Global Helioseismology and SDO

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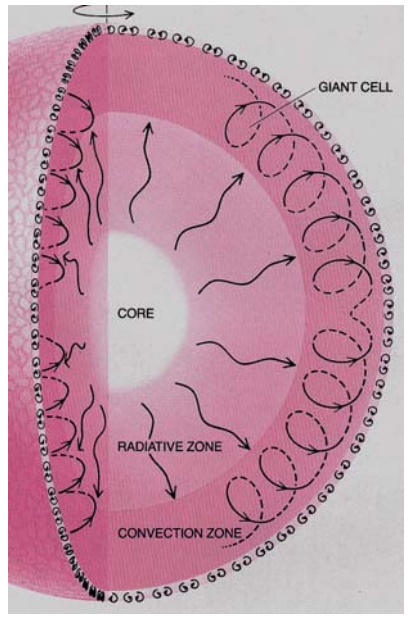
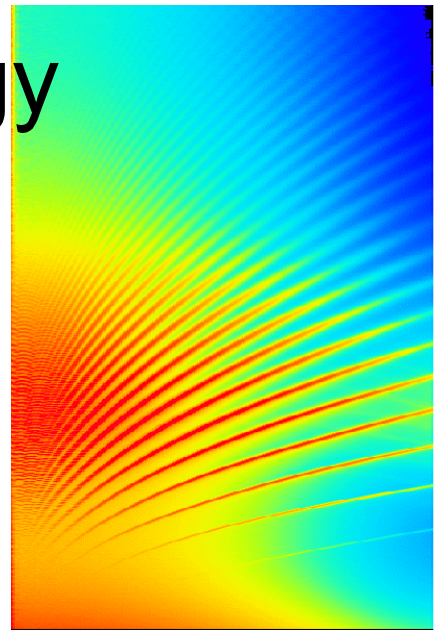
Relation to SDO objectives

- Convection zone dynamics and the solar dynamo
- Origin and evolution of sunspots, ARs and complexes of activity
- Sources and drivers of solar activity and disturbances
- Links between the internal processes and dynamics of the corona and heliosphere
- Precursors of solar disturbances for space-weather forecasts



Global-mode seismology



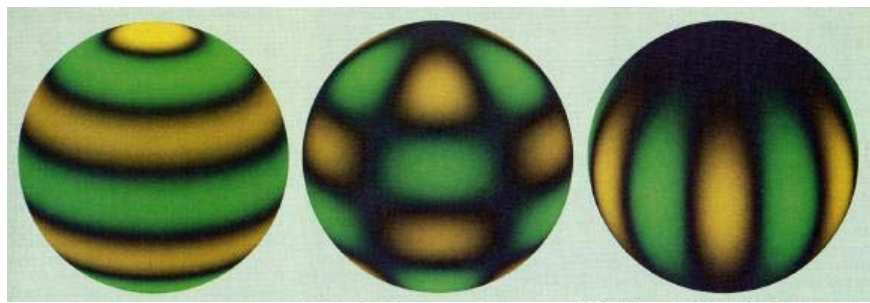
Measure mode properties ω; A, Γ; line-shapes
Eigenfunctions / spherical harmonics

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

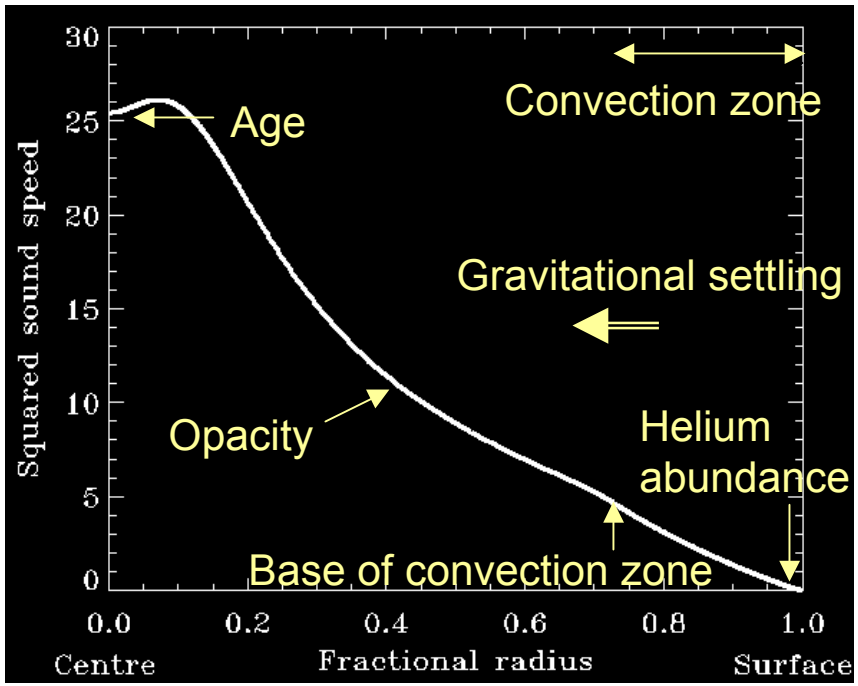
North-south averages
Snapshots at successive times: typically 2-month averages



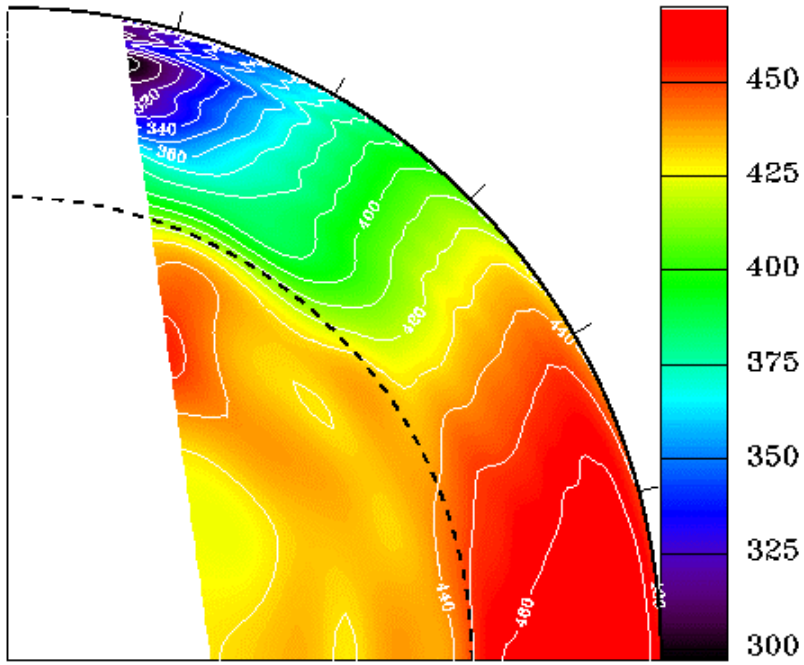
Spherical harmonics

Fundamental achievements

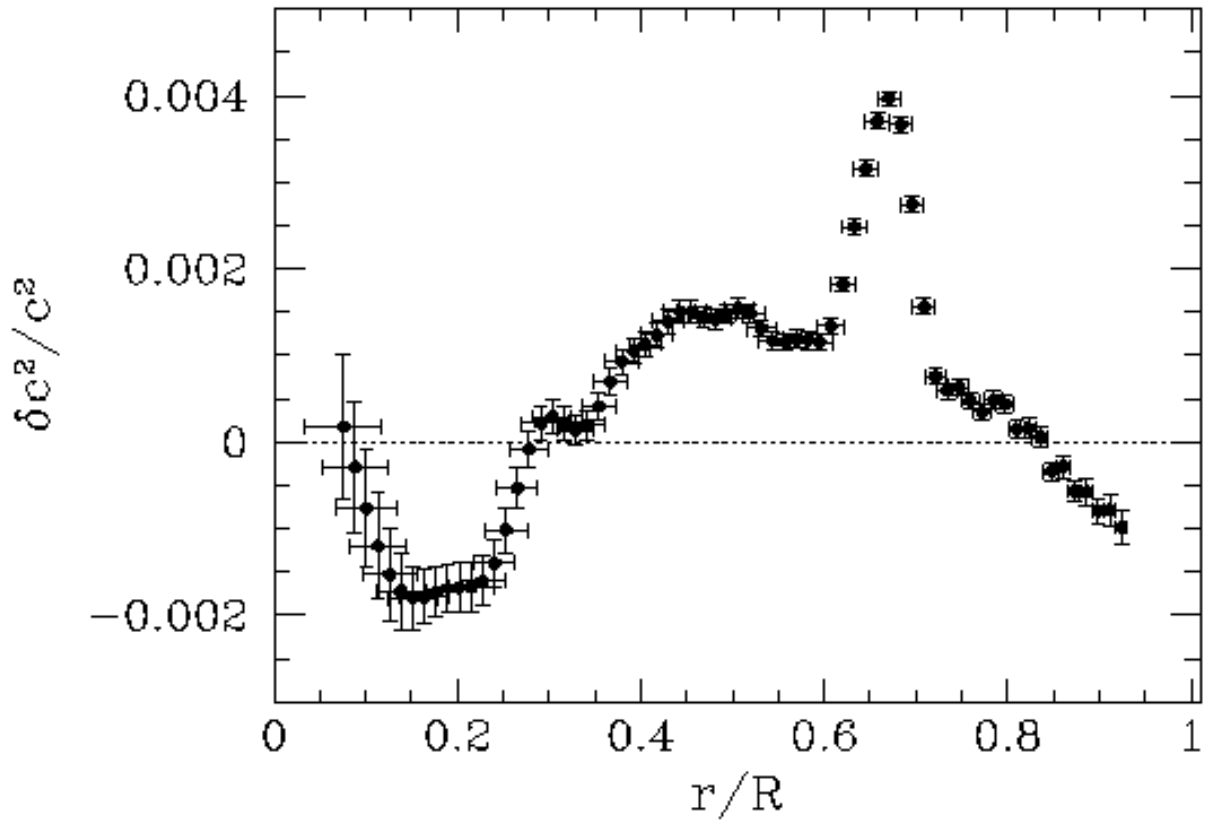
Sound speed c (r)



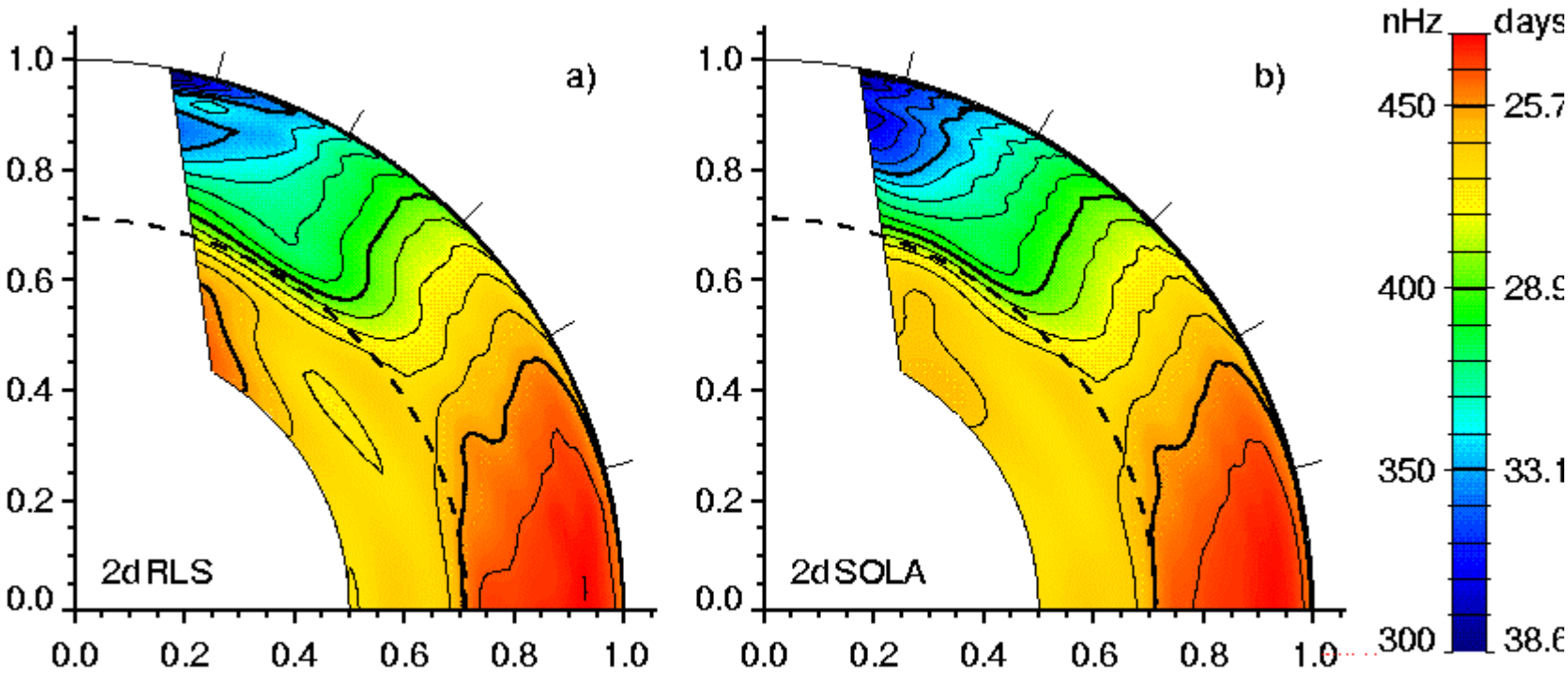
Rotation Ω (r, θ)



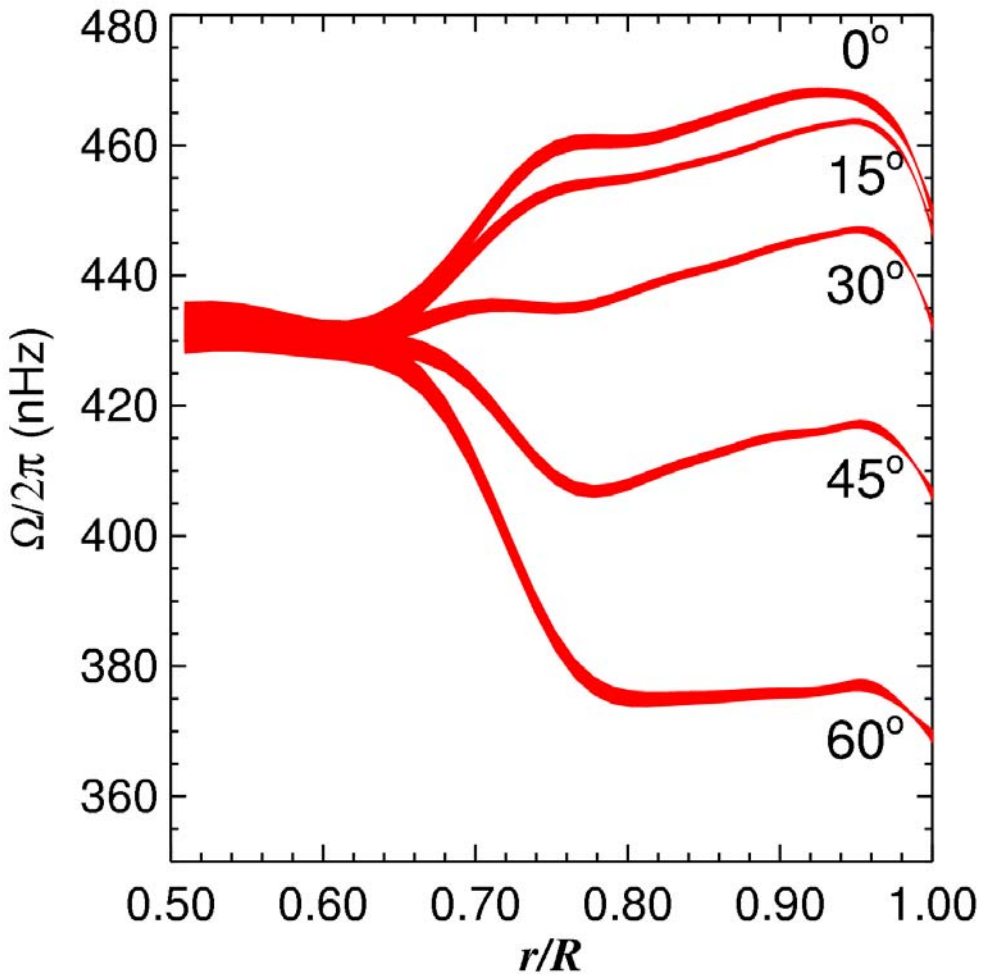
Inferred relative difference in the squared sound speed between the Sun and a solar model



Rotation rate inferred from MDI data using two different analysis techniques



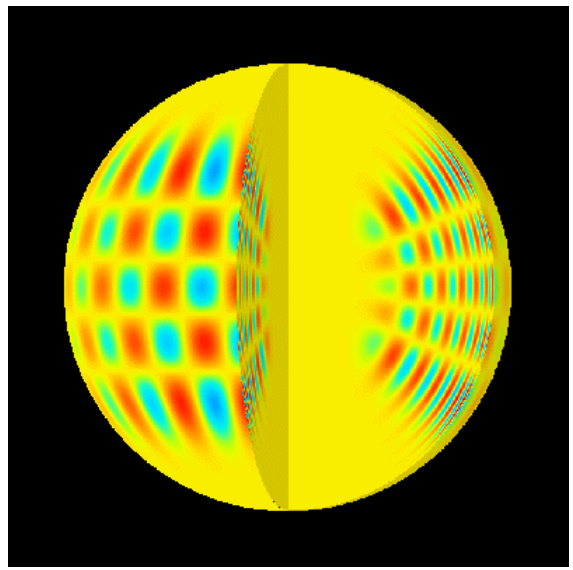
Radial cuts through inferred rotation profile of the solar interior
(at latitudes indicated)



Targets for global-mode seismology

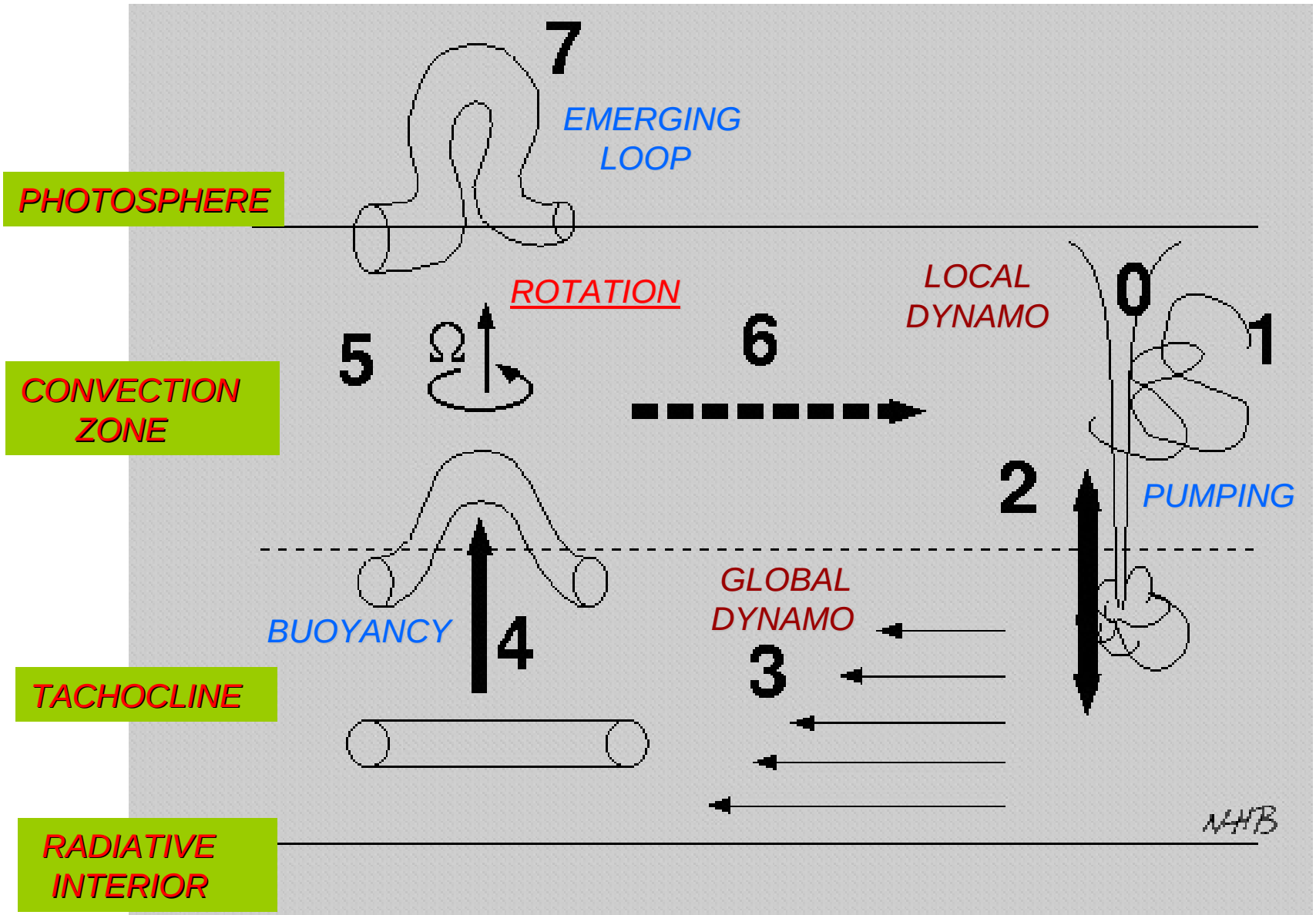
Temporal variability of solar interior – expected in tachocline and in convection zone; maybe in deeper interior also

Global-mode seismology has unique capabilities for probing
deep interior
high latitudes



- Variability in and near the tachocline
- Tachocline structure and dynamics
- Variability in the convection zone
- Magnetic and thermal anomalies
- The deep interior

Theoretical Solar Cycle



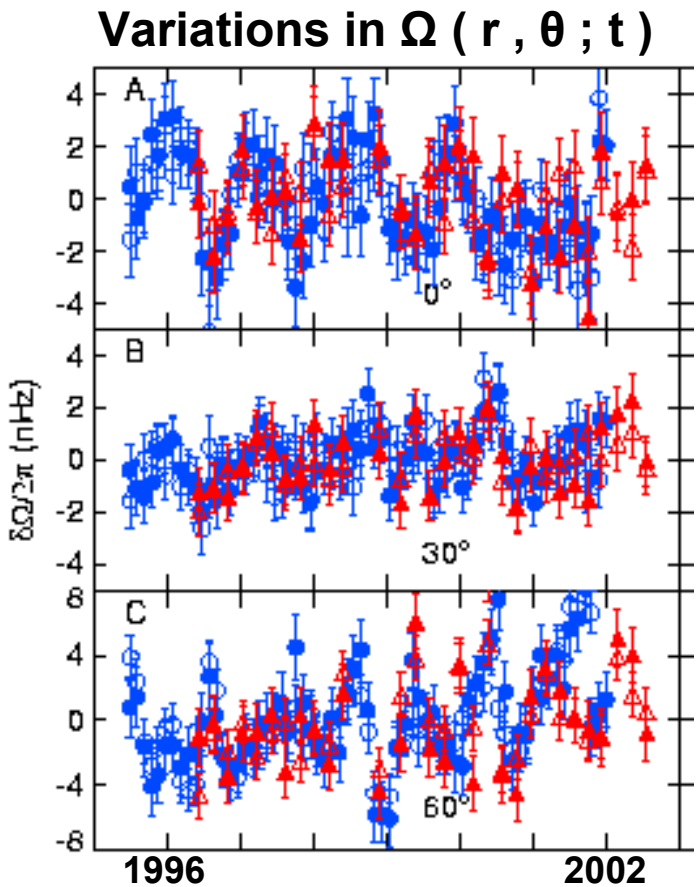
Variability in and near tachocline

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?

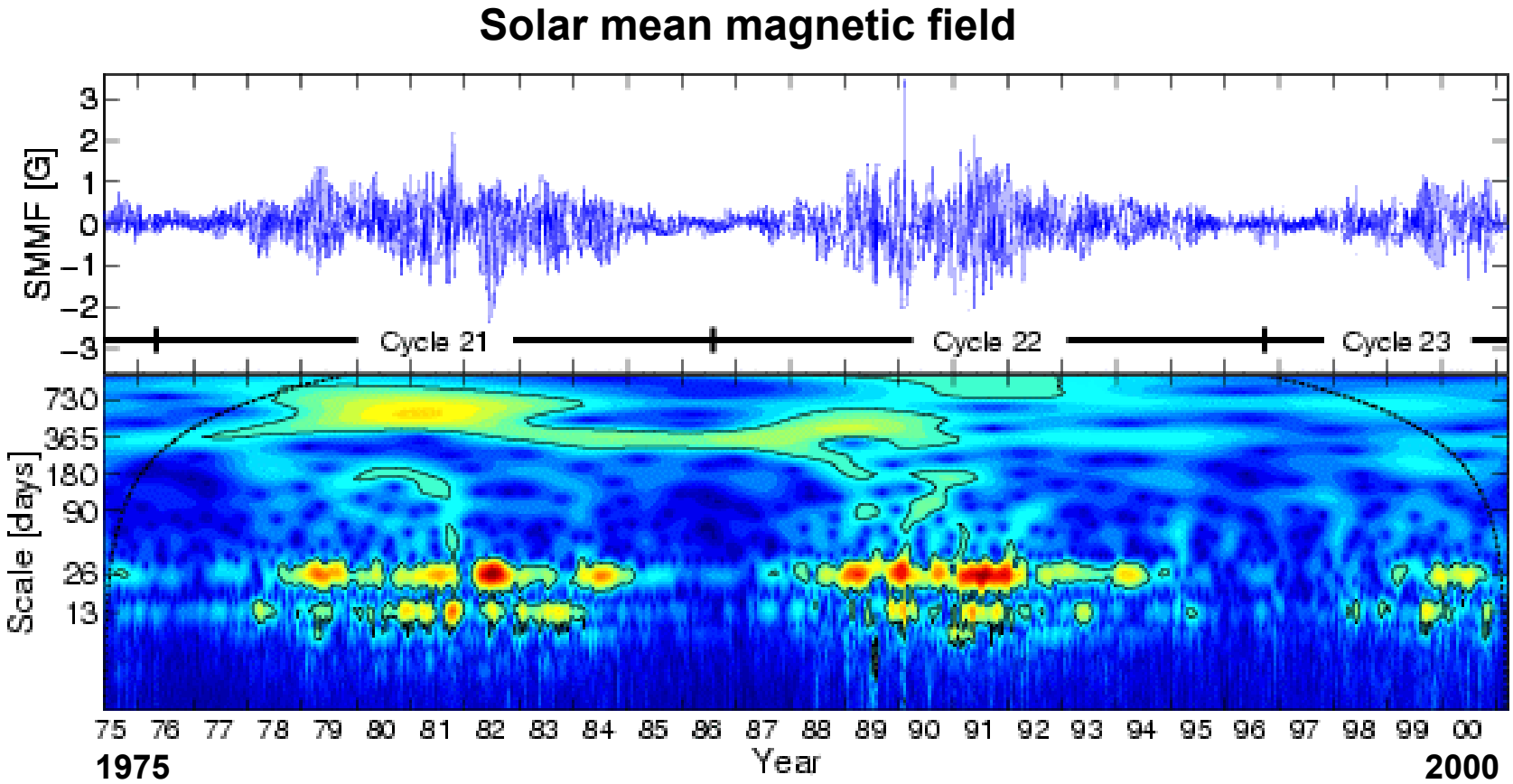
Link between tachocline and 1.3/1.4-yr variations in

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



Howe et al. 2000

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



Boberg et al. 2002

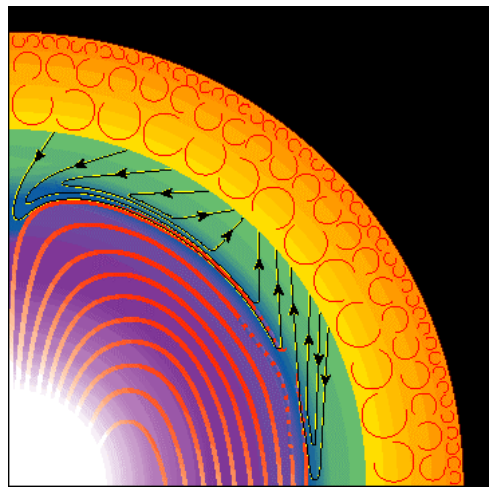
Tachocline structure and dynamics

Stratification – particularly of subadiabatic tachocline
– storage of B field, interface dynamo

Tachocline thickness and location as function of latitude (and time)

Constraints on physics: turbulent angular-momentum transport and rotational shear; instabilities; penetrative convection and meridional flow

Toroidal field belts ! force balance with zonal jets in tachocline and/or change to hydrostatic stratification
(Dikpati & Gilman)



Gough & McIntyre 1998

Variability in the convection zone

Torsional oscillations – what is relation to magnetic field?

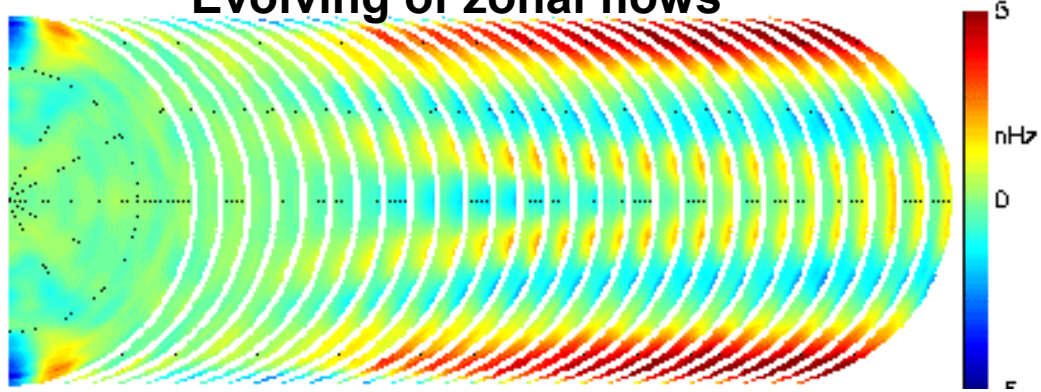
A local seismology target at low latitude and near surface

Whole convection zone involved
Strong evolution at high latitude

Role of polar open field-lines?

Physical understanding of the phase propagation of perturbations through the convection zone?

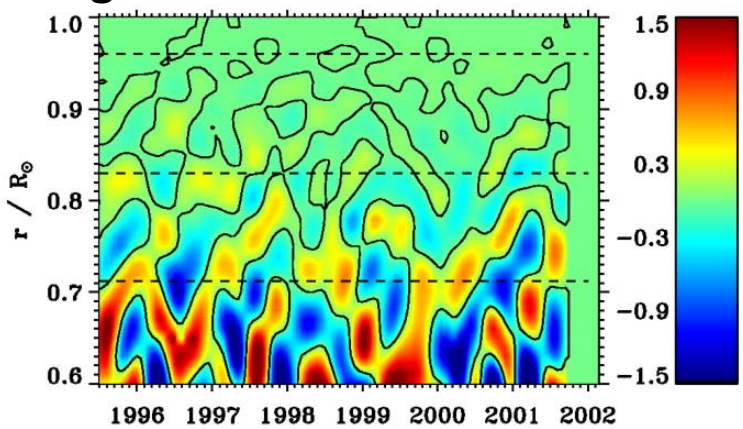
Evolving of zonal flows



May 1996 Aug 2002

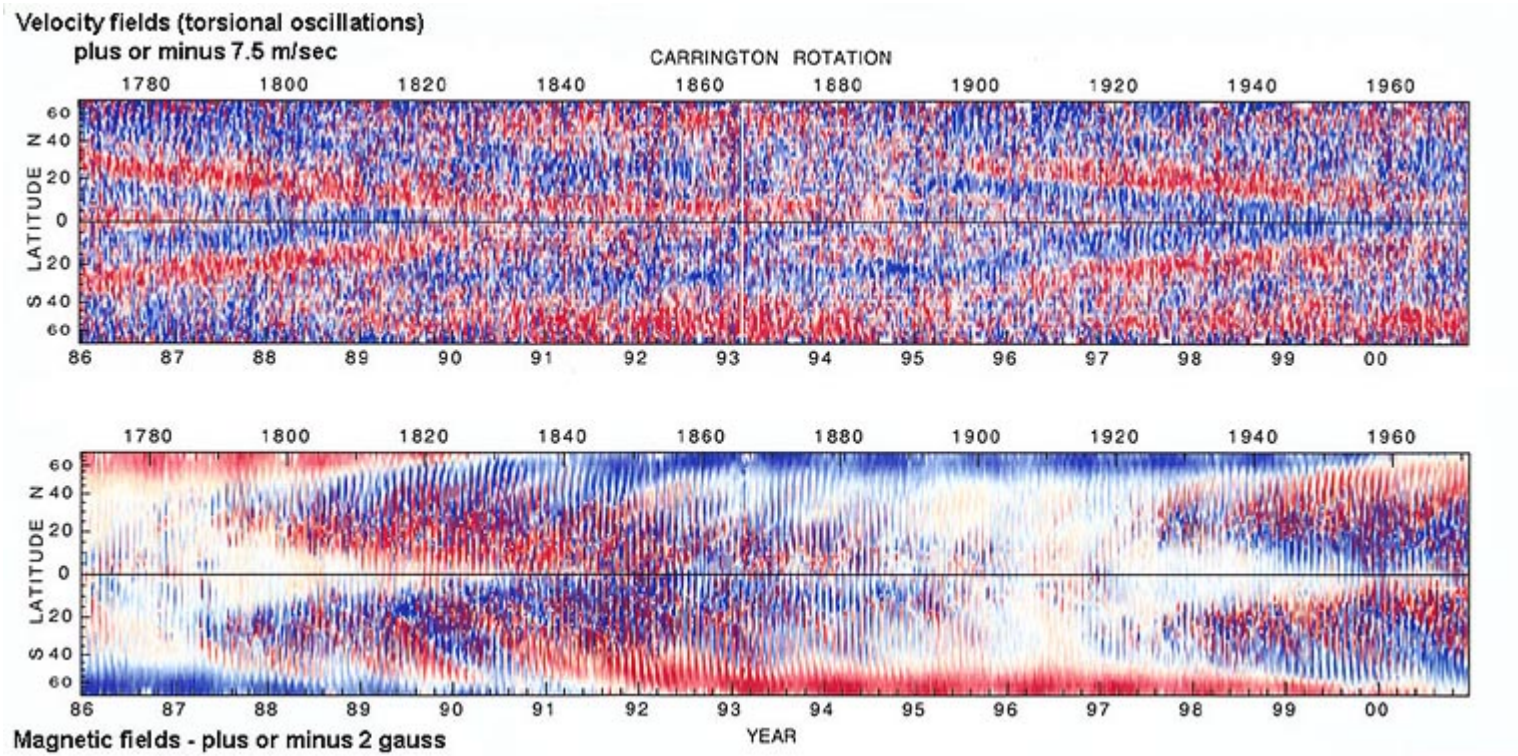
Vorontsov et al. 2002

Angular momentum variations



Komm et al. 2003

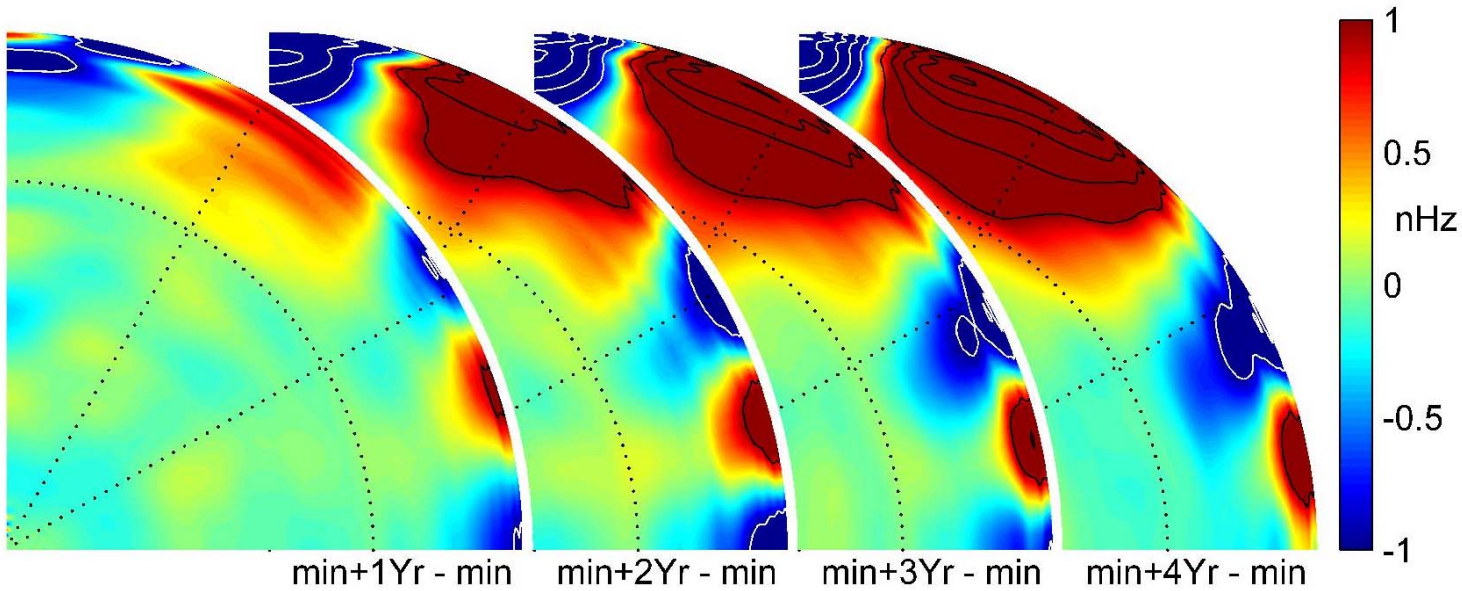
Evolution of surface velocity field (upper panel) and surface magnetic field (lower panel)



1986 **2000**

Ulrich 2001

Evolving zonal flows throughout convection zone – 1-yr snapshots



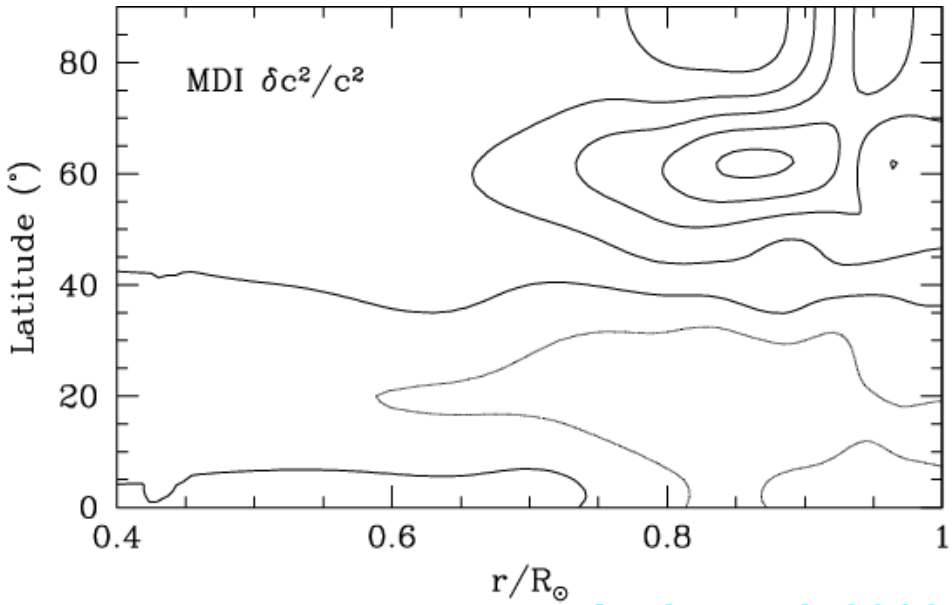
Vorontsov et al. 2002

Magnetic and thermal anomalies

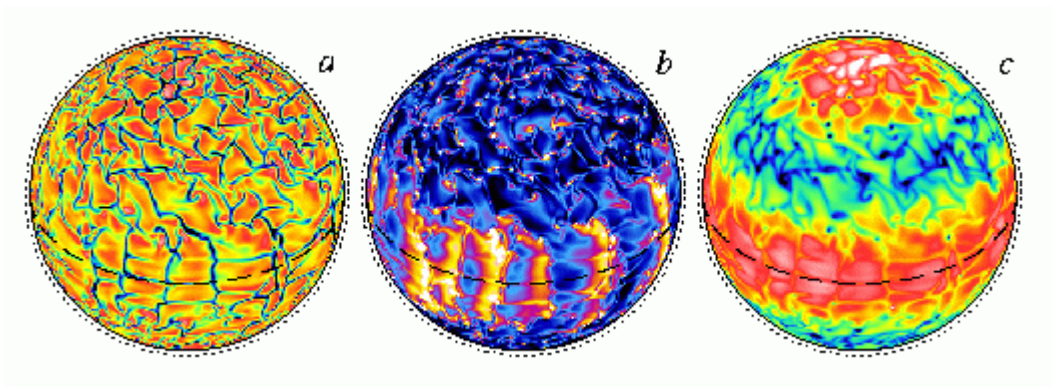
Even component of frequency
$\frac{1}{2}(\omega_{nlm} + \omega_{nl\,-m}) - \omega_{nl0}$
indicates latitudinal variation of acoustic properties: thermal or magnetic

Persistent indications of sub-photospheric wave-speed anomaly at 60° latitude in upper convection zone

Thermal? Or 10^4 Gauss field ?



Antia et al. 2003



Brun et al. 2003

The deep interior

Determination of the rotation profile and structure deep in the Sun

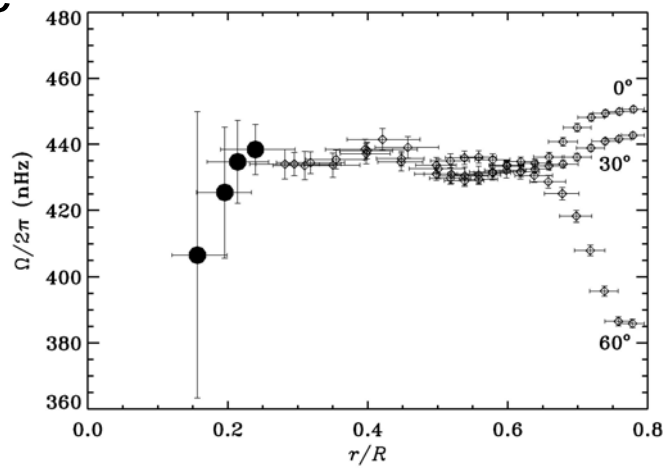
Radiative interior may be involved in solar cycle (cf. 1.3-yr variations); maybe longer time-scale variations also

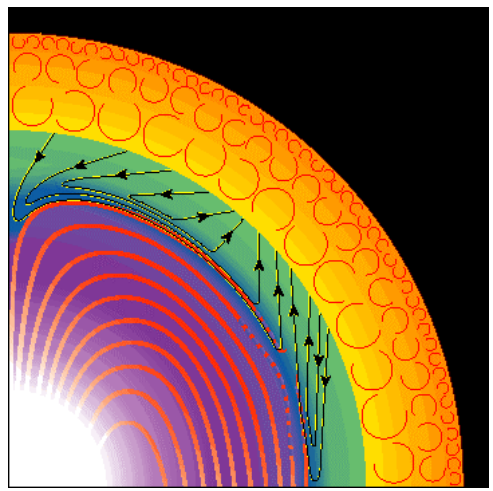
E.g. maybe solar luminosity varies on longer timescales

Radiative interior as lower boundary condition to tachocline dynamics

The linking of changes of mode properties (ω, A, Γ) and activity measures both in terms of particular events and trends

Need for long-term monitoring of solar interior





Gough & McIntyre 1998

Some issues and challenges

Resolving discrepancies in measured mode parameters between different analyses

Matching resolved and unresolved data sets in terms of what is measured and how that relates to coefficients produced at higher degree l

Utilising SDO high-degree measurements to improve deep inferences: "correcting" frequencies using far-side (and near-side) imaging; using high-l modes to remove sensitivity to near-surface conditions