The potential of pulsating sdB stars for probing helium burning cores

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Introduction

Hot B Subdwarf (sdB) stars / Extreme Horizontal Branch (EHB) stars

→ Hot (T_{eff} ~ 22, 000 – 40,0000 K) and compact (log g ~ 5.2 – 6.2 ; R ~ 0.10 – 0.25 $R_{\odot}$) stars

→ He-burning remnants of former red-giant cores with only tiny H-envelopes left: M ~ 0.47 $M_{\odot}$

→ Some develop nonradial oscillations (p- and/or g-modes) : Periods ~ 1 min up to ~ 4 hours

→ Quantitative asteroseismology (e.g., Van Grootel et al. 2013, A&A, 553, 97 ; Charpinet et al. 2011, A&A, 530, 3)

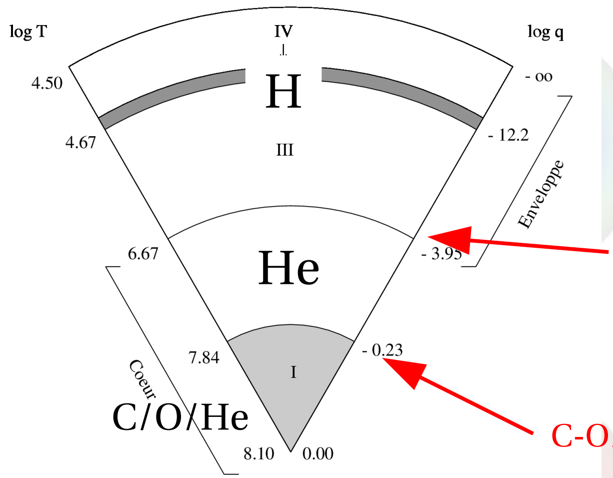
Asteroseismology

A lot of information on the stellar structure

comes from mode trapping effects

Mode trapping effects in sdB stars

sdB stars are evolved & chemically stratified

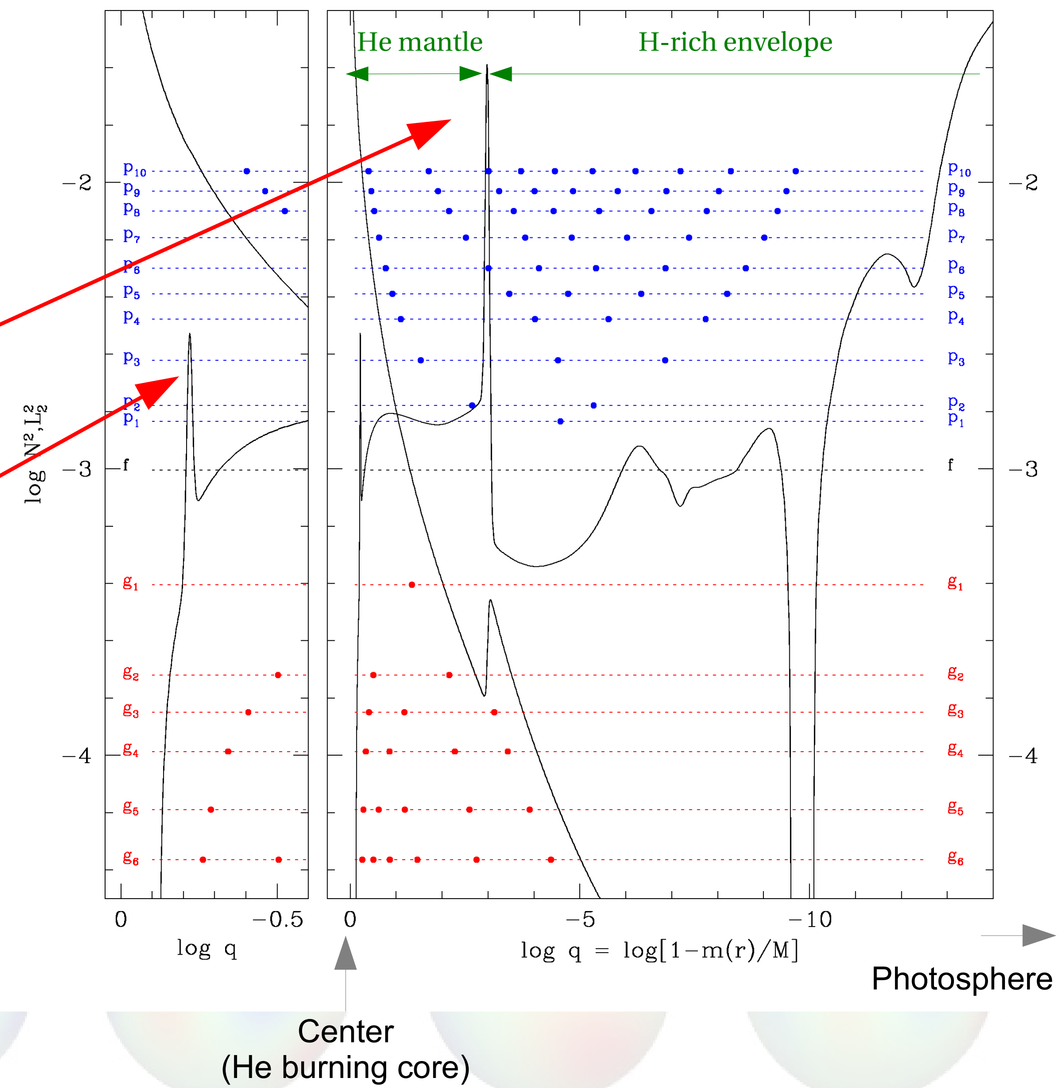


He/H transition

C-O/He transition

Sharp chemical transitions generate trapping effects

Brunt-Väisälä Frequency – Propagation diagram

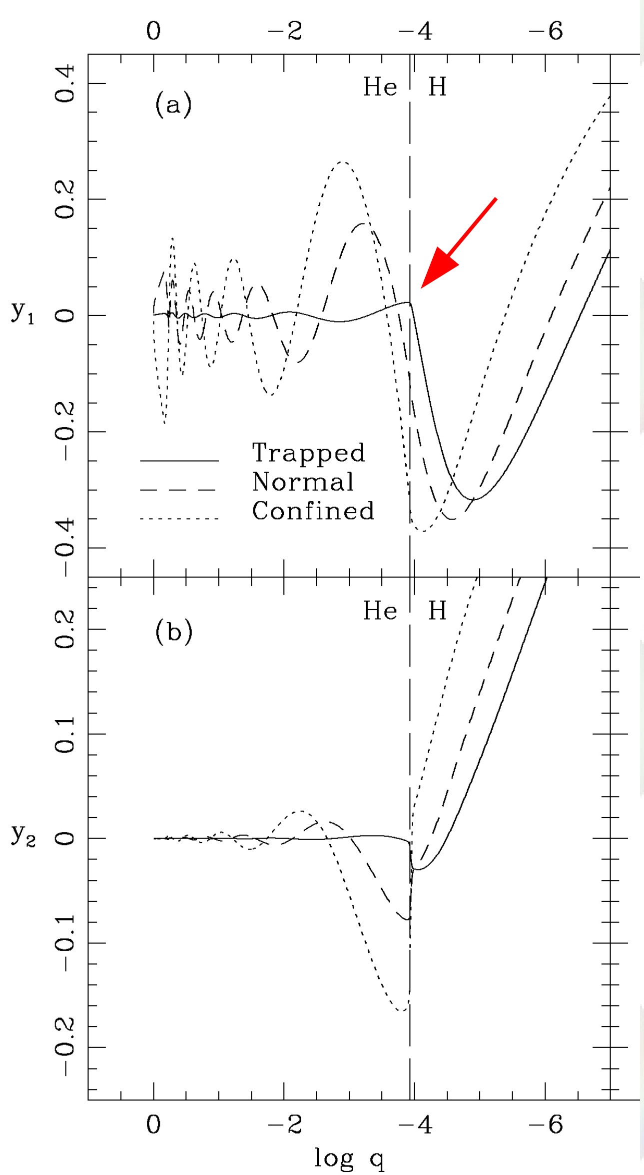


Trapped and confined modes

g-modes

Radial displacement

Horizontal displacement



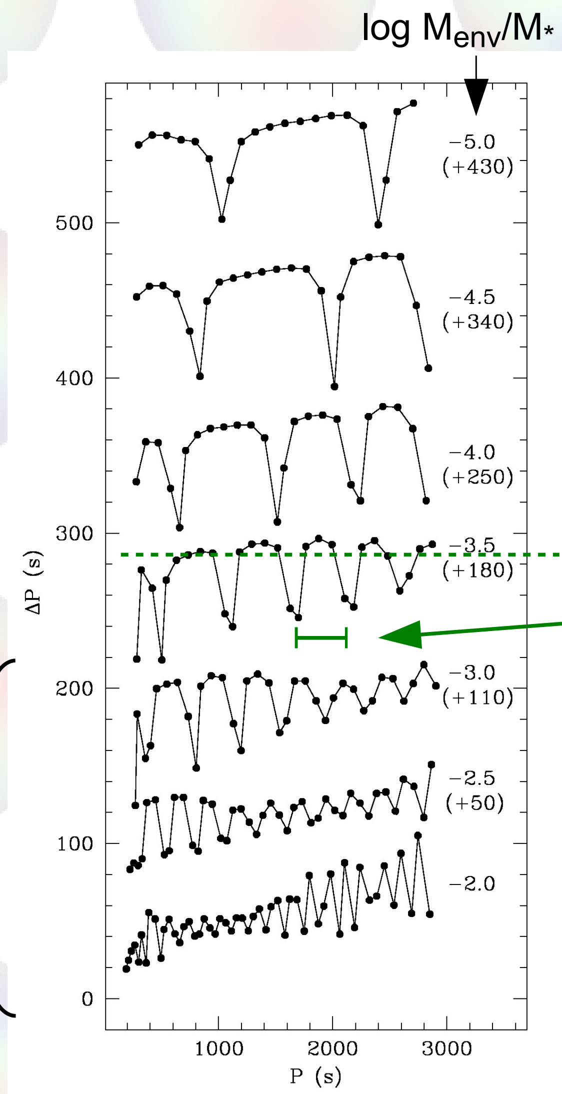
From Charpinet et al. 2000, *ApJS*, **131**, 223

Trapping occurs when a node is close to the sharp chemical interface

mode trapping ↔ partial wave reflection

Impact of trapping on the period spectrum

g-modes



G-mode sdB pulsators → Thick envelopes

From Charpinet et al. 2002, *ApJS*, **139**, 487

For evolved (chemically stratified) stars

Strong trapping expected from He/H transition

→ g-modes: non uniform period spacings

Asymptotic model with a discontinuity

$$\Pi_{0,l}^{\rm rad} \equiv \frac{\Pi_0^{\rm rad}}{\sqrt{l(l+1)}} \quad \text{with} \quad \Pi_0^{\rm rad} \equiv 2\pi^2 \left(\int_{r_c}^{R} \frac{|N|}{r}\, dr \right)^{-1}$$

$$\Pi_{H,l} \equiv \frac{\Pi_H}{\sqrt{l(l+1)}} \quad \text{with} \quad \Pi_H \equiv 2\pi^2 \left(\int_{r_H}^{R} \frac{|N|}{r}\, dr \right)^{-1}$$

(Tassoul 1980, Brassard et al. 1992, Charpinet et al. 2000)

Similar – though more subtle -- trapping effects also affect p-modes (see Charpinet et al. 2002)

Allows measurements of H-rich envelope masses in sdB stars both from p- and g- mode pulsators with asteroseismology

Trapping from the envelope transition
The full g-mode structure

Period spacings and Echelle diagrams
for g-modes up to the cutoff period
(k ~ 1 – 65; the range typically detected with *Kepler*)

Trapping from the He/H transition looses efficiency with increasing radial order
See Charpinet et al. 2014, ASPC, 481, 179
(last sdOB meeting) for an explanation of this

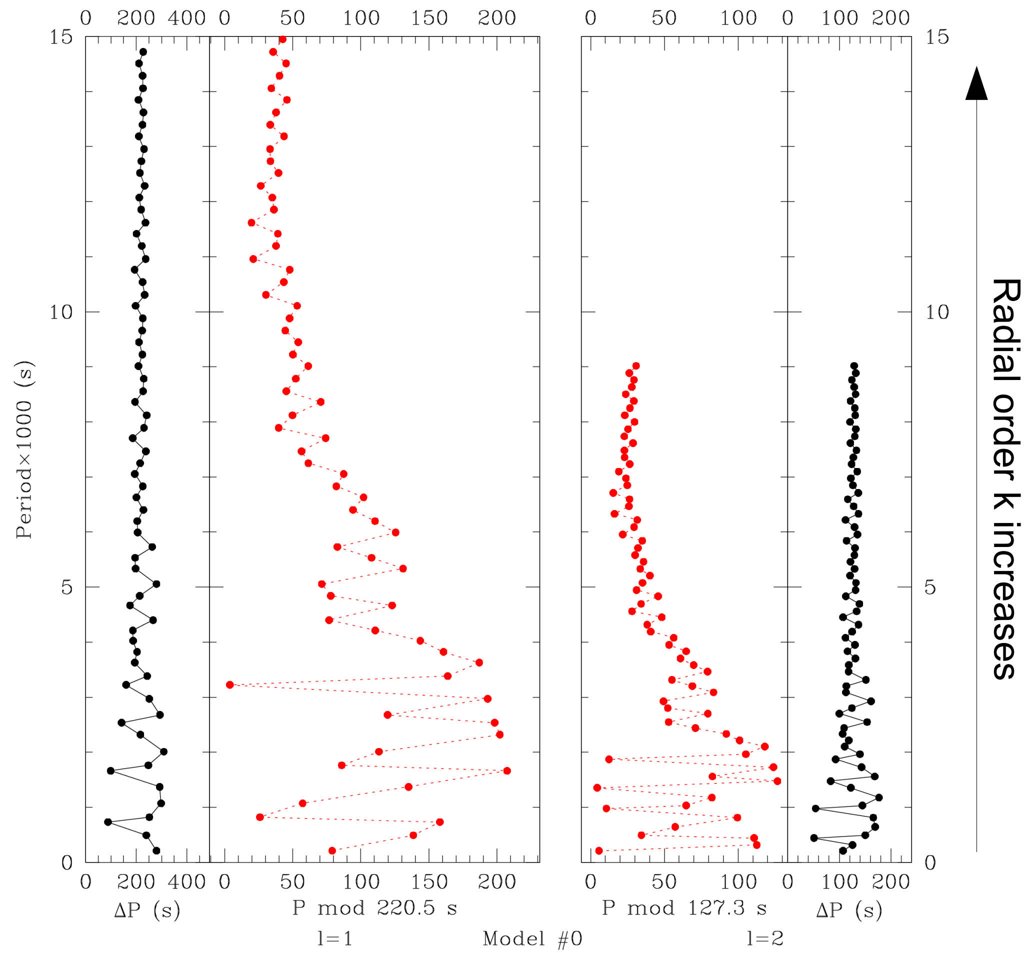
↓

The spectrum becomes nearly uniform at low frequencies (long periods)

↓

Presence of ridges in echelle diagrams at low frequencies (long periods)

From a ZAEHB model
(i.e., trapping generated by the envelope transition only)



Period spacings

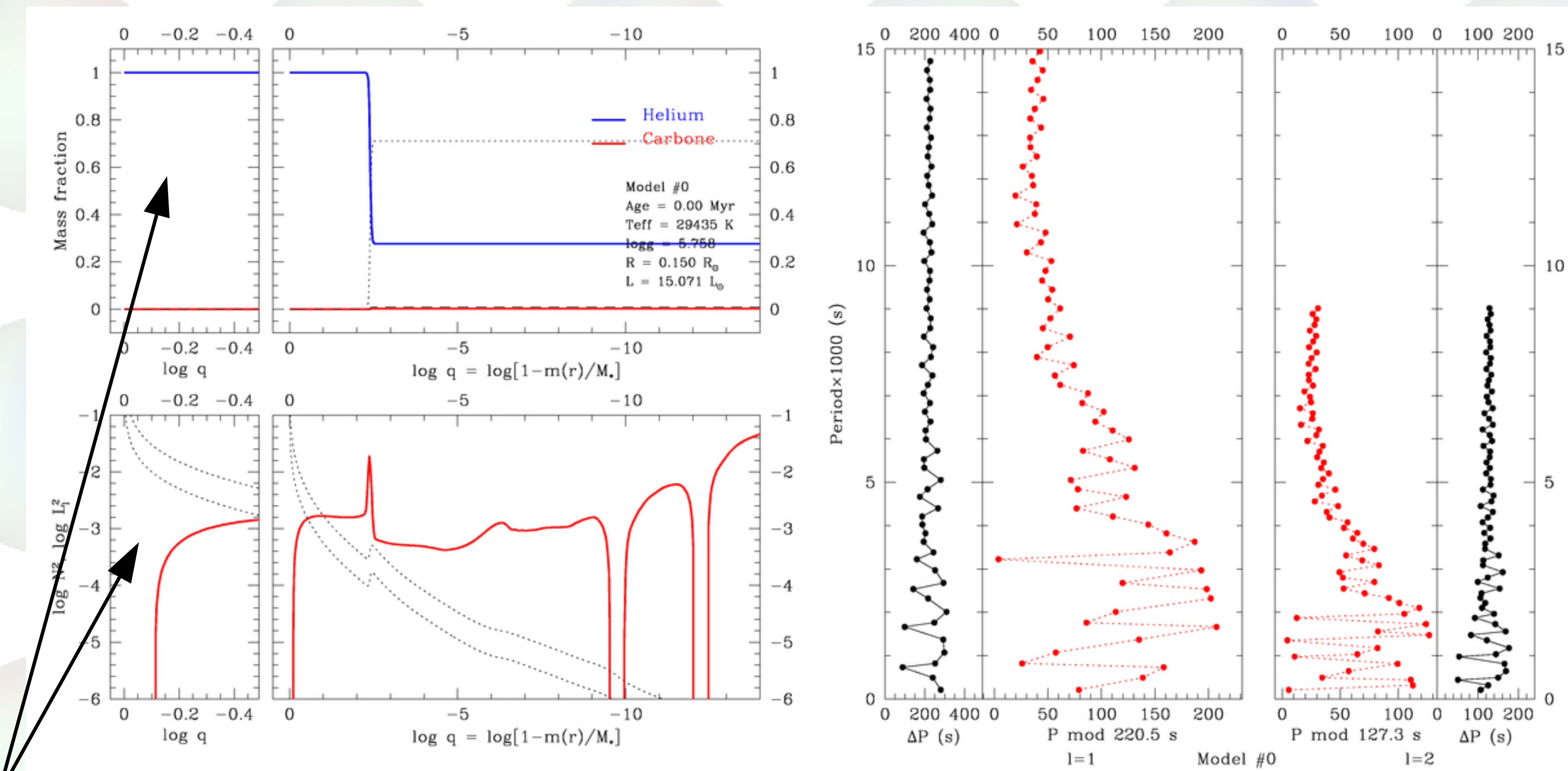
Echelle diagram

Trapping induced by the helium burning core

The envelope transition is not the only source of trapping

He core / g-mode spectrum evolution

Chemical composition



Radial order k increases

Close-up view of the core

Brunt-Väisälä frequency profile

Period spacings

Echelle diagram

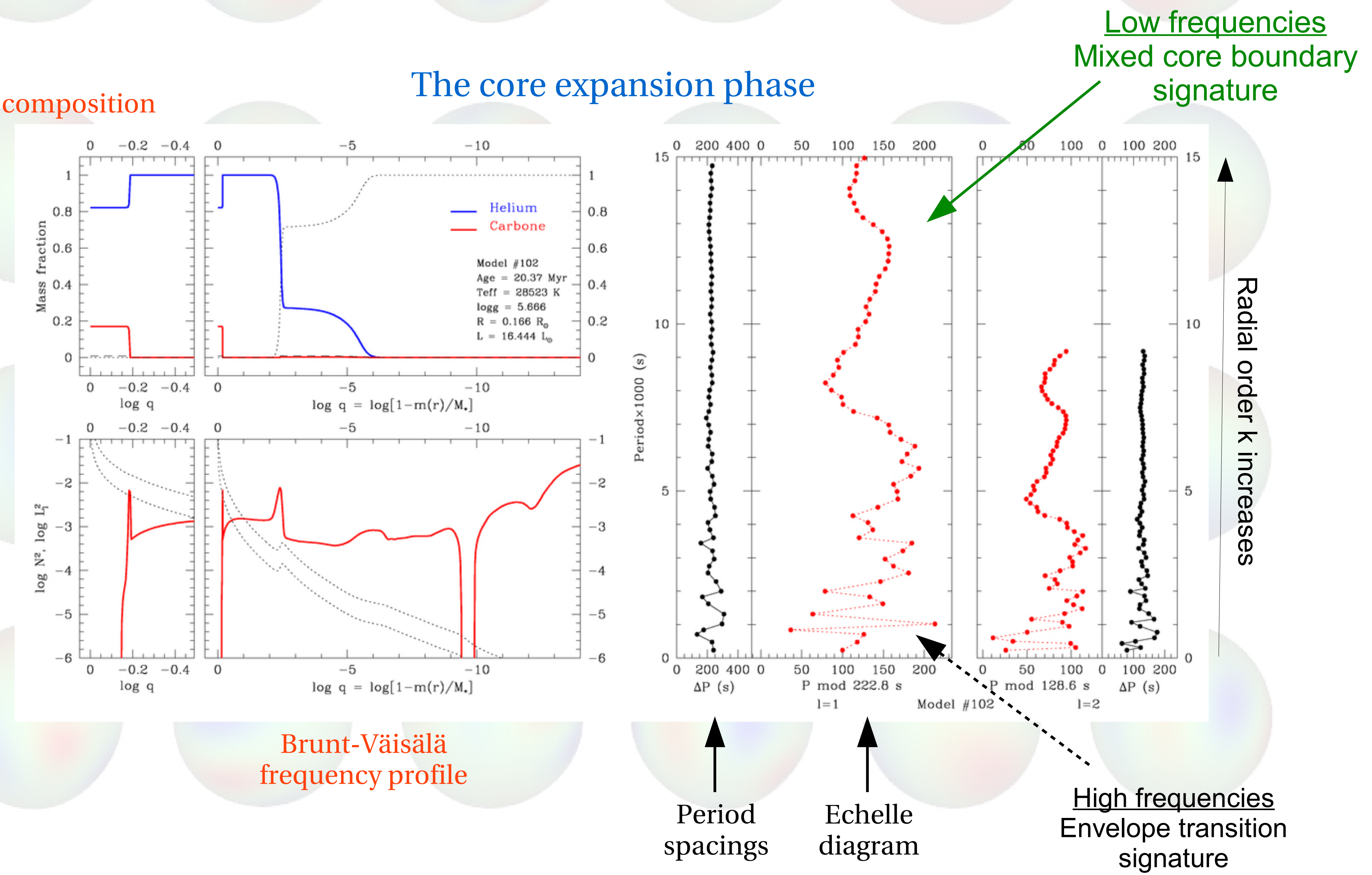
Evolutionary sequence

Trapping induced by the helium burning core

The envelope transition is not the only source of trapping

The core expansion phase

Chemical composition



Brunt-Väisälä frequency profile

Period spacings

Echelle diagram

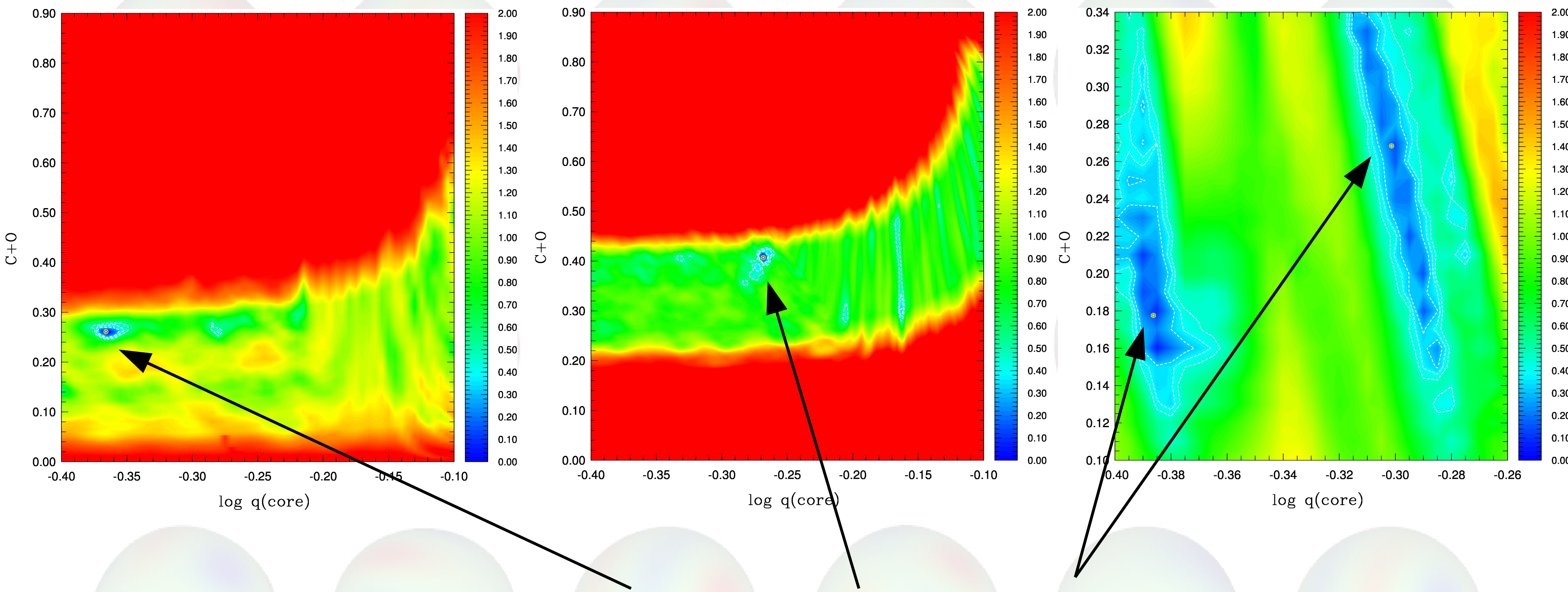
Measuring the C-O enriched core size

Attempts to measure core size based on 3rd generation models

KPD 1943+4058 (*Kepler*)
Van Grootel et al. 2010, ApJ, 718, L97

KPD 0629-0016 (*CoRoT*)
Van Grootel et al. 2010, A&A, 524, 63

KIC 02697388 (*Kepler*)
Charpinet et al. 2011, A&A, 530, 3



Optimal seismic solutions for the He core parameters

→ Testing core convection + overshooting (see J.-T. Schindler's talk)

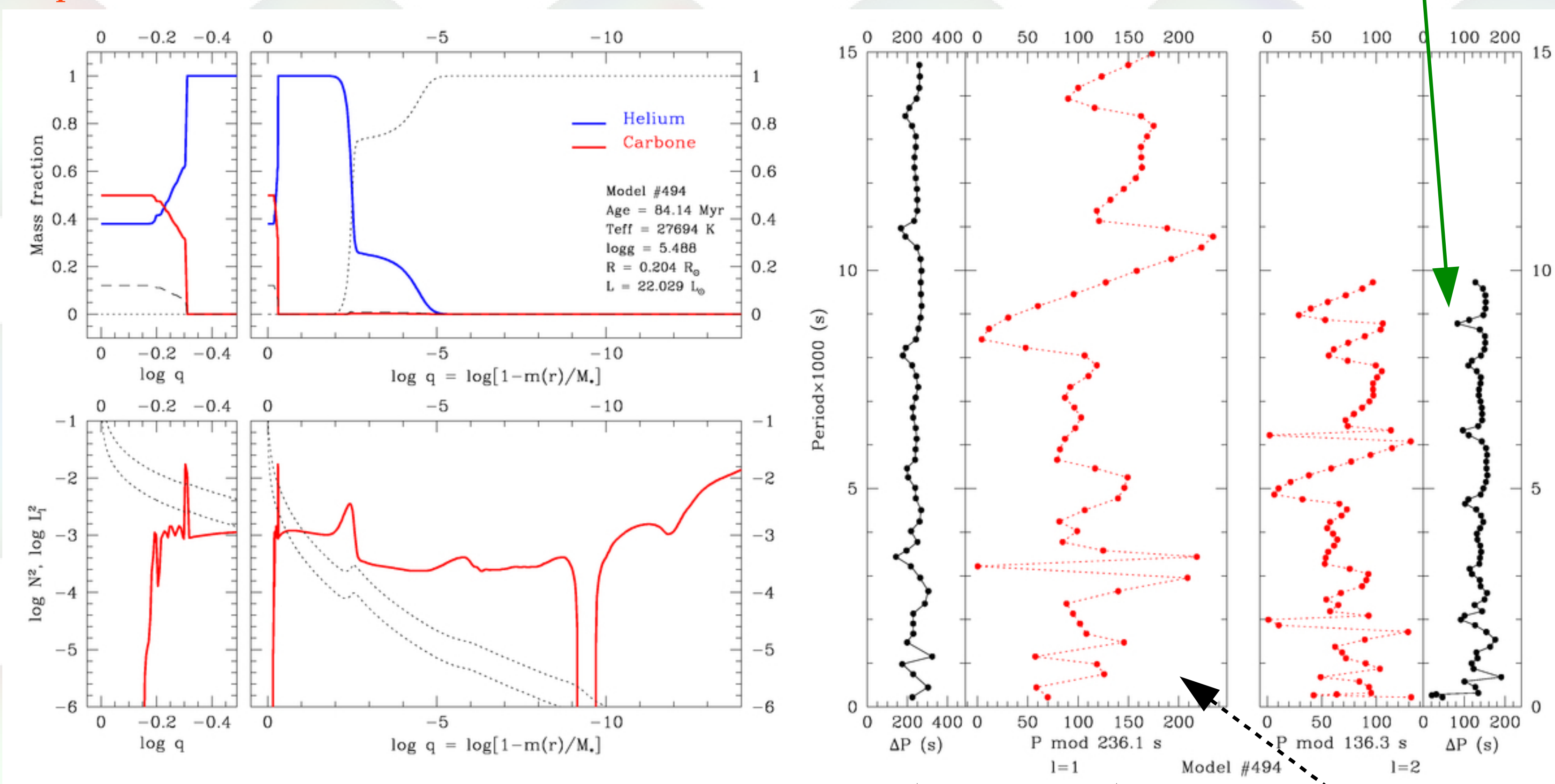
Trapping induced by the helium burning core

The envelope transition is not the only source of trapping

<u>Low frequencies</u>
Signature of composition layering

The semi-convection phase

Chemical composition



Radial order k increases

Brunt-Väisälä
frequency profile

Period
spacings

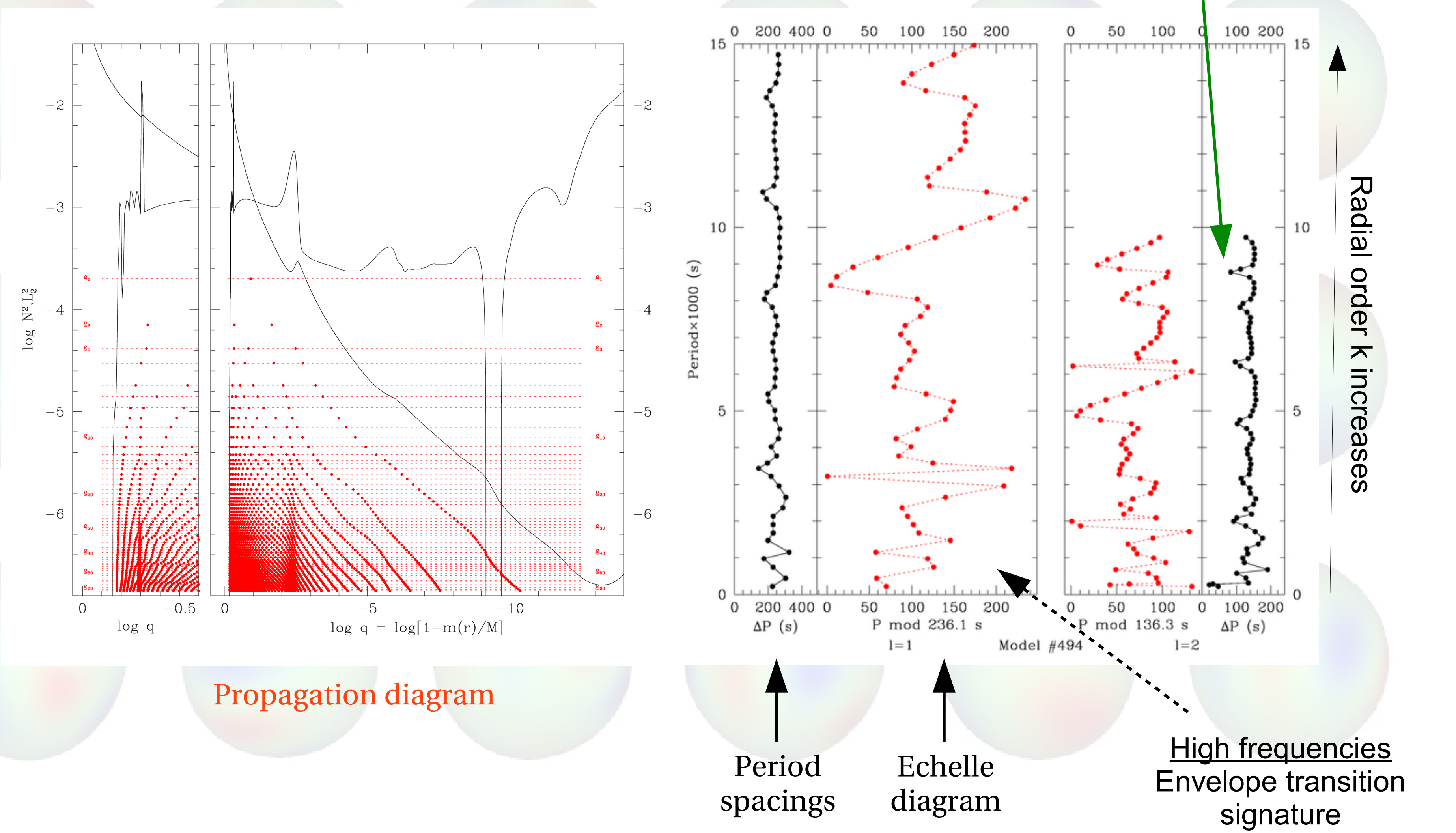
Echelle
diagram

<u>High frequencies</u>
Envelope transition
signature

Trapping induced by the helium burning core

The envelope transition is not the only source of trapping

The semi-convection phase



Propagation diagram

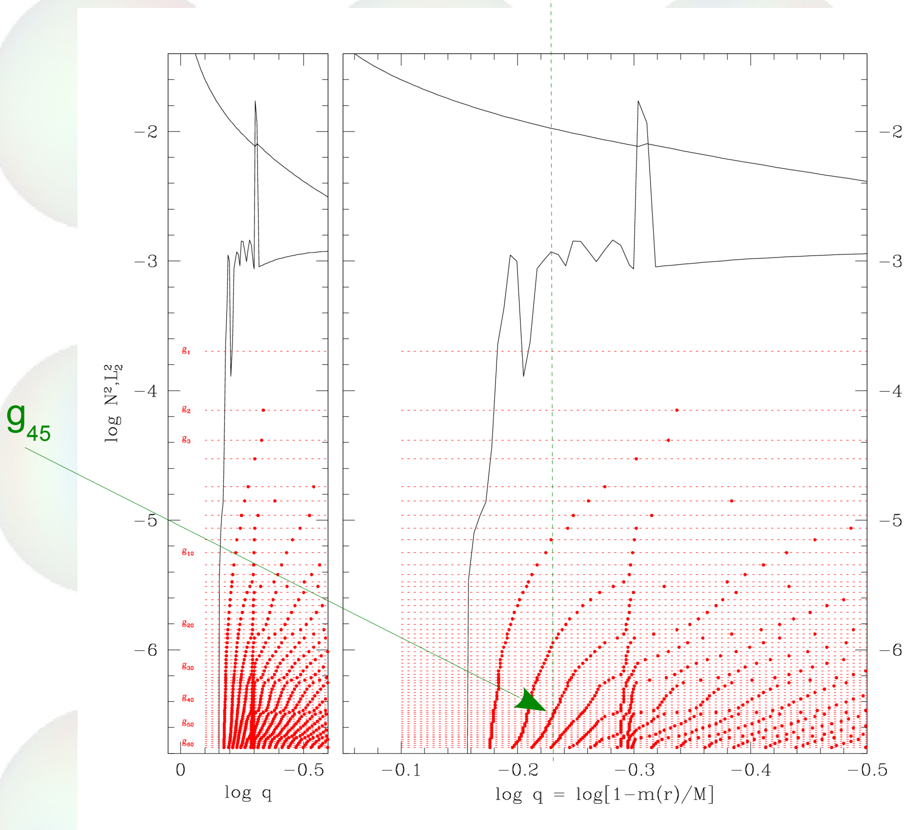
Period spacings

Echelle diagram

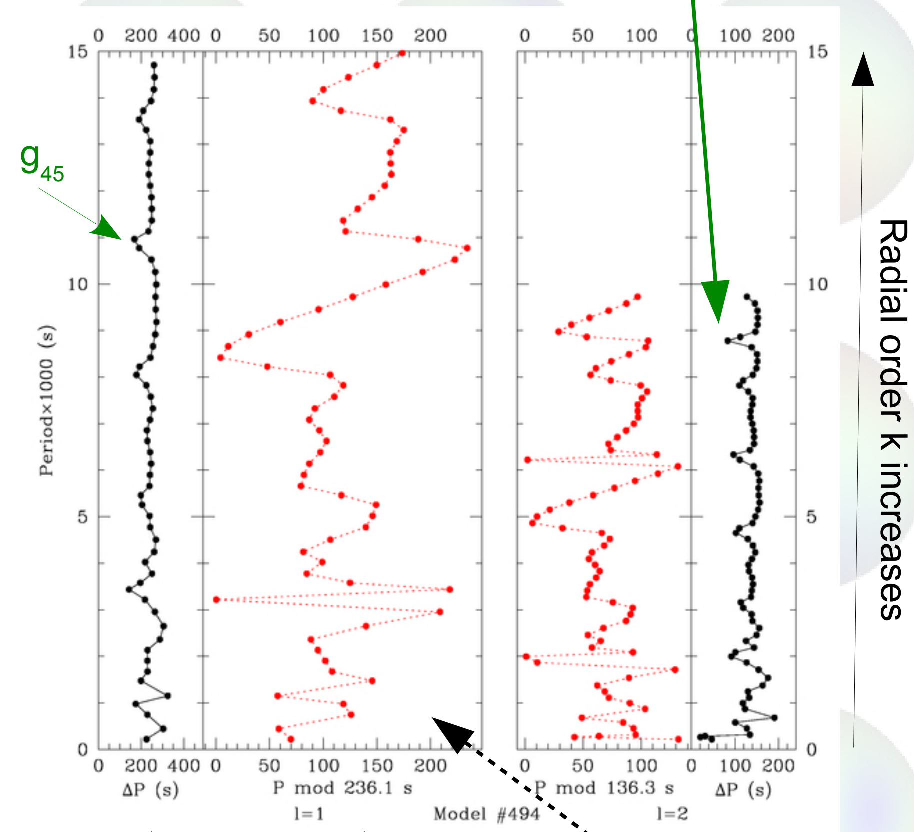
Trapping induced by the helium burning core

The envelope transition is not the only source of trapping

The semi-convection phase



Propagation diagram



Low frequencies
Signature of composition layering

Period spacings

Echelle diagram

High frequencies
Envelope transition signature

Testing semi-convection at the core boundary

Layered or not layered ?

Onset of double diffusive convection (semi-convection)

→ layered chemical stratification in the partial mixing zone

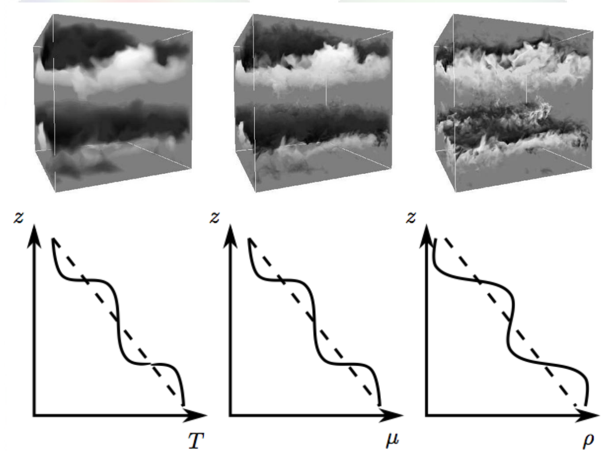
Prescription used : Langer et al. (1985), *A&A*, **145**, 179
Other prescriptions : smooth chemical gradient in PMZ

3D hydro simulations suggest composition layering

Mirouh, Garaud et al. (2012), *ApJ*, **750**, 61
Wood, Garaud et al. (2013), *ApJ*, **768**, 157
Kupka et al. (ANTARES code), private communication

But are layers stable long enough in stellar core conditions ?
Do they exist at all in stars ?

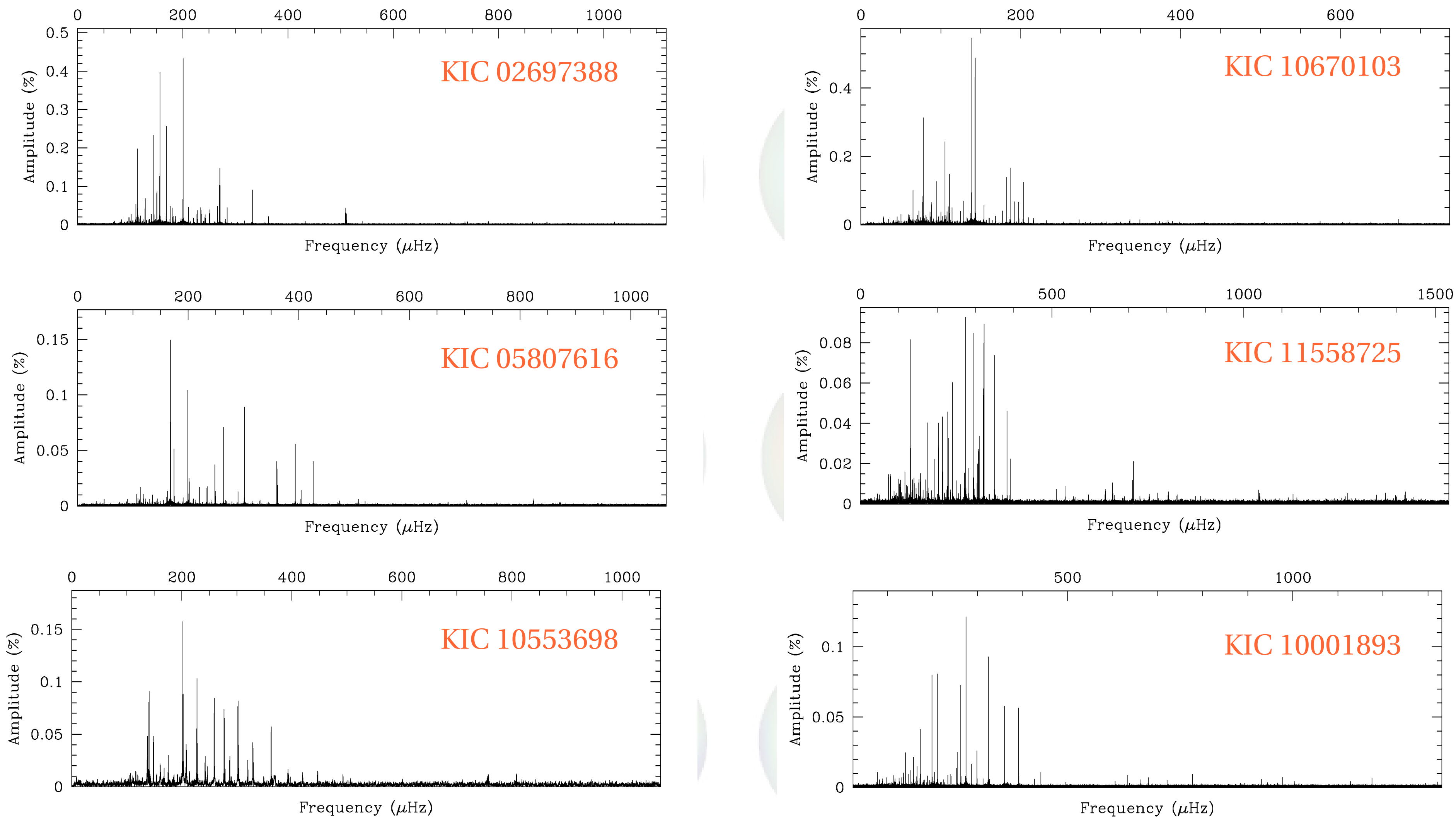
From Wood et al. (2013)



If such layering occurs, it should have a significant (detectable) impact on low frequency g-modes in sdB stars

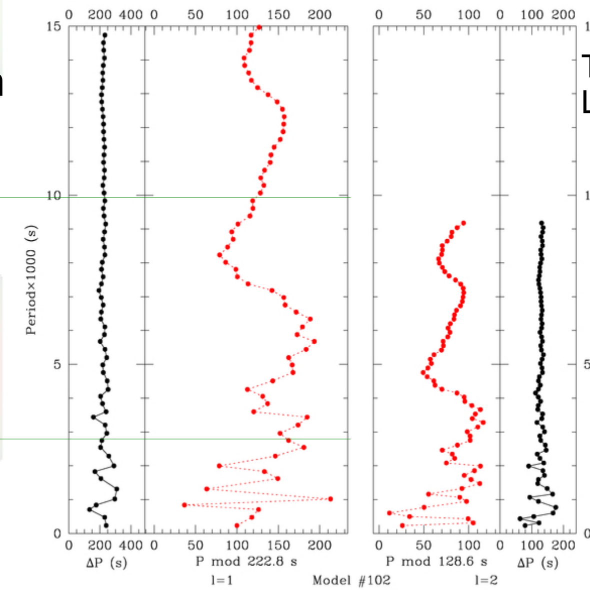
Kepler's view on the g-mode spectrum of sdB stars

A subsample of g-mode sdB pulsators monitored with *Kepler* showing rich g-mode pulsation spectra extending at low frequencies



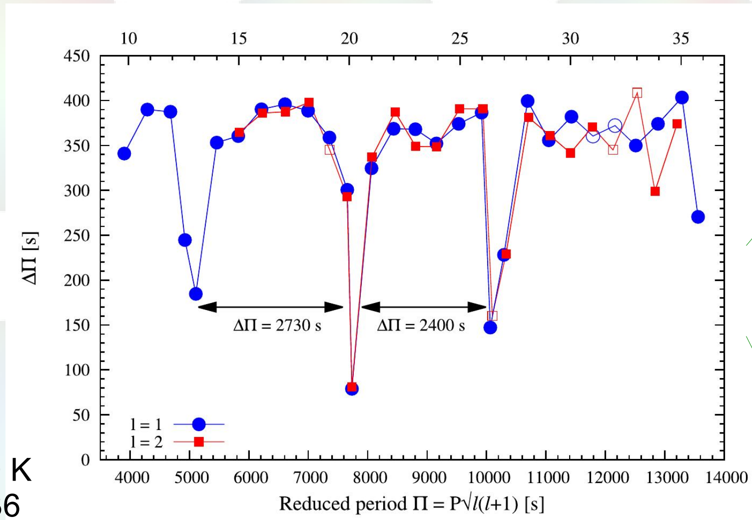
Testing semi-convection at the core boundary

Model with no semi-convection



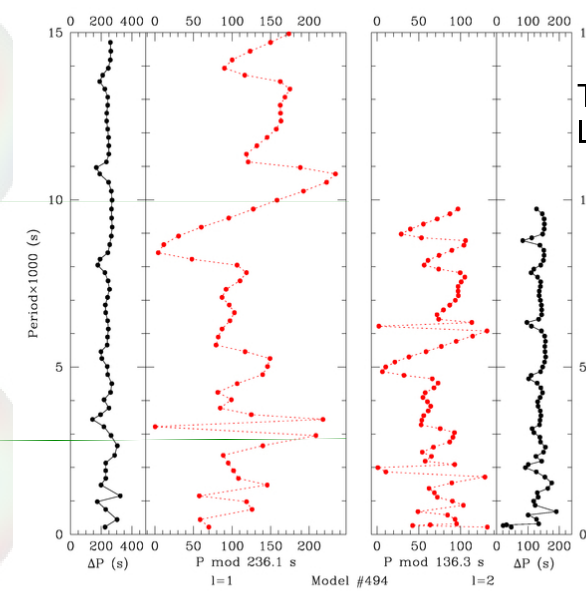
Teff = 28523 K
Log g = 5.666

Trapped mode structure in KIC 10553698A



Teff = 27420 K
Log g = 5.436

From Ostensen et al. 2014, *A&A*, **569**, 15



Teff = 27694 K
Log g = 5.488

→ These trapping structures may be due to core features and not envelope transition

But a global mode fitting approach with model optimization is needed to really conclude on this

Model with semi-convection (layers)

Strategy to exploit this potential

Toward a new (4th) generation of static stellar models for asteroseismology

↓

Incorporate parameterized representations of the chemical stratification in the core

↓

Seismic inversion of the composition stratification obtained as part of
a global forward modeling / optimization procedure

Using the tools we have been developing for quantitative asteroseismology
(see,e.g., M.J. Peters poster)

Conclusion

Pulsating sdB stars (g-mode pulsators) offer opportunities for studying

- The structure and evolution of helium burning cores of low mass stars
- The physics of convection, semi-convection, overshooting (mixing)

The legacy of the *Kepler* mission is particularly important

→ Data for 18 sdB pulsators that have yet to be fully exploited

→ Development / application of our 4^{th} generation models for asteroseismology

+ prospects from future space missions like *TESS* and *PLATO*

→ Dedicated working group focusing on compact pulsators in TASC (*TESS* mission)

→ An equivalent structure will certainly emerge for *PLATO*

Wide foreseen implications :

→ Modeling mixing in stars (convection, overshoot, semi-convection)

→ White dwarf core stratification (that depends on the He-core burning phase)