Helioseismology of high-latitude regions

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Outline

- Current status of helioseismology measurements at high latitudes
- Diagnostics of the tachocline
- Key questions and expected results of Solar-C observations
- Instrument requirements

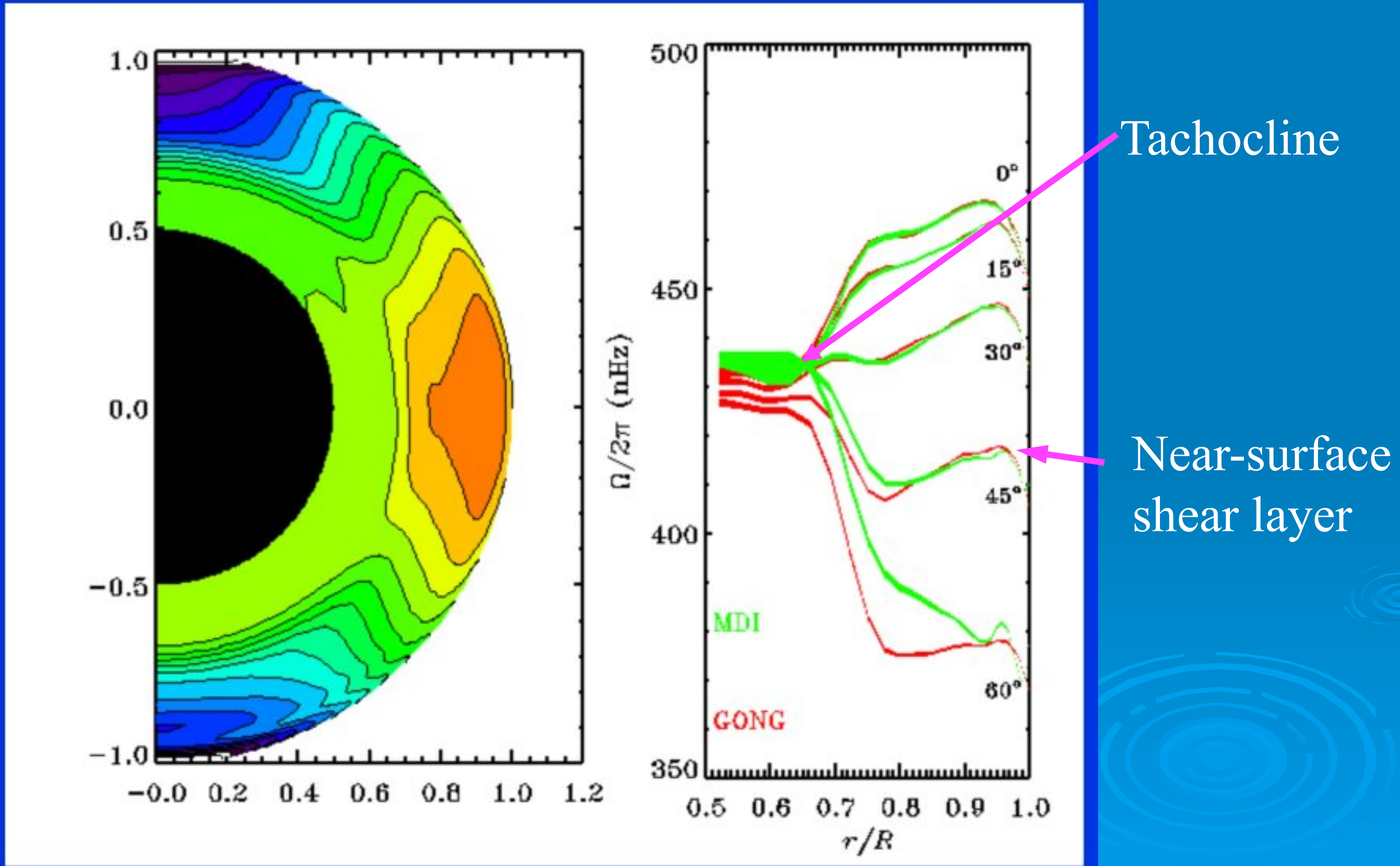
Solar-C Helioseismology Science Objectives

1. Differential rotation and torsional oscillations at high latitudes, polar jets
   - Global modes l=0-250
   - Local helioseismology
2. Meridional circulation, latitudinal and longitudinal structures, secondary cells, relationship to active longitudes, magnetic flux transport
   - Local helioseismology
3. Supergranulation and large-scale convection patterns in polar regions (super-rotation, wave-like behavior, network, flux transport, relationship to coronal holes)
   - Local helioseismology
4. Structure and dynamics of the high-latitude tachocline (oblateness, flows)
   - Local helioseismology
5. Tomography of the deep interior: stereo observations (Solar-C-SDO-GONG)
   - Local Helioseismology (time-distance, holography)

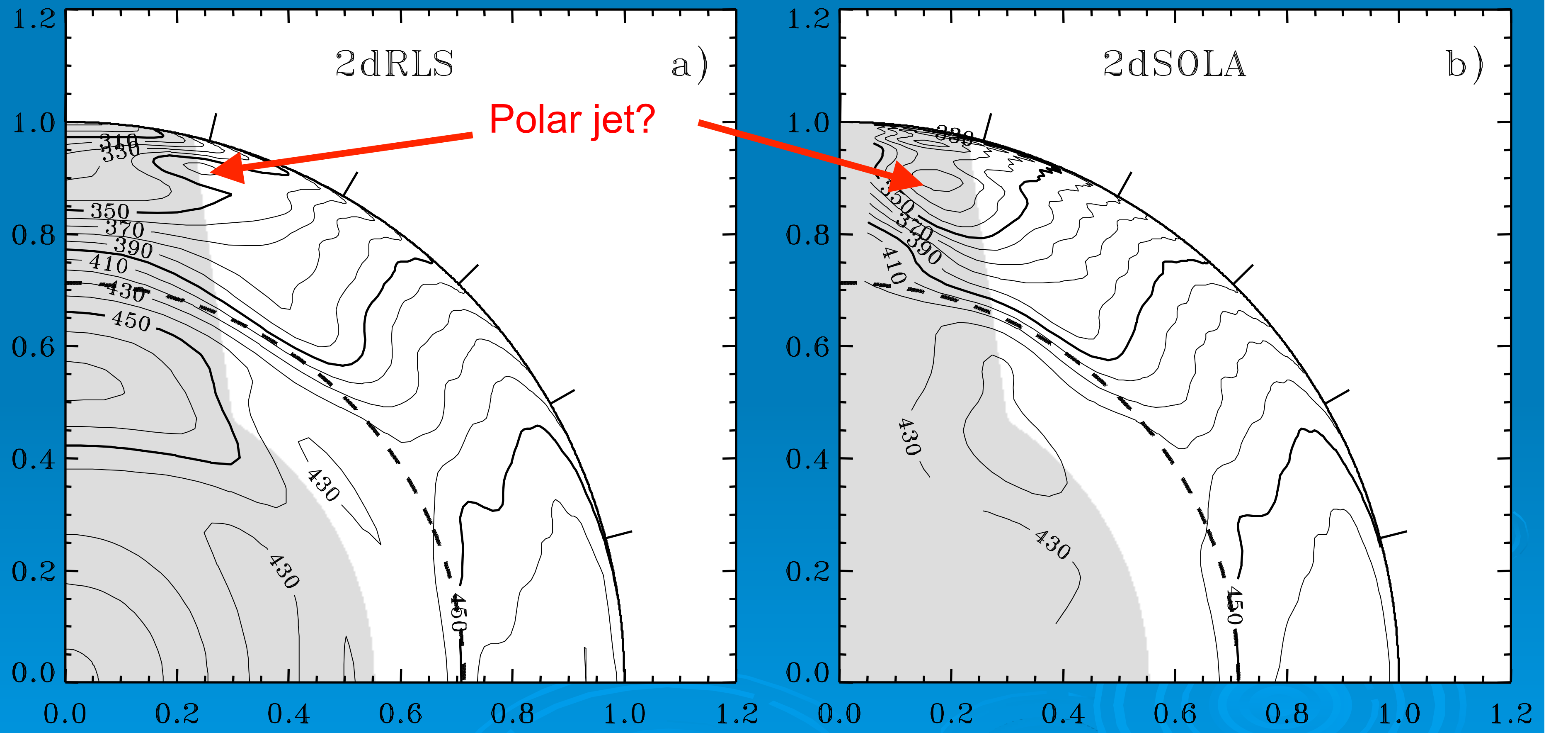
Current Status of Helioseismology

- The internal structure and differential rotation are measured with great precision throughout the Sun except the polar regions (75-90 deg latitude), the energy-generating core and the subsurface superadiabatic layer. (Global helioseismology)
- Large-scale dynamics (supergranulation, large-scale flows around magnetic regions, zonal and meridional flows) is being investigated in details in the mid-latitude zone from -60 to 60 degrees in the upper convection zone, 30 Mm deep. (Local helioseismology)

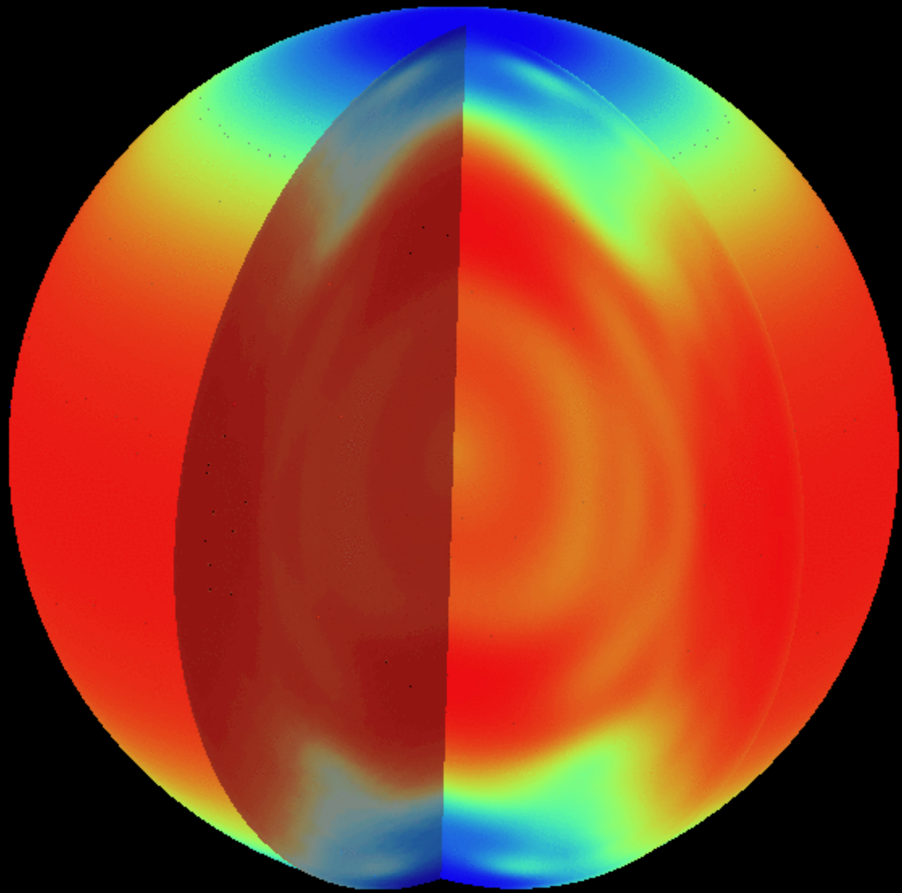
Internal Rotation



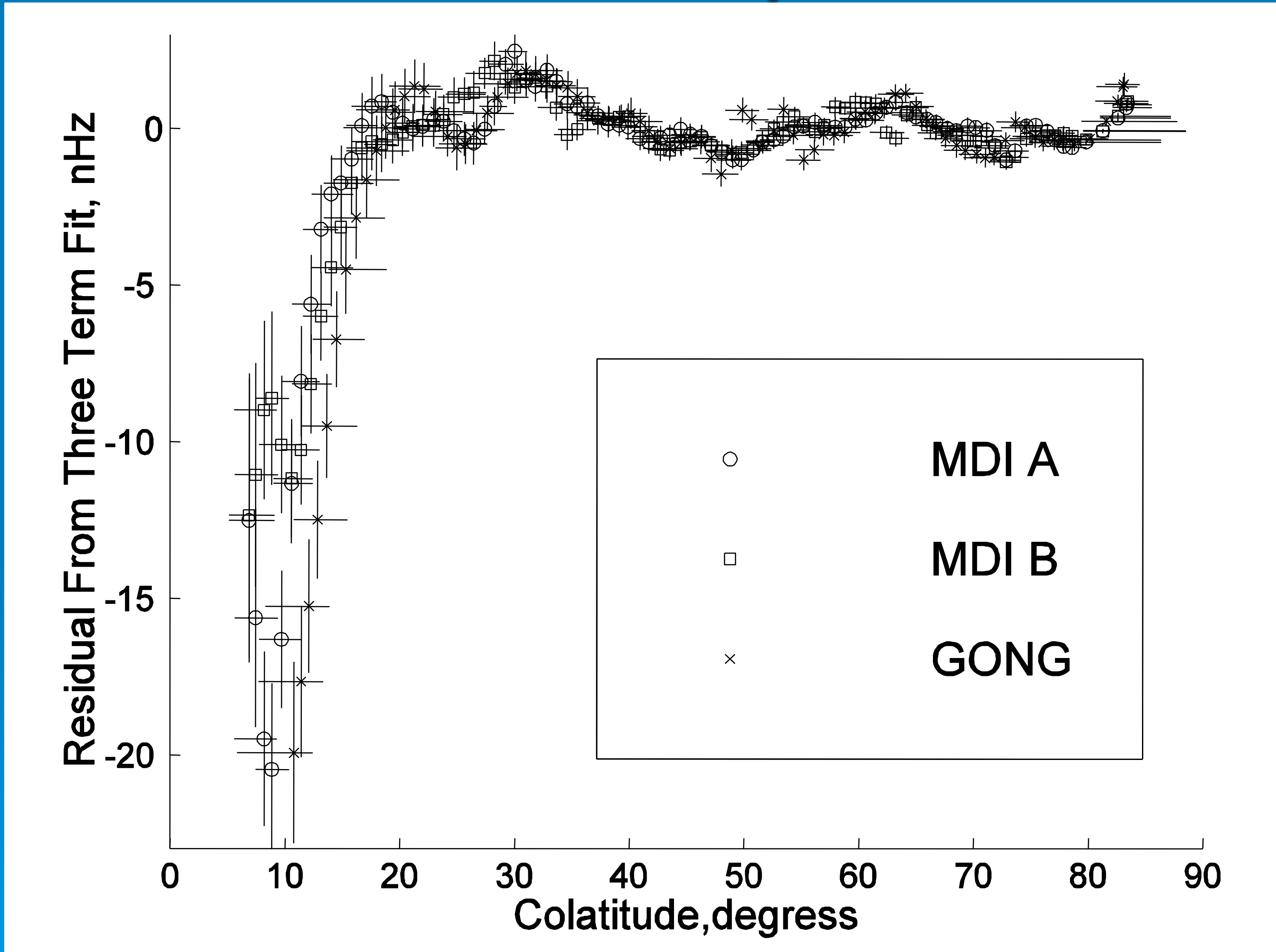
Internal differential rotation inferred from SOHO/MDI data by two different inversion techniques (in the shaded areas the inferences are uncertain)



Internal differential rotation (red – faster; blue – slower)

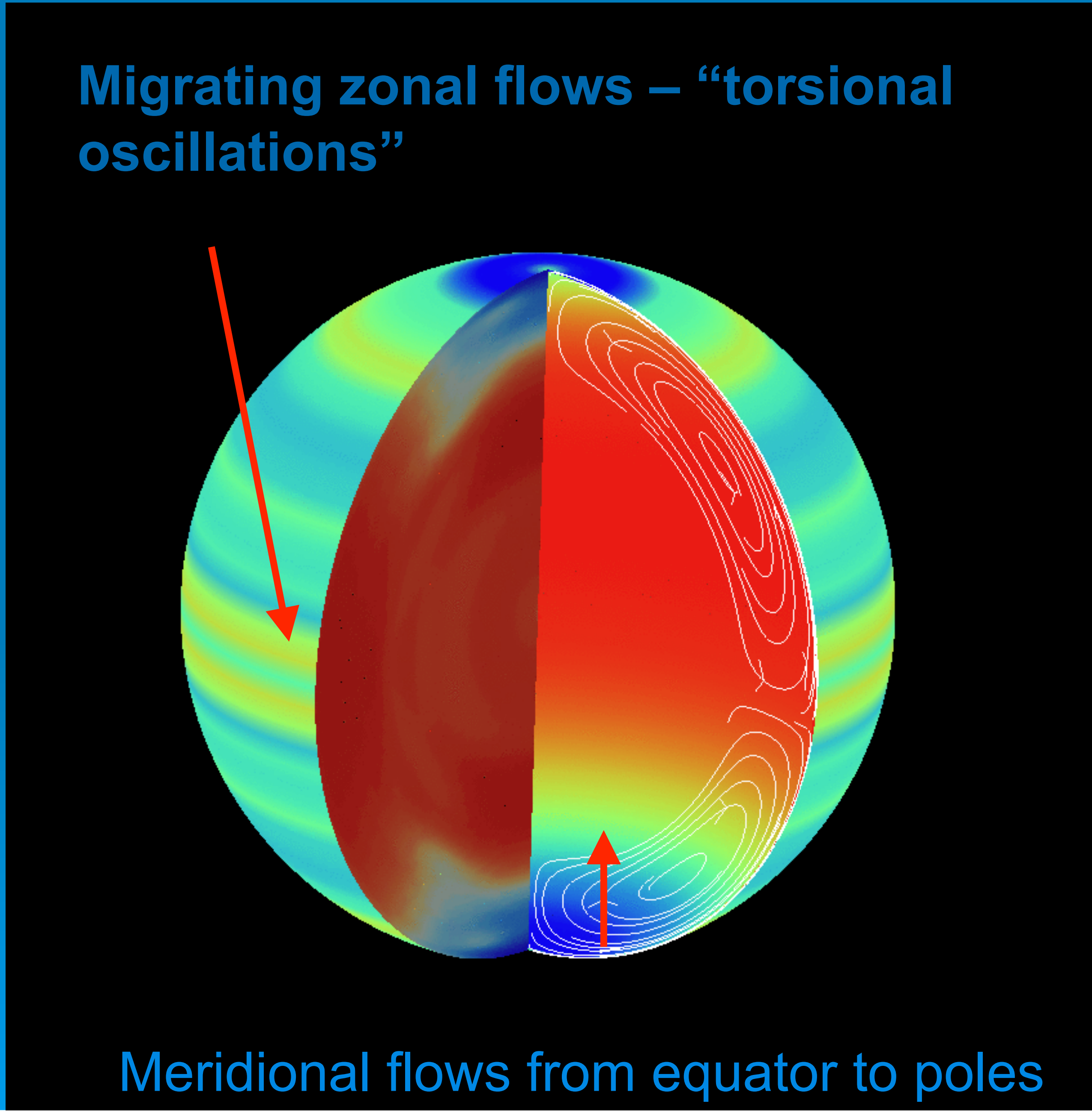


Evidence for slow polar rotation

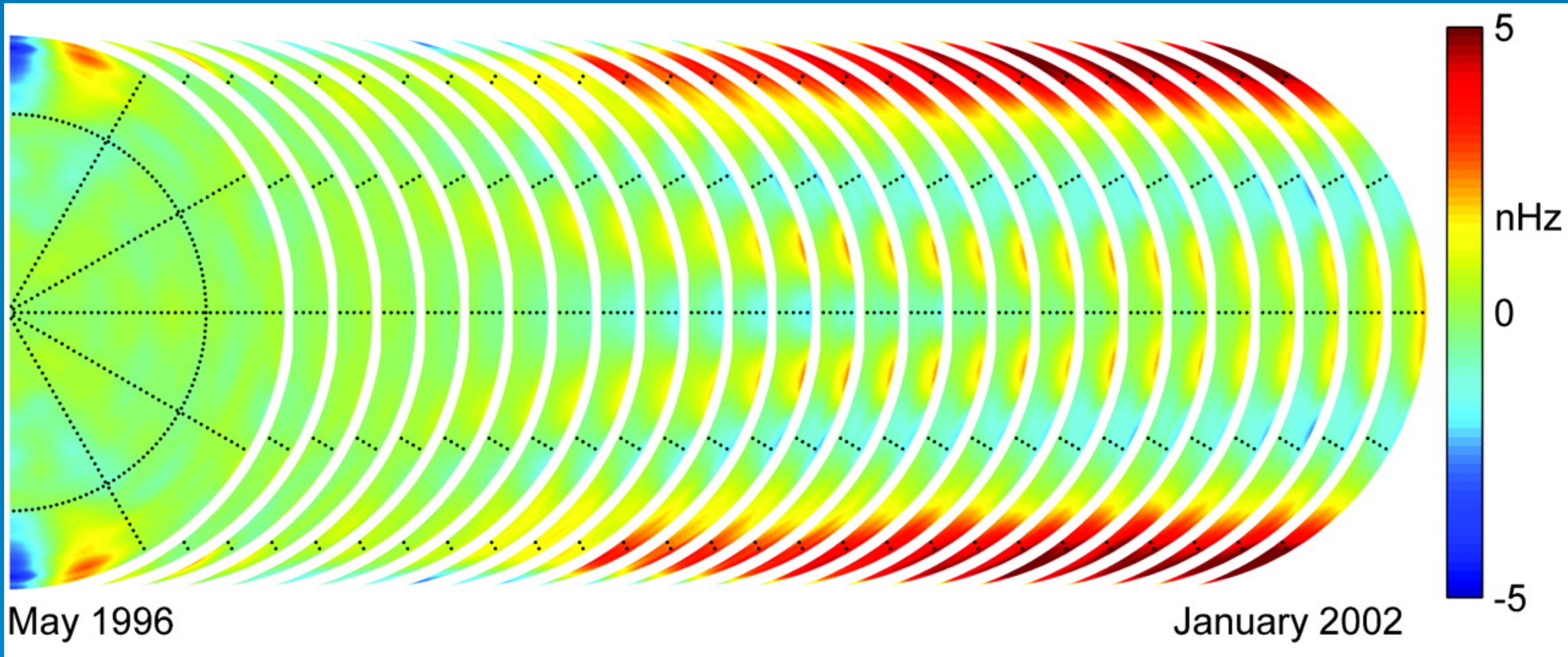


Birch & Kosovichev (1998)

Variations of differential rotation with time

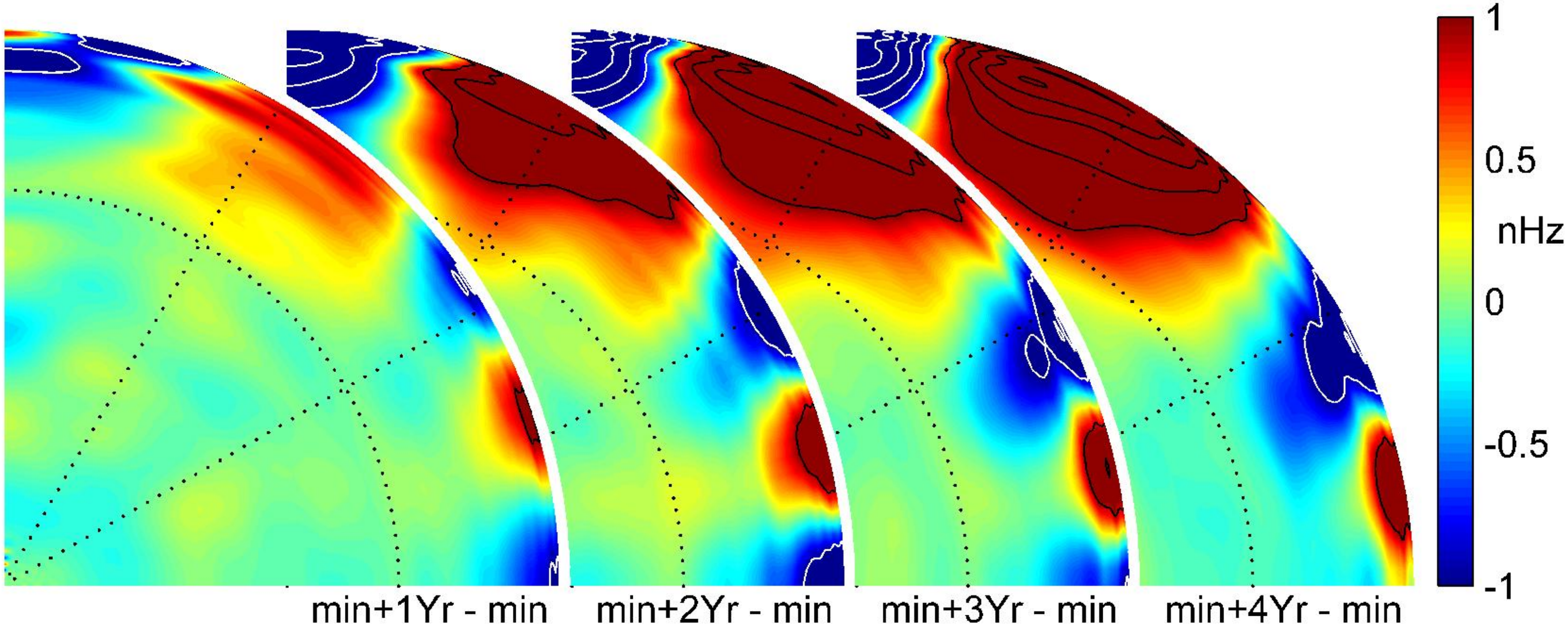


Variations of differential rotation with the solar cycle

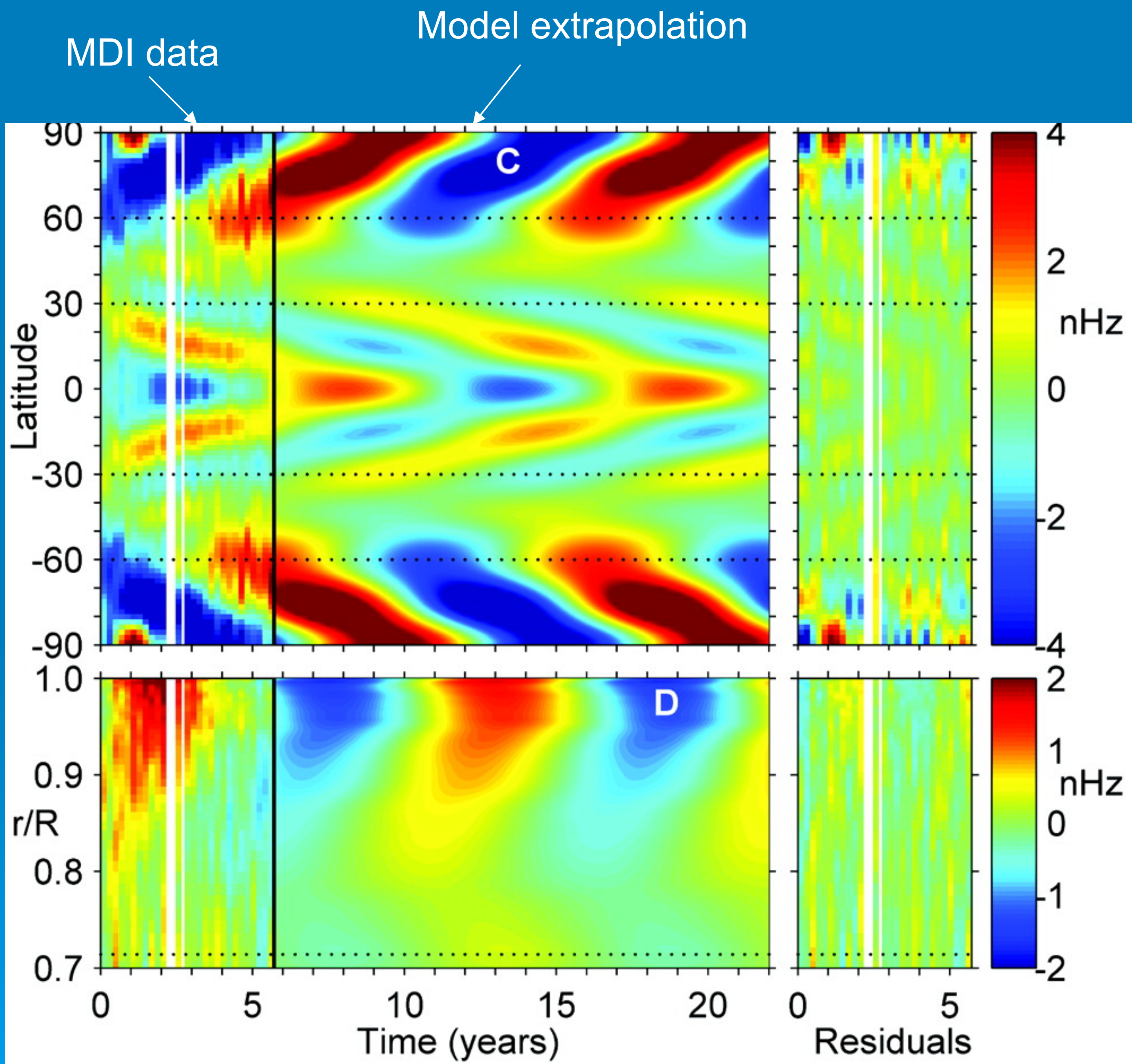


Vorontsov et al (2002)

The depth structure of the torsional oscillations
-migrate to the surface along the isorotation lines,
-penetrate to the tachocline in high-latititude regions

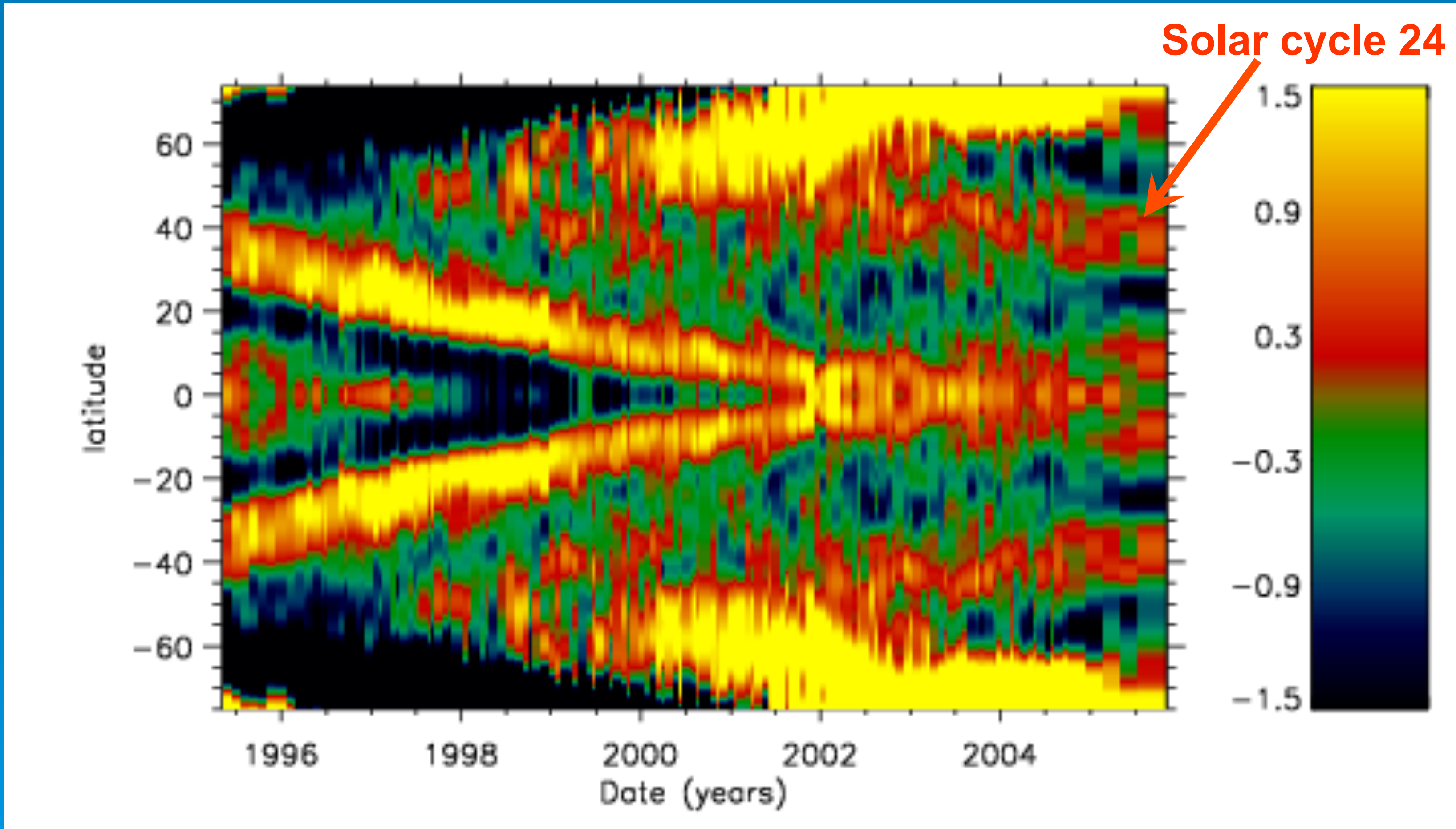


Vorontsov et al. 2002



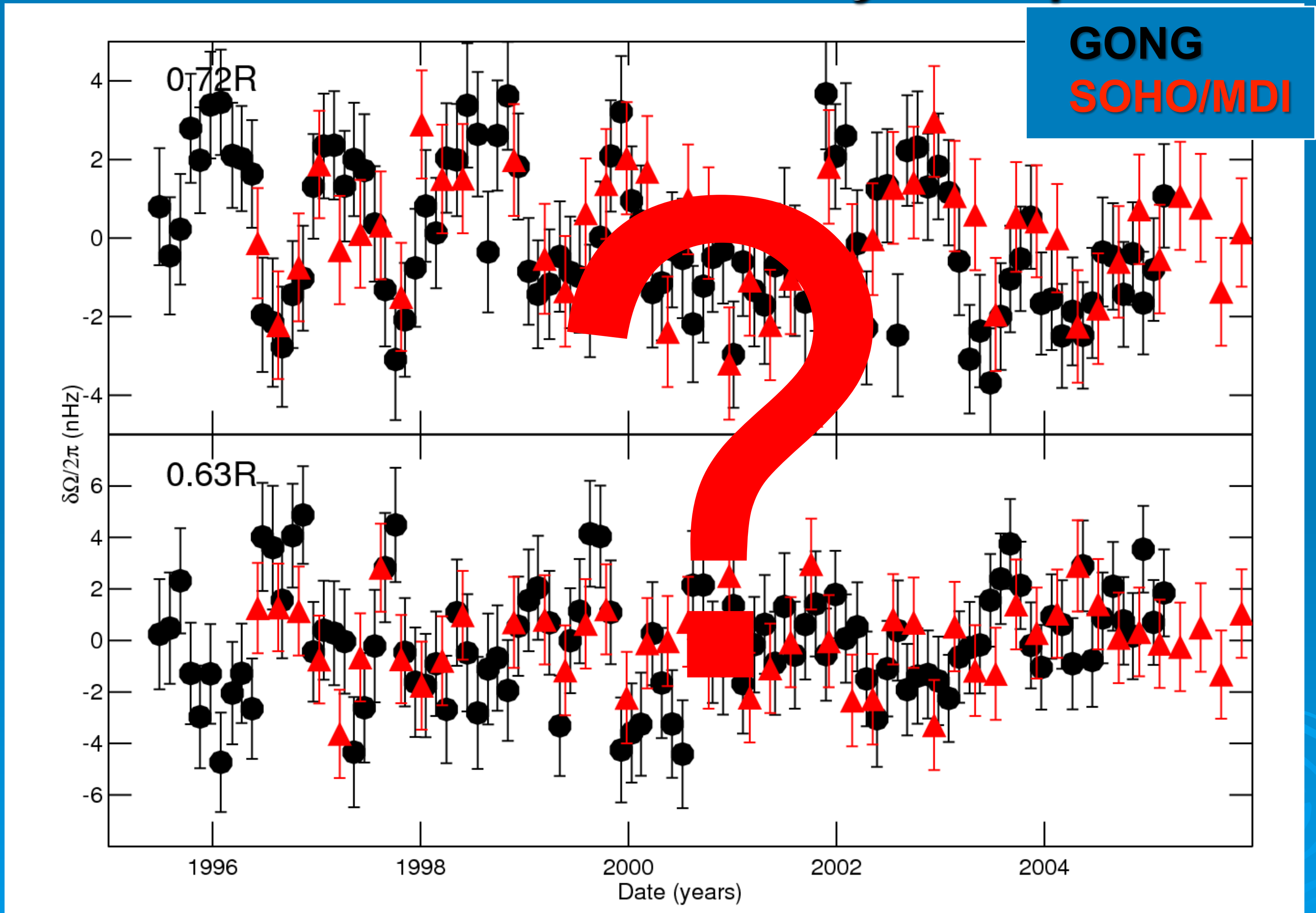
MDI data
Model extrapolation
90
60
30
0
-30
-60
-90
Latitude
C
4
2
nHz
0
-2
-4
1.0
0.9
r/R
0.8
0.7
D
2
1
nHz
0
-1
-2
0
5
10
15
20
Time (years)
0
5
Residuals

Torsional oscillations show a start of the new cycle at high latitudes where there is no significant magnetic field

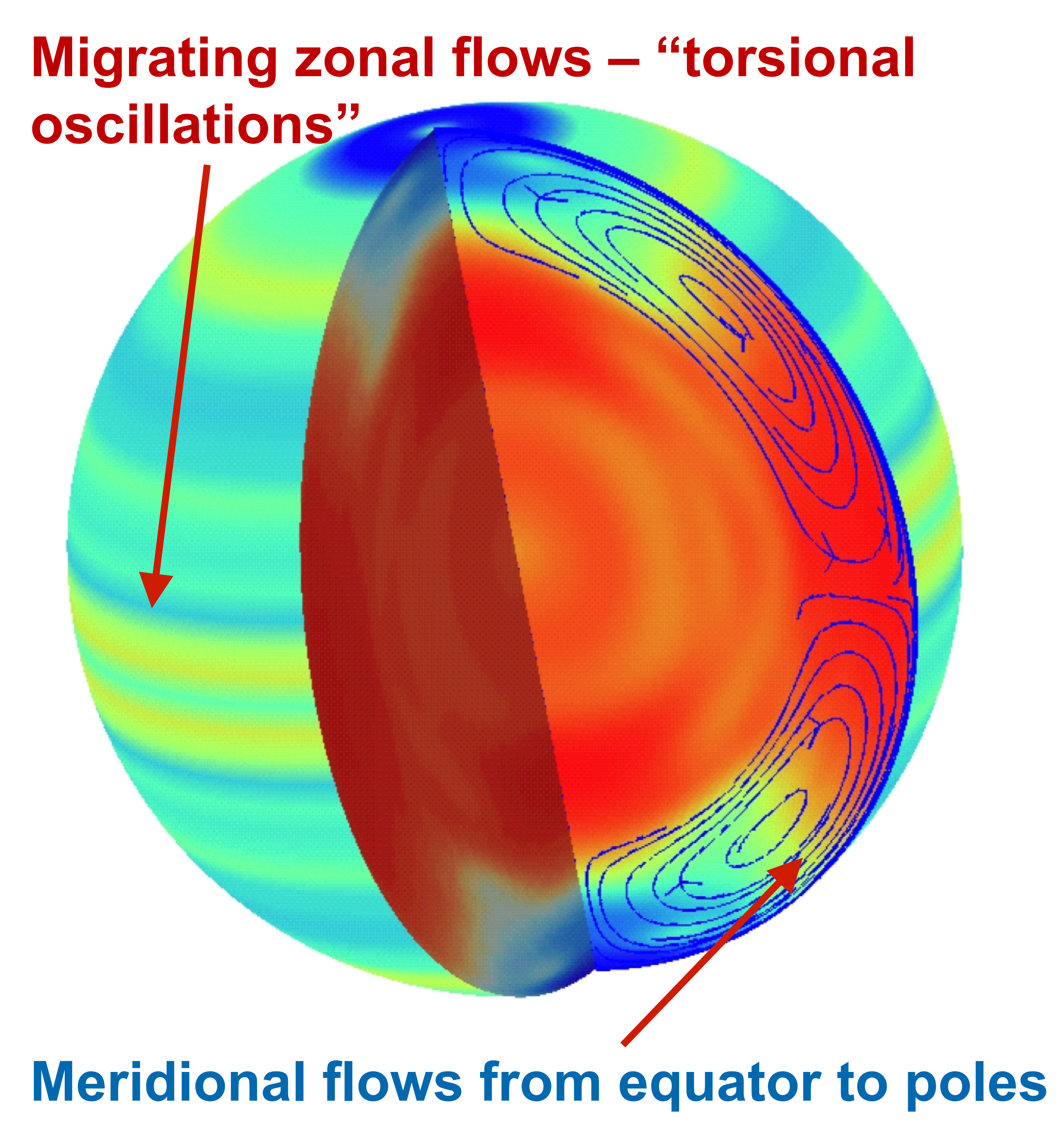


Howe et al (2006)

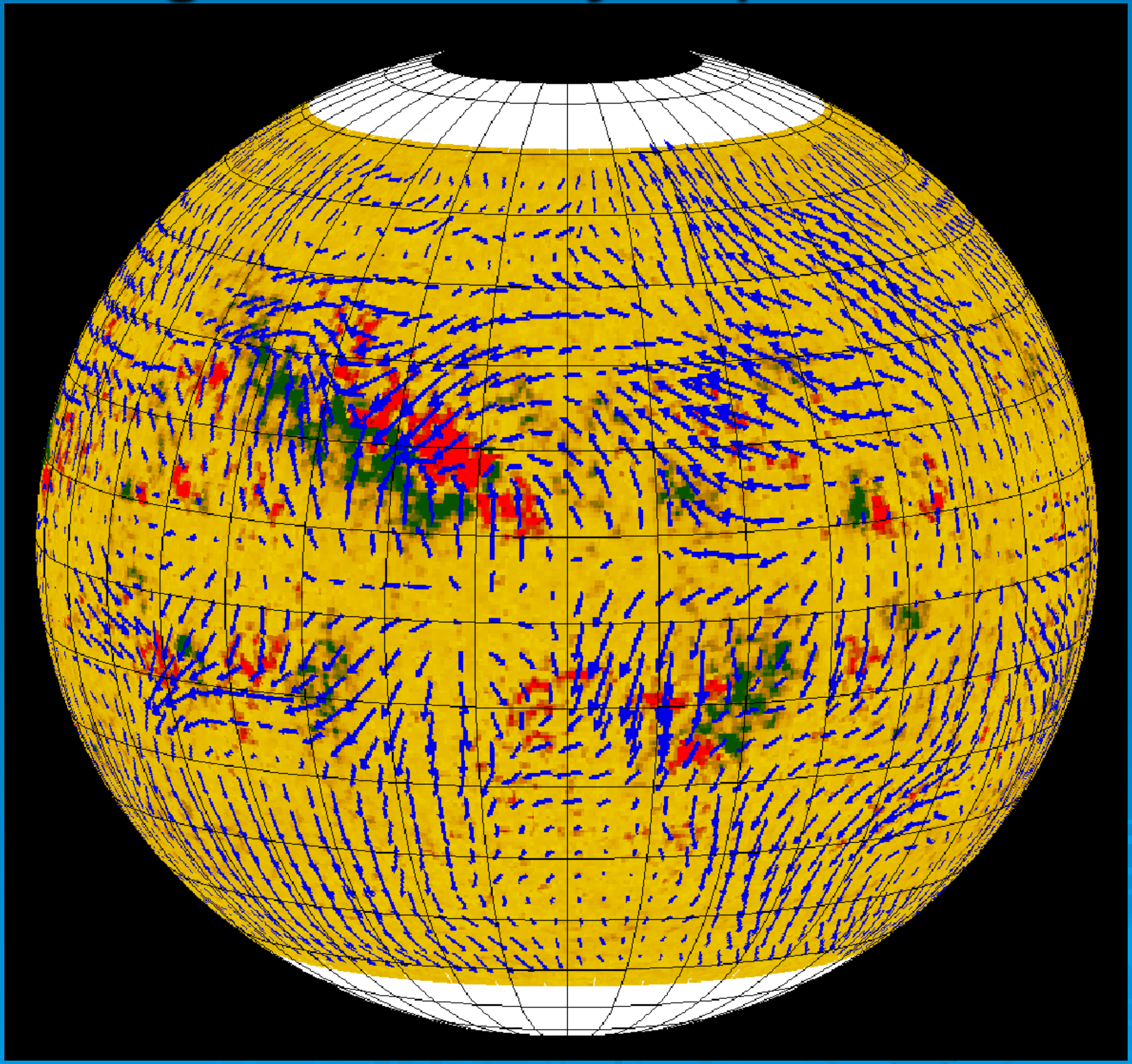
Rotation speed variations in the tachocline:1.3-year period?



Meridional flows

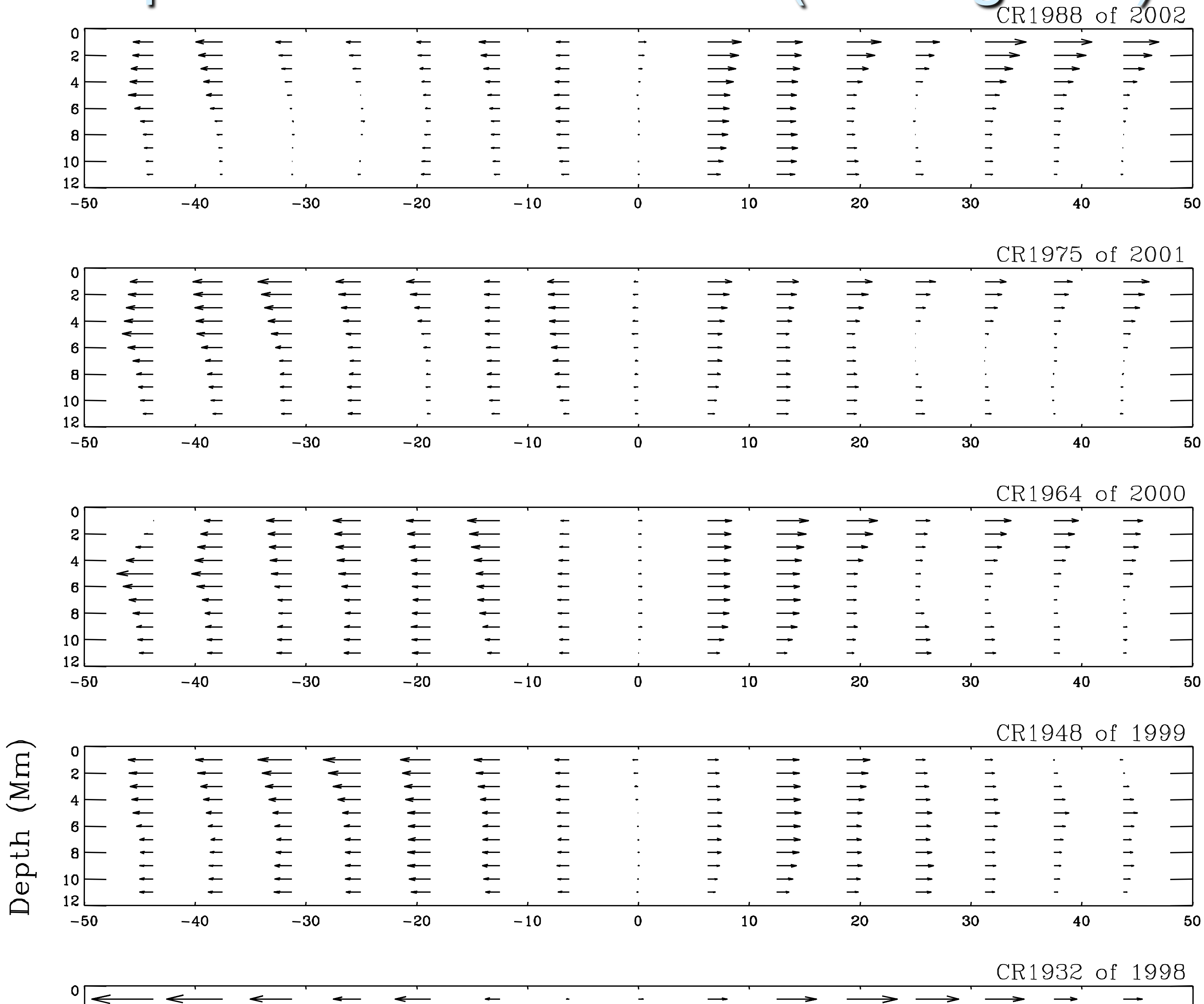


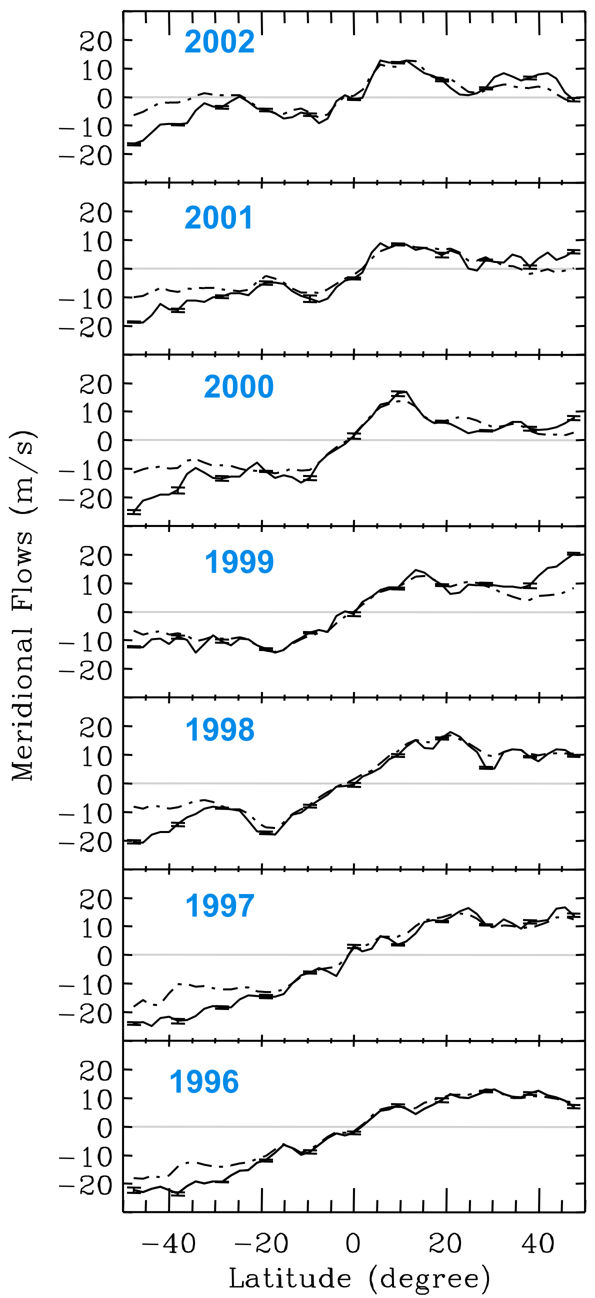
Meridional flows can be measured from the large-scale synoptic flow maps



(Haber et al. 2002)

Meridional circulation is measured from the equator to mid-latitudes (50 degrees)

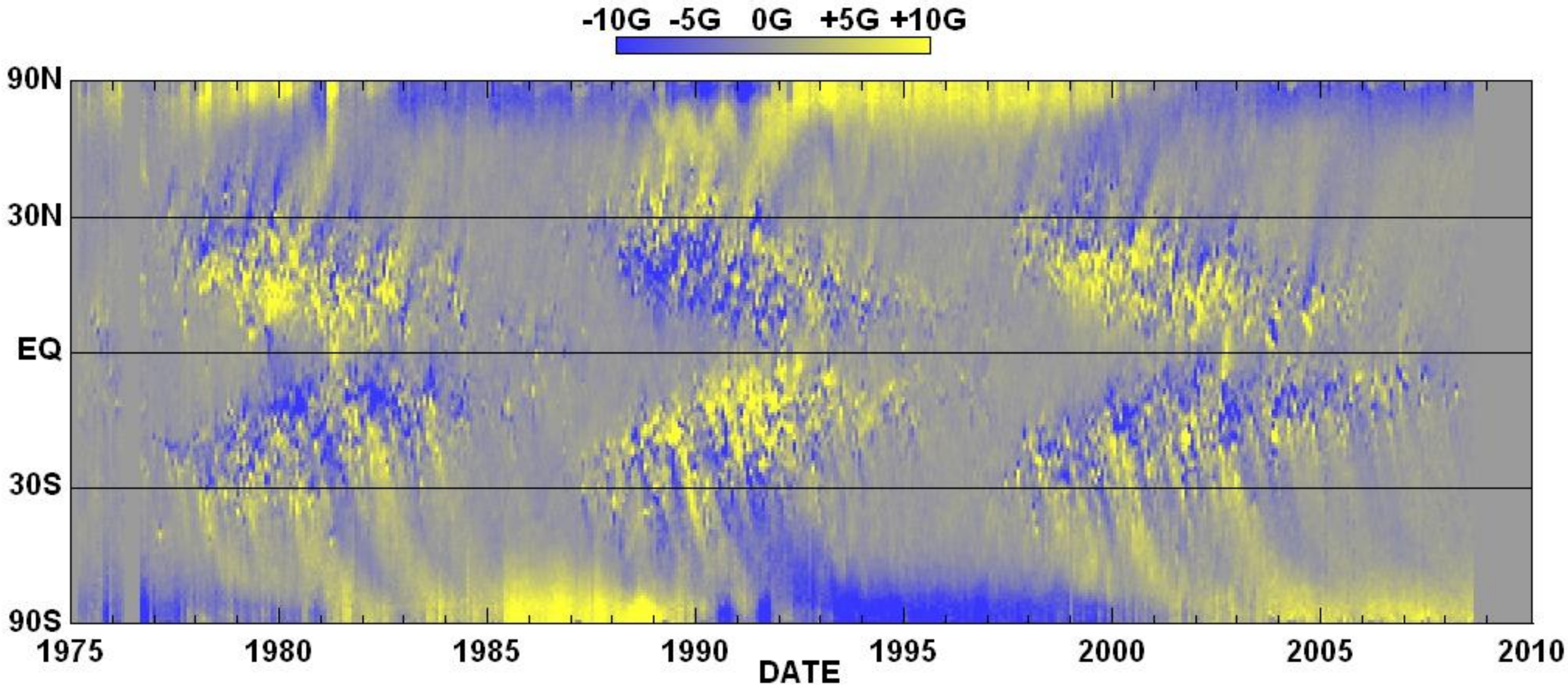




Solar-cycle variations of meridional circulation

- In addition to the mean meridional flow from the equator to the poles we find extra meridional circulation cells converging towards the activity belts and migrating towards the equator as the solar cycle progresses
- Slowing meridional circulation at the solar maximum creates difficulties for flux transport dynamo models to explain reversals of the polar magnetic fields.

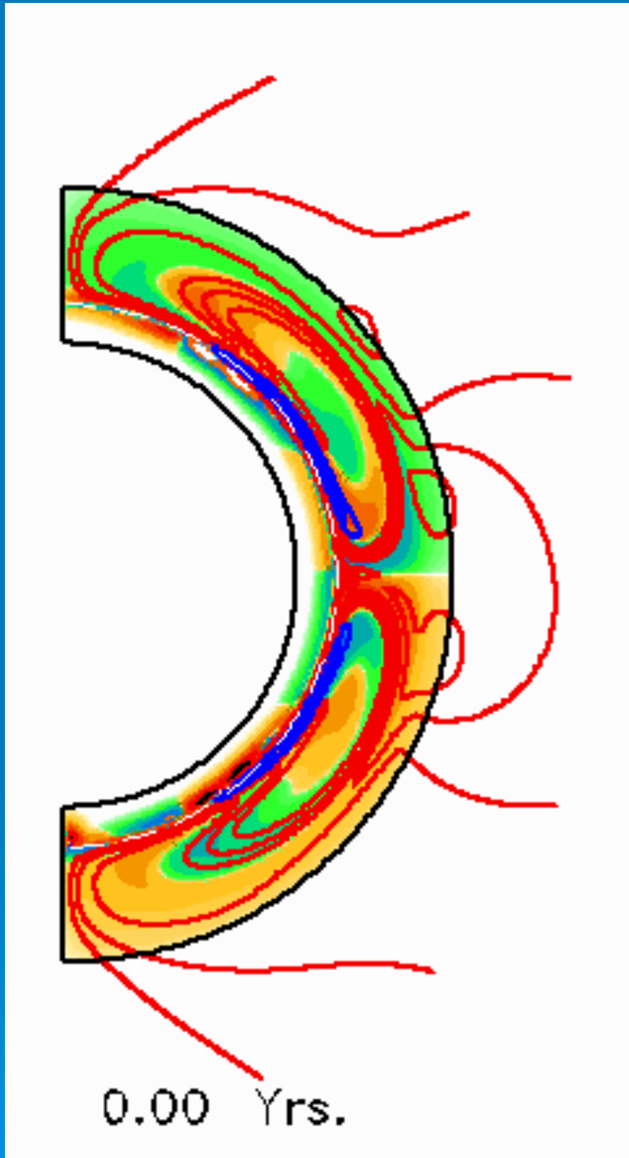
Magnetic Butterfly Diagram



NASA/MSFC/NSSTC/Hathaway 2008/10

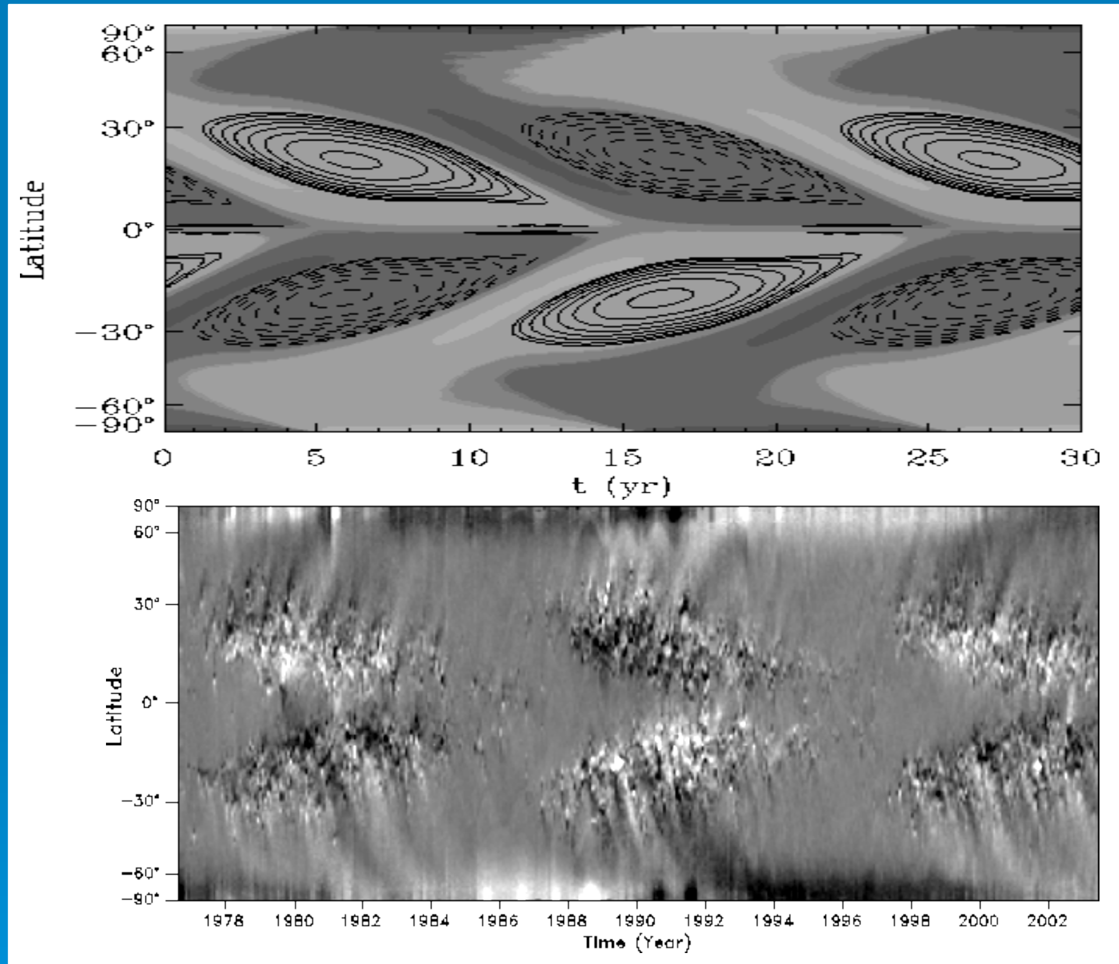
The magnetic butterfly diagram. Axisymmetrical component of the line-of-sight magnetic field averaged over a full solar rotation as a function of time. Yellow and blue colors shows positive and negative magnetic fields

Calibrated flux-transport solar dynamo



Contours: toroidal fields at CZ base

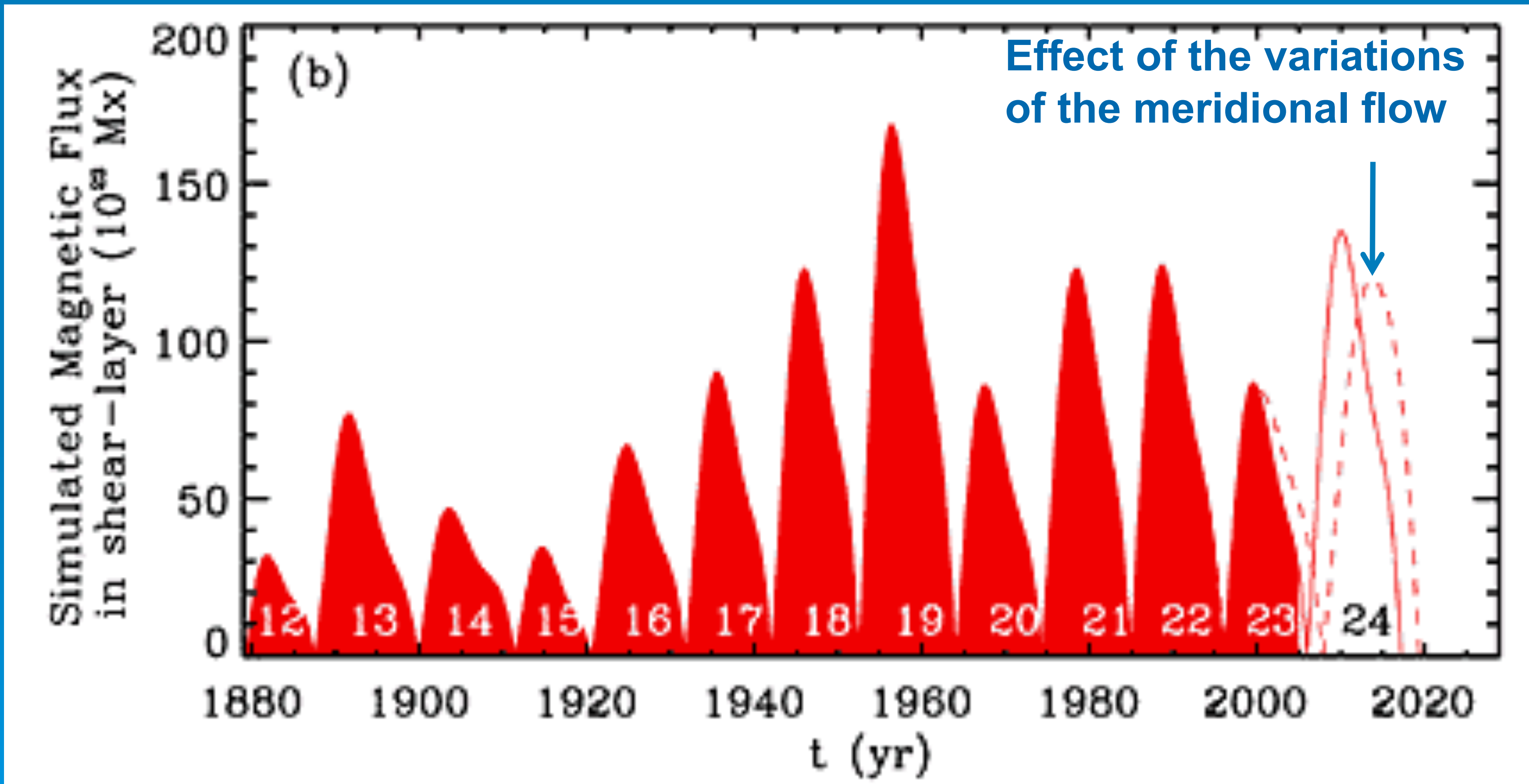
Gray-shades: surface radial fields



Observed NSO map of longitude-averaged photospheric fields

(Dikpati, de Toma, Gilman, Arge & White, 2004, ApJ, 601, 1136)

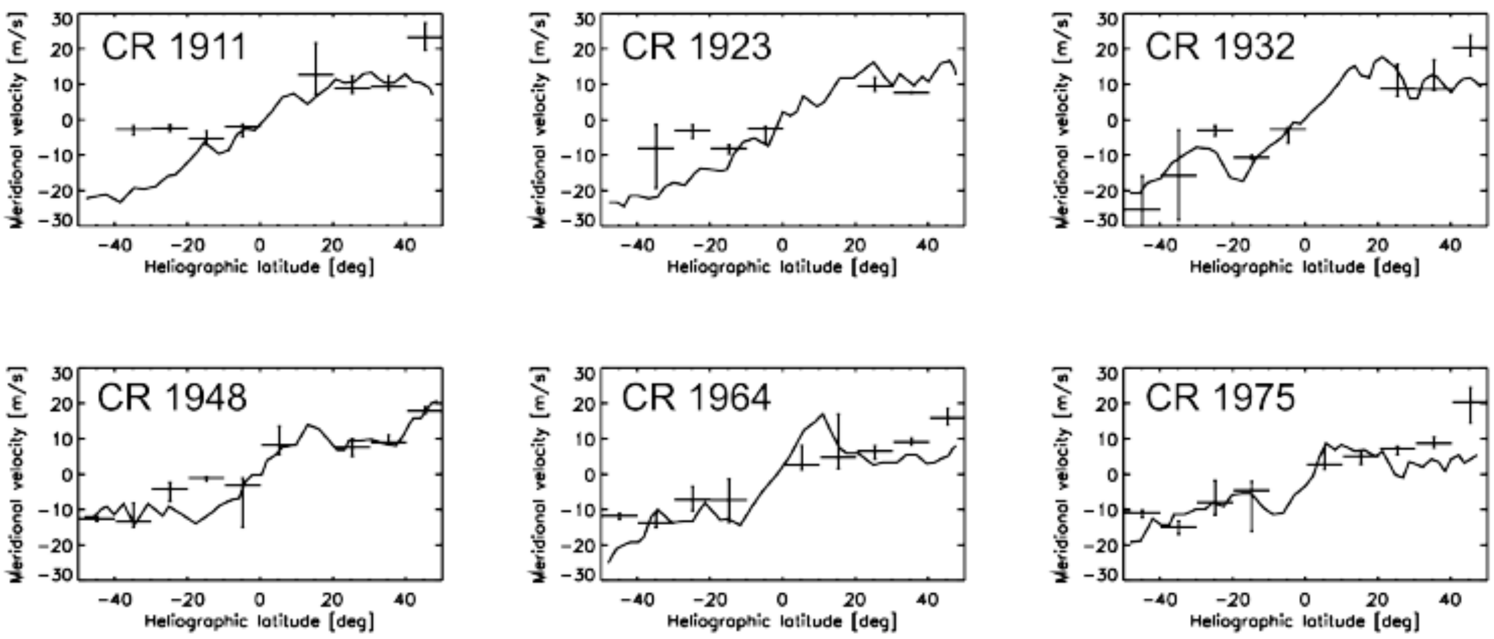
Flux-transport dynamo model predicts strong cycle (Dikpati & Gilman 2007)

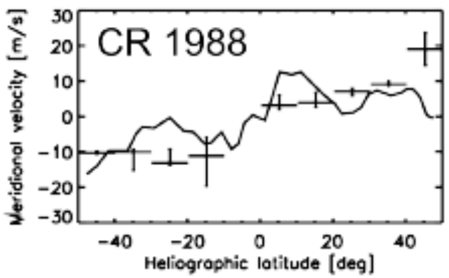


Relationship between the meridional flows and magnetic flux transport

- The mean velocity of the meridional flow decreases during periods of high activity at high latitudes.
- How does this affect the magnetic flux transport?

Comparison of the meridional flow velocity and the magnetic flux transport speed (Svanda et al 2007)

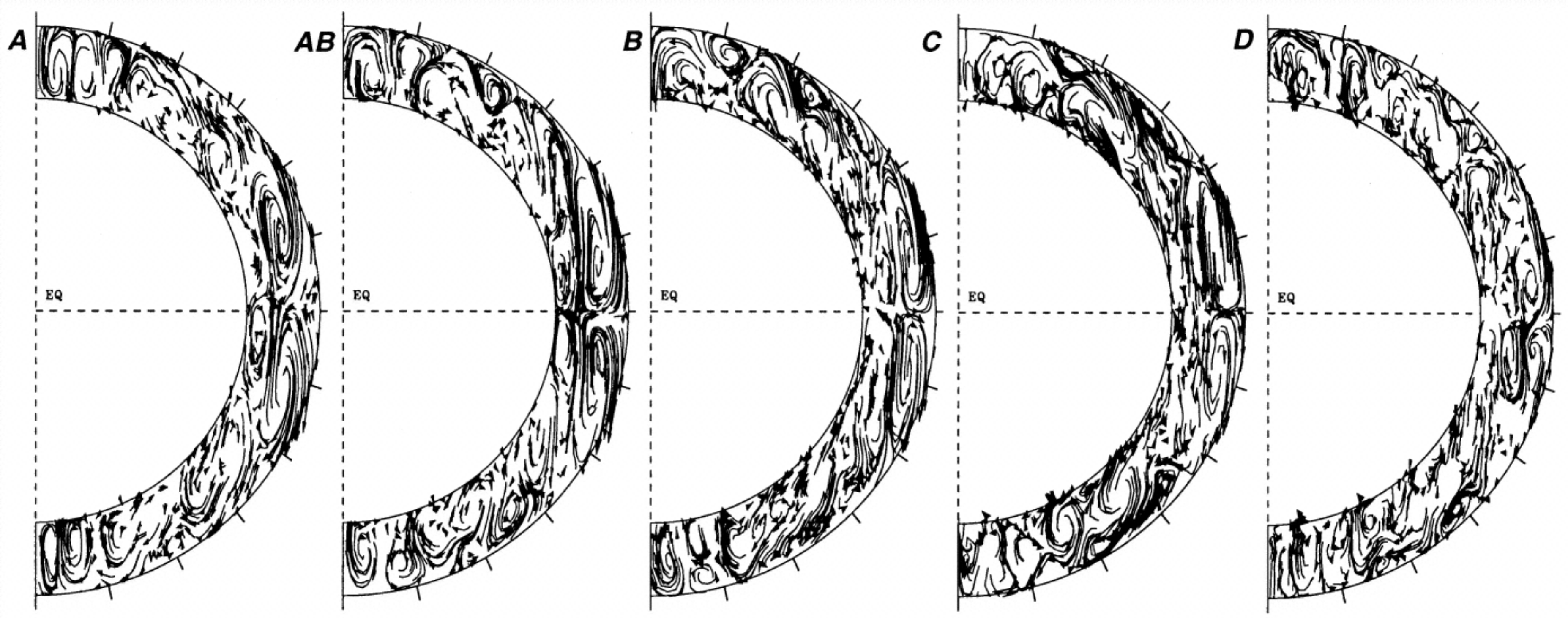




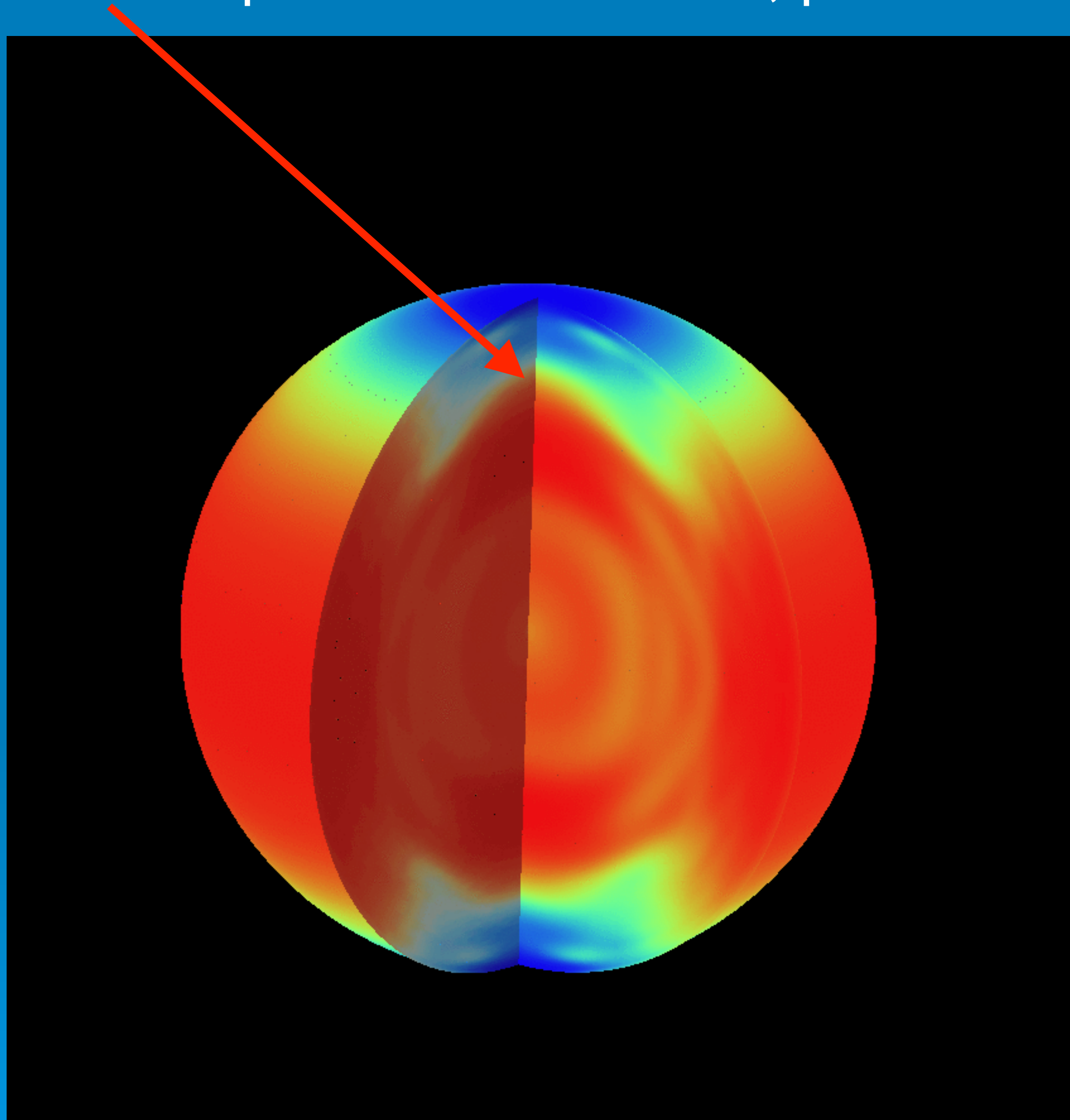
Comparison of meridional flow determined by time-distance helioseismology (solid line) and the flux transportation speed measured by the method suggested in this study (points with error-bars). It is seen that in the periods of increased magnetic activity the disagreement of both methods is quite obvious.

- The recent study by Svanda et al showed that the magnetic flux transport speed does not correspond to the observed velocity of the mean meridional flow.
- This indicates that it is important to take into account the longitudinal structure of the meridional flows and magnetic field.
- The reason is that the speed of the mean meridional flow is decreased because of inflows around strong field regions of the leading magnetic polarity. However, for the polar field reversal the transport of the following magnetic polarity is more important, around which inflows are much weaker.

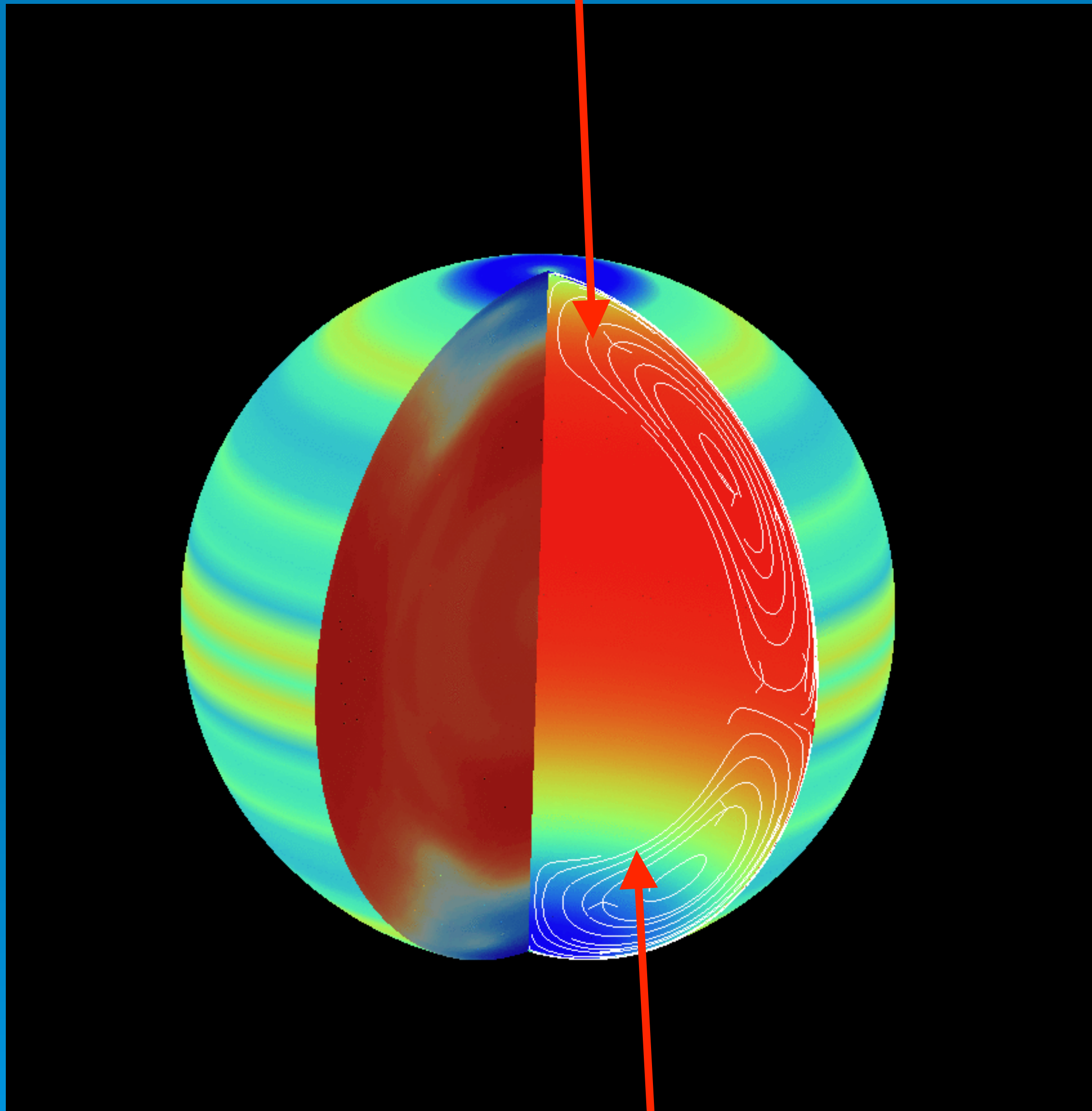
Numerical simulations show multiple cells at high latitude.
Are there multiple convective cells on the Sun?
How do these cells participate in the magnetic flux transport?



What is the shape of the tachocline, prolate?

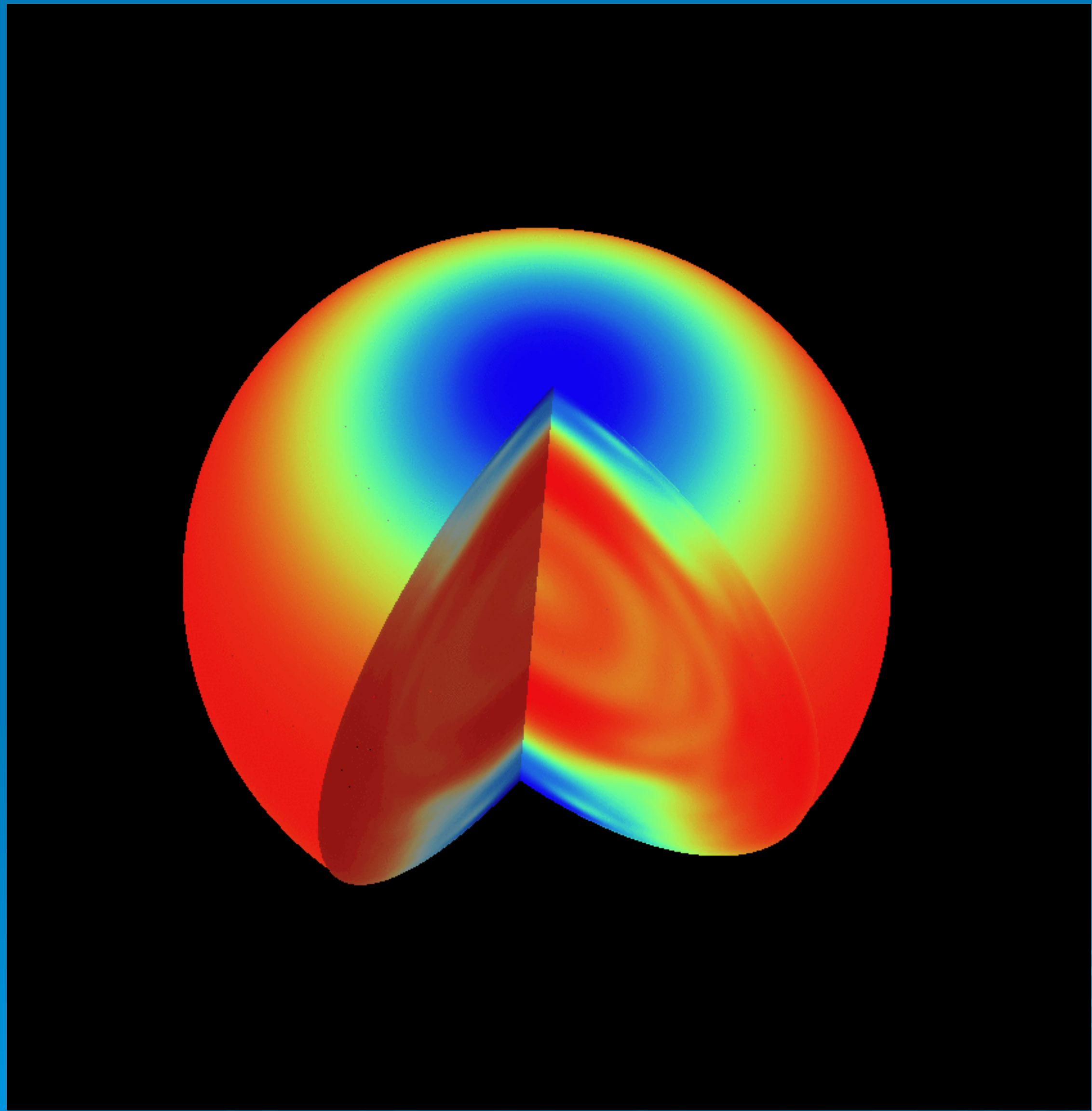


What is the high-latitude structure of the meridional circulation?

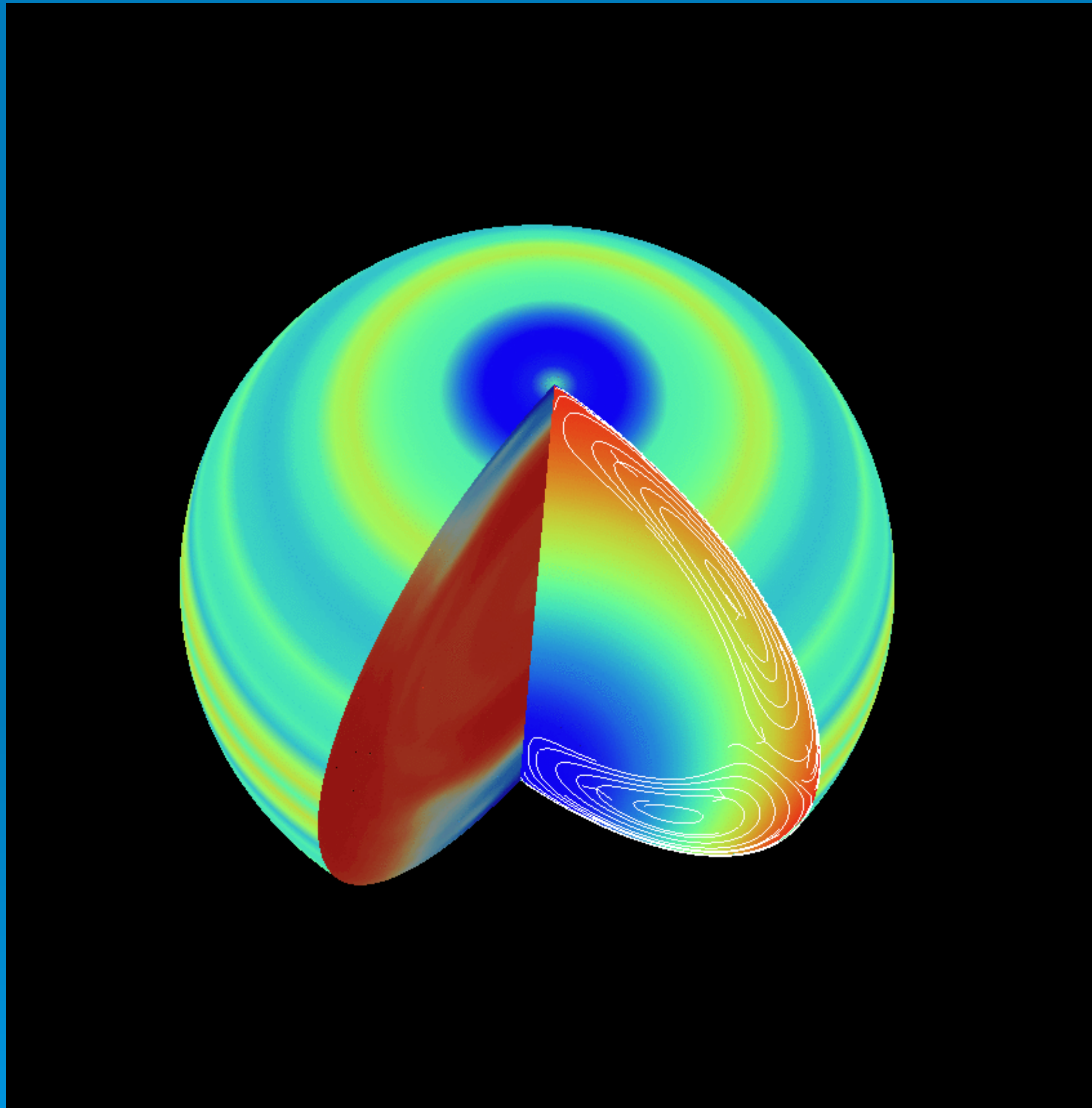


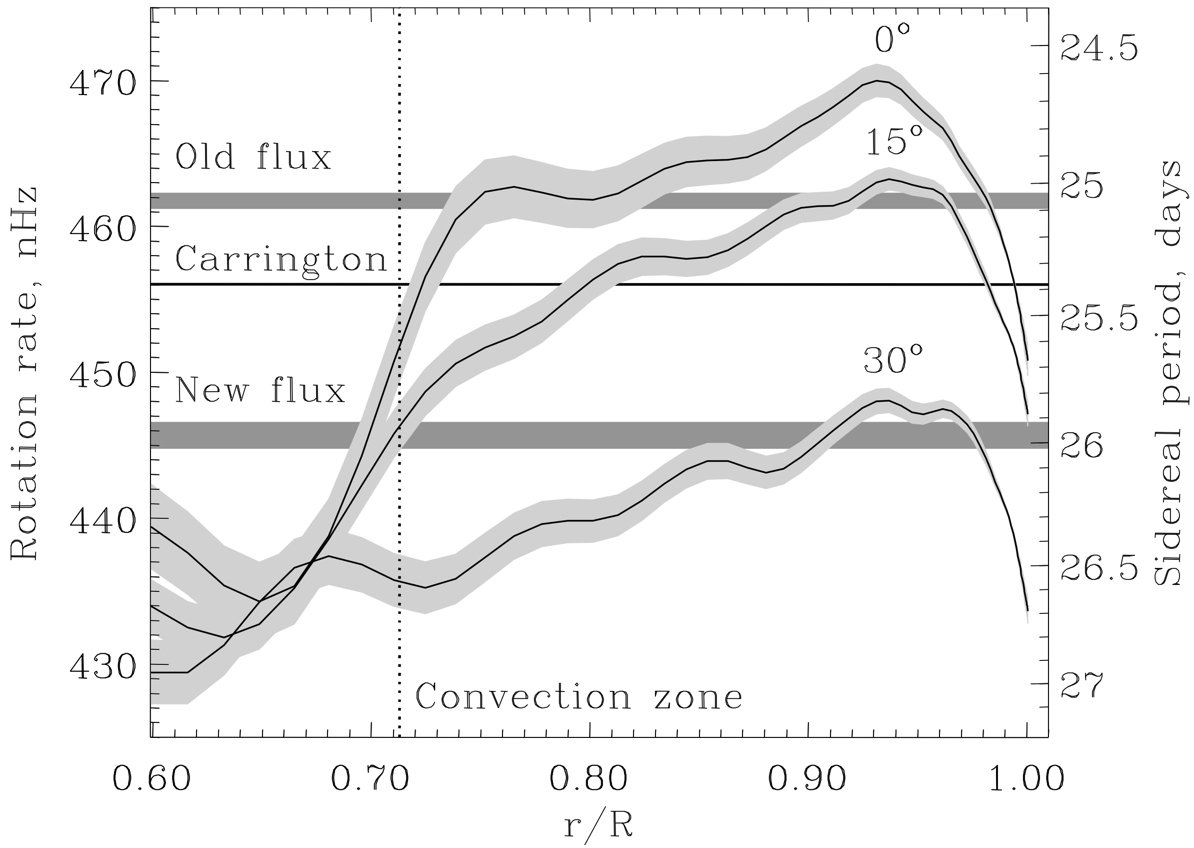
How deep is the meridional flow?

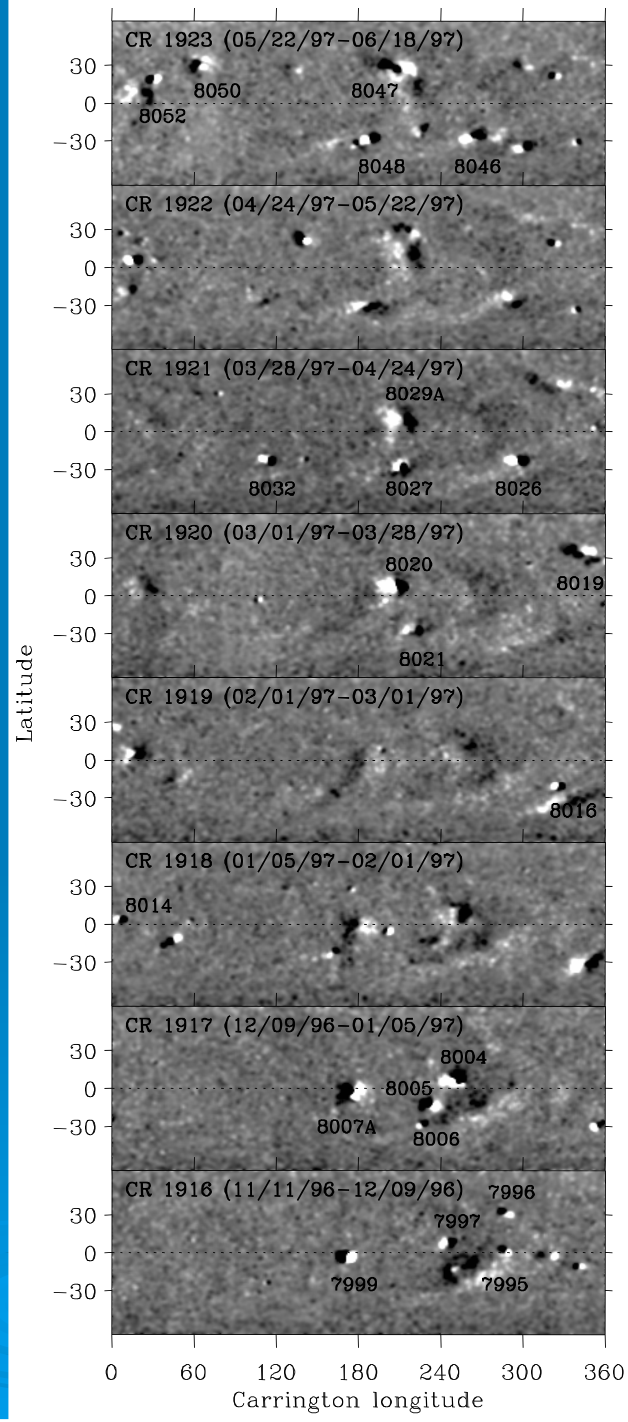
View of the differential rotation from 60 degrees



View of the zonal and meridional flows from 60 degrees





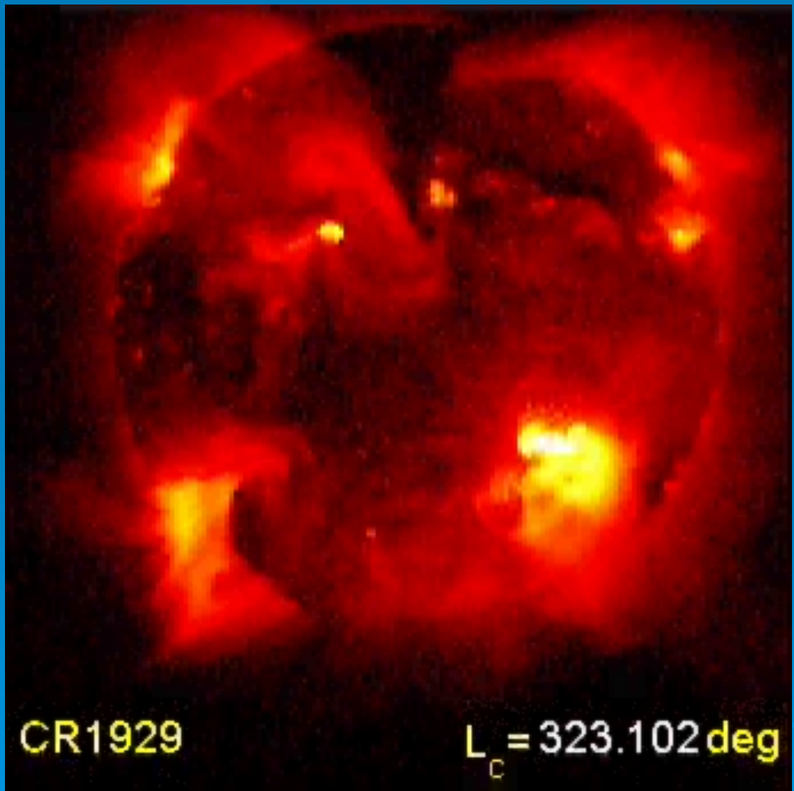


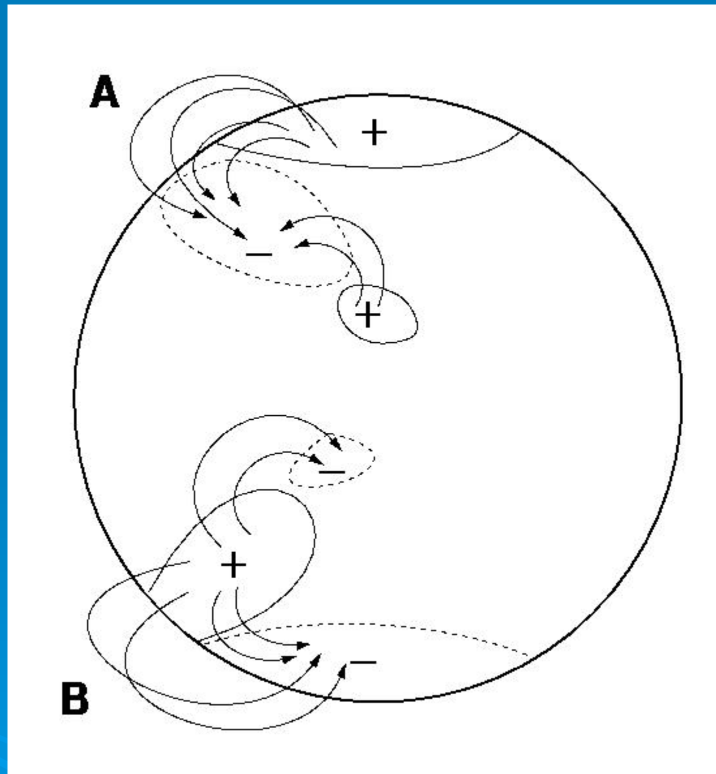
What is the relationship between active longitudes and polar magnetic field?

Yohkoh and EIT observations revealed giants loop structure connecting active regions and polar regions.

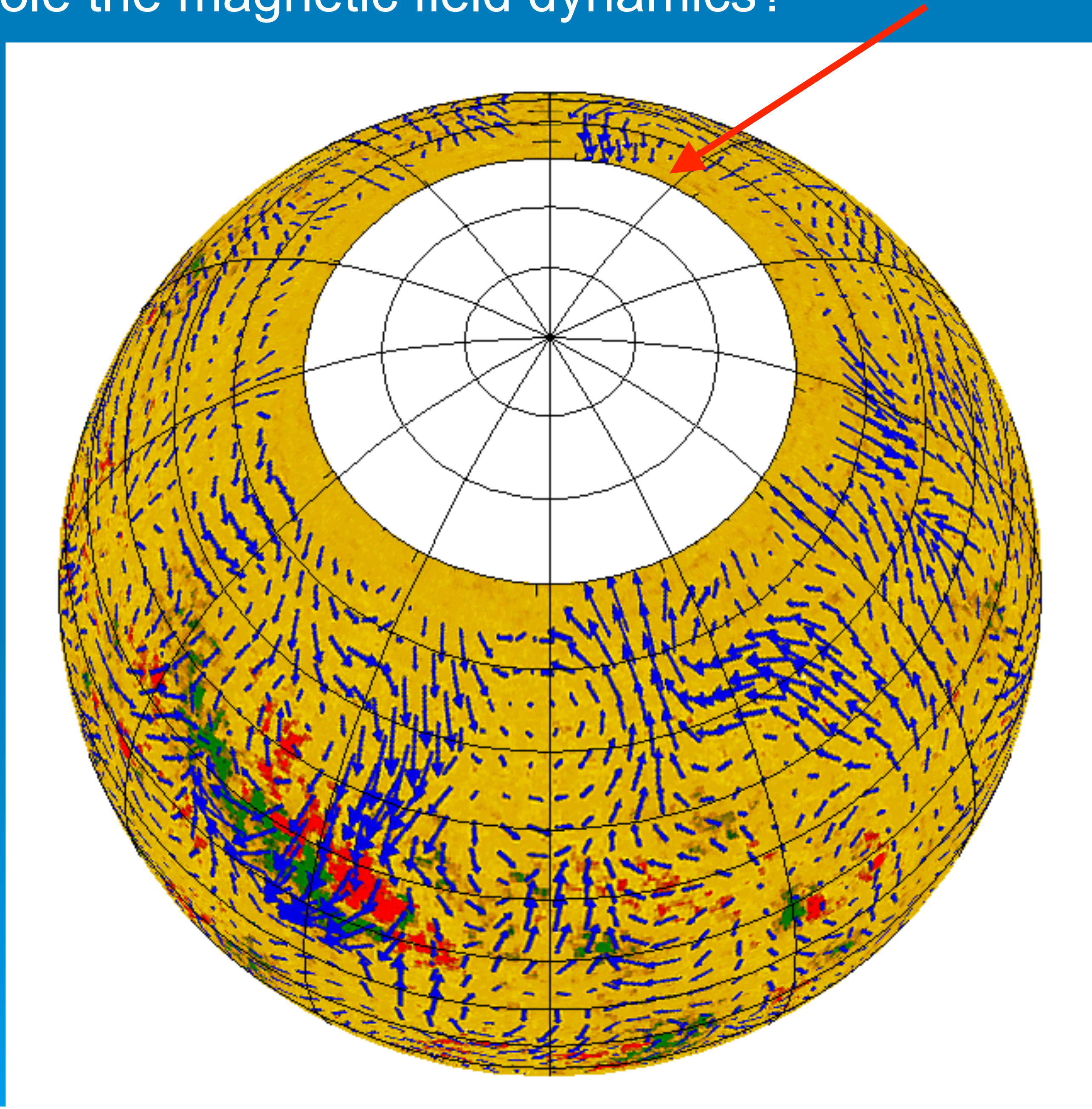
How deep is the link between plasma and flows in polar regions?

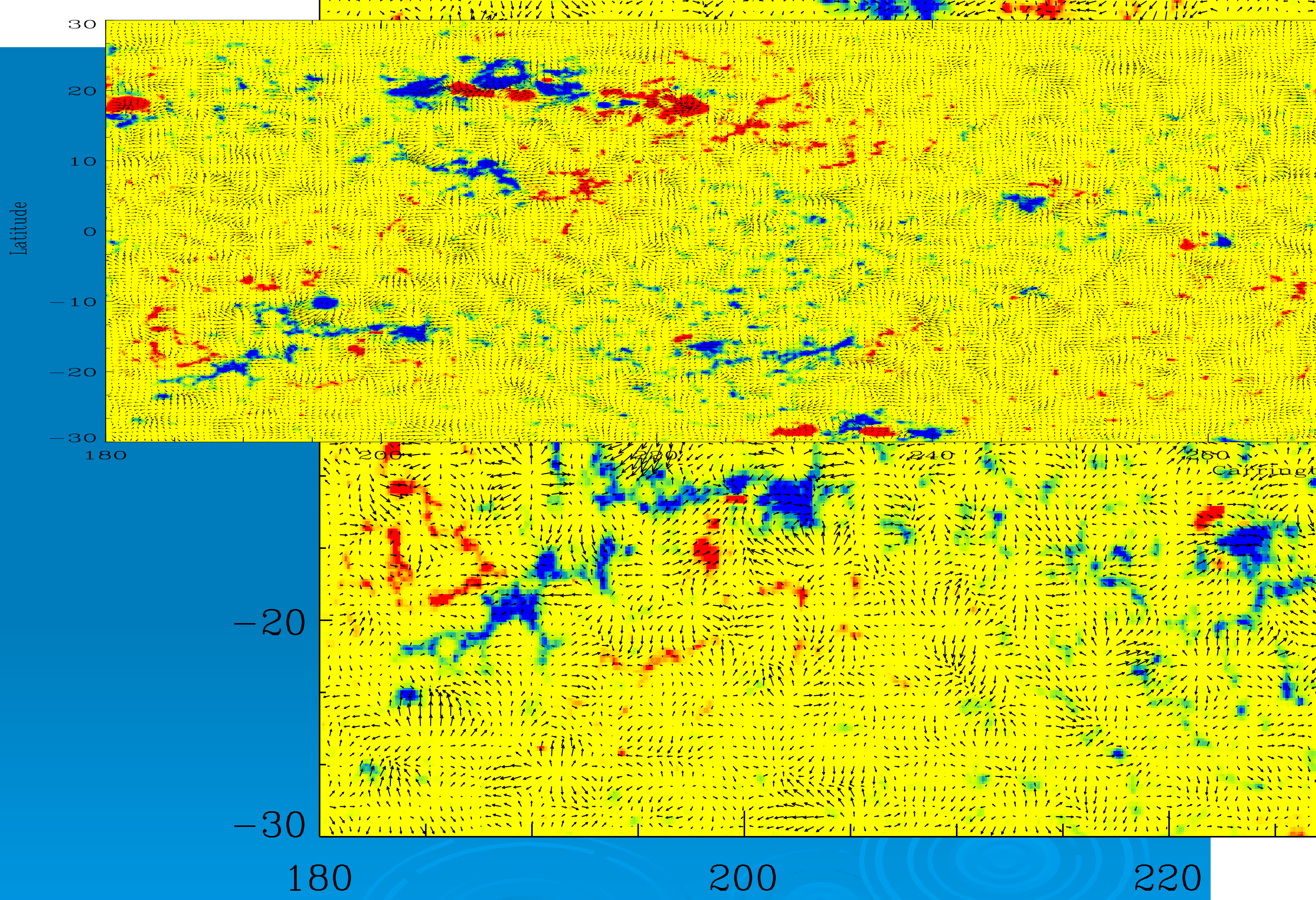
YOKHOH observations of giant coronal loops connecting polar regions and following polarities of active regions. What is the role of these connections in the solar cycle?





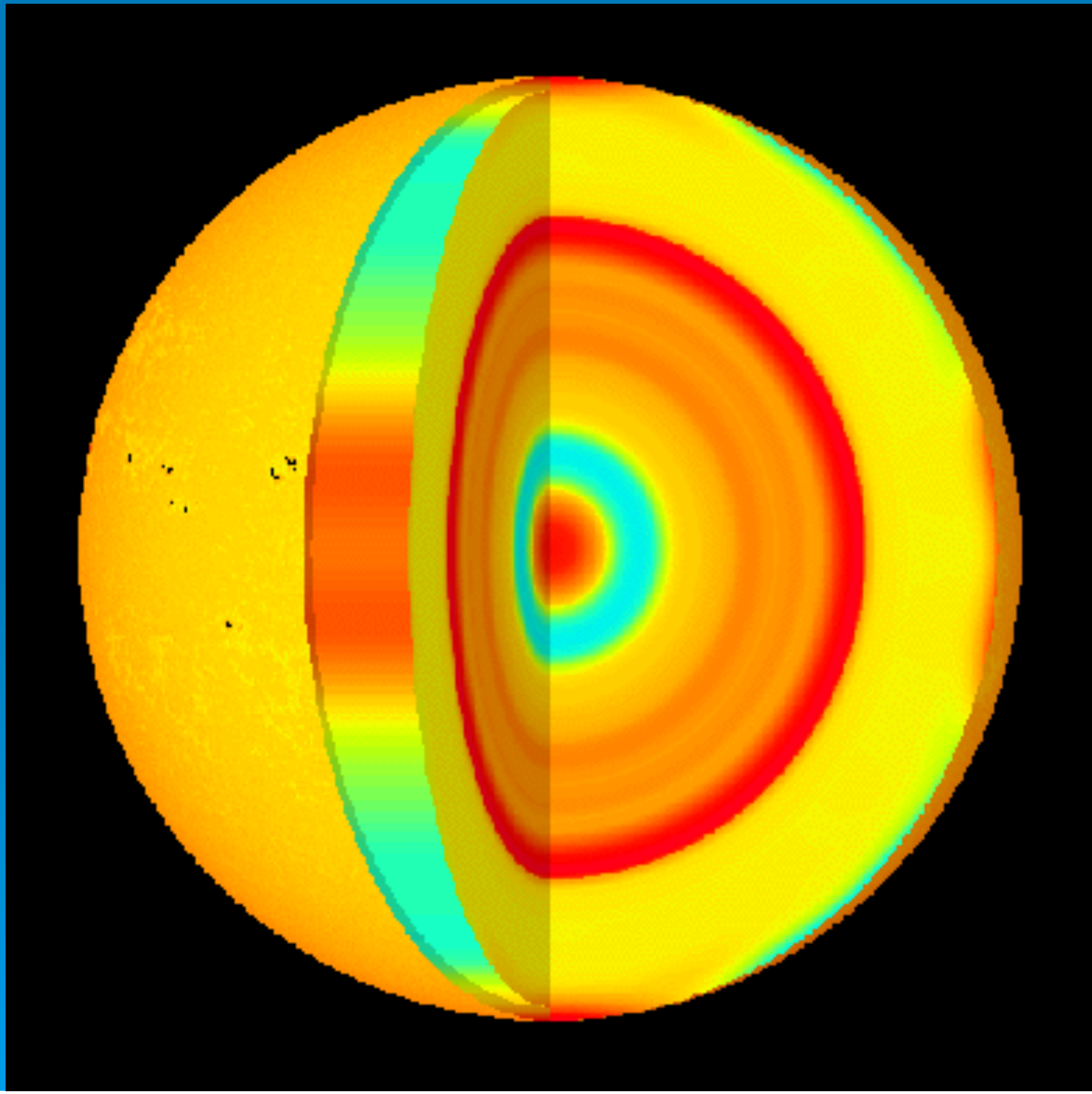
What is the large-scale circulation pattern in polar regions and its role the magnetic field dynamics?



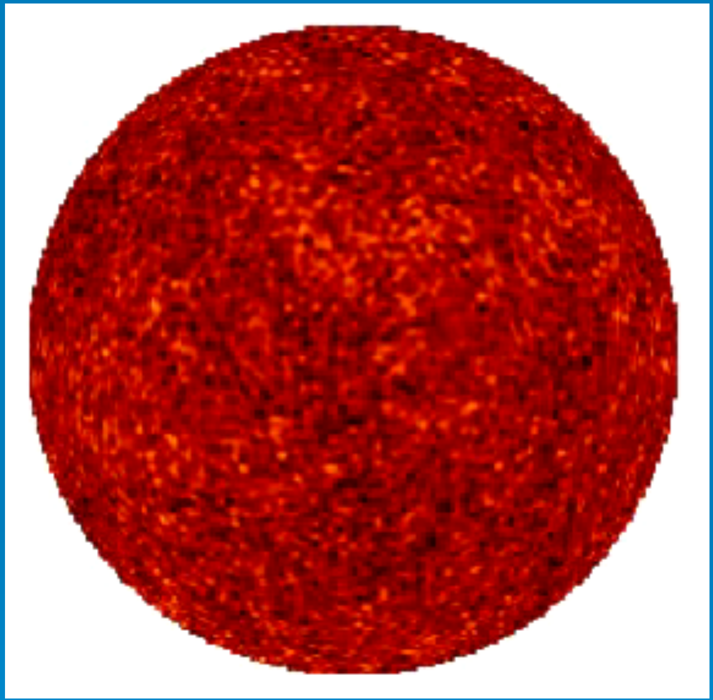


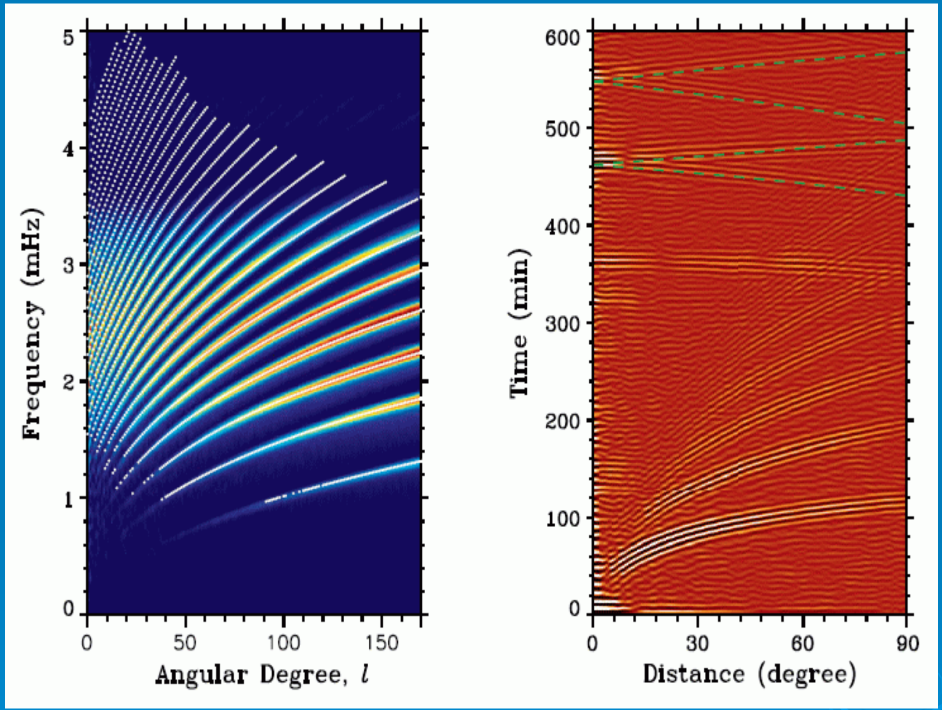
What is the structure of supergranular convection and magnetic network at high latitudes?

How well can we resolve structures and flows in the tachocline?



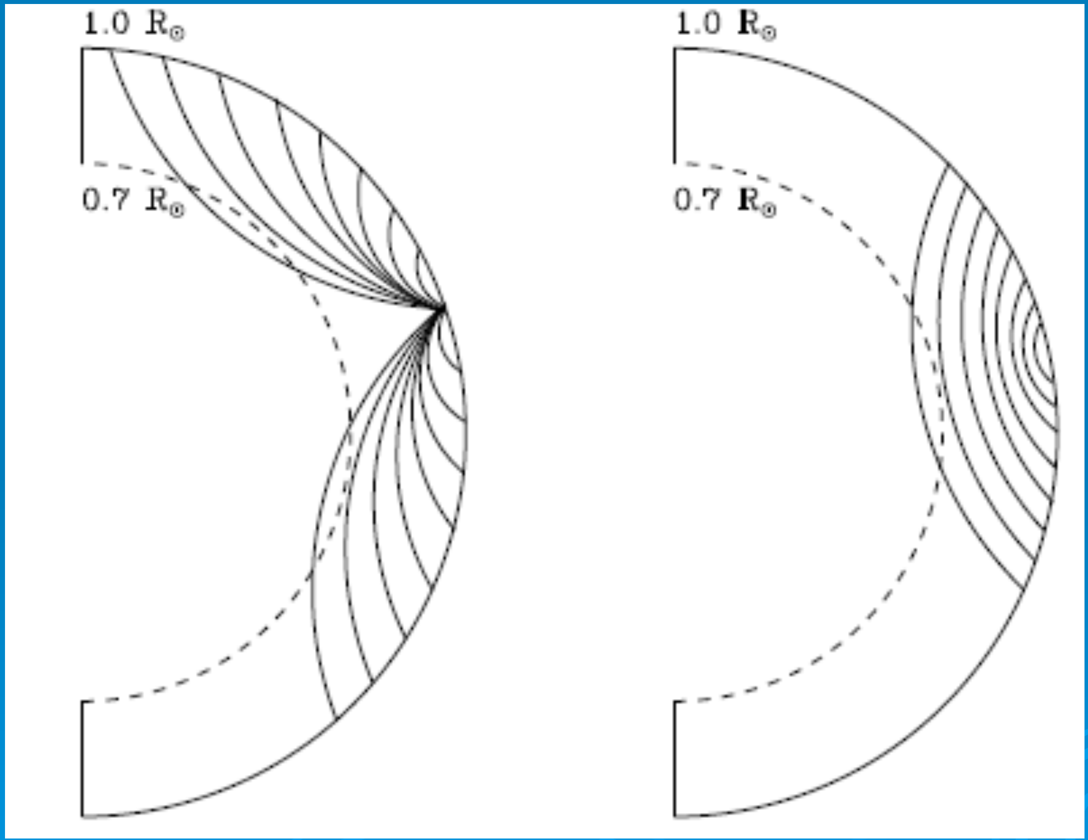
Numerical Simulation of Global Wavefields (by Hartlep & Mansour)





A linear code solving wave propagation equations, including only spherical degree from 0 to 170.

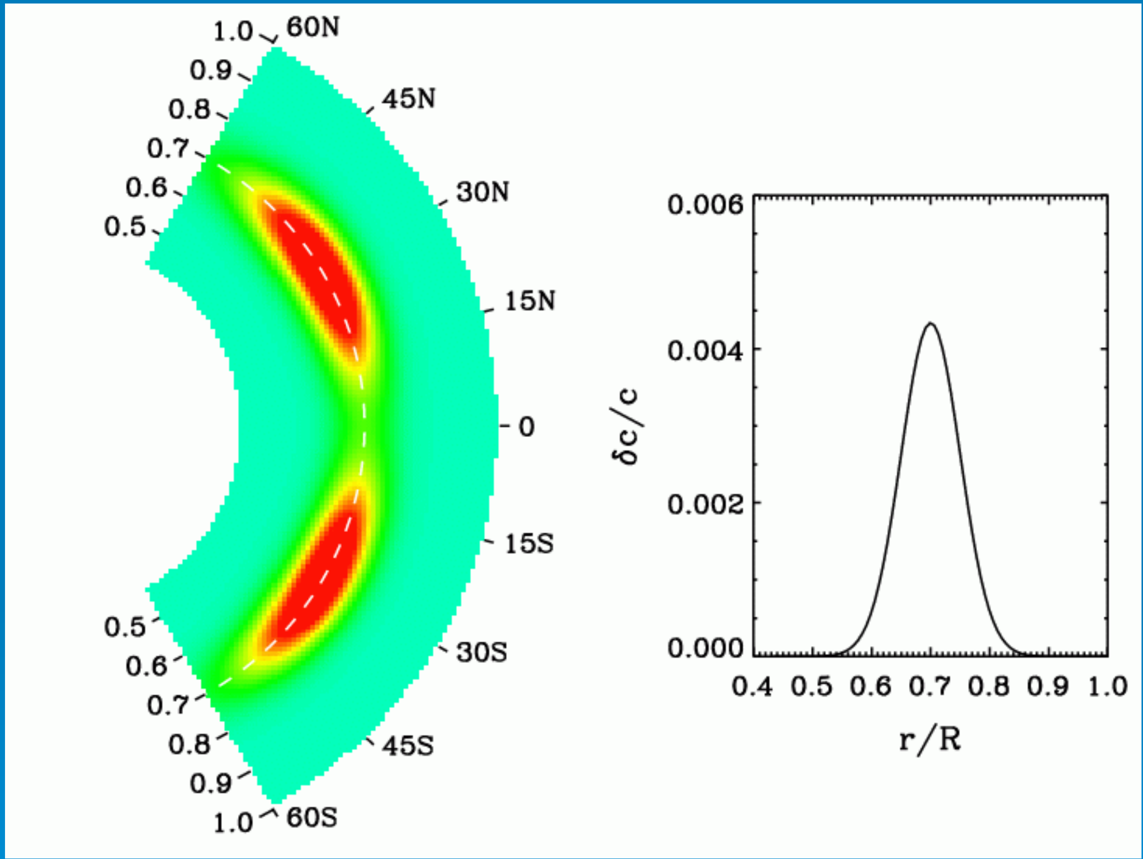
Time-distance helioseismology measurements schemes



Surface focusing

Deep focusing

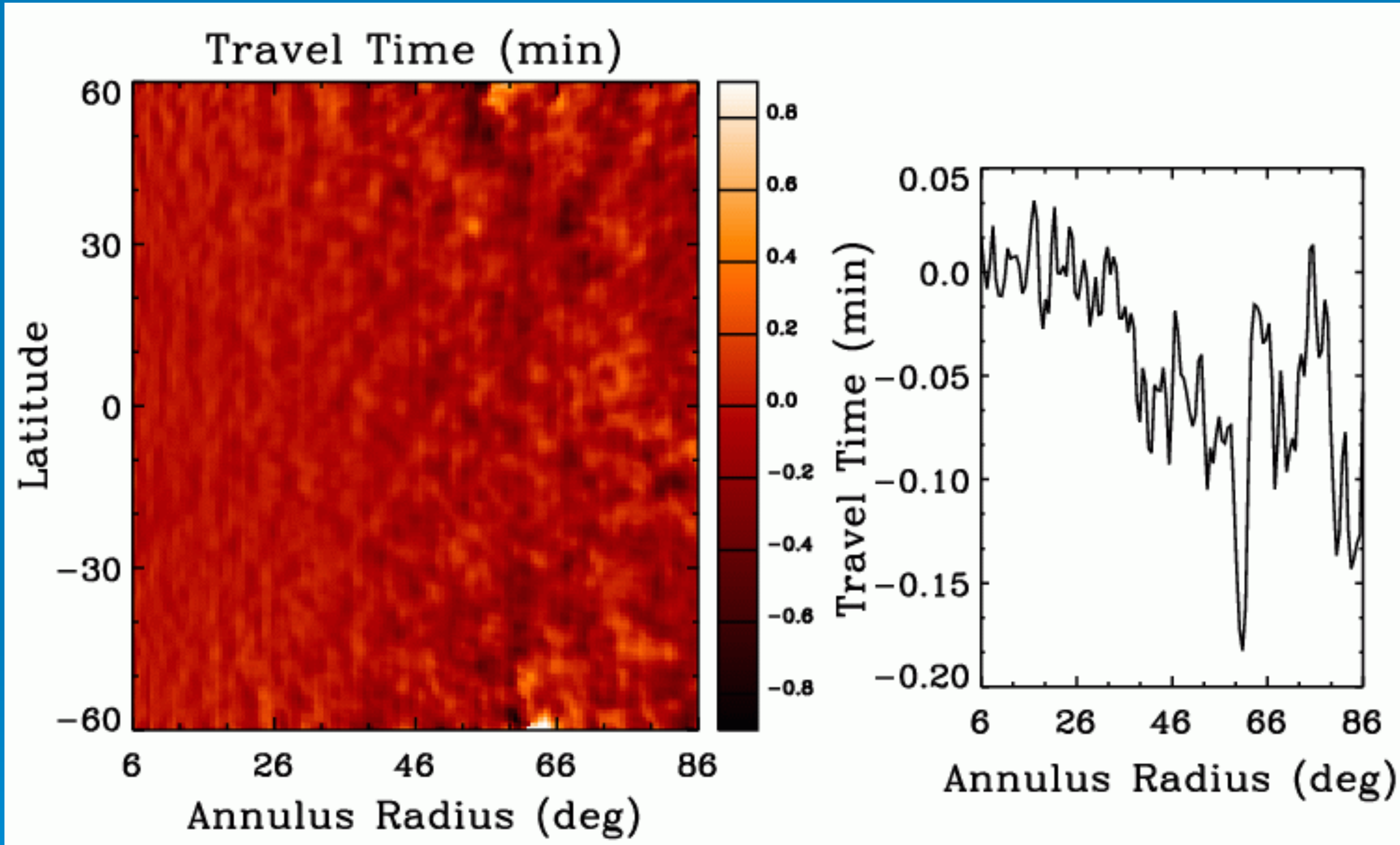
Simulation Model



Sound-speed perturbation of 0.6% is placed at 0.7R, with a latitudinal dependence, and with a Gaussian shape. It's symmetric along the equator.

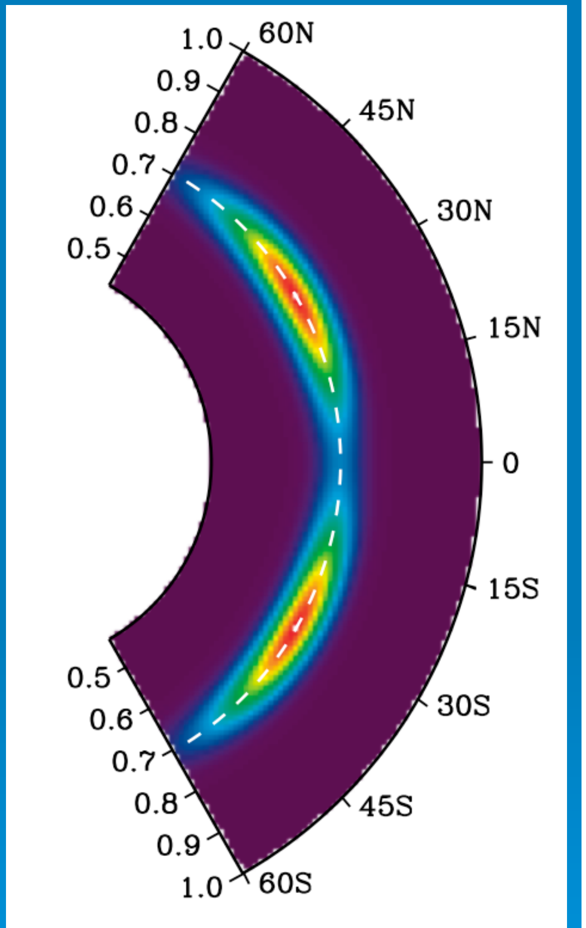
The simulation used here is 1024 minutes.

Measured Travel Times

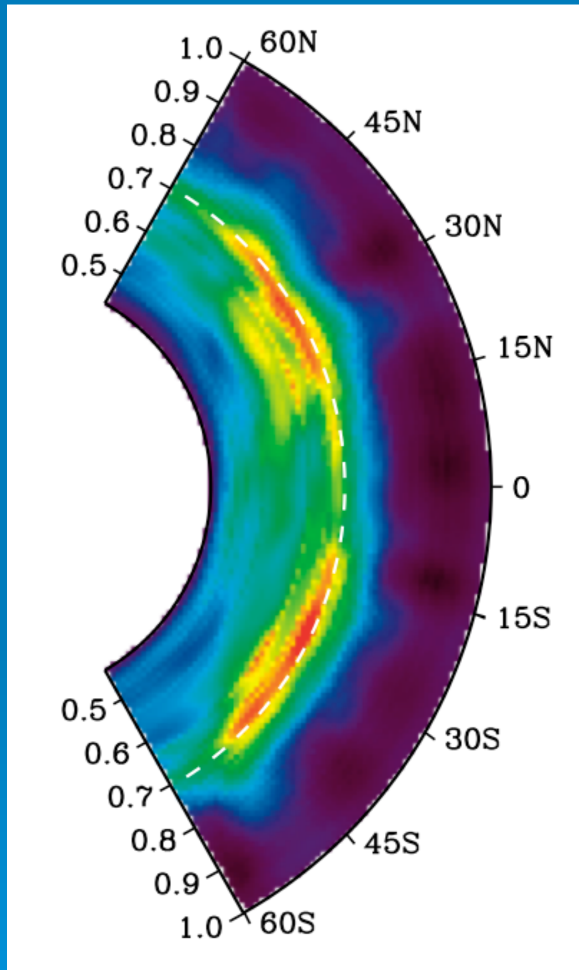


Measured travel times are displayed after a reference profile is subtracted. The reference profile is measured from a simulation that Thomas Hartlep made without perturbations.

Surface Focusing: Comparing Inversion Result with Model



Model



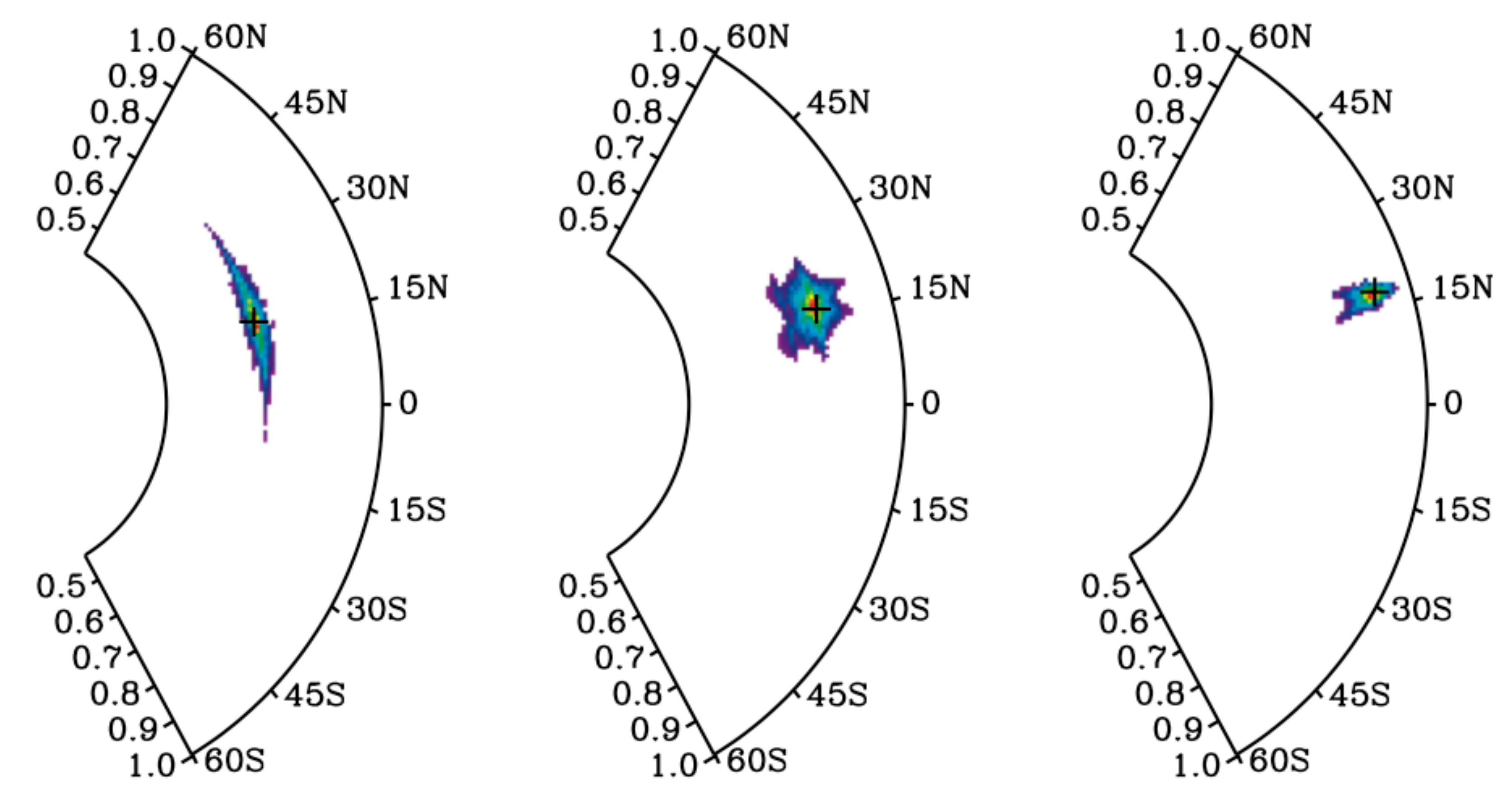
Inversion

The inversion recovers the location of the maximum perturbation well.

The results are more spread out, though, especially towards the deeper interior. (may be related to relatively high realization noise (short time series))

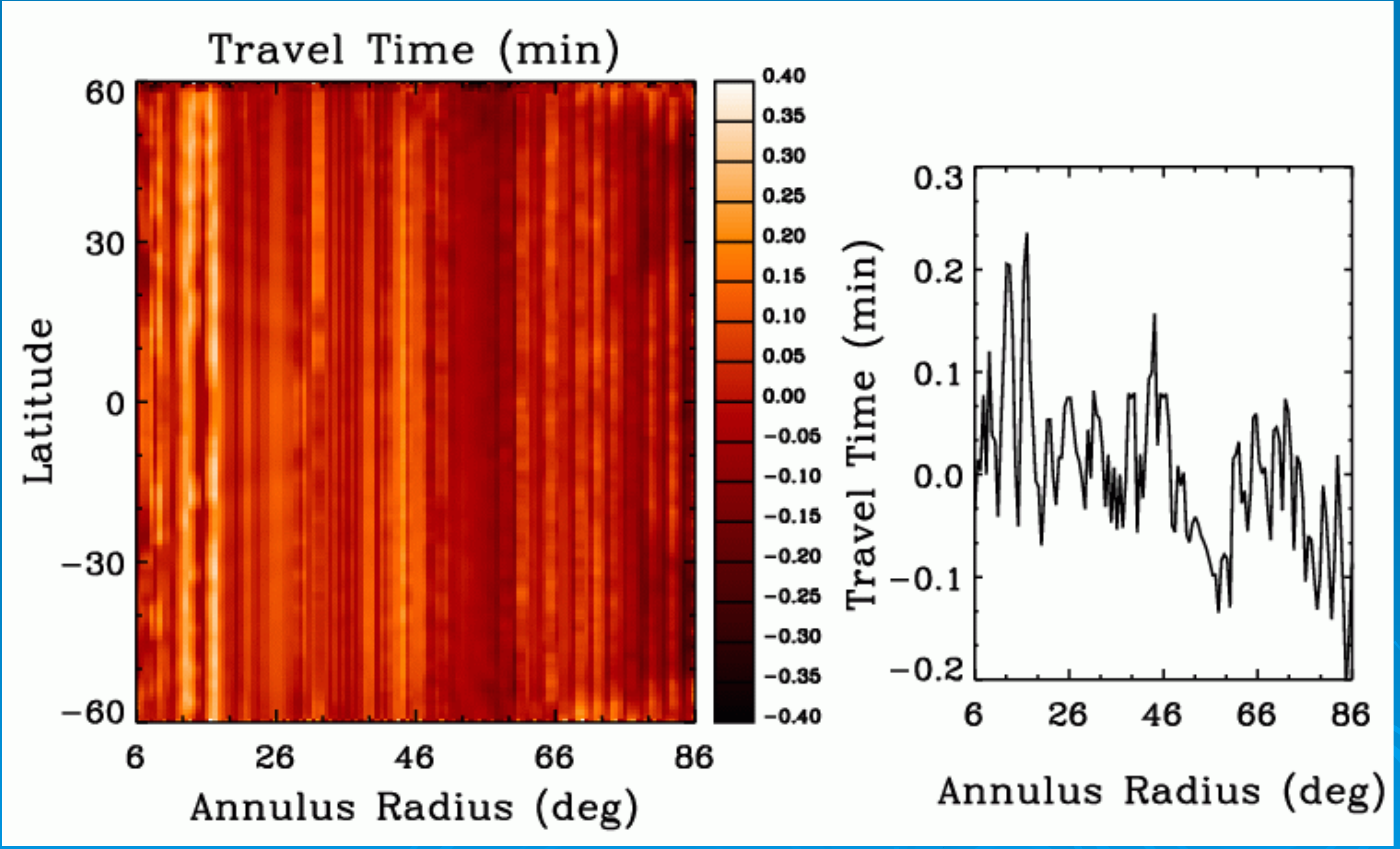
The latitudinal variation is not recovered perfectly, but still promising.

Surface Focusing: Averaging Kernels

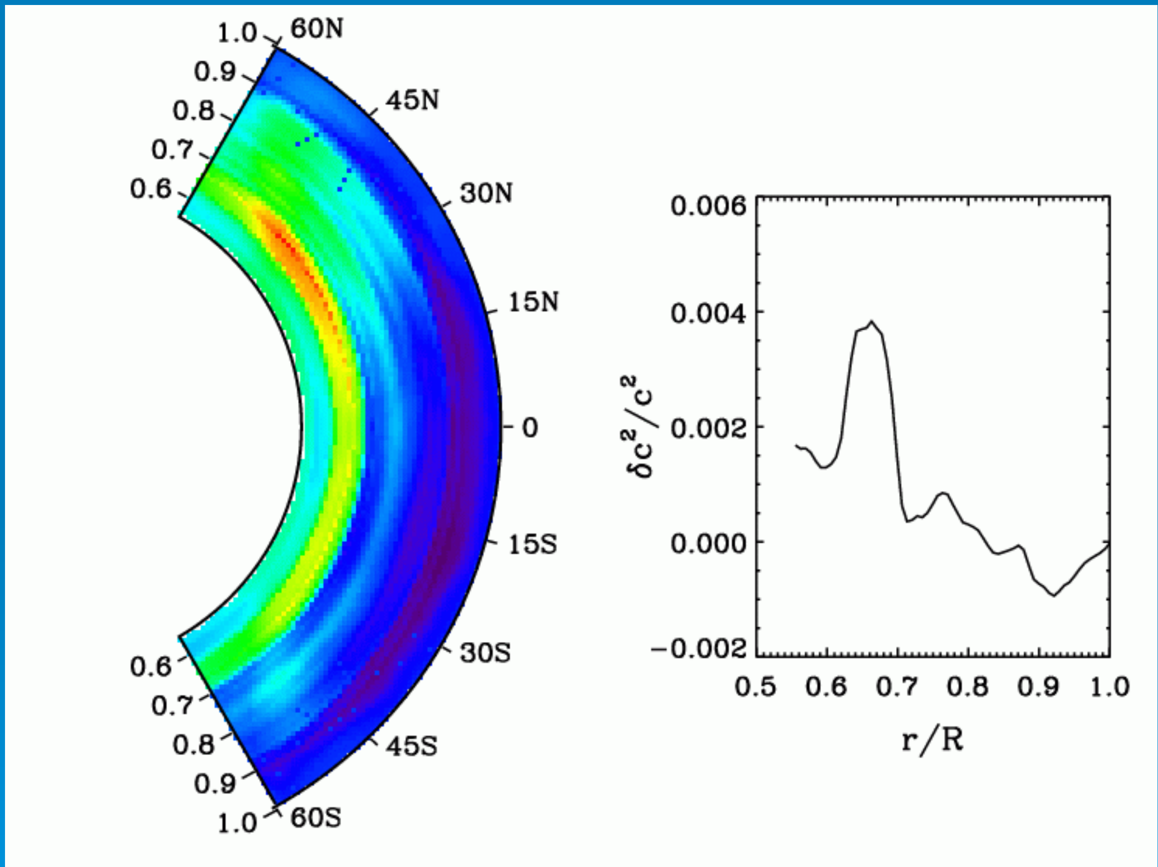


Averaging kernels obtained from surface-focusing inversions when the target location is at a latitude of 18 degree, and at 0.7R, 0.8R, and 0.9R.

Measurements from Real Sun: Surface Focusing

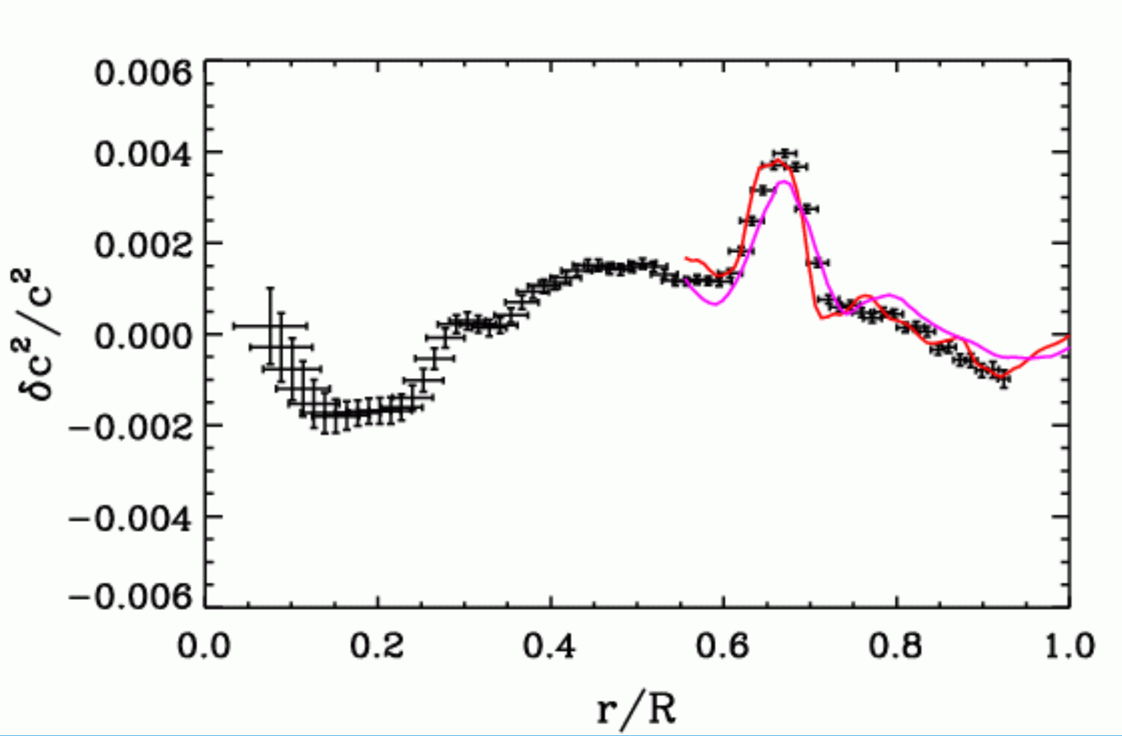


Results from Real Sun: Surface Focusing



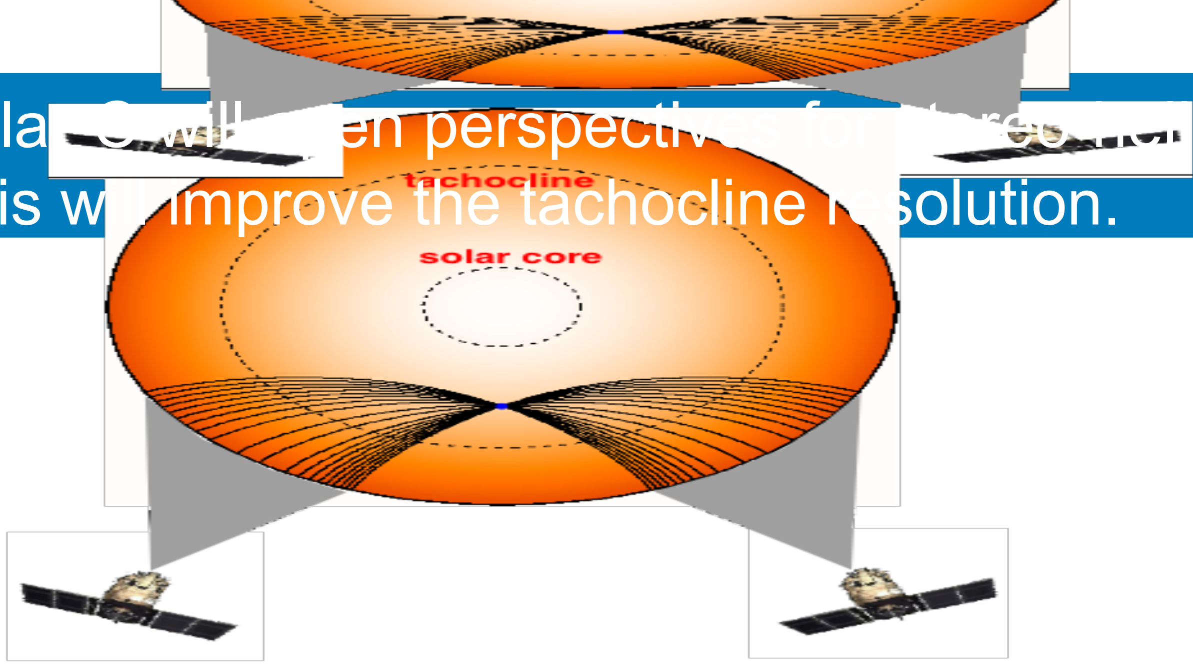
- Structures are not hemisphere symmetric.
- Tachocline is clearly seen, pretty much latitudinal dependent.
- (Zhao et al 2008,in preparation)

Results: Comparing with Global Helioseismology Result

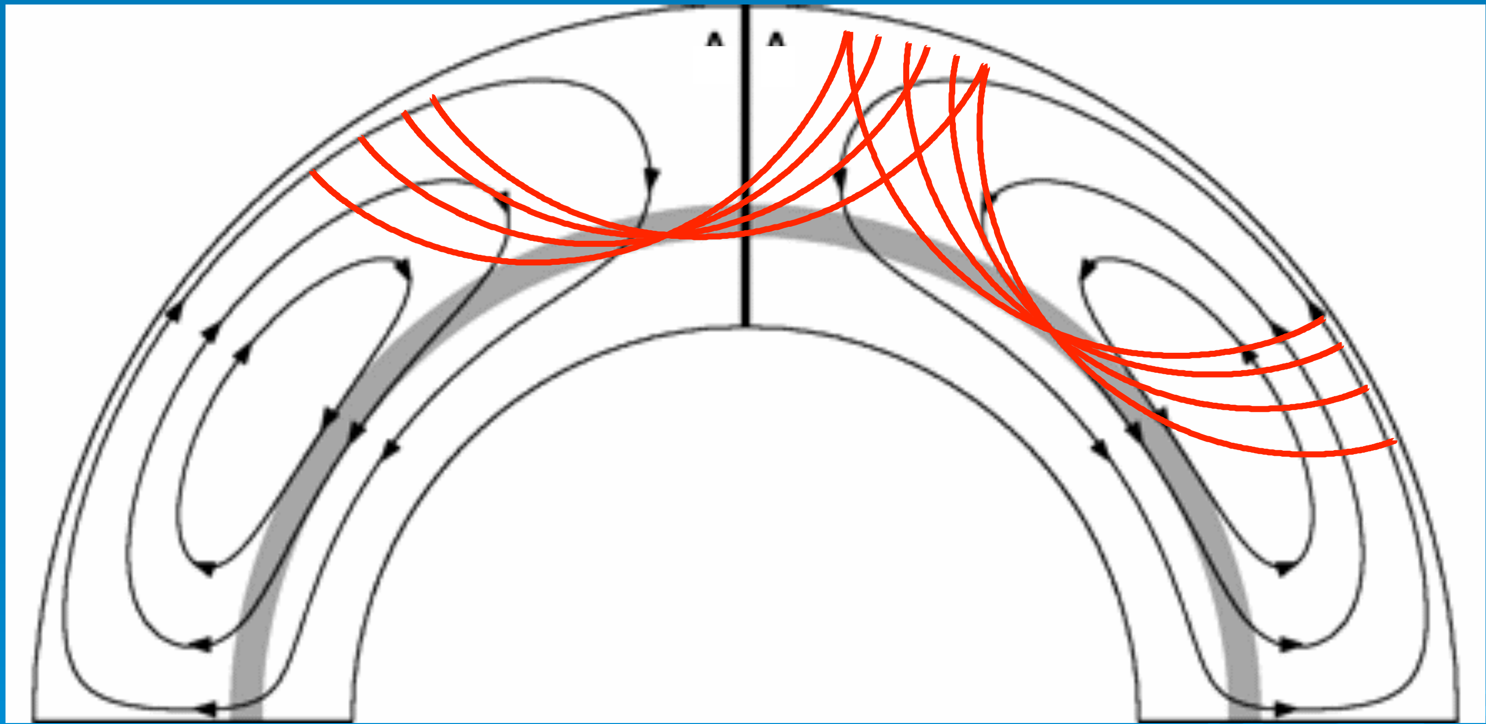


- Red and pink curves are from surface- and deep-focus, respectively.
- Tachocline is surprisingly in good agreement!
- Should keep in mind the experiments using simulated data show that results are not well localized.
- The next step is investigate variations with the solar cycle. This requires careful analysis of MDI instrumental effects.

Solar-C will open perspectives for stereo helioseismology.
This will improve the tachocline resolution.



Stereo-helioseismology observations of the tachocline in polar regions



Major goal

Knowledge of the high-latitude meridional circulation and differential rotation is crucial for understanding magnetic flux transport, polar field reversals, solar cycle models and predictions. These are the main ingredients of the solar dynamo.

Some key questions

- Are there multiple meridional cells predicted by numerical simulations?
- How fast is the polar rotation?
- How does the polar rotation changes with the solar cycle?
- Are there fast variations of the polar rotation?
- How deep are these variations?
- Is there a link to rotation of the radiative interior?
- How are these linked to the angular momentum loss?
- What are the structure, dynamics and variations with the solar cycle of the tachocline?

Data Requirements

- Global helioseismology:
  - 256x256 images,
  - 1-min cadence,
  - 36-72 days long time series
- Local helioseismology:
  - 1024x1024 images,
  - 1-min cadence,
  - 8-hour series for the upper convection zone (depth 0-30 Mm);
  - 256x256 images, 1-min cadence, 36 days series for the tachocline and deep interior tomography.

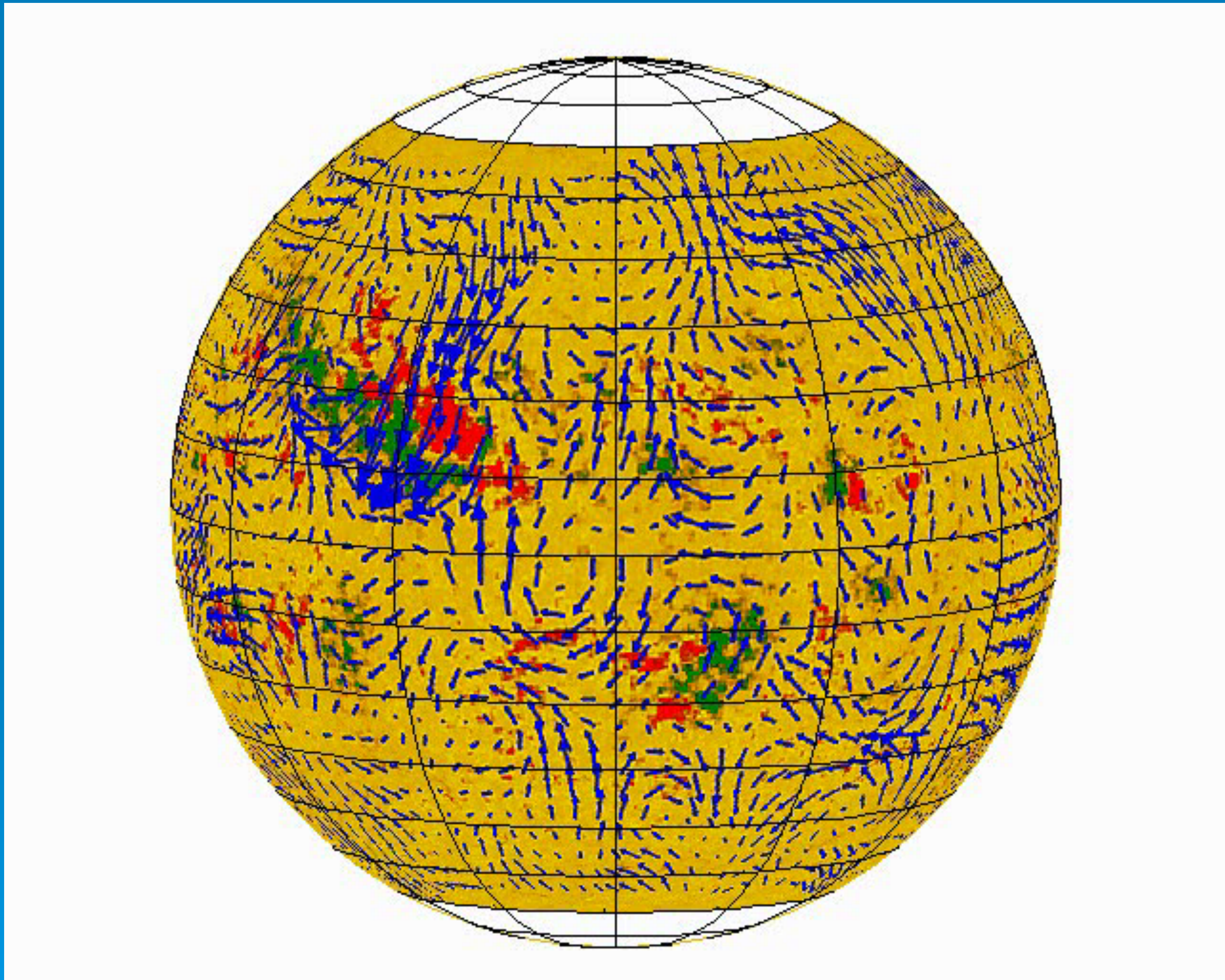
Basic methods of local-area helioseismology:

Method	Observable	Inferences
Ring-diagram analysis (Gough, Hill, November, Toomre, 1981)	Local variations of oscillation frequencies	Large-scale sound speed perturbations and horizontal flows
Time-distance helioseismology (Duvall et al. 1993)	Phase and group travel times of acoustic and surface gravity waves	3D sound speed, density and flows
Acoustic Imaging (Chou, LaBonte, et al. 1990)	Phase and amplitude variations	3D sound speed and flows
Acoustic Holography (Lindsey & Braun, 1990)	Phase and amplitude variations	Phase variations and amplitude maps: no inversion procedure yet

Helioseismology Science Plan Basics

- Low-resolution uninterrupted observations, 36-day time series.
- High-resolution short campaigns, 8-hour runs
- Coordinated observations with a ground-based or orbiting instrument
- Link science objectives to the s/c position and telemetry

View of large-scale flows from Solar-C



Views of the Sun from the SPI orbit and the Earth