Asteroseismology

Conny Aerts

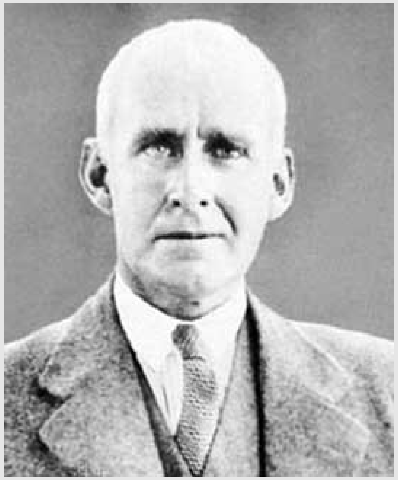
Universities of Leuven and Nijmegen

Material: Springer Monograph, 2010

FAMIAS software package (W. Zima)

Sir Arthur Stanley Eddington:
The Internal Constitution of the Stars
1926

Sir Arthur Eddington
(1882 – 1944)

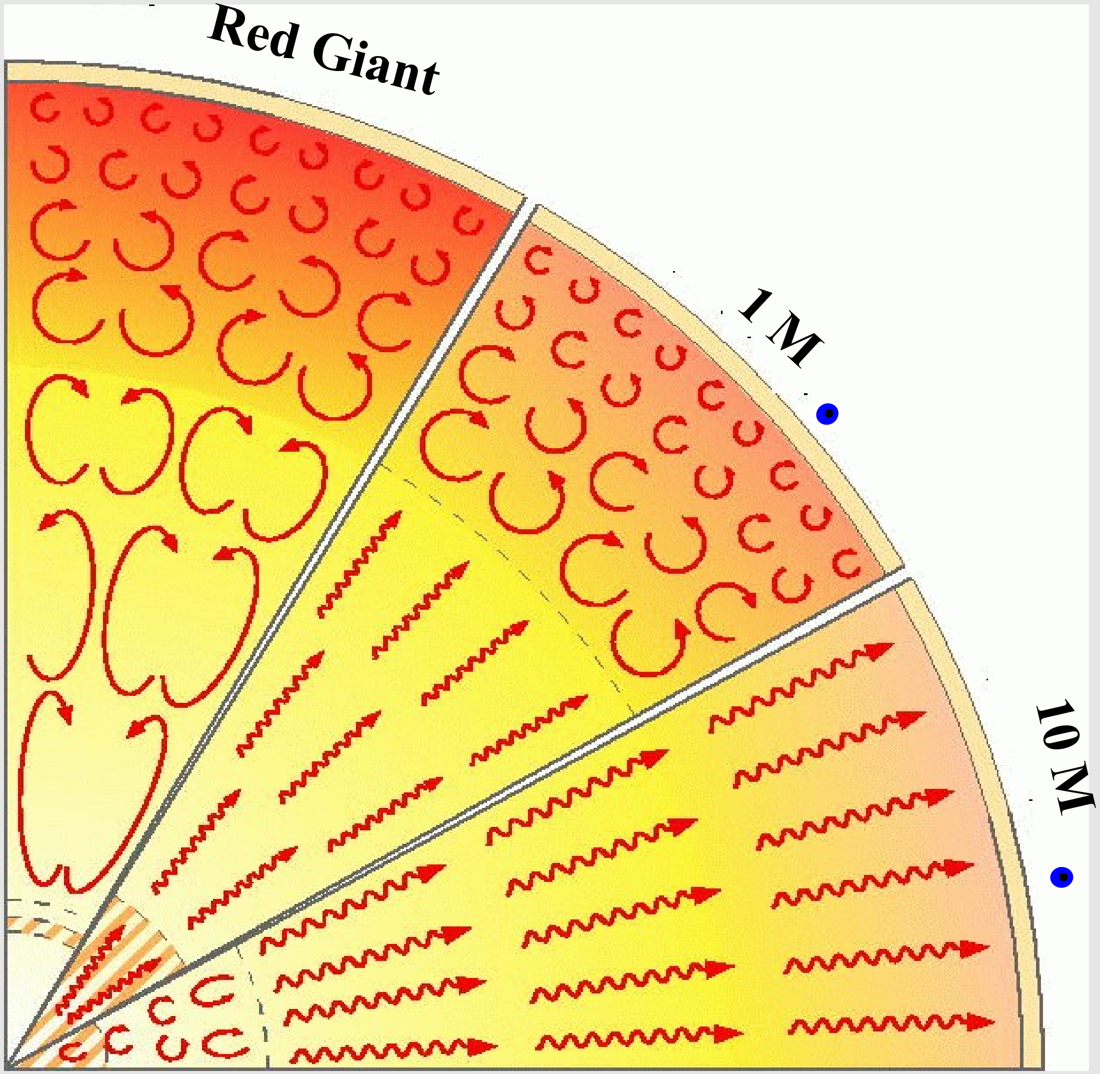


At first sight it would seem that the deep interior of the sun and stars is less accessible to scientific investigation than any other region of the universe.

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 behind substantial barriers?

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

Large variation of internal structure



We need to do much better than this !

Motivation: the crucial rôle of stars

- *Stars are the sources of the chemical evolution of the Universe:*
  - *Massive stars synthesize elements H => Fe*
  - *Stars with moderate masses form C, N, O*
  - *Chemical evolution strongly dependent on internal mixing processes*
- *Stars are local memory of history of Universe and allow to estimate its age*

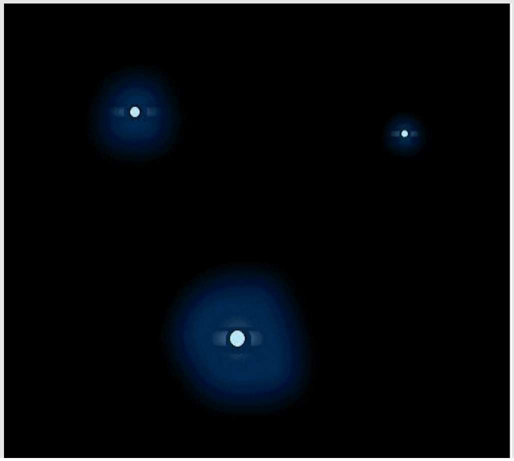
Present unknowns in stellar modelling

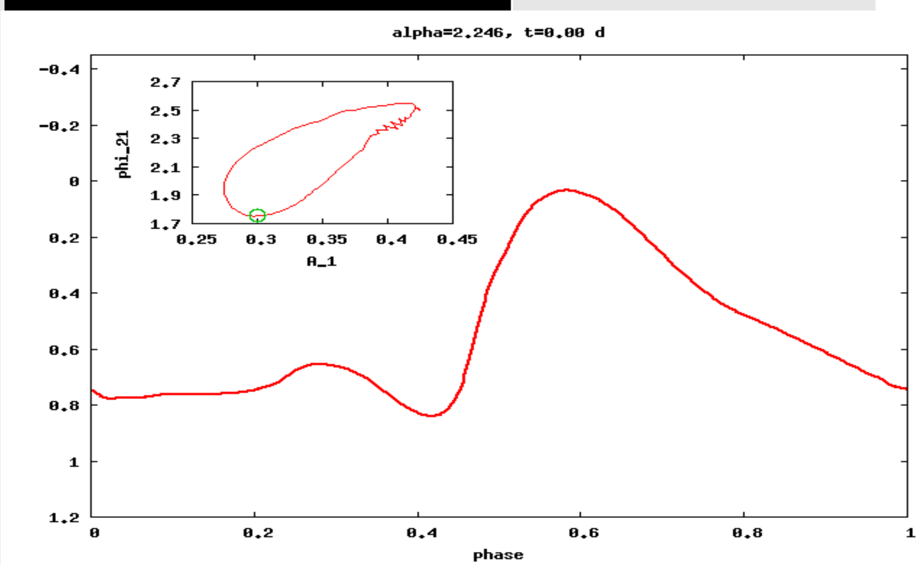
- ***Effect of (differential) internal rotation?***
- ***Effect of convective overshooting ? => how does mixing occur inside the stars ?***
- ***Preamble of supernova explosion ?***
- ***Evolution of close binary systems ?***

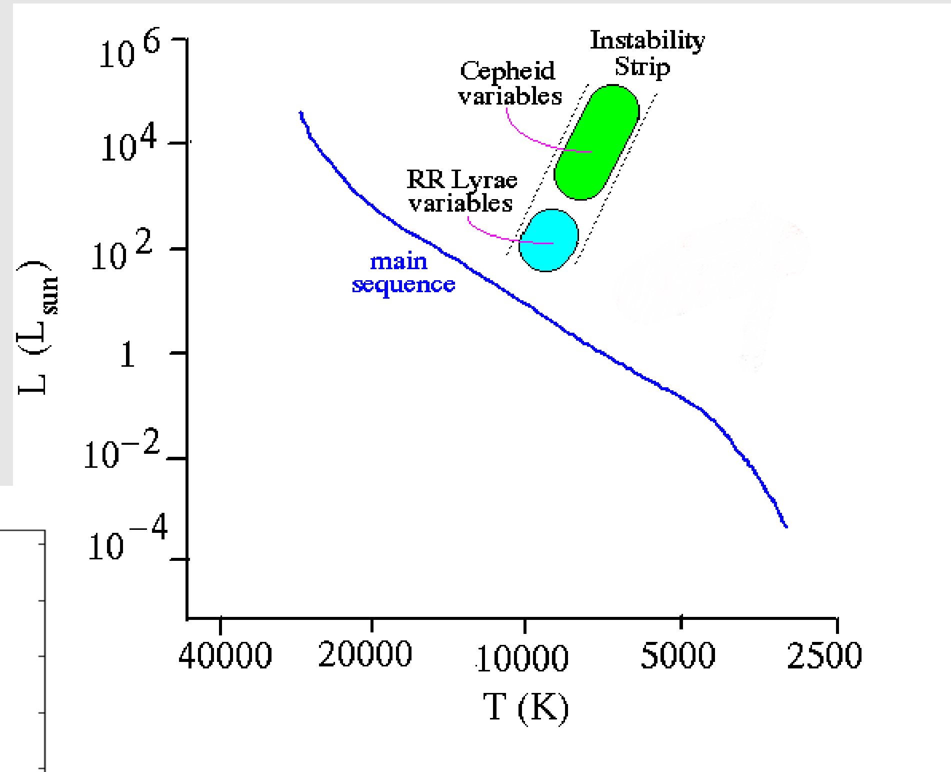
Asteroseismology will imply major steps forward in answering these questions

History of the research topic

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







History of the research topic

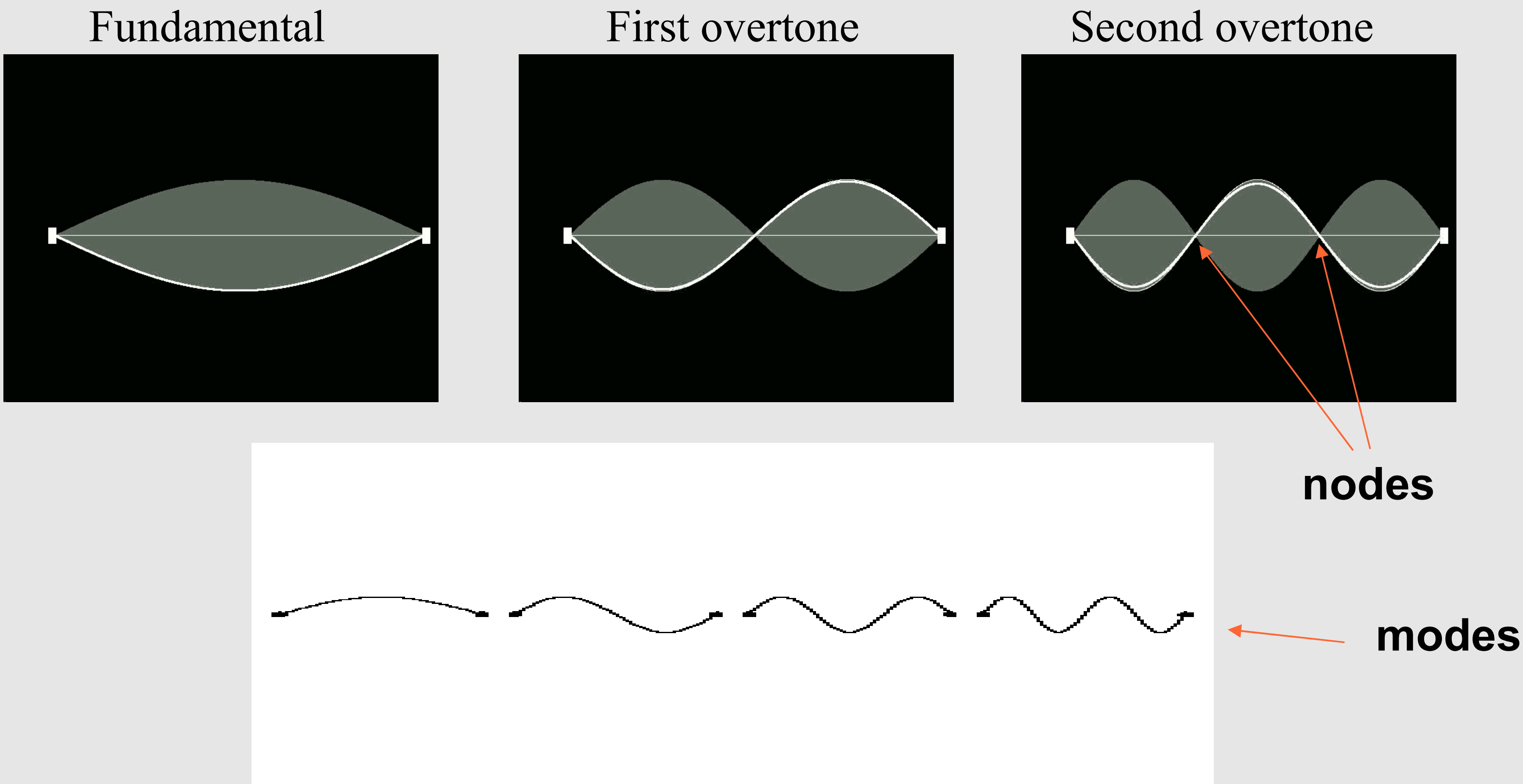
- *Periodic large-amplitue variables known since long, e.g. Cepheids, RR Lyraes*
- *Multiperiodicity at low amplitude found in many different kinds of variables*
- *Cause: non-radial oscillations*
- *Idea: every body 'sounds' according to its internal structure => the different oscillation frequencies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

Introduction into asteroseismology

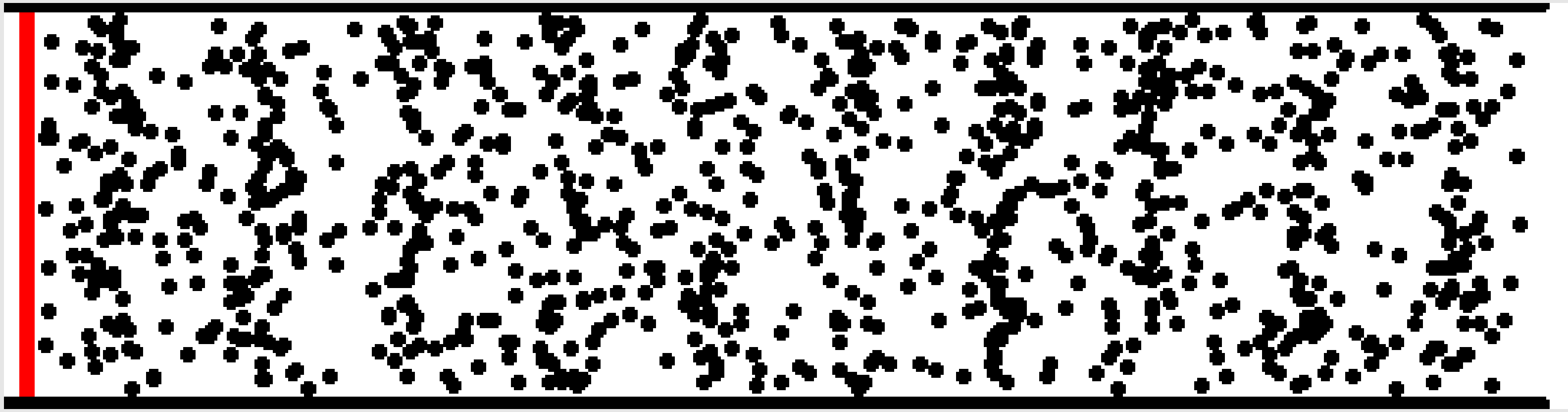
aster: star
seismos: oscillation
logos: discours, reasoning

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

1-dimensional oscillations



pressure modes

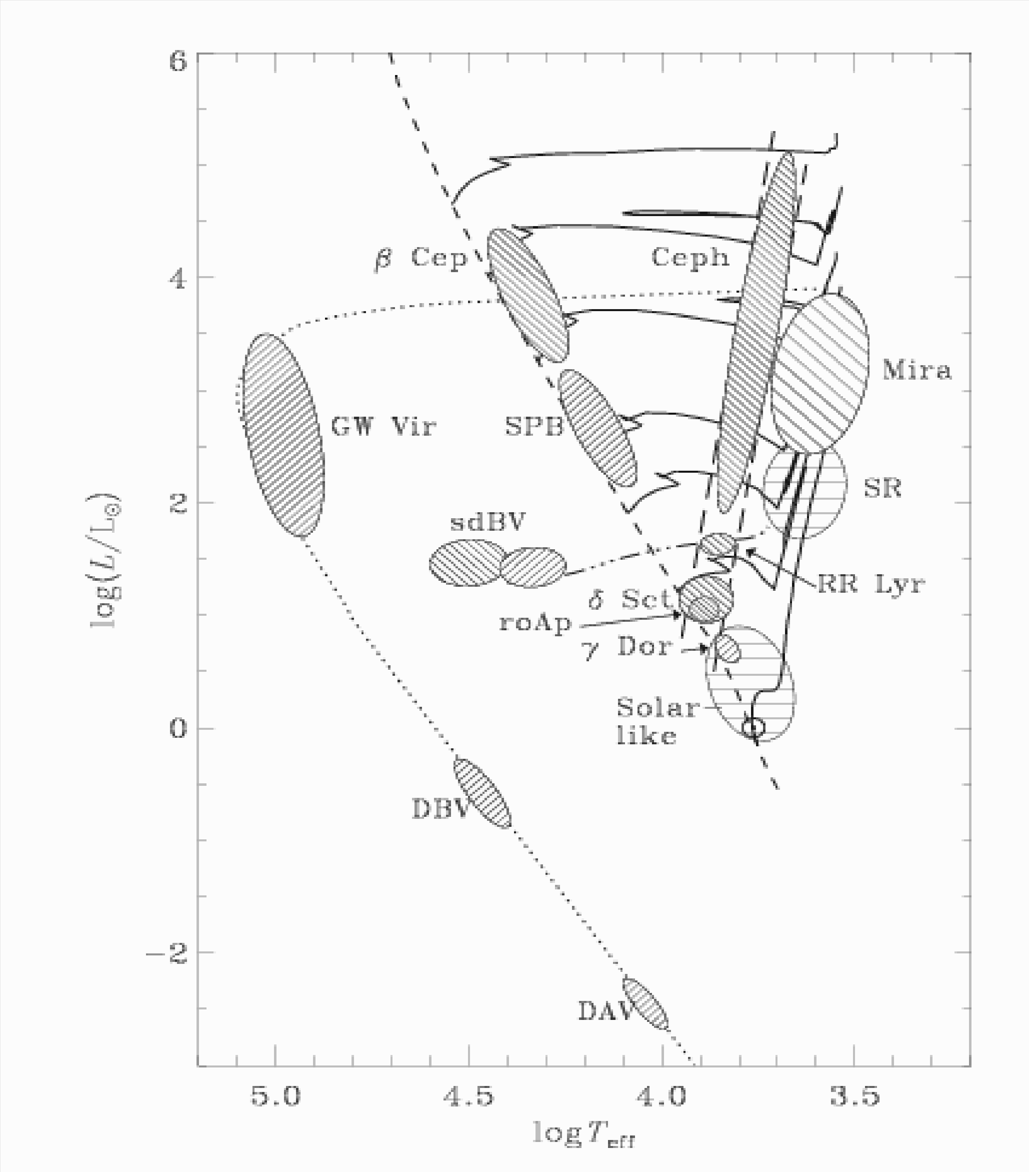


- *More frequent collisions = faster sound speed*
  - *Higher temperature = faster sound speed*
  - *Higher density = faster sound speed*
  - *Lighter gases = faster sound speed*

Why do stars oscillate ?

- ***Because they have convective outer layers which cause stochastic excitation of oscillations (cf. gong)***
- ***Because some outer layers act as a heat engine: partial ionisation zones absorb and accumulate energy generated in the stellar interior (opacity mechanism)***
- ***Forced oscillations may occur due to tidal effects in close binaries***

Pulsating stars are everywhere



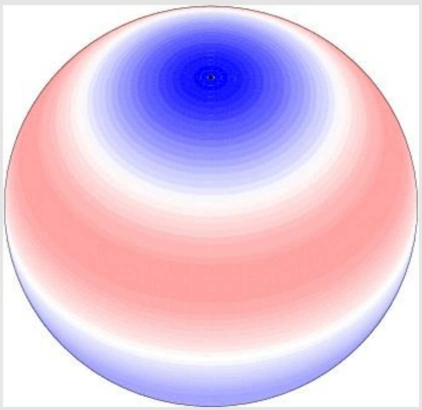
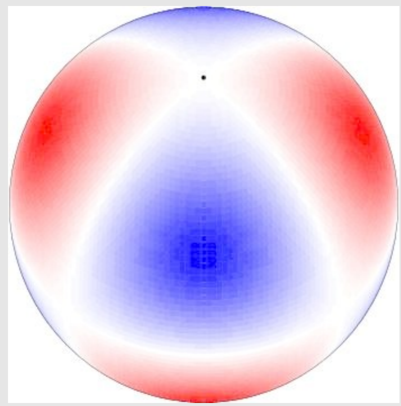
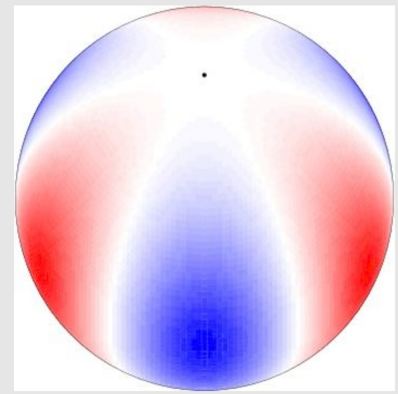
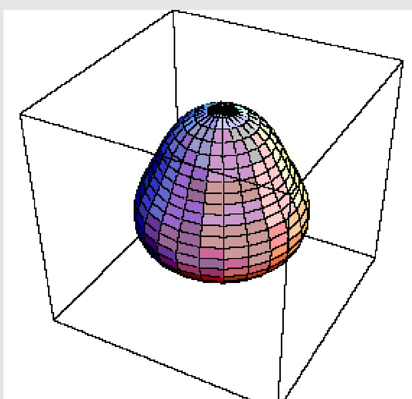
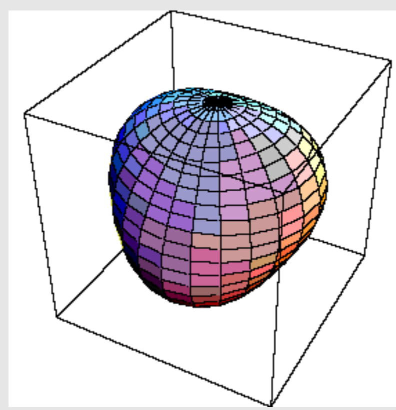
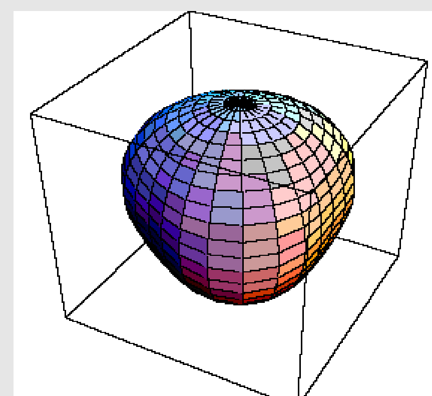
Characterization of non-radial modes

(l,m)=(3,0)
axisymmetric

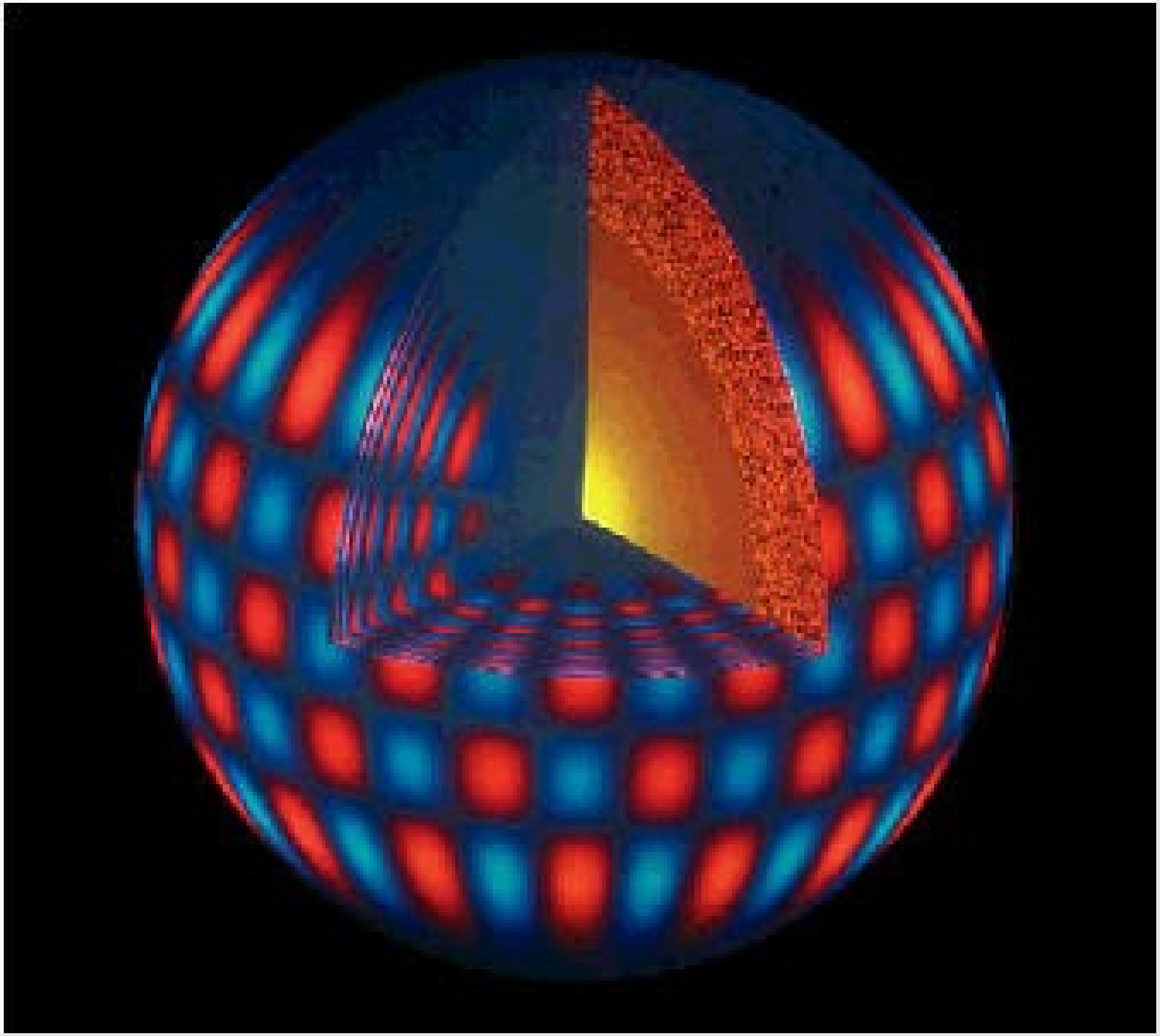
(l,m) = (3,2)
tesseral

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

Blue : Moving towards Observer
Red : Moving away from Observer

Internal behaviour of the oscillations



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.

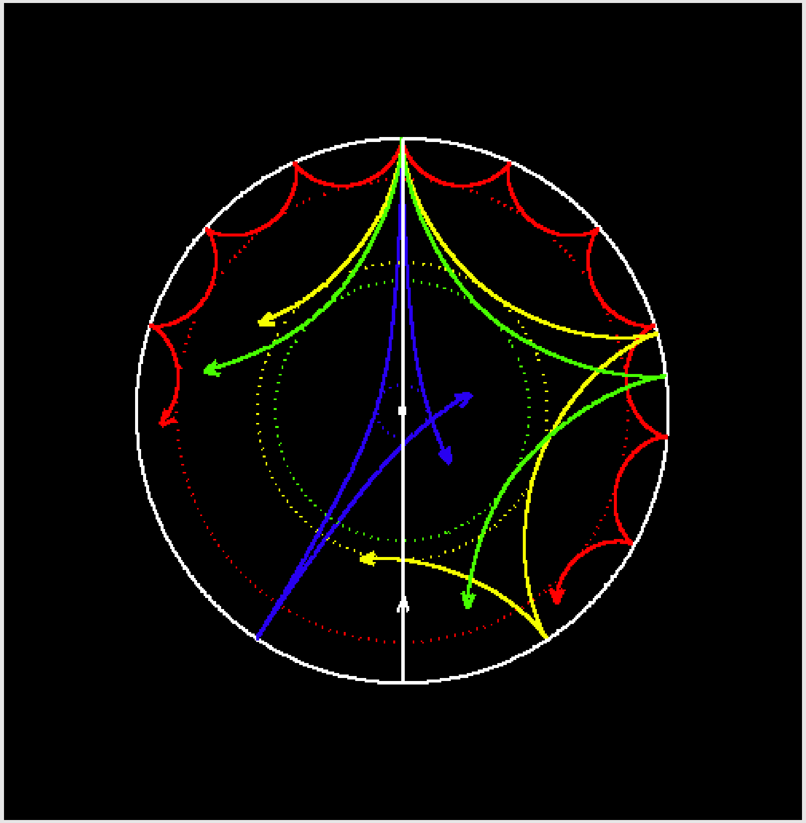
Theoretical description of oscillations

- *Perturbation of mass, momentum and energy conservation*
- *Solutions ~ exp ($2\pi i\, t\, f$) can be found, with f the oscillation frequency of one mode*
- *Velocity vector ~ spherical harmonic, consisting of Legendre polynomial with wavenumbers (l,m)*
- *Limit of large or small frequency: pressure and gravity modes*

Inversion of the frequencies

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

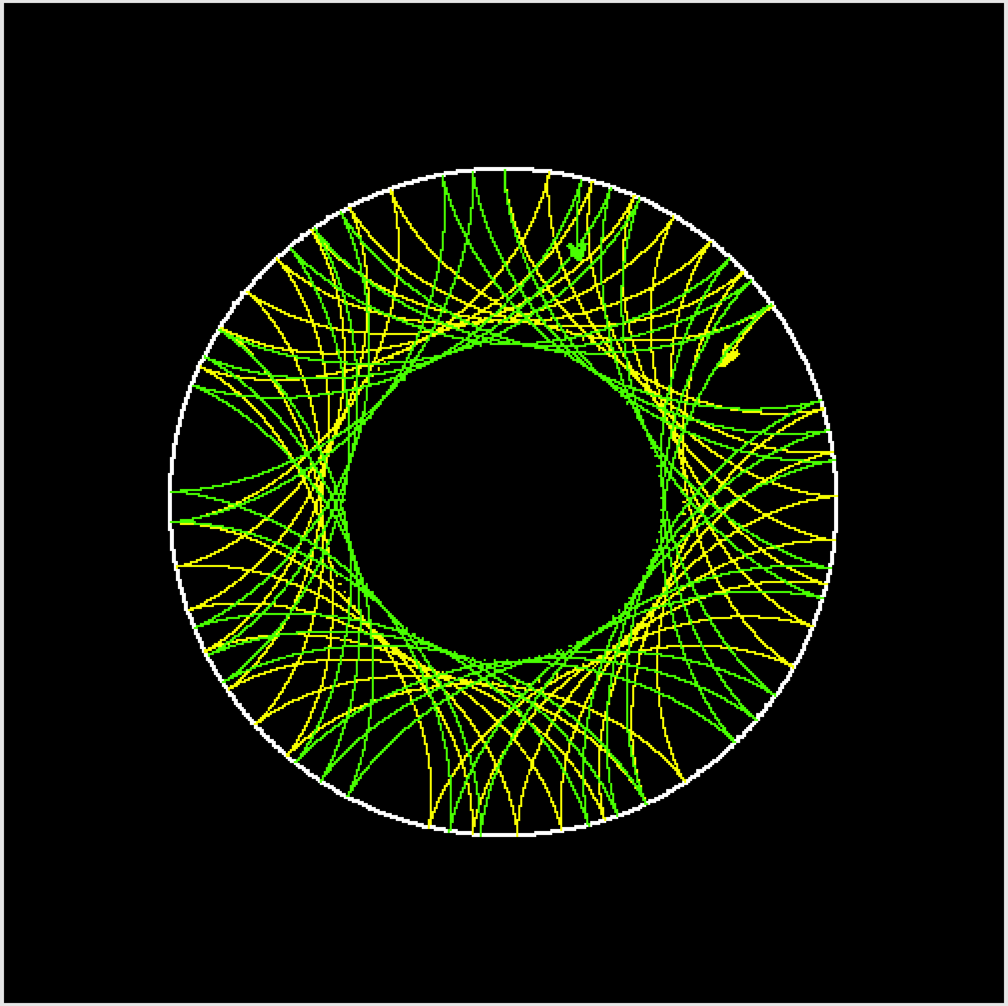
Different oscillations penetrate to different depths and hence probe different layers



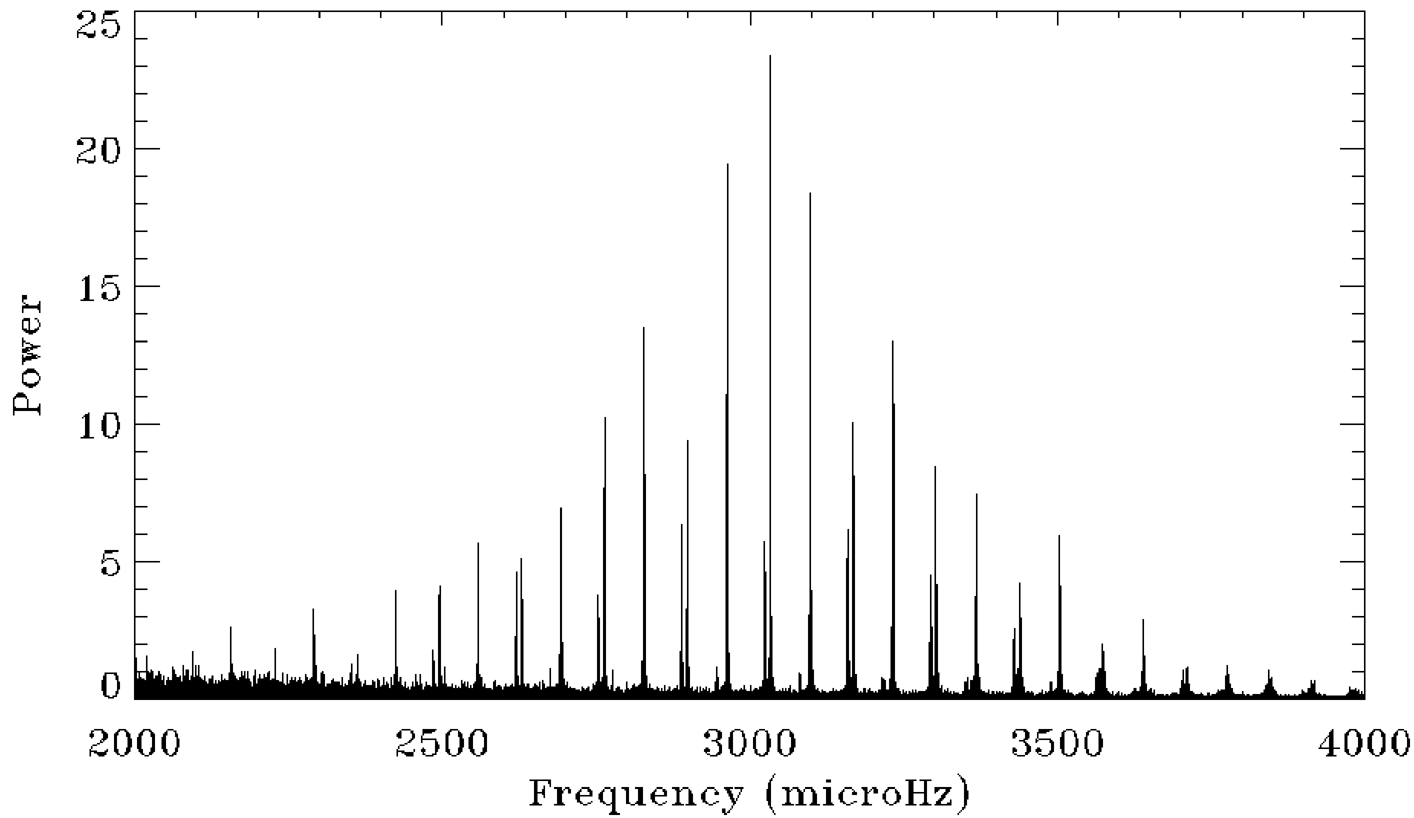
Modes with almost equal frequency

Green and yellow oscillations probe almost same region

Such oscillations allow to map the mixing processes layer by layer

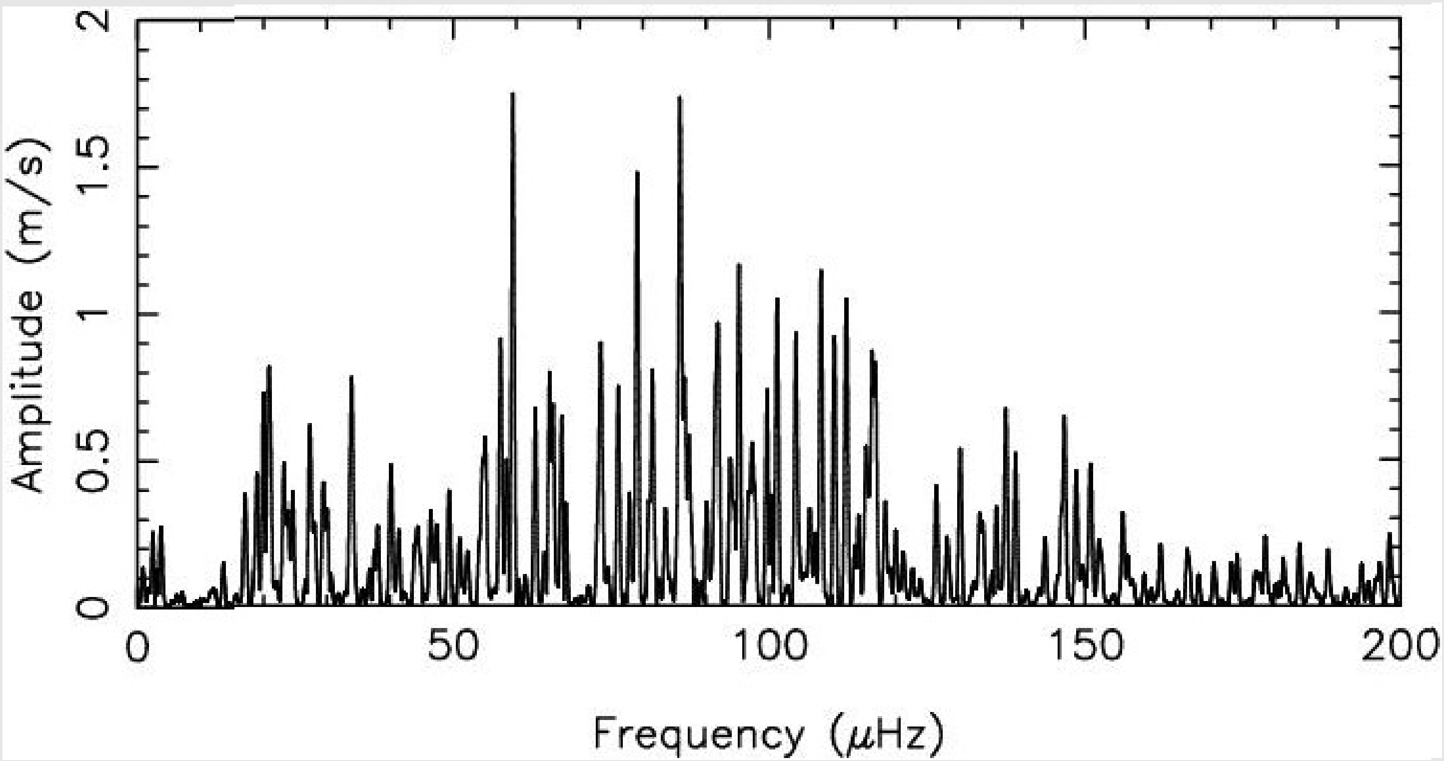


Solar frequency spectrum from ESA/NASA satellite SoHO: systematics !



Musical Intermezzo: Symphony of the Sun

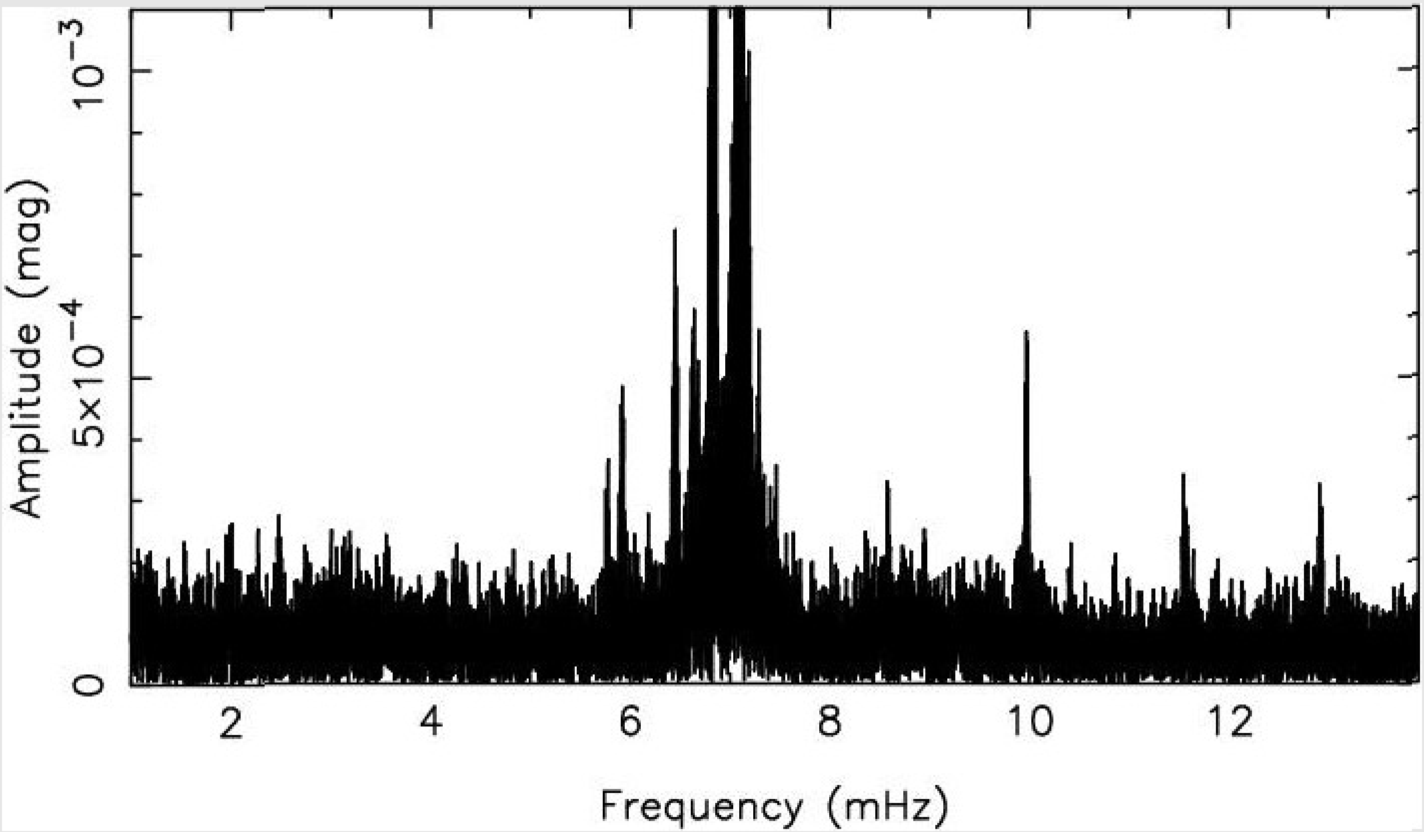
Frequencies of a red giant star



1 month RV data of Xi Hya (2002, 1.2m Euler)

Musical Intermezzo:
Symphony of a red giant

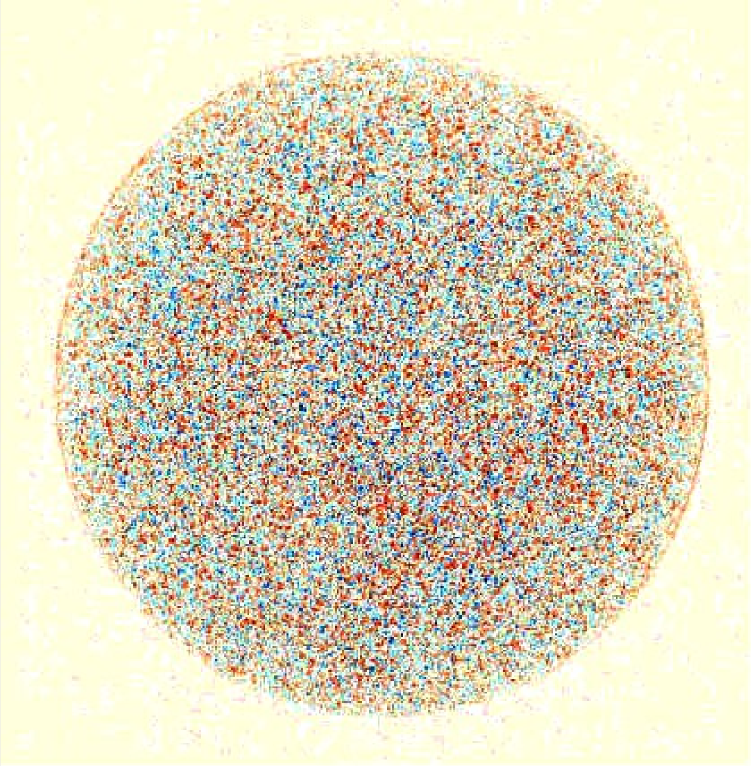
Frequencies of an sdB star



6 nights of data of PG0014+067 (2004, 4.2m WHT)

Musical Intermezzo: Symphony of PG0014+067

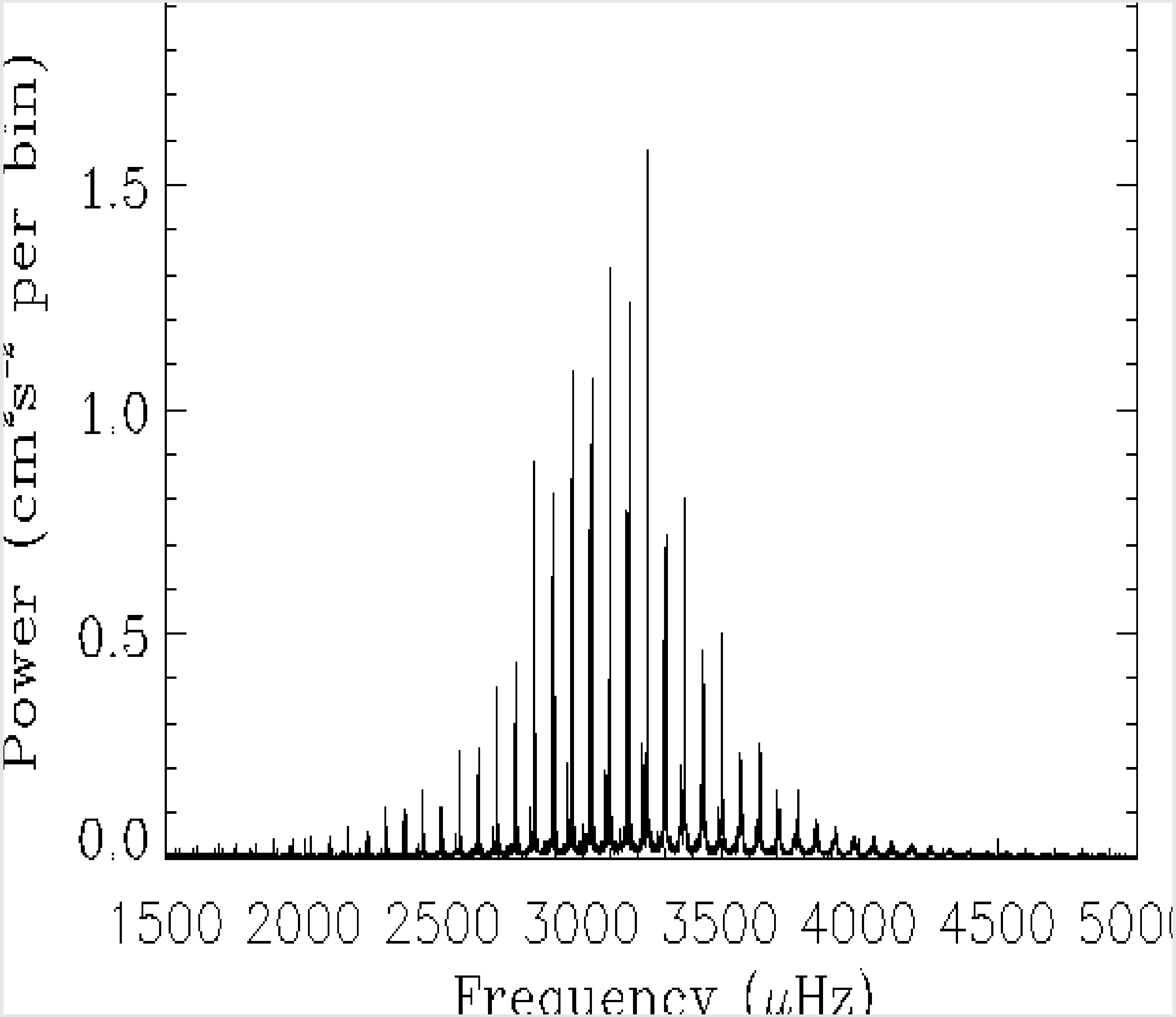
Dopplermap of the Sun



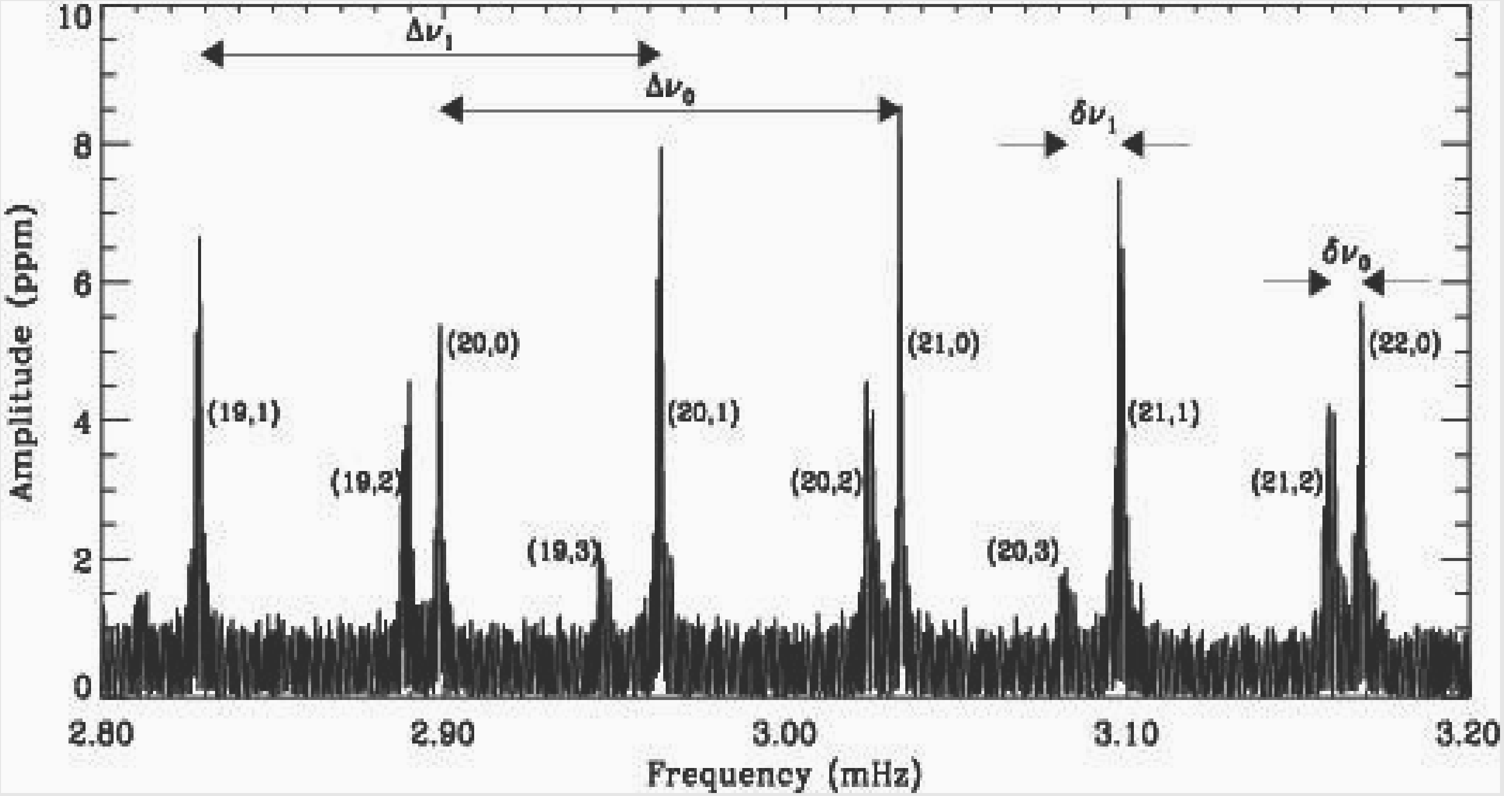
The Sun oscillates in thousands of non-radial modes with periods of ~5 minutes

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

The sun as a star - BiSON



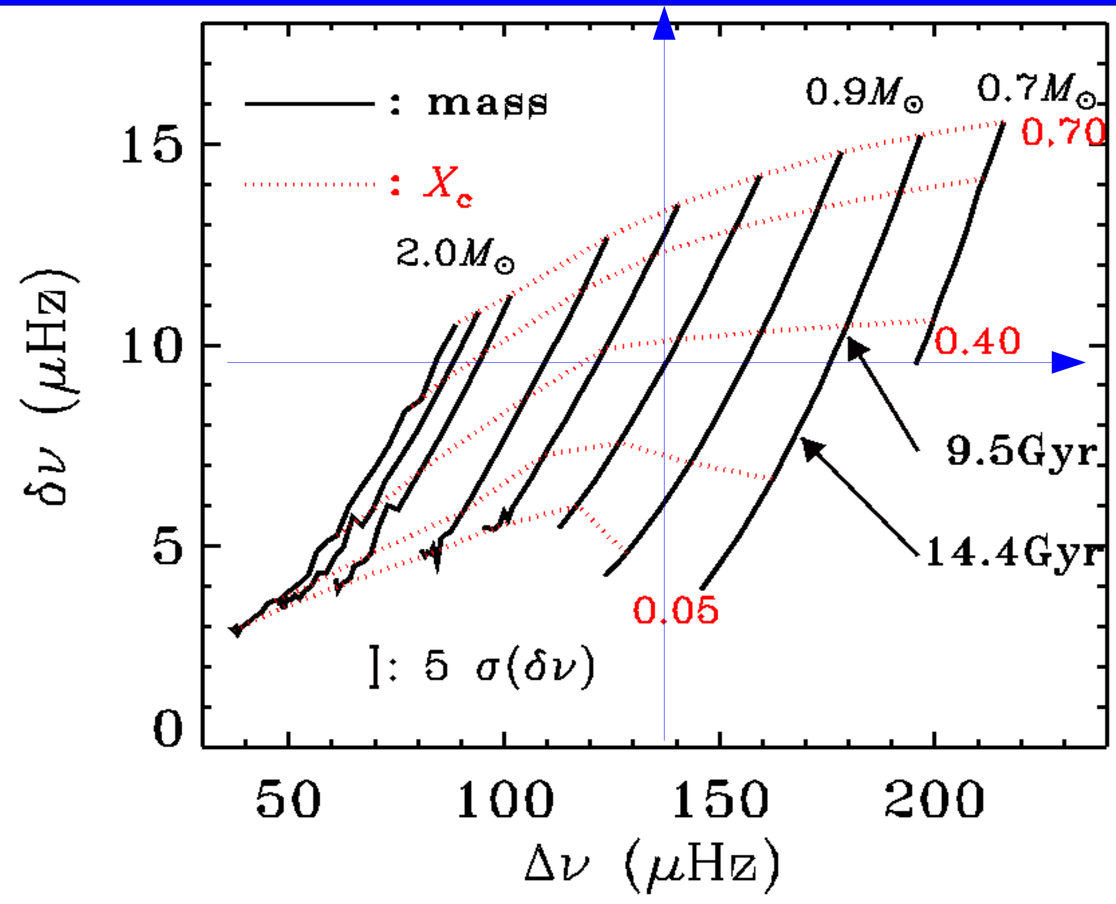
Frequency separations in the Sun



Result: internal sound speed and internal rotation could be determined very accurately by means of helioseismic data (SoHO, BiSON, GONG)

Asteroseismic HR (JCD) diagram

Large frequency separation: measure of sound speed
Small frequency separation: measure of discontinuities in the sound speed



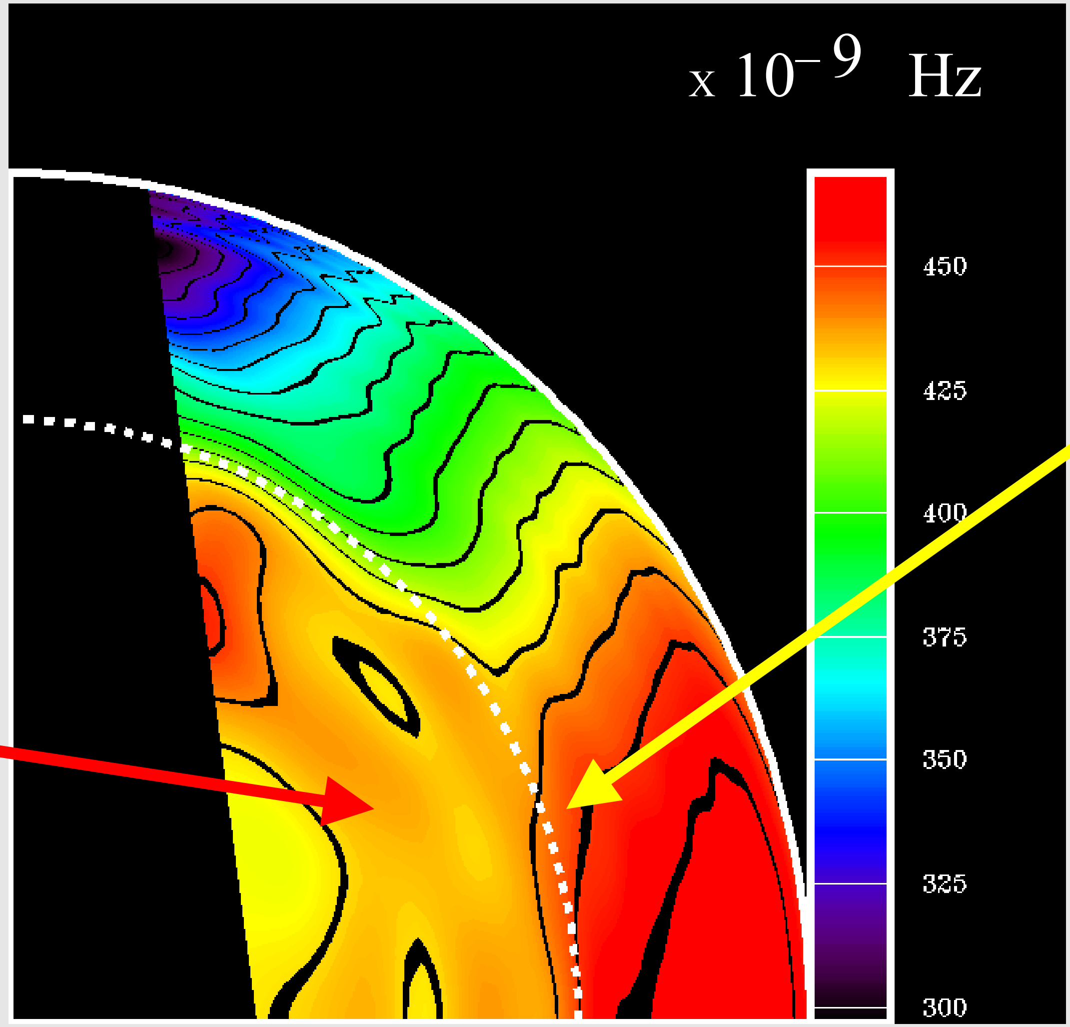
Internal rotation law ?

- ***Rotational splitting of the non-radial modes:***

$$\sigma_{n,l,m} = \sigma_{n,l} - m \int_0^R \Omega(r) K_{n,l}(r) dr + \Theta\left(\Omega^2\right)$$

- ***Needed to solve this set of equations:***
  - ***Several observed frequency splittings***
  - ***Mode identification (l,m,n)***
- ***At present: we are able to treat only slow rotation***

Internal rotation of the Sun



Solar interior has rigid rotation

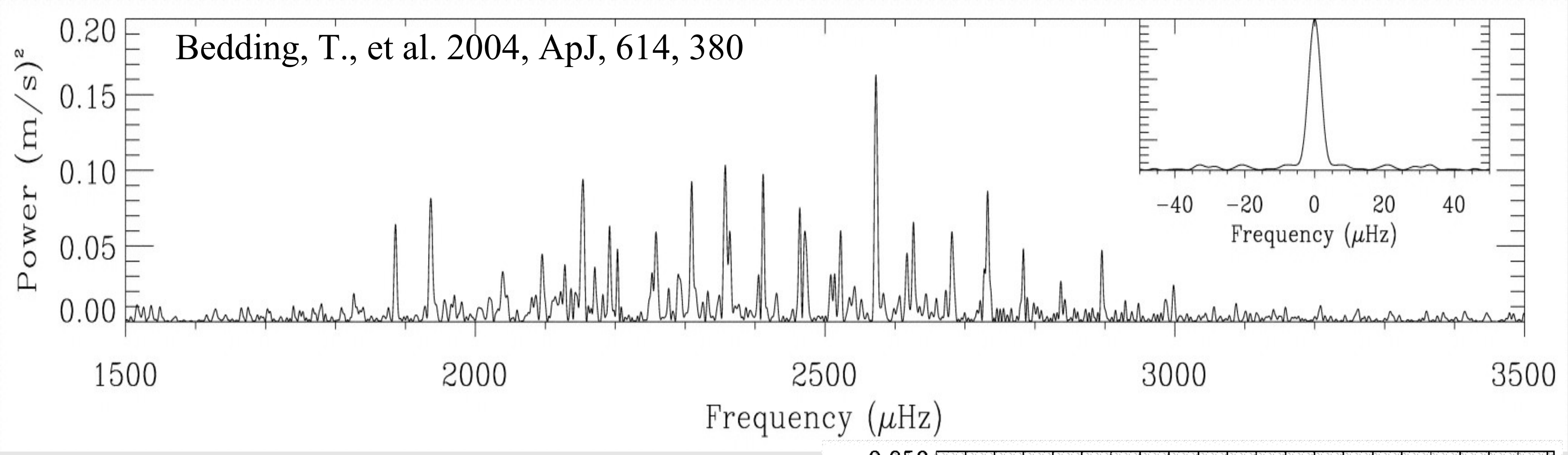
Beginning of outer convection zone

But the Sun is just one simple star...

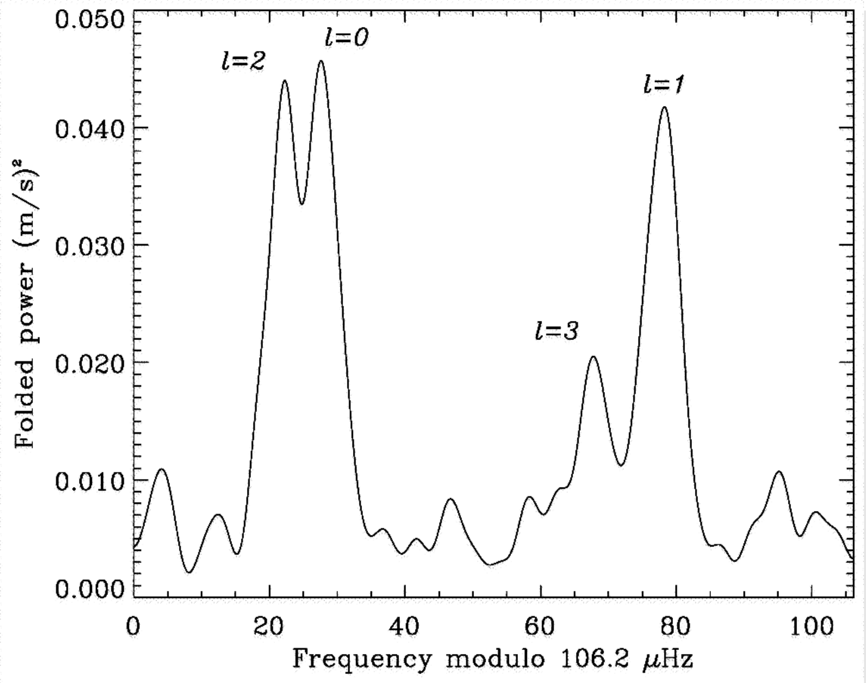
- *She does not have a large convective core*
- *She is a slow rotator*
- *She is relatively unevolved*

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

Solar-like Oscillations in α Centauri



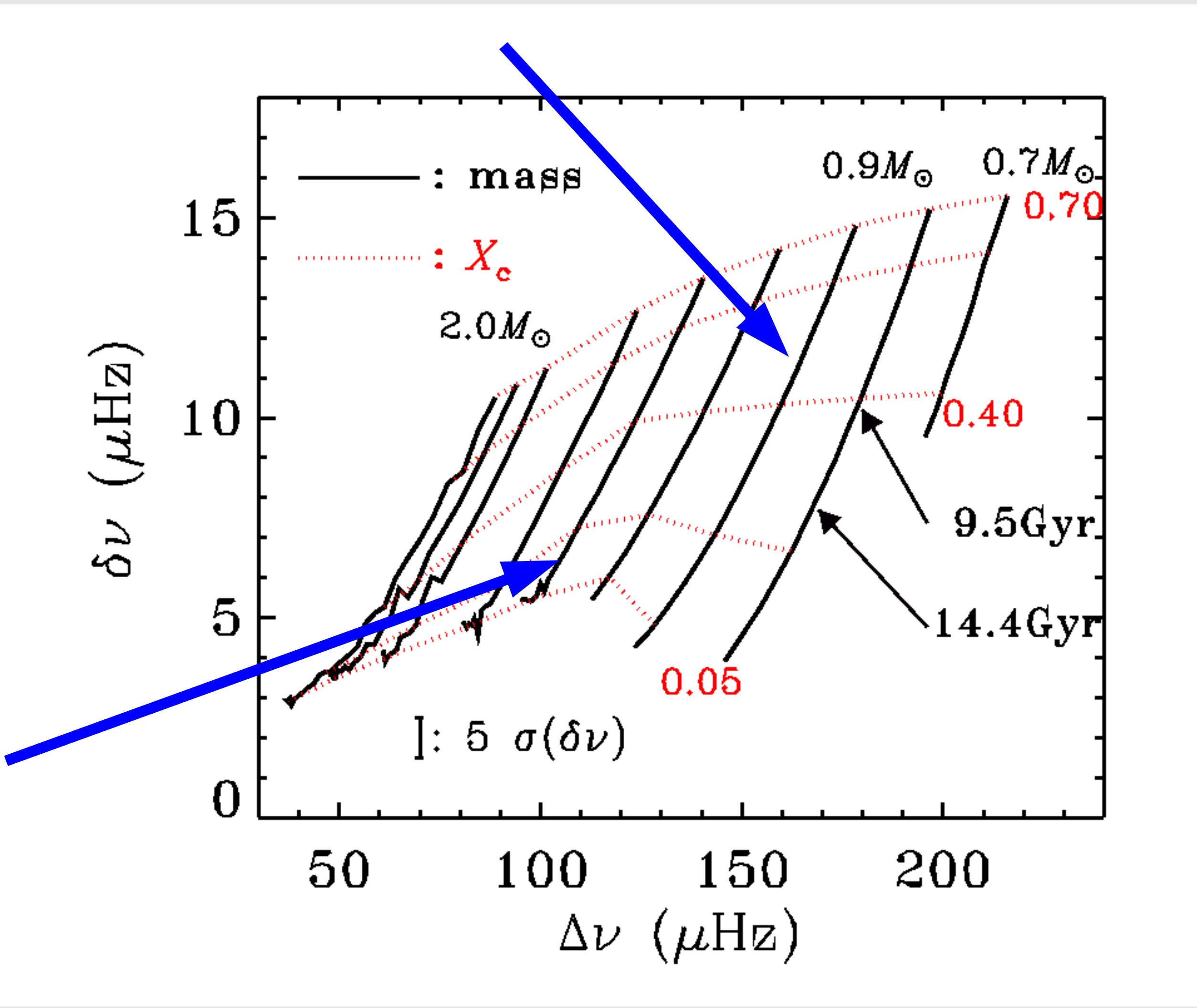
- **UVES & UCLES**
- **42 oscillation frequencies**
- **ℓ = 1-3**
- **Mode lifetimes only 1-2 days**
- **Noise level = 2 cm s^{-1}!**



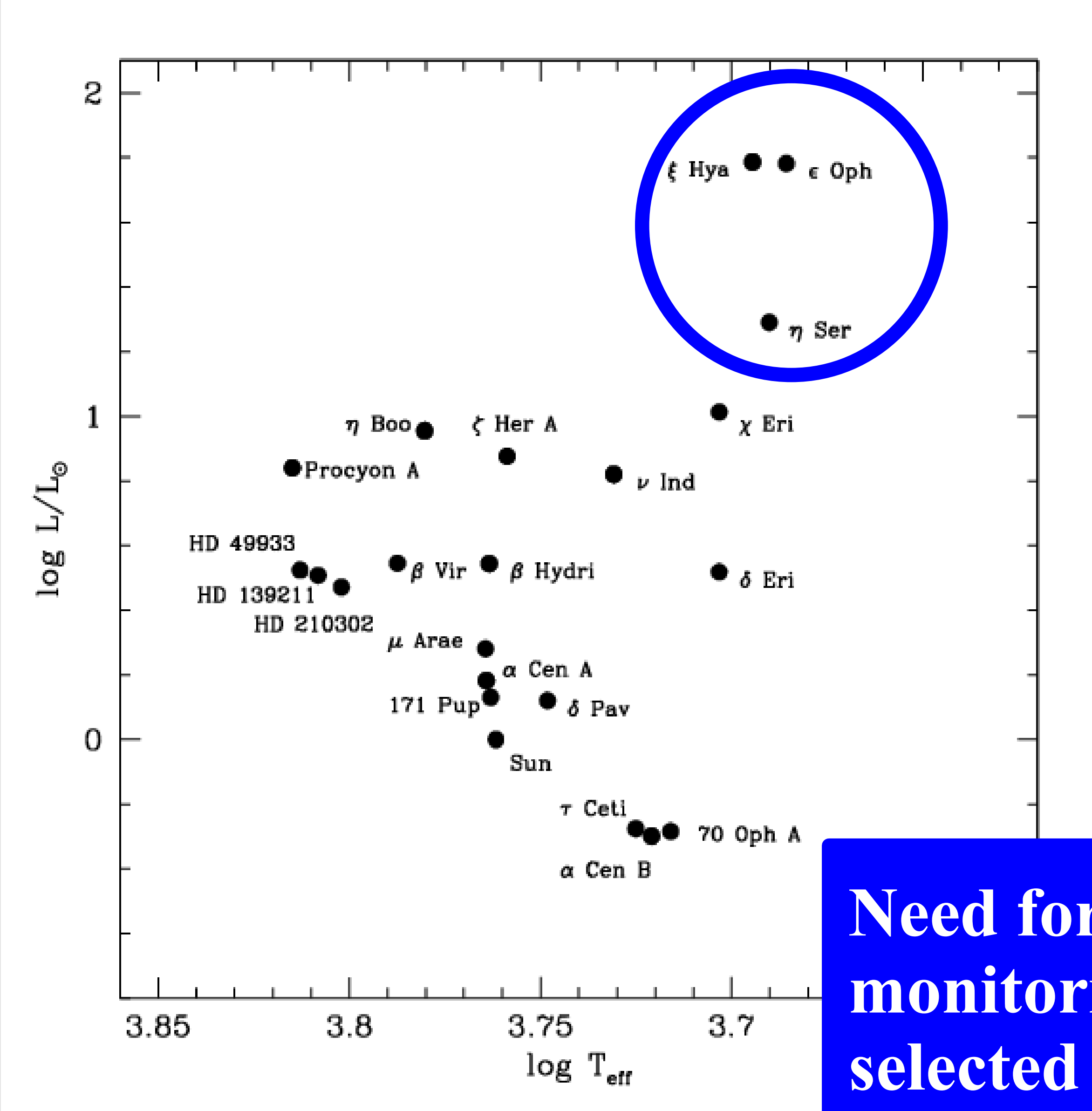
Results for Alpha Cen A+B (G2V+K1IV)

- 42 & 12 detected frequencies, in range 1.8 - 2.9 & 3.0 - 4.6 milliHertz
- Amplitudes between 2 - 44 & 8 - 14 cm/s
- Large separations = 105.5 & 161.1 micro Hz
- Small separations = 5.6 & 10.2 micro Hz
- α CenA has no convective core, although slightly more massive than the Sun (1.105 & 0.934 solar masses)
- α(A) < α(B) by 5 - 10%
  Eggenberger et al. (2004); Miglio & Montalban (2004)

Alpha Cen is more evolved than Sun



Summary of solar-like oscillators



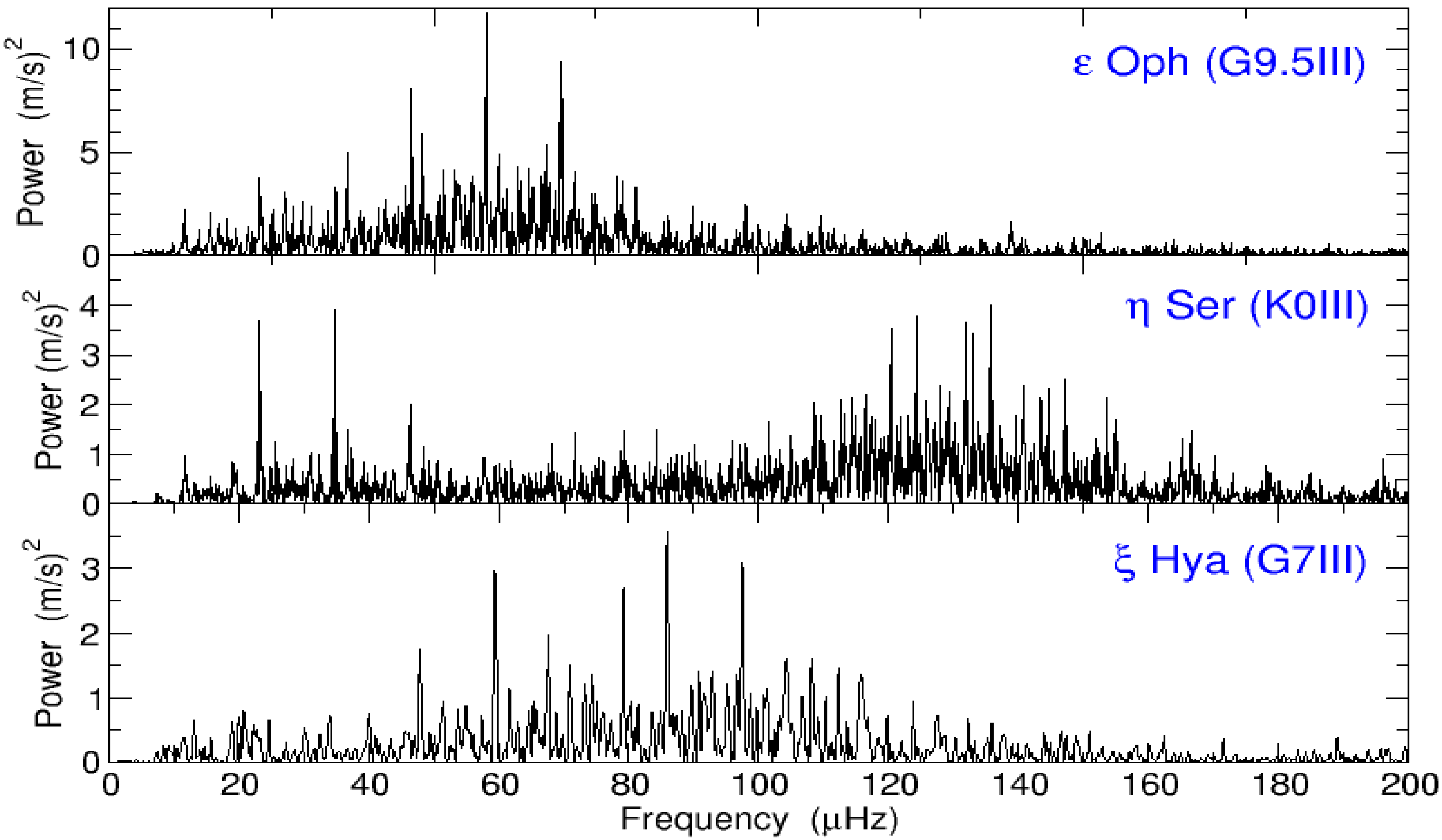
Oscillation frequencies scale as expected

Large (and small) separations derived

Too few frequencies to map interior rotation or tune mixing processes as in the Sun

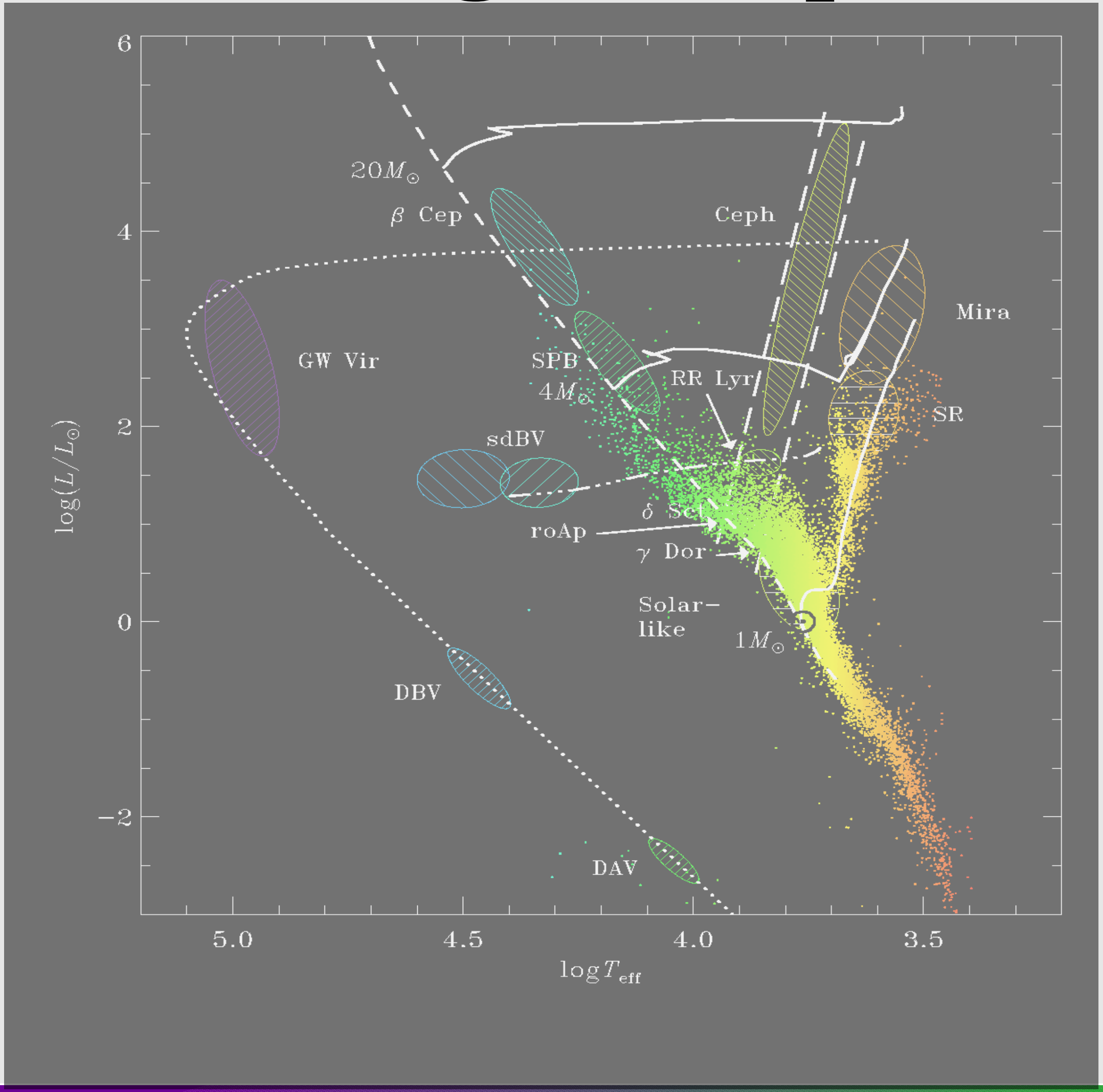
Need for long-term monitoring of a few selected targets

Frequency spectra of red giants?



Extensive RV campaigns: Frandsen et al. (2002); De Ridder et al. (2006); Hekker et al. (2006): radial modes or NRP?

White dwarfs – g-mode pulsators



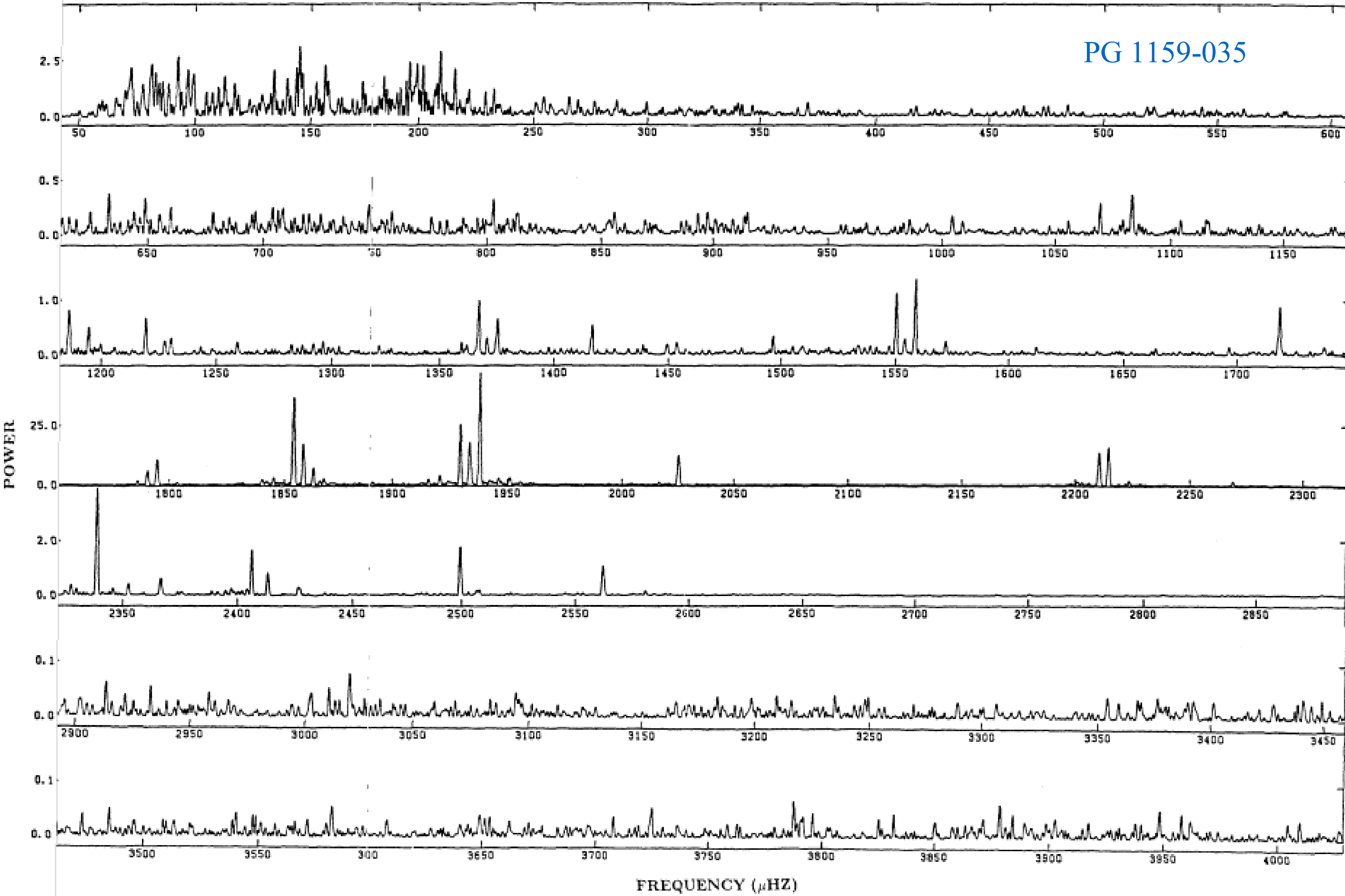


FIG. 4.—Pwer spectrum of the complete data set, shown as power in units of 10^{-6} vs. fequency in μHz. The vertical scale is different for each panel in an attempt to accommode the dynamic range.

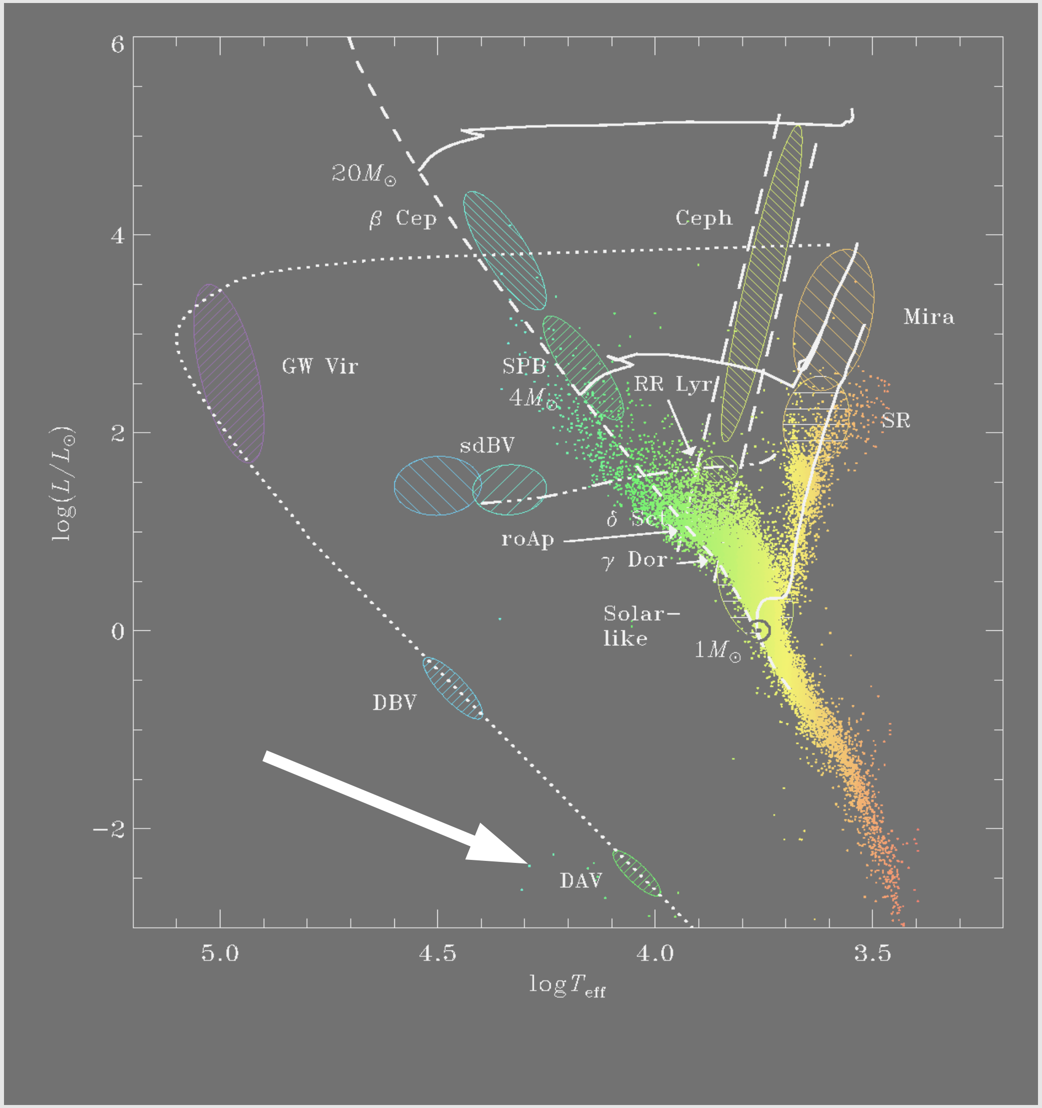
PG 1159-035

- T_{surf} = 123,000 - 124,000 K; log g ≈ 7
- 1000 ≤ f ≤ 2600 μHz; 385 ≤ P ≤ 1000 s
- 125 frequencies; >100 modes
- M = 0.586 ± 0.003 solar masses
- the star is compositionally stratified

BPM 37093

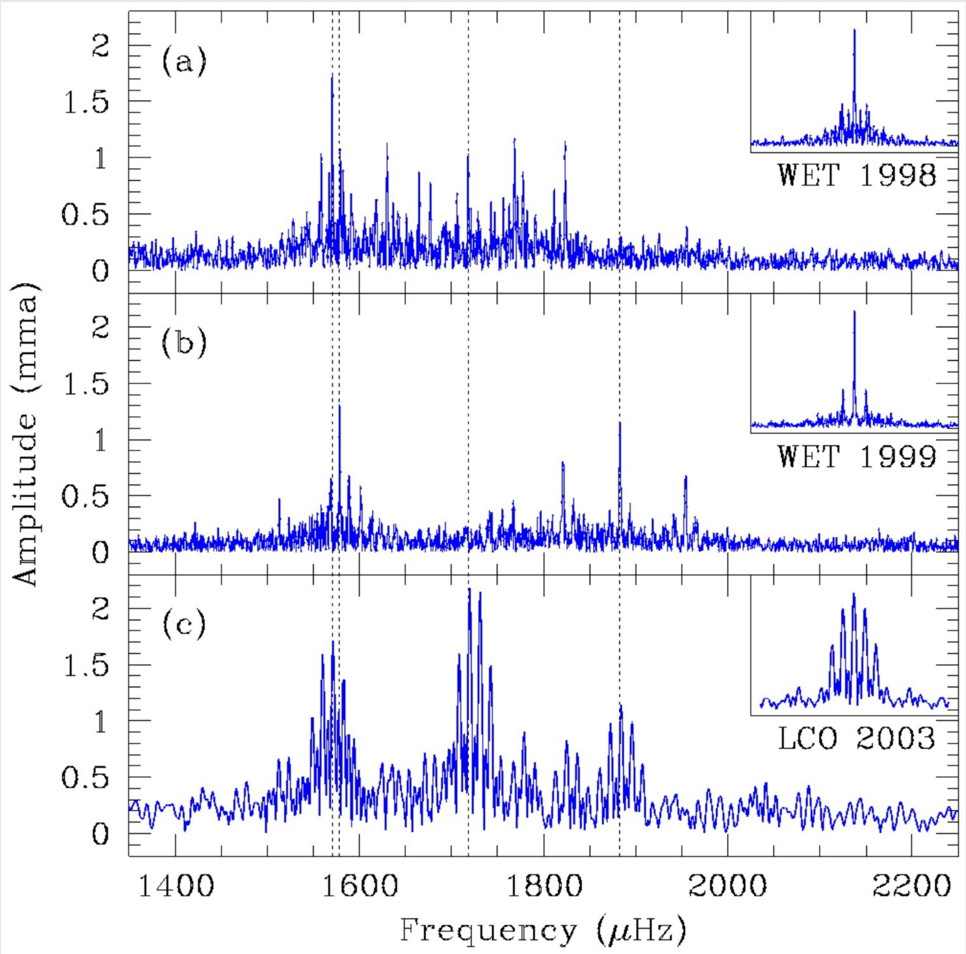
- ***DAV***
- ***M = 1.09 M*** ▯
- ***T_{eff} = 11730 K***
- ***90% crystallized***

  C-O core

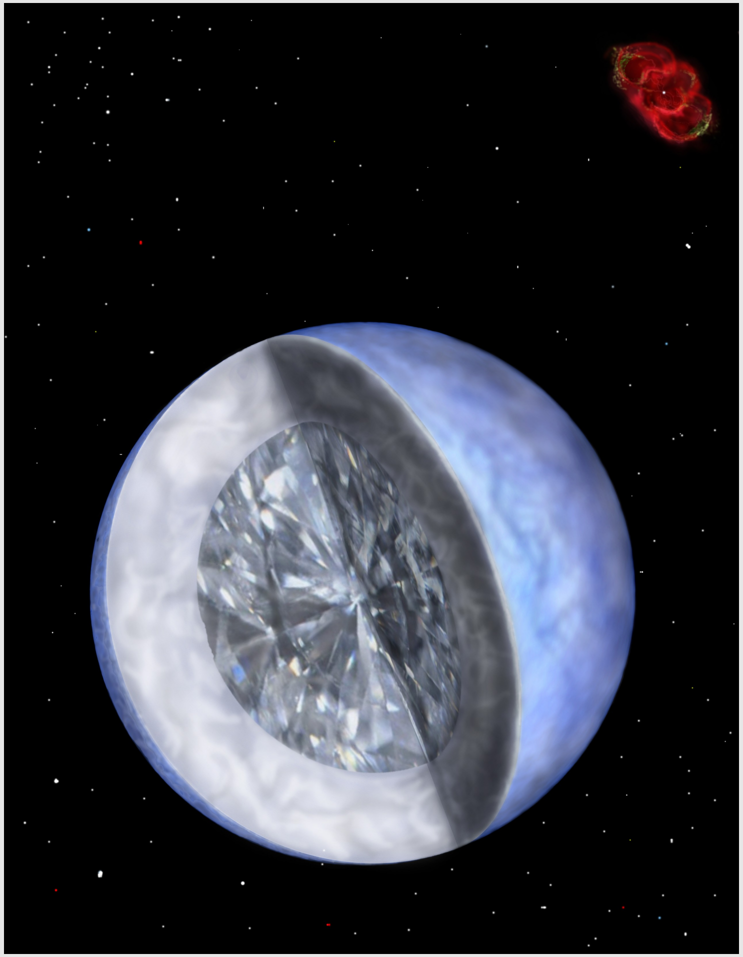


Metcalfe, T. S.; Montgomery, M. H.; Kanaan, A. 2004, ApJ, 605, 133

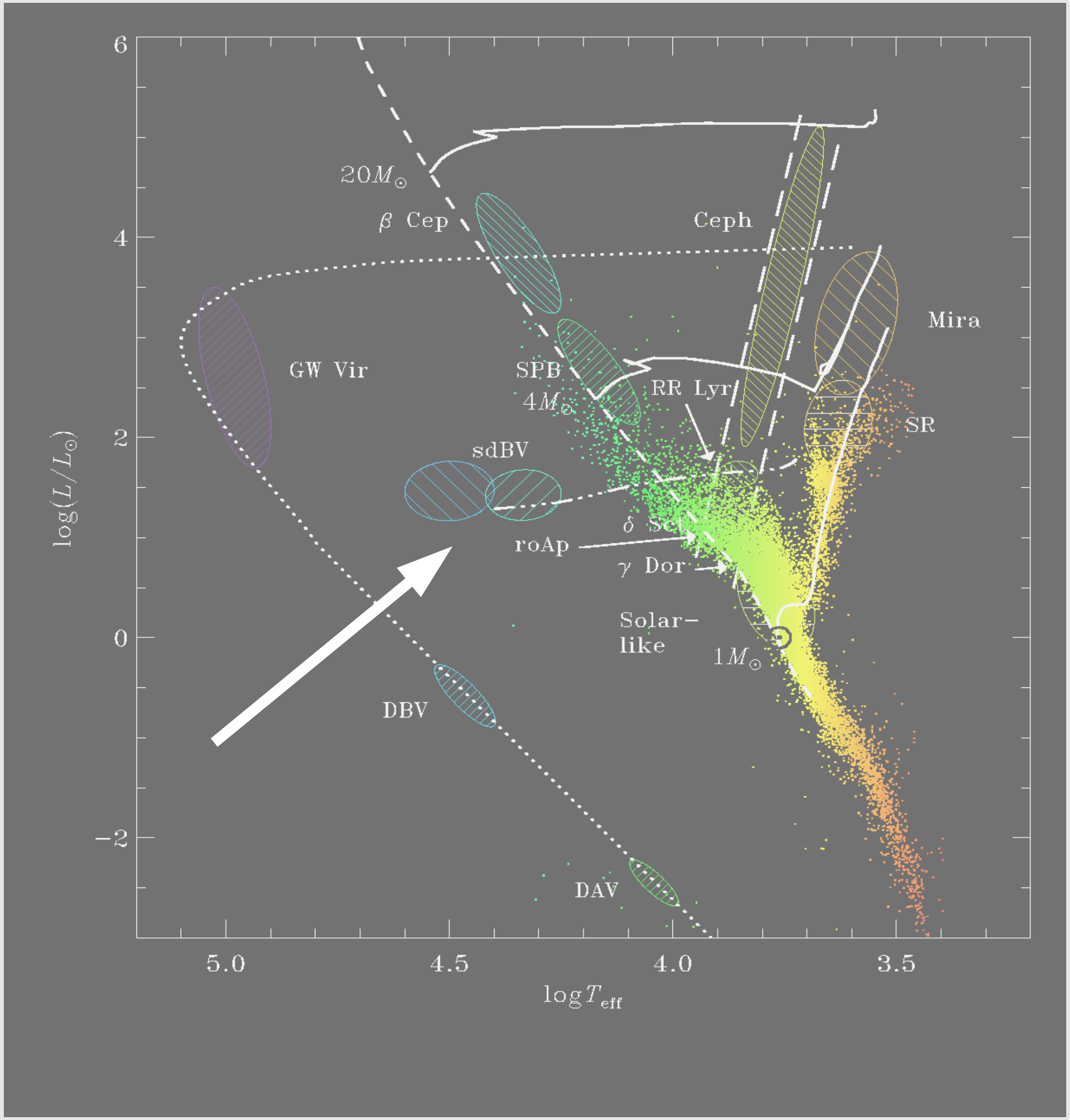
BPM 37093



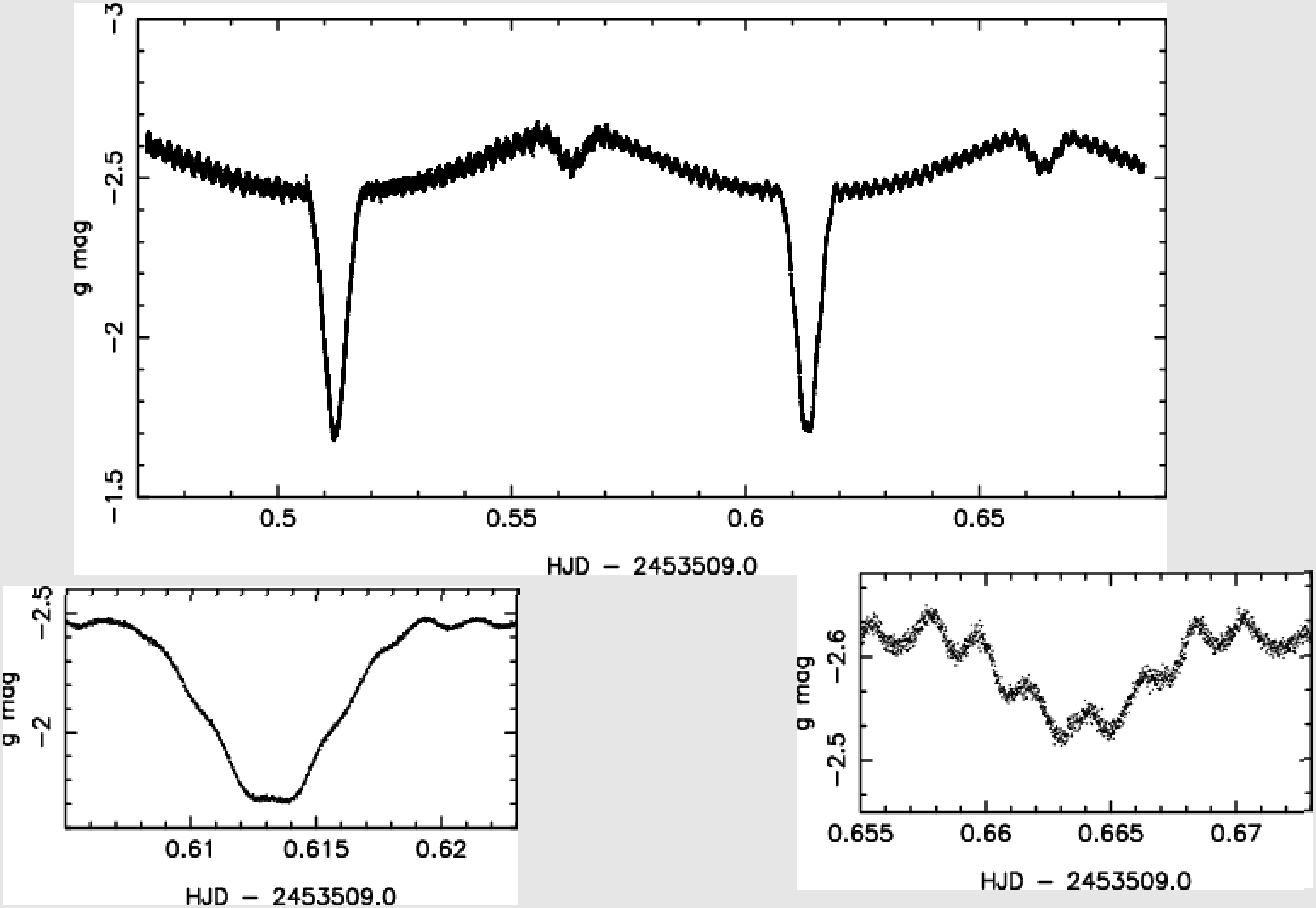
Amplitude (mma)
(a)
WET 1998
(b)
WET 1999
(c)
LCO 2003
Frequency (μHz)
1400
1600
1800
2000
2200



Pulsating subdwarf B stars: sdBV

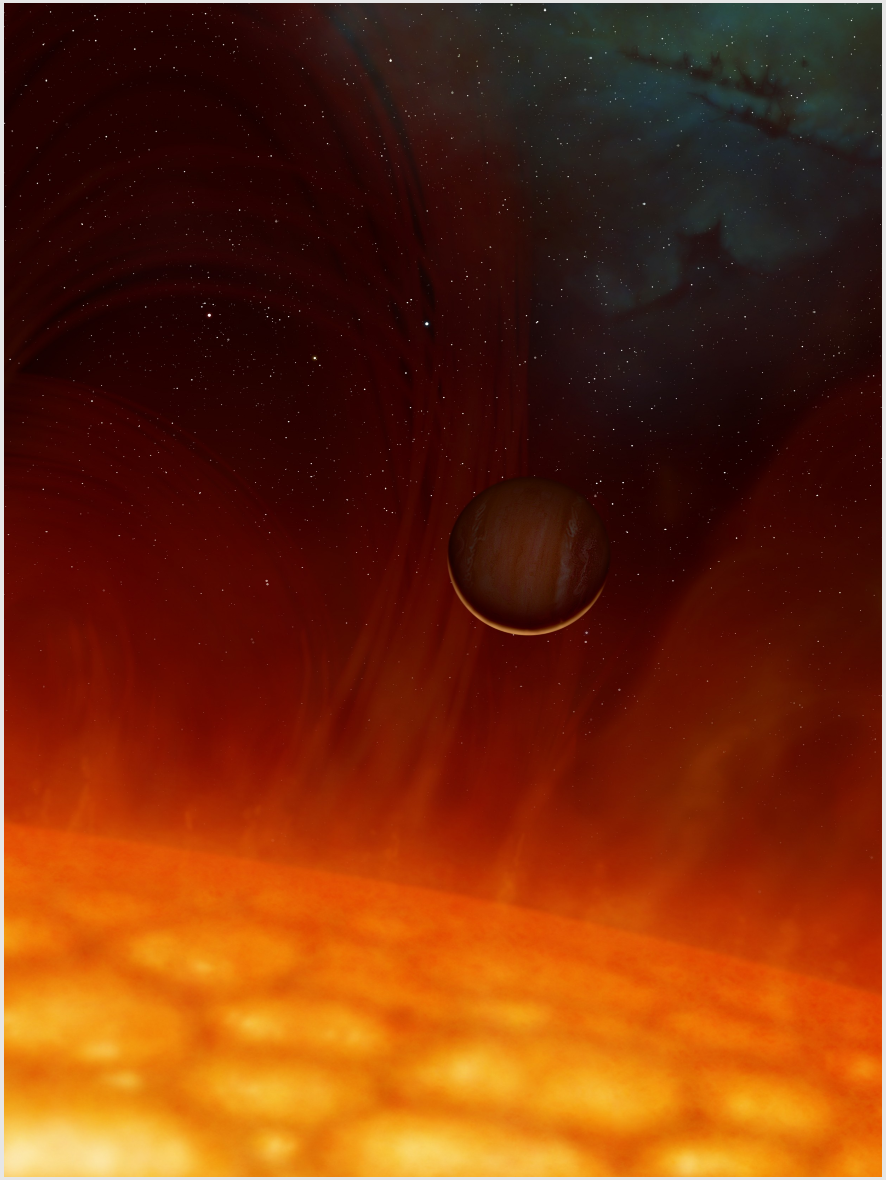


Remarkable discoveries of sdBVs



PG 1336 + 018 (Kilkenny et al. 1998, Vuckovic et al. 2007)

Remarkable discoveries of sdBVs

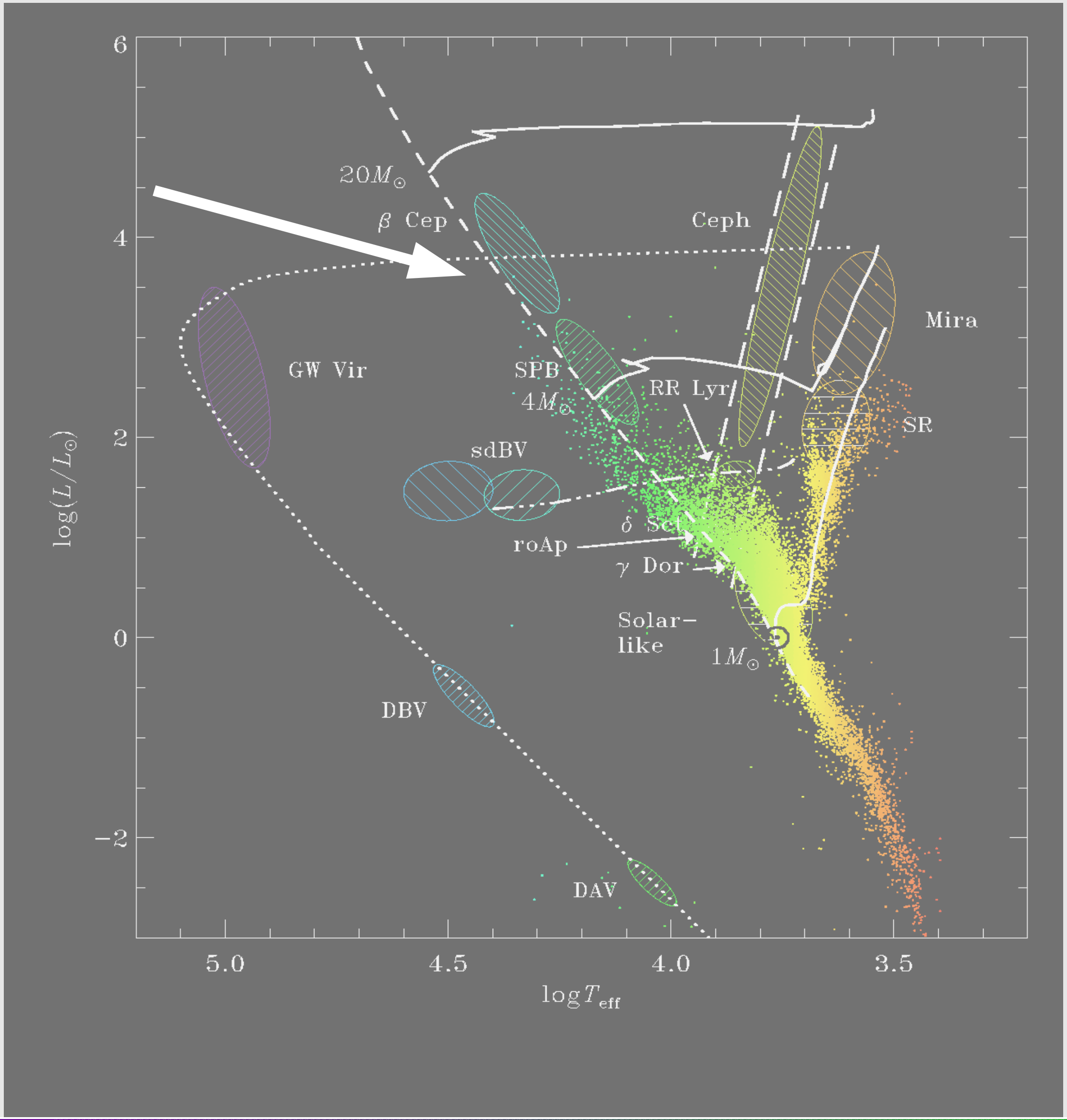


Planet survived Red Giant phase of the sdBV star V391 Pegasi... How??

Planet was discovered in the asteroseismic lightcurve

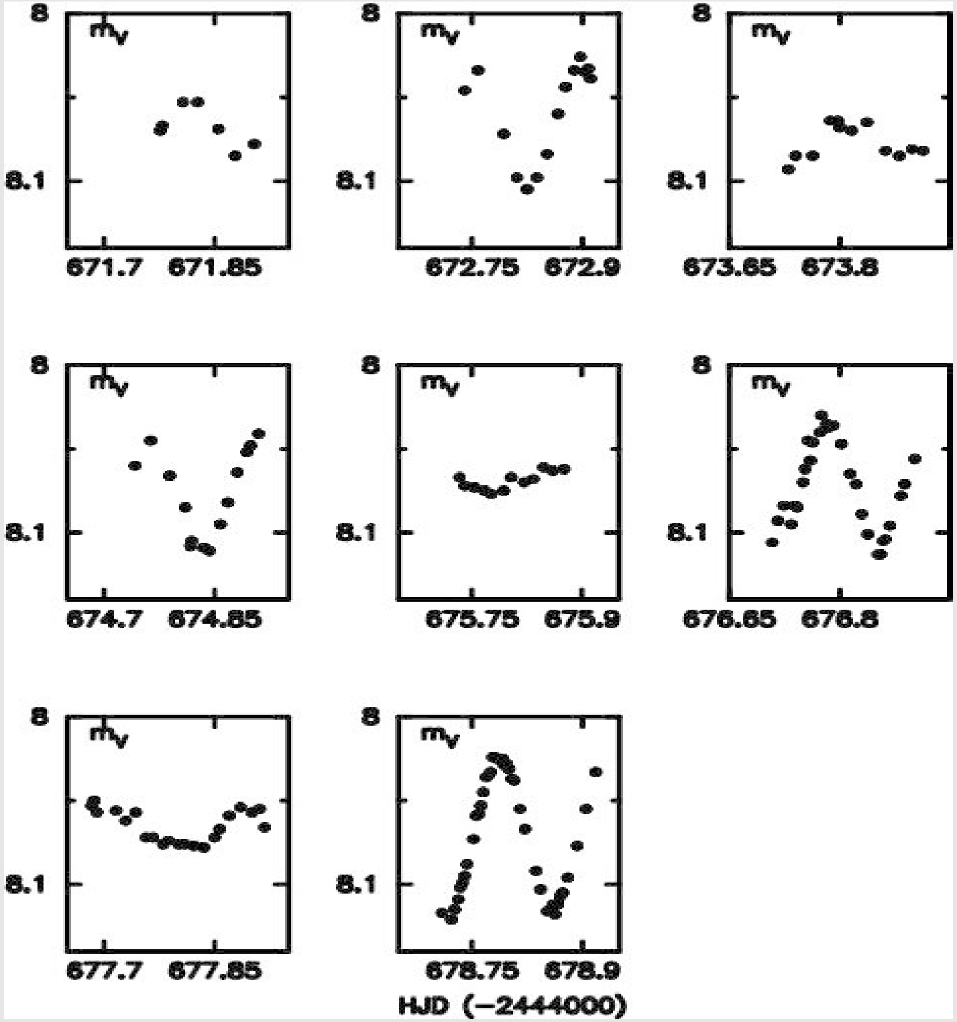
(Silvotti et al. 2007)

Low-order p & g modes: β Cephei stars

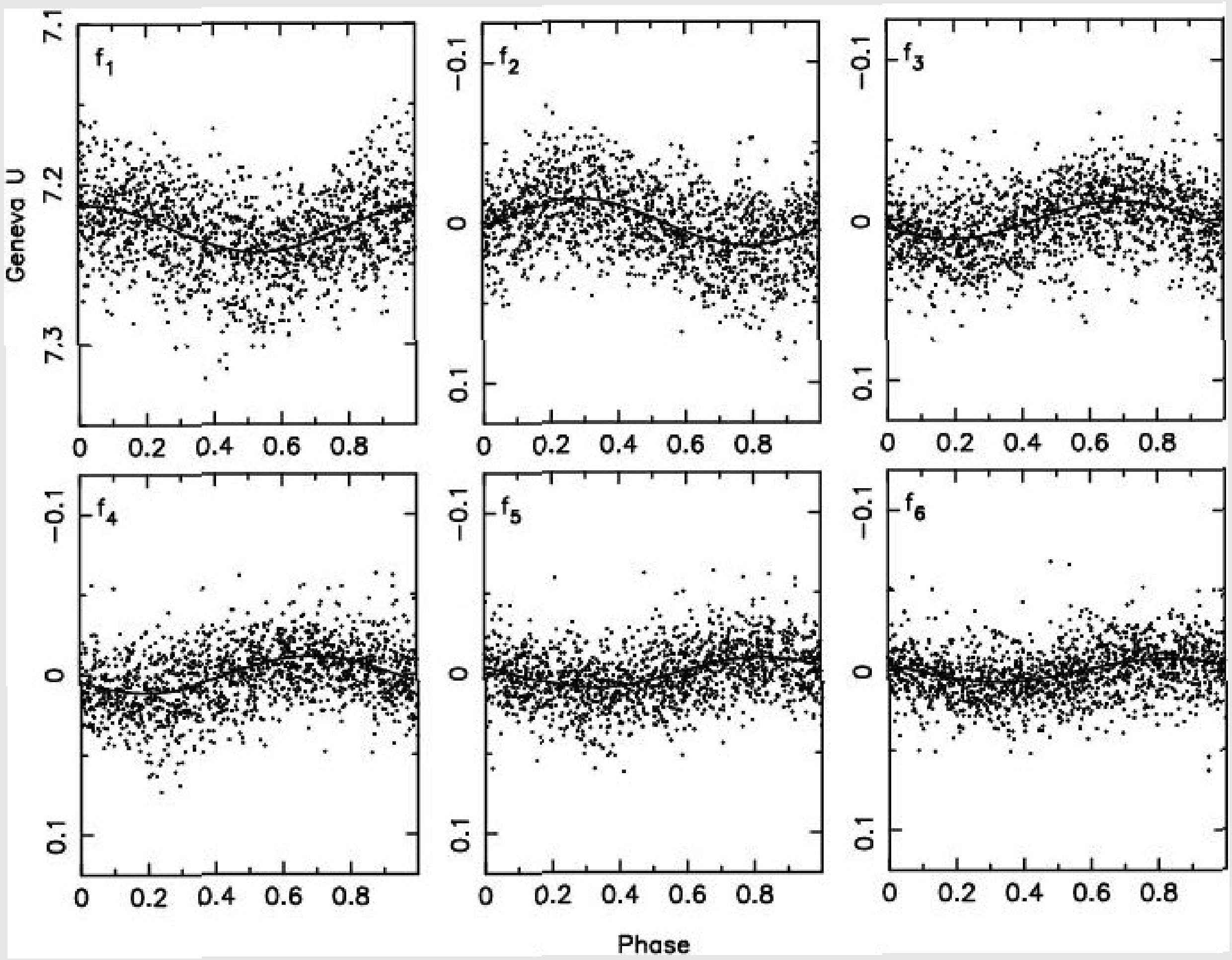


Massive star seismology: HD 129929

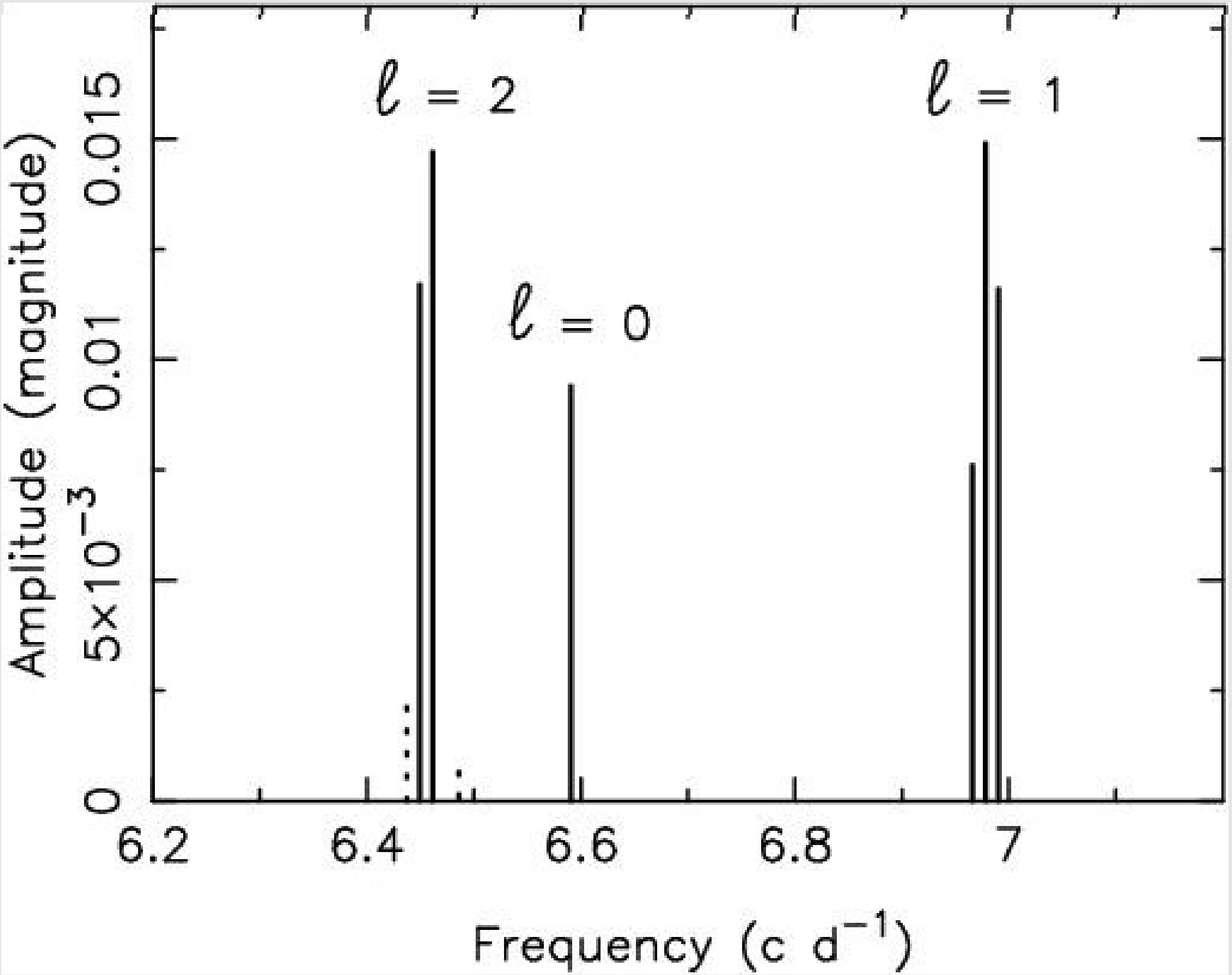
Waelkens & Aerts: observed this star during 21 years



Phase diagrams for U filter data



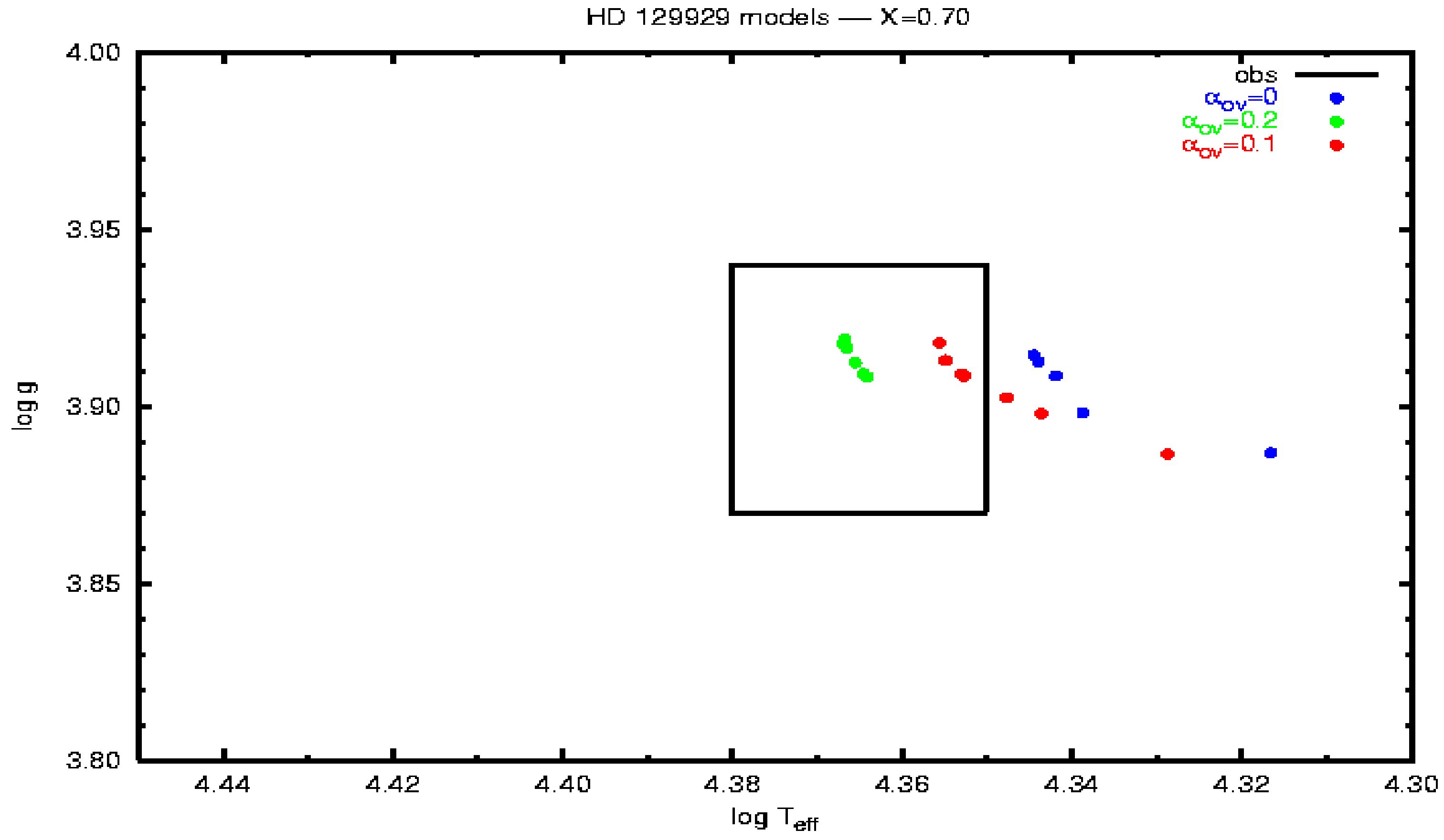
First case study: HD 129929



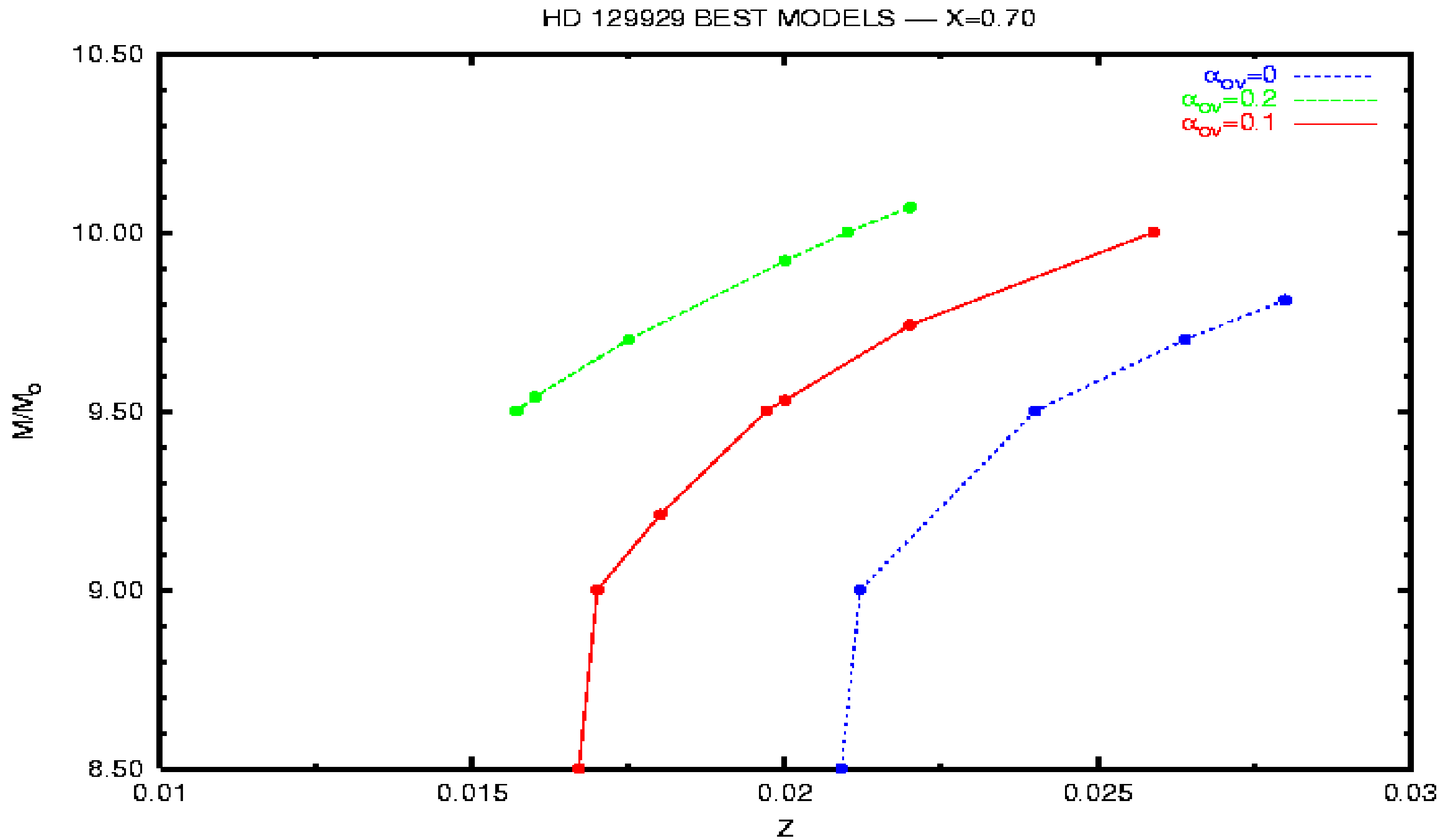
Strategy: forward modelling

- *Derive set of frequencies & amplitudes from data*
- *Compute stellar models thru error box in HR diagram + predict their unstable oscillation modes*
  X, Z (or Y), M, age (or Teff), core overshoot: 5D
- *Identify observed modes, either from*
  - *pattern recognition from theoretical models*
  - *direct methods (quasi-independent of models)*
- *Confrontation: does the input physics of the models explain the seismic data?*
  - *if yes: we get very precise stellar parameters*
  - *if no: great! Input physics is insufficient and must be upgraded to include additional effects or better descriptions until frequencies can be matched…*

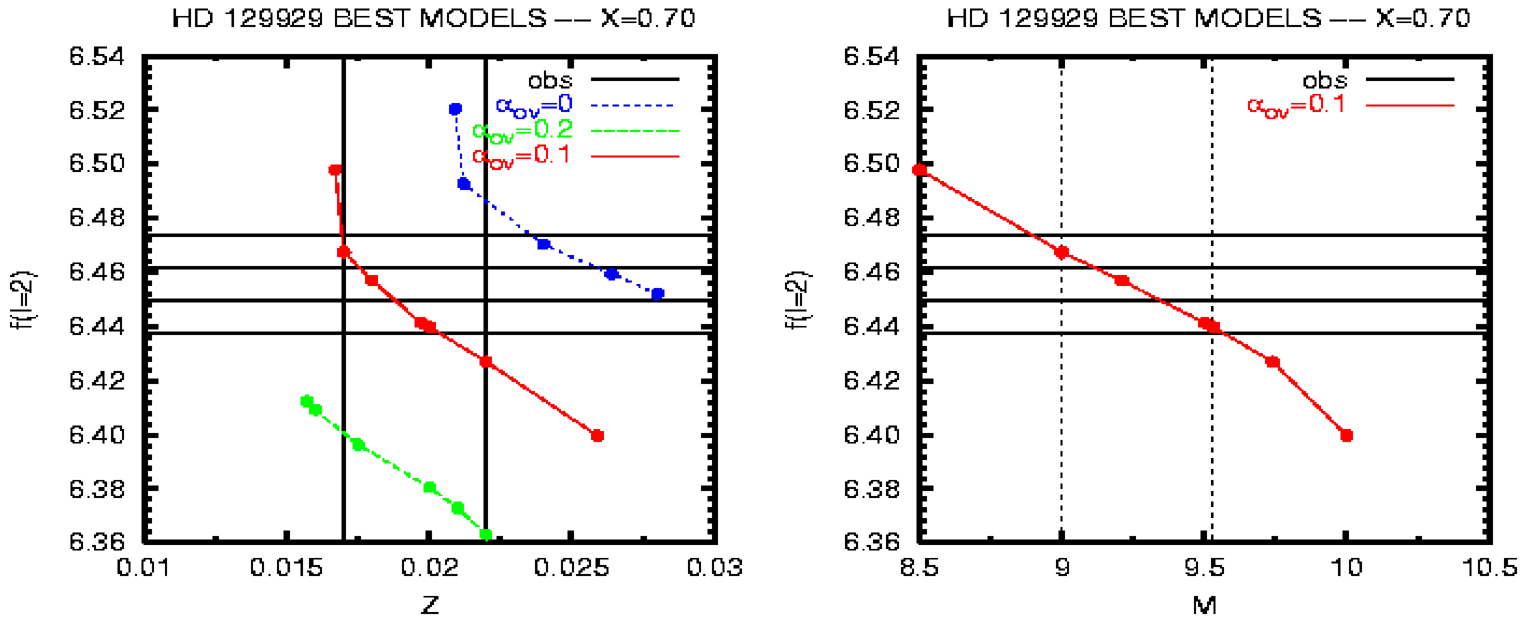
HD129929: Position in HR diagram



HD129929: M(Z) relation



Acceptable range in M,Z,overshoot



Conclusions for HD129929

- ***We need very small core-overshooting to explain the frequencies of the star using OPAL opacities and standard solar mixture***
- ***FIRST star besides the Sun in which non-rigid rotation is proven: core 3.6 times faster than surface***

Results so far for B stars

Compatible with EB & isochrone fitting

Ref.	Star	Mass (M☼)	SpT	αov (Hp)	ΩR(km/s)	Ωcore/Ωenv
(1)	HD 16582	10.2 ± 0.2	B2IV	0.20±0.10	28(14?)	
(2)	HD 29248	9.2 ± 0.6	B2III	0.10±0.05	6±2	~5
(3)	HD 44743	13.5 ± 0.5	B1III	0.20±0.05	31±5	
(4)	HD 129929	9.4 ± 0.1	B3V	0.10±0.05	2±1	3.6
(5)	HD 157056	8.2 ± 0.3	B2IV	0.44±0.07	29±7	~1

(1) Aerts et al. (2006): 20 d MOST photometry + 1 week spectra

(2) Pamyatnykh et al. (2004); Ausseloos et al. (2004):
5 months multisite photometry + spectroscopy

(3) Mazumdar et al. (2006): 4 years high-resolution spectroscopy

(4) Aerts et al. (2003, 2004); Dupret et al. (2004): 20 years photometry

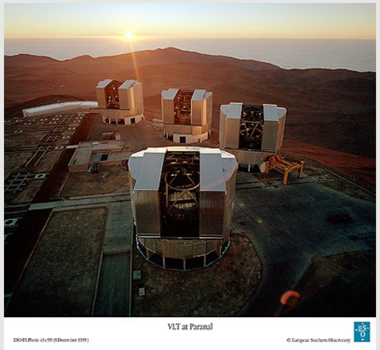
(5) Briquet et al. (2007): 2 years spectroscopy + few months photometry

Status prior to CoRoT and Kepler

- Solar-like oscillations in some 30 stars:
  - Slightly more massive Suns do not have convective core
  - Oscillation frequencies scale as predicted
  - Insufficient frequencies to derive rotational mixing
  - Mode lifetimes ?
- Discoveries of oscillations in 5 red giants since 2001
- First proof of non-rigid rotation inside massive stars since 2003: they live longer !
- Goal: beat the noise level...

Goal 1: better independent constraints

Provide an independent high-precision radius estimate for bright stars Cunha et al. (2007, A&ARev)



ESO
VLTI

Provide an independent high-precision distance estimate

2012
ESA
Gaia

Dedicated instruments for specific stars attached to private telescopes for mode identification

Mercator
HERMES
MAIA

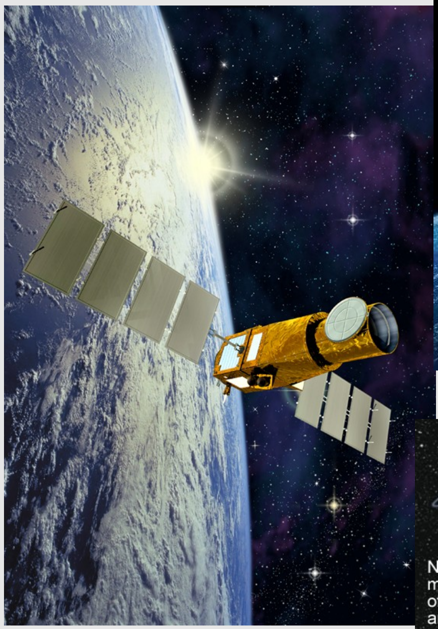
Goal 2: space asteroseismology

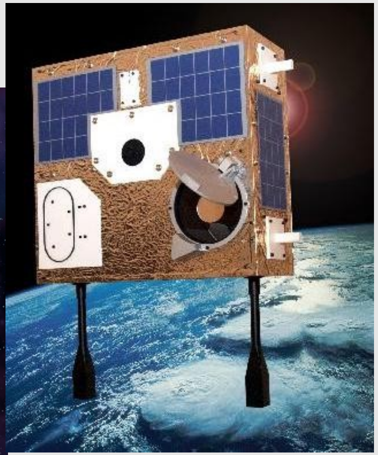
MOST: Canadian mission (15cm) launched in June 2003
max. 6 weeks, extended

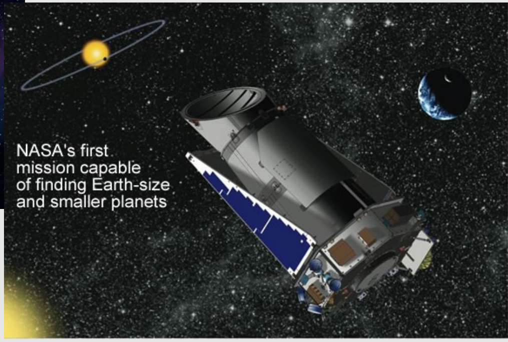
CoRoT: French-led European mission (27cm), launched 27/12/2006
max 5 months, extended 2013

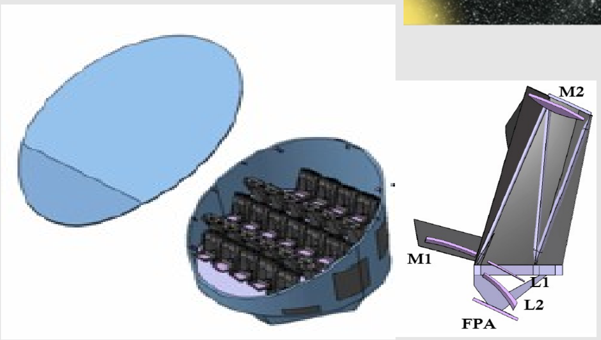
Kepler : NASA mission (95cm), launch 7 March 2009, exoplanets
4 (6?) years

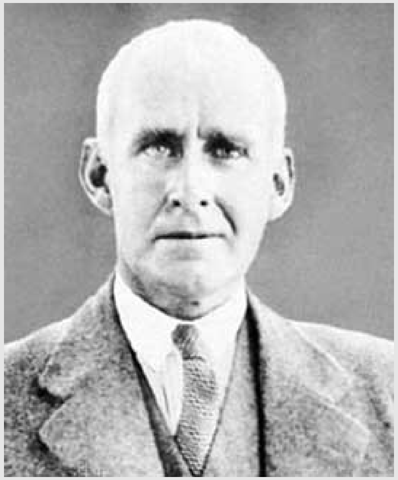
PLATO: exoplanet ESA mission with asteroseismic capabilities pre-selected for CV2015-2025
6 years











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

Asteroseismology