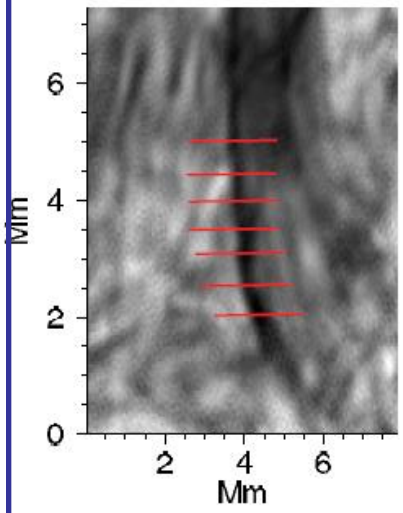
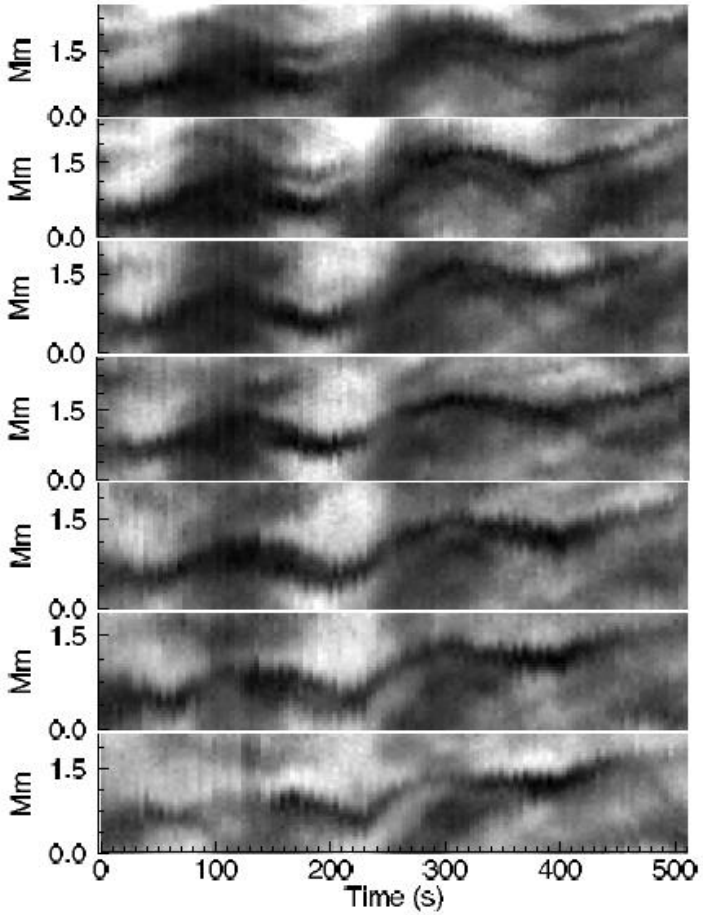
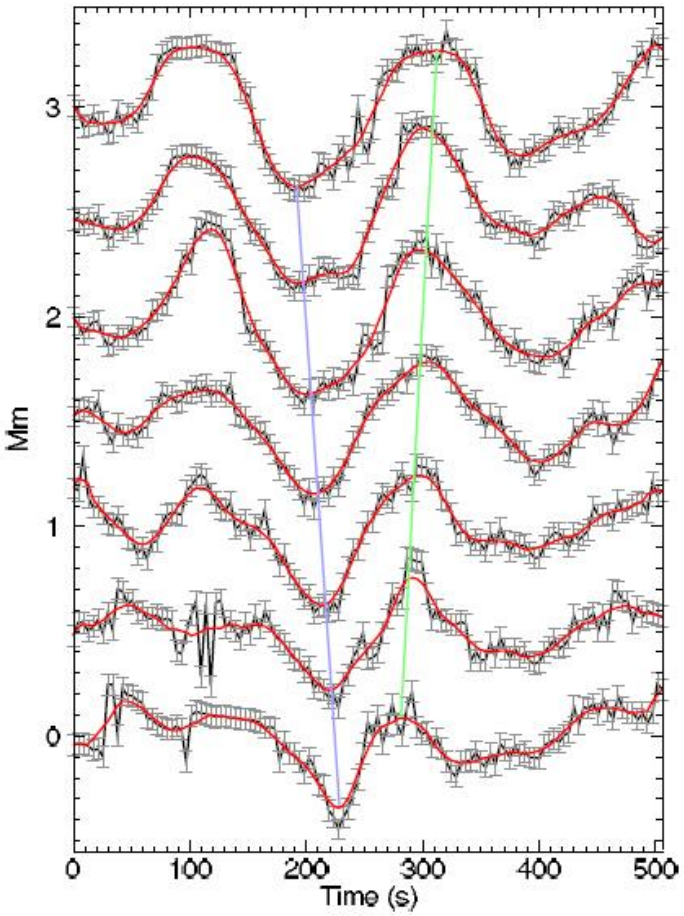
MHD waves in the solar chromosphere







Dr Gary Verth

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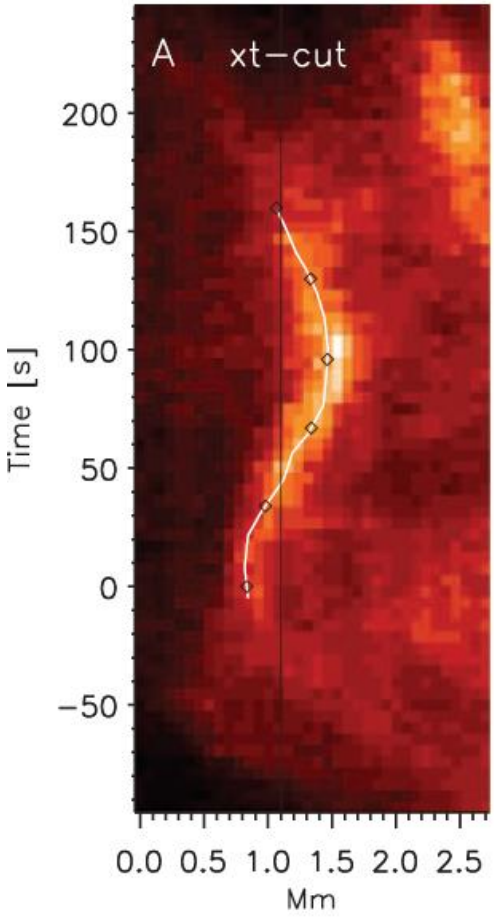
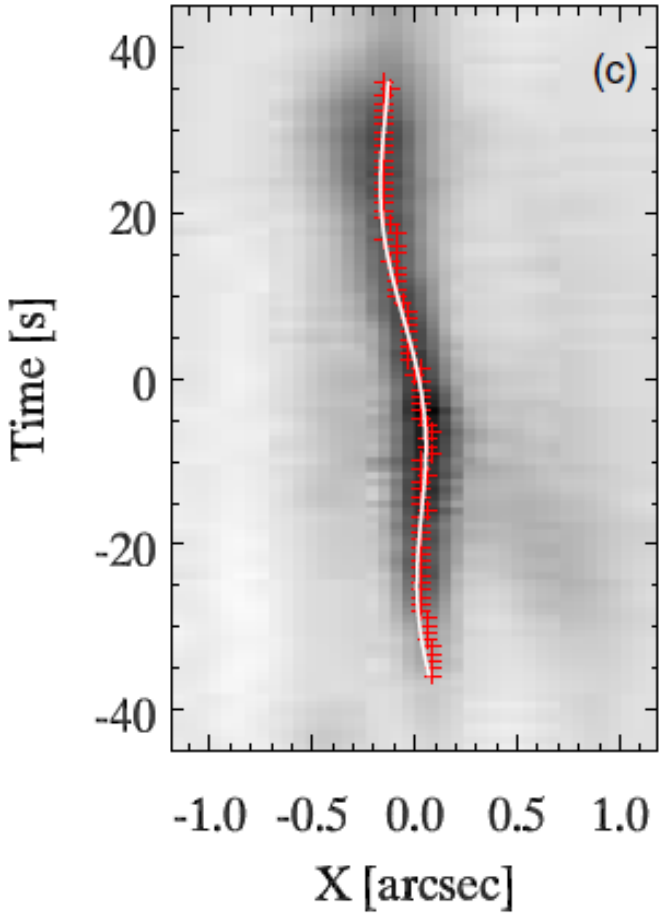
University of Sheffield

Transverse waves observed with one spectral line only, e.g. Ca II H or Hα



Off-limb **spicule** observed with Hinode/SOT (**De Pontieu et al. Science 2007**)



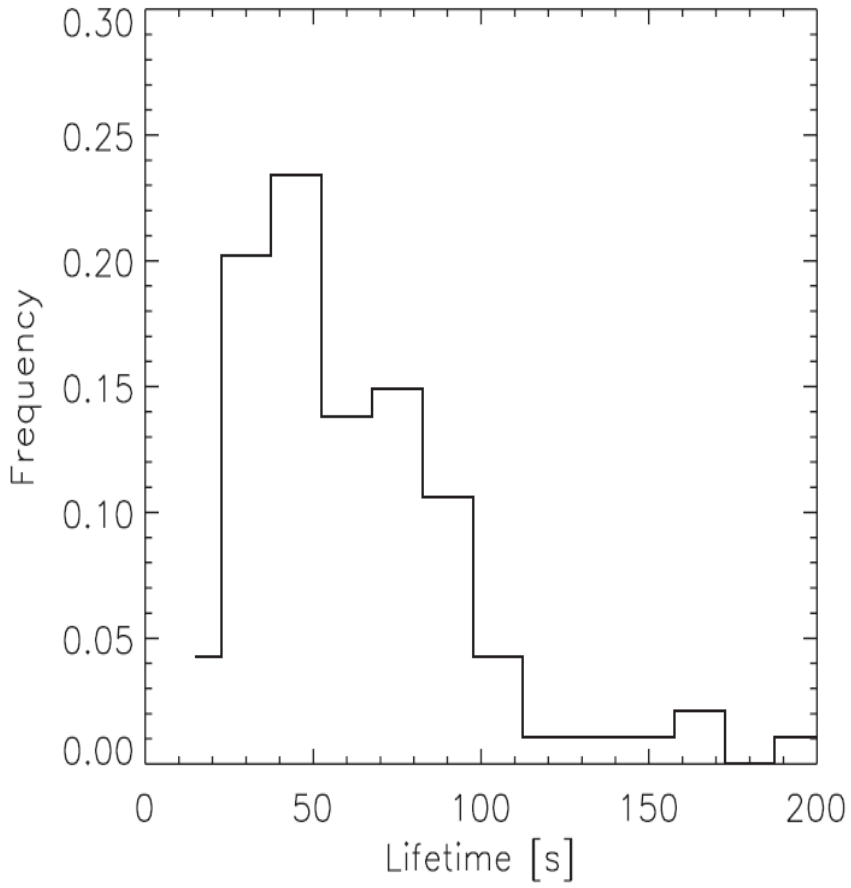
On-disc **RBE** observed with SST./CRISP (**Sekse et al. ApJ 2013**)

- Motion **perpendicular** to **magnetic field** direction
- **Velocity amplitudes** **15- 20 km/s**
- Main **restoring force** of **magnetic tension**
- **"Period"** approximately the same as **visible lifetime** of structure in e.g. **Ca II** or **Hα**

UNA PROBLEMA!

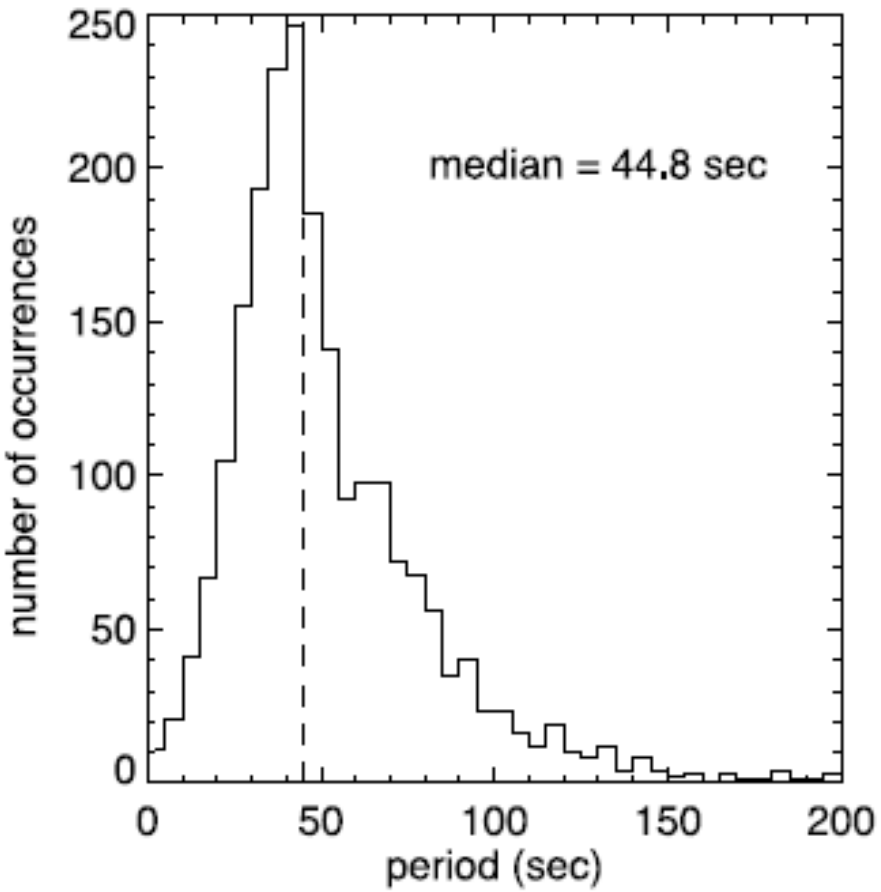
Statistics of coronal hole spicules using Ca II H

Visible lifetime



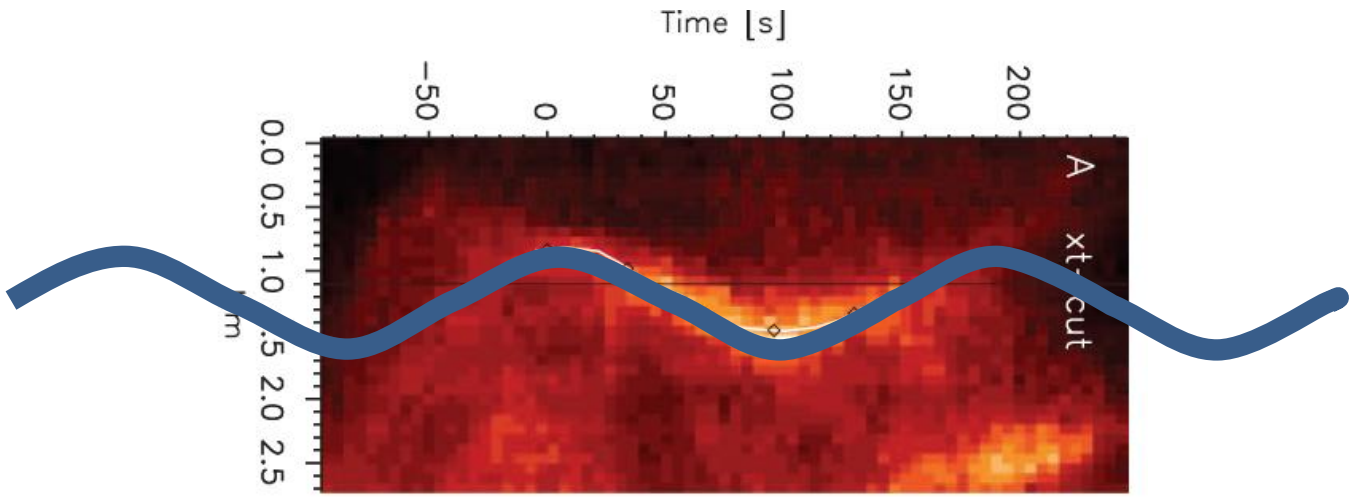
De Pontieu et al. (PASJ, 2007)
using Hinode/SOT data

Transverse "period"

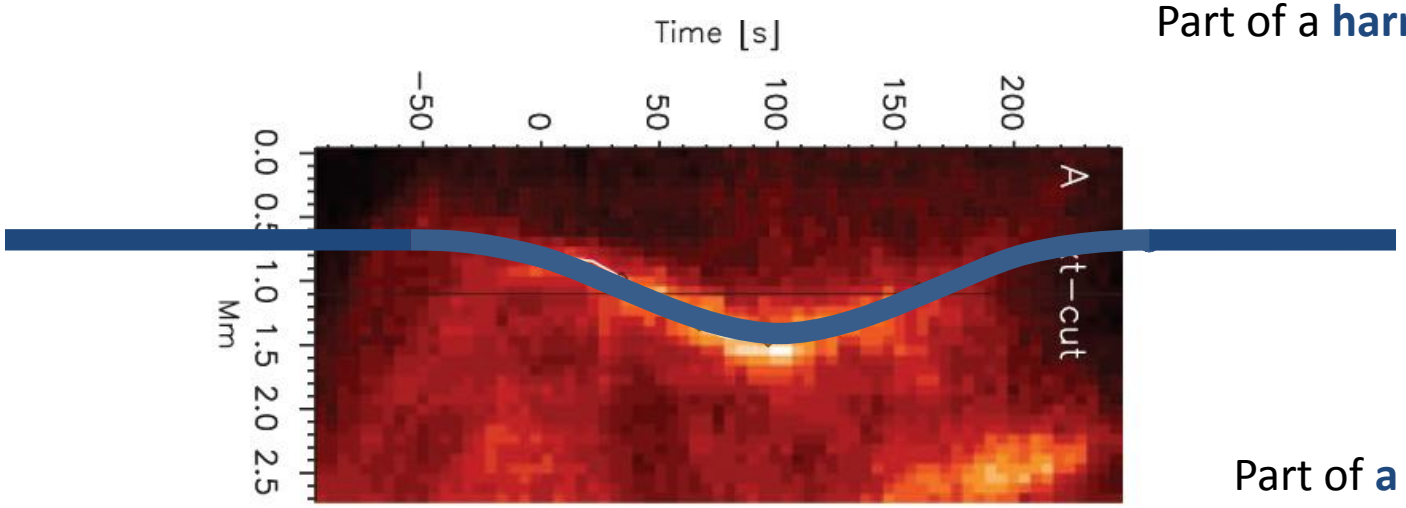


Okamoto & De Pontieu (ApJ, 2011)
using Hinode/SOT data

What are we observing here?



Part of a **harmonic wave**?



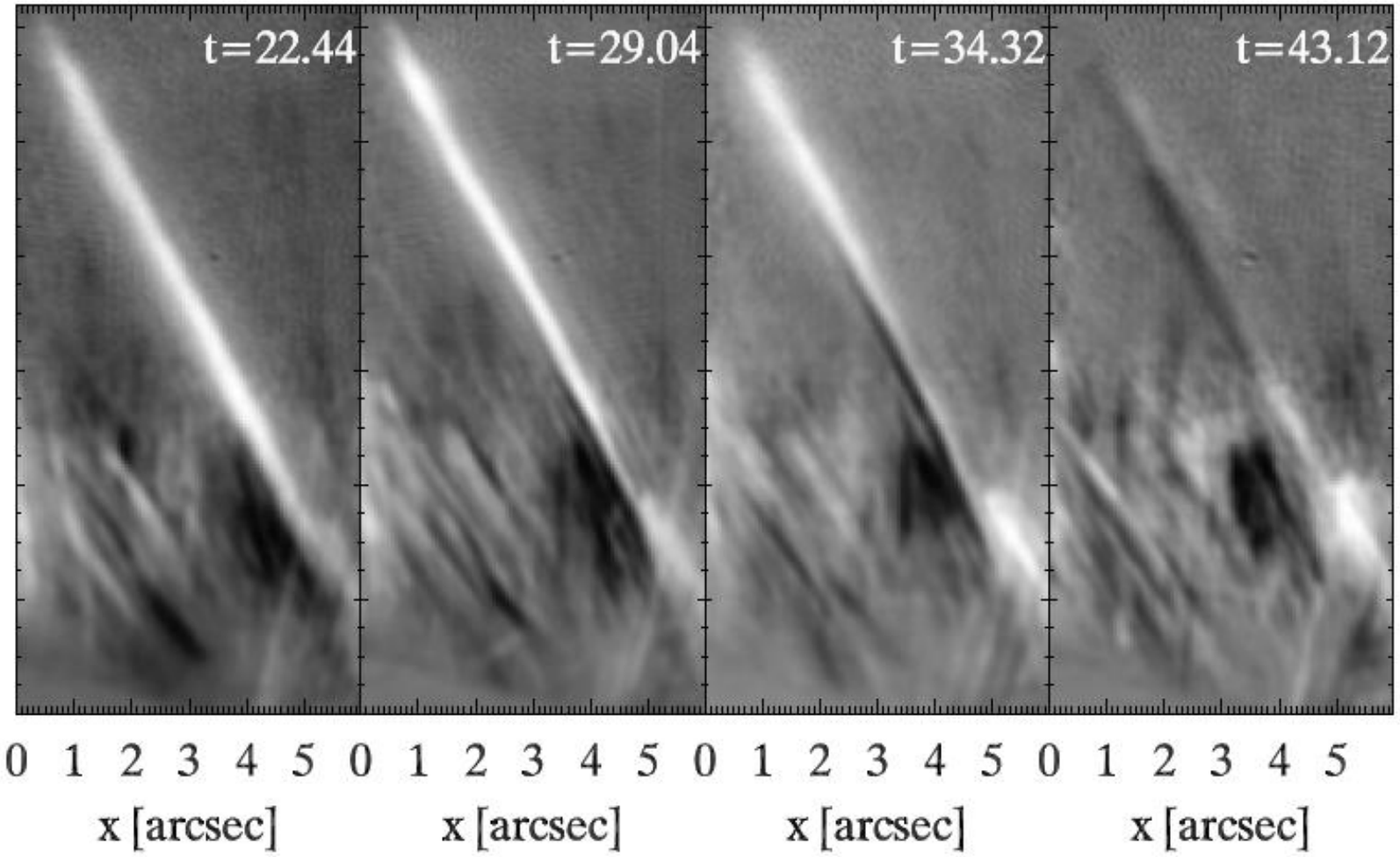
Part of **a pulse**?

Important! Determines **damping rates** due to **resonant absorption** and **phase mixing**, e.g. **Hood et al. (Proc. Roy. Soc. Lon. A, 2002, 2005)**

Also rotational motion present in spicules and RE's

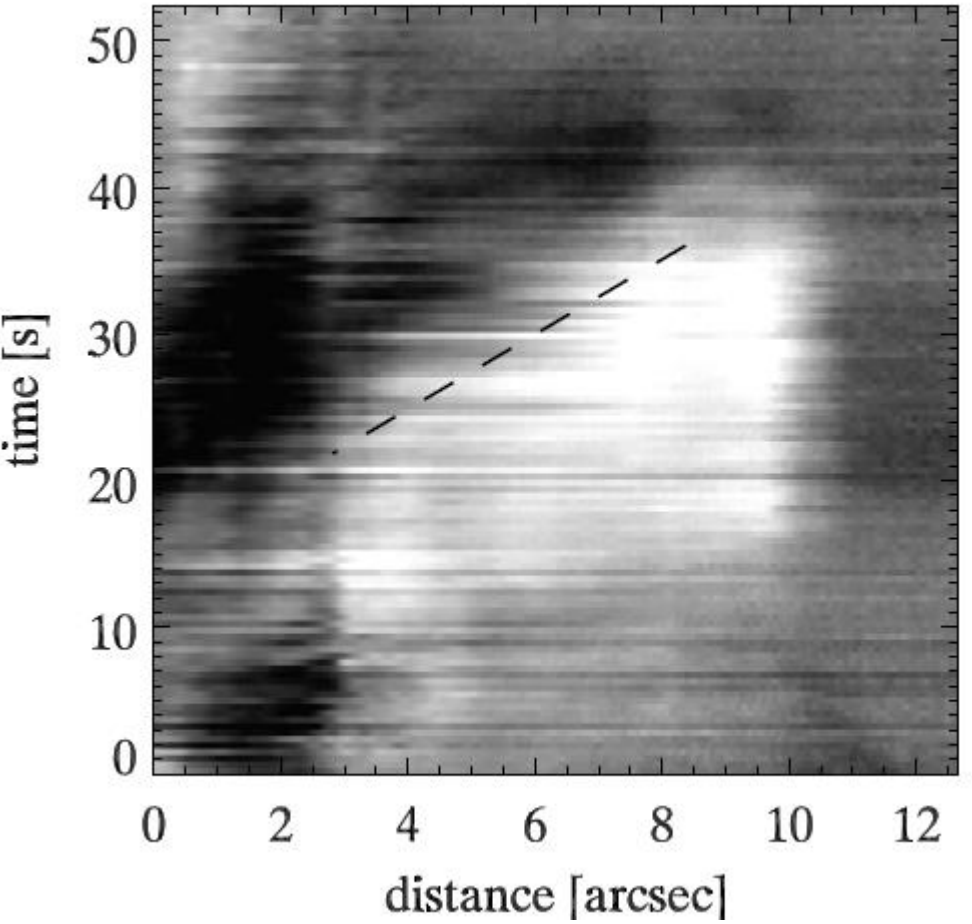
Using **TRIPPEL/SST** Ca II H data **CRISP/SST** Hα data **De Pontieu et al. (ApJ, 2012)** showed that there are pronounced **25-30 km/s rotational motions** in spicules.

Hα Doppler image of spicule

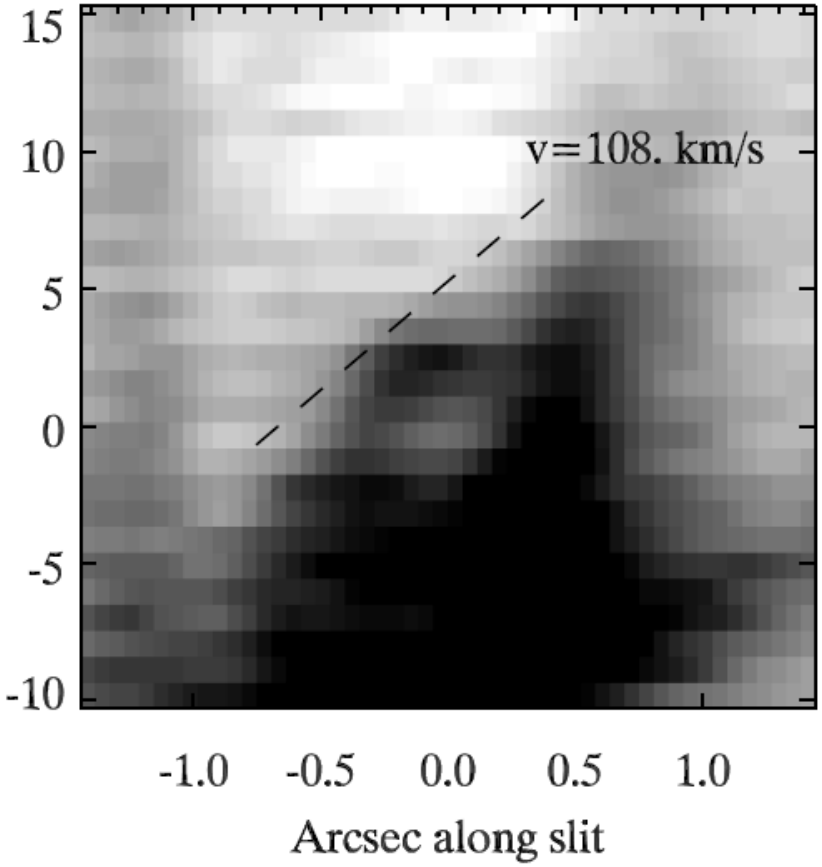


Rotational time distance along spicules and RE's

Observations show **visible lifetime** ≲ **"period"** of rotational motion

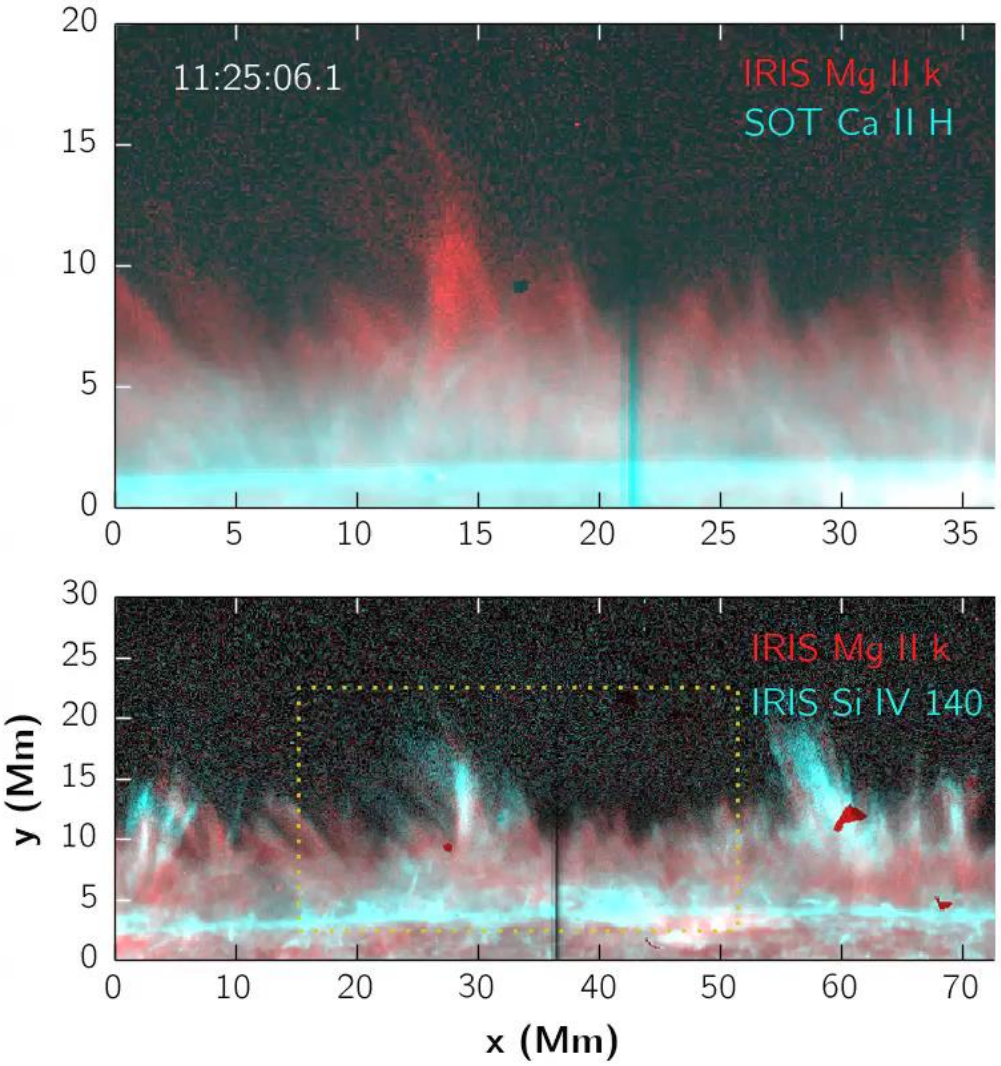


Off-limb **spicule** observed with SST/CRISP (**De Pontieu et al. , ApJ. 2011**)



On-disc **RE** observed with SST./CRISP (**Sekse et al. ApJ 2013**)

Multi-instrument/multi-wavelength observations should help!



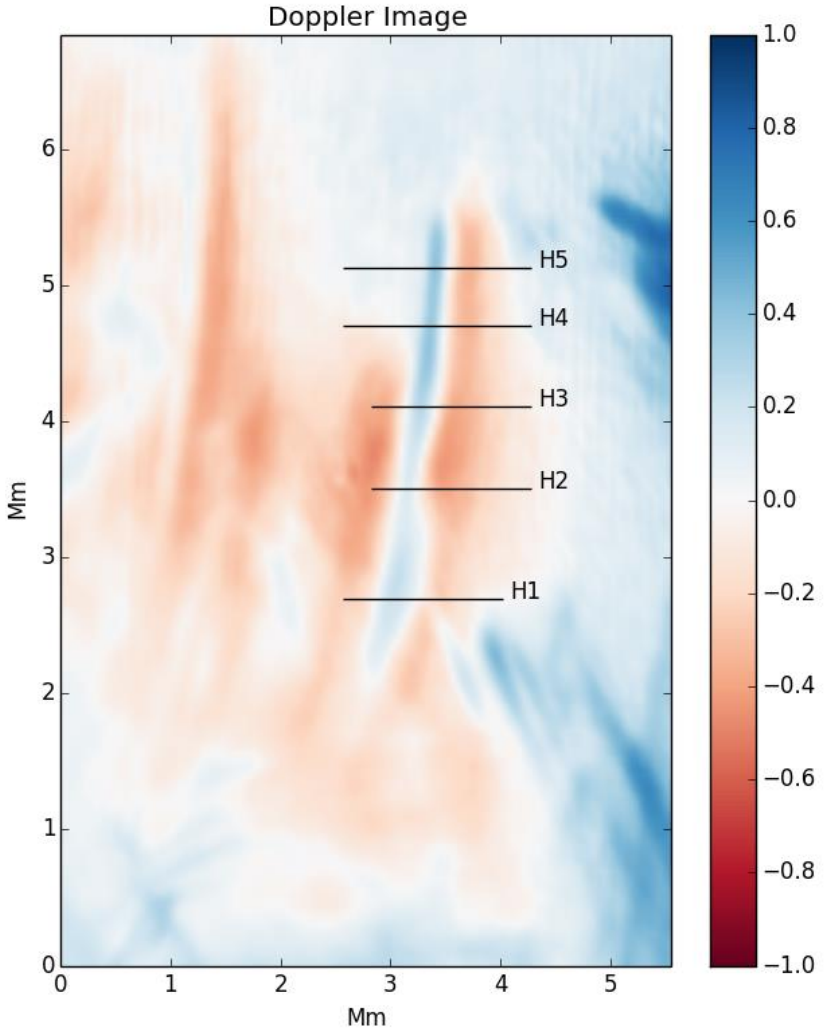
Pereira et al. (2014)

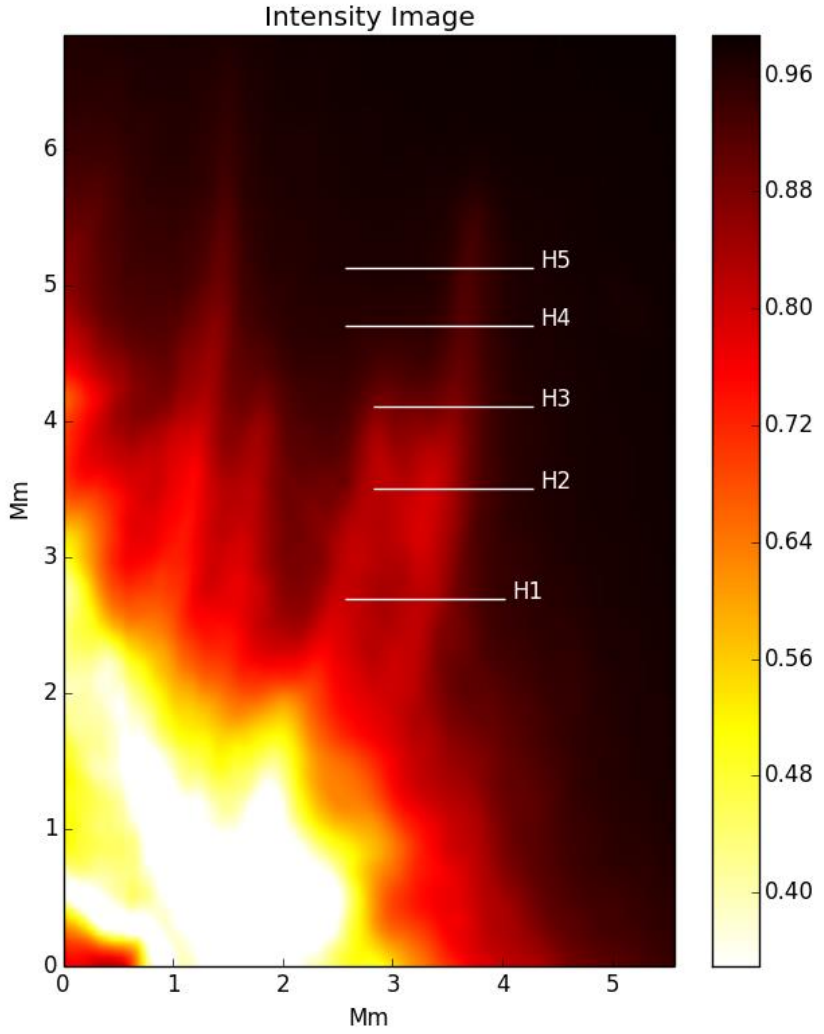
- Combined **IRIS, Hinode, SST** and **DST** observations allow us to see **spicules** and **RE's** over a **longer time period**, e.g., fading from Ca II and appearing in hotter Mg II line.

- So far, to my knowledge, **no waves study** in **spicules** and **RE's using this approach**.

Doppler imaging observations: a great boon!

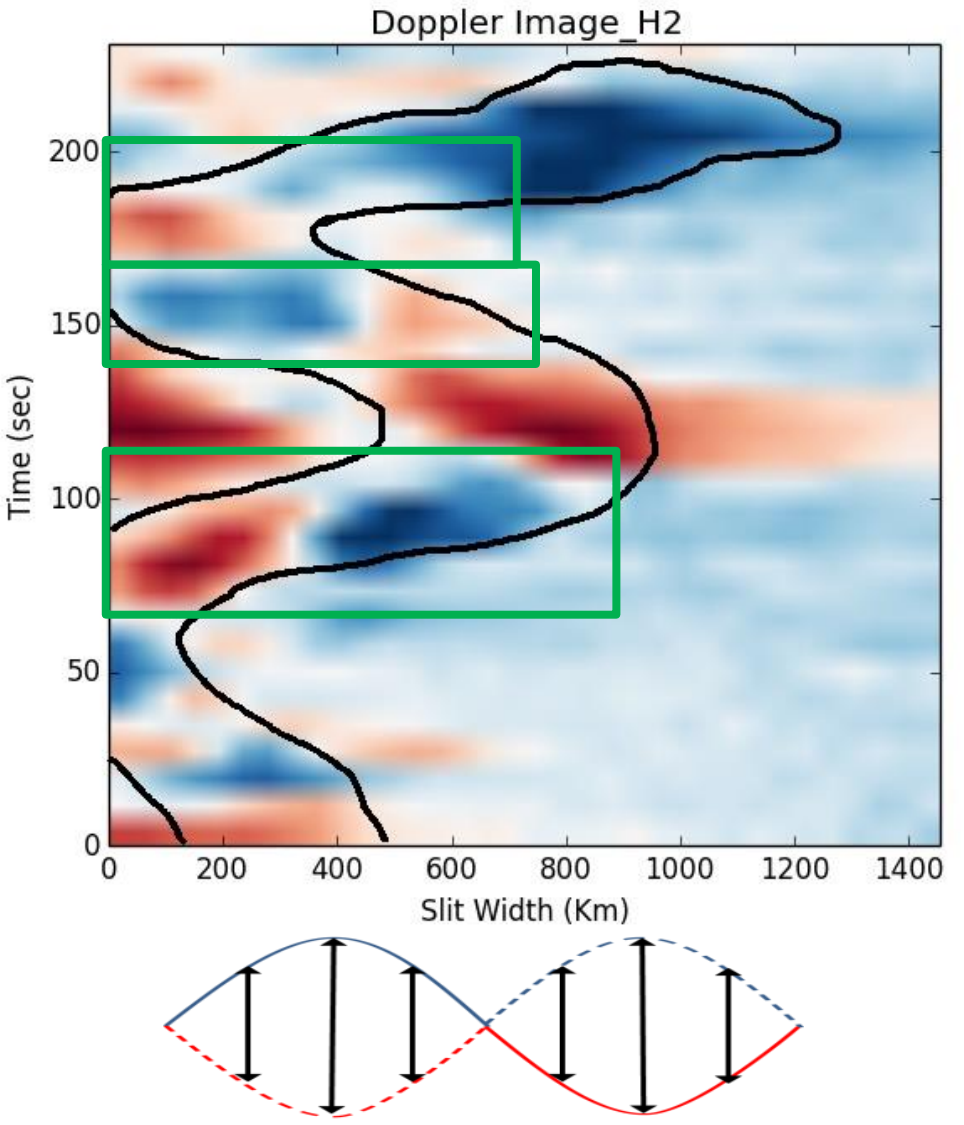
Using **CRISP/SST** Hα data **Sharma et al. (2016, in preparation)** analyse **LOS motion** (with ***Doppler***) and **POS motion** (LCT on ***intensity***)



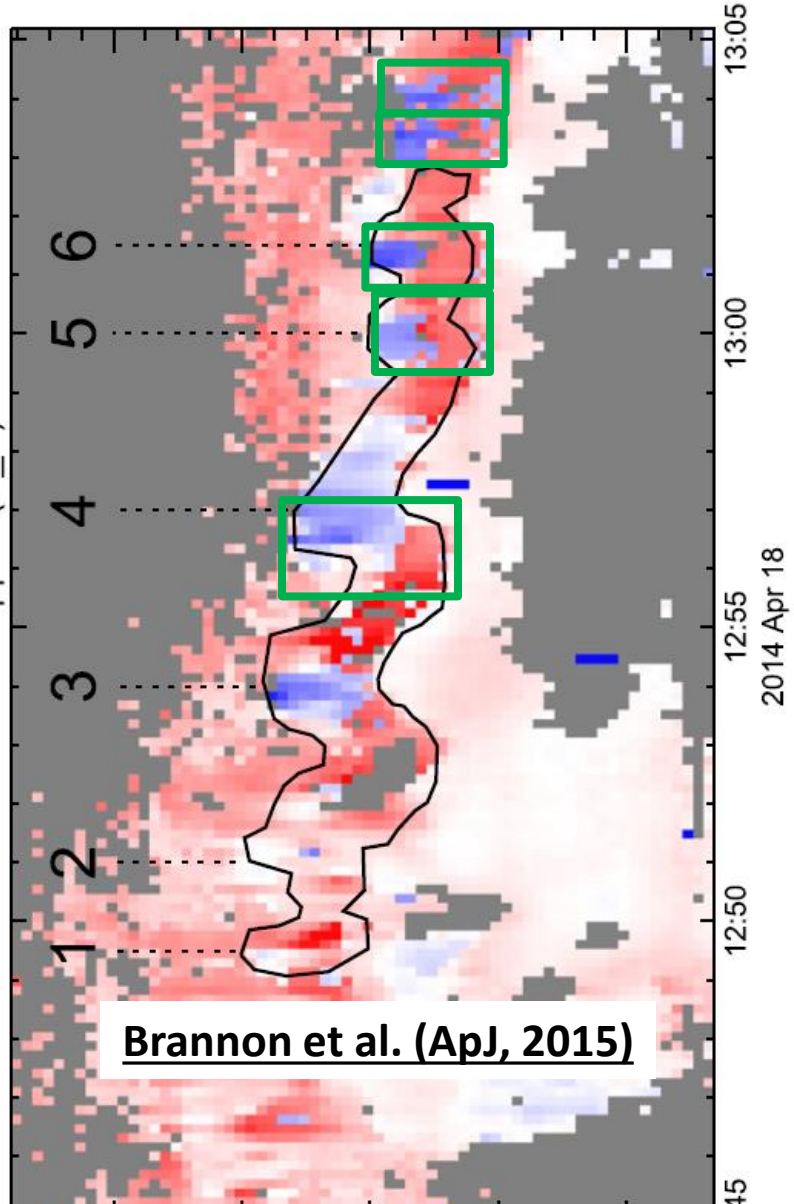


When L.O.S. ⊥ bulk transverse motion

Spicule (SST/CRISP data)

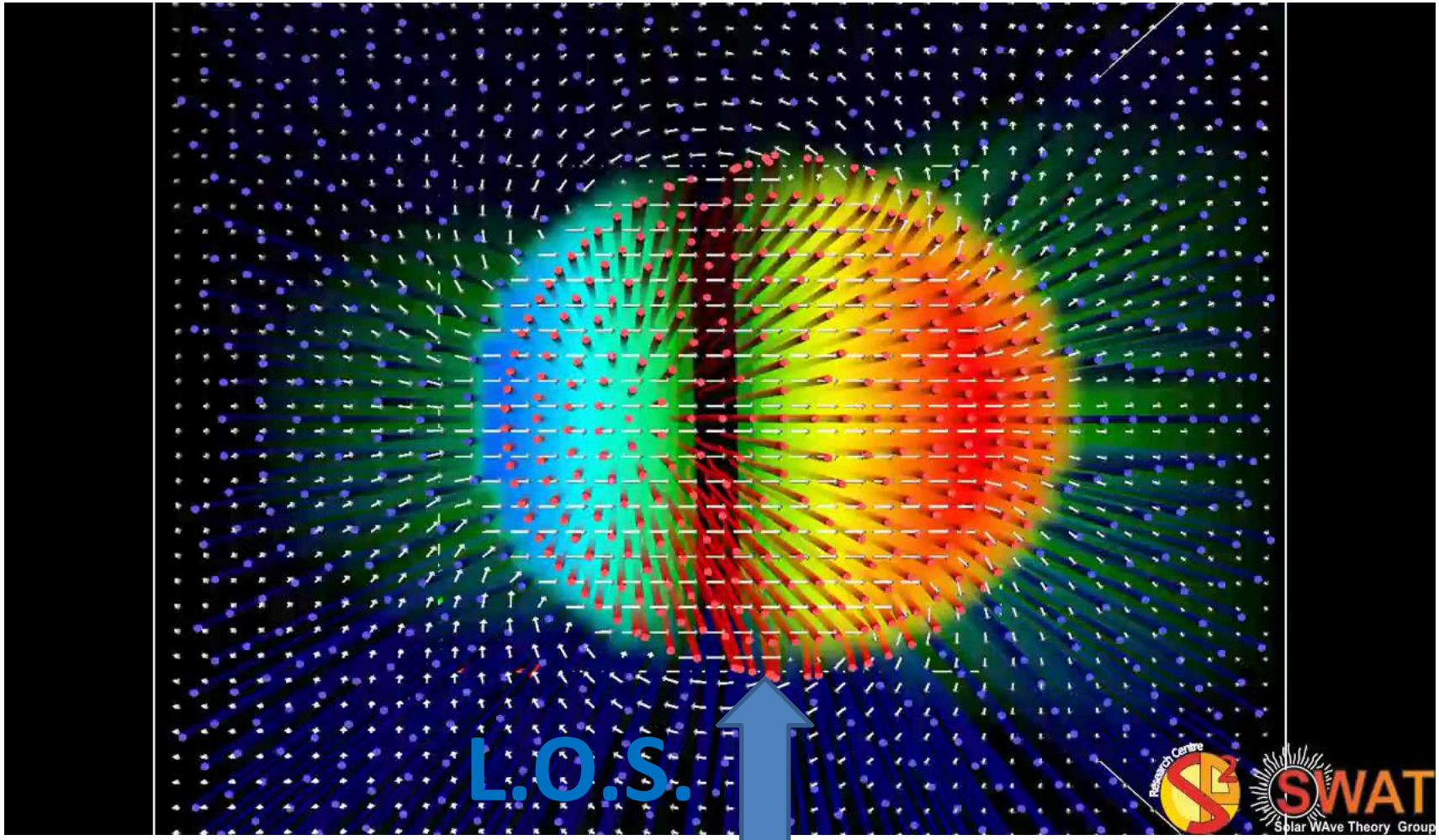


Flare ribbon (IRIS data)

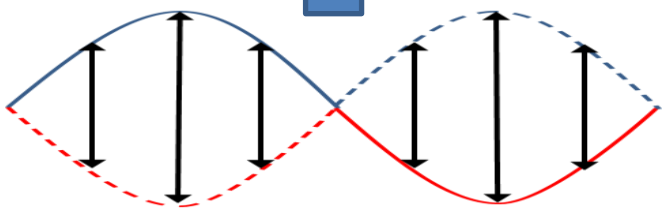


Brannon et al. (ApJ, 2015)

L.O.S. ⊥ transverse motion of linear *m*=1 kink wave



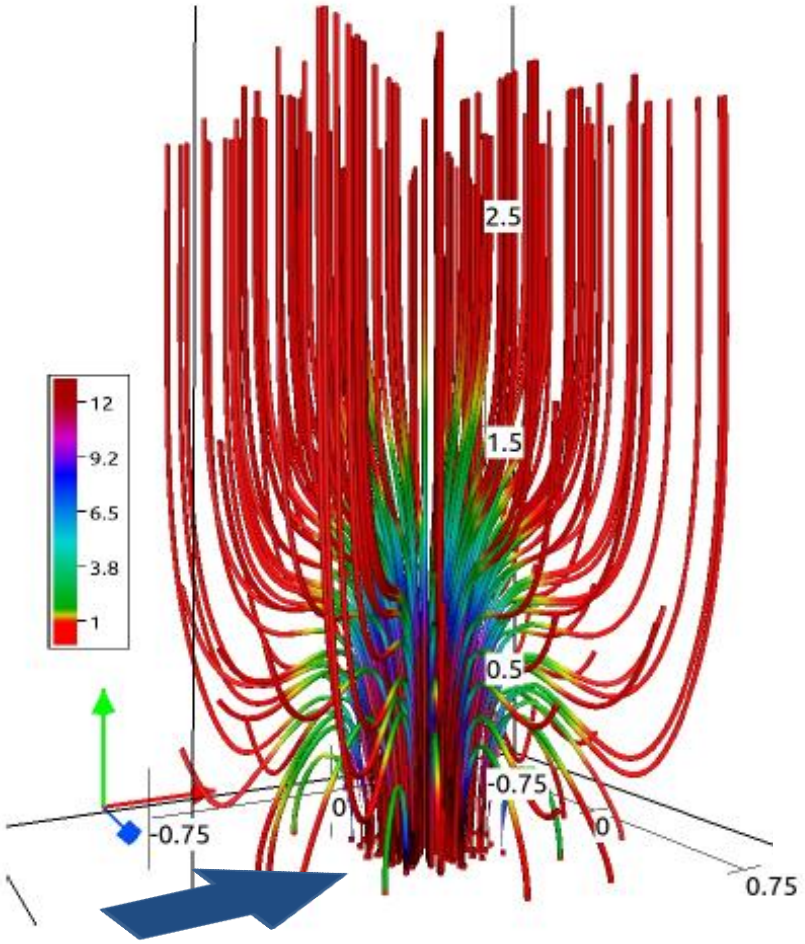
Of course depends on the **Doppler signal** obtained from the **LOS integration**



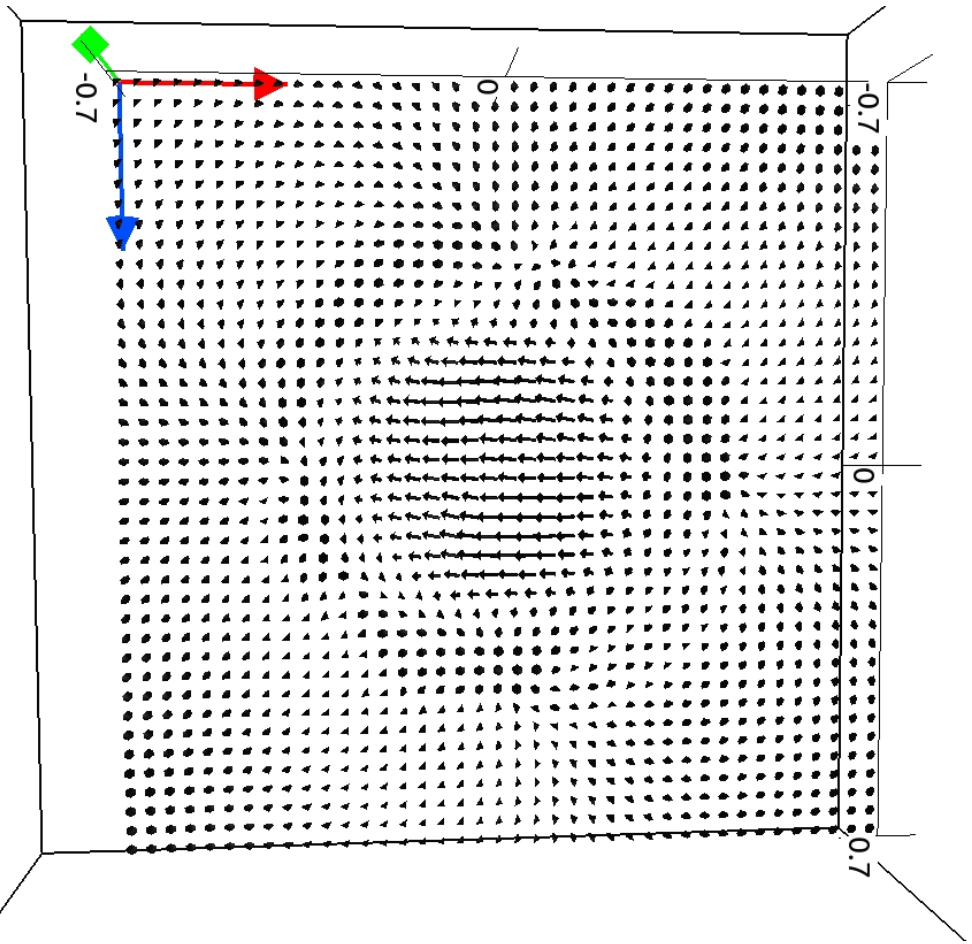
See **Goossens et al. (ApJ. 2014)**

Beyond linear analytical MHD model

FLASH code (**Lee & Deane , JCP, 2009**)



Velocity field slice at height 1.5 Mm

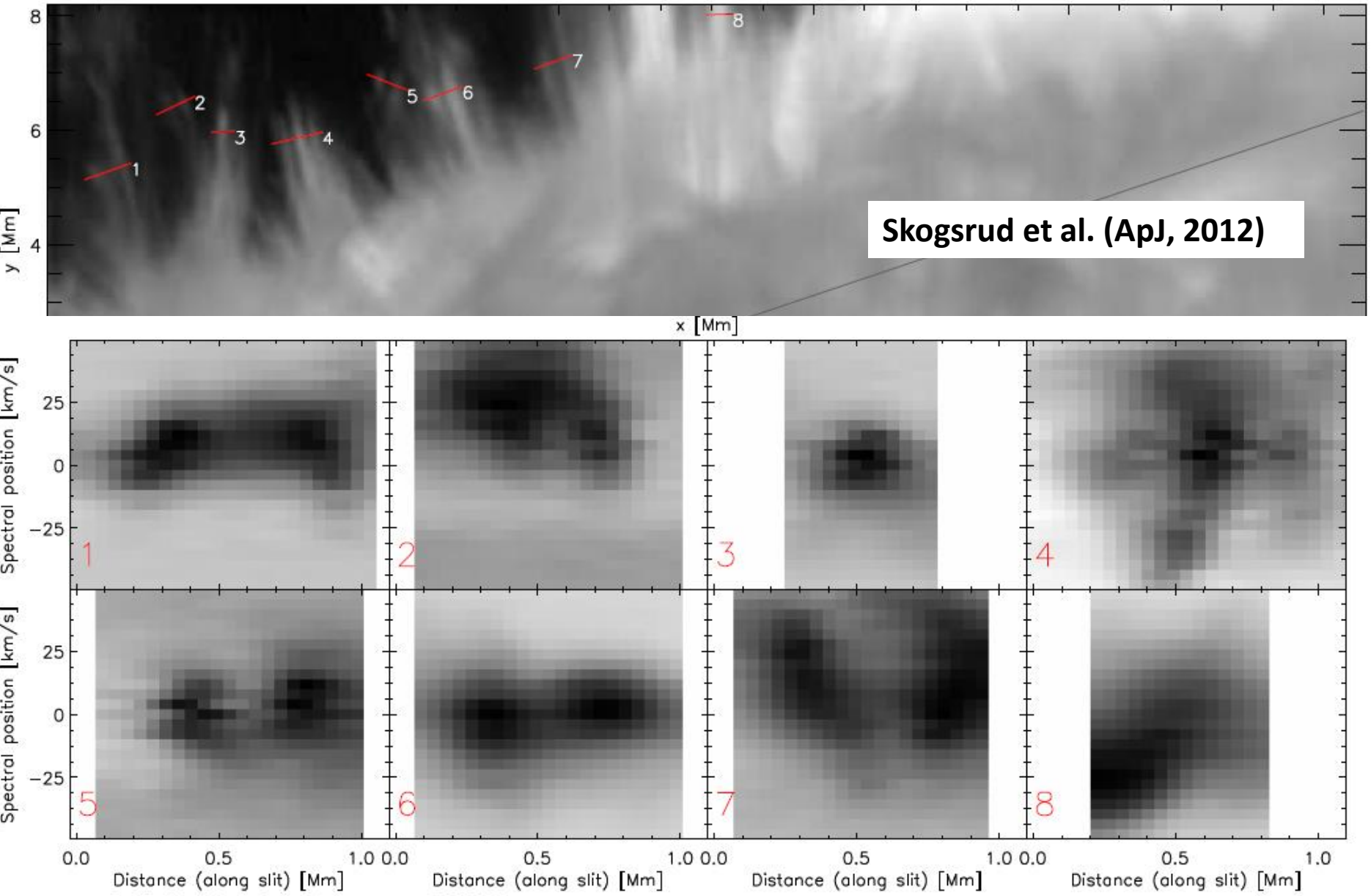


Transverse kick at footpoint

Results in *m*=1 (**non-axisymmetric**) **rotational motion**

Murwaski et al. (2016, in prep.)

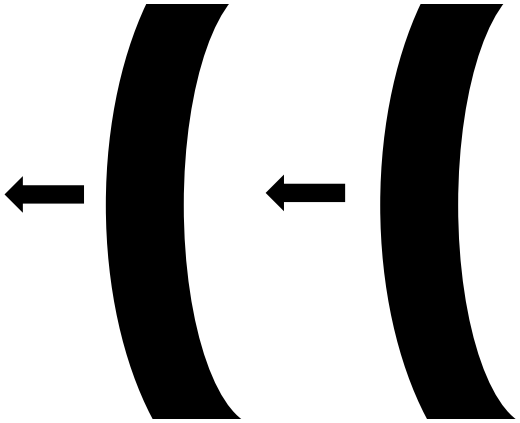
Spicule multi-thread structure

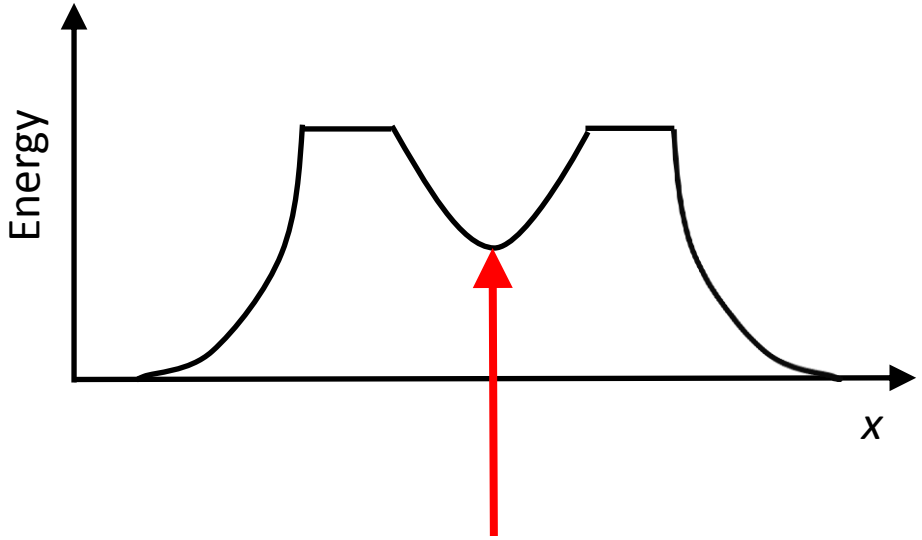


Doppler shift across spicules

Two neighbouring “spicules” with transverse waves

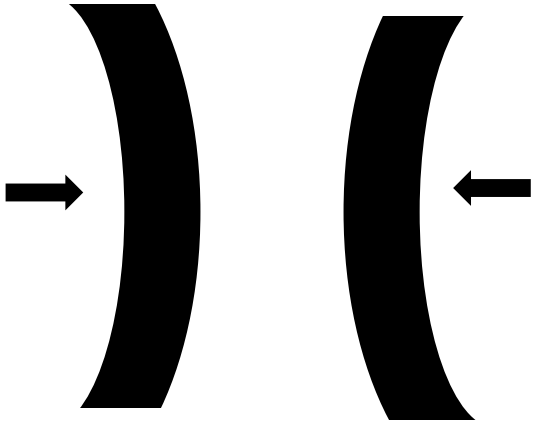
In phase

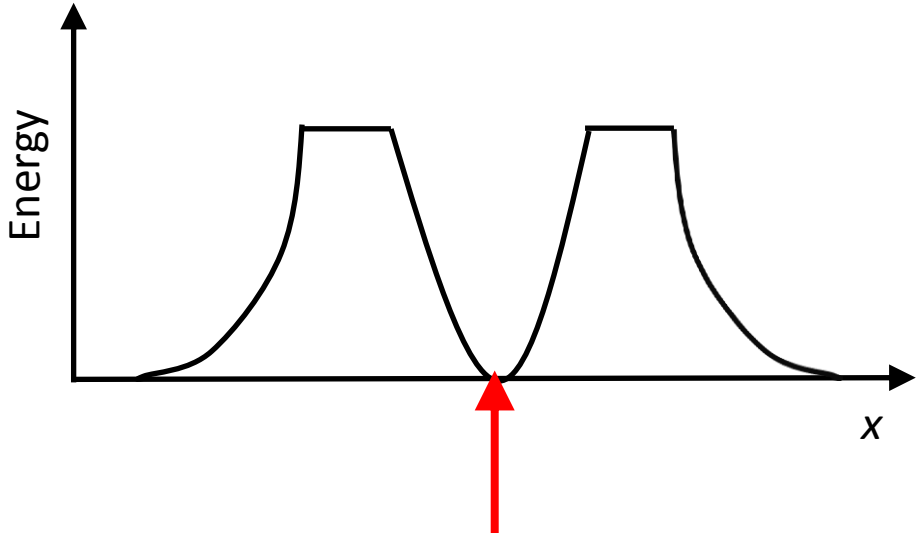




Constructive interference

Anti-phase

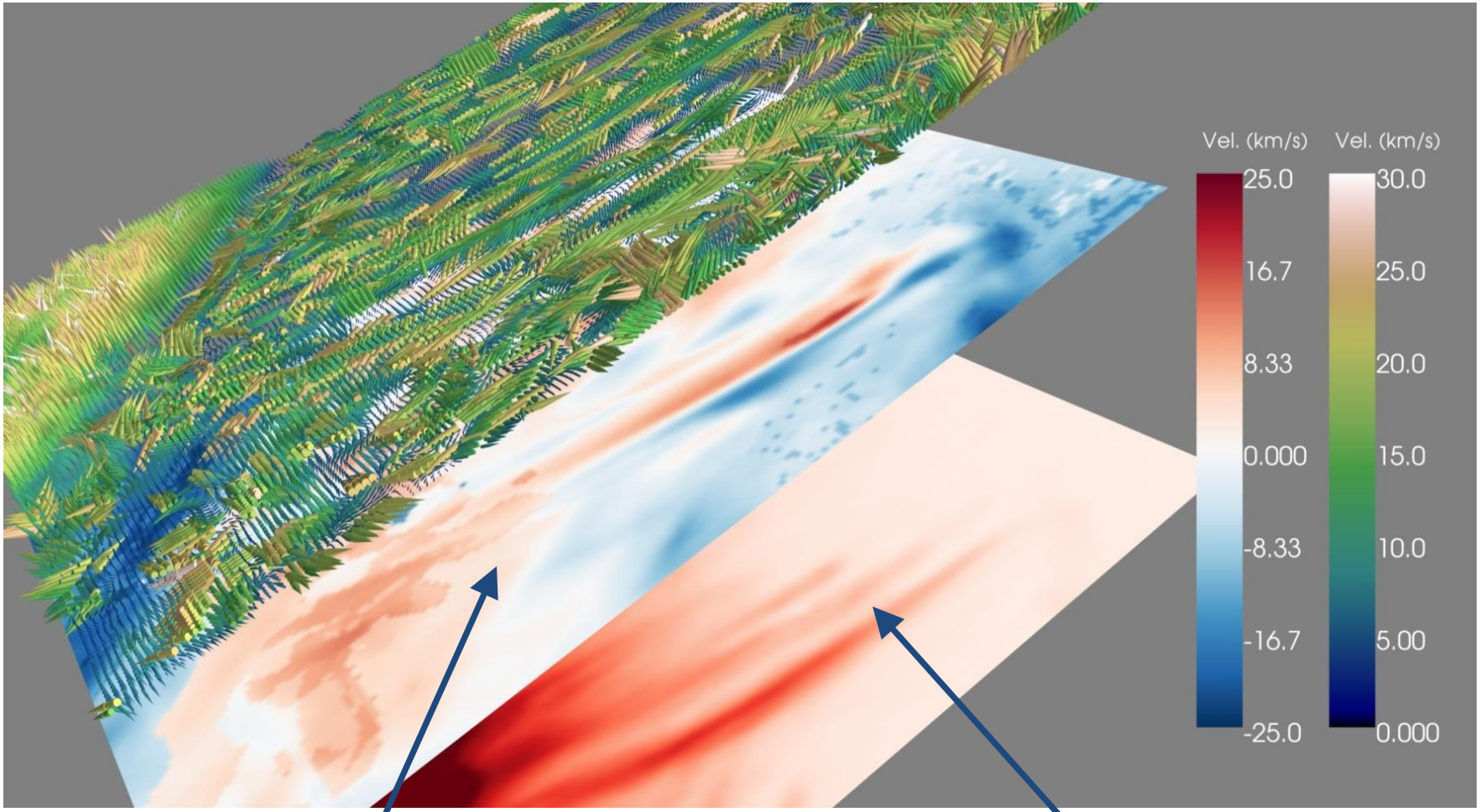




Destructive interference

Estimating spicule velocity vectors with CRISP

Can add the **LOS** and **POS** velocity vector components to give **3D velocity vectors** on a **"plane"** .



(i) Get LOS velocity from Doppler

(ii) Track POS velocity using LCT on intensity

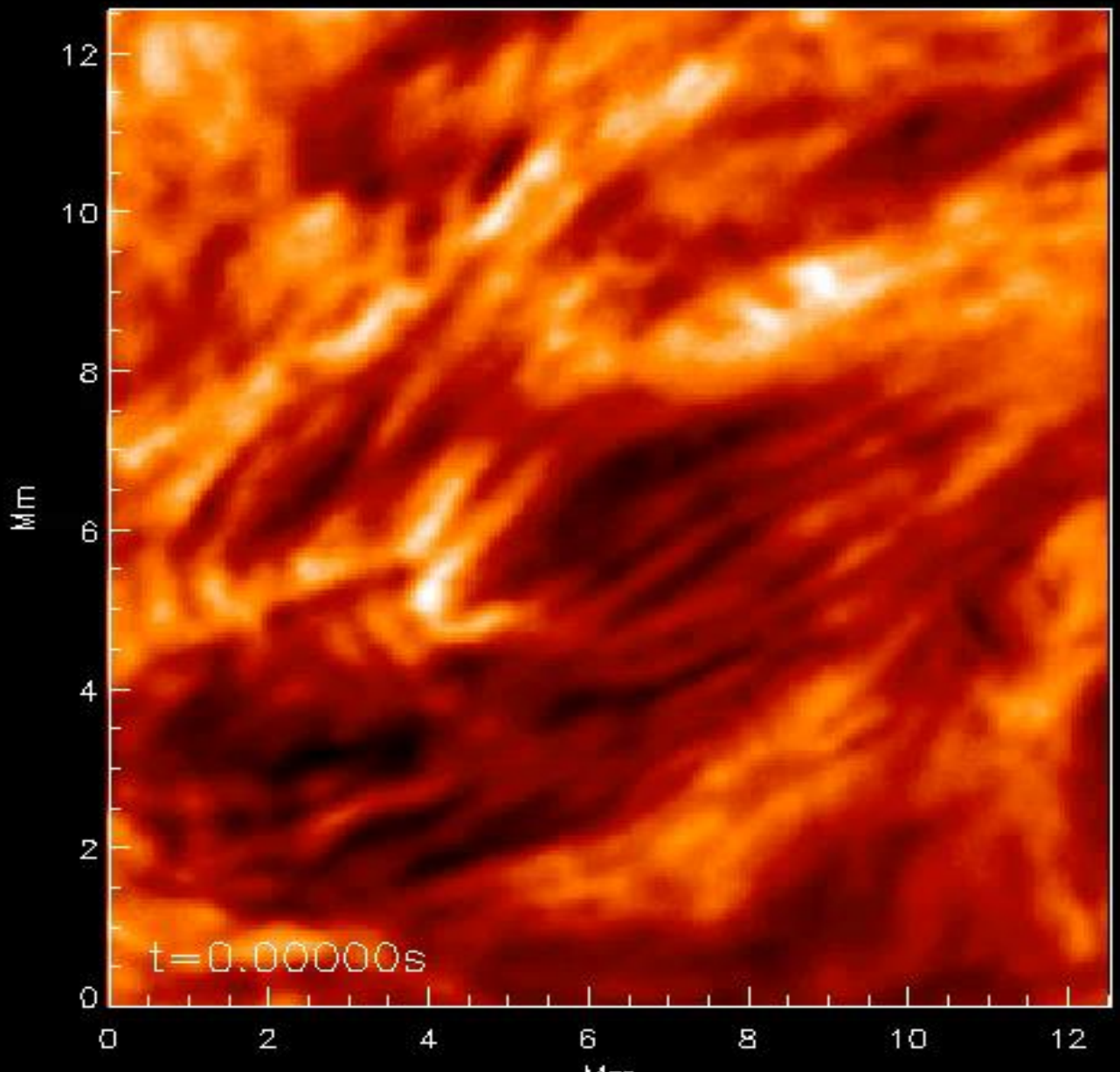
Zoom-in on spicule velocity vectors

Suggests **velocity power not uniform in space** and **weakest outside spicules**

But remember! Intensity and **Doppler** signal in **Hα** also **weakest outside spicules**

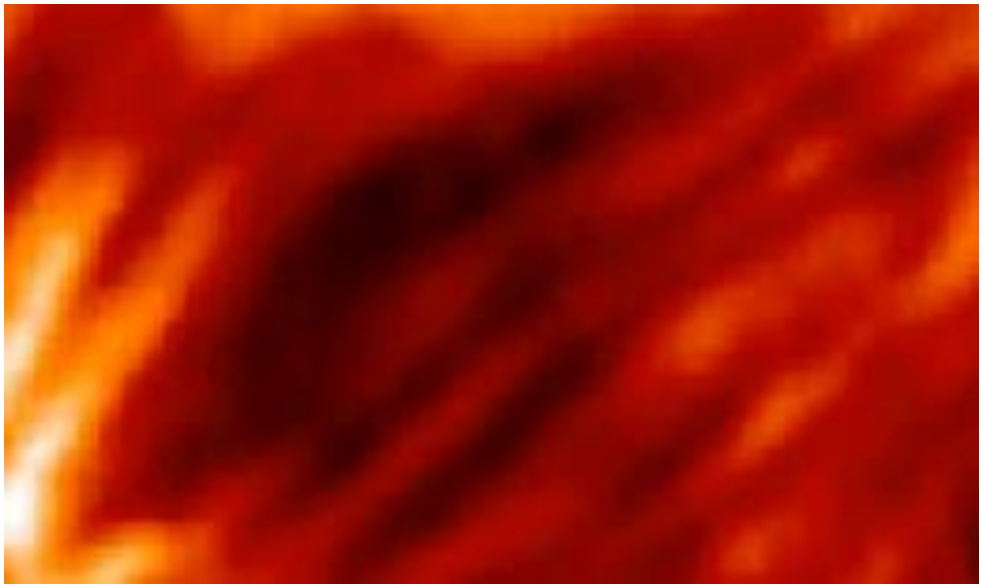
Transverse waves in fibrils

ROSA **Hα movie** showing **ever present transverse motions** of fibrils

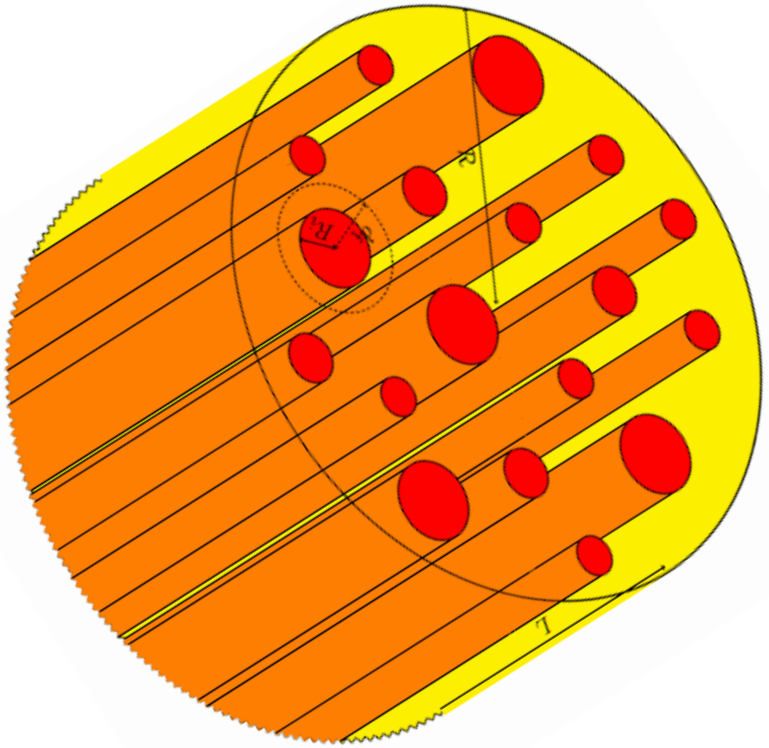


How to model fibrils as waveguides?

Is the **overdense circular cross-section flux tube model valid** for interpreting **MHD waves** observed in **fibrils**?

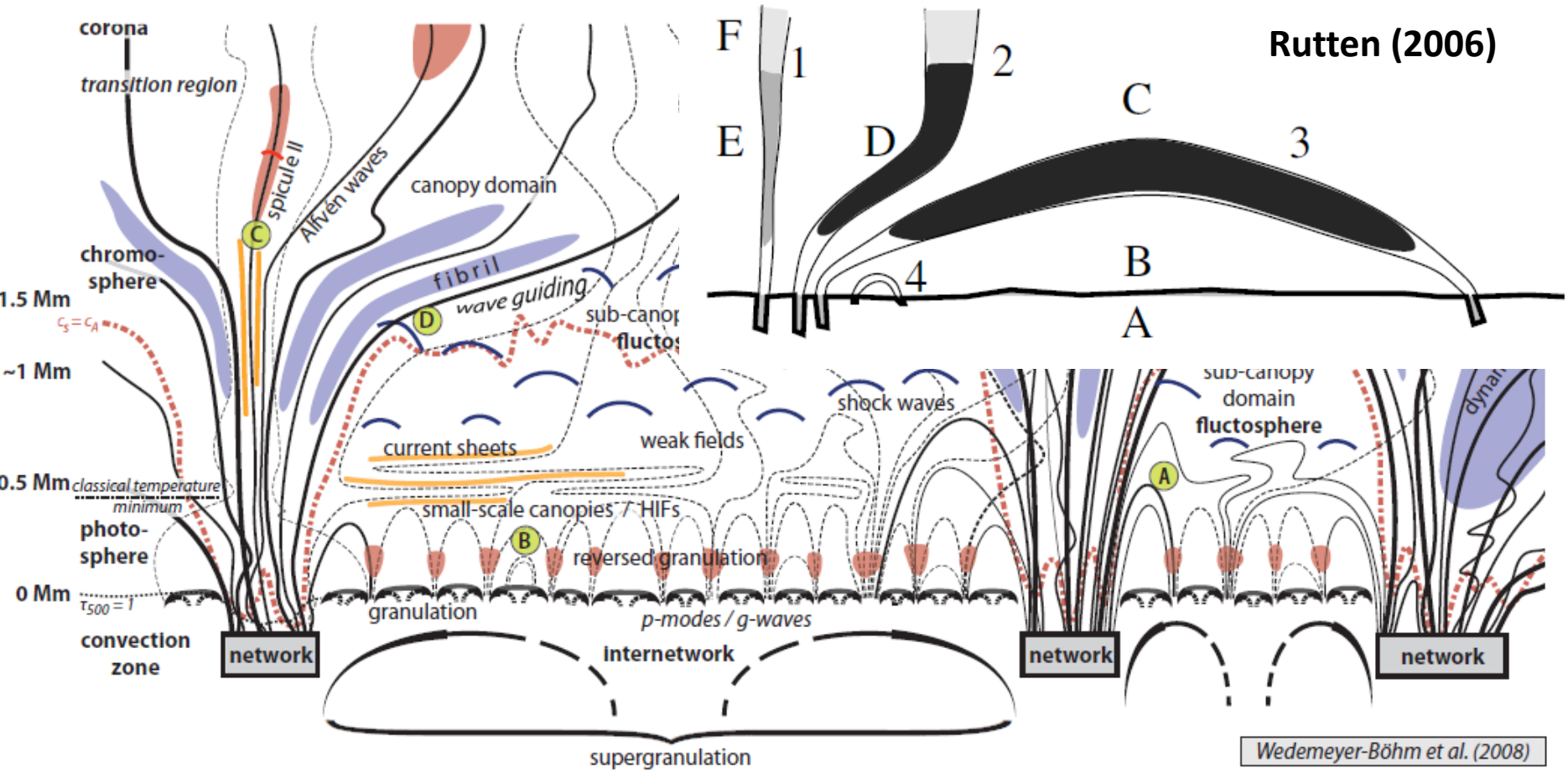


Morton et al. (2012)



Van Doorsselaere et al. (2014)

Previous ideas about fibril structure?

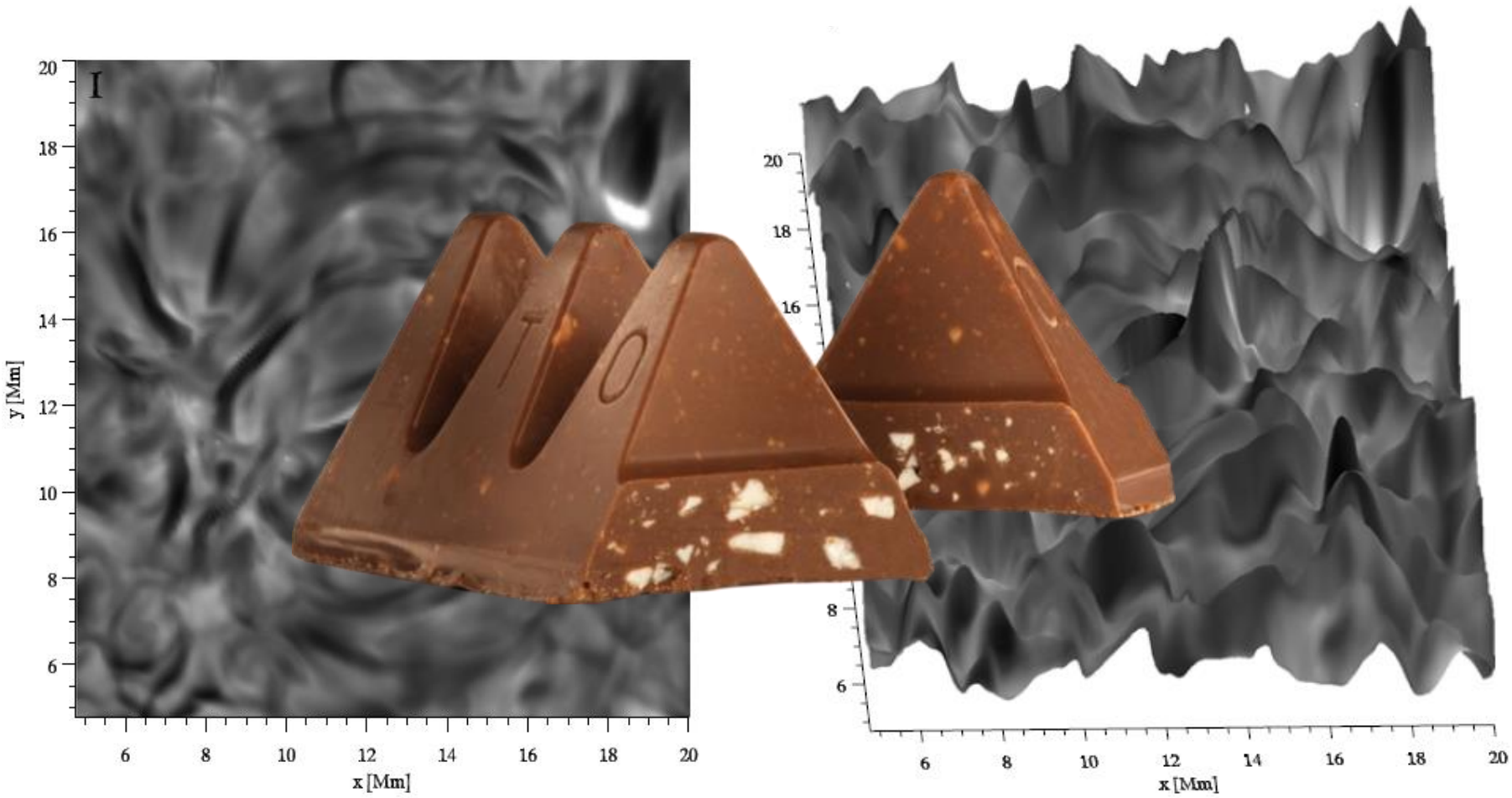


Rutten (2006)

Wedemeyer-Böhm et al. (2008)

What do Bifrost simulations tell us?

Leenaarts et al. (ApJ, 2012) state the "***dark fibrils follow ridges of enhanced chromospheric mass density***".



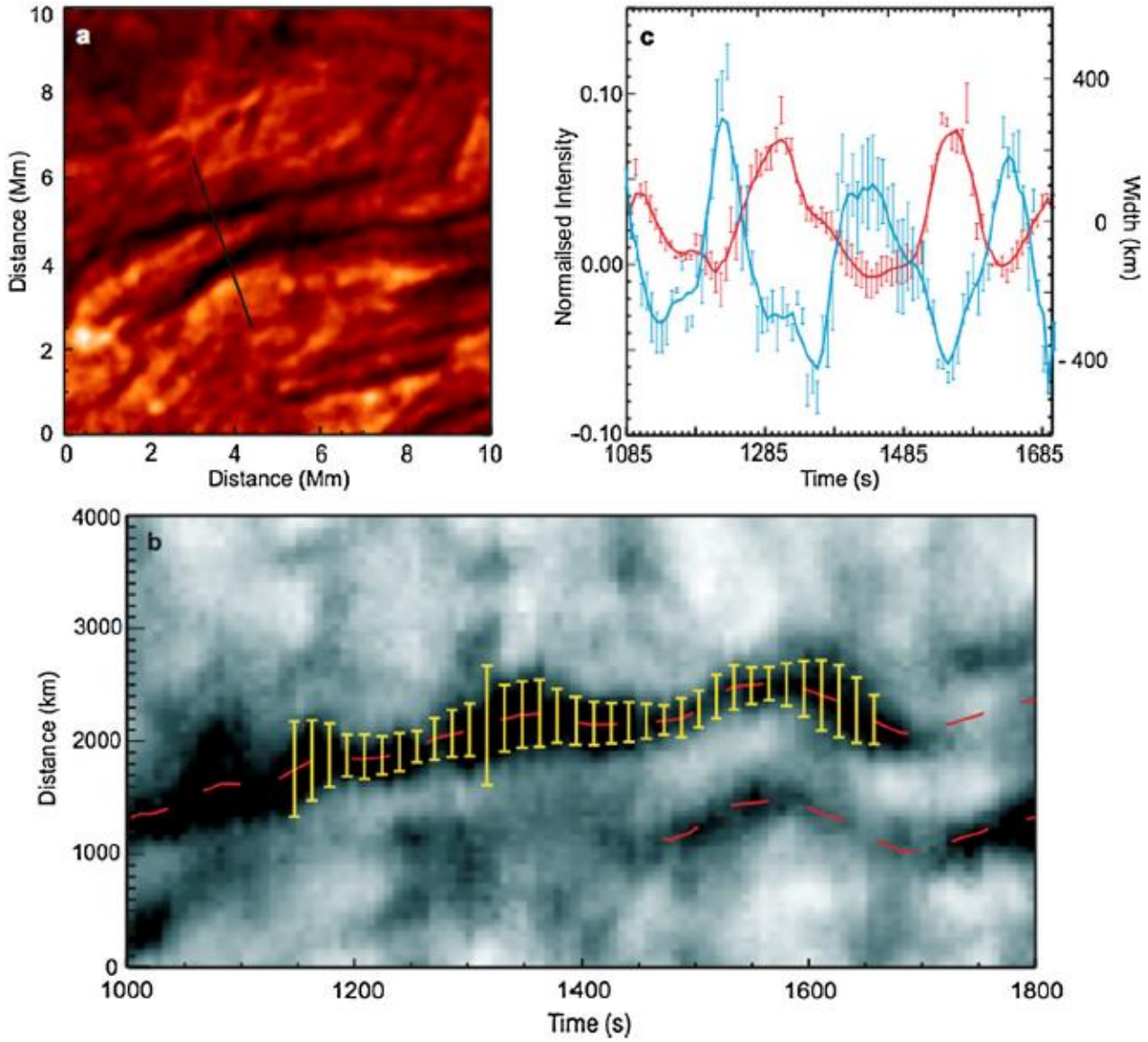
LOS integrated Hα intensity

Iso-surface of mass density 10^{-11} g cm $^{-3}$

Important! **Shape** and **plasma structure** of **fibrils** will determine their oscillatory response

Two MHD wae modes present in fibrils?

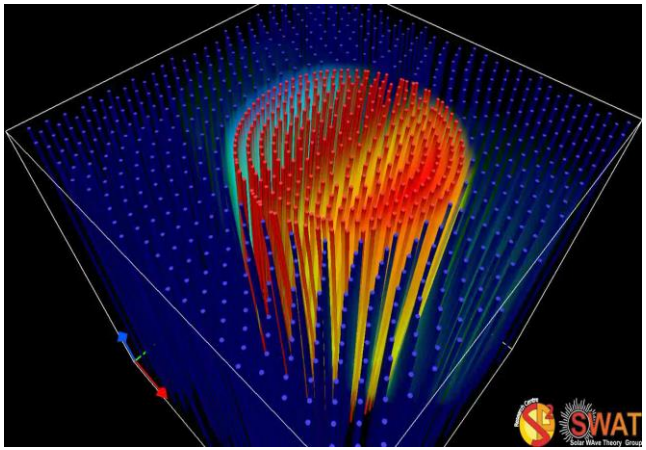
Using **ROSA** t**ime/distance** slices showed combination of **both periodic transverse motion** and **flux tube width changes** (**Morton et al., Nature Comm., 2012**)



Explanation?

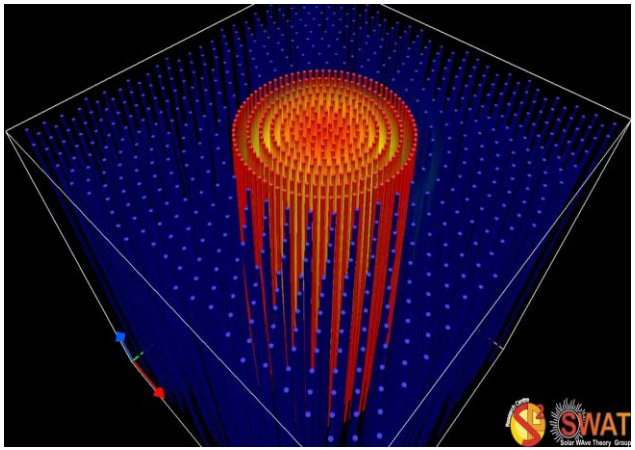
Interpreted as **concurrent kink (*m* = 1)** and **sausage (*m* = 0) modes** in on-disc ***chromospheric fibrils***.

Kink mode (*m* = 1)

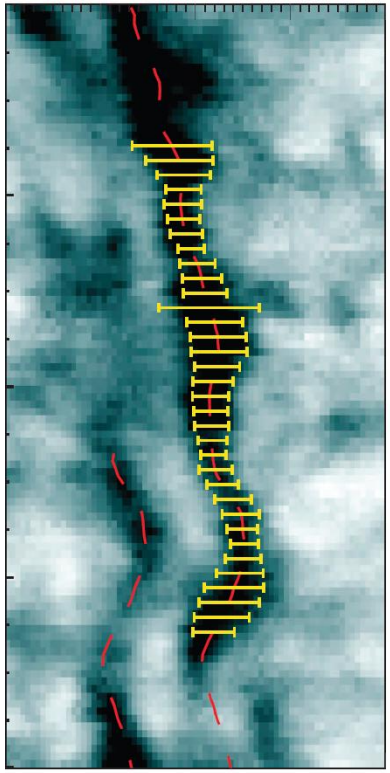


+

Sausage mode (*m* = 0)



=

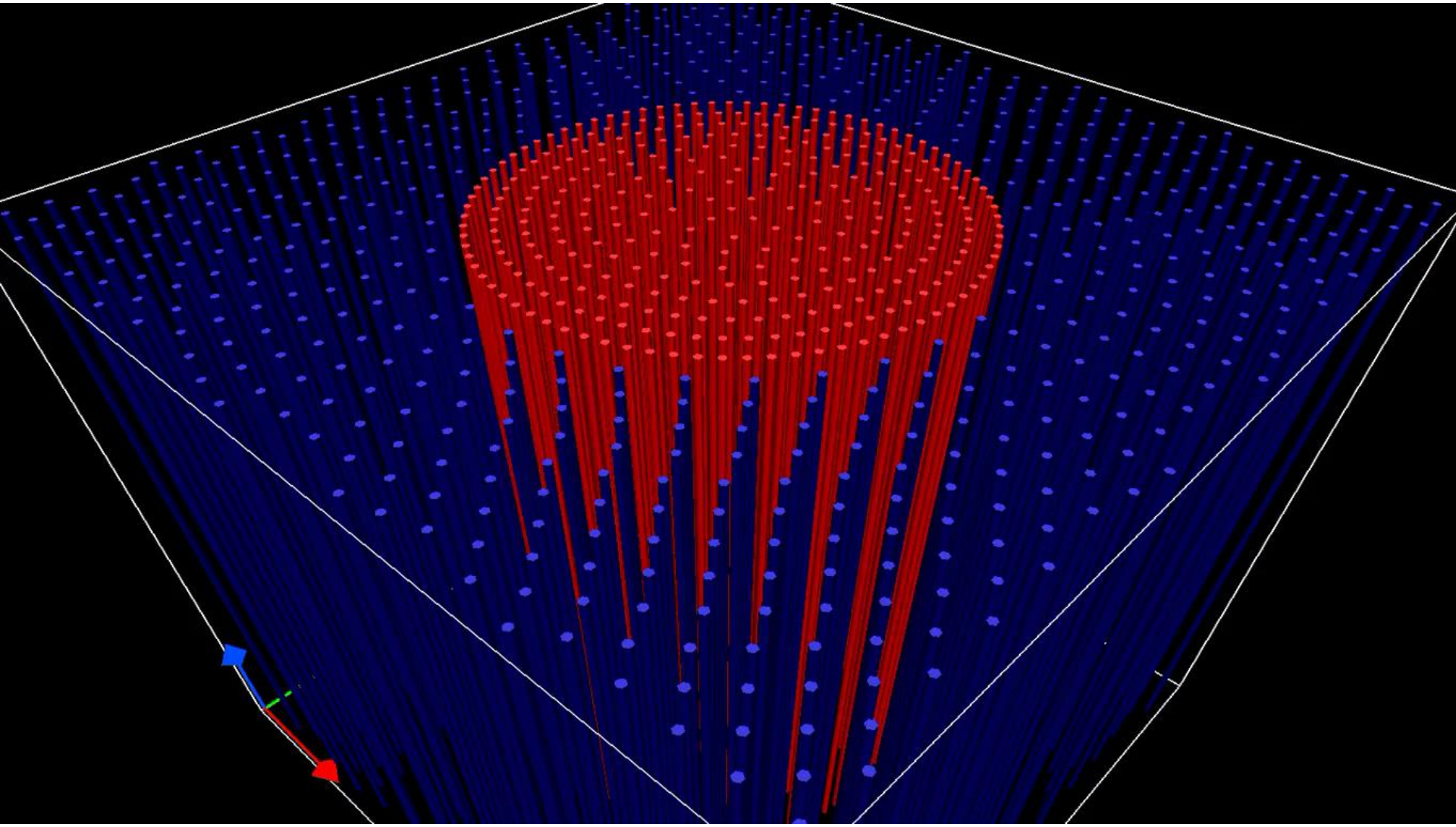


Energy flux of **sausage mode** **3 times** more than **kink mode**

This interpretation assumes a **fibril** is flux tube with **circular cross-section**.

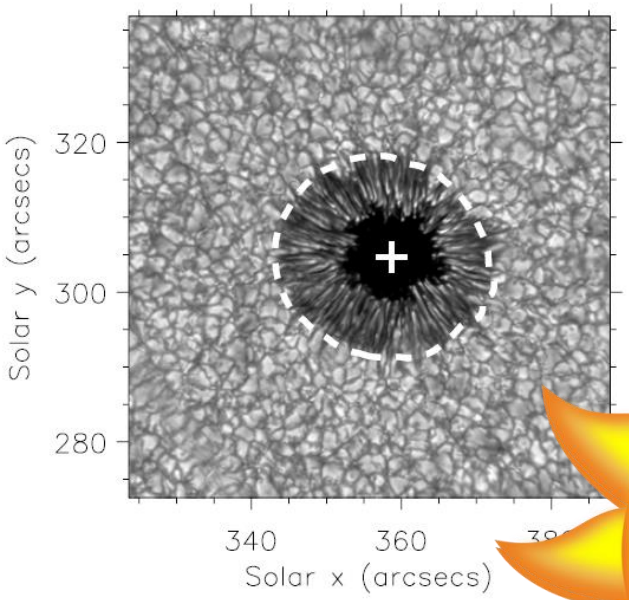
Is this actually valid?

What does a kinky sausage look like?

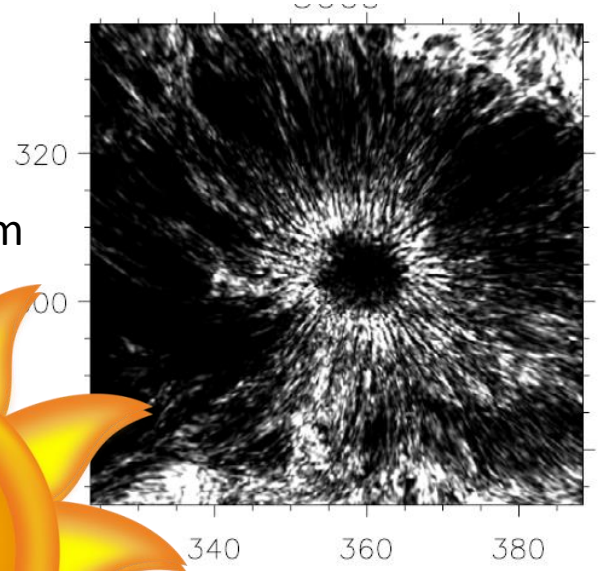


Sunspot wave fun!

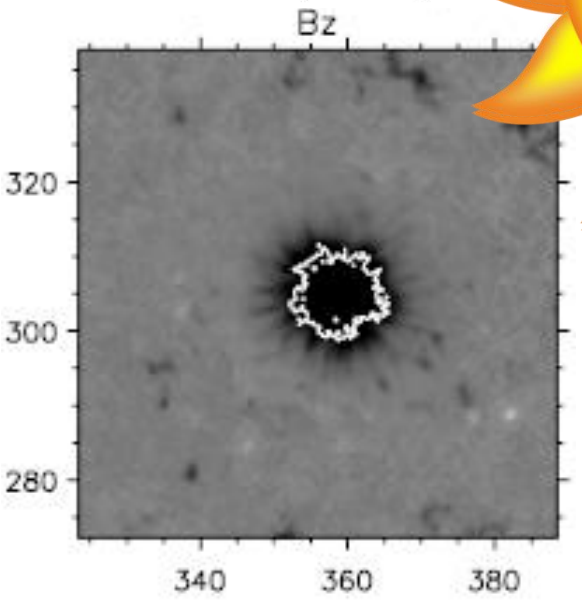
DST/ROSA and **SDO/HMI** observation of sunspot **Jess et al. (ApJ, 2013).**



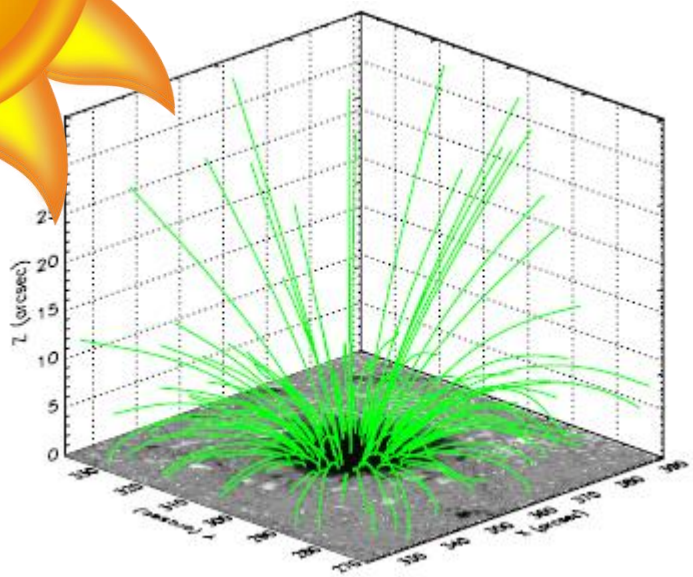
Blue continuum



Hα



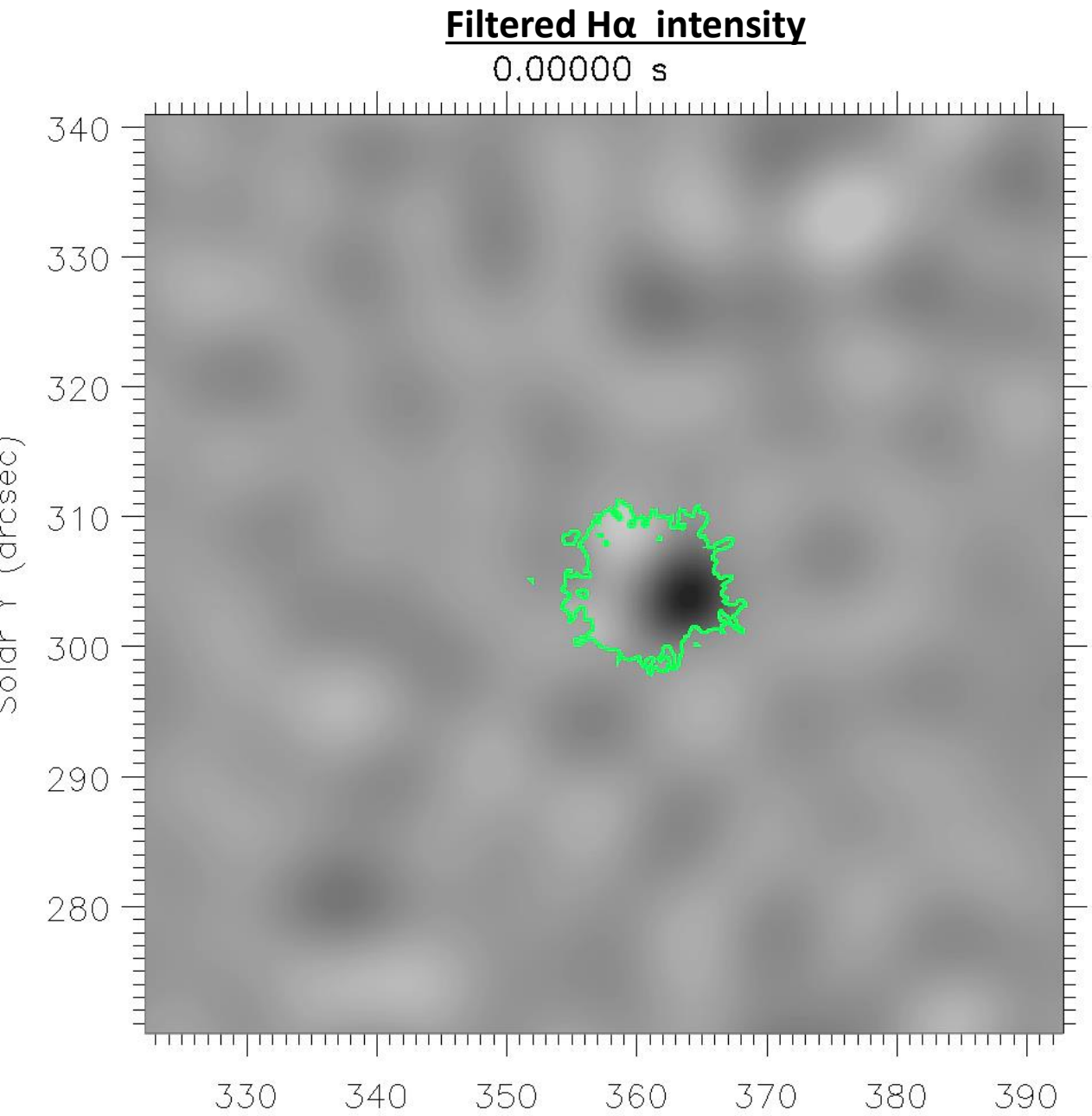
Fe I



NLFF magnetic field extrap.

(**Guo et al. ApJ, 2012**)

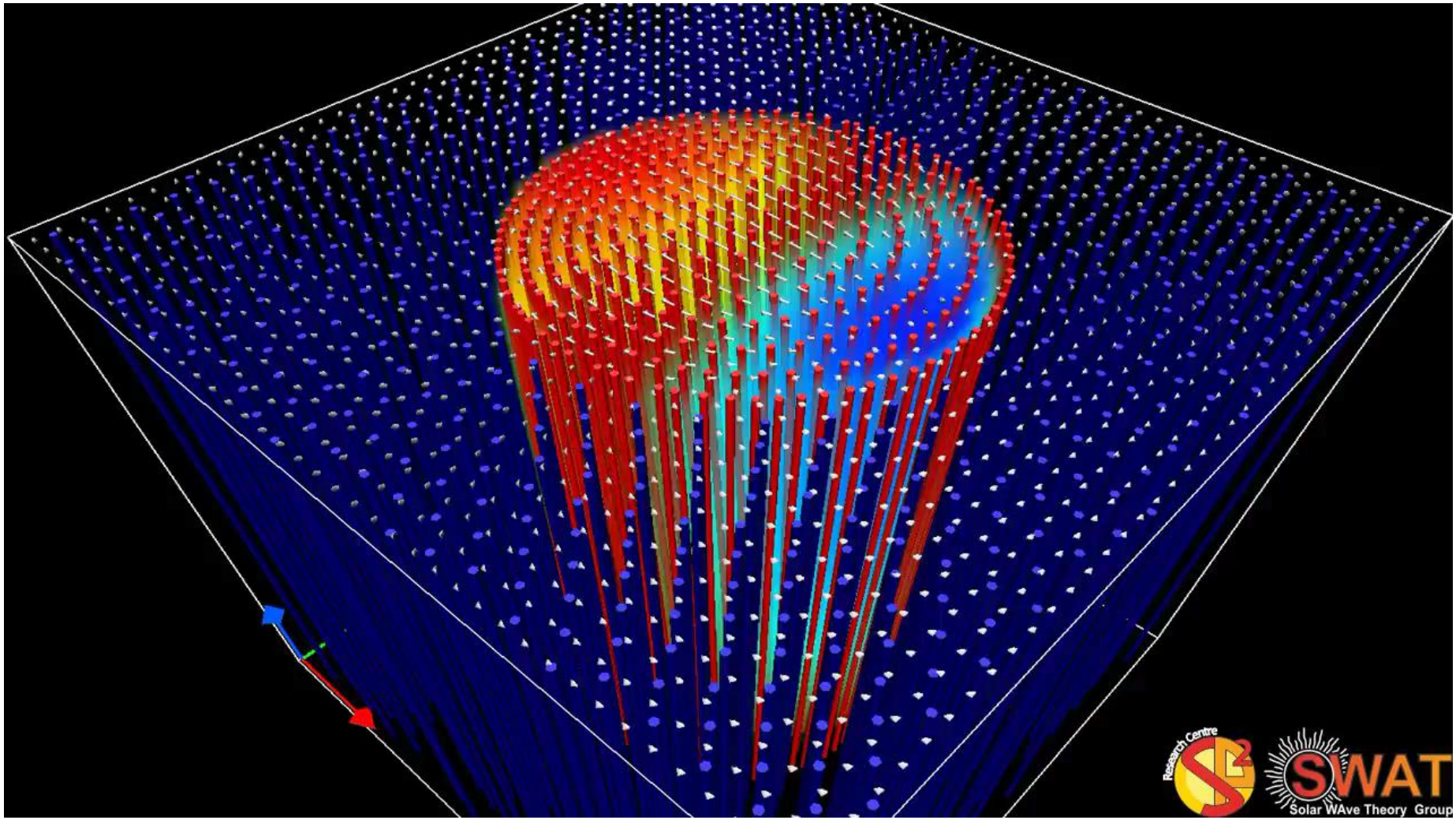
Apparent *m*=1 rotation in umbra



- **Filtered** in both **spatial** and **temporal** domain
- **Frequency filtered** at **2-4 minutes** with the Gaussian peaking at 3 minutes
- **Spatially filtered** between **5-10 “**
- **Divides** the sunspot **umbra** up into **≈ 4 quadrants.**

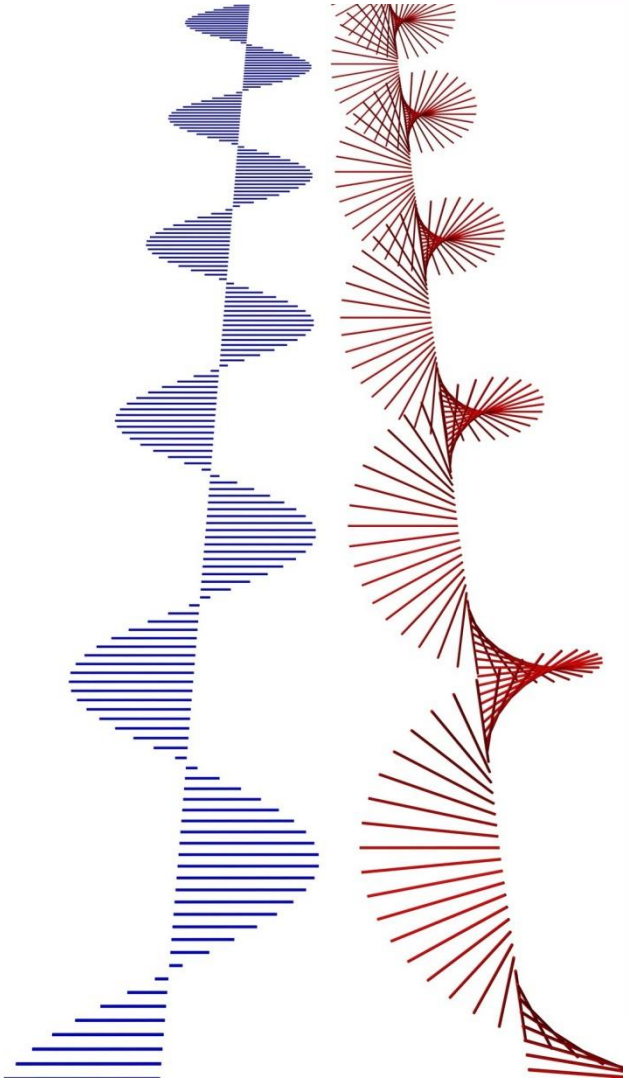
Courtesy of D. Jess

m=1 slow kink mode

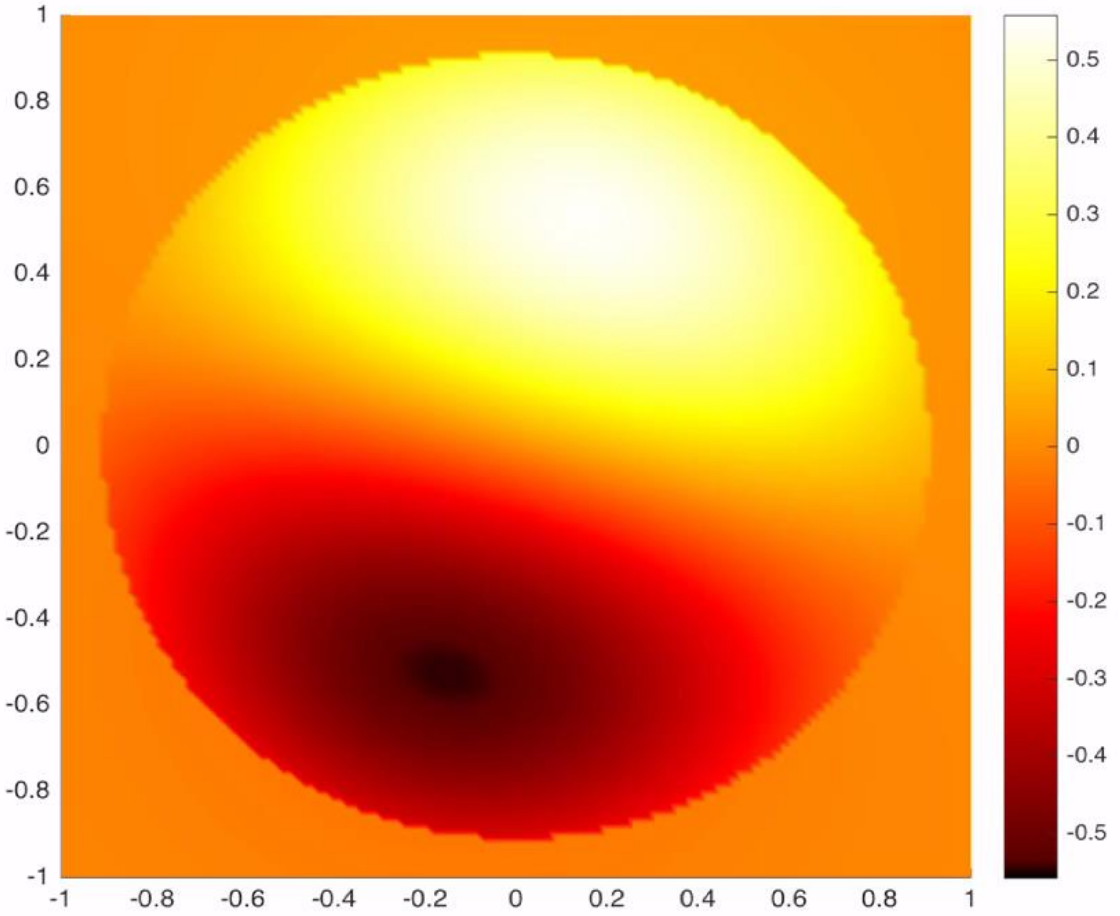


Transverse perturbations decrease at the boundary.

Adding two *m*=1 slow kink modes with circular polarization

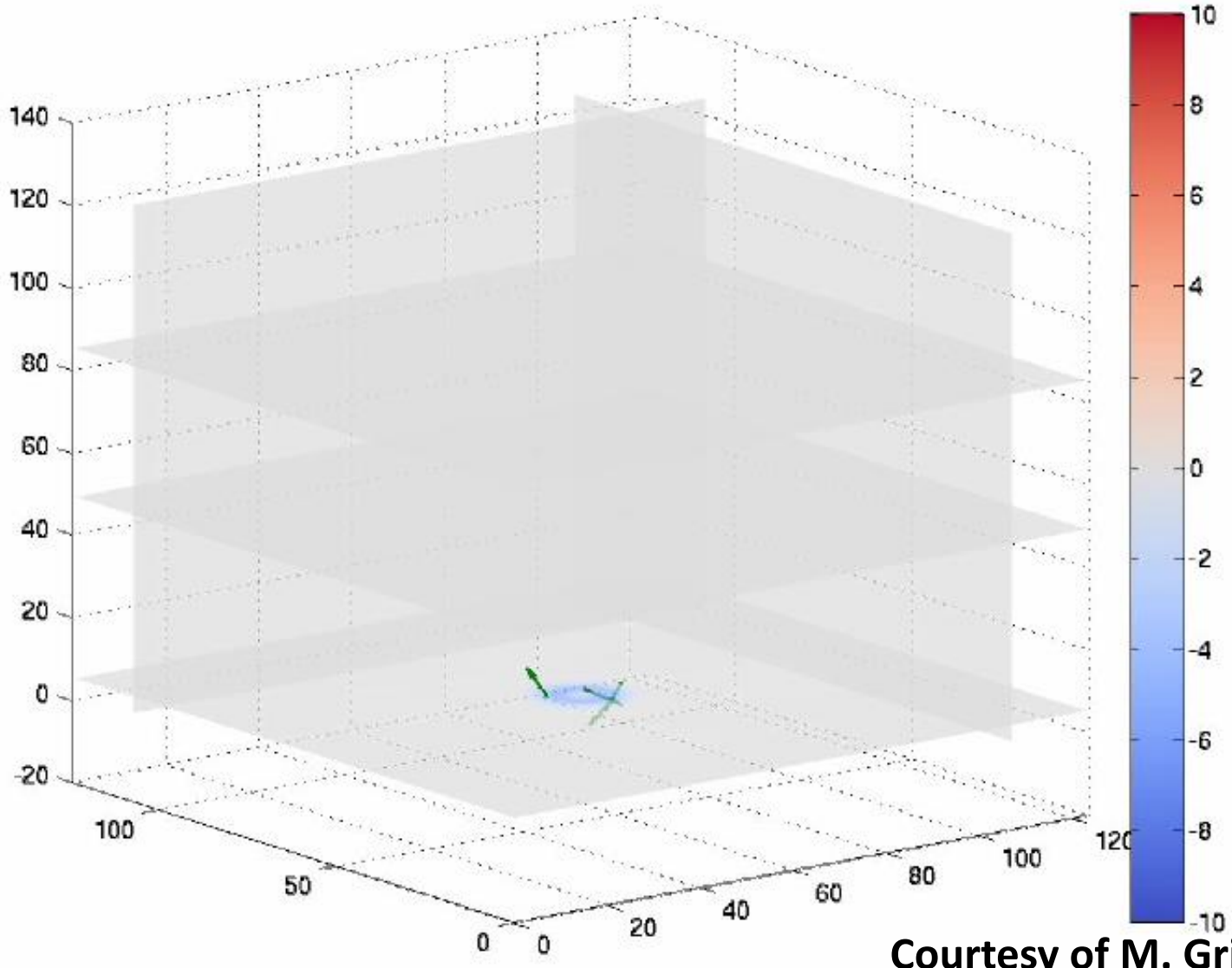


Density perturbation



Courtesy of I. Giagkiozis

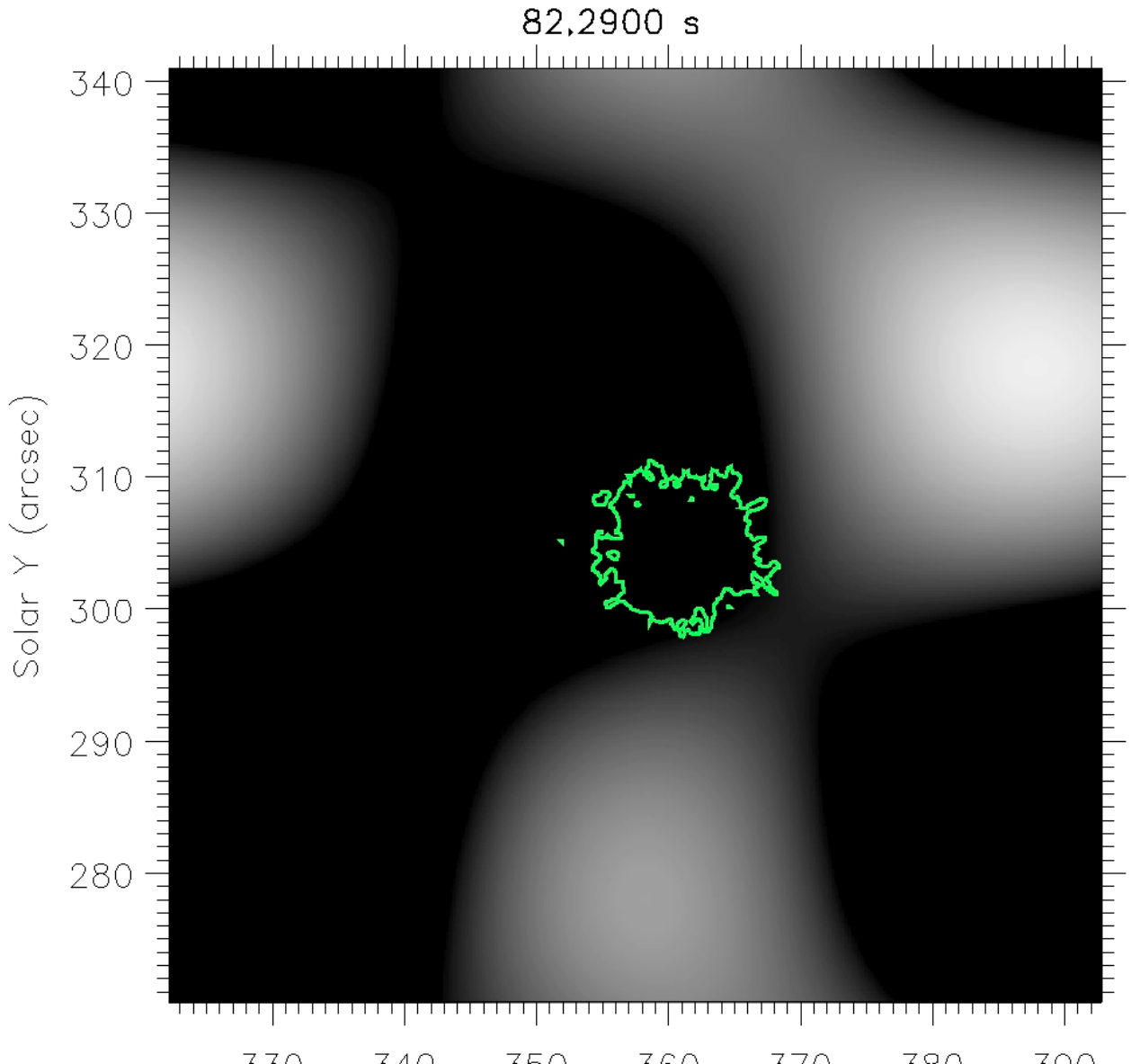
Expanding flux tube simulation with polarized *m*=1 slow kink driver



Courtesy of M. Griffiths

Photospheric driver?

Filtered photospheric blue continuum intensity



- **Filtered** in both **spatial** and **temporal domain**
- **Frequency filtered** at **2-4 minutes** with the Gaussian peaking at 3 minutes
- **Spatially filtered** between **10-15 “**
- **Disturbance** hits **sunspot** and appears to undergo both **refraction** and **reflection**

Courtesy of D. Jess

Recent chromospheric MHD wave mode review papers

Jess, D.B. et al. 2015, SSR, '*Multiwavelength Studies of MHD Waves in the Solar Chromosphere. An Overview of Recent Results*', **190**, 103

Verth, G. & Jess, D.B. 2016, AGU Monograph Series, '*MHD Wave Modes Resolved in Fine-Scale Chromospheric Magnetic Structures*', (Hoboken, NJ : Wiley & Sons Inc.), DOI: 10.1002/9781119055006.ch25