ACTIVE REGION OUTFLOWS AS A SOURCE OF THE SLOW SOLAR WIND

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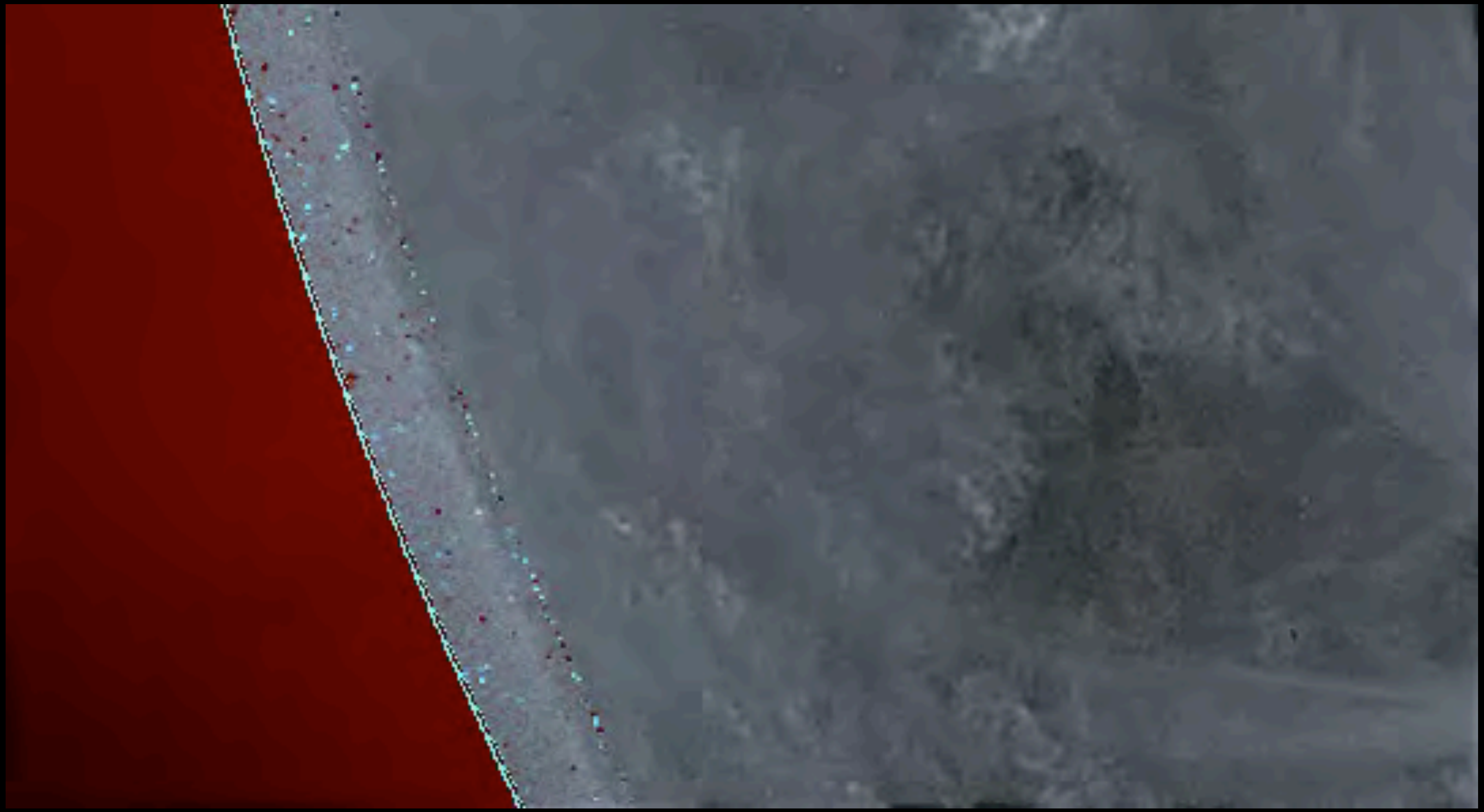
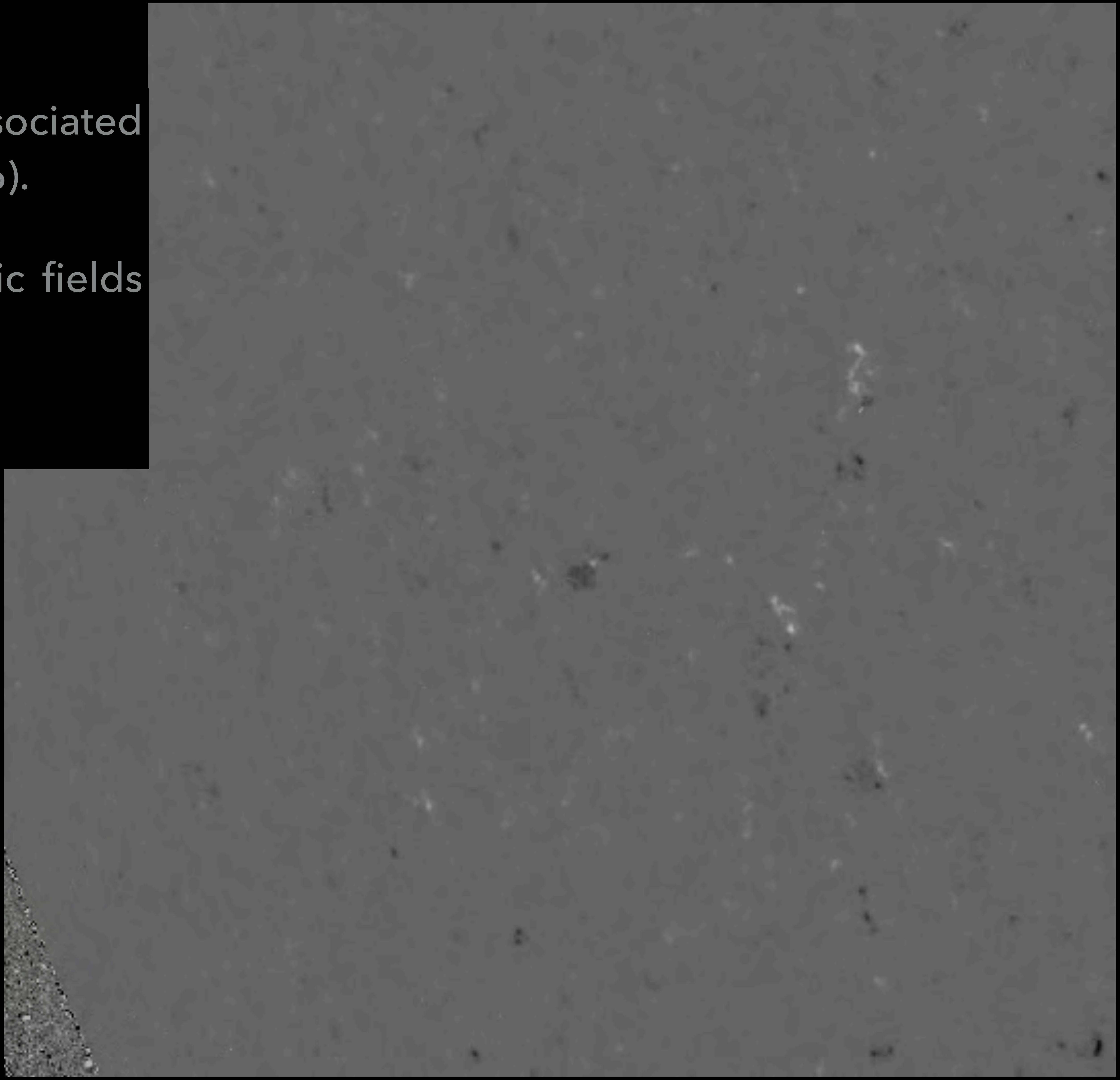
SCIENTIFIC MOTIVATION

- We want to understand how the solar wind is generated and how it controls space weather : impact on near Earth environment; propagation of CMEs etc.
- We need to know the physical properties of the source regions : models are sensitive to the boundary conditions at the formation site.
- We need to identify the source region of the slow wind.
- Recent suggestion: high temperature (few MK) outflows (100 km/s) detected at the edges of active regions by Hinode (Sakao et al. 2007).

SOLAR WIND FROM ACTIVITY BELTS?

- Slow solar wind flows from equatorial regions, may be associated with Active Regions (e.g. Liewer et al. 2004, Ko et al. 2006).
- Active Regions may be sources of heliospheric magnetic fields (Schrijver & de Rosa 2003).

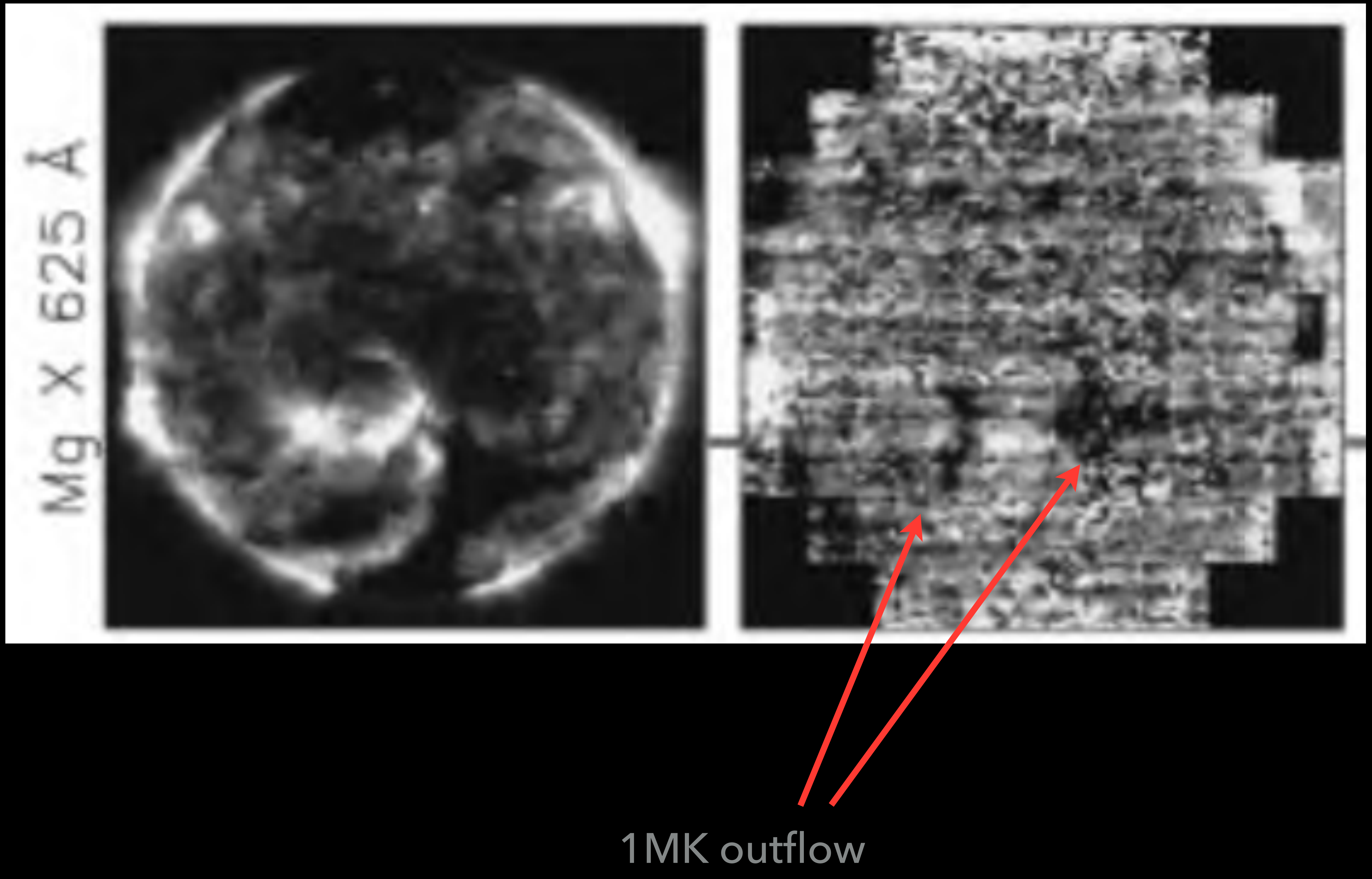




ACTIVE REGION OUTFLOWS?

- High temperature upflows associated with AR edges were recorded in spectra at least as early as 1998.
- Not noted as possible outflow sites or solar wind sources.

Upflow (Black) Downflow (White)

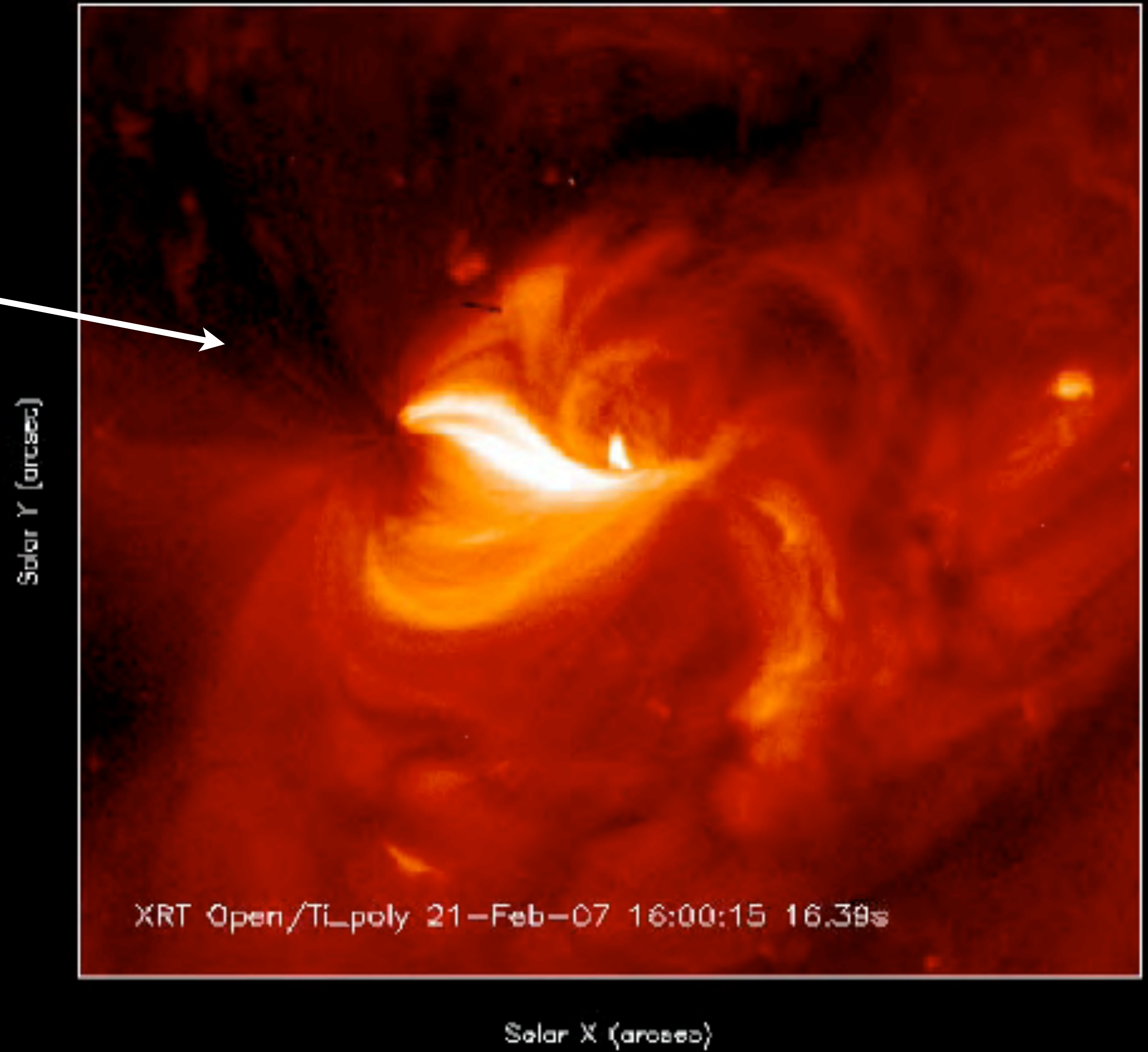


(SOHO/CDS, Thompson & Brekke 1998).

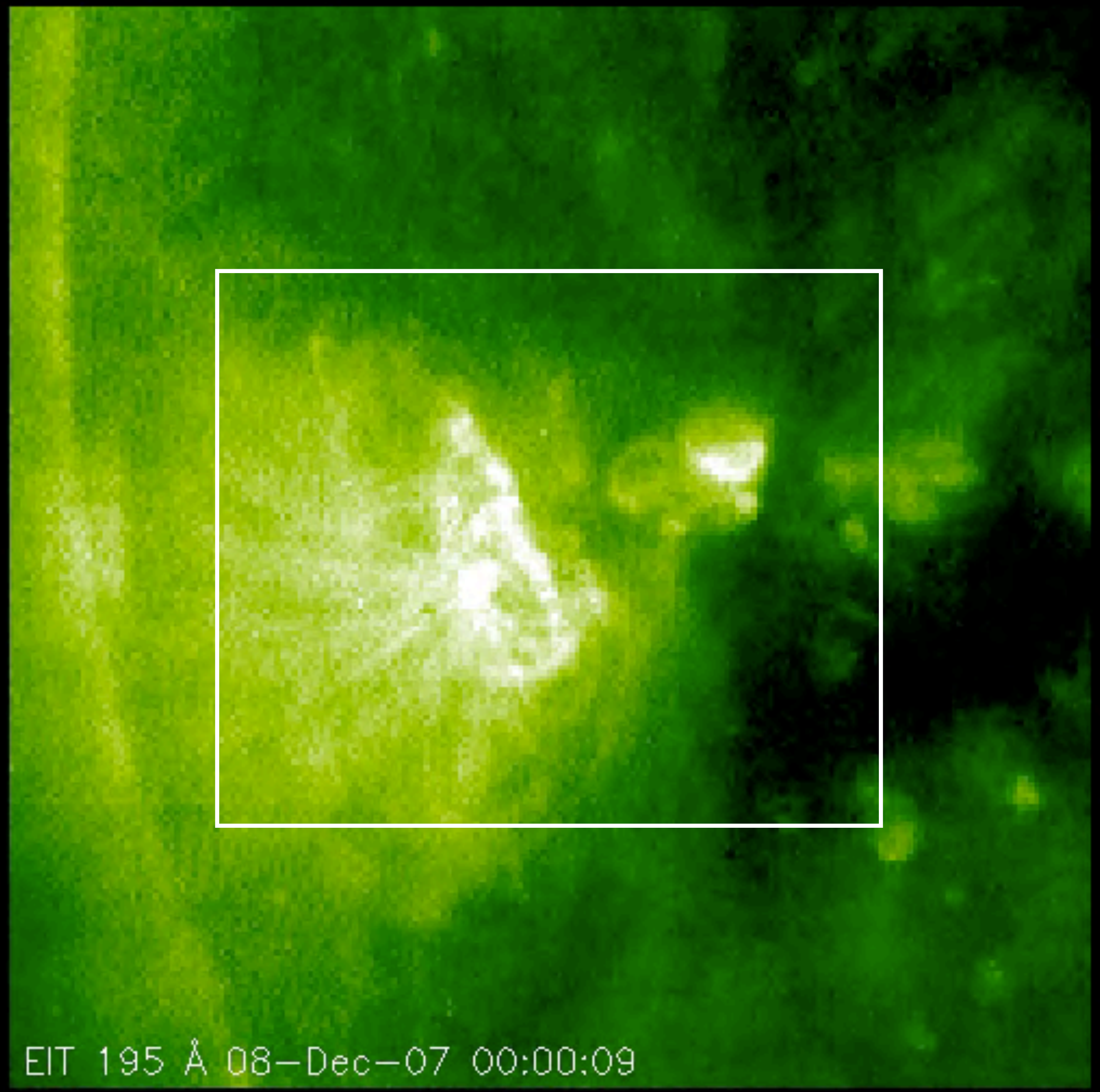
ACTIVE REGION OUTFLOWS?

- High temperature apparent upflow motions observed by Hinode/XRT (Sakao 2007, Del Zanna 2008, Harra 2008, Doschek 2008).

Outflow



- EIS spectroscopy confirms they are upflows > 50km/s (Doschek 2008, Harra 2008)

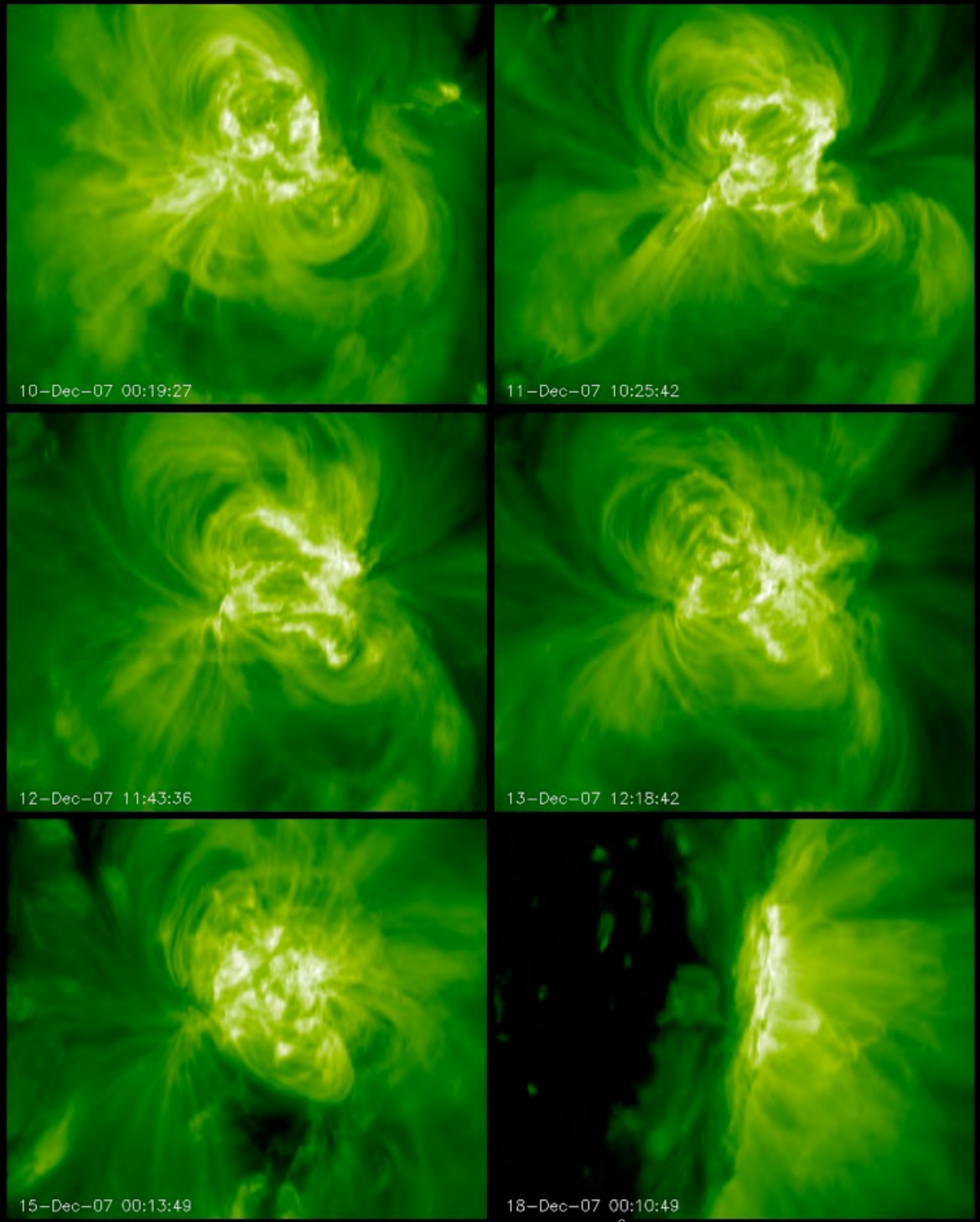


December 8 – 18, 2007

- 460″x384″ slit raster

- 1″ slit, 40s exposures, ~5 hours

- Fe VIII - Fe XVI



EIS Fe XII 195.119 Å

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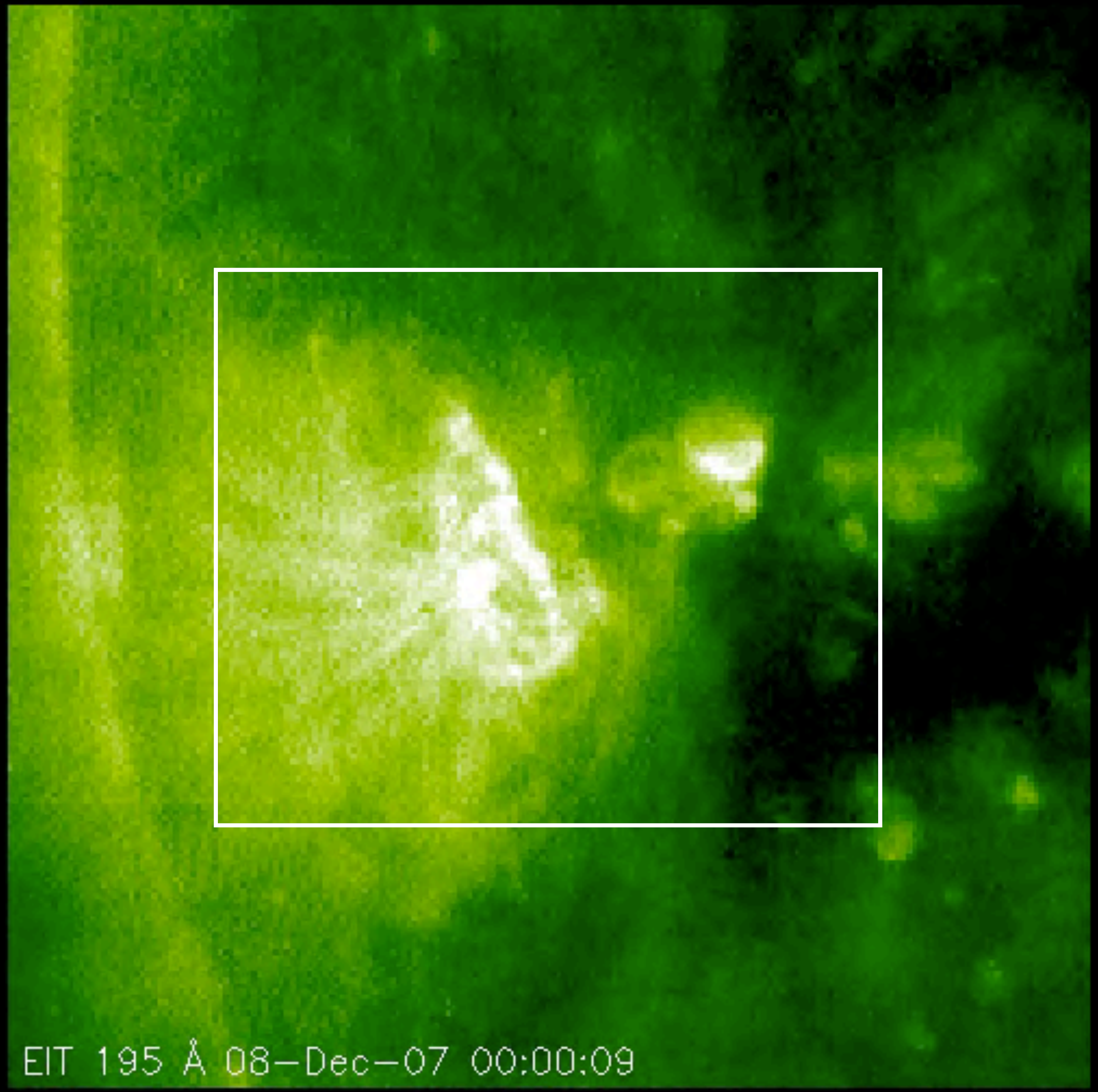

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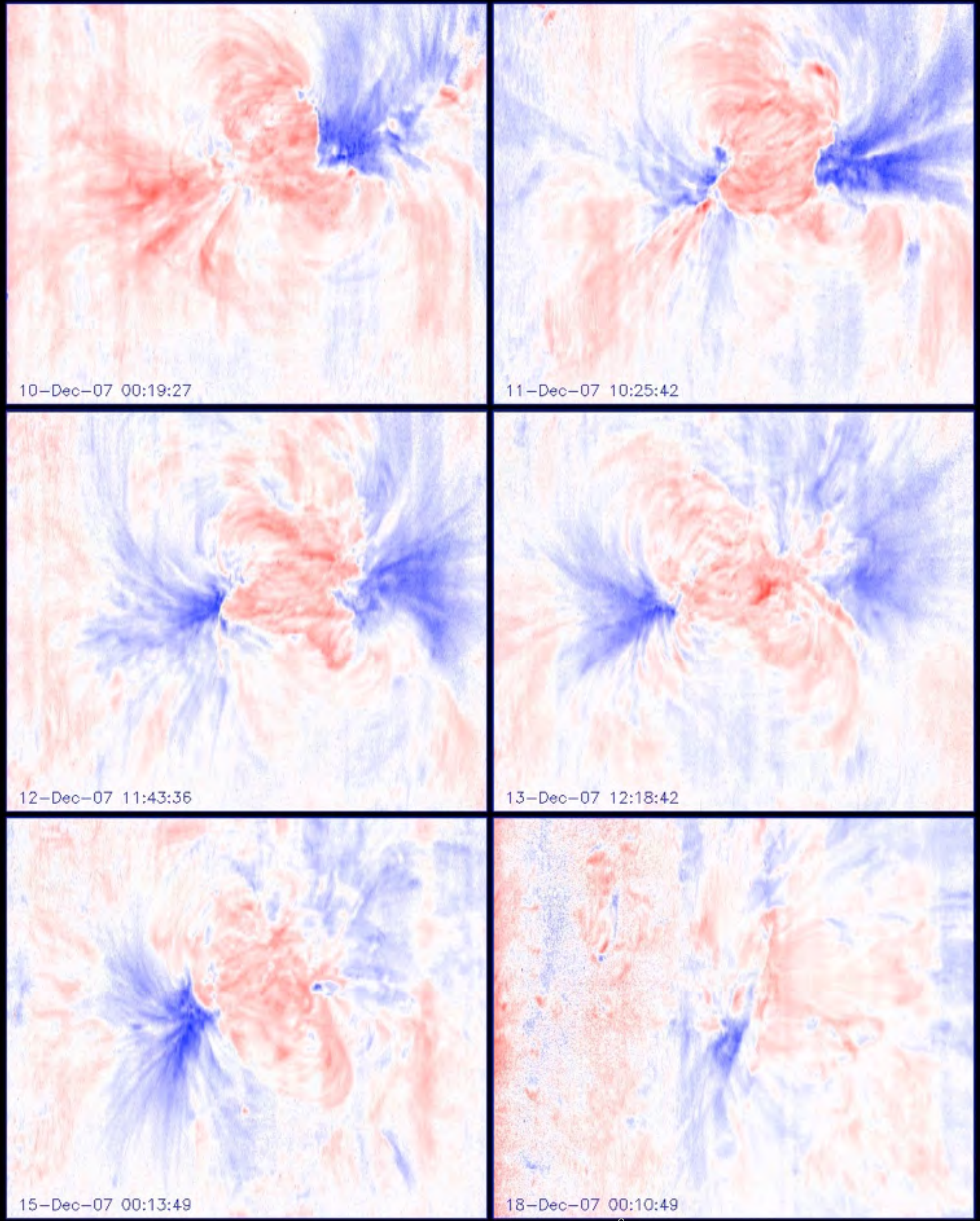
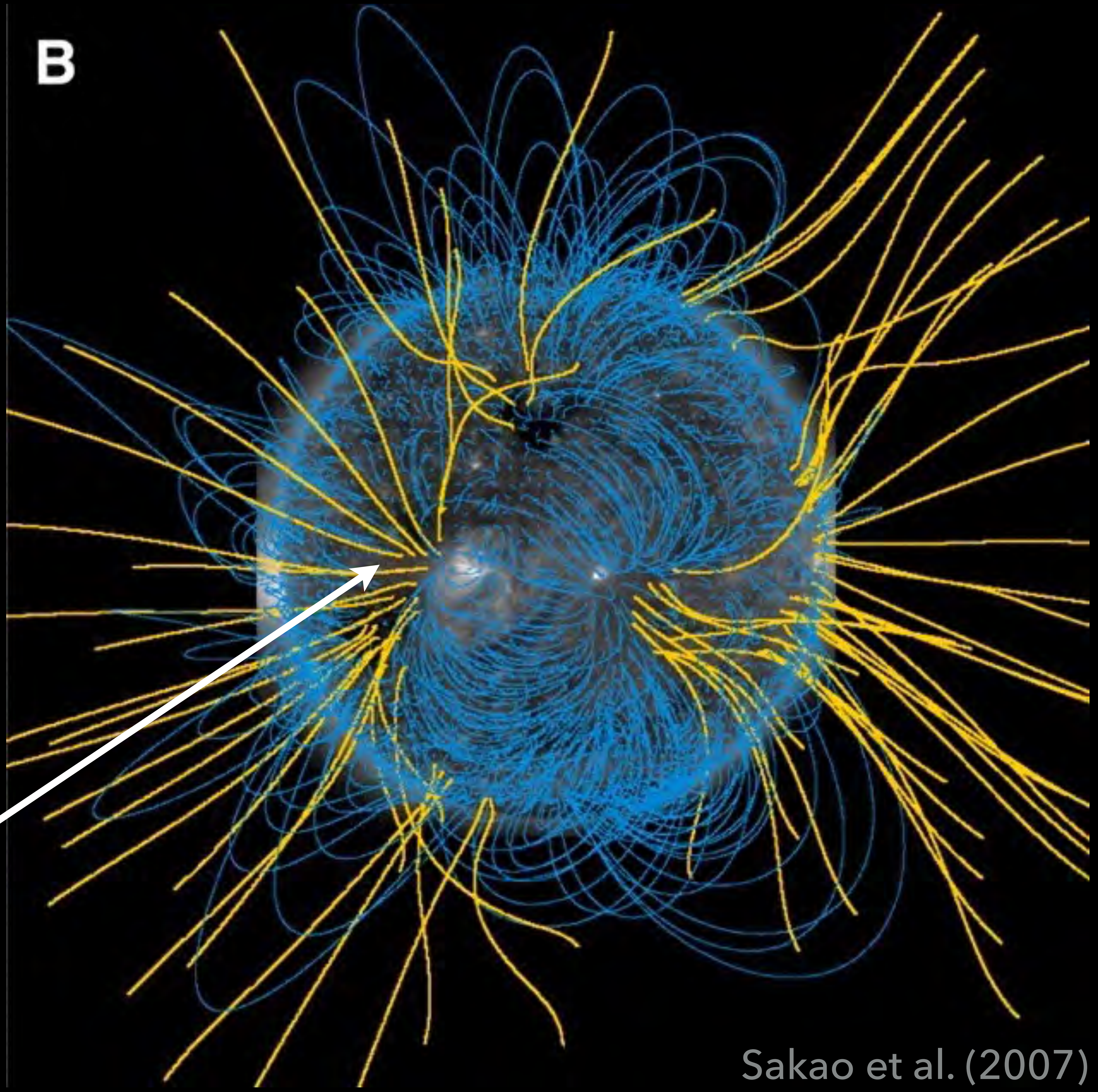


EIS Fe XII 195.119 Å

ACTIVE REGION OUTFLOWS?

- Flows sourced to open magnetic field lines.
- May connect to the heliosphere and contribute to the slow wind (Sakao 2007, Harra 2008, Doschek 2008, Baker 2009, Slemzin 2013).



Open field lines

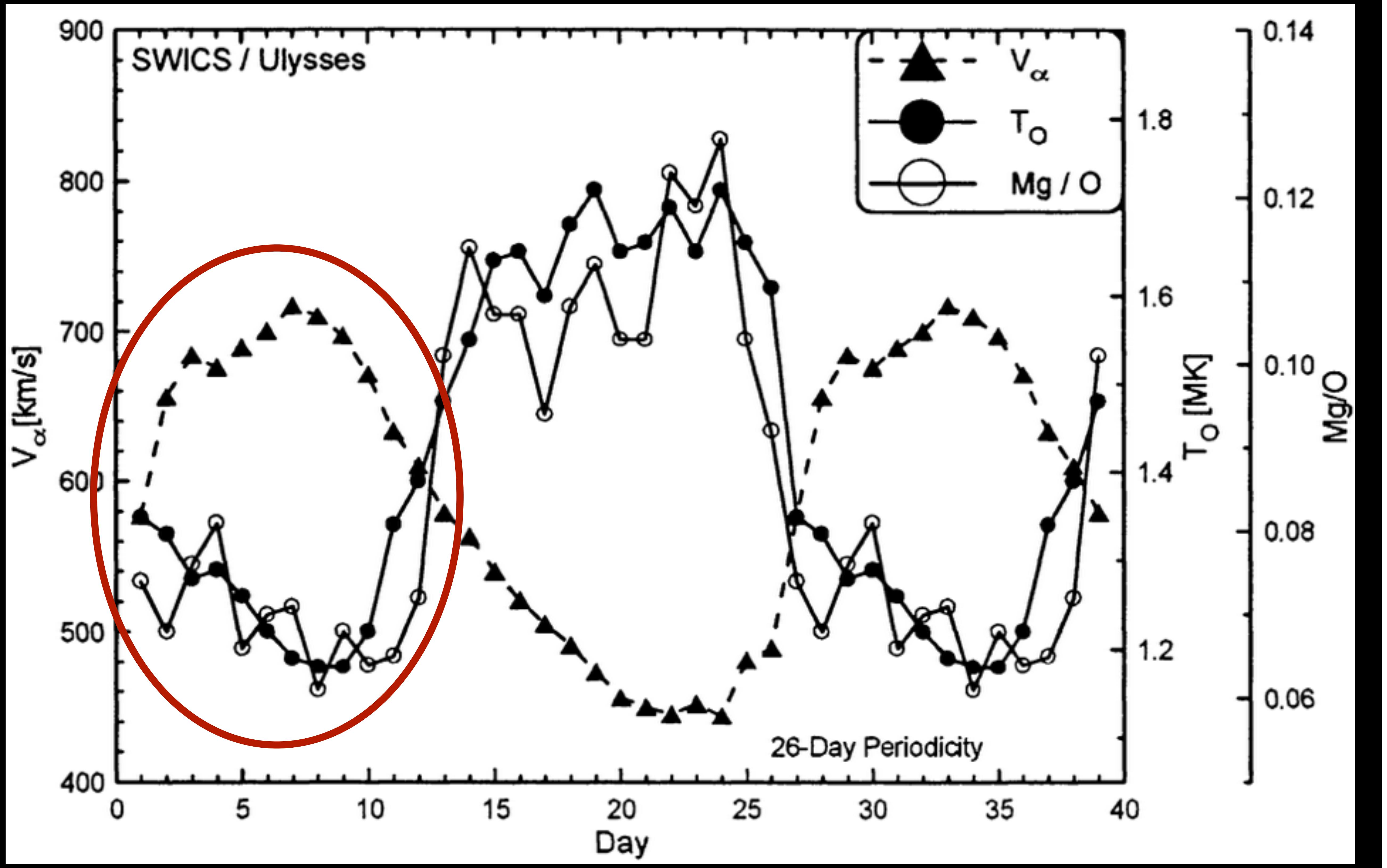
Sakao et al. (2007)

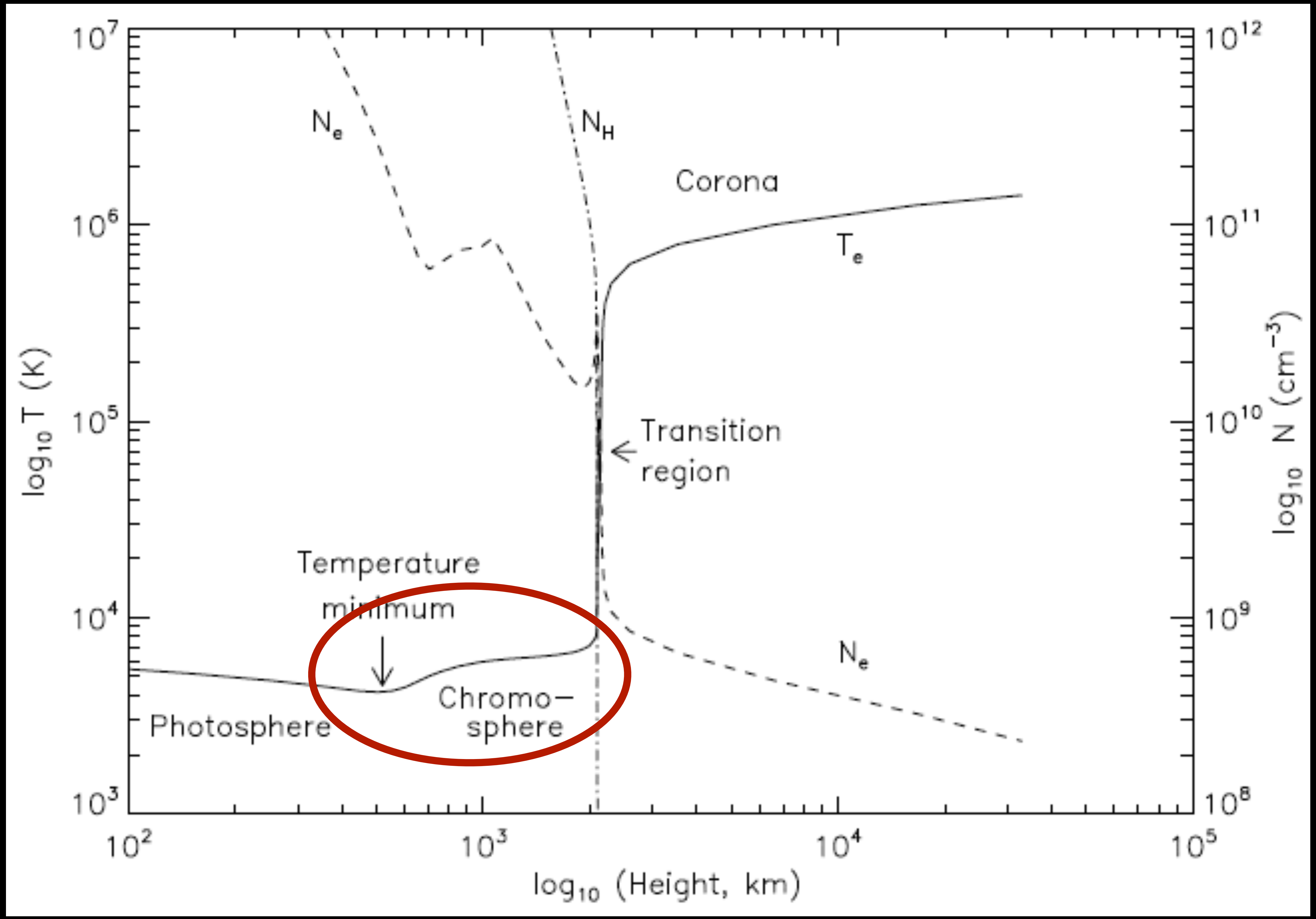
SCIENTIFIC MOTIVATION

- These measurements of AR outflows mostly provide indirect evidence (Doppler Blue-Shift; Modeled Open Field).
- How can we prove a direct link between AR outflows and the slow speed wind?
- Use Hinode/EIS to measure chemical composition in the outflows and compare to in-situ measurements in the slow solar wind.

SOLAR COMPOSITION IS NOT CONSTANT

- Mass in the corona originates in the lower solar atmosphere, but the composition is different! - Variations correlate with First Ionization Potential (FIP).





- High FIP elements neutral in the chromosphere ⟶ photospheric abundances in the corona and fast solar wind

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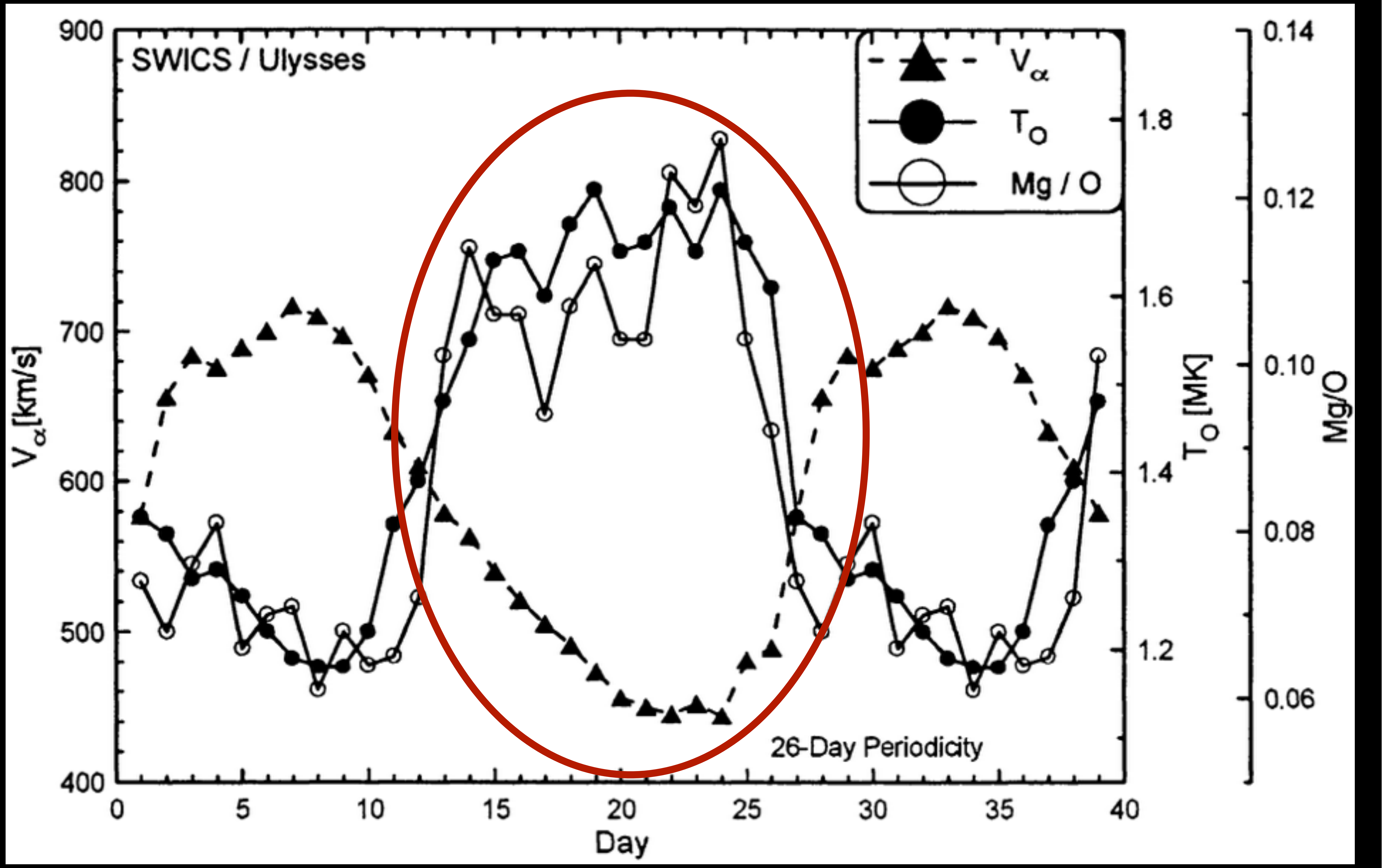

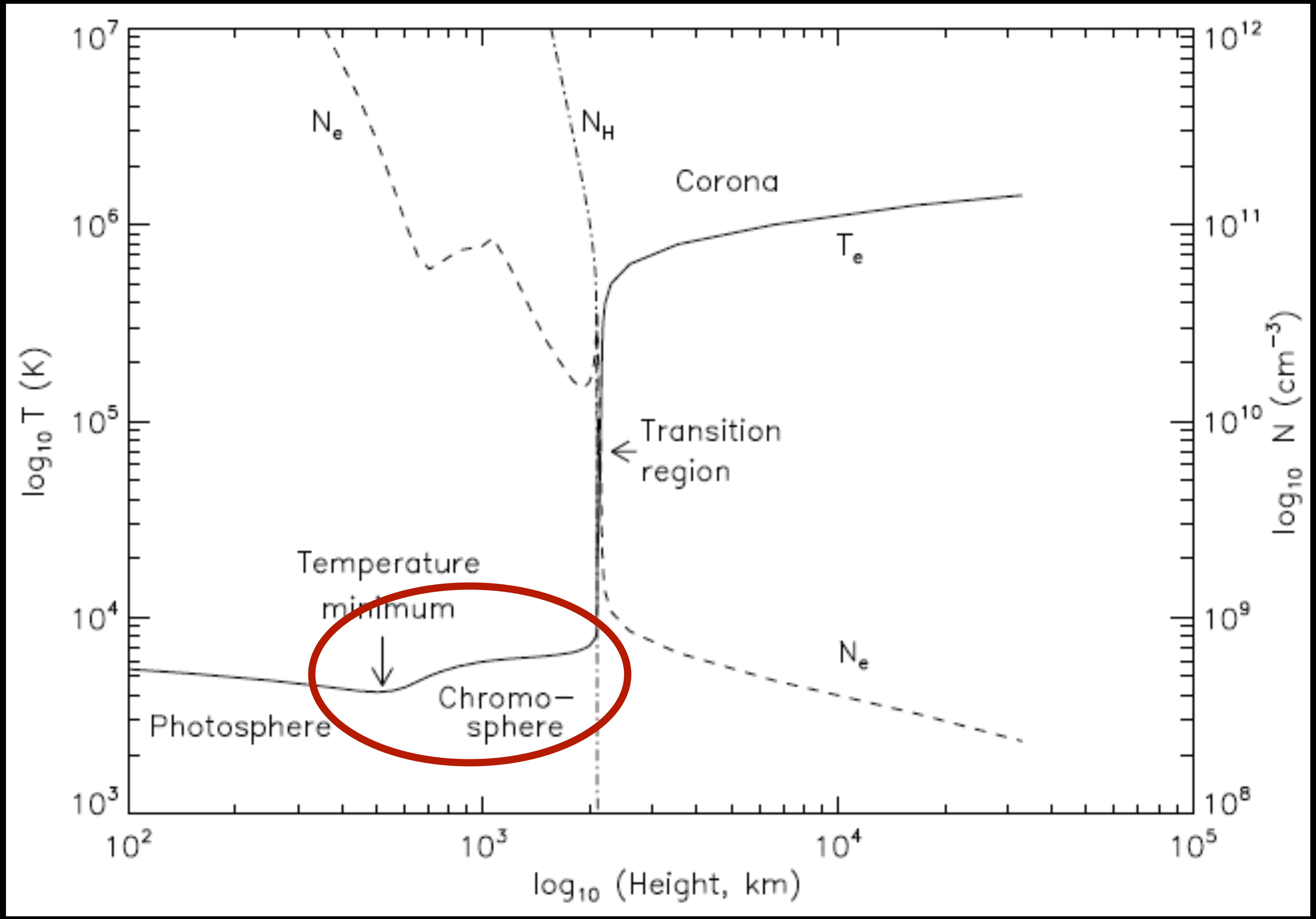

- Low FIP elements ionized in the chromosphere → enhanced abundances in the corona and slow solar wind

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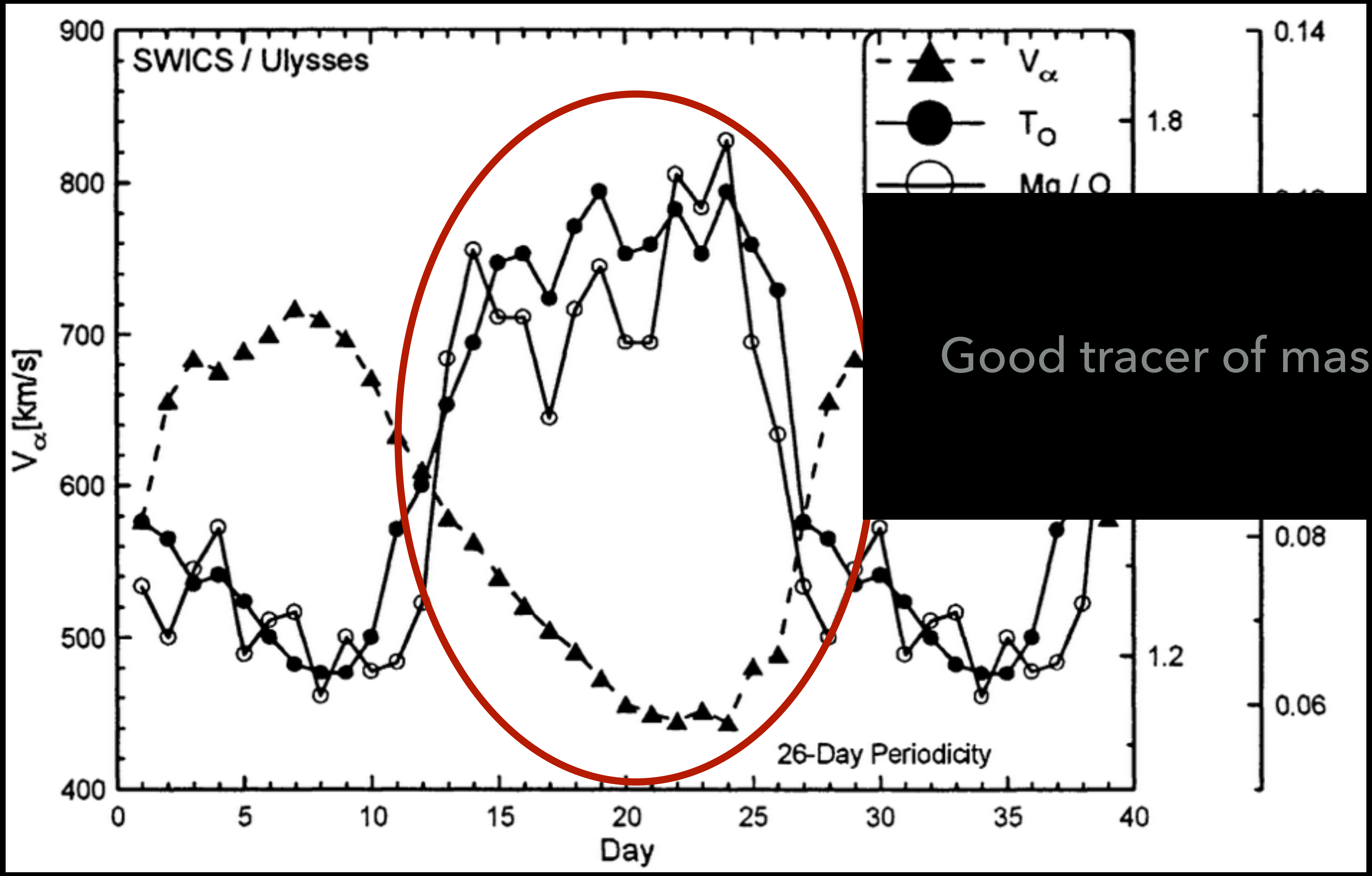
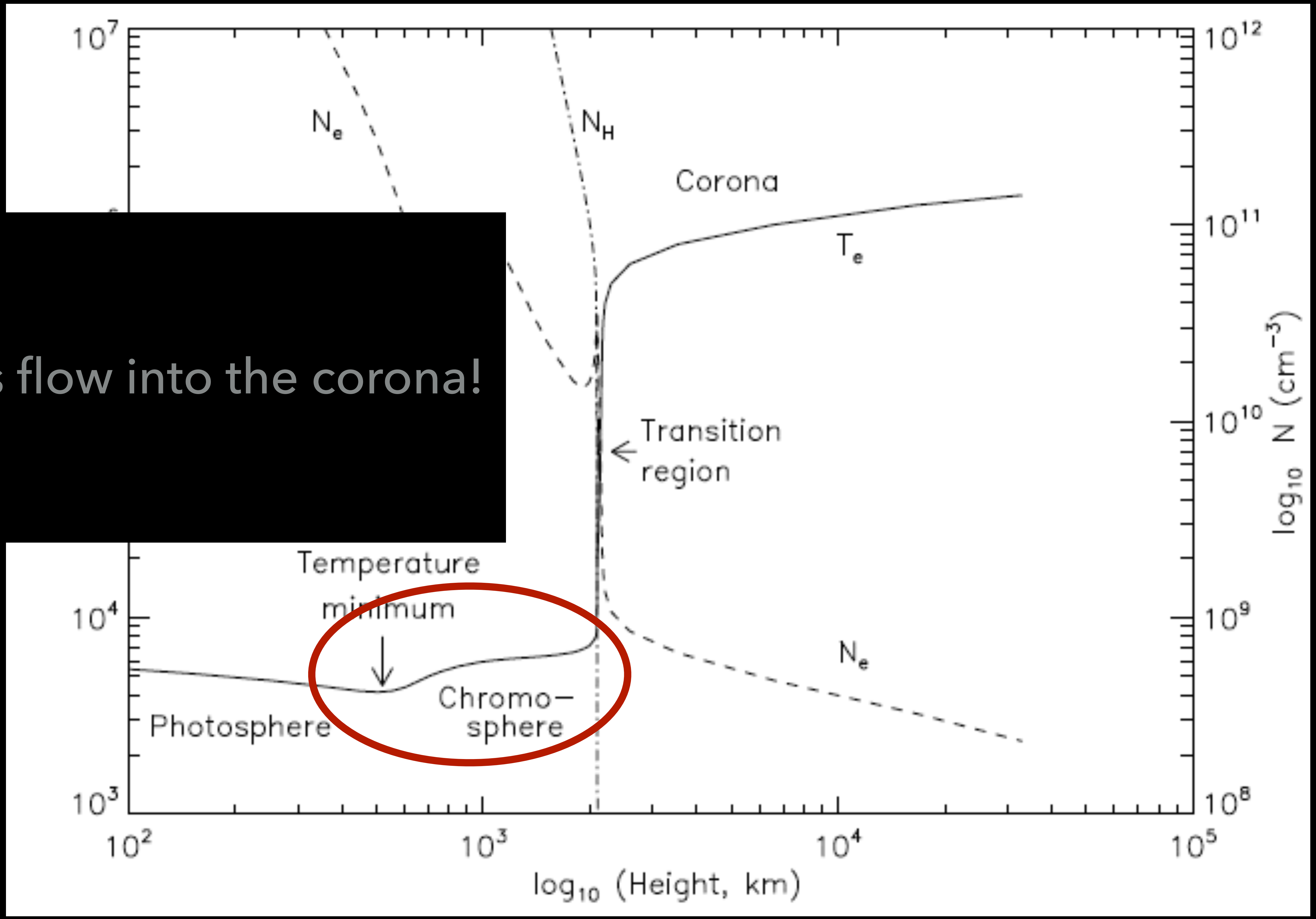




Good tracer of mass flow into the corona!

- Low FIP elements ionized in the chromosphere ⟶ enhanced abundances in the corona and slow solar wind

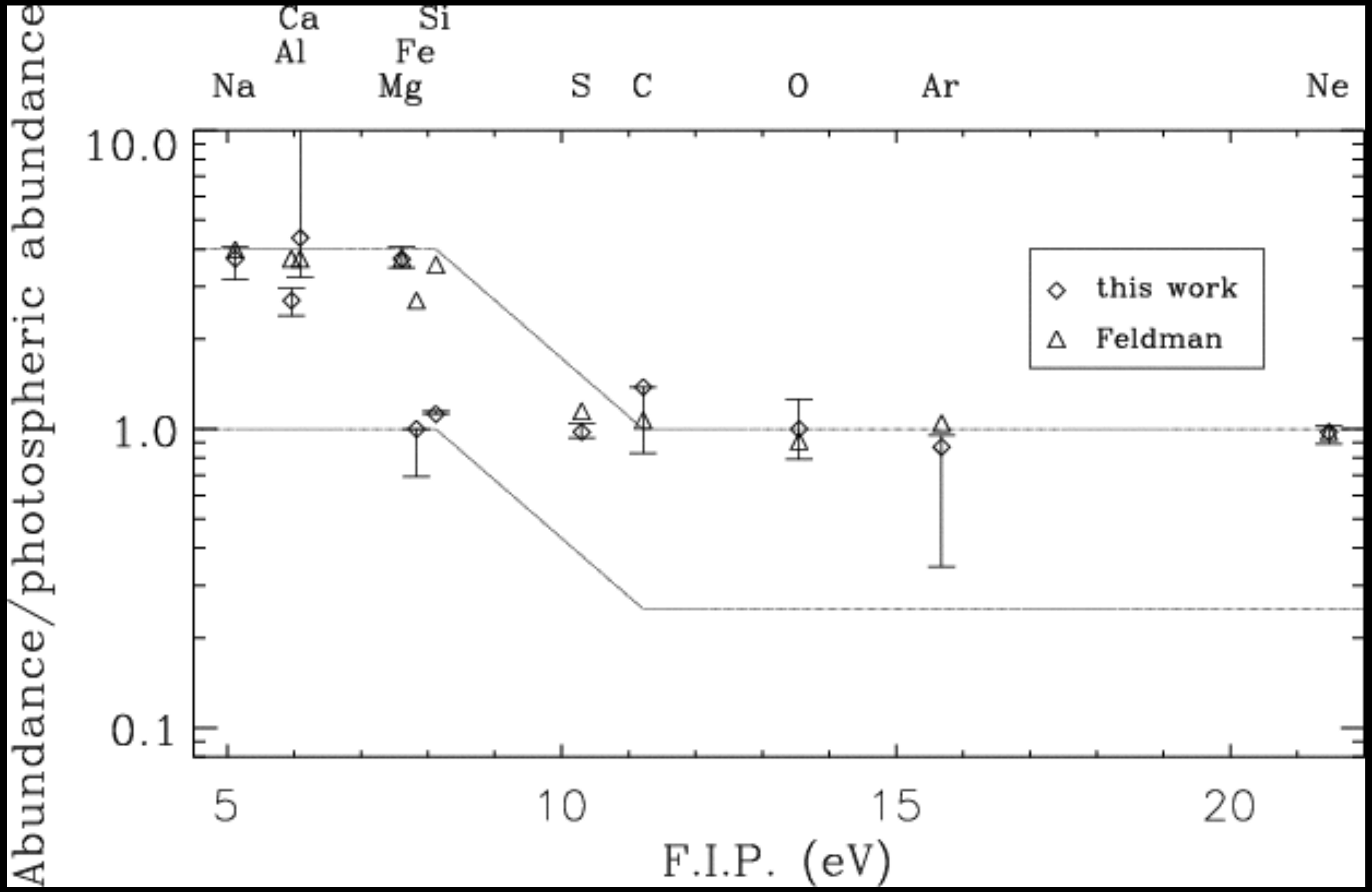
FIRST IONIZATION POTENTIAL (FIP) EFFECT

- Hinode/EIS has opened a new era of well constrained, high spatial resolution measurements of elemental abundances (Feldman et al. 2009, Brooks & Warren 2011)

- Ar XIV 188 or 194Å/ Ca XIV 194Å: useful for active regions and flares (Doschek et al. 2015, 2016, 2017).

- Si X 258Å/S X 264Å: useful for coronal holes, quiet sun, active regions (Brooks & Warren 2011, 2012).

- O, Mg, Si lines useful for impulsive events in the transition region (Warren et al. 2016).



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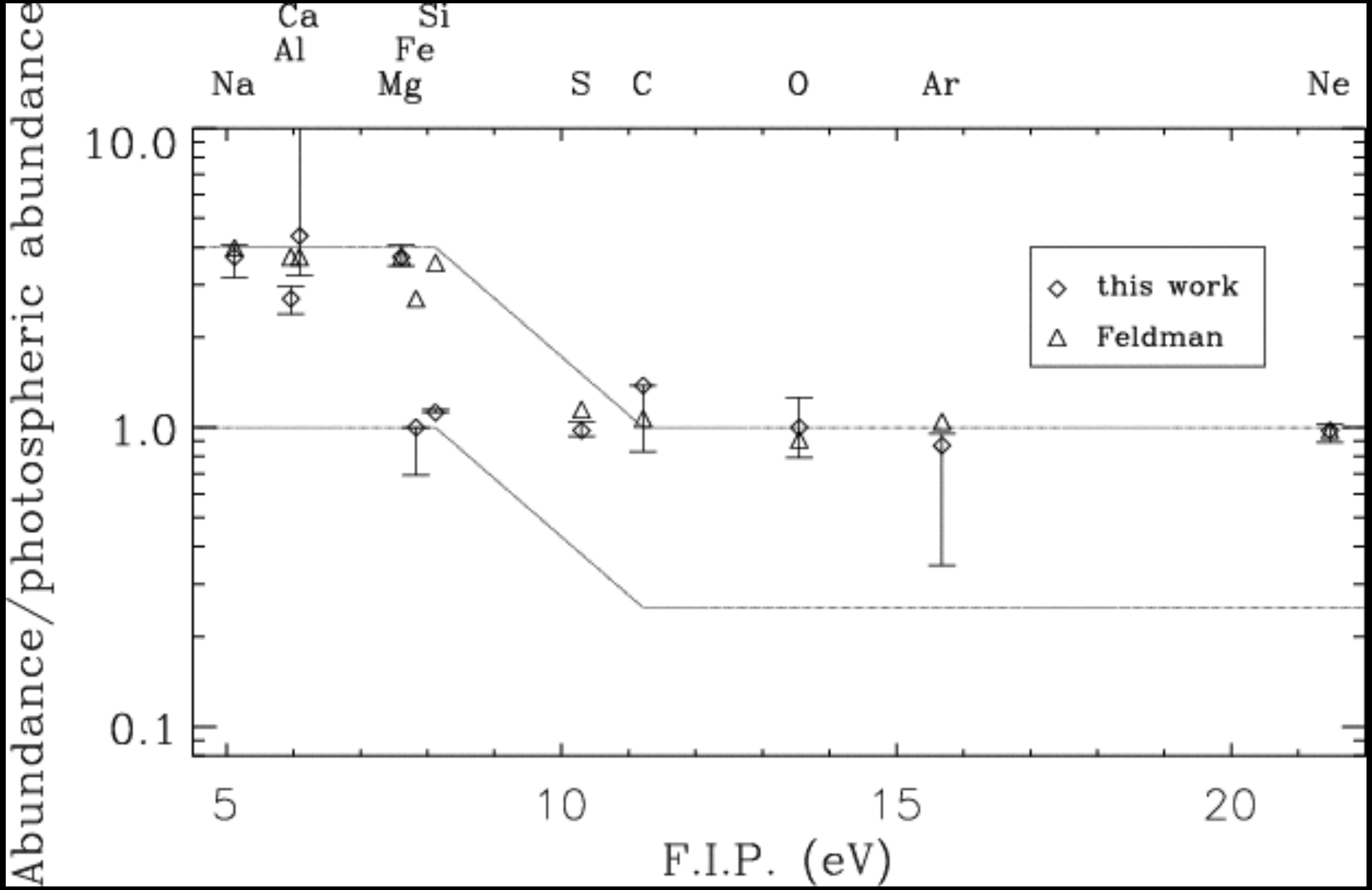
- Promising model explanation based on MHD waves (Laming 2004, 2012).
- Model is a static treatment.
- We need time-dependent simulations.



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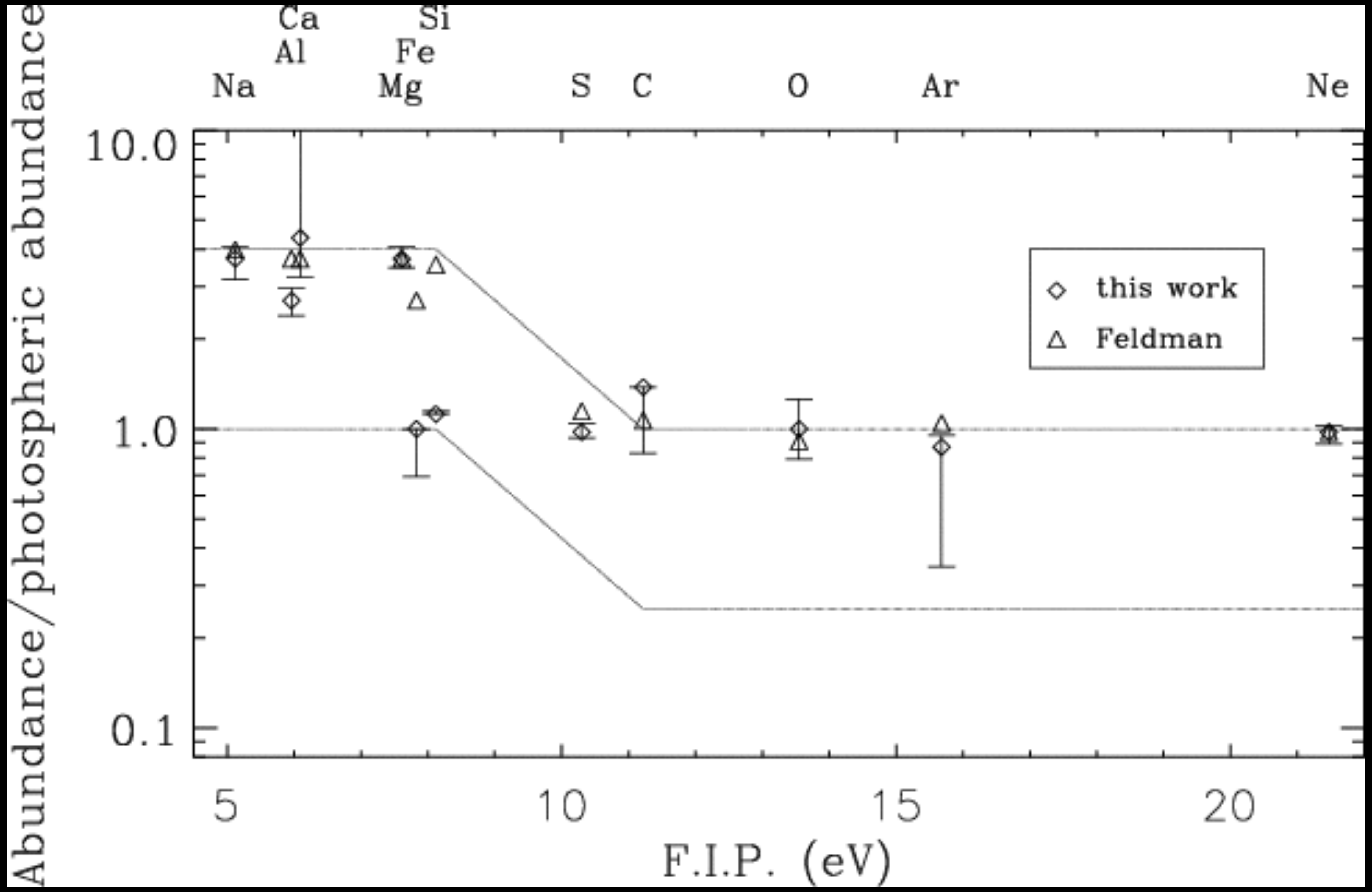
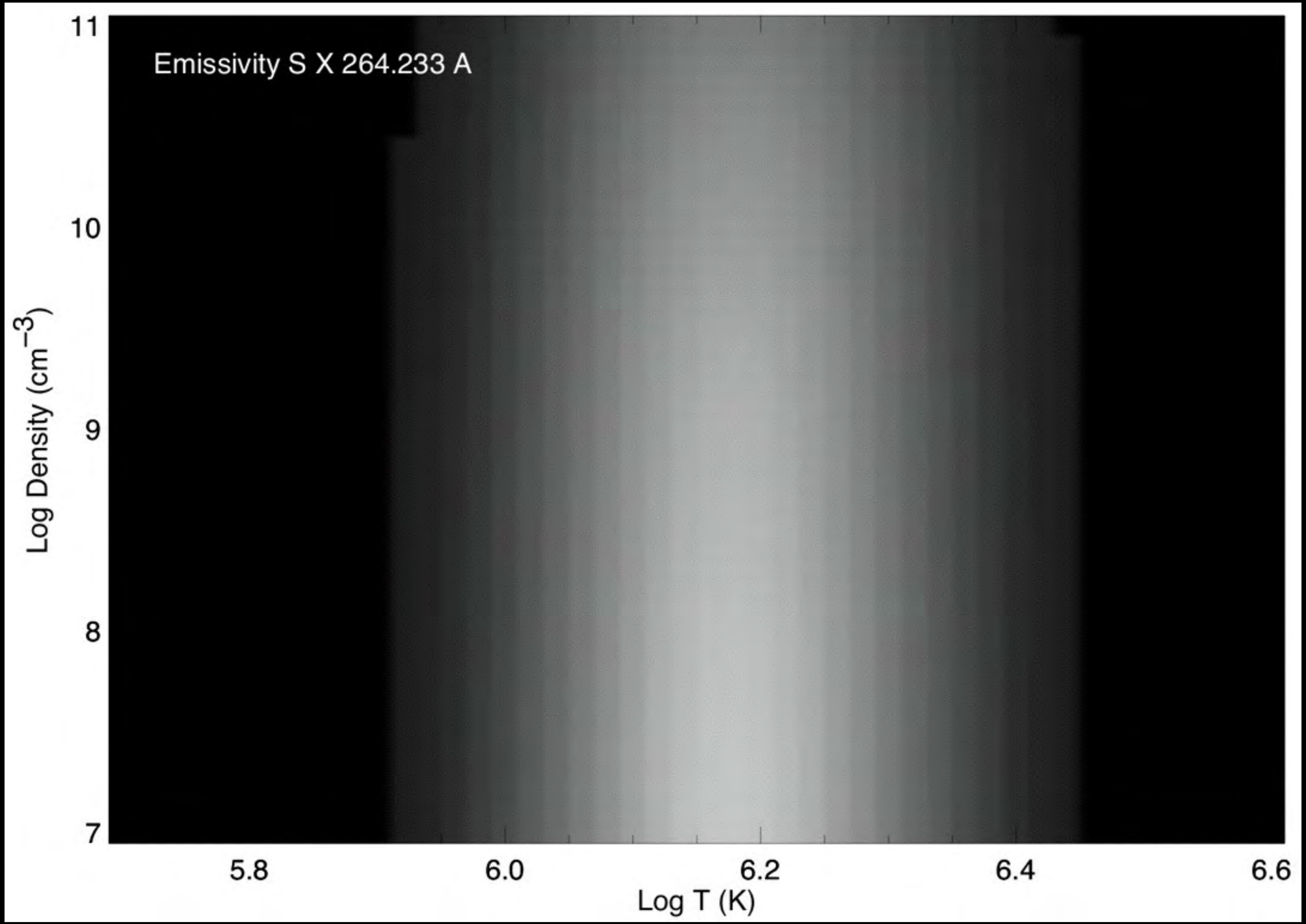
What can we learn about:

- Outflows as slow wind sources?



TECHNICAL DETAILS OF METHOD



- Theoretical emissivities for SX 264 & SiX 258 are very similar

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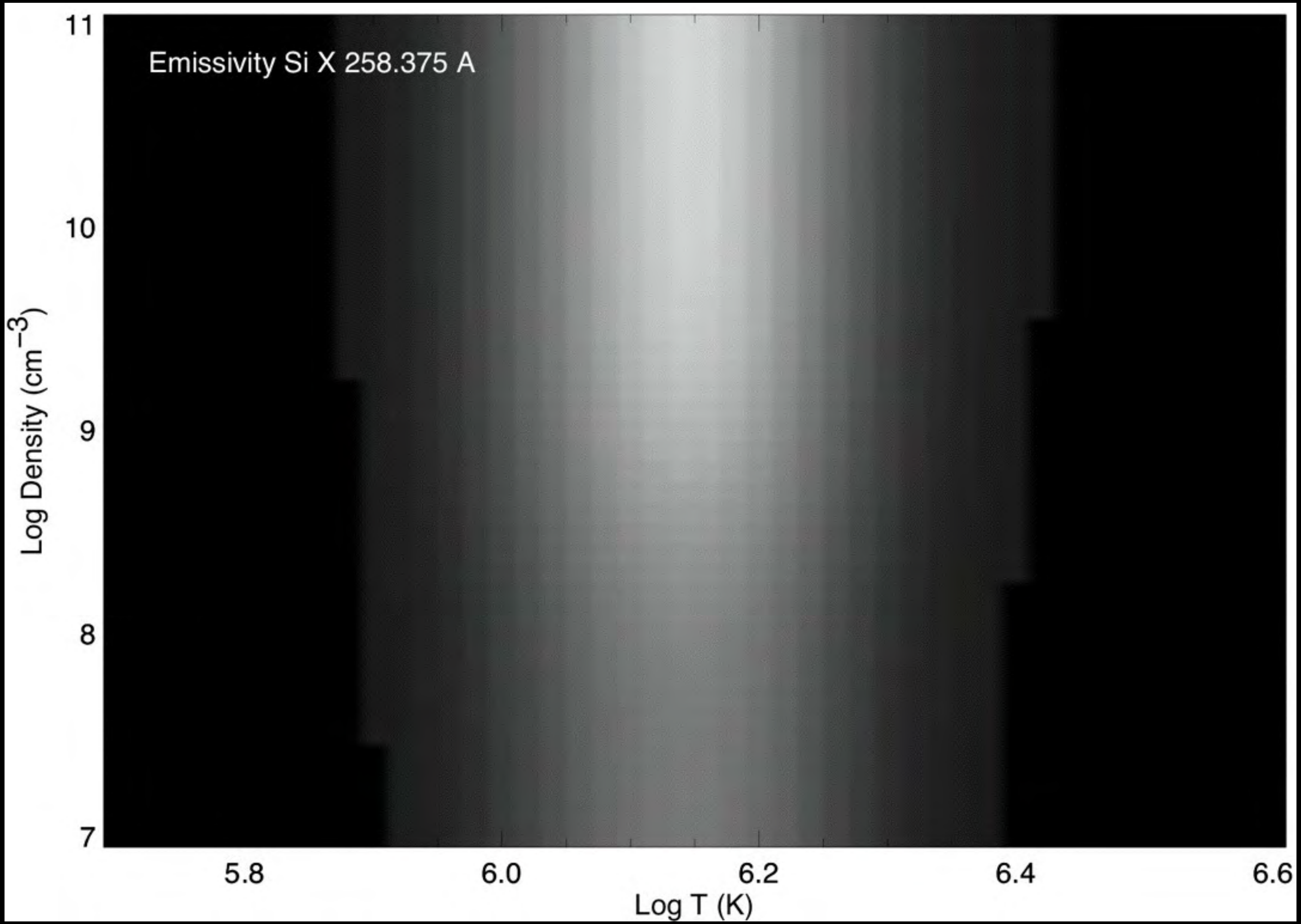
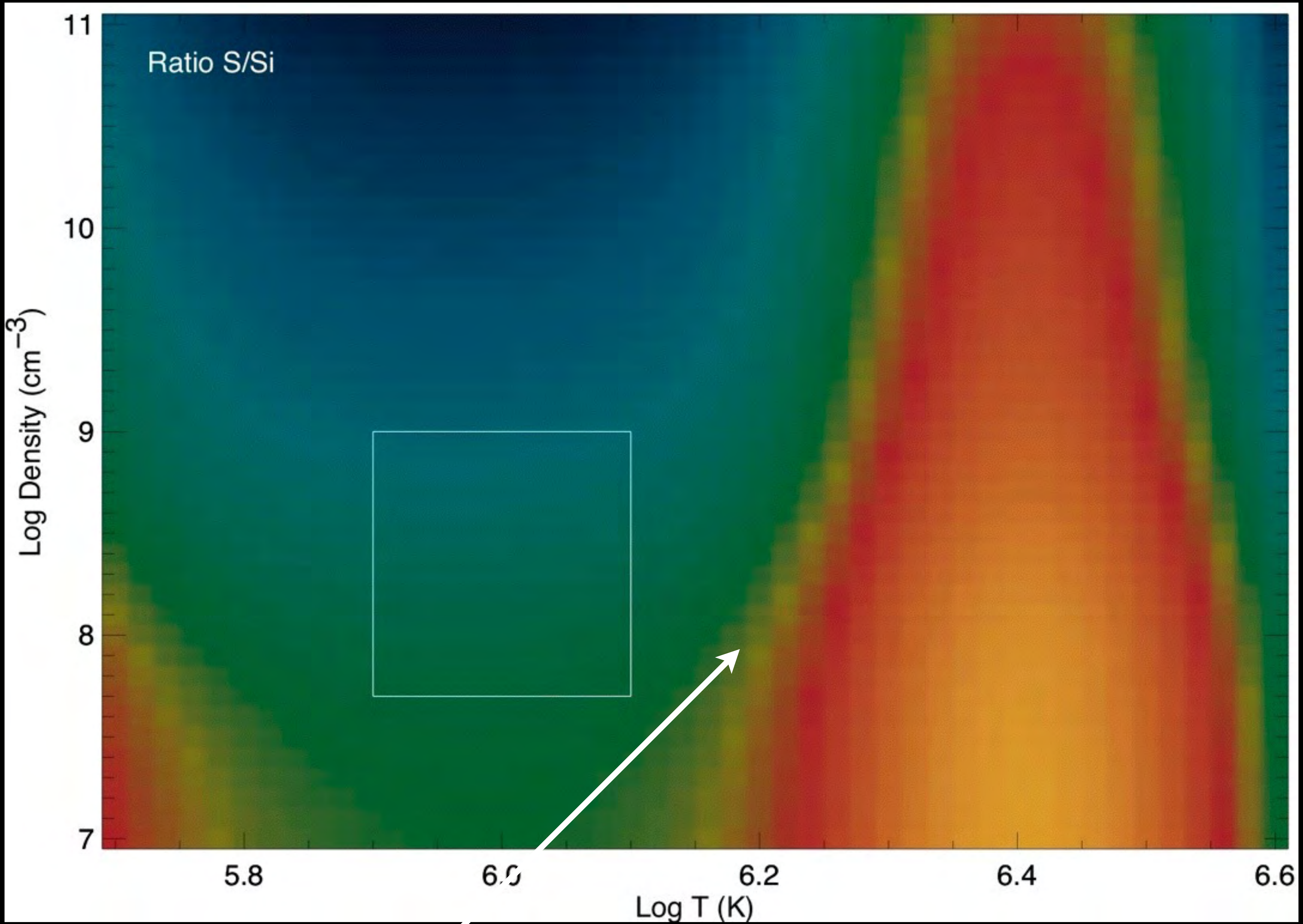


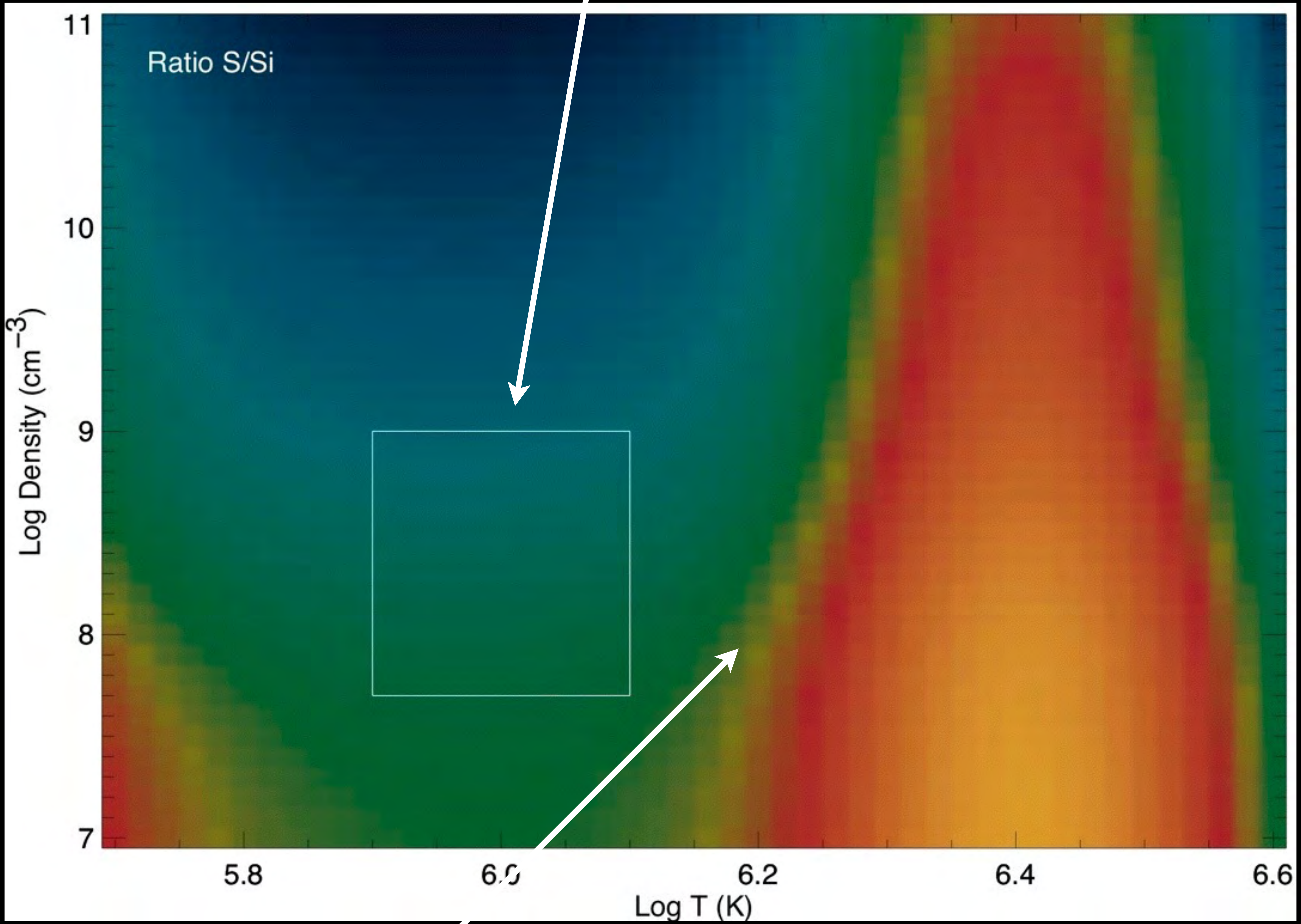
- Theoretical emissivities for SX 264 & SiX 258 are very similar

- Ratio is within ~30-40% in log T=5.7-6.3 & log N = 8-10 range



- Density and temperature removed by full DEM inversion using Si VII, Fe VIII-XVII lines

- DEM analysis shows that the AR outflows fall in this region



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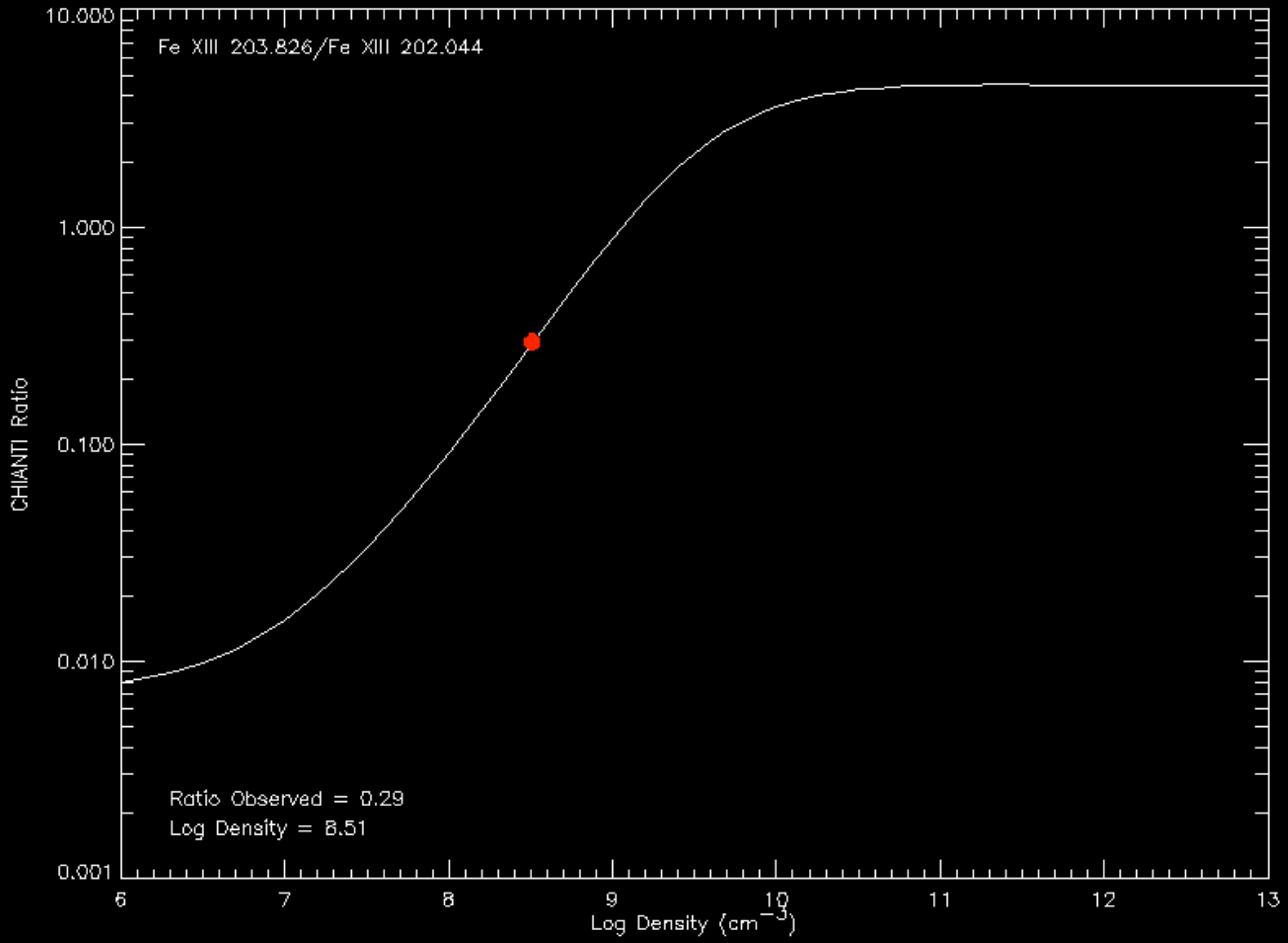
SUMMARY OF ALGORITHM:

- Measure density in outflows using Fe XIII 202/203.8 ratio.
- Derive temperature distribution (DEM) using lines from low FIP elements (Fe and Si)
- Calculate S X intensity using the DEM
- Calculated/Observed S X intensity = FIP bias

TYPICAL EXAMPLE OF DENSITY AND DEM FOR AR OUTFLOWS



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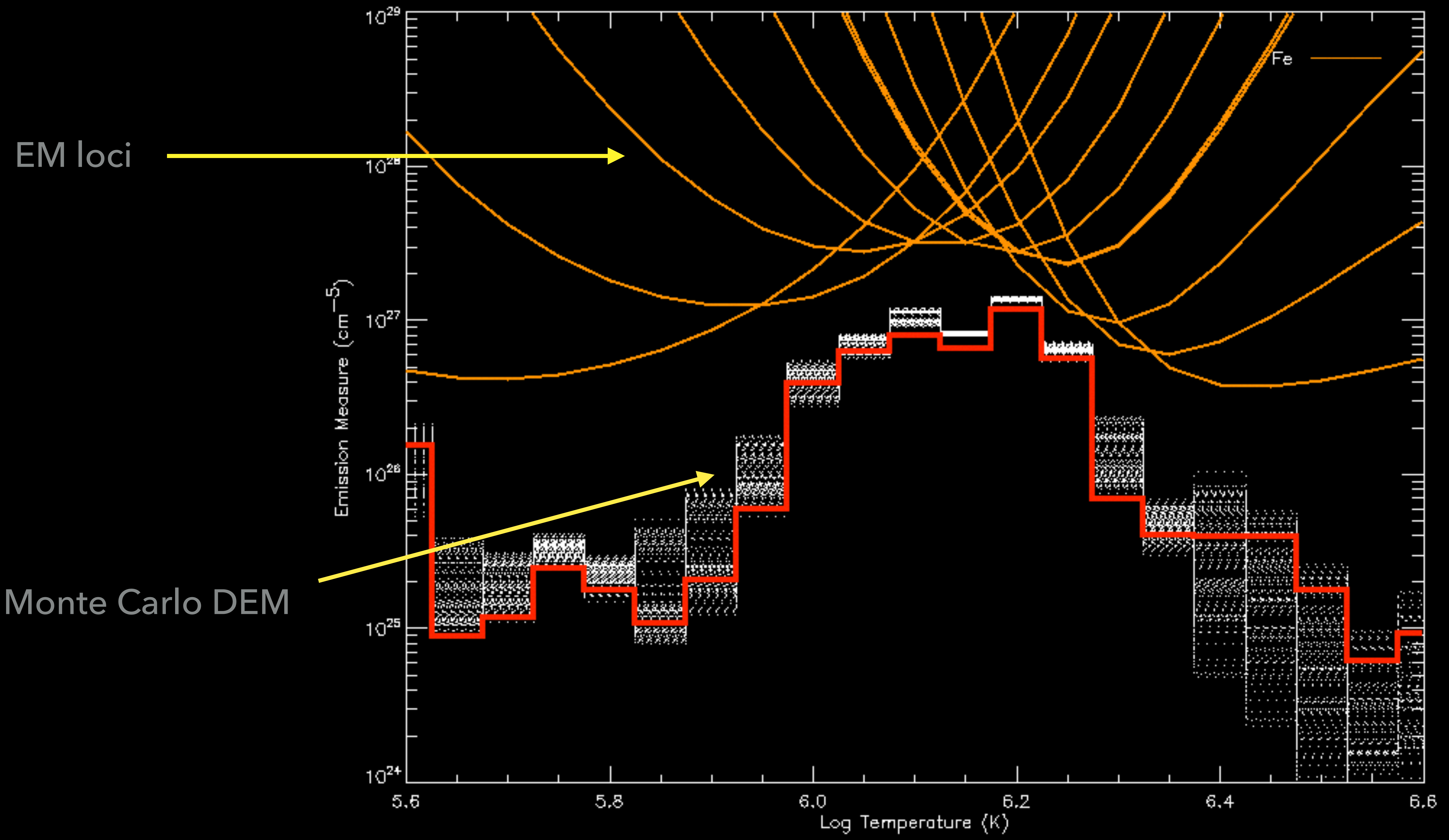
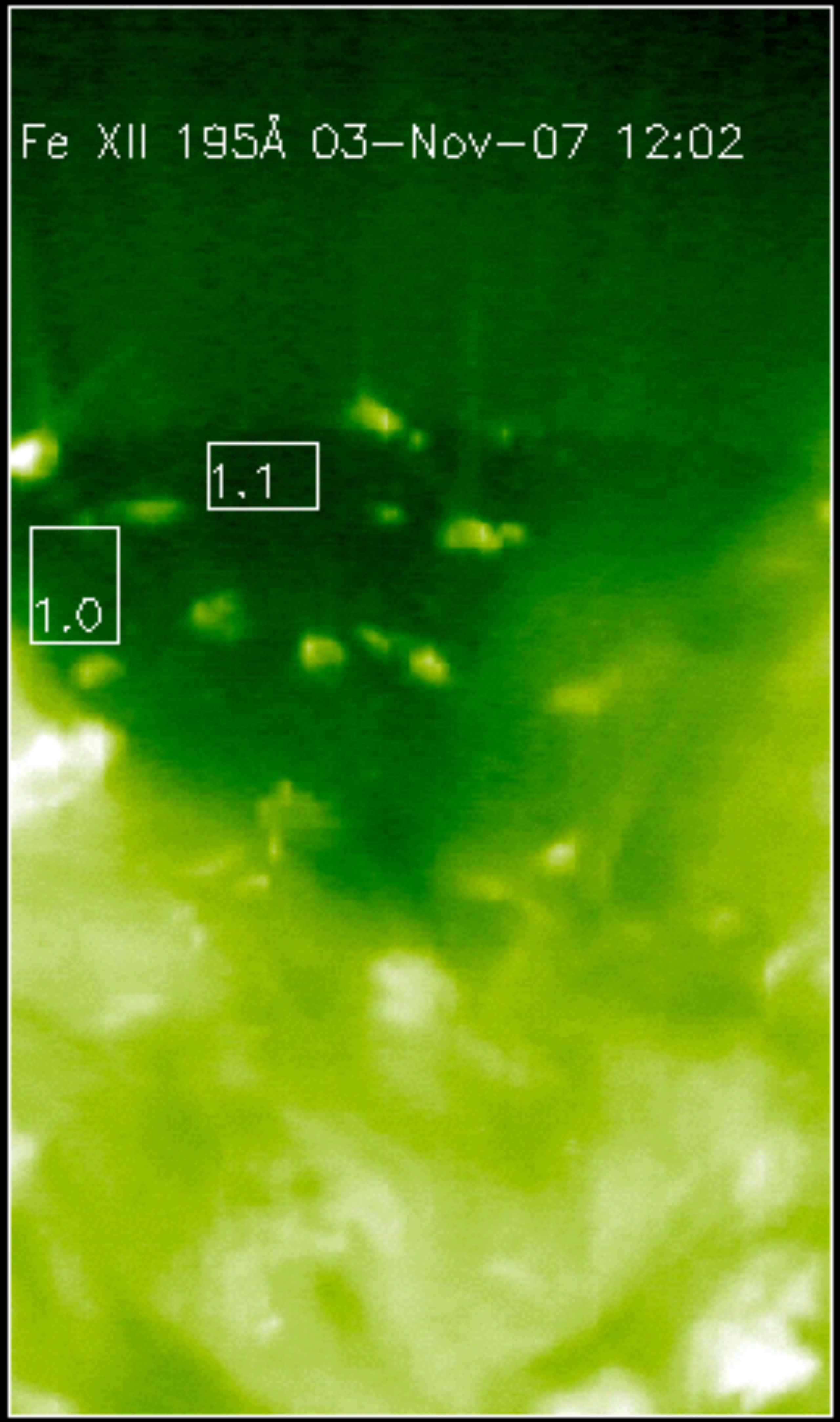


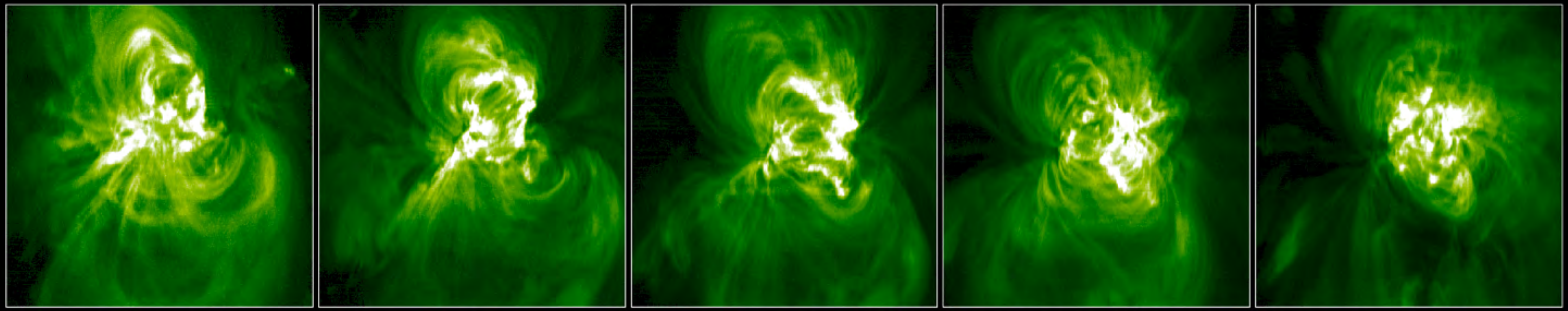
PROOF OF METHOD AT NORTH POLAR CORONAL HOLE

- FIP bias values indicate close to photospheric abundances
- Consistent with expectations for the fast wind (Von Steiger 2000)
- Sulphur FIP is 10eV which is on the edge between low and high FIP. Evidence that it behaves like high FIP in ARs (Lanzafame et al. 2002, Laming 2011).

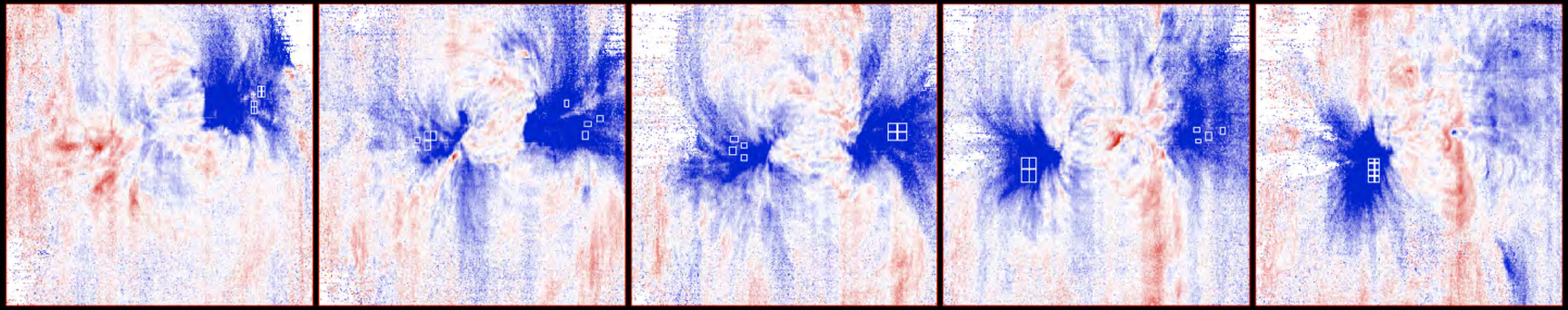


HINODE OBSERVED AR 10978 IN DEC. 2007 FROM LIMB TO LIMB

- EIS Fe XIII 202A intensity images: large FOV rasters almost every day



- Doppler velocity maps: outflows seen on West side, then both sides, then East side

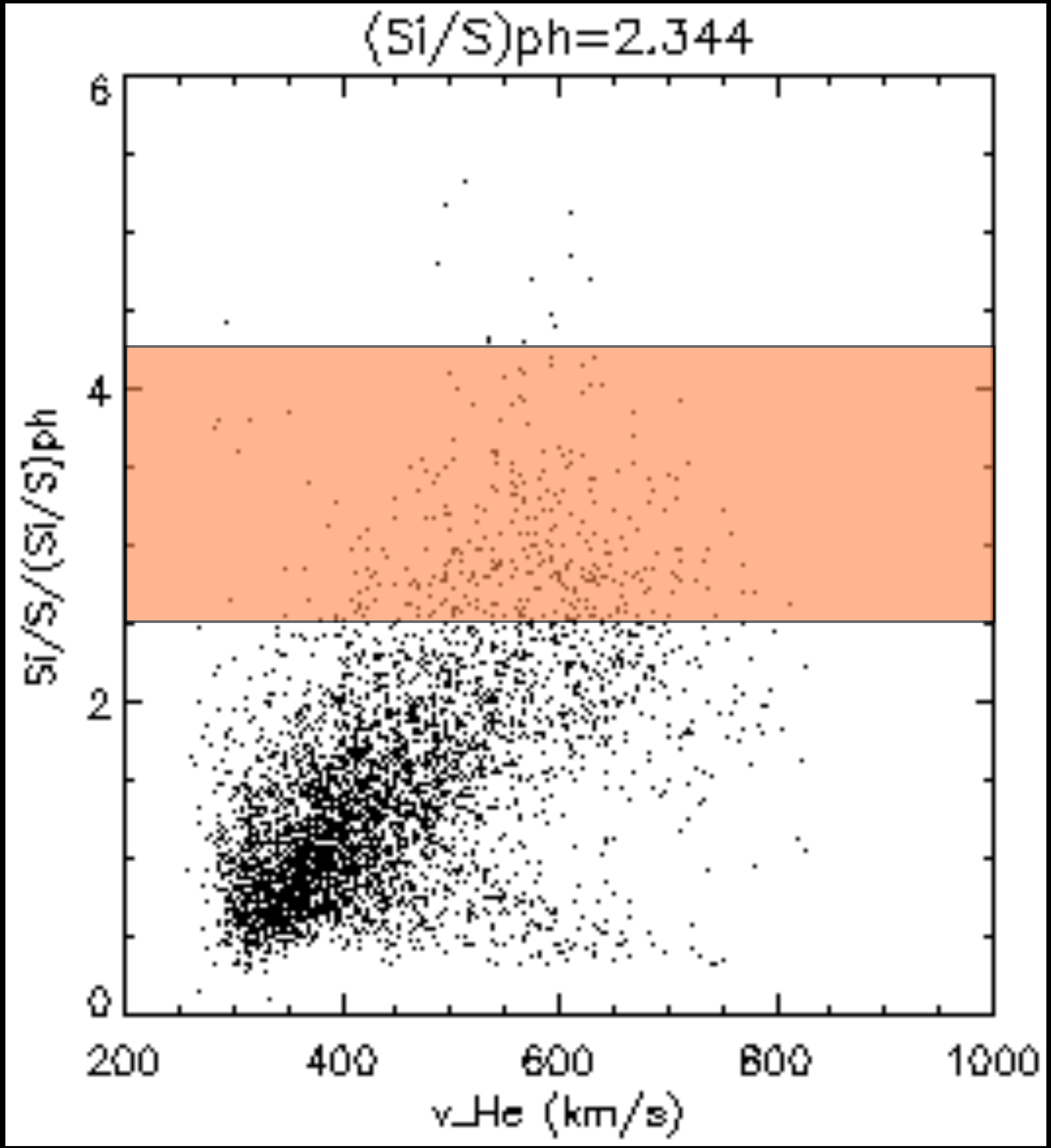


- Average profiles in small areas to bring up signal in weak S X line

ABUNDANCE MEASUREMENTS IN AR OUTFLOWS

- EIS spectroscopy confirms the composition of the outflows is consistent with slow wind values. (Brooks & Warren 2011)
- FIP enhancement factors for December 2007 region are 2.5-4.1. Average = 3.4

Outflows

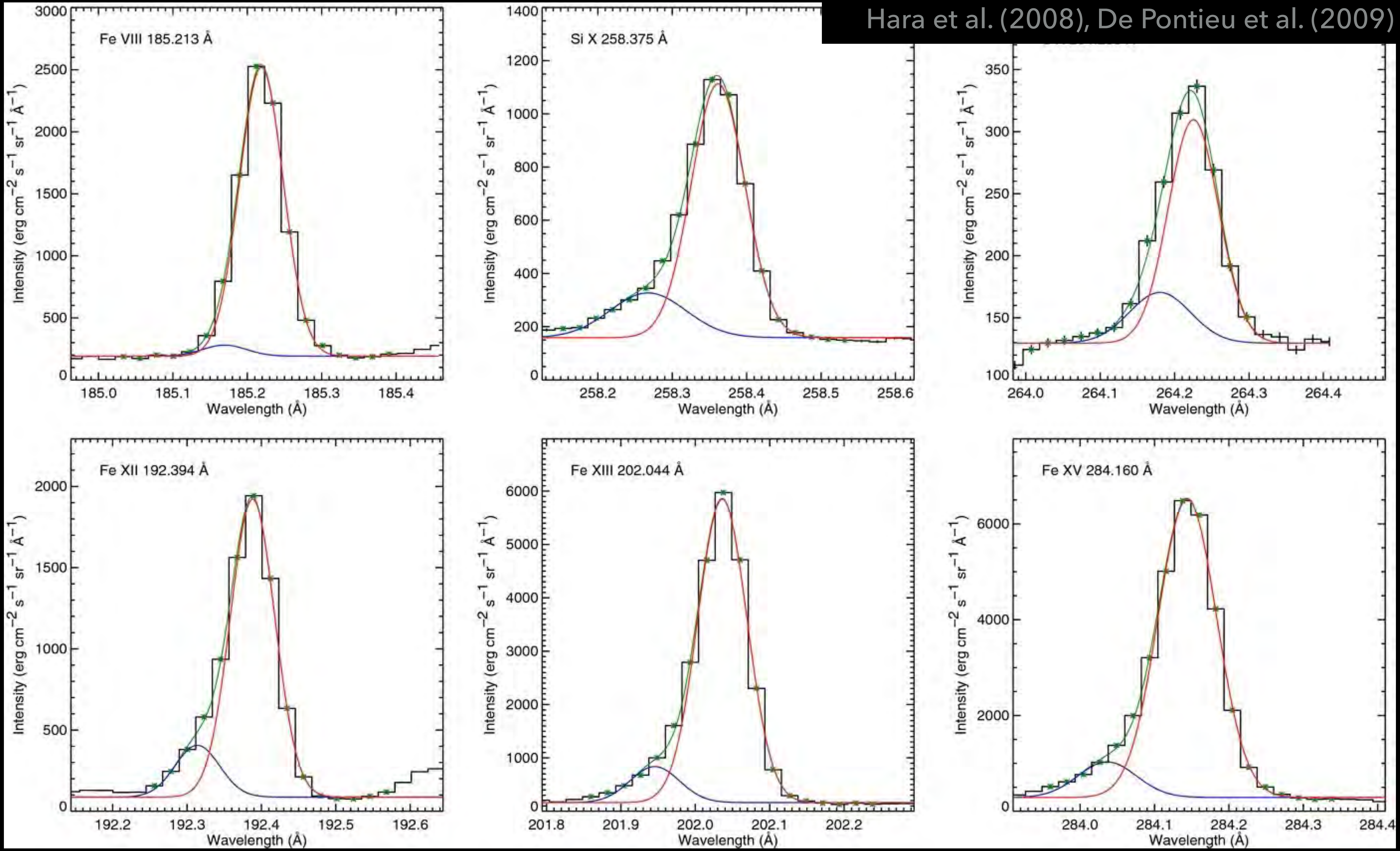


ACE/SWICS 1-day averages
Jan. 1998 - Feb. 2010

Yuan-Kuen Ko (2010)

EIS LINE PROFILES OFTEN SHOW A HIGH SPEED COMPONENT

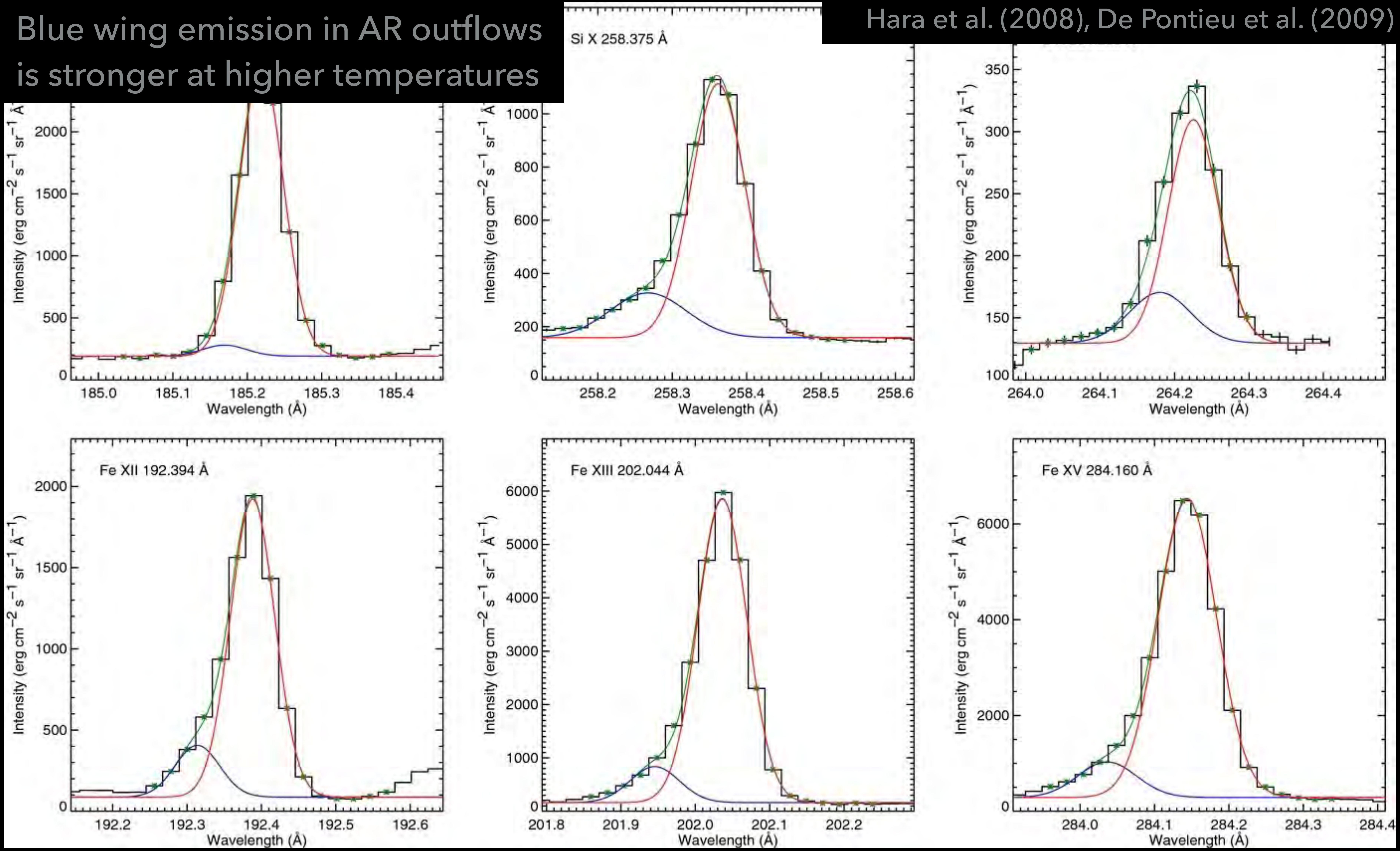
Hara et al. (2008), De Pontieu et al. (2009)



EIS LINE PROFILES OFTEN SHOW A HIGH SPEED COMPONENT

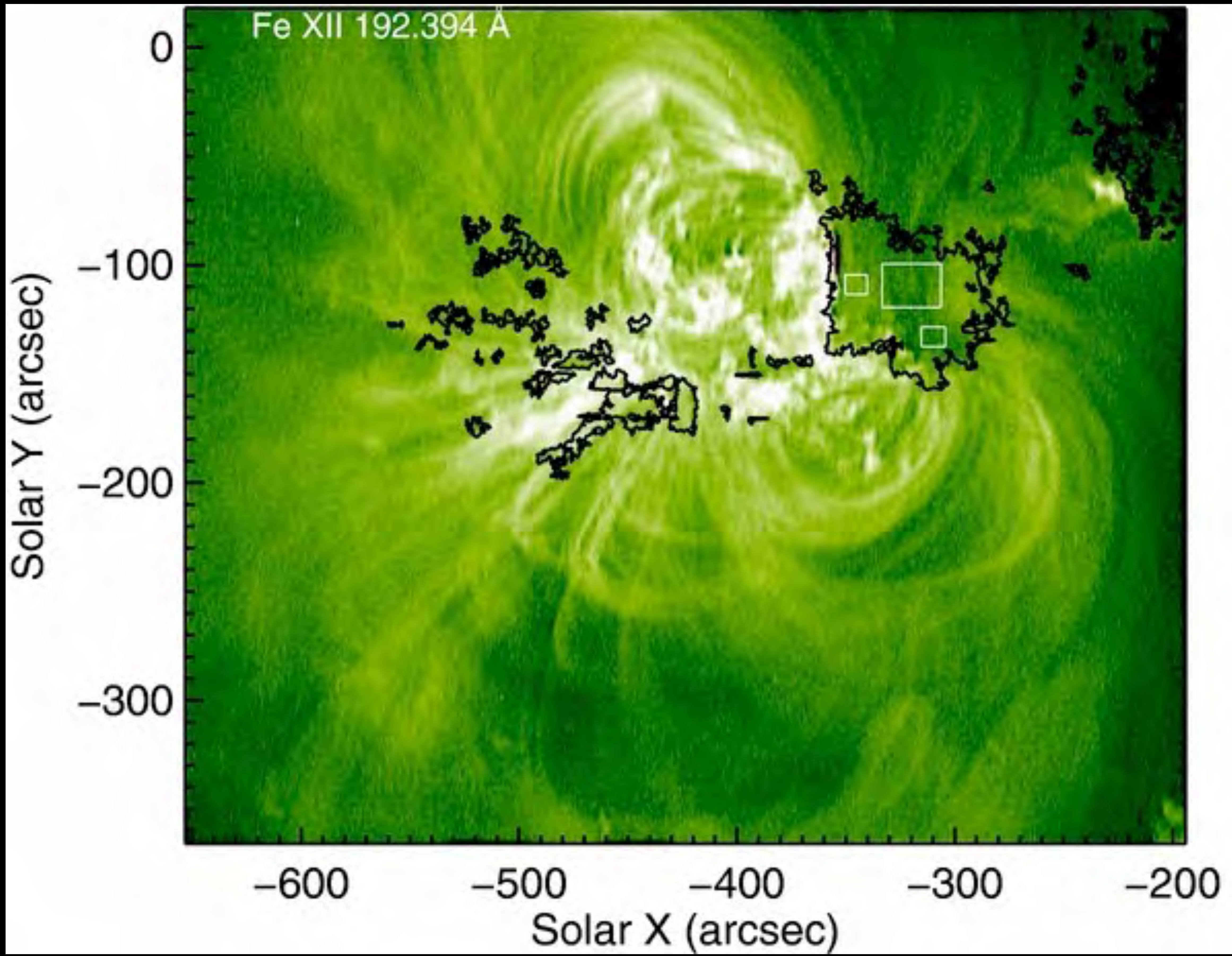
Blue wing emission in AR outflows is stronger at higher temperatures

Hara et al. (2008), De Pontieu et al. (2009)

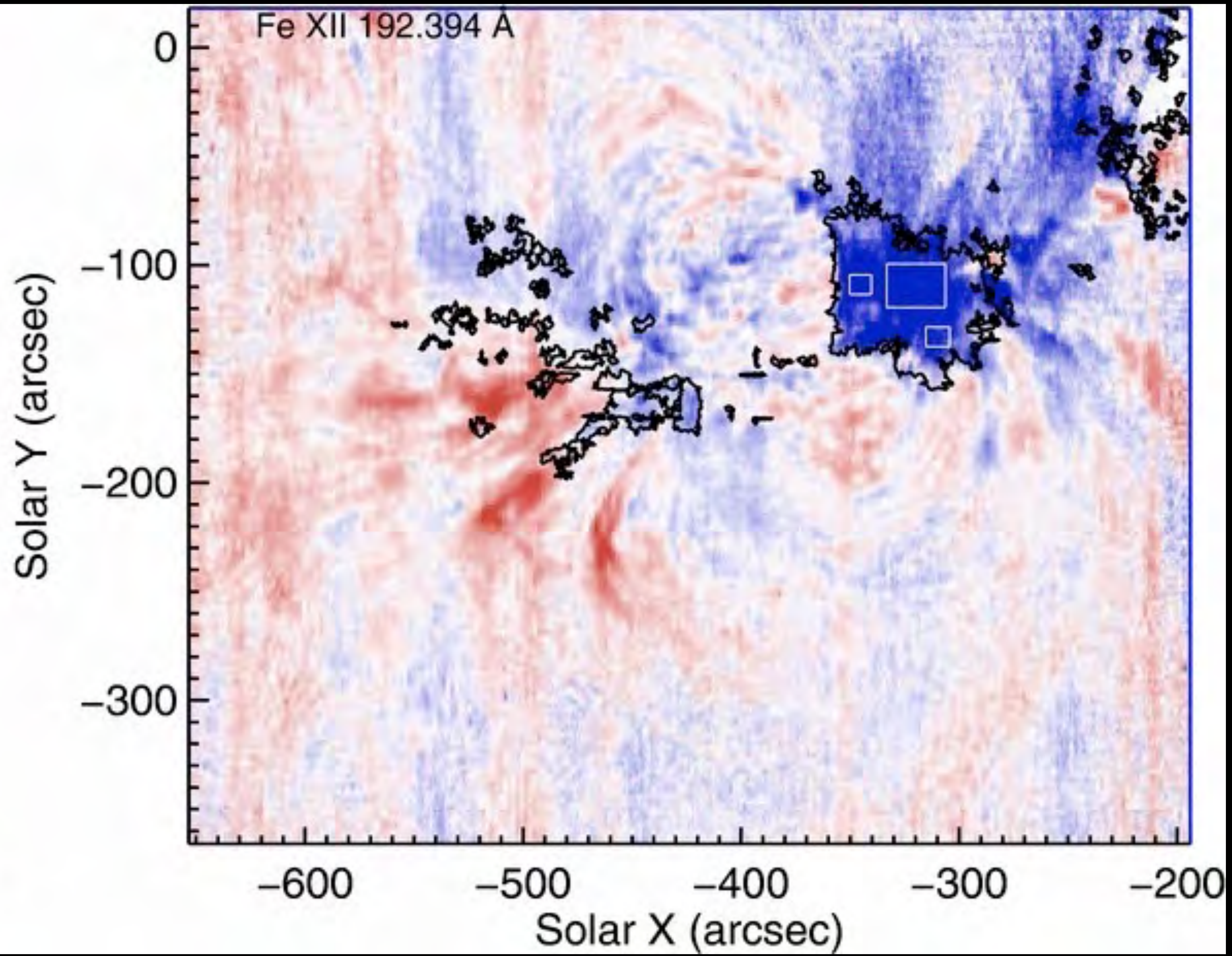


ANALYSIS OF HIGH SPEED OUTFLOW COMPONENT

- Locations of asymmetric profiles in December 2007 region.



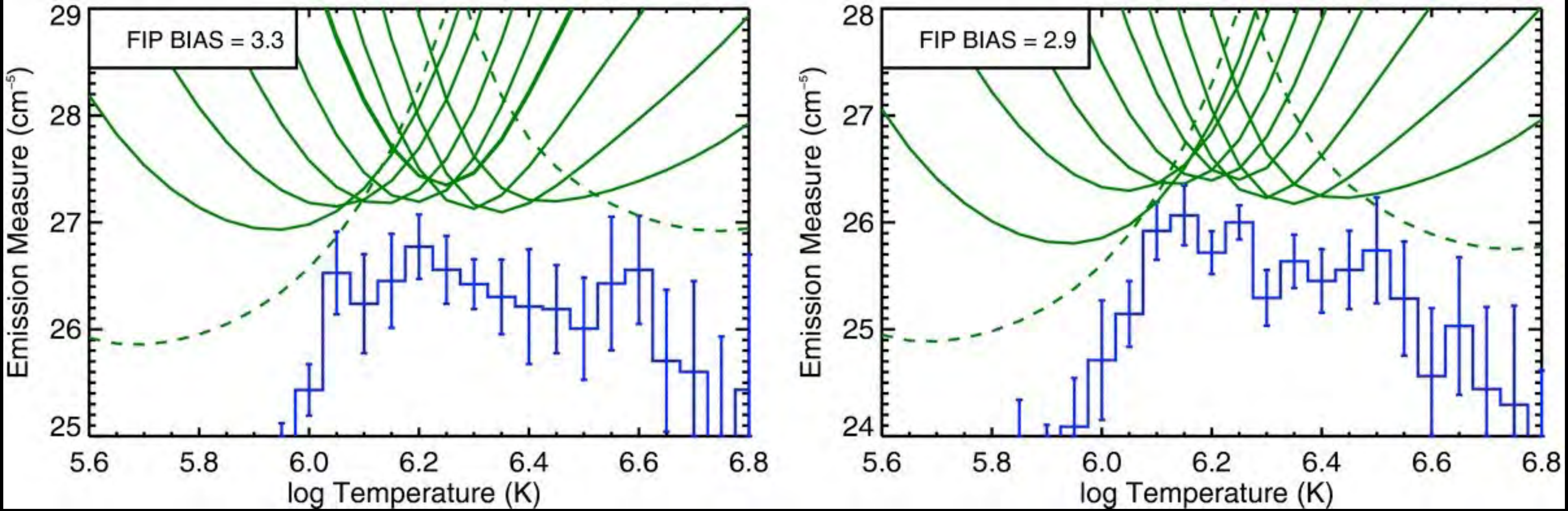
Bulk Outflow



Blue Wing

ANALYSIS OF HIGH SPEED OUTFLOW COMPONENT

- DEMs for bulk outflow and blue wing are dominated by coronal emission and the FIP bias is similar.

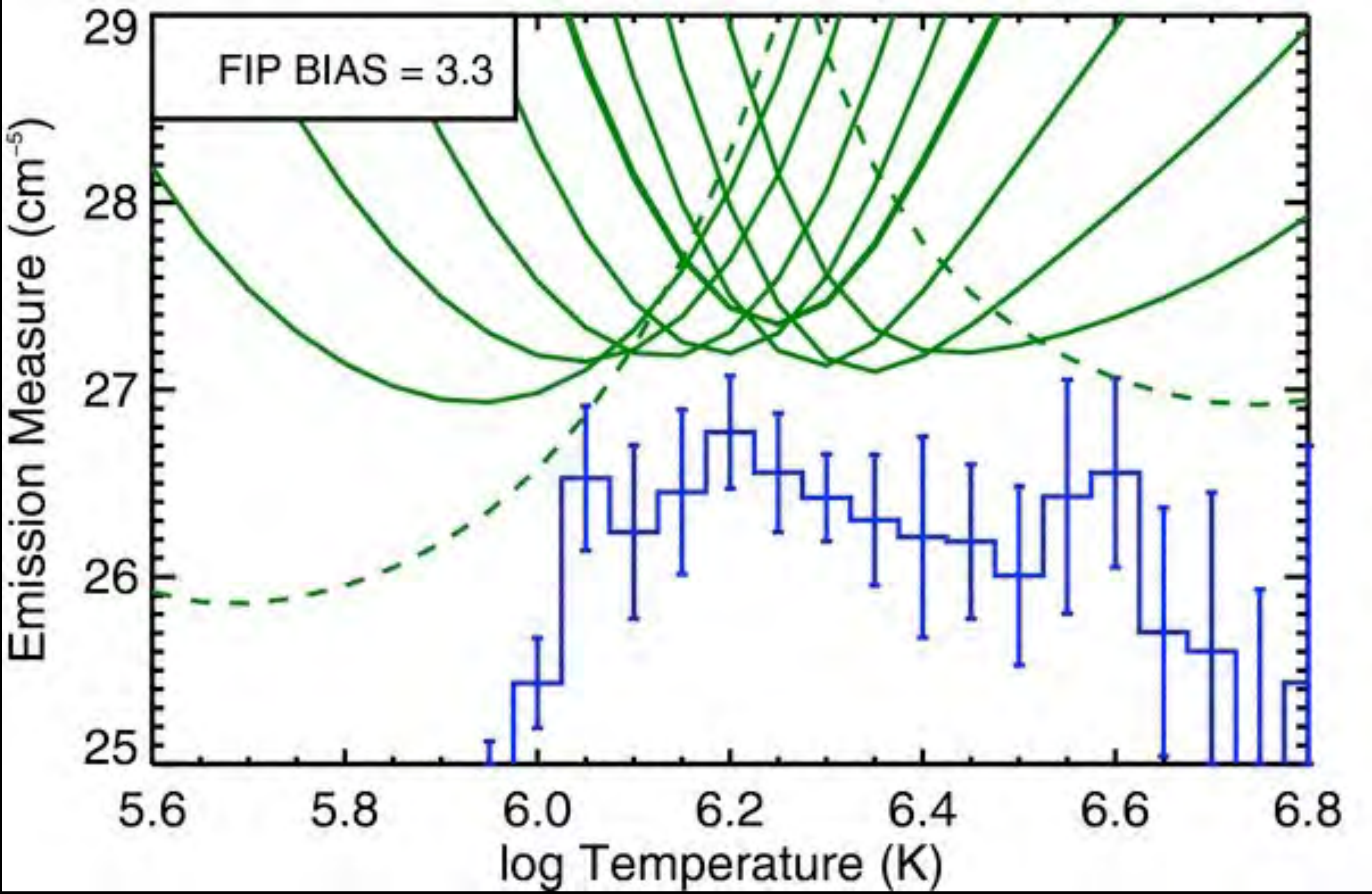


Bulk Outflow

Blue Wing

ANALYSIS OF HIGH SPEED OUTFLOW COMPONENT

Asymmetries produced by coronal plasma?



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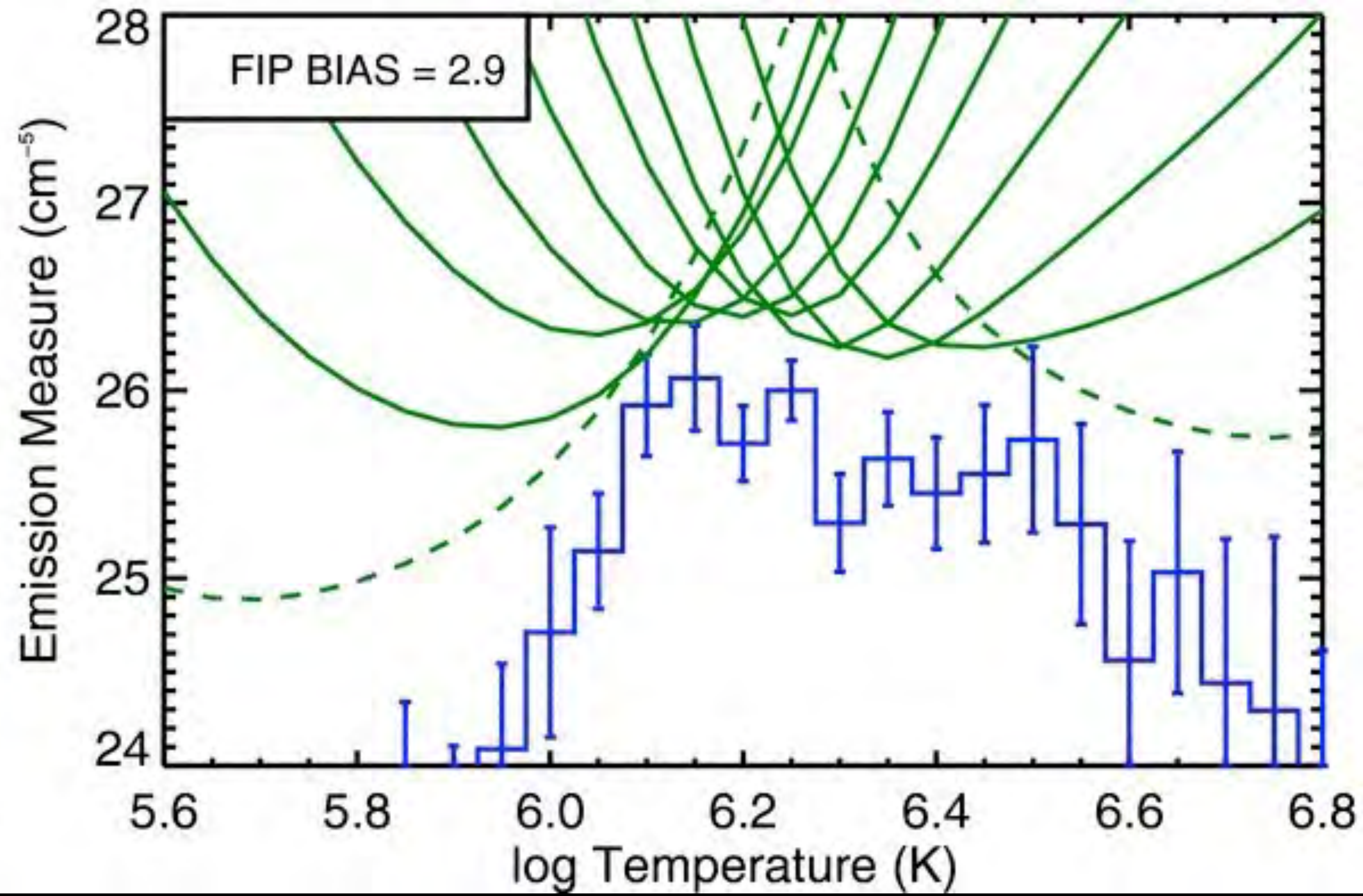
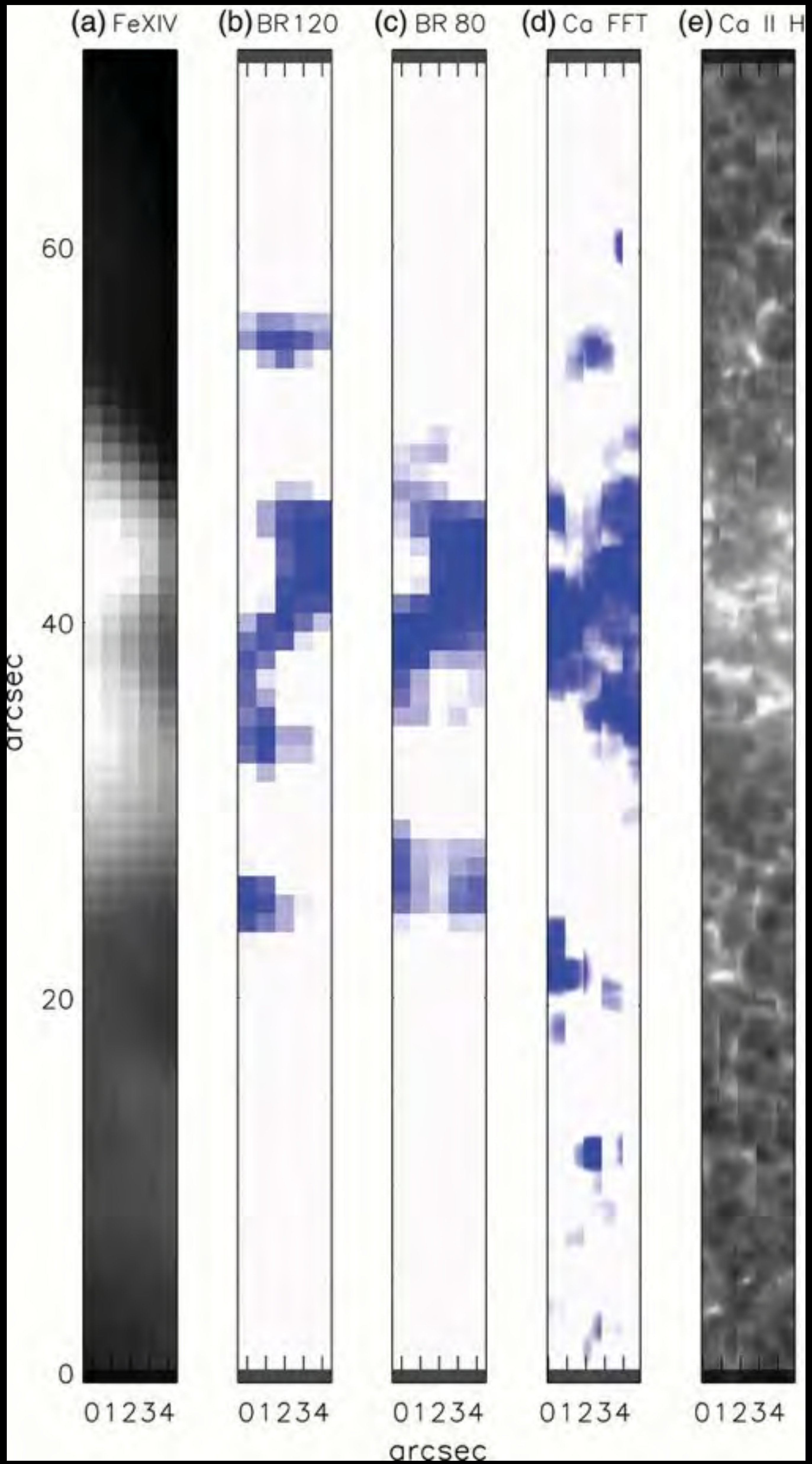


Blue Wing

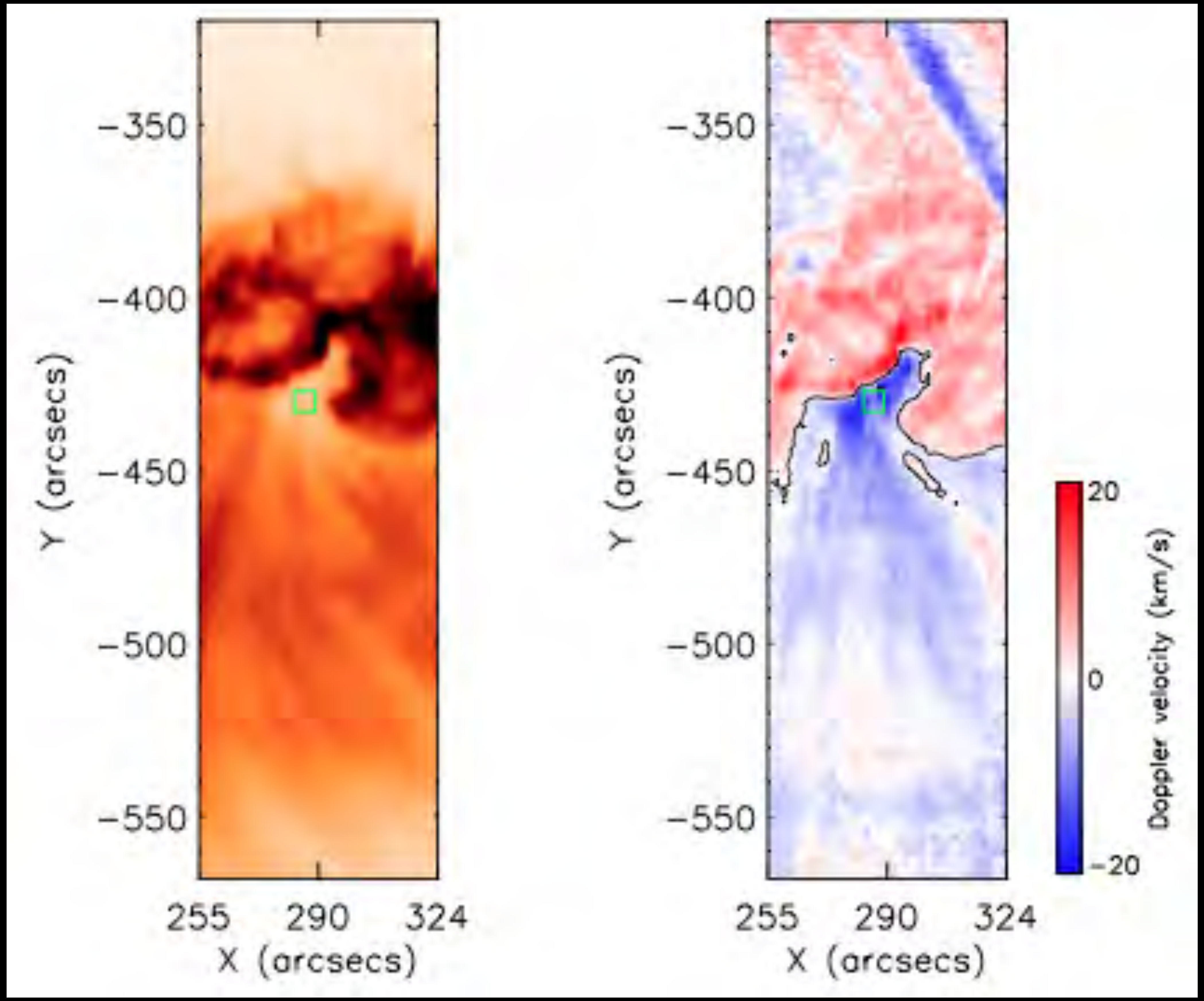
CONNECTION WITH CHROMOSPHERIC JETS?

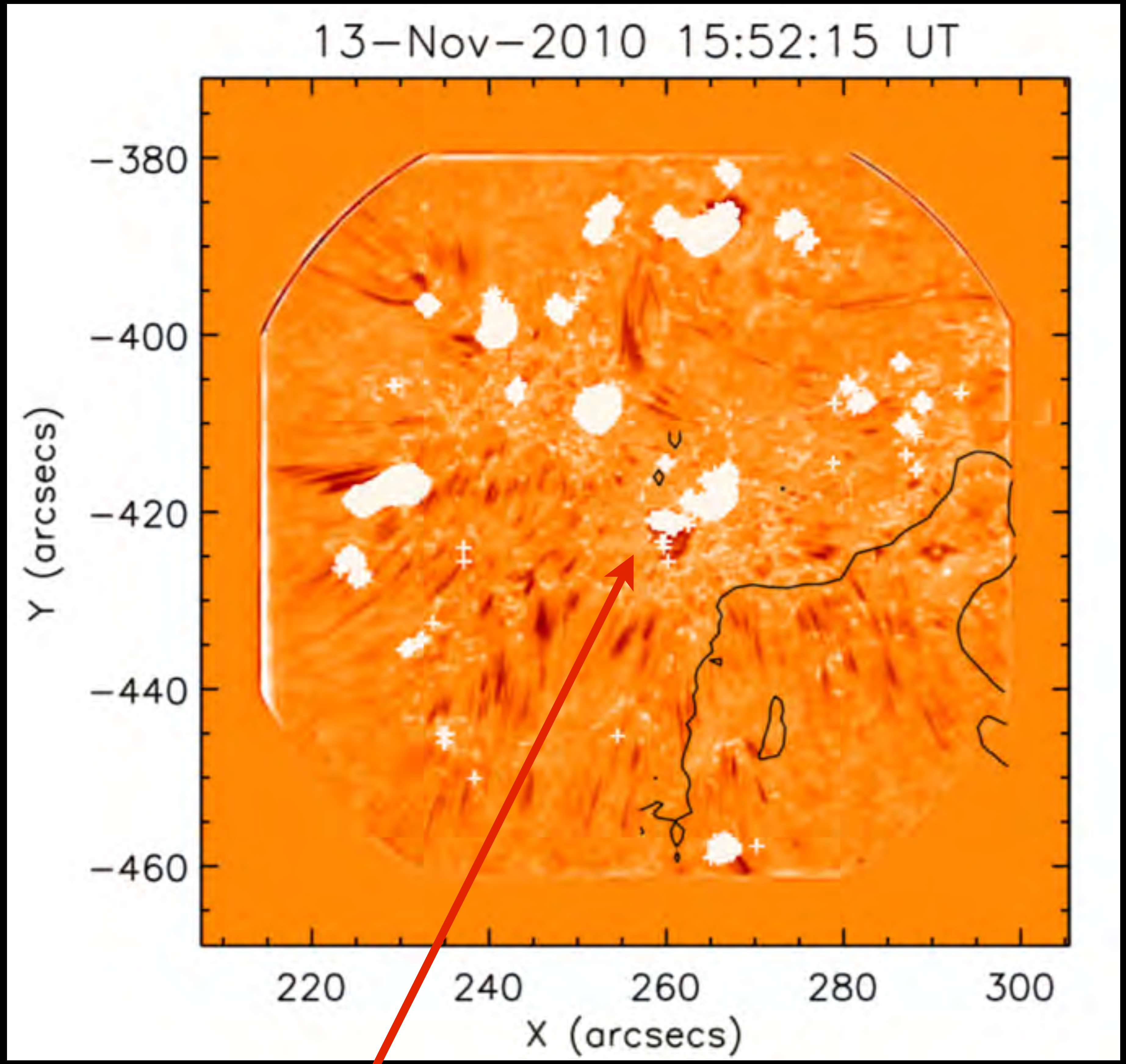
- Blue wind asymmetries in Fe XIV linked to dynamic type II spicules in SOT Ca II chromospheric filtergrams (De Pontieu et al. 2009)



CONNECTION WITH CHROMOSPHERIC JETS?

Vanninathan et al. (2015)





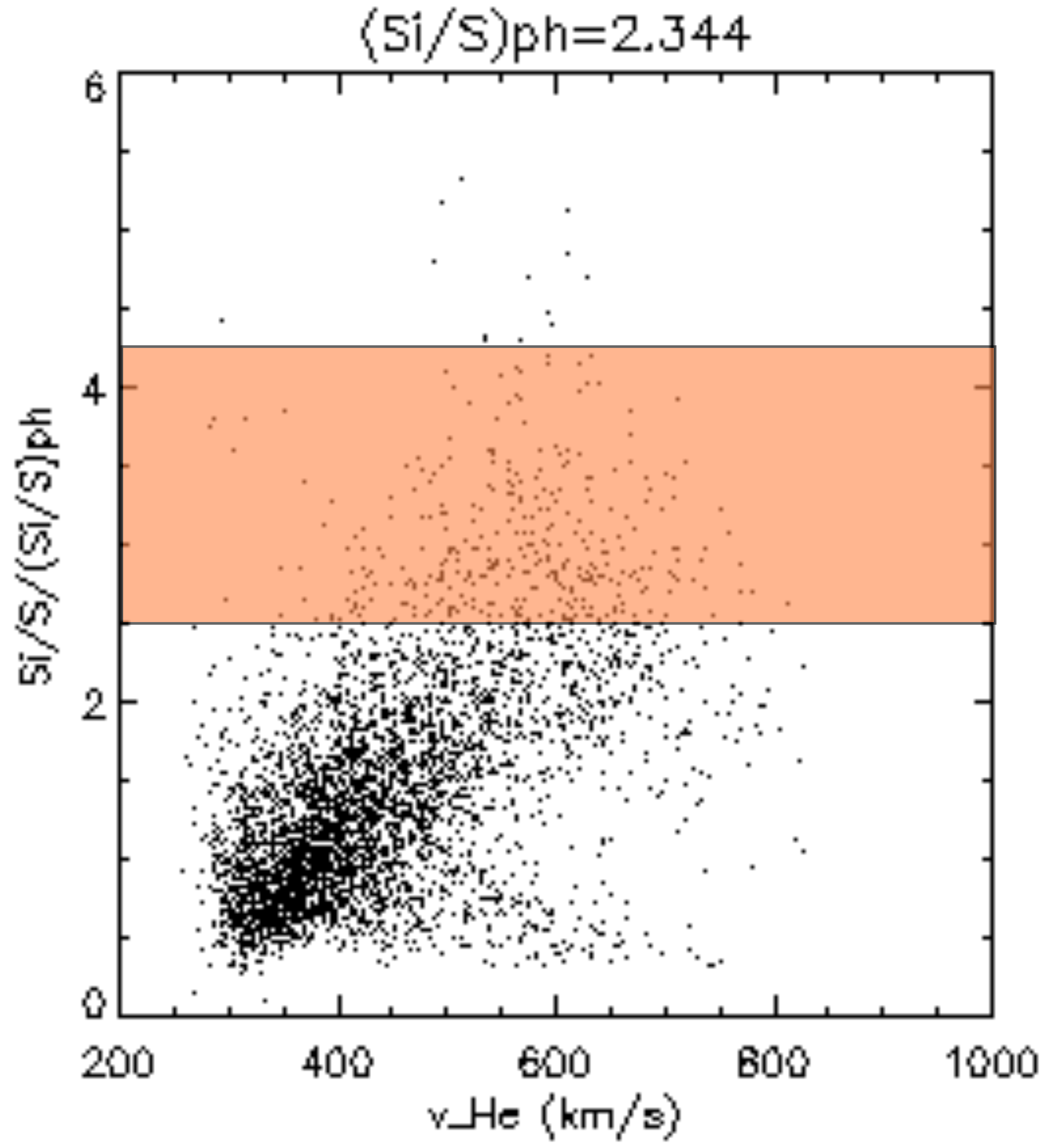
EIS scans identify outflow area

Asymmetries in H alpha blue wing (white patches)

COMPARISON TO ACE/SWICS

Asymmetric Component

Outflows



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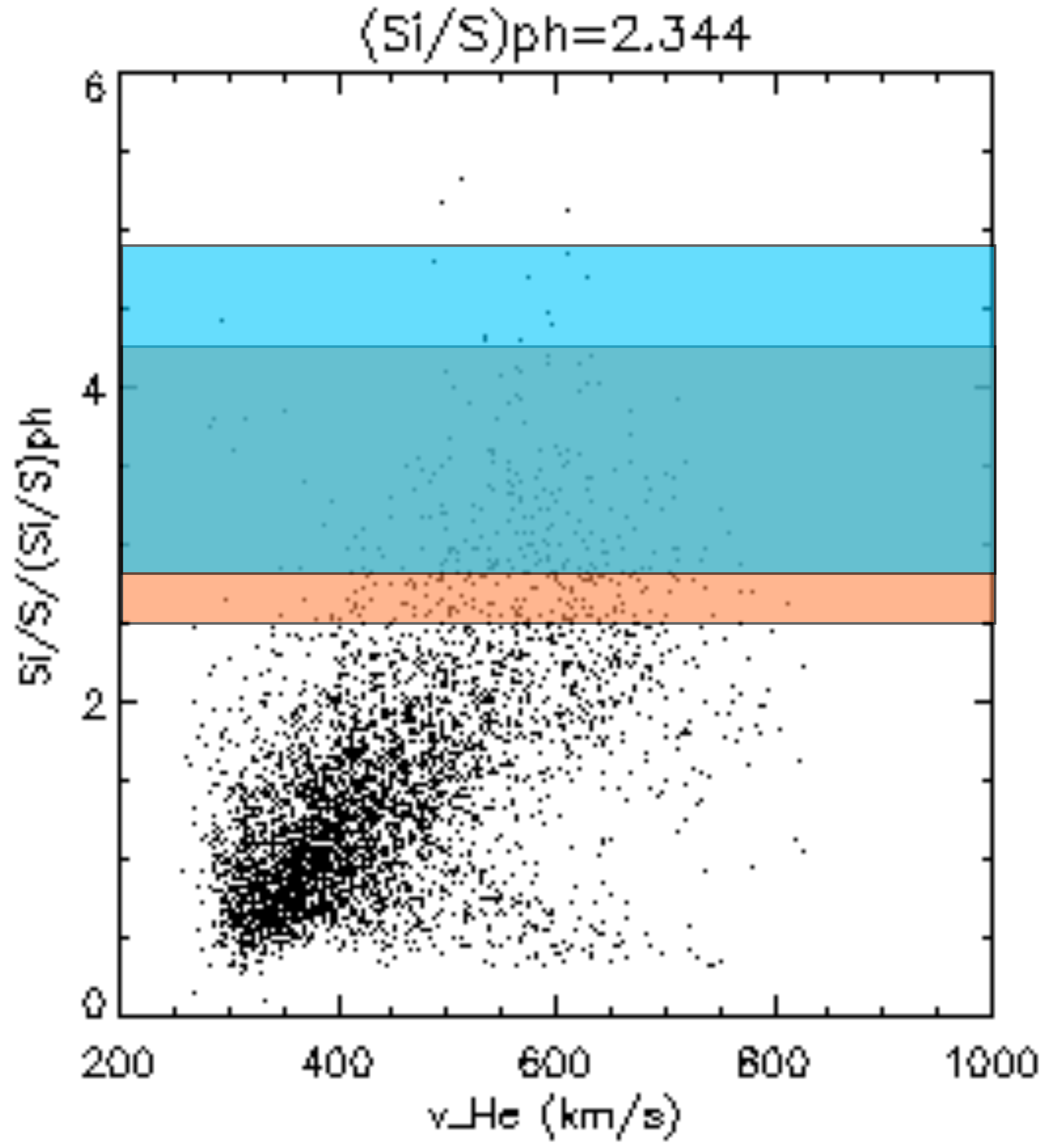

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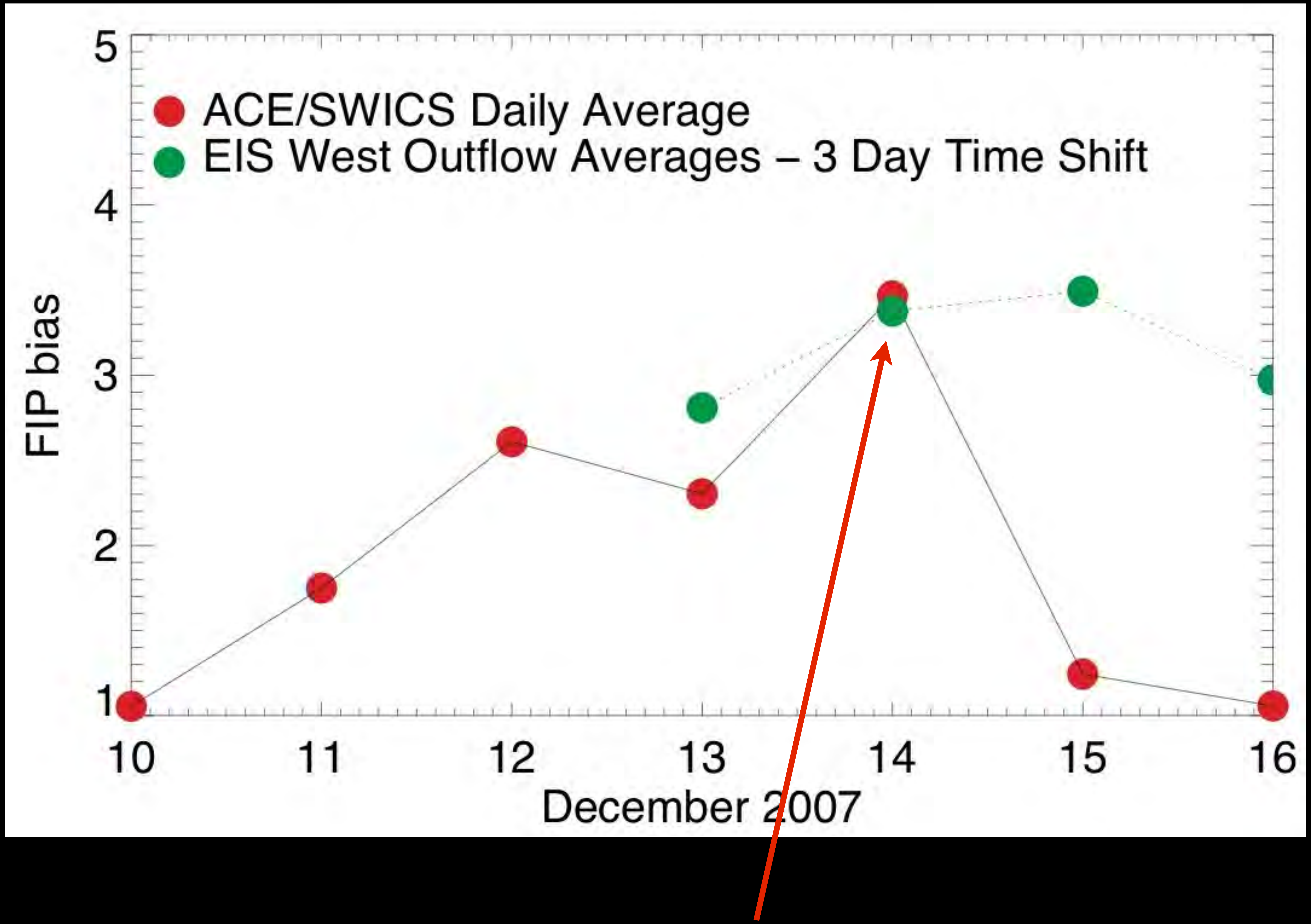
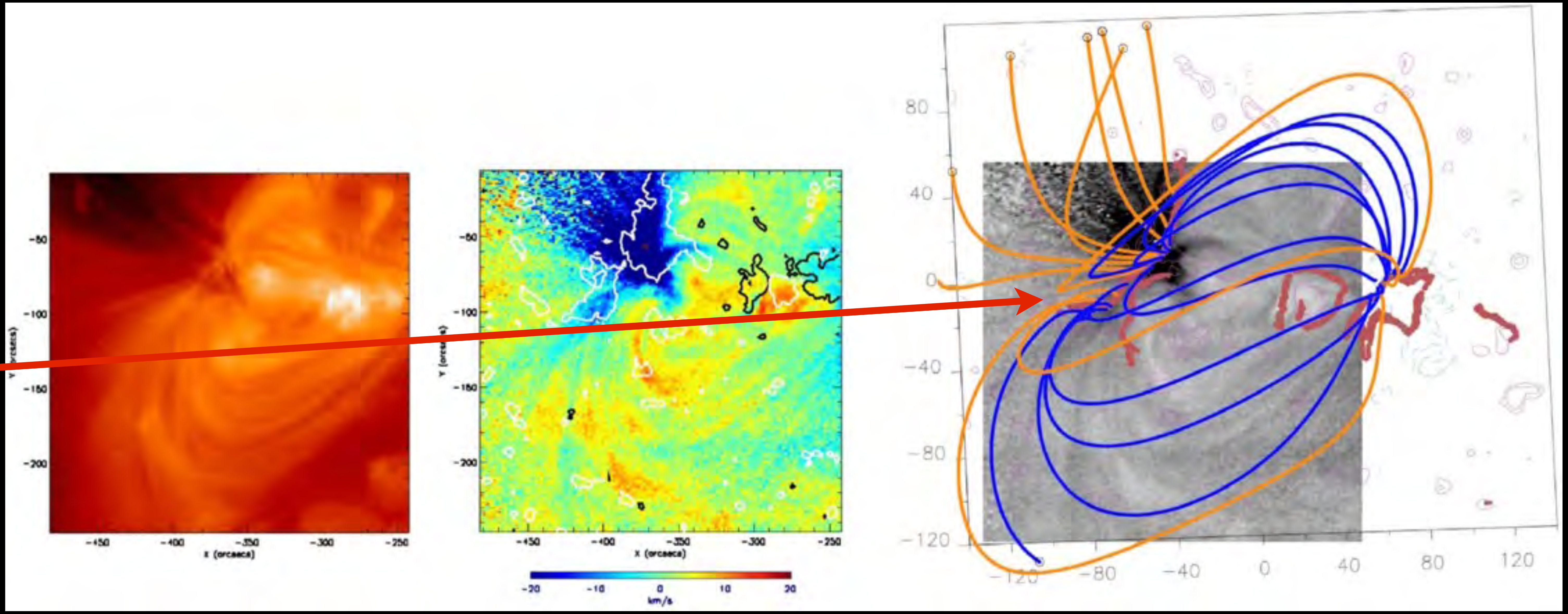


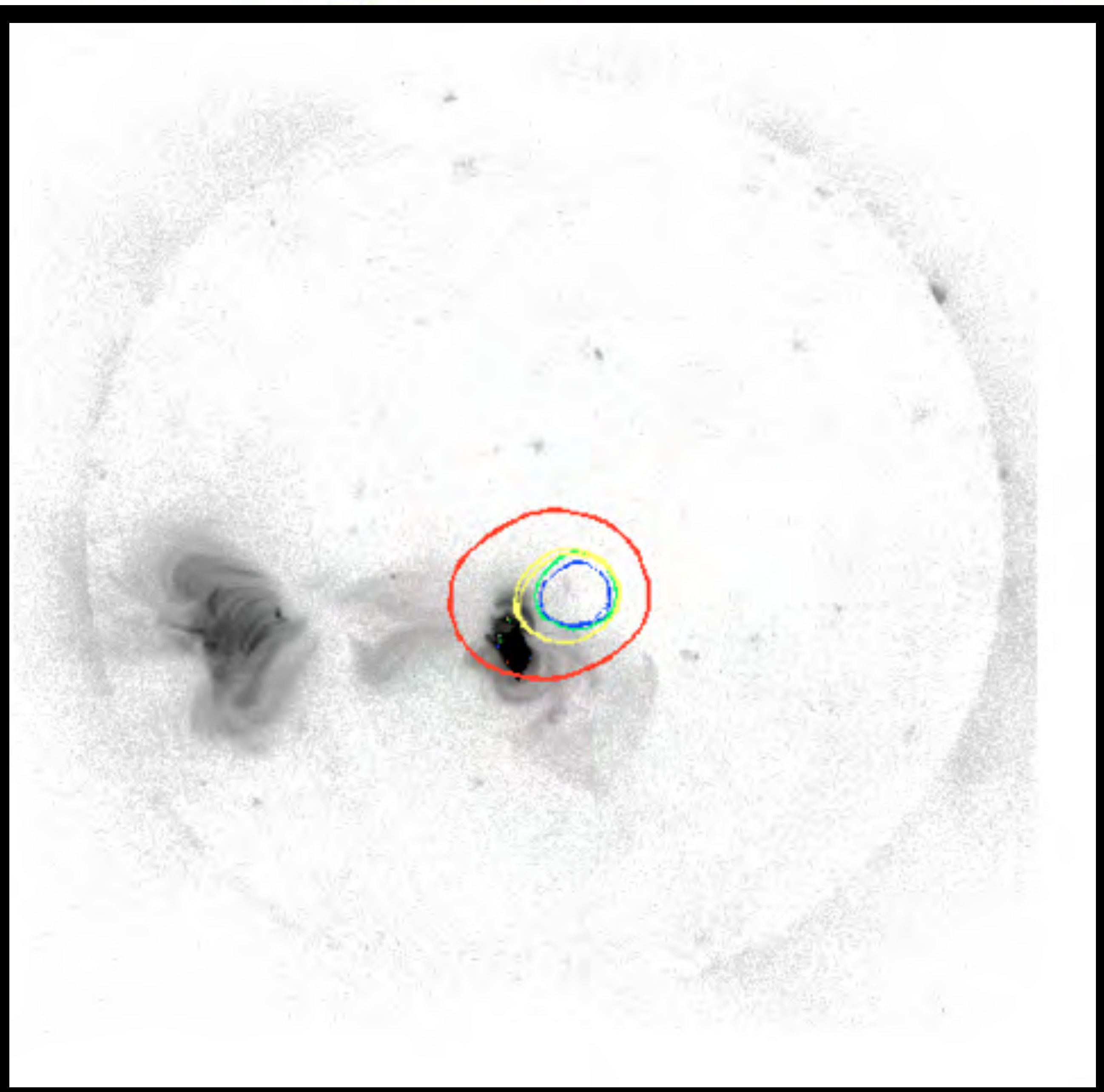
- FIP bias measured by EIS at disk center matches ACE a few days later (Brooks & Warren 2011).

ACTIVE REGION OUTFLOWS

- Possibly interchange reconnection from quasi-separatrix layers (Baker 2009, van Driel-Gesztelyi 2012).



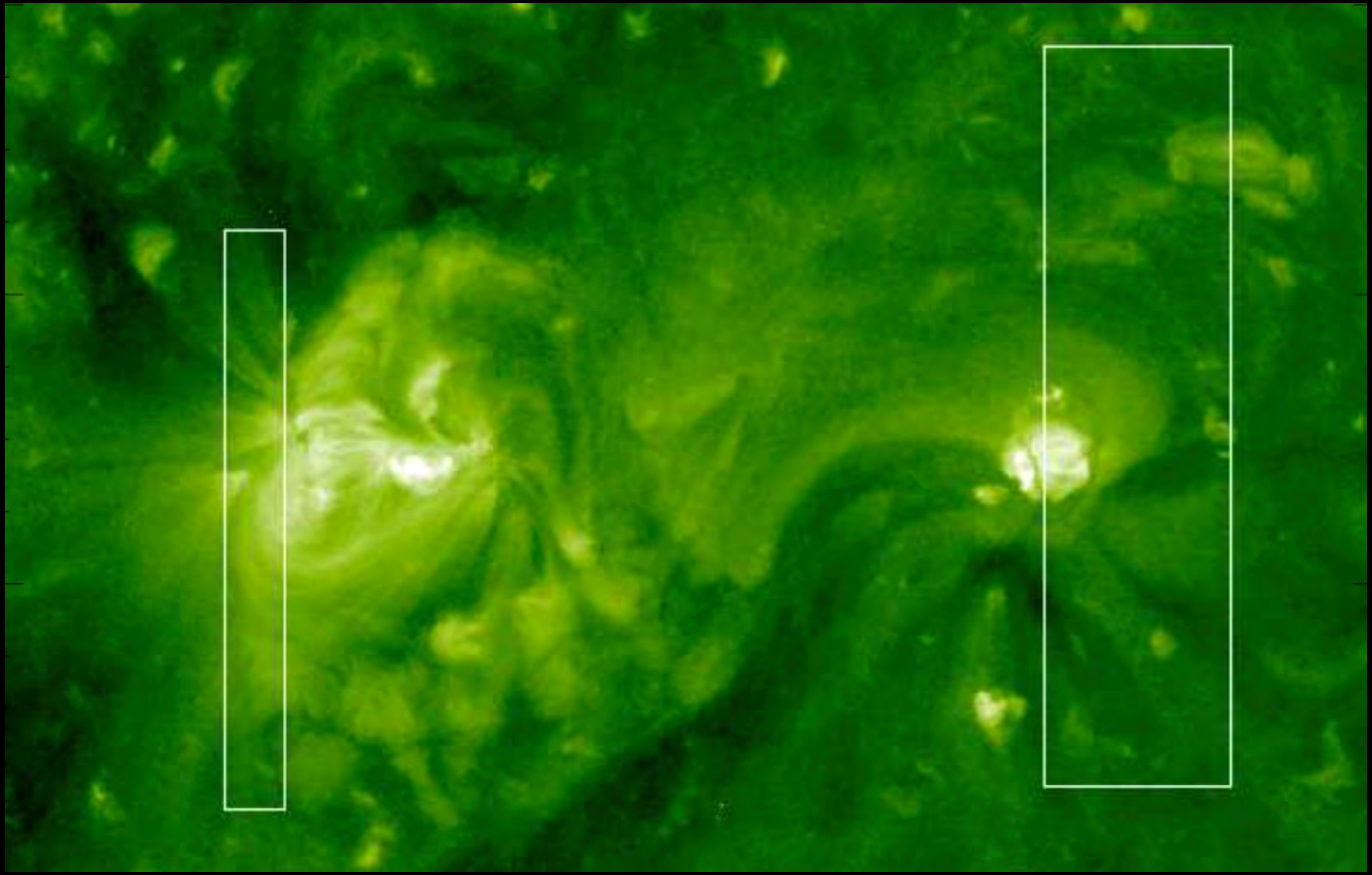
- Linked with radio noise storms and weak Type III emission (Del Zanna 2011).



NoRH 150-400MHz on XRT image

WHAT'S THE PROBLEM?

- Outflow mass flux estimates (Sakao et al. 2007) are too small: 15-30% of ACE in-situ measurements. Some fraction of this may also flow on closed loops to distant ARs.



Boutry et al. (2015)

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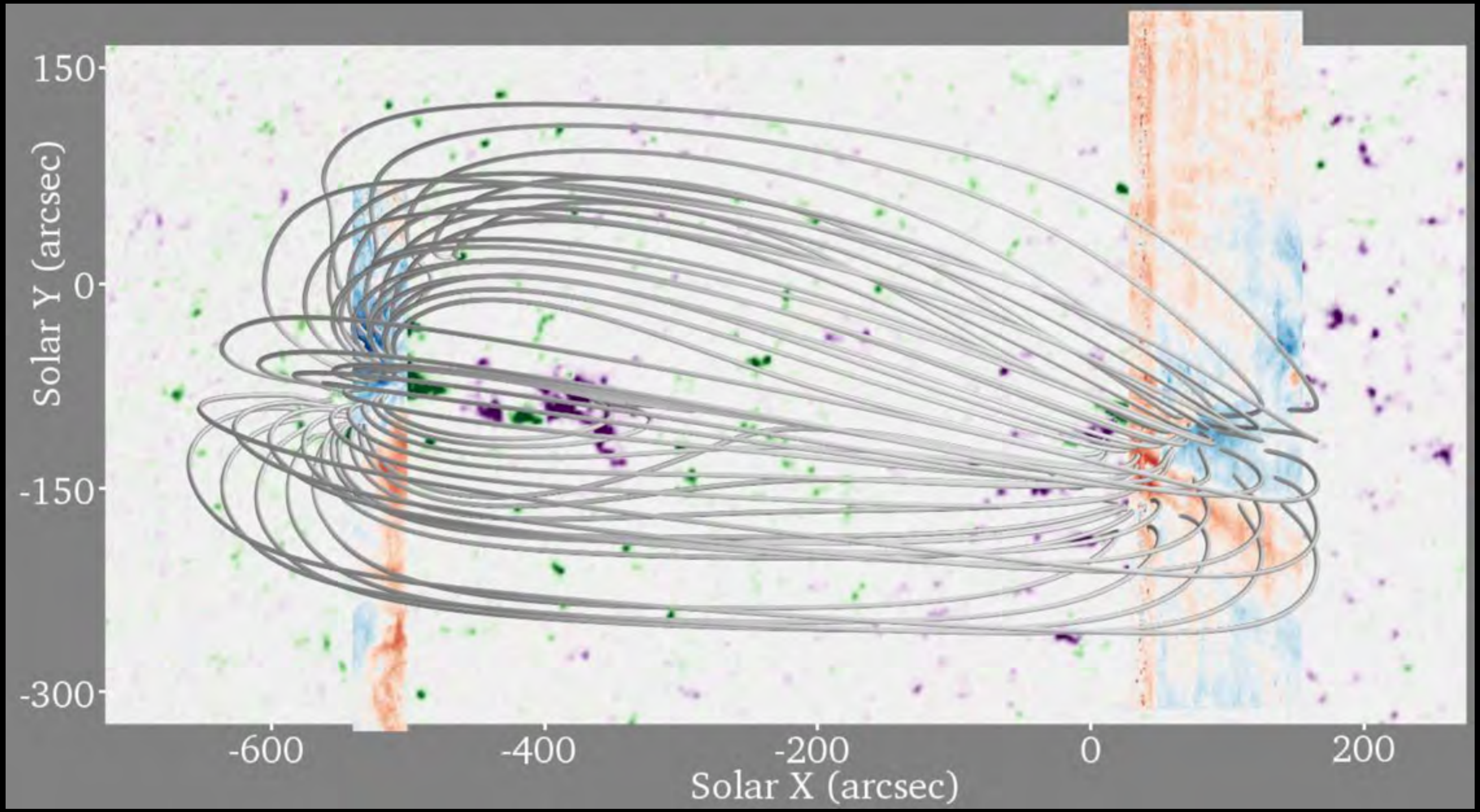

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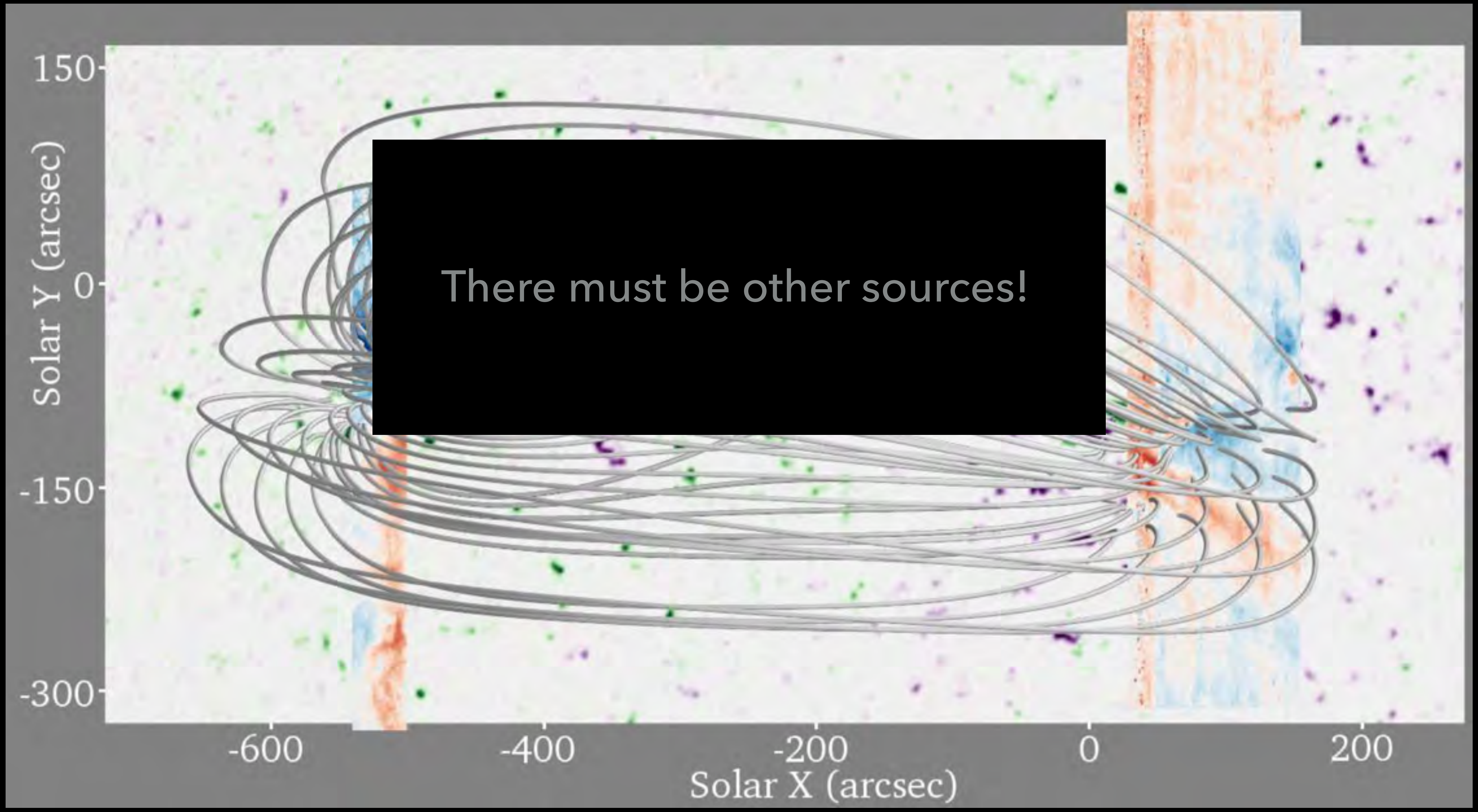

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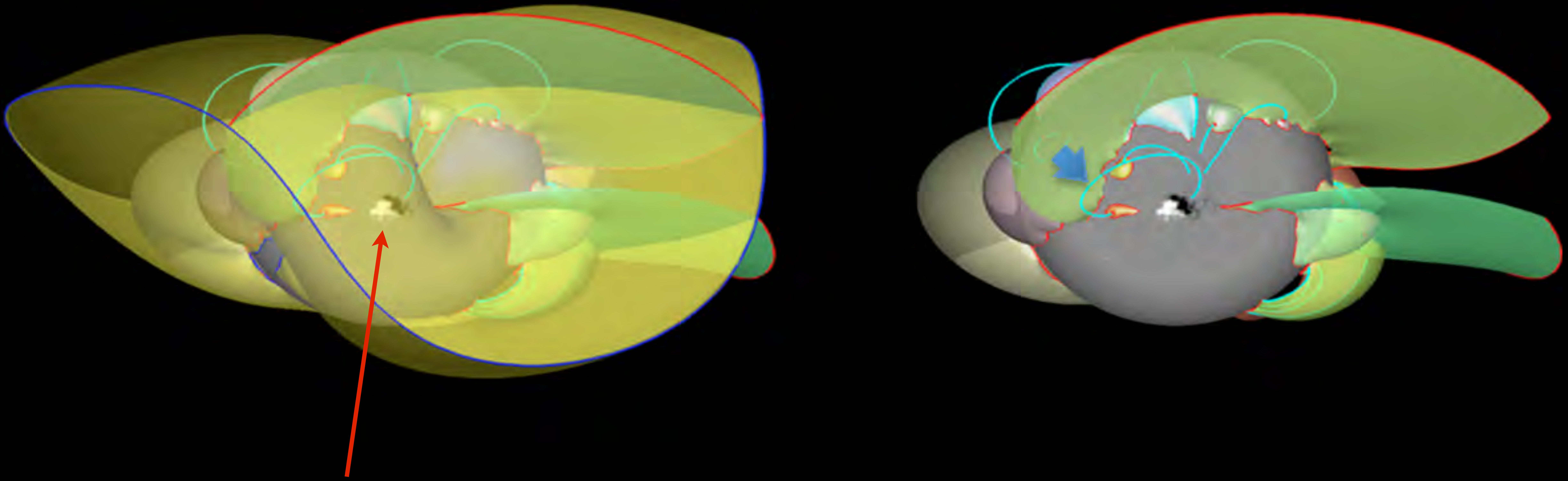
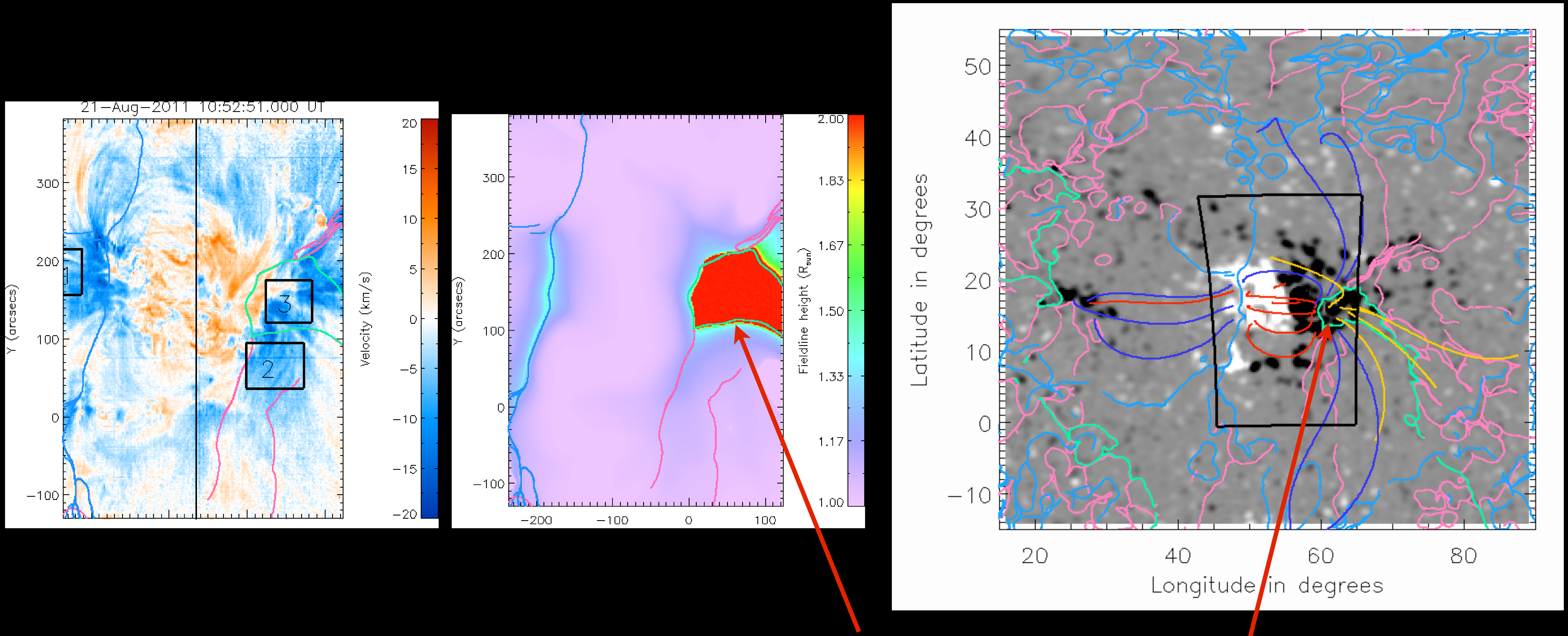


- Can the plasma even escape into the solar wind? December 2007 region is completely covered by a helmet streamer… (Culhane et al. (2014).

HOW DOES THE PLASMA ESCAPE?

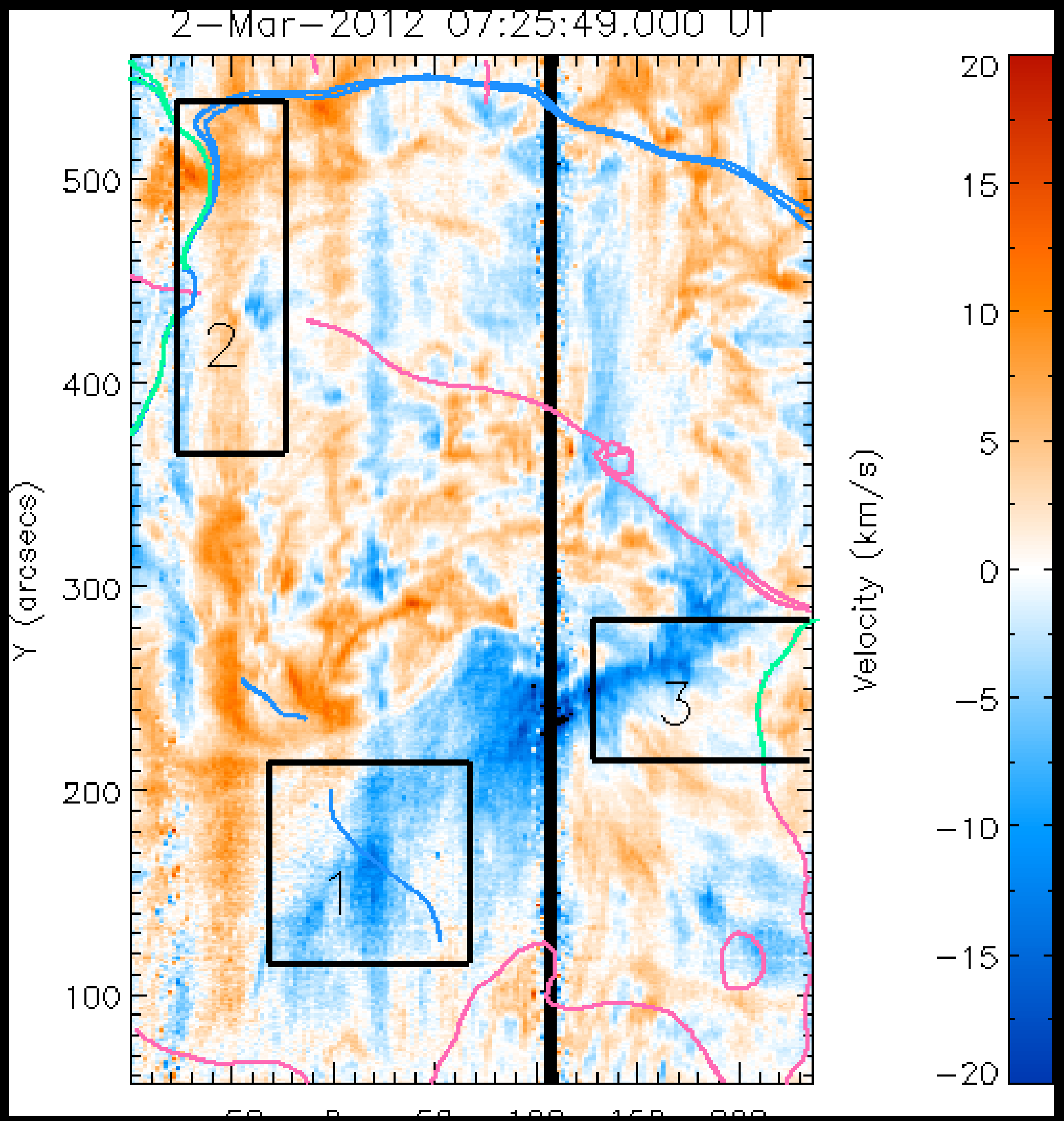
- A study of 7 Active Regions suggests this is a common problem (Edwards et al. 2015).



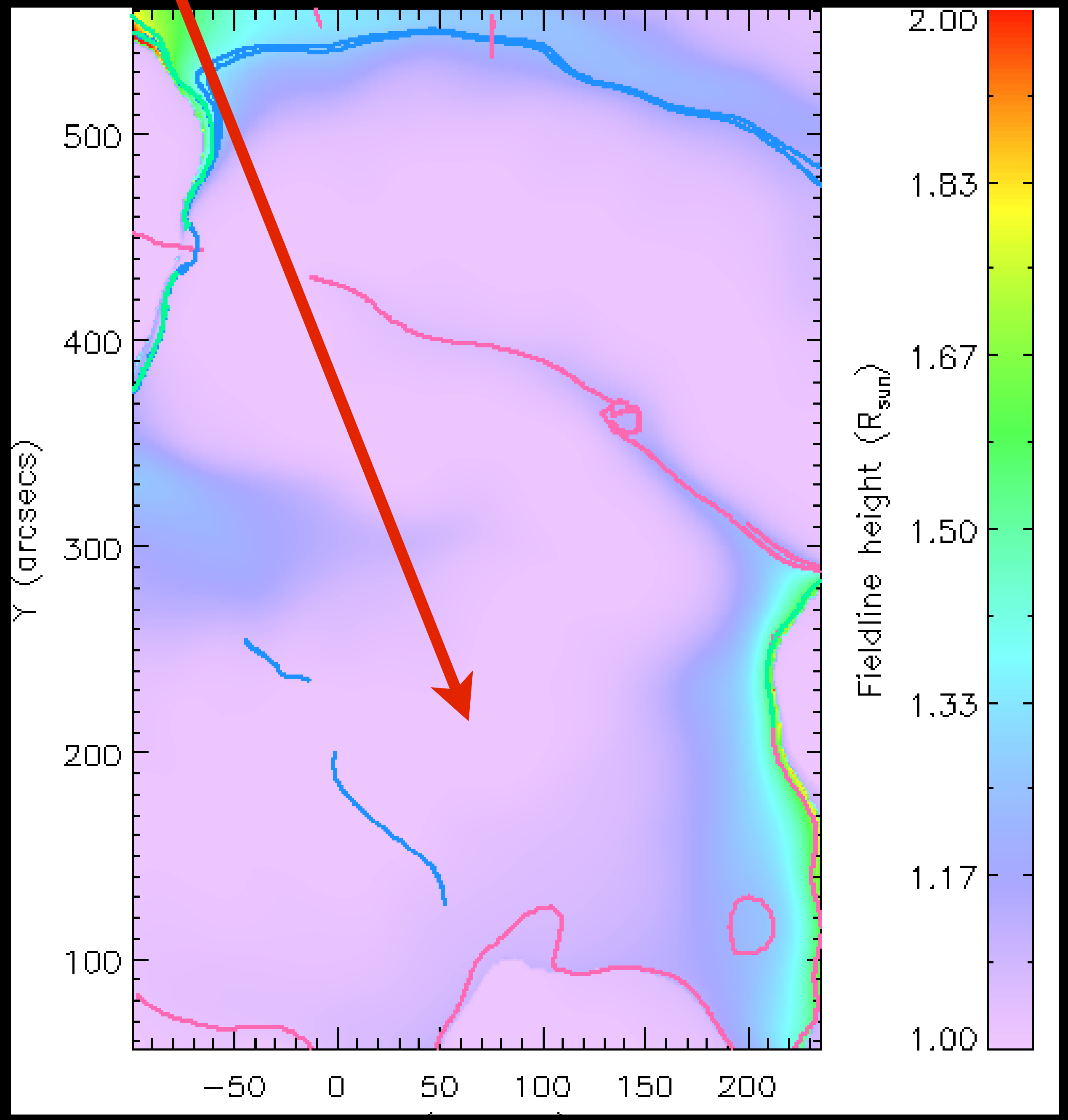
- Outflow plasma can escape on high reaching (red) or open-field (yellow lines) in this AR. But 6/7 ARs are like the next slide... (see also Fazakerley et al. 2015)

HOW DOES THE PLASMA ESCAPE?

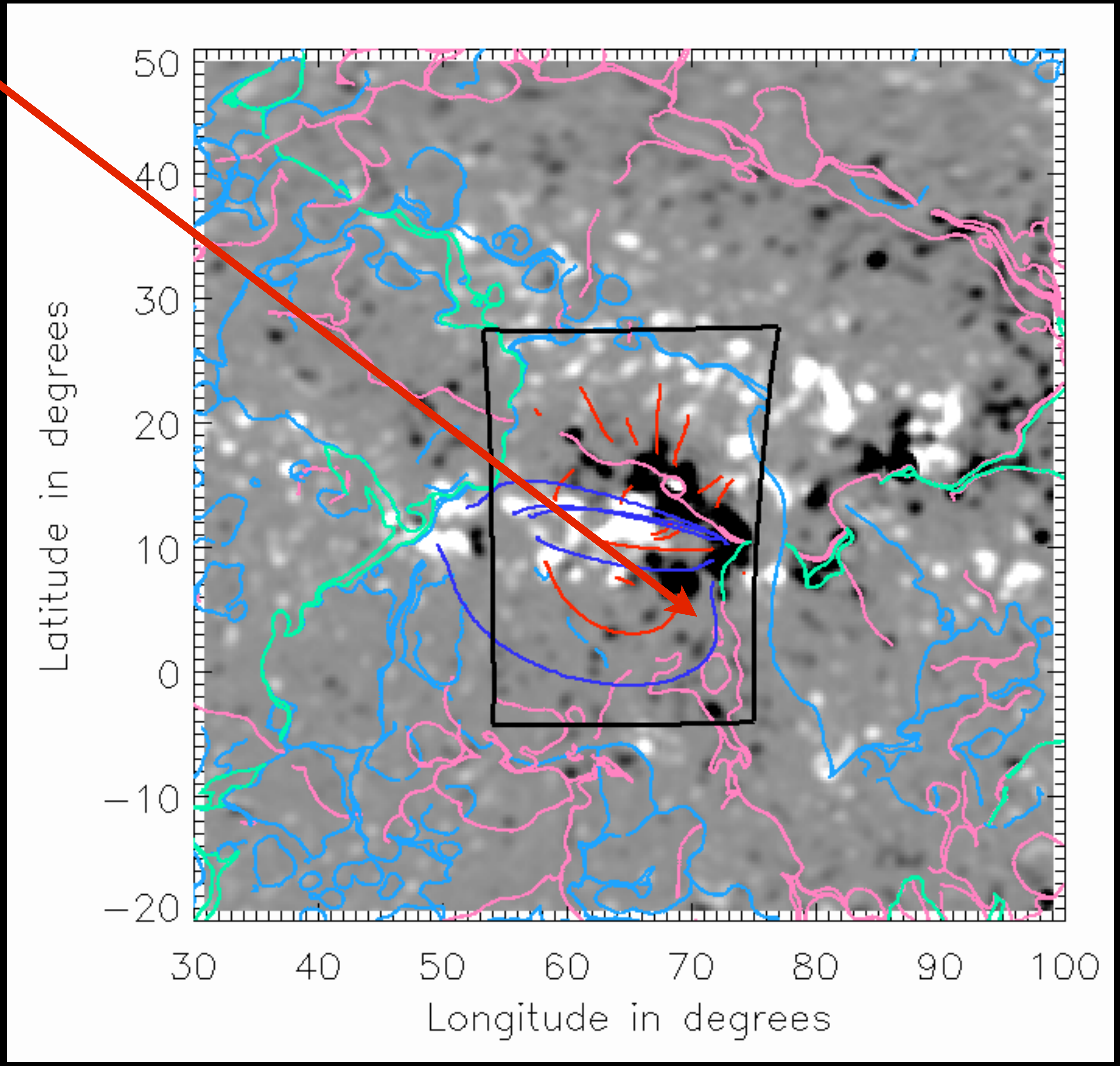
- No high reaching field lines. No open field lines. No escape channel.



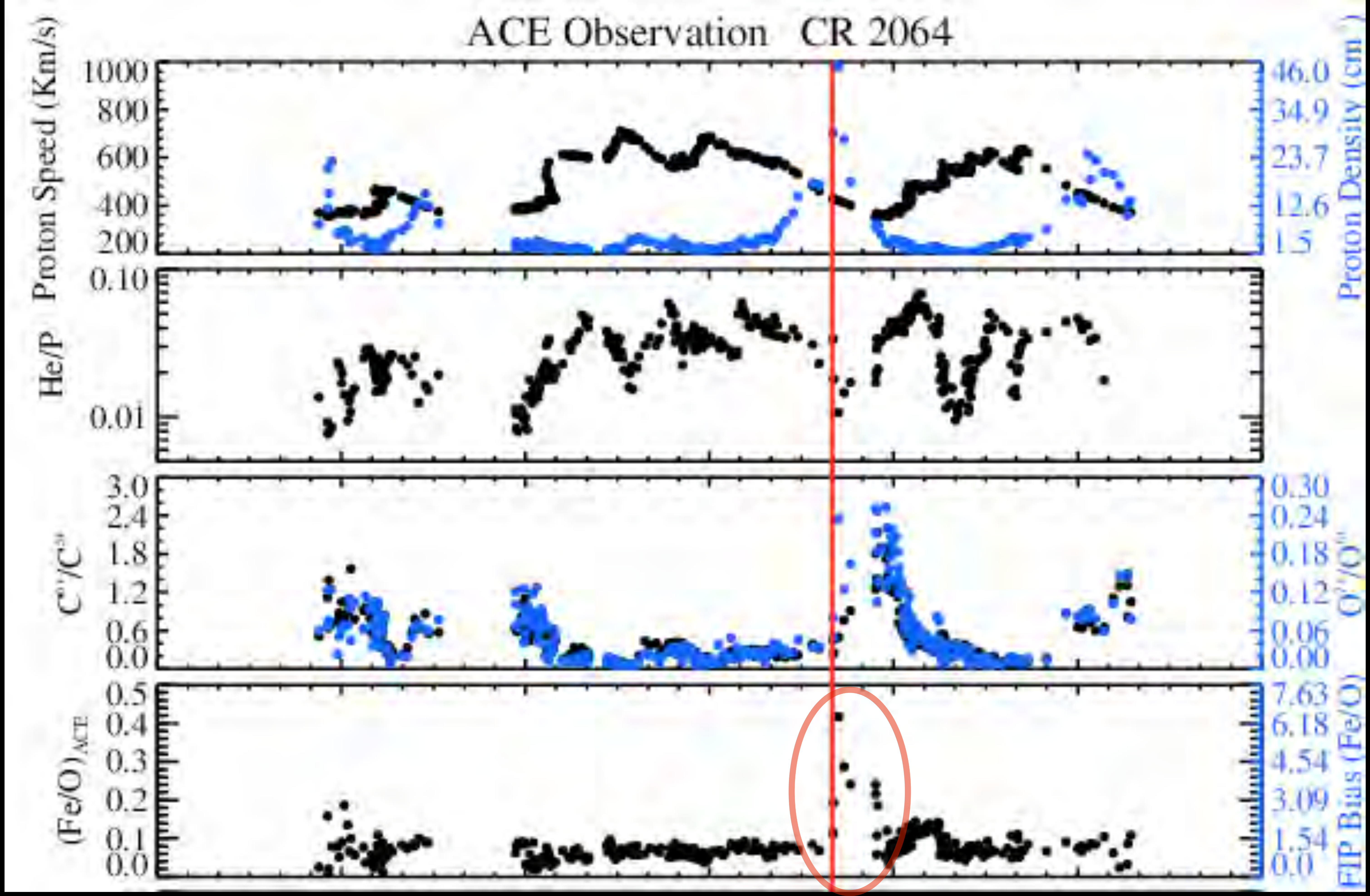
EIS Doppler Map



Height Field Lines can Reach



SIGNATURES OF OUTFLOW PLASMA ARE SEEN AT ACE



- FIP bias increase back-mapped to source surface at 2.5R☉ and linked to the AR. Dec. 2007 case (AR 10978). (Culhane et al. 2014)

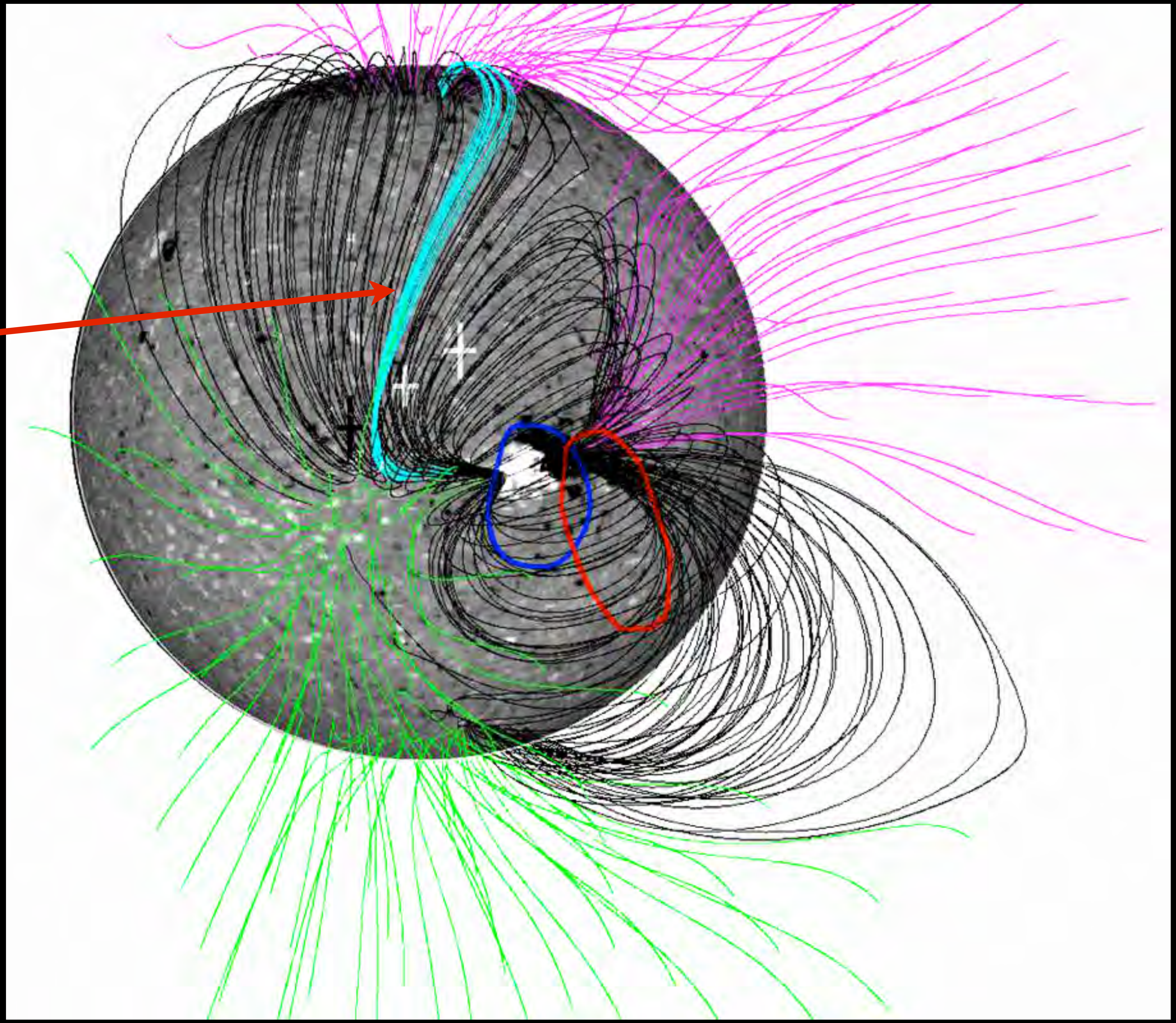
HOW DOES THE PLASMA ESCAPE?

- Two-step reconnection process:

  - closed field reconnects at QSLs with large-scale network field to produce long loops.

  - plasma delivered to high altitude null point.

  - reconnection releases plasma on open field.



(Culhane et al. 2014, Mandrini et al. 2014).

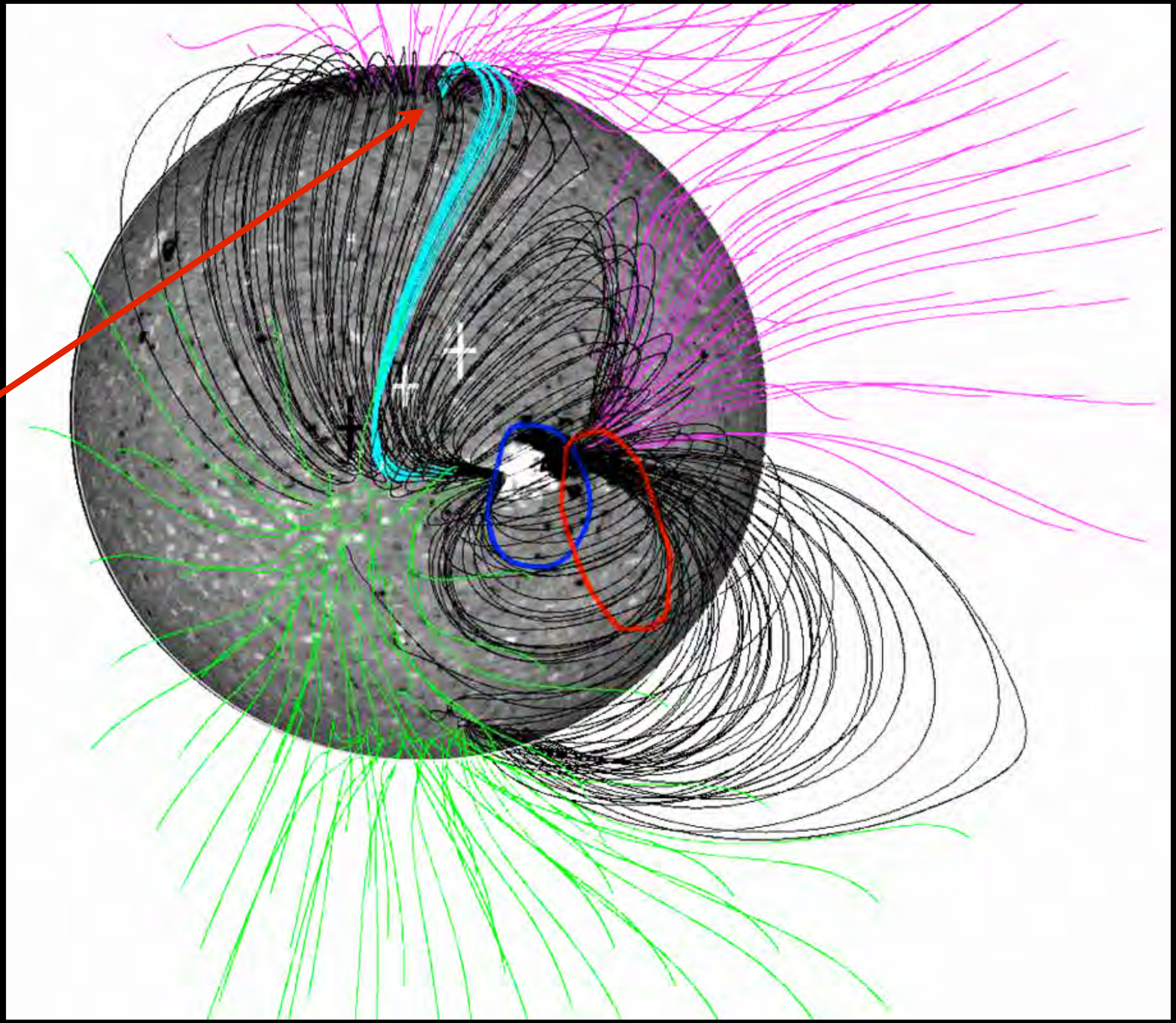
HOW DOES THE PLASMA ESCAPE?

- Two-step reconnection process:

  - closed field reconnects at QSLs with large-scale network field to produce long loops.

  - plasma delivered to high altitude null point.

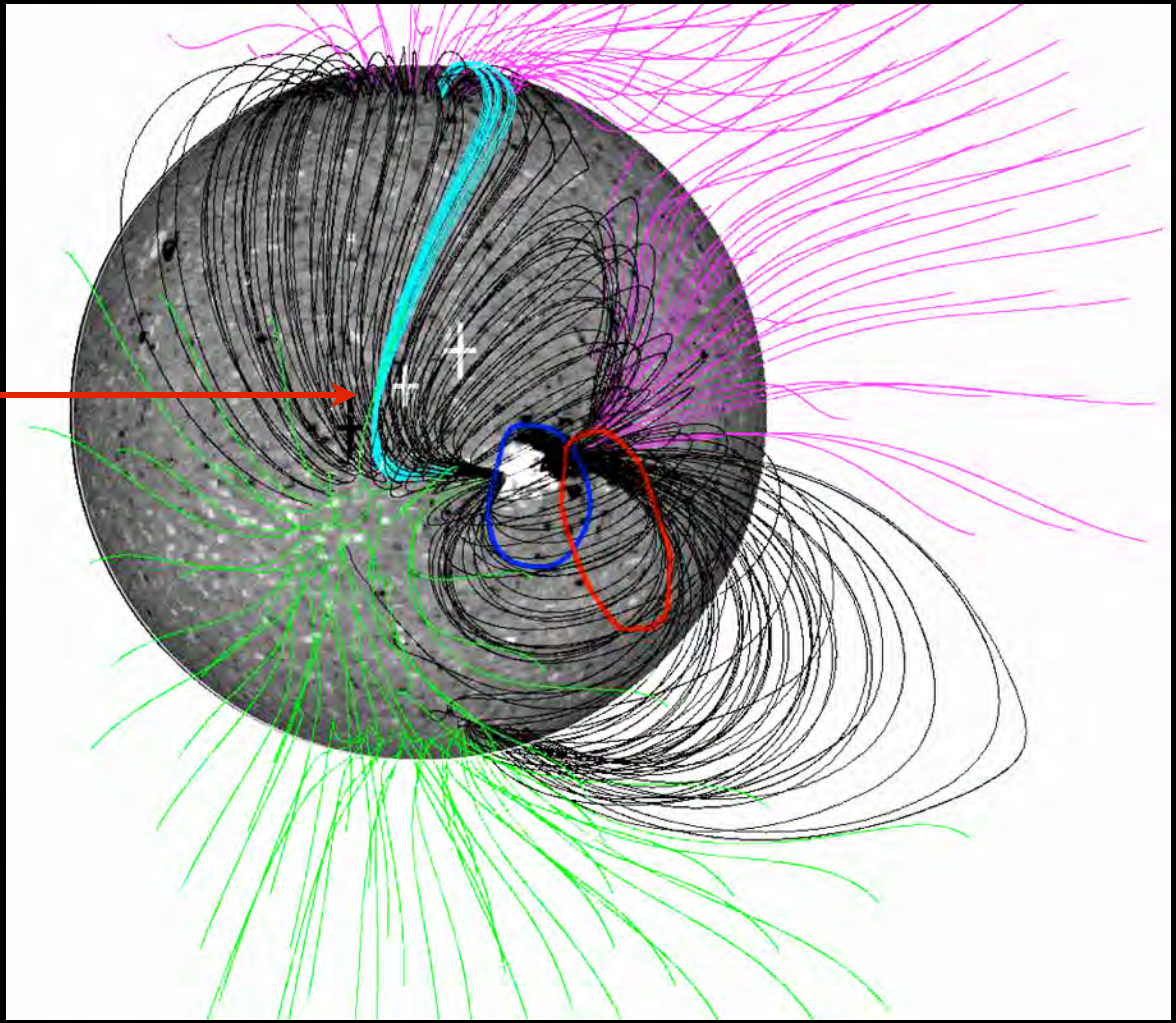
  - reconnection releases plasma on open field.



(Culhane et al. 2014, Mandrini et al. 2014).

HOW DOES THE PLASMA ESCAPE?

- This process predicts the signatures seen by ACE.
- Sporadic radio noise storms are also seen; suggestive of the first reconnection step.



- Outflow plasma can escape into the solar wind even when it appears unlikely!

(Culhane et al. 2014, Mandrini et al. 2014).

IS SUCH A COMPLEX ESCAPE PROCESS NECESSARY IN GENERAL?

- What about other sources on the Sun at the same time?

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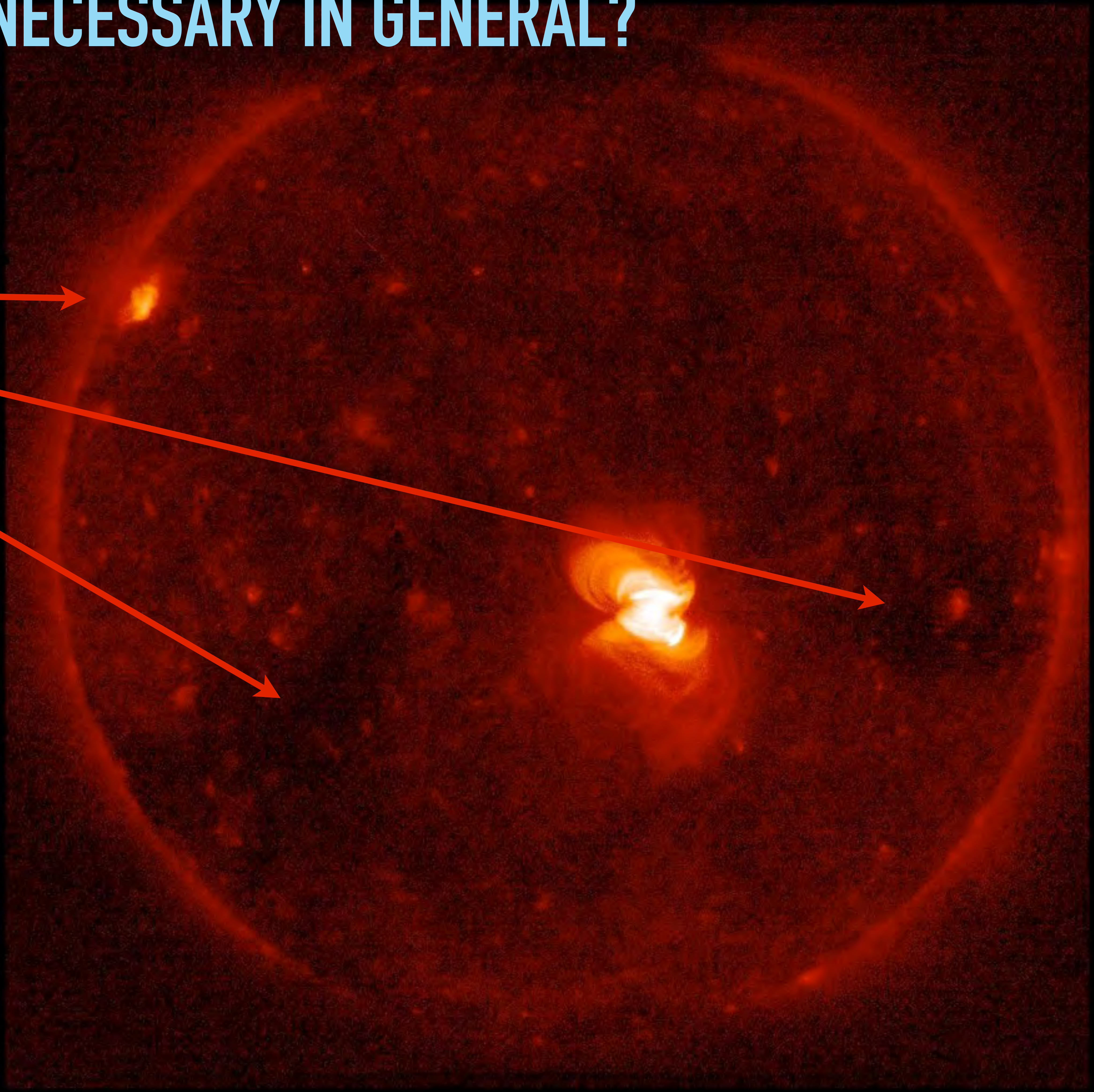


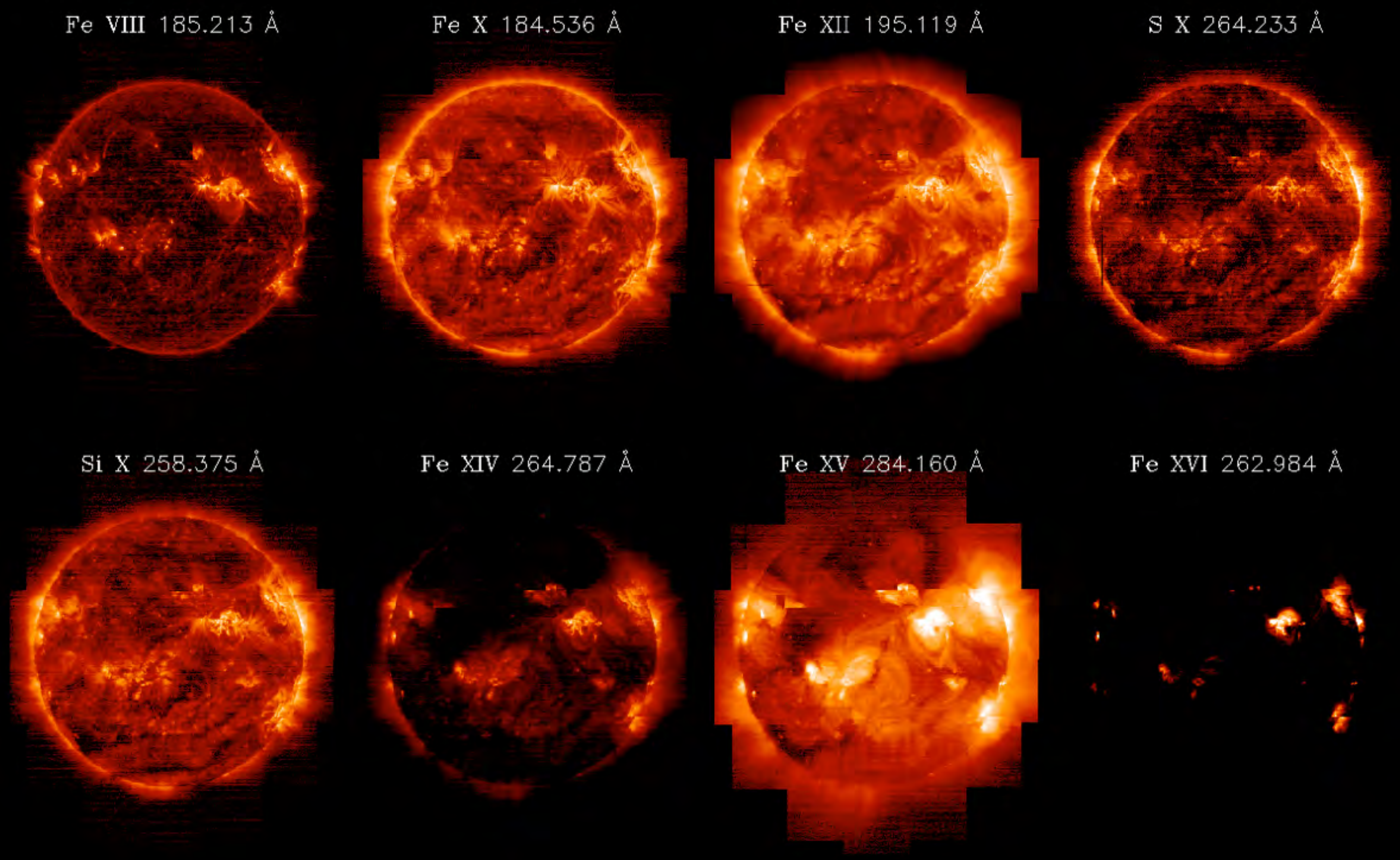
SOLUTION – EIS FULL SUN SLIT SCAN

Jan. 16- 18, 2013

- 492”x512” slit raster
- 2” slit, 30s exposures, ~2 days
- Fe VIII - Fe XVI
- Fe XIII density diagnostic
- Si/S abundance diagnostic

SLOW SOLAR WIND SOURCE MAP OF THE ENTIRE SUN

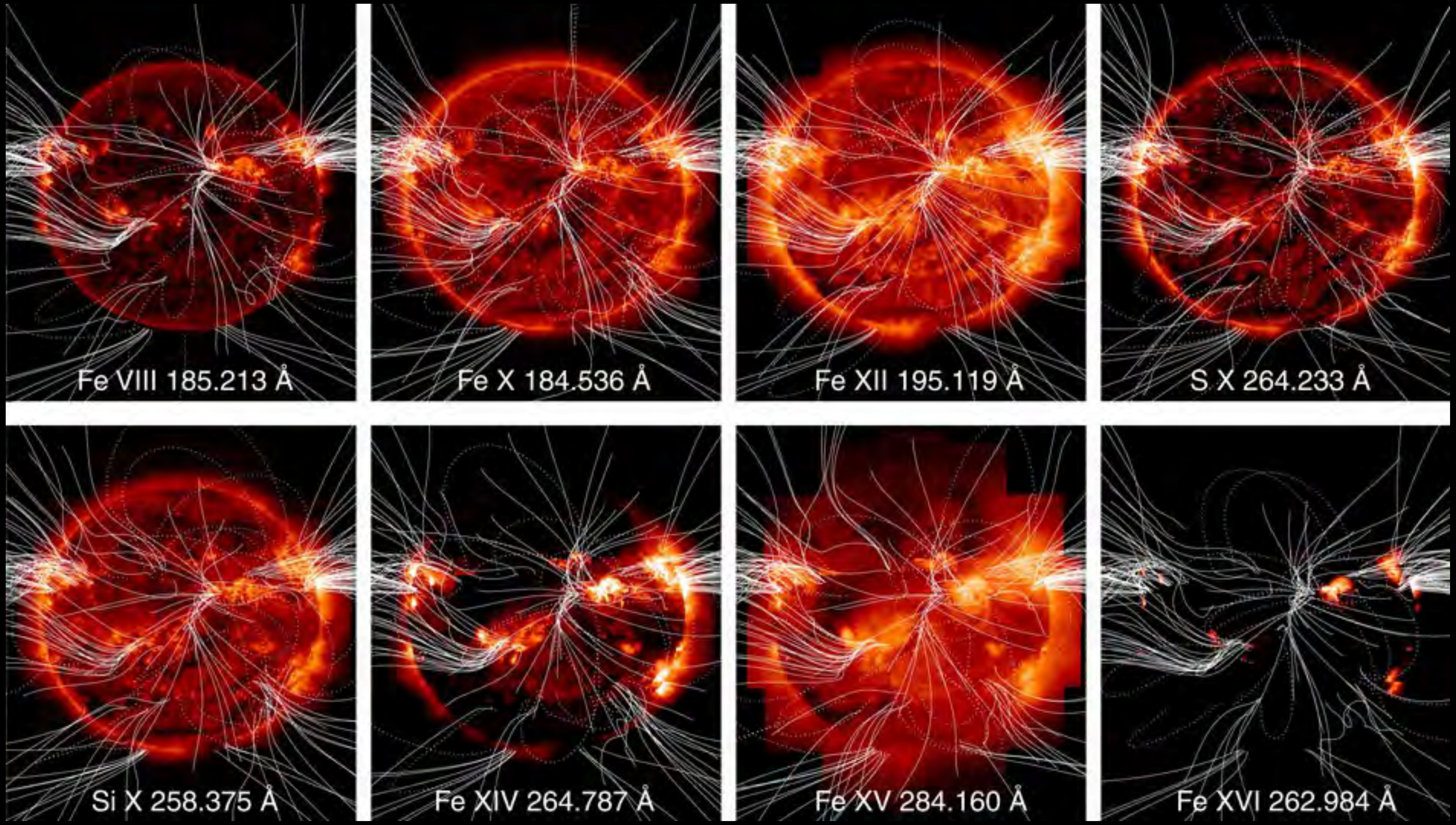
- Full Sun scan gives Doppler velocity (upflow) map
- Full Sun scan also gives plasma composition map



(Brooks et al. 2015, Nature Comms.)

SLOW SOLAR WIND SOURCE MAP OF THE ENTIRE SUN

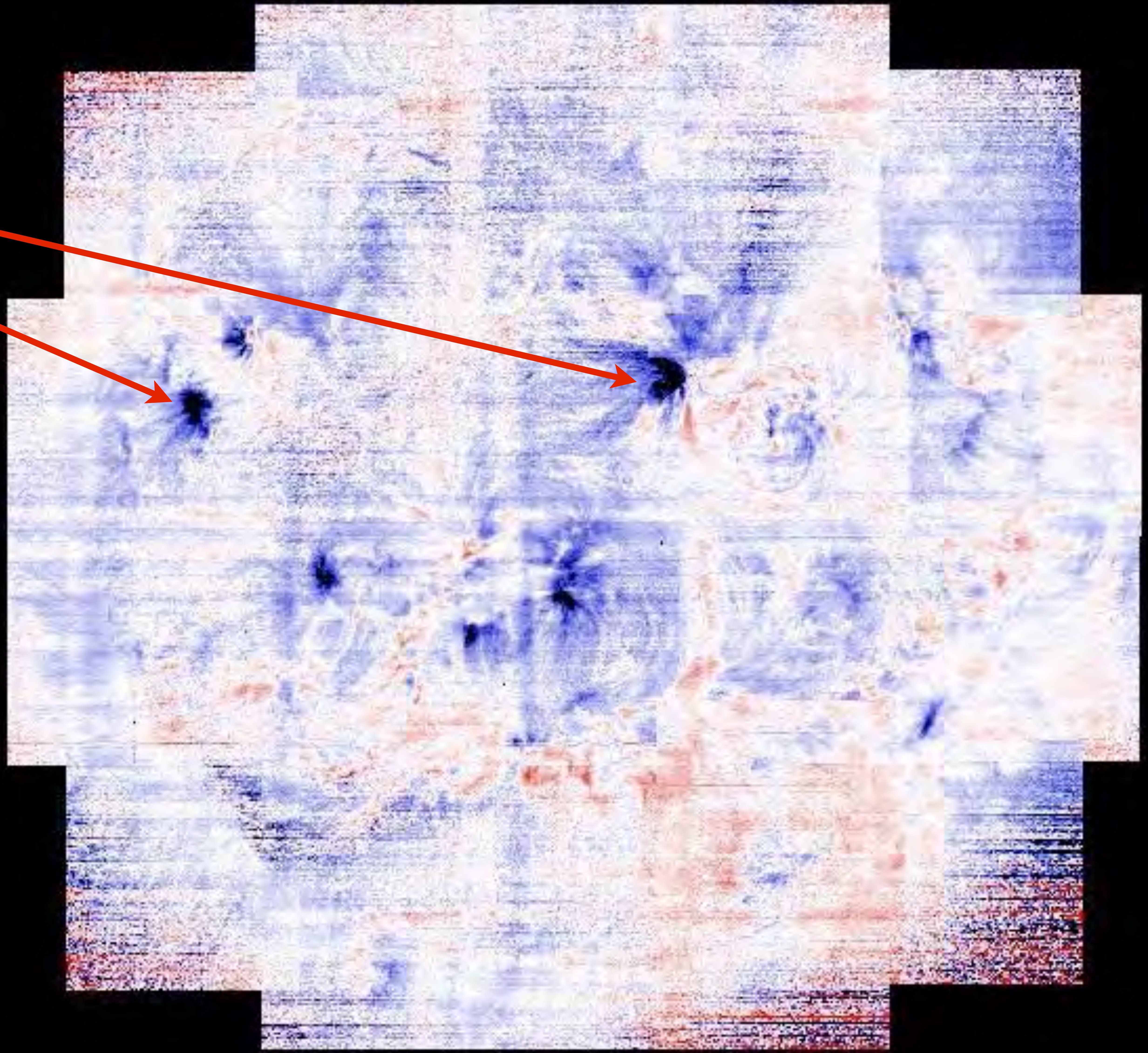
- Potential field source surface model gives magnetic topology (open field) map
- We combine the upflow, open field, and composition maps to make the SSWS map



PFSS model: De Rosa & Schrijver (2003)

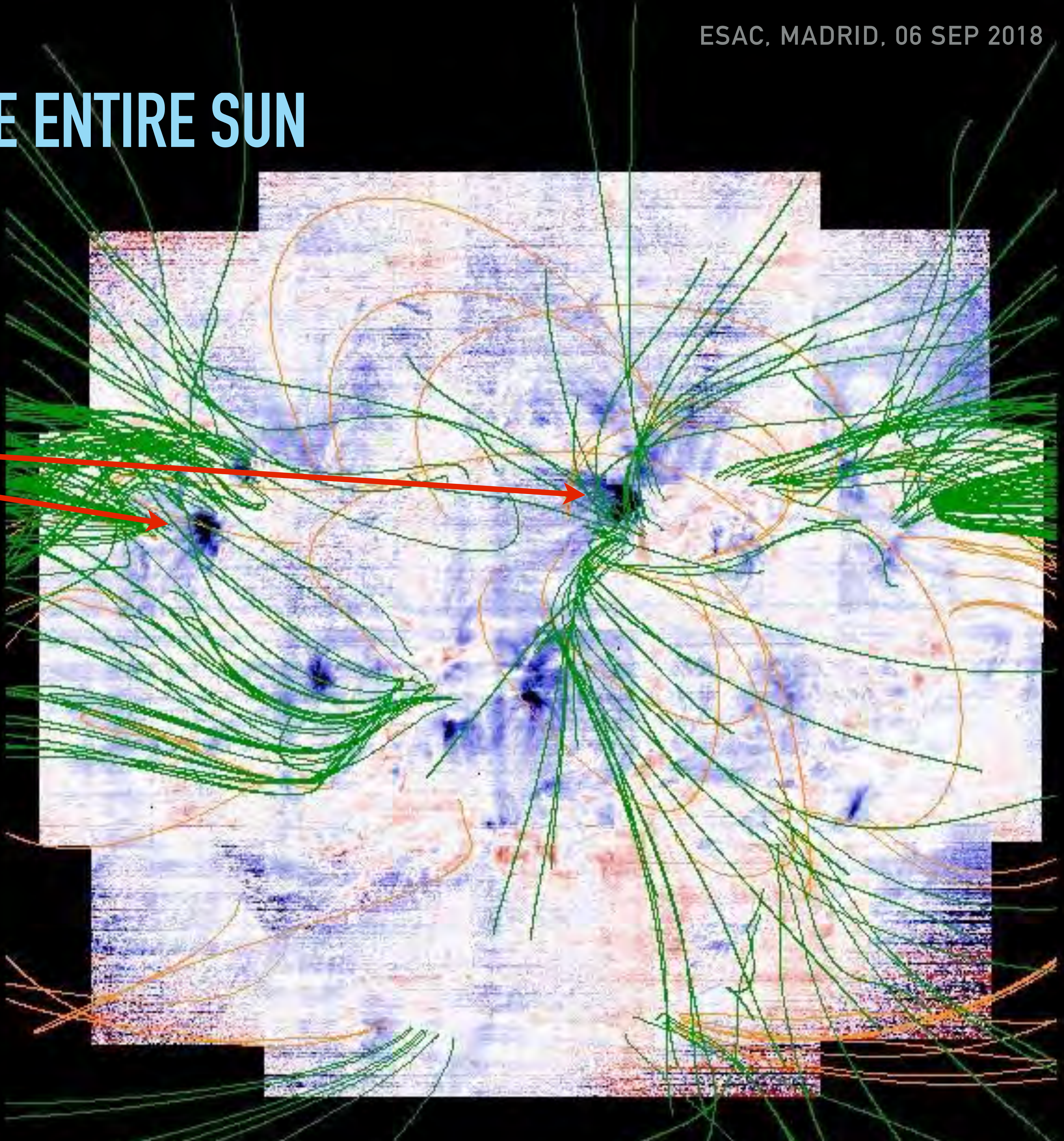
SLOW SOLAR WIND SOURCE MAP OF THE ENTIRE SUN

- Identify locations of upflow
    - Blue - Upflow
    - Red - Downflow
- Some of these upflows may be within closed magnetic field



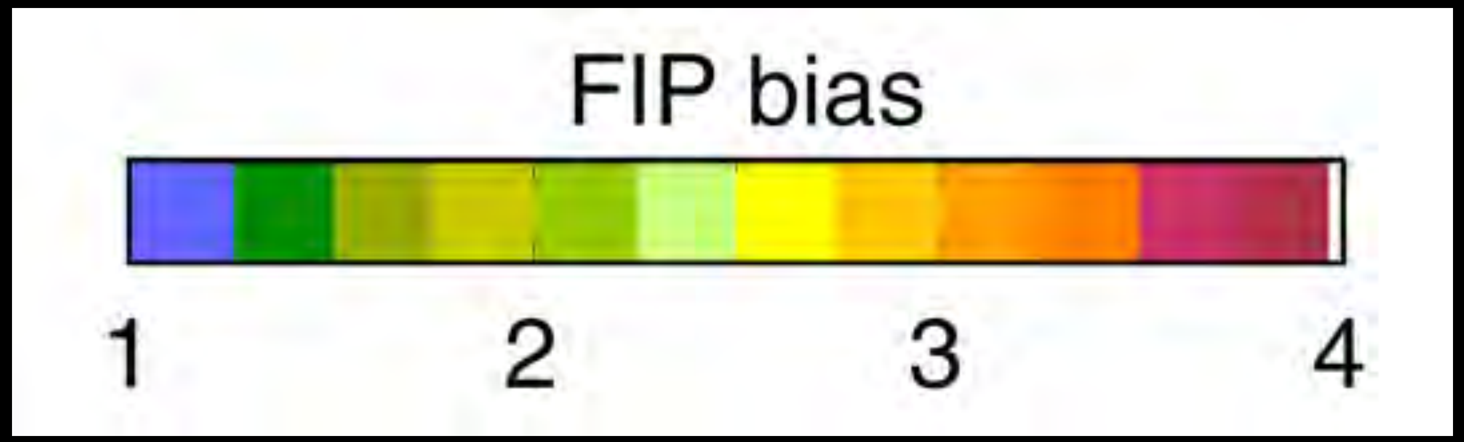
SLOW SOLAR WIND SOURCE MAP OF THE ENTIRE SUN

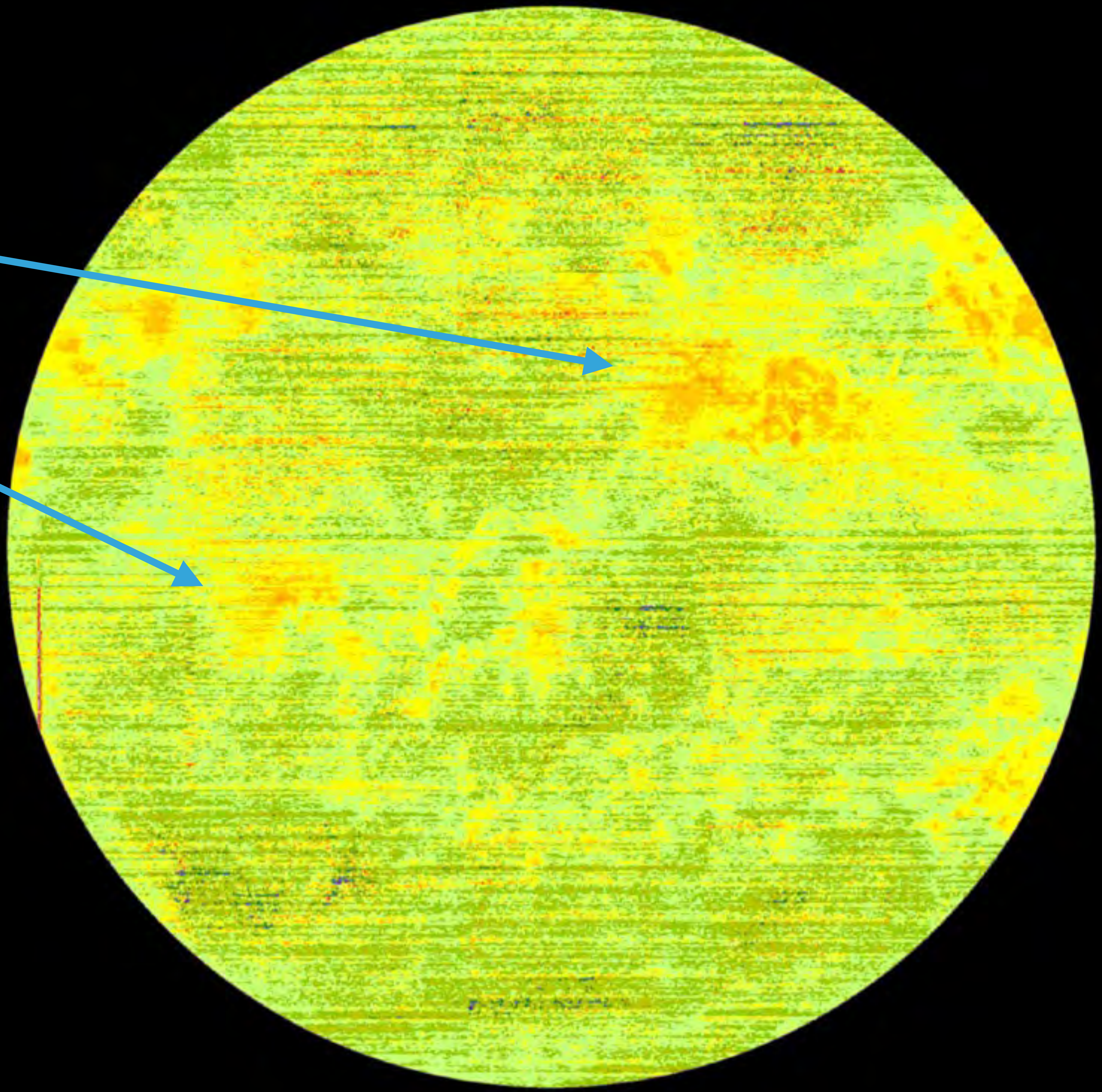
- Identify locations of upflow on open magnetic field lines.
- Upflows that are Outflows
  - Blue - Upflow
  - Red - Downflow
  - Green - Open Field
  - Orange - Closed Field



PLASMA COMPOSITION MAP FROM SI/S LINES + DEM

- Identify locations with an enhanced slow wind composition.

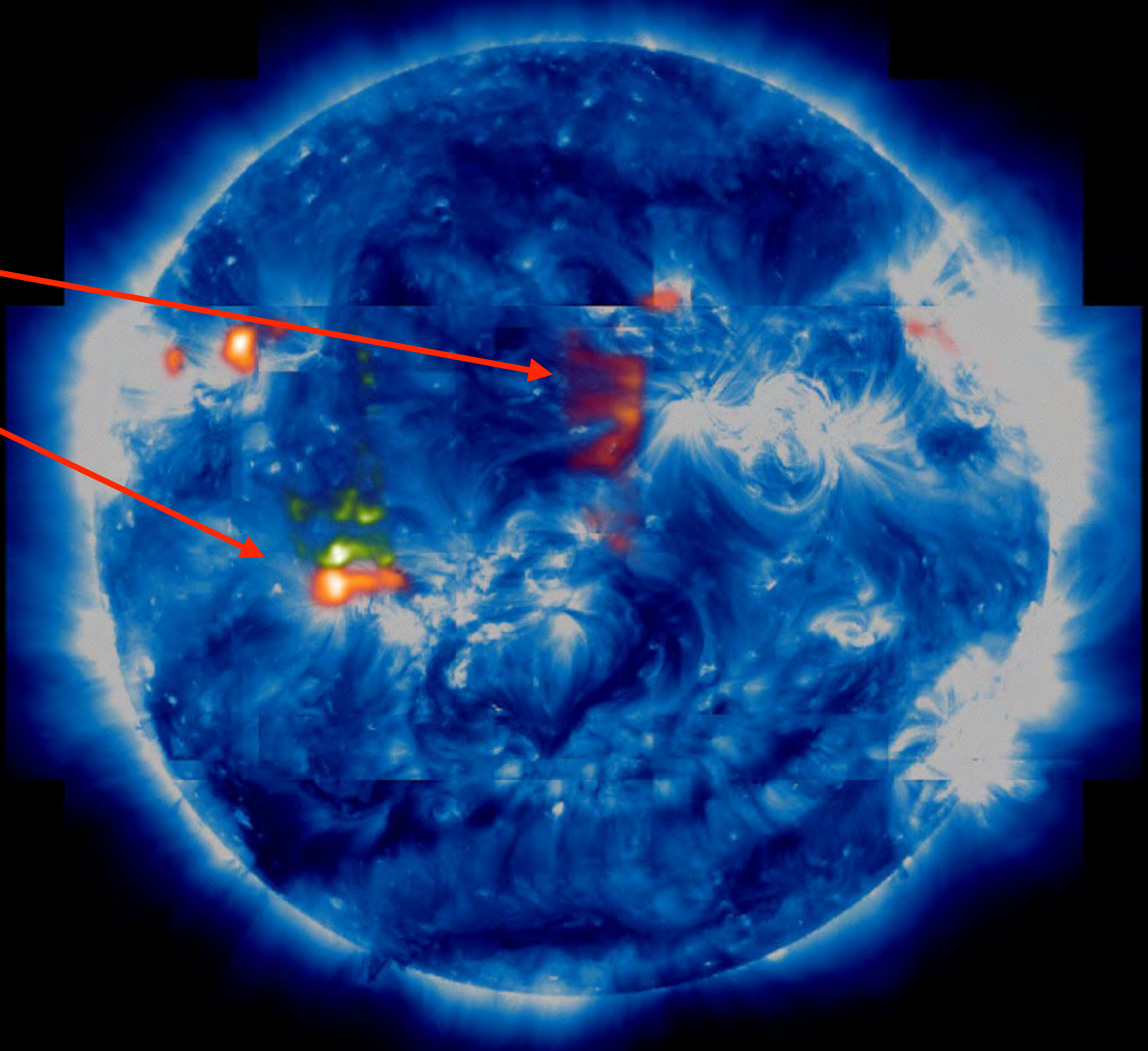




SLOW SOLAR WIND SOURCES MAP

- Identify locations of outflow on open magnetic field lines with a slow wind composition.

  - Blue - AIA 193Å image
  - Red - Slow Wind Sources

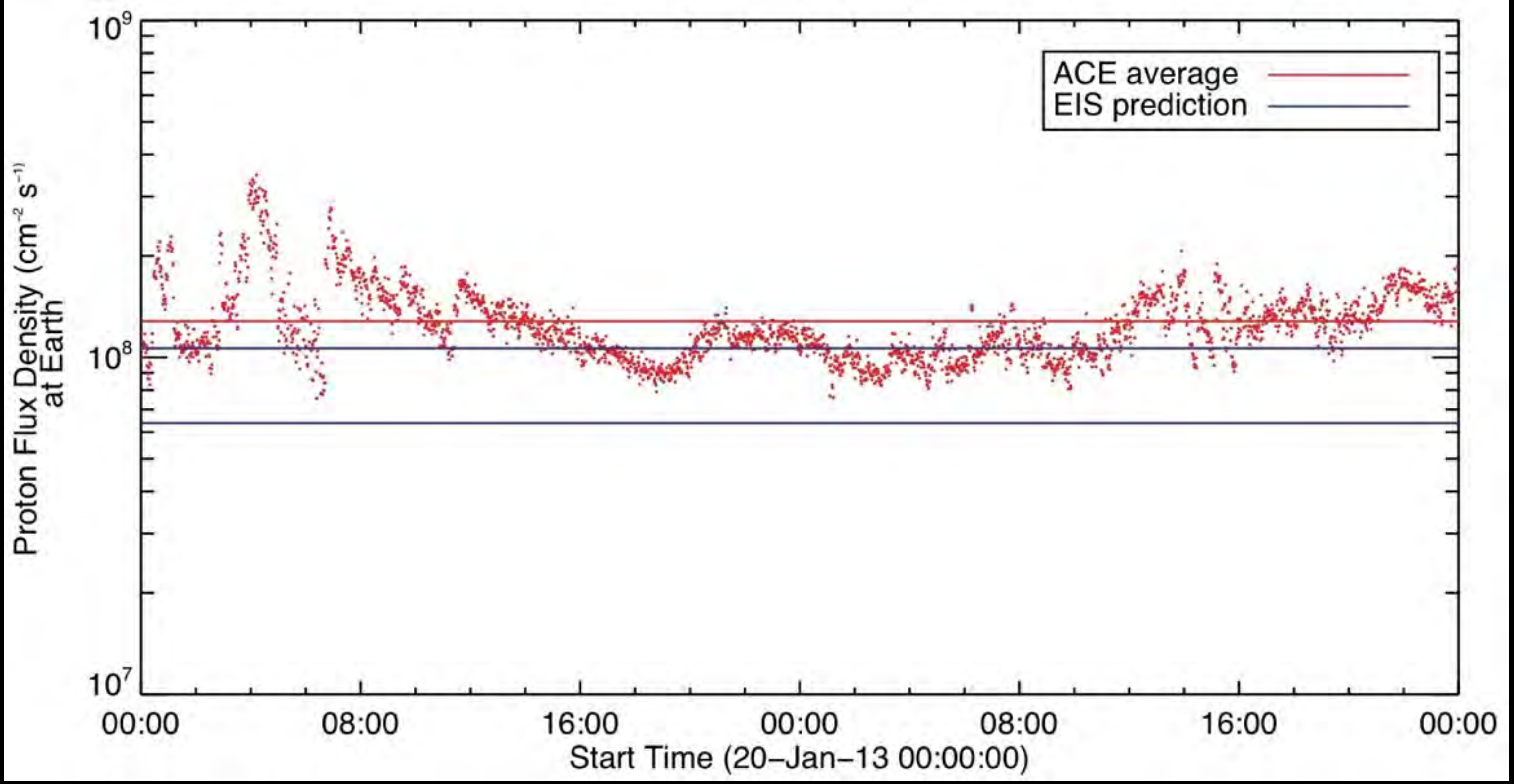


MASS LOSS RATE COMPARISON

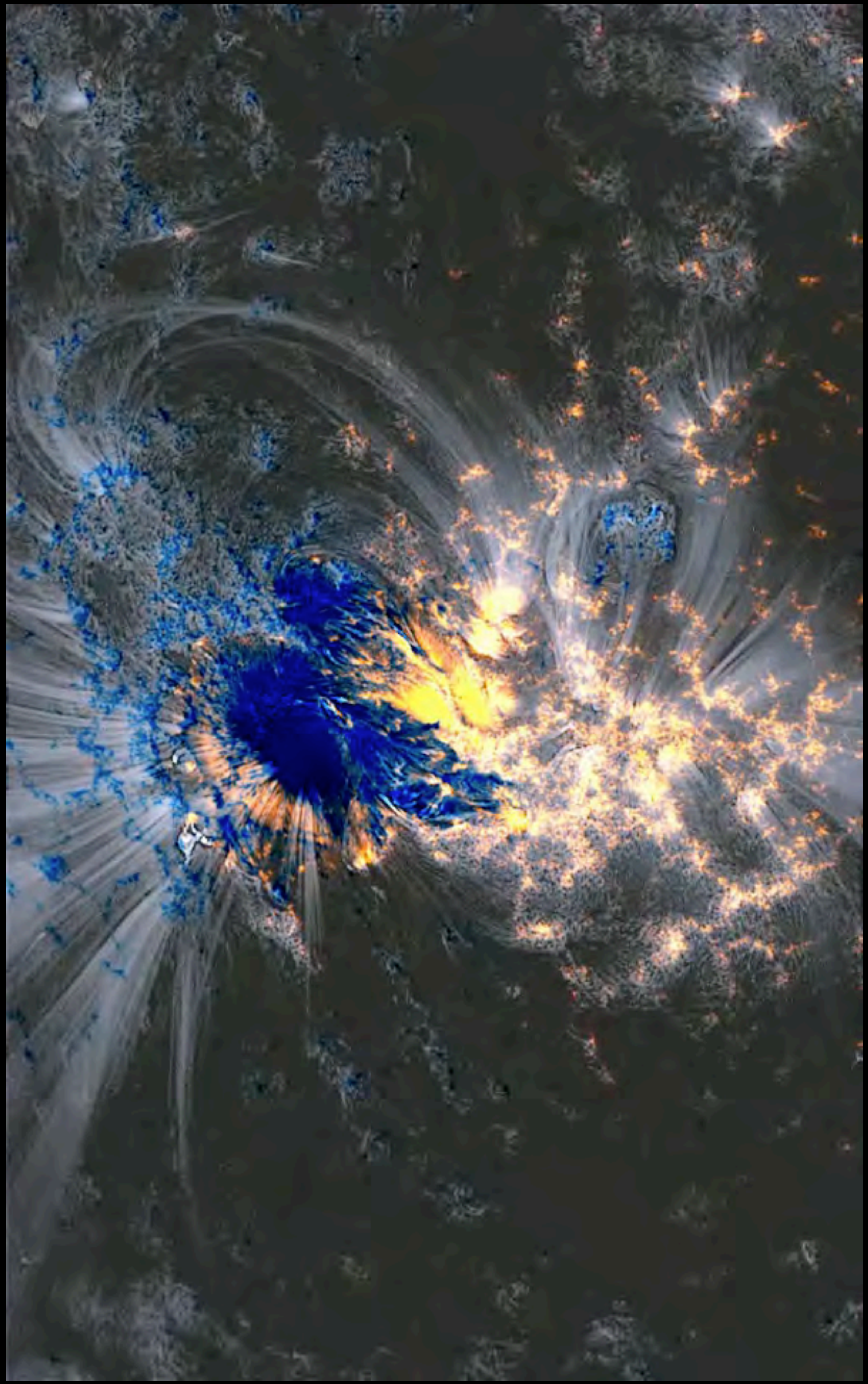
- Compute mass flux using EIS densities, velocities, area.

$$M = \sum_{i=1}^{N} m_p n_i v_i l^2$$

- 50-80% of ACE/SWEPAM average explained by SSWS map sources.
- Most of this comes from AR outflows.

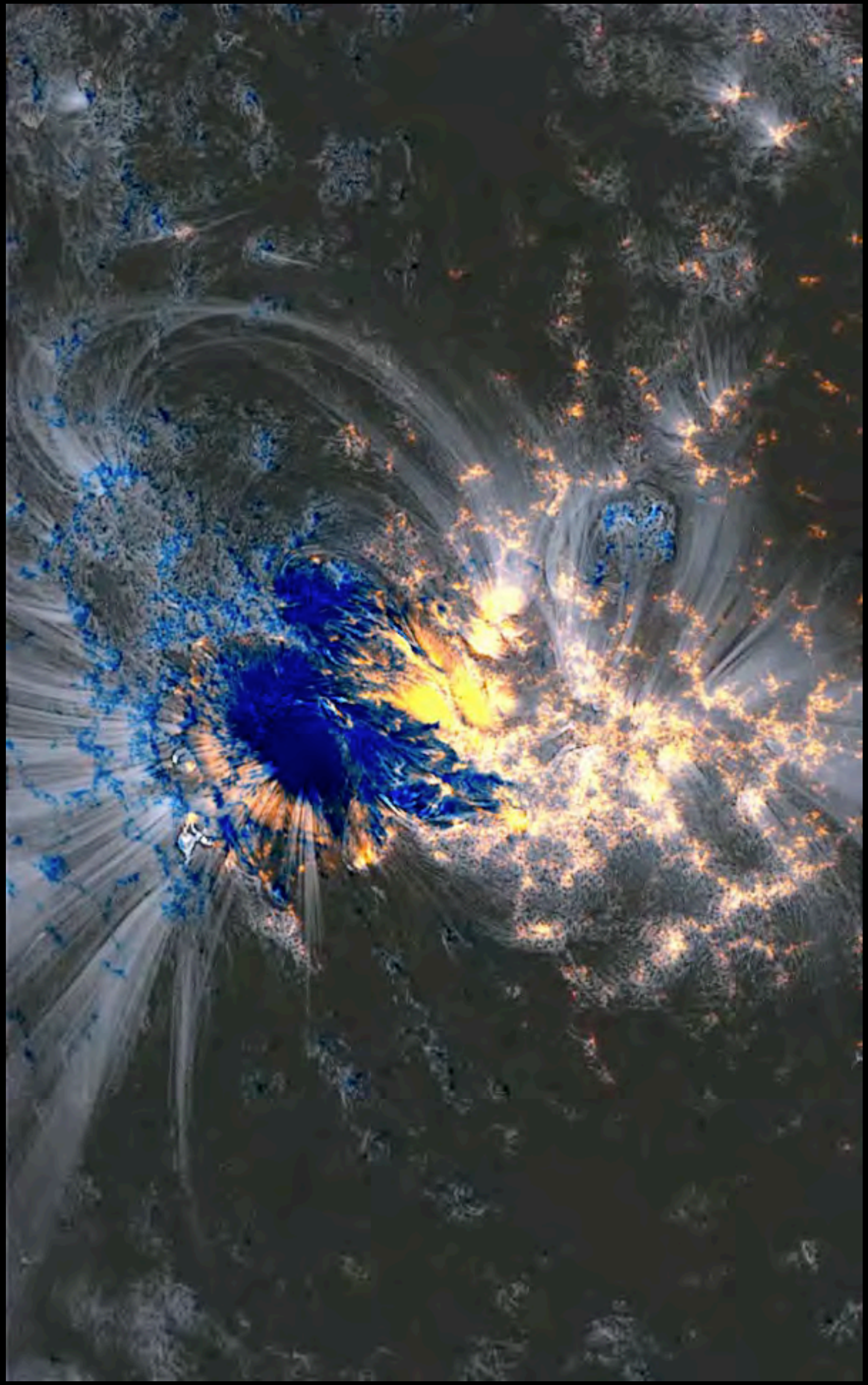


ACE/SWEPAM data 4 days later.



SUMMARY – 1

- High temperature *AR outflows* discovered by Hinode.
- EIS measurements of Si/S abundance are *consistent with slow wind values*, and signatures of the outflows are seen *in-situ at ACE.*
- Evidence that AR outflows *can contribute to the slow speed wind…*
- But, *not all outflows* are on *open field* so complex escape paths may be necessary…



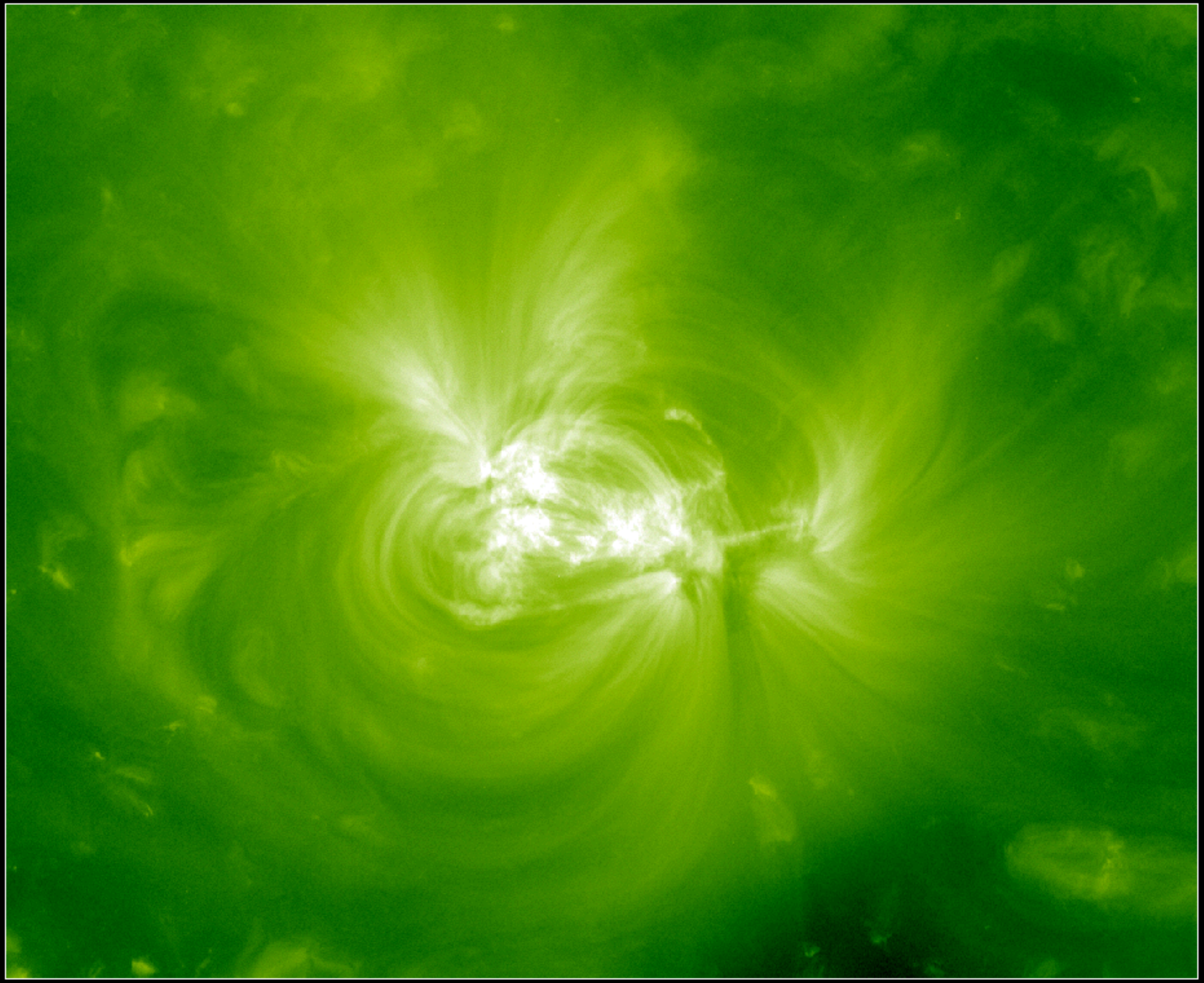
SUMMARY – 2

- *Slow Solar Wind Sources map* constructed from EIS full Sun slit scan and magnetic topology model.
- Identifies *slow wind composition* plasma *outflowing* on *open magnetic field* lines.
- The sources can deliver enough mass flux to the ecliptic to explain measurements made at ACE.
- Dominant sources *in these observations near solar max.* are *AR outflows*.

FUTURE: HI-C 2.1 OBSERVATIONS

- AR 12712 - 29 May, 2018
- Outflows are seen on either side of the AR within the Hi-C 2.1 field-of-view.
- Outflow areas observed at high spatial resolution (0.129”).

AIA 193



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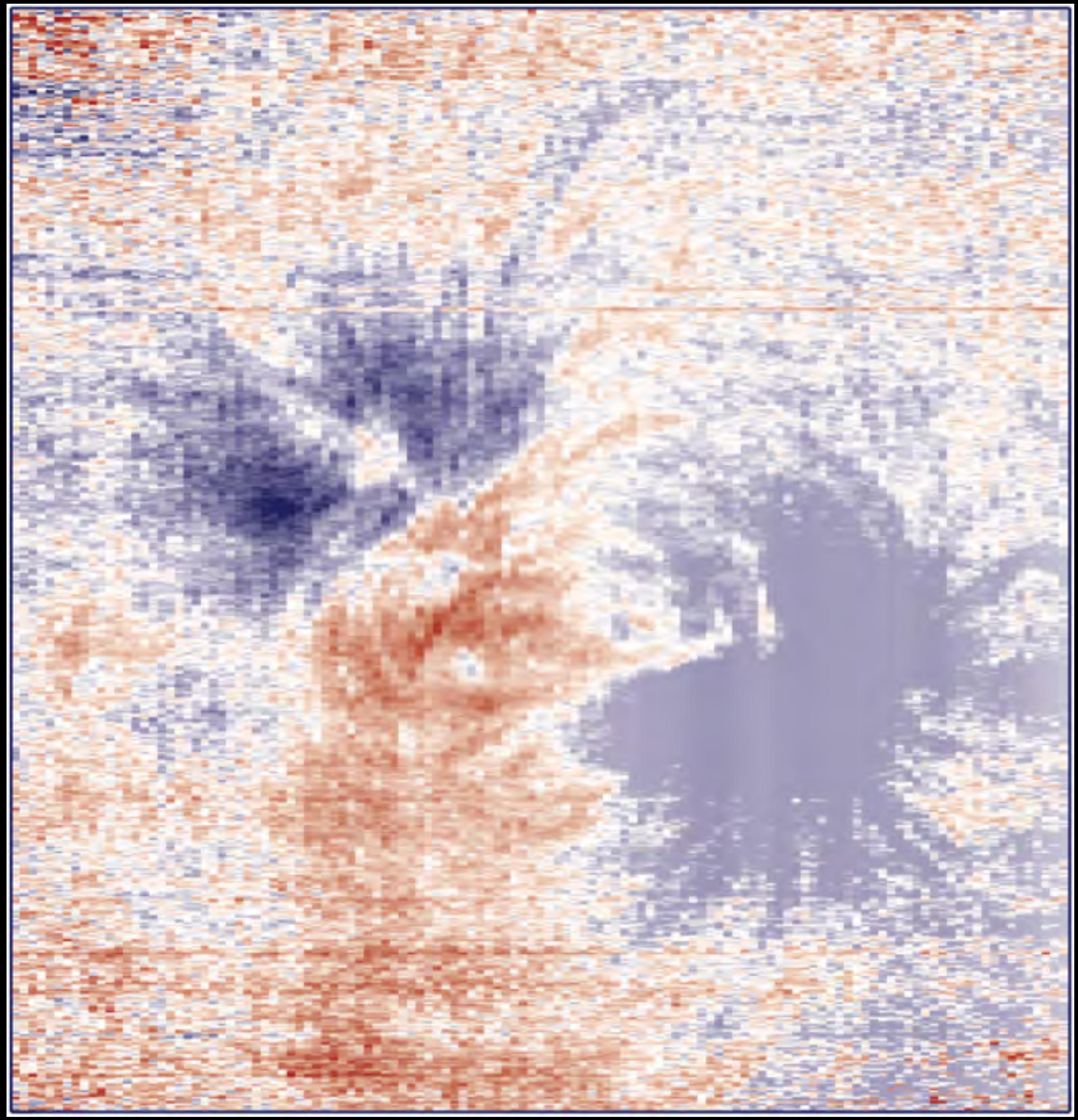
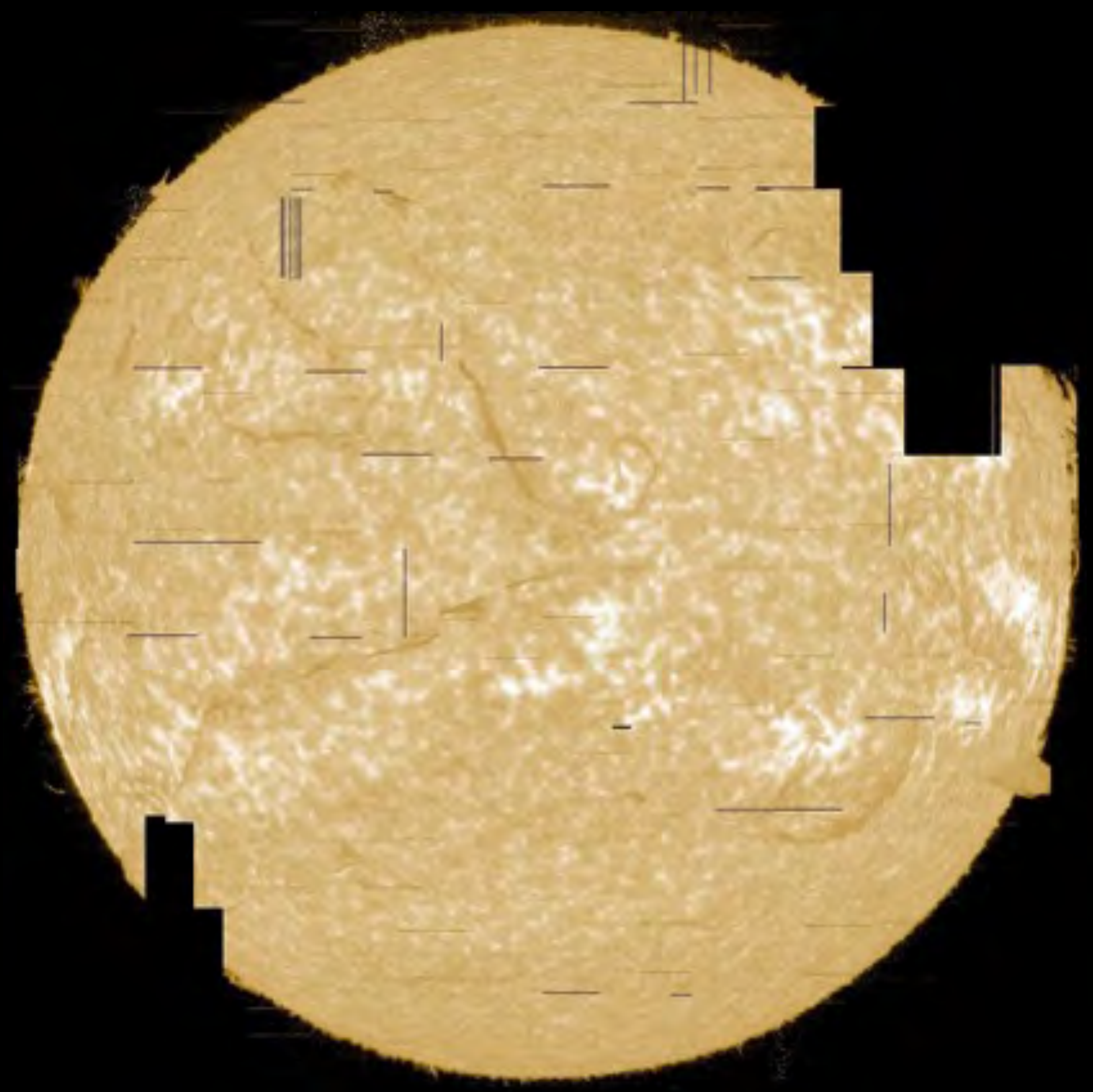
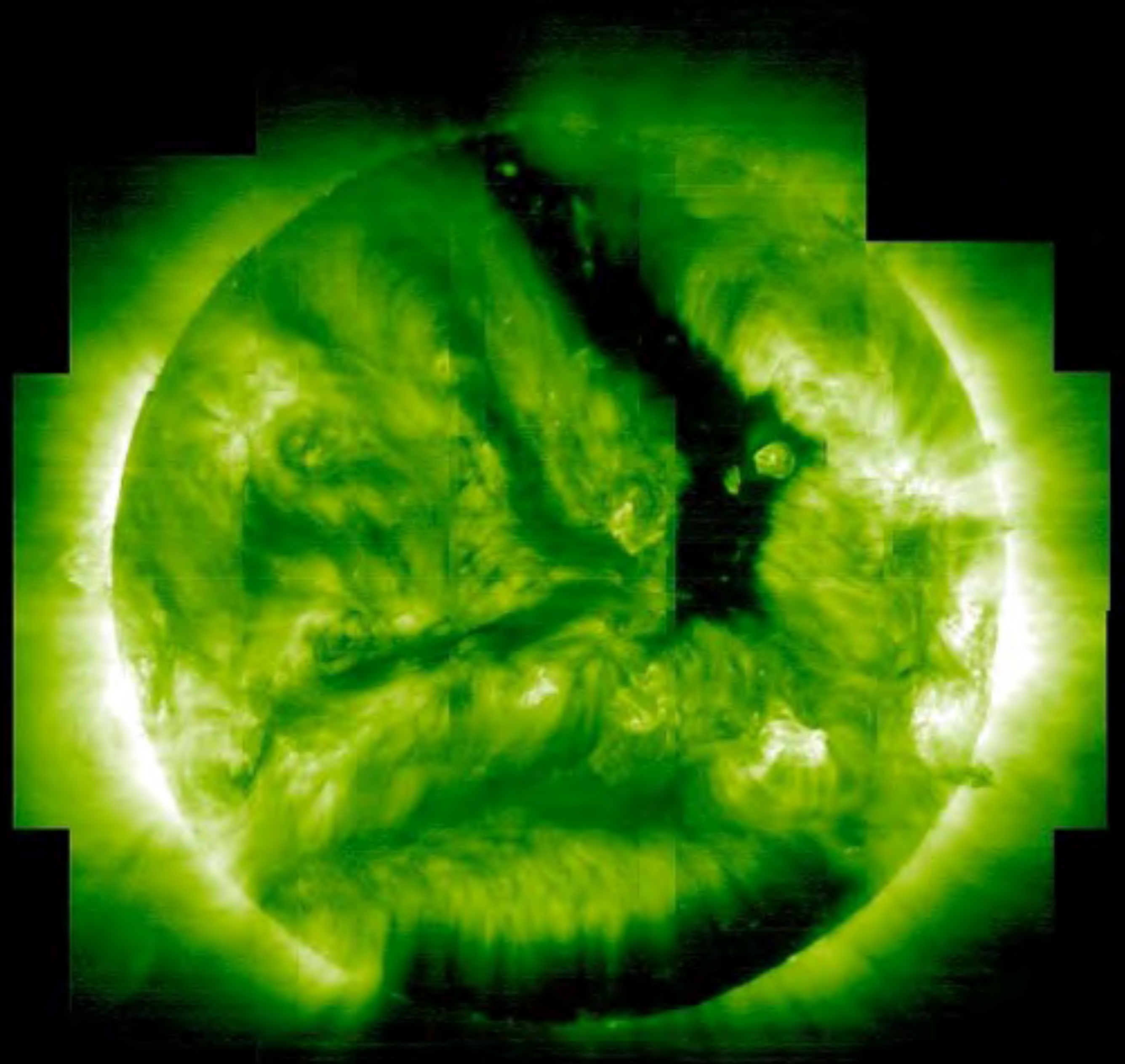


EIS Fe XIII Doppler map

FUTURE OBSERVATIONS



IRIS Mg II



EIS Fe XIII

- Hinode full Sun scans now coordinated every few months with IRIS. *Slow Solar Wind Source* maps to guide exploration of IRIS data…
- Future observations supporting Solar Orbiter:

  Stronger connection between in-situ and remote sensing measurements

- Main results in this talk published in:

  Brooks & Warren (2011), ApJ, 727, L13

  Brooks & Warren (2012), ApJ, 760, L5

  Brooks et al. (2015), Nature Comms., 6, 5947