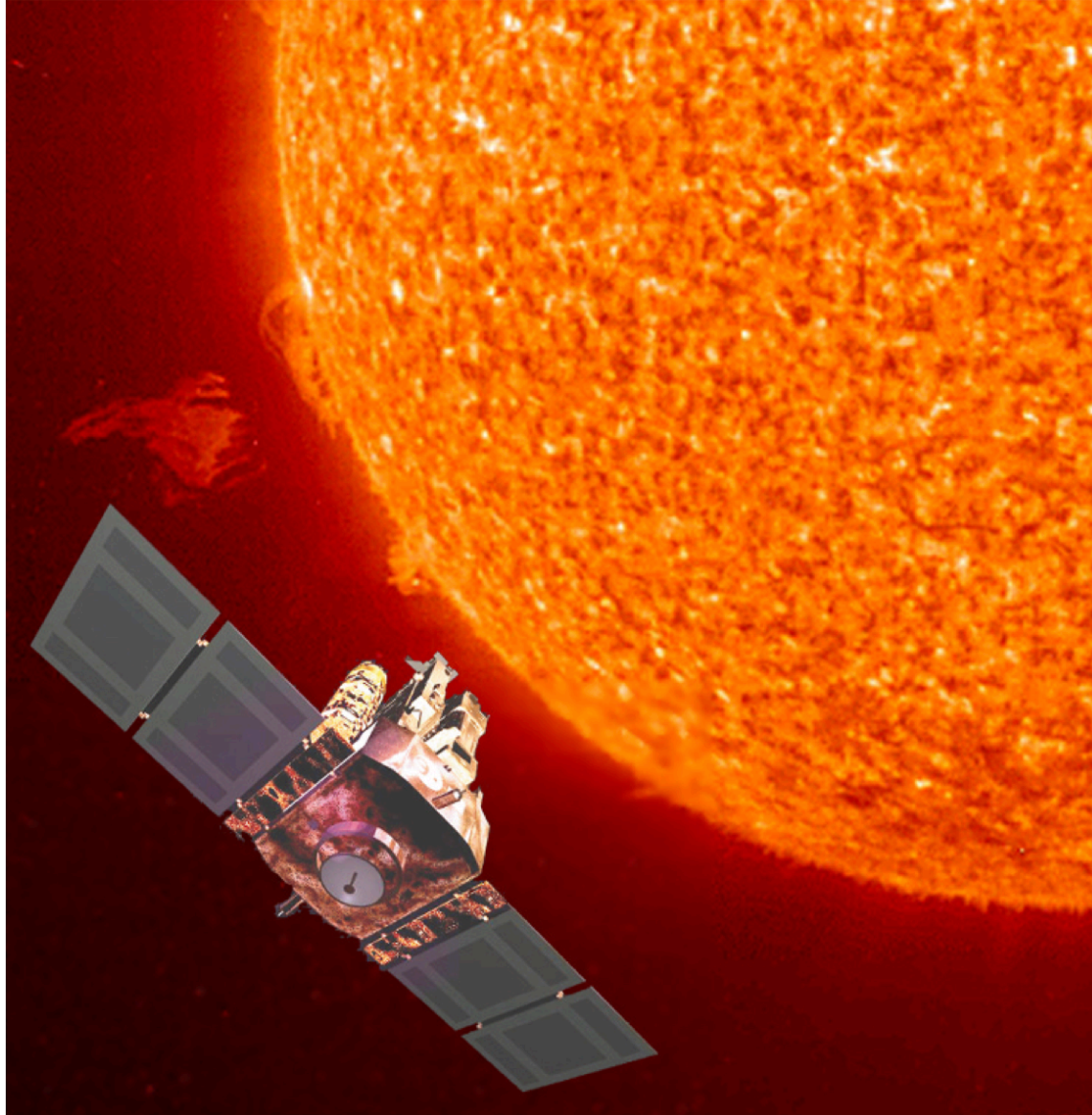


Studying the solar interior and irradiance – why and how?



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.

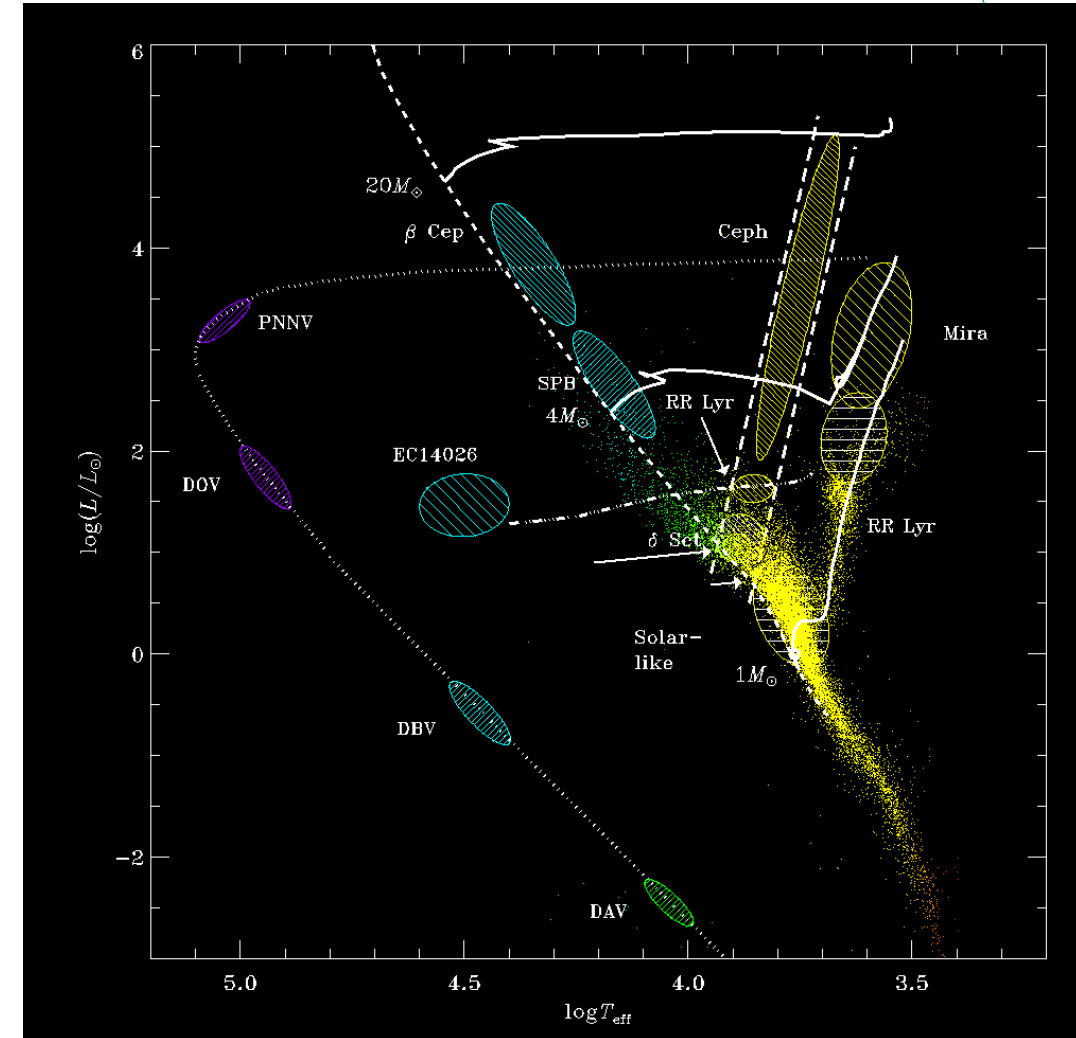
Our telescopes may probe farther and farther into the depths of space; but how can we ever obtain certain knowledge of that which is being hidden behind substantial barriers?

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?

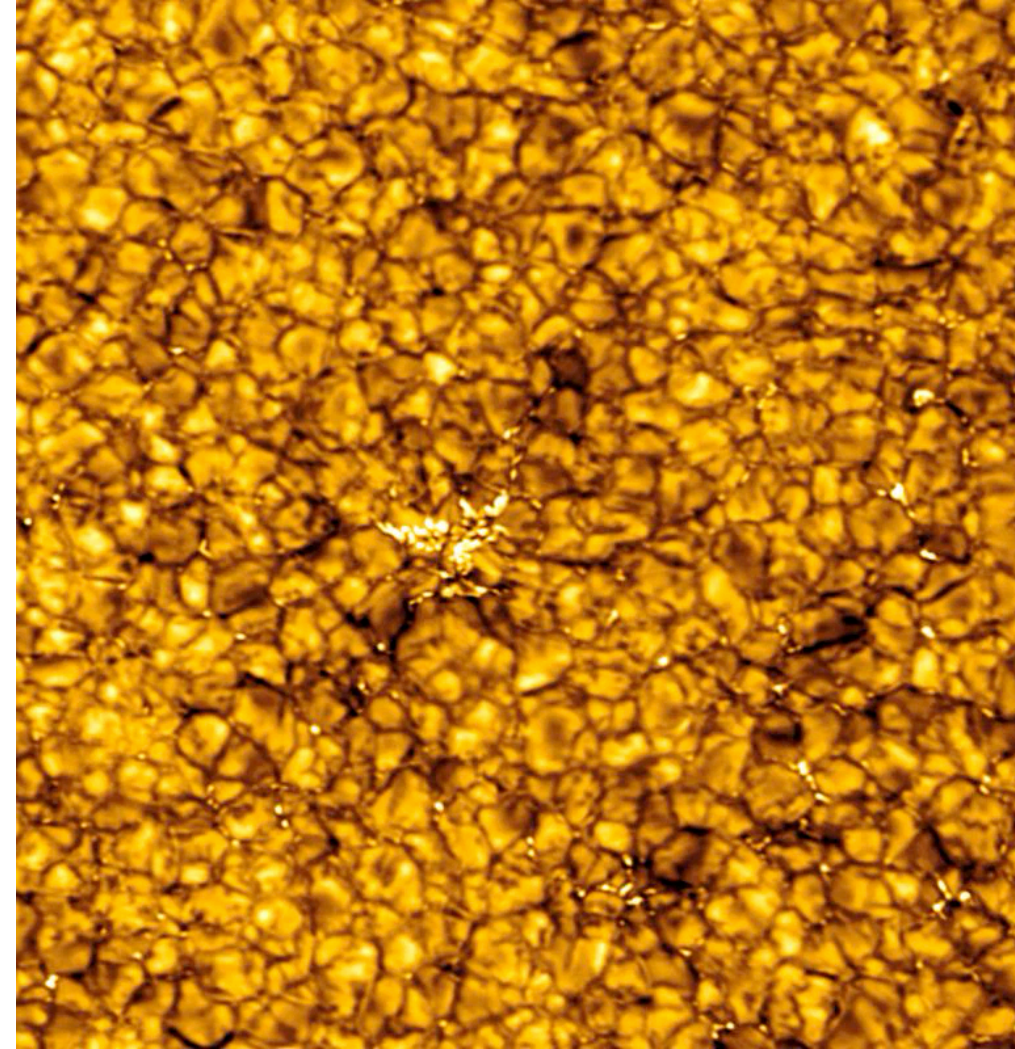
- The Sun is the closest star and the only one we can study in detail, surface and interior.
 - How does the Sun rotate?
 - How does the Sun evolve?
- The Sun drives the solar system as well as the Earth's weather and the energy comes from the fusion in the solar core.
 - Where does the solar variability originate?
- The Sun has 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?

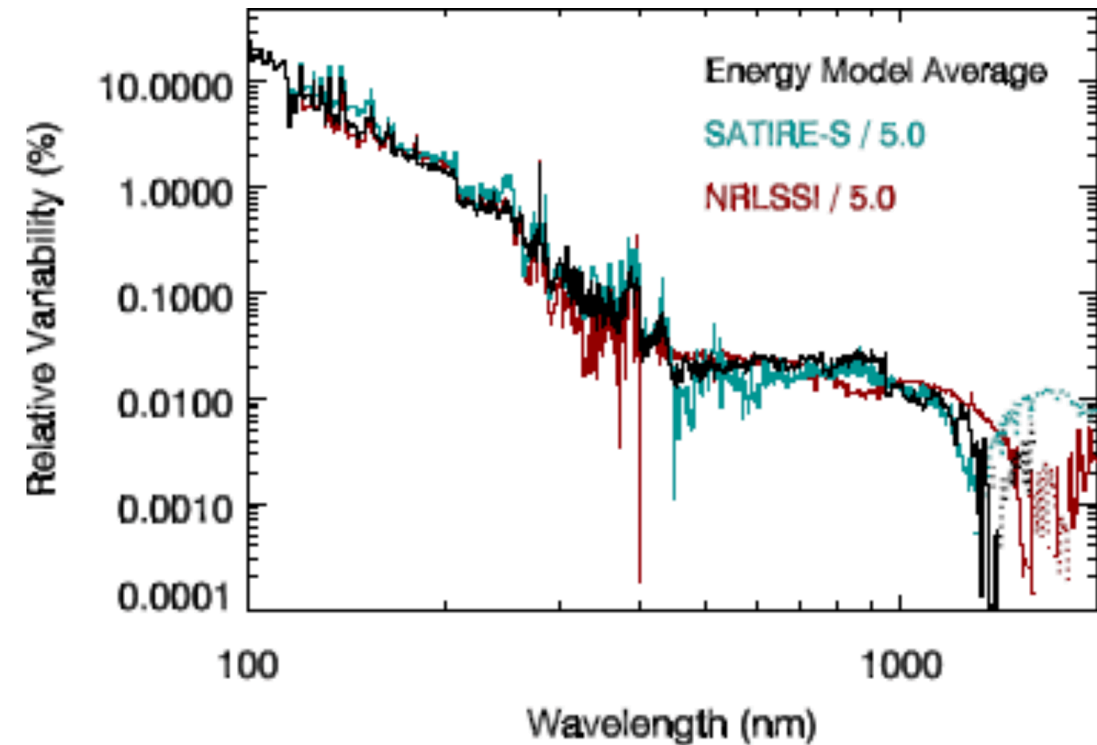


- The energy output at the surface gives a clear indication of the internal nuclear processes.
- The size and mass of the Sun sets limitations of the interior.
- The differential rotation shows that there is an internal shear.
- The presence of strong magnetic regions in sunspots show there is a dynamo 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”.

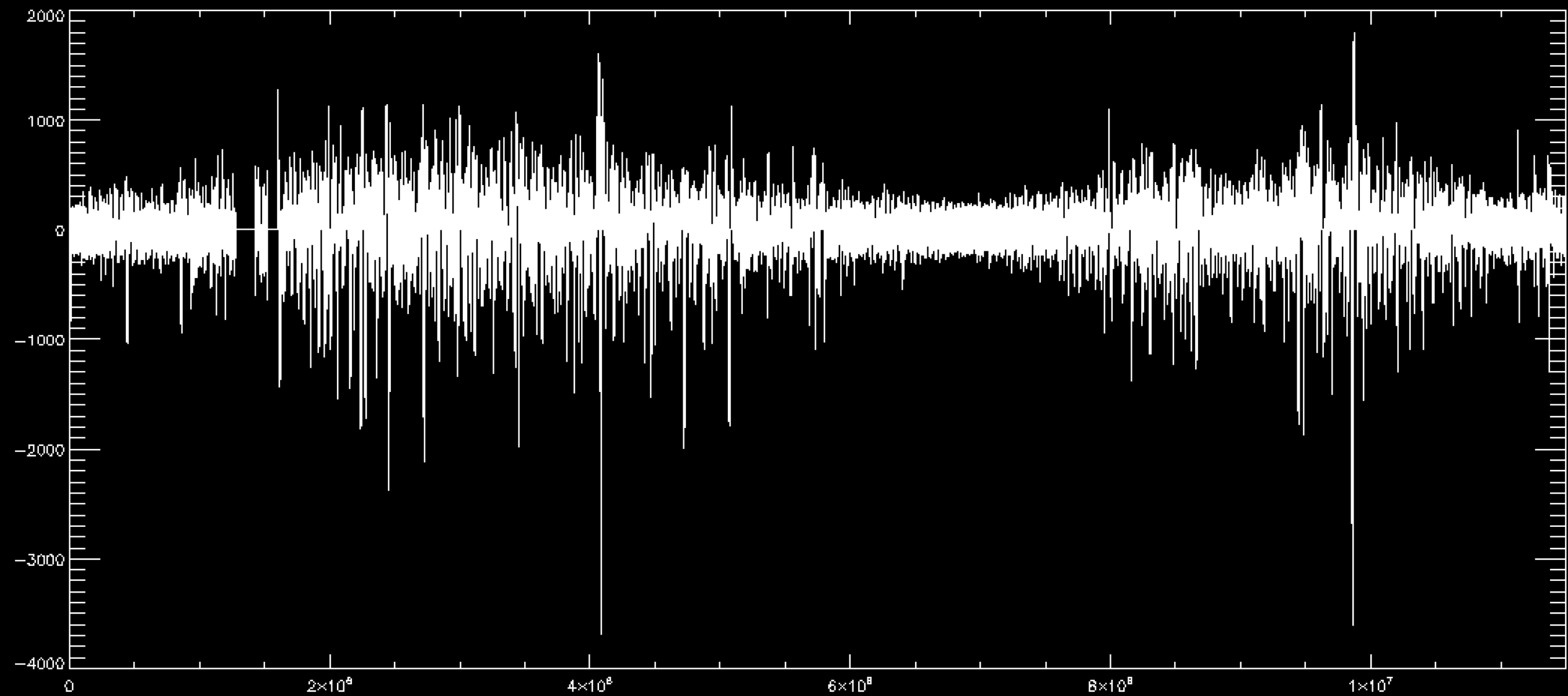


How much energy do we receive from the Sun?

- In total about 1360.4 W/m^2 at mean distance from the Sun.
- More than 99.9% of this is as electromagnetic radiation.
- But variation in electromagnetic radiation in the UV is biggest, and with the minor particle radiation, this may influence the upper atmosphere.
- Measuring total solar irradiance (TSI) is extremely difficult, because:
 - Precision - measure short term variation precisely
 - Accuracy - what is TSI in W/m^2
 - Stability - what is the TSI variation over decades

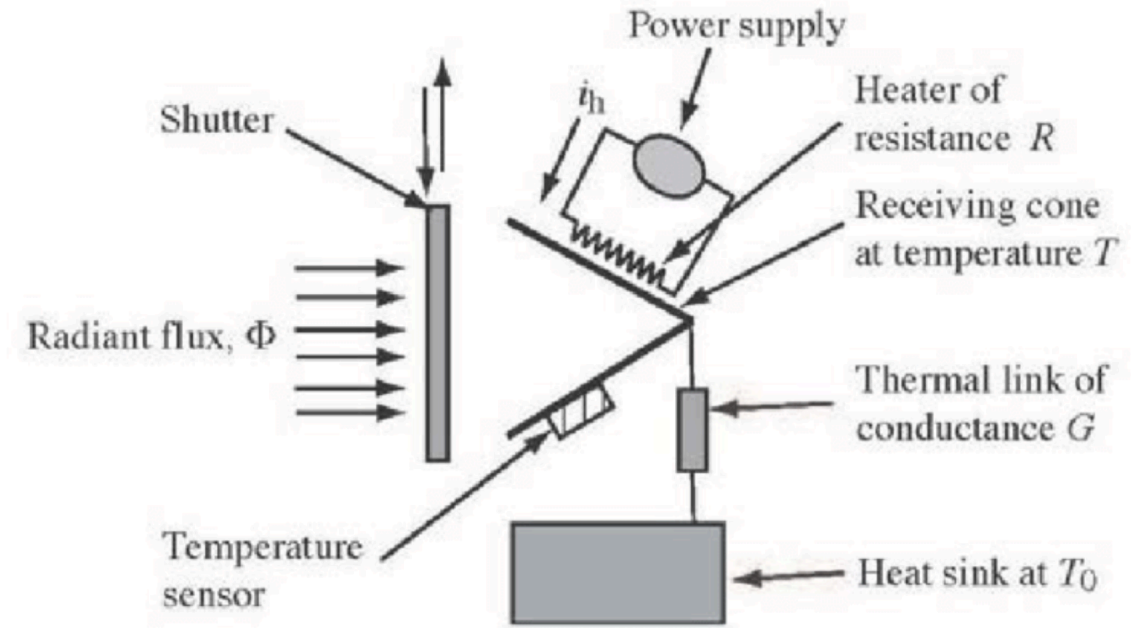


Precise observations of the Sun as a star with VIRGO (ppm)



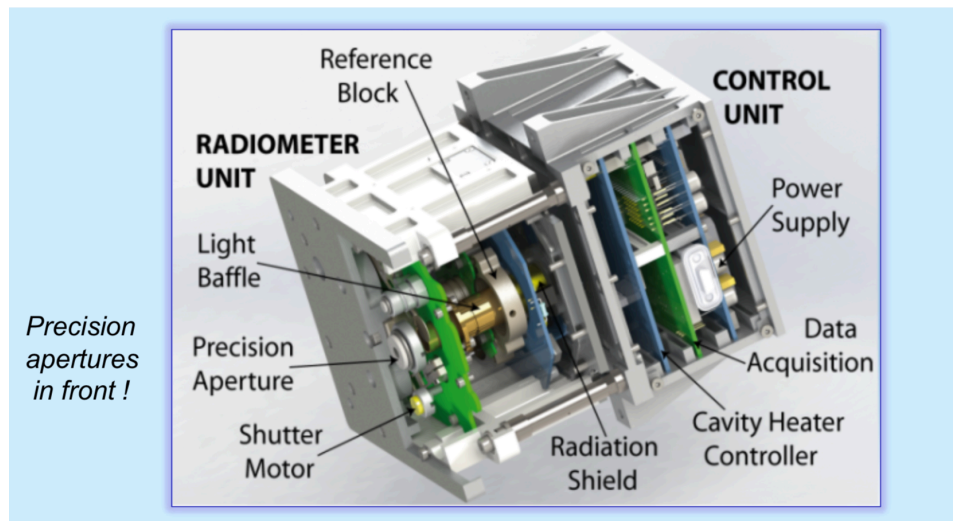
How to measure TSI accurately?

- Need knowledge of geometry
- All normal sensors degrade in space.
- Electrical substitution active cavity radiometer.
- Measure the current that is required to give the same heating of a blackbody cavity.
- Precision is 10 ppm, while accuracy is more like 400-800 ppm

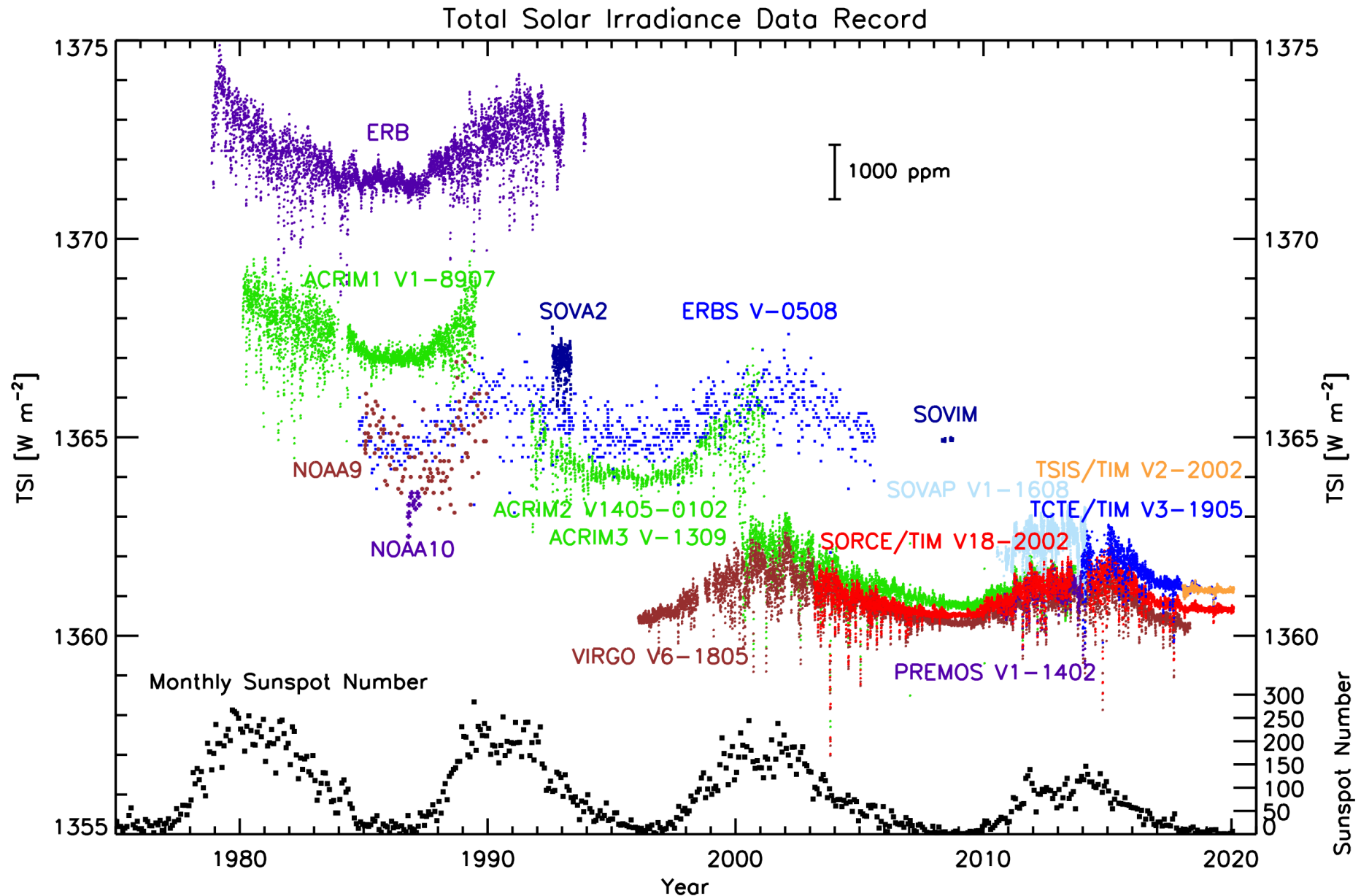


CLARA/NorSat-1

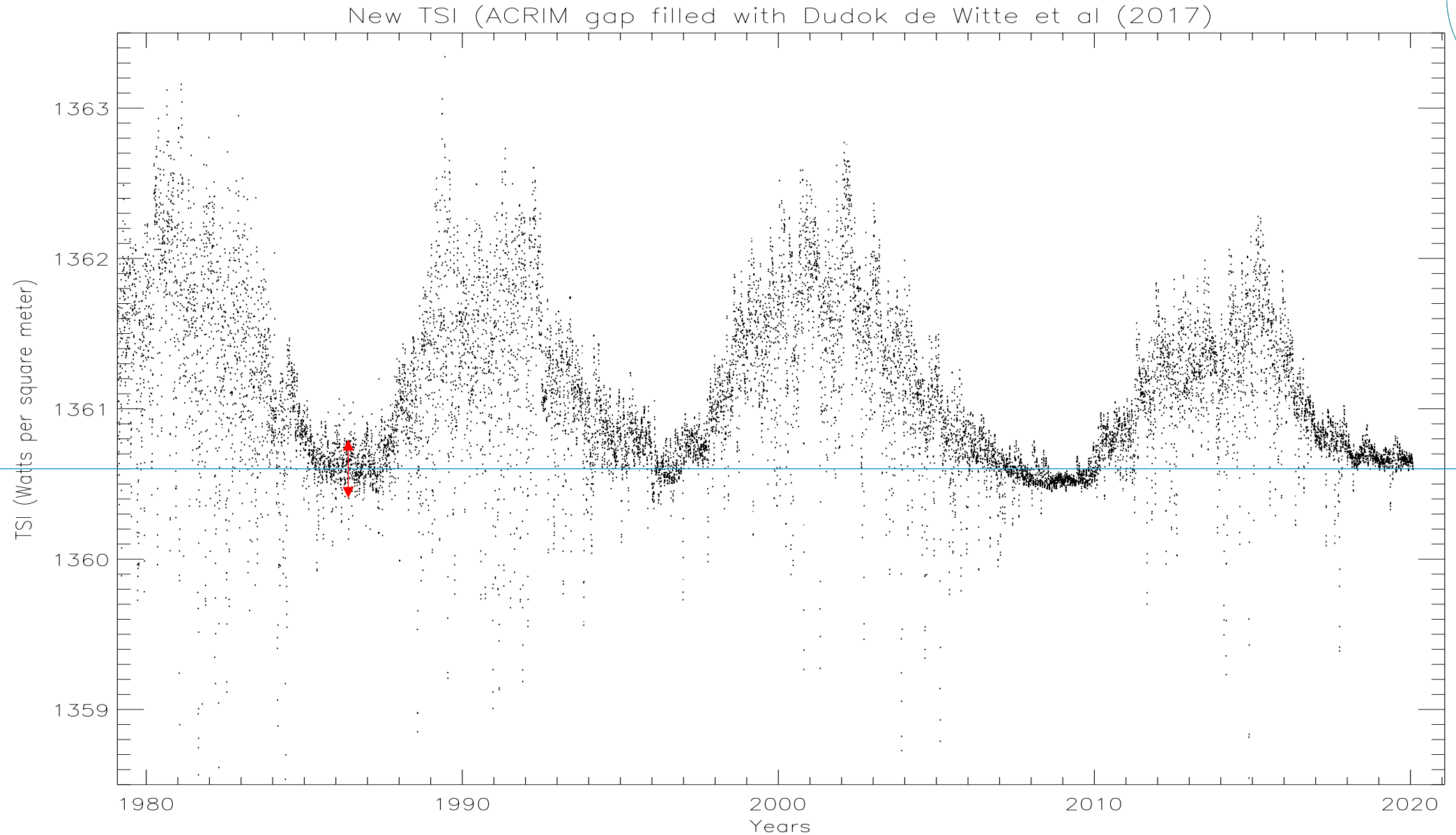
pmod wrc



It is not easy and what is the stability?

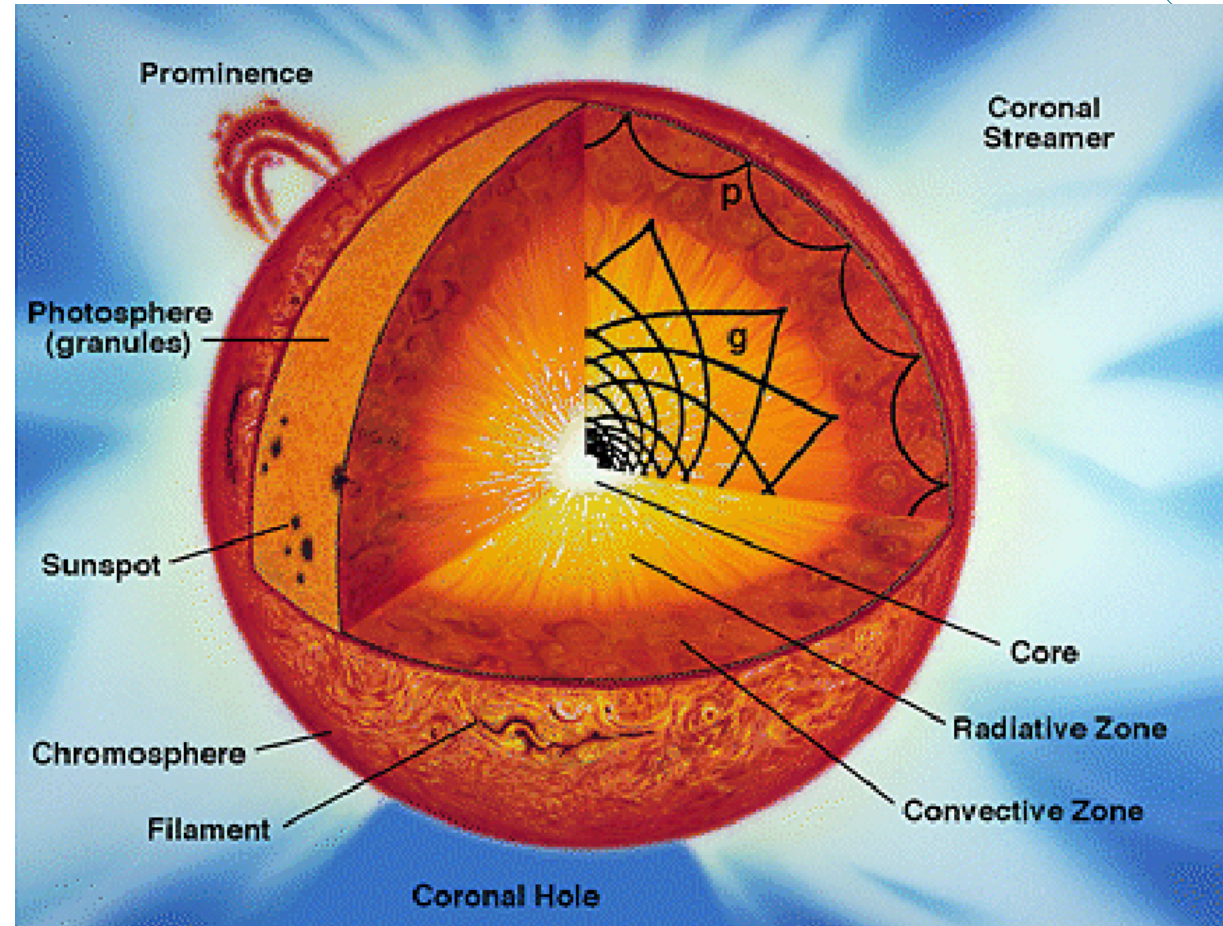


Solar energy output (TSI) as good as it gets!



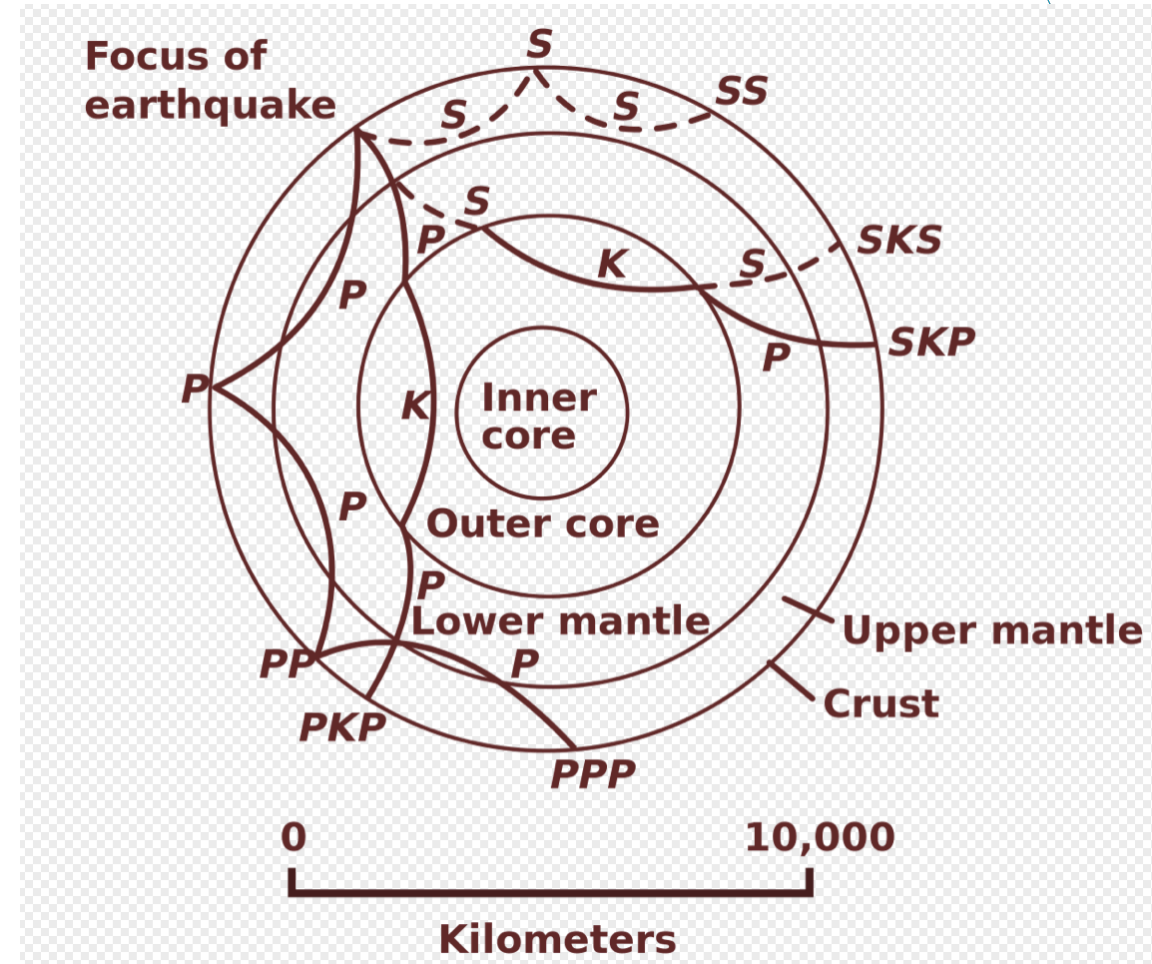
How can we observe the solar interior?

- Observation of neutrinos for the energy generating fusion.
- Use the same probing as we do with seismic measurements of the Earth's 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.

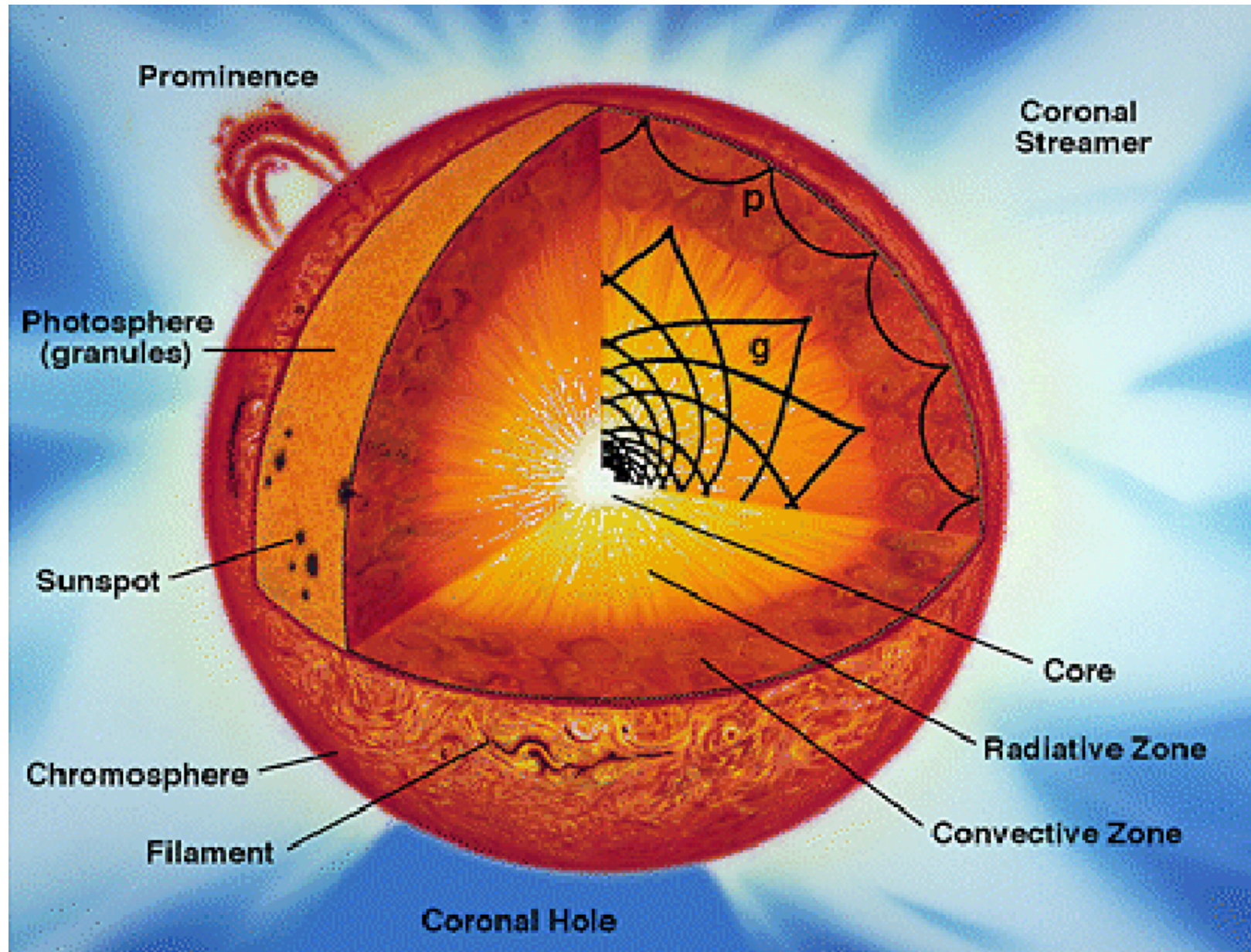


The speed of sound in different media

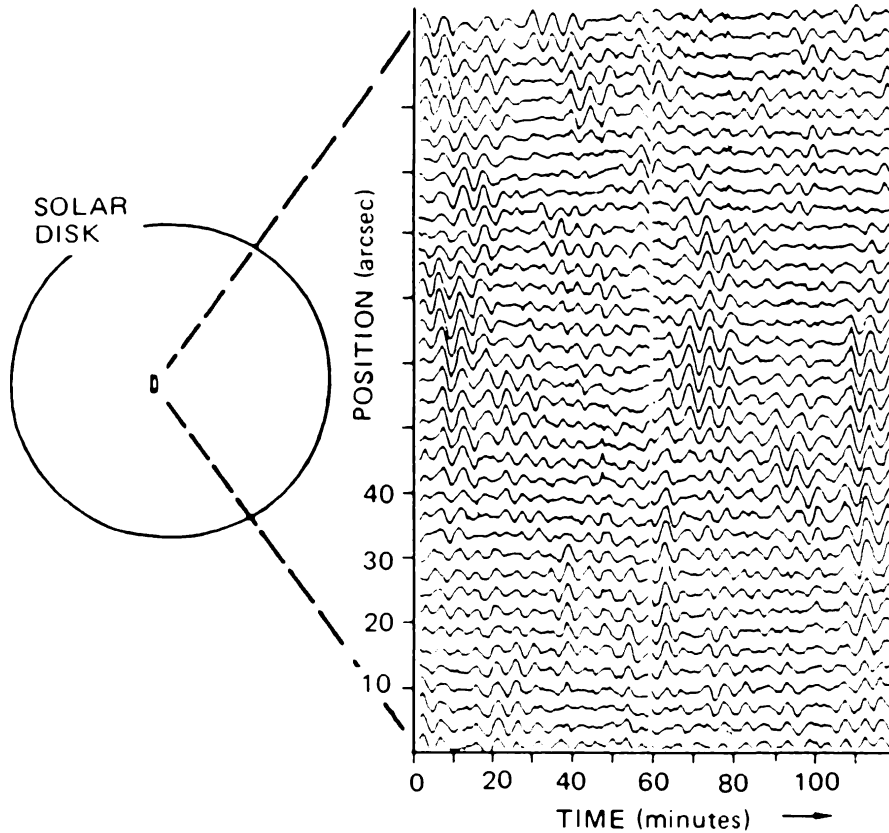
- Air = 343 m/s
- Helium = 965 m/s
- Hydrogen = 1284 m/s
- Water = 1482 m/s
- Granite = 6000 m/s
- Outer layers of the Sun = 10 km/s
- Core of the Sun = 550 km/s
- The faster the speed is, the less influence the medium has on the wave passing through.



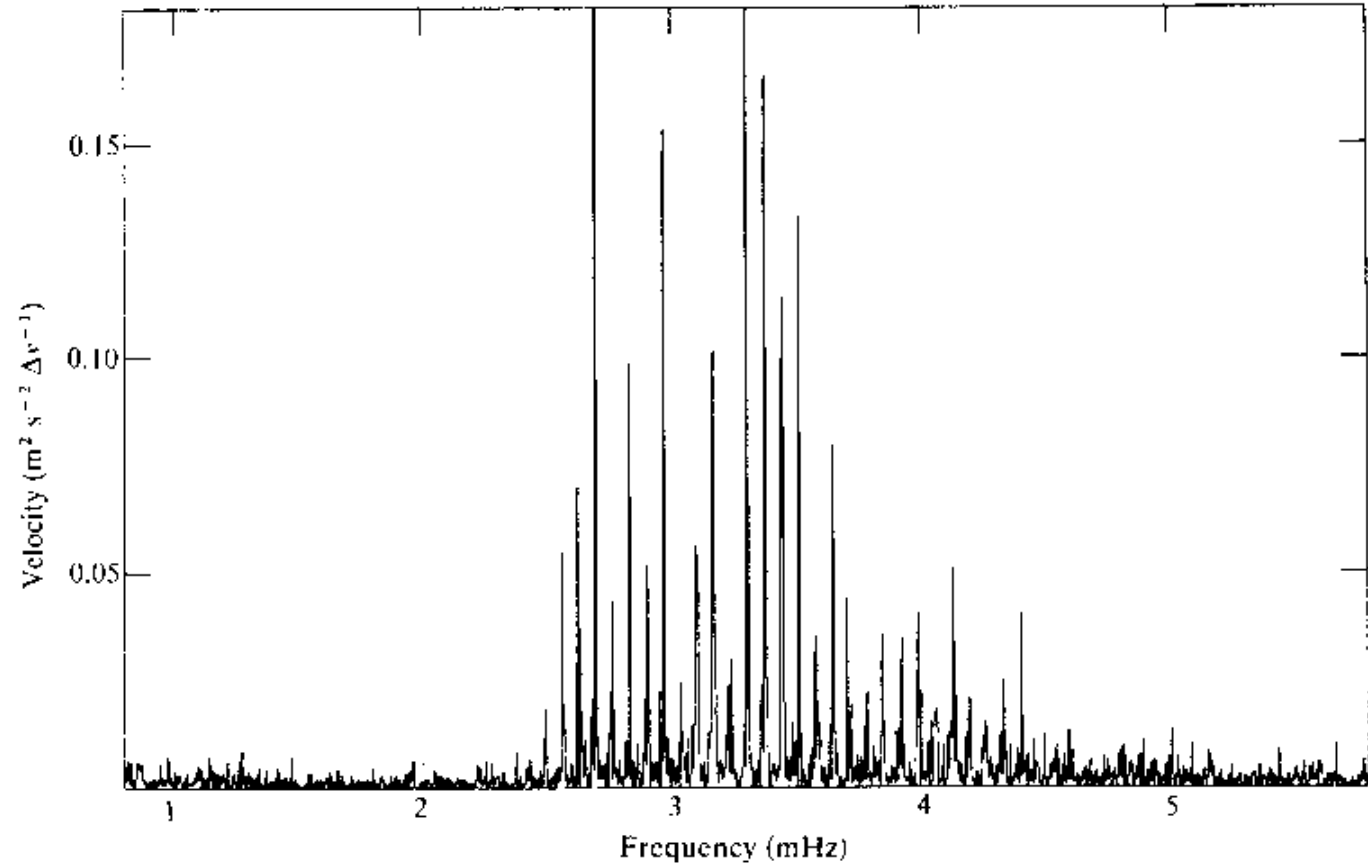
Helioseismology is the window to the solar interior



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



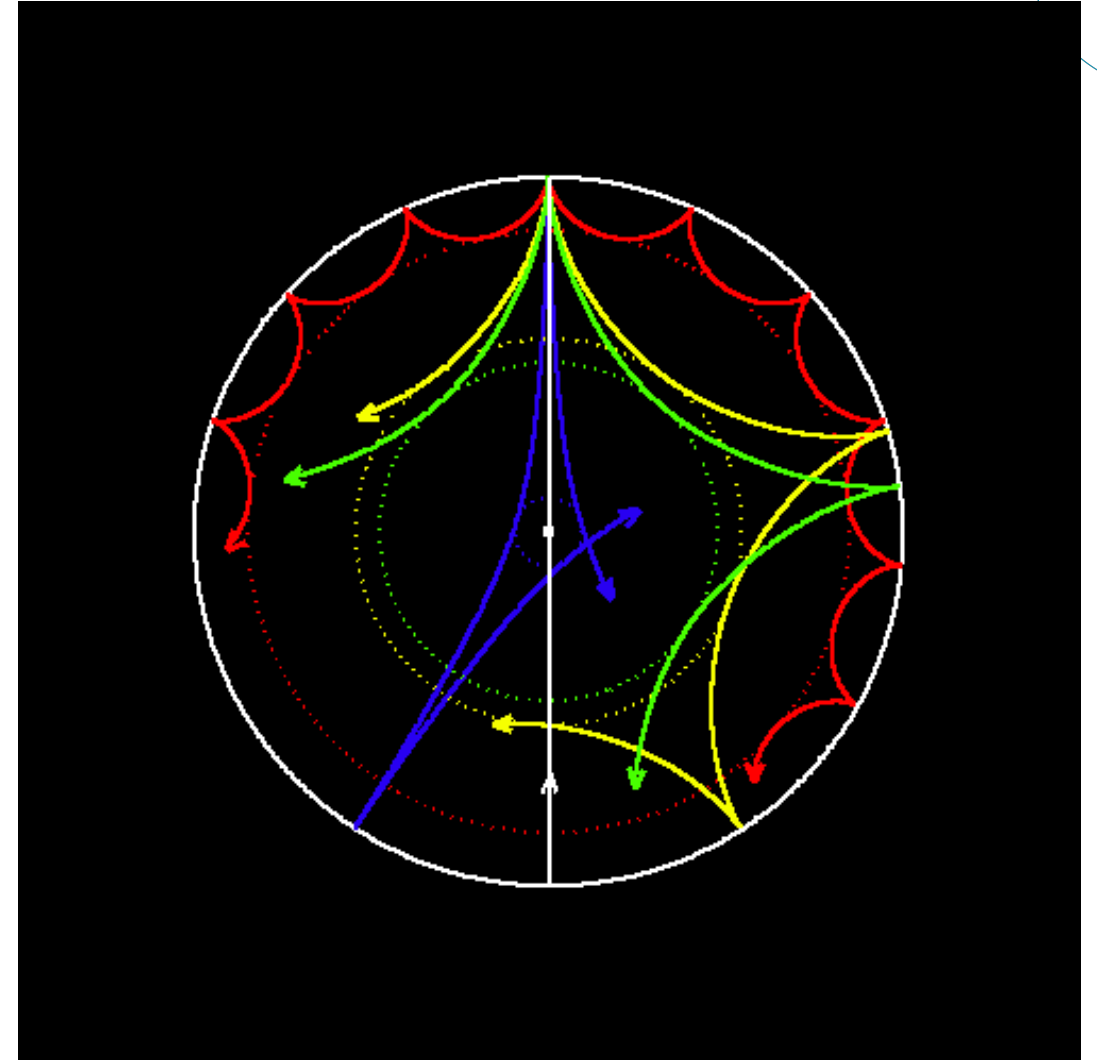
Musman & Rust
(1970; Solar Phys. 13, 261)



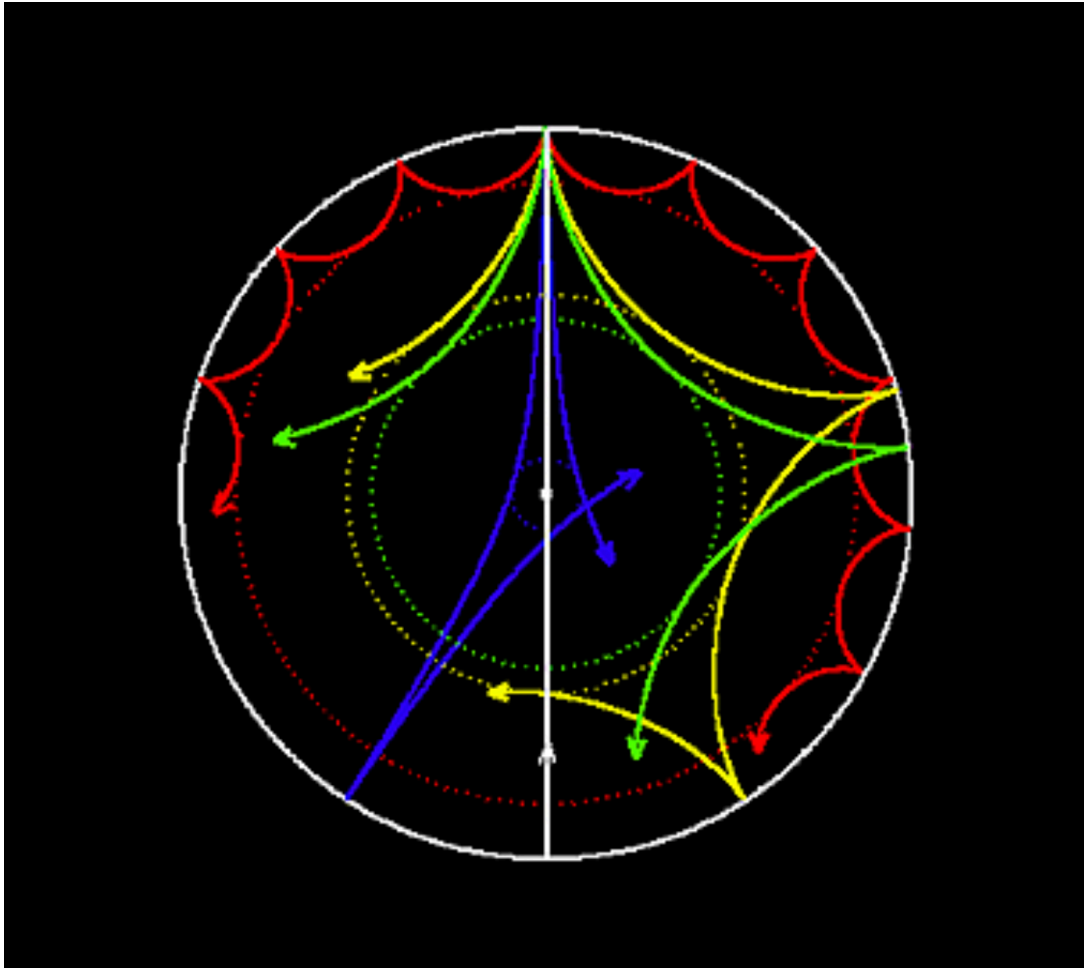
Grec et al. (1980; Nature 288, 541)

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
- Gravity mode oscillations cannot exist where we have convection, why?

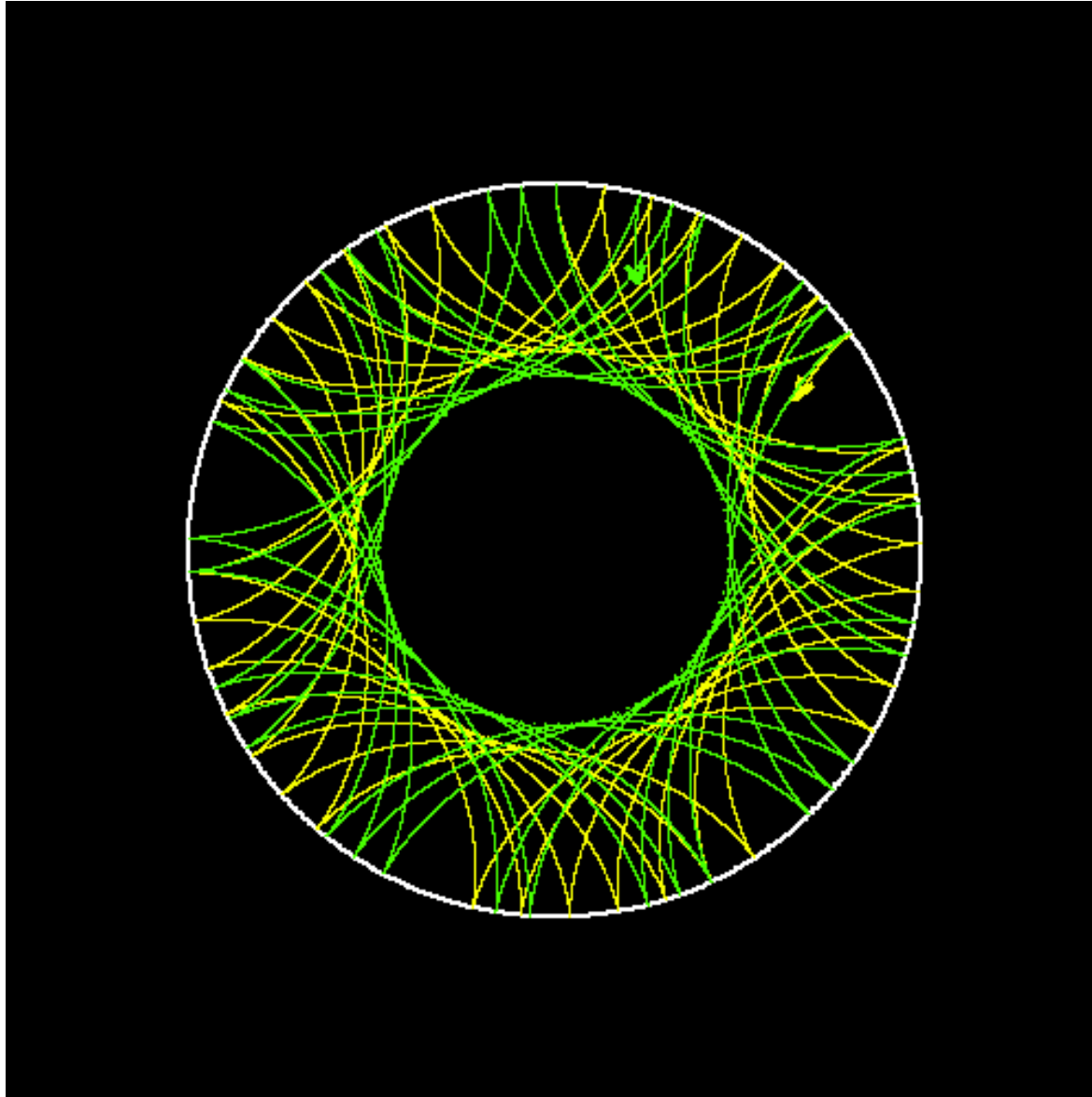


All media have resonant or eigen frequencies

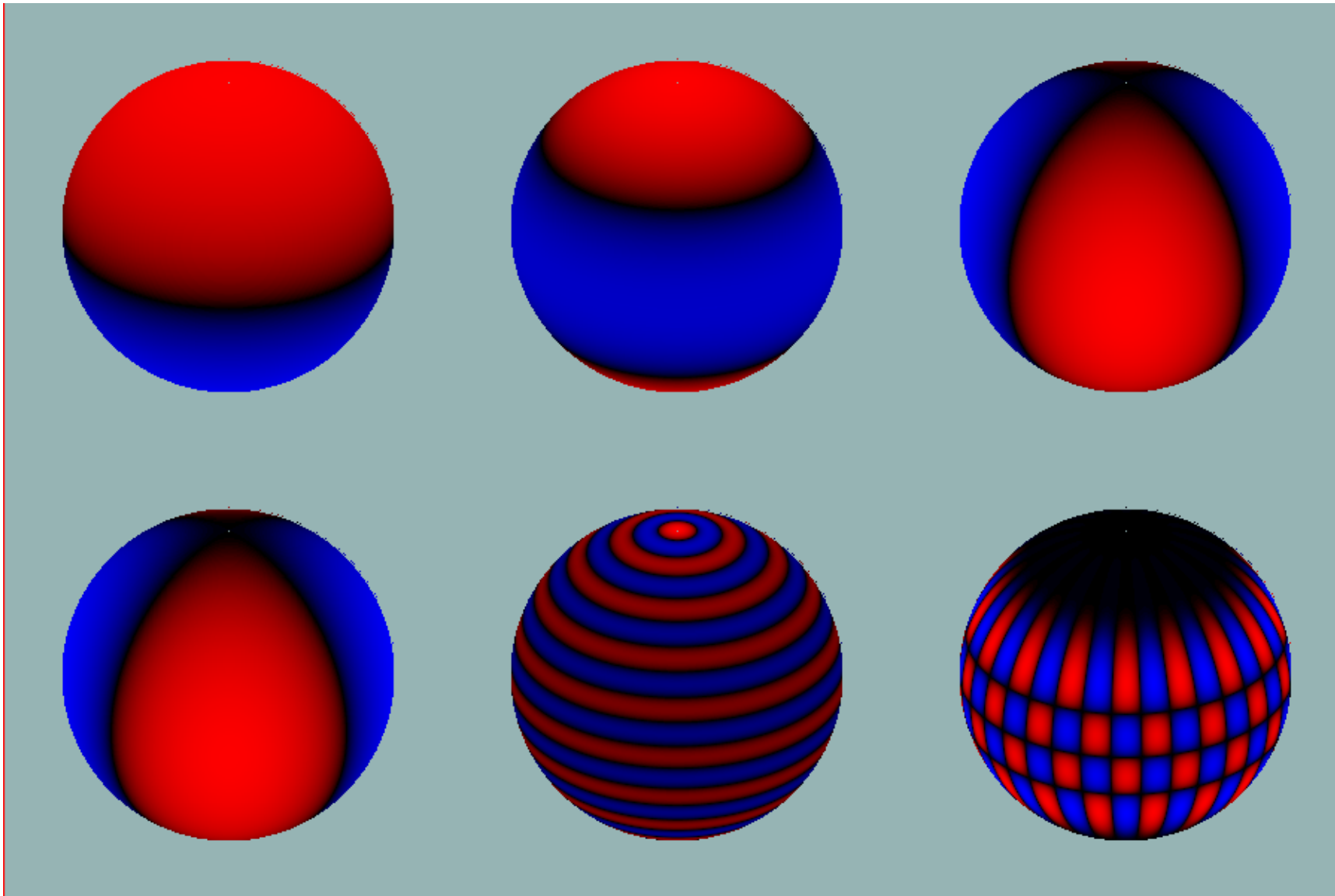


- A wavefront of a sound wave moving obliquely into the increasing temperature of the Sun will turn away from direction of the increasing temperature.
- This happens because the lower part of the wave has higher sound speed.
- Depending on the horizontal extent of the wave this will happen at different 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.

How can we probe to different depths of the Sun?

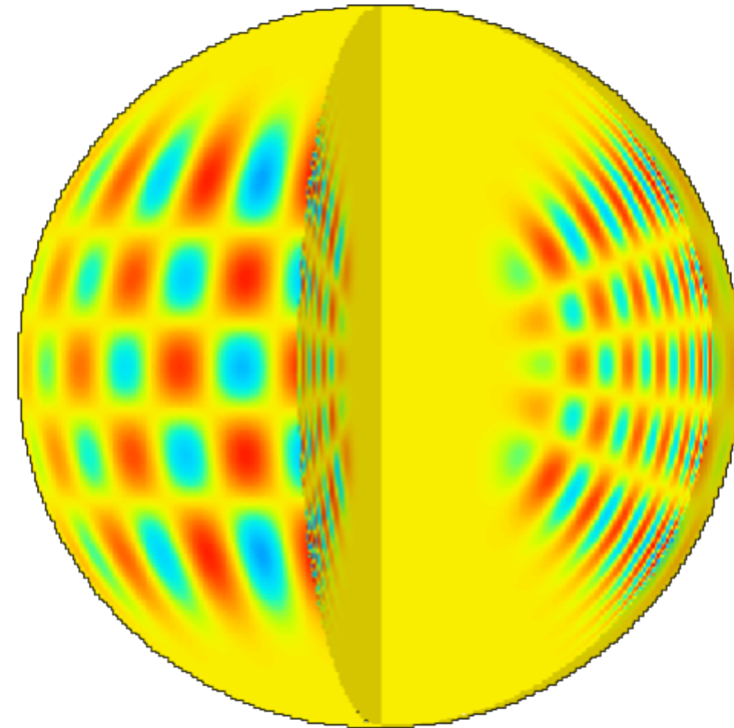


Spherical harmonics

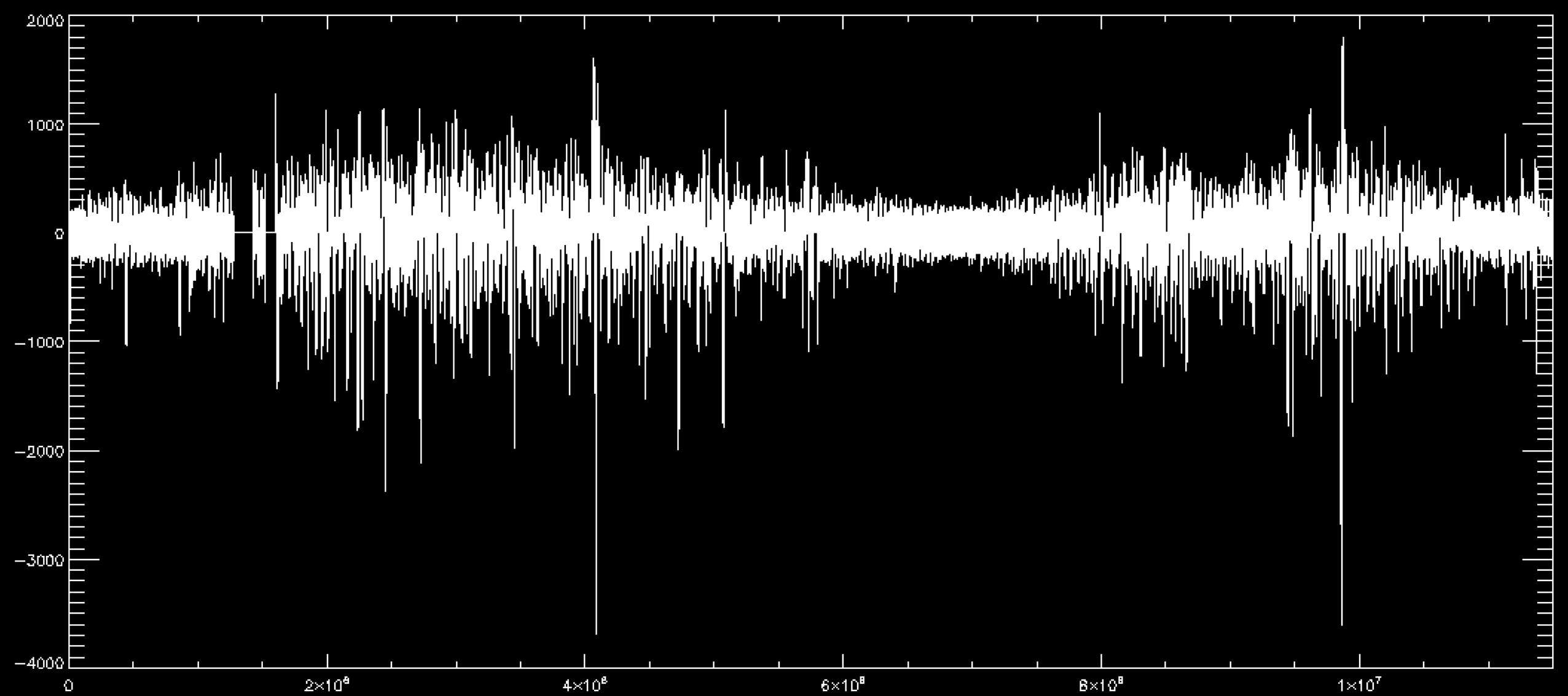


Global P-modes

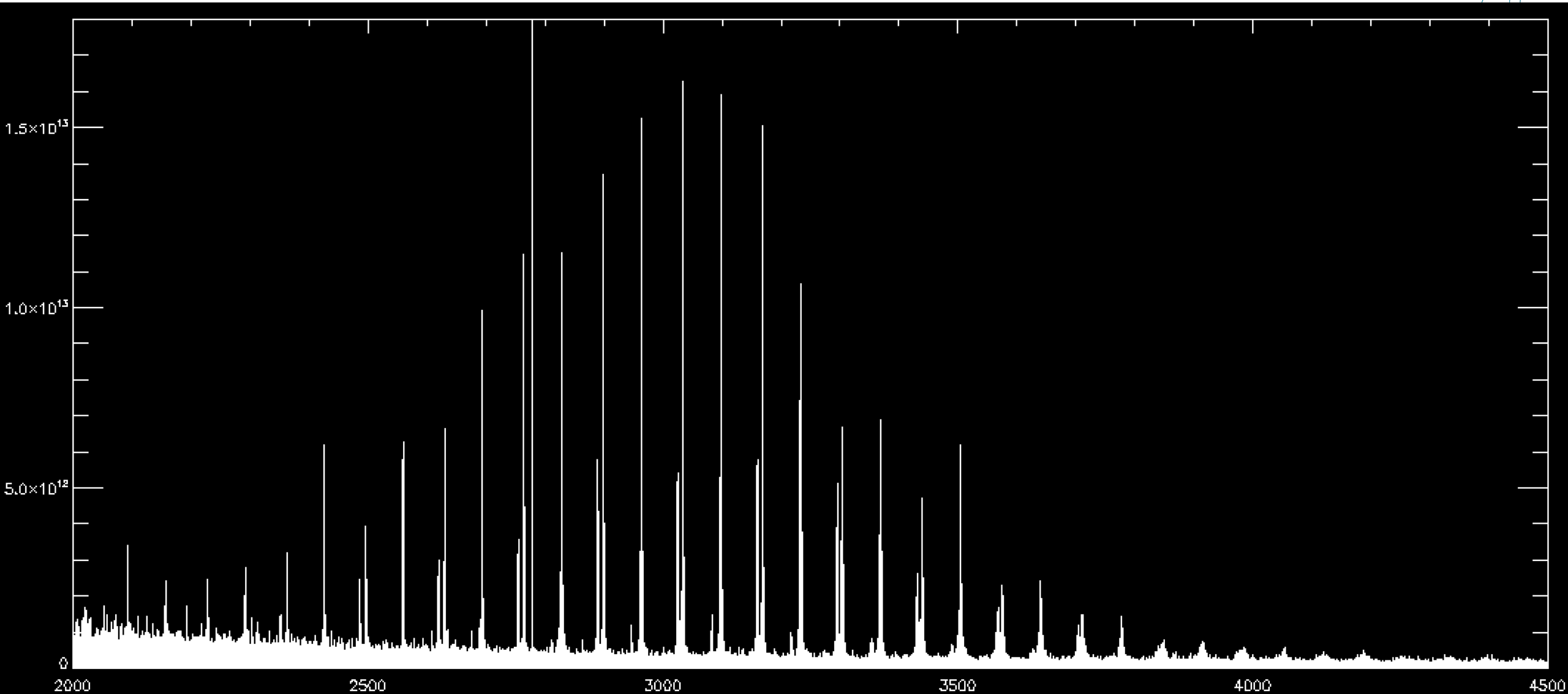
- A p mode is a standing acoustic wave with turning points at surface and at the point where the wave direction becomes horizontal.
- Each mode can be described by a spherical harmonic, describing number of radial nodes (n) and horizontal modes (l, m).
- Quantum numbers n (radial order), l (degree),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



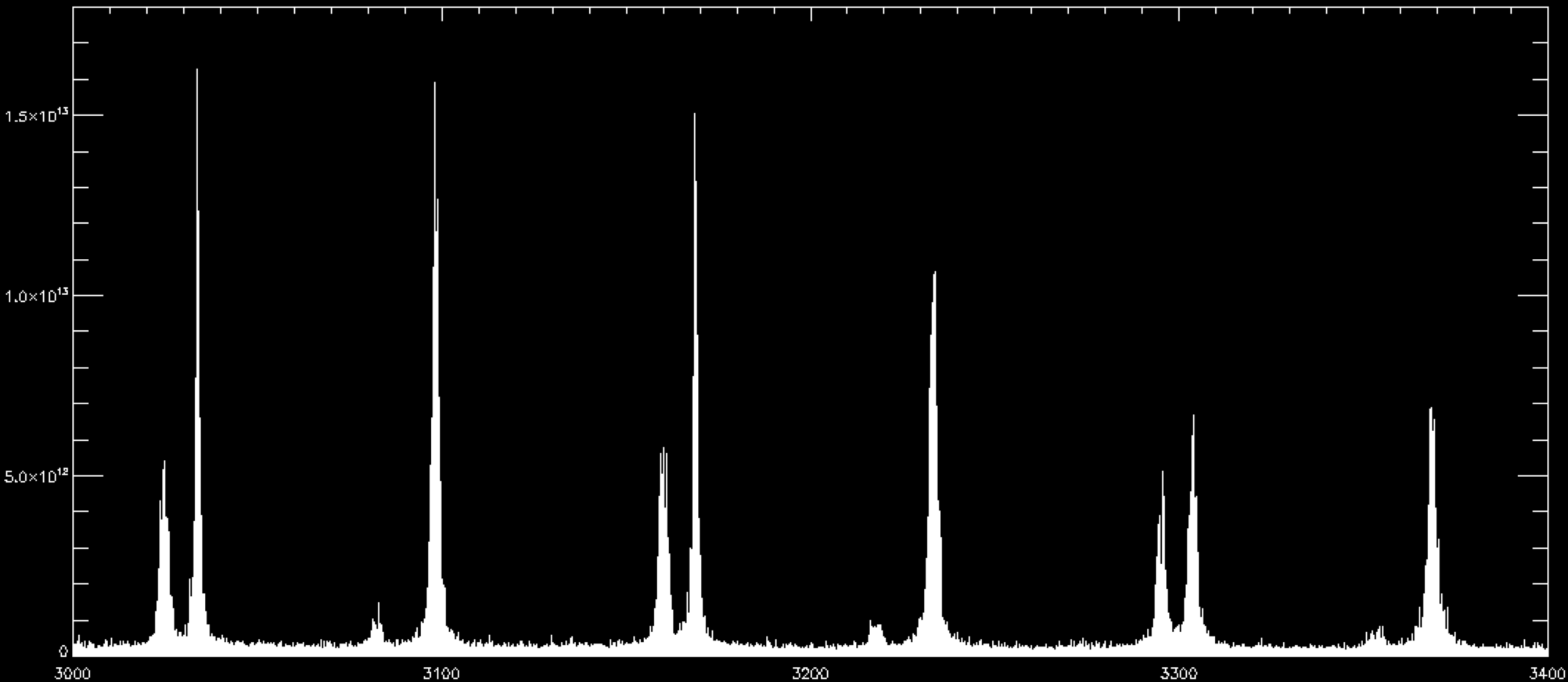
Observations of the Sun as a star with VIRGO



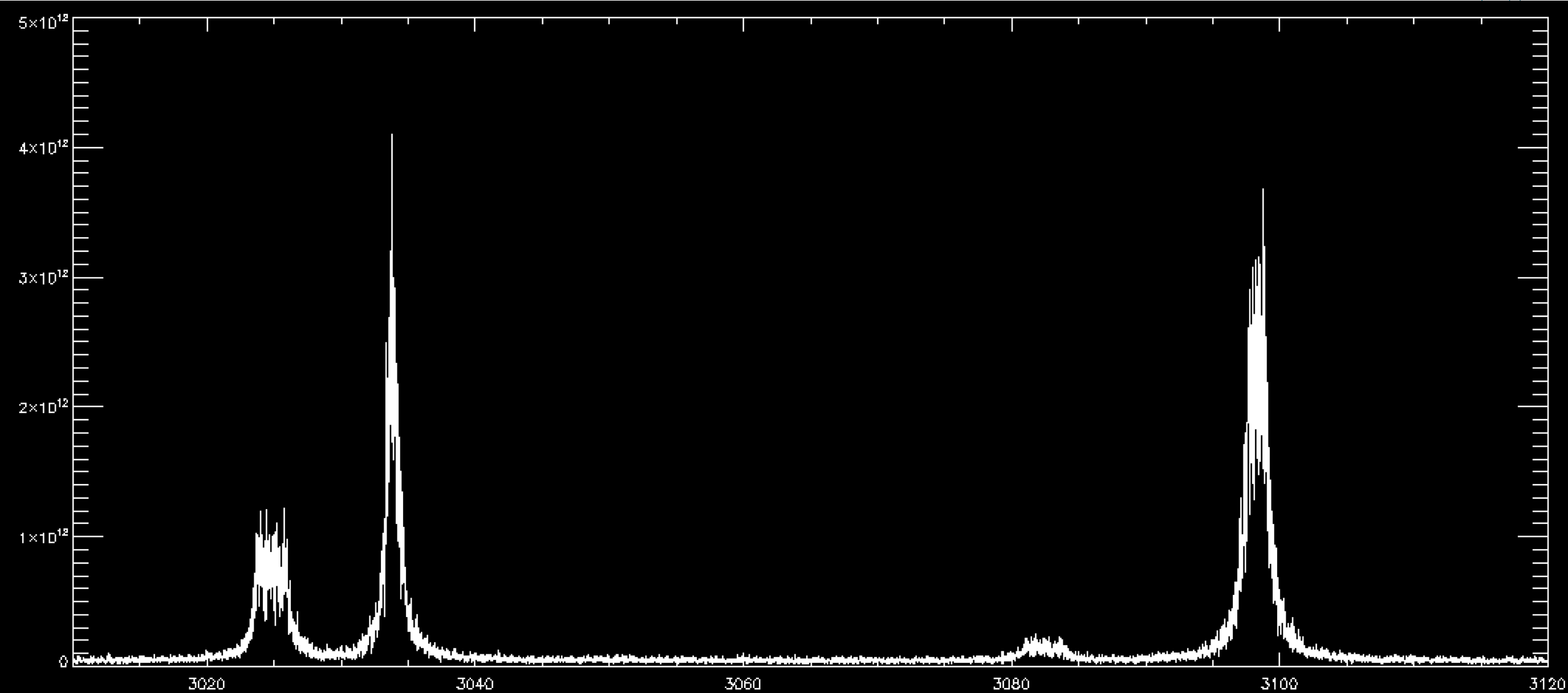
Power spectrum of Sun as a star VIRGO (1)



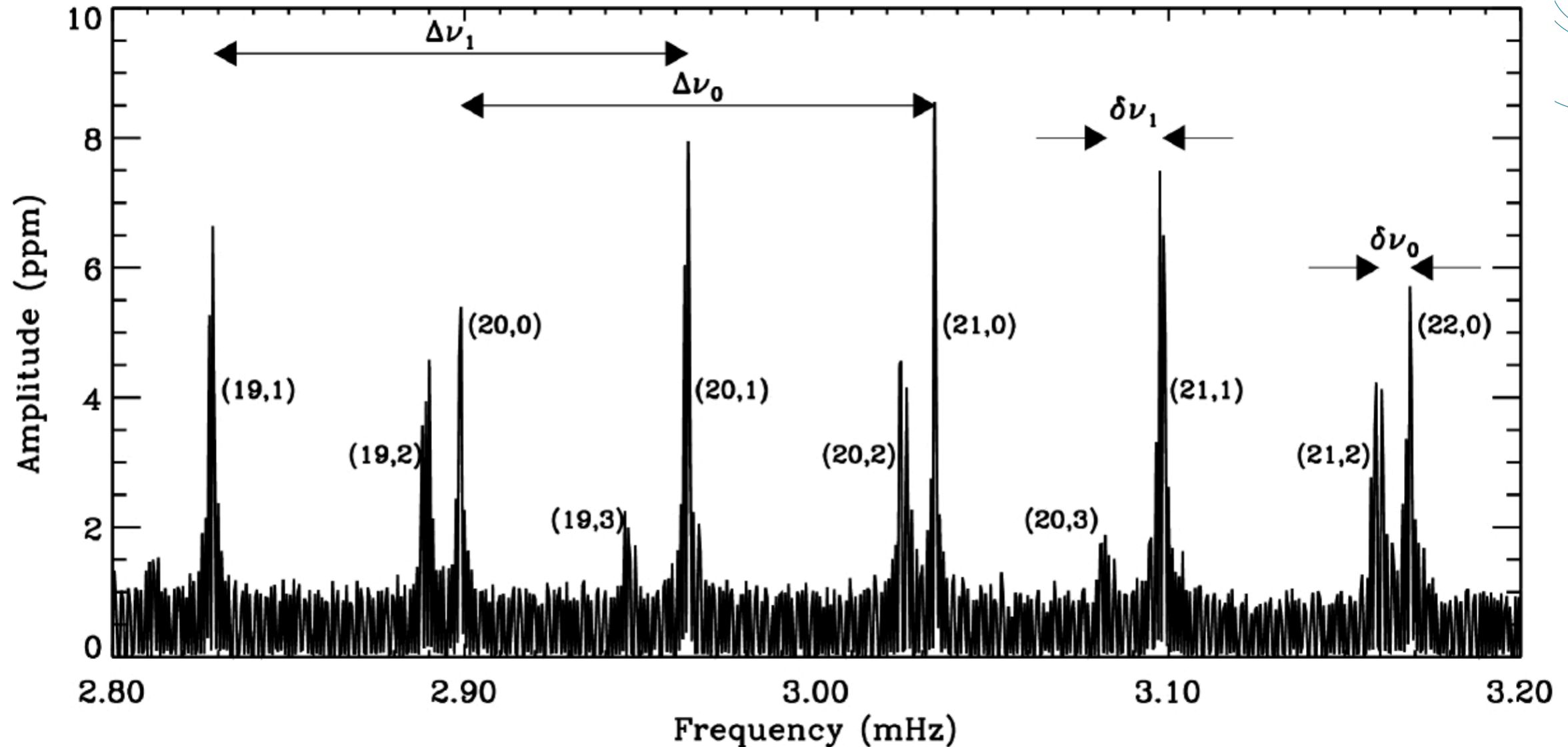
Power spectrum of Sun as a star VIRGO (2)



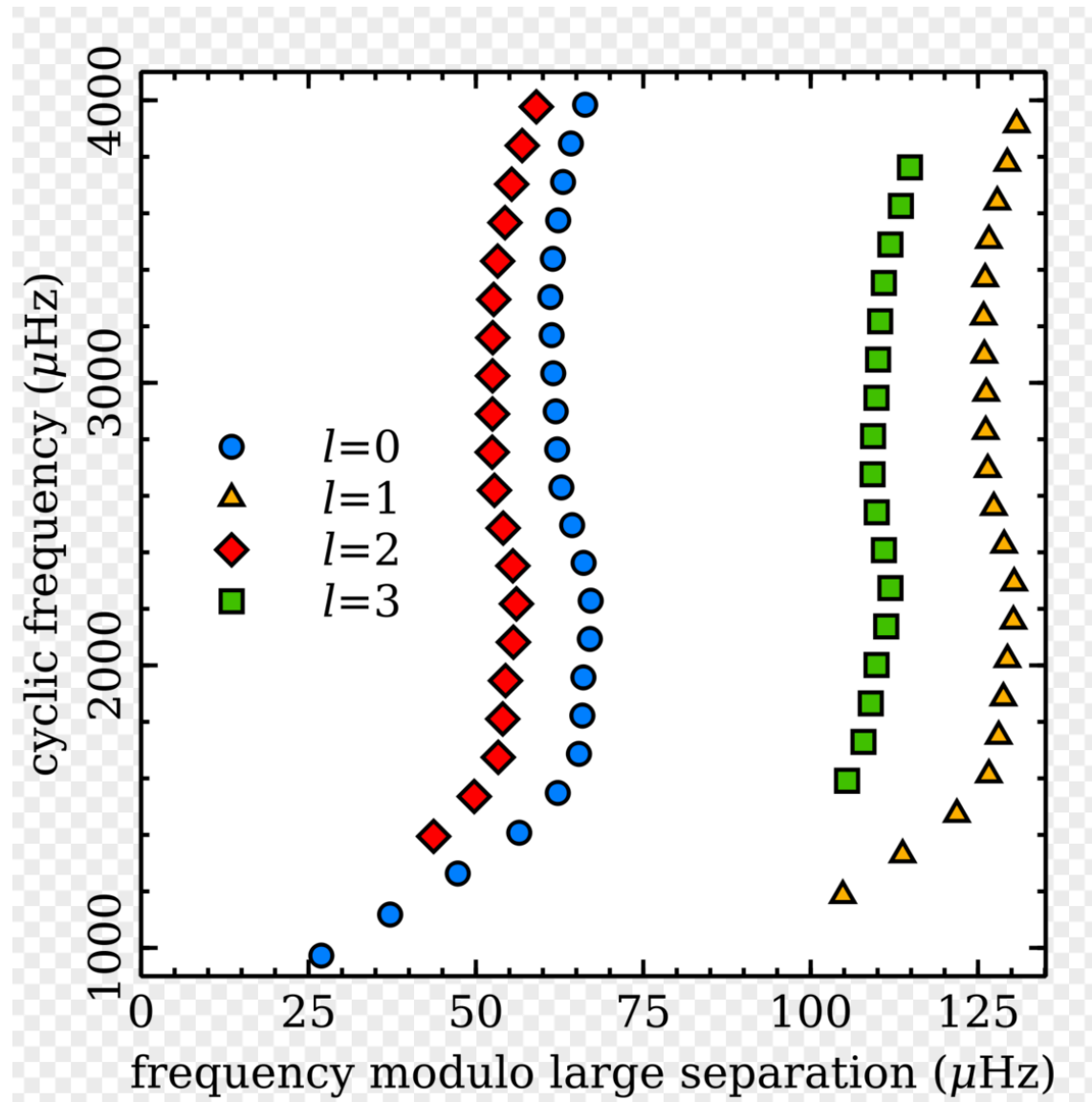
Power spectrum of Sun as a star VIRGO (3)



Systematic issues on global frequencies (1)



Systematic issues on global solar p-mode frequencies (2)



High resolution measurements from space

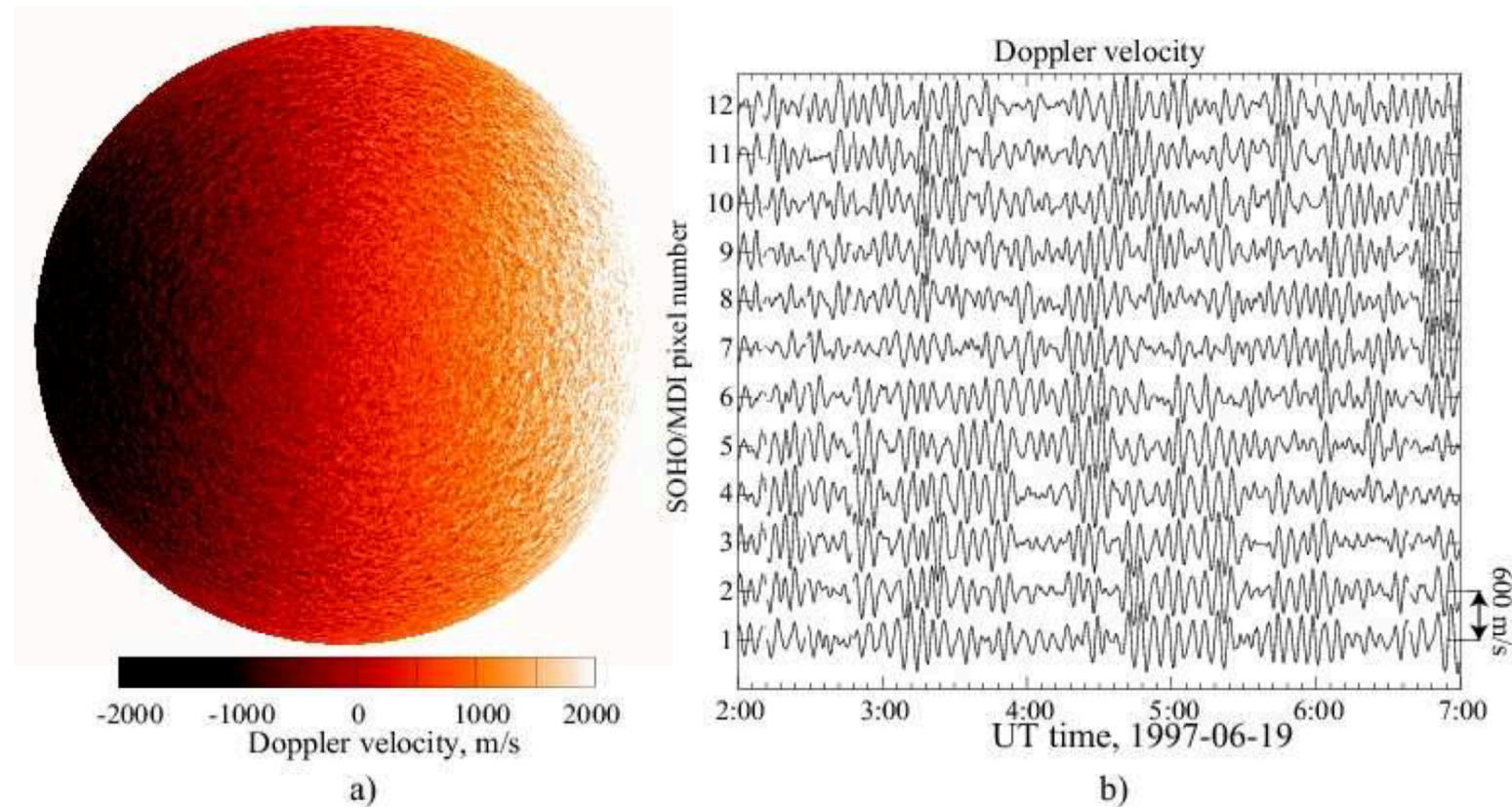
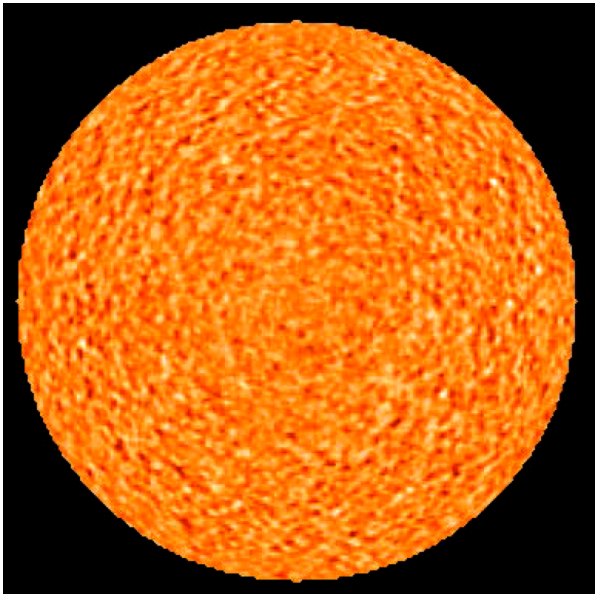


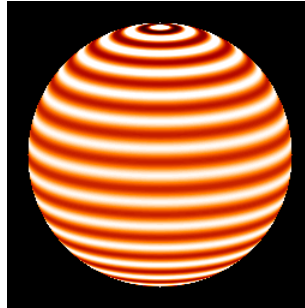
Fig. 1. a) Image of the line-of-sight (Doppler) velocity of the solar surface obtained by the Michelson Doppler Imager (MDI) instrument on board SOHO spacecraft on 1997-06-19, 02:00 UT; b) Oscillations of the Doppler velocity, measured by MDI at the solar disk center in 12 CCD pixels separated by ~ 1.4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

Observing Time Series

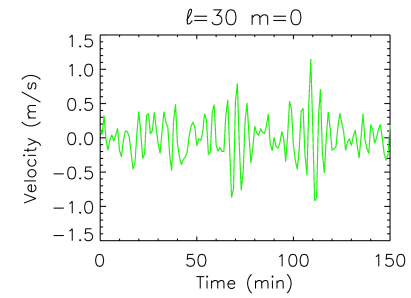
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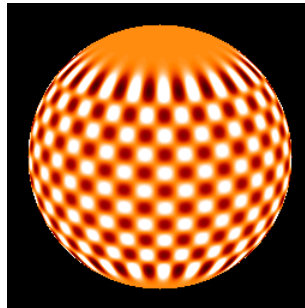
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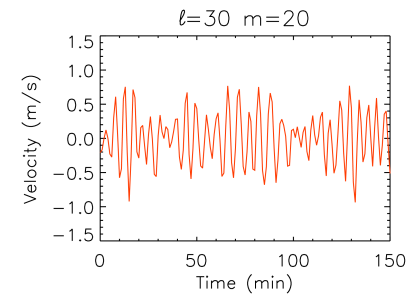
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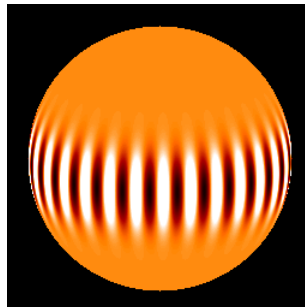
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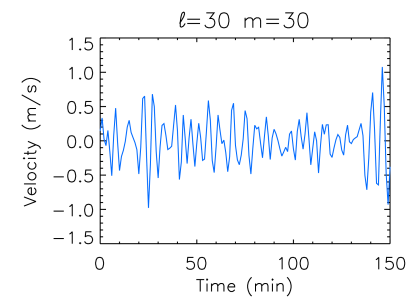
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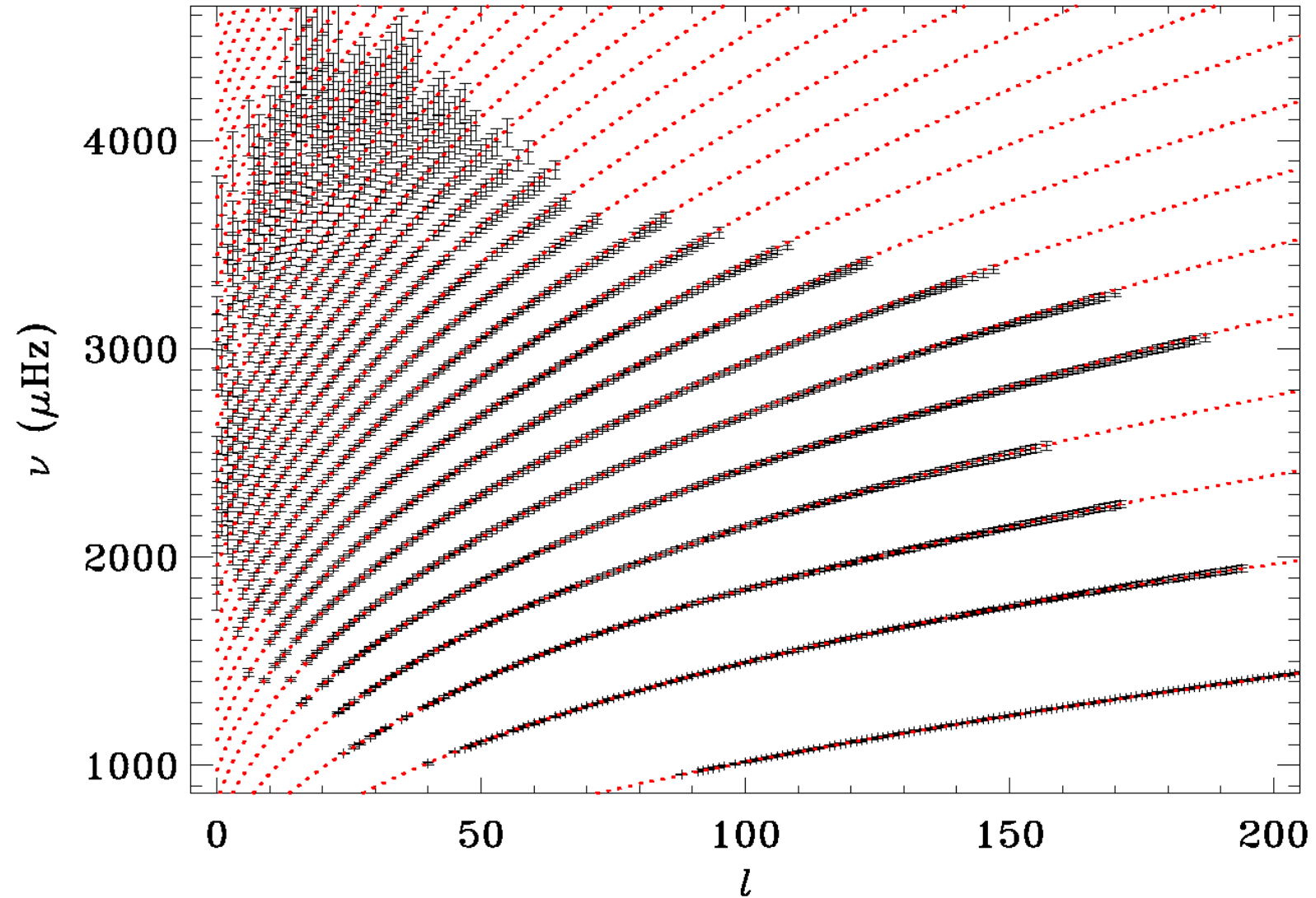
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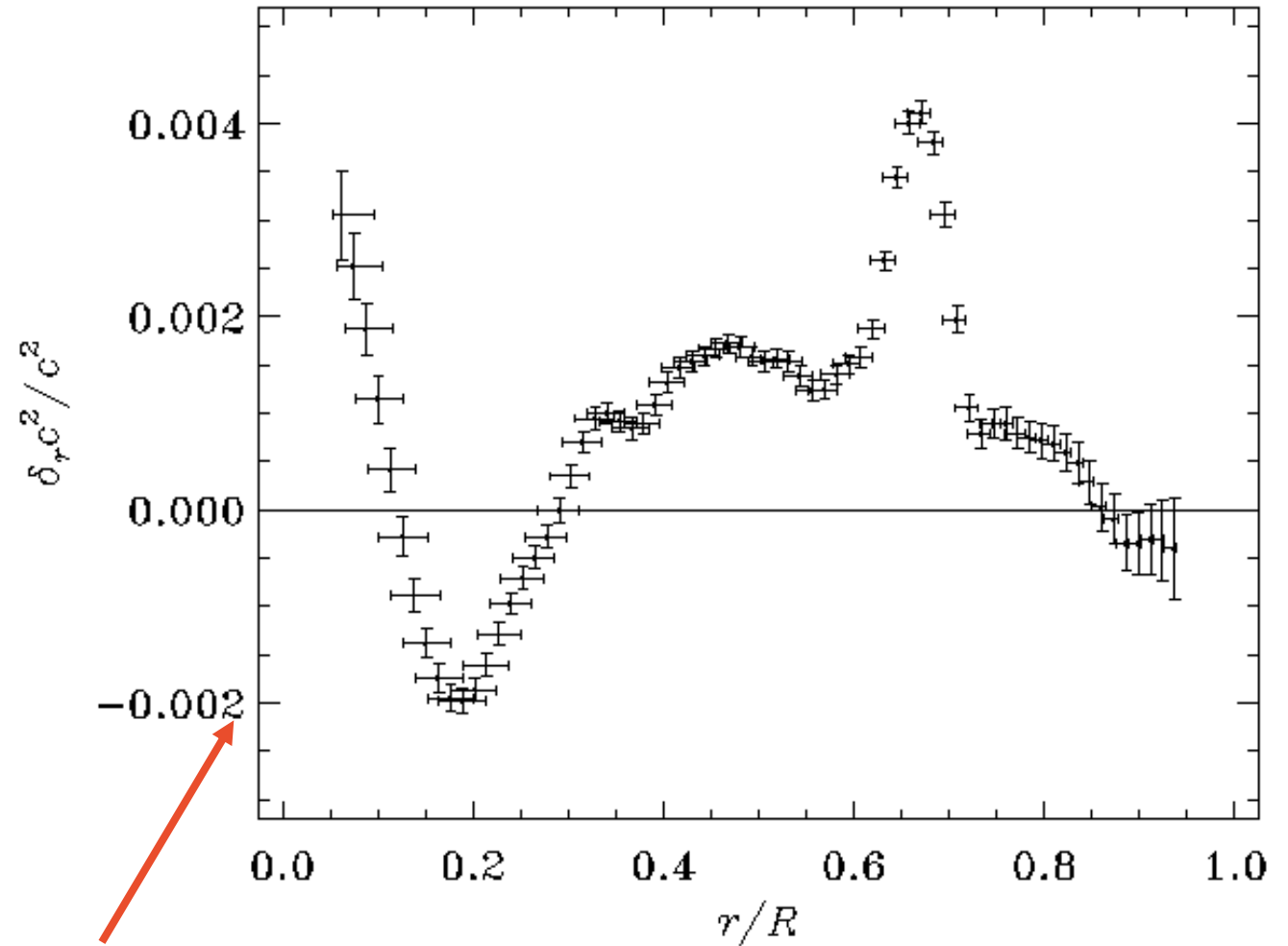
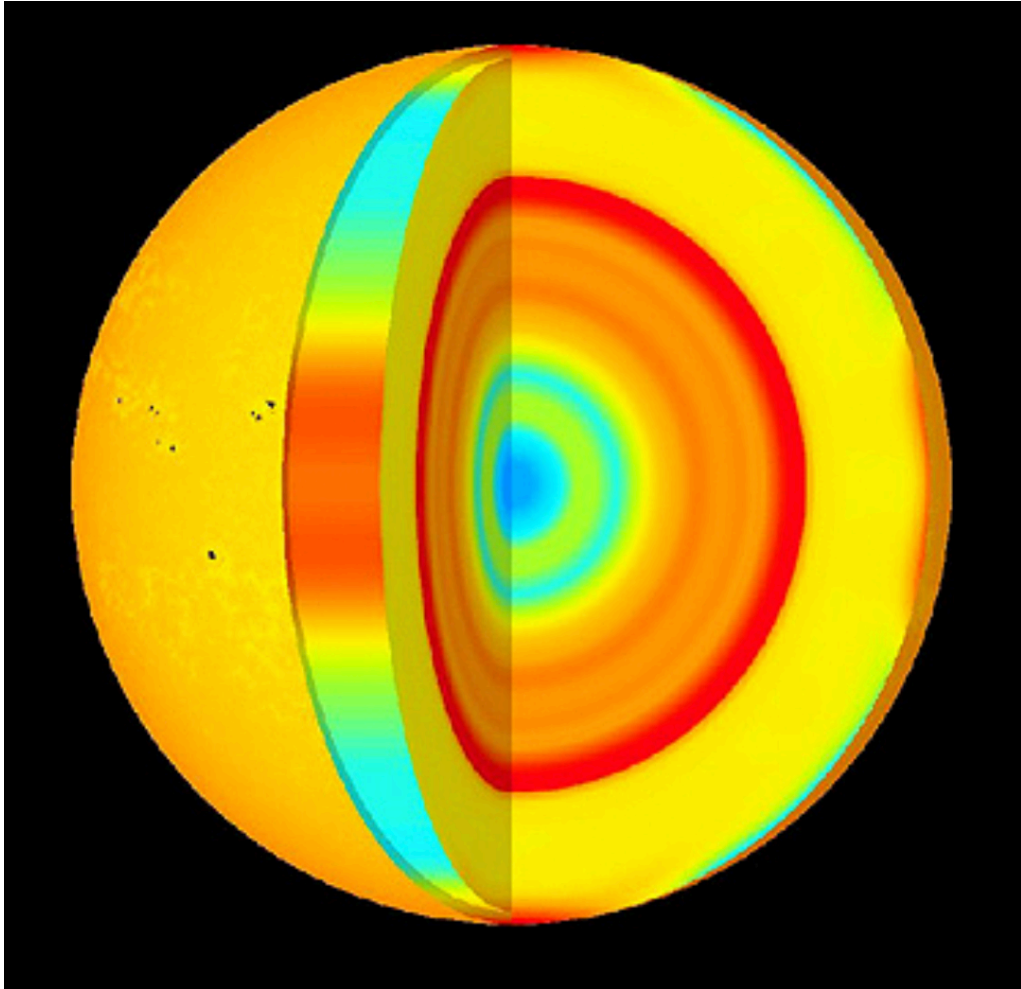


High resolution power spectra



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

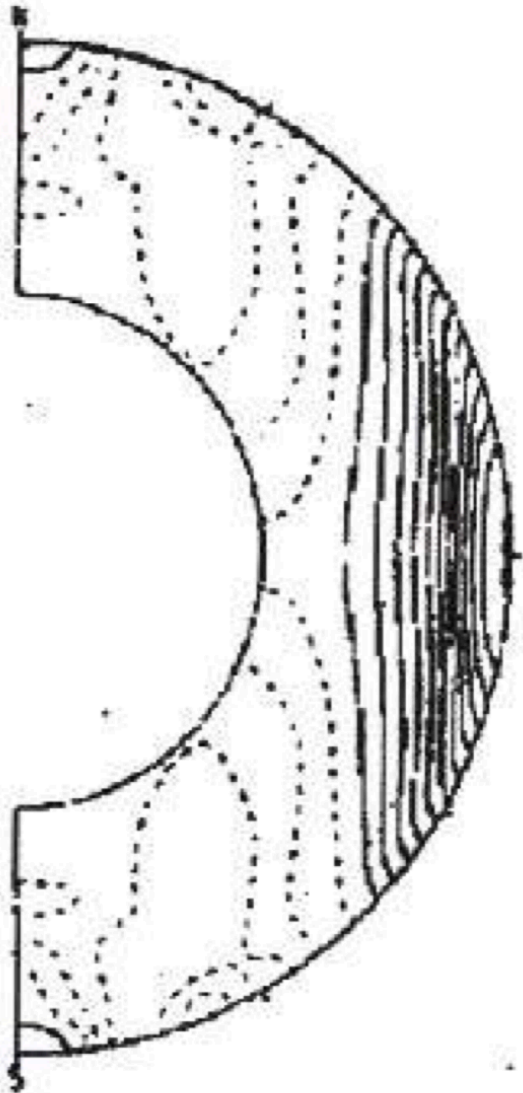
Sound speed differences from best model



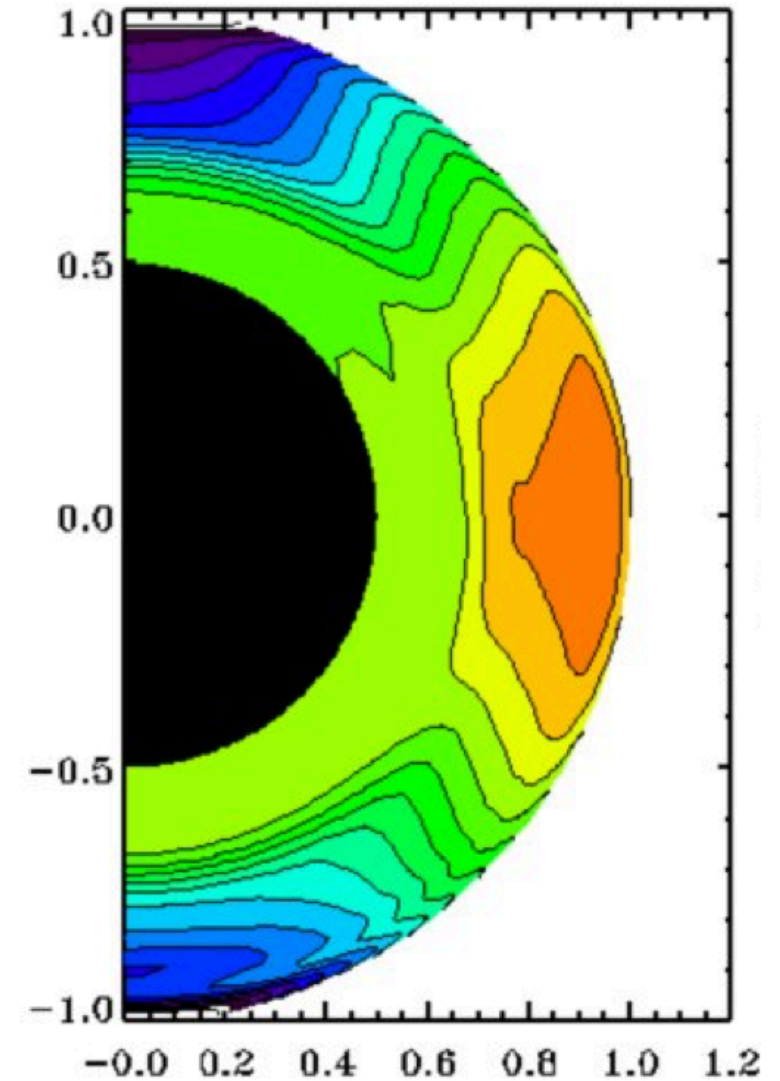
Not much

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

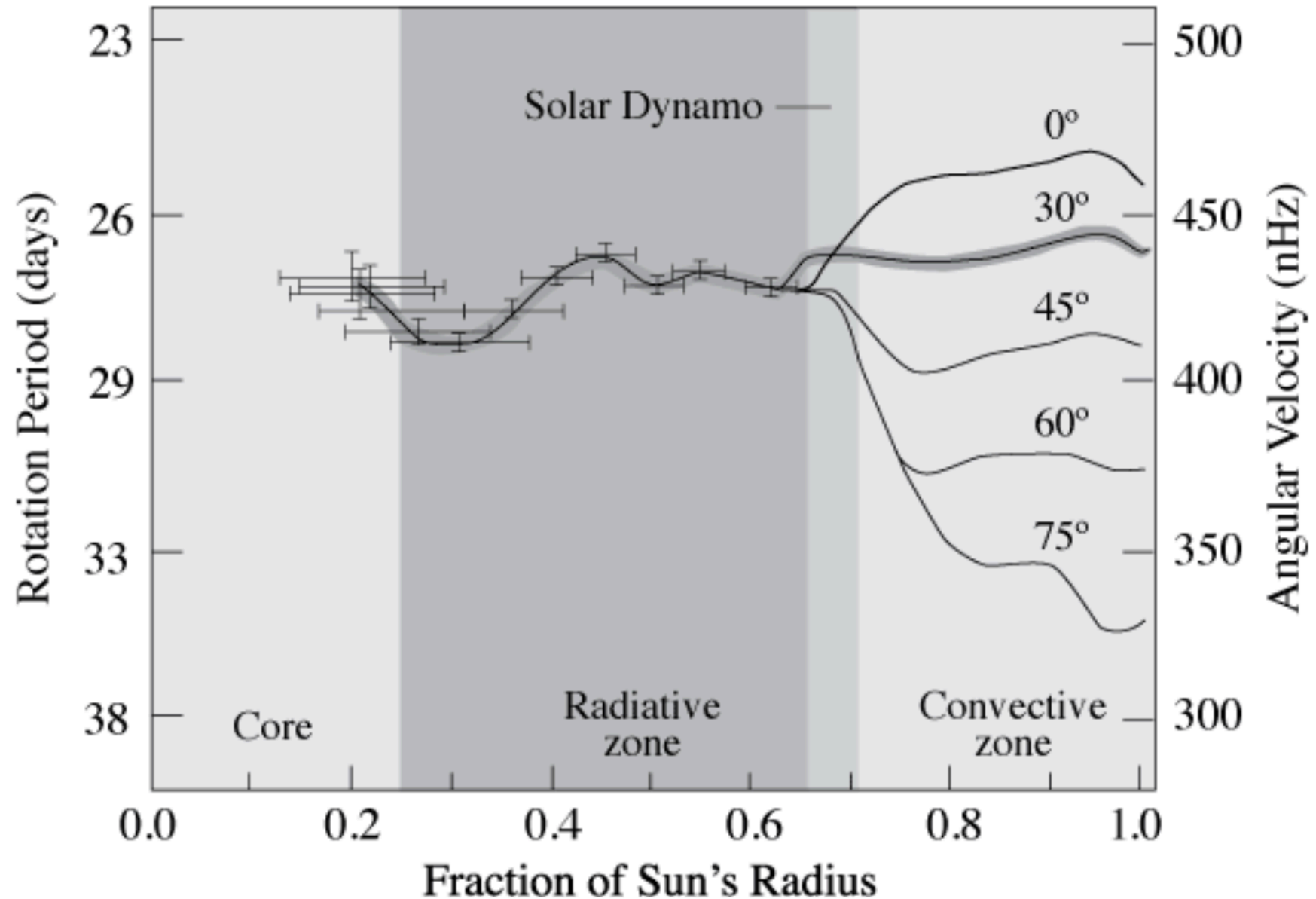
The internal rotation of the Sun



Glatzmaier 1985

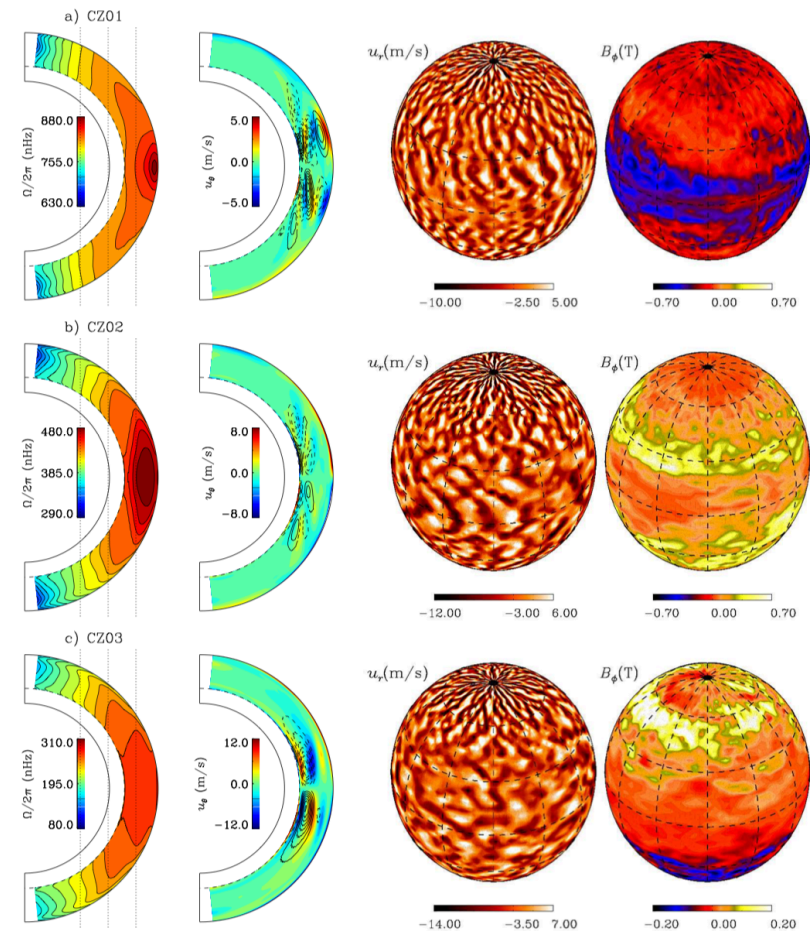


Internal rotation of the Sun



Generation of magnetic fields in the Sun

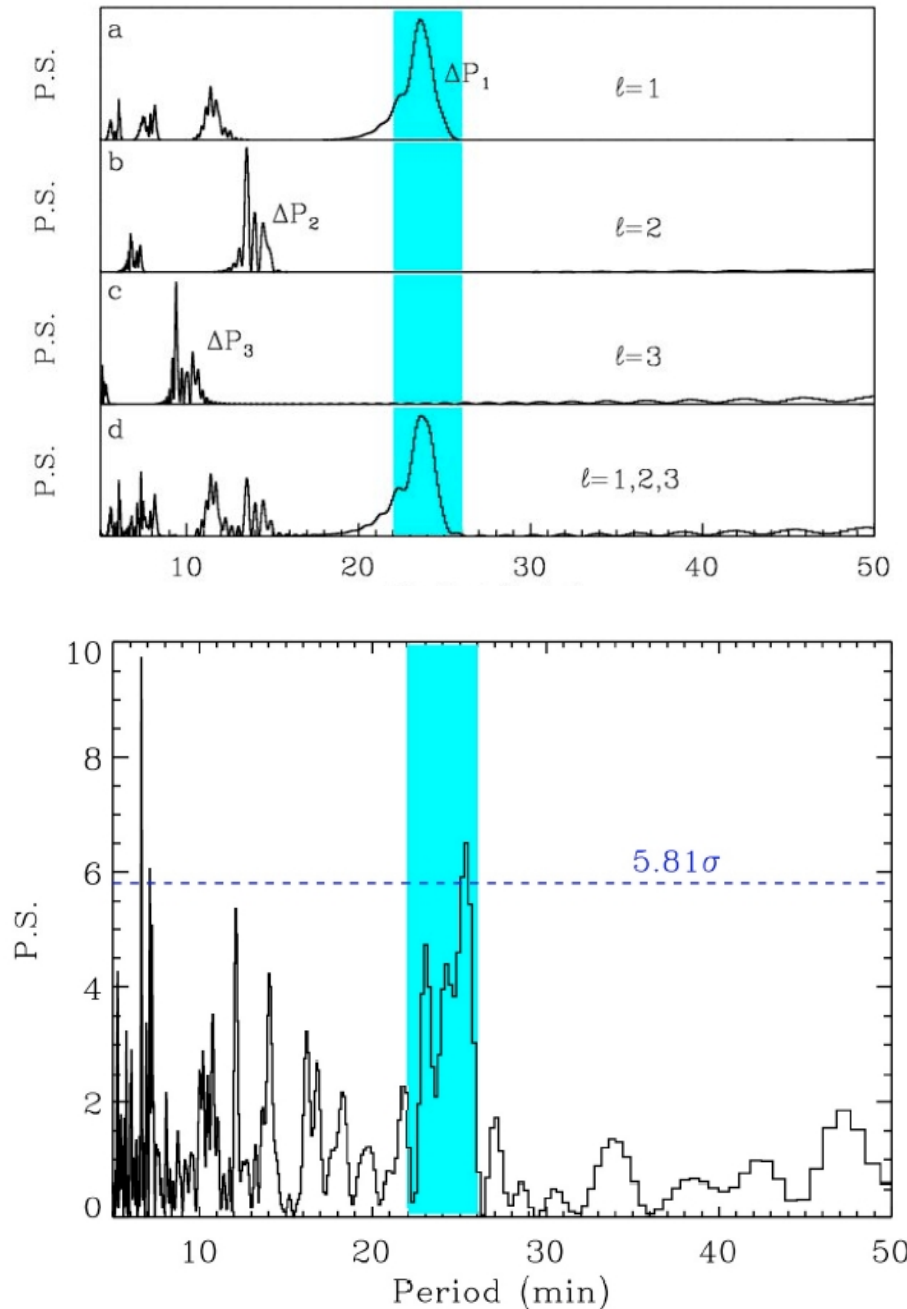
- The ionized and electrical plasma in the Sun can generate magnetic field in a dynamo effect.
- Older theories made a global dynamos from the varying rotational rate, this is wrong as the Sun rotates differently.
- Helioseismology has shown that the main magnetic field is generated at the bottom of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



From Guerro et al 2013

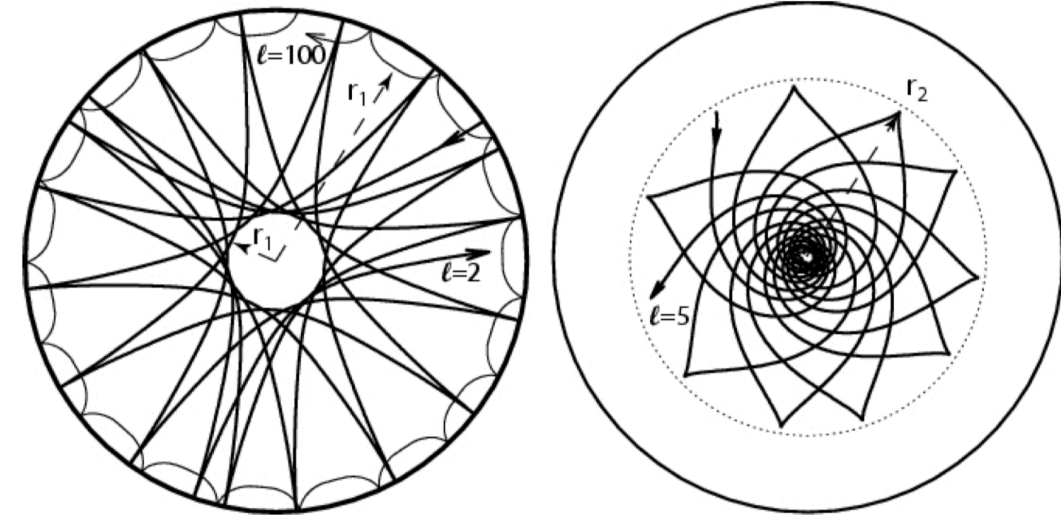
What about g-modes

- Attempts to find them for 40 years.
- No unambiguous detections, but some indications.
- I published a paper in 1995 claiming we would not observe them, but have since 1996 tried to find them.
- Plot here may 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!

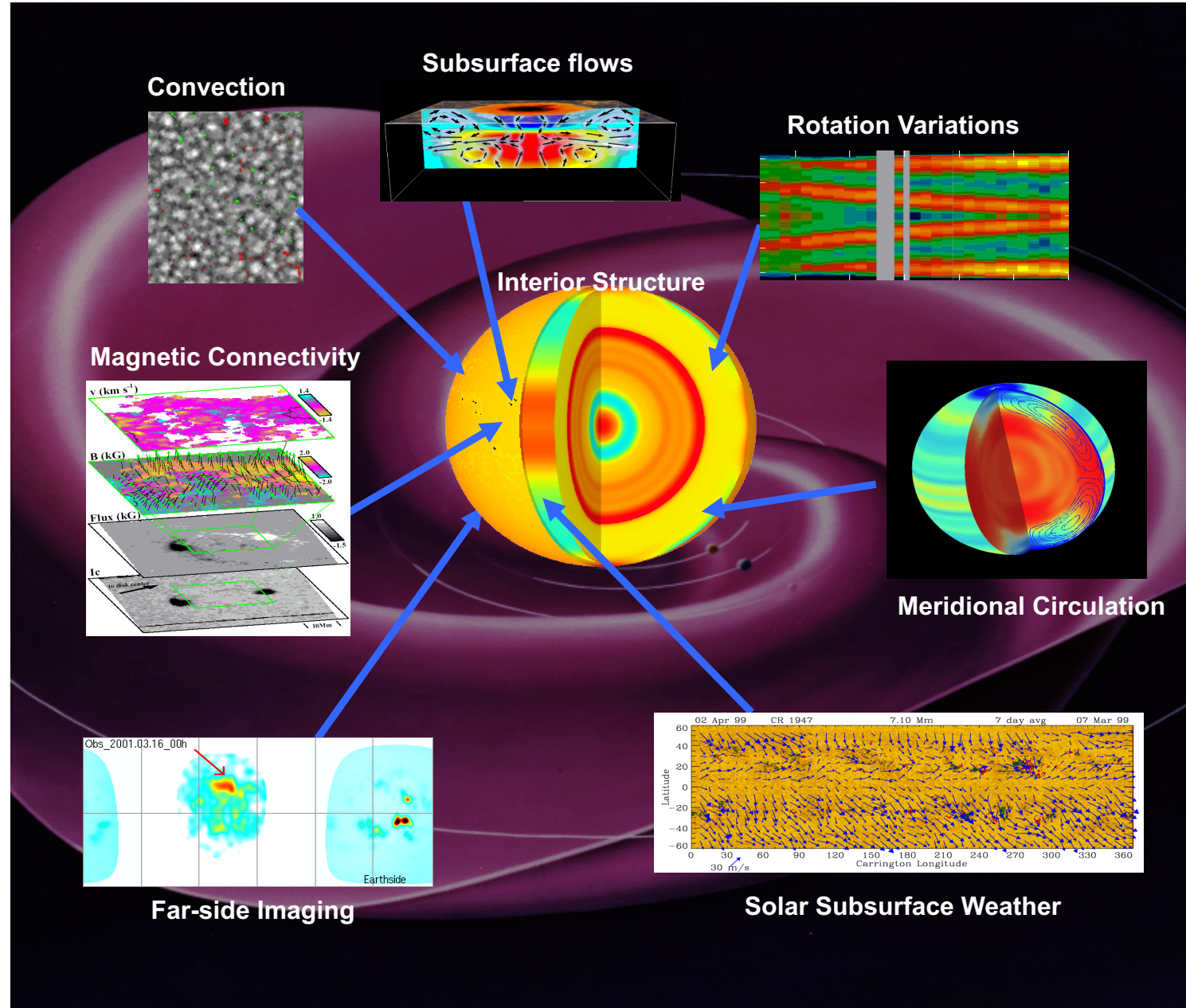


What have we found of the solar interior

- Solved the “solar neutrino problem”.
- Discovered the interior solar rotation profile.
- Have discovered the details of the interior “overshoot” region containing the main dynamo.
- 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.

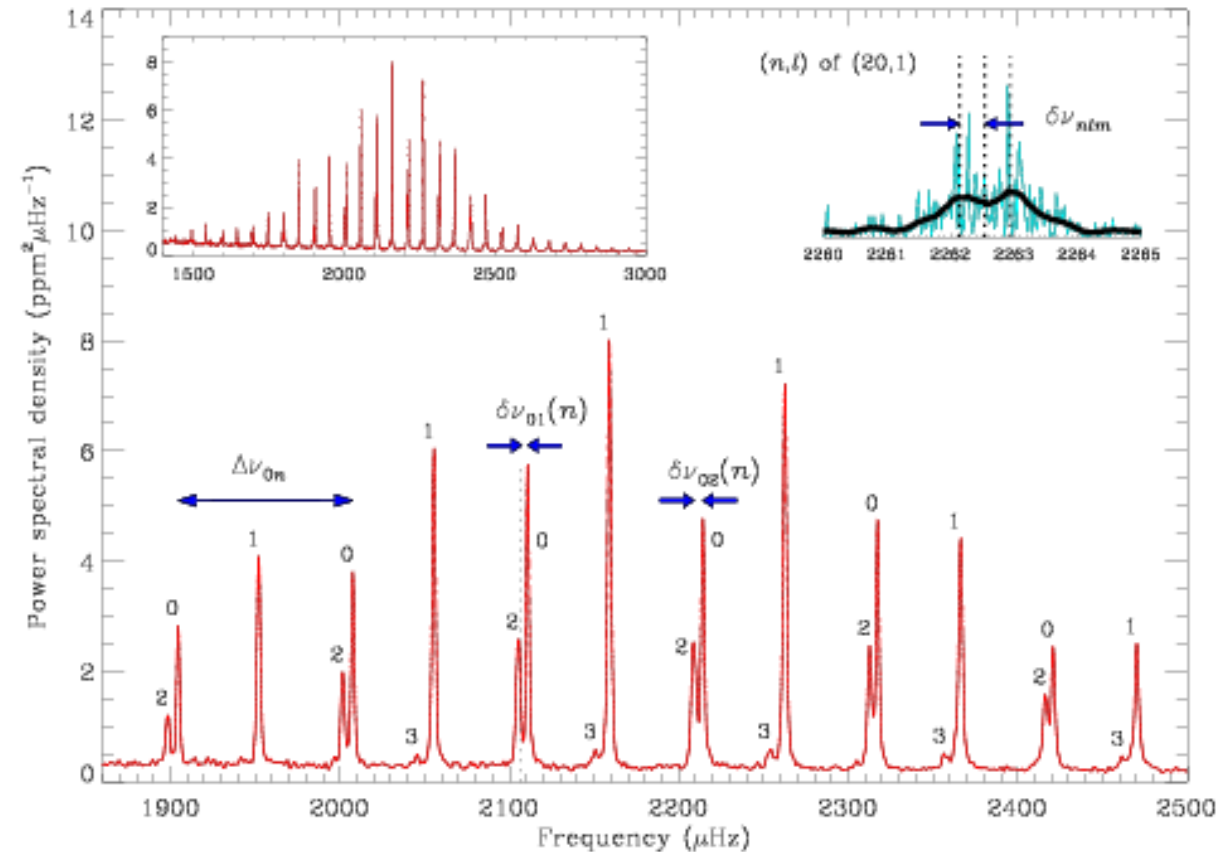


Things I have not mentioned



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 and CHEOPS missions will develop this further.
- Asteroseismology gives the possibility to completely circumvent Eddington's prediction from 1926.
- Asteroseismology gives the internals of all observable stars.



Power spectrum of a red giant, B. Chaplin