



Solar Interior and Helioseismology [and wider links]

Yvonne Elsworth, Birmingham

STFC Introductory Course in Solar and Solar-Terrestrial Physics

helioseismology, *n.*

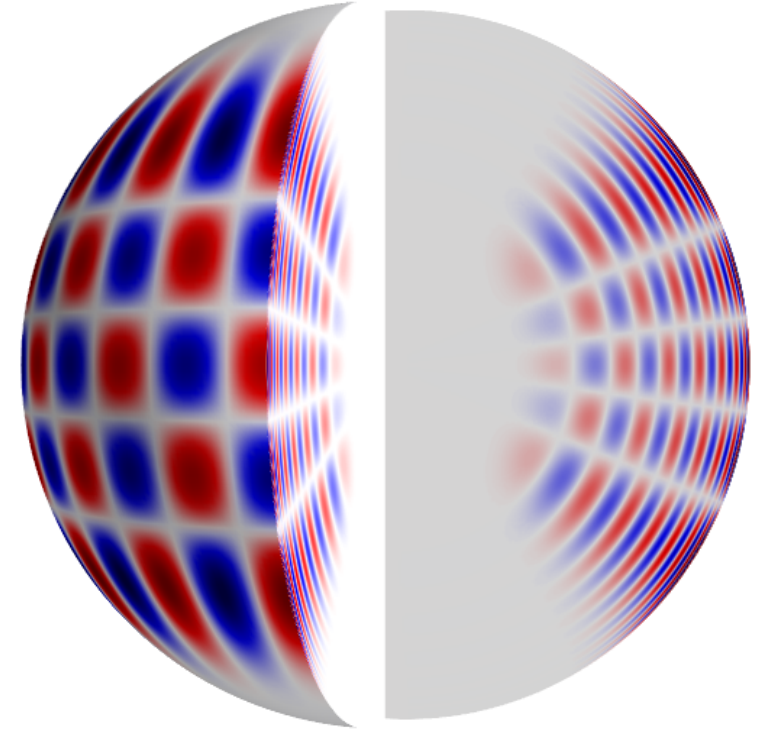
The study of the sun's interior by the observation and analysis of oscillations at its surface. Cf. asteroseismology *n.*

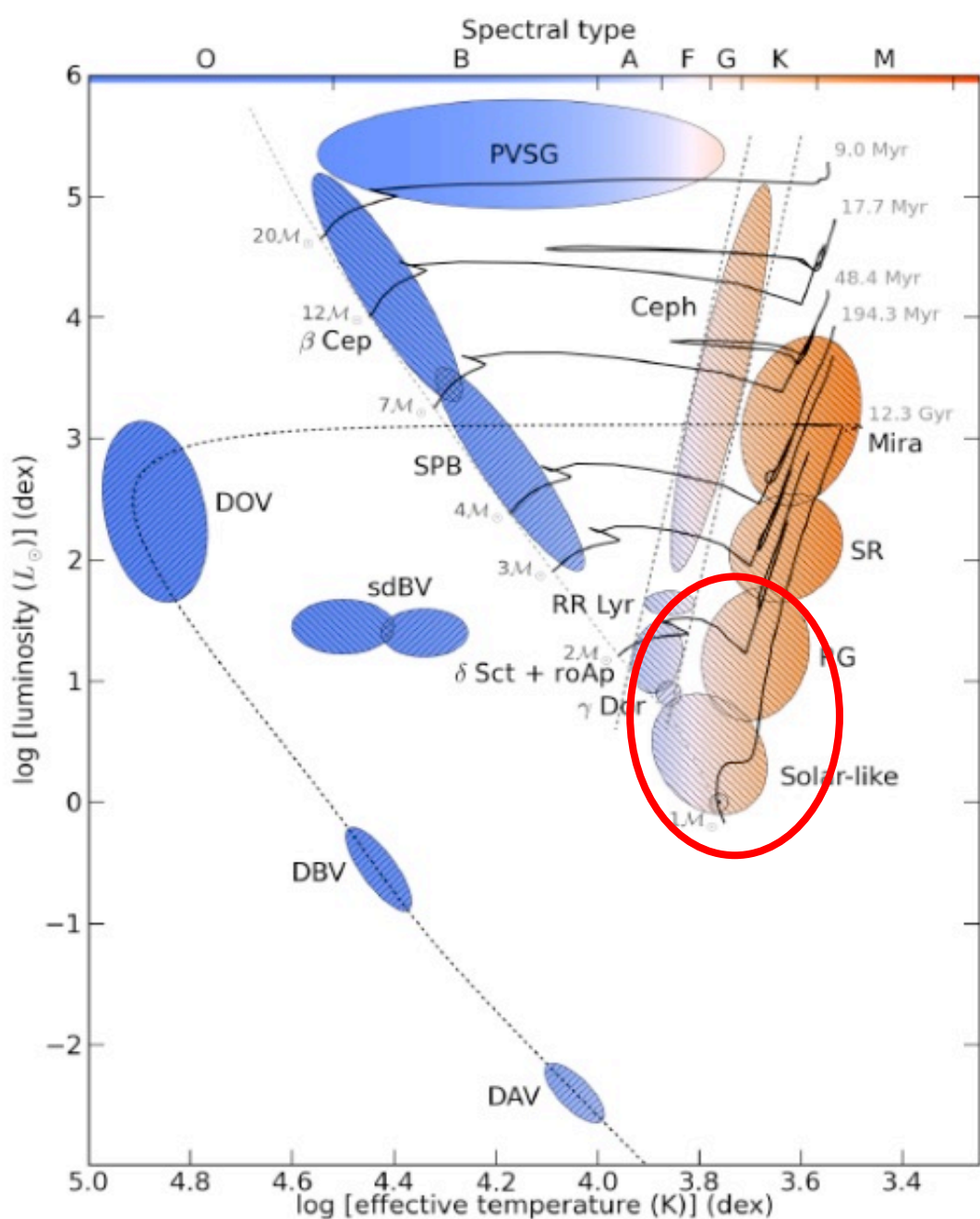
[Oxford English Dictionary]

A model of the motions associated with one of these possible oscillations.

Where there is no colour, the mode is not sensitive to the local conditions. Allows mapping

The first clear observations were in 1963.
Since then the technology has massively changed.
So has the Sun - it is a variable star.





Oscillations across the HR Diagram - asteroseismology

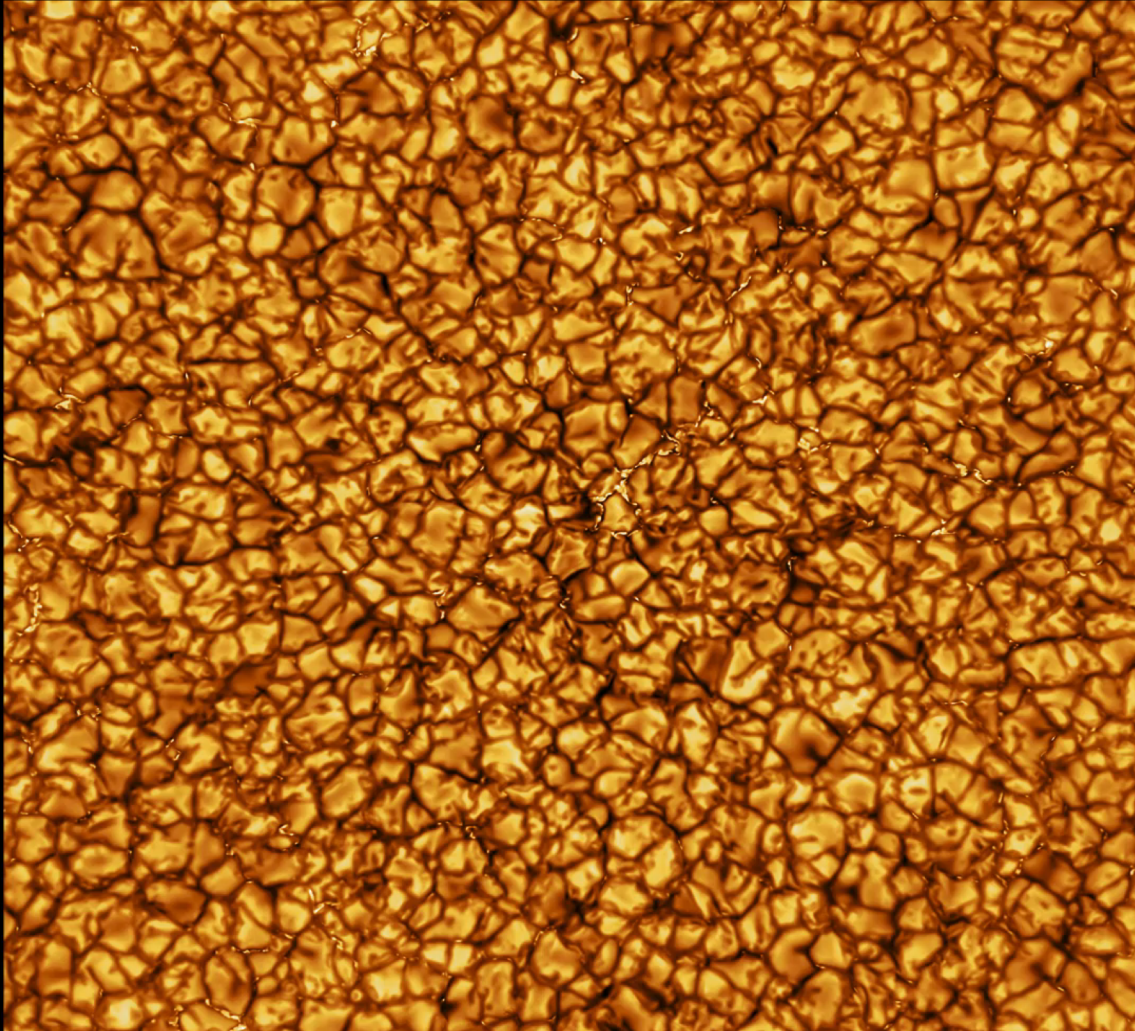
Aerts, ARAA, 2019

Many different driving mechanisms.

My interest here is in the solar like and red giant (RG) - a very small subset.

Near-surface turbulence generates acoustic noise...

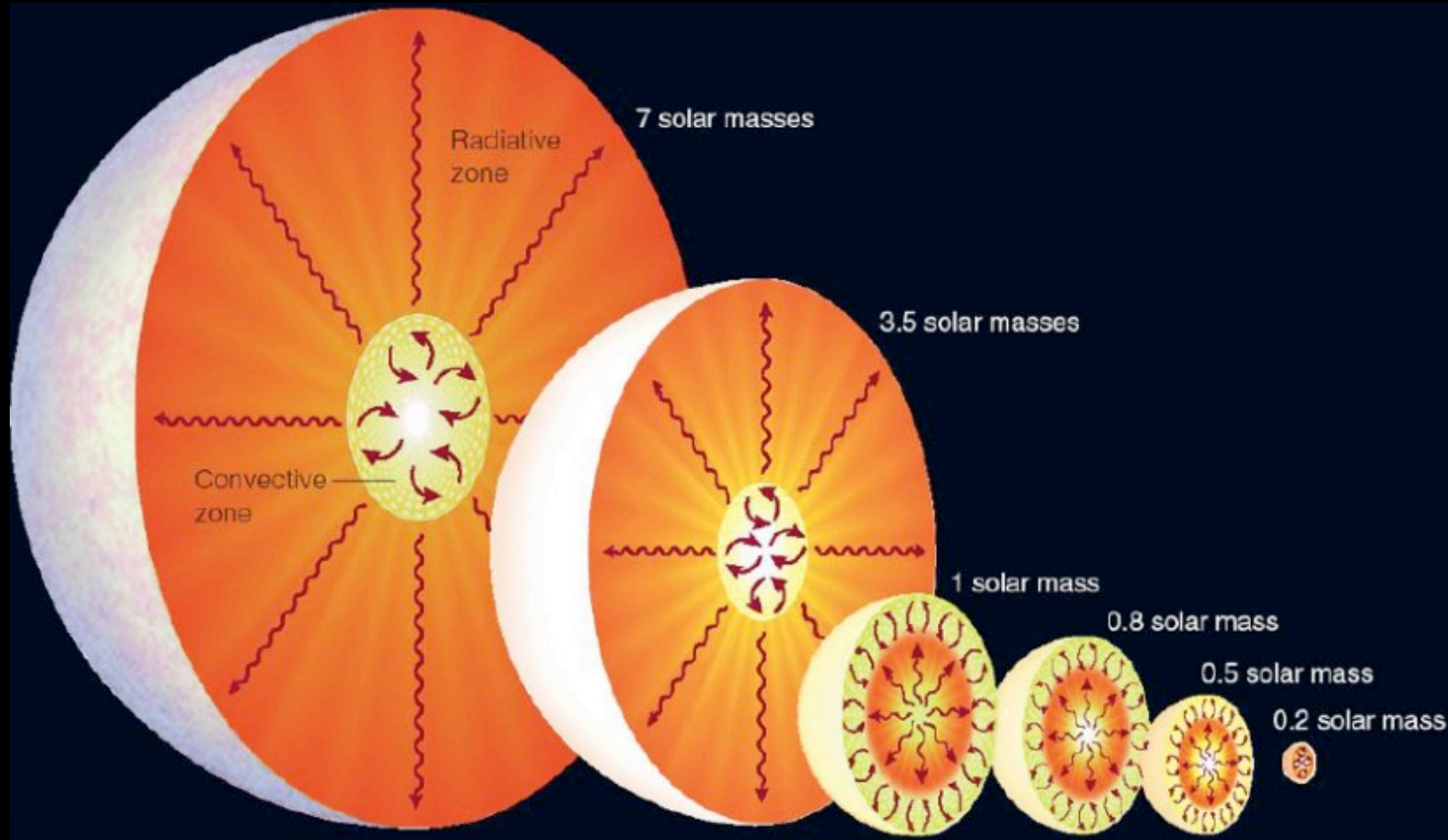
DKIST data



10 Dec. 2019 19:24:31 UT

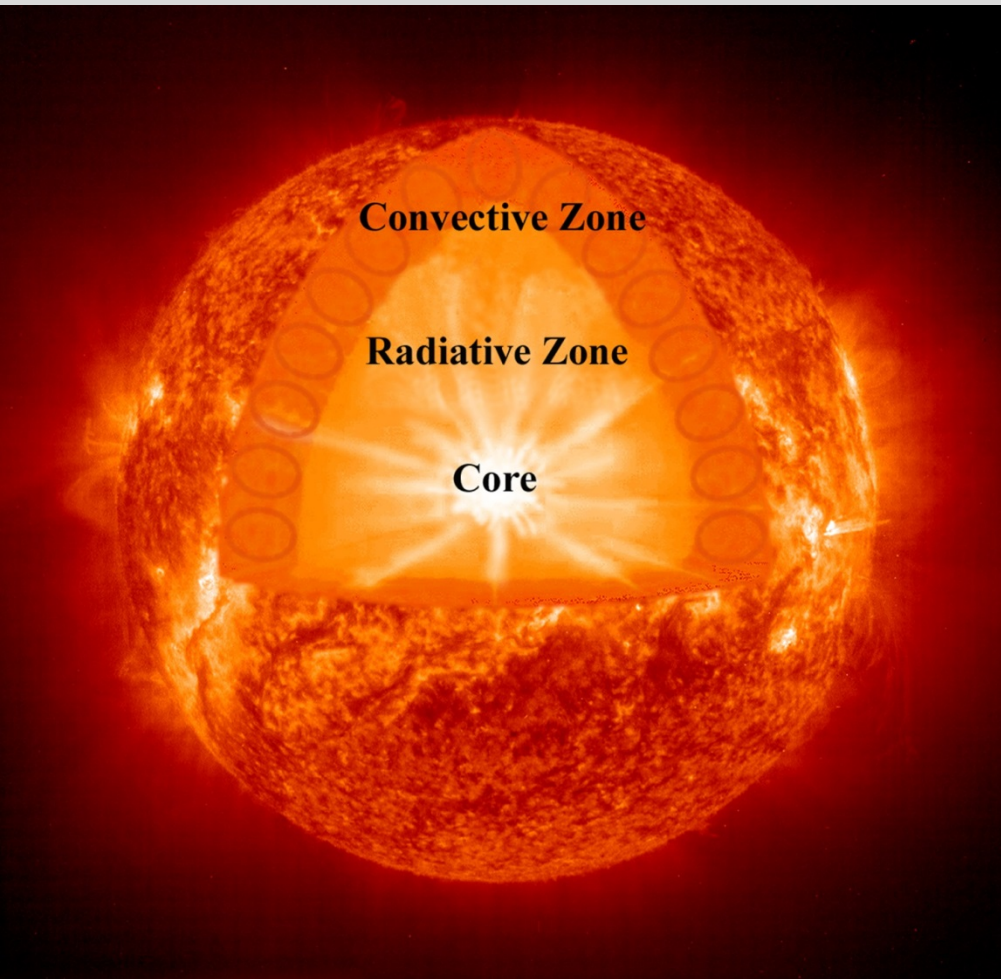
UNIVERSITY OF
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Interior Structures of Stars



Outer
convection
zone drives
the oscillations
in lower mass
stars

The Classical Sun



- Key layers in the Sun
- Core, Radiative Zone and Convection Zone
- Photosphere is the layer seen in visible radiation - 'surface'
- Above that are the outer regions of Chromosphere and Corona

So, how do we know this?

Sir Arthur Eddington

'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?'

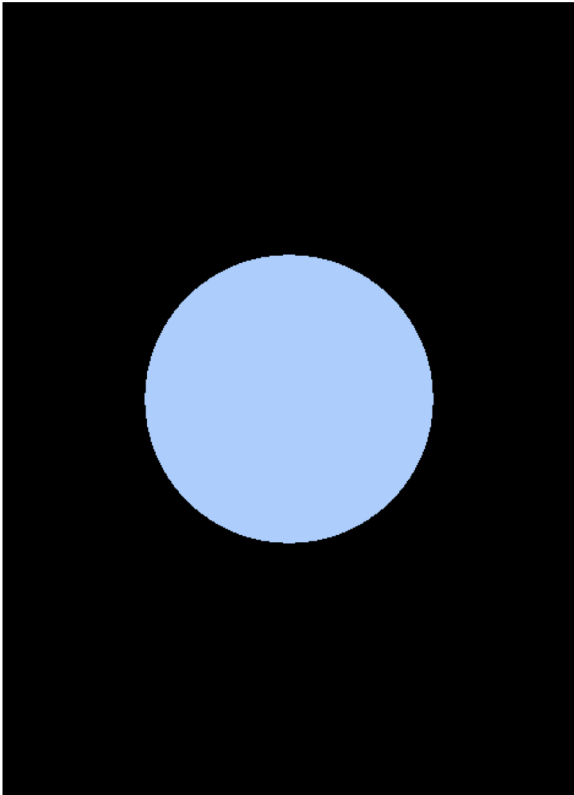


A. S. Eddington, 'The Internal Constitution of the Stars', 1926, Cambridge Uni. Press, p. 1

[Smithsonian Institution @ Flickr Commons](#)

His answer was theory but we also have observations

That some stars can oscillate is not news



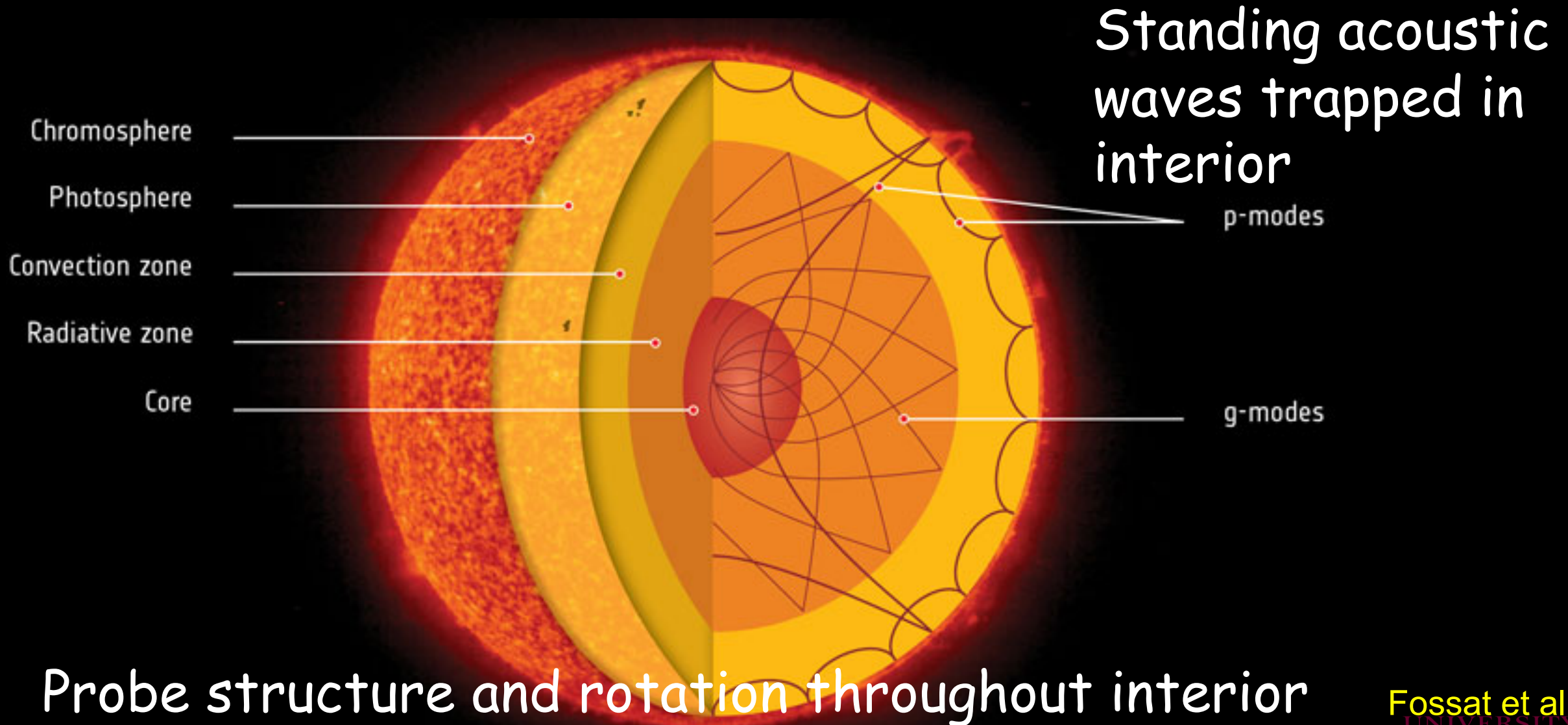
- Fundamental period of radial pulsation in terms of average density:

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

Ritter 1880; Shapley, 1914

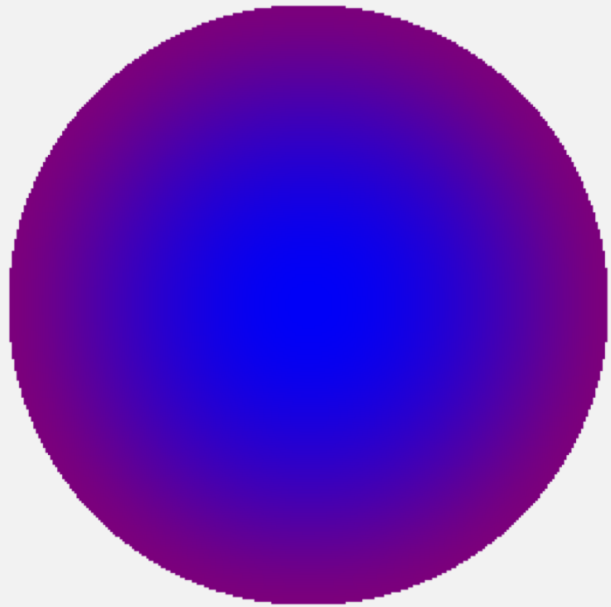
- Seen in, e.g. Cepheids (distance scale).
- Oscillations on the surface of the Sun were unexpected.
- Fundamental period expected to be just over 1 hour equivalent to a frequency of about $160\mu\text{Hz}$.
- Not what is seen

Global Solar Oscillations

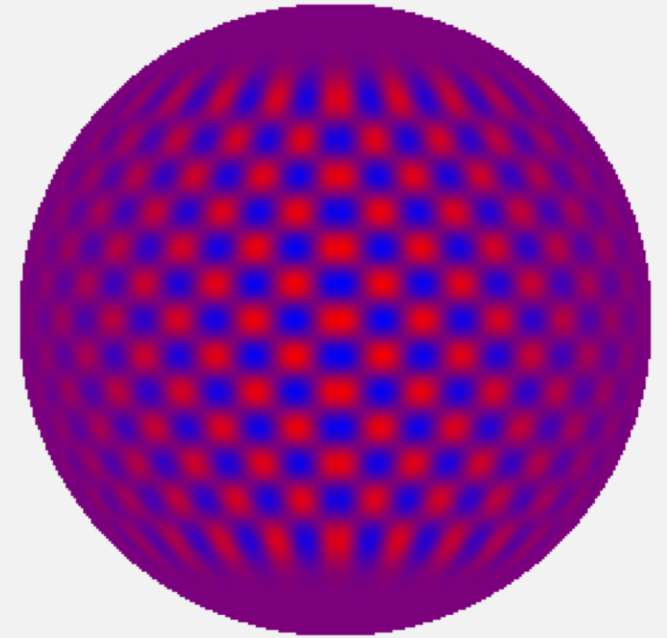


Solar Oscillations

Mode patterns correspond to spherical harmonics



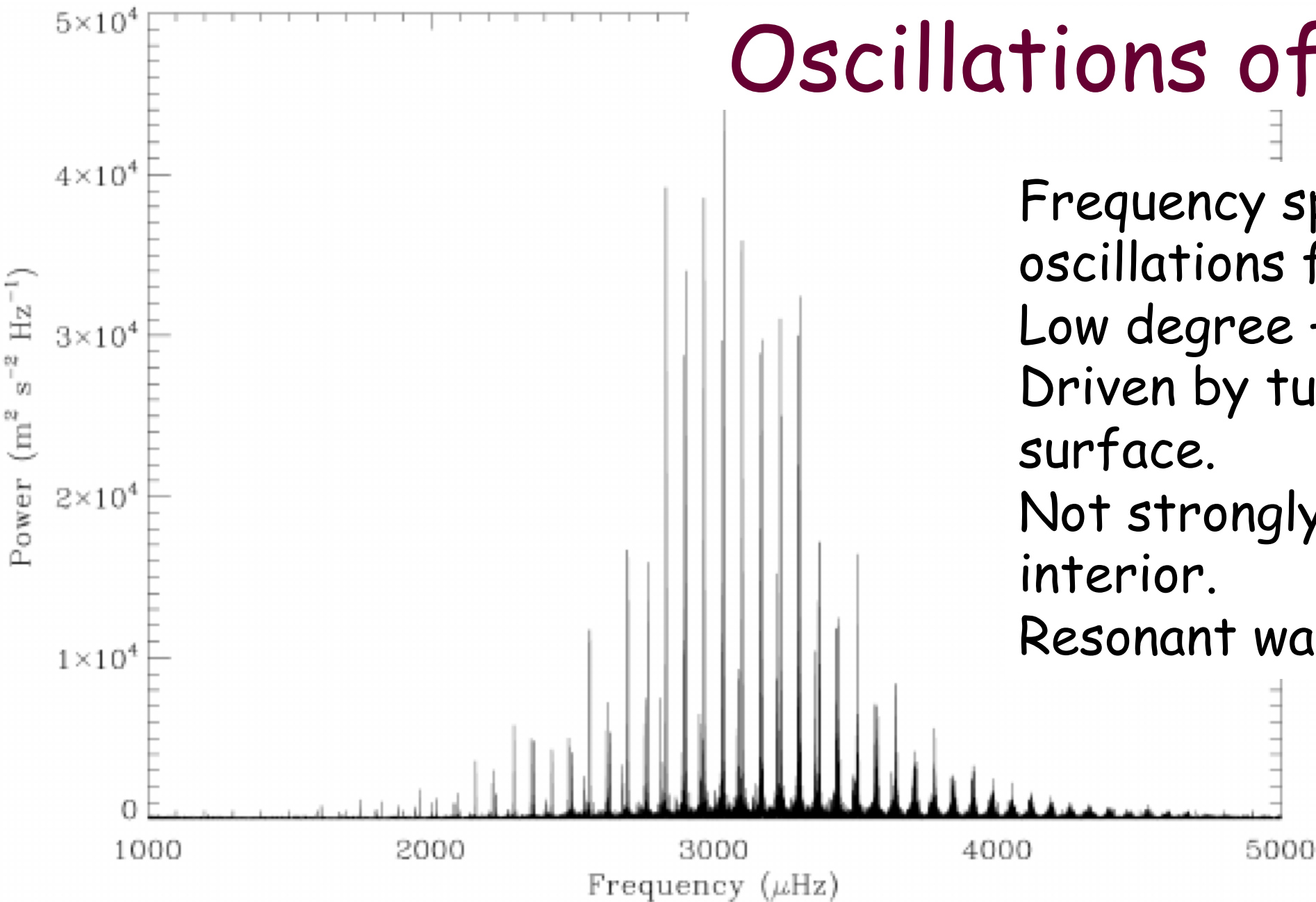
Models of
oscillations
colour-coded
for Doppler
velocity



To see modes as on right requires imaging

Modes described with 2 integers, ℓ & m [like latitude and longitude]

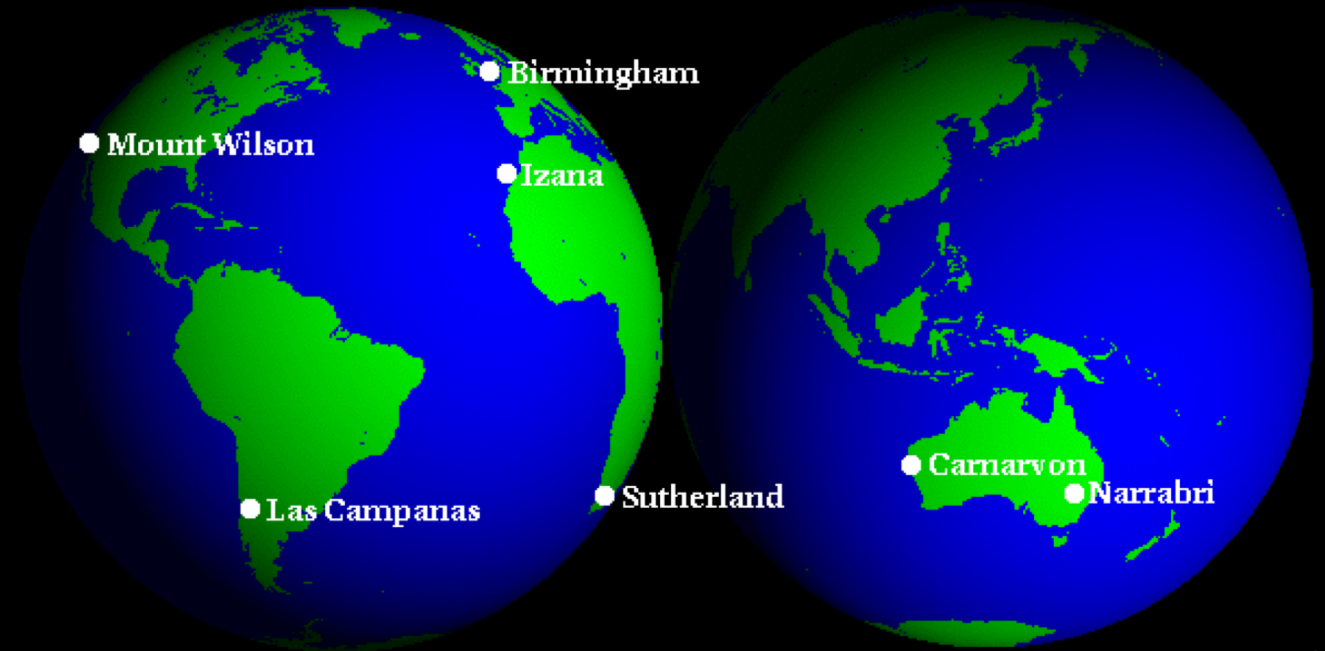
Oscillations of the Sun



Frequency spectrum of solar oscillations from BiSON.
Low degree - Sun as a star.
Driven by turbulence near surface.
Not strongly damped in the interior.
Resonant waves .

BiSON group over many years

BiSON | Birmingham Solar-Oscillations Network







New instruments on a smaller footprint



Recent upgrade in Tenerife

The automated Sky-Watcher AZ GTi Alt-Az mount and solar telescope installed on a pier inside the weather enclosure.

See Hale et al 2026, RASTI

Tenerife - Izaña 2023 problems



Helioseismic Magnetic
Imager (HMI) on SDO



Imaging Instruments

Global Oscillations
Network Group (GONG)



Polarimetric and
Helioseismic Imager
(PHI) on Solar
Orbiter



Global vs. Local Helioseismology

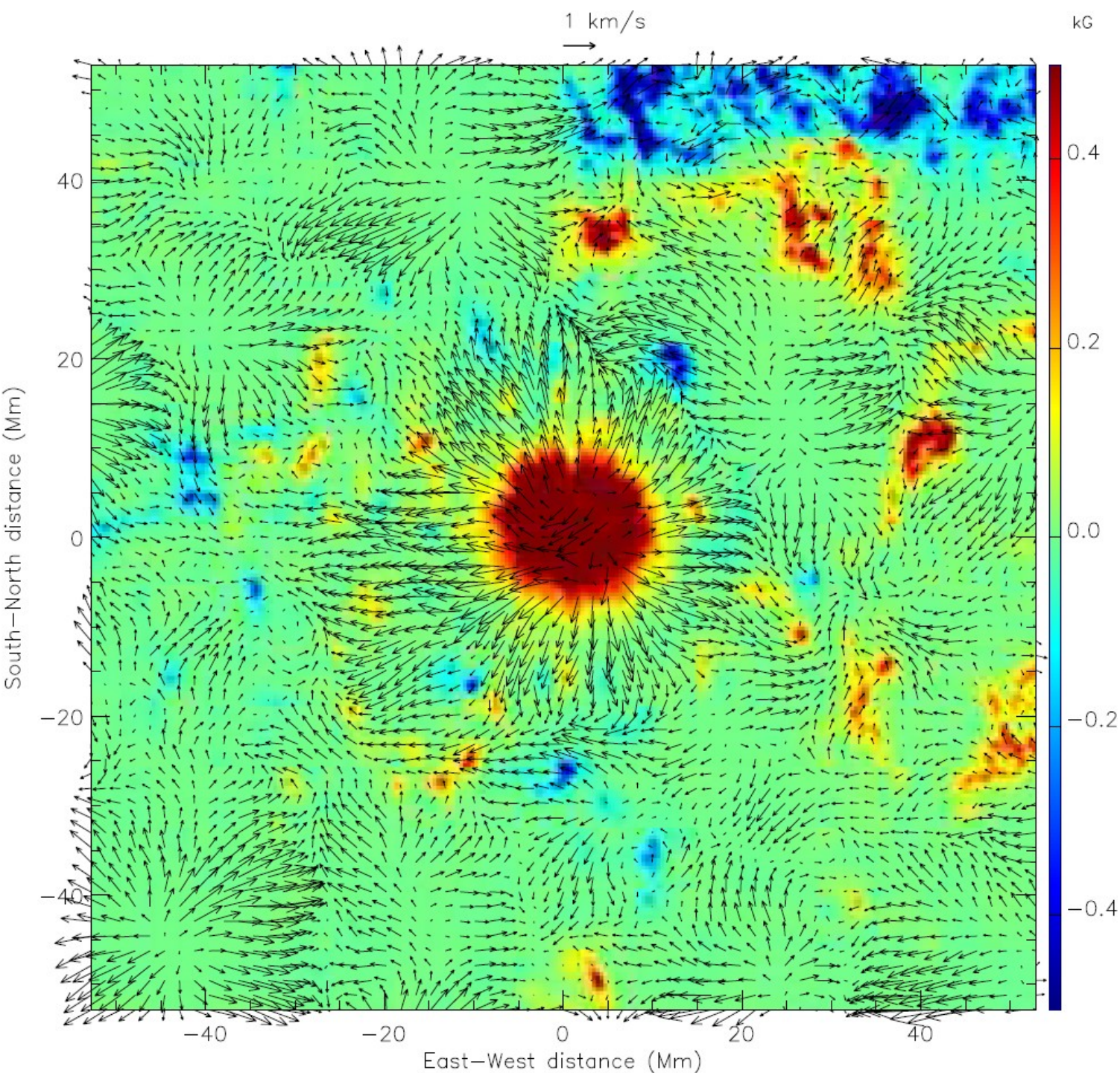
Global seismology:

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

Global vs. Local Helioseismology

Local seismology:

- Observe effects of interference in small volumes beneath surface



- Using local helioseisomogy
- Horizontal flows around a sunspot on 1998 December 6
- Also the line-of-sight magnetic field (MDI high resolution) truncated at ± 0.5 kG.
- The moat flow beyond the penumbra (red) is clearly visible.

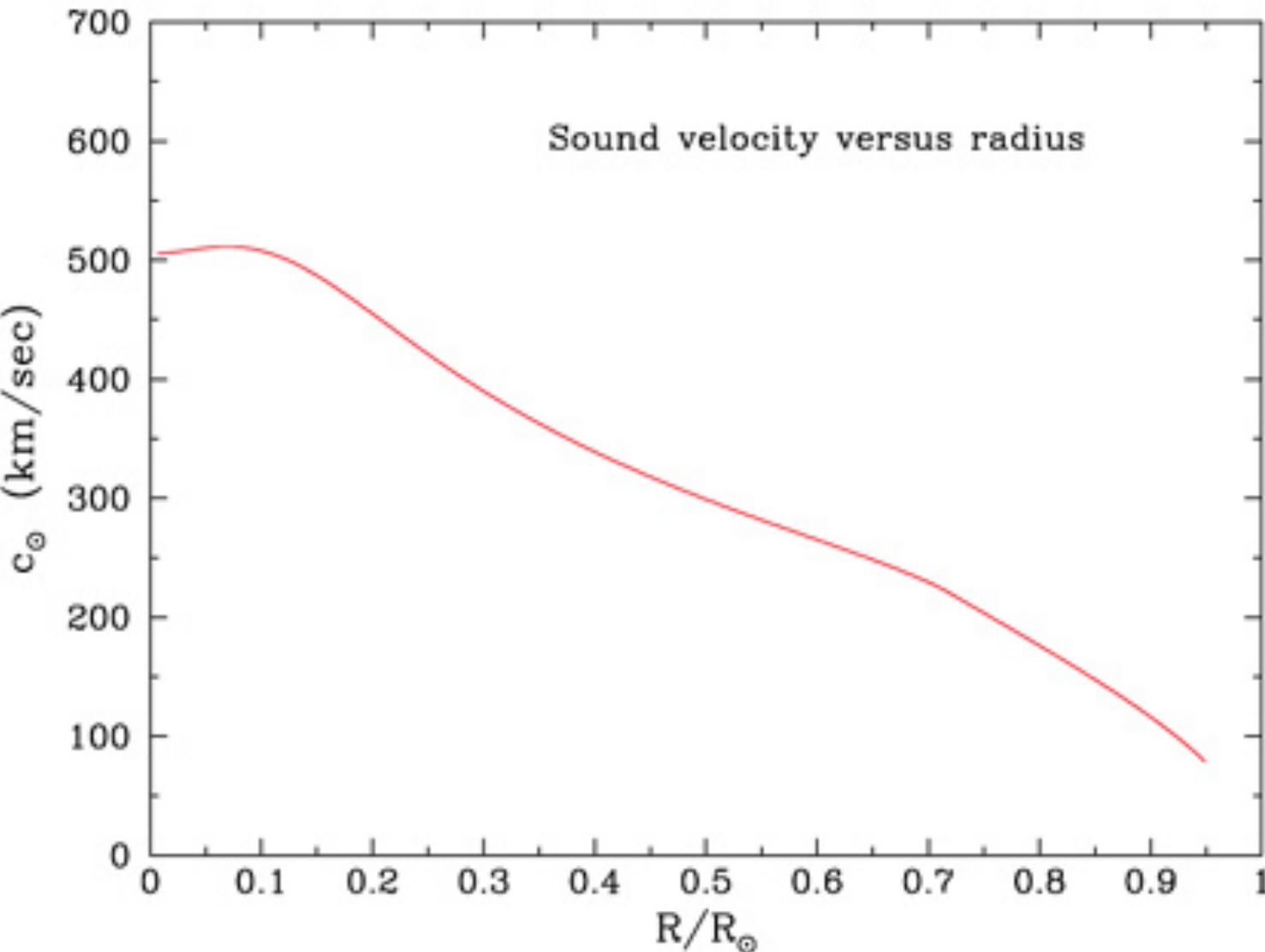
Gizon & Birch 2005.
Living reviews

Internal Structure and Rotation

Made possible by wide range of modes
that sense different parts of the Sun.
Many instruments with data over decades

Backed by theory and lab experiments

Inversions for solar sound speed

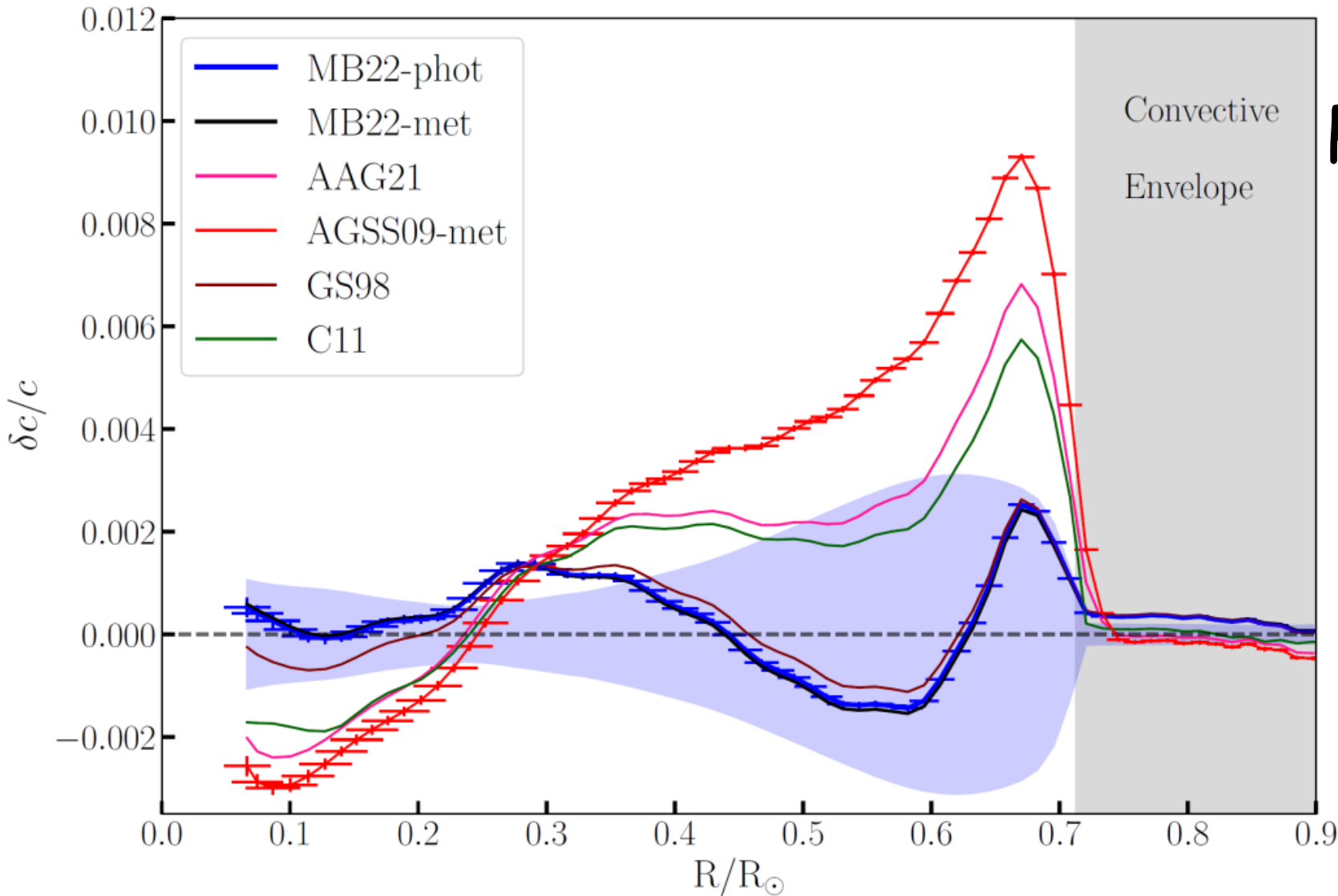


- Classical depends on local temperature, mass and other effects
- Uncertainties tiny so look at differences
- Compare with models to improve understanding

First determination - Christensen-Dalsgaard et al., 1985

Solar Abundance Problem Solved (?)

- Inversions for solar sound speed.
- Shaded blue area is input uncertainty.
- Red - problem compositions.
- New composition model does well.
- Still a few curiosities with opacities.
- **Answer is 'well maybe'**

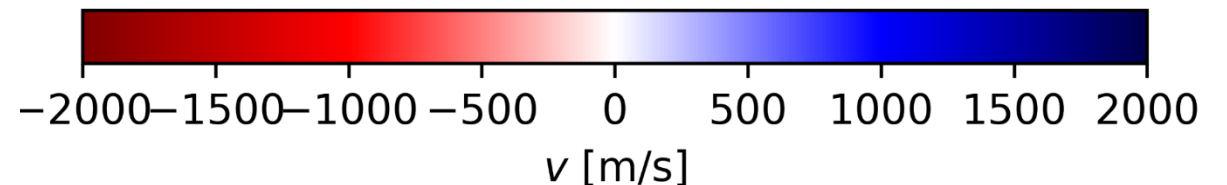
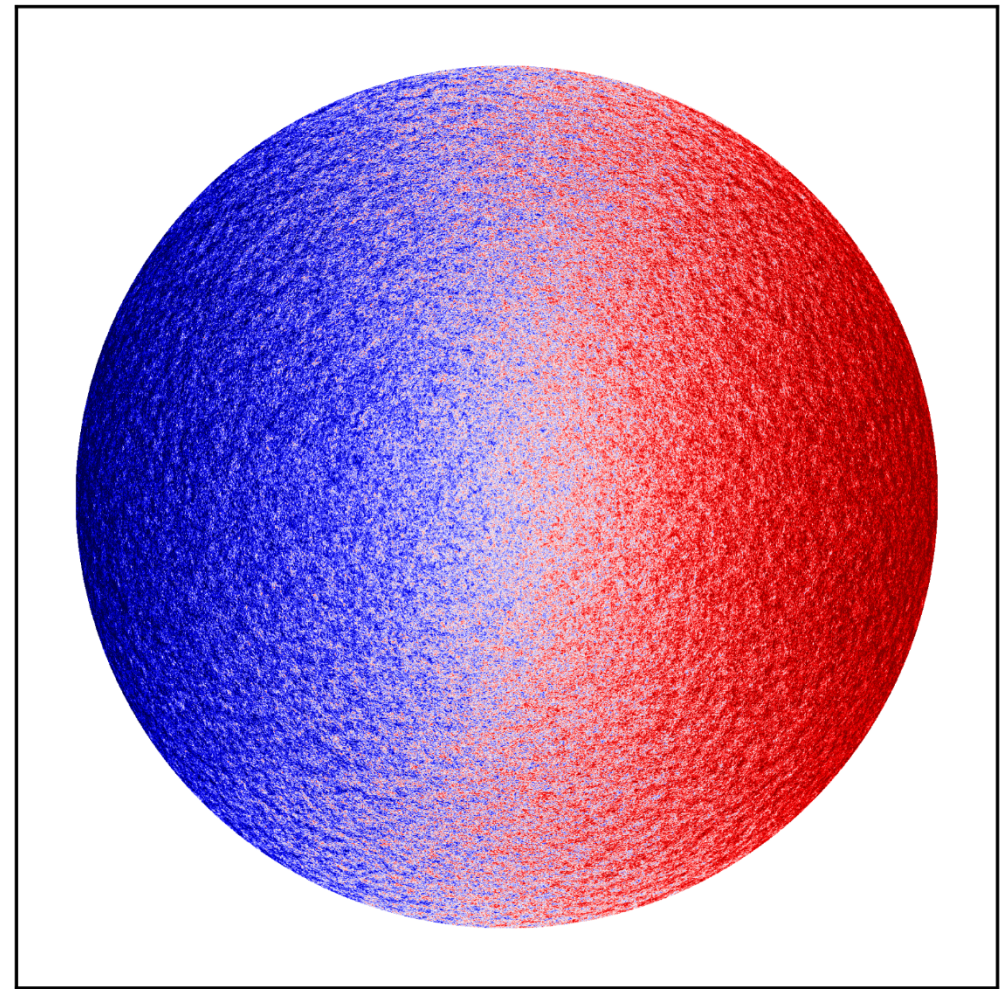


Ekaterina Magg et al. 2022

Surface Rotation of the Sun

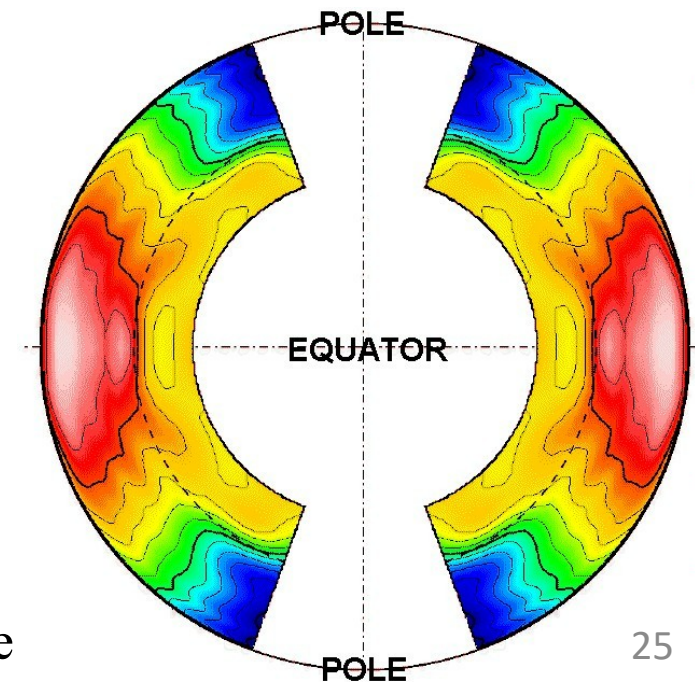
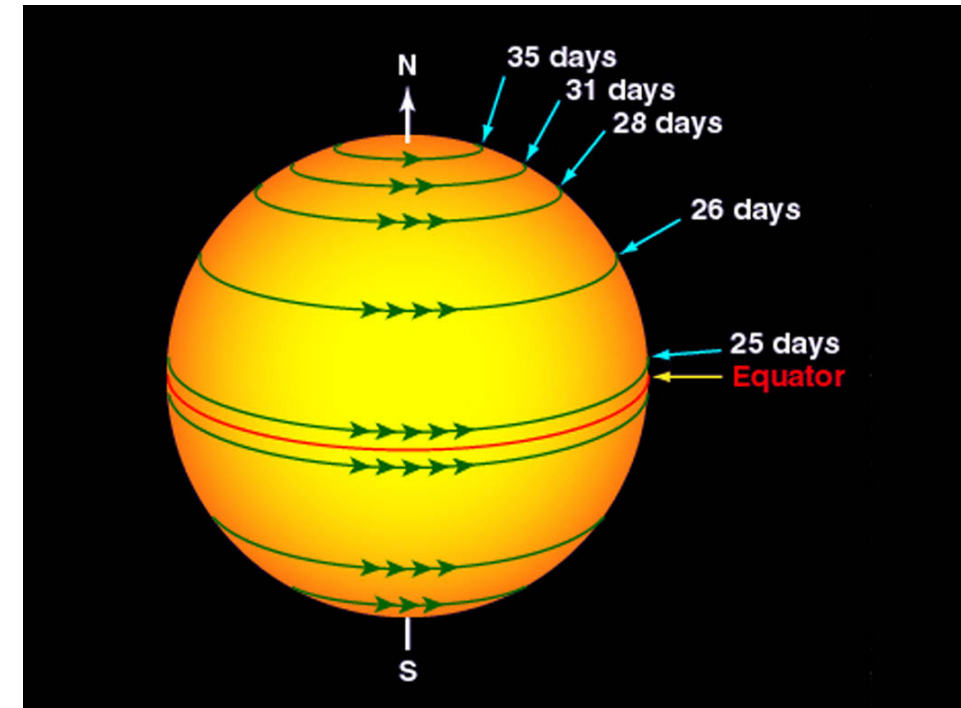
Helioseismology view - colour coded for Doppler shift towards and away

Image from Rachel Howe using satellite (HMI) data

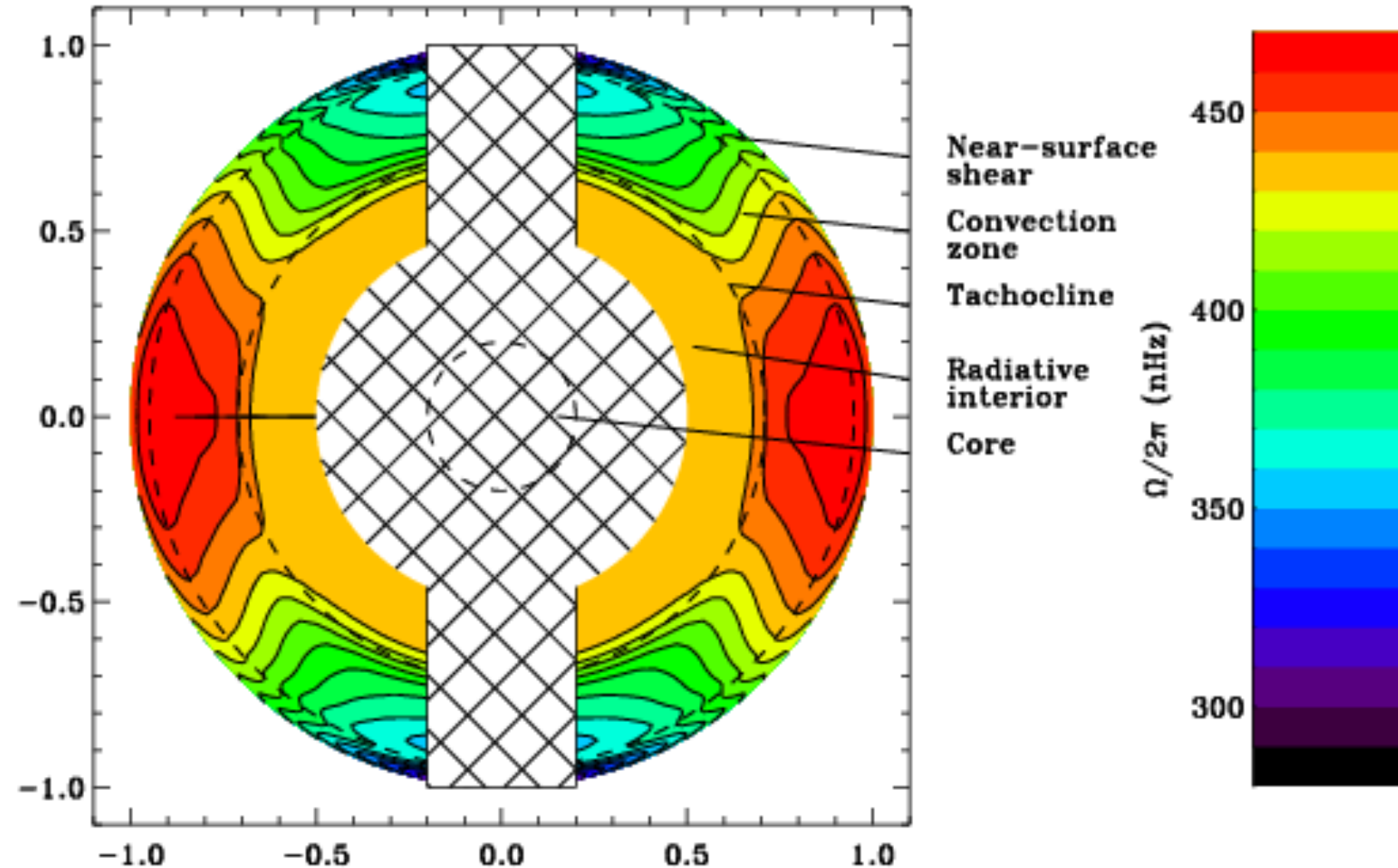


Surface and interior rotation

- Surface not solid body rotation (Scheiner)
- Fastest at the equator
- Use the resolved-Sun(2D) data to produce map
- Many modes and hence detailed mapping
- Red is fastest then yellow, green, blue
- Hard to image the poles from plane of the ecliptic
- Inner regions most probably like solid body



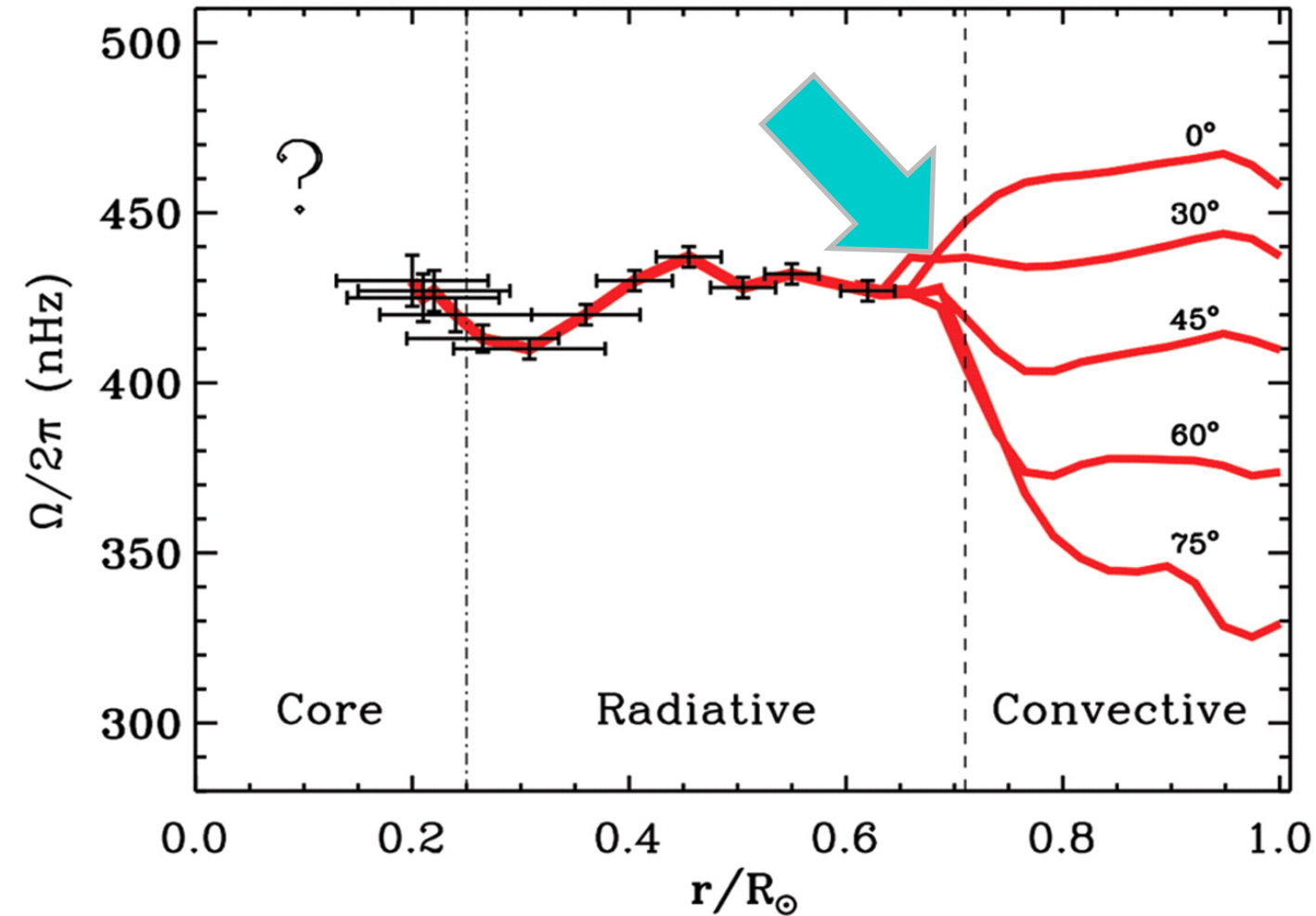
Internal Solar Rotation



GONG data

Note:
Not constant
on cylinders.

More complex



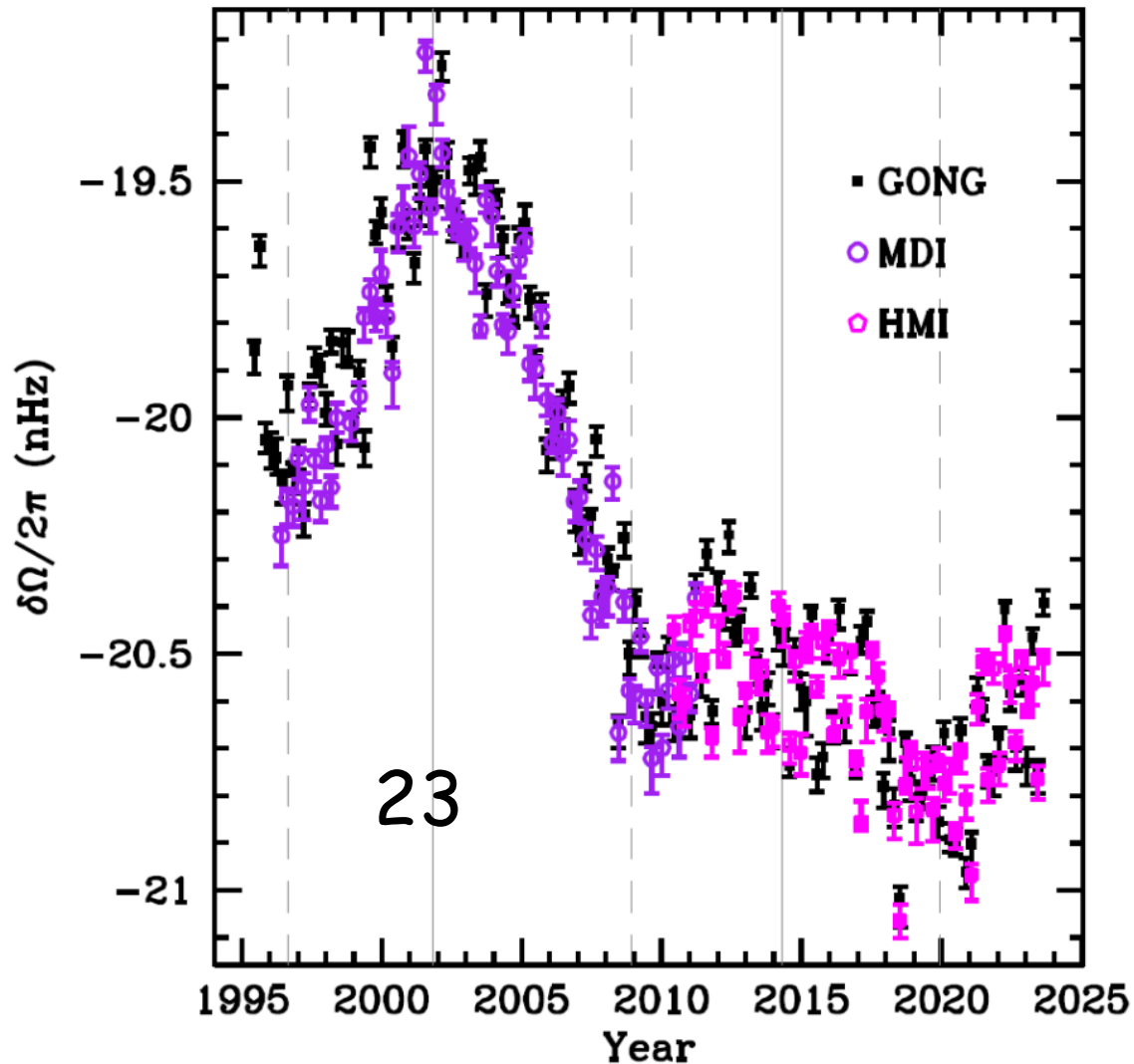
The Tachocline (‘speed slope’)

Located just around base
of convection zone.

Big question of whether
flows from convection zone
can penetrate the interior.

Key for dynamo action!

Big uncertainty about core rotation but probably uniform

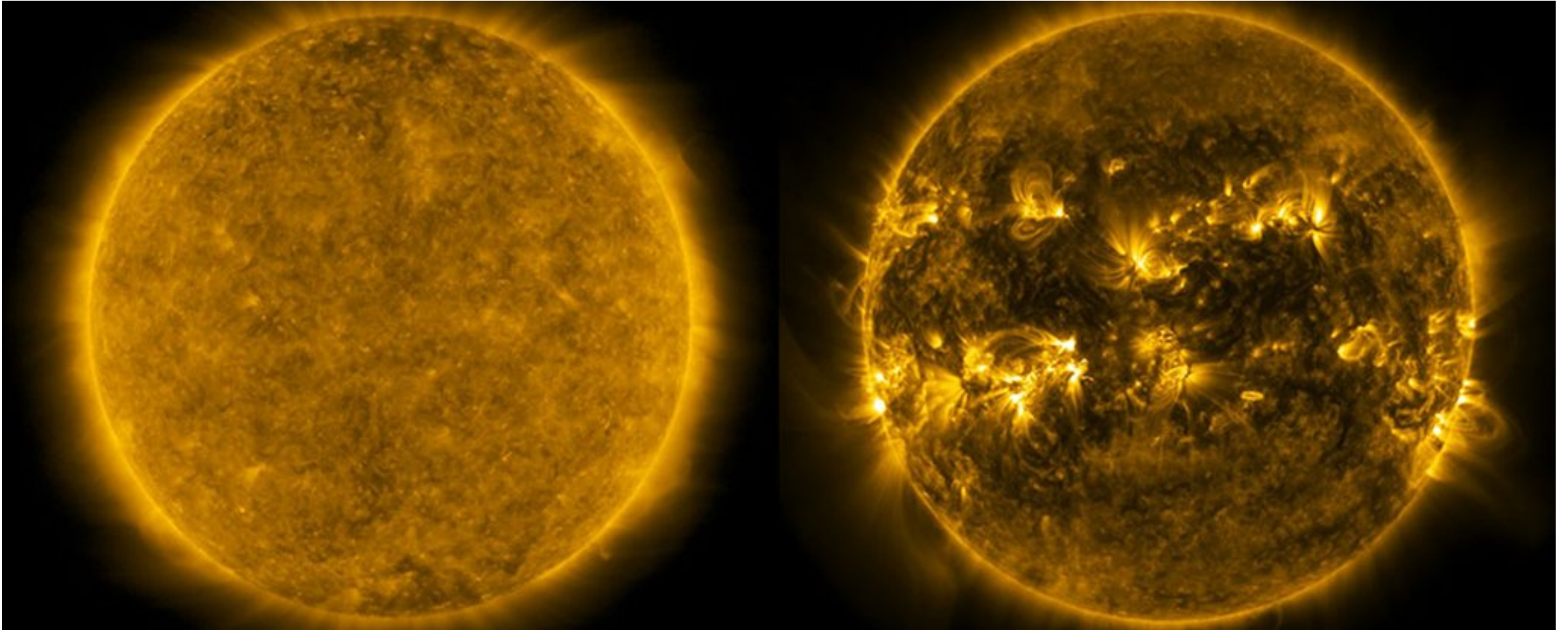


Sarbani Basu et al., 2024

Tachocline variations

- Zone where rotation changes.
- $\delta\Omega$, the jump across the tachocline.
- Uses resolved-Sun data from several sources
- Solar maximum - solid vertical lines, minimum - dashed.
- Clear trend in the rotation jump with activity but not repeating from cycle 23 (marked) to cycle 24.
- Some evidence for increase at start of cycle 25 (2020 - 2025).
- Note that minimum between 23 & 24 was unusual - extended and low activity.
- Width of zone roughly 2% of solar radius with some evidence for variation not synchronous with surface activity.

Probing activity and the solar dynamo



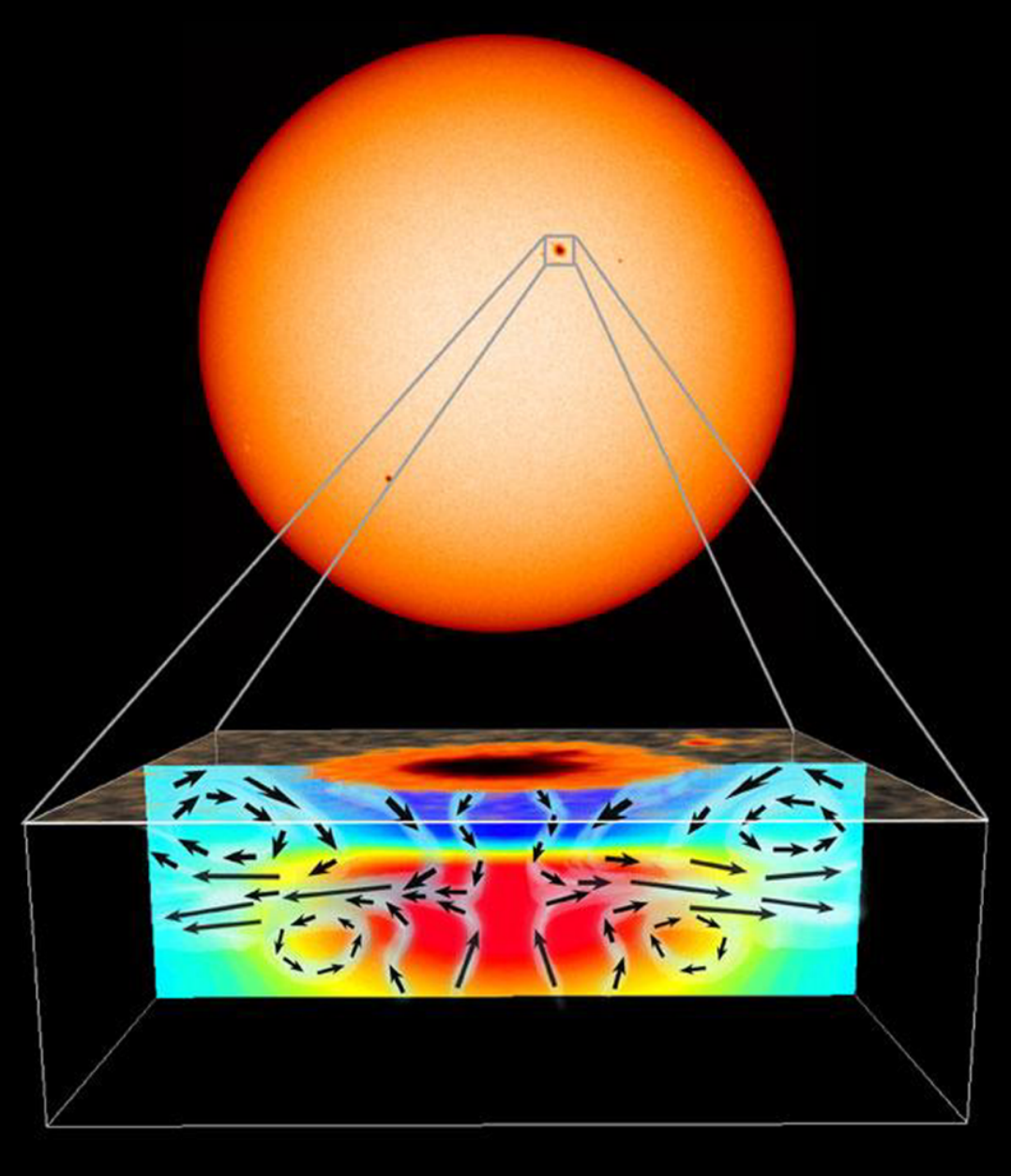
Flows and wave speed variation beneath sunspot

Arrows show flows:

Colours show wave-speed:

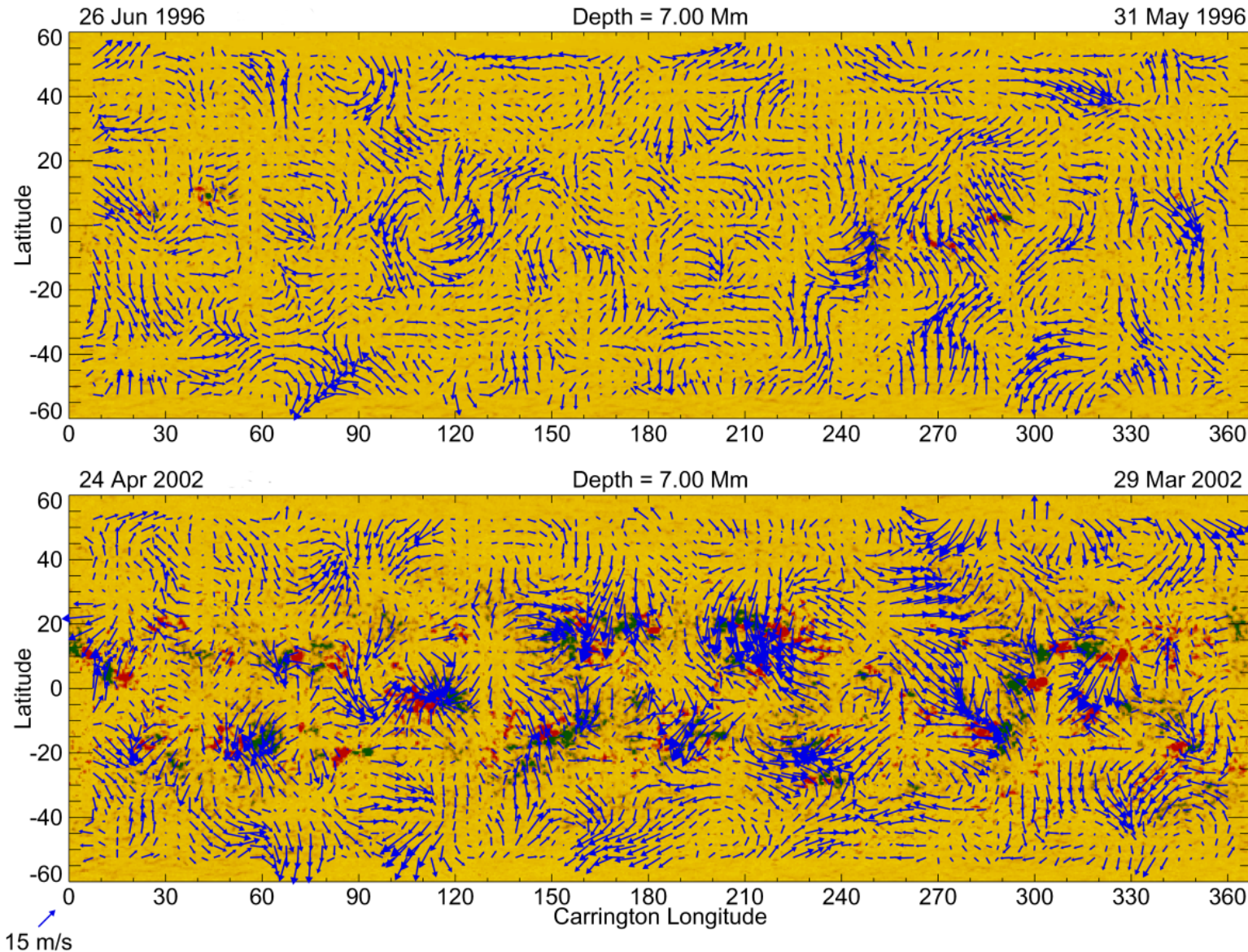
Faster... **red**

Slower... **blue**



Courtesy A. G. Kosovichev

Solar Sub-Surface Weather



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

Measure flows underneath small patches

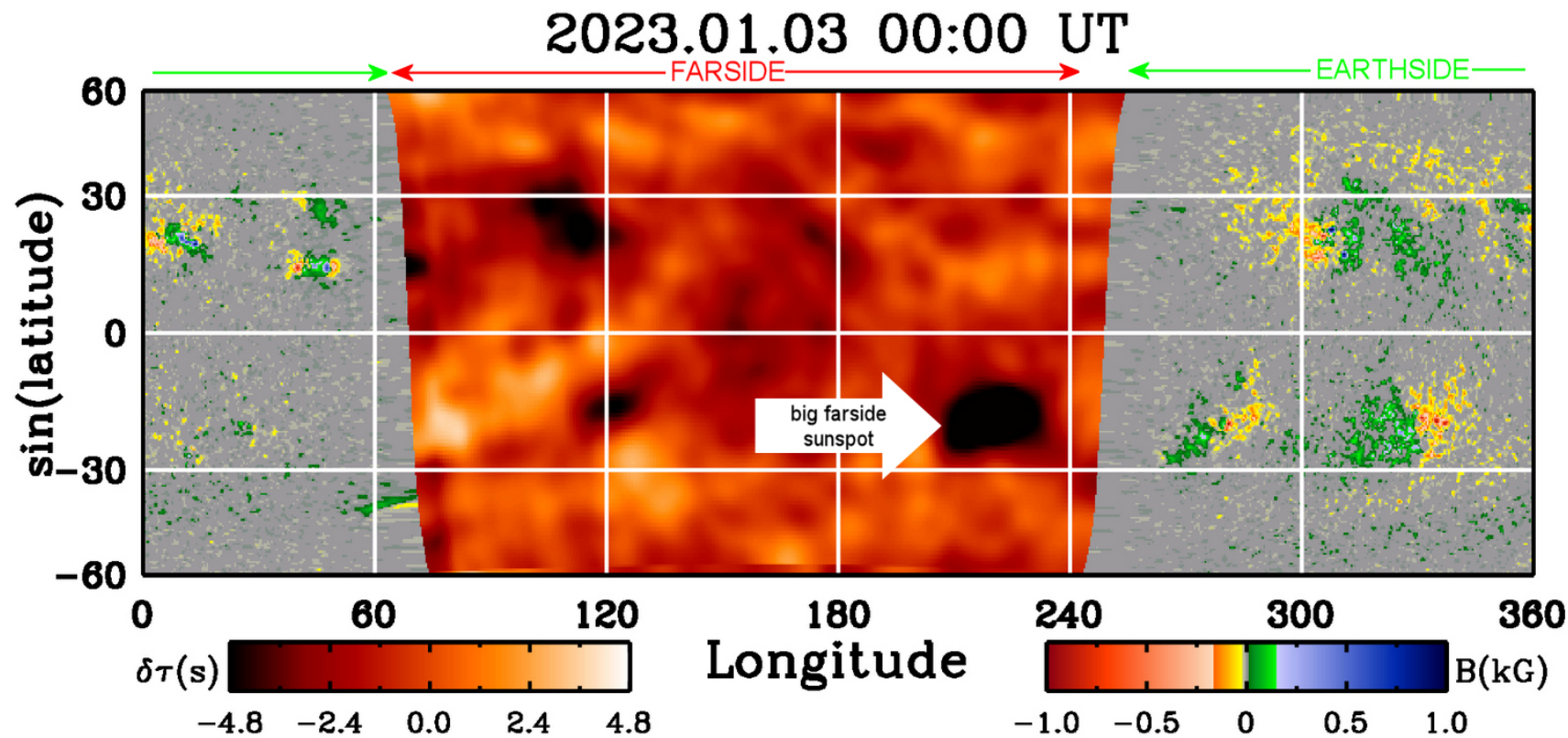
Rotation brings new patches into view

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

Used as tool in study of flares, CME etc.

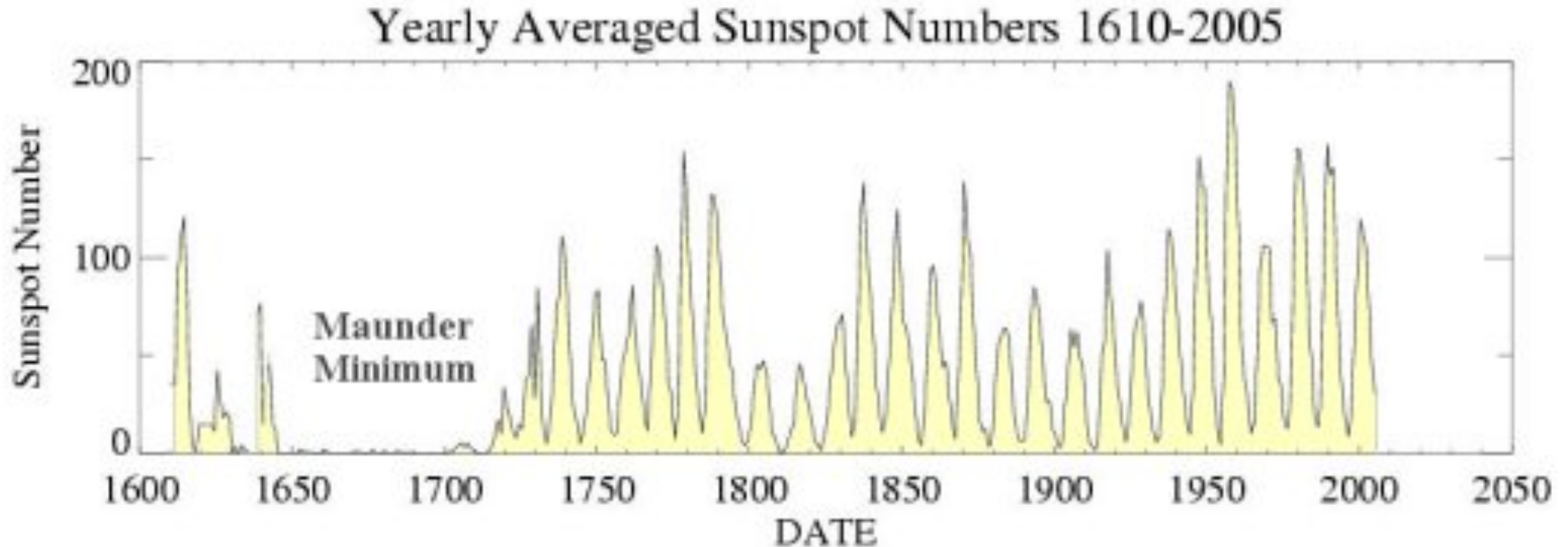
Space weather predictions

Because the oscillations sense all the Sun and not just the bit we can see - Far-side imaging of active regions



BiSON frequencies also show sensitivity to whole Sun. We cannot image but can estimate spot lifetimes!

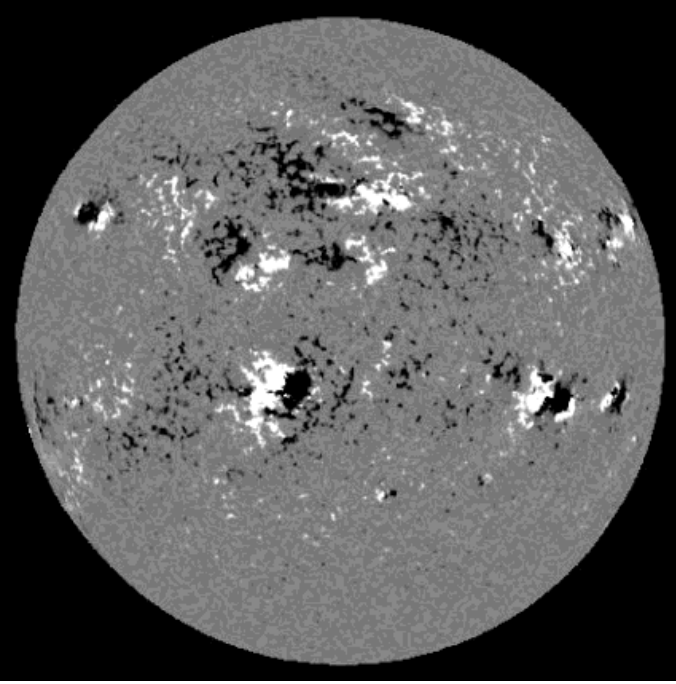
Sunspot record: solar cycles



Note the Maunder minimum - a period of quiet Sun
<https://helioforecast.space/solarcycle> for up-to-date

What is the Solar cycle?

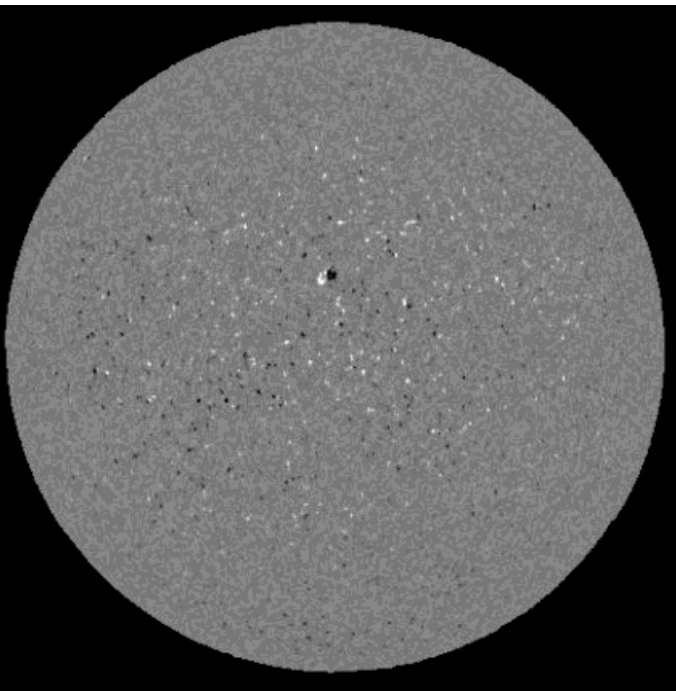
- We know that is only approximately 11 years.
- Varies in length and in the size of the changes.
- Underlying cycle, taking reversal of magnetic field into account is actually 22 years
- Is it on the surface or deep or both?
- Is one cycle like another?
- Can it be reproduced theoretically?
- Impacts on our climate

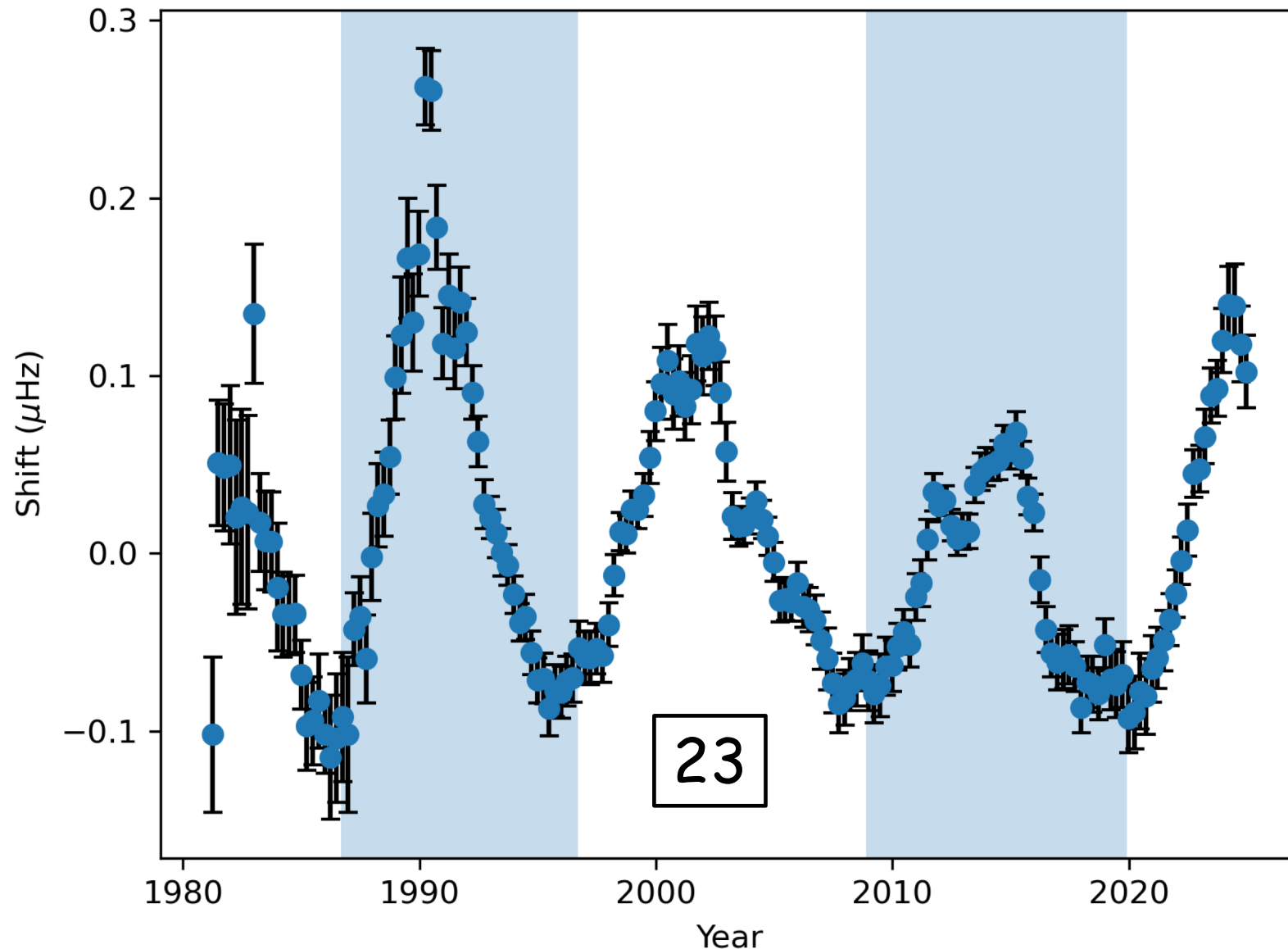


Oscillations as probes of activity and the solar cycle

Magnetic fields can change mode frequencies & splittings:

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

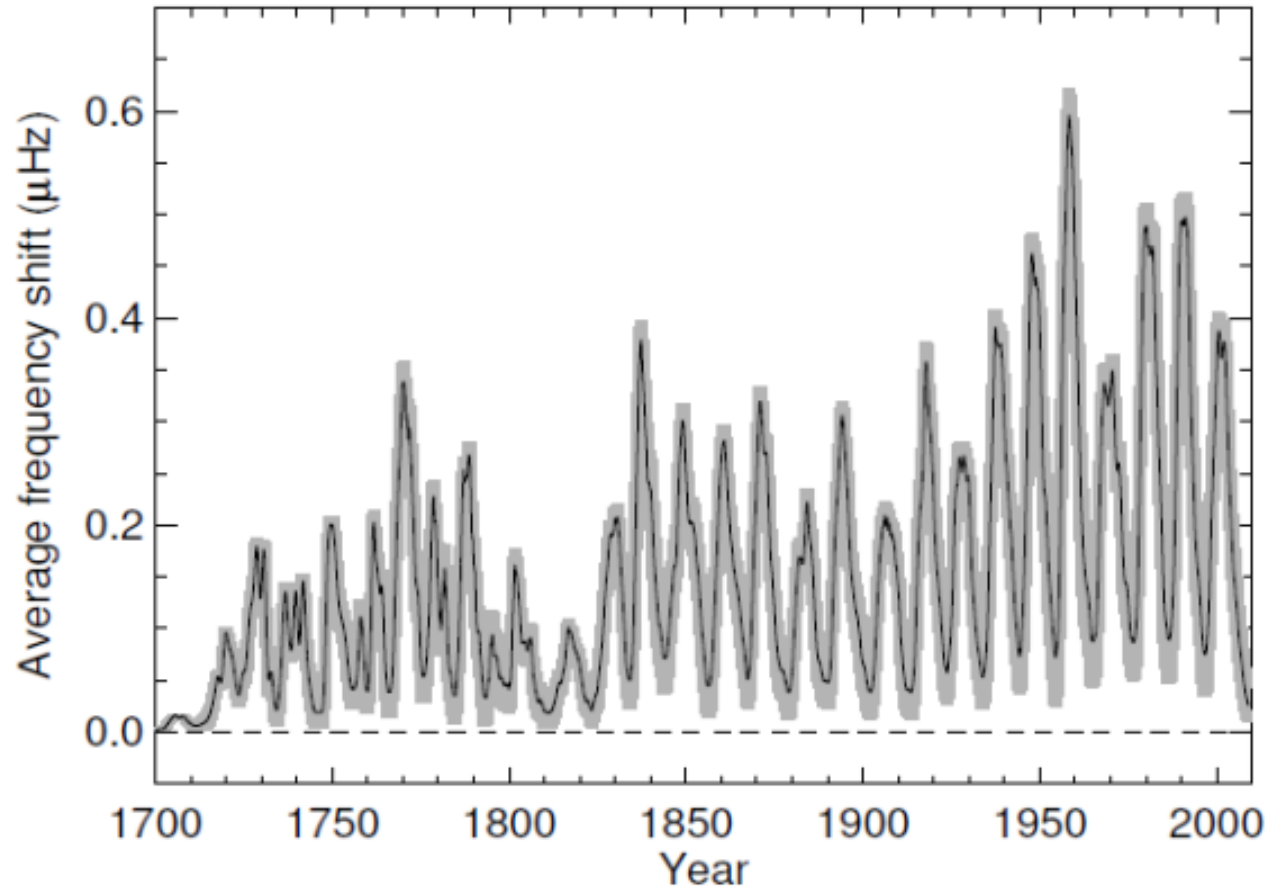




Recent BiSON average frequency shifts

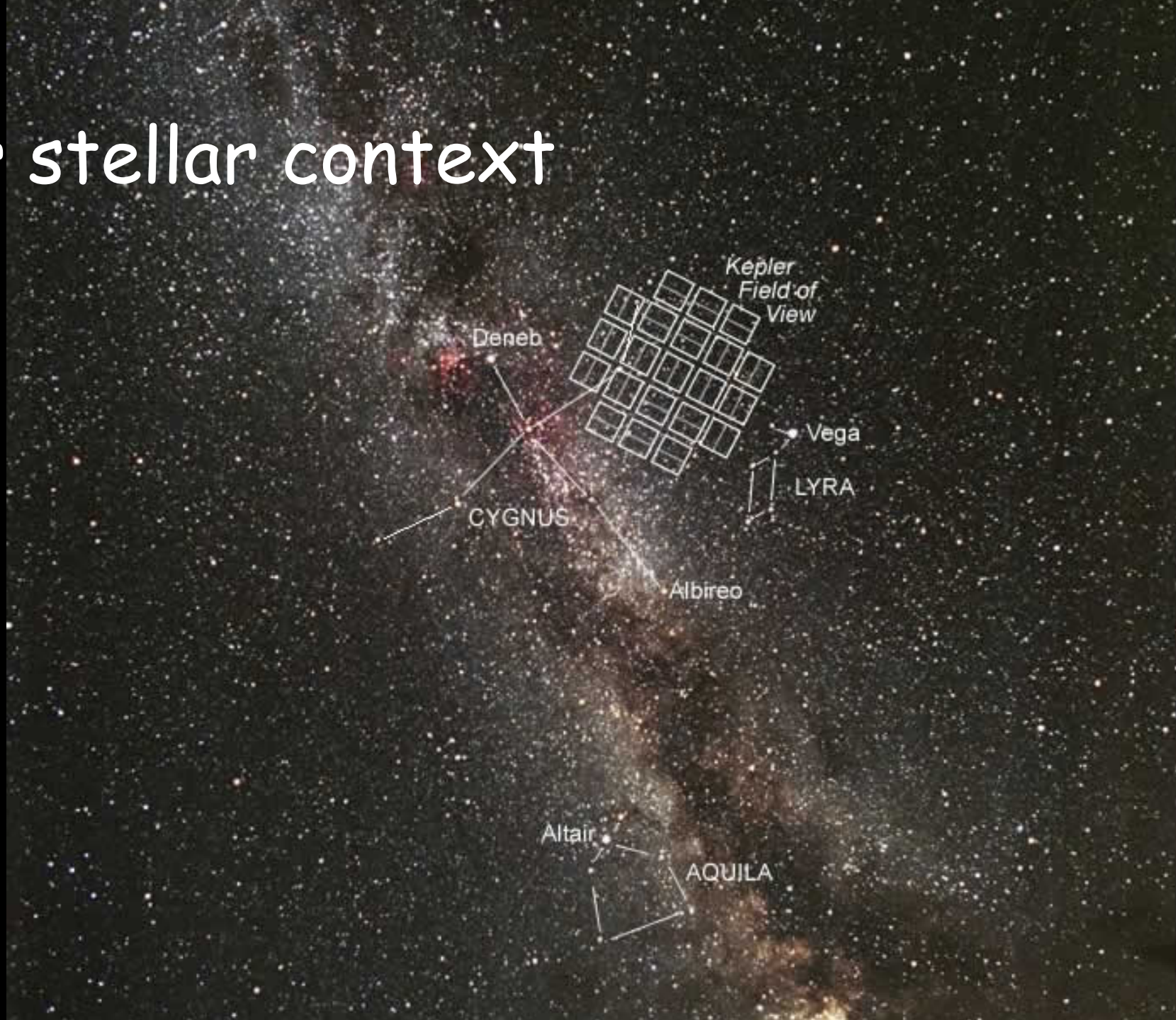
- Colour bands indicate cycles - now 5 of them
- Typical oscillations at $3000\mu\text{Hz}$.
- Changes are small $<0.5\mu\text{Hz}$
- Sun is a variable star!

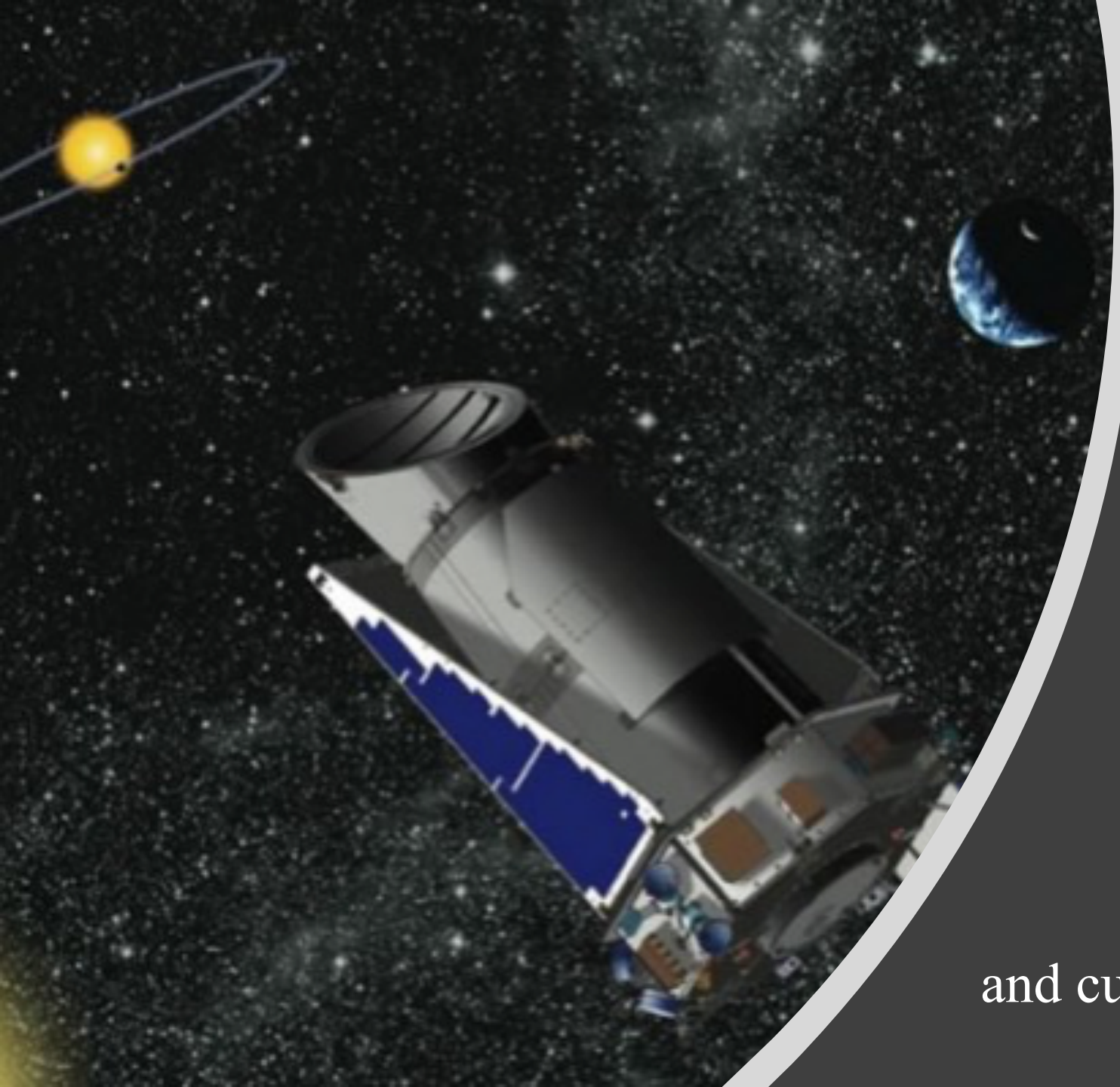
Prediction: Seismic Sun back to the Maunder Minimum



Useful for testing models with no surface magnetic fields (and other things)

Wider stellar context



An artistic rendering of the NASA Kepler Mission spacecraft in space. The spacecraft is a cylindrical telescope with a large primary mirror and a secondary mirror, mounted on a service module. It is shown in a three-quarter view, angled towards the viewer. The background is a deep black space filled with numerous stars of varying brightness. In the upper left, a bright yellow star is visible with a thin, elliptical orbit line around it. In the upper right, a small, blue and white planet, resembling Earth, is visible. The spacecraft has a blue and white color scheme, with various instruments and antennas visible on its exterior.

NASA *Kepler* Mission (+K2)

NASA convinced of the
benefits of
asteroseismology to
planet hunters - *Kepler*
Asteroseismic Science
Consortium (KASC)

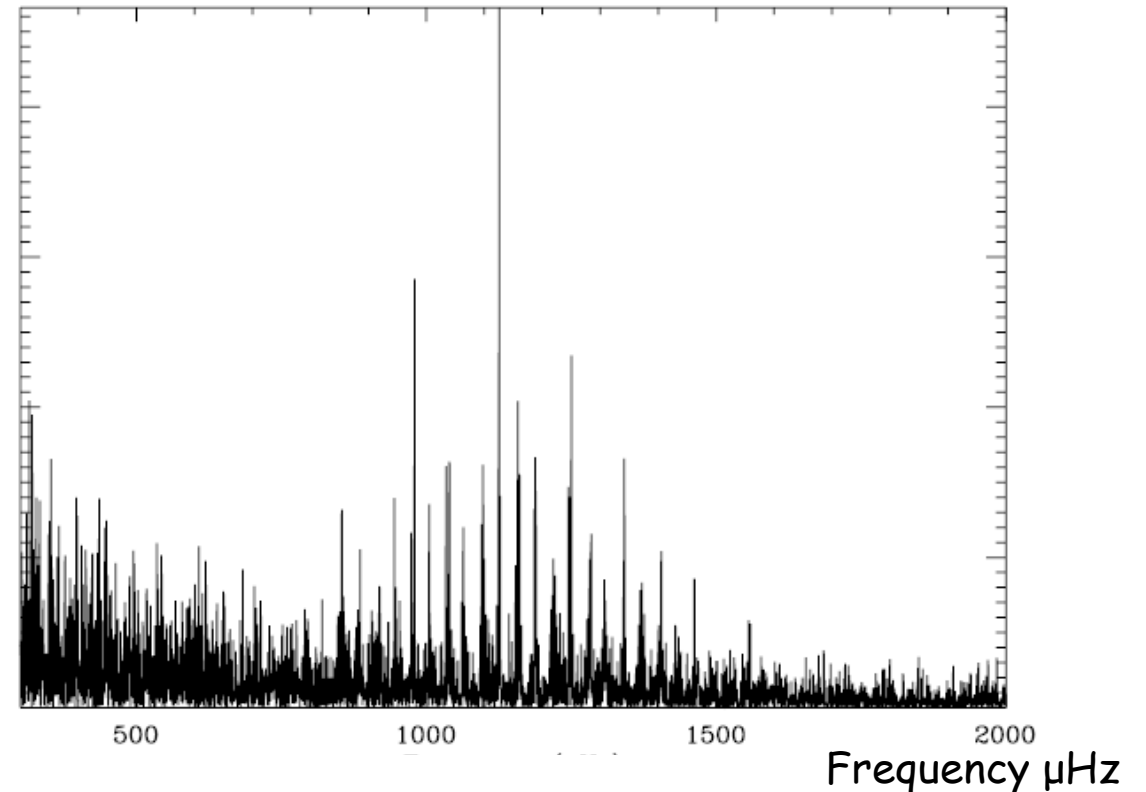
and currently TESS and soon Plato

Kepler was designed to find rocky planets using transit method.
Seismology important in determining Mass & Radius

Kepler-21. Star a bit more massive than the Sun and a bit more evolved but in a similar evolutionary state. Has a rocky planet 1.5-times size of the Earth orbiting every 2.8 days at a distance of 4.3% of the Earth-Sun distance.



<http://cache.gawkerassets.com>

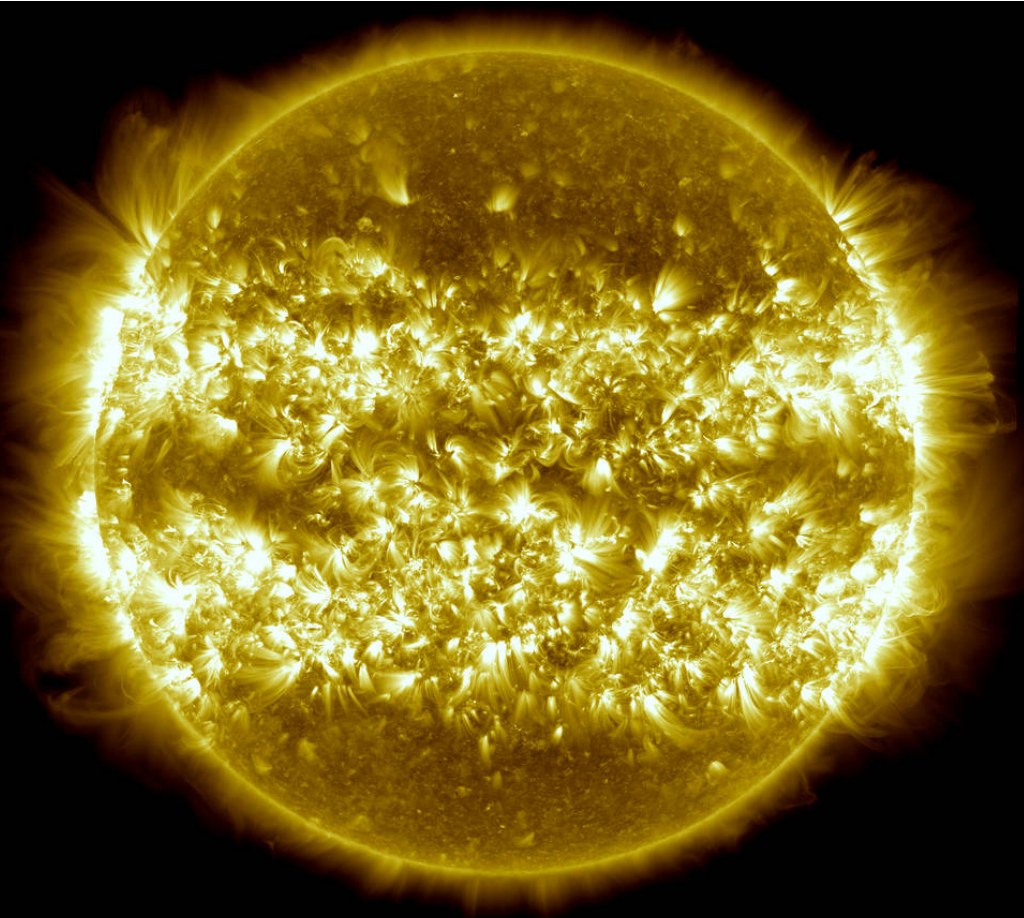


Howell et al., ApJ, Feb 2012

Noise background is a limiting factor for the detection of small planets

- For the Sun we have both Sun-as-a-star data and images.
- Very powerful combination.
- BiSON data plus resolved Sun data being used by a group in Physics at Birmingham to understand the processes influencing radial velocity noise and to drive down the noise.
- Hope to transfer the ideas to data from distant stars to increase the chances of detecting Earth analogues round them.

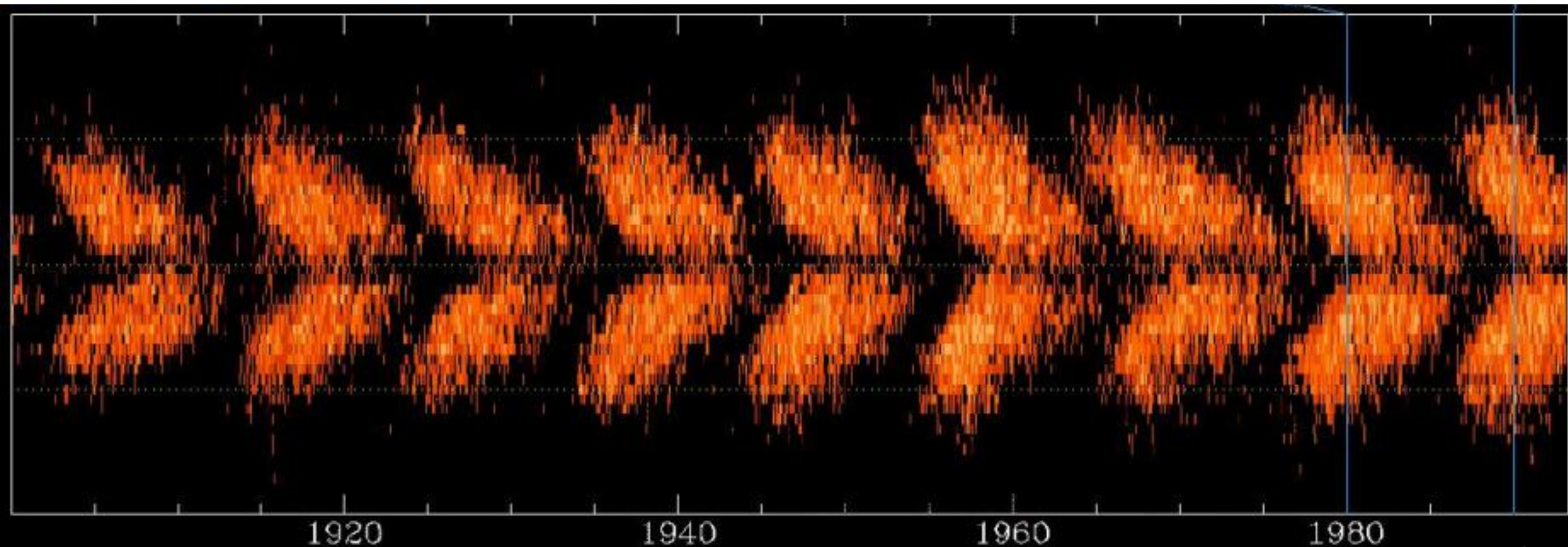
Use the Sun as a 'typical' solar-like star

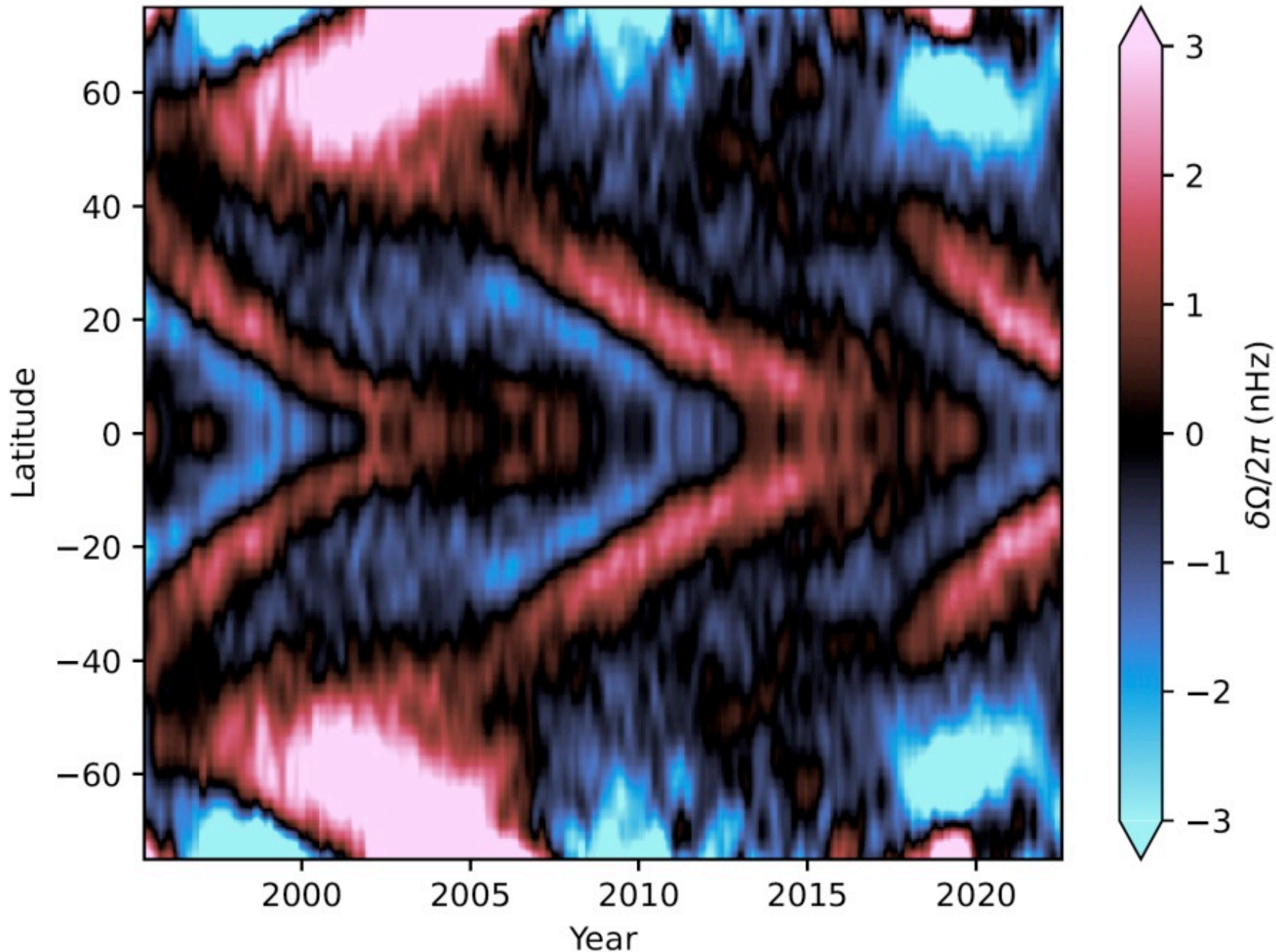


- For example - what are the active latitudes?
- Can we see this on distant stars which may have different polar orientations?
- Use the visibilities of modes of different degrees (0,1,2)
- Thomas et al., 2019, MNRAS, 485, 3857

Location of sunspots on solar surface : Butterfly Diagram

- Latitude of sunspots vs. date
- Note spots start at high latitude and are found closer to the equator as 11-year cycle progresses





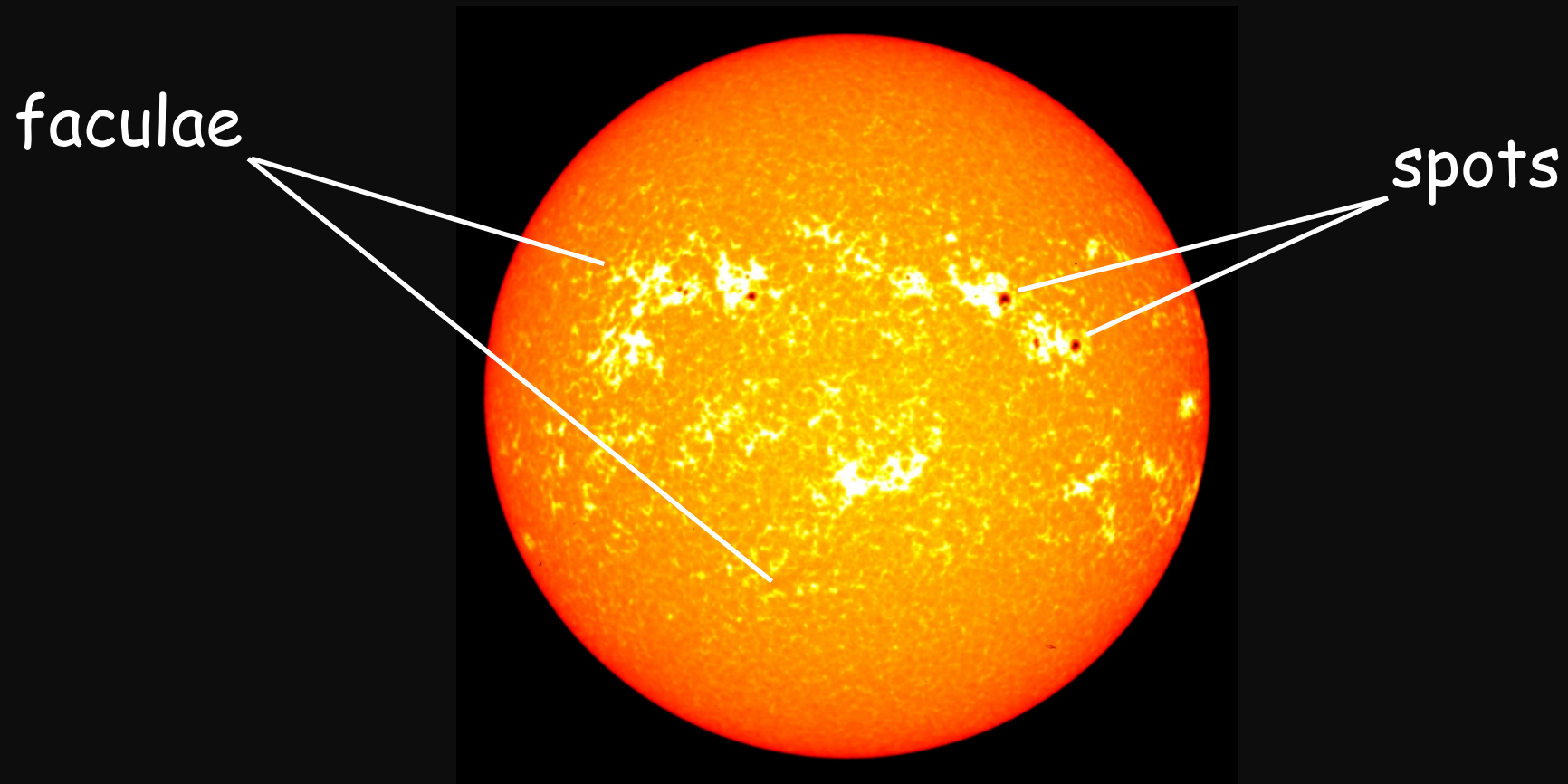
A digression to show that the solar cycle is visible below the surface as well.

Shows trends in the rotation rate.

Migrating bands of higher/lower than average speeds.

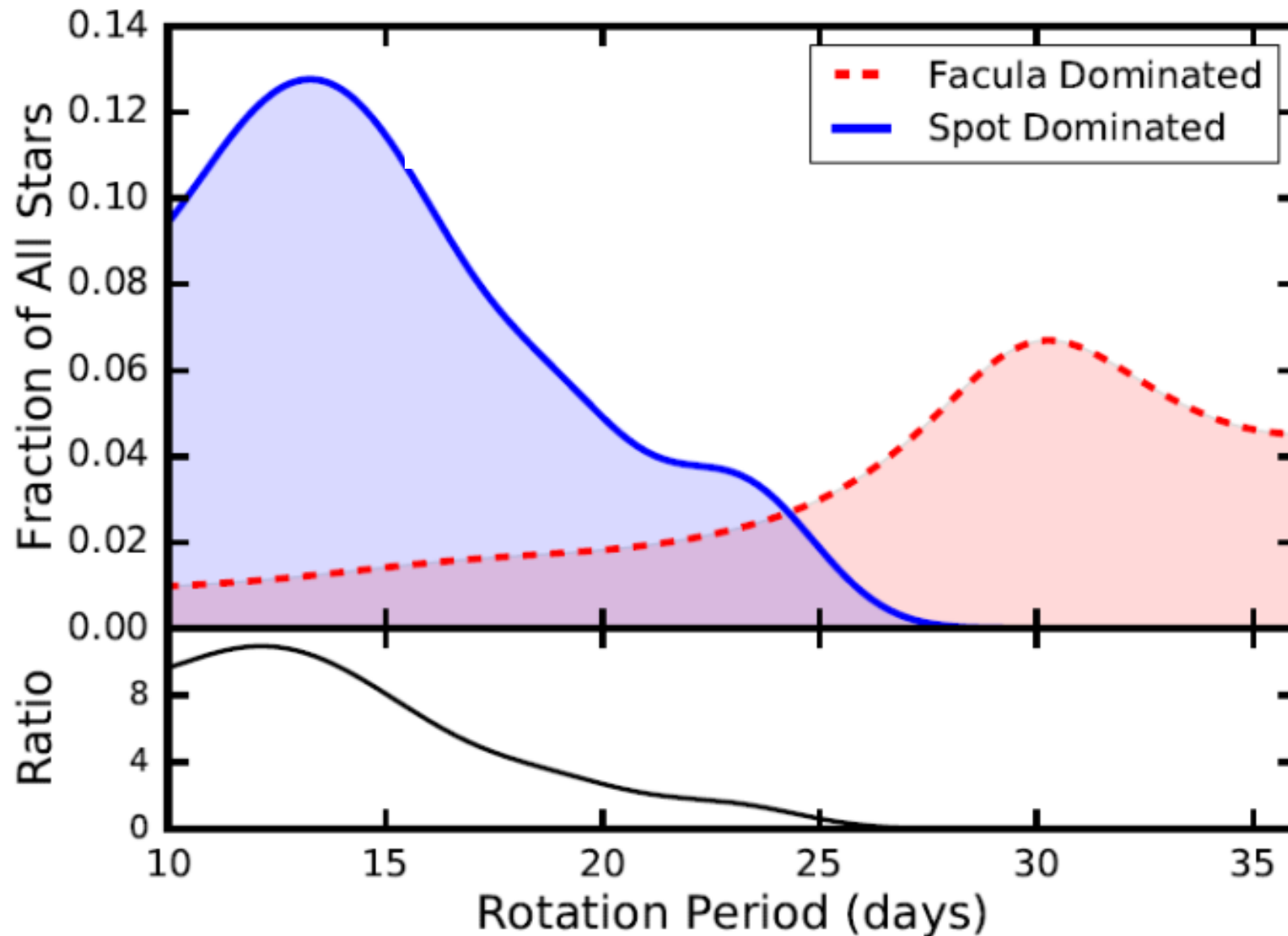
Howe et al., 2023,

Spots and Faculae



Credit: NASA/SDO/Goddard

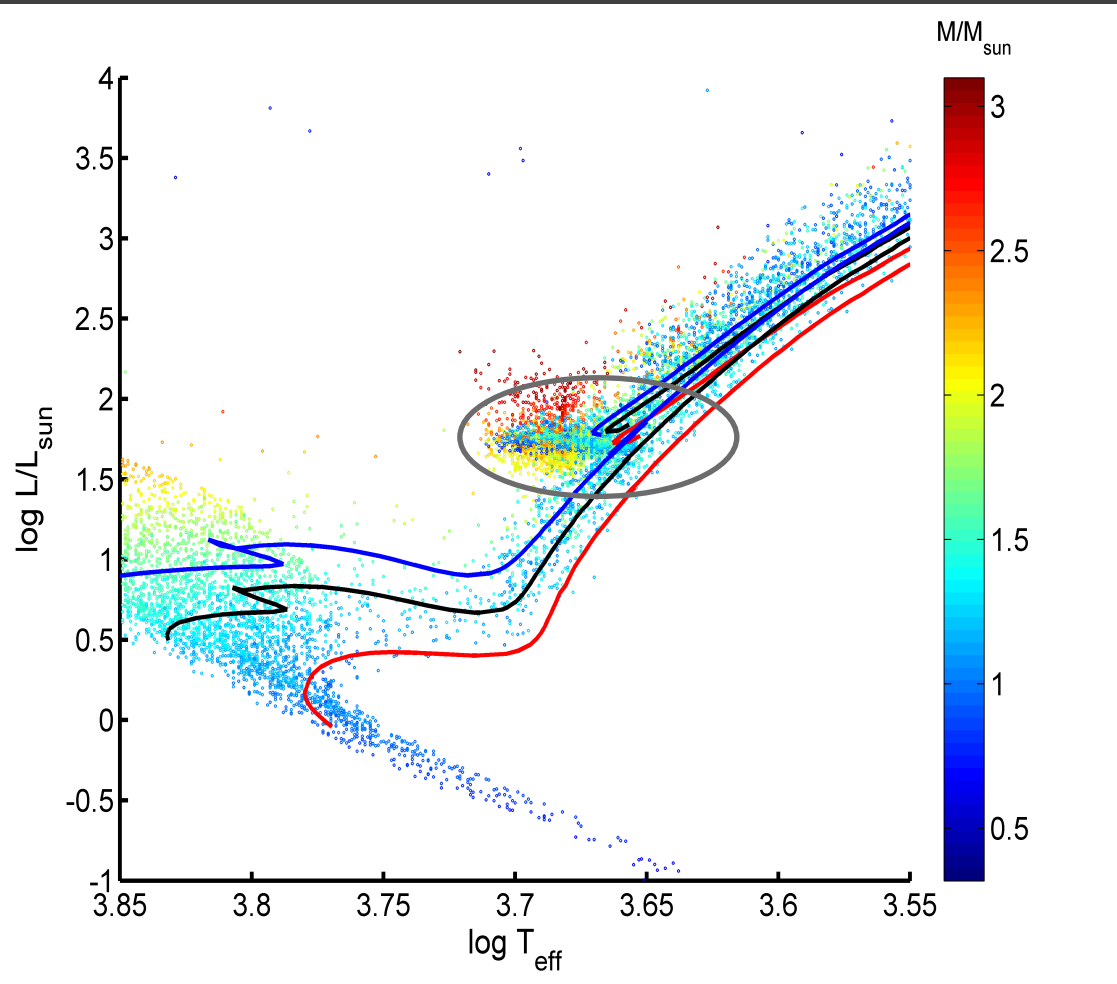
Long-term brightness variation



- *Kepler* lightcurves of solar-type stars
- Correlation between activity type and rotation period
- Sun at transition

Montet et al., 2017, ApJ, 851, 116

The size of the signals



For the low degree, solar signals in velocity 10cm/s is easy. Given time and coherent oscillations can get down to 1mm/sec (1 part in 10^{11})

For main sequence stars like the Sun, signals are at the μMag level. Periods are minutes which requires rapid cadence.

For Red Giants they are at mMag. But for Red Giants the periods are longer, a few hours. Very hard to do from the ground. 30min sampling fine.

Can use spectrum to distinguish Hydrogen shell burning and core-Helium burning in Red Giants

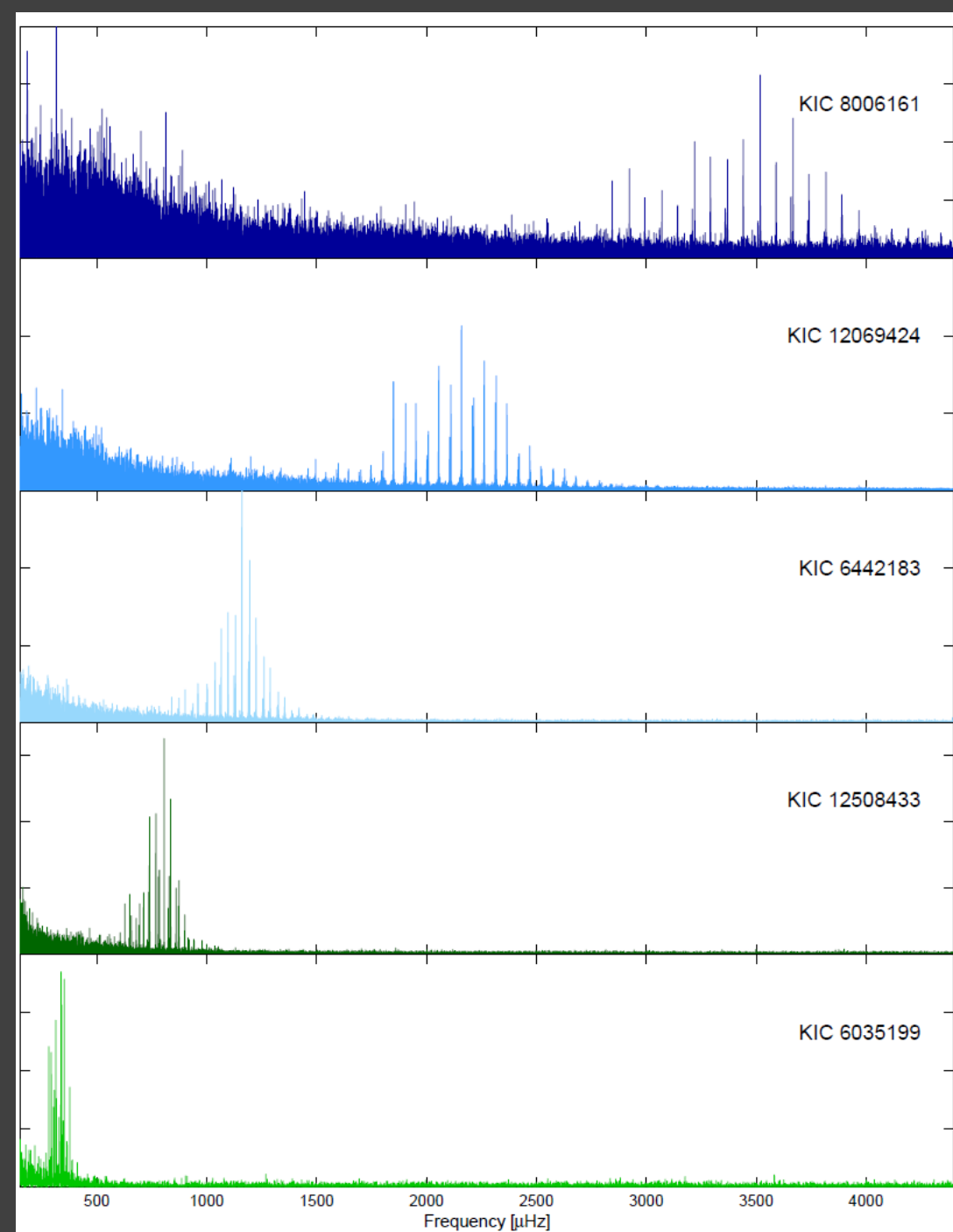


Evolution

1 solar mass sequence of Kepler stars.

From the top (main sequence) and getting older and larger with evolution

Not shown is the increase of the signal amplitude with age



ESA PLATO Mission



Studies of
other stars
gives
insights into
our local
star



Thank You

