SOLAR/STELLAR OSCILLATIONS AND MAGNETIC ACTIVITY

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- PhD from the Nice University on Helioseismology and the calibration/analysis of the observations from the ground-based IRIS network
- Several postdocs including
  - HAO/NCAR, Boulder, CO., USA
  - NSO, GONG group, Tucson, AZ., USA
  - IAC, Tenerife, Spain
- Located in room 281, second floor

Plan

1. Introduction:
   - what are the solar/stellar oscillations?
   - how do we observe the oscillations?
   - what do we learn from studying the solar/stellar oscillations?

2. The variability of the solar/stellar oscillations with magnetic activity

3. The need to measure low-frequency oscillations

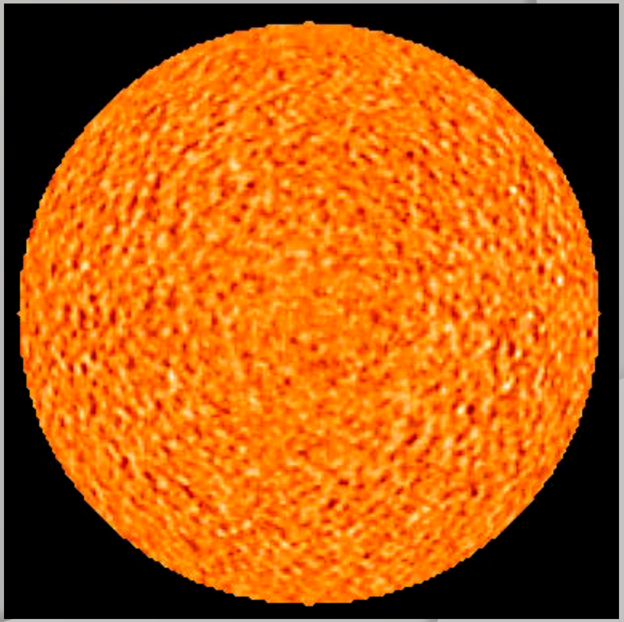
How can we infer the interior the Sun and stars?

- What happens inside the Sun (or stars) is invisible to our naked eyes…
  - *How can we test the solar/stellar models?*
  - *How can we constrain the internal structure/rotation of the Sun and stars?*
  - *How do we understand the origins of solar/stellar magnetic activity?*

- Convective motions generate surface wave motions
  - *Associated sound waves traveling through the interior of the Sun/stars*

- Small scale light and dark regions
  - *Up and down motions of the hot gas near the surface*

- Small amplitudes
  - *On the surface of the Sun, no more than 10 cm/s*

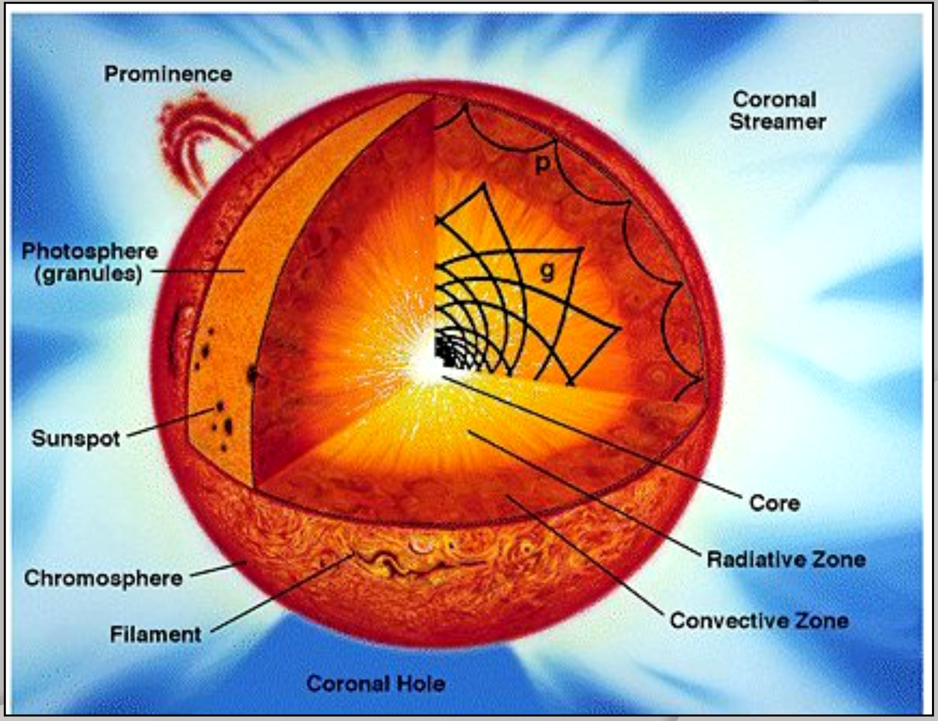


A quick view inside the Sun…

Inside

- **<u>Inner layers</u>**
  - Core (up to $0.2R_\odot$)
  - Radiative zone ($0.2R_\odot$ - $0.72R_\odot$)
  - Convective zone ($0.72R_\odot$ until photosphere - the visible surface)

Solar interior → Helioseismology

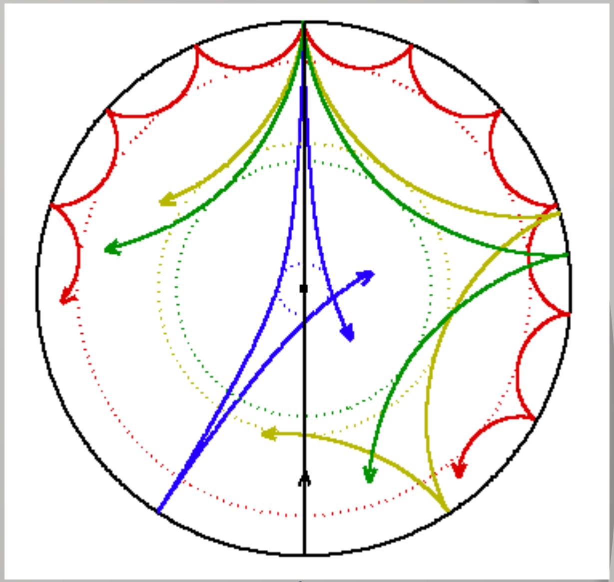


- **<u>Outer layers and beyond</u>**
  - Chromosphere
  - Corona (outermost layer of the Sun)
  - Solar flares and prominences
  - Solar wind

Outside

The Sun as a resonant cavitie

- Acoustic oscillations (p modes) excited by stochastic convective motions
- Sun acts as a resonant cavity of ~5-min period
  - standing waves with periods from 1 min to several hours
- More than 10^7 p-modes in the Sun
- Each oscillation mode samples different parts of the solar/stellar interiors
- Temperature, composition, density, magnetic field influence the oscillation periods



Ray paths of different acoustic waves inside the Sun/stars

HELIOSEISMOLOGY / ASTEROSEISMOLOGY

Yield insights into the conditions/properties of the solar/stellar interiors

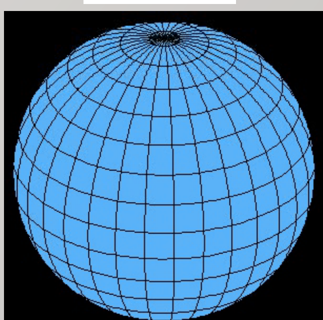
How to describe the oscillations?

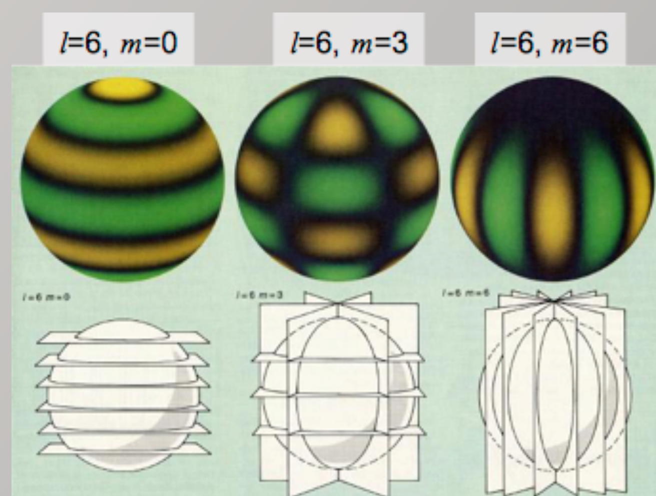
- In 3D, oscillations are distributed throughout the spherical geometry of the Sun/star

- The oscillation modes are characterized by 3 whole numbers:
  - the <u>order *n*</u>, number of nodes radially outward from the centre
  - the <u>harmonic degree *l*</u>, number of nodes found around the azimuth or total number of planes slicing through the Sun/star
  - the <u>*azimuthal order m*</u>, number of nodes found around the equator or number of planes slicing through the Sun longitudinally (*m* runs from –*l* to +*l*)

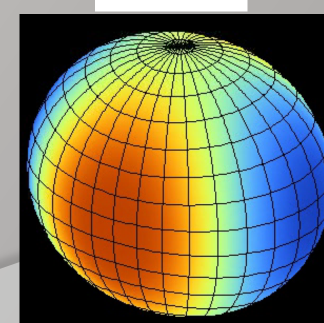
- A particular arrangement of *n*, *l*, and *m* is known as a mode of oscillation

l=0, m=0





l=2, m=2

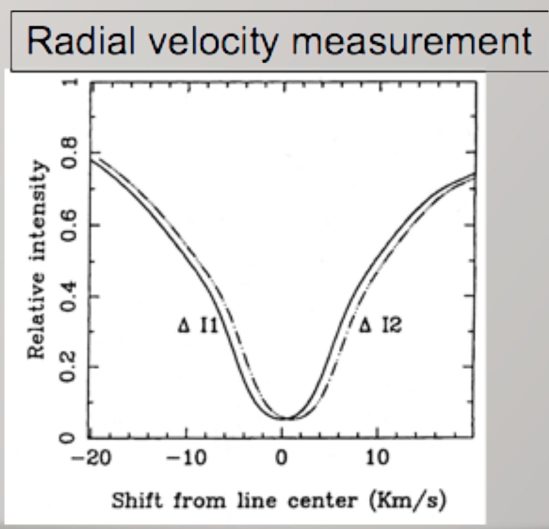


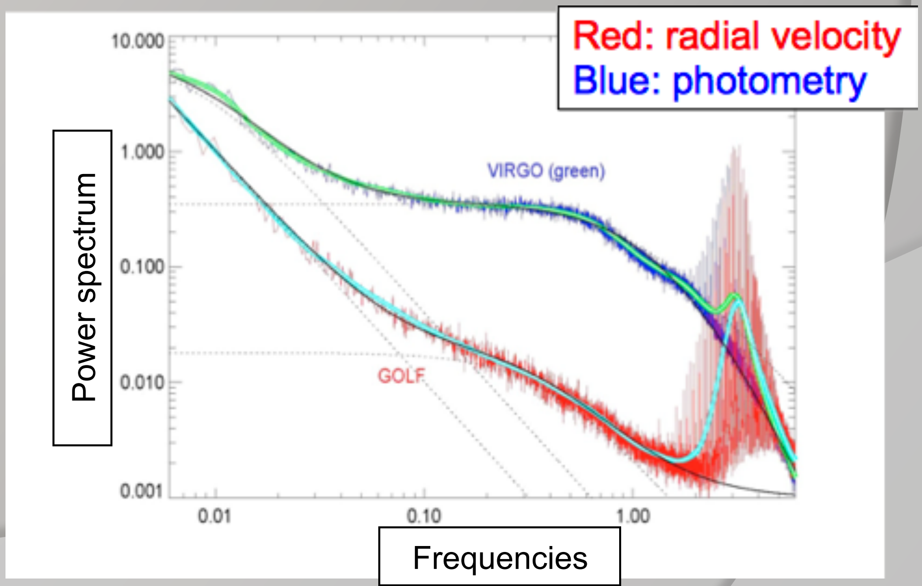
How do we observe solar/stellar oscillations?

- Detection of the individual modes needs very high frequency resolution
  - inversely proportional to the total length of the observations

- Need to observe the Sun/stars **in continue and as long as possible**

- Two ways to measure the oscillations:
  - Radial velocity: Doppler shift induced by oscillatory motions in spectral line
    - *Better SNR, but can observe only one star at a time*
  - Photometry: Variations in intensity induced by the oscillatory motions

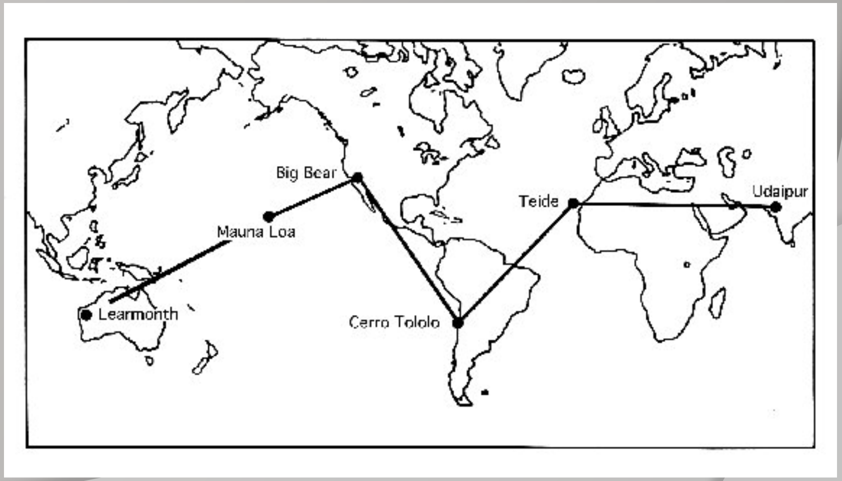




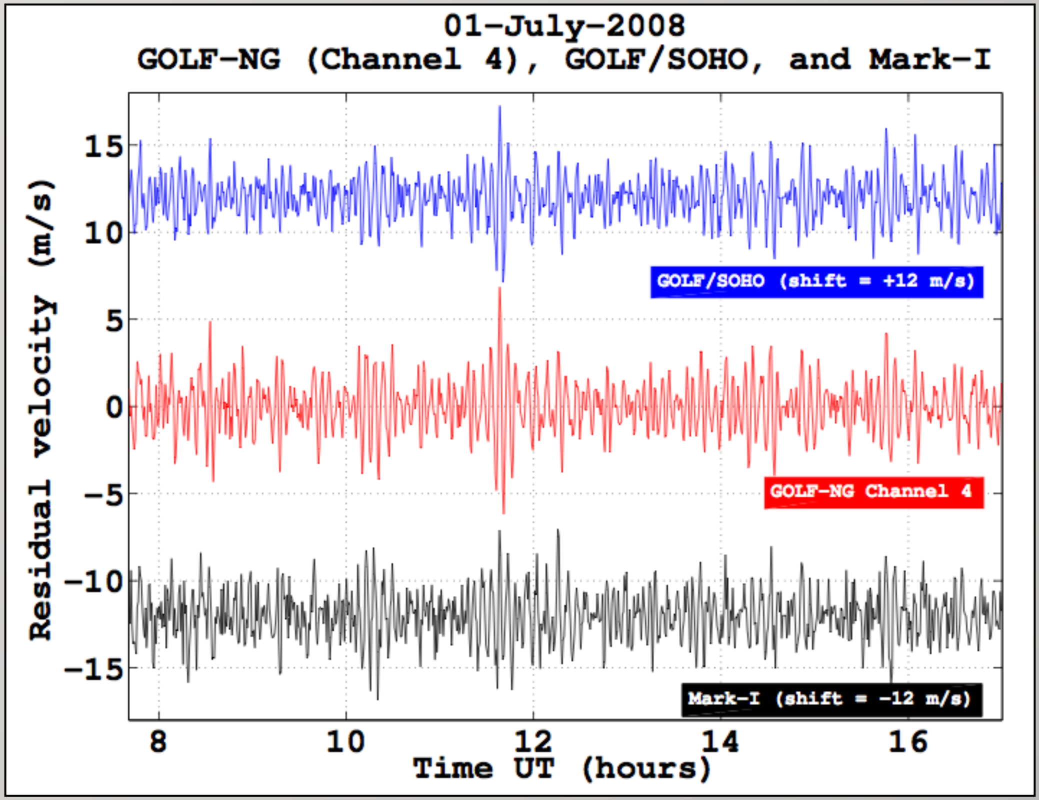
Observations of solar oscillations

- Space-based observations:
  - SOHO launched in 1995 (GOLF, VIRGO, MDI)
  - SDO launched in 2010 (HMI)
  - Radial velocity and photometric observations
  - Duty cycle > 95%

- Ground-based observations: network of similar instruments well located in longitude/latitude around the Earth to observe the Sun *almost* in continue
  - BiSON and GONG
  - Fully operative since ~1995
  - More than 80% duty cycle



Solar oscillations: Observations from GOLF/SOHO



Daily residual velocities (m/s) showing the 5-minute oscillations observed on July 1, 2008

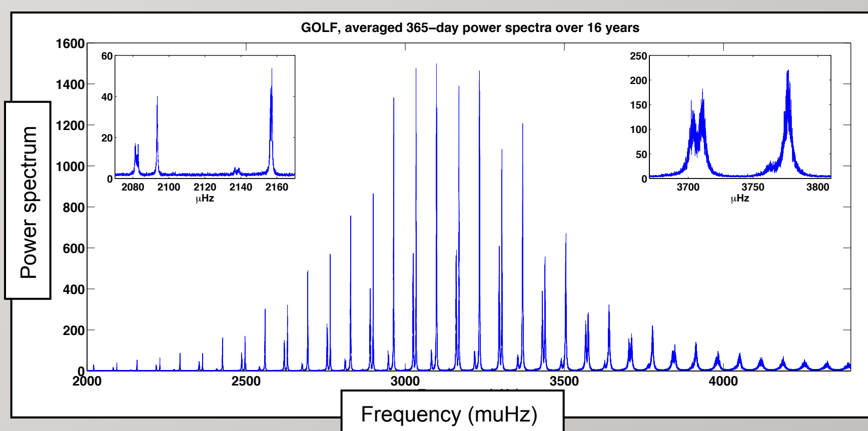
(Salabert et al., 2009)

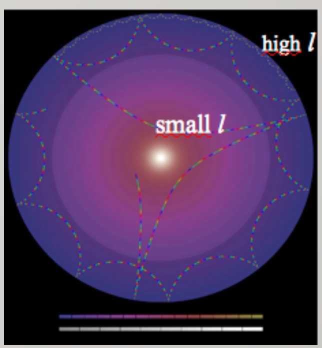
GOLF instrument is collecting continuous, high-quality data since ~17 years!

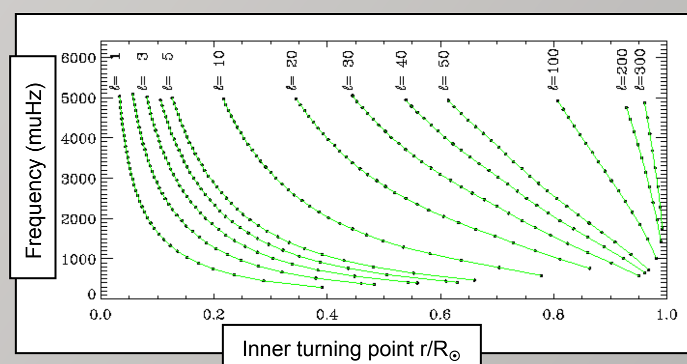
From the surface down to the deep interior

- Each mode is sensitive to the physical conditions of different parts of the solar interior.

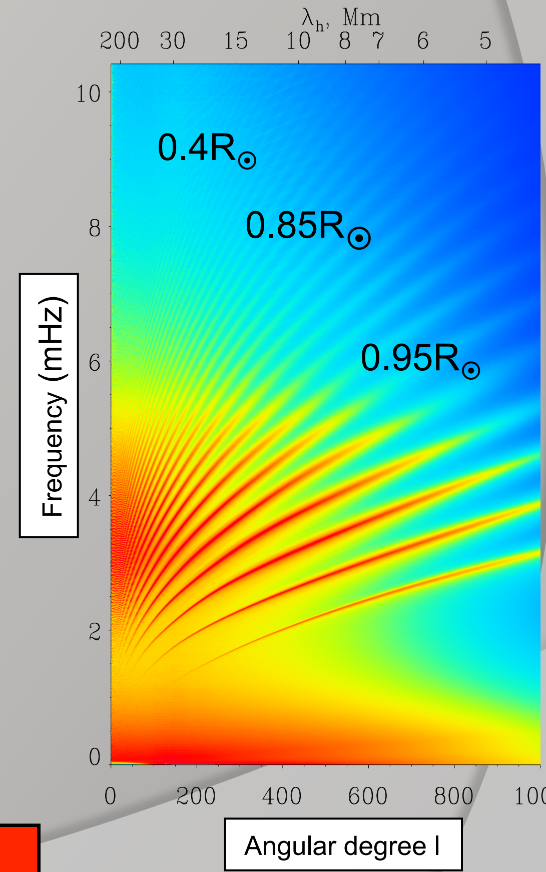
GOLF, full-disk observations







GONG and HMI,
spatially resolved observations

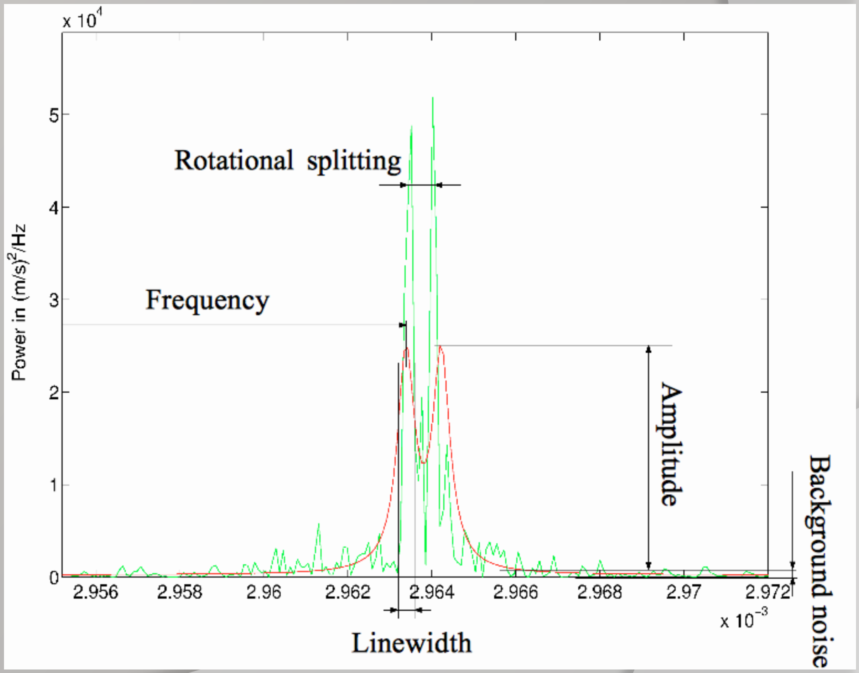


By combining a large number of modes, we can build up a consistent picture throughout the solar interior.

Modeling the oscillation modes

- Acoustic modes stochasticaly excited and damped by the convection
- Considered as harmonic oscillators
- Each oscillation mode (*n*,*l*) in the power spectrum asymptotically described by a Lorentzian profile

$$L_{n,l}(\upsilon)=\frac{A}{1+\left(\frac{\upsilon-\upsilon_{n,l}}{\Gamma/2}\right)^2}+B \quad \begin{cases} A\text{, amplitude} \\ \Gamma/2\text{, linewidth} \\ \upsilon_{n,l}\text{, frequency} \\ B\text{, background noise} \end{cases}$$



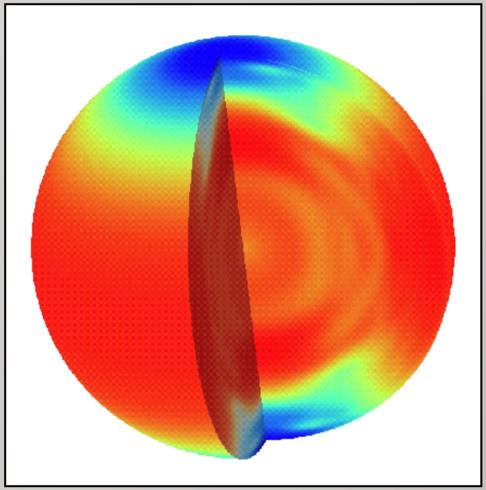
- Background modeled by power laws
  (convective noise, granulation, ...)
  + a flat component for photon noise
- Parameters extracted using Maximum-Likelihood Estimators

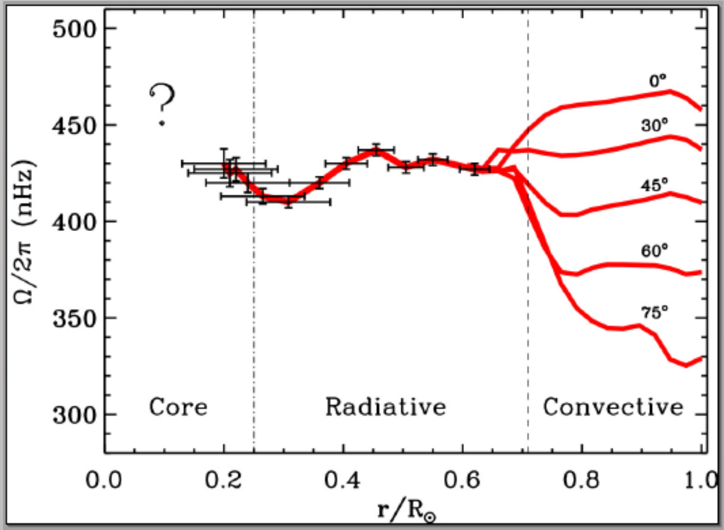
From the extracted p-mode parameters

$$2\nu = \int_0^{R_S} \frac{dr}{c}$$

- <u>Mode frequencies</u>: related to sound speed inside the Sun
  - Inversion of internal structure and rotation *(e.g., Thompson et al.)*
    - Internal sound speed profiles
    - Depth of convective zone, surface helium composition, density profile
    - Meridional circulation

(Scherrer et al.)



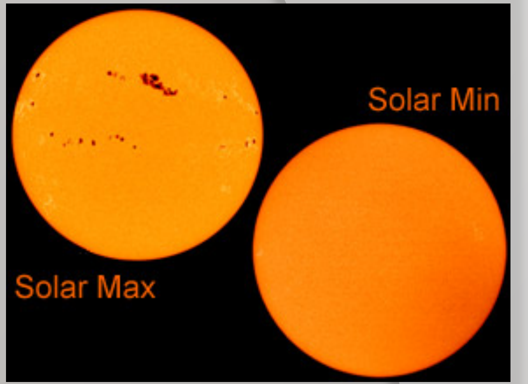


(Garcia, R.A, et al. 2007)

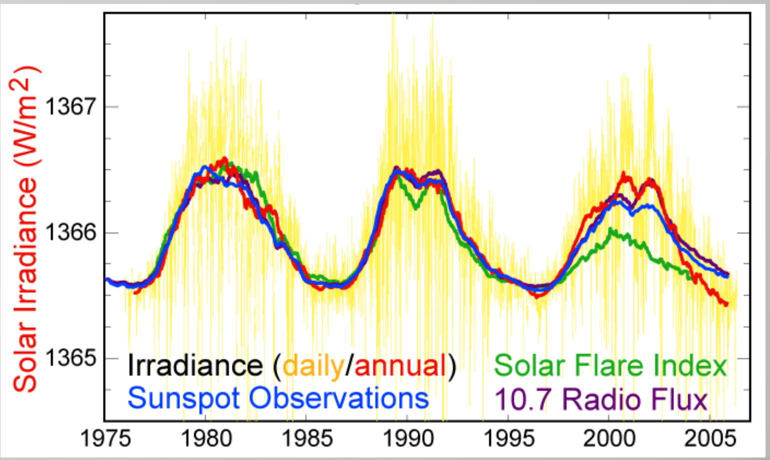
- <u>Mode linewidths and heights</u>
  - Study of the excitation and damping mechanisms *(e.g., Belkacem et al, 2010)*

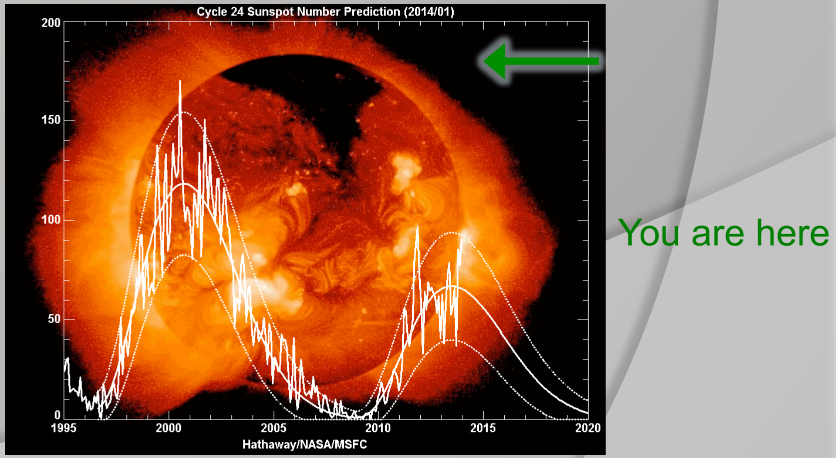
- Study the complex magnetism and activity cycle: active regions, magnetic field

Solar Magnetic Activity Cycle

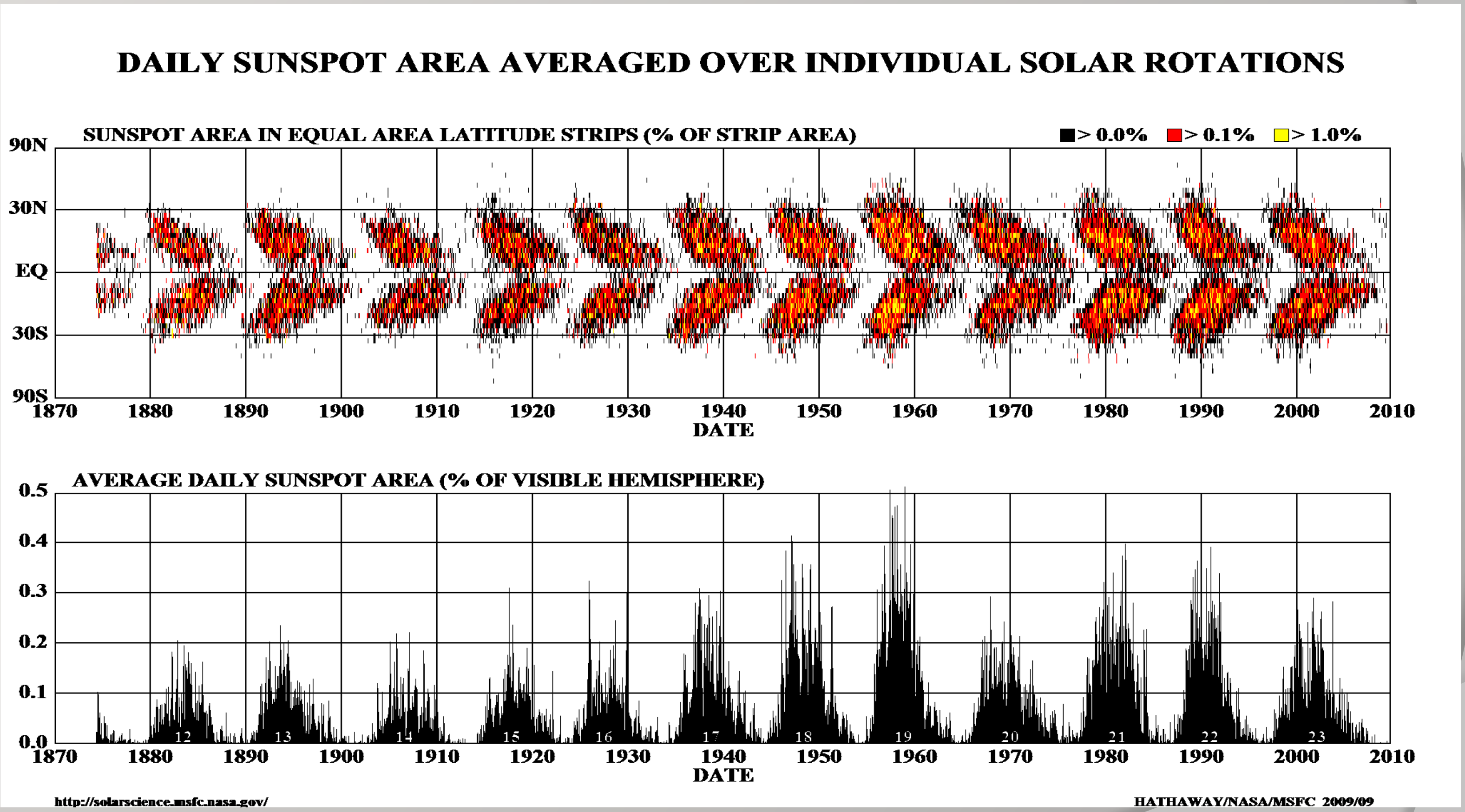


- 11-year periodic variation in the solar magnetic activity
- Several surface activity proxies: Sunspots, F10.7, CaHK, Irradiance,...
- Explained by the presence of a magnetic dynamo
- Generated in the shear layer between radiative and convective zones*: tachocline*
  - solid rotation in radiative zone
  - differential rotation in convective zone



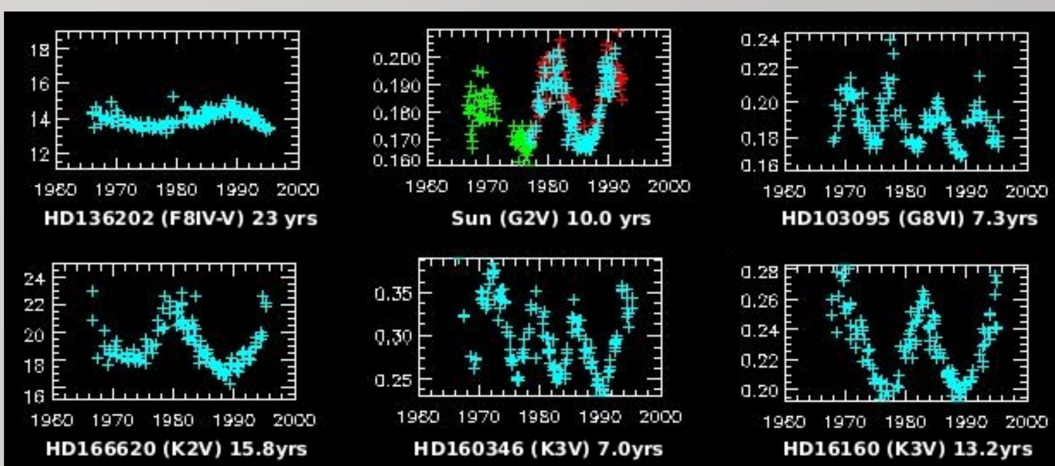


Solar Magnetic Activity Cycle

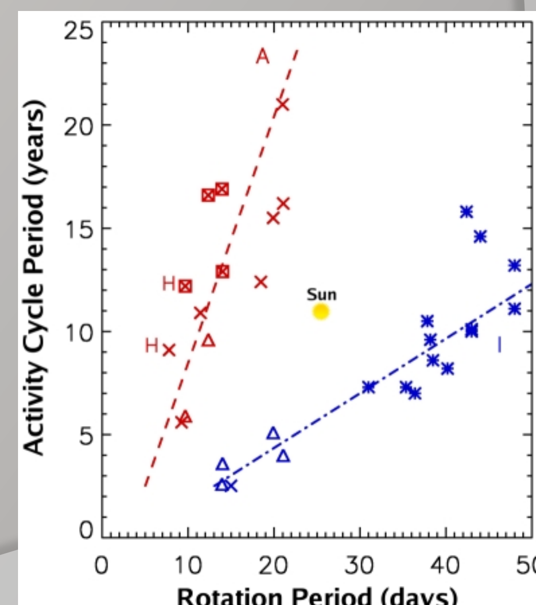


Stellar Magnetic Activity Cycles

- Spectroscopic measurements of Ca II H and K emission lines
- Magnetic activity variations in a large sample of solar-type stars
- Cycle periods ranging from 2.5 and 25 years *(Wilson 1978; Baliunas et al. 1995; Metcalfe et al. 2009)*
- Periods of activity cycles increase proportional to stellar rotational periods along two distinct paths:
  - *The relatively young, active sequence*
  - *The older, less active sequence* *(Saar & Brandenburg 1999; Böhm-Vitense 2007)*
- Spectroscopic measurements only good proxies of surface magnetic fields



http://www.hao.ucar.edu/research/siv/siv_stellar.php
Based from Mount Wilson survey (Baliunas et al. 1995)

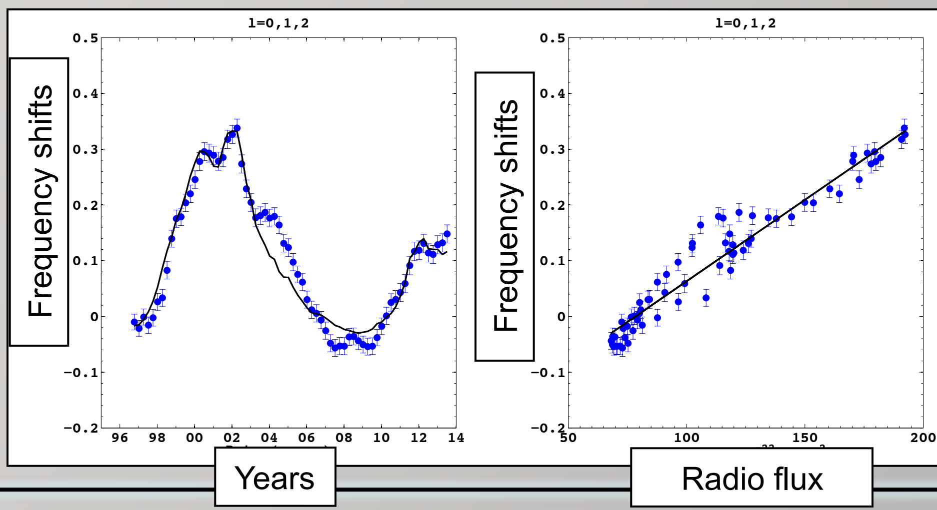


Adapted from Böhm-Vitense 2007

Temporal Variations of the Oscillation Frequencies

- More than 16 years of continuous GOLF observations between 1996 and 2014
    - Frequencies change of ~0.4 μHz between minimum and maximum
    - Highly correlated (> 0.9) with surface activity proxies

- Oscillation frequencies: a proxy of solar activity



GOLF observations

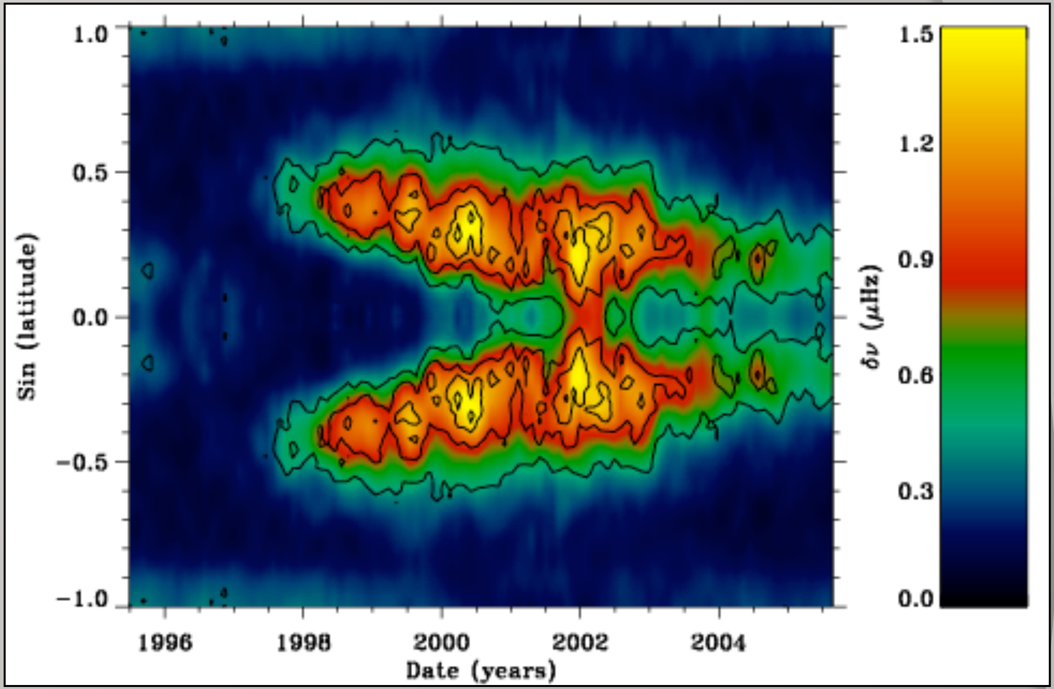
(Salabert et al., 2014, In prep.)

- Last minimum of solar cycle (2007-2009) unusually long and deep
    - Almost no surface activity for 2 years and quietest Sun in a century
    - Signatures of activity appeared in p modes before they became evident in solar surface activity proxies *(Broomhall et al. 2009; Salabert et al. 2009; Jain et al. 2011)*
    - Streams associated with sunspots migrated slower than usual: lack of sunspots *(Howe et al., 2009)*

Localizing the Solar Cycle Frequency Shifts

<u>Latitudinal 1-D inversions</u>

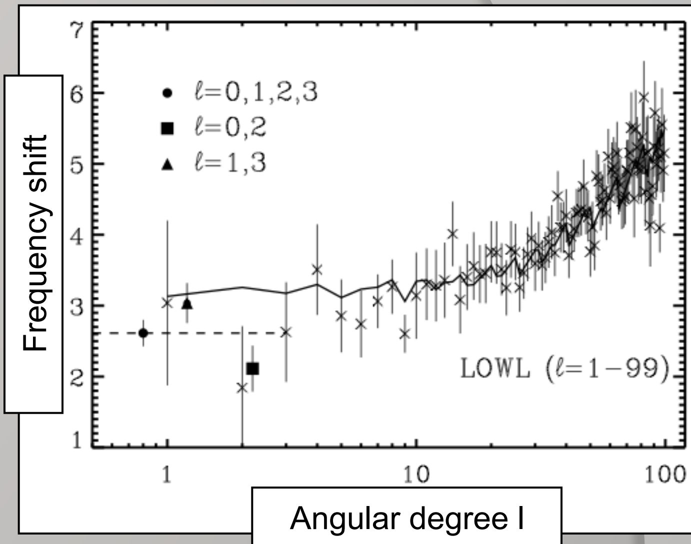
Howe et al. 2002
(GONG observations)



<u>Contours</u>: symmetric version of the Kitt Peak synoptic magnetic data

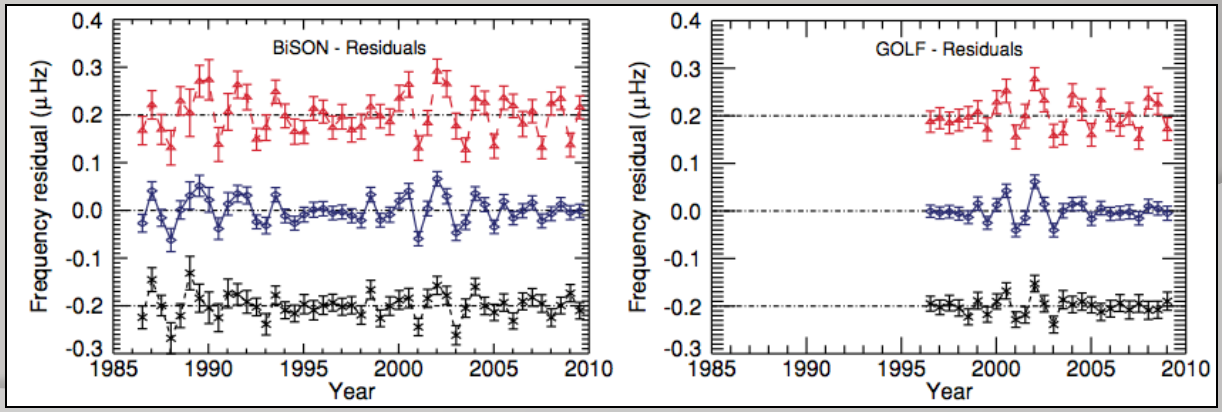
- Frequencies shifted in presence of surface magnetic activity
- Close temporal and spatial distribution of the shifts with magnetic activity

Possible Mechanisms for Frequency Shifts



(Jimenez-Reyes et al., 2001)

- Far from being properly understood
- Form and angular-degree dependence of the shifts
  - Near-surface phenomenon
  - Arise from structural changes in the outer layers
    - Indirect effect of temperature changes *(Kuhn 1988)*
    - Effect of a change in acoustic cavity size *(Dziembowski & Goode 2005)*
- Recently, observations of a 2-year periodicity in the oscillation frequencies
  - A 2nd dynamo action seated below the solar surface (region with strong rotational shear)?



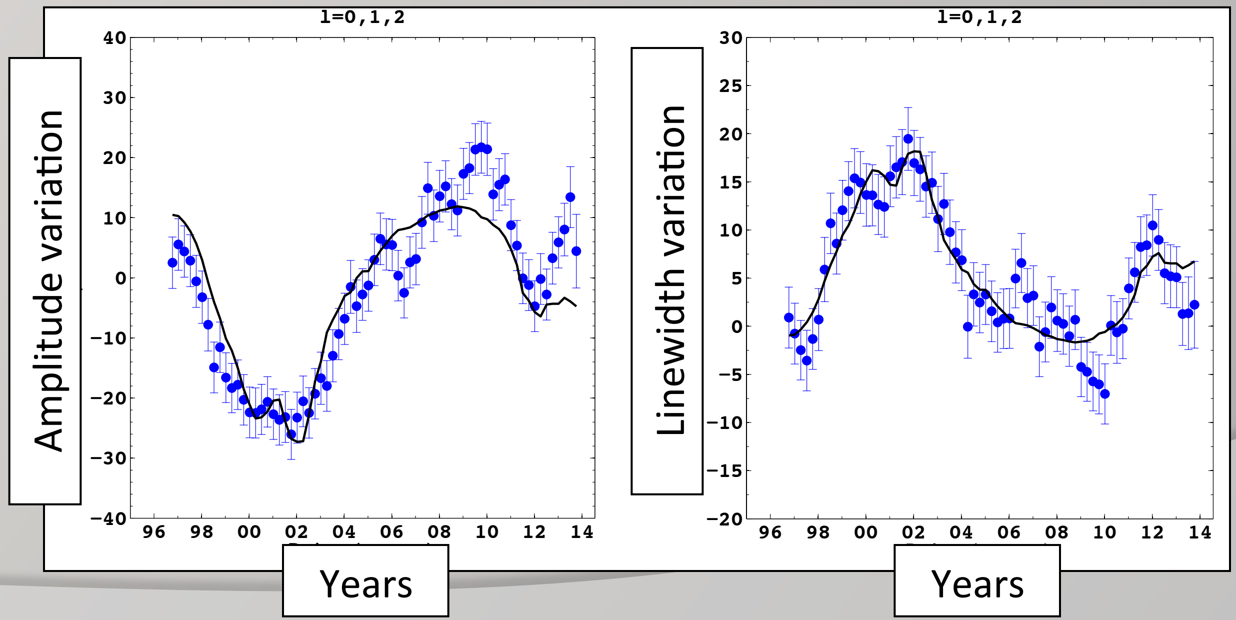
(Fletcher et al. 2010)

The Others p-Mode Parameters Vary Too…

- Presence of surface activity reduces power in the 5-minute band
  - Mode energy absorbed by strong magnetic field

- Decrease of mode amplitudes with increasing solar activity by about 40%
- Increase of mode linewidths with increasing solar activity by about 20%

- Anticorrelation between amplitude and { linewidths temporal variations / frequencies }



VIRGO observations

(Salabert et al. 2014, in Prep.)

HD49933: 1st Signature of Magnetic Activity Observed With Asteroseismology

- CoRoT target HD49933 (observed 60 days in 2007 and 137 days in 2008

(Appourchaux et al. 2009; Benomar et al. 2009)

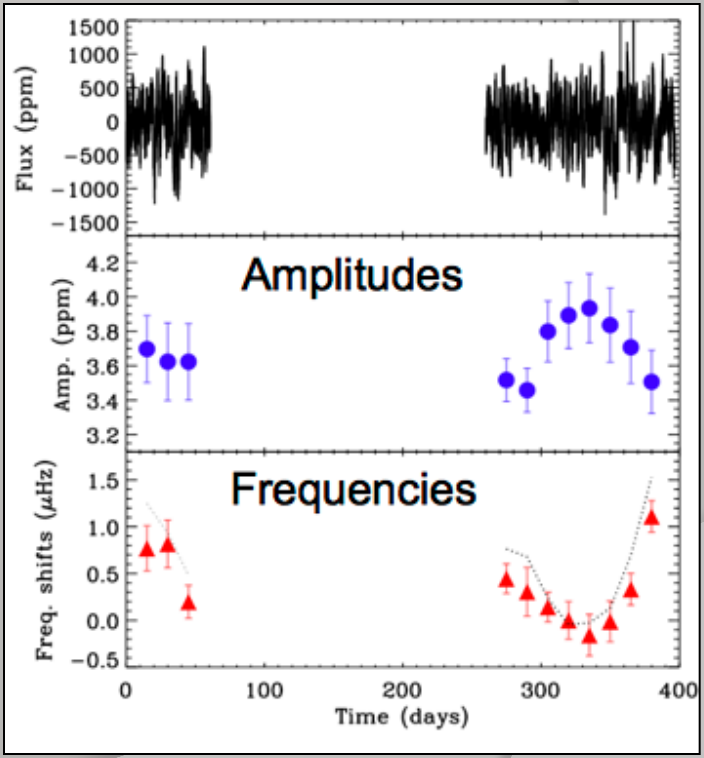
- F5V main sequence star: $1.3R_\odot$ and $1.2M_\odot$; Teff = 6780K; P_{rot} = 3.4 days

- Anticorrelated modulation between amplitudes and frequencies as for the Sun

- Variations related to magnetic activity of at least 120 days

- Frequency shifts about 5 times larger than in the Sun

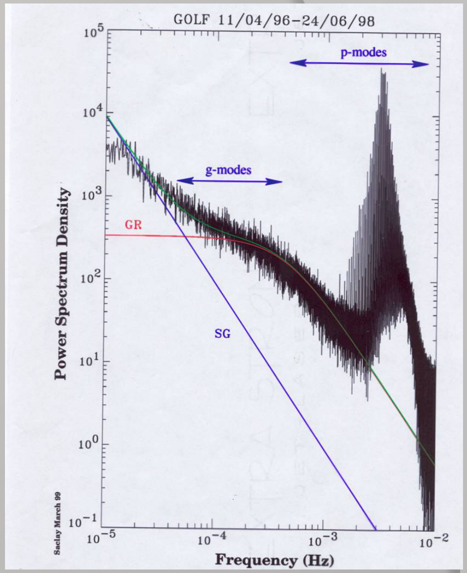
- Supports prediction of frequency shifts *(Metcalfe et al. 2007)*
  - Larger frequency shifts in stars hotter than the Sun



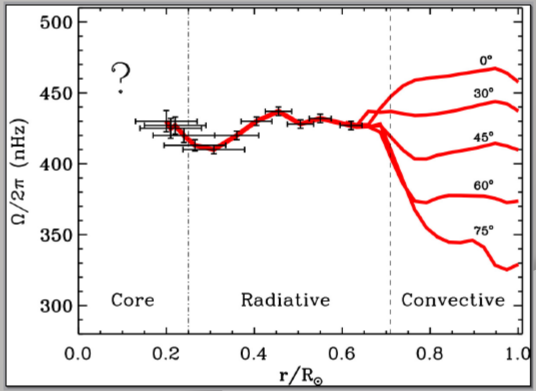
(Garcia et al. 2010; Salabert et al. 2011)

The need for low-frequency modes

- 2 main problems
  - mode amplitudes decrease, solar noise increases
    - *classic methods of peak fitting the individual-m spectra fail*
  - modes with very long lifetimes
    - *long-duration, high-quality observations needed*



- Low-frequency p-modes: great interest for improving resolution throughout the solar interior
  - Cover a broad range of depths of penetration
  - Lower reflection points in the outer part of the Sun
    - *Less sensitive to turbulence and magnetic fields*

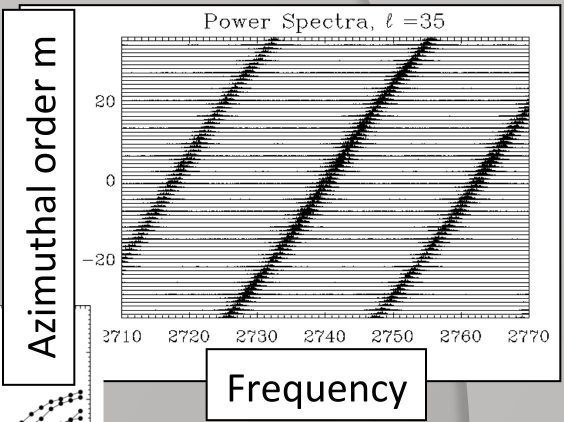


(Garcia, R.A, et al. 2007a)

- Gravity modes: necessary to infer the core
  - No detection of individual modes yet (few mm/s)
  - Detection of the asymptotic spacing of the dipole gravity *(Garcia, R.A, et al. 2007b)*

m-averaged spectrum: Methodology

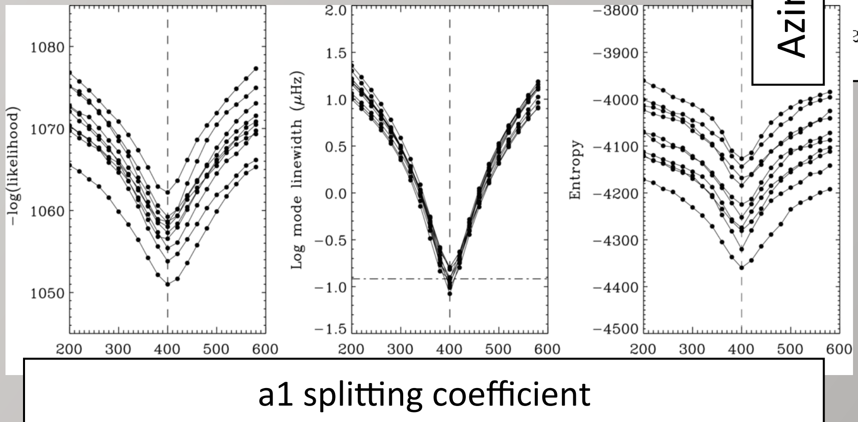
- Rotational and structural effects: degeneracy lift of mode frequency into (2l+1) m-multiplets



- The shifts (a-coefficients) are determined as $\nu_{n,l,m} = \nu_{n,l} + \sum_{k=1}^{k_{max}} a_k(n,l) P_k^{(l)}(m)$

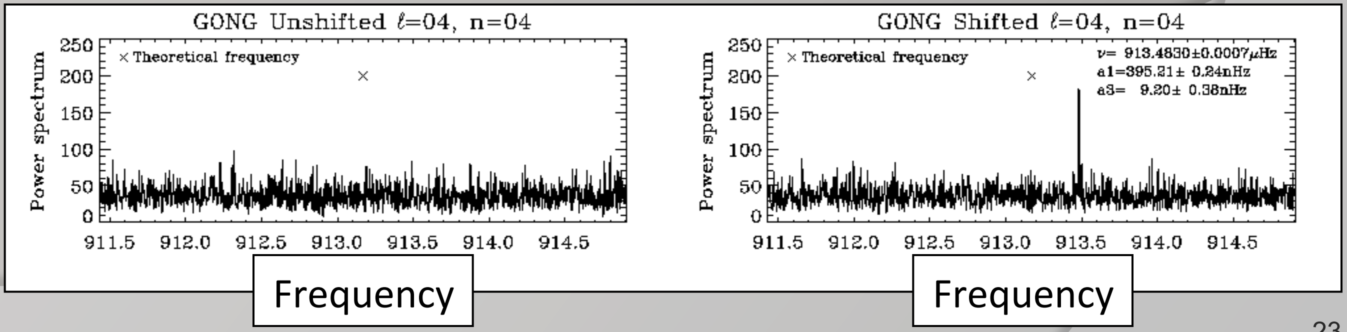
  we are searching for the low-frequency modes.

- Several way to find the best estimates of the a-coefficients
  - *minimum likelihood*
  - *narrowest peak*
  - *smallest entropy*



Figures-of-Merit

- Considerably improves SNR even when the m-components have too low SNR to be measured in the individual-m spectra.



(Salabert et al., 2009)

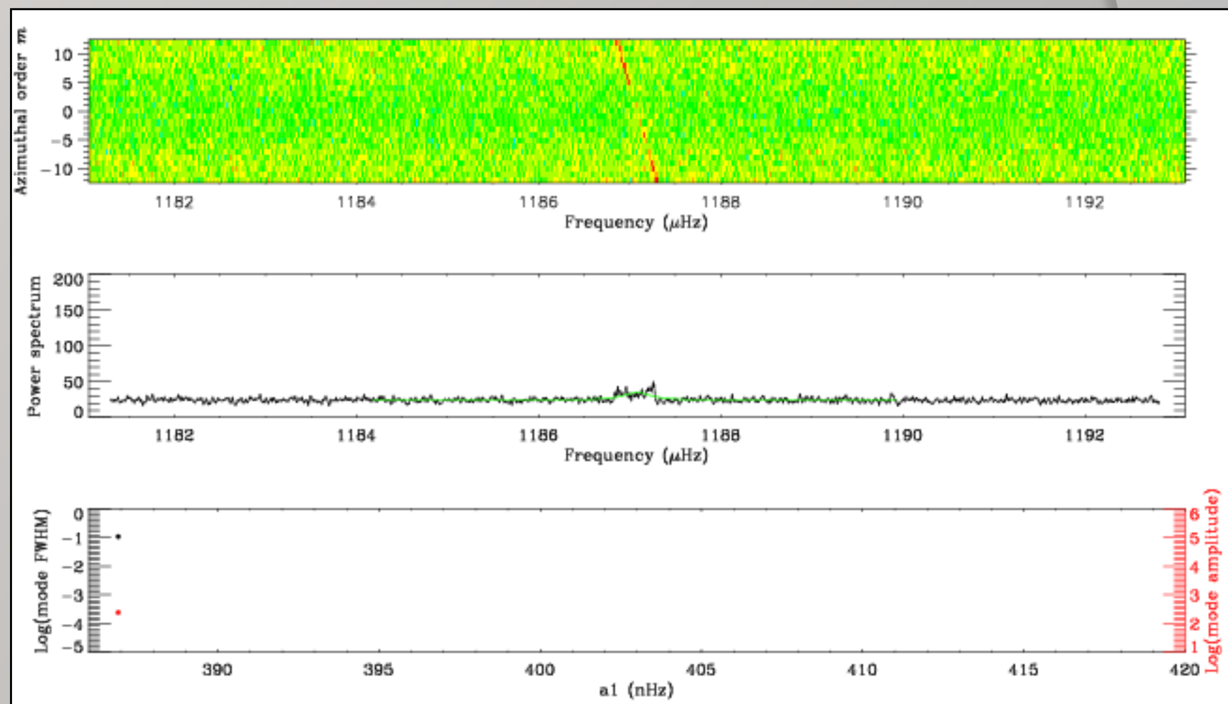
m-averaged spectrum: Example

l = 12, n = 4 mode at ~ 1187 μHz

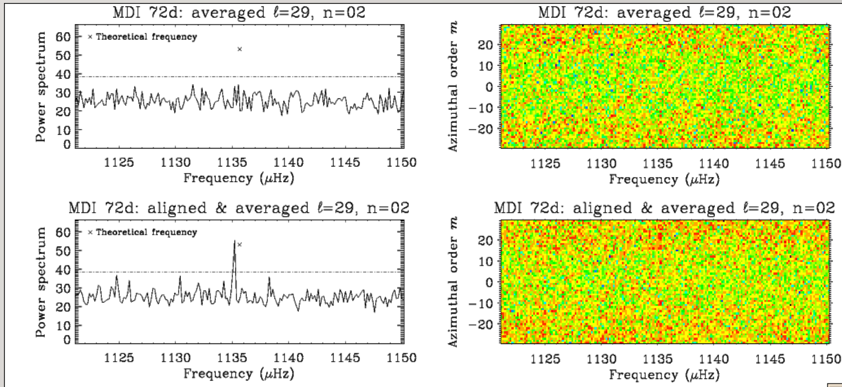
m-ν diagram

m-averaged spectrum

Figure-of-merit (a1)



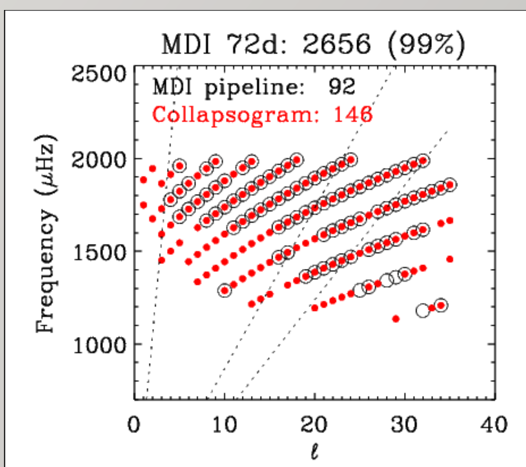
MDI 72-day & GONG 108-day time series



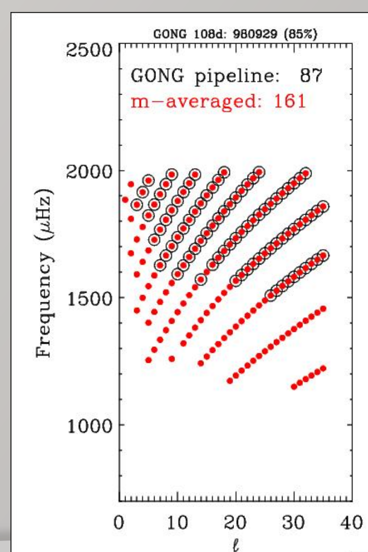
Example of a m-averaged spectrum with 72 days of MDI observations

- Between 40% and 50% measured new modes below 2000μHz
- 25% deeper in radiative zone down to $0.3R_\odot$ *(Leibacher, Salabert, 2007)*

MDI 72-day time series



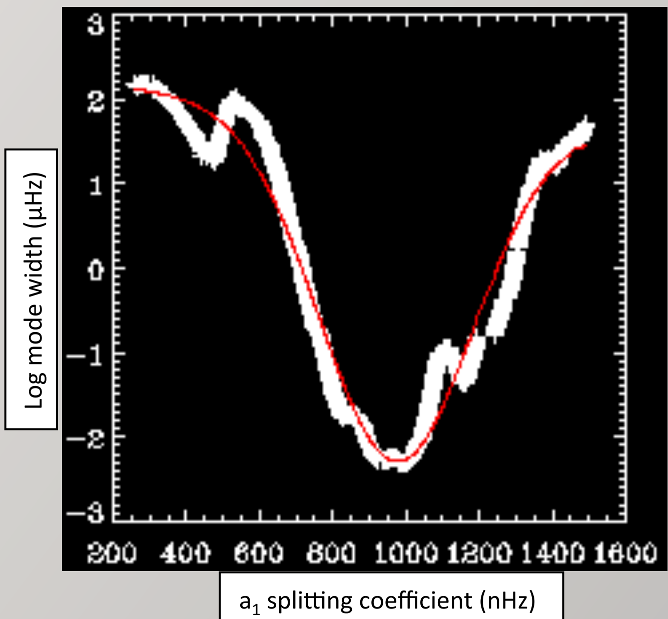
GONG 108-day time series

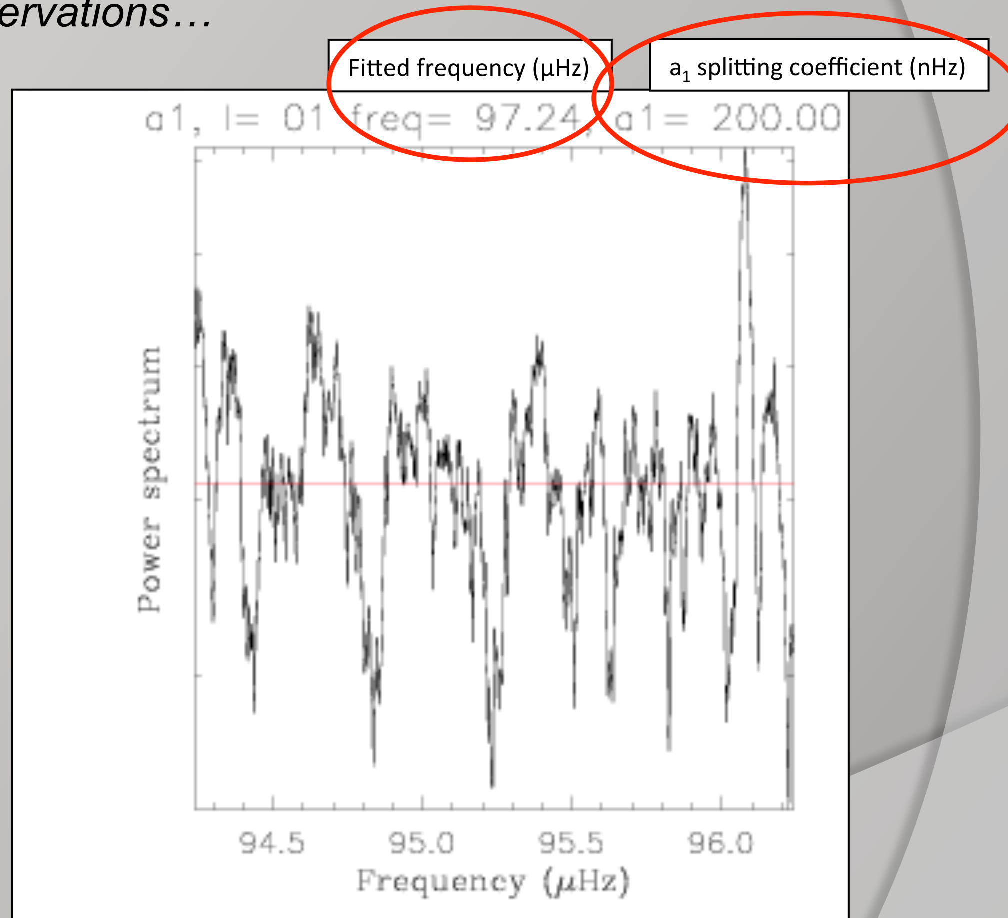


Application for the g-mode search

Preliminary results using GOLF observations…

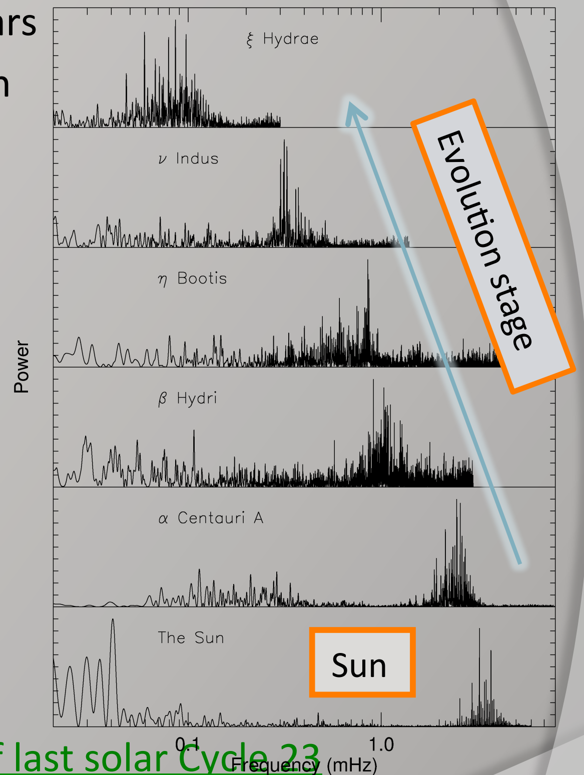
l=1 gravity mode:





Summary

- Helio / Asteroseismology: a unique and powerful tool to "see" inside the Sun and stars
  - to infer the internal rotation and structure of the Sun/stars
  - to constrain the solar/stellar models and stellar evolution
  - to study solar/stellar magnetic activity cycles



Kjeldsen & Bedding (2003)

- Asteroseismology: CoRoT and Kepler observations
  - Magnetic activity in a wide variety of stars
  - Inferences for our understanding of the dynamo processes, generating magnetic fields
  - Put the Sun into context
  - Explore the impacts of magnetic activity on possible planets hosted by these stars

- Helioseismology and the peculiar deep and long minimum of last solar Cycle 23
  - Frequencies sensitive to magnetic effects before their signatures appear at the surface
  - Slower east-to-west stream: explaining lack of sunspots during minimum of Cycle 23