Wave Heating in the Solar Corona

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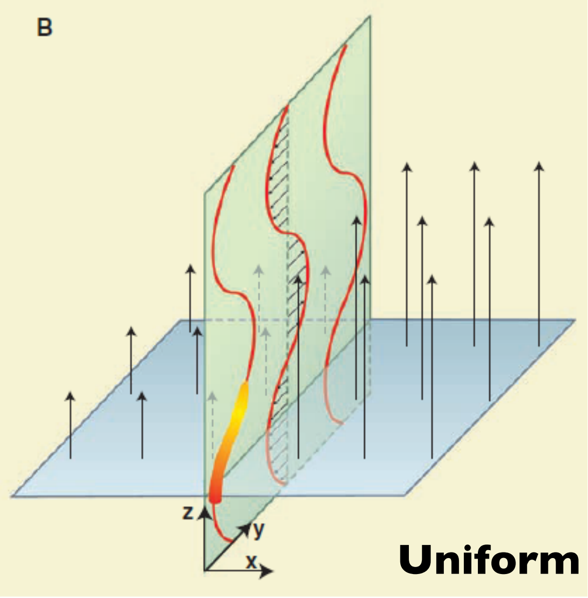
Overview

- **Some thoughts on the generation of [Alfvén(ic)] waves in the solar atmosphere**
- **Some recent observations of [Alfvén(ic)] waves in the chromosphere and corona**
- **Line-of-Sight effects (“Dark Energy”)**
- **Mode coupling to explain the observed damping of Doppler shift oscillations**
- **Observational signatures of wave heating**

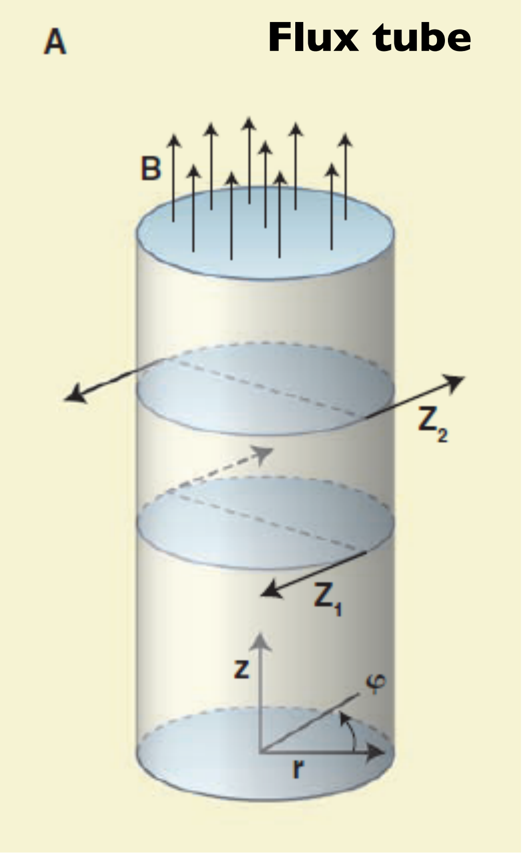
Generation of Alfvén(ic) Waves

- **'Wave' flux at top of convection zone ~ 10^7 erg cm^{-2} s^{-1}** *(Narain & Ulmschneider 1996)*
  - Reflection of Chromosphere and Transition Region
    - Only some fraction of energy will be transmitted into the corona
  - Mode coupling (β=1)
    - Probably not a straightforward or one-to-one correspondence between footpoint/surface motions and observed coronal 'motions' (waves).



- **How do these Alfvén(ic)/kink waves get there?**
  - Flares, reconnection events and other disturbances can generate Alfvén waves.
  - With almost any kind of footpoint motion you will generate Alfvén waves.

- Uniform: transverse motion → Shear Alfvén waves
- Non-uniform: transverse motion → kink wave → mode coupling → (azimuthal) Alfvén wave
- Non-uniform: vortex motion →Torsional Alfvén wave

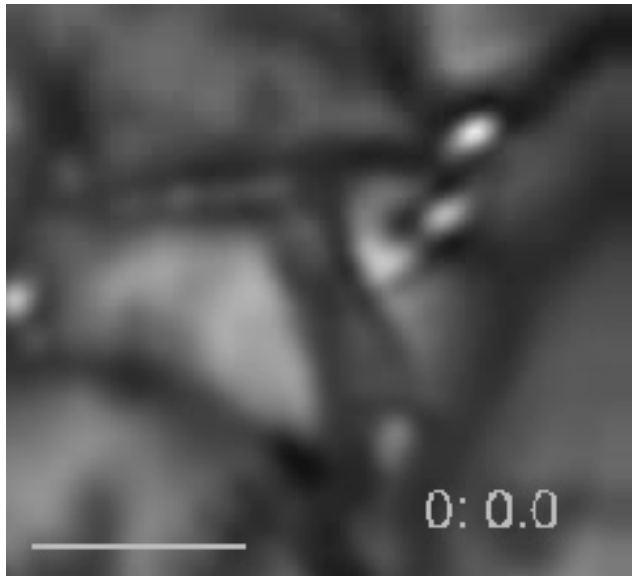


- **All of the above apply largely to plane-parallel and static atmosphere.**
  - Is there such a thing as a 'stable' wave guide?
  - What happens if the 'flux tubes' are continuously evolving?

Erdelyi & Fedun 2007

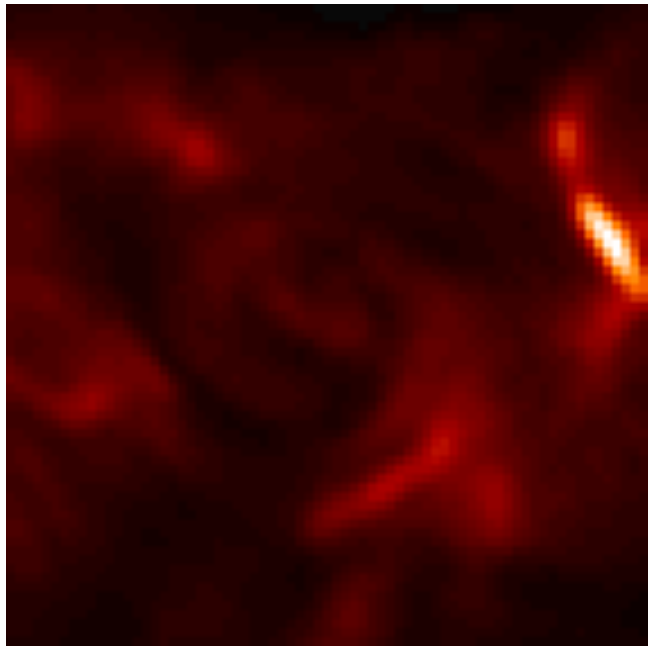
Vortex Driving Motions

Photospheric G-band movie



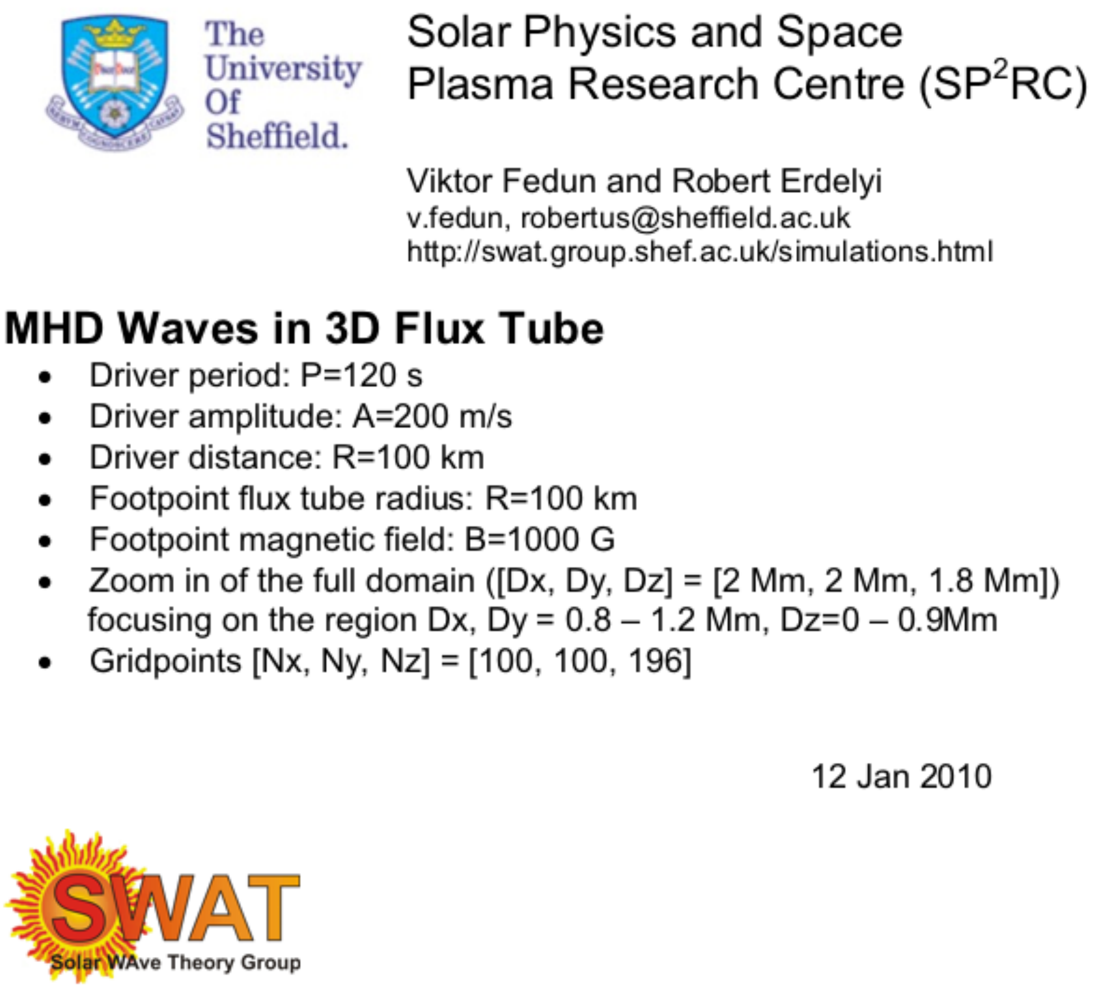
Bonet et al 2008

Chromospheric Ca II movie



Wedemeyer-Bhöm & Rouppe van der Voort (2009)

- Simulations show that convection naturally leads to vortex motions of magnetic flux elements *(Vogler et al. 2005; Carlsson et al. 2010; Shelyag et al. 2010)*
- *Bonet et al (2008):* SST observations of magnetic bright points show vortex motions (lifetimes ~ 5 mins)
    - ➢ **Torsional Alfvén waves generated all over photosphere?**



The University Of Sheffield.

Solar Physics and Space
Plasma Research Centre (SP^{2}RC)

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http://swat.group.shef.ac.uk/simulations.html

MHD Waves in 3D Flux Tube

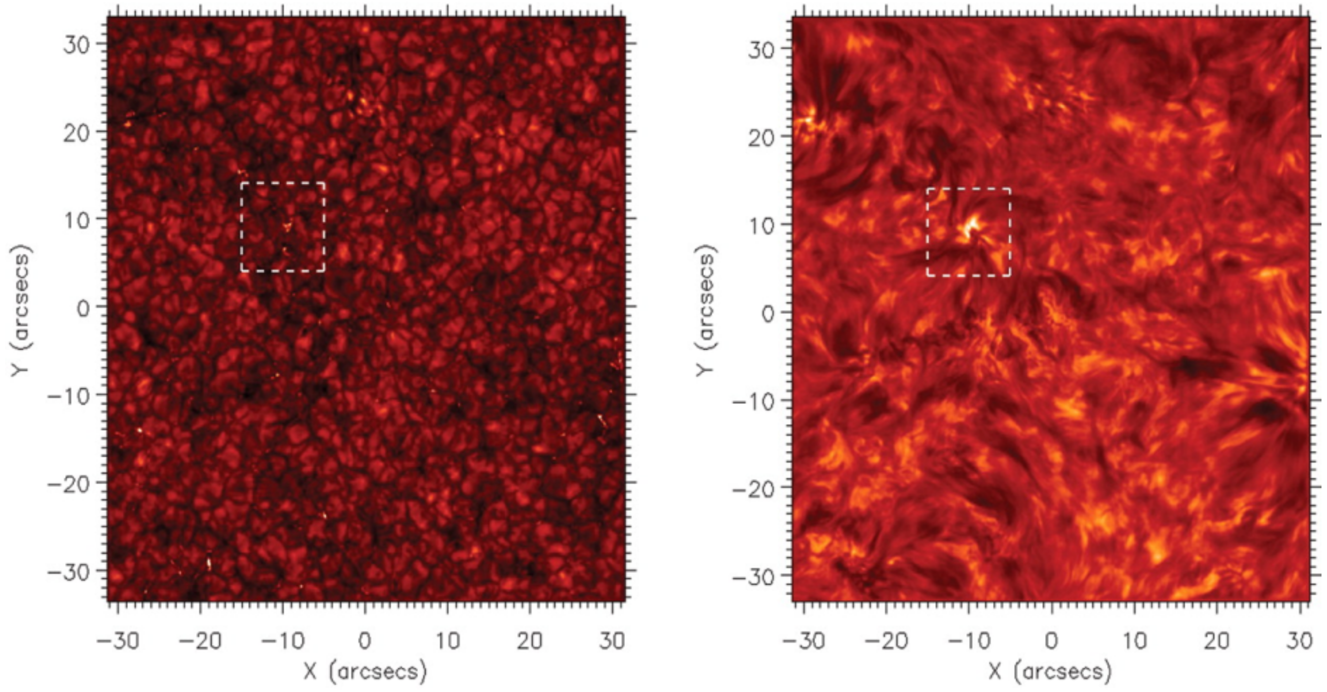
- Driver period: P=120 s
- Driver amplitude: A=200 m/s
- Driver distance: R=100 km
- Footpoint flux tube radius: R=100 km
- Footpoint magnetic field: B=1000 G
- Zoom in of the full domain ([Dx, Dy, Dz] = [2 Mm, 2 Mm, 1.8 Mm]) focusing on the region Dx, Dy = 0.8 – 1.2 Mm, Dz=0 – 0.9Mm
- Gridpoints [Nx, Ny, Nz] = [100, 100, 196]

12 Jan 2010

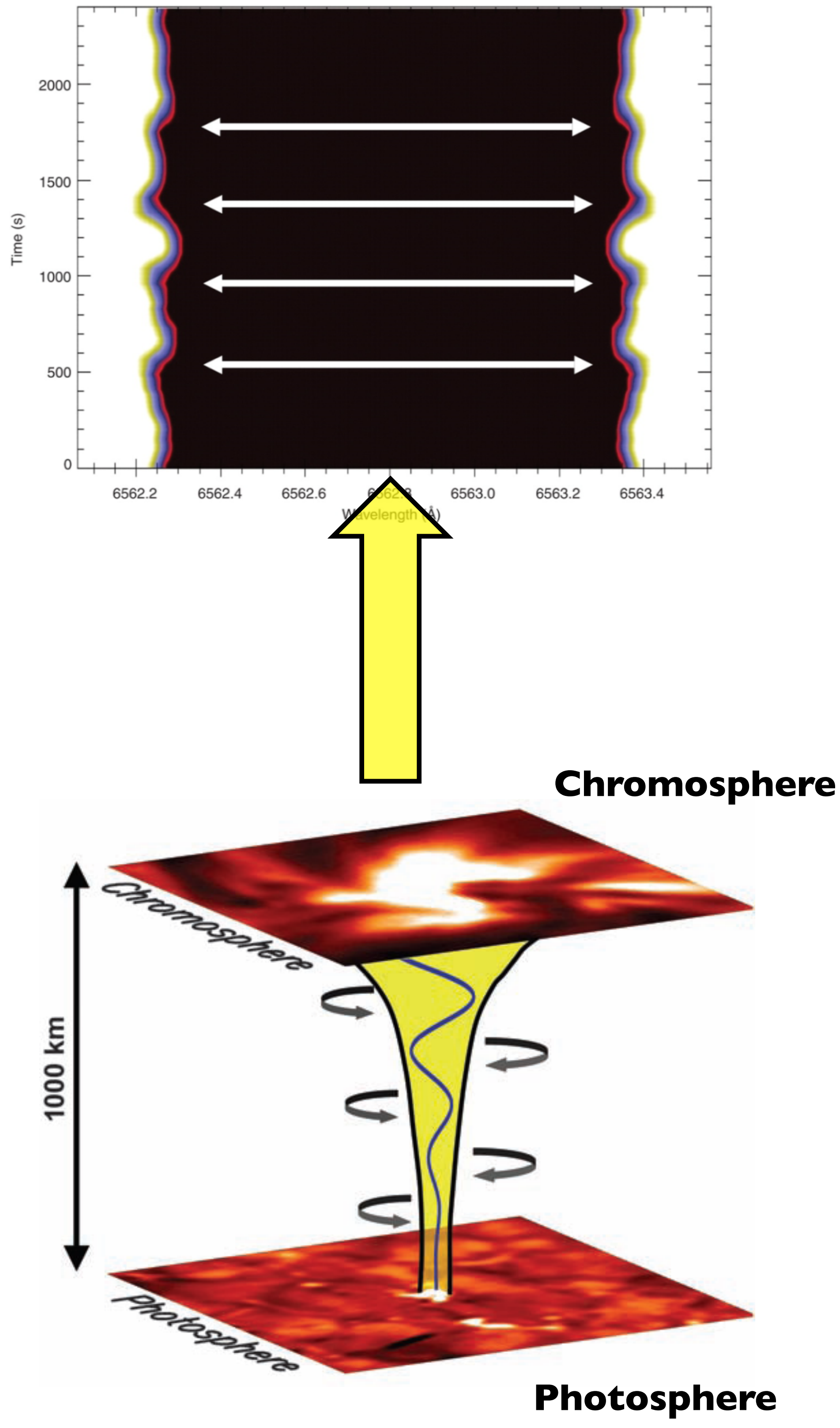
SWAT
Solar WAve Theory Group

Fedun & Erdélyi 2011; Erdélyi et al 2011

Alfvén(ic) Waves in the Chromosphere



Jess et al (2009)

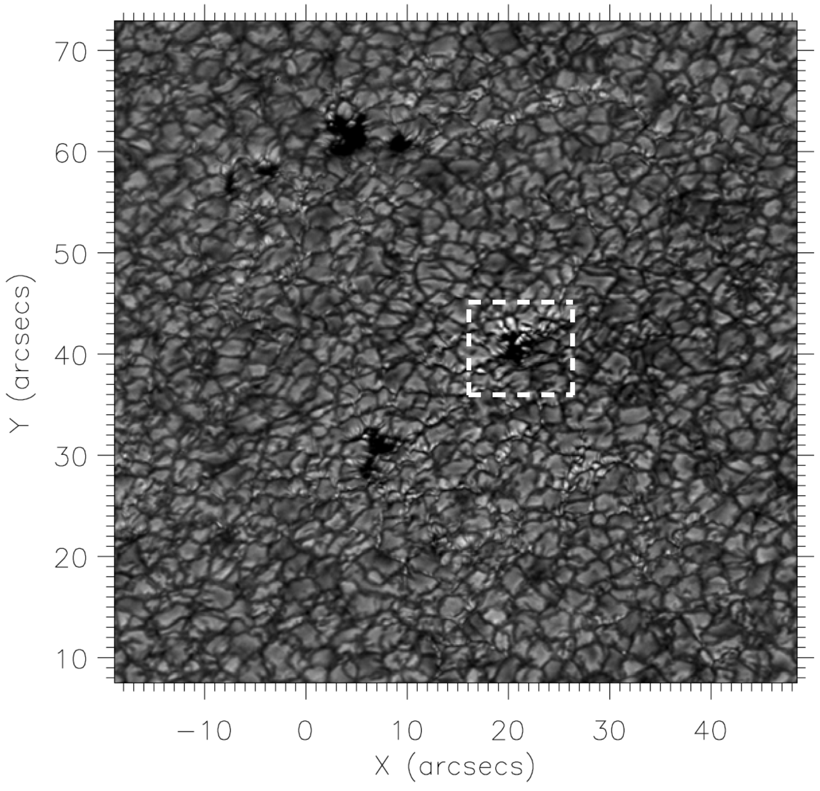


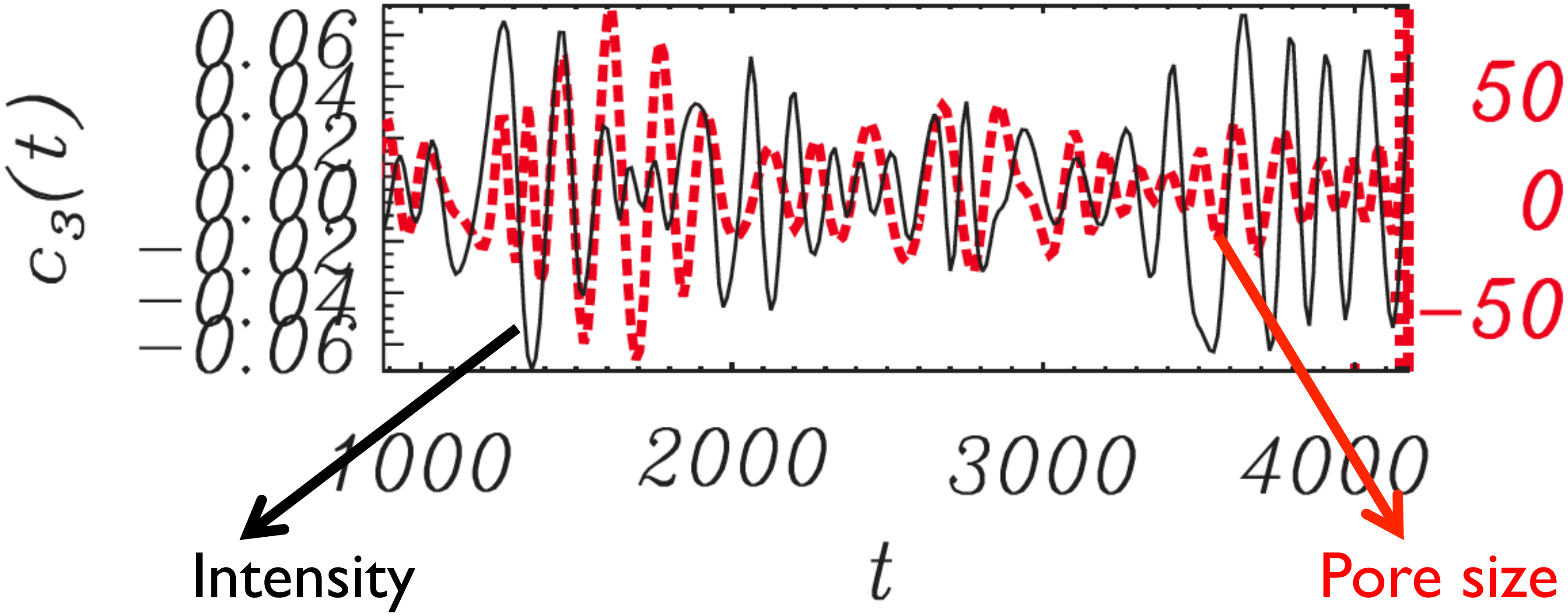
- ➢ Chromospheric bright point oscillations (SST)
- Periodic spectral line broadening; no intensity oscillations
    - Interpreted as torsional Alfvén waves

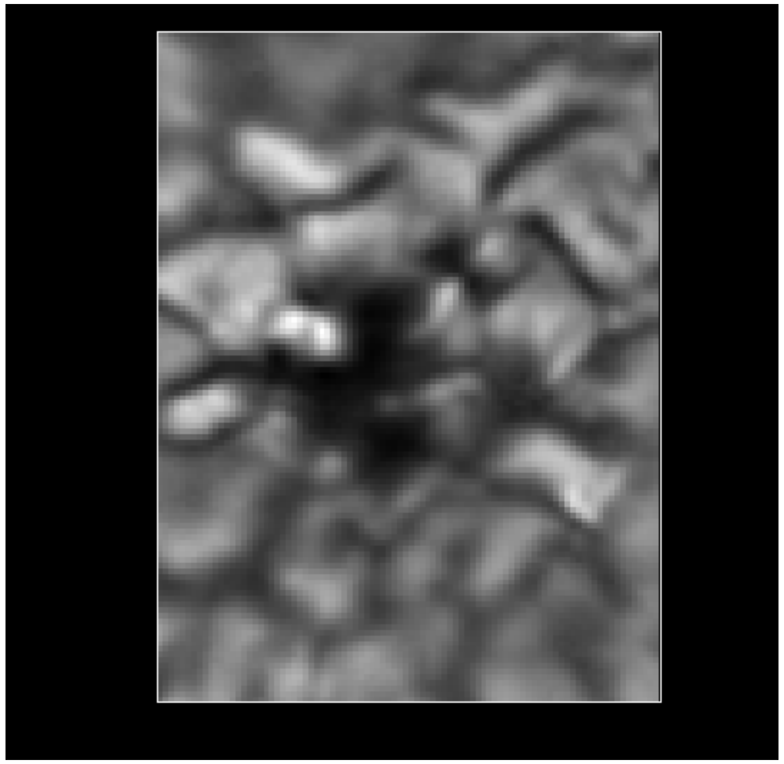
- Chromospheric energy flux ~ 15,000 W m^{-2}
  - 1.6% of surface covered in Bright Points
    - Global average ~ 240 W m^{-2}
  - Transmission coefficient ~ 42%
    - Coronal energy flux ~ 100 W m^{-2}

Sausage Oscillations in Photospheric Pores

Morton et al (2011)

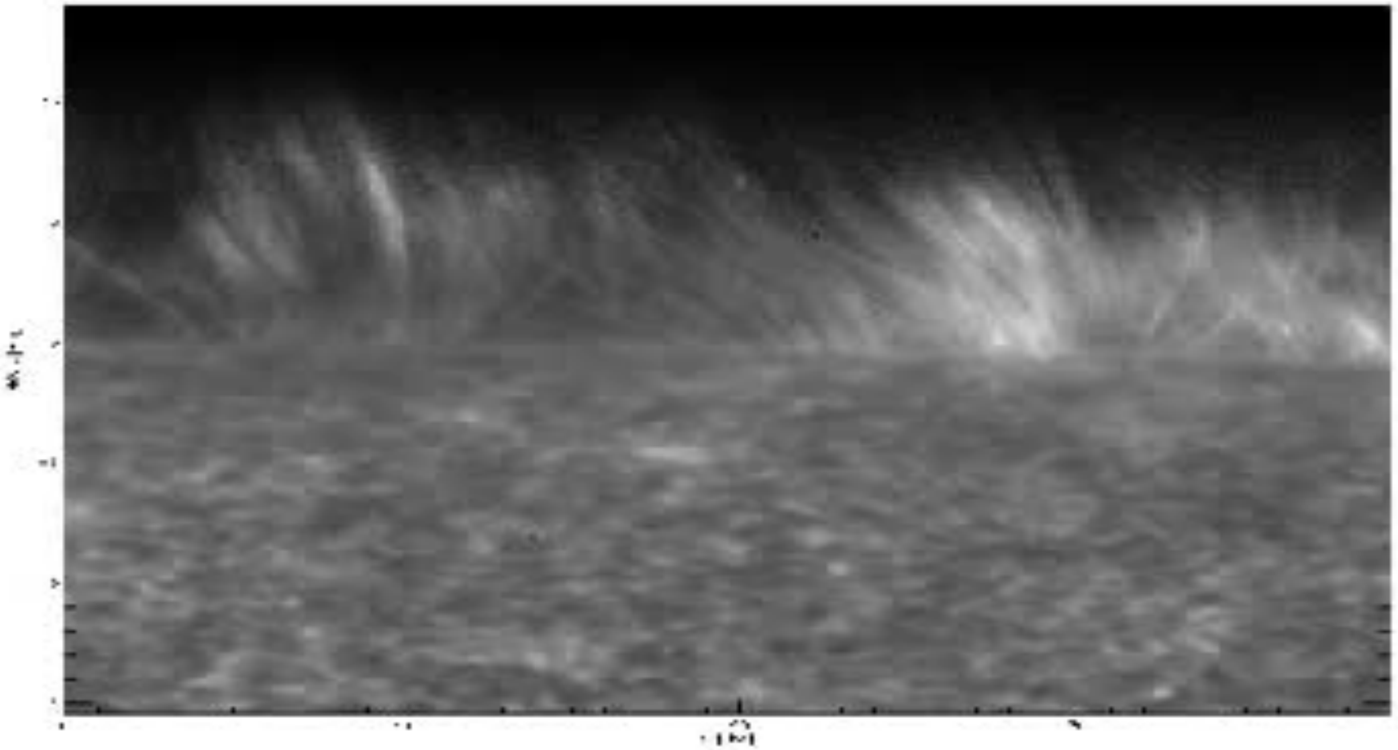




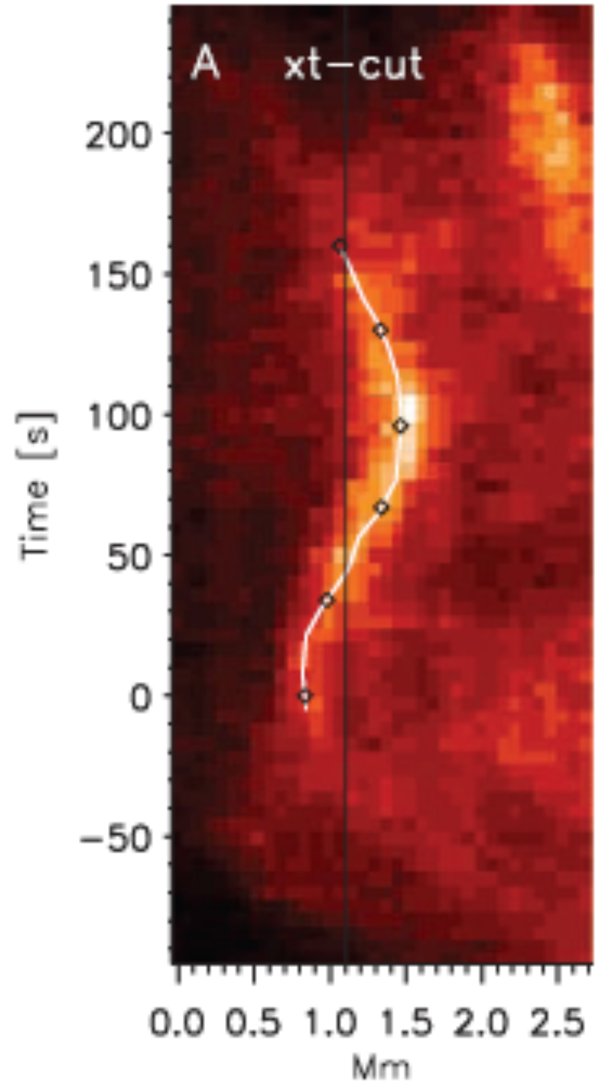


- ➢ Oscillations in Photospheric Magnetic Pores (ROSA 4170A line)
- Use Empirical Mode Decomposition to separate out timescales.
- Periods: 30 – 450 seconds
- Sausage modes: oscillations in pore size and intensity are 180 degrees out of phase.
- Wave energy: E = 10^{8} ergs cm^{-2} s^{-1} → ~10% transmission coeff needed?

Alfvén(ic) Waves in the Chromosphere



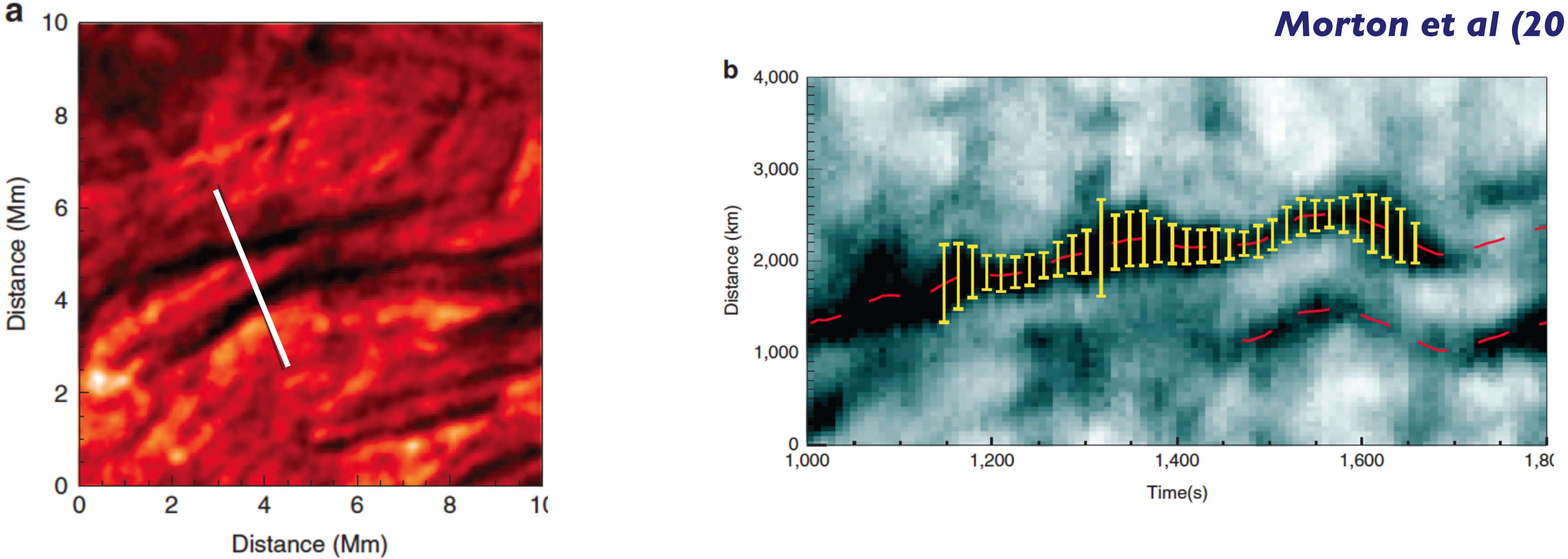
De Pontieu et al (2007, 2012)



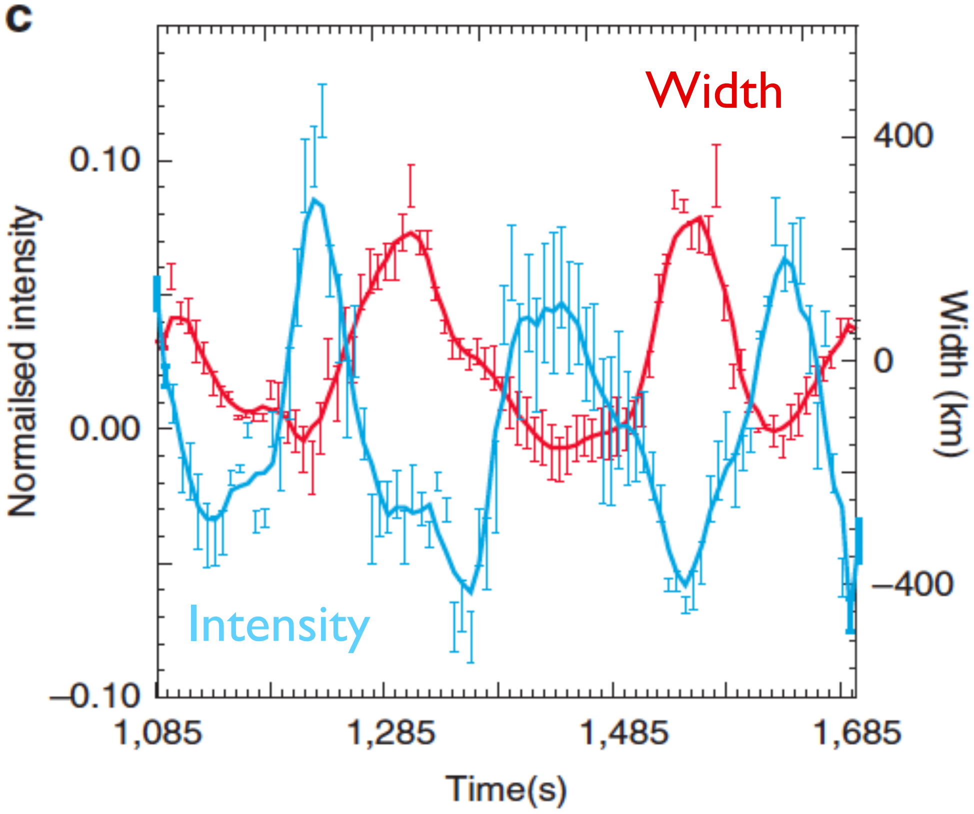
- “Swaying” spicules everywhere (Hinode/SOT)
  - Transverse motions ~ 500-1000km
  - Periods ~ few minutes
  - Chromospheric energy flux ~ 4-7 kW m^{-2}
  - Coronal energy flux ~ 120 W m^{-2} (transmission coefficient ~ 3%)
  - Sufficient to heat the Quiet Sun corona and/or drive the solar wind (~100 W m^{-2})
  - Additional torsional motions reported by De Pontieu et al (2012) → double energy budget?

Compressive Waves in the Chromosphere

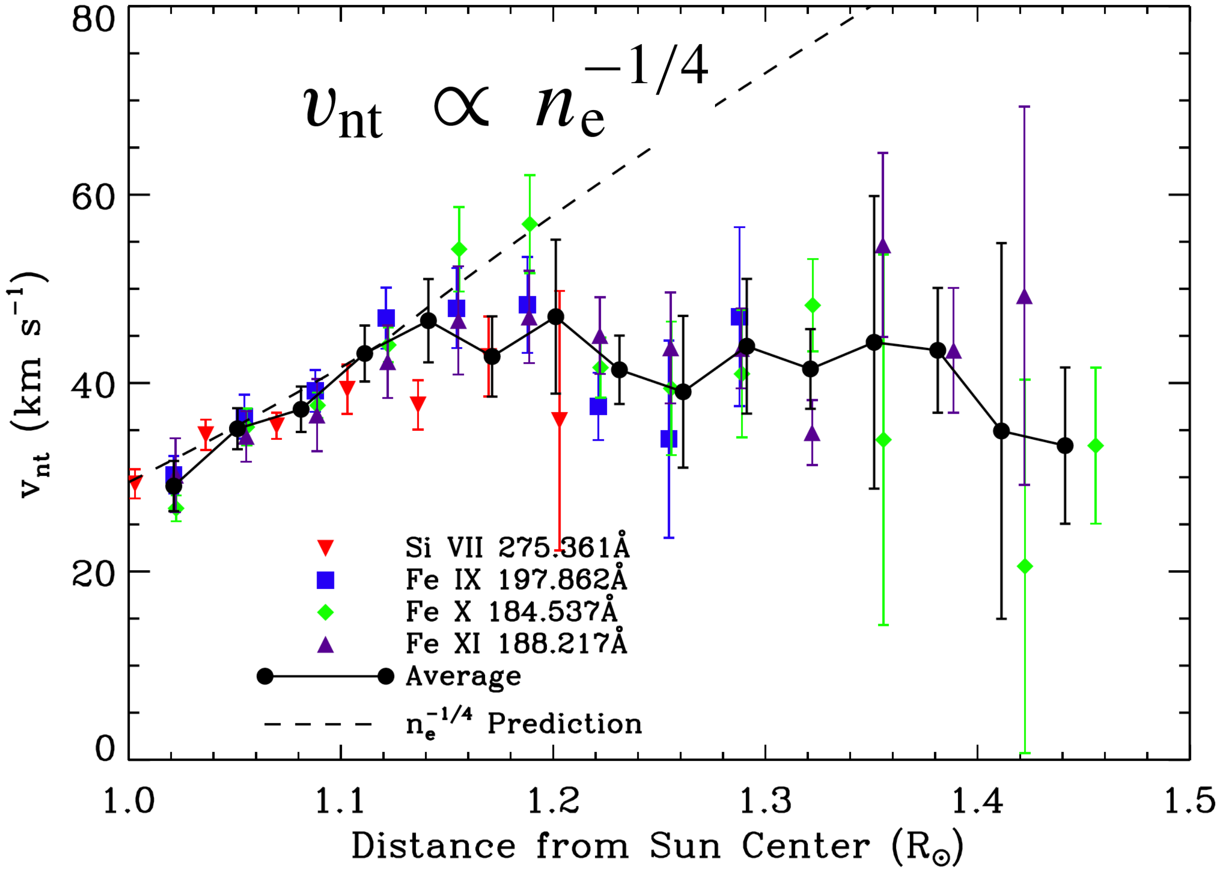
Morton et al (2012)

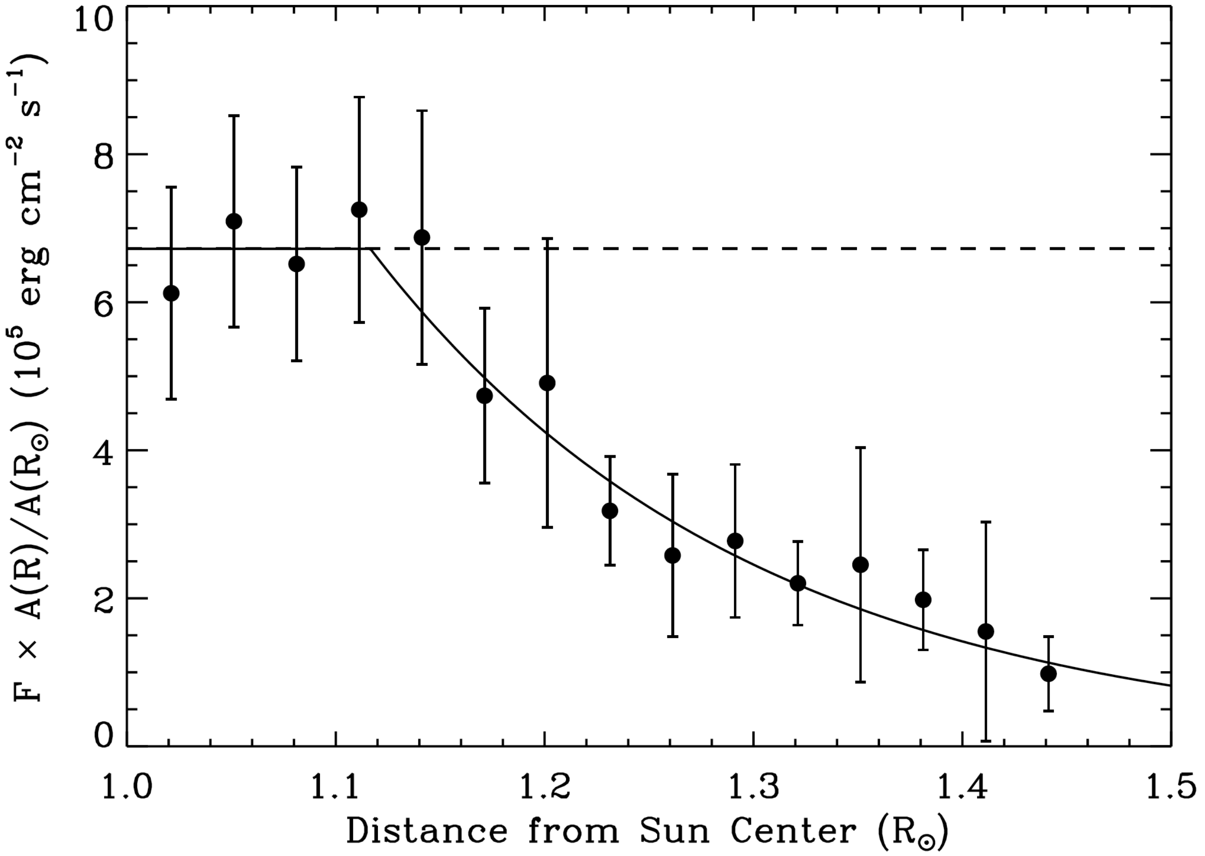


- Concurrent observations of (on disk) compressible and incompressible wave modes (ROSA).
  - Transverse motions – fast kink wave
  - Periodic changes in intensity & cross section – fast MHD sausage mode
    - Incompressible energy ~ 4300 ± 2700 W m^{-2}
    - Compressible energy ~ 11700 ± 3800 W m^{-2}
  - Assume 4-5% connected to corona
    - Incompressible energy ~ 170 ± 110 W m^{-2}
    - Compressible energy ~ 460 ± 150 W m^{-2}



Alfvén Waves in the Coronal Holes

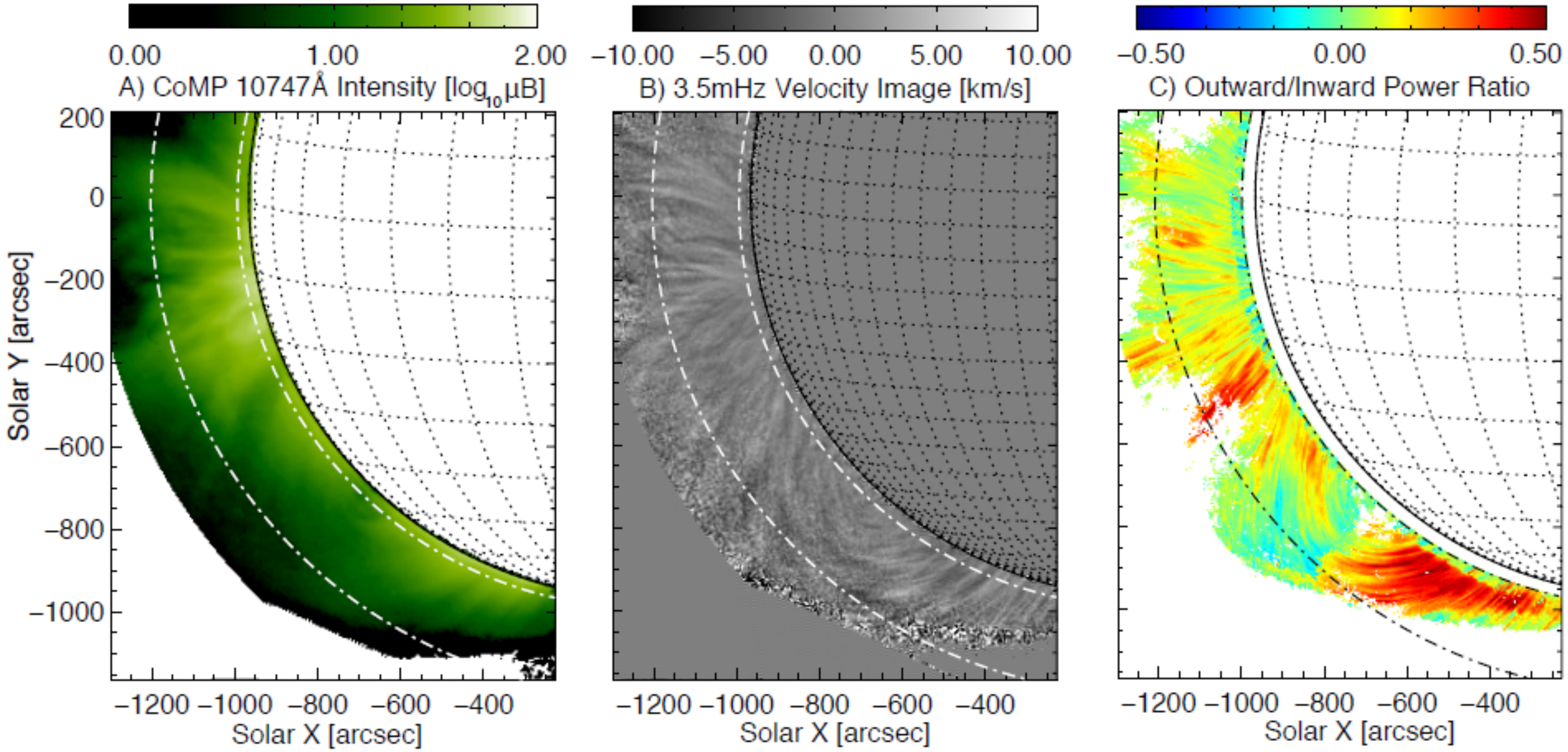




- Alfven waves in coronal holes (Hinode/EIS)
  - Line widths from (double) Gaussian fits to EIS lines
  - At larger heights, v_{nt} < undamped waves → wave damping
  - Wave energy at base of coronal hole: E = 6.7 ± 0.7 x10^5 ergs cm^{-2} s^{-1}
  - Waves lose ~85% of energy by 1.44 R_o
  - Damping length L_D=0.18 ± 0,04 R_o and damping time = 68 ± 15 seconds

Hahn & Savin 2013

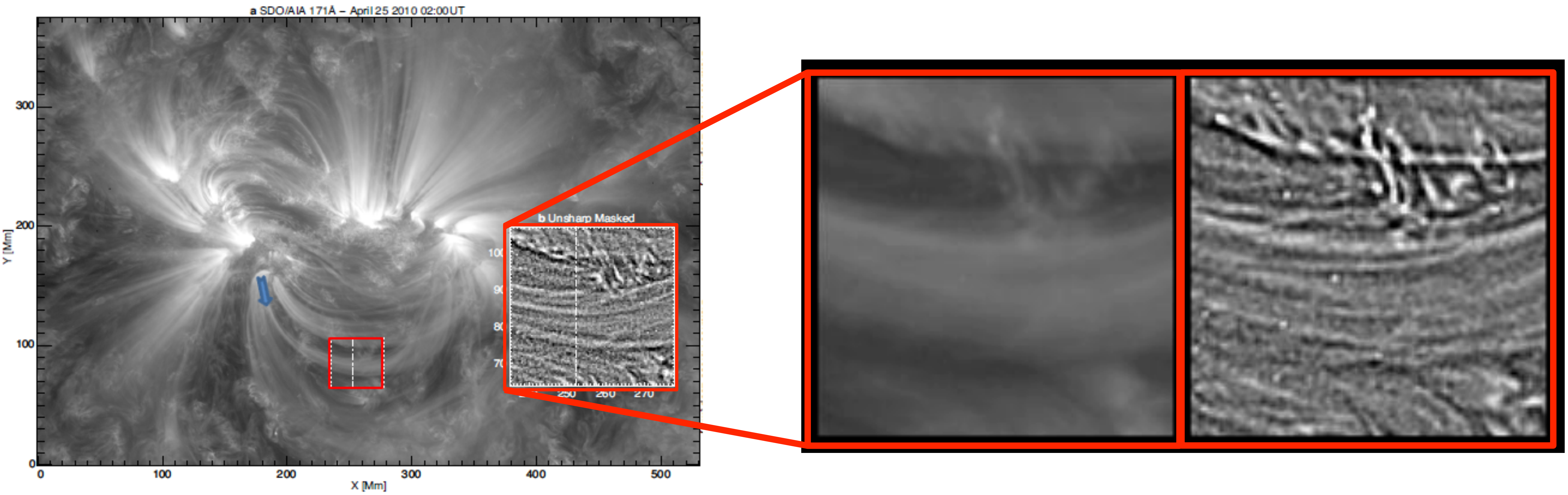
Alfvén(ic) Waves in the Corona



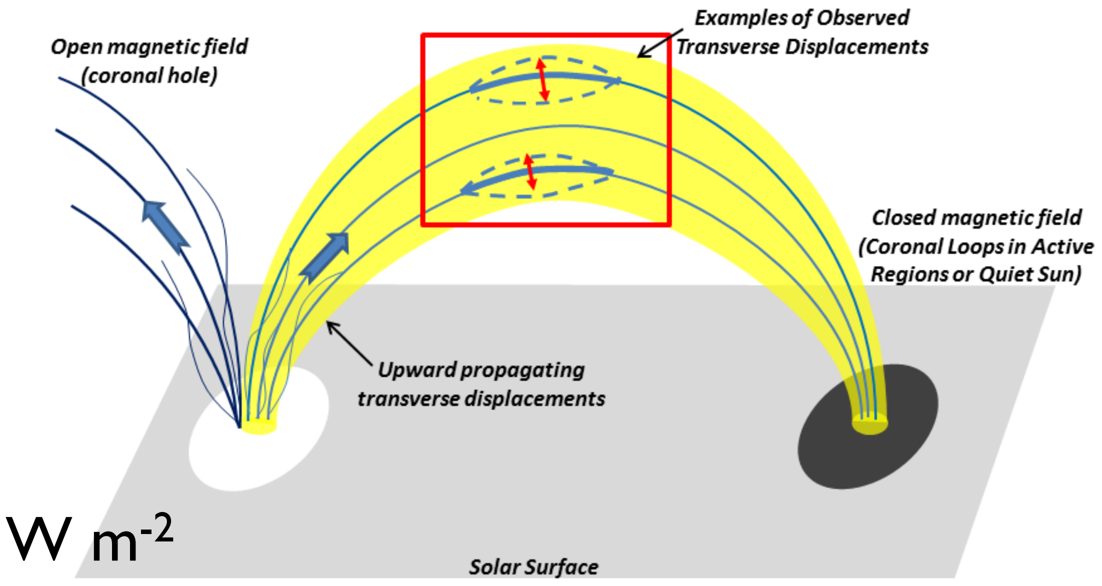
- ➢ Ubiquitous quasi-periodic fluctuations in velocity but no fluctuations in intensity
- Interpretation as propagating Alfvén waves based on high phase speeds (~ 1 Mm/s), field-aligned, and very small intensity fluctuations (incompressible)
- Disparity between outward and inward wave power (even along closed loops) suggests significant amplitude decay *in situ*
- Energy insufficient to account for heating?
    - F_W = 10–100 erg $cm^{-2}s^{-1}$ vs 3×10^5 erg $cm^{-2}s^{-1}$ needed for Quiet Sun

Tomczyk et al 2007; Tomczyk & McIntosh 2009

Alfvén(ic) Waves in the Corona

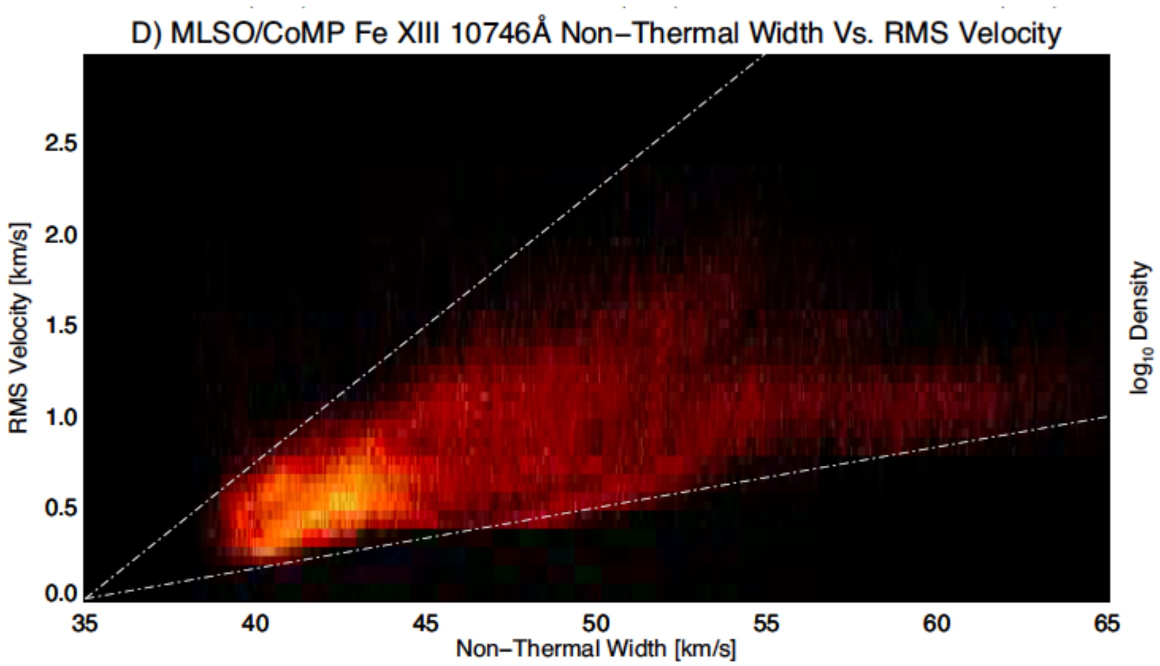


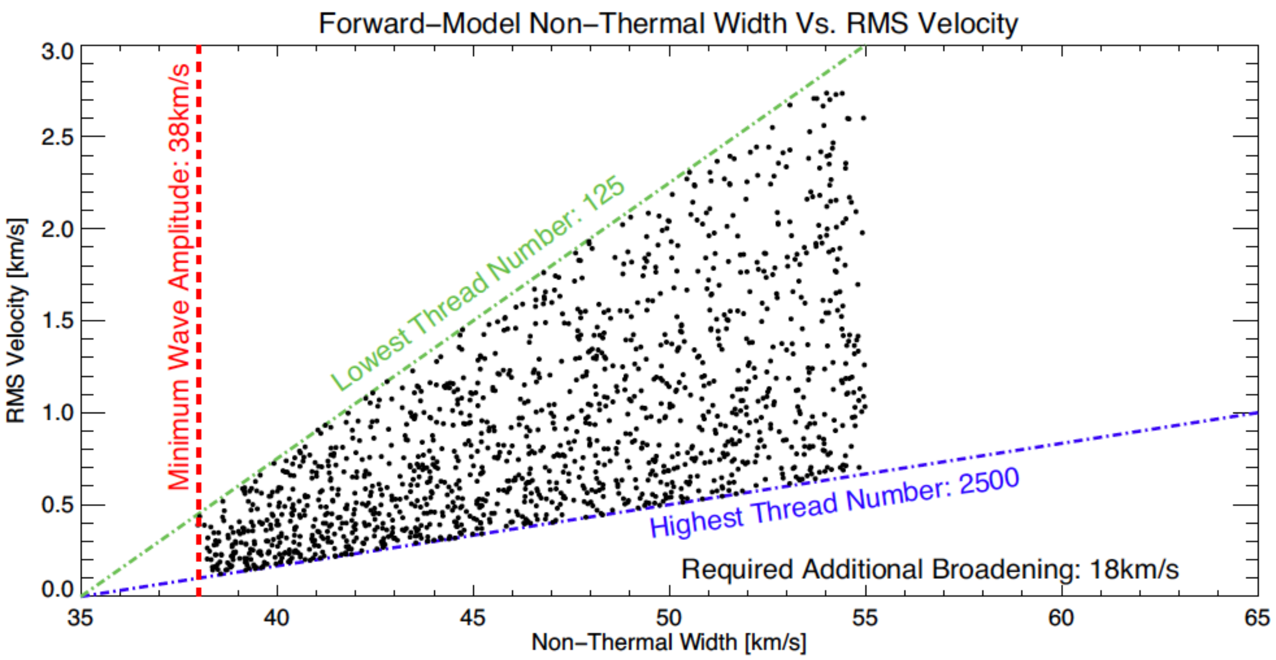
- Alfvénic motions everywhere (SDO/AIA)
  - Amplitudes ~ 5-20 km/s
  - Periods ~ 100 – 500 sec (lifetimes ~ 50-500 sec)
  - Energy flux Quiet Sun & Coronal Holes ~ 100 – 200 W m^{-2}
  - Active Region Loops ~ 100 W m^{-2} (2000 W m^{-2} needed)



McIntosh et al 2011

Observing “Dark” Energy

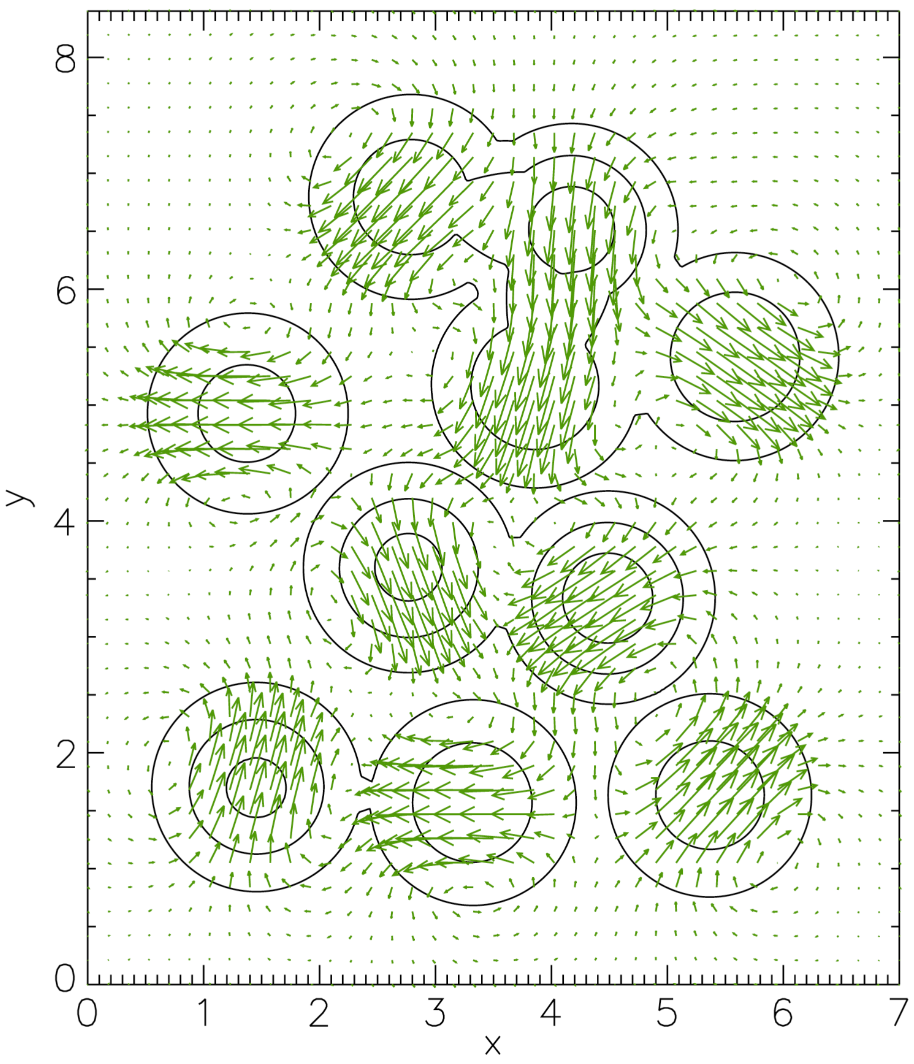

D) MLSO/CoMP Fe XIII 10746Å Non–Thermal Width Vs. RMS Velocity

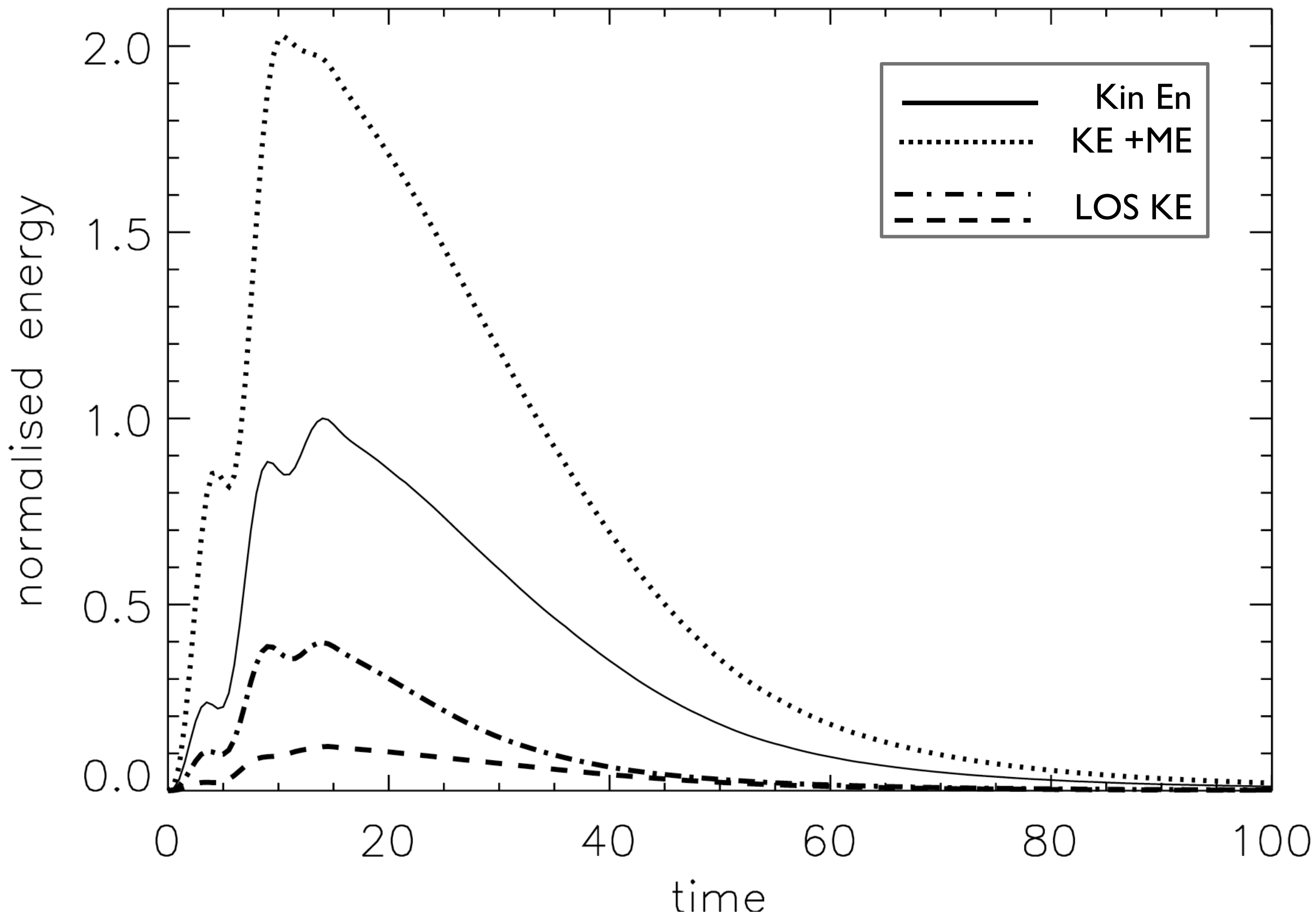

Forward–Model Non–Thermal Width Vs. RMS Velocity

- ➢ Apparent discrepancy between CoMP velocities (~0.5 km/s) and Hinode & SDO (~20 km/s)
- Monte Carlo model of Alfvenic waves based on threads (“*elementary oscillating structures*”)
- Vary number of threads and input wave amplitude – determine v_{RMS} and line broadening
- “Real” CoMP wave amplitudes estimated as 40-60 km/s
- Most of the CoMP non-thermal line broadening < LOS superposition of low frequency waves

McIntosh & De Pontieu 2012

Modelling “Dark” Energy


Lower boundary of 3D box

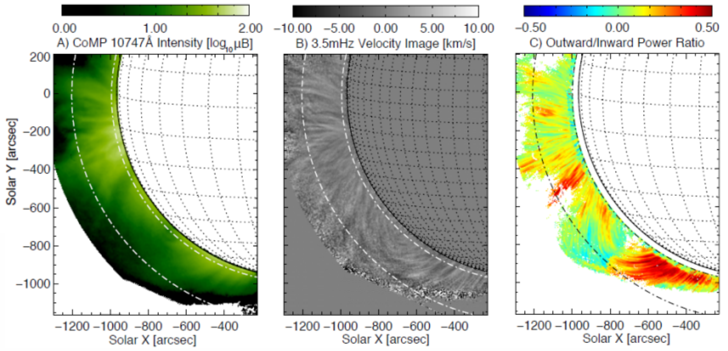


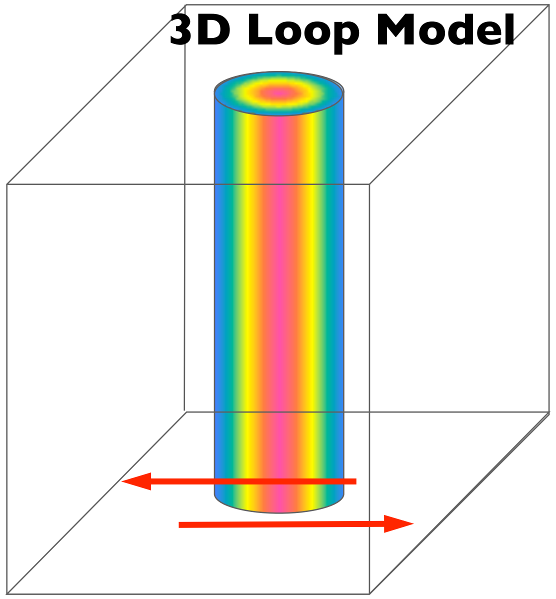
- Randomly directed driver at bottom boundary; loops have different densities and driver periods.
- LOS Integrated Doppler velocities much smaller than actual perturbations in domain
- Compare 3D kinetic energy with kinetic energy derived from LOS velocities
- Observed LOS (Doppler) energy only 3 – 10% of total energy in 3D domain (kinetic + magnetic)

De Moortel & Pascoe 2012

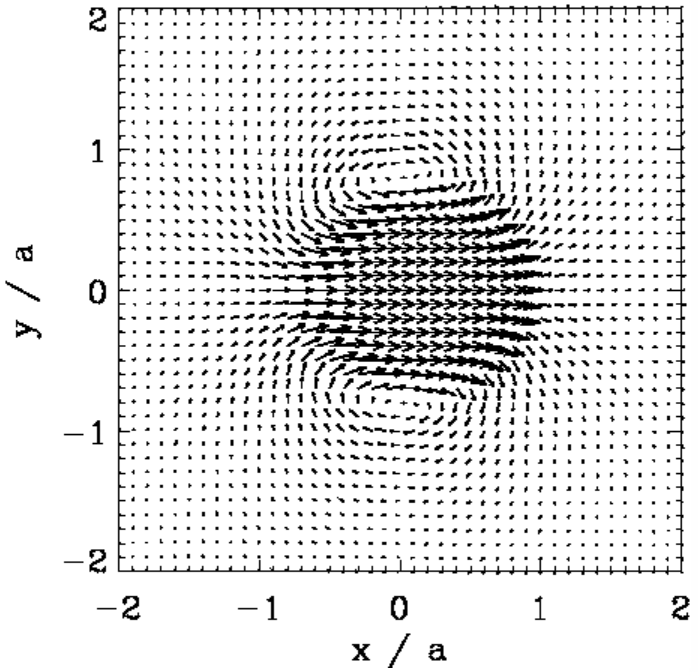
Mode Coupling

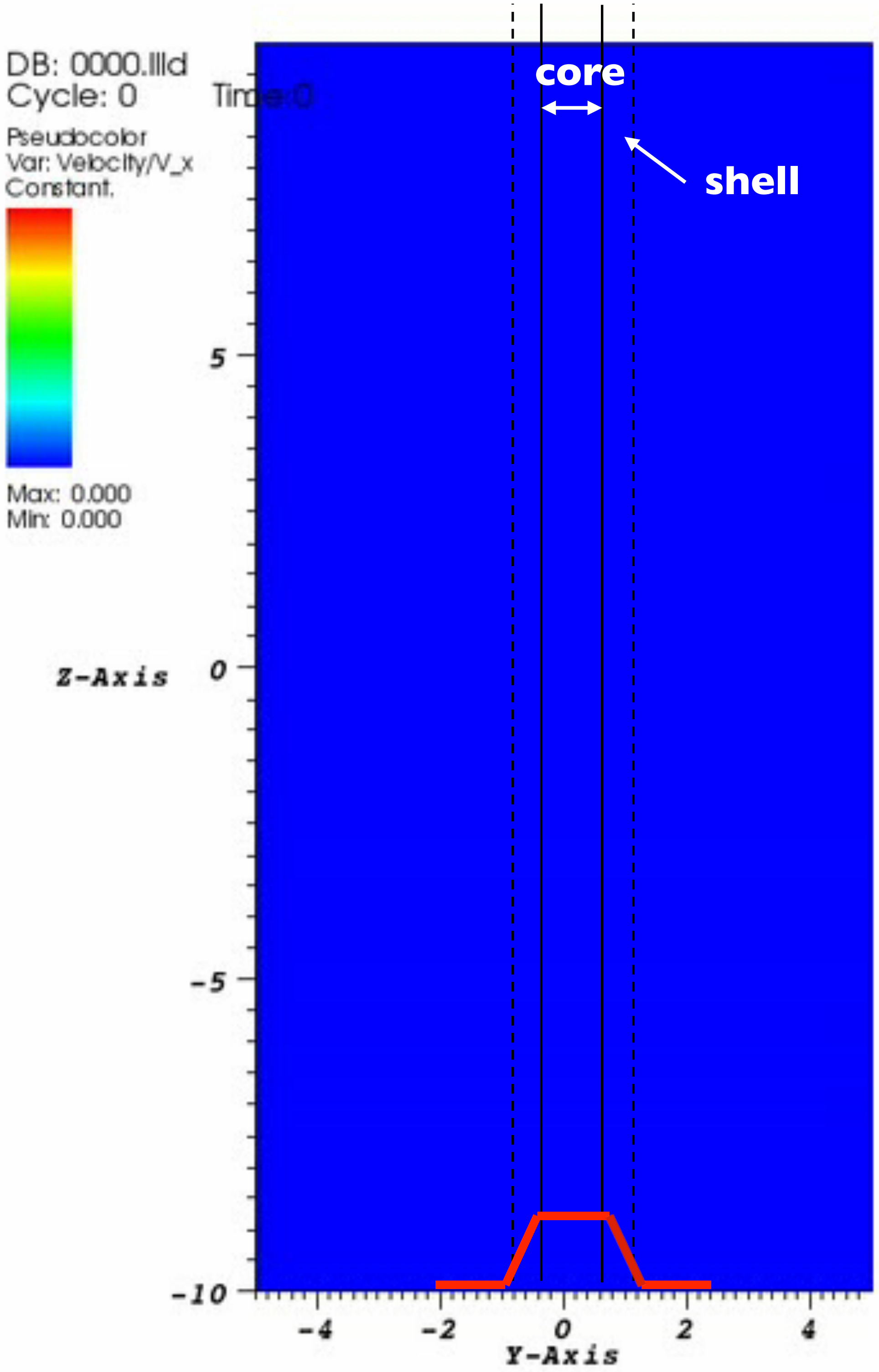
Pascoe et al 2010





<u>Driver</u>: models buffeting by solar surface motions





Kink mode propagating along coronal loop

↓

Mode conversion to Alfvén wave

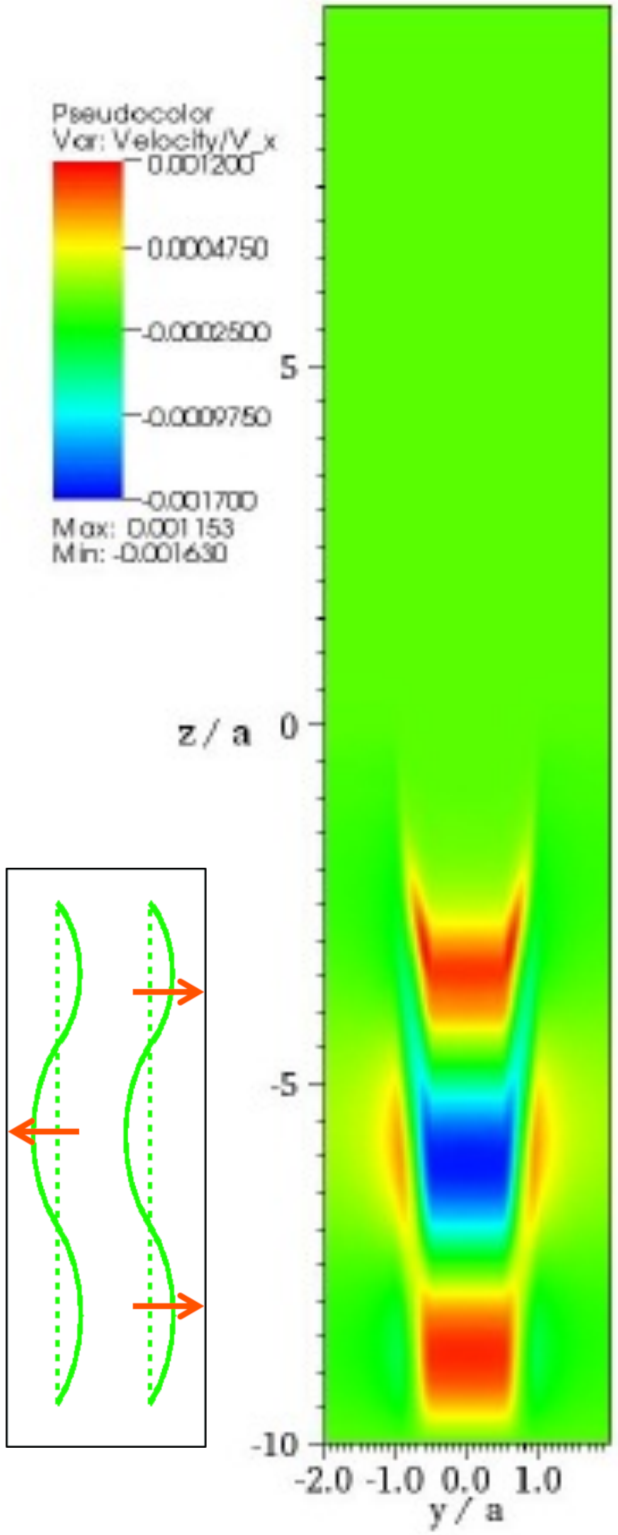
↓

Damping of original kink mode

user: dpascoe
Wed Dec 3 23:25:29 2008

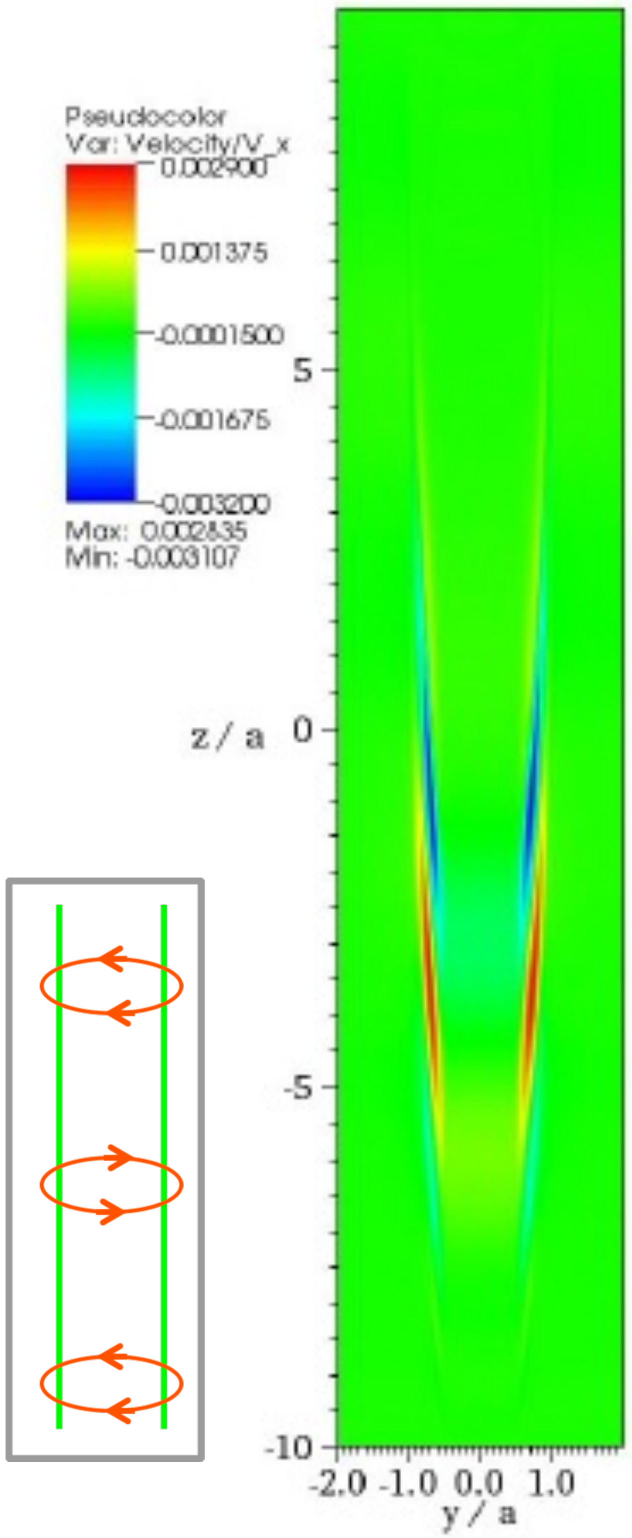
Coupled (*Alfvénic*) Mode

Kink

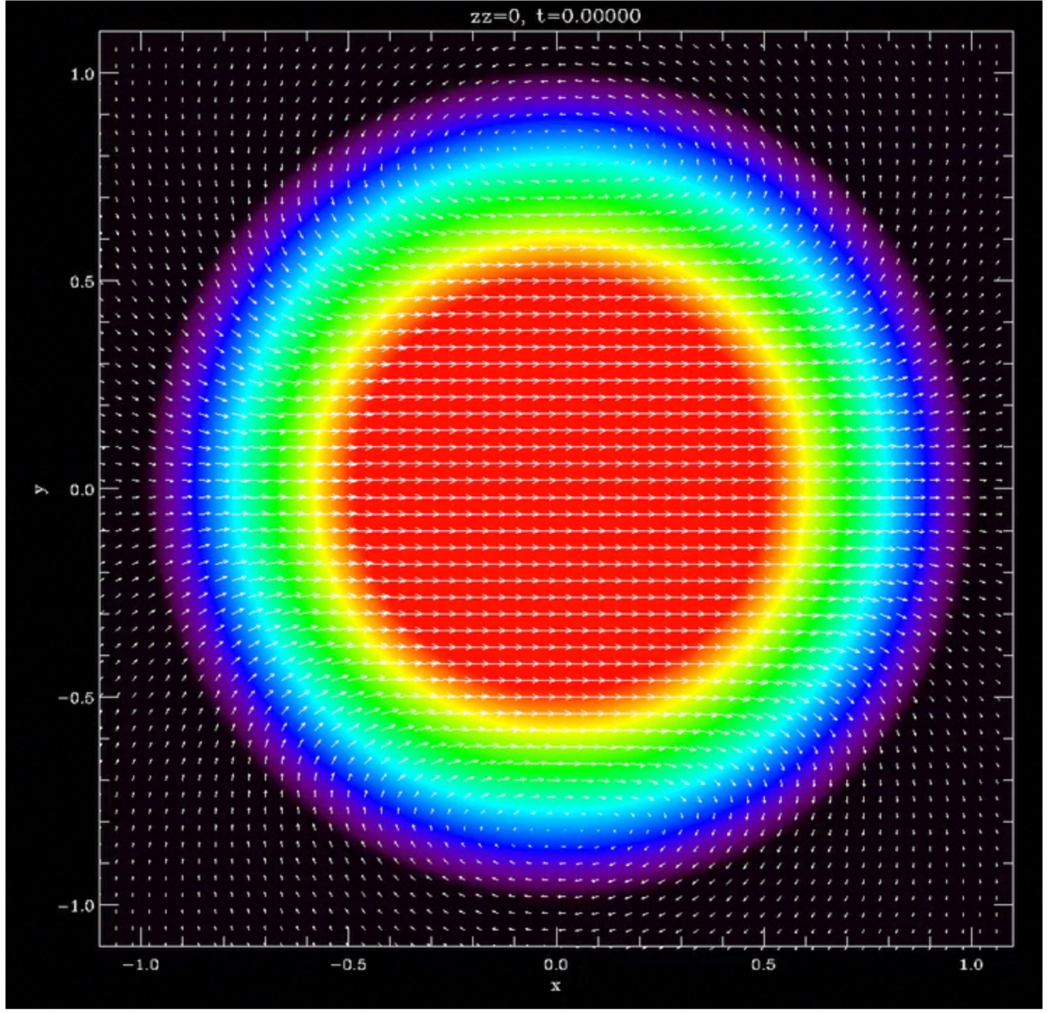


$t = P_0$

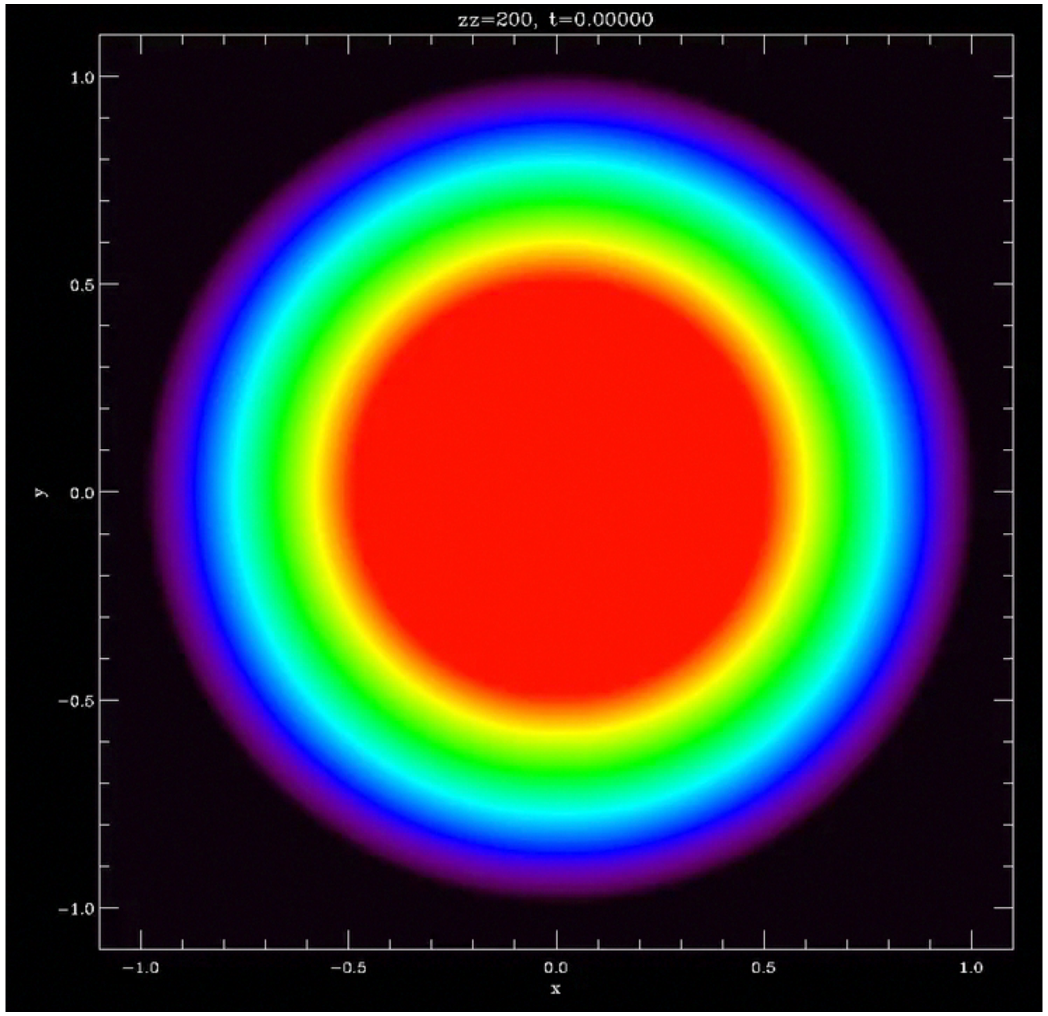
Alfvén (m=1)



$t = 5P_0$

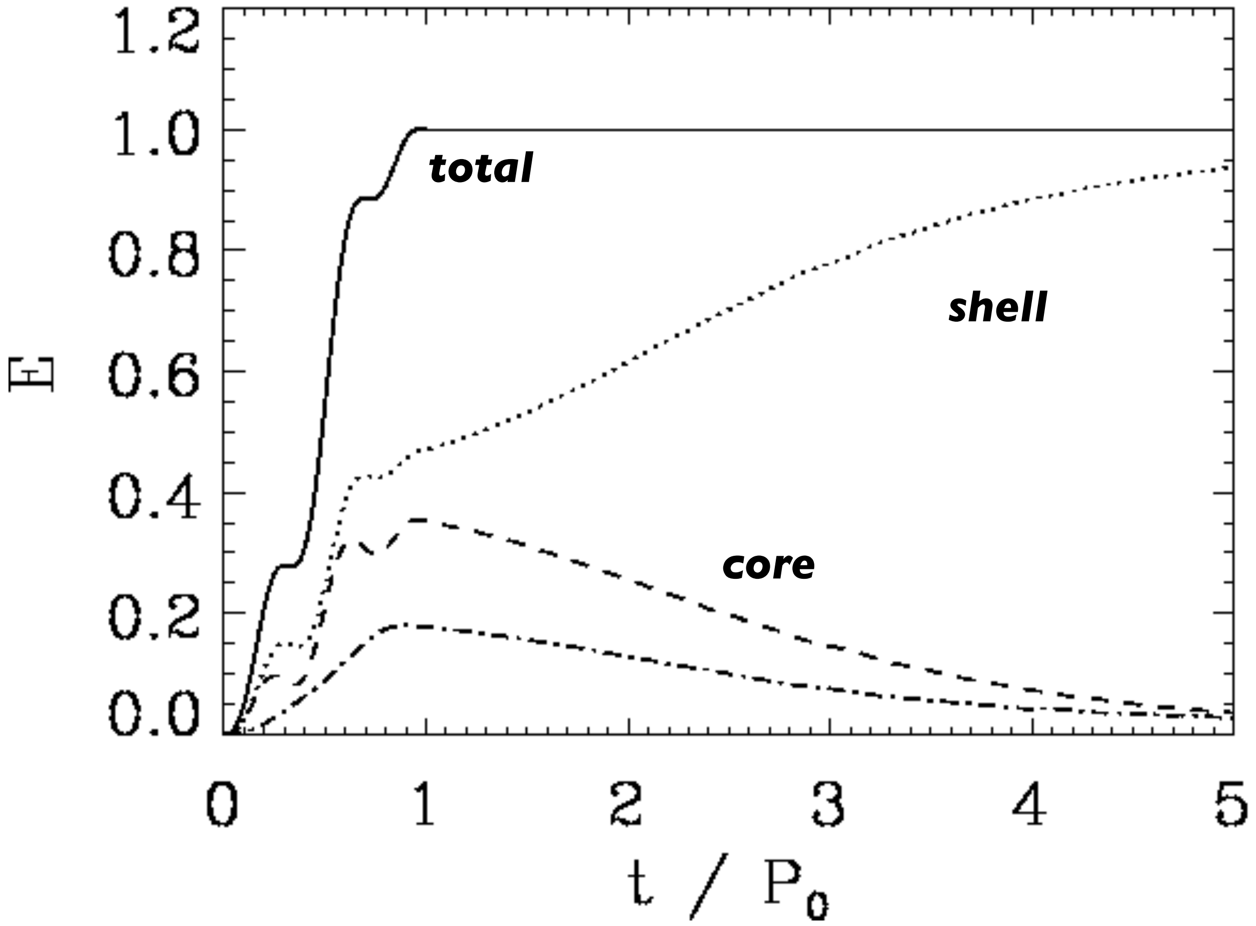


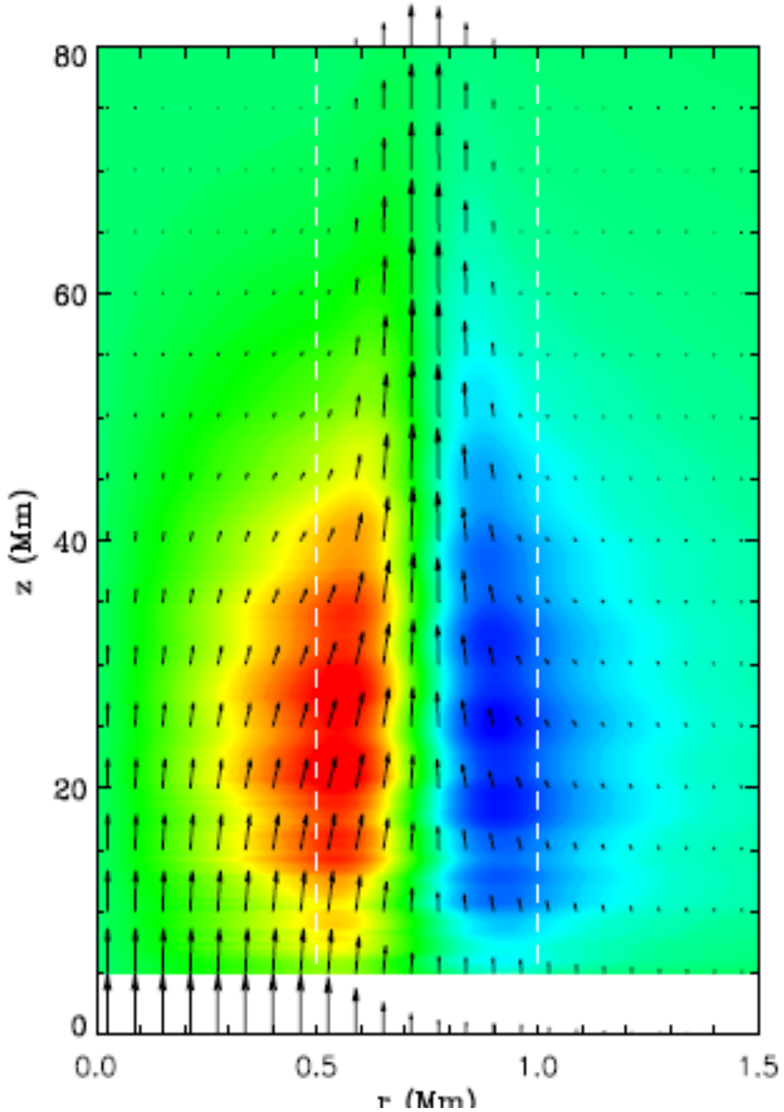
Z=0

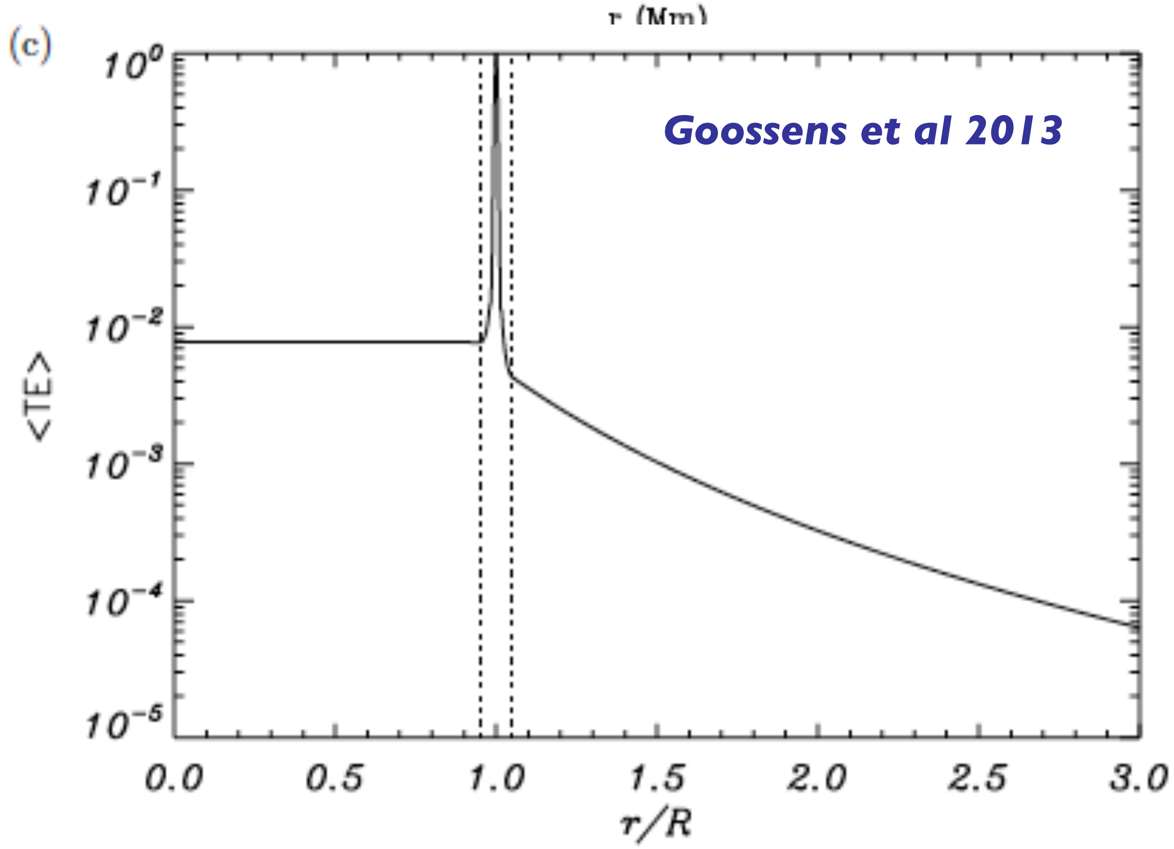


Z=200

Wave Energy







Goossens et al 2013

- Wave energy becomes increasingly localised in tube boundary.
- Damping in qualitative agreement with CoMP observations

➢ **Damping ≠ Dissipation!**

Pascoe et al 2010 - 2013; Terradas et al 2010; Verth et al 2010; Soler et al 2011a,b,c; Hood et al 2013; Goossens et al 2013

Wave Heating

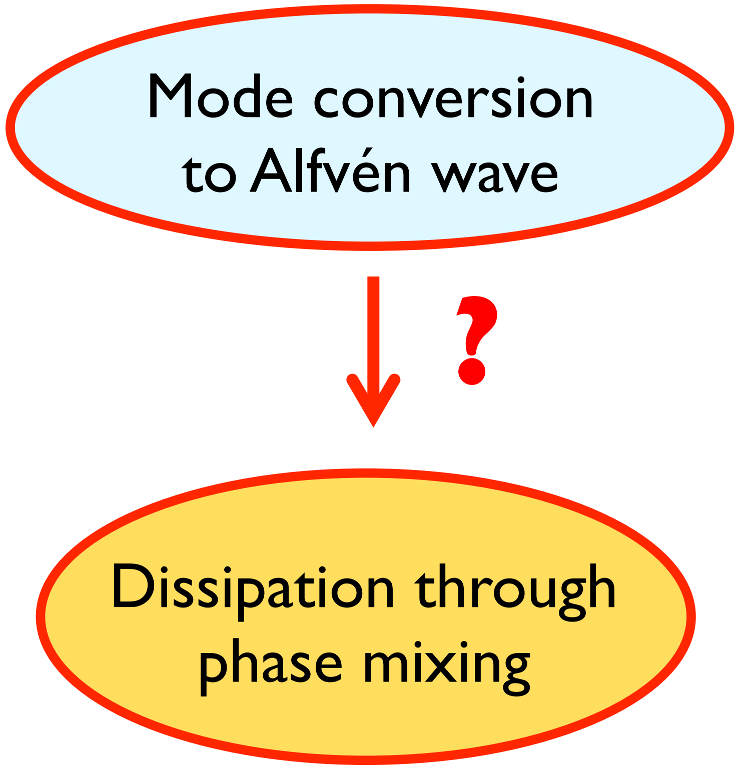
- Historically first suggested as heating mechanism *(Biermann 1946, 1948; Schwarzchild 1948)*
- (Some) Alfven waves not reflected at chromosphere *(Hollweg 1978,1984,1985)* and hence could heat corona *(Wentzel 1974, 1976)*
  - Resonant absorption *(Ionson 1978; Goossens 2011)*
  - Phase mixing *(Heyvaerts & Priest 1983)*
- ***Vast literature…***

➢ **In the context of the recent observations:**

  - Sufficient flux ≠ (right) heating
  - Damping ≠ Dissipation

    (e.g. Lee & Roberts 1986)

- Timing? (dissipation time >> damping time?)



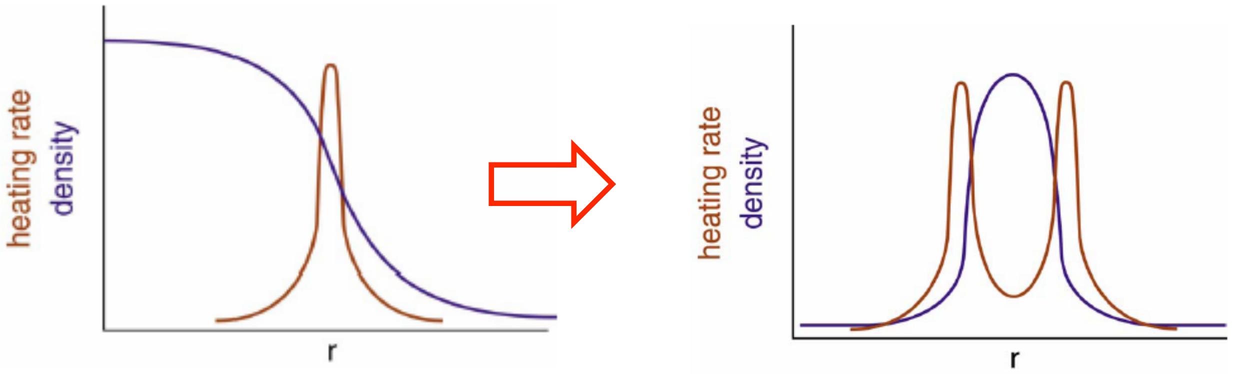
Mode conversion to Alfvén wave

?

Dissipation through phase mixing

Observational Signatures of Wave Heating

Ofman et al 1998



- **So what does wave heating look like?**

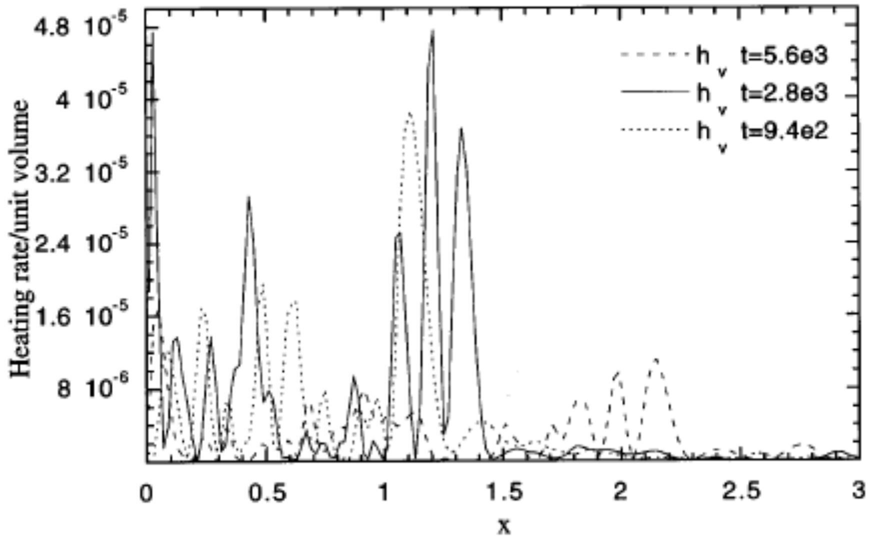
- Heating leads to chromospheric evaporation:
    - Modification of the density profile
    - Drifting of the heating layer?

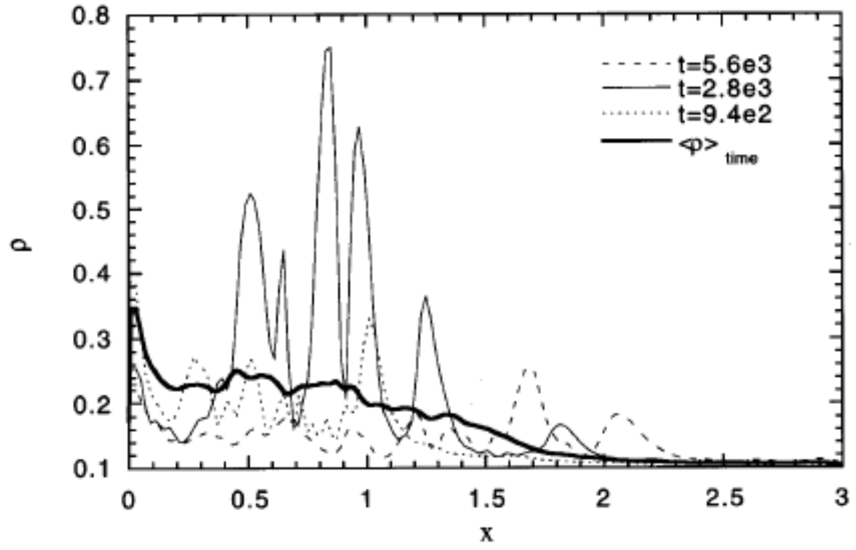
- *Ofman et al (1998):* simulations of resonant absorption
    - Scaling laws for quasi-static heating & volumetric heating rate

$$Q \approx \frac{3}{7}\kappa_0 \frac{T^{7/2}}{L^2} \approx \frac{3}{4}\rho_0^2\Lambda(T)$$

- Multi-structured heating and density

- **Can wave heating look implusive?**
    - Timescales?
    - Difference with other heating mechanism?



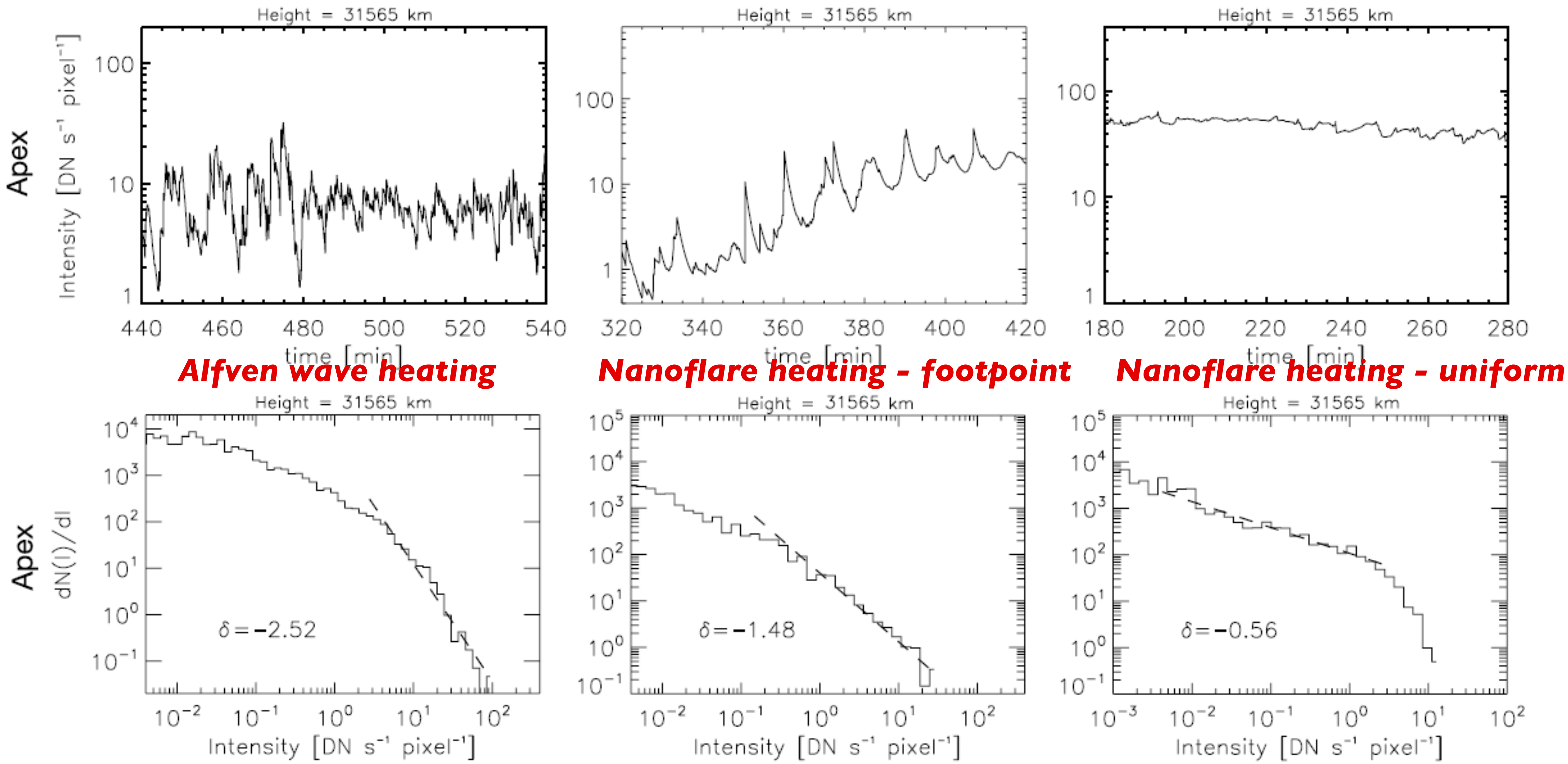


Klimchuk 2006

Observational Signatures of Wave Heating

Antolin et al 2008

- 1.5D model to try and distinguish between waves and nanoflares



Alfven wave heating   **Nanoflare heating - footpoint**   **Nanoflare heating - uniform**

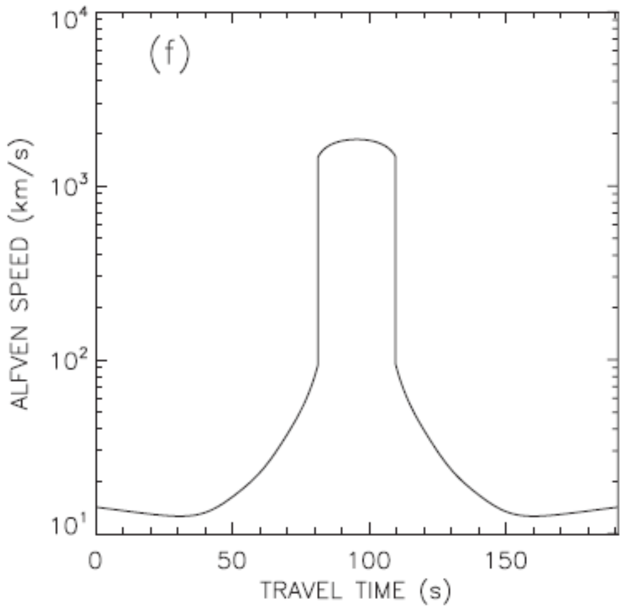
OBSERVATIONAL SIGNATURES FOR CORONAL HEATING MECHANISMS

Heating Model (1)	Flow Pattern (2)	Mean Velocities $\langle v_p \rangle$ (km s^{-1}) (3)	Max Velocities $\langle v_p \rangle$ (km s^{-1}) (4)	Intensity Flux Pattern (5)	Mean Power-Law Index (6)
Alfvén wave........................	Nonuniform, alternating	~50	>200	Bursty everywhere	$\langle \delta \rangle < -2$
Nanoflare footpoint.............	Uniform, simultaneous	~15	>200	Bursty close to TR	$-1.5 > \langle \delta \rangle > -2$
Nanoflare uniform................	Uniform, simultaneous	~5	<40	Flat everywhere	$\langle \delta \rangle \sim -1$

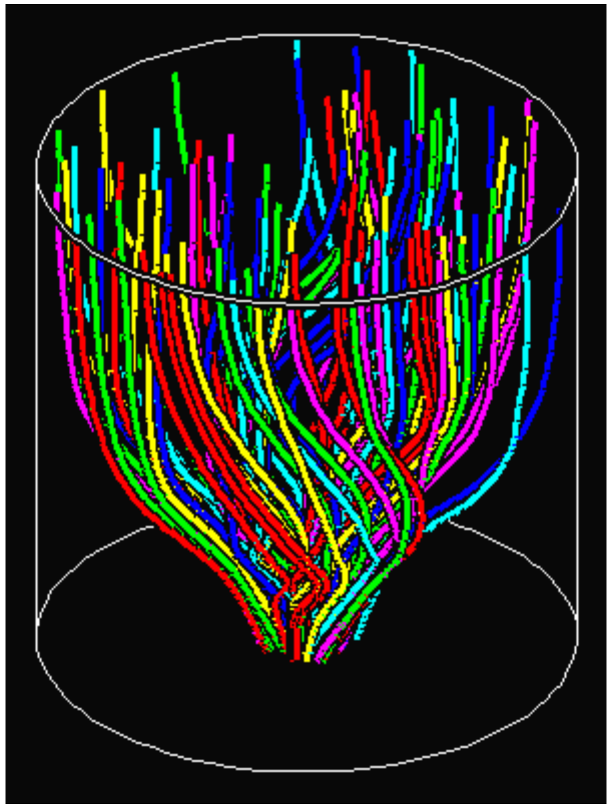
Moriyasu et al 2004; Taroyan et al 2007; Taroyan & Erdelyi 2009

Observational Signatures of Wave Heating

Van Ballegooijen et al 2011

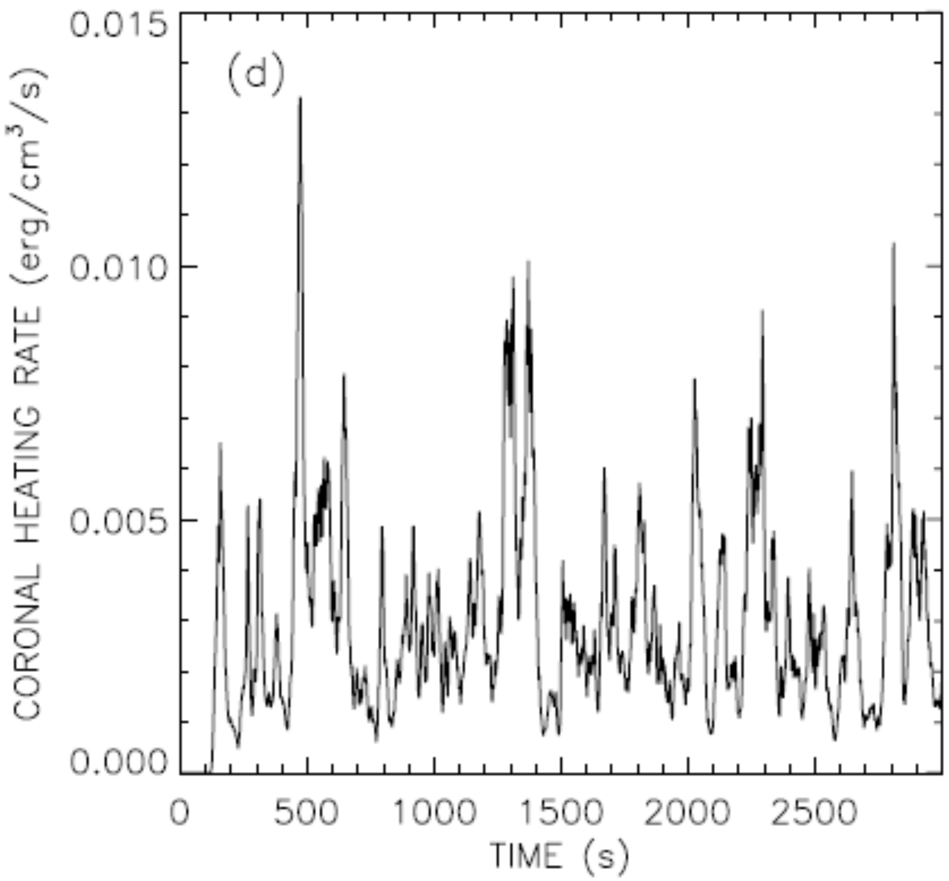


- Reduced MHD
- Small scale footpoint motions (< 100 km) - incompressible
- Assume AR flux tube maintains identity
- Strong reflection of chromosphere and TR → complex pattern of counter-propagating waves → Alfvénic turbulence
- *Coronal heating pattern similar to nanoflare storm!*



Z = 0 - 2 Mm

Z = 2 - 50 Mm



Kudoh & Shibata 1999; Mendoza-Briceno 2002,2005; Moriyasu et al 2004; Antolin & Shibata 2010; Matsumoto & Shibata 2010

Observational Signatures of Wave Heating

- Thermodynamics not included so no predictions of emissions

- Predictions of heating rate in terms of footpoint motions and loop length:

$$Q_{\rm cor} \approx 2.97 \times 10^{-3} \left(0.45 + \frac{33}{\tau_0}\right) \left(\frac{\omega_0}{0.04\ {\rm s}^{-1}}\right)^{1.65} \times \left(\frac{L_{\rm cor}}{50\ {\rm Mm}}\right)^{-0.92} {\rm erg\ cm^{-3}\ s^{-1}},$$

- Heating rate dependence of magnetic field strength

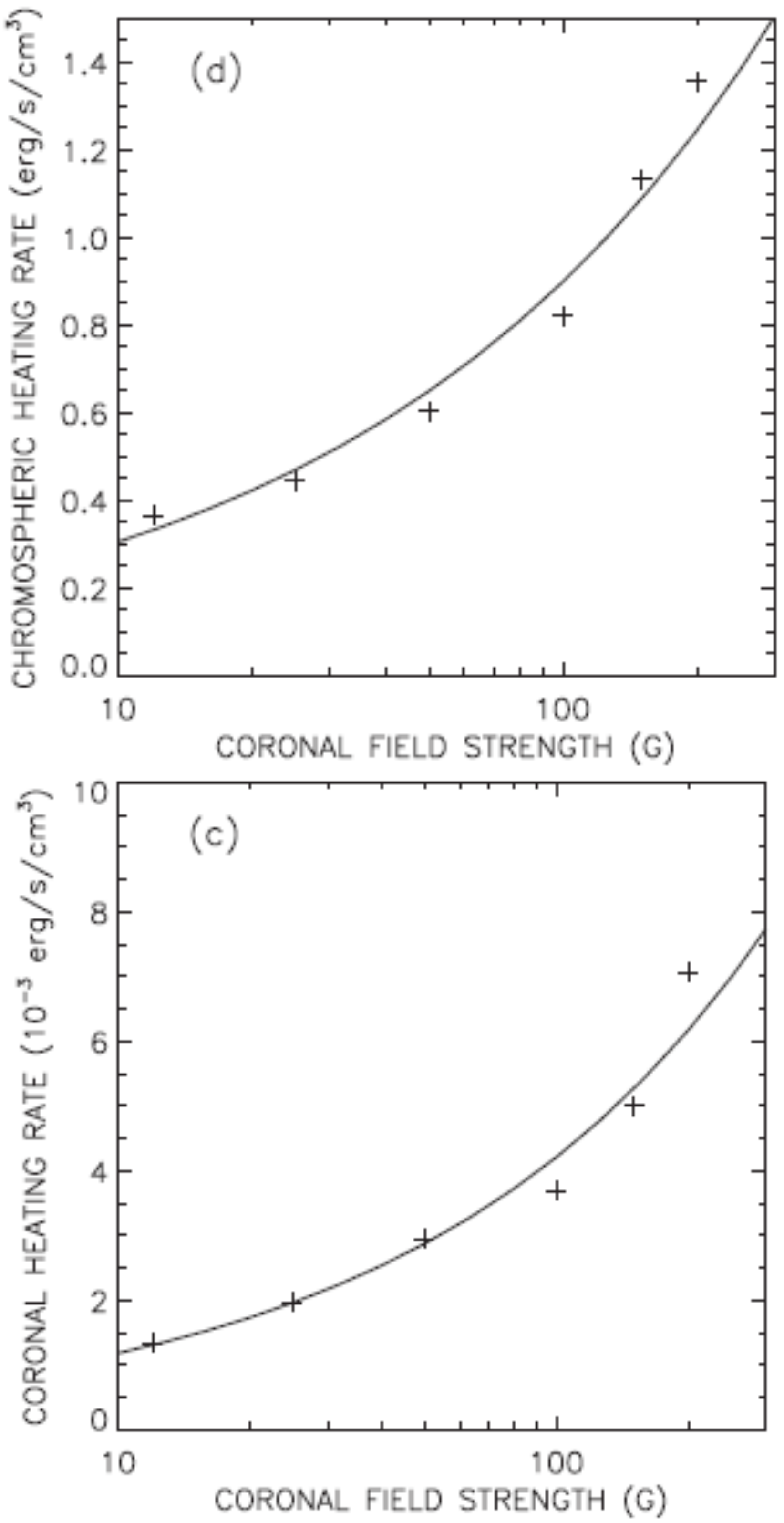
$$Q_{\rm chrom} \approx 6.49 \times 10^{-1} \left(\frac{B_{\rm cor}}{50\ {\rm G}}\right)^{0.47} {\rm erg\ cm^{-3}\ s^{-1}}$$

$$Q_{\rm cor} \approx 2.88 \times 10^{-3} \left(\frac{B_{\rm cor}}{50\ {\rm G}}\right)^{0.55} {\rm erg\ cm^{-3}\ s^{-1}}$$

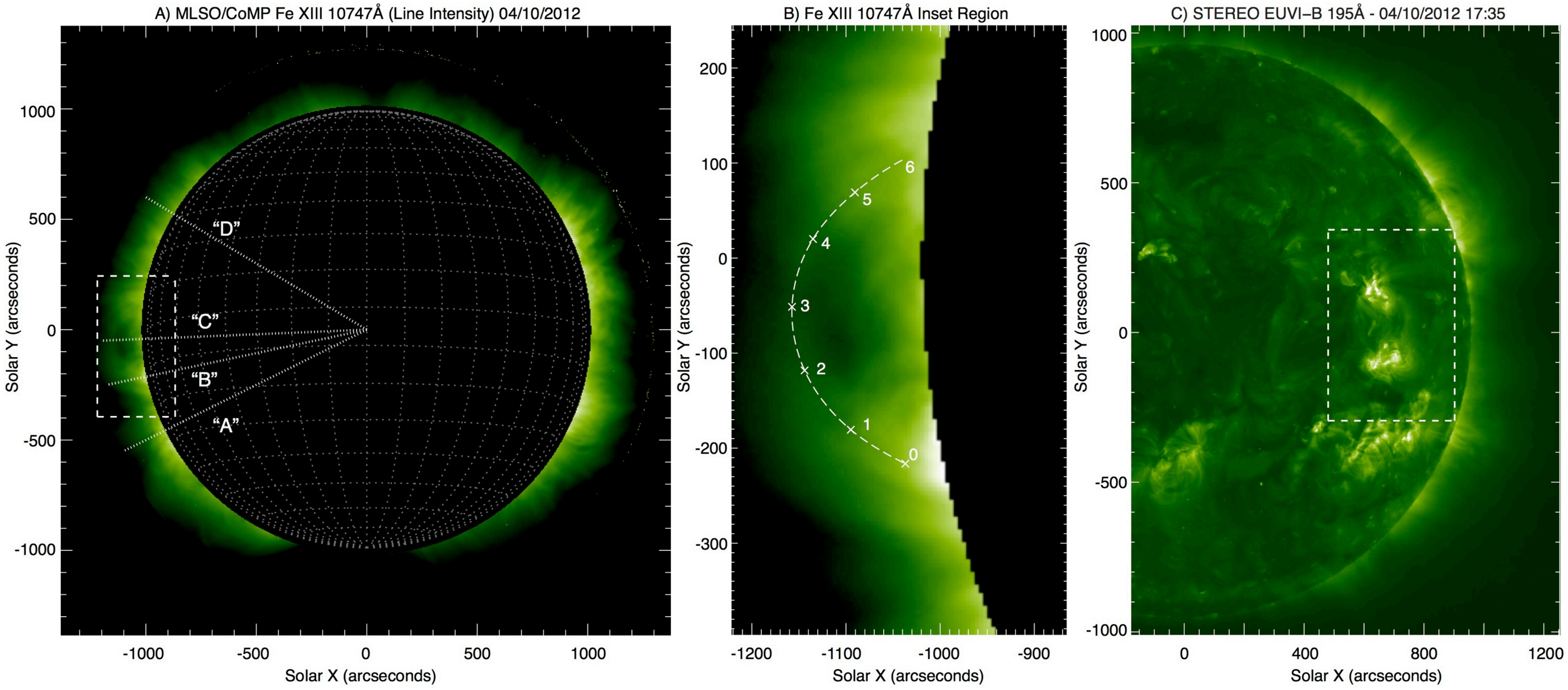
➢ Coronal heating rate increases for stronger |B| & shorter loops

❖ Most heating in lower atmosphere (< 10% energy transmitted)
~ De Pontieu et al (2009)

Van Ballegooijen et al 2011



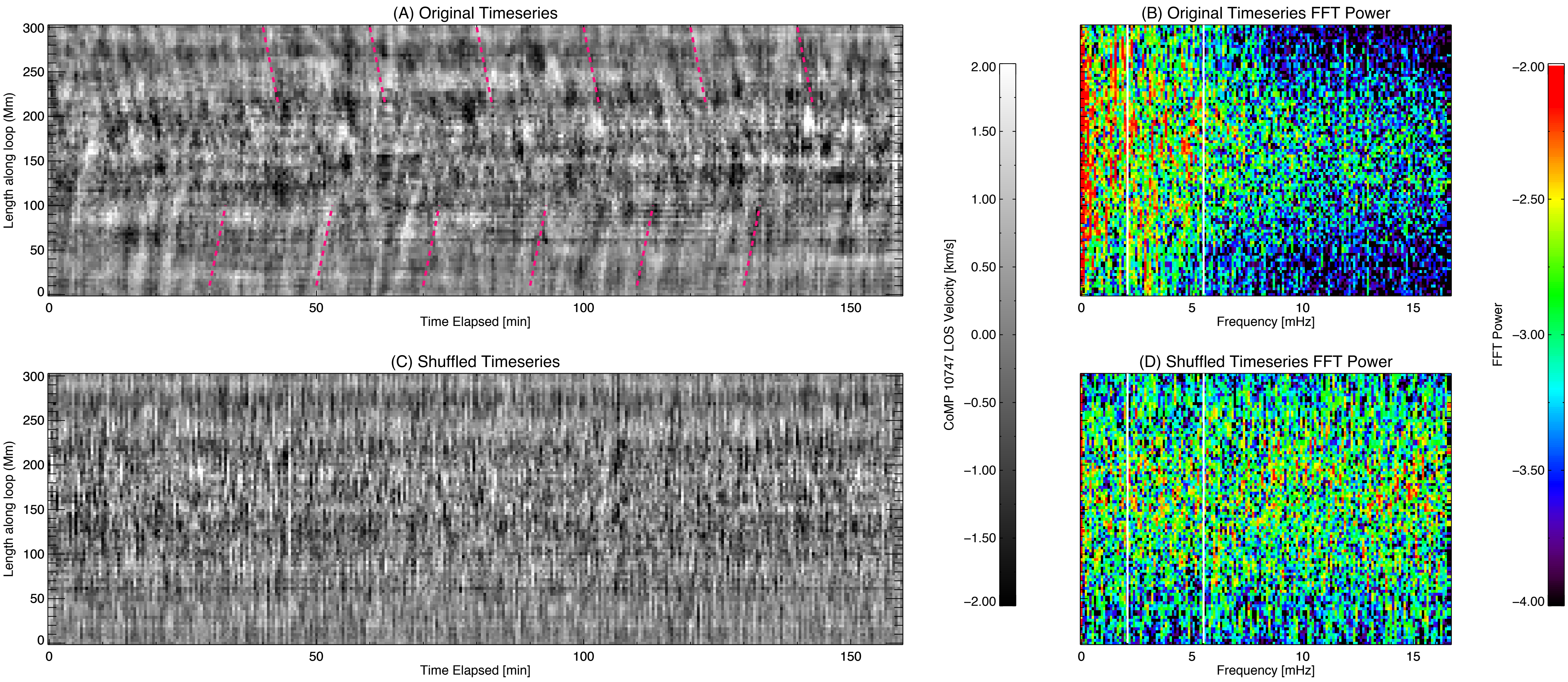
Observational Hint of (Alfvénic) Turbulence?



- Doppler shift oscillations in large, diffuse, trans-equatorial coronal loop (CoMP)
- STEREO/EUVI-B: very isolated systems and loops almost perfectly N-S aligned

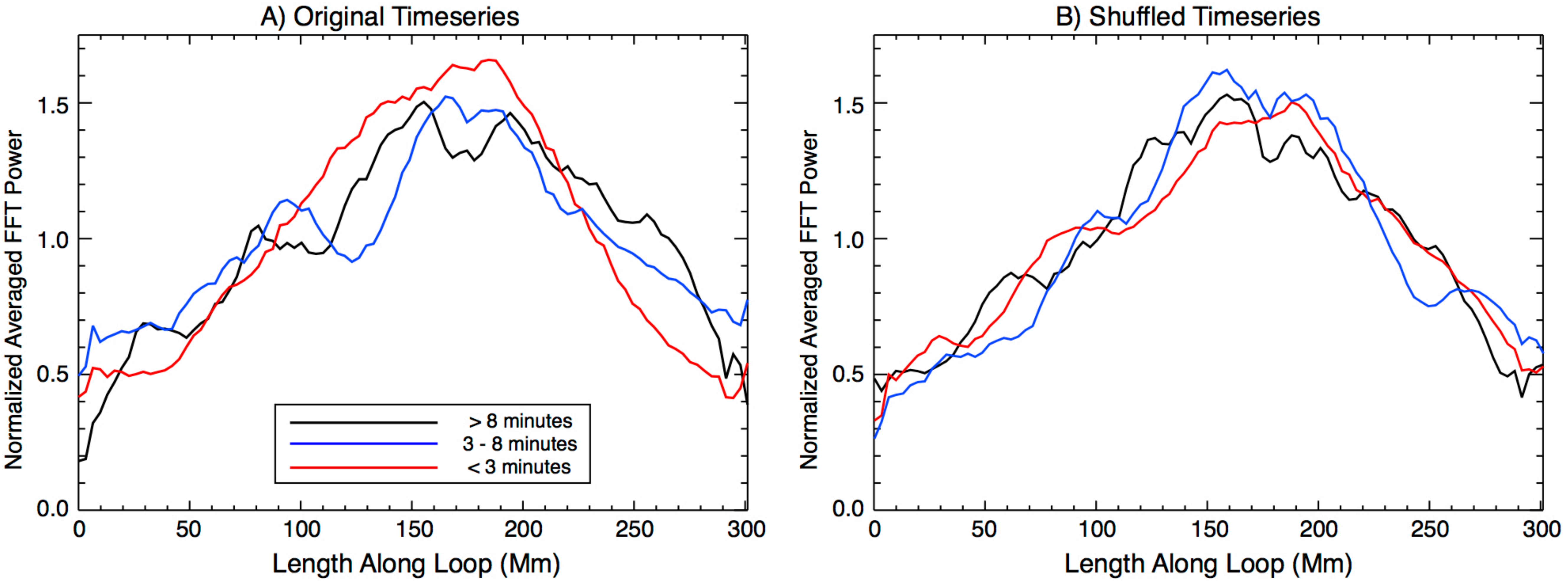
De Moortel et al 2013

Observational Hint of (Alfvénic) Turbulence?



- Time-Distance plot: typical herringbone pattern of counter-propagating waves (propagation speed ~ 500 km/s)
- FFT power along the loop: V-Shaped pattern → significant high-frequency power at the apex
- Randomly shuffled time series: null result

Observational Hint of (Alfvénic) Turbulence?



- Normalised high-frequency power is indeed higher at loop apex.

- From mode coupling we would expect $L_d \sim P$ so higher frequencies should damp quicker…

Conclusions/Future Directions

- Observations: waves are present beyond doubt in a wide range of structures in all layers of the solar atmosphere.
- Wave heating has come full circle and is now back at the forefront of the coronal heating debate.
    - Vast amount of literature!
- Theoretical/numerical modelling needs to catch up:
    - Issues with mode identification and complexity of models.
    - Wave models need to include highly dynamic 'wave guides'.
    - More work needed to identify observational signatures.
        - ➢ Isolated/individual MHD wave modes are unlikely

➢ ***Can heating be "delivered" in the right locations and on the right timescales by waves?***

Parnell & De Moortel 2012; De Moortel & Nakariakov 2012; Komm et al 2013