Helioseismic probes of the solar interior

Anne-Marie Broomhall

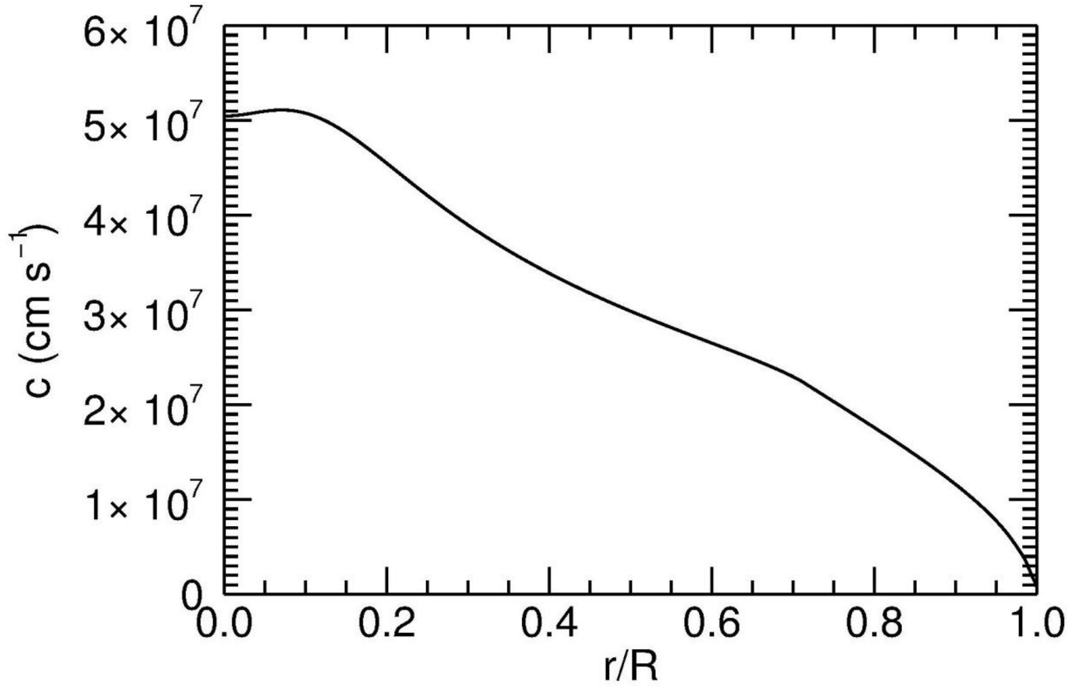
Institute of Advanced Study, University of Warwick
Centre for Fusion, Space, and Astrophysics, University of Warwick

Outline

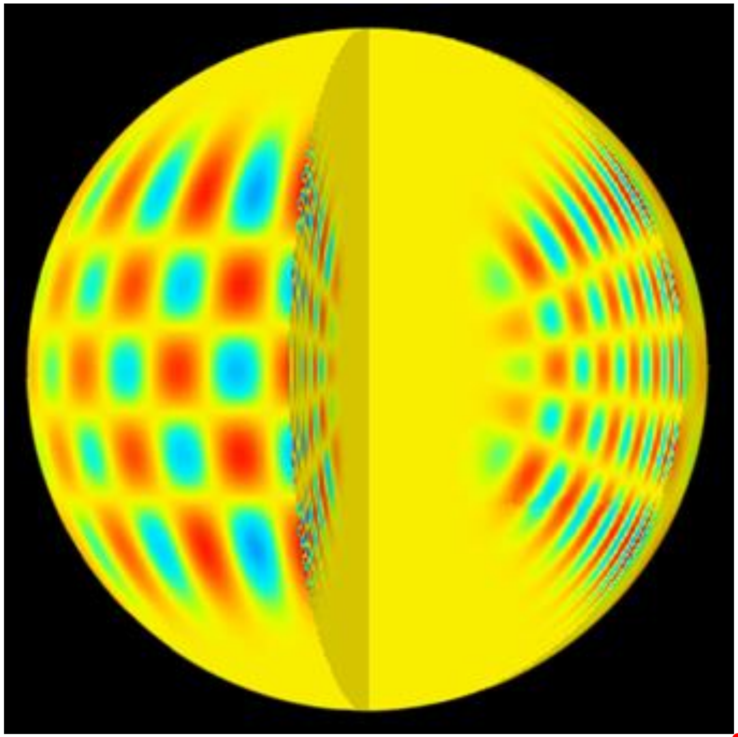
- Time-averaged conditions in the solar interior
  - The surface term
  - Solar abundance problem
  - Rotation
  - Gravity modes
- Variations with solar cycle
  - Variations in helioseismic mode properties
  - Evidence for solar cycle structure variations
  - Variations in flows

What is helioseismology?

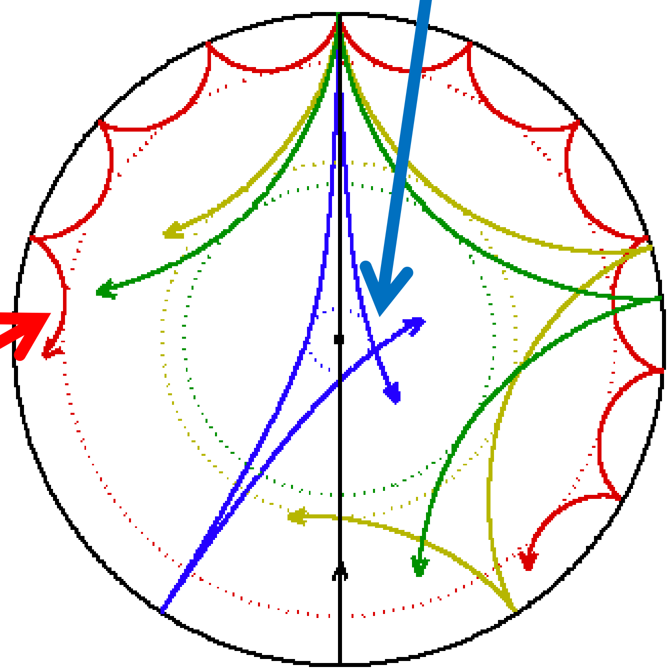
- At any one time there are thousands of oscillations trapped in the solar interior.
- Dominant modes are acoustic p modes.
- Enable us to build up profiles of internal sound speed, c_s.
- $c_s^2 \propto \Gamma_1 T/\mu$ (Γ_1=1st adiabatic exponent, μ=mean molecular weight).

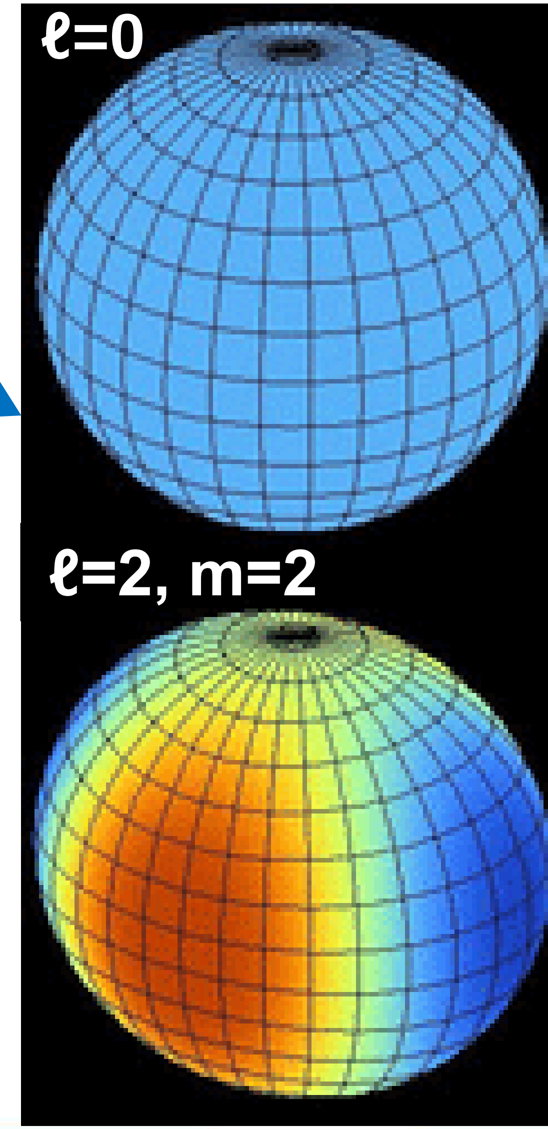


Harmonic degree, ℓ



Low degree (ℓ)

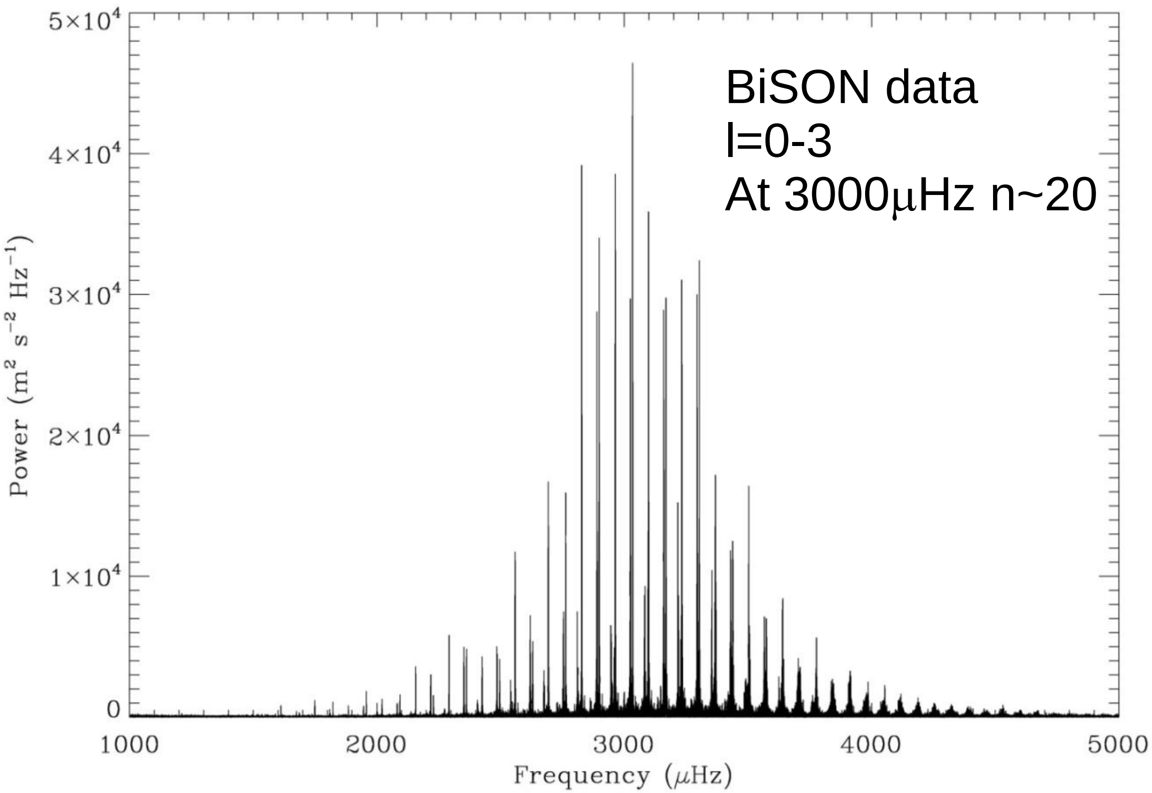


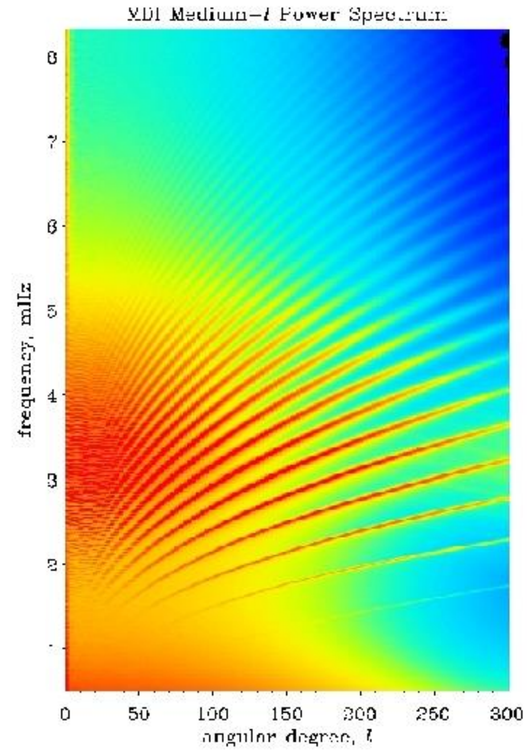


Intermediate or high degree (ℓ)

Frequency-power spectrum

- Modes with largest amplitudes have frequencies around 3000μHz or periods ~5min.
  - Period of fundamental radial mode ~1hr.



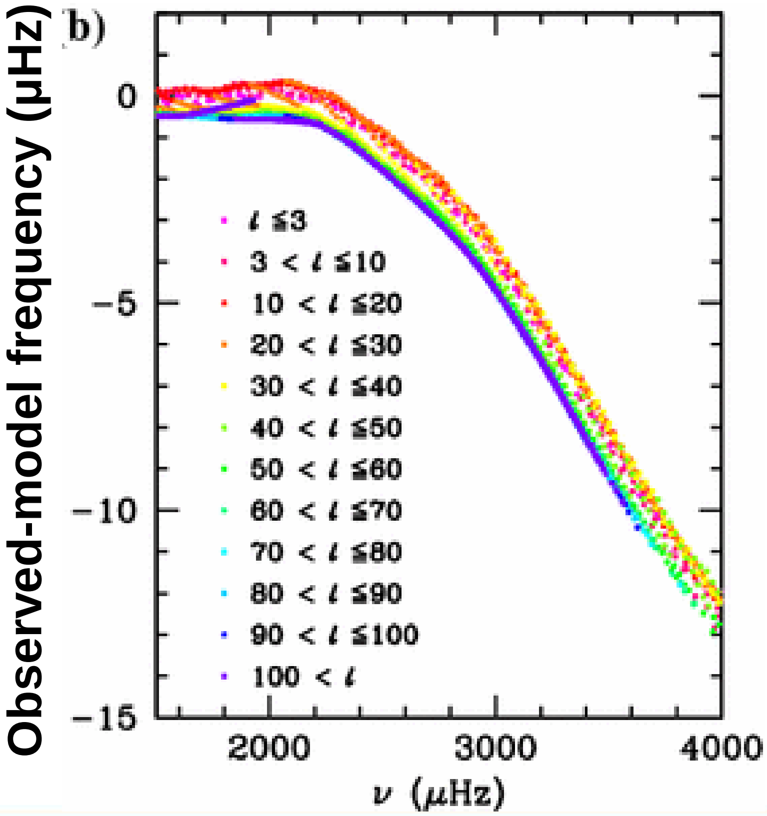


SOHO (ESA & NASA)

Structure and flows in the solar interior

Testing solar models

- Comparisons can be made between model and helioseismic observations
- But discrepancies are observed.

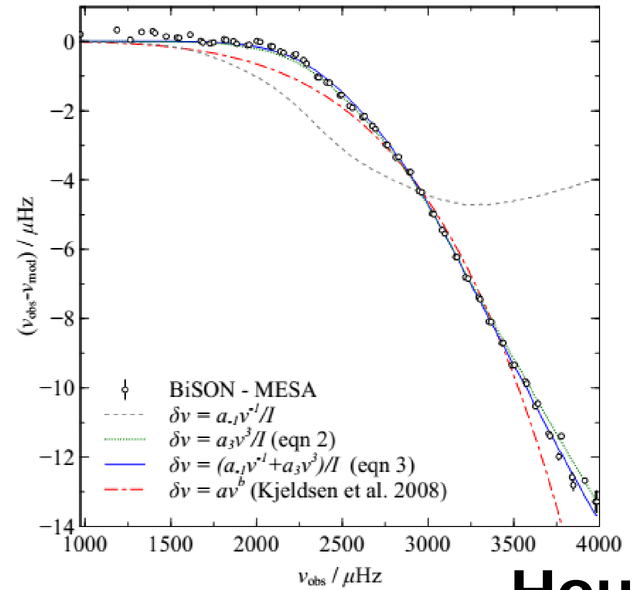


Basu, 2016, LRSP

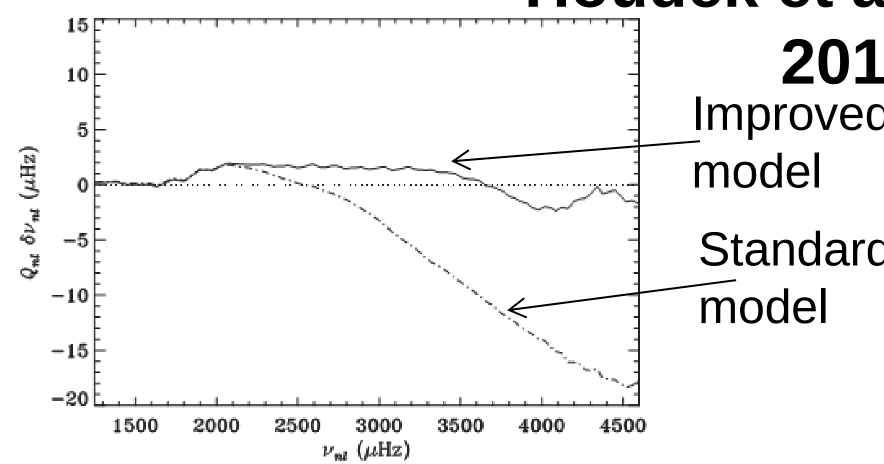
The ‘surface term’

- Corrections based on parametric fit to Sun-as-a-star frequencies.
- 3D hydrodynamical simulation, nonadiabatic effects, and a consistent treatment of the turbulent pressure.
- See Lionel Bigot’s talk

e.g. Gough, 1990; Ball et al., 2016



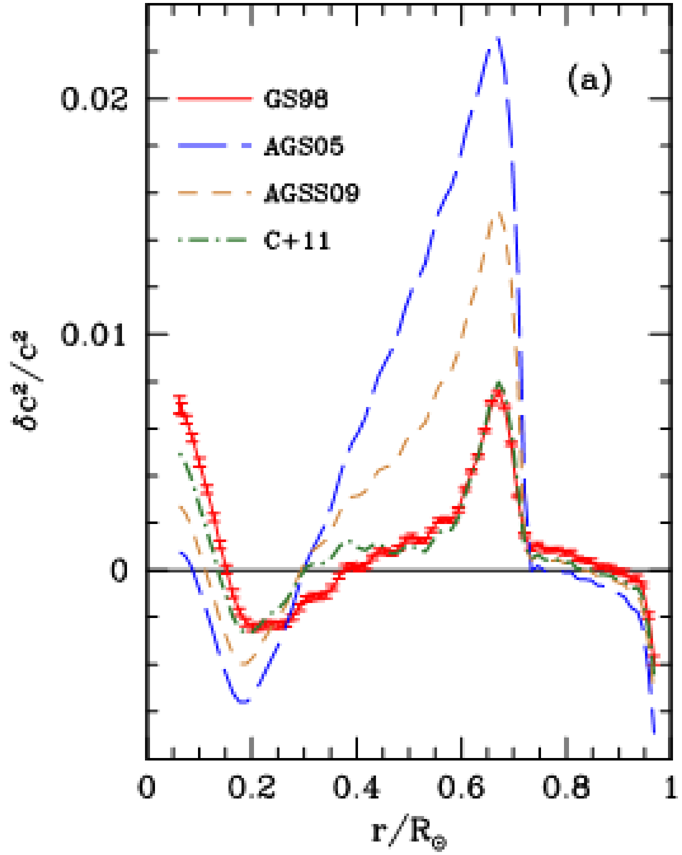
Houdek et al. 2017



Solar abundance problem

- Numerous attempted solutions include modified opacities, gravitational settling, enhanced diffusion, dark matter…

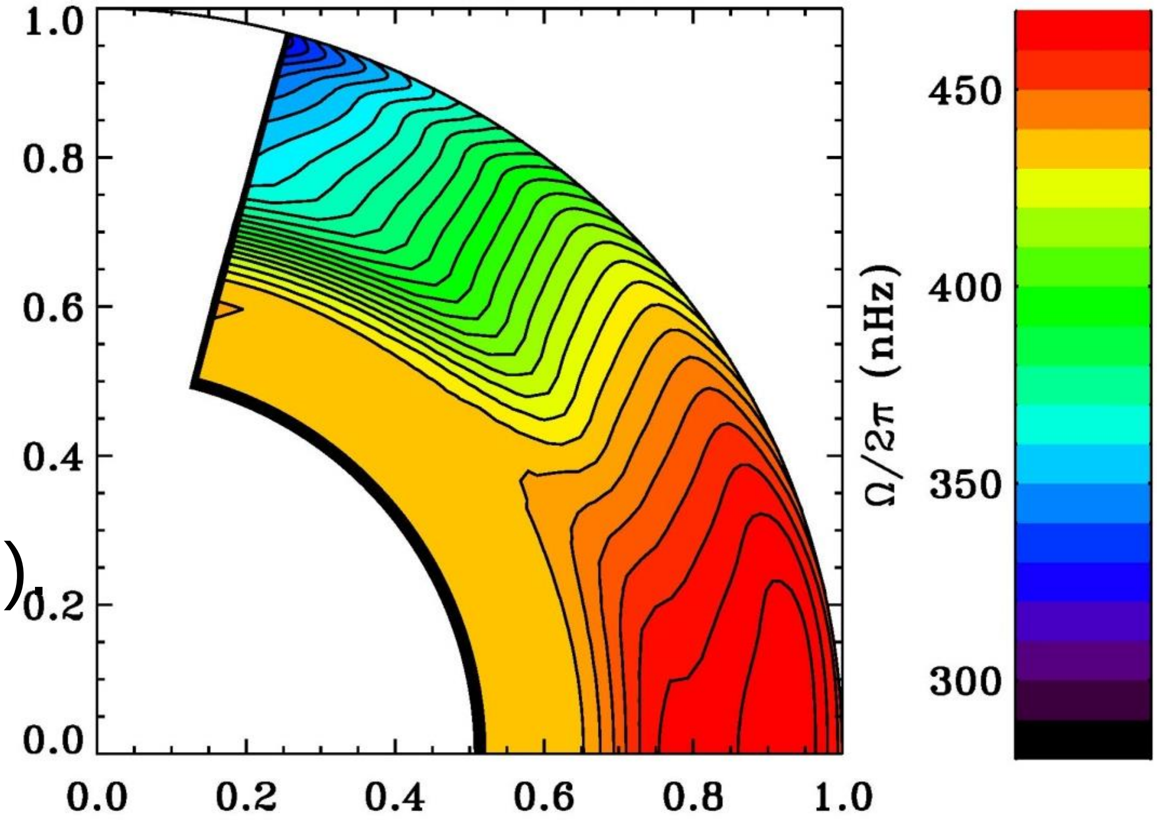
Z/X:
GS98 – 0.023
AGS05 – 0.016
AGSS09 – 0.018
C+11 – 0.0209



Basu, 2016, LRSP

Internal rotation profile

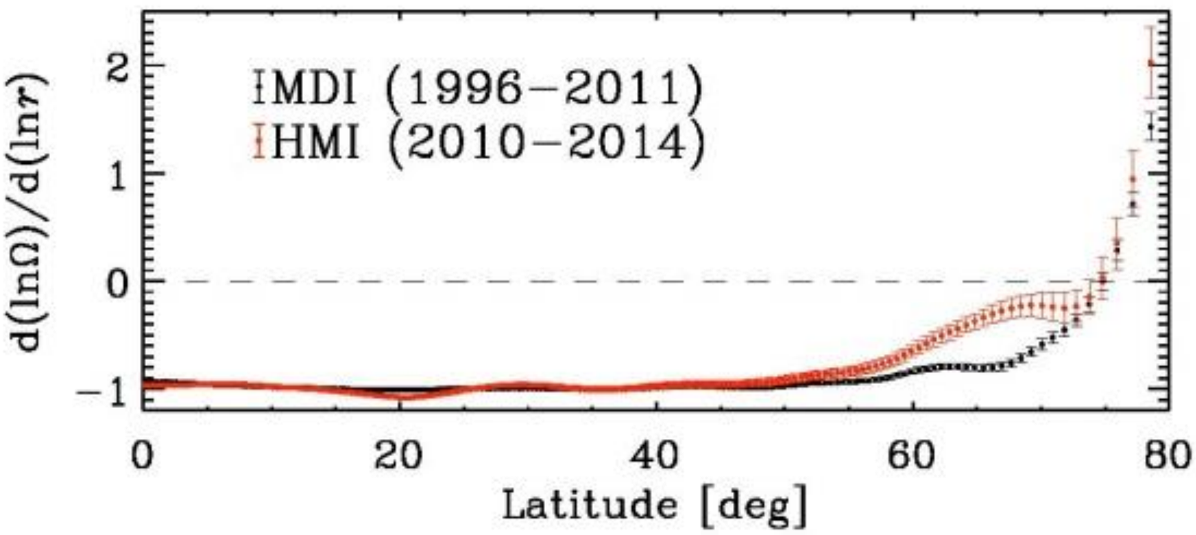
- Differential rotation extends over outer 30%
- Two regions of shear
  - Tachocline & near surface shear layer
  - Most estimates place tachocline around $0.69R_\odot$, with a thickness of $0.05R_\odot$ (Howe, 2009).
- See talks by Yuhung Fan & Roxanne Barnabé



Courtesy of Michael Thompson

Near-surface shear layer

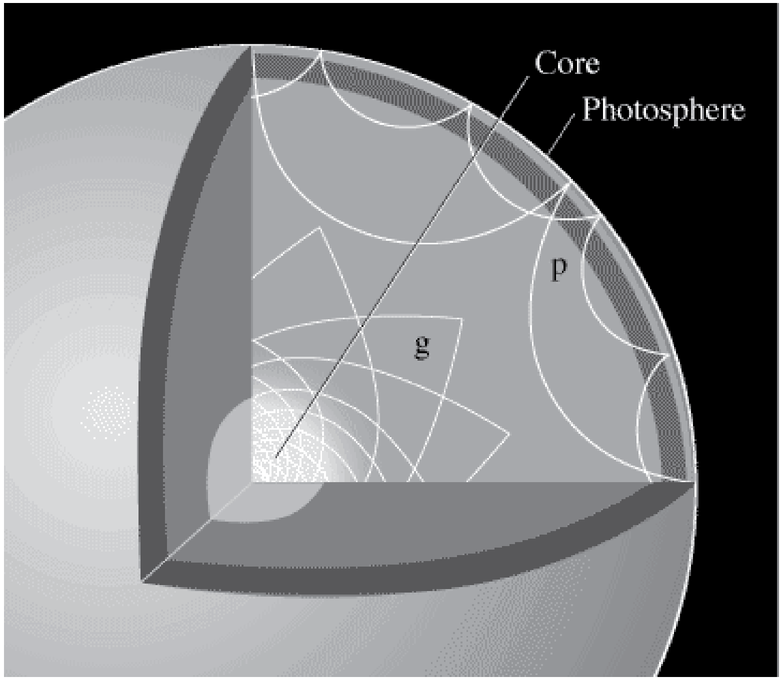
- Gradient of shear not what expected from conservation of angular mom'm (i.e. -2).
- Presence of NSSL not fully explained:
  - Cunnyngham et al. (2016): radiation → angular mom'm loss → torque (like Poynting-Robertson drag).

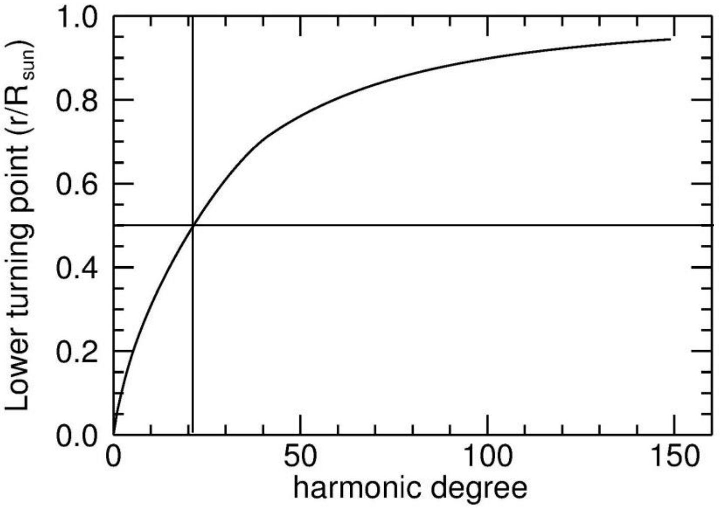


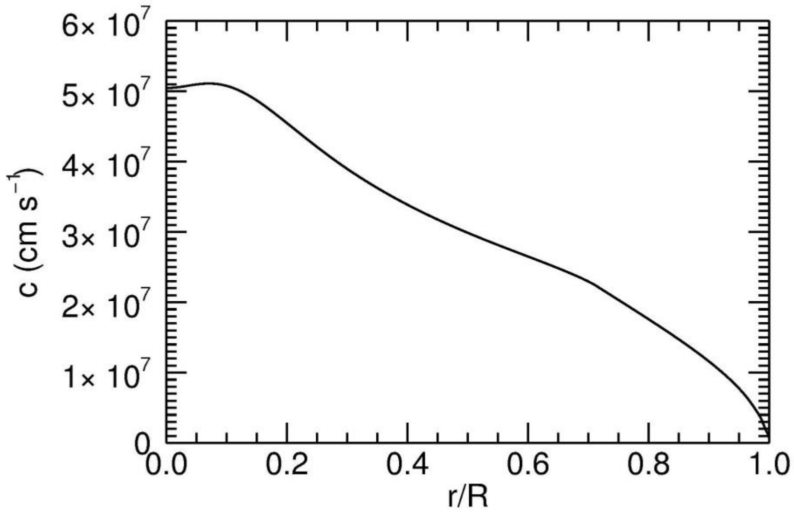
Barekat, Schou & Gizon, 2014

Limitations of p modes

- Inversions of core conditions poorly constrained by p modes.
- Gravity modes far more sensitive to solar core.

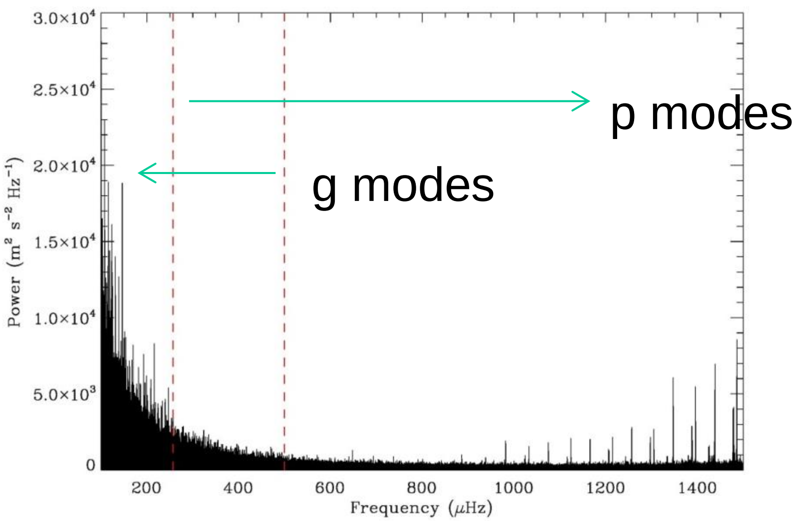


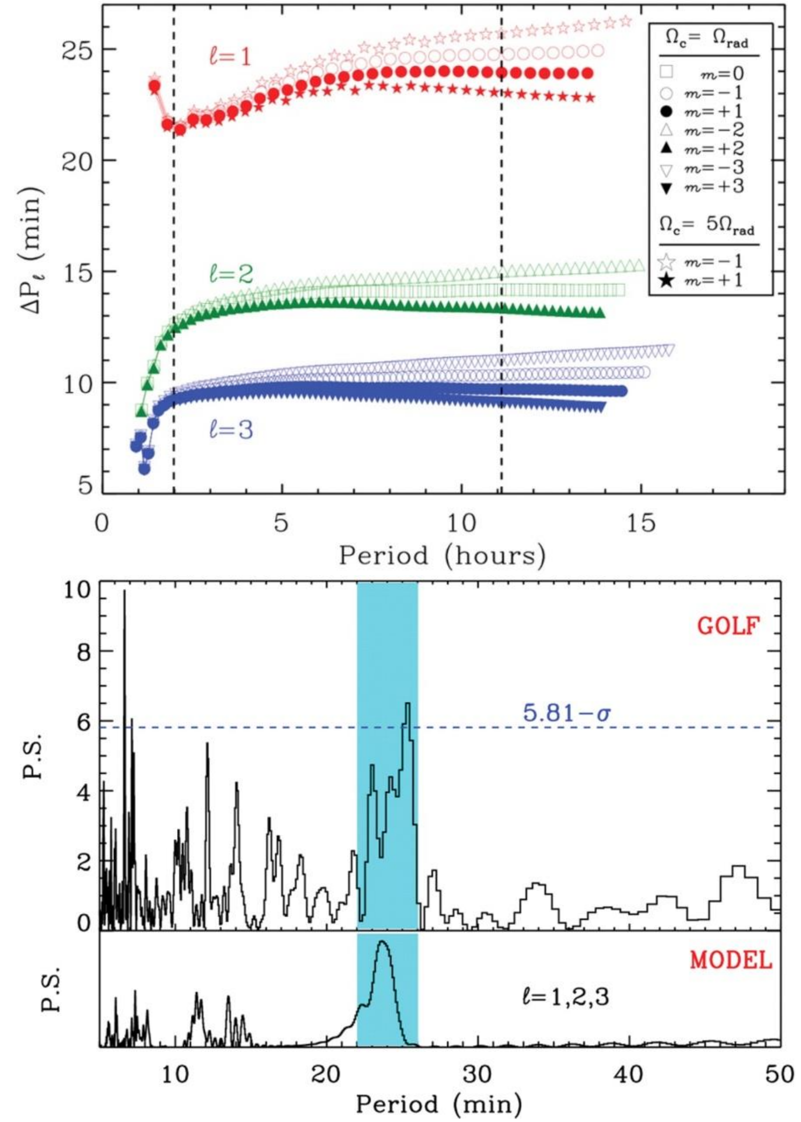




Detections of gravity modes

- No independently confirmed detections of individual g modes.
- Some evidence in periodogram of periodogram.



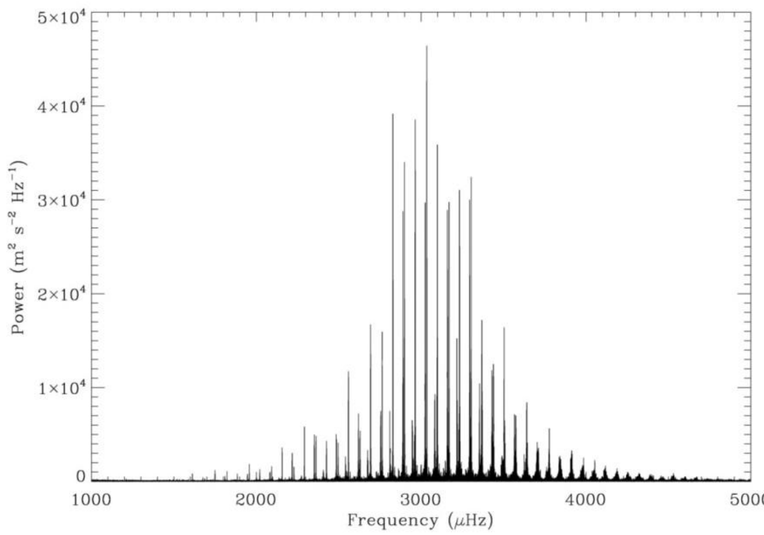


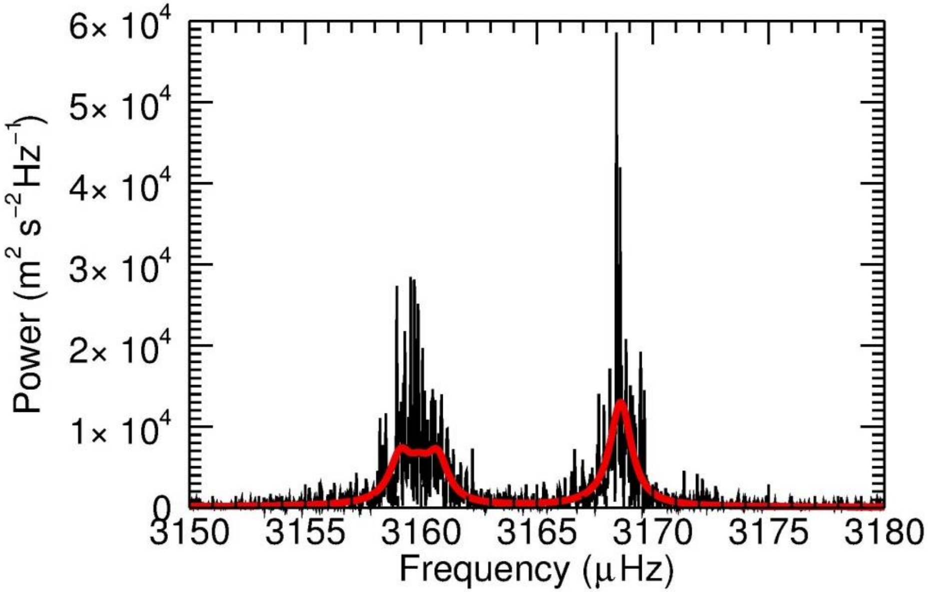
Garcia et al., 2007

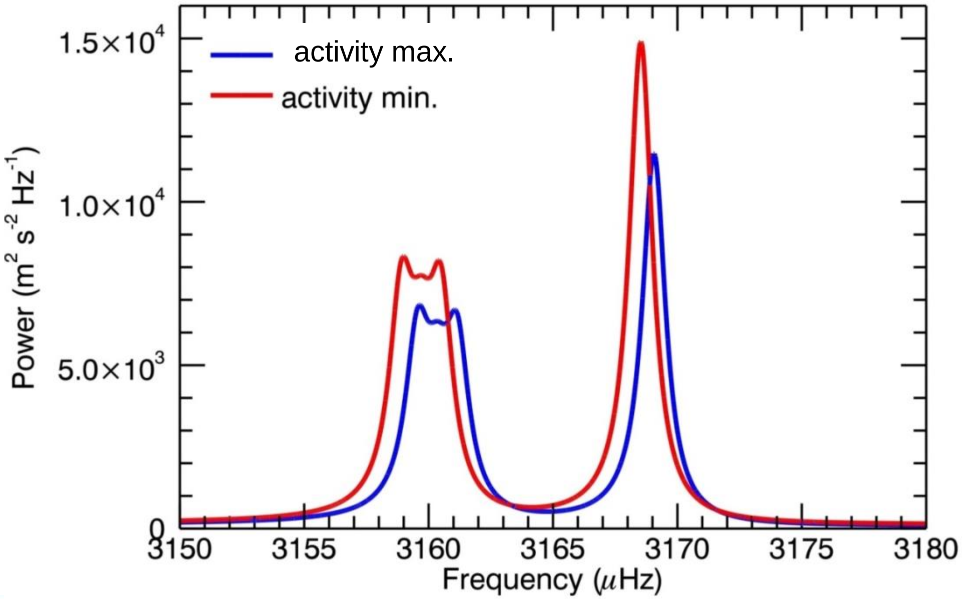
Helioseismology and the solar cycle

Solar cycle variations in p modes

Unresolved
BiSON
data





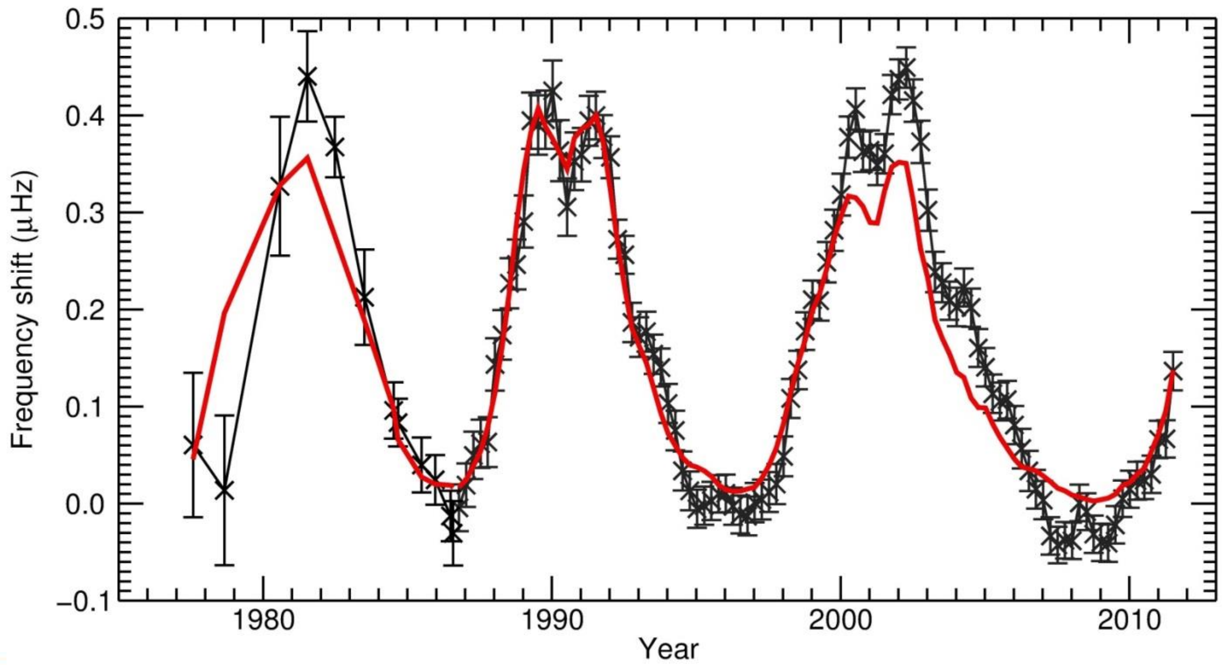


Seismic frequencies and the solar cycle

- Seismic frequencies respond to changes in the surface activity (Woodard & Noyes ,1985).
- Causes:
  - Direct – Lorentz force.
  - Indirect – change in cavity properties.

Shifts from BiSON

Scaled 10.7cm flux

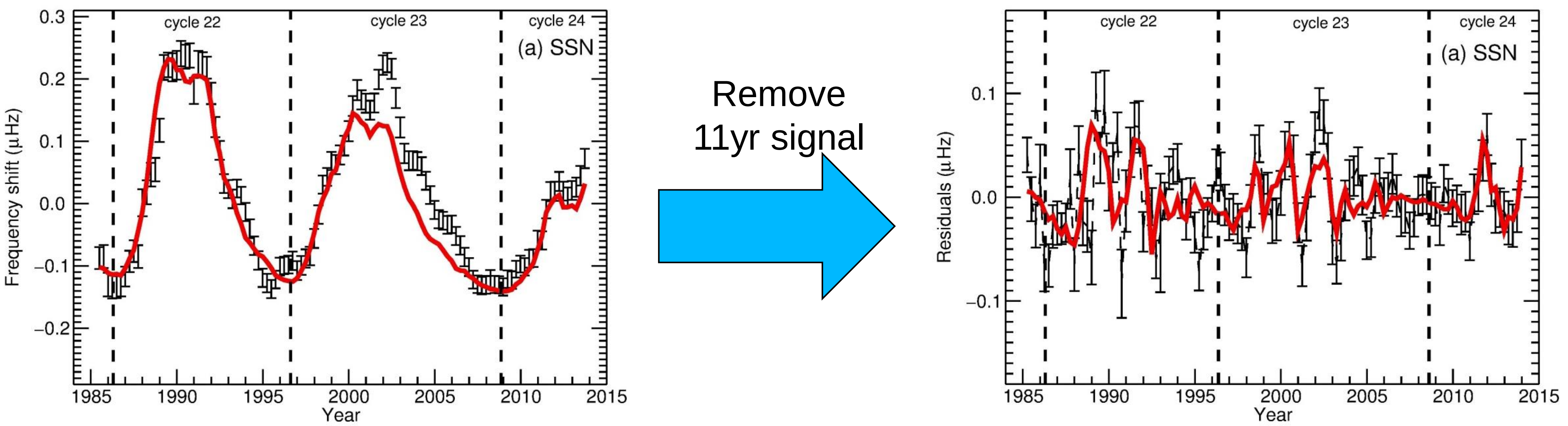


shift ≈ 0.01% of mode frequency

Shift of ≈ 0.03μHz G^{-1}

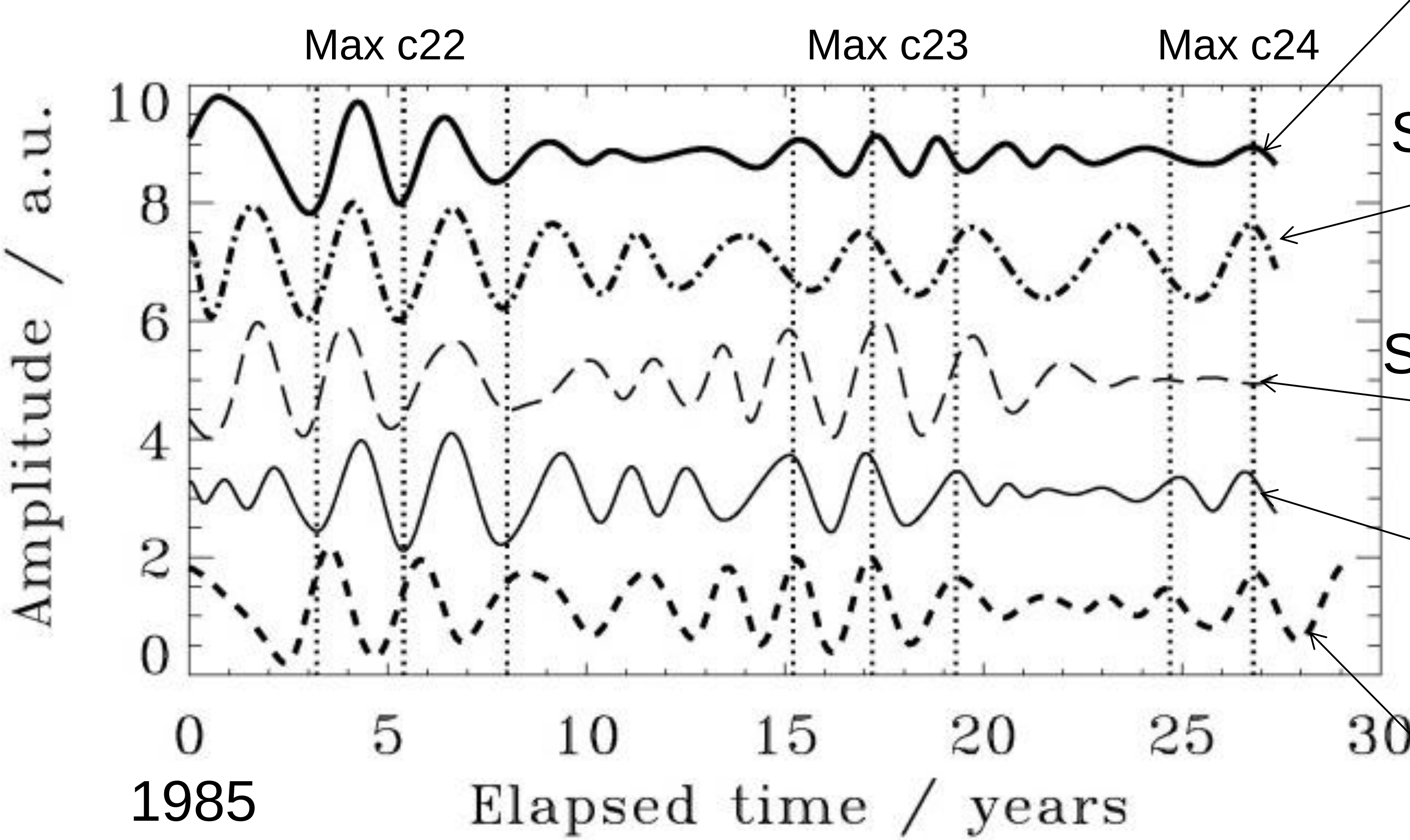
Shorter term variations in the seismic frequencies

- Persistent shorter-term variations are visible in frequency shifts – quasi-biennial oscillation (QBO).



Broomhall & Nakariakov, 2015

Empirical Mode Decomposition of QBO



Sunspot area whole

$P=2.55^{+0.49}_{-0.52}$ yr

Sunspot area north

$P=2.61^{+1.31}_{-0.22}$ yr

Sunspot area south

$P=2.28^{+0.21}_{-0.09}$ yr

F10.7

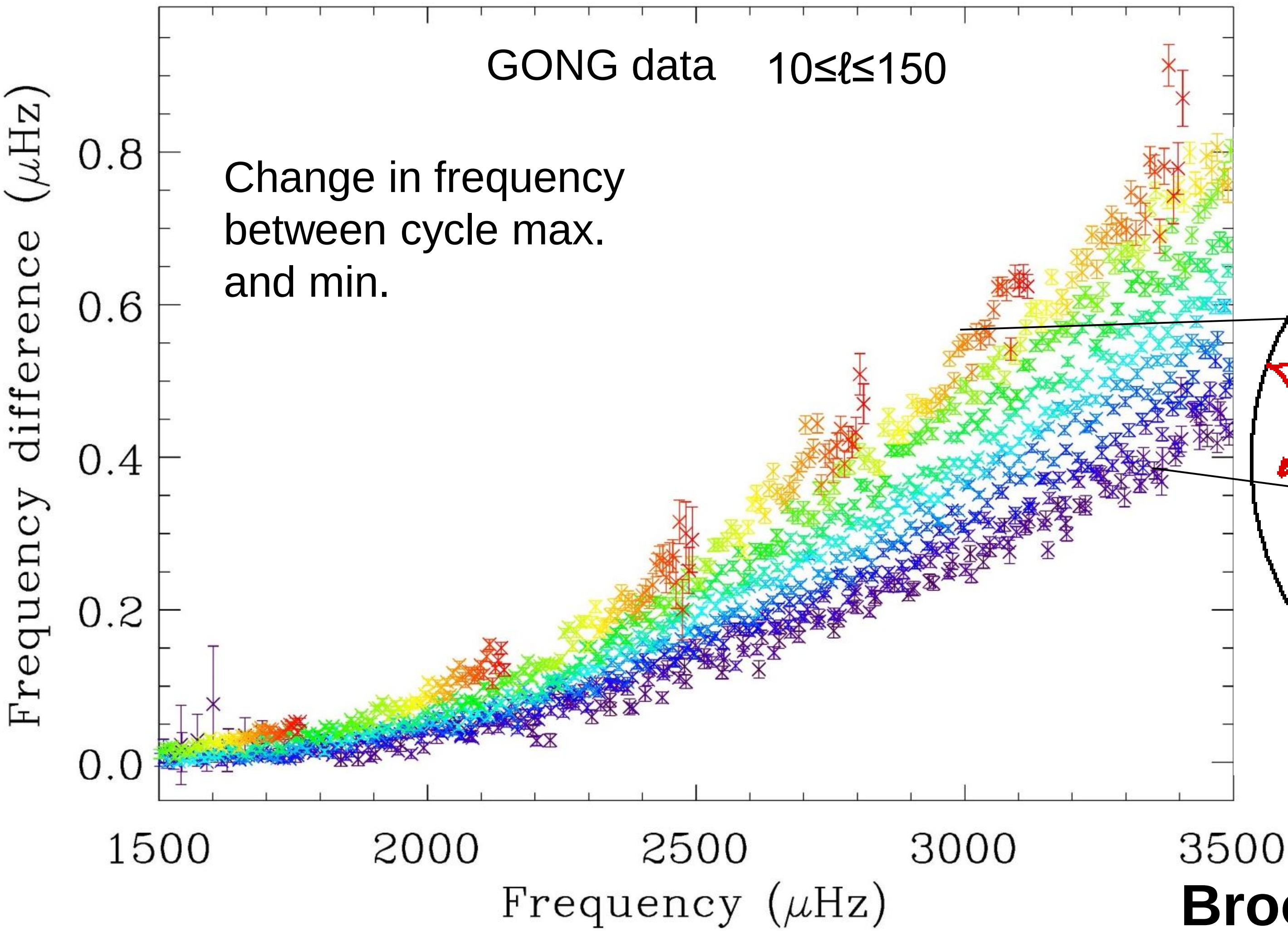
$P=2.28^{+1.14}_{-0.17}$ yr

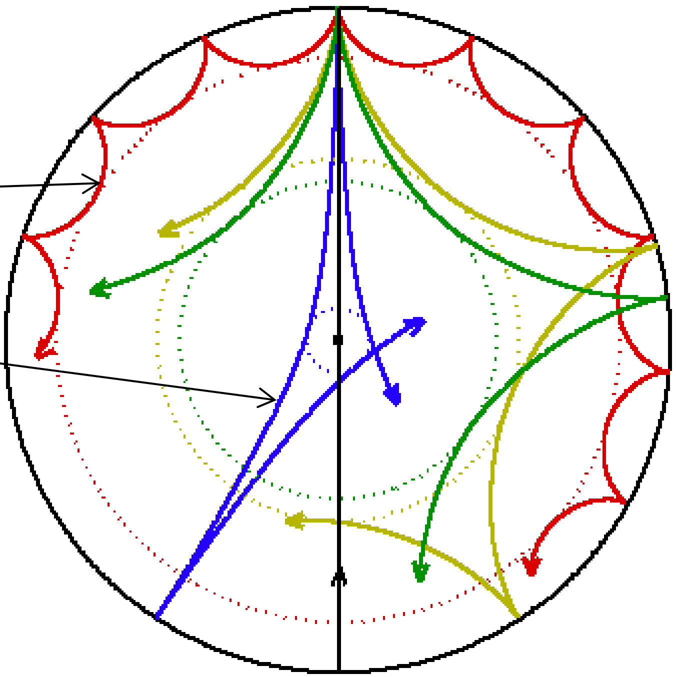
Helioseismic

$P=2.64^{+0.13}_{-0.64}$ yr

Kolotkov, Broomhall & Nakariakov (2015)

Max-min frequency shift

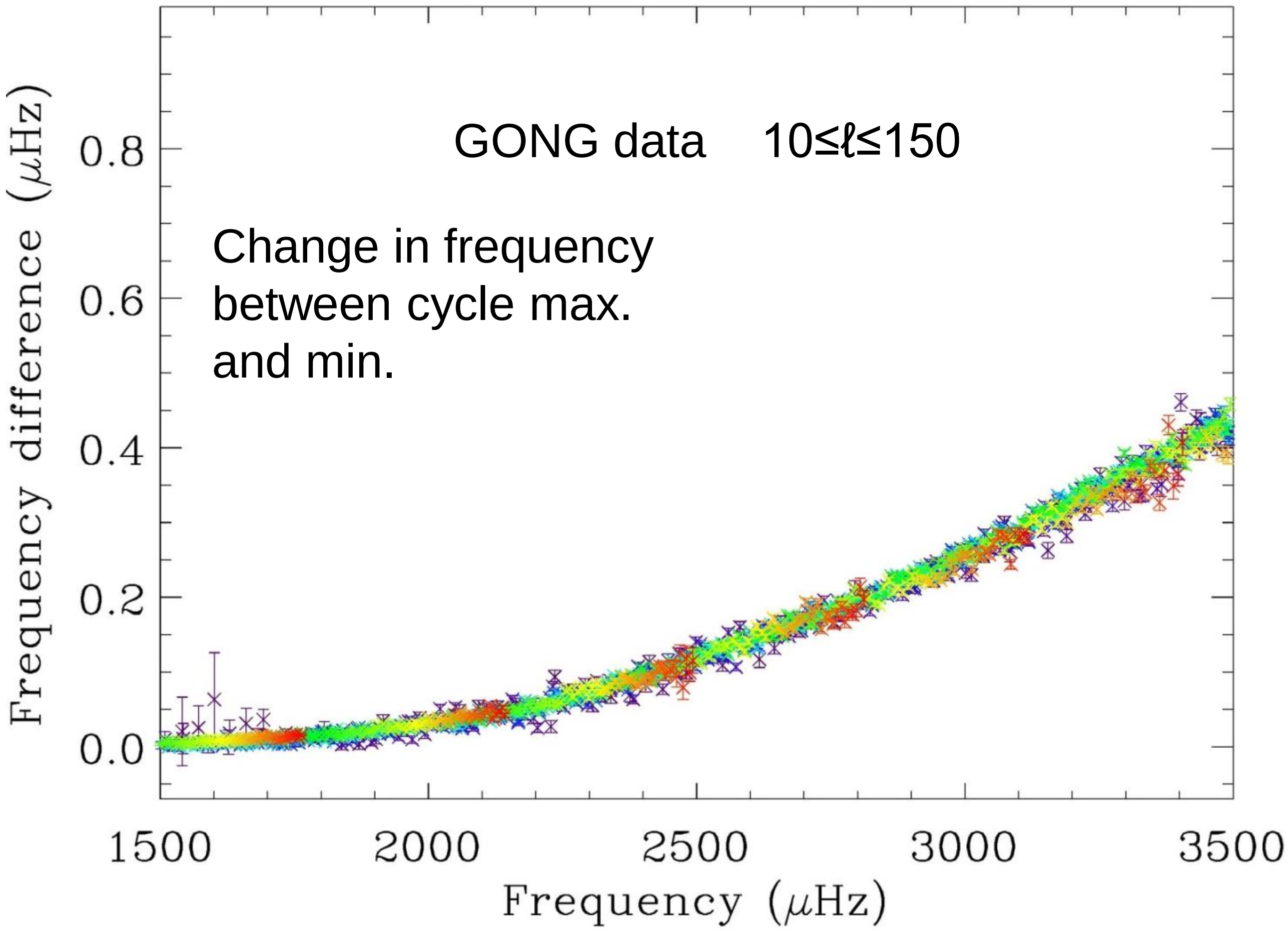




Broomhall, 2017, in press

Max-min frequency shift

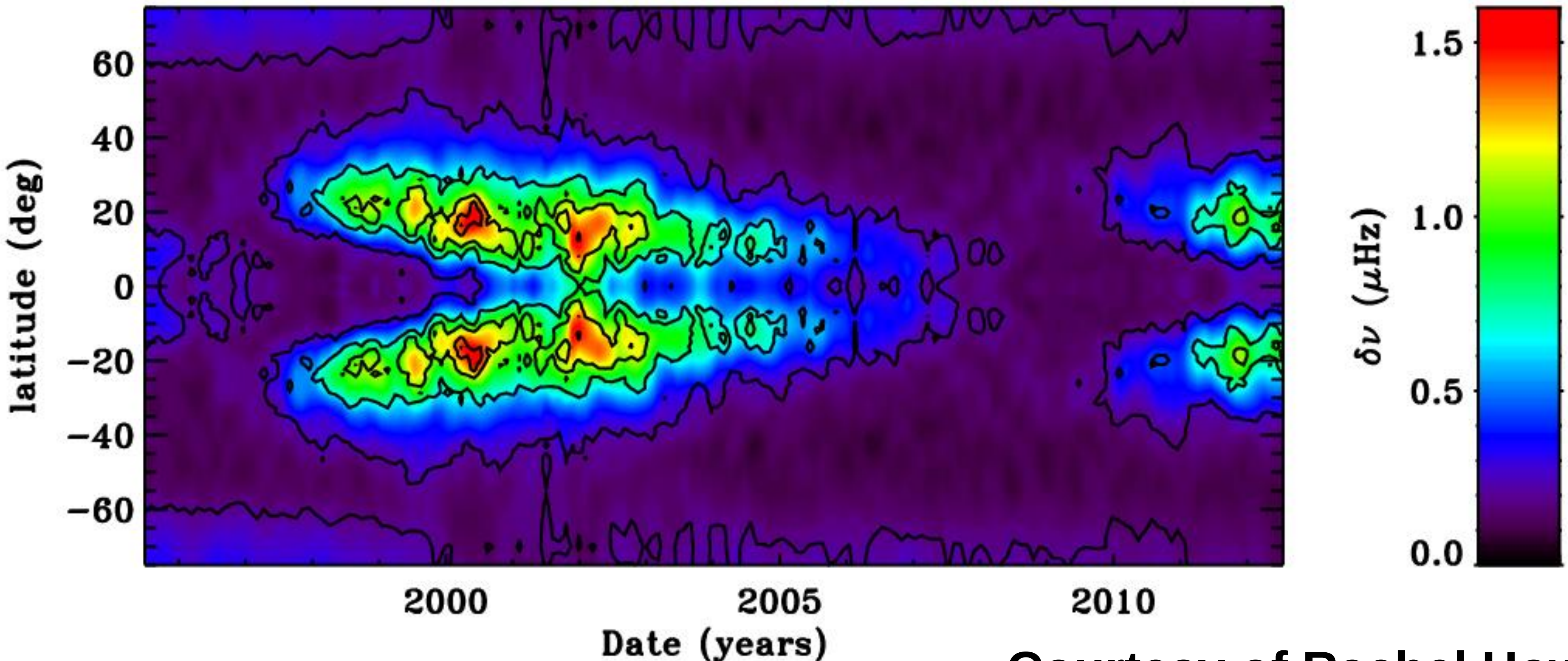
- Mode inertia given by $M_{n,l}/M_{sun}$



Broomhall, 2017, in press

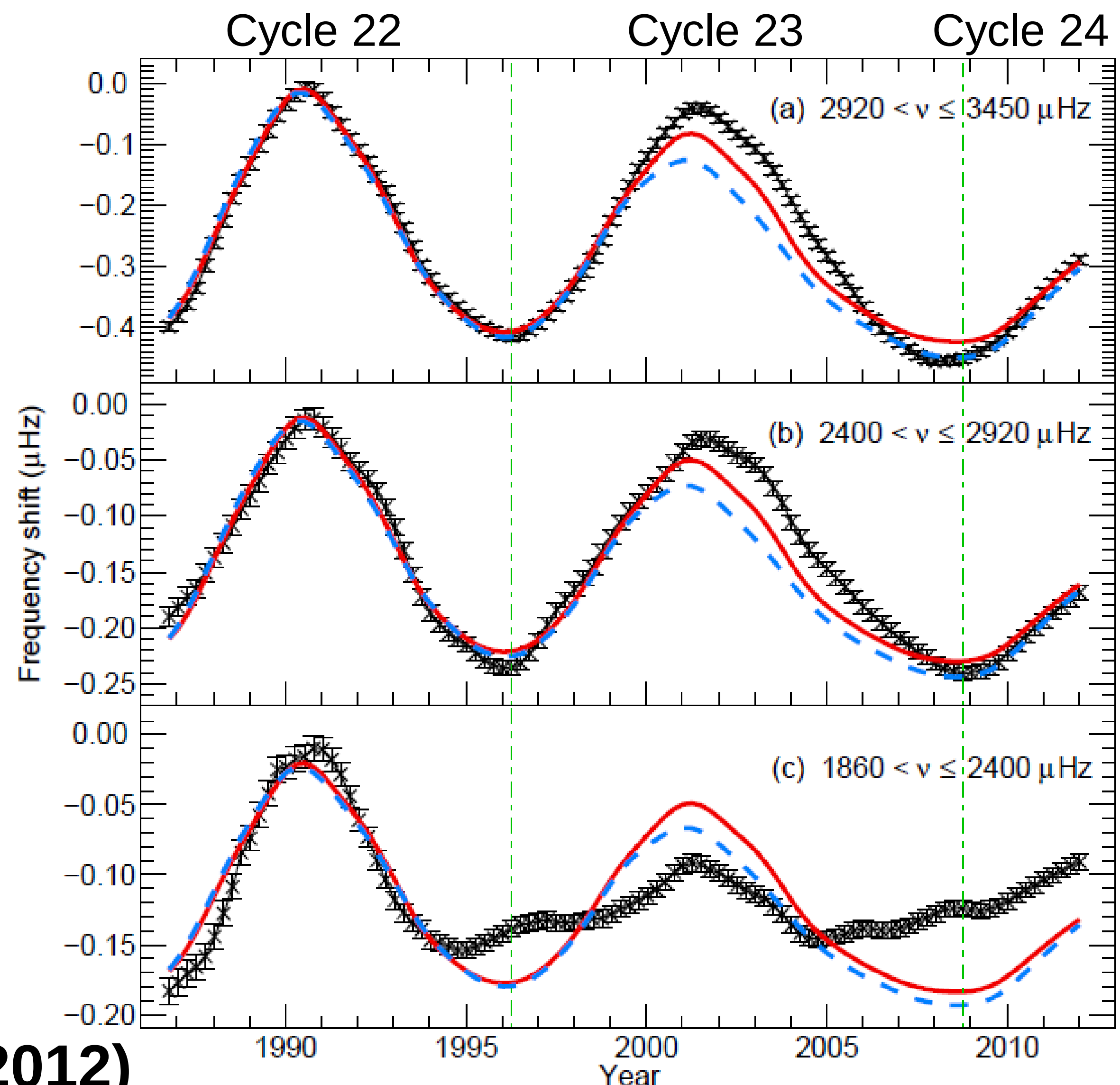
Frequency shift inversions

- Howe et al. (2002) localized the frequency shifts in latitude.



Courtesy of Rachel Howe

The unusual solar cycle – smoothed



Black=average frequency shift

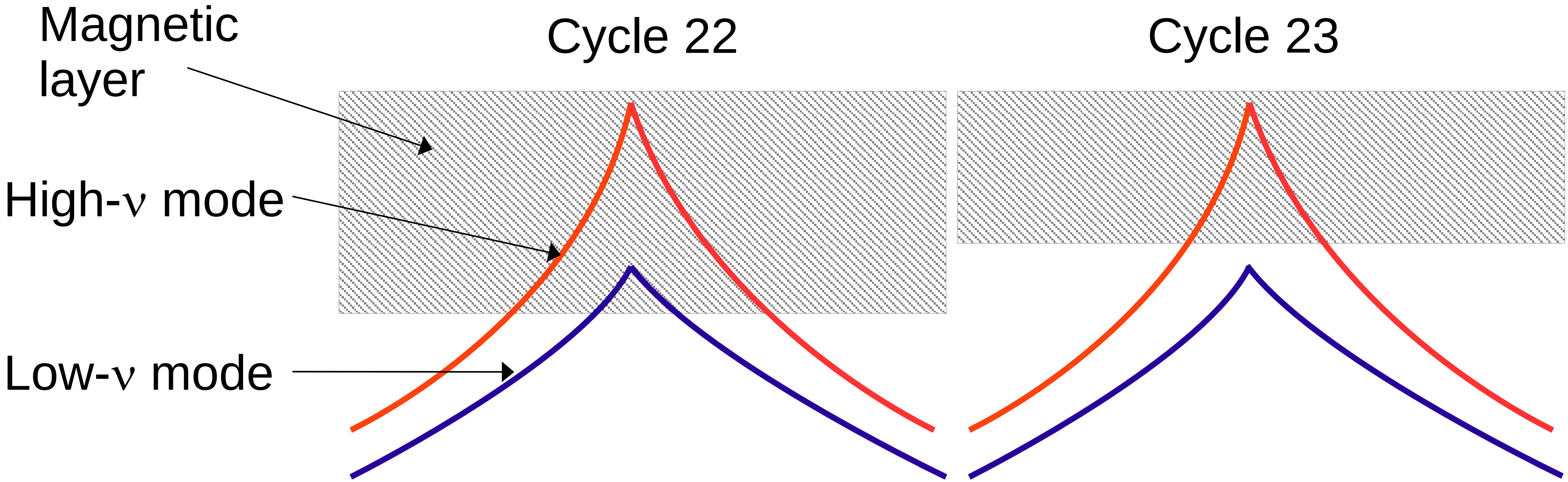
Red=10.7cm flux

Blue=ISN

Basu et al. (2012)

Changes in the magnetic layer

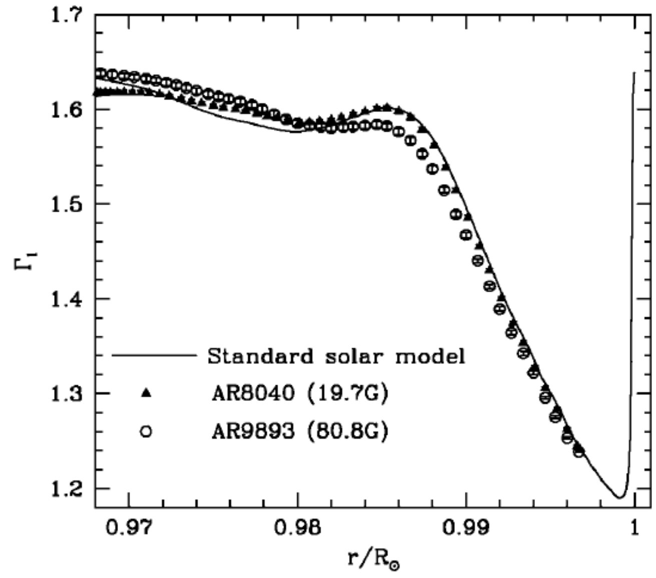
- The upper turning point of the low-ν modes are beneath the magnetic layer in cycle 23
- The changes must occur above 0.9965$R_\odot$ (upper 2Mm).

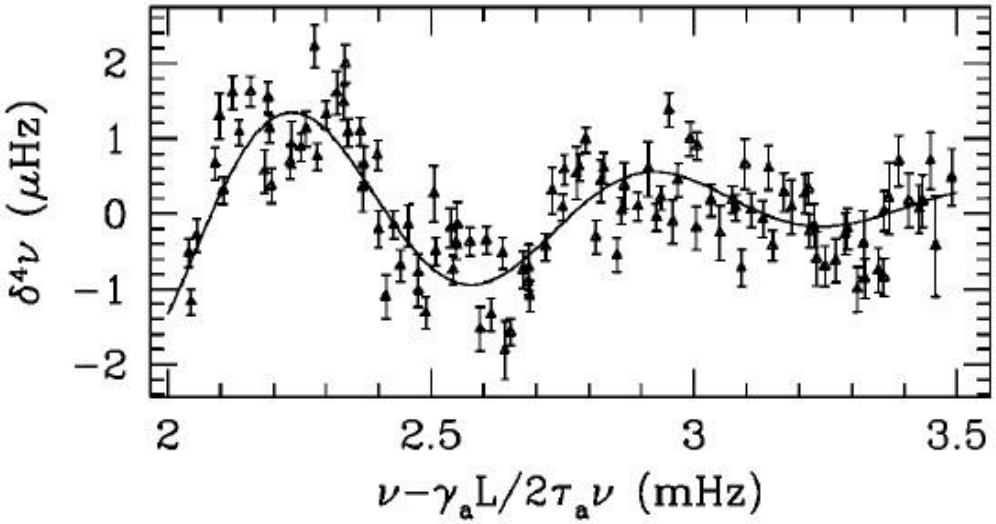


Is there any evidence for the influence of magnetic field deeper in the solar interior?

Cycle variations at $0.98R_\odot$

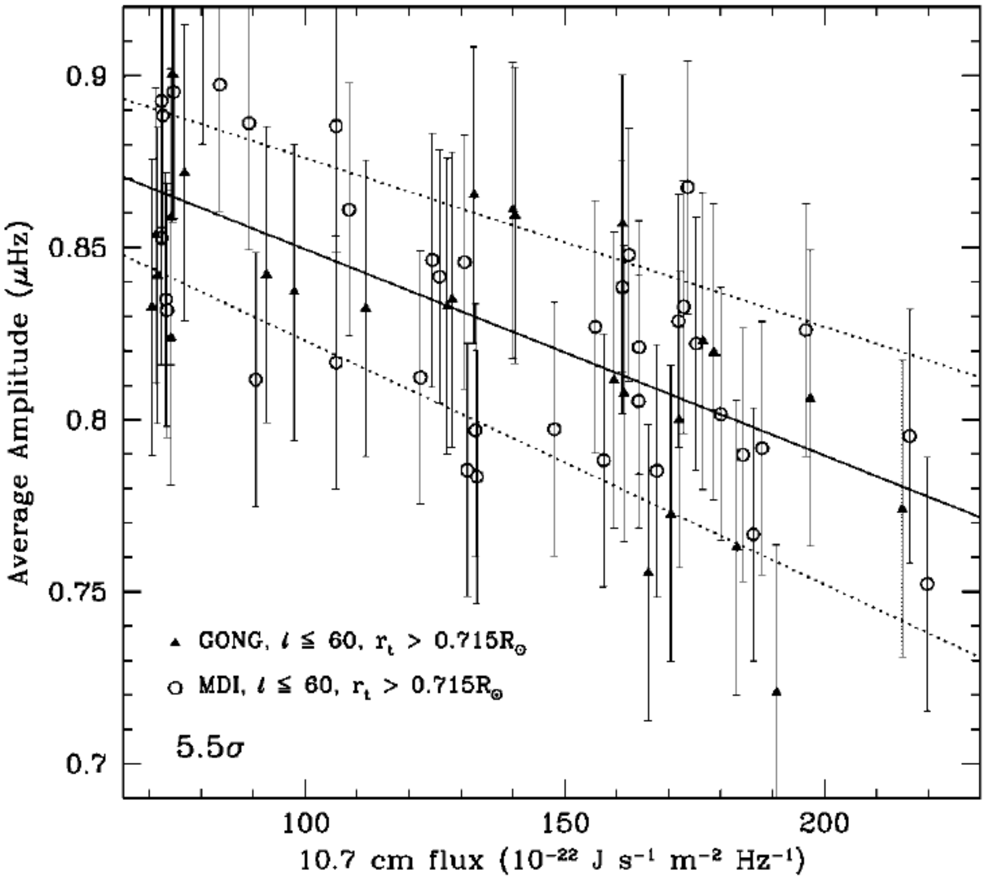
- Helium ionization causes a discontinuity in the sound speed.
- The discontinuity causes oscillatory component in mode frequencies.
- Basu & Mandel looked at amplitude of oscillation through solar cycle.





Cycle variations at $0.98R_\odot$

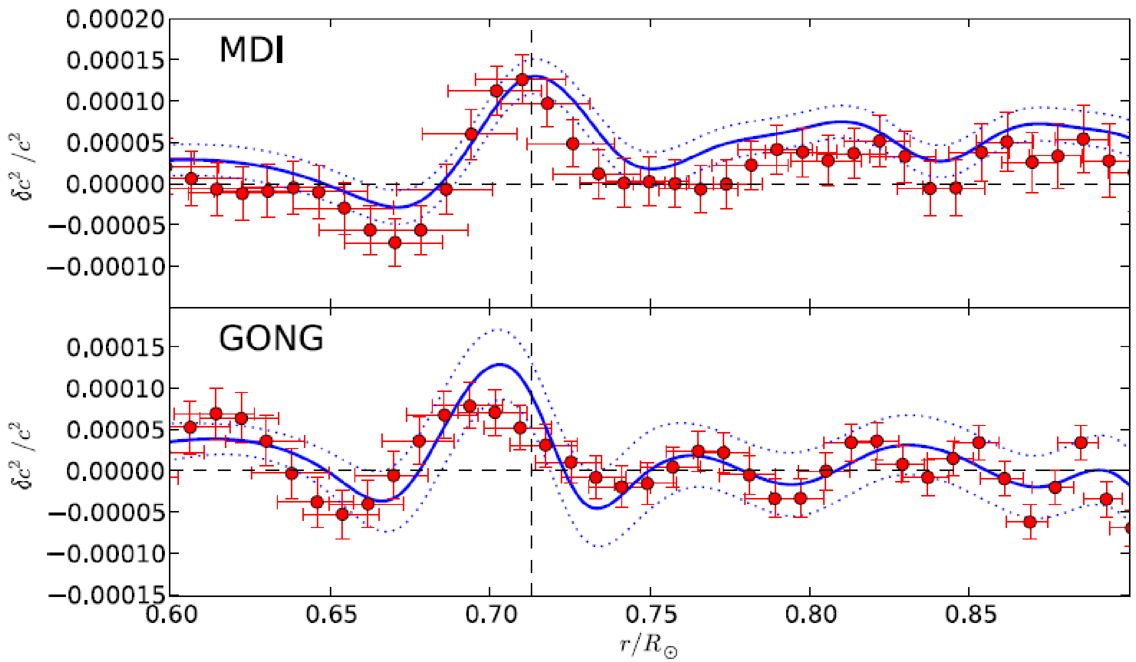
- Basu & Mandel (2004) showed evidence for solar structure changes around HeII ionization zone using intermediate modes.
- Verified by Verner et al (2006) for low-degree modes.



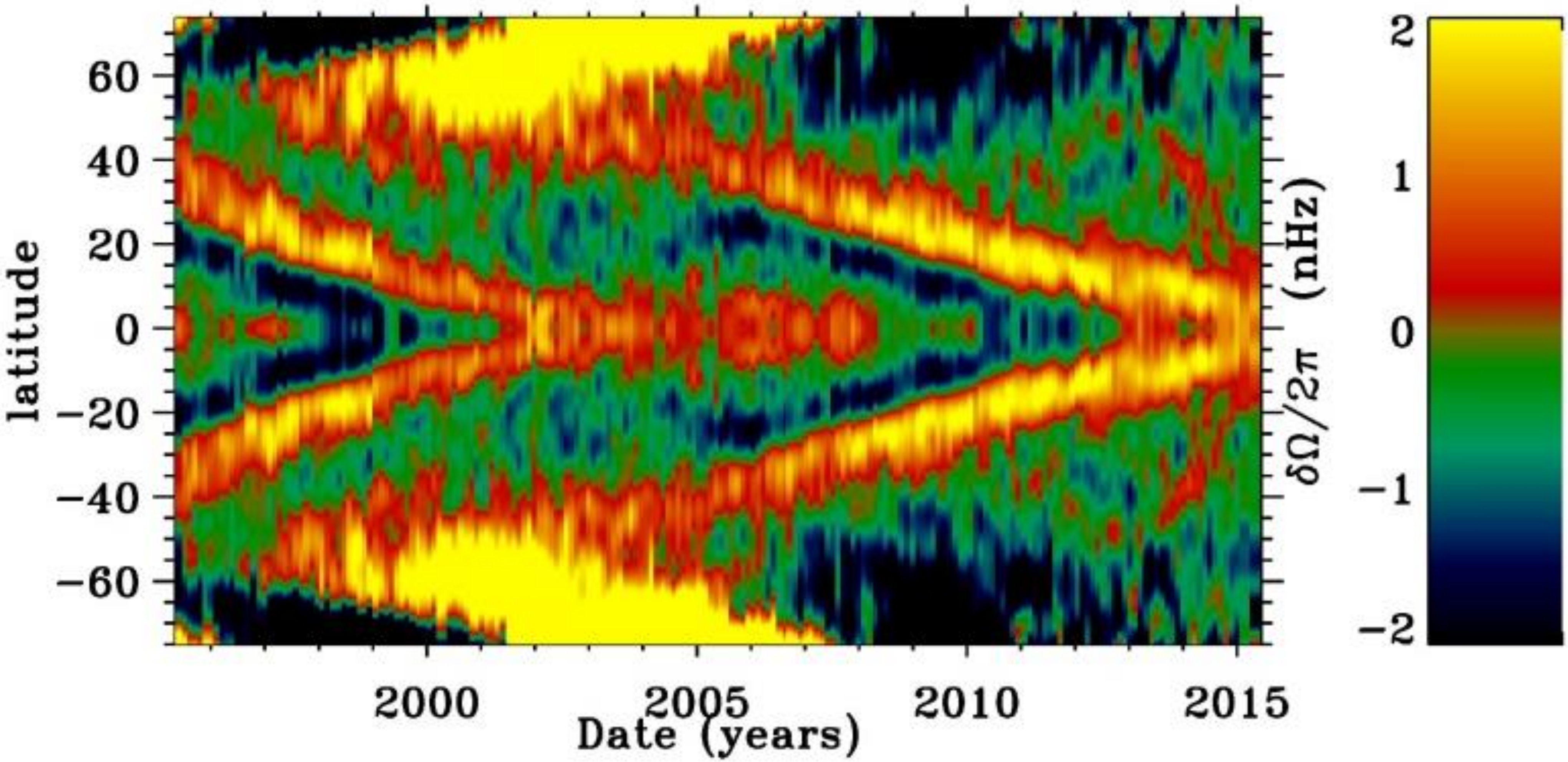
- Christensen-Dalsgaard et al (2011) found no evidence for it.

A change in sound speed at the base of the convection zone?

- Limits on strength of magnetic field at BCZ e.g.
  - magnetic field < 300kG (Basu, 1997; Antia et al, 2000).
- First evidence Serebryanskiy & Chou (2005)
  - $\delta c/c = 1\text{-}3 \times 10^{-5}$
  - 170-290kG change in field strength.
- Baldner et al. (2009): Change in field strength of 390kG.

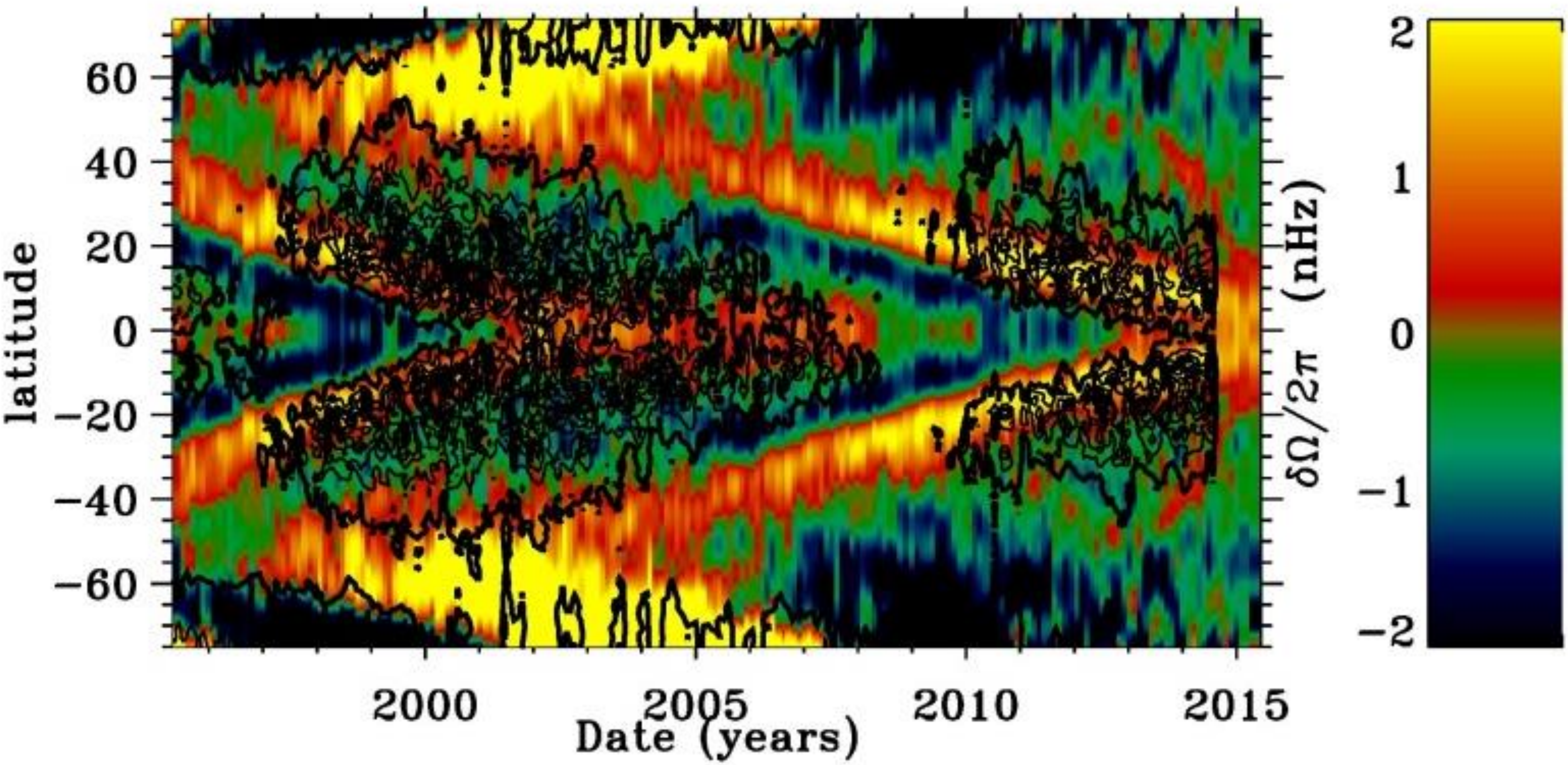


Torsional Oscillation



Courtesy of Rachel Howe

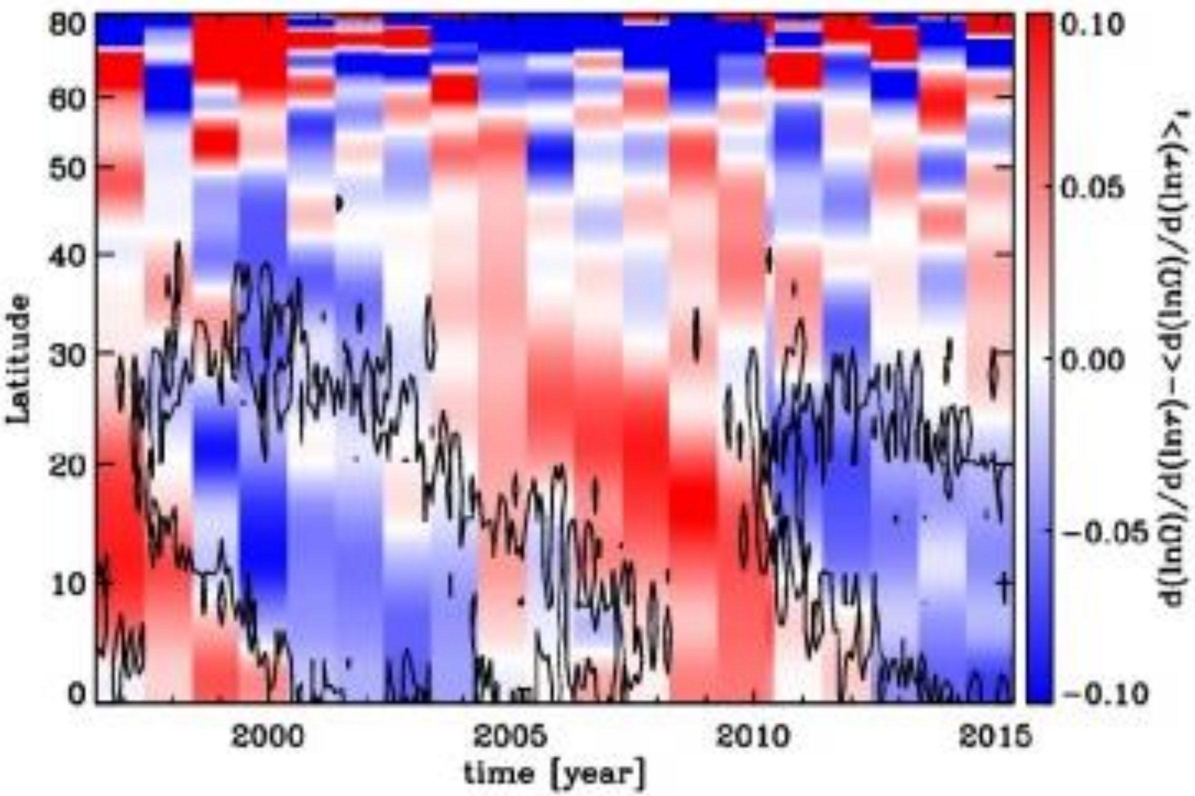
Torsional Oscillation



Courtesy of Rachel Howe

Time variation of near-surface shear

- Results consistent with theoretical impact of strong magnetic fields (Kitchatinov, 2016).
  - Possible probe of sub-surface **strong** magnetic field.



Barekat, Schou, & Gizon (2016)

Summary

- Numerous helioseismic challenges remain.
  - Many of these have applications for stellar physics as well.
- Helioseismic observations offer important constraints for standard solar and stellar models and dynamo models.
- We now at the stage where we can start comparing different activity cycles.

Summary

- Numerous helioseismic challenges remain.
  - Many of these have applications for stellar physics as well.
- Helioseismic observations offer important constraints for standard solar and stellar models and dynamo models.
- We now at the stage where we can start comparing different activity cycles.

Thank you for listening!