Energy and Mass Transfer through the Chromosphere

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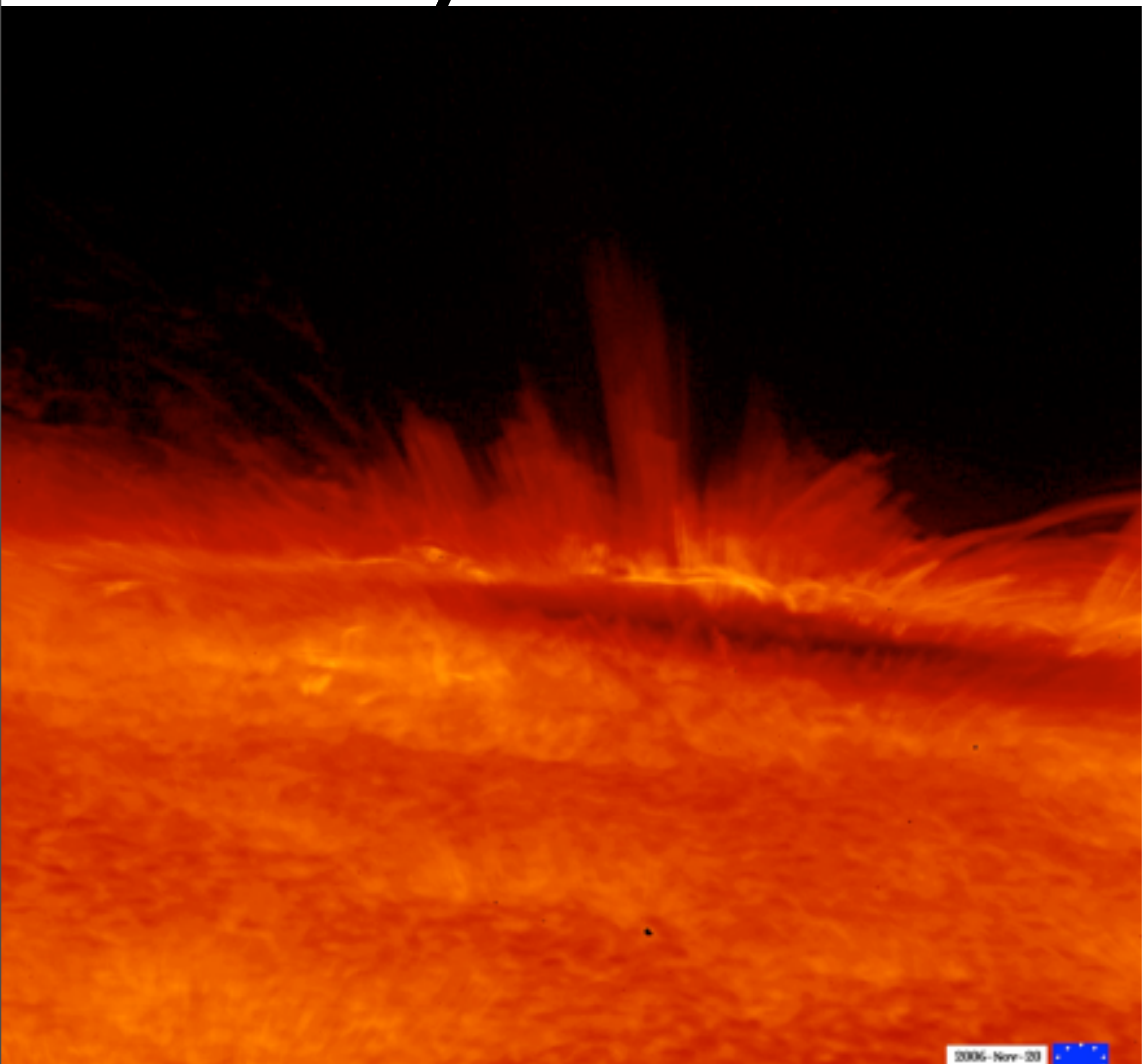
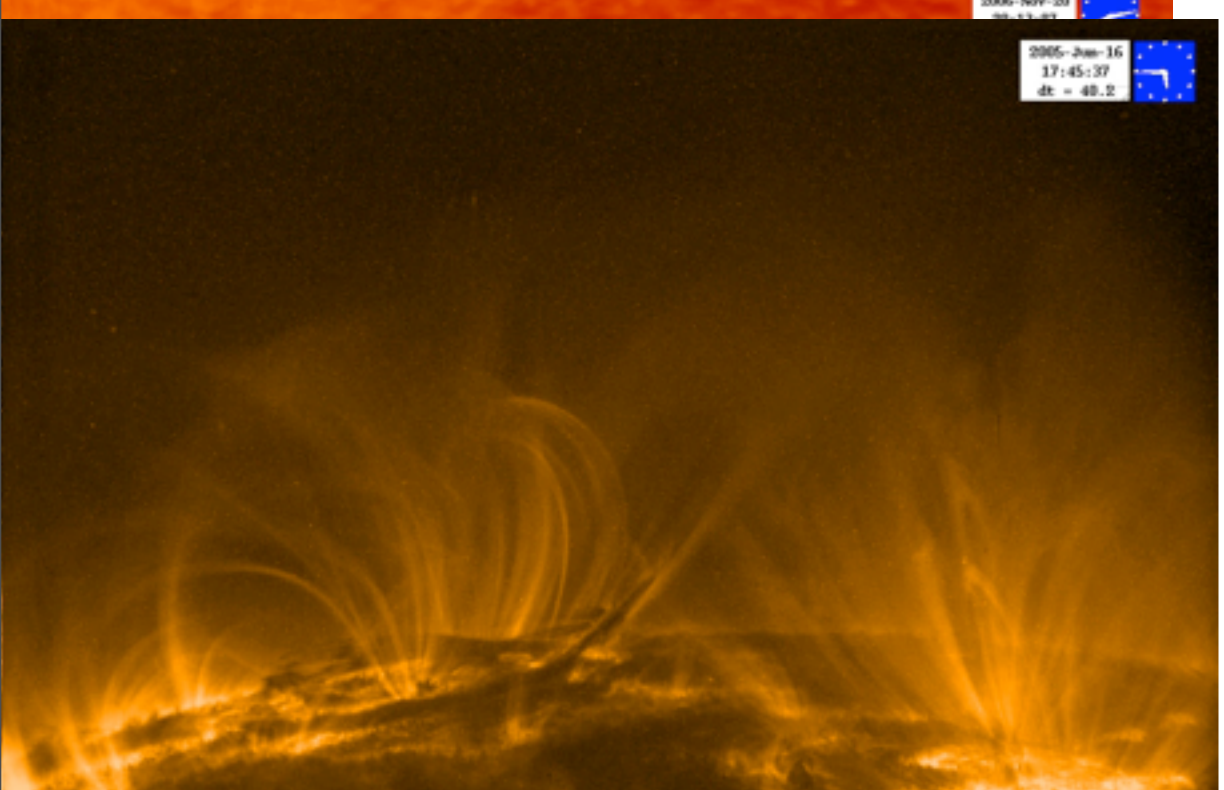
Why do we care about the chromosphere?





The chromosphere is where most of the non-thermal energy that creates the corona and solar wind is released or transformed.

Chromosphere requires 50 times heating rate of corona, and provides all mass to heliosphere

A. What types of non-thermal energy dominate in the chromosphere and beyond?

B. How does the chromosphere regulate the mass and energy supplied to the corona and heliosphere?

C. How does magnetic flux and matter rise through the lower atmosphere, and what role does flux emergence play in powering flares and mass ejections?

movies courtesy of Alan Title

Why do we care about the chromosphere?

- Compatible high spatial and temporal resolution from photosphere to corona
- Wide spectral coverage
- Magnetic Field in Chromosphere
- Context/Complementarity (Great Observatory)
- Numerical Simulations

Tremendous discovery space

The chromosphere is where most of the non-thermal energy that creates the corona and solar wind is released or transformed.

Chromosphere requires 50 times heating rate of corona, and provides all mass to heliosphere

A. What types of non-thermal energy dominate in the chromosphere and beyond?

B. How does the chromosphere regulate the mass and energy supplied to the corona and heliosphere?

C. How does magnetic flux and matter rise through the lower atmosphere, and what role does flux emergence play in powering flares and mass ejections?

Solar C plan B will provide major breakthrough science

1. Source, propagation and dissipation of Alfven waves that help drive solar wind,

2. Connection between chromosphere and corona: mass cycle, constrain coronal heating models,

3. Magnetic field extrapolations from chromospheric vector-magnetic data into heliosphere will allow detailed accounting of helicity and magnetic free energy that drive solar activity,

4. Heating of quiescent and active chromosphere.

5....

To determine energy and mass transfer from chromosphere into corona/heliosphere, we need

1. A large observatory that obtains spectra and images that simultaneously cover the photosphere, chromosphere, TR and corona (from 4,000K to 10 MK),

2. simultaneously at high spatial resolution (~0.2 arcsec),

3. temporal resolution (<10 s) over a large FOV (120 arcsec),

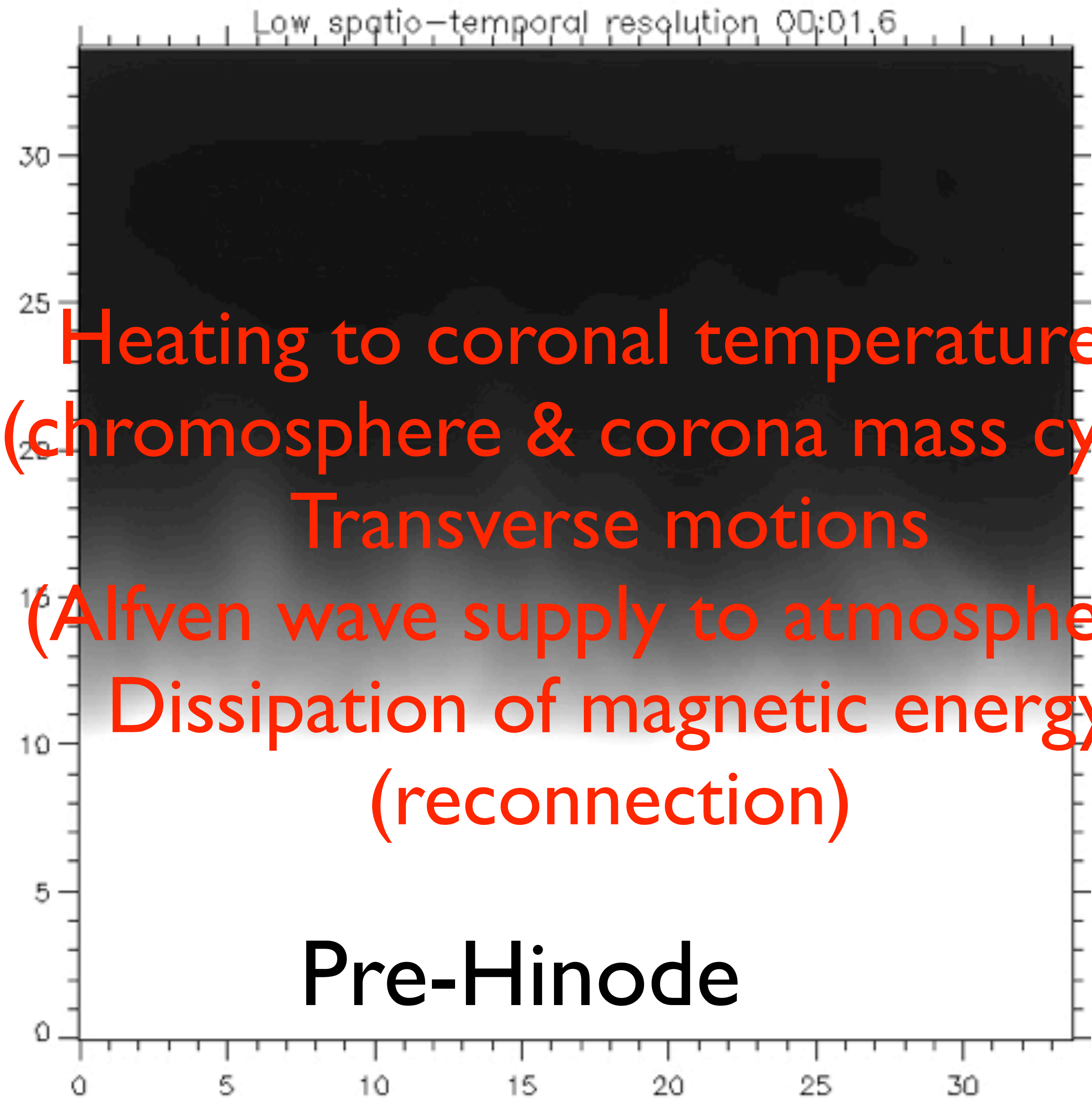
4. and spectral resolution (0.5 km/s in TR/corona from centroiding)

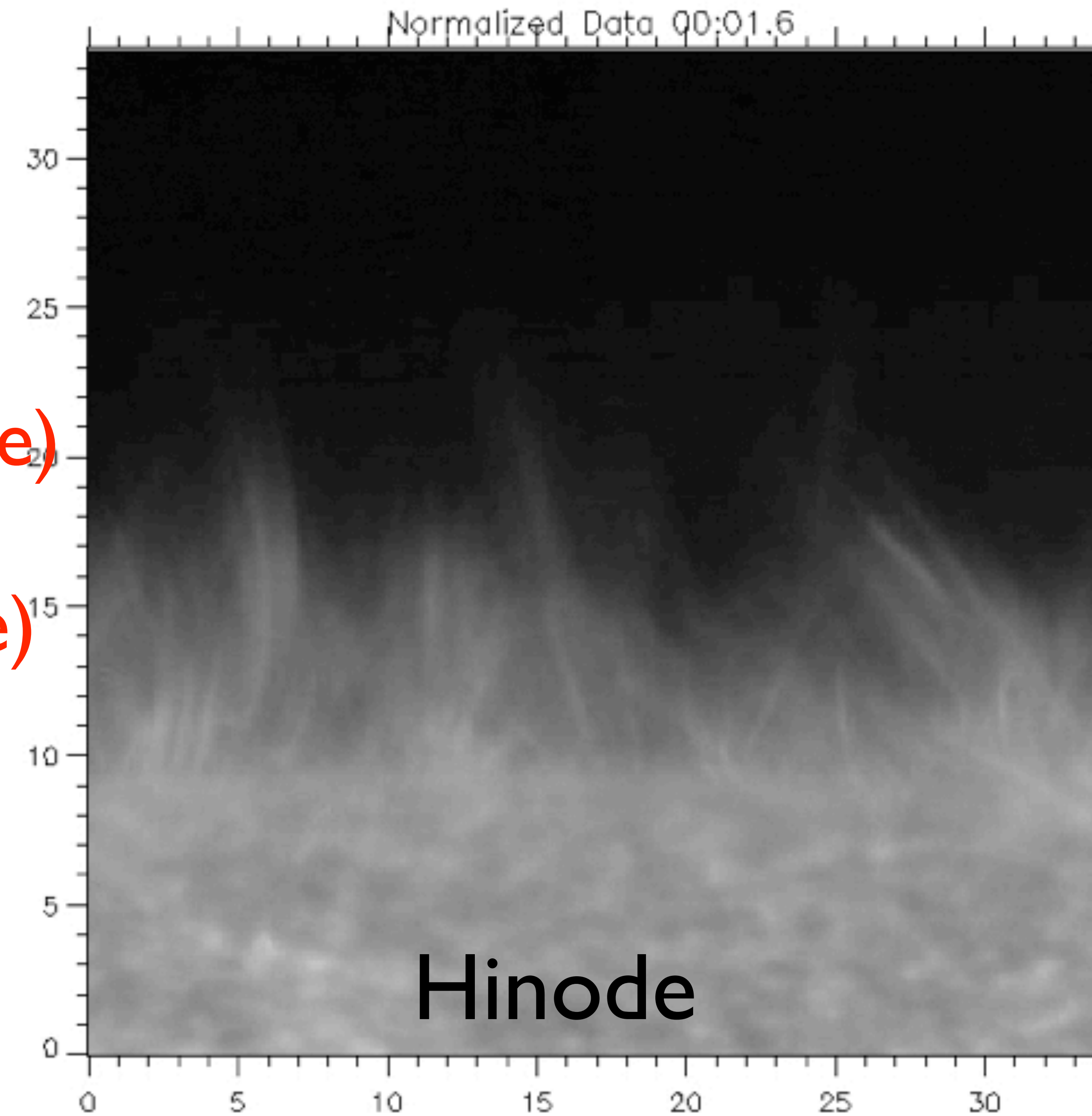
5. without issues of co-alignment (i.e., different instruments with predefined co-alignment strategies, slit-jaw),

6. with high S/N polarimetry in photosphere and chromosphere.

The chromosphere then... vs now...

1 arcsec, 30 s resolution vs 0.2 arcsec, 1.6 s resolution



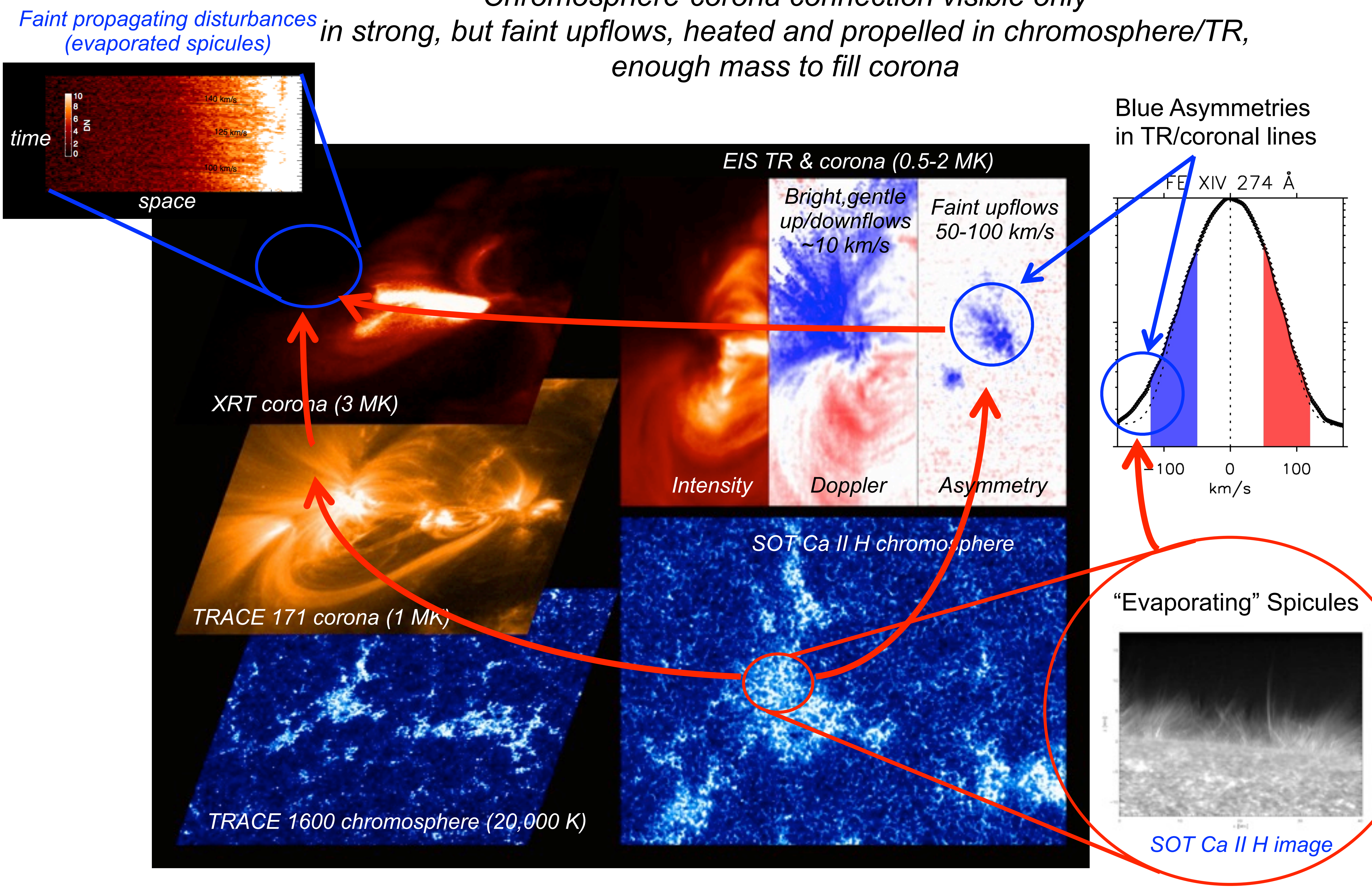


Heating to coronal temperatures?
(chromosphere & corona mass cycle)
Transverse motions
(Alfven wave supply to atmosphere)
Dissipation of magnetic energy
(reconnection)

Chromospheric dynamics occurring
on timescales of order 1-10 s
Finescale structures on scales of <0.2 arcsec

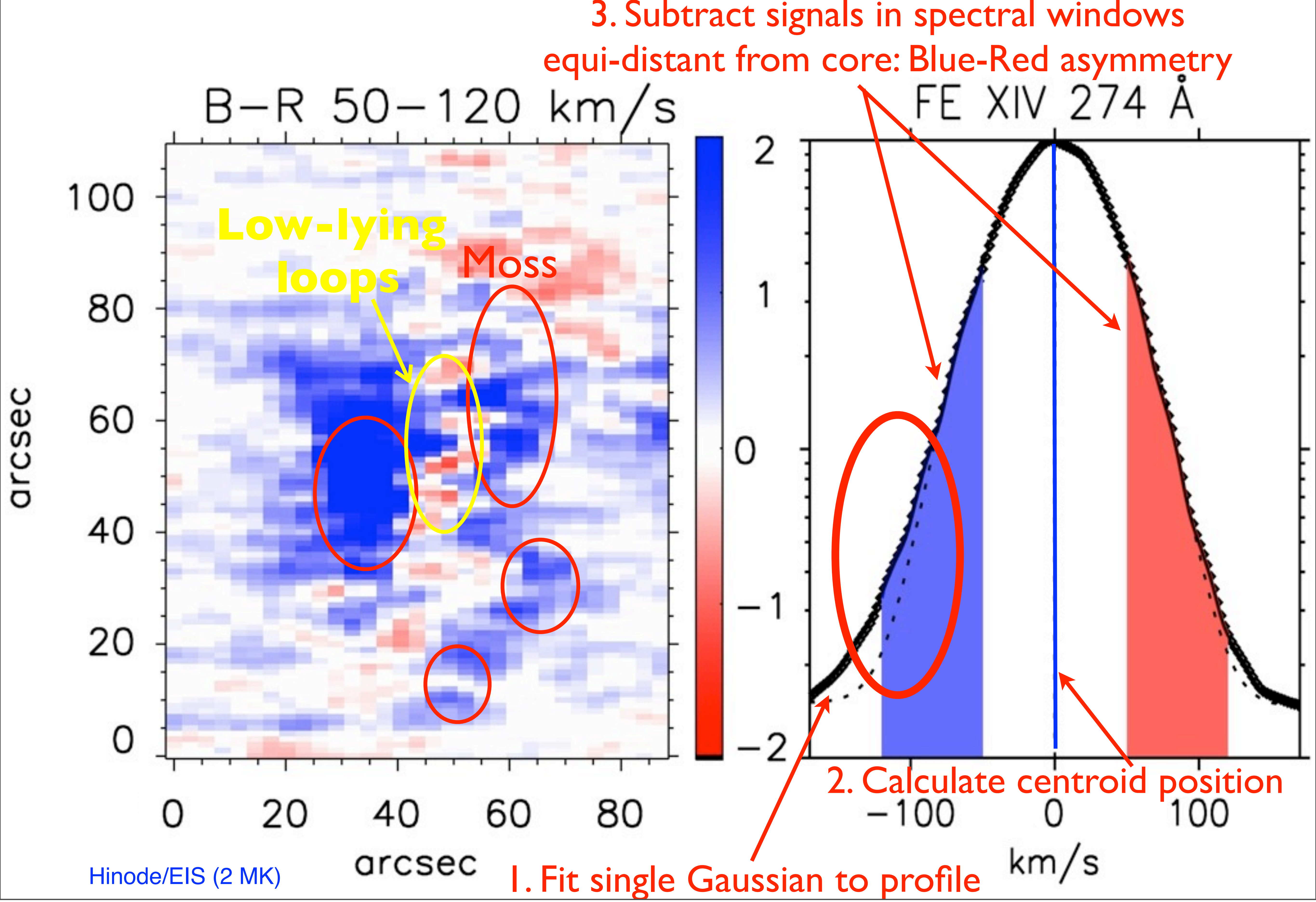
Observing the Roots of Coronal Heating -- In The Chromosphere

Chromosphere-corona connection visible only in strong, but faint upflows, heated and propelled in chromosphere/TR, enough mass to fill corona



Chromosphere-Corona connection visible in faint upflows (3rd and 4th moment of spectral lines)

Using Line Asymmetries to Study Coronal Upflows



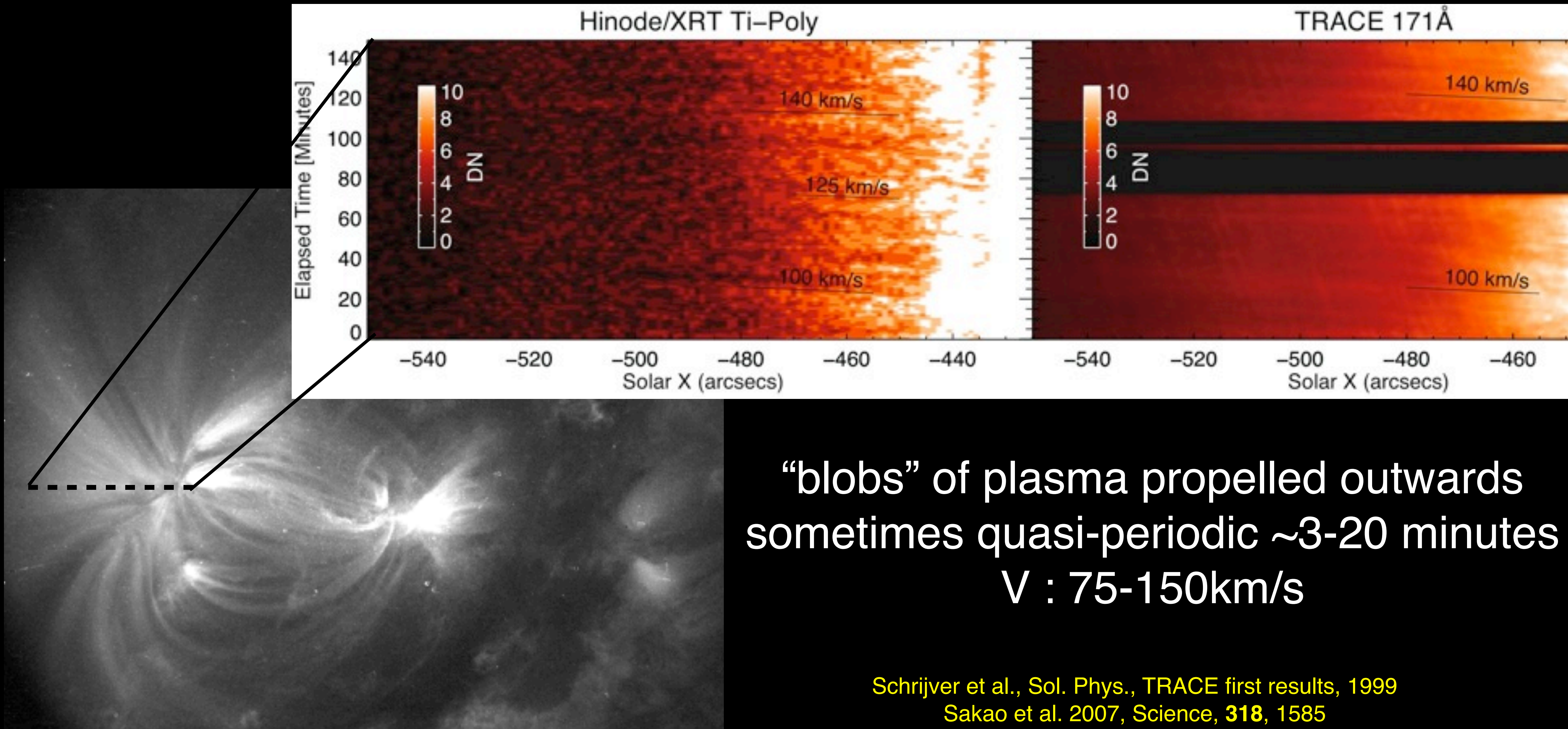
Using Line Asymmetries to Study Coronal Upflows

Ubiquitous, faint (5-10%) upflows of 50-100 km/s seen in many TR and coronal lines above AR/QS/CH network/plage with EIS, SUMER (incompatible w/current coronal nanoflare models)

Requires: High S/N spectroscopy from chromosphere to corona at high spatial resolution (0.2-0.3 arcsec) and cadence (<10 s)

1. Fit single Gaussian to profile

Outflows have been seen with TRACE and XRT, sometimes interpreted as propagating slow-mode waves



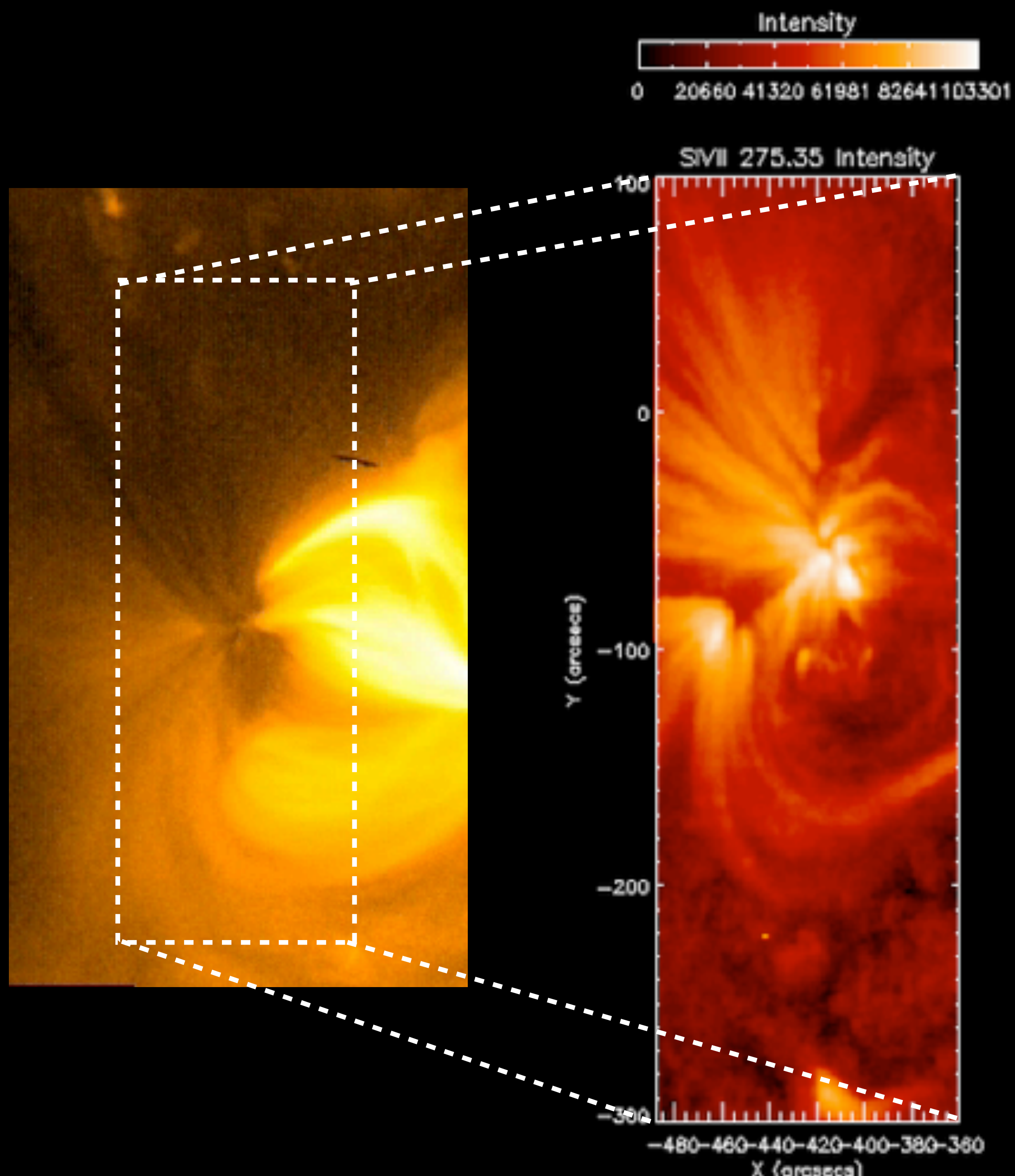
TRACE 171Å / Hinode/XRT

"blobs" of plasma propelled outwards
sometimes quasi-periodic ~3-20 minutes
V : 75-150km/s

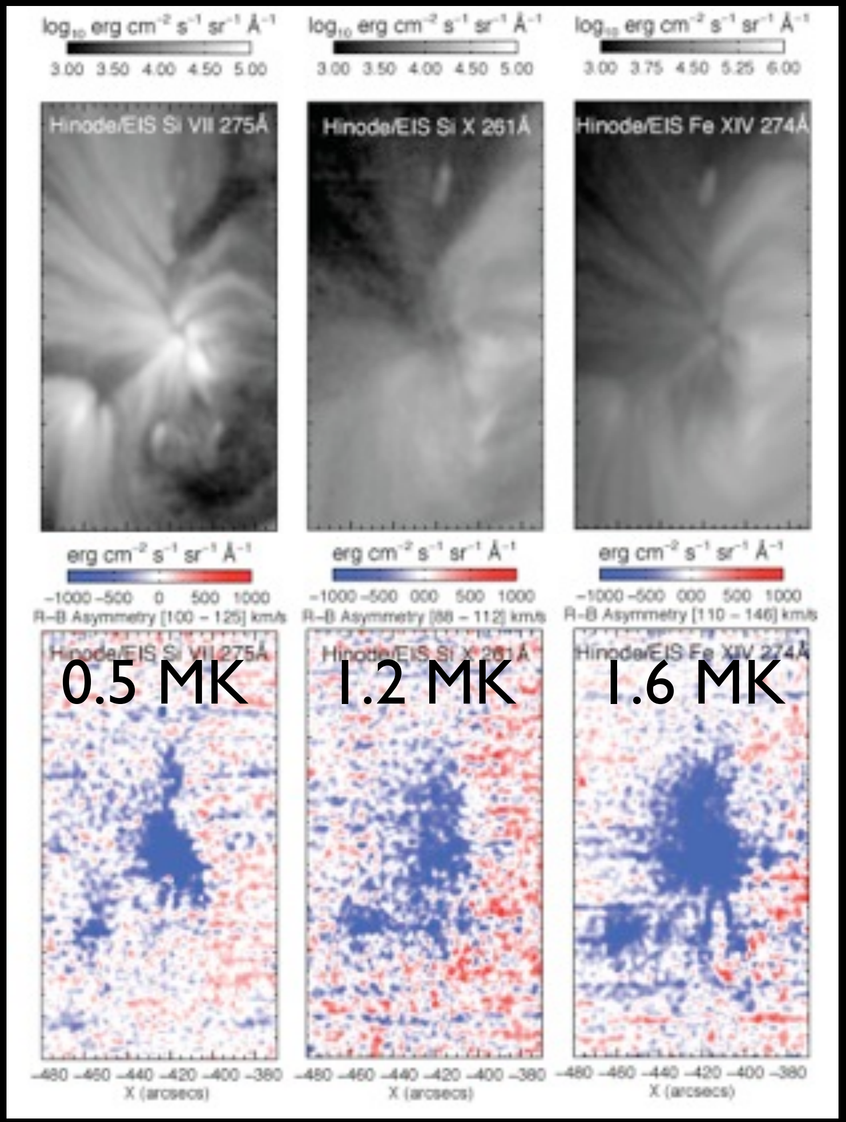
Schrijver et al., Sol. Phys., TRACE first results, 1999
Sakao et al. 2007, Science, **318**, 1585
De Pontieu, McIntosh, Hansteen & Schrijver 2009, ApJL, **701**, 1
McIntosh & De Pontieu 2009, ApJL, **706**, 80

Asymmetries in EIS/SUMER profiles suggest TRACE/XRT/AIA should see short-lived (~100s) upflows of 100 km/s at 1-10% of background loop emission:
Requires high S/N coronal imaging for wide range of T at high spatial resolution

Loops with propagating "blobs" show strong blueward line asymmetries (EIS) at the footpoints for T=0.5 to 2 MK



Compare EIS & XRT

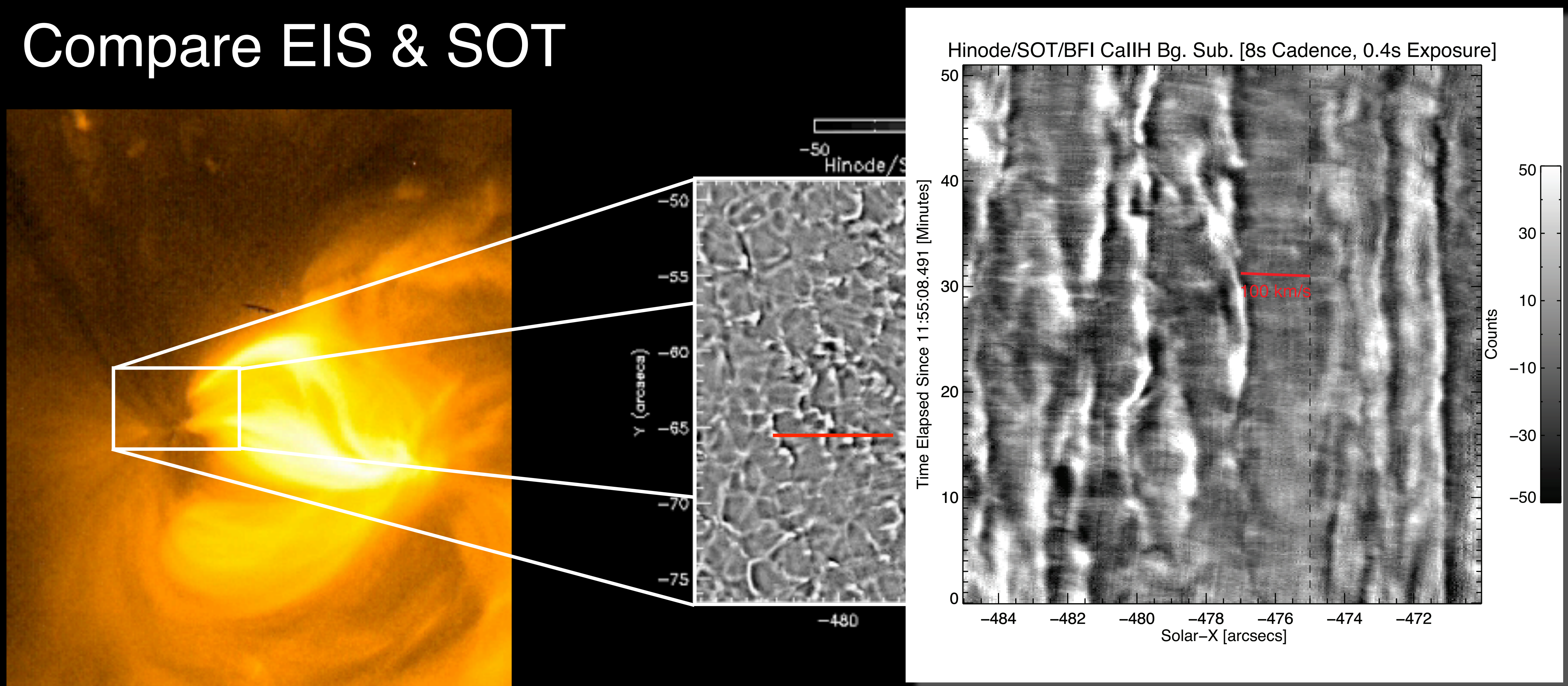


5% Asymmetry - Same velocity!
Visible in Unipolar Magnetic Regions
Across Many Temperatures
Co-spatial/temporal with "blobs"

De Pontieu, McIntosh, Hansteen & Schrijver 2009, ApJL, **701**, 1
McIntosh & De Pontieu 2009, ApJL, **706**, 80

Plage below TR/coronal upflows (100 km/s) shows type II spicules in Ca H at similar speeds

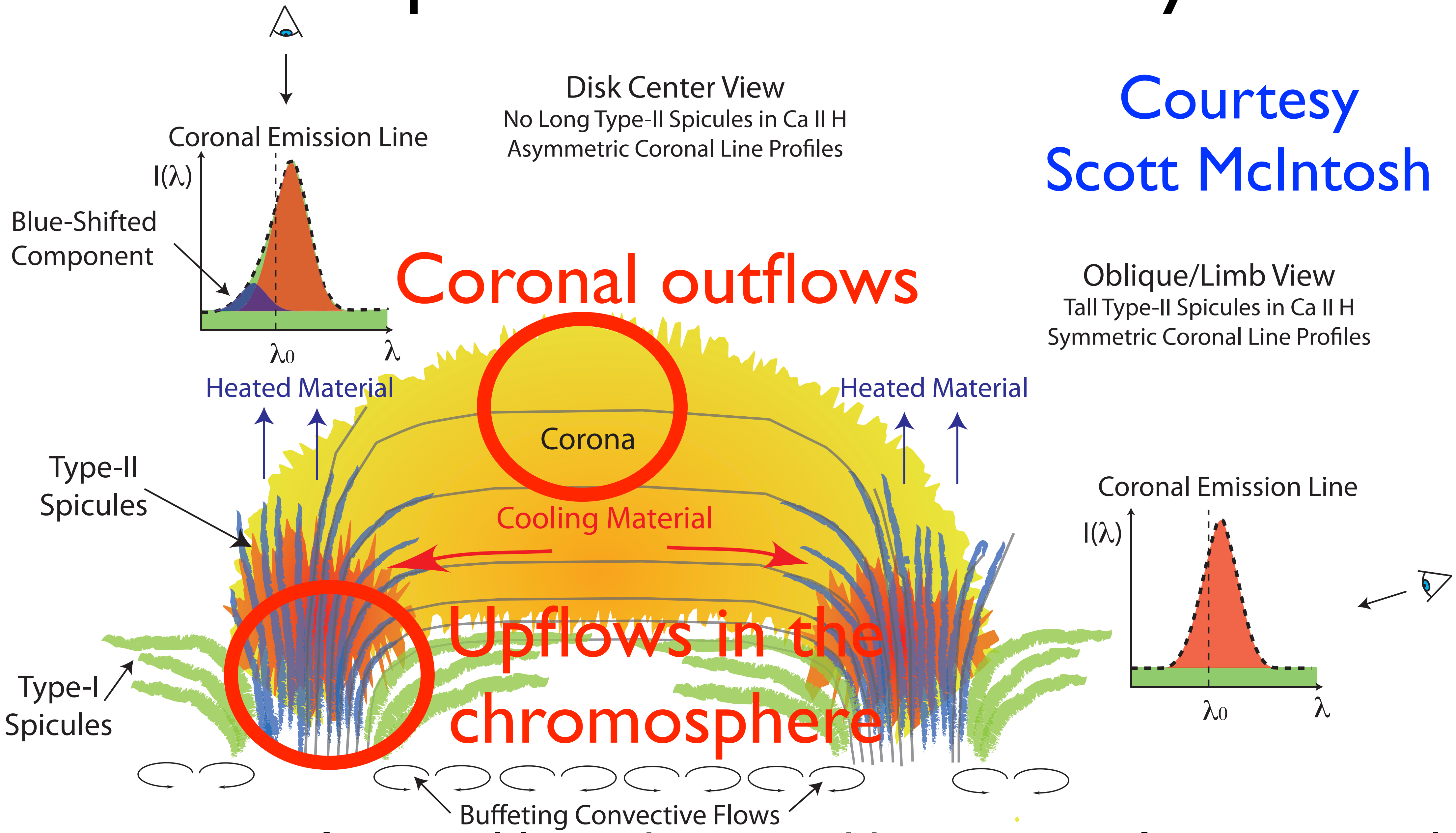
Compare EIS & SOT



5% Asymmetry - Same velocity!
Visible in/from unipolar magnetic regions!
Type-II Spicules!
Co-spatial/temporal with “blobs”

De Pontieu, McIntosh, Hansteen & Schrijver 2009, ApJL, **701**, 1
McIntosh & De Pontieu 2009, ApJL, **706**, 80

Chromosphere/Corona Mass Cycle

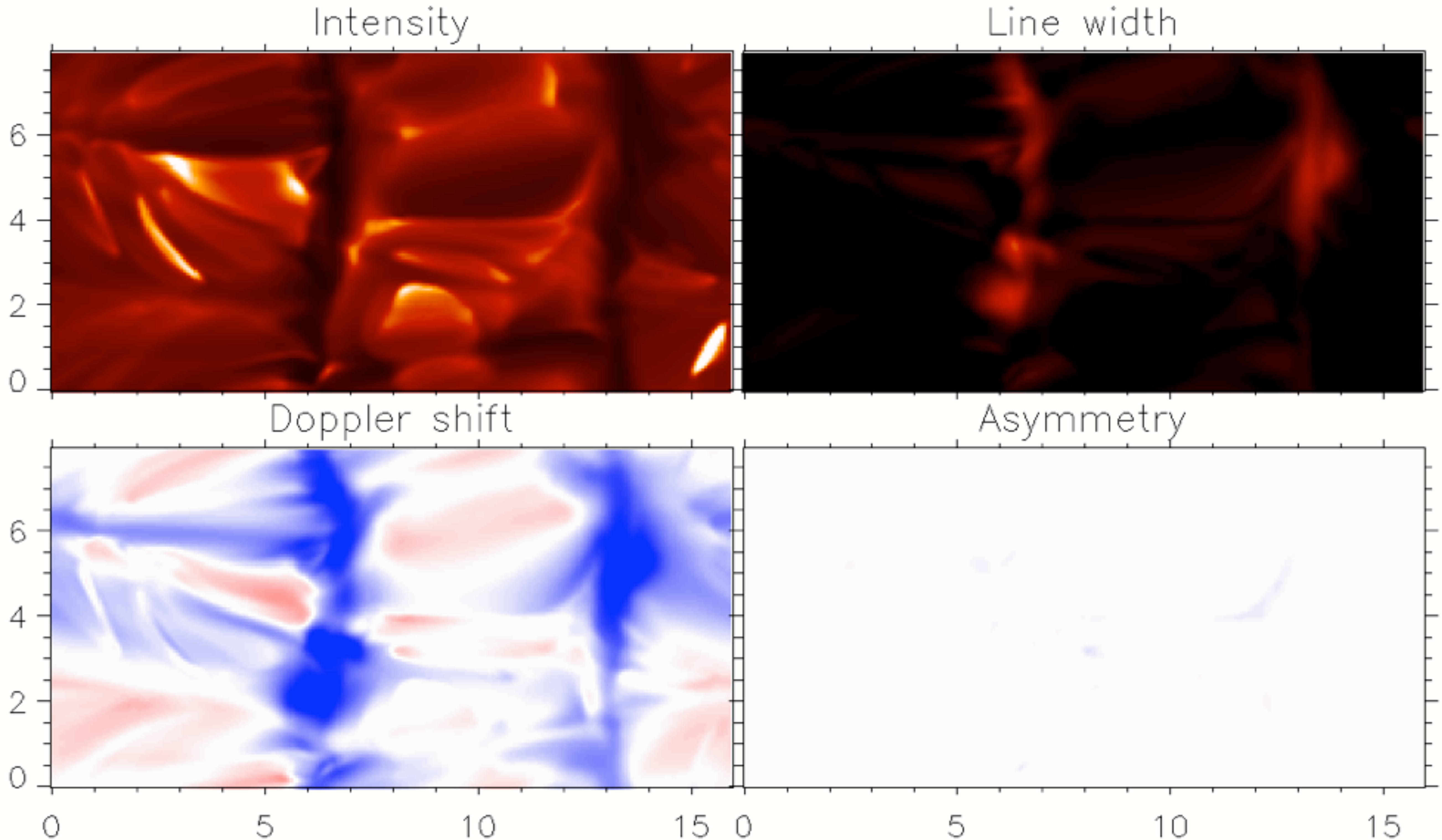


Courtesy Scott McIntosh

1. Emission in core of coronal lines dominated by emission from previously filled loops (slowly cooling/evaporating plasma)
2. Chromosphere-Corona connection visible in faint upflows (3rd and 4th moment of spectral lines)
3. Constrains coronal heating theories: coronal heating occurring at low heights?

Requires: High S/N spectroscopy & imaging from chromosphere to corona at high spatial resolution (~0.2 arcsec) and cadence (<10 s)

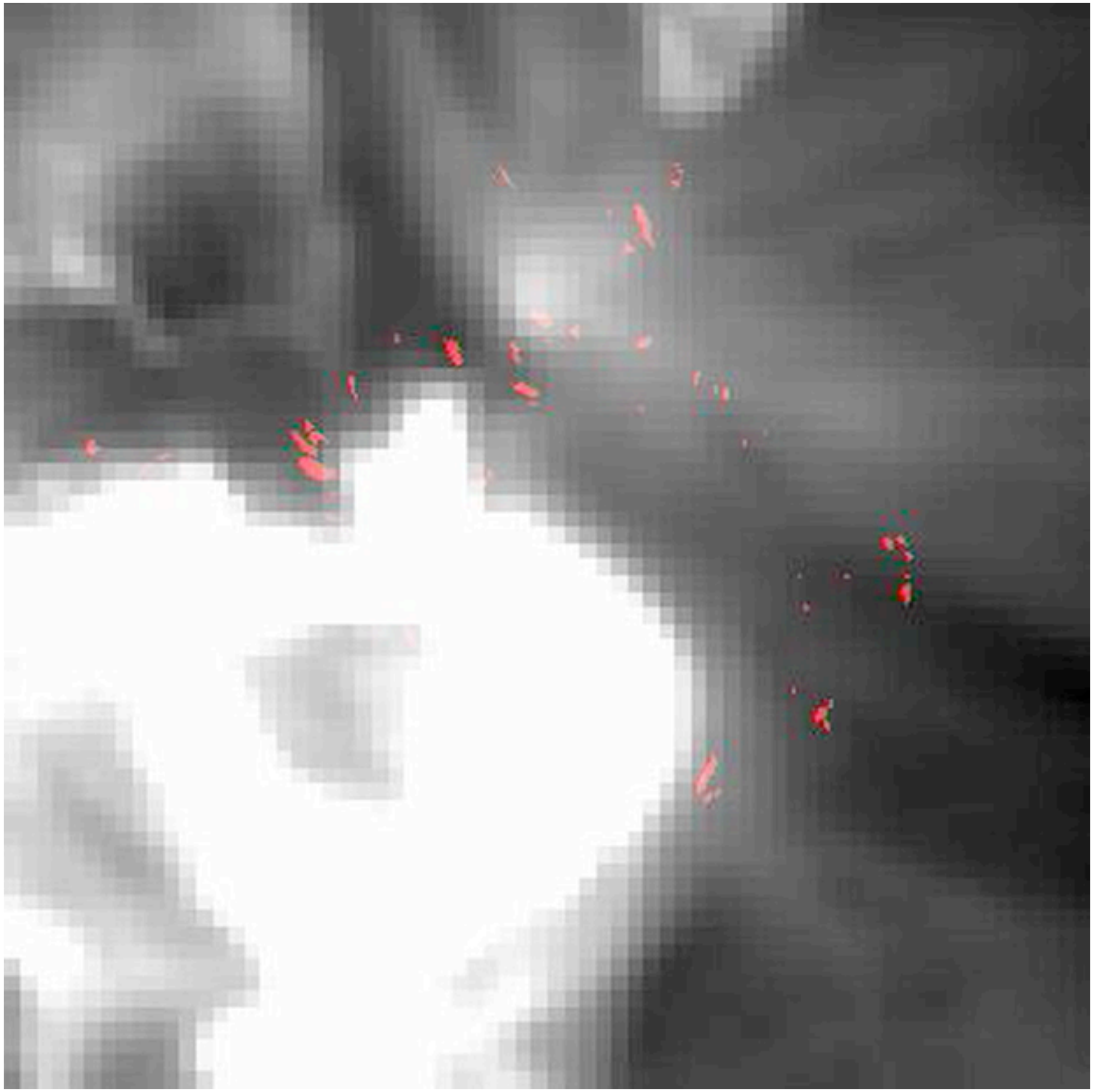
Measuring line profile shapes important



Simulations courtesy Viggo Hansteen

Requires: High S/N spectroscopy & imaging from chromosphere to corona at high spatial resolution (~0.2 arcsec) and cadence (<10 s)

Compatible resolutions for all T crucial

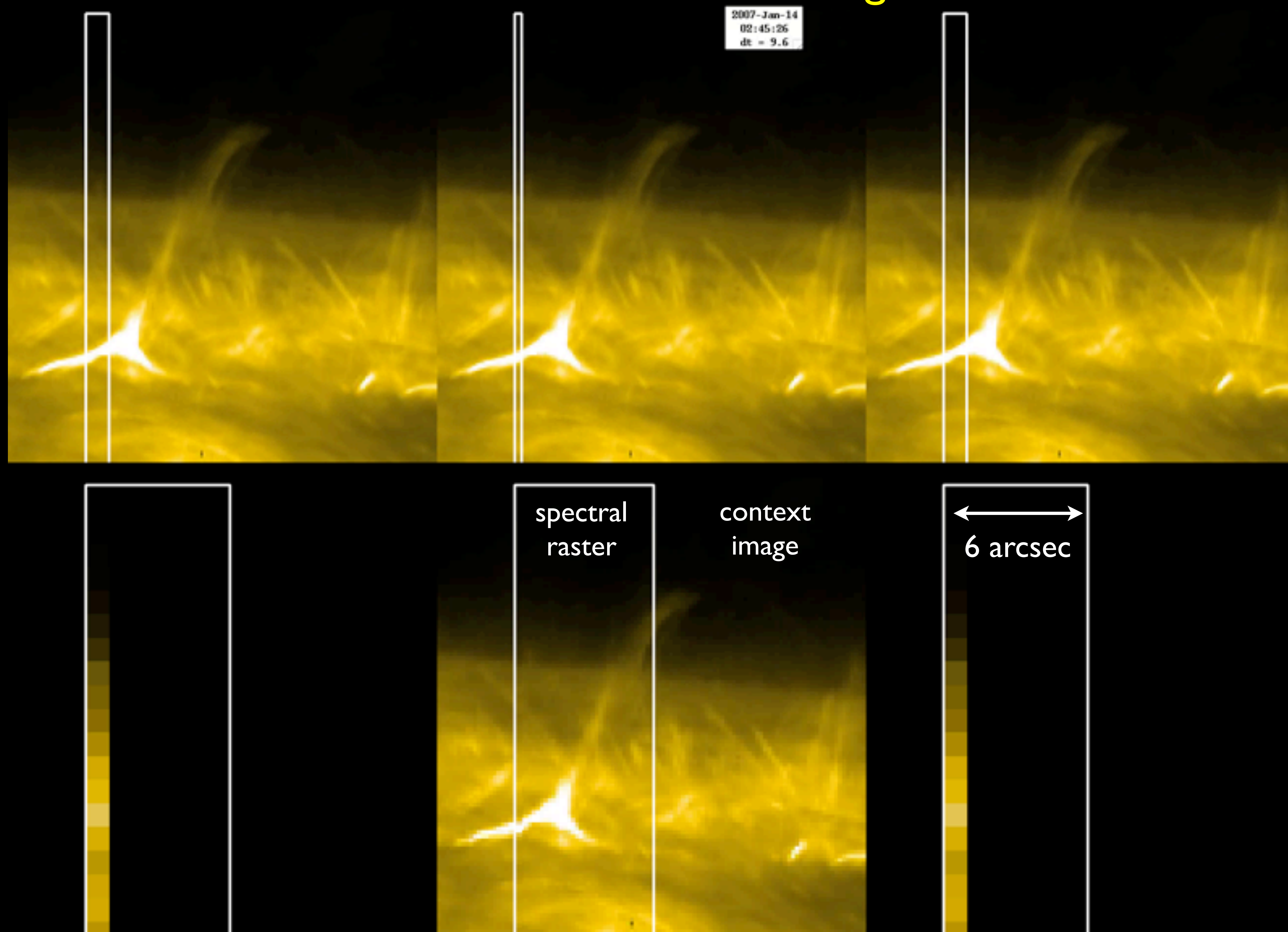


STEREO movie
171 A (1 MK)
80 s cadence
2.5 arcsec
pixels

CRISP overlay
Hα (0.01 MK)
10 s cadence
0.08 arcsec pixels

High throughput crucial for slit-scanning spectrograph to allow rapid rasters that track chromospheric/TR/coronal evolution

Simulated rasters on HINODE background

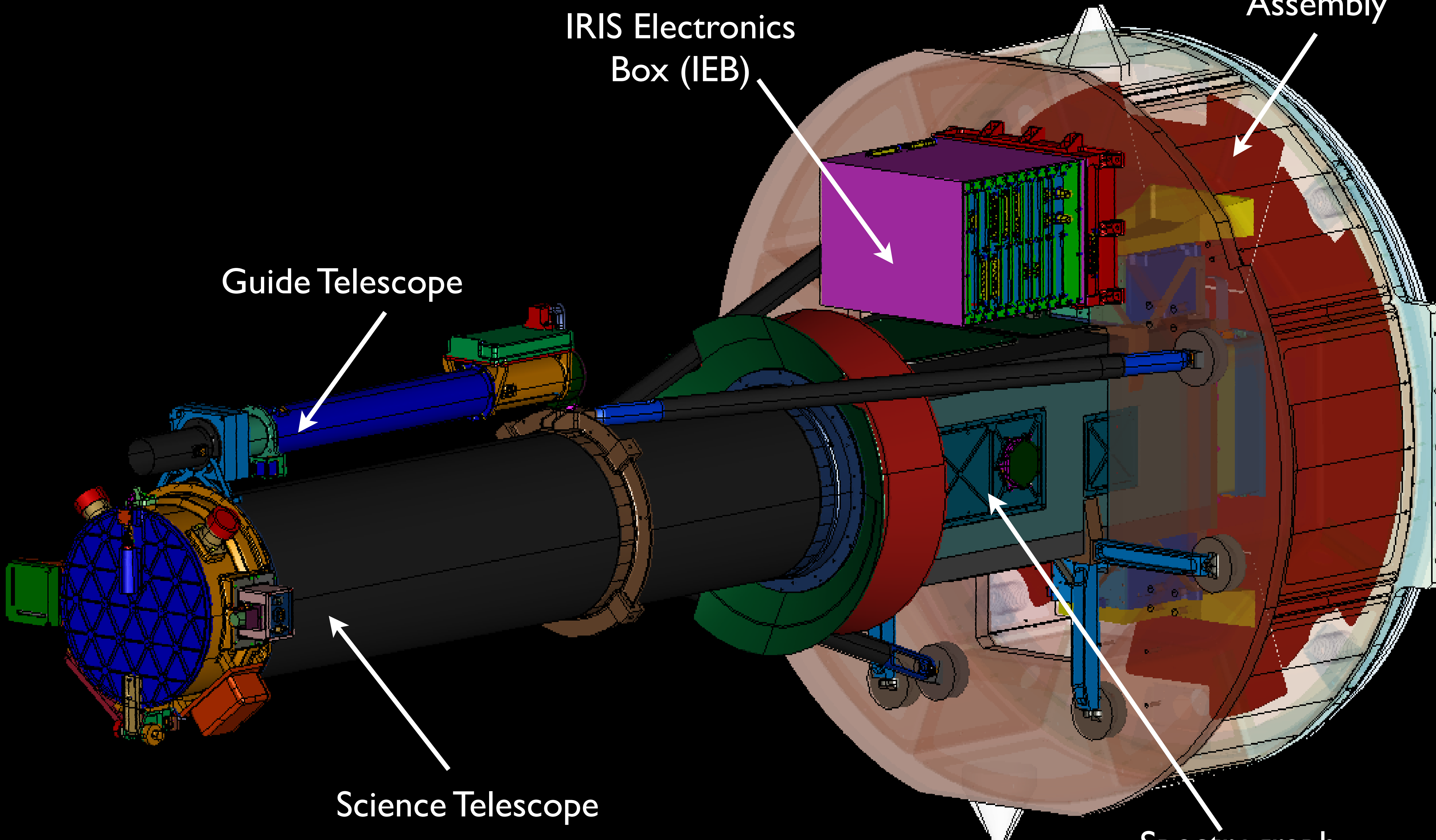


“SUMER” raster

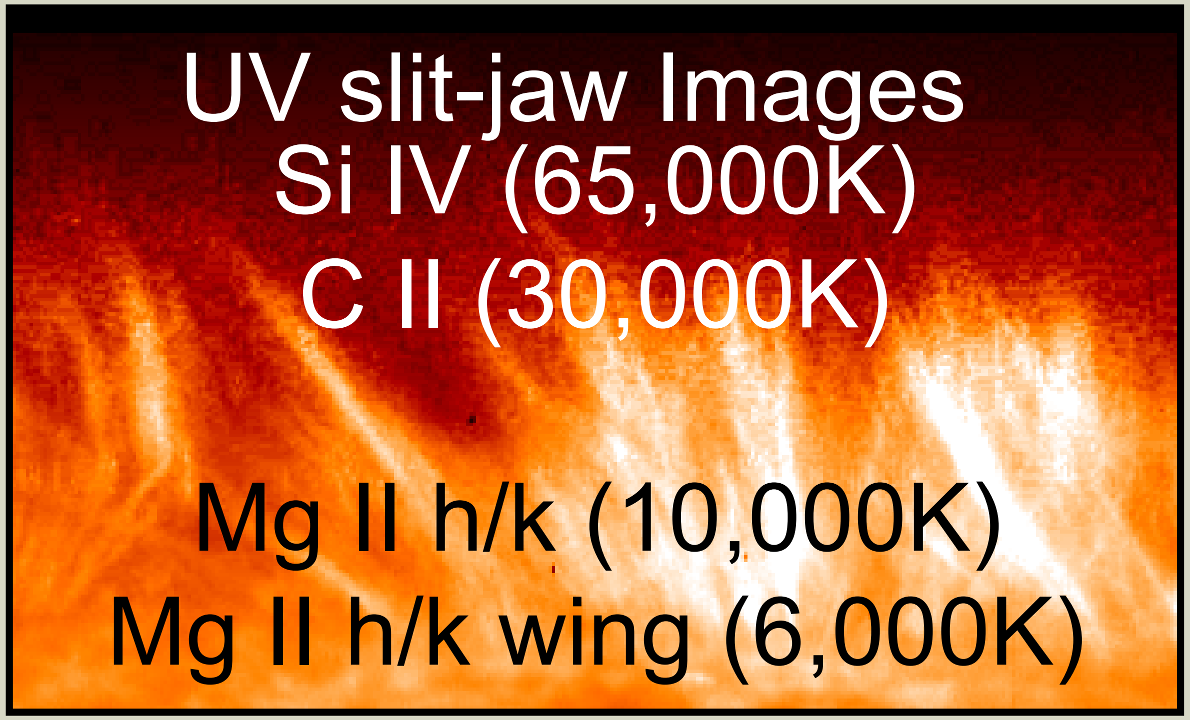
“IRIS” spectral raster & context slit-jaw images

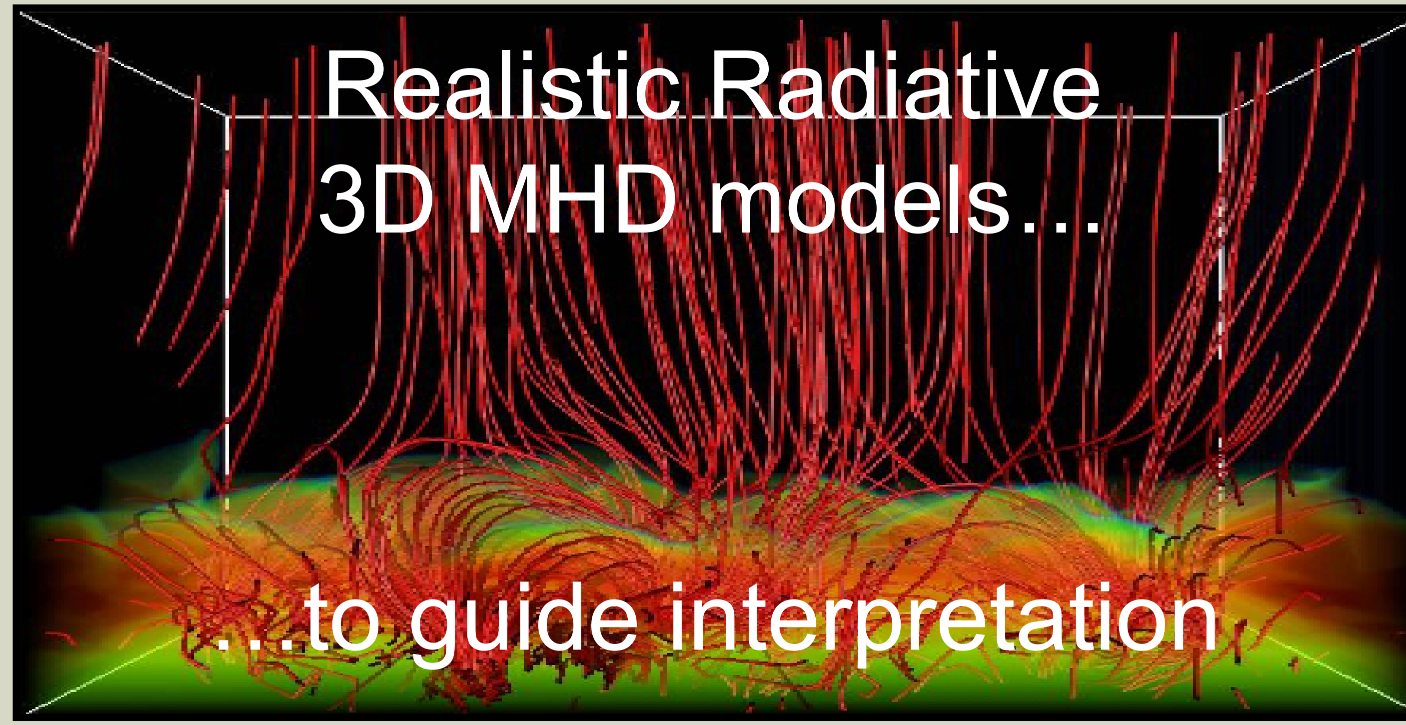
“EIS” raster

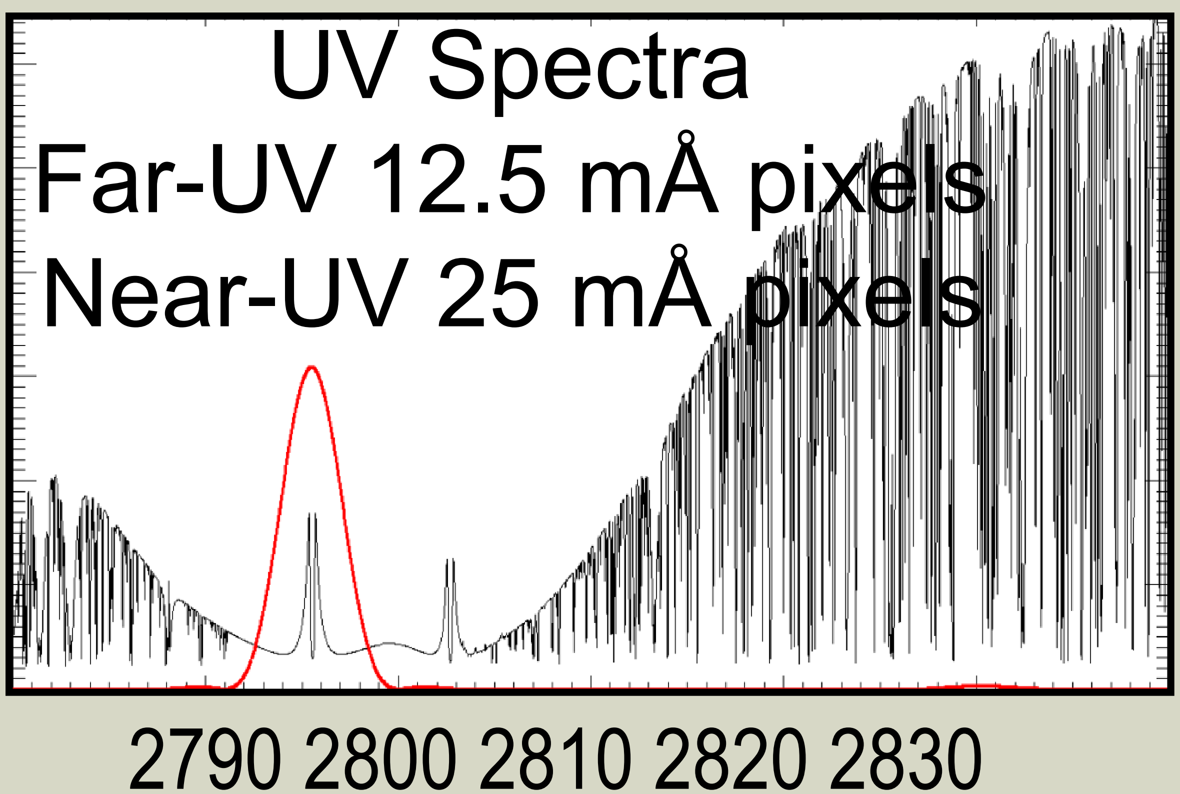
Solar C plan B will have great synergies with Interface Region Imaging Spectrograph (IRIS) Small Explorer



IRIS in brief





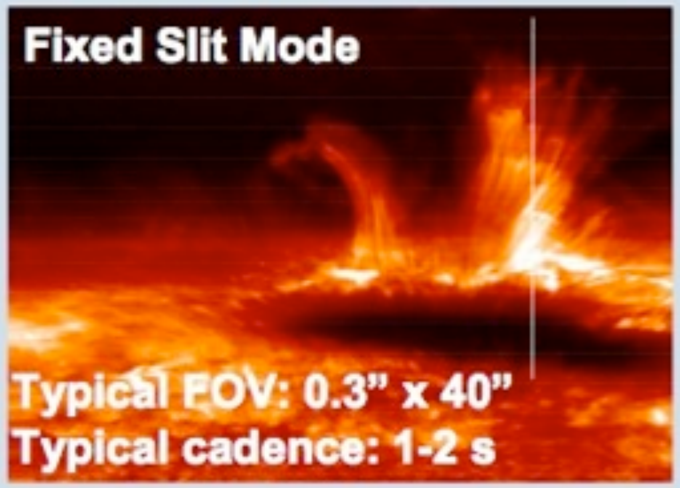


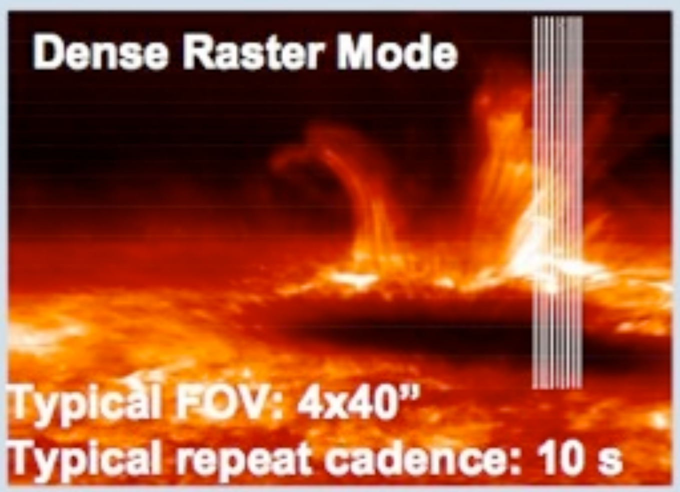
20 cm UV telescope:
1/6 arcsec pixels

multi-channel spectrograph
far-UV: 1332-1358 Å, 1390-1406 Å,
40 mÅ resolution, effective area 2.8 cm^2
near-UV:2785 - 2834 Å,
80 mÅ resolution, effective area 0.3 cm^2

slit-jaw imaging
1335 Å & 1400 Å with 40 Å bandpass each;
2796 Å & 2831 Å with 4 Å bandpass each.

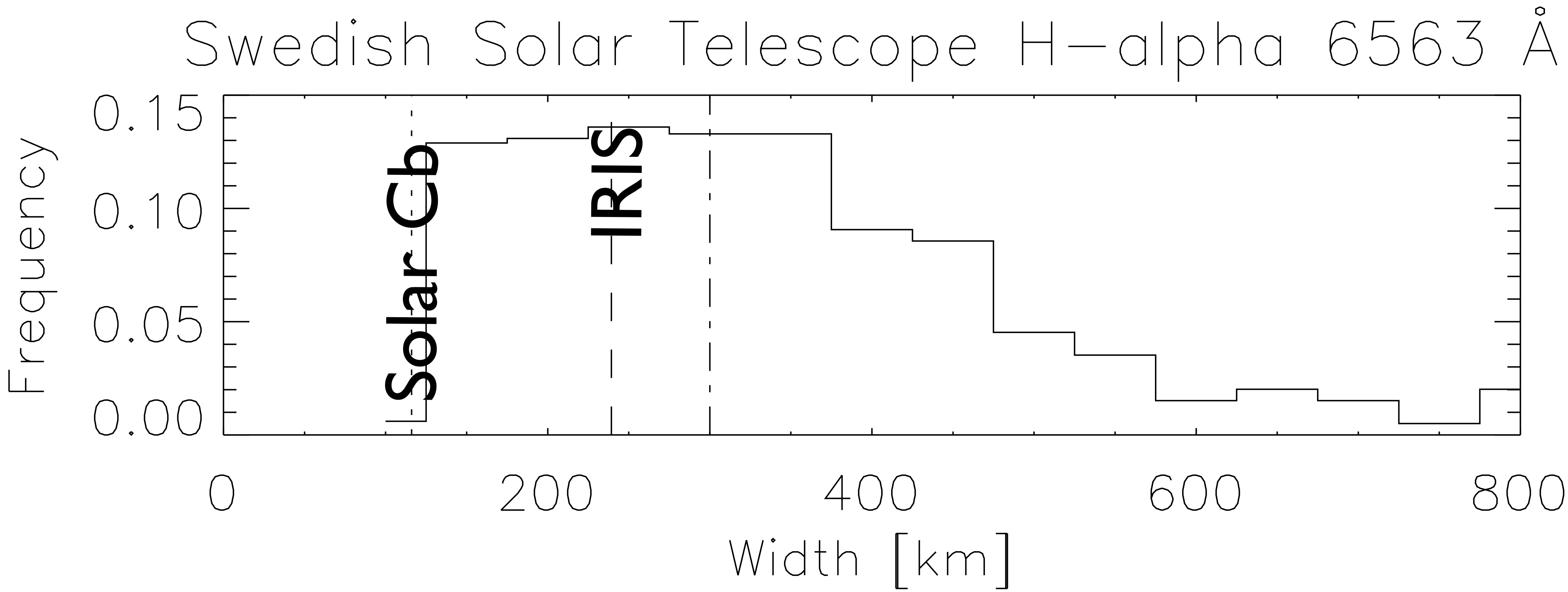
IRIS spectra and slit-jaw imaging covers the photosphere, chromosphere, transition region





Ion Spectrum	λ	Δλ	Log T	Estimated Count Rate (counts/s/line/spatial pixel)			Detector
	Å	mÅ	K	Quiet Sun	Active Region	Flare	
UV Spectra (effective area of 2.8 cm^2 for far-UV, 0.3 cm^2 for Mg passband, continuum is 1 Å) †: Count rates for Mg II wing, h and k are in counts/s/spectral pixel/spatial pixel							
Si I (3P) Cont	1335	12.5	3.7	40	80	---	1
Mg II wing	2820	25	3.7-3.9	2100†	7500†	7500†	3
O I	1356	12.5	3.8	50	100	250	1
Mg II h	2803	25	4.0	870†	3400†	13000†	3
Mg II k	2796	25	4.0	1100†	4500†	10000†	3
C II	1335	12.5	4.3	540	1970	22000	1
C II	1336	12.5	4.3	500	1780	20000	1
Si IV	1403	12.5	4.8	400	1000	1e6	2
Si IV	1394	12.5	4.8	640	2200	3e6	2
O IV	1401	12.5	5.2	65	116	2e5	2
O IV	1400	12.5	5.2	25	60	1e5	2
Fe XII	1349	12.5	6.2	30	50	500	1
Fe XXI	1354	12.5	7.0	10	40	4e4	1
UV Slit-Jaw Images				**Estimated Count Rate (counts/s/pixel)**			
Effective area 0.005 cm^2 with 5 Å FWHM filter for Mg II; 0.7 cm^2 with 40 Å FWHM for far-UV.							
Mg II wing	2816		3.7-3.9	1500	3500	3500	4
Mg II k	2796		4.0	750	3500	8500	4
C II	1335		4.3	400	1300	13000	4
Si IV	1400		4.8	300	1200	2e5	4

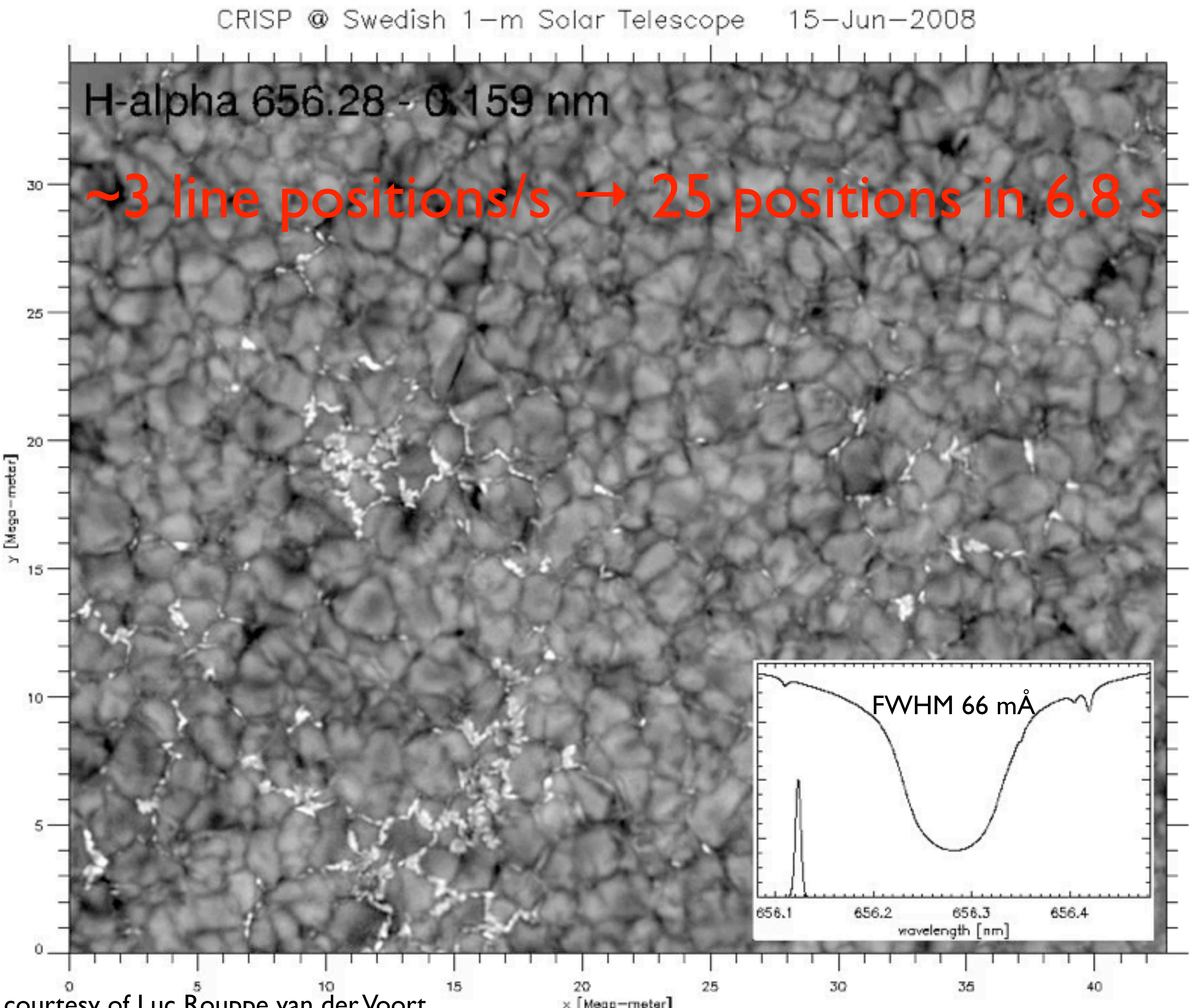
Solar C plan B will be able to resolve structures from chromosphere to corona



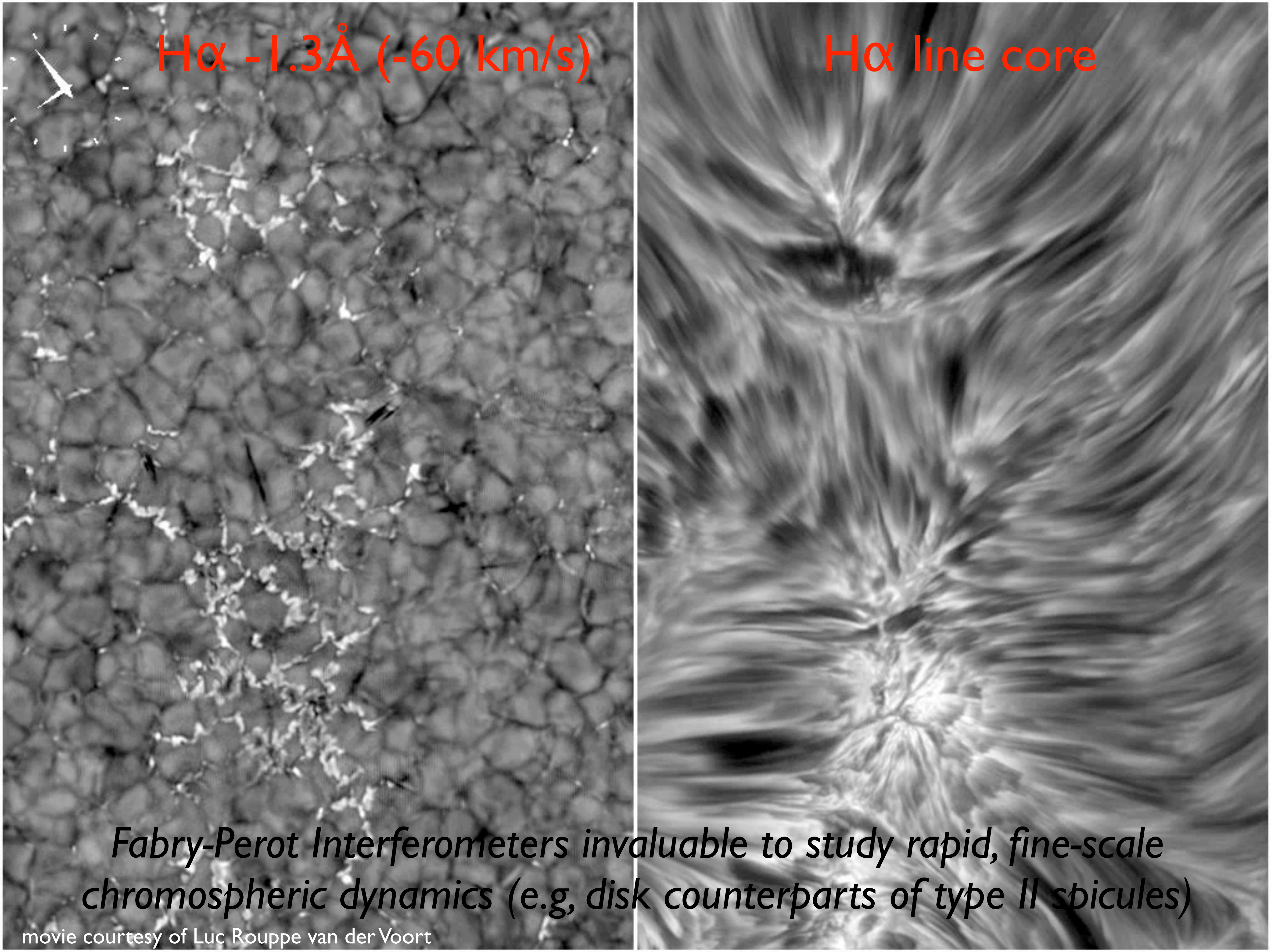
Compared to IRIS, Solar C plan B will

1. provide better spatial resolution for a wide range of temperatures,
2. provide critical magnetic field measurements (photosphere, chromosphere),
3. will have much larger FOV (using FPI) compared to IRIS' slit-based spectrograph: flares, large-scale evolution,...
4. provide the high temperature coverage that IRIS lacks (much higher S/N spectra and imaging).

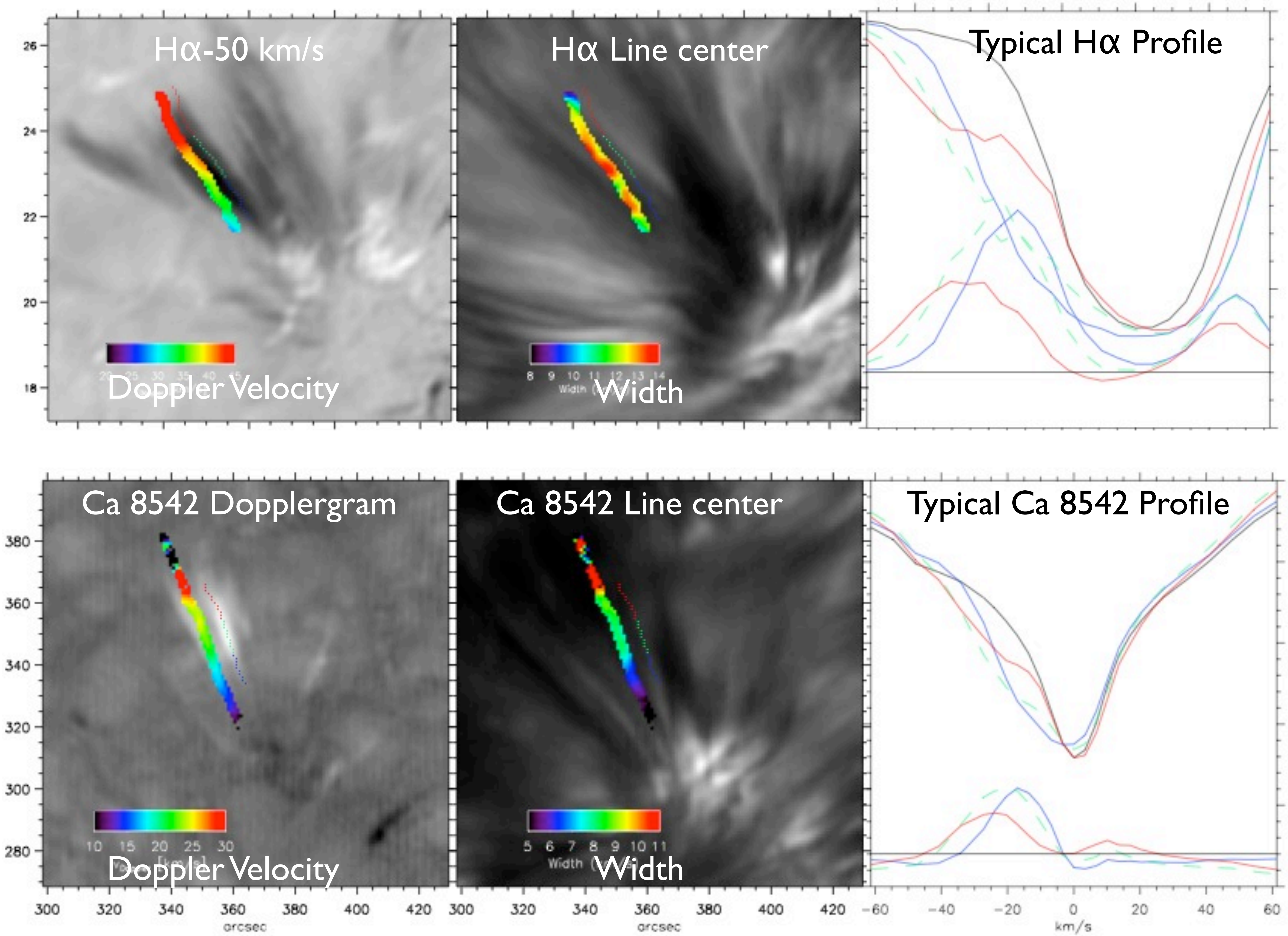
Fabry-Perot Interferometers (FPI) required to track rapid chromospheric dynamics



movie courtesy of Luc Rouppe van der Voort

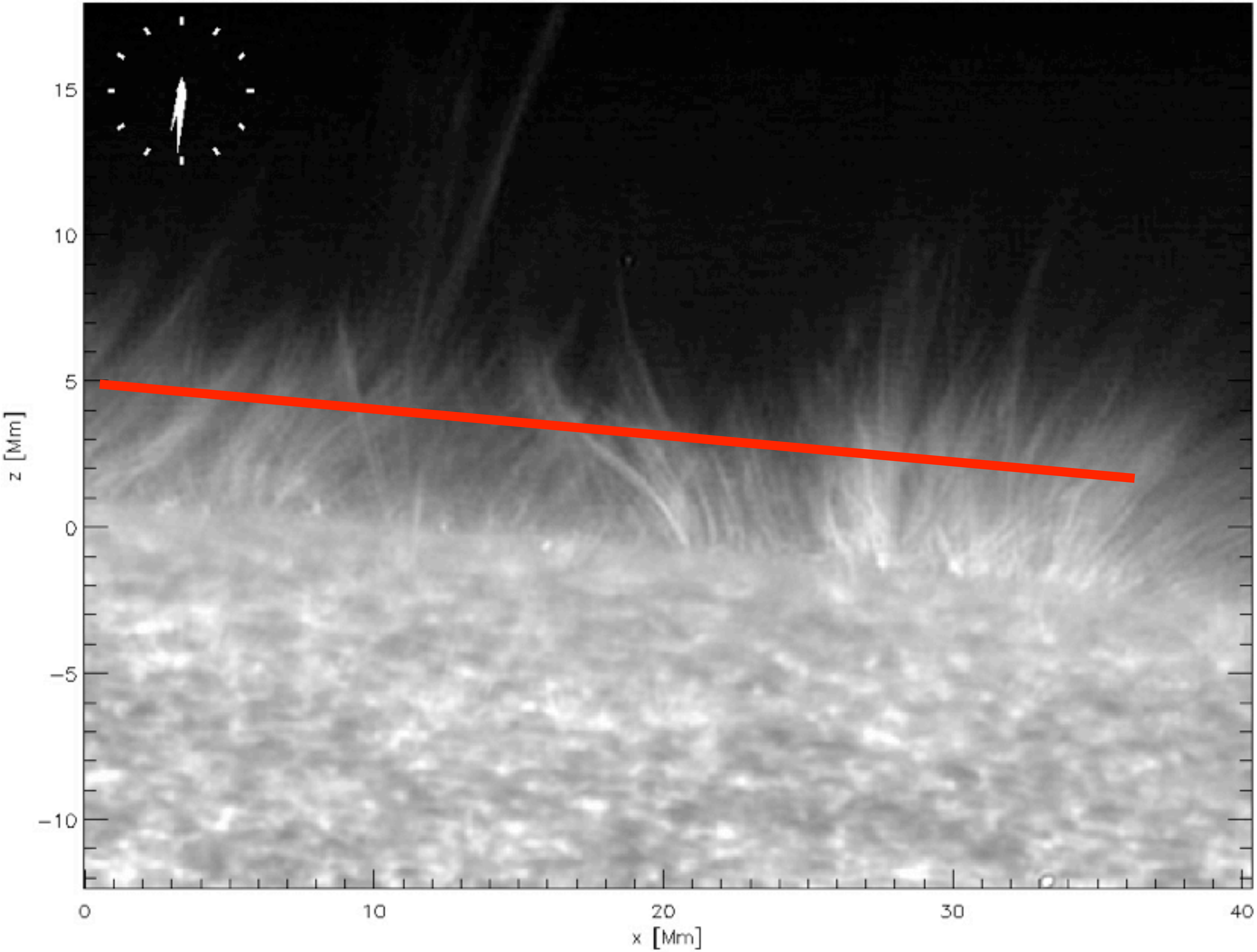

Hα -1.3Å (-60 km/s)
Hα line core
Fabry-Perot Interferometers invaluable to study rapid, fine-scale chromospheric dynamics (e.g, disk counterparts of type II spicules)
movie courtesy of Luc Rouppe van der Voort

FPI observations reveal rapid blueshifted events, constraining formation mechanism of type II spicules by showing heating and acceleration



Rouppe van der Voort, Leenaarts, De Pontieu, Carlsson, Vissers, 2009

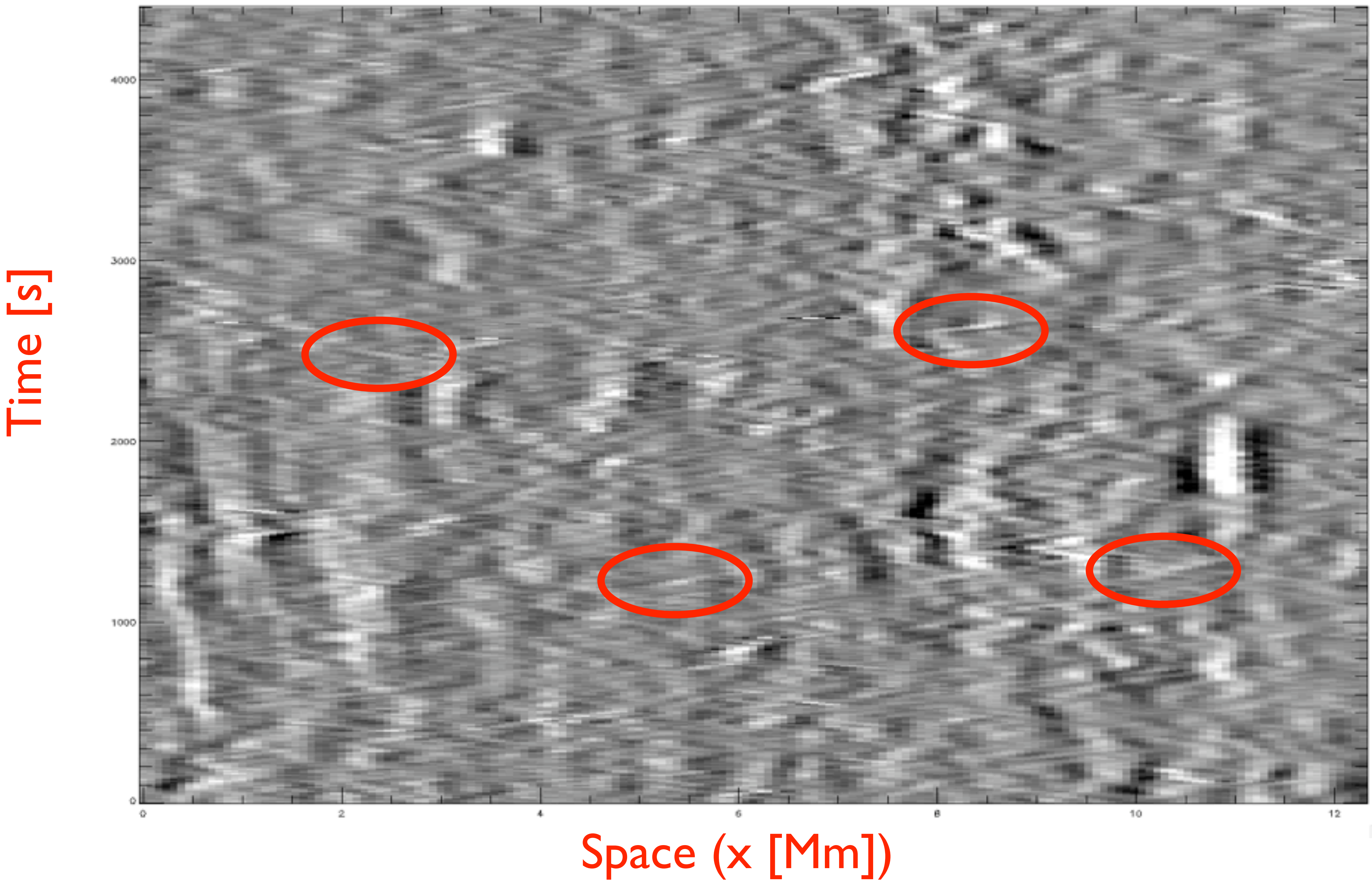
Seeing-free observations critical for chromospheric studies



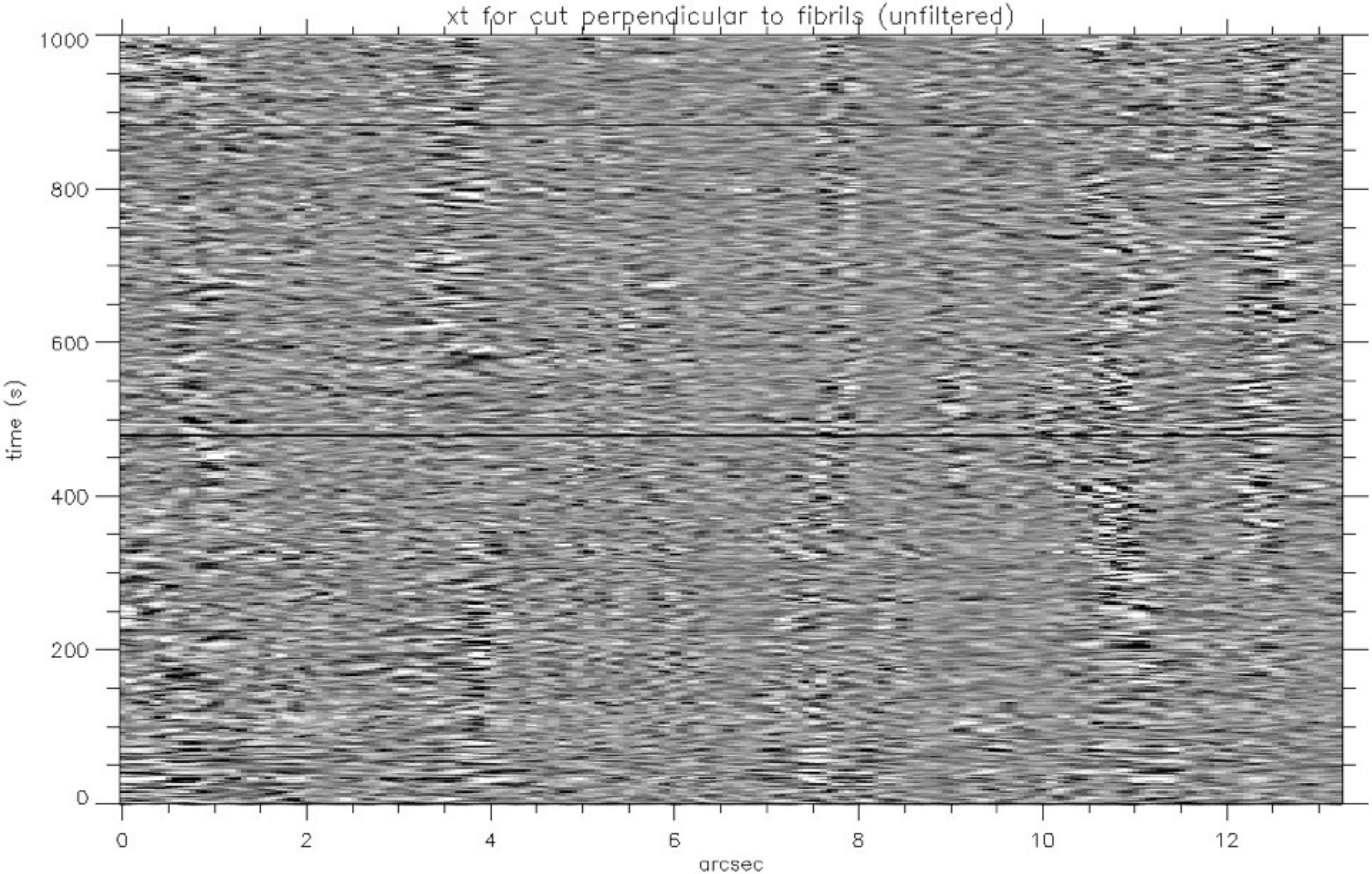
Case study: Alfven waves carried by spicules
(with enough flux to power solar wind)

***Very general*:** many inclined lines in xt-cuts of unsharp masked data

Typically: thin spicules moving laterally by 0.5 Mm, at ~10-25 km/s



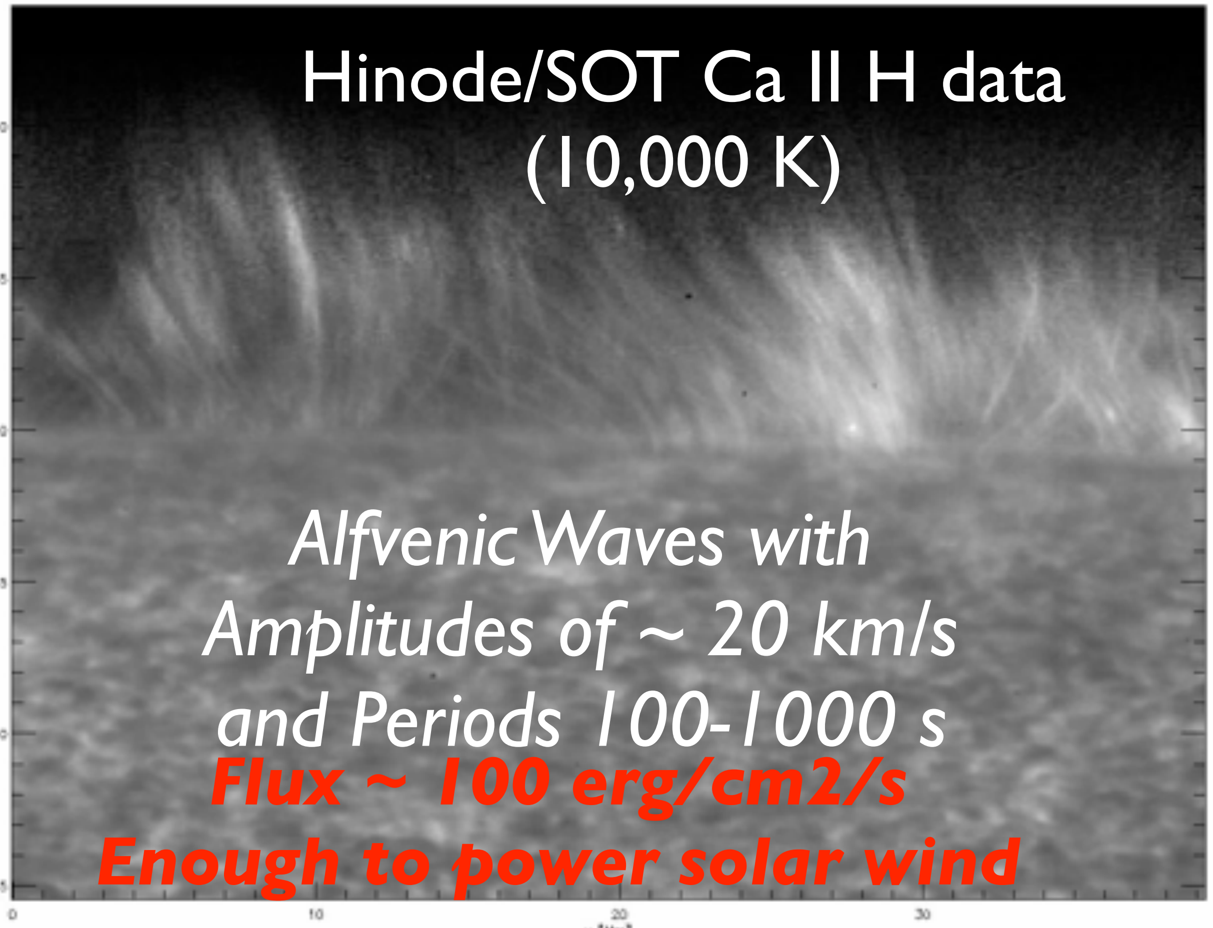
These transverse motions had been detected before in ground-based data



Transverse motions of order 0.1-0.5 arcsec ~ same scale as seeing distortions

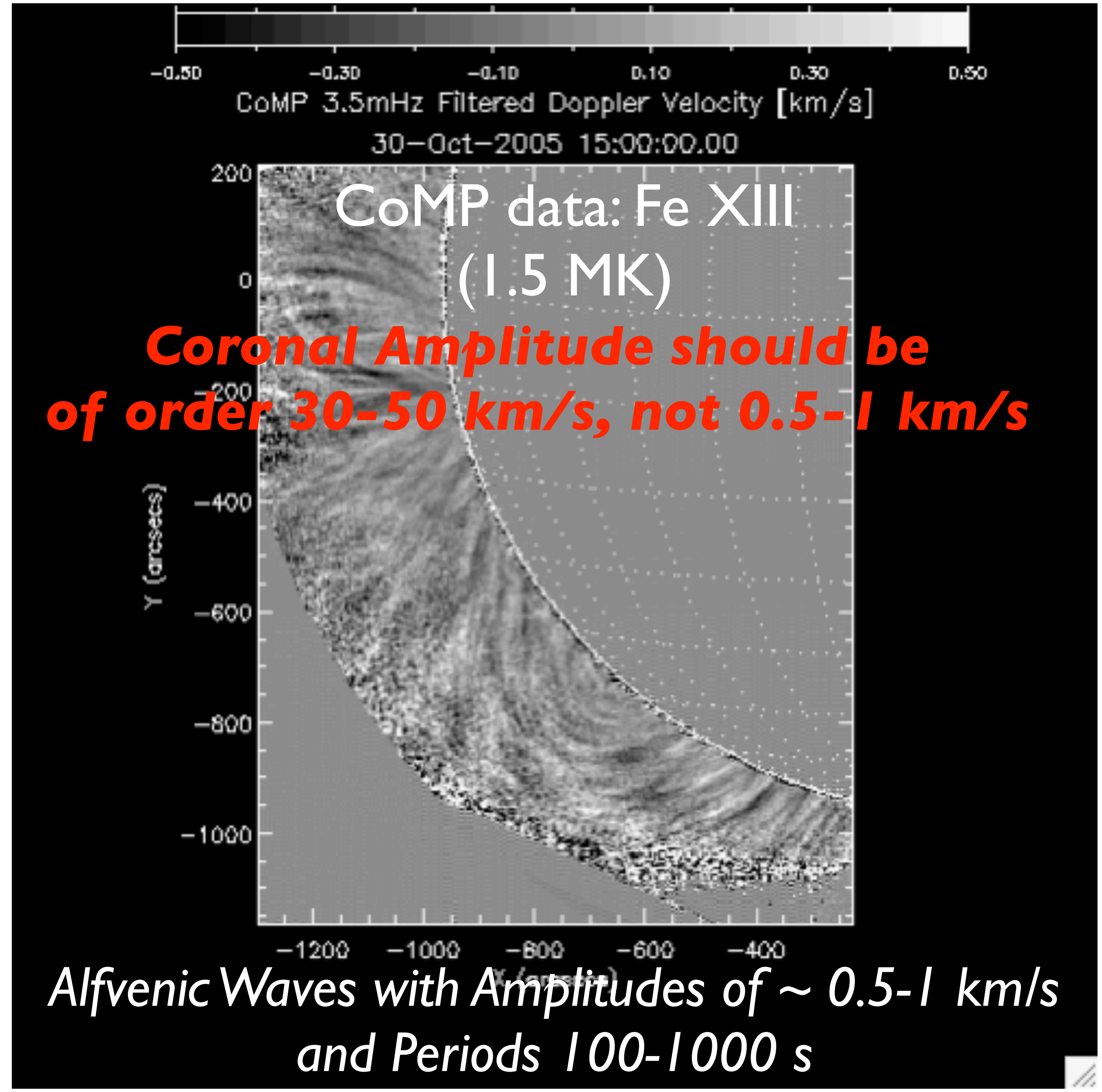
Seeing-free observations crucial

Non-thermal energy deposition: Alfven waves



De Pontieu et al., 2007

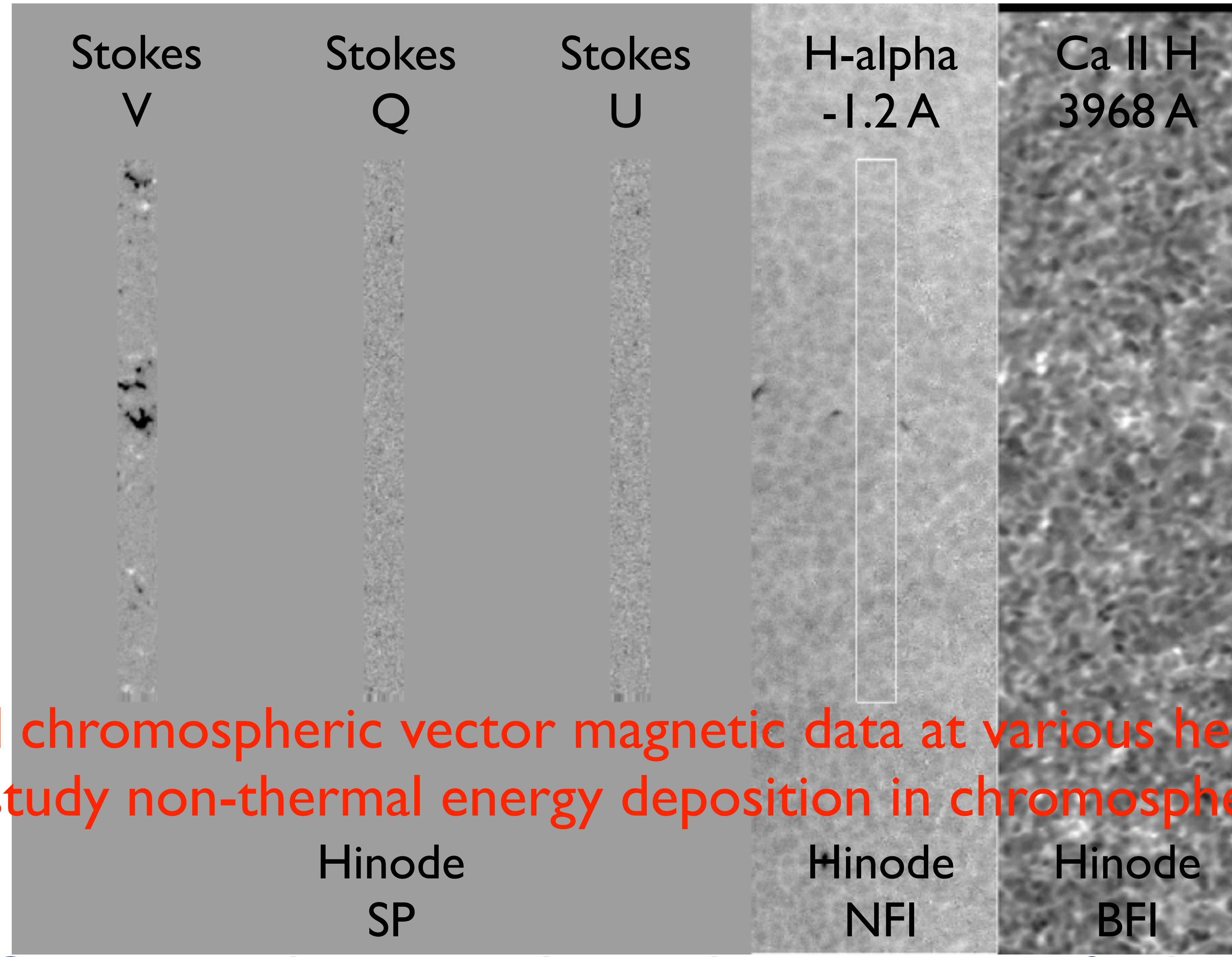
Solar C chromospheric data will help reveal origin of these waves



Tomczyk et al., 2007, Tomczyk & McIntosh, 2009, McIntosh et al., 2010

High-resolution CoMP-like observations of transverse incompressible waves in the corona can provide seismology, but also insight in non-thermal energy deposition

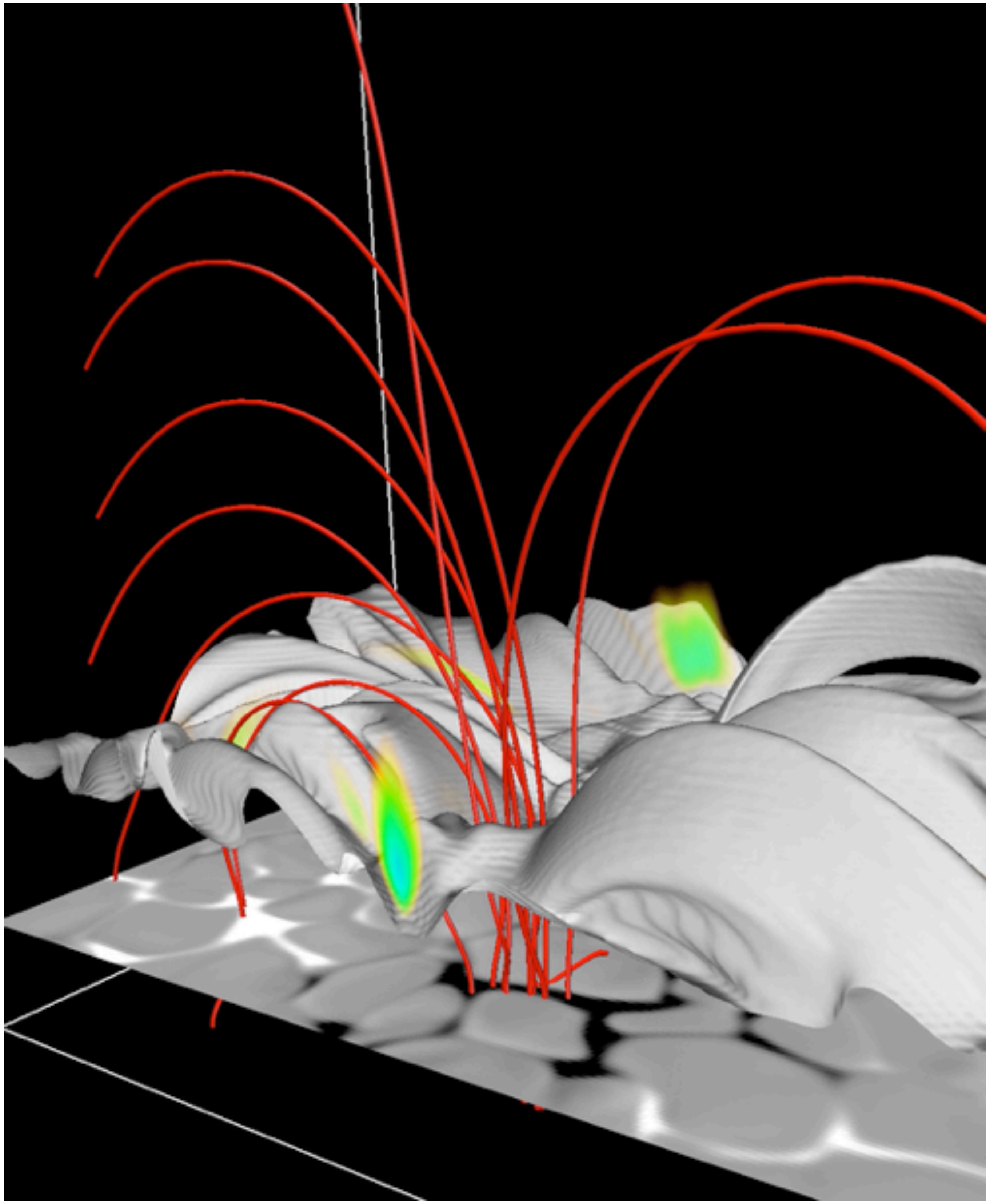
How do magnetic fields impact chromosphere dynamics?
Formation of type II spicules



Need chromospheric vector magnetic data at various heights to study non-thermal energy deposition in chromosphere

Connection between photospheric magnetic fields and chromospheric energy deposition difficult to establish

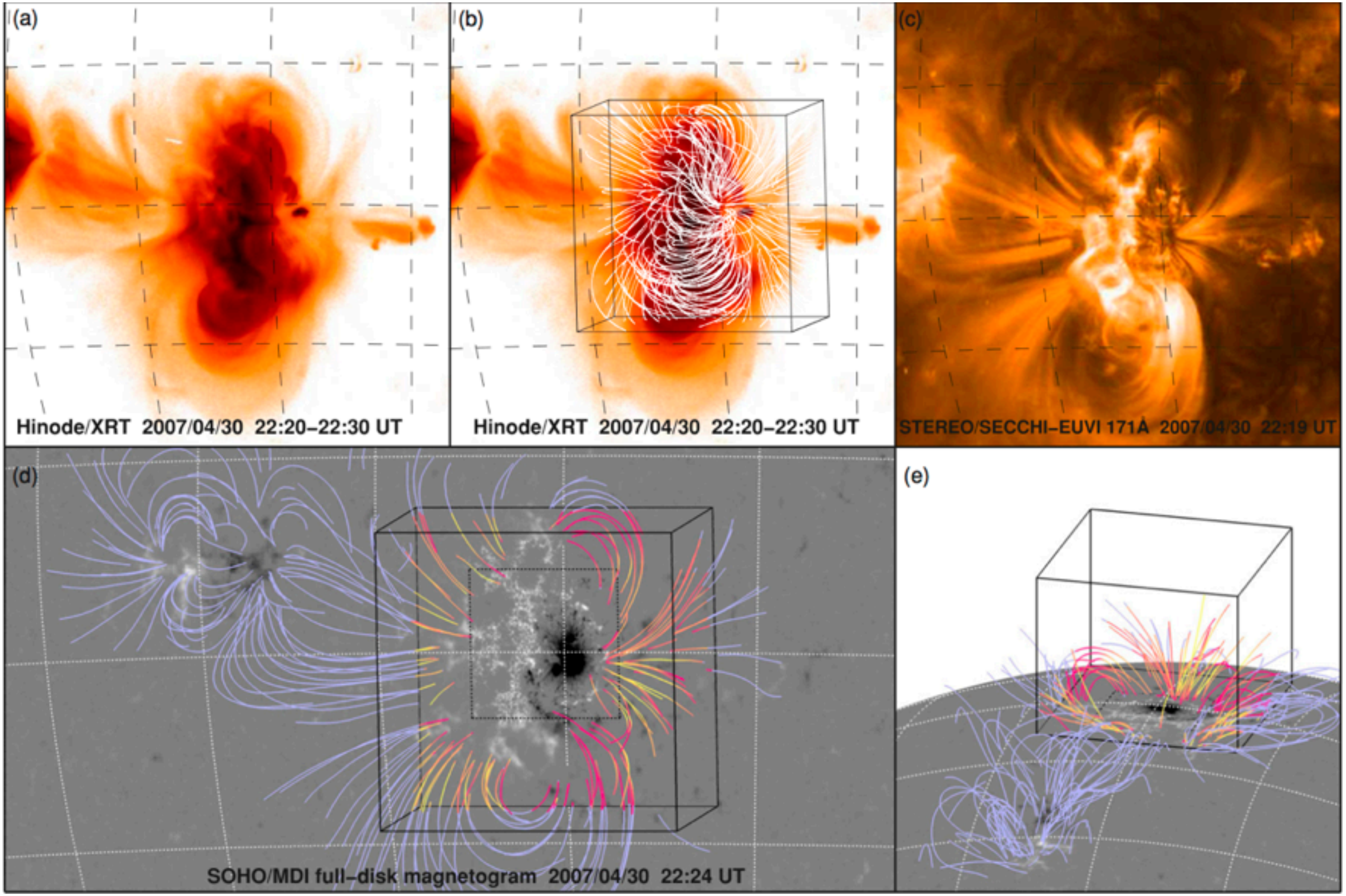
Importance of chromospheric field measurements



green: Joule heating
grey: TR
courtesy Juan Martinez Sykora
(LMSAL, UiO)

3D radiation MHD simulations indicate
jet formation triggered at chromospheric heights

Magnetic Field
non-linear force free field extrapolations



Extrapolation from photospheric field magnetograms problematic

Images from DeRosa et al., 2009

Magnetic Field
non-linear force free field extrapolations

Table 1
NLFFF Model Extrapolation Metrics[a] for AR 10953

Model[b]	E/E_{pot}[c]	$\langle CW \sin\theta \rangle$[d]	$\langle \lvert f_i \rvert \rangle$[e]$(\times 10^8)$	$\langle \phi \rangle$[f]
Pot	1.00	···	0.02	24°
Wh+	1.03	0.24	7.4	24°
Tha	1.04	0.52	34.0	25°
Wh−	1.18	0.16	1.9	27°
Val	1.04	0.26	71.0	28°
Am1−	1.25	0.09	0.72	28°
Am2−	1.22	0.12	1.7	28°
Can−	1.24	0.09	1.6	28°
Wie	1.08	0.46	20.0	32°
McT	1.15	0.37	15.0	38°
Rég−	1.04[g]	0.37	6.2	42°
Rég+	0.87[g]	0.42	6.4	44°

Extrapolation from photospheric field magnetograms problematic

courtesy DeRosa et al., 2009

Non-linear force free field (NLFFF) extrapolations

- ***NLFF algorithms do not yield consistent solutions for solar data***

- Photosphere is not force-free, i.e., many (most?) currents seen at the photosphere do not reach the corona

- Successful application likely requires :
  - large field of view at high resolution (connectivity to surroundings)
  - 'preprocessing' of lower-boundary vector field (non-force free to force-free)
  - *measurement of vector field at top of chromosphere?*

- *[Schrijver et al. 2006 (SPh 235, 161), 2008 (ApJ 675, 1637), Metcalf et al. 2008 (SPh 247, 269), DeRosa et al. (2008, ApJ 696, 1780).*

To determine energy and mass transfer from chromosphere into corona/heliosphere

1. A large observatory that obtains spectra and images that simultaneously cover the photosphere, chromosphere, TR and corona (from 4,000K to 10 MK),

2. simultaneously at high spatial resolution (~0.2 arcsec),

3. temporal resolution (<10 s) over a large FOV (120 arcsec),

4. and spectral resolution (<0.3 km/s in TR/corona)

5. without issues of co-alignment (i.e., different instruments with predefined co-alignment strategies, slit-jaw),

6. with high S/N polarimetry in photosphere and chromosphere (FPI, seeing-free).