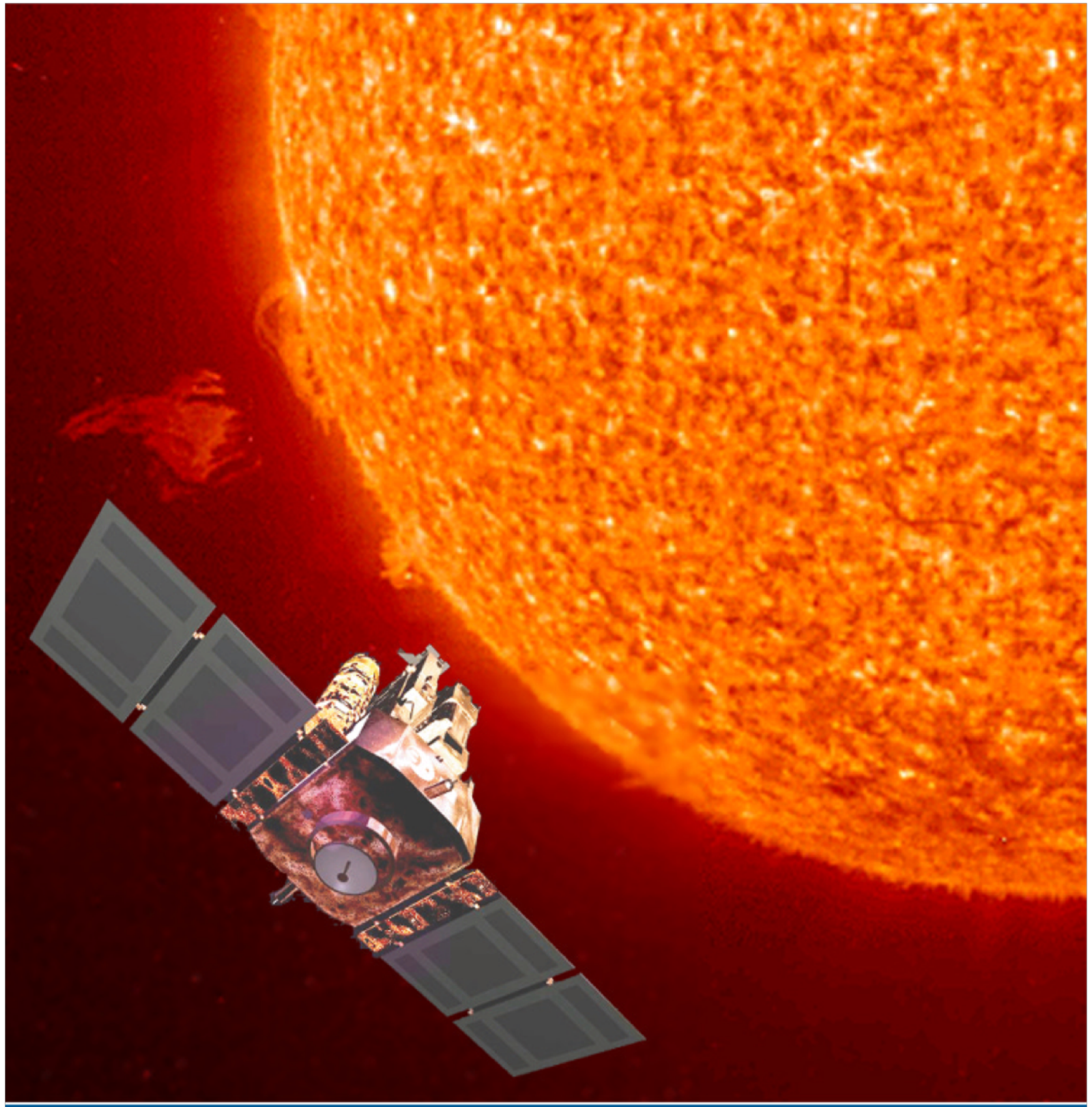
Studying the solar interior – why and how?



Norsk Romsenter
Norwegian Space Agency

Bo Andersen
Norwegian Space Agency/SIOS

What our great forefather thought

“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.

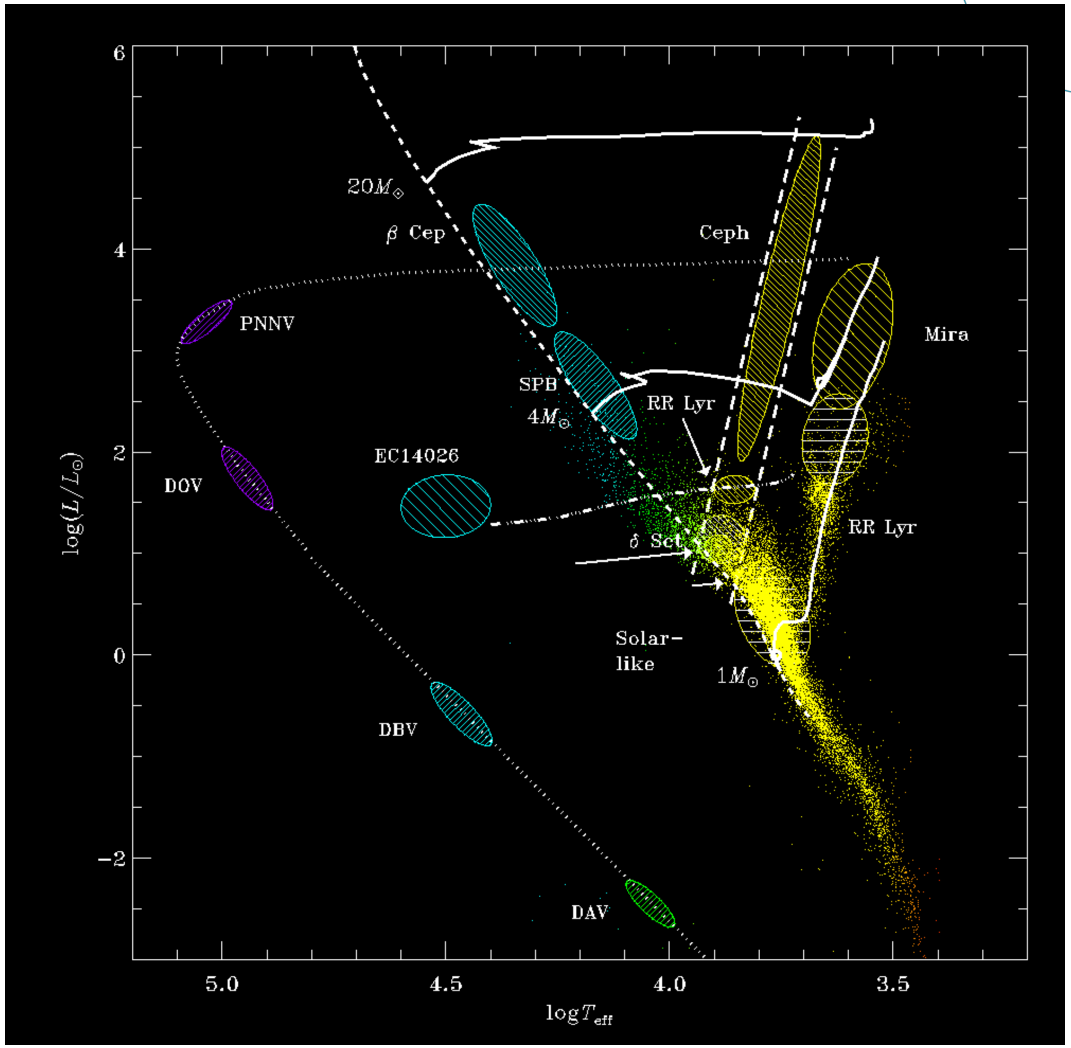
Our telescopes may probe farther and farther into the depths of space; but how can we ever obtain certain knowledge of that which is being hidden behind substantial barriers?

What appliance can pierce through the outer layers of a star and test the conditions within?”

Sir Arthur Eddington in “The internal constitution of stars” (1926)

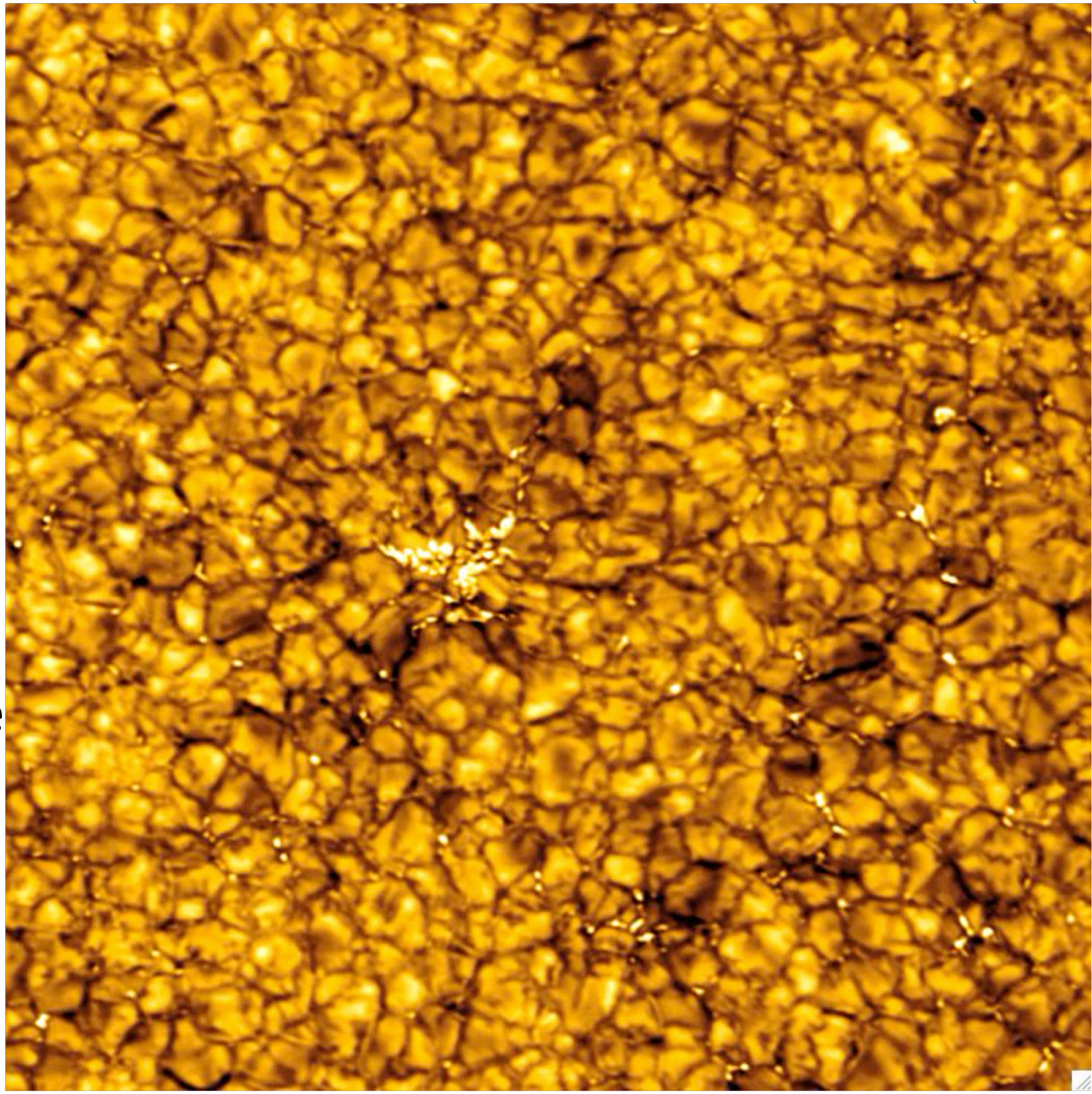
Why understand the solar interior?

- The Sun is the closest star and the only one we can study in detail, surface and interior.
  - How does the Sun rotate?
  - How does the Sun evolve?
- The Sun drives the solar system as well as the Earths weather and the energy comes from the fusion in the solar core.
  - Where does the solar variability originate?
- The Sun has closeby physical conditions that cannot be made on Earth and is a closeby nuclear physical laboratory.
  - The solar neutrino problem and the solar core
- The solar interior give information on the evolution of all stars.
  - Is the Sun unique?



What can we infer from only observing the solar surface?

- The energy output at the surface gives a clear indication of the internal nuclear processes.
- The size and mass of the Sun sets limitations of the interior.
- The differential rotation shows that there is an internal shear.
- The presence of strong magnetic regions in sunspots show there is a dynamo somewhere in the solar interior.
- The variability of the solar activity indicates that there are significant changes at least in the outer parts of the solar interior.
- The presence of more than a million granules at the visible surface creates a "noisy environment".



The Swedish Solar Telescope, Luc van der Rouppe

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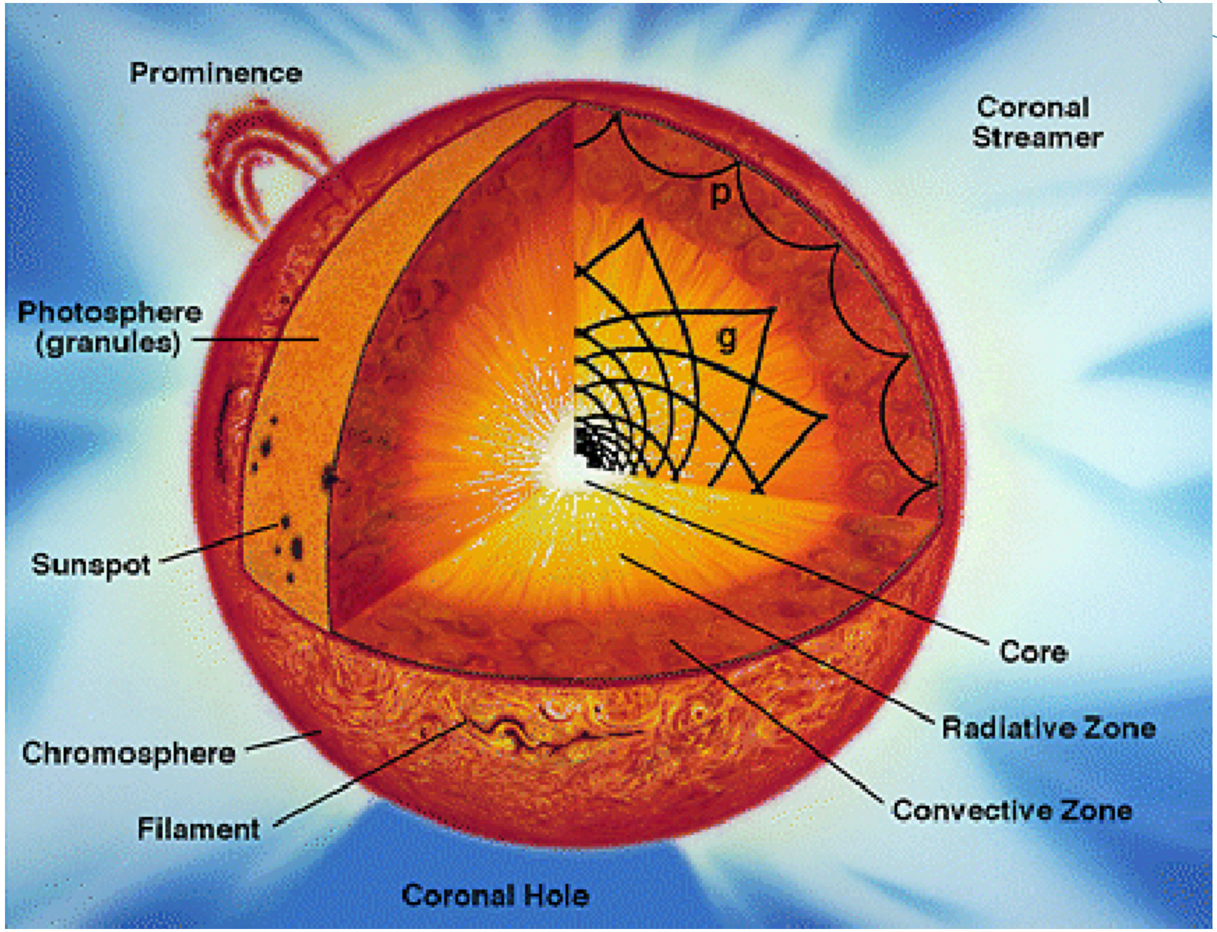
How can we observe the solar interior?

- Observation of neutrinos for the energy generating fusion.
- Use the same probing as we do with seismic measurements of the Earths interior or ultrasound of a baby before it is born.
- If we have sound waves, these can be used to probe the solar interior.
- All entities of finite size have resonance frequencies, so does both the Earth and the Sun.



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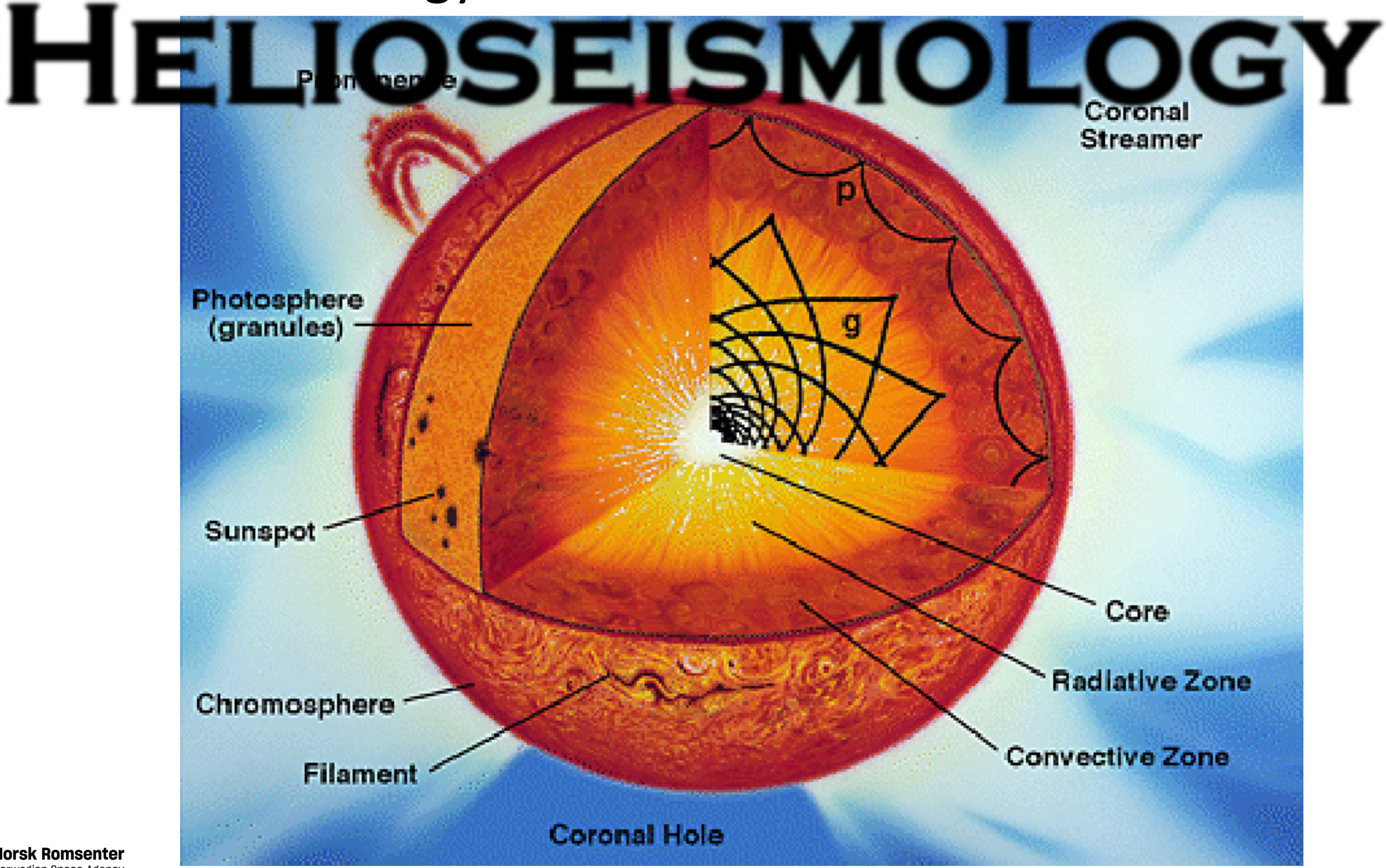
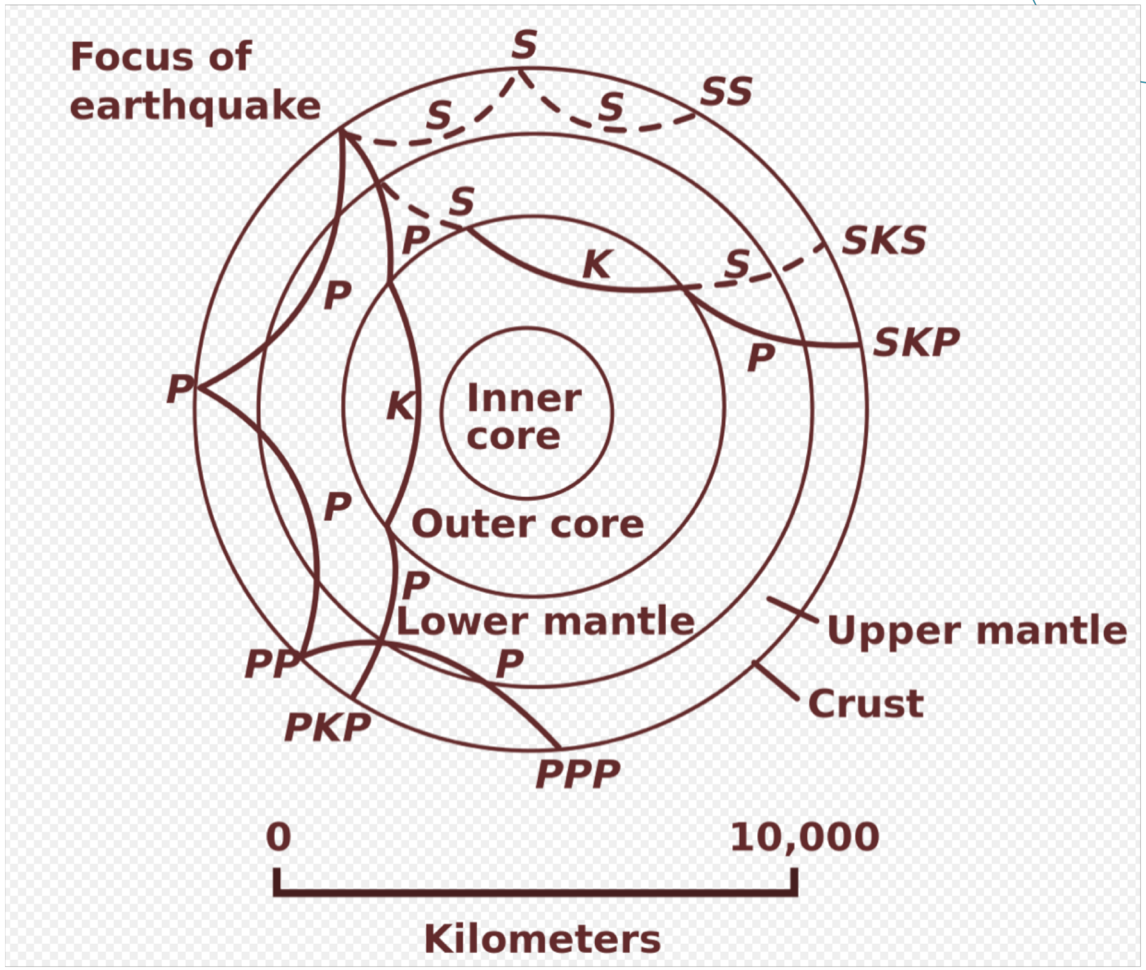
Helioseismology is the window to the solar interior



The speed of sound in different media

- Air = 343 m/s
- Helium = 965 m/s
- Hydrogen = 1284 m/s
- Water = 1482 m/s
- Granite=6000m/s
- Outer layers of the Sun = 10 km/s
- Core of the Sun = 550 km/s

- The faster the speed is, the less influence the medium has on the wave passing through.



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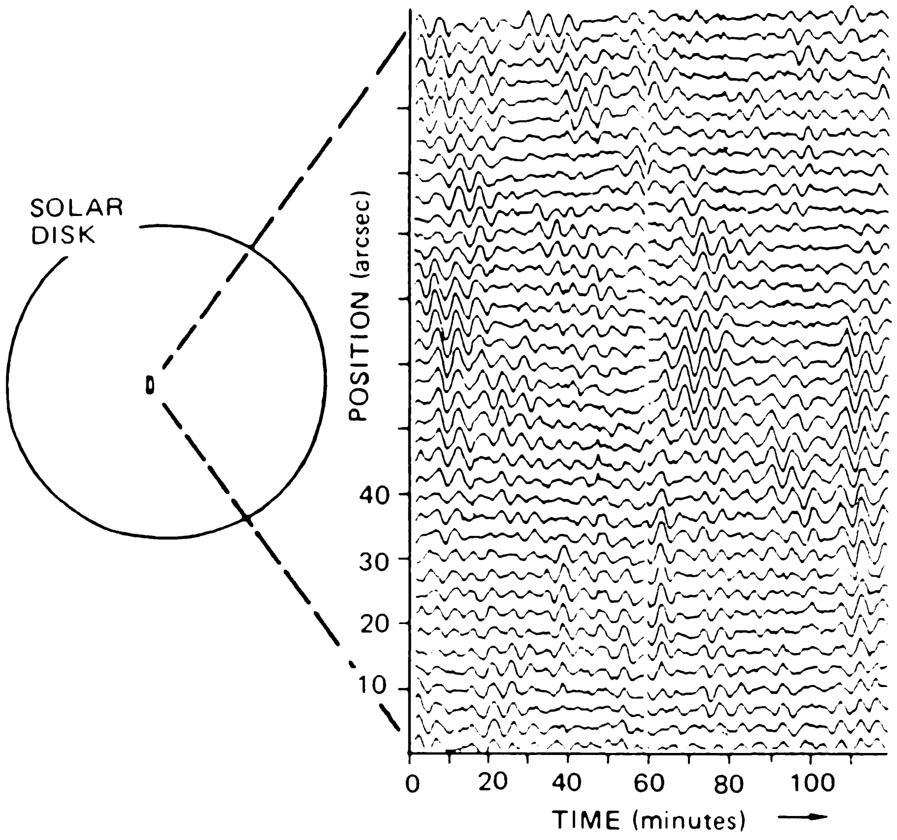
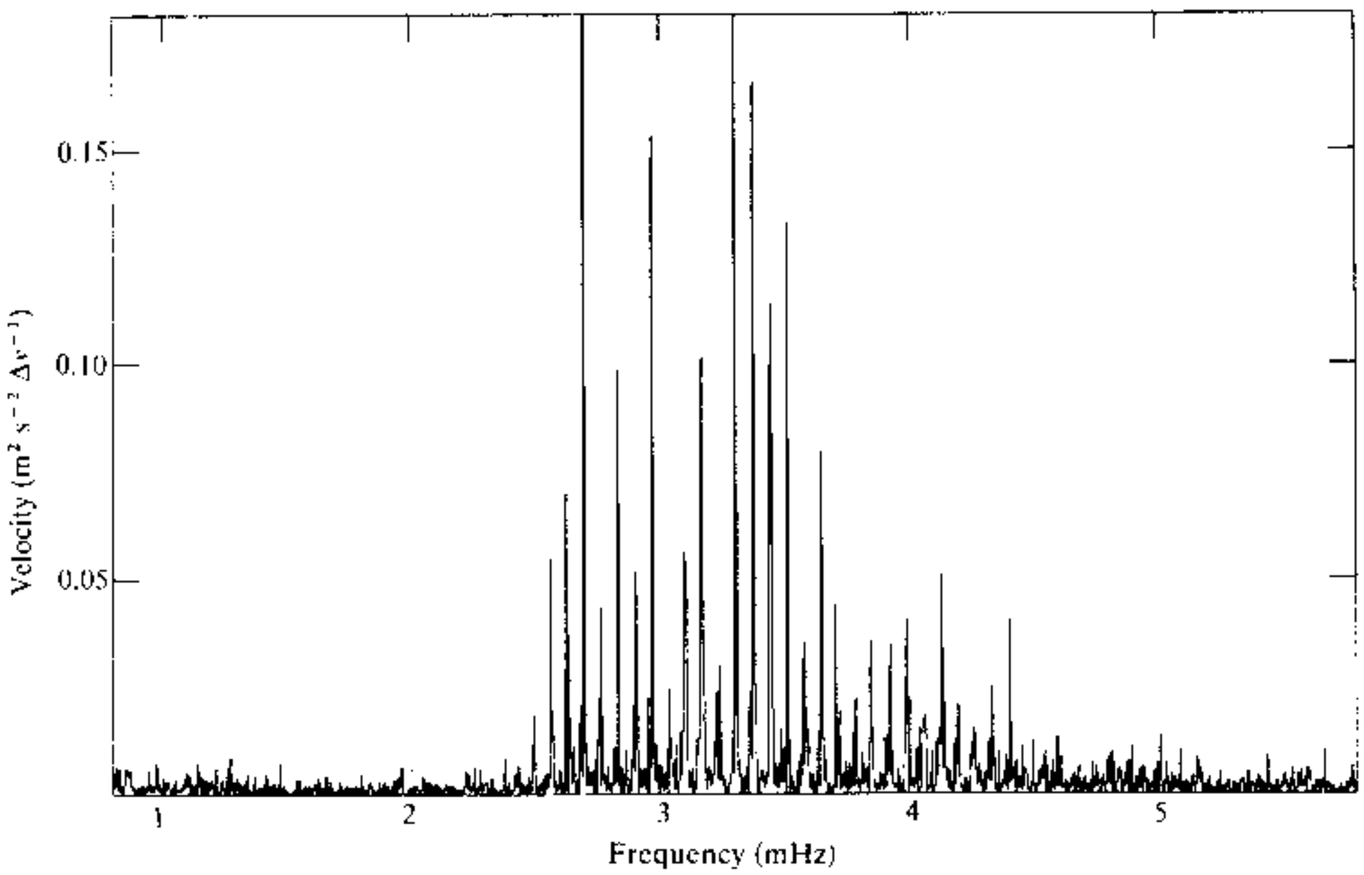
Some early local and global solar oscillation measurements of the “5-minute oscillations” of what turned out to be p-modes



Musman & Rust

(1970; Solar Phys. 13, 261)



Grec et al. (1980; Nature 288, 541)

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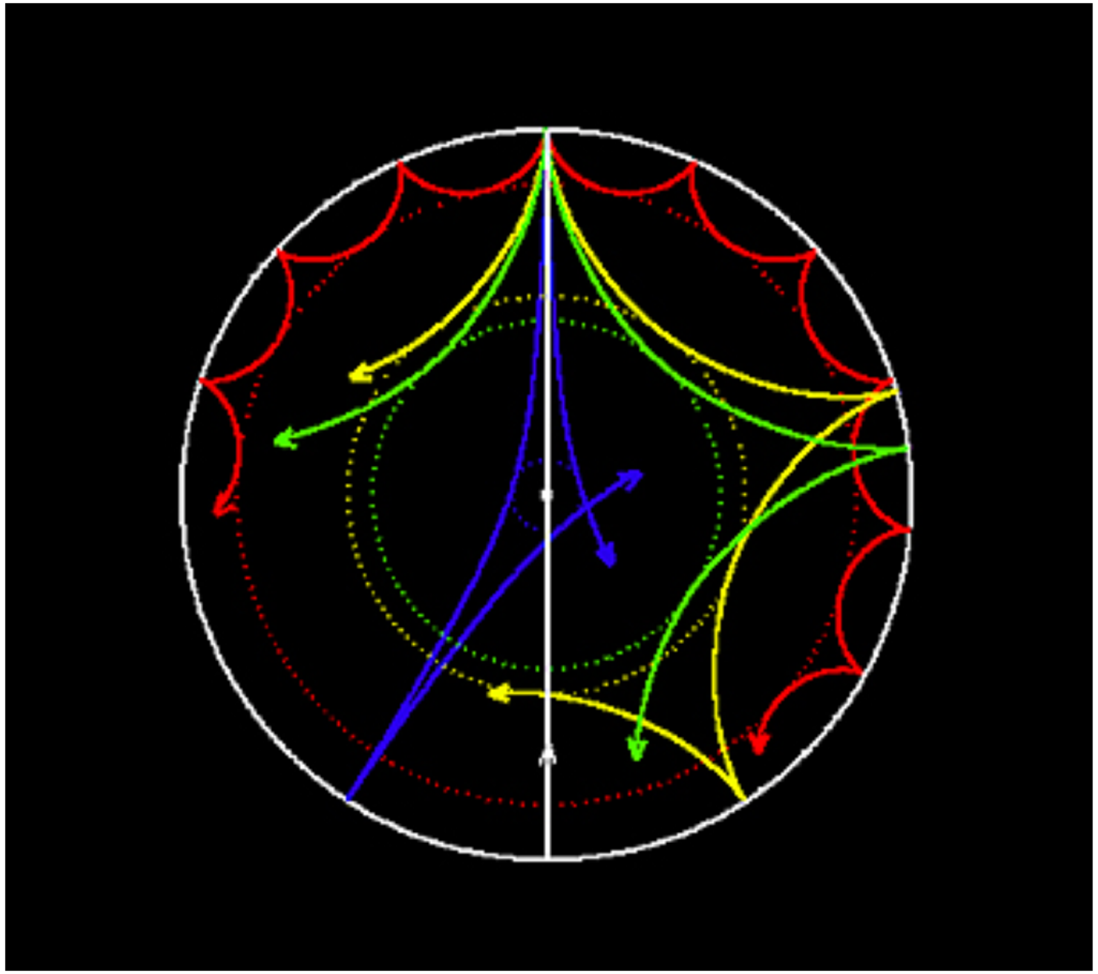
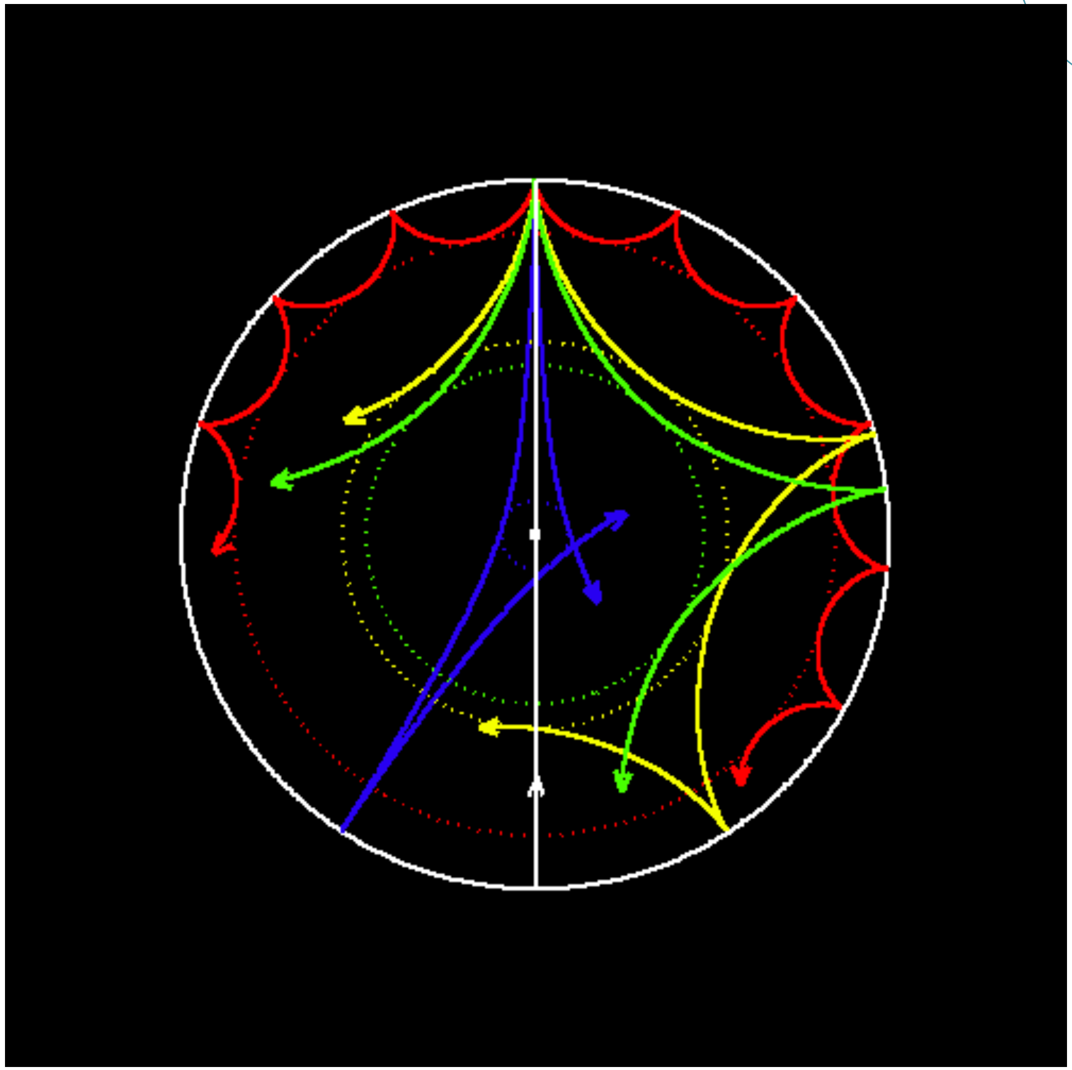
All media have resonant or eigen frequencies



- A wavefront of a sound wave moving obliquely into the increasing temperature of the Sun will turn away from direction of the increasing temperature.
- This happens because the lower part of the wave has higher sound speed.
- Depending on the horizontal extent of the wave this will happen at different depths, more shallow for the the smallest horizontal extent.
- The upper part of the cavity is where we see the surface.
- Only completely radial sound modes pass through the solar core.

What kind of waves? g, p and f

- The granular noise at the surface dies out, except where there are resonances!
- **p**(ressure) Modes – restoring force is pressure (sound waves)
- **g**(ravity) Modes – restoring force is buoyancy – internal gravity waves
- **f**(undamental) Modes – restoring force is buoyancy modified by density interface, that is surface gravity waves
- The linearized wave equation gives the structure for all waves in the SUN:
  $\rho_0\, \partial v / \partial t = -\nabla P' + \rho' g$



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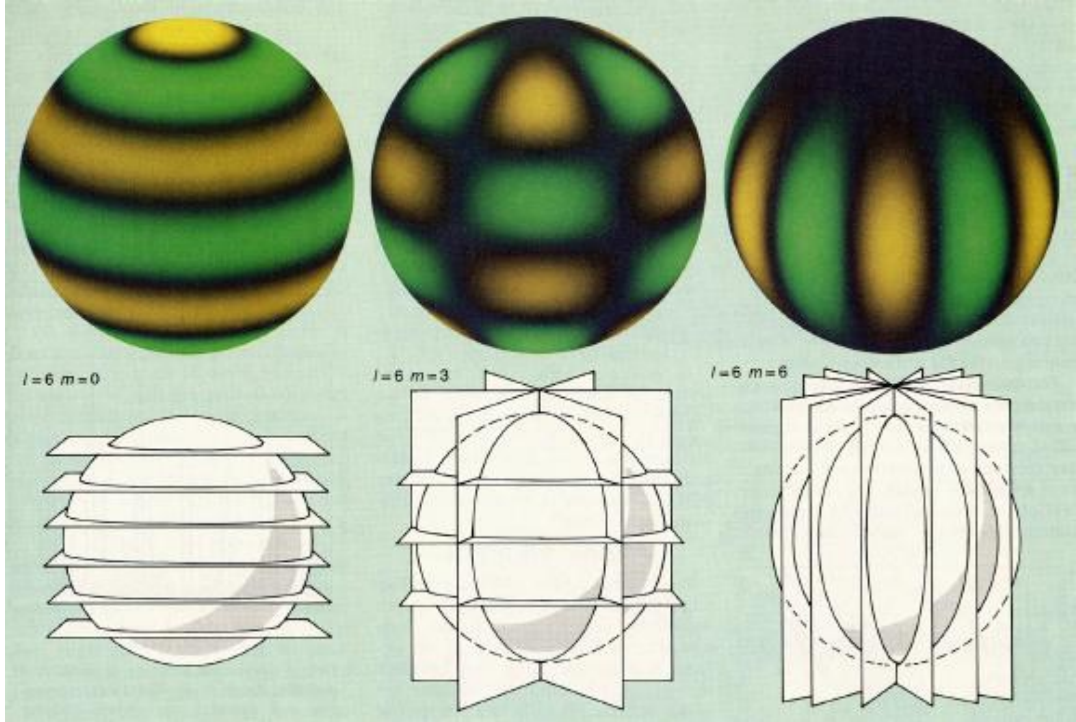
Spherical Harmonics

l=6 m=0 l=6 m=3 l=6 m=6



•Picture credits: Noyes, Robert, "The Sun", in _The New Solar System_, J. Kelly Beatty and A. Chaikin ed., Sky Publishing Corporation, 1990, pg. 23.

- *l*, the harmonic degree, gives the node lines on the surface.
- *m*, the azimuthal degree gives the amount of nodes crossing the equator.
- We always have $-l \leq m \leq l$

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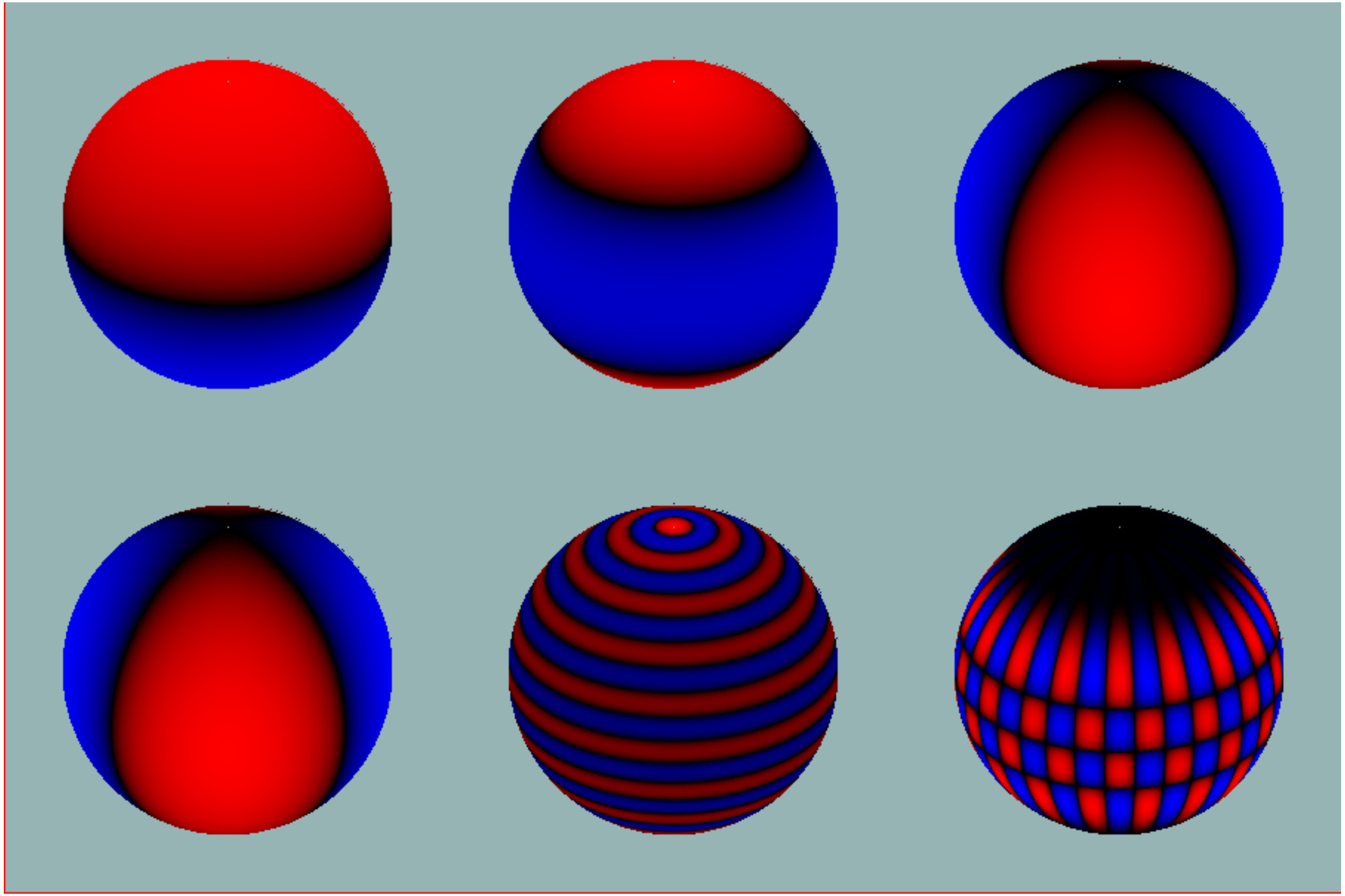
Spherical harmonics



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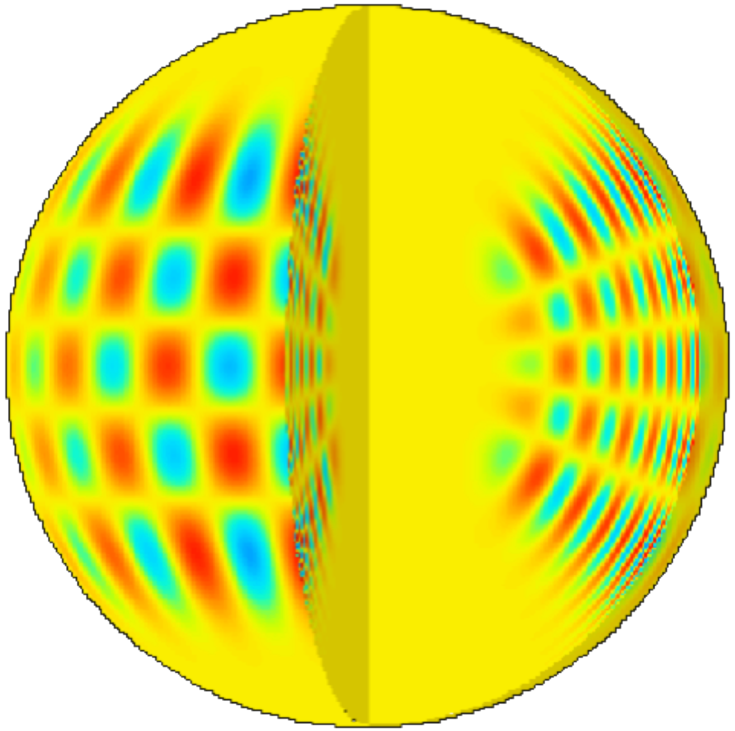
Global P-modes

- A p mode is a standing acoustic wave with turning points at surface and at the point where the wave direction becomes horizontal.
- Each mode can be described by a spherical harmonic, describing number of radial nodes (*n*) and horizontal modes (*l, m*).
- Quantum numbers *n* (radial order), *l* (degree), and *m* (azimuthal order) identify the mode.



Different global modes

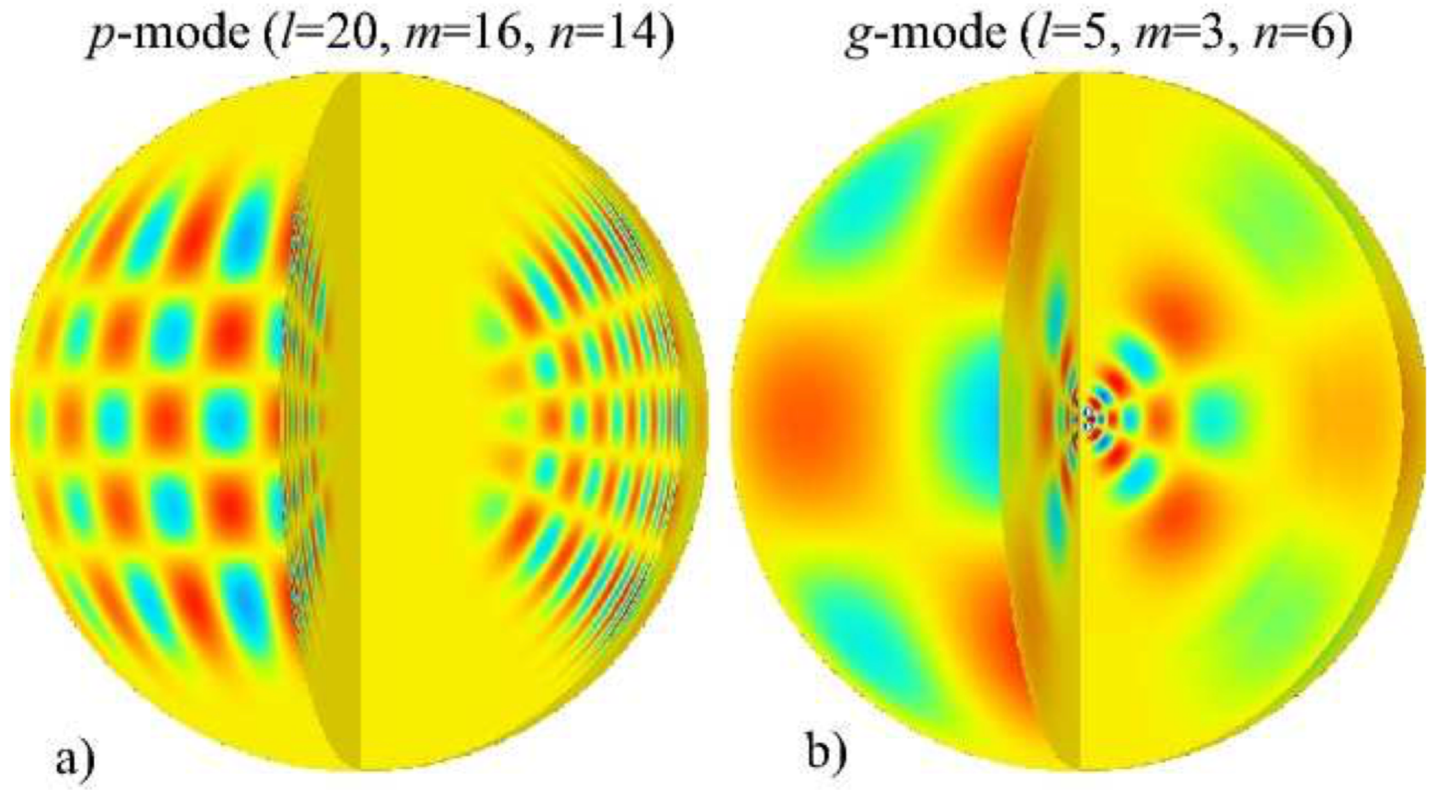


Fig. 15. Eigenfunctions (42) of two normal oscillation modes of the Sun: a) p-mode of angular degree $l = 20$, angular degree $m = 16$, and radial order $n = 16$, b) g-mode of $l = 5$, $m = 3$, and $n = 5$. Red and blue-green colors correspond to positive and negative values.

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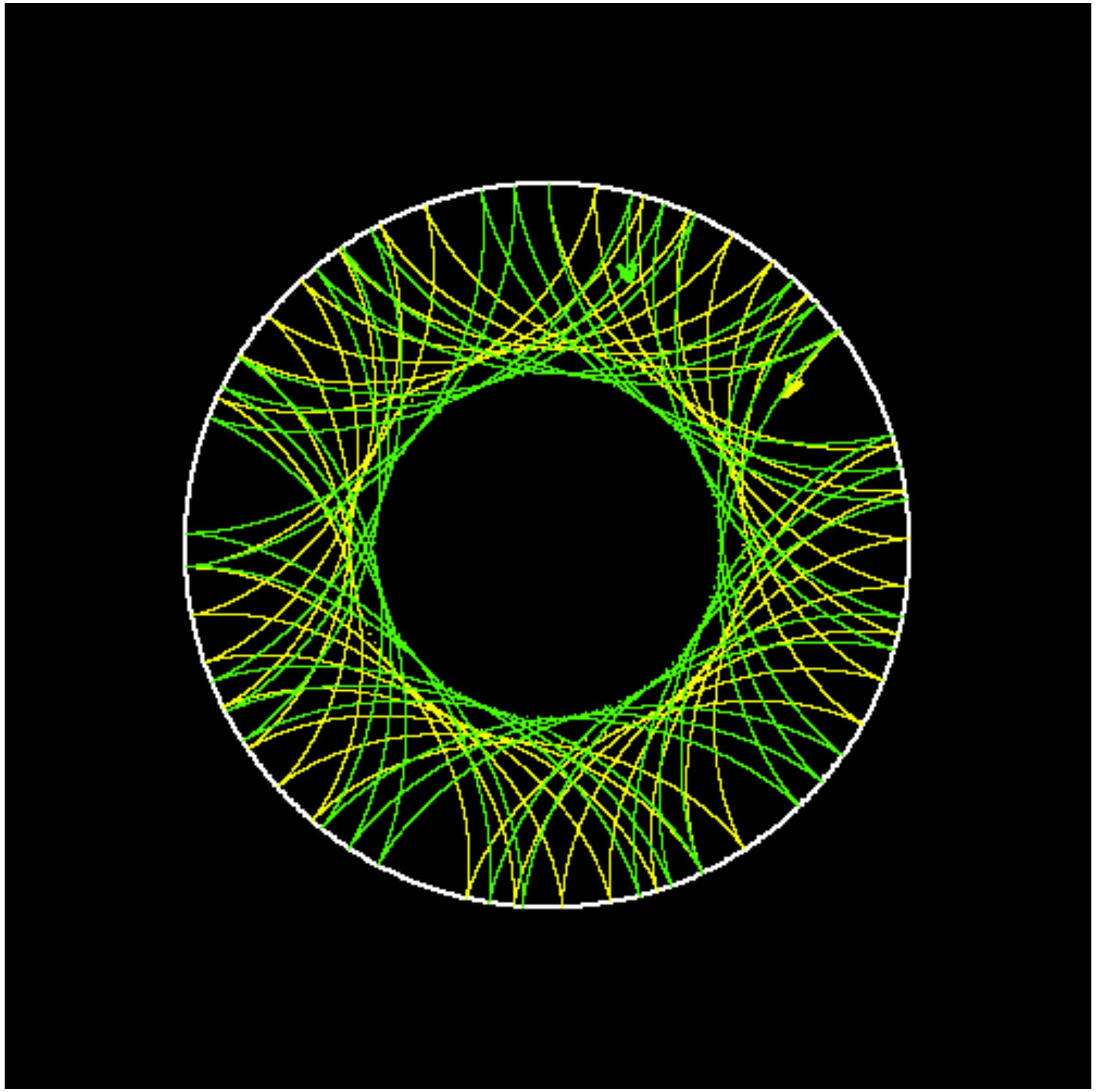
Kosovichev 2010, Advances in Global and Local Helioseismology

How can we probe to different depths of the Sun?



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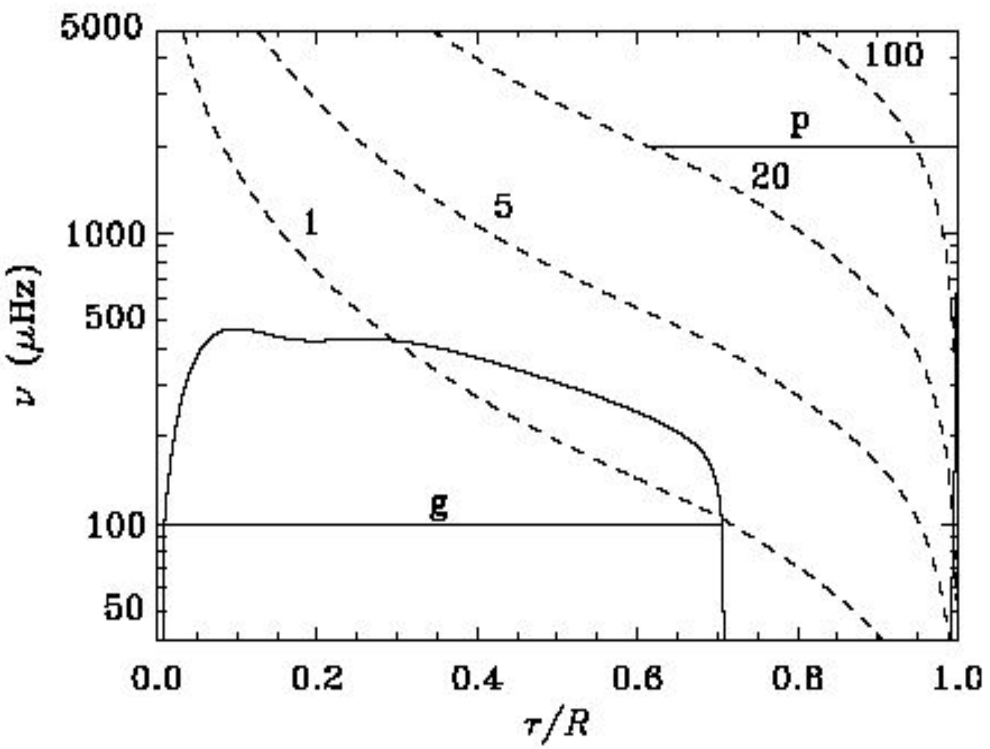
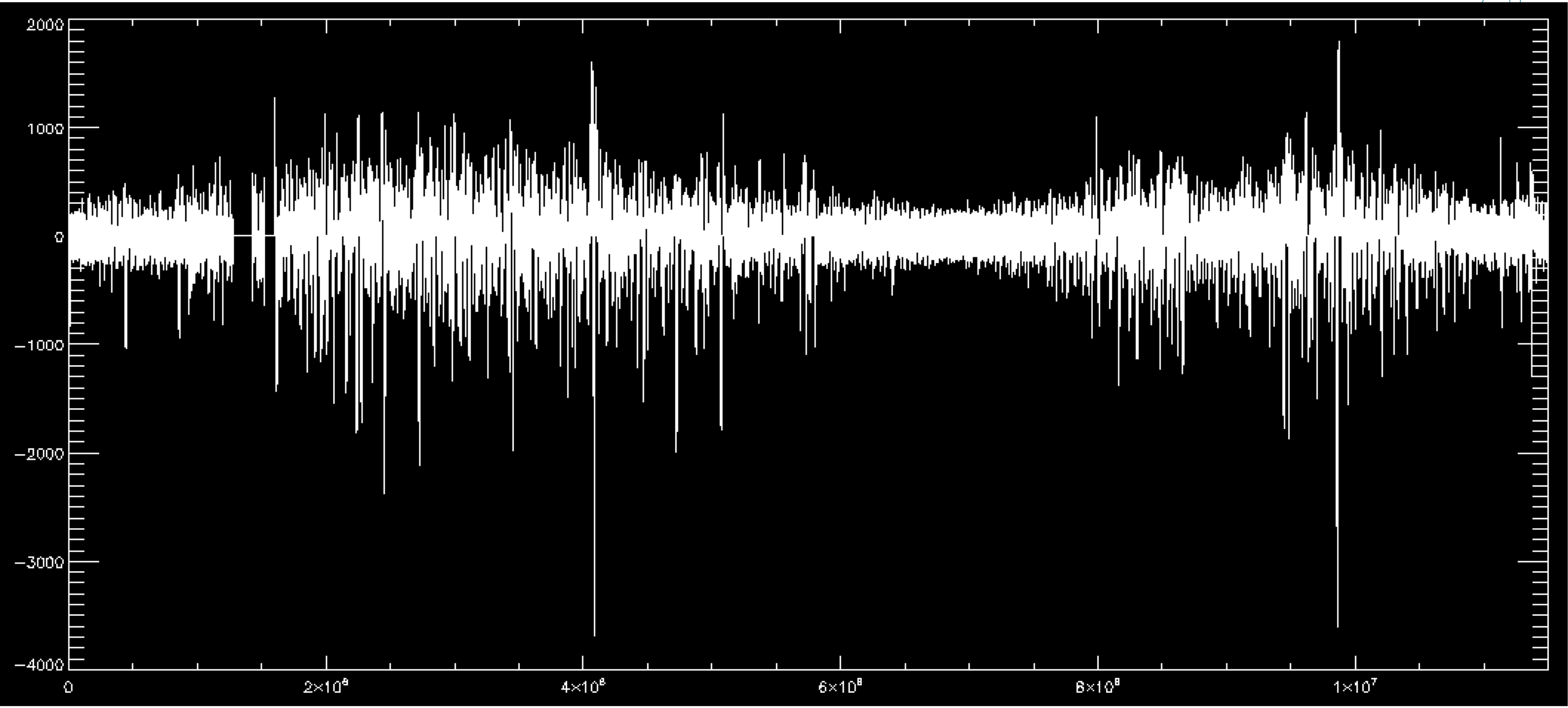
Wave trapping



- G modes exist where ω < N^2 (Brunt-Väisälä frequency) – cannot exist where there is convection, in general they oscillate slower than p-modes and are probably excited by overshoot at the bottom of the convection zone.
- P modes exist where $\omega < \omega_{ac}$ (acoustic cut-off frequency) and ω > S (Lamb frequency), they are excited by the noise of solar granulation
- F modes are analogous to surface water waves

Observations of the Sun as a star with VIRGO



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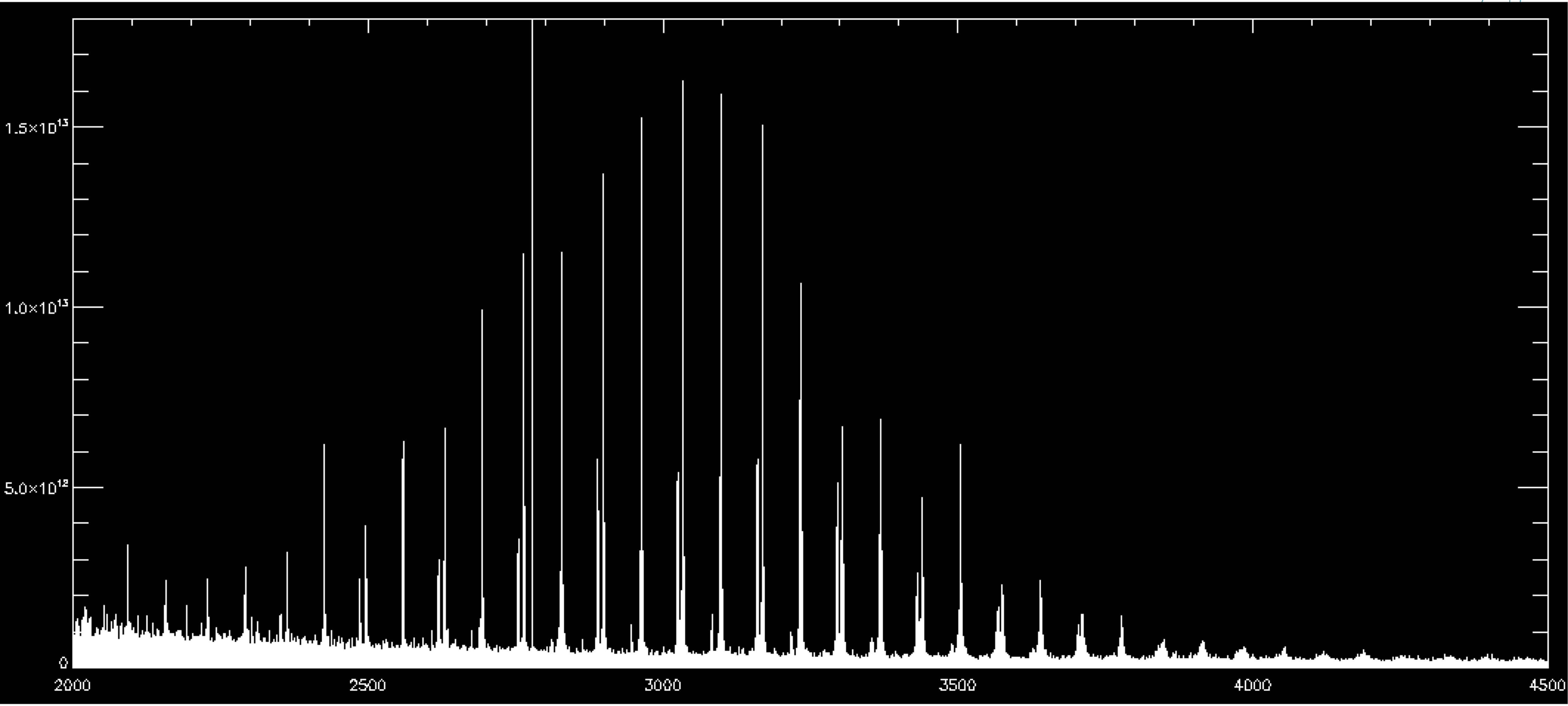
Power spectrum of Sun as a star VIRGO (1)



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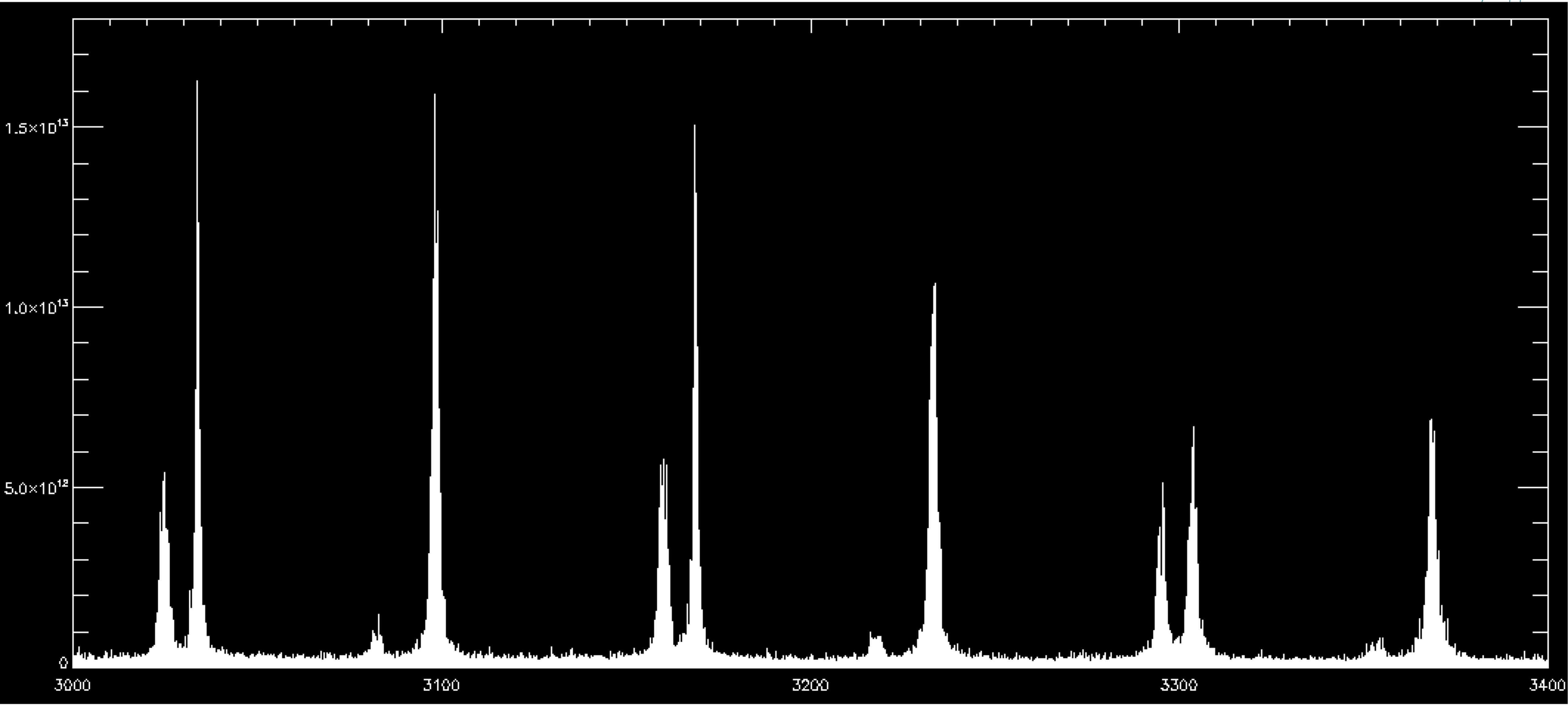
Power spectrum of Sun as a star VIRGO (2)



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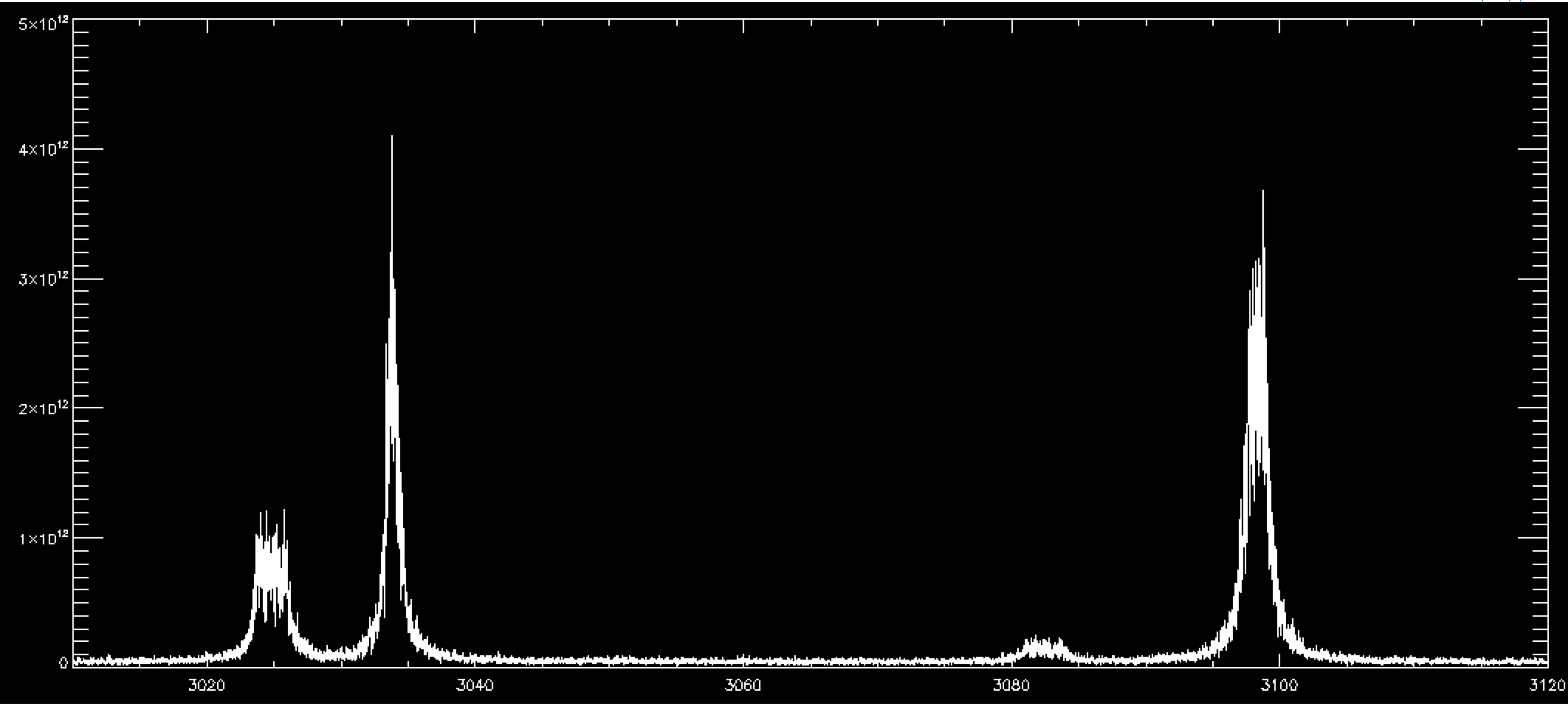
Power spectrum of Sun as a star VIRGO (3)



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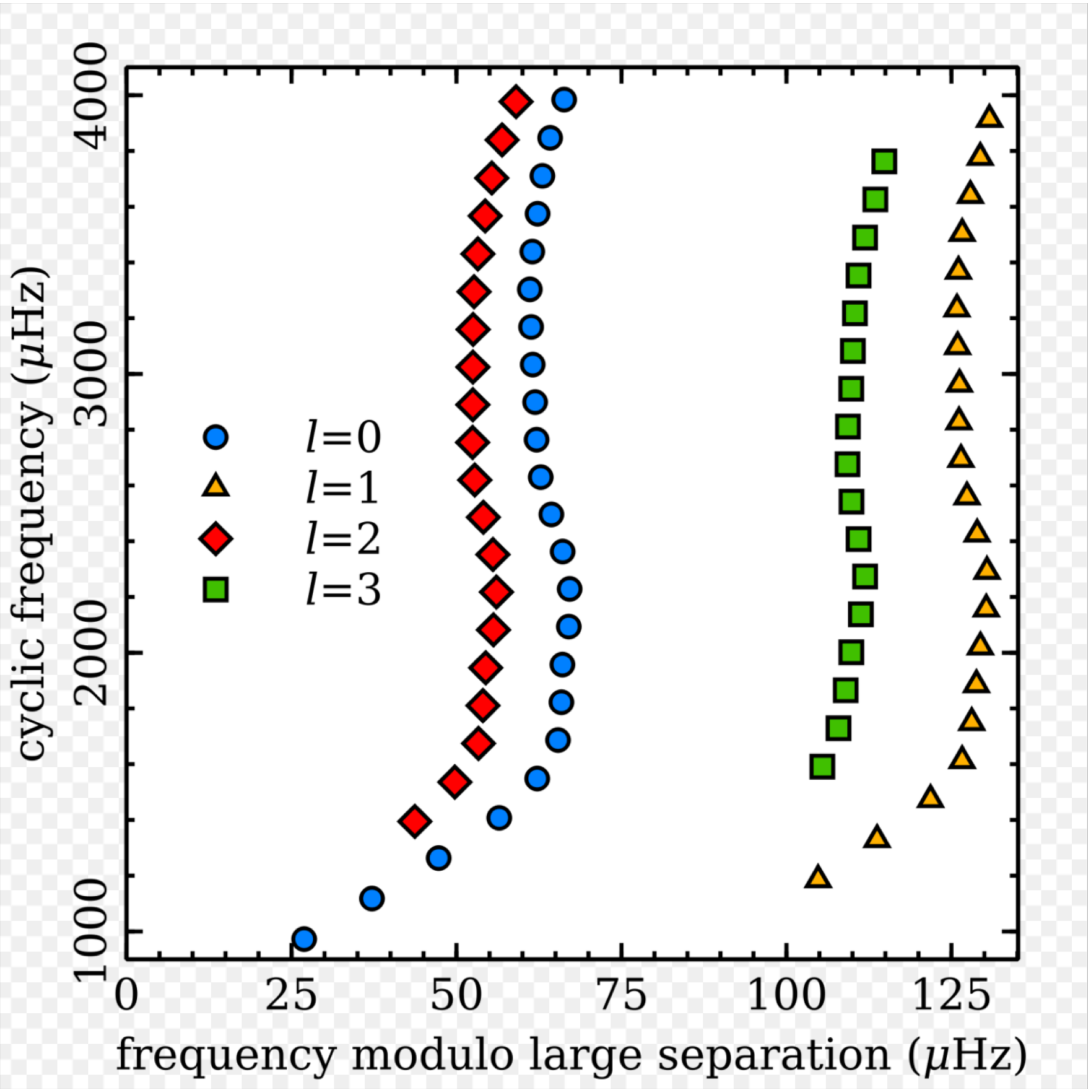
Systematic issues on global solar p-mode frequencies (1)



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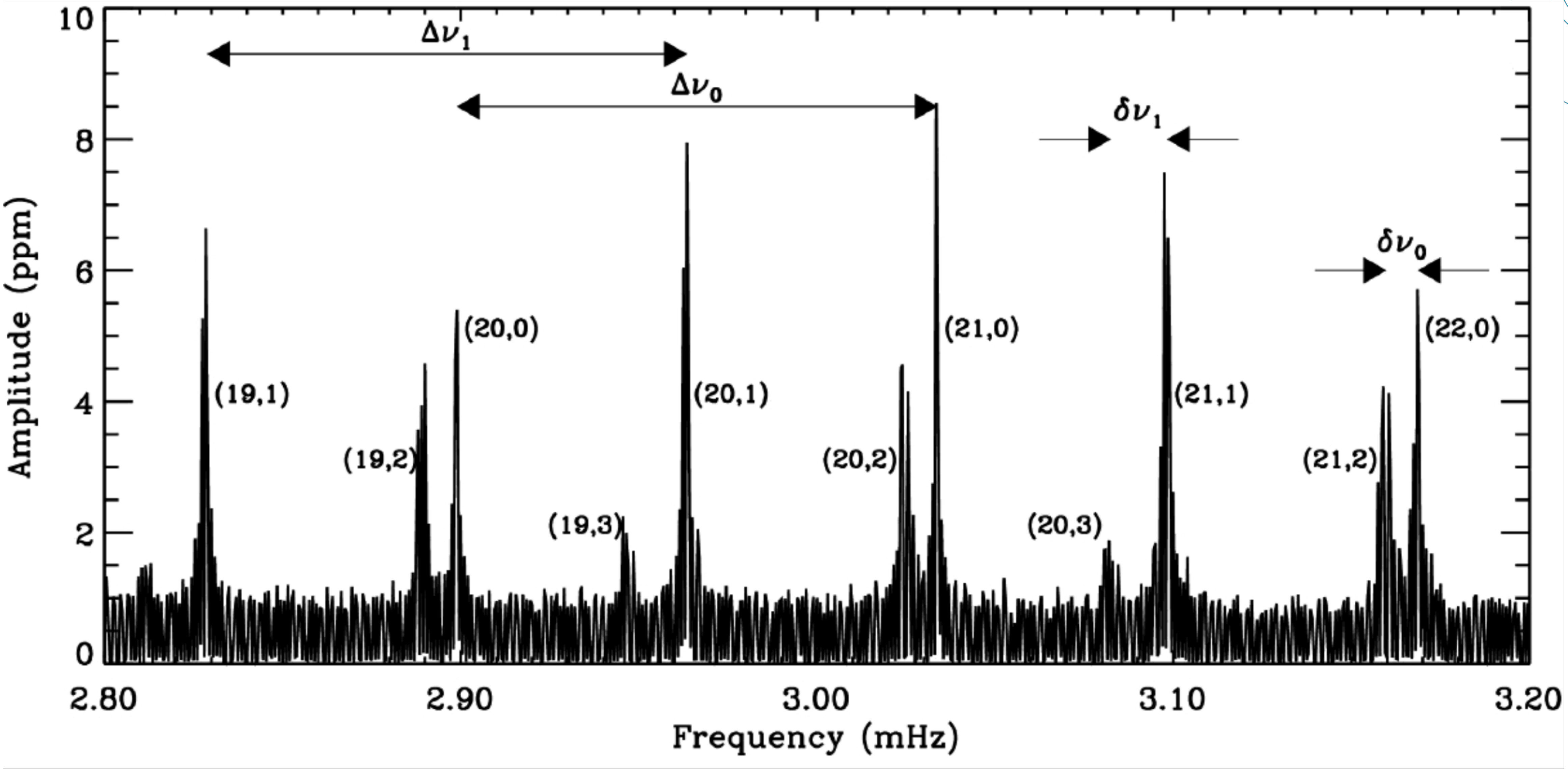
Systematic issues on global frequencies (2)



Large and small separations from VIRGO

High resolution measurements from space

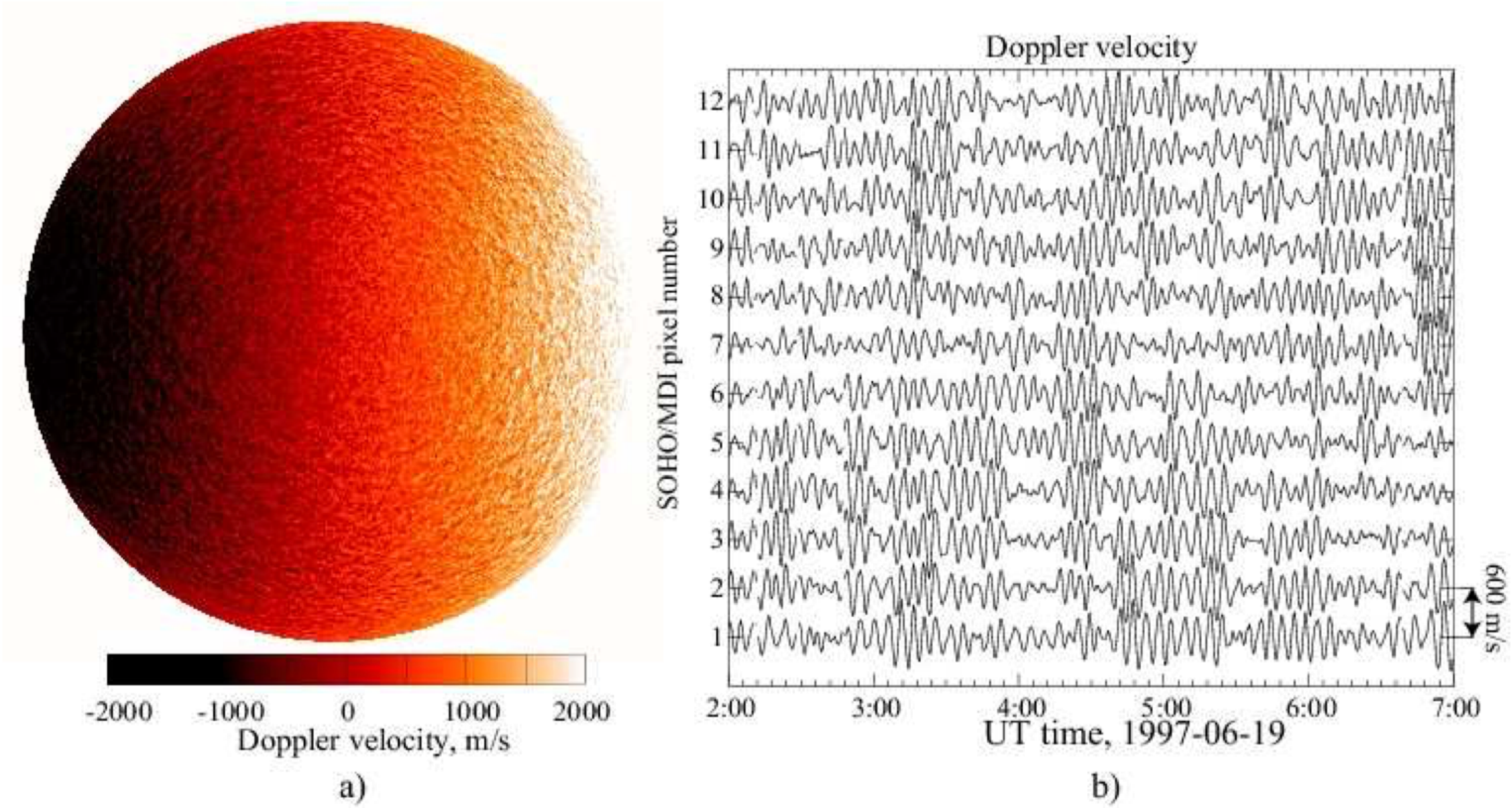
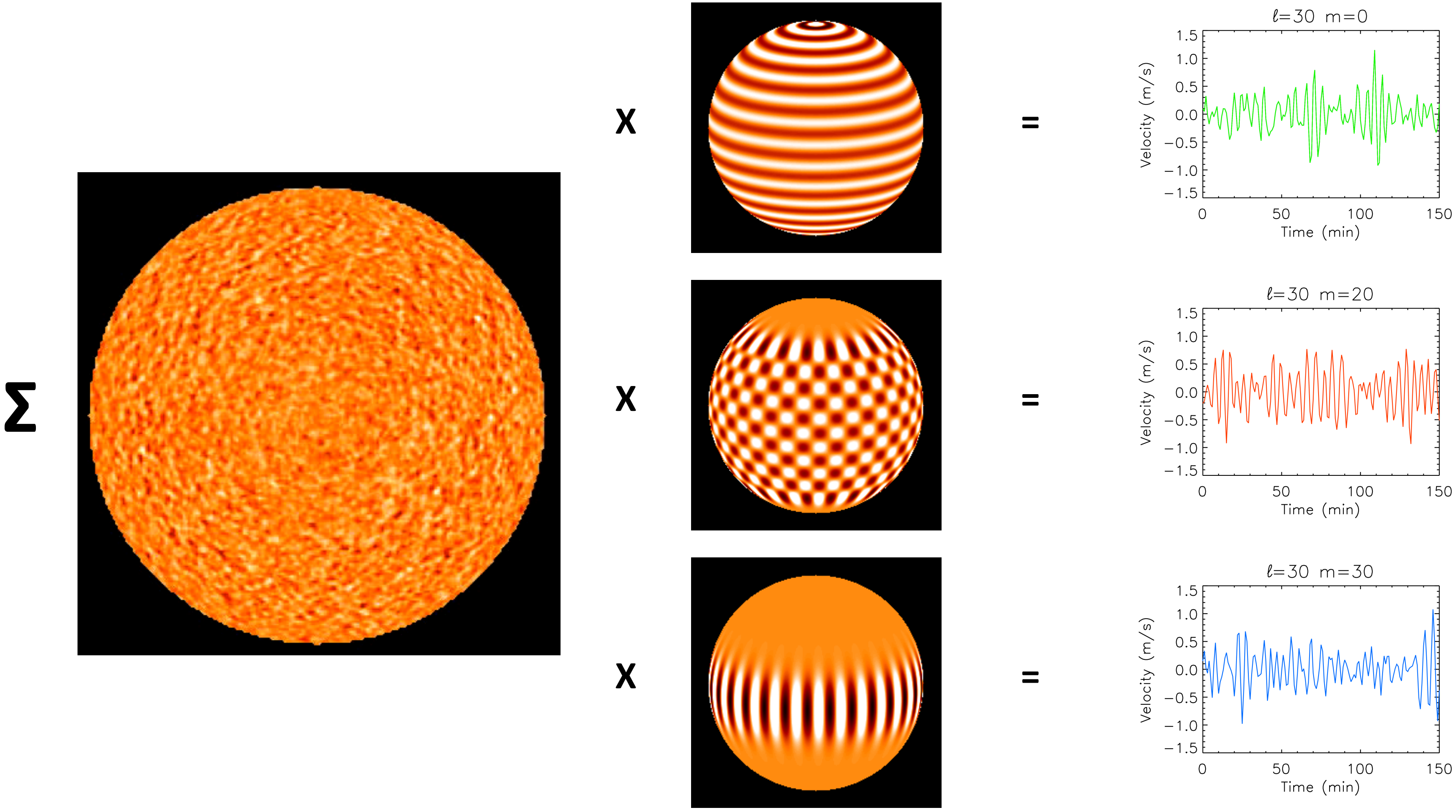


Fig. 1. a) Image of the line-of-sight (Doppler) velocity of the solar surface obtained by the Michelson Doppler Imager (MDI) instrument on board SOHO spacecraft on 1997-06-19, 02:00 UT; b) Oscillations of the Doppler velocity, measured by MDI at the solar disk center in 12 CCD pixels separated by $\sim$ 1.4 Mm on the Sun.

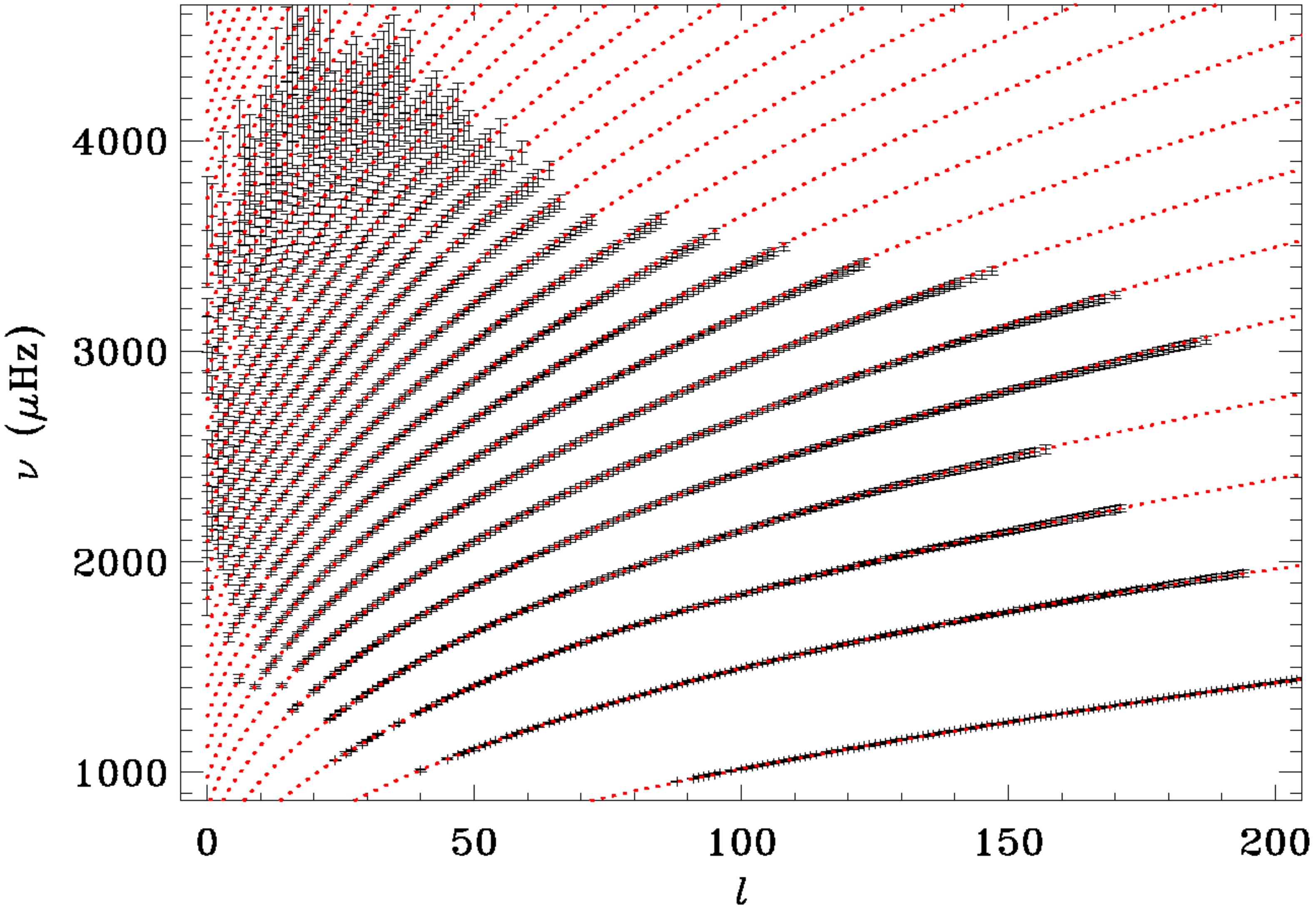
Kosovichev 2010, Advances in Global and Local Helioseismology

Observing Time Series



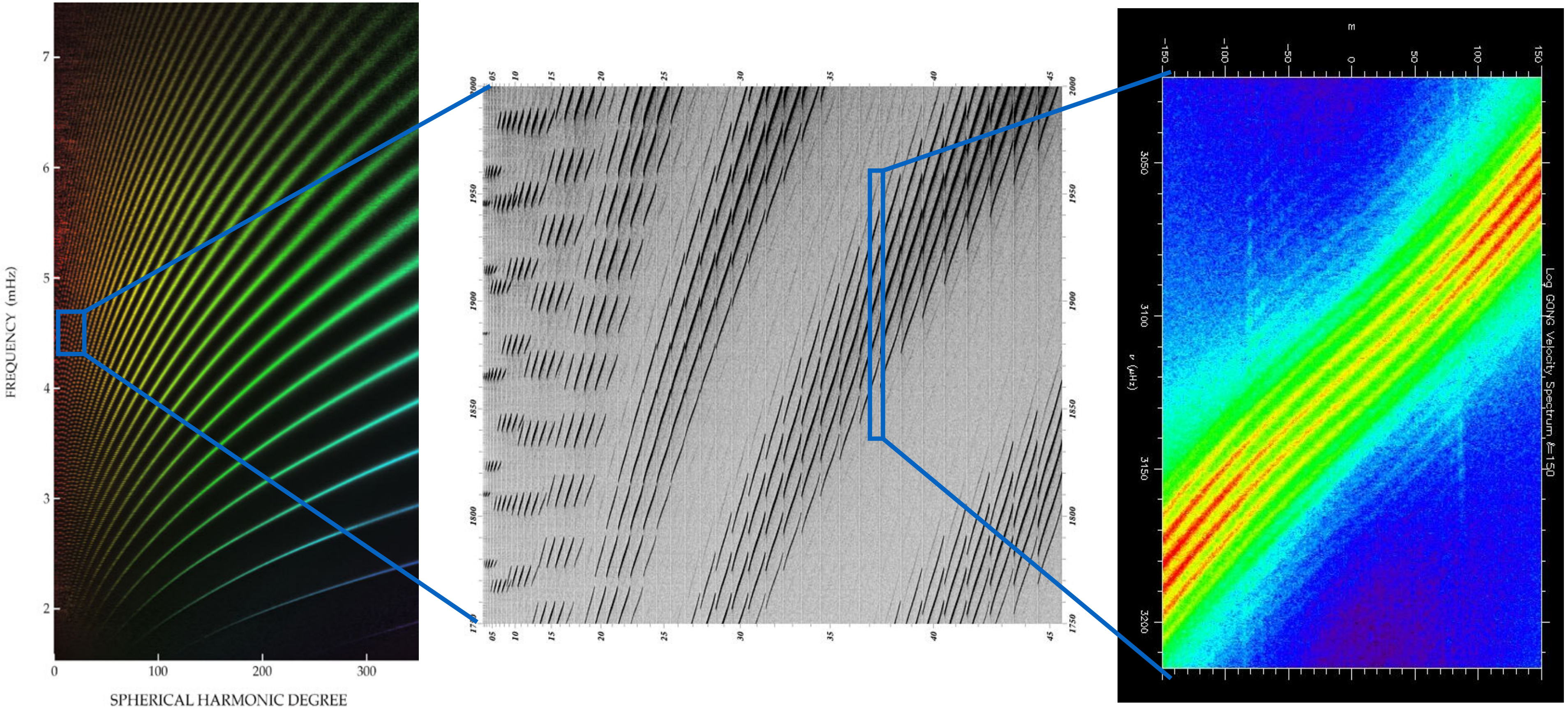
From 2008 Solar Physics Summer School, Sac.Peak

High resolution power spectra



m-averaged frequencies from MDI instrument on SOHO 1000 σ error bars

Details of high resolution spectra

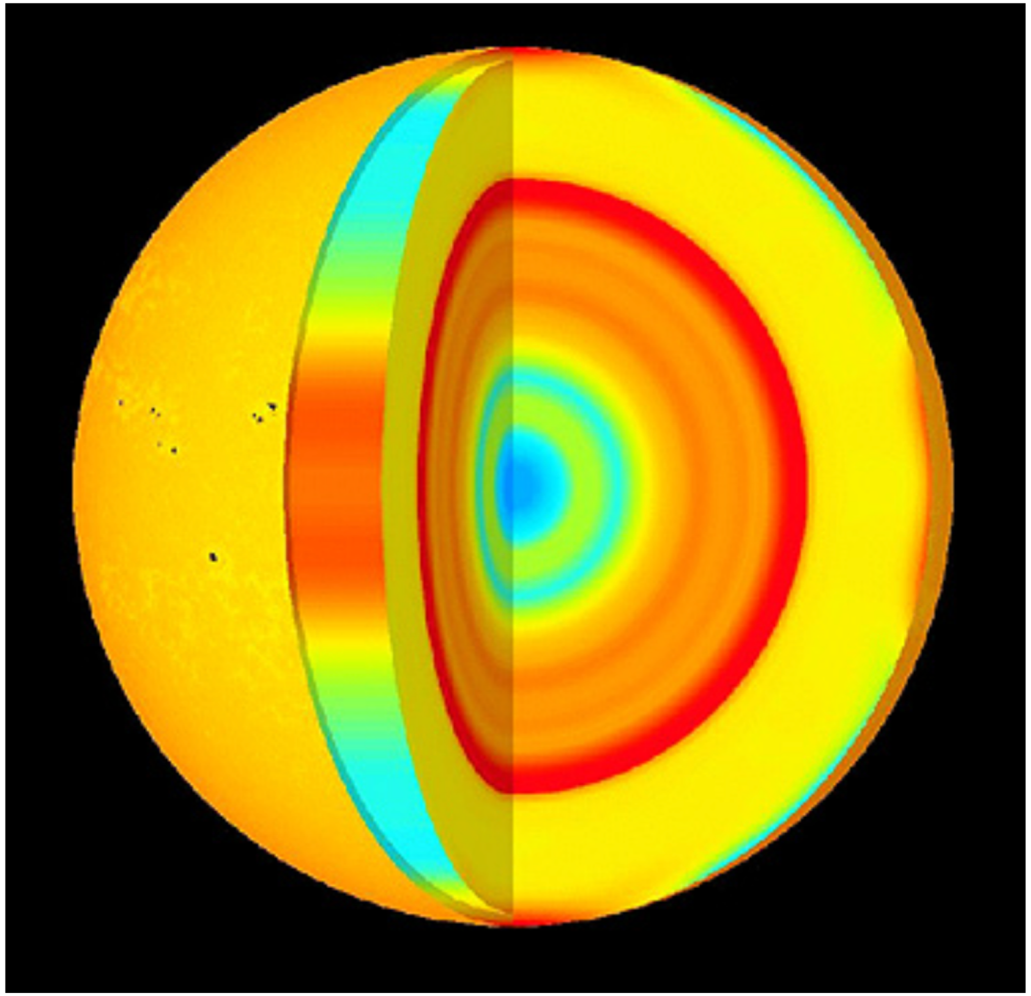


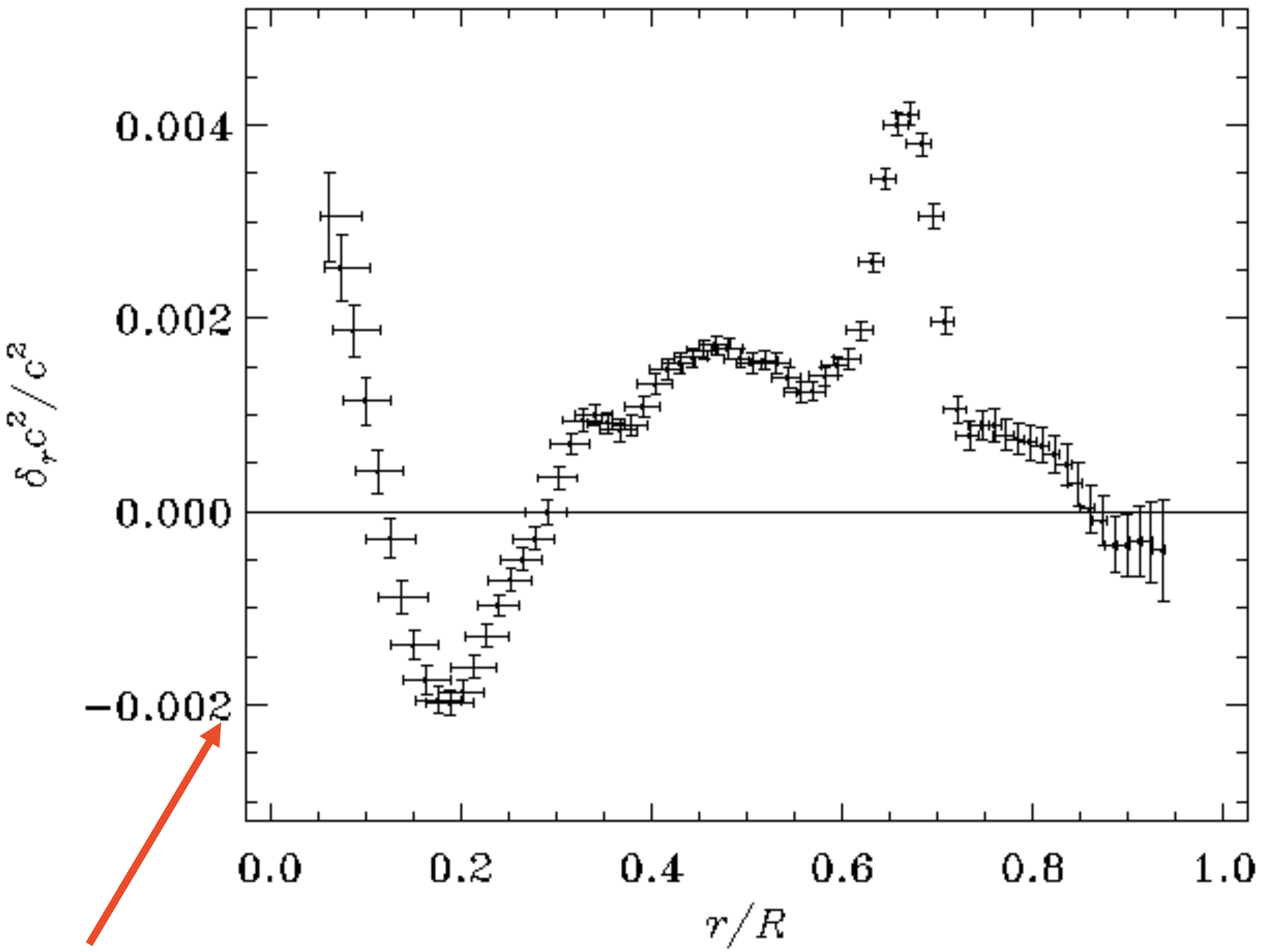
ℓ-ν Diagram

ℓ-m-ν Diagram

m-ν Diagram

Sound speed differences from best model

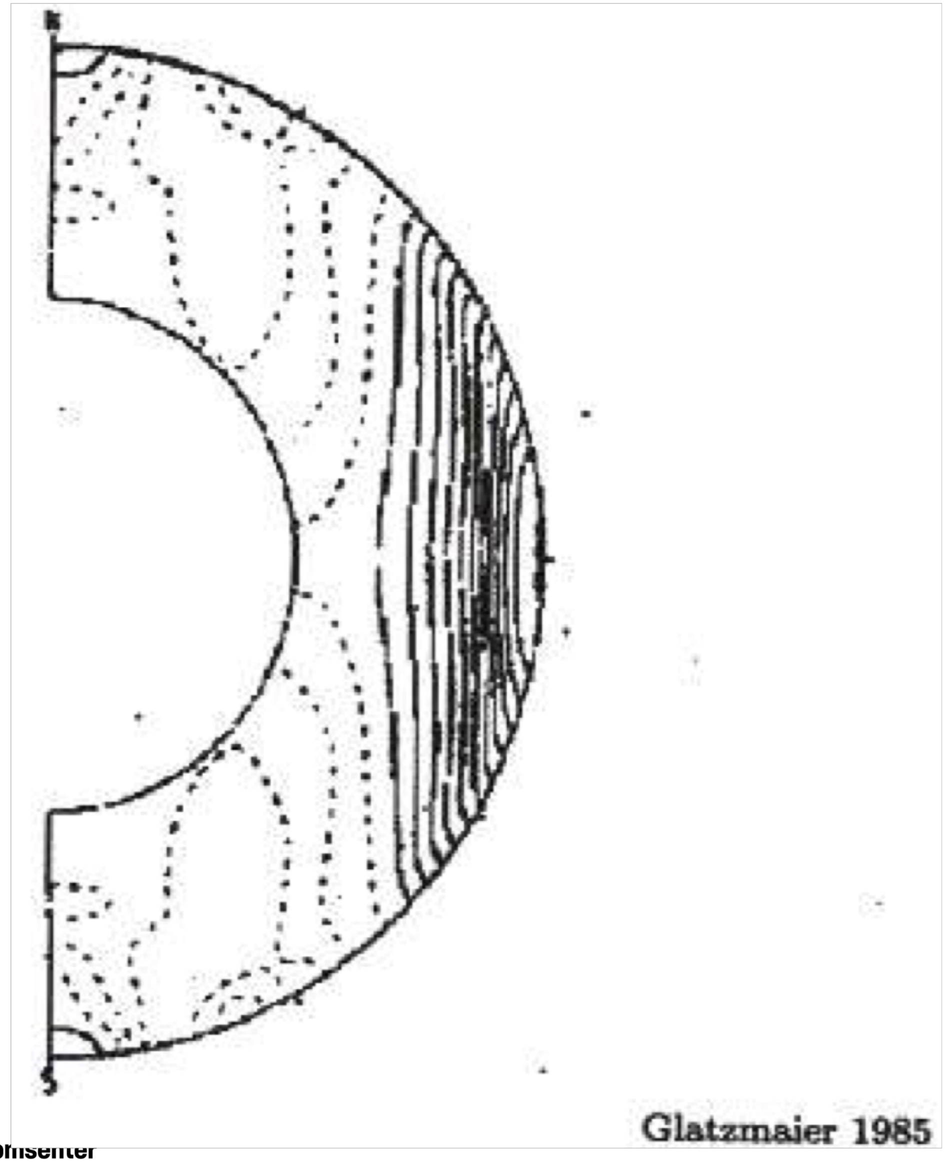


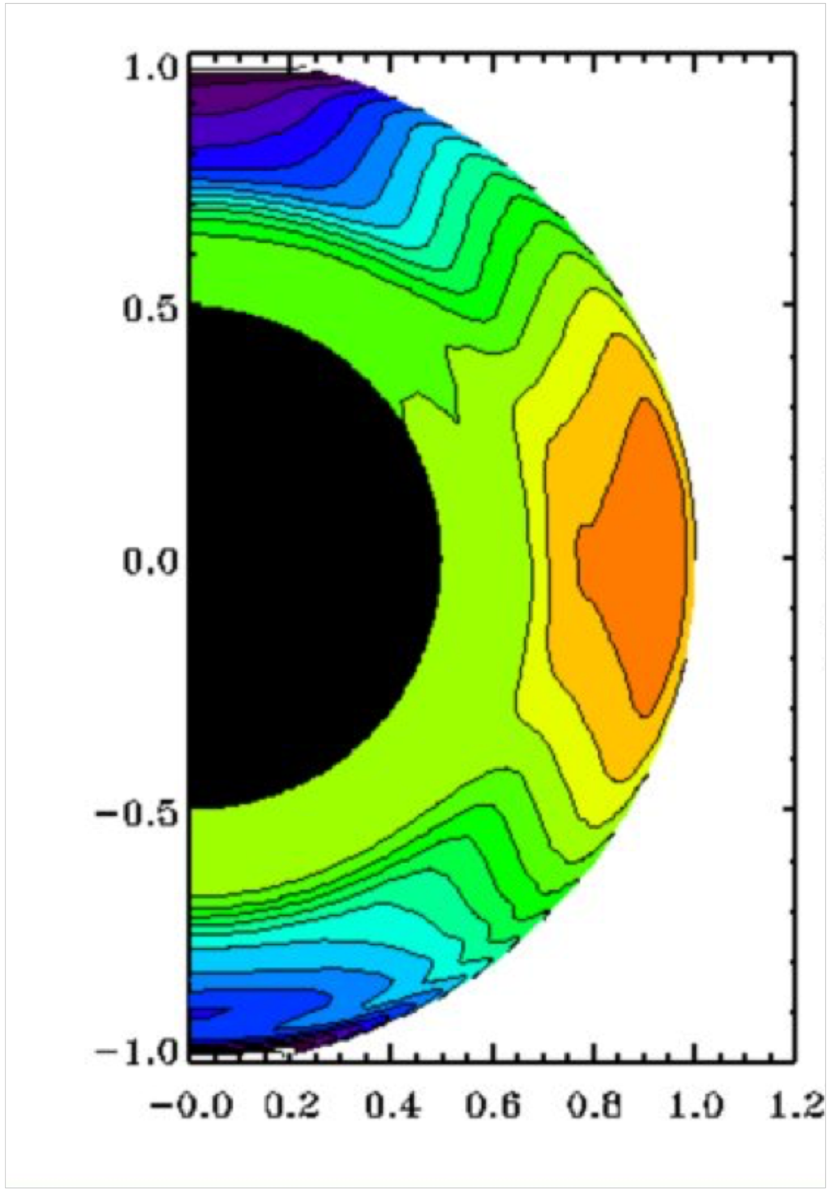


Not much

Basu et al. (1997; MNRAS 292, 243)

The internal rotation of the Sun





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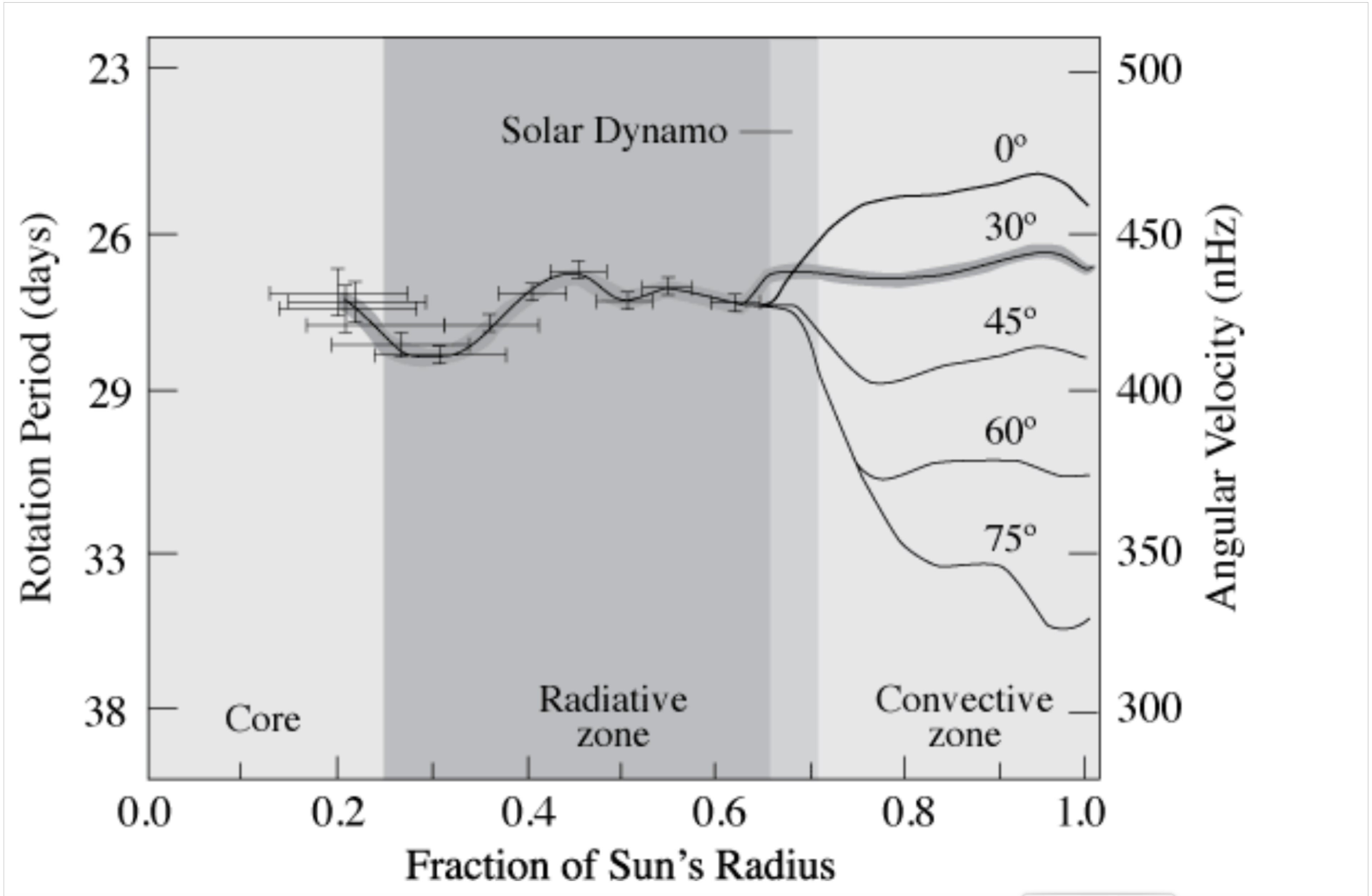
Internal rotation of the Sun



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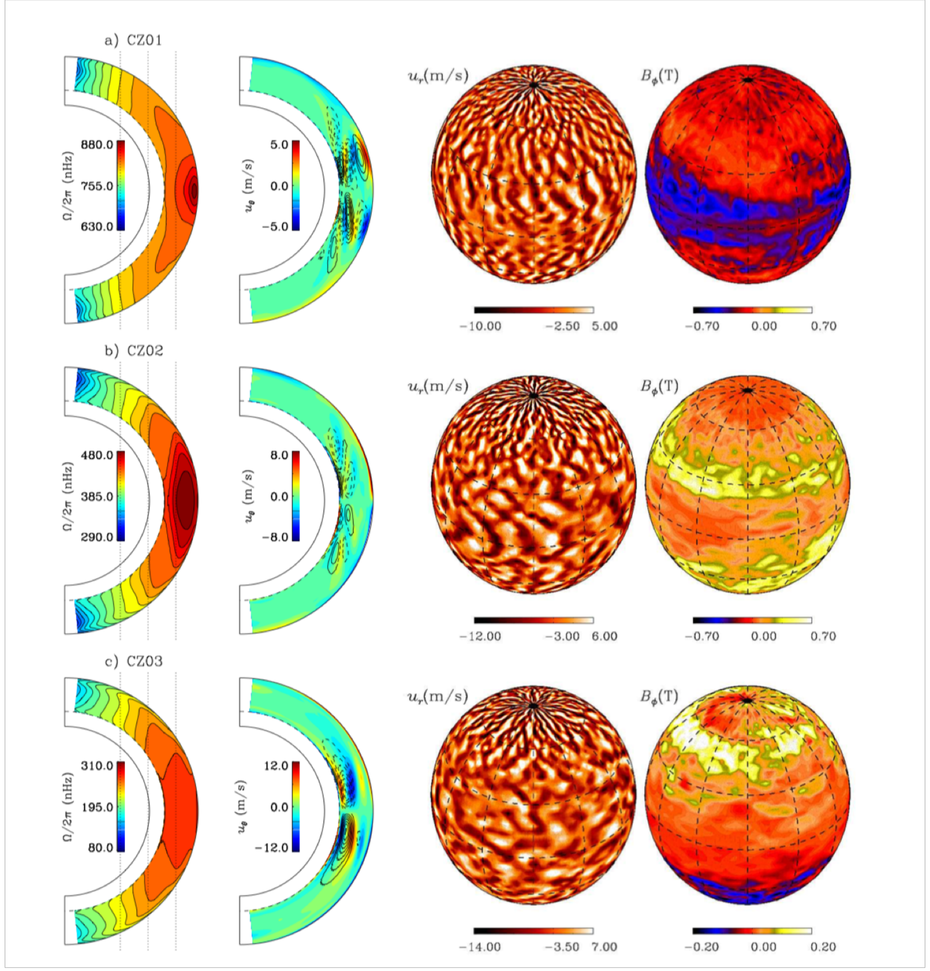
Generation of magnetic fields in the Sun

- The ionized and electrical plasma in the Sun can generate magnetic field in a dynamo effect.
- Older theories made a global dynamos from the varying rotational rate, this is wrong as the Sun rotates differently.
- Helioseismology has shown that the main magnetic field is generated at the bottom of the convection zone at about 0.7 solar radii, also called the "tachocline".



From Guerro et al 2013

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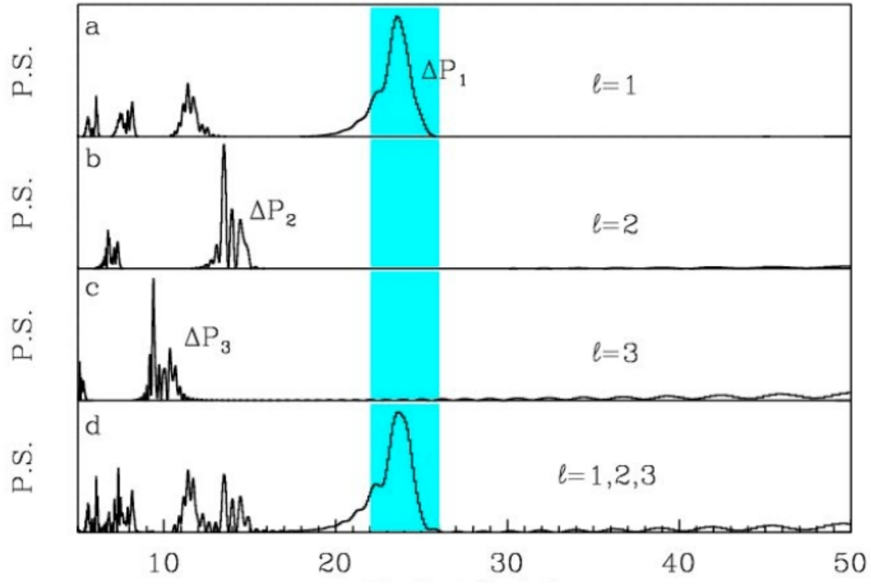
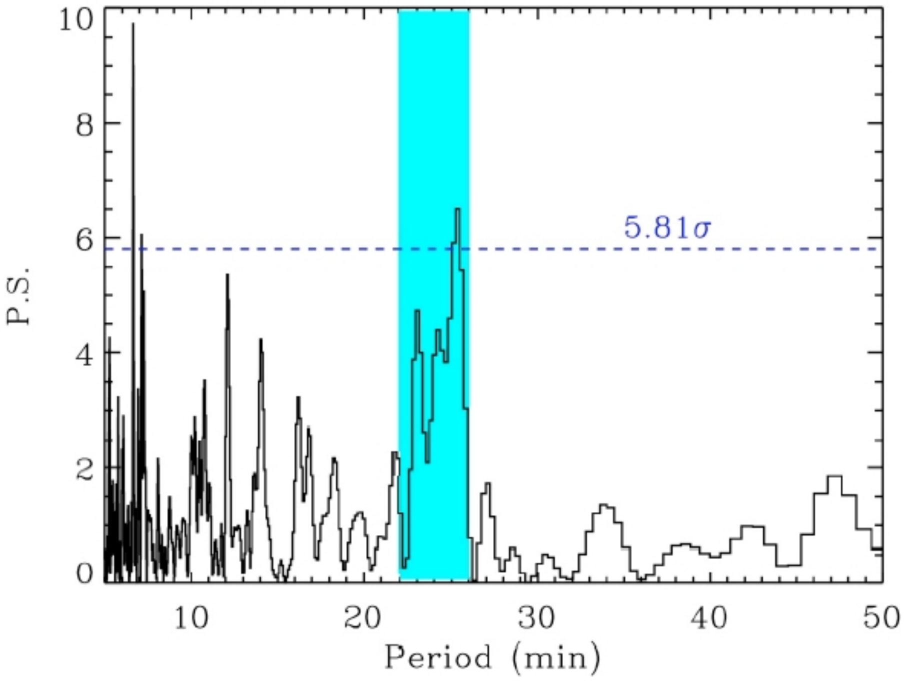
What about g-modes

- Attempts to find them for 30 years.
- No unambiguous detections, but many indications.
- I published a paper in 1995 claiming we would not observe this, but have since 1996 tried to find them.
- Plot from R. Garcia show something?
- We see g-modes on other stars, but different stellar types than the Sun.
- New effort is started now, but the solar noise dominates the signal makes it very difficult!





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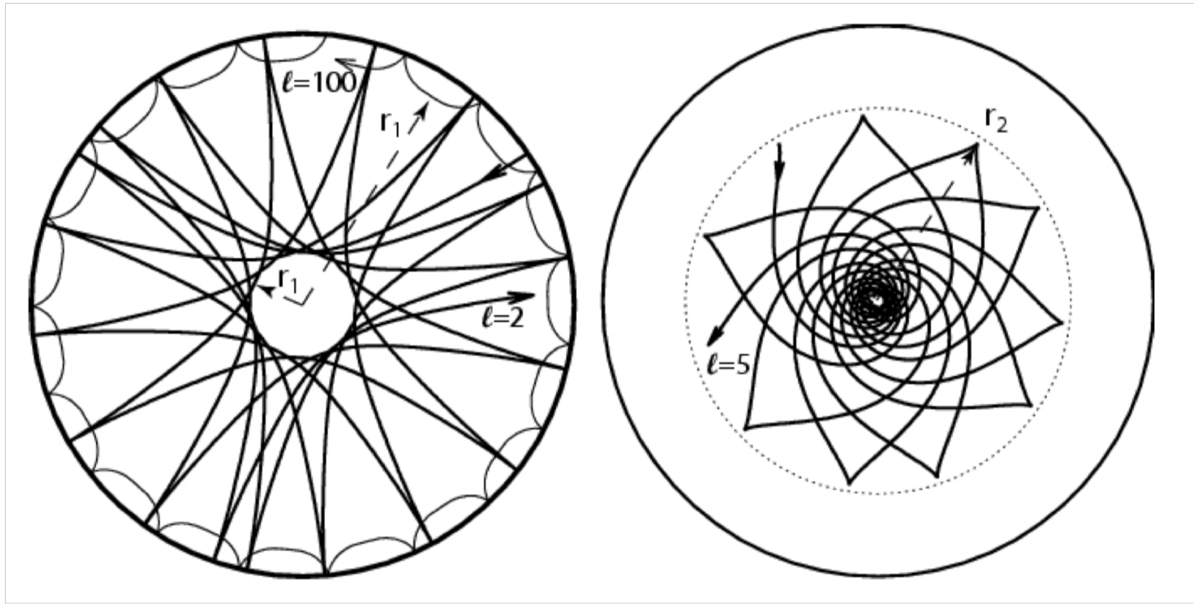
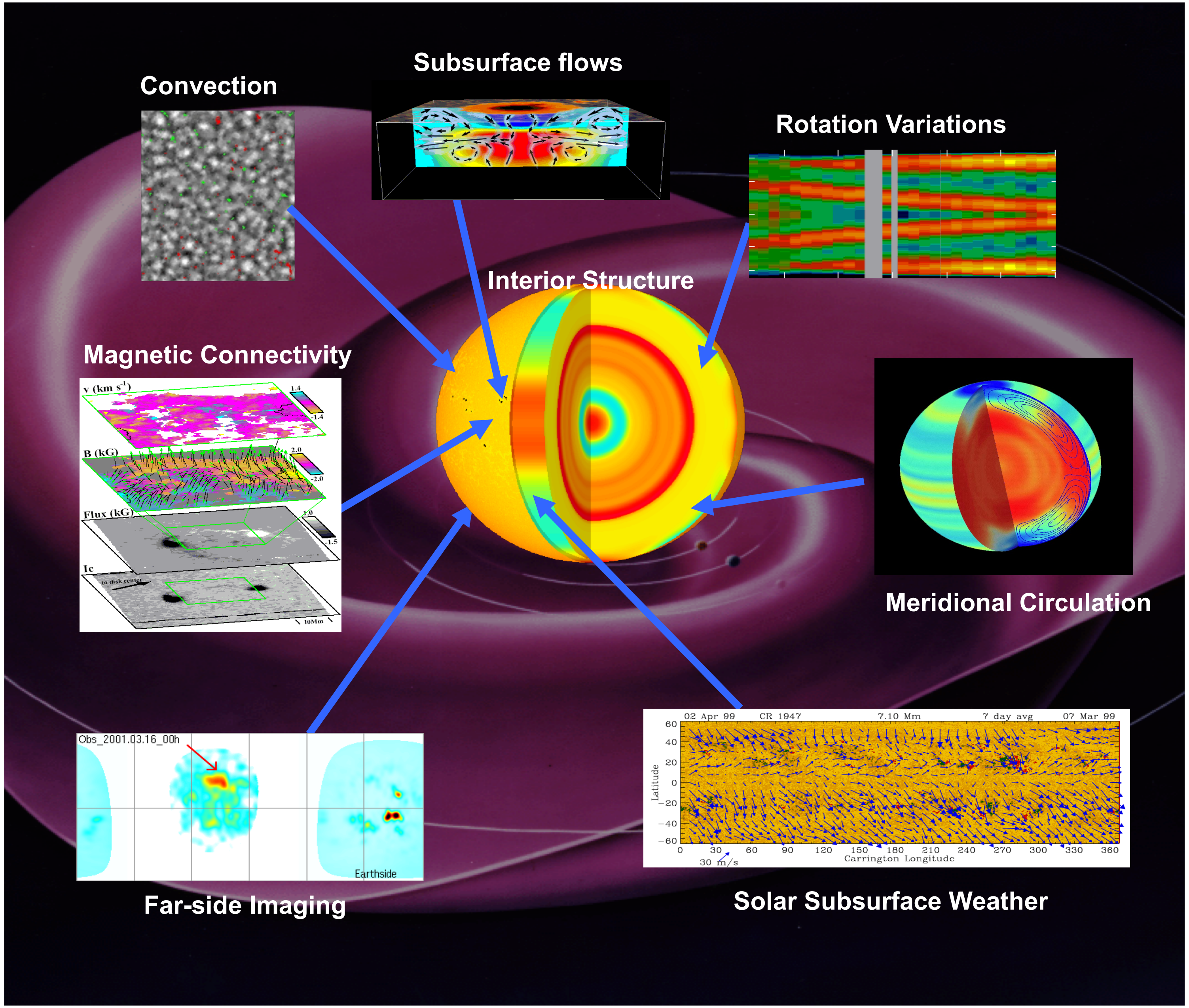
What have we found of the solar interior

- Solved the "solar neutrino problem".
- Discovered the interior solar rotation profile.
- Understand the position of the solar dynamo
- Have discovered the details of the interior "overshoot" region.
- Have created models that are within fractions of a percent of observations.
- Have discovered that the main causes of the solar cycle are in the convection zone.
- Solar core not observed in detail with g-modes.

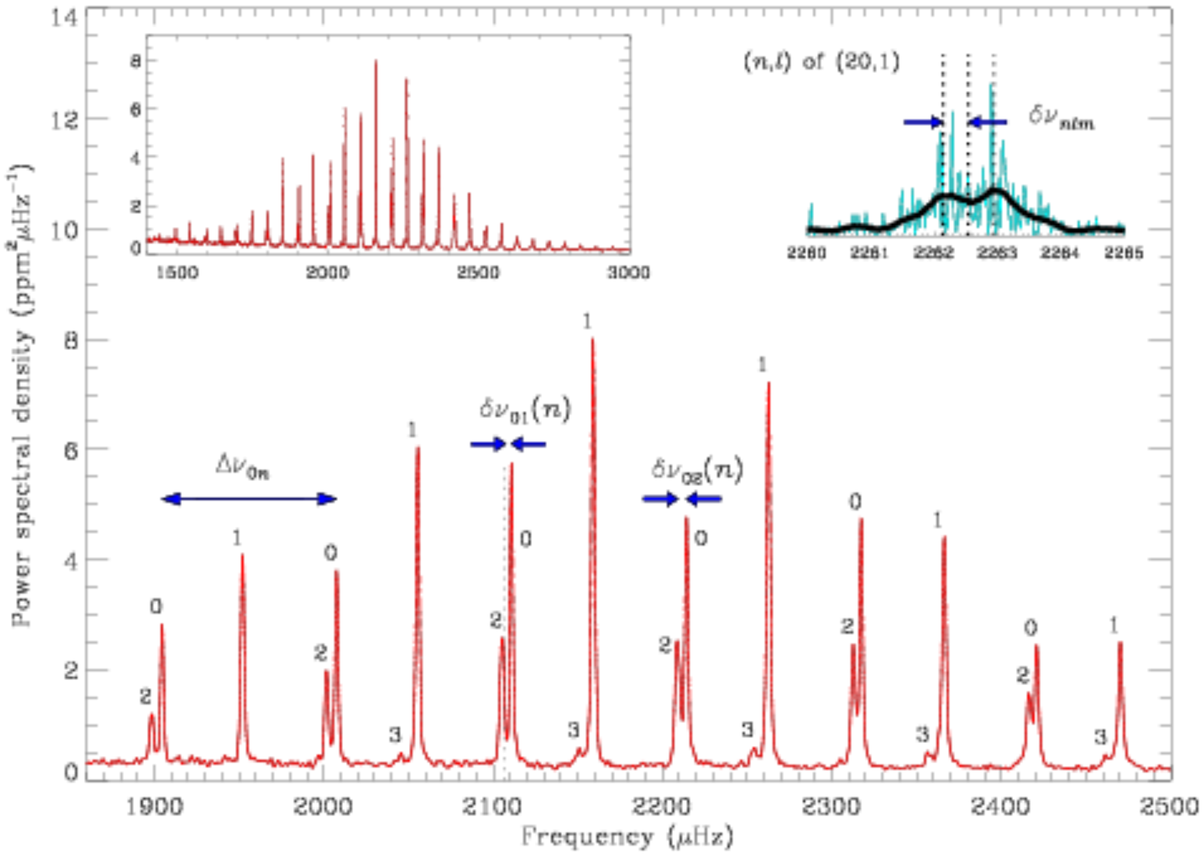


Things I have not mentioned



From Helioseismology to Asteroseismology

- From space it is easy to do the same with stars as VIRGO on the SOHO spacecraft does on the Sun.
- The NASA Kepler spacecraft has demonstrated this magnificently!
- The ESA PLATO mission will develop this further from 2026.
- Asteroseismology gives the possibility to completely circumvent Eddingtons prediction from 1926.
- Asteroseismology gives the internals of all observable stars.



Power spectrum of a red giant, B. Chaplin