



The Solar Interior

Helioseismology

Bill Chaplin, Birmingham

*STFC Introductory Course in Solar
and Solar-Terrestrial Physics,
University of St Andrews*

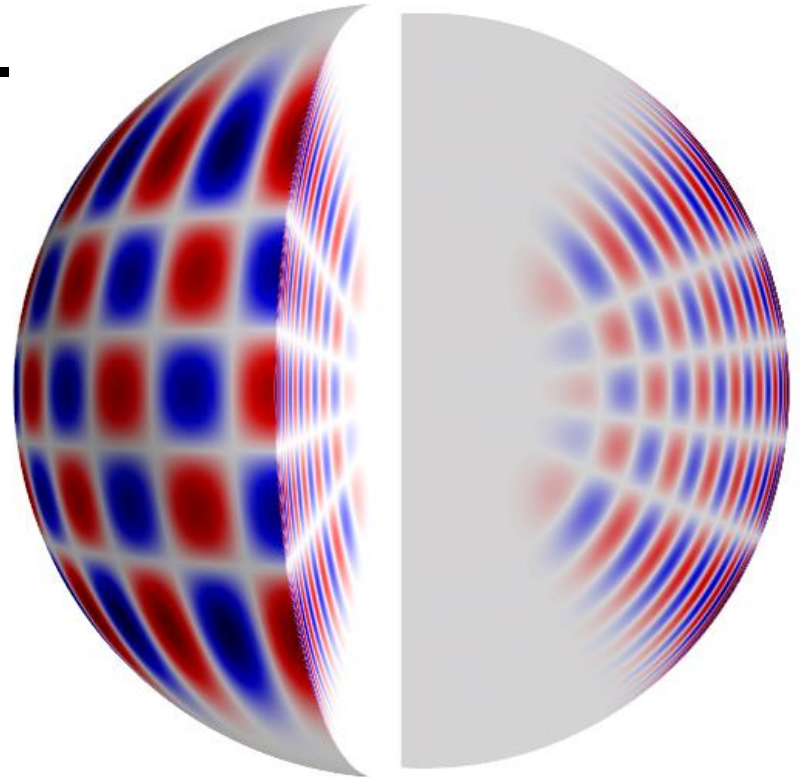
21 August 2023

helioseismology, *n.*

The study of the sun's interior by the observation and analysis of oscillations at its surface.

Cf. asteroseismology *n.*

[Oxford English Dictionary]



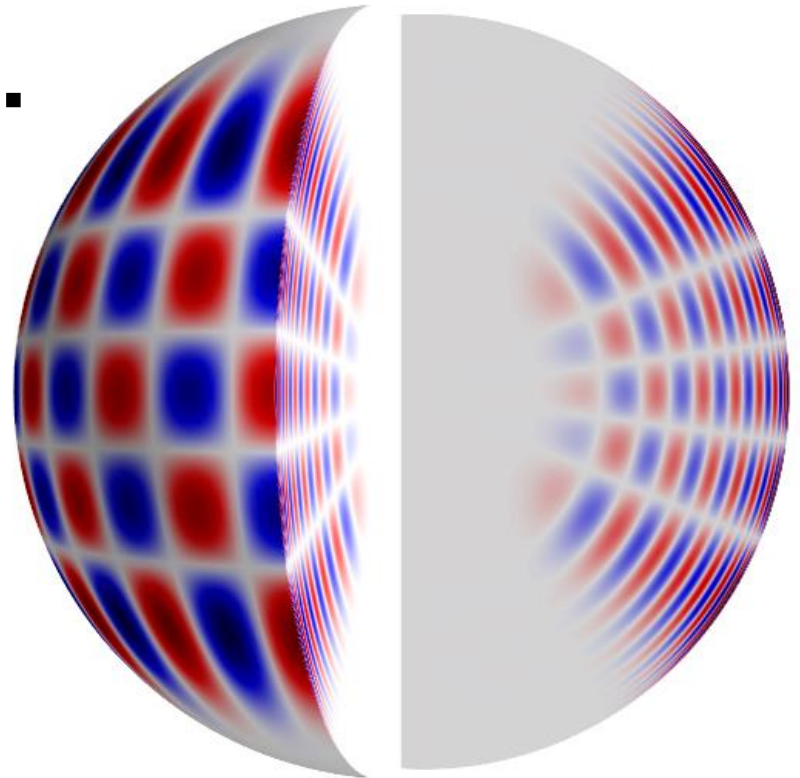
NSO Workshop #27

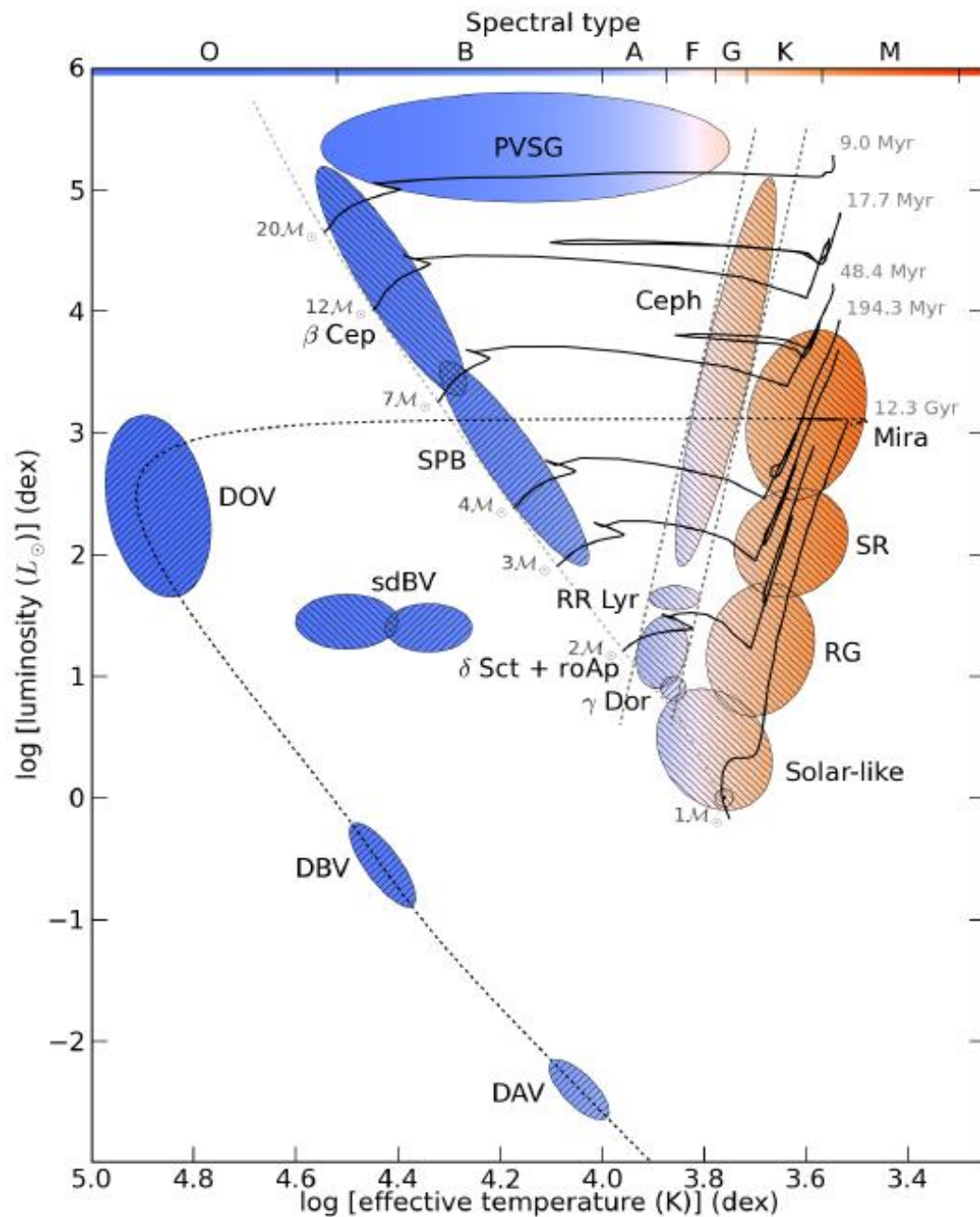
FIFTY YEARS OF SEISMOLOGY OF THE SUN & STARS

May 6-10, 2013 • Tucson, AZ, USA

helioseismology, *n.*

Now 60 years
and counting...





Oscillations across the HR Diagram

Aerts, ARAA, 2019

Asteroseismology, *n.*

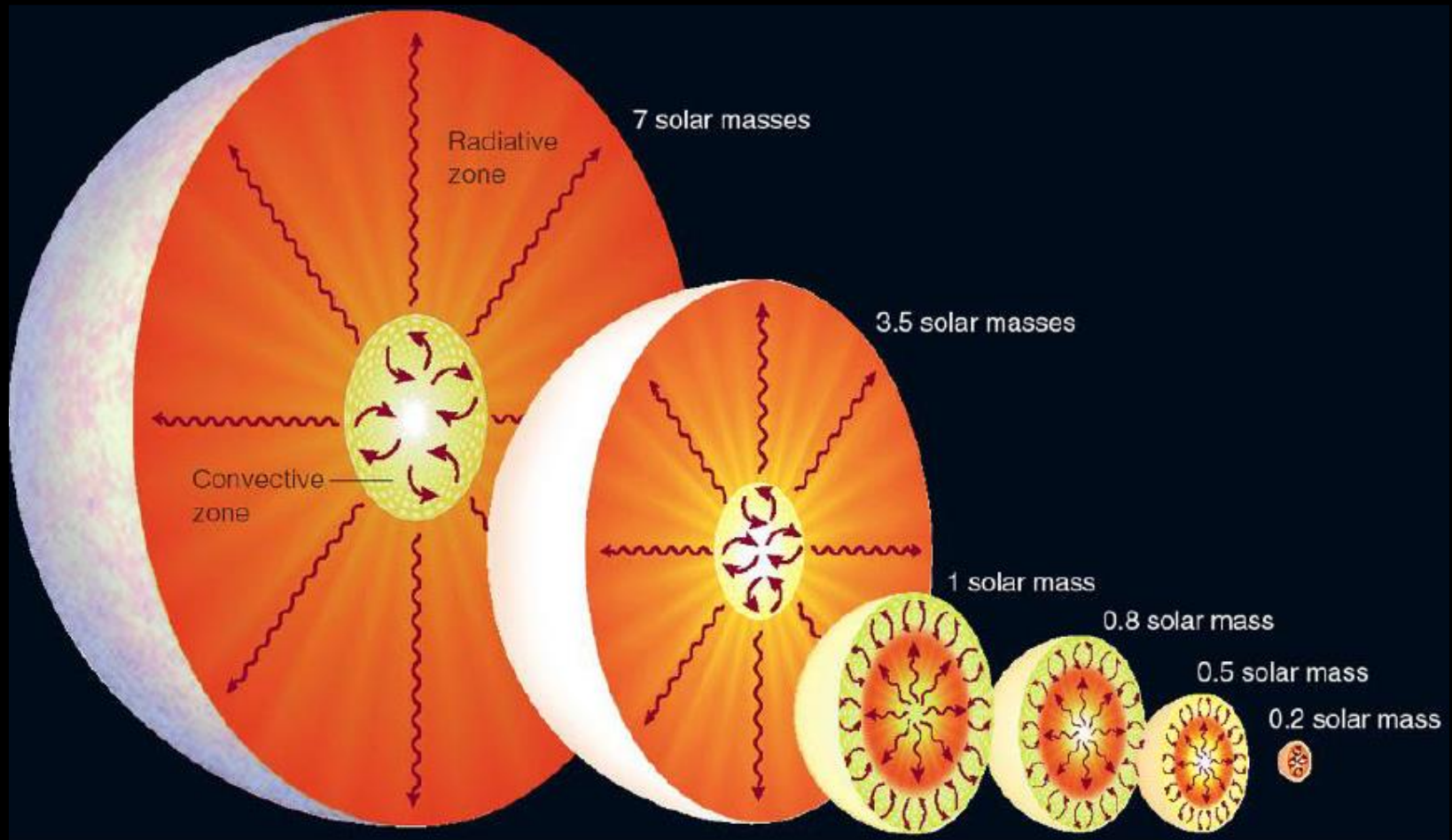
The study of the interior of stars by the observation and analysis of oscillations at their surface.

Cf. helioseismology *n.*

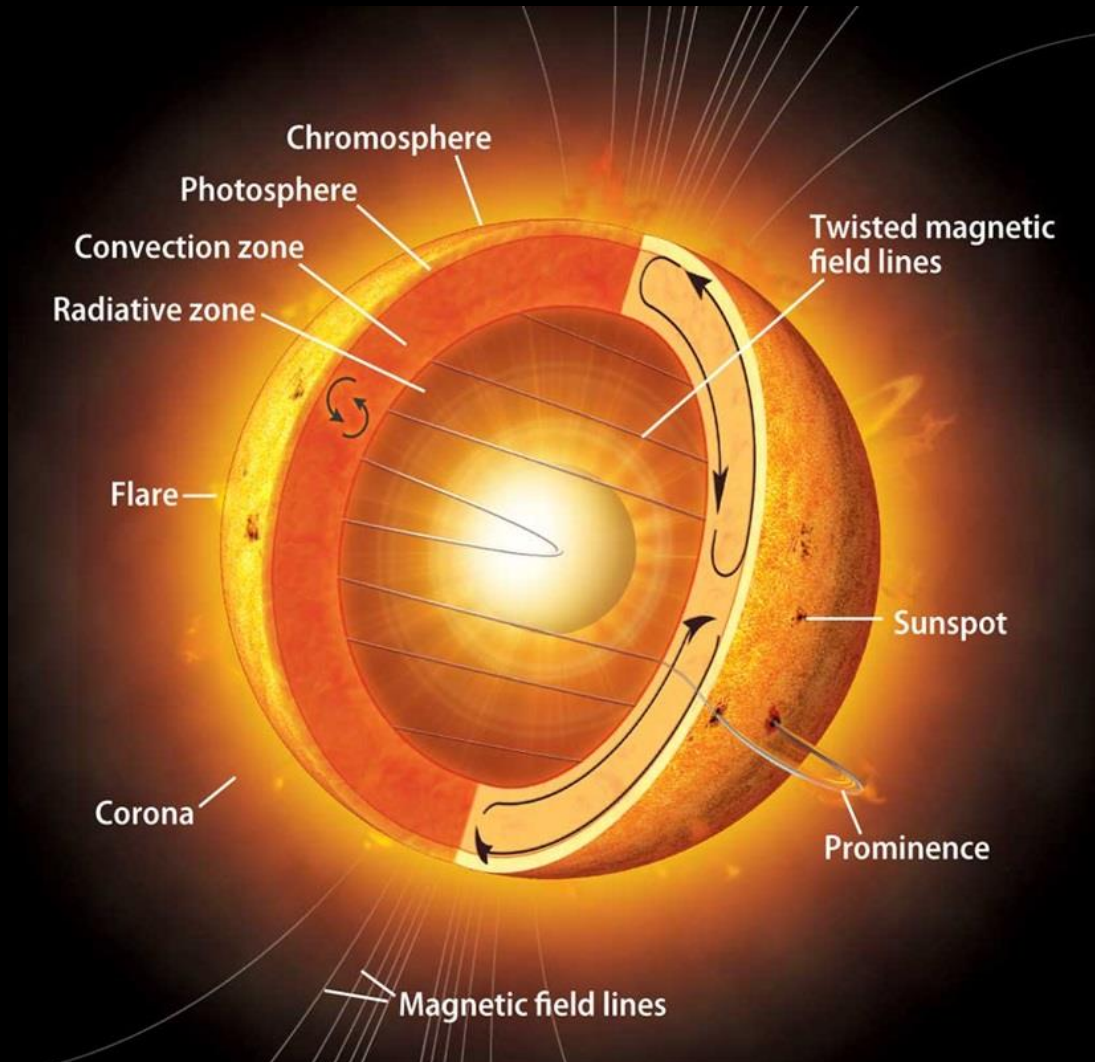
[Oxford English Dictionary]



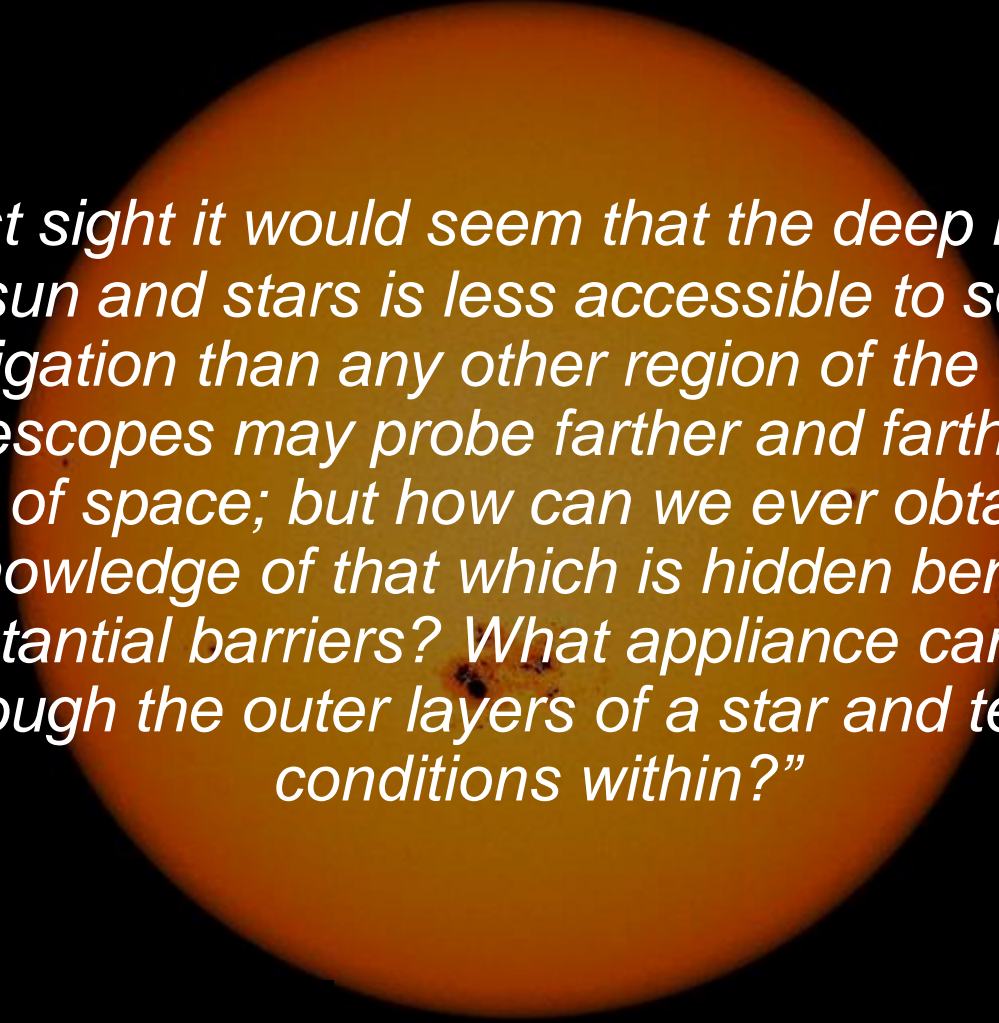
Interior Structures of Stars



Interior Structures of Stars



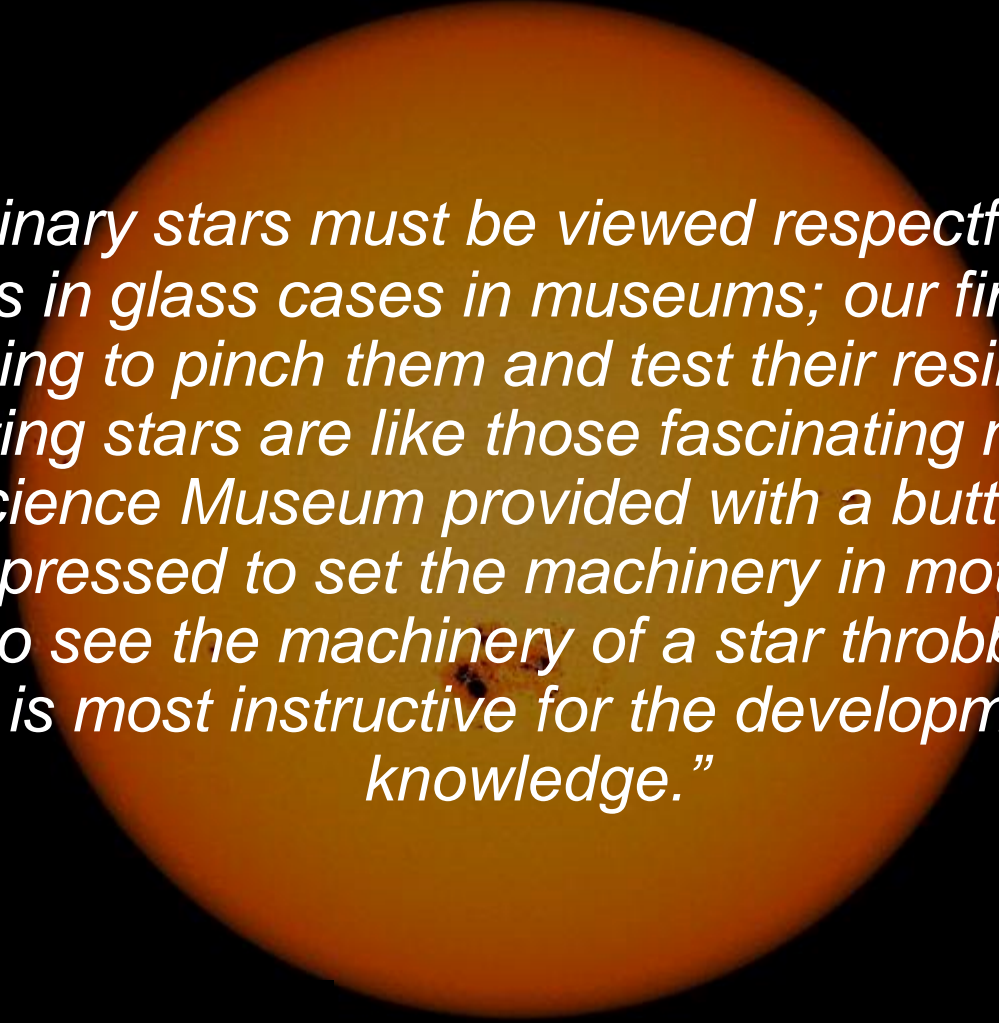
The Unseen Solar Interior



“At first sight it would seem that the deep interior of the sun and stars is less accessible to scientific investigation than any other region of the universe. Our telescopes may probe farther and farther into the depths of space; but how can we ever obtain certain knowledge of that which is hidden beneath substantial barriers? What appliance can pierce through the outer layers of a star and test the conditions within?”

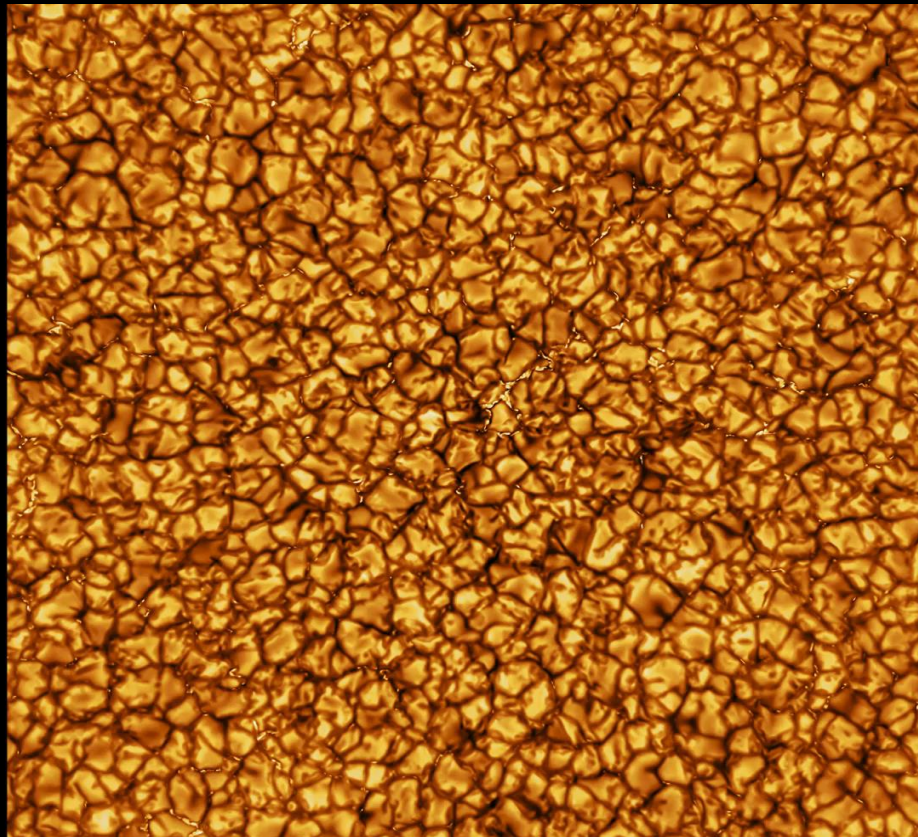
A. S. Eddington, ‘The Internal Constitution of the Stars’, 1926

Pulsations Open a Window



“Ordinary stars must be viewed respectfully like objects in glass cases in museums; our fingers are itching to pinch them and test their resilience. Pulsating stars are like those fascinating models in the Science Museum provided with a button which can be pressed to set the machinery in motion. To be able to see the machinery of a star throbbing with activity is most instructive for the development of our knowledge.”

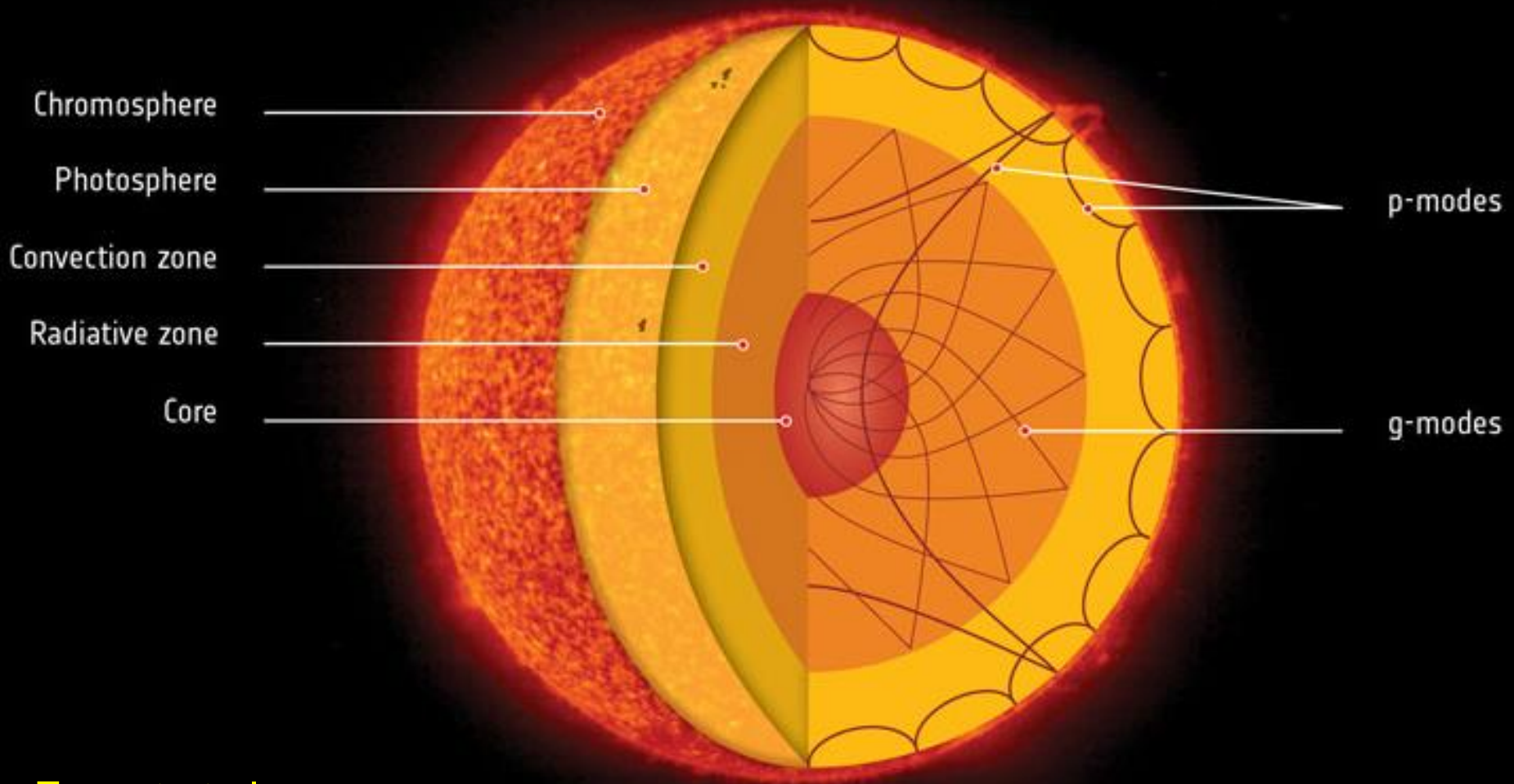
Near-surface turbulence generates acoustic noise...



10 Dec. 2019 19:24:31 UT

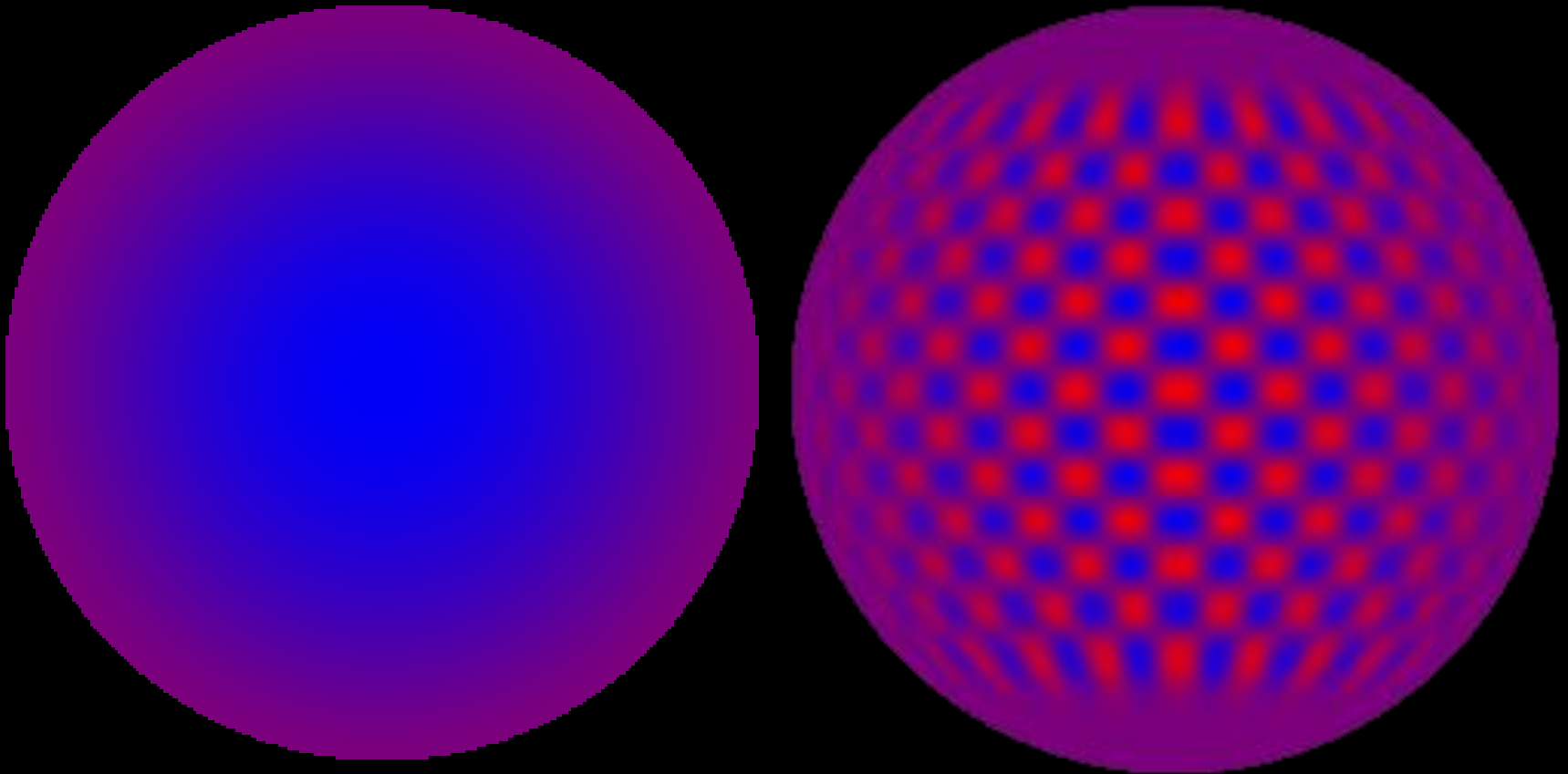
Solar Oscillations

Standing acoustic waves trapped in interior

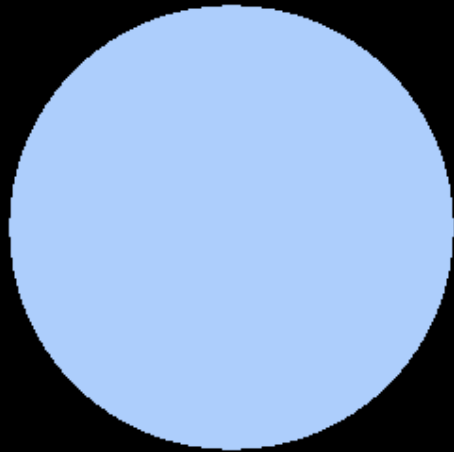


Solar Oscillations

Mode patterns correspond to spherical harmonics



Pulsation Timescale

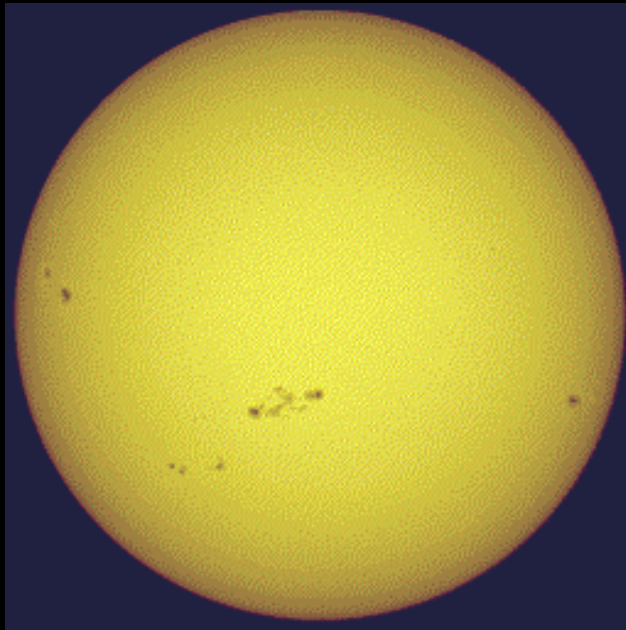


Fundamental period of radial pulsation:

$$\Pi \propto \langle \rho \rangle^{-1/2}$$

Ritter 1880; Shapley, 1914

Pulsation Timescale



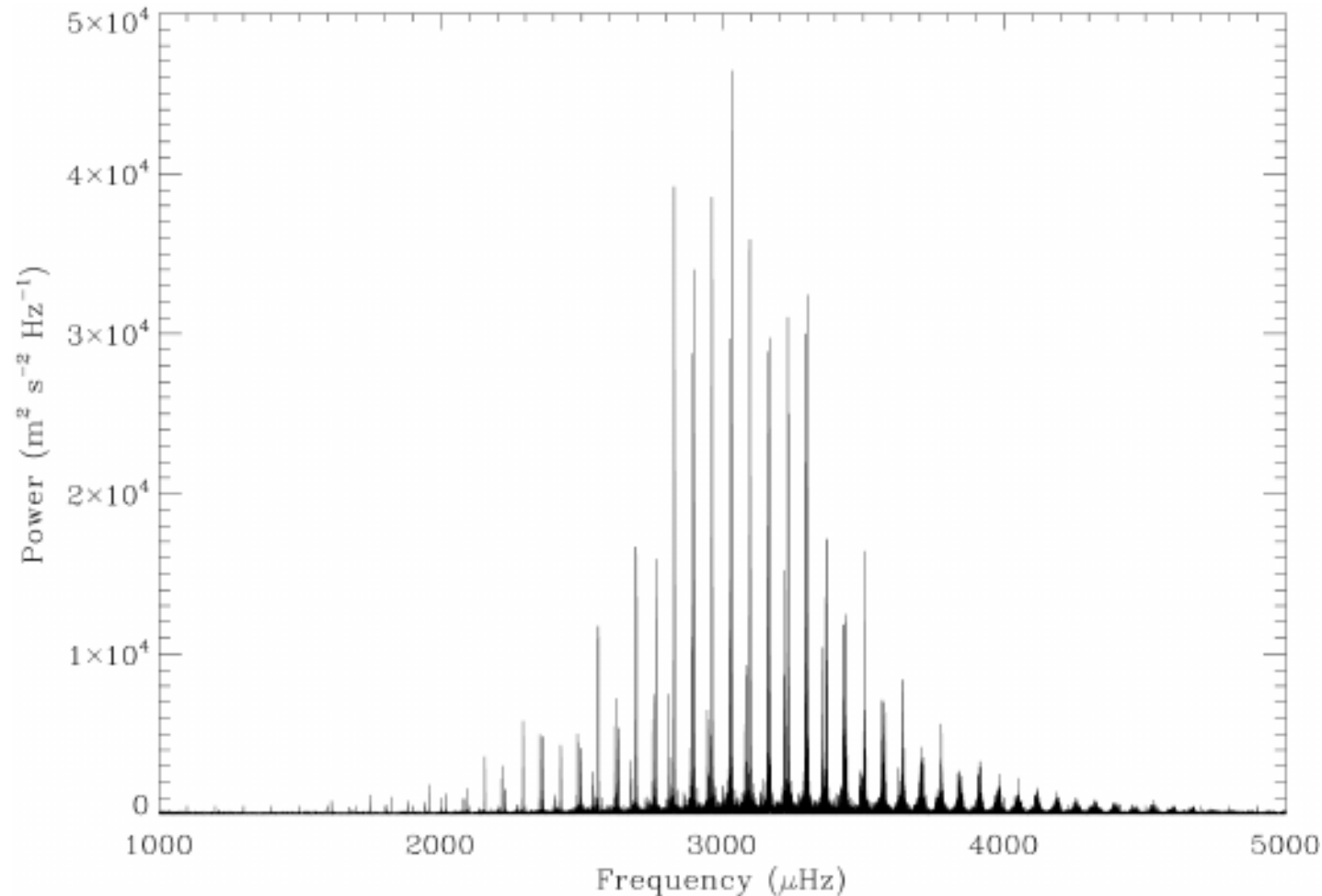
Sun: fundamental
radial-mode period

$$\Pi_f \approx 1.8 \text{ hours}$$

$$\nu_f \approx 160 \mu\text{Hz}$$

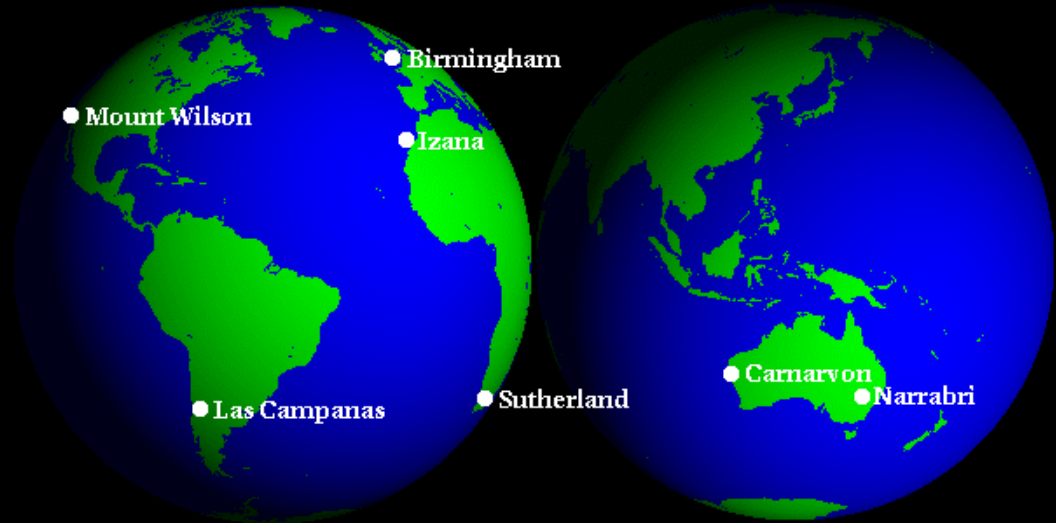
Oscillations of the Sun

Frequency spectrum of solar oscillations



BiSON

Birmingham Solar-Oscillations Network





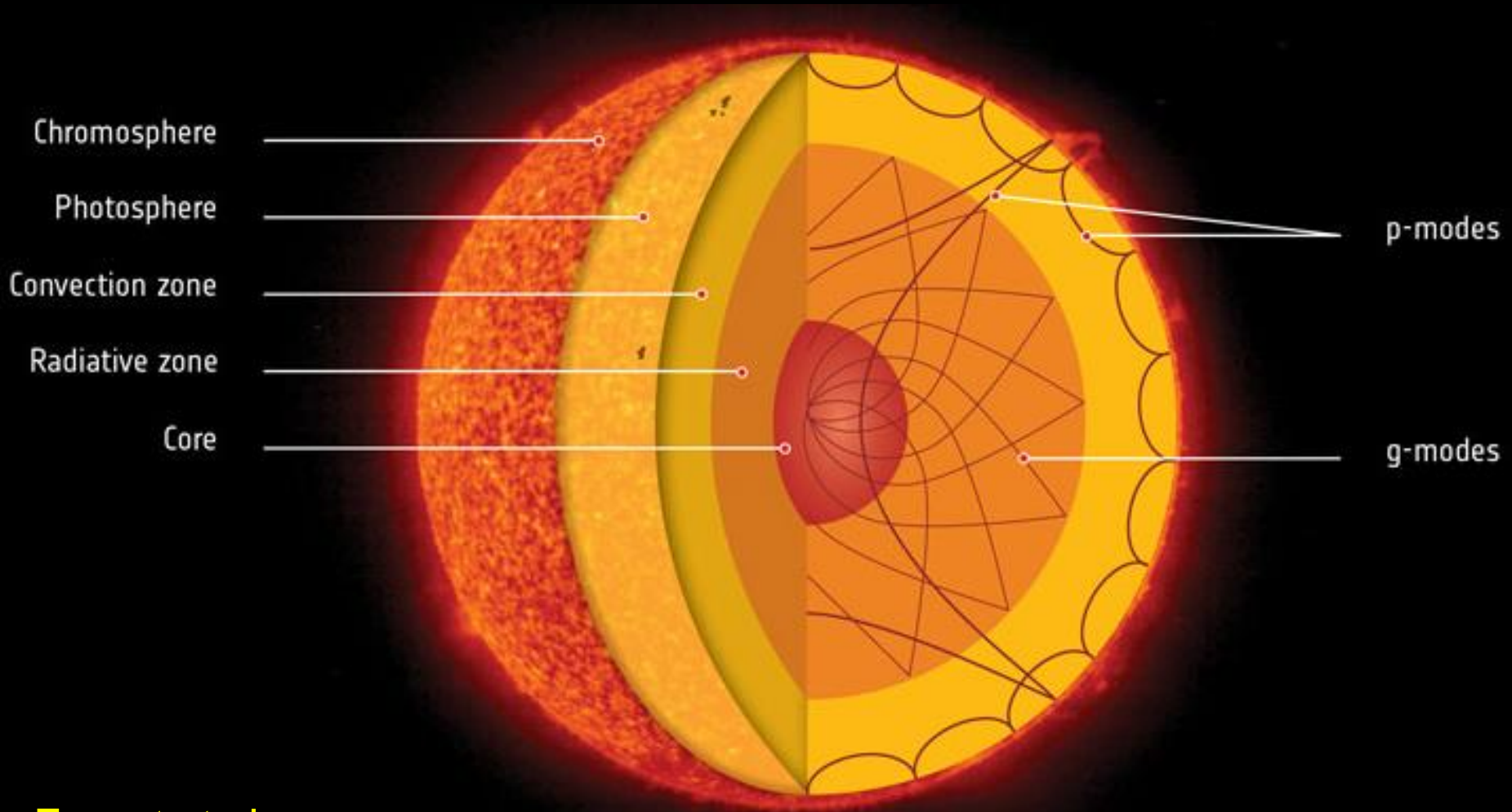
Global and Local Helioseismology

Global seismology:

- Constituent waves live long enough to travel round the Sun
- Modes give longitudinal average of properties (also cannot distinguish asymmetry in properties above and below equator)

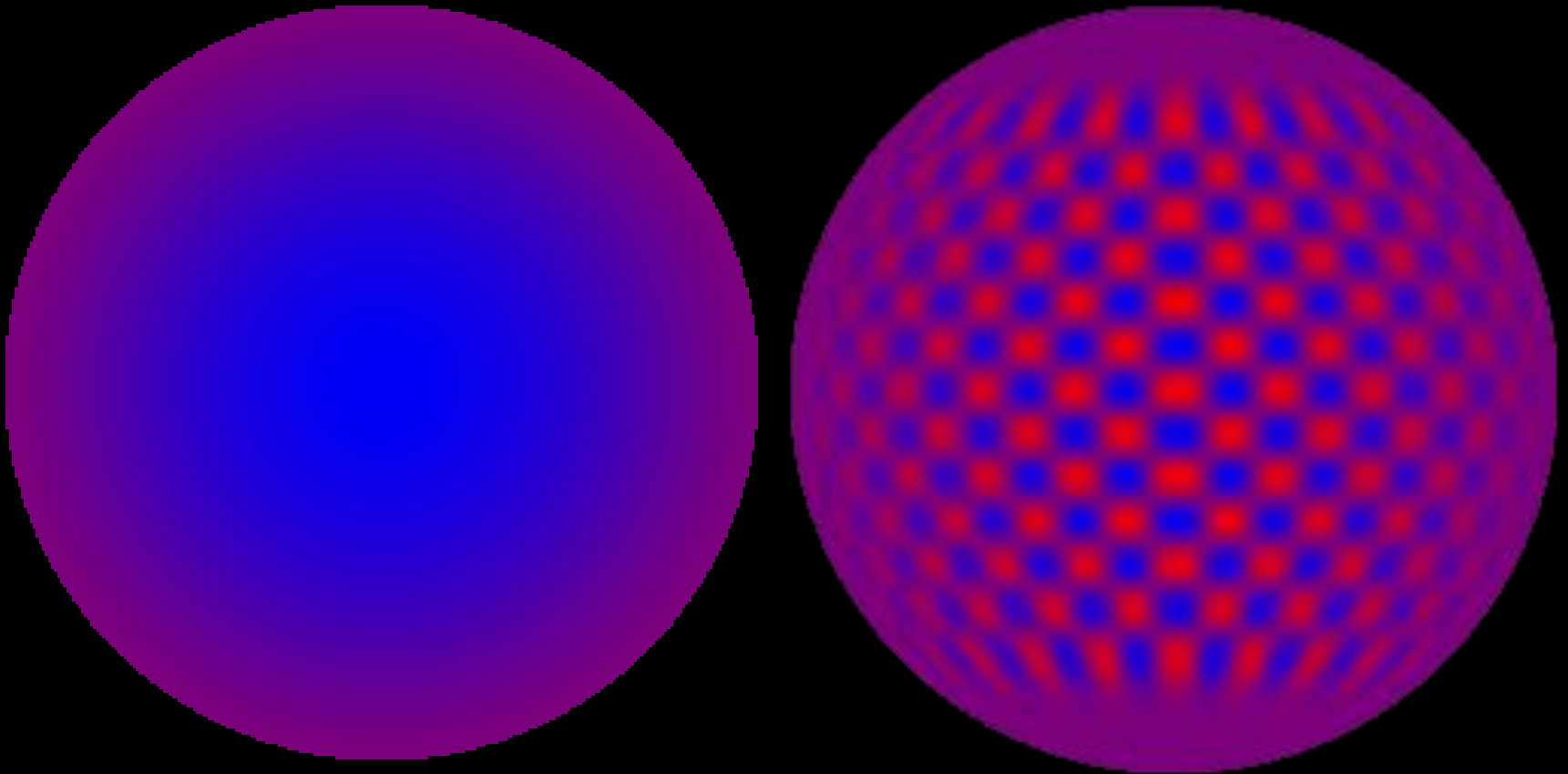
Solar Oscillations

Probe structure and rotation throughout interior



Solar Oscillations

Mode patterns correspond to spherical harmonics



Helioseismic Magnetic Imager (HMI) on SDO



Global Oscillations Network Group (GONG)



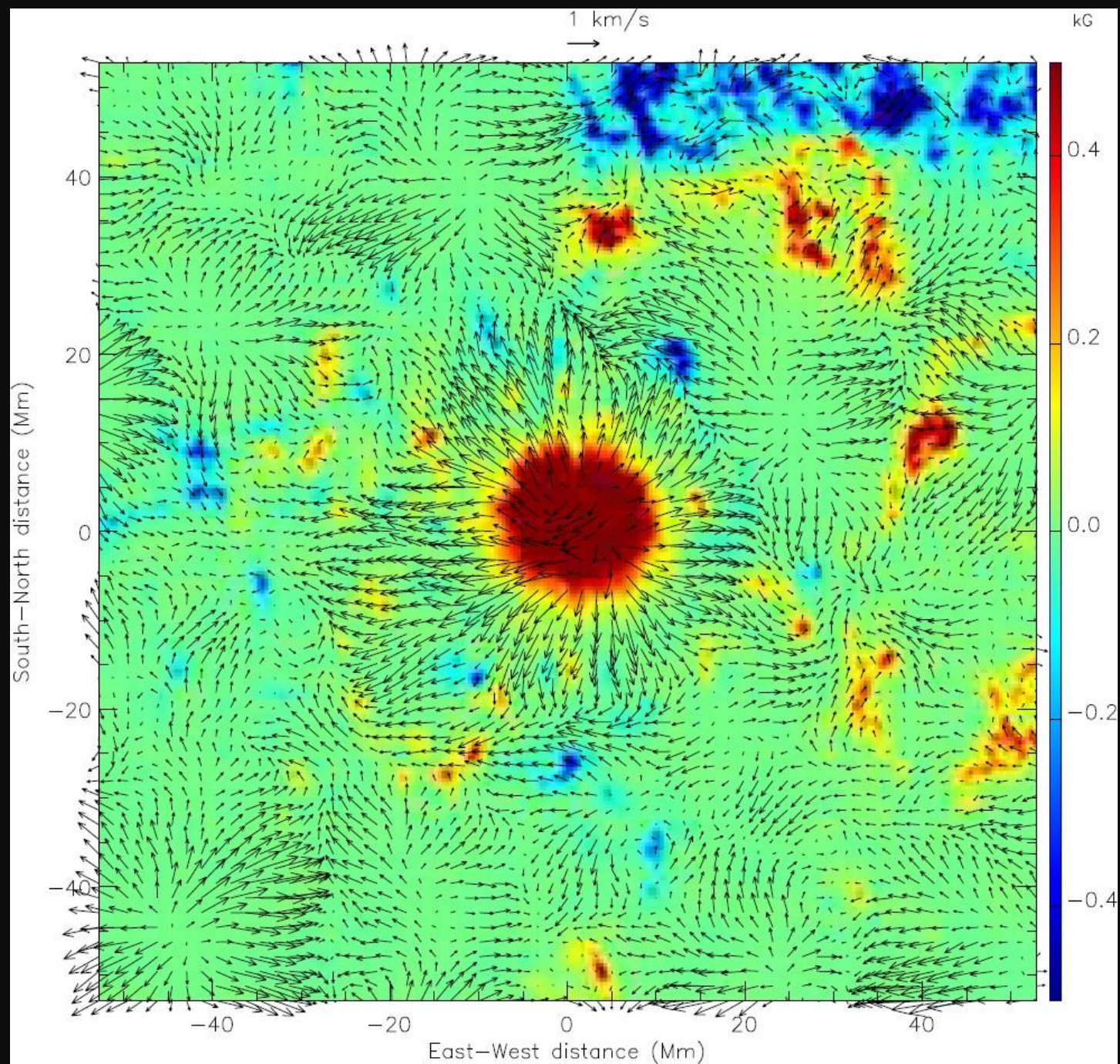
Polarimetric and Helioseismic Imager (PHI) on Solar Orbiter



Global and Local Helioseismology

Local seismology:

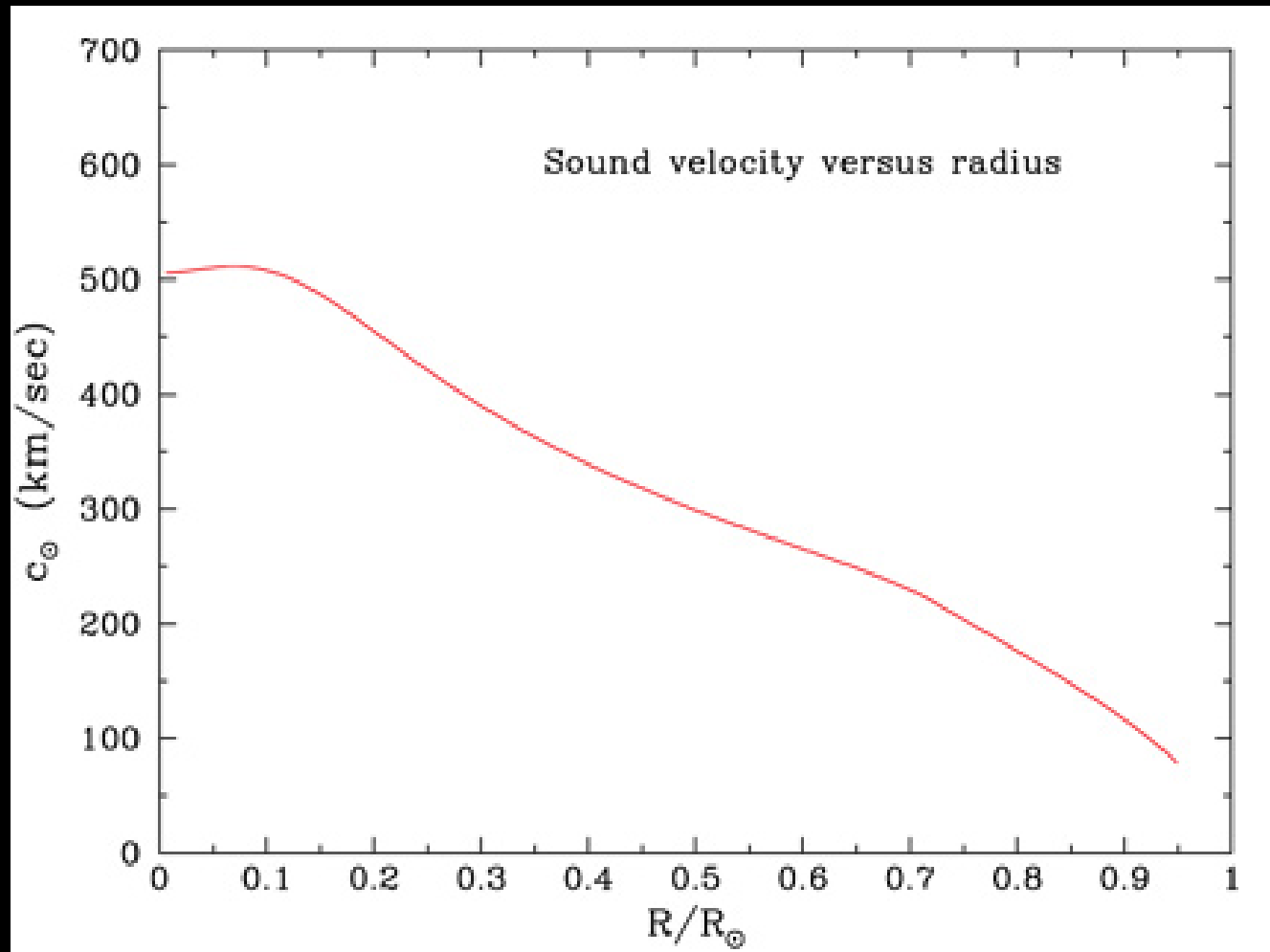
- Do not wait for resonance to establish globally
- Observe effects of interference in local volumes beneath surface



Internal Structure and Rotation

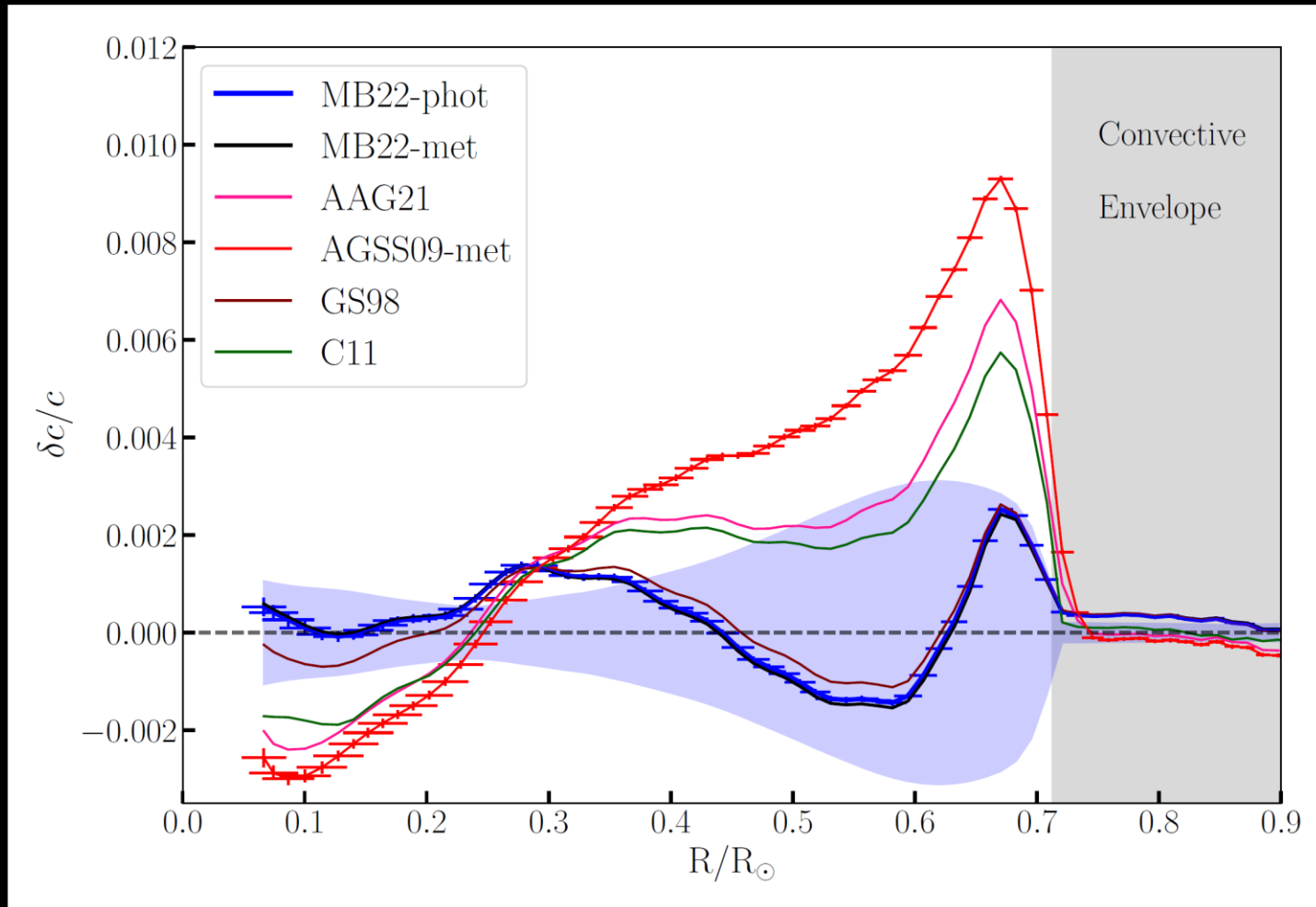
Solar Abundance Problem

Inversions for solar sound speed

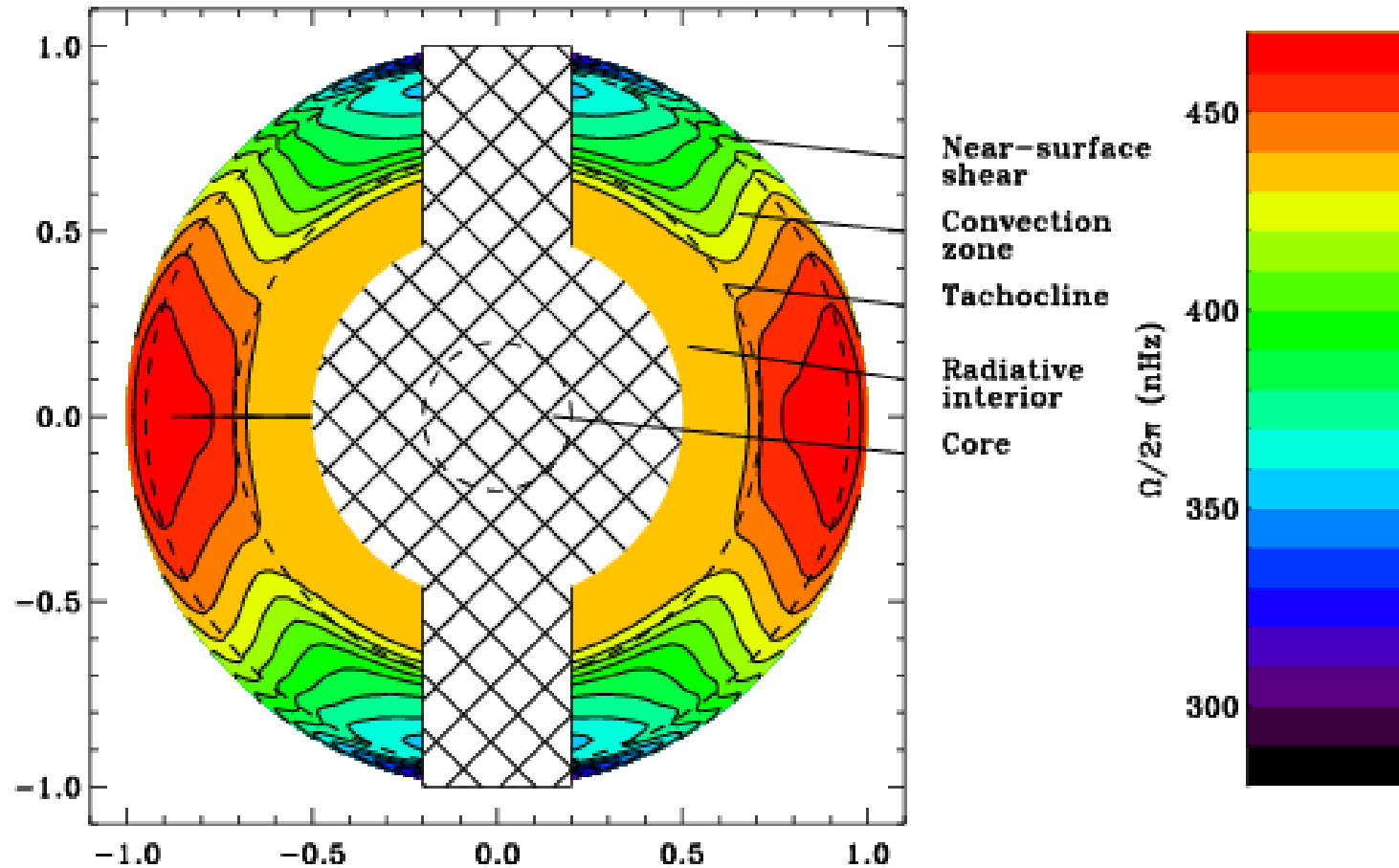


Solar Abundance Problem

Inversions for solar sound speed

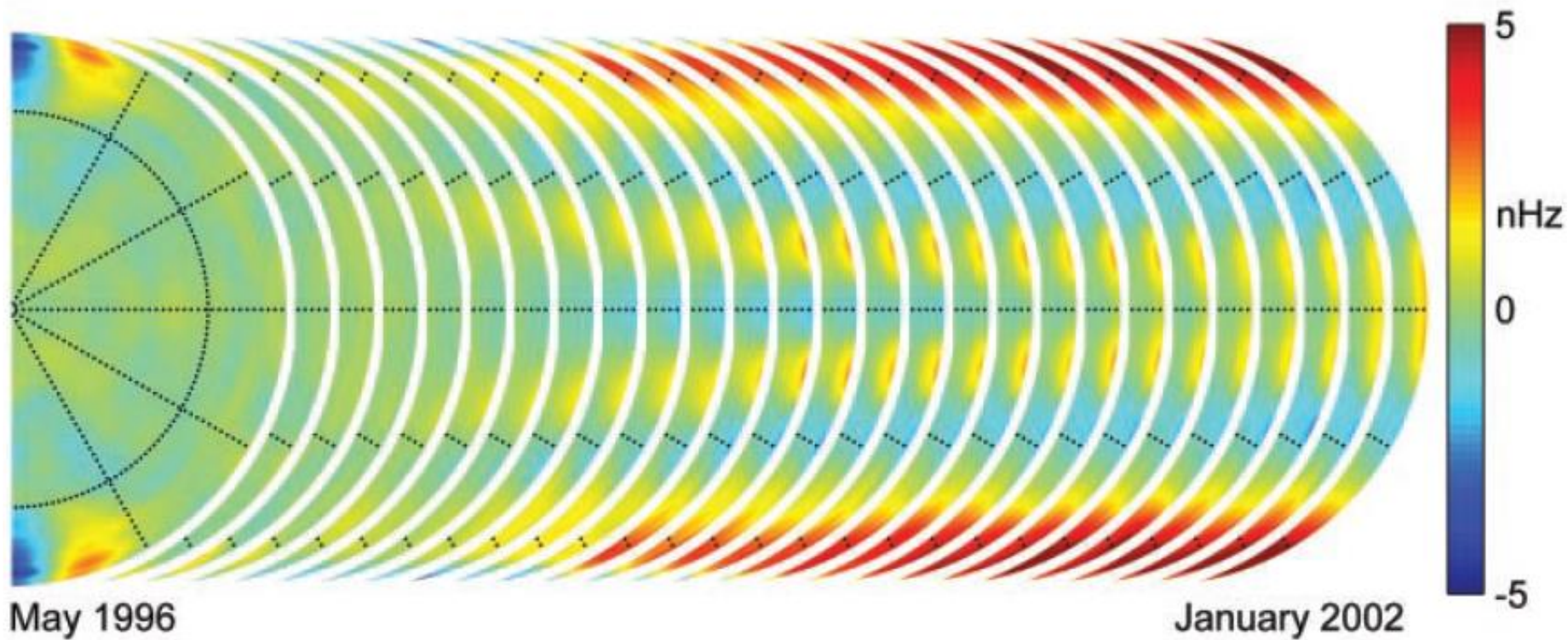


Internal Solar Rotation

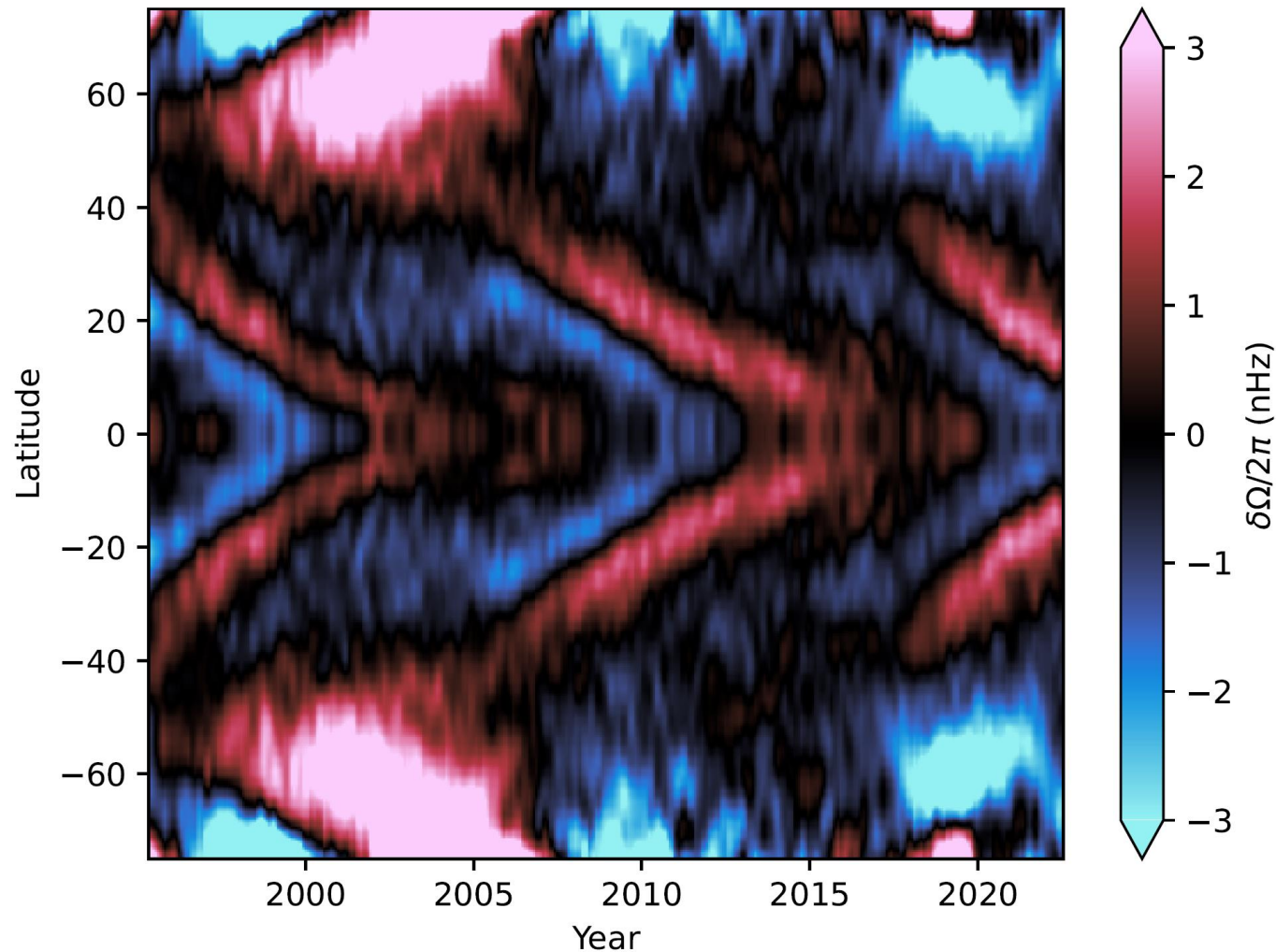


GONG data

Torsional oscillations penetrating the convective envelope

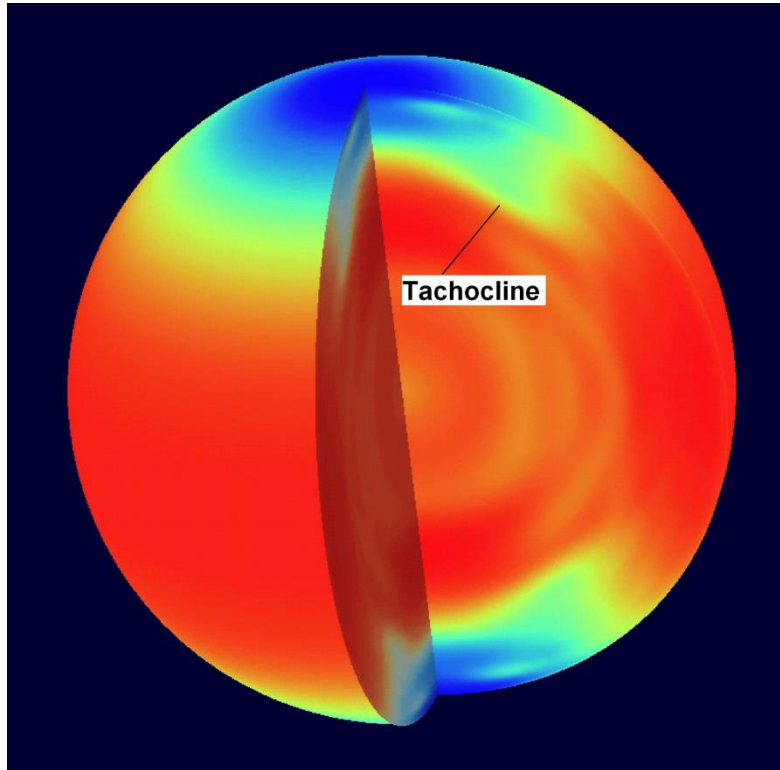


Solar sub-surface zonal flows



Howe et al., 2023, in preparation

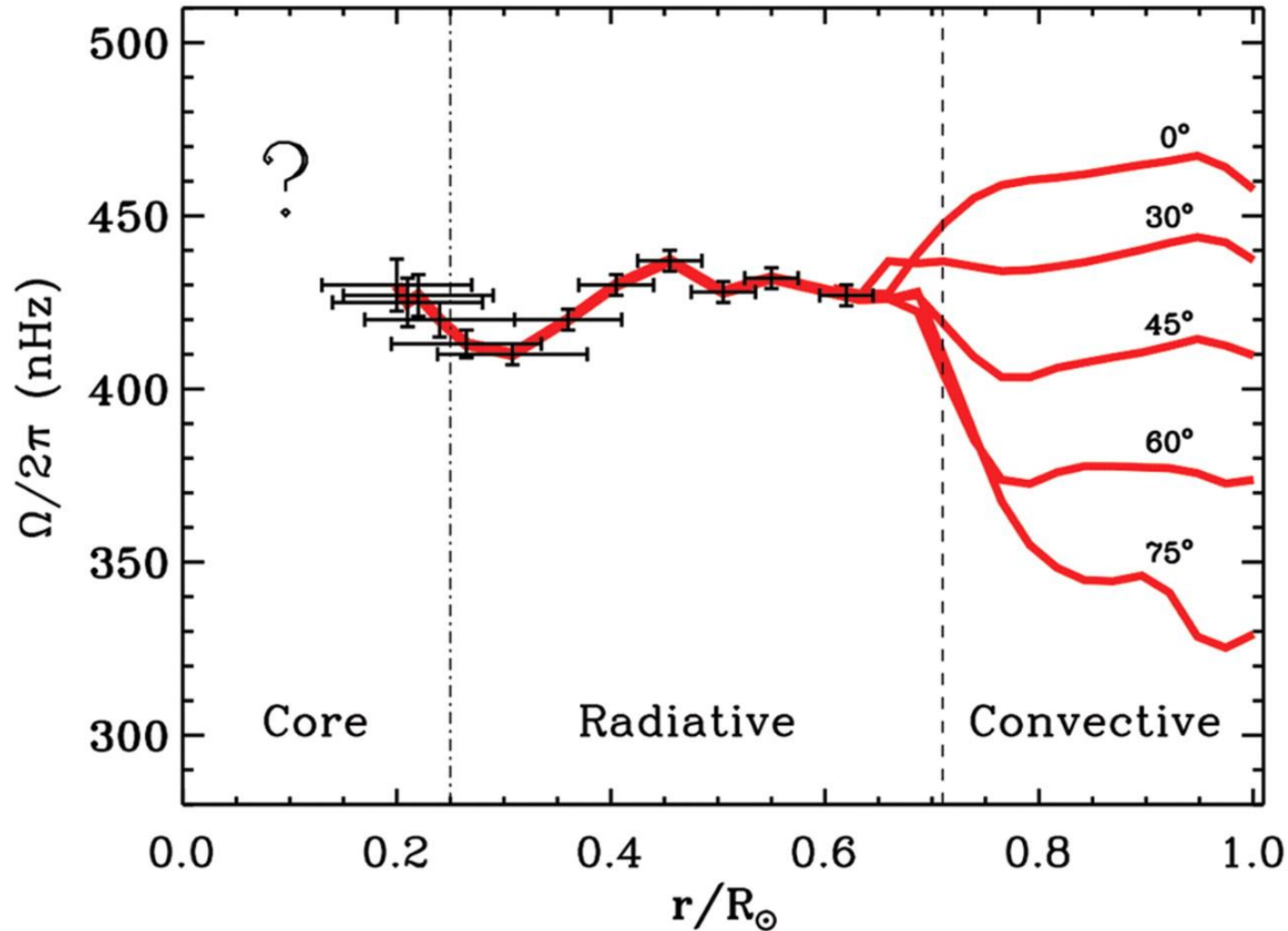
The Tachocline ('speed slope')



Located just
beneath base of
convection zone

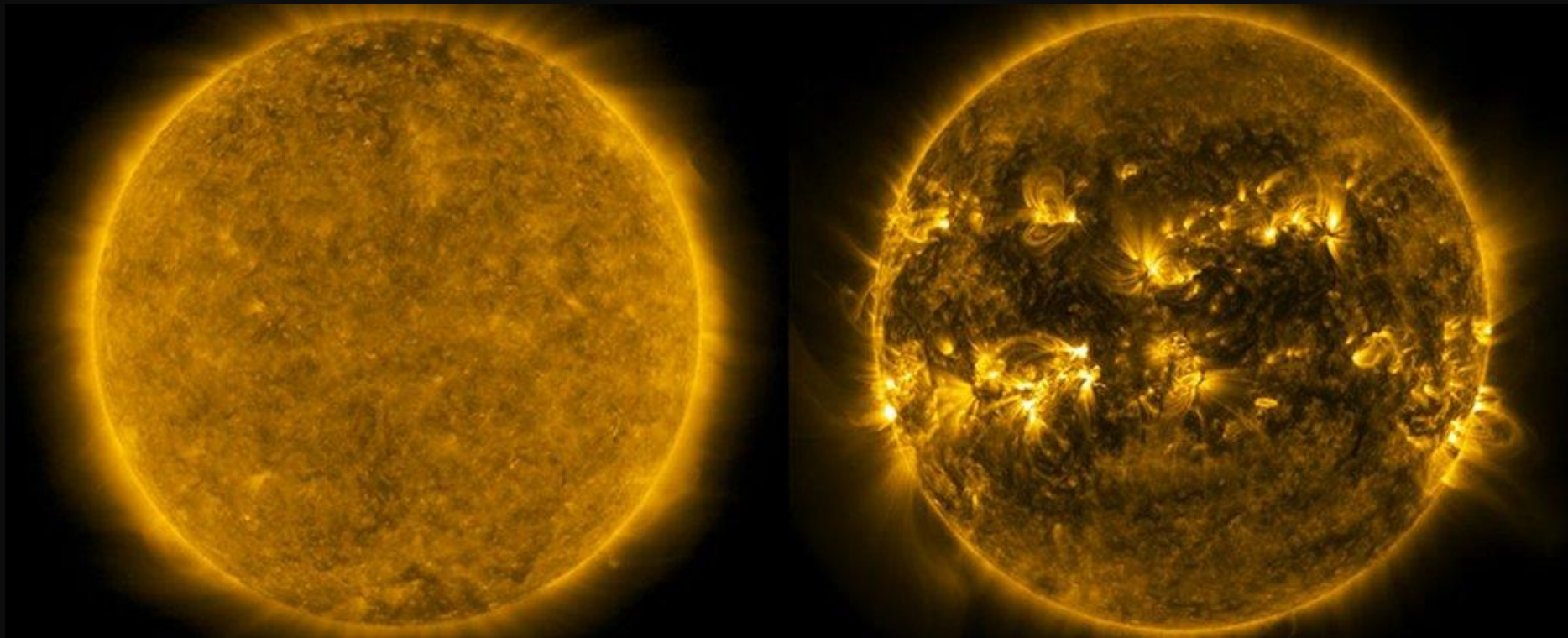
Key for dynamo
action!

Solar internal rotation

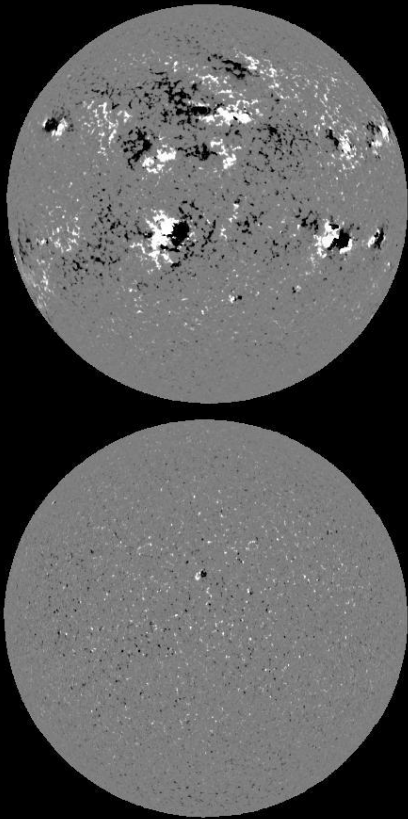


Garcia et al., 2010, Science, 316, 1591

Probing activity and the solar dynamo



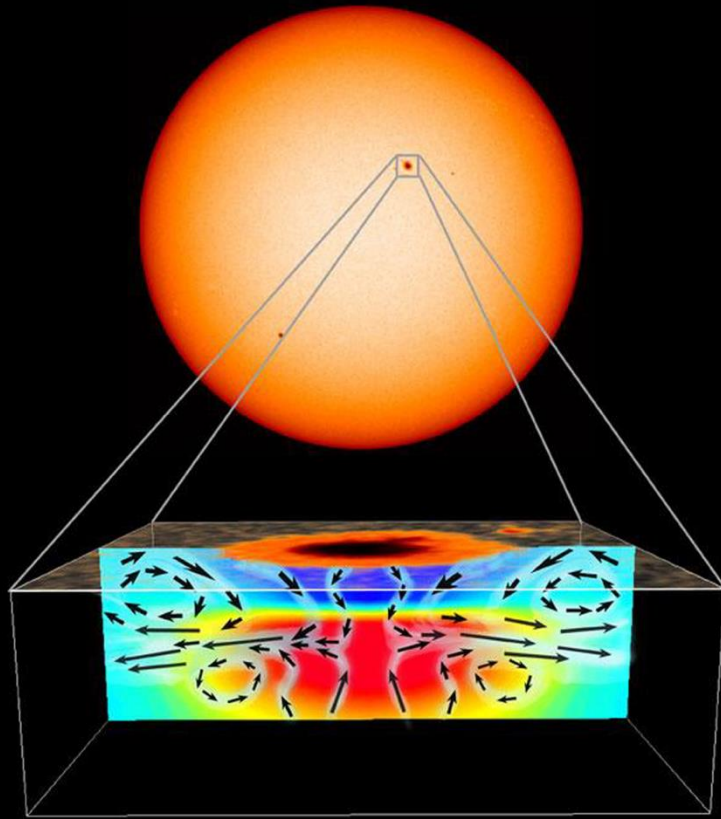
Oscillations as probes of activity and the solar cycle



Magnetic fields can change mode frequencies & splittings:

- Directly, by action of Lorentz force
- Indirectly by changing stratification

Flows and wave speed variation beneath sunspot



Arrows show flows:

Larger \longrightarrow

Smaller \longrightarrow

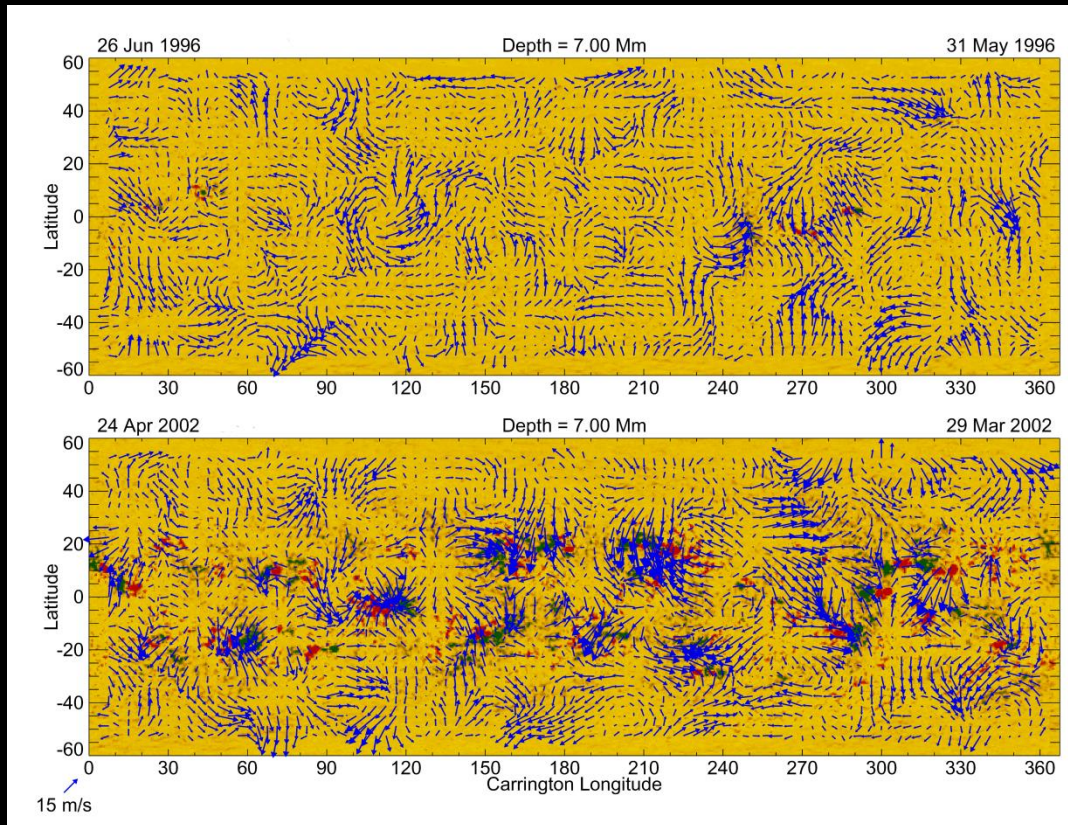
Colours show
wave-speed:

Faster... in **red**

Slower... in **blue**

Solar Sub-Surface Weather

Flows (arrows) beneath regions of magnetic flux (red)



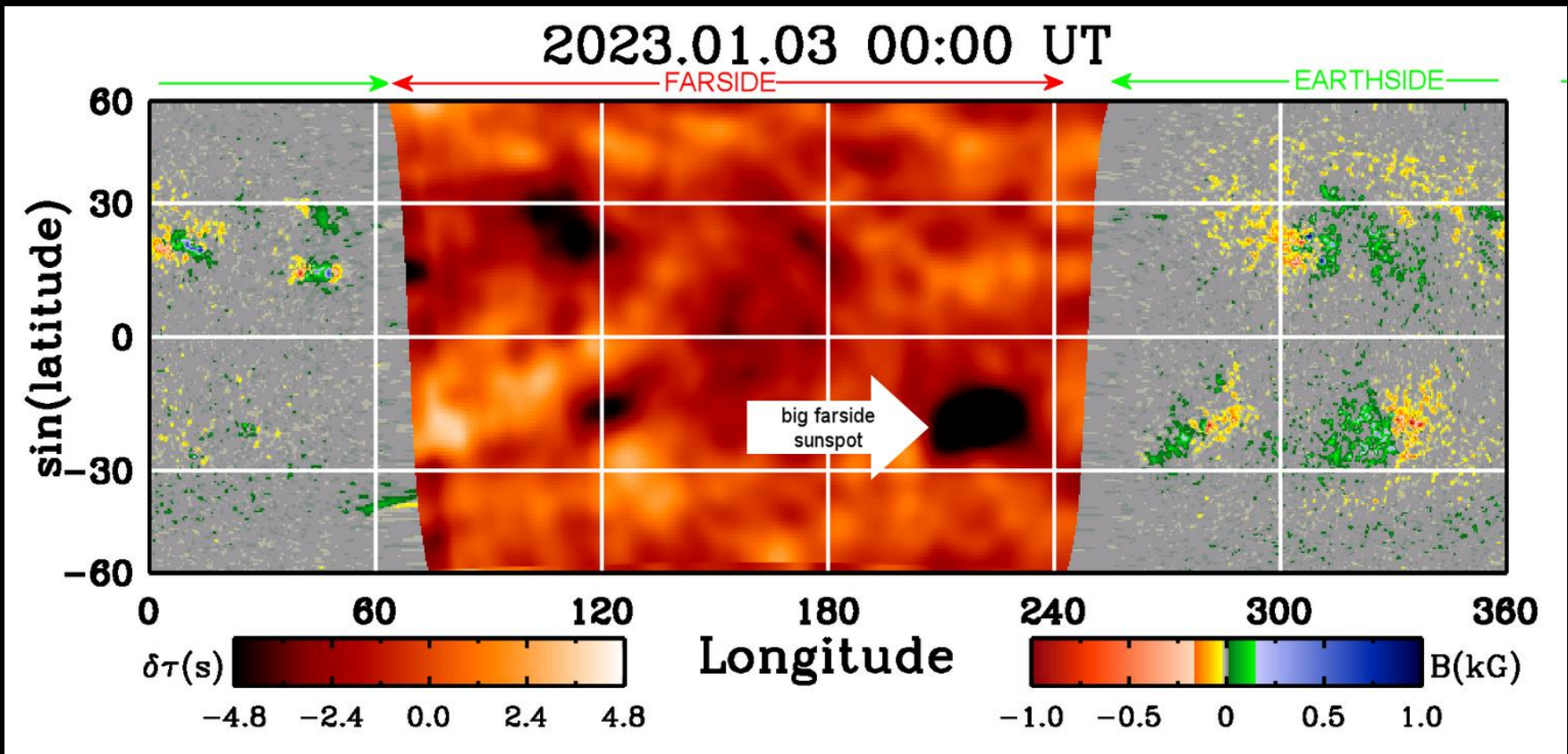
Measure flows underneath small patches

Rotation brings new patches into view

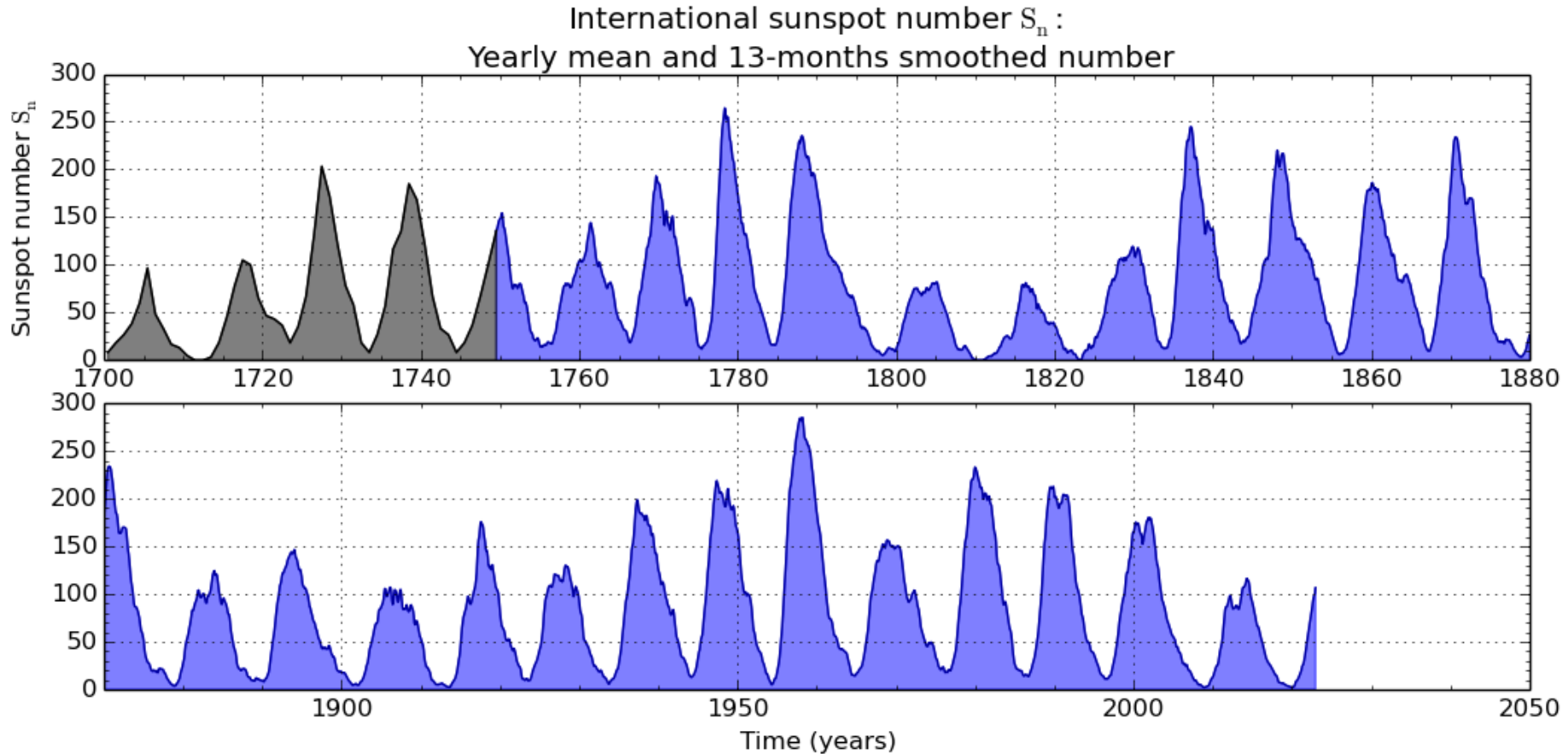
Build up strips, side-by-side, in longitude

Space weather predictions

Far-side imaging of active regions



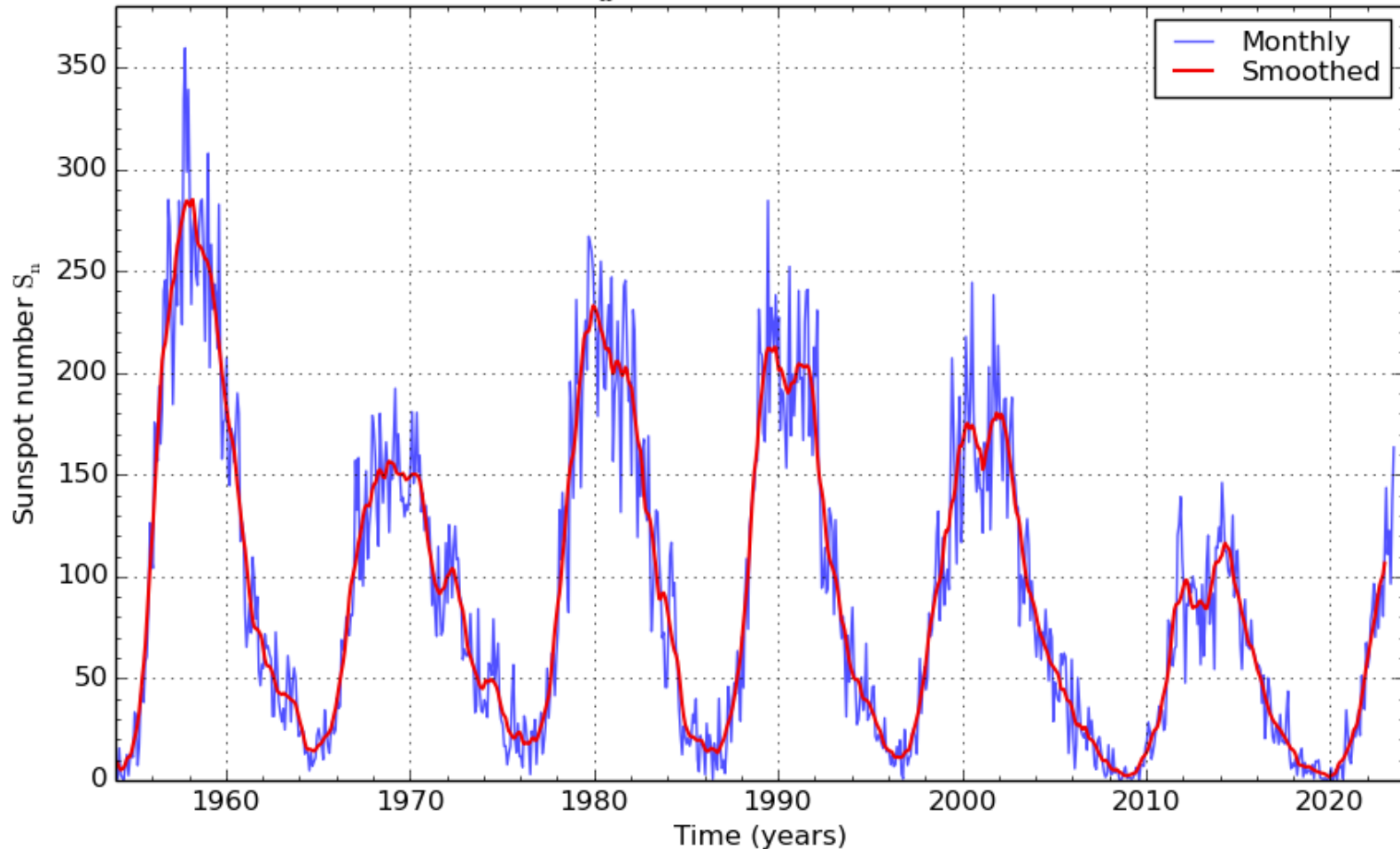
Sunspot record: solar cycles



SILSO graphics (<http://sidc.be/silso>) Royal Observatory of Belgium 2023 July 1

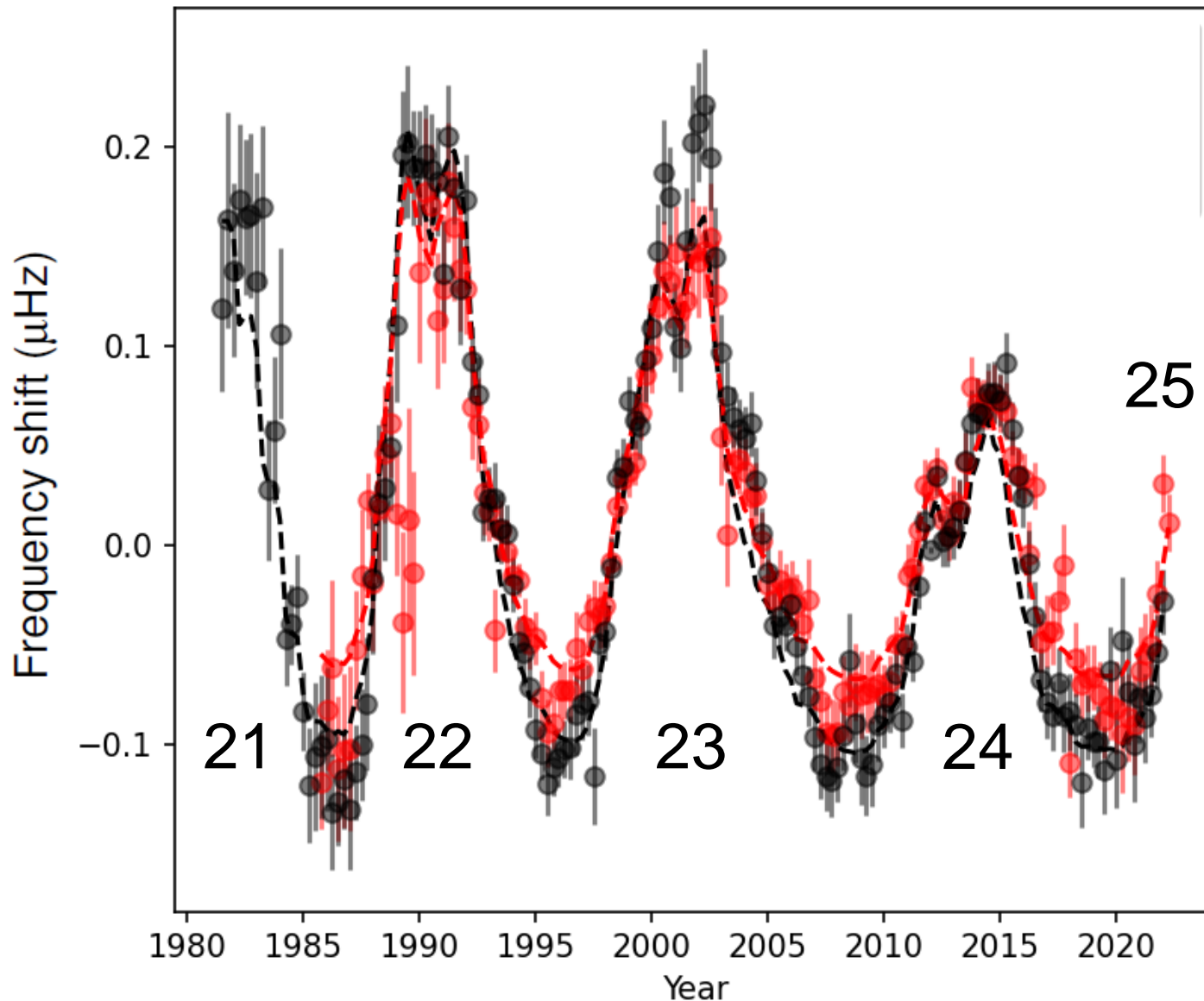
Sunspot record: solar cycles

International sunspot number S_n : monthly mean and 13-month smoothed number



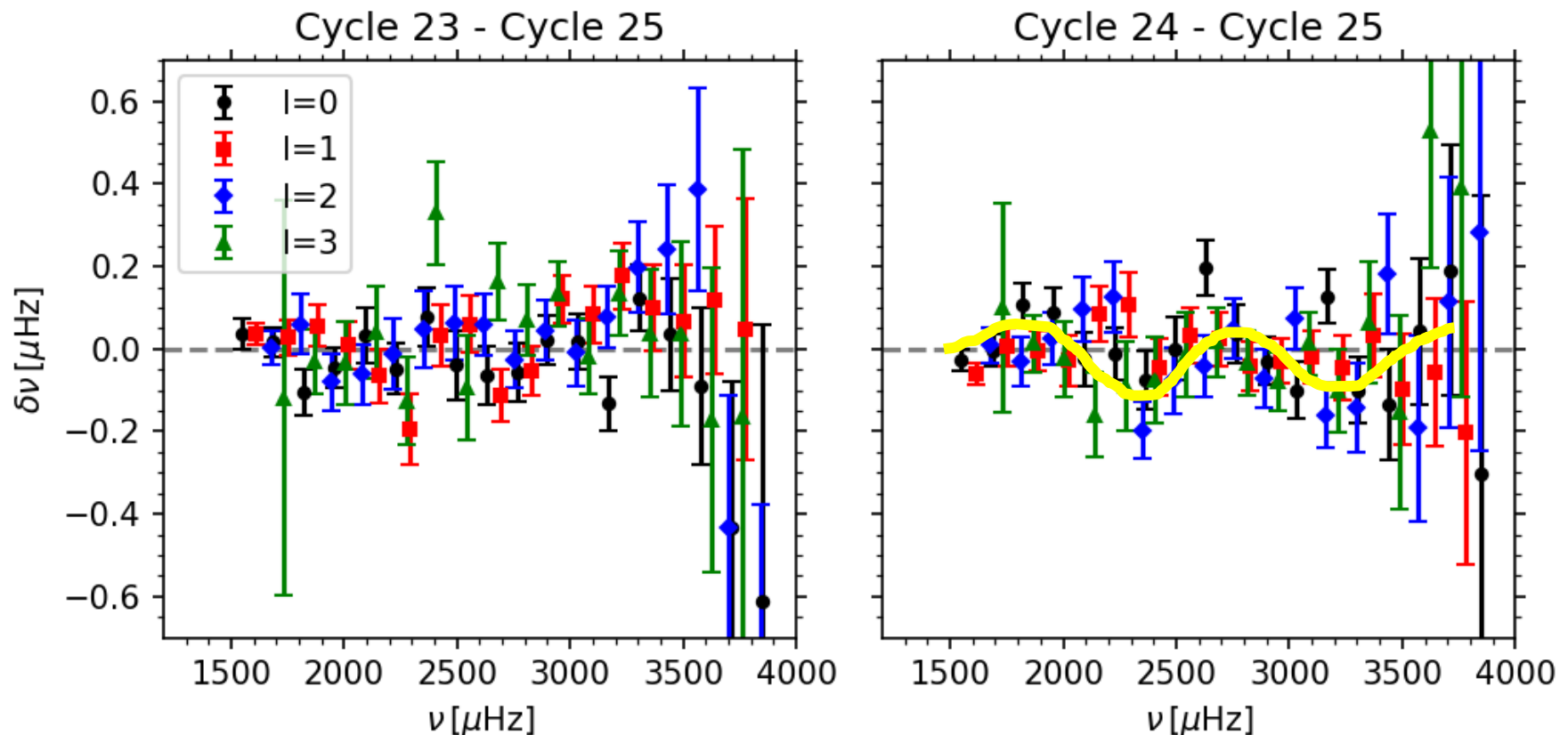
SILSO graphics (<http://sidc.be/silso>) Royal Observatory of Belgium 2023 July 1

Five seismic solar cycles with BiSON

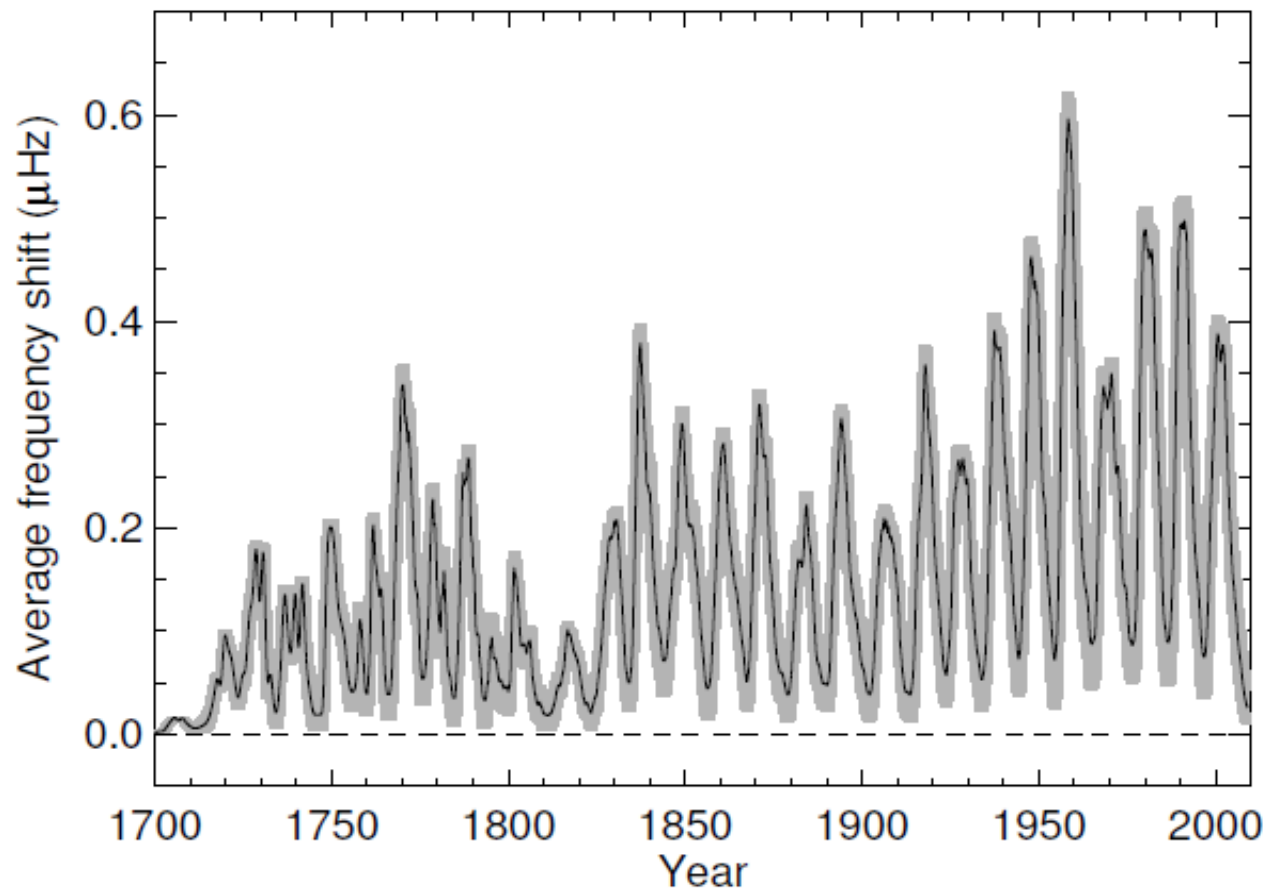


Comparison of oscillation frequencies at cycle minima

Systematic differences reveal structural changes



Prediction: Seismic Sun back to the Maunder Minimum



Asteroseismology, *n.*

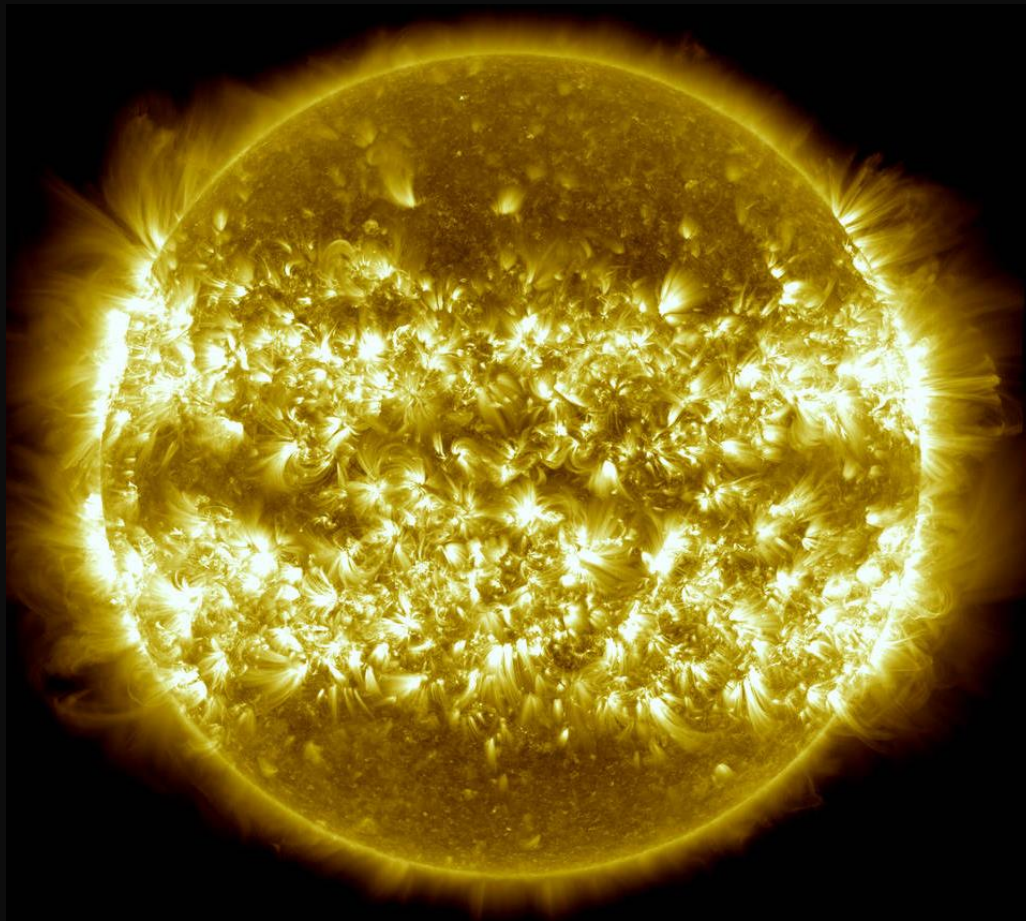
The study of the interior of stars by the observation and analysis of oscillations at their surface.

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[Oxford English Dictionary]



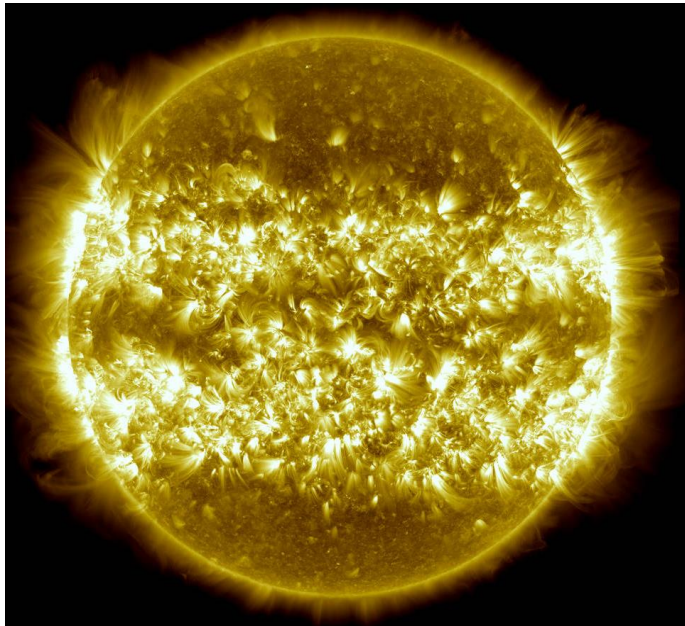
Seismic inference on active latitudes



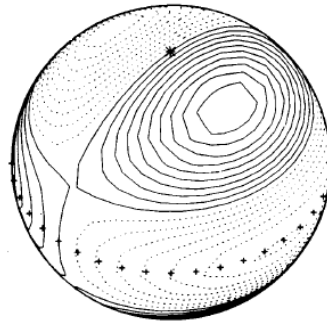
Credit: NASA/SDO/Goddard

Inference on active latitudes

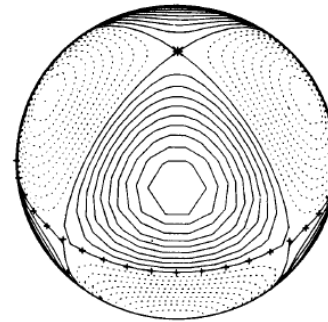
Frequency shifts depend on (l, m)



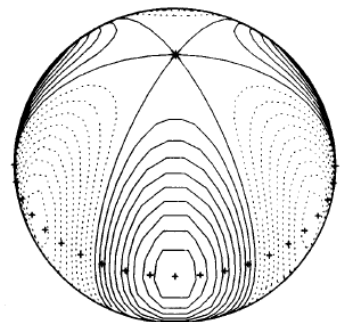
$(3,1)$



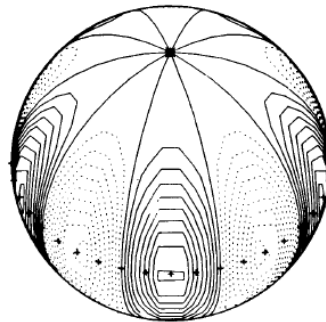
$(3,2)$



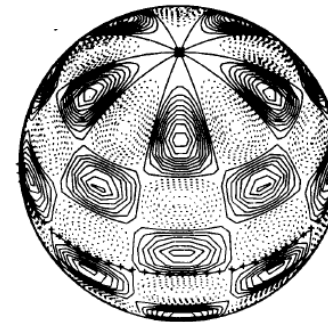
$(3,3)$



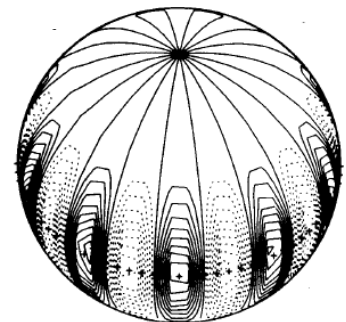
$(5,5)$



$(10,5)$

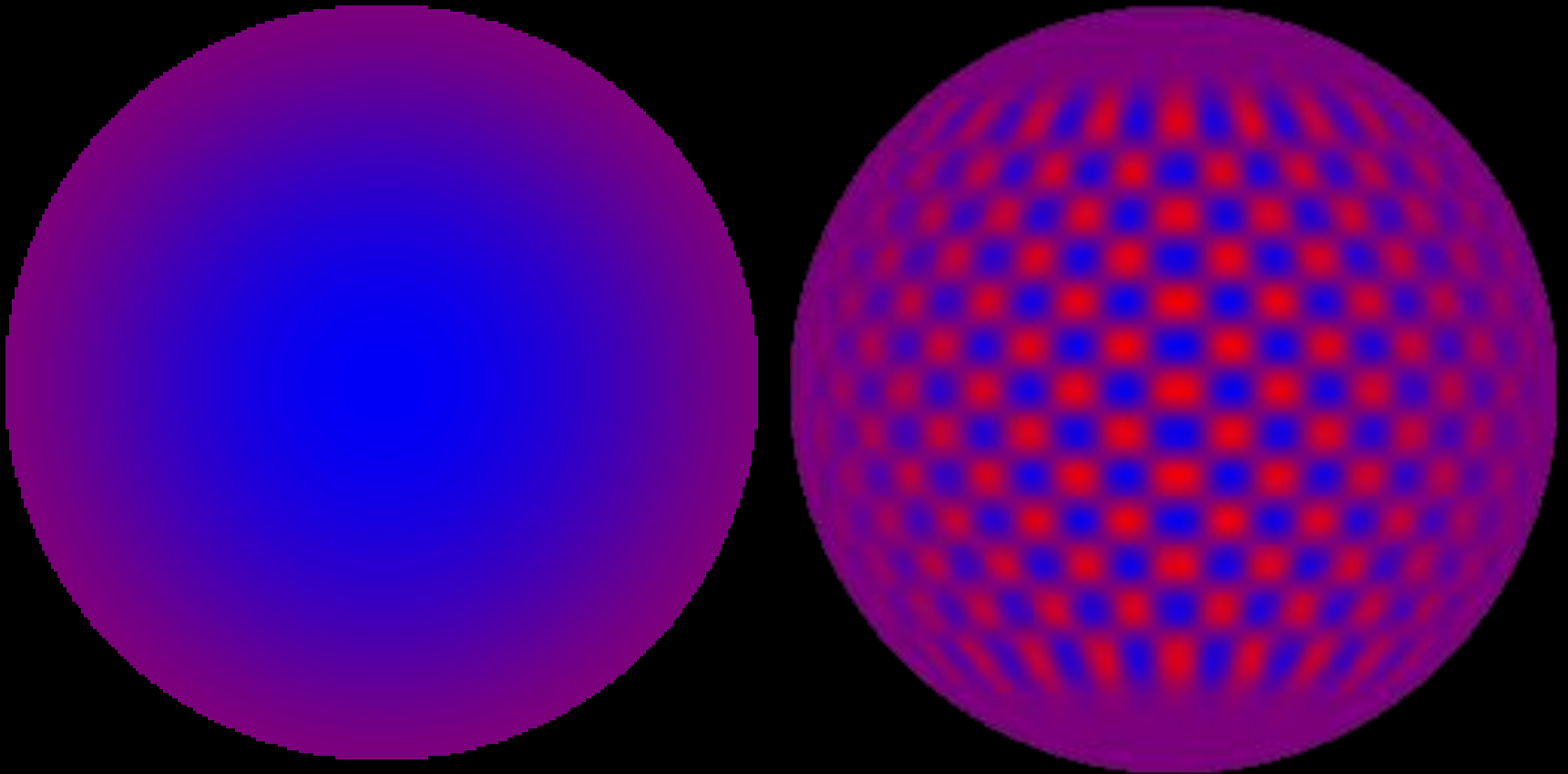


$(10,10)$



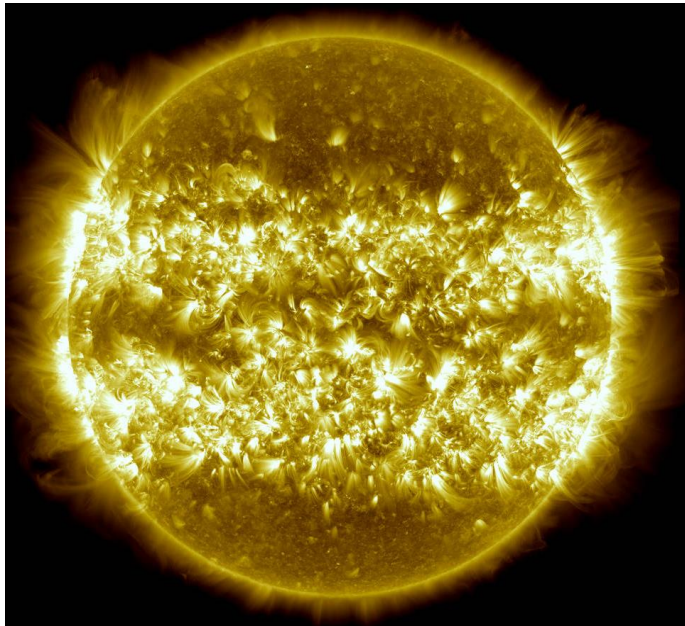
Solar Oscillations

Mode patterns correspond to spherical harmonics

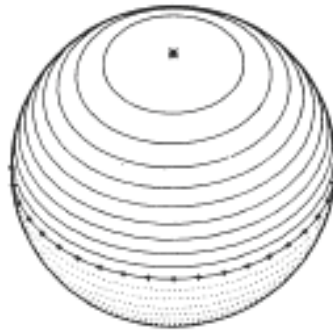


Inference on active latitudes

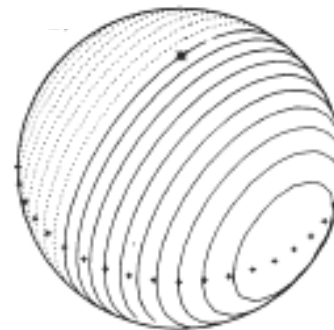
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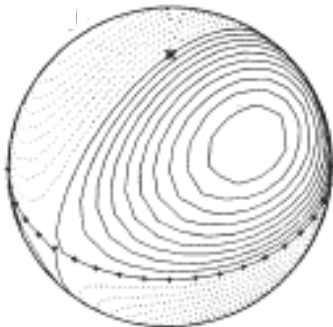
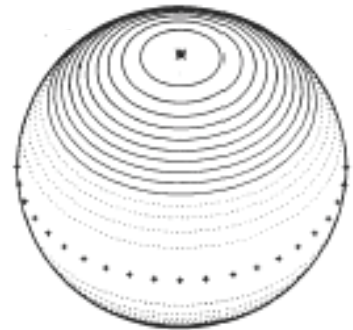
$(1,0)$



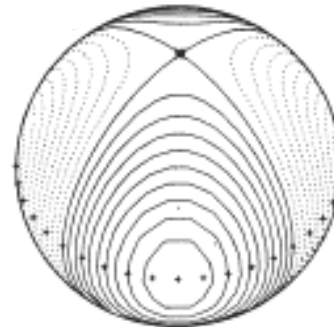
$(1,1)$



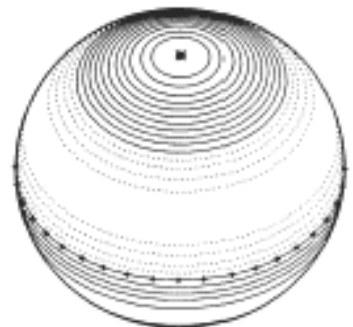
$(2,0)$



$(2,1)$



$(2,2)$



$(3,0)$

Principles of the method

$$\delta\nu_{lm} \propto \left(l \text{ constant } \frac{(l-|m|)!}{(l+|m|)!} \right)$$

Observable

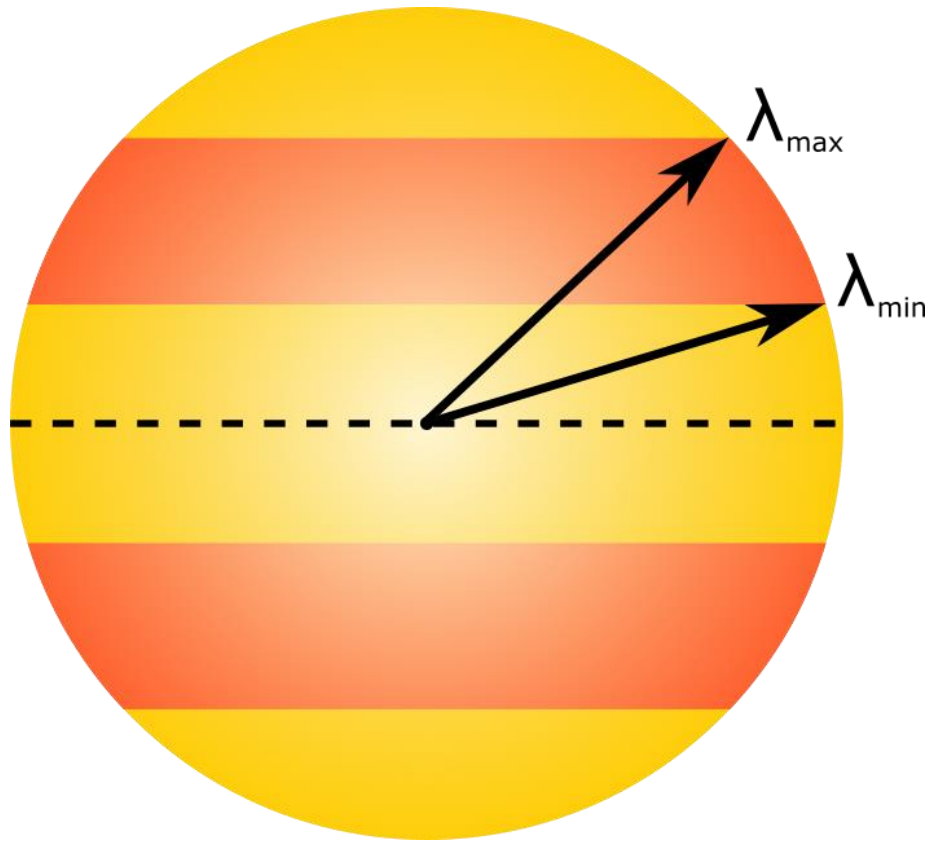
$$\times \int_{\theta_{\max}}^{\theta_{\min}} |P_l^{|m|}(\cos \theta)|^2 d\theta$$

Spherical harmonic

$$\times \int_{\lambda_{\min}}^{\lambda_{\max}} \sin \theta d\theta$$

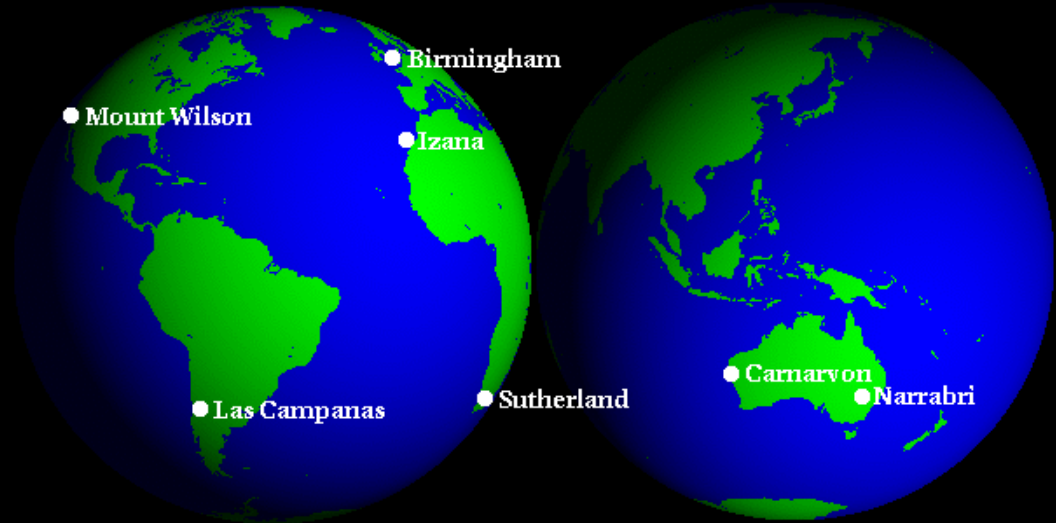
Activity distribution

Principles of the method

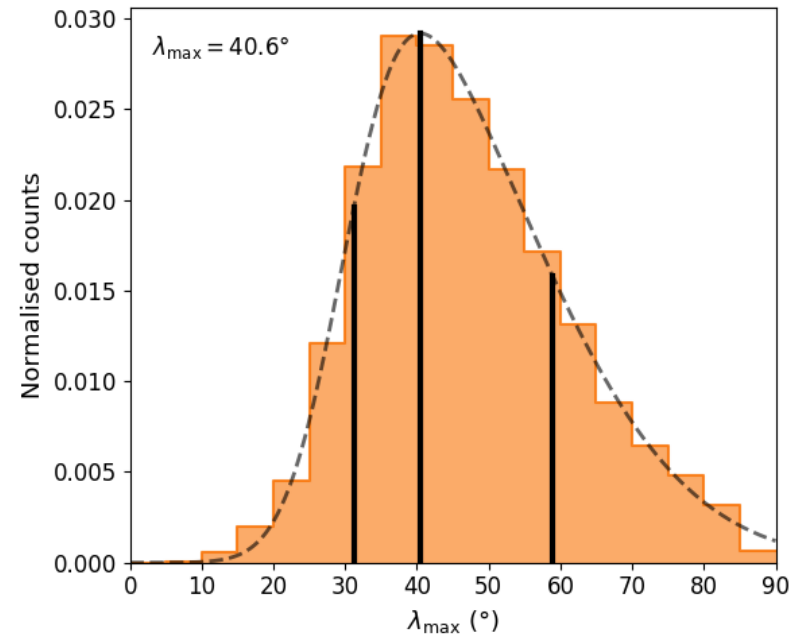
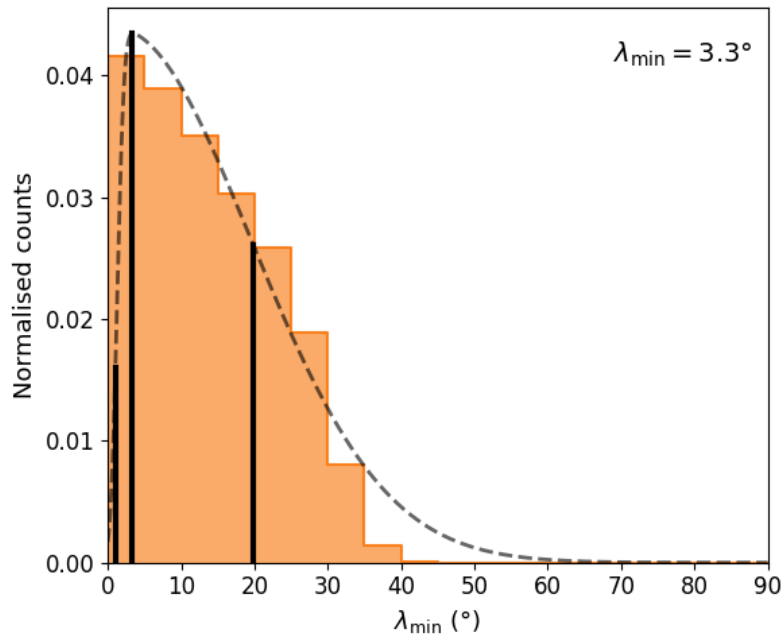


BiSON

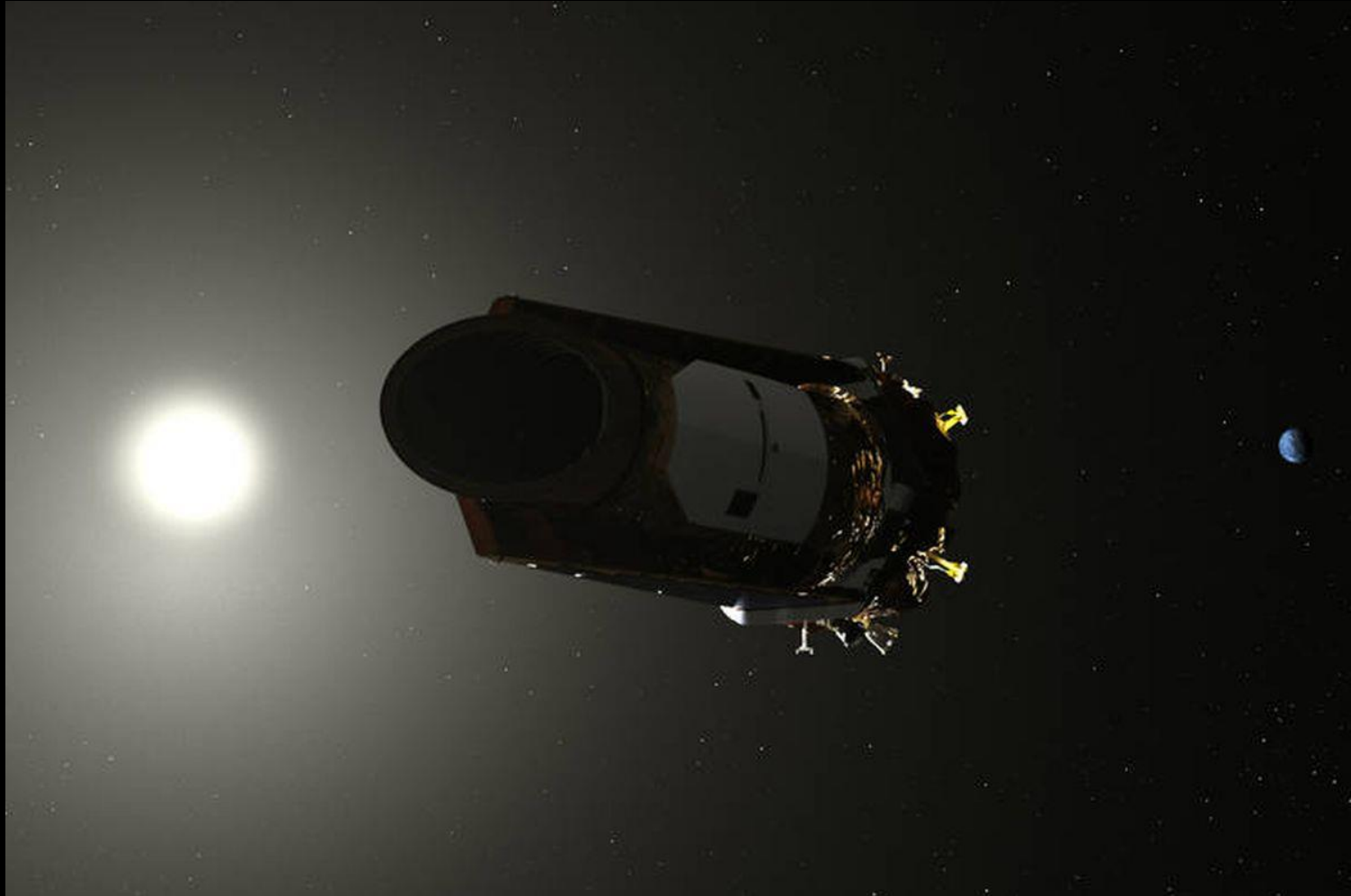
Sun-as-a-star helioseismology



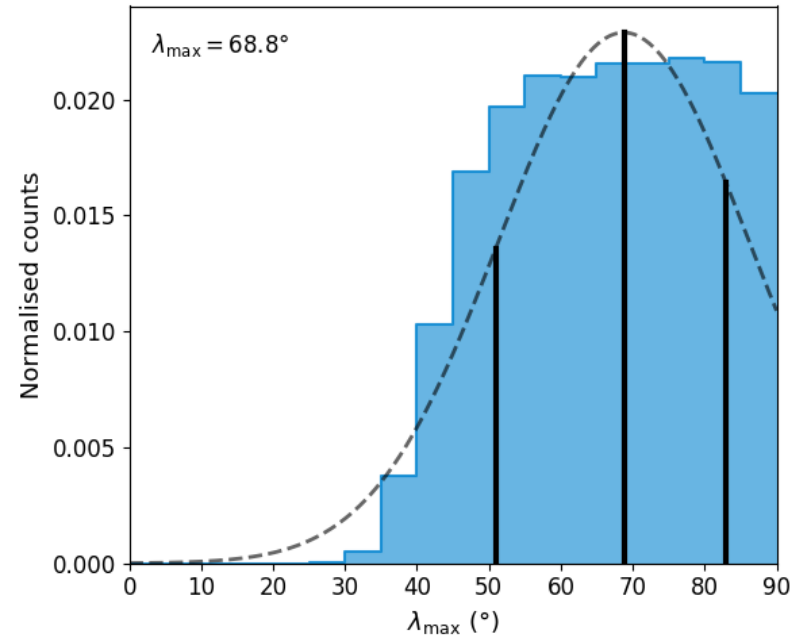
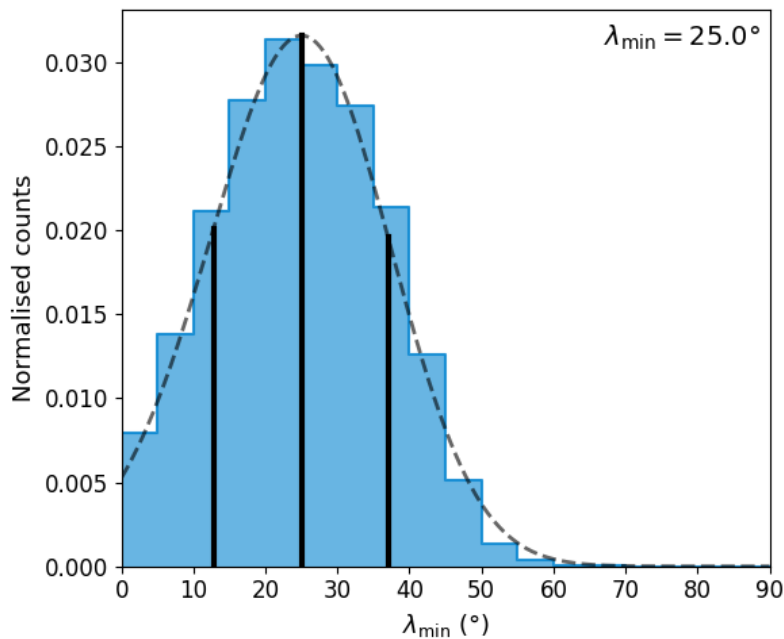
Results: Sun-as-a-star BiSON data



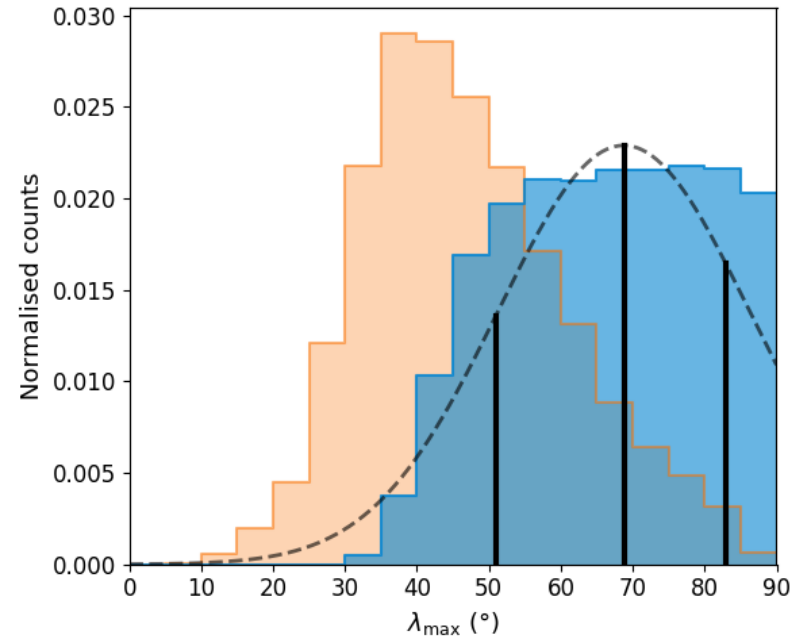
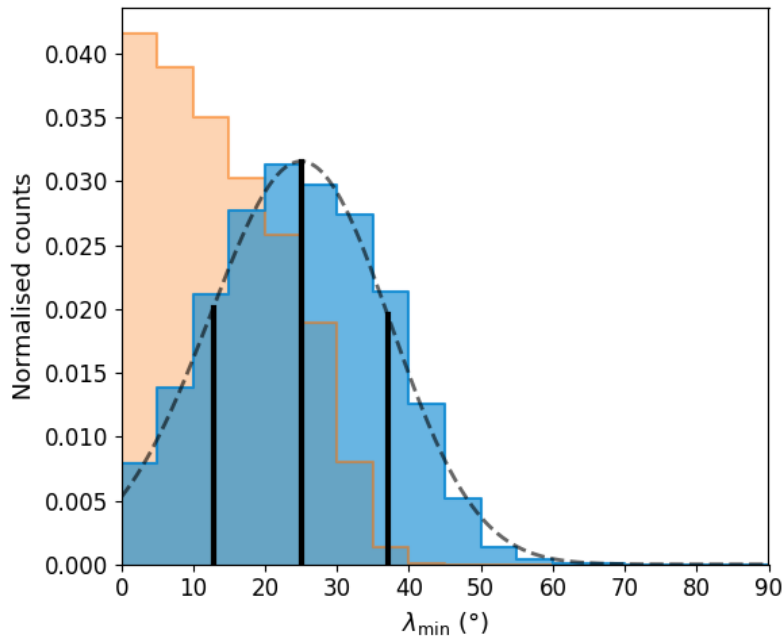
NASA *Kepler* Mission



Results: solar analogue HD173701



Results: solar analogue HD173701



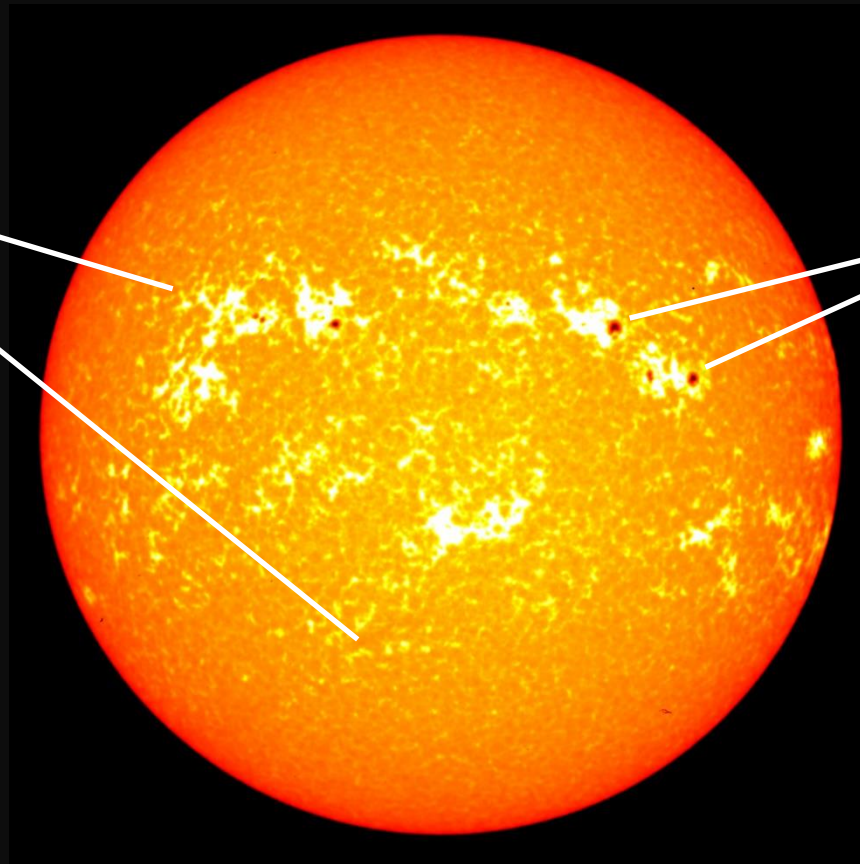
■ Sun with BiSON

■ HD173701 with *Kepler*

Spots and Faculae

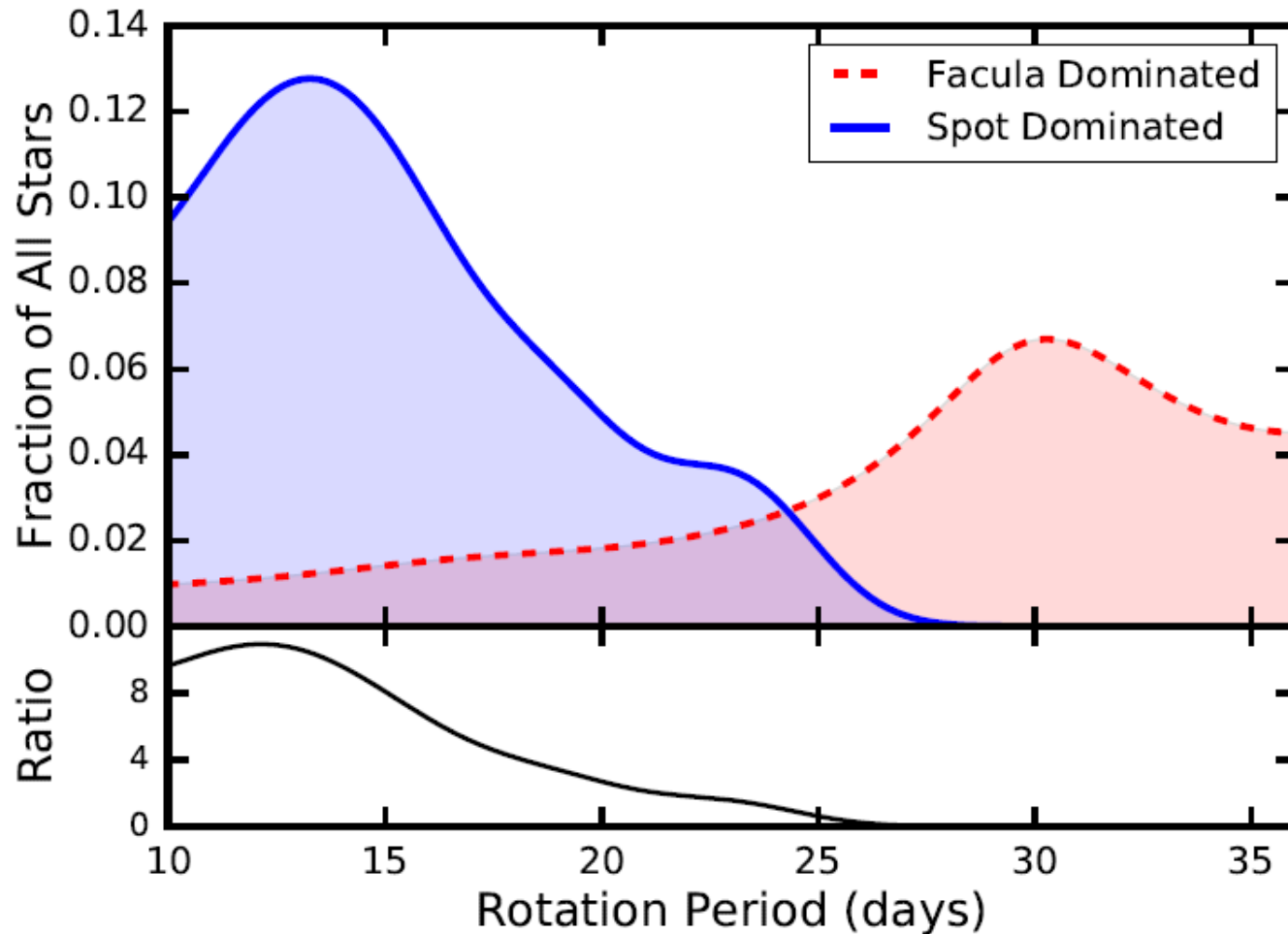
faculae

spots



Long-term brightness

Kepler lightcurves of solar-type stars



NASA TESS Mission



ESA PLATO Mission



"Beautifully written narrative"

John Leibacher
Institut D'Astrophysique Spatiale, University of Paris

MUSIC OF THE SUN

THE STORY OF HELIOSEISMOLOGY

WILLIAM J. CHAPLIN

PRINCETON SERIES IN MODERN OBSERVATIONAL ASTRONOMY

ASTEROSEISMIC DATA ANALYSIS

FOUNDATIONS
AND TECHNIQUES

SARBANI BASU &
WILLIAM J. CHAPLIN

A large, bright orange sphere, resembling a sun or a planet, is centered against a solid black background. The sphere has a slightly textured surface with some darker orange and black spots, particularly a cluster of dark spots near the bottom center. The word "END" is written in a large, white, sans-serif font across the middle of the sphere.

END