Helioseismology of the Tachocline

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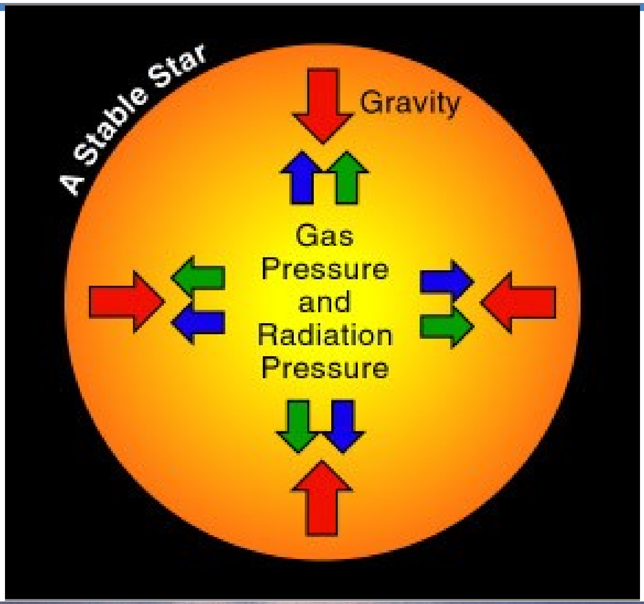
History of Solar Activity Recorded in Polar Ice
Dübendorf, 14.11.2016

Theoretical Knowledge about the Solar Interior

What is the structure of the Sun?

Theory of the internal structure of the stars is based on the fundamental principles of physics:

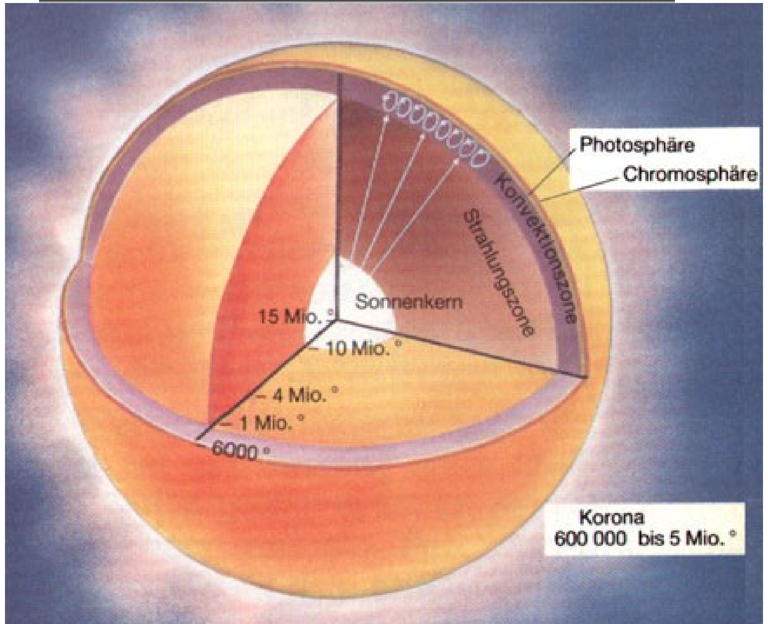
Energy conservation,
Mass conservation,
Momentum conservation



Pressure and gravity are in balance; hydrostatic equilibrium

 the Sun is stable

A *theoretical model* of the Sun can be built on these physical laws.



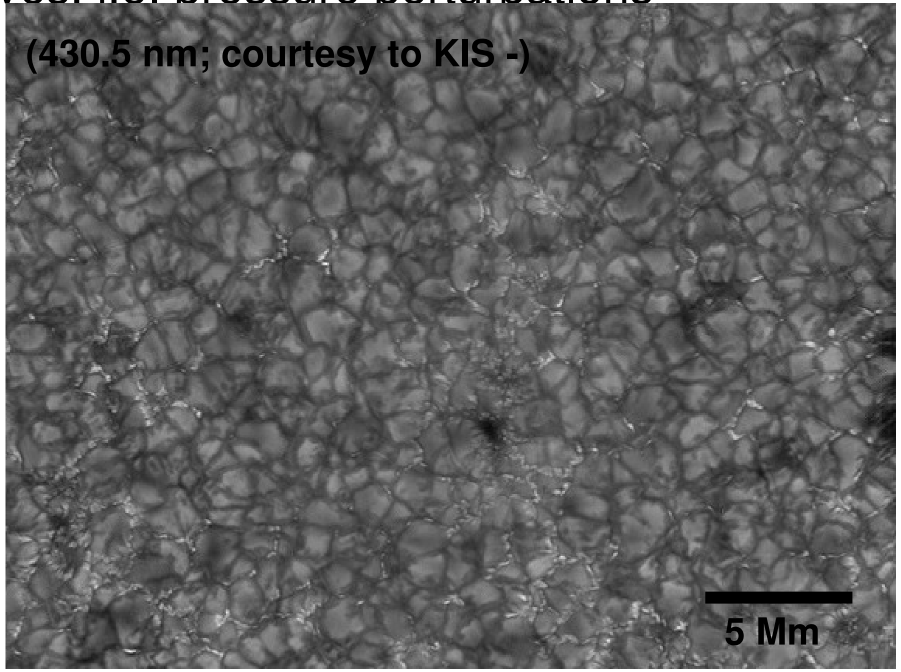
Is there a possibility to „look inside" the Sun?

Oscillations in the Sun and the Stars

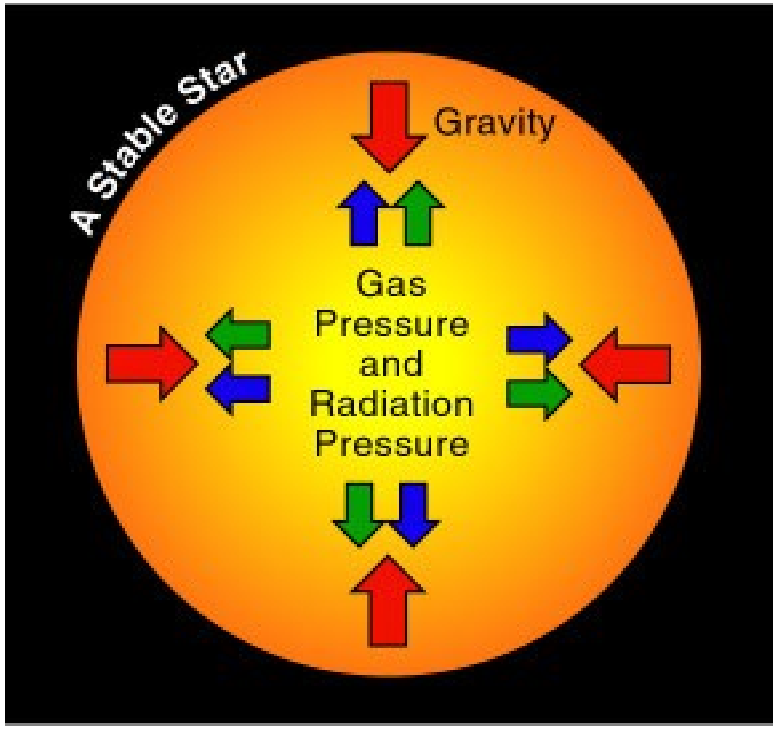
The Sun and the stars exhibit resonance oscillations!

Excitation Mechanism:
Small perturbations of the equilibrium lead to oscillations

Origin:
Granulation (turbulences) that generate sound waves, i.e. pressure perturbations



(430.5 nm; courtesy to KIS -)



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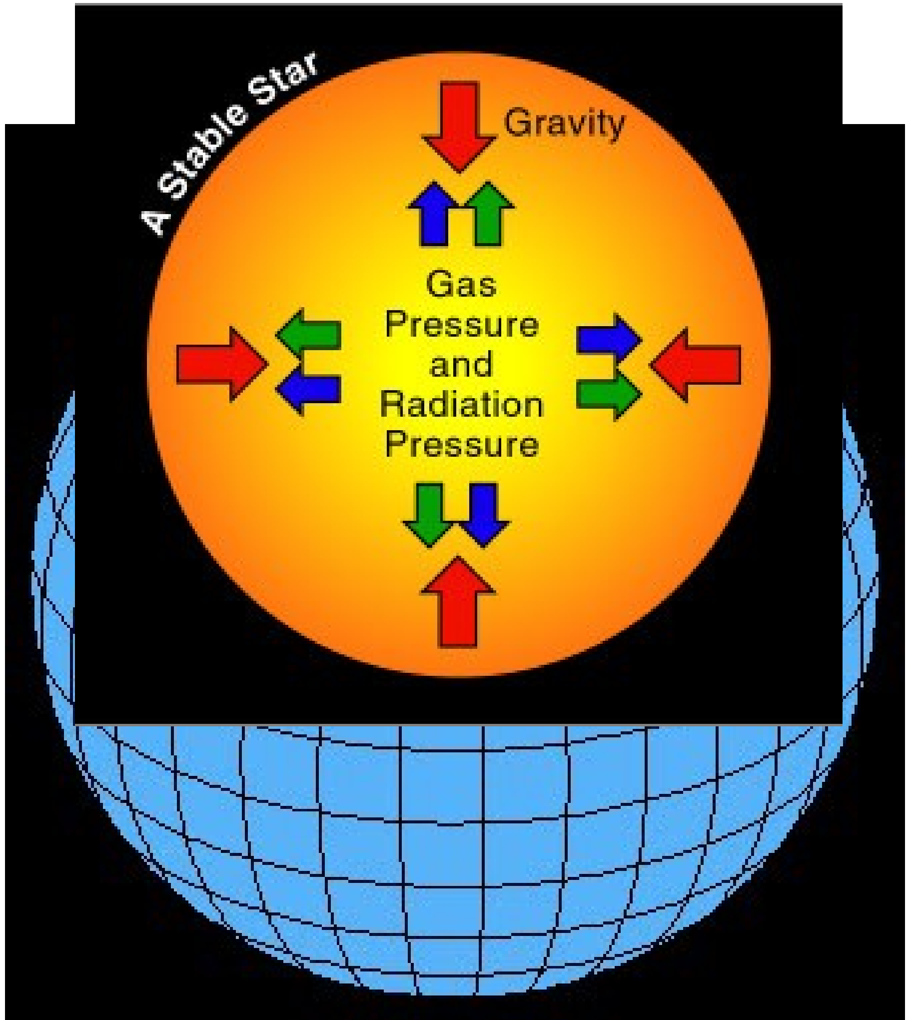
The superposition of sound waves lead to interferences: amplifications or annihilations.

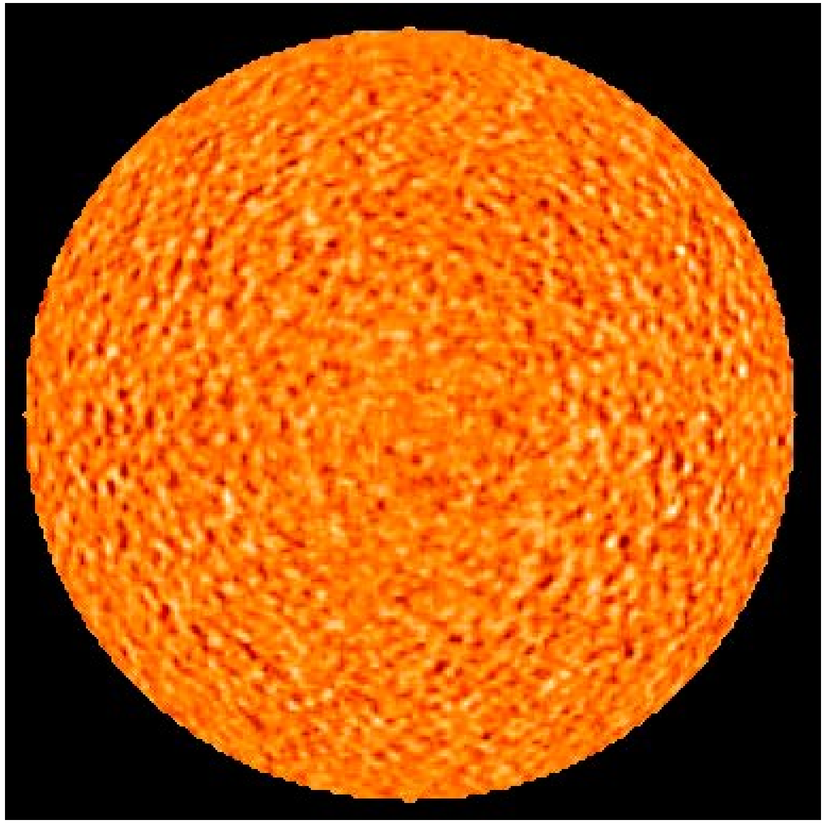
Sun and stars act as resonators

? Fundamental mode and higher harmonics are possible



Modern Era of Helioseismology

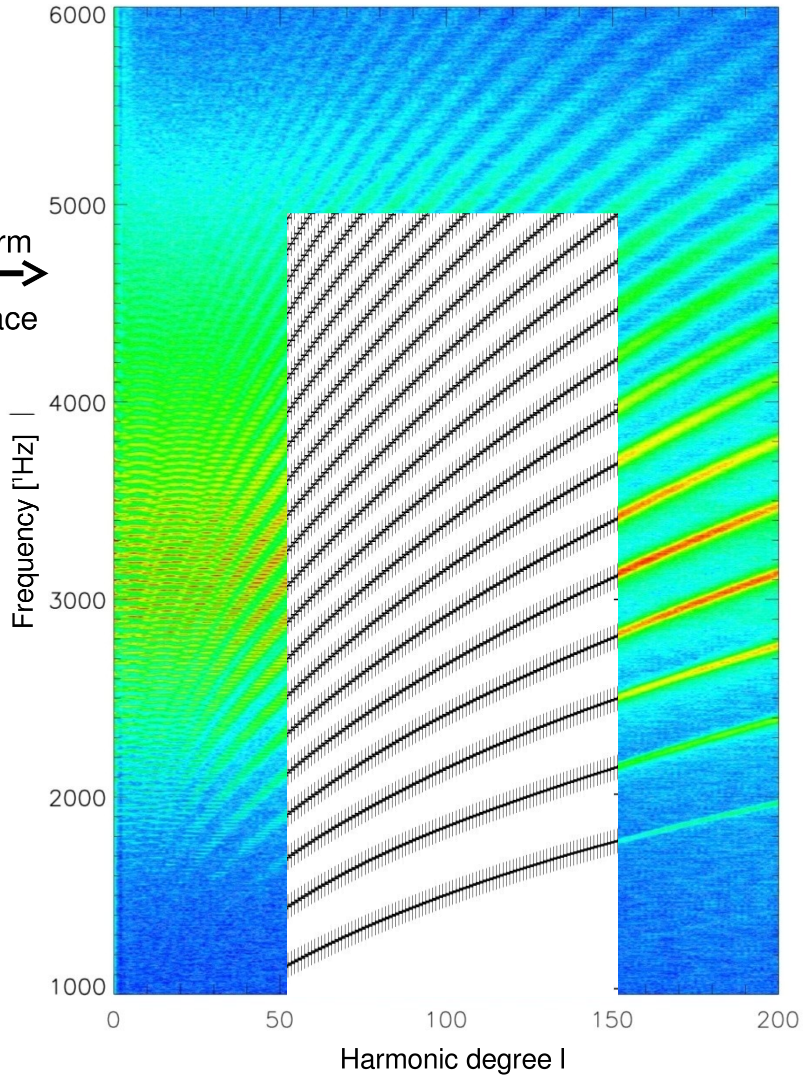
10 million oscillations, simultaneously excited



Fourier transform

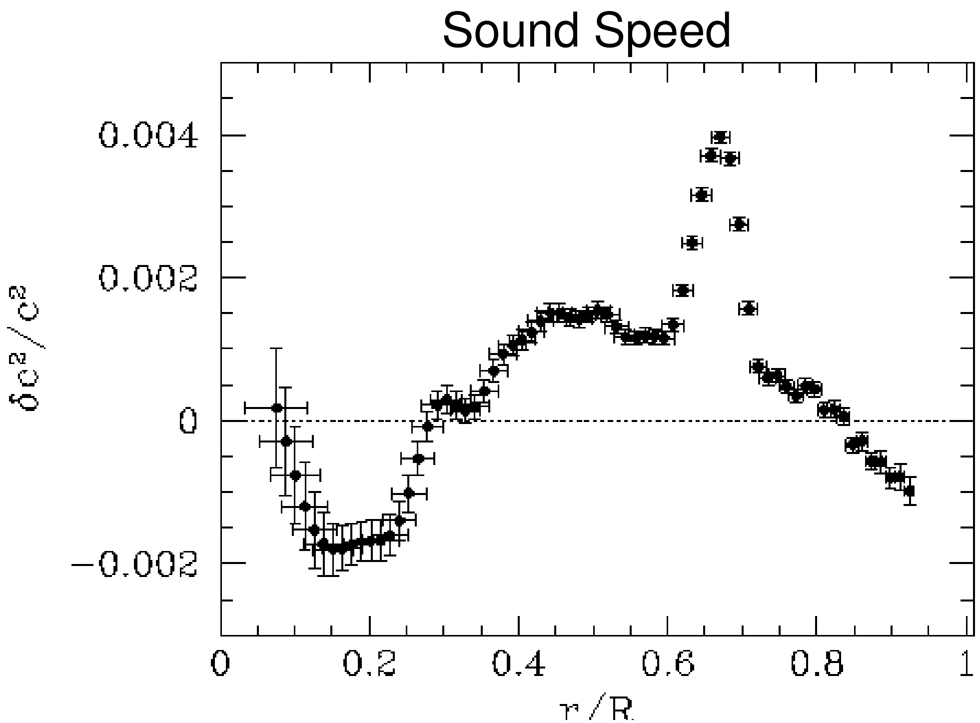
in time and space

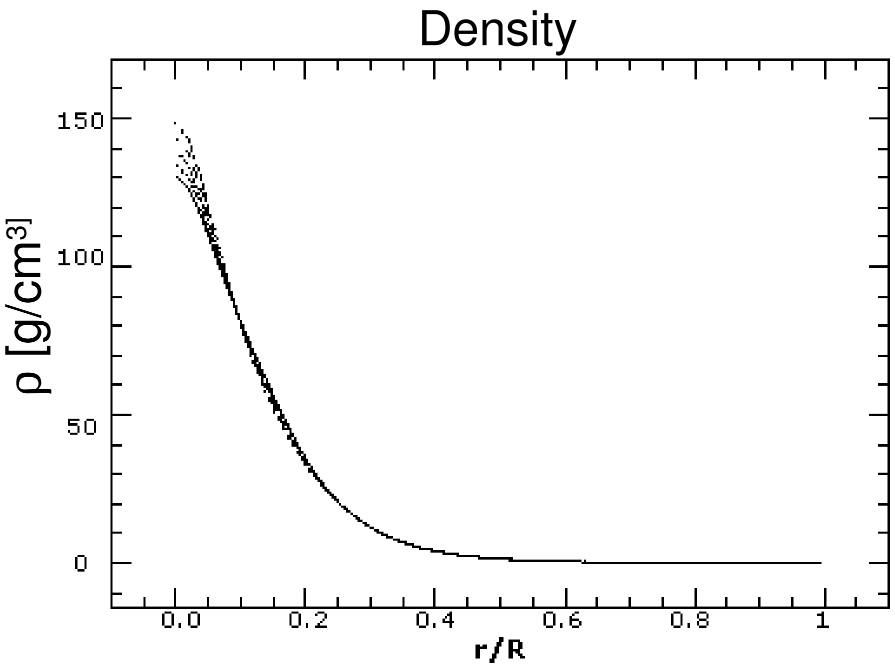
Spectral Energy Density
Solar p modes



Roth, 2004, SuW 8, 24

First Successes of Helioseismology: Internal Structure of the Sun





Difference between theoretical model on the Sun‘s internal structure and helioseismology: **approximately 3%**

Transition between radiative interior and convection zone shows most significant differences

(Kosovichev et al., 1997, Solar Phys.170, 43)

(Christensen-Dalsgaard et al., 1985, Nature 315, 378)
Antia & Chitre, 1995, Astrophys. J. 442, 434)

Tachocline Studies with Local Helioseismology

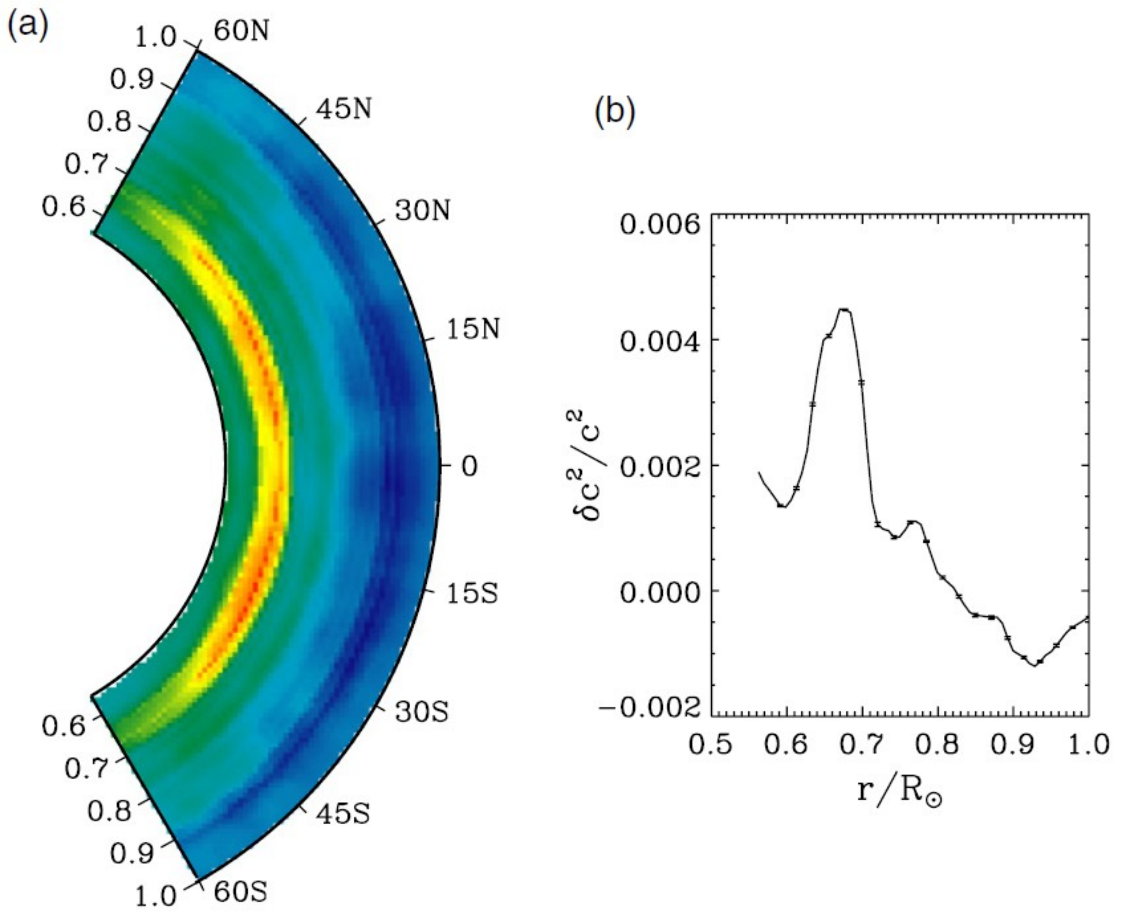


Figure 11. Same as panels (c) and (d) in Figure 9, but for the combined inversion of the surface- and deep-focusing measurements.

Sound speed perturbation at the base of the convection zone is not uniform

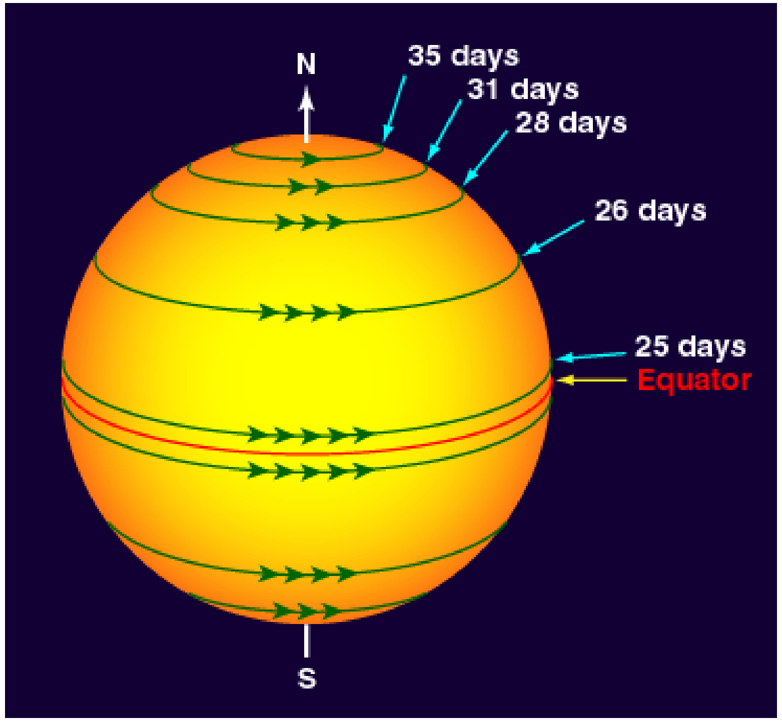
Clear dip around the equator

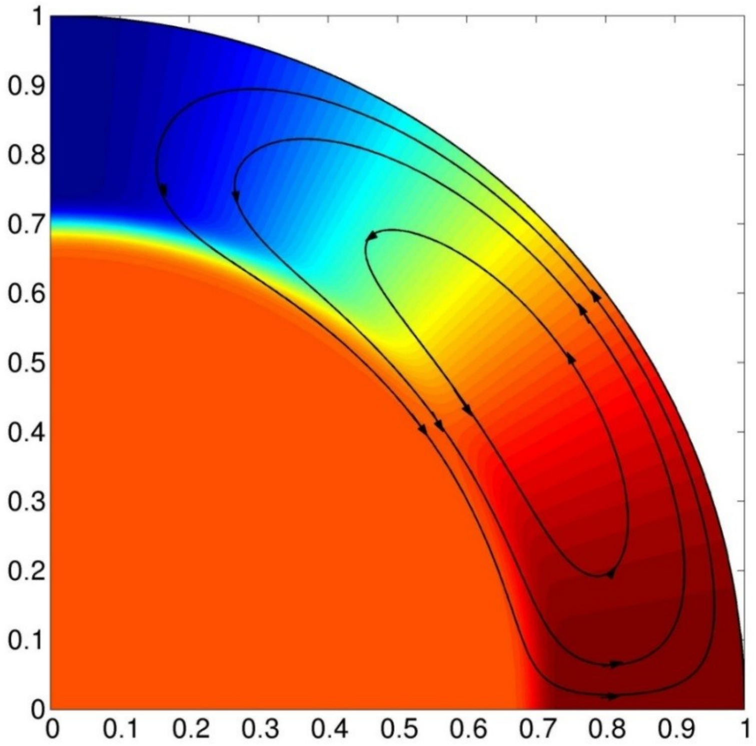
Stronger sound speed perturbation at higher latitudes

North-South asymmetry

(Zhao et al. 2009 ApJ)

Large-scale Flows: Differential Rotation & Meridional Flow





The Sun rotates differentially:

Equator rotates faster than the polar regions

The Sun has a meridional flow:

On the surface the flow is poleward
v ? 15 m/s

Surface flow must sink inward at poles and return to the equator at some depth

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The Solar Dynamo

Flows inside the Sun are important for solar dynamo action:

A possible solar/stellar dynamo

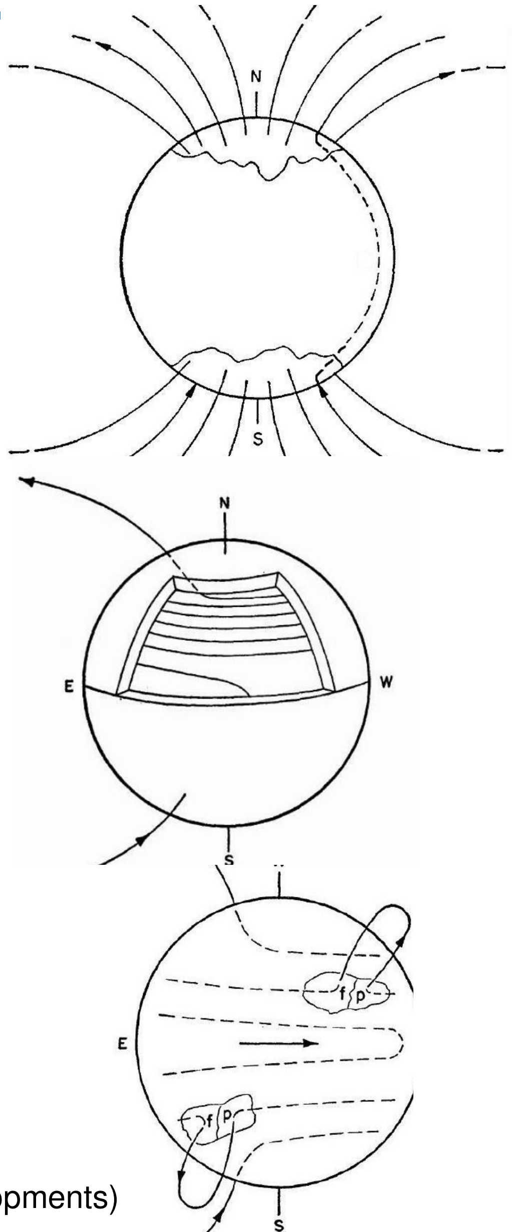
- **At cycle minimum:**
  a dipolar field threads through a shallow layer below the surface.

- *Differential rotation shears out this dipolar field*
  to produce a strong toroidal field
  (first at the mid-latitudes then progressively lower latitudes).

- **Around solar maximum:**
  Buoyant fields erupt through the photosphere forming,
  e.g. sunspots and active regions

- The *meridional flow* away from the mid-latitudes
  gives reconnection at the poles and equator.

The Sun's internal rotation
and meridional flow need to be measured

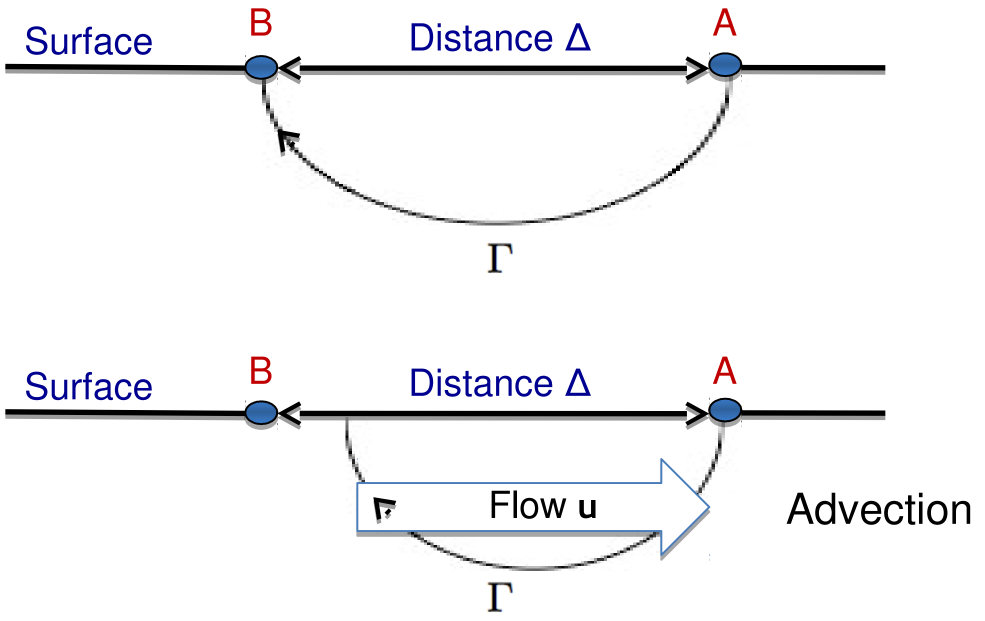


(Babcock, 1961; and later developments)

Perturbation of Waves by Flows

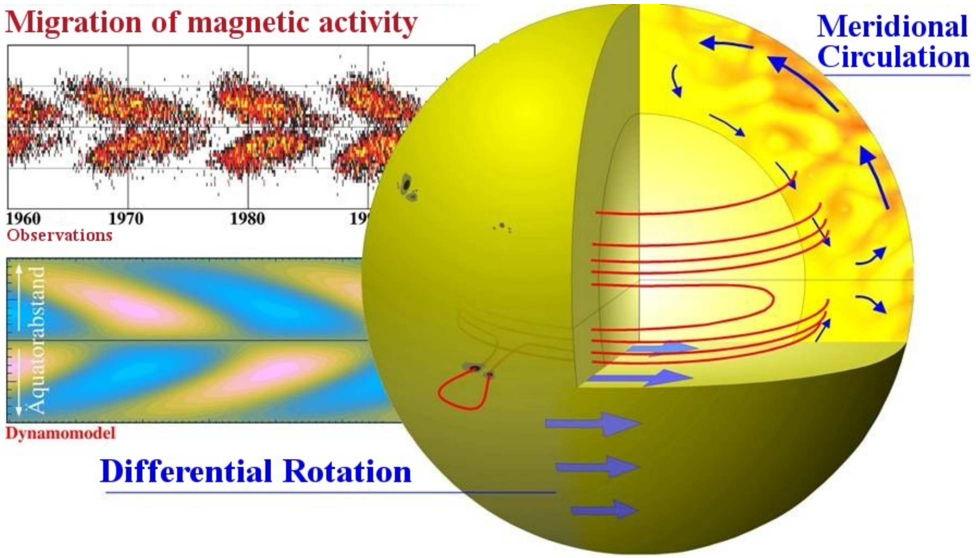
Equation of motion for sound waves: $\mathcal{L}\boldsymbol{\xi}_k = -\rho_0\omega_k^2\boldsymbol{\xi}_k$

Flow induces advection of the sound wave: $\mathcal{L}_1\boldsymbol{\xi}_k = -2\mathrm{i}\omega_k\rho_0(\mathbf{u}\cdot\nabla)\boldsymbol{\xi}_k$



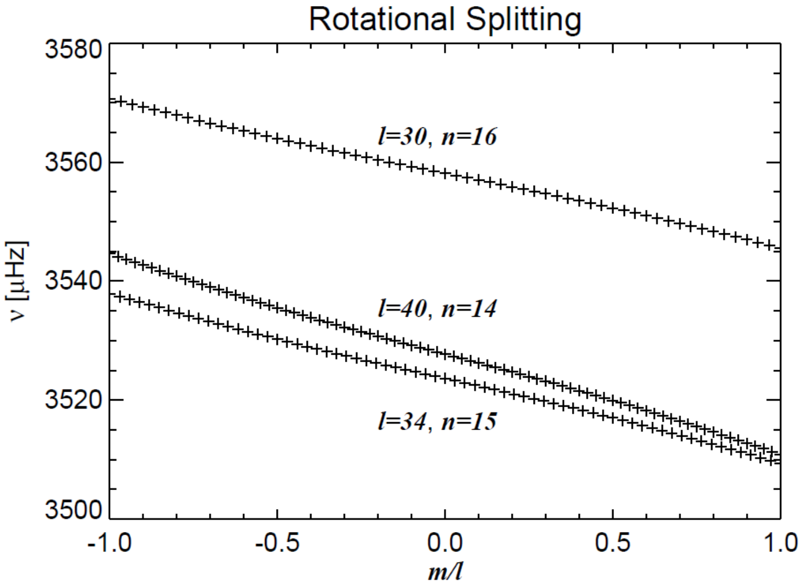
! Perturbation of wave eigenfunction and eigenfrequency

Global Diagnostics for Different Flow Geometries

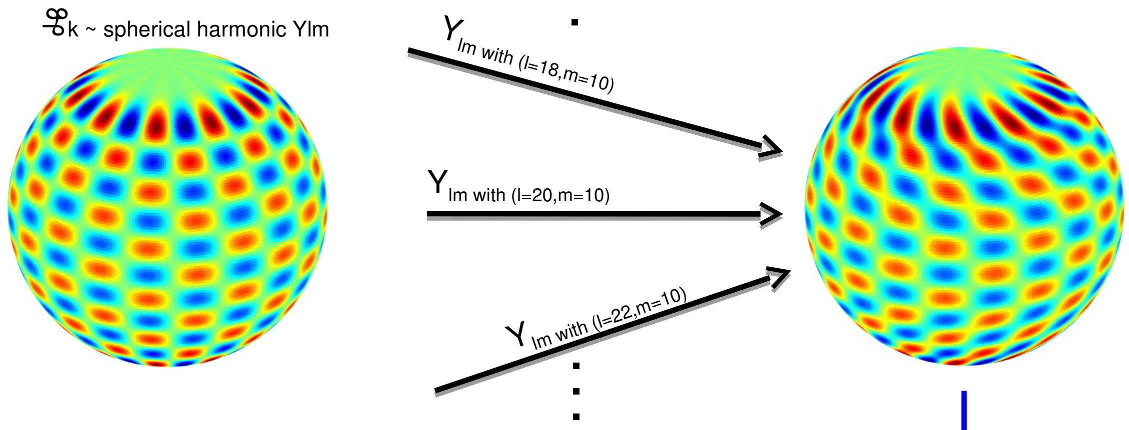


(Figure: R. Arlt)

- **Classical helioseismic approach:** Toroidal axissymmetric flows (differential rotation) measured from frequency splittings

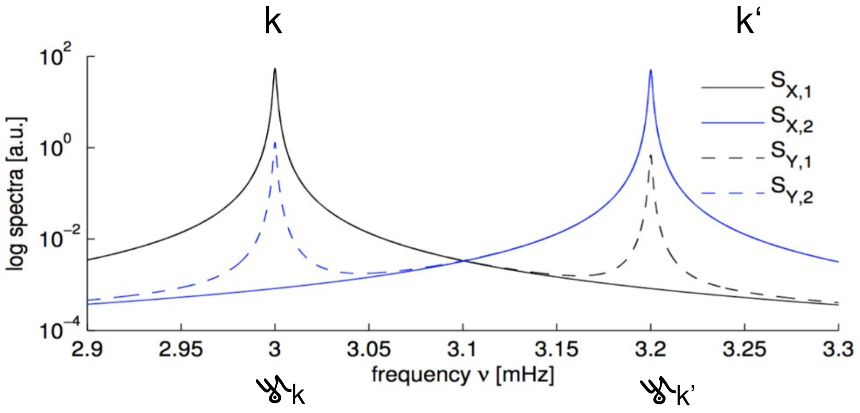


Analysis of Eigenfunction Perturbations



Wave „shape“ deformation

$$\boldsymbol{\xi}_k(r,\theta,\phi) = \sum_{k' \in K_k} c_{kk'} \boldsymbol{\xi}^0_{k'}(r,\theta,\phi)\,,$$



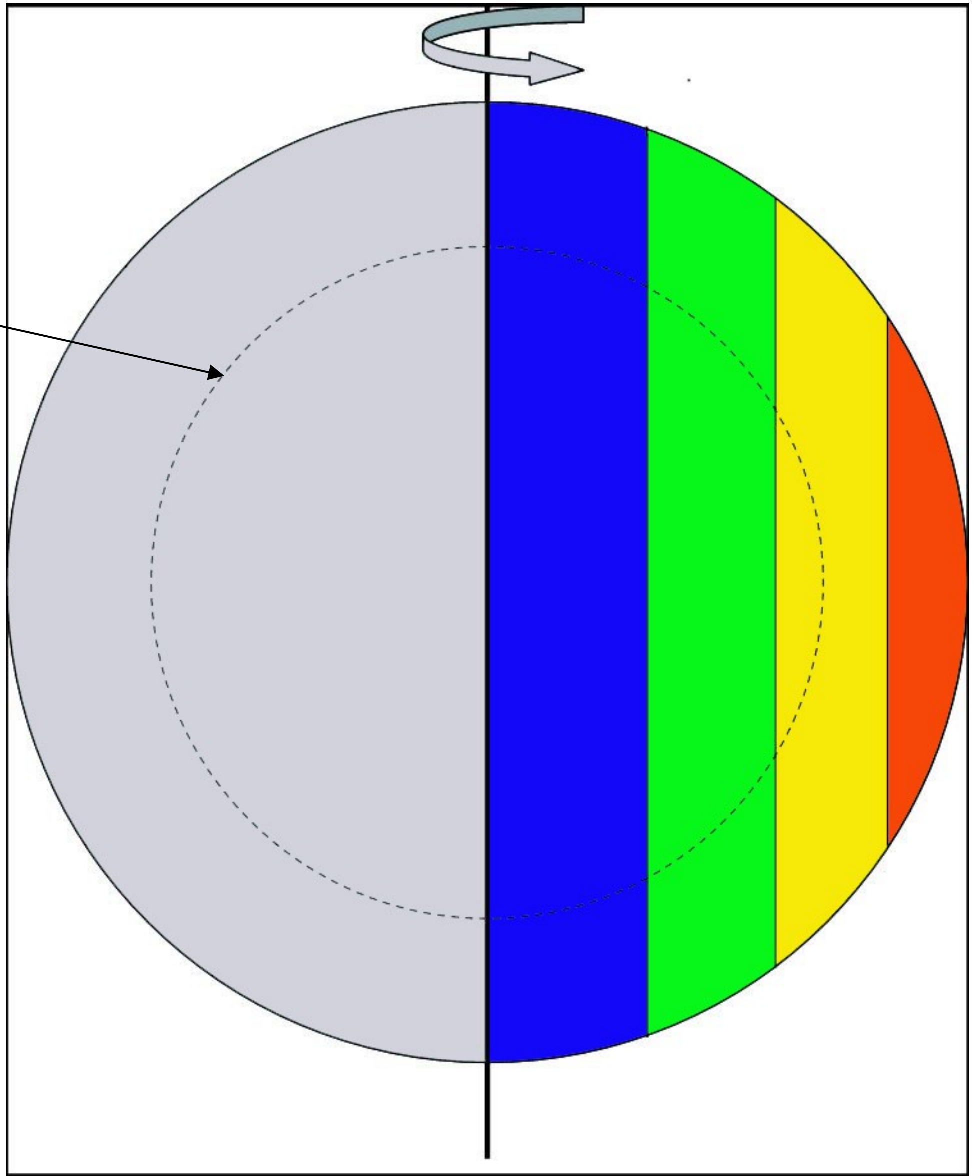
SHT + Spectralanalysis

Cross-talk between SH time series of adjacent (l,m)

Cross-spectral analysis of Dopplergrams

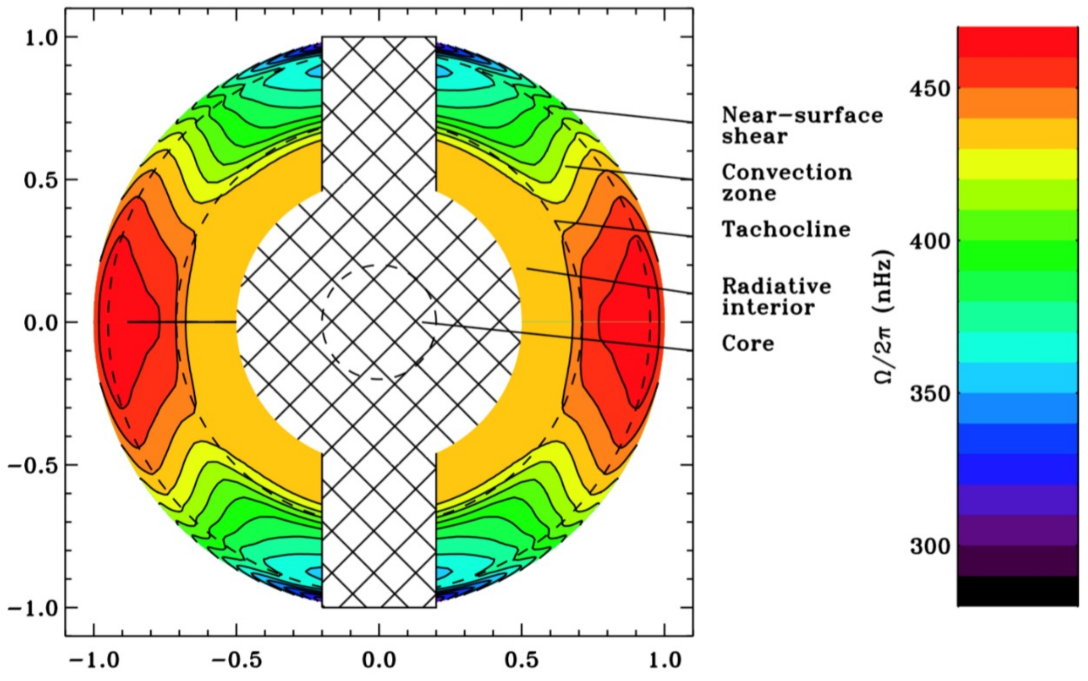
New:
Toroidal & Poloidal flows to be measured by measuring eigenfunction perturbations

What Theory predicted



Rotation in the Solar Interior

Long-term North-South average derived from 12 years of SoHO/MDI observations of “frequency splittings” (Howe 2009):



Below the surface:
Extended area of fast rotation

Depth: ca. 200.000 km
Width: ca. 500.000 km

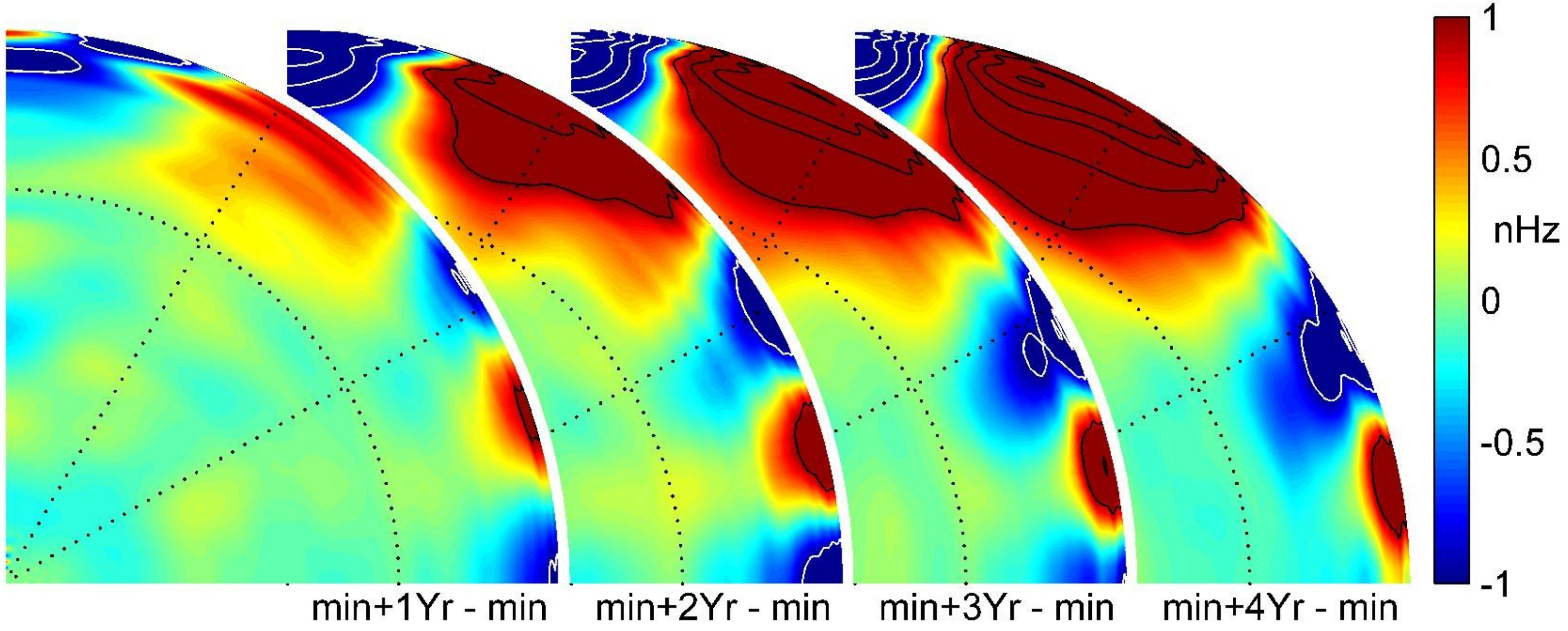
Red areas move faster than the blue areas by approximately 2000 km/h

Tachocline:
Shear layer at the bottom of the convection zone is important for generation of toroidal magnetic field

Higher latitudes & deep interior?

Rotational Residuals

Here we difference rotation inversions relative to solar minimum at successive 1-year epochs. The evolution of the rotation rate in the whole convection zone can be seen.



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Solar Rotation & Zonal Flows – Temporal Evolution

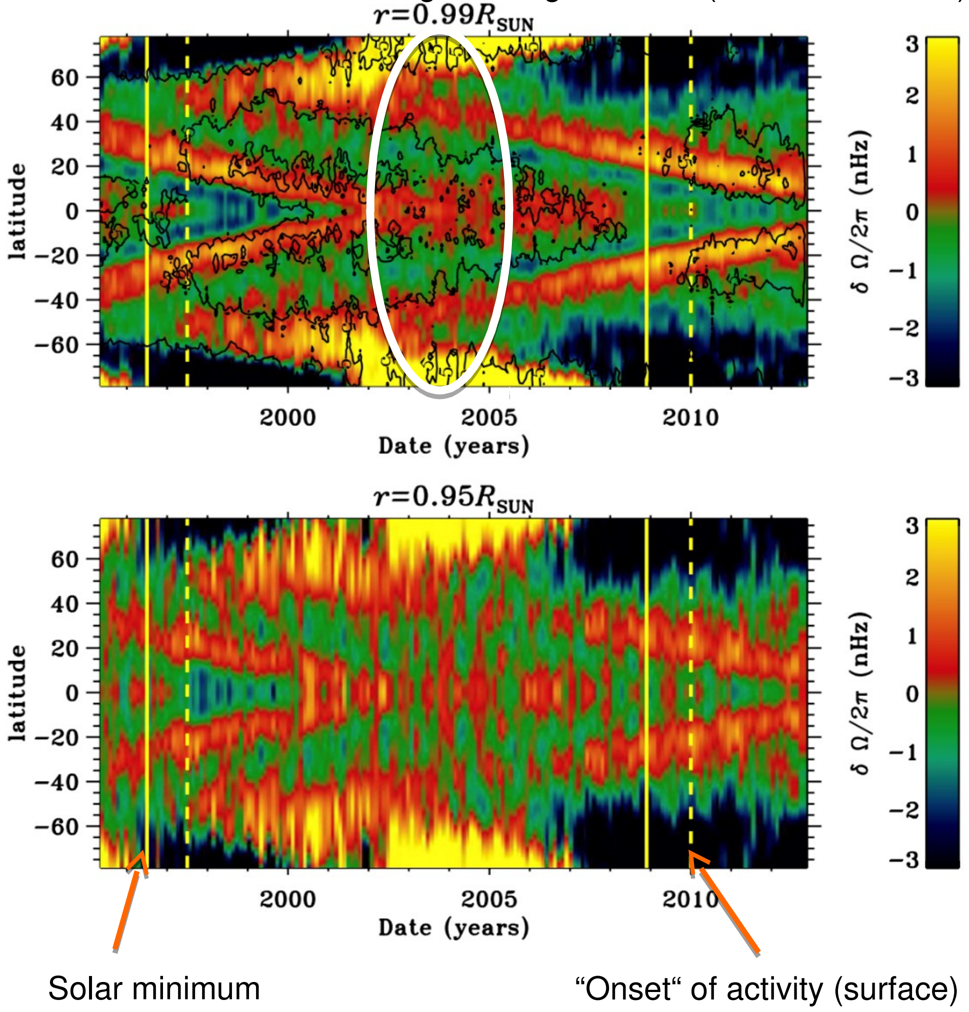
Torsional oscillations

- Temporal variations around mean rotation - equator/poleward propagating branches
- 1% of mean rotation
- Extends to the bottom of the convection zone (e.g. Vorontsov et al. 2002)

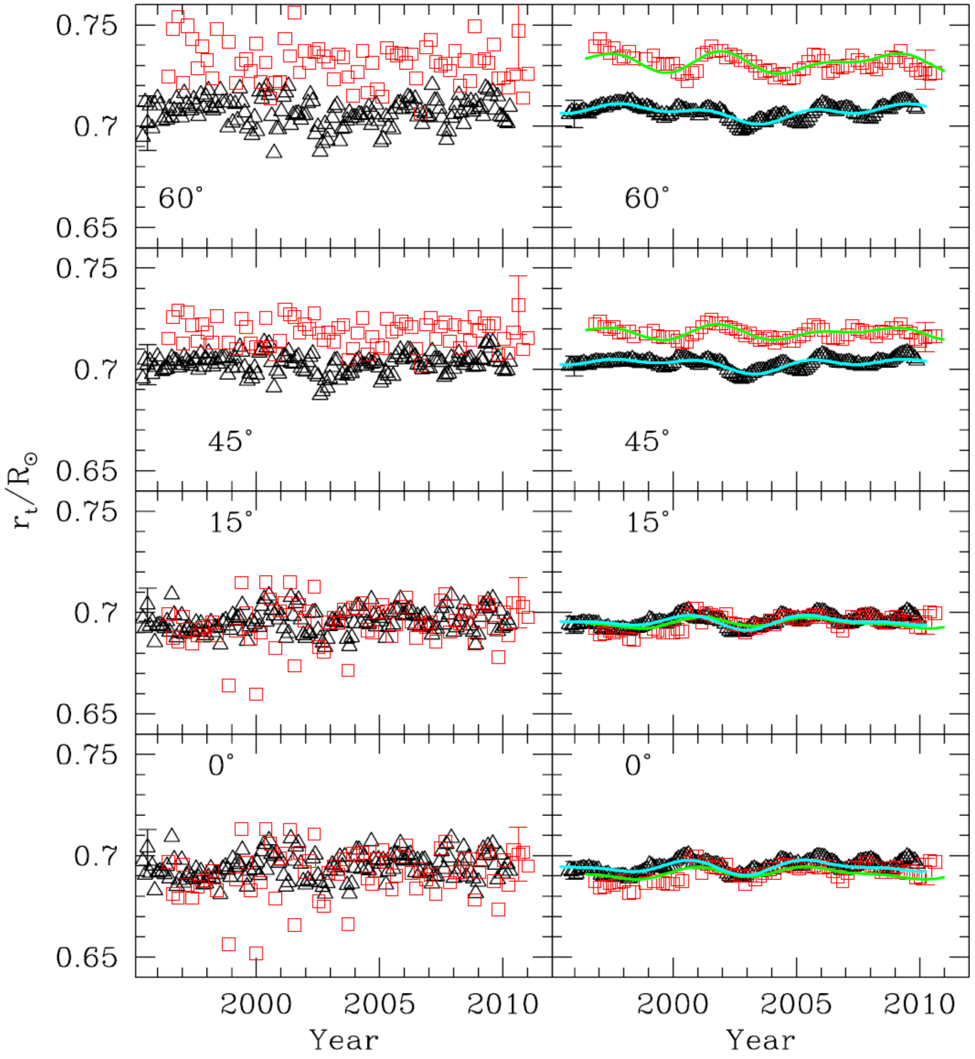
Precursor for upcoming surface activity? (Howe et al. 2011, 2013, Komm et al. 2014)

Connection to merdional flow?

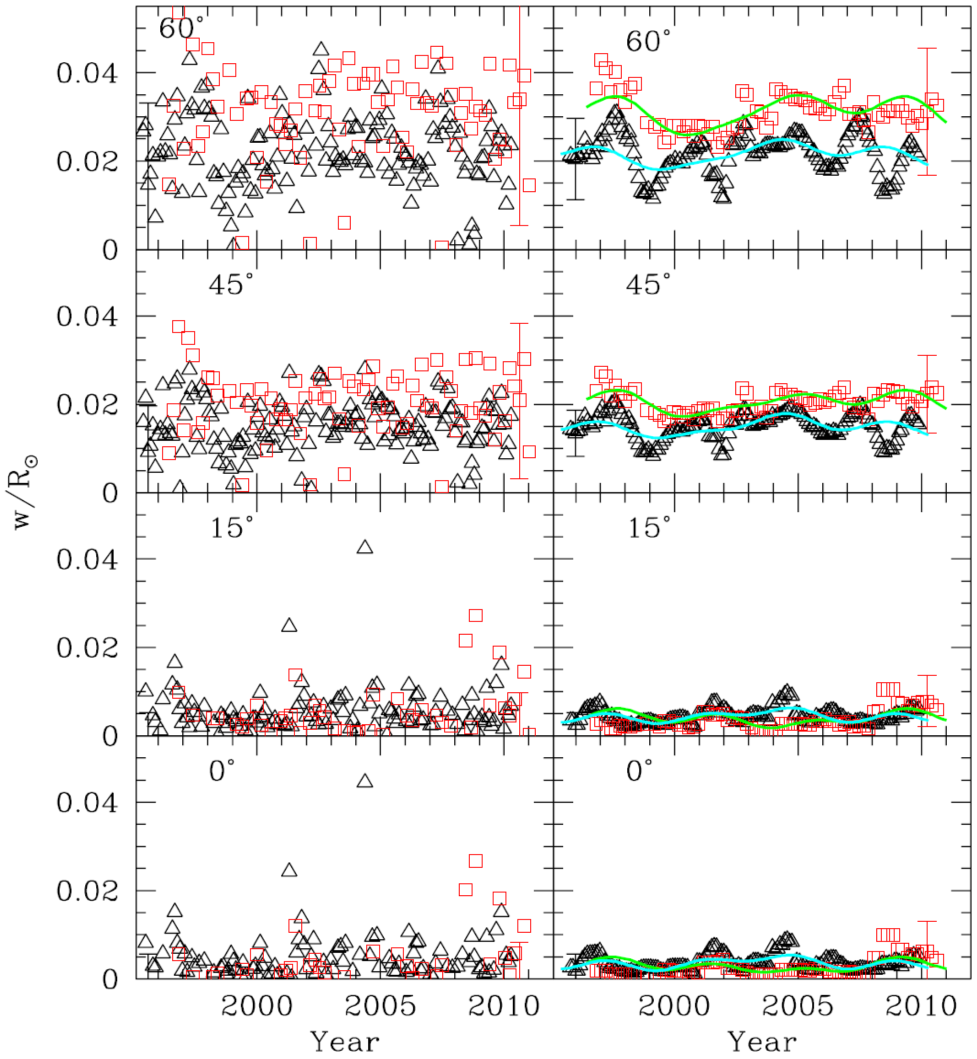
Flow residuals + unsigned magnetic field (Howe et al. 2013)



Mean Position of the Tachocline



Mean Width of the tachocline



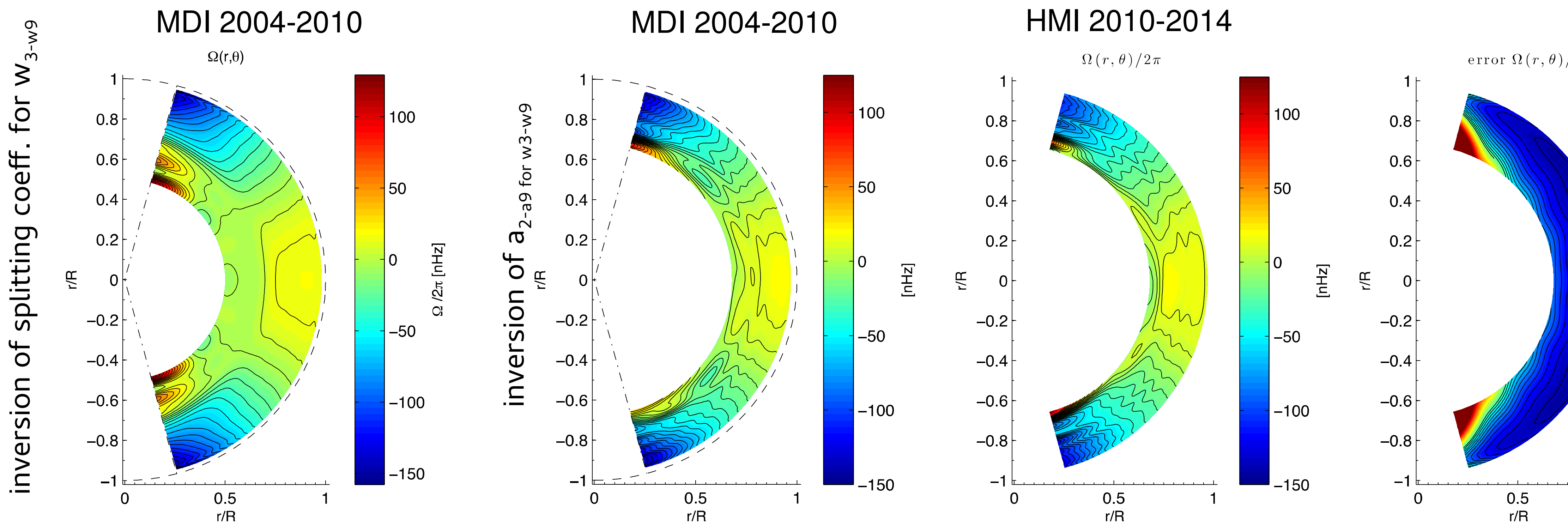
Red: MDI
Black: GONG

Prolate strucure of tachocline? Difference between 0° and 60°: 0.012±0.002 Rsun (GONG); 0.040±0.003 Rsun(MDI)
(Antia & Basu, ApJL, 2011)

Differential Rotation from Eigenfunction Perturbations

HISTORY OF SOLAR ACTIVITY RECORDED IN POLAR ICE

$$\Omega(r,\theta) r \sin\theta = -\sum_s w_s(r) \partial_\theta Y_s^0(\theta,\phi)$$



- Sensitive to **antisymmetric rotation rate component** ("frequency splittings" are not!)
- Interesting for differential rotation studies in depth

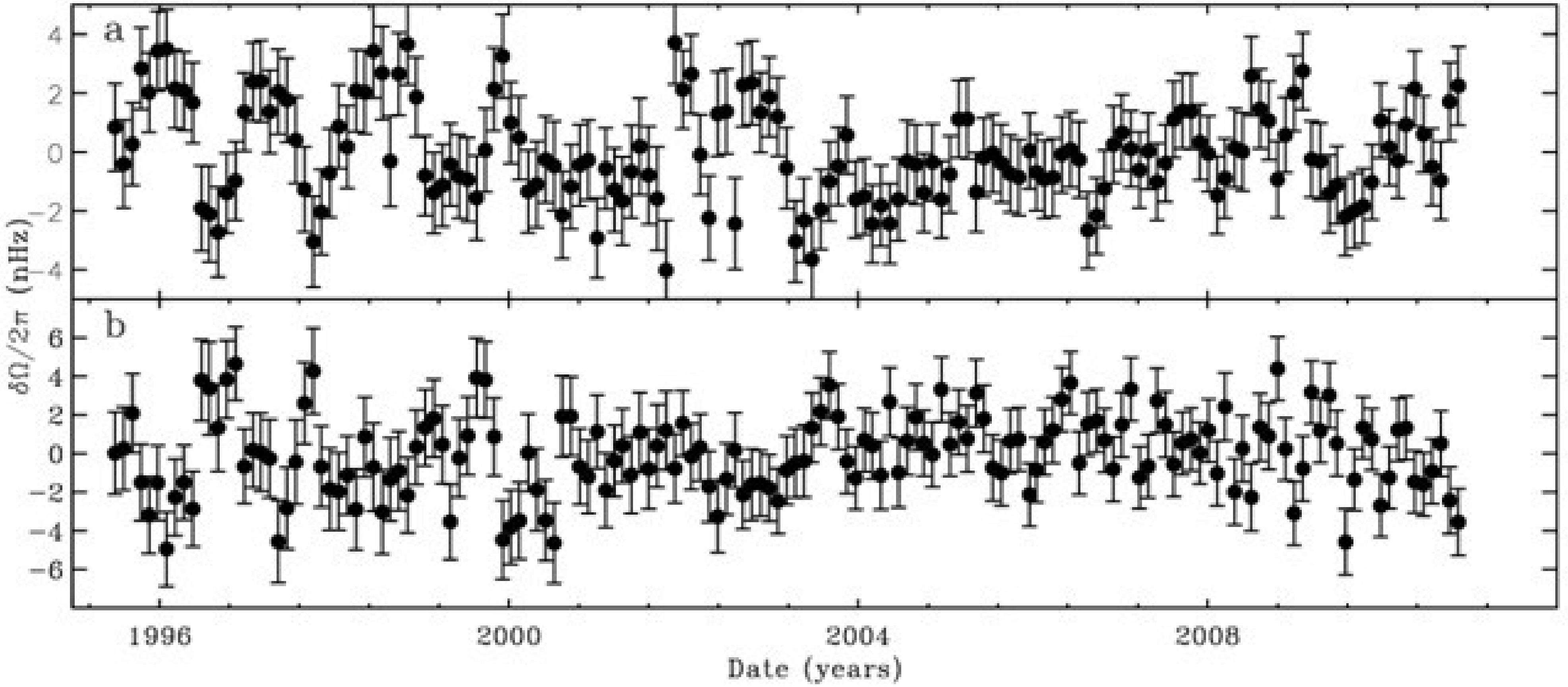
(Schad & Roth., in prep.)

Rotatonal Residues at the Base of the Convection Zone

At mean latitudes, there might be a quasi-periodic oscillation near the bottom of the convection zone.

Top: 0.72R

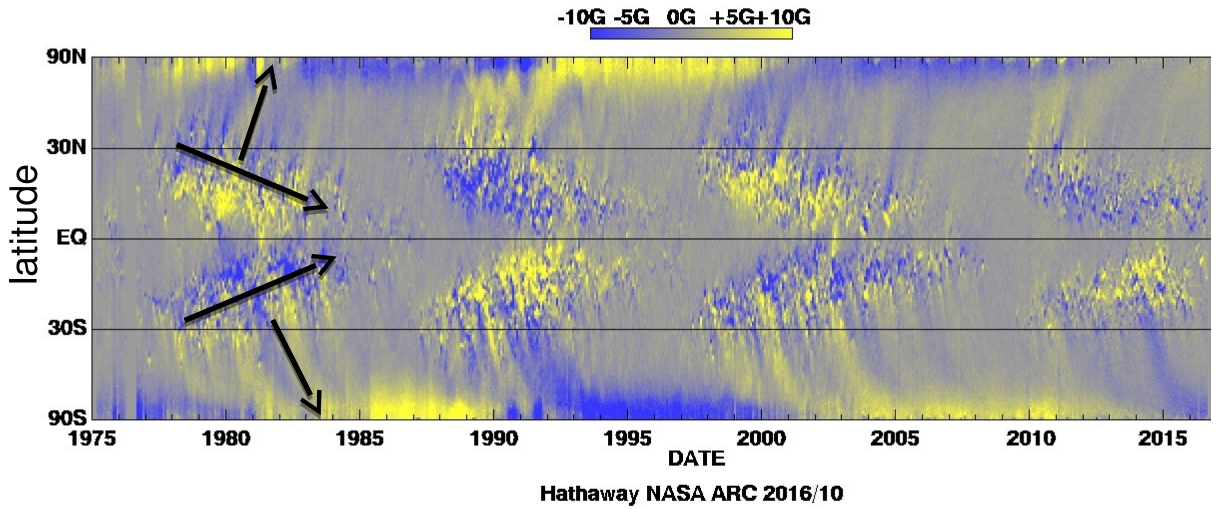
Bottom: 0.63R

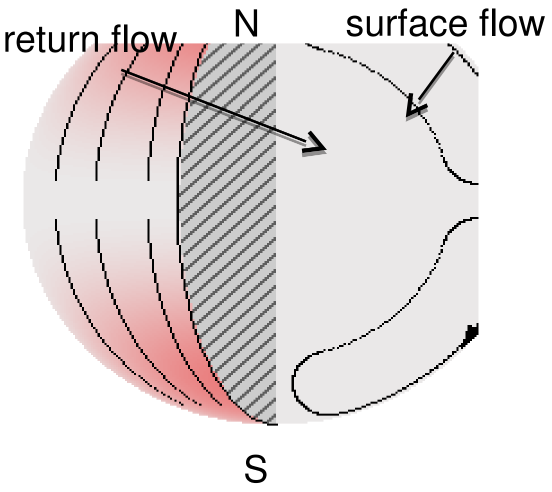


(See Howe, R., et al., Science, 2000)

The Solar Meridional Flow

Magnetic butterfly diagram





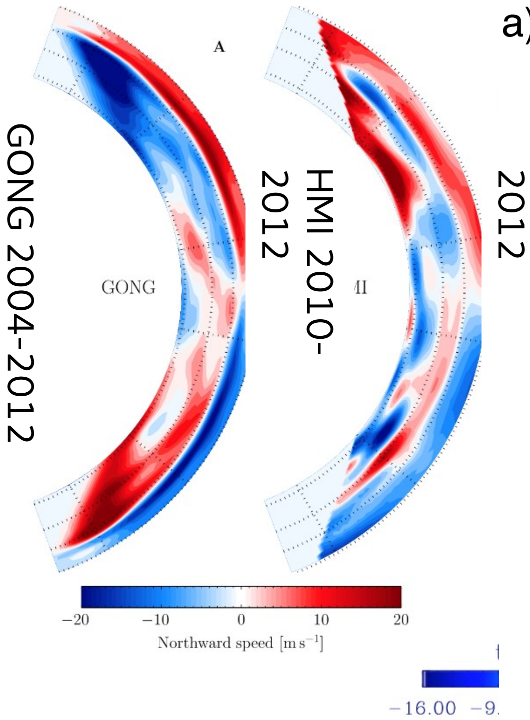
(Figure: Hathaway, NASA)

- Essential element of **flux transport dynamo models** (Wang & Sheeley 1991, Choudhuri et al. 1995, Dikpati & Schüssler 1999,...)
- Location & amplitude of return flow determines timing and strength of solar activity cycle (Hathaway et al. 2003, Dikpati et al. 2004,...)

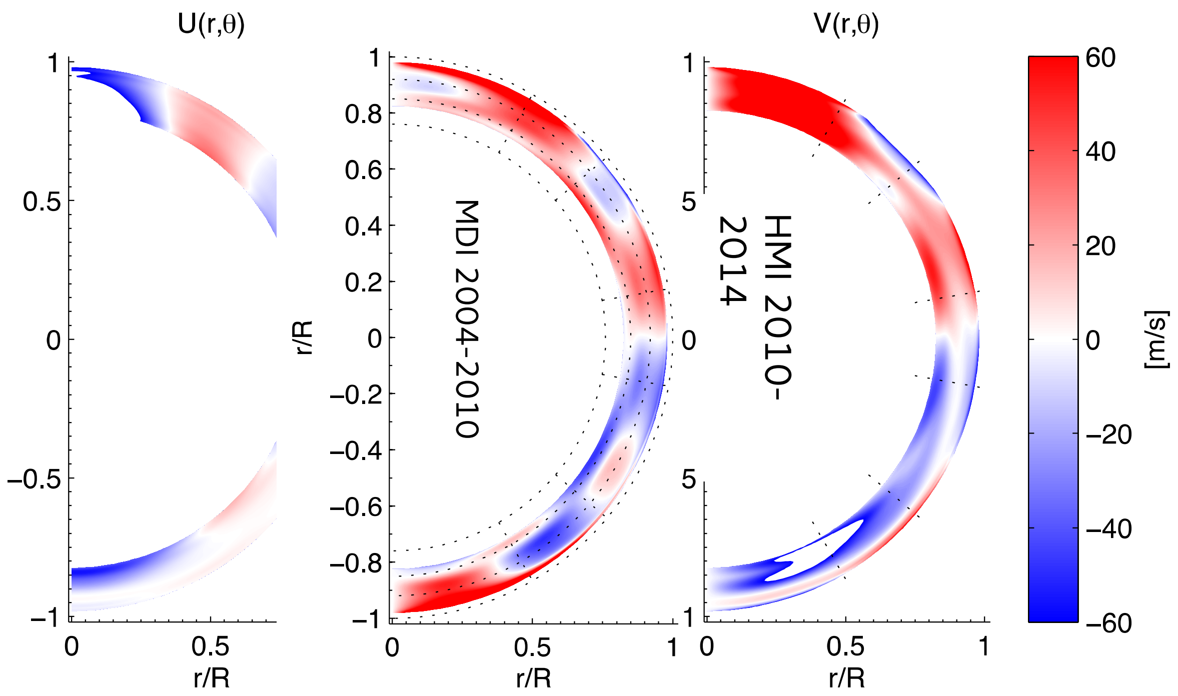
- **Where is the return flow?**

➢ Measurement of the flow profile in depth helps to constrain models/simulations of dynamo & convection zone (Dikpati et al. 2006, Miesch et al. 2012,...)

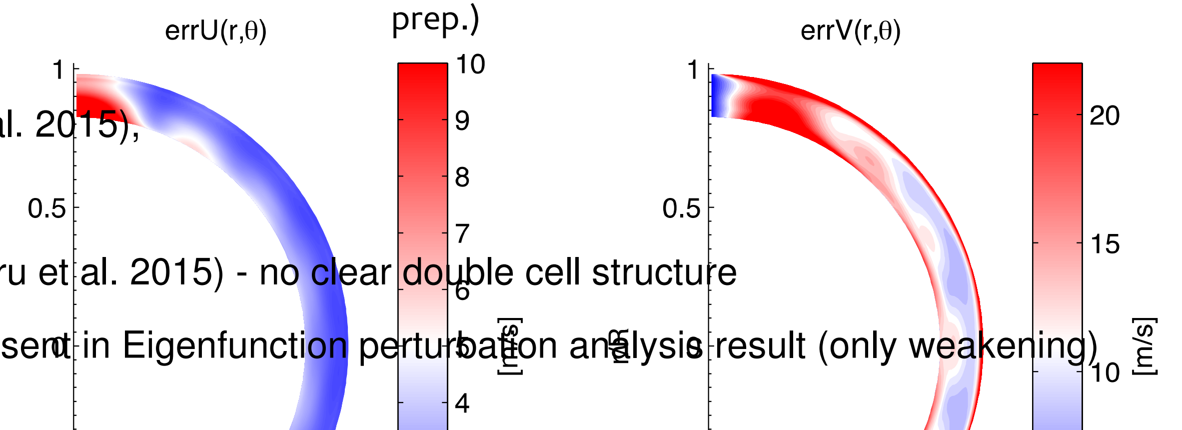
Comparison of Meridional Flow Measurements



(Jackiewicz et al. 2015; Zhao et al. 2015)



(Schad et al. 2013; Schad & Roth 2016 in prep.)



Various Results:

- **Single cell** (Jackiewicz et al 2015., Rajaguru et al. 2015);
  Double-cell flow (Zhao et al. 2013)
  Multiple "cells" (Schad et al. 2013);
  incorporating mass conservation to TDA (Rajaguru et al. 2015) - no clear double cell structure
- Flow reversal at 0.93 R by Time-Distance not present in Eigenfunction perturbation analysis result (only weakening)

Consequences of Helioseismic Results on Dynamo Models

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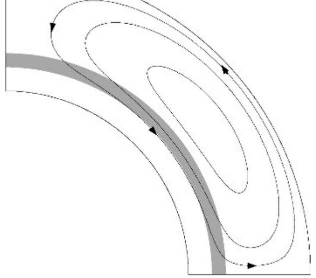
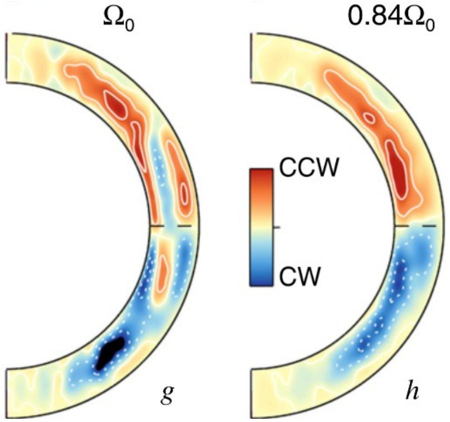
- Helioseismic results with multiple cells (depth, latitude) have inspired new dynamo simulations
  (e.g. Hazra et al. 2014, Belucz et al., 2015)

- Multiple cells produce solar-like dynamos given there is an equatorward flow near BCZ
  (Jouve et al. 2007, Hazra et al. 2014, Choudhuri 2015, Passos et al. 2016)

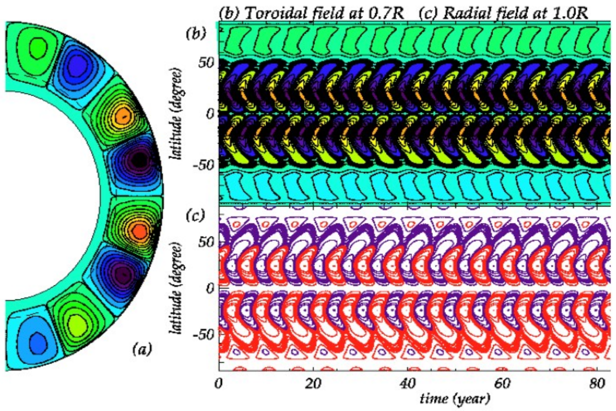
- HD convection simulations – Sun at transition from single to multiple meridional flow cells with anti-solar (poles faster) to solar rotation (poles slower) profile
  (e.g., Featherstone et al., 2015)

(Nandy, 2004)

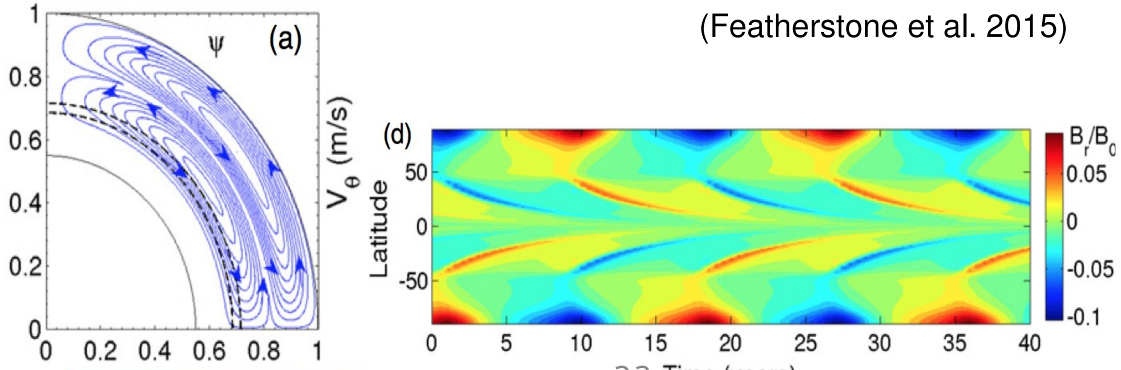




(Featherstone et al. 2015)



(Belucz et al., 2015)



(Hazra et al. 2014)

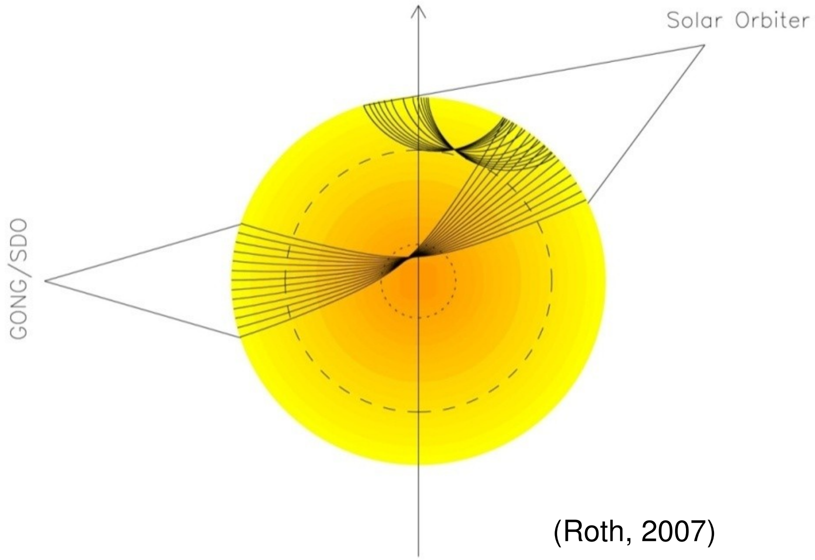
Summary

Helioseismology provides insight on tachocline region

- Always an average over time & longitude
- Classical helioseismology in addition averages over North & South
- New methods are under development t
  tachocline region

In Future:

Hope on Solar Orbiter to provide possiblities for stereoscopic seismology



(Roth, 2007)