Helioseismology and the Changing Solar Dynamo

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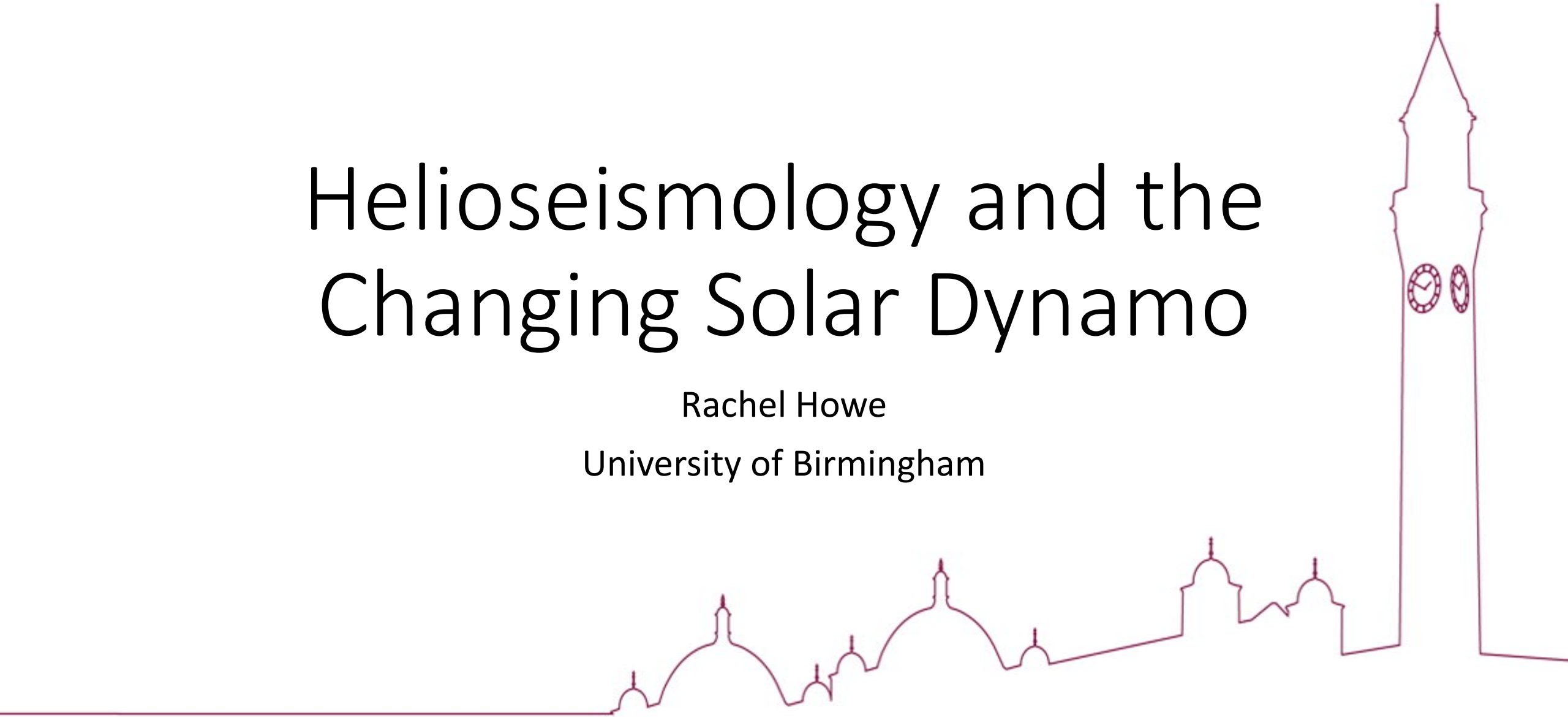
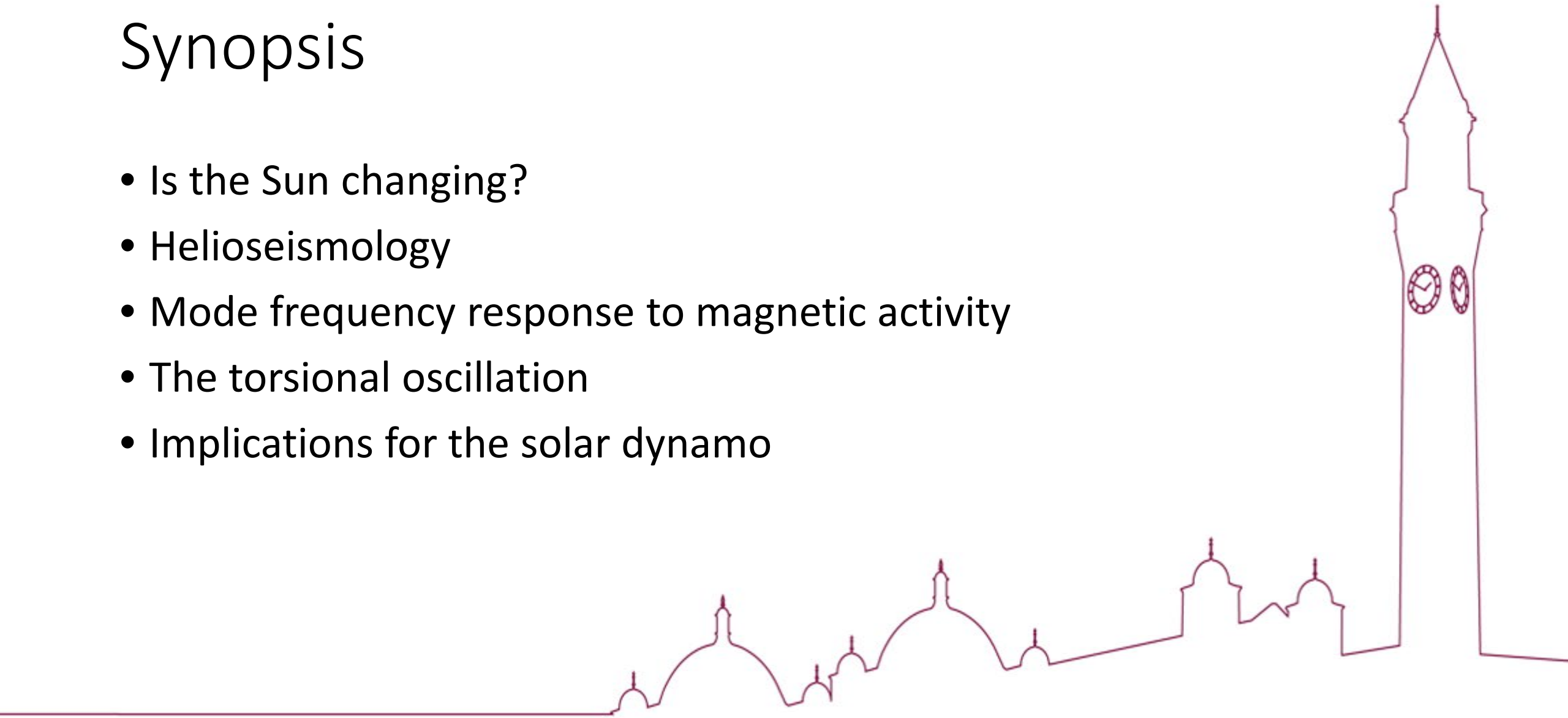


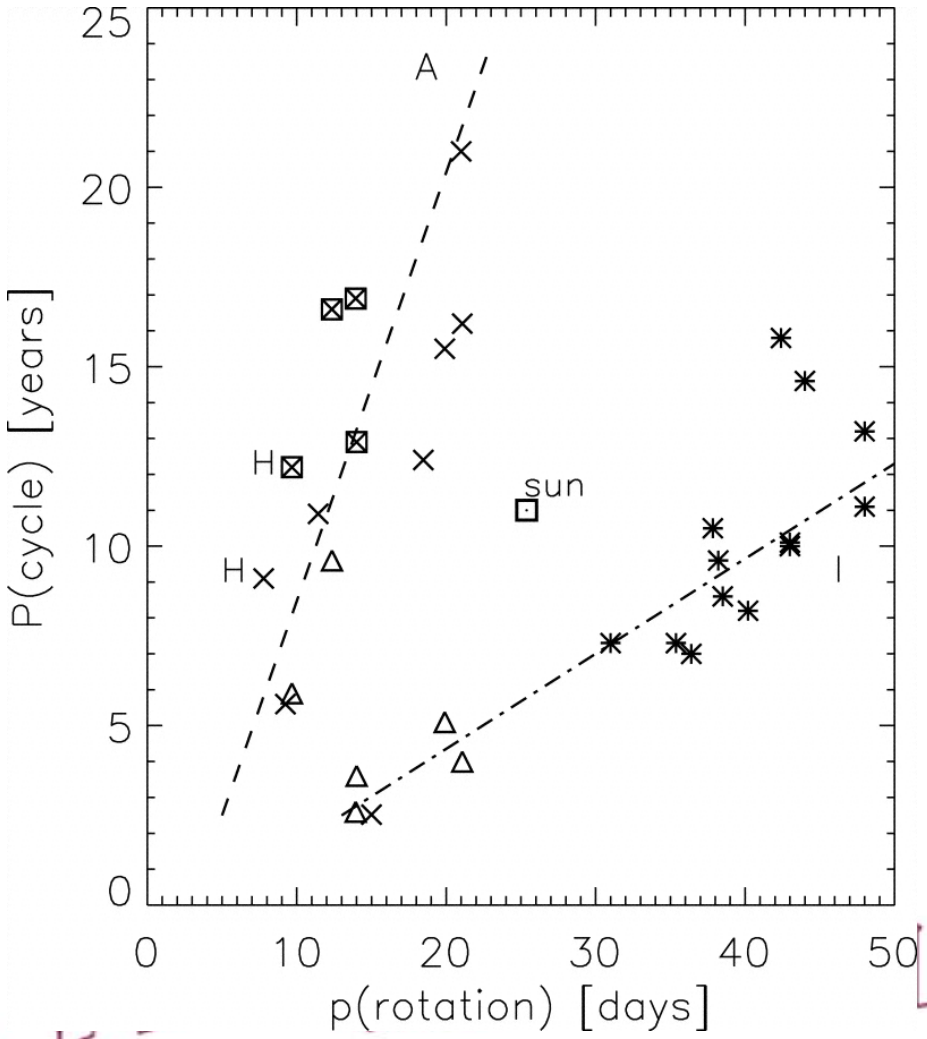
Synopsis

- Is the Sun changing?
- Helioseismology
- Mode frequency response to magnetic activity
- The torsional oscillation
- Implications for the solar dynamo



Is the Sun changing?

Bohm-Vitense (2007 *Astrophys. J.* 657, 486) – Stellar populations seem to lie along two branches on the rotation/cycle period plot, but the Sun lies somewhere in the middle.

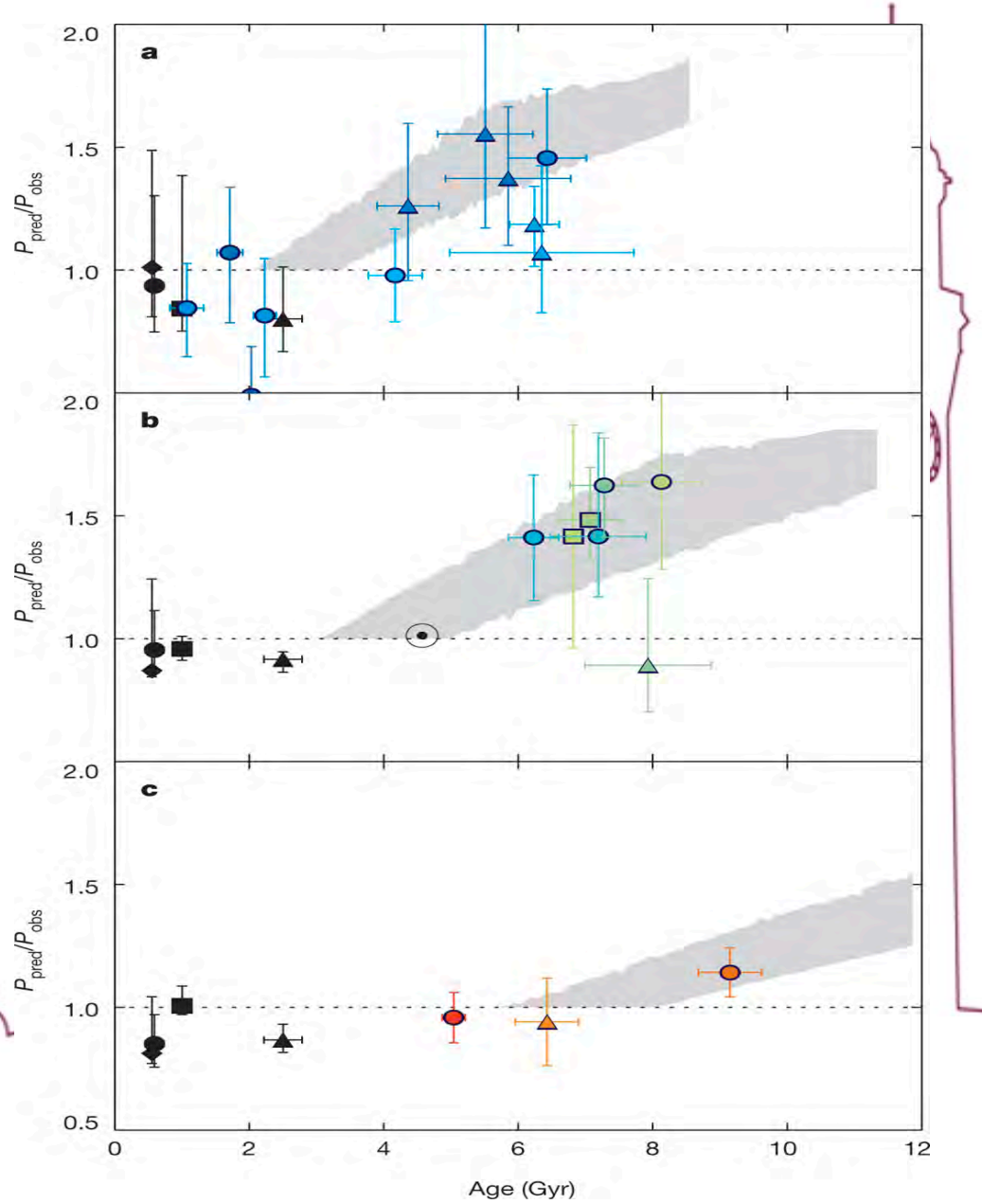


Ratios of the predicted rotation period to the observed period.

J L van Saders *et al. Nature* 1-4 (2016)
doi:10.1038/nature16168

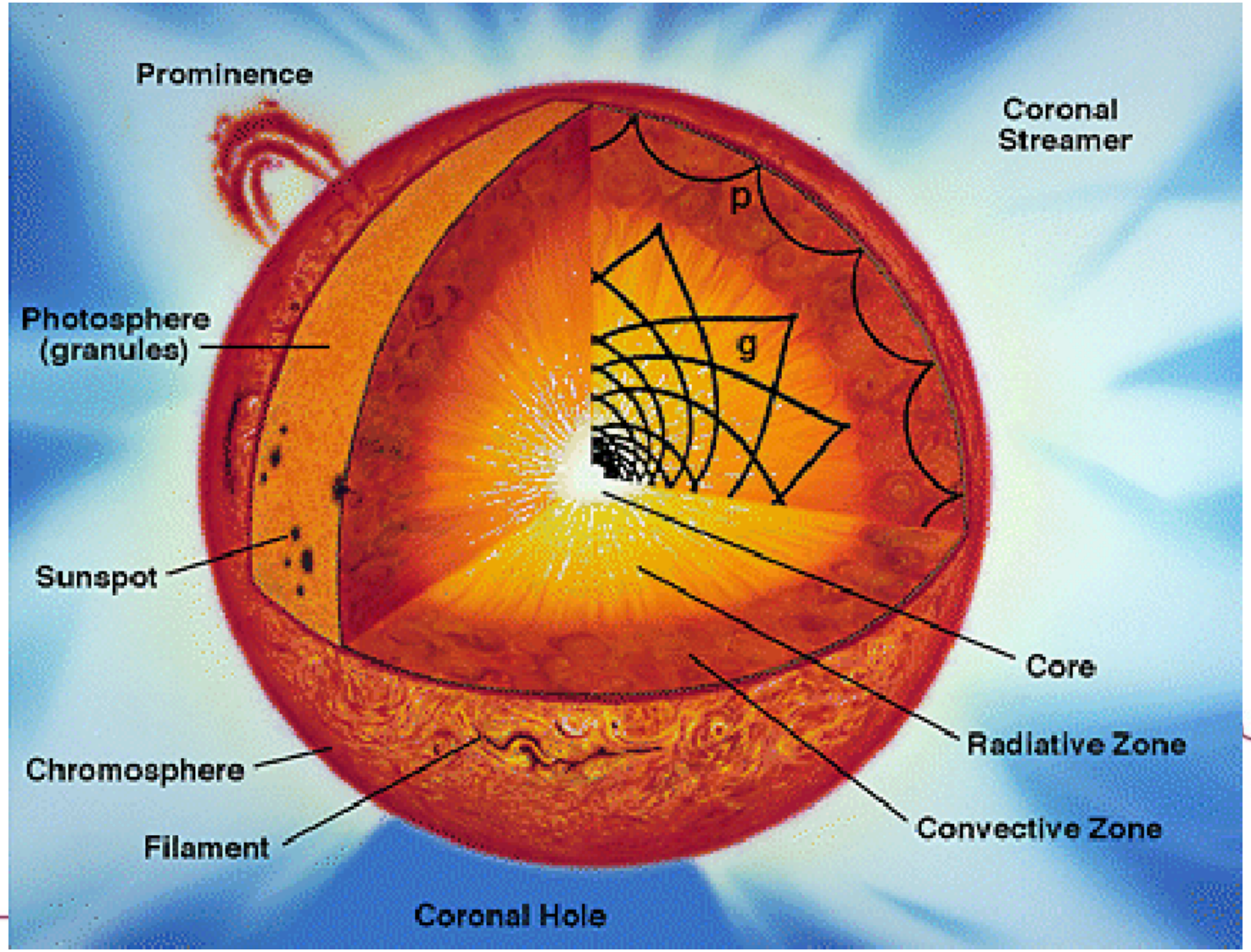
Older stars rotate faster than expected – reduced magnetic braking?

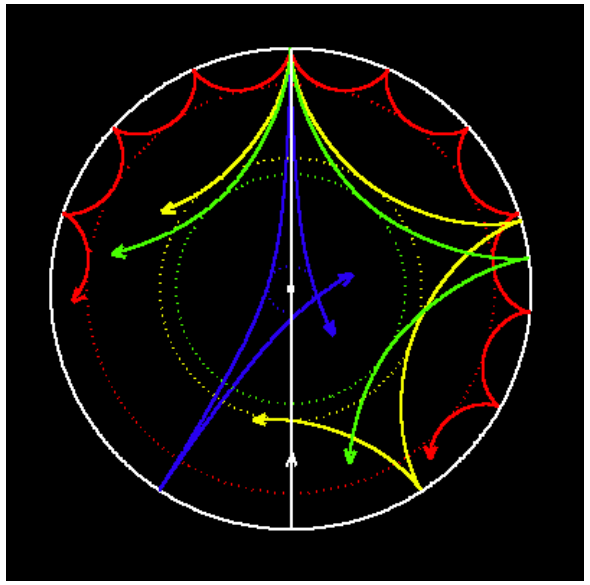
"Our findings might suggest a fundamental change in the nature of ageing stellar dynamos, with the Sun being close to the critical transition to much weaker magnetized winds."

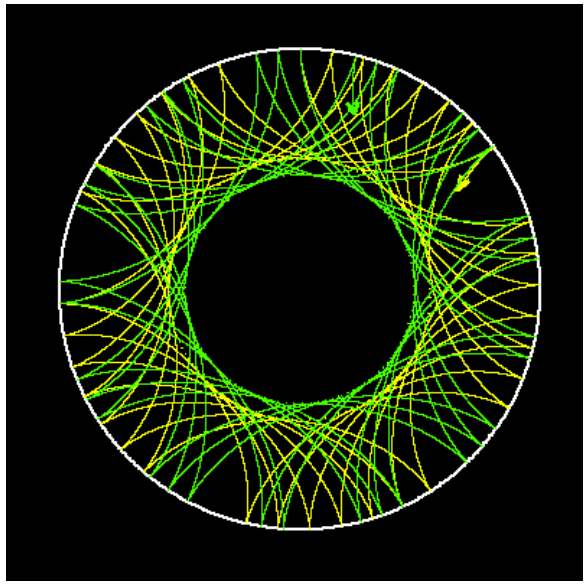


nature

Inside the Sun







Inversions

- Combining information from different modes lets us build up a picture of properties at different depths.
- Rotational splittings (*m*) give us latitude information.

Frequency shifts with solar cycle

- AC
  19
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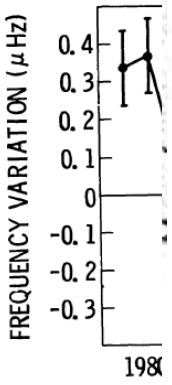
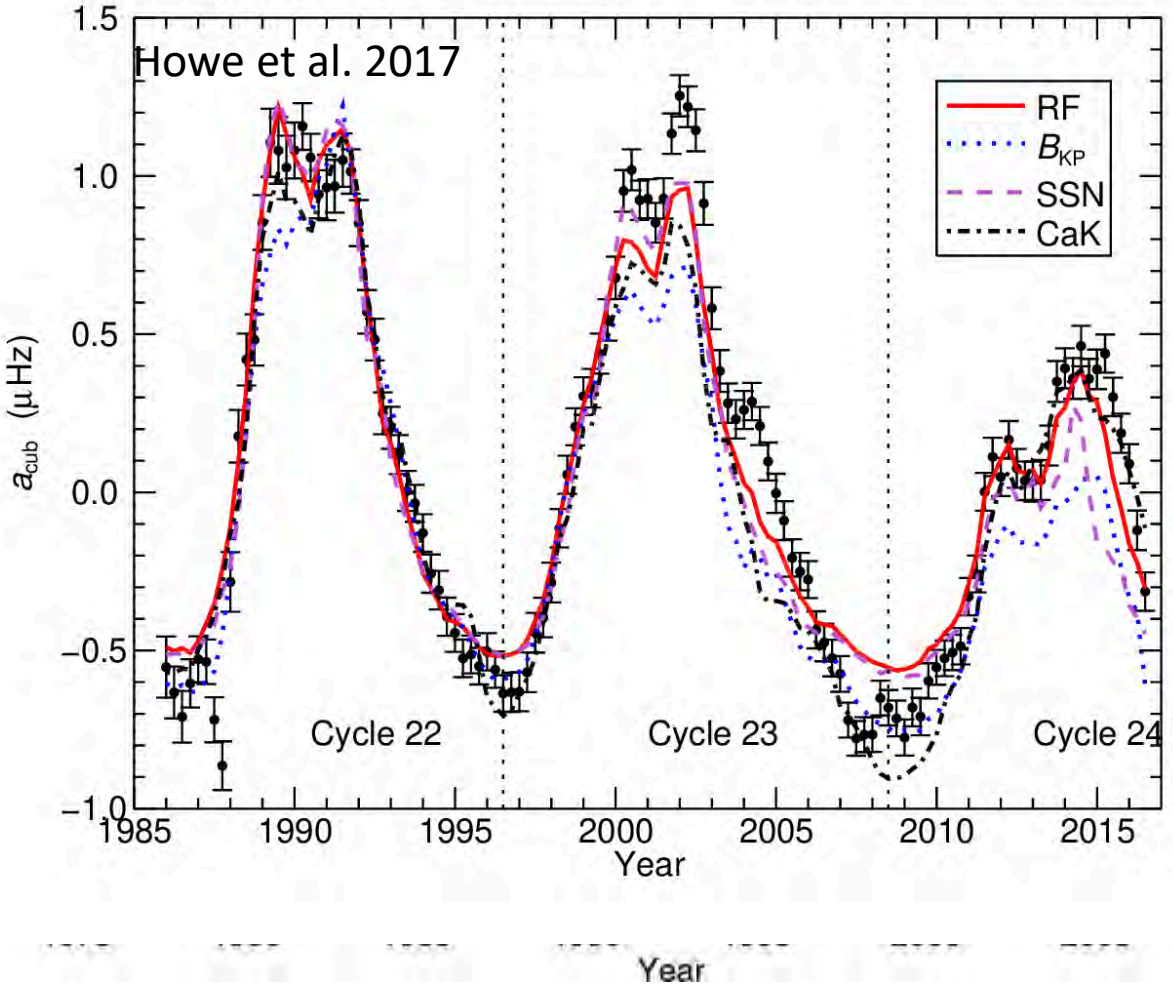
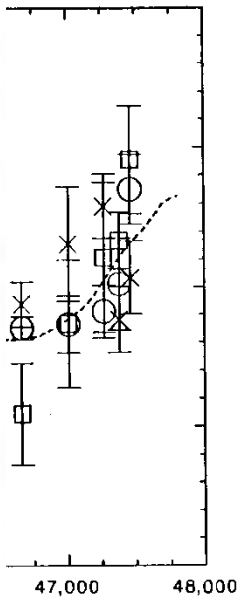
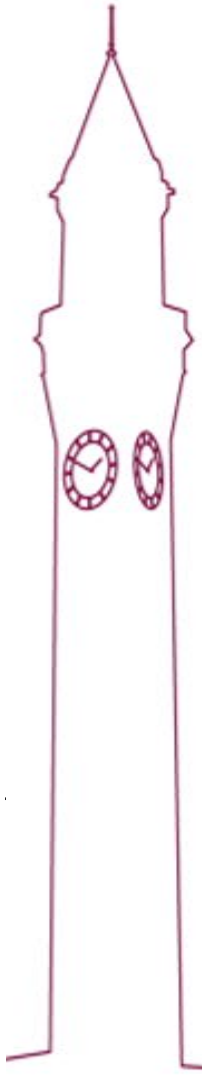








Frequency shifts with solar cycle

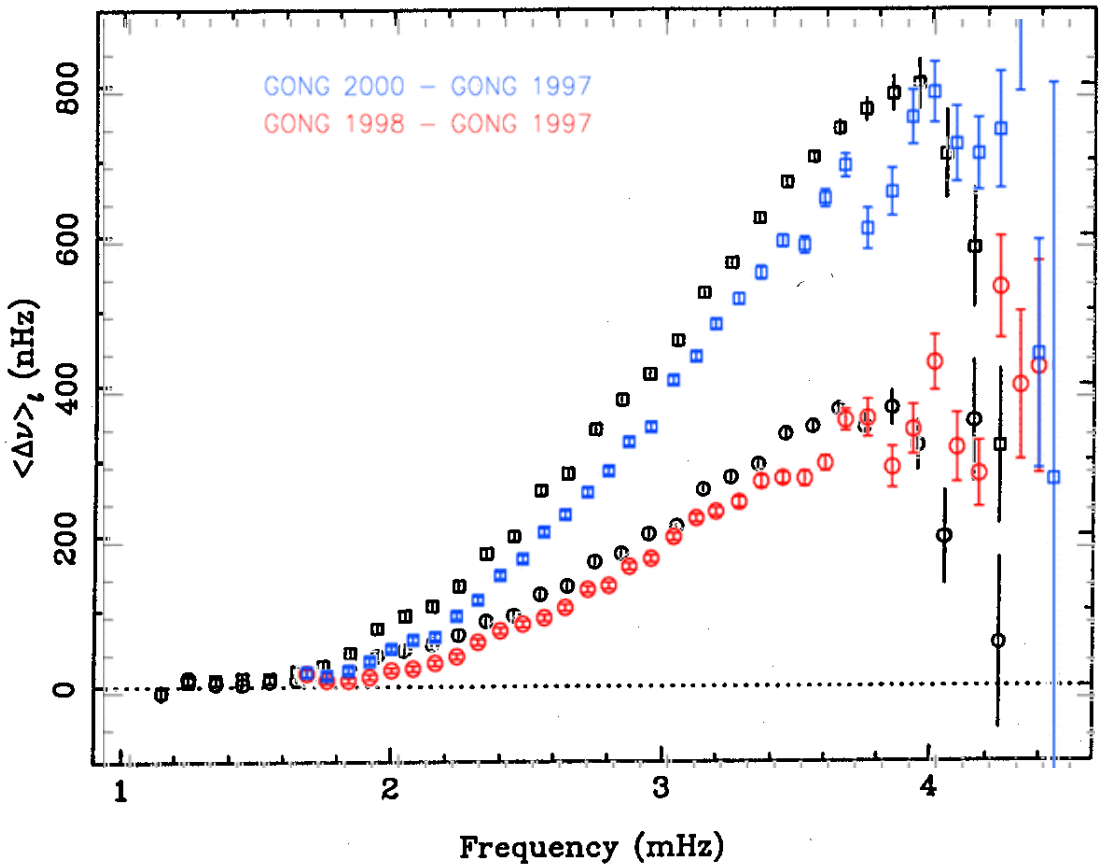


Figure 18. Frequency shift as a function of frequency, using frequencies from 1986 as a reference. The frequency dependence was obtained by averaging over modes in the range $4 \leq l \leq 140$ in degree. Data from 1988 are denoted by circles, data from 1989 by squares. From Woodard and Libbrecht (1991).

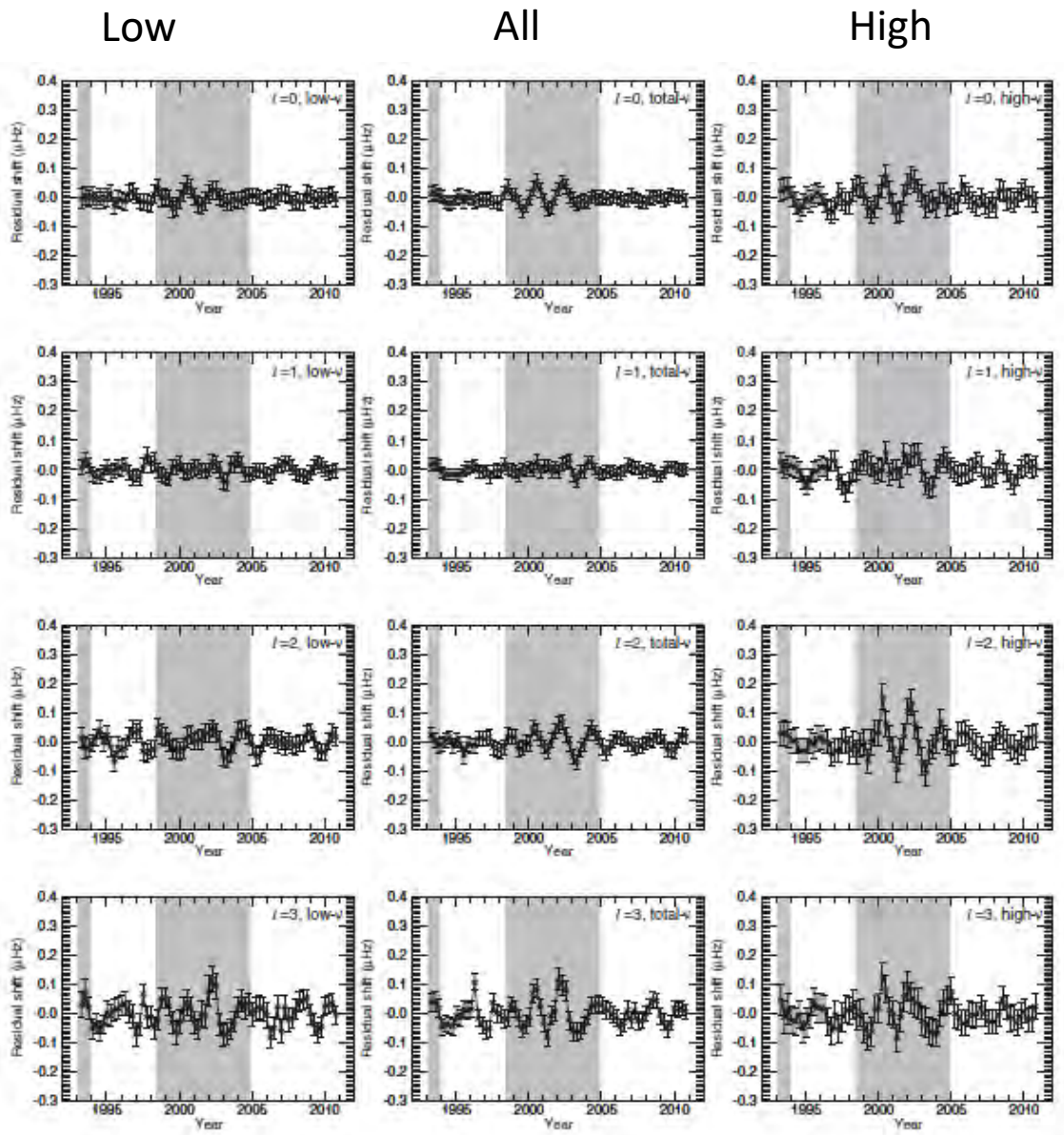
Quasi-biennial oscillation

(Broomhall et al. 2014, etc.)

Short-term variations in activity index and corresponding frequency change after main 11-year cycle removed.

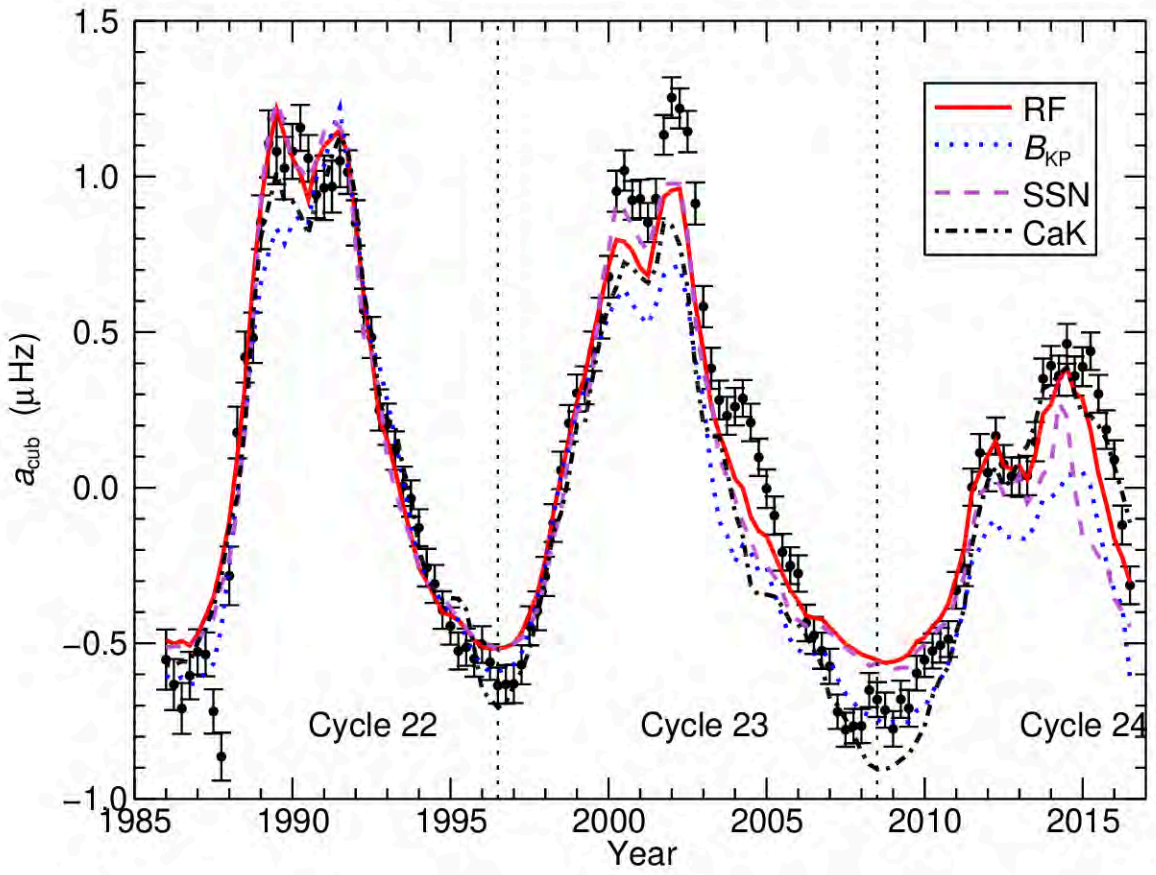
Modulated by the solar cycle

Frequency response varies less steeply with frequency than for main cycle – deeper fields?



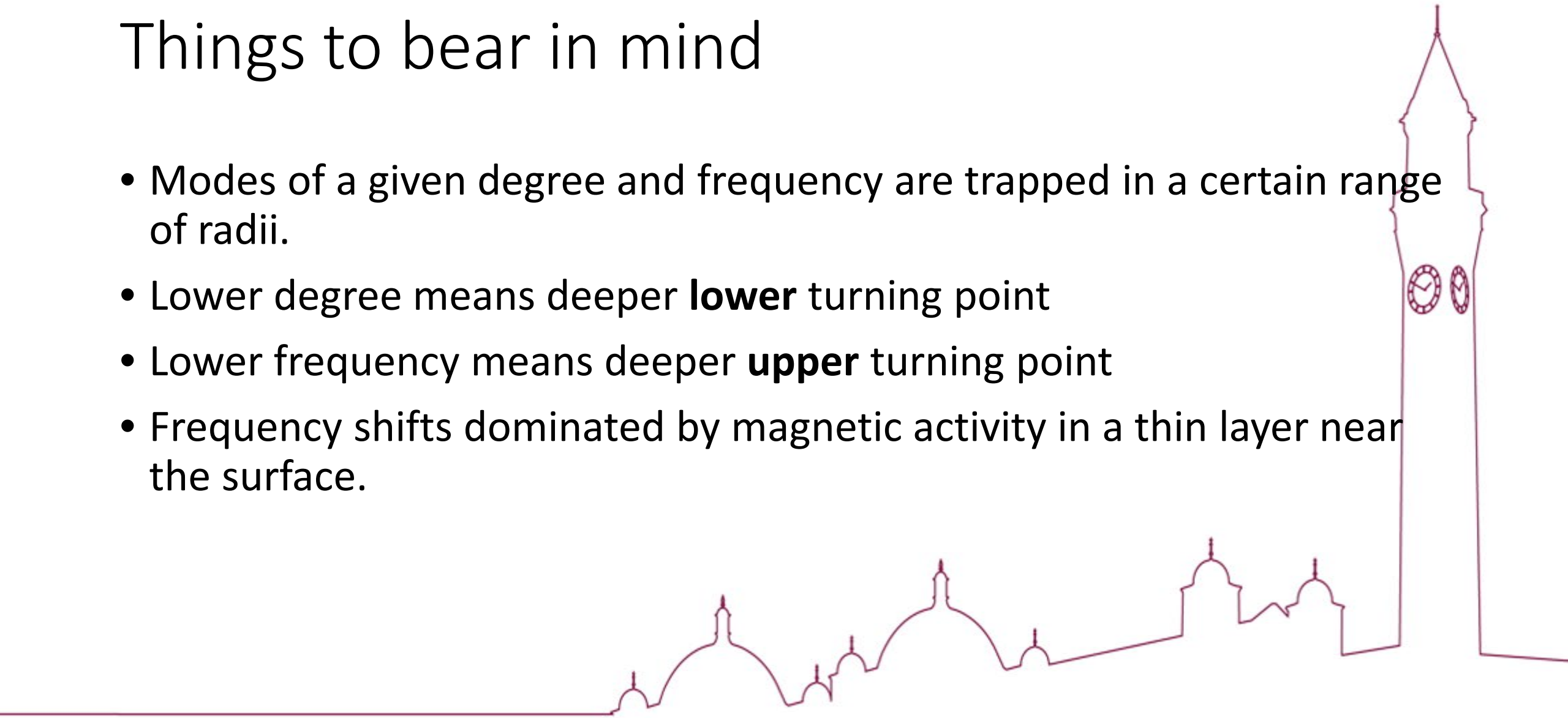
BiSON frequency shifts over three cycles

Proxies scaled to Cycle 22 – not such a good fit for Cycles 23 and 24



Things to bear in mind

- Modes of a given degree and frequency are trapped in a certain range of radii.
- Lower degree means deeper **lower** turning point
- Lower frequency means deeper **upper** turning point
- Frequency shifts dominated by magnetic activity in a thin layer near the surface.

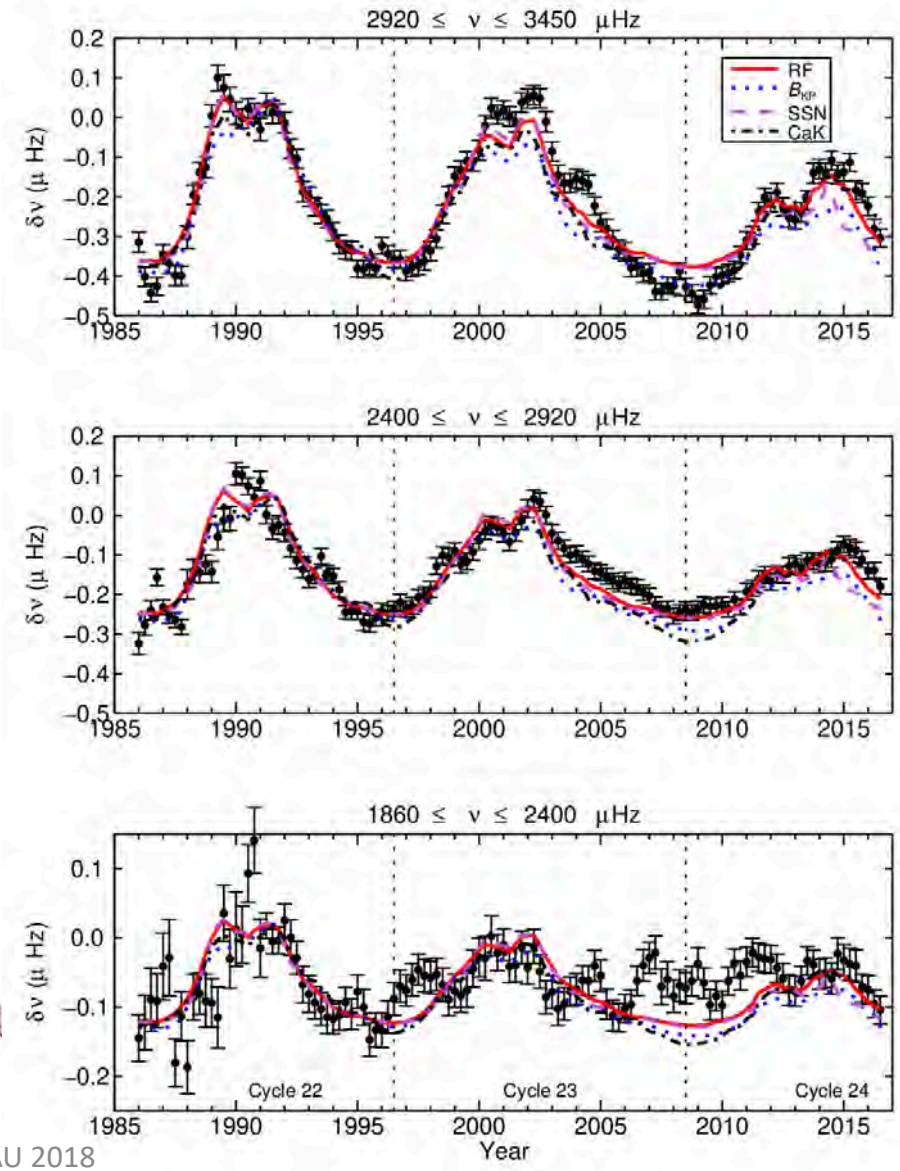


BiSON frequency shifts over three cycles

In three frequency bands

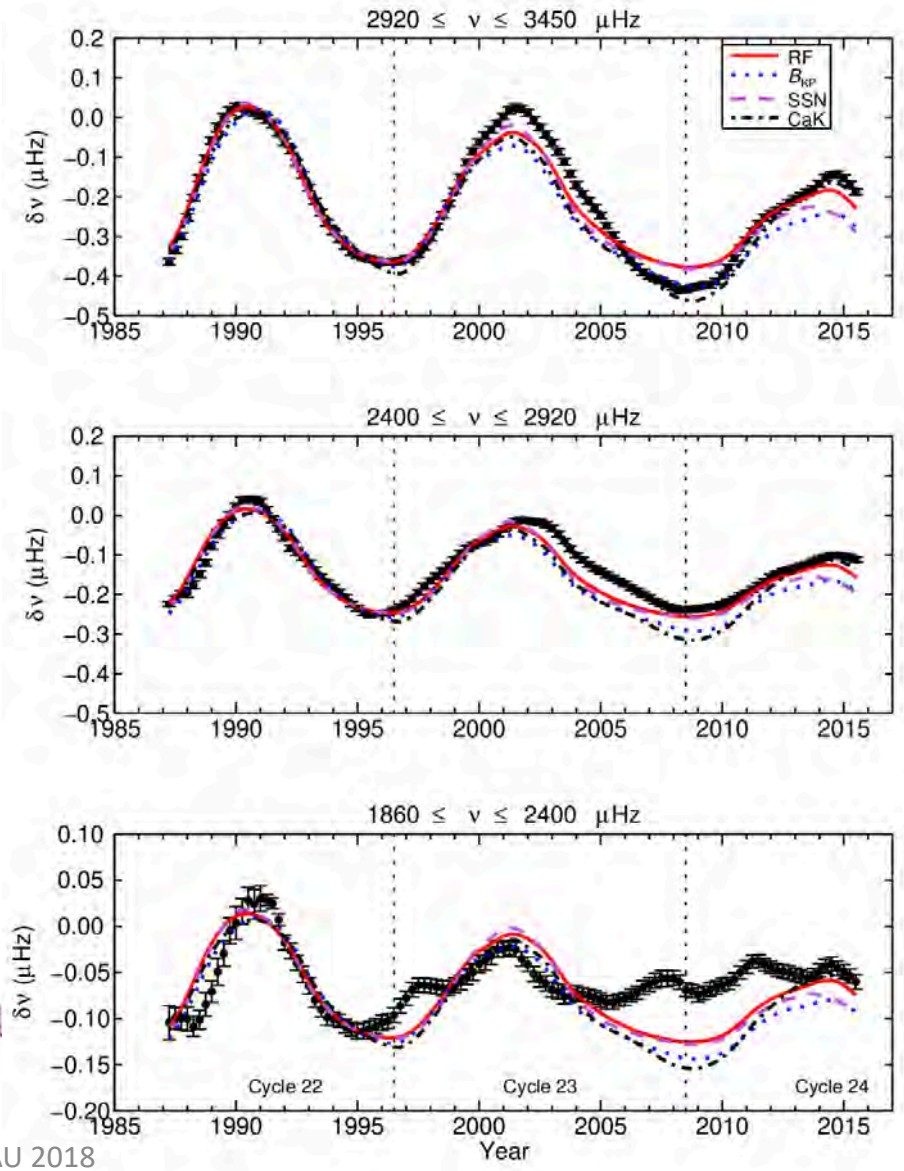
Howe et al., 2018, *MNRAS* **480L,**79

c.f. Basu et al. 2012, *ApJ* **758**, 43

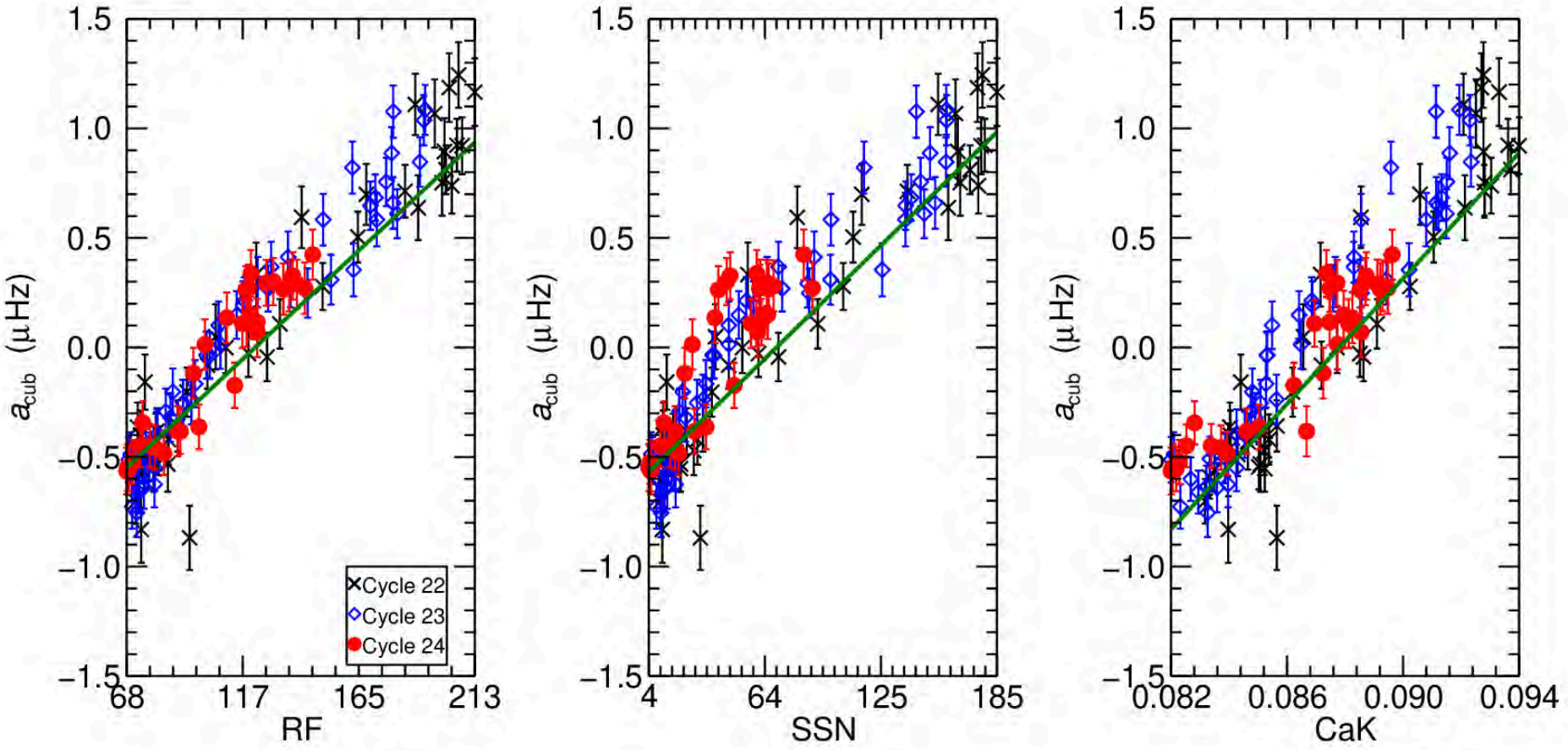


BiSON frequency shifts over three cycles

In three frequency bands, smoothed



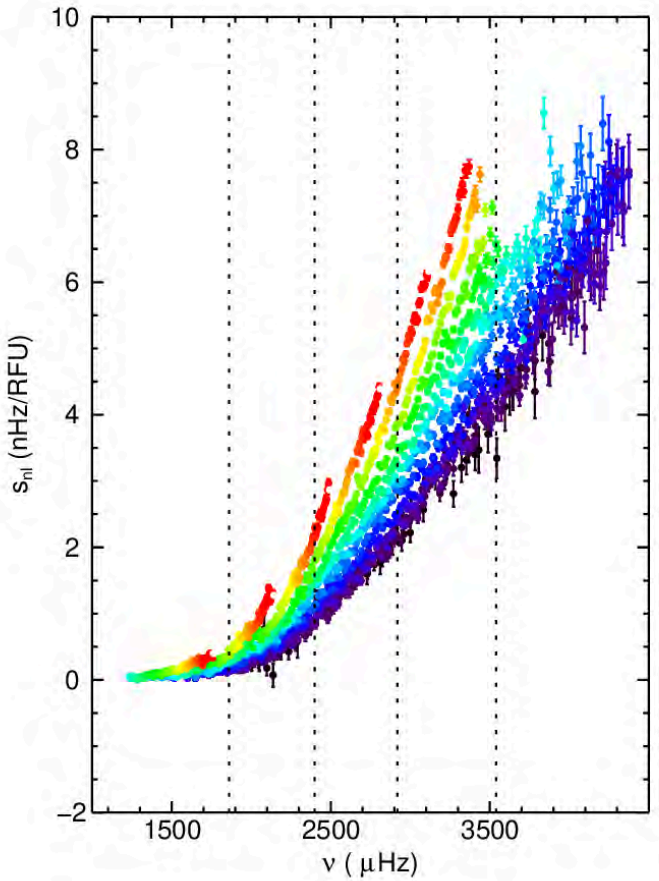
Frequency shift vs activity proxy



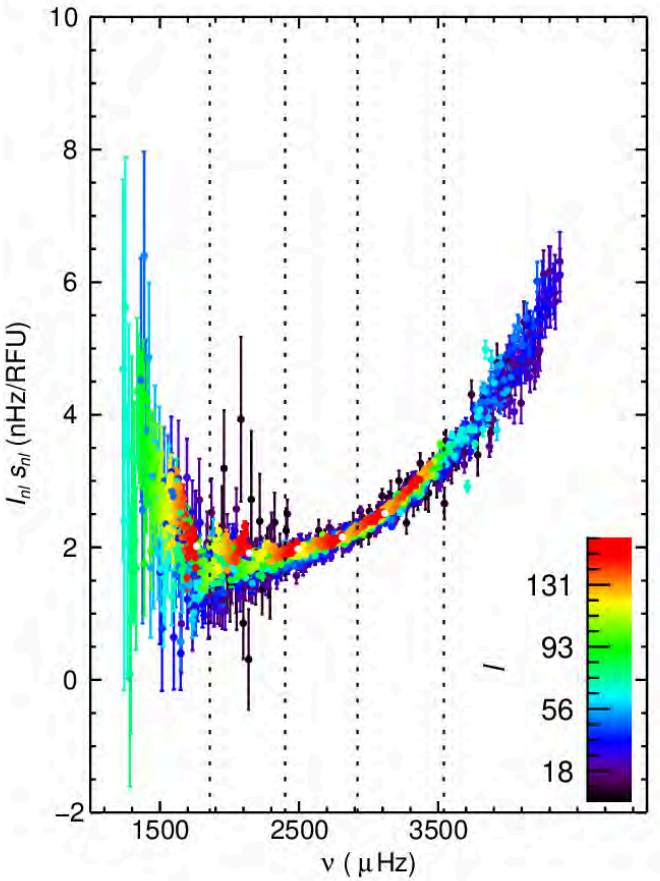
Sensitivity vs frequency

Color-coded by degree *l*

Unscaled

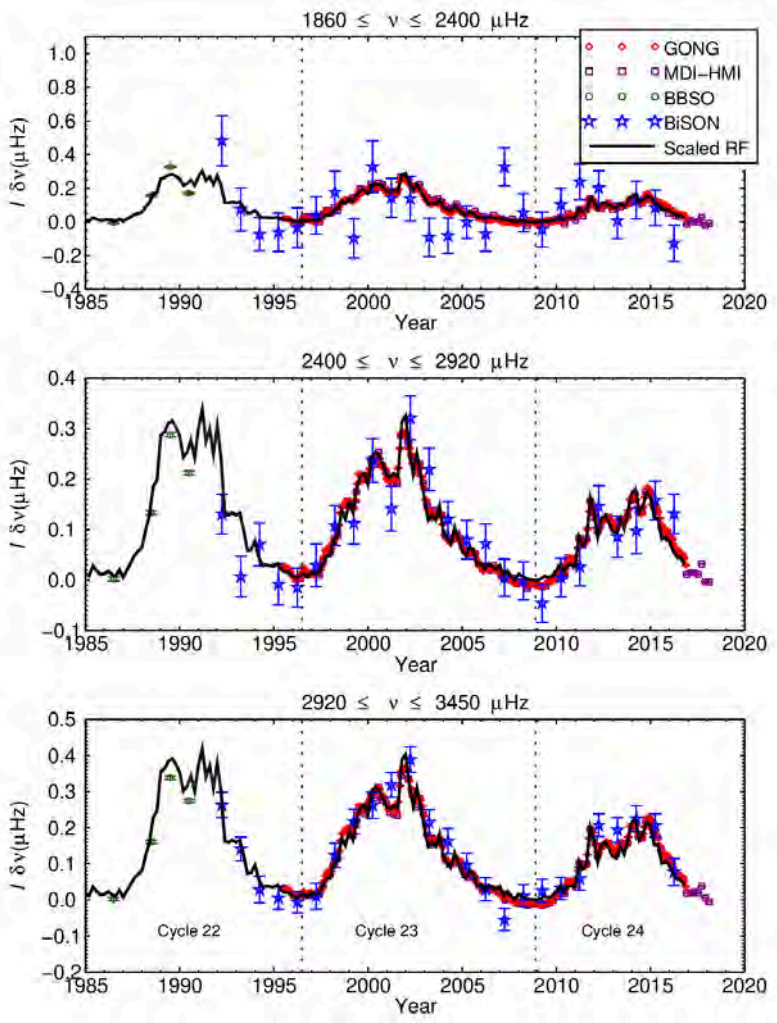


Mode-inertia scaled

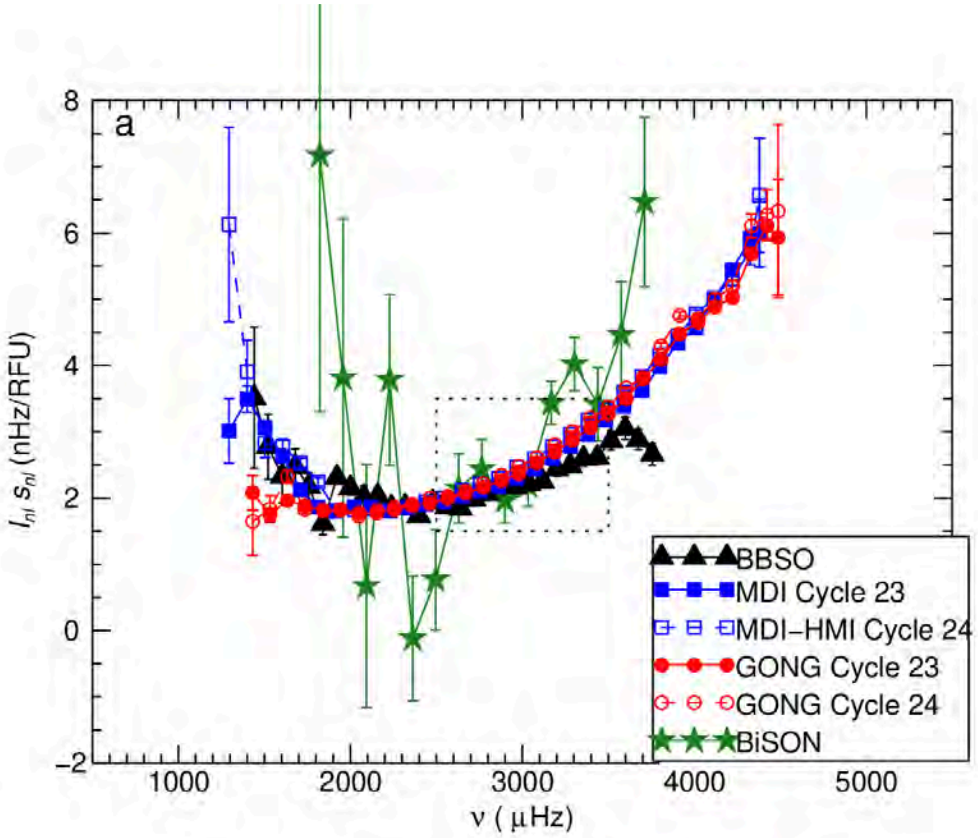


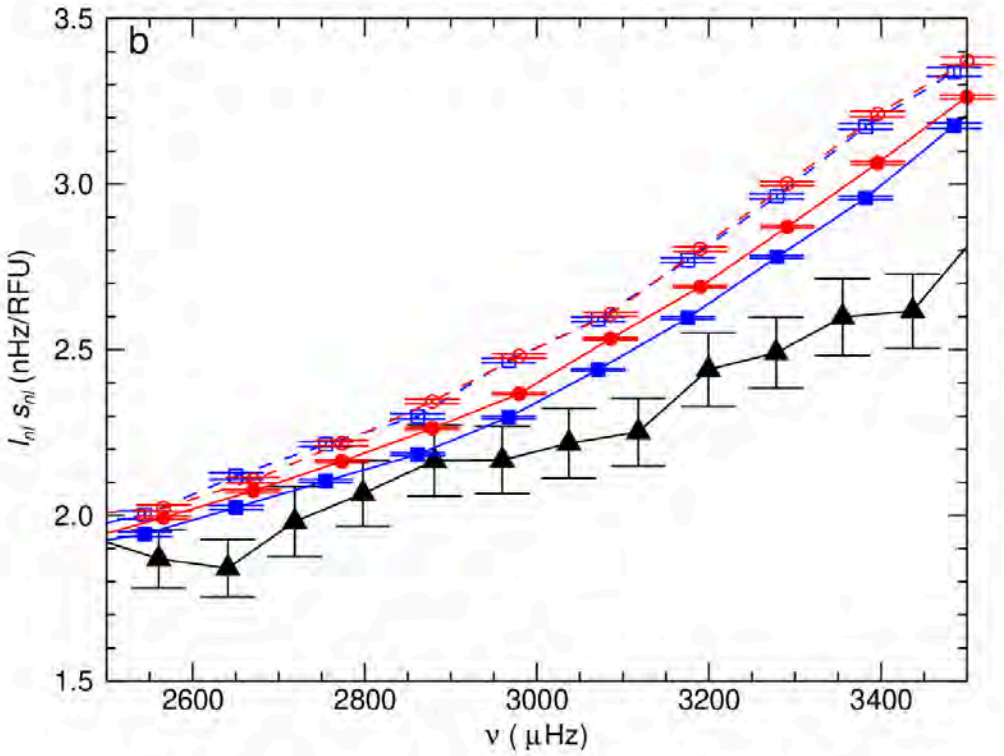
Comparing medium- and low-degree frequency shifts

GONG, MDI/HMI, BBSO, and BiSON l=0



Frequency-binned, scaled shifts



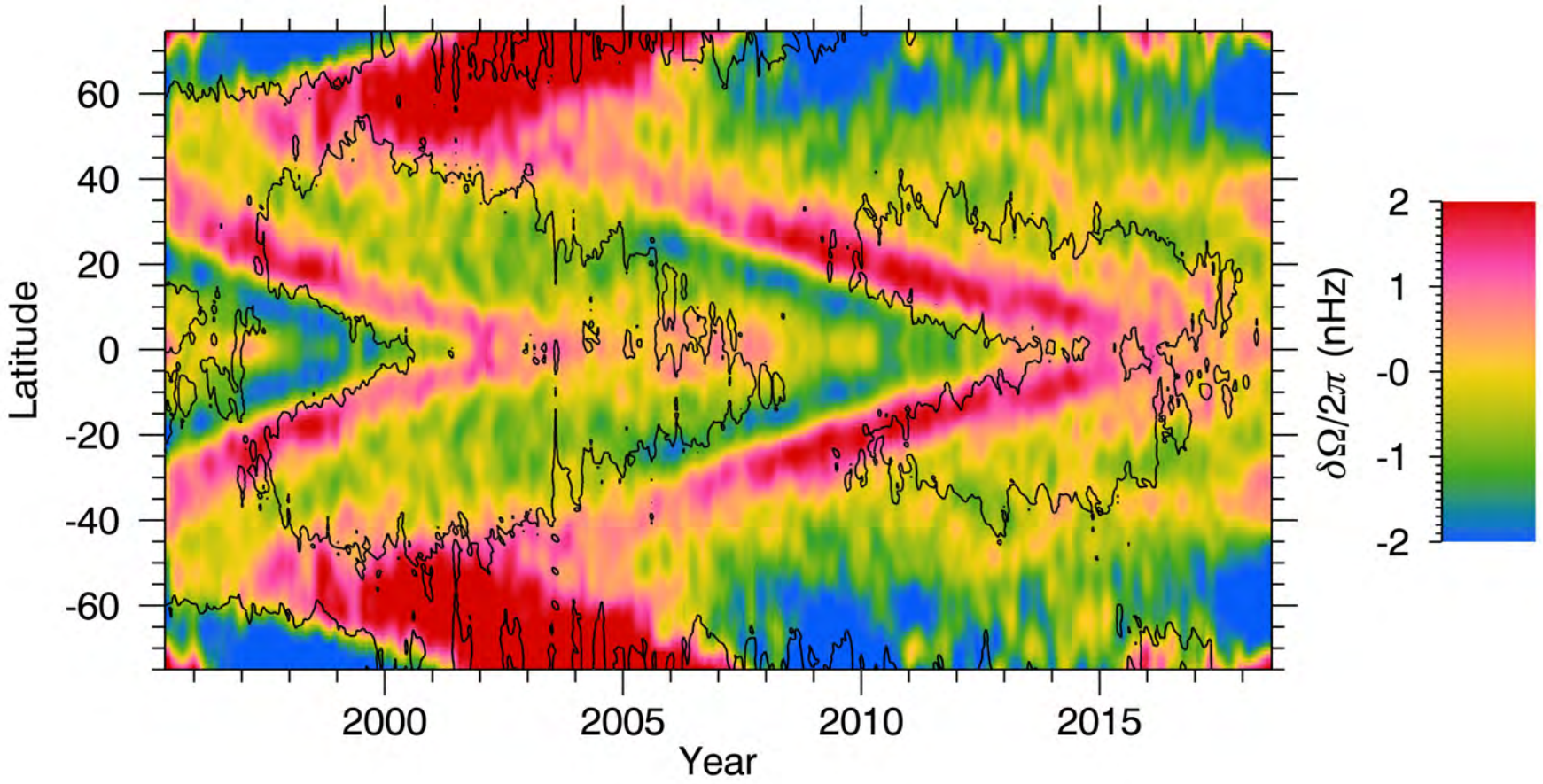


Frequency Shifts - Summary

- Frequencies follow the activity level
- Low-degree, low frequency modes barely correlated with activity in the most recent two cycles – thinning magnetic layer?
- Medium-degree data does show correlation even at low frequencies.
- Both medium and low-degree data show slightly higher sensitivity to activity in Cycle 24 than Cycle 23 --- again, this could point to a thinning magnetic layer.

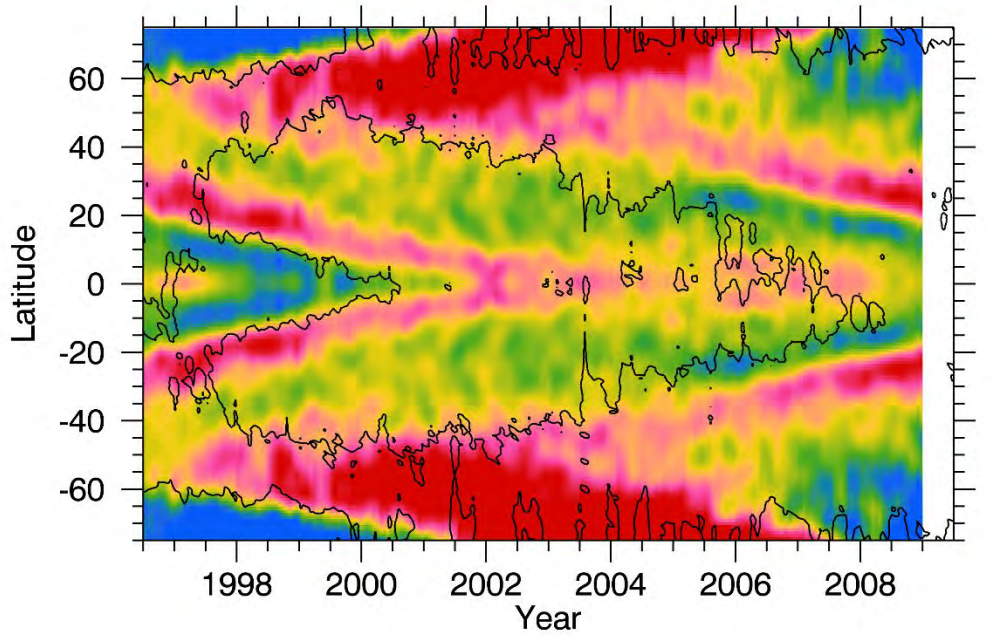
The torsion oscillation

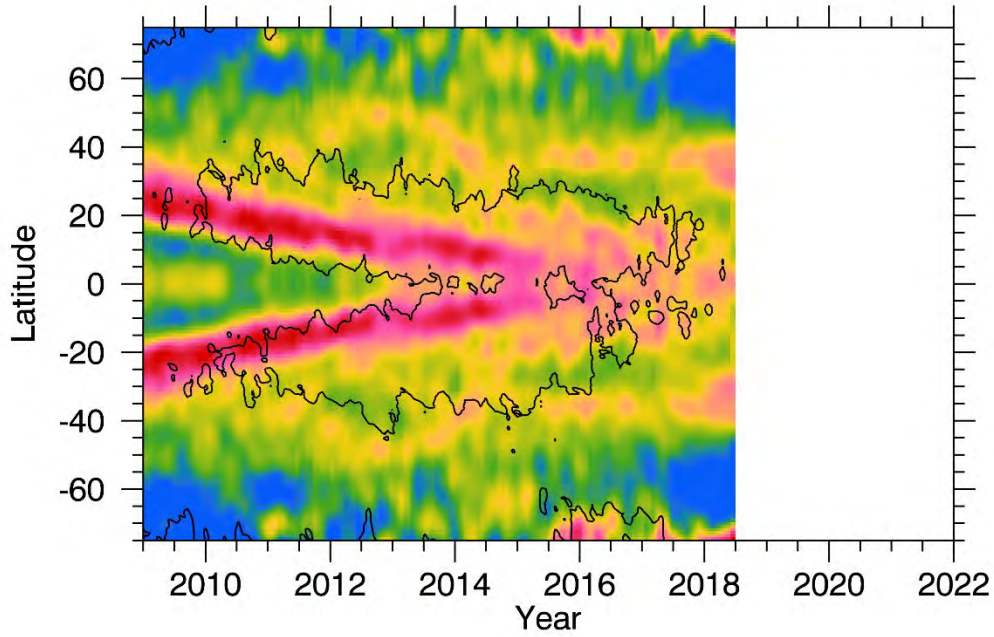
- 23 years of observations from GONG, MDI, HMI.
- Mean subtracted over whole time series of 2d rotation inversions at each location.

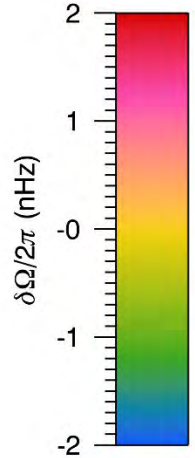


Comparing Cycles 23 and 24

Mean subtracted over whole time series

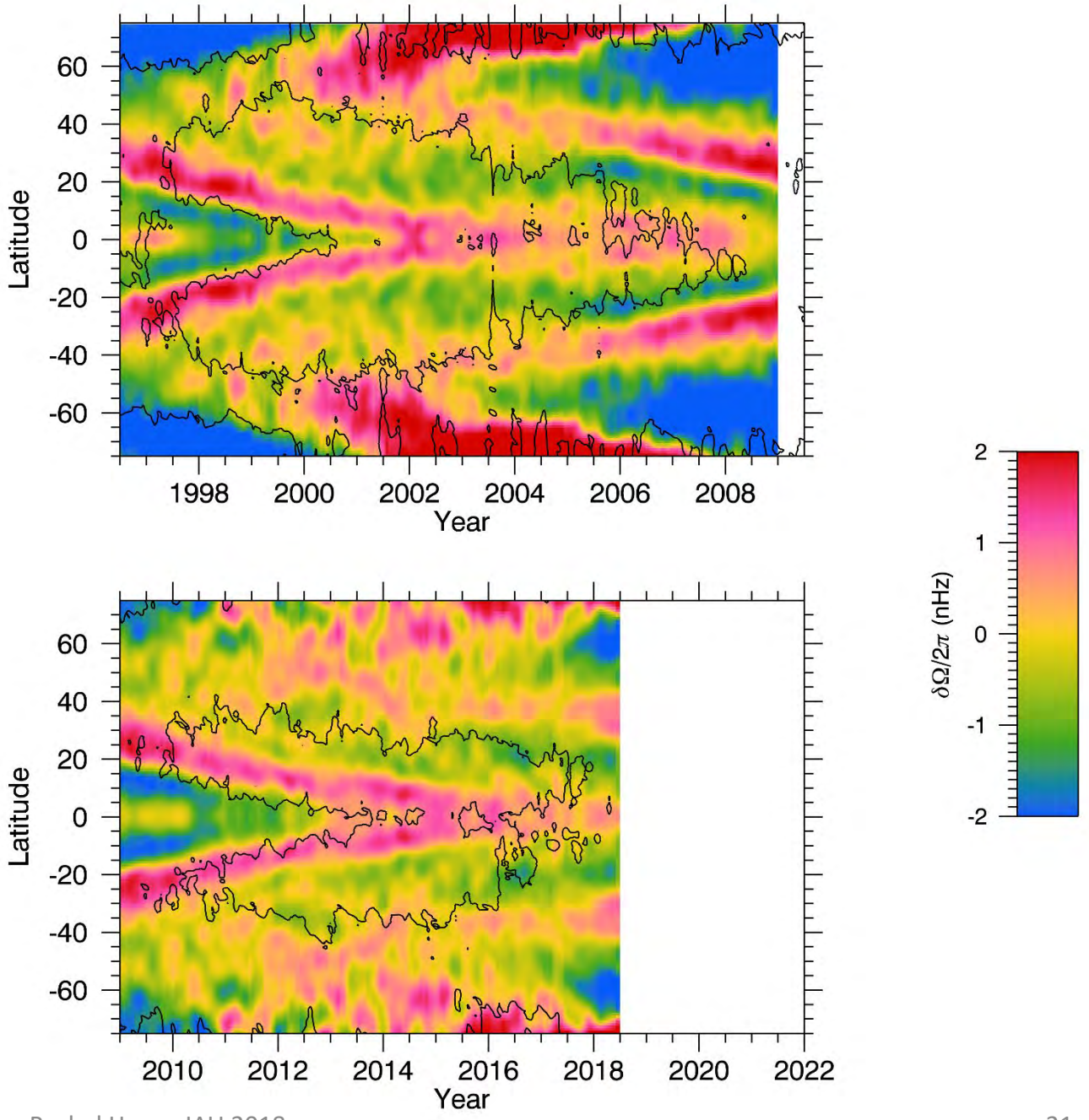






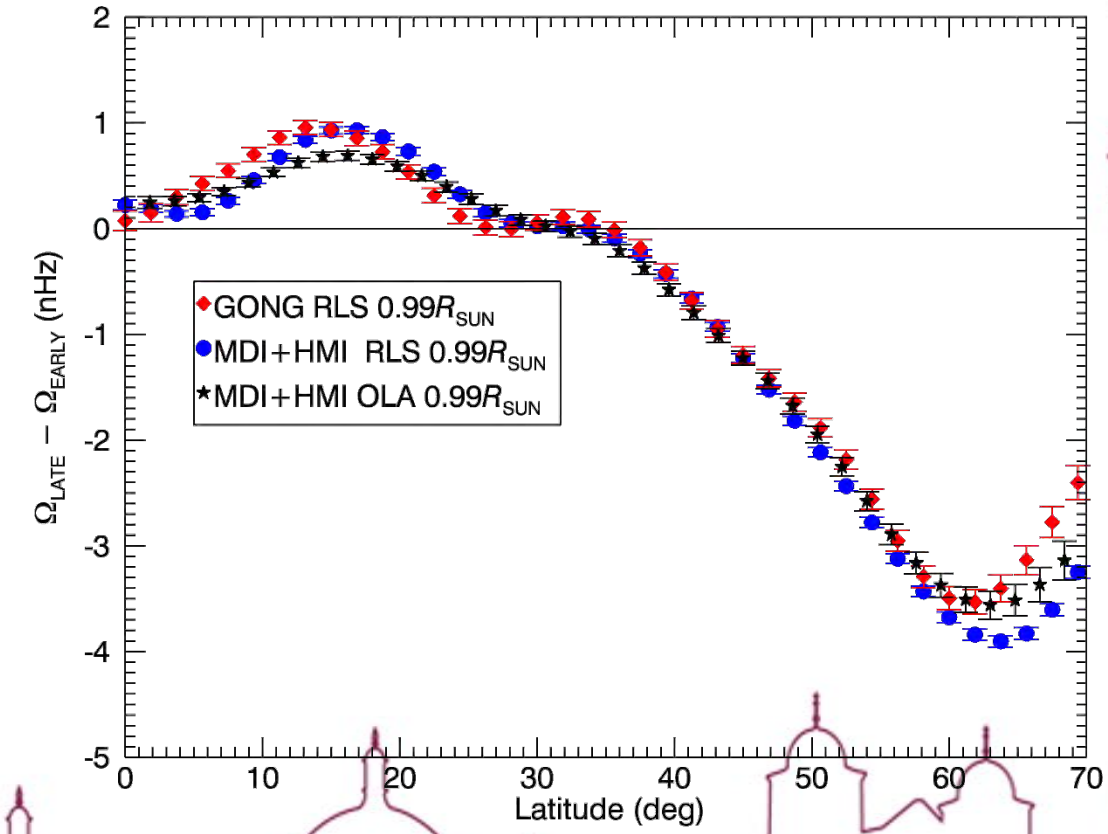
Comparing Cycles 23 and 24

Mean subtracted over 8.5 years starting a year before solar minimum



Difference between Cycle 24 and Cycle 23 mean rotation rate

Mean taken over 8.5 years starting one year before minimum



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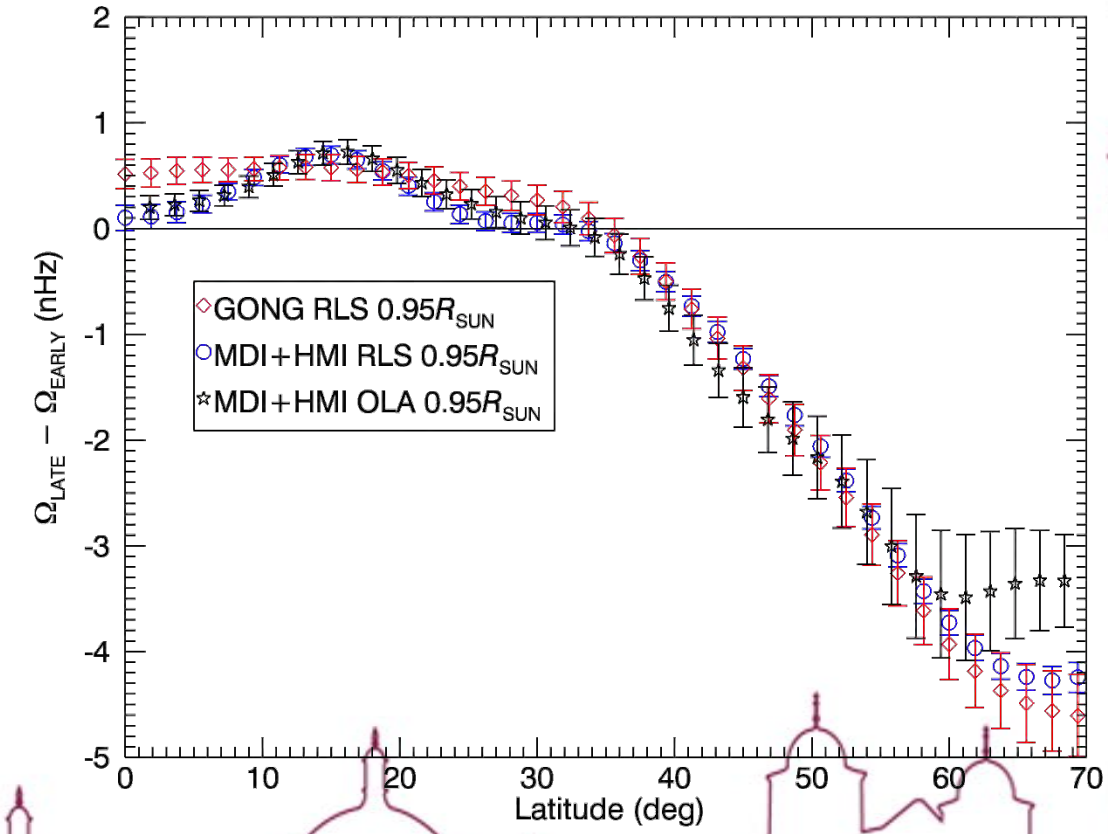
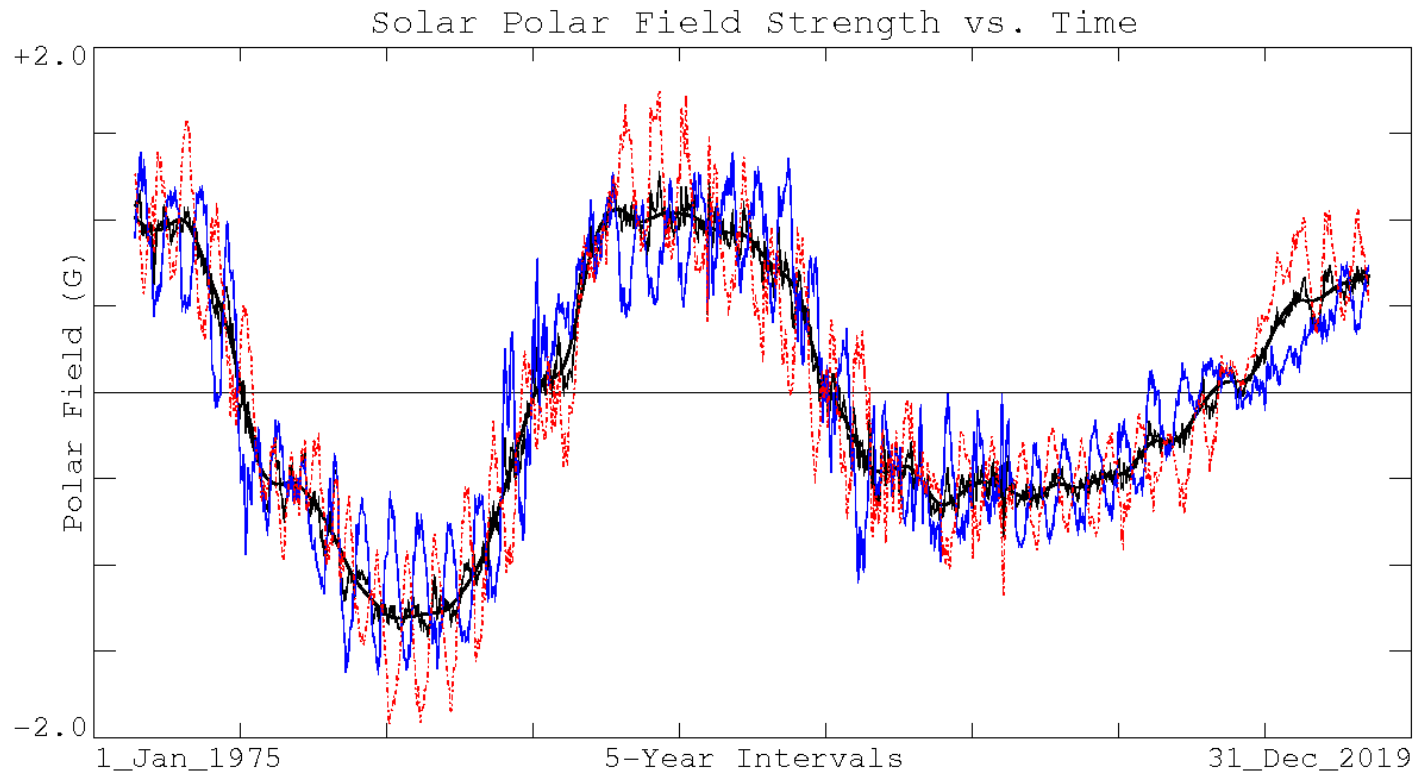


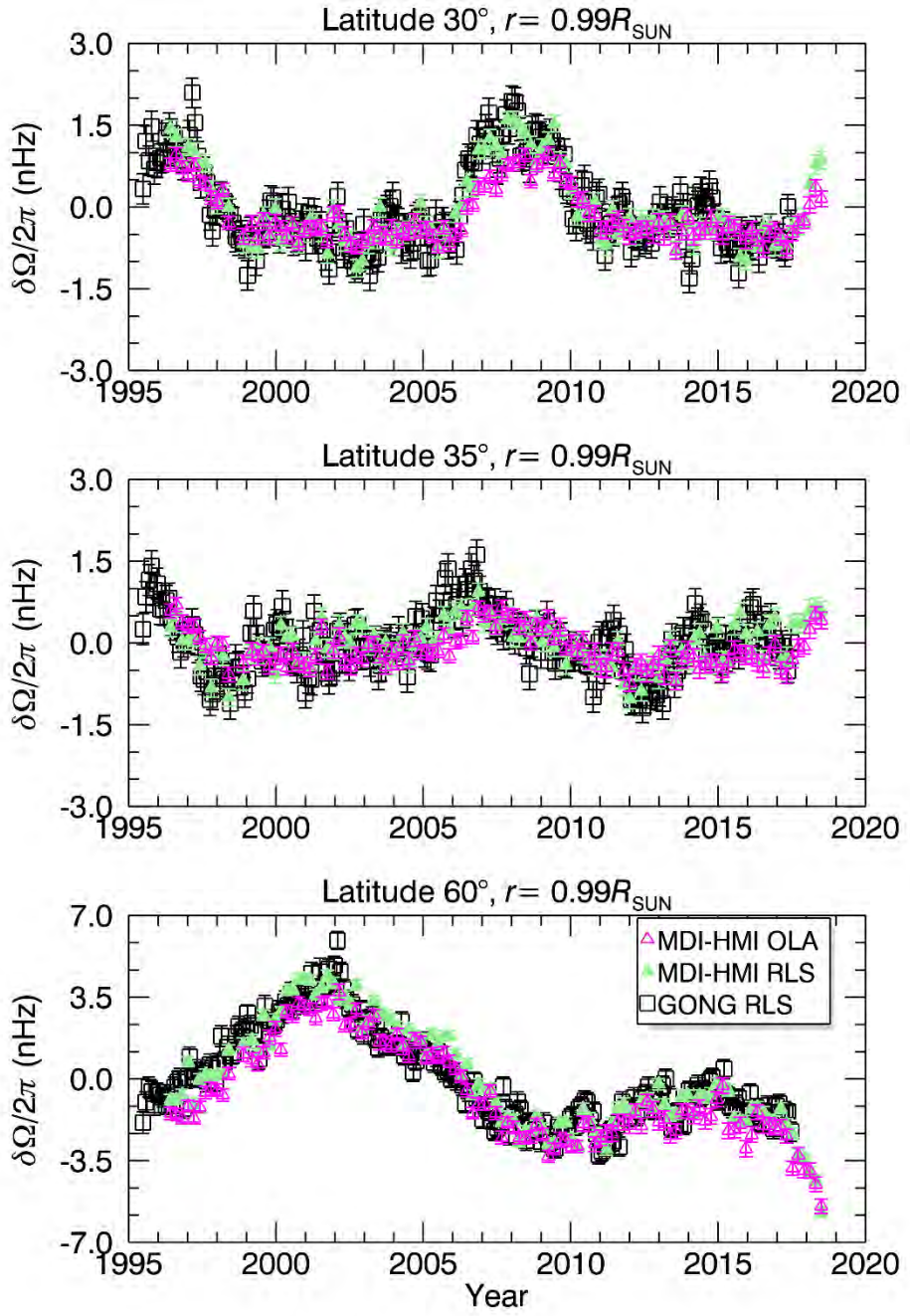
Polar Field from Wilcox Solar Observatory



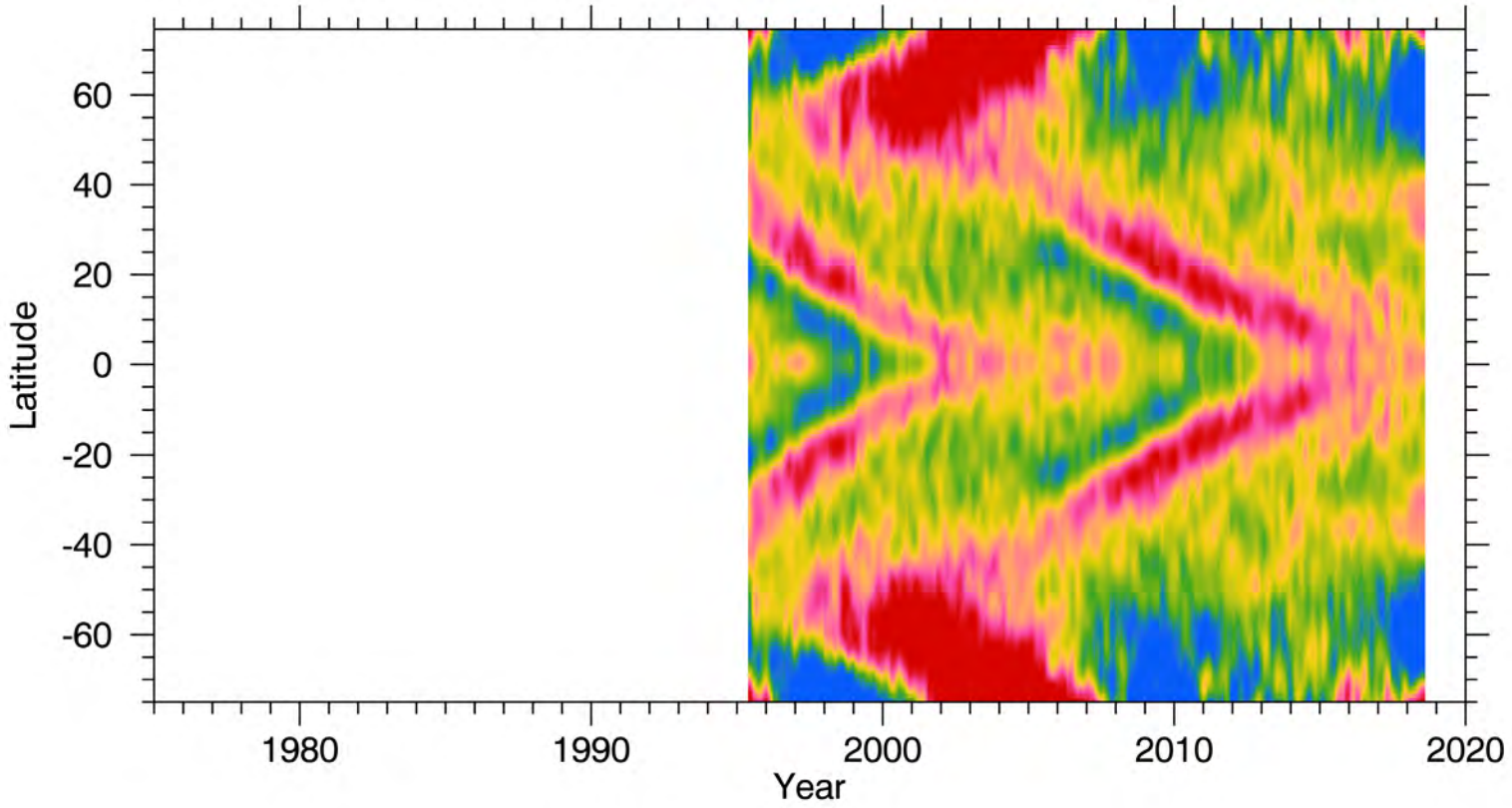
Key: Lt.Solid = North; Dashed = -South; Med.Solid = Average: (N-S)/2; Hvy.Solid = Smoothed Average

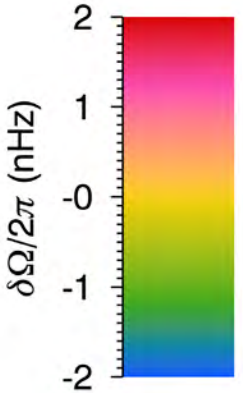
Near-surface residuals at selected latitudes

- Acceleration at 30-35 degrees
- Deceleration at 60 degrees.



Historical Context





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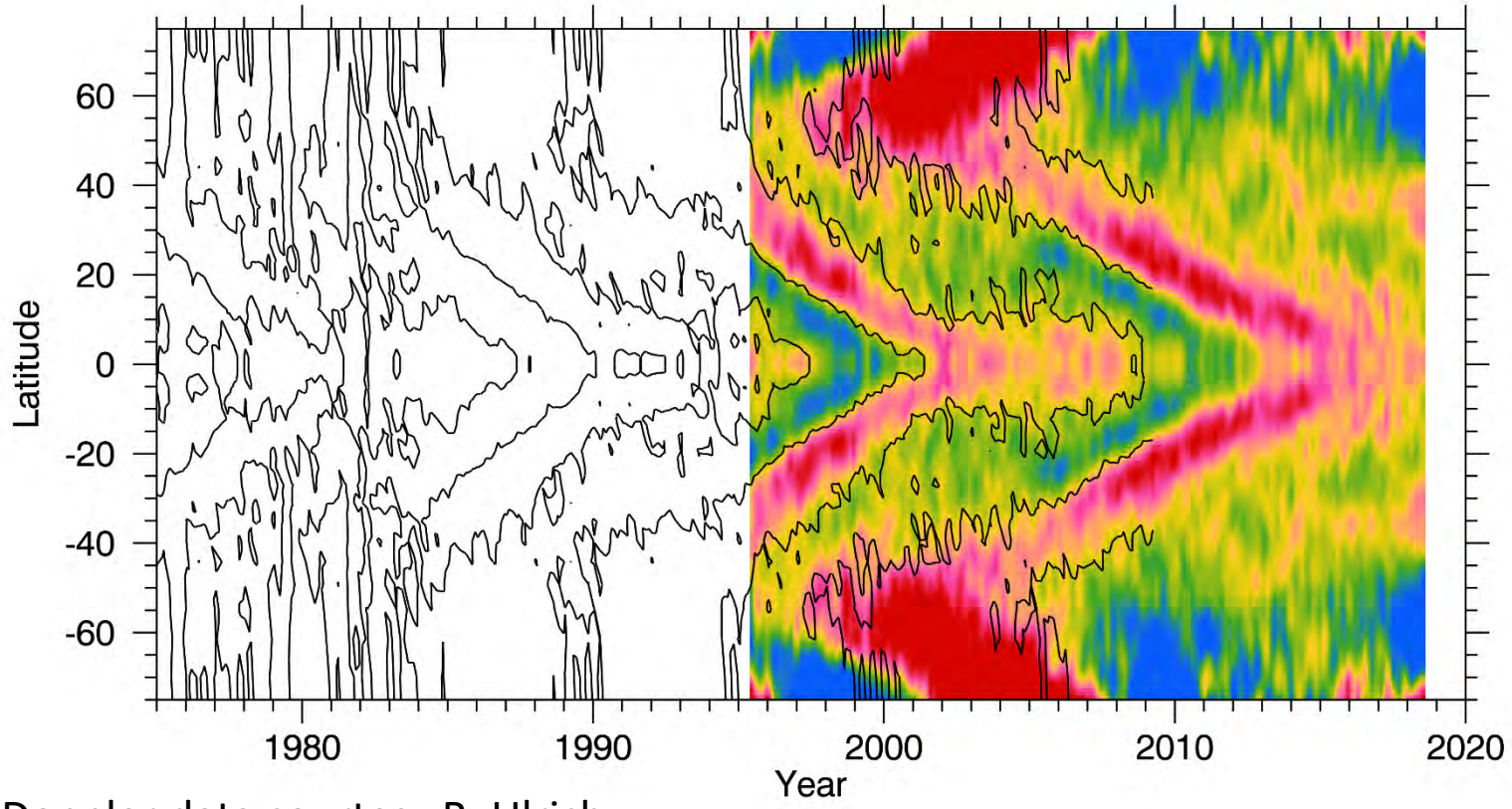
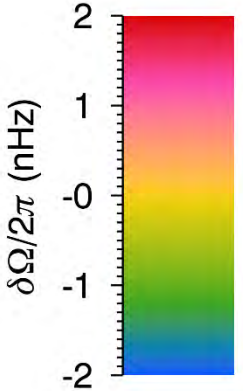
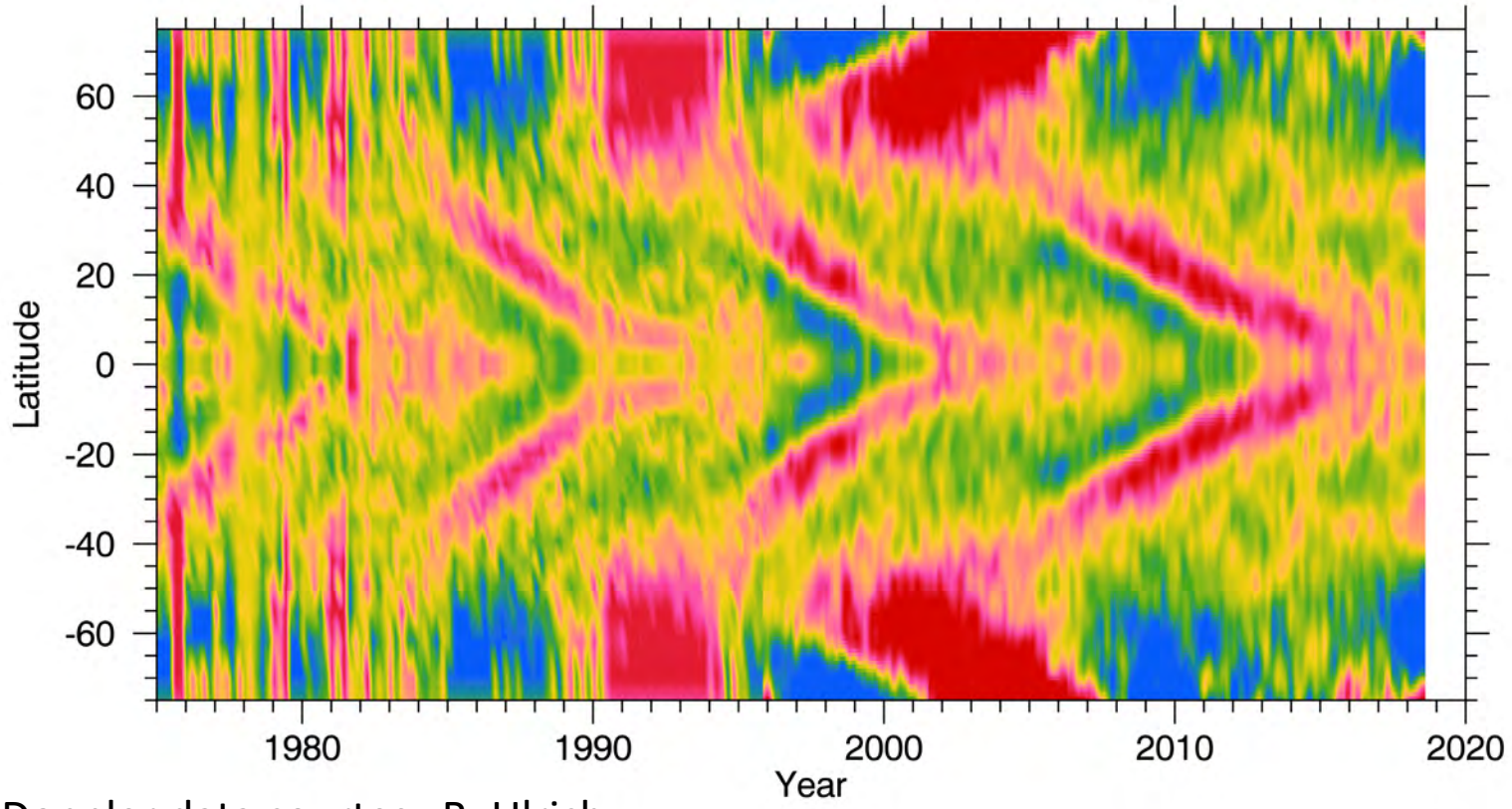
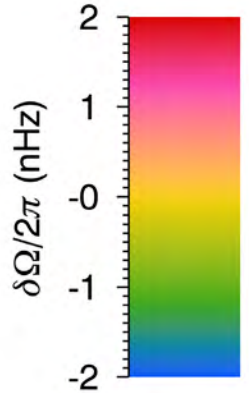




Mount Wilson Doppler data courtesy R. Ulrich

Historical Context





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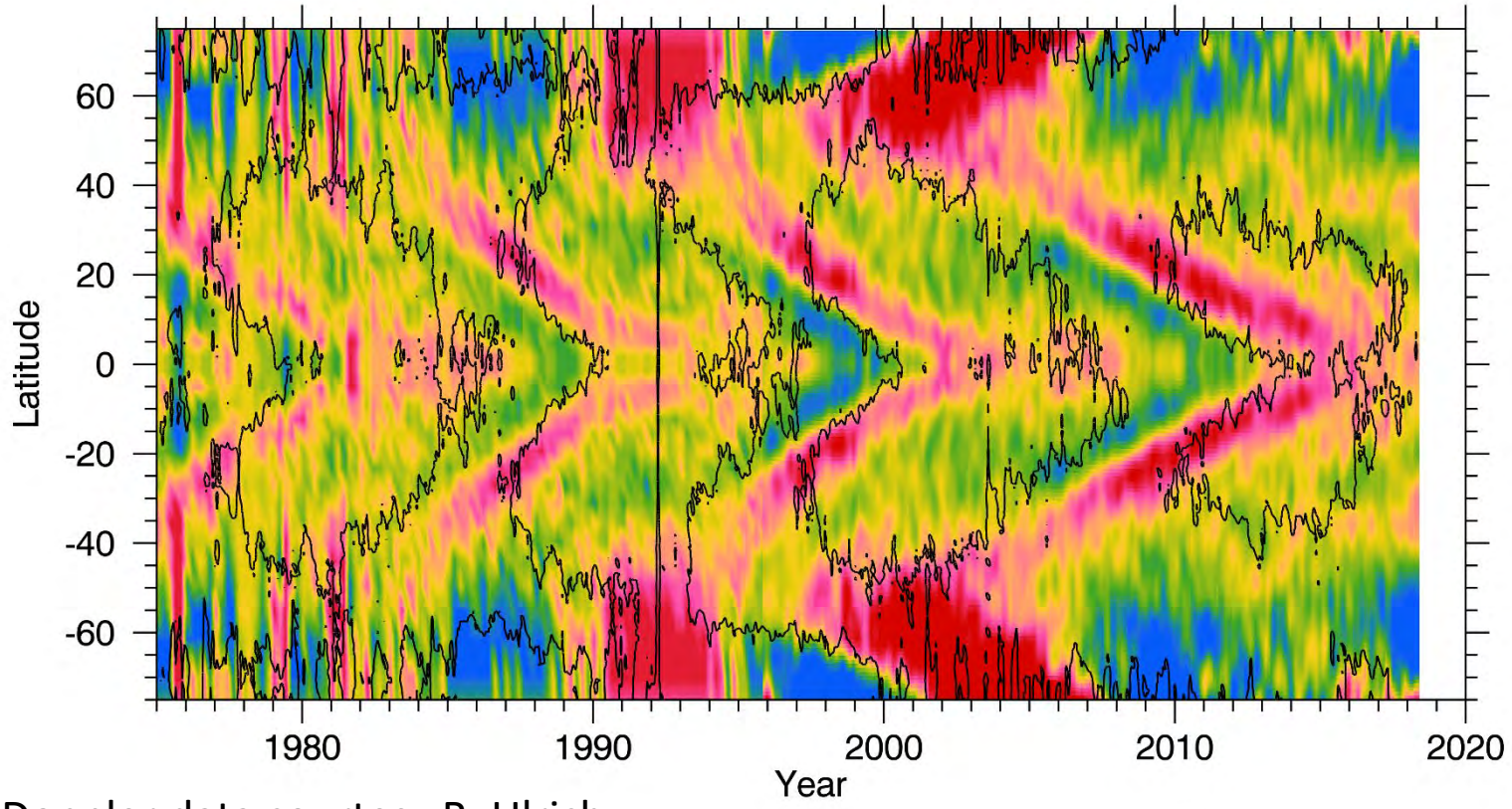

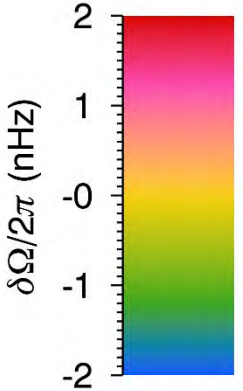

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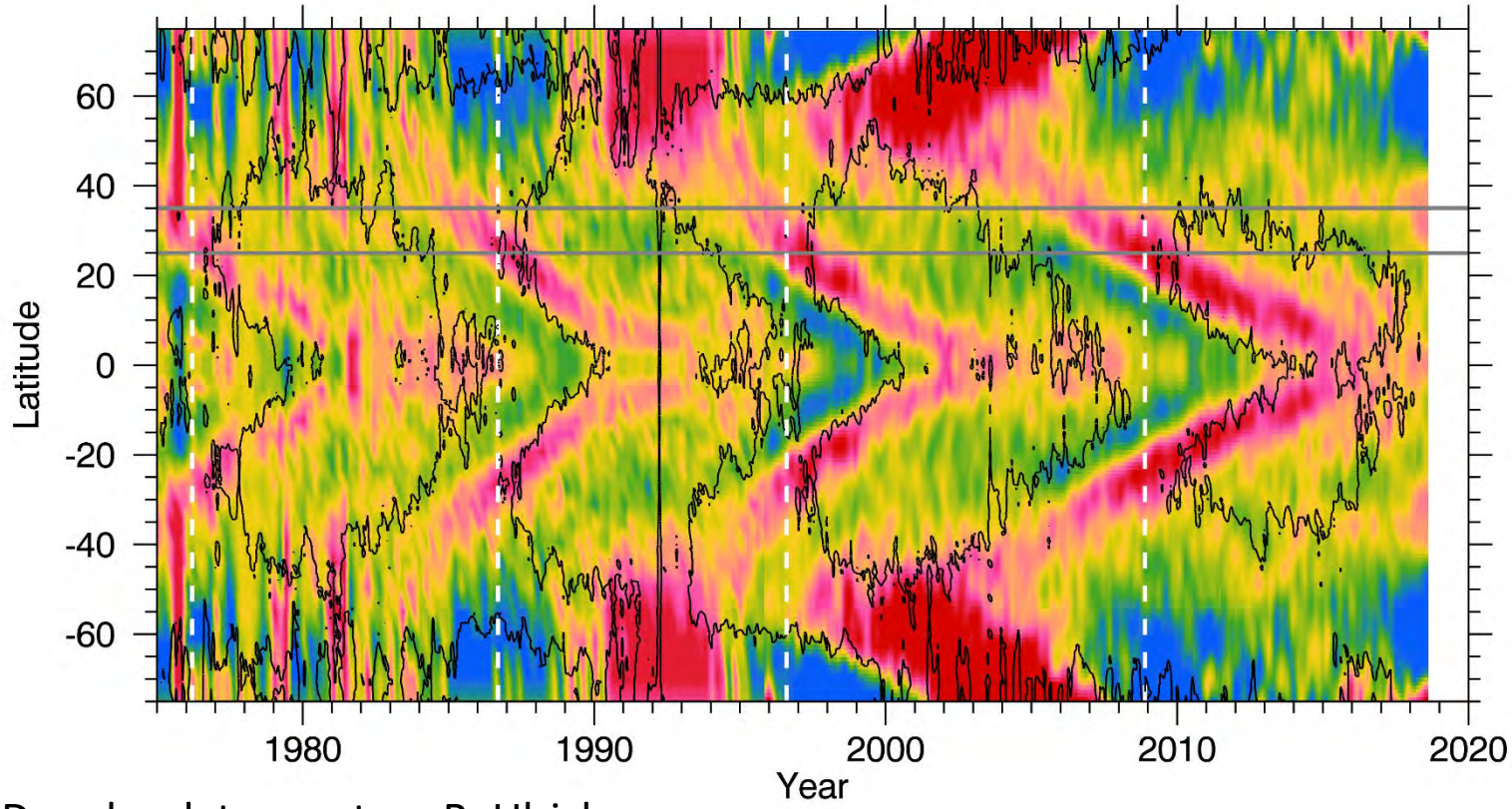
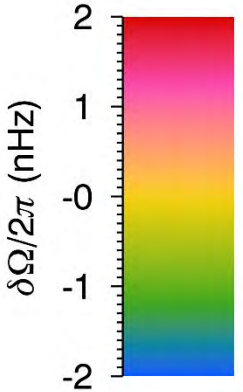
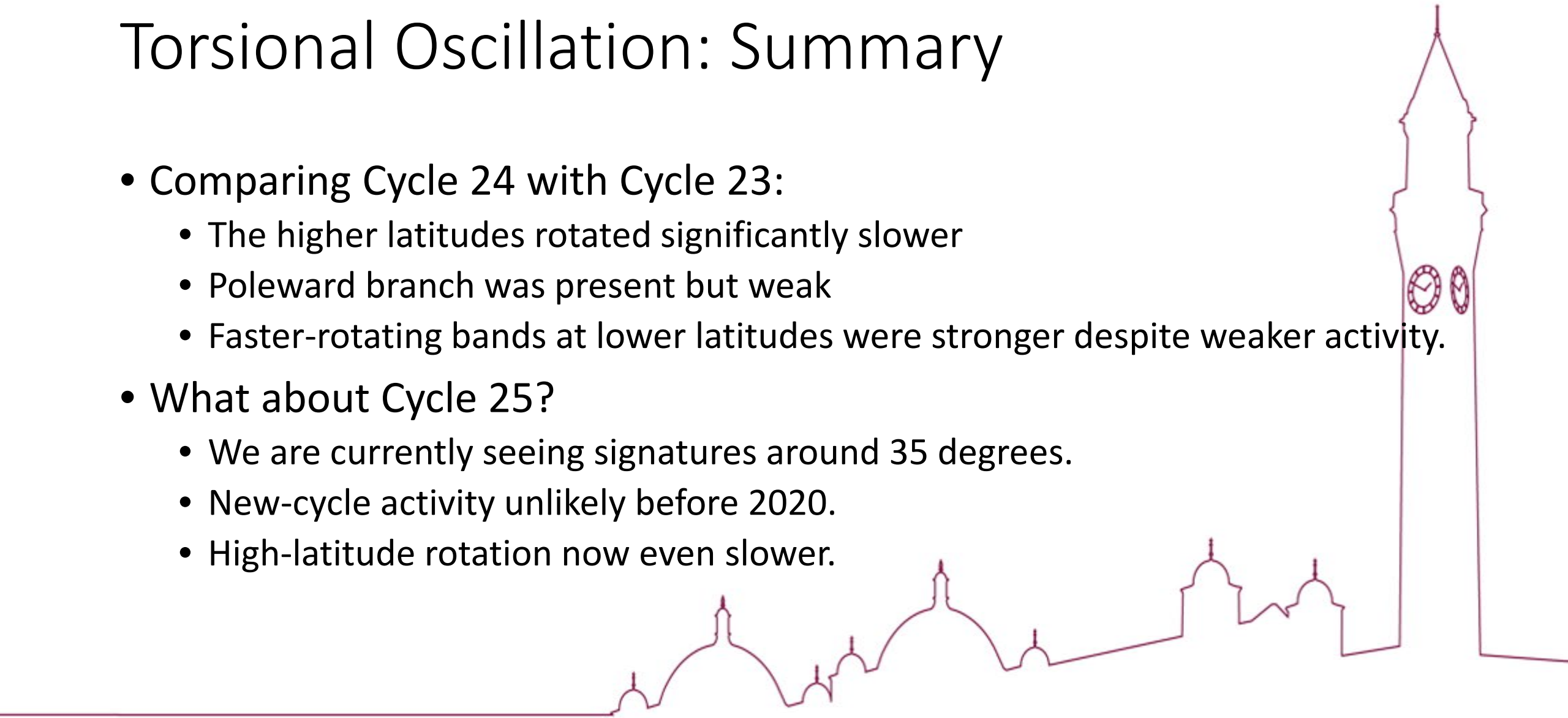




Mount Wilson Doppler data courtesy R. Ulrich

Torsional Oscillation: Summary

- Comparing Cycle 24 with Cycle 23:
  - The higher latitudes rotated significantly slower
  - Poleward branch was present but weak
  - Faster-rotating bands at lower latitudes were stronger despite weaker activity.
- What about Cycle 25?
  - We are currently seeing signatures around 35 degrees.
  - New-cycle activity unlikely before 2020.
  - High-latitude rotation now even slower.

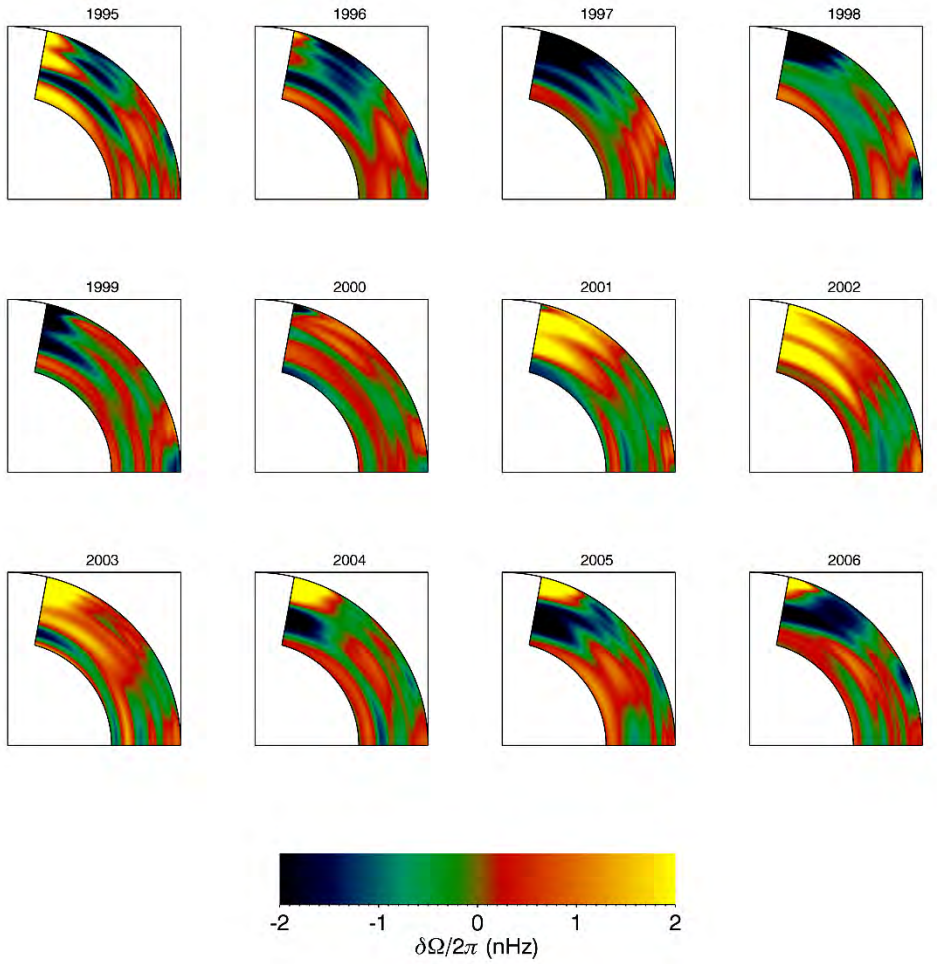


Conclusions

- Changes in the sensitivity of mode frequencies to activity hint at a thinner near-surface magnetic layer.
- Polar fields are weaker and this has been linked to slower rotation at high latitudes.
- Could these be signs that the solar dynamo is about to change to the weaker mode associated with aging stars? Maybe?
- Or it could `just' be a grand minimum (or at least the end of a grand maximum?)

Yearly average residuals 1995-2006

Mean for Cycle 23



Yearly average residuals 2007-2018

Mean for Cycle 24