Observations of
Solar Waves and Oscillations
With MDI and HMI

Jesper Schou

Stanford University

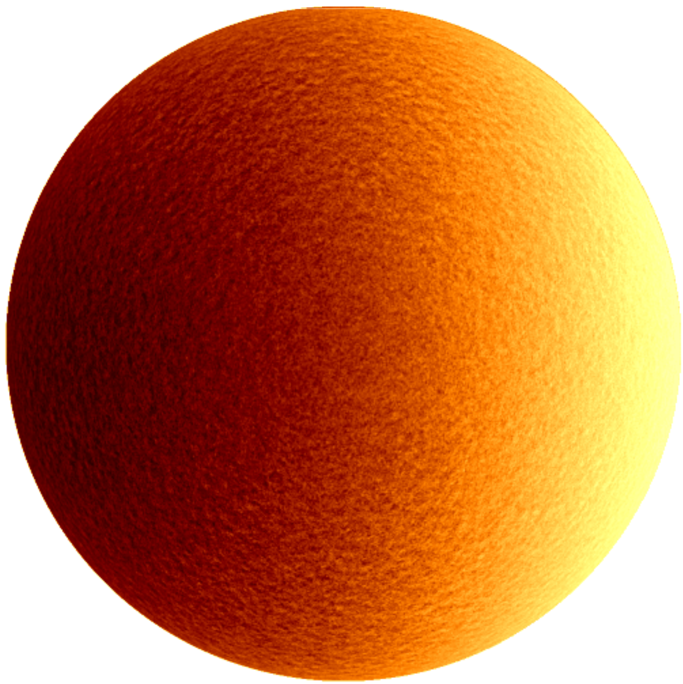
schou@sun.stanford.edu

Overview

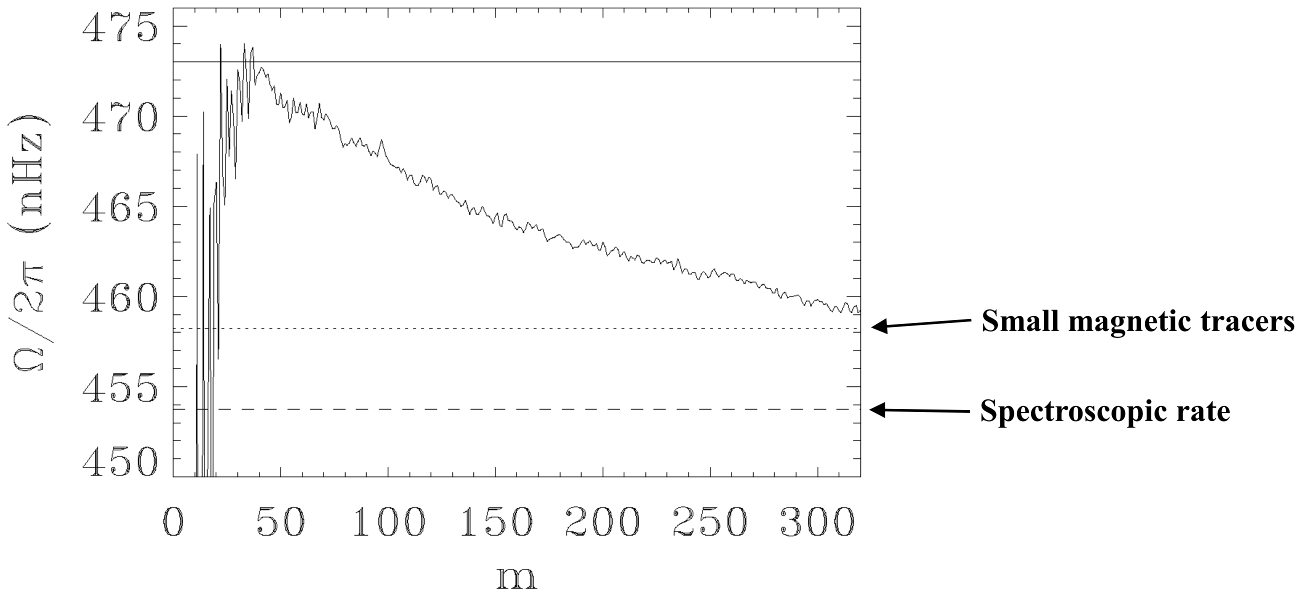
- Observations
- Waves
- Modes
- Oscillations
- A Flow Result
- Something Else
- Conclusion

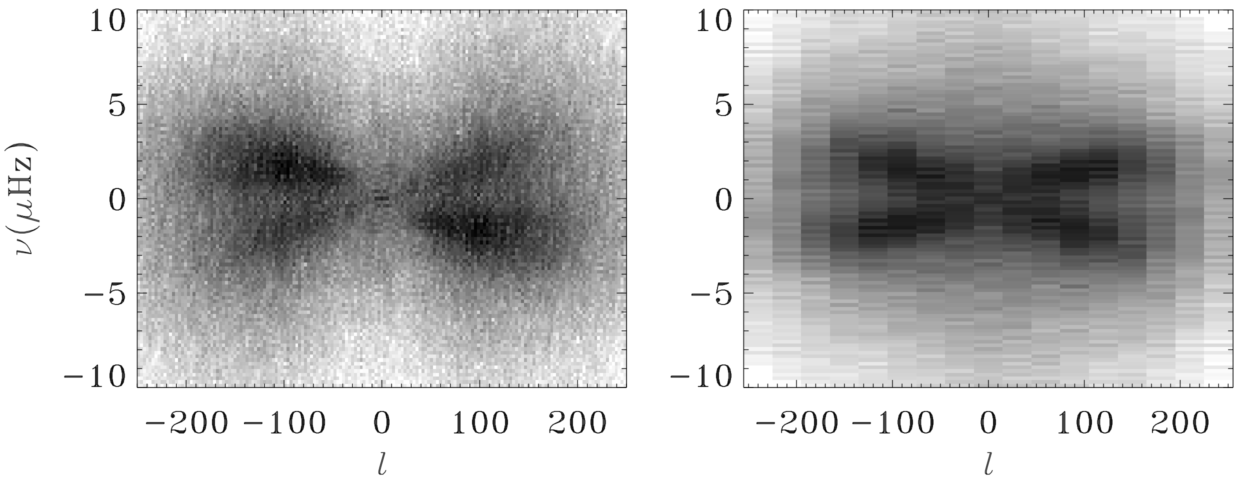
Observations

- **MDI (1996-2011)**
  - All the time: 200x200 pixels heavily apodized. Velocity only.
  - Part of the time: 1024x1024 unapodized. Sometimes Intensity.
- **HMI (2010-????)**
  - All the time: 4096x4096 unapodized. All variables.
- **GONG (1995-????)**
  - All the time: Roughly 800x800 unapodized. All variables.
- **What we see in Doppler shift:**
  - Solar differential rotation
  - Supergranulation
  - Granulation
  - p and f modes
  - Meridional circulation
- **What we don't see**
  - g modes
  - Other convection scales



Supergranular Waves





Global Modes

- **Describe oscillations in terms of normal modes**
- **Horizontal dependence roughly given by spherical harmonics**
  - Depend on degree l and azimuthal order m
  - Perturbed from spherical harmonics by asphericities
- **Radial dependence given by eigenfunctions depending on structure**
  - Depend on l and radial order n (number of nodes in radius)
  - Sensitive to sound speed and density
- **Frequencies ω depend on l and n but not m for spherical Sun**
  - Degeneracy broken by rotation and other asphericities
  - Equations can generally be linearized to give sensitivity, eg.

$$\omega_{nlm} - \omega_{nl} = \int K_{nlm}(r,\theta)\Omega(r,\theta)drd\theta$$

  - Where K is a known function of radius r and co-latitude θ and Ω is the rotation rate

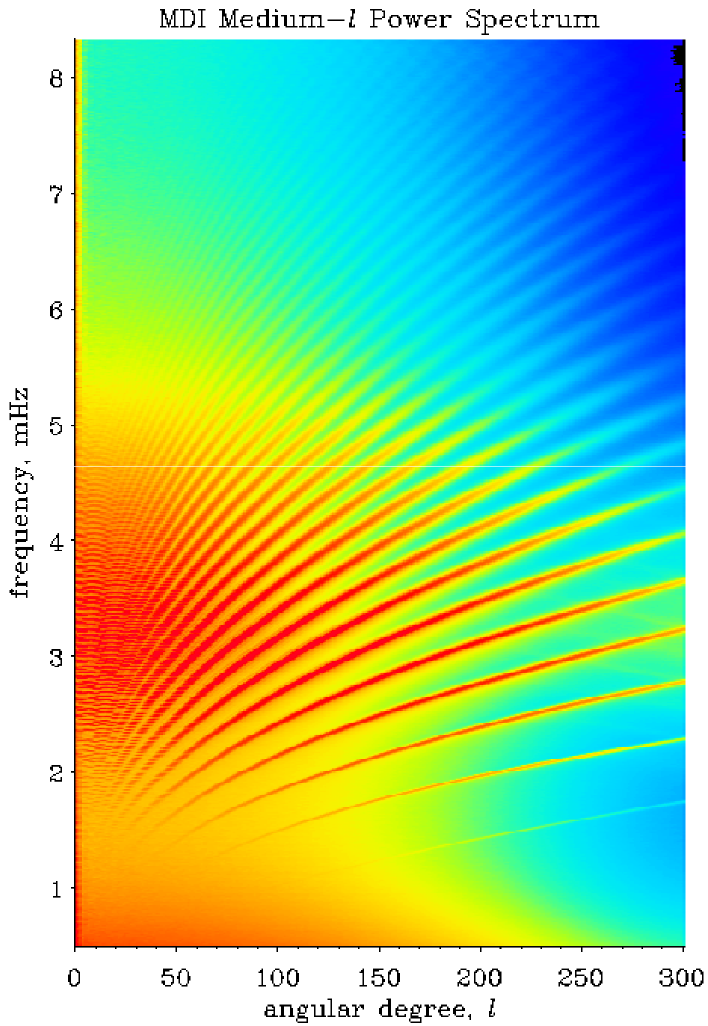
Global Modes – Data Analysis

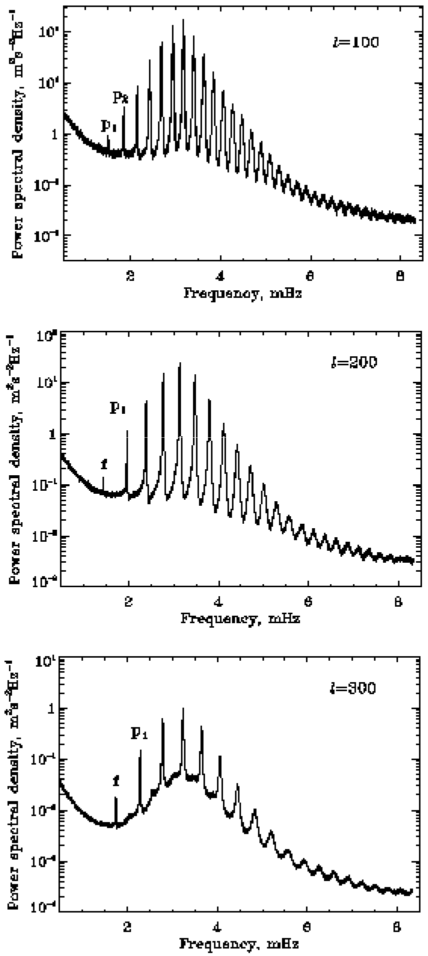
- **Analysis generally done in a standard series of steps**
- **Images are interpolated to grid in longitude and sin(latitude)**
  - Gaps in images filled
  - Also remove solar rotation and apodize
- **Remapped images are multiplied by spherical harmonics**
  - Isolates modes – kind of
- **Time-series Fourier transformed**
  - Gaps filled
  - Often turned into power spectra
- **Spectra fit to find frequencies – Aka. peakbagging**
  - As well as amplitudes, linewidths, background power, …
  - Frequencies are often expanded using so-called a-coefficients:

$$\frac{\omega_{nlm}}{2\pi} = \nu_{nlm} = \nu_{nl} + \sum_{j=1}^{j_{\max}} a_j(n,l) P_j^l(m)$$

- **Frequencies inverted to determine sound speed, rotation, etc.**
- **Papers published**

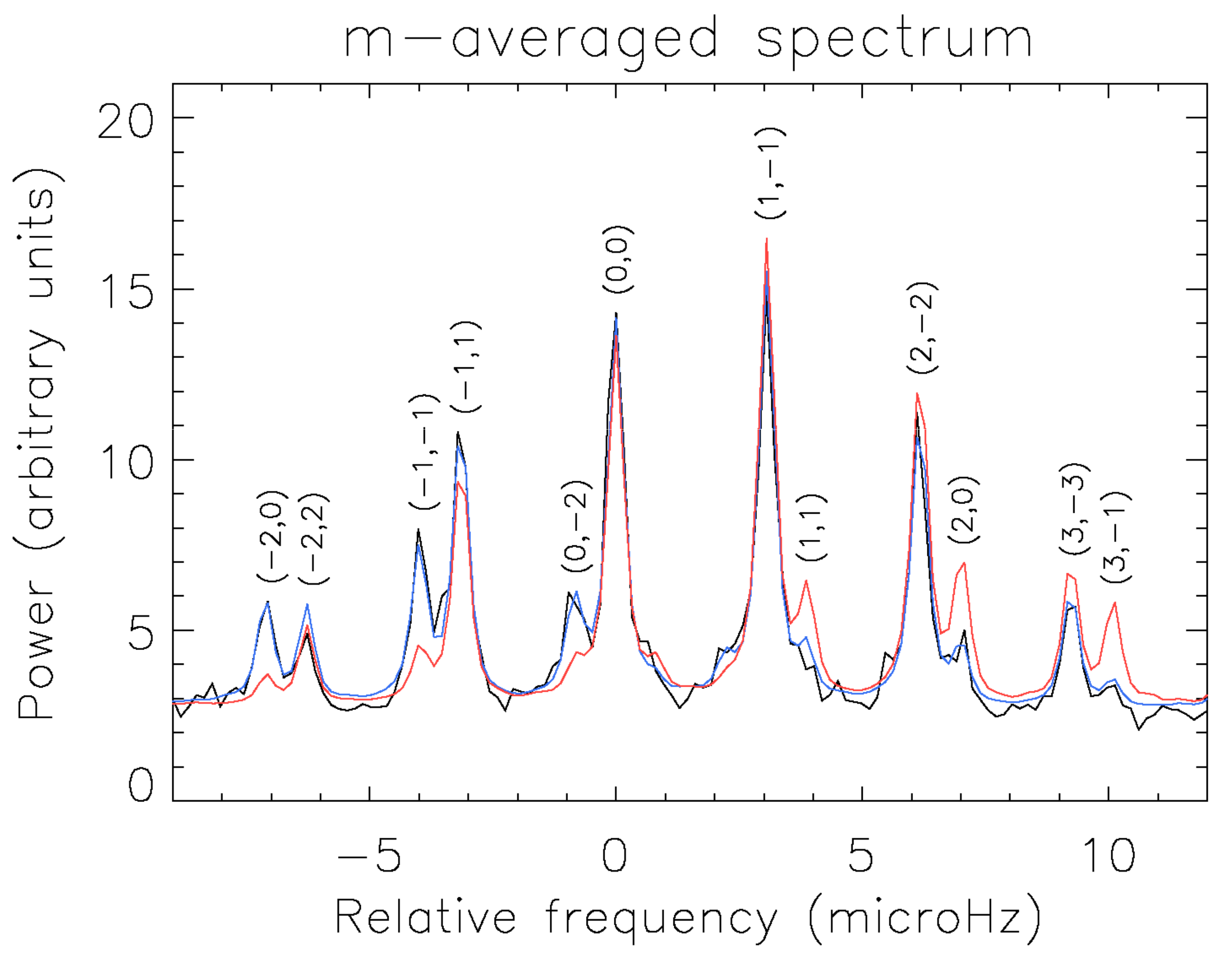
Observed Power Spectra



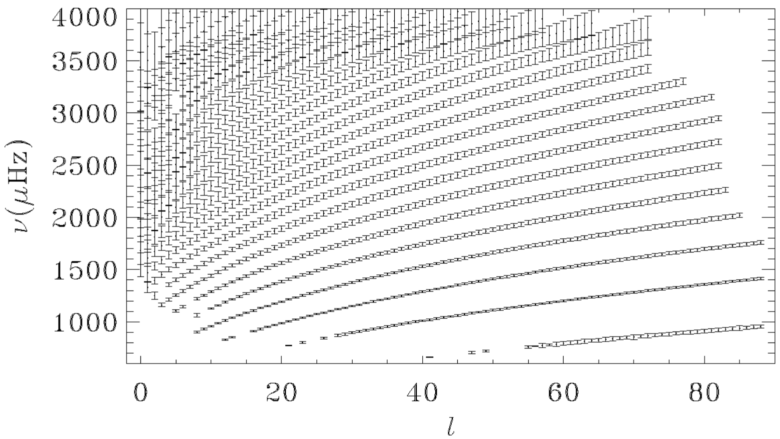


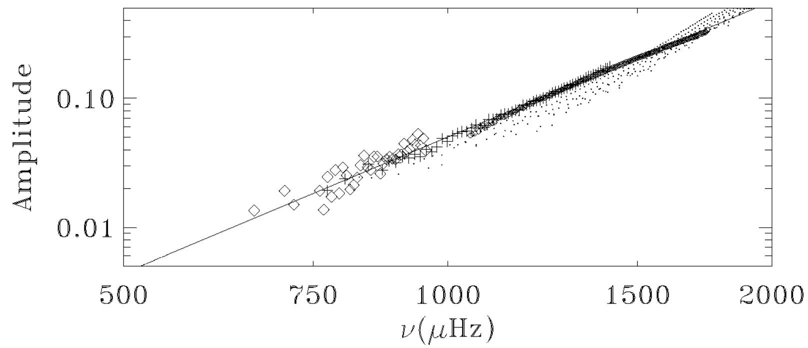
Spectra have been averaged over m

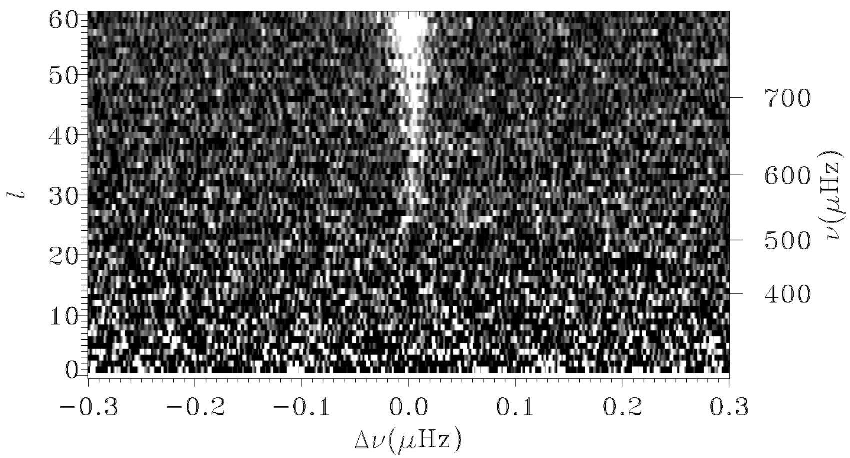
Observed and Model Spectra

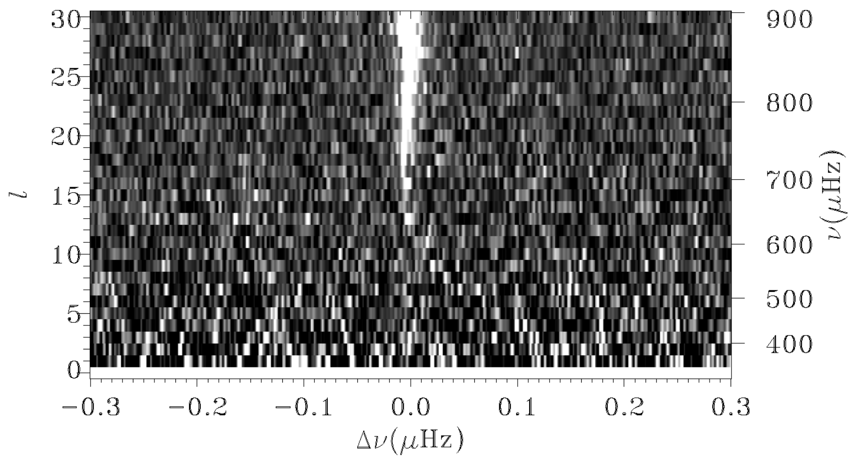


Low Frequency Modes





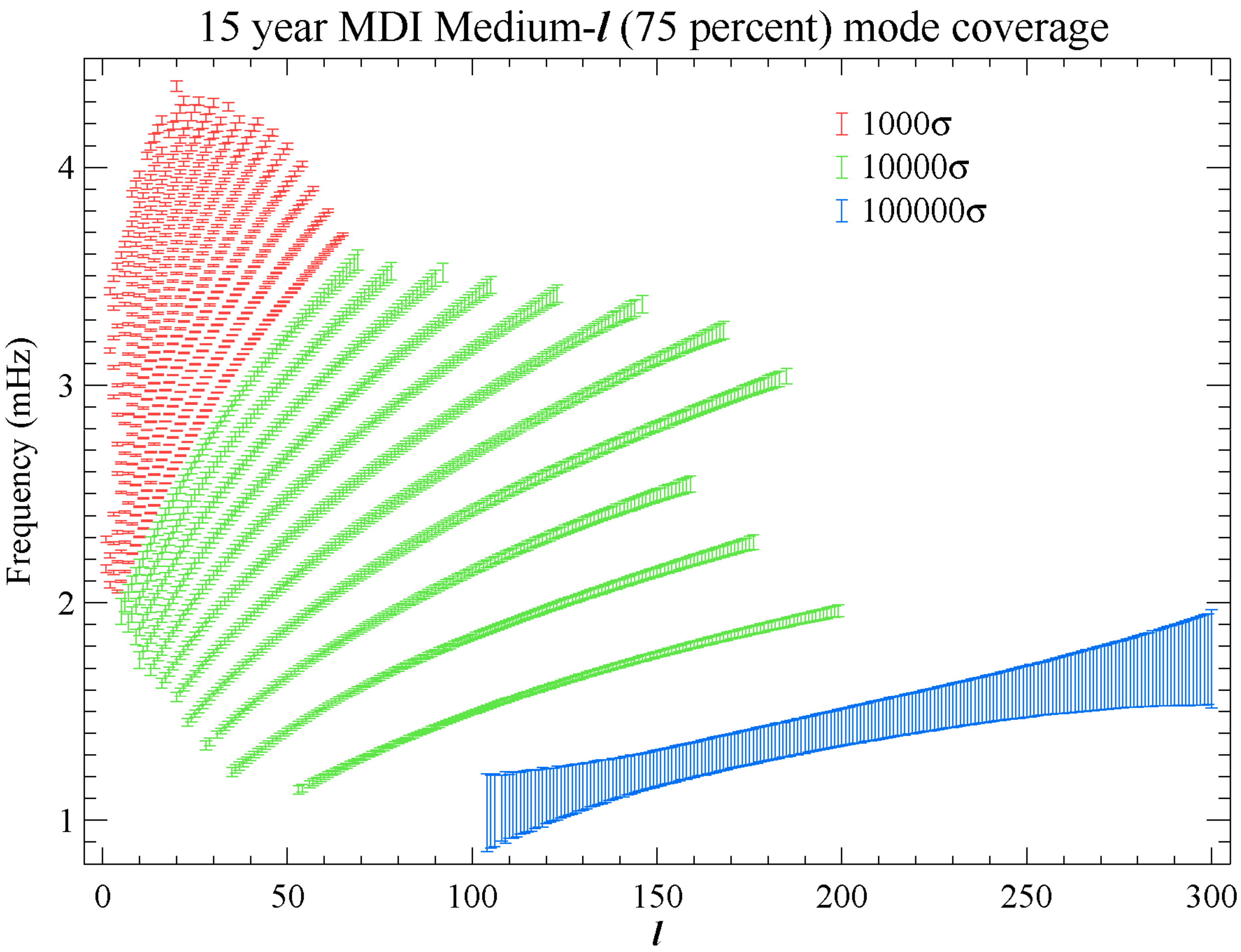




SOHO14, 2004

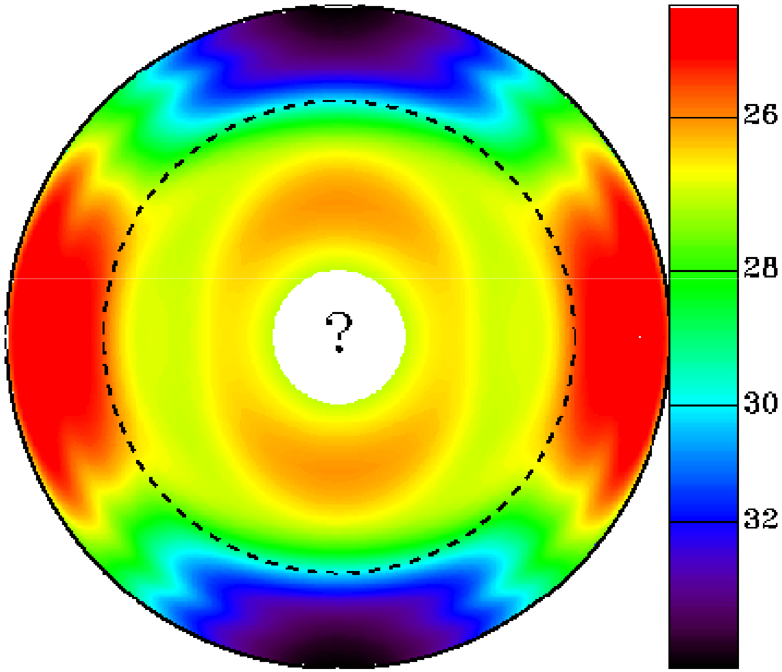
Peakbagging

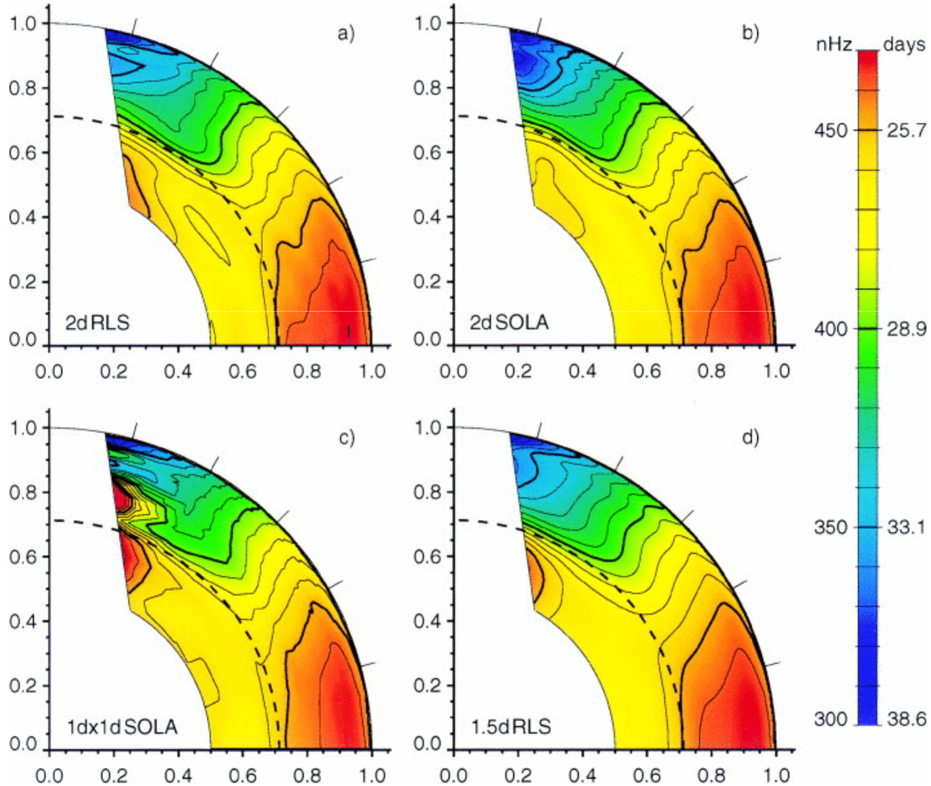
Modes With Error Bars



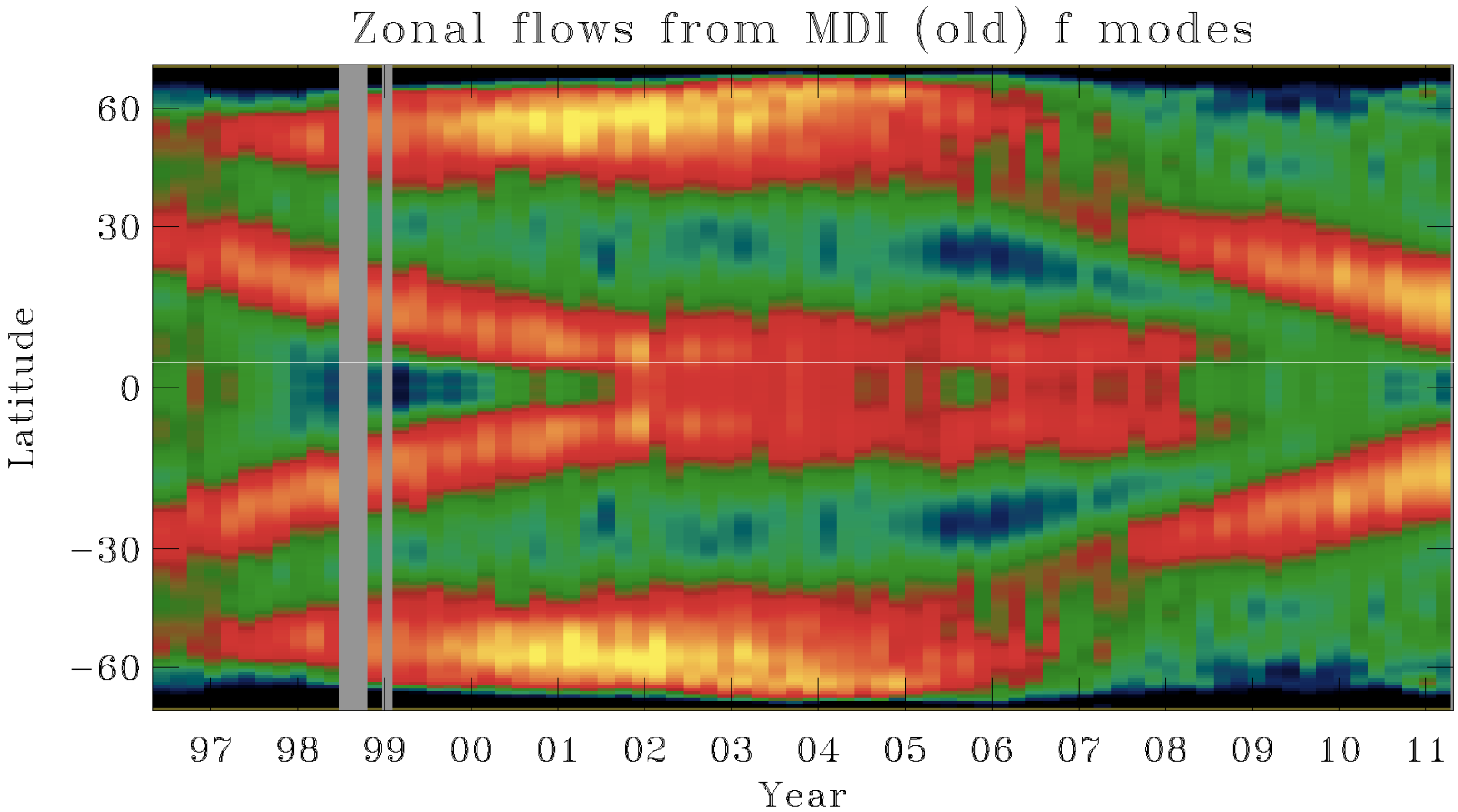
Overall scale measured to one part in 51e6.

Rotation Rate as a function of Radius and Latitude



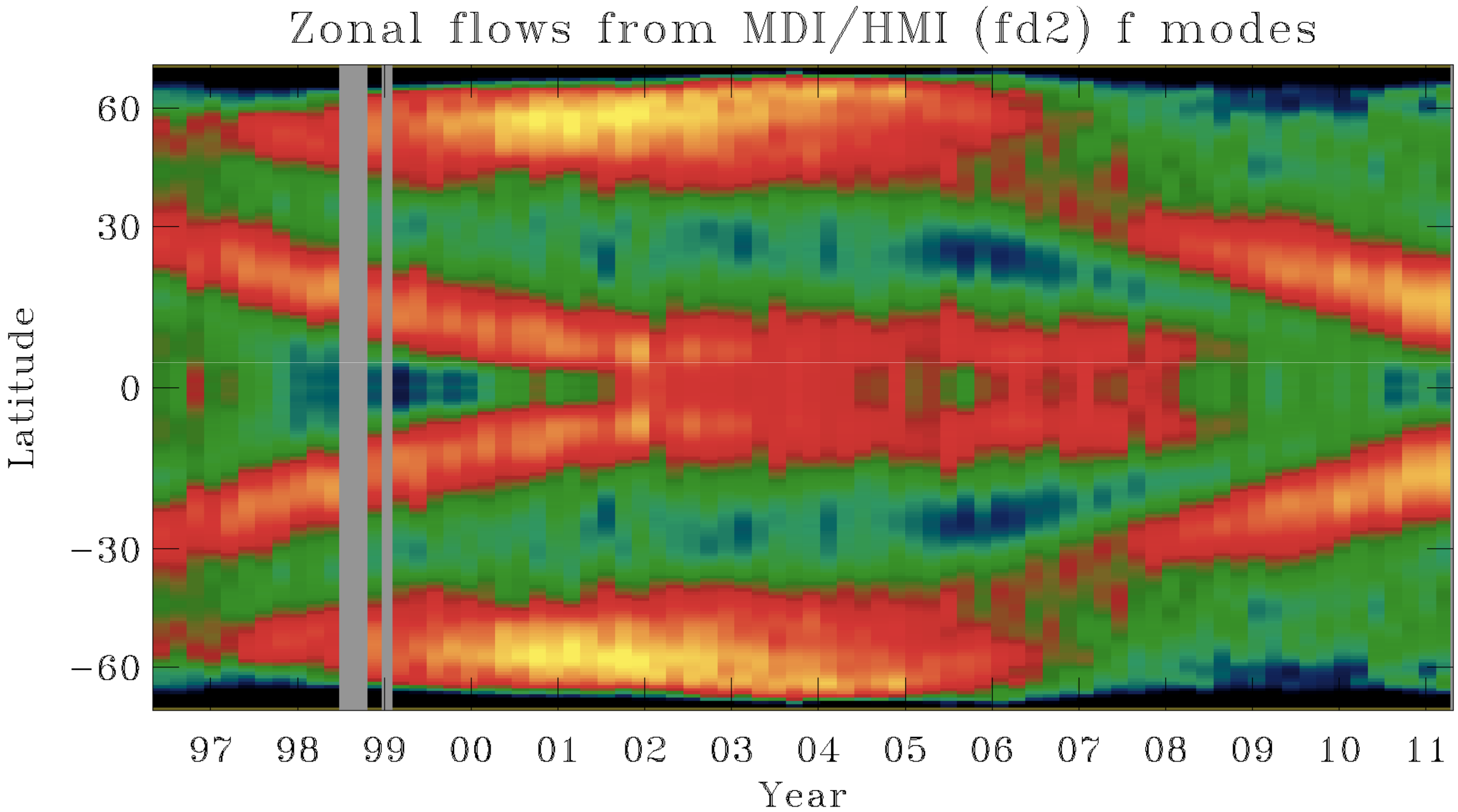


Torsional Oscillations From MDI



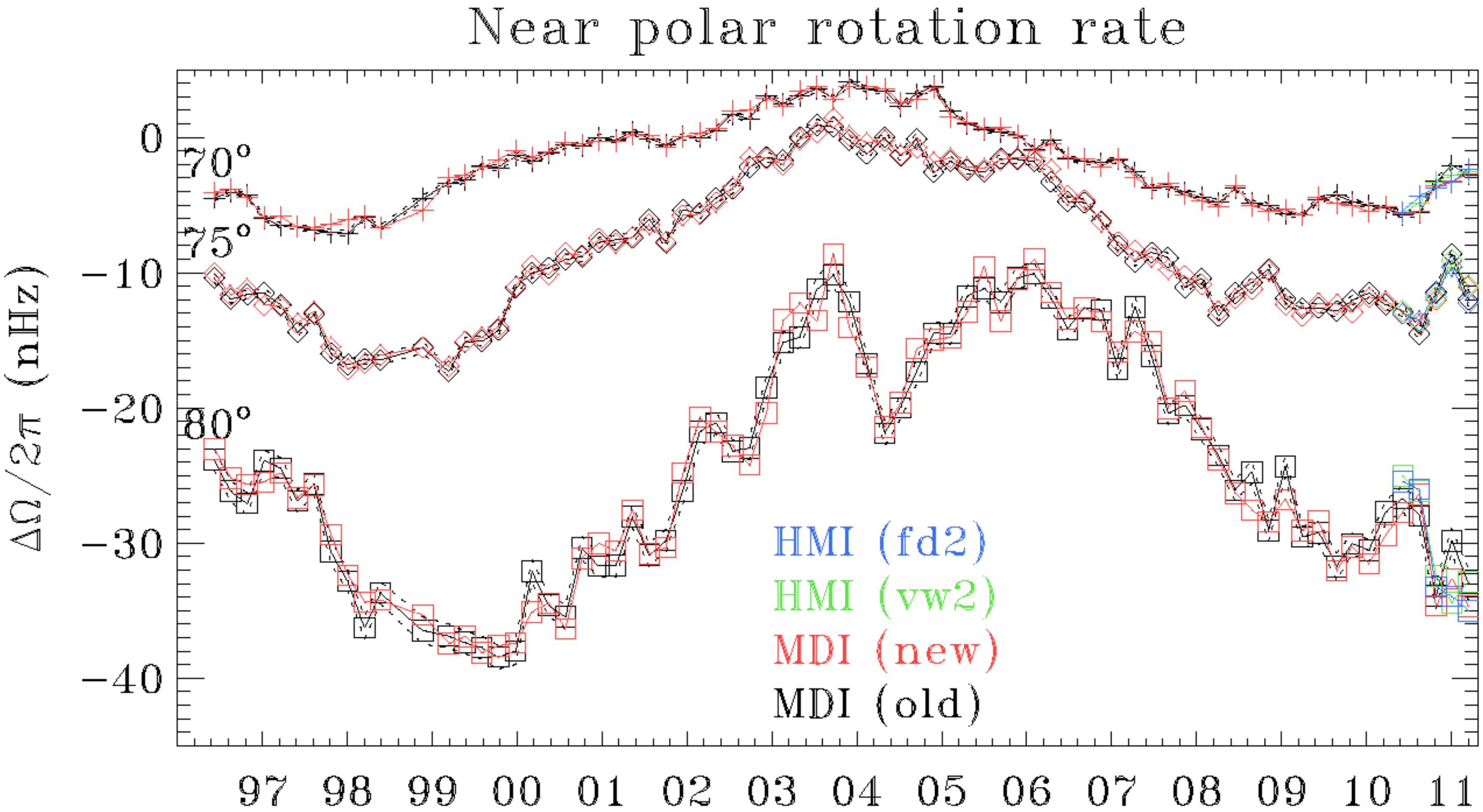
Outer 1%. Relative to smooth variation with latitude. +/- 9m/s.

Torsional Oscillations Looking Forward

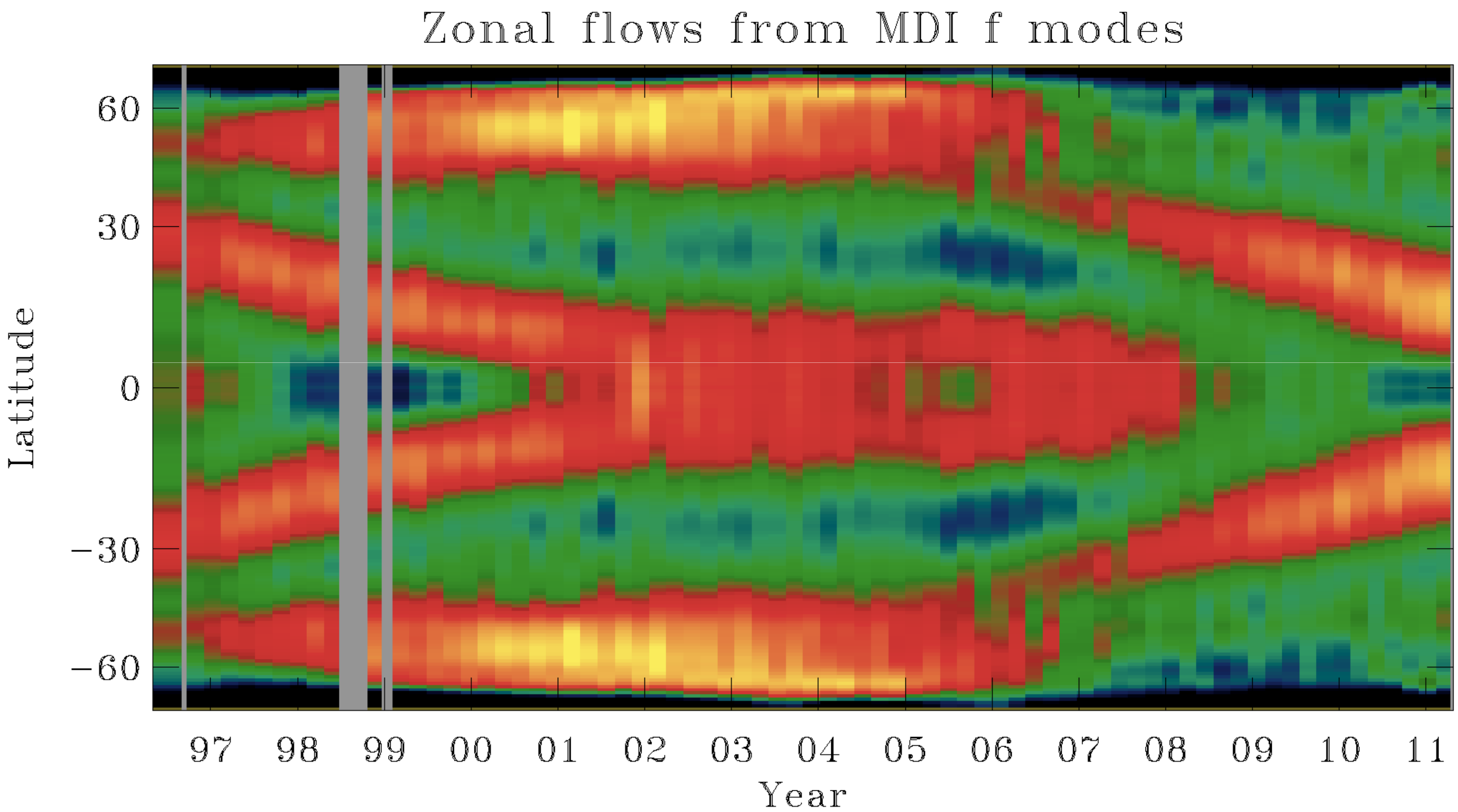


Outer 1%. Relative to smooth variation with latitude. +/- 9m/s.

Near Polar Rotation

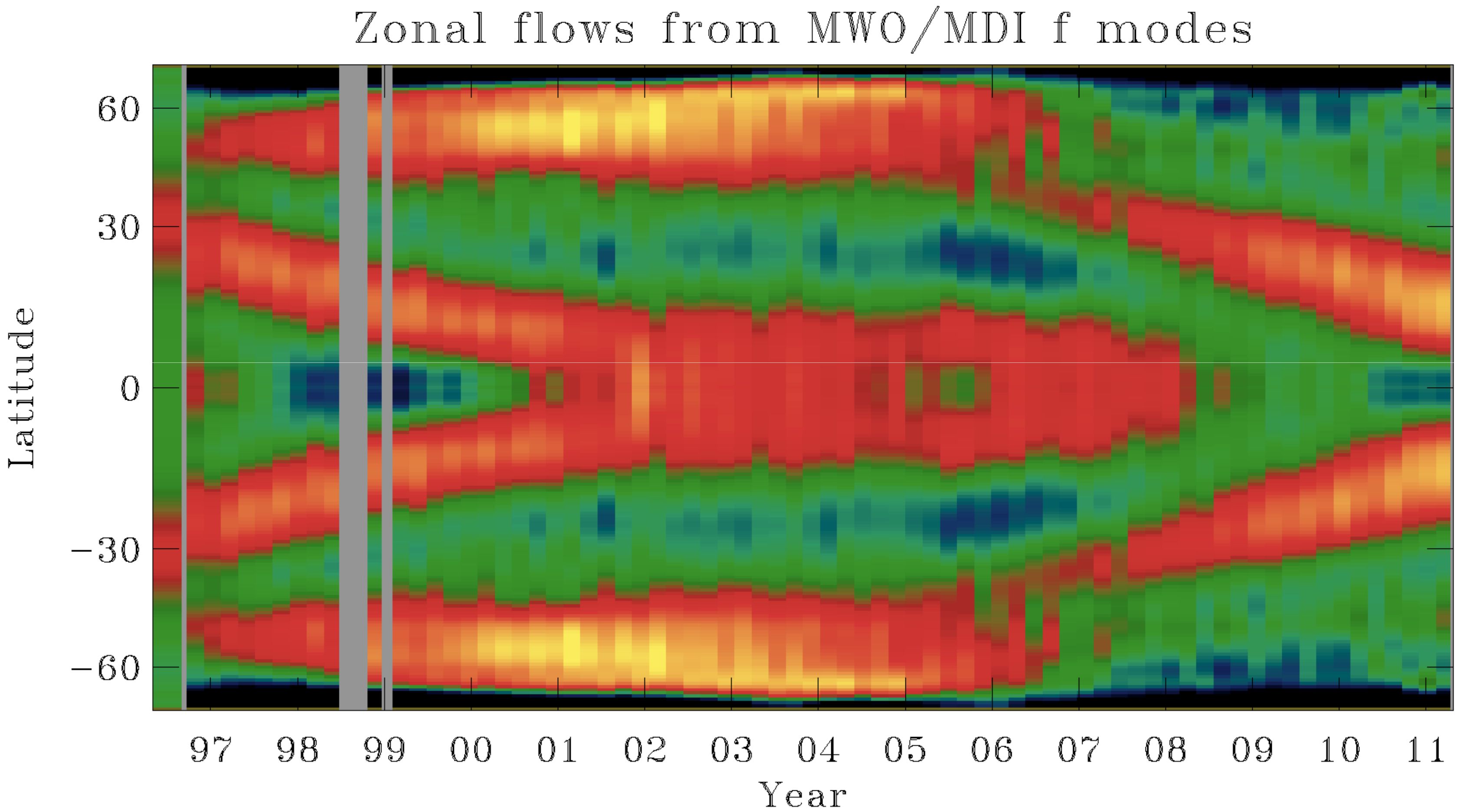


Torsional Oscillations From MDI (18 a-coeff.)



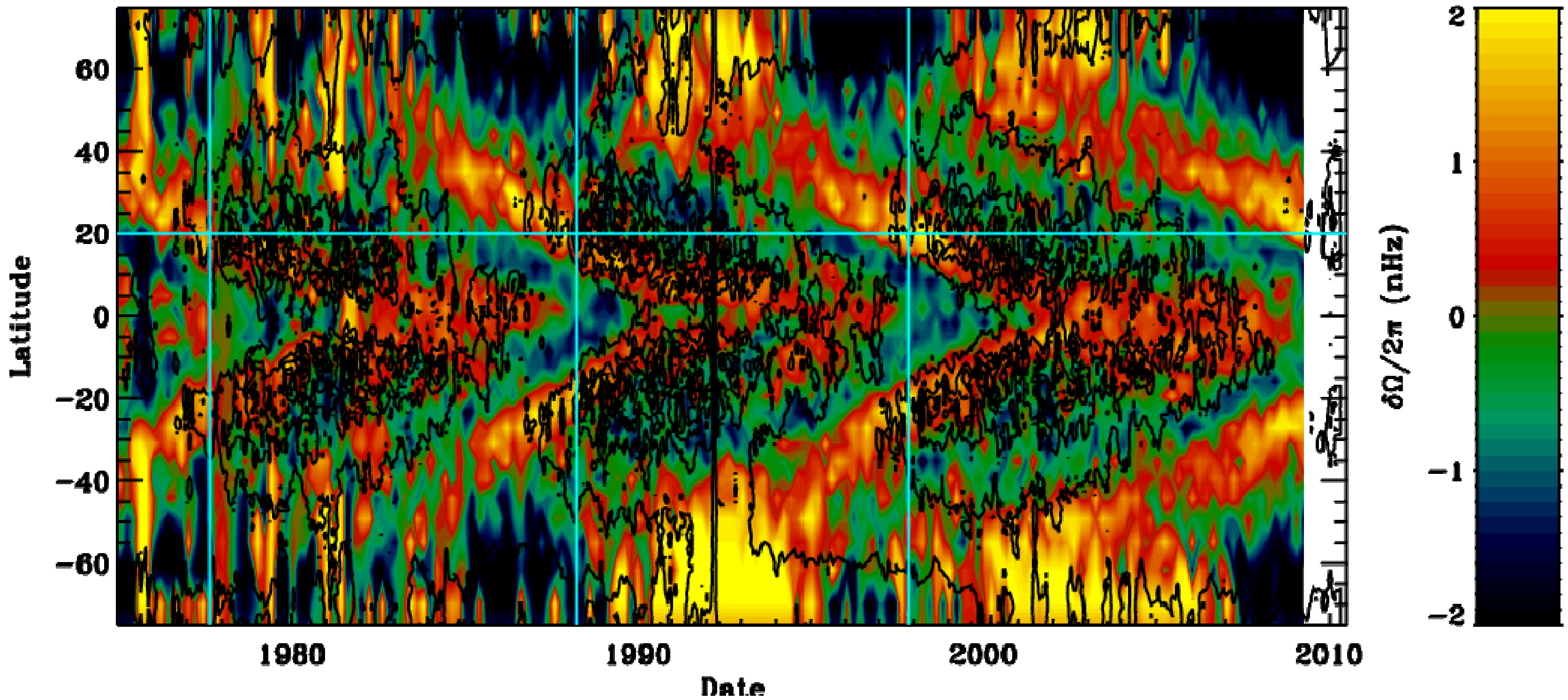
Outer 1%. Relative to smooth variation with latitude. +/- 9m/s.

Torsional Oscillations Looking Back (18 a-coeff)



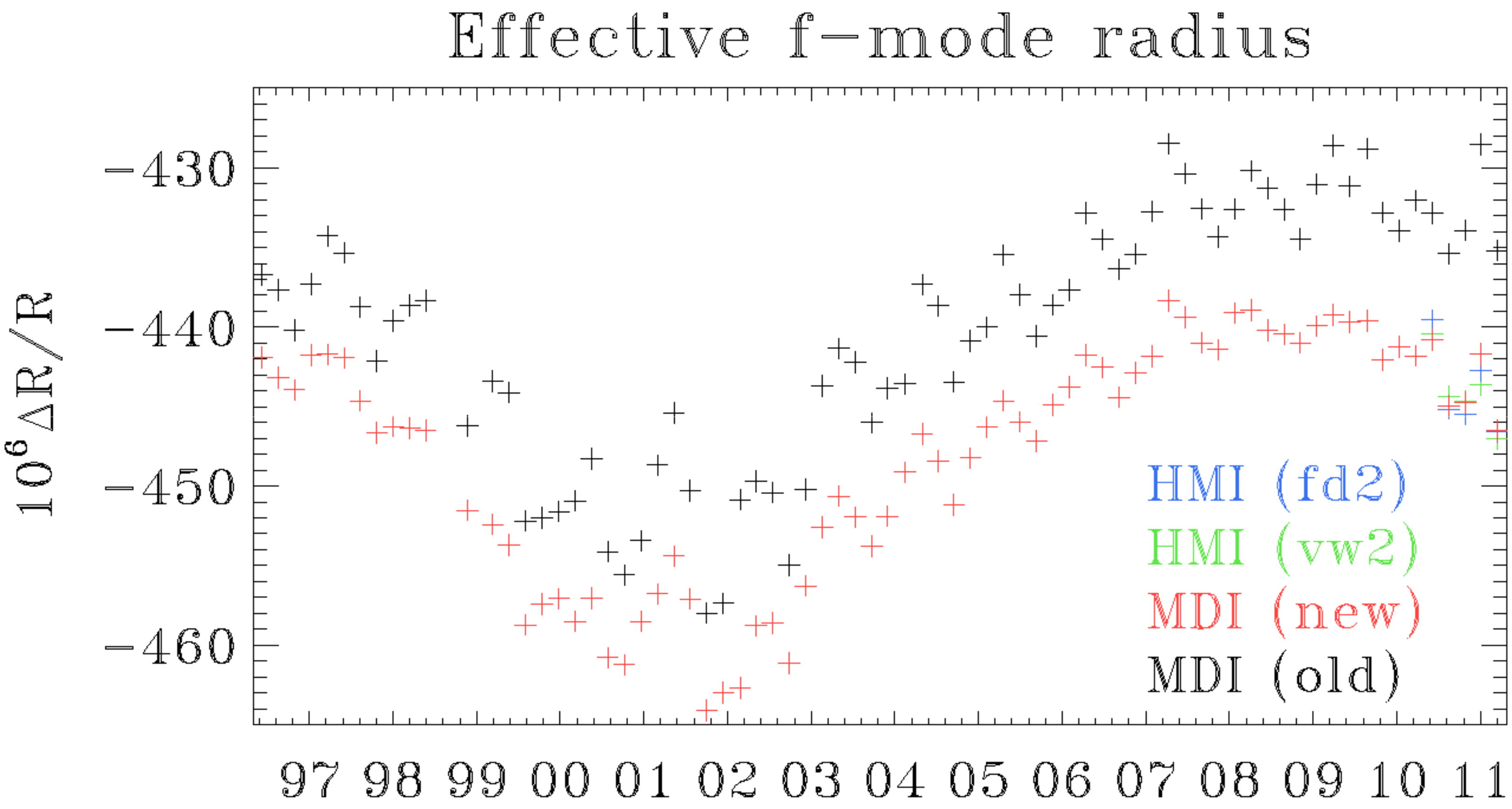
Outer 1%. Relative to smooth variation with latitude. +/- 9m/s.

Zonal Flows (Torsional Oscillations) From Mt. Wilson



Data courtesy, R. Ulrich

Effective Solar Radius

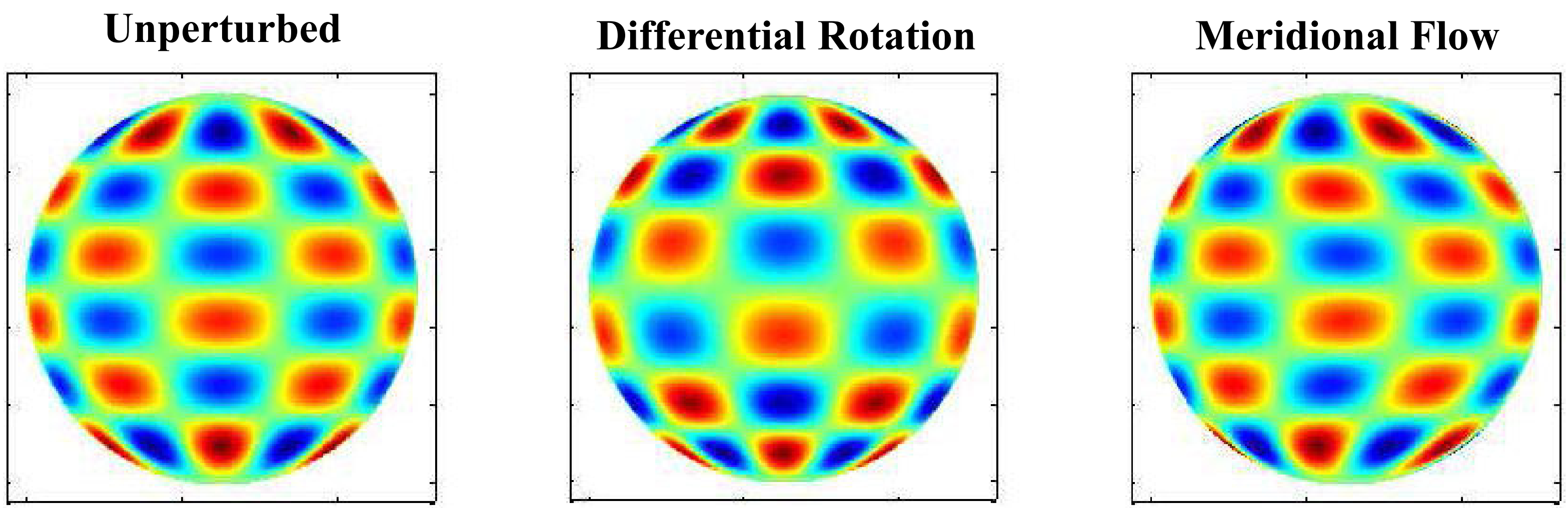


$$\omega_l \propto l^{1/2} R^{-3/2}$$

Relative to standard solar model

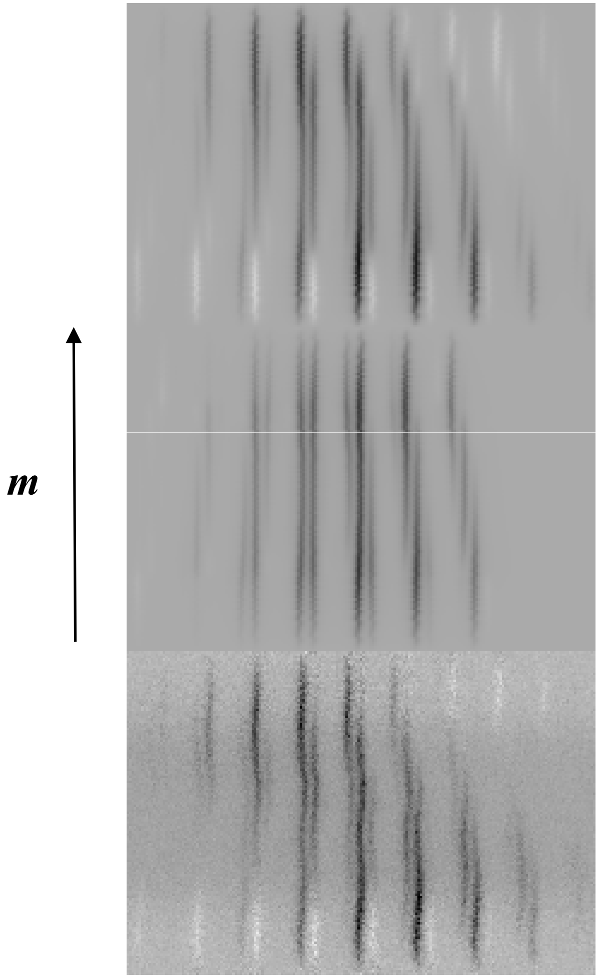
Eigenfunction Distortion

- **Eigenfunctions are distorted to first order by meridional flow**
  - Only second order for frequencies
  - Differential rotation perturbs both to first order
- **This results in additional "leaks" in the spectra**
  - Real for differential rotation
  - Complex for meridional flow
  - Visible in cross-spectra

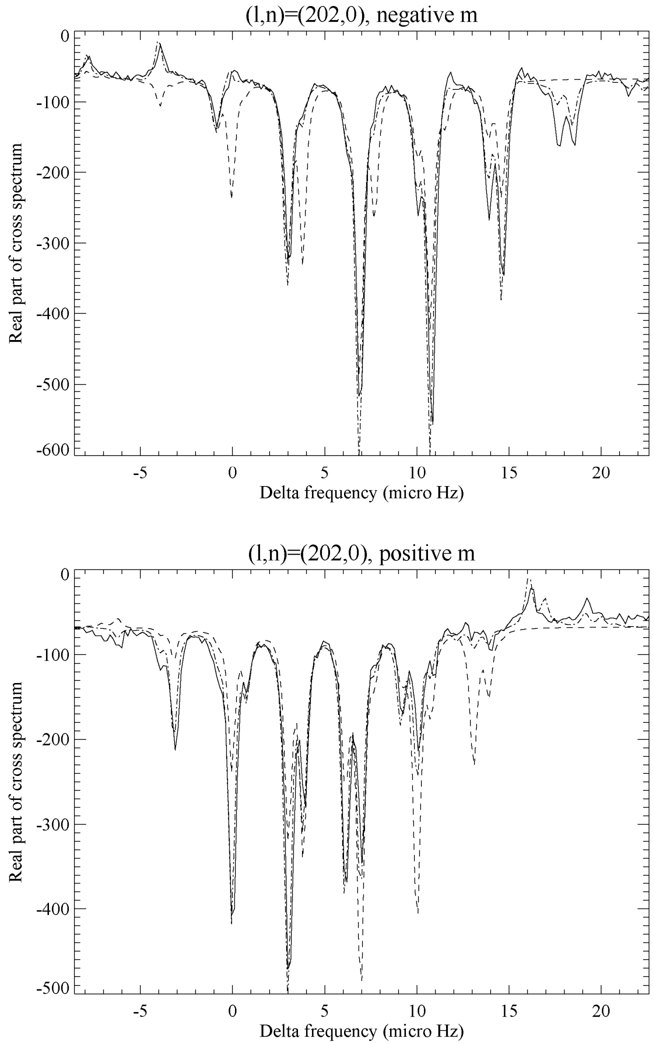


Differential Rotation

Delta l=2 cross spectra

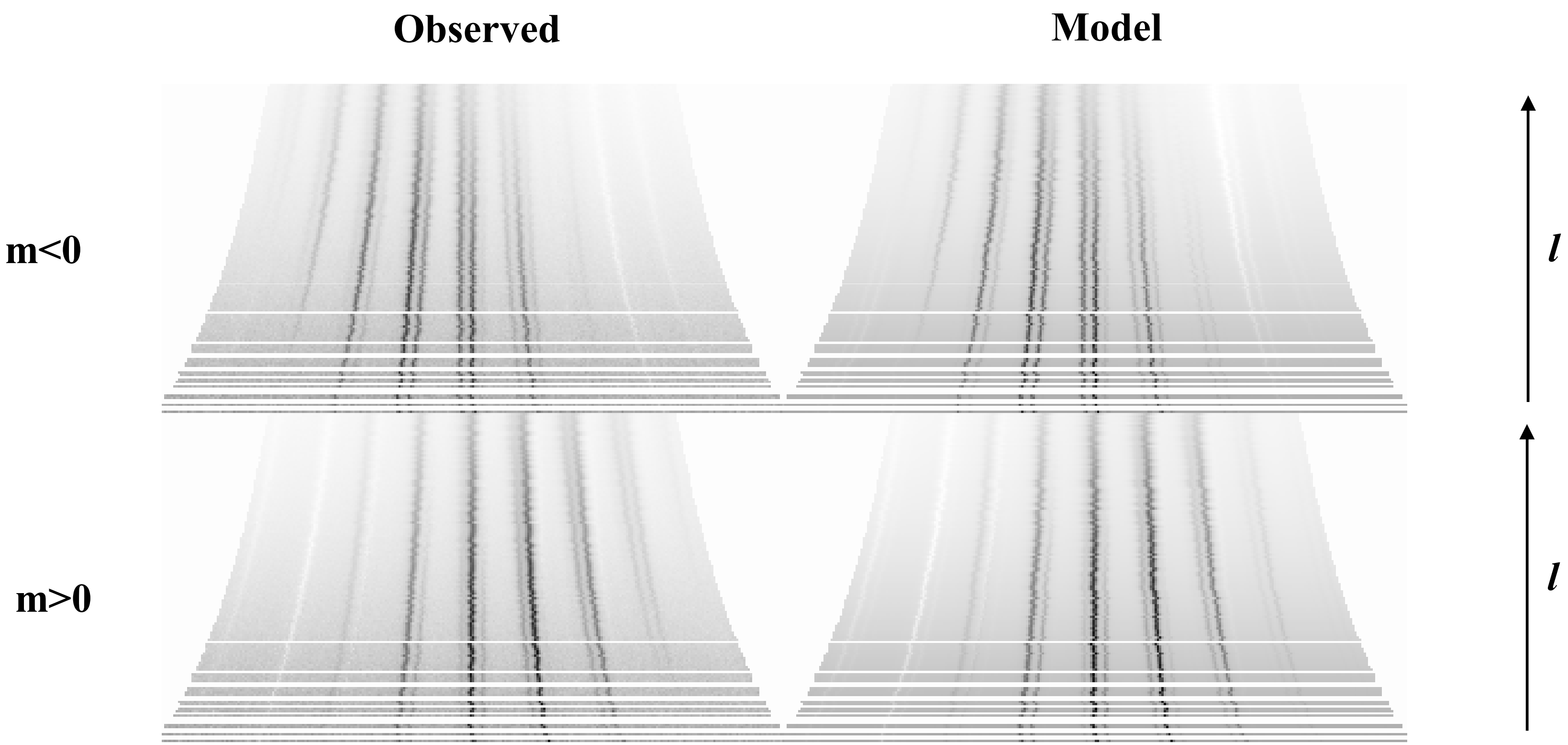


Frequency

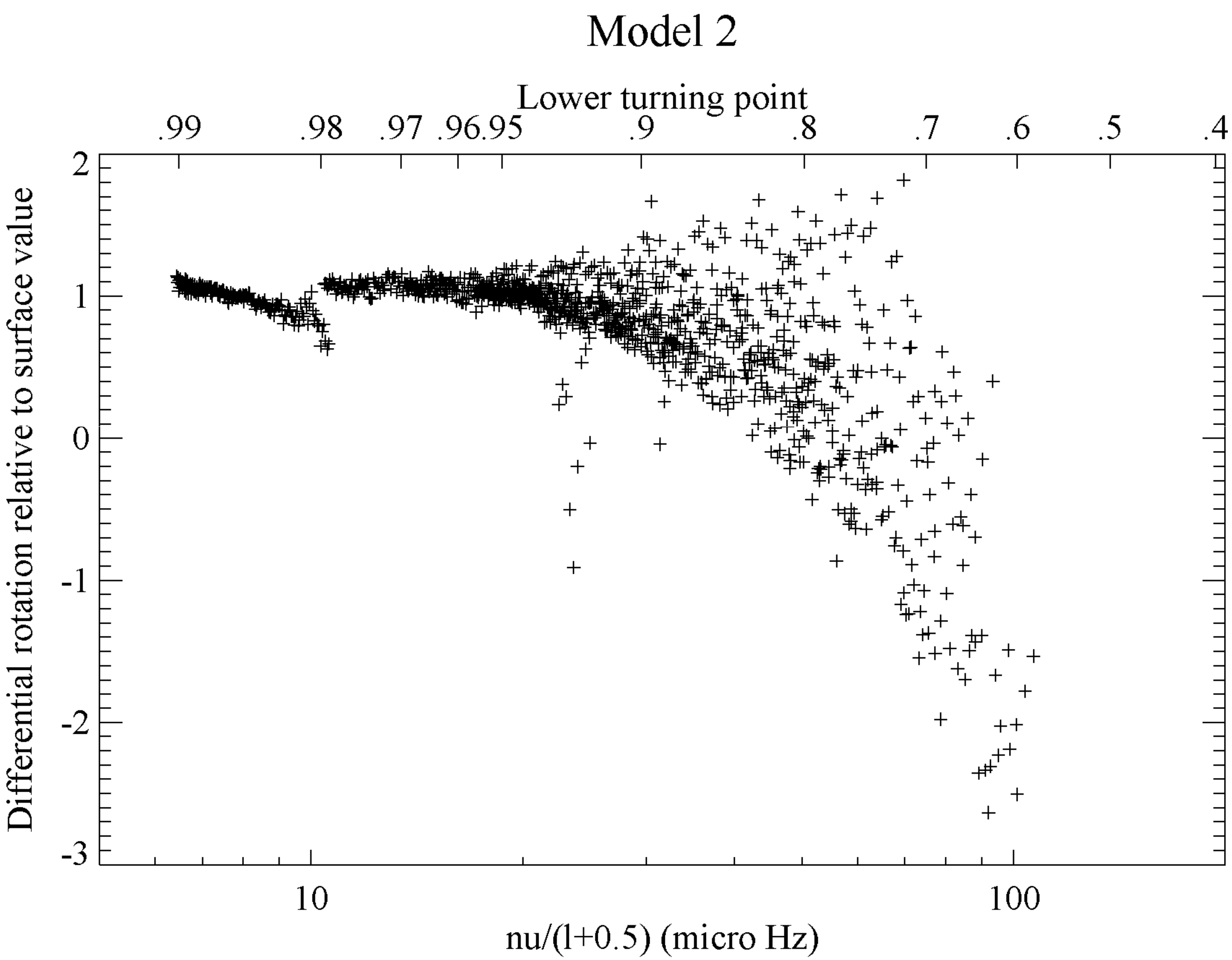


Differential Rotation

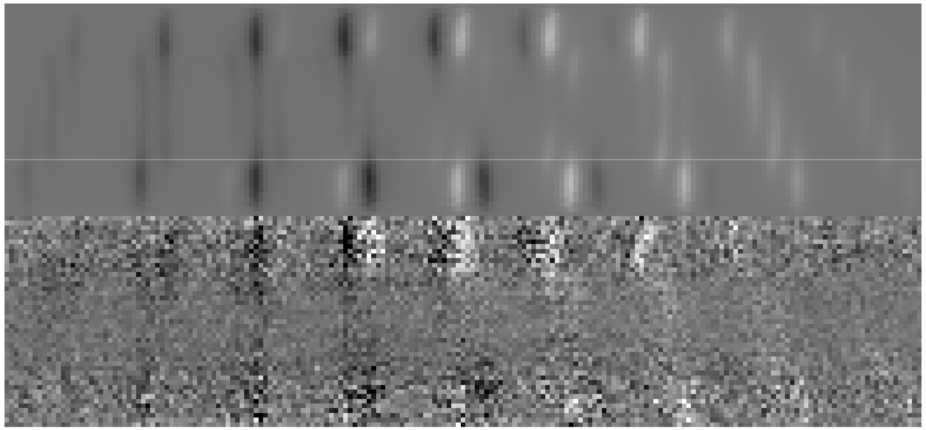
n=0 m-averaged

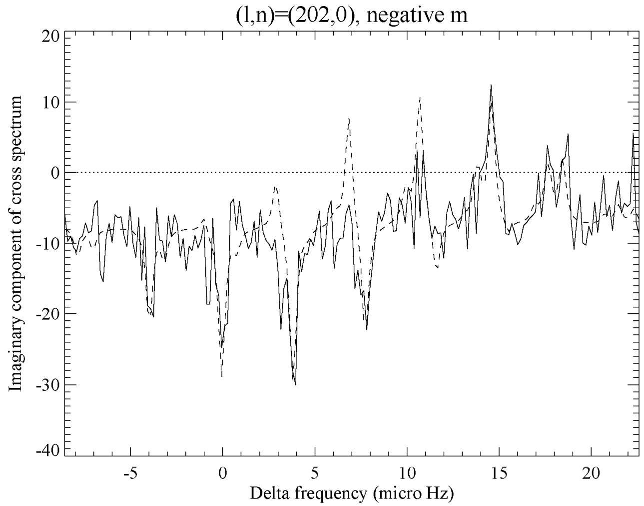


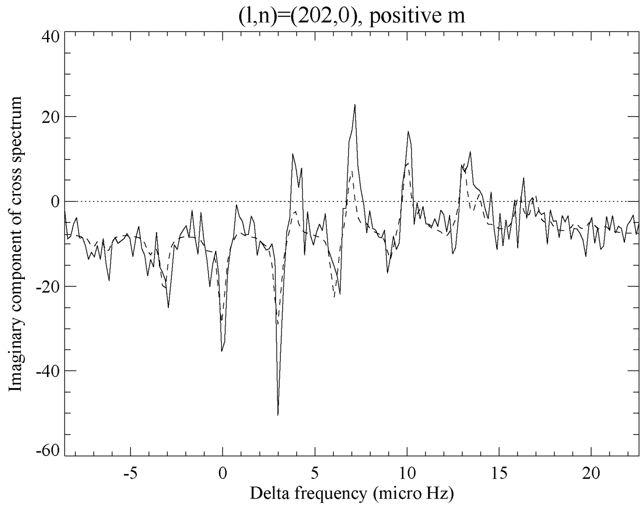
Differential Rotation Result



Imaginary Part of Cross-Spectrum







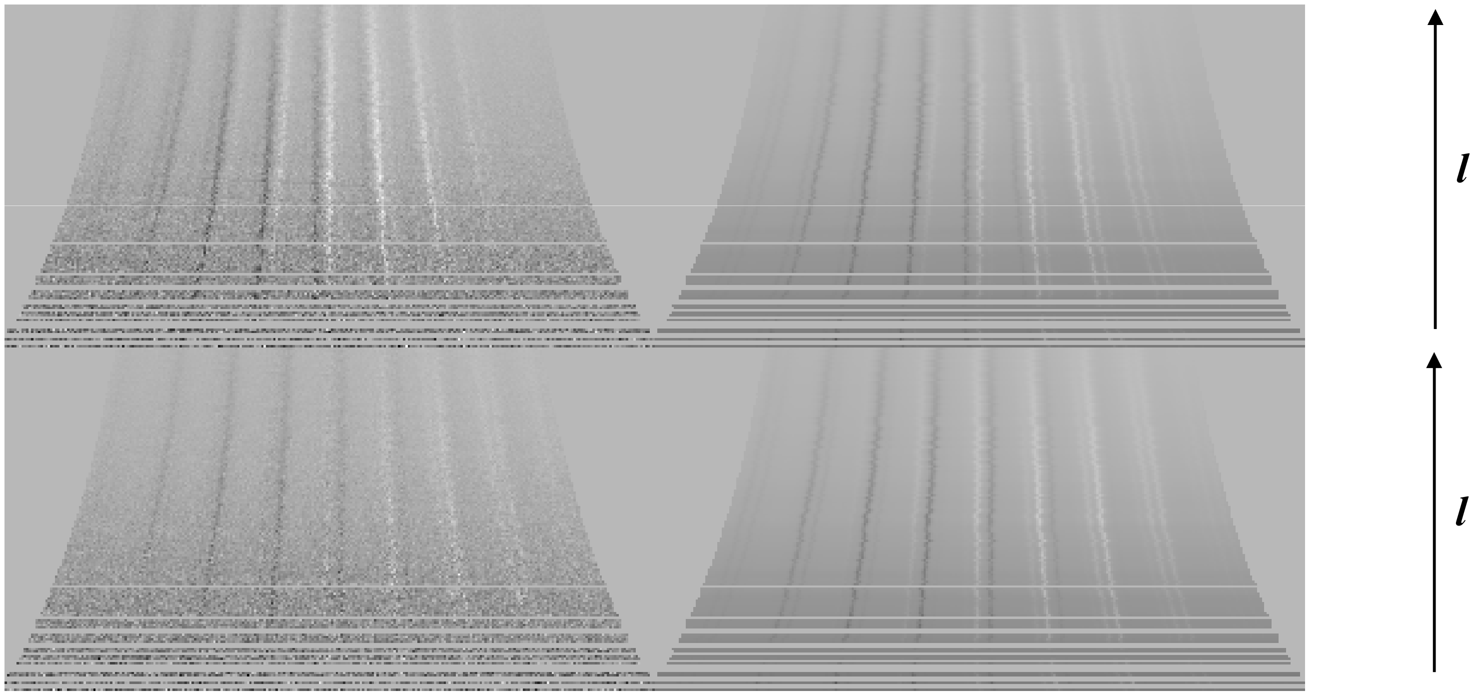
Differential Rotation

n=0 m-averaged

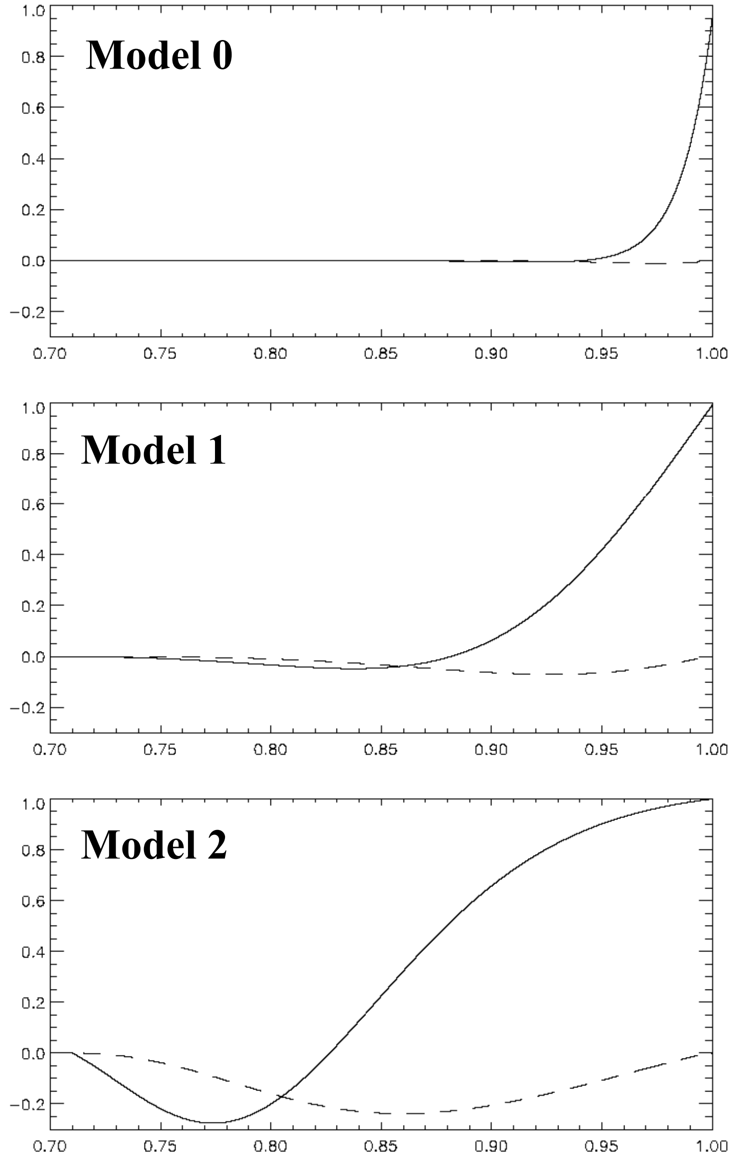
Observed **Model**

m<0

m>0



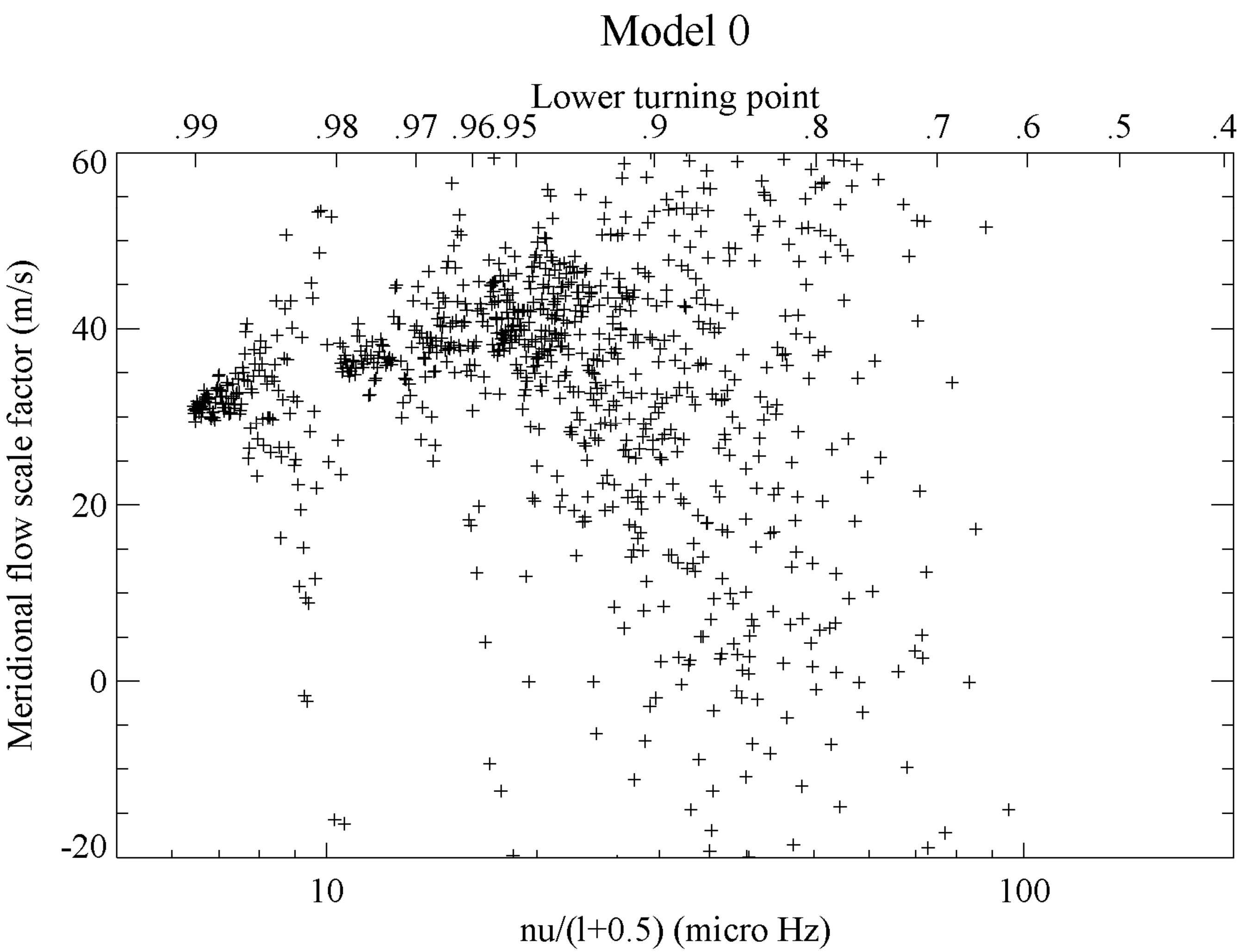
Meridional Flow Models



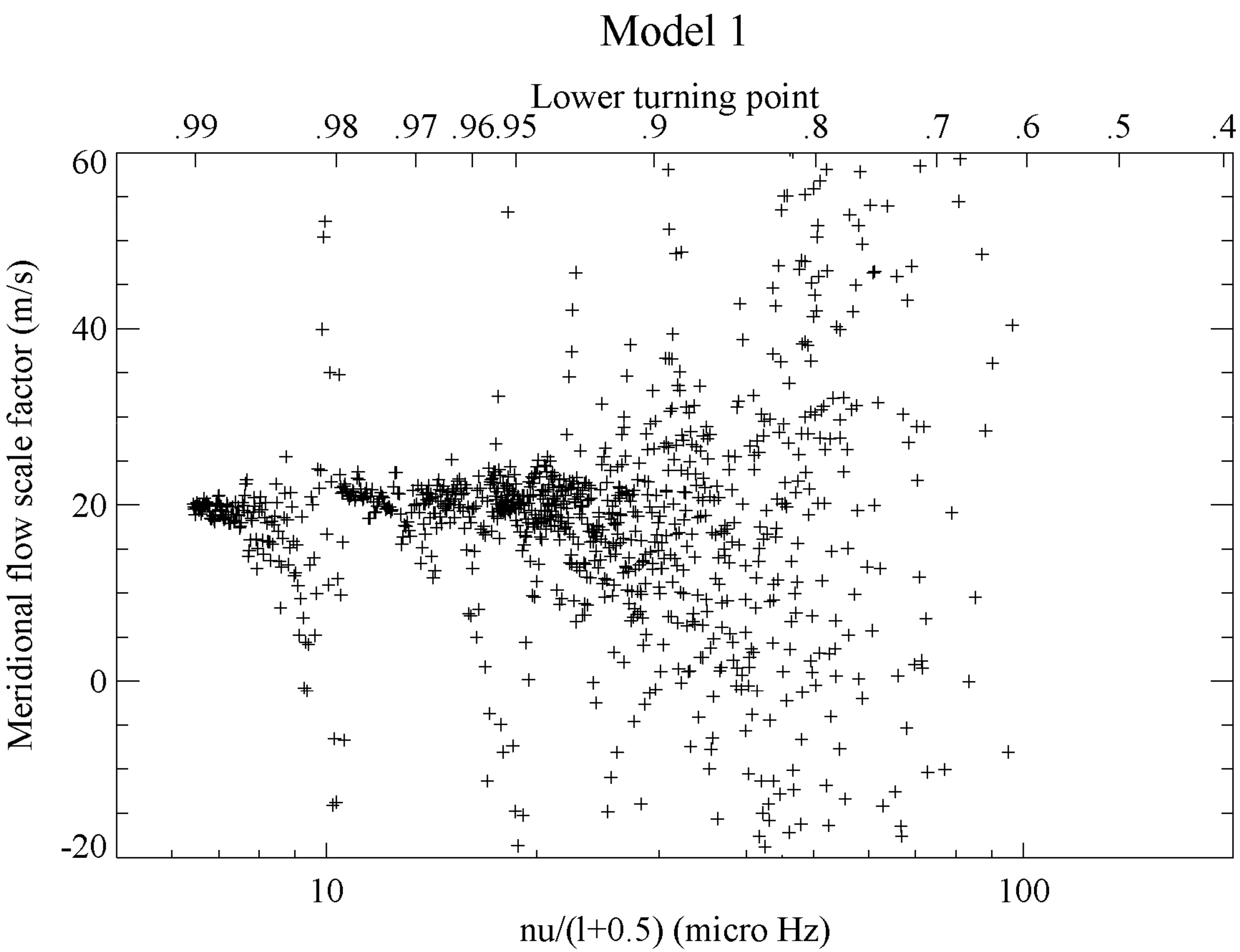
Solid: sin (2*latitude) meridional flow

Dashed: Radial return flow

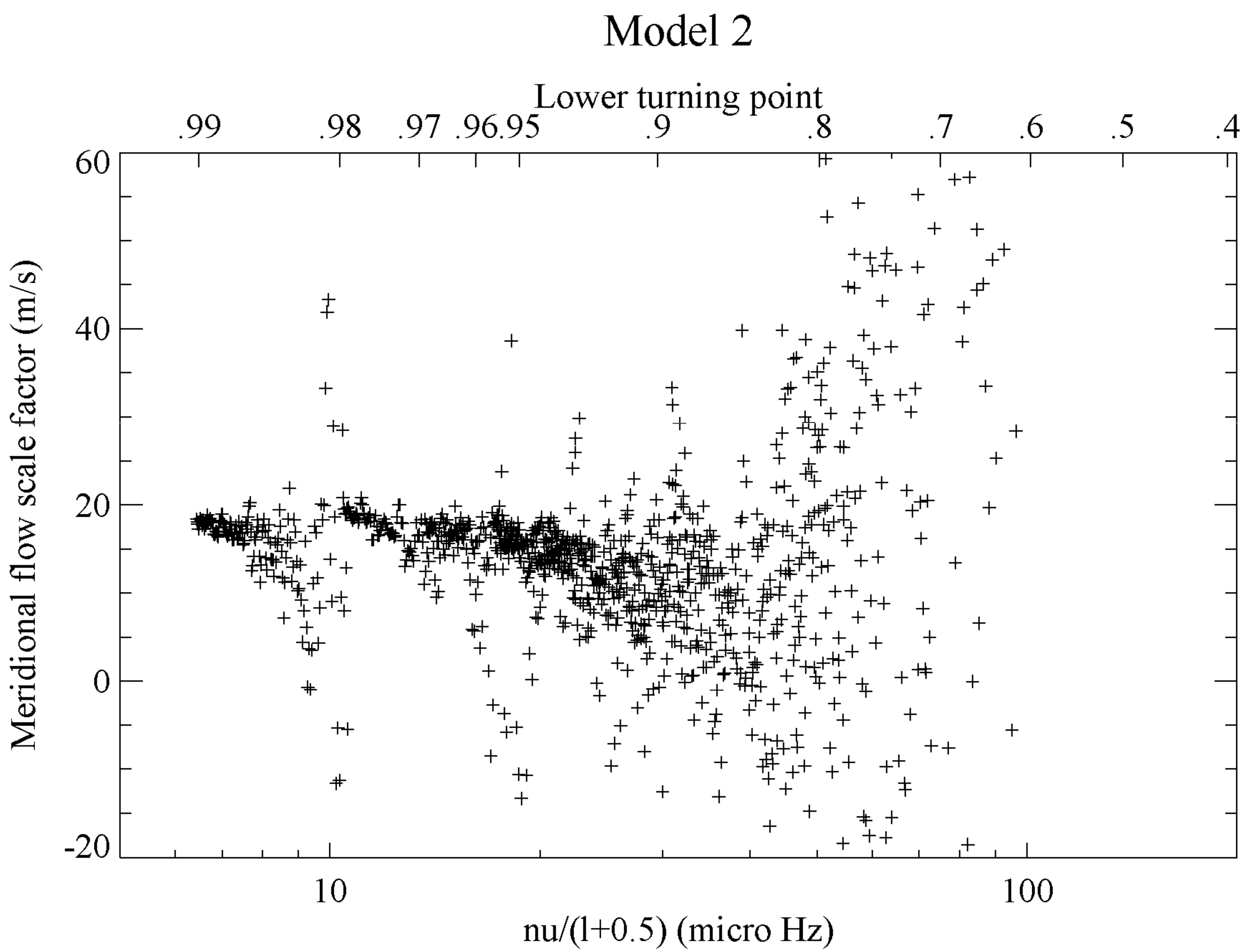
Meridional Flow Model 0



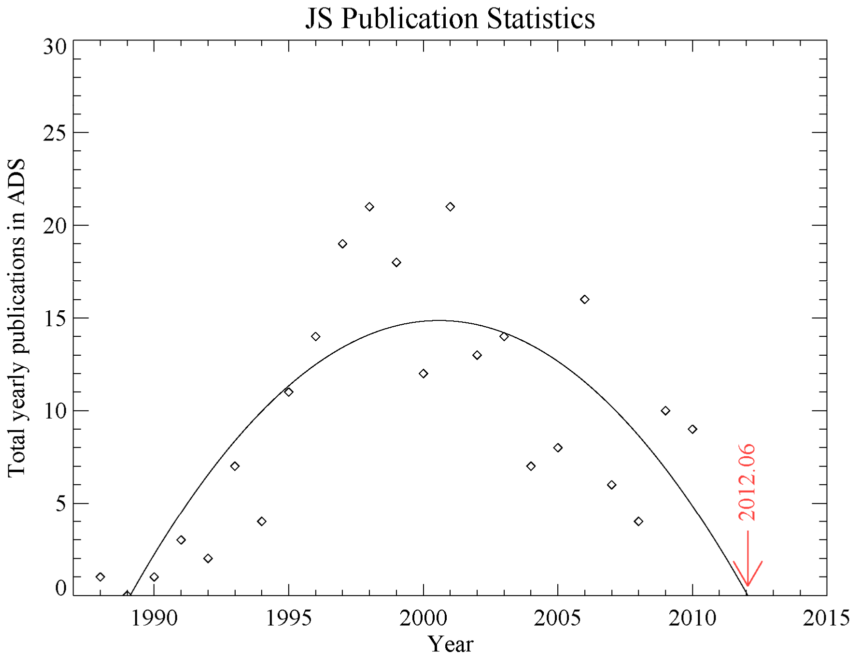
Meridional Flow Model 1

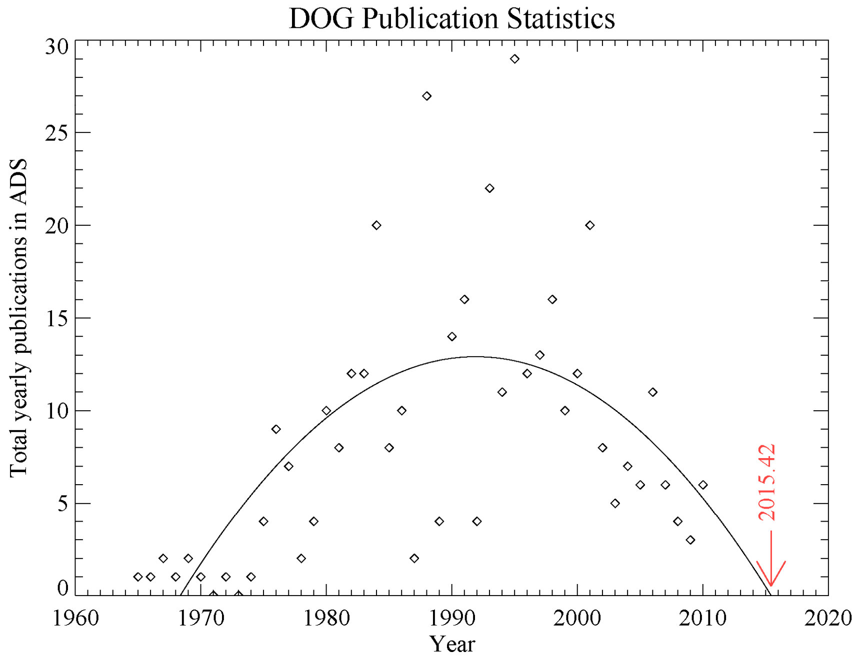


Meridional Flow Model 2



JS vs. DOG





Second order/max= - 0.00760

Second order/max= -0.00181

Up to and including 2010

Conclusion

- **The future looks bright!**
  - For helioseismology
  - For DOG
    - Less so for JS