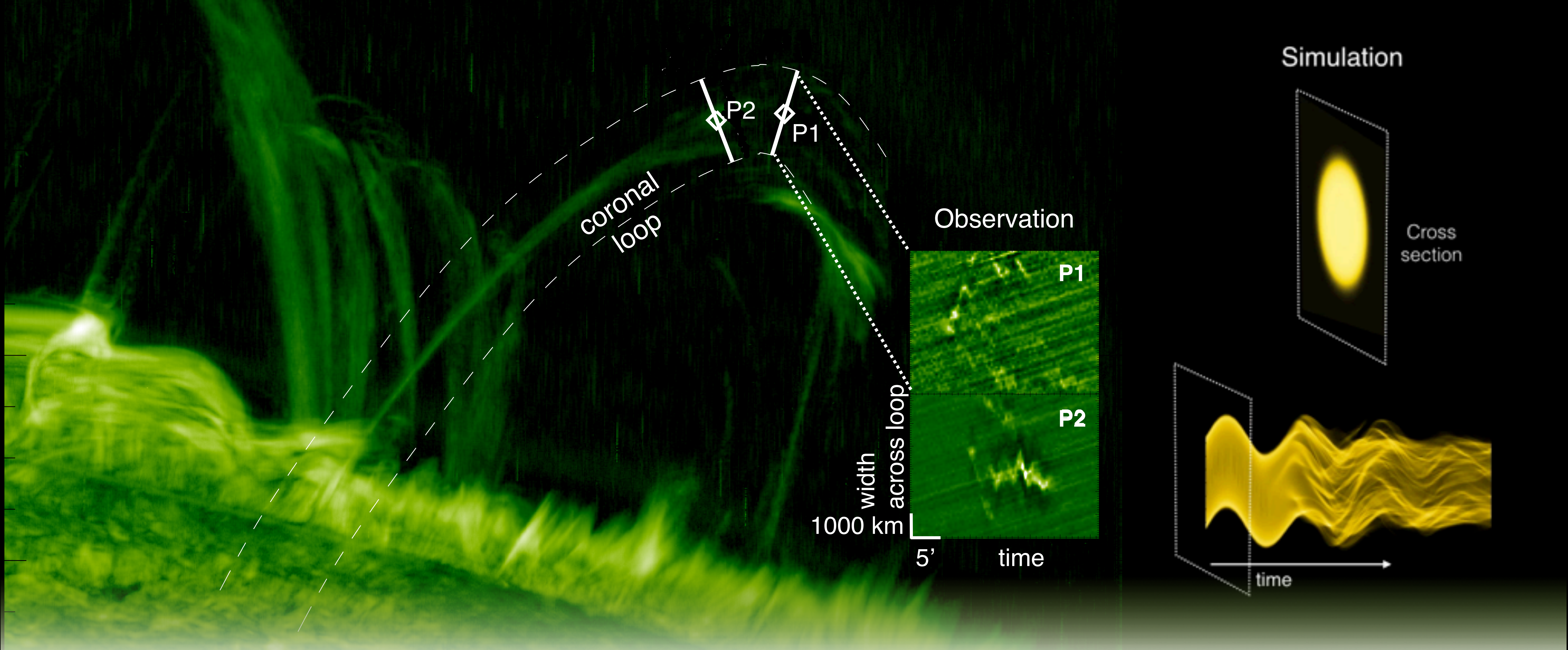
Resonant Absorption as a Feeding Mechanism for Alfvénic Turbulence and its Observable Characteristics in the Solar Atmosphere



IRIS-6@Stockholm, 20-24 June 2016

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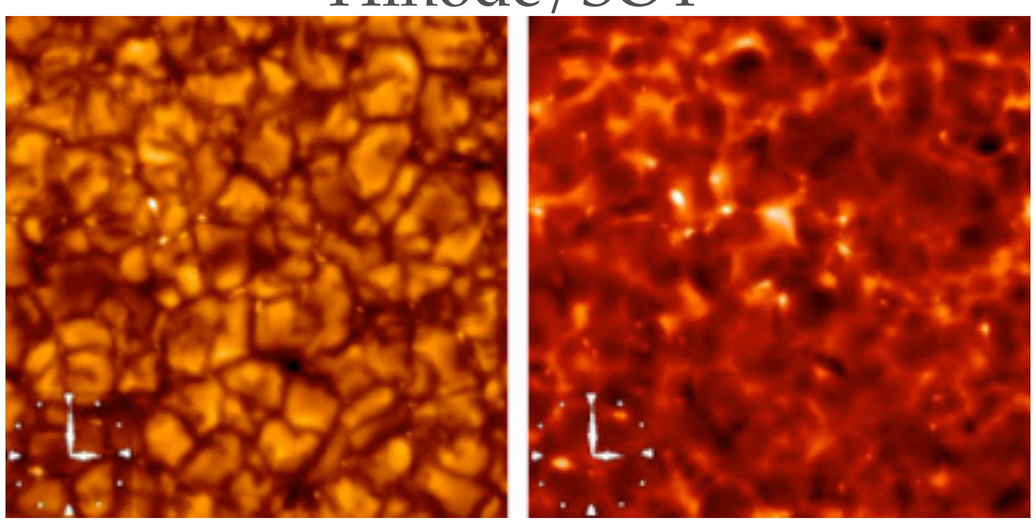
Wave generation in the lower atmosphere

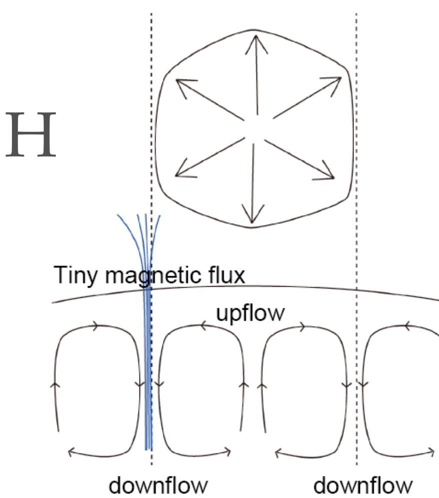
- Convective turbulent motion (*Biermann 1946, Schwarzschild 1948*)
- p-mode leakage ('ramp' effect) (*Michalitsanos 1973; Bel & Leroy 1977; Suematsu 1990, De Pontieu+ 2004*)
- Magnetic reconnection
- Large Poynting flux: heating candidates for chromosphere & corona *(Uchida & Kaburaki 1974, Wentzel 1974, Narain & Ulmschneider 1996)*

Hinode/SOT

G-band



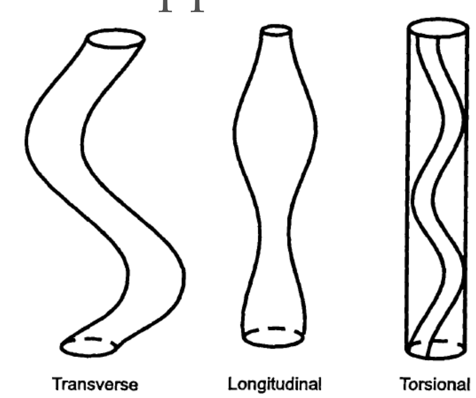
Ca II H



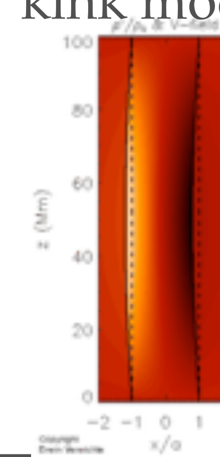
Large Poynting flux

- Strong inhomogeneity & stratification: strong linear & nonlinear mode coupling *(Dewar 1970, Stein & Schwartz 1972, Cally 1981, Hollweg 1982, Einaudi 1996, Bogdan+2003):* **infinite # of modes**

trapped modes



kink mode



Observations of Alfvénic waves in the solar atmosphere

Transverse MHD waves ubiquitous in the solar atmosphere

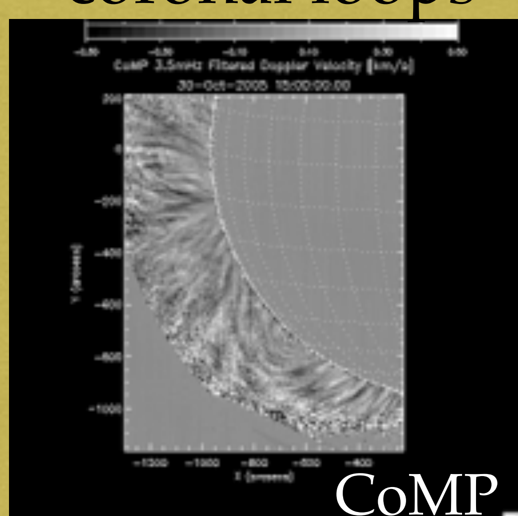
What is the role of such waves in the solar atmosphere?

Are we detecting all the wave power?

Small amplitudes < coronal heating

Large amplitudes > chromospheric heating

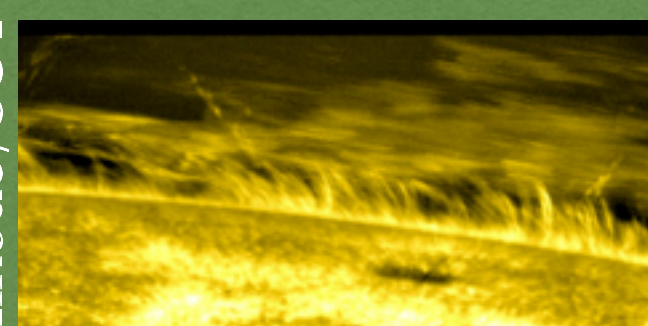
coronal loops



Tomczyk et al. 2007
McIntosh et al. 2011

Rainy loops & prominences

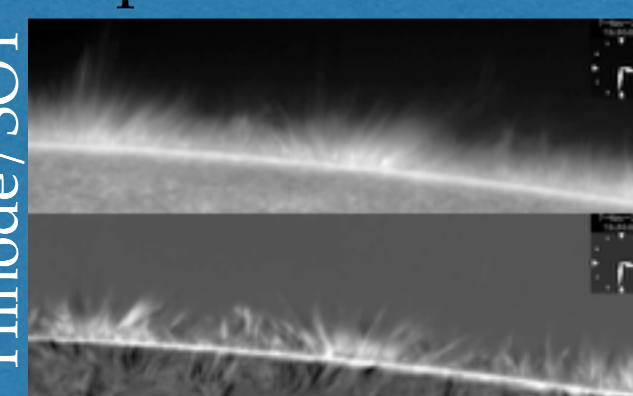
Hinode/SOT



Okamoto et al. 2007

Chromosphere Spicules & fibrils

Hinode/SOT



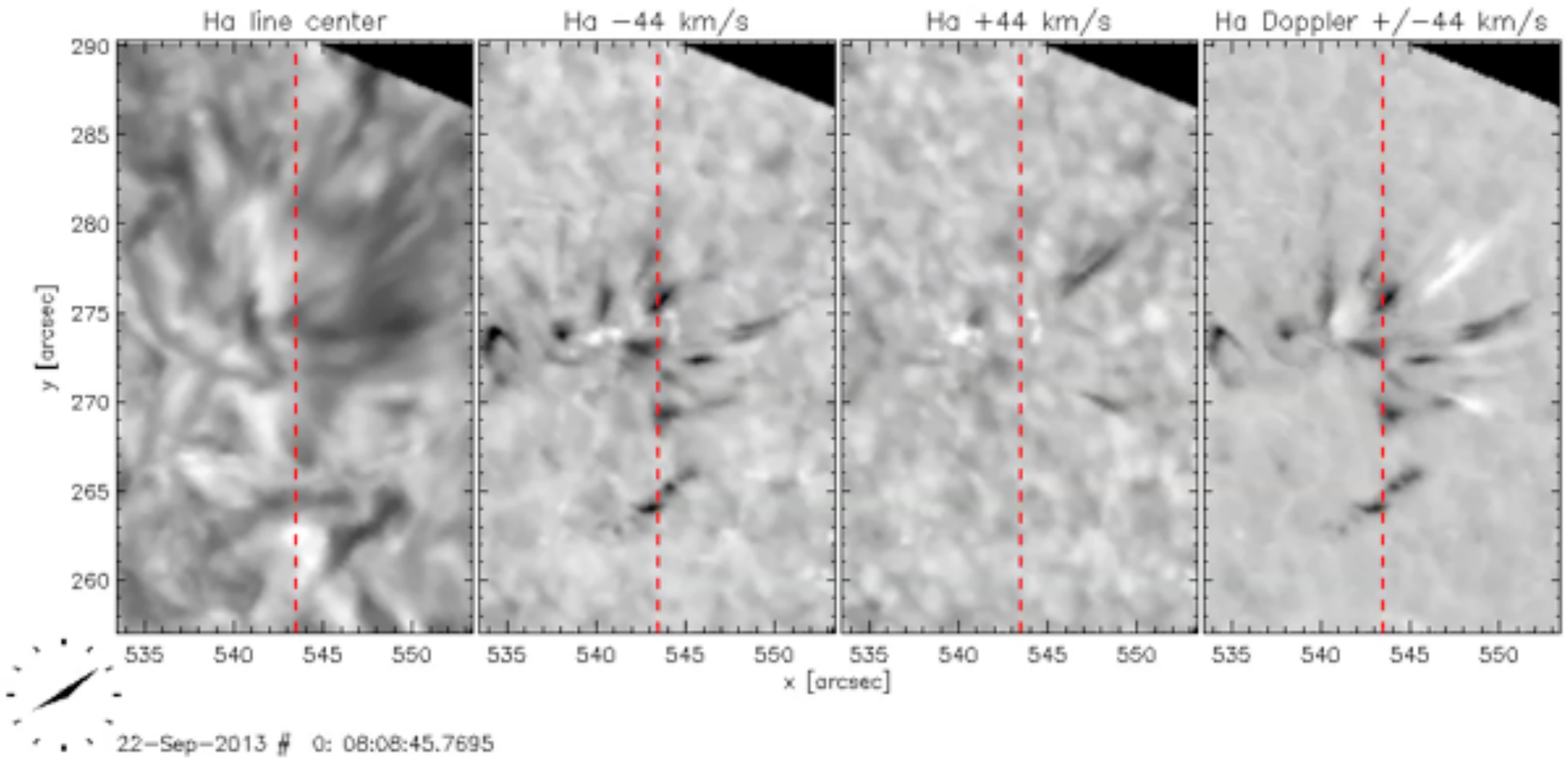
De Pontieu et al. 2014
Morton+ 2012

(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)

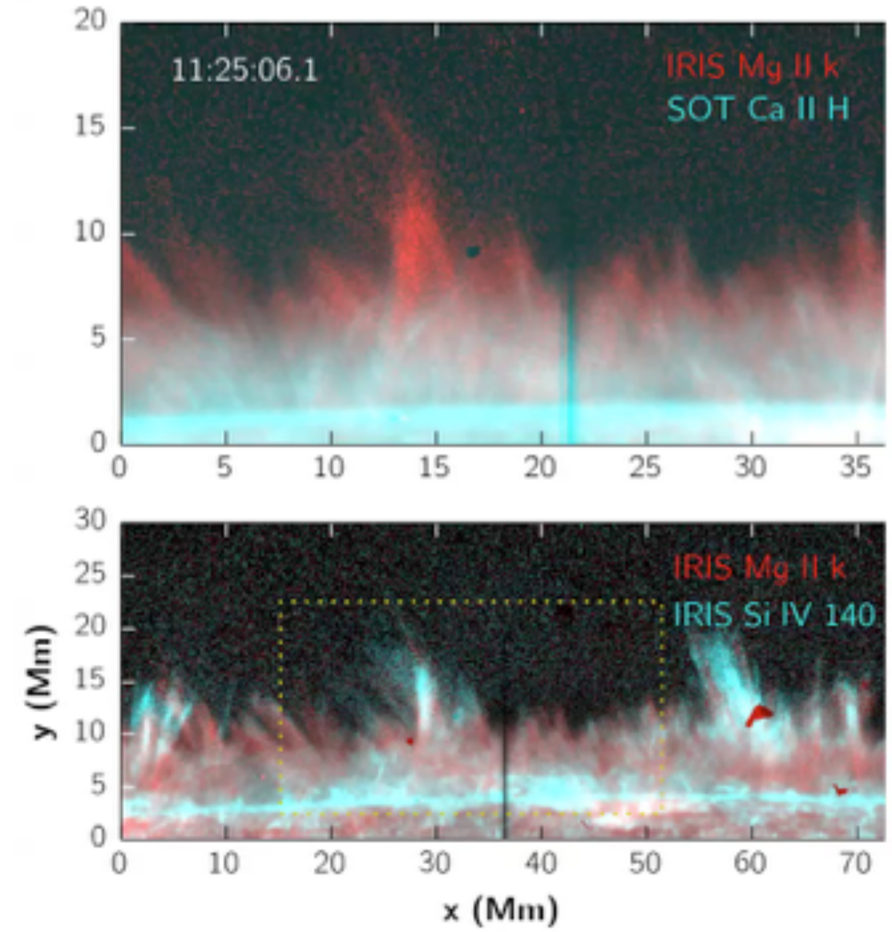
Dynamics of spicules

Alfvénic motions

SST/CRISP Observations *Rouppe van der Voort+ 2015*



SST + IRIS



Pereira et al. 2014

- Ubiquitous jets protruding from the chromosphere into the corona
- 2 types: I - magneto-acoustic wave driven (ballistic, v<40 km/s) *(Beckers 1968, Sterling 2000)*

  II - Fast disappearance in Ca II H, fast upflow (v<110 km/s), mostly in QS, RBE & RBB on-disc *(De Pontieu+ 2007, Rouppe vd Voort 2009, Sekse 2012, 2013)*
- New features for type II: **Multi-stranded, strong heating, swaying and torsional motions** *(Suematsu+ 2008, Pereira+2012, Skogsrud+ 2014, De Pontieu+ 2014, Rouppe v.d. Voort 2015)*

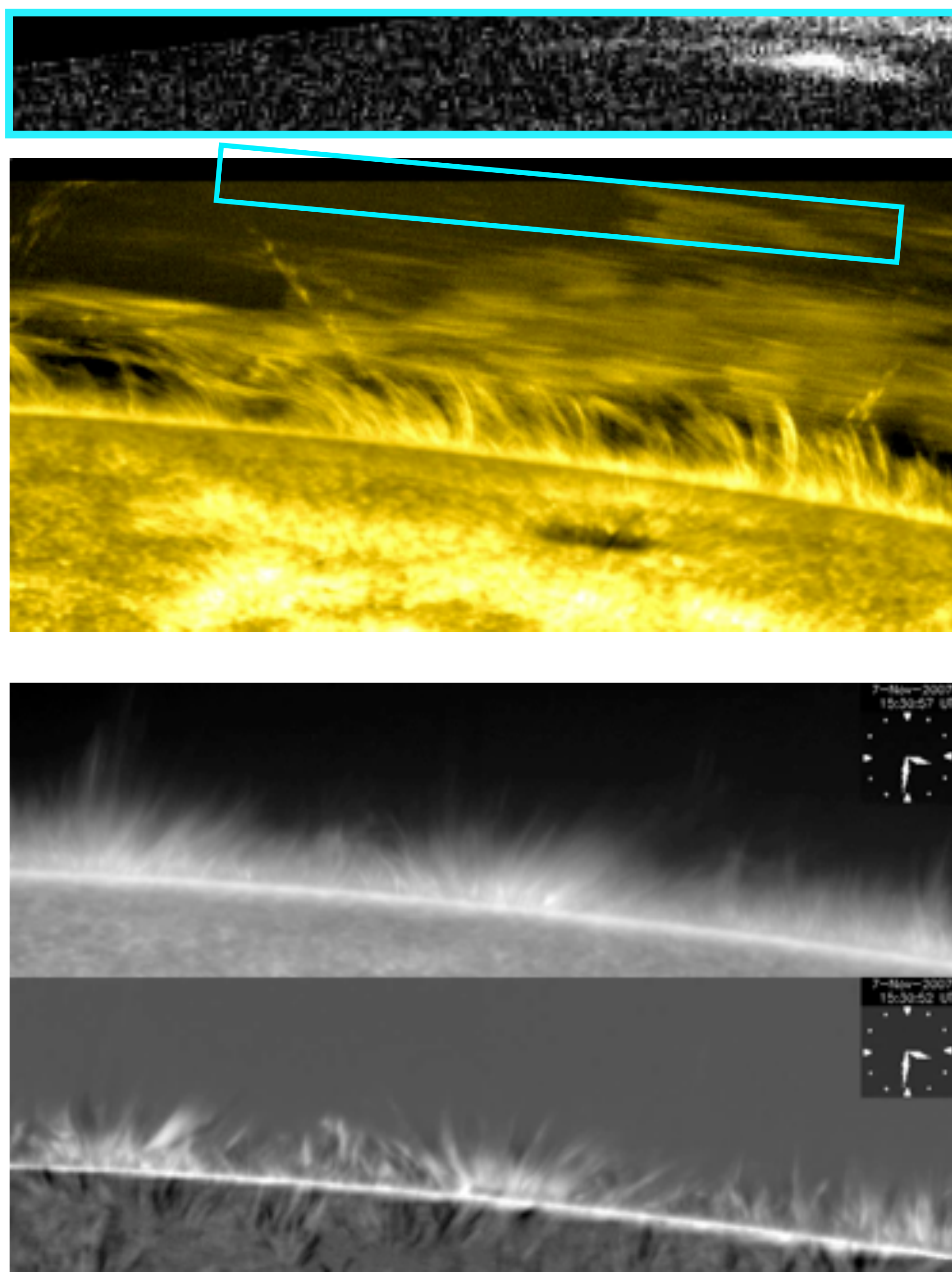
Observations of Alfvénic waves in the solar atmosphere

Transverse MHD waves ubiquitous in the solar atmosphere

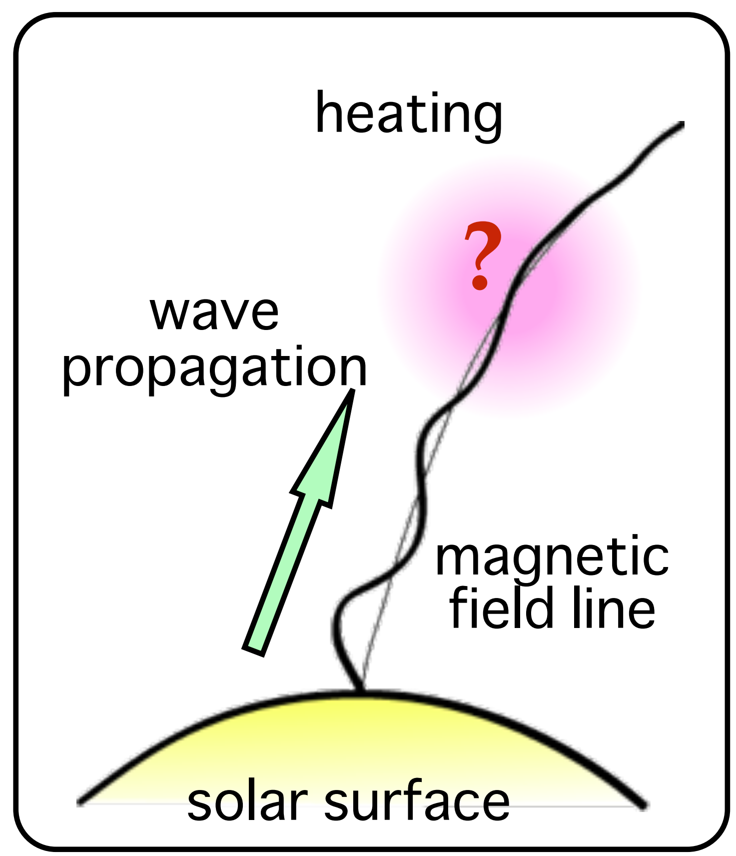
Do they play an important role in the solar atmosphere?

(Okamoto+2007)

Hinode/SOT



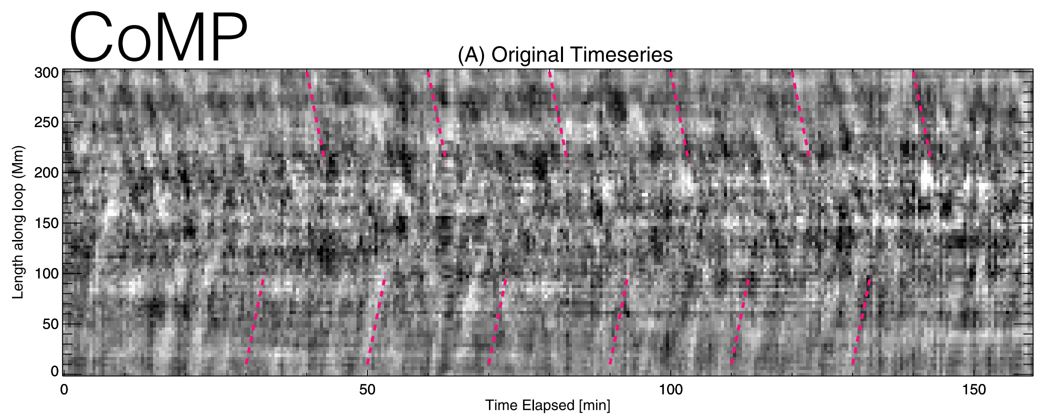
Corona: ~ 3-10 km/s
Damping often observed

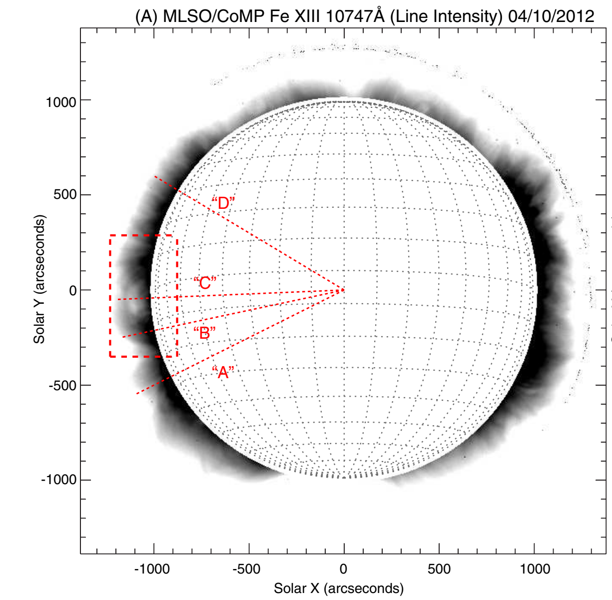


Damping can be caused by **resonant absorption (mode coupling)**: transverse waves convert into azimuthal waves

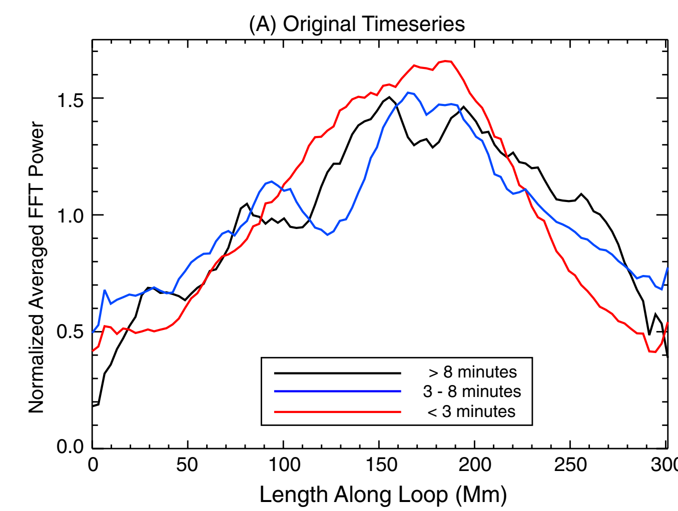
Chromosphere: ~20 km/s
(sufficient energy flux)

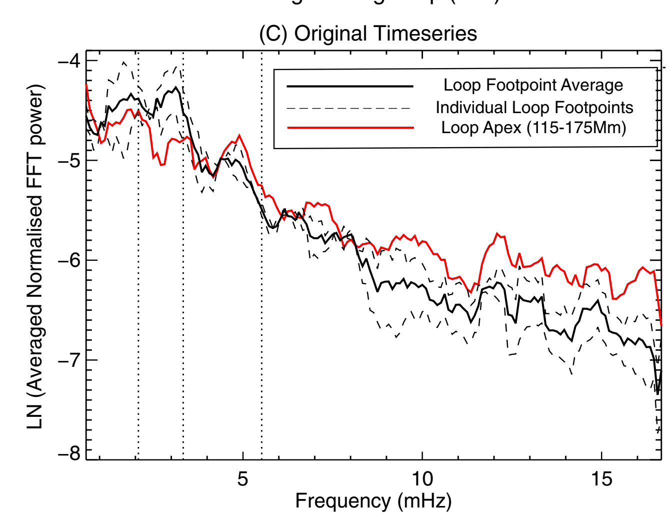
Alfvénic turbulence

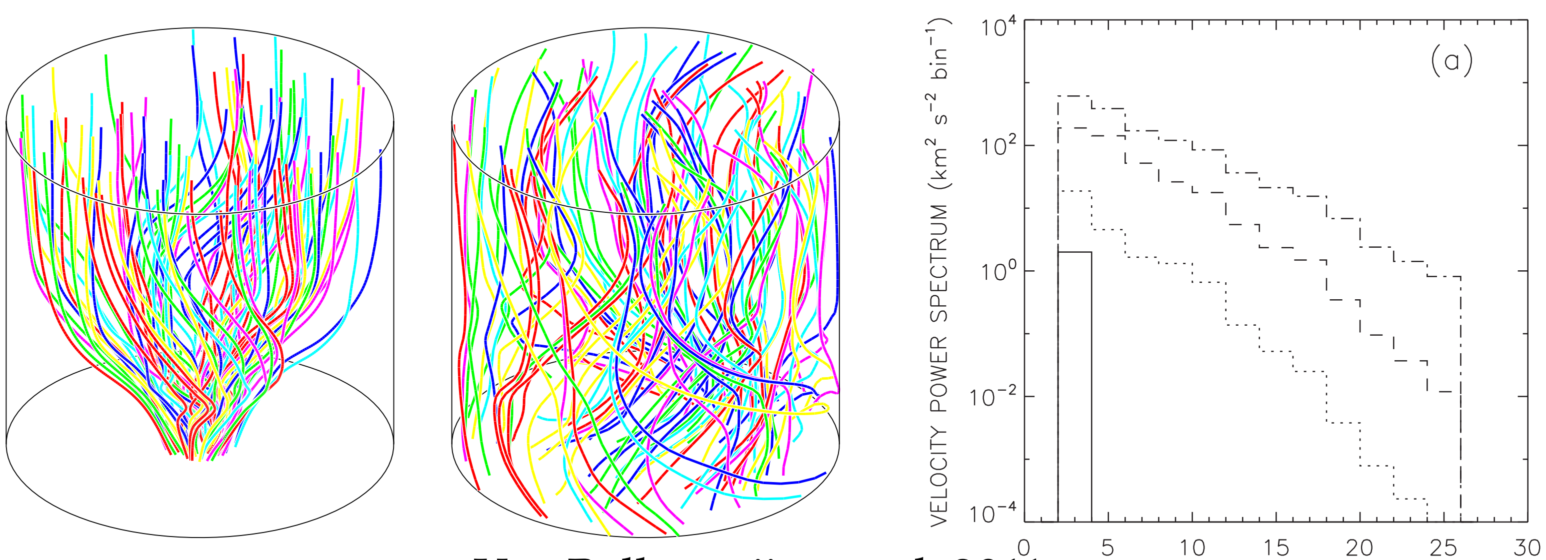




- Large imbalance upward/downward wave energy flux. Increase of high frequency wave power at loop apex -> Alfvénic turbulence? (*De Moortel+ 2014, Tomczyk 2007, Tomczyk & McIntosh 2009*)
- Significant heating from Alfvénic turbulence (*Van Ballegooijen+ 2011, Matsumoto & Suzuki 2014*)
- Large non-thermal line widths may be hiding most of the wave power *(McIntosh & De Pontieu 2012)*





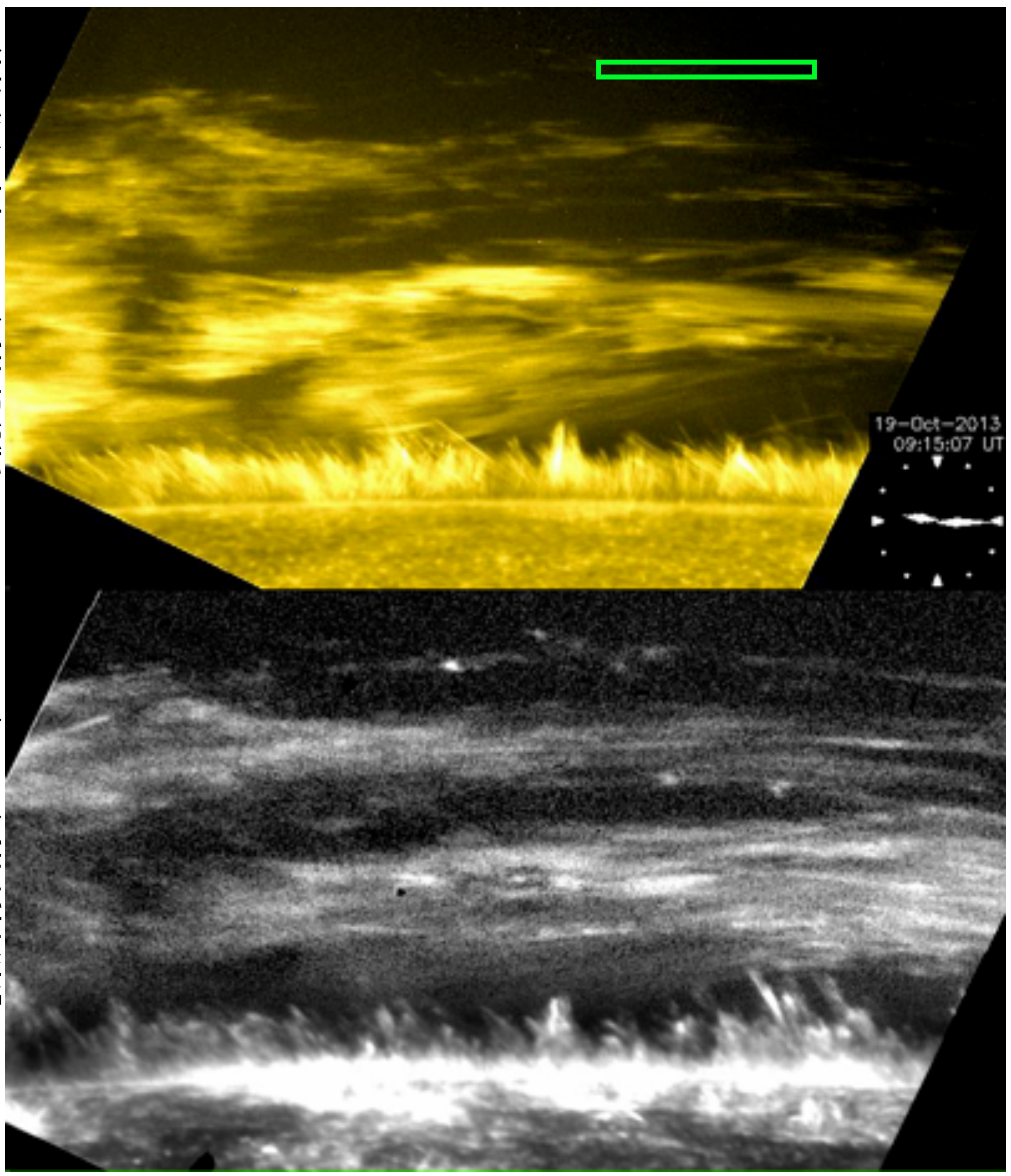


Van Ballegooijen et al. 2011

De Moortel et al. 2014

Signatures of resonant absorption

Hinode/SOT（Ca II, 10,000 K)



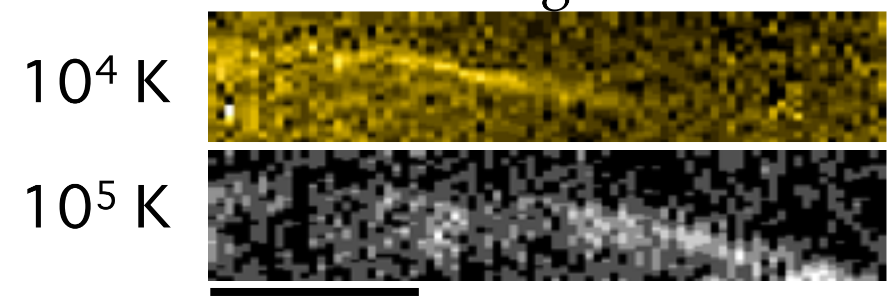
「ひの可視光画像（JAXA/国立天文台）

「IRIS」紫外線画像（NASA）

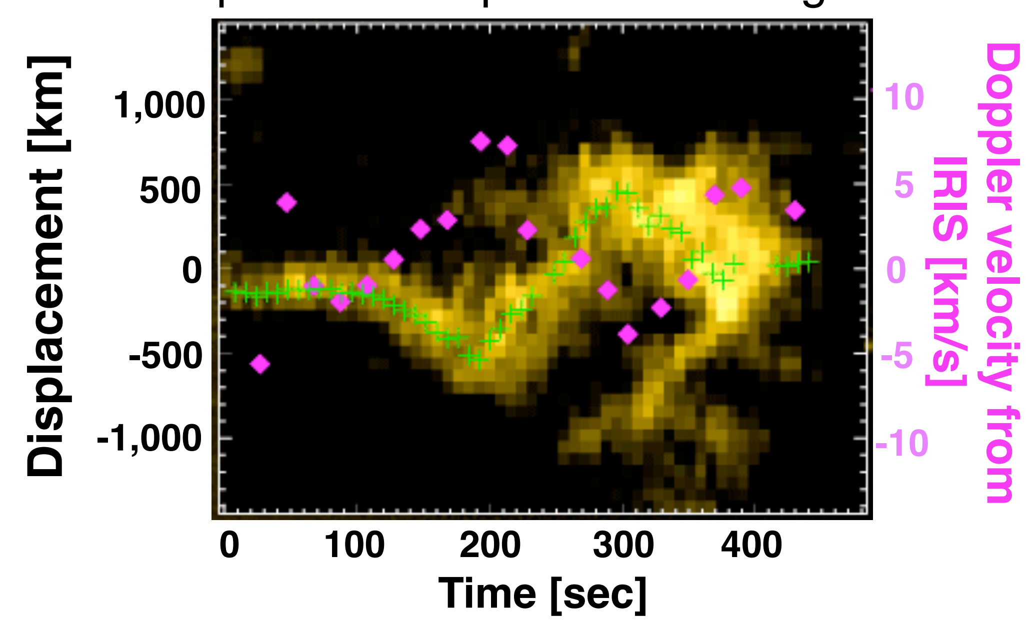
IRIS/SJI (Si IV, 100,000)

(Okamoto+2015, Antolin+2015)

x-t diagram



Motion of prominence plasma crossing the slit

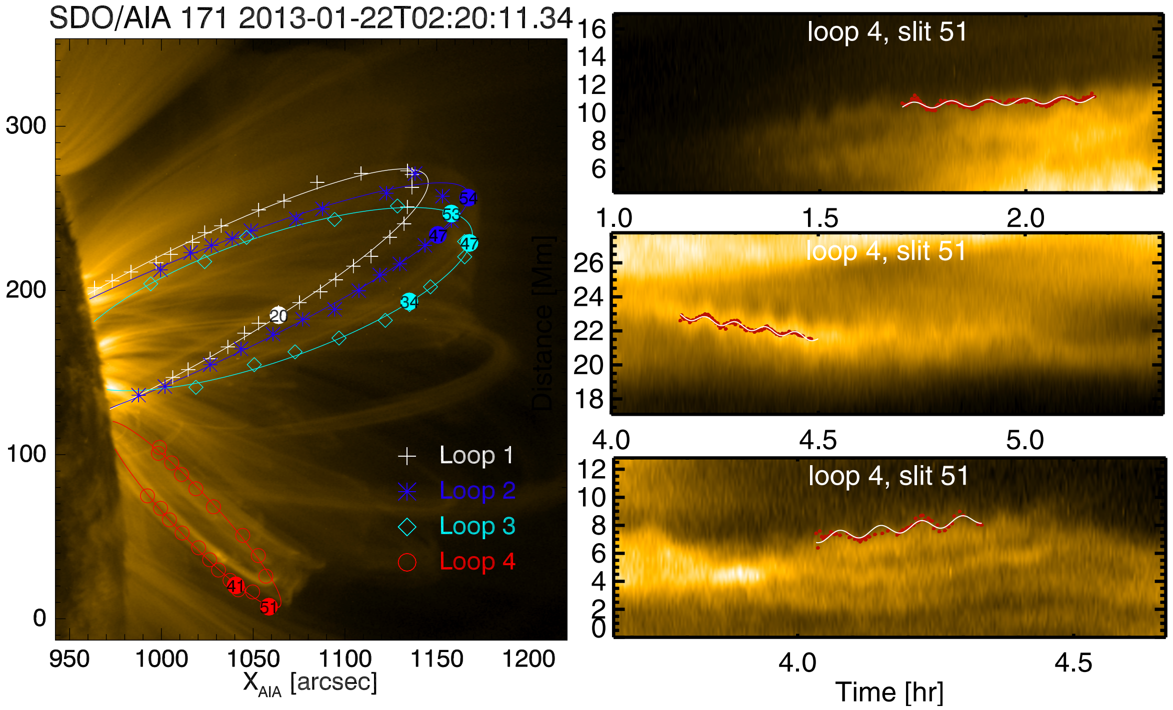


- Heating: Fading in cool line (10^4 K), subsequent appearance in hot line (10^5 K)
- POS motion out-of-phase with LOS velocity
- Thread-like structure

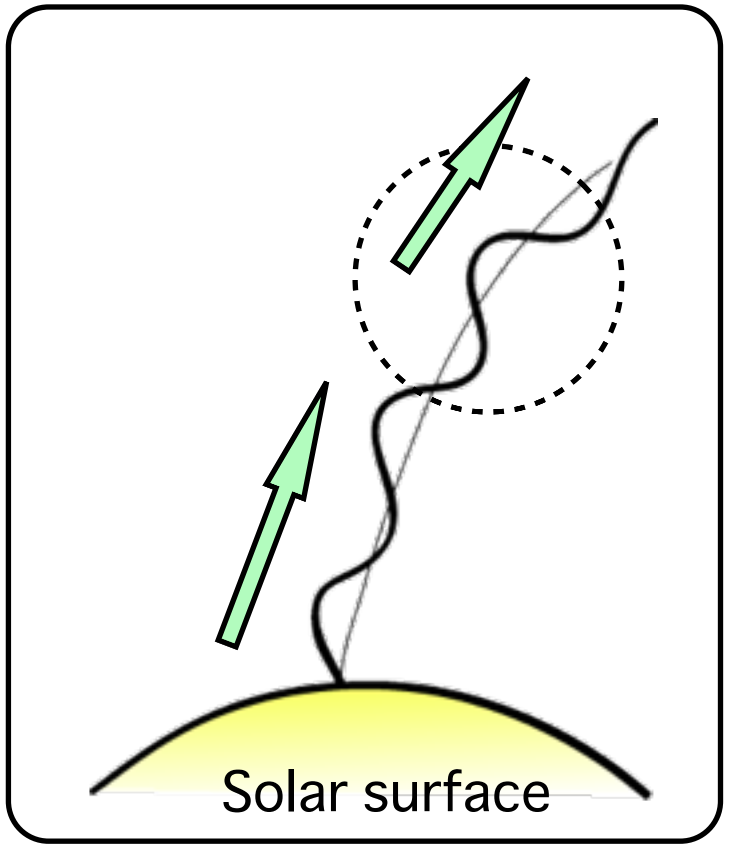
➡ Explained with 3D MHD transverse wave model: KHI + resonant absorption (current model)

Decay-less oscillations

Nisticò+(2013), Anfinogentov+ (2013, 2015), Goddard+(2015)



Anfinogentov+ 2013



- Decayless
- Common
- Standing kink

Decay-less oscillations: damping+continuous low-amplitude harmonic driver?

Outline

Observations:

- Alfvénic waves are everywhere: damping & decayless
- Strong amplitudes in chromosphere > Chromospheric heating, small POS & LOS v amplitudes in corona <? coronal heating
- Wave energy expected to be in azimuthal motions -> non-thermal line widths
- Alfvénic turbulence in corona?

Need for determination of observational (imaging + spectroscopic) signatures of transverse MHD waves and define their role in the solar atmosphere

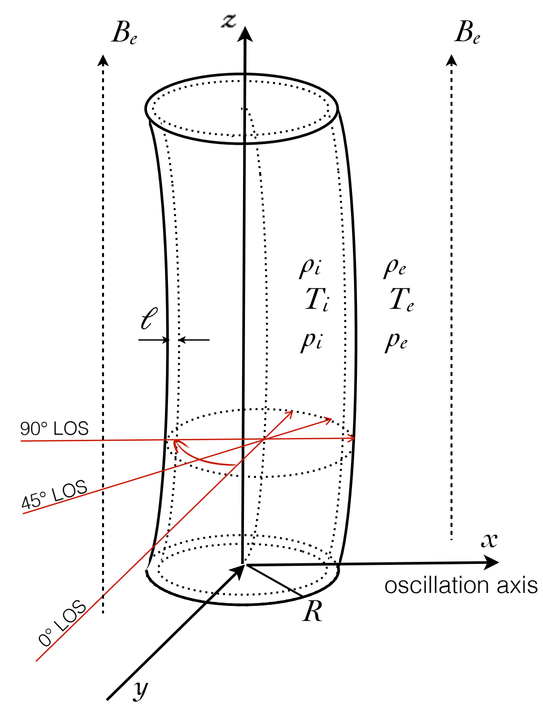
Present study:

- Modelling of transverse MHD waves (kink)
  - Prominences
  - Corona
  - Spicules

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): 1/4 tube= (512, 256, 100) - (1024, 512, 100) $S, R \approx 10^4 - 10^7$
- Initial condition: sinusoidal velocity perturbation in x-direction

parameters	coronal loop	prominence	spicule
$\frac{T_i}{T_e}, T_i$ [K]	1/3, $T_i = 10^6$	1/100, $T_i = 10^4$	1/100, $T_i = 10^4$
$\frac{\rho_i}{\rho_e}, \rho_i$ [cm^{-3}]	3, ρ_i =3x10^9	10, ρ_i =10^{10}	50, ρ_i =6x10^{10}
B [G]	22.8 G	18.6 G	14.5 G
c_k [km/s]	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

$L = 200\ R$

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

spicule model

transition region

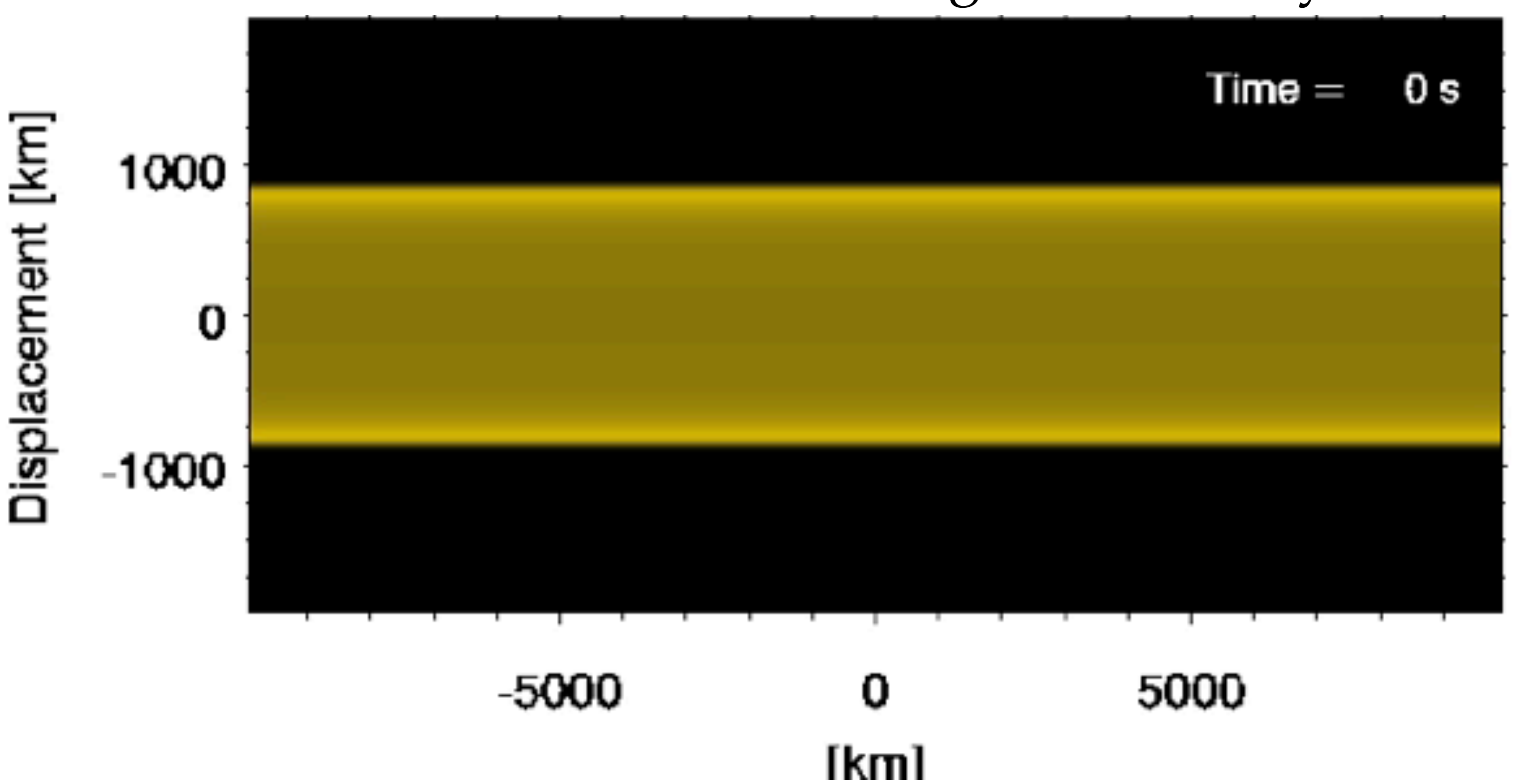
Forward modelling

- Optically thin: **FoMo** (Van Doorsselaere+ 2016, Antolin & Van Doorsselaere 2013)
- Optically thick: **RH** (Uitenbroek 2011)

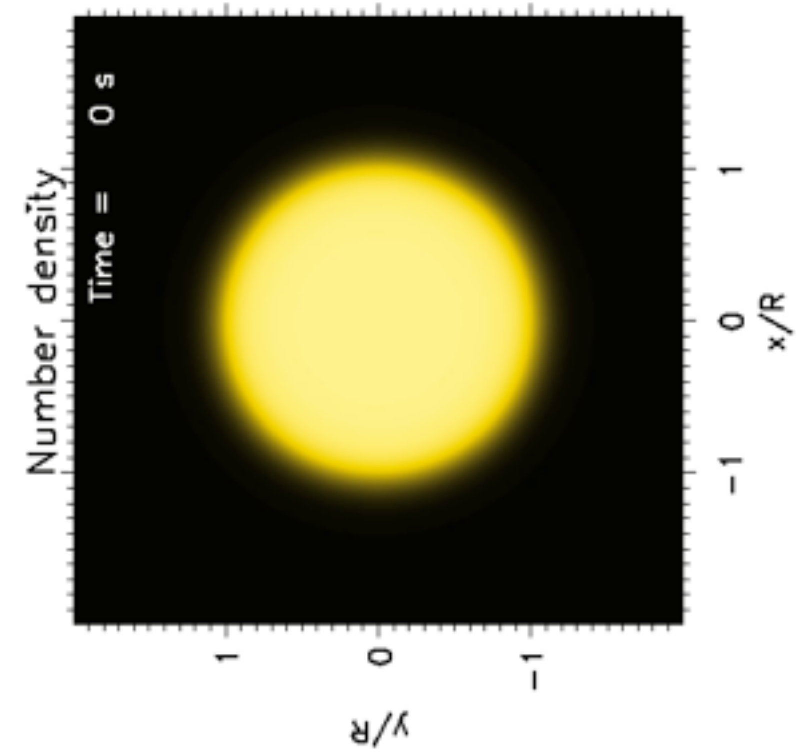
https://wiki.esat.kuleuven.be/FoMo

Numerical simulation

Prominence thread - Mg II k intensity

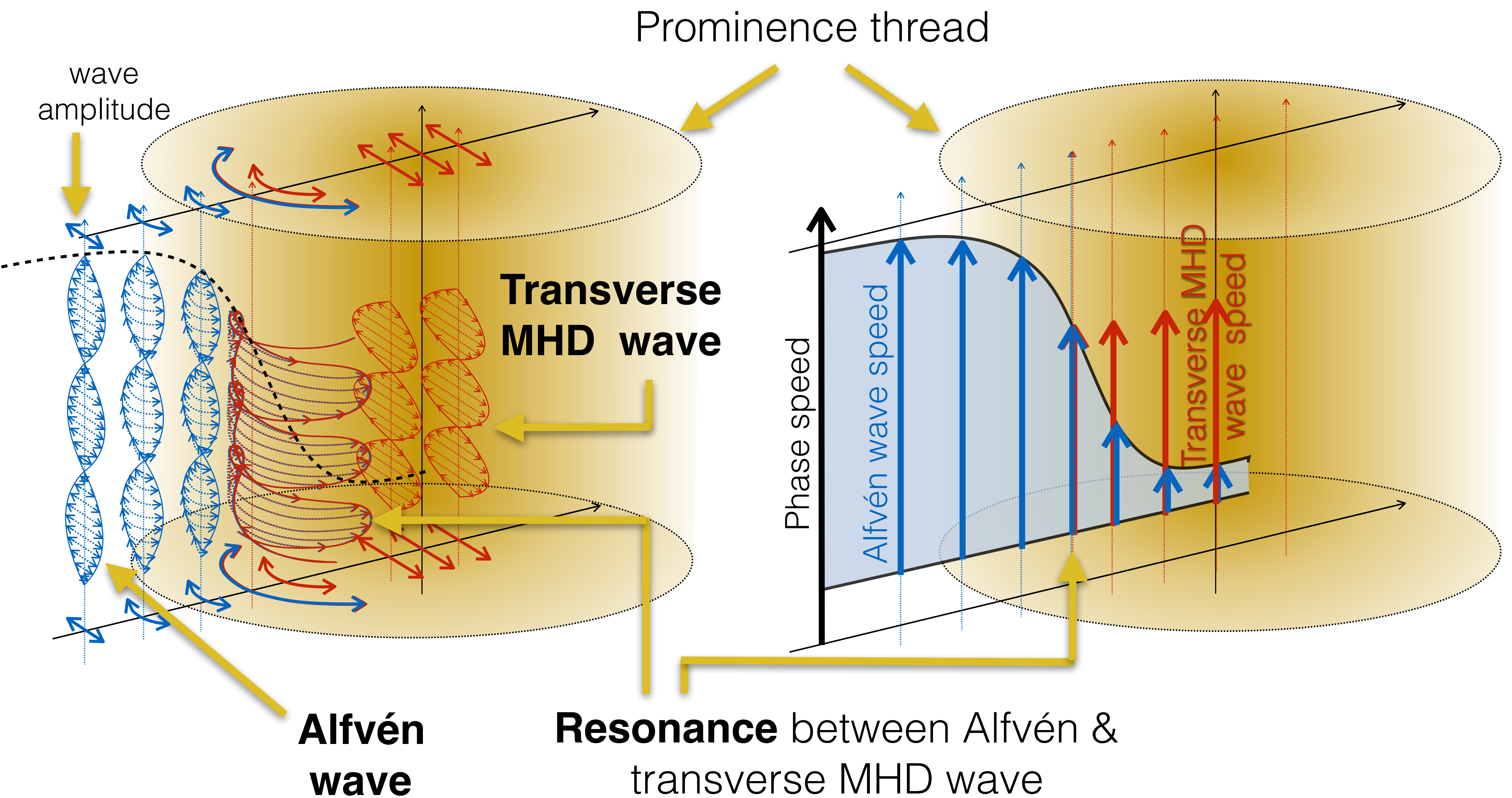


Cross-section



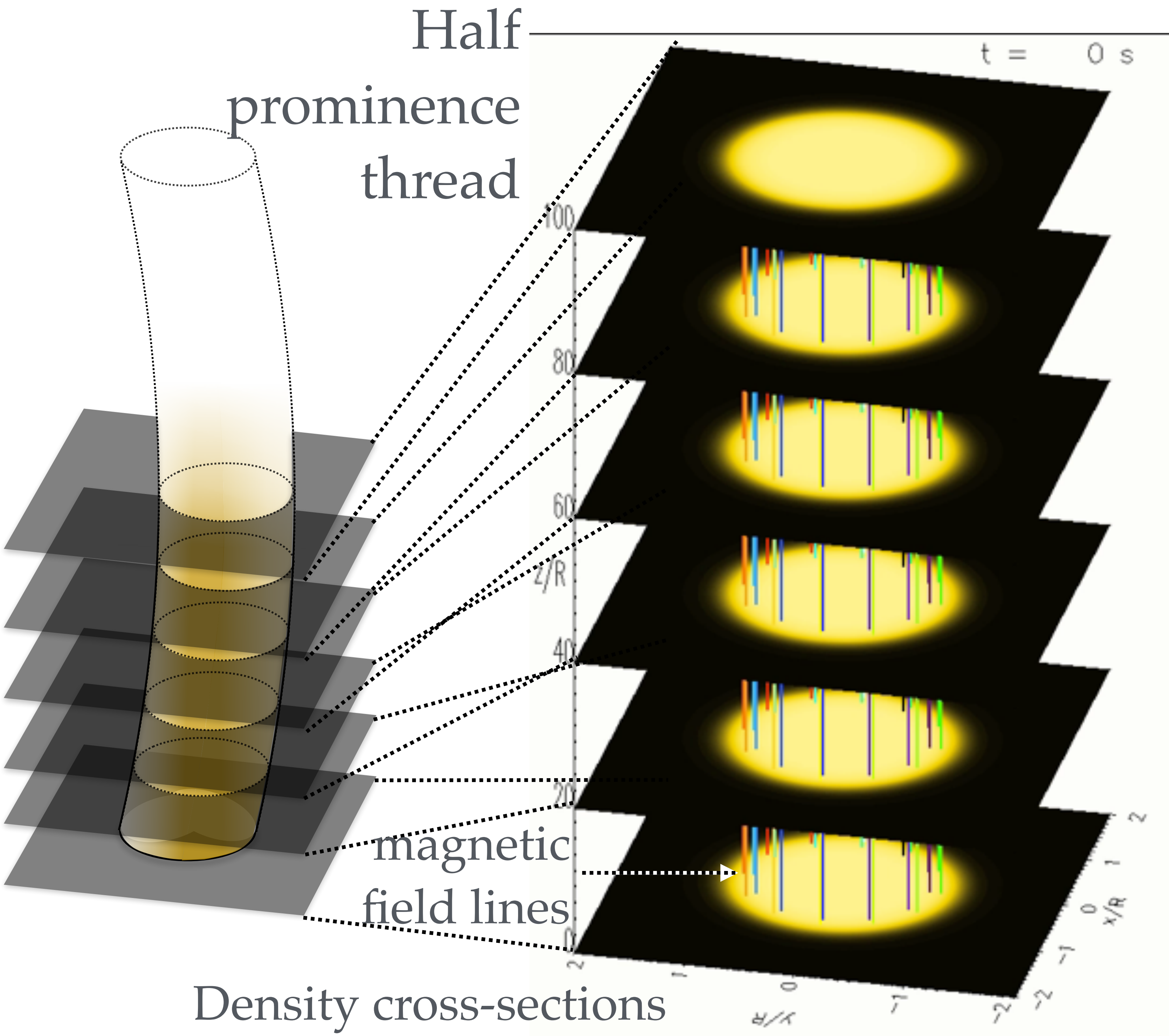
2 kinds of motion: transverse+azimuthal
Resonant absorption transfers energy from a transverse (global) wave to azimuthal (local) Alfvén waves near the boundary

Resonant absorption

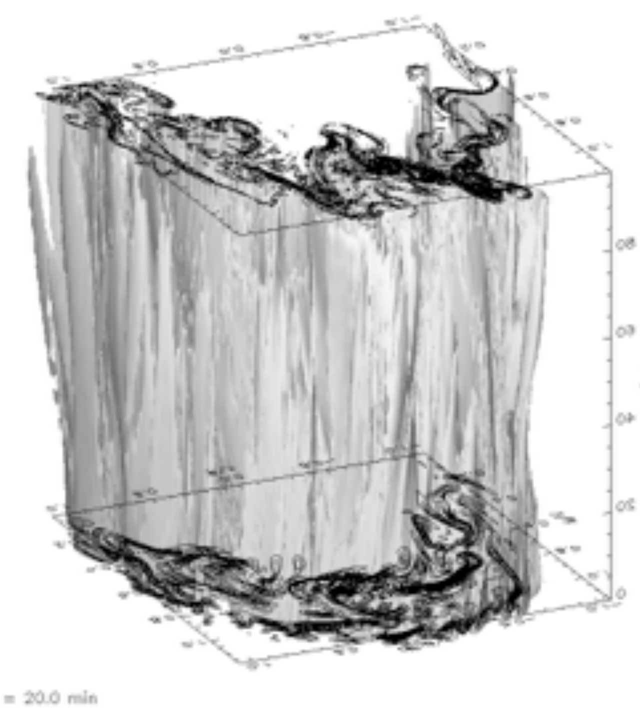


Ionson 1978, Hollweg+ 1990, Sakurai+ 1991, Goossens+ 1992, 2002, 2012; Van Doorsselaere+ 2004, Arregui+ 2008, 2011; Verth+ 2010, Soler+ 2010, 2012; Pascoe+ 2010, 2012

Two mechanisms combined



Iso-contours of current density



Vortices break-up into turbulence, producing twisted current sheets

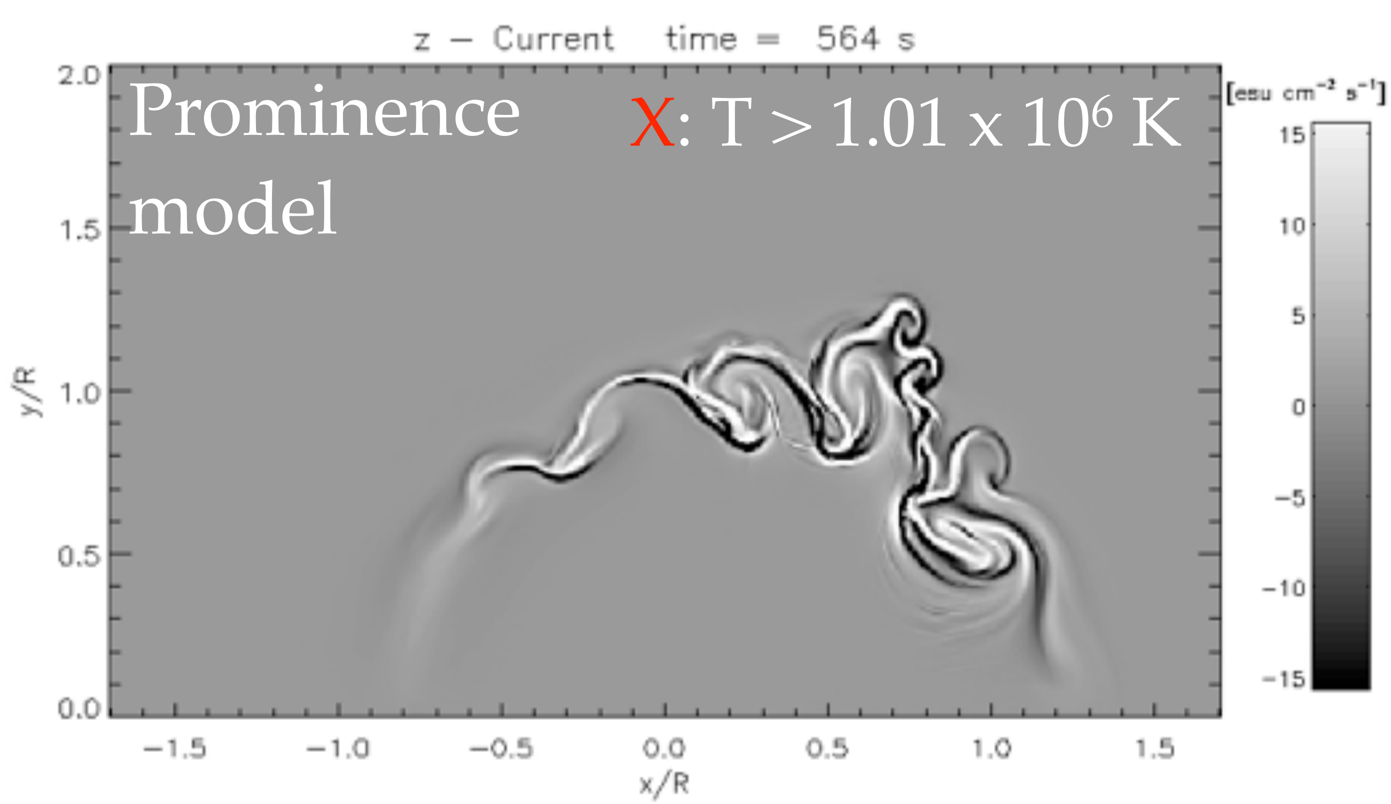
Model: *Uchimoto+. 1991; Karpen+ 1993, Ofman+ 1994; Ziegler & Ulmschneider 1997; Terradas+ 2008, Soler+ 2010*

Resonant absorption & onset of K-H instability

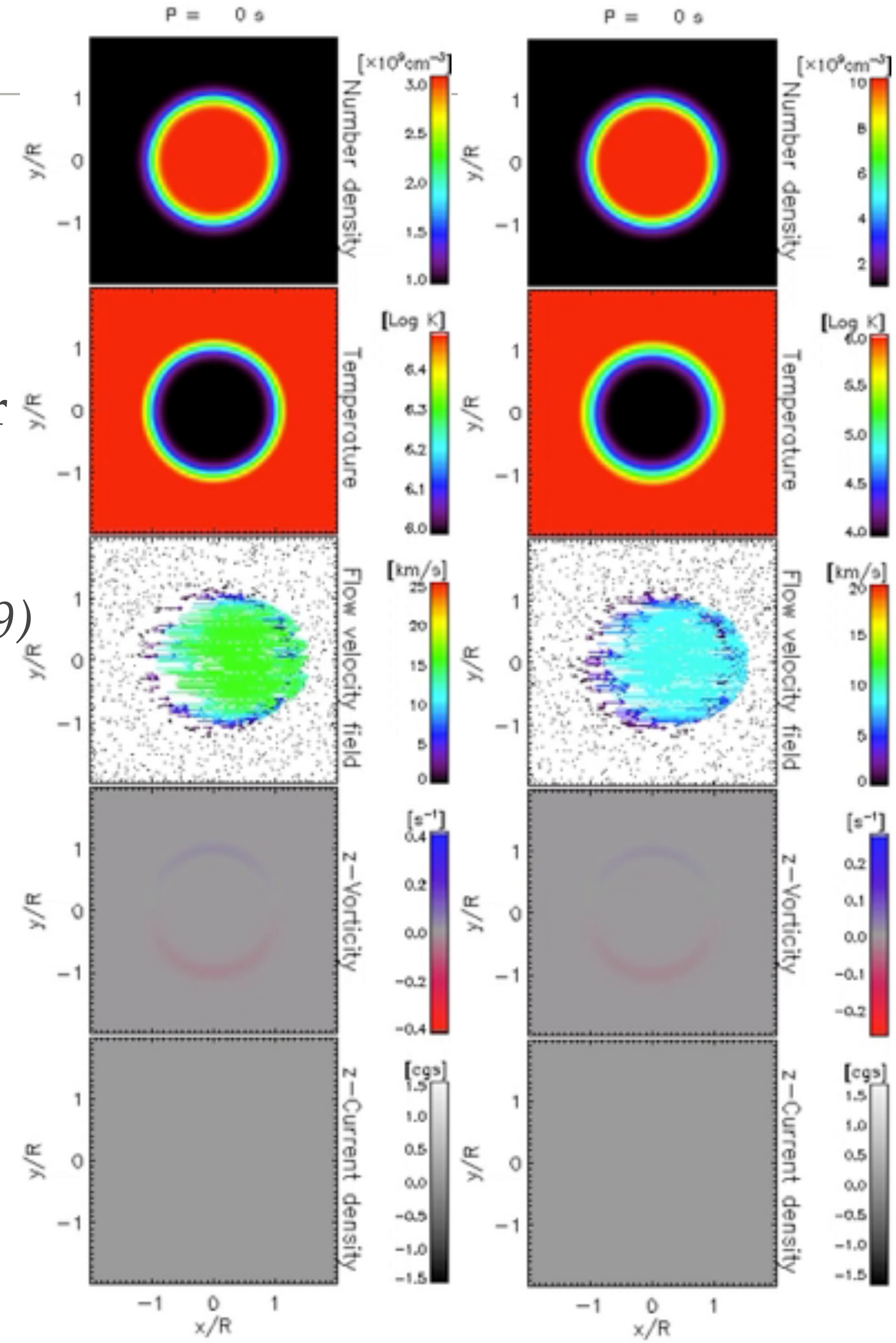
- Onset of instability *(Zaqarashvili+ 2015)*

$$\frac{v_0}{v_{A_i}} > \frac{\pi}{\sqrt{|m|-1}}\frac{R}{L}\sqrt{\left(1+\left(\frac{B_e}{B_{z_i}}\right)^2\right)\left(1-\frac{|m|-1}{\frac{\rho_i}{\rho_e}+|m|}\right)}$$

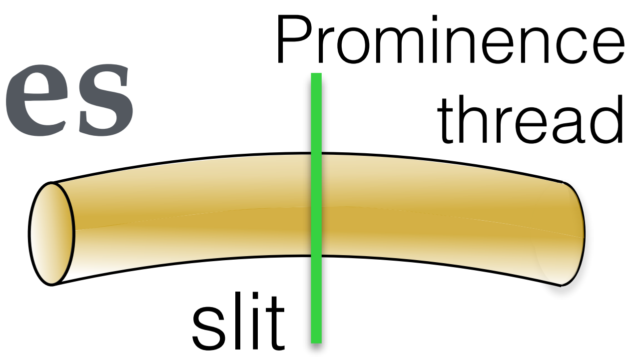
- KHI vortices obtain momentum from resonant layer
- Non-uniform boundary layer widens, mixing of plasma *(Fujimoto & Terasawa 1994)*
- Multiple vortices & current sheets *(Ofman 1994, 2009)*

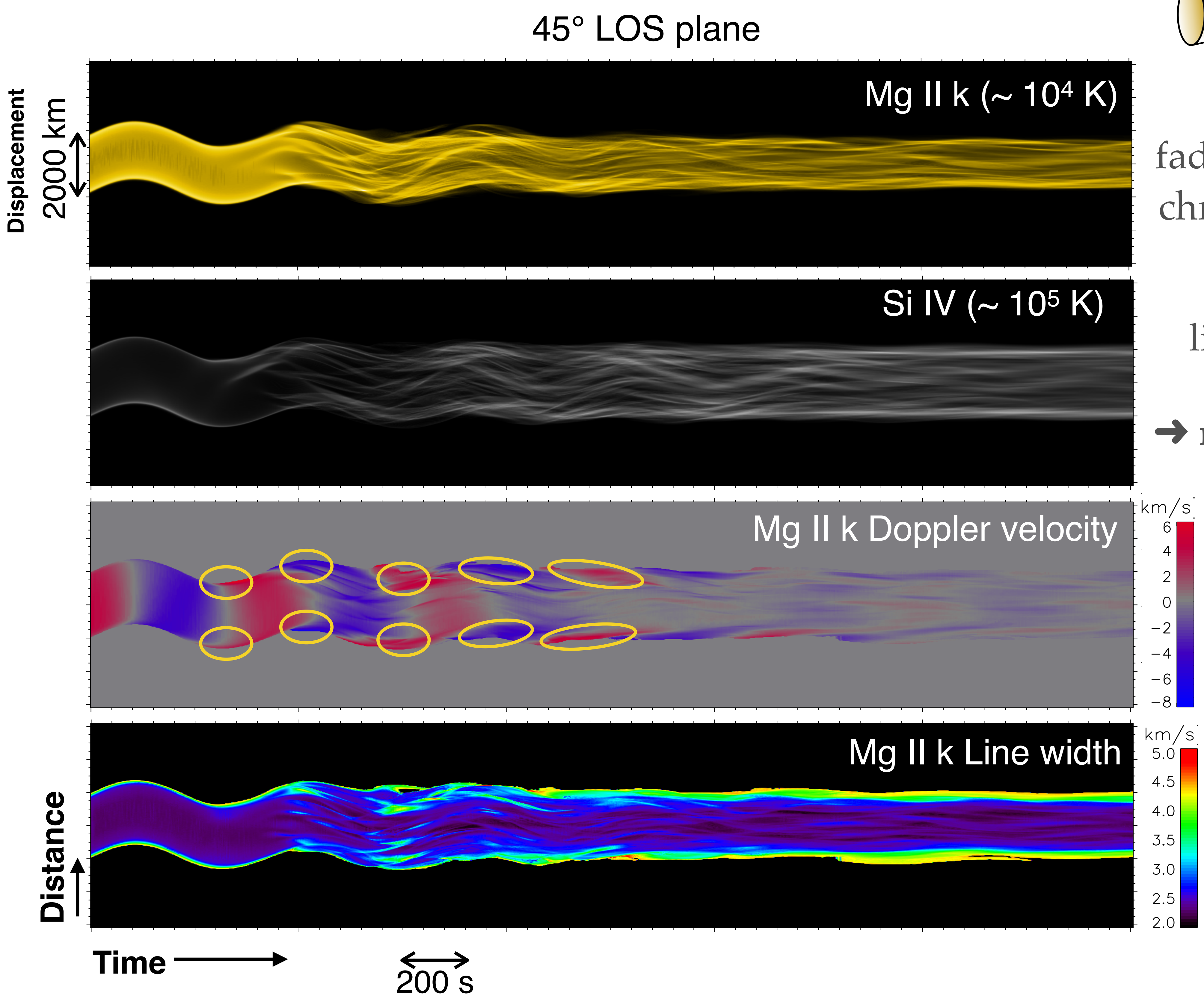


Coronal model	Prominence model
v~14 km/s, 1/R ~ 0.4	v~8 km/s, 1/R ~ 0.4
P = 255 s, Amp = 414 km	P = 515 s, Amp = 711 km



Observational signatures





fading & thinning in chromospheric lines

appears in TR lines, broadened

➜ **mixing & heating**

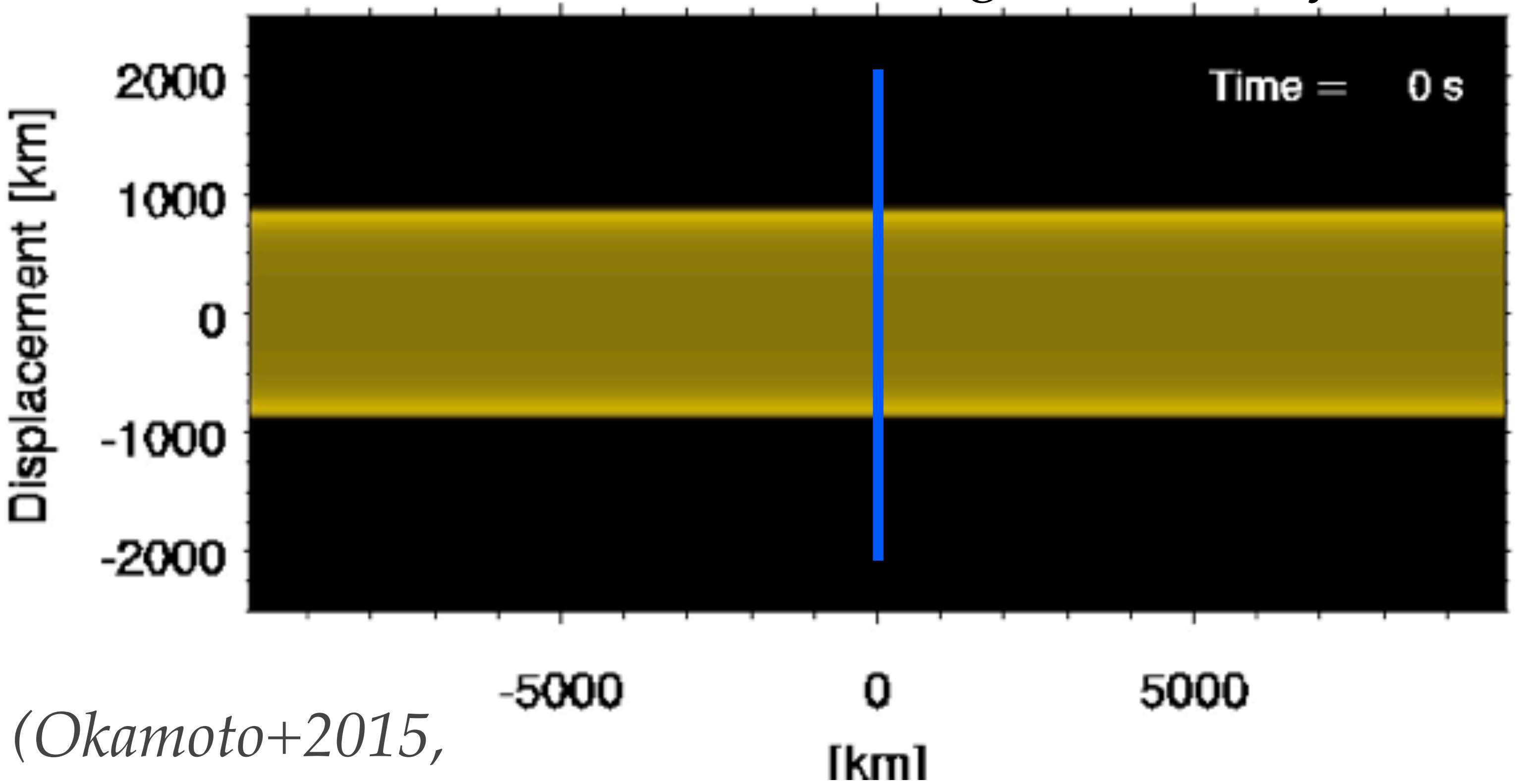
LOS velocity out-of-phase with POS motion

➜ **RA+phase mixing**

Line broadening at edges

Comparing with Hinode & IRIS observations

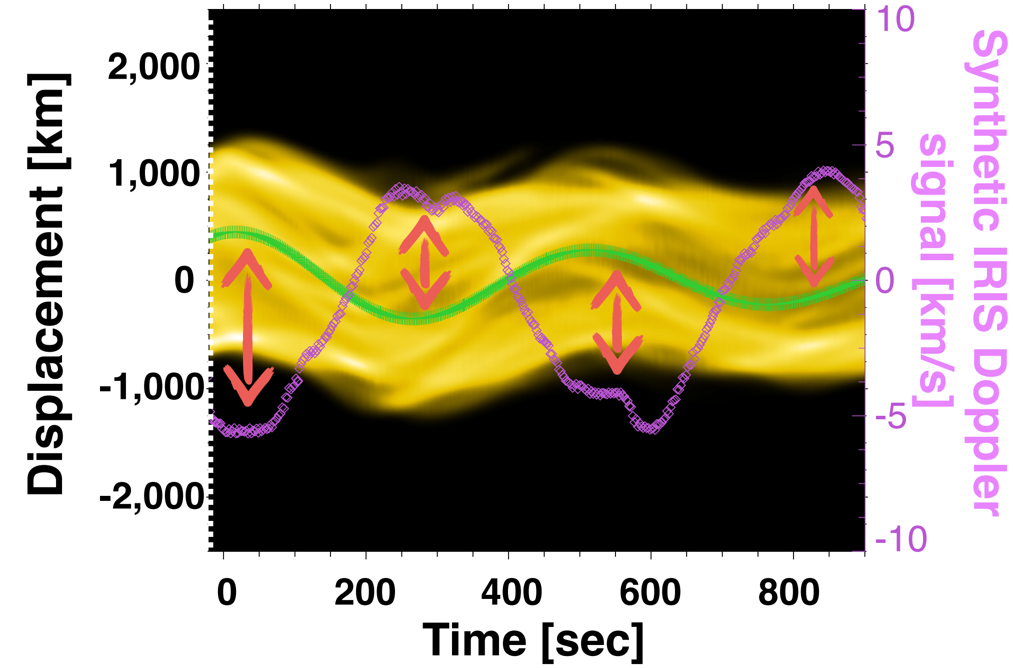
Prominence thread - Mg II k intensity



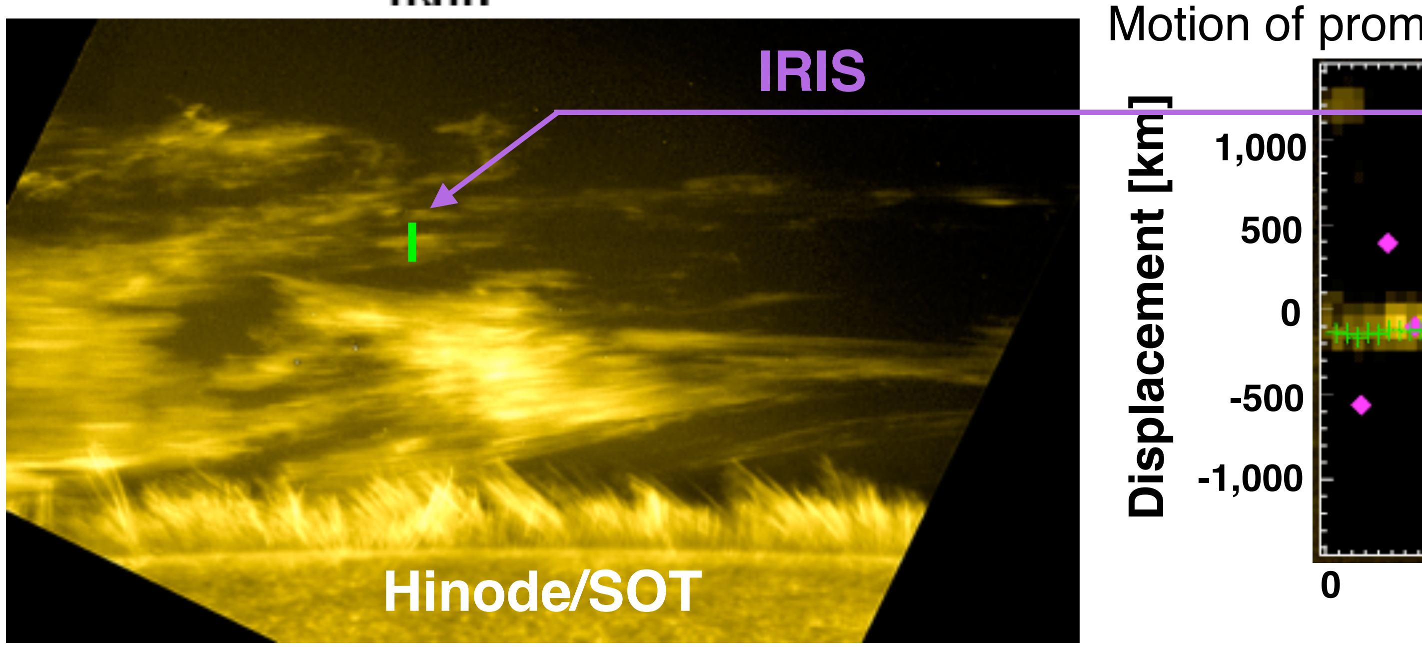
(Okamoto+2015, Antolin+2015)

Numerical results

Motion of prominence plasma crossing the slit

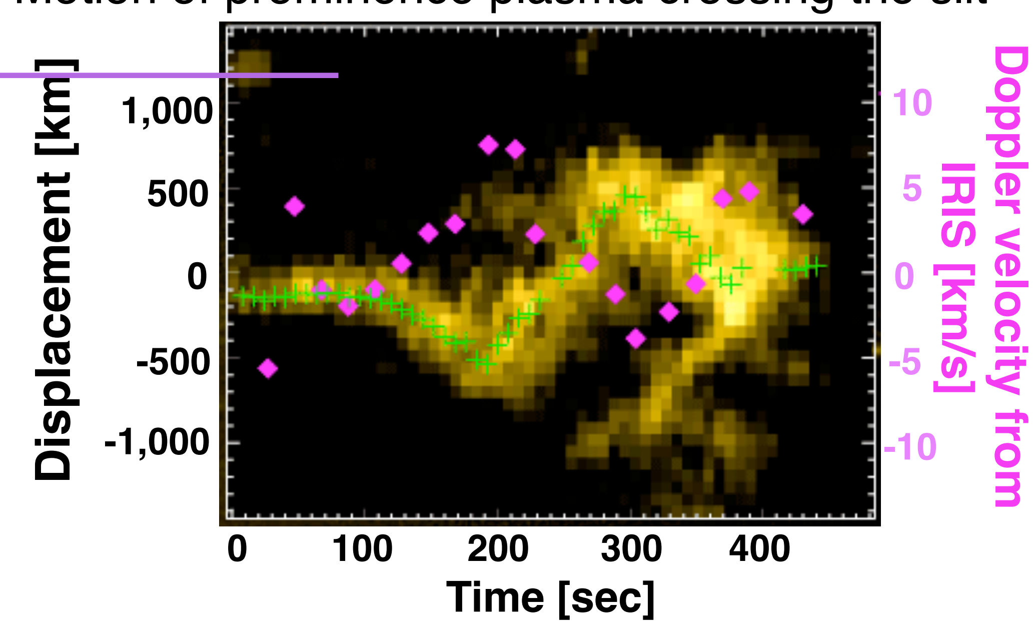


KHI takes up the resonant dynamics to the observable scale: **match**



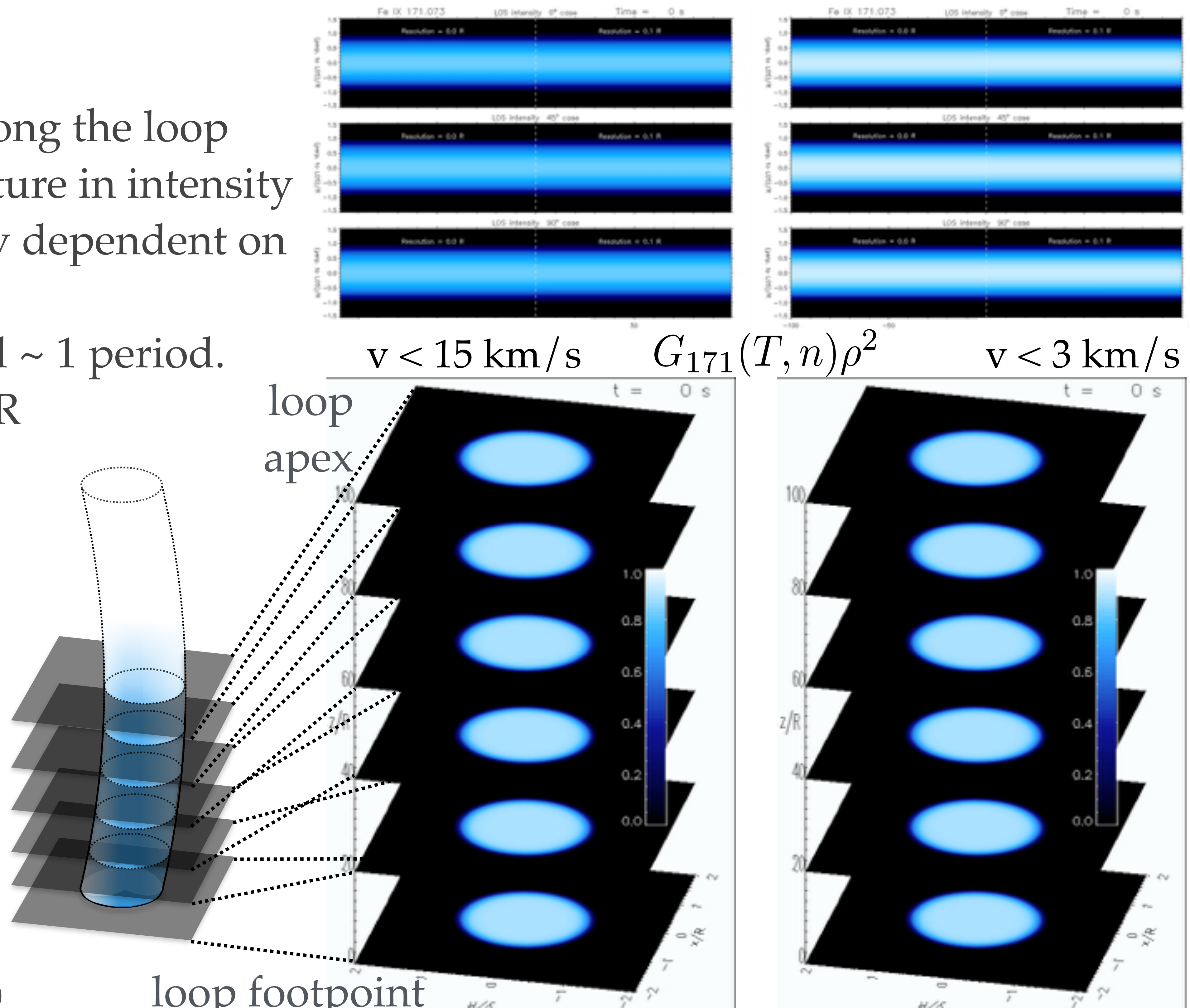
Observational results

Motion of prominence plasma crossing the slit



Strand-like structure in the corona

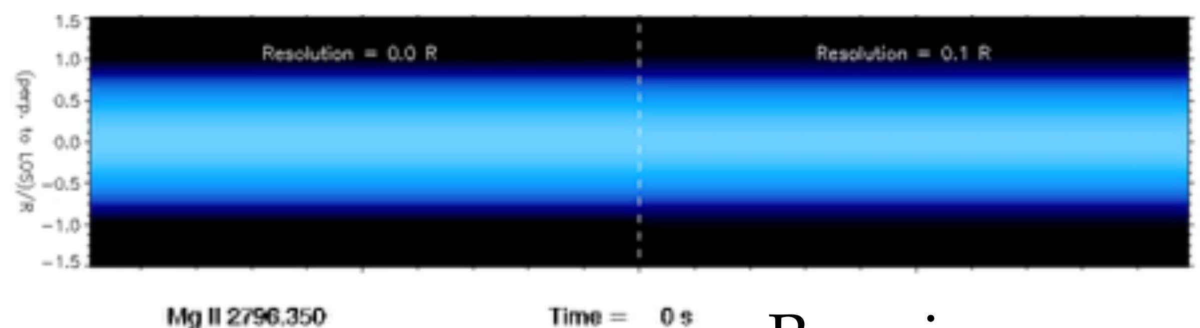
- Roll-ups (eddies) along the loop
  ➙ strand-like structure in intensity
- Detection is strongly dependent on spatial resolution
- Lifetime for 1 strand ~ 1 period. Widths: 0.01 R - 0.5 R



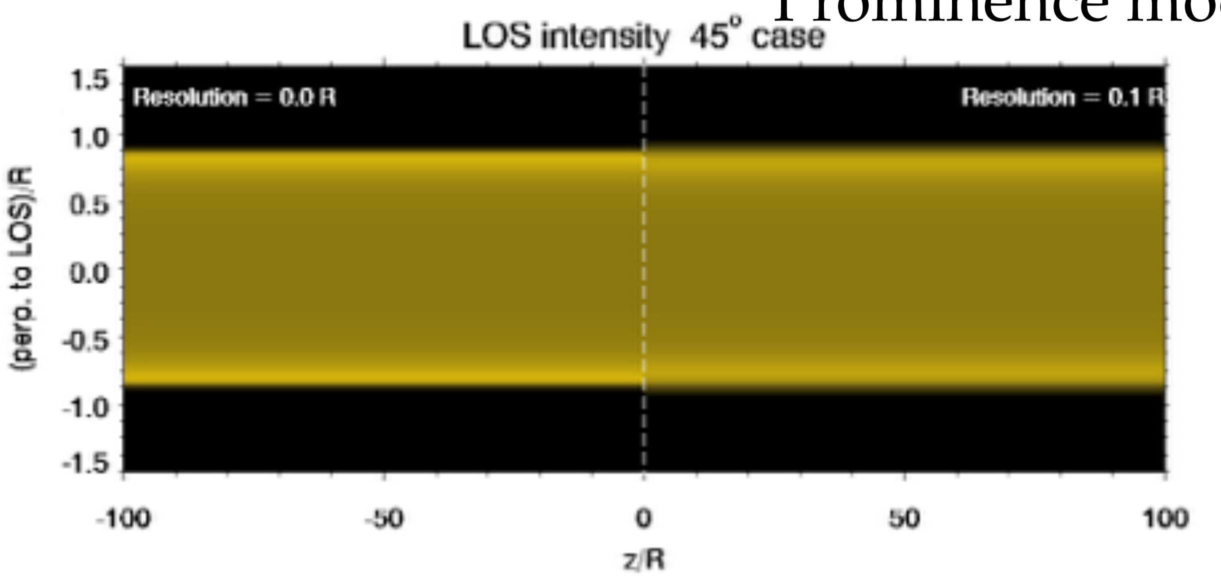
Antolin, Yokoyama & Van Doorsselaere (2014)

Strand-like structure

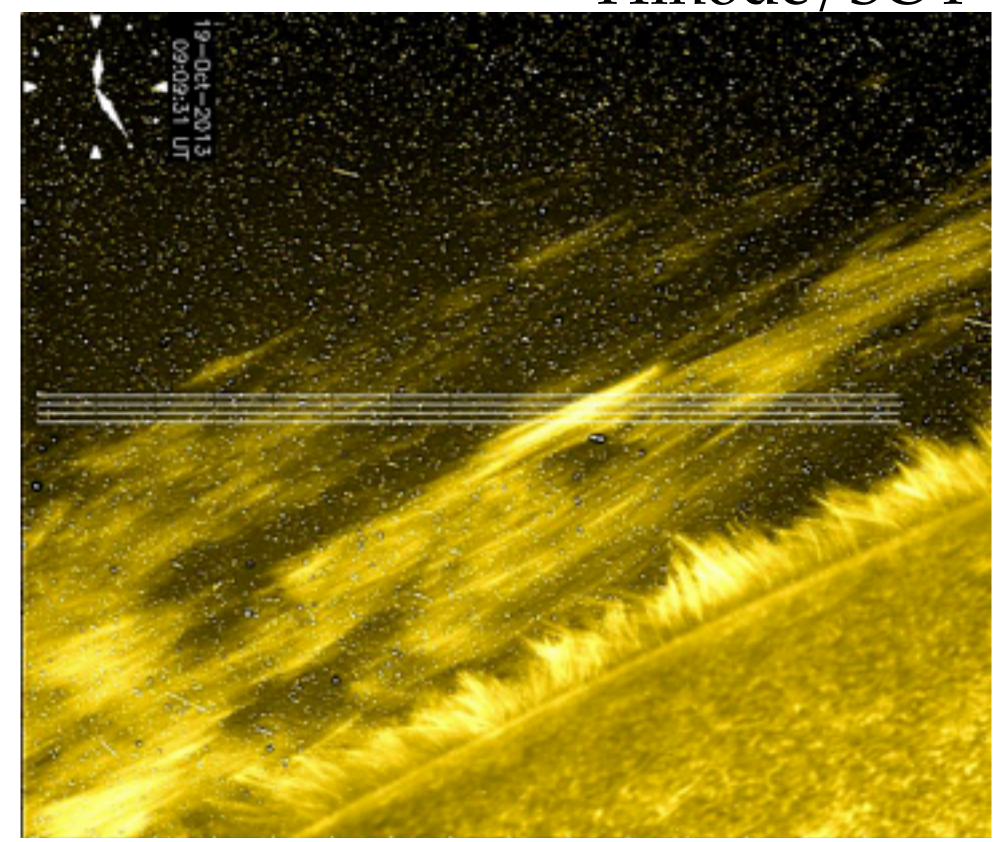
v < 15 km/s, l/R ~ 0.4 Coronal model



Prominence model



Hinode/SOT

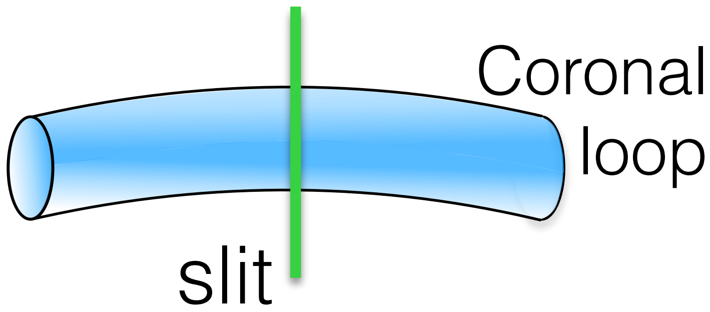


- Roll-ups (eddies) along the loop + line-of-sight effects

  ➙ **strand-like or thread-like structure in intensity images**

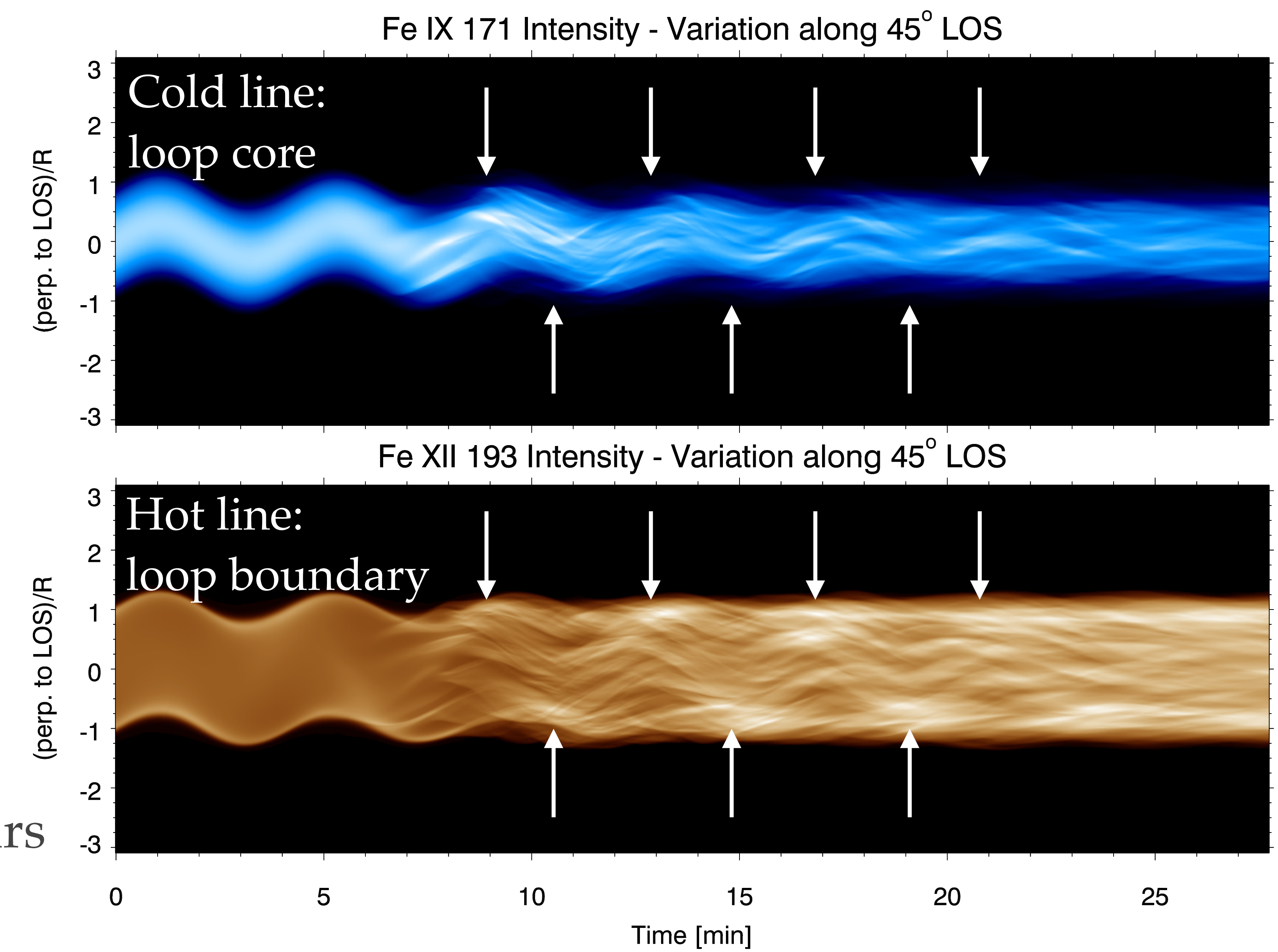
  ➙ **KHI vortices <—> part of prominence threads?**
- Lifetime for 1 strand ~ 1 period. Widths: 0.01 R - 0.5 R
- Apparent crossing of strands/threads

Intensity variation



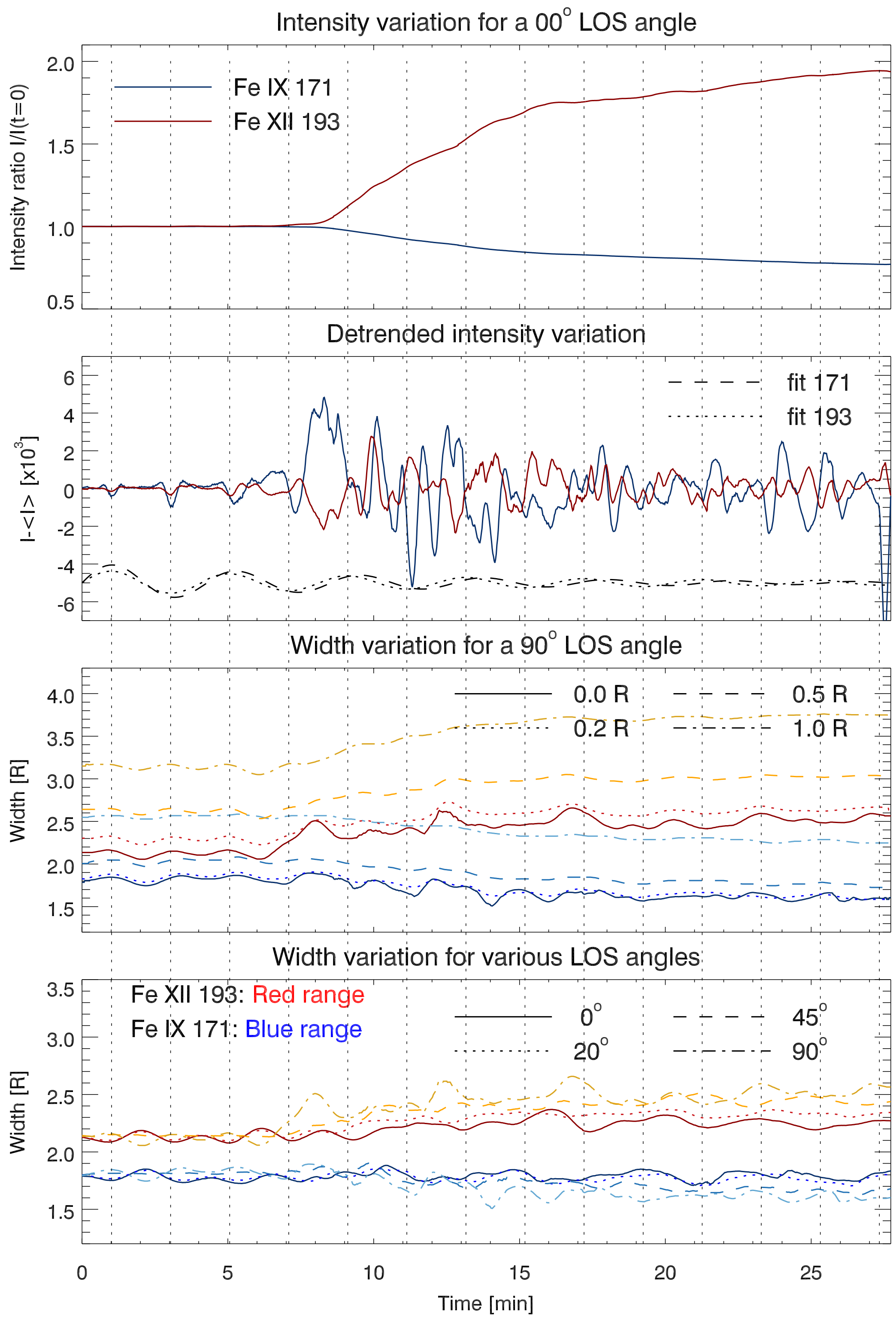
- Brightening when KHI with strand-like pattern
- Impulsive character at times of maximum displacement
- Gradual dimming in 171, intensity enhancement in 193
- Thinning in 171, enlargement in 193
- Observed damping appears different in 171 & 193

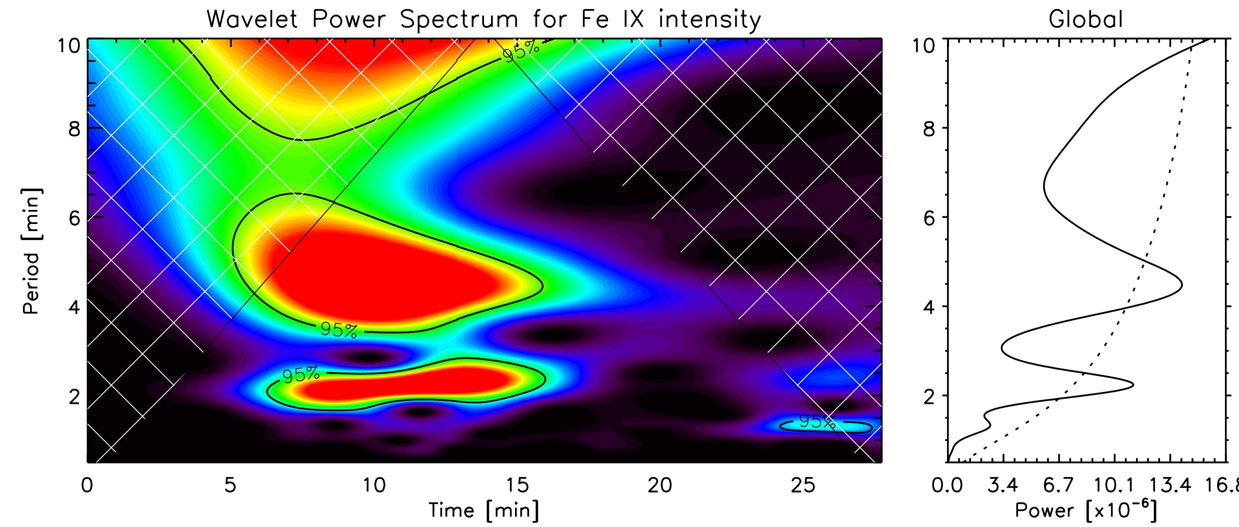
Antolin, De Moortel, Van Doorsselaere, Yokoyama (2016, submitted)

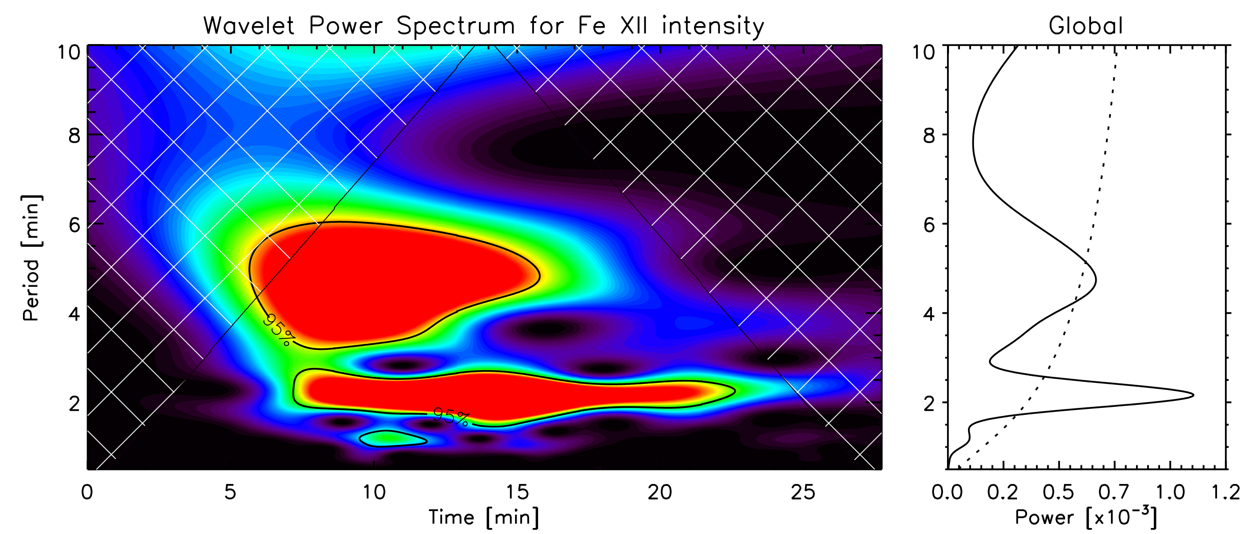


➡ Hotter channel more sensitive to vortex dynamics (and to the resonant flow)

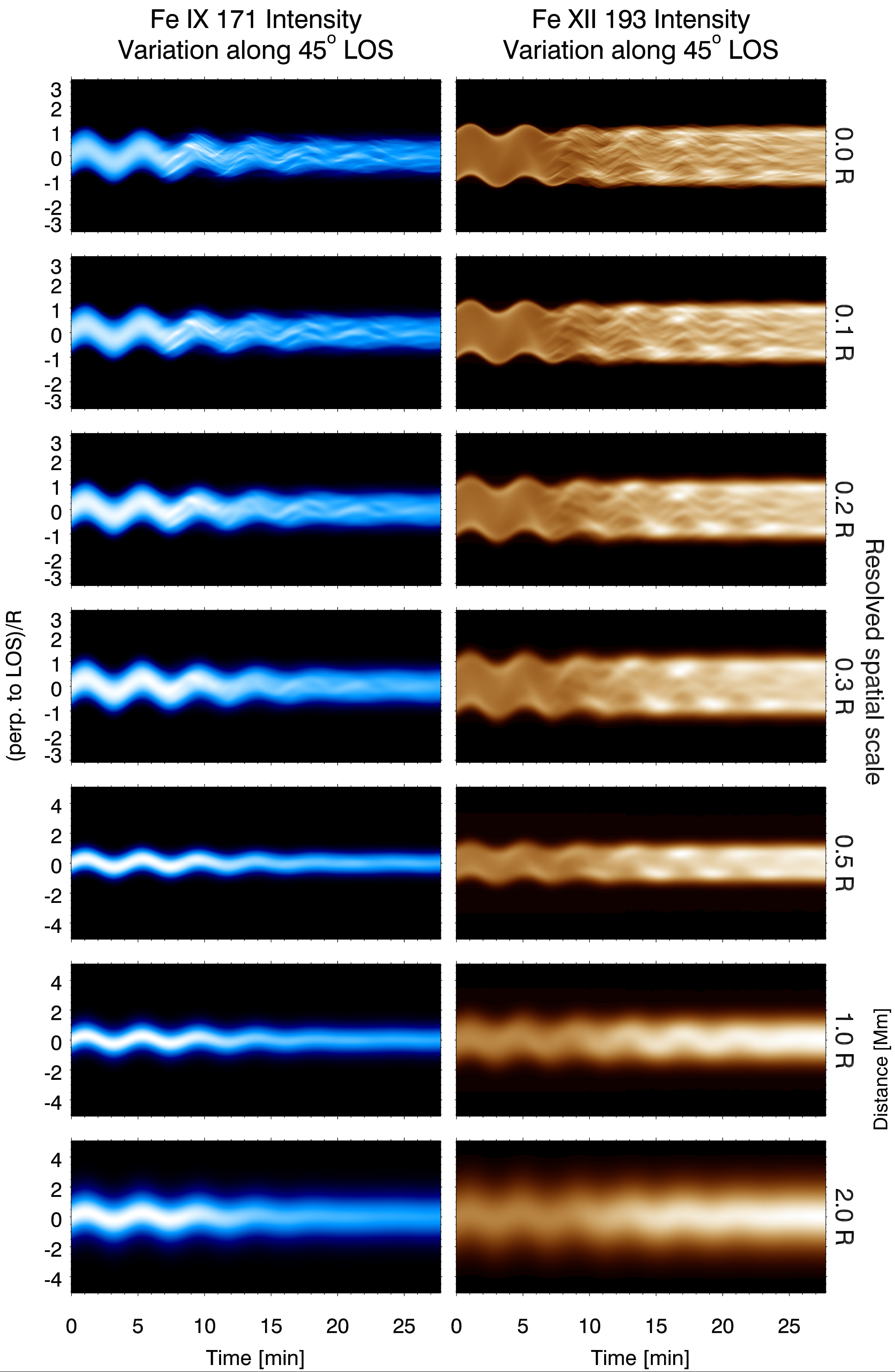
Intensity & loop width variation





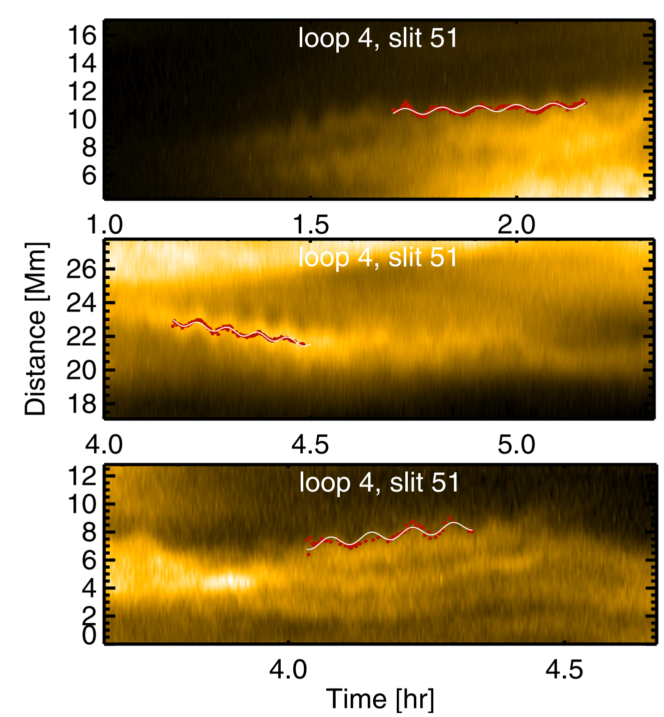


- Double periodicity in intensity linked to KHI vortex generation
- Width variation linked to centrifugal force or flute modes



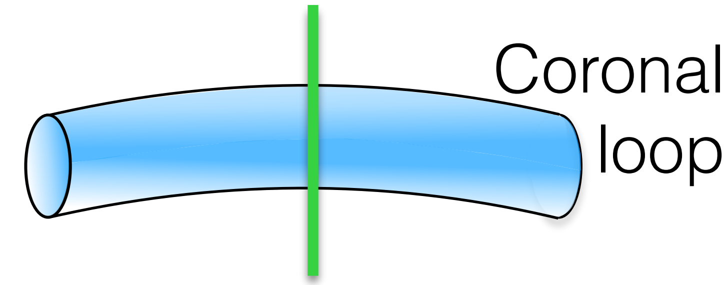
Decay-less oscillations: Alfvén waves

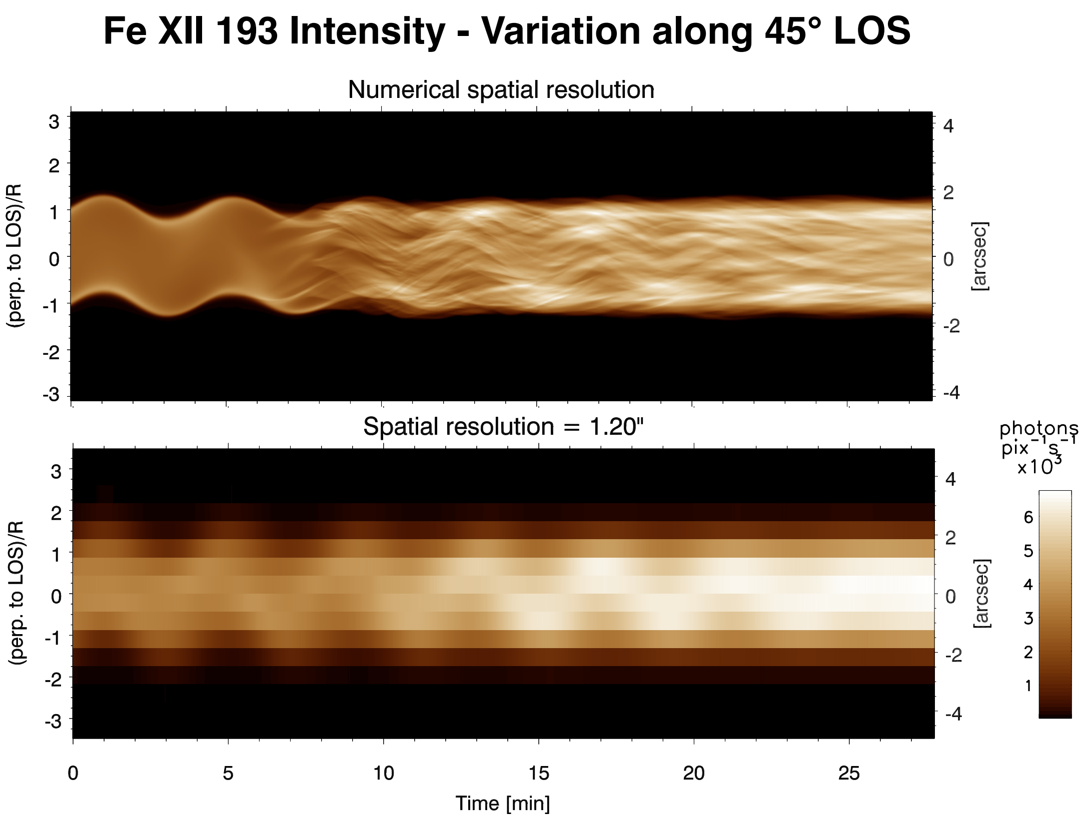
- Damping observed in 171 is not observed in 193 at low resolution
- Due to ensemble of correlated vortices (which show much less damping due to resonance) & brightening at maximum displacement

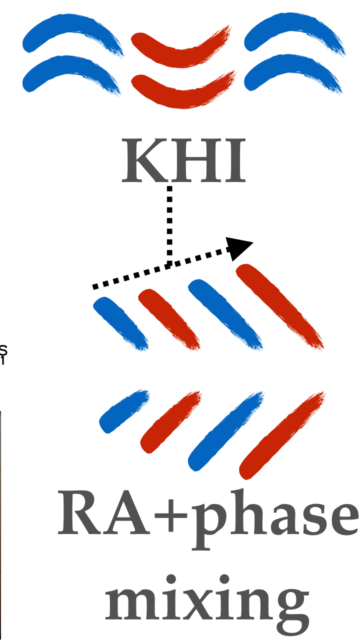


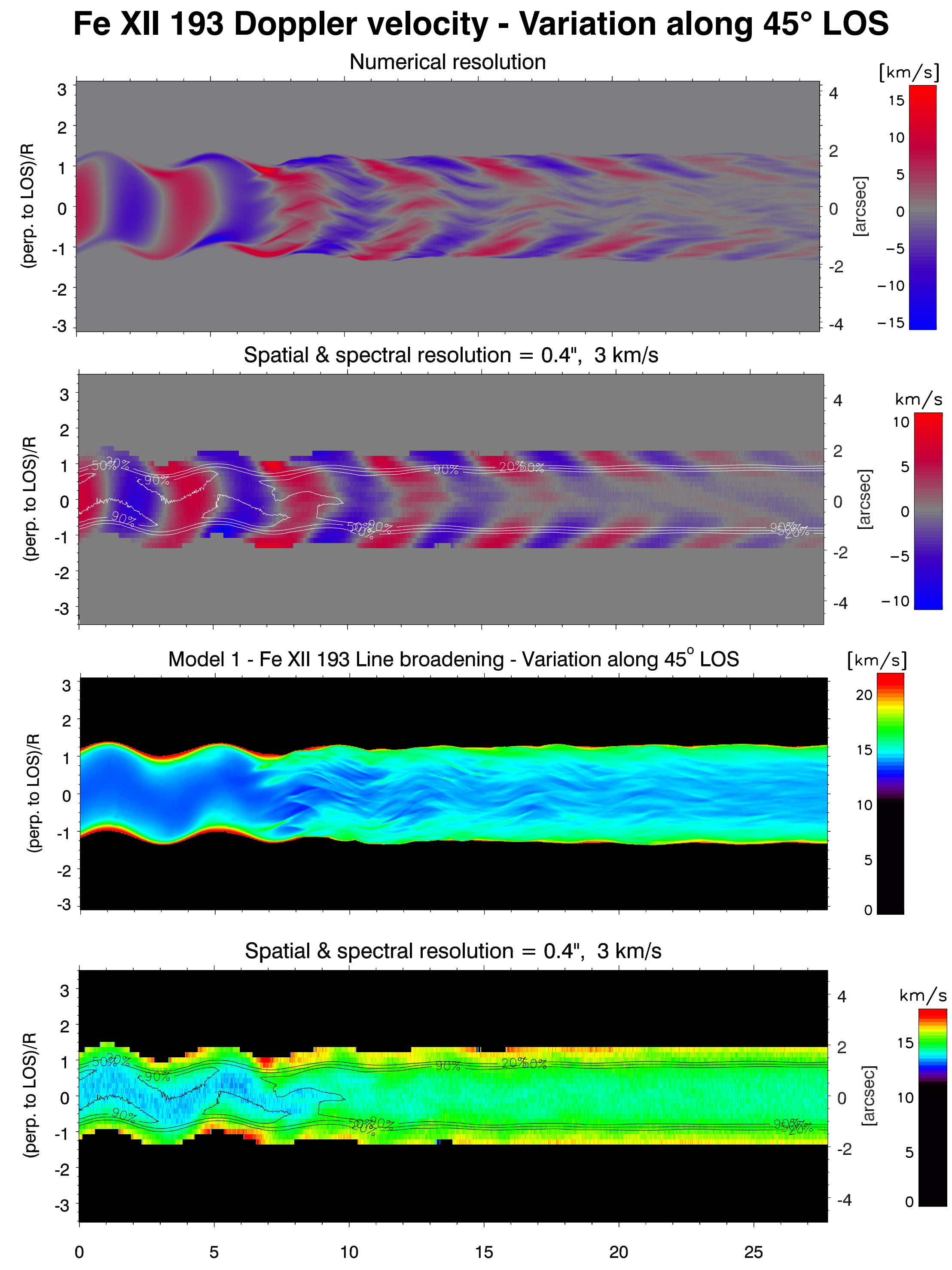
Nisticò+(2013), Anfinogentov+ (2013, 2015), Goddard+(2015)

Doppler velocities & line widths







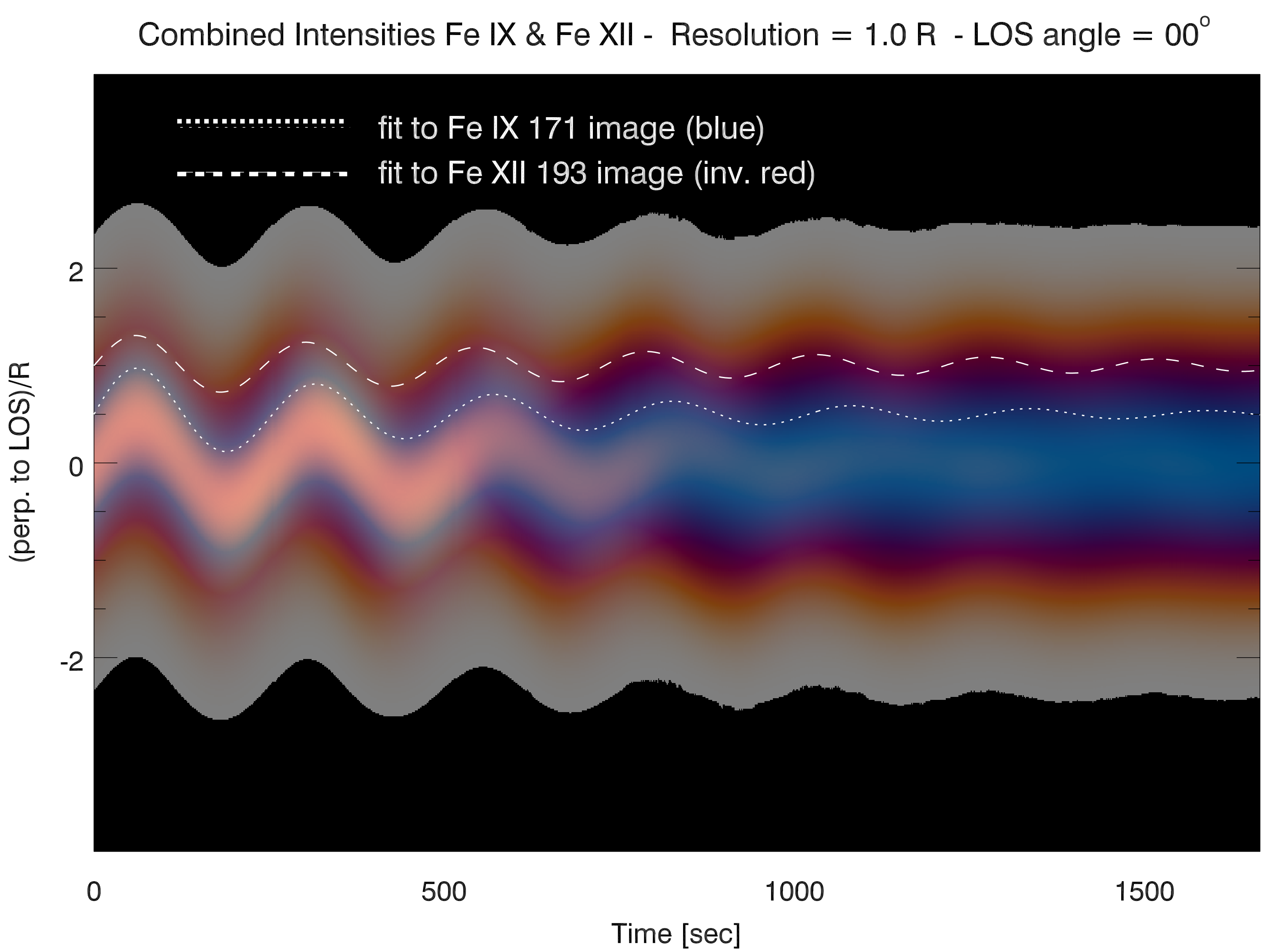


- Apparently decay-less
- Strand-like structure
- Broad arrow-shaped Doppler maps
- Broad line widths at edges

(*Antolin+2016, submitted*)

Decay-less oscillations: Alfvén waves

Antolin+ (2016, submitted)



Period in 171 ~ 255 s

Period in 193 ~ 243 s

- Oscillation in 193 and 171 go out-of-phase: effect of phase mixing
- Oscillation in 193 reflects azimuthal Alfvén wave oscillation at boundary

$$\frac{\rho_b}{\rho_i} = \frac{1}{2}\left(1 + \frac{\rho_e}{\rho_i}\right)\left(\frac{P_b}{P_k}\right)^2$$

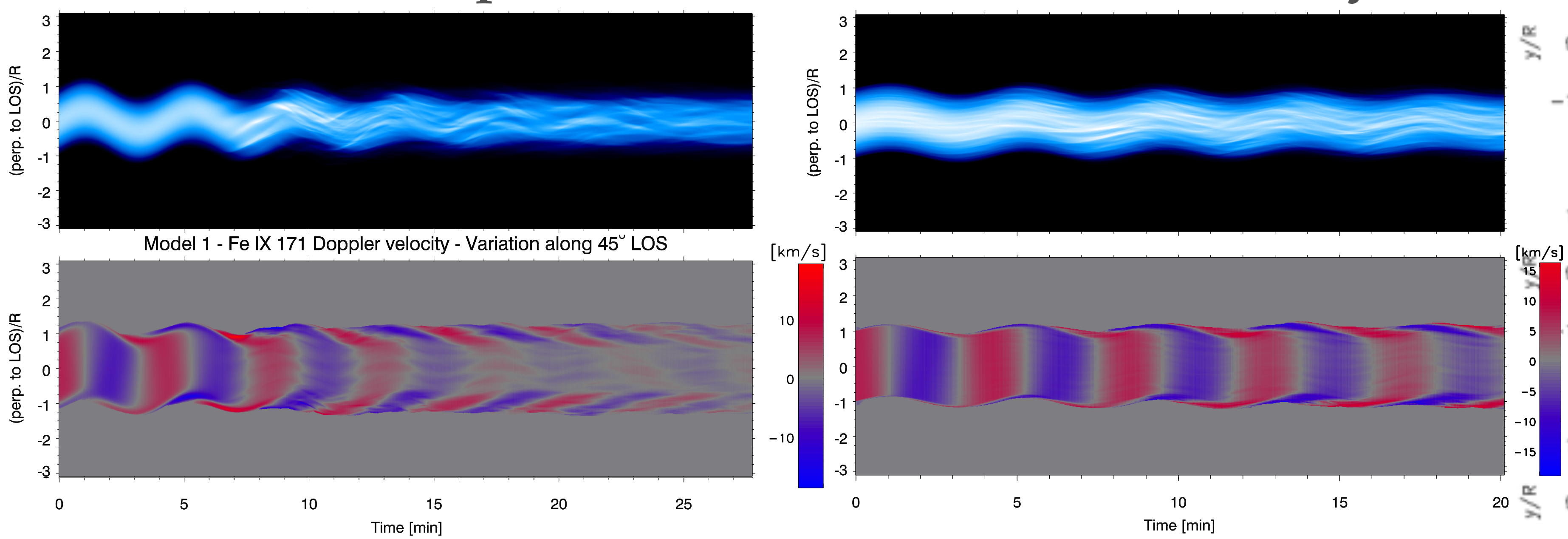
$$\rightarrow n = 1.8 \times 10^9 \text{ cm}^{-3}$$

➡Combining channels sensitive to different temperatures we can perform high resolution seismology

Effect of resonant absorption

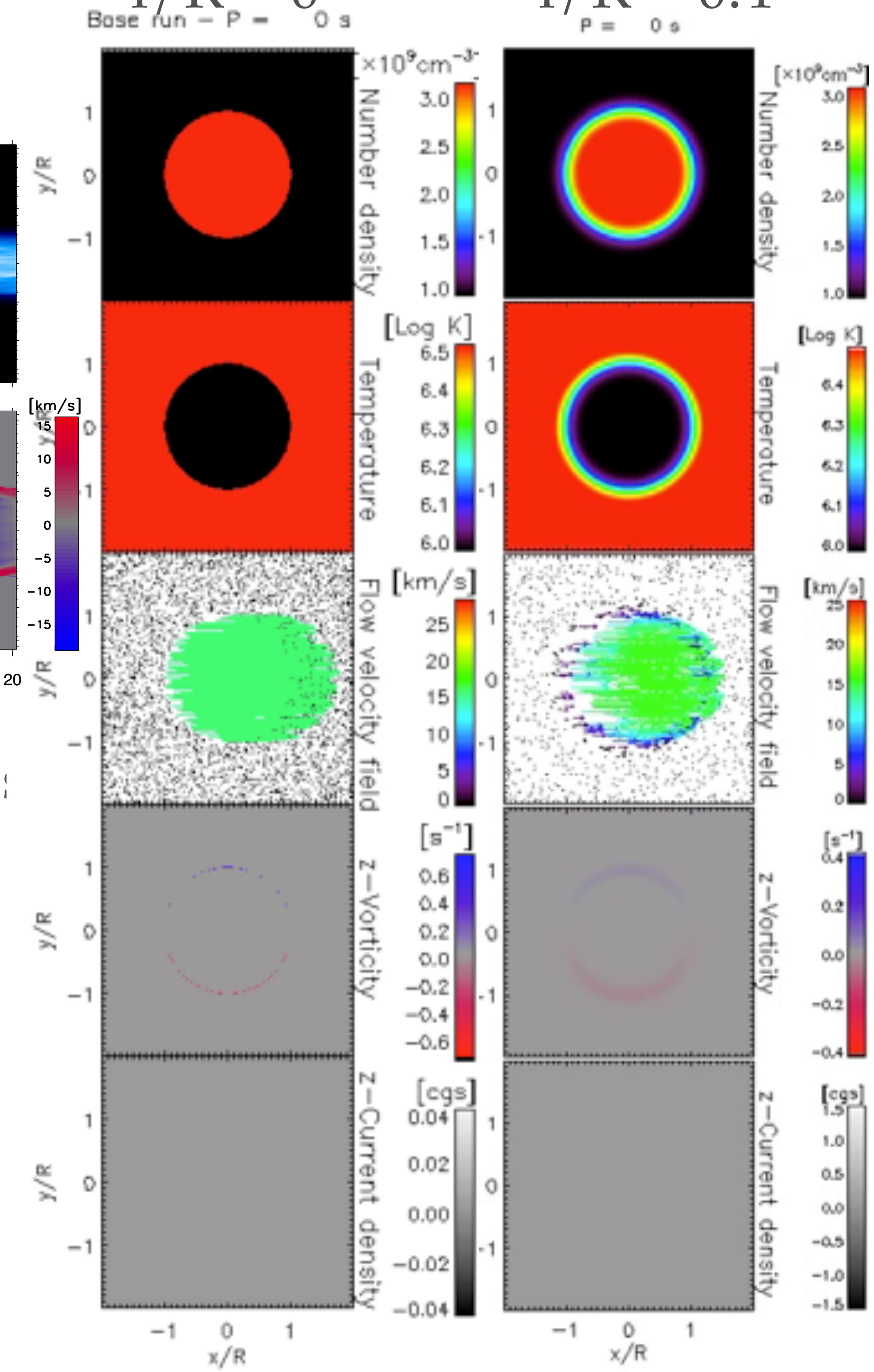
1/R ~ 0.4 Fe IX 171 1/R ~ 0

Resonant absorption (RA) **no RA initially**



Coronal model

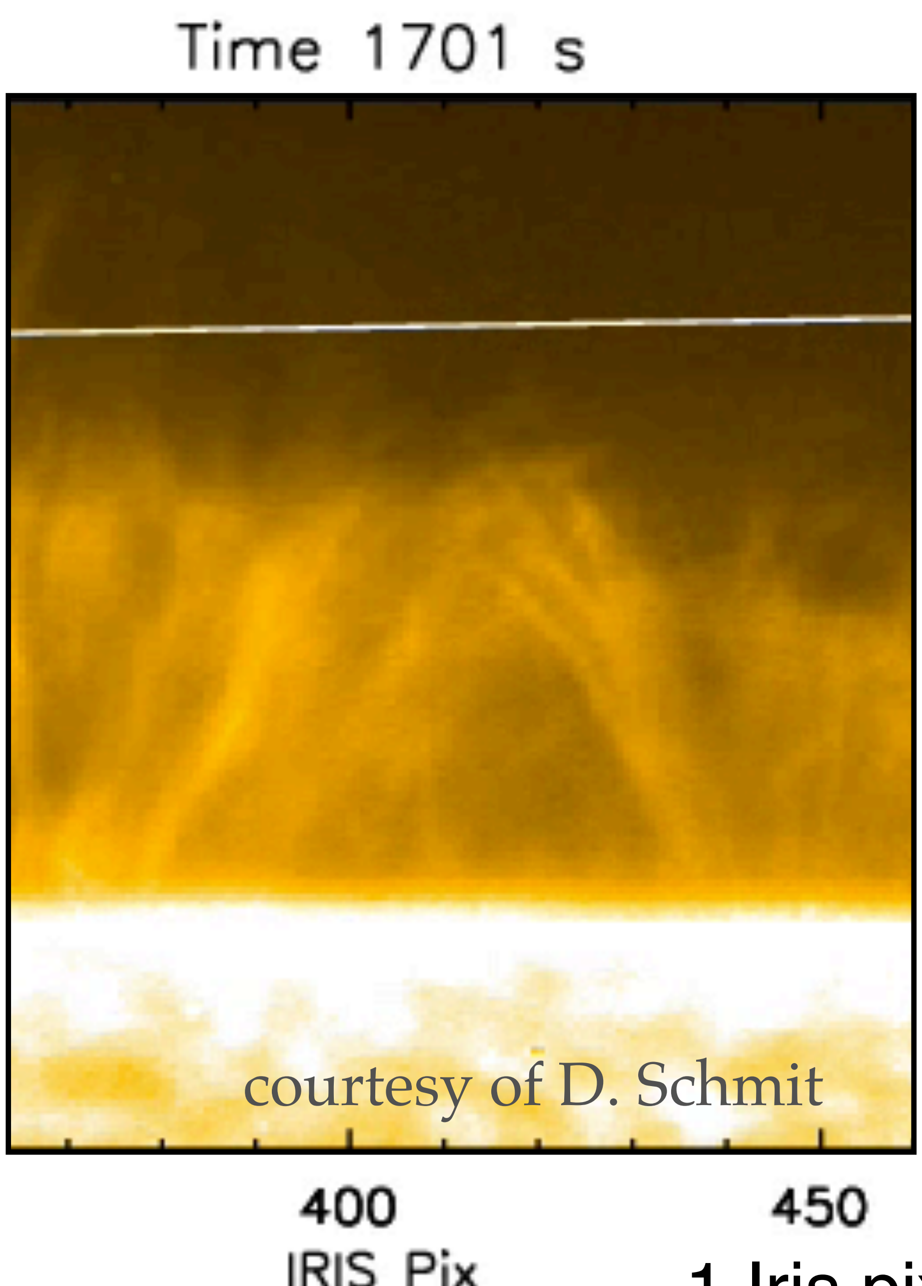
1/R ~ 0 1/R ~ 0.4

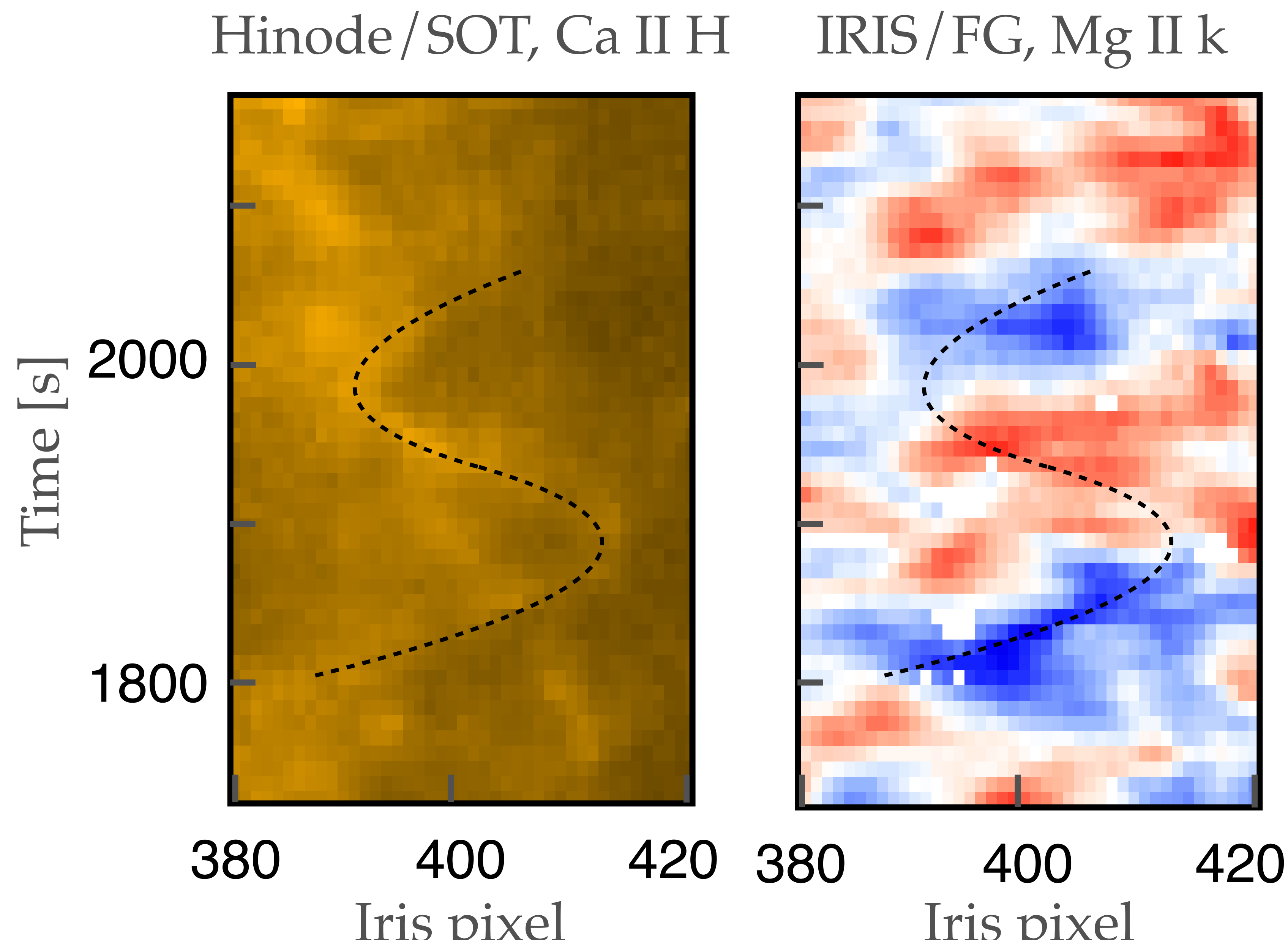


- Larger wavenumbers dominate first for thinner boundaries (higher growth rates). “Inverse” cascade.
- No RA in boundary layer -> less kinetic energy in boundary layer. Small wavenumbers have lower growth rates (no large vortices)
- No boundary layer: less damping
- **Significant difference in dynamics of core & boundary layer**

IRIS/Hinode observations: spicules

Antolin, Schmit, De Pontieu, Pereira (2016, in prep.)

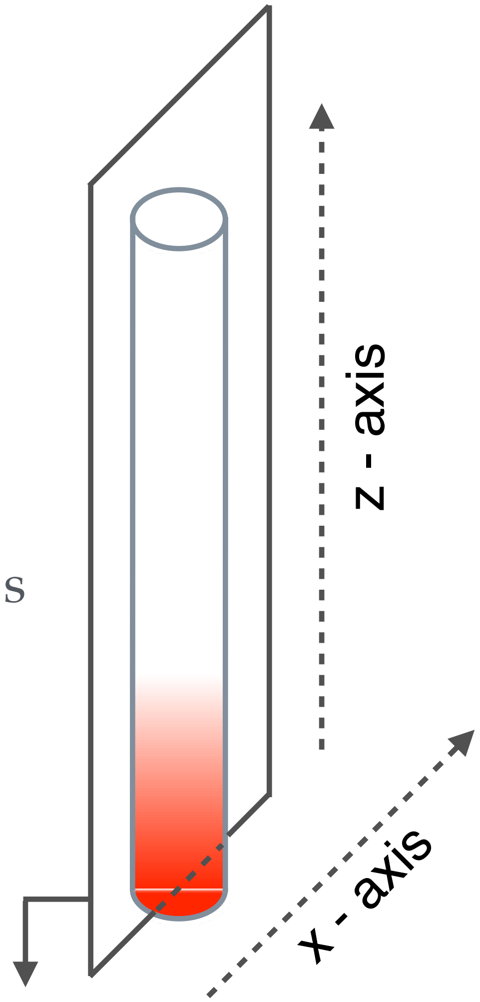




1 Iris pixel = 0.166”

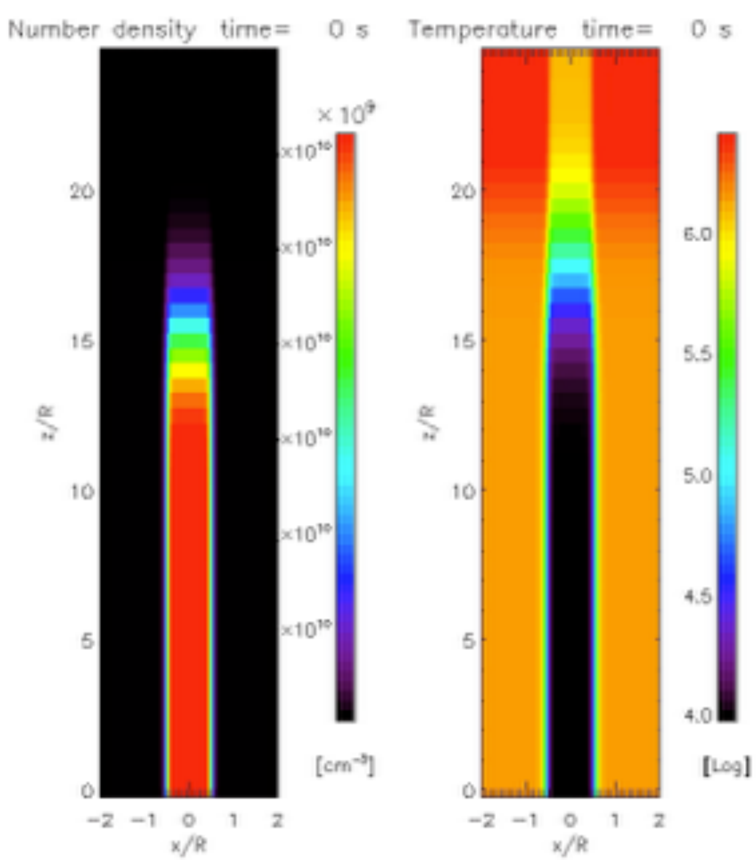
Spicule model

standing

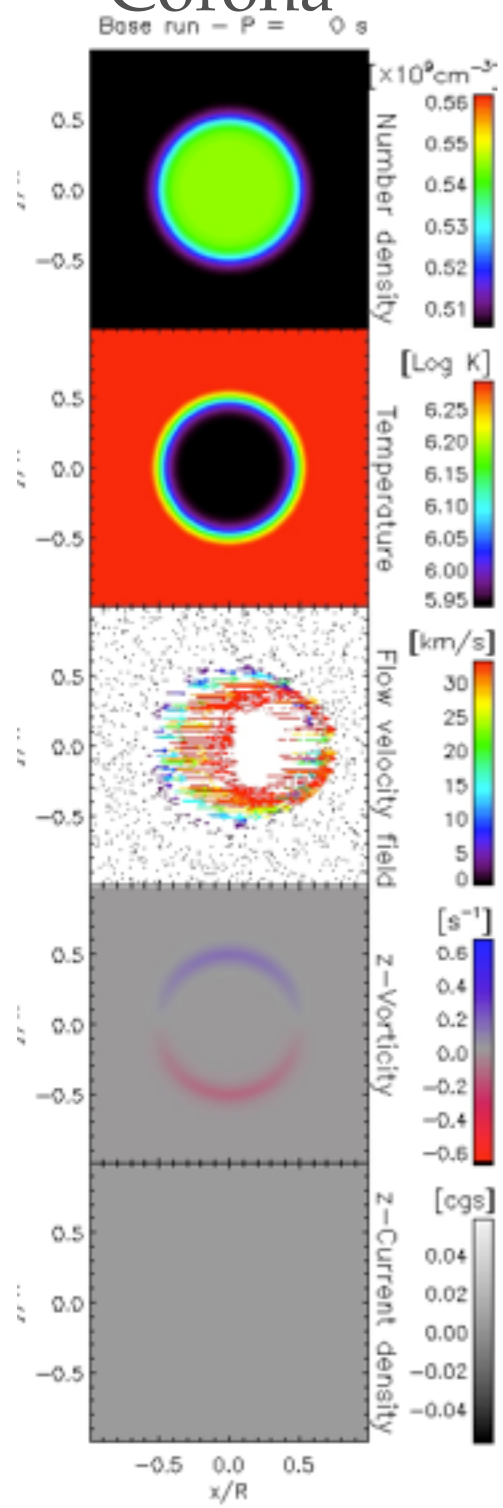


Amp. ~ 12 km/s

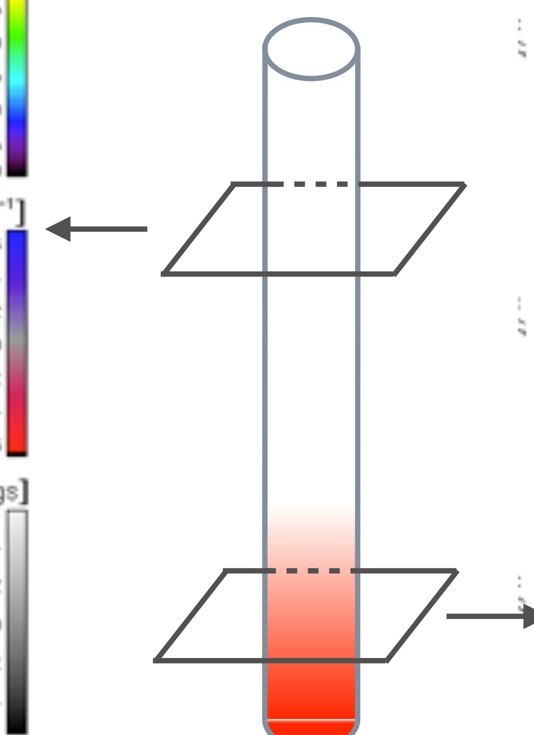
Period ~ 245 s



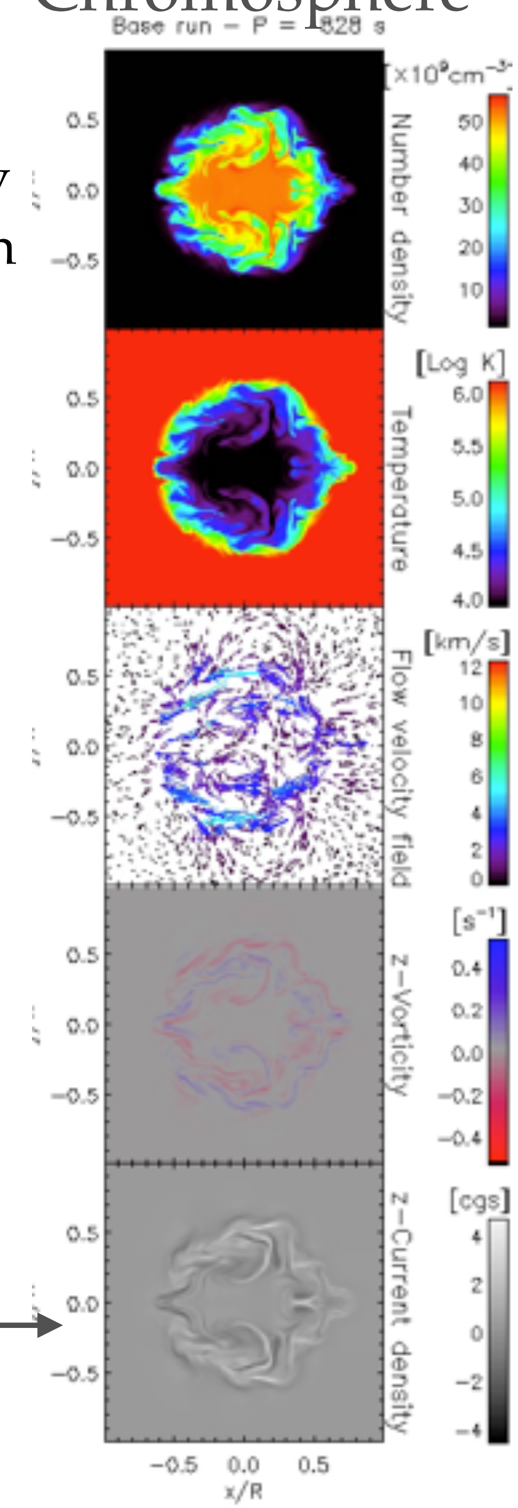
Corona



Strong vorticity destroys loop in corona *(Magyar & Van Doorsselaere 2016)*



Chromosphere

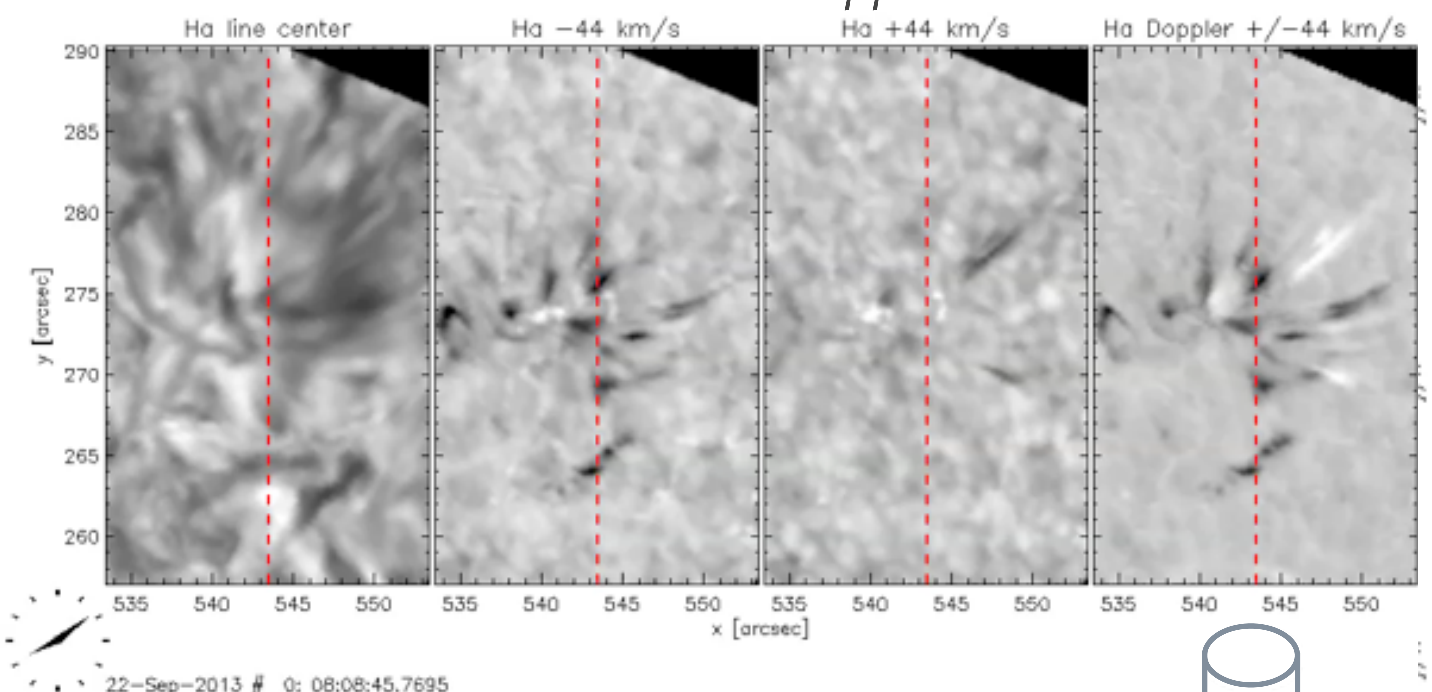


Spicule dynamics

standing kink

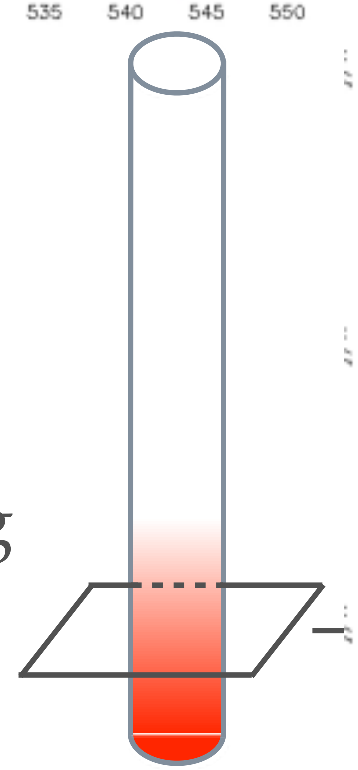
SST / CRISP Observations

Rouppe van der Voort+ 2015

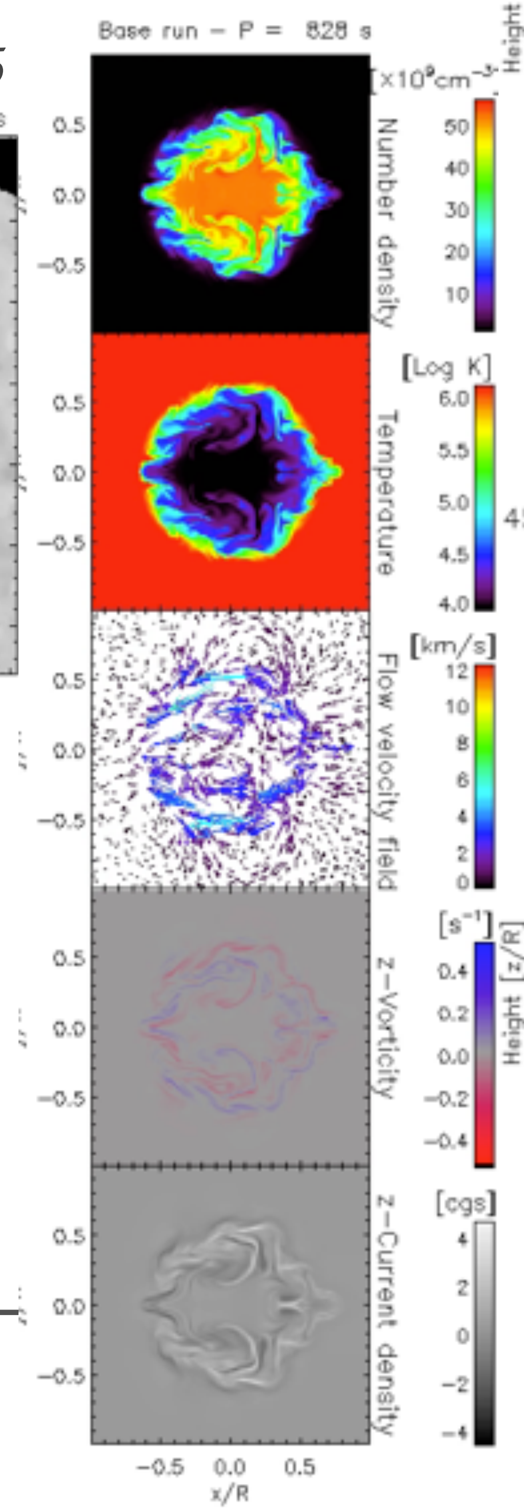


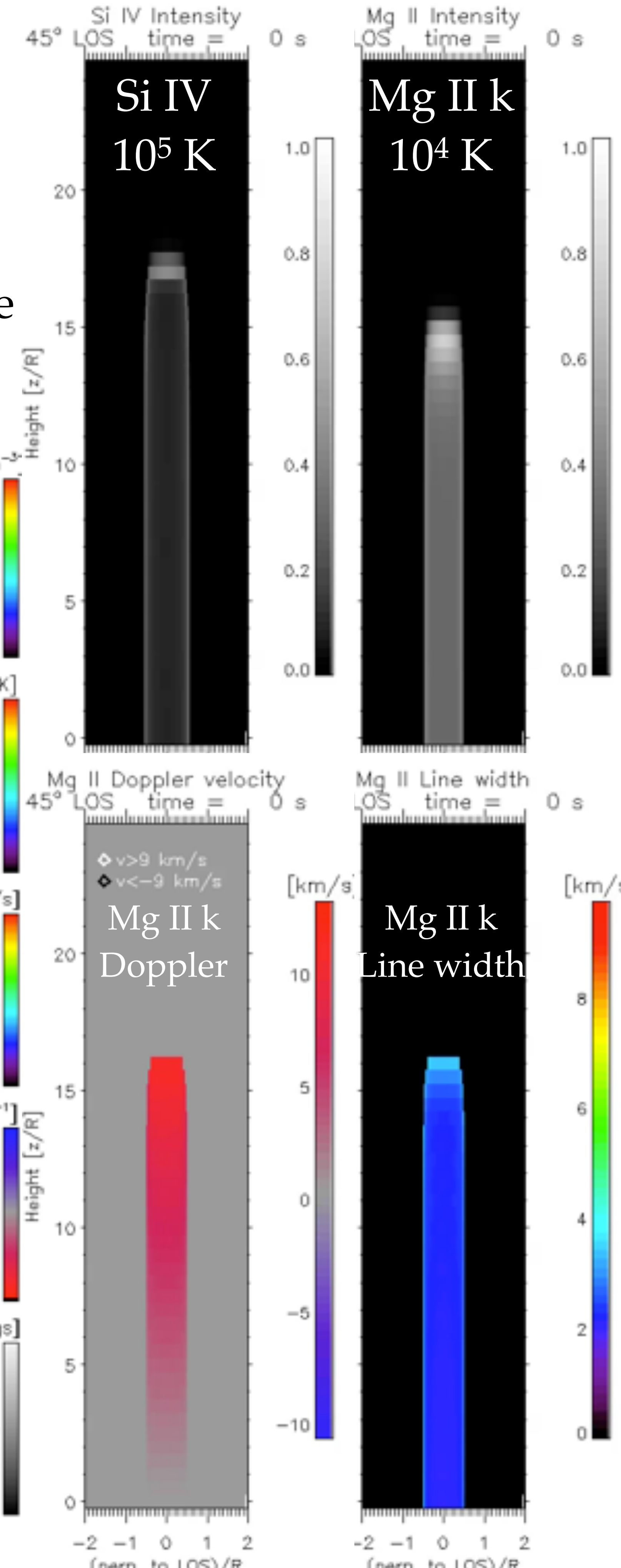
- KHI vortices +RA can explain spicular transverse dynamics
- Potential candidate for heating signatures

(*Antolin+2016, in prep.*)

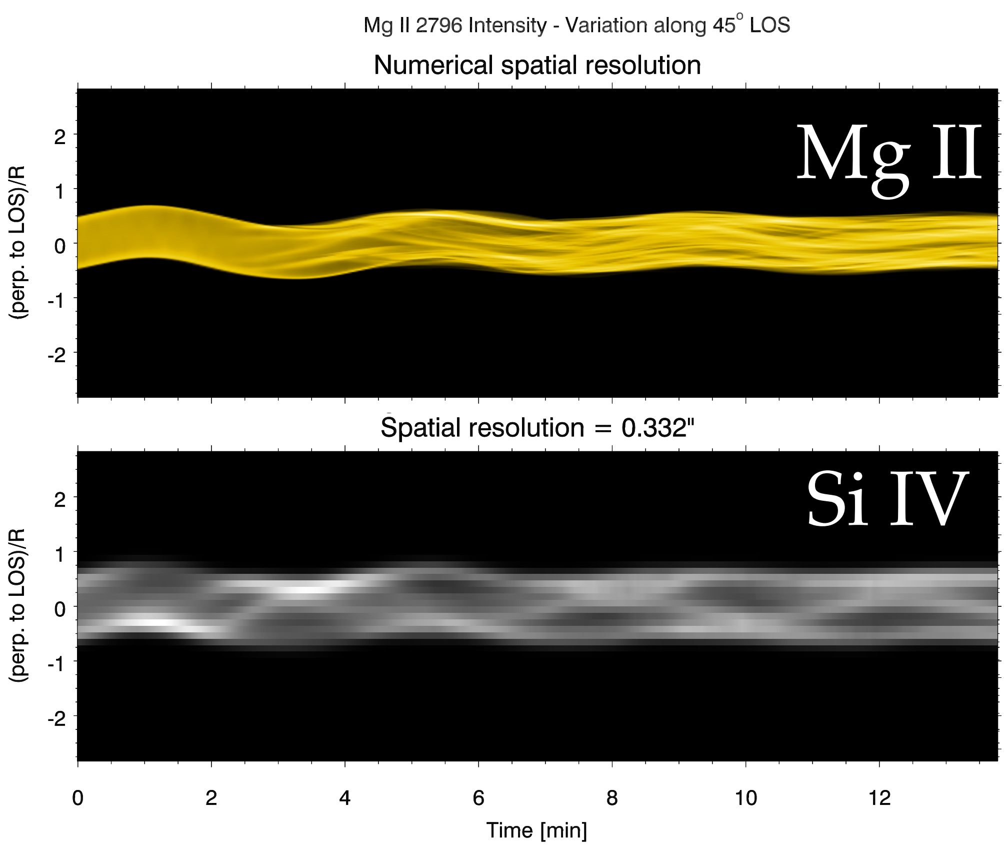


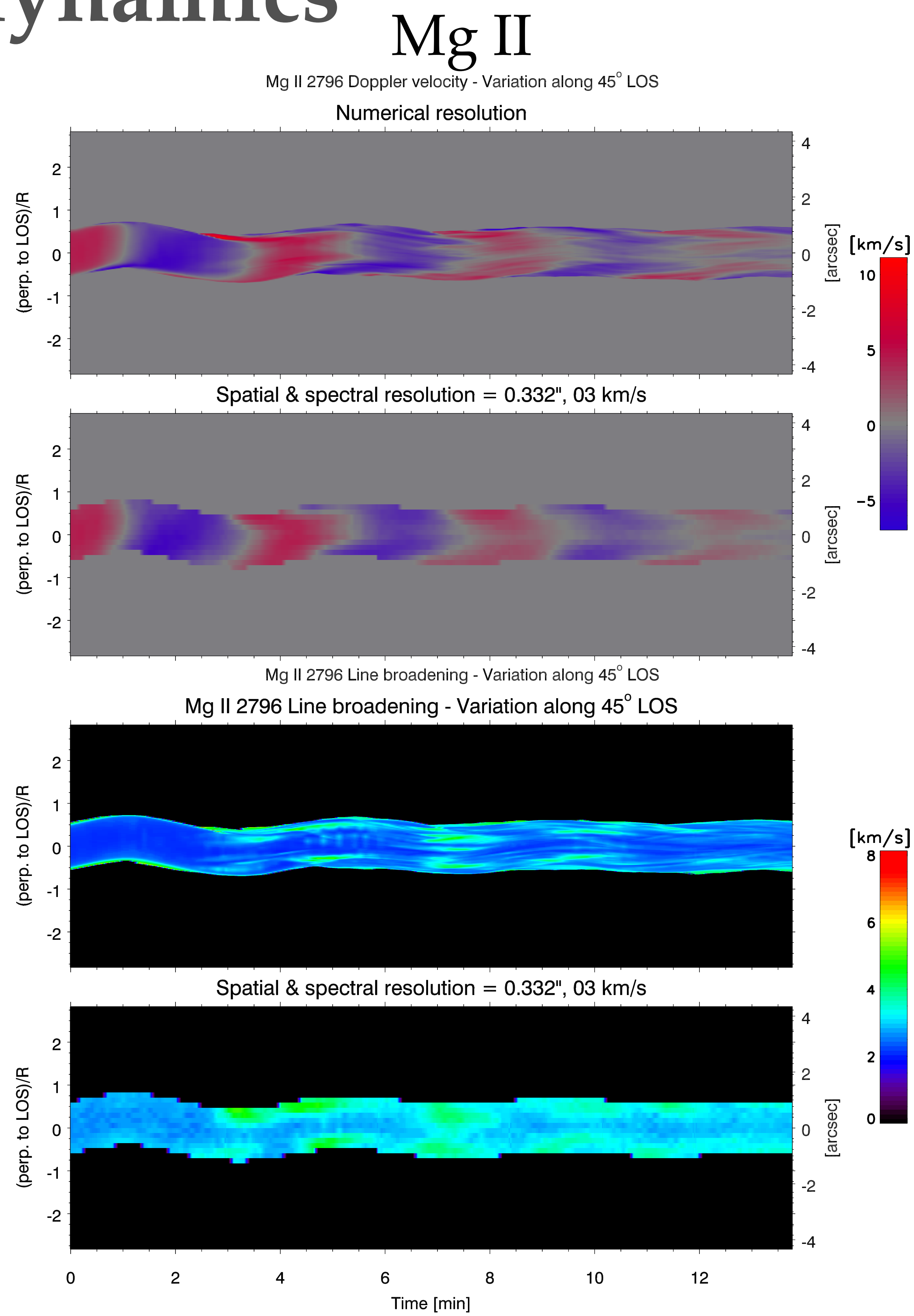
Simulated spicule cross-section





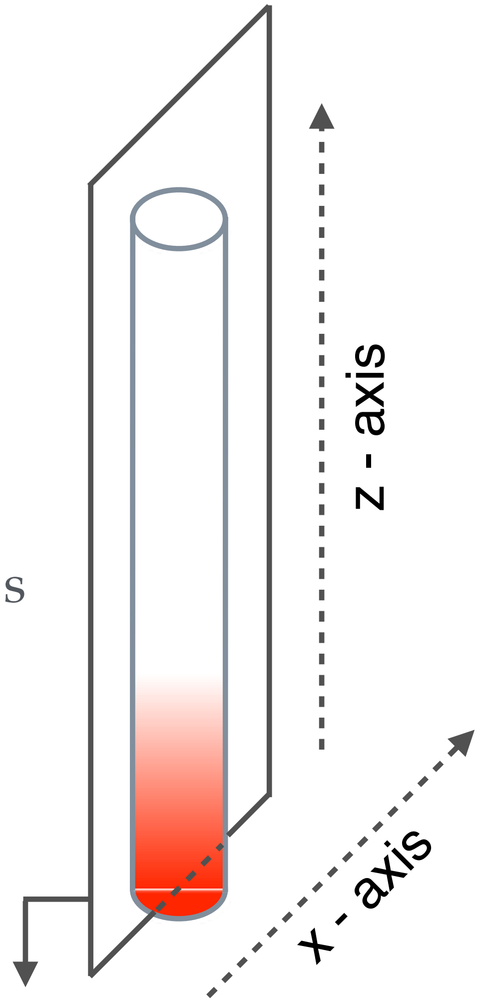
Spicule dynamics





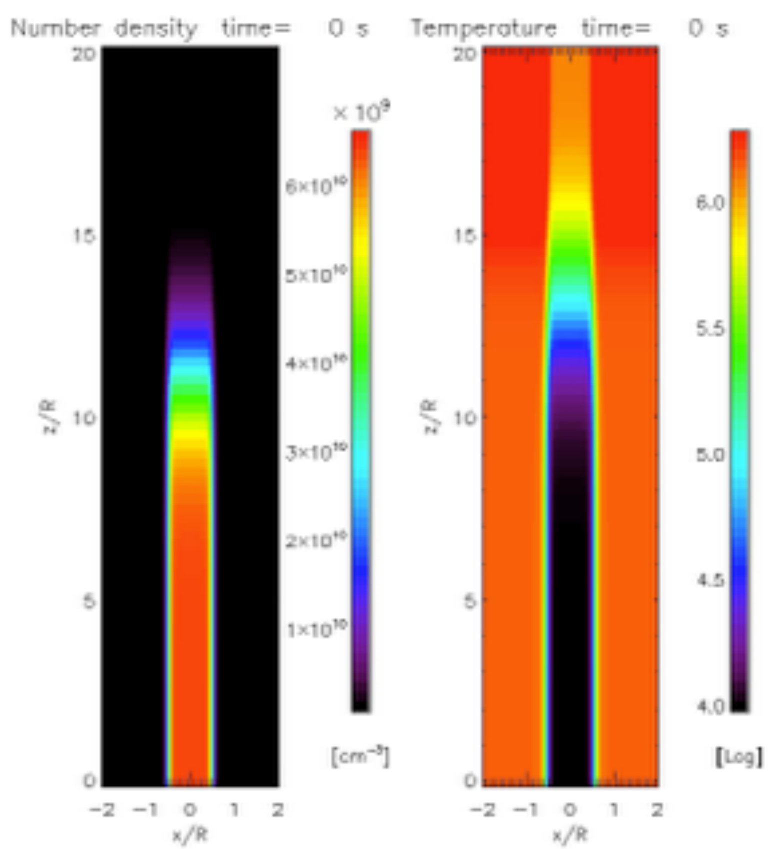
- Similar features as for the prominence and the coronal model

Spicule model
propagating

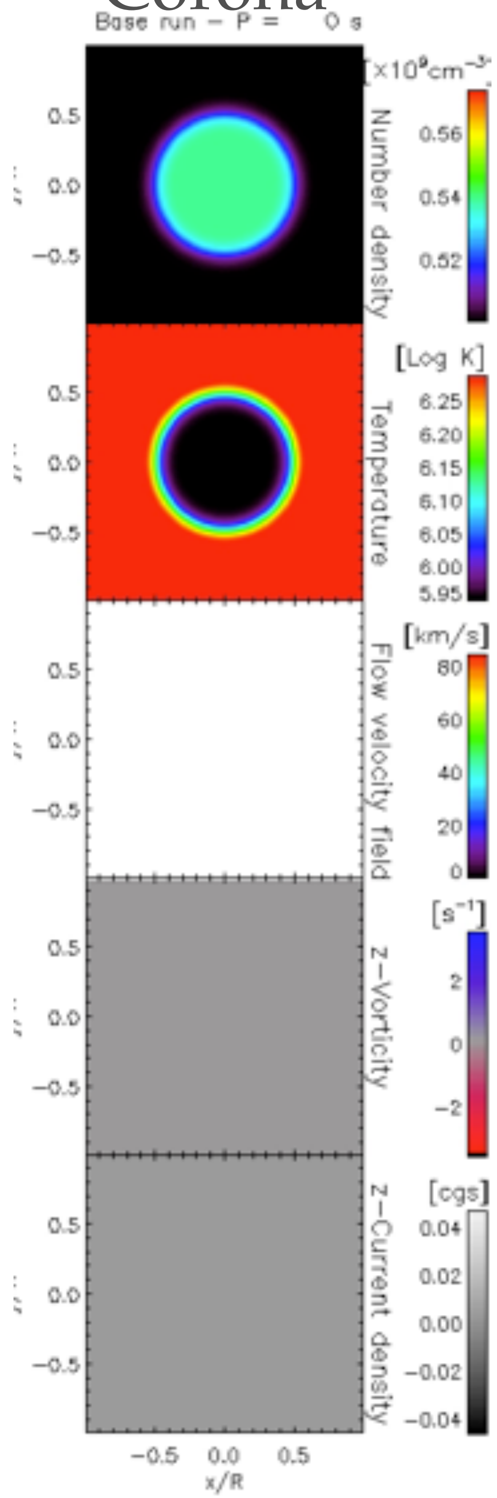


Amp. ~ 30 km/s

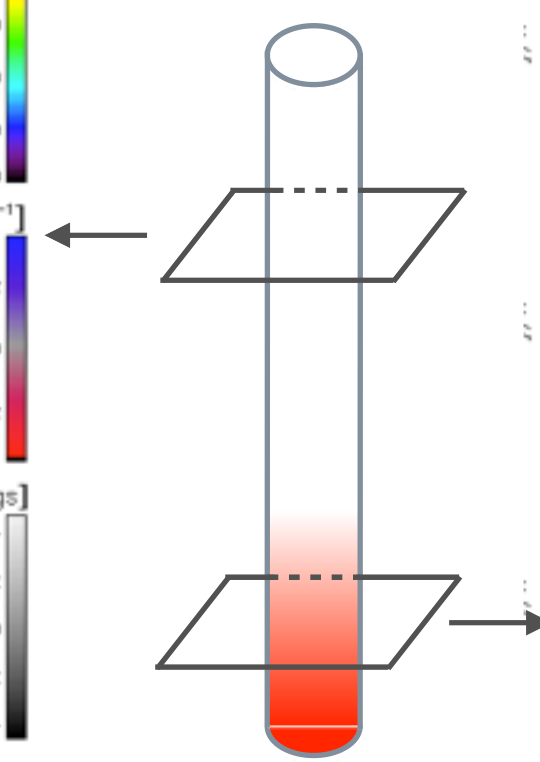
Period ~ 245 s



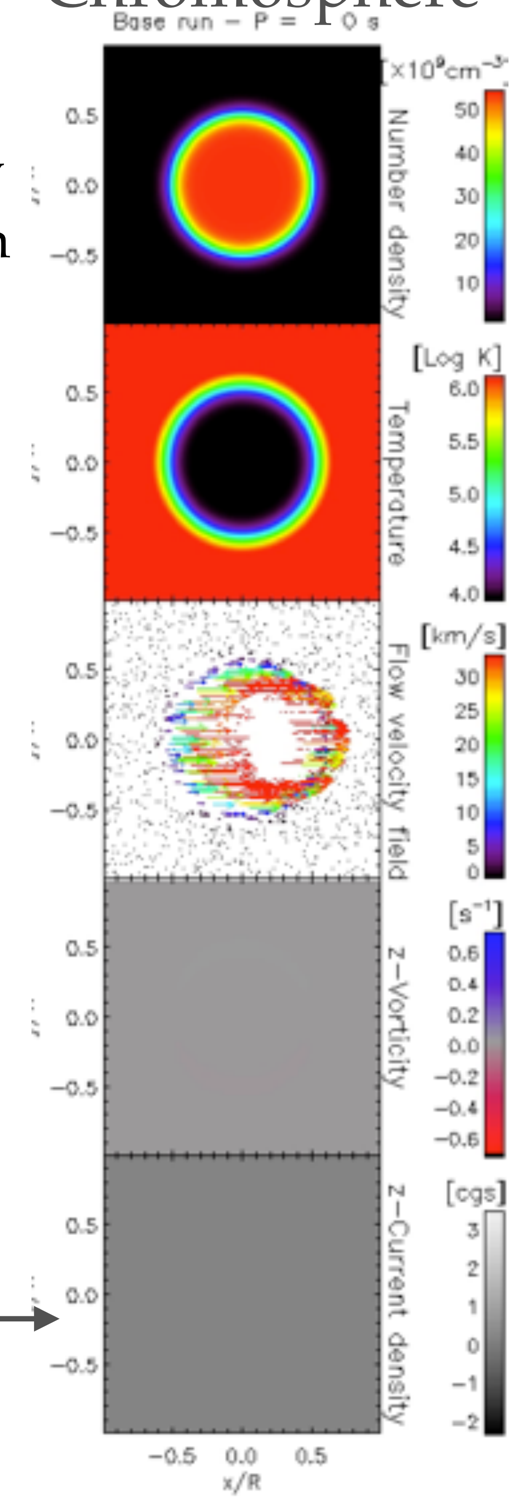
Corona



Strong vorticity destroys loop in corona *(Magyar & Van Doorsselaere 2016)*

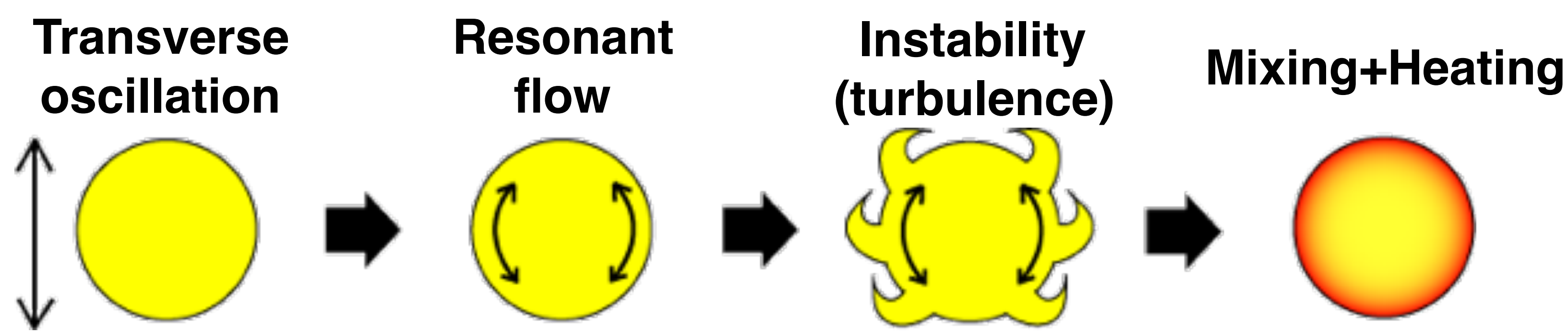


Chromosphere



Conclusions

Evolution of a flux tube cross-section



- 3D MHD model of transverse MHD wave in prominence shows 2 mechanisms at play
- Resonant absorption + dynamic (KHI) instabilities = heating
- KHI fine structure leads to **strand-like structure** in intensity images *(Antolin+ 2014)*. T**hread-like structure/strand-like structure in observations = Alfvénic vortices**?
- Out-of-phase (90°-180°) behaviour between POS motion in cool lines and hot lines: **very good match with IRIS/Hinode observations** *(Okamoto+ 2015, Antolin+ 2015)*
- Resonant absorption enhances significantly KHI dynamics: **Alfvénic turbulence**
- Damping in cool lines (probing loop core temperature). O**scillation in hot line can be decay-less (probing boundary layer). Due to ensemble of vortices and heating.** May explain observed decay-less observations (*Nisticò+2013, Anfinogentov+2013)*
- KHI fine structure dependent on boundary layer width & amplitude. Differences in damping and phase between cool/hot emission lines: **seismology tool**
- May explain observed spicule transverse dynamics
- Model valid for **corona, prominences and spicules.**

Thank you for your attention!

European Research Council

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IAUS 327 @ Colombia

- Deadline for early registration is **July 4**
- www.iaus327.unal.edu.co