Heating diagnostics with MHD waves

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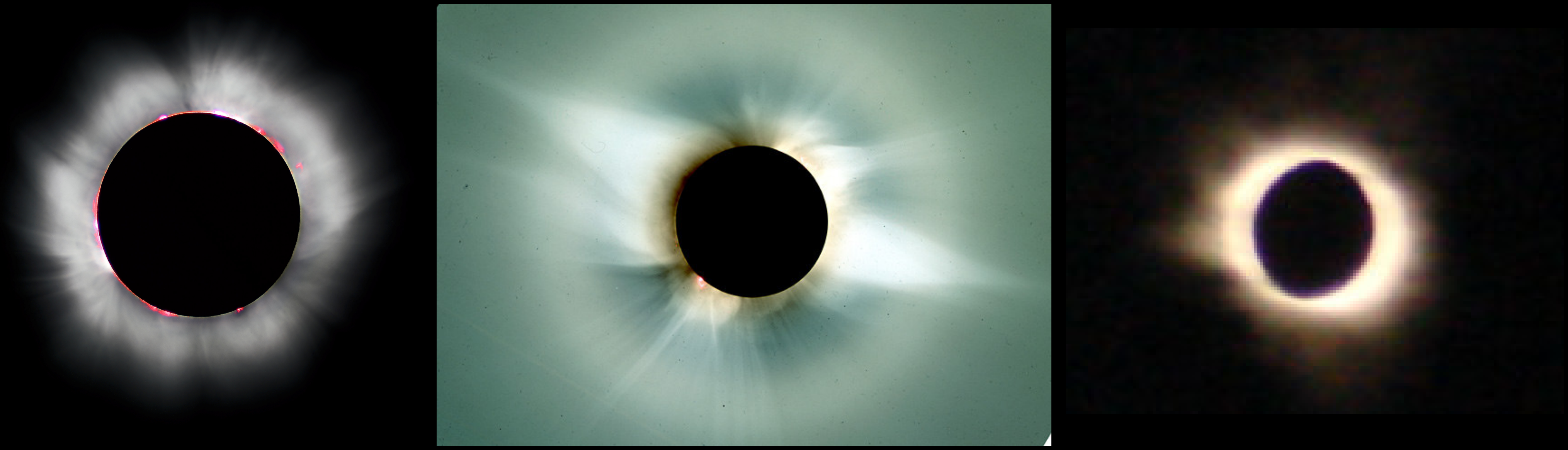
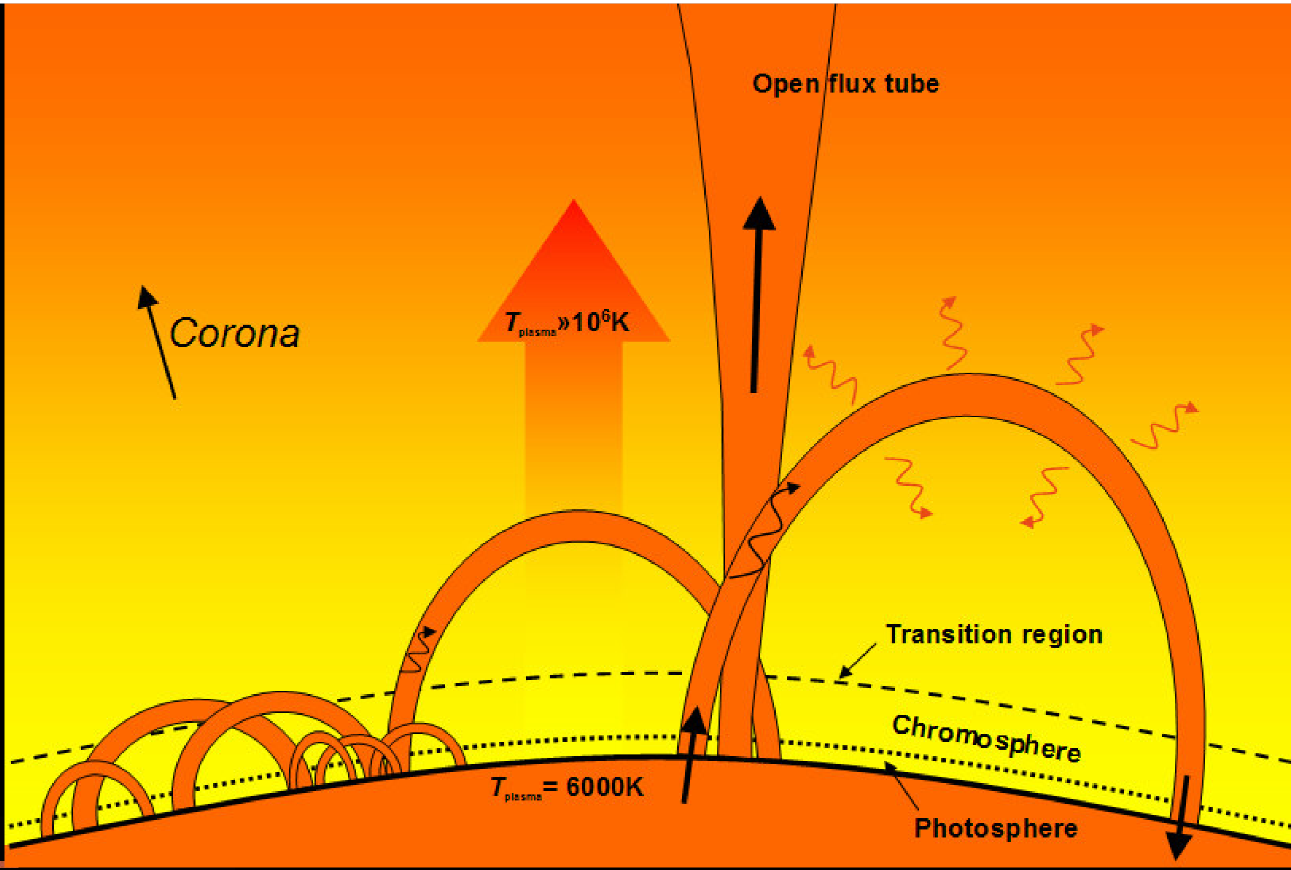
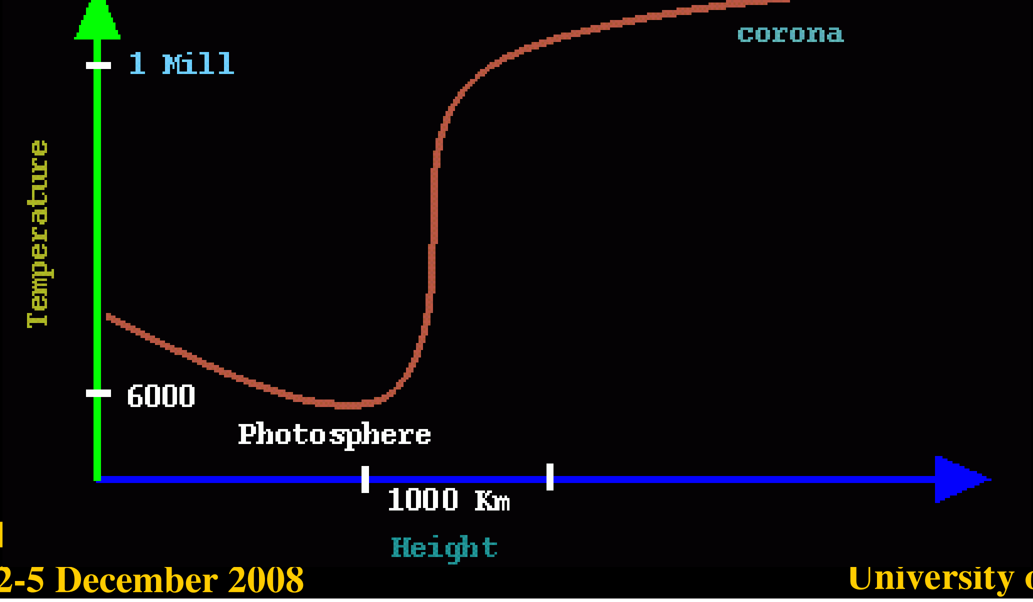
The solar corona



- 1860s – “coronium” discovered
- 1902 – “coronium” has lesser atomic weight than hydrogen (Mendeleev)
- 1930s – spectral lines due to known elements at very high stages of ionisation (Grotrian, Edlén)

The heating enigma

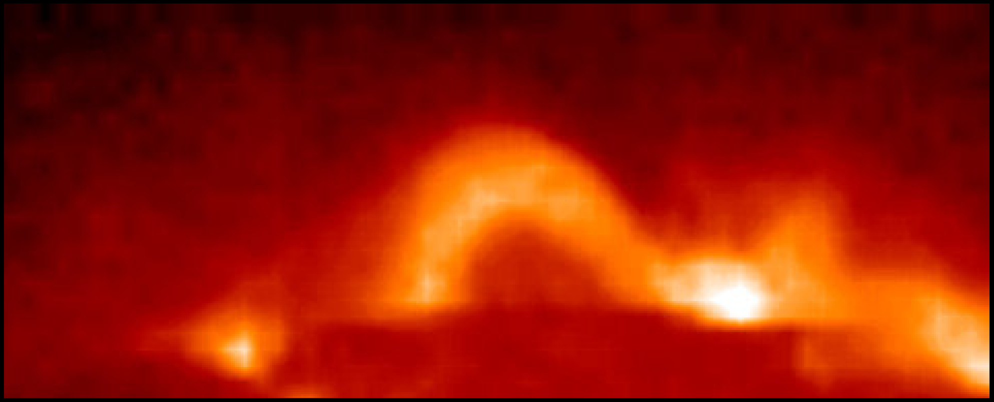




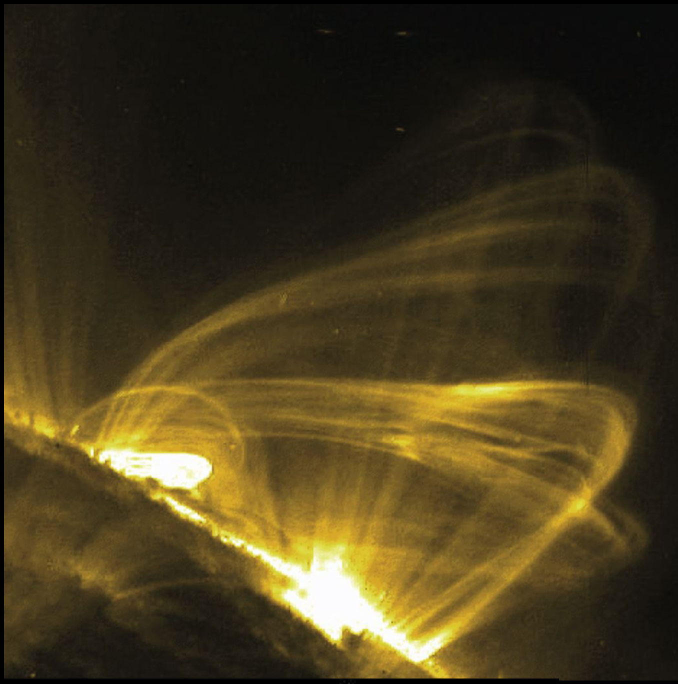
Courtesy: Unknown Nice Person

Loop structures are building blocks” of corona

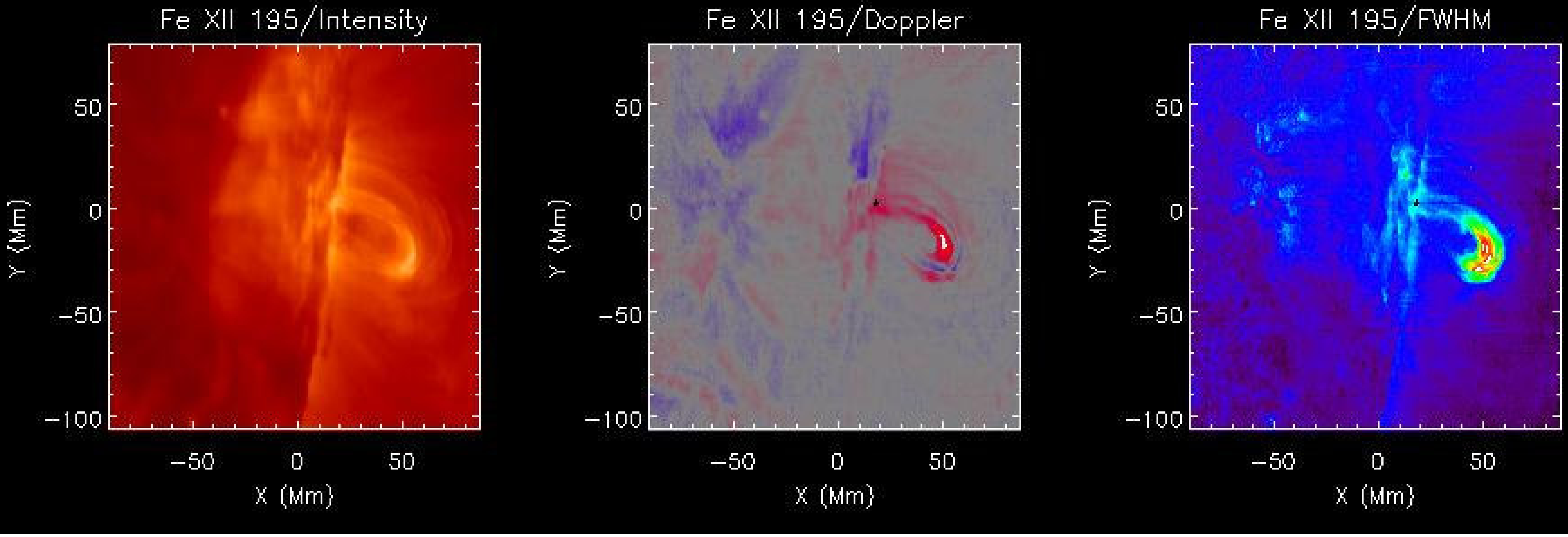
Yohkoh/SXT



TRACE



Hinode/EIS

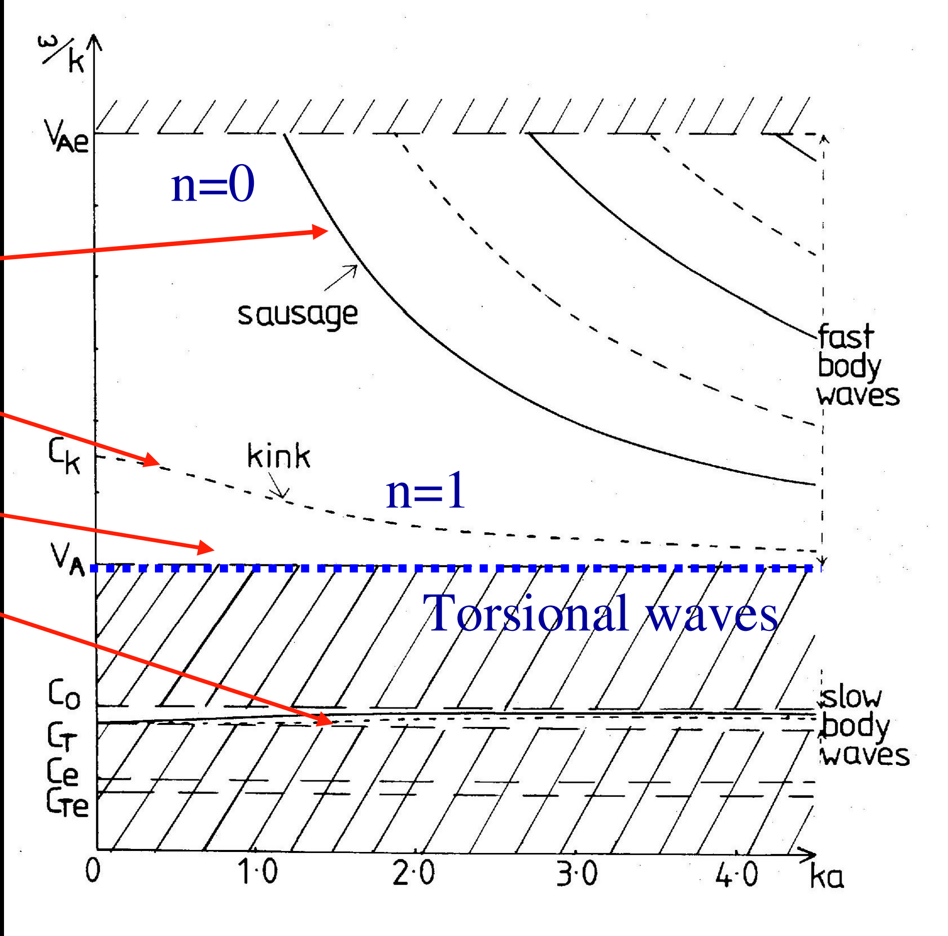


Theory of loop oscillations

Coronal loops

Main modes:

- fast sausage (|B|, ρ)
- fast kink (almost incompressible)
- (Alfvenic) torsional (incompressible)
- slow (acoustic) type (ρ, v)



Theory of loop oscillations

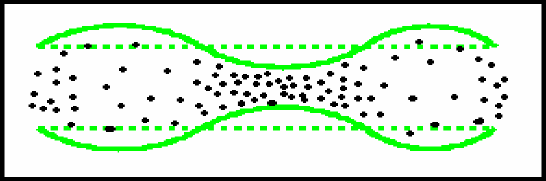
Closed tubes

Main modes:

Expected oscillation periods in coronal loops

- sausage

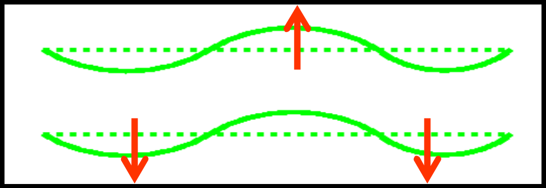
$B' > 0, \rho' > 0$



sausage modes: P = 0.1 – 5 s

- kink

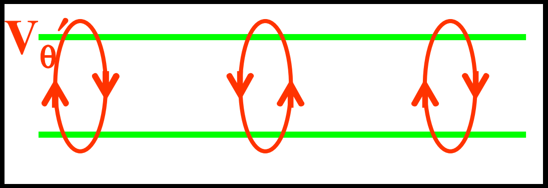
$\rho' \approx 0$



kink modes: P = 1.4 – 14 min

- (Alfvénic) torsional

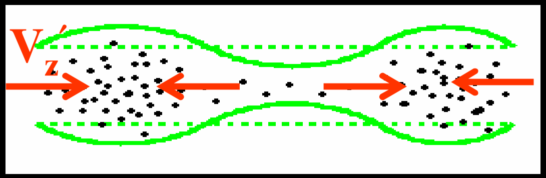
$\rho' = 0$



Alfvénic modes: P = 1 s

- slow (acoustic) type

$B' > 0, \rho' < 0$



slow modes: P = 7 –70 min

Aschwanden 2003, Wang 2004, Erdélyi 2008

Energetic & magneto-seismological implications of MHD waves

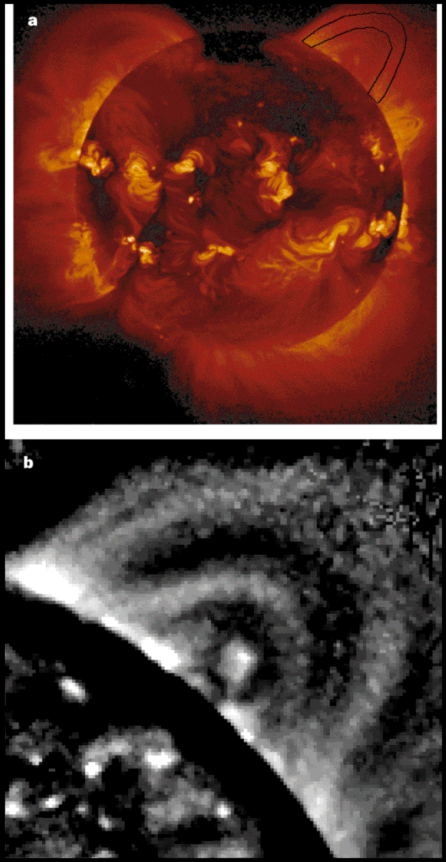
- Extraction and transfer of energy over long distances
- Energy deposition through various processes (nonlinear wave conversion and MHD shock formation, resonant absorption, phase mixing, etc.)
- Important dynamic (spicules, explosive events, etc.) and energetic consequences (plasma heating and acceleration)

- Coronal waves provide information about the **magnetic field**, **transport coefficients**, **heating function,** etc. ➔ **diagnostics of corona**

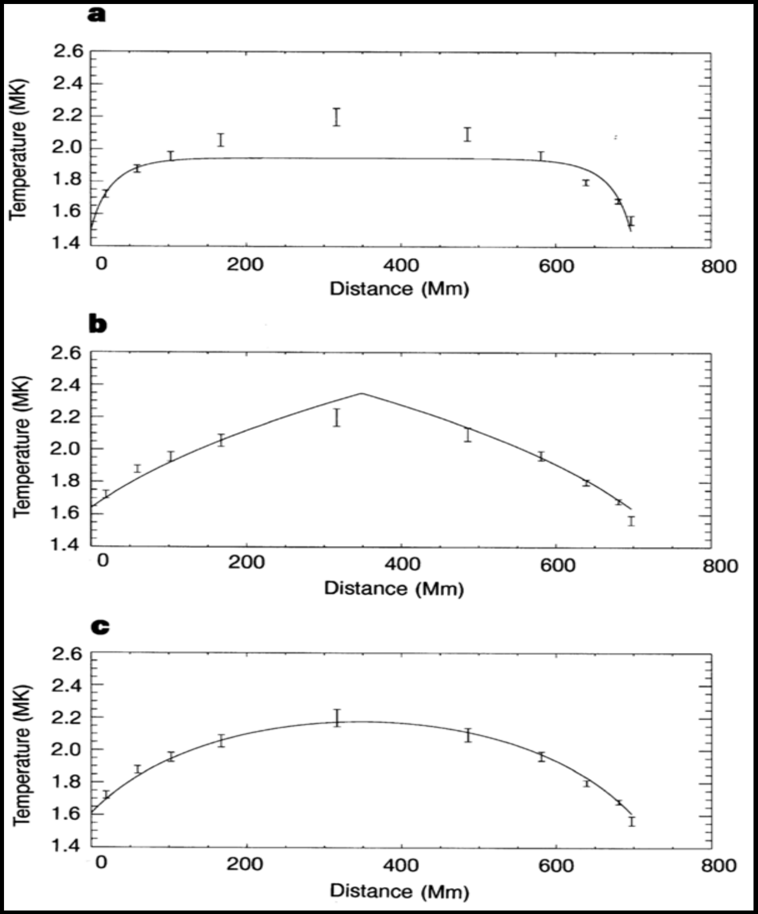
Heating footprints predicted by various mechanisms

- MHD waves
- Magnetic reconnection
- Wave-particle resonant interactions

“Traditional” methods for temperature measurements



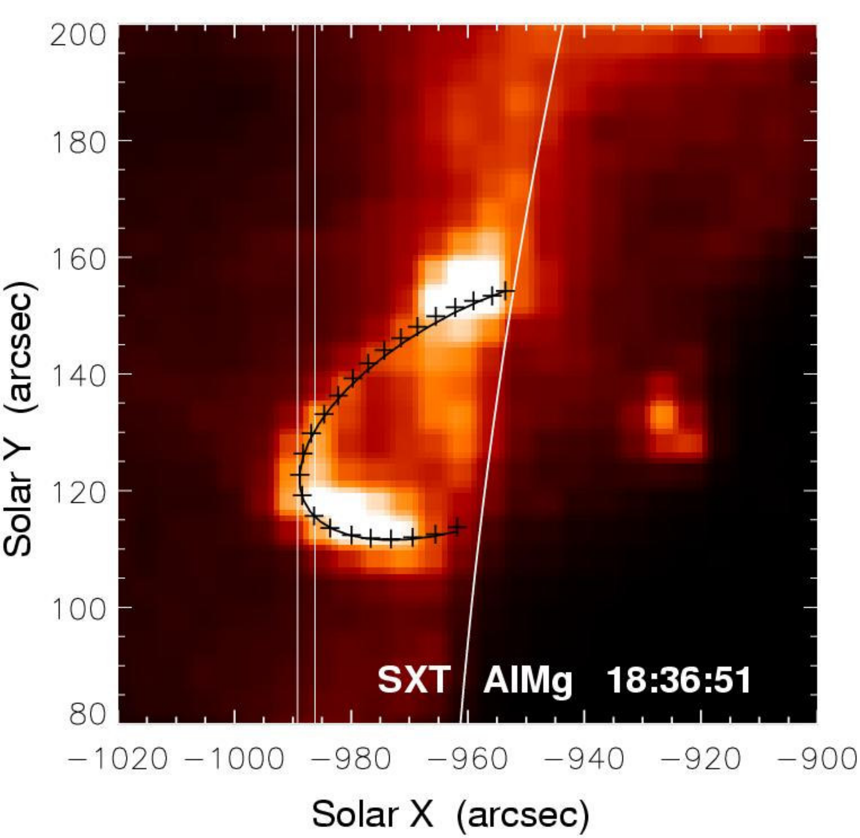
Filter ratio analysis

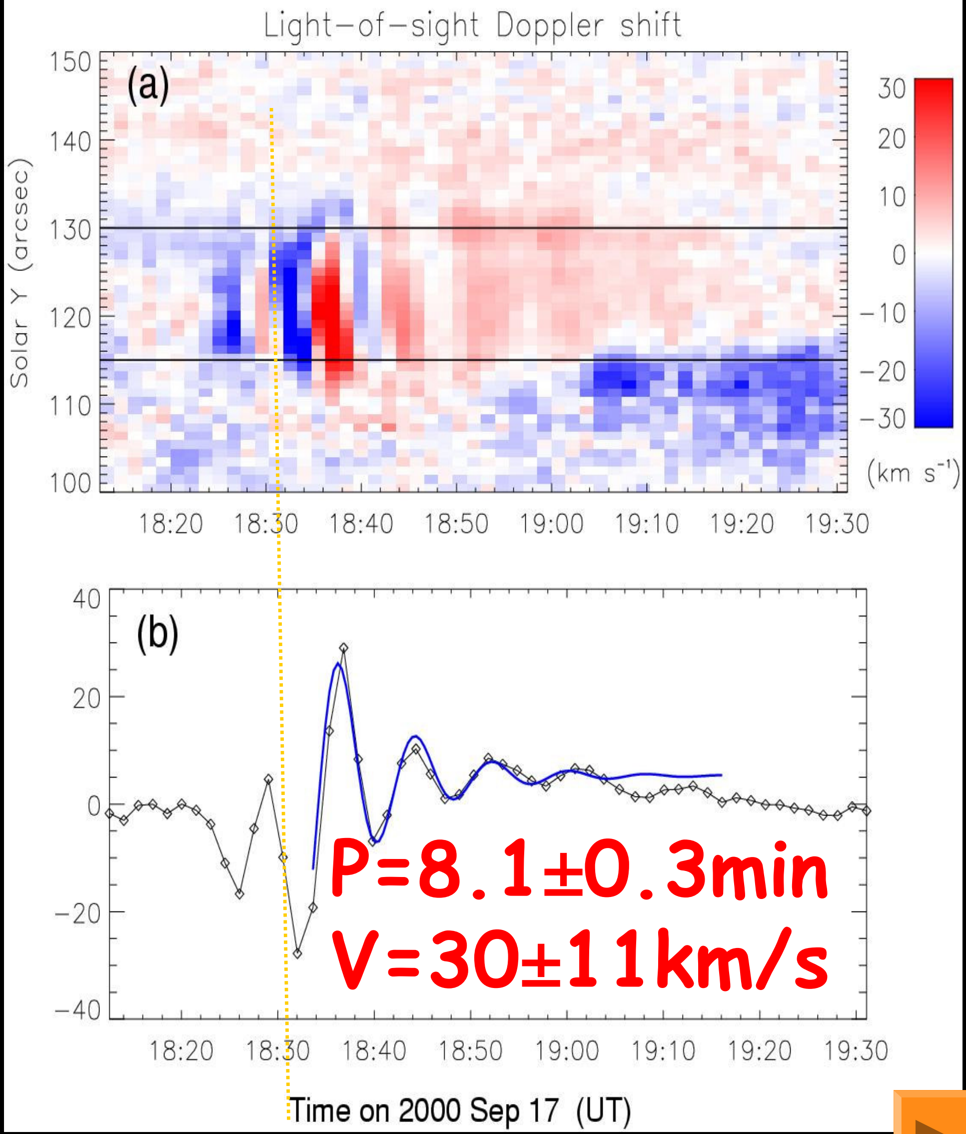


Background subtraction

Isothermal approximation

Case study: SXT and SUMER observations of hot loop oscillations





P=8.1±0.3min

V=30±11km/s

1D loop modelling (with TR!)

Thermal conduction

Heating rate

Radiation

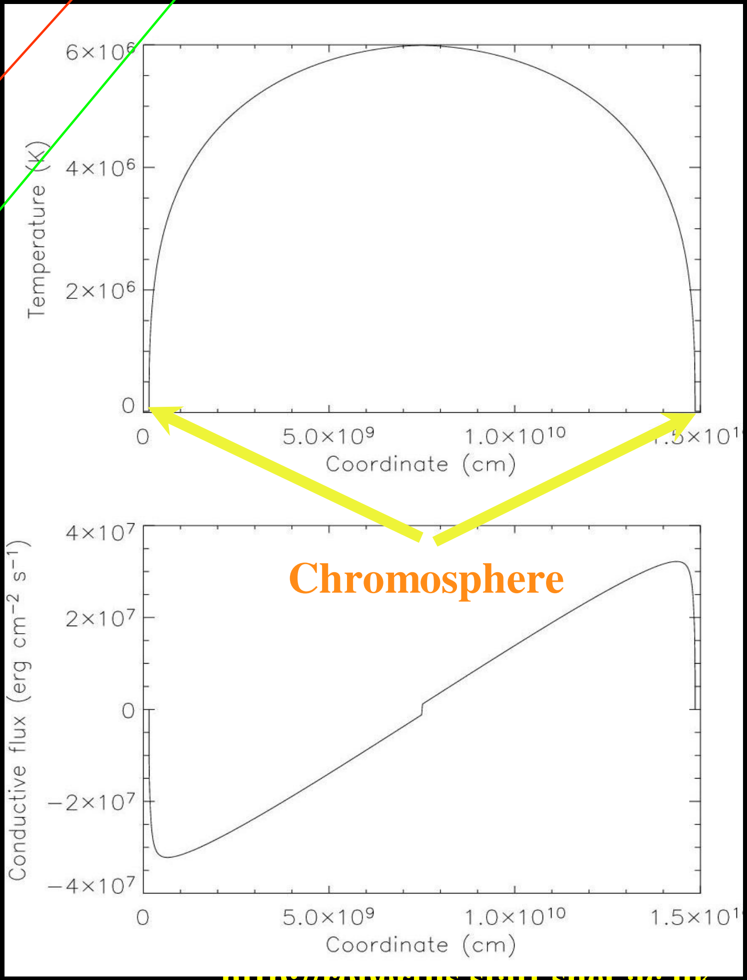
$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial s}(\rho v) = 0,$$

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial s}(\rho v^2) = -\left(\frac{\partial P}{\partial s} + \rho g_B\right),$$

$$\frac{\partial E}{\partial t} + \frac{\partial}{\partial s}(Ev) = -\frac{\partial}{\partial s}(Pv) + \rho v g_B$$

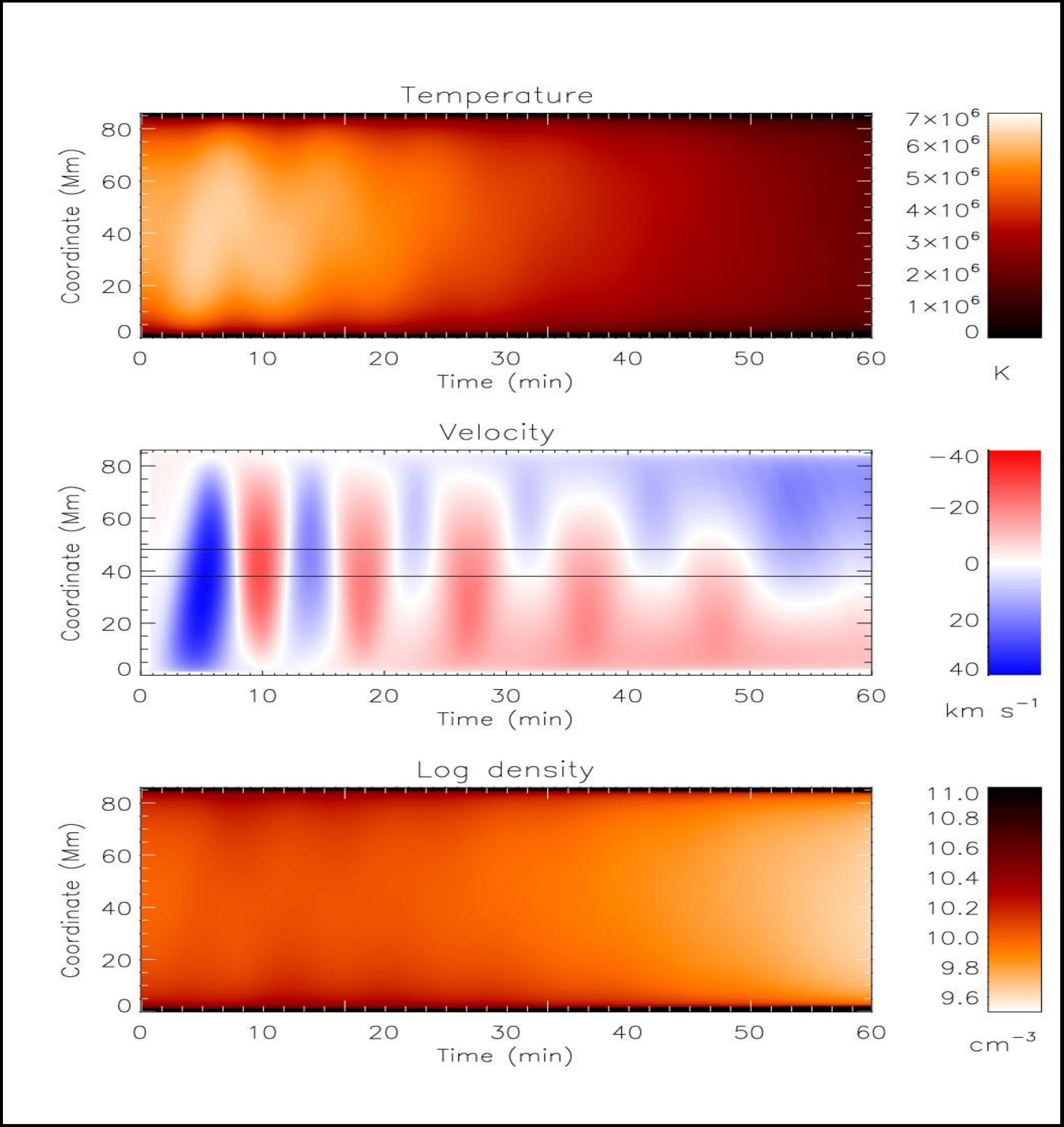
$$-\frac{\partial}{\partial s}\left(-\kappa T^{5/2}\frac{\partial T}{\partial s}\right) + (H - L),$$

$$E = \frac{\rho v^2}{2} + \frac{P}{\gamma - 1}$$



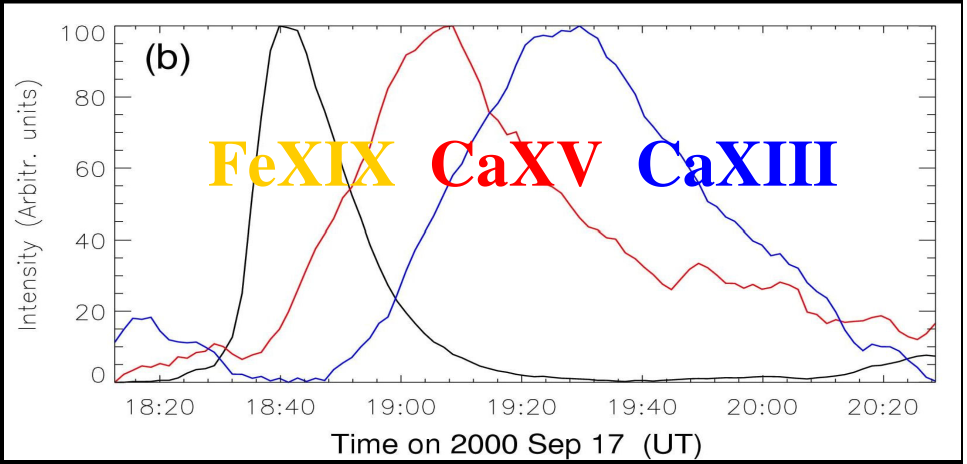
Hydrodynamic evolution of the loop

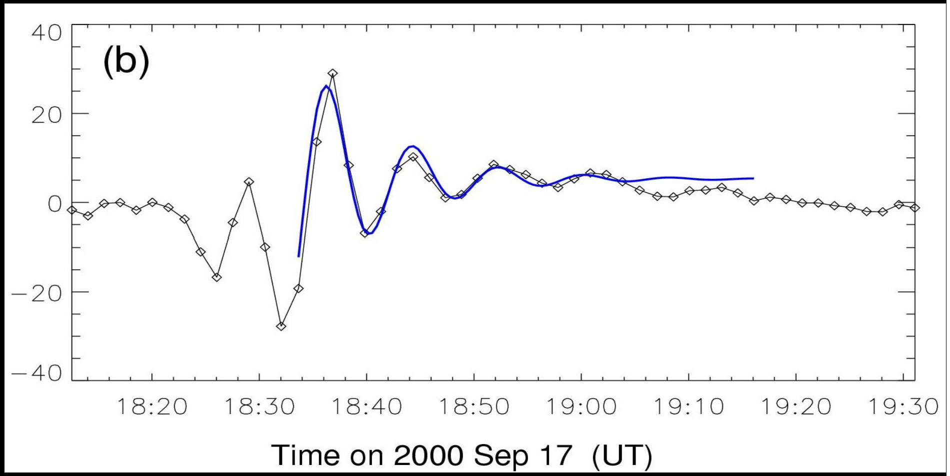
Footpoint excitation by pulse

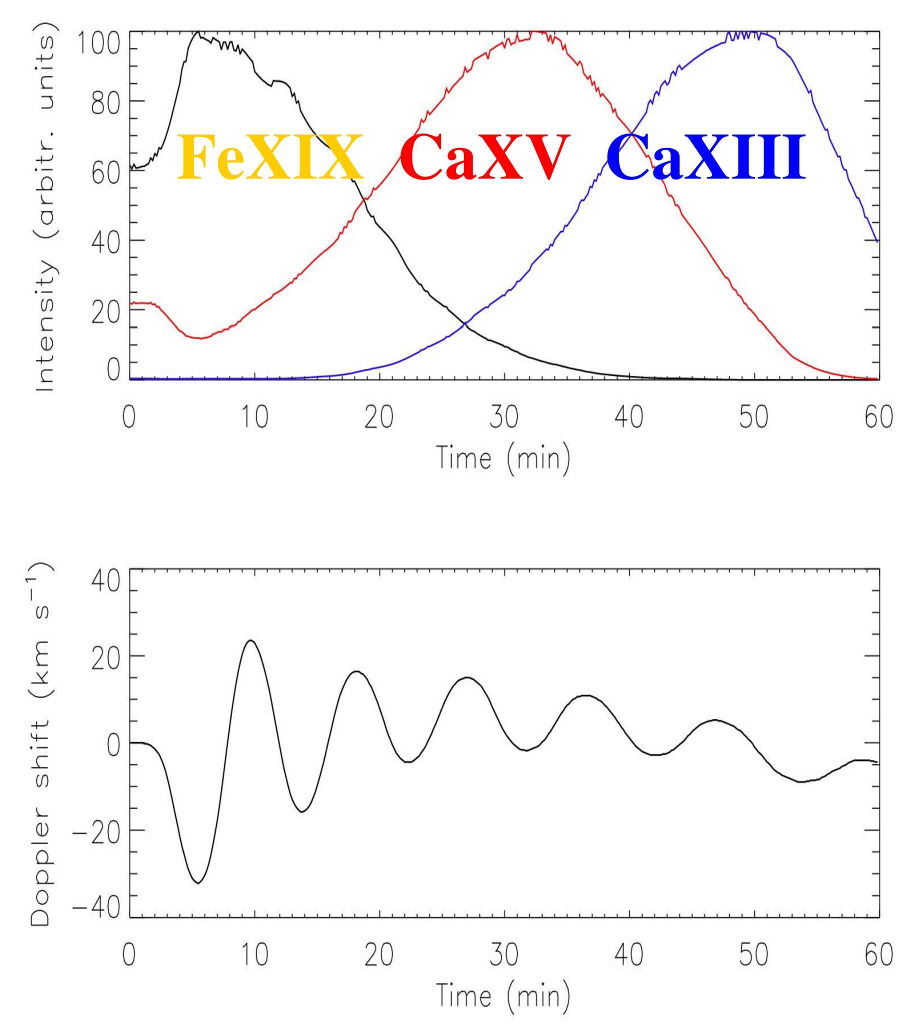


SUMER measurements

Results of line profile synthesis

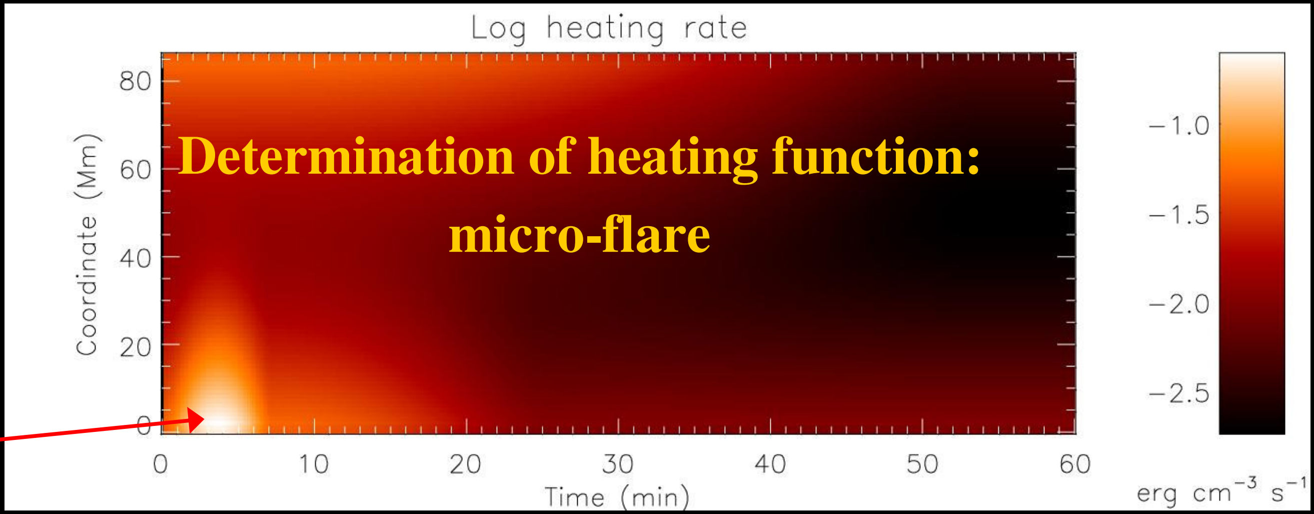






Results of combined observations and forward modelling (from Taroyan, Erdélyi et al. ApJ 2007)

- Establish the nature of the observed hot loop oscillations (Cauchy problem ➔ unique solution)
- Standing acoustic waves set up by a footpoint microflare
- Reproduce the time-distance profile of the heating function (important for understanding the nature of the heating process)



Determination of heating function:

micro-flare

$1.5\text{x}10^{27}$ erg

- Why only hot loops? Where are the SWs in cooler EUV loops?

Quest: Compute synthesized Hinode/EIS observations (i.e. theory)

Question: Can standing waves exist in cooler loops?

Selected lines -FeX 190Å, FeXI 188.23Å, FeXII 195Å

Imaging mode - 40’’ slot

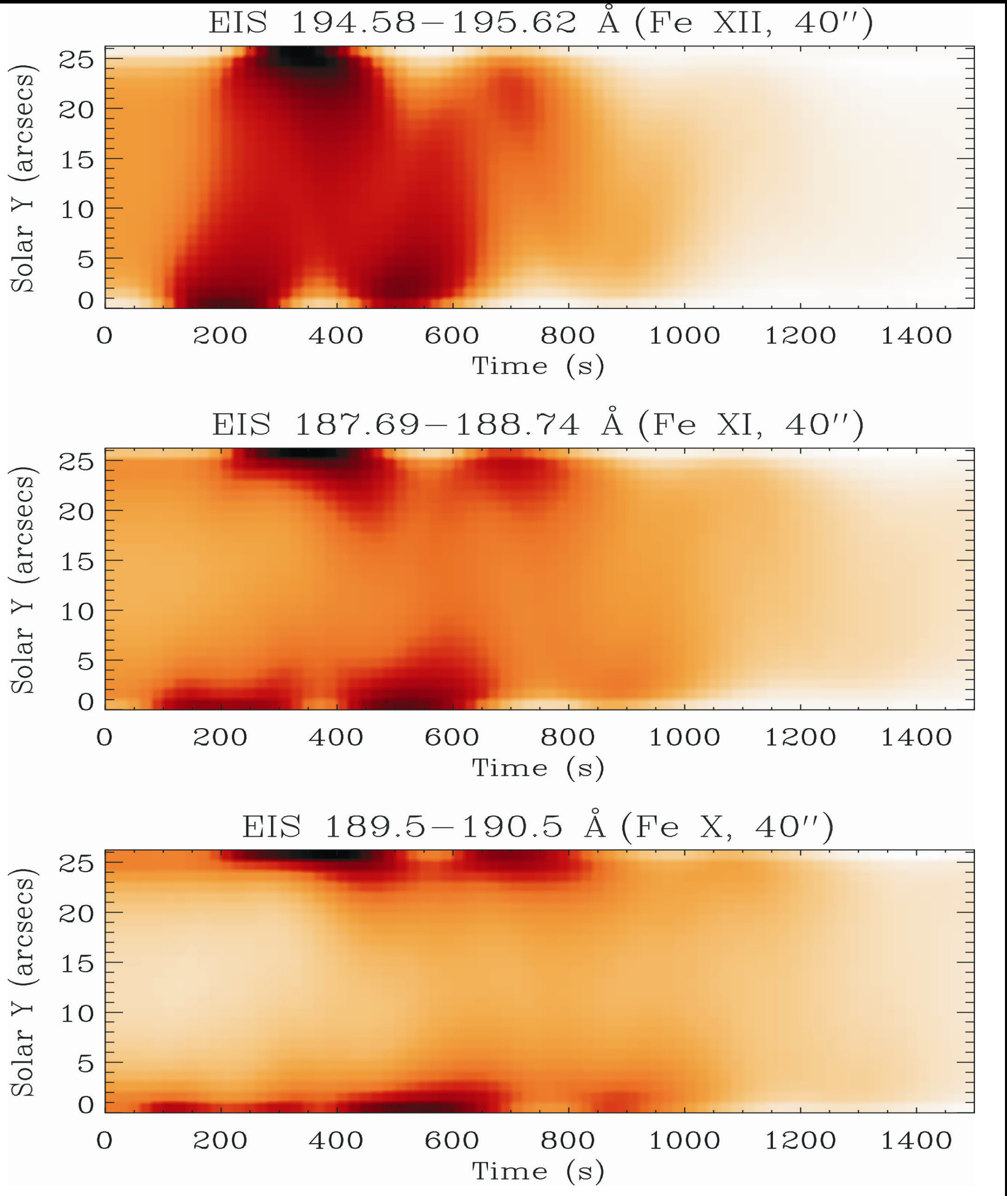
Spectroscopy mode – 1’’ slit

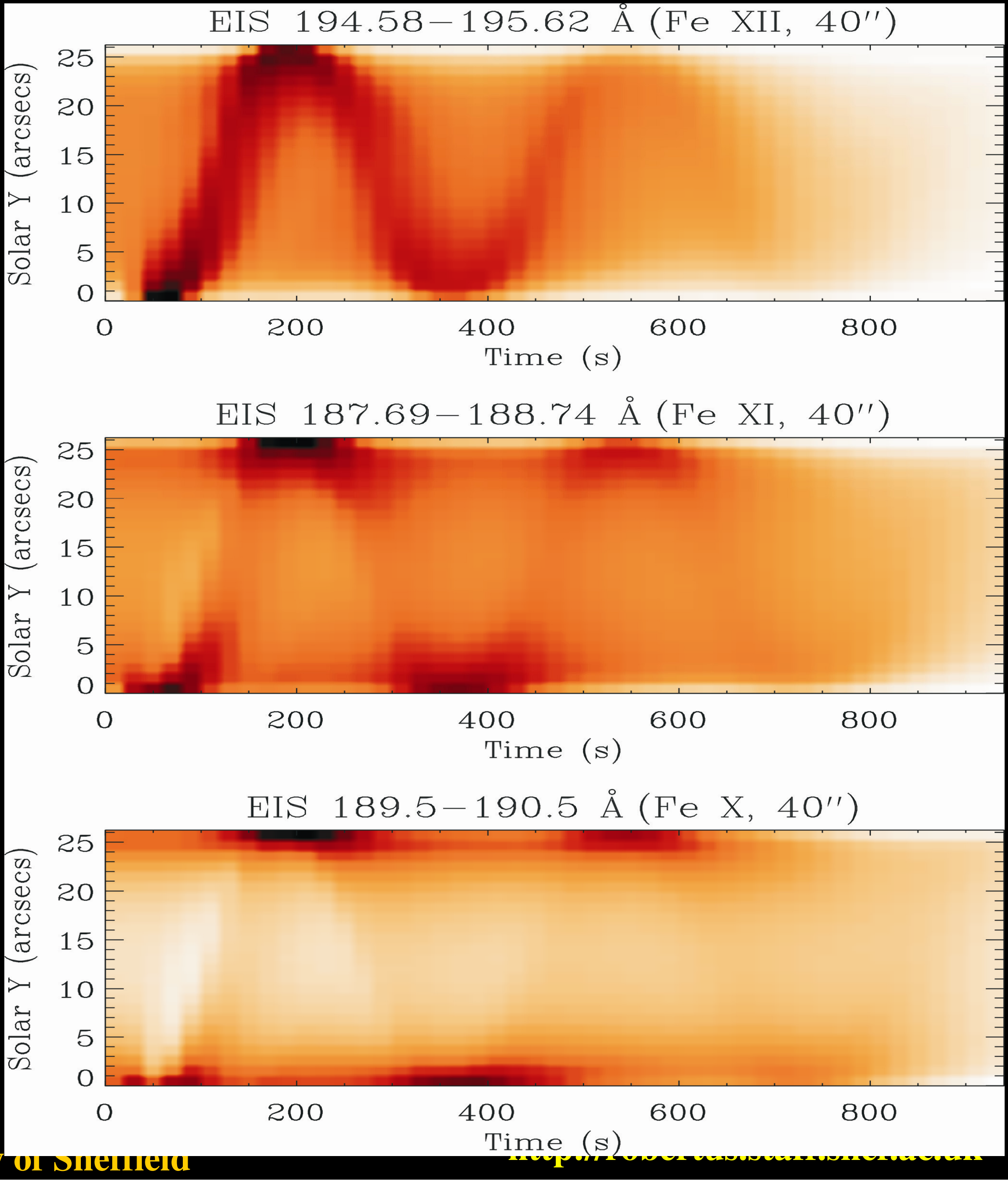
Loop location – disc centre

Orientation – south-north

Standing waves (P_pulse=P_f) Propagating waves (P_pulse<P_f)

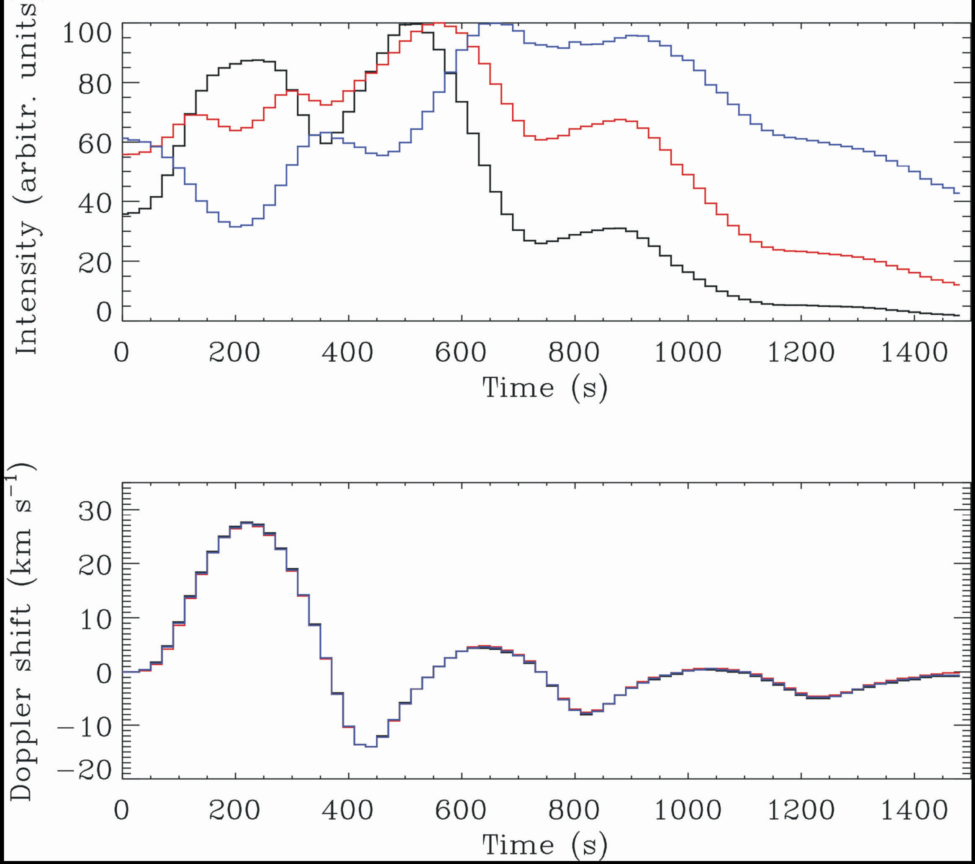
(both types of waves are formed but not very well seen in imaging mode
see Taroyan et al. 2005 for theory)



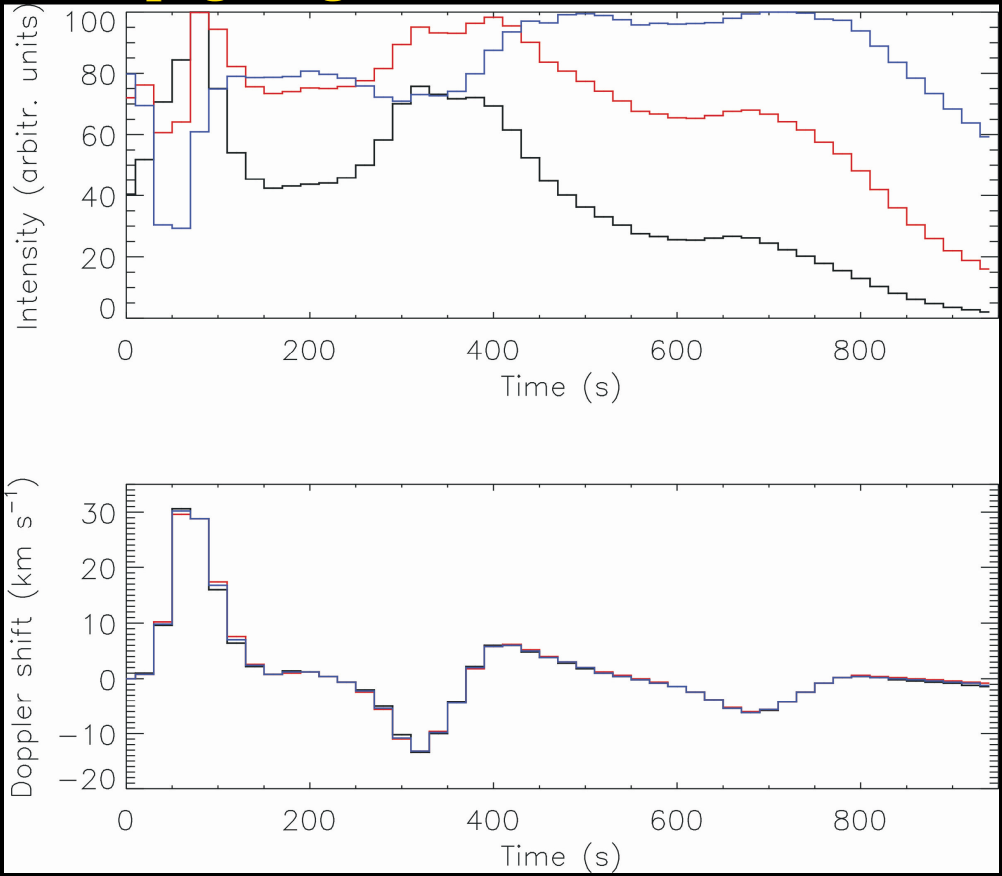


Best seen in spectroscopy mode

Standing waves



Propagating waves



FeXII 195Å, 1'' **FeXI 188.23Å, 1''** **FeX 190Å, 1''**

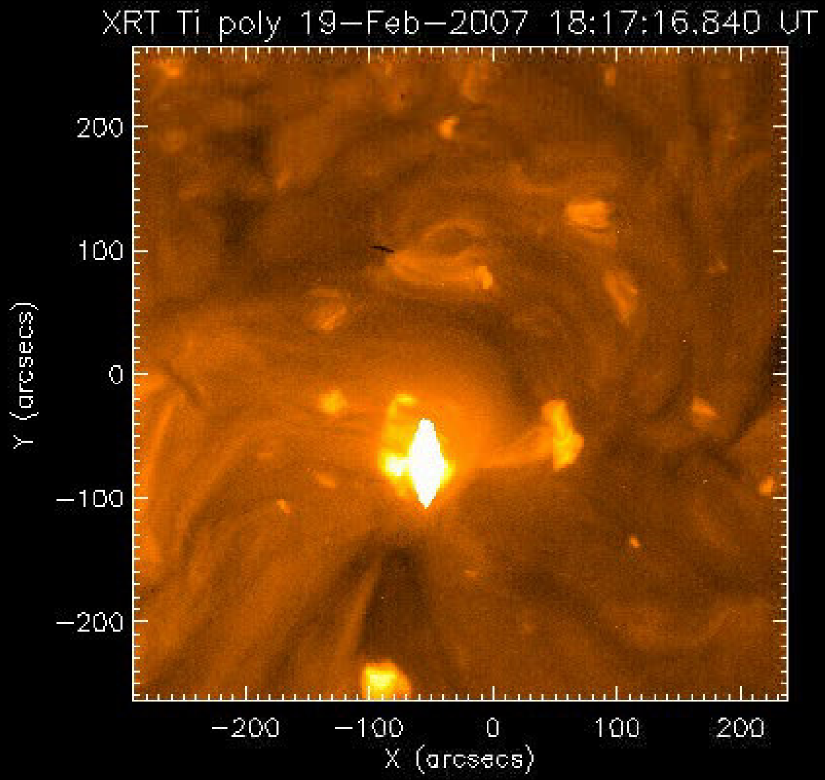
- Oscillations are seen in all three lines;
- Oscillations are in phase for Doppler but NOT in phase in intensity because of heating/cooling

Quest: Reality check #1 Hinode/EIS observations (i.e. real data)

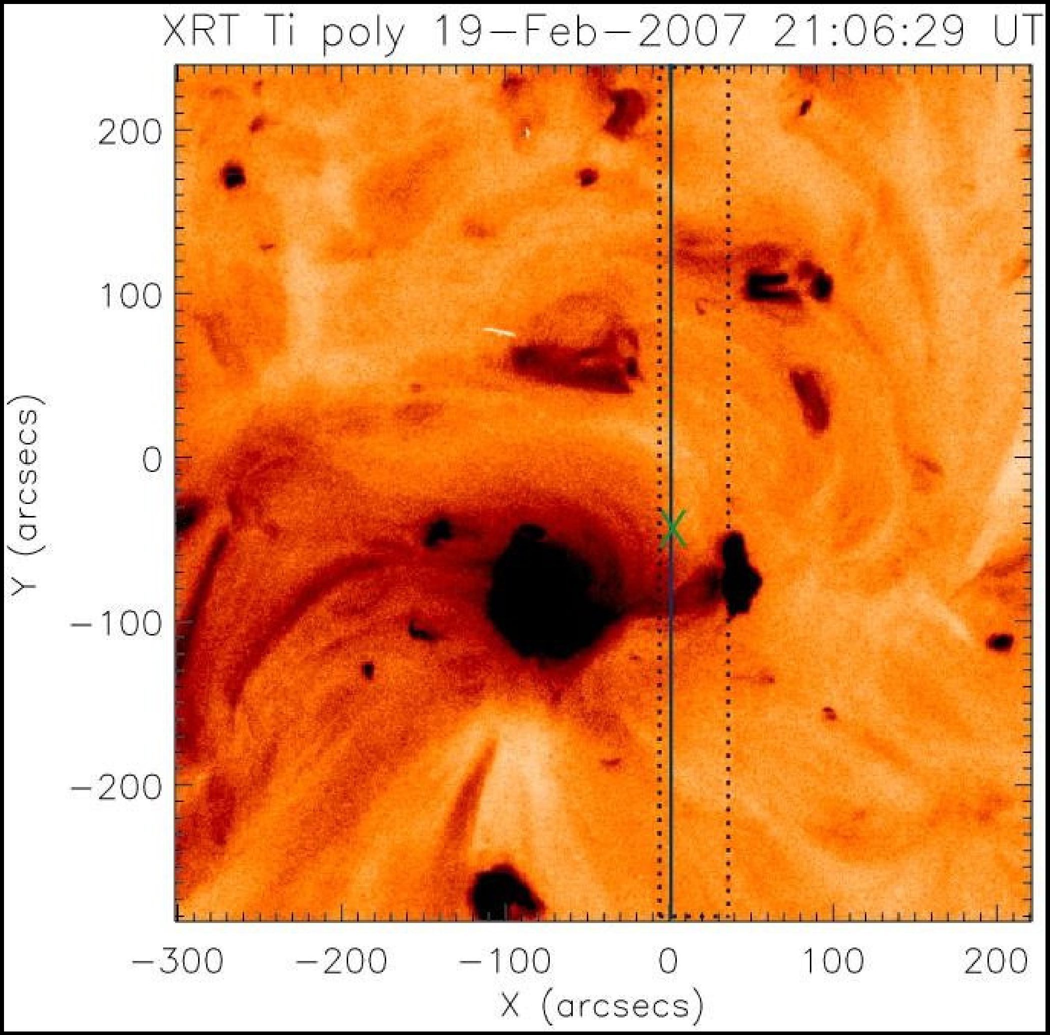
- There is nothing to prevent oscillations in EUV loops

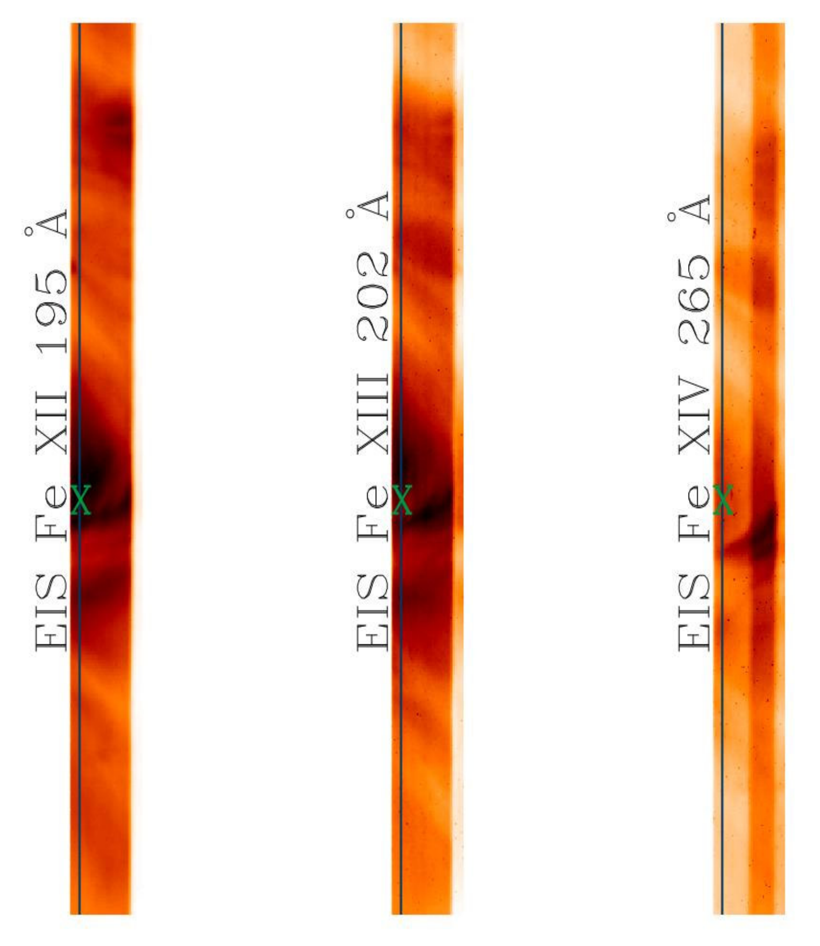
•Oscillations are best seen in Doppler shift

➔ let's analyse Hinode data!

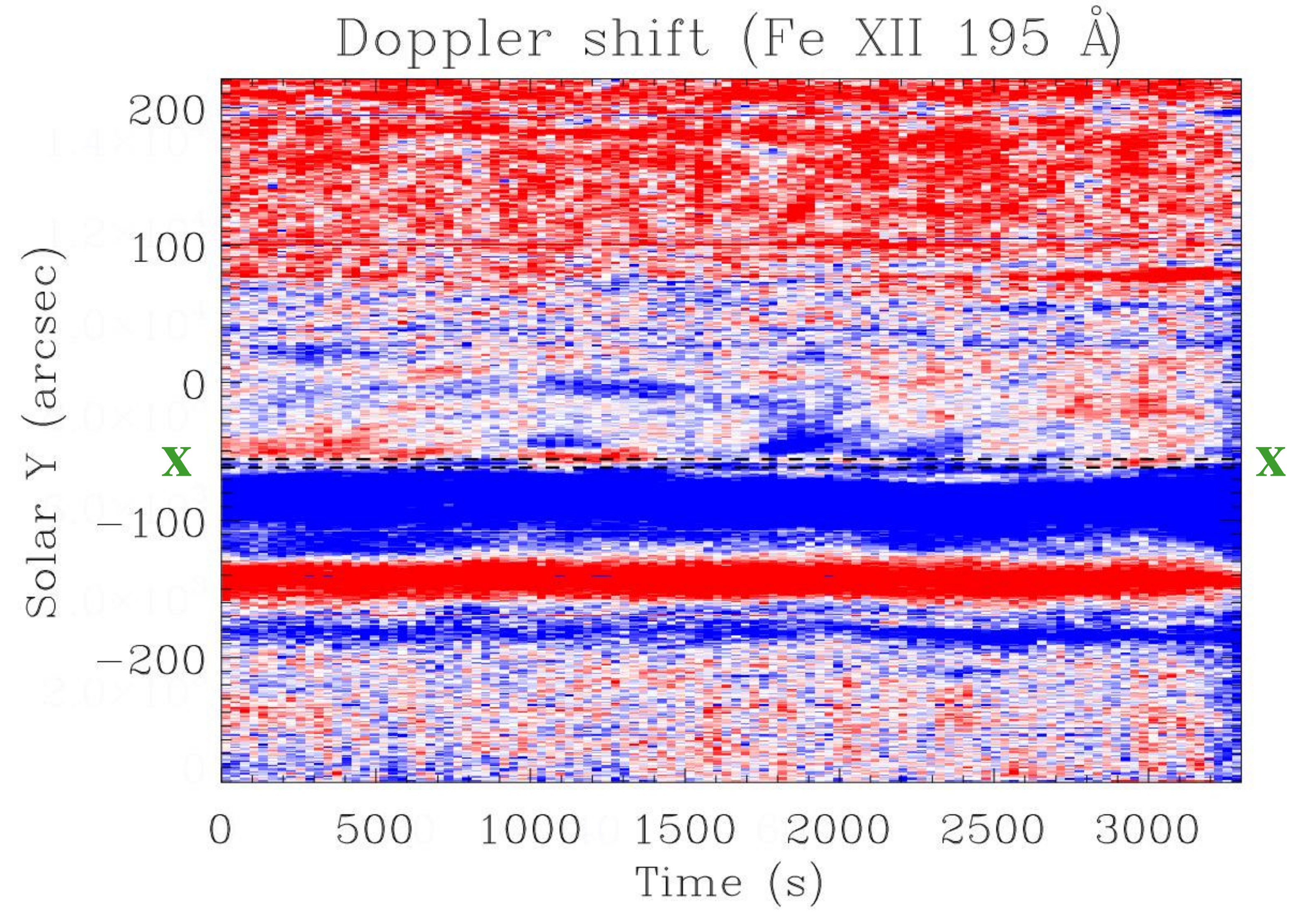


XRT and EIS observations

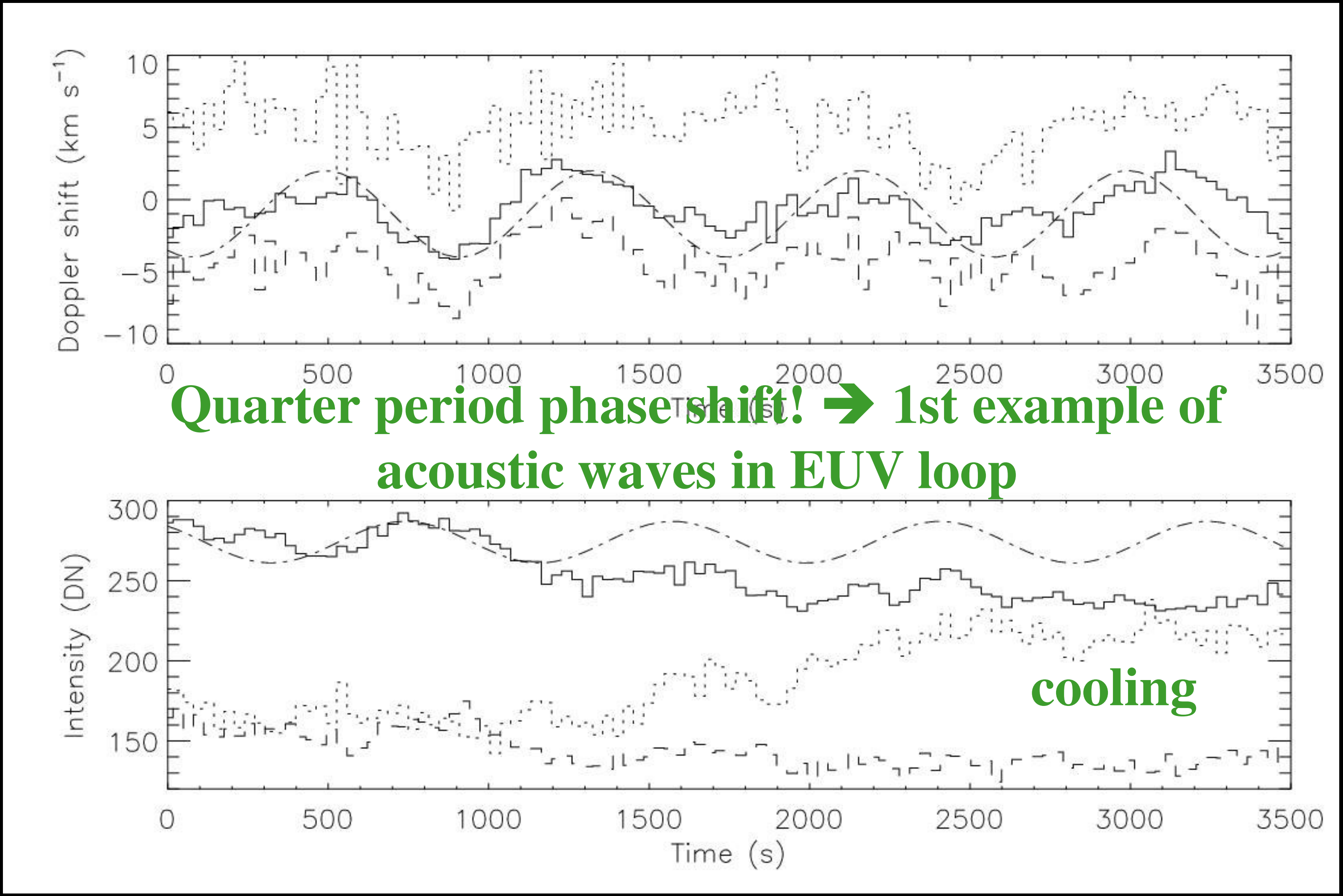




Doppler shift along the slit



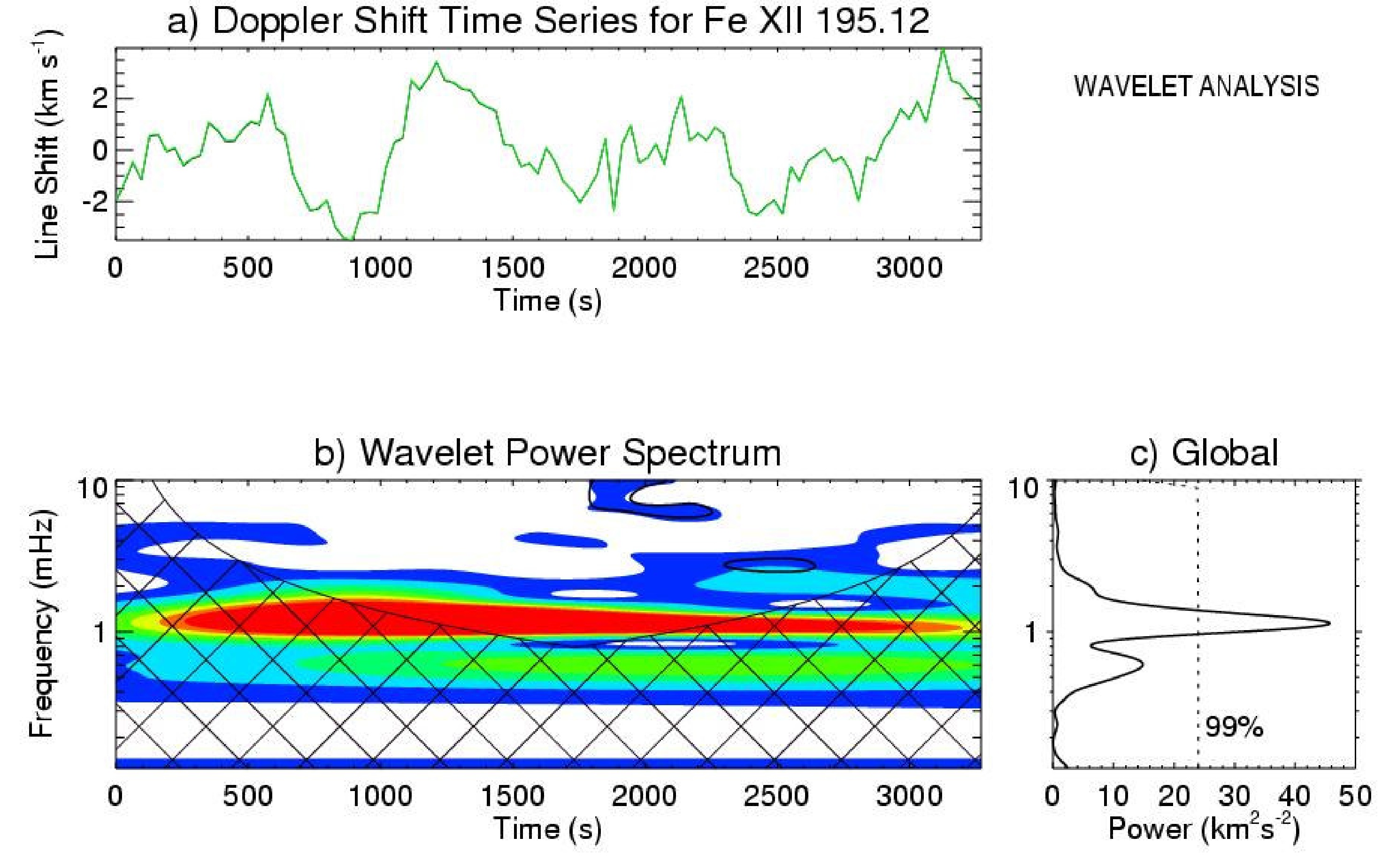
Doppler shift and intensity time series averaged over 5 pixels



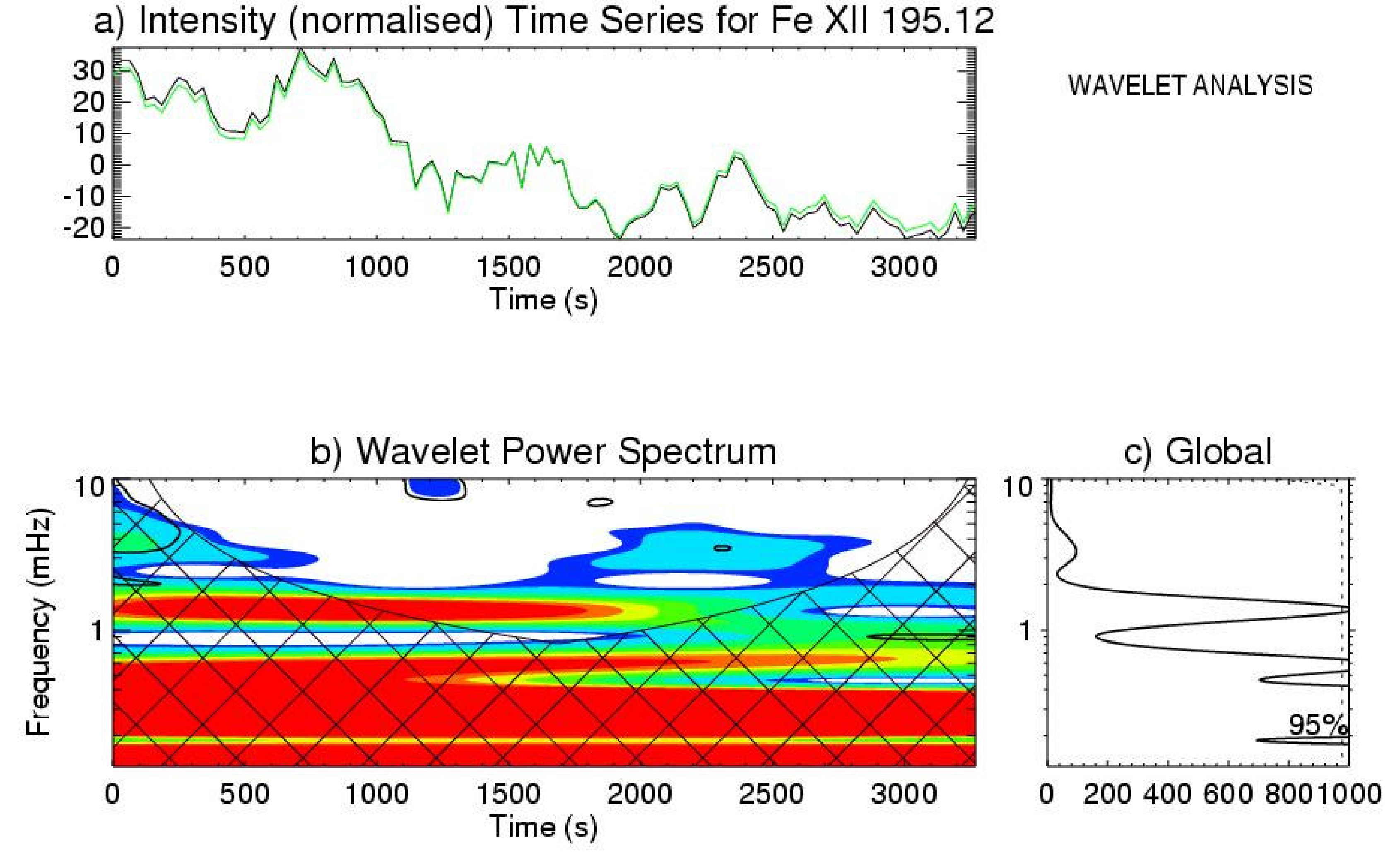
Quarter period phase shift! ➔ 1st example of acoustic waves in EUV loop

cooling

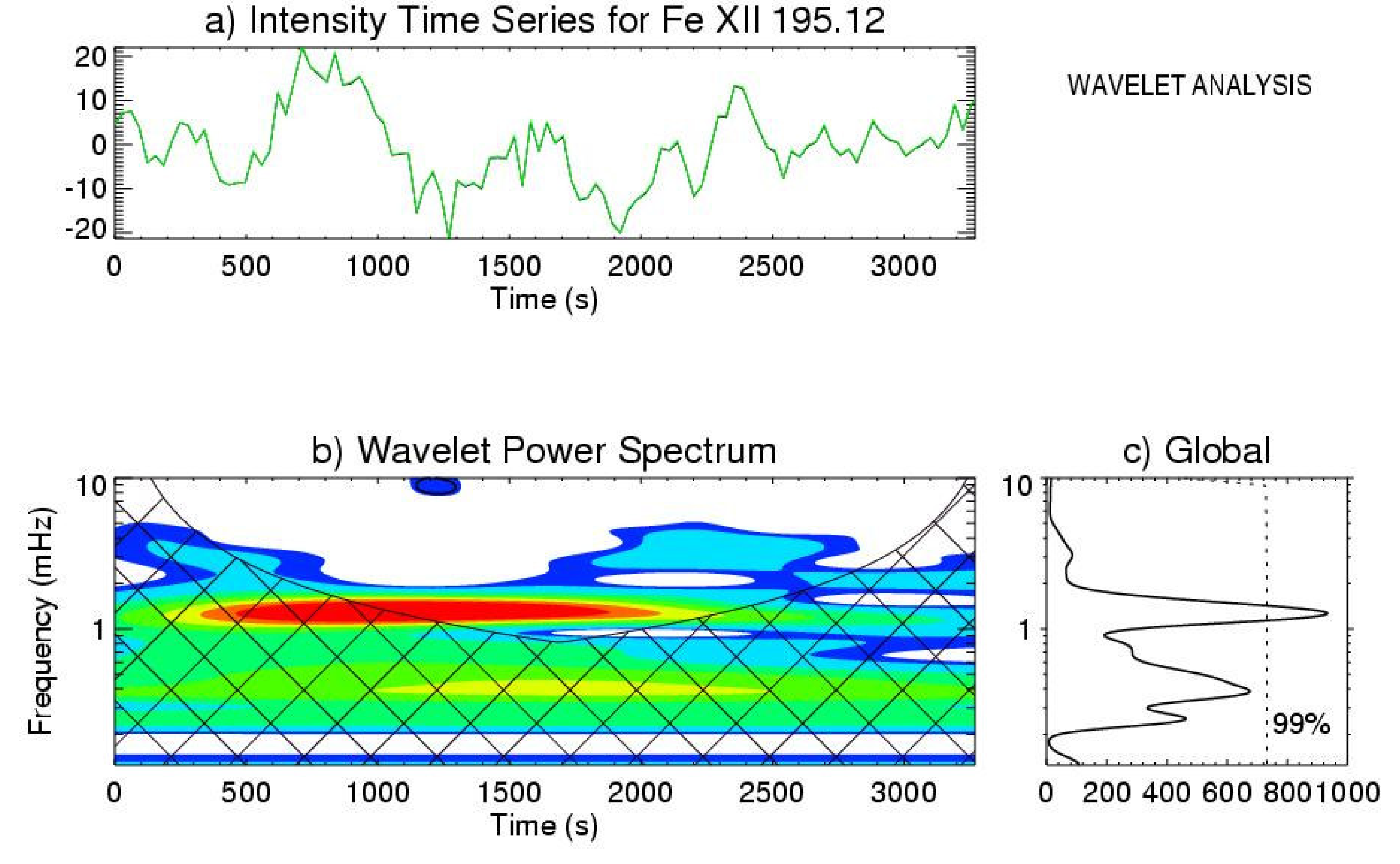
Properties of wave: Wavelet analysis →1.2mHz



Wavelet analysis (w. background cooling)



Wavelet analysis (cooling substructed): 1.2 mHz

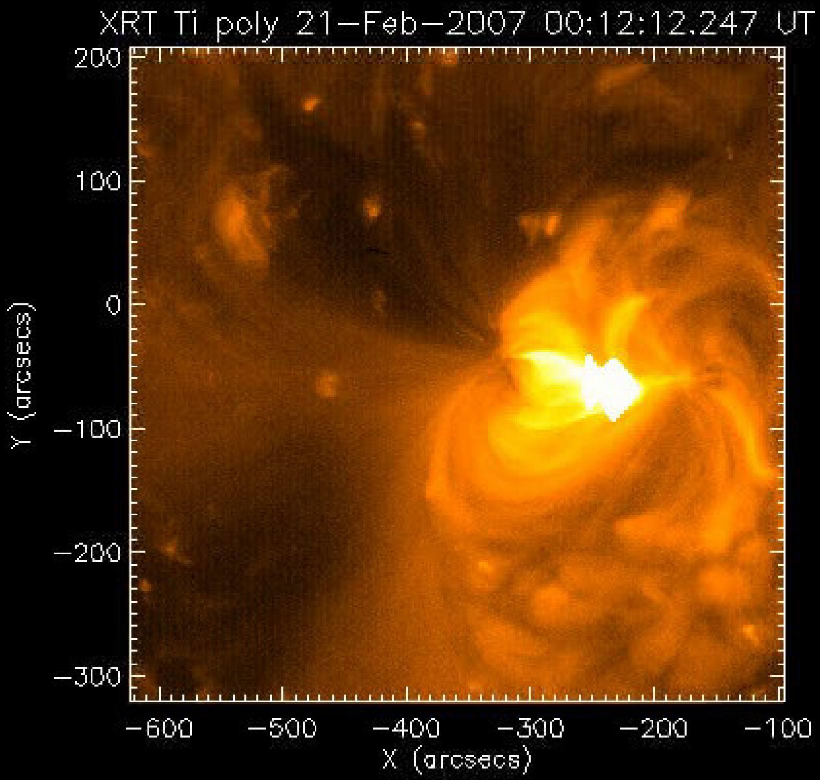


Interpretation

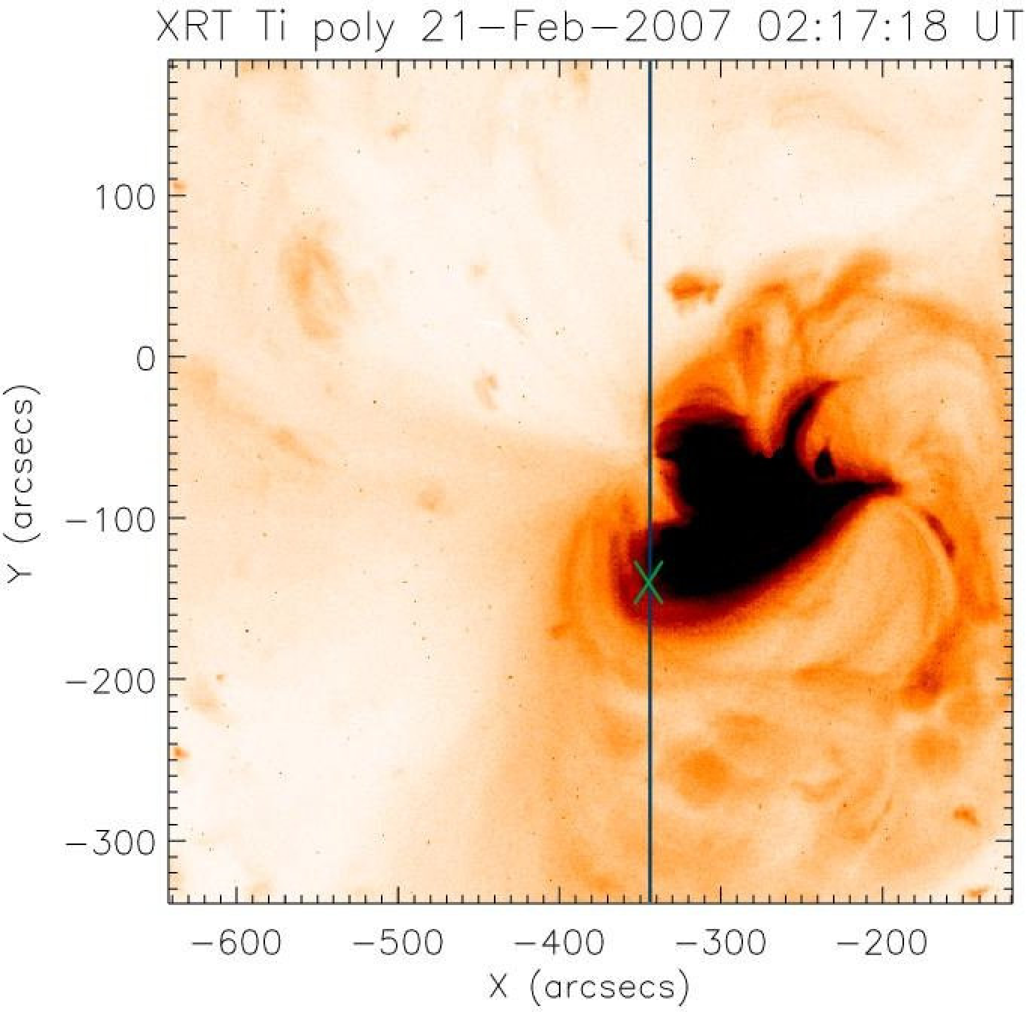
The XRT and EIS snapshots suggest that

- The oscillations seen by EIS in spectroscopy mode correspond to a footpoint region of a loop;
- The oscillations are preceded by a microflare near the footpoint.
- Intensity increase in lower temperature lines (Fe VIII) and decrease in higher temperature lines (Fe XII, FeXIII, Ca XIII)
- Quarter period phase shifts between the intensity and Doppler shift oscillations.
- Most likely interpretation: standing acoustic wave in an EUV loop

Quest: Reality check #2 Hinode/EIS observations (i.e. kink oscillation)

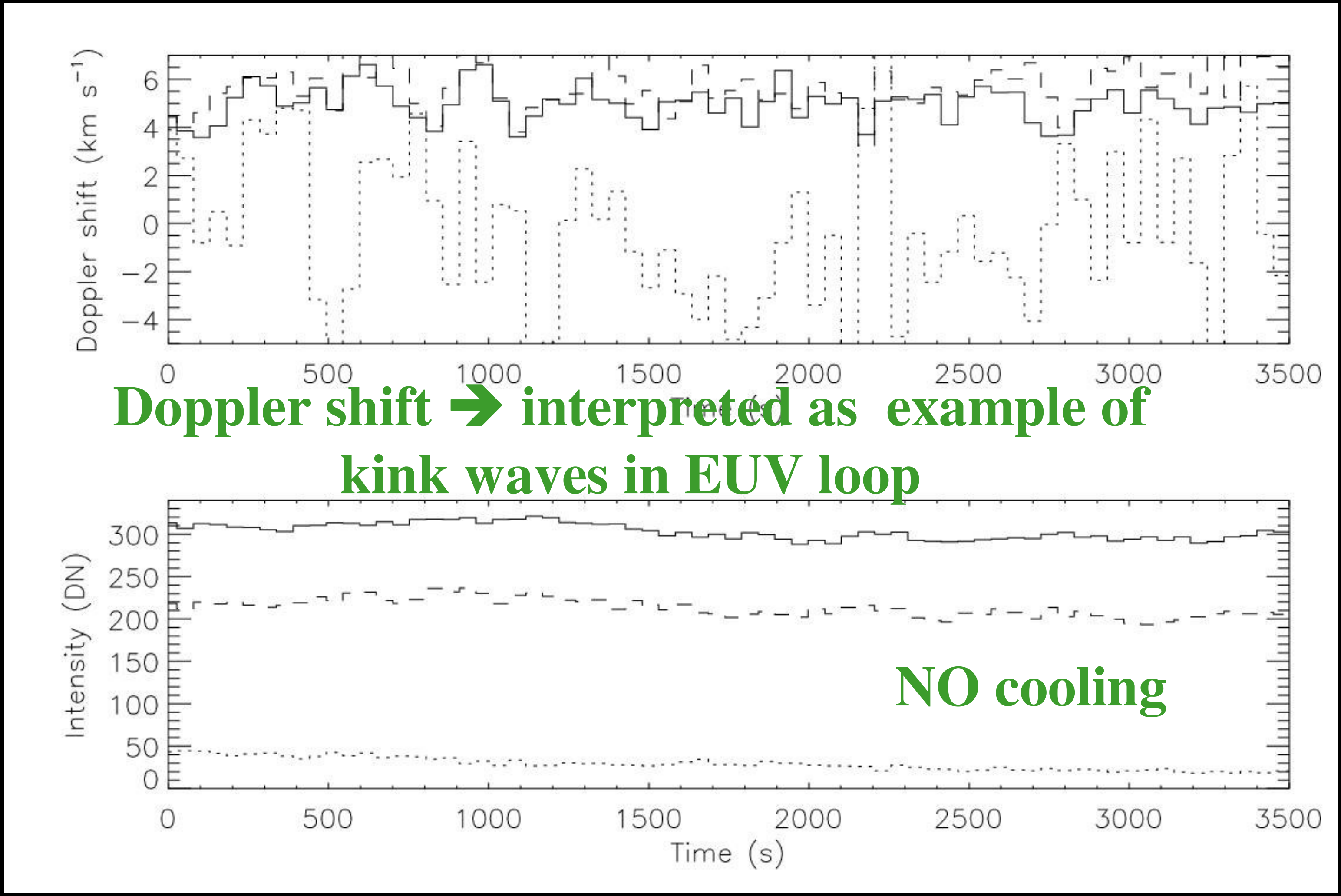


XRT and EIS observations



- Slit close to apex ➔ detected wave motion is likely to be transversal
- No EIS images were available

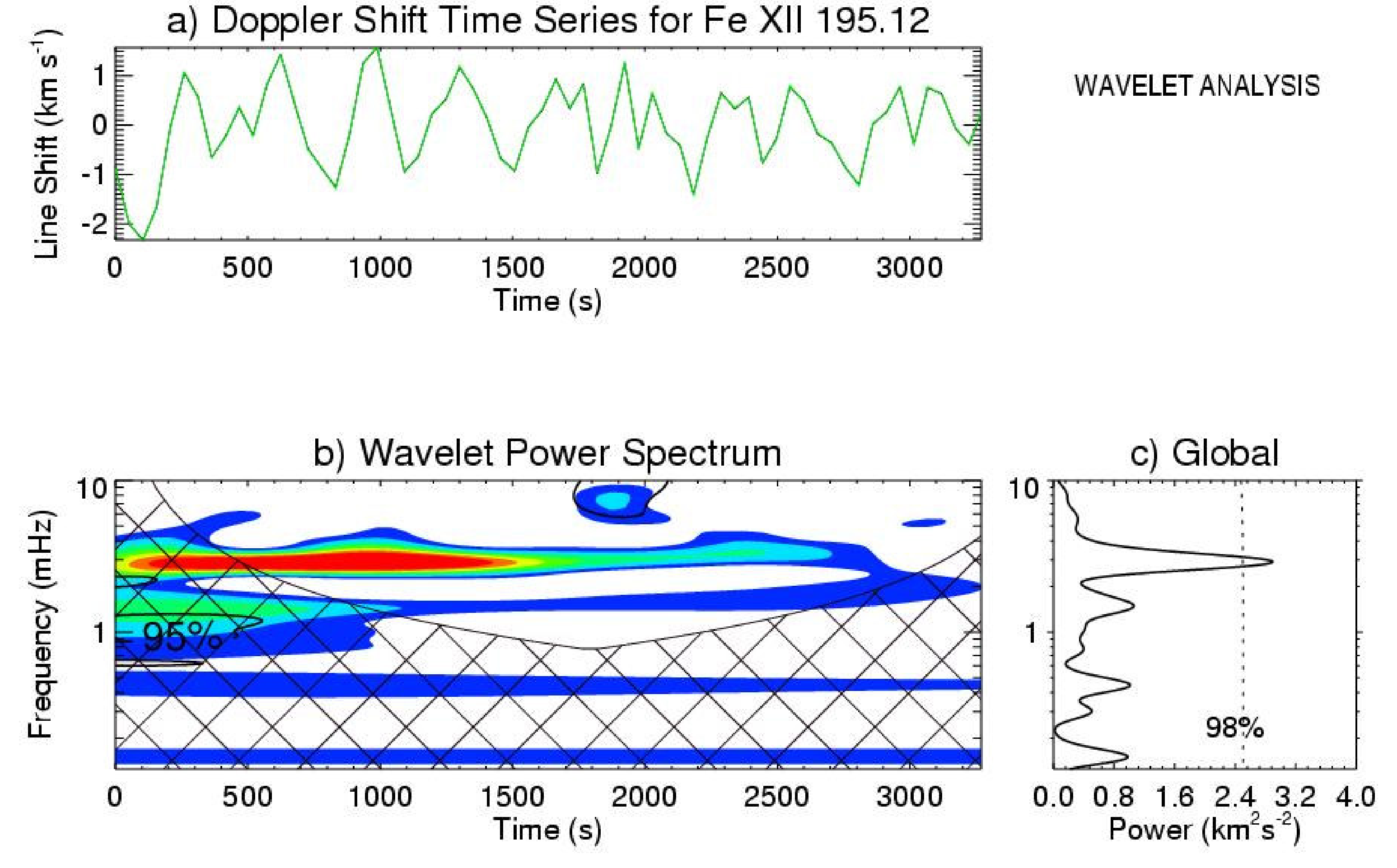
Doppler shift and intensity time series averaged over 5 pxs



Doppler shift ➔ interpreted as example of kink waves in EUV loop

NO cooling

Wavelet analysis: 3 mHz



Interpretation

- The XRT snapshots suggest that the oscillations seen by EIS correspond to an apex region of a loop crossed by the slit;
- Transverse motions should have a line-of-sight component
- Doppler and no intensity oscillations --> magnetoacoustic kink waves
- Magnetic field measurements using intensity ratios between different Fe lines: **B~10 G**

Summary so far…

- Hinode/XRT and Hinode/EIS observations in sit-and-stare mode are carried out to study oscillations in active region loops.
- Small amplitude oscillations are seen in different lines and pixels along the slit.
- Doppler shift and intensity oscillations (1 mHz) are detected near loop footpoints and are interpreted as standing longitudinal acoustic type waves.
- 3 mHz oscillations in the Doppler shift are present at near apex regions and are most likely to be kink waves. These waves have small amplitudes and have different origins from previously studied examples of flare-triggered oscillations. The oscillations are used to measure the magnetic field.

(Erdélyi & Taroyan A&A 2008)

Problem

- The diagnostic methods currently used in coronal seismology rely on the presence of *coherent* standing/propagating waves
- The presence of such waves is not guaranteed!

New method

Analysis of Doppler shift time series as a diagnostic tool

(What we propose to do when we do not see waves and oscillations)

Simple loop model: linear ideal (M)HD

$0 < s < L$

$$\text{(Wave operator) } v = -\frac{\partial}{\partial s} \text{ Heating}(t,s)$$

Heating(t,s) = Σ Dirac delta or finite duration random pulses

Boundary conditions at s=0, s=L

Green's function

(Wave operator) $G(t,s;\tau,\xi) = \delta(t-\tau)\,\delta(s-\xi)$

Boundary conditions at $s=0$, $s=L$

↓

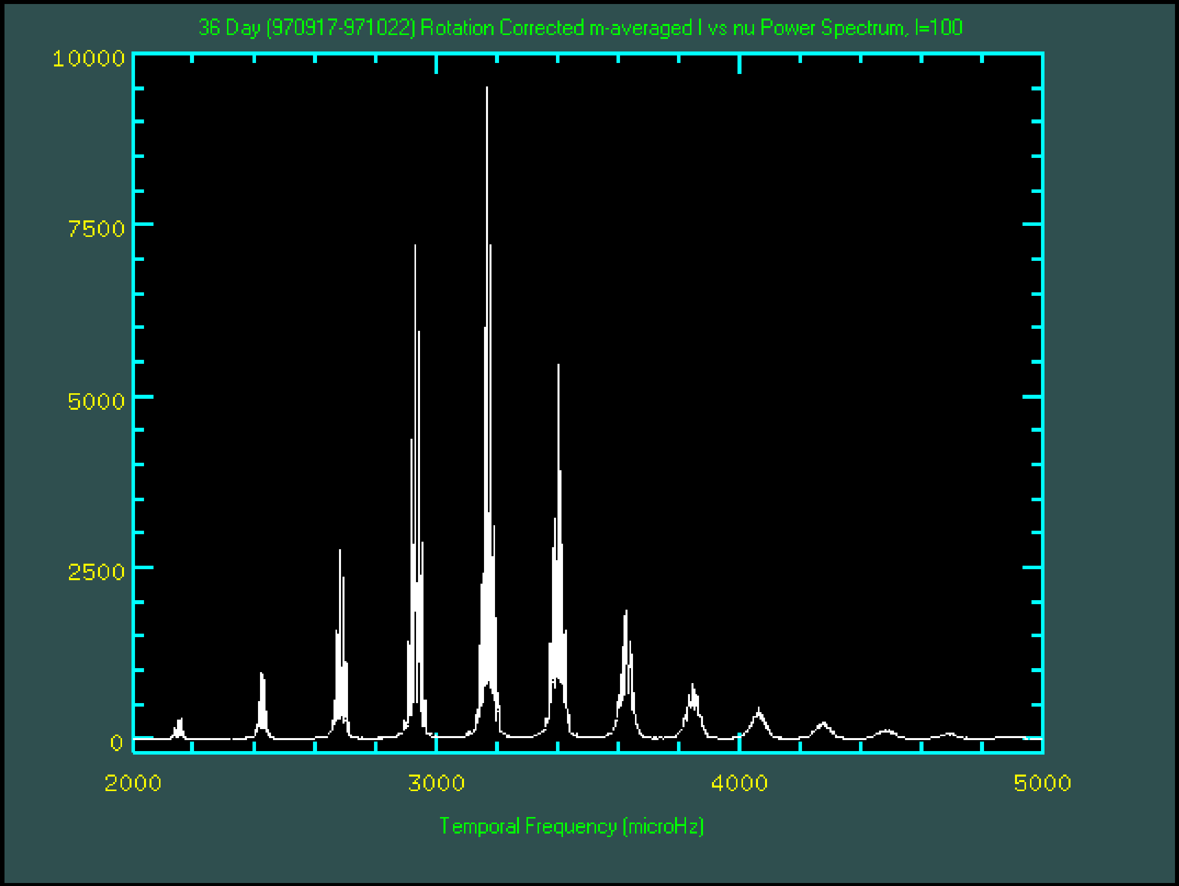
Solution uniquely determined by the Green's function, BCs and the random Heating(t,s)

Results of the analytical study

- The Fourier analysis shows that the power spectrum for the time series of **velocity has peaks at the frequencies of the standing waves**(!) during random heating

- The height and shape of the peaks depends on the spatio-temporal properties (e.g., length, duration, spatial distribution, etc.) of heating

Analogy with helioseismology

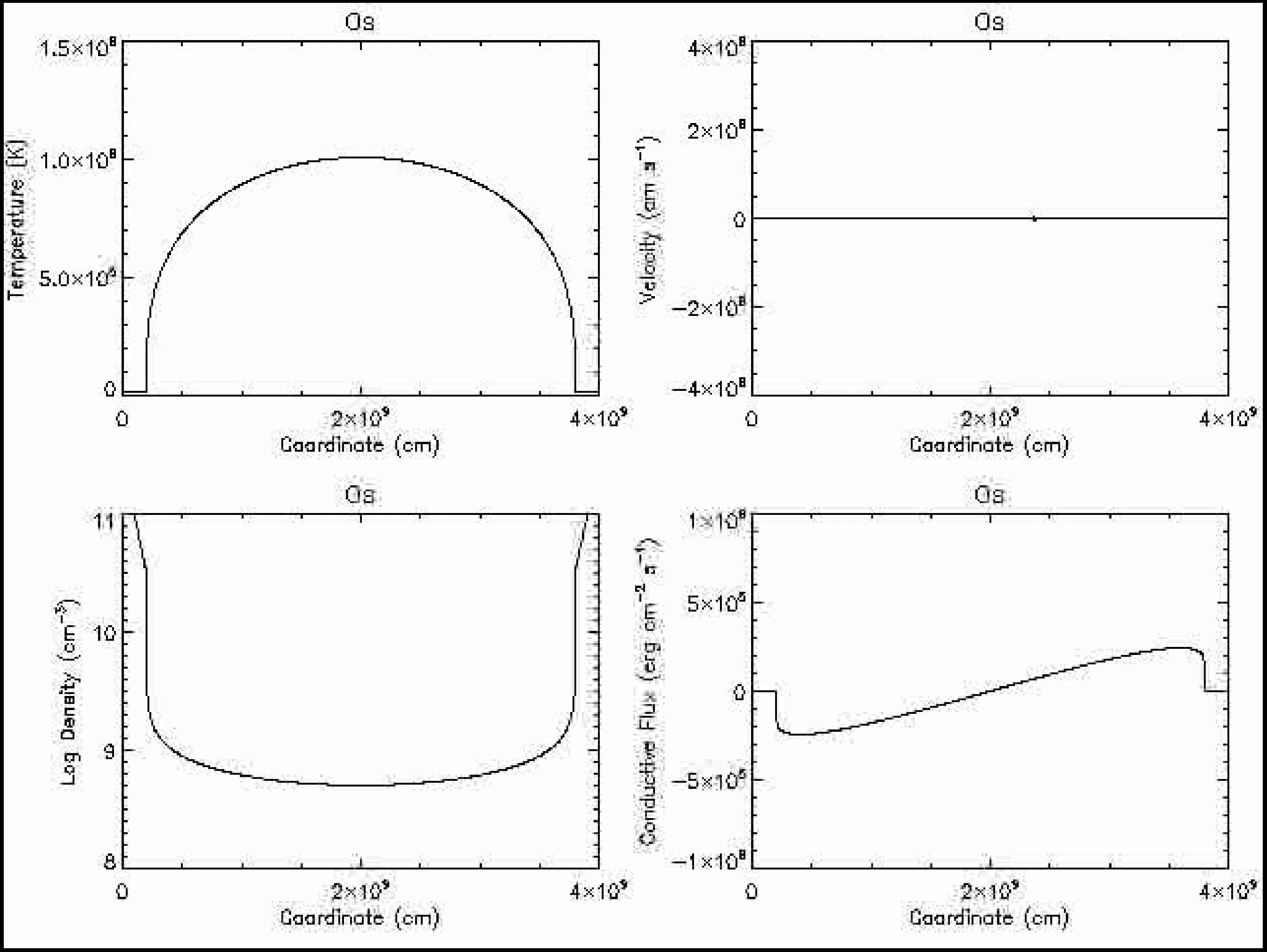


Corona?

Major problems:

- **Damping**
- **Localisation**
- **Limited observation duration**

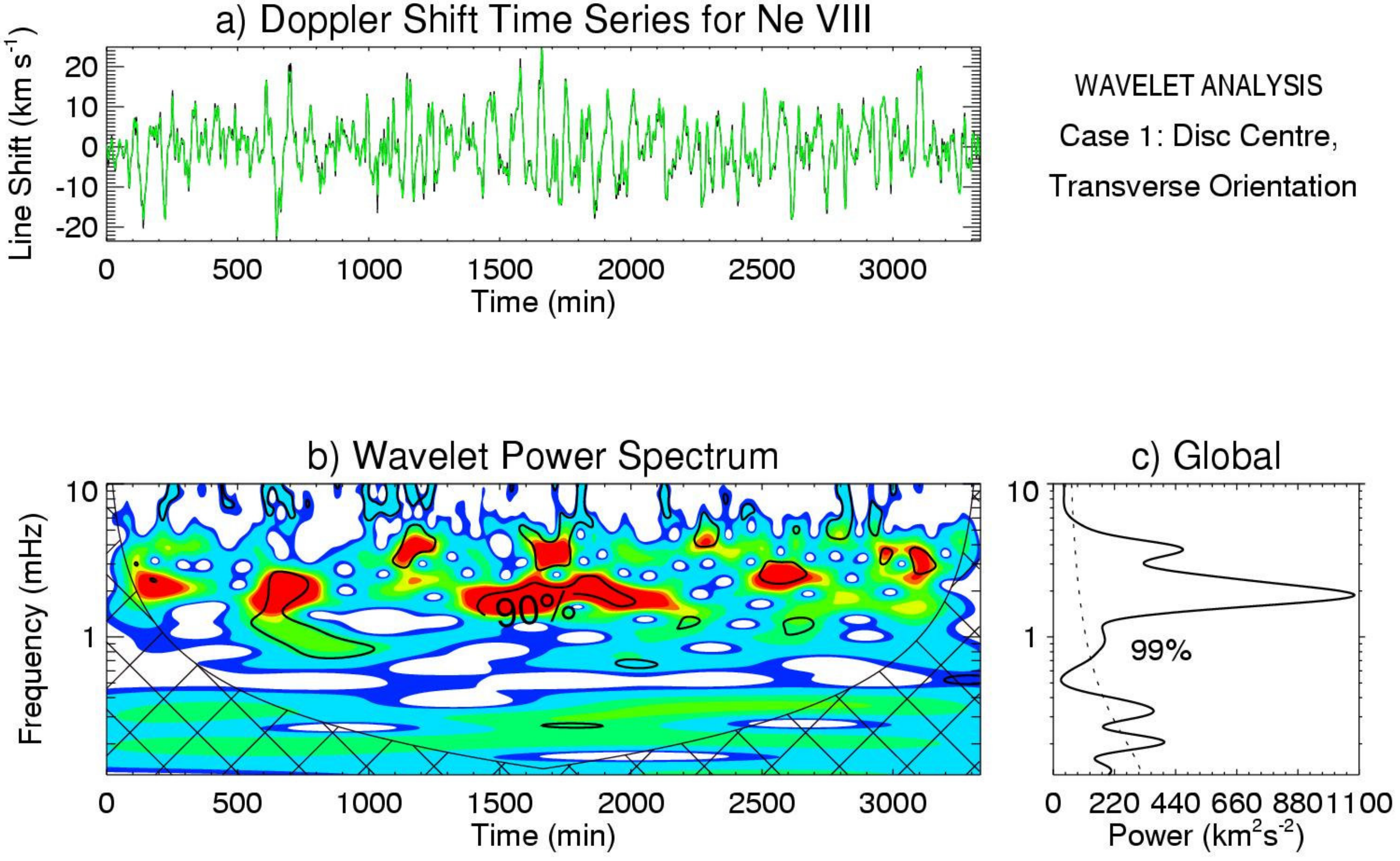
Case study: Results of a numerical study



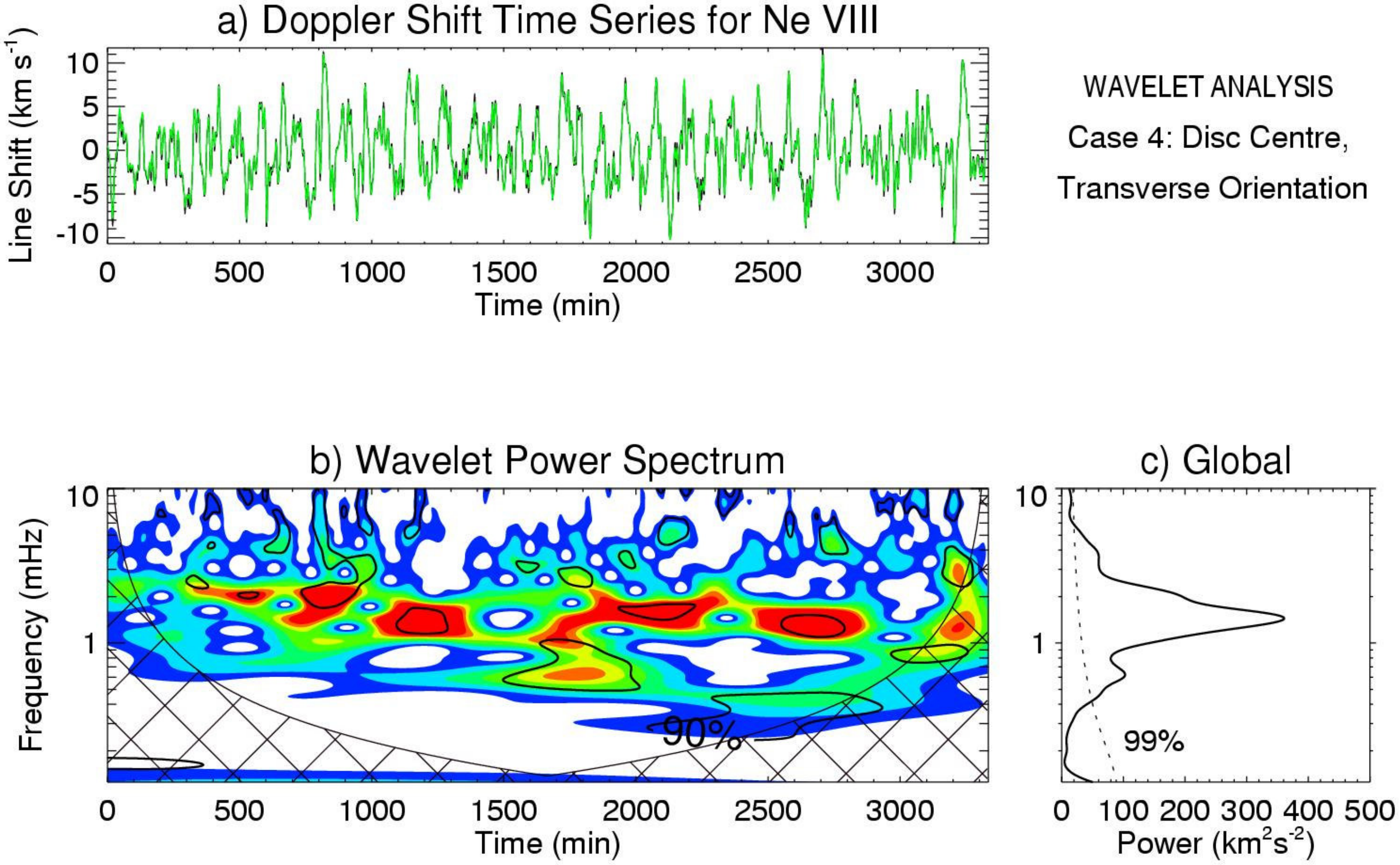
Line synthesis

- Ne VIII (~0.8 MK), Mg X (~1.2 MK) resonant lines
- Emissivities along the loop
- Doppler width of the line
- Projection of bulk velocity on the line of sight
- Line broadening function
- Total intensity

Line profiles



Uniformly random heating

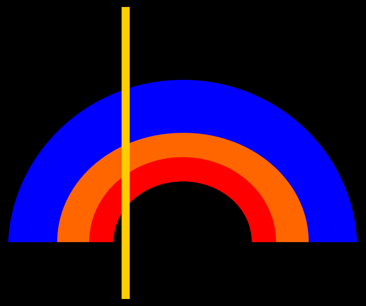

a) Doppler Shift Time Series for Ne VIII

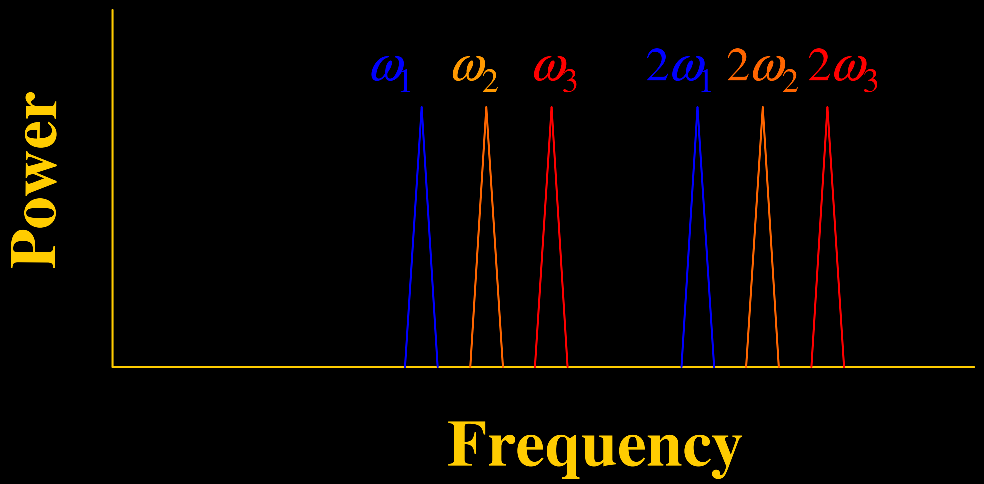
b) Wavelet Power Spectrum

c) Global

Footpoint random heating

Multi-threaded loops





Distribution of frequencies would allow to derive info about fine-structure of the system

What we propose to do when we do not see waves and oscillations

(Taroyan *et al*. A&A 2007)

The power spectra to be used to

- Estimate the energies involved in the random pulses
- Study the multi-thermal structure of the loops

- Determine average loop temperature
- Distinguish uniformly heated loops from loops heated at their footpoints

The power spectrum analysis of the Doppler shift time-series for coronal line profiles is a potentially powerful tool for the diagnostics of the solar coronal plasma