Dynamic magneto-seismology: Avenues and roadblocks

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ISSI Meeting 2017

The Leverhulme Trust

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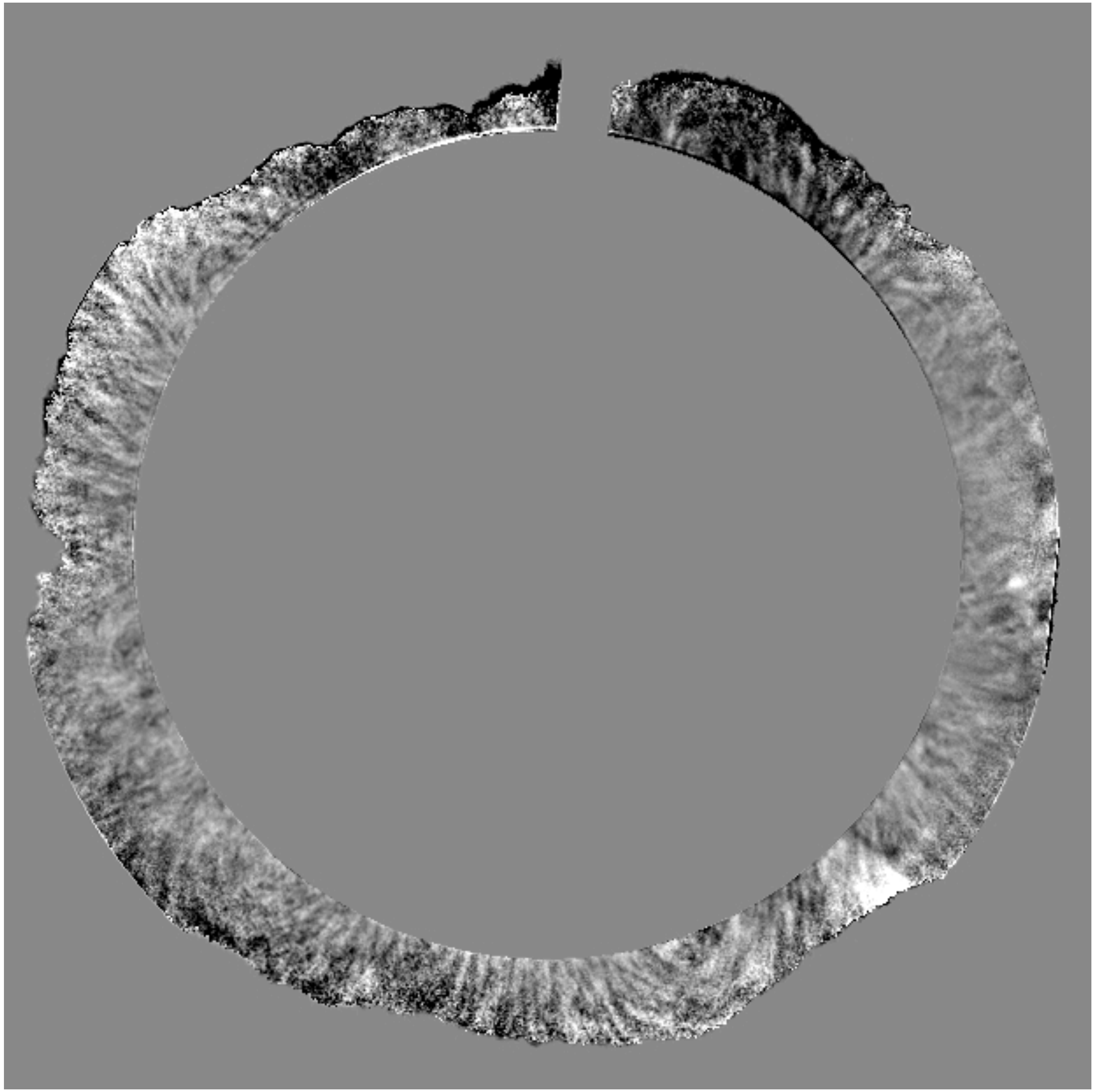
Outline

- **Avenues with CoMP Doppler velocities**
  - Power spectra & wave damping
  - Coronal seismology with propagating waves
    - Magnetic fields
    - Flows in the corona

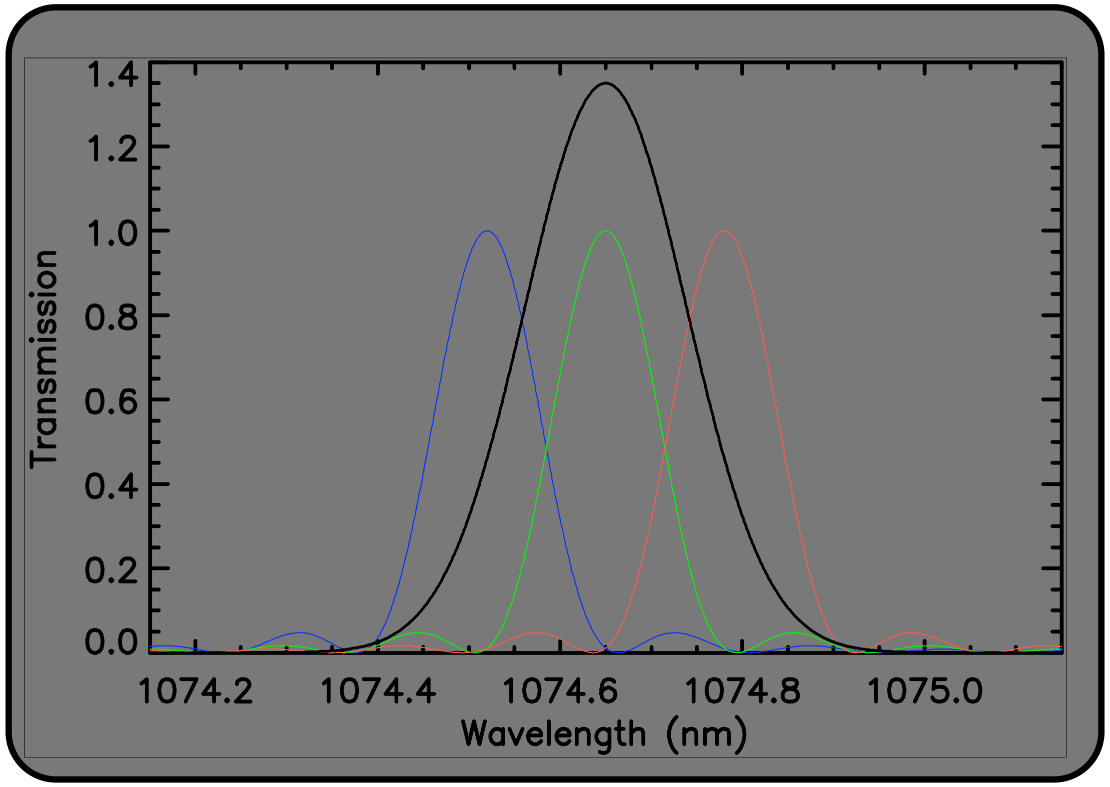
- **Roadblocks in the Chromosphere(?)**
  - Attempts at spicule seismology
  - Attempts at fibril seismology

How prevalent are Alfvénic waves in the corona?



Clearly everywhere - CoMP is a unique tool to study them!

CoMP basics & Data products

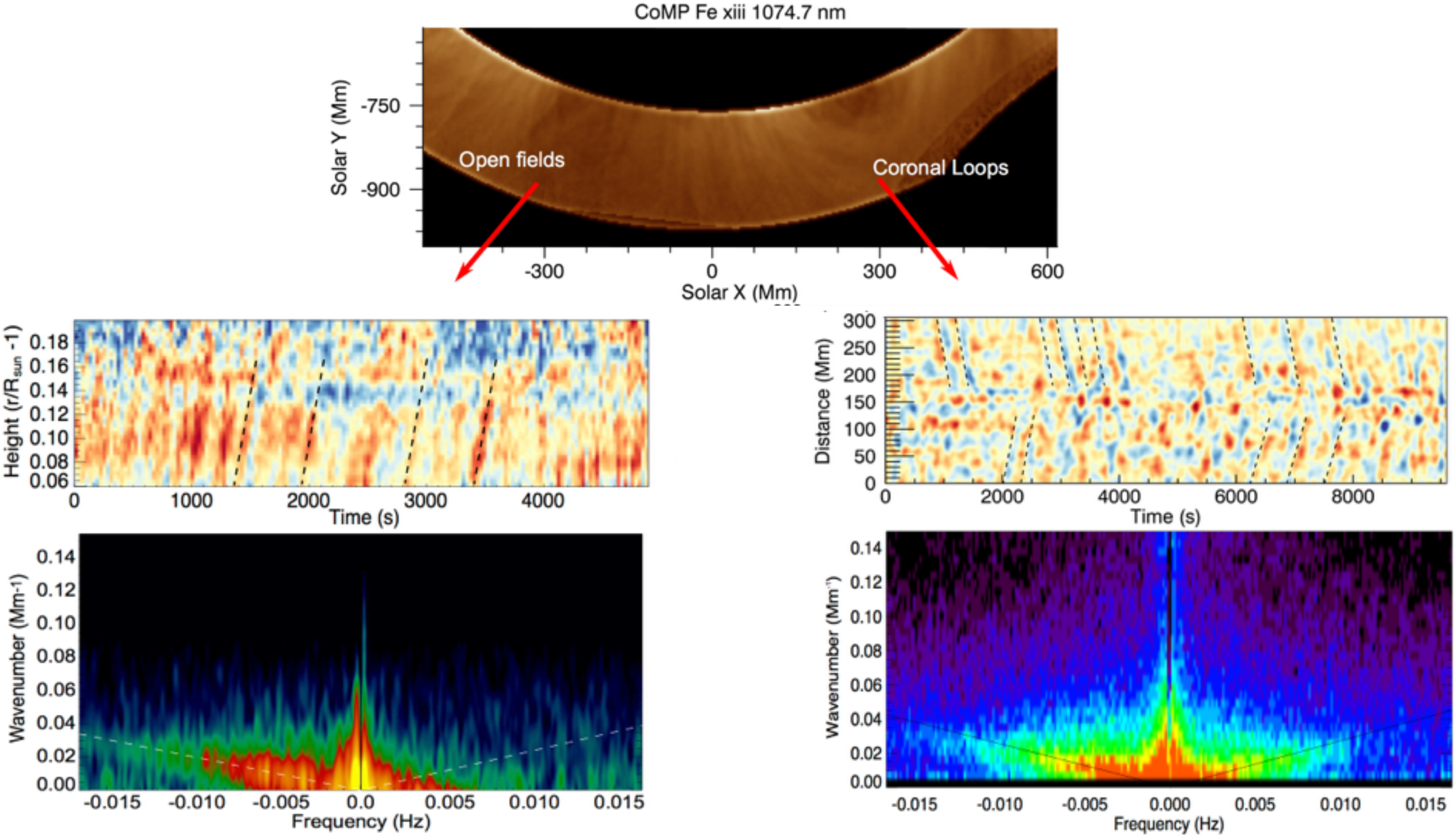


$$v = \frac{w^2}{4d}(a-b),$$
$$w = \sqrt{\frac{-2d^2}{a+b}}, \quad a = \ln\frac{I_3}{I_2}, \qquad b = \ln\frac{I_1}{I_2}$$
$$i = I_2 \exp\frac{v^2}{w^2},$$

Solar rotation removed from Doppler shift by 5th order polynomial fit to east-west trend (Tian et al. 2013).

Infrared doppler measurements

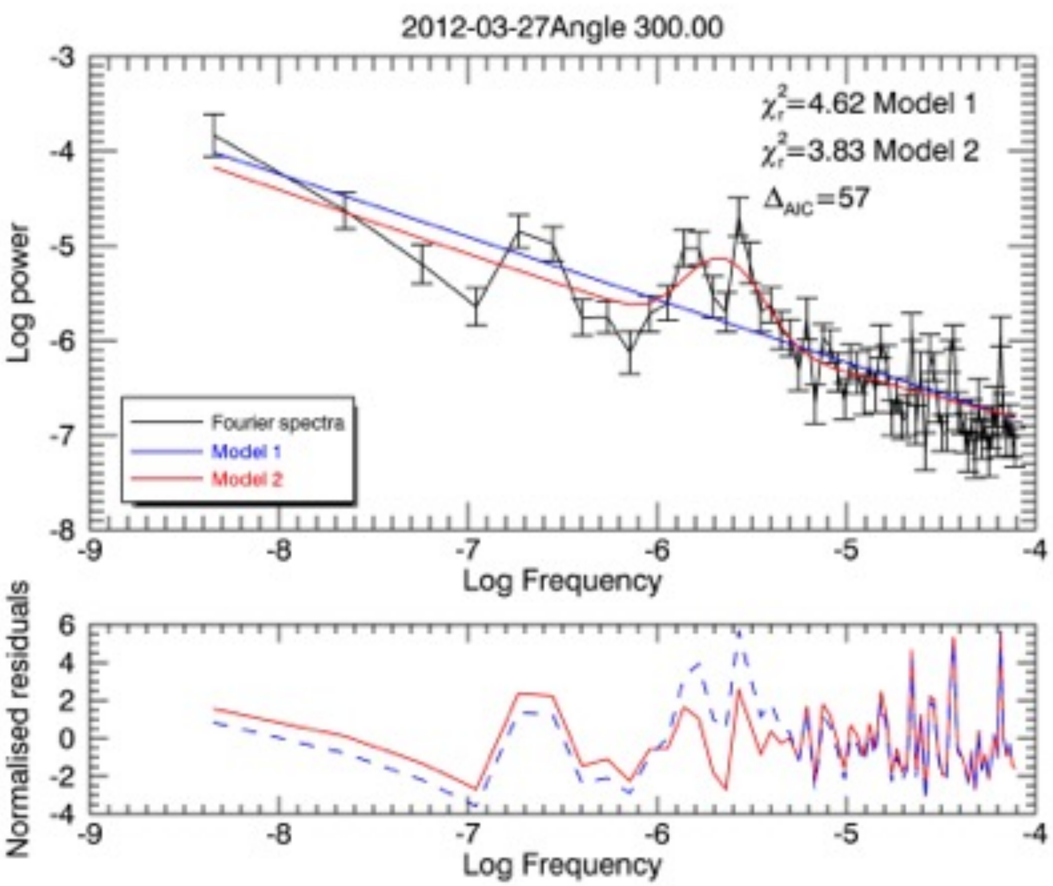
Velocity signal appears to follow magnetic field and propagate at average local Alfvén speed (Tomczyk et al., 2007, Tomczyk & McIntosh 2009).

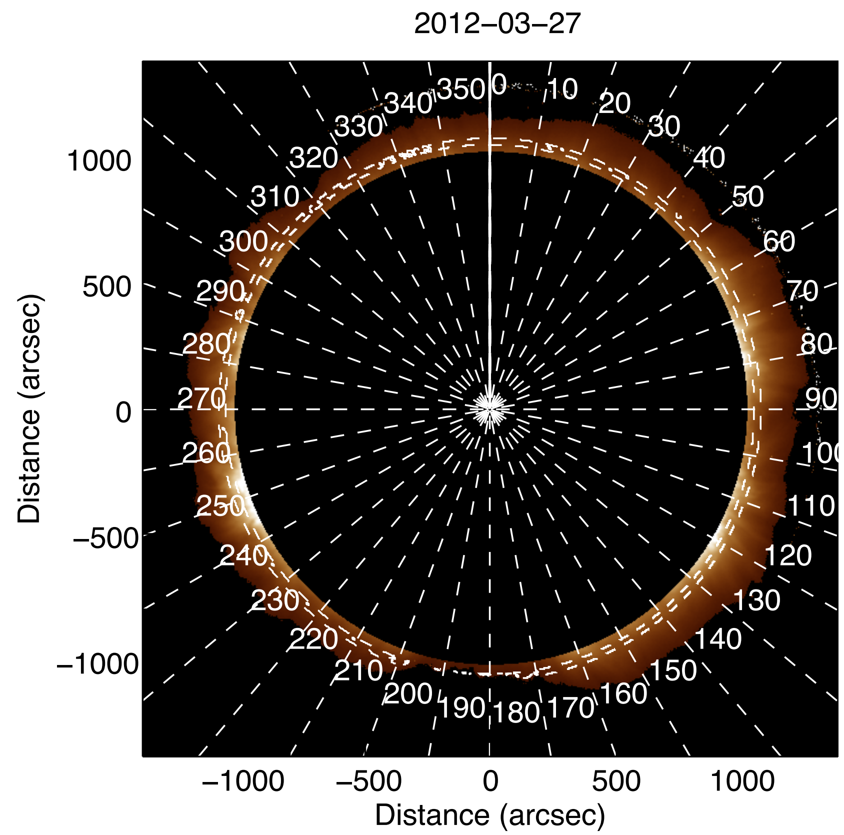


Predominantly uni-directional - evidence for frequency dependent reflection.

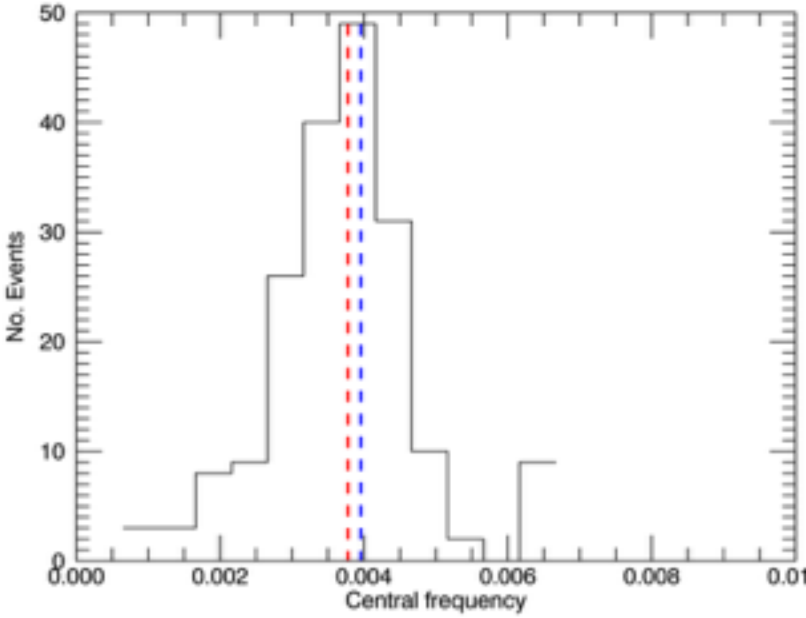
Bi-directional - evidence for frequency dependent damping (Verth et al., 2011).

Relation to waves in SDO/AIA

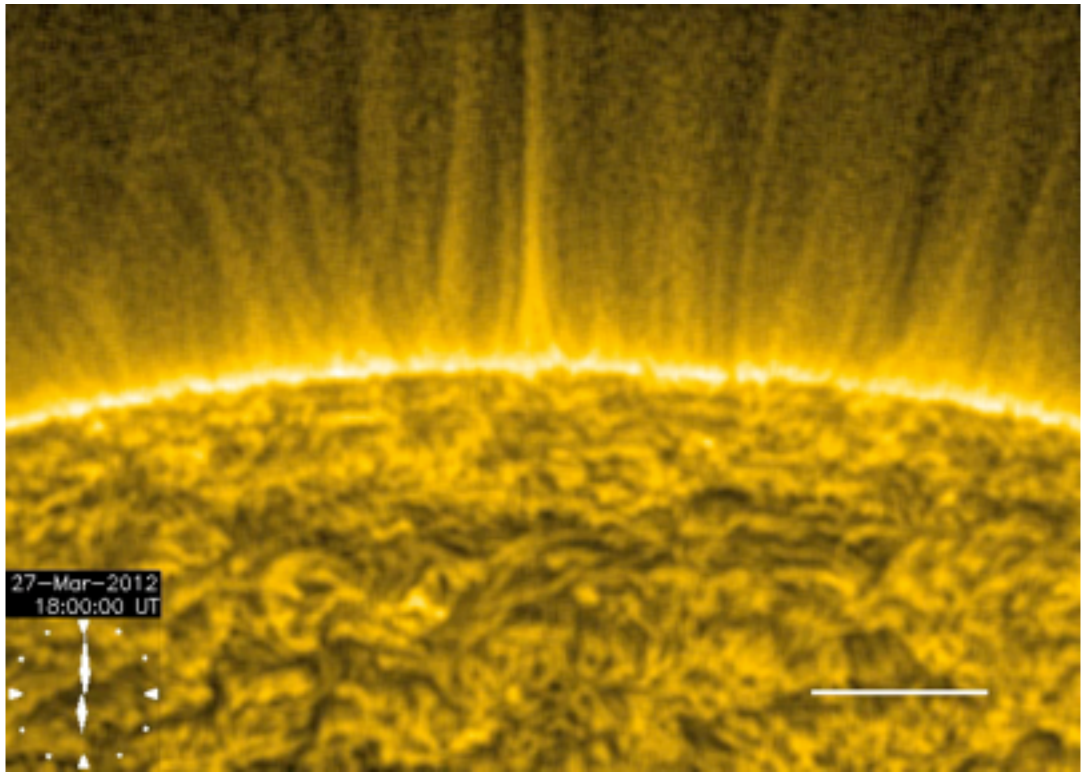


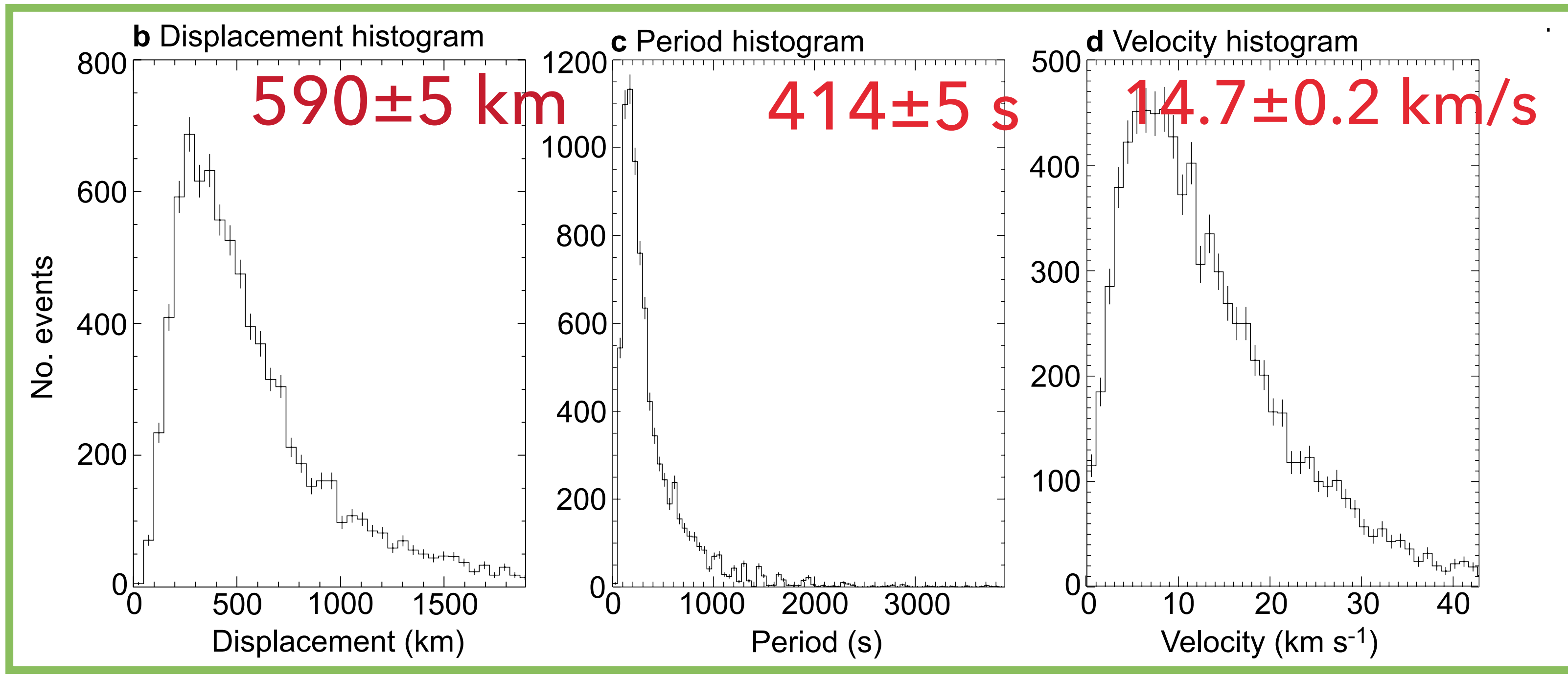


Morton (2017), In Prep



>90% show enhancement of power.



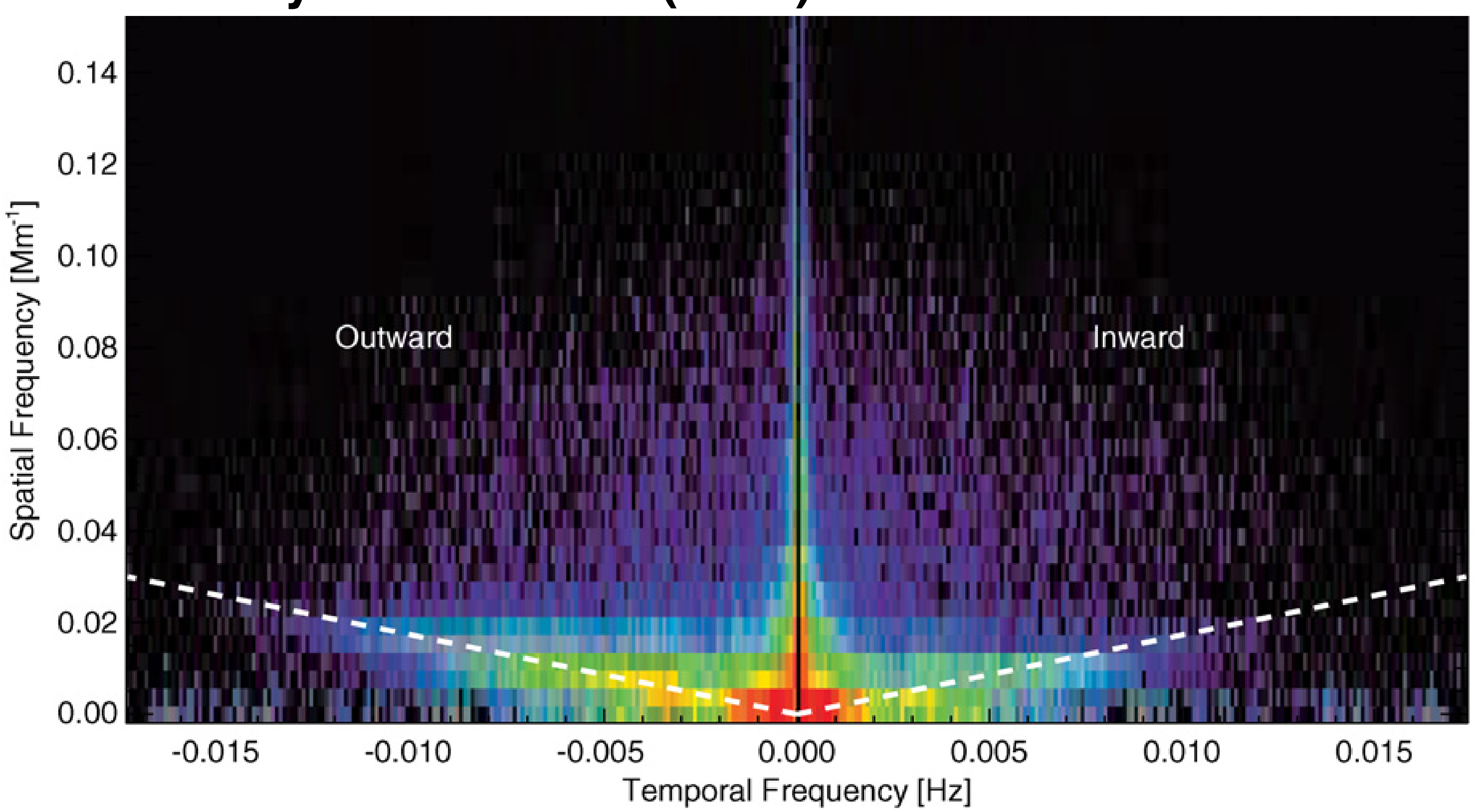


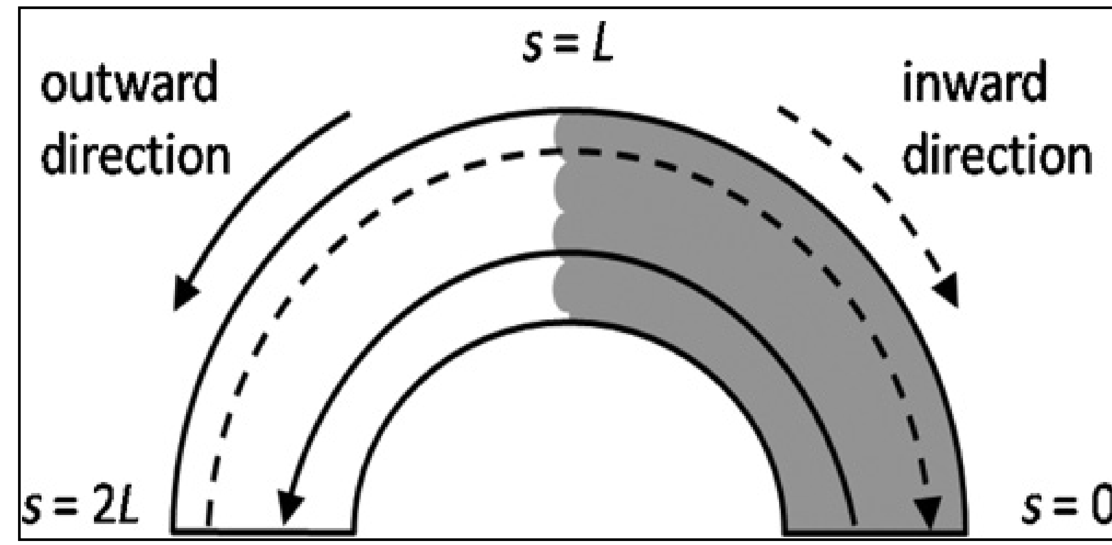
Damping of coronal waves

Opportunity to probe damping length-scales and plasma parameters.

One published example to date (many good candidates in CoMP archive - so opportunity for study, more man power needed!!).

Tomczyk & McIntosh (2009)





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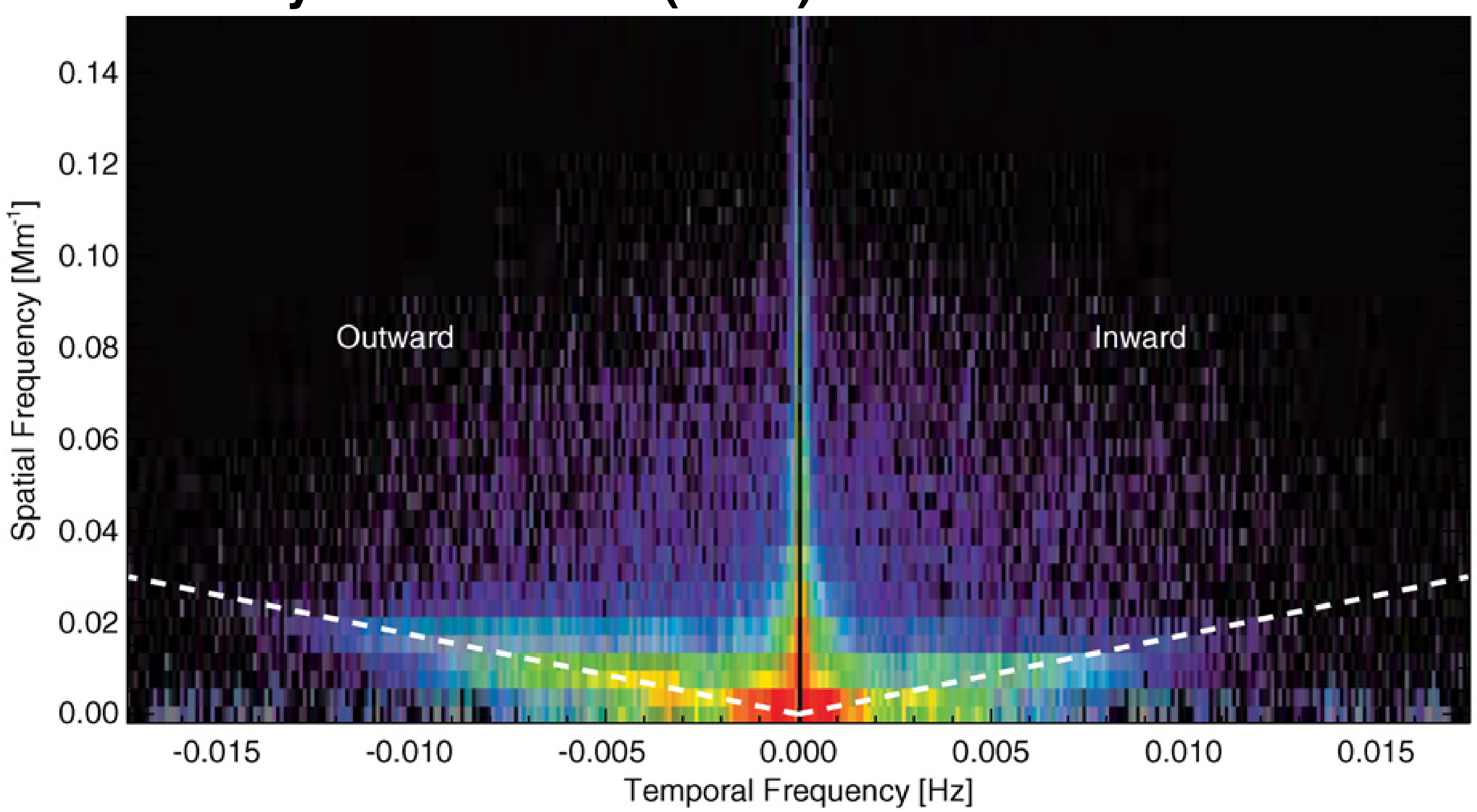


Verth et al (2010)

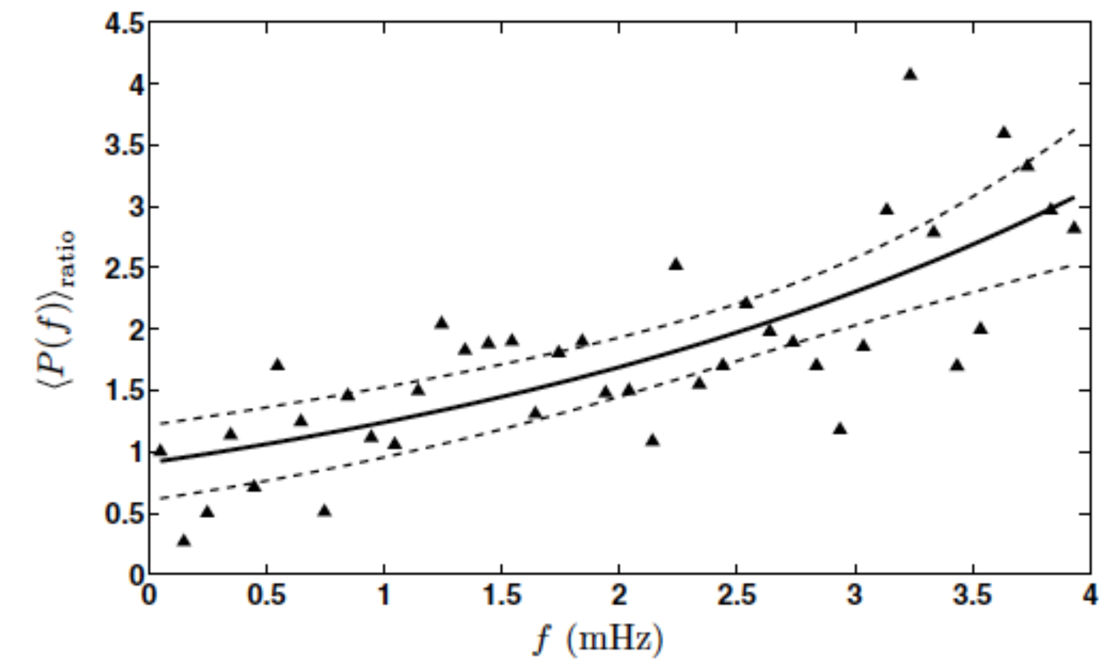
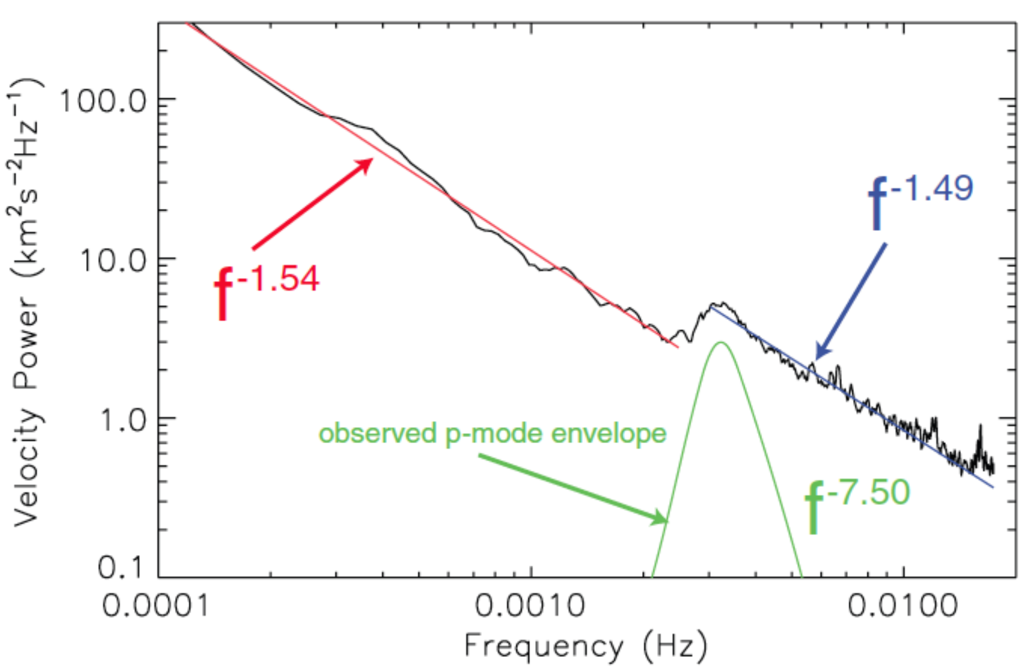


Figure 2. Power ratio against frequency best fit using Equation (7) with CoMP data. Fixed parameters are $v_{ph} = 0.6$ Mm s^{-1} and $L = 250$ Mm. Best-estimated parameters are $P_{out}/P_{in} = 0.91$ and $\xi_E = 2.69$ (solid line). The 95% confidence intervals for the simultaneous functional bounds are shown by the dashed lines. Note that in the CoMP data S/N decreases with increasing frequency.



Least squares-fit of:

$$\langle P(f)\rangle_{ratio} = \frac{P_{out}(f)}{P_{in}(f)} \exp\left(\frac{2L}{v_{ph}\xi_E} f\right)$$

Verwichte et al (2013) also examine results.

A quick foray into statistics

In general, 'standard' techniques used in data analysis assume uncertainties of measurements are Normally distributed.

Probably true if averaging over many measurements!

In general not true - ignorance can lead to poor estimate of results and confidence levels.

Example

Fitting a function to data points.

Maximise Likelihood

$$L(\theta, x_i) = \prod_{i=1}^{n} f(x_i \mid \theta)$$

For Normally distributed data:

$$L(\theta, x_i) = \prod_{i=1}^{n} (2\pi\sigma_i^2)^{-1/2} \exp\left(-\frac{(O(y_i) - M(\theta, x_i))^2}{\sigma_i^2} \right)$$

i.e., minimise normalised sum of squared errors.

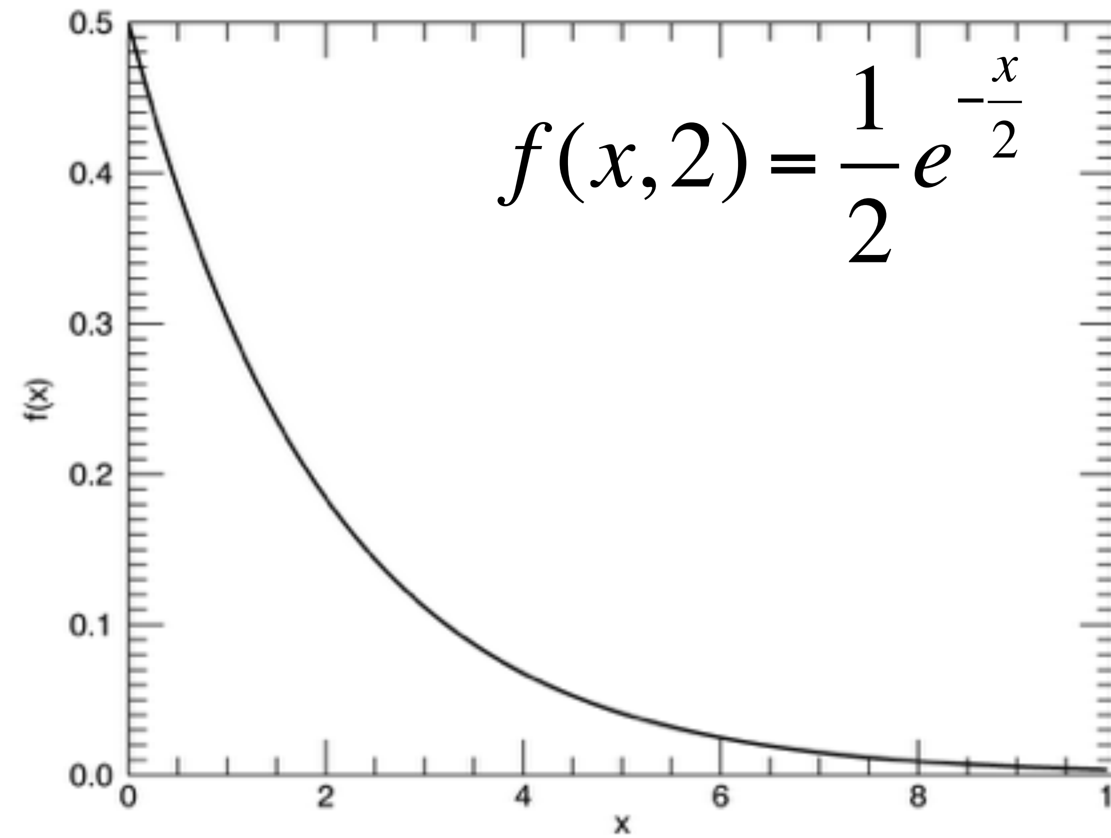
A quick foray into statistics (Time-series)

When using discrete Fourier transforms, using N observations to estimate N parameters.

Hence DFT not a consistent estimator of power (i.e., N increases, accuracy doesn't.)

Real & Imaginary DFT terms $\sim N(0,\sigma^2)$

$$\hat{P}(f_j) \propto P(f_j)\frac{\chi_2^2}{2}$$



Variance scales with P! For power law type spectra in corona, uncertainties are heteroscedastic.

To reduce variance:

- smooth power spectrum (average f bins) - lose resolution
- average over number of time-series.

Averaging over large number of series, uncertainty of mean tends to Normal distribution (Central limit theorem).

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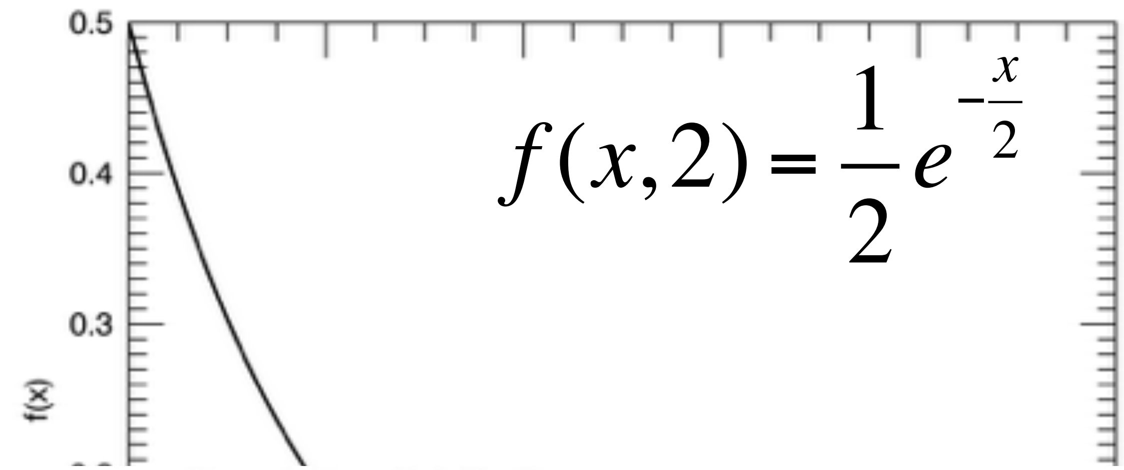

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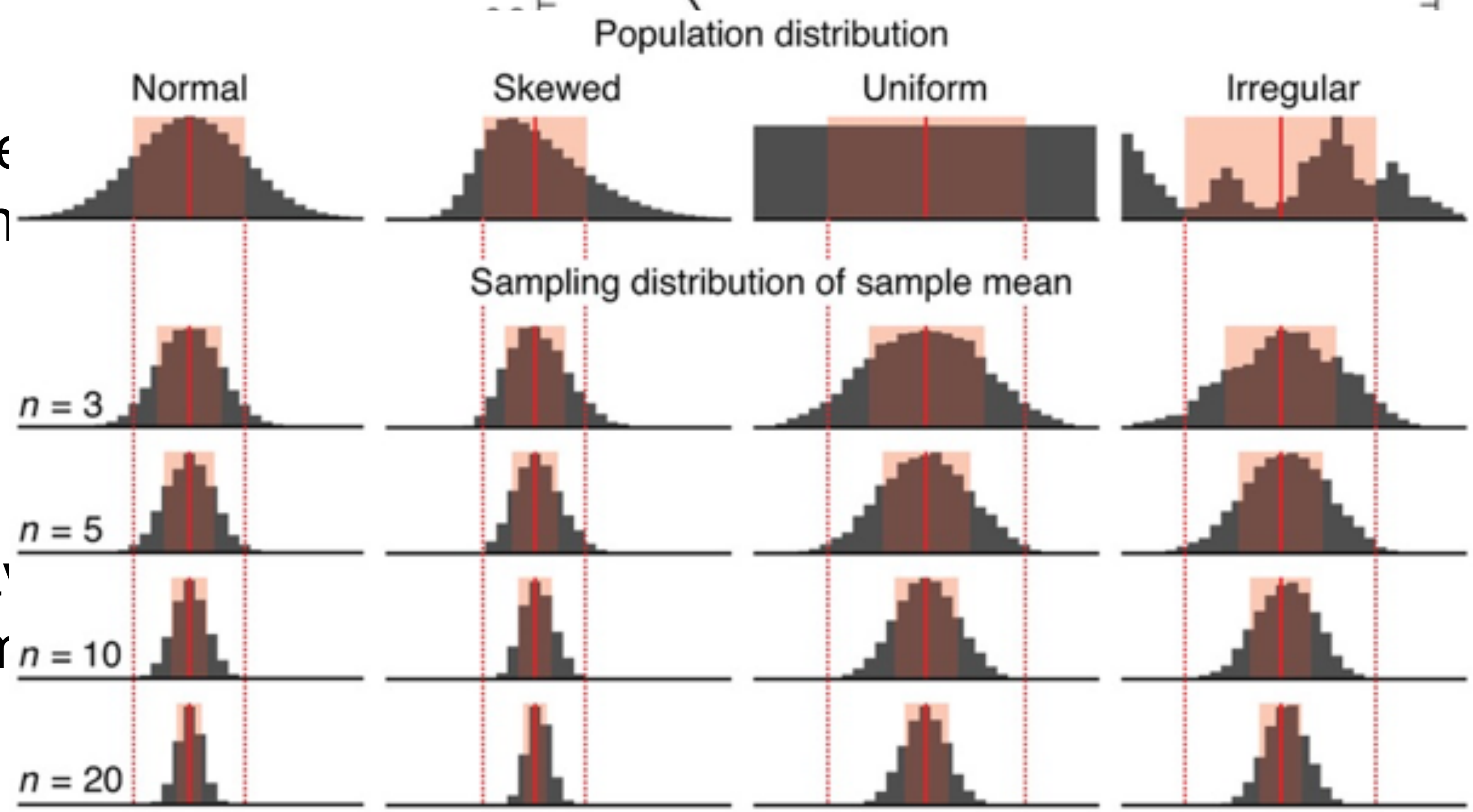

To reduce variance:

  * smooth power spectrum (a
  * average over number of tir

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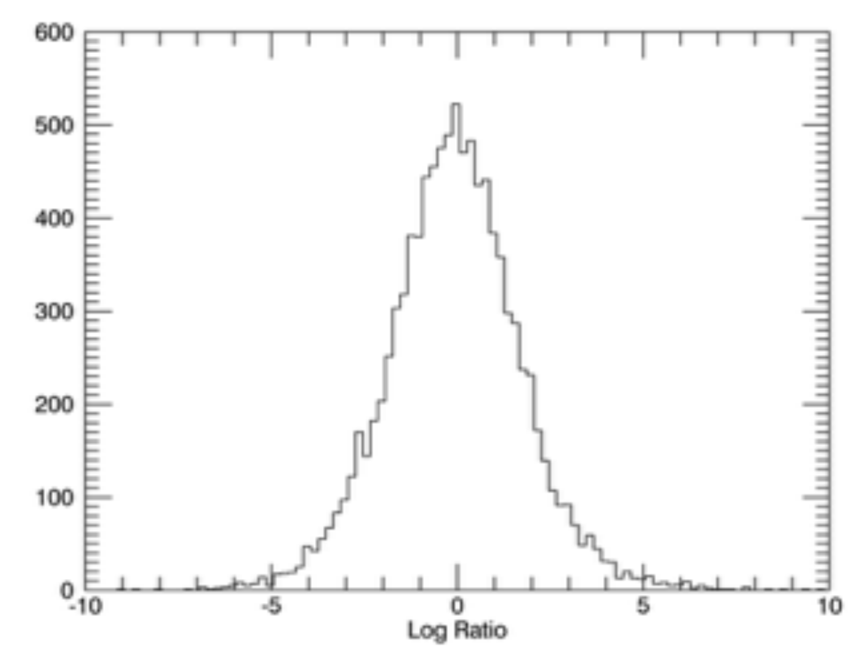
How do we improve accuracy of results?

Best method is still unclear!

Ratio of two exponential distributions is distributed as *1/(z+1)^2* where *z=x/y* (*z >0*) (Cauchy-esq).

Maximum likelihood of above distribution
- requires good estimate of true power to understand uncertainties on power!

Fit inward & outward power spectra in log-space - uncertainties become additive and fixed value - so homoscedastic & approximately normal **(Vaughan 2005)**.

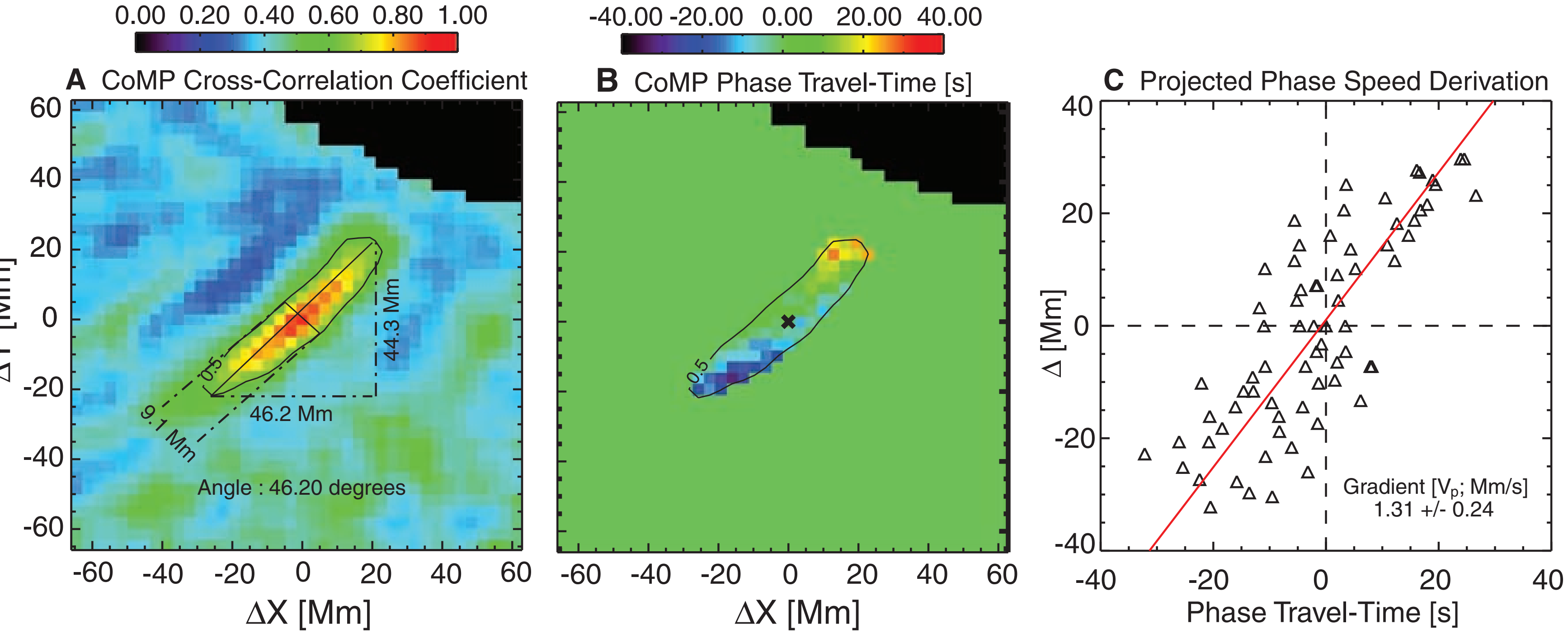


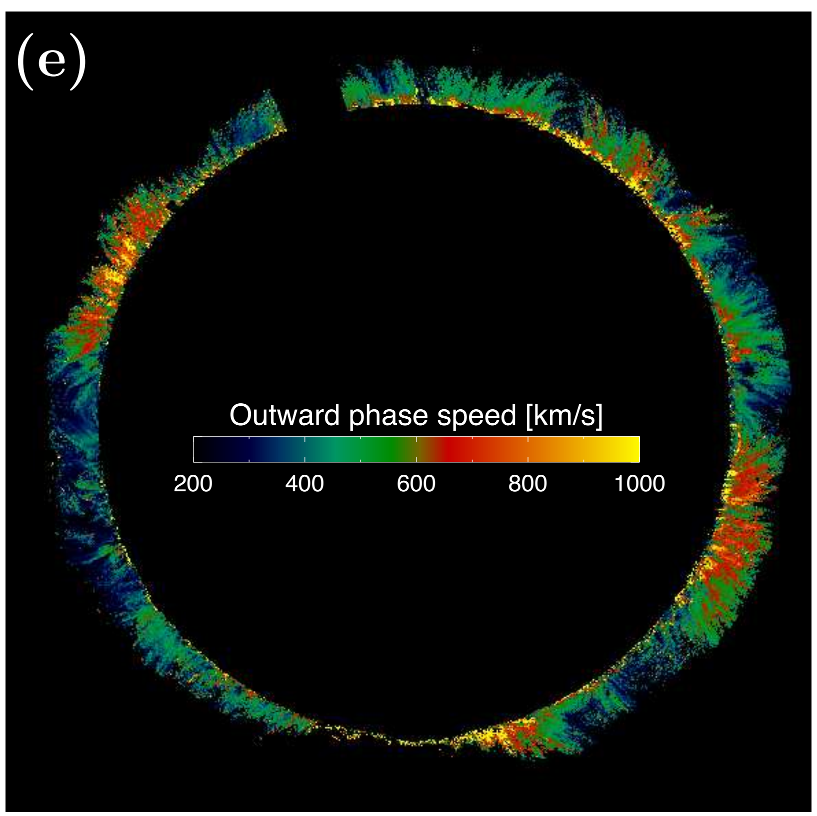
Or fit log of ratio - sharply peaked function (Logistic - nearly Gaussian but fatter tails) & uncertainties homoscedastic!

Currently trialling with Monte Carlo tests.

Perhaps Helioseismology can teach us something (e.g., Appourchaux 2014).

Global coronal seismology: magnetic field



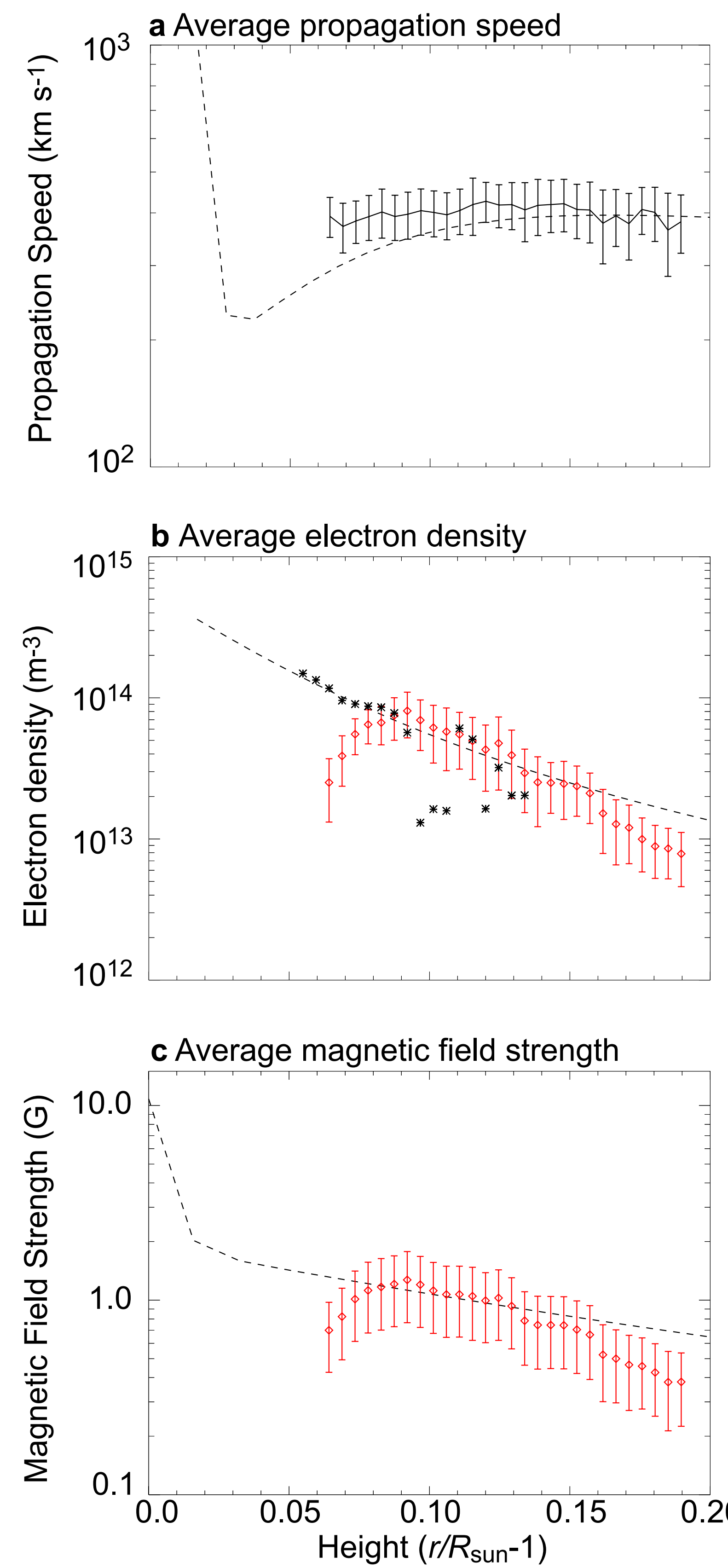


Use density ratio from line pair.

Check with Potential Field extrapolations.

Model comparison (e.g., Cranmer et al., 2007)

Coronal Hole (**Morton et al 2015**)



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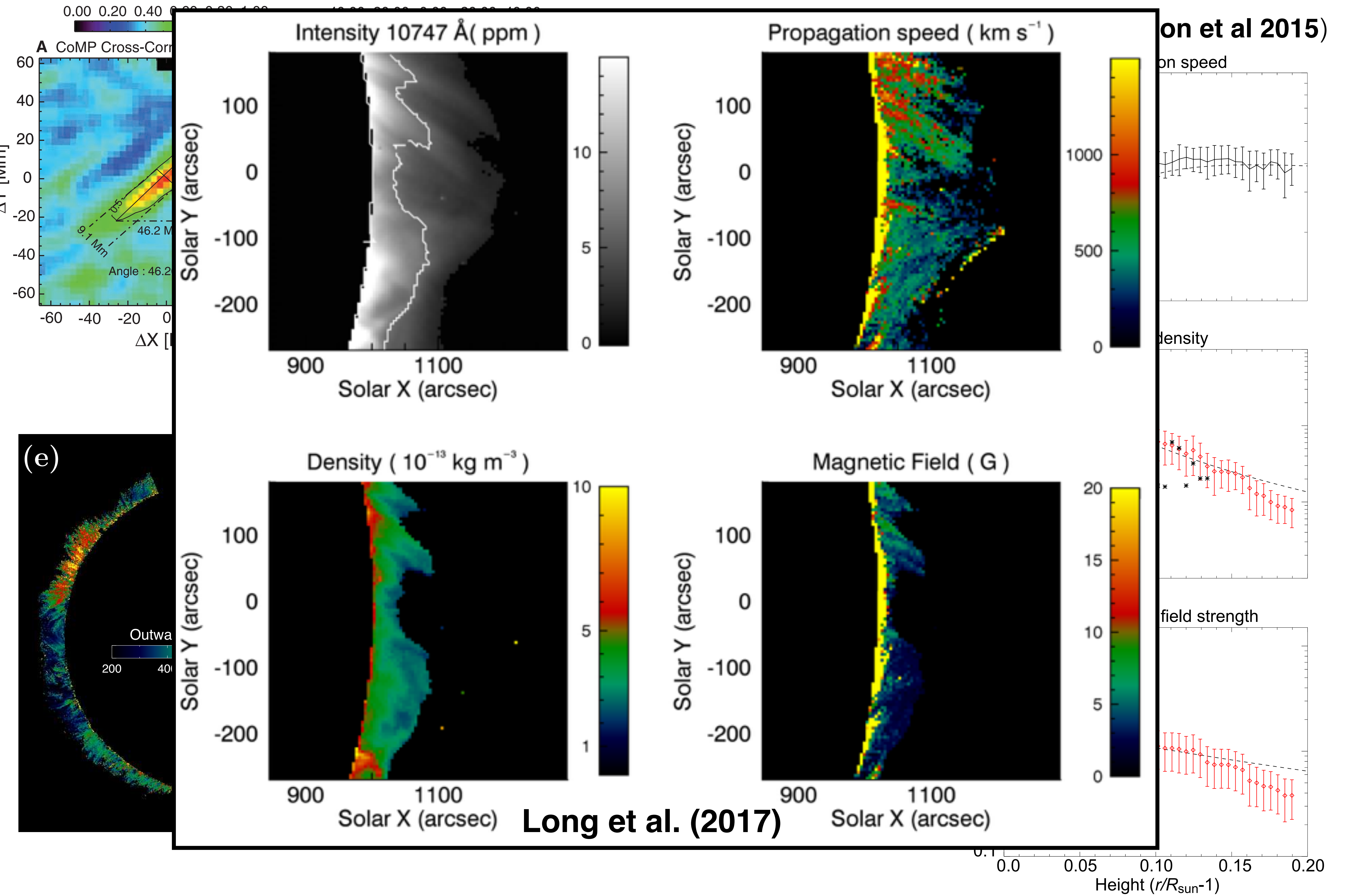
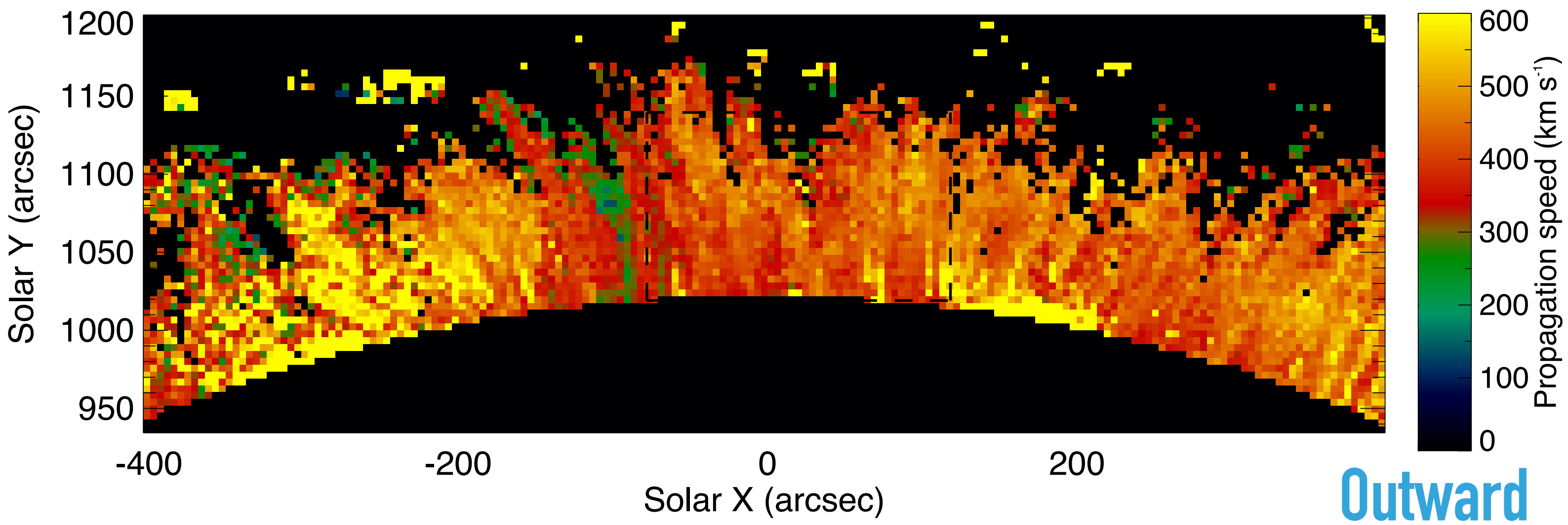


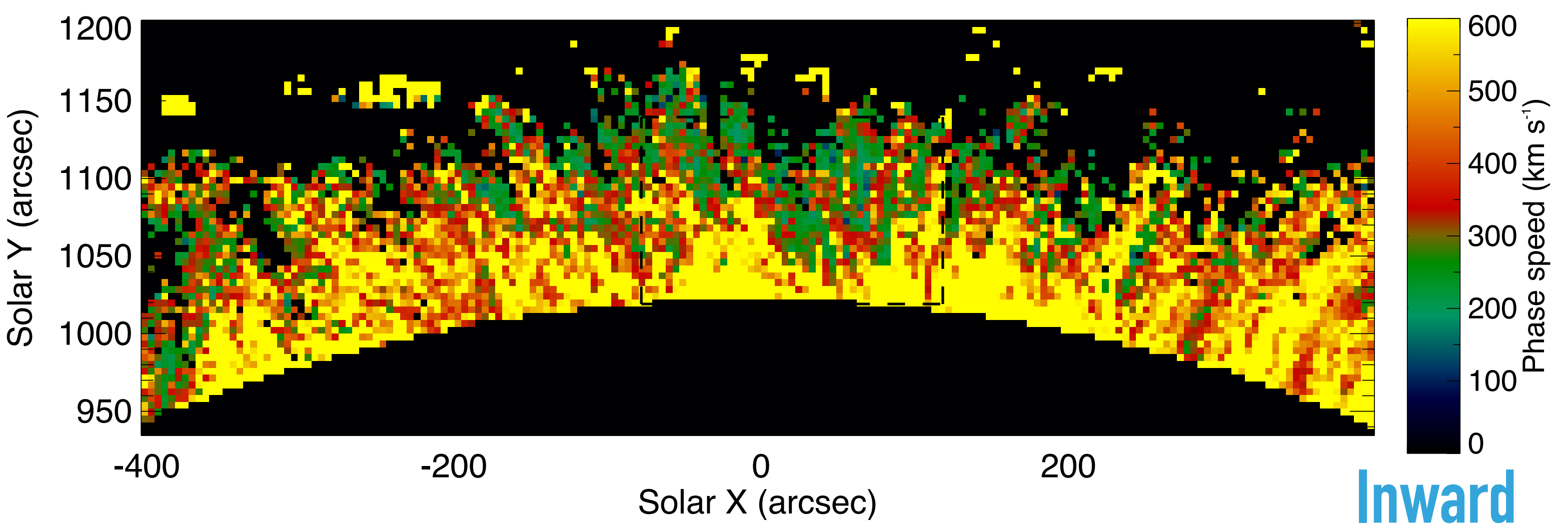
Global coronal seismology:Flows

Estimating the solar wind speed

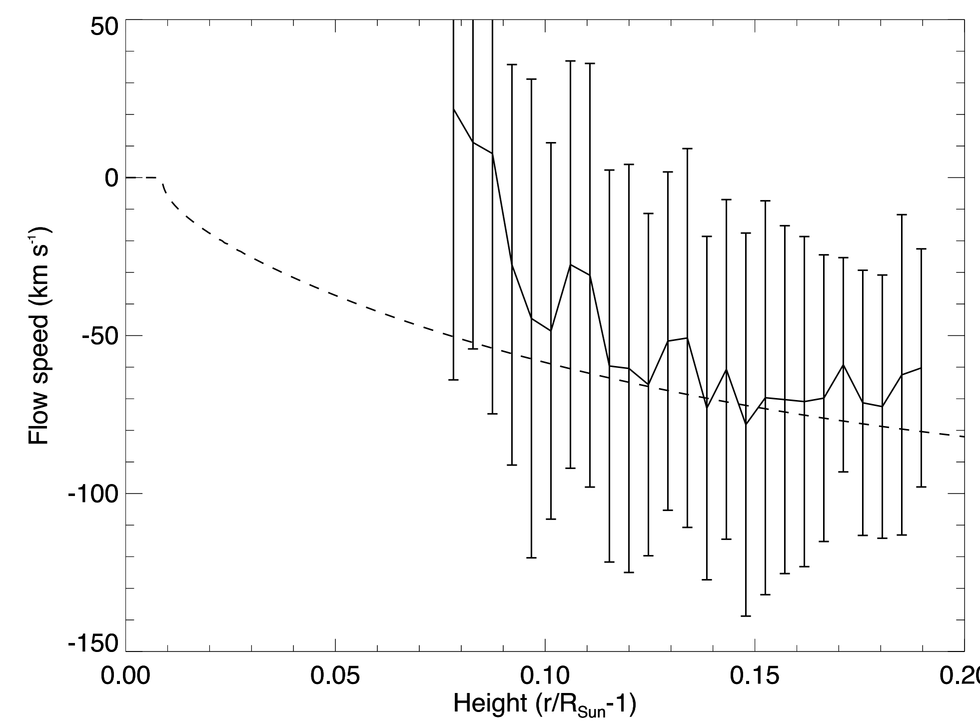


Outward

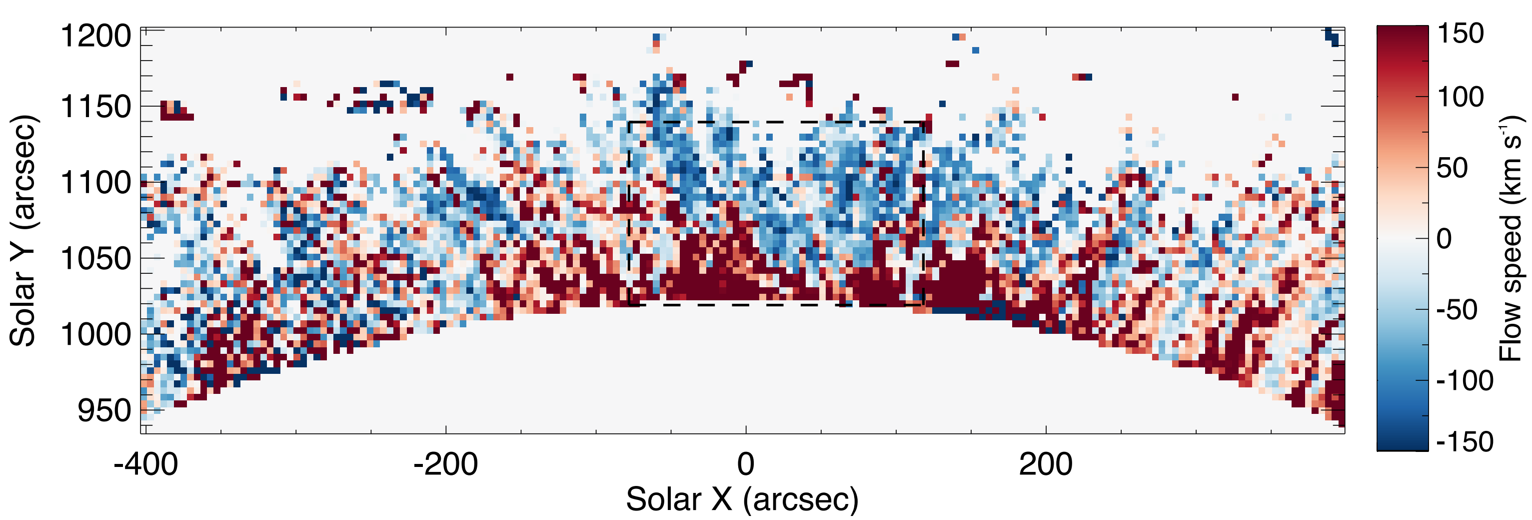
$$\frac{\partial^2 v}{\partial t^2} = -(U \pm c_{ph})\frac{\partial^2 v}{\partial z^2}$$



Inward



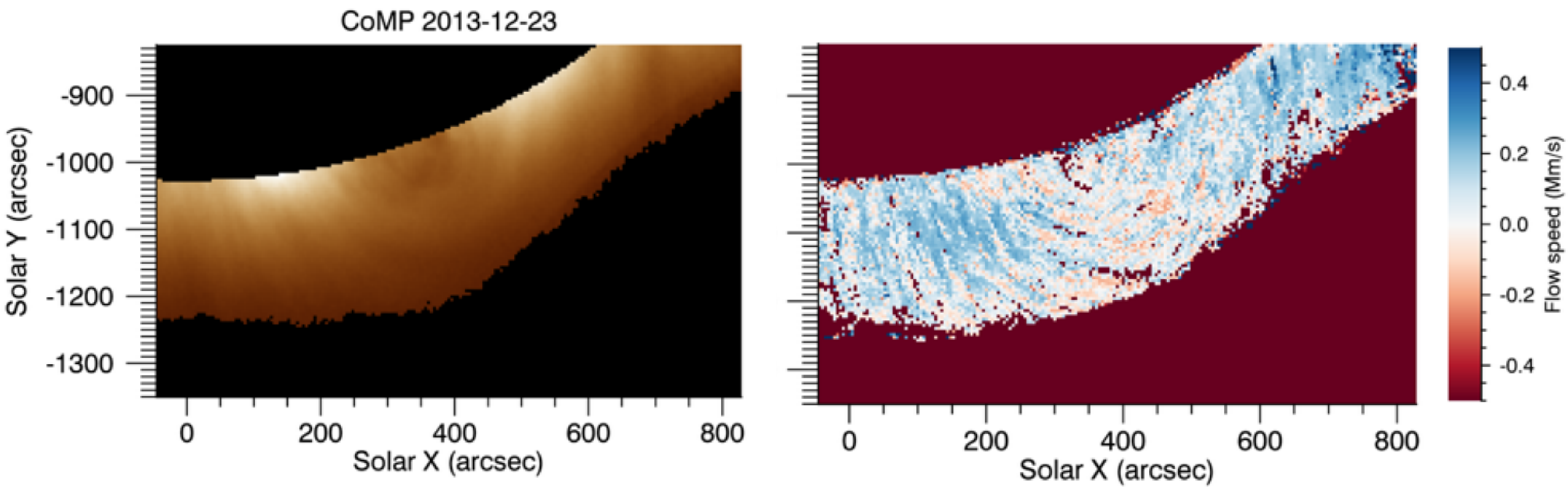
Pinto et al (2009) hydro wind model.



Improvement in propagation speed measurements required (?!).

Global coronal seismology:Flows

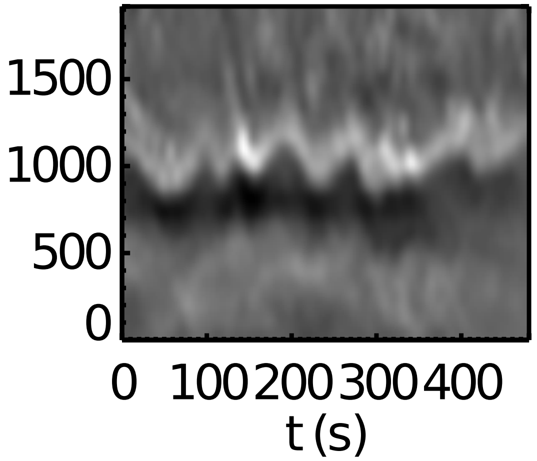
Flows along coronal loops

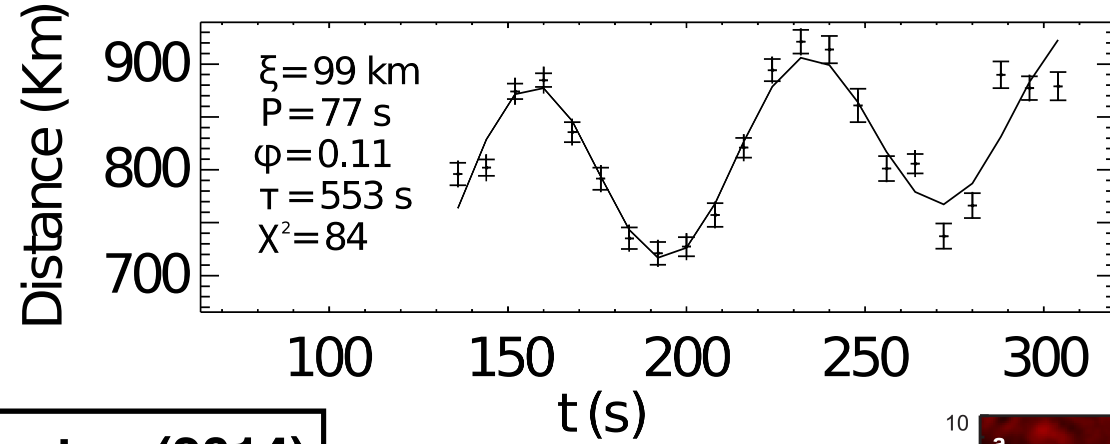


Plenty of measurable counter-propagating waves - so should be able to get reasonable diagnostics of flows.

Flow profiles and speeds may be useful for constraining heating models. (Negates problems with imagers/Doppler shifts!)

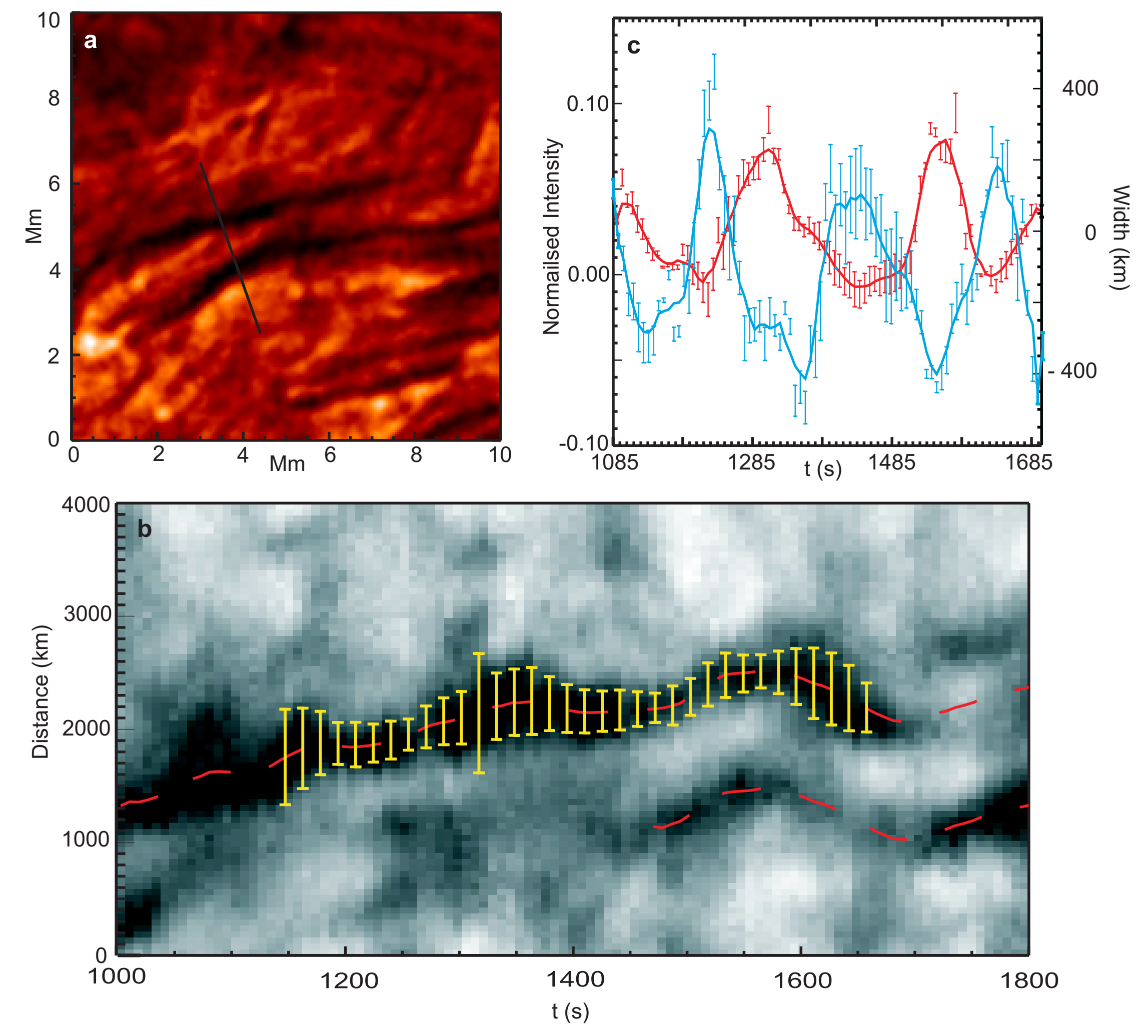
Potential to look for enhanced/reduced damping factors due to flows.



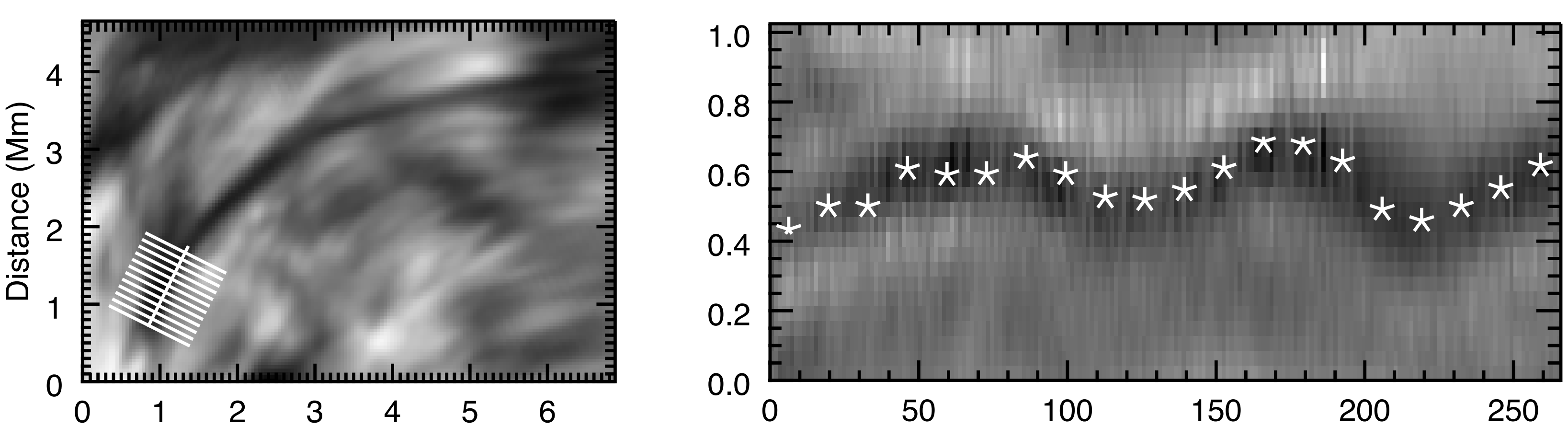


Morton (2014)

Can we do seismology in the chromosphere?

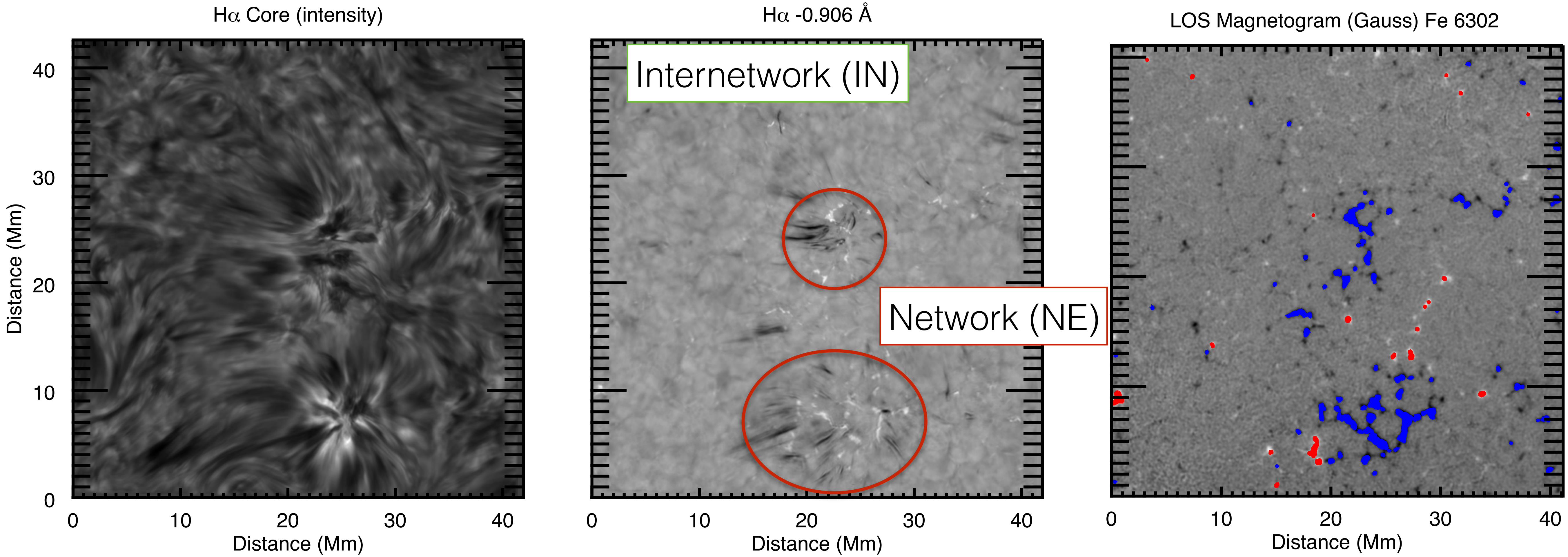


Morton et al (2012)



Mooroogen et al (2017)

Chromospheric features



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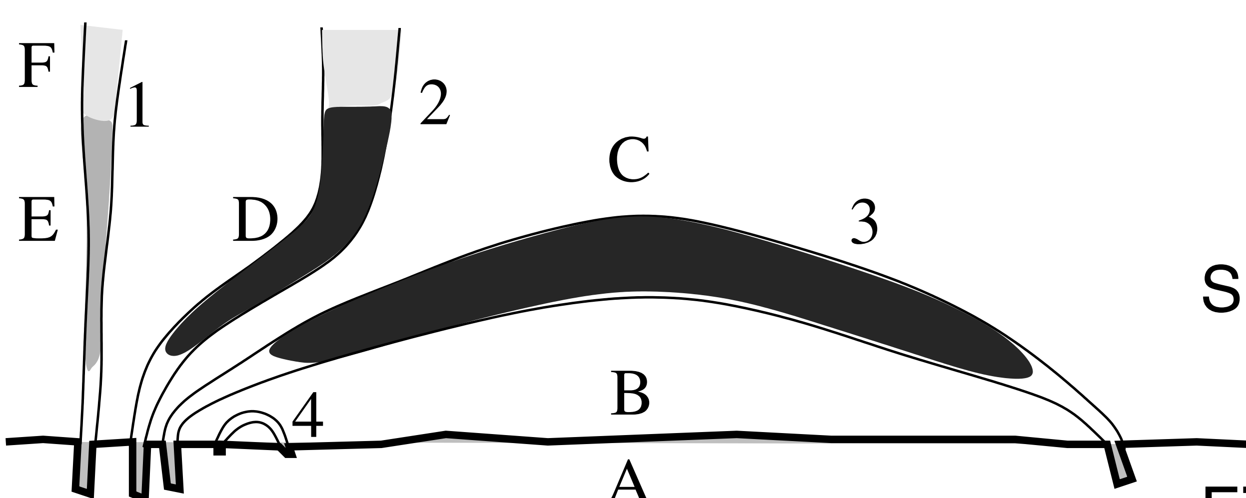
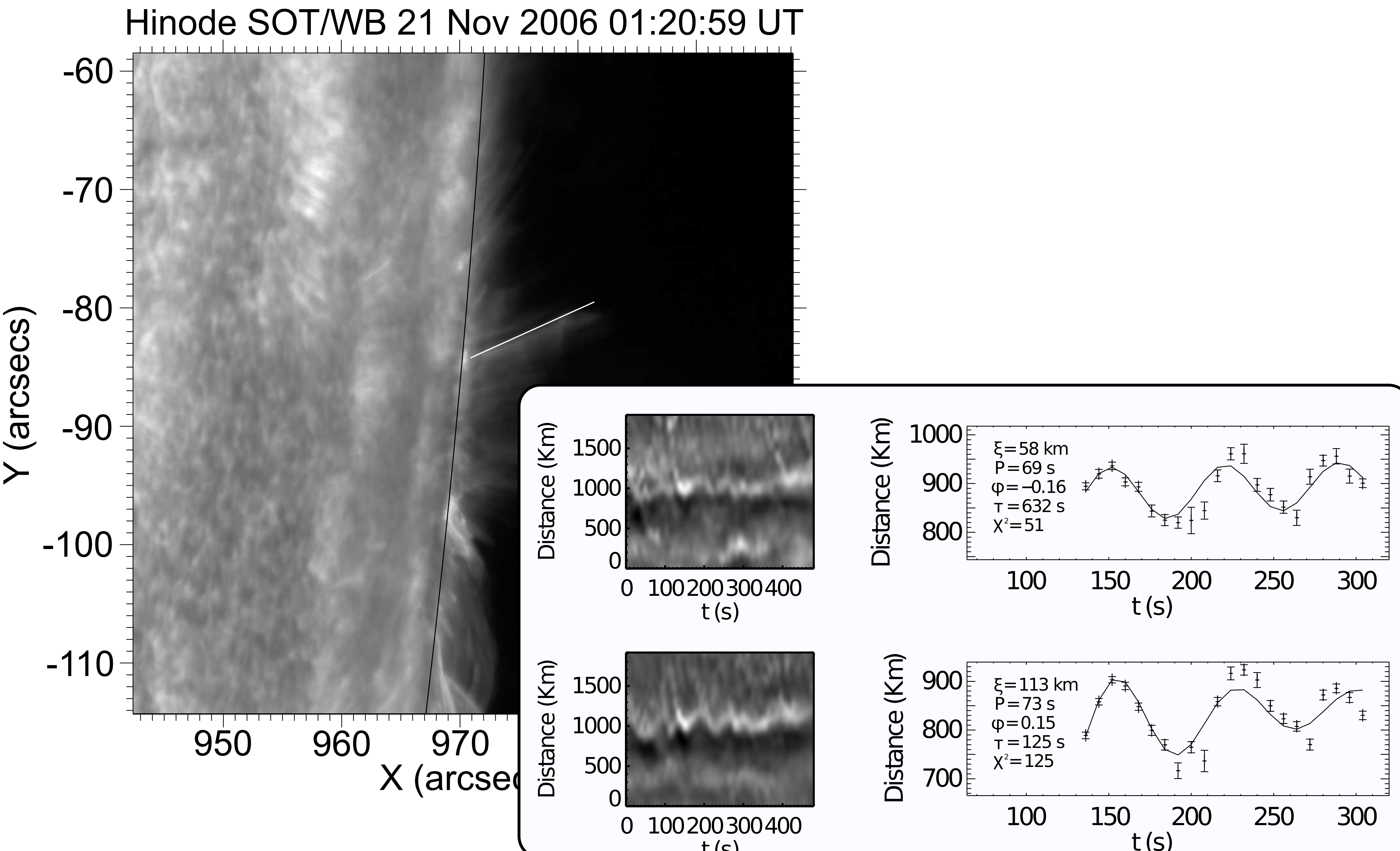


Rutten (2006)

Spicules - Originate in NE, vertical magnetic field

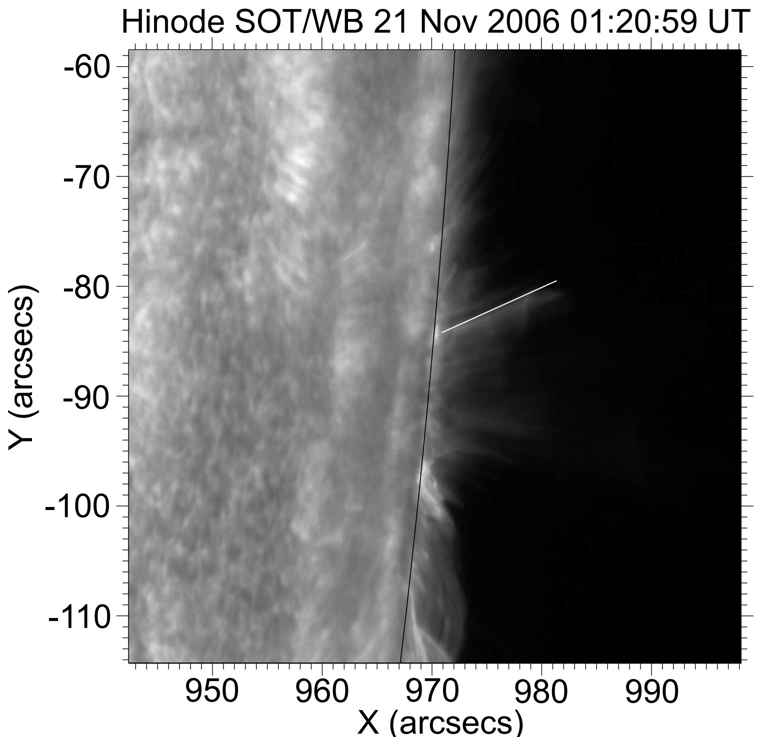
Fibrils - Originate in NE & IN, ~ horizontal magnetic field

Seismology with spicules



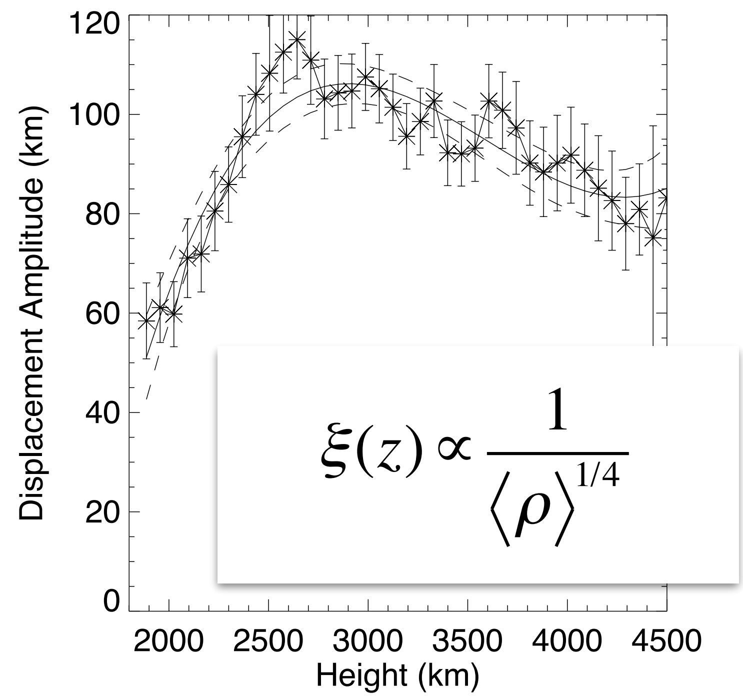
Morton (2014)

Seismology with spicules

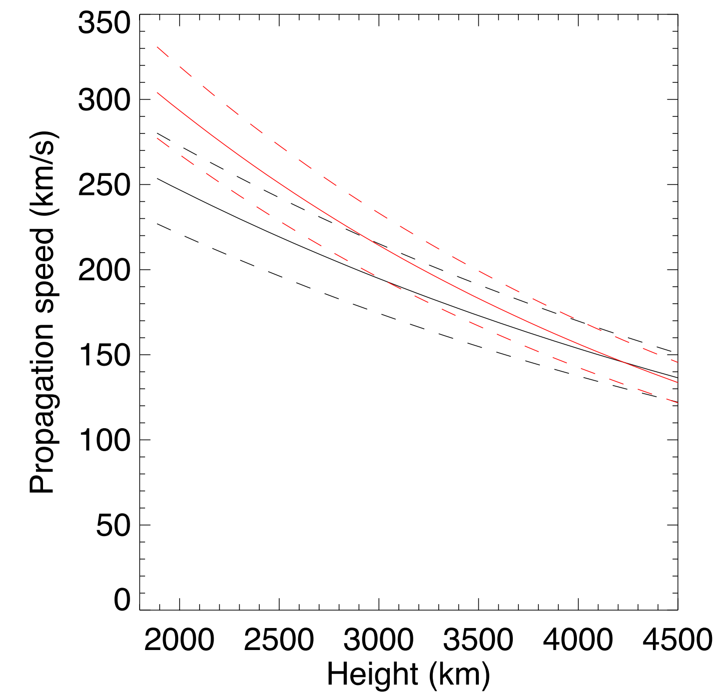


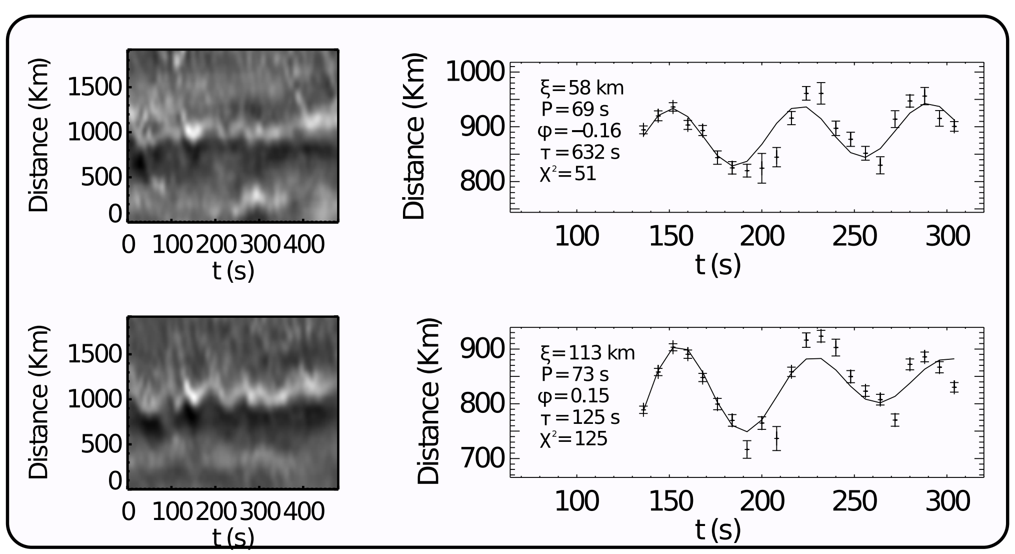
$$\xi(z) = \sqrt{\frac{c_k(z)}{\omega}} R(z)$$

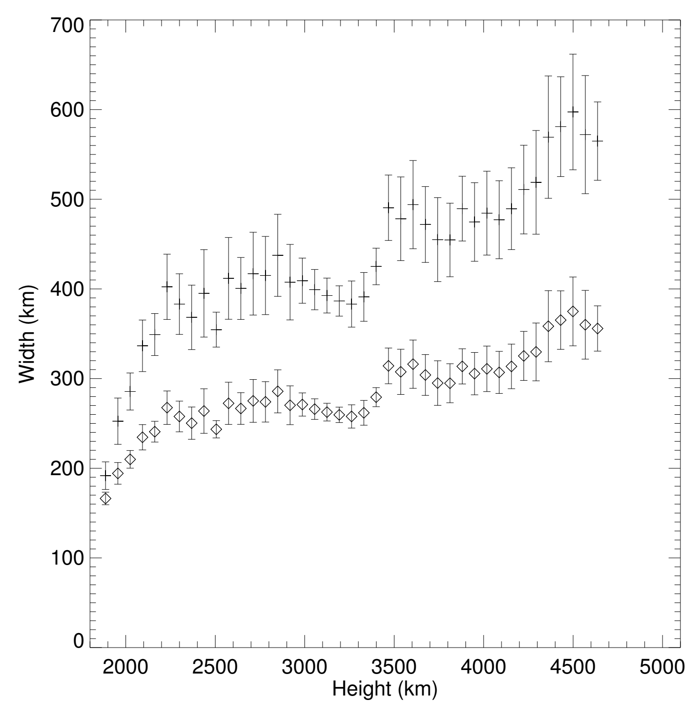
WKB approx.

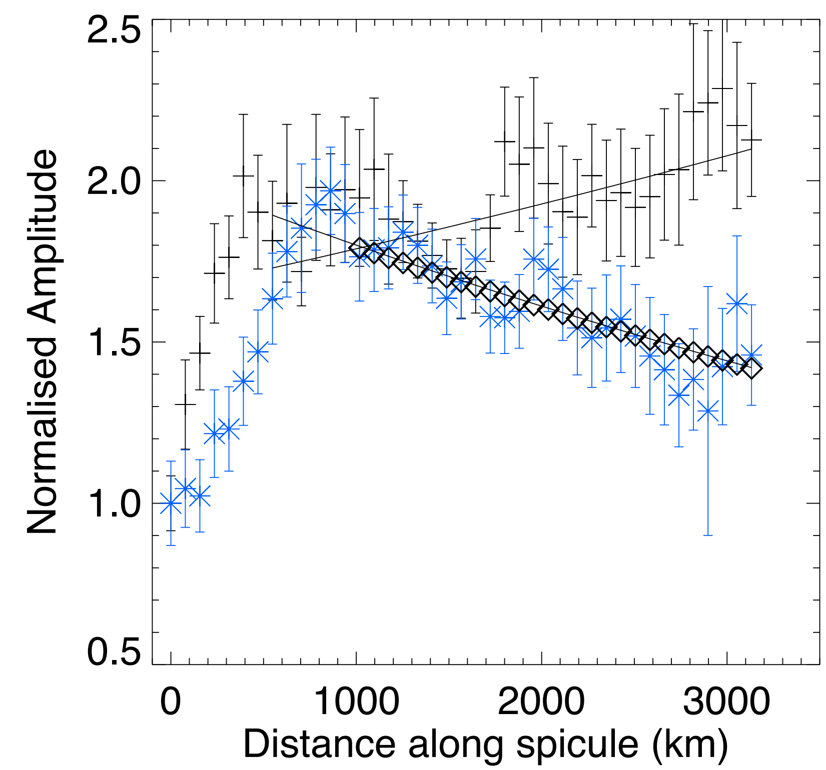


$$\xi(z) \propto \frac{1}{\langle \rho \rangle^{1/4}}$$





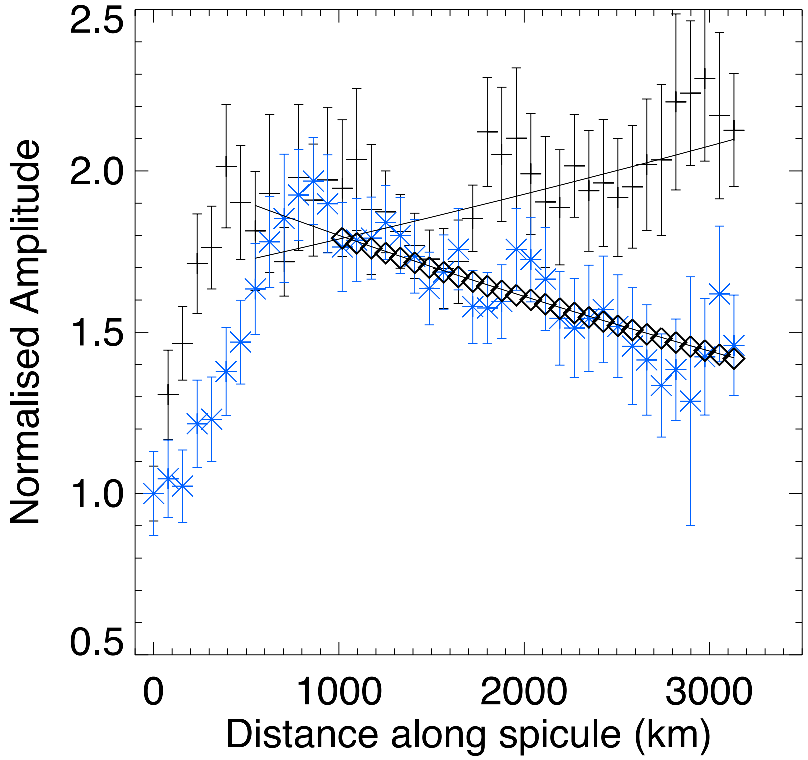


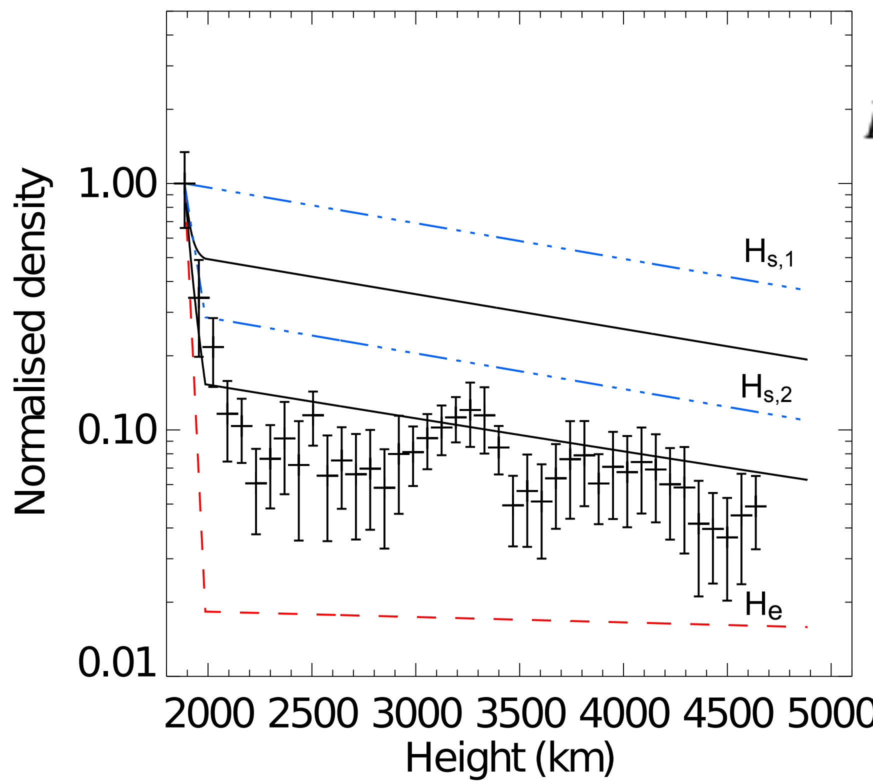


Quality factor of 0.34

Morton (2014)

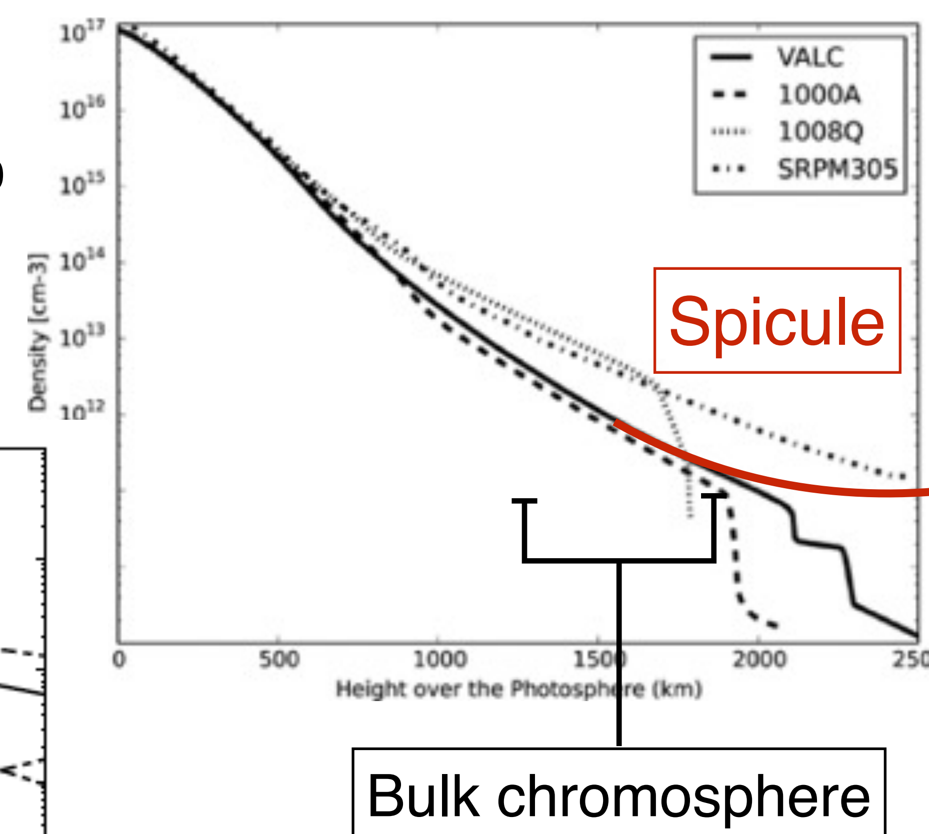
What sort of density profile is required?



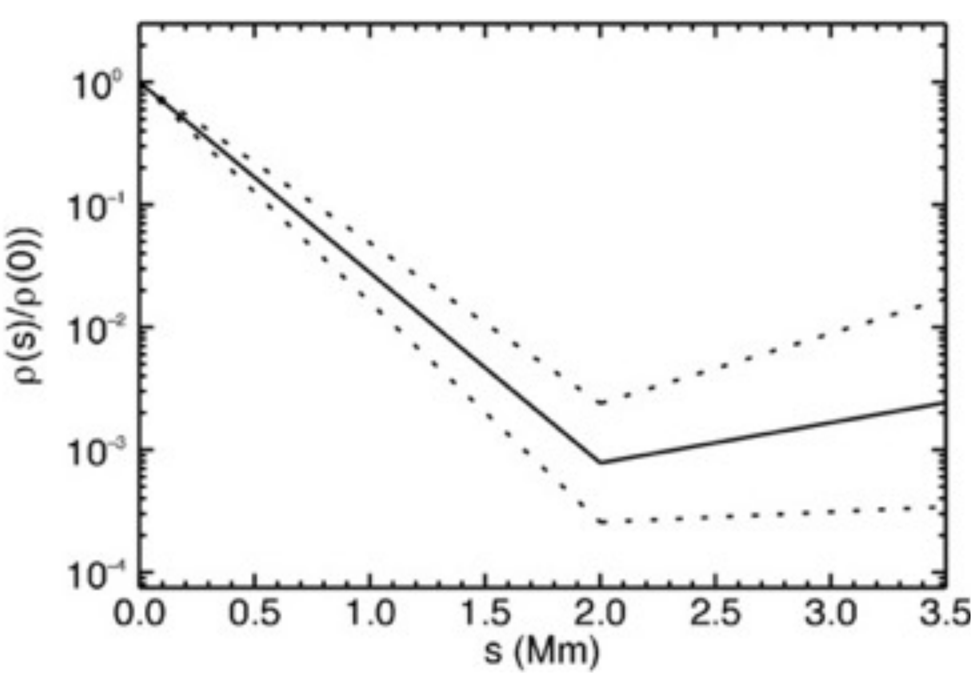


$$H_{\rm ex} = \begin{cases} 25\ \text{km} & 0 \le z < 100\ \text{km}, \\ 20\,000\ \text{km} & 100 \le z < 2800\ \text{km}. \end{cases}$$

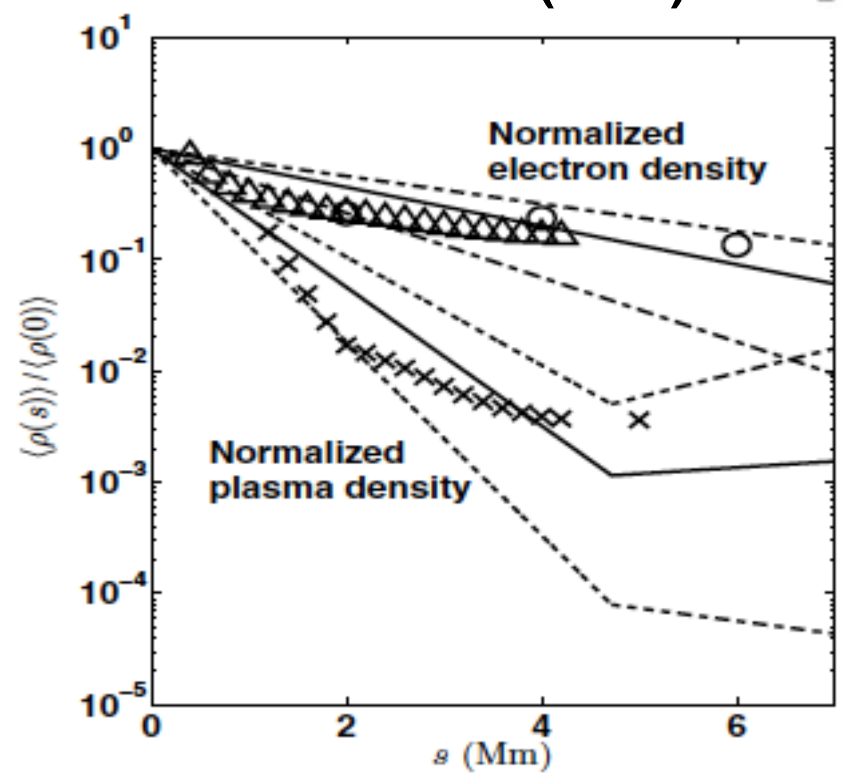
$$H_{\rm s,2} = \begin{cases} 80\ \text{km} & 0 \le z < 100\ \text{km}, \\ 3000\ \text{km} & 100 \le z < 2800\ \text{km}. \end{cases}$$



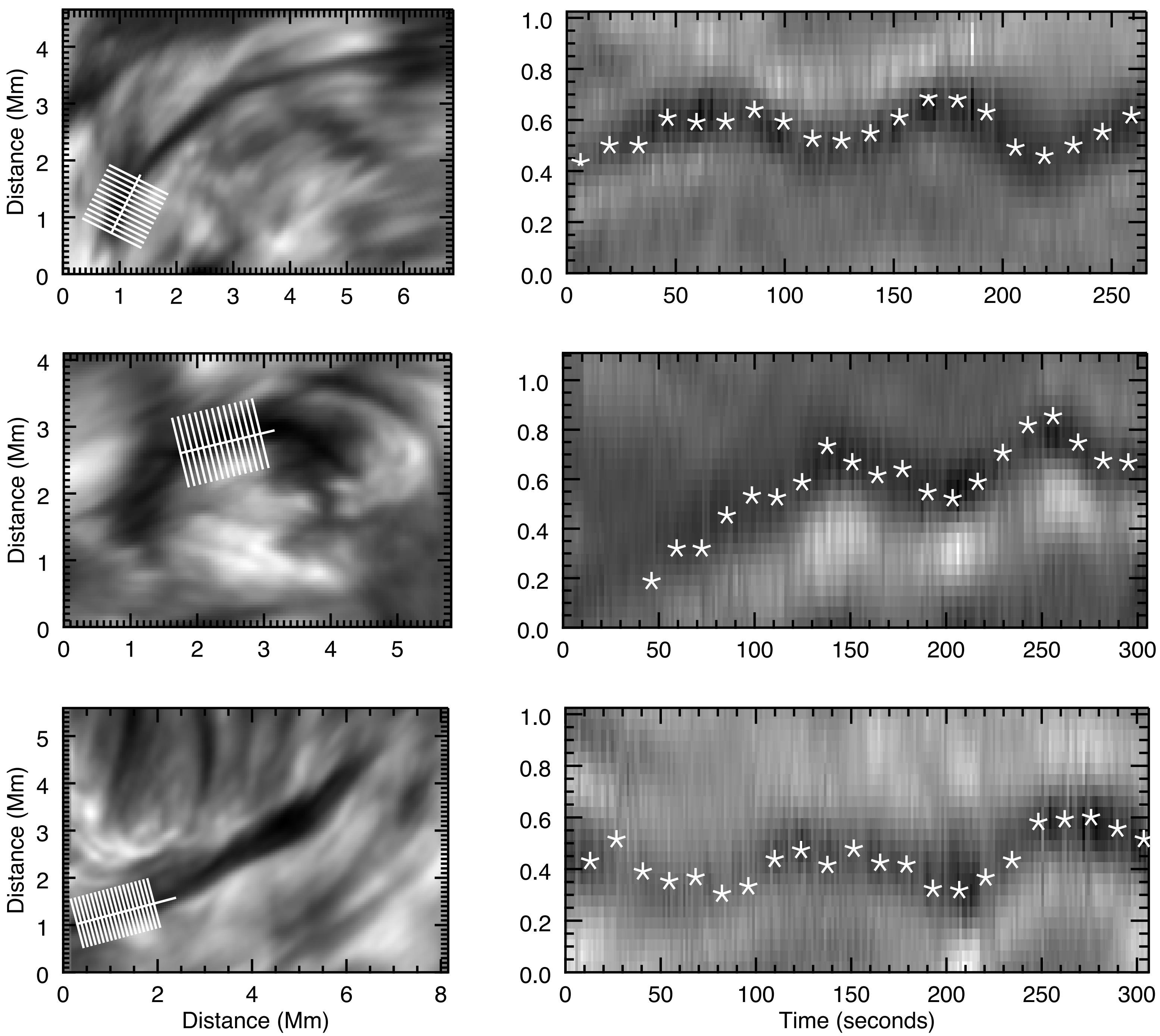
Kuridze et al

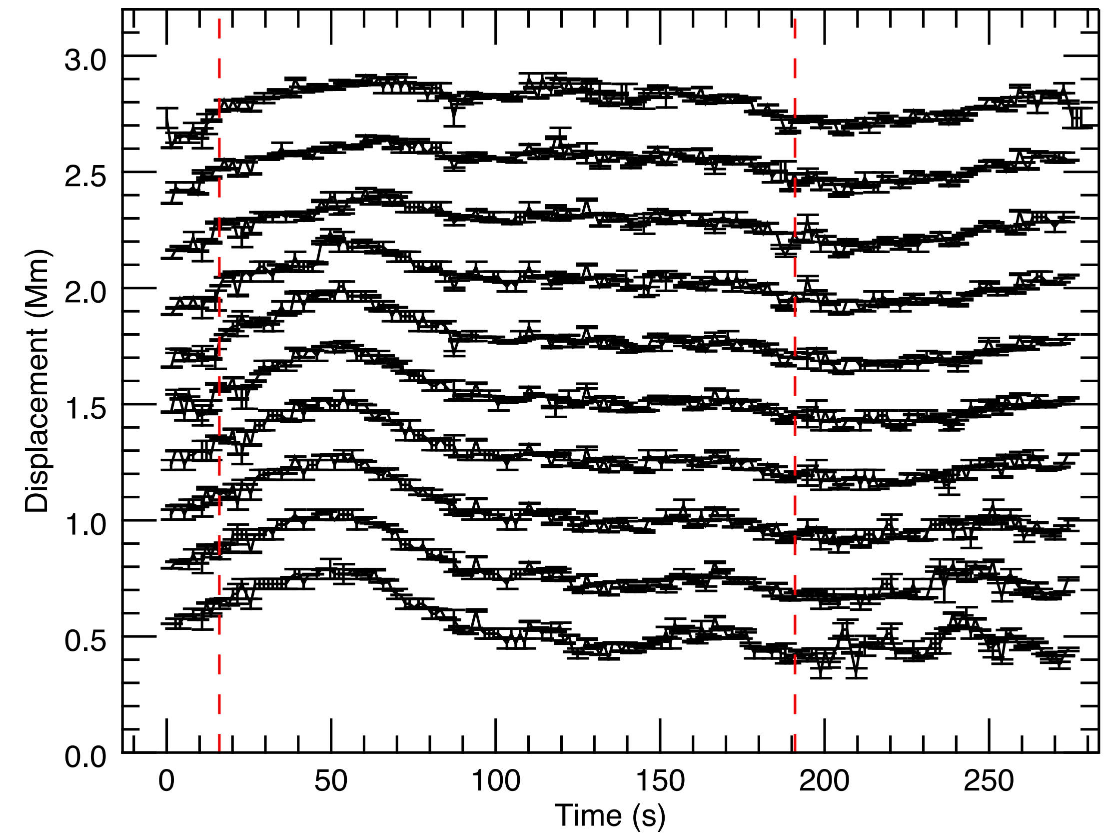


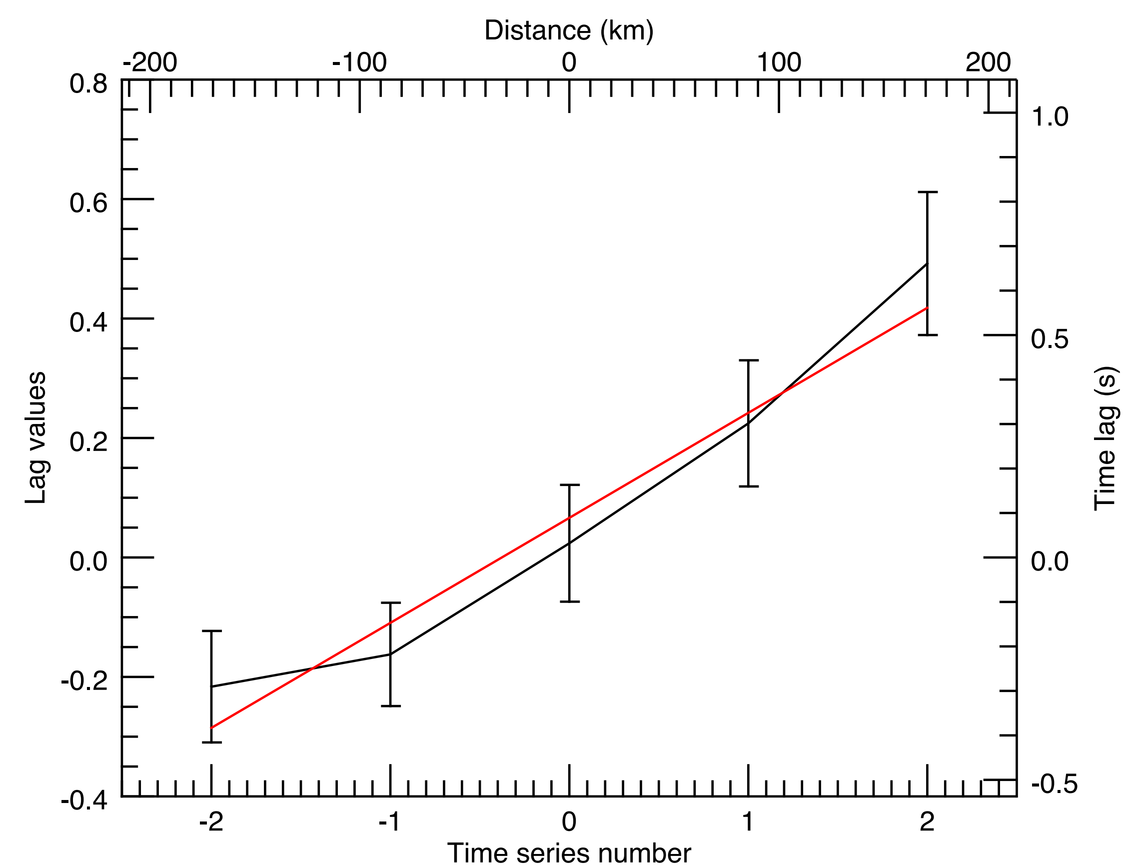
Verth et al (2011)



What about fibrils?







Mooroogen et al (2017)

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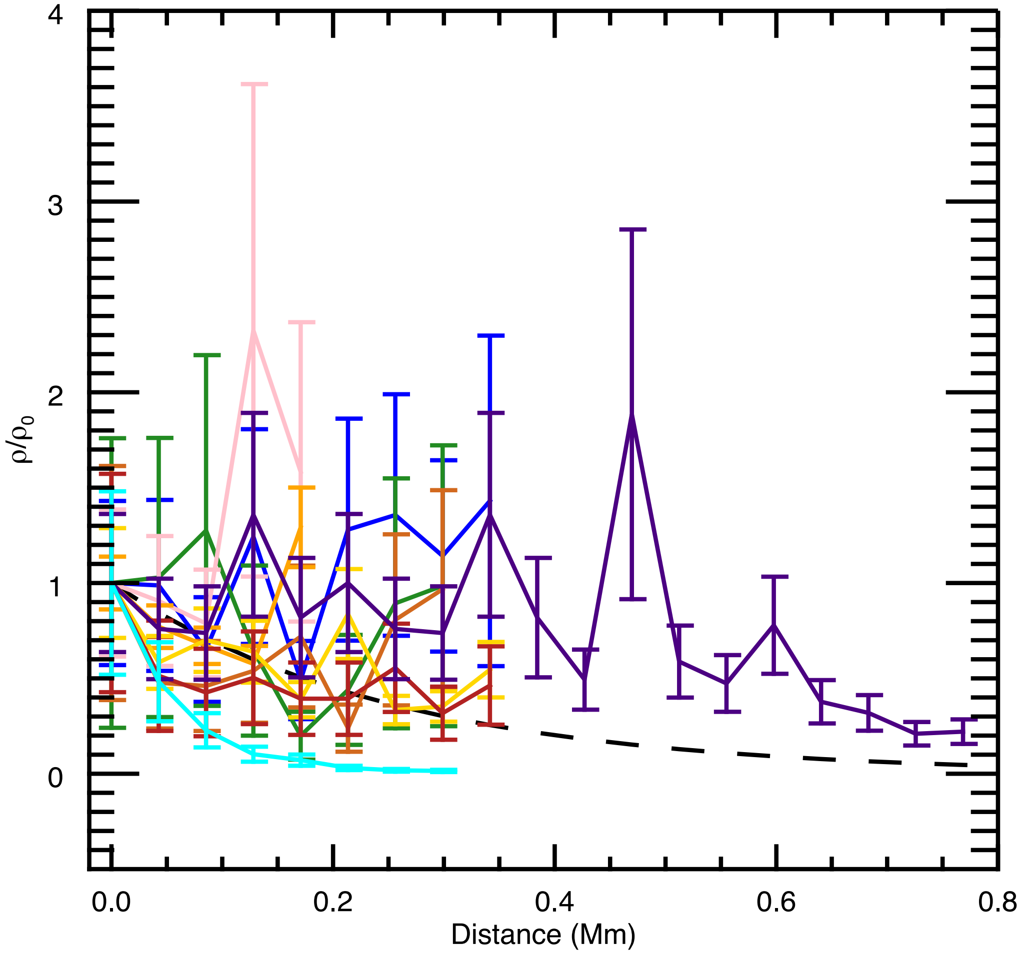

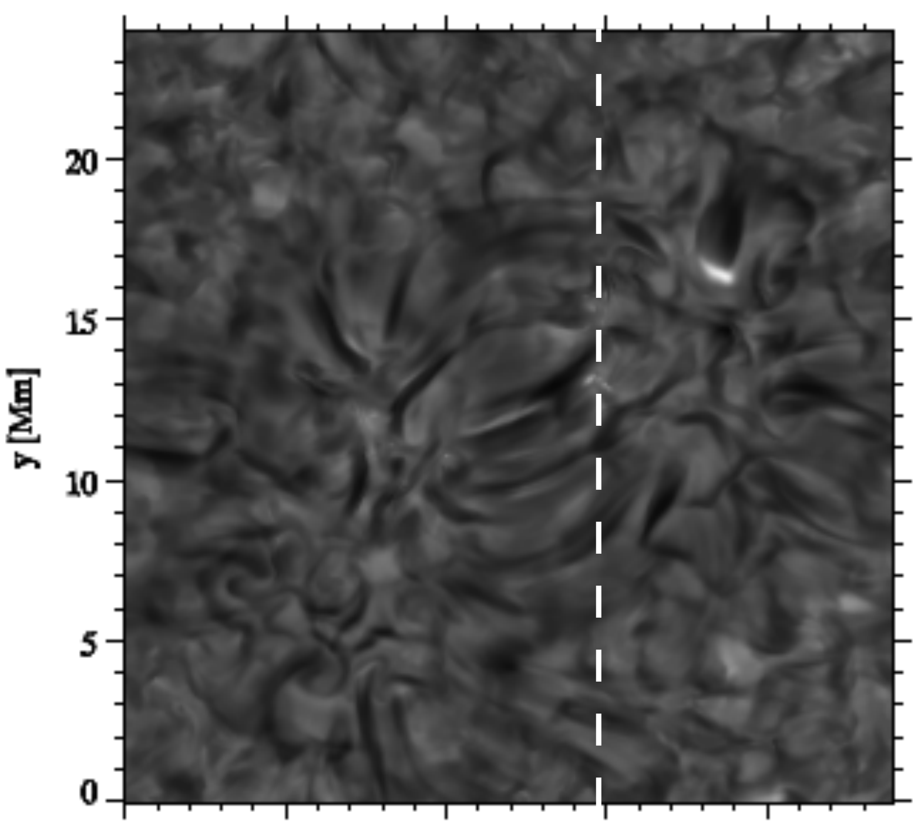

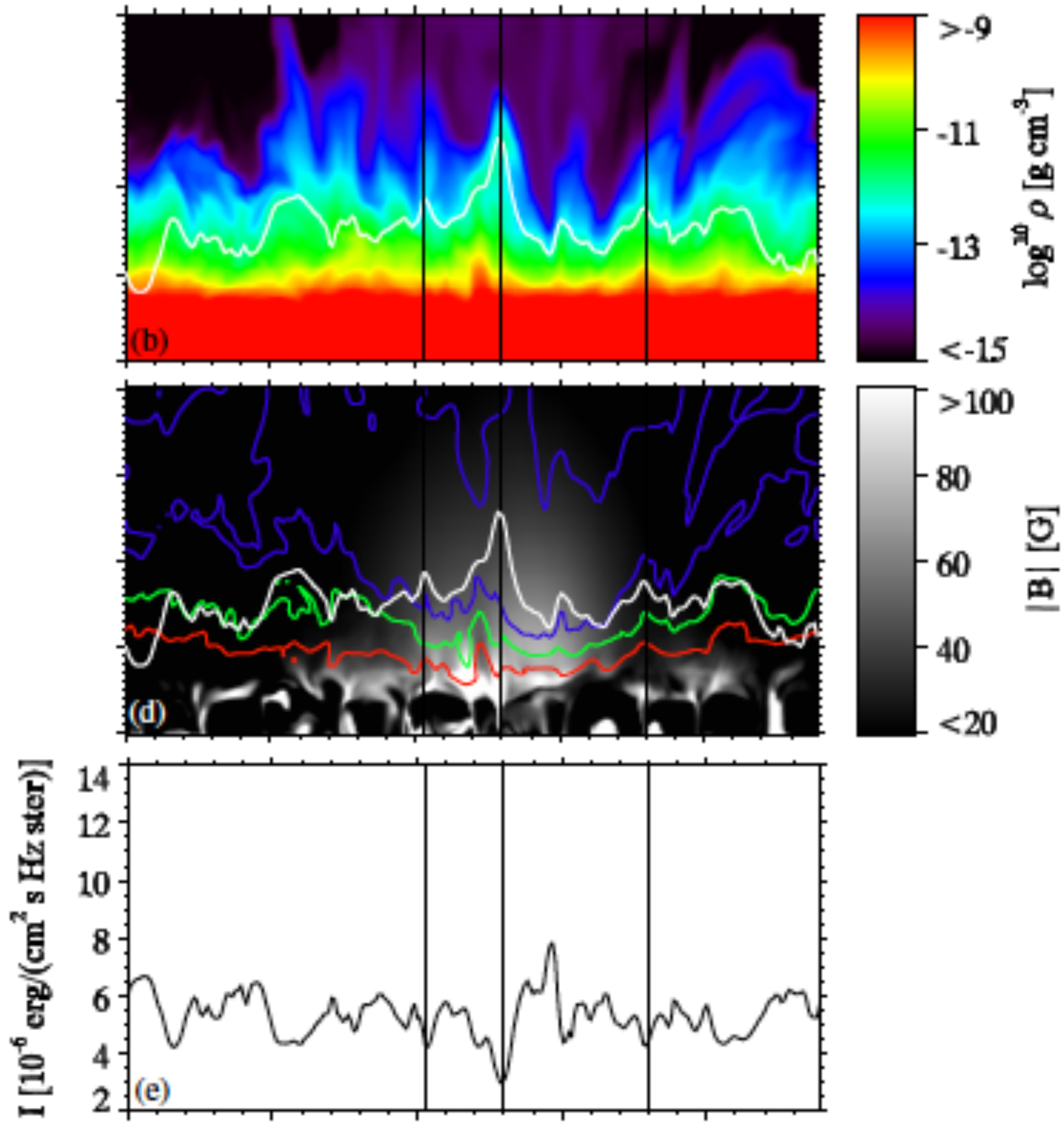

BIFROST - **Leenaarts et al (2012)**

Problems with chromospheric seismology!

Need a MS inversion that incorporates damping & stratification.

WKB approx. is not realistic. Plasma parameters can change rapidly.

Many options for internal & external density profiles - how can this be narrowed down/incorporated into inversions?

Flows are inherent to chromospheric structures (as probably any solar structure).

Is it time for an MS inversion model al la radiative transfer (e.g., NICOLE)?