Oscillations and Convection Simulations

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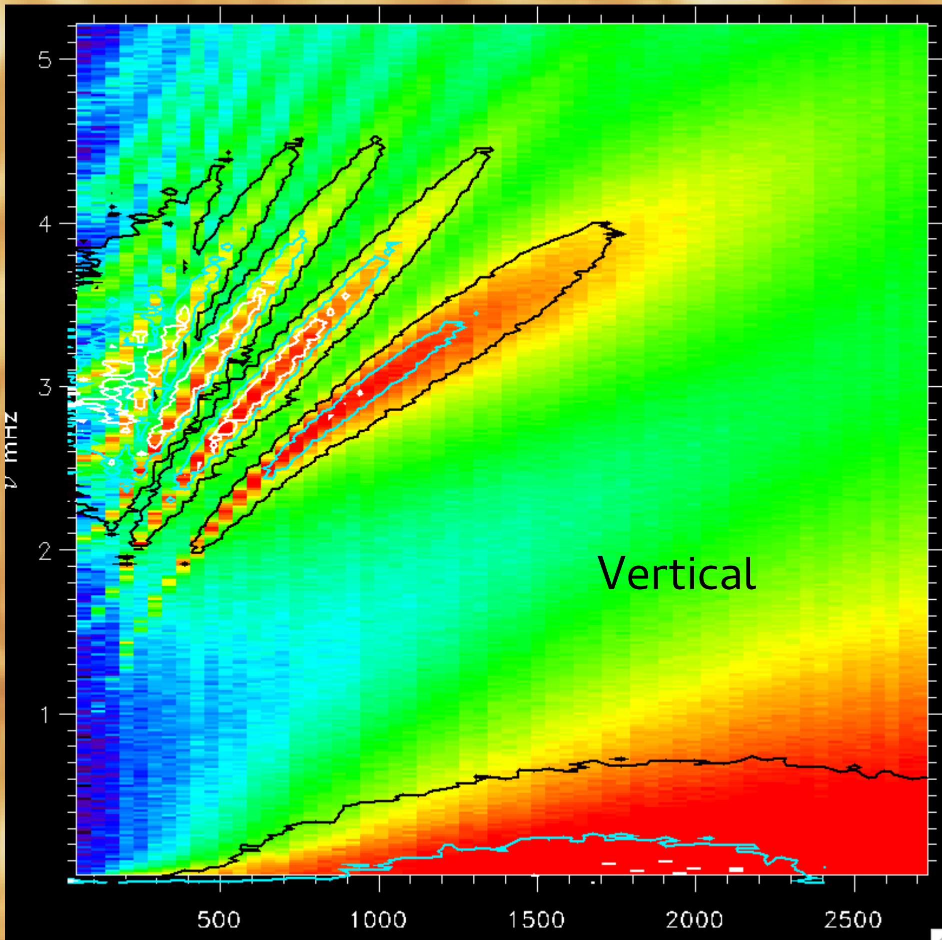
movie was made by Timothy Sandstrom of the NASA Ames Research Center visualization group

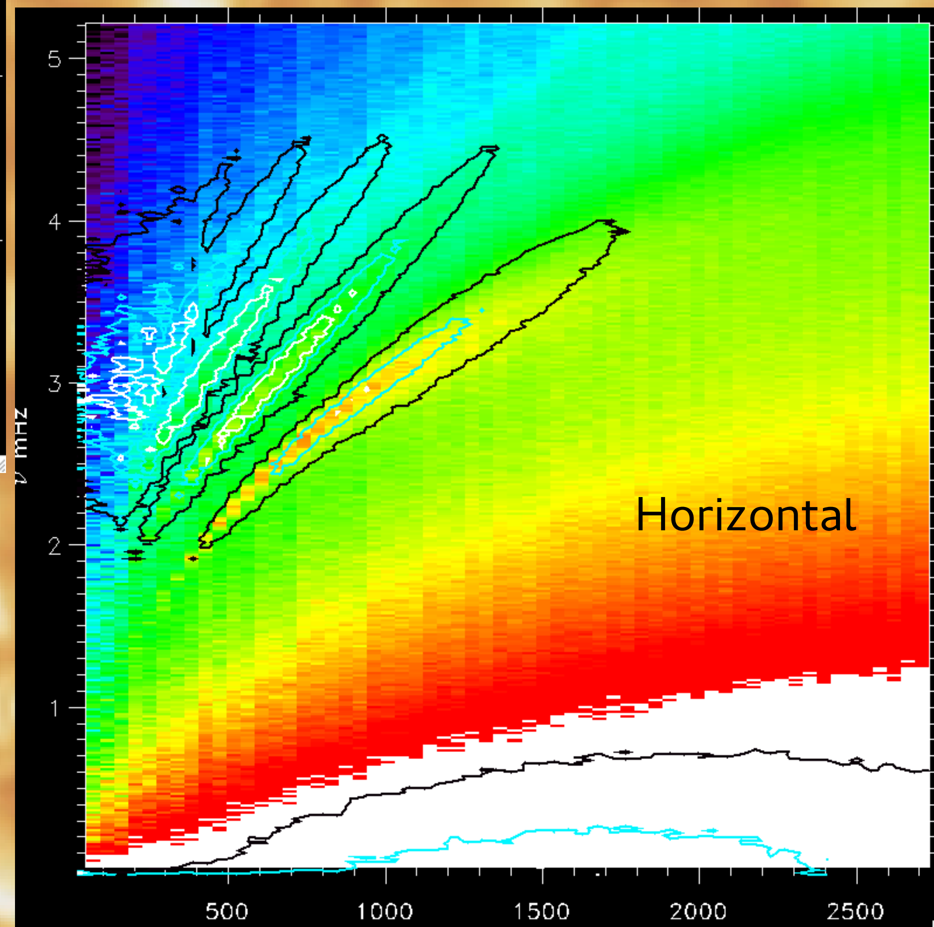
Two Simulation Sequences: Quiet Sun and Active Region

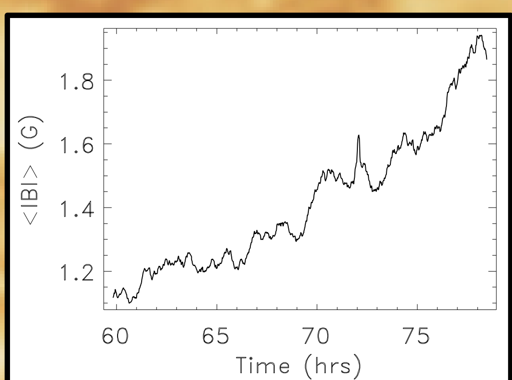
- QS: 96 Mm wide x 20 Mm deep
  19 hours, 1 minute cadence
  Resolution horizontal 48 km, vertical 11-80 km
- Active Region: 48 Mm wide x 20 Mm deep
  24 hours, 1 minute cadence
  Resolution horizontal 24 km, vertical 11-80 km

Oscillation Modes QS Velocity:

Image = simulation Contours are HMI

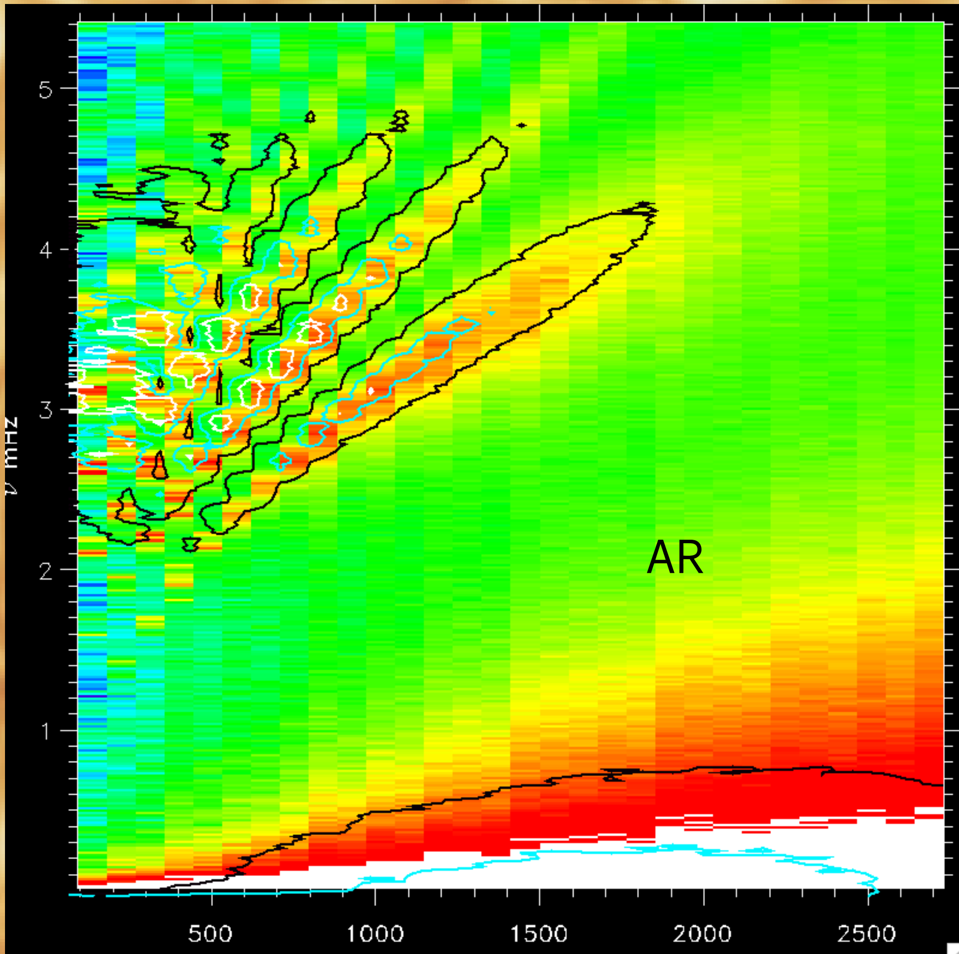


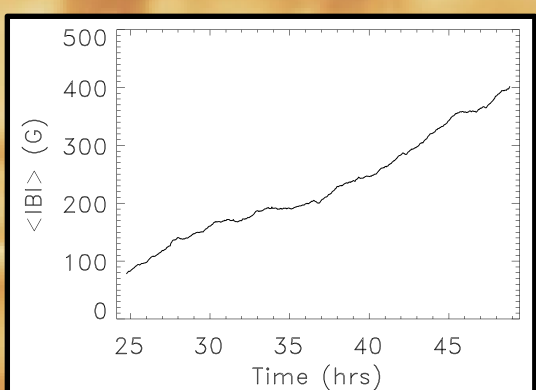


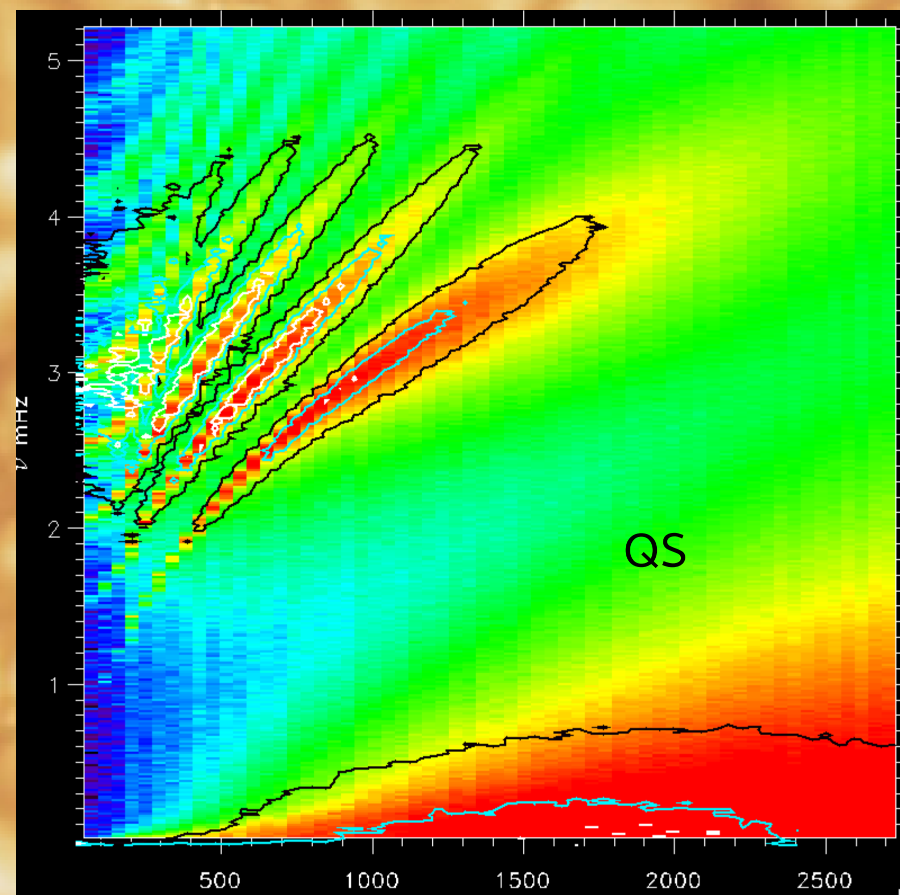


Oscillation Modes QS & AR, V_{vert}

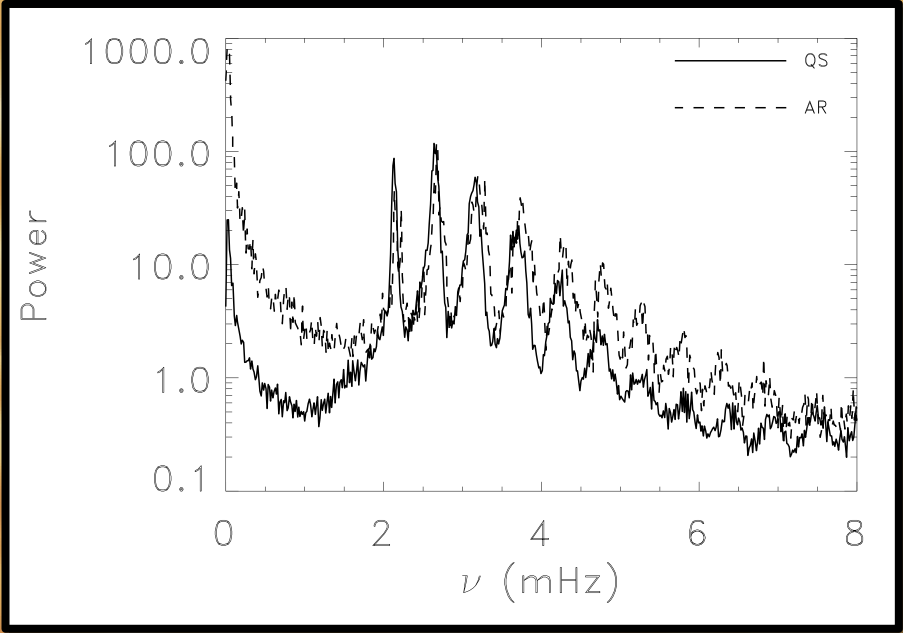
AR has more convection power, less oscillation power

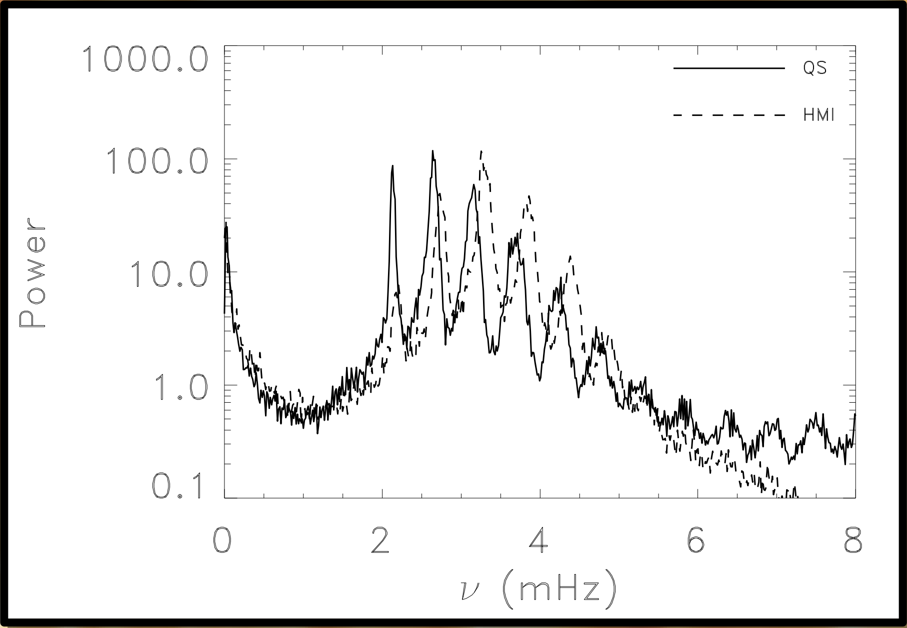


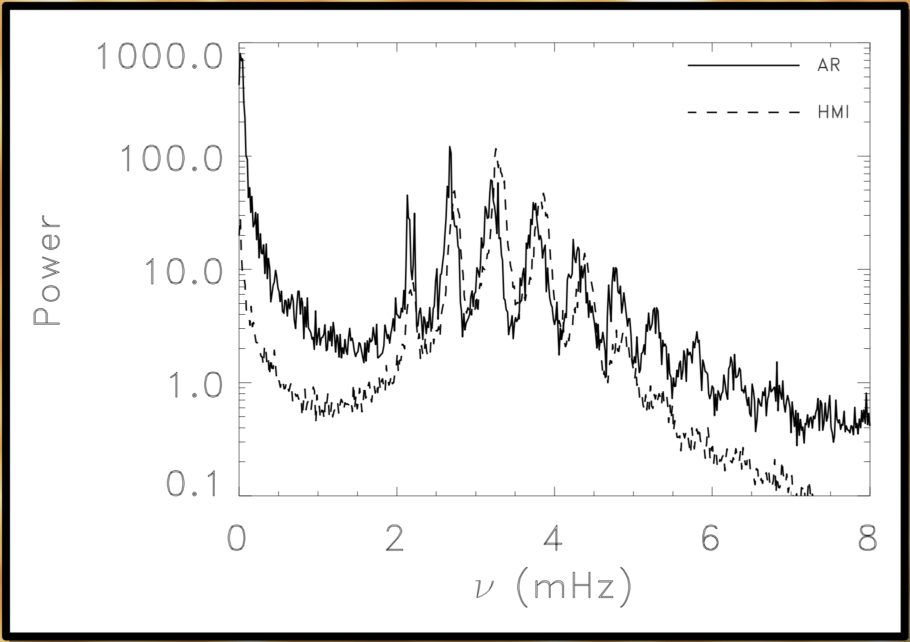




Frequency Spectra
l=455



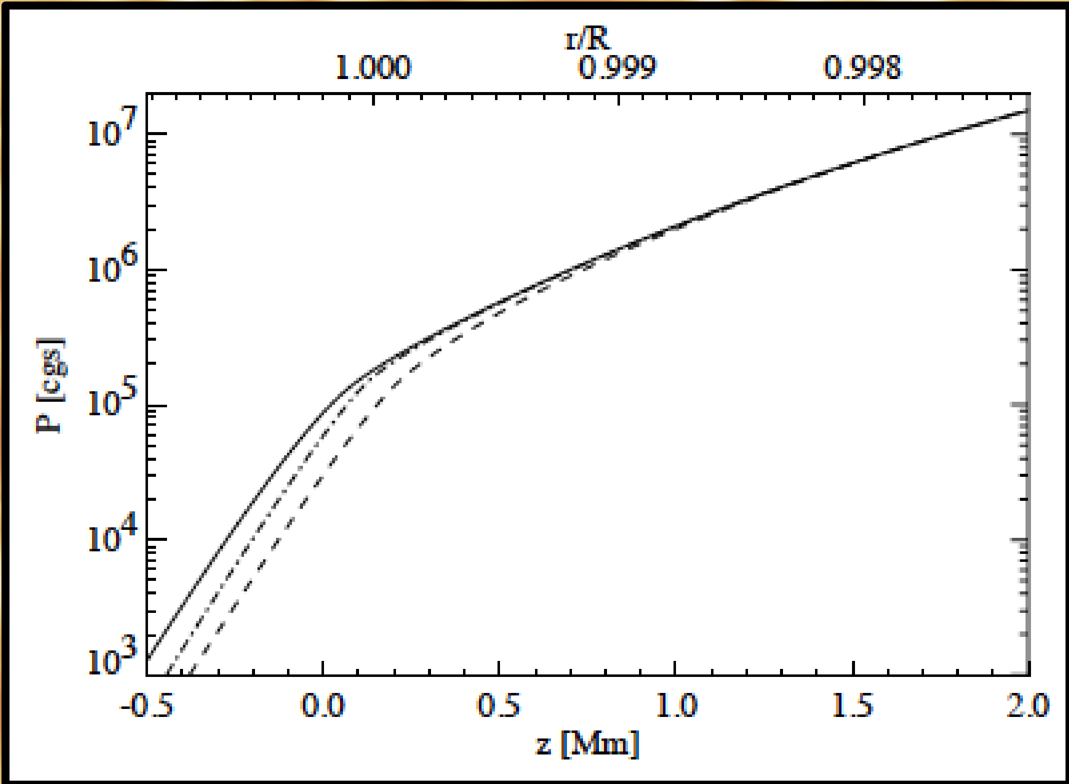




Surface Effects

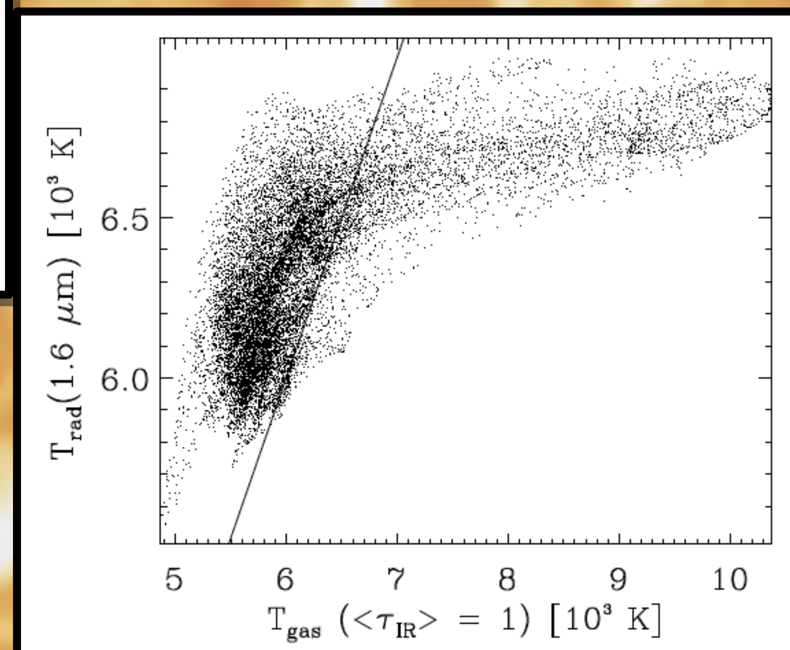
- Convection changes the size of the resonant cavity for the modes with turning points above the superadiabatic layer due to TWO effects:
  - Turbulent pressure extends the atmosphere
  - Inhomogeneous temperature structure leads to higher average temperature than a 1D model with the same radiative flux.
- For the Sun, each enlarges the cavity about half a scale height.

Atmospheric Expansion

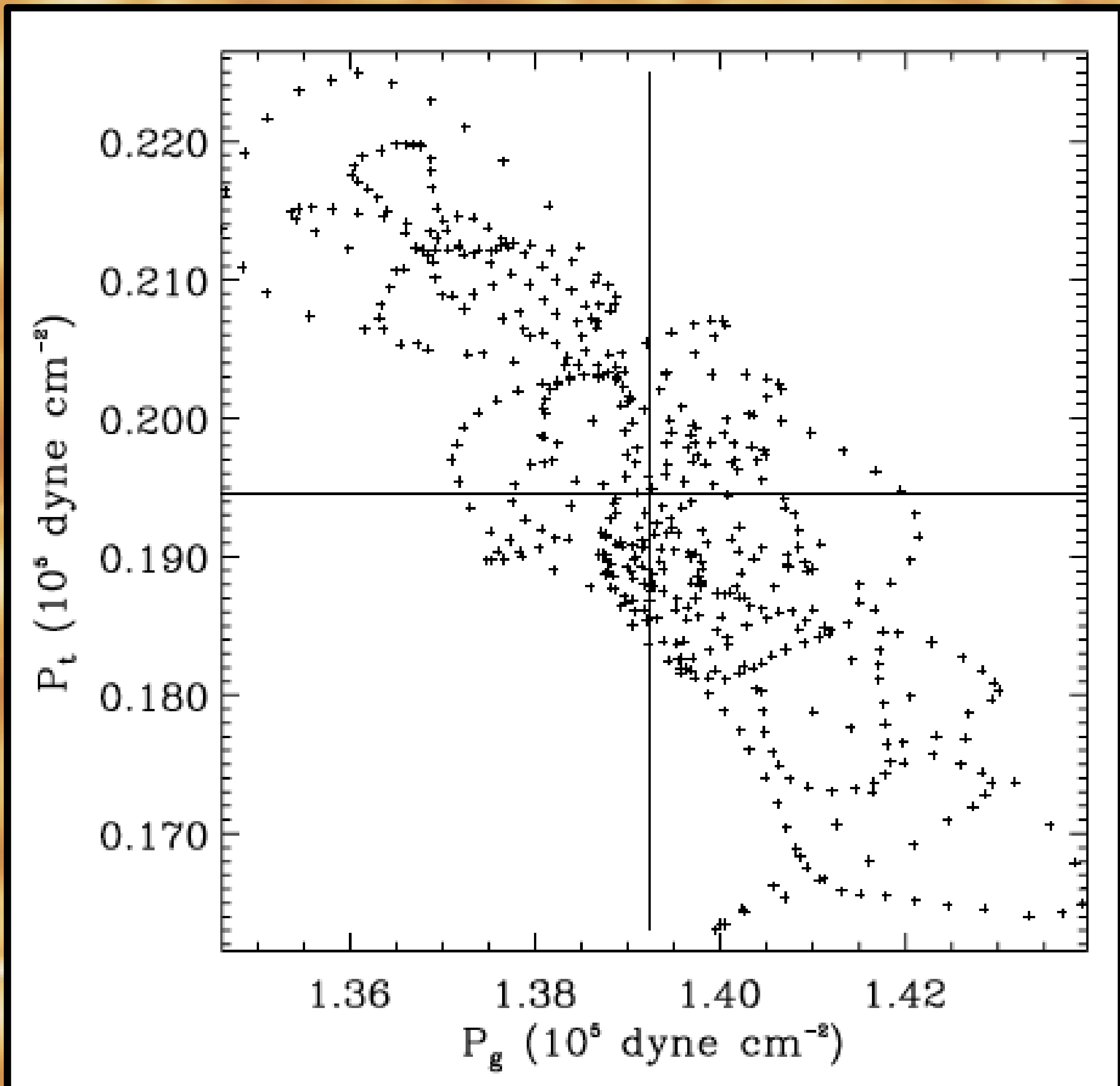


Solid-=3D simulation
Dashed=1D
Dash-Dot=3D, no Pturb

Rosenthal et al. 1999, A&A, **351**, 689



Turbulent Pressure



$P_{t} \sim P_g/7$

$\delta P_{t} \sim \delta P_g$

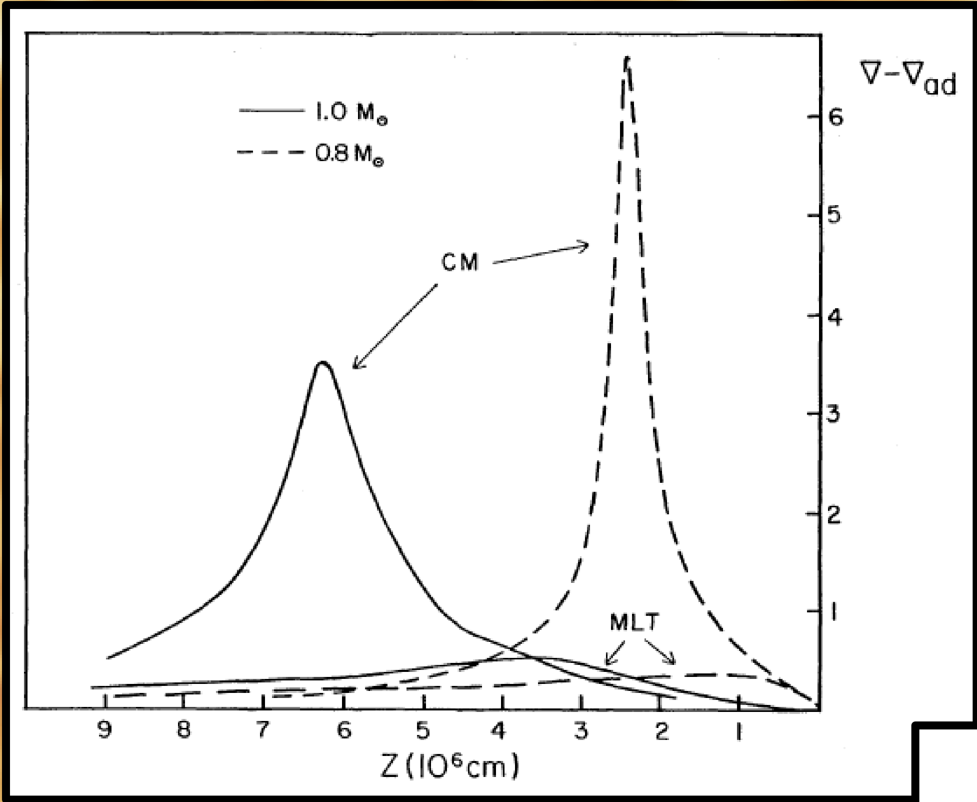
In Quadrature

Stein & Nordlund, 2001, ApJ, **546**, 585

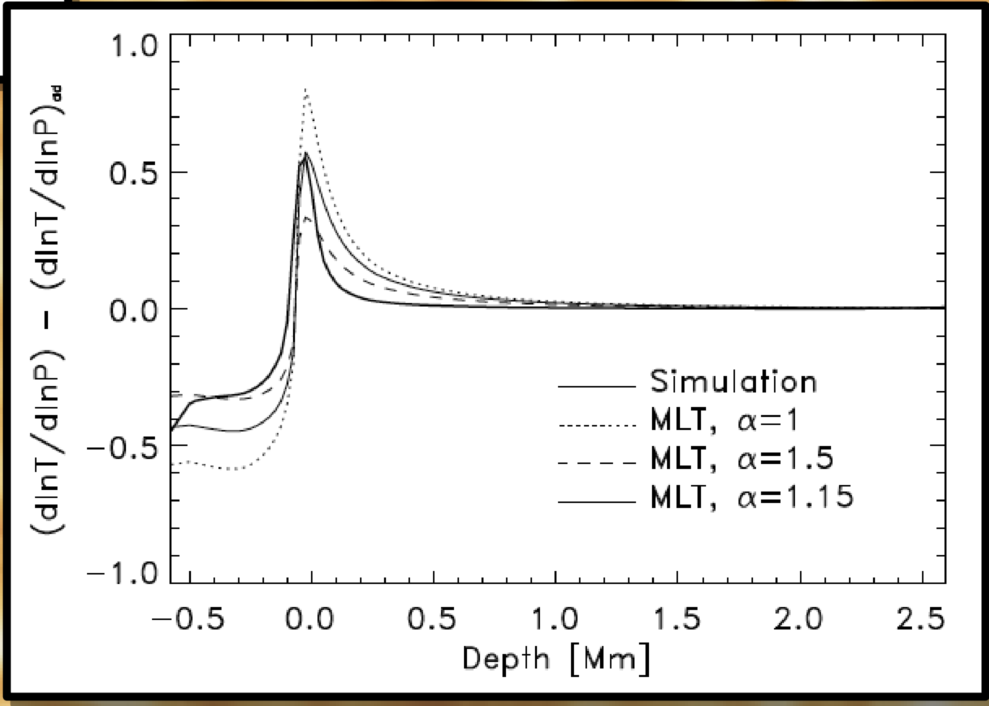
Matching Observed Mode Frequencies

- **Matching the observed mode frequencies is a necessary but not sufficient test of convective models.**
- **DIFFERENT atmosphere structures can produce the SAME mode frequencies!!**

Superadiabatic gradient, $\overline{\nabla} - \overline{\nabla}_{ad}$



Canuto Mazzitelli (1992, ApJ, **389**, 724) convection model gave better frequencies, but had very different structure than 3D models.



Tests:

- Compare with:
  - ✓ atmospheric structure of 3d models
  - ✓ observed oscillation mode line widths (damping)
  - ✓ observed oscillation excitation rates
  - ✓ oscillation mode eigenfrequencies

Mode Excitation

P-modes are excited by three processes:

- ✓Reynold's stresses
- ✓Entropy fluctuations
- ✓Lorentz forces

In the absence of magnetic fields the excitation can be calculated as the PdV work of the non-adiabatic gas pressure and the turbulent pressure.

First there was Lighthill

$$\frac{\partial^2 \rho}{\partial t^2} - c^2 \nabla^2 \rho = \frac{\partial^2 T^{ij}}{\partial x_i \partial x_j}$$

$$T_{ij} = \rho v_i v_j + p_{ij} - \rho c^2 \delta_{ij}$$

$$\rho - \rho_0 = \frac{1}{4\pi a_0^2} \frac{\partial^2}{\partial x_i \partial x_j} \int T_{ij}\left(\mathbf{y}, t - \frac{|\mathbf{x}-\mathbf{y}|}{a_0}\right) \frac{d\mathbf{y}}{|\mathbf{x}-\mathbf{y}|}.$$

This includes both the Reynolds stress and the entropy fluctuations, but was evaluated only in the far field, whereas the oscillations modes exist inside the turbulent source region – the convection zone.

Then there was Goldreich et al.

$$\frac{dE_\omega}{dt} = \frac{\omega^2}{2}\int d^3r \left|\frac{d\xi}{dr}\right|^2 \int_0^{h_{\max}} dh\, h^2 \tau_h \left[(\rho u_{\mathrm{h}}^2)^2 + \left(\left(\frac{\partial P}{\partial s}\right)_\rho \delta s_{\mathrm{h}} \right)^2 \right]$$

This replaced the arbitrary displacement in the inhomogeneous wave equation of Lighthill with the oscillation eigenmode displacement, so the expression applies inside the source region. However, the compression is assumed to be the same for all modes and it neglected correlations between oscillations and convection.

Nordlund & Stein, PdV work on KE

The work integral is

$$W = \int dt \int dr\, \delta P \frac{\partial \dot{\xi}}{\partial r}$$

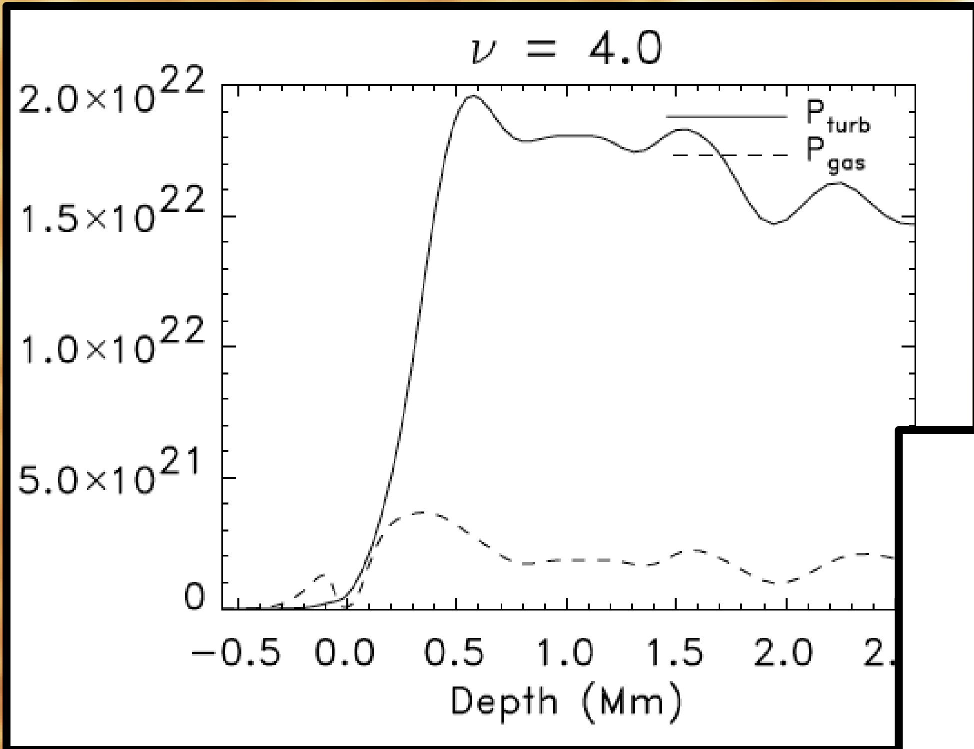
This is a stochastic process, so the pressure fluctuations occur with random phases with respect to the oscillation modes. Therefore the excitation expression must be averaged over all possible relative phases.

$$\frac{\Delta \langle E_\omega \rangle}{\Delta t} = \frac{\omega^2 \left| \int_r dr\, \delta P^*_\omega (\partial \xi_\omega / \partial z) \right|^2}{8 \Delta \nu E_\omega} .$$

$$\delta P = \delta P_{\rm turb} + \delta P^{\rm nad}_{\rm gas}$$

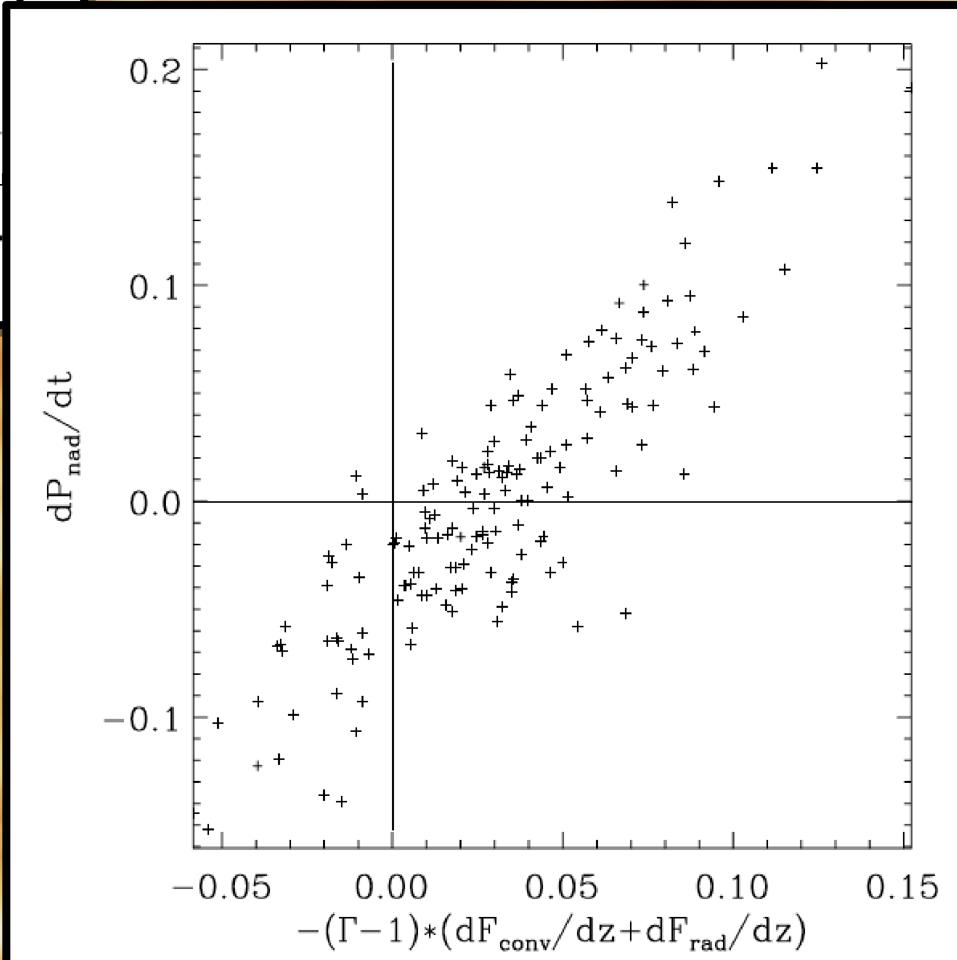
$$\delta P^{\rm nad}_{\rm gas} = P_{\rm gas} \left(\delta \ln P_{\rm gas} - \Gamma_1 \delta \ln \rho \right)$$

*Nordlund & Stein 2001, ApJ, **546**, 576, Stein & Nordlund 2001, ApJ, **546**, 585*

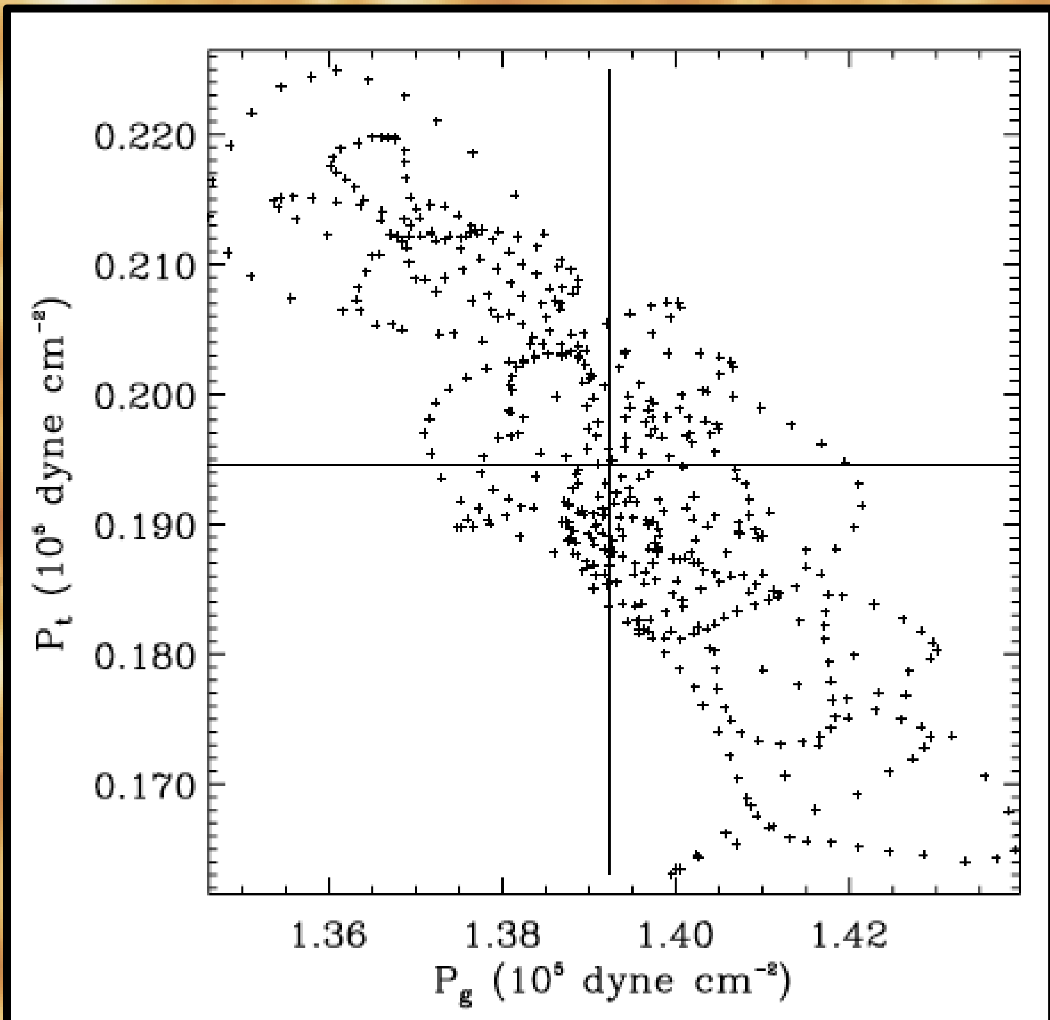


P_{turb} main driver

P_{gas}^{nad} near surface



Most of the excitation is by the Reynolds stress (turbulent pressure). The entropy fluctuations (non-adiabatic gas pressure fluctuations) are due to the local imbalance between the divergence of the radiative and convective fluxes.



δP_{turb} in quadruature with δP_{gas}

Pturb ~ 1/7 Pgas,

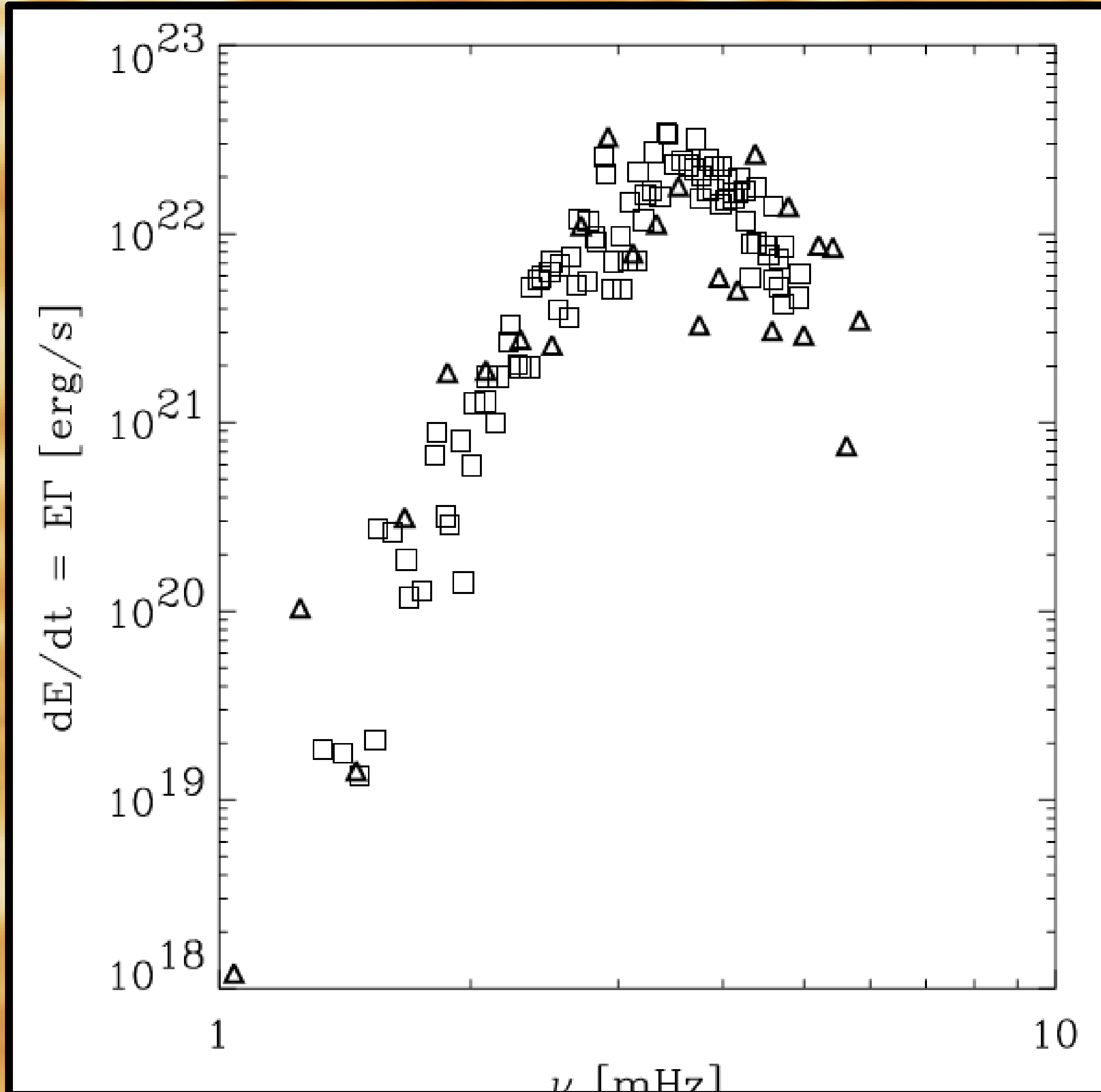
δPturb ~ δPgas

Excitation Radial Modes

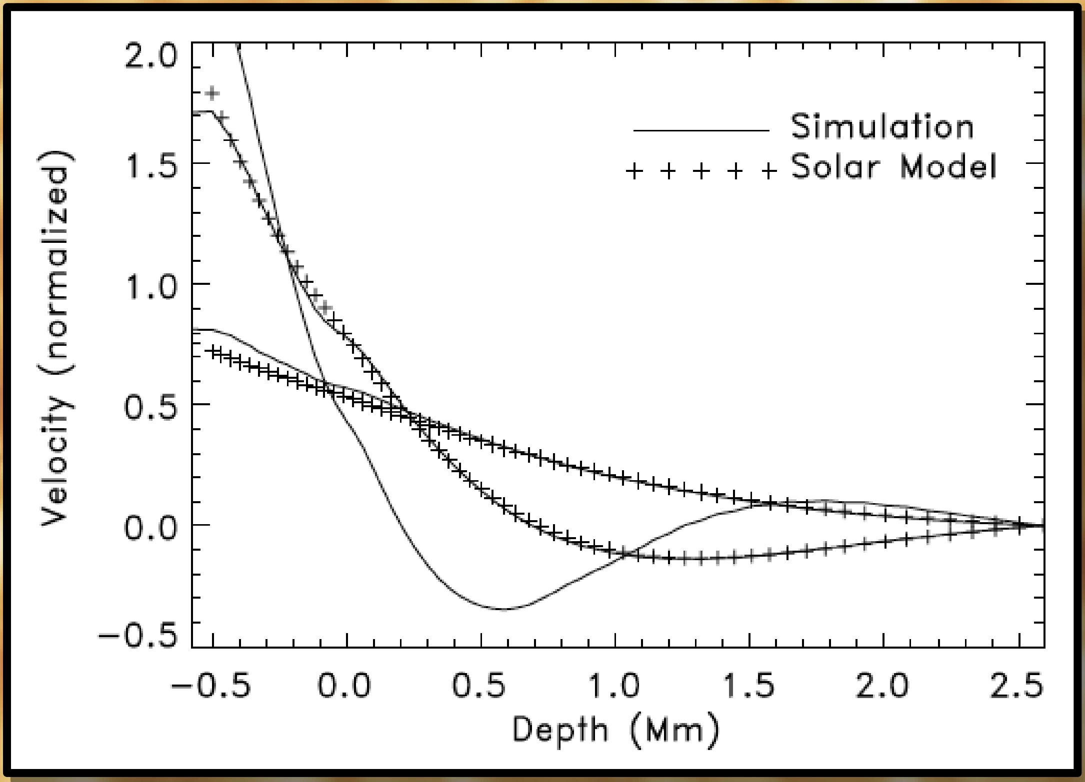
△ = simulation

□ = GOLF l = 0-3

Stein & Nordlund 2001, ApJ, ***546****,* *585*



Eigenfunctions



The transform of the velocity at the frequency of the mode is divided by its most common phase among all depths. To reduce the noise, the result is averaged over a frequency band, approximately equal to the FWHM of the mode, centered on the mode.

Chaplin Excitation expression

$$\frac{dE}{dt} = \frac{\pi}{9I_\omega}\int_0^{R_\odot} dr\left(r\delta P\frac{\partial\xi}{\partial r}\right)^2 S(r;\omega)$$

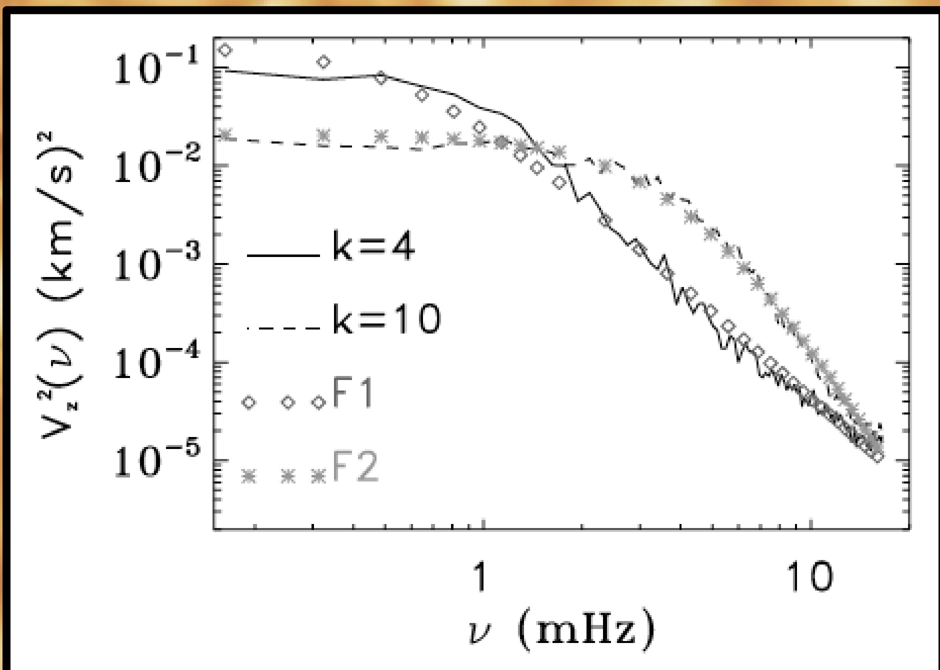
Chaplin et al. 2005, *MNRAS, 360, 859*

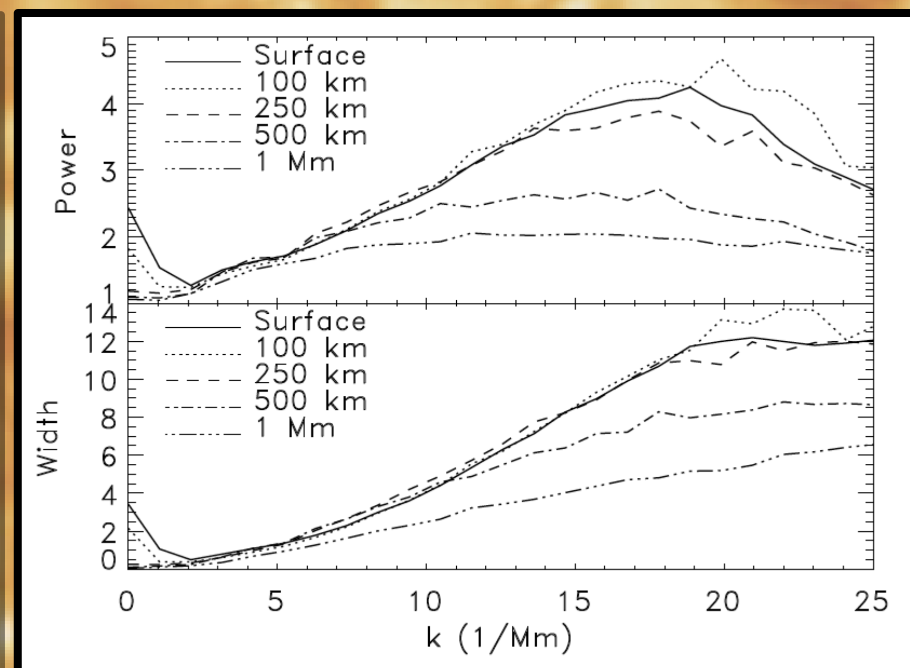
Here convection--mode correlations are included.
Two problems:

1. Some people still separately square δP and $d\xi/dr$
2. Most people factor the convective spectrum into separate spatial and temporal terms

The Turbulence Spectrum is NOT Separable

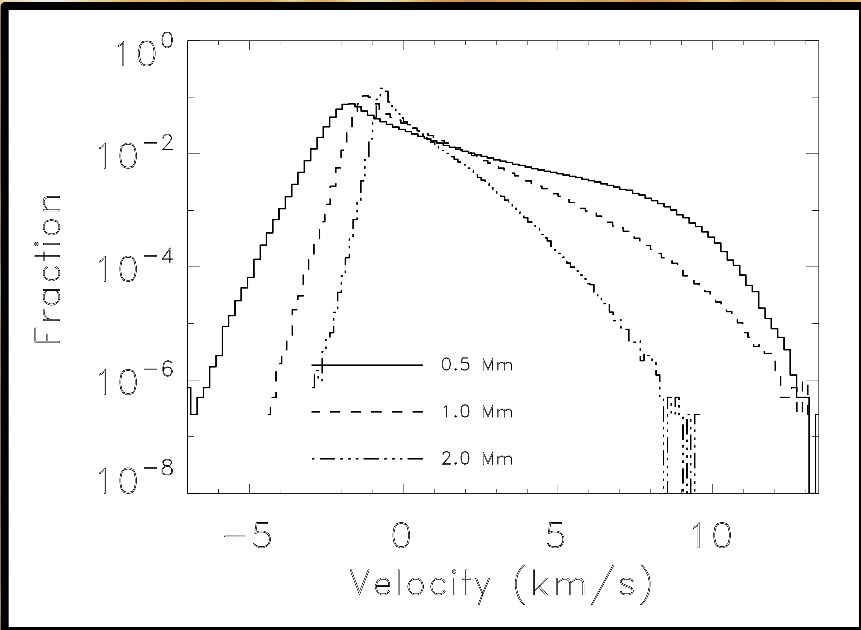
$$P(\lozenge,k) = A[\lozenge+w(k)]^{-n(k)}$$

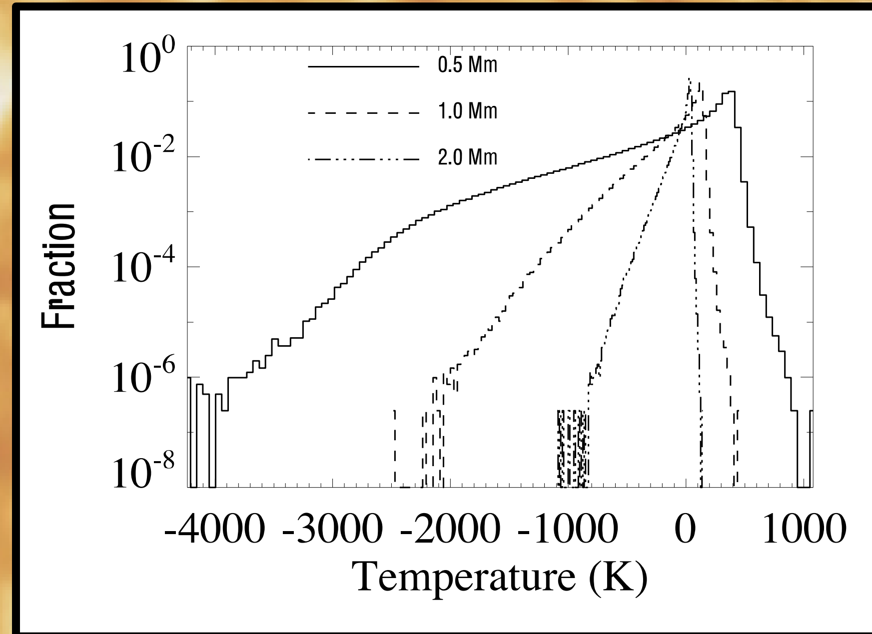


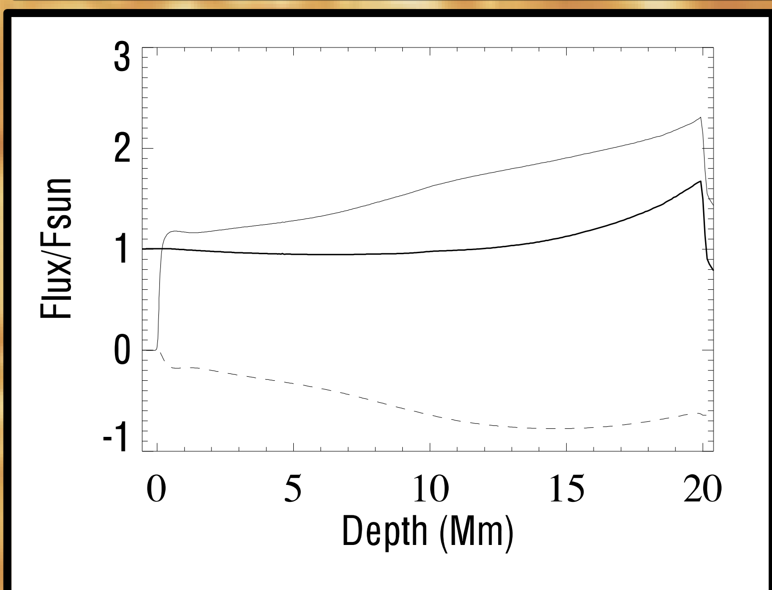


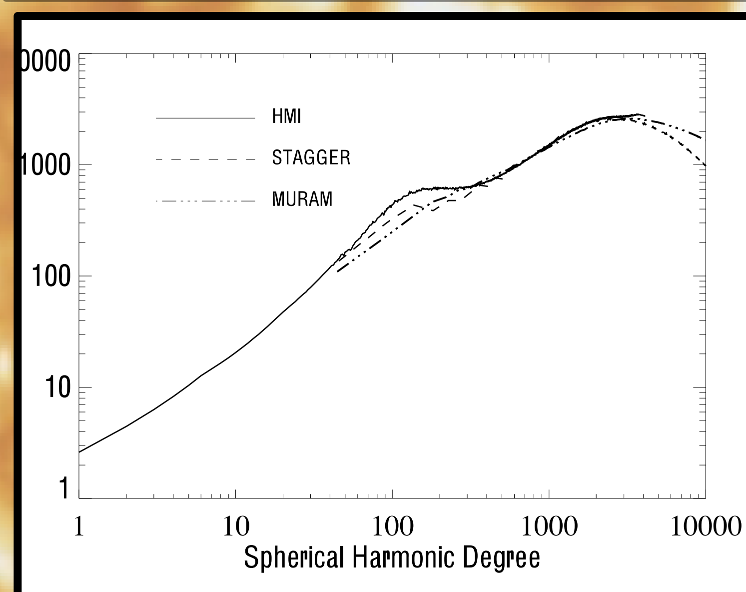
Georgobiani, 2006, ASP conf. ser. ***354****, 109*

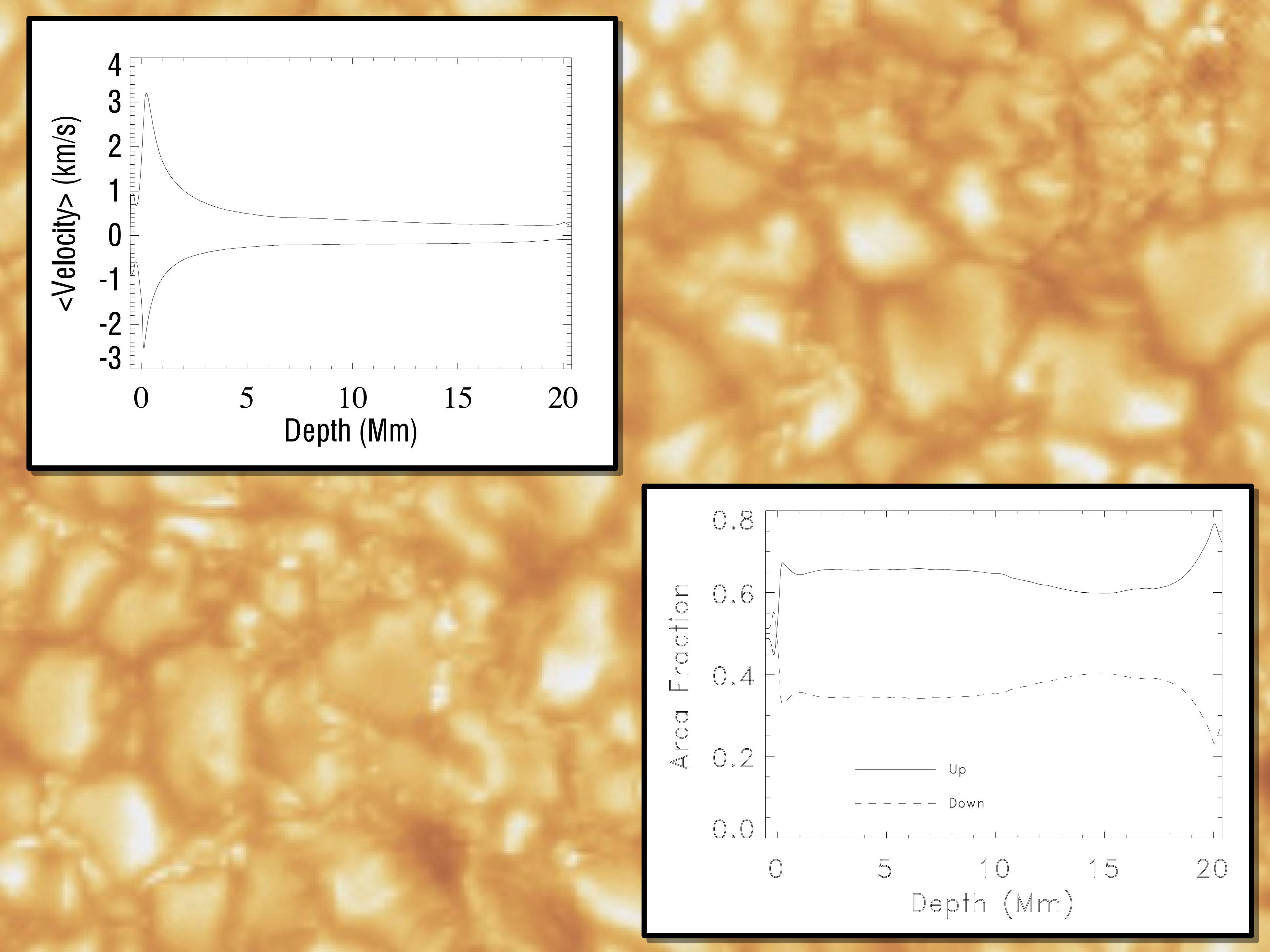
Convection Properties





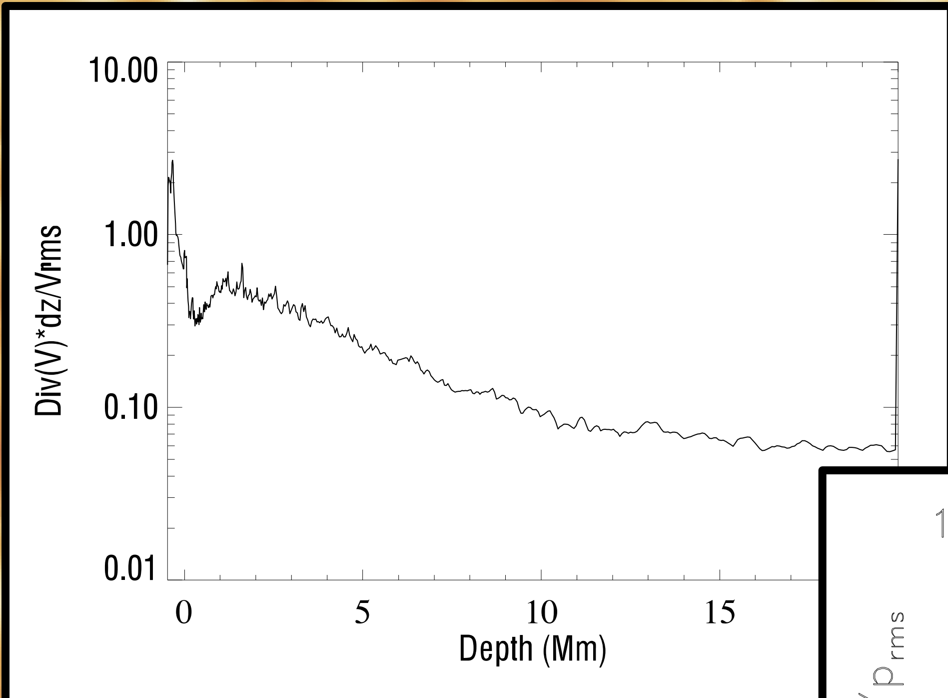






<Velocity> (km/s)
4
3
2
1
0
-1
-2
-3
0
5
10
15
20
Depth (Mm)
Area Fraction
0.8
0.6
0.4
0.2
0.0
Up
Down
0
5
10
15
20
Depth (Mm)

Boussinesq is a BAD approximation



Anelaastic is okay,
but not near surface