8th Coronal Loops Workshop @ Palermo, 27-30 June 2017

Transverse Wave Induced Kelvin-Helmholtz rolls in Spicules ('*twikhis*')

Patrick Antolin[1]

D. Schmit[2], T. Pereira[3], B. De Pontieu[2,3], I. De Moortel[1]

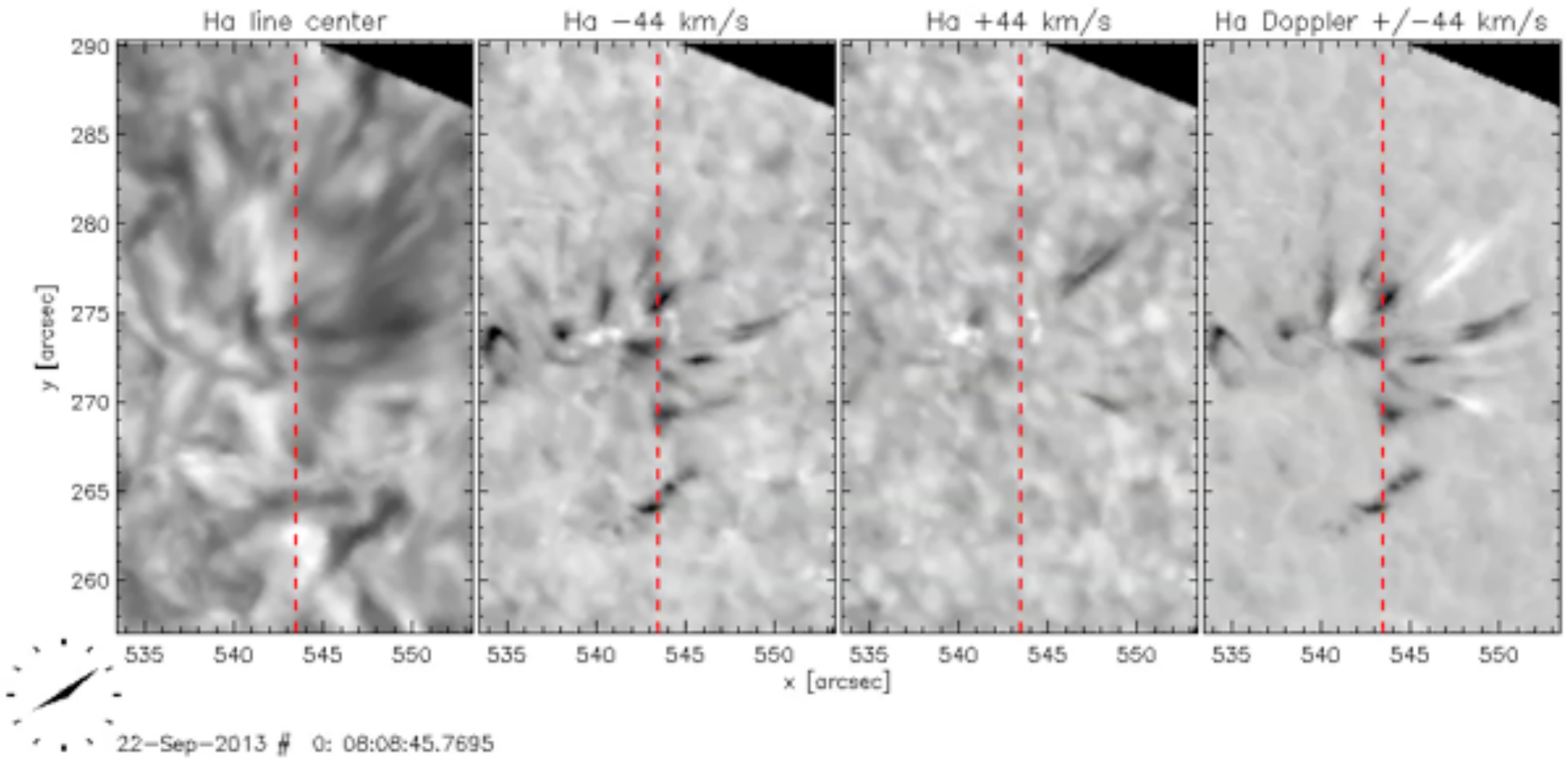
[1]: *University of St Andrews (UK)*, [2]: *LMSAL (US)*, [3]: *University of Oslo (Norway)*

Outline

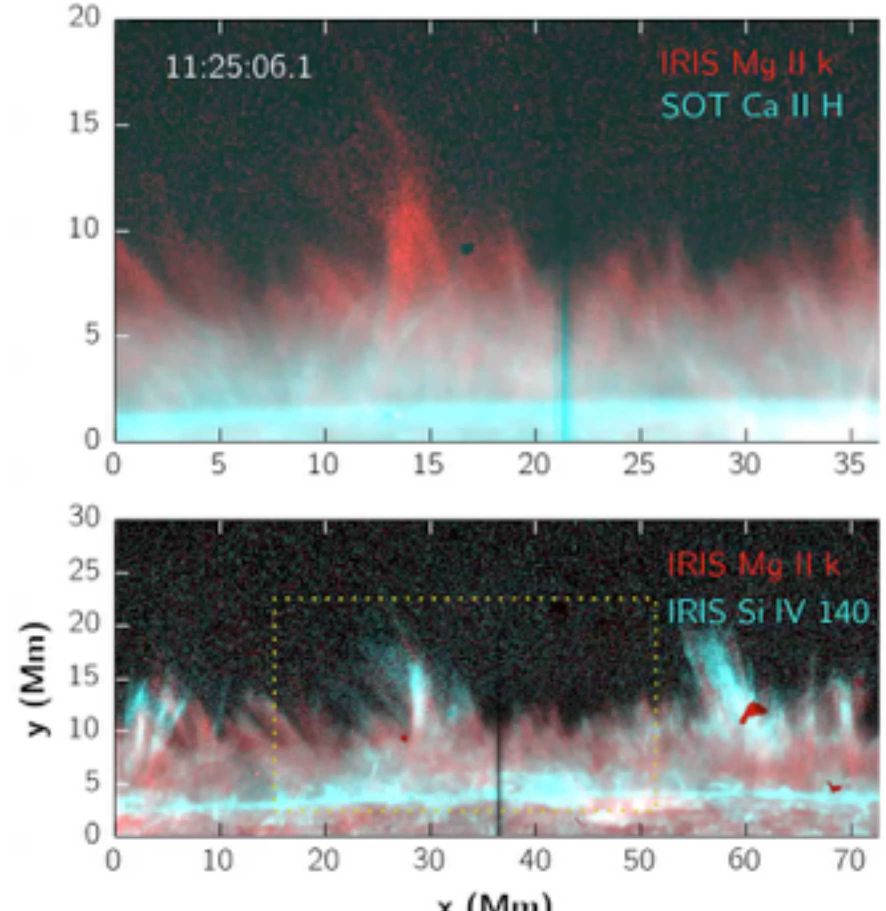
- Introduction
- IRIS & Hinode observations of spicules
    - Imaging & spectral properties
- Numerical modelling - interpretation
    - Effects of a Transverse MHD wave on a spicule
- Discussion & Conclusions

Introduction

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



SST + IRIS



Pereira et al. 2014

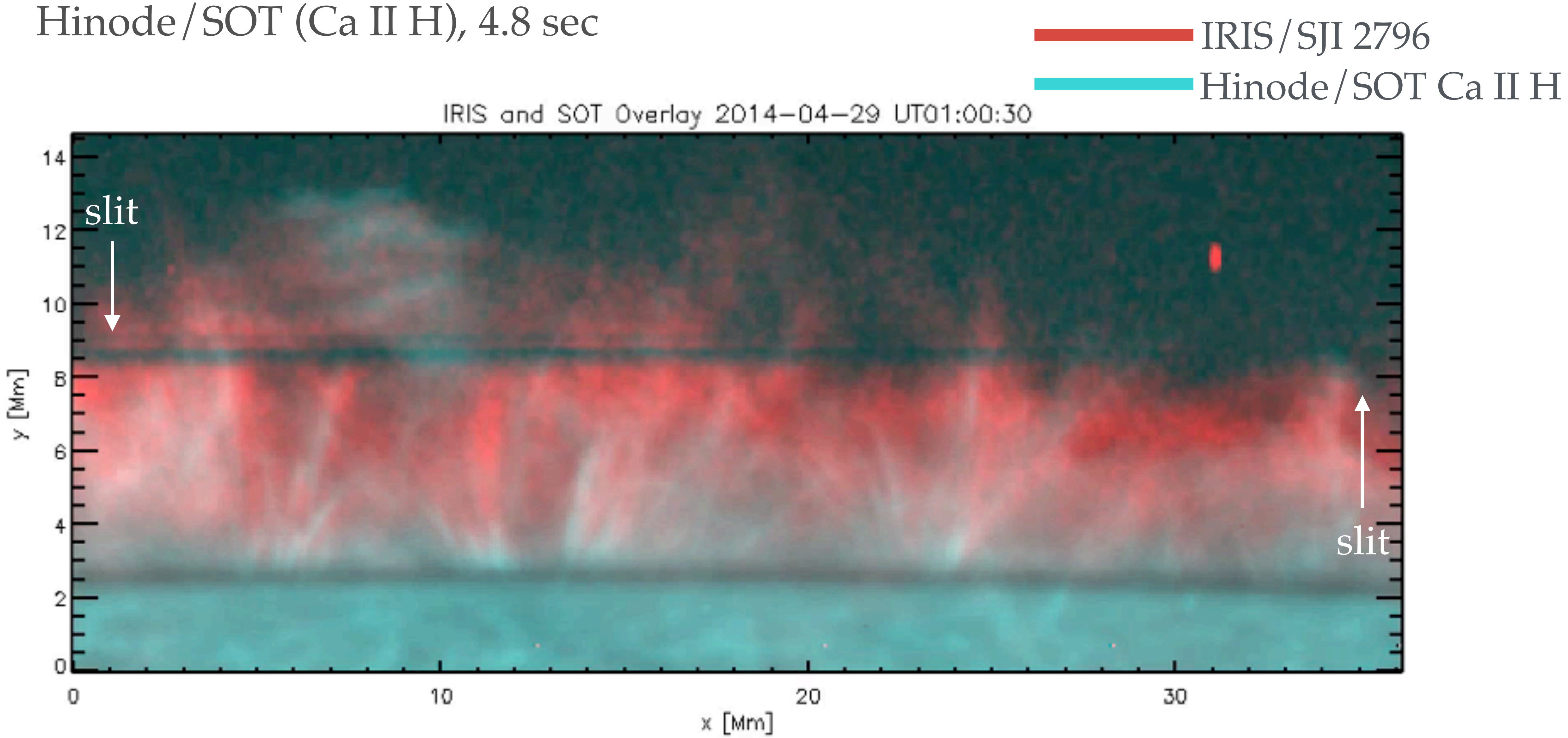
- Ubiquitous jets protruding from the chromosphere into the corona, type I-II
- I - magneto-acoustic wave driven (ballistic, v<40 km/s) *(Beckers 1968, Sterling 2000)*

  II - Heating, fast upflow (v<110 km/s) *(De Pontieu+ 2007, Rouppe vd Voort 2009, Sekse 2012, 2013).*
- **Multi-stranded, swaying and torsional motions** *(Suematsu+ 2008, Pereira+2012, Skogsrud+ 2014, De Pontieu+ 2014, Rouppe v.d. Voort 2015).* **Large transverse amplitudes (~10-20 km/s)**

➡ **Important transverse component. Which observational characteristics can be attributed to Alfvénic waves?**

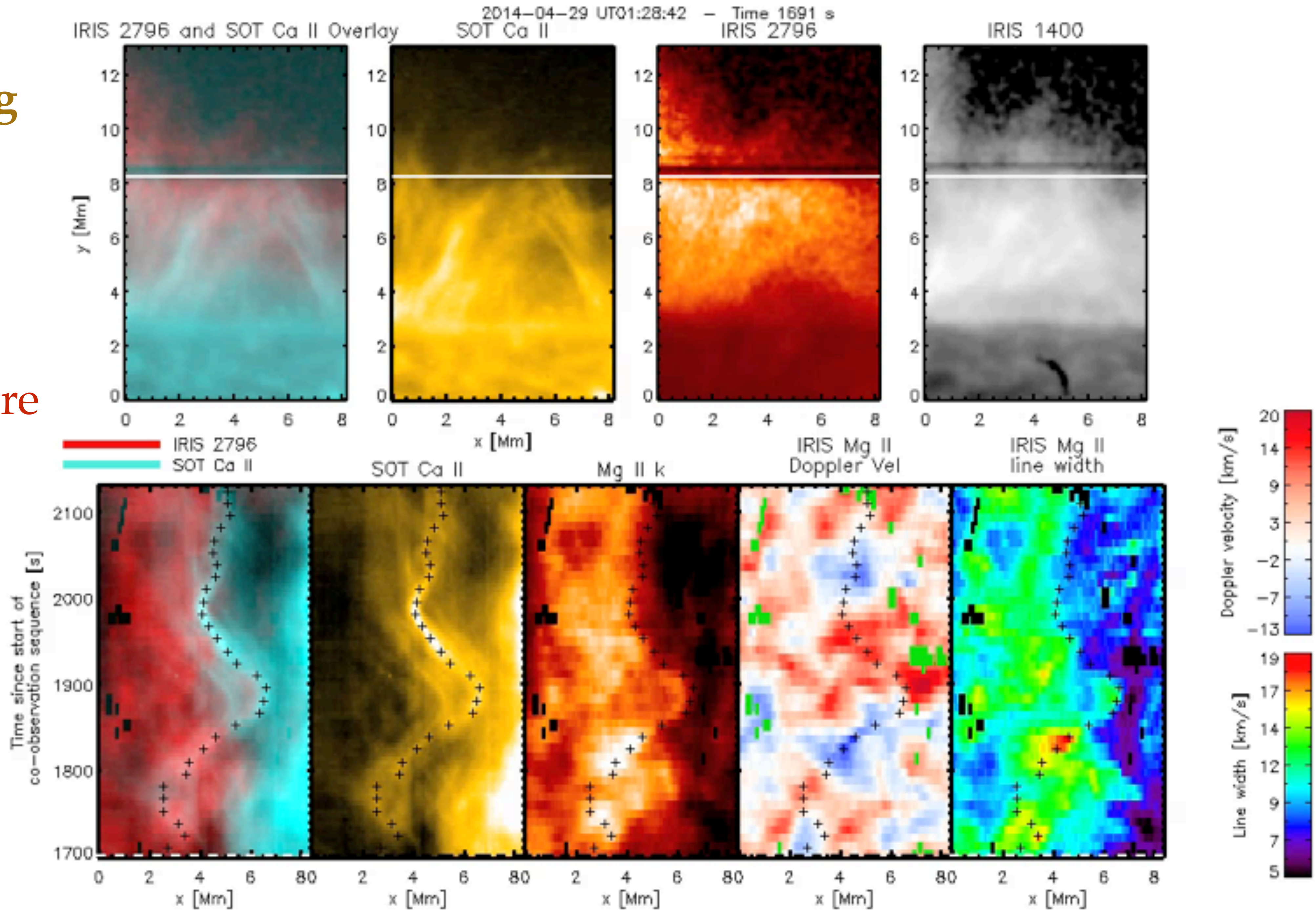
IRIS & Hinode Observations

- @North limb on 2014 April 29 01:00 - 02:00 UT (IHOP 249)
- IRIS sit-and-stare, 9.5 sec (SG), 19 sec (SJI 1400+2796)
- Hinode/SOT (Ca II H), 4.8 sec



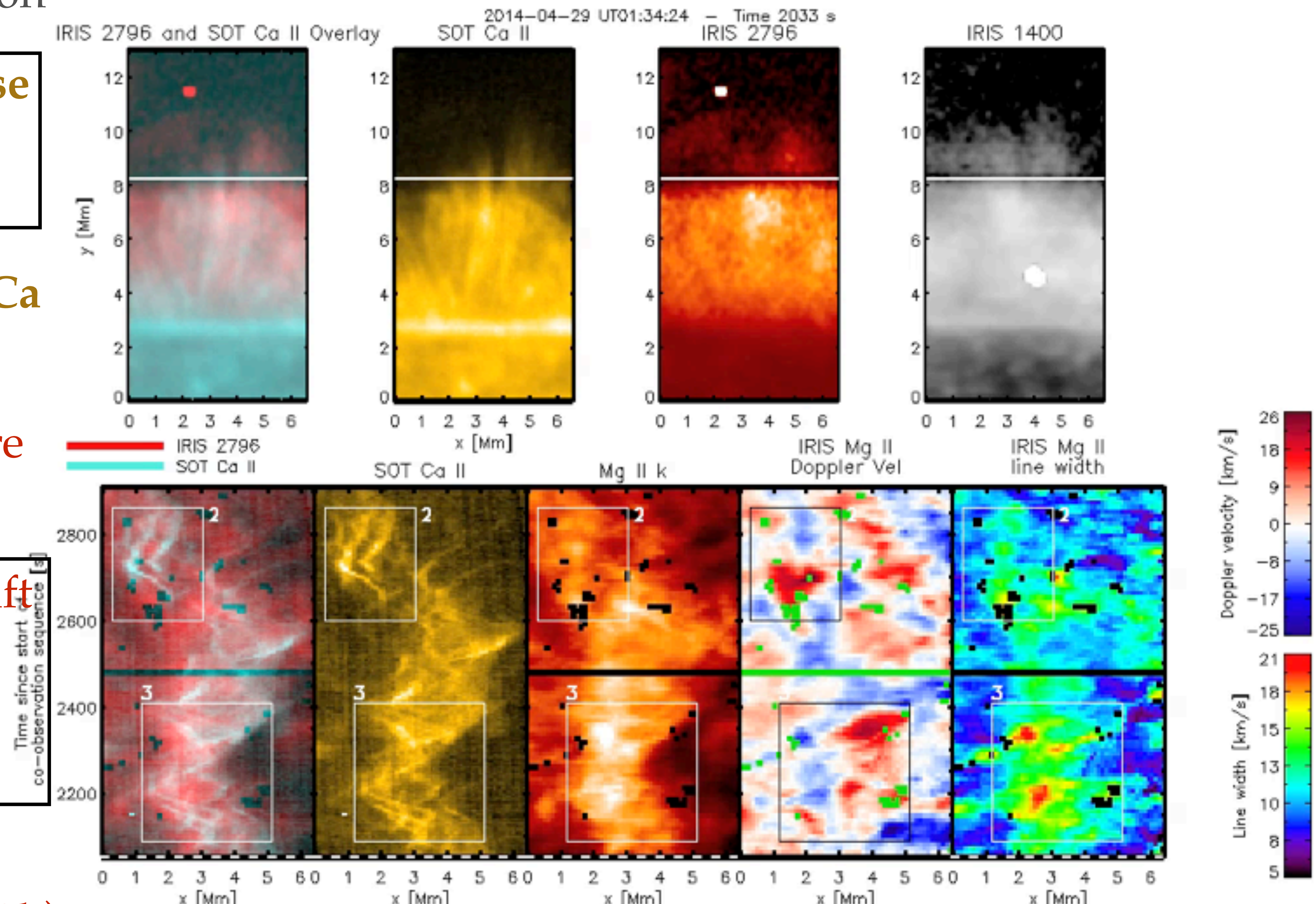
Case 1

- Transverse oscillation (1 period~200±20 sec)
- **Coherent motion of strands (SOT) -> collective standing mode**
- **Disappearance in Ca II H (SOT)**
- Monolithic structure (SJI 2796 & 1400)
- Doppler shift sign change at max displacement (Mg II k)
- Line width enhancement (Mg II k)



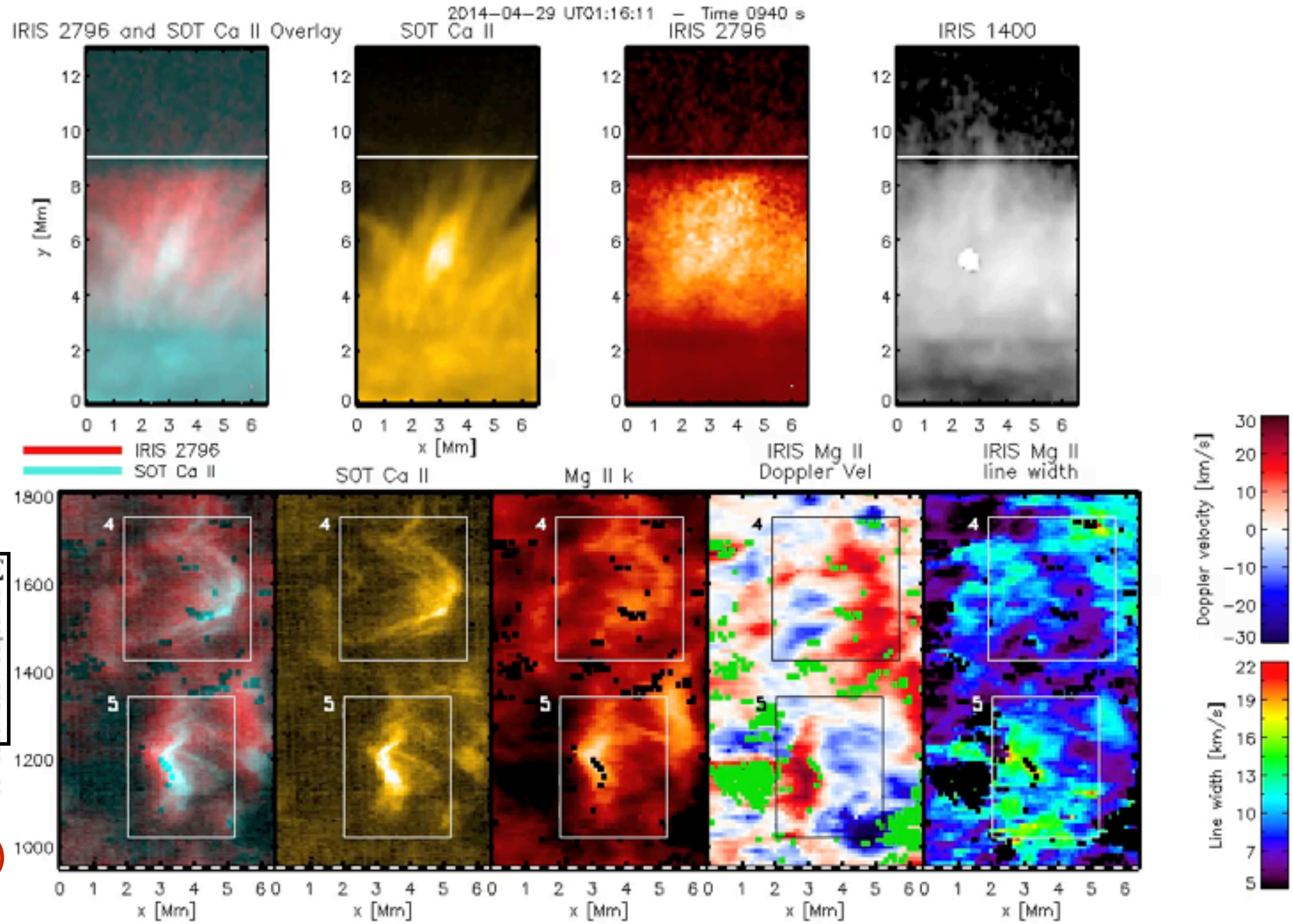
Cases 2 & 3

- Case 2 ~ Case 3, but propagating disturbance
- Transverse oscillation
- **Case 3: out-of-phase motion of strands (SOT)**
- **Disappearance in Ca II H (SOT)**
- Monolithic structure (SJI 2796 & 1400)
- Case 3: Doppler shift sign change fixed along spicules axis (Mg II k)
- Line width enhancement (MgII k)



Cases 4 & 5

- Transverse oscillation
- **Case 3: out-of-phase motion of strands (SOT)**
- **Disappearance in Ca II H (SOT)**
- Monolithic structure (SJI 2796 & 1400)
- Doppler shift sign change fixed along spicules axis (Mg II k)
- Line width enhancement (MgII k)



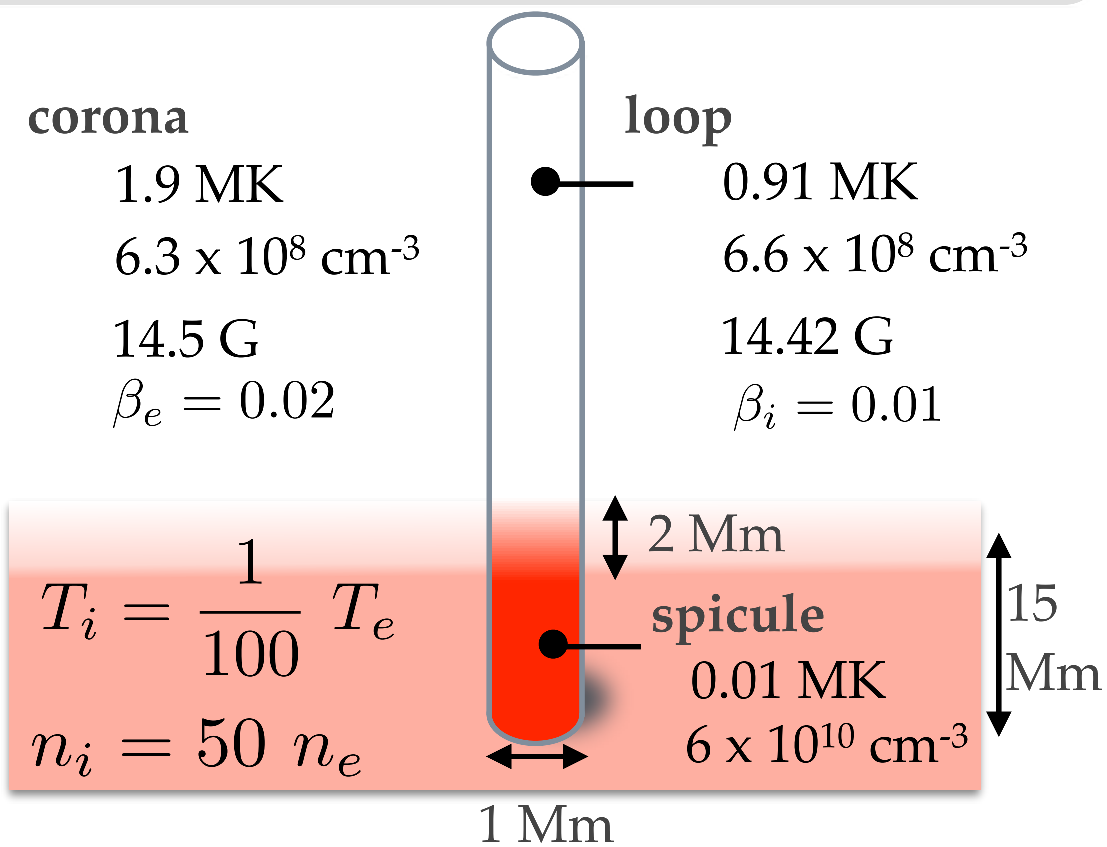
Numerical simulations

Numerical setup

- 3D MHD ideal simulations. CIP-MOCCT code (Kudoh et al. 1999). Adiabatic conditions.
- non-uniform grid, 1/4 tube (x,y,z)= (512, 256, 100) -> $\Delta x, \Delta y$=7.8 km, Δz=500 km
- Symmetric boundary conditions. Periodic in x

Loop & spicule model

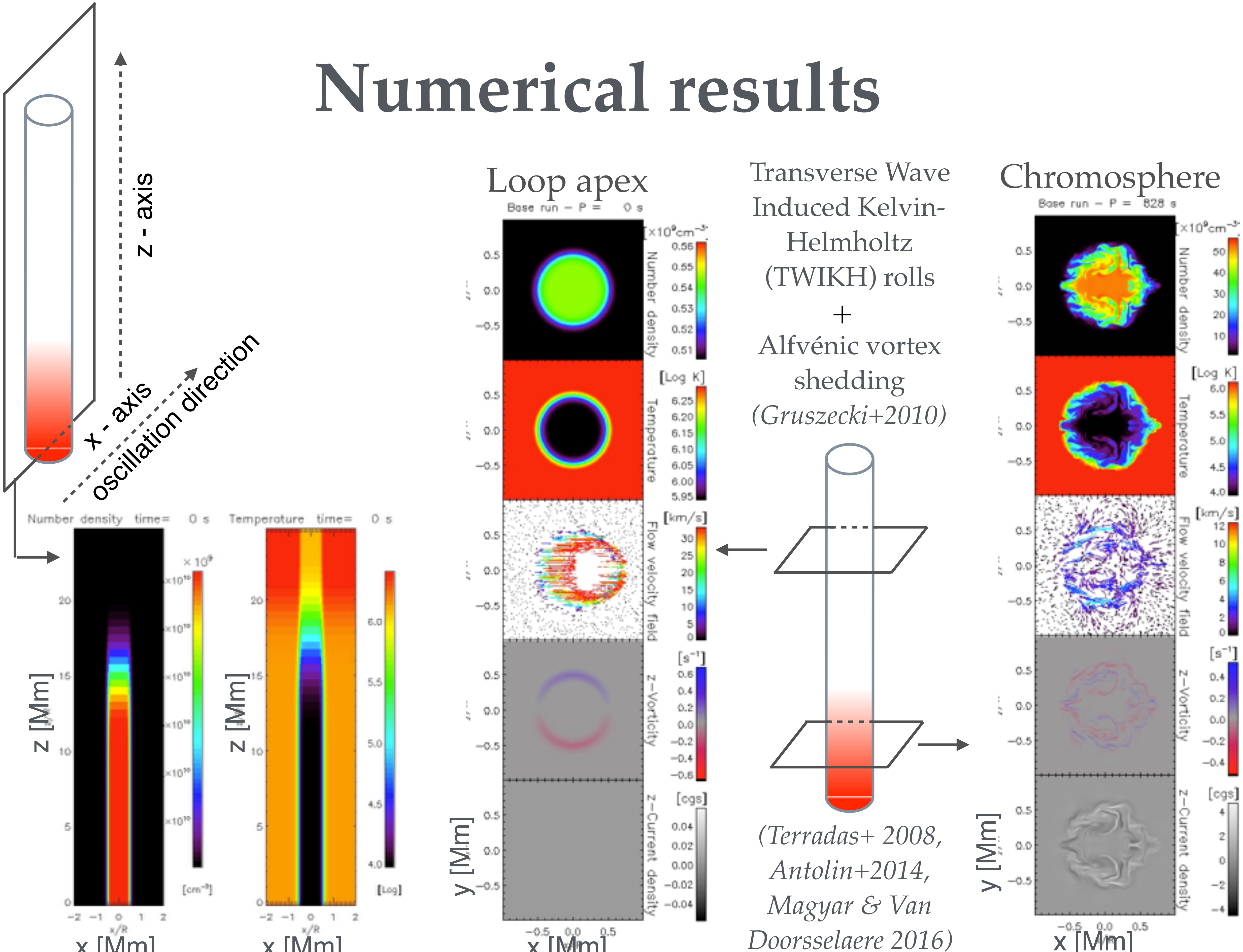
- Straight loop, static spicule, L = 100 Mm, radius = 500 km, boundary layer width = 200 km
- Fundamental kink mode, P~ 255 s
- v_0 ~ 33 km/s (12 km/s at spicule top)



Forward modelling

- Optically thin approximation: FoMo code (Van Doorsselaere et al. 2016)
- Radiative transfer: 1.5-D RH code in PRD (Pereira & Uitenbroek 2015)

Numerical results



Transverse Wave Induced Kelvin-Helmholtz (TWIKH) rolls

+

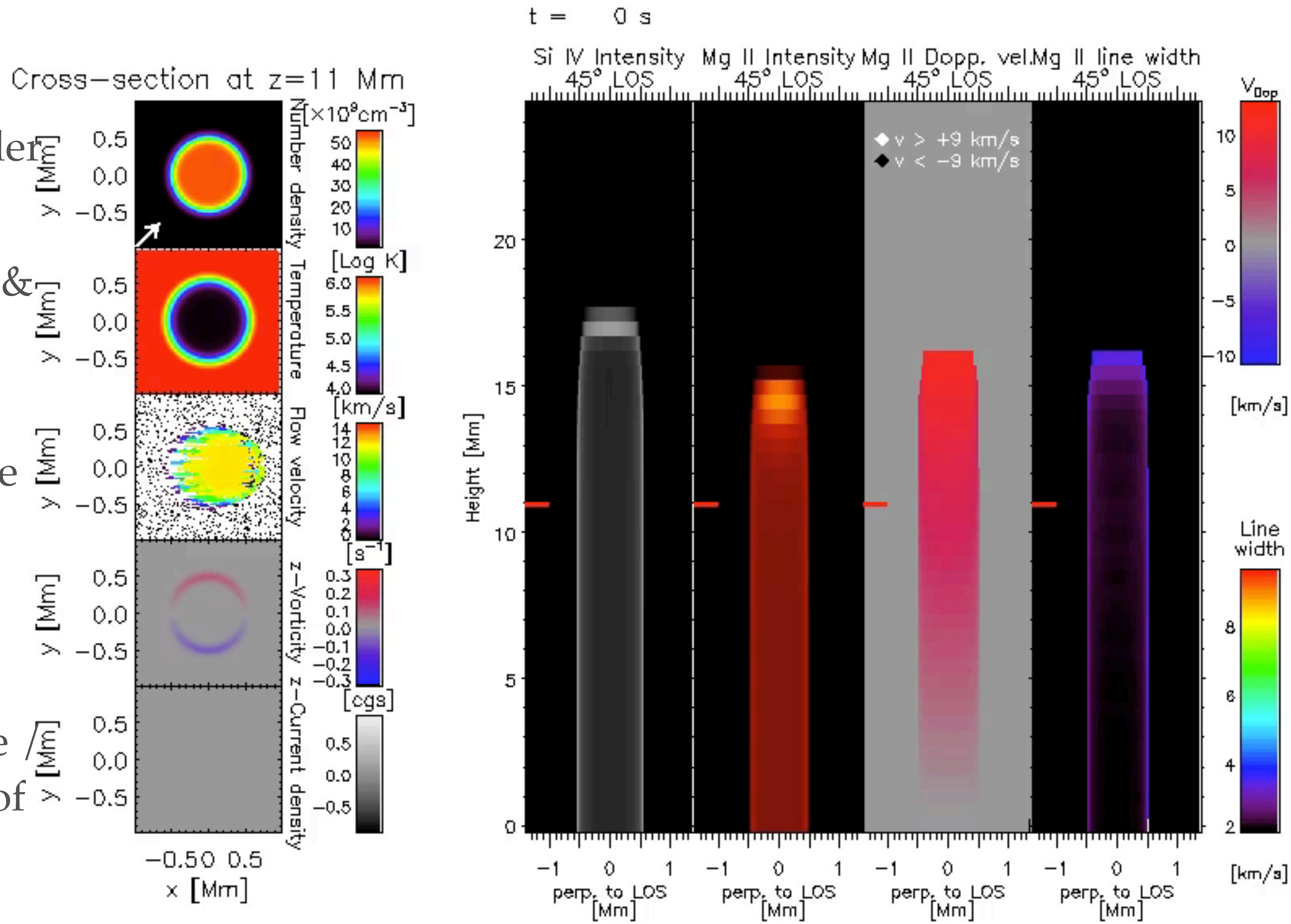
Alfvénic vortex shedding

(Gruszecki+2010)

(Terradas+ 2008, Antolin+2014, Magyar & Van Doorsselaere 2016)

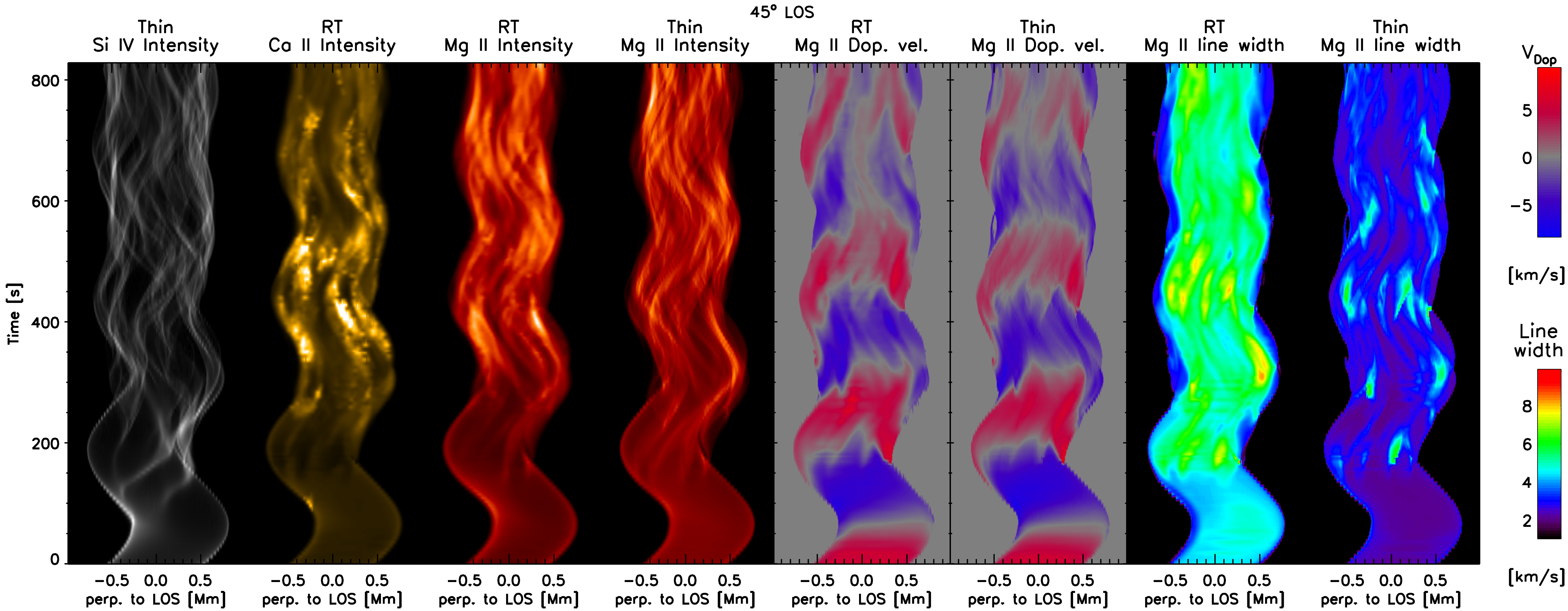
Numerical results

- Stranded structure in intensity, Doppler & line widths
- Apparent twist & upward propagation
- Large amplitude Doppler shifts
- Enhanced line widths
- Fast appearance / disappearance of strands



Numerical results

cut at z=11 Mm



- Loop body visible in Mg II, but invisible in Ca II H & Si IV
- Bursty intensity profiles, particularly in Ca II H
- Doppler shift change at max displacement, but ragged: TWIKH rolls
- Maximum Doppler values at edges (out-of-phase with POS motion, *Okamoto+2015, Antolin+2015*)

Discussion

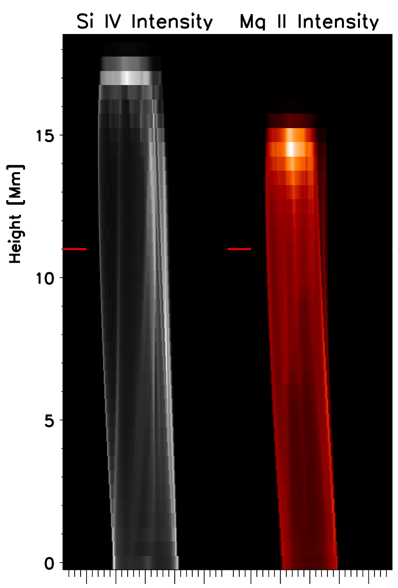
Simulations

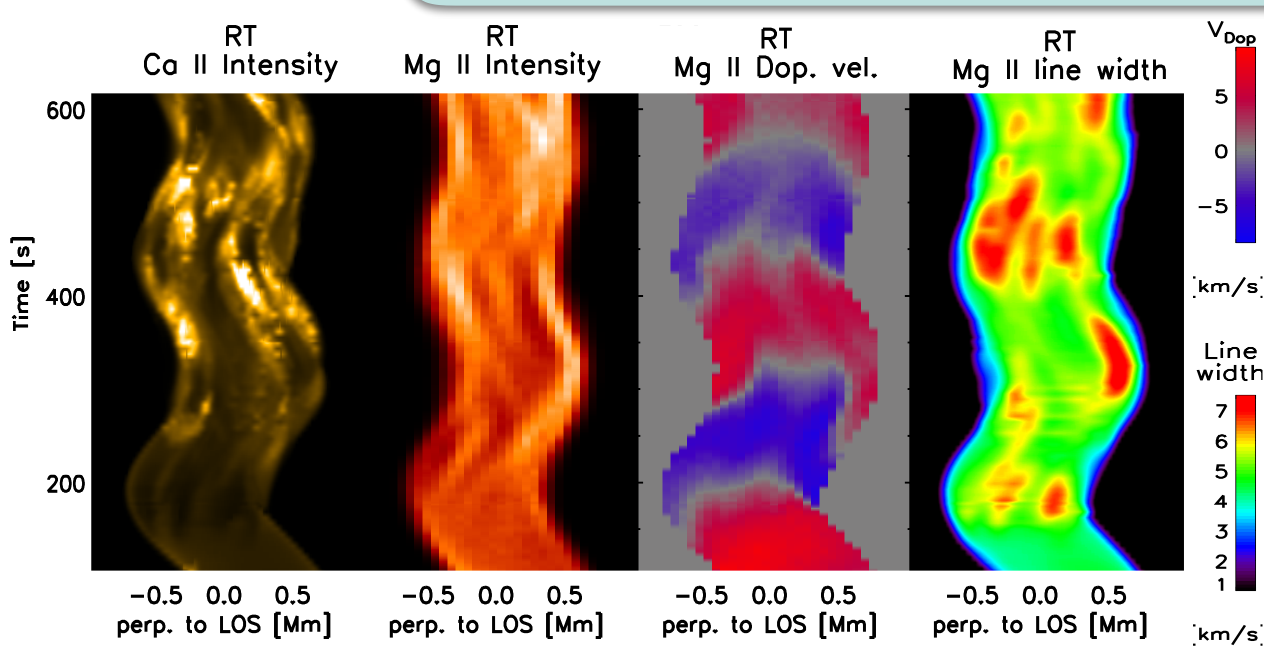
In agreement…

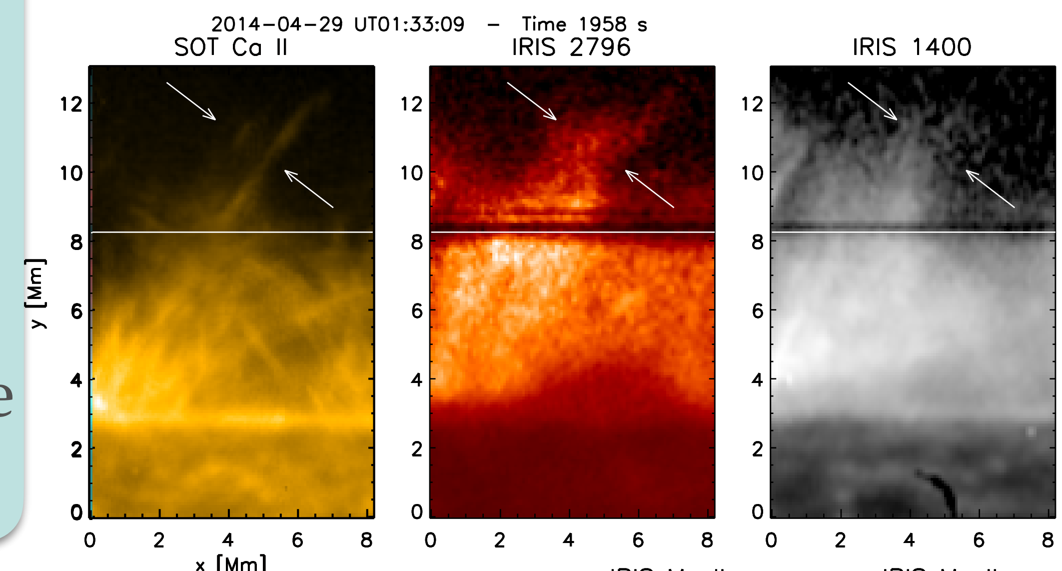
- Collective motion
- Doppler shift sign change at max displacement, with ragged transition
- Line width enhancement
- Loop body visible in Mg II k
- Fast appearance / disappearance of Ca II H strands

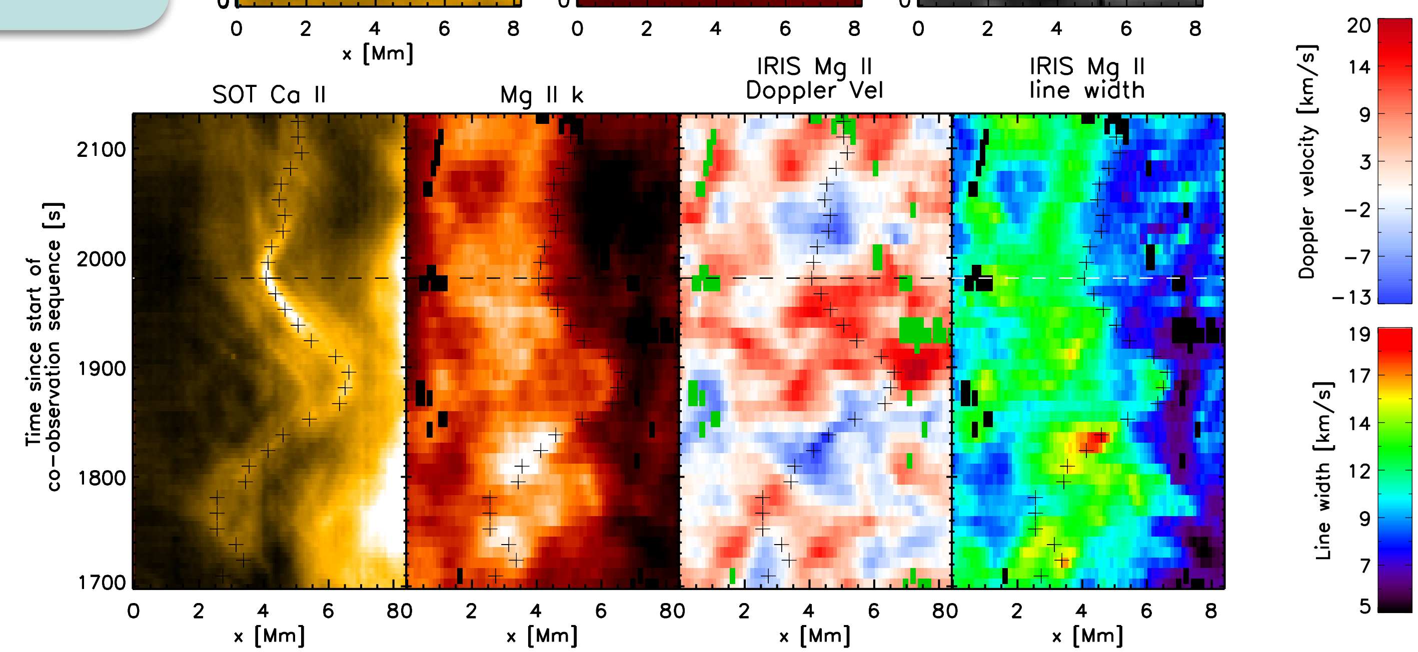
Observations

What is the spicule? The individual strand or the collection?



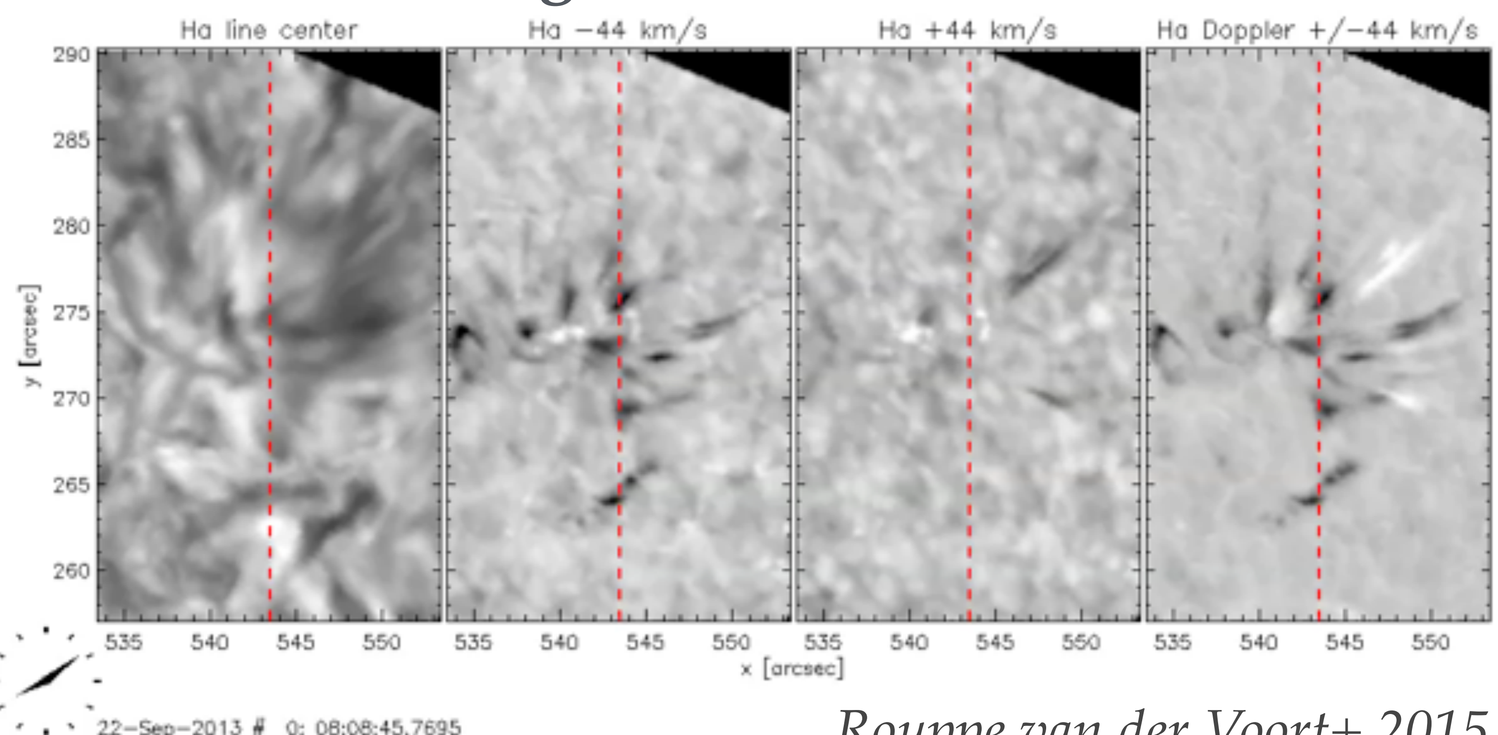






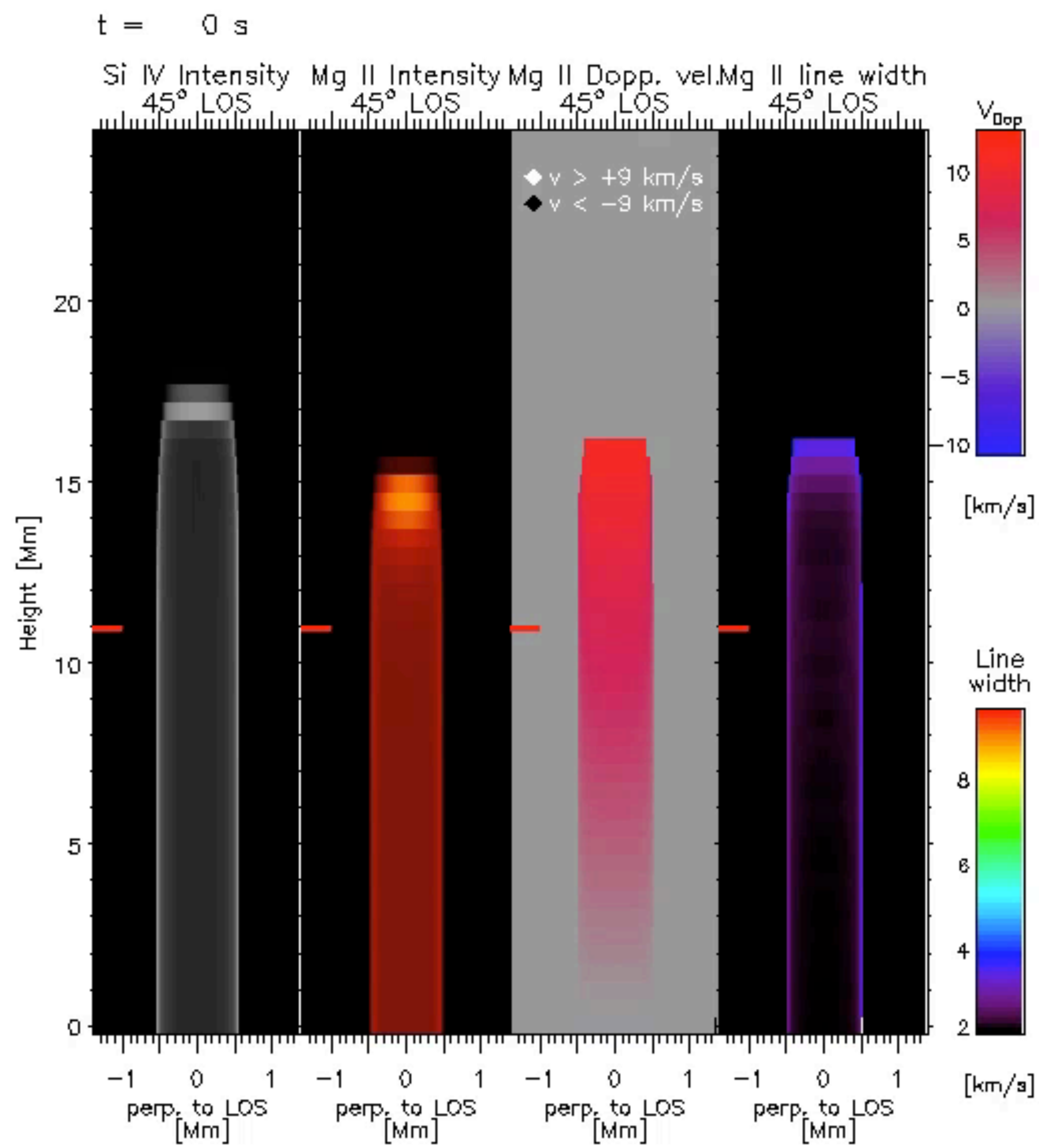
Discussion

At higher resolution, with a tuneable wavelength filter (SST/CRISP)



Rouppe van der Voort+ 2015

- Collective motion suggests existence of larger flux tube
- Fast appearance/disappearance of strands in Doppler & line width maps
- Increase of amplitude with height -> apparent upward propagation



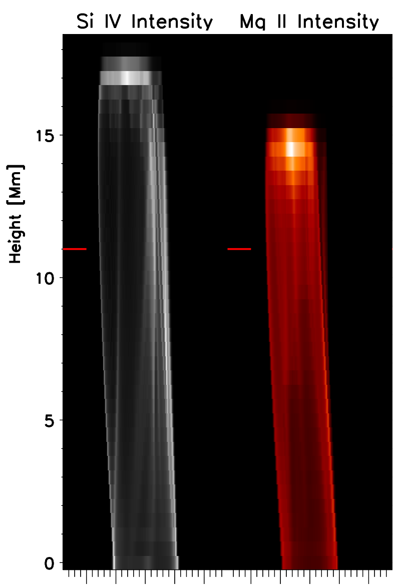
Discussion

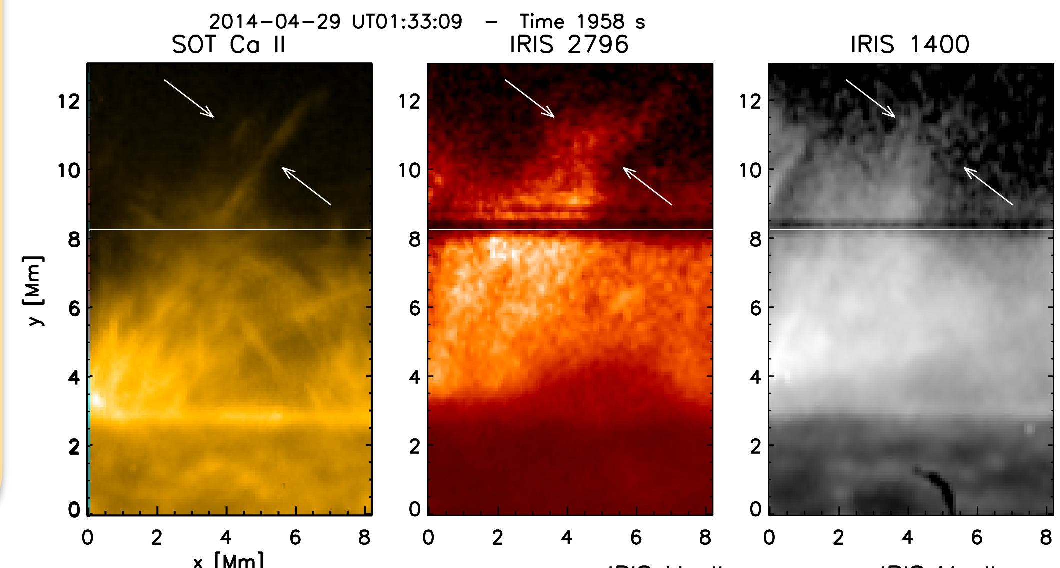
Simulations

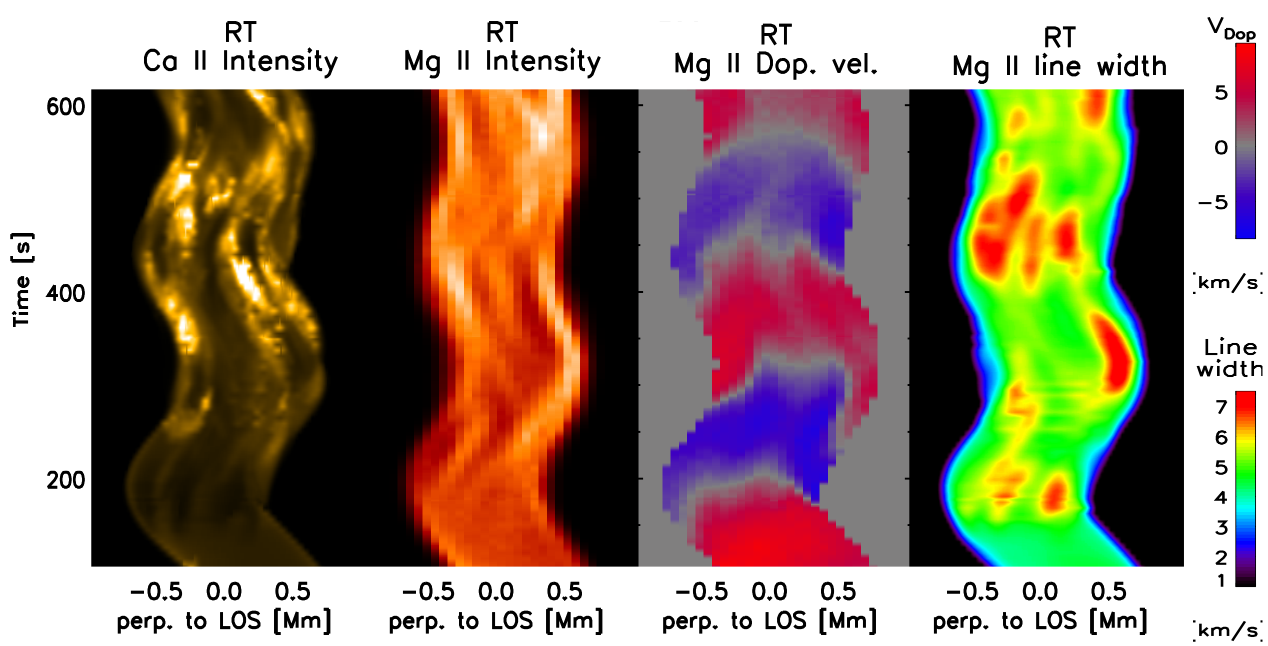
Observations

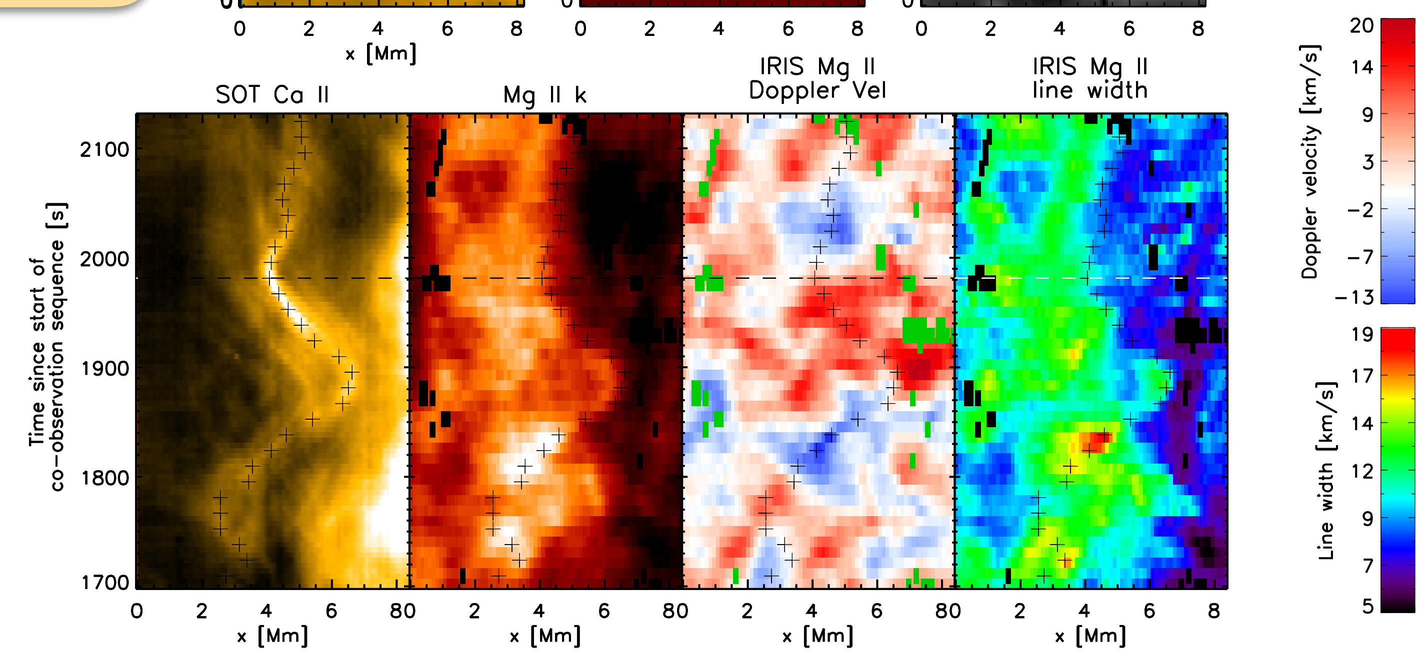
In disagreement…

- No strong temperature rise from KHI mixing *(Magyar & Van Doorsselaere +2016, Karampelas+ 2017)*
- Little intensity enhancement in Si IV
- No fast longitudinal speeds

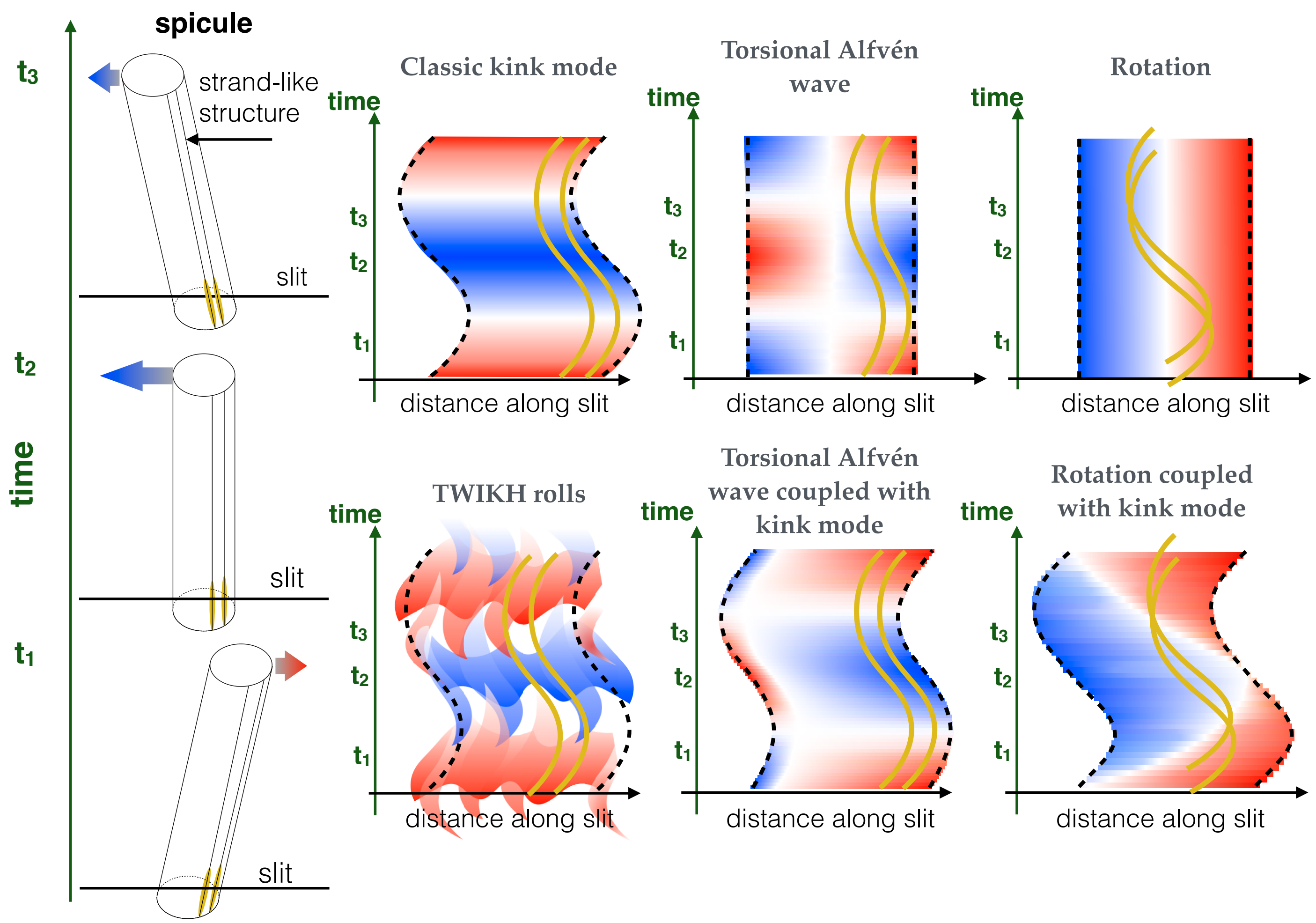


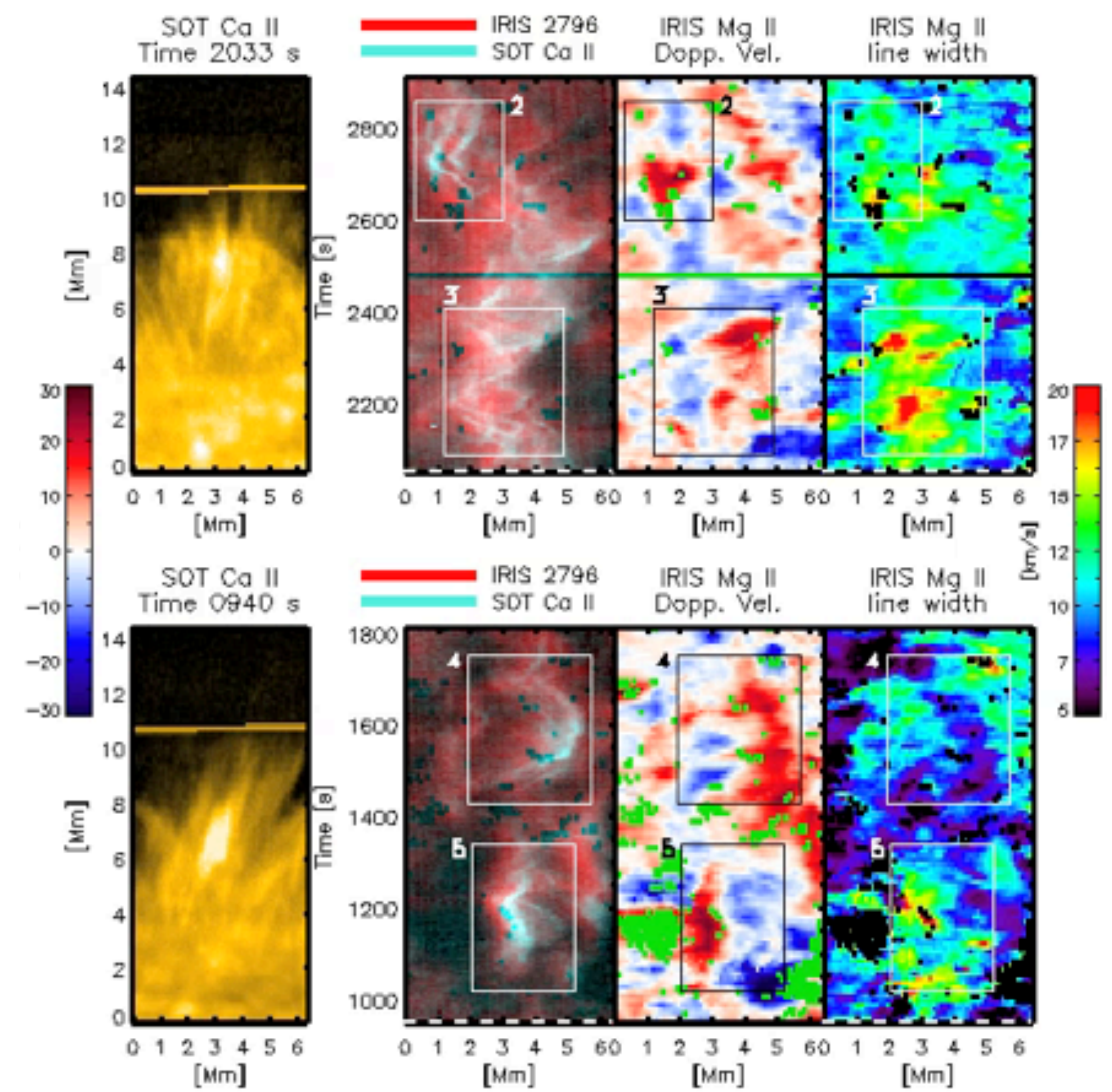






Discussion





- Rotation: Doppler shift transition fixed in space & out-of-phase motion of sub-structure: match cases 3, 4 & 5 (similar to *Okamoto+ 2016*)
- Also propagating long wavelength torsional Alfvén wave? However, periodic asymmetry for half/part of flux tube is not observed. Also, sum over multiple shells of constant Alfvén speeds should decrease Doppler signal

Conclusions

- IRIS&Hinode/SOT Observation of spicules: 2 major cases
    - Little coherence among strands and Doppler shift sign change along spicule axis -> *rotation or long wavelength torsional Alfvén waves*?
    - Coherent motion of strand sub-structure & Doppler shift sign change at maximum displacement -> *kink waves*?
- 3-D MHD model of spicule/loop oscillating with a transverse MHD wave -> TWIKH rolls:
    - Strand-like structure in intensity, Doppler shifts and line widths
    - Coherent motion of sub-structure on average
    - Doppler shift sign change (ragged) at maximum displacement & increased line widths
    - Strong variations in Doppler shifts, line widths & Ca II H intensity due to KHI mixing: agreement with observations
    - Small increase in Si IV: disagreement. -> existence of additional mechanism at work in spicules

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 647214).