Theoretical studies of wave interactions in the Sun

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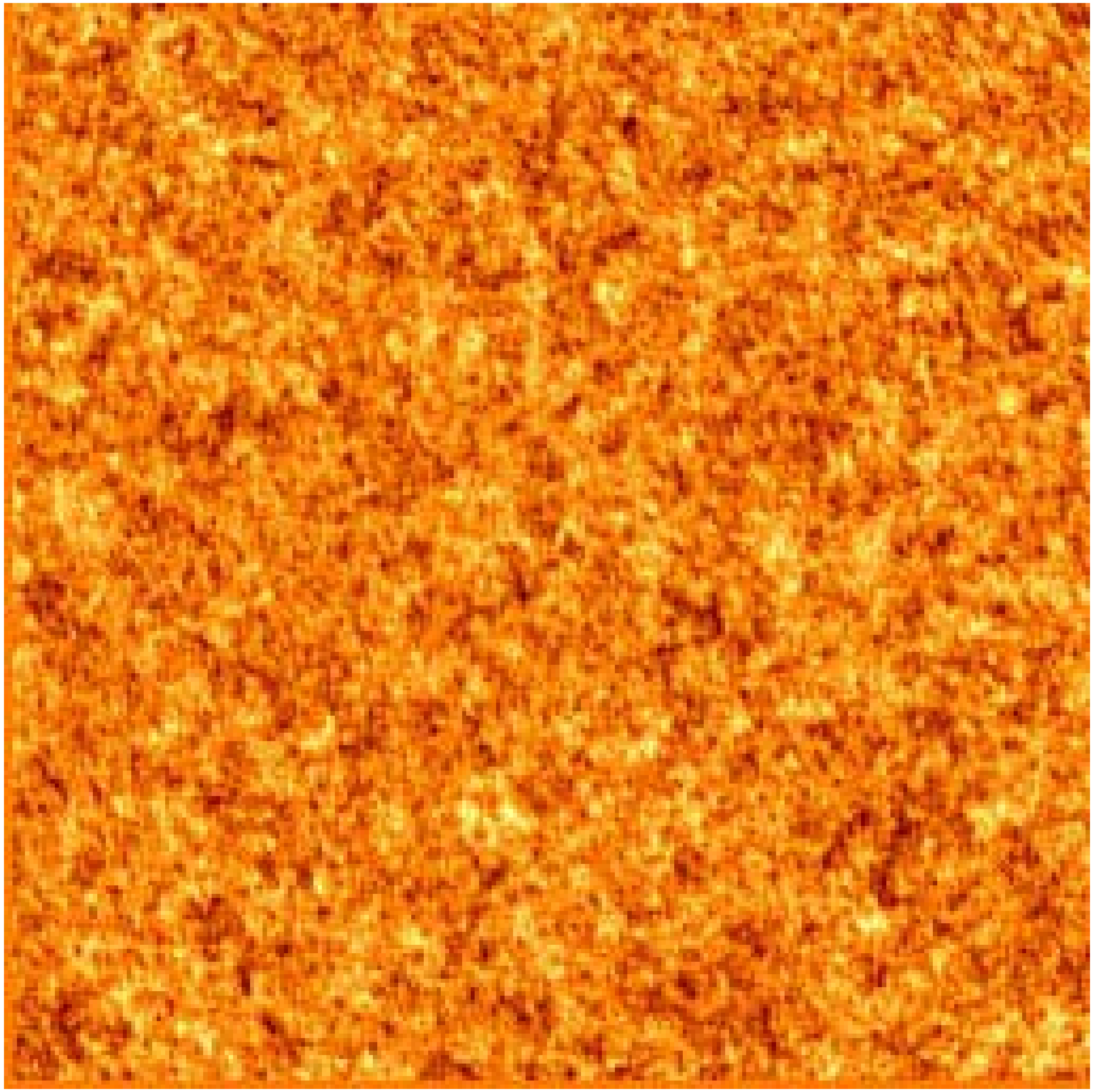
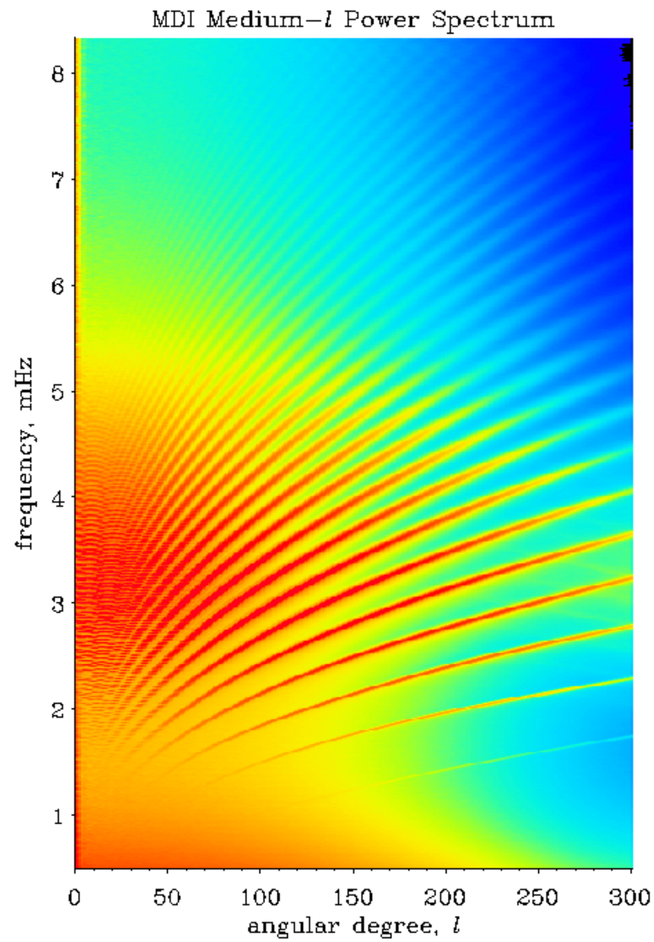
Outline

- Introduction
- Motivation
- Basic structure of simulations
- How to interpret helioseismic data?
- Potential problems with current view of the sunspot interior
- Seismic halos: fast mode conversion?
- Sub-wavelength resolution helioseismology
- Detectability of interior convection
- Conclusions

MDI Observations



Power Spectrum

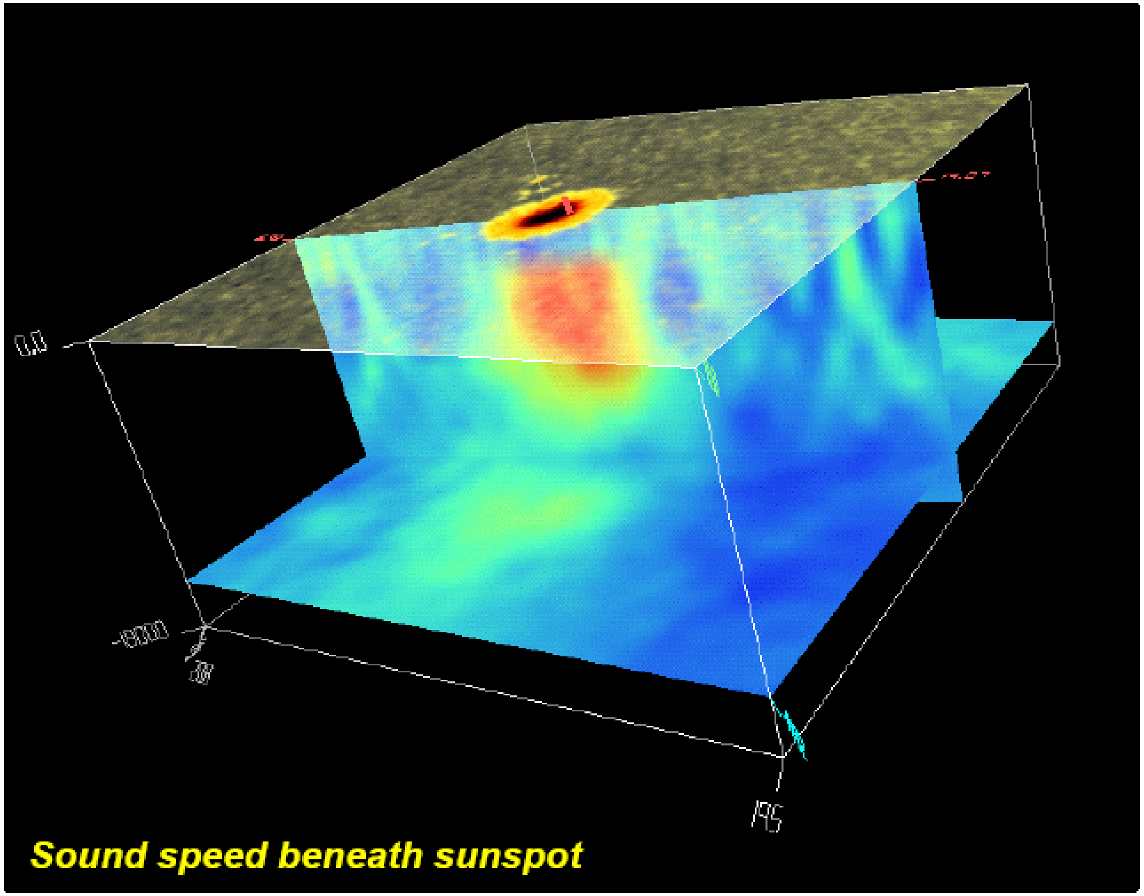


Time-Distance Helioseismology

- Cross correlate signals at two points on the surface
- Fit the cross correlations by a Gabor wavelet/ other methods
- Call a parameter in this fit the *travel time*
- Statistically significant time shifts interpreted as arising from "perturbations" to the quiet Sun

Sunspot Structure Inversion

A possibly oversimplified view



Sunspot data from MDI High Resolution, 18 June 1998

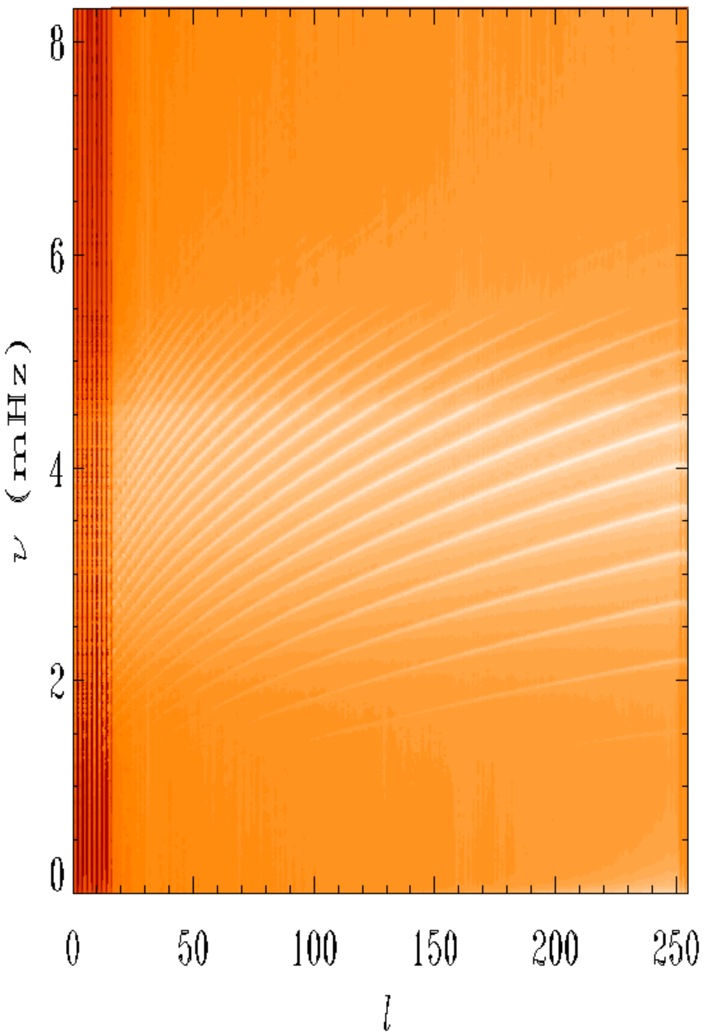
Motivation

- Interpreting measurements: fundamental gaps in our understanding
- Deconstructing active region structure and dynamics
- Improve existing methods
- Observe something new in the Sun based on numerical/theoretical predictions

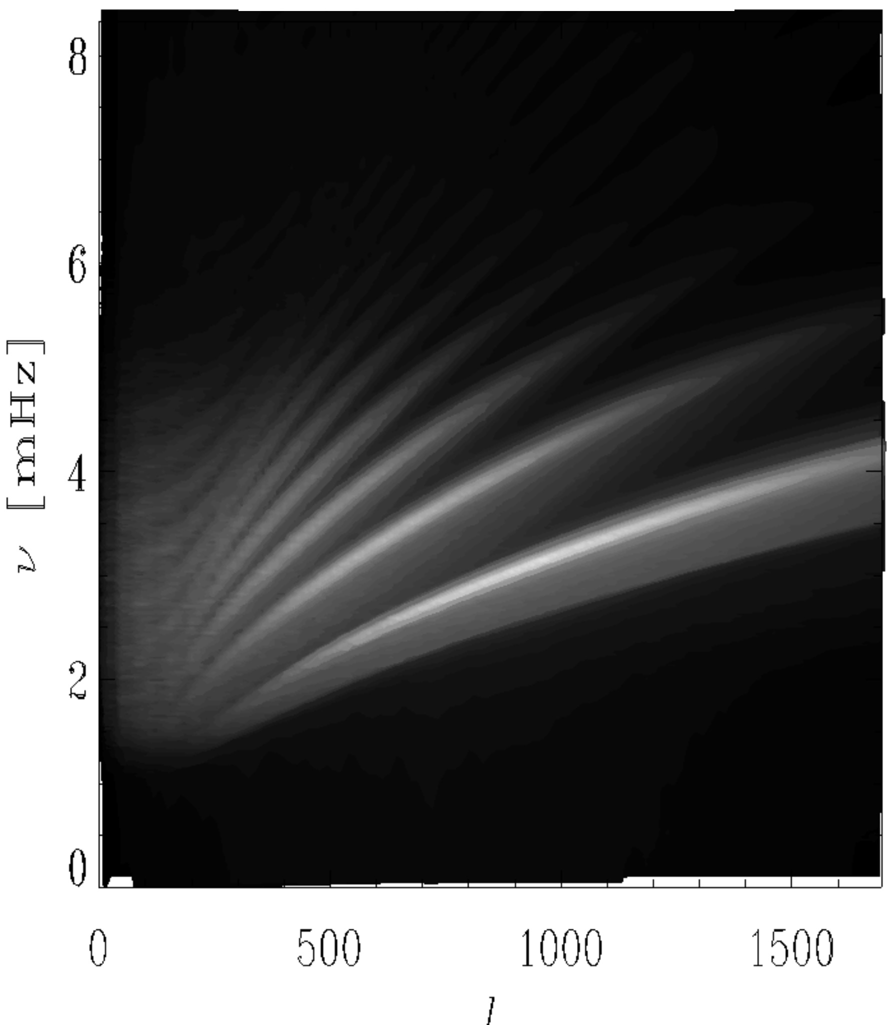
Wave Simulations

- Linearized wave propagation: study of differential effects
- Solve the 3D Euler equations (Spherical: local helioseismology of global structures/ Cartesian MHD: local helioseismology) - Hanasoge et al. 2006, 2007; Hanasoge & Duvall 2007; Hanasoge 2007
- Wave excitation by distributed multiple sources
- Velocities extracted 200 km above photosphere ~ to simulate MDI Ni line measurements

Simulated Wave Power Spectra



Spherical geometry



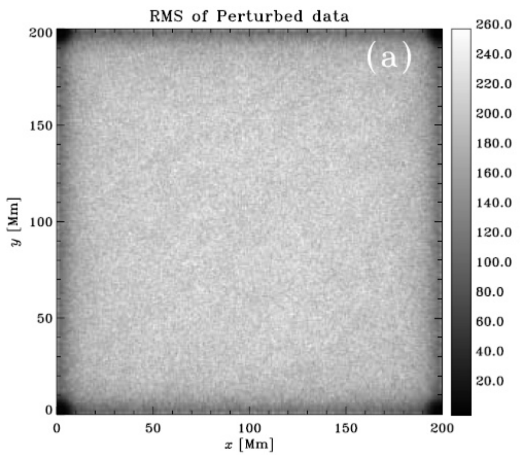
Cartesian geometry

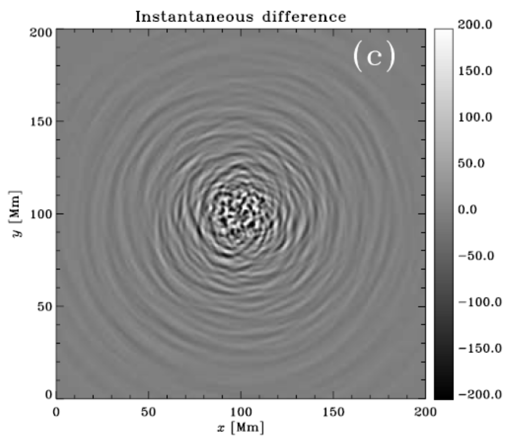
MULTIPLE SOURCES: NOISE SUBTRACTION

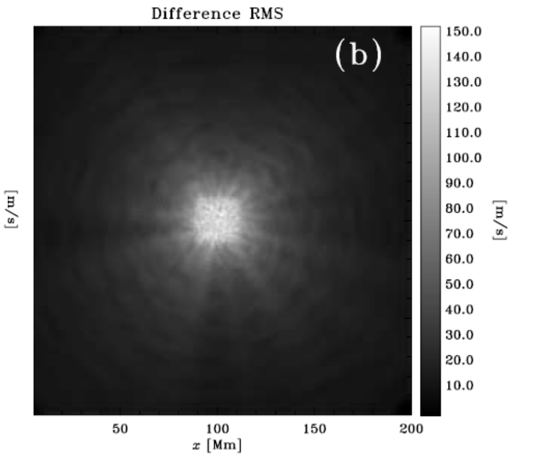
Scattering off a sound-speed perturbation

Noisy data

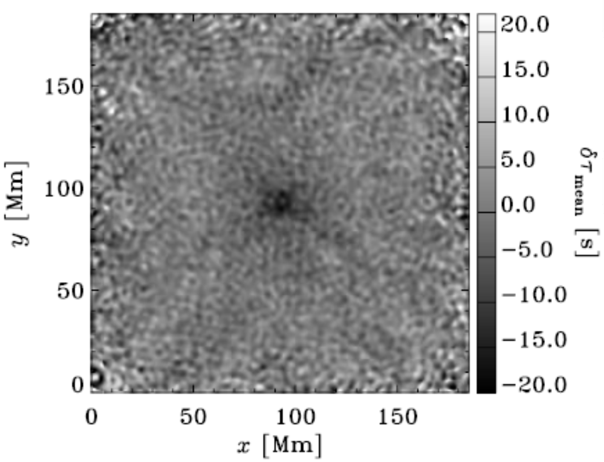
Noise-subtracted



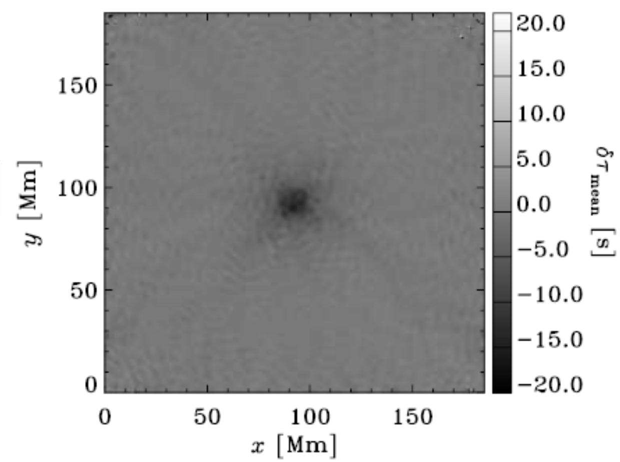




RMS velocities



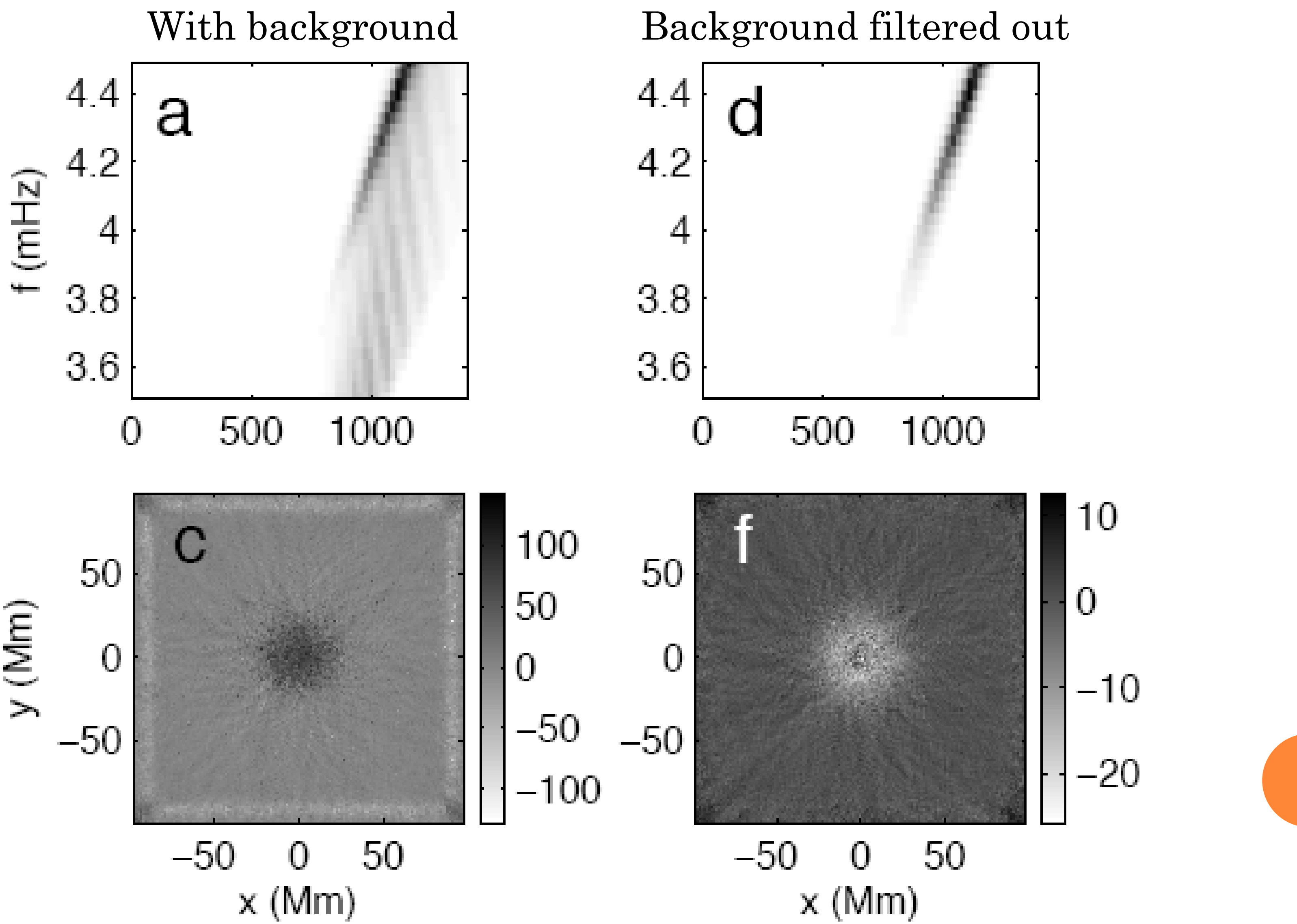
Travel times



Interpreting Observations

- Dramatically different statistics (travel times) recovered based on filtering (Birch et al. 2008)
- Simulations and MDI observations show similar effects
- The background – a significant contributor to measurements of travel times/ holographic statistics
- Non-unique sunspot structure inversions

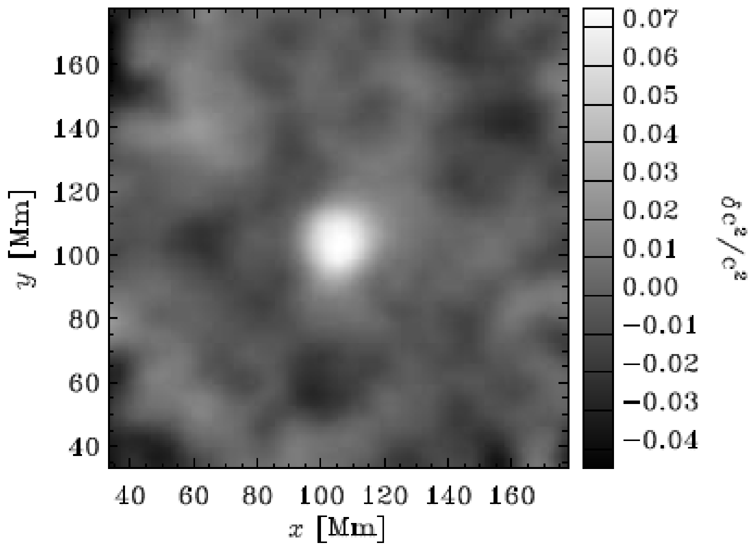
FILTERING PROFOUNDLY ALTERS RESULT

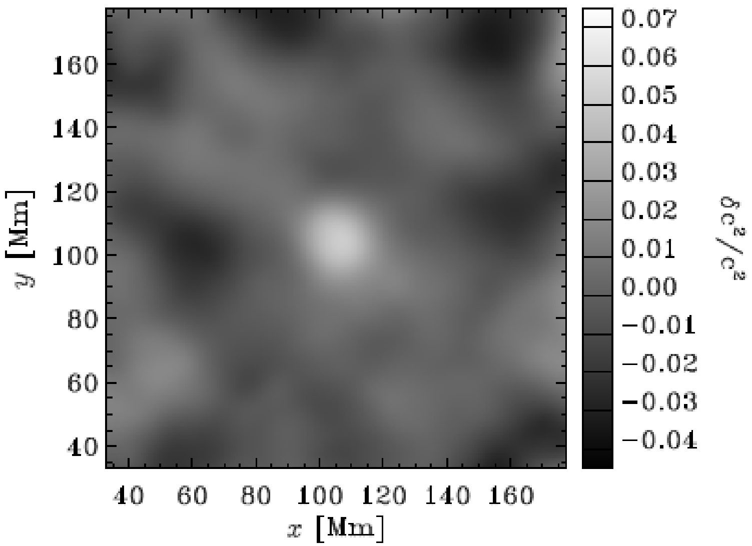


Suppressed Sources Are Non-Negligible

- Assumption: Granules are wave sources
- Sources are suppressed to the tune of 80% or more in a sunspot
- Anisotropies in wave-source distribution create large time shifts
- Misinterpretations of shifts: sound-speed and flow perturbations (Hanasoge et al. 2008)

Ray Inversions of time shifts





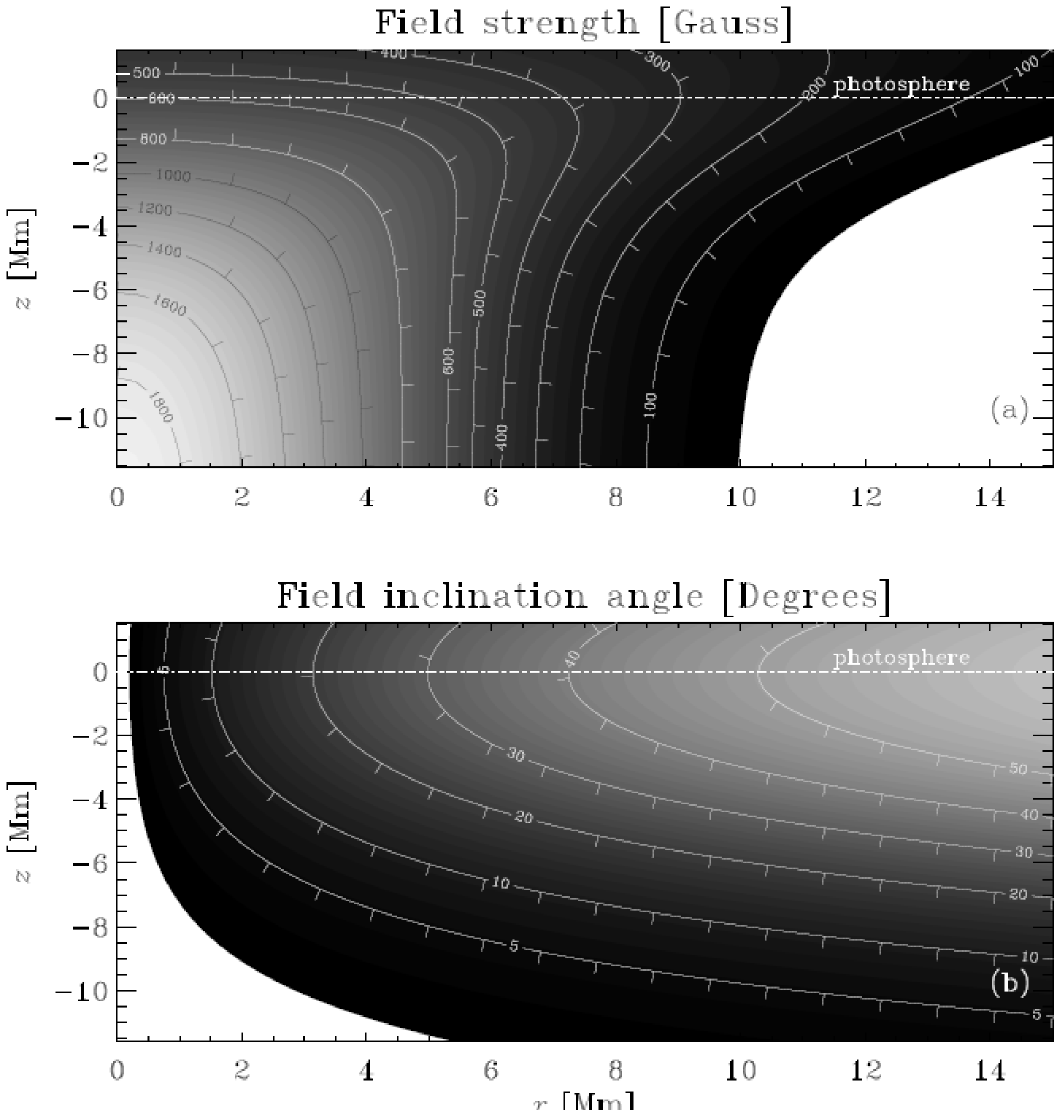
Average over [-0.62, 0.0]

Average over [-1.35, -0.62]

Sunspot Structure and Dynamics

- Effects of source suppression and appropriate filtering increase uncertainty about sunspot inversions
- MDI observations of strong magnetic regions are inaccurate
- Wilson depression in sunspots introduces further interpretational complexity
- Inescapable: forward modeling of MHD interactions

Seismic Halos Around Active Regions



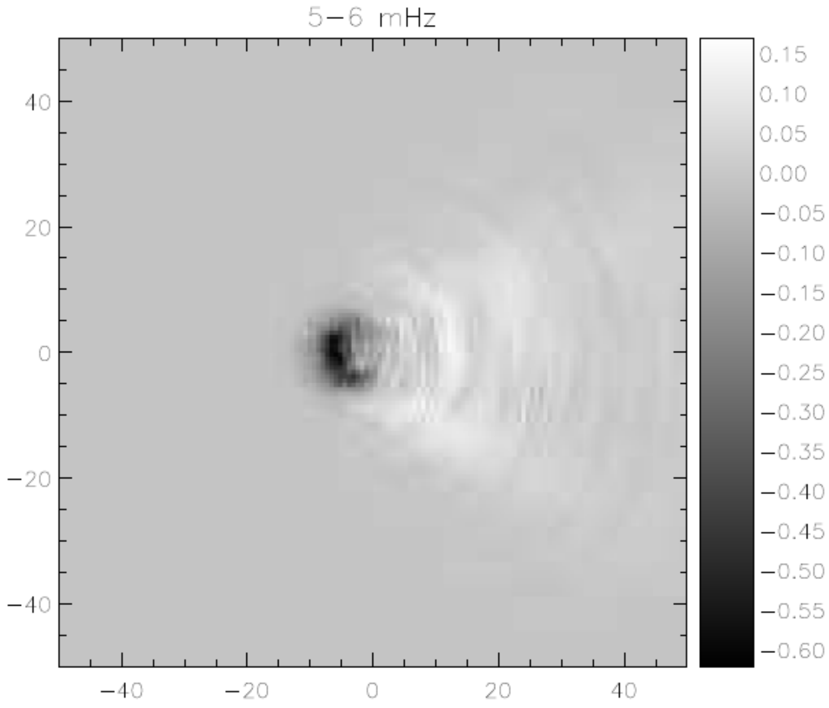
Peak Photospheric strength 600 G

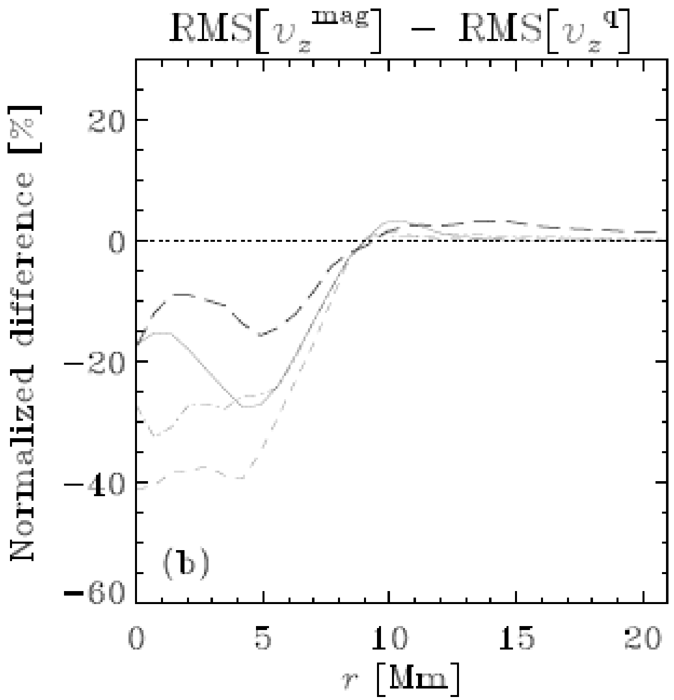
FWHM ~ 9 Mm

Linear MHD simulations

Hanasoge 2007

High Freq. Seismic Enhancements

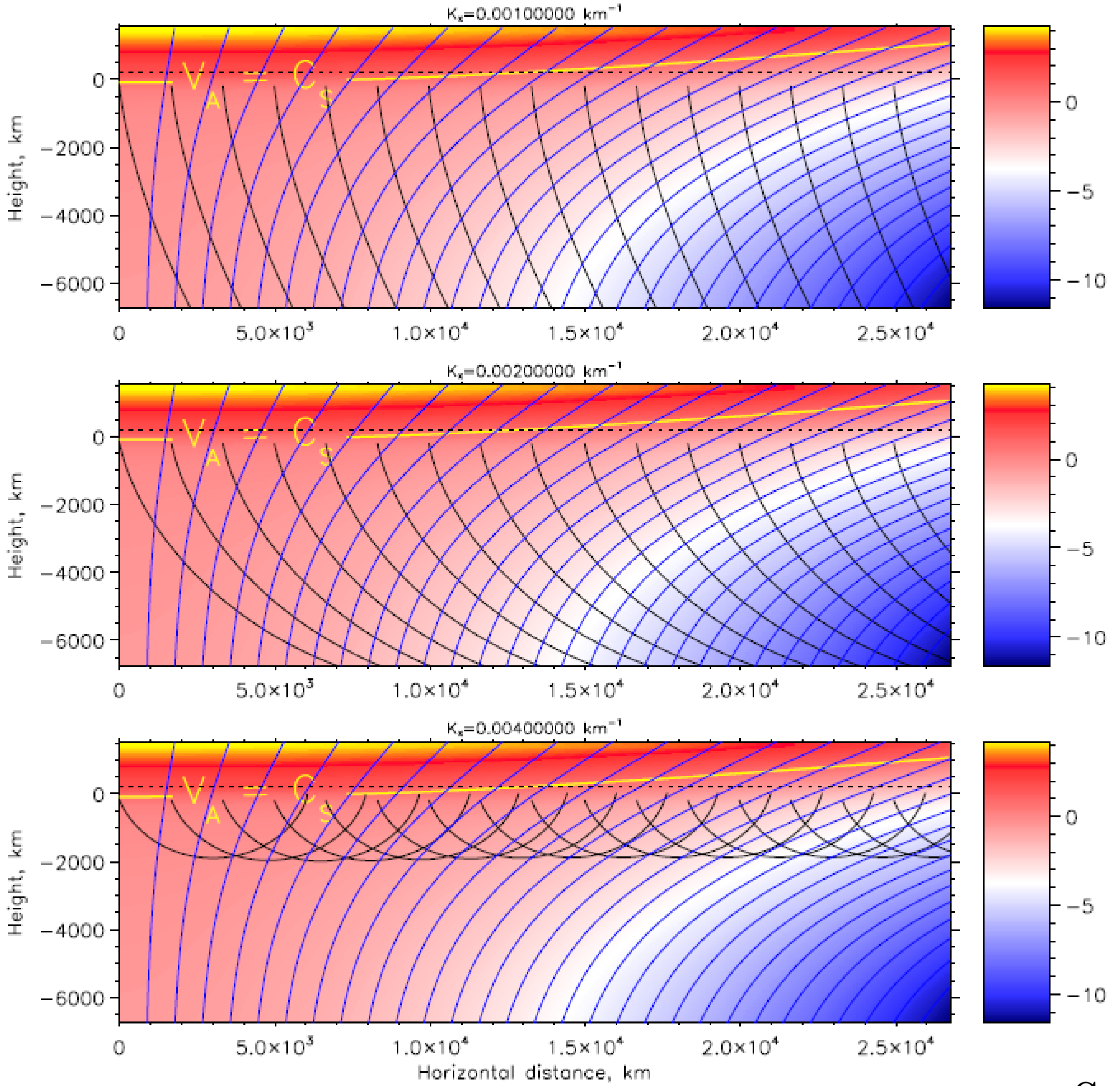




Why Only At High Frequencies?

- Above acoustic cut-off, waves leak out into the atmosphere
- In a flux tube, acoustic waves are converted to fast + slow + Alfven waves
- Slow and Alfven waves leak out into atmosphere
- Fast modes are refracted by the rapid increase in Alfven speed, channeled back into the solar interior to re-emerge at the photosphere

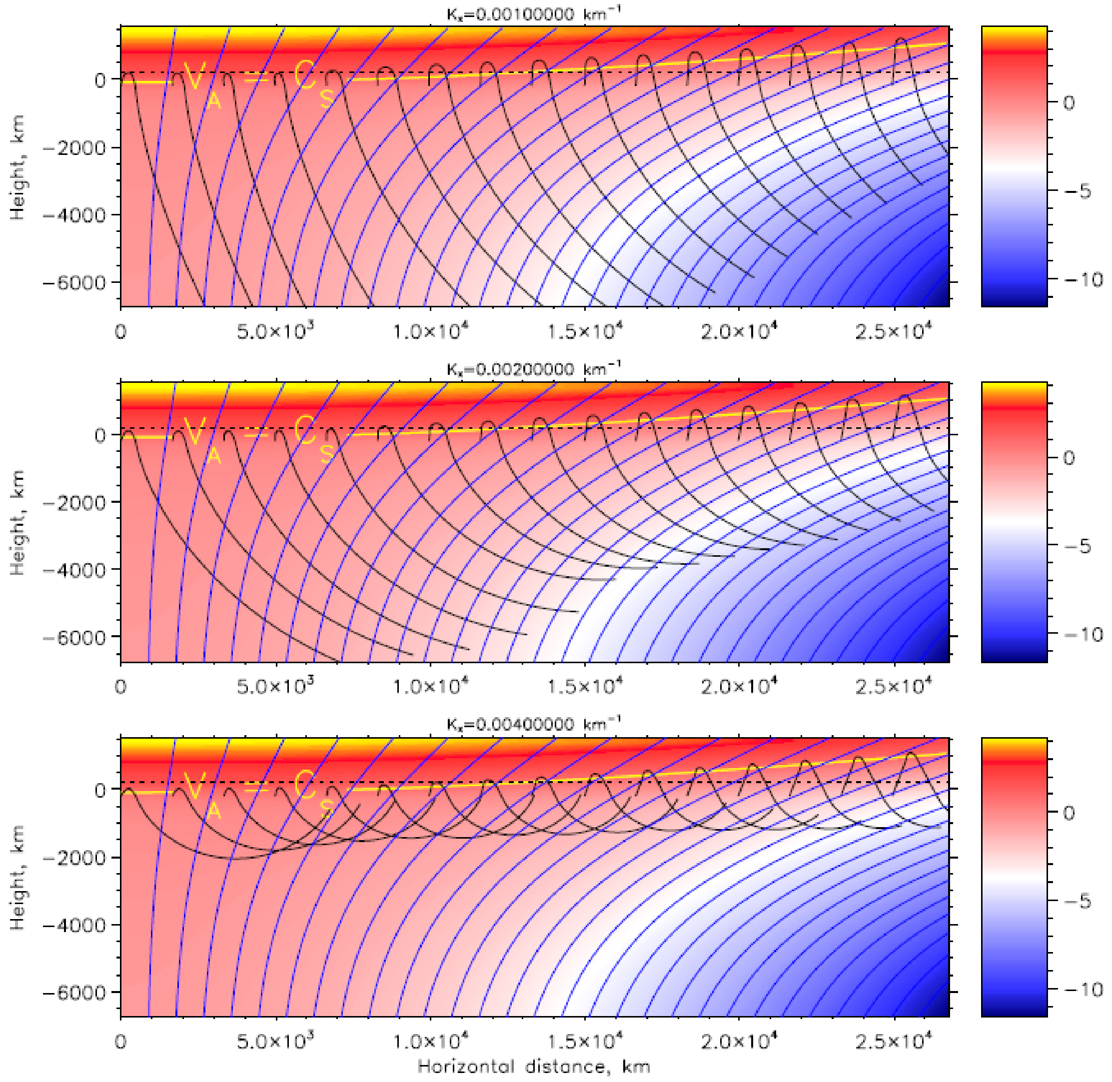
WKB I: Fast Mode Propagation



Initial condition: Downward propagating

Courtesy: Elena Khomenko

WKB II: Fast Mode Propagation



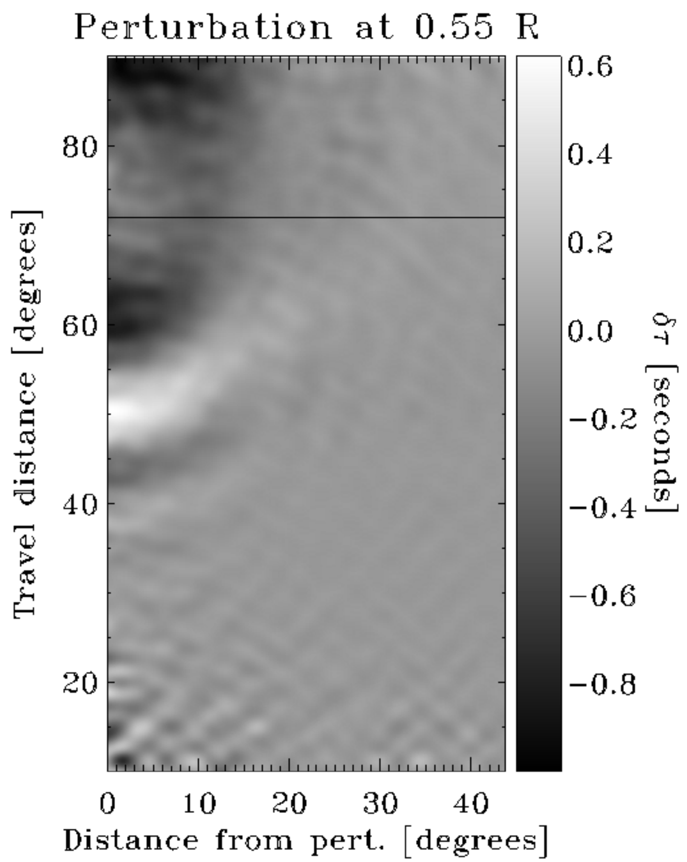
Initial condition:
Upward propagating

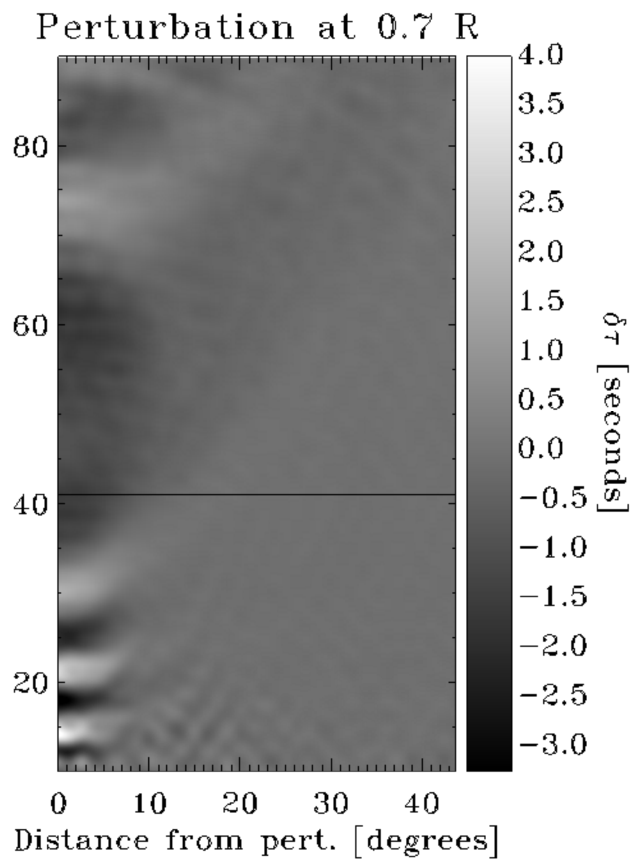
Courtesy: Elena Khomenko

Observing the Deep Interior

- Motivation: To see in and around the tachocline, and perhaps even deeper (Hanasoge & Duvall 2008)
- Put in flows/ sound-speed perturbations
- Perturbations are pancake like; thin in the radial direction; horizontally extended in comparison
- Calculations are performed in spherical geometry; analyses involve deep focusing/ common mid-point method and noise subtraction

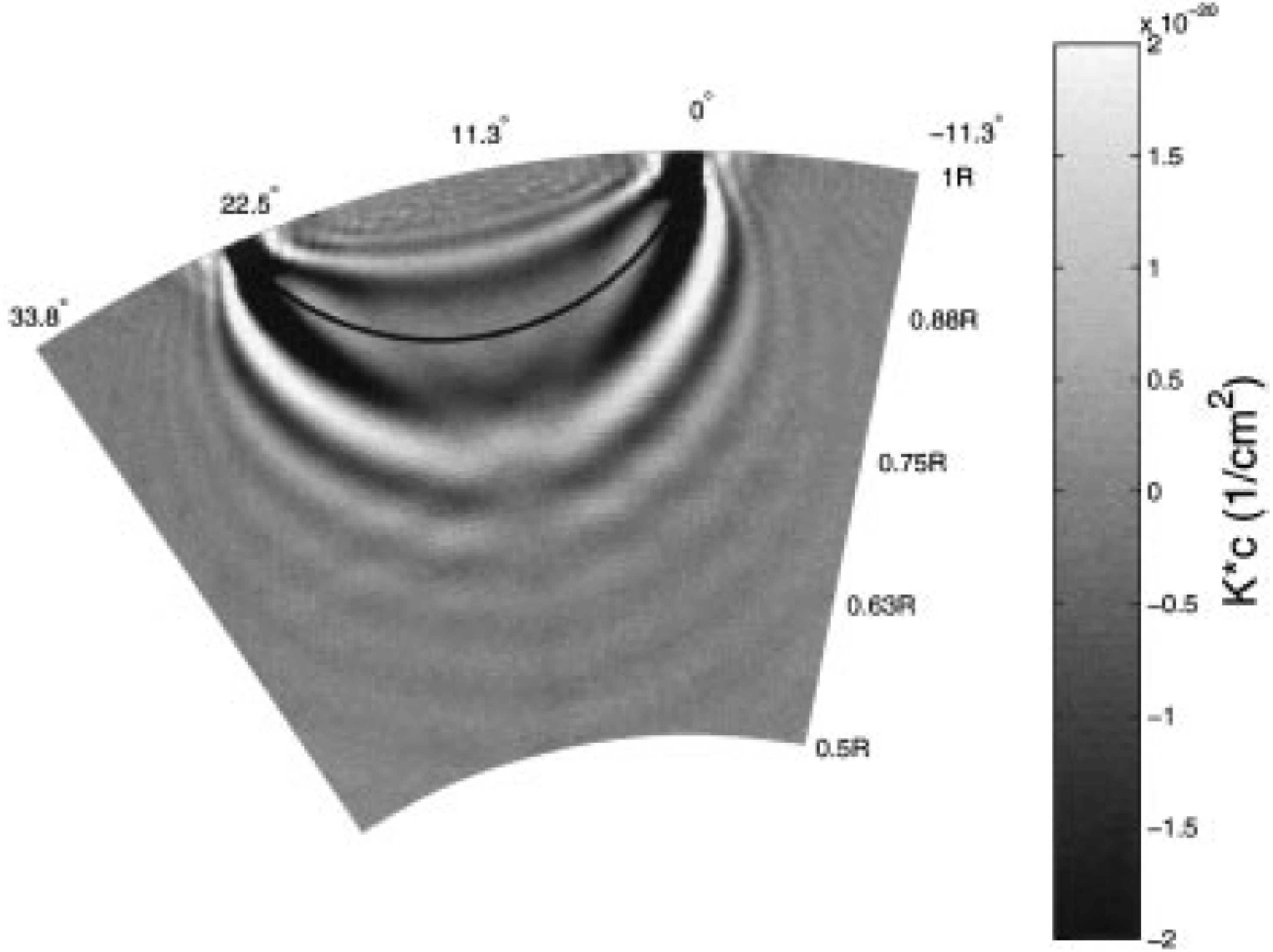
Detectability of Thermal Anomalies



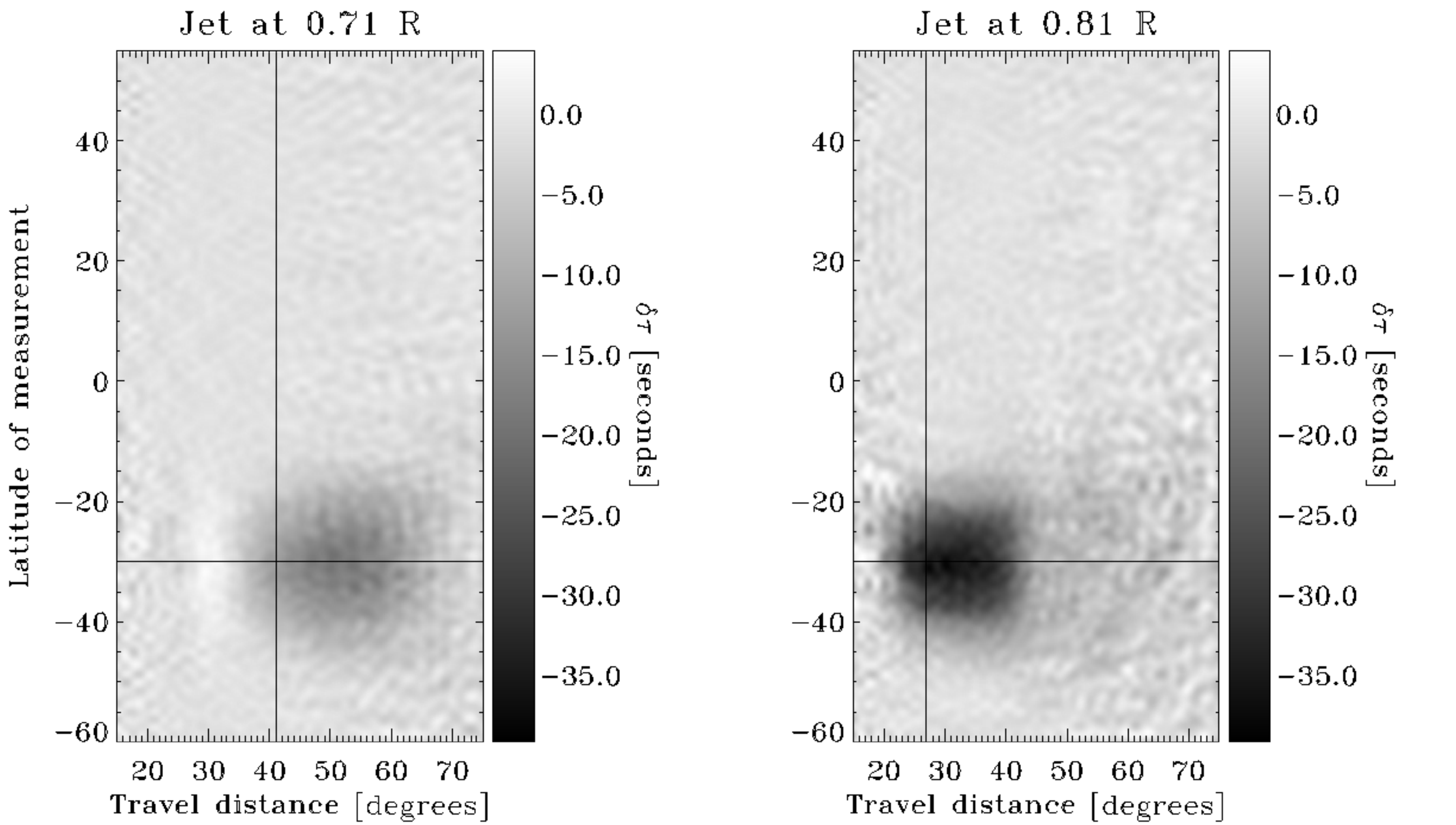


- FWHM (r): 11 Mm (1.6 % solar radius)
- FWHM (θ, φ): 97 Mm (~ 8 degrees)
- Strength: 5 % increase in sound speed

Sound-speed Kernel



Detectability of Jets

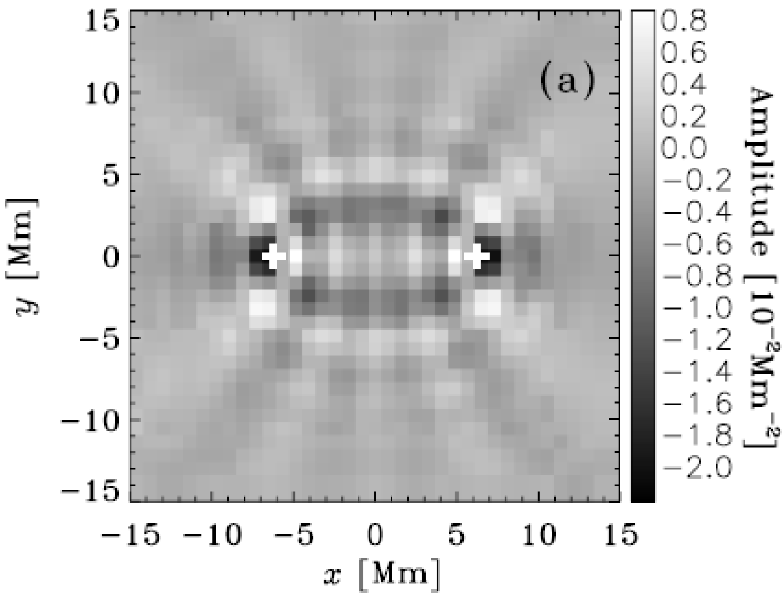


- FWHM (r): 23 Mm (3.5 % solar radius)
- FWHM (θ): 200 Mm (16 degrees)
- Speed: 11.2 km/s, 8.5 km/s

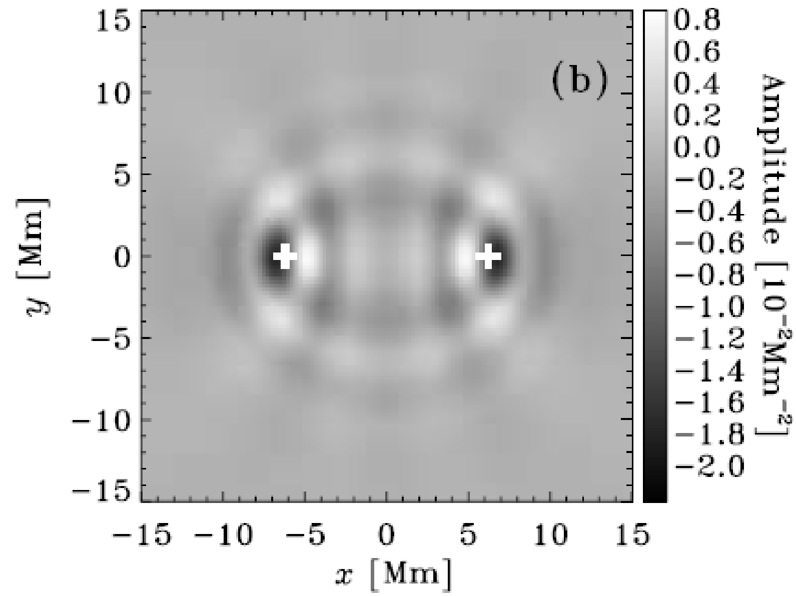
Sub-Wavelength Resolution Helioseismology

- Use magnitude of Fresnel zone time shifts in comparison to the signal to place bounds on size of the “anomaly”
- Use frequency filters: ratio of perturbation size to wavelength changes with frequency
- Sadly, does not work on Tachocline: severe systematical errors overwhelm the calculation (simulations and observations)

Experiment: Sound-speed Perturbation



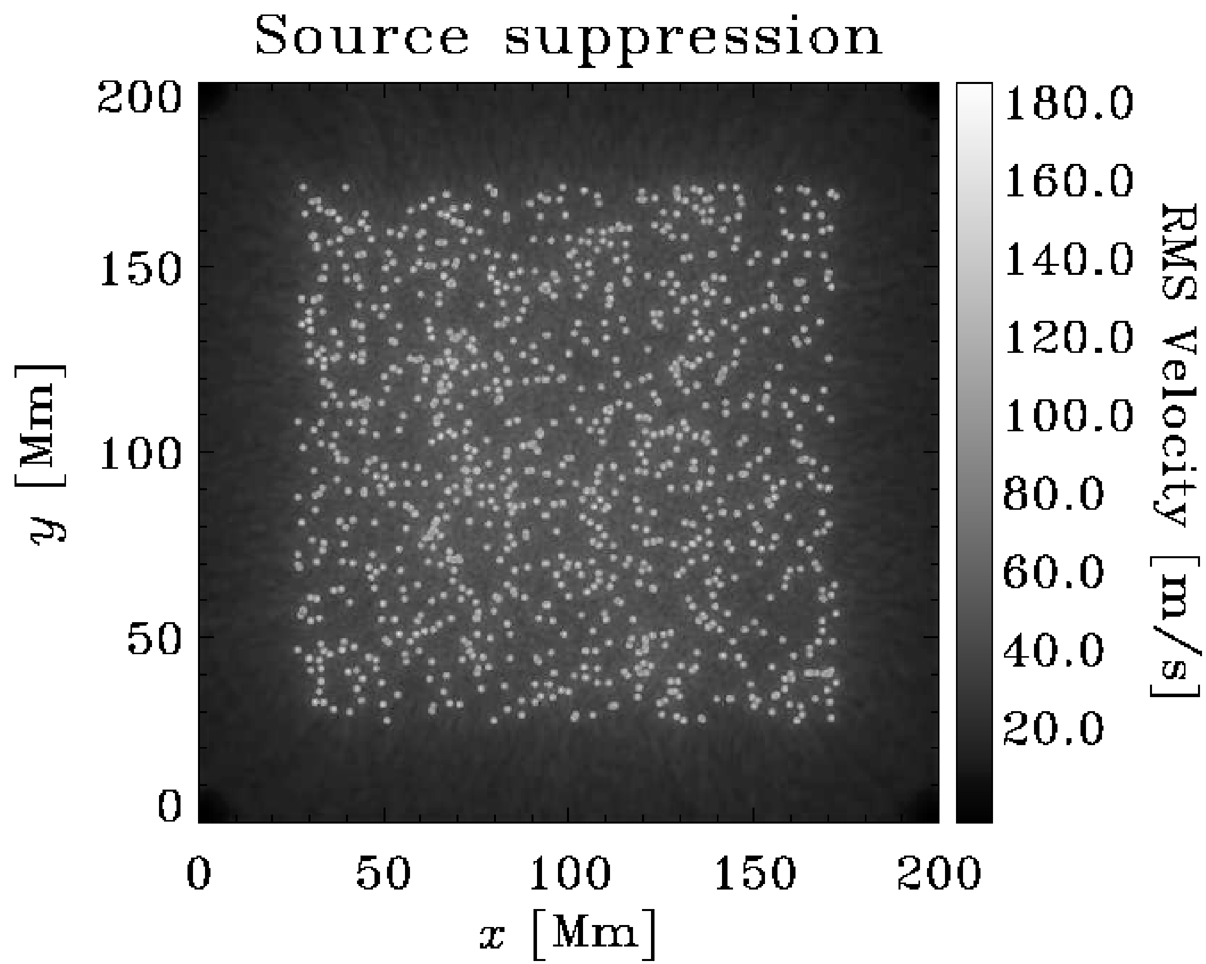
Feature Method



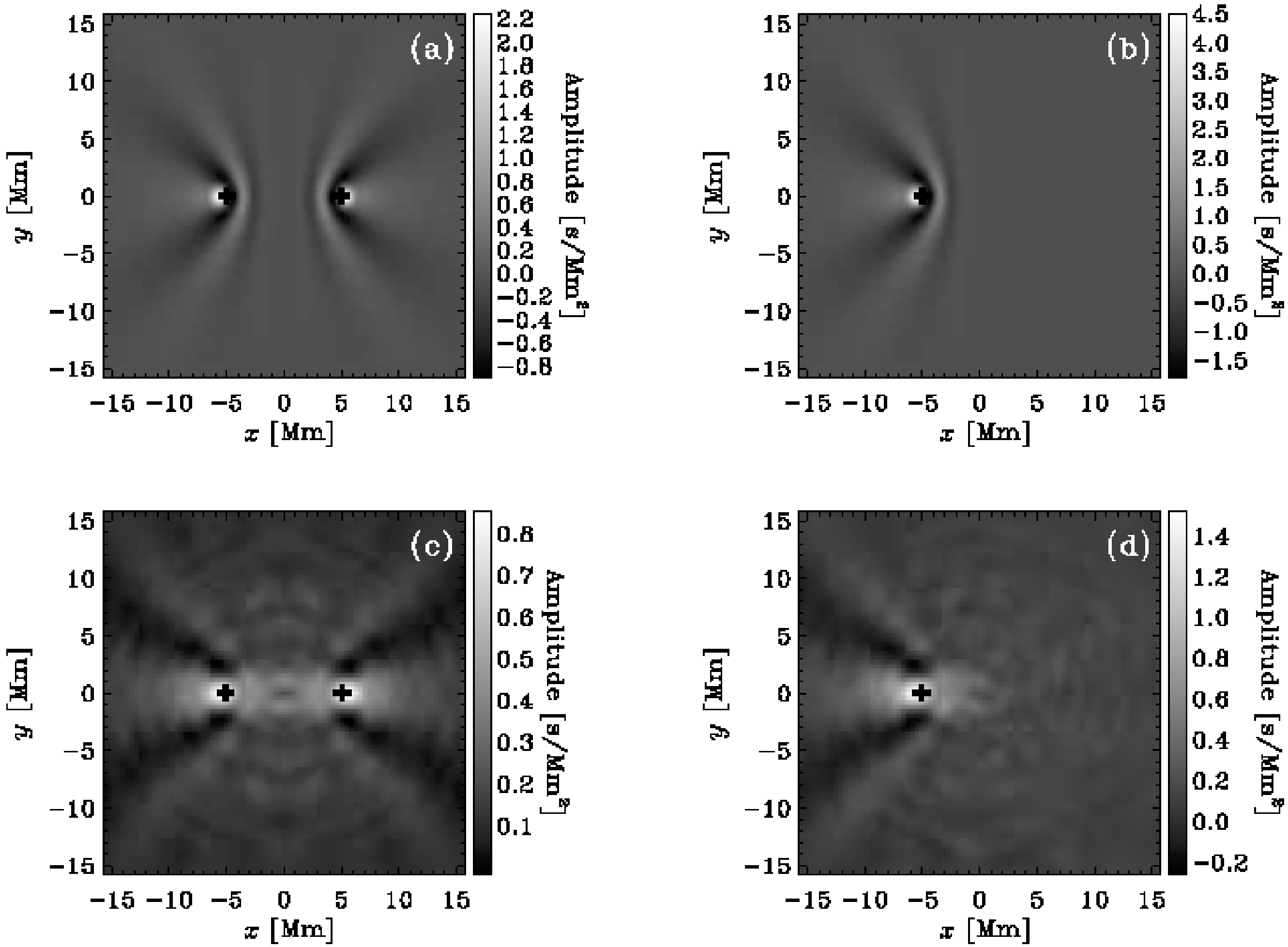
Theory
Birch et al. (2004)

Sub-wavelength features can thus be identified

Experiment: Source-strength Anomalies



AVERAGE SOURCE KERNEL

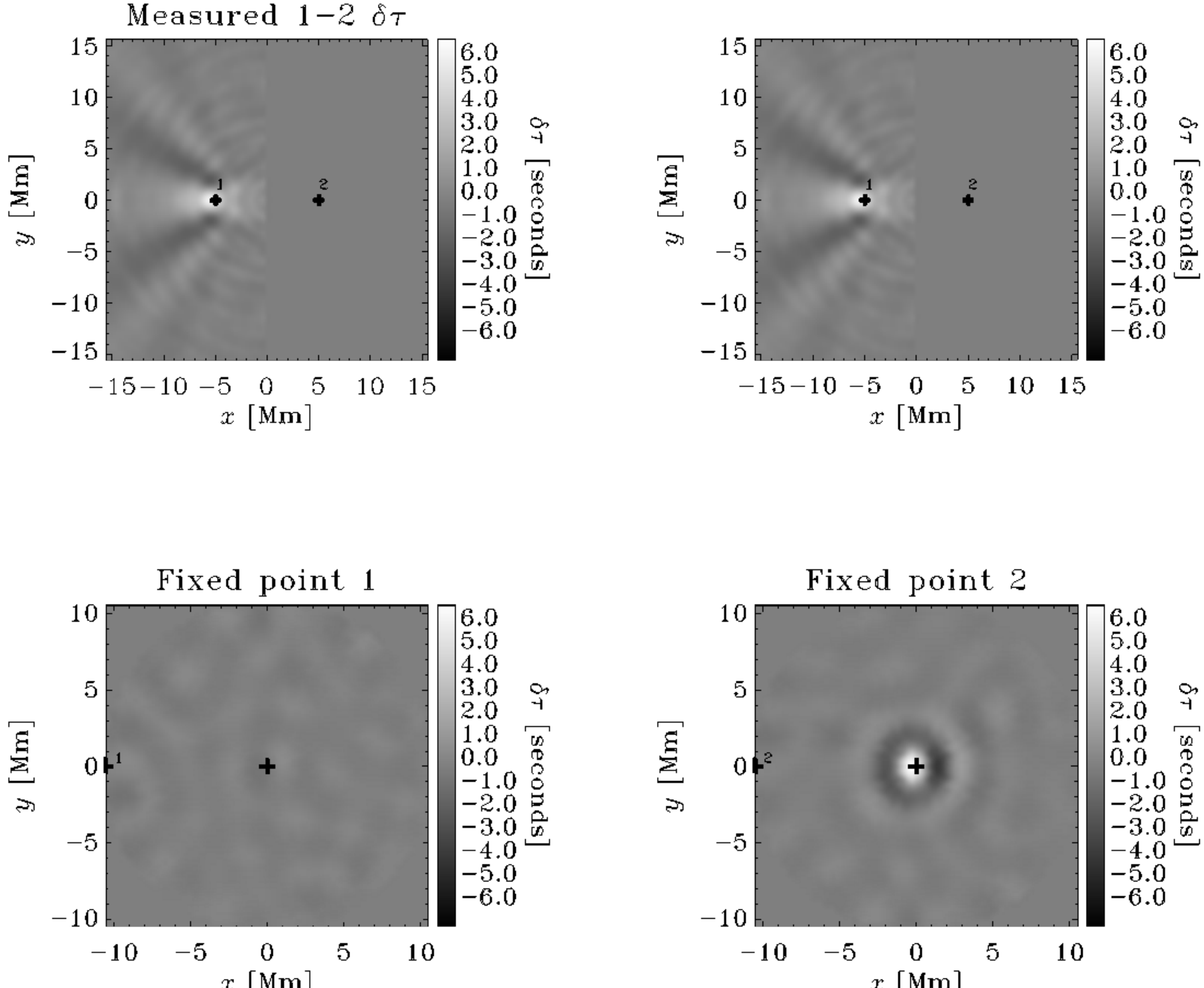


Theory

Feature Method

Figure from Hanasoge et al. (2007)

Measuring cross sections



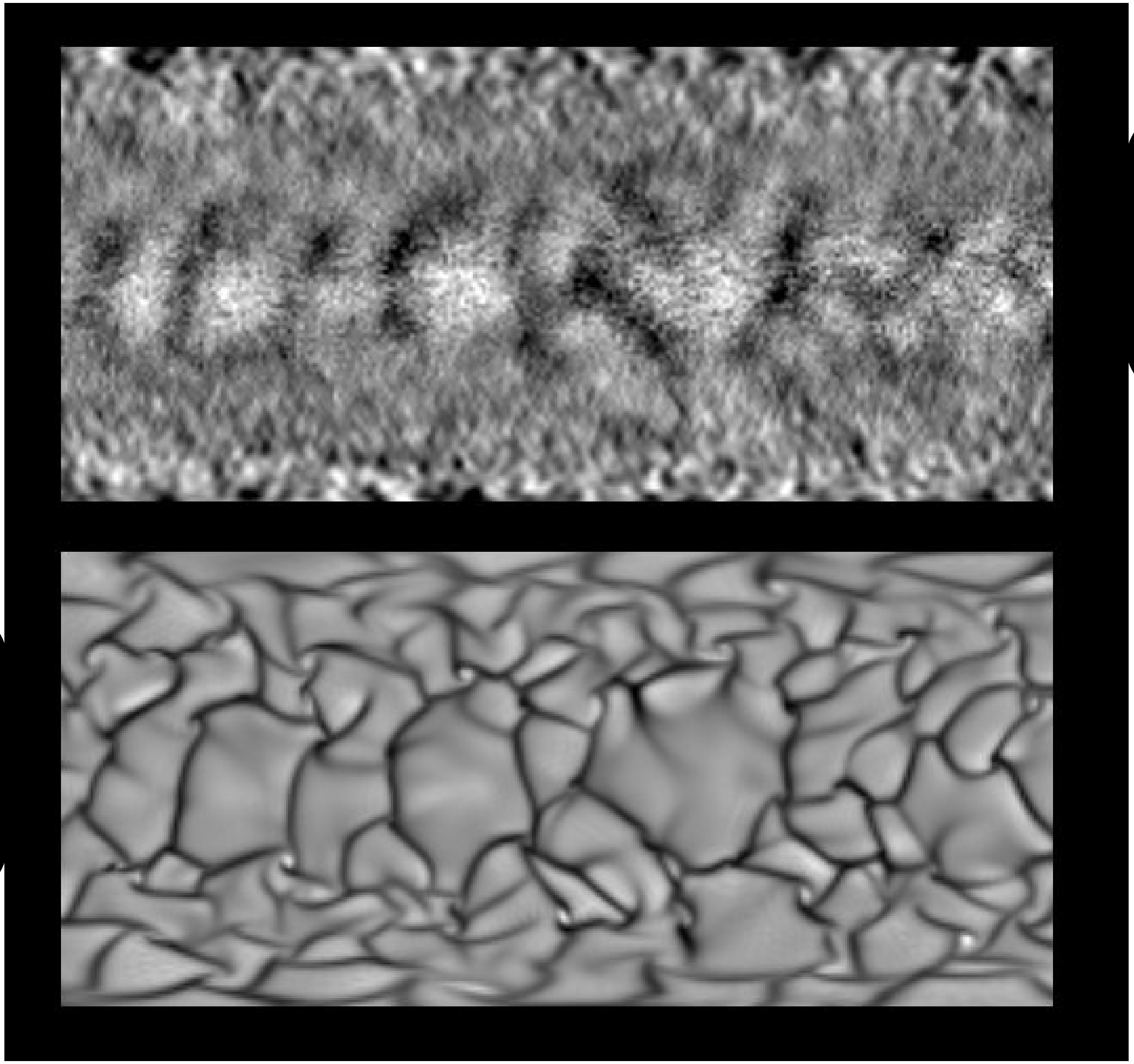
Thin Flux Tubes In The Sun

- "Scattering cross section" has been measured from MDI observations
- Attempts to replicate results using MHD simulations of thin flux tubes, thereby constraining the structure
- Work in progress

Detectability of Interior Convection

- Use ASH convection model, frozen in time
- Turnover time scale << acoustic propagation time
- Use geo-physical deep-focusing method to get at the flows
- Estimate the signal to noise ratio

Detectability of Interior convection



As seen by the waves

ASH radial velocity

Conclusions

- How to treat helioseismic data?
- Revising our understanding of active regions
- Determining what is detectable and what is not
- Observations + forward models = more reliable
- Collaborators: Tom D., Sébastien, Rajaguru, Aaron, Doug, Elena, Ashley, Robert, Tom B., Laurent Gizon