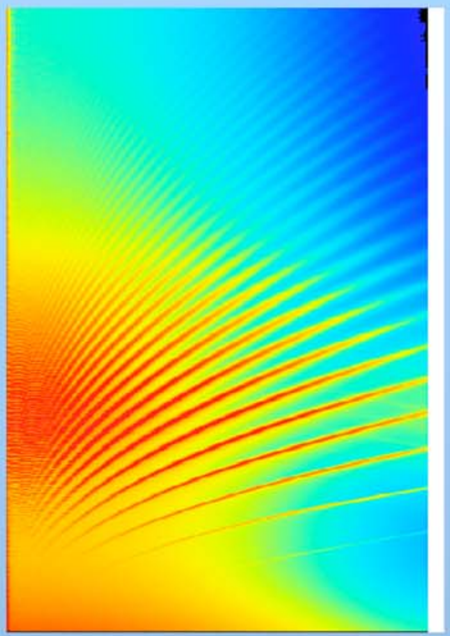
What we have learned from *global* helioseismology

that may be relevant to the solar dynamo

Michael Thompson, University of Sheffield
With thanks to Rachel Howe (NSO)

KITP, 15th July 2008

Global-mode seismology



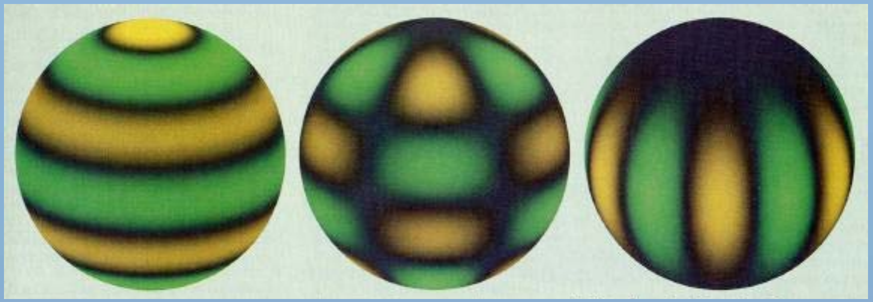
Measure mode properties ω; A, Γ; line-shapes
Eigenfunctions / spherical harmonics

Frequencies $\omega_{nlm}(t)$ depend on conditions in solar interior determining wave propagation

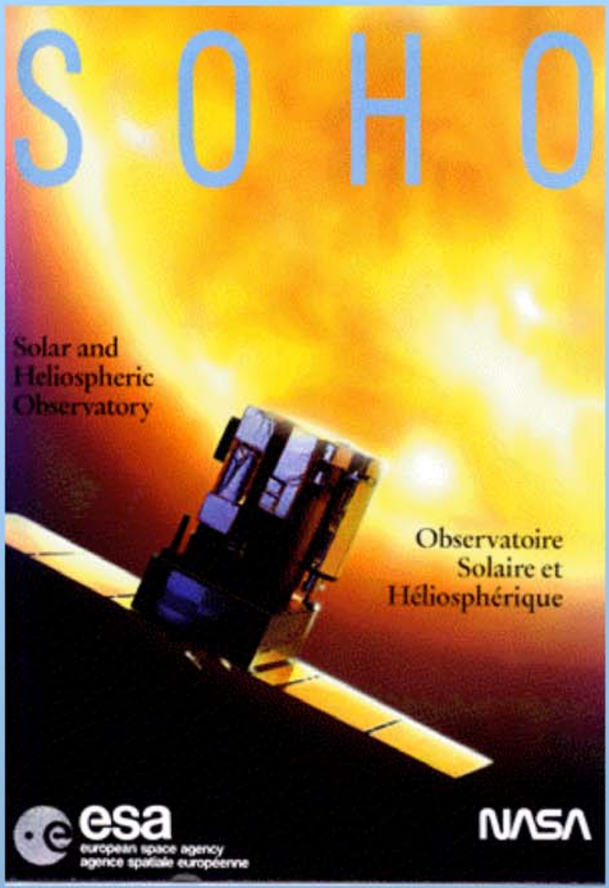
ω_{nlm} – degeneracy lifted by rotation and by structural asphericities and magnetic fields

Inversion provides maps such as of c and ρ and rotation and wave-speed asphericities

North-south averages
Snapshots at successive times: typically 2-month averages

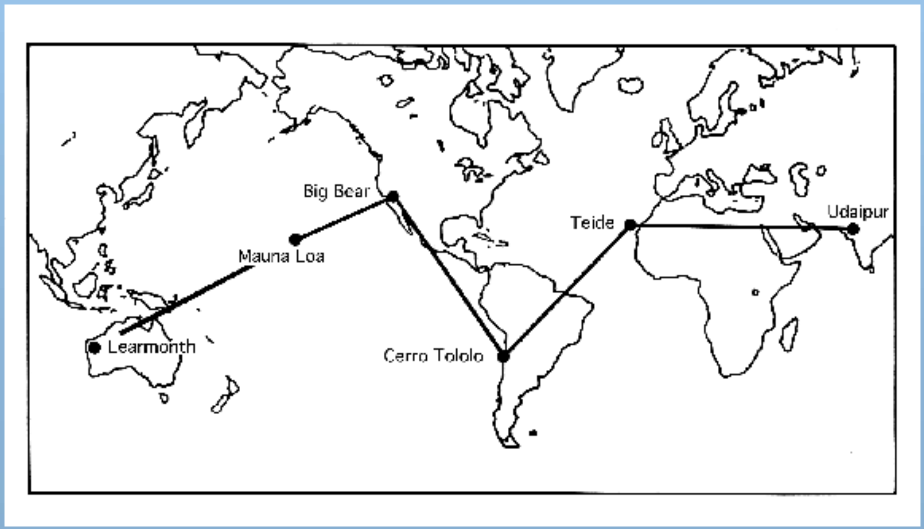


Spherical harmonics



Helioseismology from space

MDI, GOLF, VIRGO on SoHO
In 2009: HMI on Solar Dynamics Observatory (SDO)



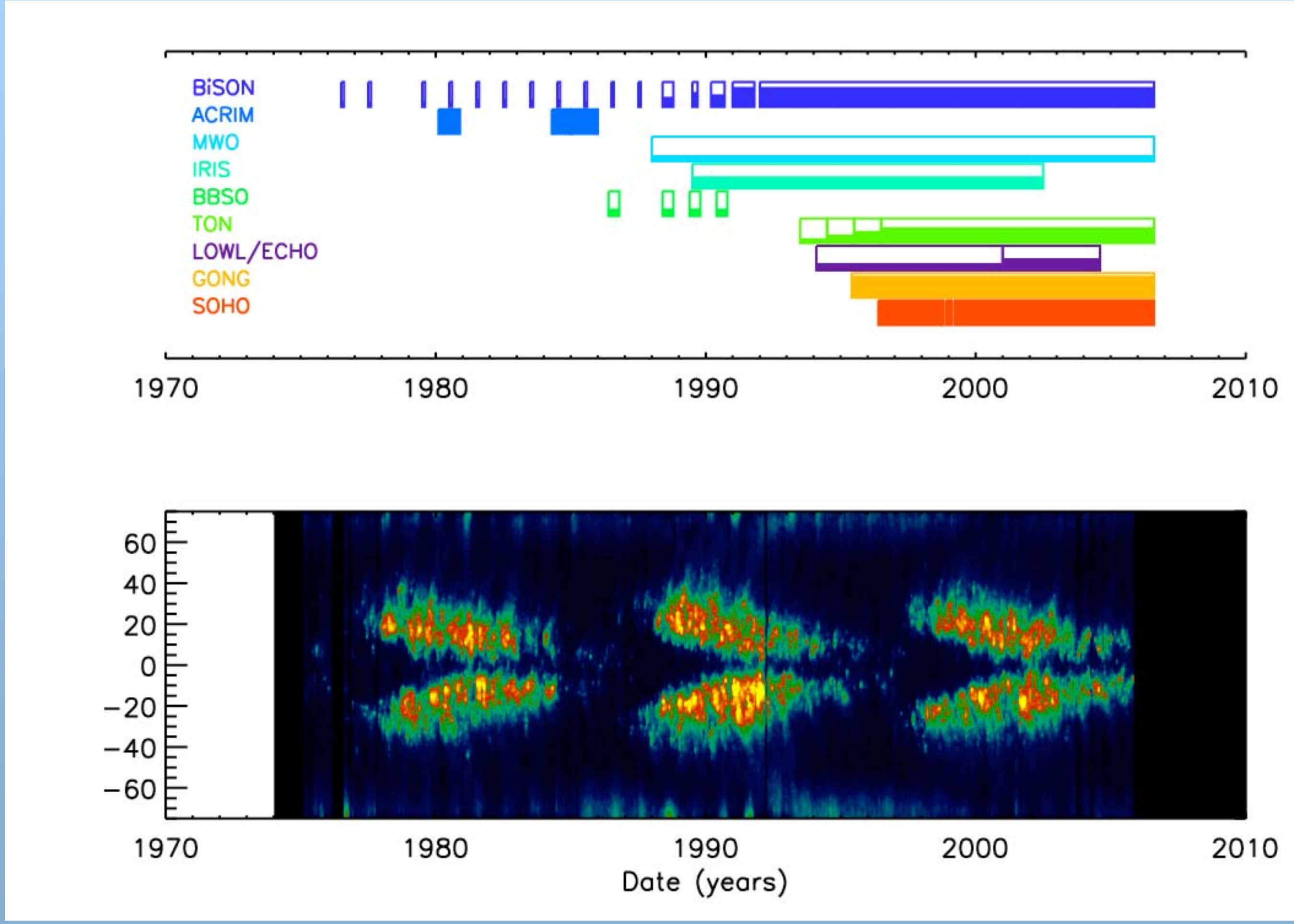
Helioseismology from ground-based networks
BiSON, GONG

GONG network sites

Introduction: History

- ACRIM observations 1980, 1984-5
- Birmingham/Tenerife: sun-as-a-star observations going back to 1975 (BiSON)
- IRIS: sun-as-a-star 1989-2003
- Big Bear Solar Observatory (Libbrecht and co-workers): resolved-sun observations 1986-1990.
- Mount Wilson: high-degree observations since 1988.
- LOWL/ECHO medium degree, 1994-present
- GONG (1995-present), MDI (1996-present); continuous resolved-sun observations.

History (schematic)

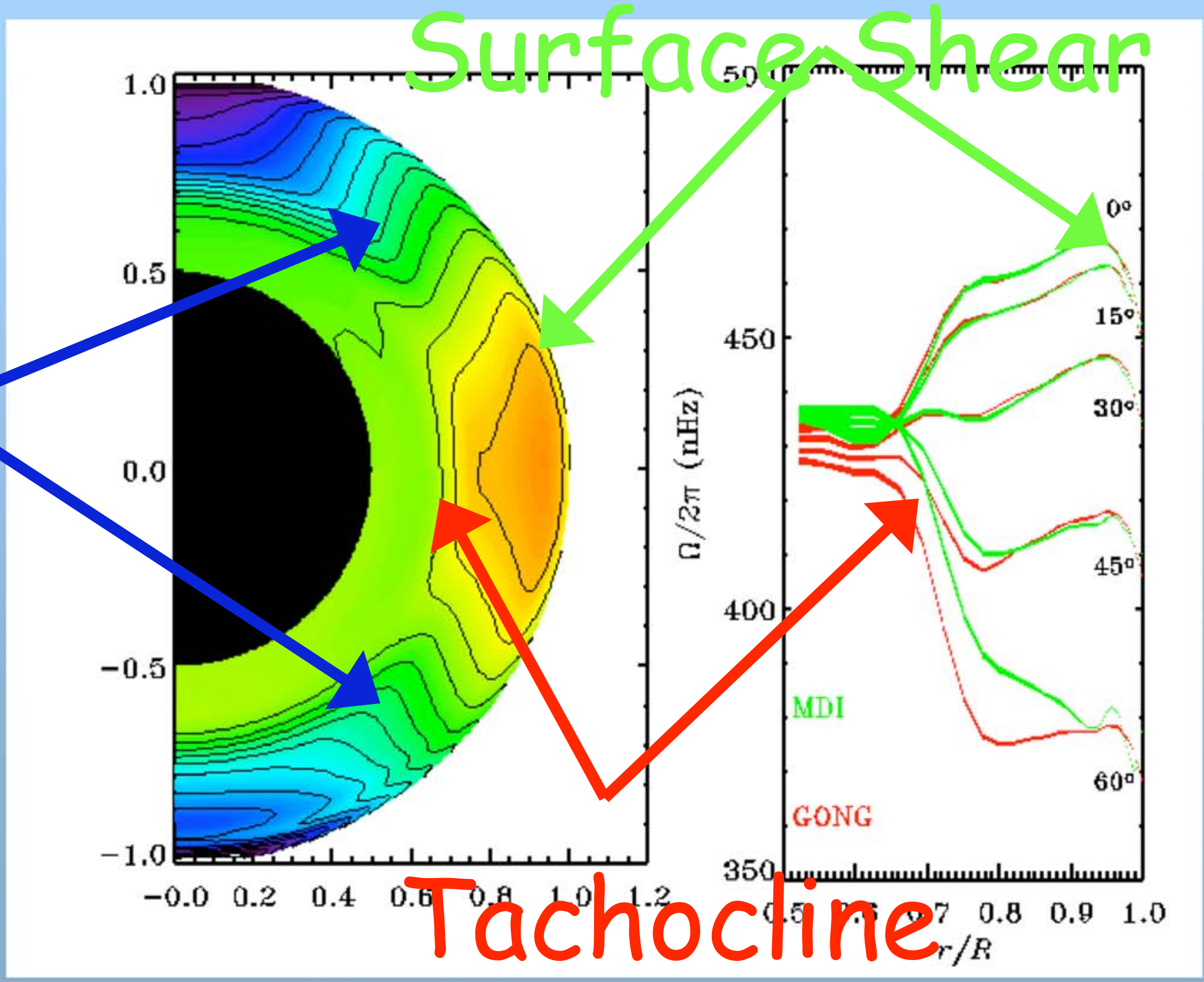


Rotation Inversion Results

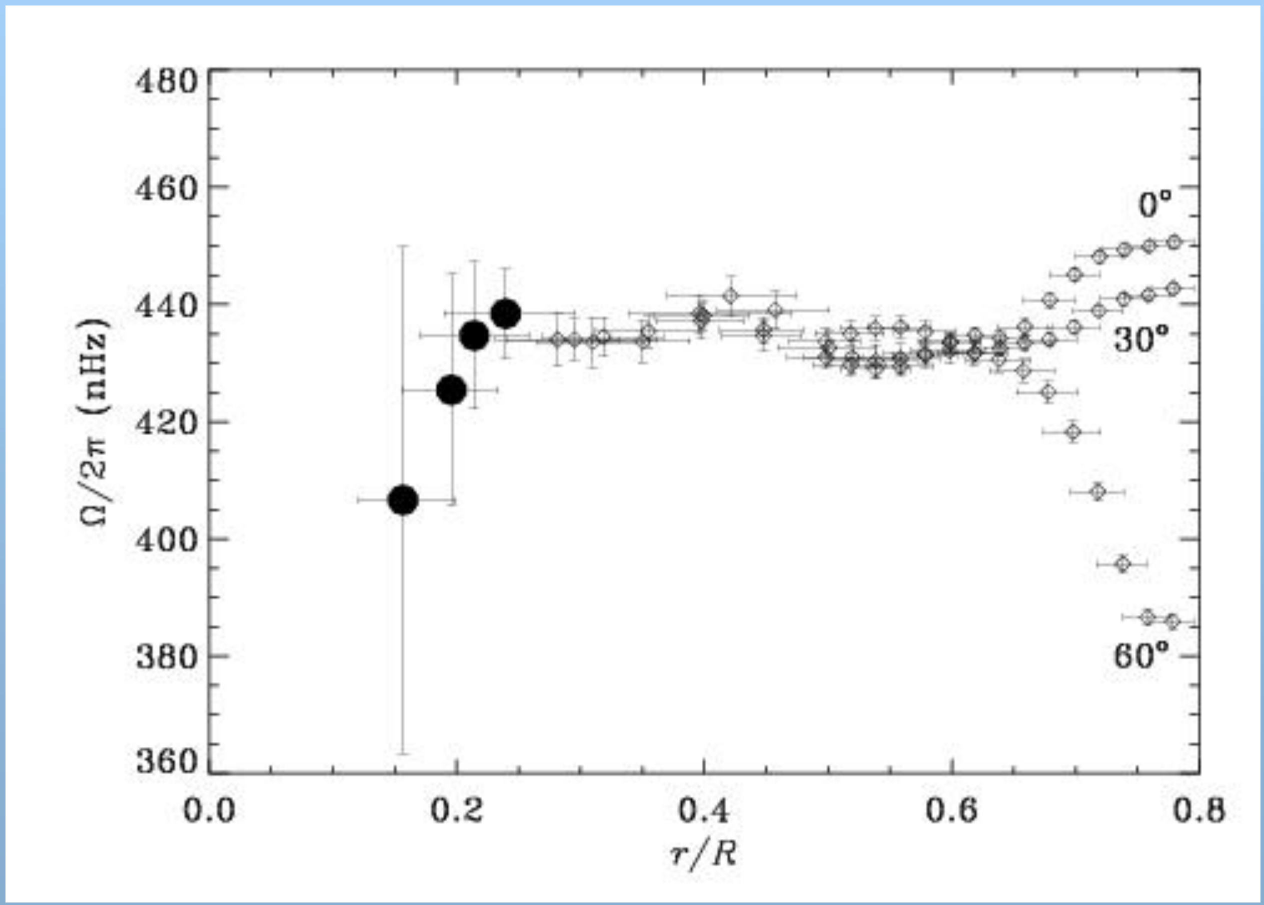
- The continuous medium-degree observations covering an 11-year solar cycle (GONG, MDI) have revealed the deep-penetrating structure of the migrating zonal flow pattern known as the torsional oscillation,
- as well as giving hints of possible other periodicities in the rotation rate close to the tachocline.
- Temporal changes in the structure of the solar interior are more challenging to measure, as the obvious solar-cycle effects are dominated by the surface.

Rotation Inversion Results

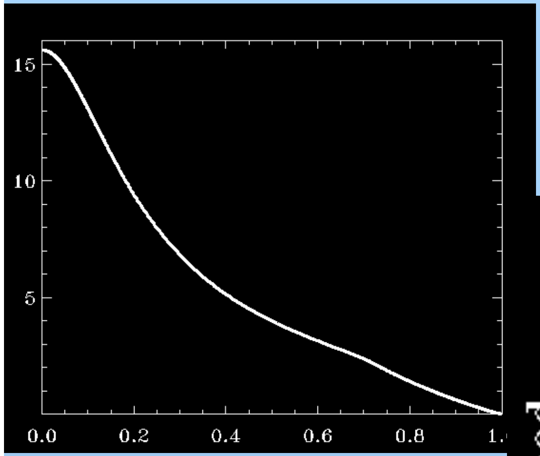
Contours at approx. 25^{o} to axis



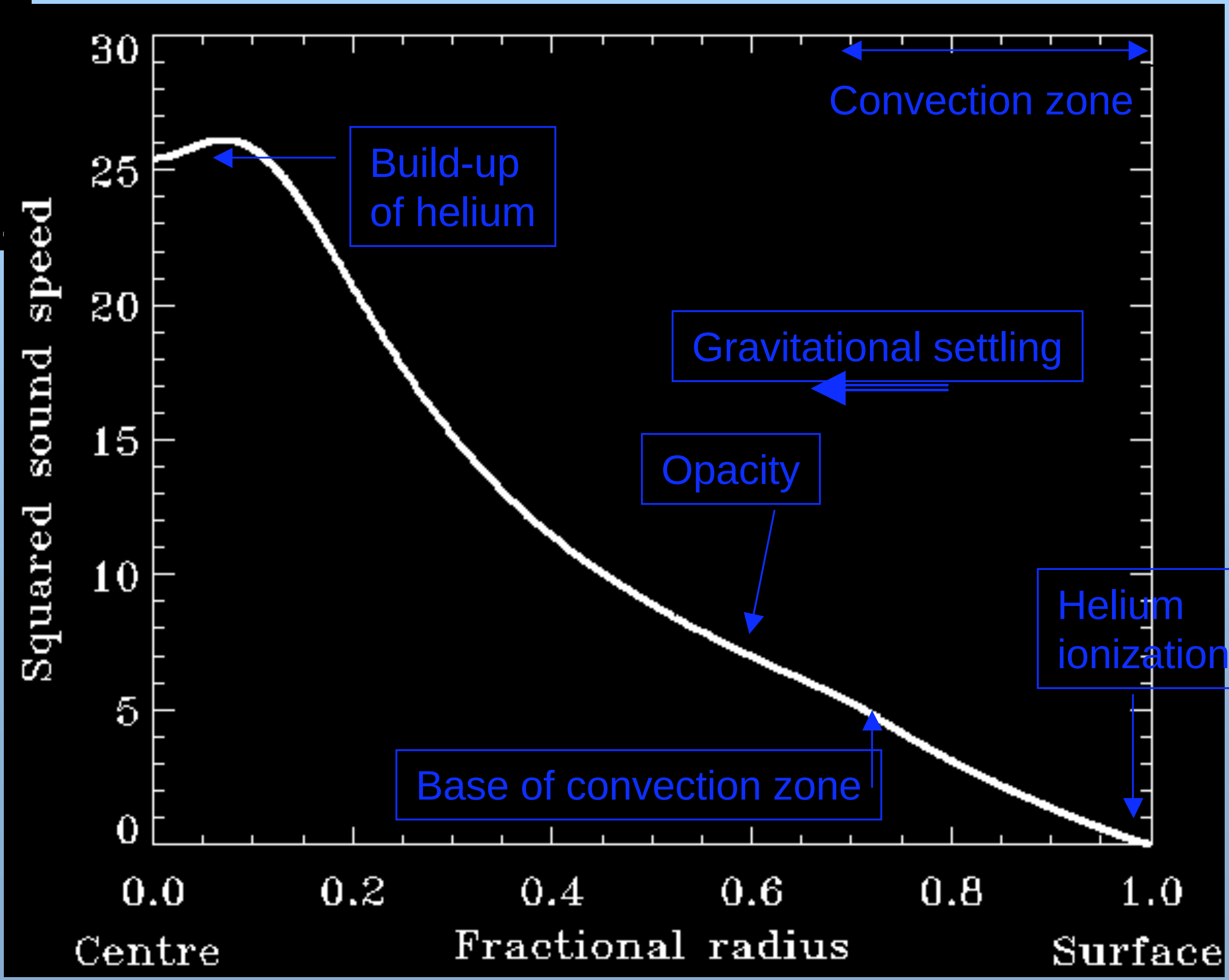
Rotation of the deeper solar interior from BiSON and LOWL data



Sound-speed inferences



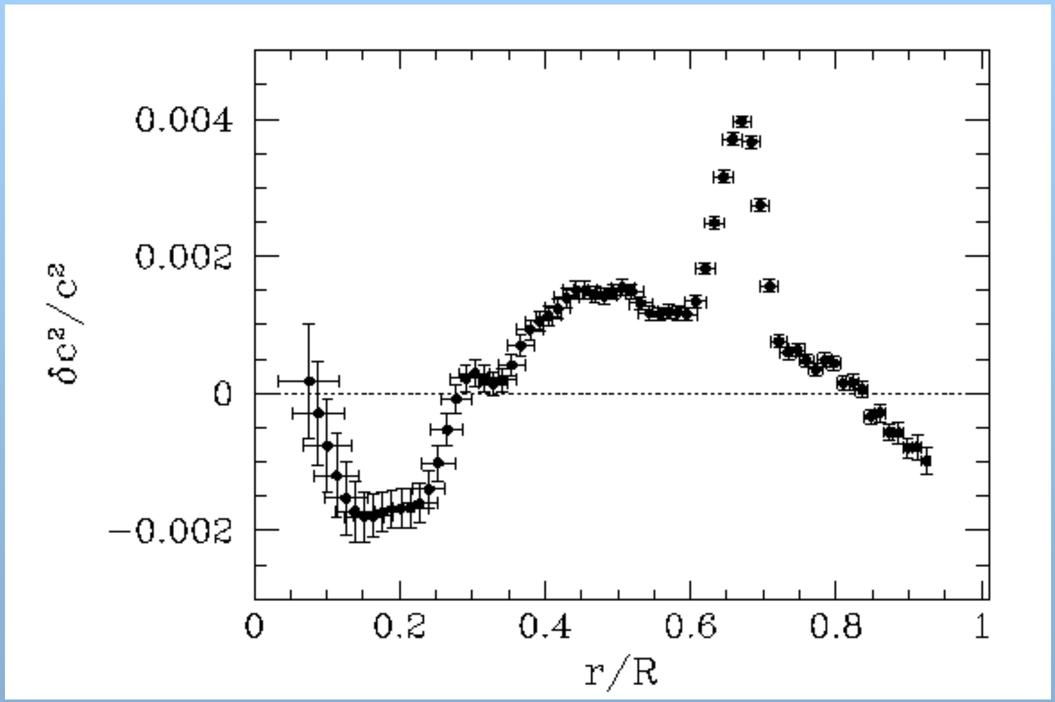
$$c^2 \propto \Gamma_1 T / \mu$$



(Sound speed is in units of hundreds of km/s)

Discrepancy between Sun and our models

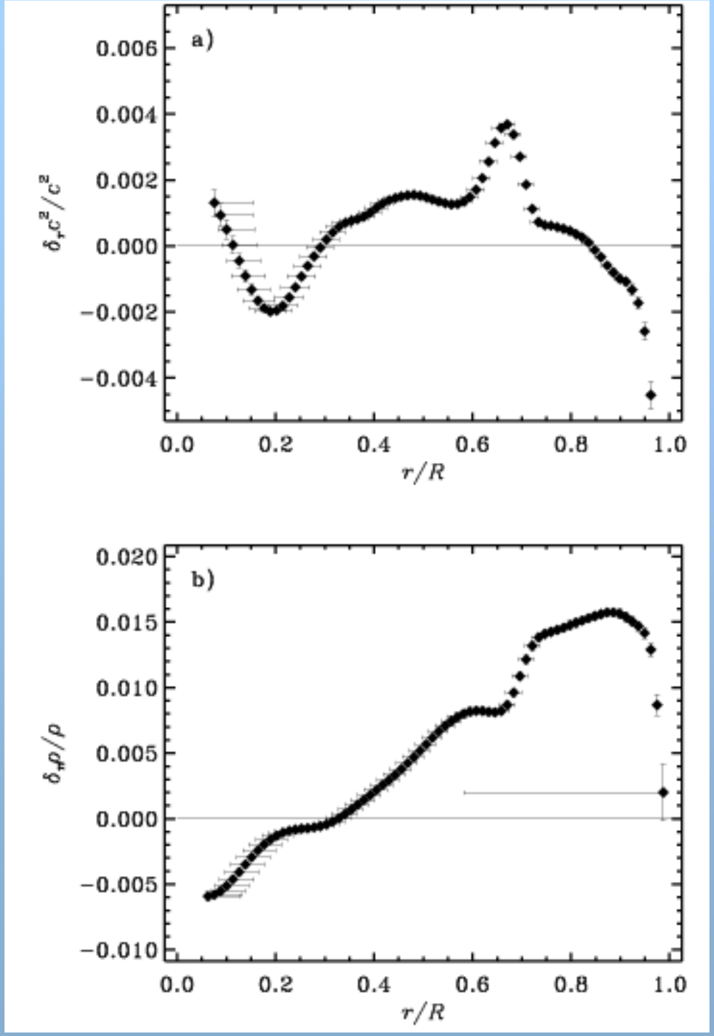
Fractional difference in squared sound speed (sun minus model)



Centre

Surface

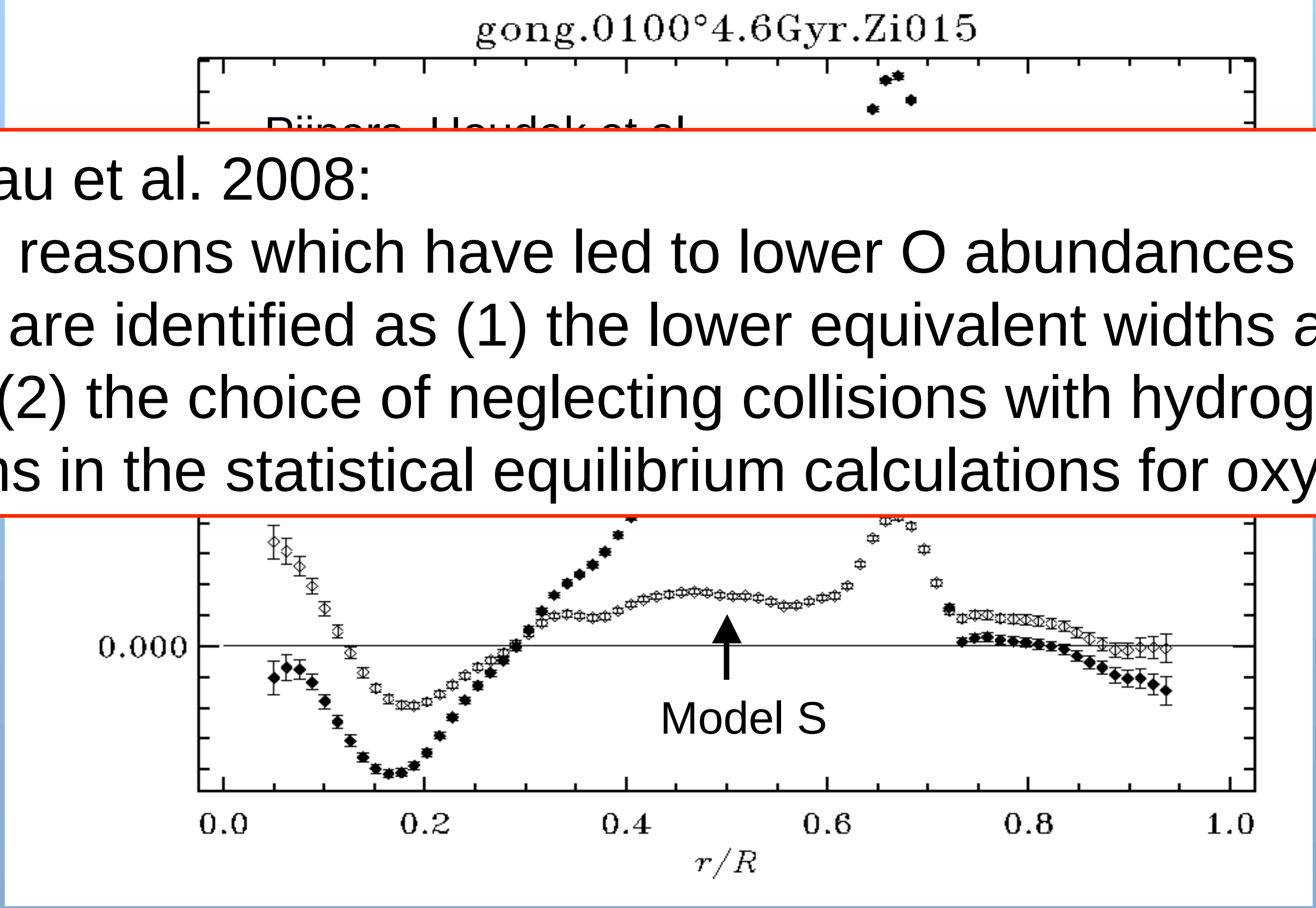
Structure Inversions



Courtesy Sarbani Basu et al.

Corrections to a reference model

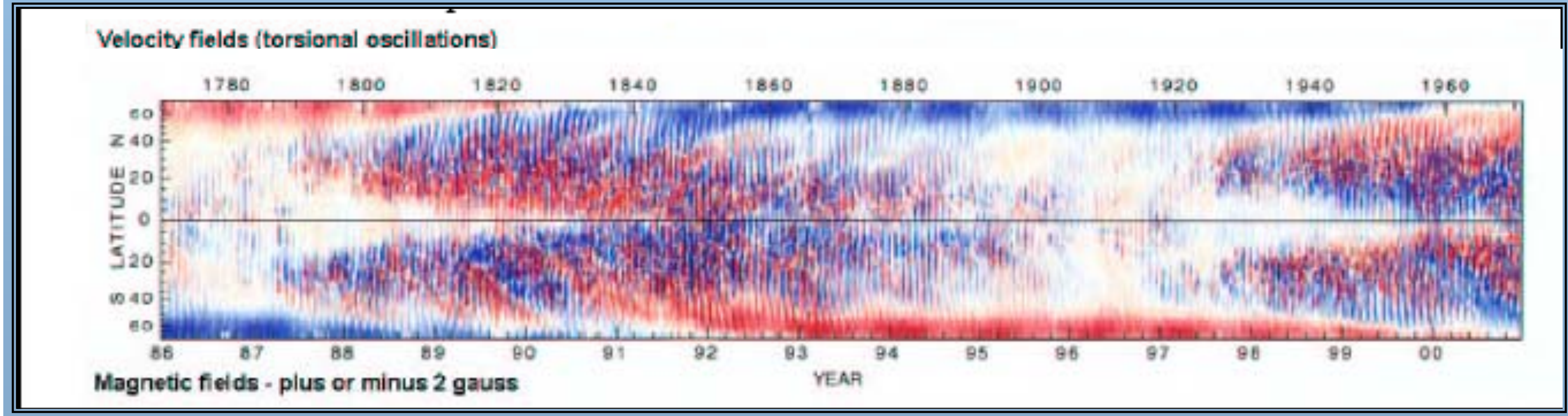
Revision of solar surface abundances



Caffau et al. 2008:
“The reasons which have led to lower O abundances in the past are identified as (1) the lower equivalent widths adopted, and (2) the choice of neglecting collisions with hydrogen atoms in the statistical equilibrium calculations for oxygen.”

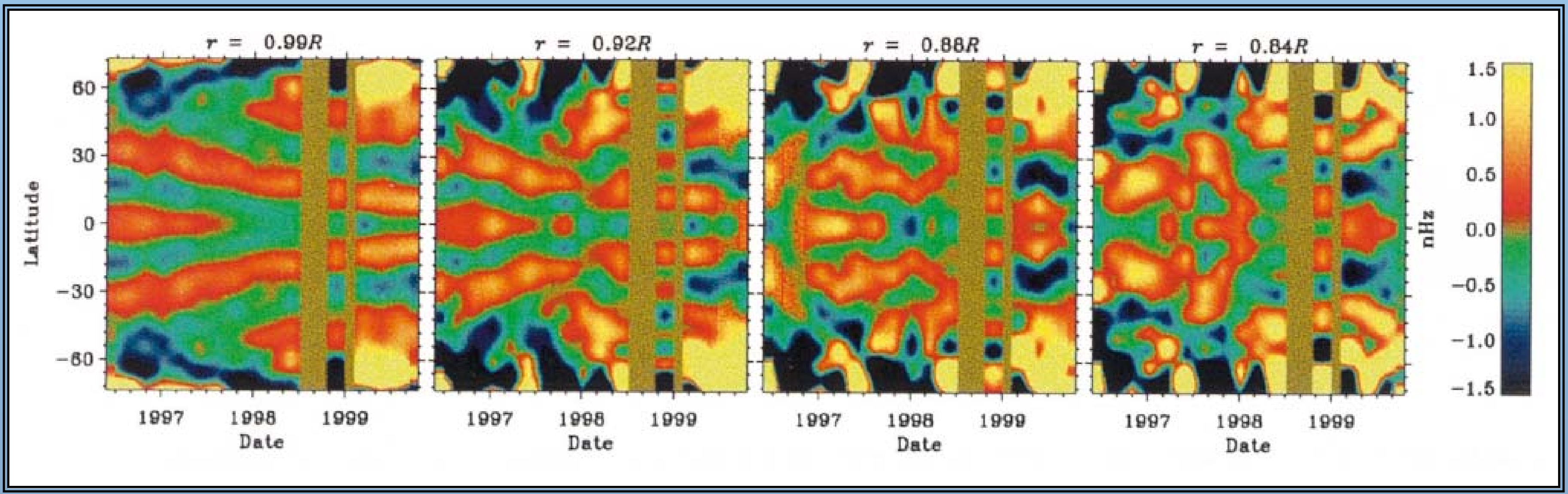
Convection-Zone Dynamics

- So-called ‘torsional oscillation’ is a pattern of weak slower and faster zonal flows migrating from mid-latitudes to the equator and poles over the solar cycle.
- First observed by Howard and Labonte (1980) in surface observations
- Surface Doppler measurements from Mt Wilson go back to 1986. (Ulrich 2001).



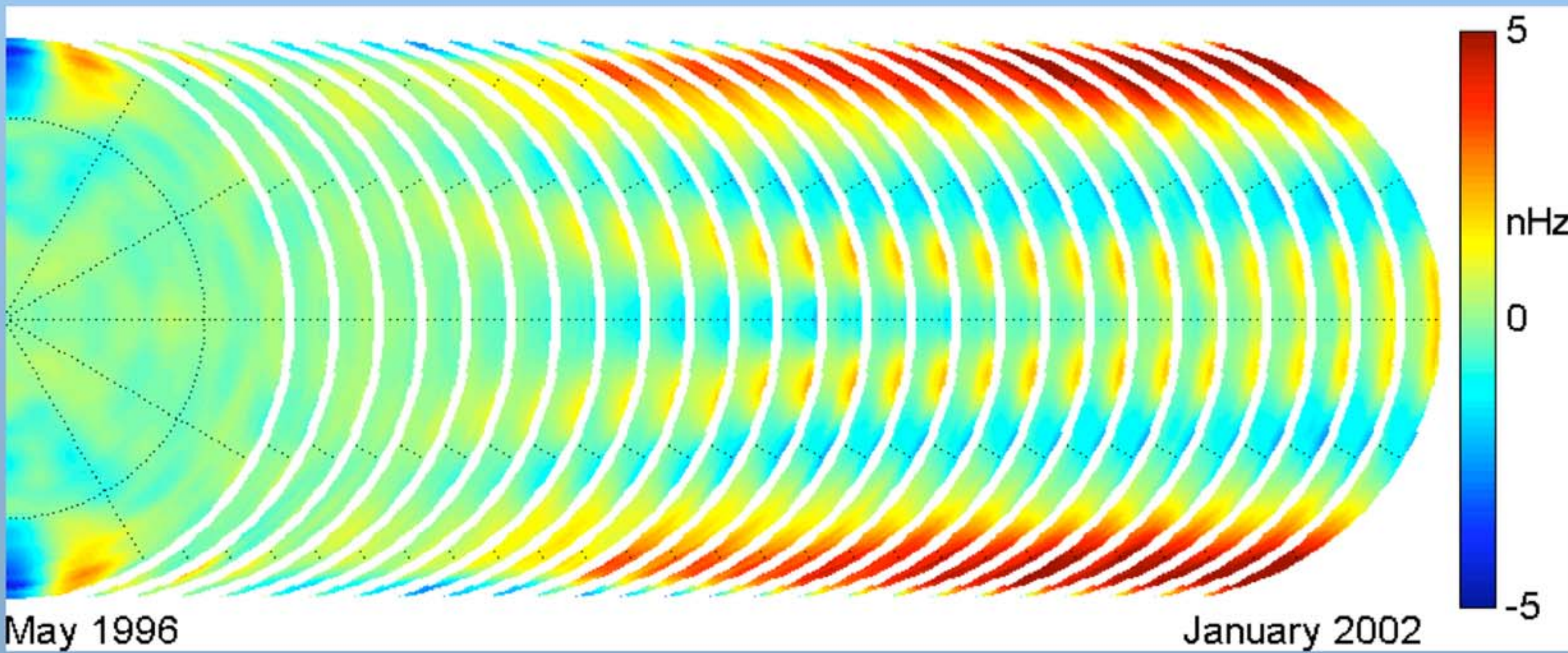
Helioseismic Detection of the Torsional Oscillation

- Woodard & Libbrecht (1993), Kosovichev & Schou (1997)
- Penetration depth at least 0.92*R* (Howe et al. 2000).

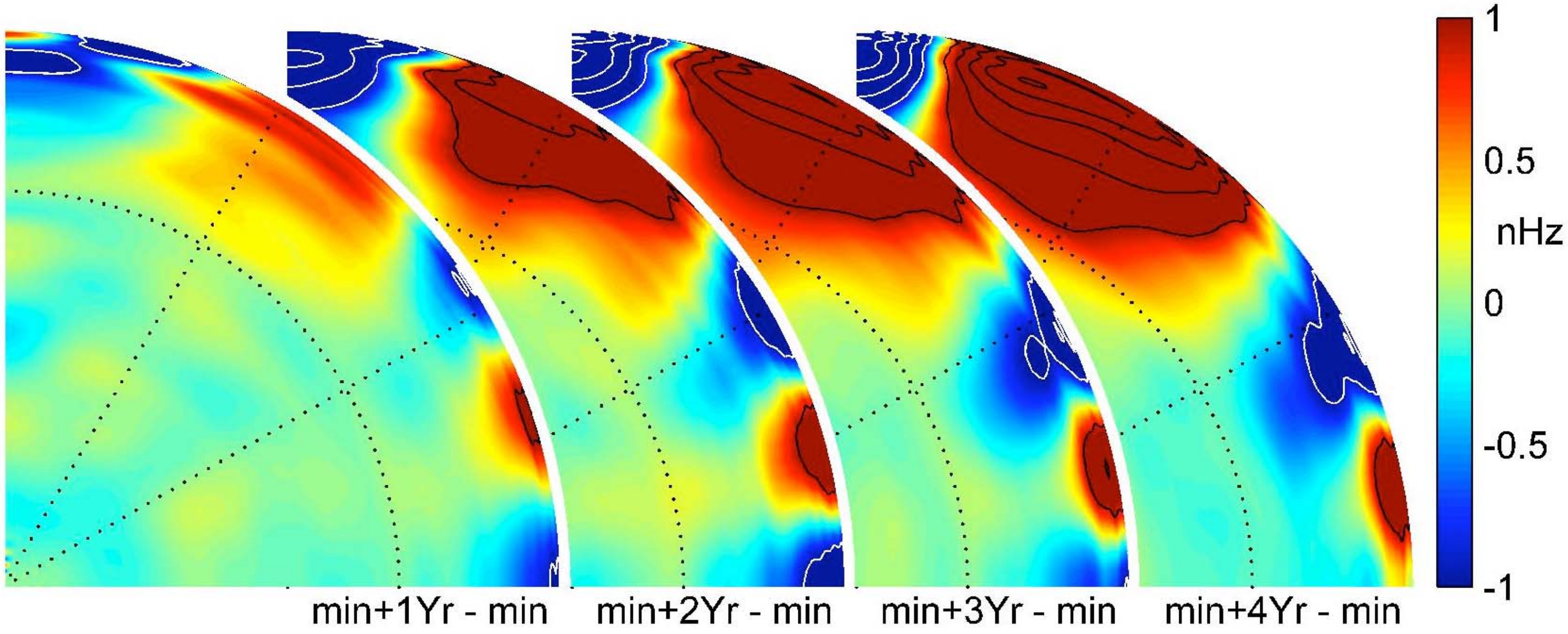


Torsional oscillations of whole convection zone

Differencing rotation inversions relative to solar minimum (1996) at successive 72-day epochs reveals the torsional oscillations at low and high latitudes through much of the convection zone.

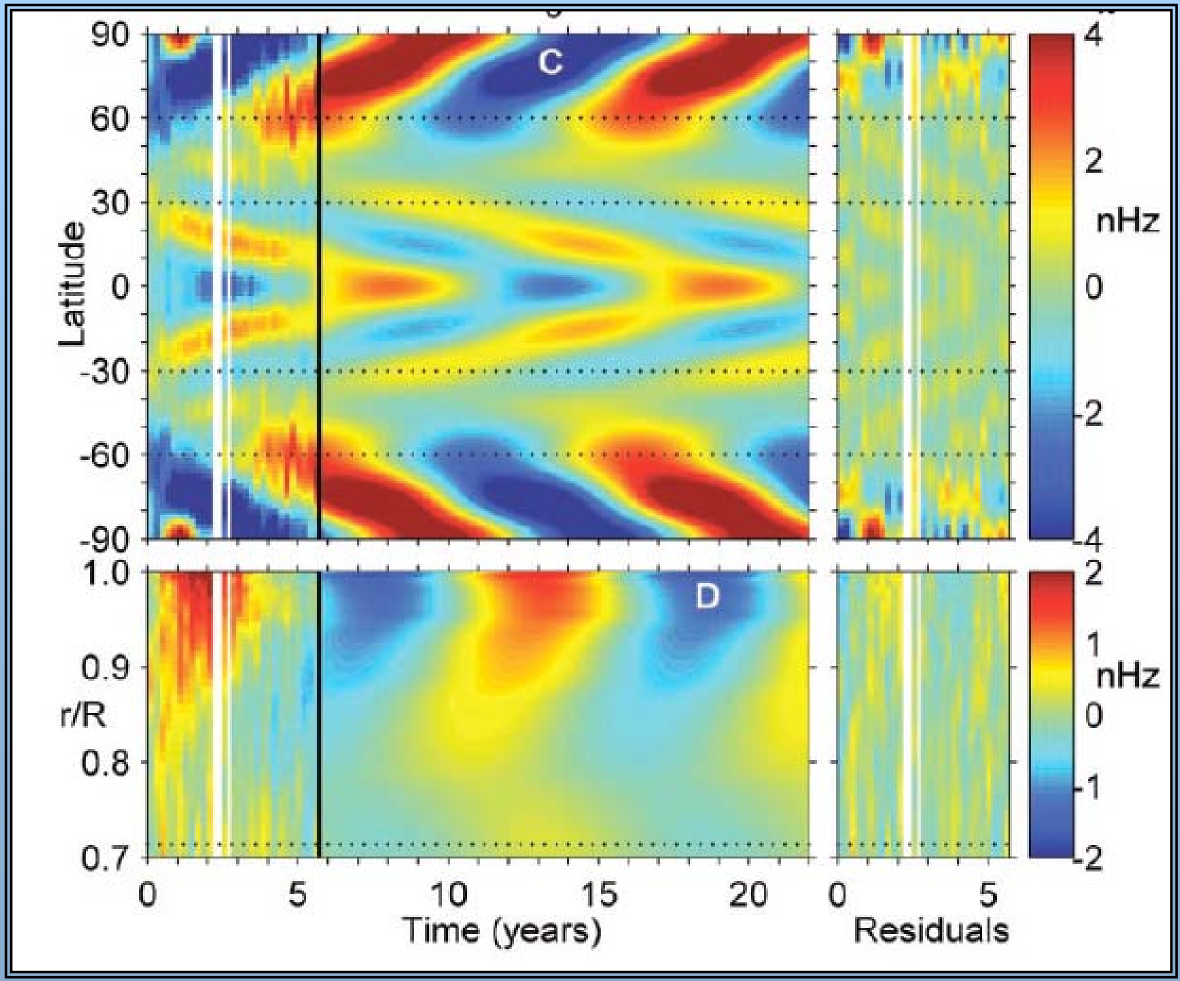


It is also revealing to stack fewer results, so the evolution of the whole convection zone can be seen. Here we difference rotation inversions relative to solar minimum at successive 1-year epochs.

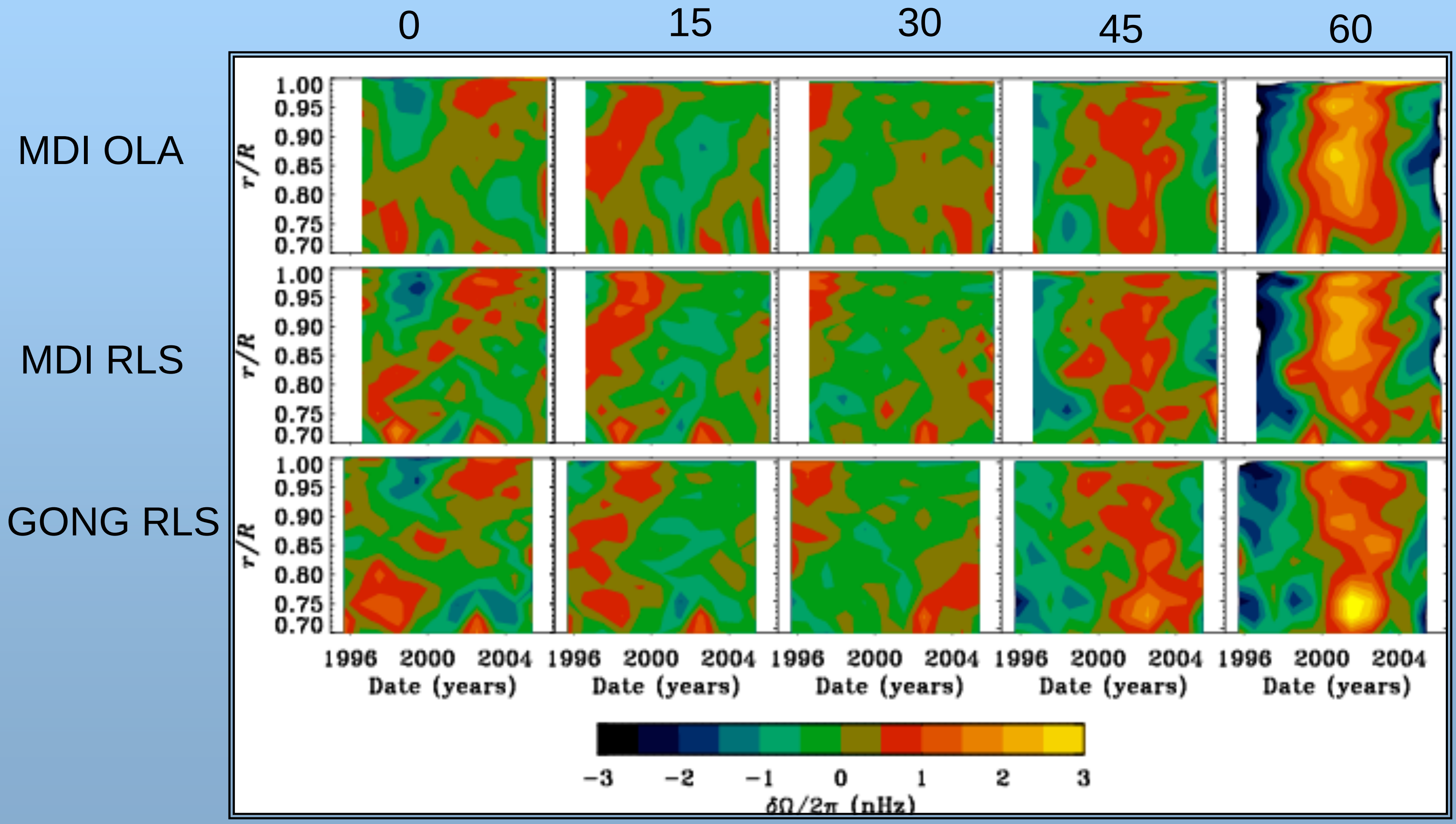


Torsional Oscillation

- Vorontsov et al 2002
- Extrapolation using 11-yr sinusoid



Zonal Flow Patterns (Time-Radius)



Howe et al 2005

Variability in and near tachocline

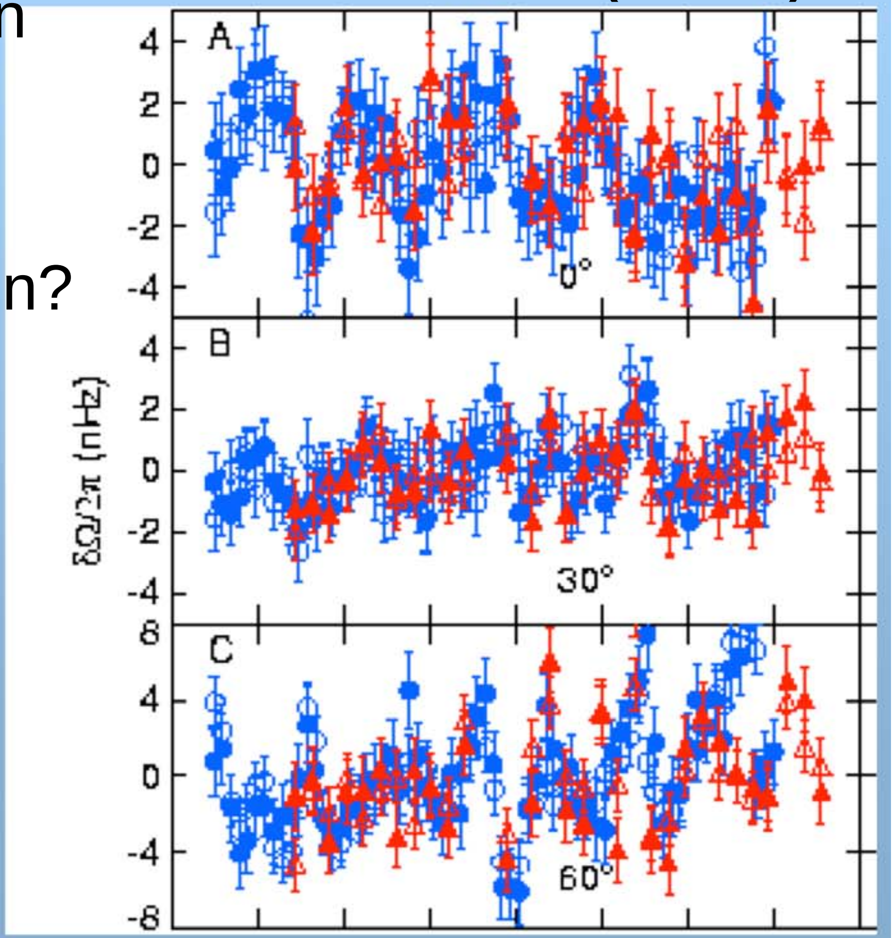
1.3-yr variations in inferred rotation rate at low latitudes above and beneath tachocline

Signature of dynamo field evolution? Radiative interior also involved in solar cycle?

Link between tachocline and 1.3/1.4-yr variations in

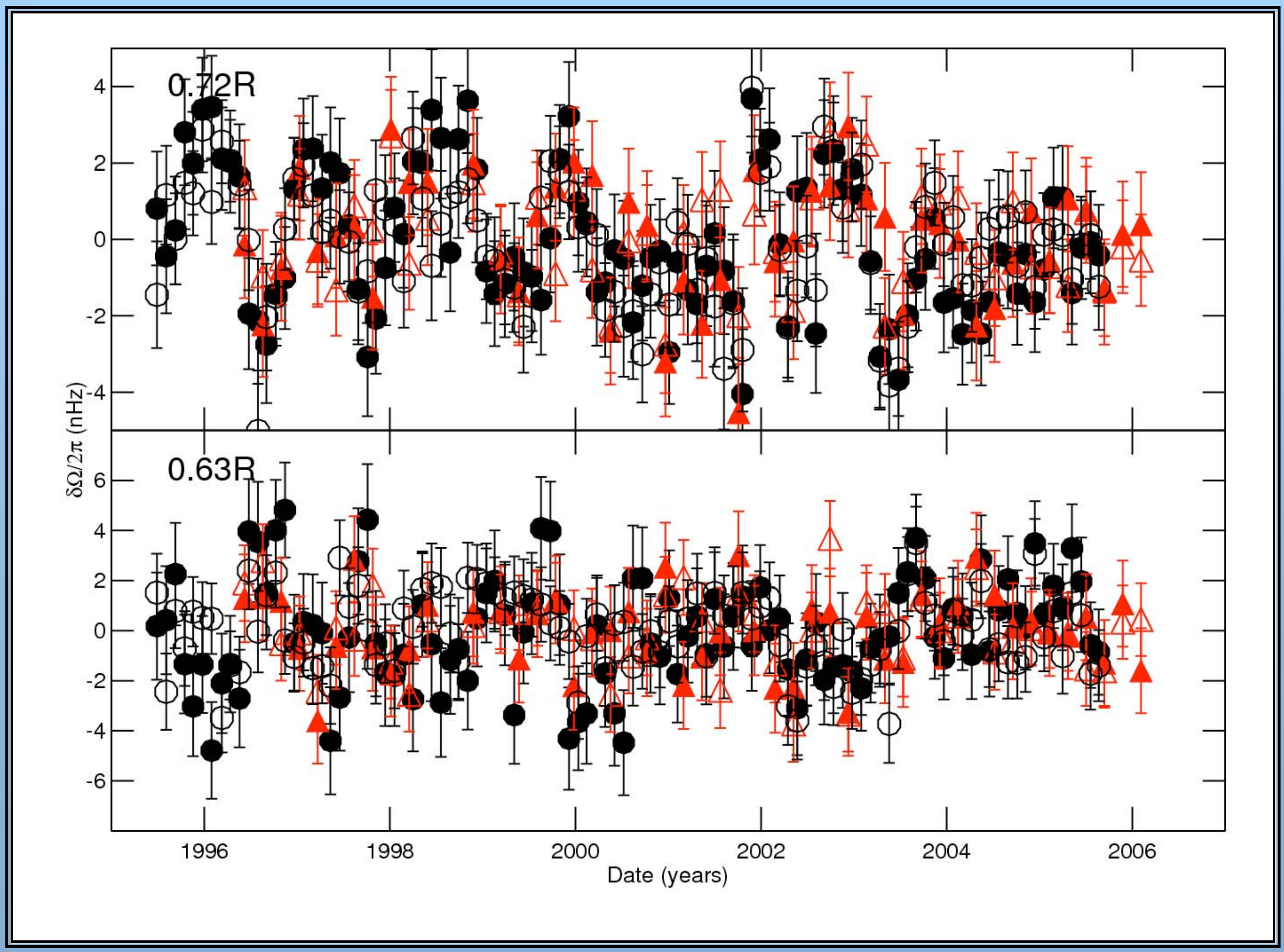
- solar wind,
- aurorae,
- solar mean magnetic field ?

Variations in Ω (r , θ ; t)

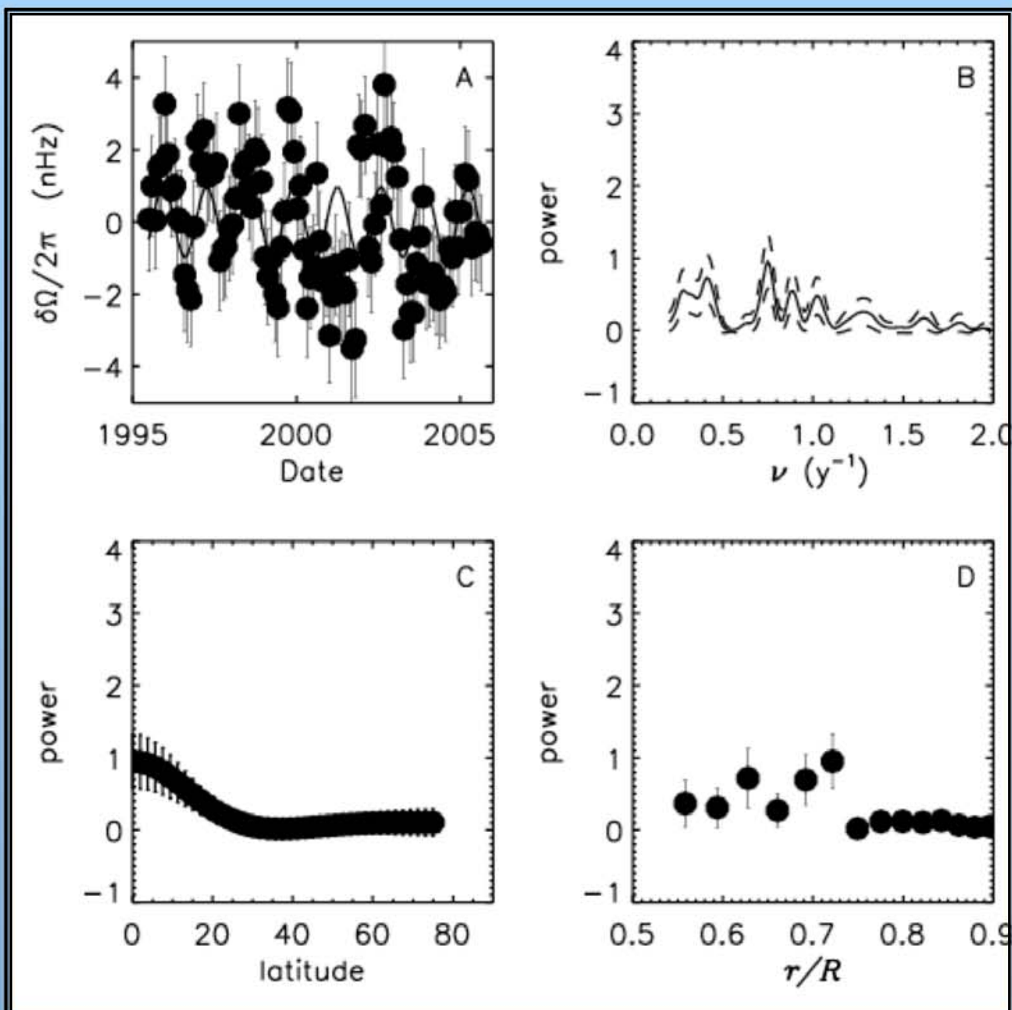


1996 **2002**

Variations at the Tachocline



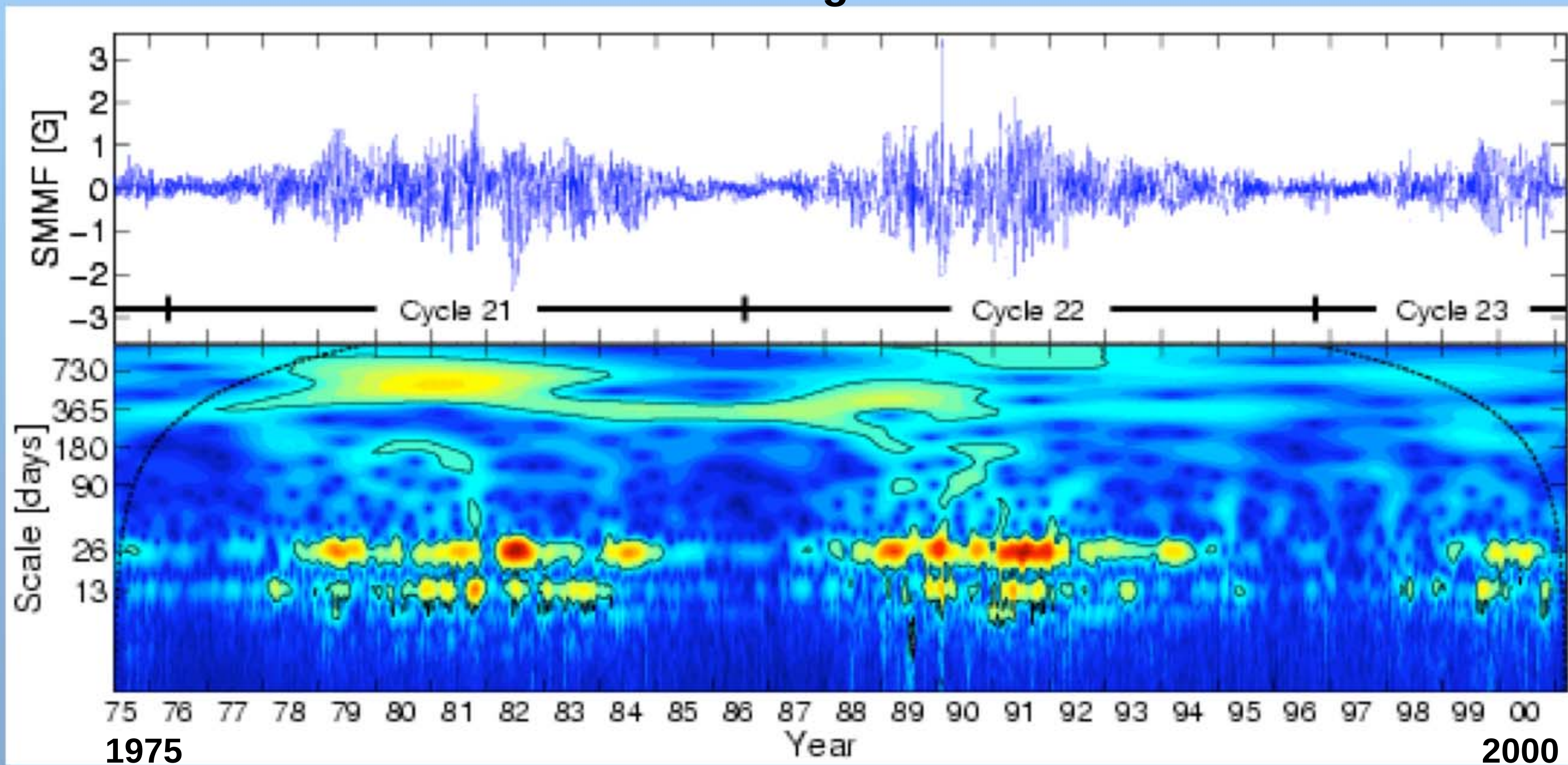
The ‘1.3 year oscillation’



A. 0.71R, equator residuals
B. Power spectrum
C. Power in max. power frequency bin, vs latitude
D. Power in max. power frequency bin, vs radius.

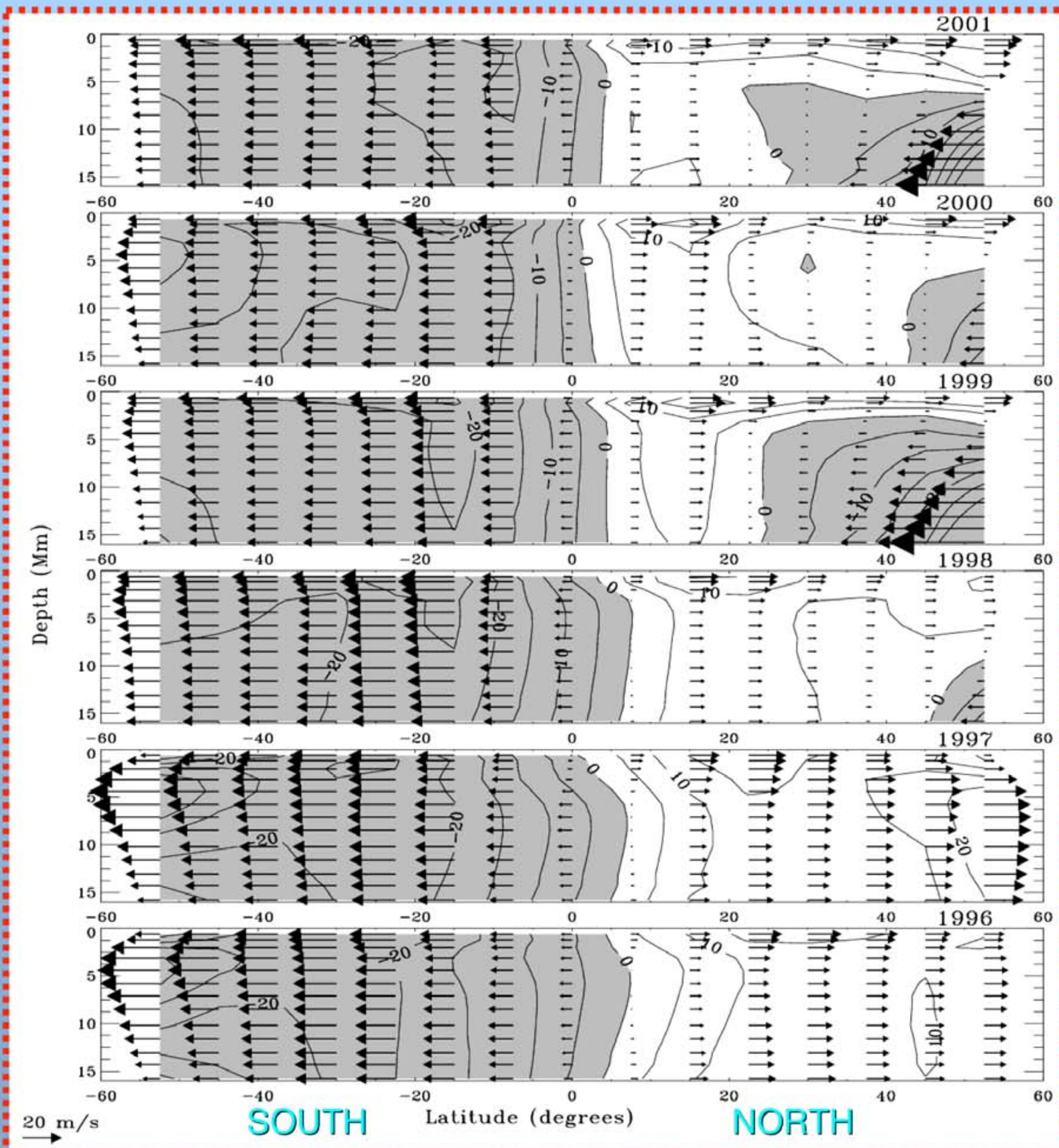
Wavelet analysis of the Sun's mean photospheric magnetic field: prominent periods are the rotation period and its 2nd harmonic, and the 1.3/1.4-yr period

Solar mean magnetic field



Boberg et al. 2002

Varying Pattern of Meridional Circulation Cells



2001
2000
1999
1998
1997
1996

SOUTH: SINGLE CELL

NORTH: DOUBLE CELL

POLEWARD FLOW NEAR SURFACE

REVERSED FLOW AT DEPTH

MULTI-ROTATION AVERAGES

Courtesy J. Toomre

Asphericities (rotation, magnetic field, etc.) raise m-degeneracy of mode frequencies.
Commonly expressed as:

$$\nu_{nlm} = \nu_{nl} + \sum_{k>0} a_k(n,l)\mathcal{P}_k^{(l)}(m)$$

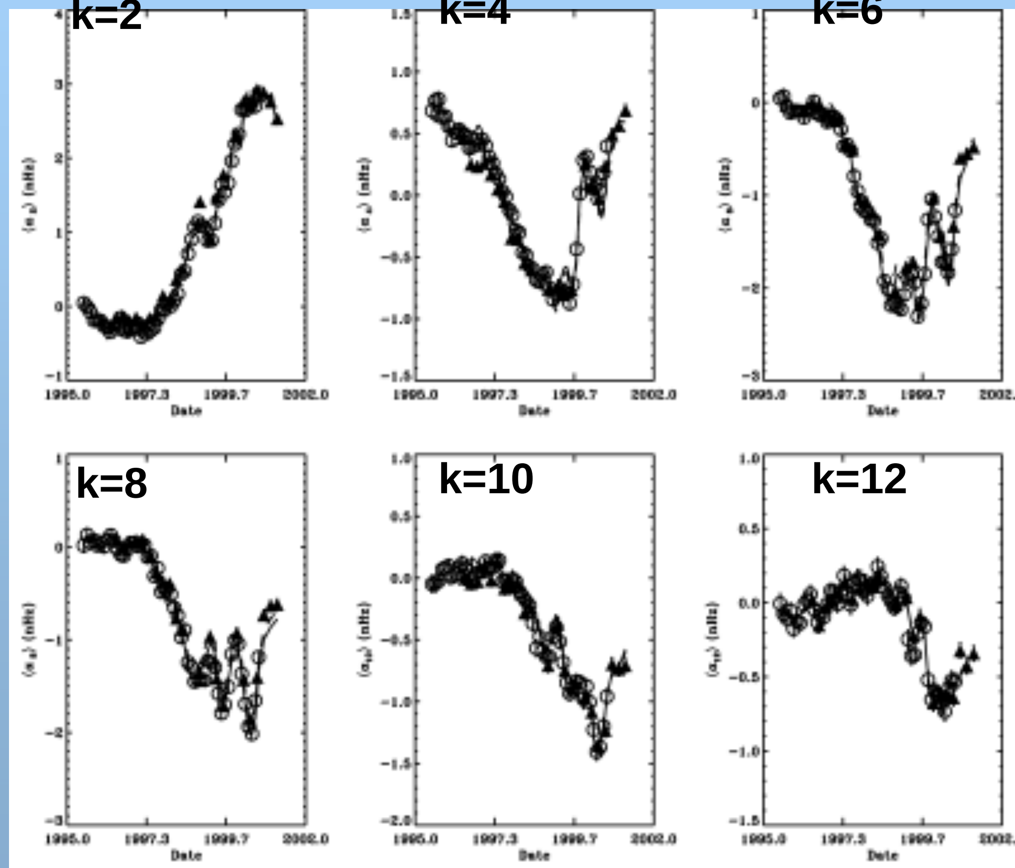
where $P_k^{(l)}$ are orthogonal polynomials of degree k.

Odd order coefficients a_k arise from rotation.

Even order coefficients arise a_k from magnetic fields and other asphericities (incl. centrifugal distortation) which do not distinguish between westward- and eastward-propagating waves.

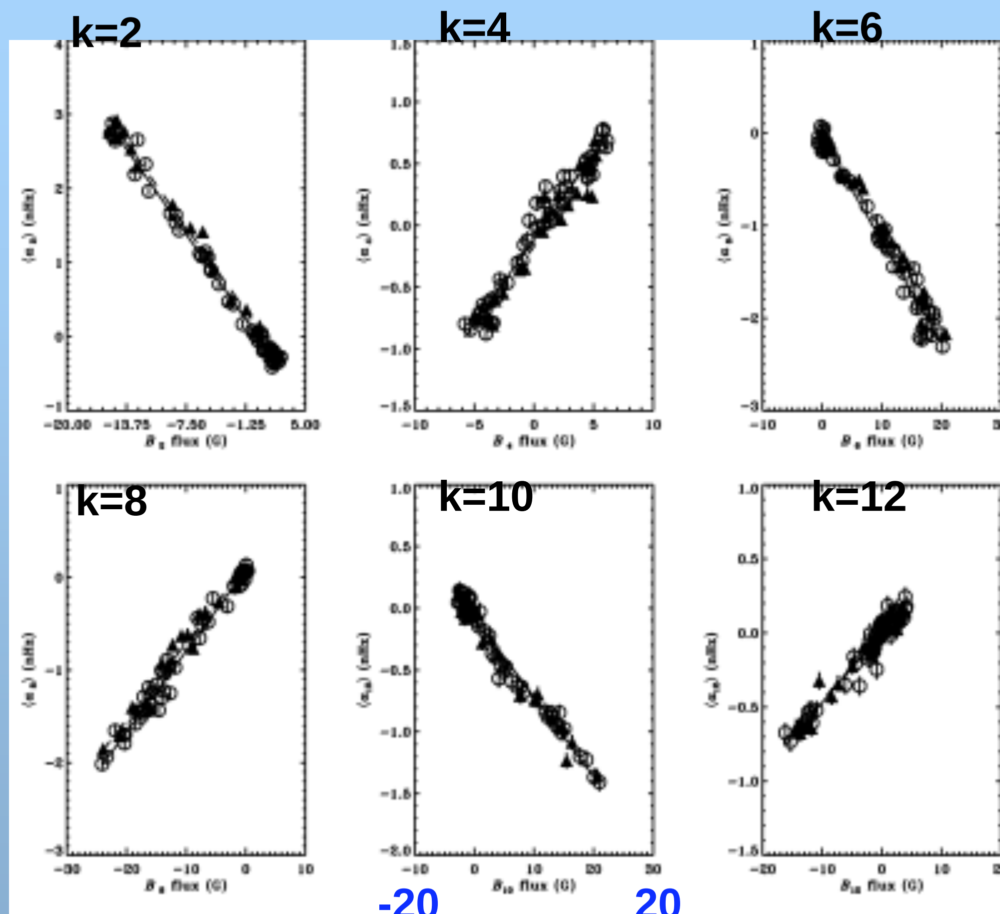
Solar results

Mode-averaged $\langle a_k \rangle$ as a function of time



Antia et al. 2001

$\langle a_k \rangle$ as a function of B_k



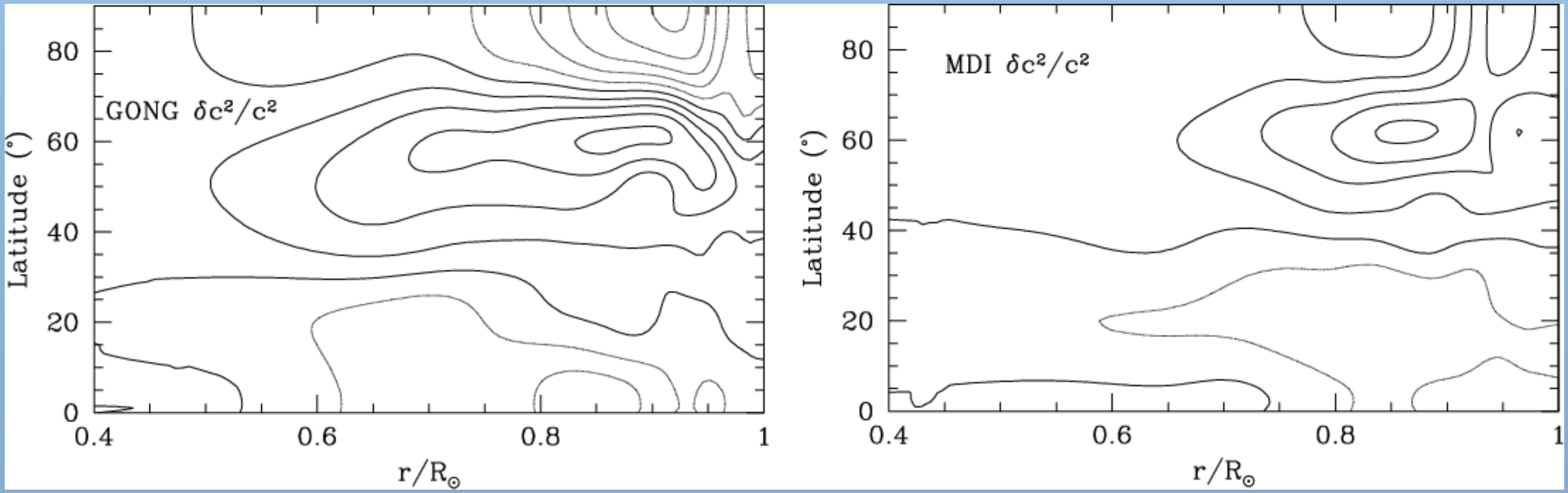
where $$B_k \propto \int |B(\theta)| \, [P_k(\cos\theta)]^2 \, \mathrm{d}(\cos\theta)$$

Antia et al. 2001

Treat magnetic field or other non-rotational contribution to even a-coefficients as an aspherical wave-speed perturbation.

$$a_k = \text{contribution from solar interior} + \text{(surface effect)} / \text{(mode mass)}$$

Results of inverting both GONG (left) and MDI (right) data averaged over time show a wave-speed anomaly in convection zone at latitude 60 degrees..



Latitude 60 degrees anomaly varies little with time