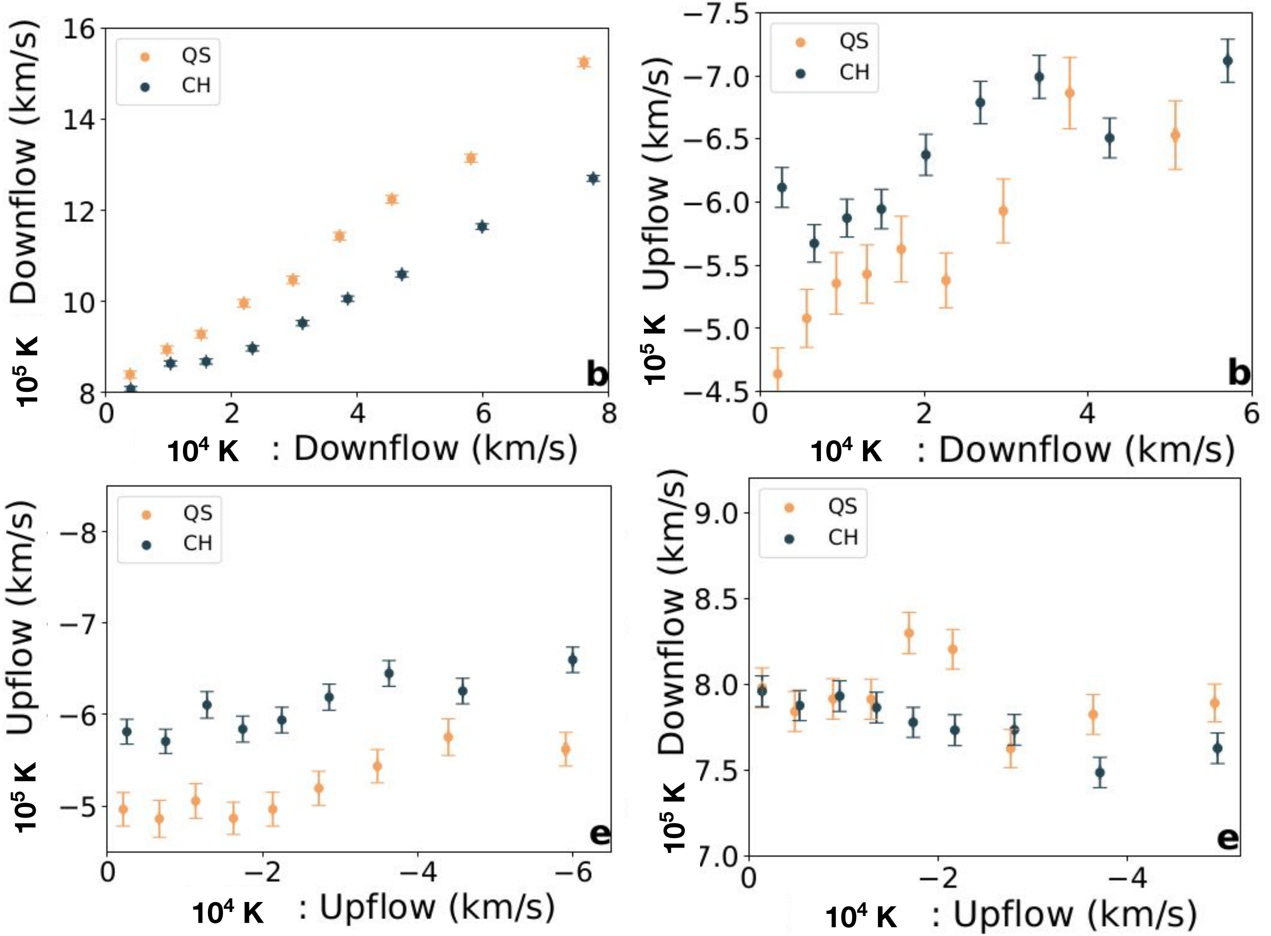
Mg II k line intensity: Also see Kayshap+ 2018; expanded in this work.
Si IV 1394 Å dynamics: Also see Tripathi, Nived and Solanki, 2021; expanded data in this work.



Intensities, Velocities with |B|

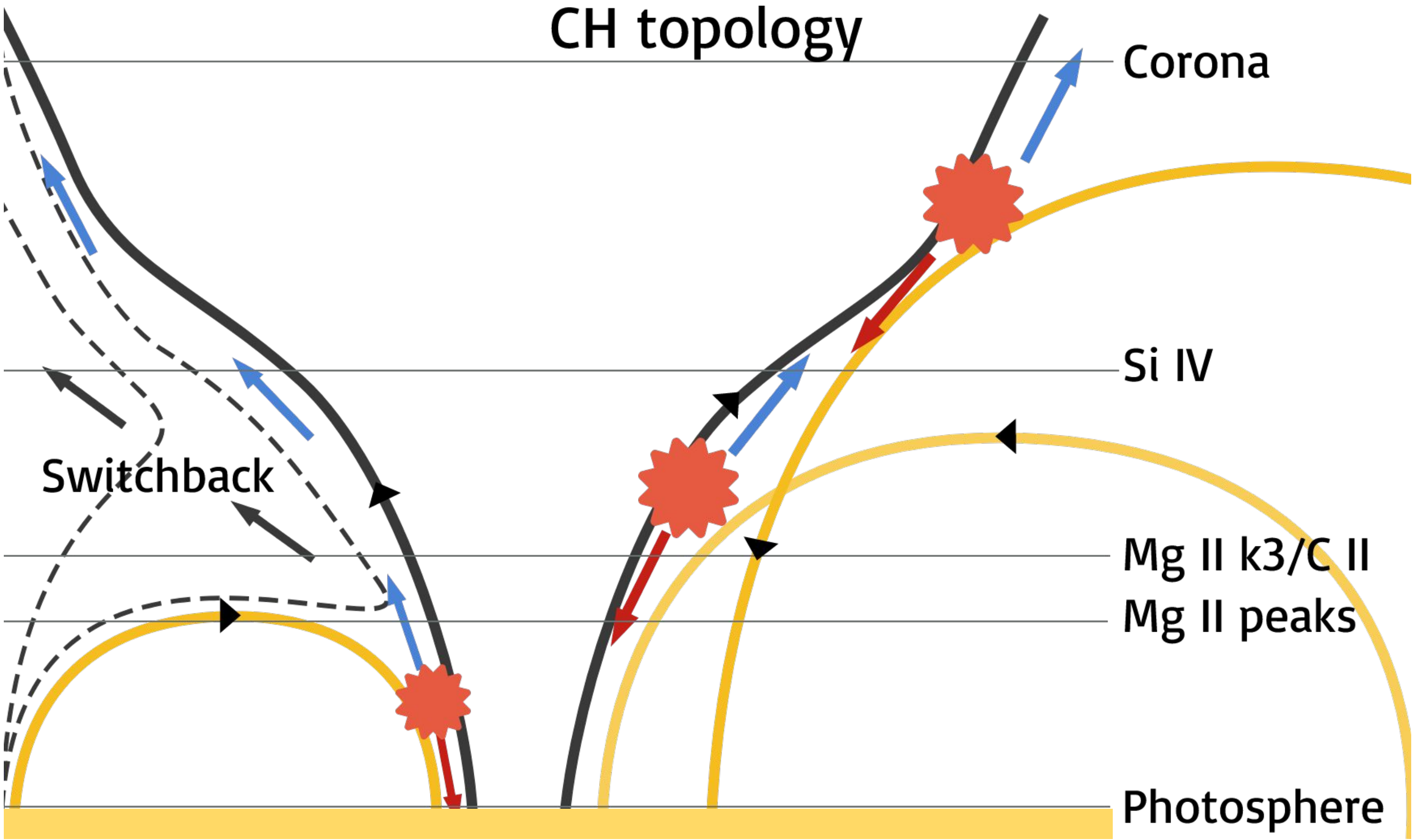


Velocity cross-correlation: Mg II k3 (10^4 K) - Si IV(10^5 K)

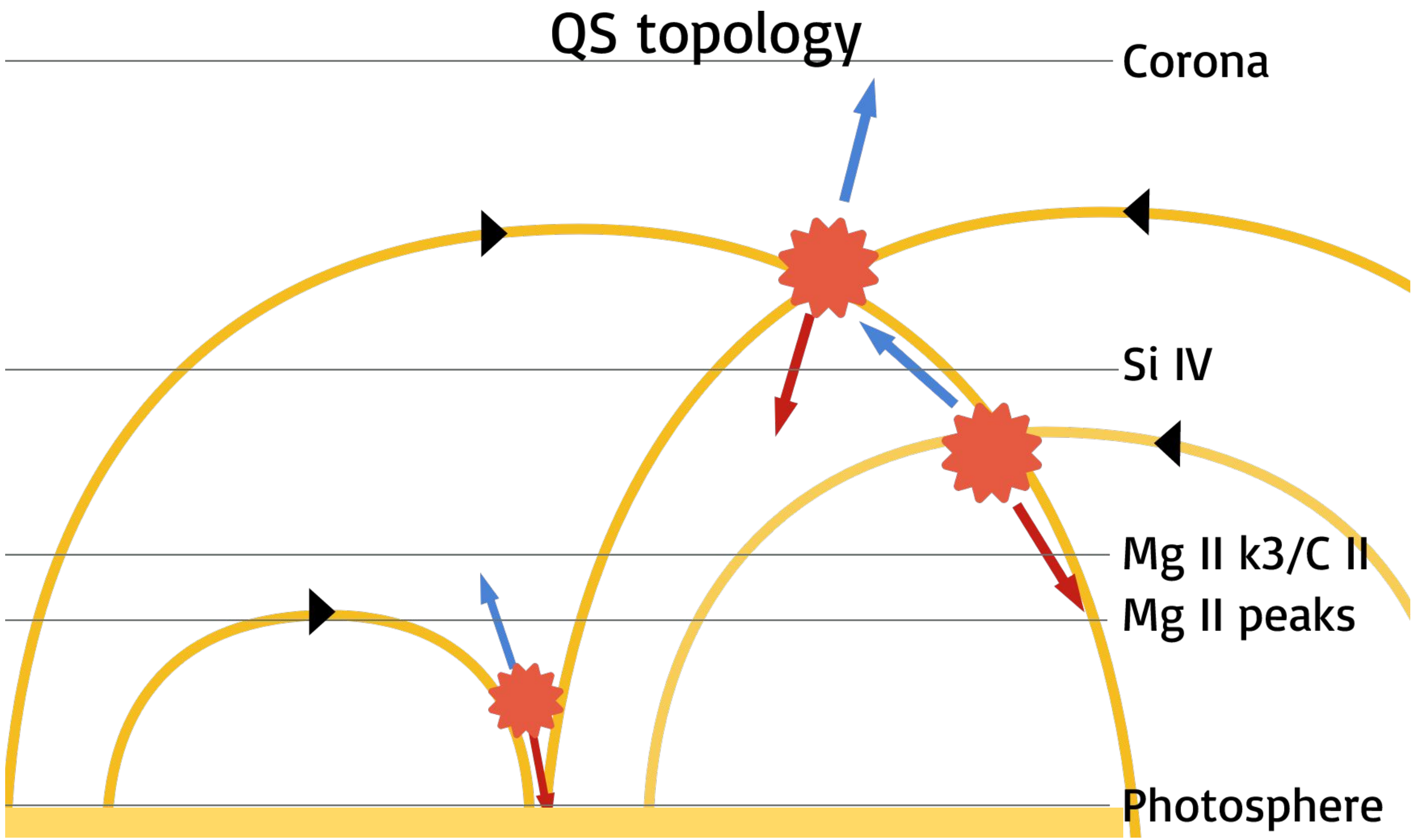


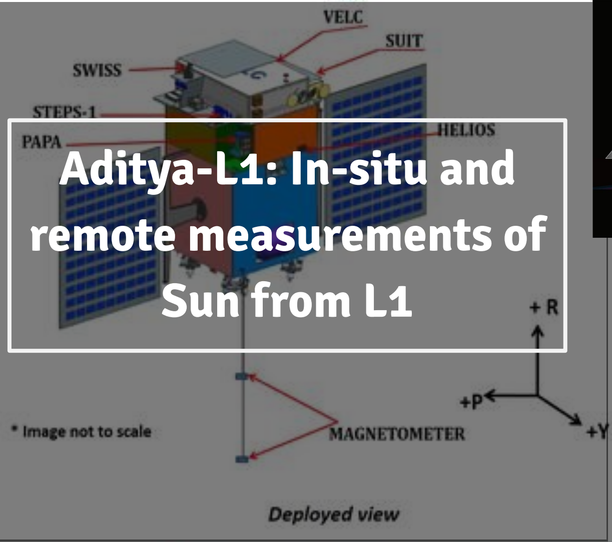
- TR downflows & upflows correlated with chromospheric downflows & upflows.
- TR upflows correlated with chromospheric downflows.

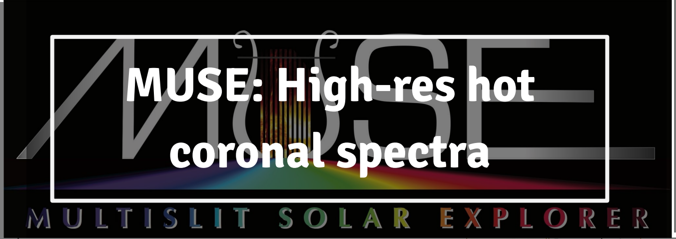
Unified scenario of solar wind emergence and coronal heating



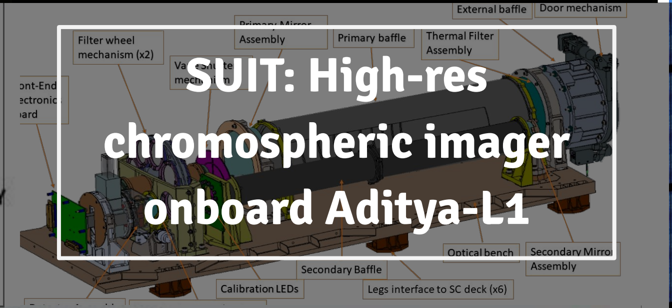
Unified scenario of solar wind emergence and coronal heating

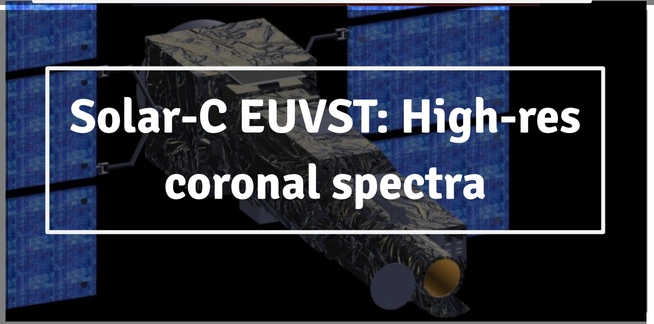


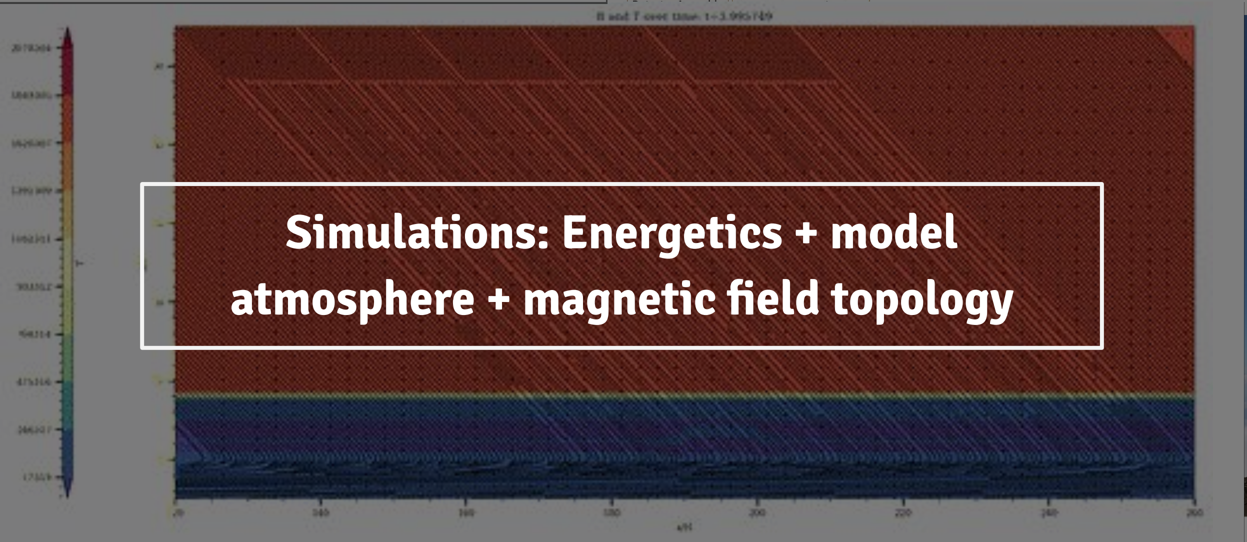

VELC
SUIT
SWISS
STEPS-1
PAPA
HELIOS
Aditya-L1: In-situ and remote measurements of Sun from L1
+R
+P
+Y
* Image not to scale
MAGNETOMETER
Deployed view

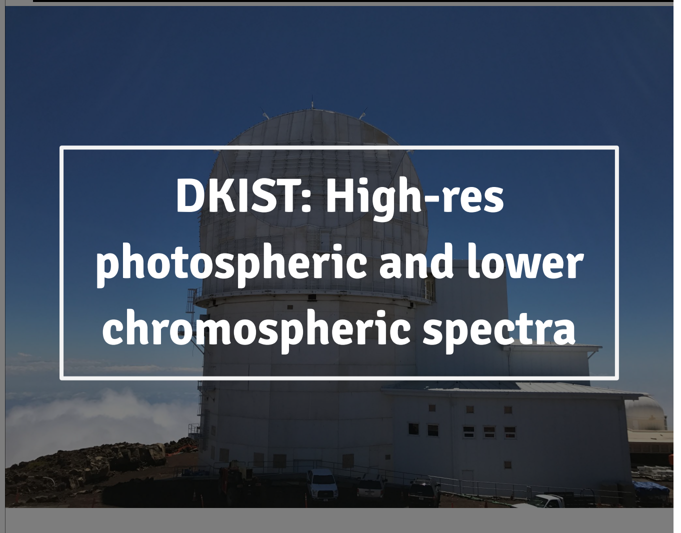

MUSE: High-res hot coronal spectra
MULTISLIT SOLAR EXPLORER


Solar Orbiter: Near-Sun high-res images and spectra


External baffle
Door mechanism
Filter wheel mechanism (x2)
Assembly
Primary baffle
Thermal Filter Assembly
SUIT: High-res chromospheric imager onboard Aditya-L1
Optical bench
Secondary Mirror Assembly
Secondary Baffle
Calibration LEDs
Legs interface to SC deck (x6)


Solar-C EUVST: High-res coronal spectra


Simulations: Energetics + model atmosphere + magnetic field topology

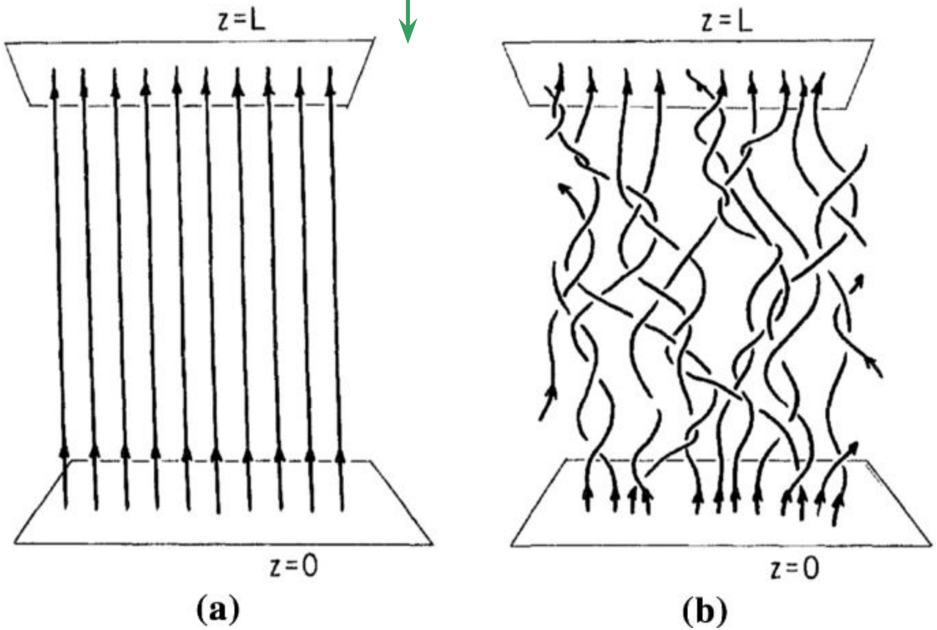

DKIST: High-res photospheric and lower chromospheric spectra

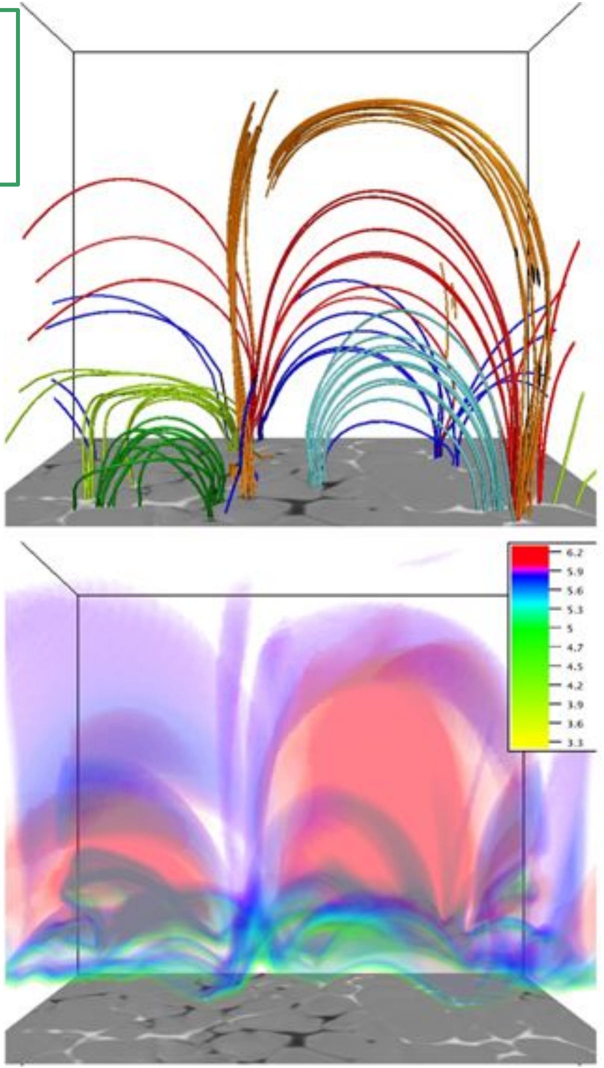
Extra slides

Field line braiding

Field line braiding: From Parker EN (1994), International Series in Astronomy and Astrophysics, vol 2. Oxford University Press, Oxford

Field line braiding: From V. Hansteen et al 2015 ApJ 811 106





Differentiation: Gross properties with Magnetic fields

Figure from Tu+ 2005.

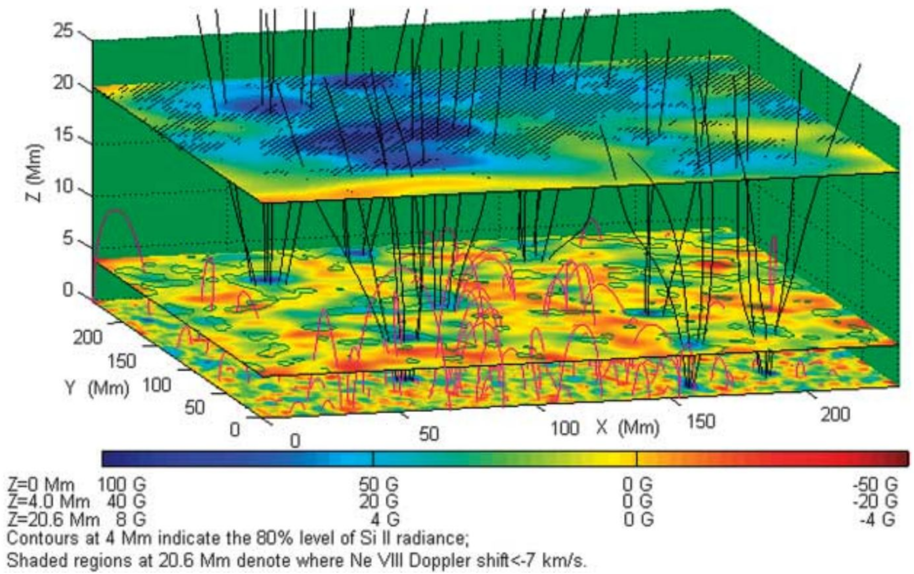
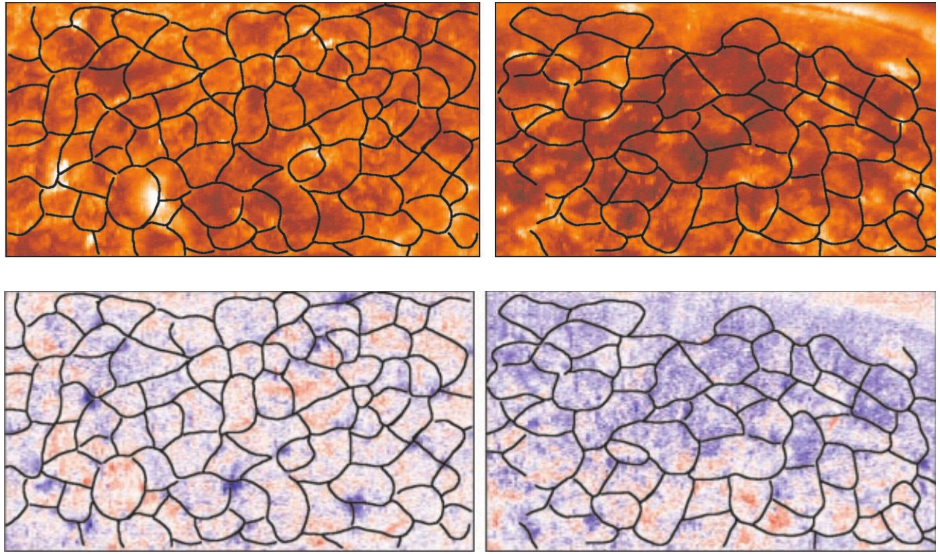
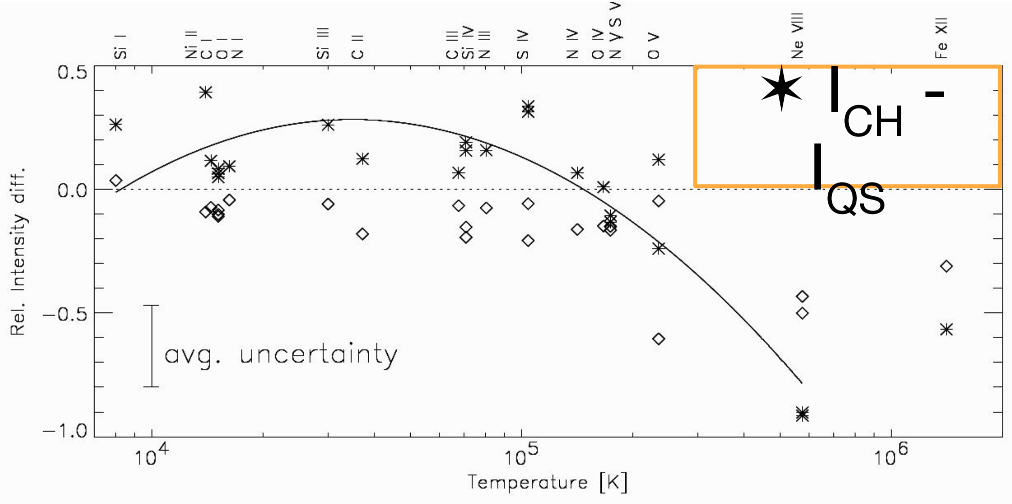


Figure from Hassler+ 1999.



- Network boundaries ⟵⟶ Ne VIII Los velocity (Hassler+ 1999).
- Ne VIII: Largest Doppler shifts ← X → Intensity maps.
- Heating process either dumps energy locally for heating corona, or for accelerating solar wind.
- Solar wind originates in “coronal funnels” (Tu+ 2005).

Differentiation: Gross properties



Gross intensity difference between CHs and QS:

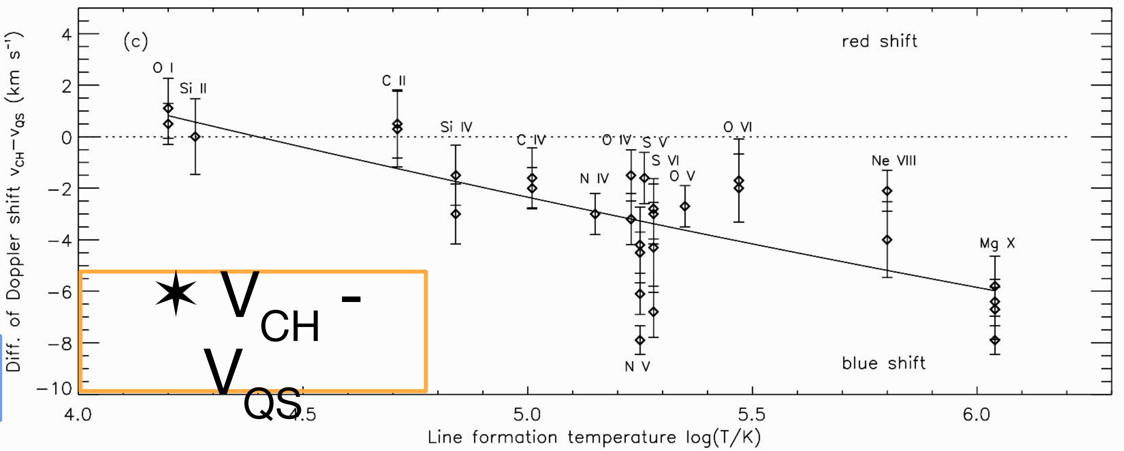
- Large scatter in the stars (✶)
- High temperature → $I_{CH} < I_{QS}$ clearly seen.
- No such difference at low temperatures.

Figure from Stucki+ 2000.

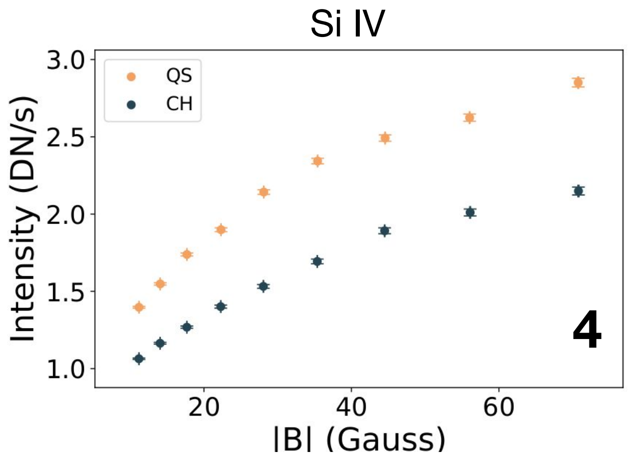
Gross velocity difference between CHs and QS:

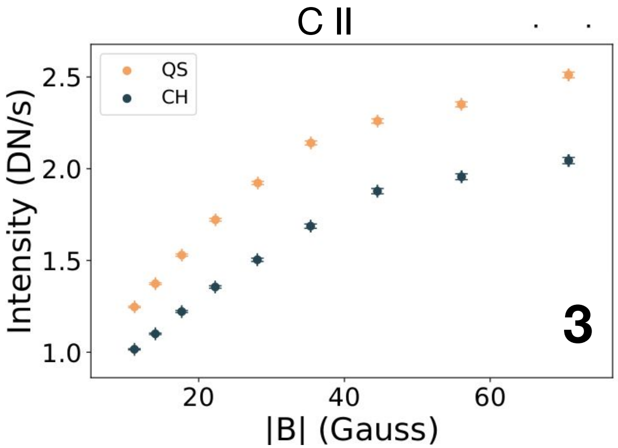
- CH velocities are systematically lower than QS with temperature.
- Uncertain at low temperatures!

Figure from Xia+ 2004.

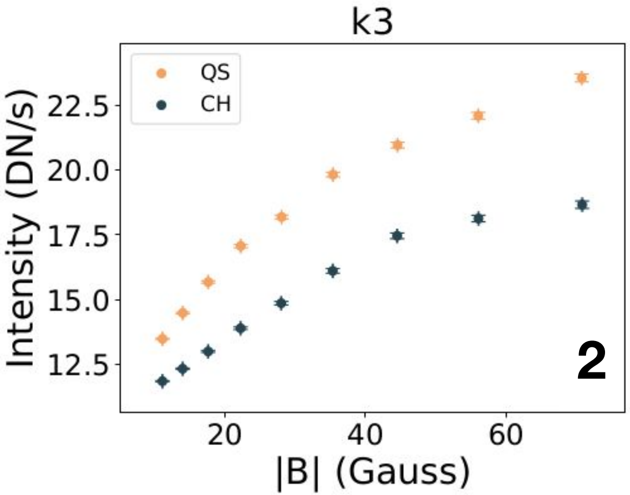


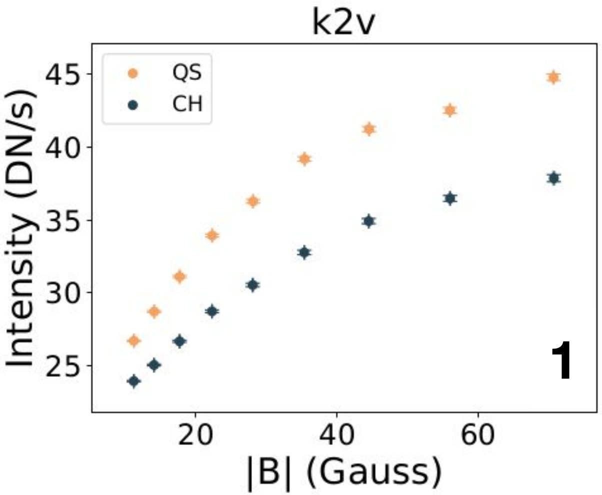
Intensities with |**B**|

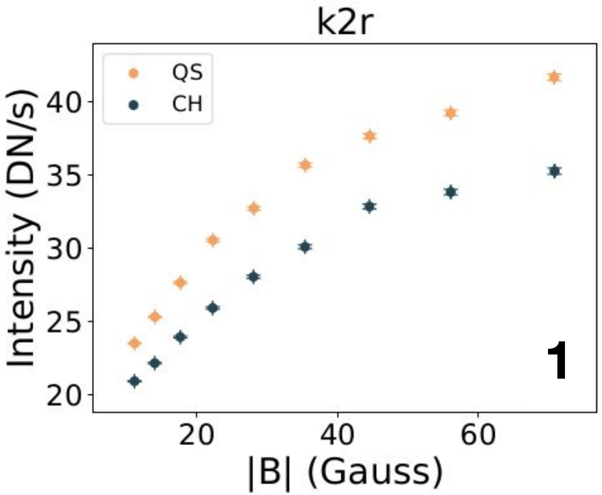




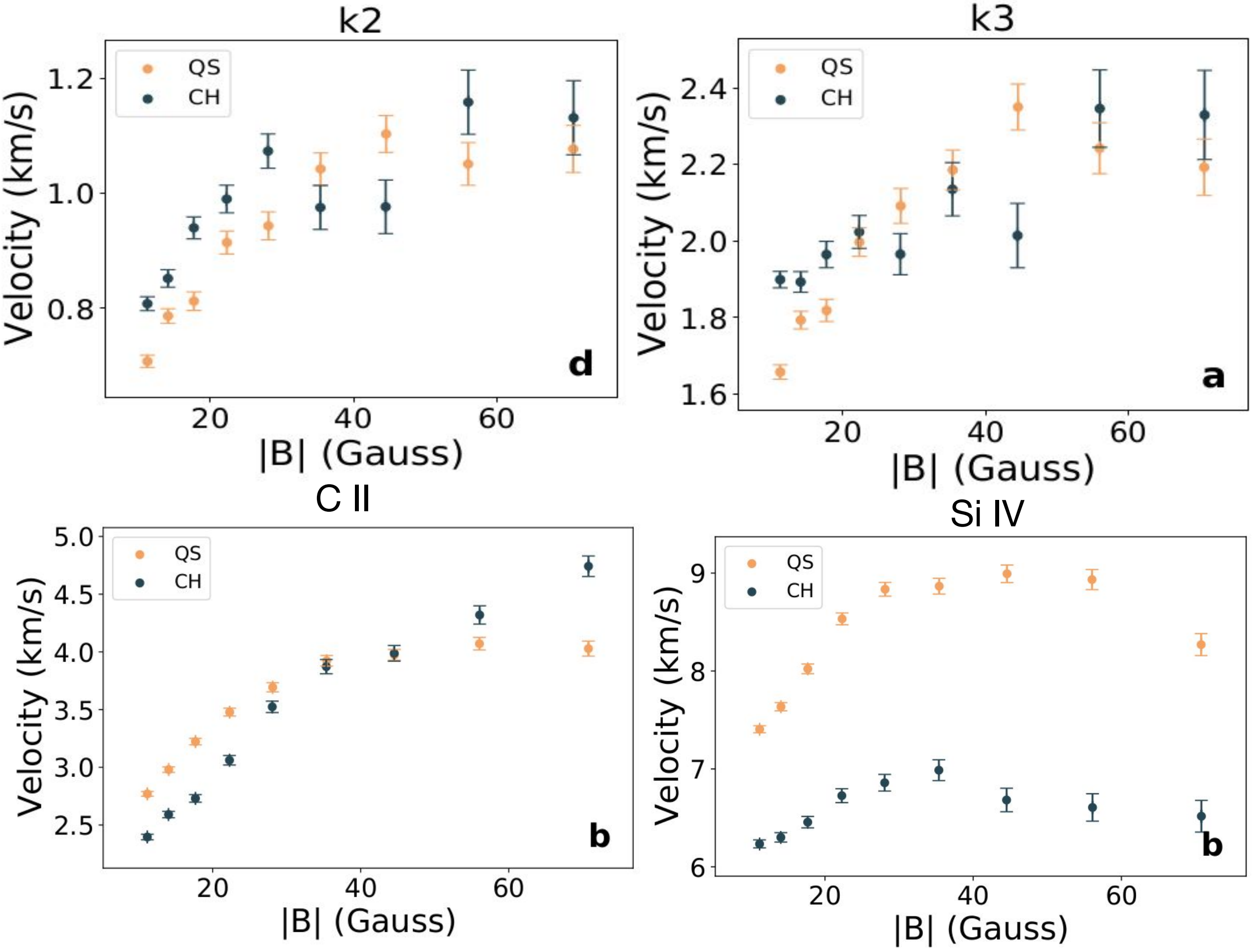
- CHs have lesser intensity w.r.t QS for similar |**B**|.
- CH-QS differentiation already present at chromosphere.





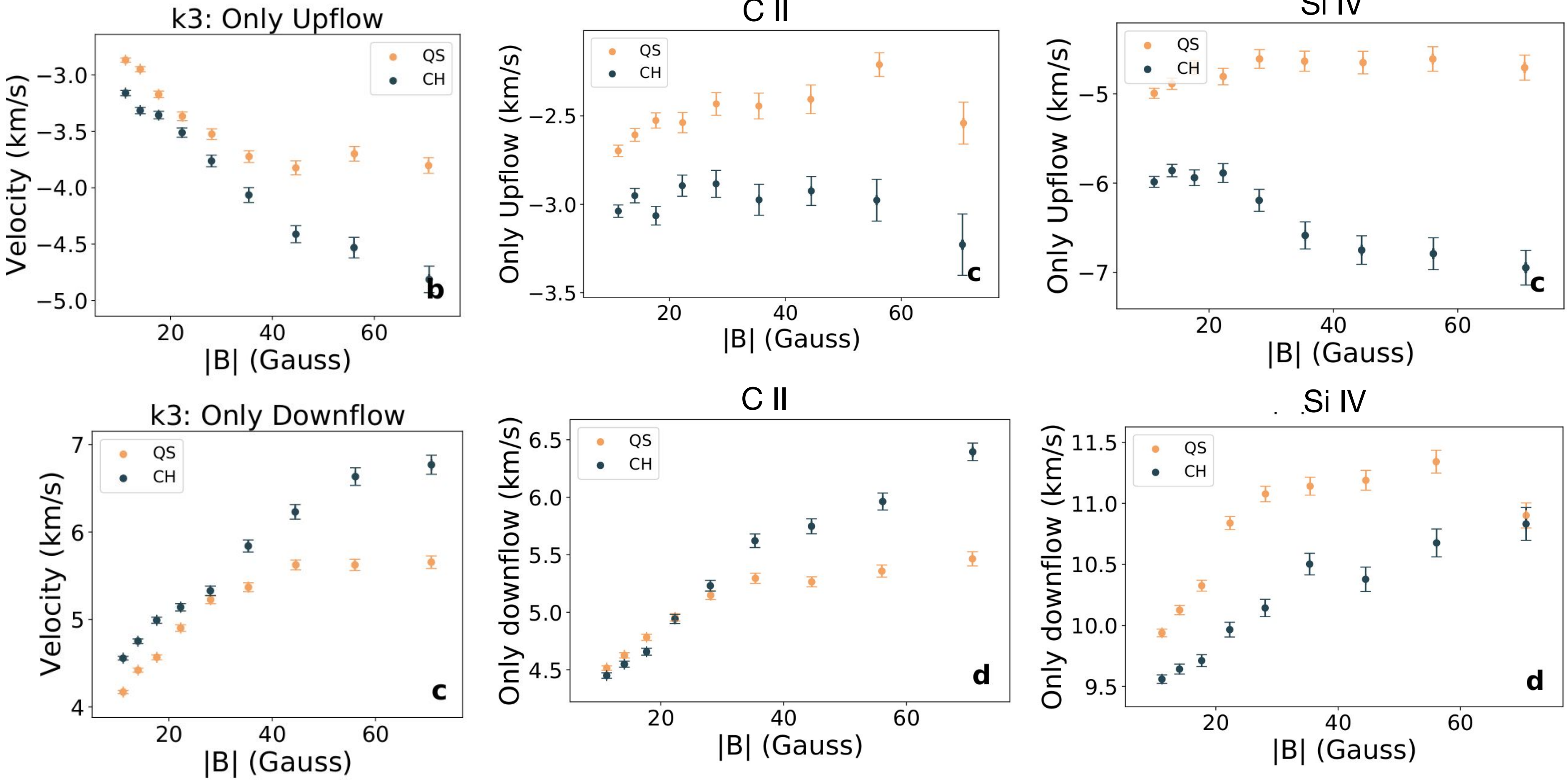


Average velocities with |**B**|



- Chromosphere and TR redshifted on an average
- Average velocity almost consistent across CH and QS.
- Velocity increase: k2 < k3 < C II < Si IV.

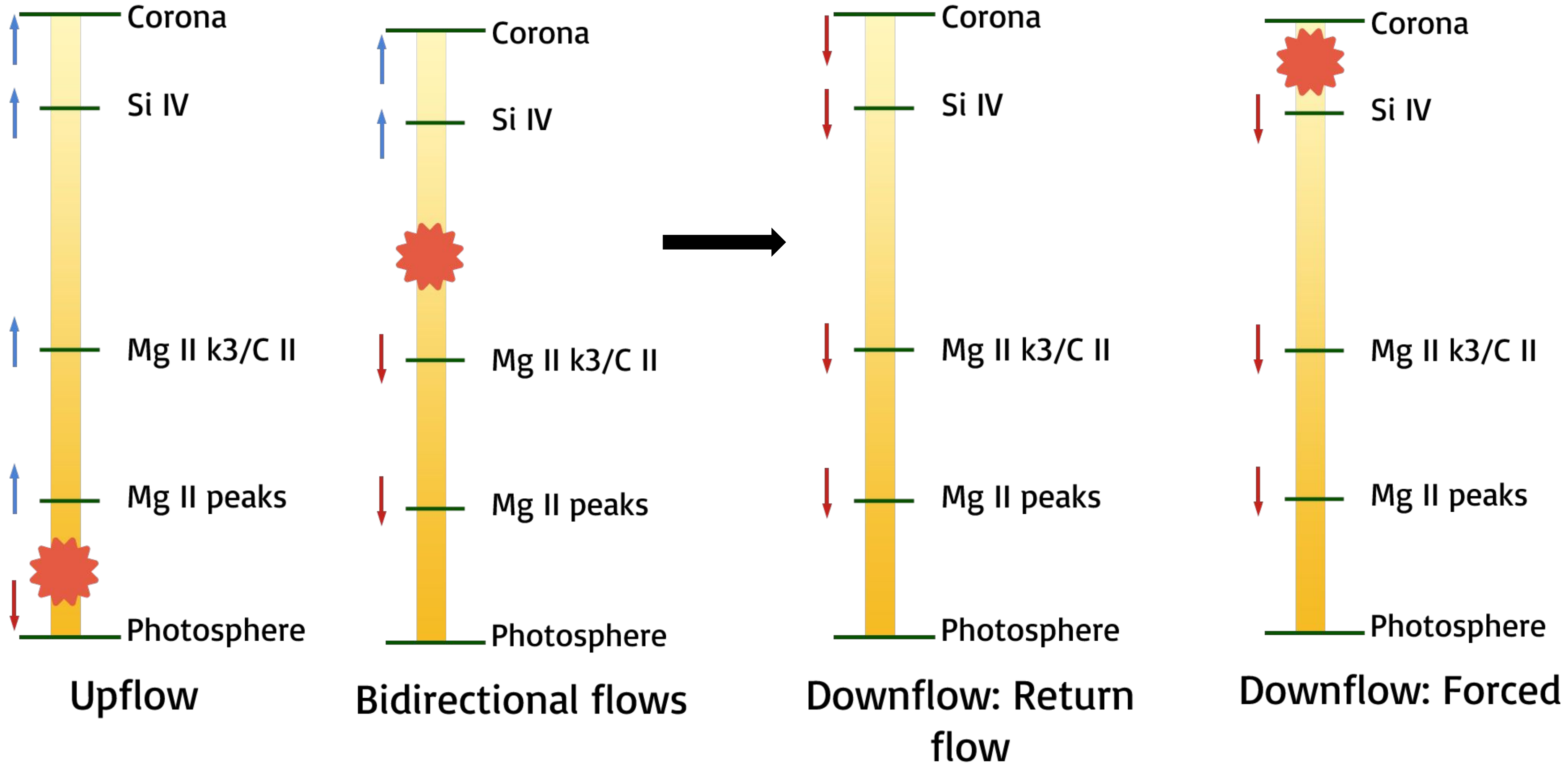
Systematic blue and redshifts with |**B**|



Main observations: summary

- CHs have lesser **intensity** w.r.t QS for similar |**B**|.
- Chromosphere and TR redshifted on an average
- Average velocity **almost consistent** across CH and QS.
  - Velocity increases with height (~ Temperature).
- **Excess redshifts and blueshifts** in CHs over QS → flows increase with |**B**|.
- TR upflows **correlated** with chromospheric upflows and downflows.
  - CH upflows larger for similar chromospheric flows.
- TR downflows only **correlated** with chromospheric downflows.
  - QS TR downflows larger.

Explaining velocity correlations



Explaining intensity differences: From TNS2021

- Loops in QS are longer than CHs.
- More open field in CHs → more trapped plasma in QS → larger intensity in QS (Weigelmann & Solanki, 2004).
- What about the velocity differences?
- **Final picture**: combine with "impulsive heating" of correlated flows!

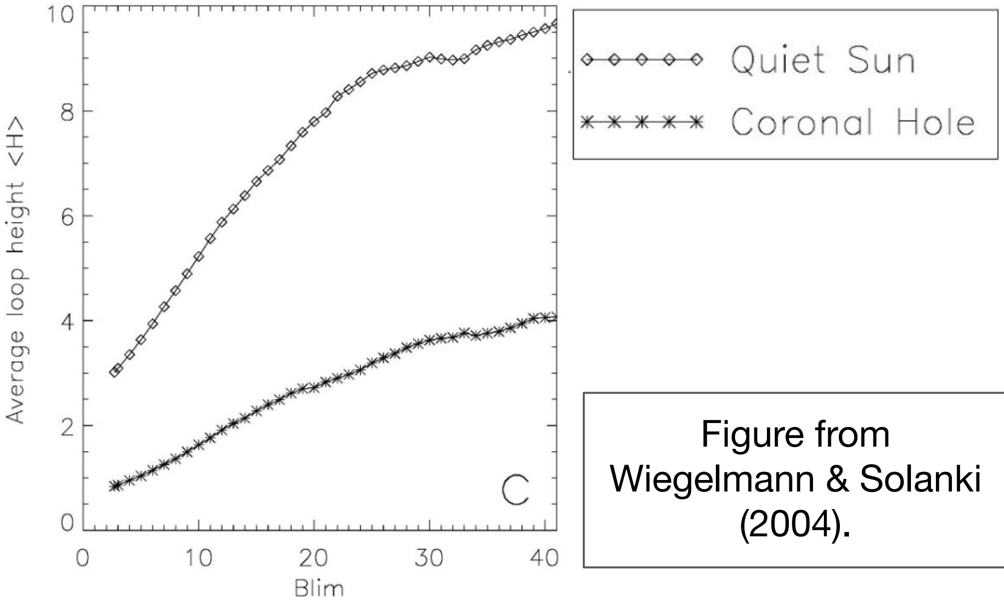


Figure from Wiegelmann & Solanki (2004).

Similar processes: Deviations from Gaussianity

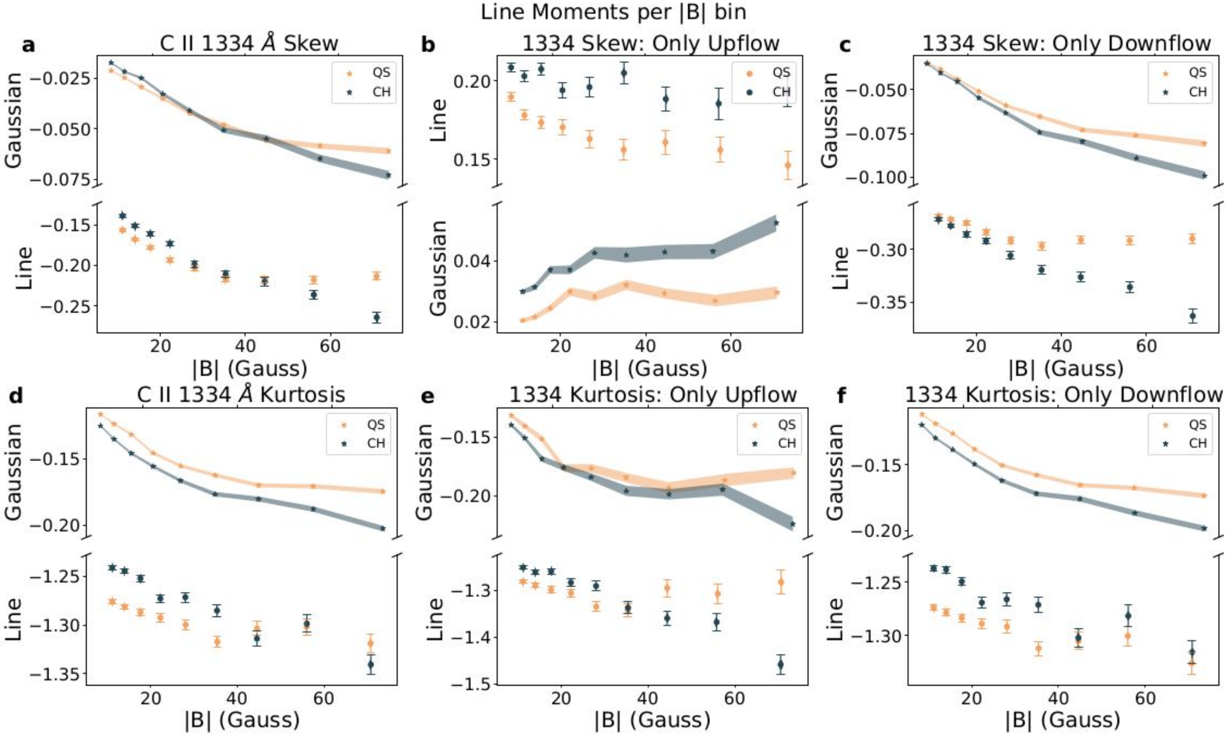
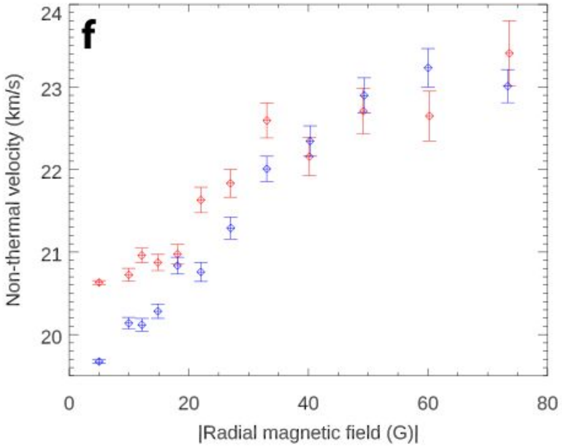


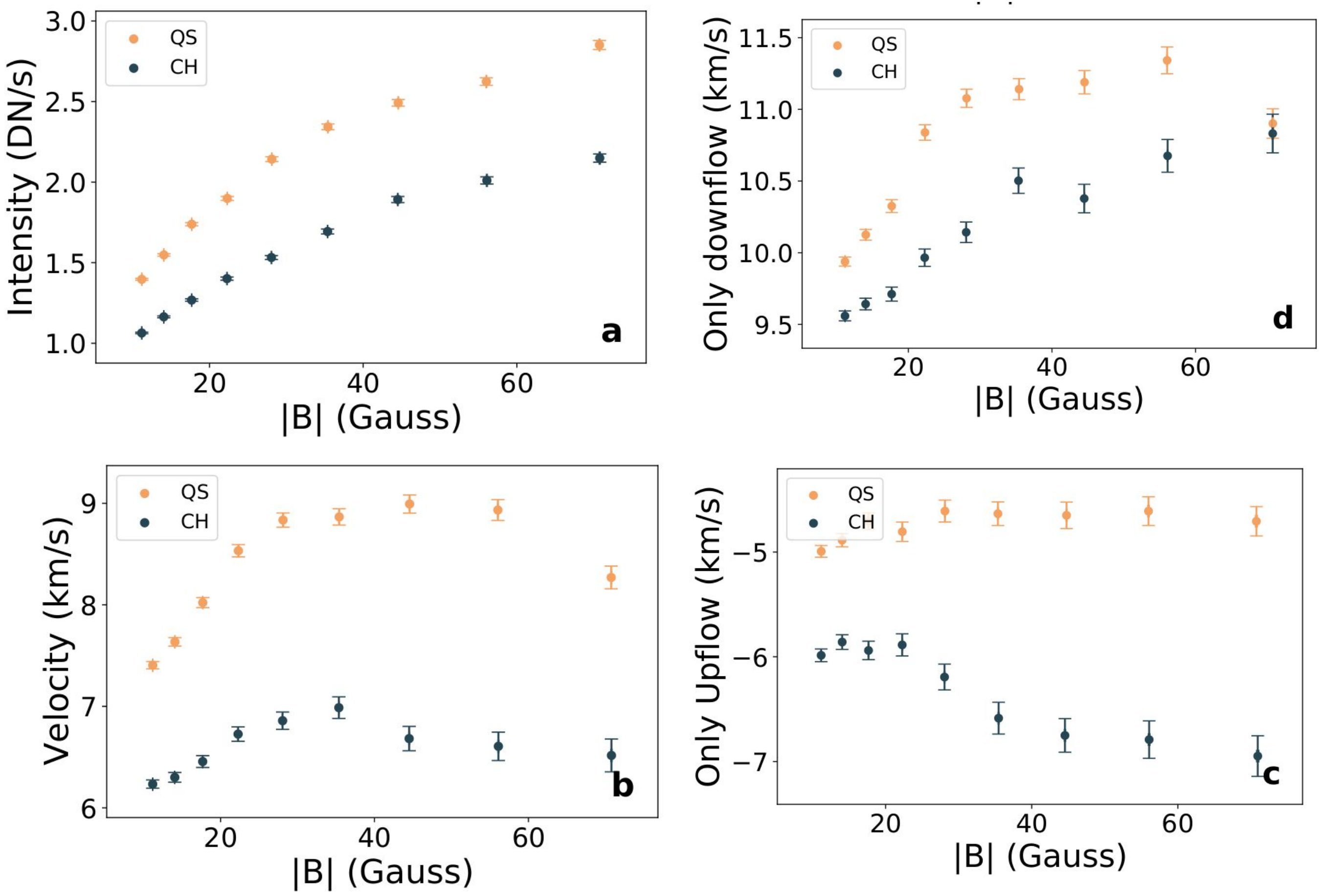
Figure 11. C II skew and kurtosis as a function |B|, for all data sets taken together. The top row corresponds to line skew, while the bottom row corresponds to kurtosis. Panels **a** and **d** correspond to the variation of moments of all profiles, while **b** and **e** (**c** and **f**) correspond to moments of blueshifted (redshifted) profiles. The bands of black and orange, with stars over-plotted, correspond to the respective moment of a single Gaussian fit. The y-axis has been broken to depict the variation with |B| better.



Si IV non thermal width from Tripathi+ 2021.

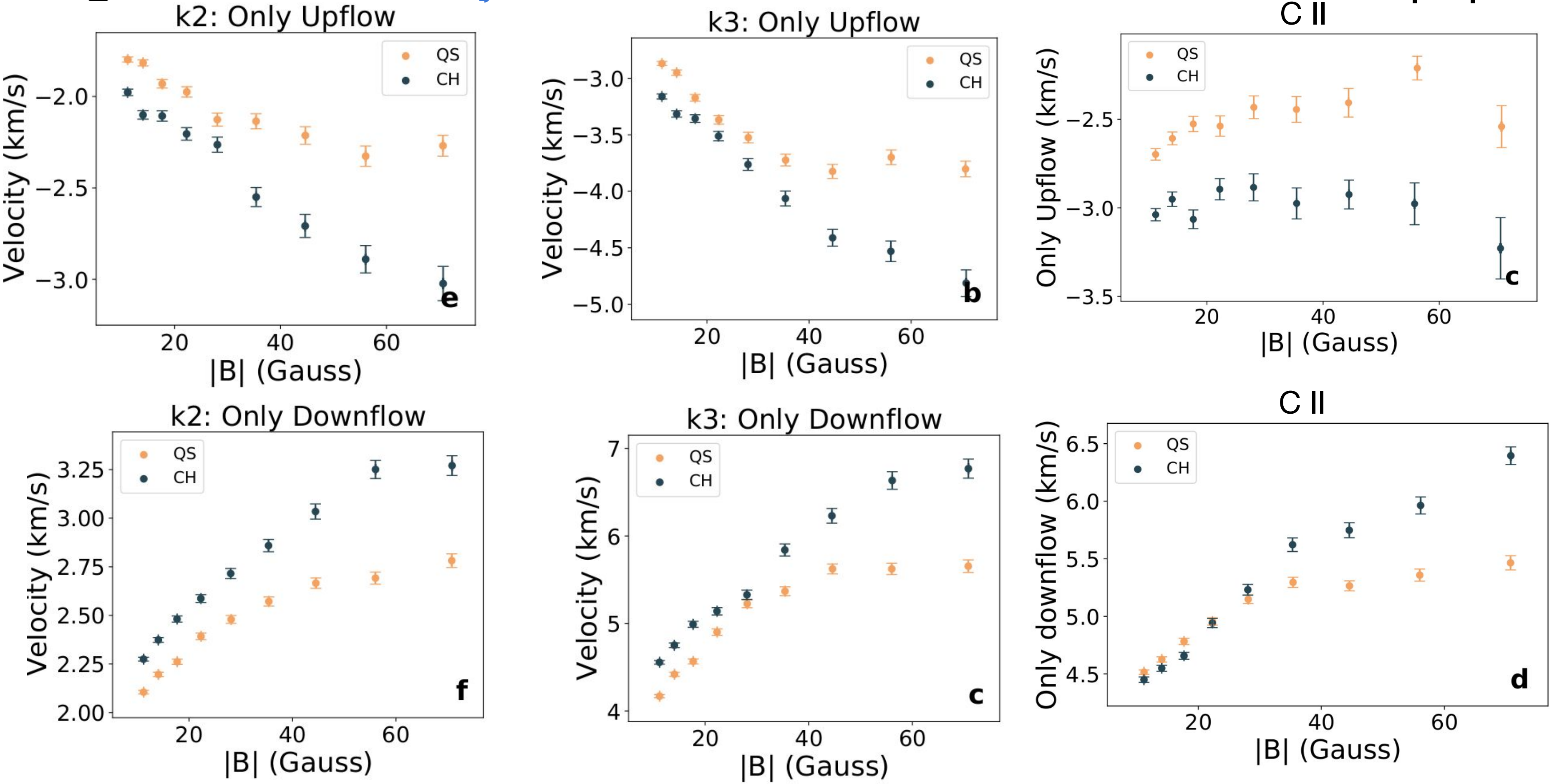
C II moments from Upendran & Tripathi 2021.

Si IV 1394 Å dynamics: Tripathi+ 2021, expanded data

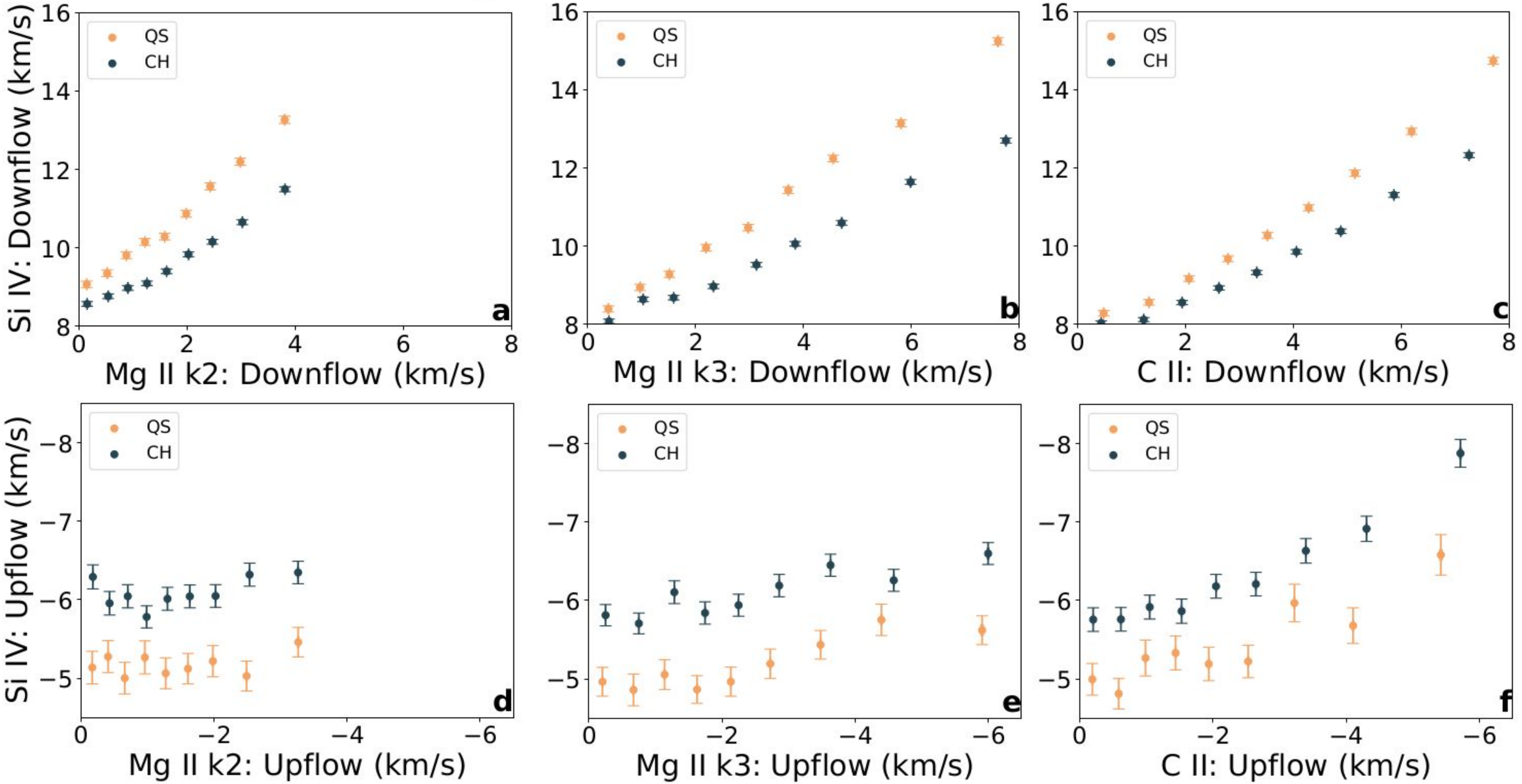


- CHs are darker than QS.
- CHs are less redshifted and more blueshifted than QS.
- The excess blueshifts in CH are shown to be a signature of solar wind emergence.

Mg II and C II: Systematic blue and redshifts with |B|



Velocity cross correlation: Same direction



Velocity cross correlation: Opposite direction