The theoretical spectra of g-modes in subdwarf B stars

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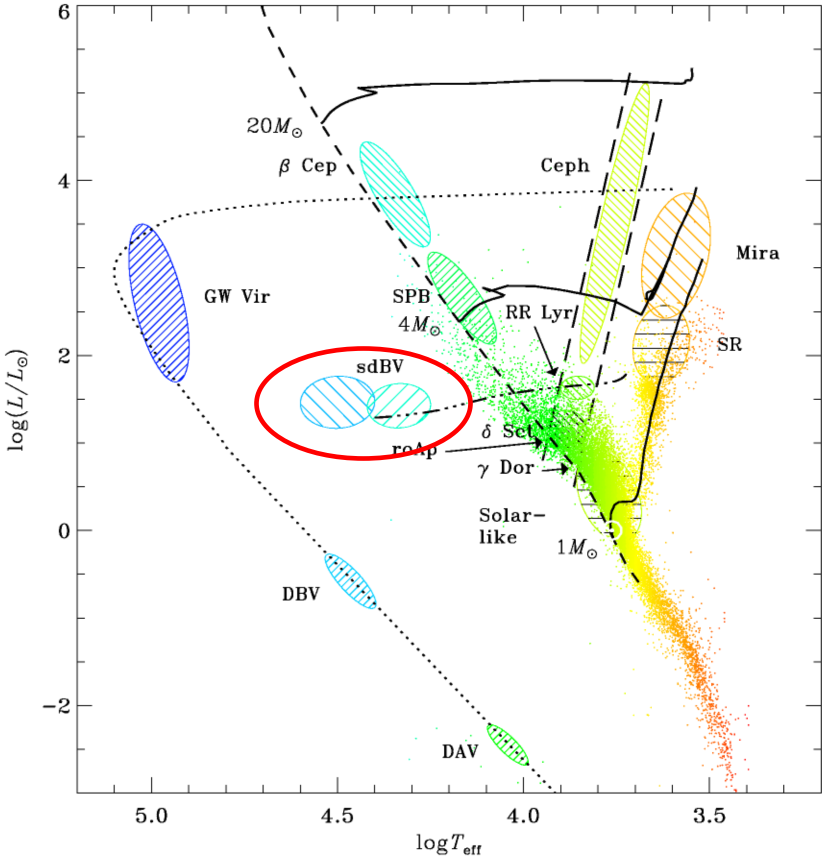
Subdwarf B (sdB) stars

Hot (T_{eff} = 20 000 - 40 000 K) and compact (log g = 5.2 - 6.2) stars
belonging to Extreme Horizontal Branch (EHB)

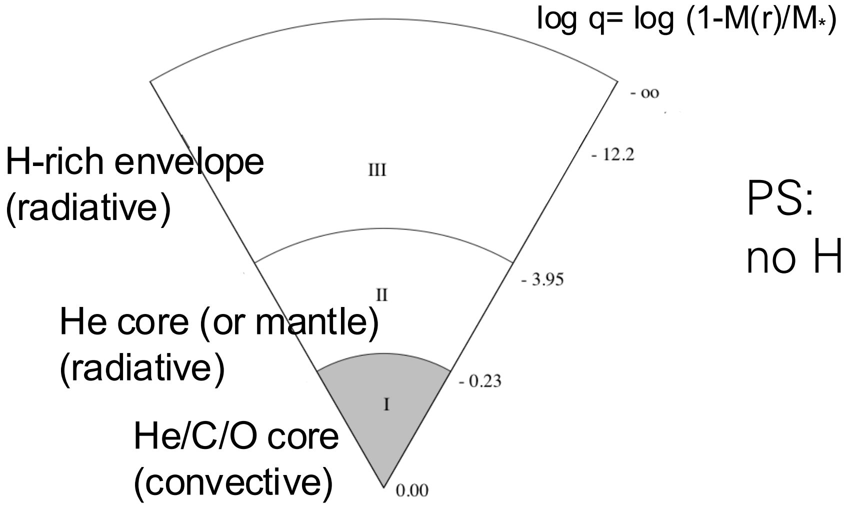
convective He-burning core (I), radiative He core (aka mantle) (II) and very thin H-rich envelope (III)



Two main classes of multi-periodic sdB pulsators:

> short-periods (P ~ 1 - 10 min), A ≤ 1%, p-modes

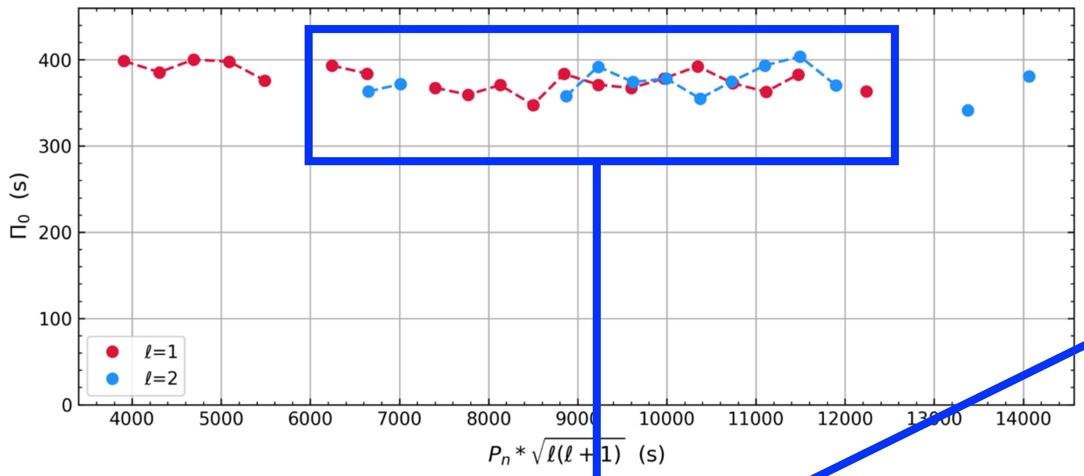
> long-periods (P ~ 0.5 - 3 h), A ≤ 0.1%, g-modes



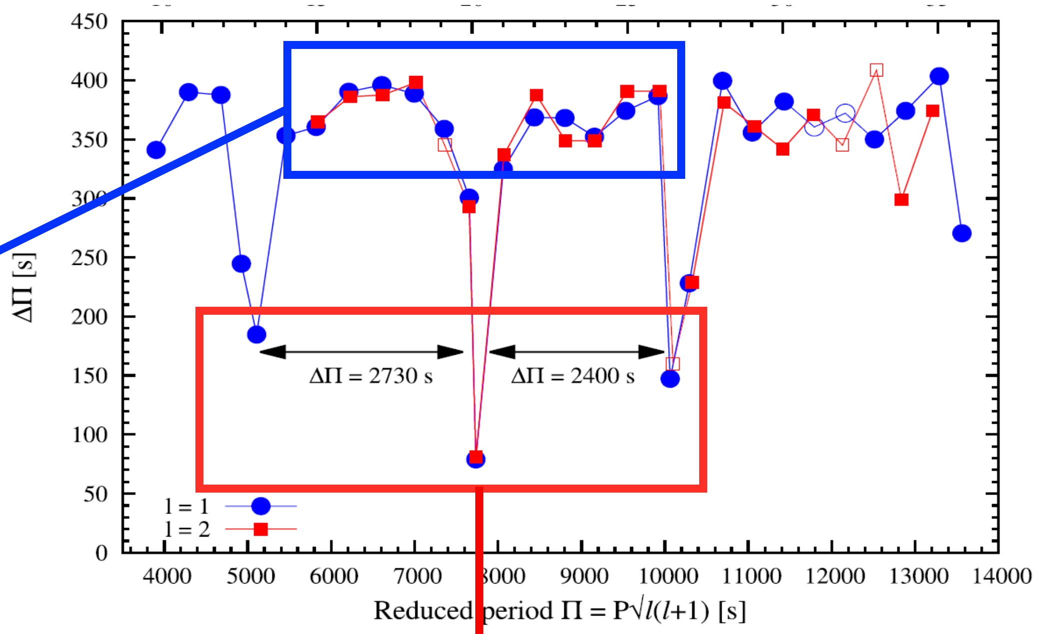
PS:
no H-burning shell

sdB g-mode pulsators in Kepler and TESS

TIC 441725813 (2 years of data), Su et al. 2024



KIC 10553698 (3 years of data), Ostensen et al. 2014



The majority of sdB stars by TESS and Kepler:
« normal » modes

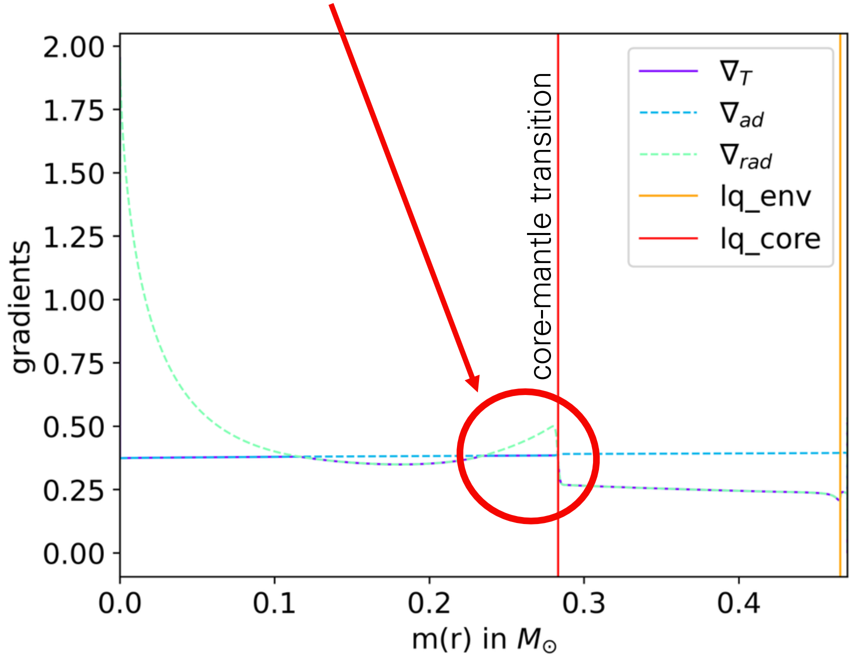
3 (confirmed) on 16 Kepler pulsators, one K2 star, hints for some TESS targets: « trapped » modes

Trapping cavity constraint
(yet to be formally identified for sdB stars)

The convective/radiative core transition problem

Old well-known problem for core-He burning (CHeB) stars:

As He burns, the radiative temperature gradient (∇_{rad}) grows and develops a minimum => at some point, it surpasses the adiabatic gradient (∇_{ad}) => splitting of the core in two separate convection zones ? Non physical !



= mantle-envelope transition

= core-mantle transition

Possible (1D) solutions:

(1) semi-convection (composition adjusted to produce $\nabla_{rad} = \nabla_{ad}$ => smooth mixing of elements), aka convective premixing scheme in MESA

(2) Maximal overshoot or predictive mixing in MESA (Constantino et al. 2015)

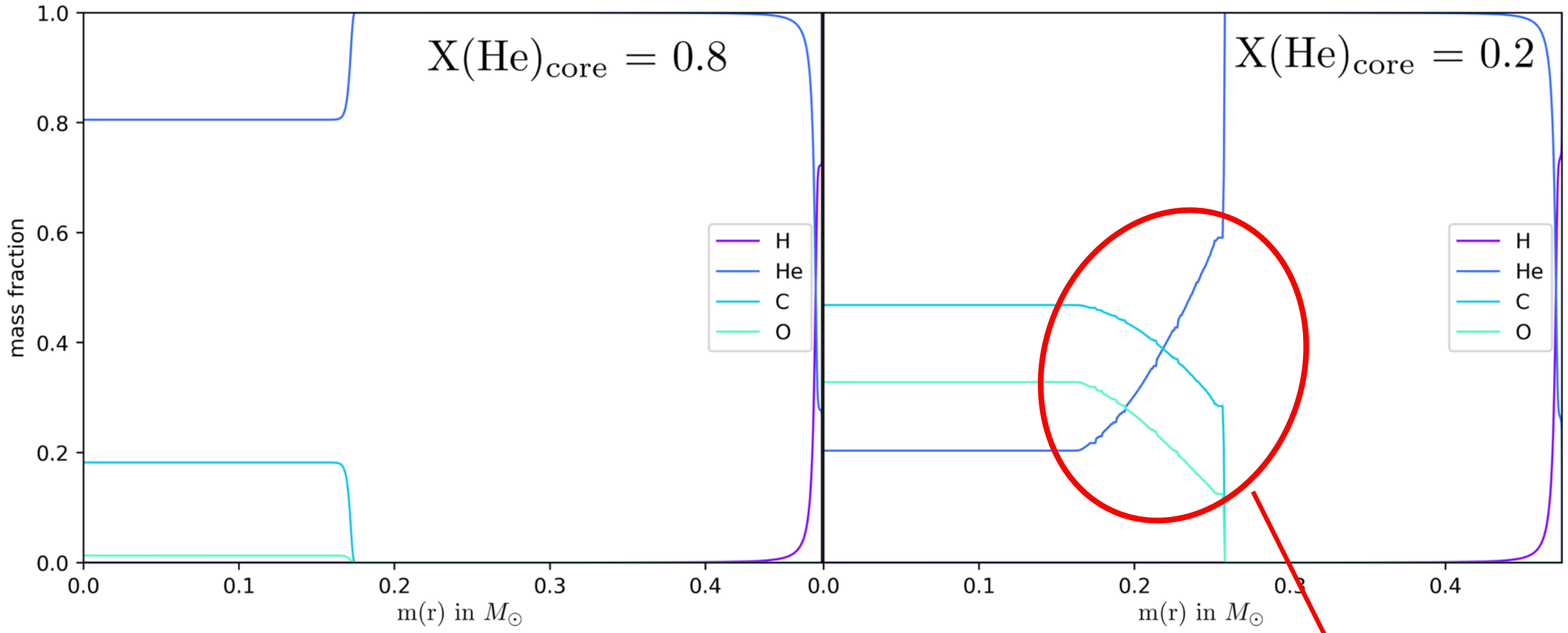
(3) « 1D simulation » by interaction between convection, overshooting and gravitational settling (implemented in STELUM)

STELUM models for sdB stars

Evolutionary models

with « 1D simus » by following in time the interactions between convection, overshooting and gravitational settling

Chemical profiles at $X(He)_{core}$=0.8 (left) and $X(He)_{core}$=0.2 (right)

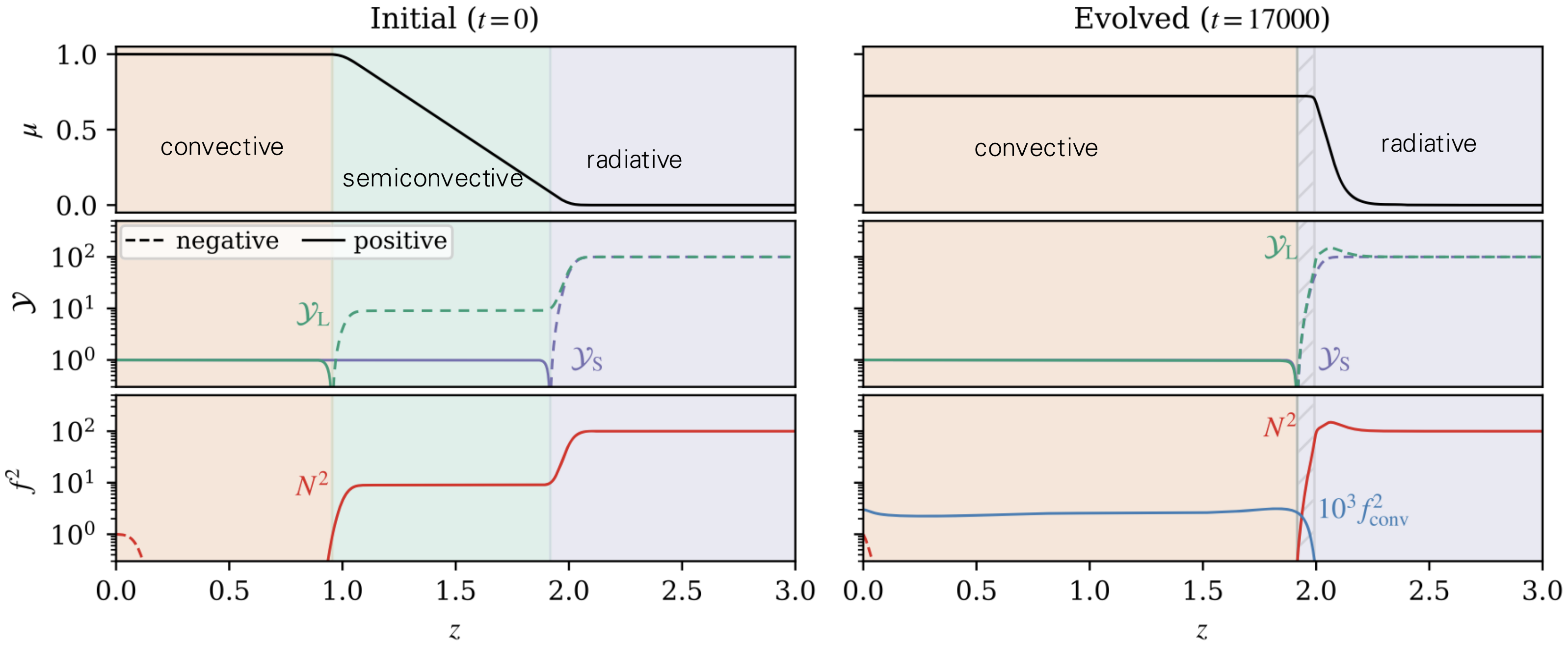


Semiconvection as Partial Mixing Zone (PMZ)

The convective/radiative core transition problem

Recent hydrodynamical simulations (3D: Blouin et al. 2024; Anders et al. 2022; 2D: Baraffe et al. 2023; 2.5D and 3D: Andrassy et al. 2024):

NO SEMICONVECTION/PARTIAL MIXING ZONE ABOVE CONVECTION ZONES

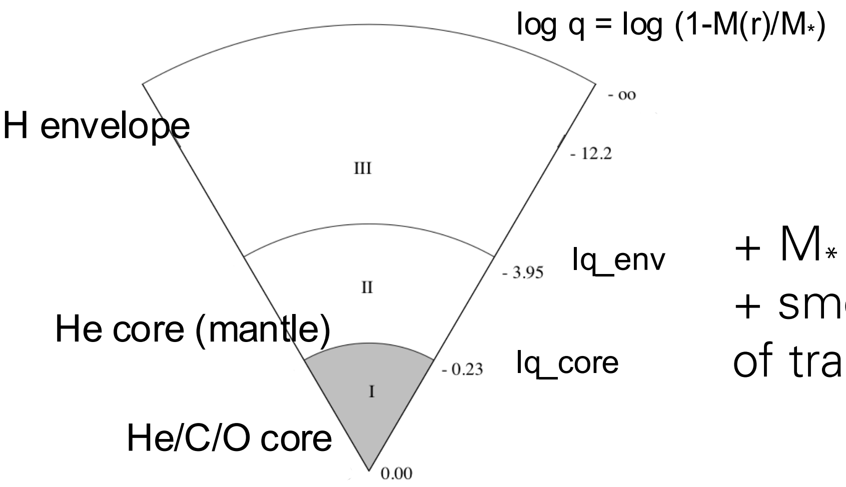


Anders et al. 2022

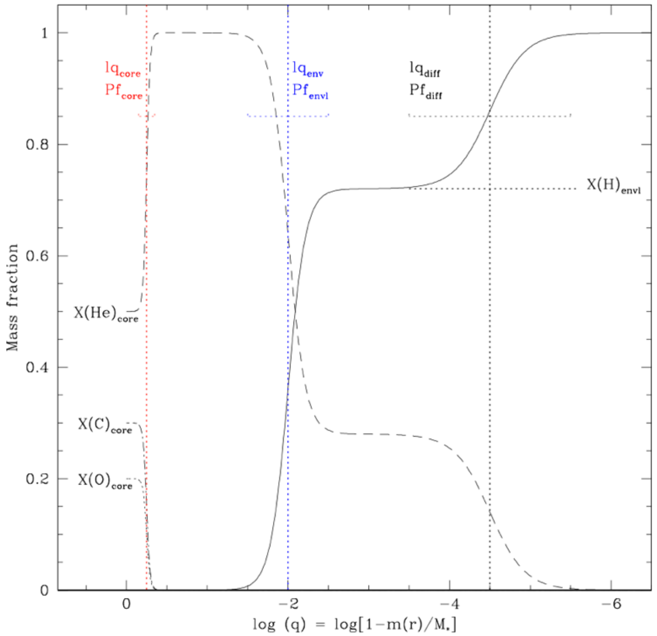
STELUM models for sdB stars

Static (parametric) models, for capturing by seismic modeling the « instantaneous » structure of an sdB star (the very definition of a « seismic model »)

- Complete structure models in thermal and mechanical equilibrium, currently in their 4th generation (4G)



+ M_*
+ smoothness of transitions

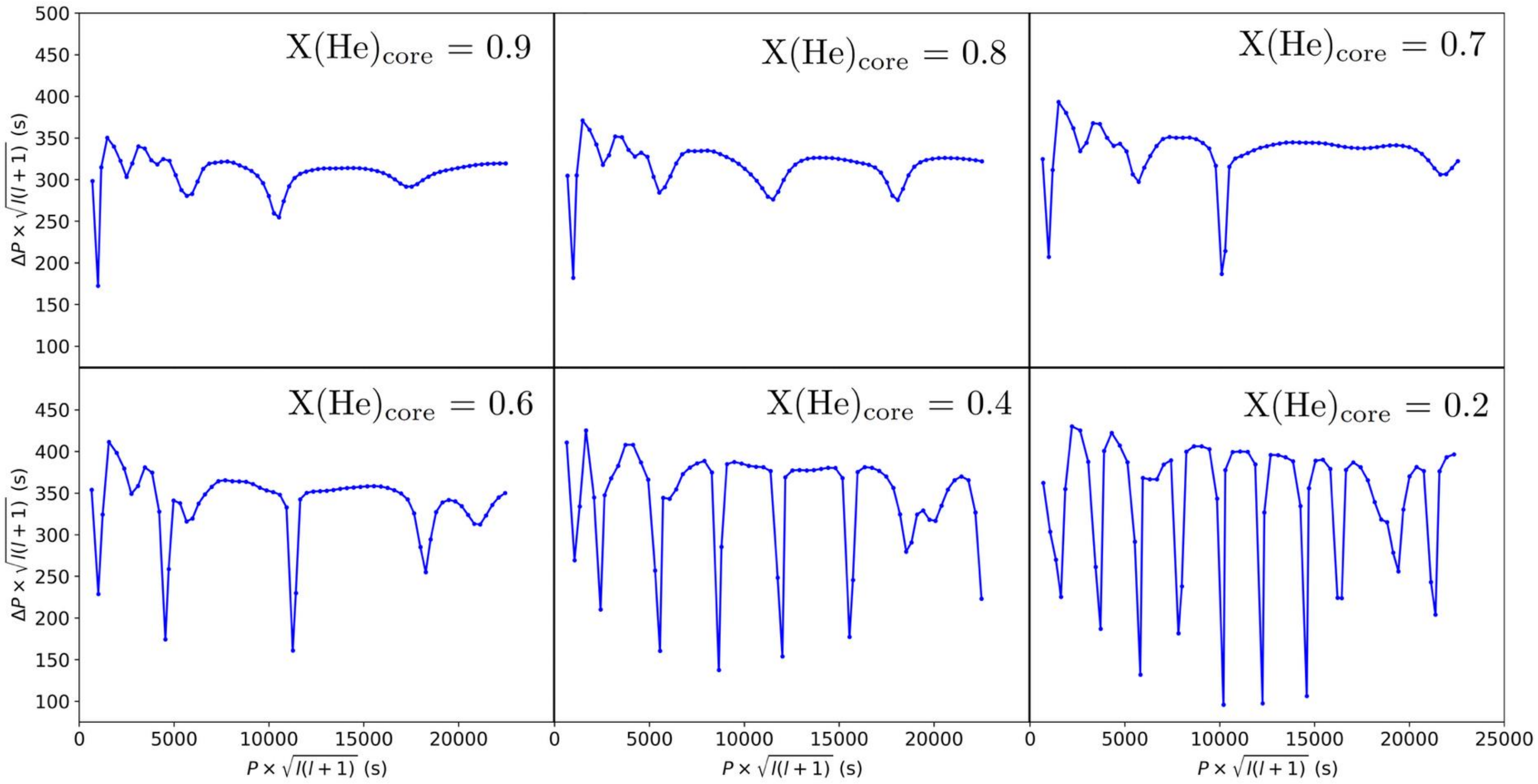


- **4G models:** Decoupled structural (set by lq_core, lq_env, etc) and thermal (set by Schwarschild criterion) stratifications
- **4G+ models:** same, but imposing $\nabla_T = \nabla_{ad}$ below lq_core (=> close to 3D simus results)

Model spectra for g-modes in sdB stars

Reference evolutionary sequence: 0.47 Msun, lq_env=-2, at decreasing $X(He)_{core}$

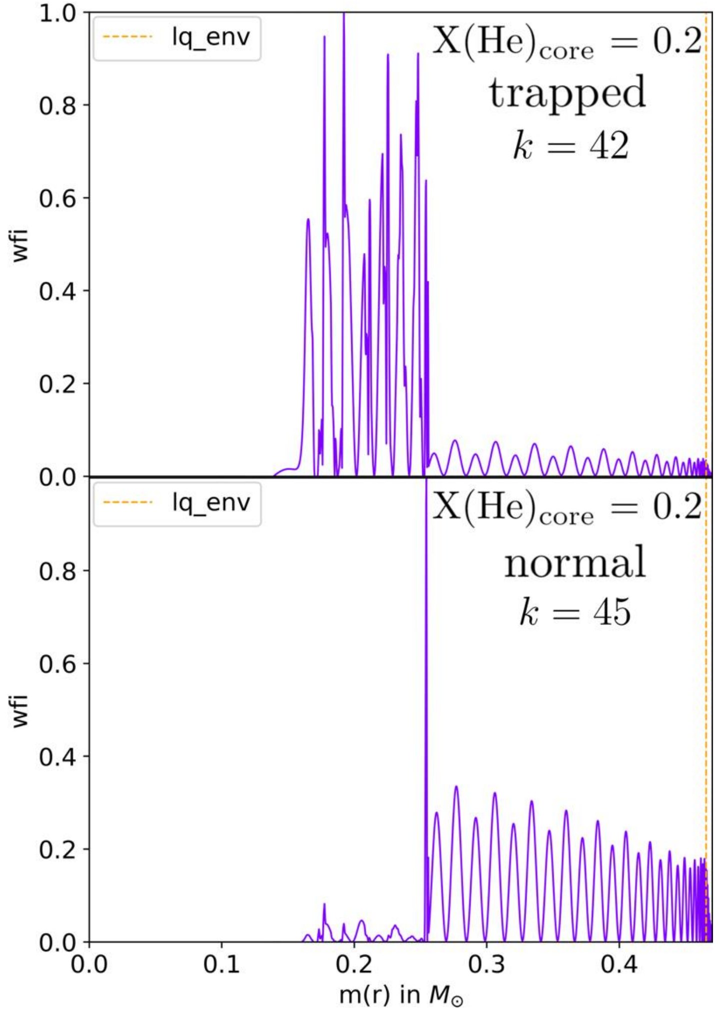
Reduced period spacing diagram:
reduced period spacing as a function of reduced period

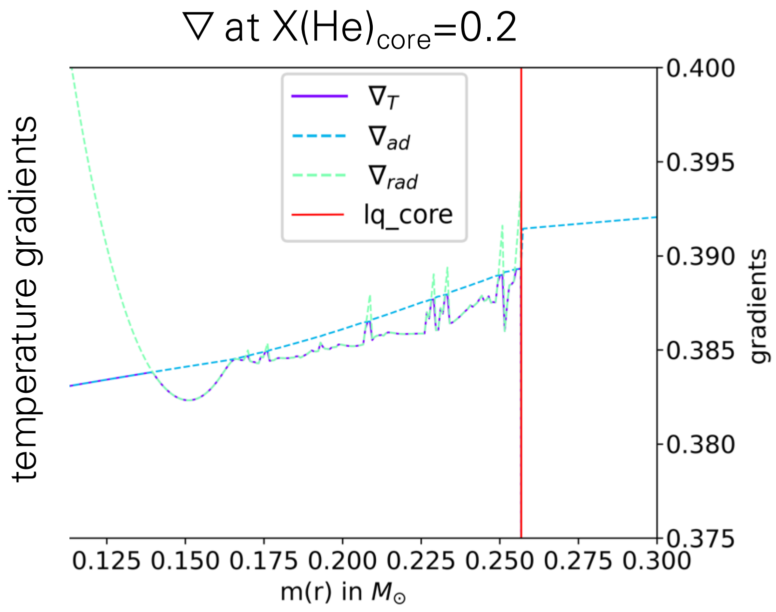


Weak trapping (« wavy spectra ») evolving to stronger trapping (deeper and more numerous minima) as the star evolves

Reference evolutionary sequence: Identification of trapping regions

Weight functions (**give the contribution of the different regions of the star on the frequencies of the modes)** for a trapped and a normal mode, $X(He)_{core}$=0.2

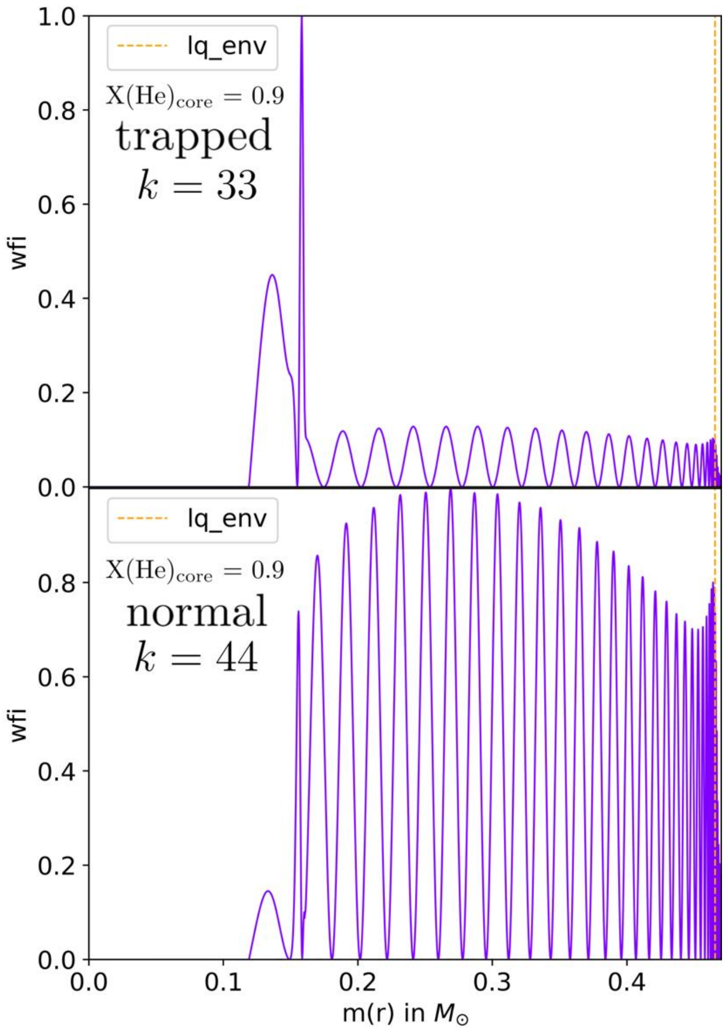




The trapping region at $X(He)_{core}$=0.2 is the semiconvection (partial mixing) zone. Strong trapping

Reference evolutionary sequence: Identification of trapping regions

Weight functions for a trapped and a normal mode, $X(He)_{core}$=0.9



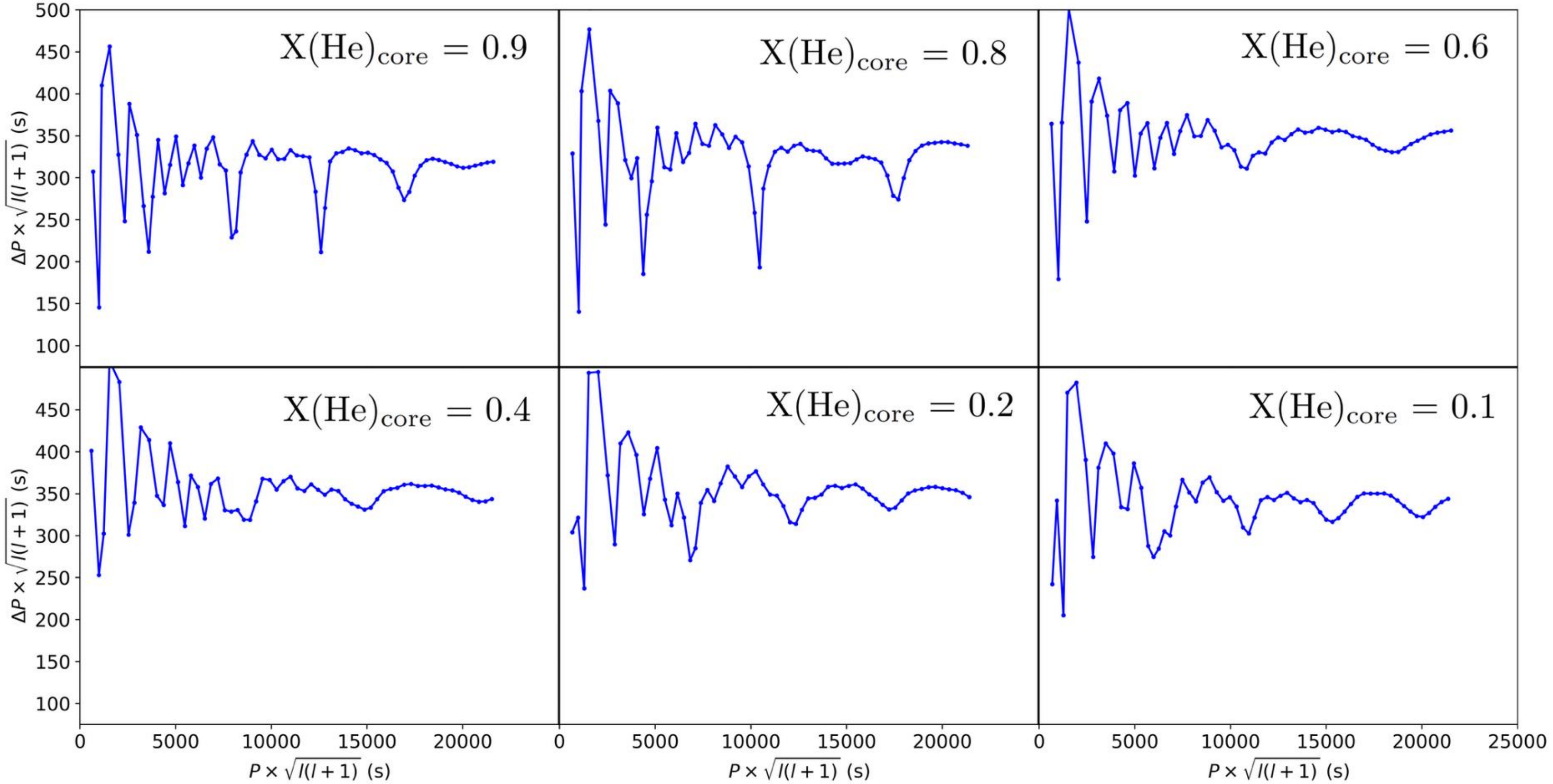
A trapped (normal) mode has a high (low) amplitude in the overshooting region and a low (high) amplitude in the radiative core.

So at high X(He)core, before the onset of semiconvection:

Trapping region= overshooting zone
Weak trapping

Model spectra for g-modes in sdB stars

Static 4G reference model: 0.47 Msun, lq_core=-0.25, lq_env=-2, as long as the star evolves



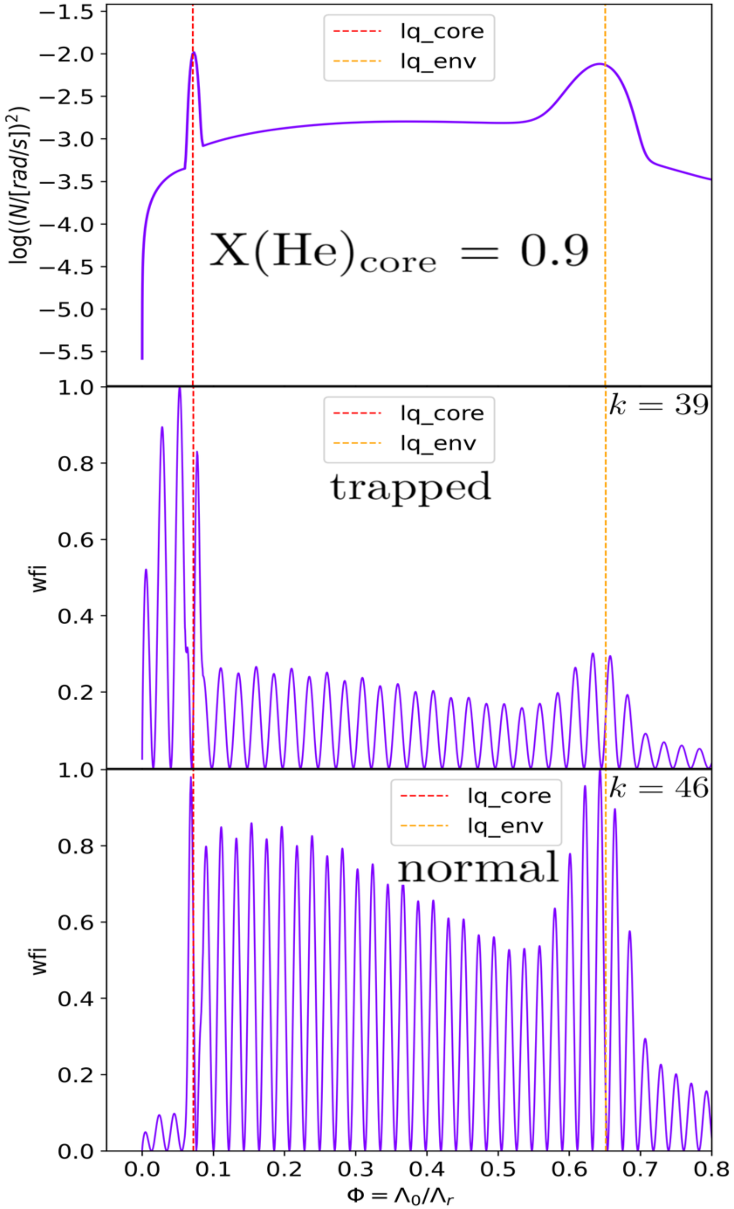
Trapped modes at high $X(He)_{core}$, which progressively disappear as long as the star evolves, to more « wavy » pulsation spectra

Model spectra for g-modes in sdB stars

BV frequency and weight functions as a function of normalized buoyancy radius

For 4G models at $X(He)_{core}$=0.9:
the trapping region is a small radiative region below lq_core
(« overshooting region »)

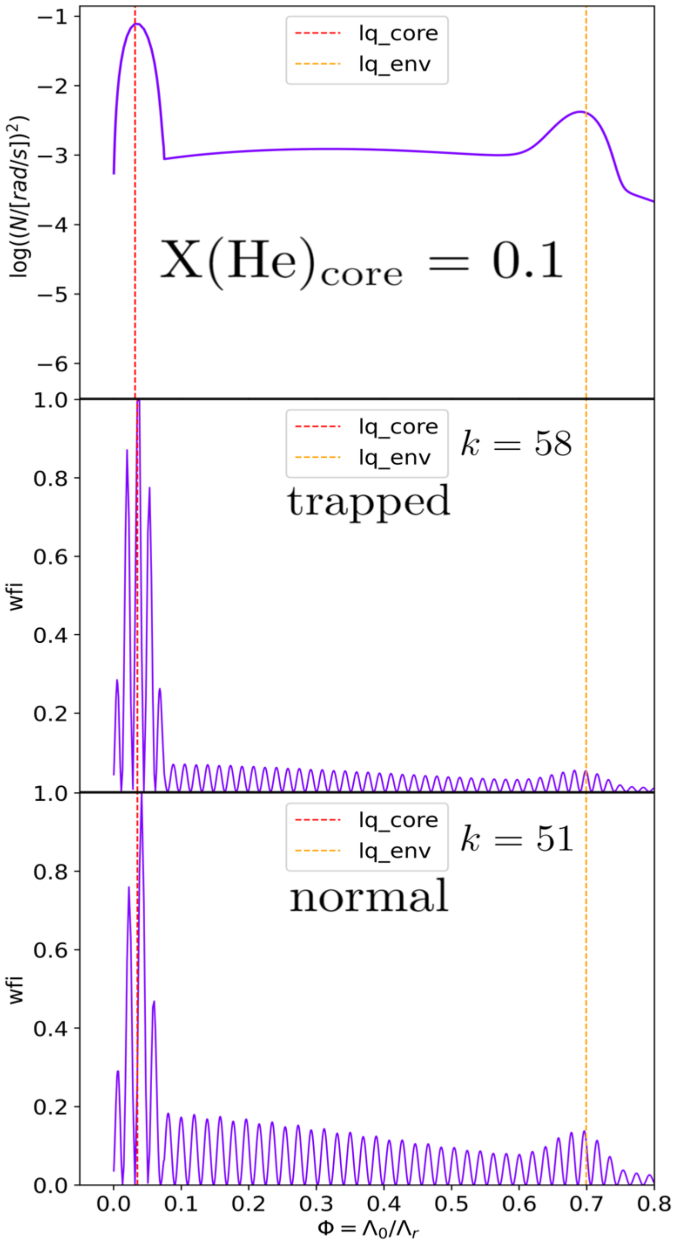
This radiative core disappears as long as the convective part of the core grows with decreasing X(He)core
(lq_core is fixed!)



Model spectra for g-modes in sdB stars

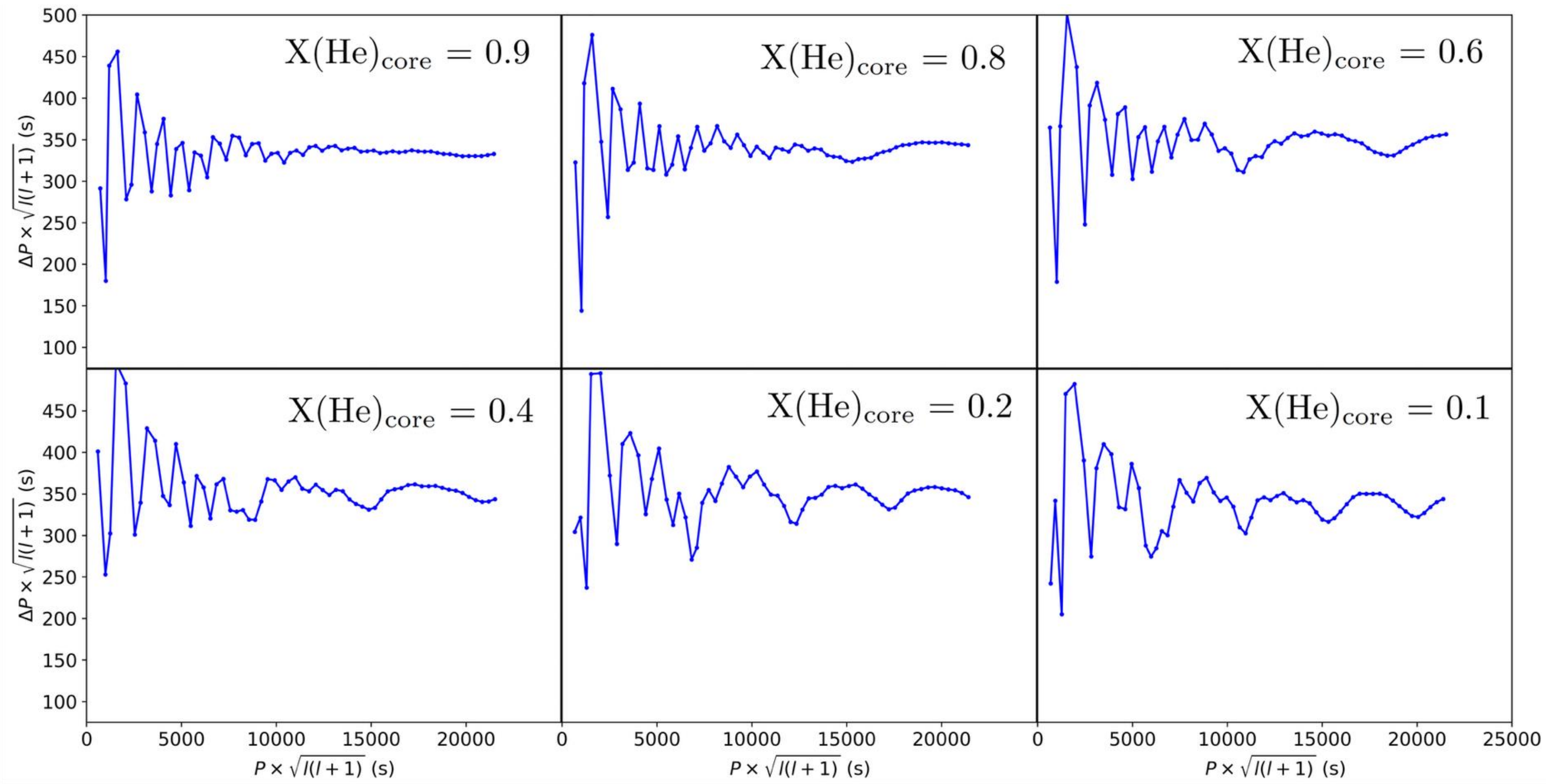
BV frequency and weight functions as a function of normalized buoyancy radius

For 4G models at $X(He)_{core}$=0.1:
Weak trapping of modes in the width of the lq_core transition (« wavy spectra »)



Model spectra for g-modes in sdB stars

4G+ g-mode spectra as long as the star evolves. **Remind: the core (the region below lq_core) is imposed to be always fully convective in 4G+ models**



Flat (regular spacing, no trapping) spectra at high $X(He)_{core}$!

Low X(He)core: similar to 4G models (the region below lq_core is fully convective anyway)

Model spectra for g-modes in sdB stars

Want full details (influence of total mass, core mass/size, envelope mass, etc.)?

A&A, 696, A13 (2025)
https://doi.org/10.1051/0004-6361/202452423

Astronomy & Astrophysics

The theoretical pulsation spectra of hot B subdwarfs

Static and evolutionary STELUM models

N. Guyot[1,★], V. Van Grootel[1], S. Charpinet[2], M. Farnir[1], M.-A. Dupret[1], and P. Brassard[3]

Model spectra for g-modes in sdB stars

- In summary, for static models:

High He-core abundance (ZA-EHB)

All core sizes (-0.40<lq_core<-0.10):

- 4G models: strong trapped modes in the radiative region below lq_core
- 4G+ models: regular period spacing for high-order g-modes, except for very small cores

Low He-core abundance (TA-EHB)

Large core size (lq_core=-0.4):

- 4G models: strong trapping in the radiative region below lq_core
- 4G+ models: « wavy spectra » or weak trapping in the width of the lq_core transition

Medium and small core sizes (-0.25<lq_core<-0.1):

- 4G and 4G+ models: « wavy spectra » or weak to mild trapping in the width of the lq_core transition

- For evolutionary models:

High He-core abundance (ZA-EHB):

- Weak trapping (« wavy spectra ») in the overshooting region above the convective core

Low He-core abundance (TA-EHB):

- Strong trapping in the semiconvective (partial mixing) region

Model spectra for g-modes in sdB stars

- In summary, for static models:

Take-home messages:

- Presence and strength of trapping depend on the model prescriptions for the structural and thermal stratifications, in particular on the presence of semiconvection or not

- Trapping regions are always related to the convective/radiative core transition

g-modes of sdB stars (CHeB stars) hold a unique opportunity to progress in this problem

- For evolutionary models:

- Weak trapping (« wavy spectra ») in the overshooting region above the convective core
- Strong trapping in the semiconvective (partial mixing) region

Teaser: current work for asteroseismic modeling of sdB stars

General forward modeling approach
(from Brassard et al. 2001 to Charpinet et al. 2019)

+ 5G models (able to mimic a semiconvection zone)

+ automatic mode identification (based on two quality criteria and Genetic Algorithm, N. Guyot)

+ deriving global seismic indicators with EGGMIMOSA (Farnir et al. 2021)

Teaser: current work for asteroseismic modeling of sdB stars

General forward modeling approach

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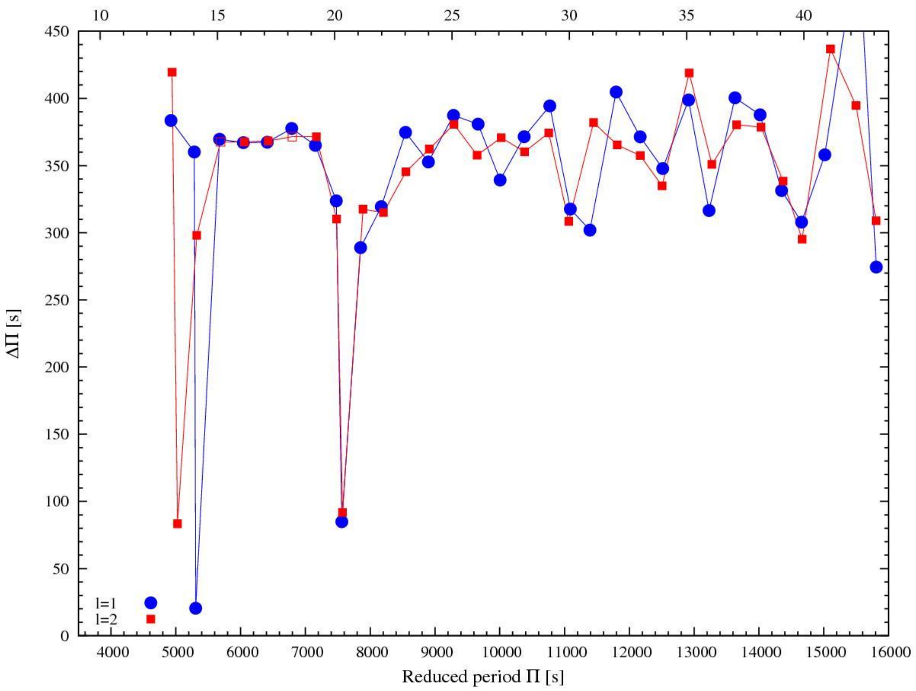
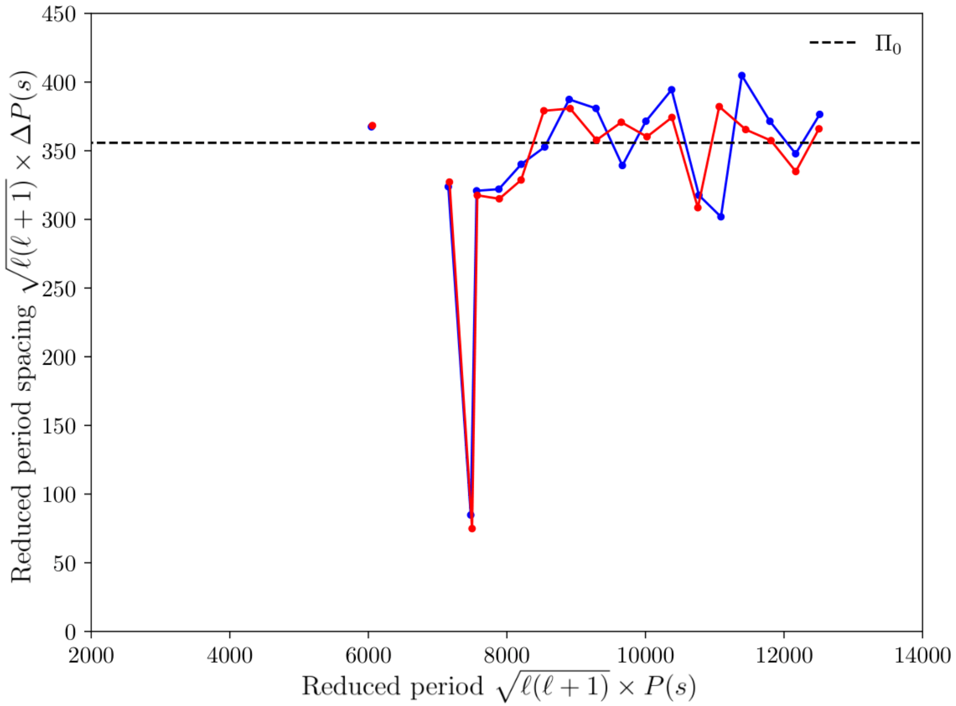
+ automatic mode identification (based on two quality criteria and Genetic Algorithm, N. Guyot)

EPIC 211779126, Baran et al. 2016



Pulsation spectrum recovered by our algorithm



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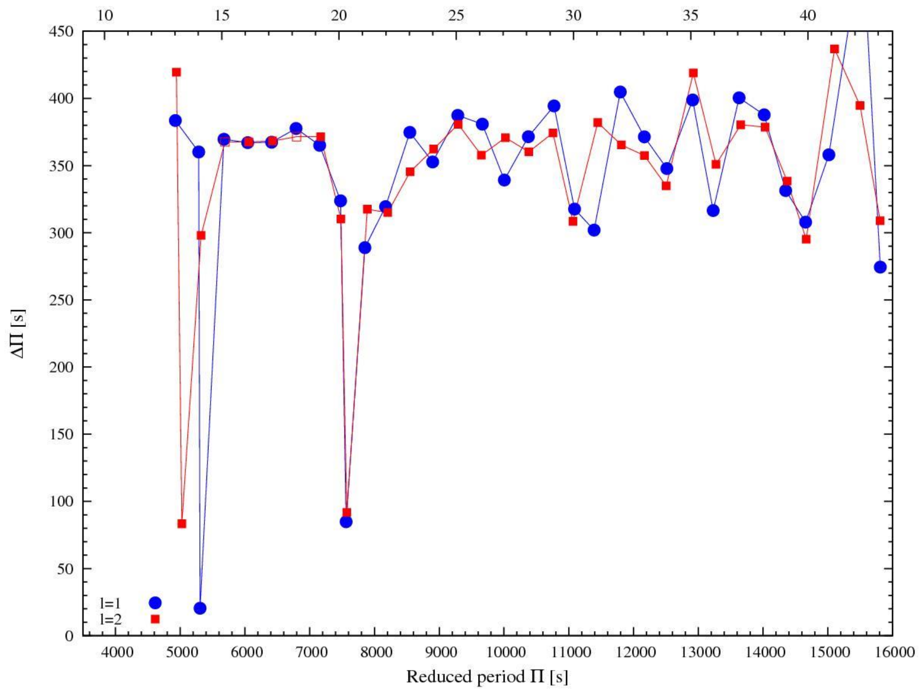
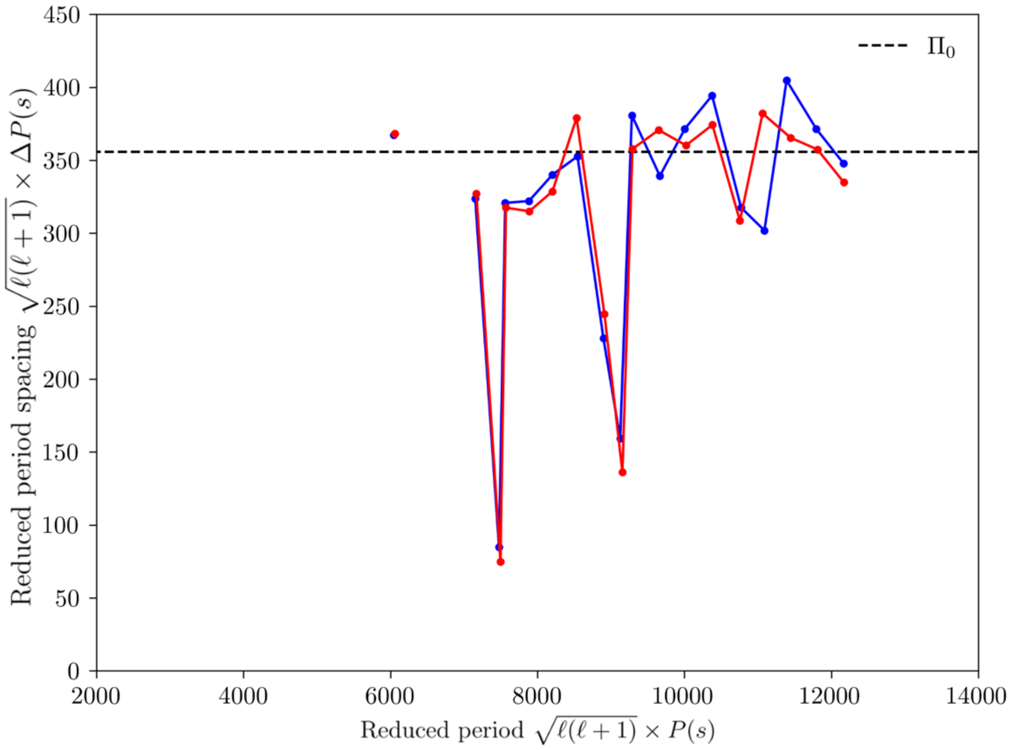


Another pulsation spectrum recovered by our algorithm



Joint conferences announcement

- *IAUS 408: Unraveling the joint lives of Stars and Exoplanets*

August 17-21, 2026

https://pandore.astro.uliege.be/IAUS408
Email: IAUS408@uliege.be

- *PLATO Stellar Science Conference*

August 24-26, 2026
https://plato-stars2026.sciencesconf.org

Liège, Belgium

Venue: salle Académique, Place du XX-août, Liège city center