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Institute of Astronomy
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- ***History of the research topic***
- ***Introduction into asteroseismology***
- ***What did helioseismology learn us ?***
- ***Solar-type oscillations in other stars***
- ***White-dwarf seismology***
- ***The future***

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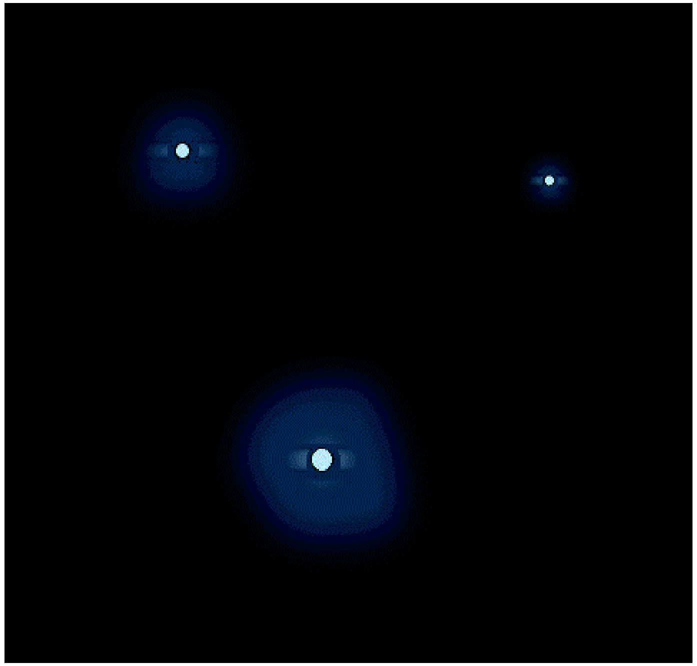
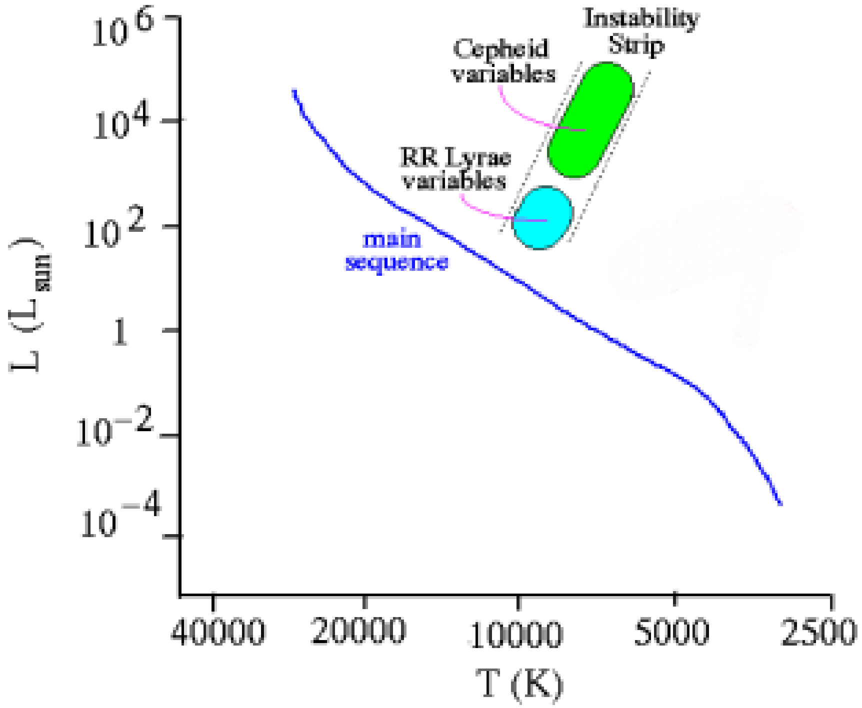
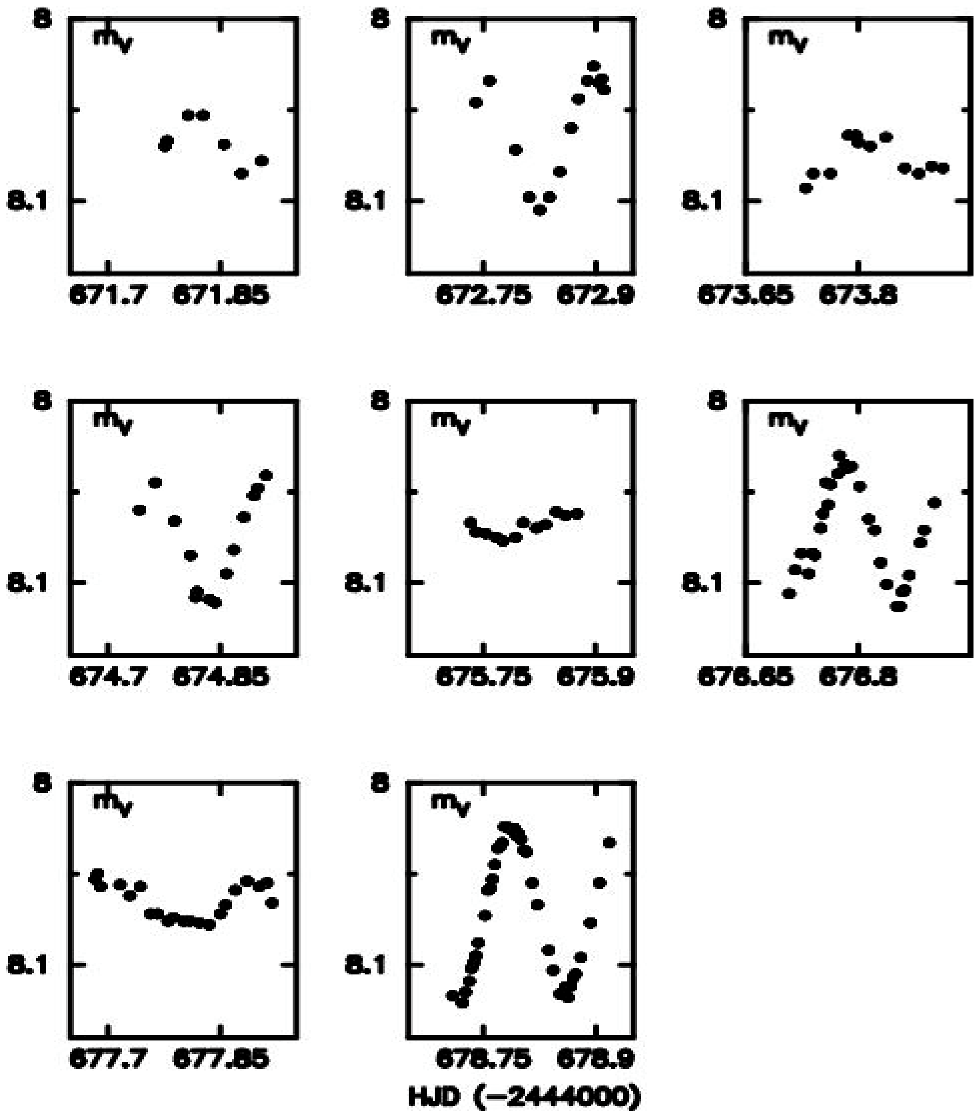
With your naked eye: 3% of the stars is variable






8
8.1
mV
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671.85
672.75
672.9
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673.8
674.7
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675.75
675.9
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676.8
677.7
677.85
678.75
678.9
HJD (−2444000)

- ***Periodic variables known since long, e.g. Cepheids, RR Lyraes***
- ***Multiperiodicity is found meanwhile in many different kinds of variables***
- ***Cause: non-radial oscillations***
- ***Idea: every body ``sounds" according to its internal structure => the different oscillation frequencies learn us something about the stellar interior***
- ***Between 1900 - 1990: mainly inventarisation of periodic variables***
- ***Since 1990: use frequency content to derive internal structure parameters***

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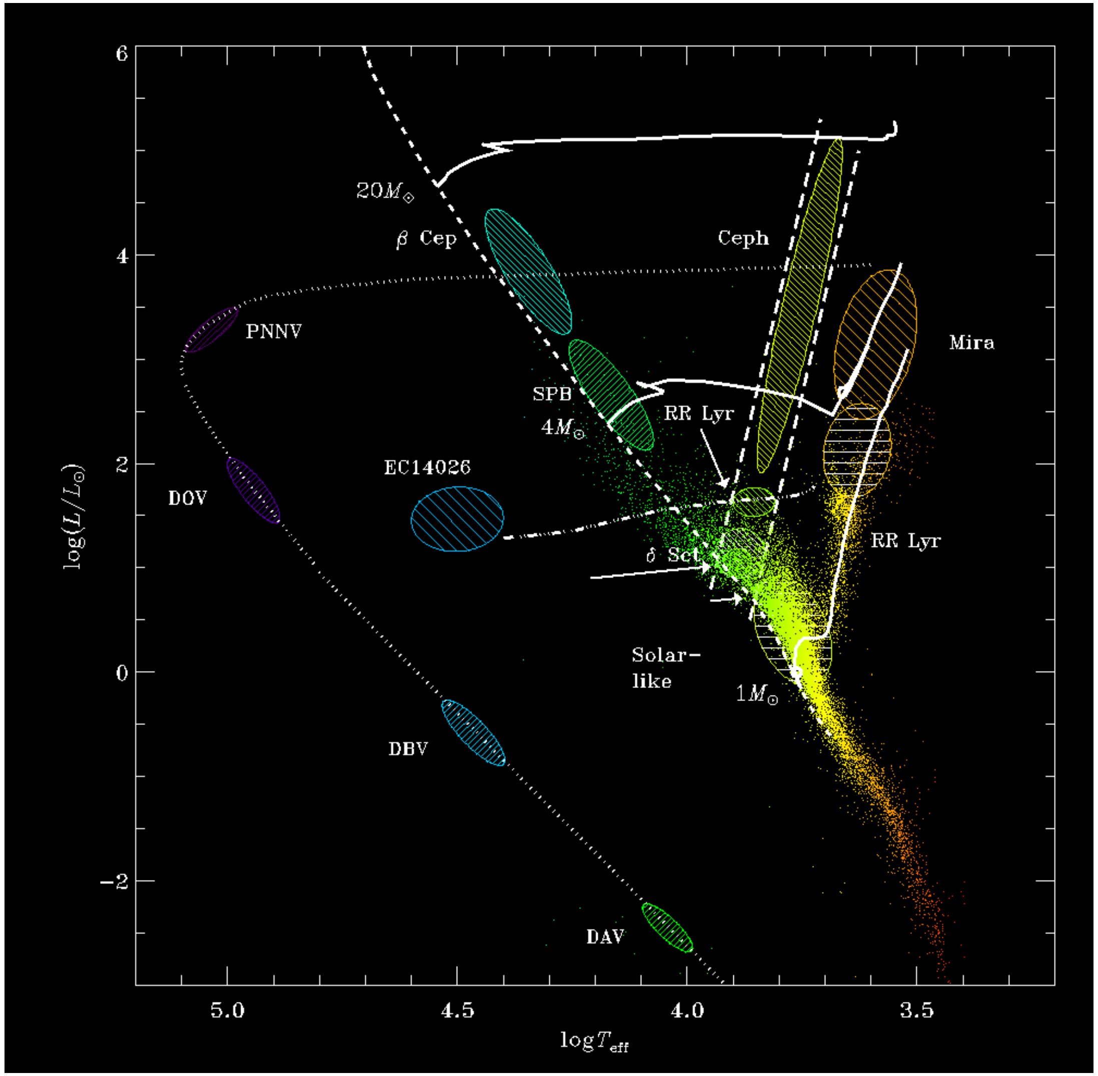

6
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5.0
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log T_eff
20M⊙
β Cep
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PNNV
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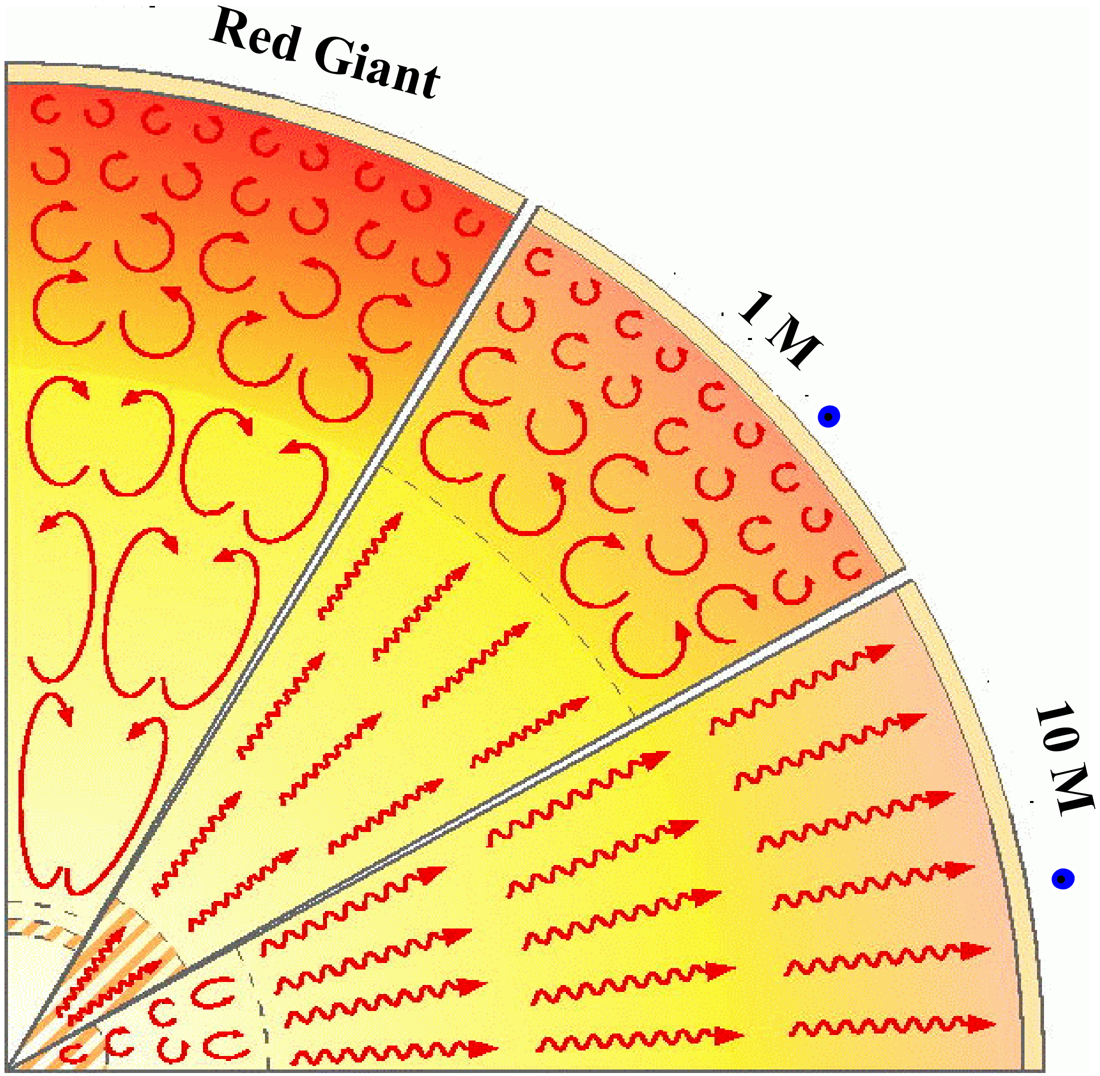
EC14026
DOV
δ Sct
RR Lyr
Solar-like
1M⊙
DBV
DAV

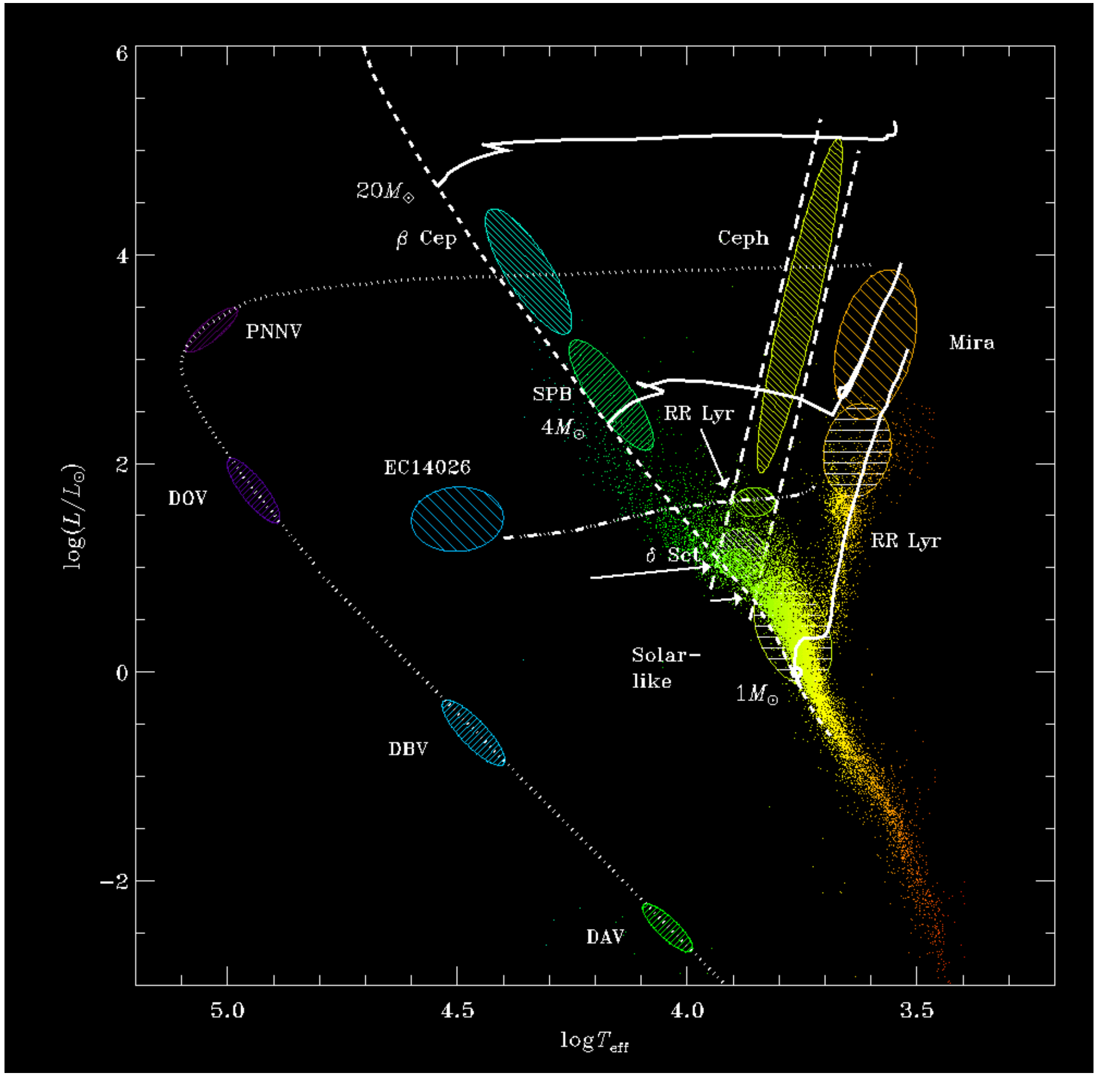
- ***Because they have convective outer layers which cause stochastic excitation of oscillations (cf. Gong, organ pipe)***
- ***Because some outer layers act as a heat engine. Partial ionisation zones can be very efficient in absorbing and accumulating energy generated in the stellar interior.   This accumulation can give rise to a self-driven oscillation (opacity mechanism)***

- *Stars are the sources of the chemical evolution of the Universe:*
  - Massive stars synthesize all elements up to iron
  - Stars with moderate masses form C, N, O
  - The chemical evolution is strongly dependent on internal mixing processes
- *Stars are the local memory of the history of the Universe and allow to estimate its age*

- *Effect of internal rotation rotation ?*
- *Effect of convective overshooting ?   => how does mixing occur inside the stars ?*
- *Preamble of supernova explosion ?*
- *Evolution of chemical abundances ?*

Asteroseismology will imply major steps forward in answering these questions


Red Giant
1 M
10 M



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aster: star

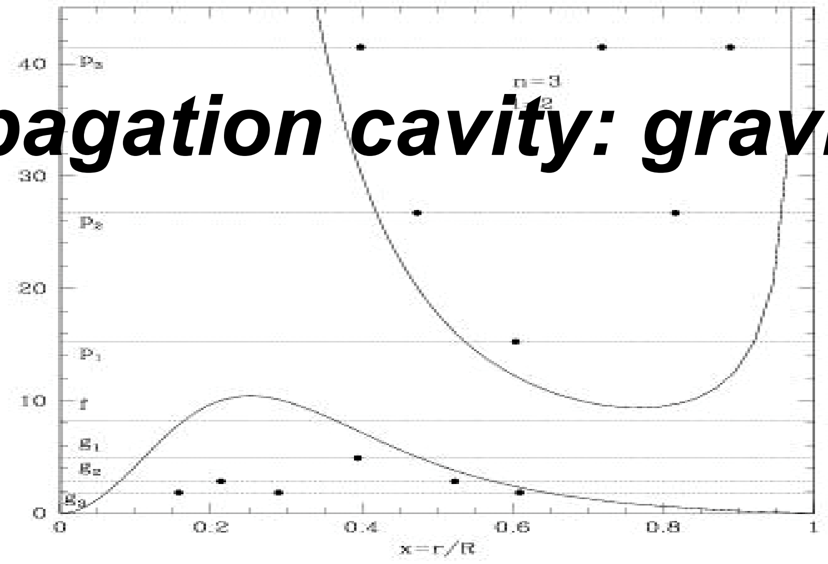
seismos: oscillation

logos: discours, reasoning

Through the analysis of stellar oscillations we want to study the stellar interior

- ***Perturbation of eq. of motion, continuity eq., eq. expressing entropy conservation and Poisson's eq.***
- ***Solutions ~ exp (it⬩ⓘcan be found, with ⬩ the oscillation frequency of one mode***
- ***Velocity vector ~ spherical harmonic, consisting of Legendre polynomial with wavenumbers (l,m)***
- ***Problem is of Sturm-Liouville type for l=0, large or small ⬩***

- ***Outer propagation cavity: acoustic modes***
- ***Inner propagation cavity: gravity modes***



Figuur 6.1: Propagatiediagram van golven van graad $\ell = 2$ in een polytropisch model met index 3

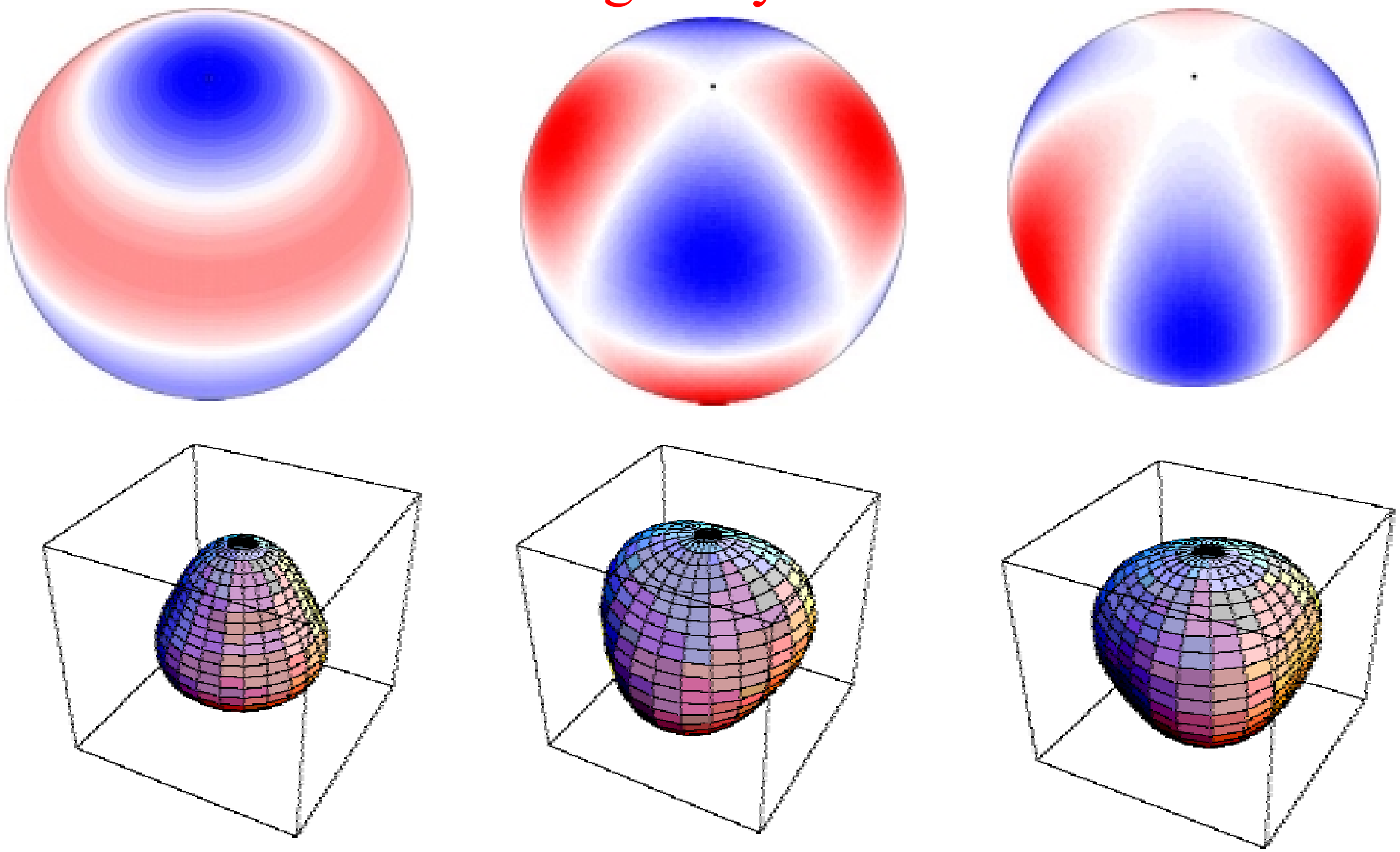
93

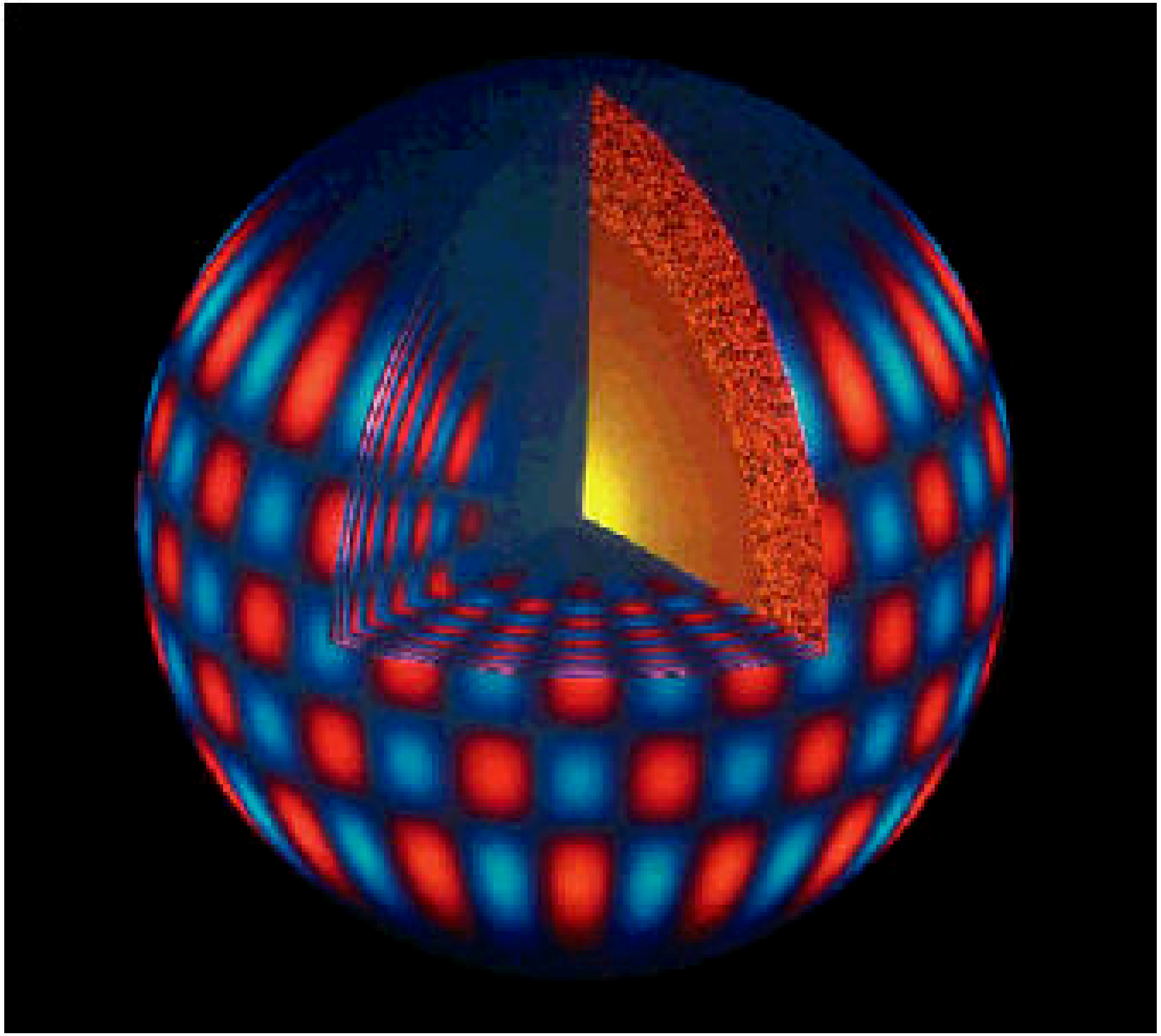
(l,m) = (3,2) *tesseral*

(l,m)=(3,3) *sectoral*

Blue ? Moving towards Observer

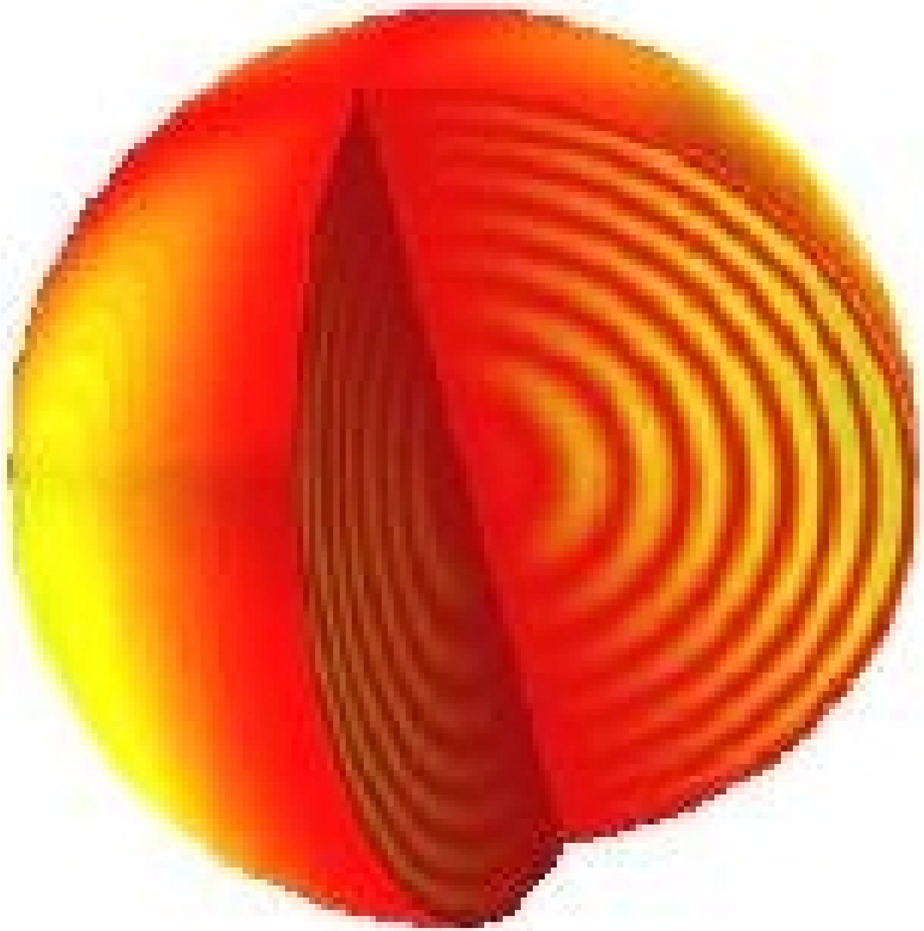
Red ? Moving away from Observer

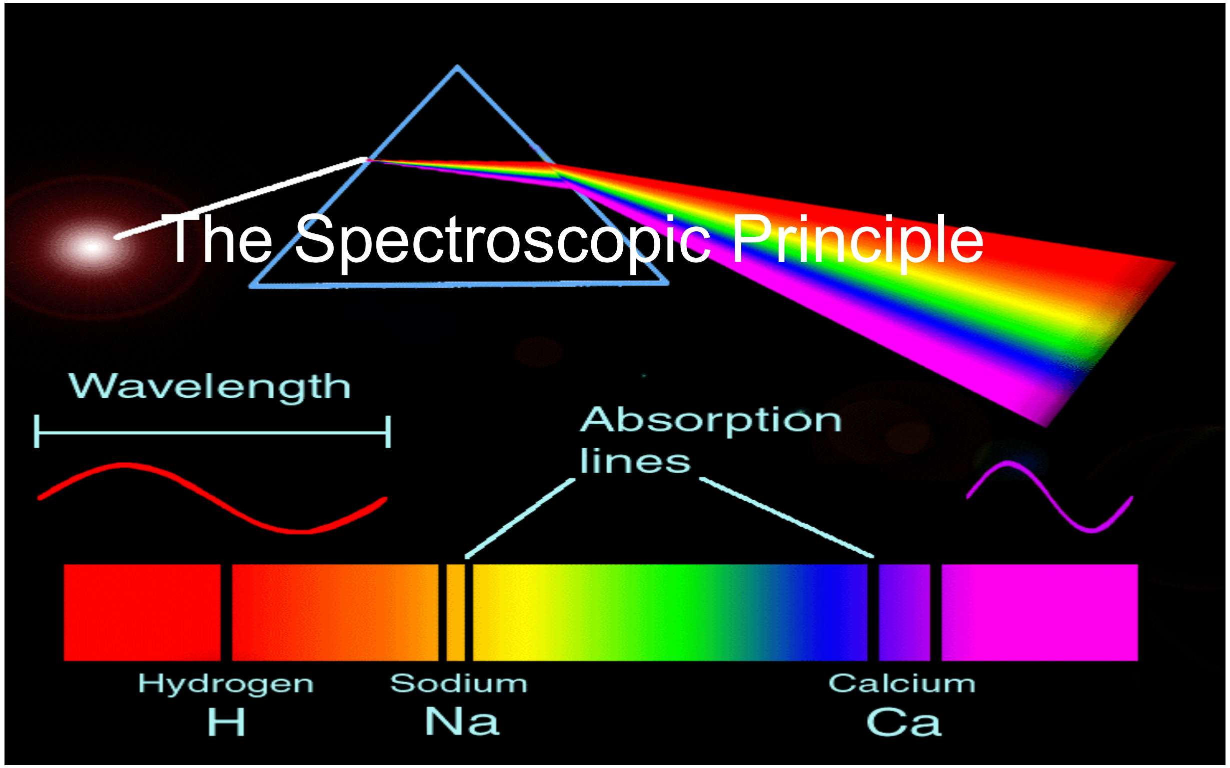




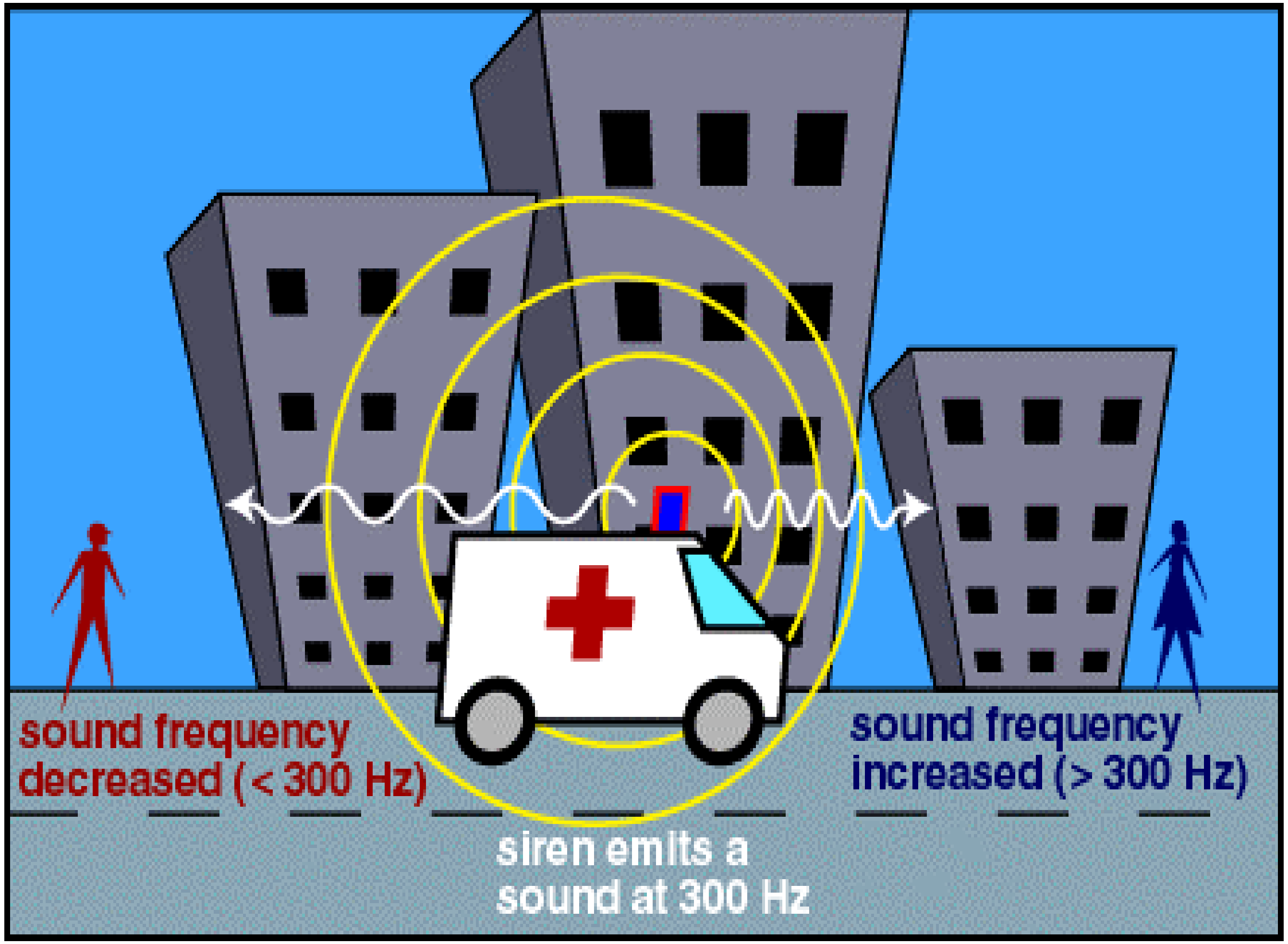
The oscillation pattern at the surface propagates in a continuous way towards the stellar centre.

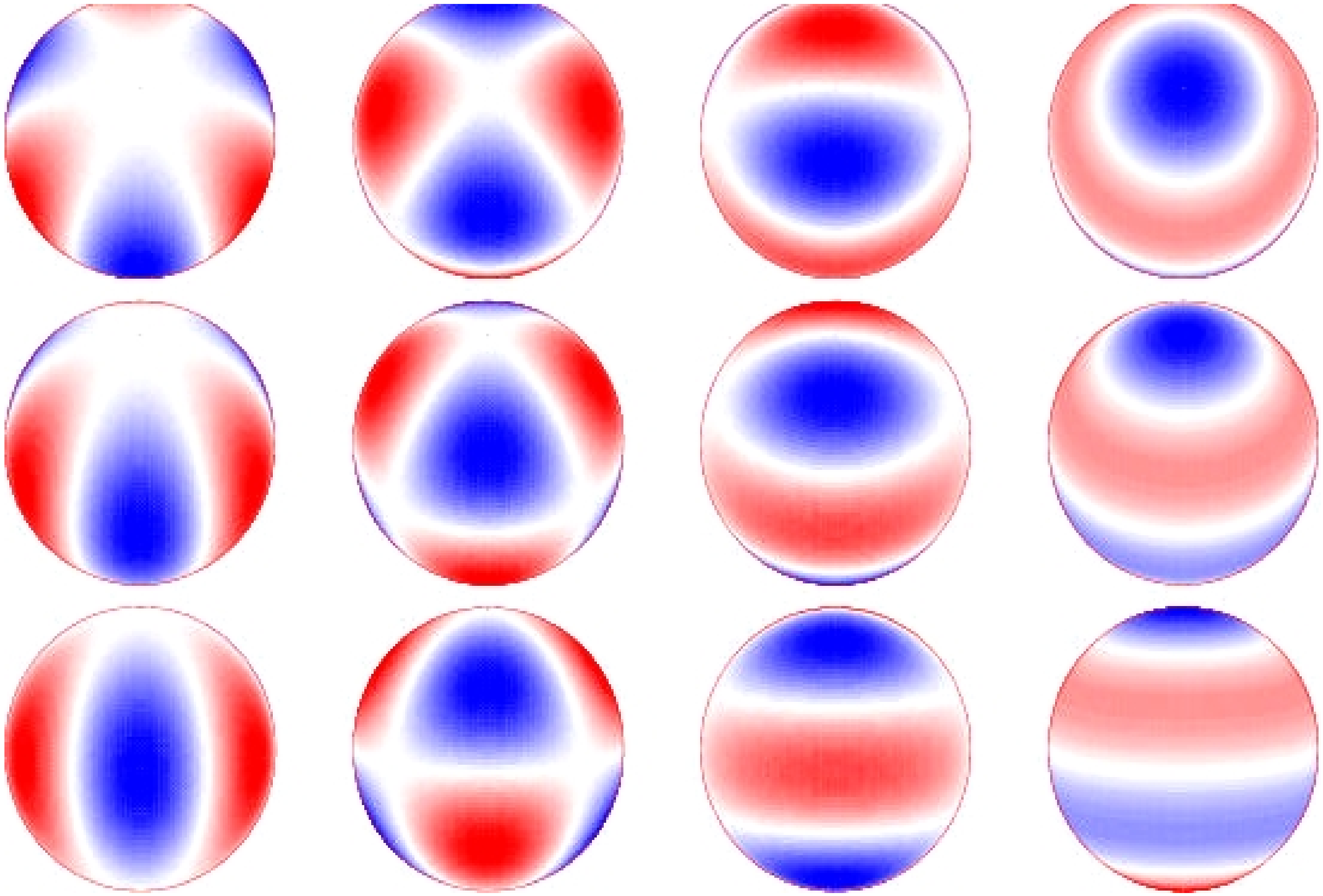
Study of the surface patterns hence allows to characterize the oscillation throughout the star.

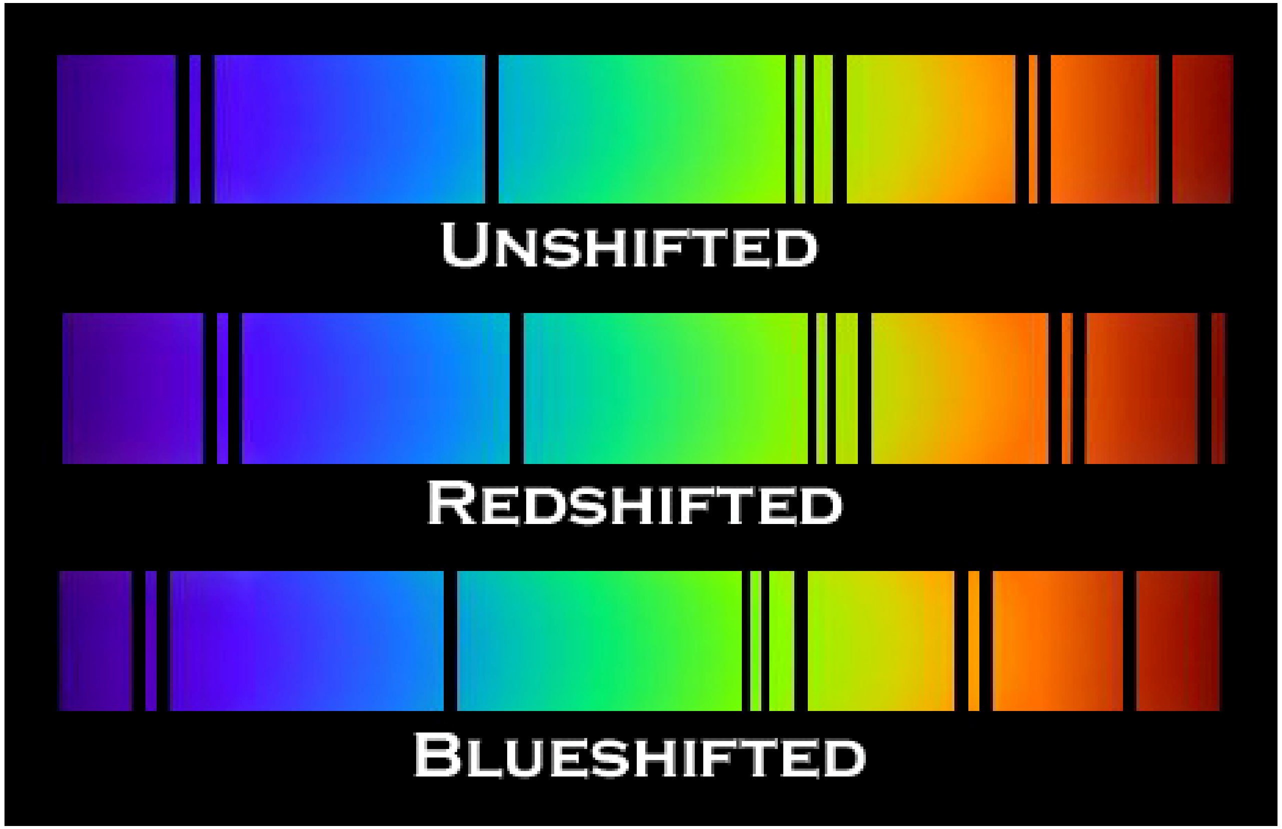




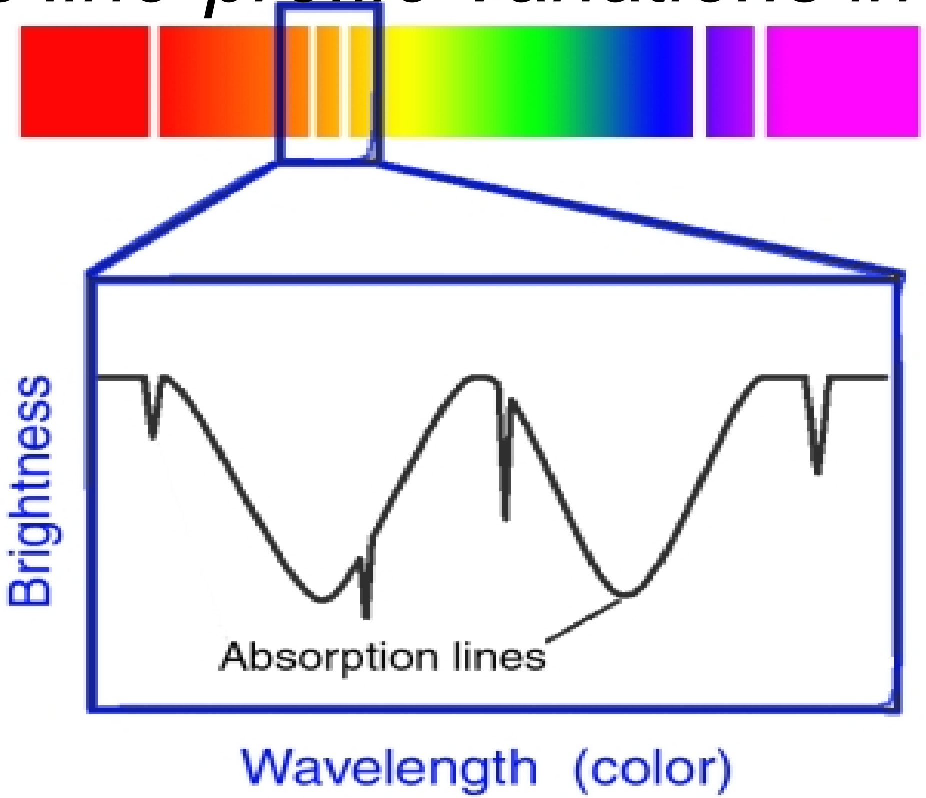
By unravelling the spectrum in all of its details...


sound frequency
decreased (< 300 Hz)
sound frequency
increased (> 300 Hz)
siren emits a
sound at 300 Hz

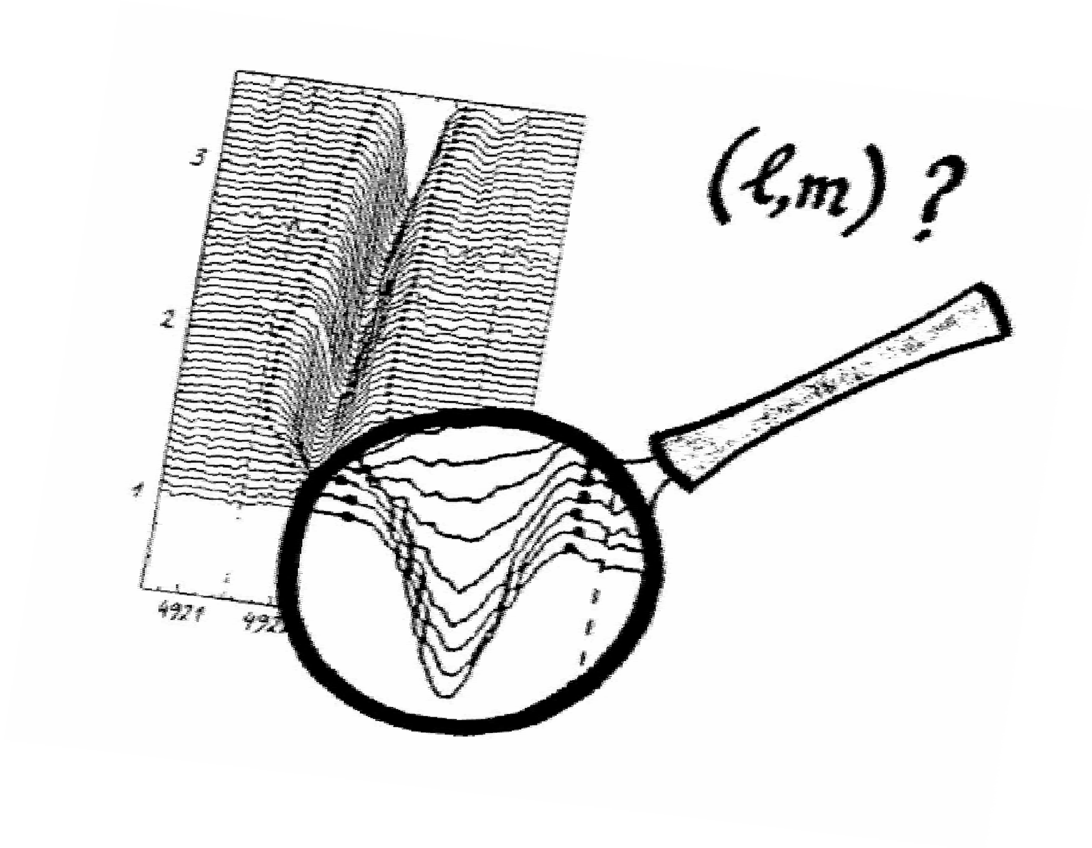


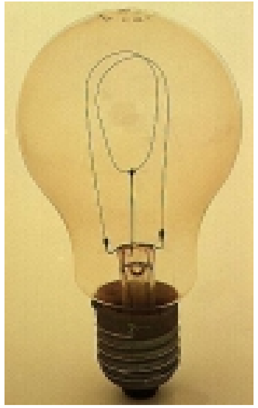

UNSHIFTED
REDSHIFTED
BLUESHIFTED

- *Select an unblended isolated absorption line*
- *Study its line-profile variations in time*



- *Gather time series of one suitable spectral line*
- *Study its evolution in time = line-profile variations*





Derive which (l,m) gives the best agreement

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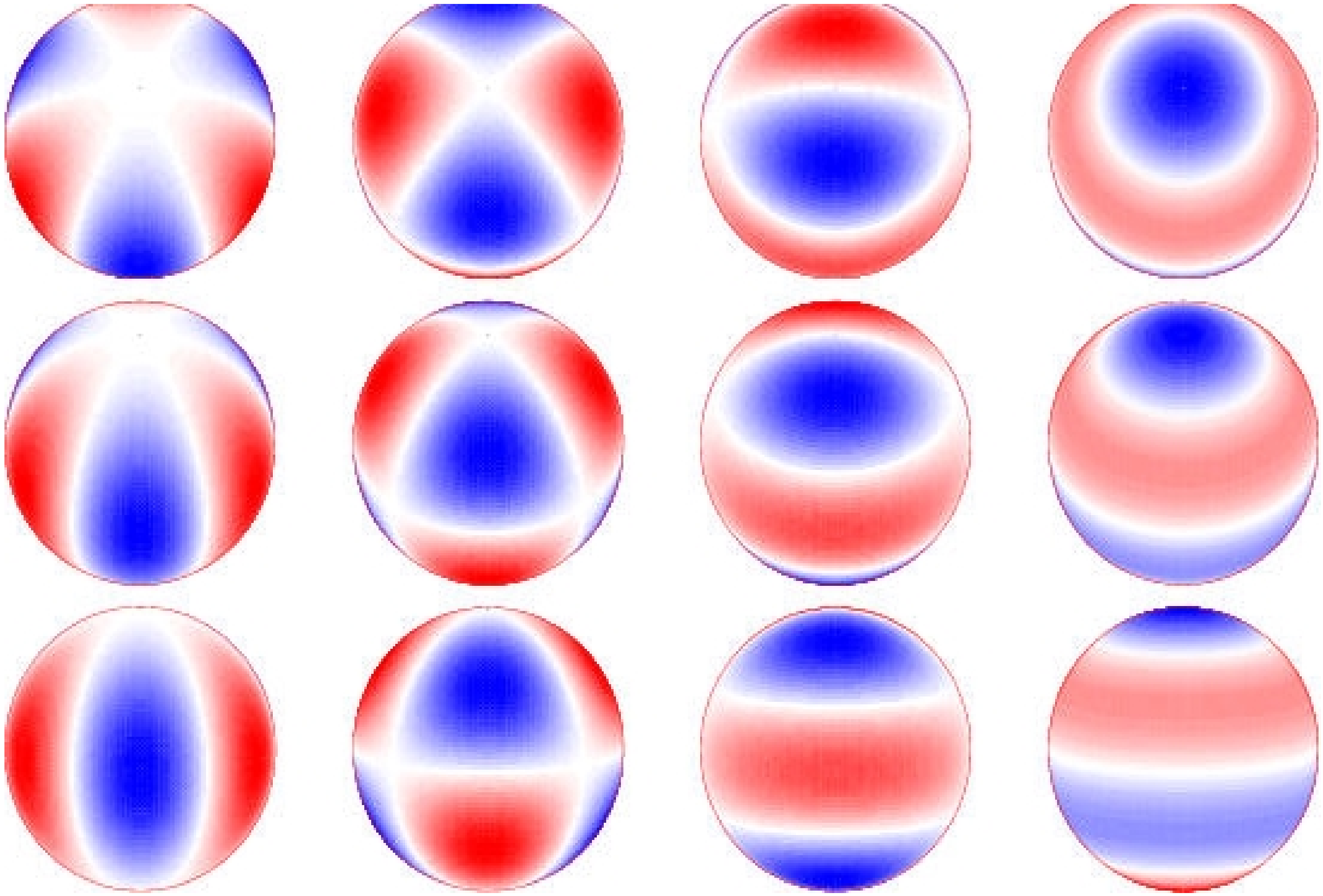

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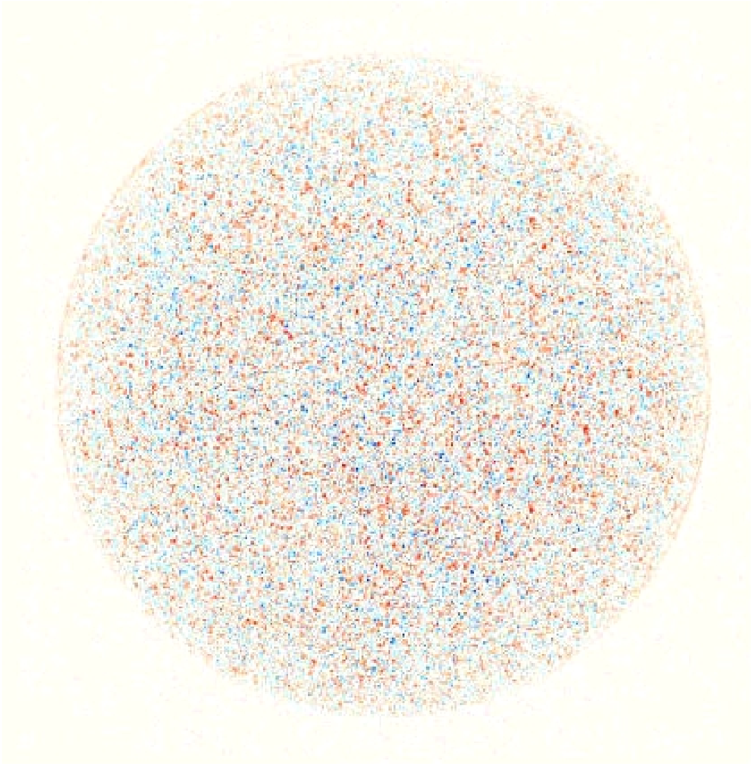
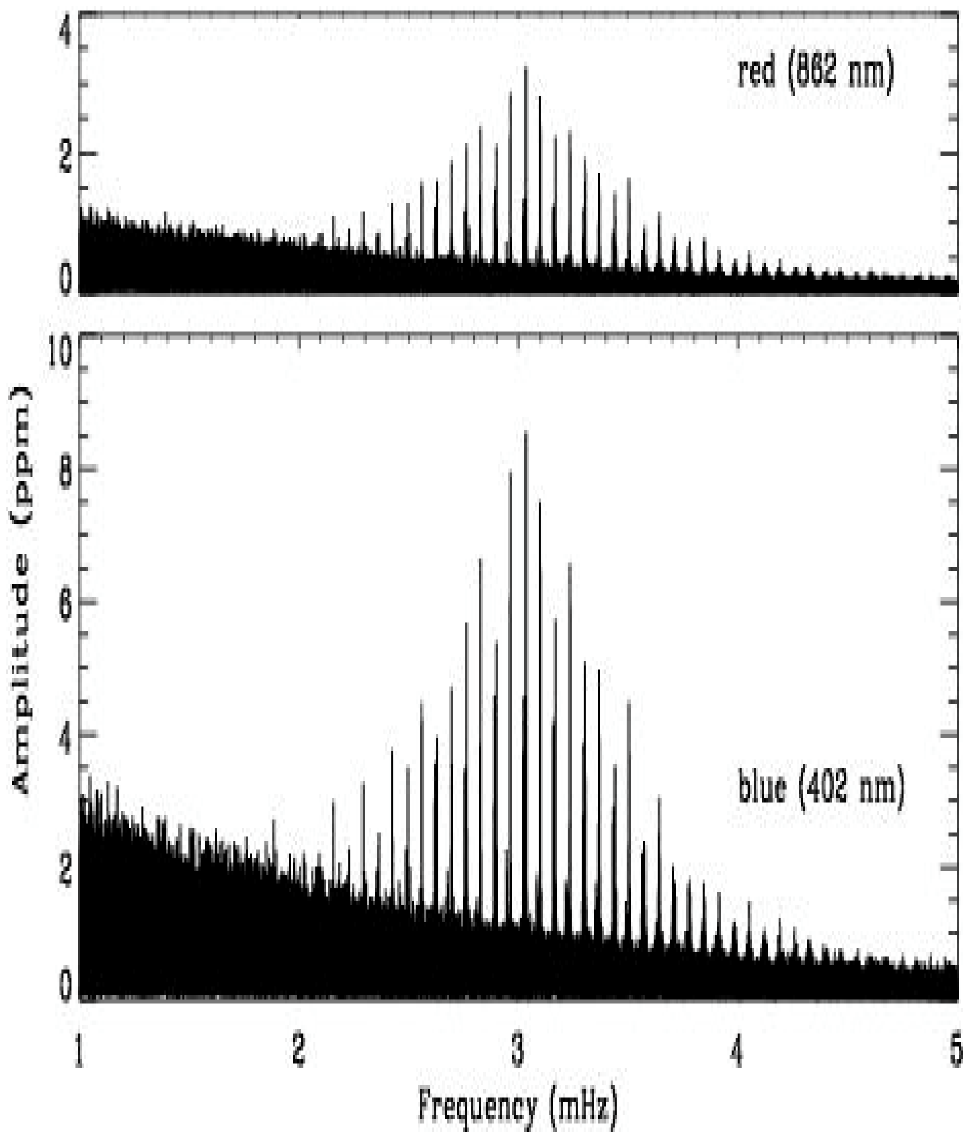


The Sun oscillates in thousands of non-radial modes with periods of ~5 minutes

The Dopplermap shows velocities of the order of some cm/s



Fourier analysis of the time series gives us the oscillation frequencies of the solar oscillations

The eigenvalues are determined by the internal structure of the star, such as the internal temperature, density and pressure

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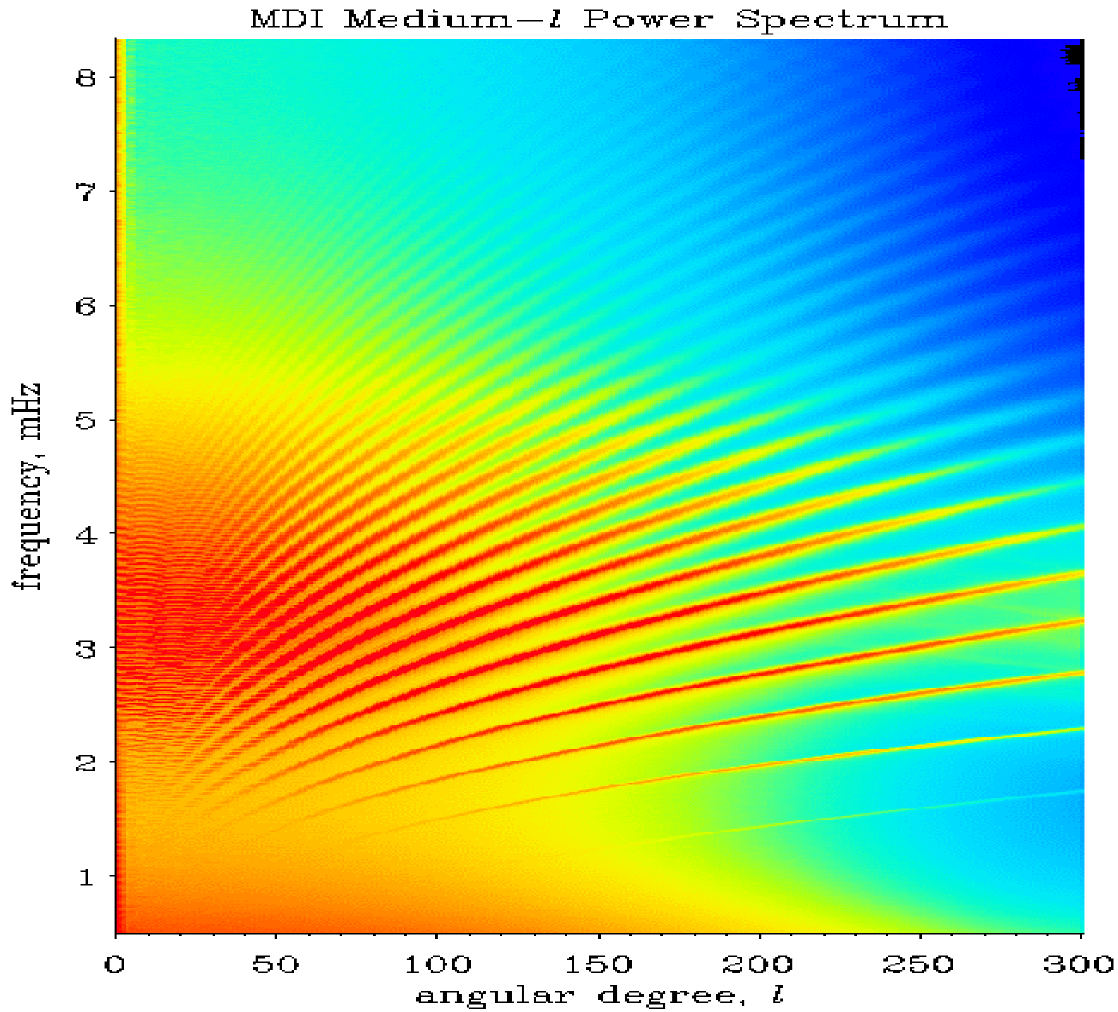
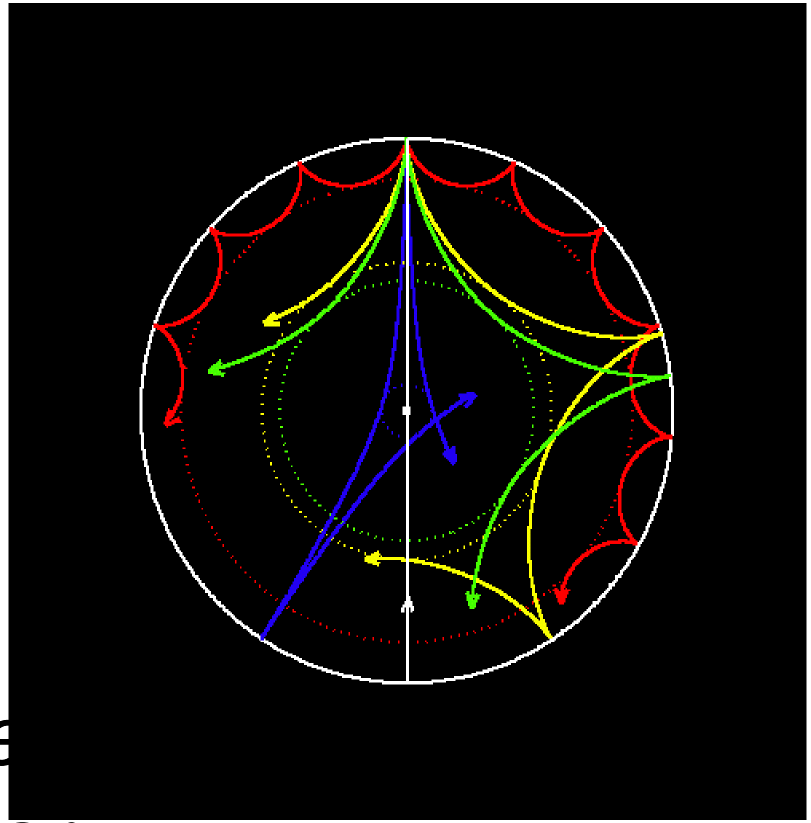


MDI Medium-l Power Spectrum
frequency, mHz
1
2
3
4
5
6
7
8
0
50
100
150
200
250
300
angular degree, l

De oscillations are standing sound waves that are reflected within a cavity



Different oscillations penetrate to different depths and hence probe different layers of the star

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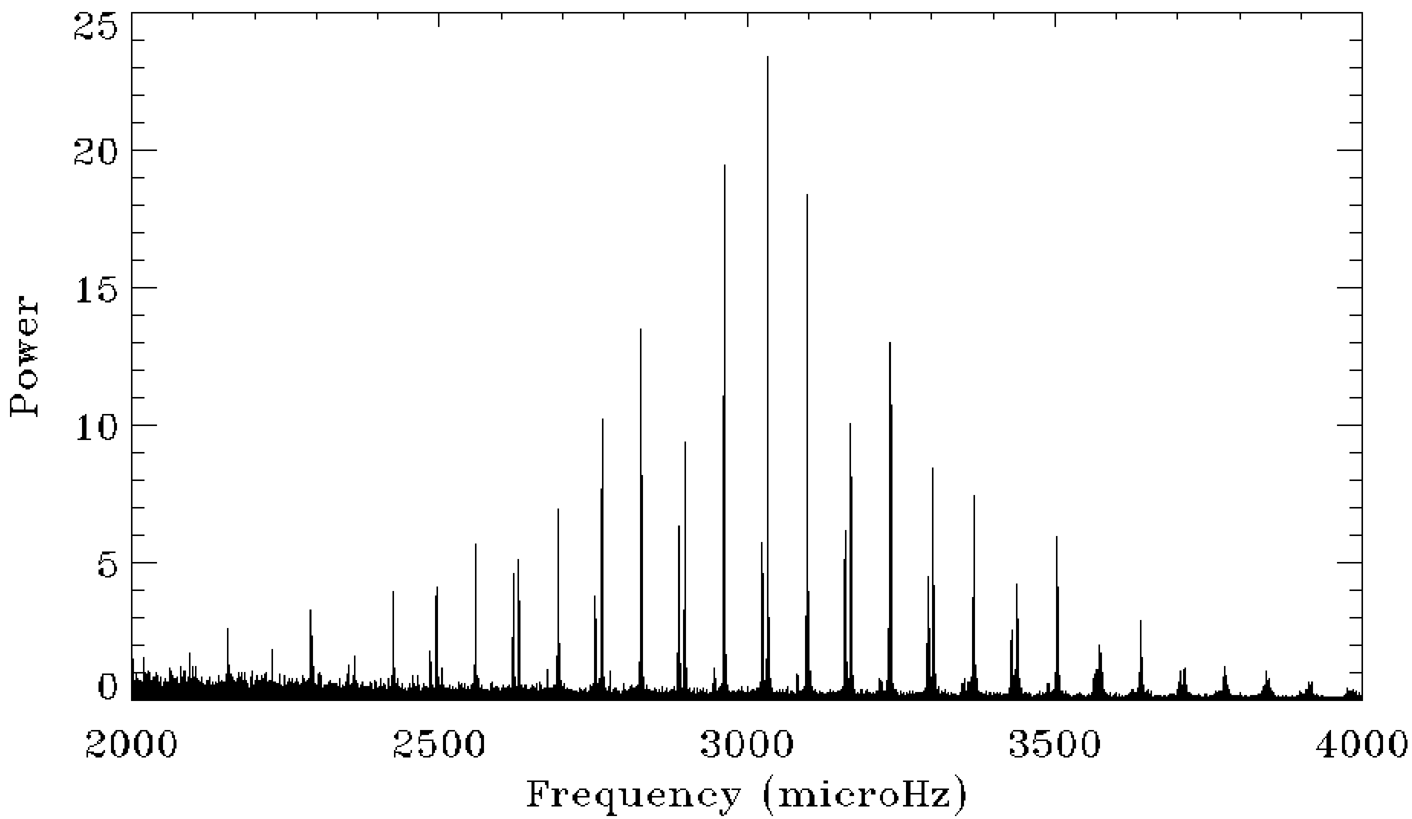


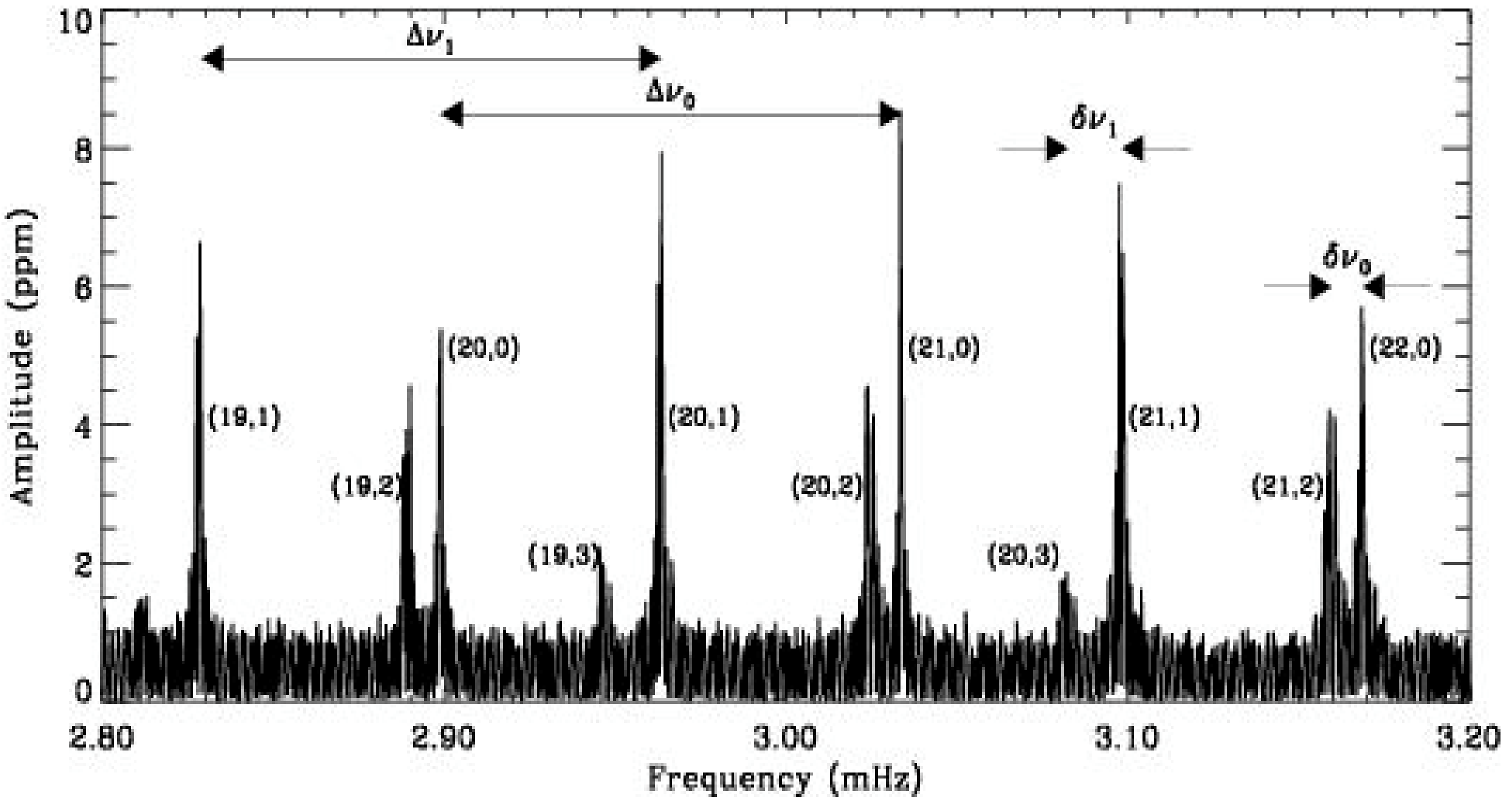
25
20
15
10
5
0
Power
2000
2500
3000
3500
4000
Frequency (microHz)

Frequency separation determined by stellar structure

Frequency splitting determined by rotation

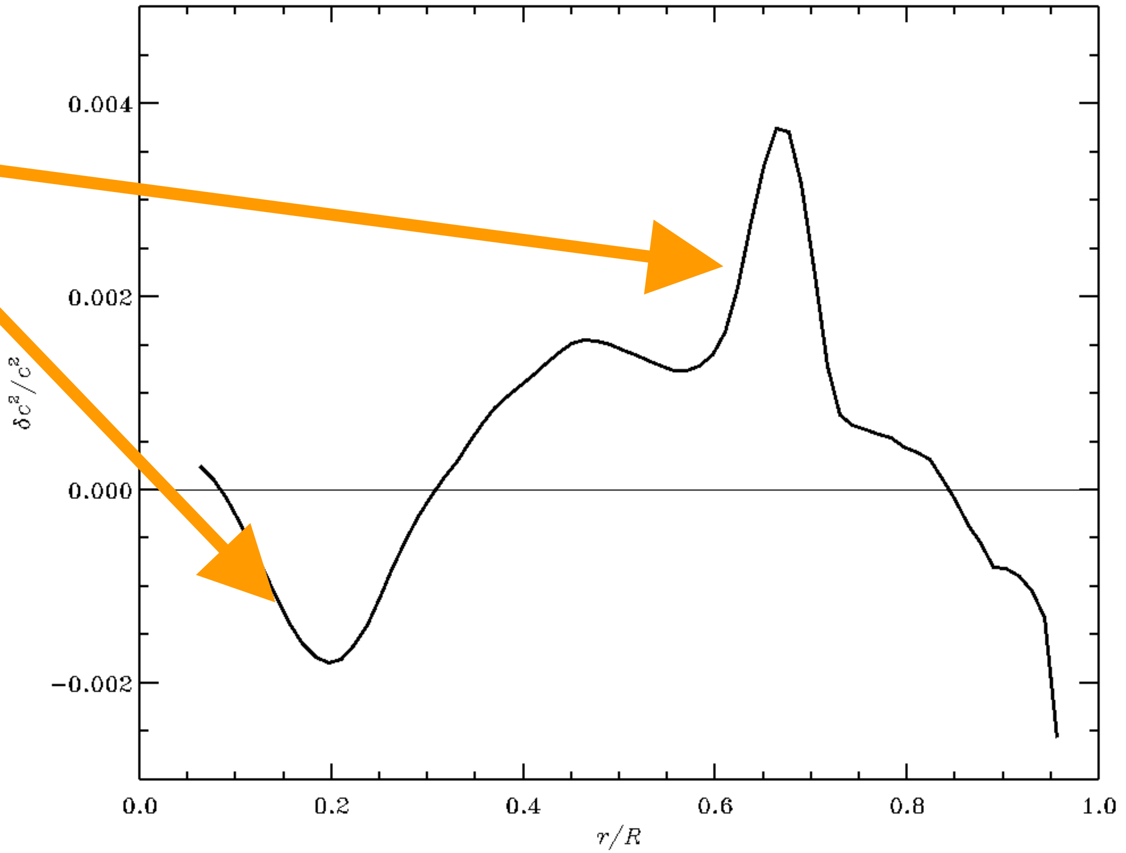
$$\sigma_{n\ell} \simeq \sigma_0 \left(n + \frac{\ell}{2} + \varepsilon\right); \sigma_0 = \left(2\int_0^R \frac{dr}{c(r)}\right)^{-1}$$

$$\sigma_{n\ell m} = \sigma_{n\ell} - m\Omega(1 - C_{n\ell}) + \Theta\left(\Omega^2\right)$$

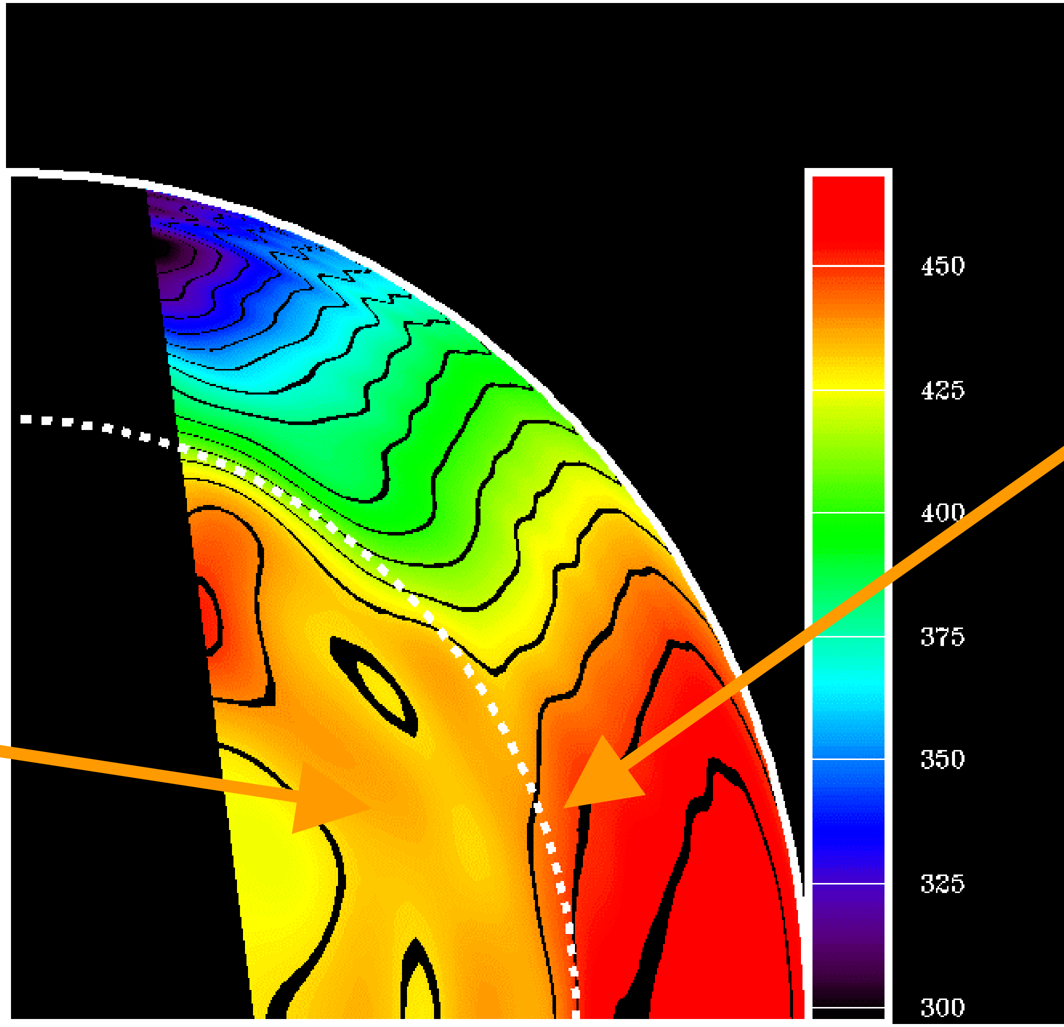


Result: internal sound speed and internal rotation could be determined very accurately by means of helioseismic data from SoHO

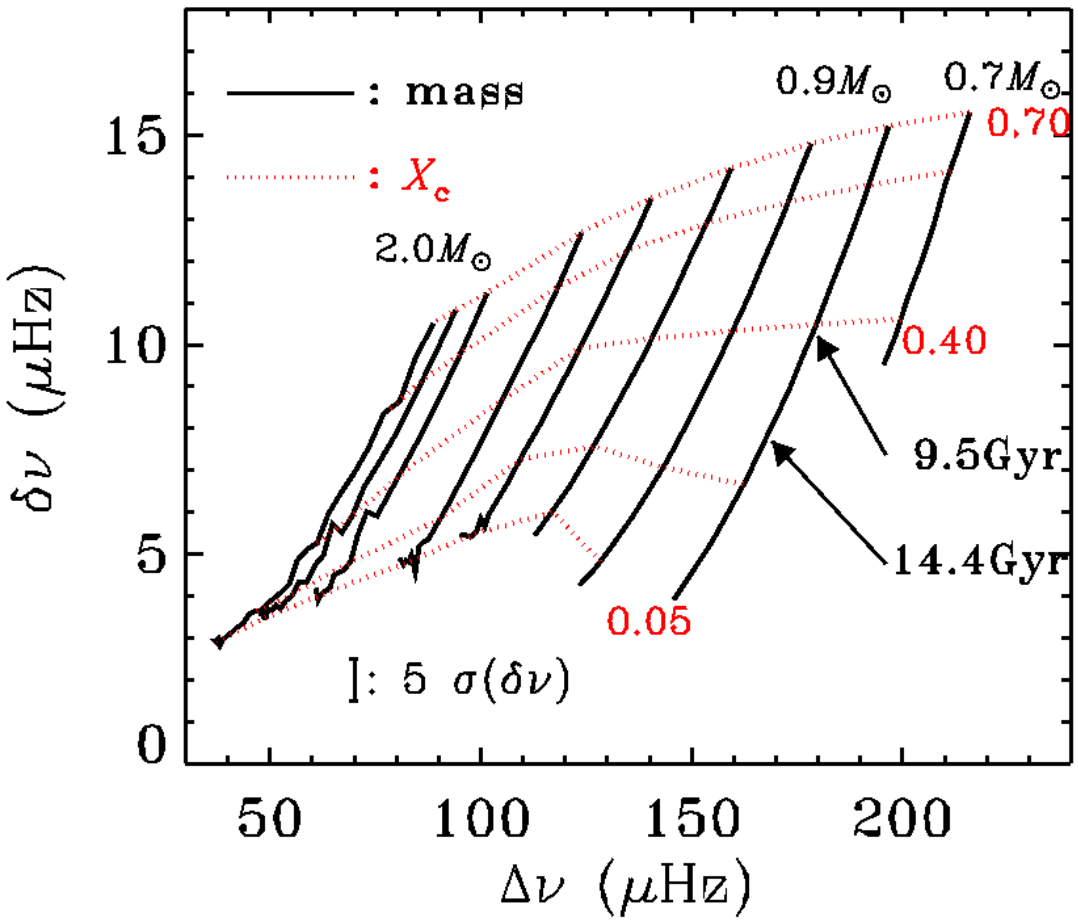
Indication
of
unknown
mixing



Solar interior has rigid rotation



Beginning of outer convection zone



: mass
: X_c
2.0$M_\odot$
0.9$M_\odot$
0.7$M_\odot$
0.70
0.40
0.05
9.5Gyr
14.4Gyr
]: 5 $\sigma(\delta\nu)$
15
10
5
0
50
100
150
200
$\delta\nu$ (μHz)
$\Delta\nu$ (μHz)

- *She does not have a considerable convective core*
- *She is a slow rotator*
- *She is relatively unevolved*

How do all these results/techniques change for other types of stars ?

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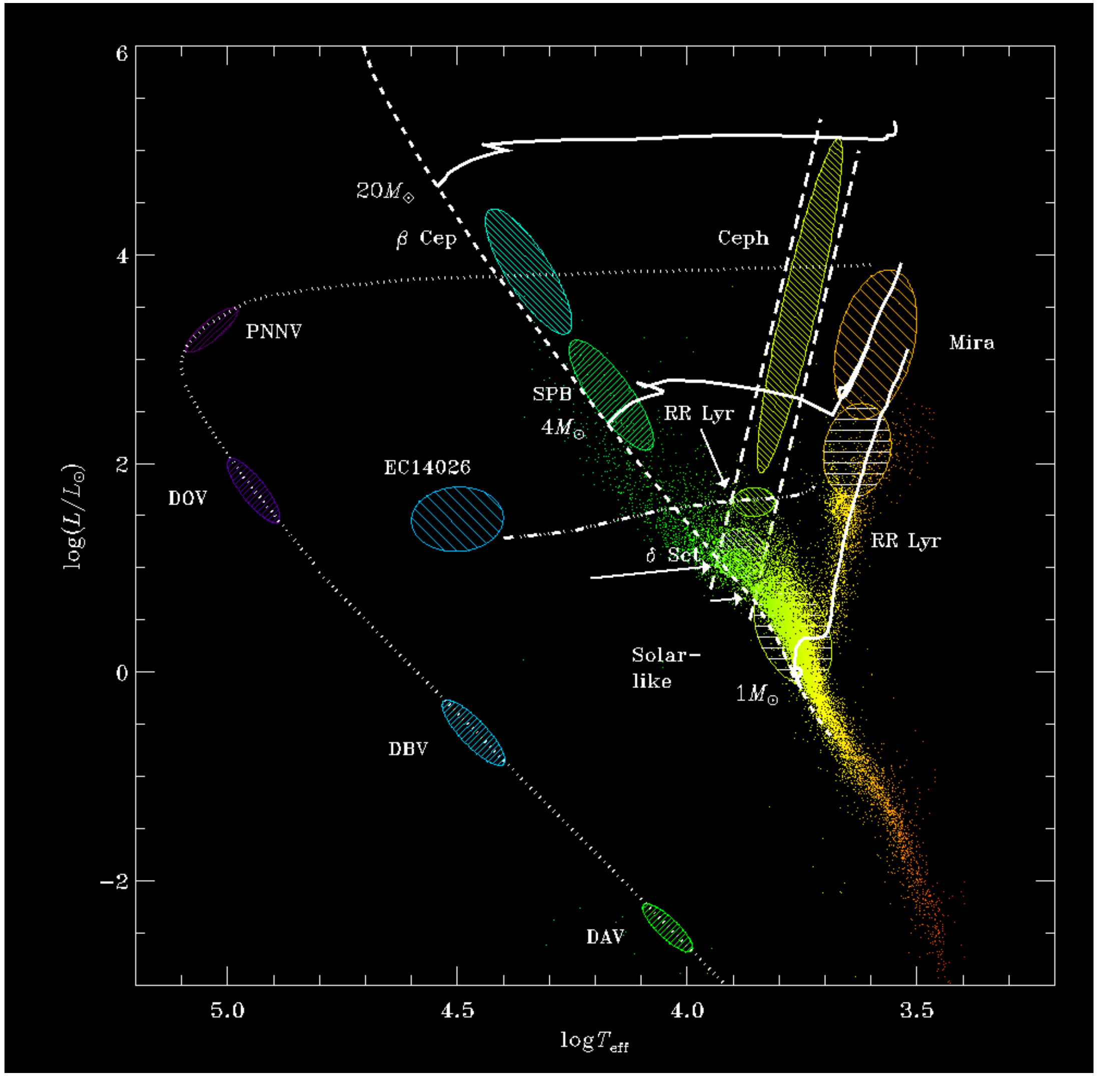
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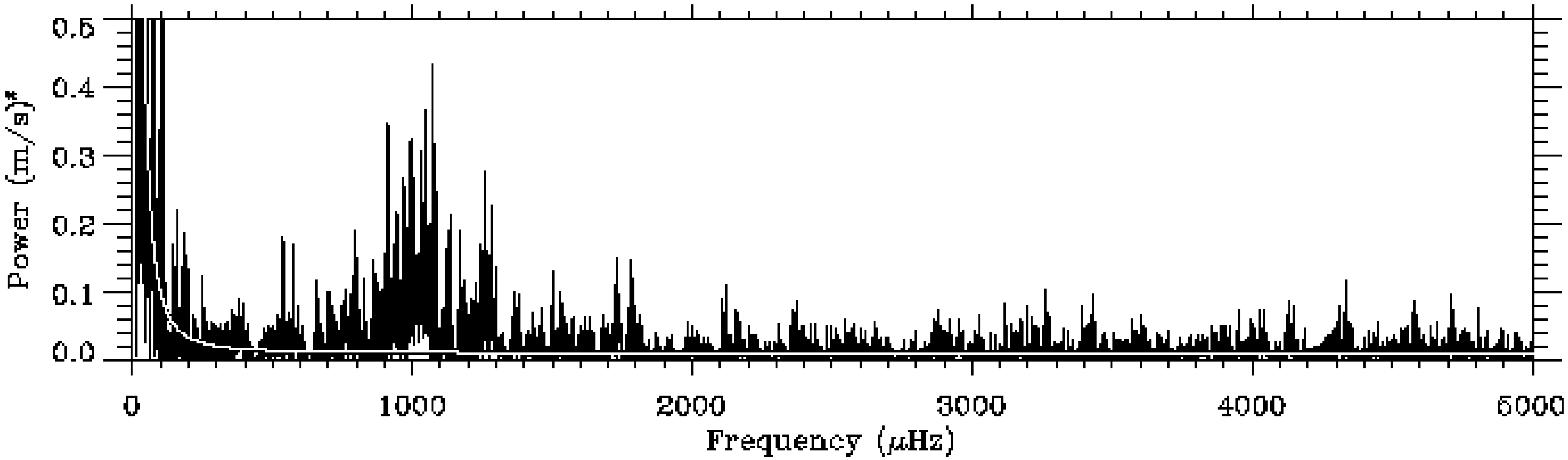
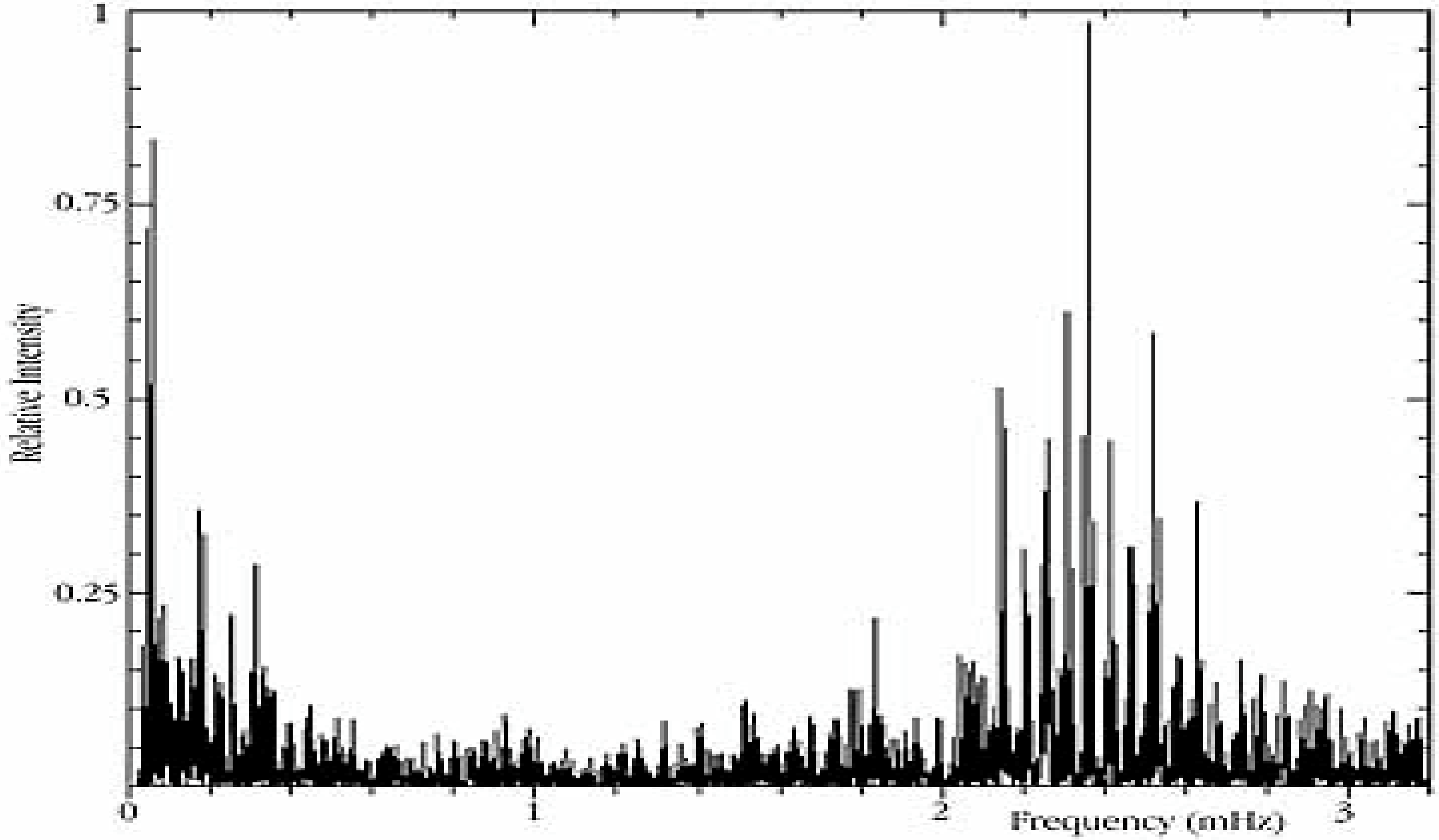


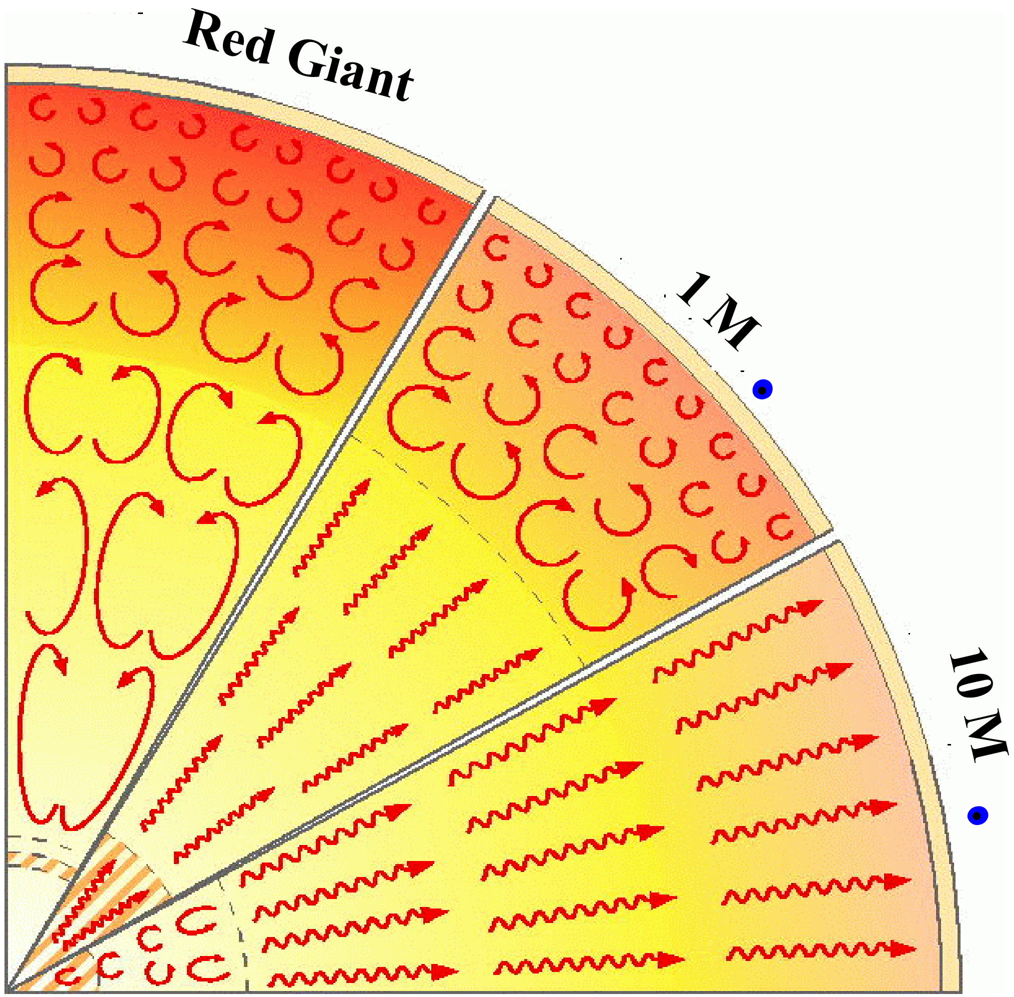
Subgiant with the same temperature as the Sun
Frequency range: between 0.7 and 1.4 milliHertz
Maximum amplitude: 40 cm/s



Acoustic Spectrum of Alpha Centauri A

ESO PR Photo 23b/01 (27 June 2001)

- *28 detected frequencies, in the range 1.8 - 2.9 milliHertz*
- *Amplitudes between 12 and 44 cm/s*
- *Average large separation = 105.5 microHertz*
- *Average small separation = 5.6 microHertz*
- *Star has no convective core, although slightly more massive than the Sun (1.105 solar masses)*

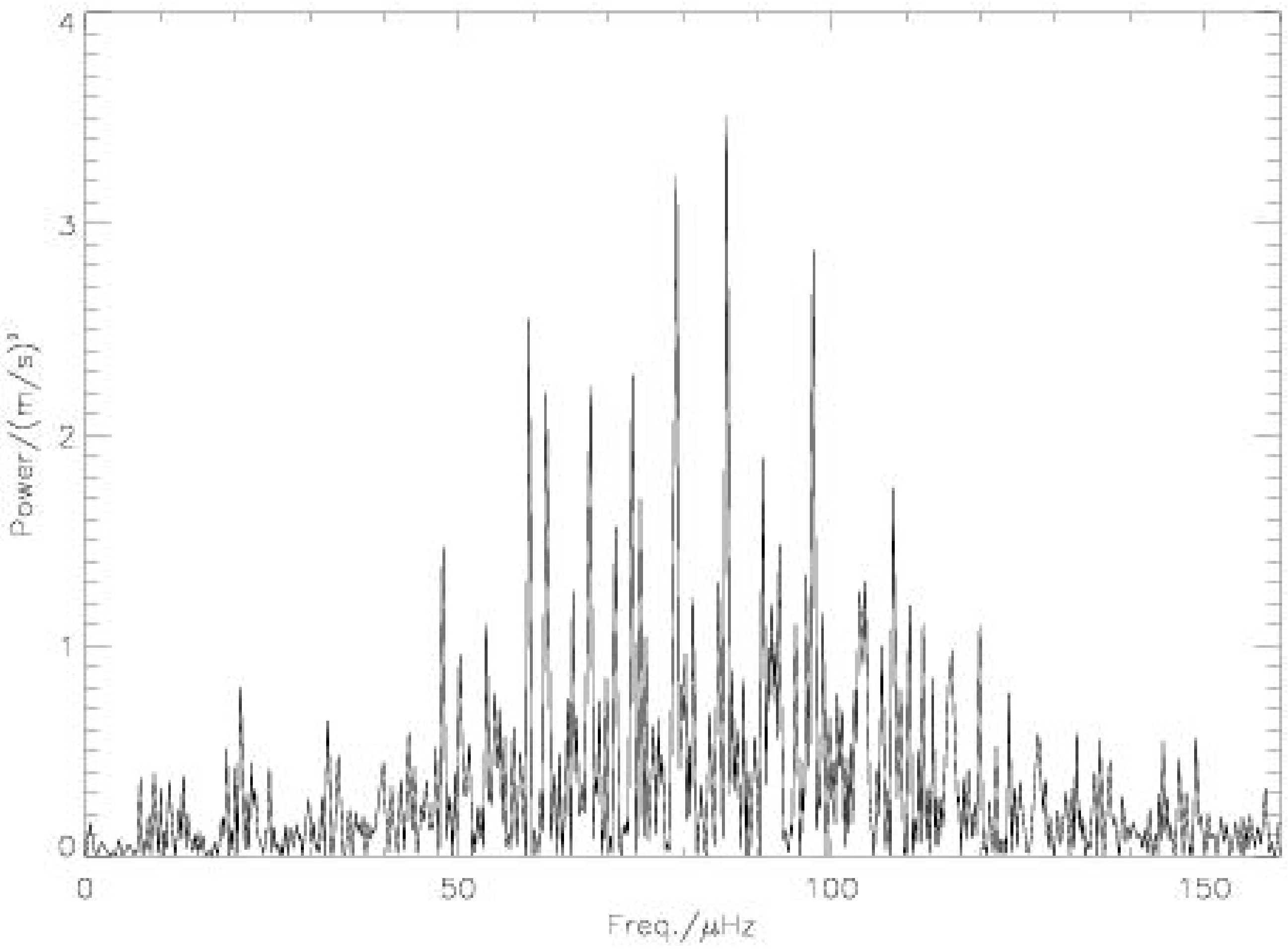

Red Giant
1 M
10 M

- *Existence of solar-like oscillations well established in other stars now, e.g. Beta Hydri, Alpha Cen A*
- *Solar-like oscillations are acoustic non-radial modes excited by the outer convective layers*
- *Also stars evolved off the main-sequence have large convective outer layers: do they have non-radial modes ?*
- *Answer to question is important: if yes, asteroseismology can also be applied in evolved stars with compact cores and large envelopes...*

- *Arcturus (Merline 1999): RV data in the framework of planet search*
- *Alpha Uma, brightness variations with WIRE (Busazi et al. 2000)*
  - Problems

    Detections are controversial

    Theoretical models do not predict modes at these frequencies...
- *Our attempt: use Swiss Euler Telescope with CORALIE to observe the G7 giant Xi Hya*
  - 433 spectra during one month taken by European team: Aarhus (DK), Leuven (B), Geneva (CH)
  - Use cross-correlation technique to obtain accurate RV data



Power/((m/s)²)
Freq./μHz
0
1
2
3
4
0
50
100
150

- *CORALIE on 1.2m Swiss Euler telescope: Xi Hya*
  - G7III giant, 11 solar radii, Teff=4950 K
  - 433 echelle spectra spanning 1 month
  - Use cross-correlation technique to derive accurate RV
  - Detection of some 12 oscillation frequencies :

    Main frequency is 87 microHz

    All frequencies between 40 and 130 microHz

    Amplitudes between 1.5 - 0.9 m/s
  - Theoretical models DO predict modes at these frequencies
  - Frequency separation of some 6.8 microHz ??

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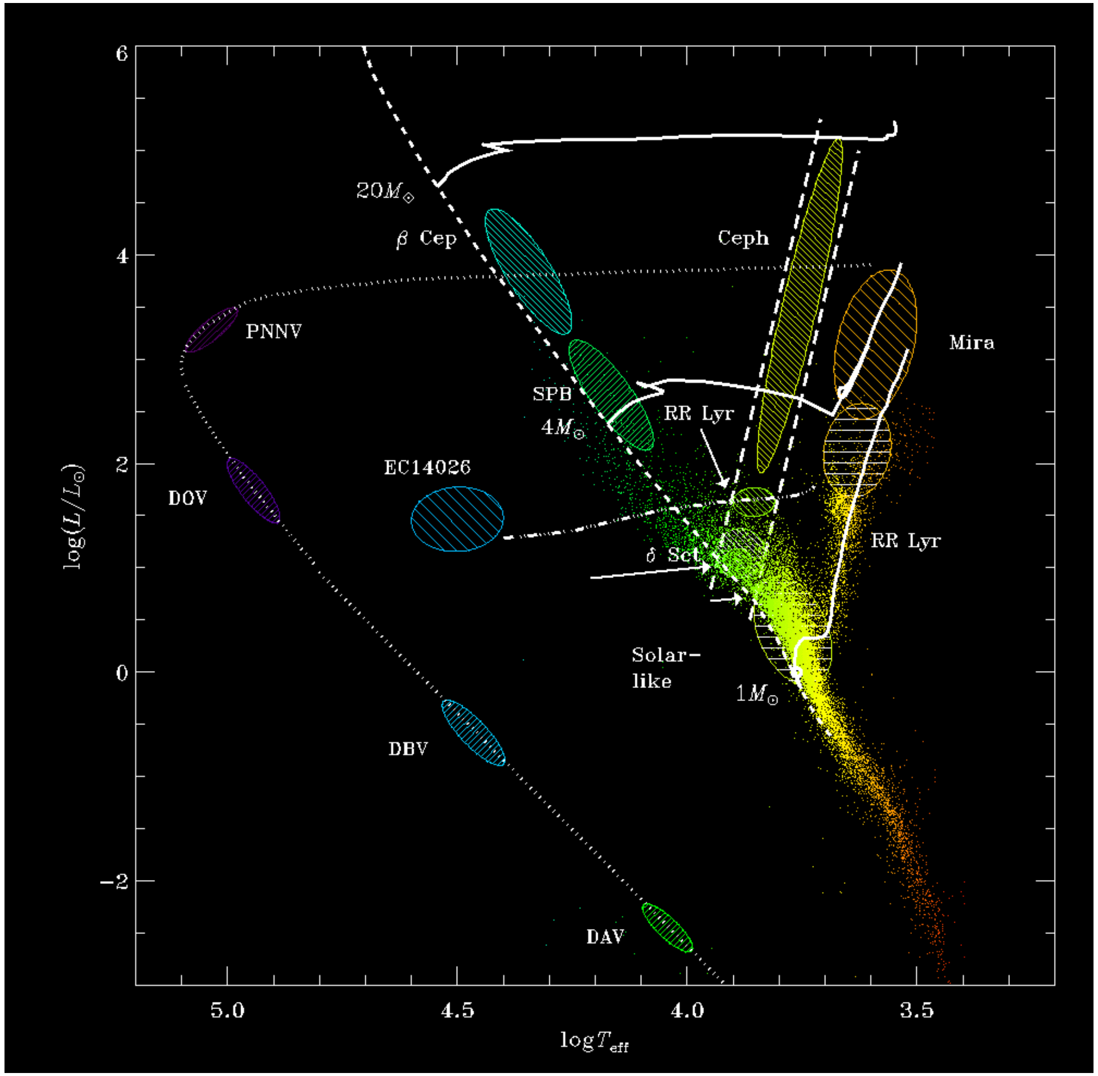

20M⊙
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log T_eff
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4.5
4.0
3.5

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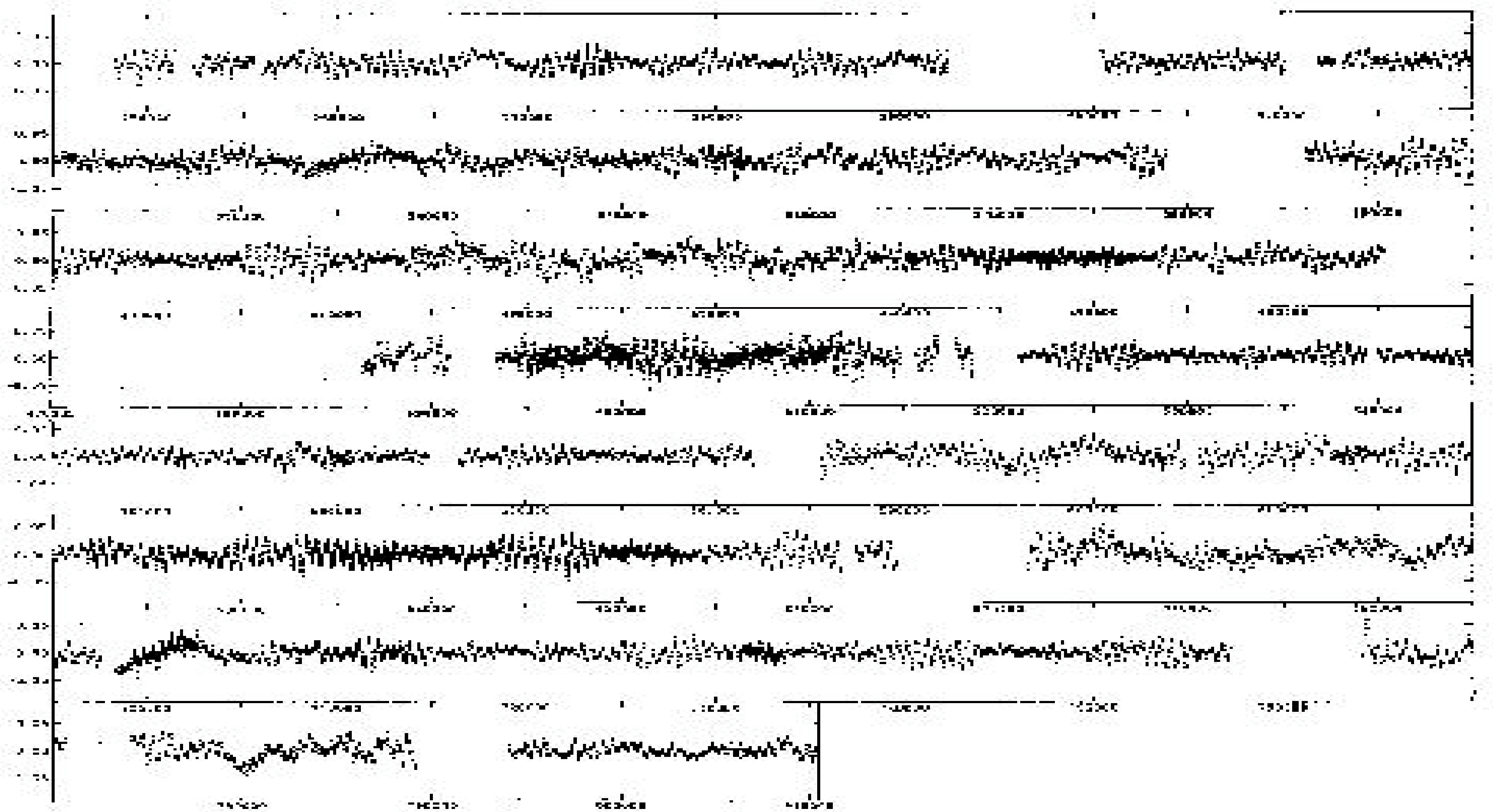
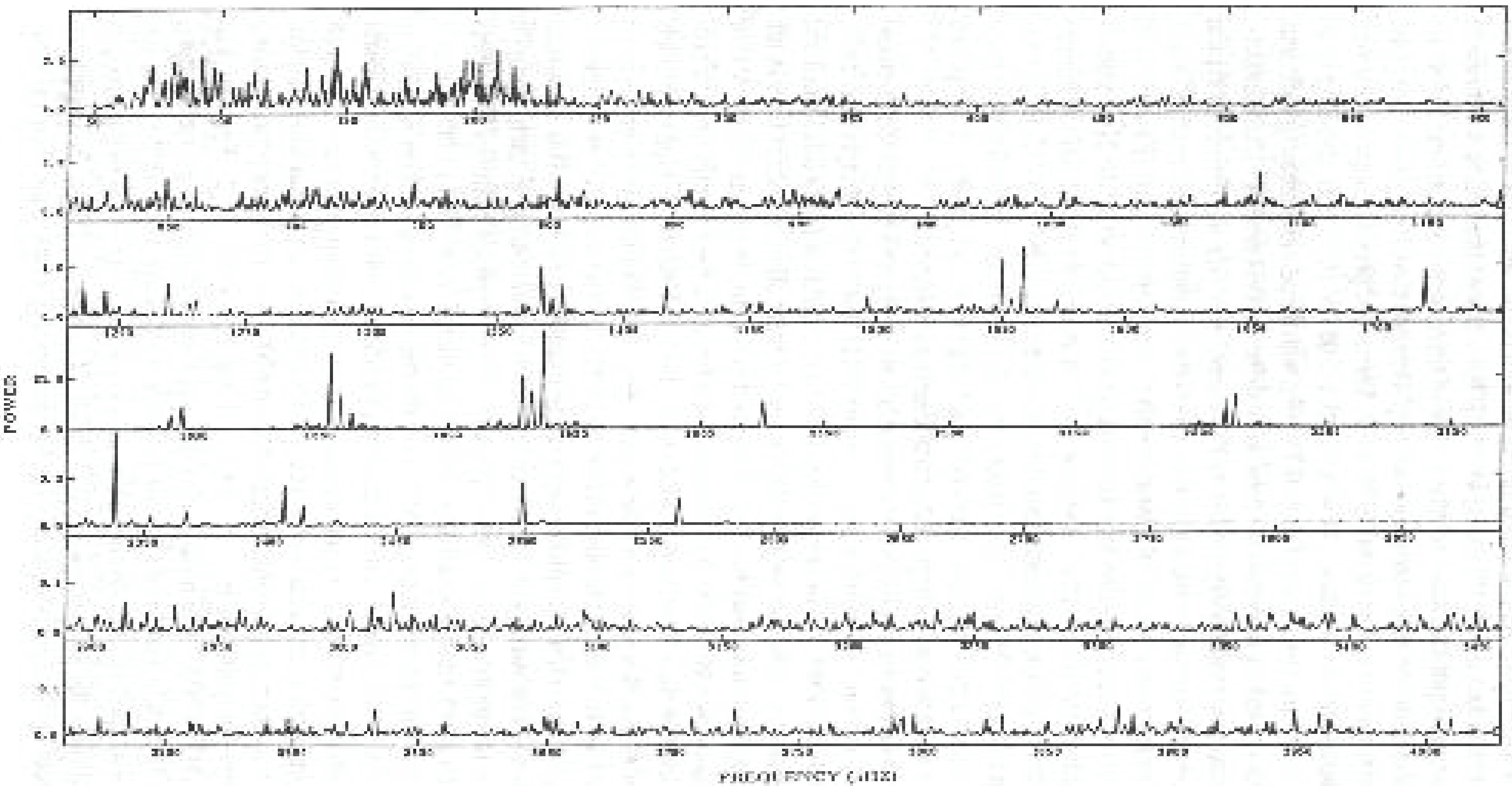
- *Successful since PG1159-035 (Winget et al. 1991)*
- *White dwarfs have multiple gravity modes with periods of the order of minutes, hence beat-periods of weeks*
- *Whole Earth Telescope played key-rôle for seismic studies*
- *Example shown is representative*




POWER

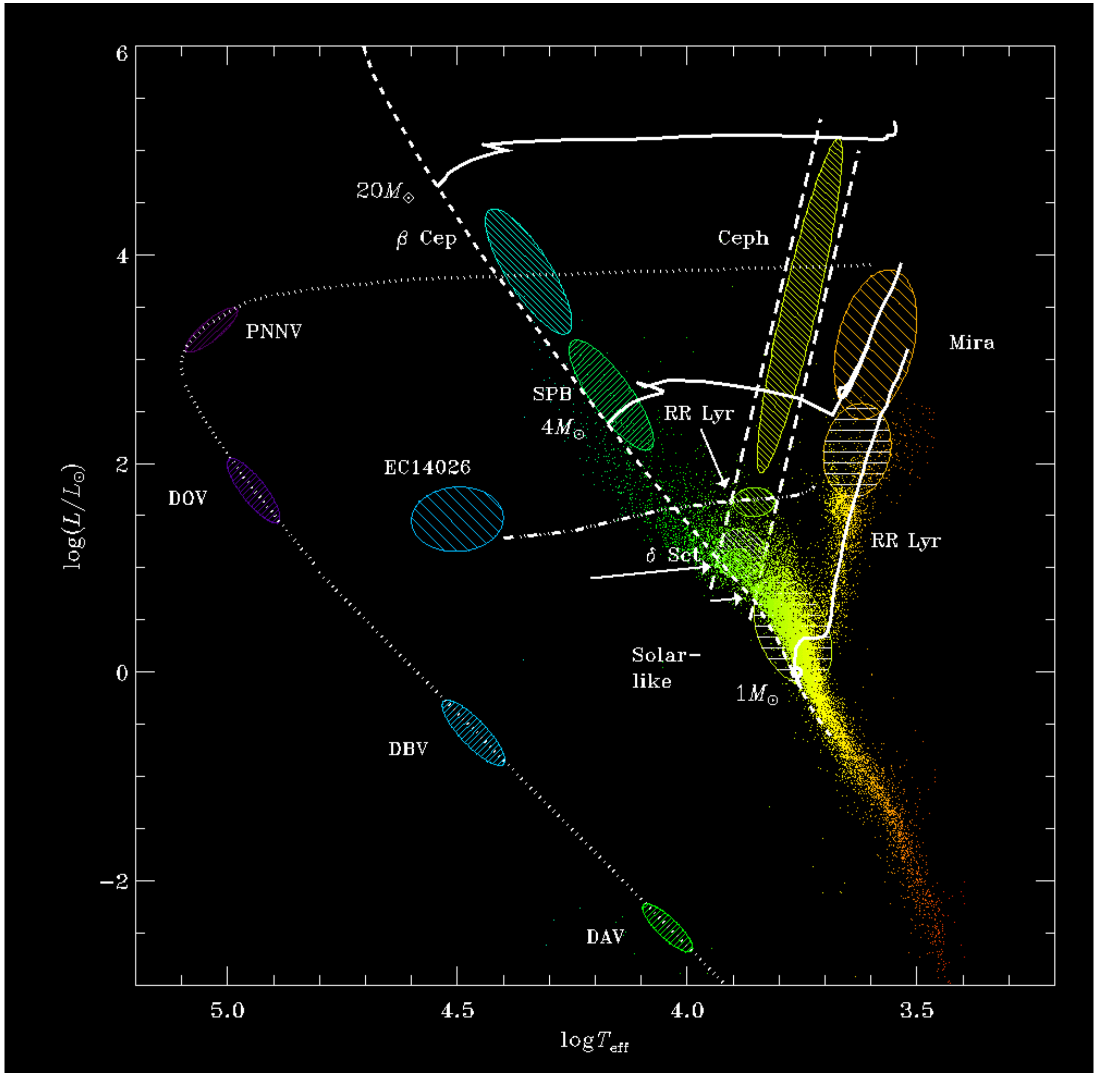
$$\Pi_{n\ell} \simeq \frac{\Pi_0}{\sqrt{\ell(\ell+1)}}\left(n + \frac{\ell}{2} + \varepsilon\right);$$

$$\Pi_0 = (2\pi)^2 \left(\int_0^R \frac{N(r)}{r} dr\right)^{-1};$$

$$N^2(r) \equiv \left(\frac{d \ln \rho}{dr} - \frac{1}{\Gamma_1}\frac{d \ln P}{dr}\right) g$$

UVEN

- *122 frequencies detected for PG1159-035*
- *Main frequency = 1938 microHz (516 seconds)*
- *Frequency triplets and quintuplets*
- *Period separation = 21.1 seconds*
- *Separation in triplets = 21.5 seconds*
- *Separation in quintuplets = 12.5 seconds*
- *Mass = 0.586 solar masses*
- *Only 3-layer model H/He/C can reproduce data*



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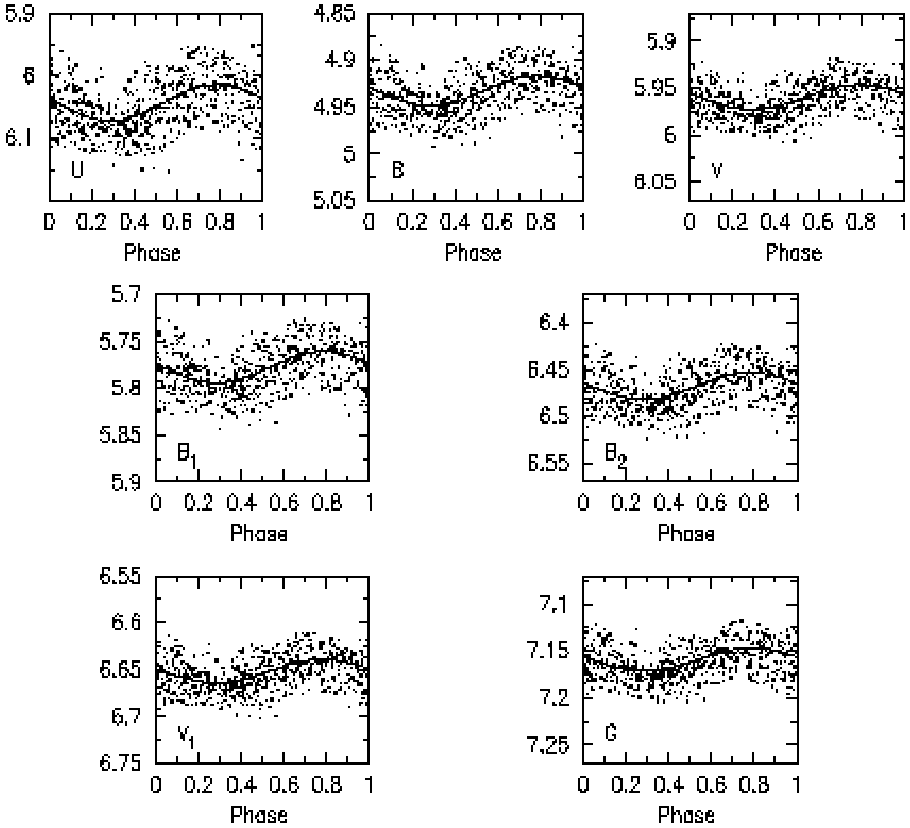
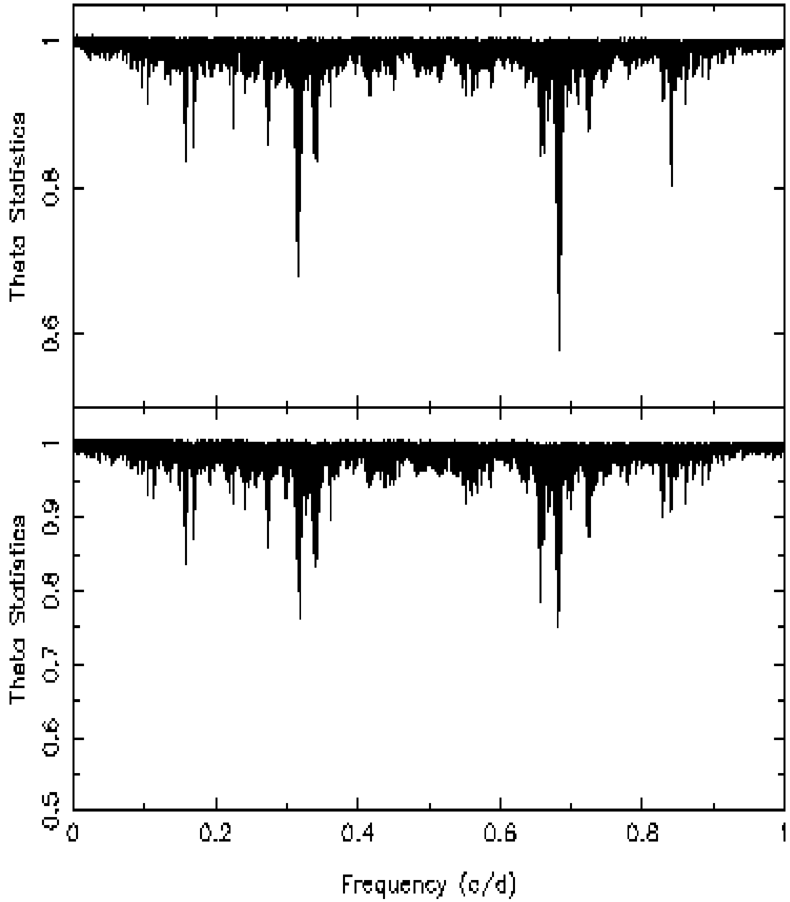
- ***Pulsating stars along the main sequence: gamma Dor, delta Scuti, Beta Cep, SPB***
- ***Main problems:***
  - **detection of sufficient amount of modes**
  - **mode identification (not in asymptotic regime !)**
  - **daily aliases and long beat periods**
- ***Solutions:***
  - **very accurate line-profile variation studies**
  - **Measurements from space**

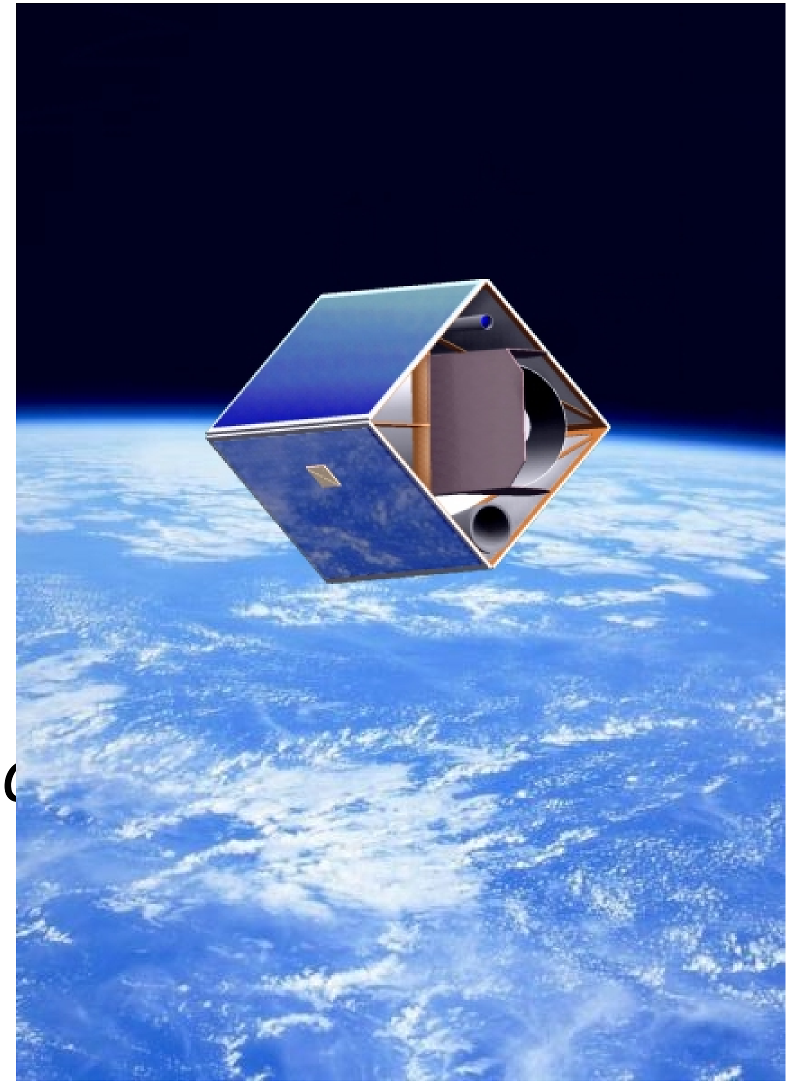

U
B
V
B1
B2
V1
G
Phase


Theta Statistics
Frequency (c/d)

Danish mission onboard the satellite Rømer
- main telescope (34cm)
- 2 star trackers
- 1 field monitor

Prime time: mainly devoted to solar-type stars, but also some B-A-F-stars, measured during 1 month

Launch: 2005, operations 2 years



French-European mission.
Main telescope (27cm)

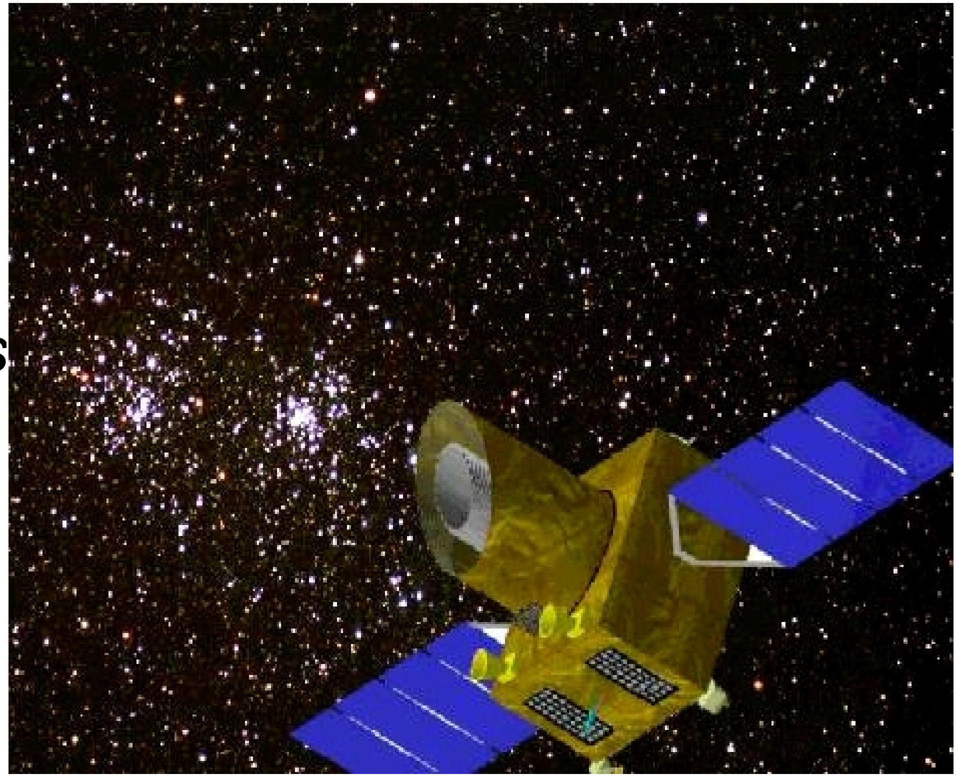
Prime time is divided between asteroseismology of 50 stars and planet search around 30000 stars

Each field is followed during 5 months

Laucnh: 2005, duration 2,5 years

Same basic idea as COROT but 4 telescopes (60cm)

- Asteroseismology of thousands of stars, including stars in old and young clusters
- Planet finding for several 100000 stars



Each field followed during 1-several months

Launch: 2007/8, operations 5 years