Coronal Loops Workshop VII 21-23 July 2015

Fine-scale structuring, braiding and heating of loops from thermal and wave instabilities

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[7]: Northumbria U.

& ISSI Team on coronal rain*

National Astronomical Observatory of Japan

* http://www.issibern.ch/teams/coronalrainobserve/

Outline

1. Role of fine structure in the solar atmosphere
2. Thermal instability in the solar corona: a tracer and a mechanism for fine structure
    - Coronal rain & prominences
3. Alfvénic waves & instabilities: strands, current sheets, reconnection, turbulence & heating (nanoflares)
    - corona, prominences, spicules

Fine-scale structure in the solar corona

- How do small-scale processes translate into very large scales, and vice-versa?

  → organisation of the magnetic field in the solar corona

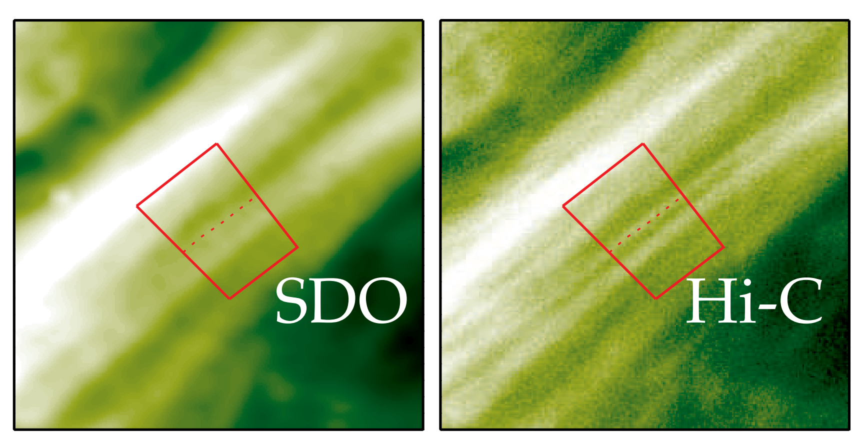
Some observational facts:

- **Long lifetimes** of coronal loops (Reale & Peres 2000; Warren et al. 2003, Klimchuk 2006)
- Broad DEMs: **multi-temperature** profiles (Warren et al.,)
- **Unresolved motions** (De Pontieu+ 2015, D. Brooks & Hara-san’s talk)
- Tendency for **strand-like structure** at higher spatial resolution

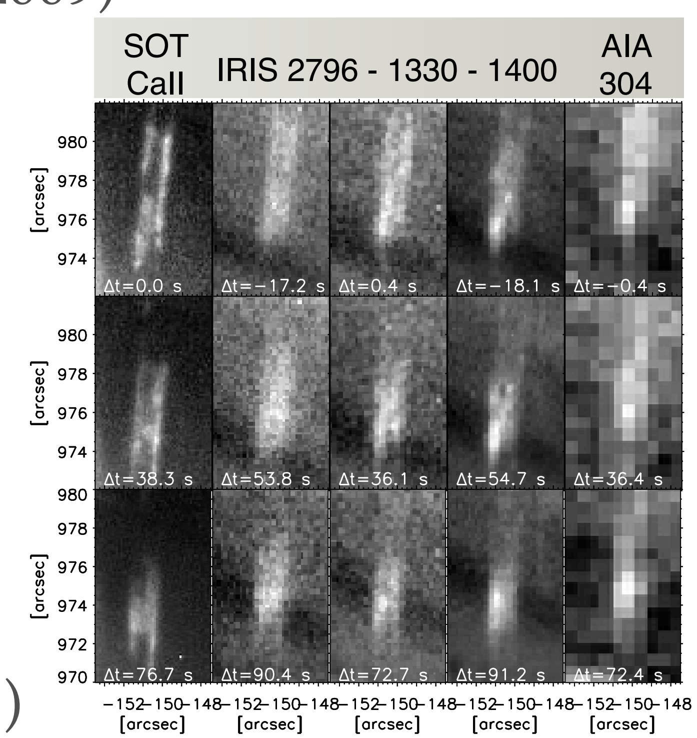
→ Ensemble of **unresolved independently heated strands**? (Klimchuk 2006, Reale 2010, Brooks et al. 2013, Peter et al. 2013, Cirtain et al. 2013, Winebarger et al. 2013)

→ **Strands ⟷ reconection & nanoflares?** (Parker 1988, Vekstein 2009)

~ 1000 Mm widths ~ 100 km



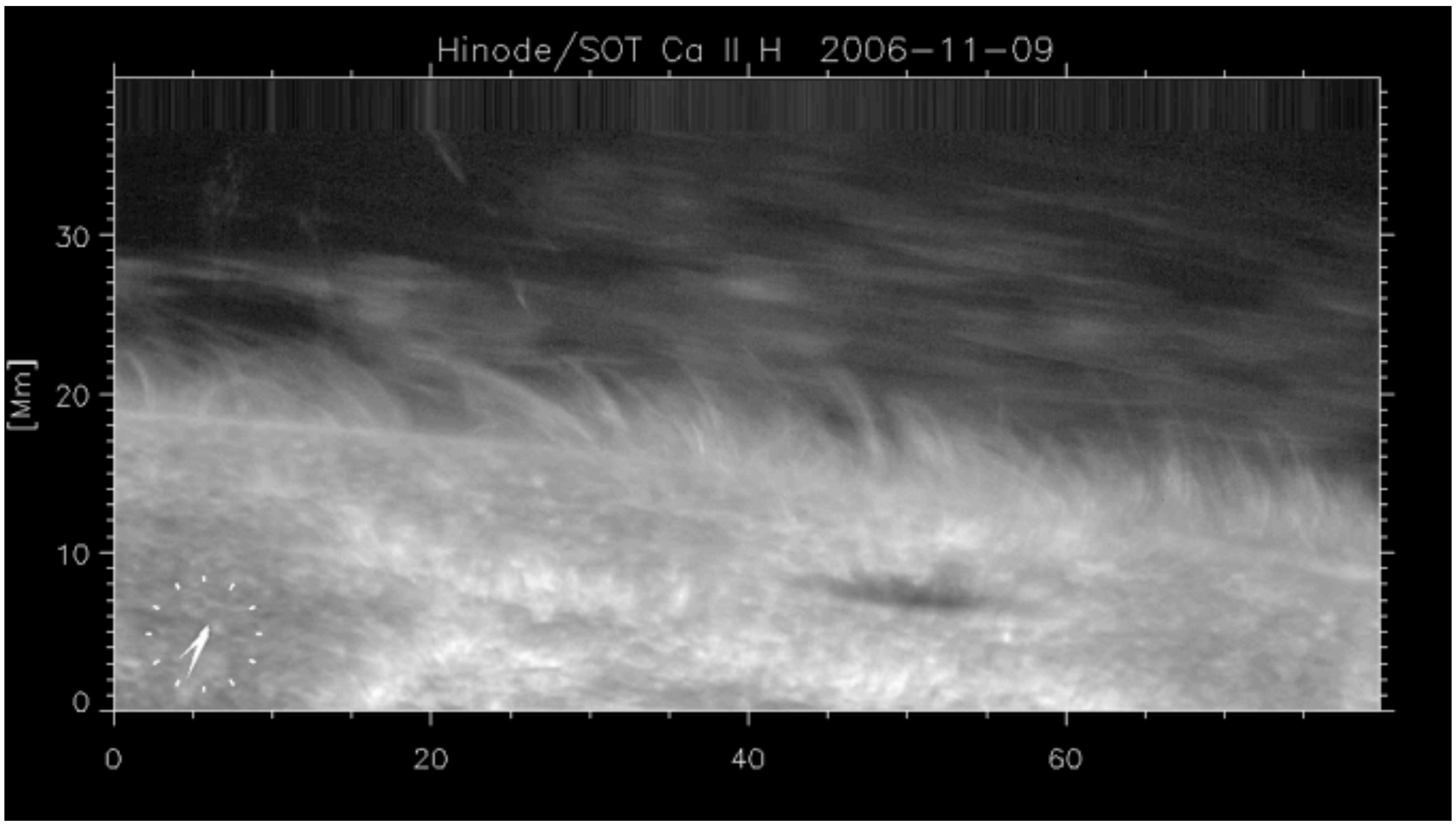
Antolin+ 2015



(Aschwanden & Nightingale 2005, Reale 2010, Peter+ 2010, Brooks+ 2012-3)

Fine-scale structure in the corona

Thermal instability phenomena (prominences & coronal rain) provide the highest resolution windows into fine-scale structure in the corona



Not only a tracer but also a mechanism of fine-scale generation

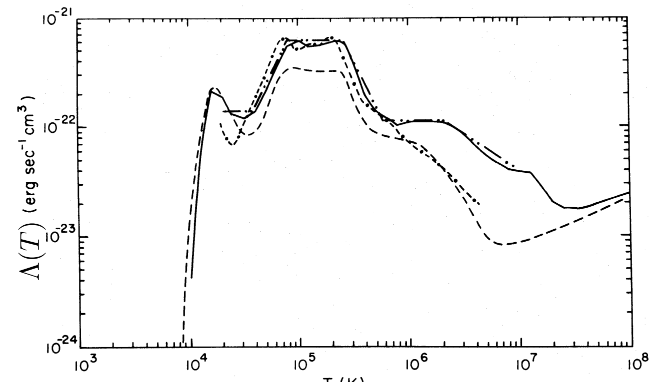
What is the role of thermal instability in the corona? What can we learn from it about coronal heating?

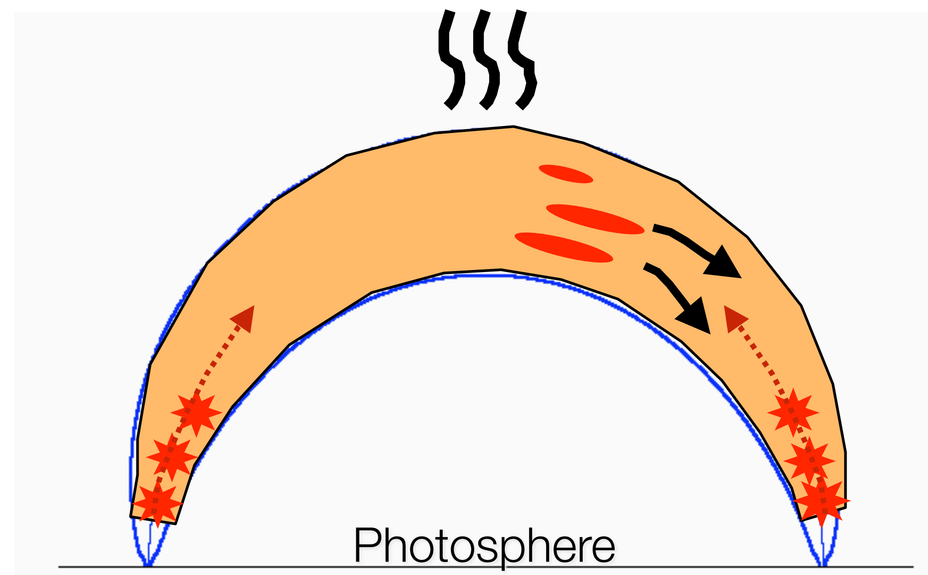
Thermal instability in coronal loops

State of thermal non-equilibrium: A coronal loop subject to footpoint heating can be thermally unstable (Mok+ 1990, Antiochos & Klimchuk 1991, van der Linden & Goosens 1991, Wiik+ 1996, Antiochos+ 1999, Karpen+ 2001, Müller+ 2003-4, Mendoza-Briceño+ 2005, Reale+1996-97, Mok+ 2008, Xia+ 2011)

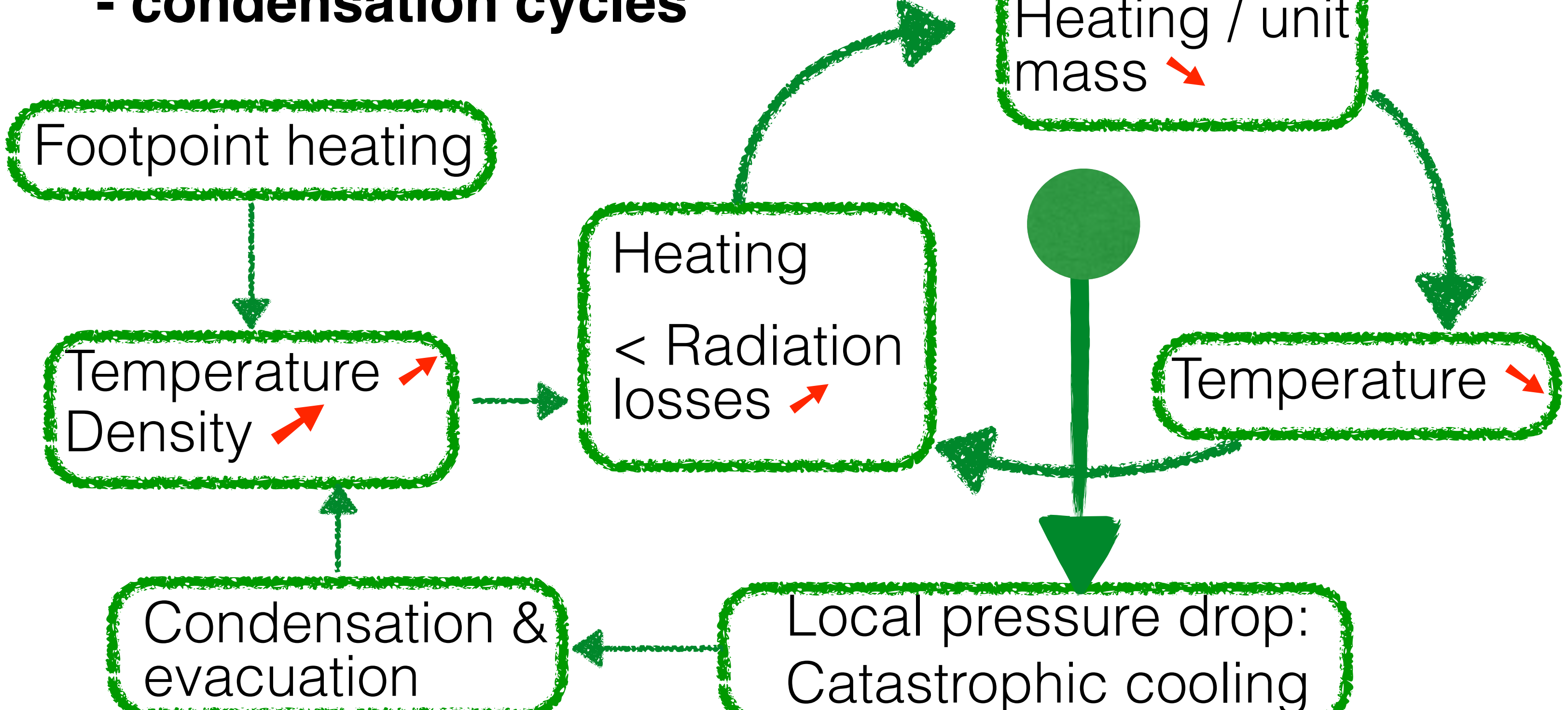
Parker (1953), Field (1965), Goldsmith (1971), Hildner (1974), Heyvaerts (1974), Heasley & Mihalas (1976),…

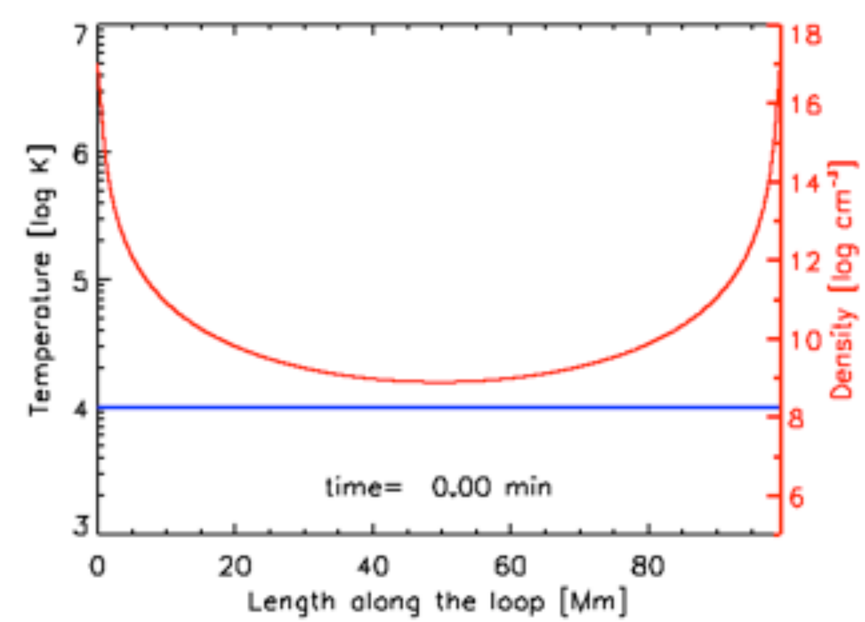
Rosner et al. 1978



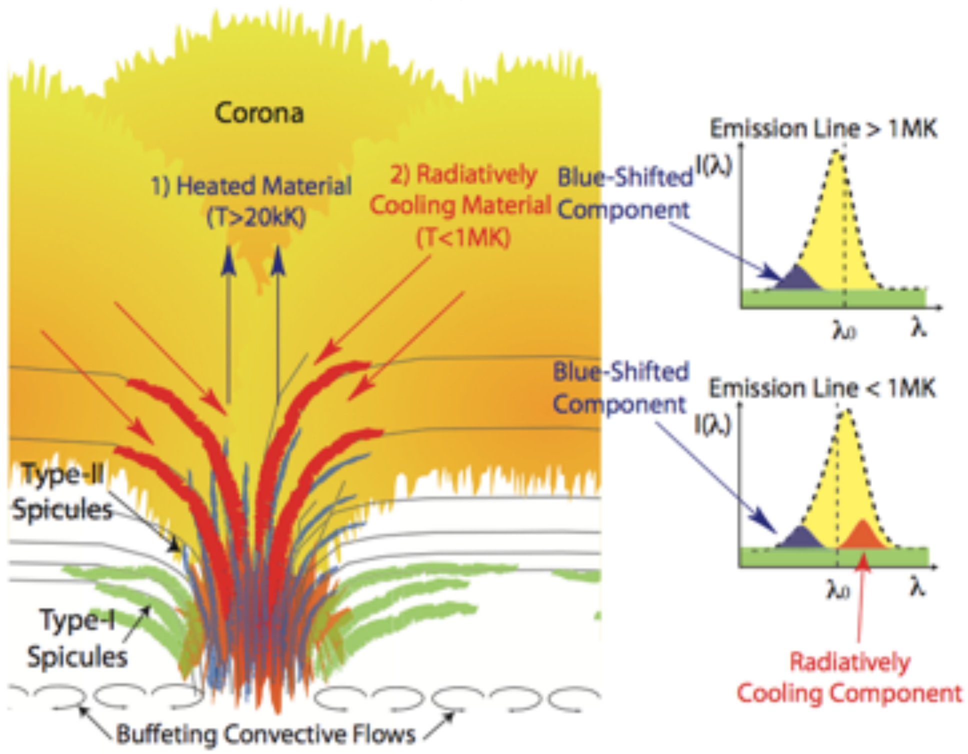


limit cycles, evaporation - condensation cycles





Return flows of chromosphere–corona Mass Cycle: prominence and coronal rain



(McIntosh et al. 2012)

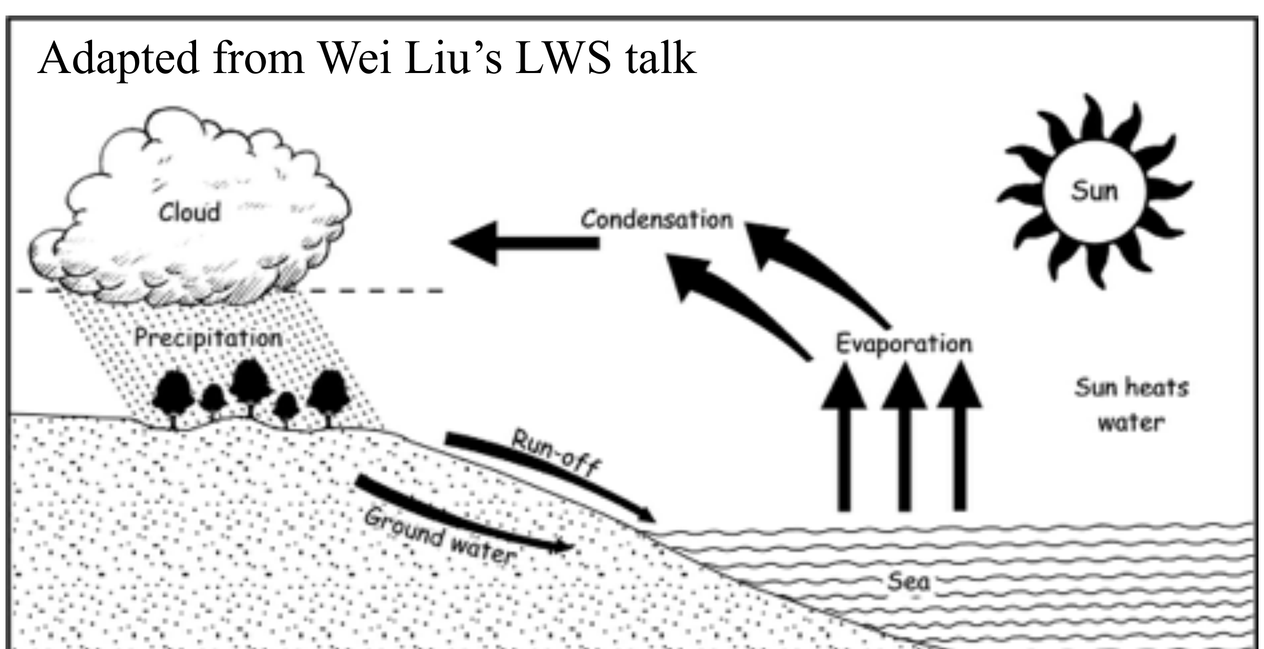
(1) Hot mass/Magnetic flux Up:

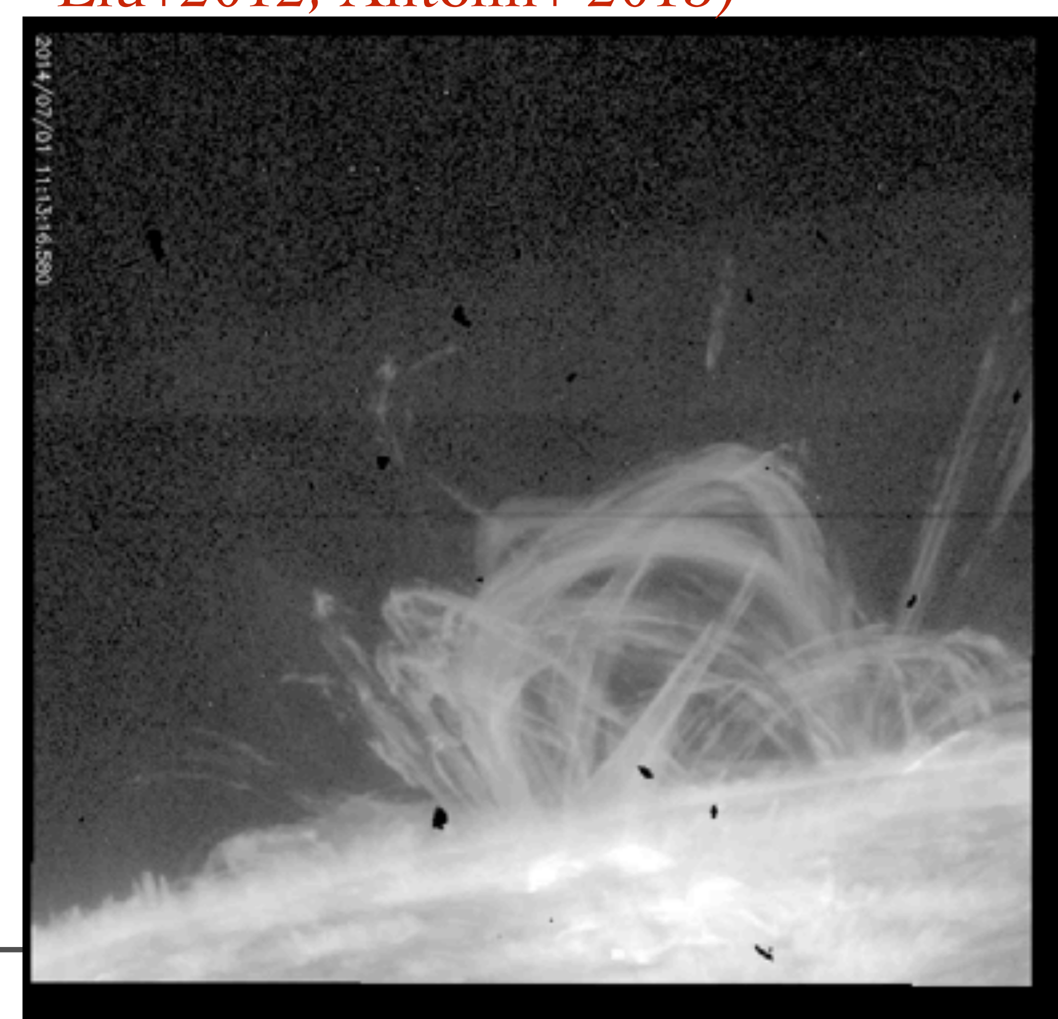
- Spicules, footpoint upflows, flux emergence (e.g., bubbles/plumes)

(2) Cool mass down:

- **Prominences, Coronal rain**
- **Mass flux: 1 - 5 × 10^9 g s^{-1}**

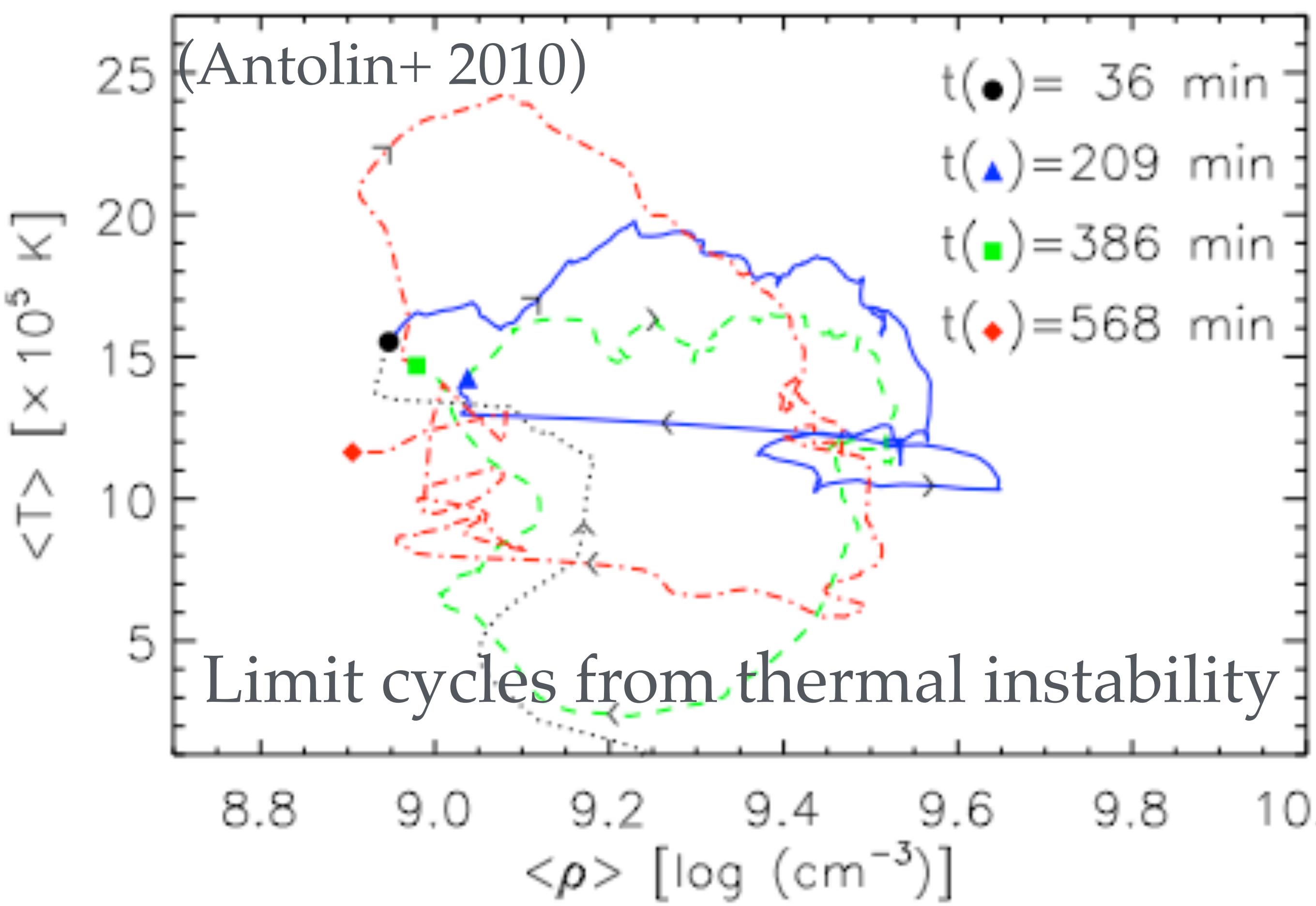
(Antolin&Rouppe v.d.Voort 2012, Liu+2012, Antolin+ 2015)


Adapted from Wei Liu's LWS talk

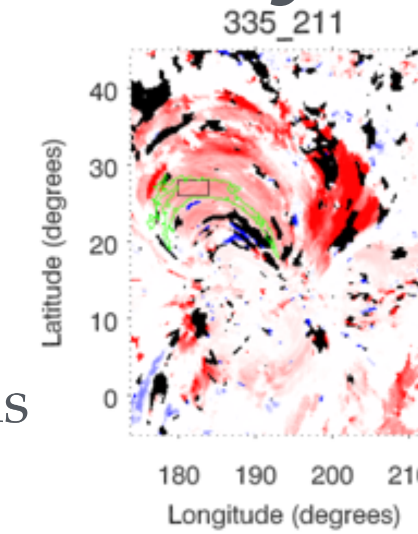


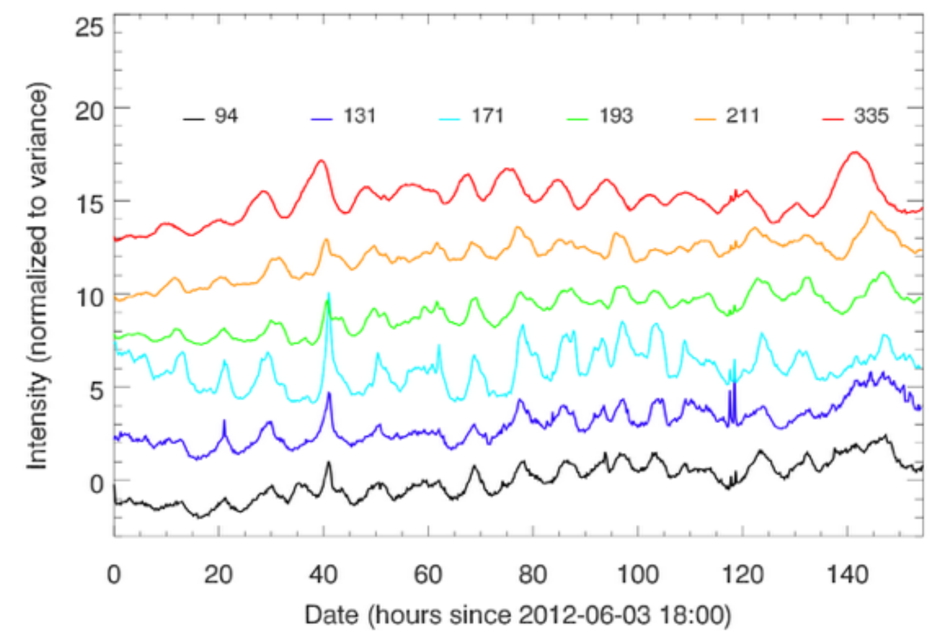
Relation to coronal heating: variability

(Antiochos+ 1999, Karpen+ 2001, Müller+ 2003-4, Mendoza-Briceño+ 2005, Antolin+ 2010, Susino+ 2010, Peter+ 2011, Mikiç+ 2013)



Froment+ (2015): long period intensity pulsations in loops (2-16 hrs)





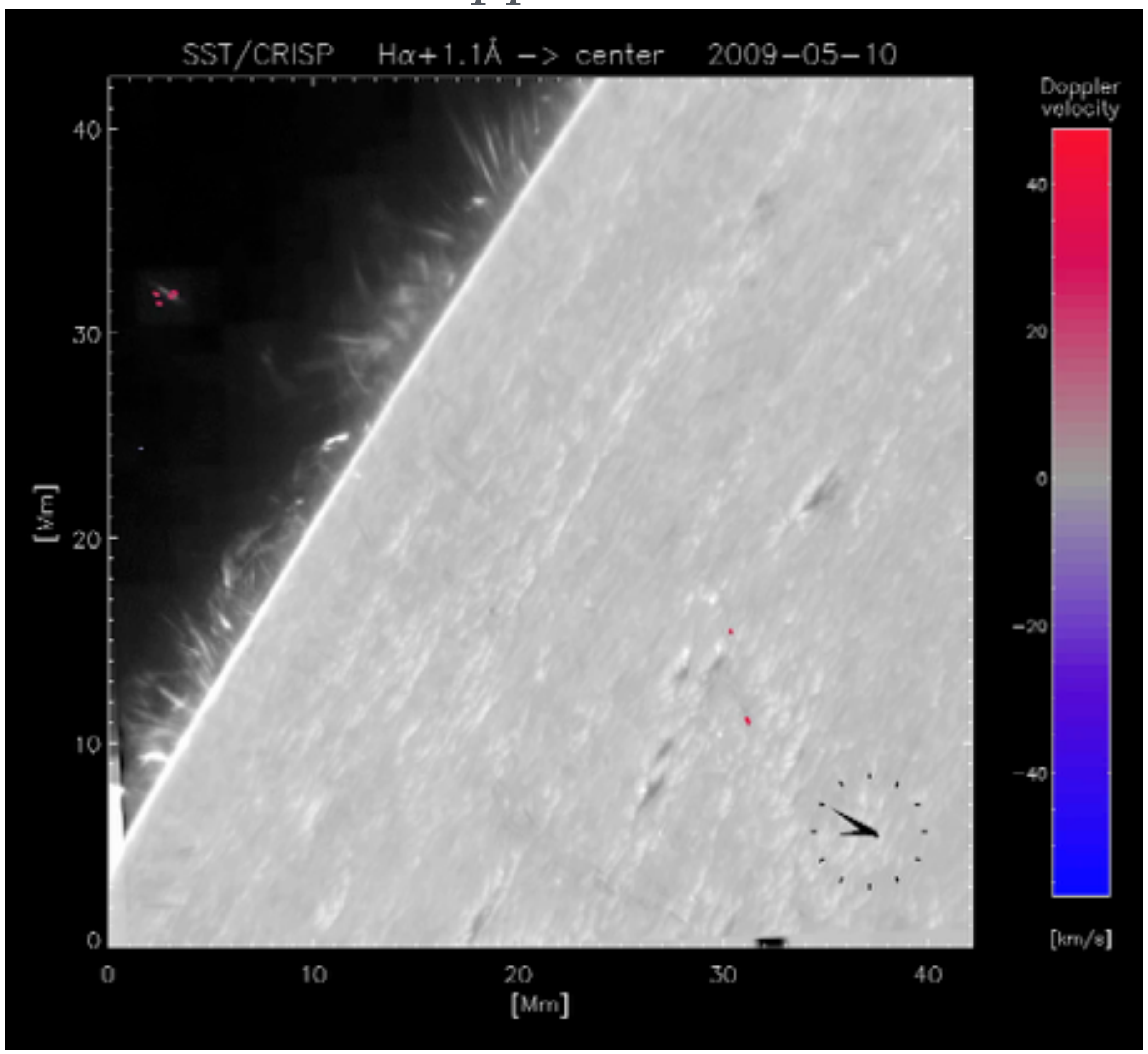
Periodicity in the occurrence of coronal rain: link to heating parameters (geometry, spatial & temporal distribution of heating)

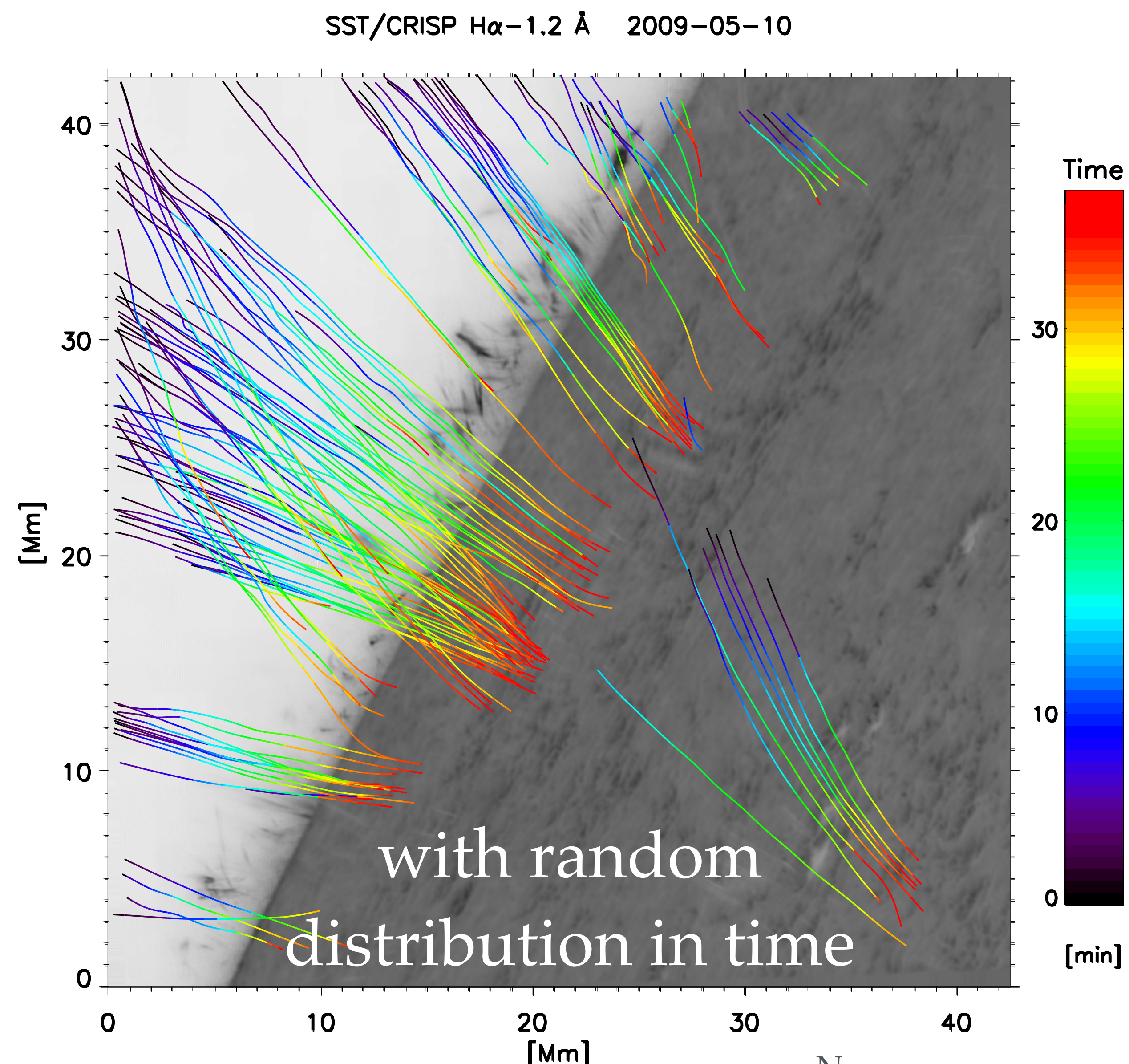
➡ Important information about the heating characteristics (and mechanisms)

cf. Amy's talk

Relation to coronal heating: heating scales

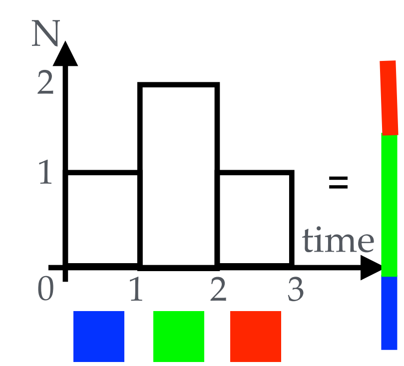
Antolin & Rouppe van der Voort (2012)



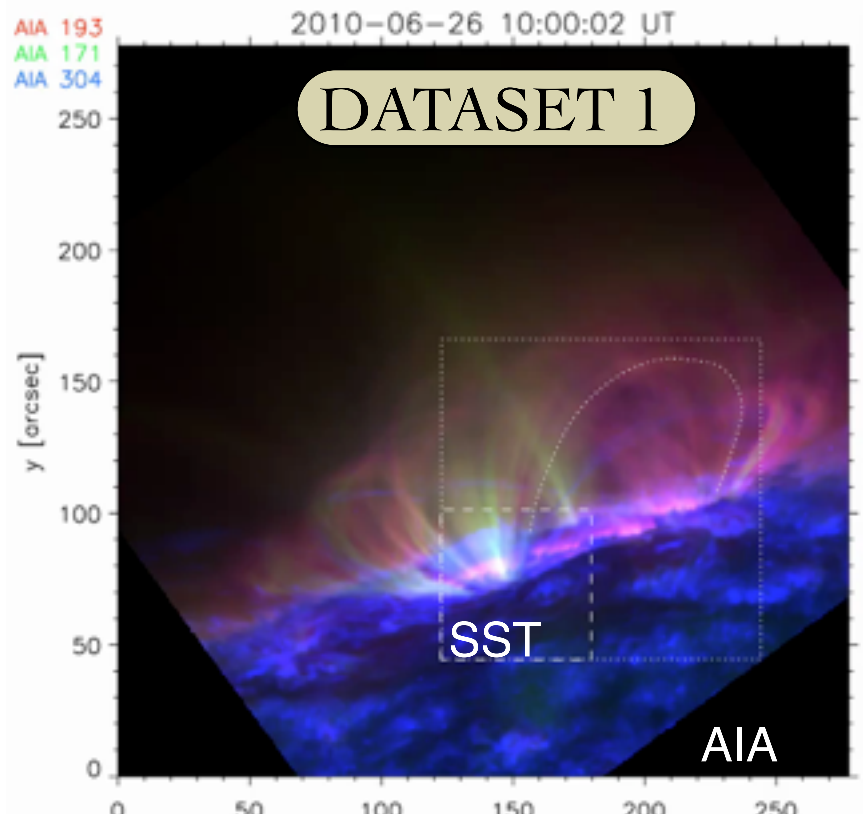


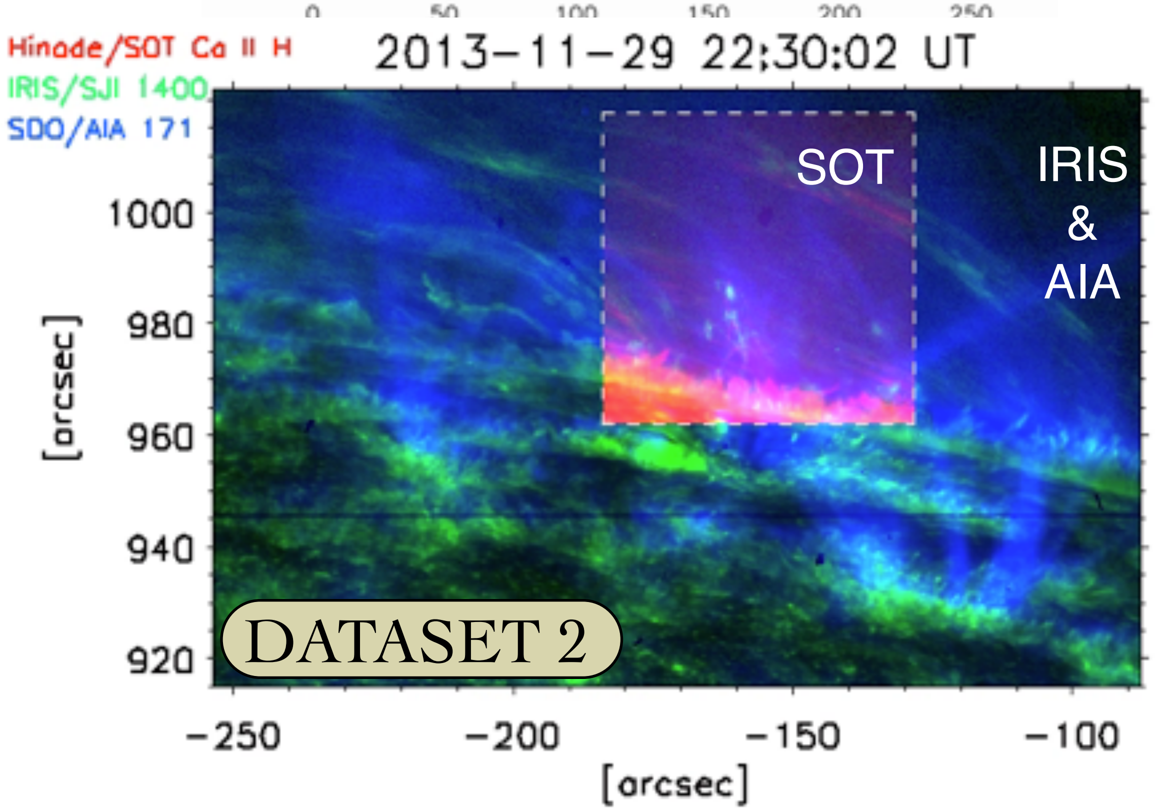
Strands may not evolve always independently

→ existence of coherent thermodynamic transverse scale: ~ 2 Mm



Case study: multi-wavelength observations



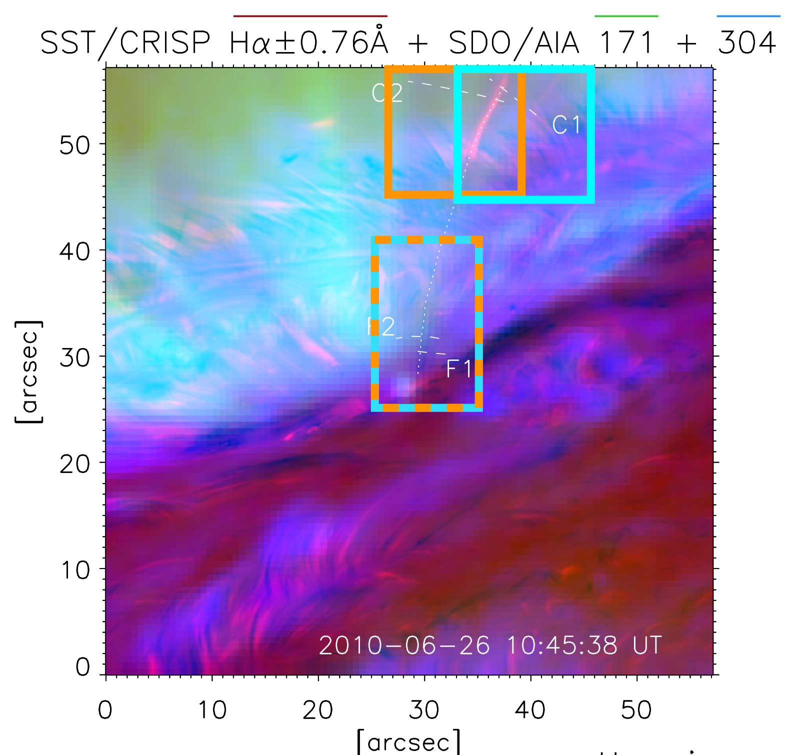


Antolin+ (2015, ApJ 806, 21)

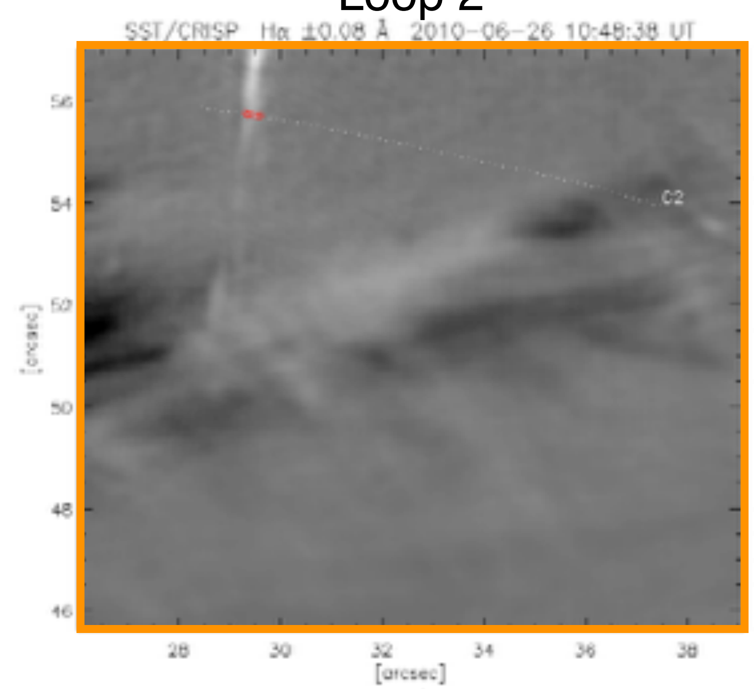
Instrument & Wavelengths	Dataset	Spatial (& spectral) resolution	Cadence [sec]	Formation temperature [log K]
SST/CRISP Hα	1	0.14” (0.085 Å)	9	3.3-4.2
Hinode/SOT Ca II H	2	0.2”	4.8	4-4.2
IRIS/SJI Mg II 2796 Å	2	0.4”	36.5	4-4.2
IRIS/SJI C II 1330 Å	2	0.33"	36.5	4.3
IRIS/SJI Si IV 1400 Å	2	0.33”	36.5	4.8
SDO/AIA He II 304 Å	1 & 2	1.2”	12	5
SDO/AIA Fe IX 171 Å	1 & 2	1.2”	12	5.9
SDO/AIA Fe XII 193 Å	1	1.2”	12	6.2

- Dataset 1: 26/06/2010, 10:03-11:40 UT, centred on AR 11084 at [-875”,-319"]
- Dataset 2: 29/11/2013, 22:30-23:30 UT, centred on AR 11903 at [944”,264”]

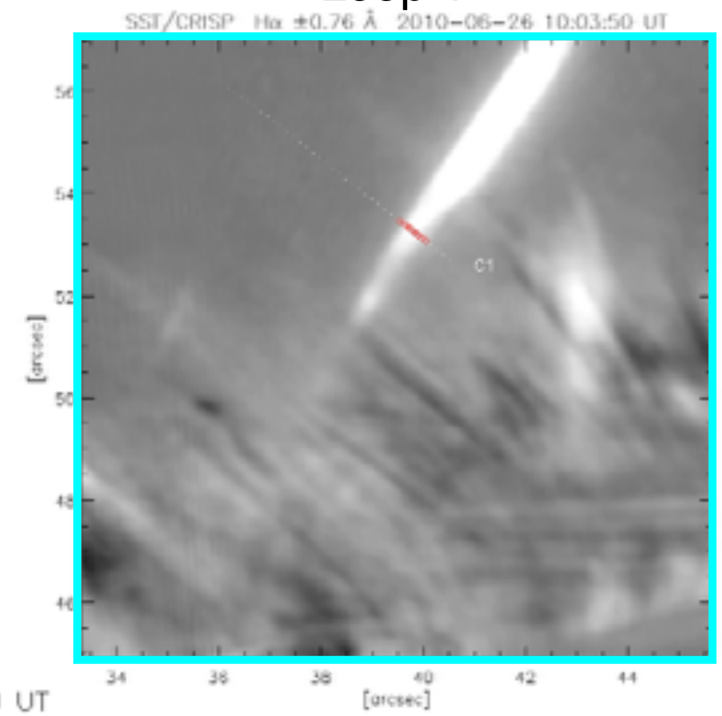
Clumpy vs. continuous



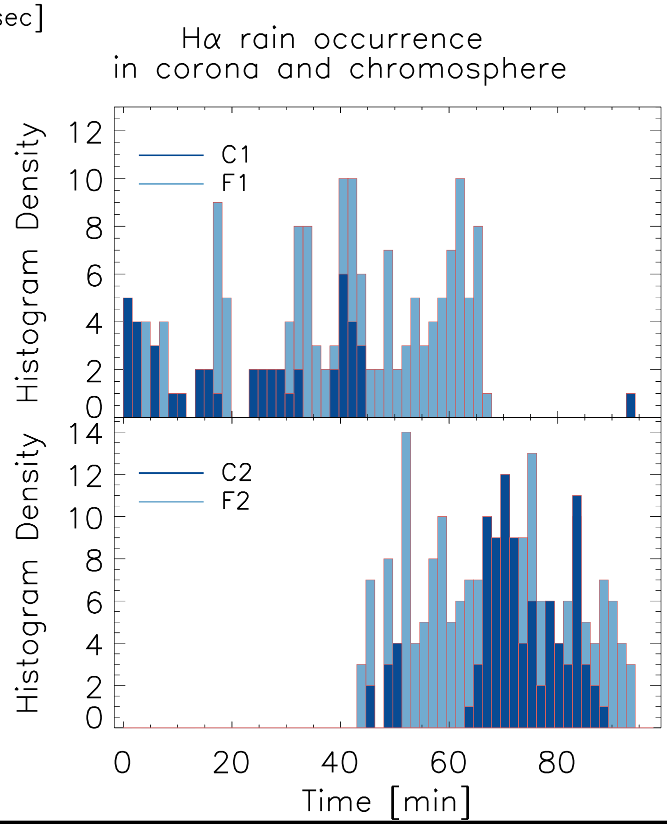
Loop 2

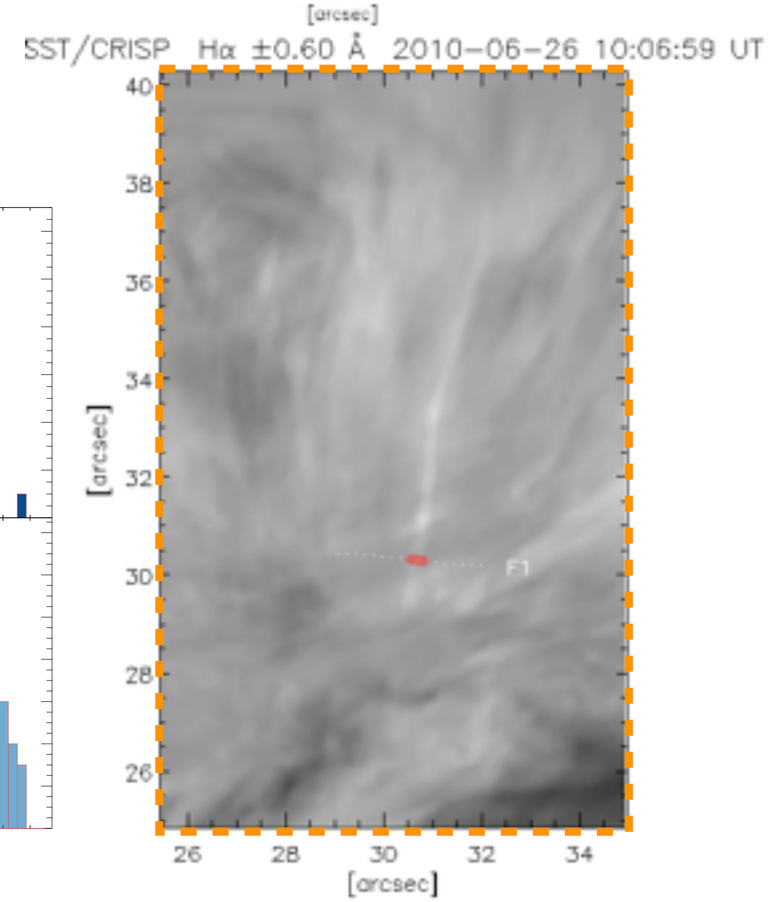


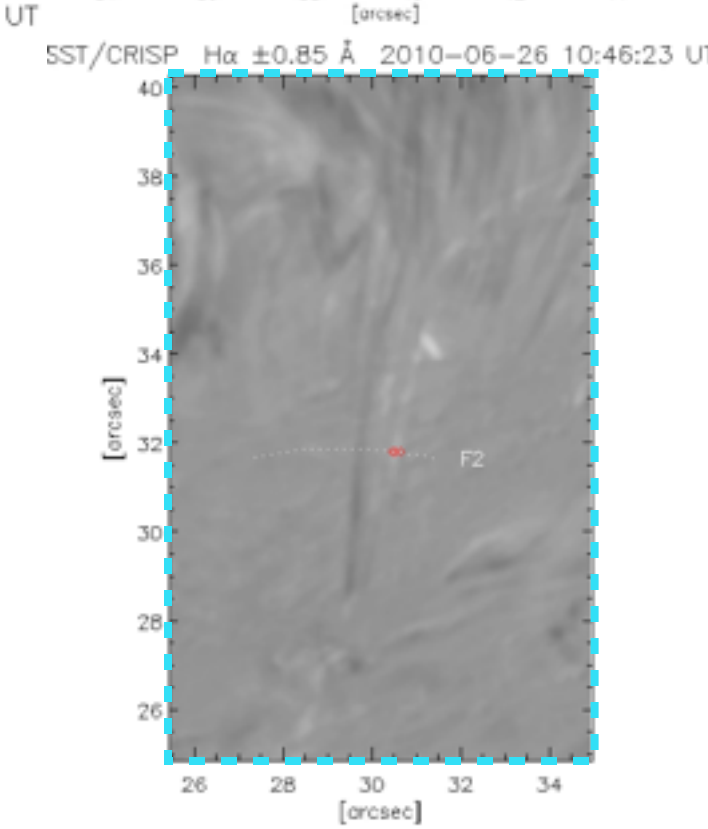
Loop 1



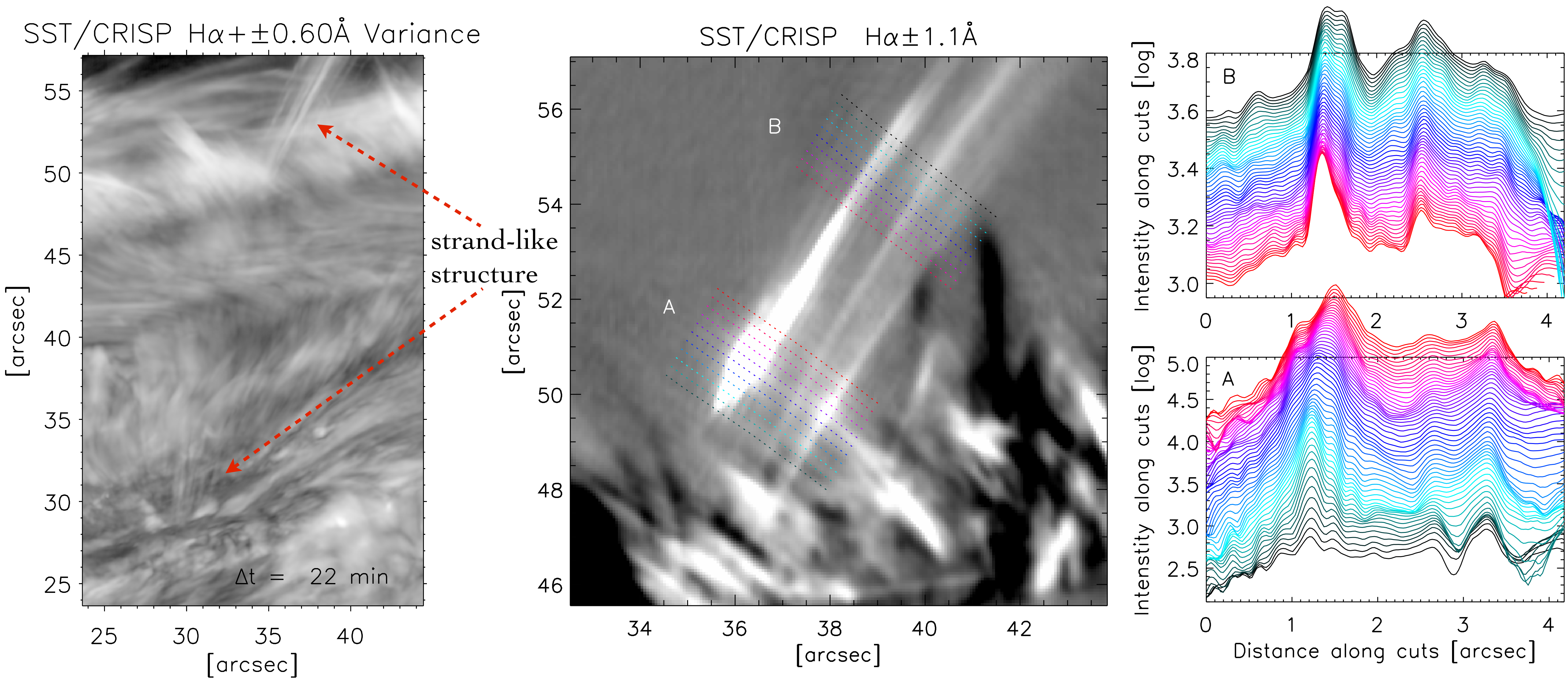
The clumpy and sporadic character of the rain at coronal heights (C1&C2) becomes persistent & continuous at chromospheric (F1&F2) heights







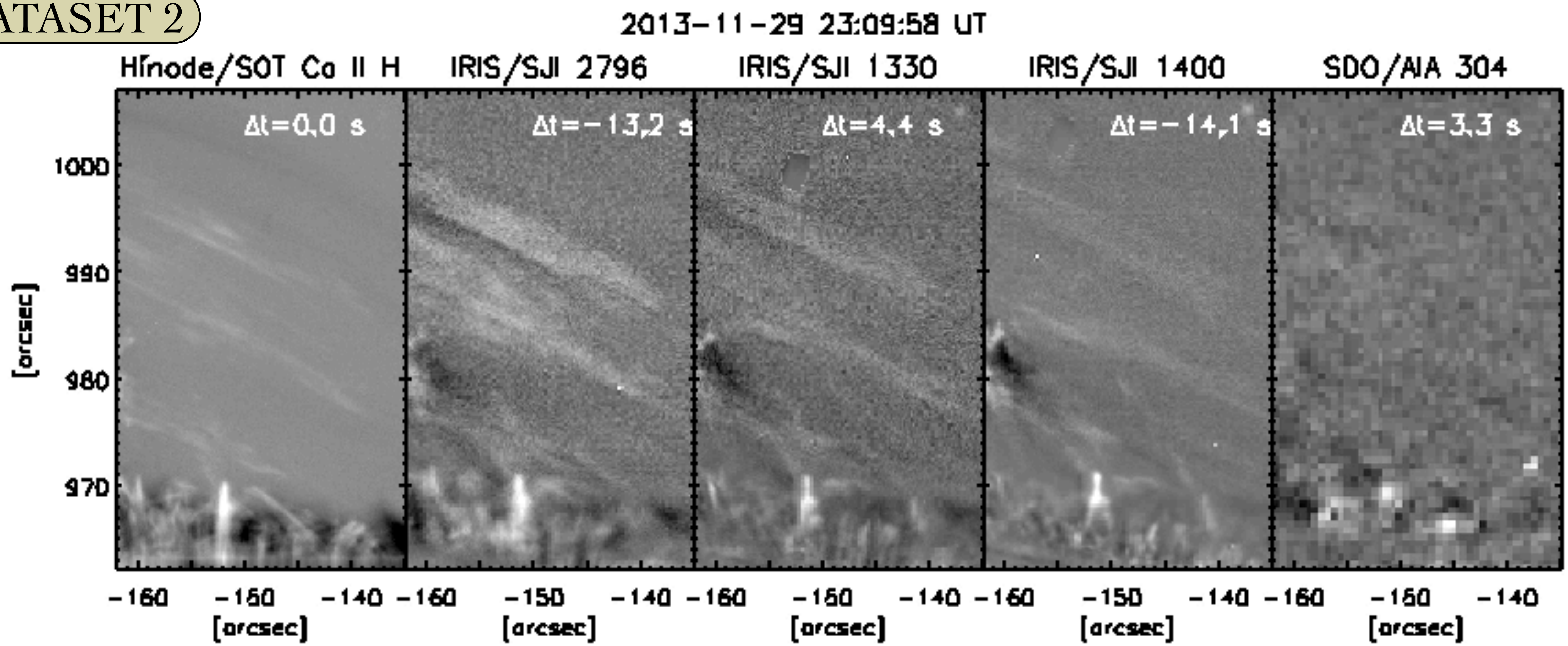
Multi-stranded structure

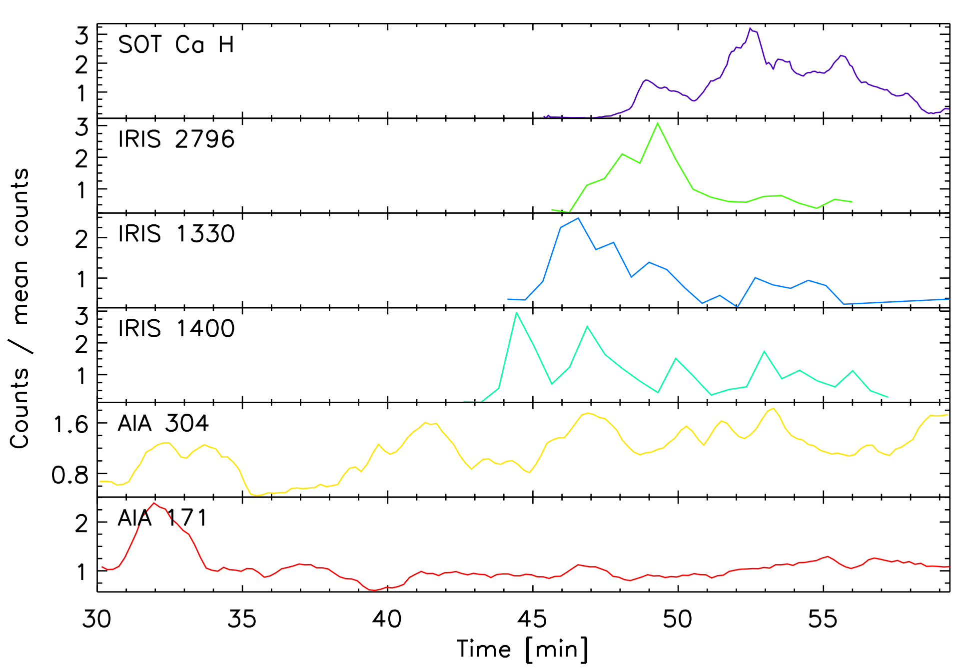


Multiple ripples next to large clumps: highly reminiscent of the MHD thermal mode (entropy mode) (Van der Linden & Goossens 1991). Characteristic sizes (widths & lengths) in rain may be defined by spatial structure of unstable modes (Field's length)

Cooling through TR lines

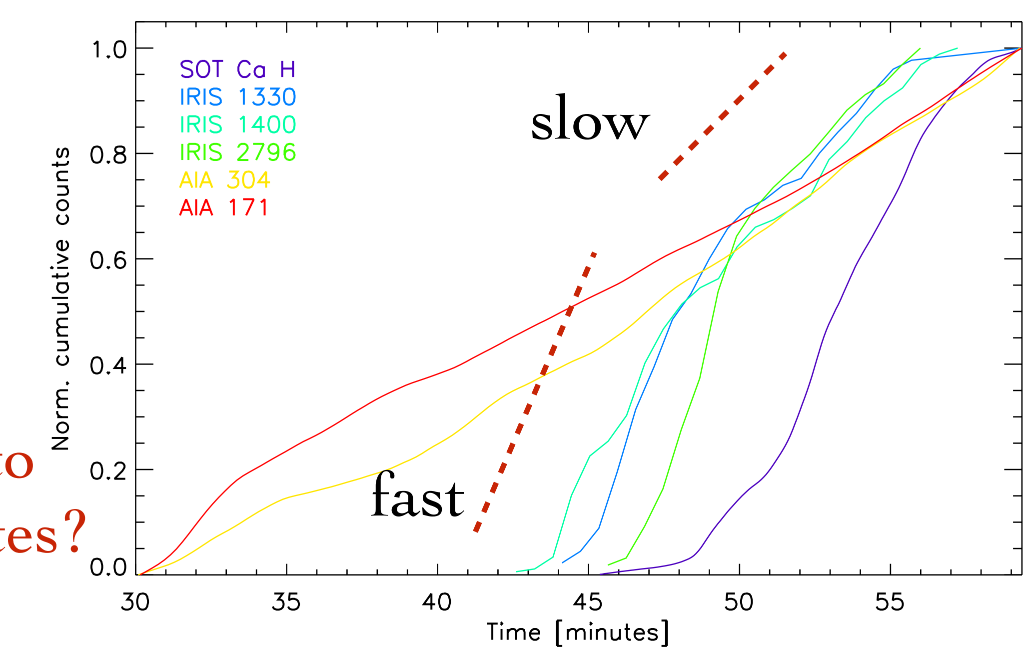
DATASET 2



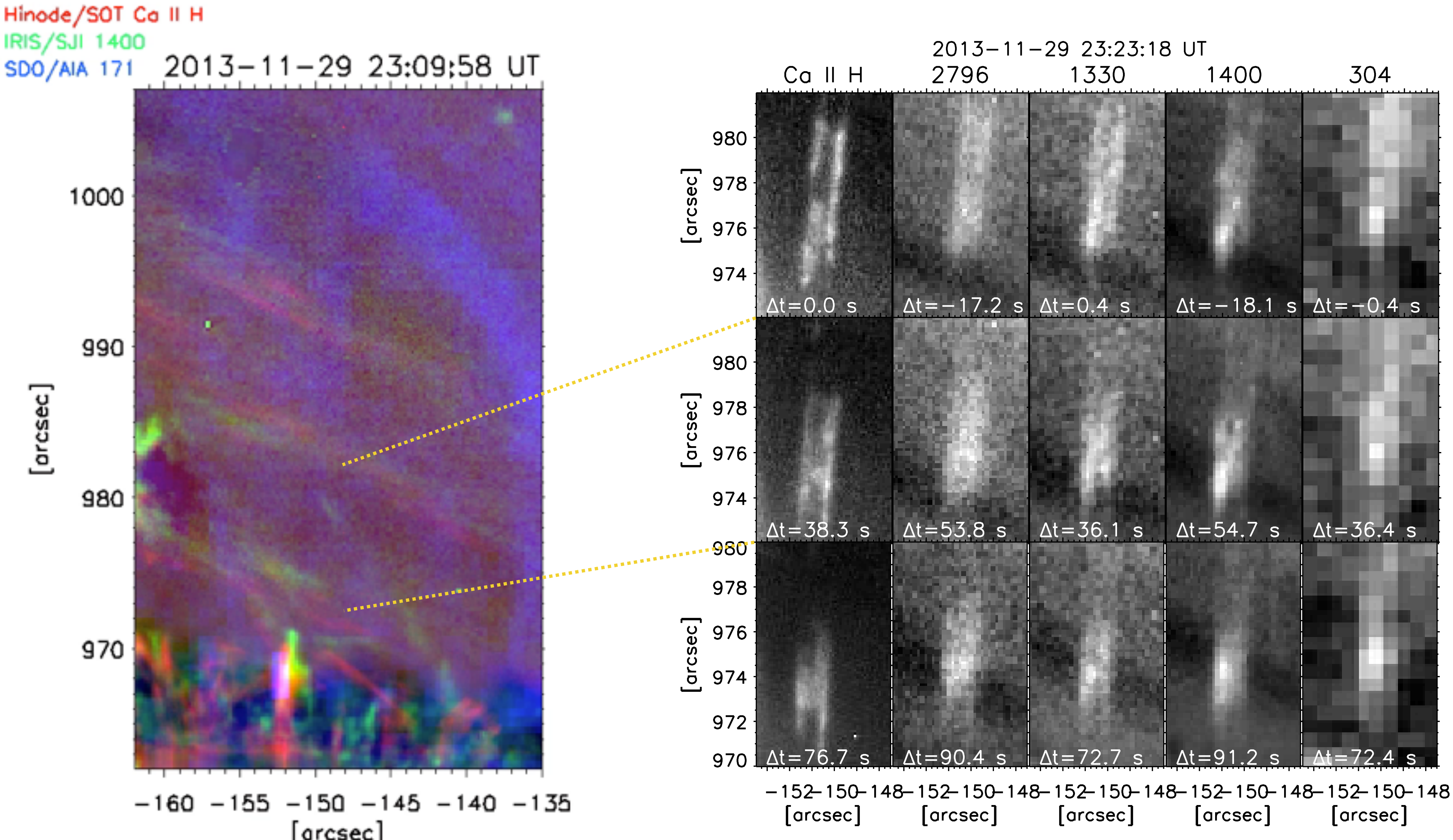


Progressive cooling from TR to chromospheric temperatures with a **fast-slow two step behaviour**

➡ Phase transition to optically thick states?



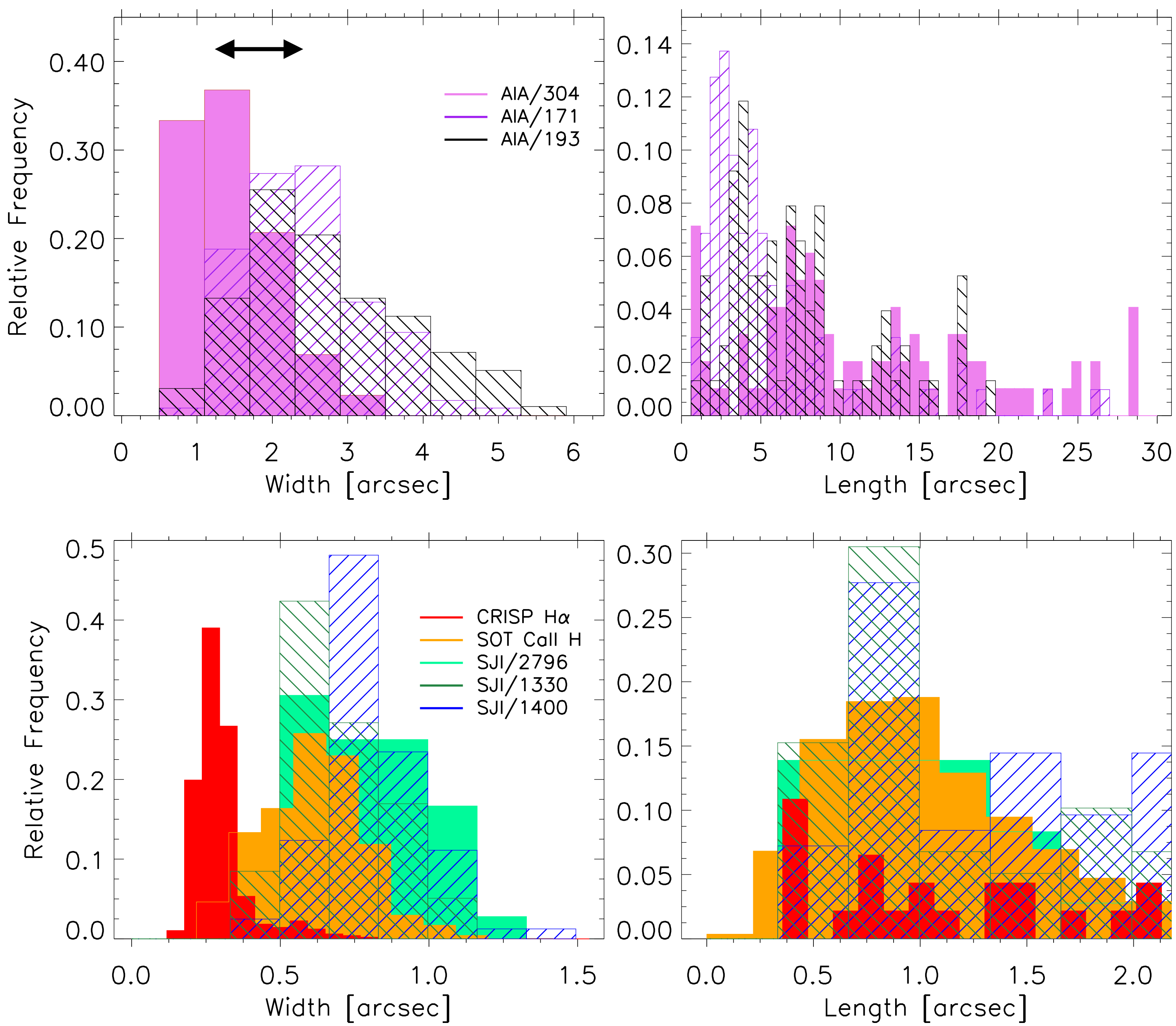
Multi-thermal and multi-stranded



- Strong co-spatial emission in TR and chromospheric lines
- Differences in structure appear at the smallest scales: chromospheric to TR temperature transition must exist at scales below Iris resolution (0.33”)
- Strand-like structure extends to TR range

Instrument & filter	Dataset	Width [arcsec]	Length [arcsec]	Blobs / min
CRISP - Hα	1	0.3 ± 0.093	3.85 ± 5.77	5.
SOT - Ca II H	2	0.61 ± 0.17	1.05 ± 0.51	9.7
SJI - 2796	2	0.8 ± 0.19	2.49 ± 1.97	2.6
SJI - 1330	2	0.7 ±0.15	1.75 ± 1.35	3.7
SJI - 1400	2	0.8 ±0.17	1.76 ± 1.26	4.6
AIA - 304	2	1.56 ±0.15	10.8 ± 6.5	2.2
AIA - 304	1	1.4 ±0.7	12.7 ± 9.2	1.2
AIA - 171	1	2.45 ±0.81	5.5 ± 5.2	1.2
AIA - 193	1	2.69 ±1.07	7.4 ± 4.6	1.2

Tip of the iceberg?



- Significant difference in clump widths in AIA from TR to coronal temperatures (~0.5”) width of PCTR?
- Shape of width distribution is independent of temperature: sharp peak + long tail. Strong increase in clump numbers at lower temperatures but especially at higher resolution

➡Tip of the iceberg scenario? (Antolin & Rouppe 2012, Fang+ 2013, Scullion +2014)

- Lengths distribution is more random: reflects other factors at play (longitudinal) -> X. Fang’s poster
- Resolution & temperature intertwined

Discussion

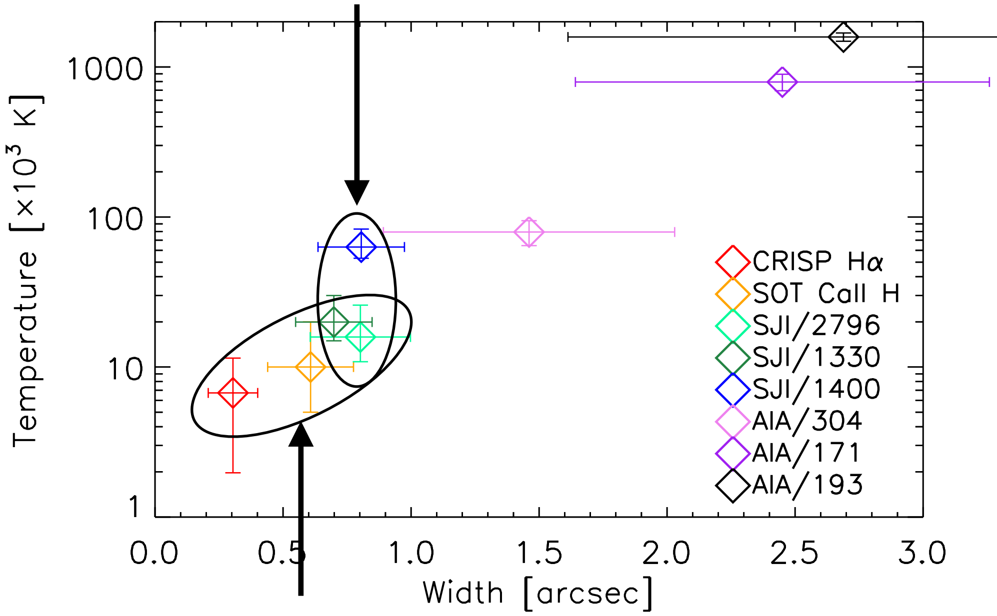
Elemental scales

- Main limiting factor: resolution
- Strand-like structure extends into TR range

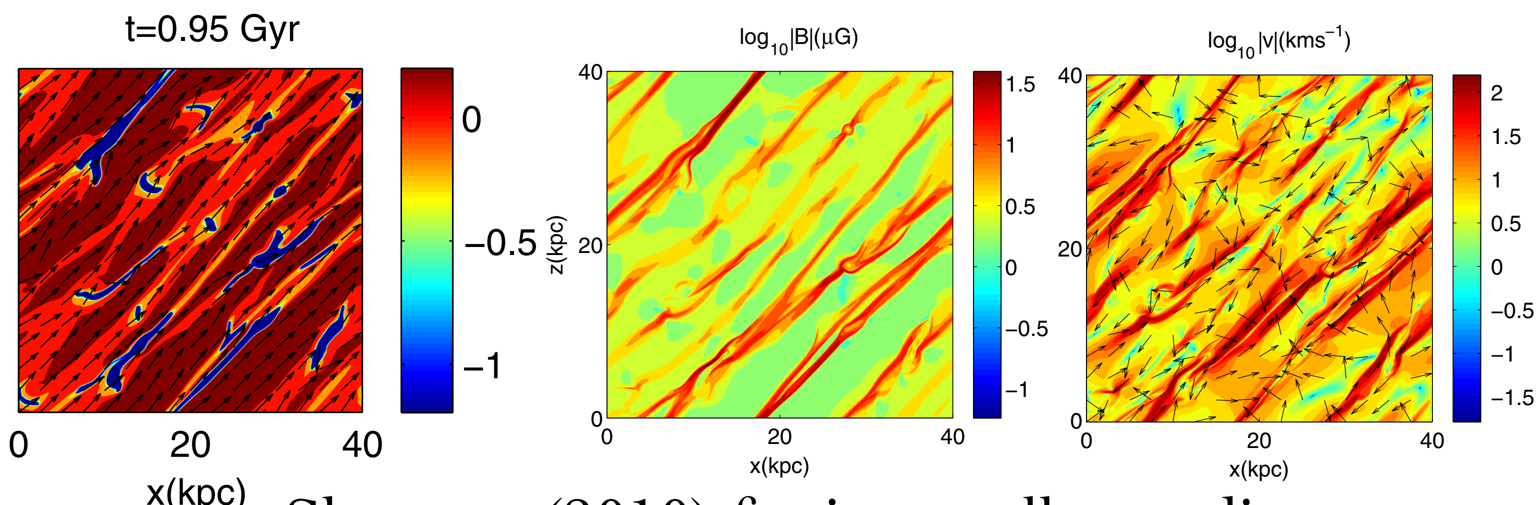
➡ Existence of elemental structures?

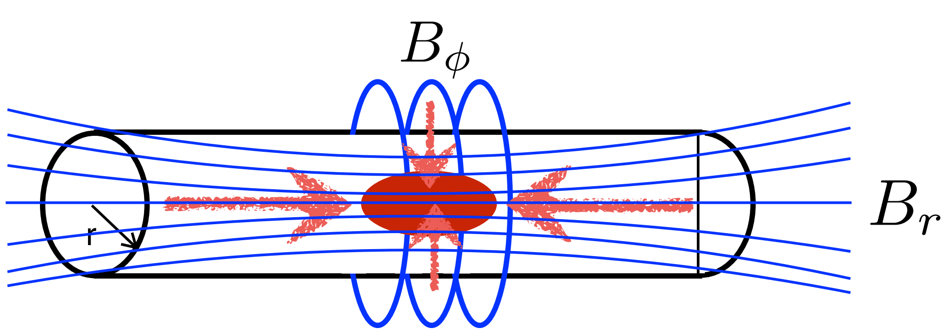
- Does thermal instability may play a main role in the morphology
  - MHD thermal mode (Field 1965, Van der Linden & Goossens 1991): seed for density enhancements in neighbouring loops
  - Flux freezing & high Alfvén speed: can affect plasma up- and downstream

same resolution, drastic temperature change: insignificant width change



significant improvement in resolution, no drastic temperature change: significant width change





Sharma+ (2010) for interstellar medium

Conclusions (1/2)

Thermal instability in the solar corona: strongly link to heating mechanisms

- Observed EUV common variability linked to catastrophic cooling (Froment's talk)
- Persistent redshifts (clumpy structure becomes continuous at low heights)
- Multi-temperature phenomenon: chromospheric & TR emission
- Fast-slow 2-step cooling transition observed: phase transition to thick regime?
- Multi-stranded structure in TR and chromospheric lines: strong inhomogeneity where chromospheric to TR temperatures occurs at <0.3″
- Significant increase of number at higher resolution. Tip of the iceberg scenario?
- Elemental strand-like structure of effect from thermal instability? (MHD thermal mode? pinching from flux freezing?)

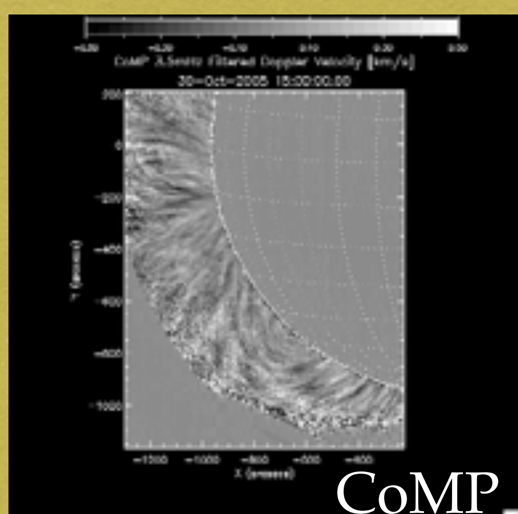
Observations of Alfvénic MHD waves in the solar atmosphere

Transverse MHD waves ubiquitous in the solar atmosphere

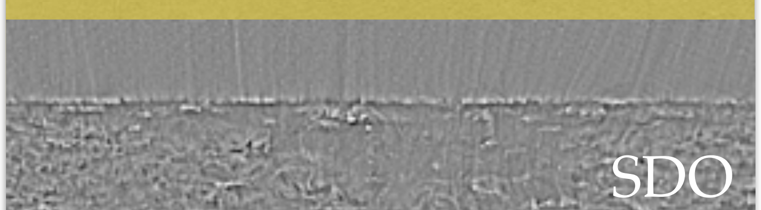
→ small amplitude (~km/s), few min periods

What is the role of such waves in the solar atmosphere?

Large-scale corona



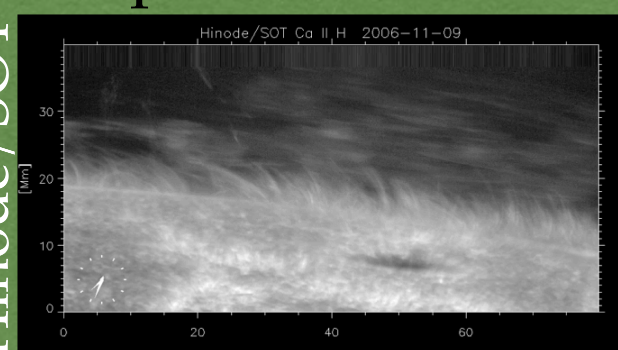
Tomczyk et al. 2007



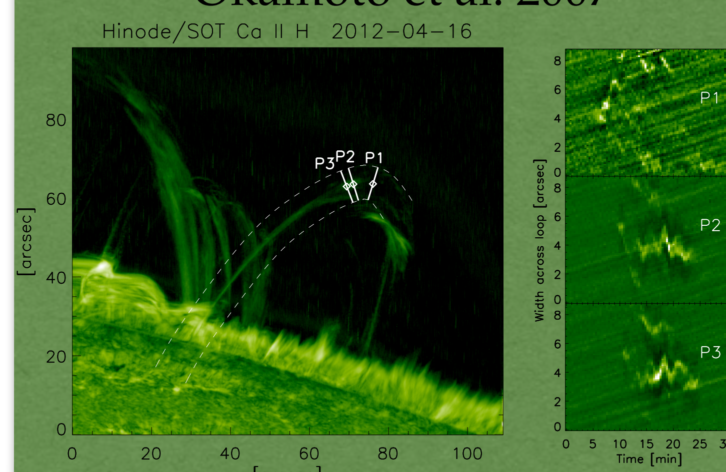
McIntosh et al. 2011

Coronal loops & prominences

Hinode/SOT



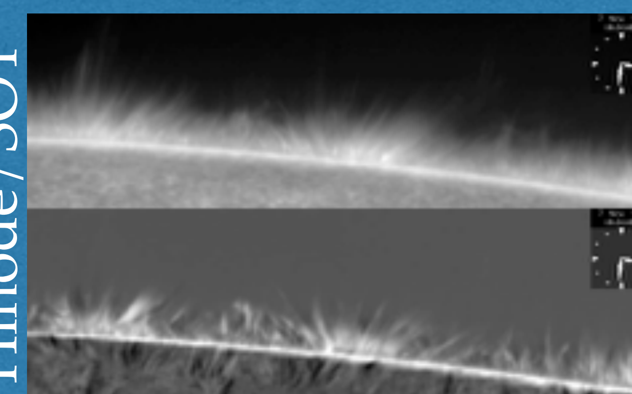
Okamoto et al. 2007



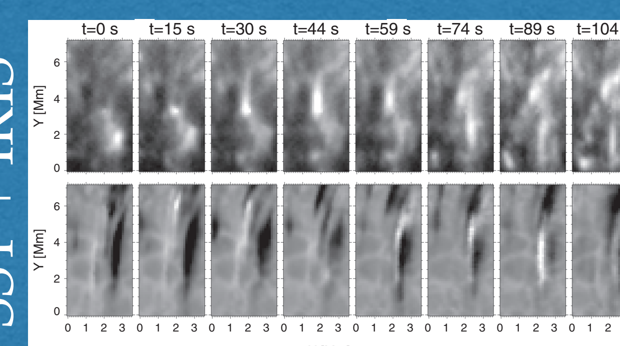
Antolin & Verwichte 2011

Chromosphere

Hinode/SOT



SST + IRIS



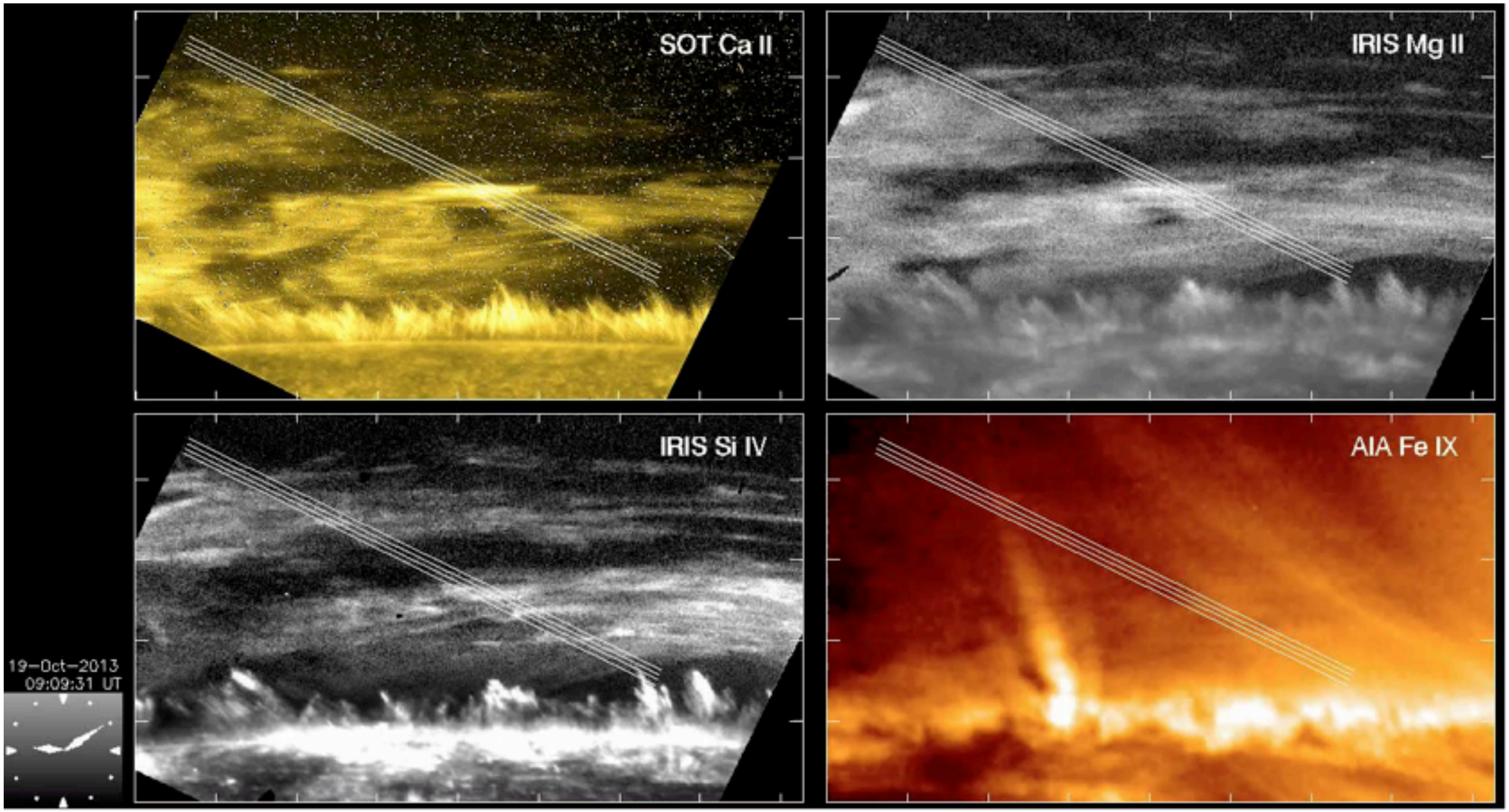
De Pontieu et al. 2014

Skogsrud et al. 2014

(Tomczyk+ 2007, Okamoto+ 2007, De Pontieu+ 2007, Lin 2011, McIntosh+ 2011, Morton+ 2011, Antolin & Verwichte 2011, Okamoto & De Pontieu 2012, Hillier+ 2013, Schmieder+ 2013, Morton & McLaughlin 2014, De Pontieu+ 2014, Anfinogentov+ 2013, Nisticó+ 2013)

IRIS/Hinode observations

Okamoto et al. (2015,accepted), Antolin et al. (2015, accepted)



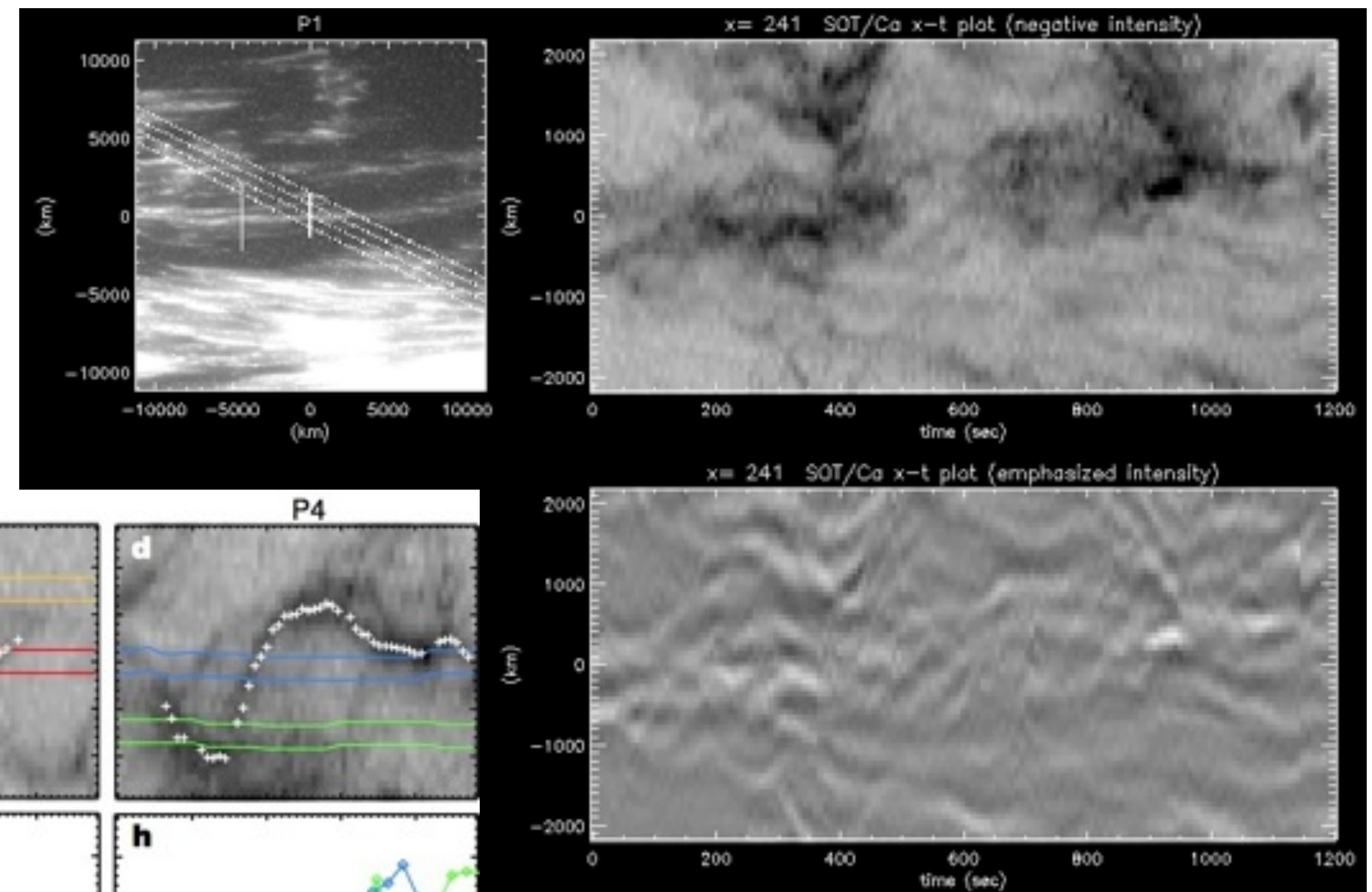
IRIS
- 9-11 UT, 19 October 2013
- 4-step sparse raster
- SJI - Si IV & Mg II (10 s), SG (20 s)

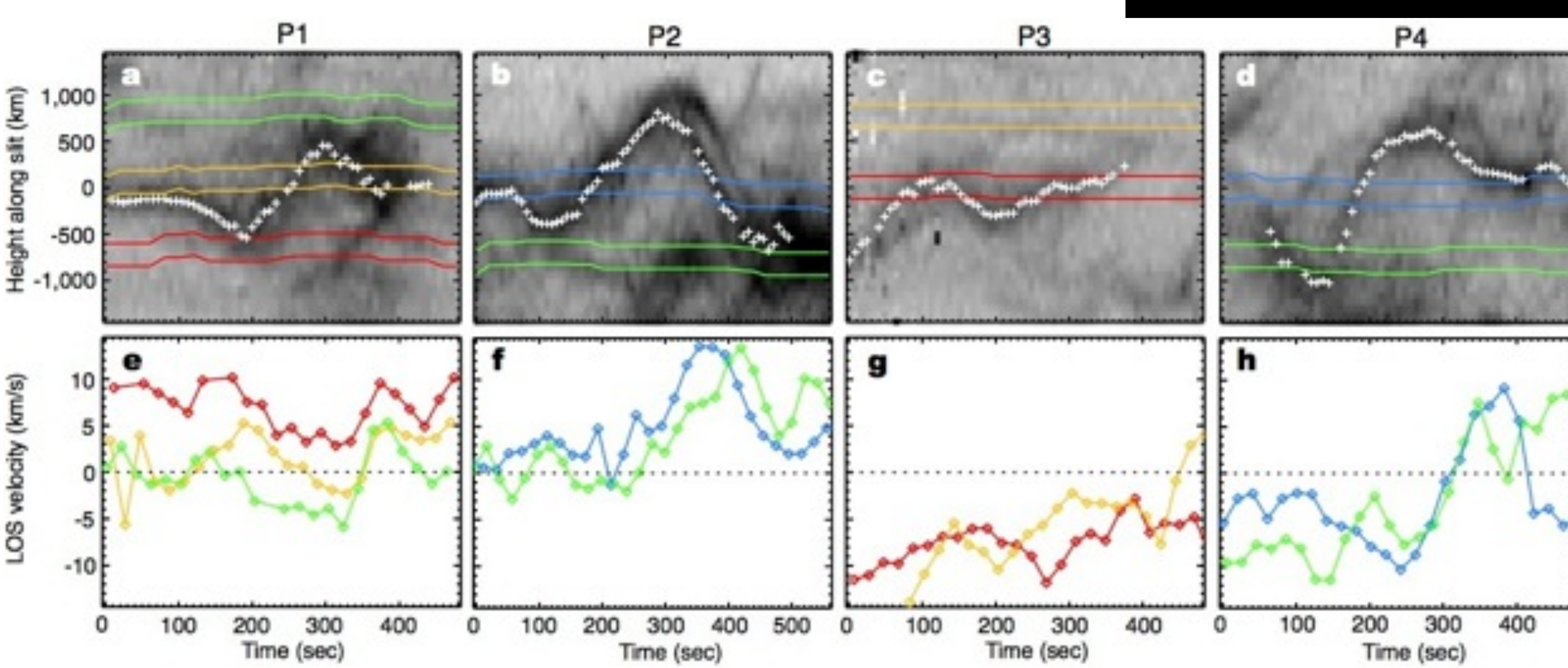
SOT
- Ca II H filtergrams at 0.2" res.
- Cadence: 8 s

IRIS/Hinode observations

- Thread-like structure
- Transverse oscillations
- Signatures of damping
- Strong transverse coherence in the plane-of-the-sky (POS) motion and the line-of-sight (LOS) velocity

Hinode/SOT

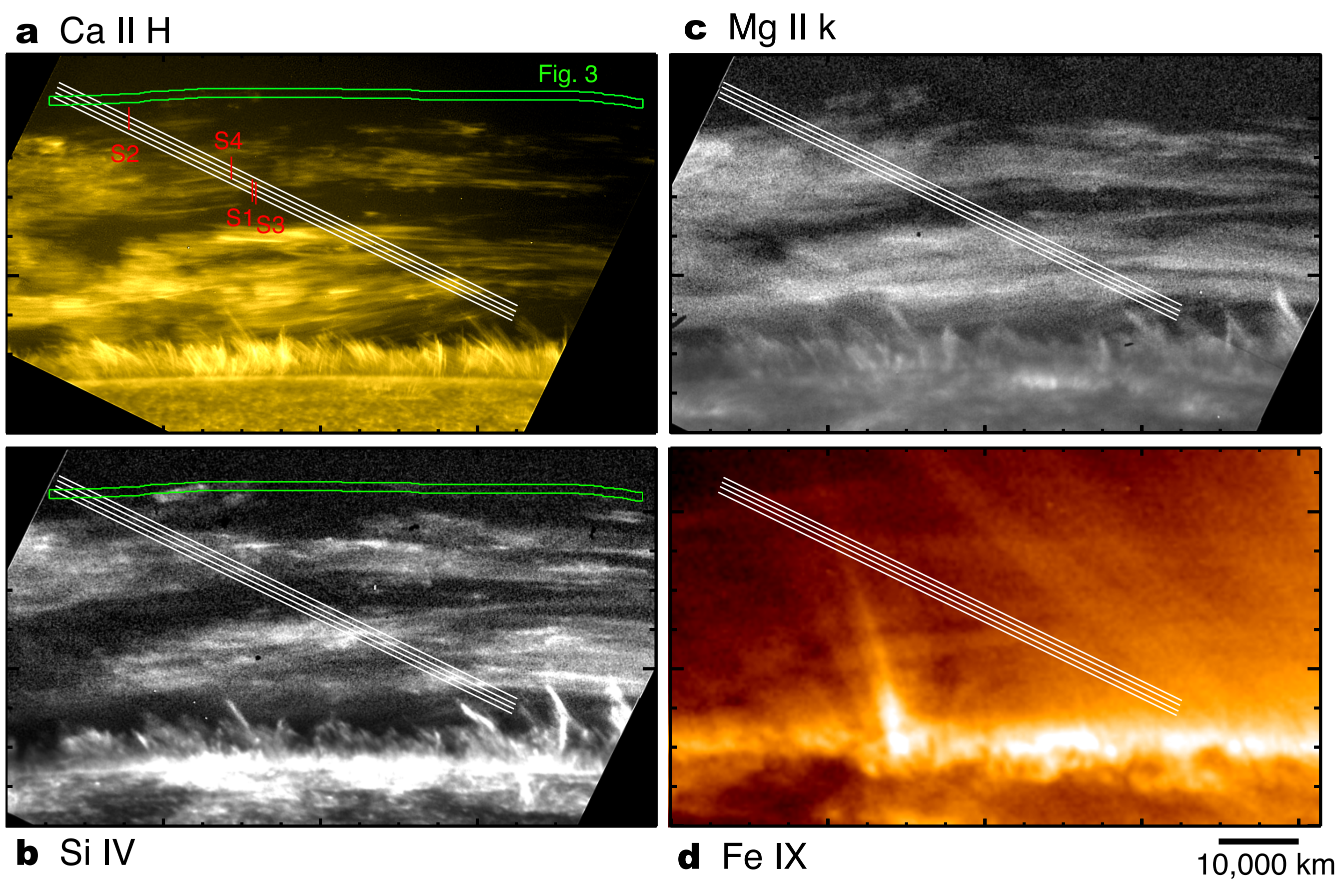


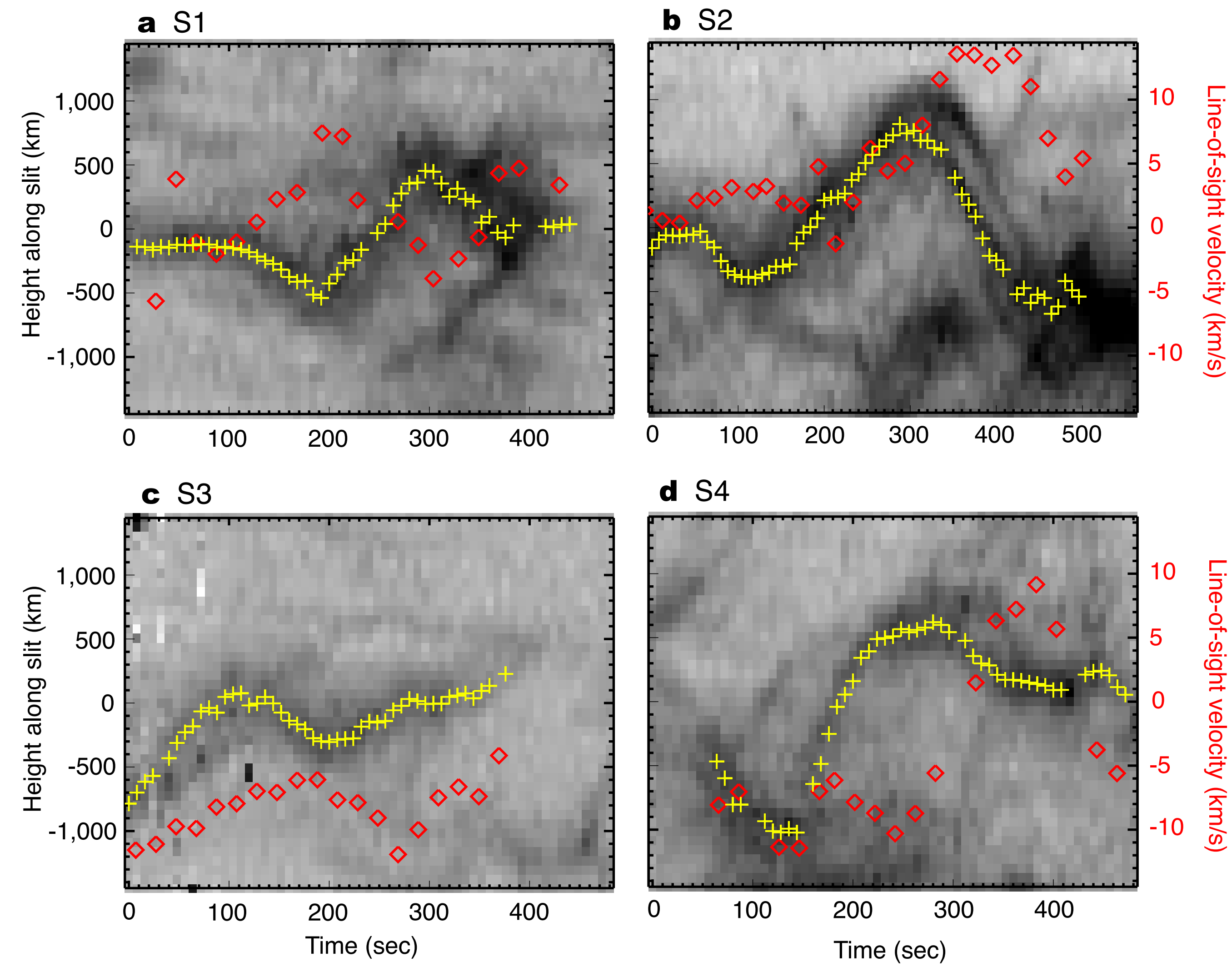


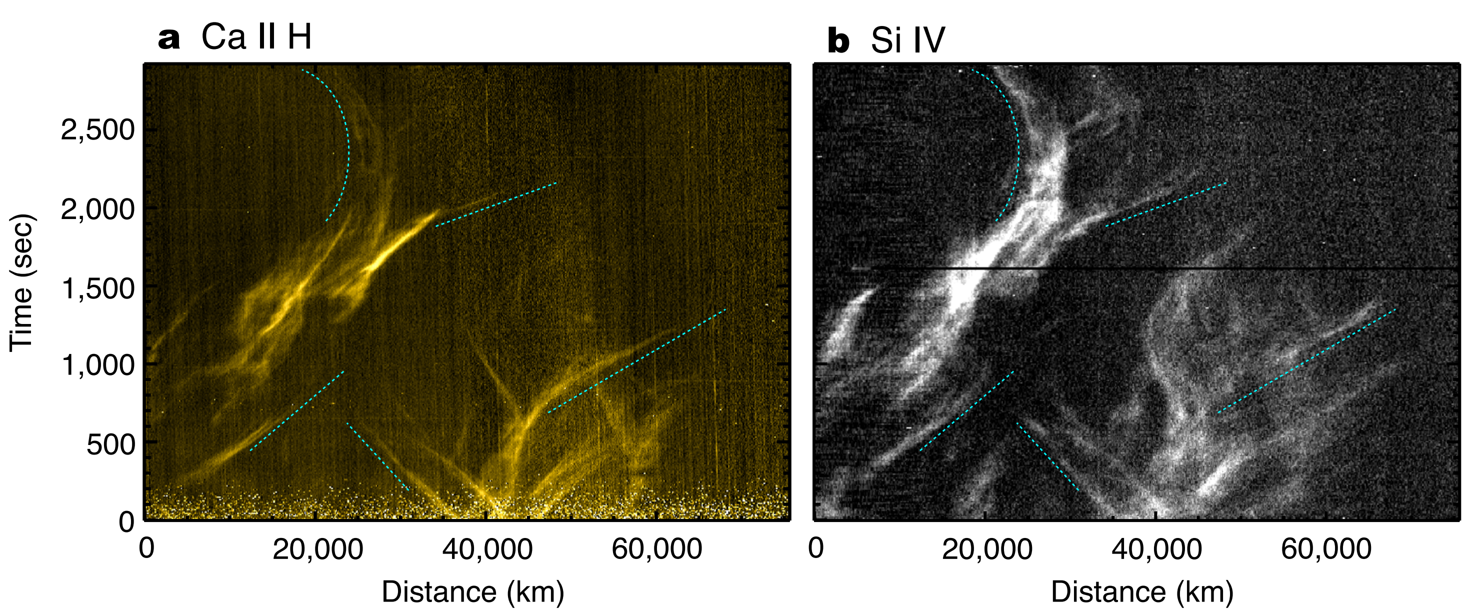
IRIS/SG

IRIS/Hinode observations

Okamoto et al. (2015, ApJ accepted)

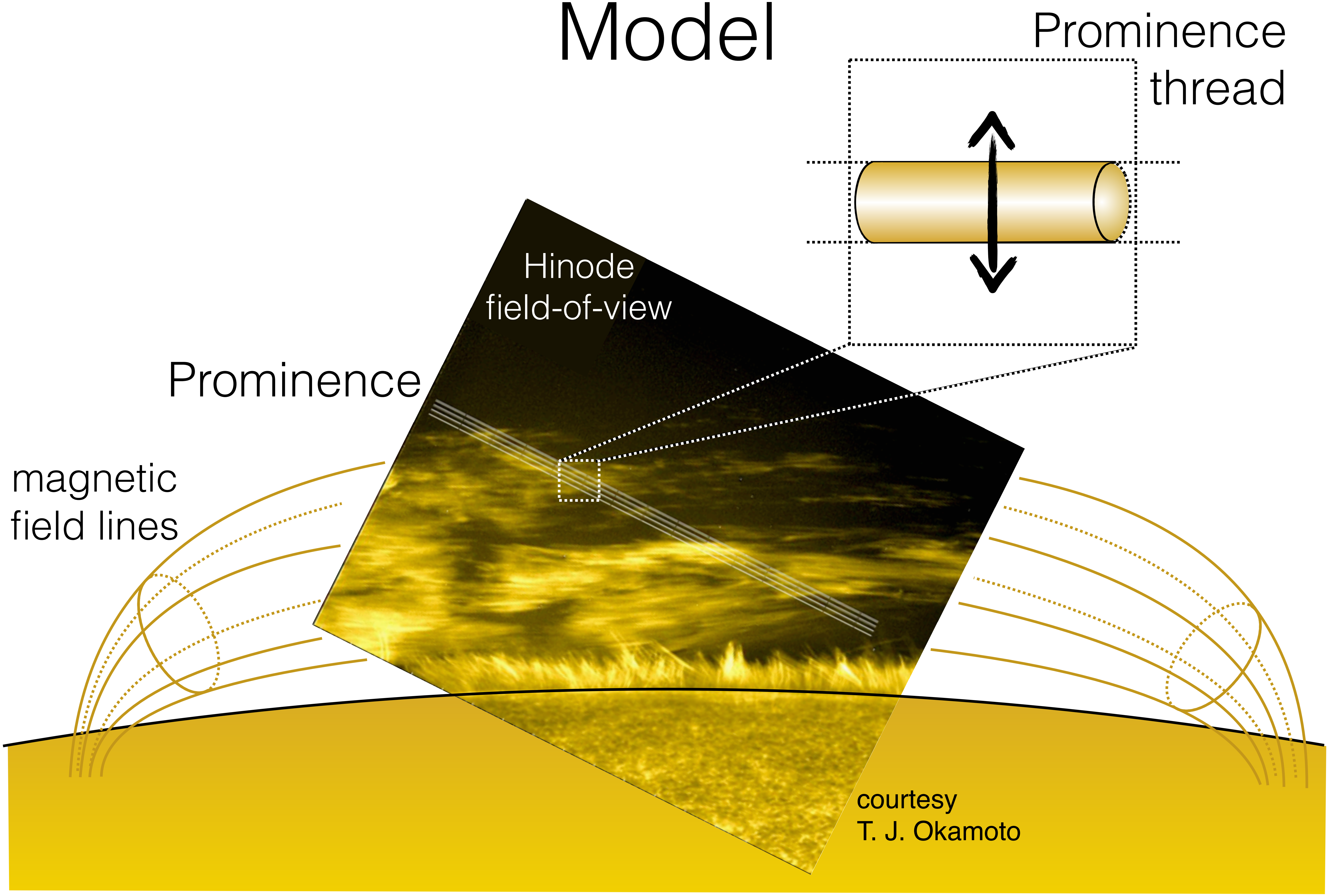




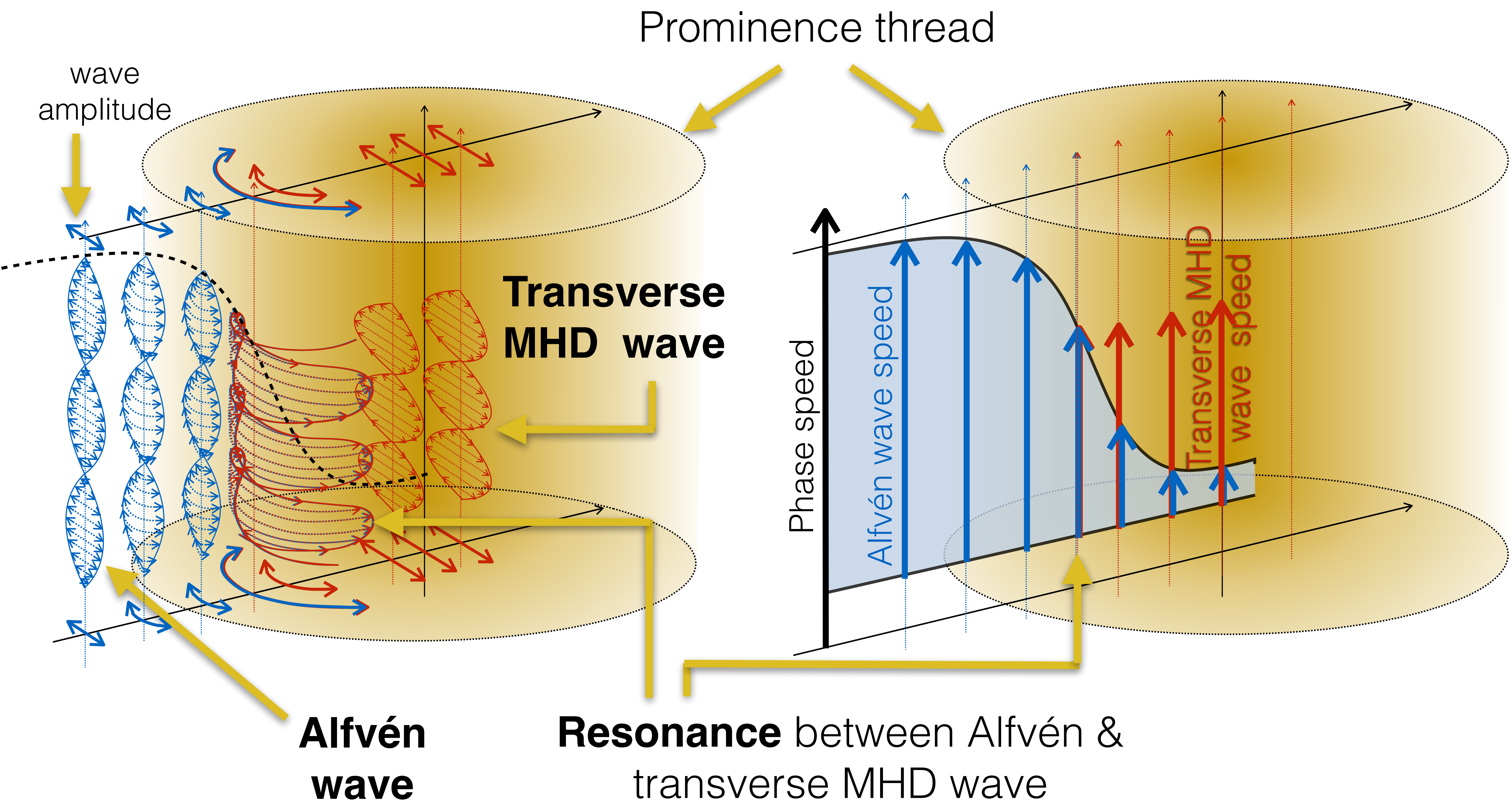


- 90°-180° phase difference between displacement in POS and LOS velocity
- Heating from chromospheric to TR temperatures
- Thread-like structure

Model

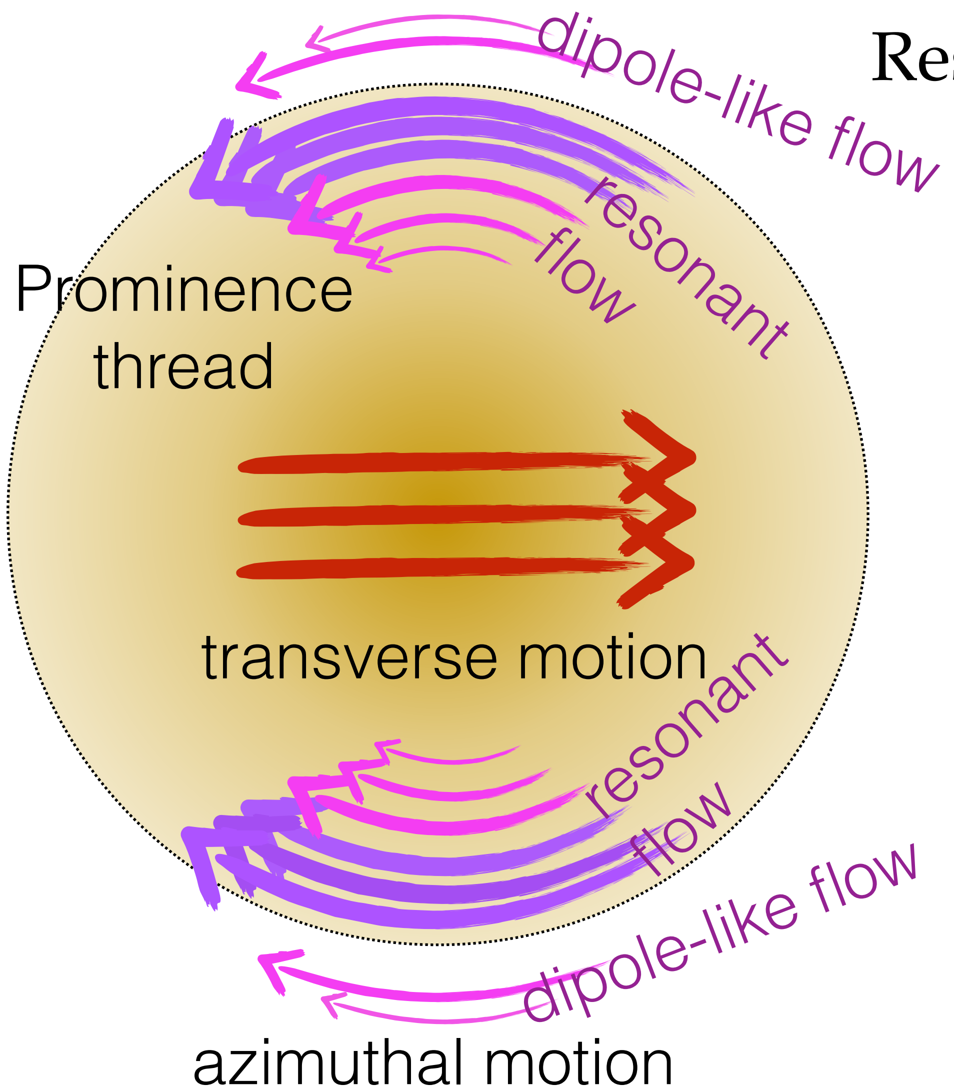

Prominence
thread
Hinode
field-of-view
Prominence
magnetic
field lines
courtesy
T. J. Okamoto

Resonant absorption

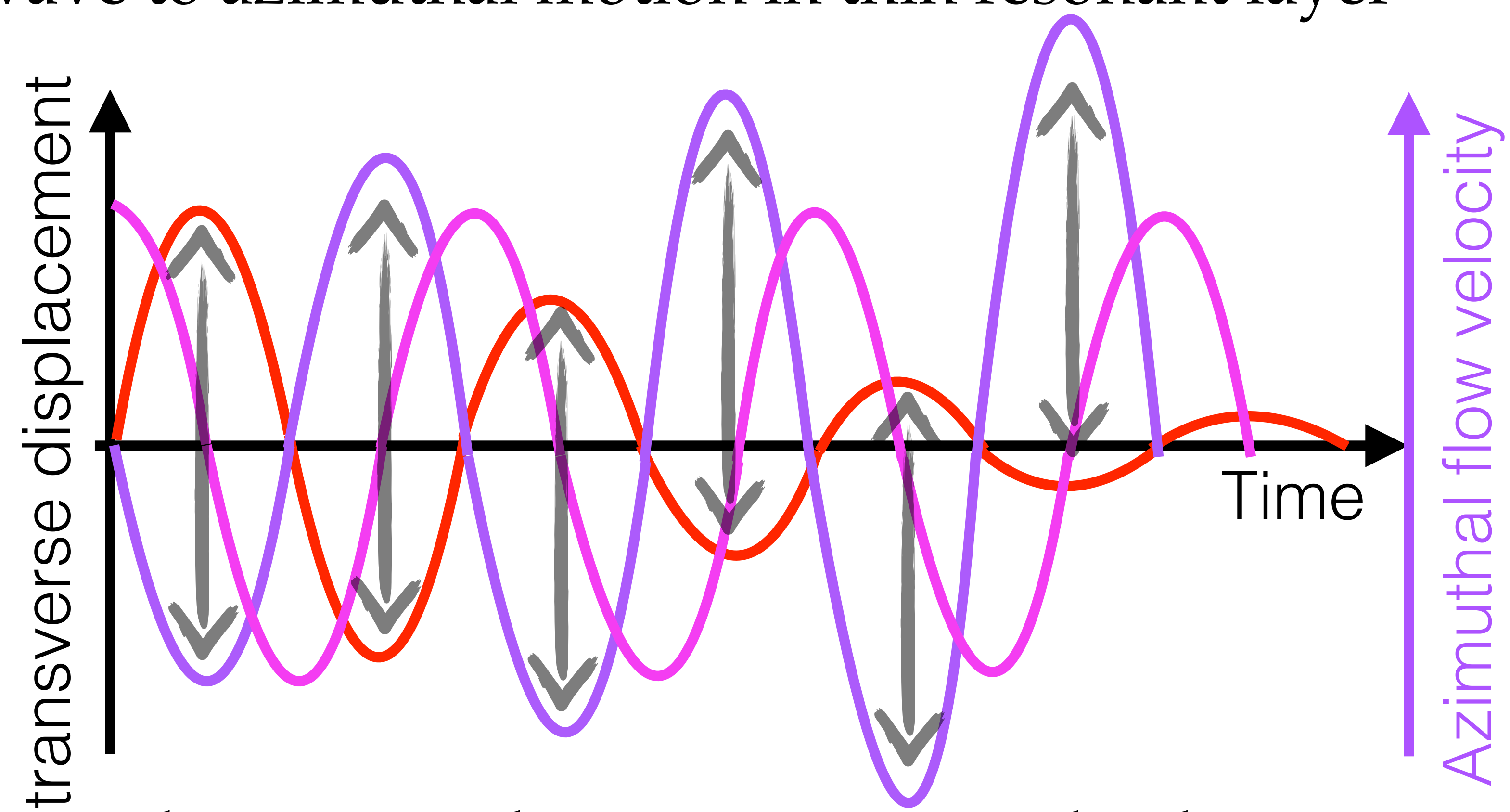


Ionson 1978, Hollweg+ 1990, Sakurai+ 1991, Goossens+ 1992, 2002, 2012; Van Doorsselaere+ 2004, Arregui+ 2008, 2011; Verth+ 2010, Soler+ 2010, 2012; Pascoe+ 2010, 2012

Resonant absorption



Resonant absorption transfers energy from transverse wave to azimuthal motion in thin resonant layer



The drift of phase speed across the thread generates an increasing phase difference between the transverse and azimuthal motion

- Very successful in explaining observed fast and frequency dependent damping (Nakariakov+1999, Verth+ 2010, Arregui & Ballester 2011)

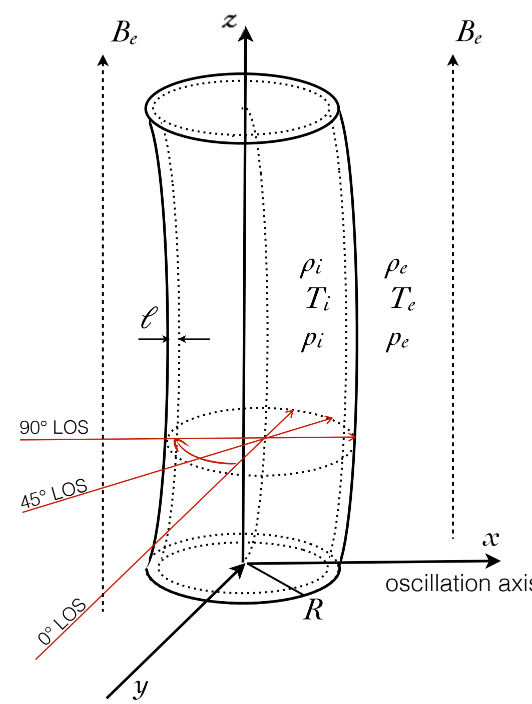
Problems: **-** resonant layer is too small in order to detect the azimuthal flow
- efficient for mode conversion but inefficient for heating (phase mixing)

Numerical model

- 3D MHD simulations of a flux tube oscillating with the kink mode. CIP-MOCCT code (Kudoh et al. 1999) with constant resistivity and viscosity
- Grid (x,y,z): (512, 256, 100) - (1024, 512, 100) $S, R \approx 10^4 - 10^7$
- Initial condition: sinusoidal velocity perturbation in x-direction

spicule model

parameters	coronal loop	prominence	spicule
$\frac{T_i}{T_e}, T_i$ [K]	1/3, T	1/100, T	1/100, T
$\frac{\rho_i}{\rho_e}, \rho_i$[cm	3, ρ	10, ρ	50, ρ
B [G]	22.8 G	18.6 G	14.5 G
c	1574	776	255
$P \approx \frac{2L}{c_k}$ [s]	525	256	245
β_i	0.02	0.001	0.01
ℓ [R]	0.2-0.8	0.4	0.4

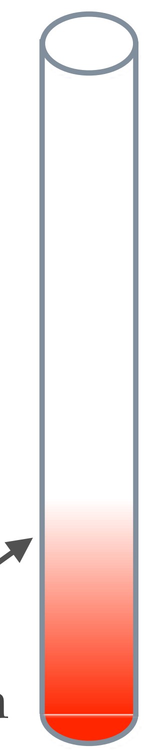


Amplitude: <15 km/s

$R = 1$ Mm

$L = 200\ R$

$k = \frac{\pi}{L} \approx 0.015$



transition region

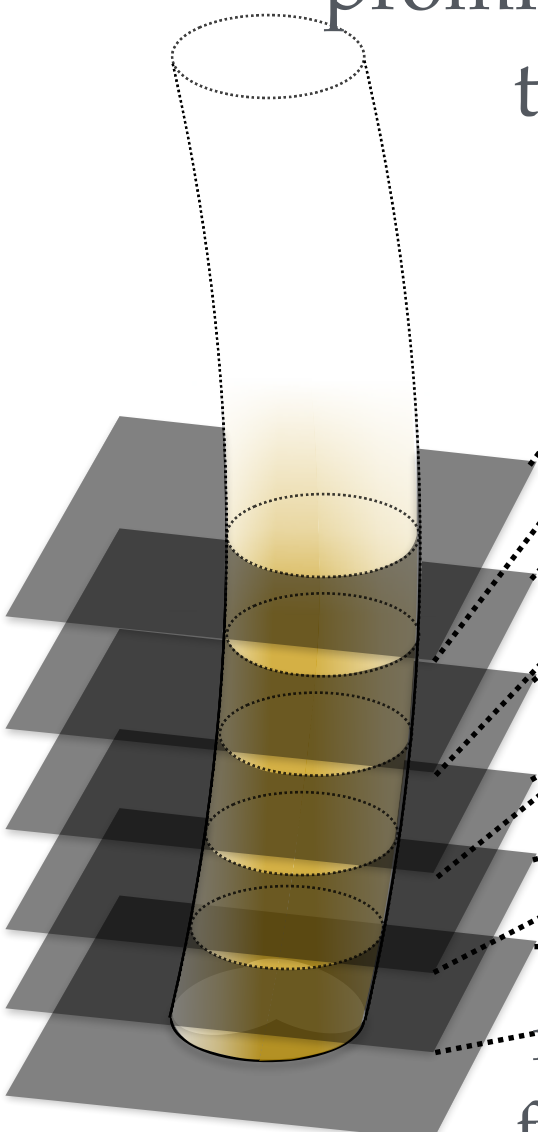
Forward modelling

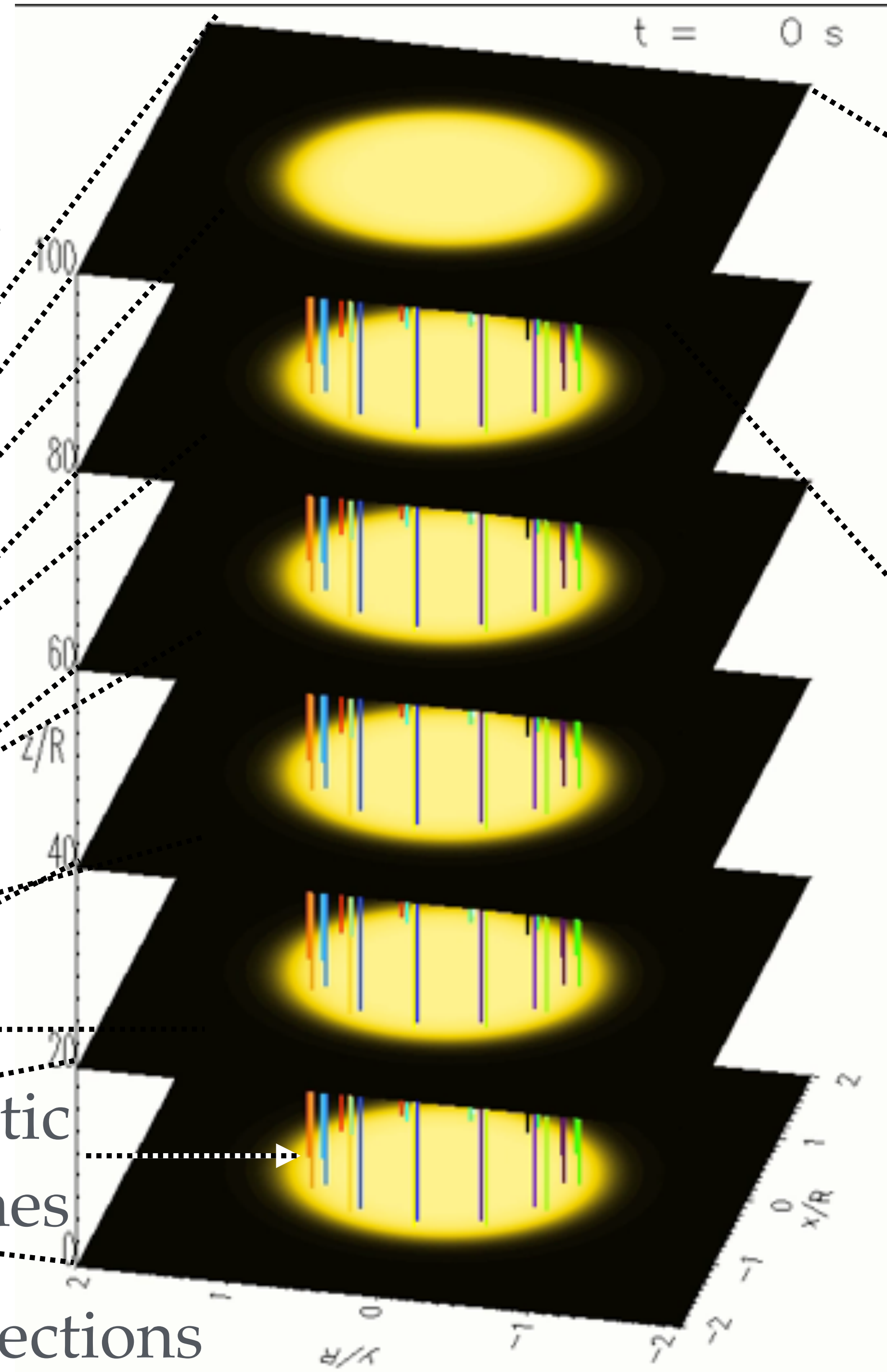
- Optically thin: **FoMo** (Antolin & Van Doorsselaere 2013)
- Optically thick: **RH** (Uitenbroek 2011)

https://wiki.esat.kuleuven.be/FoMo

Two mechanisms combined

Half prominence thread

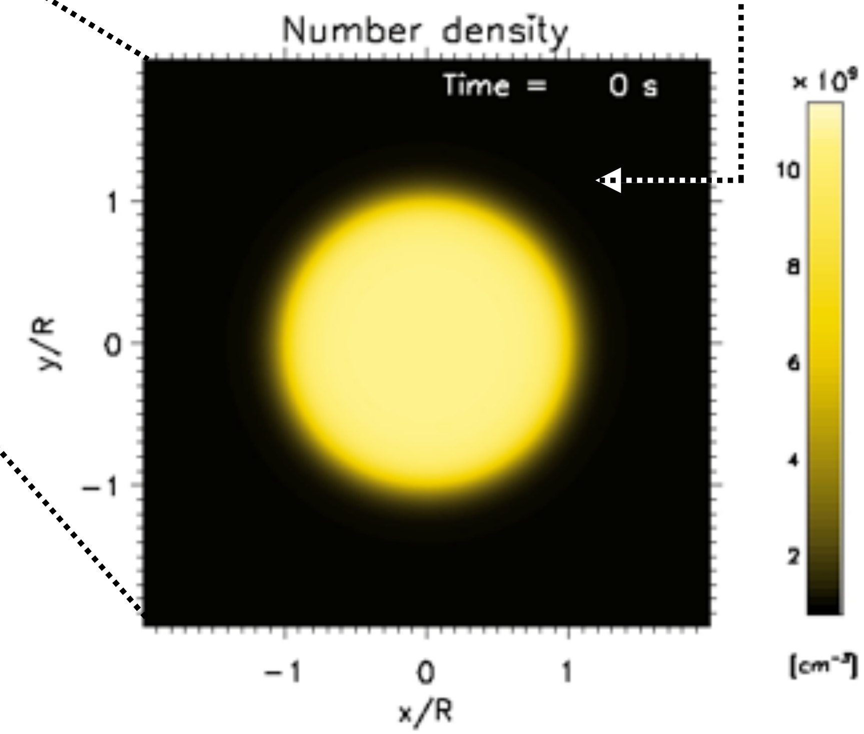




magnetic field lines

Density cross-sections

Azimuthal flow inside the thread is due to **resonant absorption**



Flow generated by transverse + azimuthal motion triggers an instability: **turbulence is generated**

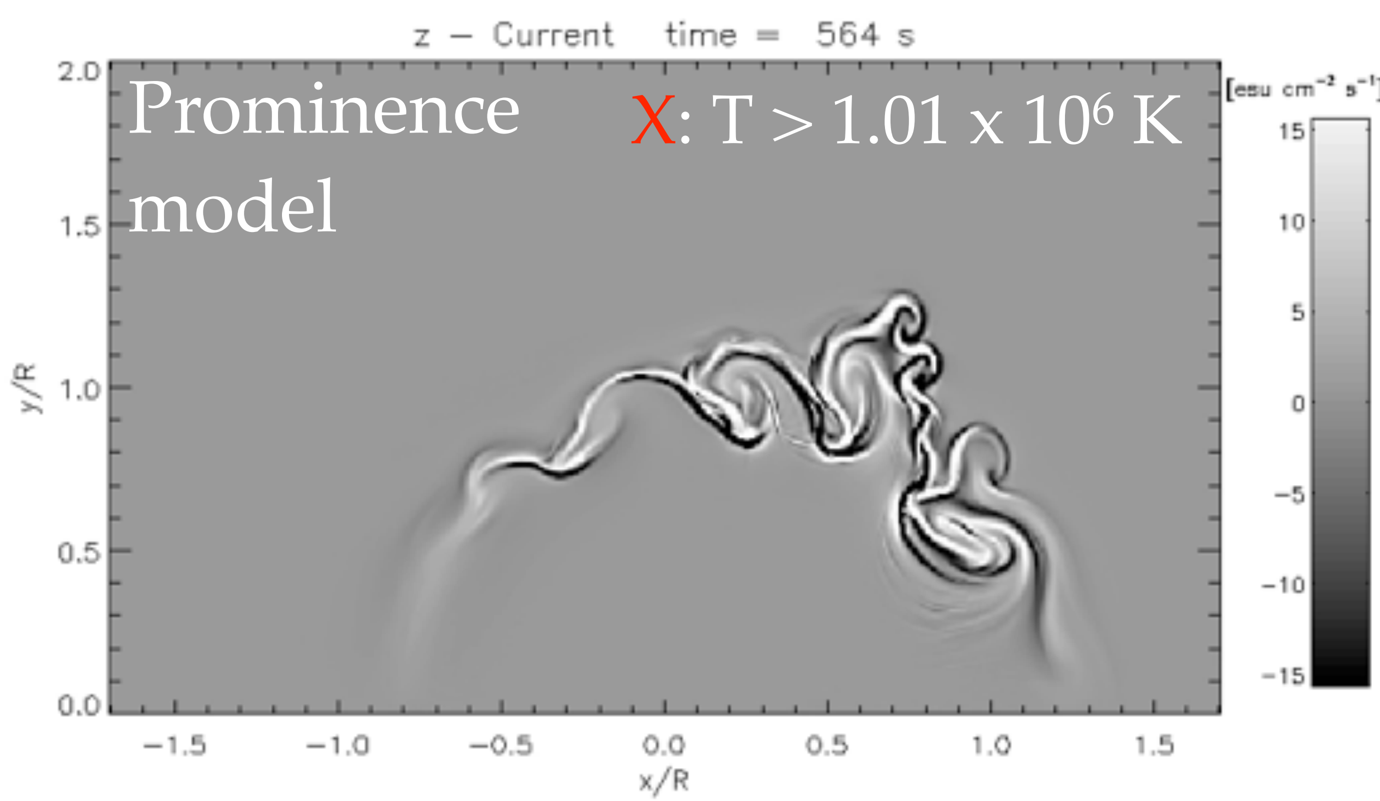
Model: Uchimoto+. 1991; Karpen+ 1993, Ofman+ 1994; Ziegler & Ulmschneider 1997; Terradas+ 2008, Soler+ 2010; **Obs**: Foullon+ 2011; Ofman & Thompson 2011, Berger+ 2010).

Resonant absorption & onset of K-H instability

- Onset of instability ~ 1-3 P

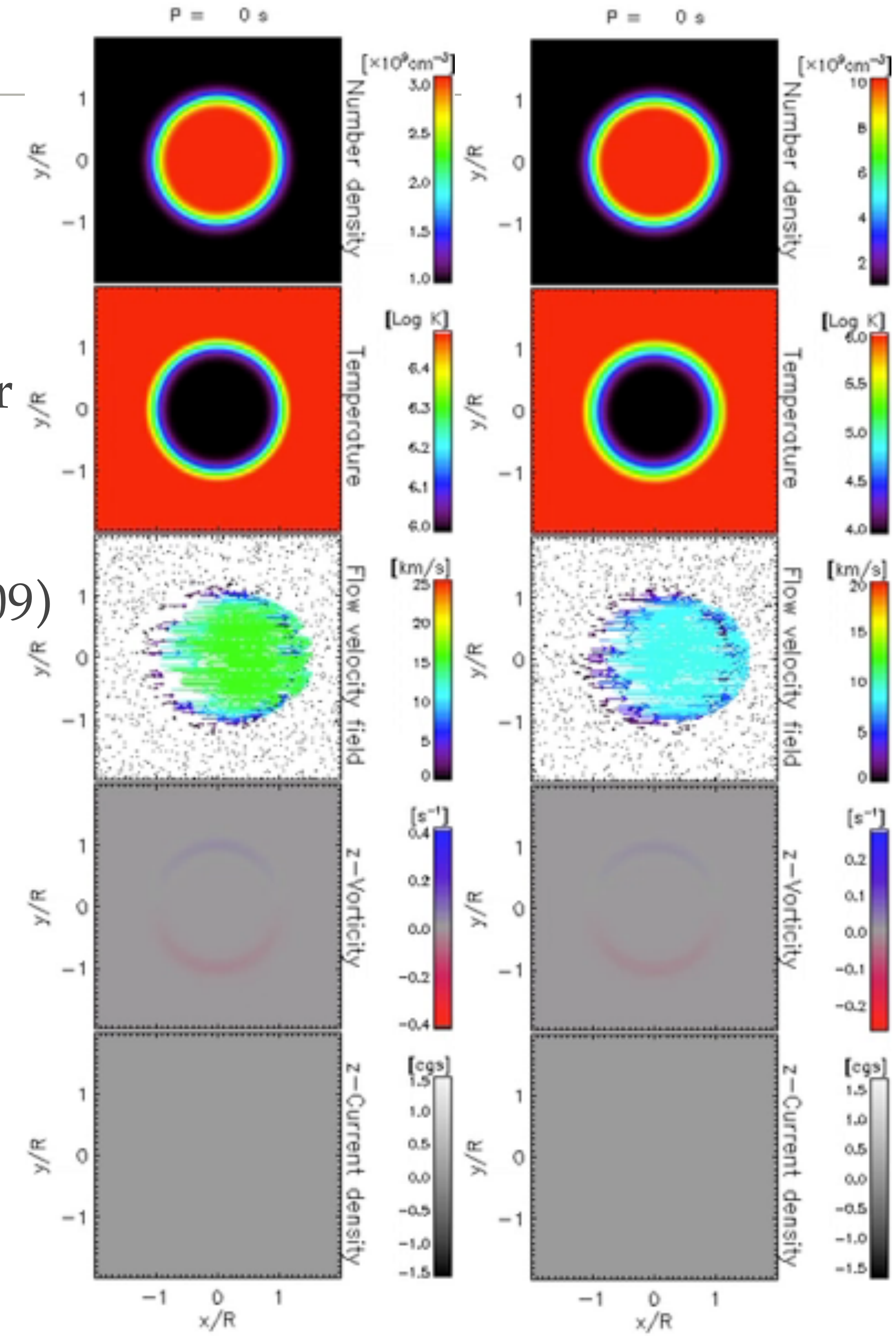
$$\frac{v_0}{v_{A_i}} > \frac{\pi}{m\sqrt{2}}\frac{R}{L}\sqrt{1+\frac{\rho_i}{\rho_e}}$$

- KHI vortices obtain momentum from resonant layer
- Non-uniform boundary layer widens, apparent mixing of plasma (Fujimoto & Terasawa 1994)
- Multiple vortices & current sheets (Ofman 1994, 2009)



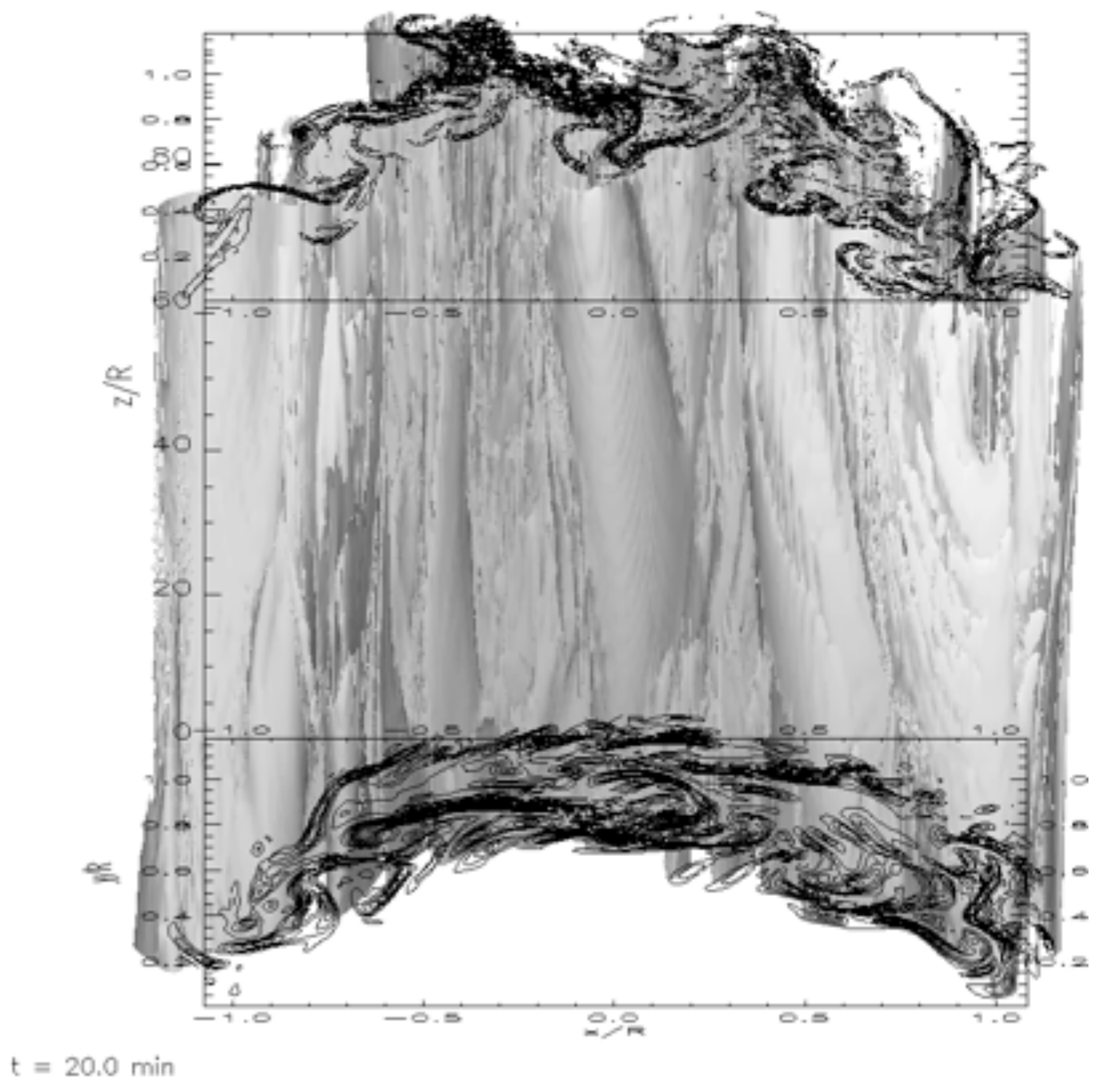
Coronal model
v~14 km/s, 1/R ~ 0.4
P = 255 s, Amp = 414 km

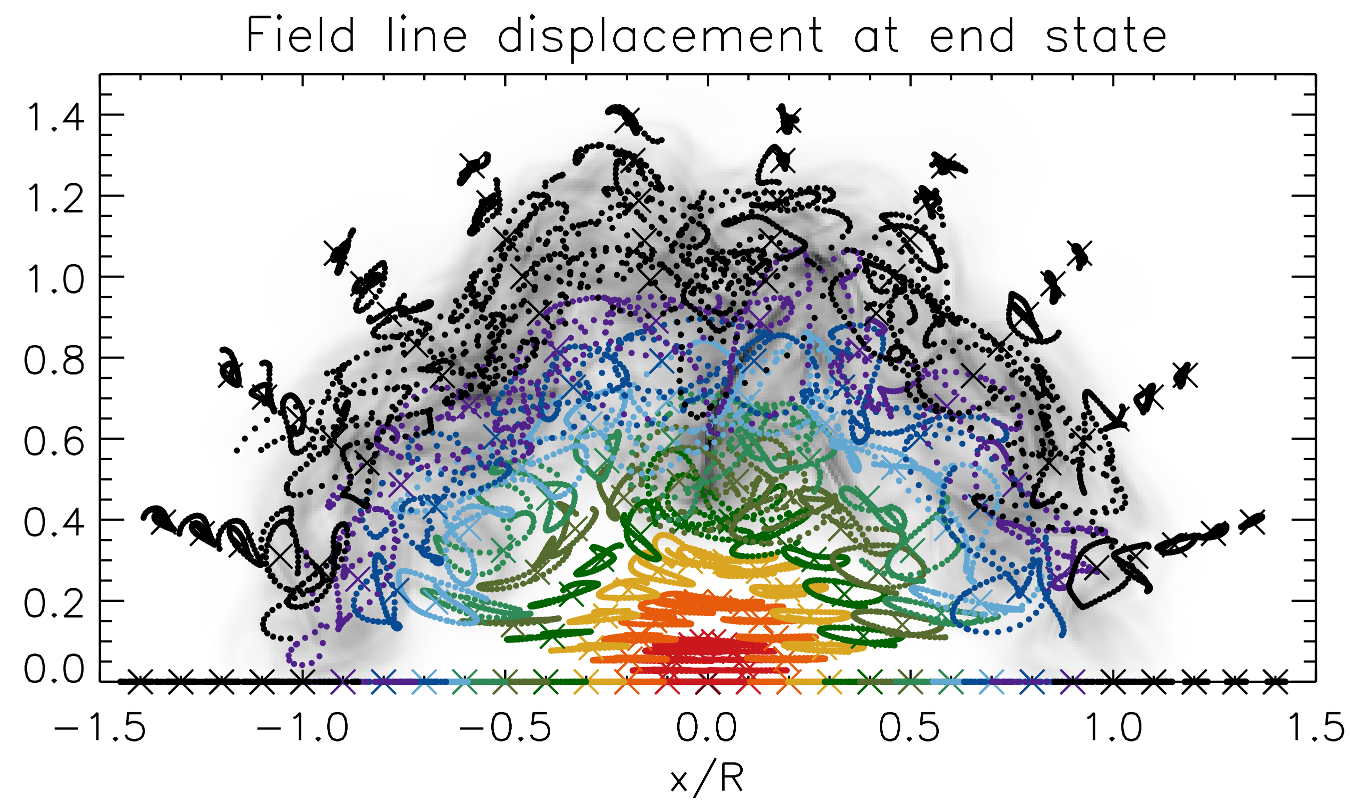
Prominence model
v~8 km/s, 1/R ~ 0.4
P = 515 s, Amp = 711 km



Braiding

Isocontour of |j|

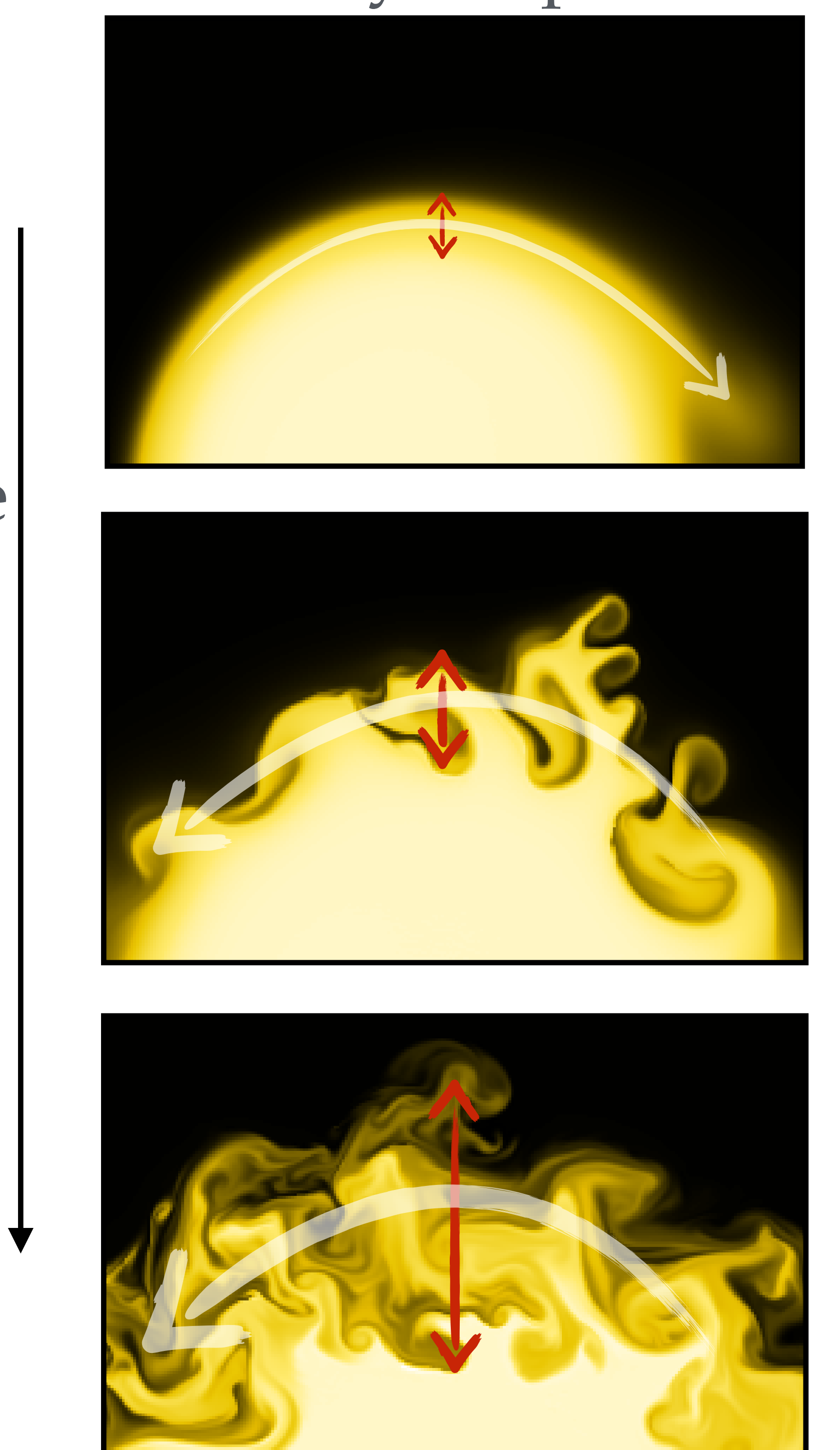




- Vortices degenerate into turbulence, producing twisted current sheets which may be preferential locations for reconnection

The role of the instability

Density snapshots



Time

“The great wave off Kanagawa” by Hokusai (1830)

Vortices (and turbulence) are generated by the Kelvin-Helmholtz instability. A similar instability generates waves in the ocean

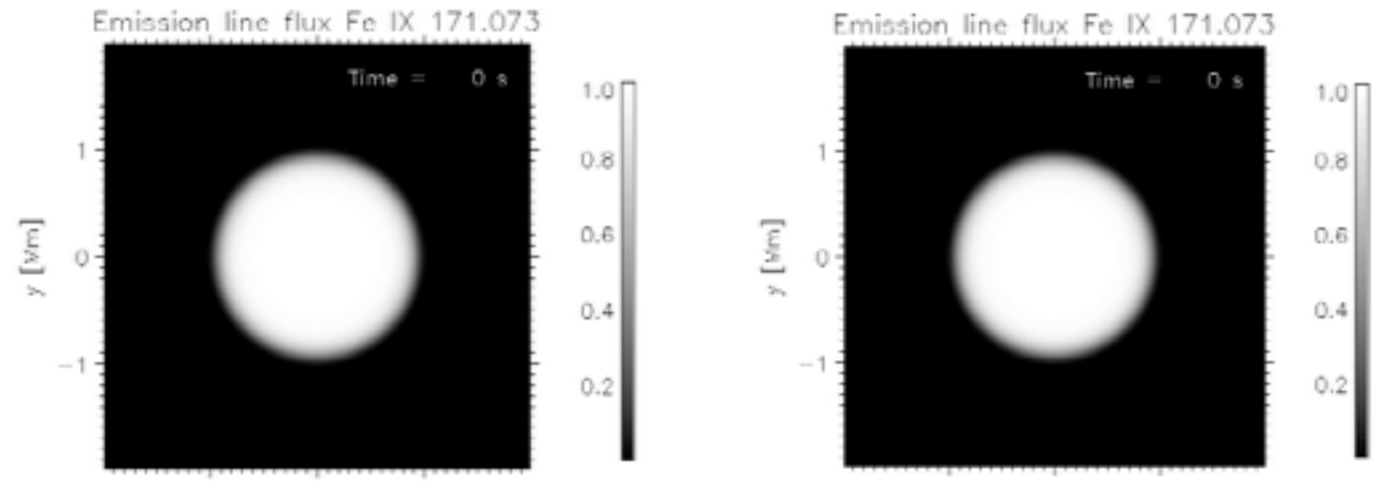
The instability couples with resonant absorption to:

- **Heat the thread significantly**
- **Enlarge** the azimuthal flow from the resonance: **IRIS is able to detect it**

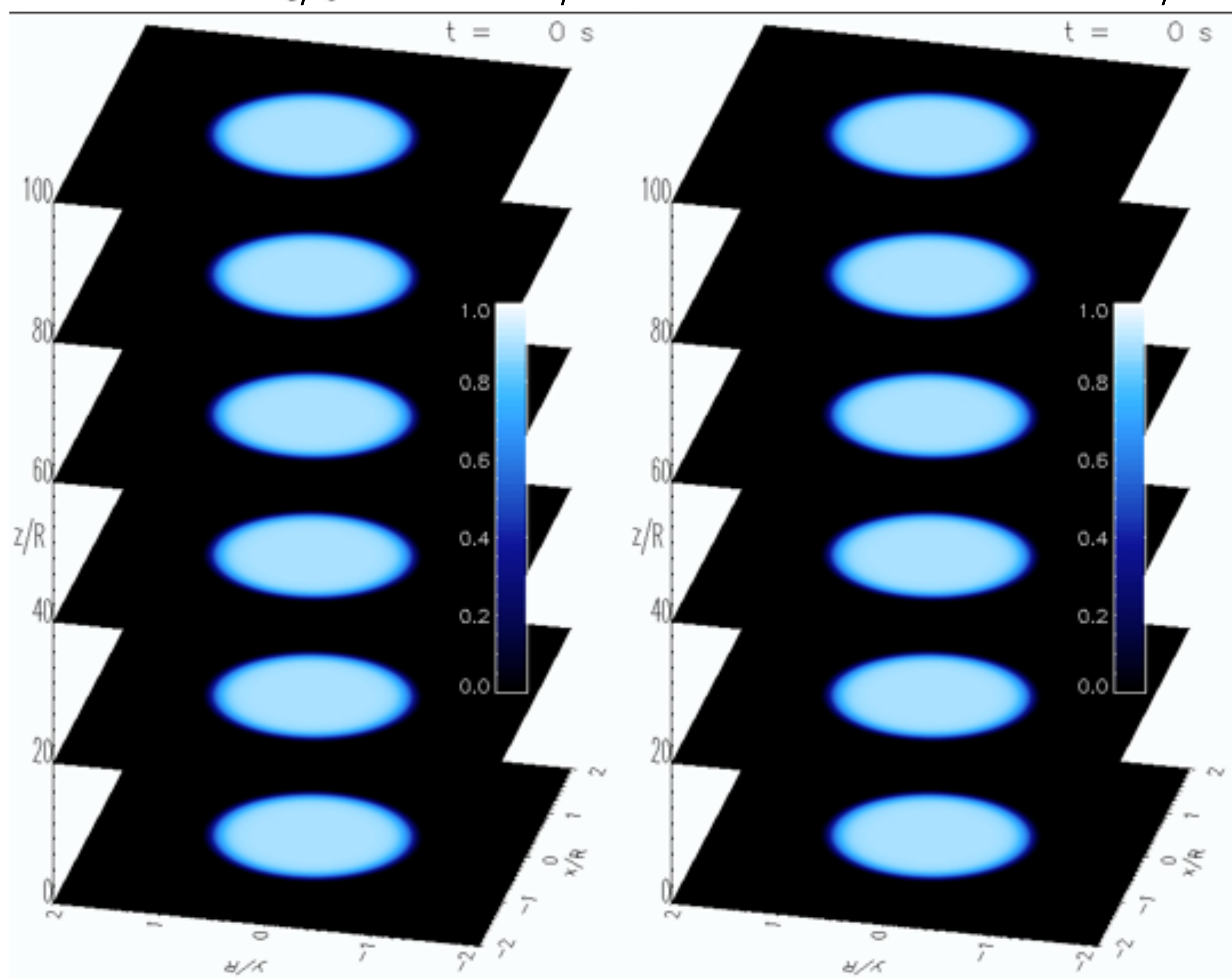
Forward modelling

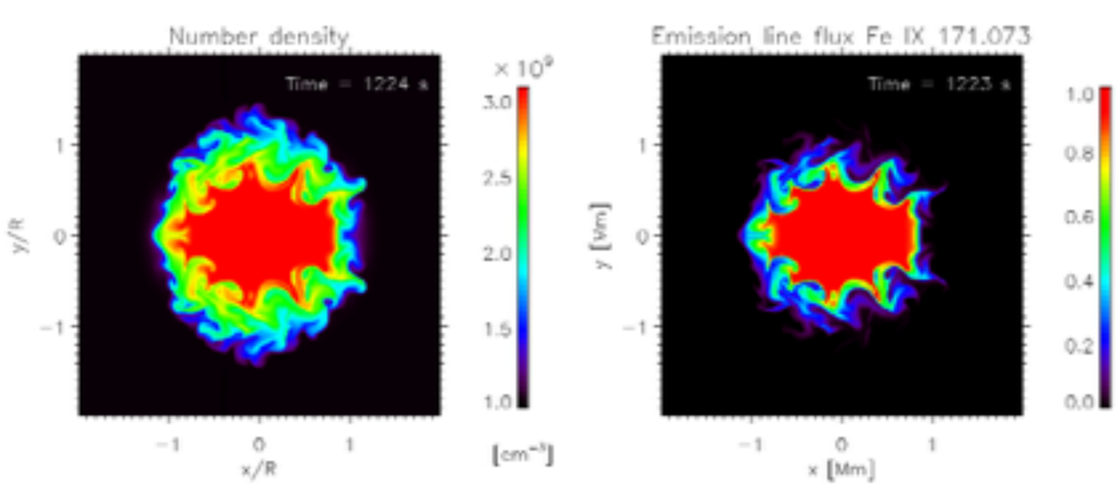
$G_{171}(T,n)\rho^2$ for coronal model

- Protruding eddies appear as distinct emission features
- Eddies <-> roll-ups in 3D
- Shuffling of field lines: twisting and possible braiding of loops from magnetic reconnection (Lapenta & Knoll 2003)
- Widening of boundary layer does not show up in emission line flux: constraint for seismology estimates (Soler et al. 2014)



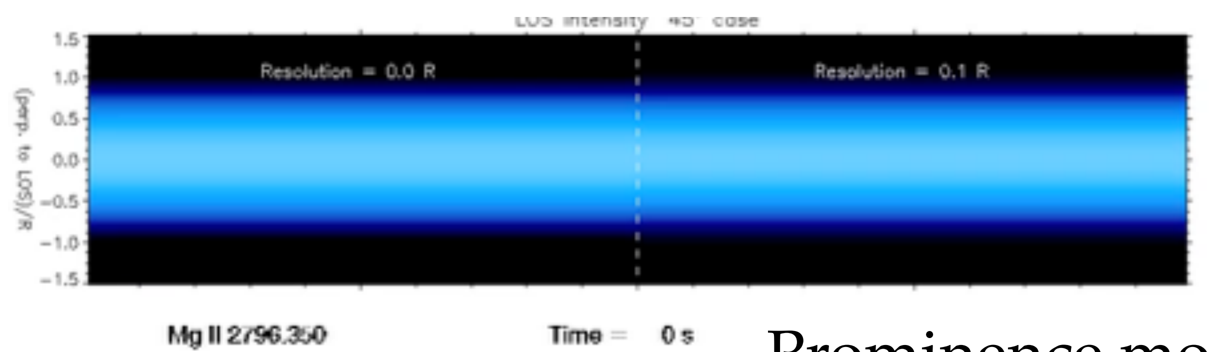
v < 15 km/s   1/R ~ 0.4   v < 3 km/s



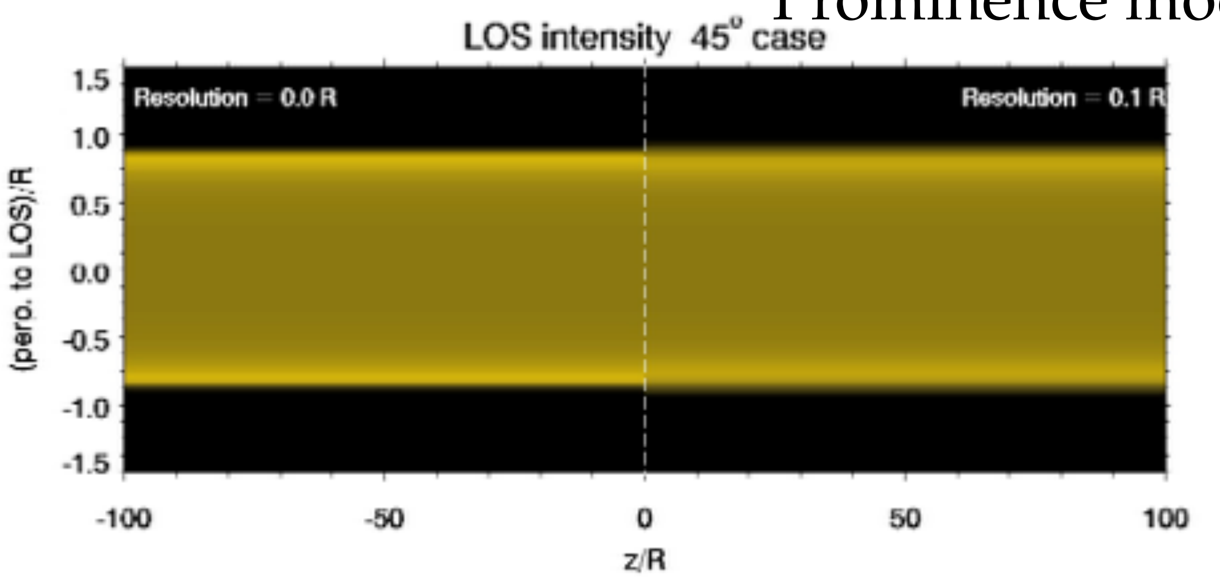


Strand-like structure

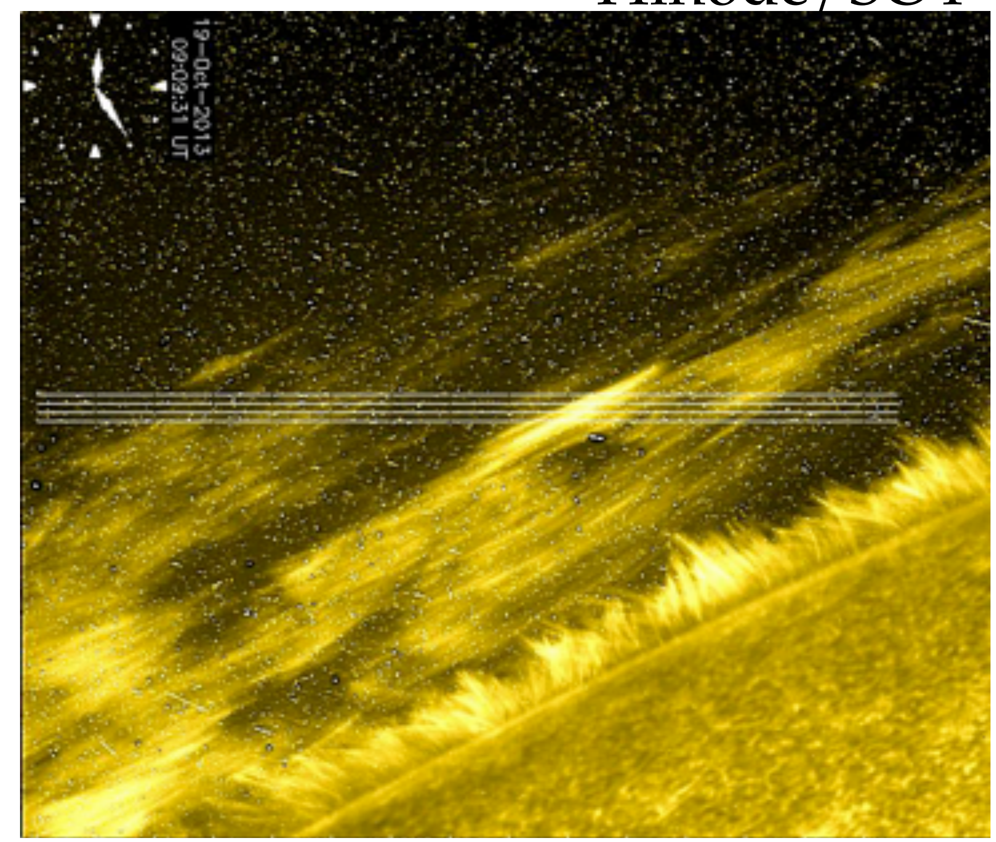
v < 15 km/s, l/R ~ 0.4 Coronal model



Prominence model



Hinode/SOT



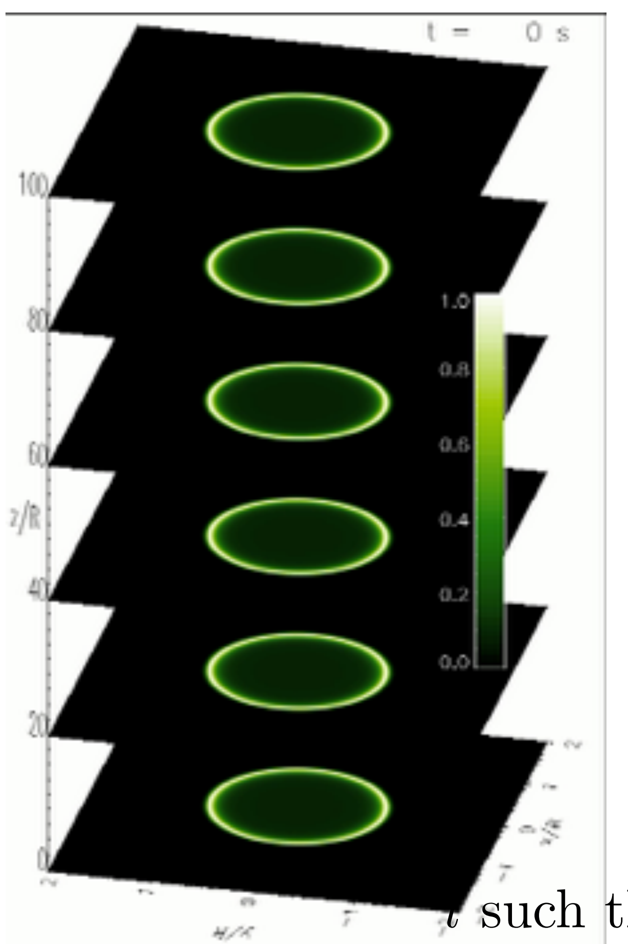
- Roll-ups (eddies) along the loop + fine scale+ line-of-sight effects
  - ➝ **strand-like or thread-like structure in intensity images**
  - ➝ **KHI vortices <—> prominence threads?**
- Lifetime for 1 strand ~ 1 period. Widths: 0.01 R - 0.5 R
- Apparent crossing of strands/threads

Prominence modelling

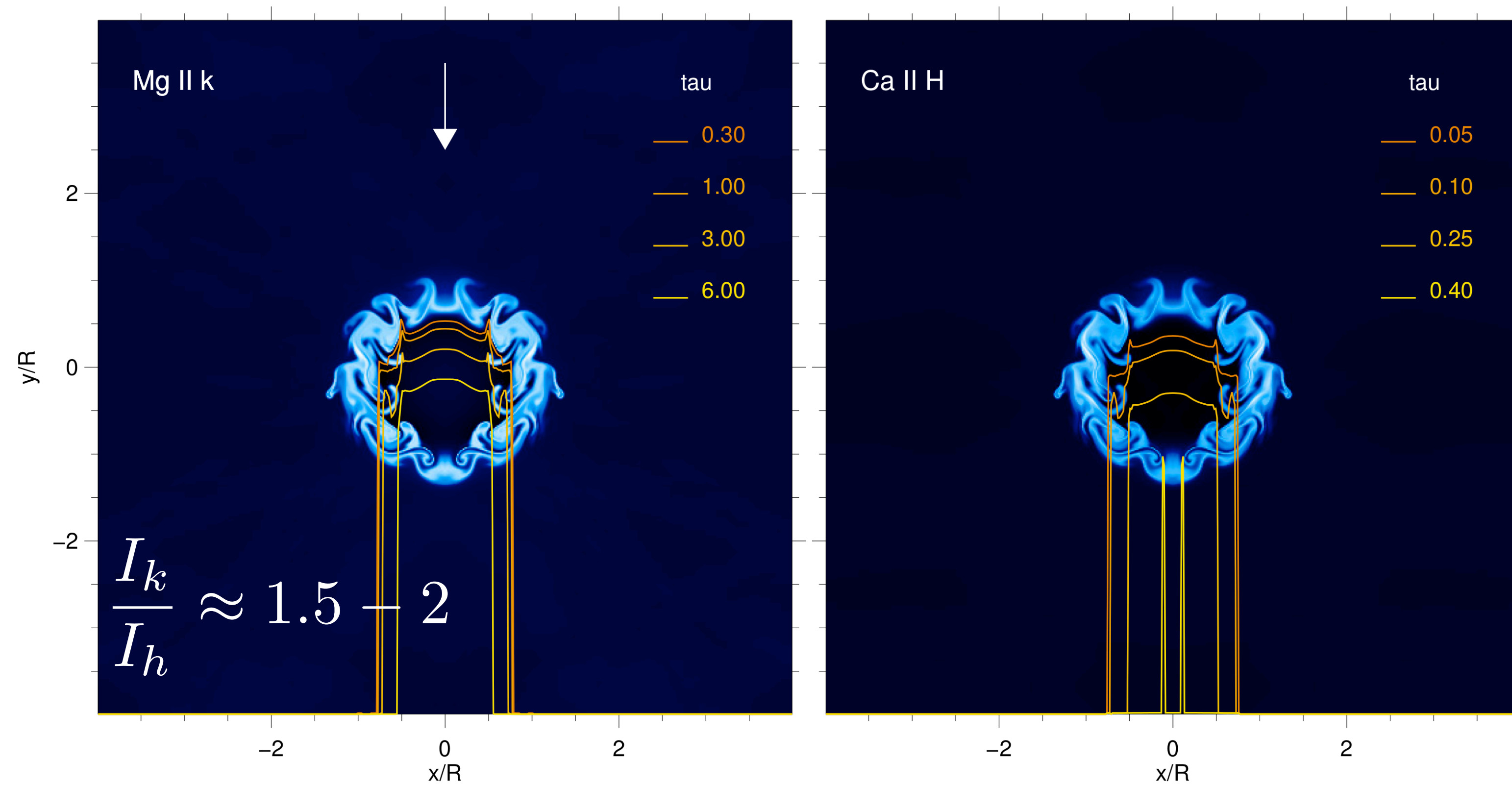
Forward modelling of Mg II h & k and Ca II H & K with RH code

- Emission comes mostly from ring, mostly optically thin. The prominence core is optically thick in Mg II h&k (temperature effect due to LTE formation)

Mg II k emissivity cross-sections



Source function with RH



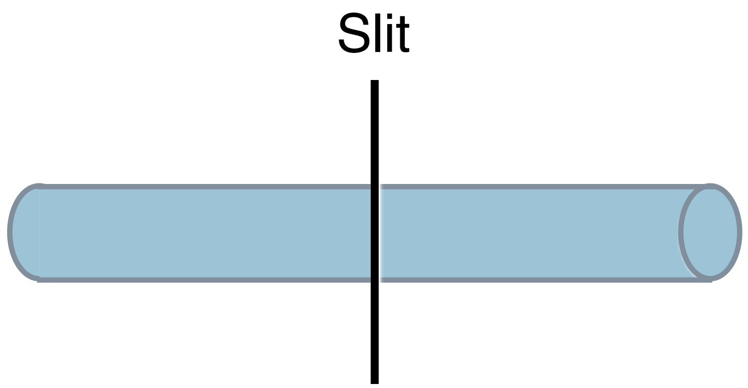
Resonant flow is visible to IRIS

Approximation to optically thick rays with CHIANTI:

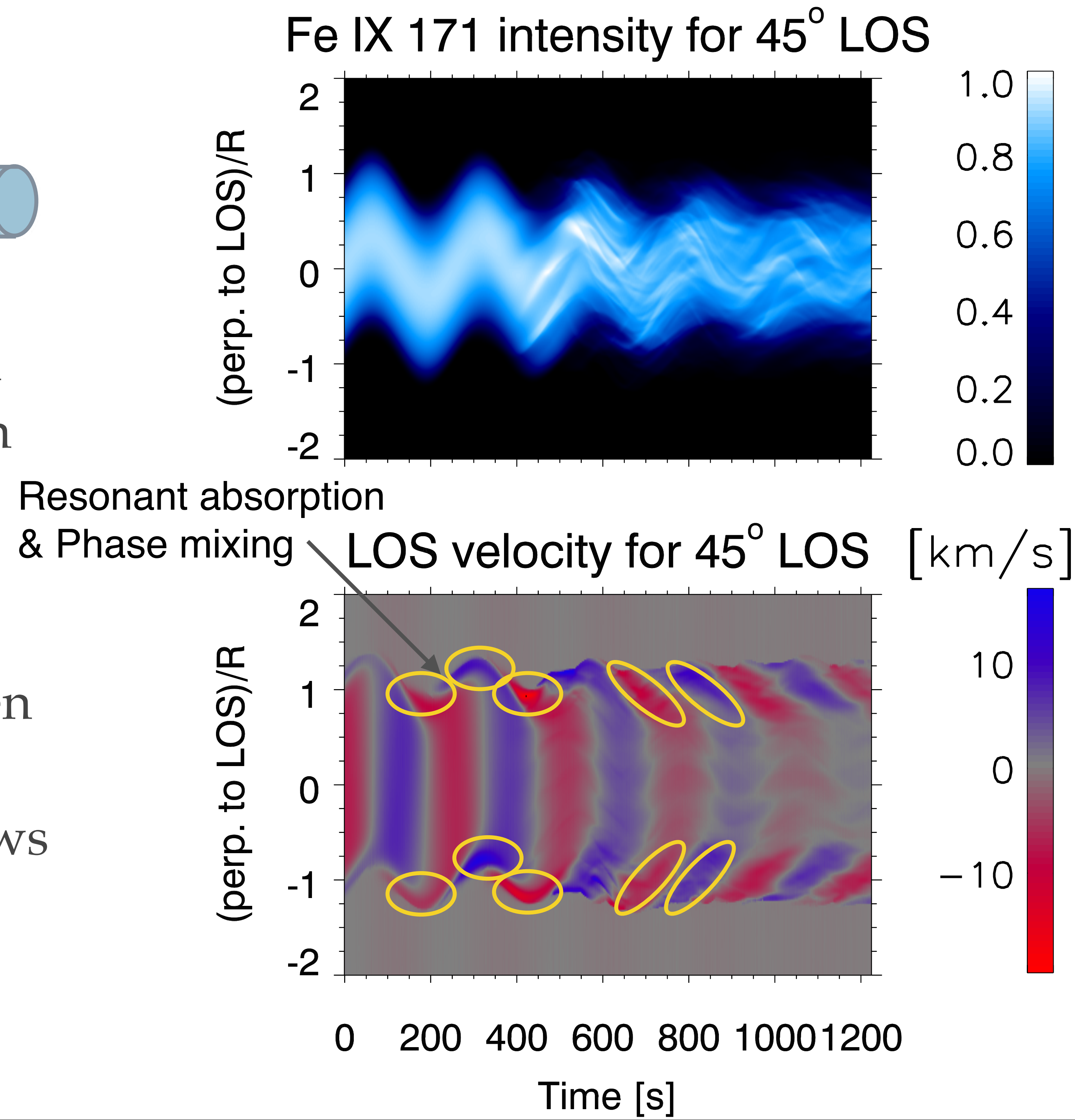
$$I^{\mathrm{OT}}_{\lambda,\mathrm{ray}} \propto \int_0^l G_\lambda(T,n) n_e^2 dl' \quad G_\lambda(T,n) \approx E_{ij} A_{ij} \frac{N_j(X^{+m})}{N(X^{+m})} \frac{N(X^{+m})}{N(X)} \frac{1}{N_e}$$

l such that $\int_0^l G_\lambda(T(t),n(t)) n_e(t)^2 dl' = \mathrm{OT} \times \int_0^{L_{\max}} G_\lambda(T(0),n(0)) n_e(0)^2 dl'$

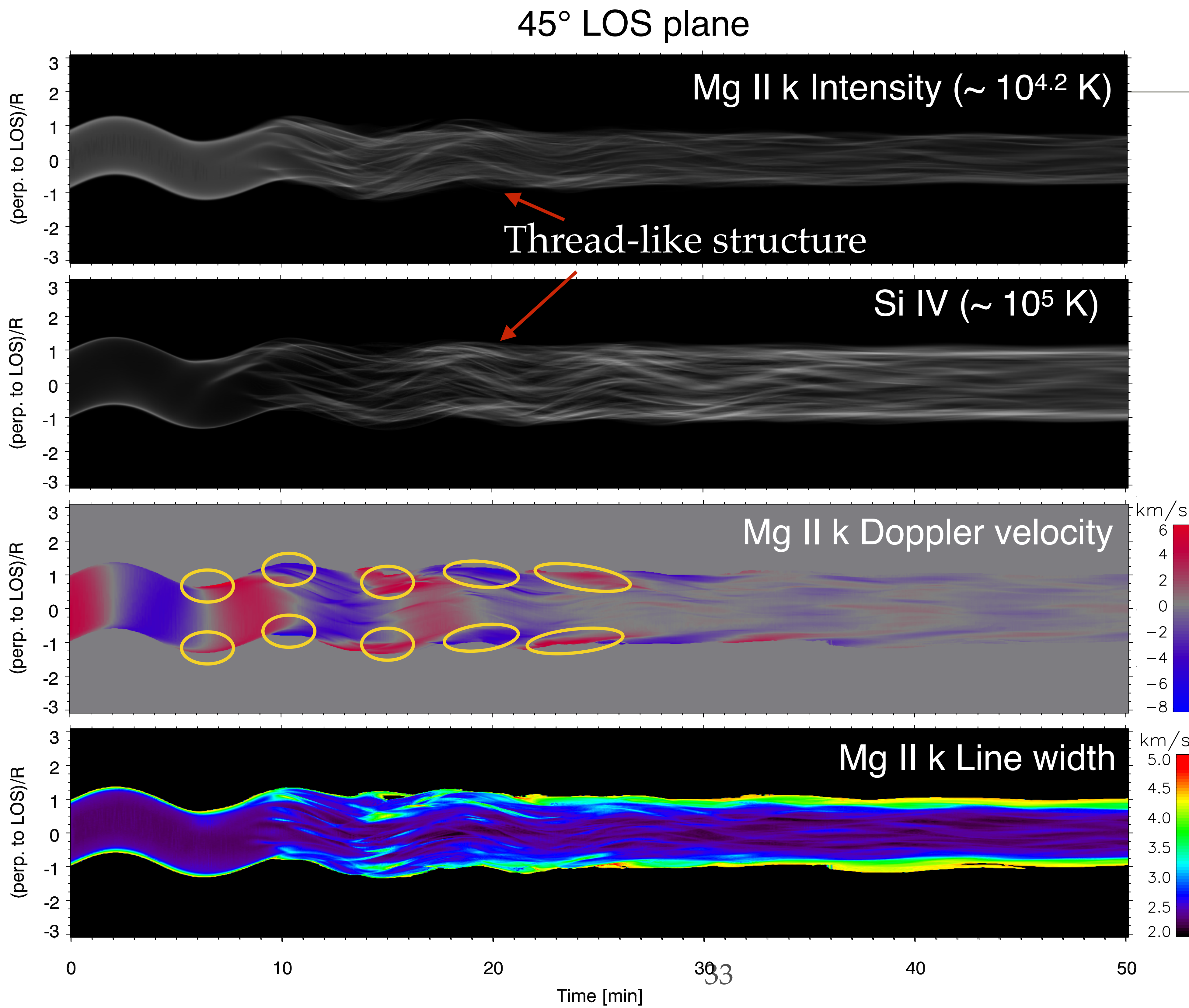
Spectral signatures



- Azimuthal flows with torsional character (m=1 torsional Alfvén waves) are created around the boundary due to resonant absorption
- Out of phase behaviour between azimuthal flows (Doppler component) and transverse flows (plane-of-the-sky component)



Observational signatures



fading & thinning in chromospheric lines

appears in TR lines, broadened

LOS velocity out-of-phase with POS motion

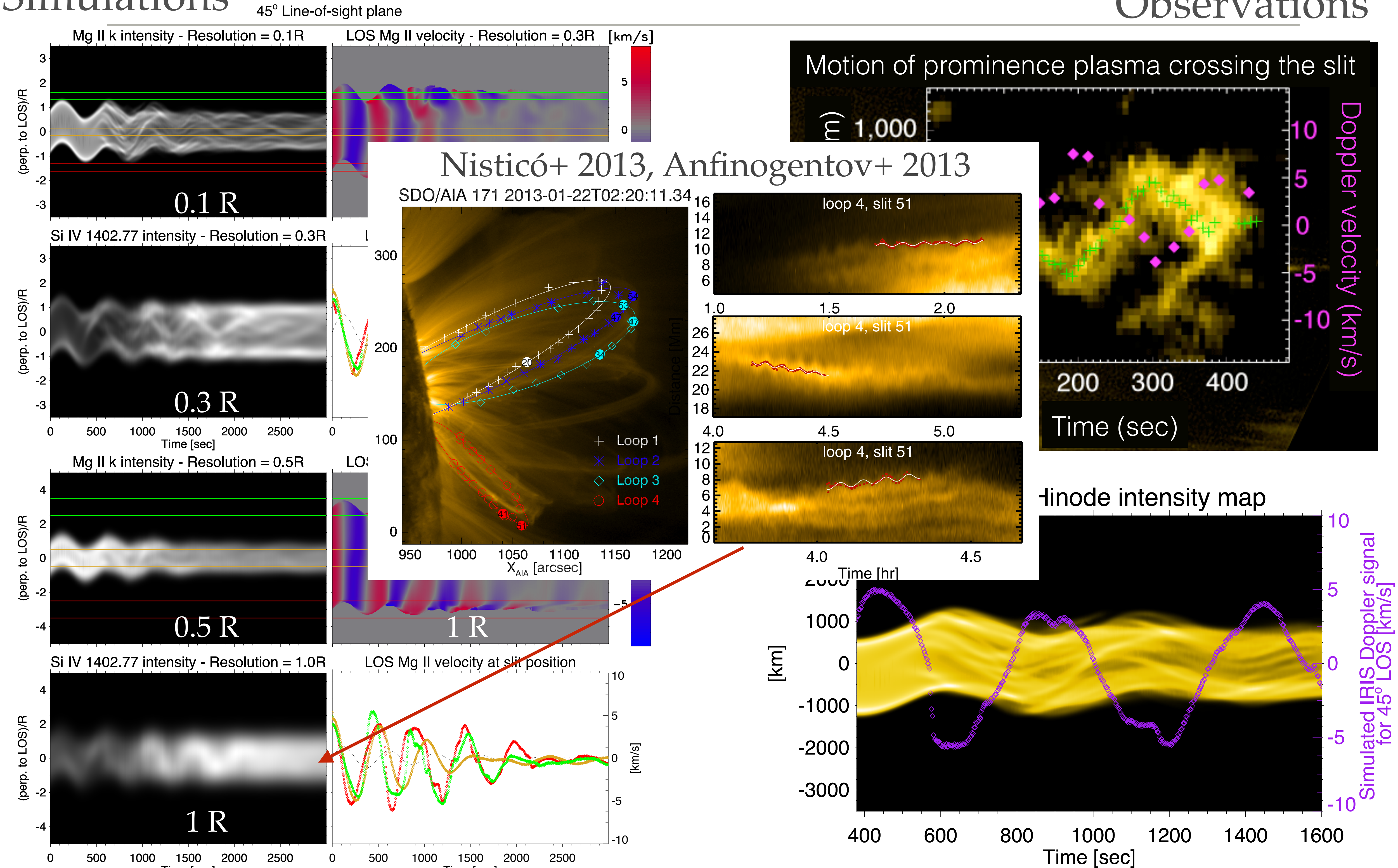
Line broadening at edges, stronger in TR lines

IRIS/Hinode Observations explained

Okamoto+ (2015, accepted) Antolin + (2015, accepted)

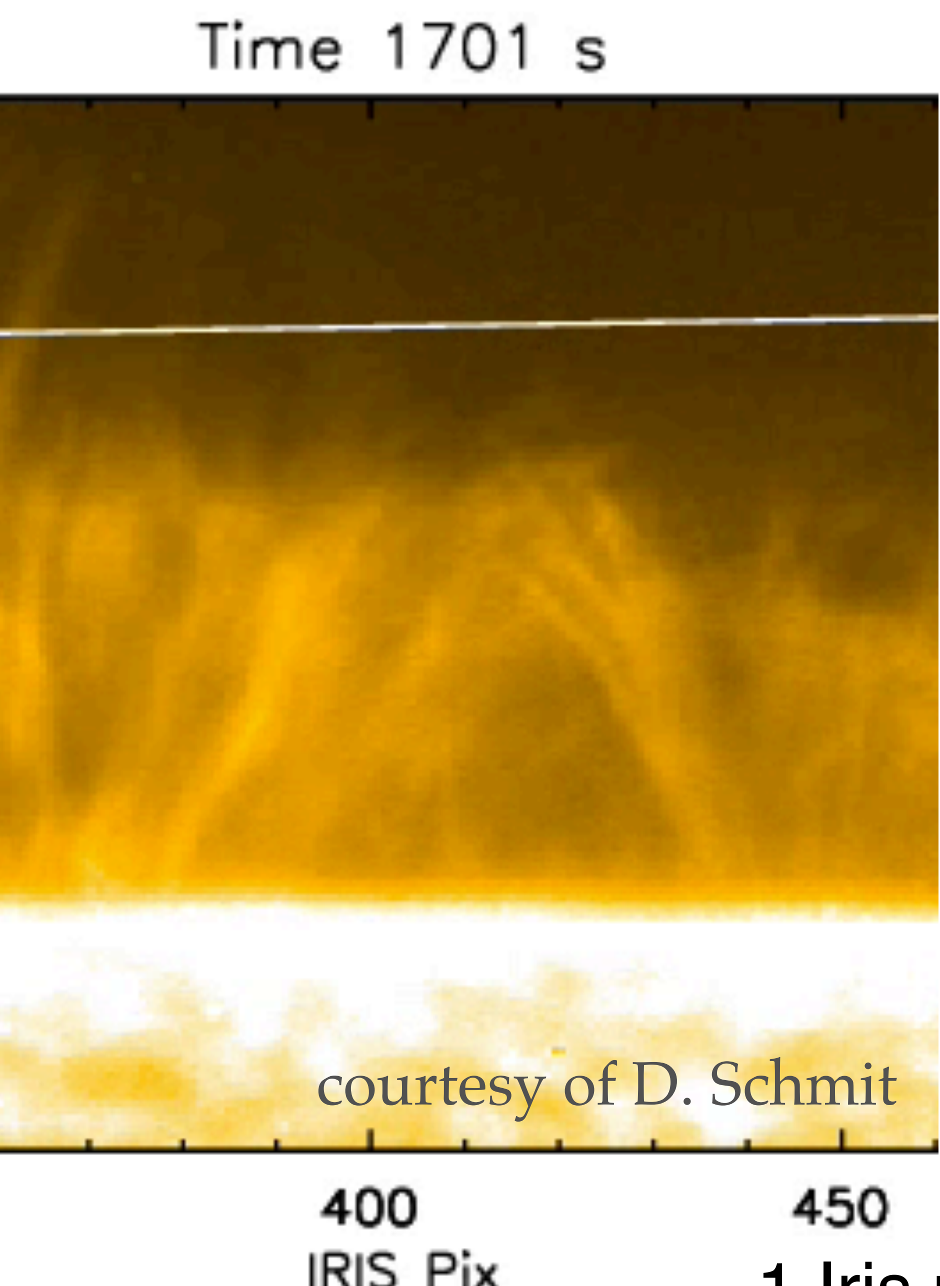
Simulations

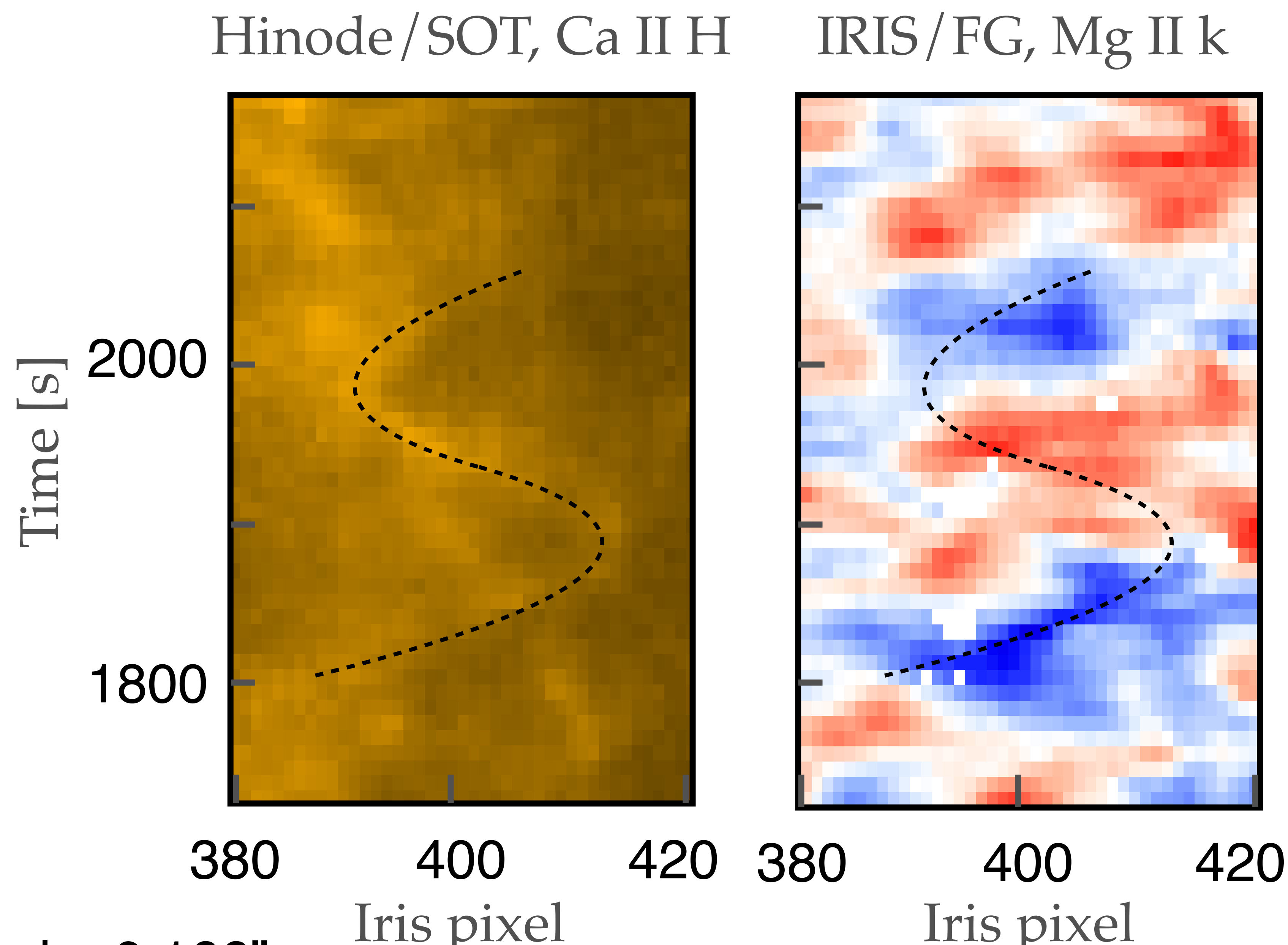
Observations



IRIS/Hinode observations: spicules

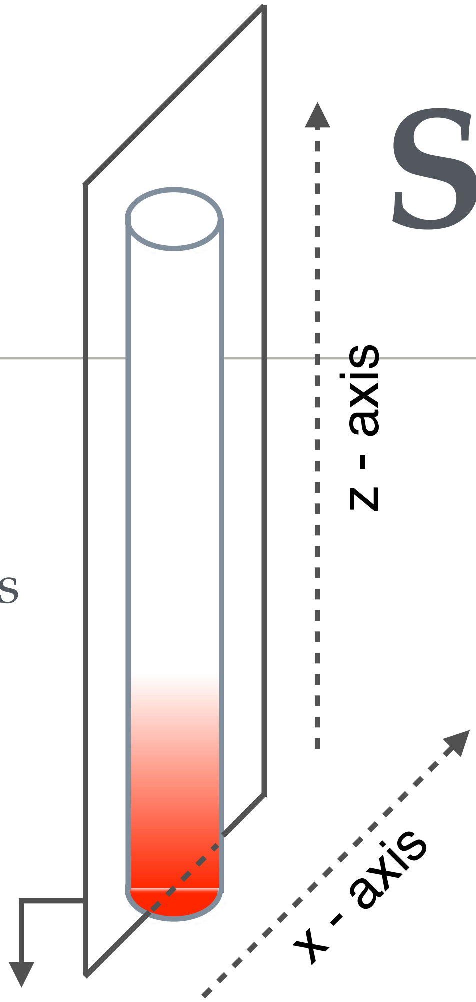
Antolin, Schmit, De Pontieu, Pereira (2015, in preparation)





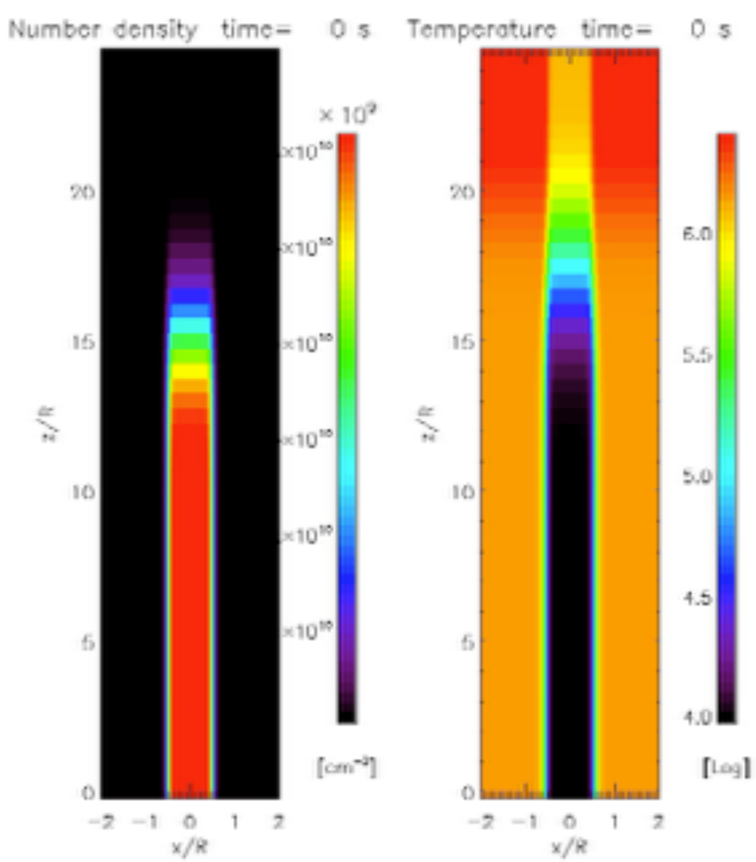
1 Iris pixel = 0.166”

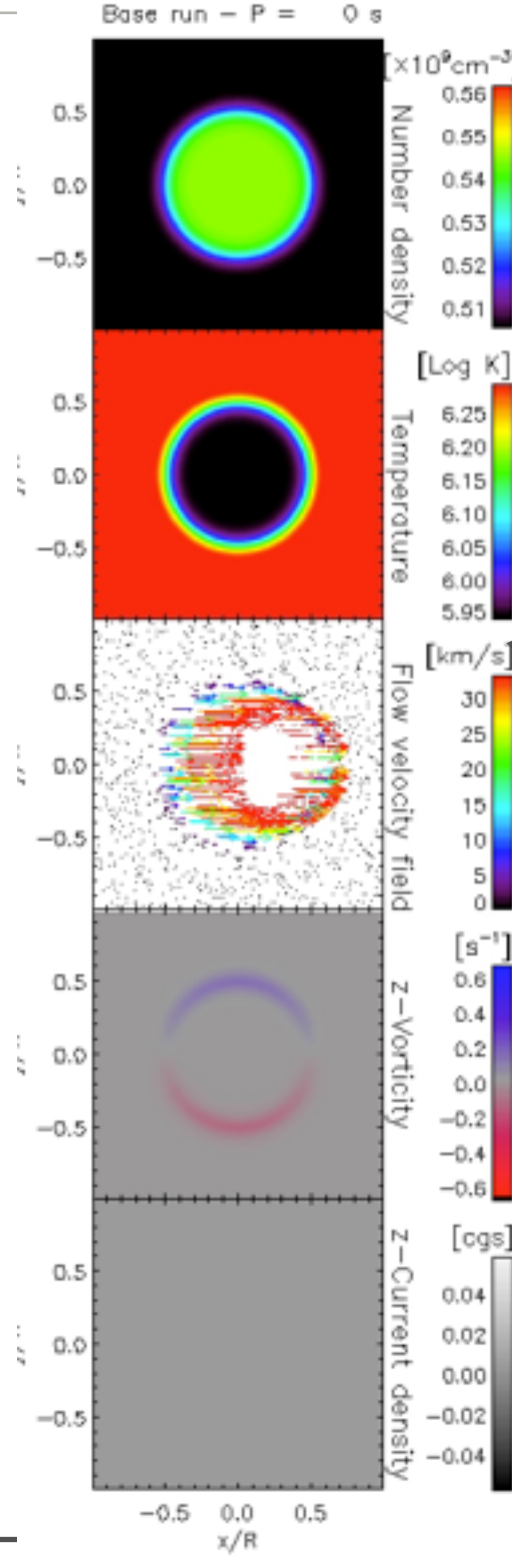
Spicule model

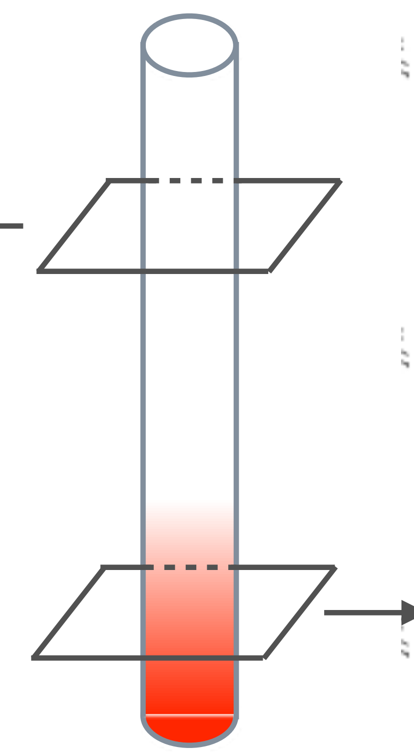


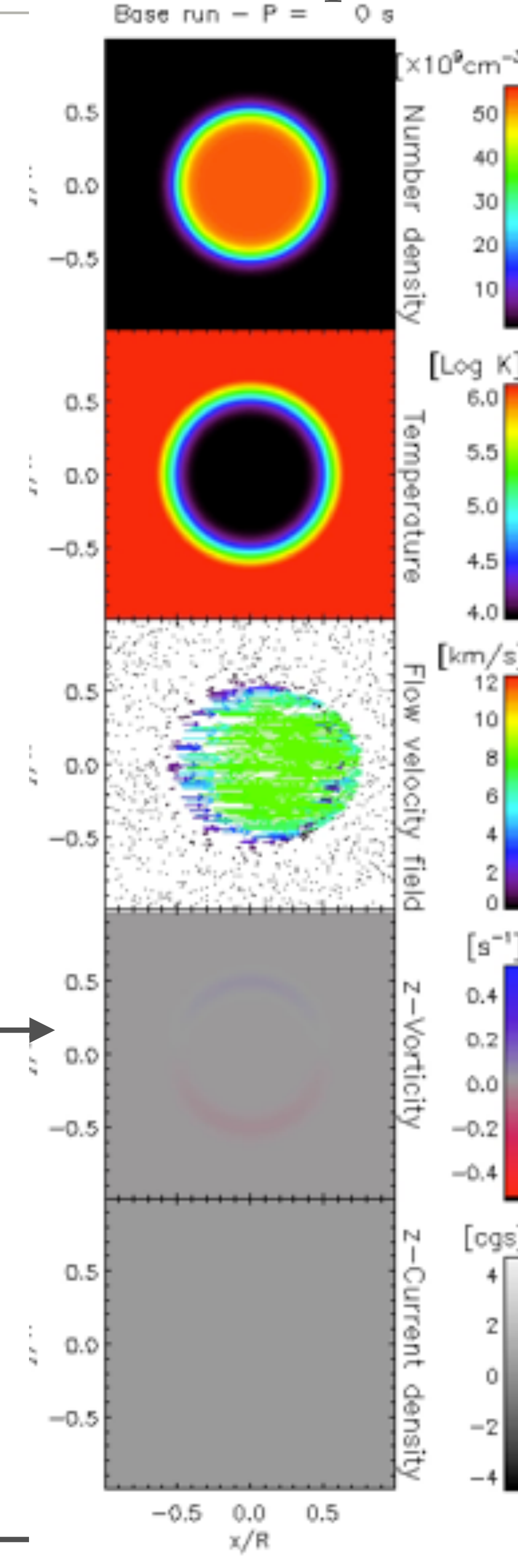
Amp. ~ 12 km/s

Period ~ 245 s





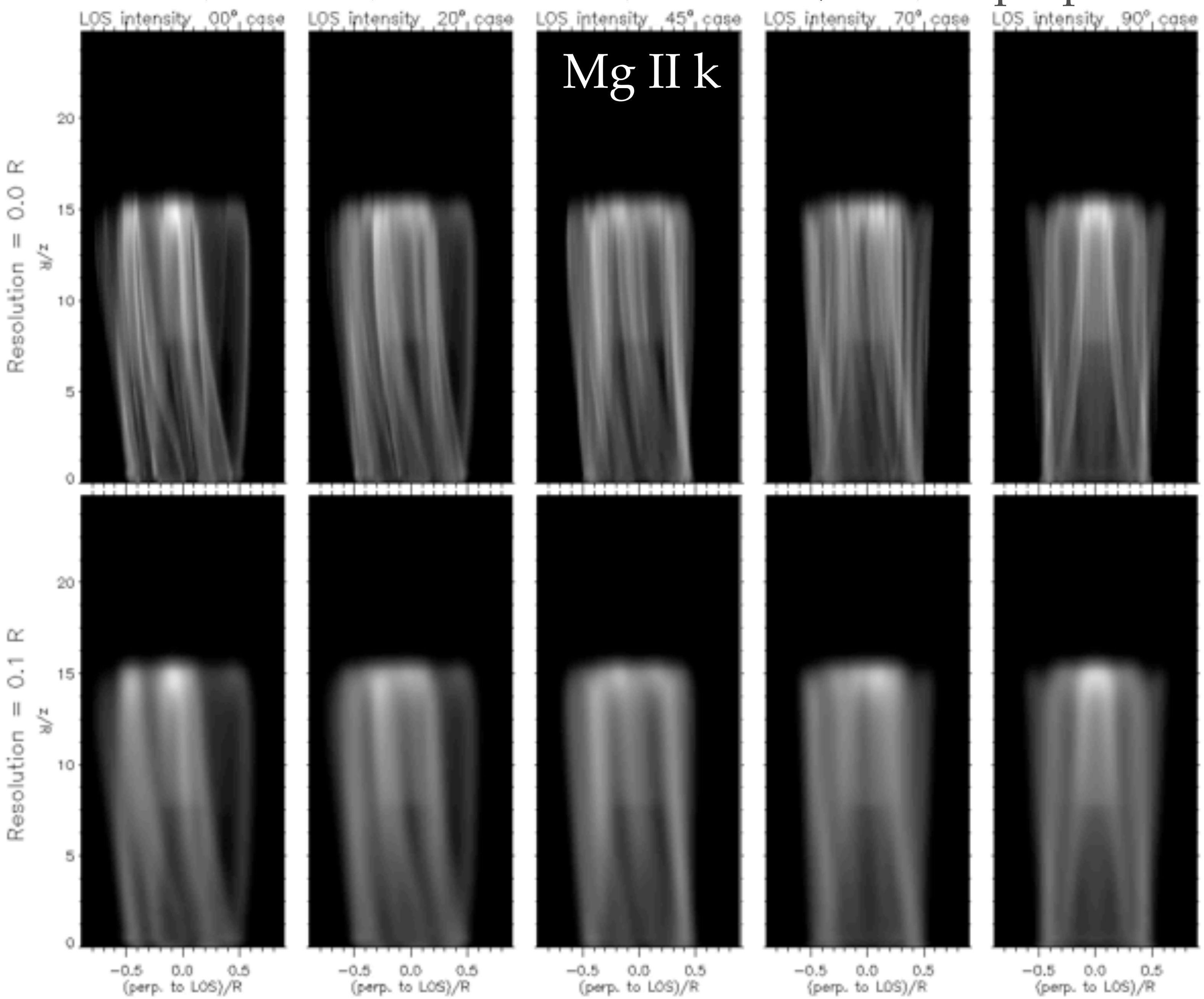




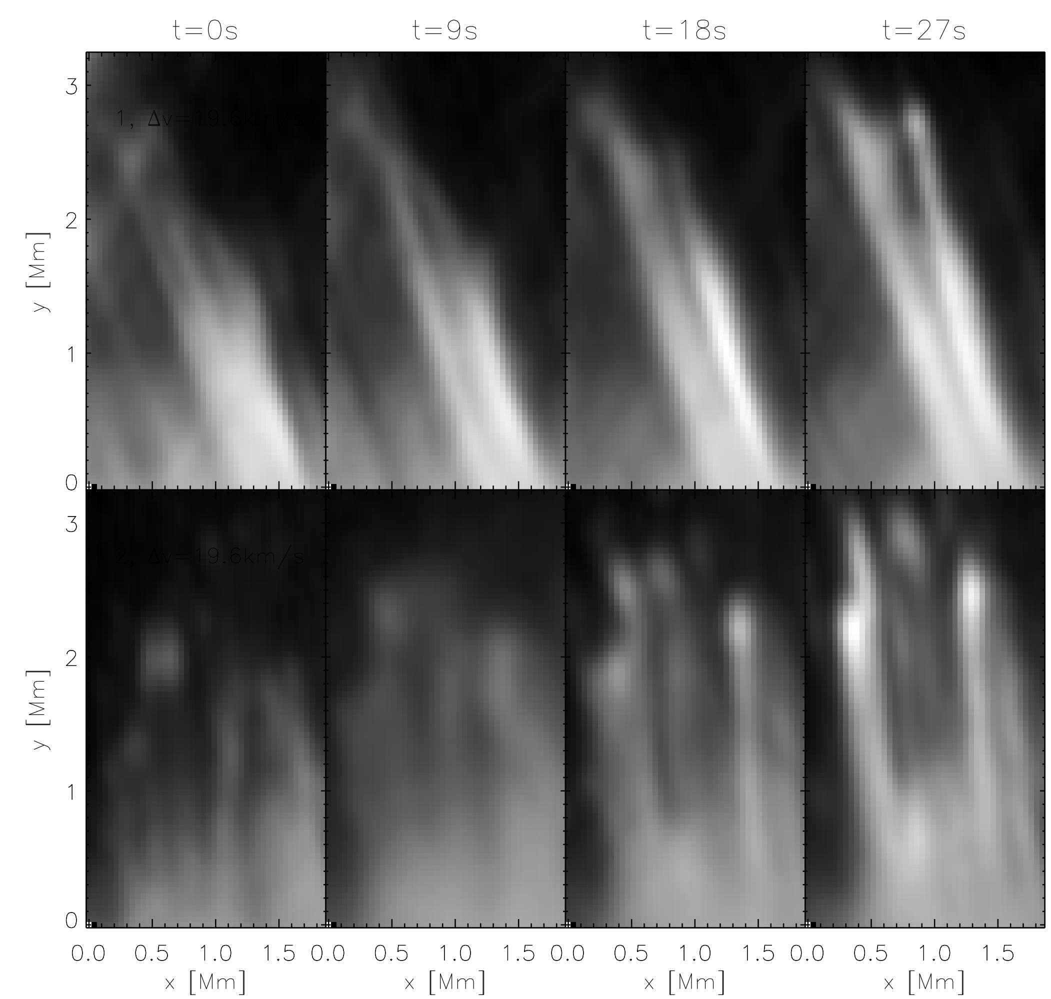
Spicule model

Strand-like structure in spicules may correspond to KHI vortices

Antolin, Schmit, De Pontieu, Pereira (2015, in preparation)

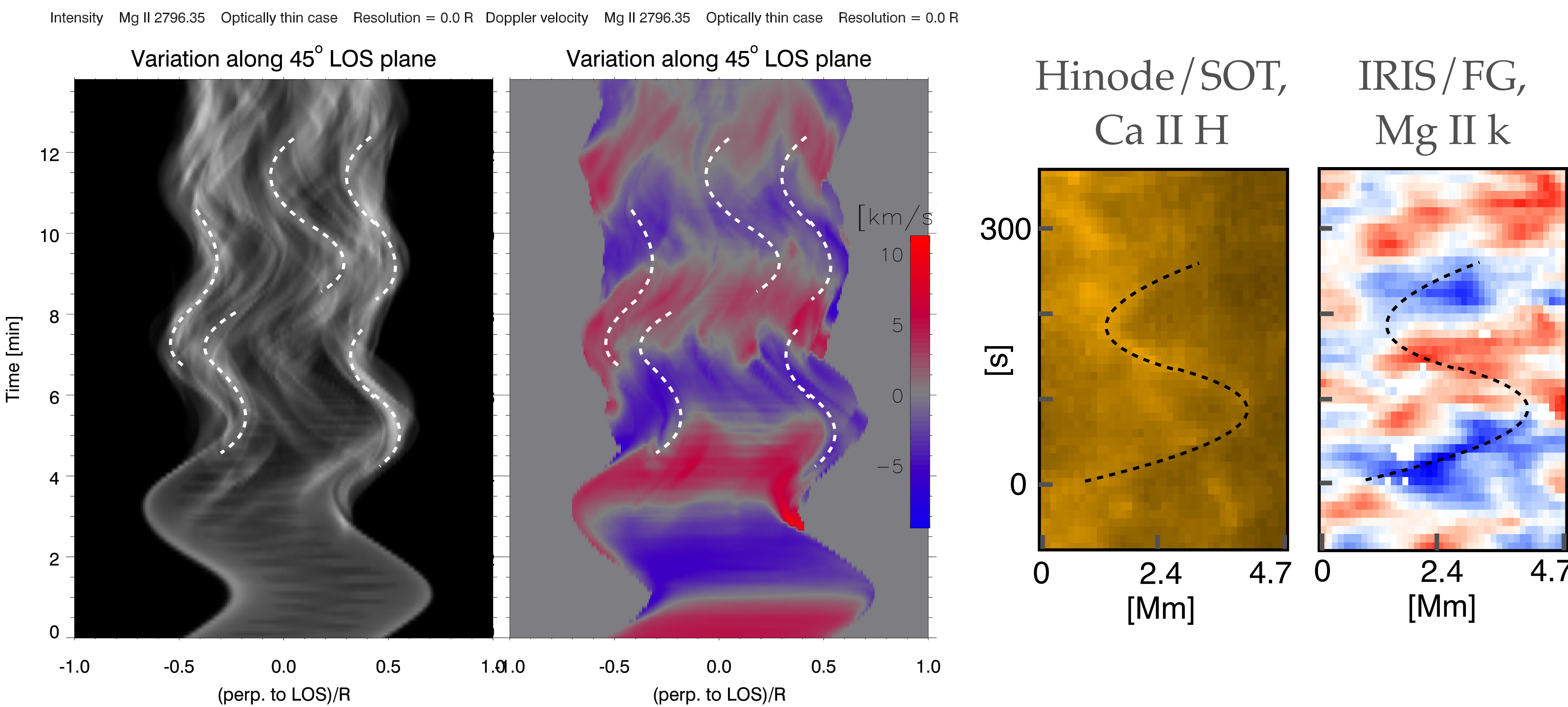


Skogsrud+ (2014)



SST, Hα

Spicule model vs observations



Antolin, Schmit, De Pontieu, Pereira (2015, in preparation)

Conclusions (2/2)

- Transverse MHD waves may play an important role in the heating and morphology of structure in the solar atmosphere. Mainly 2 mechanisms at play:
- Global kink ➙ azimuthal Alfvénic motions at boundary from resonant absorption mechanism ➙ Kelvin-Helmholtz instabilities (KHI)
- **KHI combines with resonant absorption**: energy extracted from resonance layer and dissipated through viscous and ohmic heating
- Turbulence generation: small-scale enhanced emissivity regions with large vorticity and strong currents: vortices and current sheets are created along loop: **heating, possible reconnection leading to braiding**.
- KHI fine structure + line-of-sight effects = **strand-like structure** in intensity images (Antolin+ 2014). **Observed threads /strands = KHI vortices**?
- Characteristic **out-of-phase behaviour between POS motion and LOS velocity + strong dynamic coherence across the flux tube**: match with observations (Okamoto+ 2015, Antolin+ 2015, accepted)
- Model valid for **corona, prominences and spicules** (Antolin+, 2015 in prep.)

Thank you!