Sun-as-a-star Helioseismic Observations from SoHO over a 22-year Magnetic Cycle

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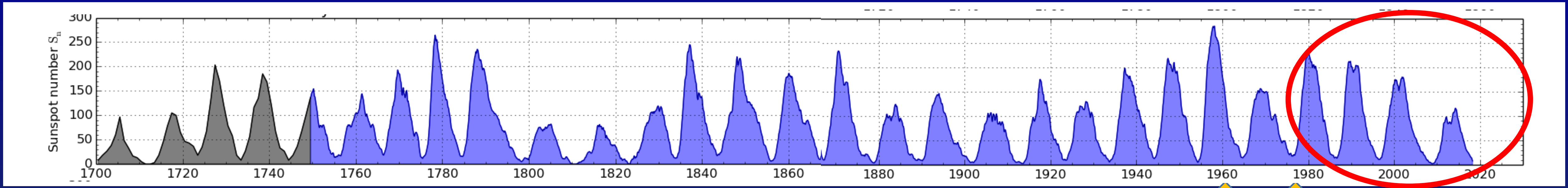
Sun-as-a-star Helioseismic Observations: A background

Sunspot number record

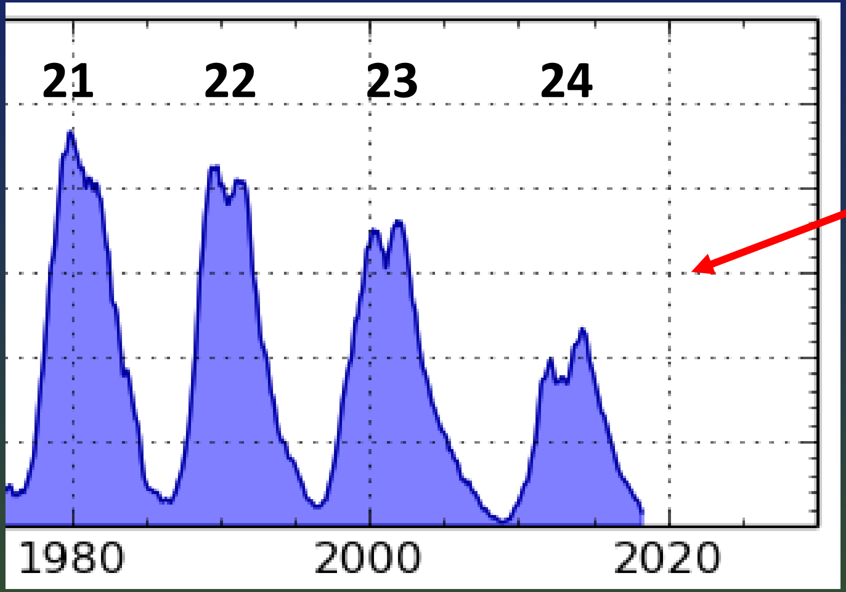
Source: WDC-SILSO, Royal Observatory of Belgium, Brussels



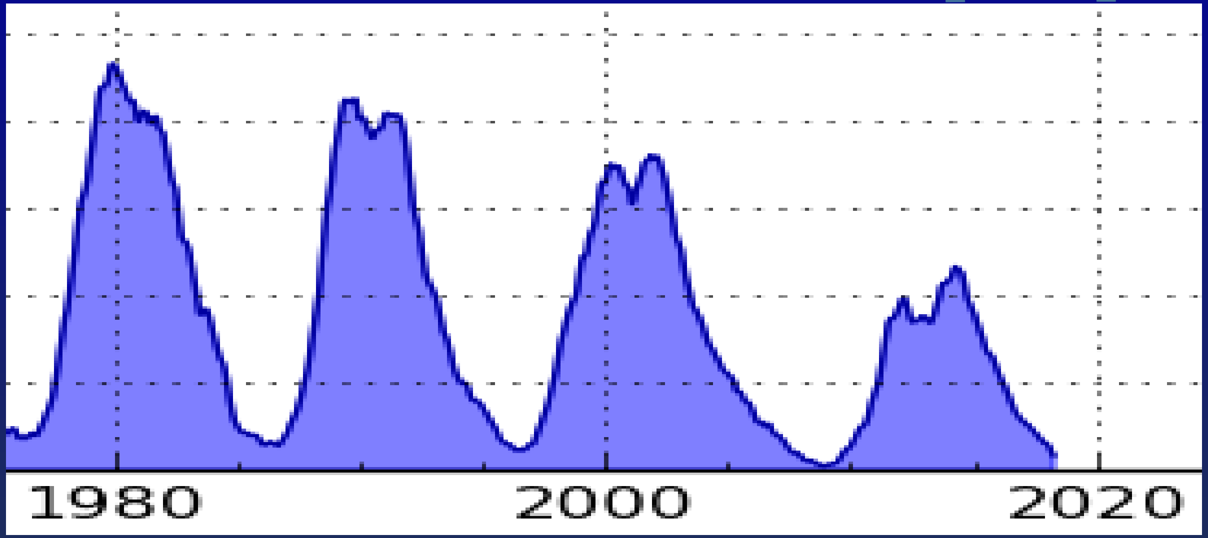
First detection of solar oscillations

(Leighton, Noyes & Simon, 1962)

Start of an observing network for low-degree modes



Un-interrupted Helioseismic Observations: Sun-as-a-star (Unresolved)



Instruments onboard SDO

1600 Å and 1700 Å
Continuum intensity

Integrated light

Ground-based Networks

Instruments onboard SoHO

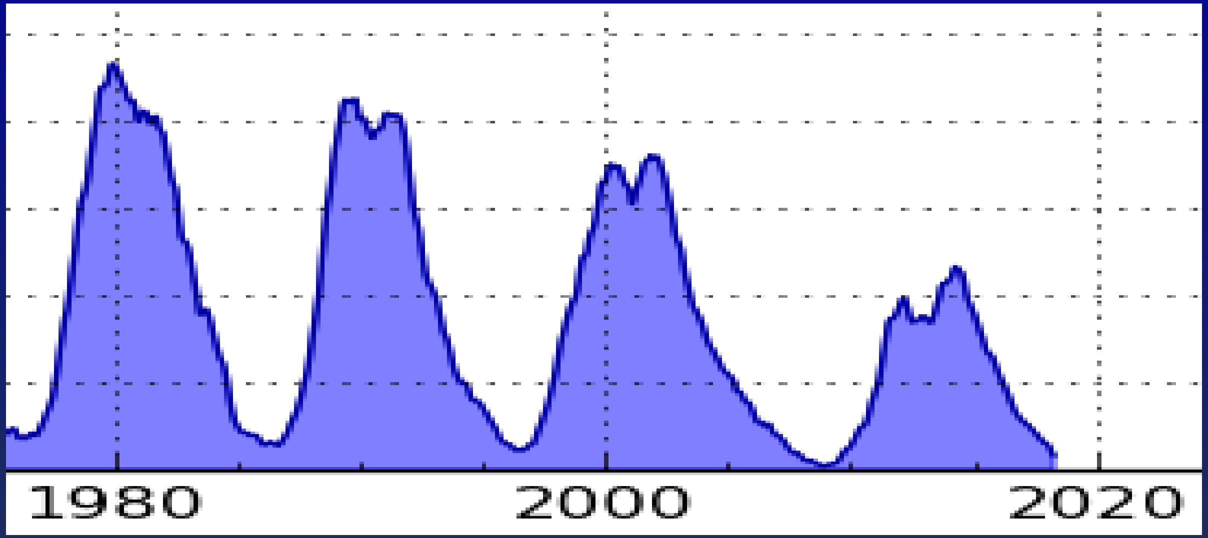
International
Reseach on the
Interior of the Sun
(IRIS)
1988-2001

Birmingham Solar
Oscillations Network
(BiSON)

Global Oscillations at
Low Frequencies
(GOLF)

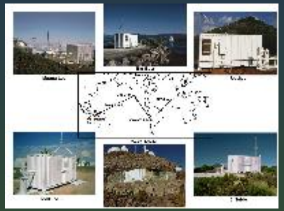
Variability of IRradiance
and Gravity Oscillations
(VIRGO)

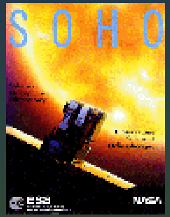
Un-interrupted Helioseismic Observations: Resolved Disk



Space Missions

Ground-based Network





Global Oscillations Network Group (GONG)
1995 -

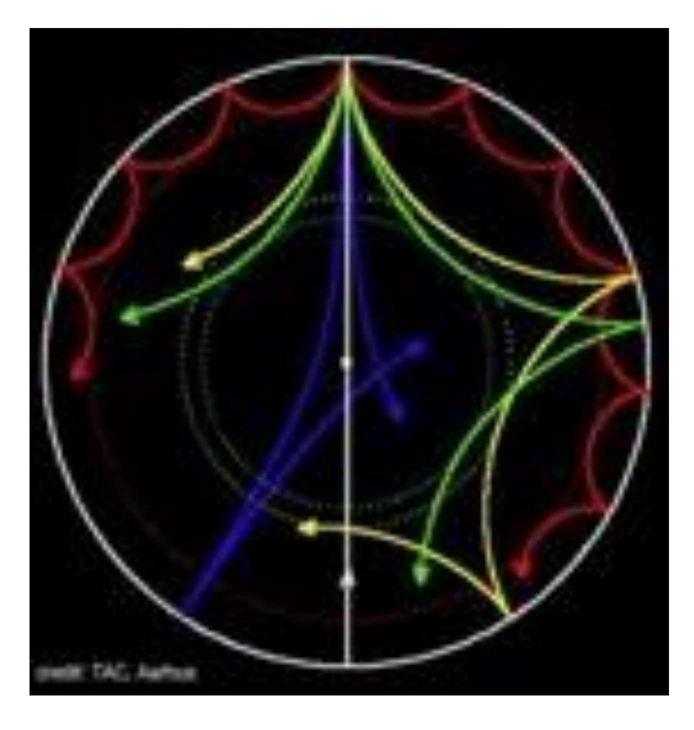
SoHO / Michaelson Doppler Imager (MDI)
1996 - 2011

SDO / Helioseismic and Magnetic Imager (HMI)
2010 -

Plan

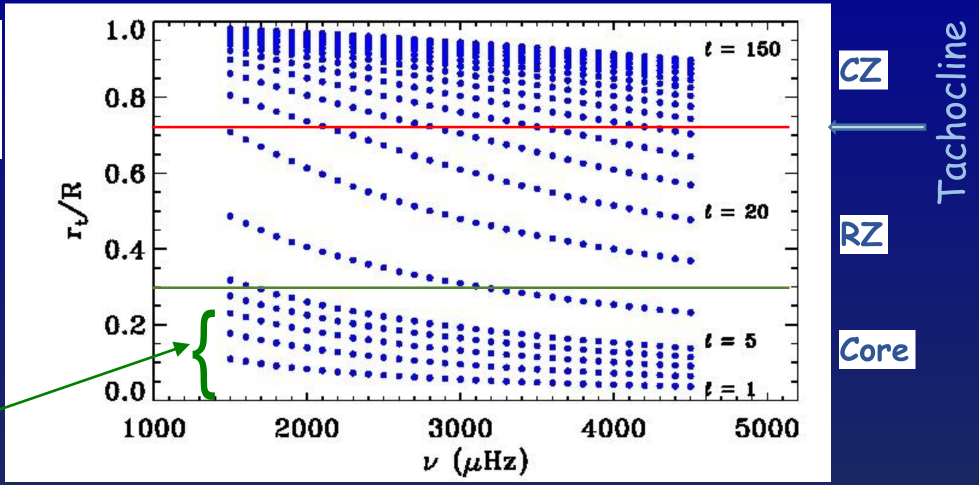
- ✓ Sun-as-a-star observations - Some basics
- ✓ Why are these observations important?
- ✓ Results
- ✓ Summary

Sun-as-a-star Observations: Propagating modes



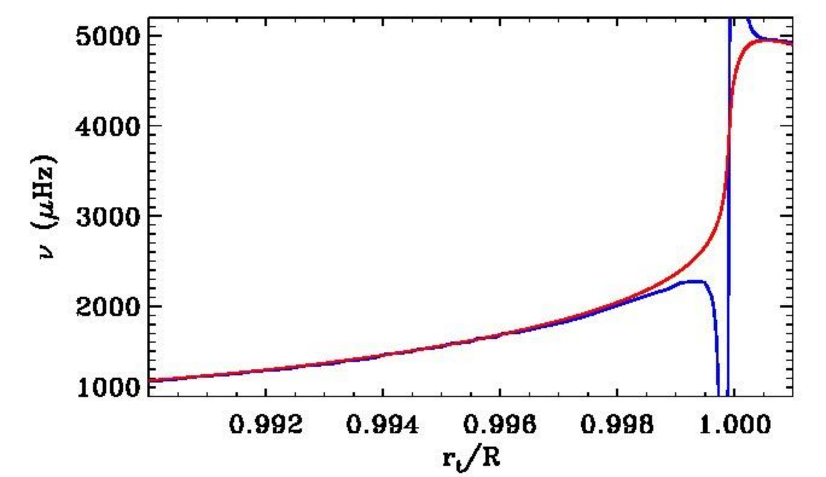
Lower turning point

$$r_t = \frac{c(r_t)}{2\pi} \frac{\sqrt{l(l+1)}}{\nu},$$



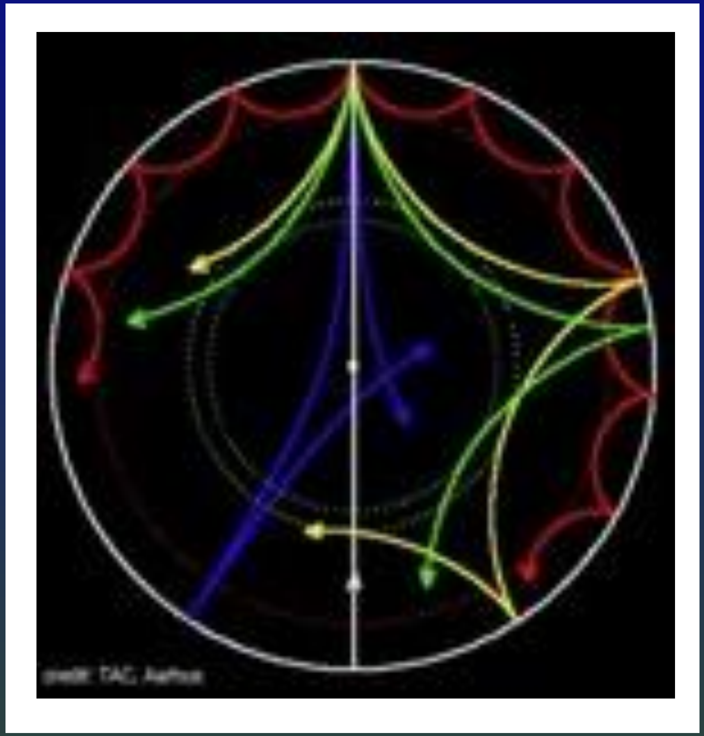
Upper turning point (Acoustic cutoff frequency)

$$\nu_{ac} = \nu$$



Adapted from Basu et al. (2012)

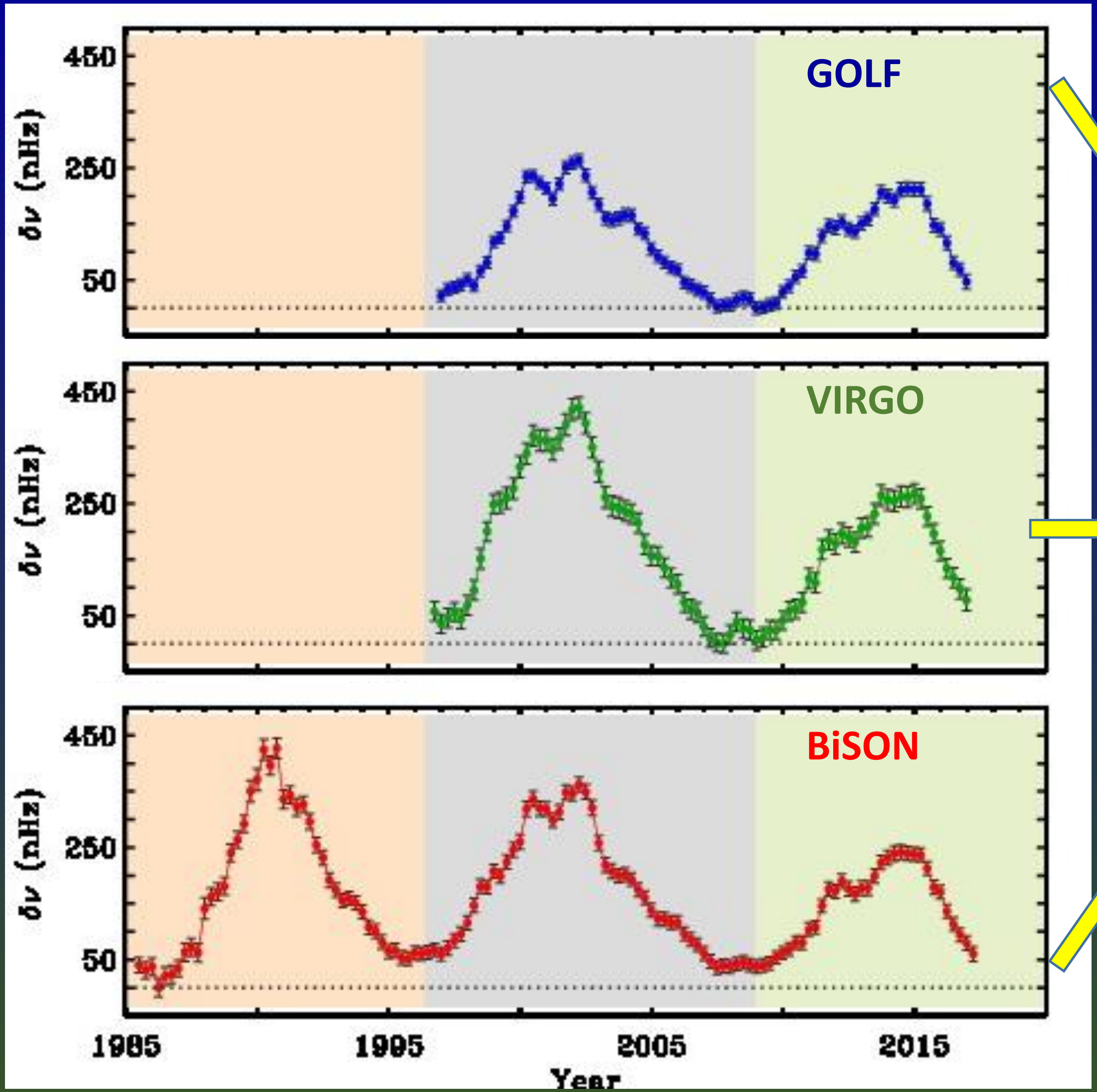
Sun-as-a-star Observations: Why are these important?



- Variability of the solar interior
- Model the solar core
- Search for g modes - Rotation of the core
- Tested methods are laying paths for asteroseismic studies

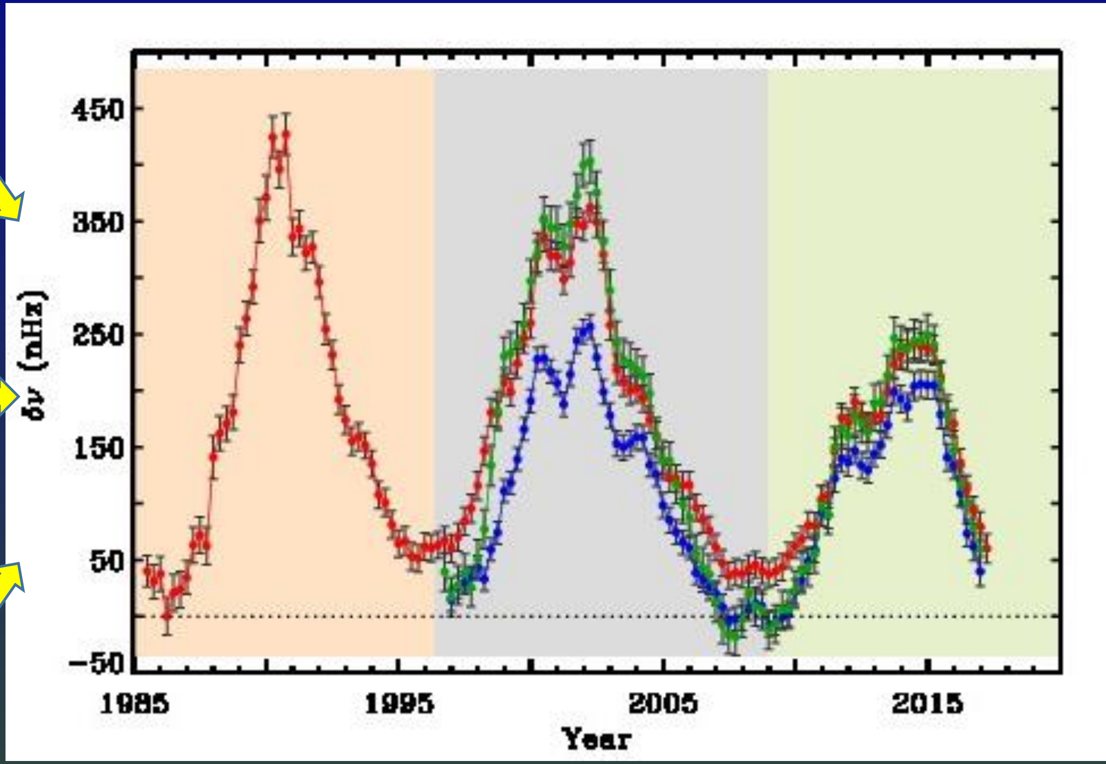
as inferred from the acoustic mode frequencies and compare with disk-resolved mode frequencies

Sun-as-a-star observations – Temporal Variation

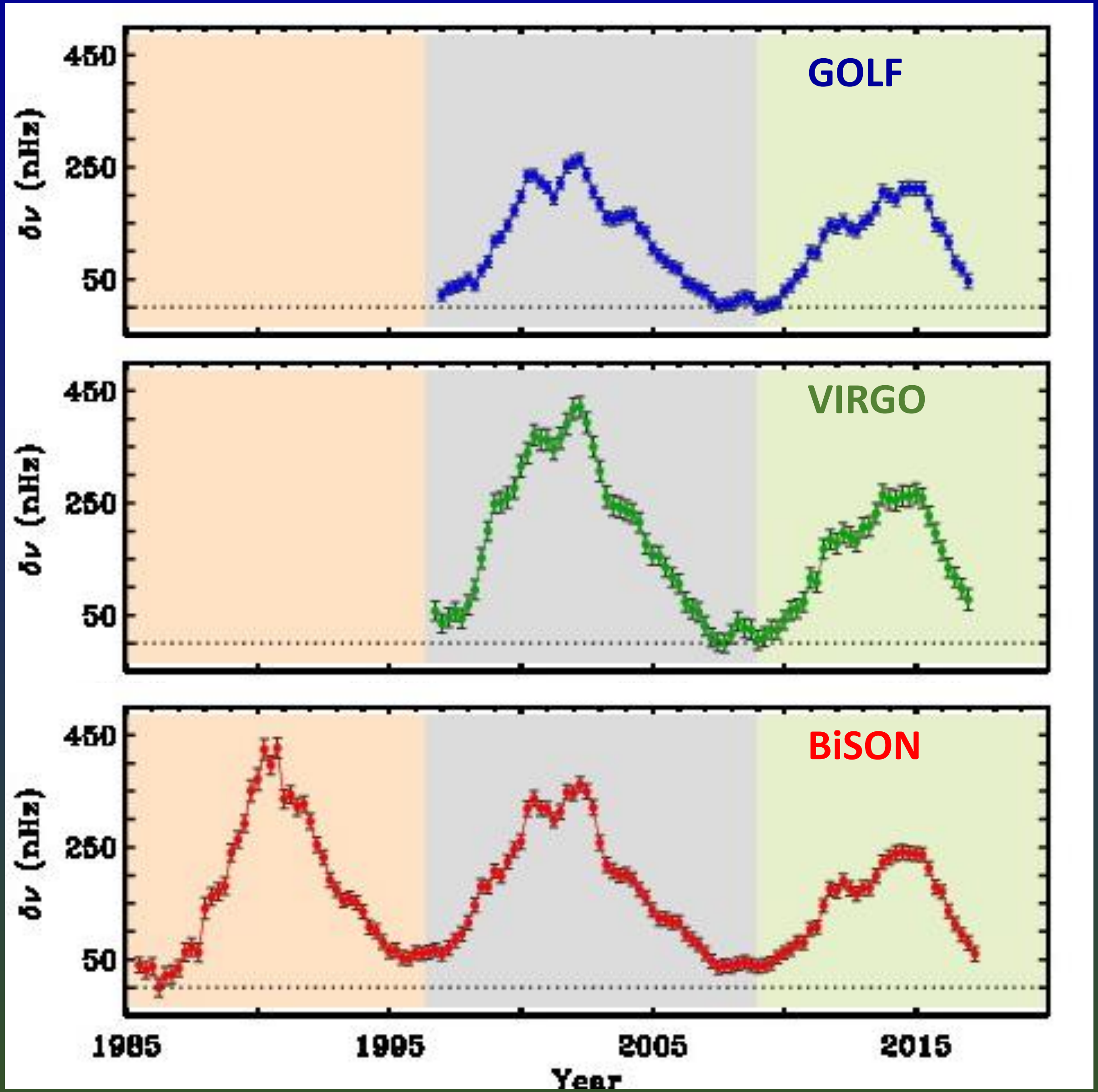


1860 μHz ≤ ν ≤ 3450 μHz; ℓ = 0 – 3

Common modes in individual data sets.

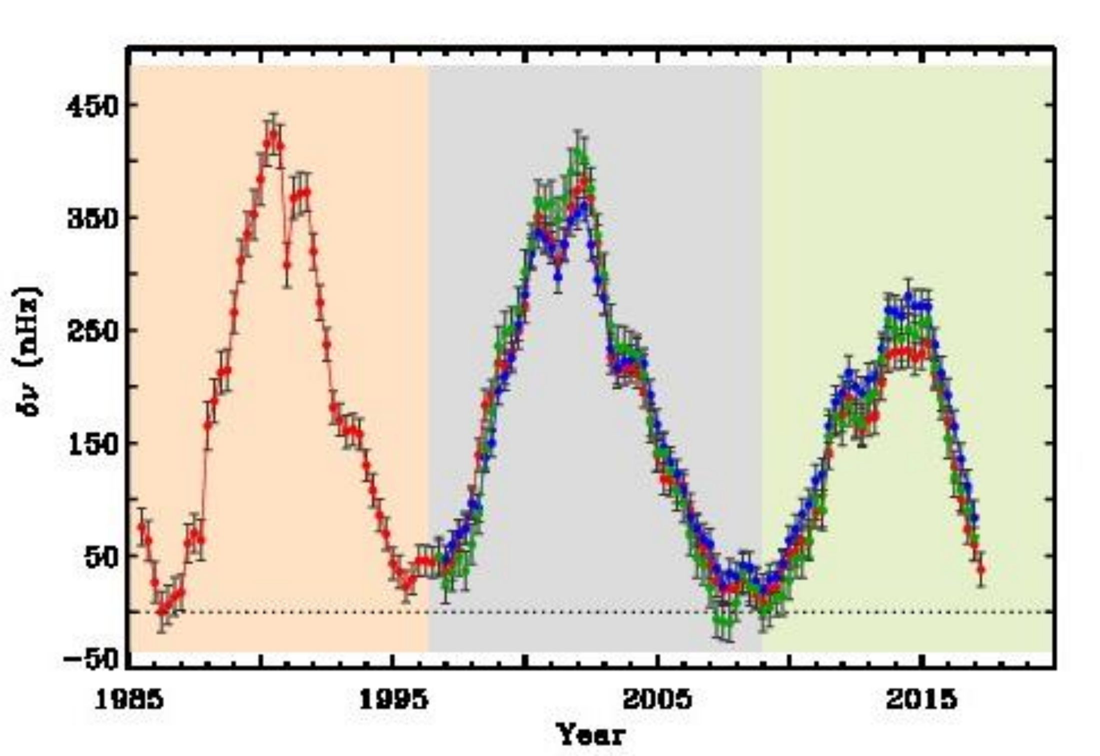


Sun-as-a-star observations – Temporal Variation



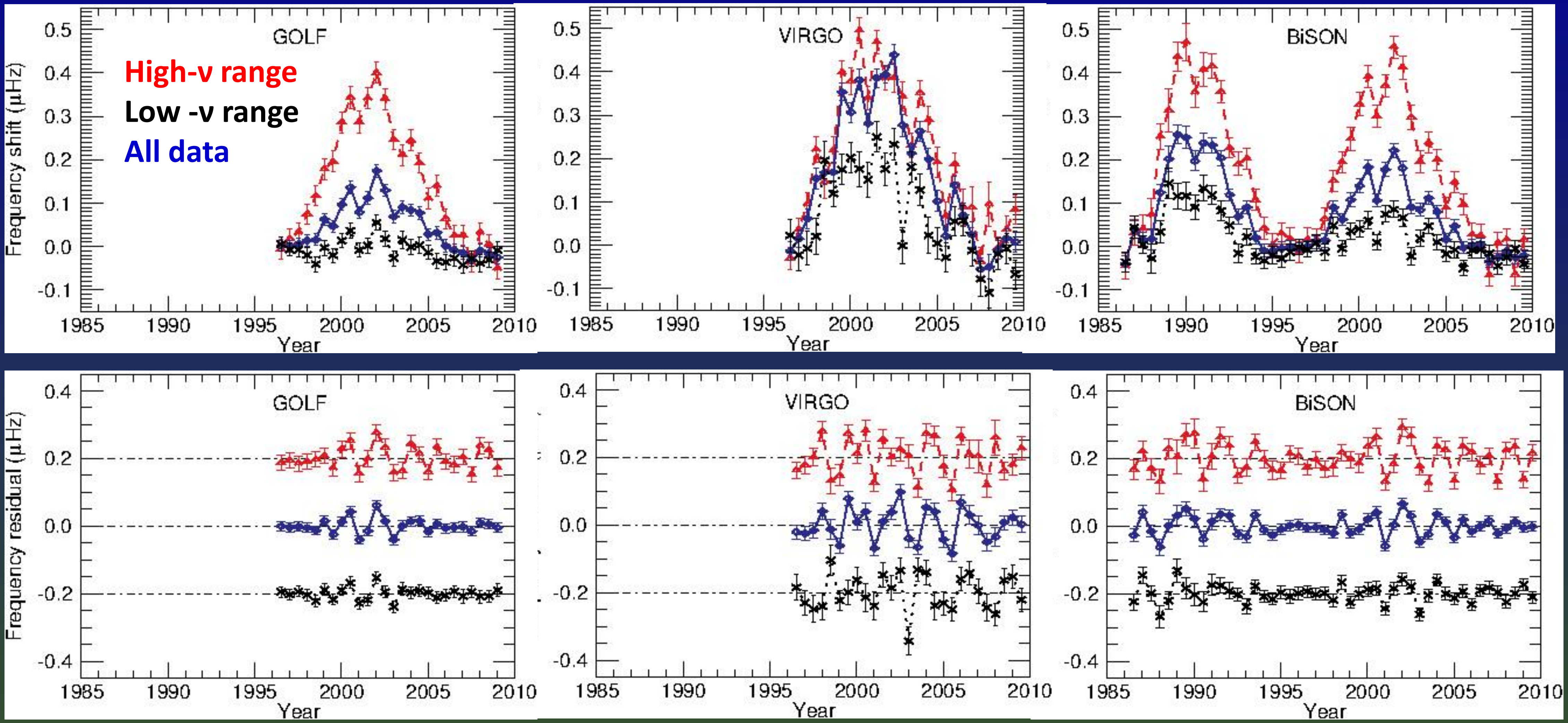
1860 μHz ≤ ν ≤ 3450 μHz; ℓ = 0 – 3

Common modes in all 3 data sets.



Quasi-biennial Periodicity – A Hint for the Second Dynamo

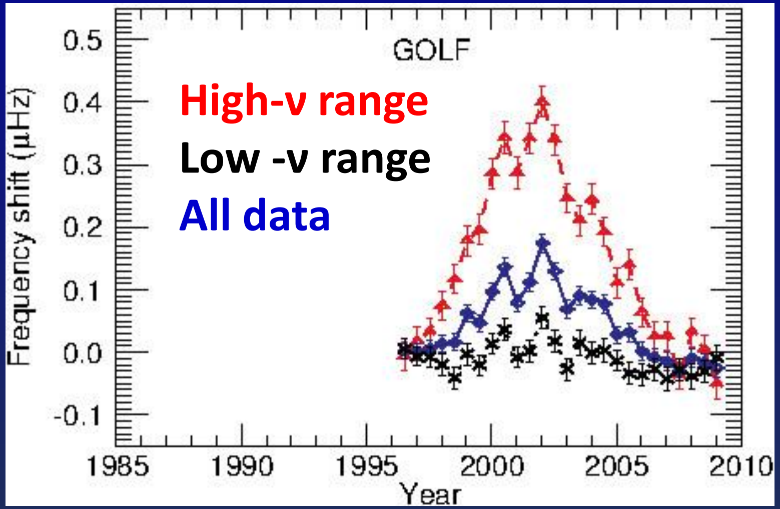
Unresolved observations: Low-degree Modes (0 ≤ ℓ ≤ 2)

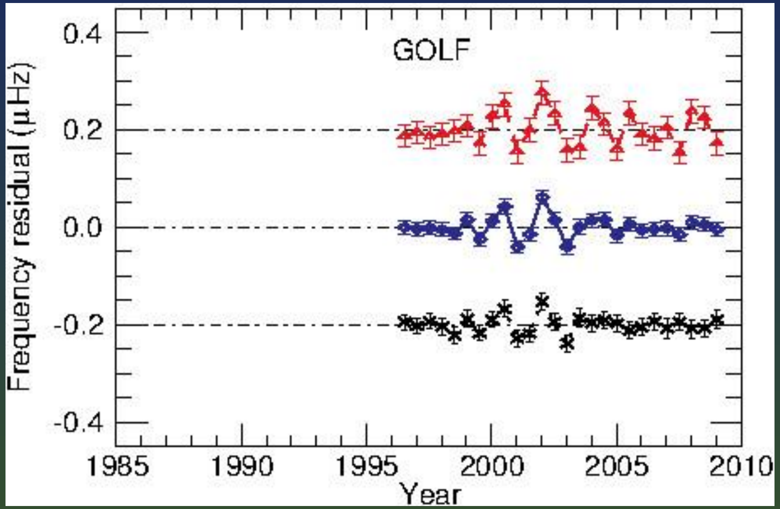


Broomhall et al. (2011) JPCS

Quasi-biennial Periodicity – A Hint for the Second Dynamo

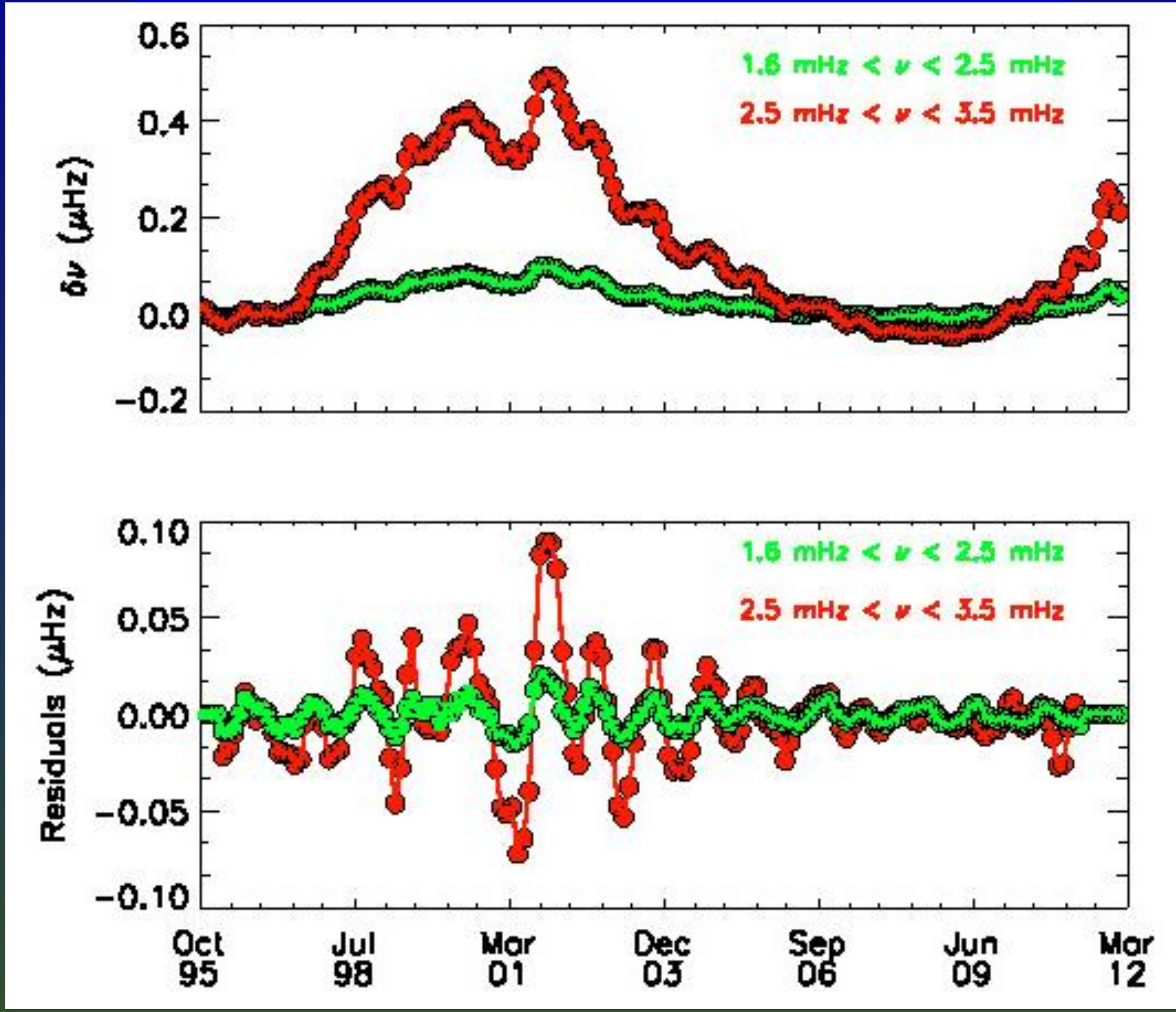
Unresolved observations from GOLF
Low-degree Modes ($0 \le \ell \le 2$)





Broomhall et al. (2011) JPCS

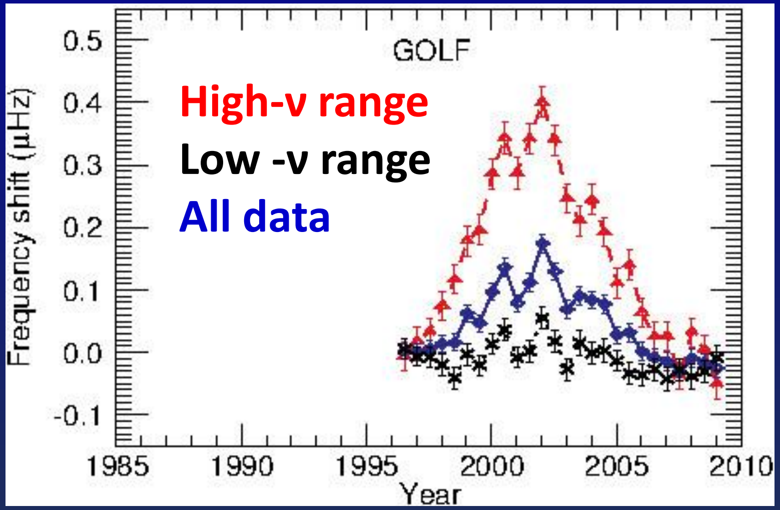
Resolved observations from GONG
$0 \le \ell \le 120$

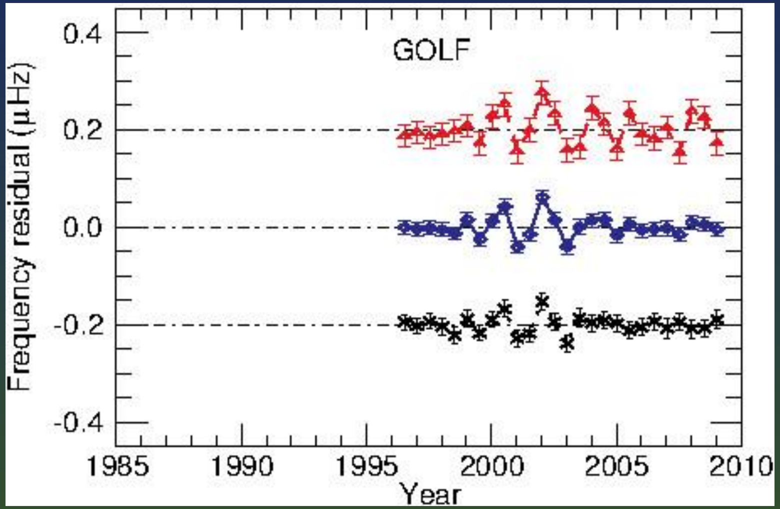


Simoniello et al. (2013) ApJ

Quasi-biennial Periodicity – A Hint for the Second Dynamo

Unresolved observations from GOLF
Low-degree Modes ($0 \leq \ell \leq 2$)





Broomhall et al. (2011) JPCS

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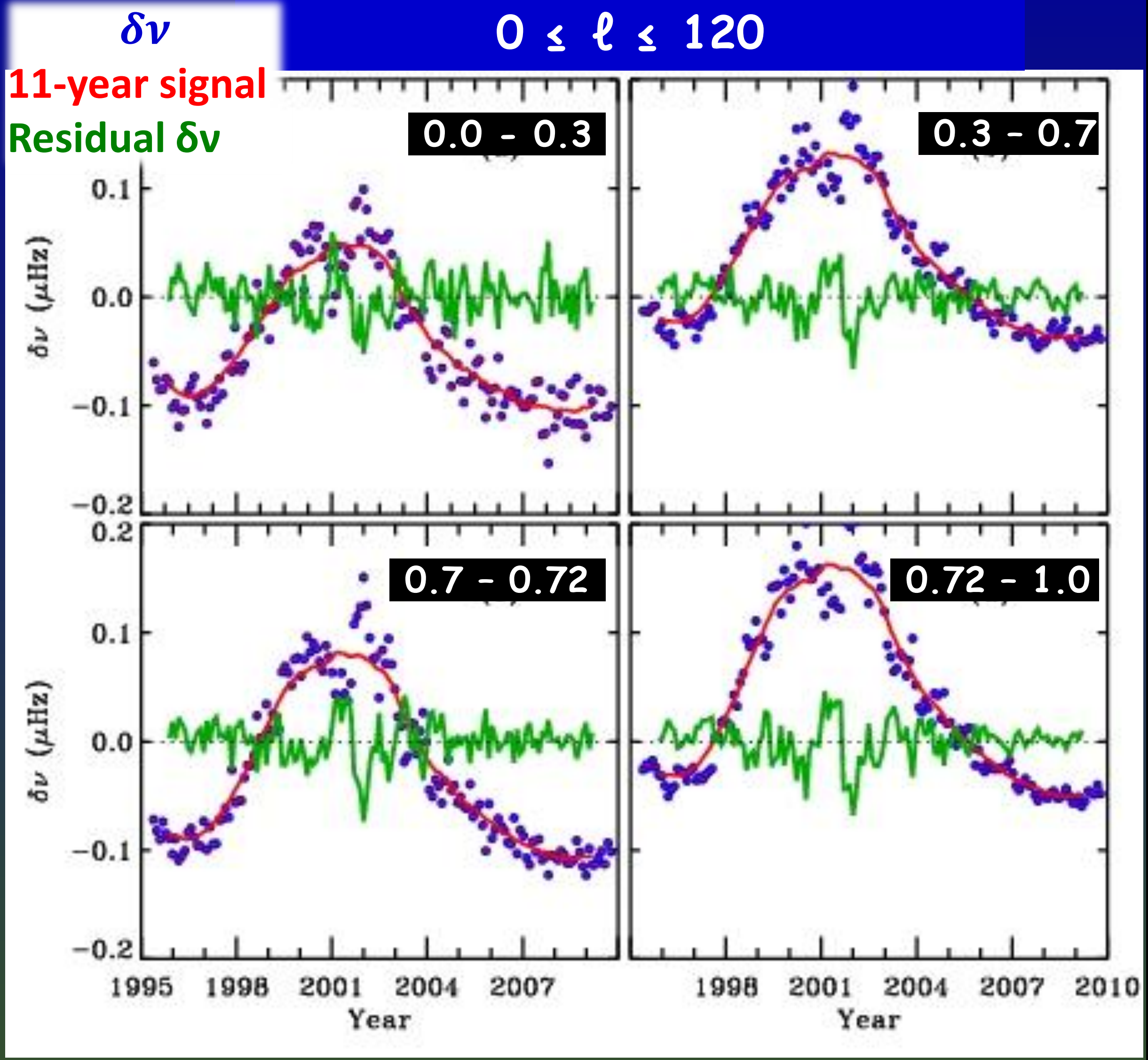
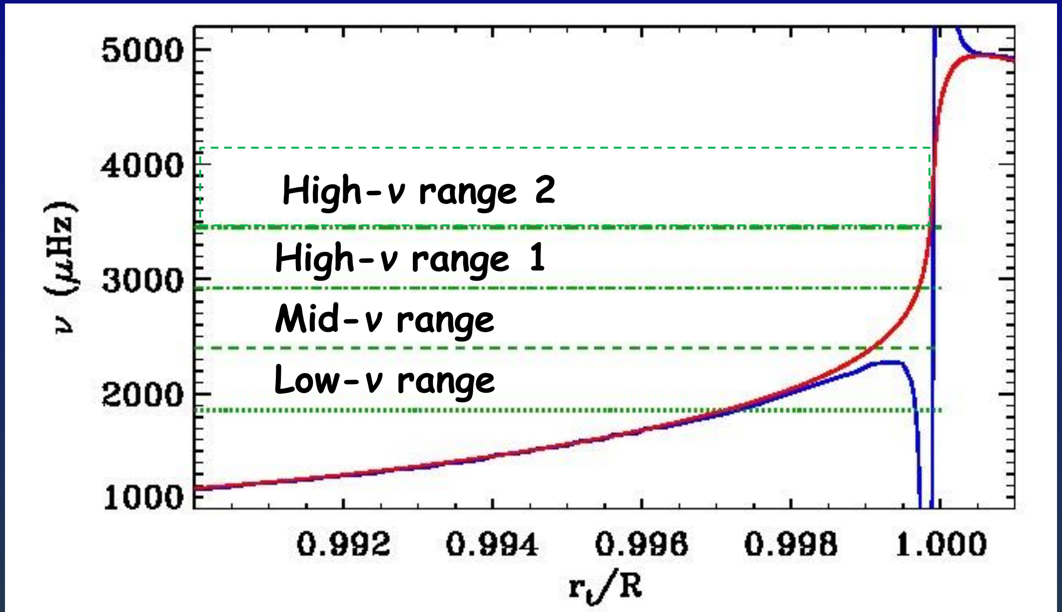


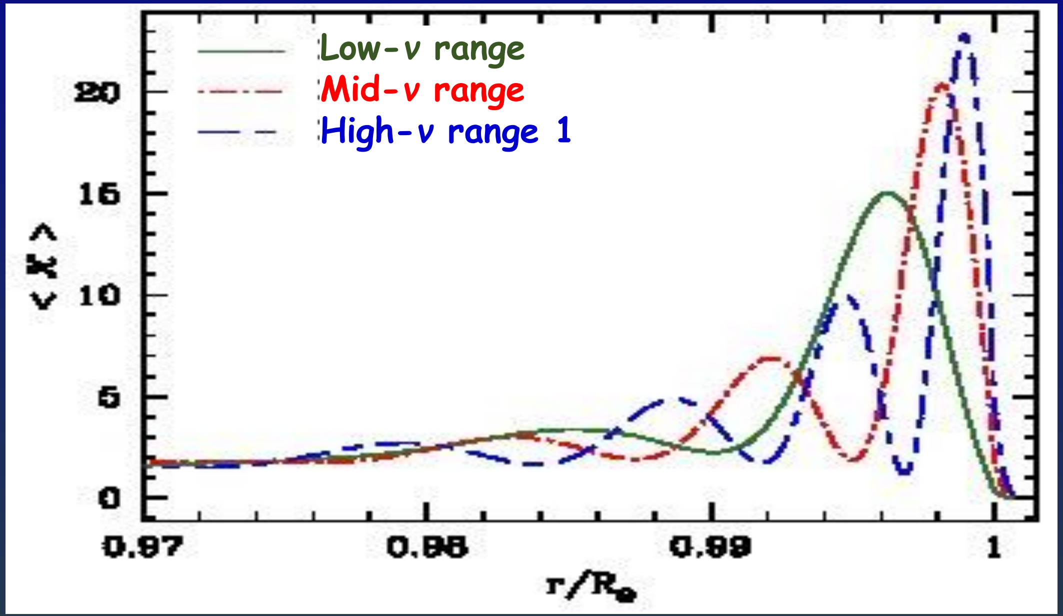
Grouped on the basis of lower-turning points

Jain et al. (2011) ApJ

Temporal Variations - Based on Upper Turning Points

Acoustic cutoff frequency as a function of radius.

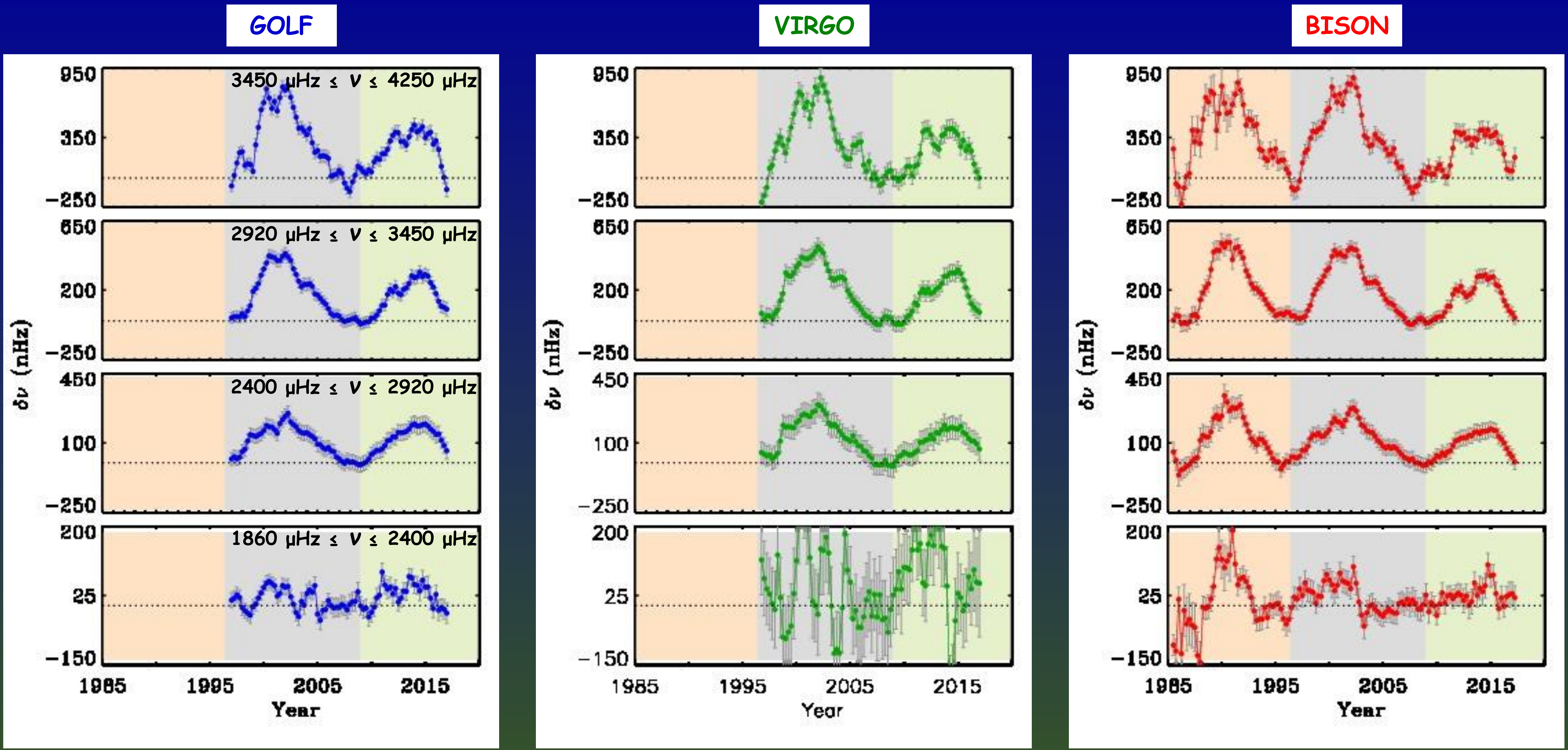




Low-frequency range:	1860 μHz < ν ≤ 2400 μHz
Mid-frequency range:	2400 μHz < ν ≤ 2920 μHz
High-frequency range 1:	2920 μHz < ν ≤ 3450 μHz
High-frequency range 2:	3450 μHz < ν ≤ 4250 μHz

Adapted from Basu et al. 2012, ApJ

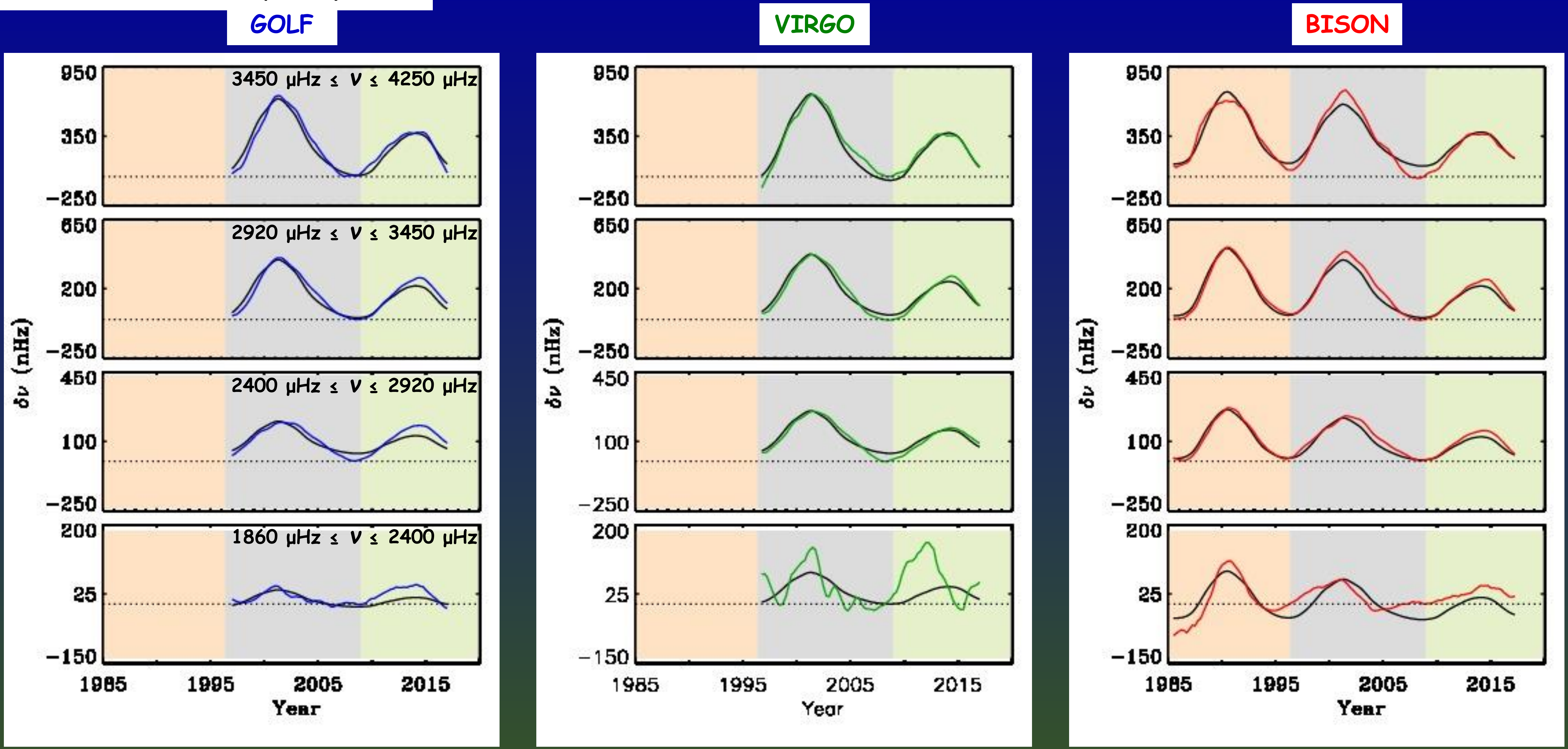
Temporal Variations - Based on Upper Turning Points: Contemporaneous Data



Jain et al. (2018), Proc. IAU Symposium 340

Temporal Variations - Based on Upper Turning Points: Contemporaneous Data

Black: F10 ; Color: Frequency shifts



Jain et al. (2018), Proc. IAU Symposium 340

Contemporaneous Data Sets: Quantitative Analysis

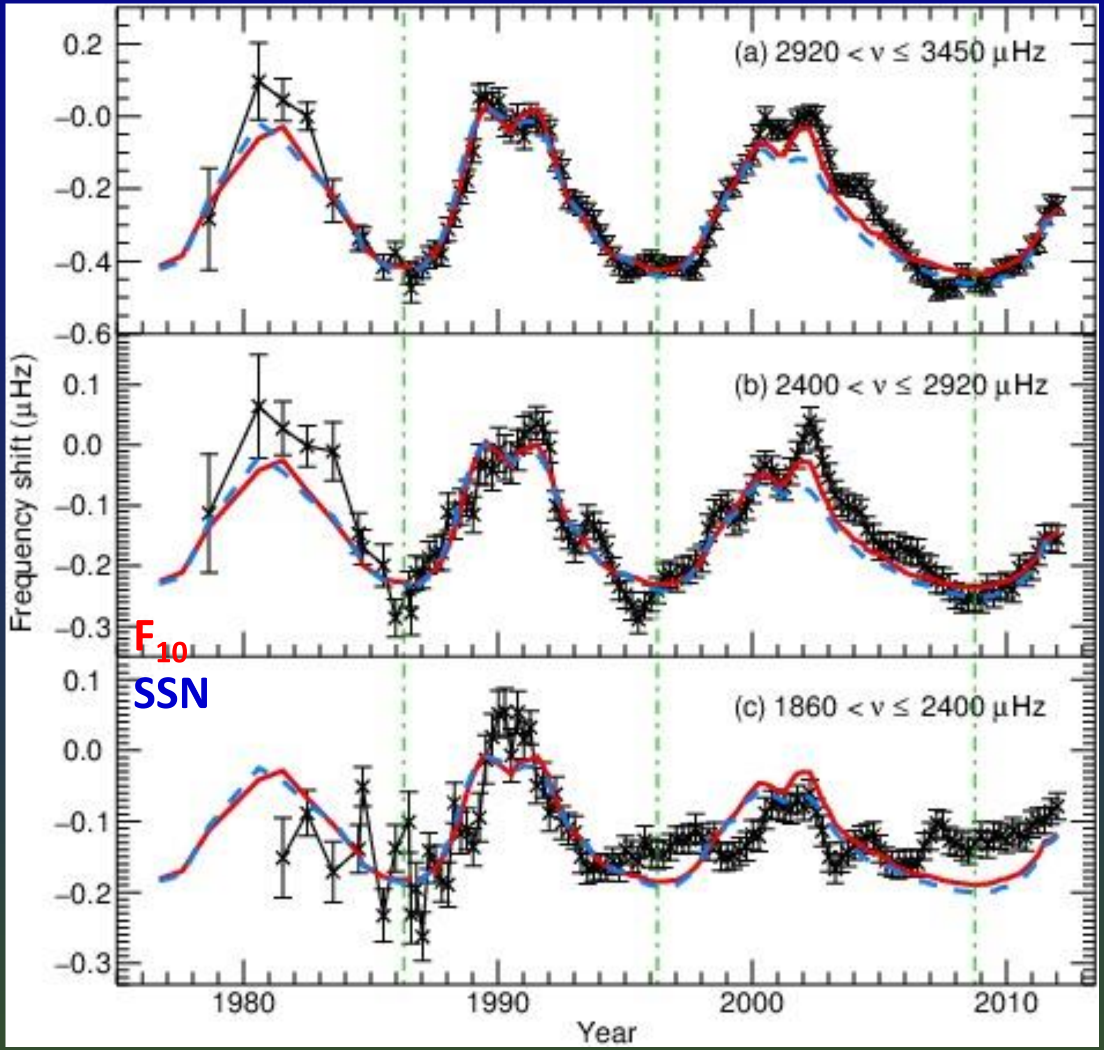
Data Source →	BiSON					GOLF					VIRGO				
Solar Cycle →	22-24	23-24	22	23	24	22-24	23-24	22	23	24	22-24	23-24	22	23	24
Low-ν range	0.66	0.56	0.79	0.58	0.63	-	0.54	-	0.59	0.65	-	0.39	-	0.41	0.19
Mid-ν range	0.94	0.95	0.95	0.96	0.96	-	0.95	-	0.94	0.95	-	0.95	-	0.95	0.94
High-ν range	0.97	0.97	0.97	0.97	0.97	-	0.96	-	0.96	0.97	-	0.96	-	0.96	0.97
High-ν range 2	0.92	0.96	0.87	0.96	0.95	-	0.95	-	0.95	0.92	-	0.94	-	0.94	0.94

Pearson's linear correlation coefficients

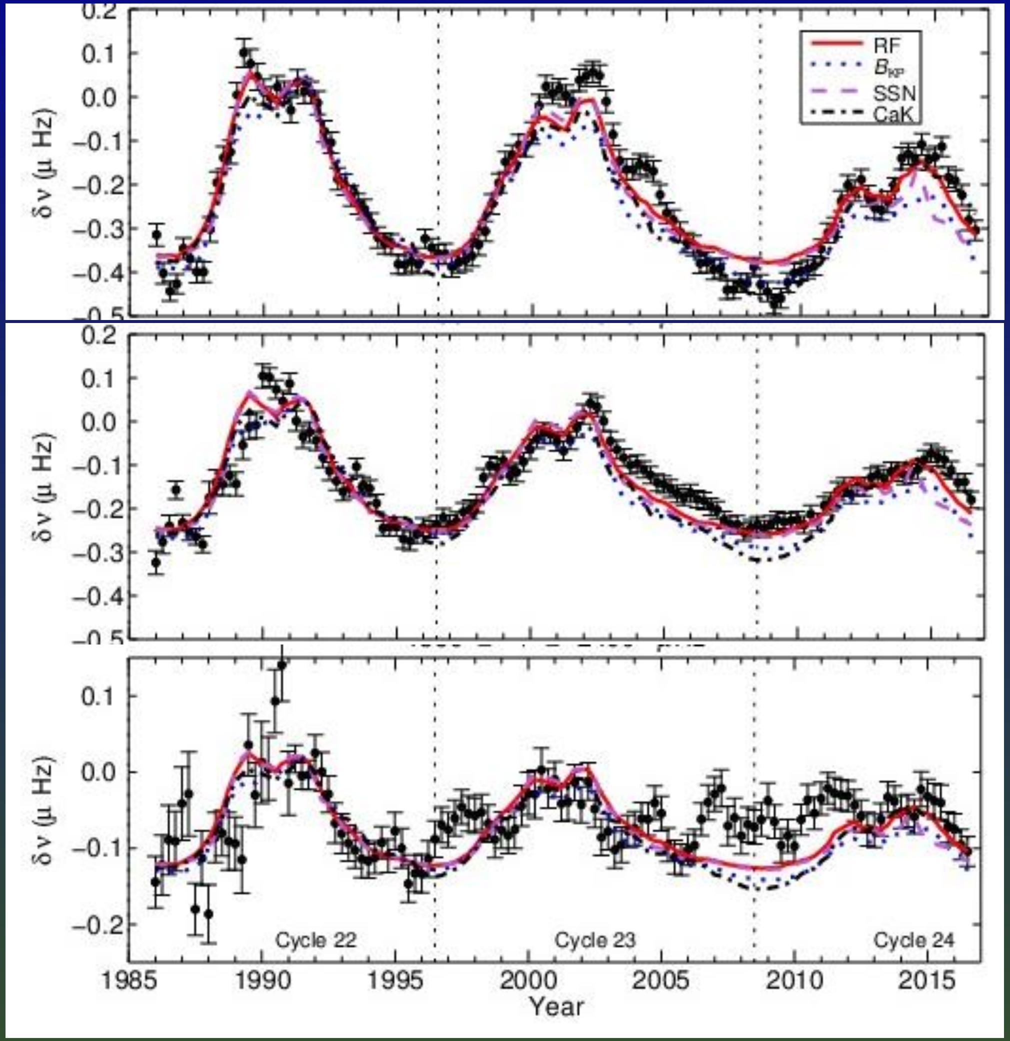
Jain et al. (2018), Proc. IAU Symposium 340

Temporal Variations - Based on Upper Turning Points

Previous Studies from BiSON

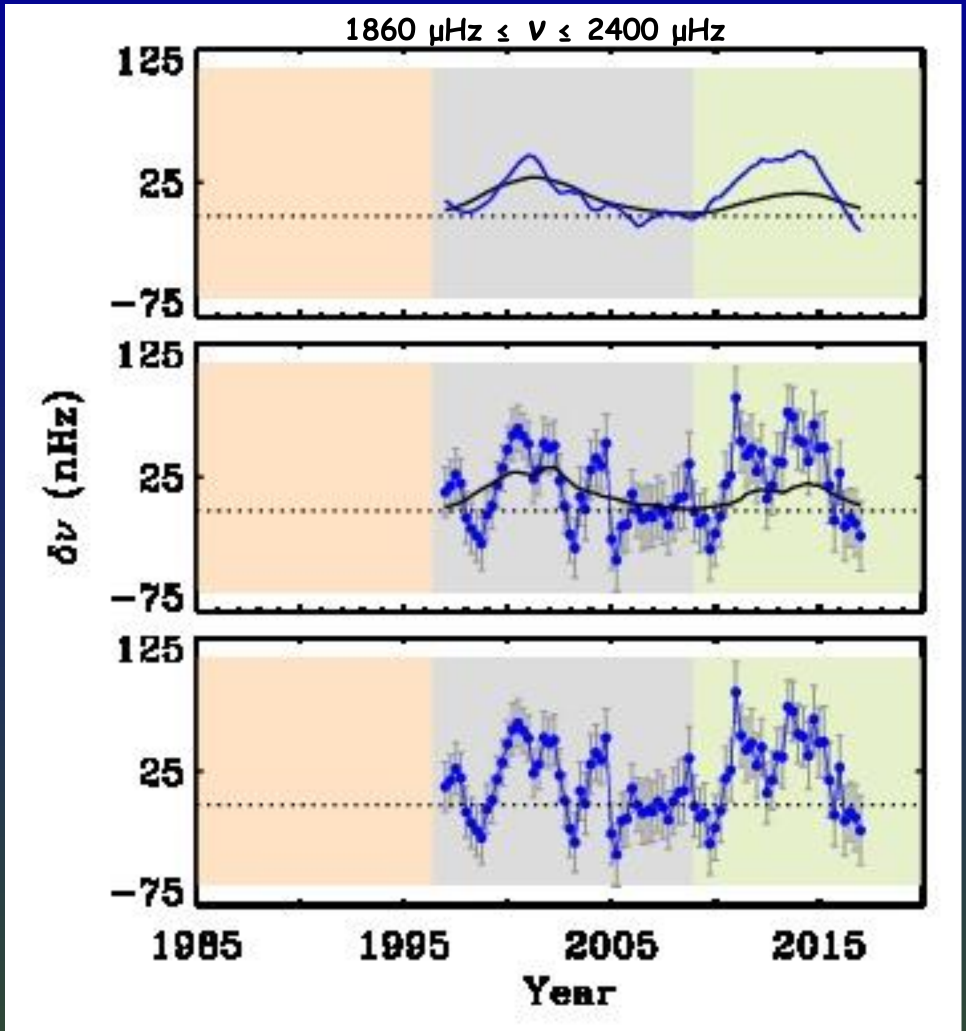


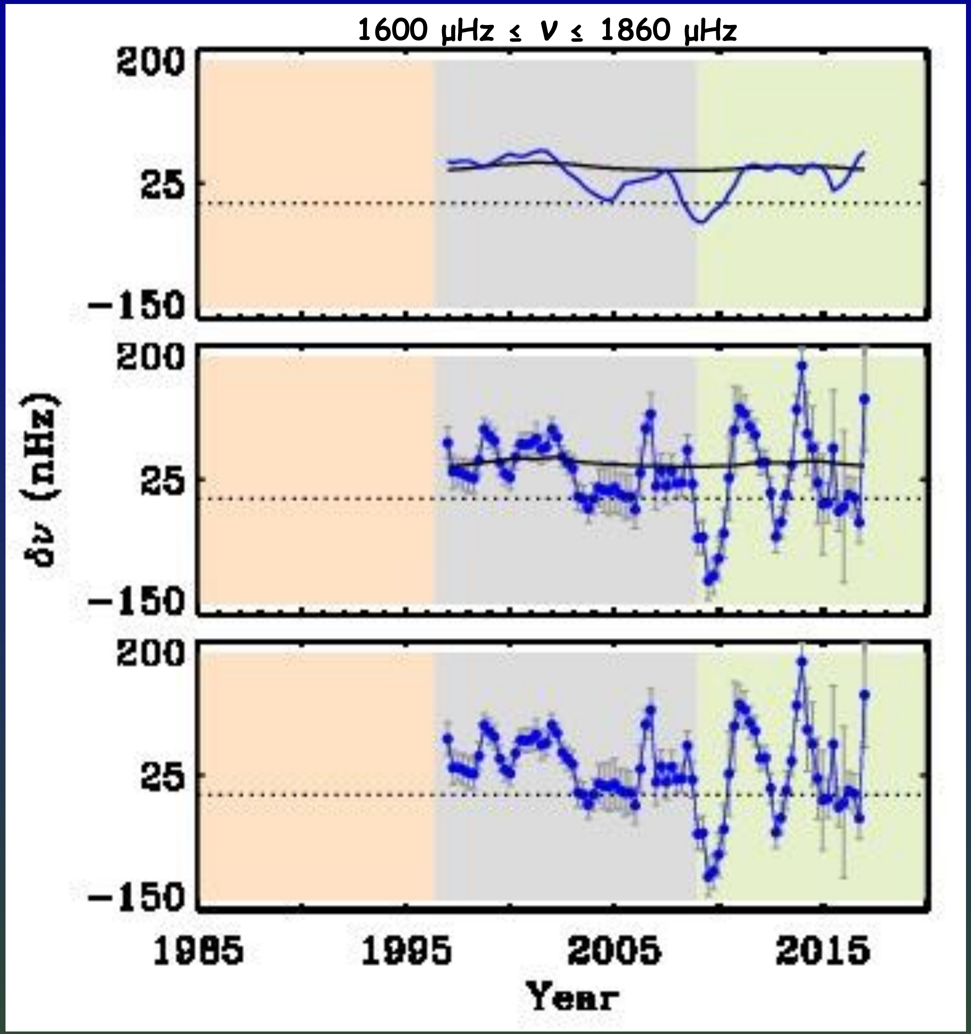
Basu et al. 2012, ApJ



Howe et al. 2017, MNRAS

Very low-frequencies from GOLF





Pearson's linear correlation coefficients: 0.54 0.36

Very low-frequencies from GOLF

Thus, the studies, based on un-interrupted Sun-as-a-star (unresolved) observations from about 3 solar cycles, suggest that

- the solar cycle-related changes in oscillation frequencies are different from cycle to cycle.
- the magnetic layer has become thinner after cycle 22 and this change is confined to shallower layers of the Sun.

If this is true, we should see similar variations in intermediate degree modes that do not travel to the solar core.

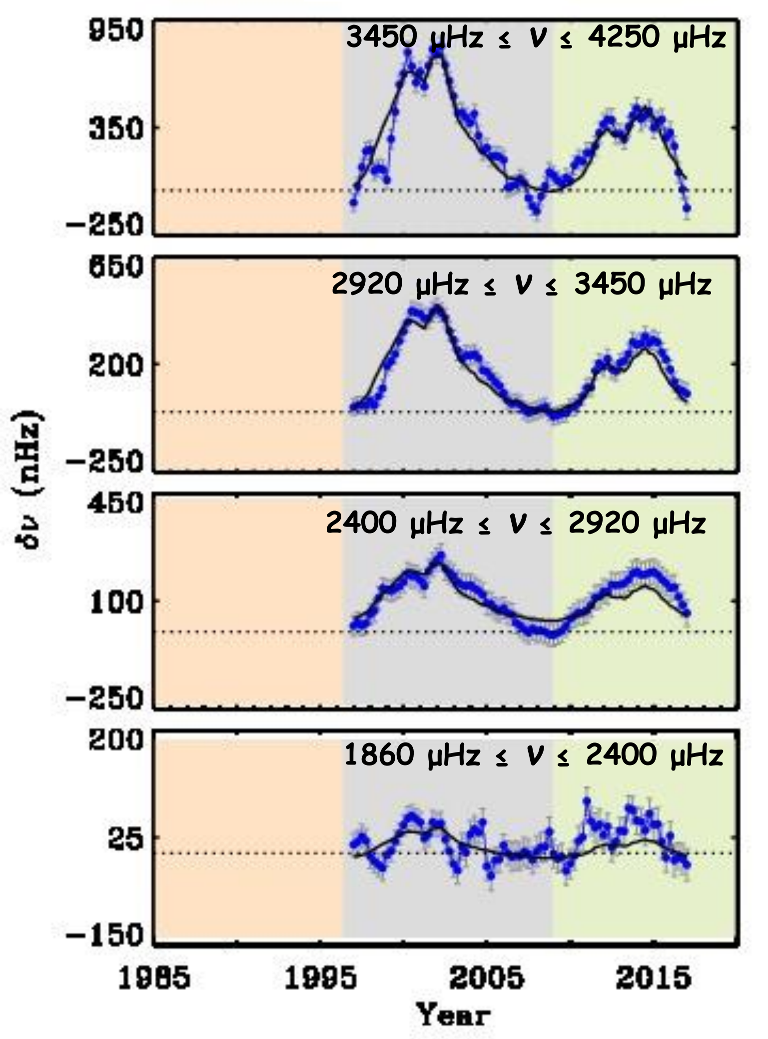
Comparison with the modes confined to convection zone

Black: F10 ; Color: Frequency shifts

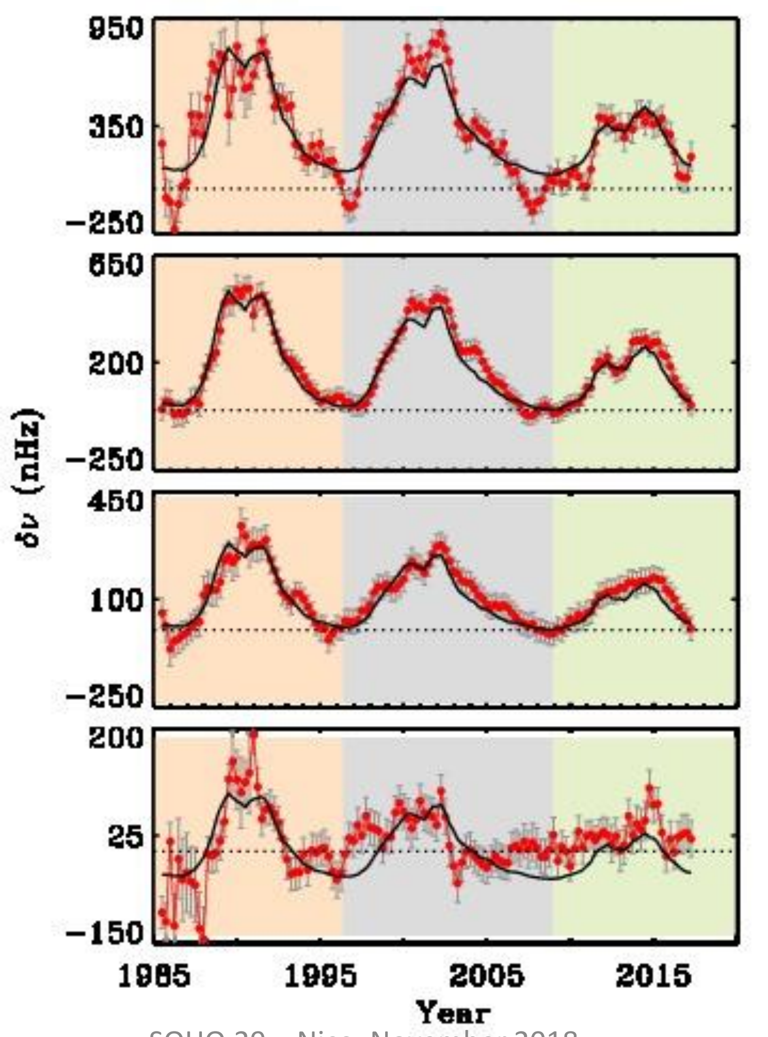
Unresolved observations Low-degree Modes (0 ≤ ℓ ≤ 2)

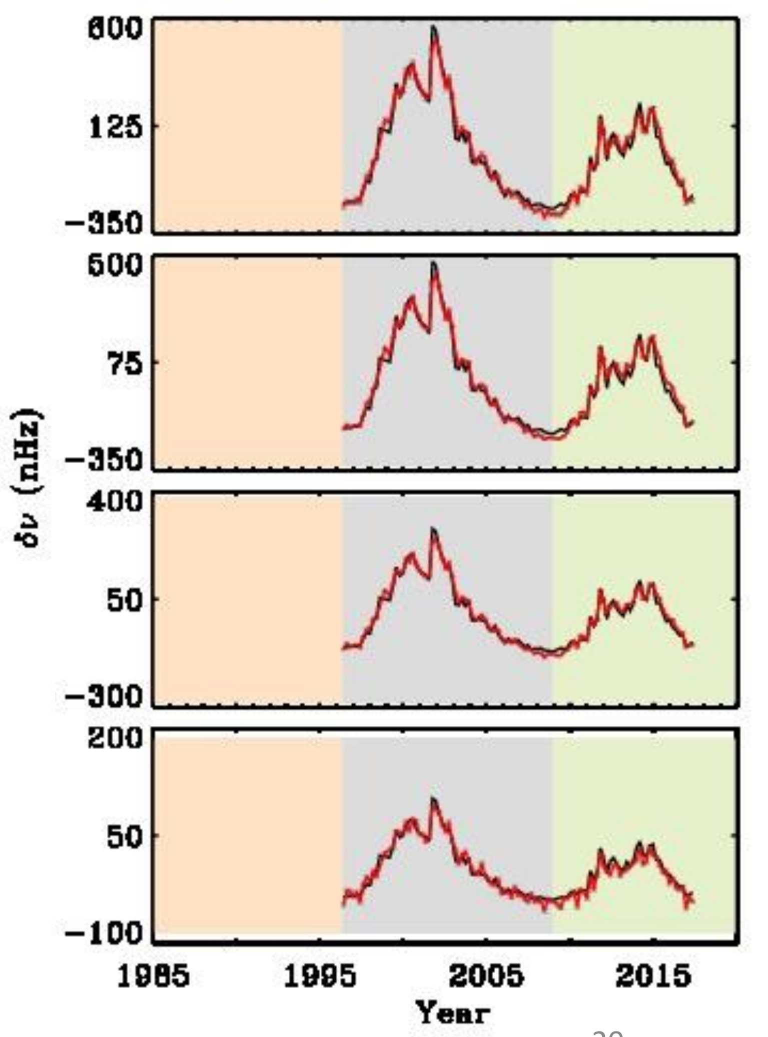
Resolved observations from GONG Intermediate-degree Modes

GOLF



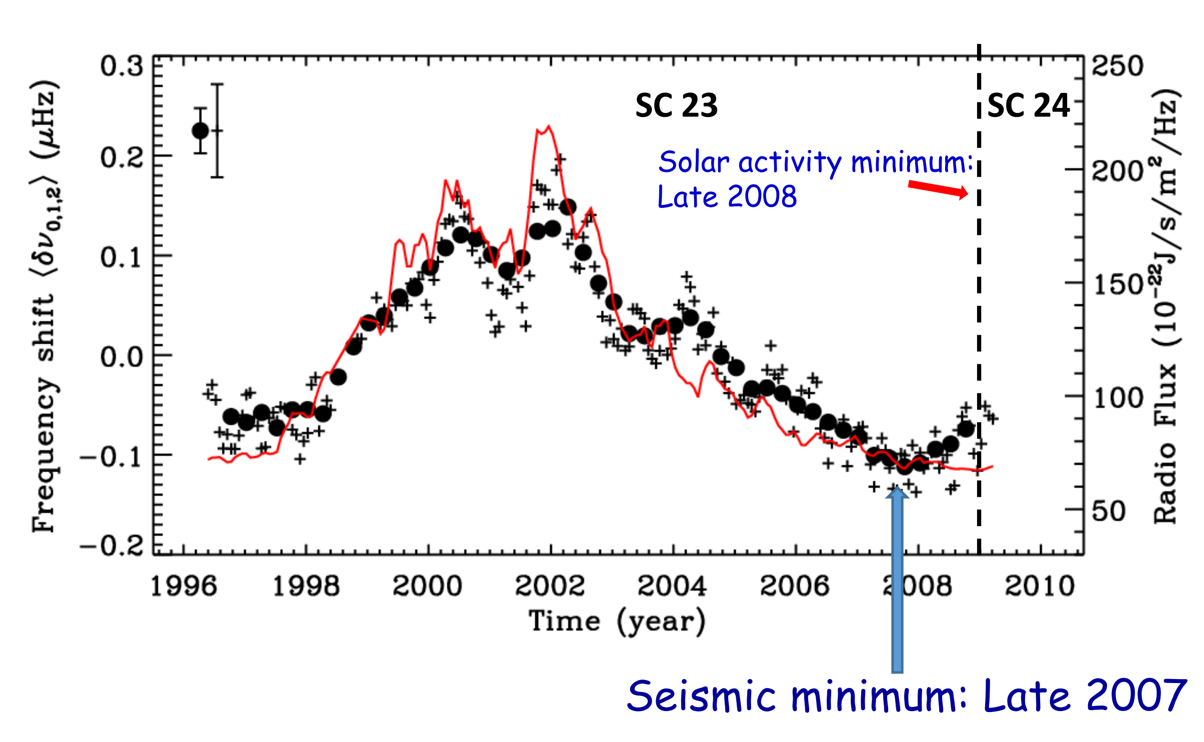
BiSON





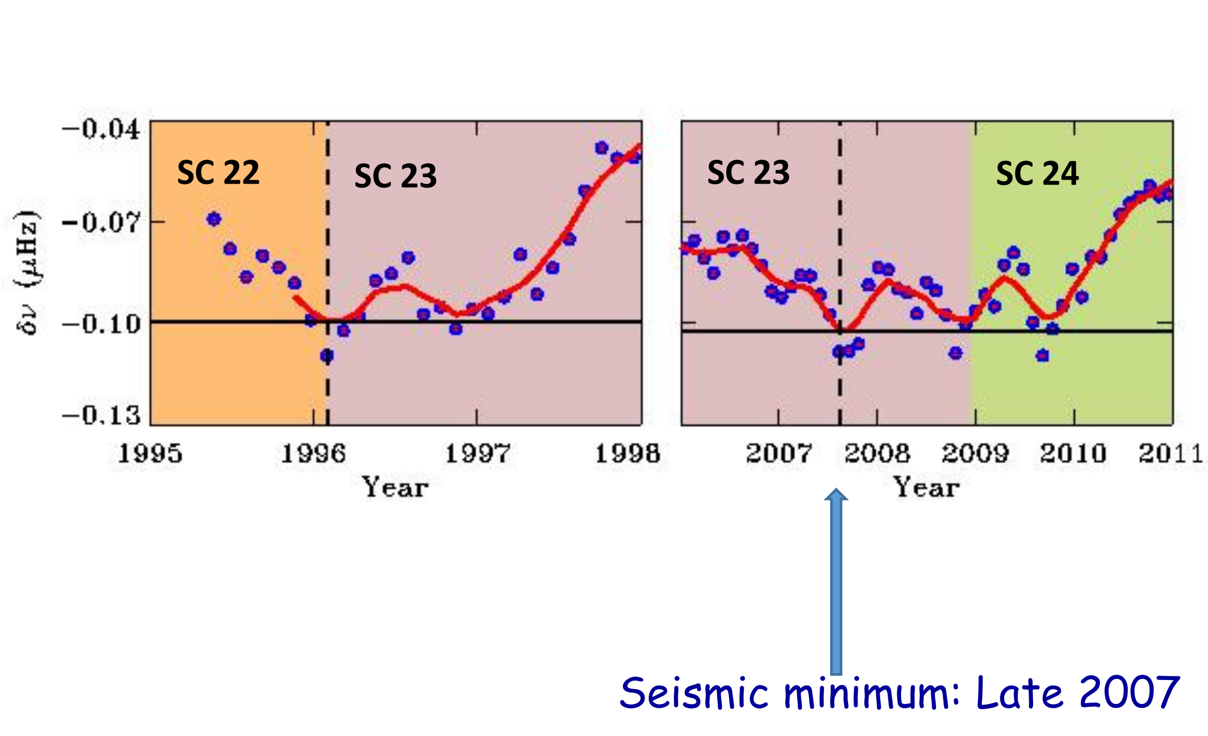
Seismic minimum between Cycles 23-24

Unresolved observations from GOLF
Low-degree Modes (0 ≤ ℓ ≤ 2)



Salabert et al. (2009) A&A Letters

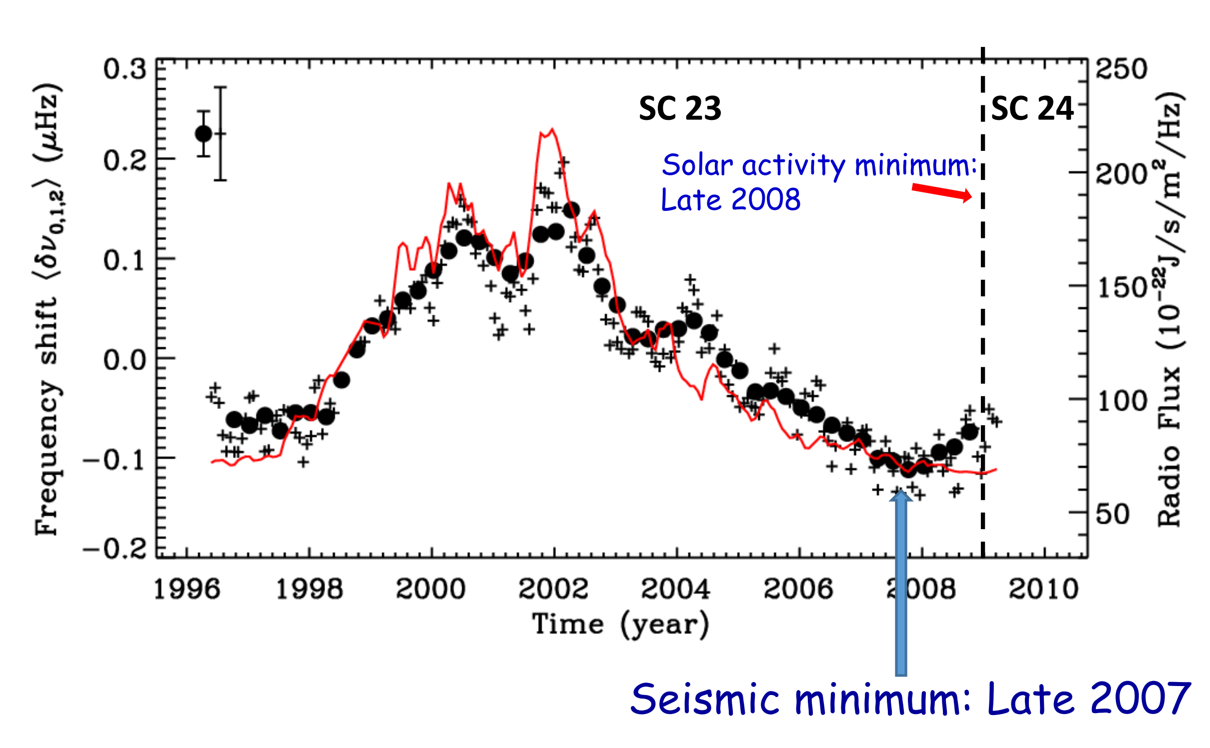
Resolved observations from GONG
Low/Intermediate-degree Modes with
r_t / R ≤ 0.3



Adapted from Jain et al. (2011) ApJ

Seismic minimum between Cycles 23-24

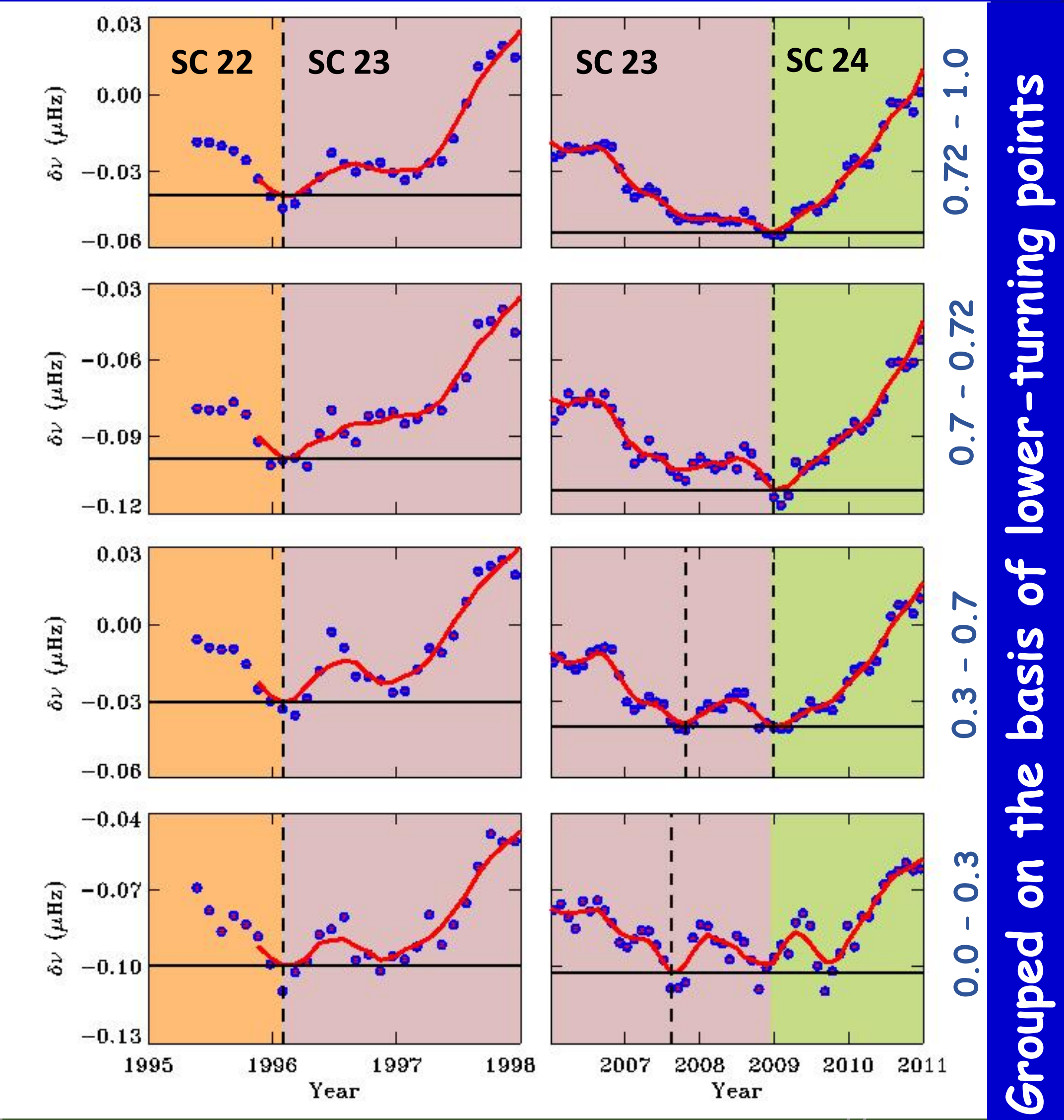
Unresolved observations from GOLF
Low-degree Modes (0 ≤ ℓ ≤ 2)



Salabert et al. (2009) A&A Letters

These results clearly show that the modes travelling to the solar core have different sensitivity to the magnetic field observed above the surface.

Resolved observations from GONG
Low/Intermediate-degree Modes (0 ≤ ℓ ≤ 120)



Adapted from Jain et al. (2011) ApJ

Summary

- ✓ Long-term simultaneous Sun-as-a-star observations from GOLF and VIRGO onboard SoHO, along with ground-based BiSON and resolved-disk observations from GONG clearly show that there are similarities as well as differences between unresolved- and resolved-disk observations.
- ✓ The oscillation frequencies from all observations do vary in phase with the solar activity cycle, however the minimum sensed by the modes confined to the convection zone happened around the same time as in the solar activity indicators while the modes travelled to the core sensed minimum about a year earlier.
- ✓ Based on Sun-as-a-star observations, it has been suggested that the magnetic layer of the Sun is changing gradually and has become thinner in last 2 solar cycles. Similar analysis with modes in intermediate-degree range do not support this findings.

Thus, the helioseismic observations covering all regions below the surface for several solar cycles are necessary to understand the variability of different layers in the solar interior and its link to the surface magnetic activity.