Helioseismology

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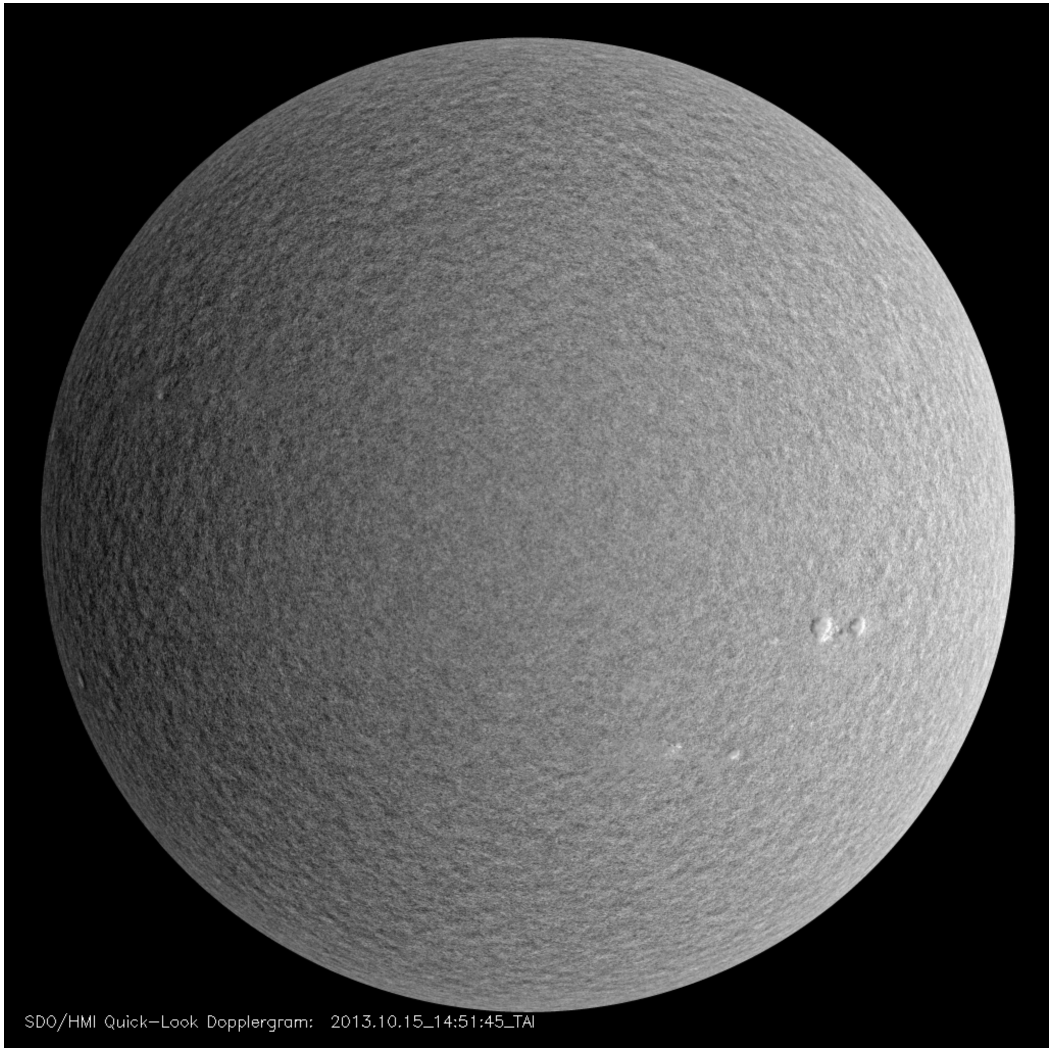
Helioseismology

- **The study of the Sun using waves – Similar to Earth seismology**
- **Sounds waves are trapped in the Sun**
  - Refracted at bottom of cavity by increase in sound speed
  - Reflected at surface by steep density gradient
- **Excited near the surface by convective motions**
- **Damped by non-linear effects**
  - Radiation, interaction with convection, …
- **Observed at surface in Doppler shift or intensity**
  - Essentially spatially white at any given time
- **Various approaches**
  - Global modes
  - Time-distance
  - Ring diagrams
  - Holography
  - Direct modeling

Observables

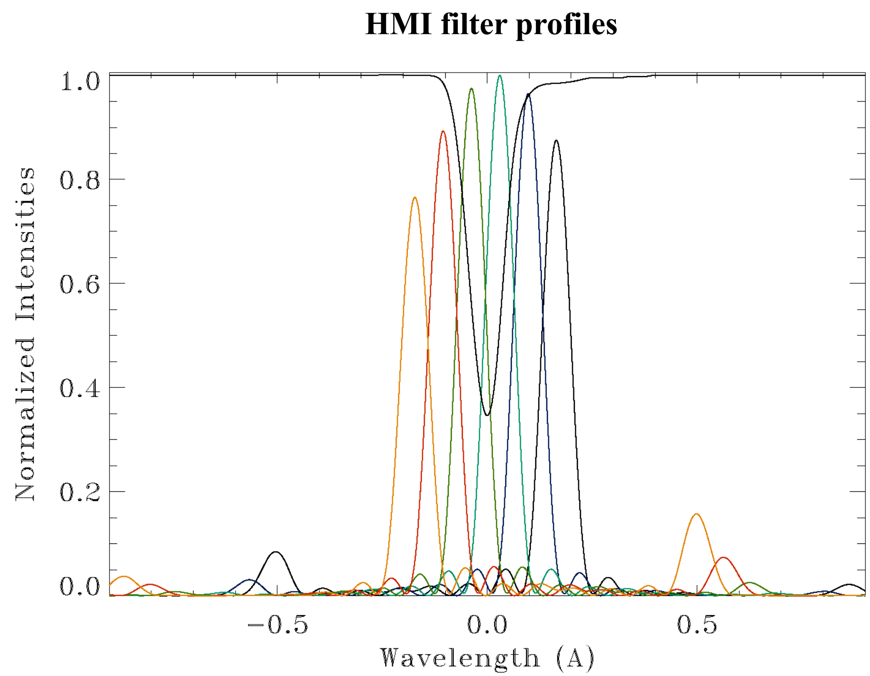
- **Intensity**
  - Broadband continuum
  - Computed continuum near line
  - Very sensitive to atmospheric effects
- **Velocity**
  - Can be made insensitive to some atmospheric effects
  - Many different spectral lines
    - 6768, 6173, Na, K, …
  - Different heights in solar atmosphere, even within one spectral line
- **Others**
  - Line depth
  - Line width
  - Equivalent width
  - Core intensity
- **Various resolutions from integrated light to 4096x4096 pixels FD**
  - And higher for smaller regions

Example Velocity Image (Dopplergram)



Velocity Imaging – Measurement Methods

- **Lyot/UBF/Michelsons**
  - Fixed prefilter
  - Tune several elements to scan line - complex
    - •Rotating waveplates - stable
    - •Electro-optical devices – no moving parts
  - E.g. MDI and HMI
- **Fourier Tachometer**
  - Single Lyot or Micelson for tuning - simple
  - FSR>>linewidth
    - •Simple prefilter, good dynamic range
  - E. g. Fourier Tach and GONG
- **Fabry-Perot**
  - Use Fabry-Perot for tuning
    - •Typically electro-optical – no moving parts
    - •E.g. SO/PHI
- **MOF**
  - Vapor (Na or K) in cell+magnetic field
    - •Simple, stable, poor dynamic range (limits orbits)
  - E.g. Mt. Wilson



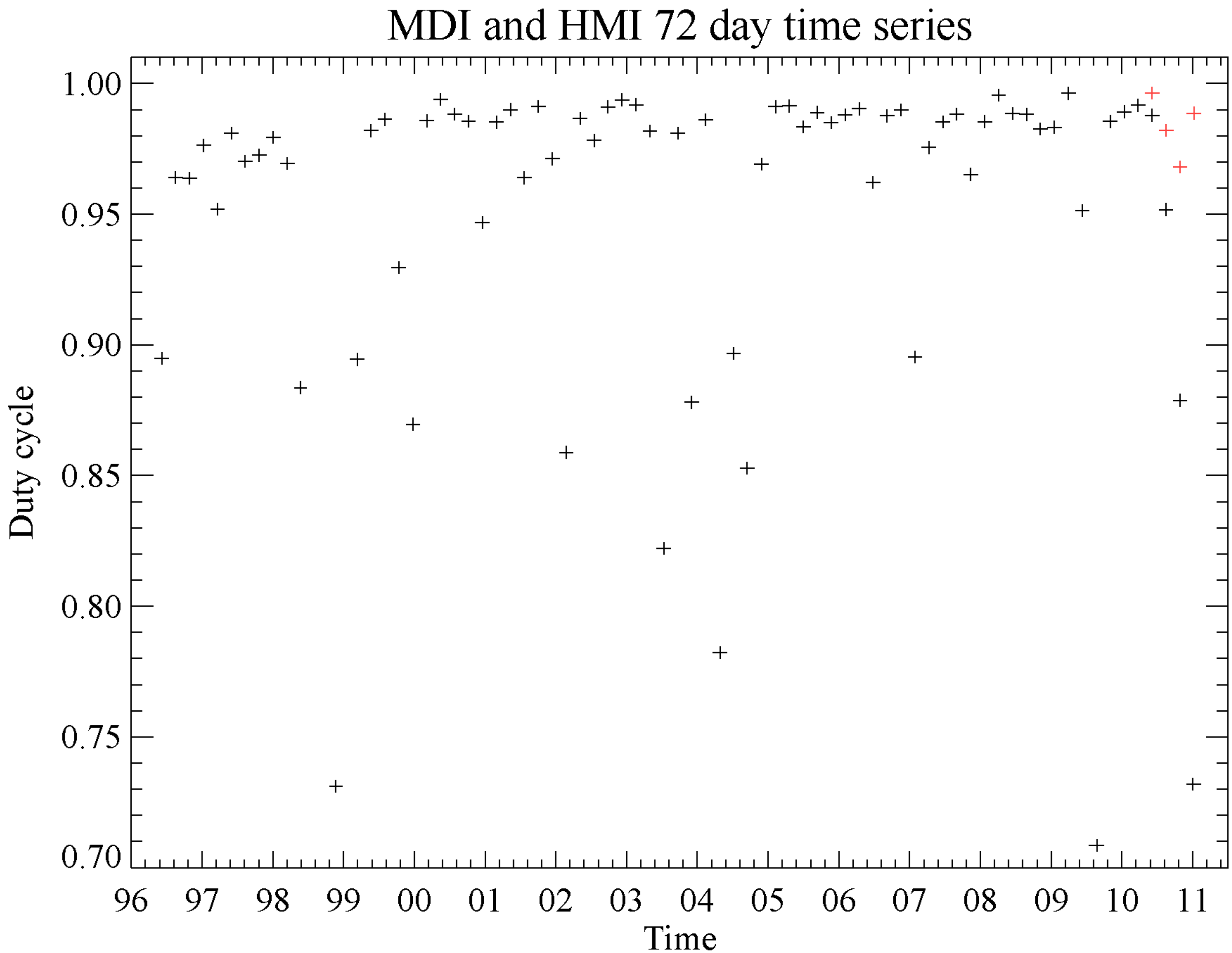
Main Data Sources - Helioseismology

- **GONG (1995-)**
  - All the time: Roughly 800x800 unapodized
    - I, V, Blos
    - Mostly 60s cadence
- **MDI (1996-2011)**
  - All the time: 200x200 pixels heavily apodized
    - Velocity only
  - Part of the time: 1024x1024 unapodized.
    - Almost always velocity. Sometimes Intensity
    - Blos every 96 minutes
  - Mostly 60s cadence
- **HMI (2010-)**
  - All the time: 4096x4096 unapodized
    - All variables. I, V, Blos, Bvec, …
    - Mostly 45s cadence. Bvec at 720s

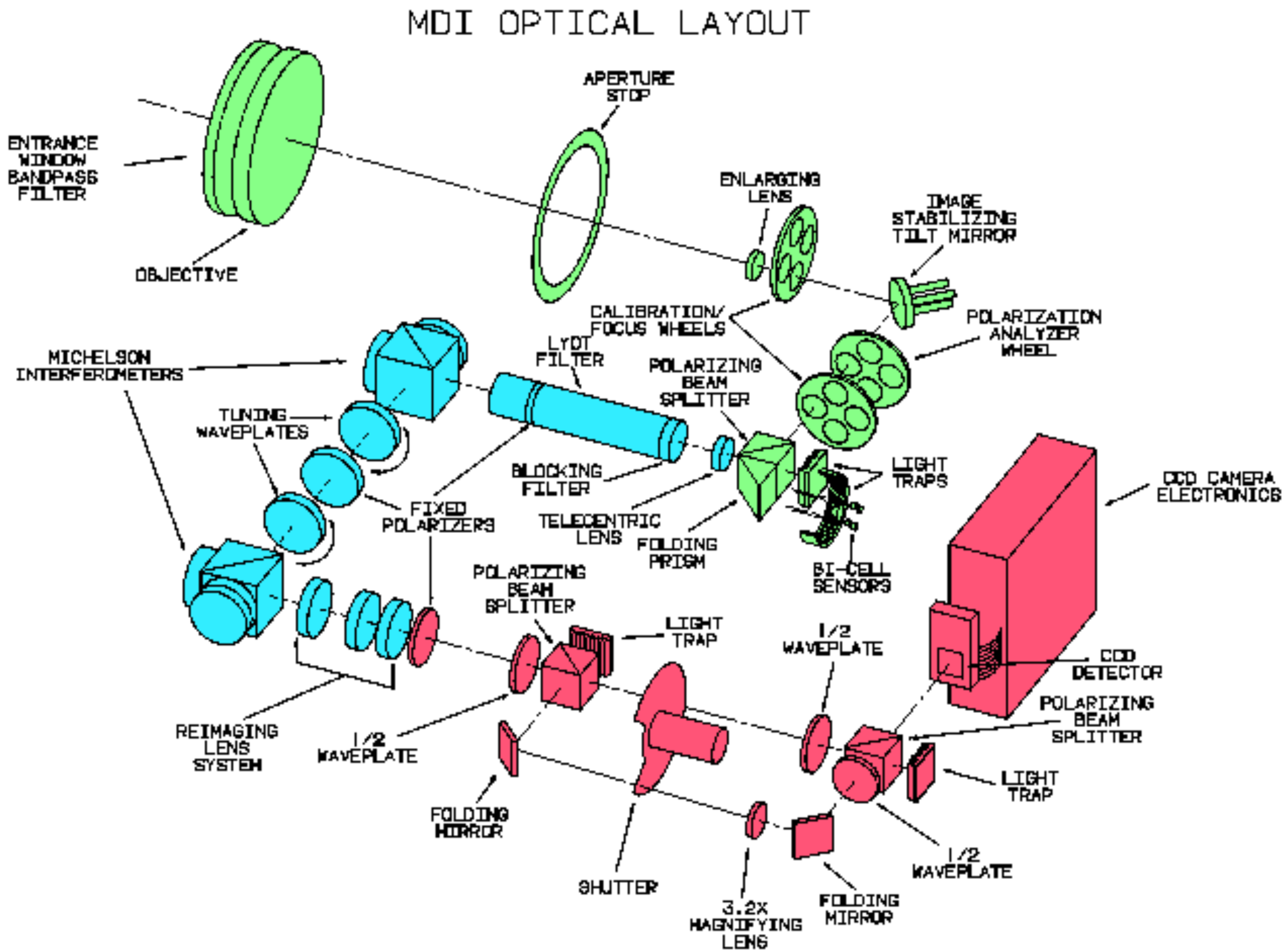
Ground vs. Space

- **Resolution**
  - For small fields of view ground works well using adaptive optics
  - Space needed for large FOV at high resolution
- **Temporal coverage**
  - Major problem on the ground
    - Networks work but many stations needed
- **Wavelength**
  - Optical and near infrared works from ground
  - UV, in particular, can’t be observed from the ground
- **Stability**
  - It is very difficult to provide uniform high quality time-series from the ground
- **See only one side of Sun from ground**
- **But:**
  - Space is costly!
  - Easy to fix thing one the ground. At best difficult to fix things in space!

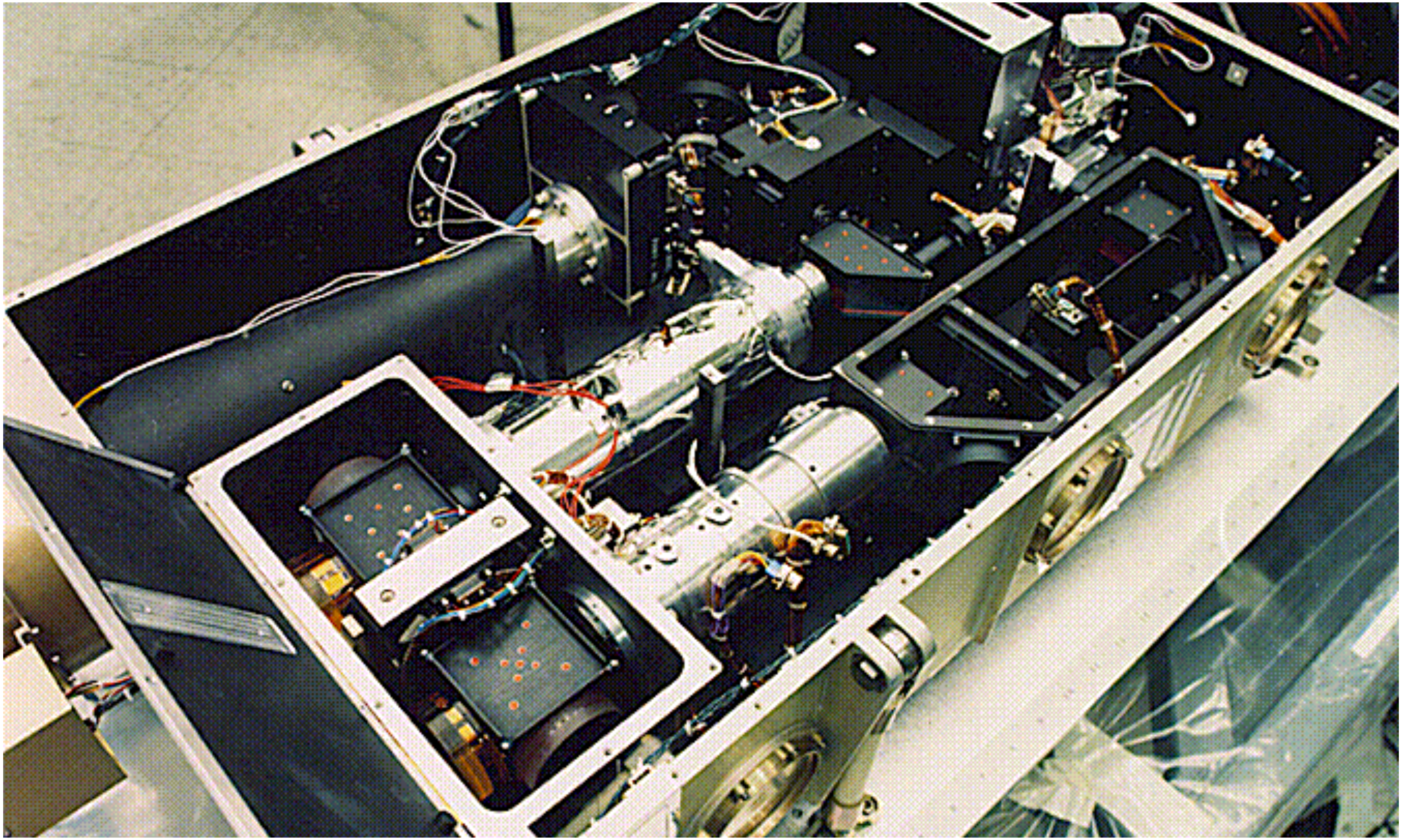
Temporal Coverage



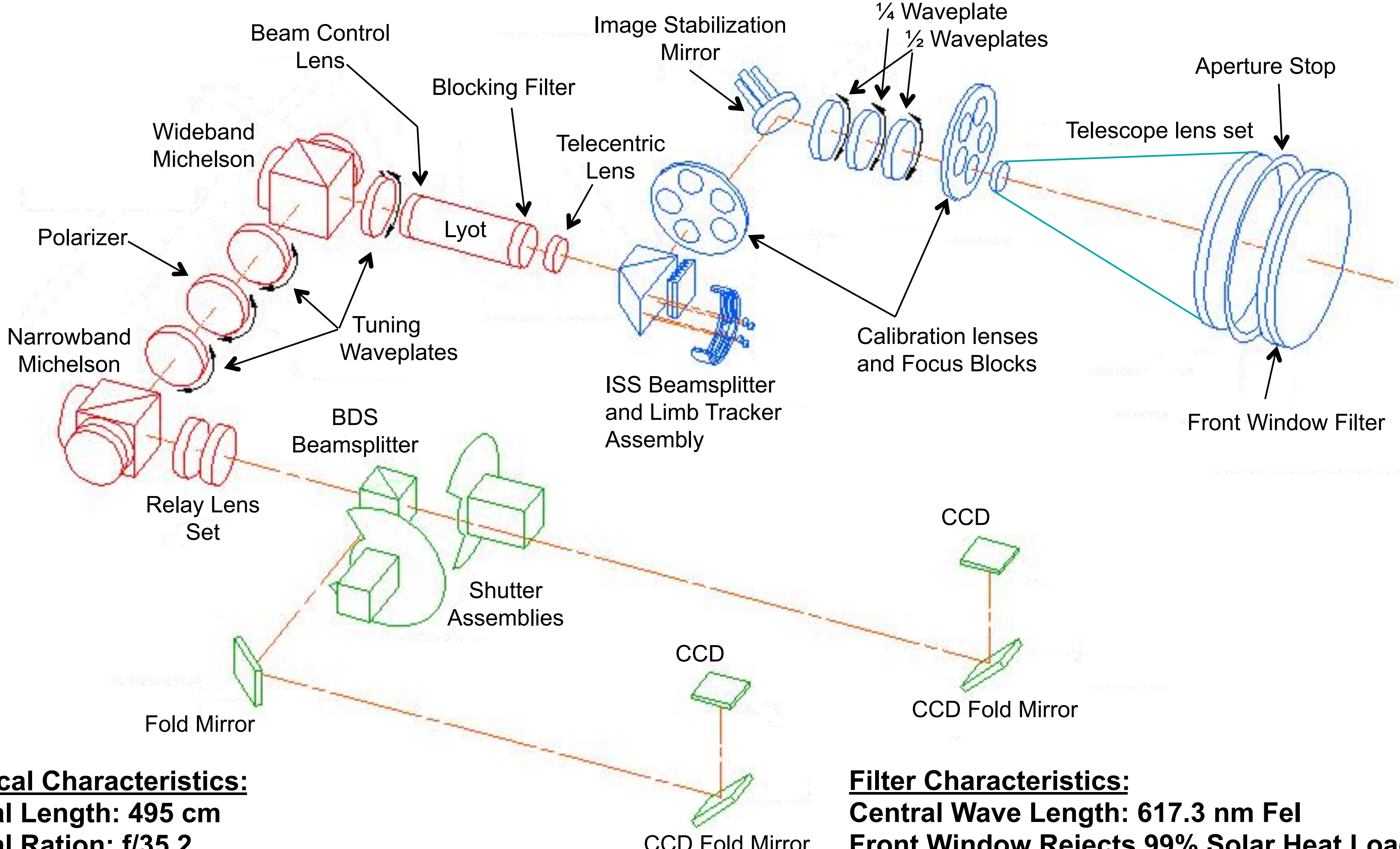
MDI Optical Layout



MDI Optics Package



HMI Optical Layout



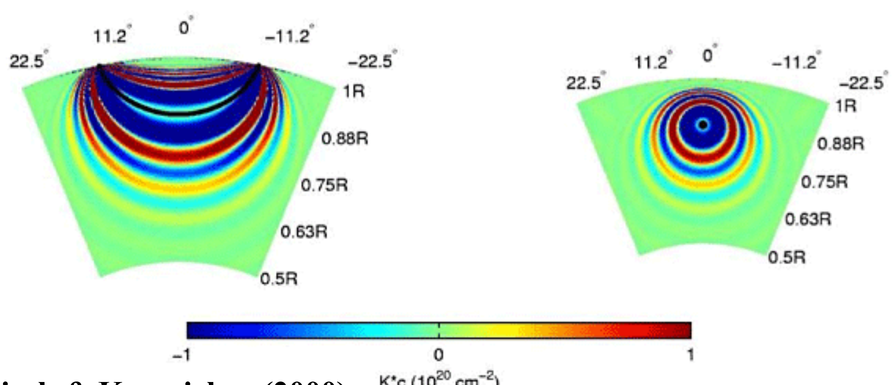
<u>Optical Characteristics:</u>
Focal Length: 495 cm
Focal Ration: f/35.2
Resolution: 1”
Re-imaging Lens Magnification: 2
Focus Adjustment Range: 16 steps

<u>Filter Characteristics:</u>
Central Wave Length: 617.3 nm FeI
Front Window Rejects 99% Solar Heat Load
Bandwidth: 0.0076 nm
Tunable Range: 0.05 nm
Free Spectral Range: 0.0688 nm

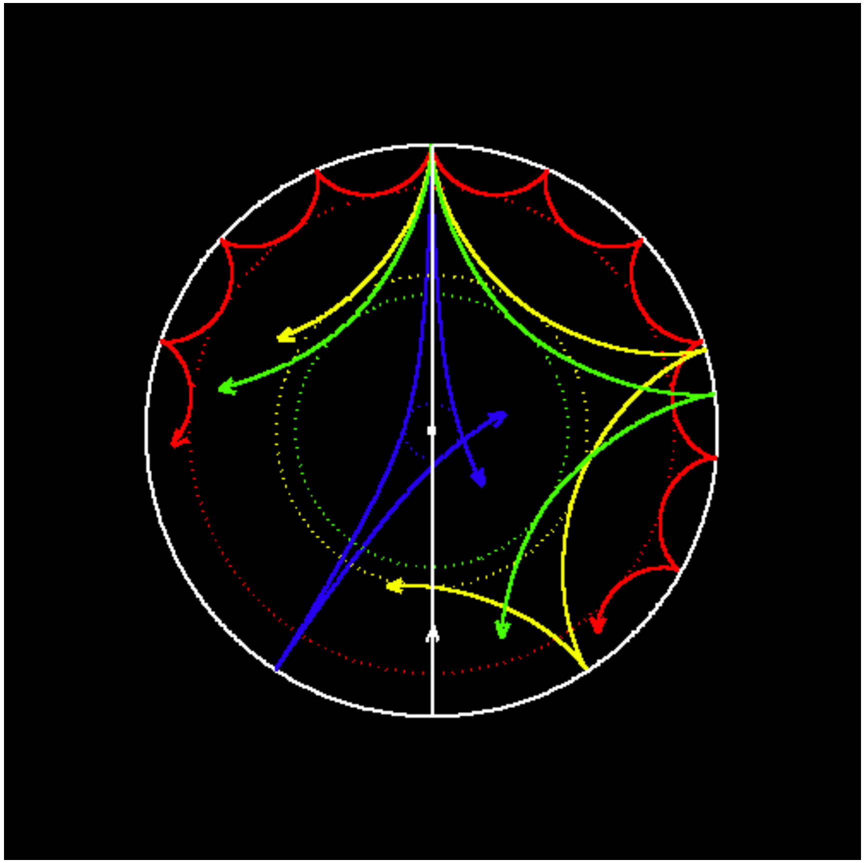
HMI Optics Package

Time-Distance View and Data Analysis

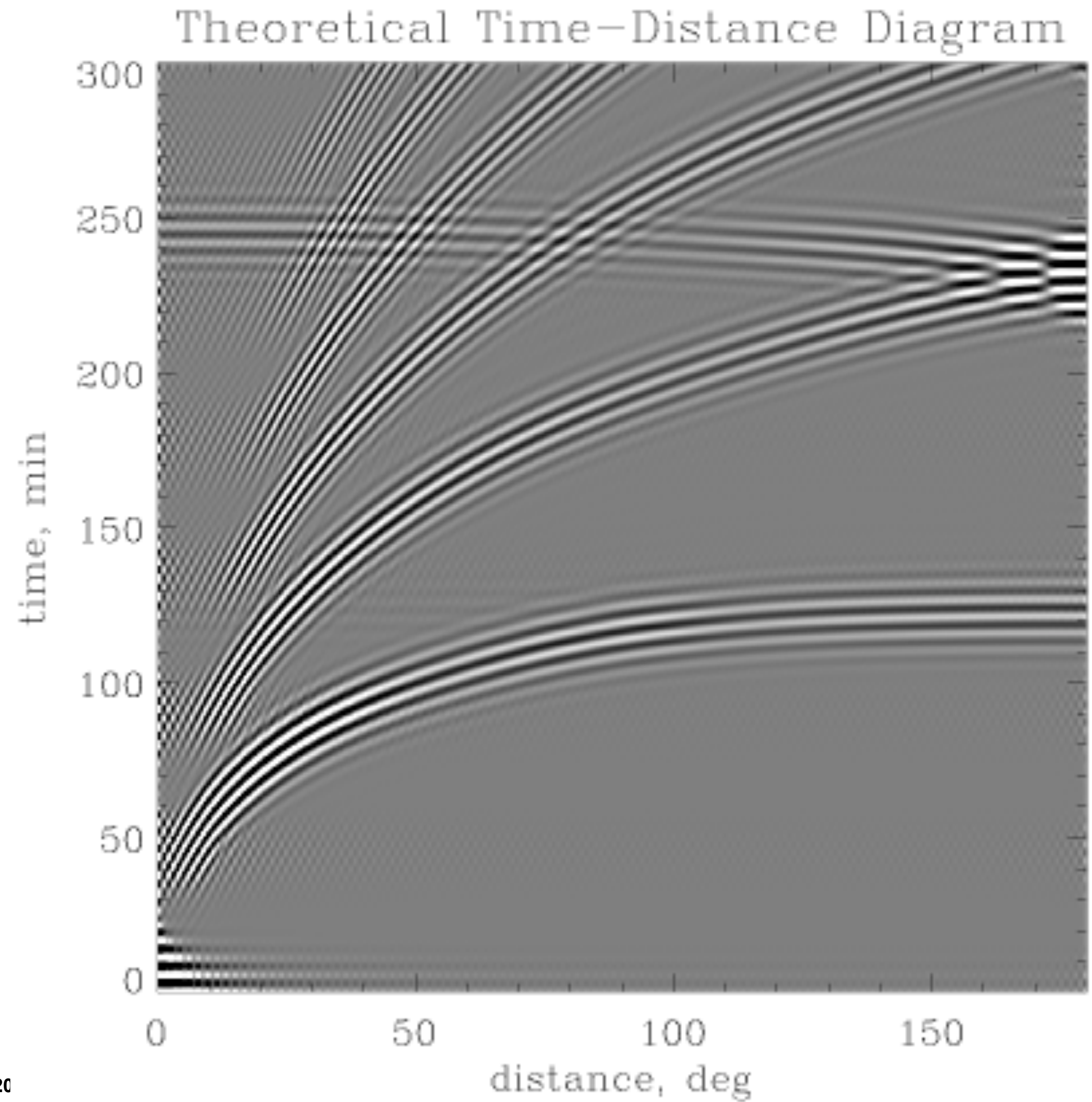
- **Describe oscillations as waves bouncing around**
- **Measure travel times between pairs of points using cross-correlations**
  - Low S/N
- **Kernels describing sensitivity to sound speed and flows can be found**
  - Computationally intensive
  - Accuracy issues
- **Data inverted**
  - Very computationally intensive
  - Simplifications made
- **Papers published**



Birch & Kosovichev (2000)



Theoretical Cross Correlation



Gizon & Birch (2005) courtesy of A. Kosovichev

Global Mode View

- **Describe oscillations in terms of normal modes**
- **Horizonal dependence given by spherical harmonics**
  - Depend on degree l and azimuthal order m
- **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
- **Perturbations and deviations from reference model small**
  - Equations can be linearized to give sensitivity, eg.

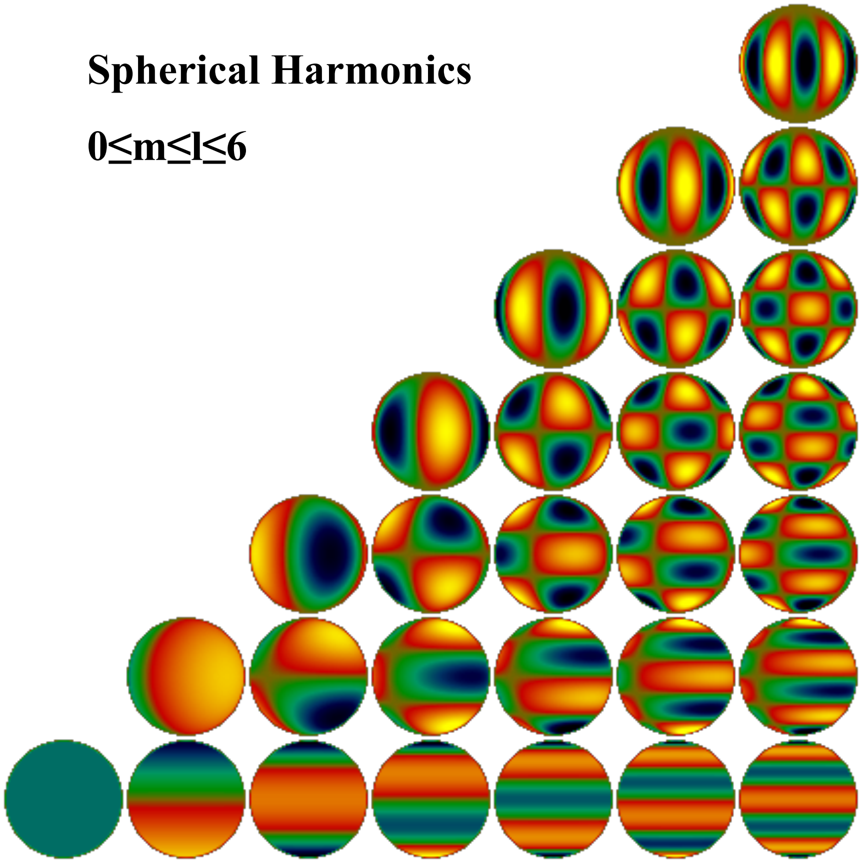
$$\omega_{nlm} - \omega_{nl} = \int K_{nlm}(r,\theta)\Omega(r,\theta)drd\theta$$

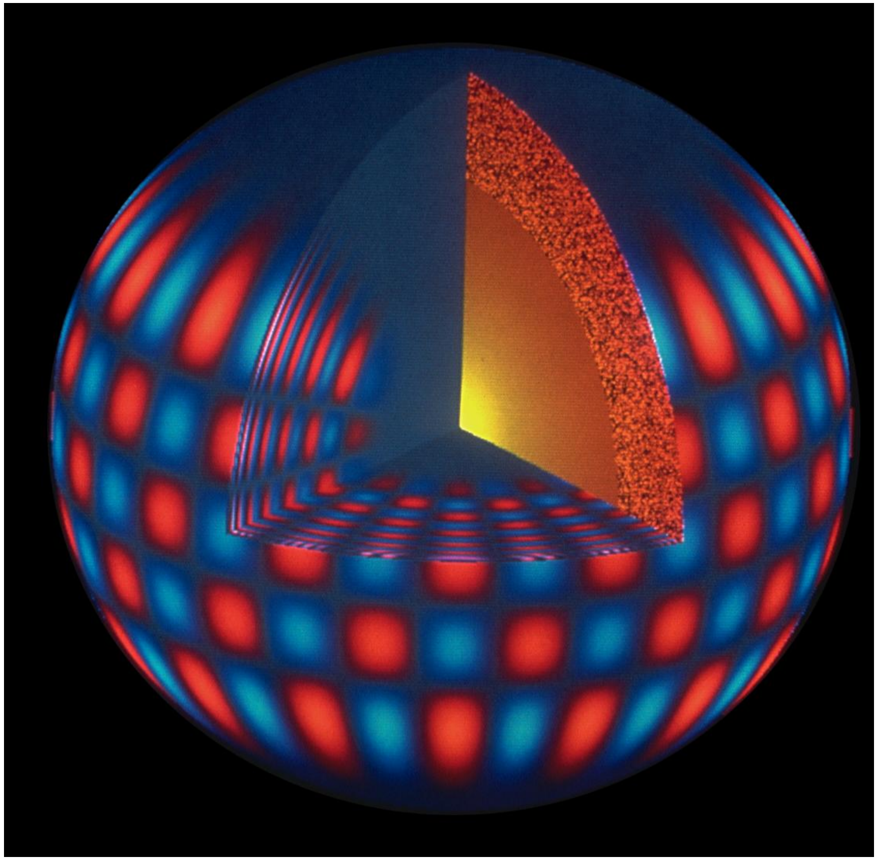
  - Where K is a known function of radius r and co-latitude θ and Ω is the rotation rate

Global Mode Eigenfunctions

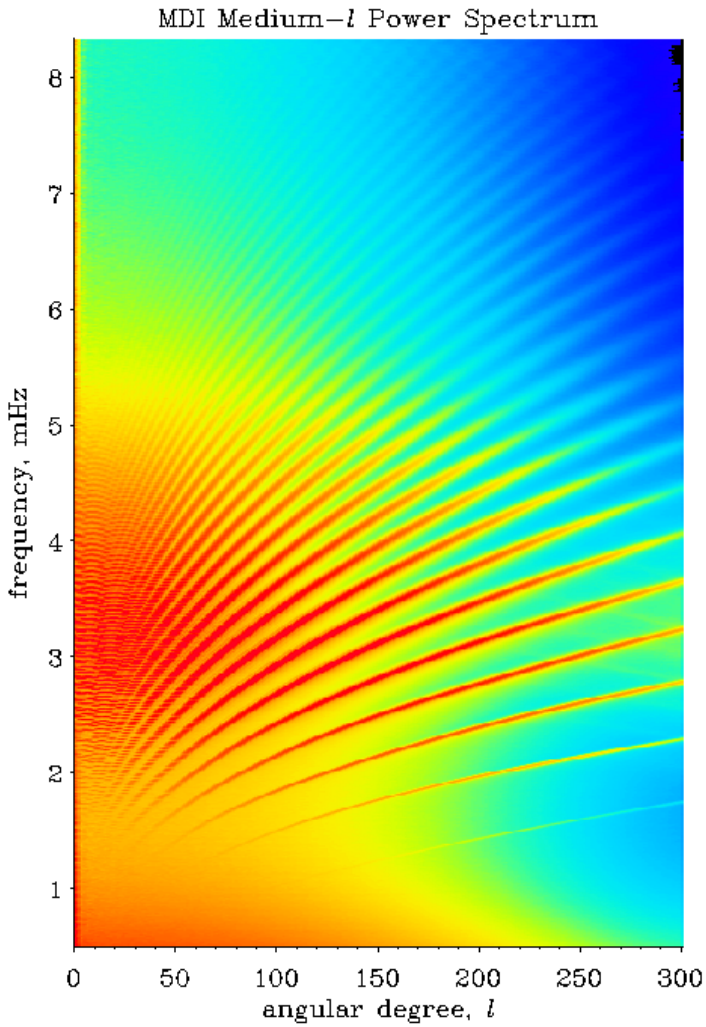
Spherical Harmonics

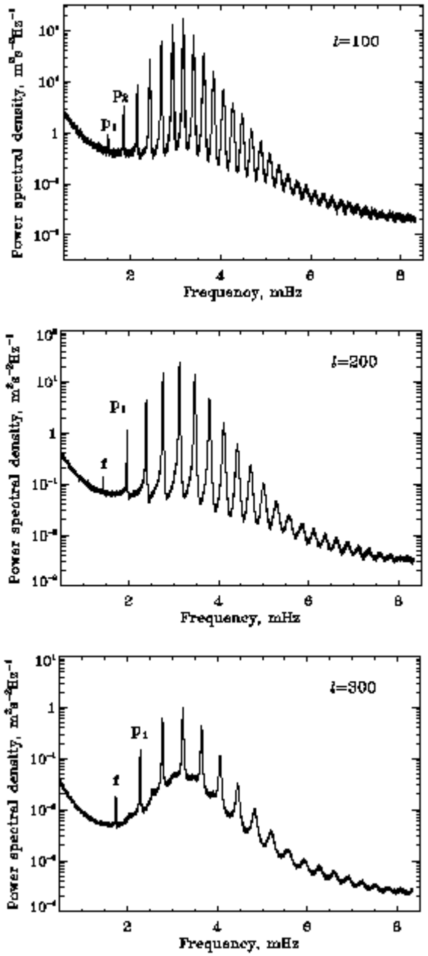
$0 \leq m \leq l \leq 6$





Observed Power Spectra



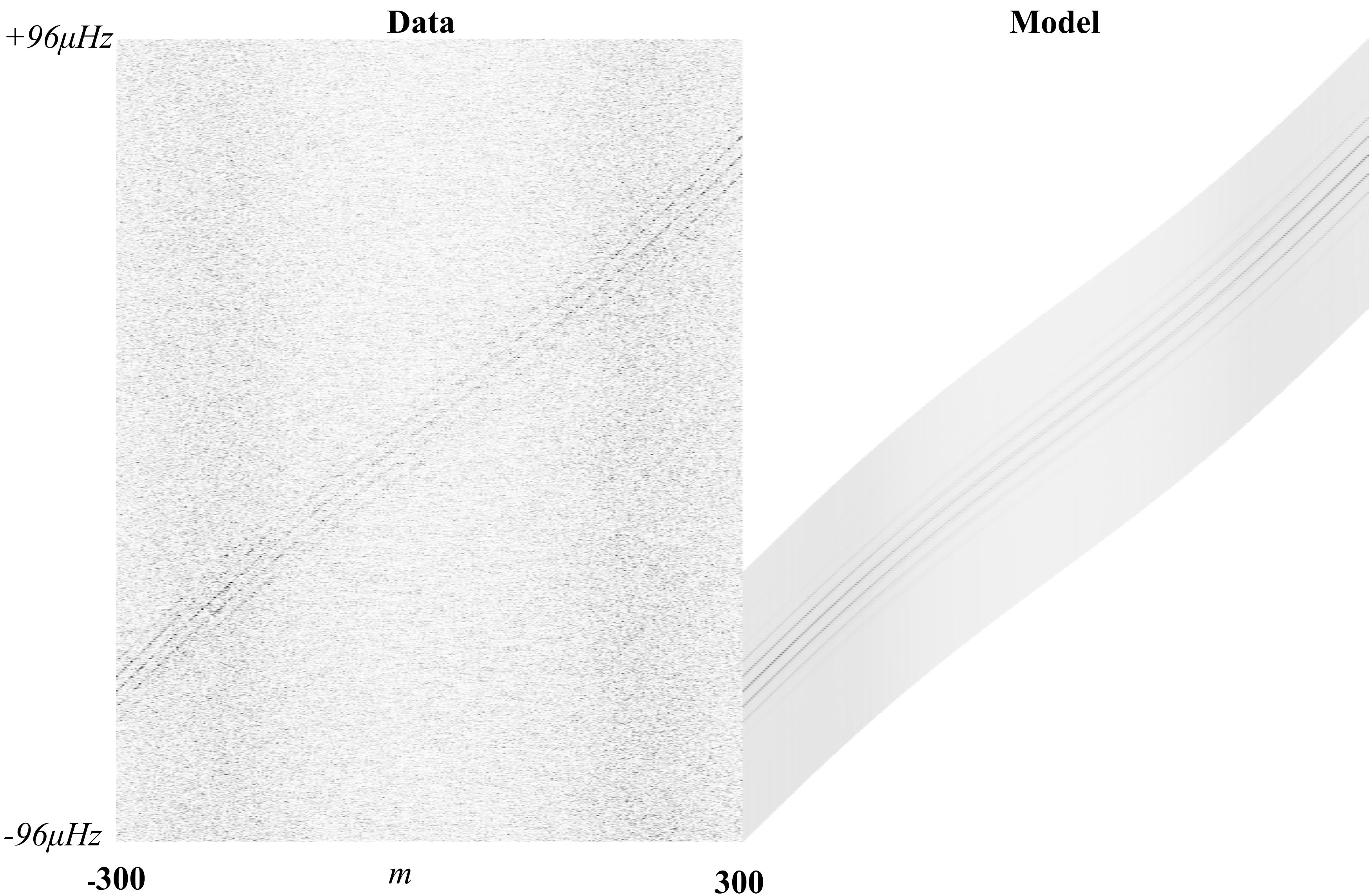


Spectra have been averaged over m

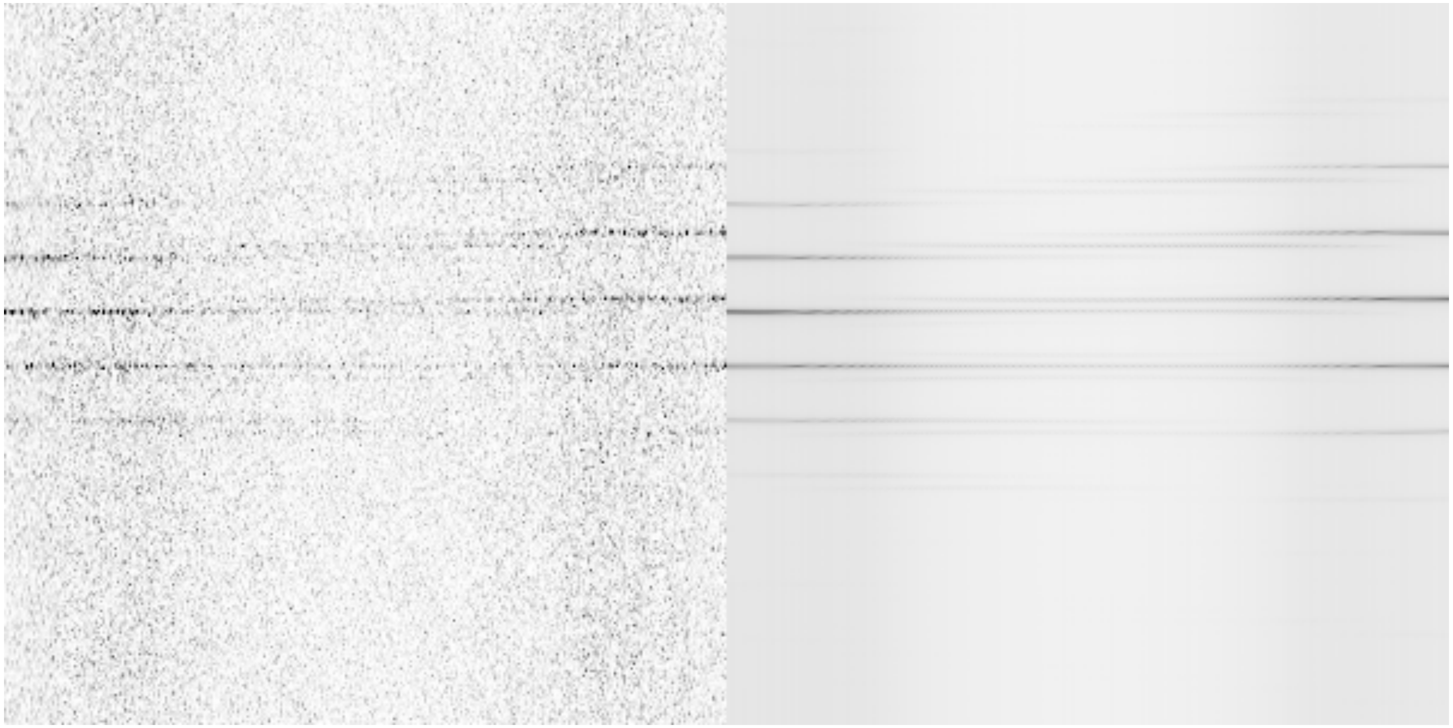
Global Modes – Data Analysis

- **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
- **Time-series Fourier transformed**
  - Gaps filled
  - Often turned into power spectra
- **Spectra fit to find frequencies**
  - As well as amplitudes, linewidths, background power, …
  - Aka. peakbagging
- **Frequencies inverted to determine sound speed, rotation, etc.**
- **Papers published**

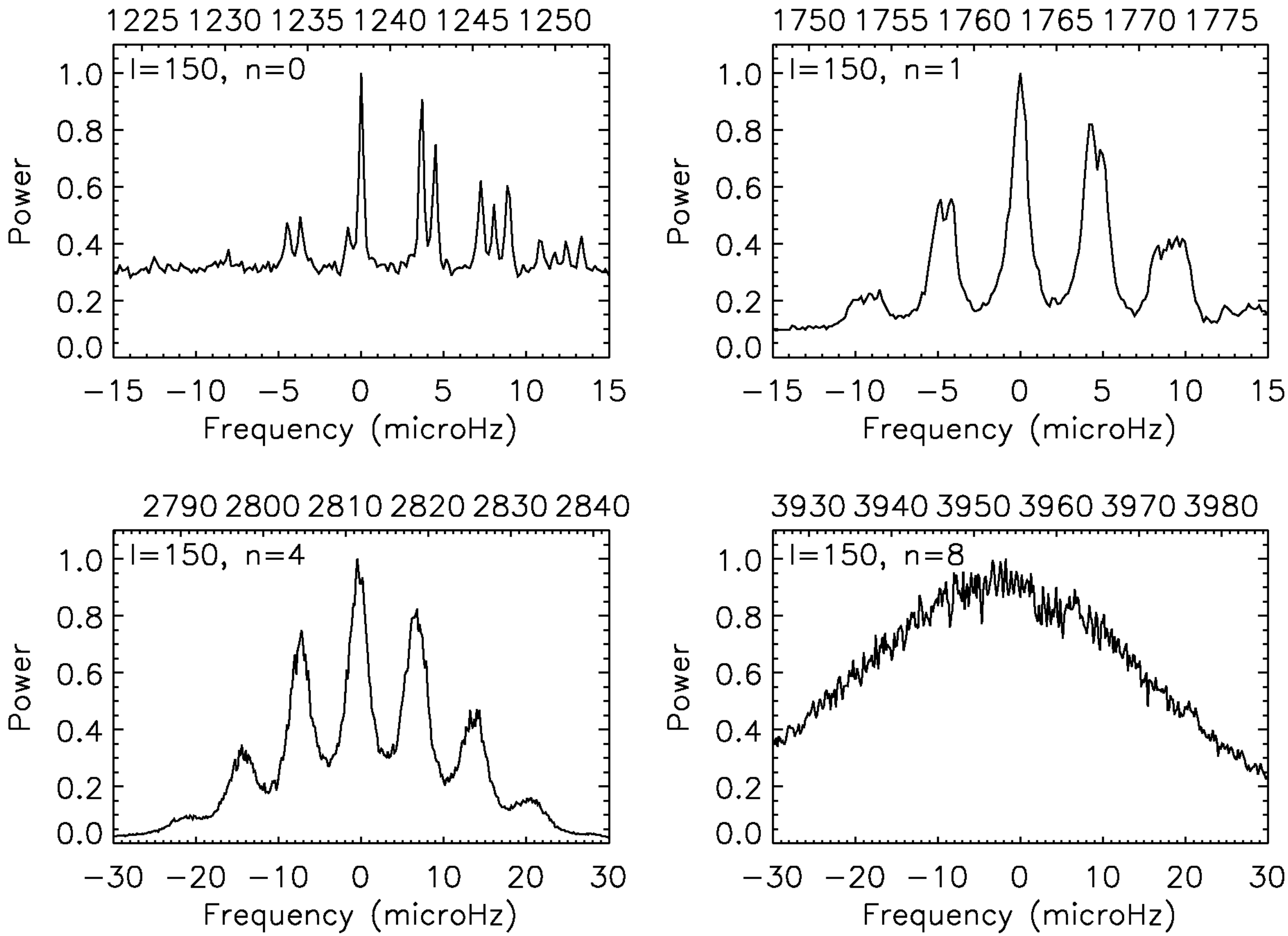
Observed Power Spectra



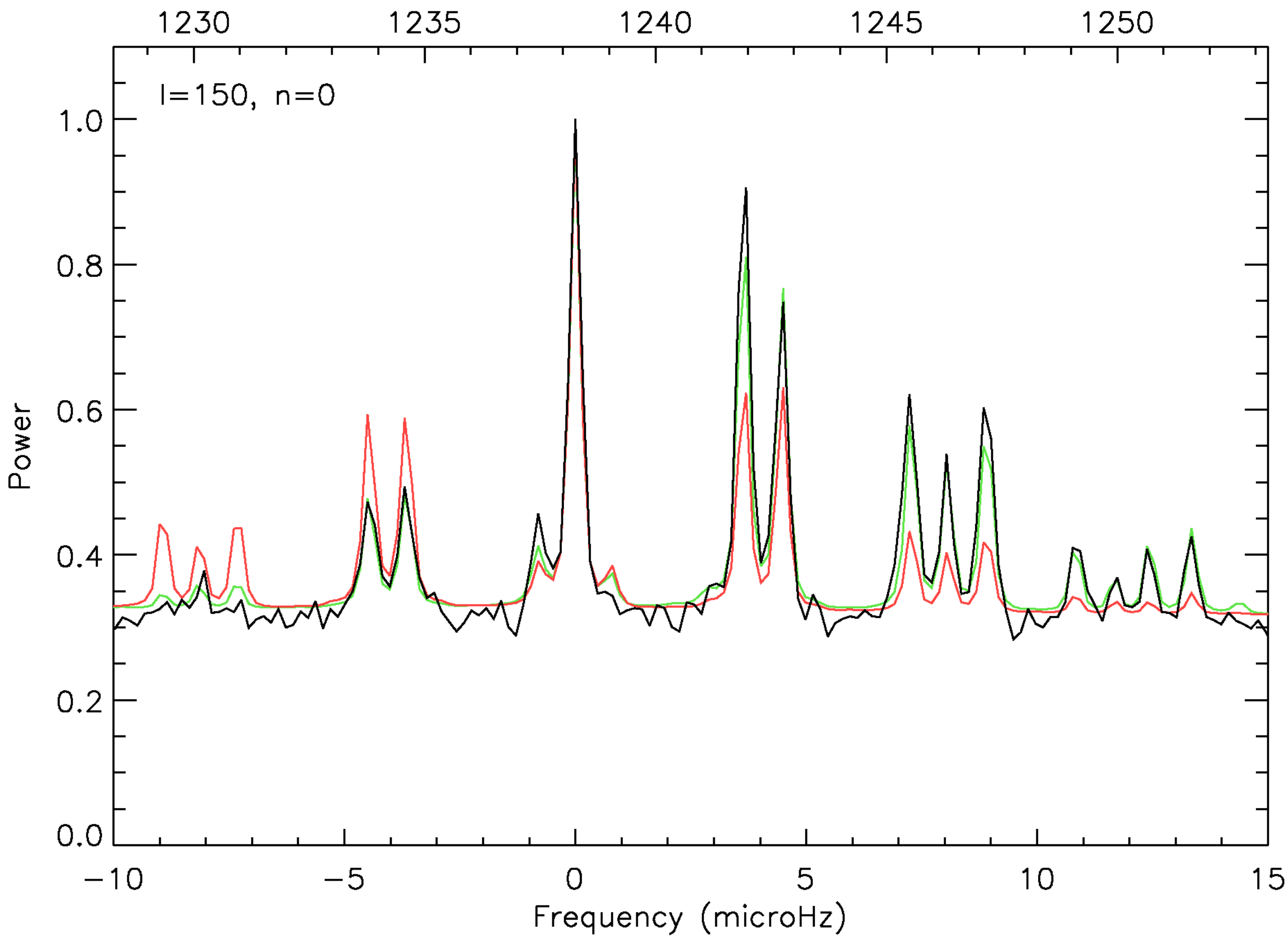
Power Spectra Shifted



Average Over m



Spectrum With Model



Red and green are two different models.
Black is observations.

Real Peakbagging ™

Cerro Vicuñas, 6087m, Chile, March 15, 2013

Inversions - General

- **Measurements d are related to rotation rate Ω by known kernels K**

$$d_i = \int K_i(r,\theta)\Omega(r,\theta)drd\theta$$

  – where i=1,…M can be (nlm) or a-coefficients

- **Considering linear methods only, coefficients c exist such that the inferred rotation rate is given by**

$$\overline{\Omega}(r_0,\theta_0) = \sum_{i=1}^{M} c_i(r_0,\theta_0)d_i$$

  – Where (r_0,θ_0) labels the inverted point (eg. it is the target radius and latitude)
  – Errors can be propagated using c

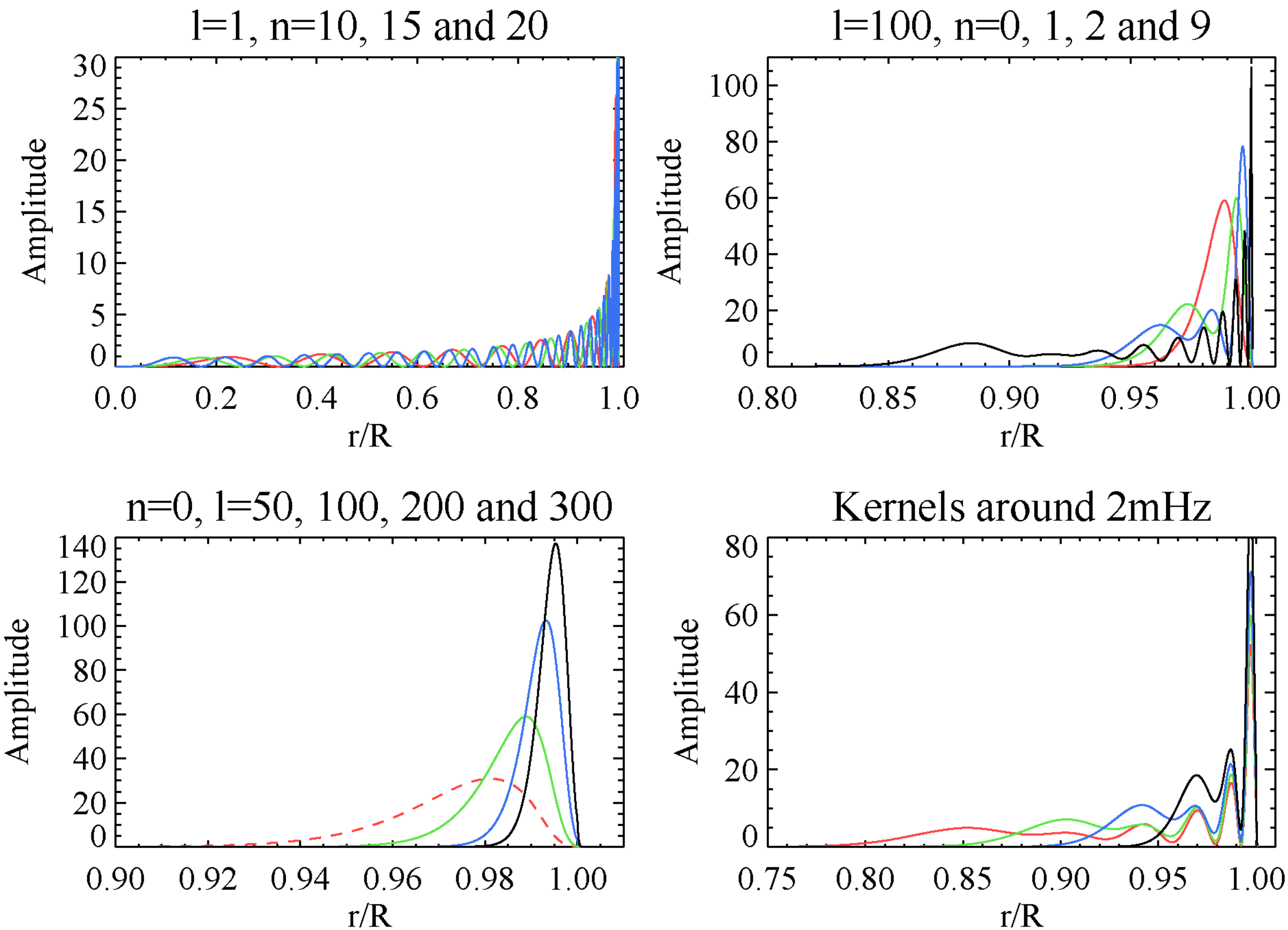
- **Combining these equations shows that averaging kernels K exist such that**

$$\overline{\Omega}(r_0,\theta_0) = \int K(r_0,\theta_0,r,\theta)\Omega(r,\theta)drd\theta$$

  – In other words the inverted rotation rate depends linearly on the true rotation rate

- **Done in 1D, 1.5D and 2D**

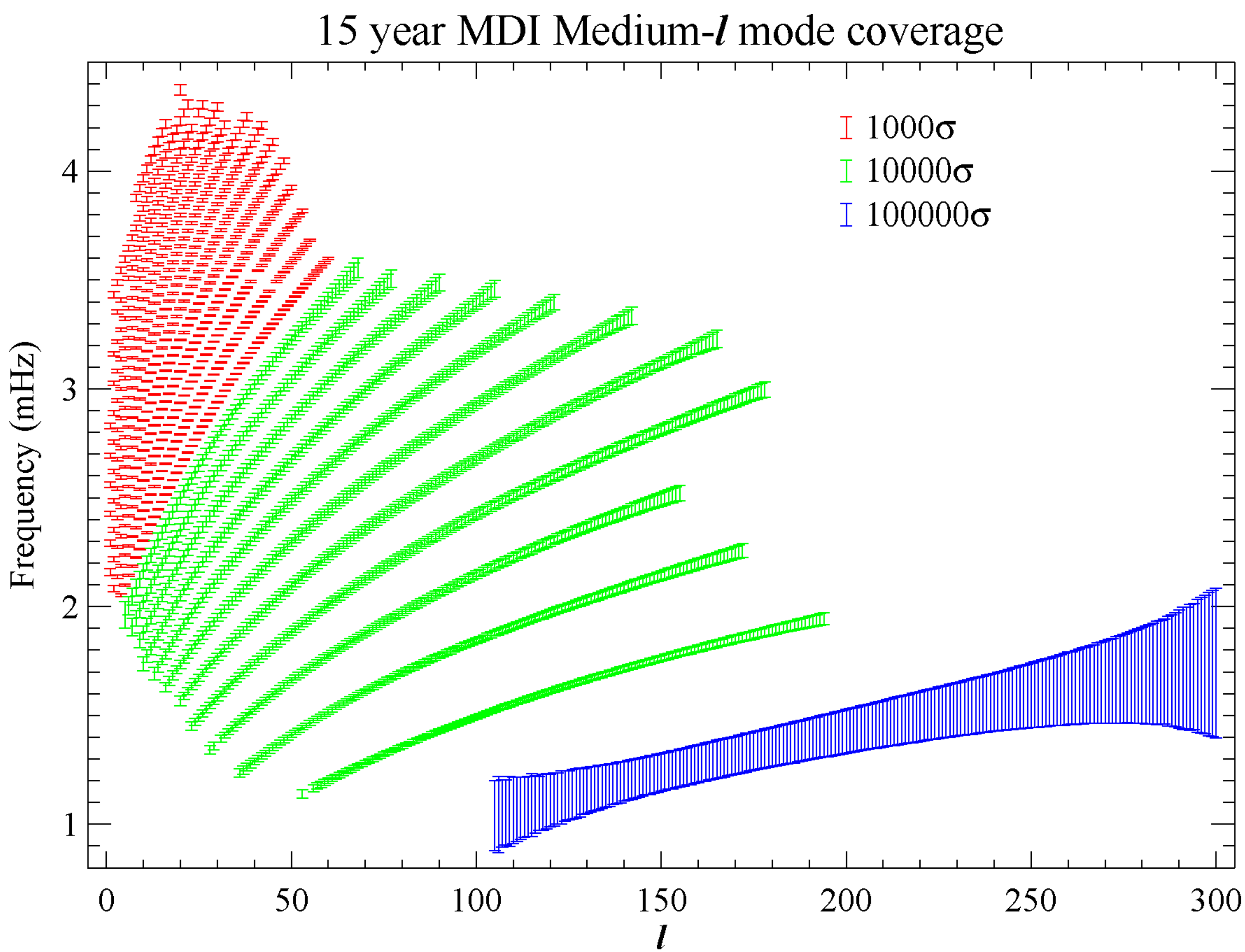
Example Kernels



Selected Results

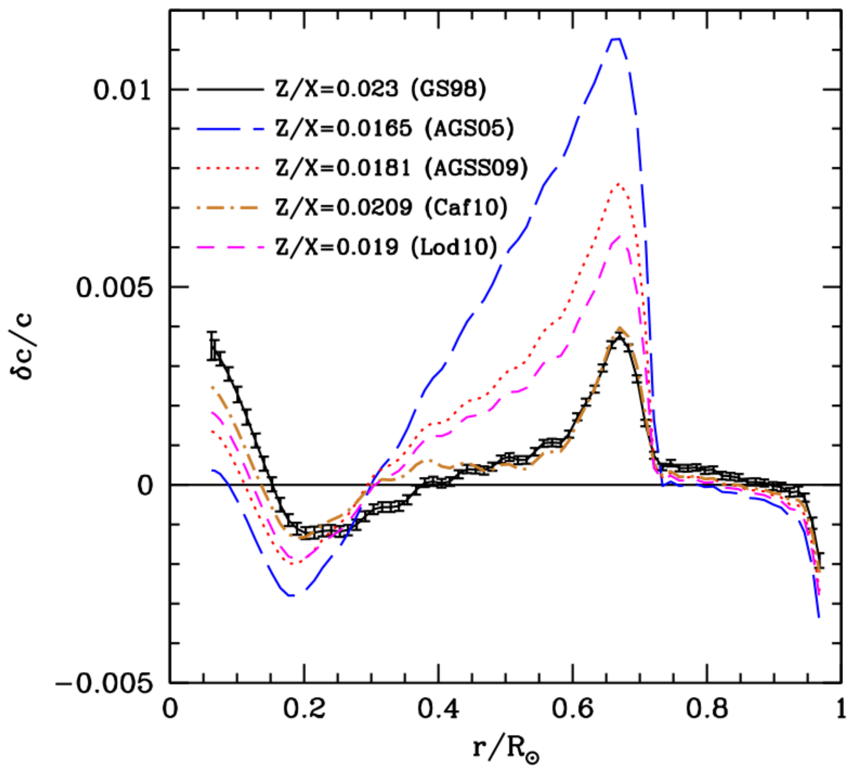
- Next few pages show some results
- Not enough time for details about measurements
- Not enough time for details about interpretation

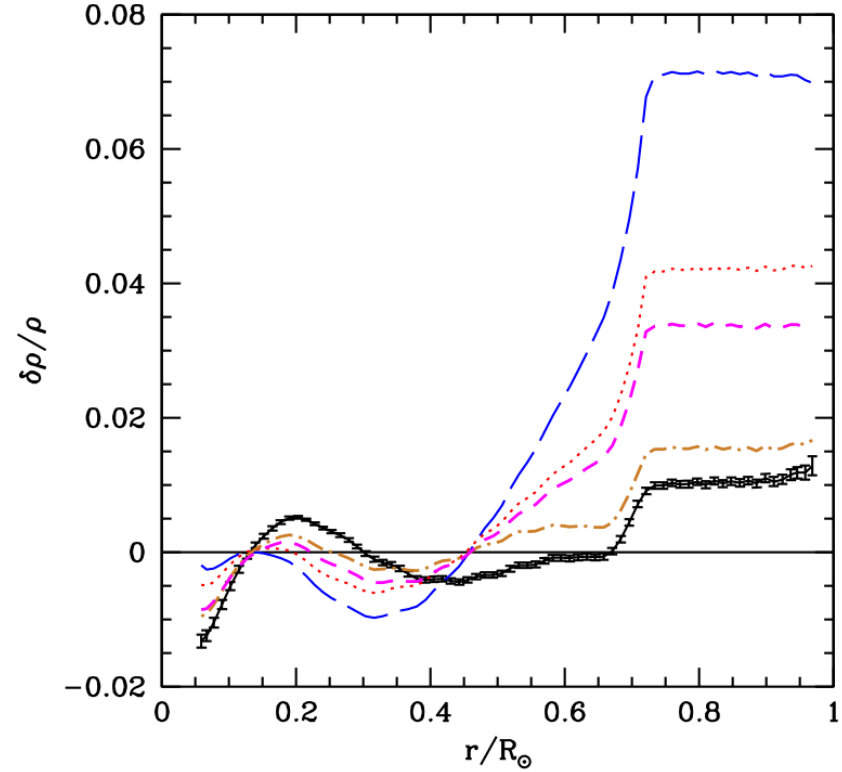
Very Precise Measurements!



74x72 days. Present 75% of time. Fractional error is 1 part in 50 million, for f-modes: 16 million

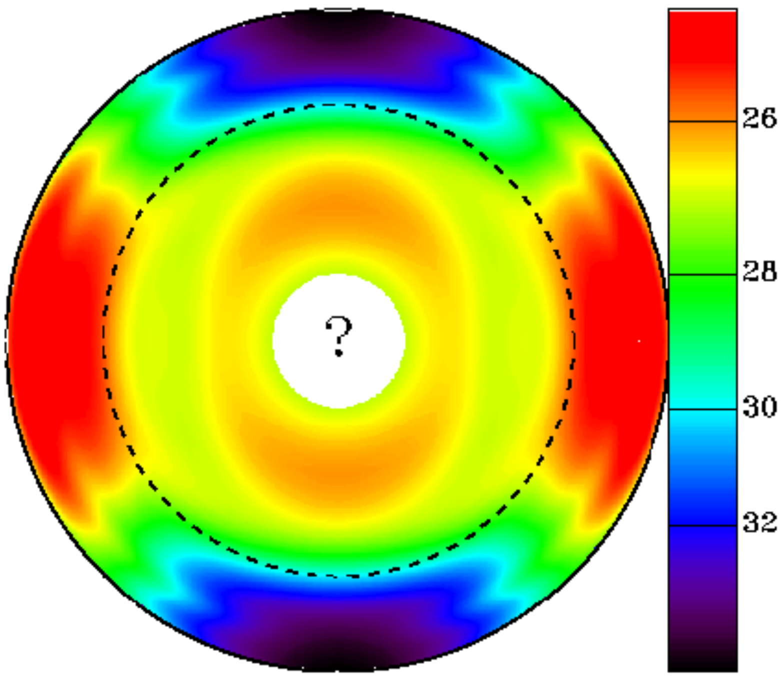
Structure Errors as a Function of Radius

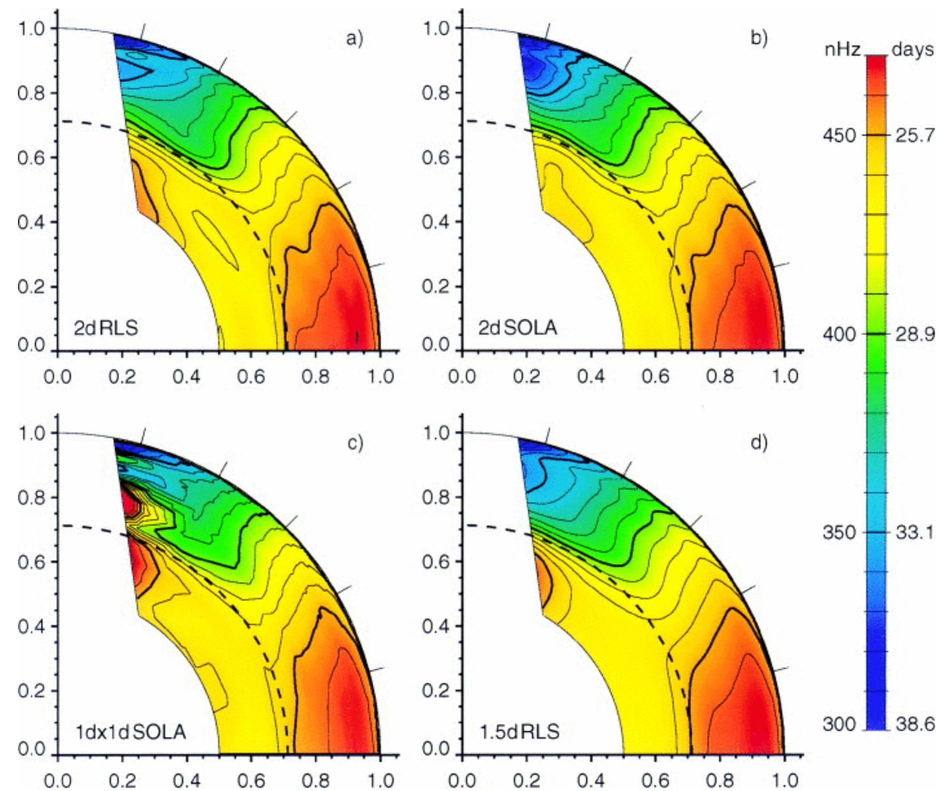




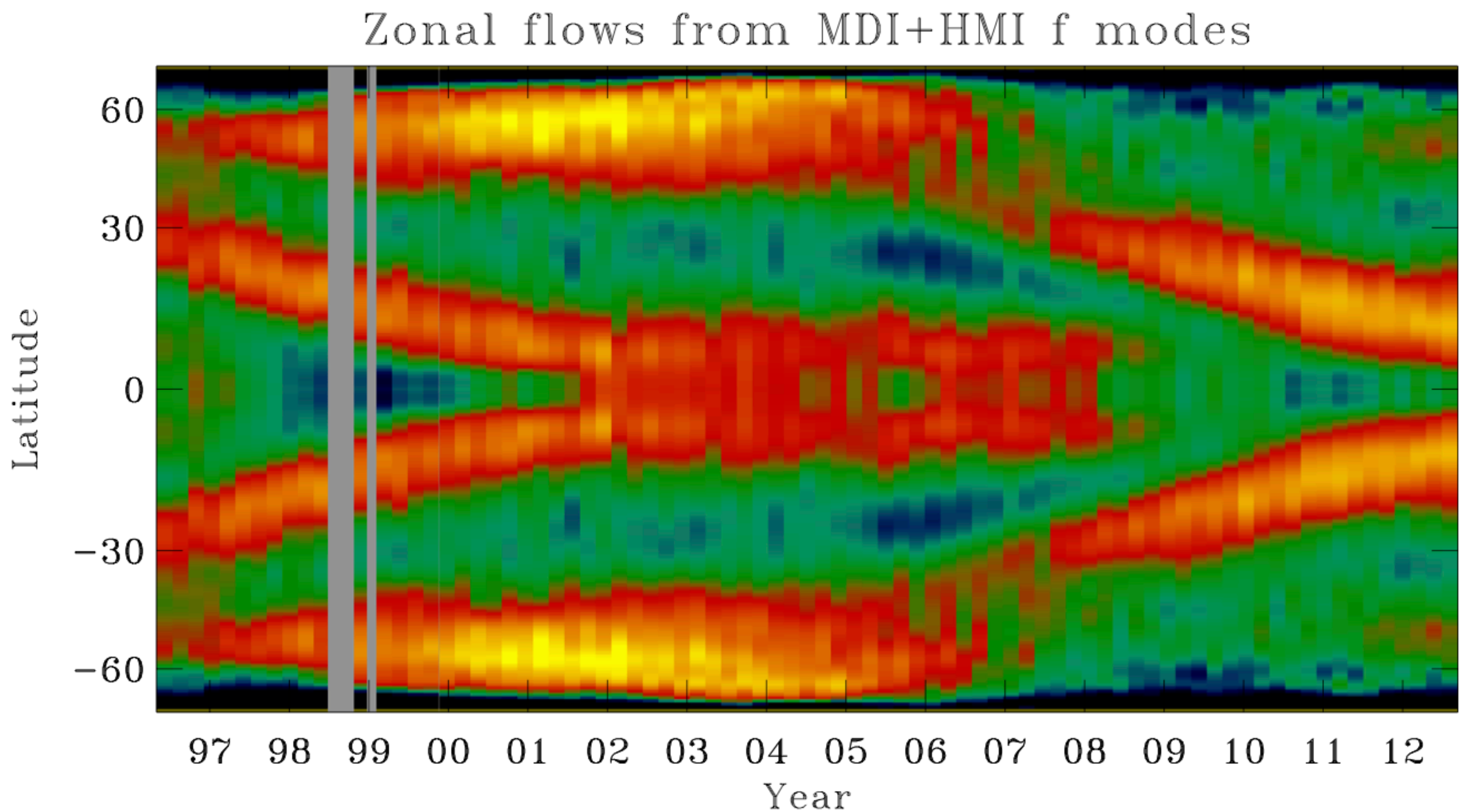
Plots courtesy of Sarbani Basu

Rotation as a function of Radius and Latitude

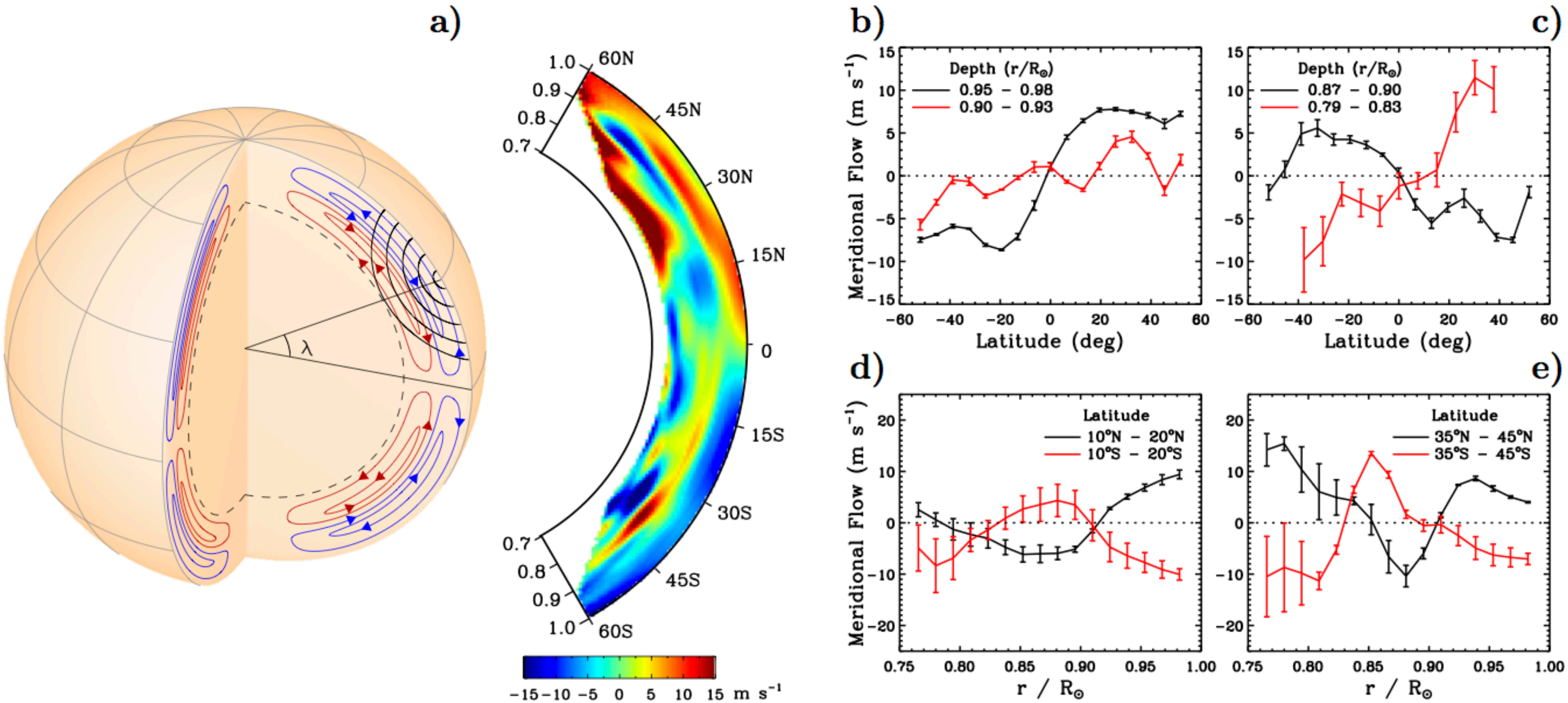




Changes in Solar Rotation Rate



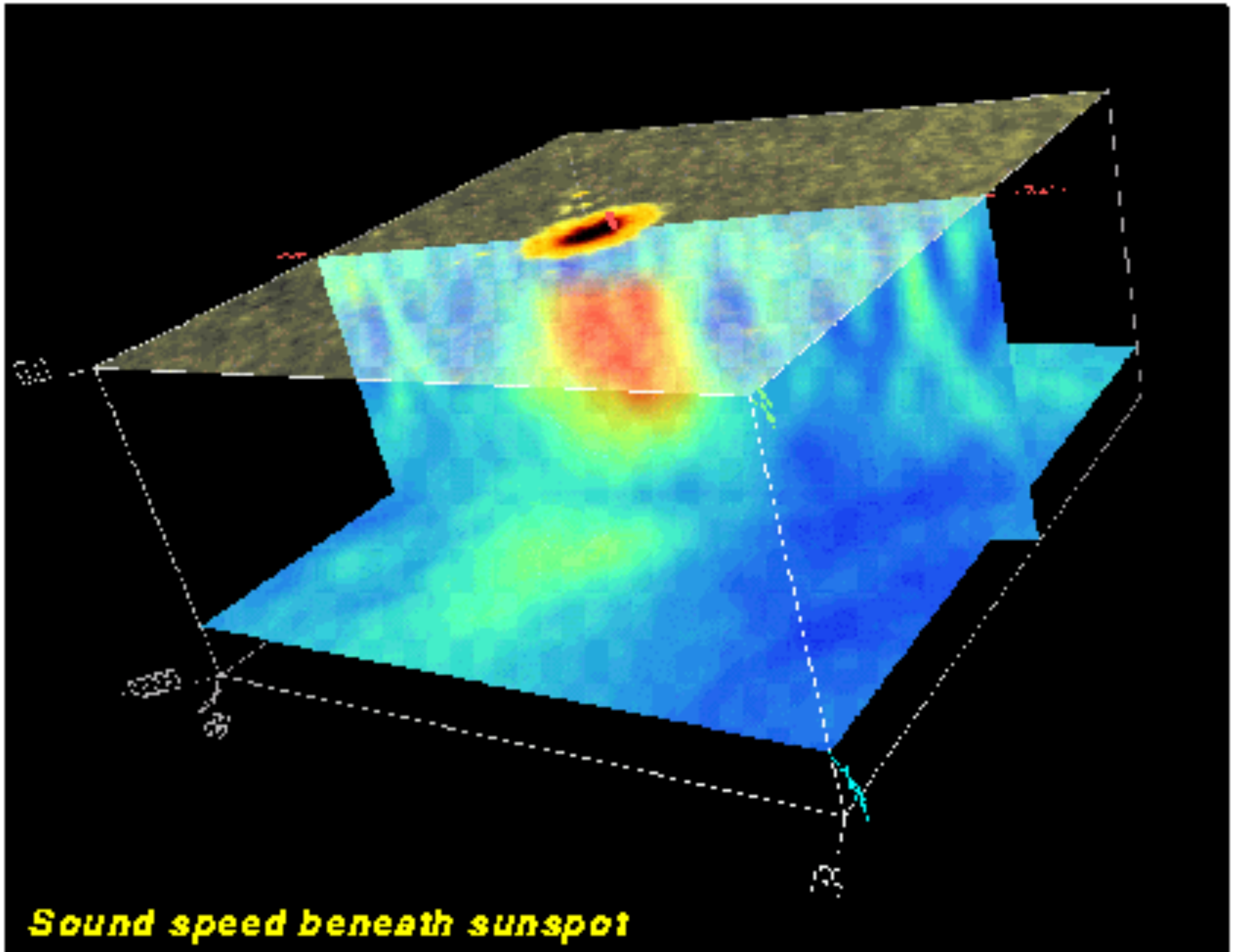
Meridional Circulation



From Zhao et al. (2013) - controversial

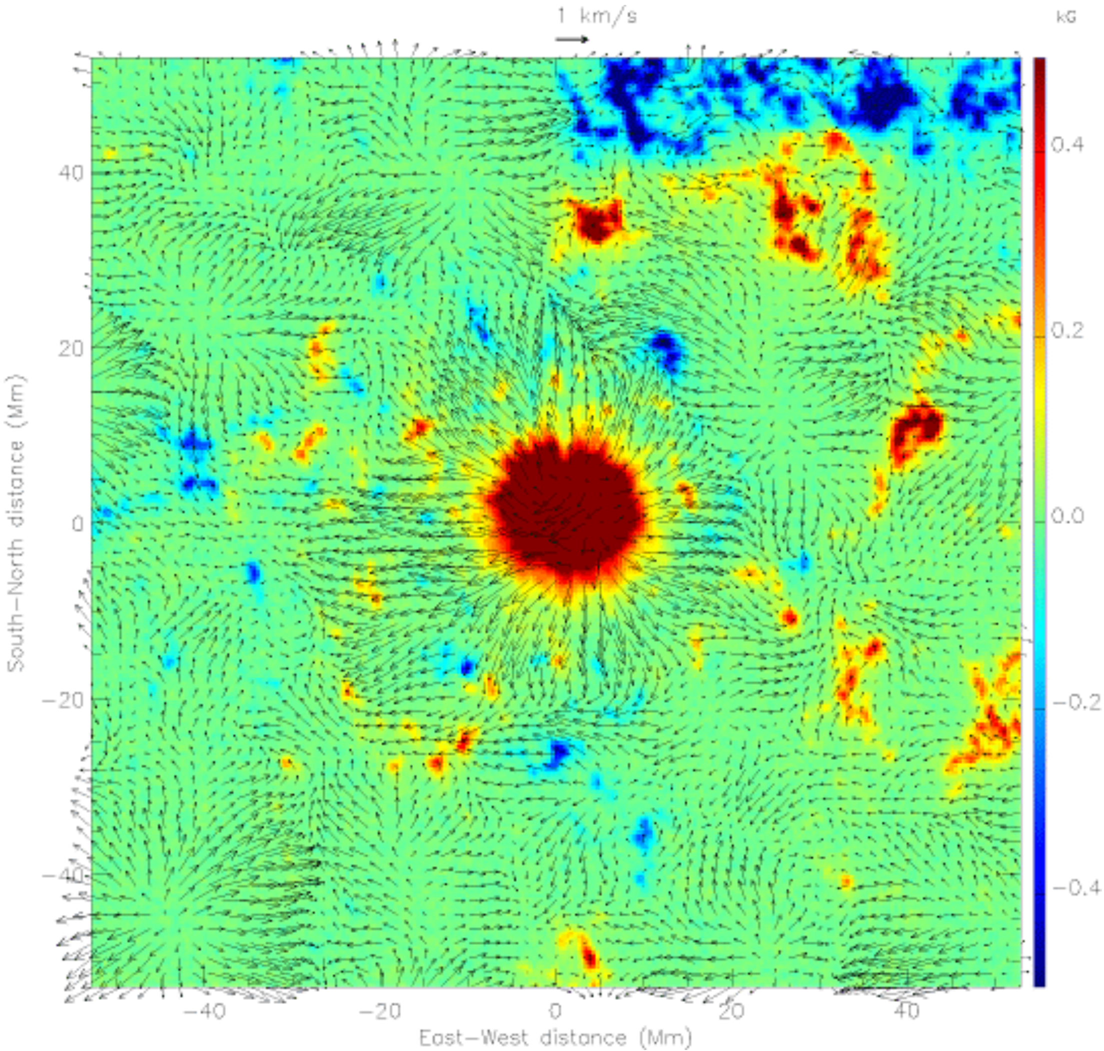
Time-Distance Results

Pretty but questionable!



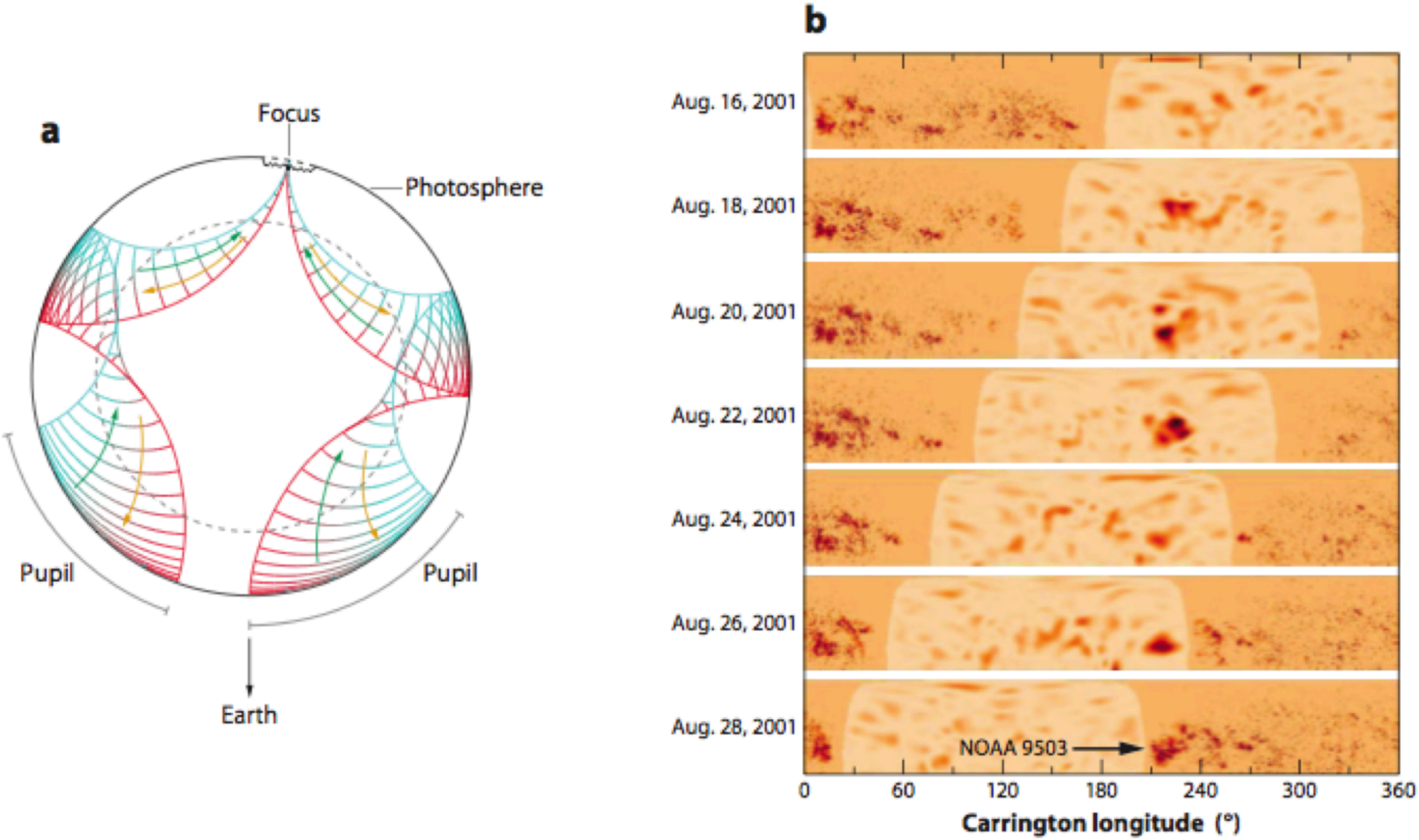
Sunspot data from MDI High Resolution, 18 June 1998

Flows Around Sunspot

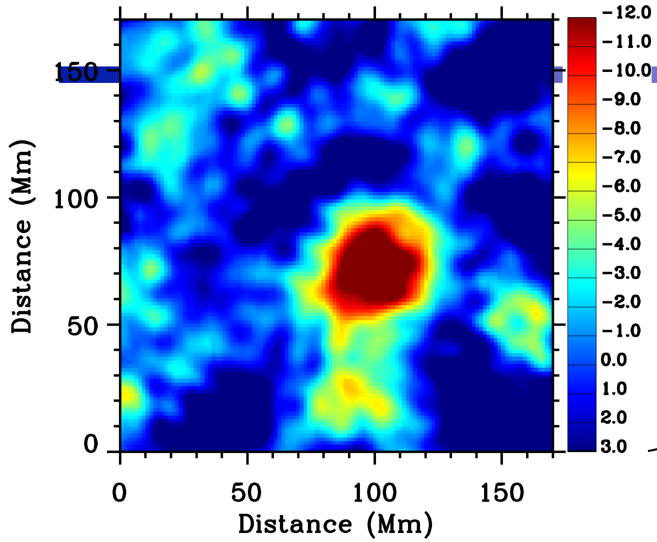


Gizon et al. (2000)

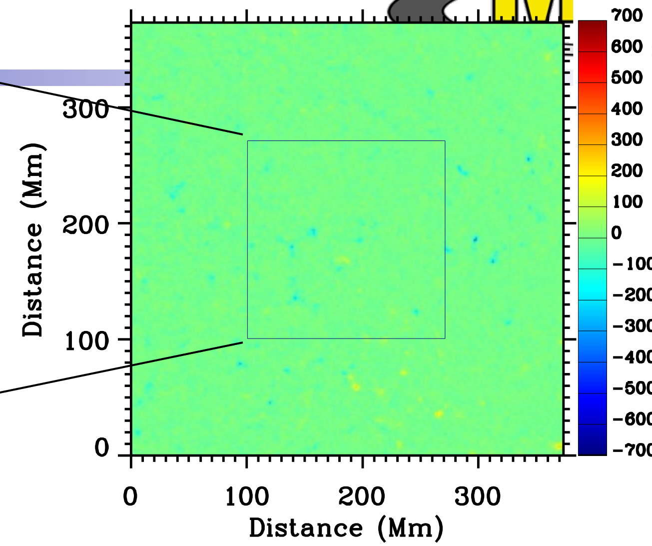
Farside Imaging



Results of AR 10488



03:30 UT 26 Oct 2003



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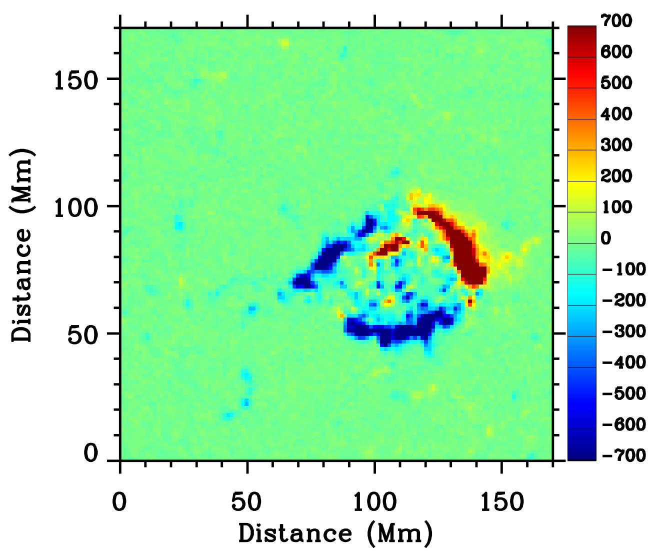

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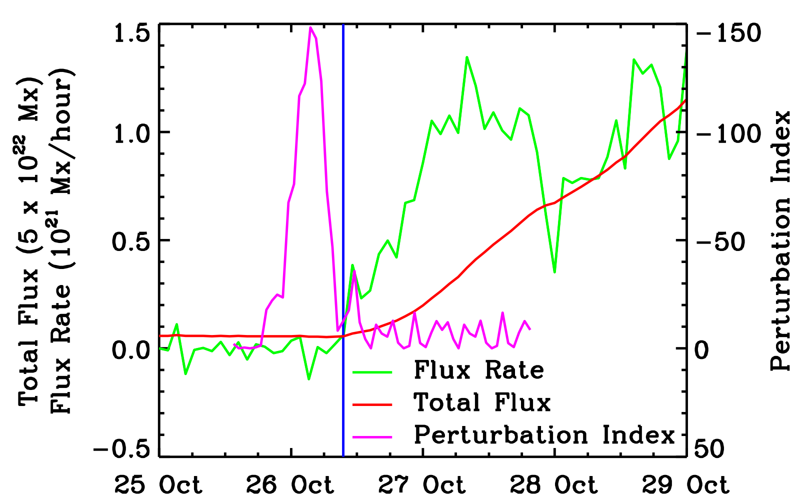
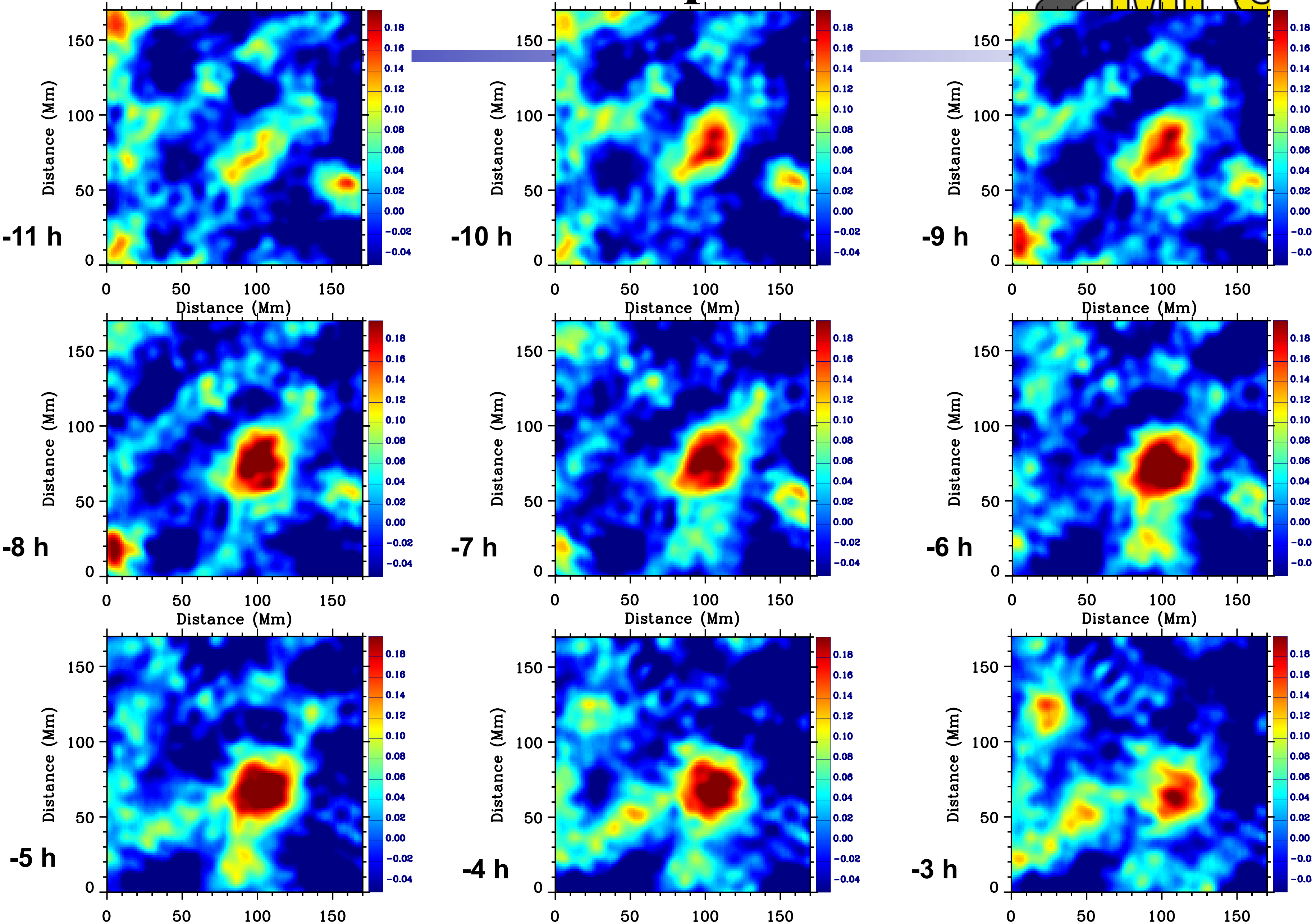


Courtesy Stathis Ilonidis –
Controversial!

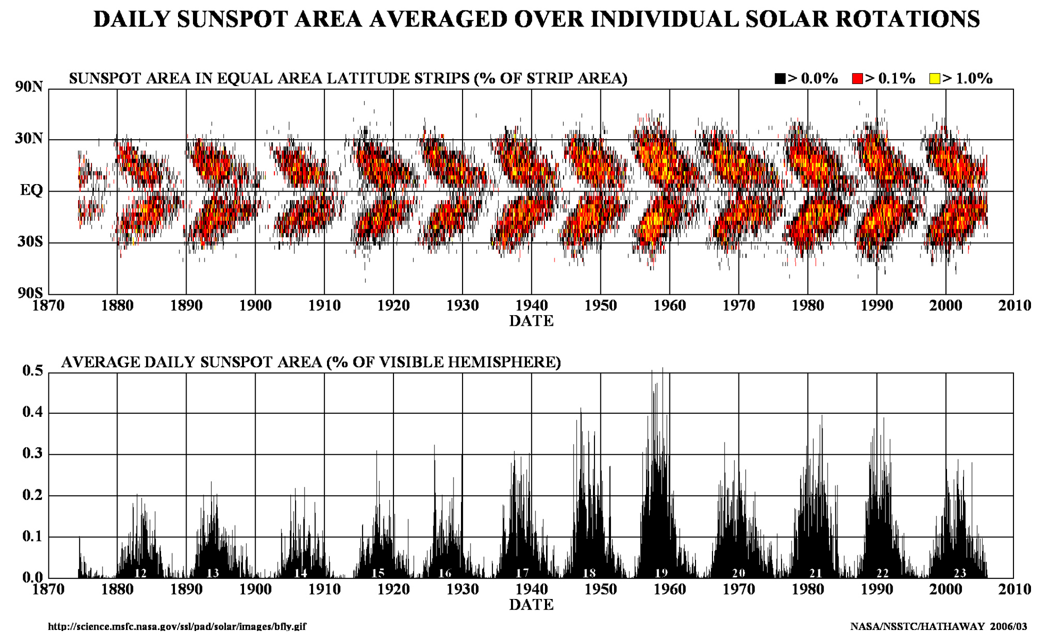
Travel-time maps of AR 10488



Courtesy Stahis Ilonidis

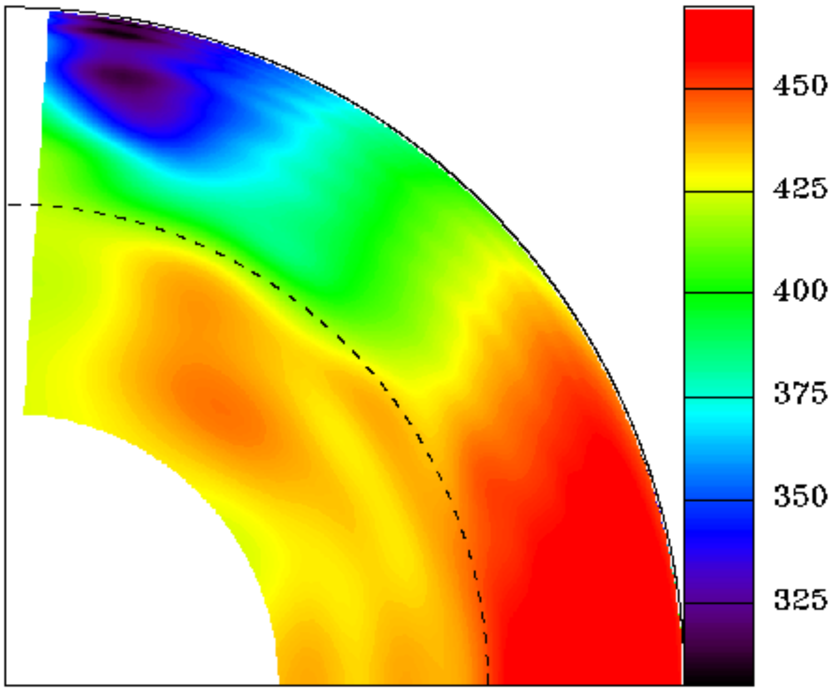
Some Outstanding Issues

- **Origin of solar cycle**
  - Likely some sort of dynamo
- **Prediction of cycle**
  - Satellite orbits etc.
- **Short term prediction**
  - Satellite upsets
  - Communications
  - GPS inaccuracies
- **Understand solar dynamo**
  - See talk by Miesch
  - Measure meridional flow from surface through tachocline
  - Measure longitudinal structure of tachocline
- **Sunspot structure**
  - Can we measure the field below the surface?
  - Can we see flux emergence below surface?



Some Remaining Science Objectives

- **Understand origin of rotation**
  - How fast is the core rotating?
  - How is angular momentum lost?
  - What happens near the solar poles?
  - Tachocline
  - Near surface shear
- **Nature of supergranulation**
  - Why don't we see giant cells?
- **Sound speed discrepancy**
  - New abundances



Solar internal rotation rate in nHz from MDI

Conclusion

- The basic physics of the solar interior is reasonably well understood
- Helioseismology has provided significant constraints
- Still many unresolved issues in the physics
- Need better theory
- Need better simulations
- Need better observations
- Need better data analysis