Large-scale flows inferred from helioseismology related to the solar cycle

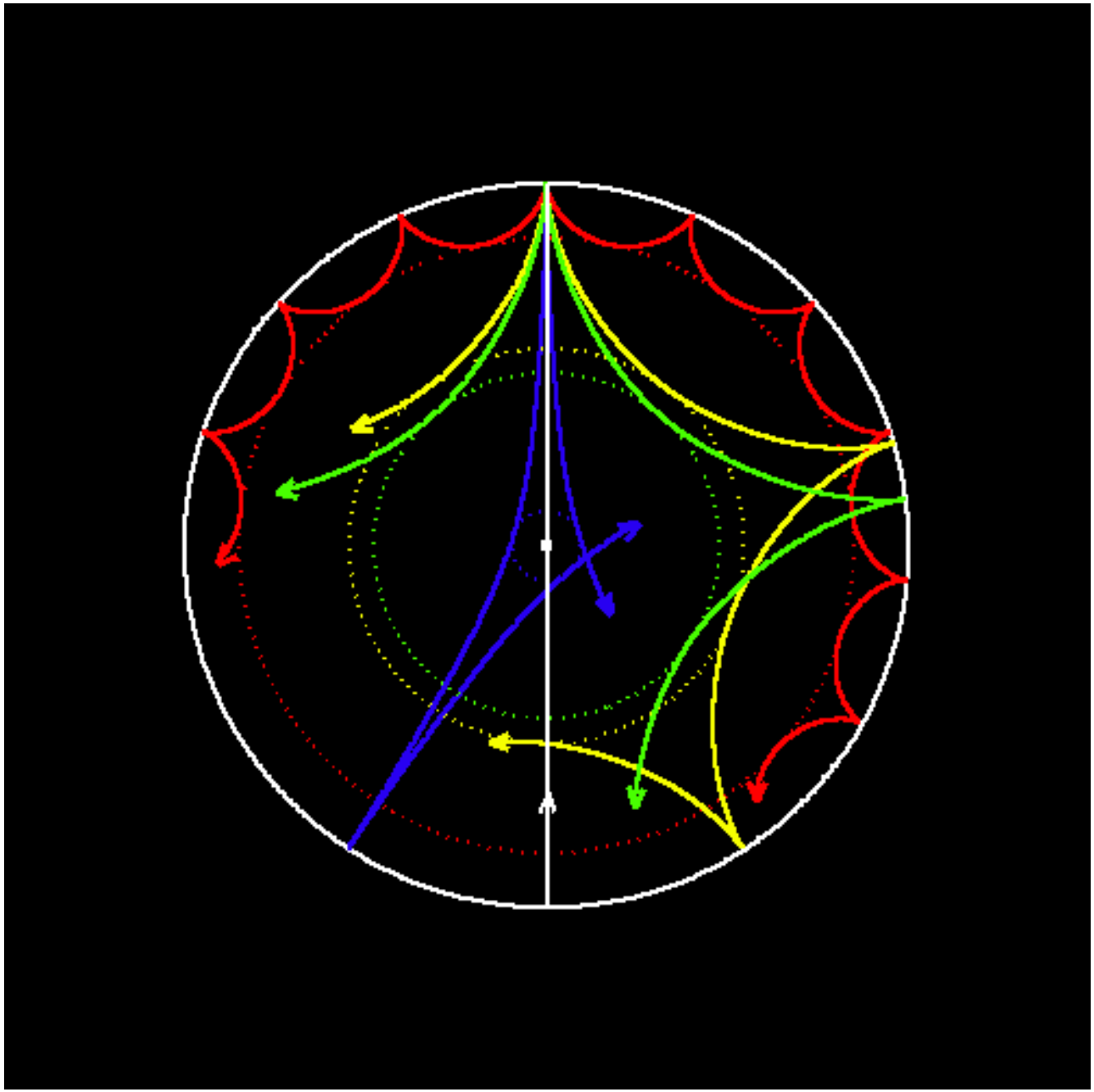
Frank Hill

National Solar Observatory

Boulder, CO

Helioseismology 101 - 1

- The sun is analogous to a huge musical instrument – it rings like a bell
- Acoustic waves are generated by convection at all temporal frequencies
- Sound is trapped inside the sun by the inwardly increasing temperature – a sonic mirage
- The depth to which an acoustic wave penetrates depends on its path
- Only modes that have nodes at the two turning points survive destructive interference



Helioseismology 101 - 2

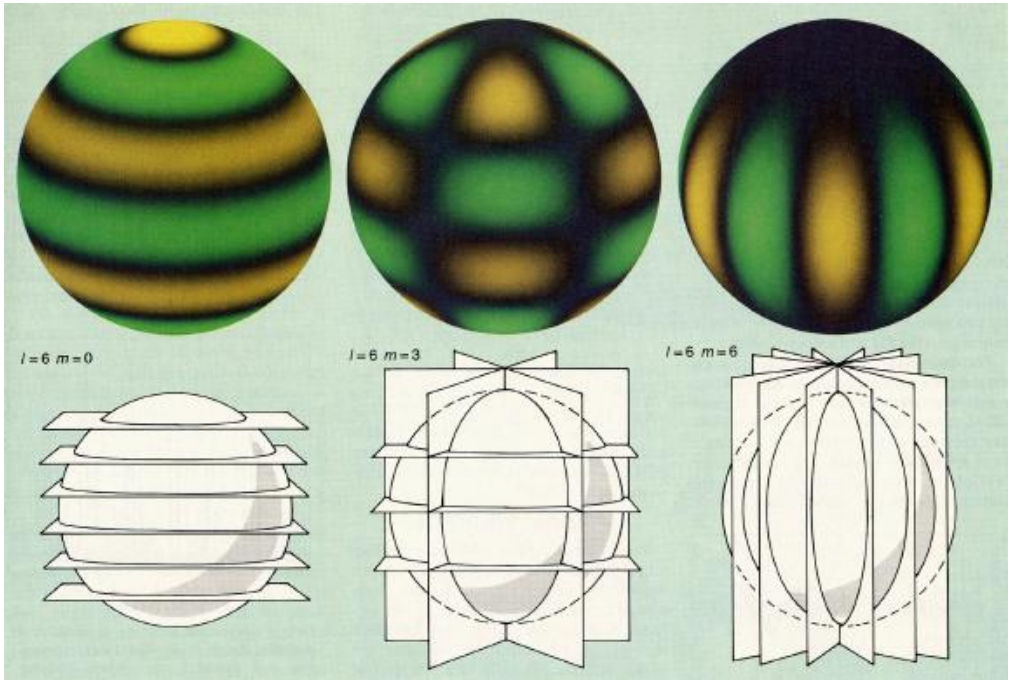
- About 5,000,000 modes survive the destructive interference in the temperature gradient
- Since there are thus lots of ray paths propagating to different depths, we can use them to infer the physical conditions below the photosphere via inversions
- Can use globally resonant modes for globally averaged studies, described by spherical harmonics
- Also use waves that are not globally resonant for localized studies, i.e. in active regions.

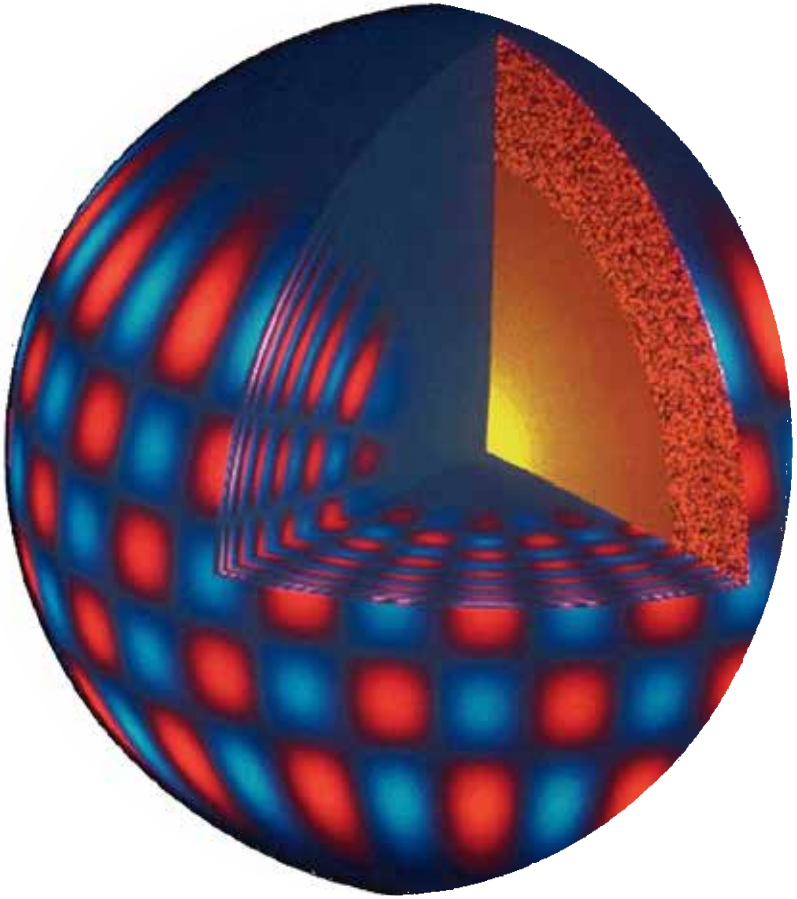
Waves in a Sphere: Spherical Harmonics

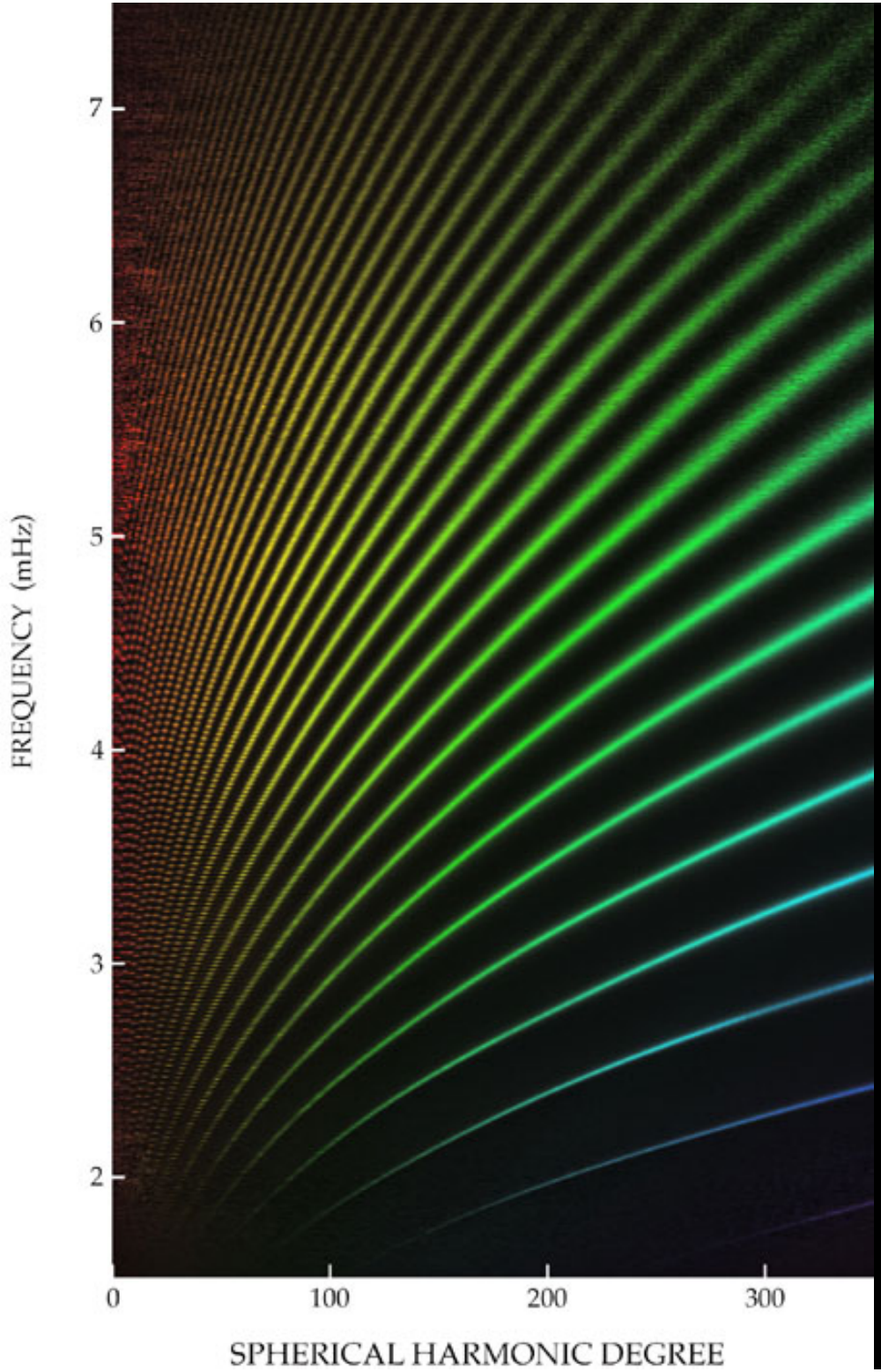
ℓ – spherical harmonic degree: $0 \leq \ell \leq 4000$

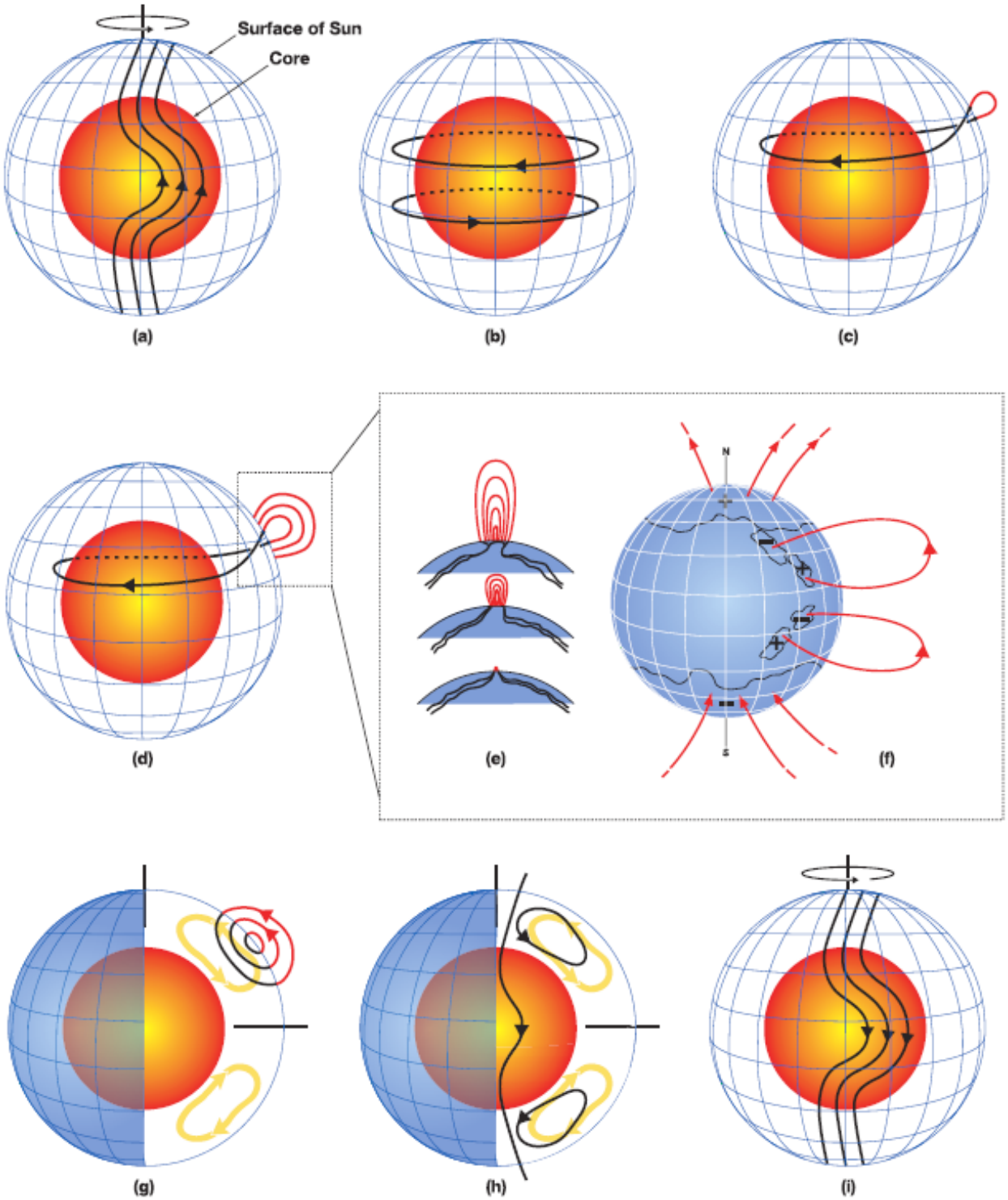
m – azimuthal degree: $-\ell \leq m \leq \ell$

n – radial order: $0 \leq n \leq 80$






FREQUENCY (mHz)
7
6
5
4
3
2
0
100
200
300
SPHERICAL HARMONIC DEGREE

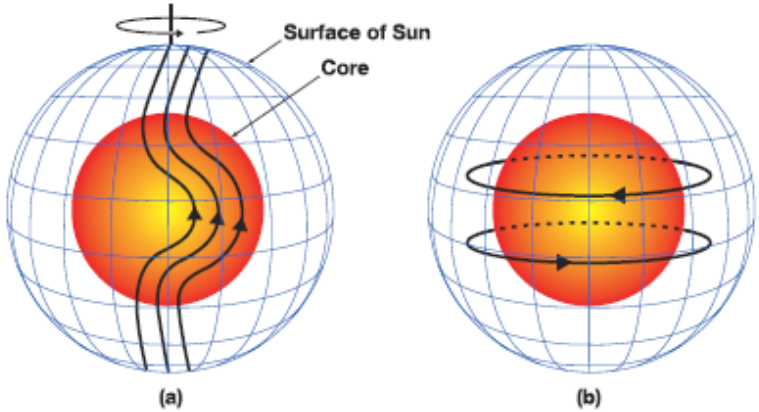


Flux transport dynamo

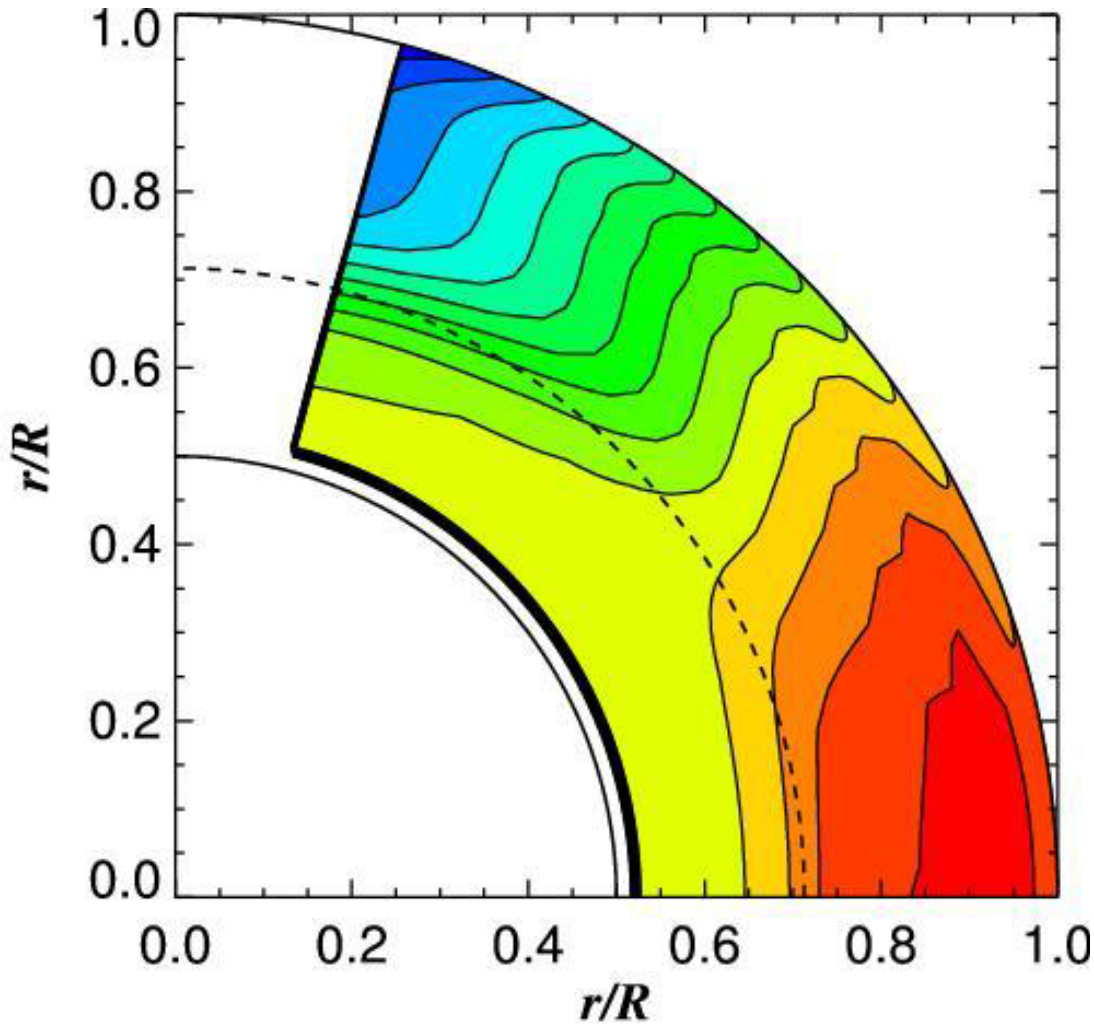
Two large-scale flows of importance: differential rotation and meridional flow

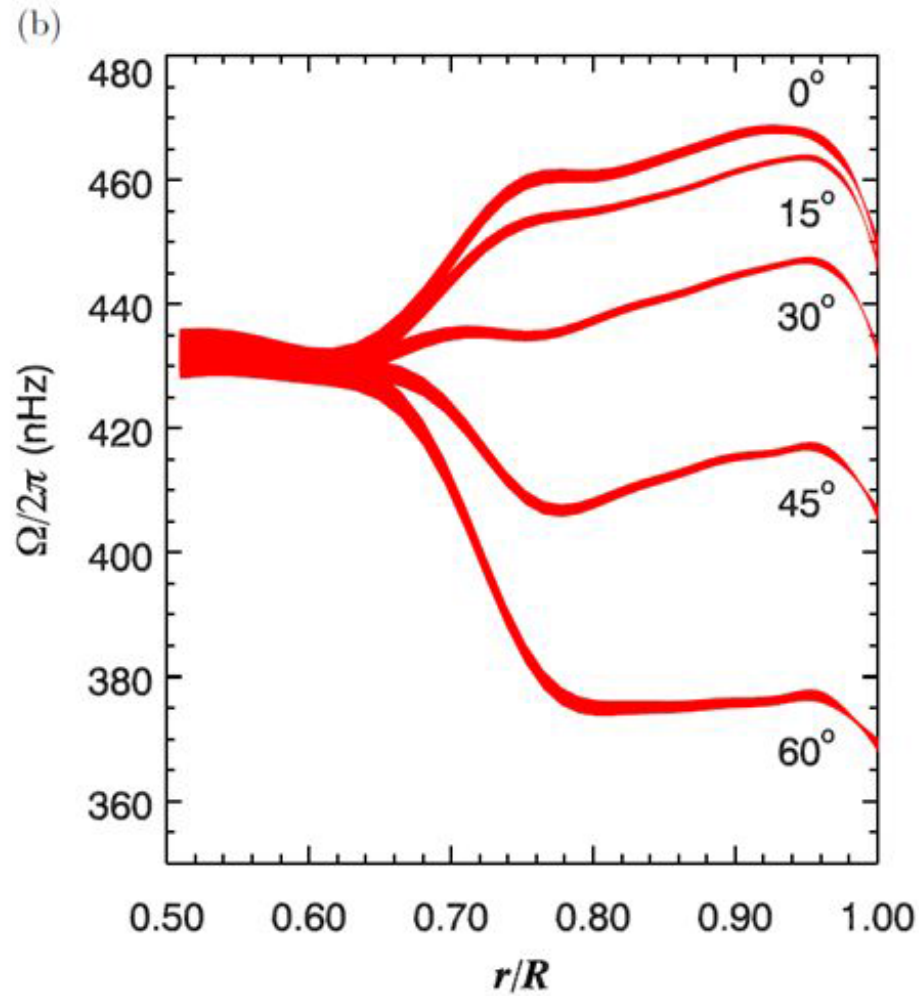
Internal rotation

- Rotation transforms magnetic field from poloidal (N-S) to toroidal (E-W)
- Early dynamo theories assumed internal solar rotation was “constant on cylinders”
  - Iso-rotation contours parallel to rotation axis
  - Taylor-Proudman theorem was satisfied
- Helioseismology showed otherwise



Internal rotation

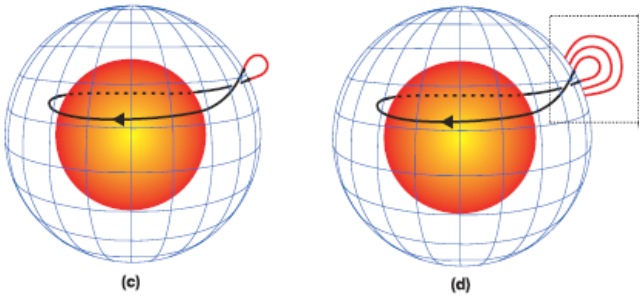




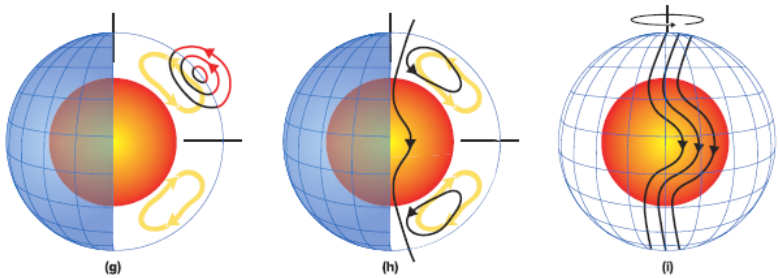
Intrigue!

- Differential rotation (DR) persists through the CZ
- Near the base of the convection zone, DR transitions to solid-body rotation (SBR) in the radiative zone (the tachocline)
- The DR at around 50° latitude is equal to the SBR – this is also the latitude where sunspots first appear in the cycle
- Dynamos require velocity shear, and there is also a shear layer immediately below the photosphere, so two dynamos?

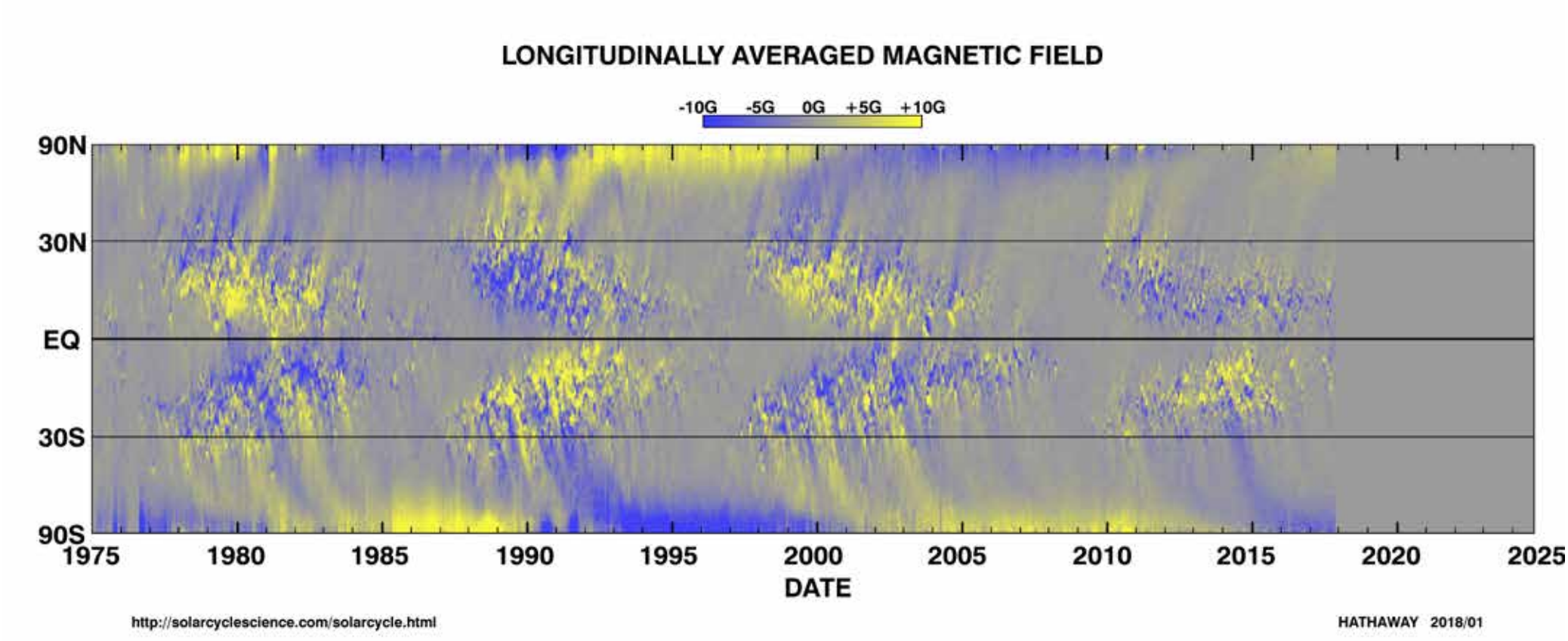
Meridional flow



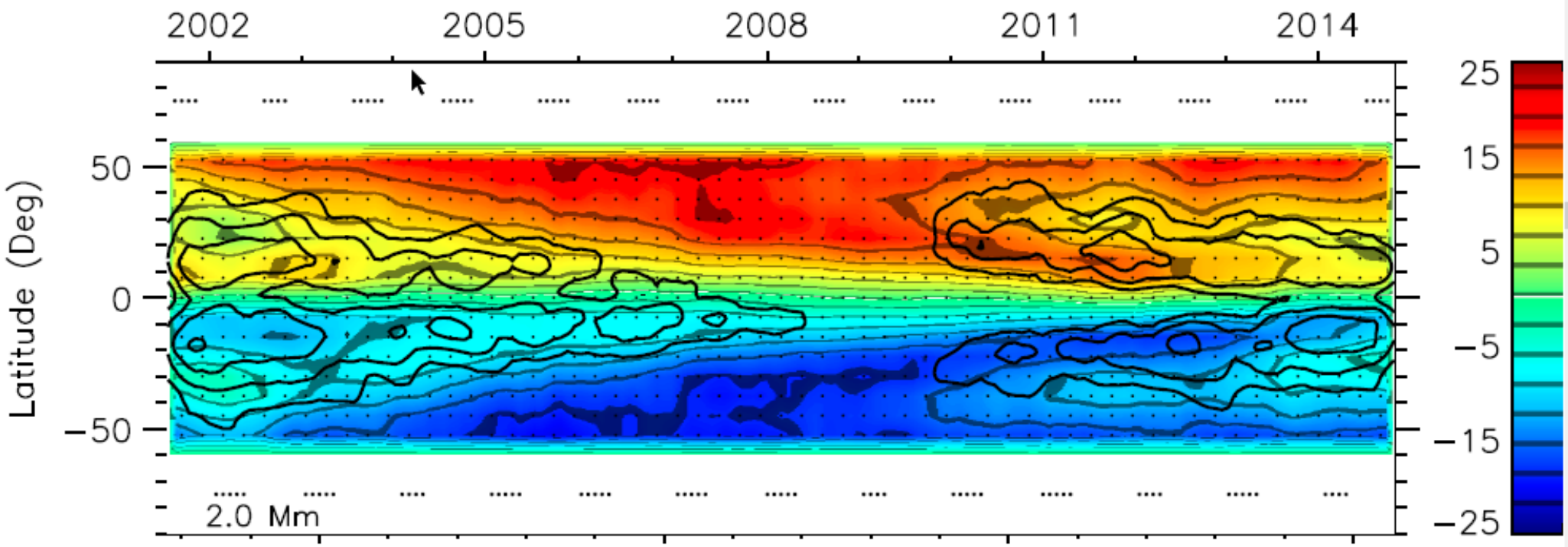
- After active regions emerge, reconnect, and decay, a surface poleward meridional flow (MF) advects the field to the poles
- Presumably, the MF converges and submerges at the poles, taking the magnetic field with it (not yet observed)
- Also presumably, a subsurface return equatorward flow transports the magnetic field back towards lower latitudes and completes the transition from toroidal to poloidal field
- Dynamo models assume uni-cellular MF in the two hemispheres and in depth



The surface magnetic field over four solar cycles



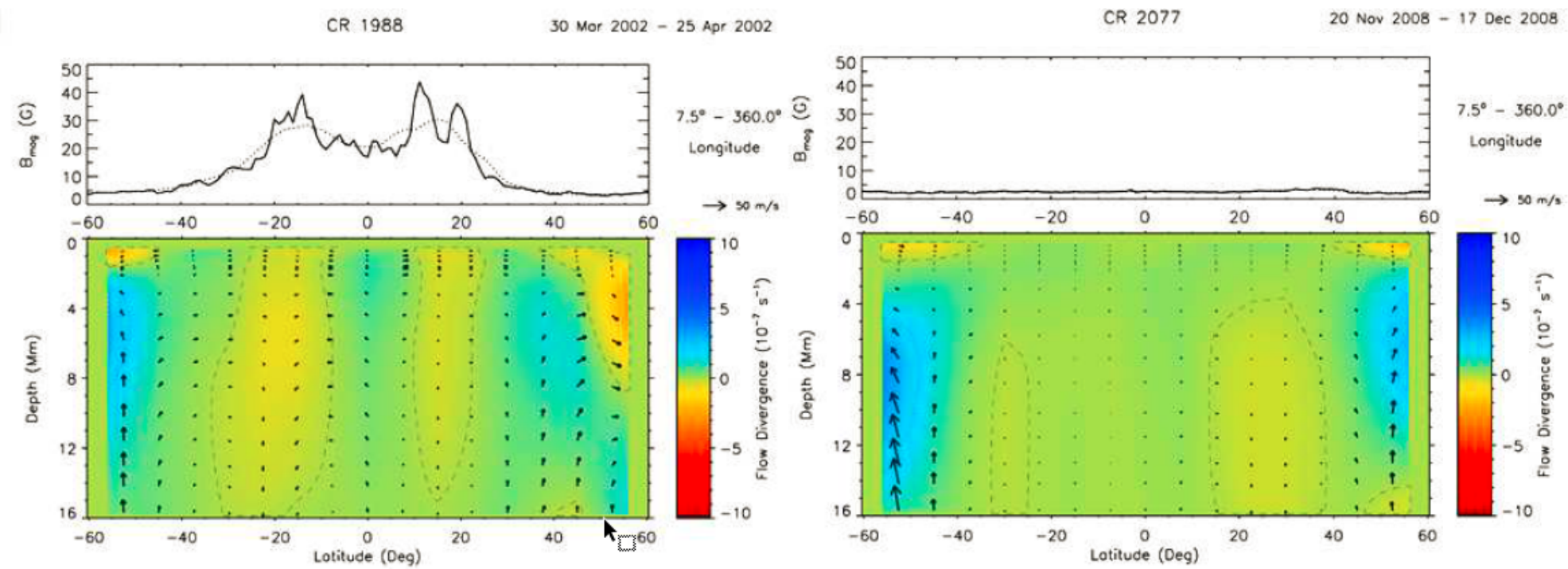
Meridional flow from ring diagrams and GONG data



The speed of the meridional flow changes over the cycle and is correlated with the strength of the next cycle

Flow Divergence

Blue: source/upflow
Yellow: sink/downflow

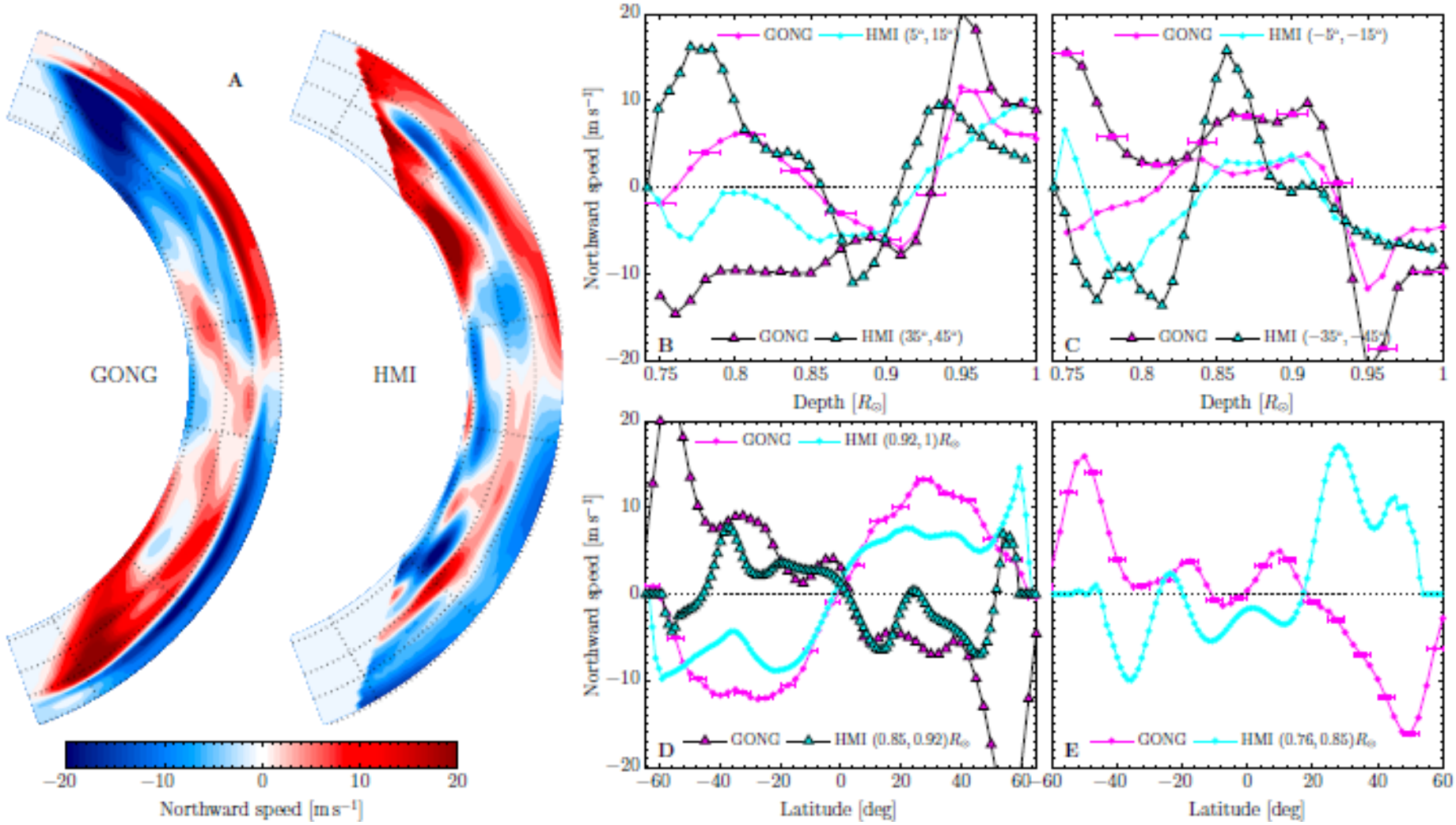


High activity: inflows and downflows in active latitudes

Low activity – pattern much weaker but still present

Three cells in latitude in each hemisphere

Deep meridional flow estimates



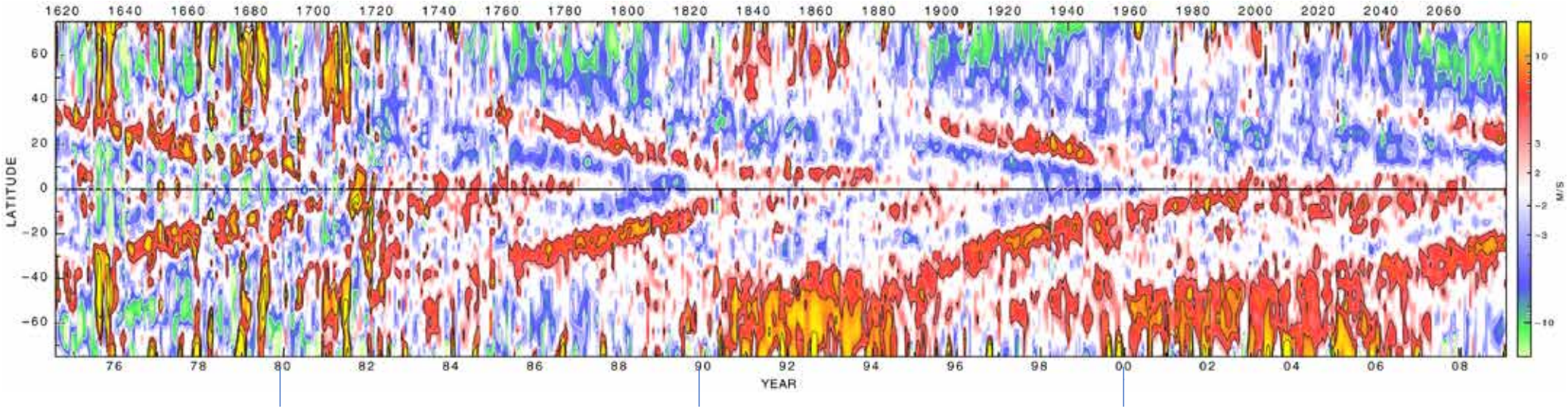
Complex flow, maybe multiple cells in depth, return flow surprisingly shallow (80 Mm)

BUT still little agreement between methods, questions of energy and mass conservation

Torsional oscillation

- Appears as a very weak “jet stream” zonal flow with amplitude ~5 m/s above background DR
- Seen on the surface and down through at least 70 Mm depth
- Moves in latitude during the cycle
- Two branches: poleward and equatorward – total length of time for a flow cycle is ~22 years
- Solar activity appears on equatorward side of flow
- Evolution of flow toward lower latitudes in C24 was correlated with length of cycle and extended minimum
- Does the magnetic field cause the TO, or does the TO influence the activity evolution?

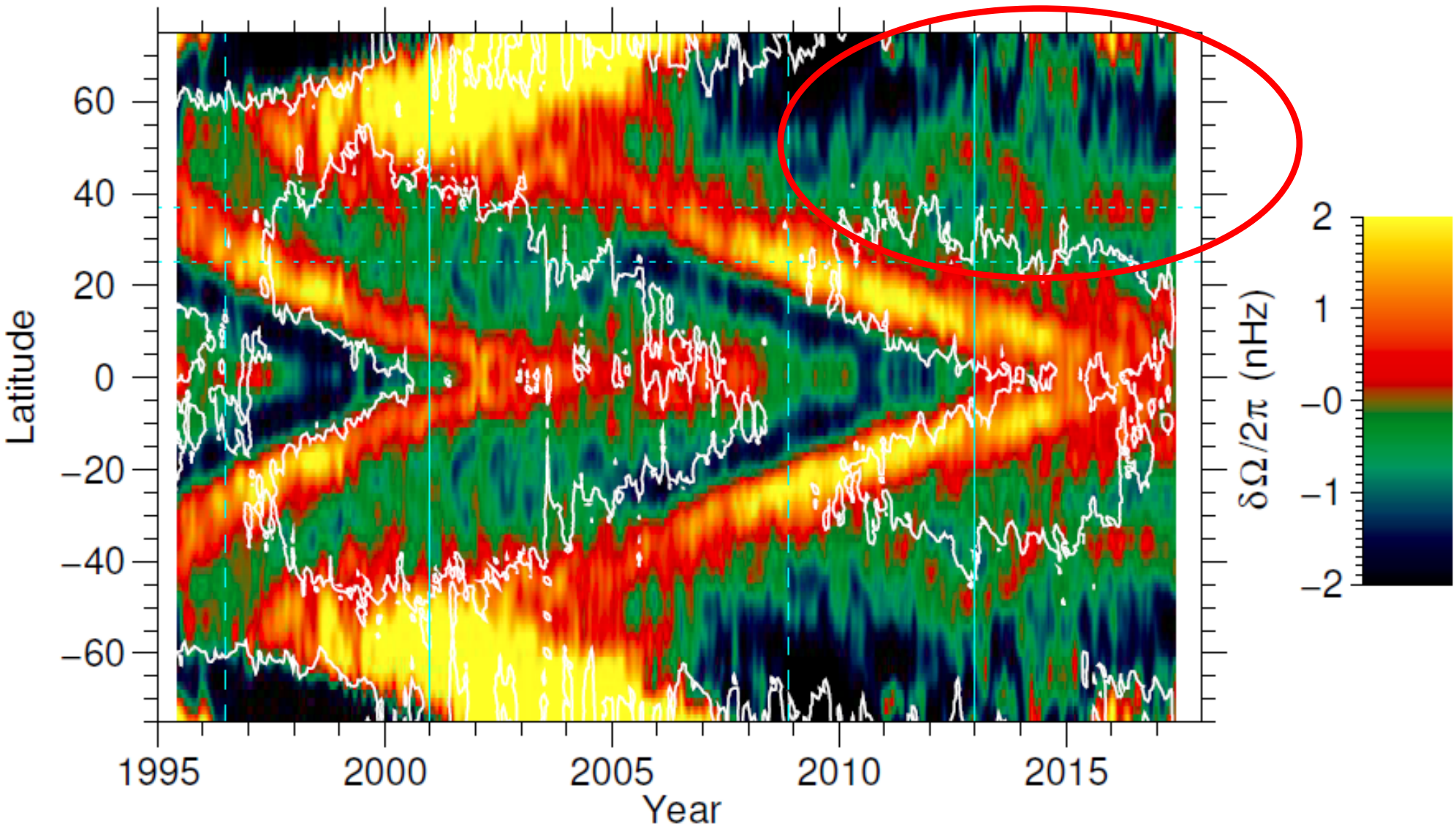
Surface “Torsional Oscillation”



1980 1990 2000

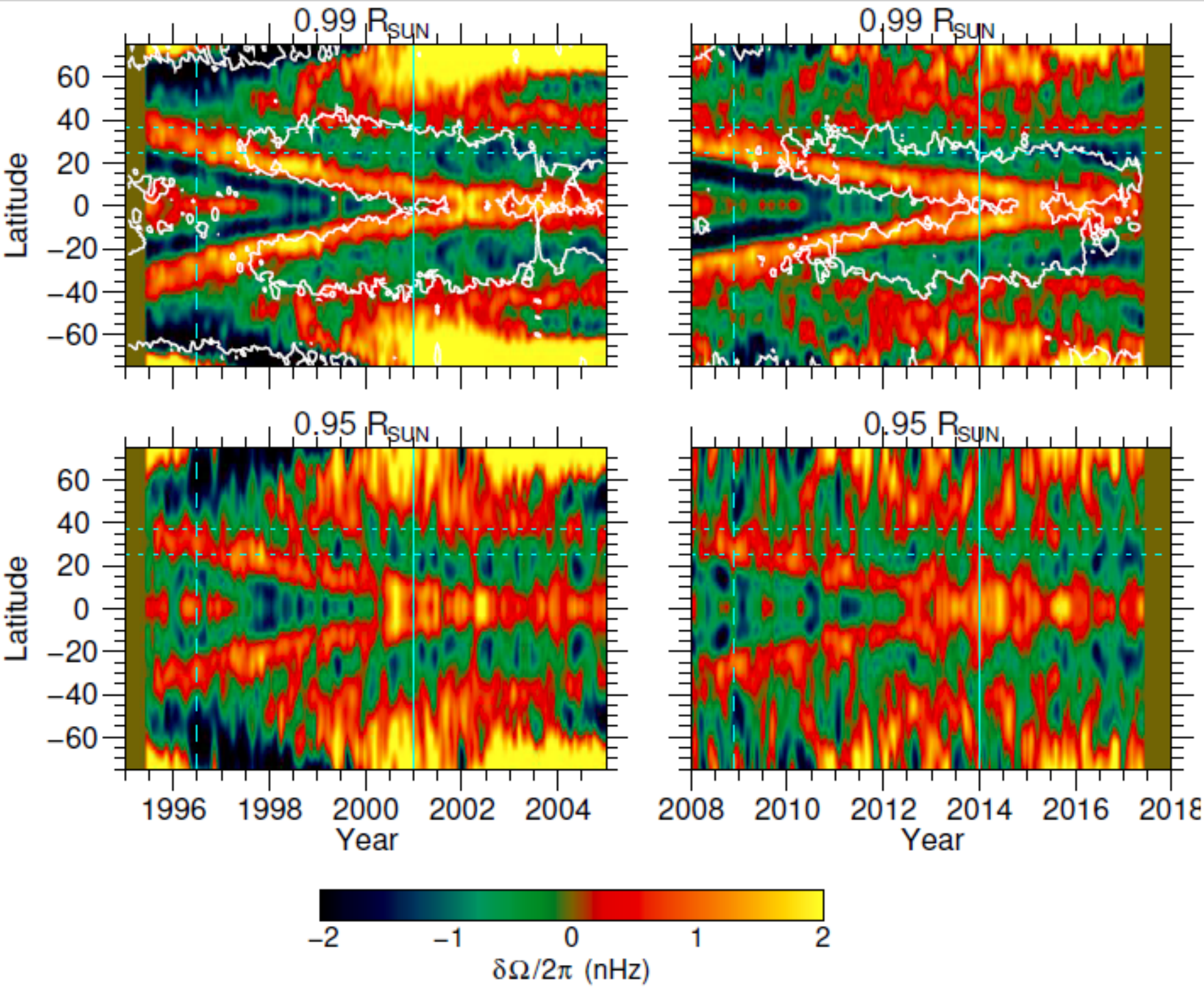
There are no observations of the surface flow past 2009

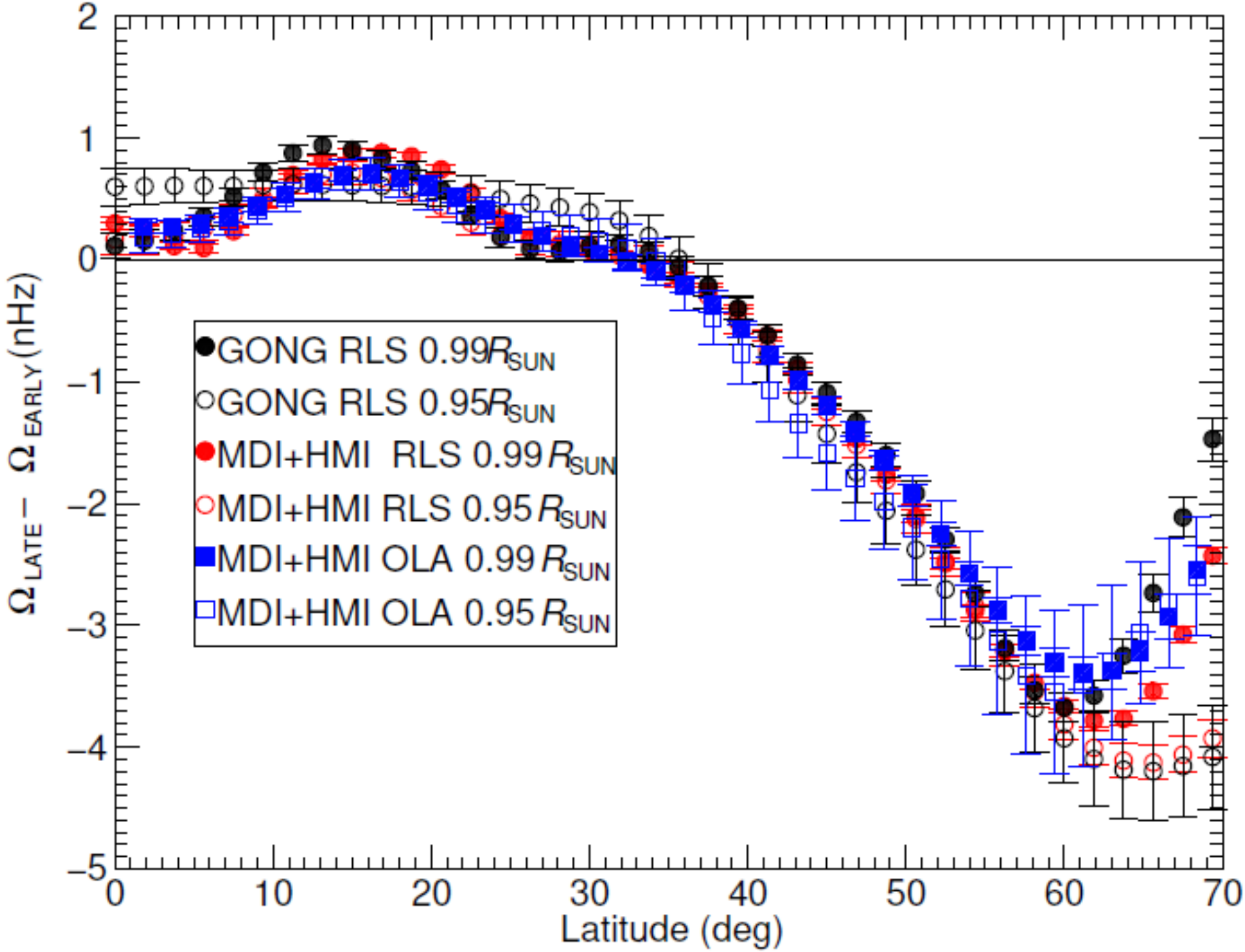
Torsional oscillation at $R_{\odot}$=0.99



Where is Cycle 25?

- Poleward flow should have appeared in 2009
- Equatorward flow should have appeared in 2015
- WTF?
- One possibility: background differential rotation changed with time


0.99 R_SUN
0.99 R_SUN
0.95 R_SUN
0.95 R_SUN
Latitude
Latitude
60
40
20
0
−20
−40
−60
1996
1998
2000
2002
2004
2008
2010
2012
2014
2016
2018
Year
Year
−2
−1
0
1
2
δΩ/2π (nHz)


GONG RLS 0.99R_{SUN}
GONG RLS 0.95R_{SUN}
MDI+HMI RLS 0.99 R_{SUN}
MDI+HMI RLS 0.95 R_{SUN}
MDI+HMI OLA 0.99 R_{SUN}
MDI+HMI OLA 0.95 R_{SUN}
$\Omega_{LATE} - \Omega_{EARLY}$ (nHz)
Latitude (deg)
2
1
0
−1
−2
−3
−4
−5
0
10
20
30
40
50
60
70

Conclusions

- Helioseismology has revealed that the flows driving the solar cycle are more complex than assumed by dynamo theory
- New dynamo models are being constructed incorporating the helioseismic flows
- The torsional oscillation for the next cycle (25) is very different from predecessors – did the Sun's rotation profile change or is there a grand minimum coming?
- But we only have four cycles of observations so far (less than two with helioseismology)
- Stay tuned!