The instability strip of ZZ Ceti white dwarfs

and its extension to extremely low mass pulsators

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Introduction of Time-Dependent Convection (TDC):
Van Grootel et al. 2012, A&A, 539, 87
Extension to Extremely Low Mass (ELM) pulsators: Van Grootel et al., ApJ, in press

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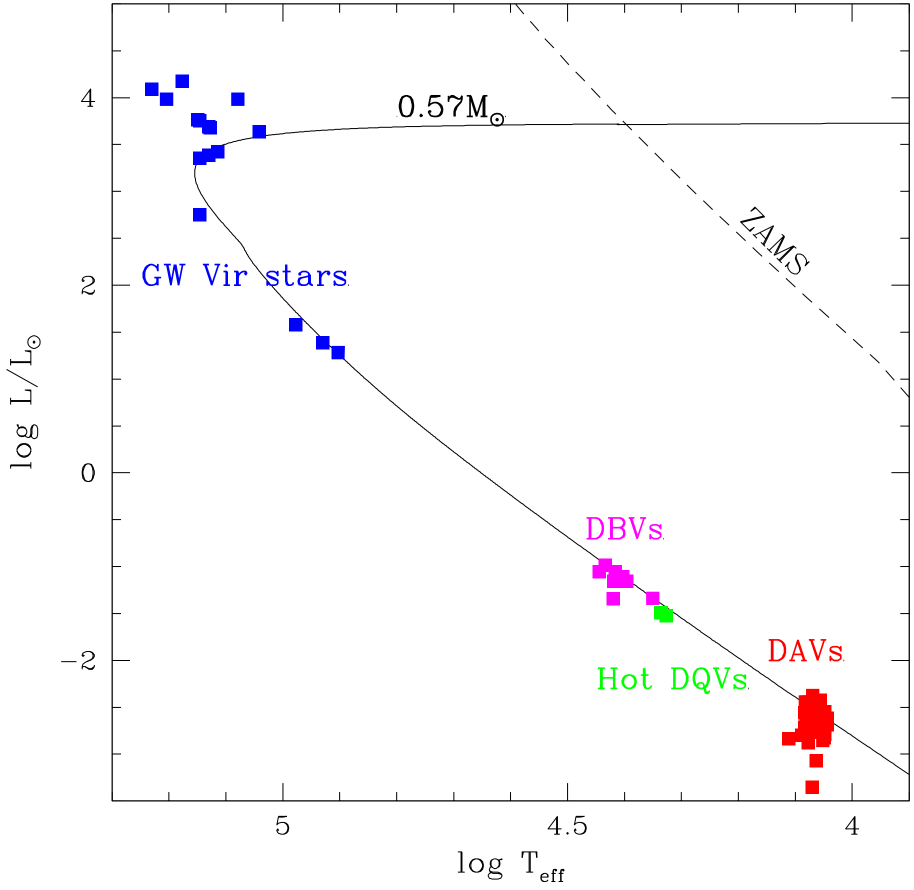
1. Introduction to ZZ Ceti, DA white dwarfs pulsators

1. White dwarfs

Late stages of evolution of ~97% of stars in the Universe

DA (H-rich atmosphere): ~80%; DB (no/little H atmosphere): ~20% of WDs



From Saio (2012), LIAC40 proceedings

4 types of g-mode pulsators along the cooling sequence:

- GW Vir stars (He/C/O atmospheres) T_{eff} ~ 120,000 K, discovered in 1979
- V777 Her stars (He-atmosphere), 1982 T_{eff} ~ 25,000 K
- Hot DQ stars (C-rich/He atmosphere) T_{eff} ~ 20,000 K, discovered in 2007
- ZZ Ceti stars (H-atmosphere, DA) T_{eff} ~ 12,000 K, discovered in 1968

Most numerous (~160 known including SDSS+Kepler)

Excitation mechanism of ZZ Ceti stars (general picture)

- Don Winget (1981):

H recombination around T_{eff}~12,000 K

⇒ envelope opacity increase

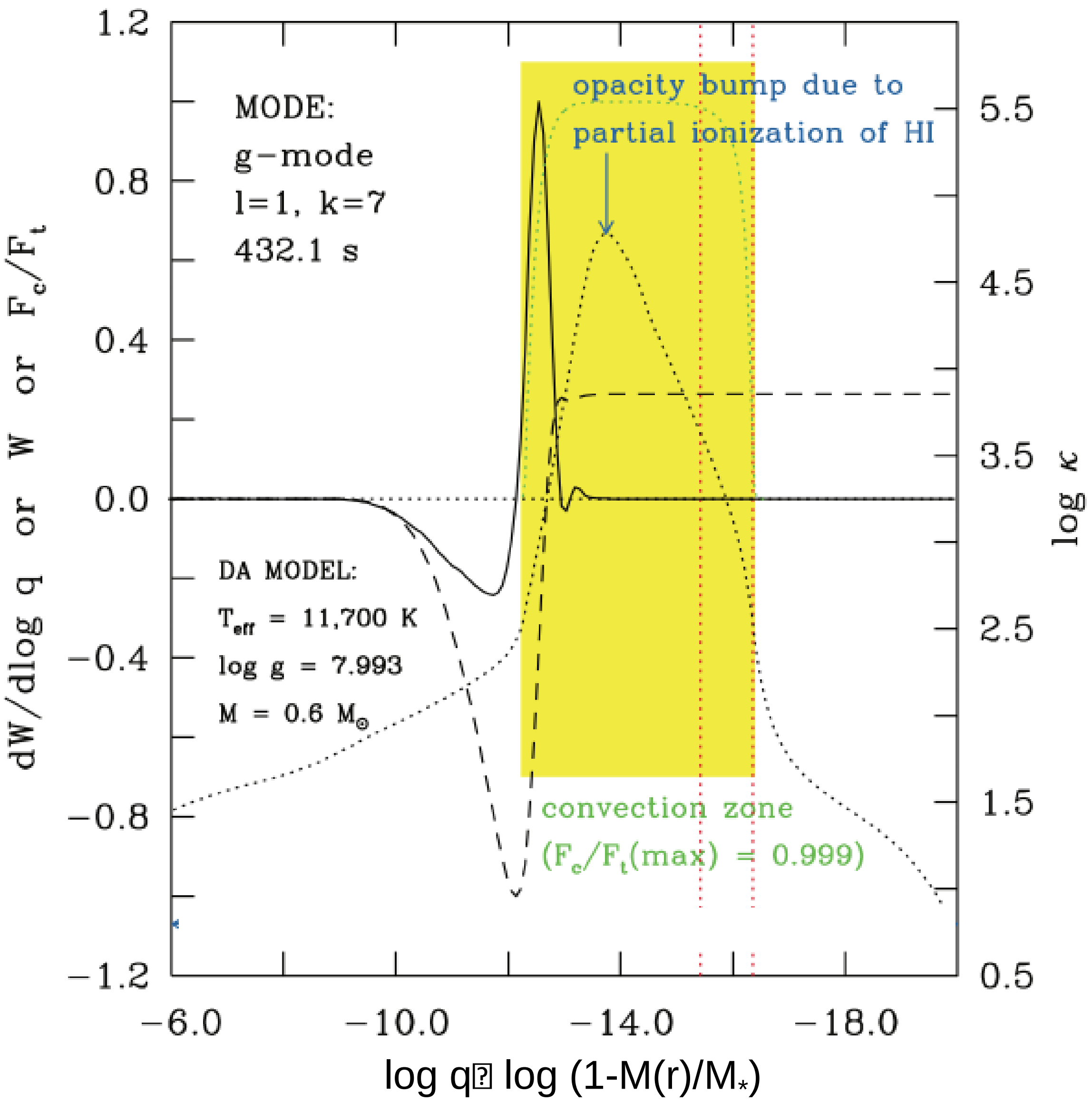
⇒ strangle the flow of radiation

⇒ modes instabilities

- Pulsations are destabilized at the base of the convection zone

(details: e.g. Van Grootel et al. 2012)

“convective driving”



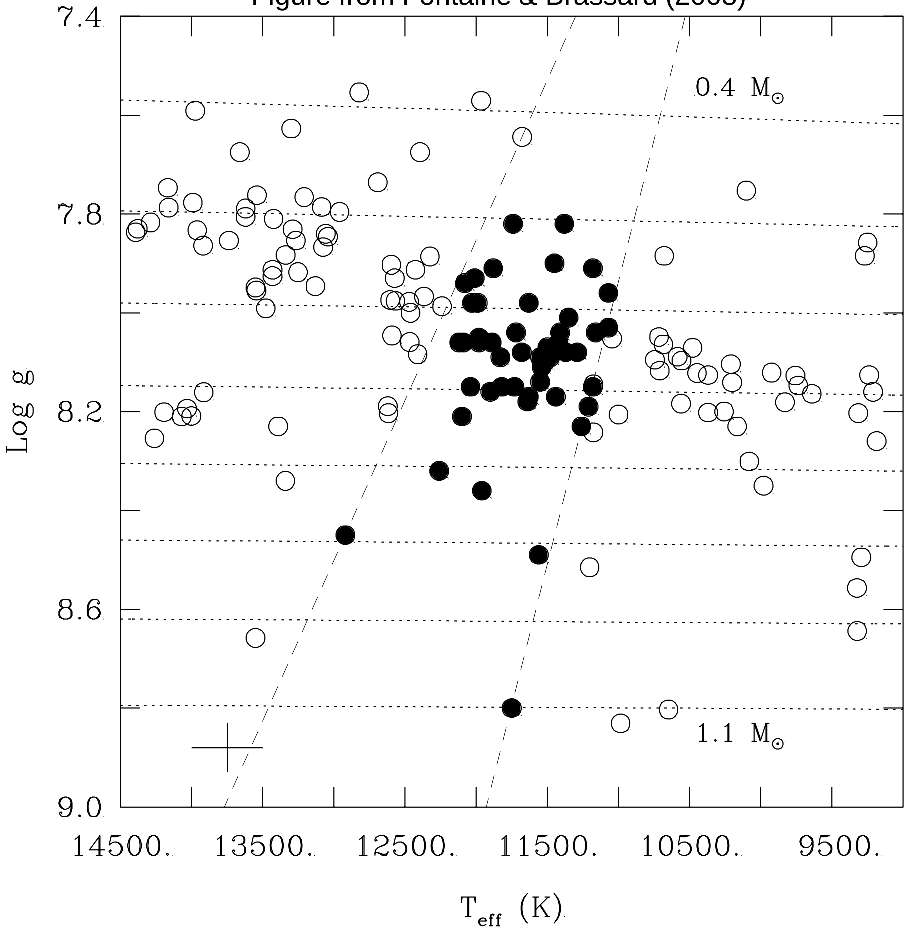
(H envelope)

1. Pulsating DA white dwarfs

Empirical ZZ Ceti instability strip (classic view)

● Observed pulsator ; O non-variable DA white dwarf

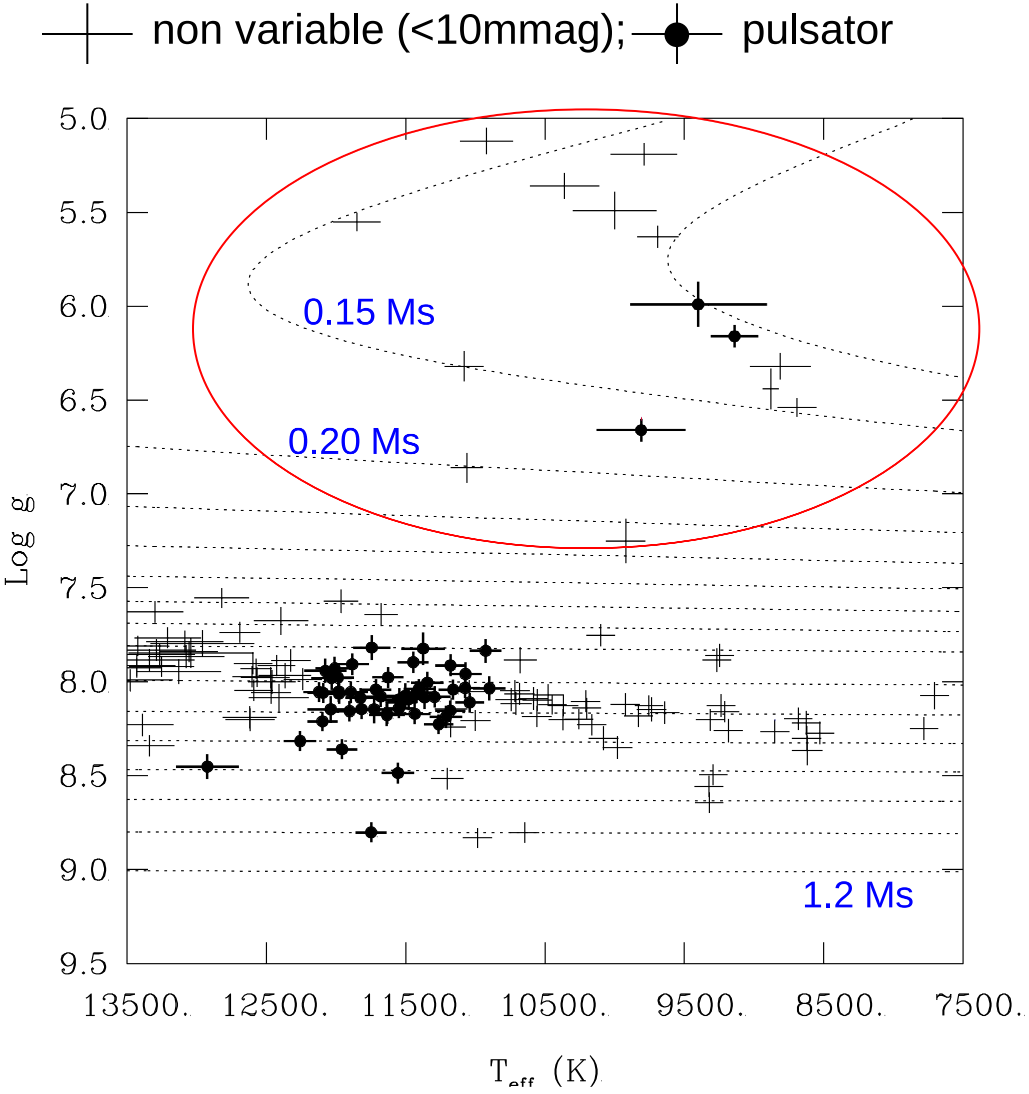
Figure from Fontaine & Brassard (2008)



- Multiperiodic pulsators, observed period range: 100-1500 s (g-modes)
- Reliable atmospheric parameters: work of Bergeron et al., ML2/α=0.6
- Long-term observational efforts: Montreal (Gianninas et al.), Texas (McGraw et al.), Brazil (Kepler et al.), etc. + SDSS
- (most probably) a **pure** strip
- log g/T_{eff} correlation (with a more pronounced slope for red edge): the lower log g, the lower edge T_{eff}

1. Pulsating DA white dwarfs

Empirical ZZ Ceti instability strip (2012 view)



~40 Extremely Low Mass (ELM) DA white dwarfs known (Kilic et al., Brown et al. 2010-2012)

Spectroscopic estimates from model atmopsheres of D. Koester, ML2/α=0.6

Hermes et al. (2012a,b): 3 ELM pulsators (SDSS J1840+6423, J1112+1117, J1518+0658)

Multiperiodic pulsators, 1500-5000 s

2. Evolutionary ZZ Ceti Models

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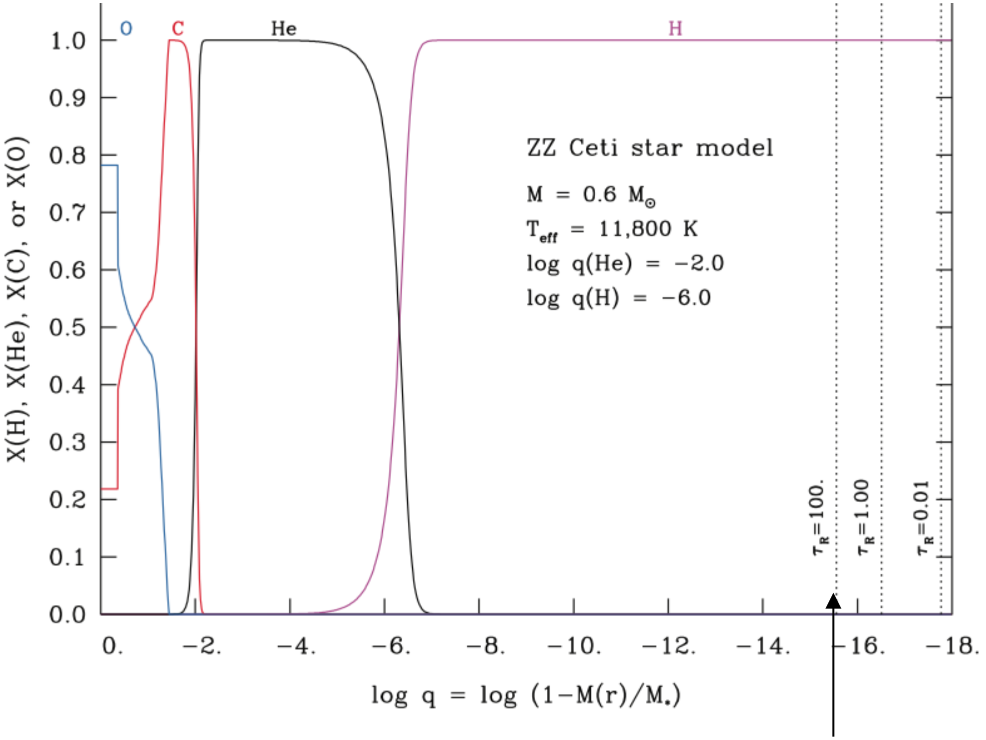
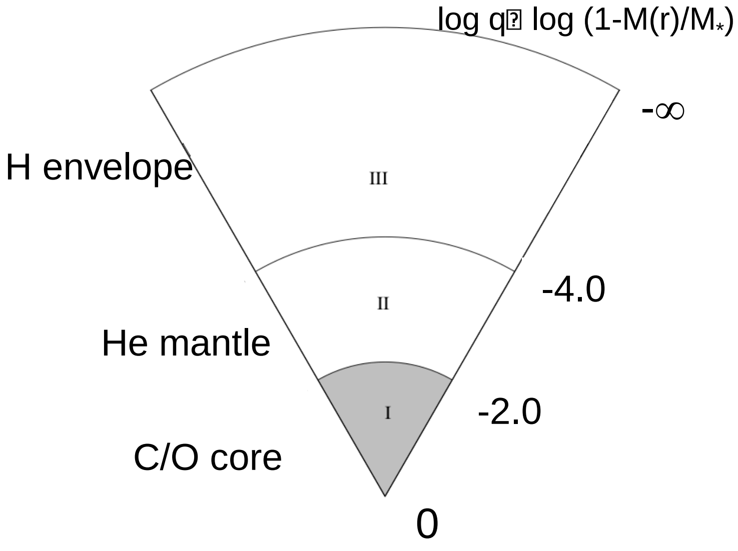
- A standard ZZ Ceti model (C/O core)

"onion-like" stratification

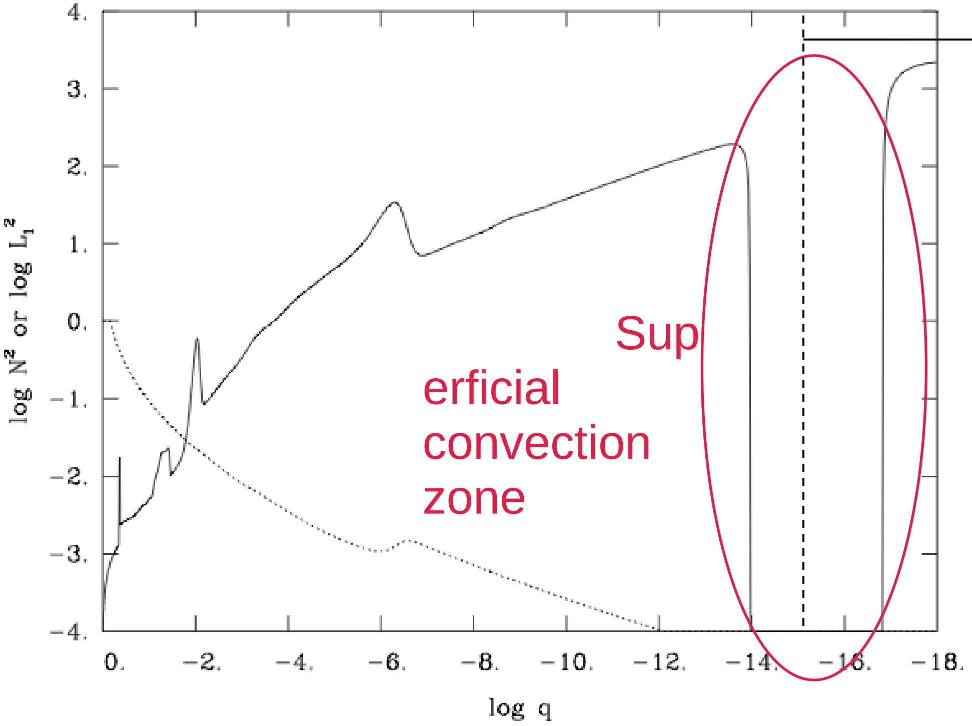


Base of the atmosphere



- Evolutionary tracks computed for $0.4M_s$ to $1.1M_s$ ($0.1M_s$ step)
- from T_{eff}=35,000 K to 2,000 K (~150 models)
- with ML2 version (a=1,b=2,c=16); $\alpha = 1$ (ie $l = Hp$)

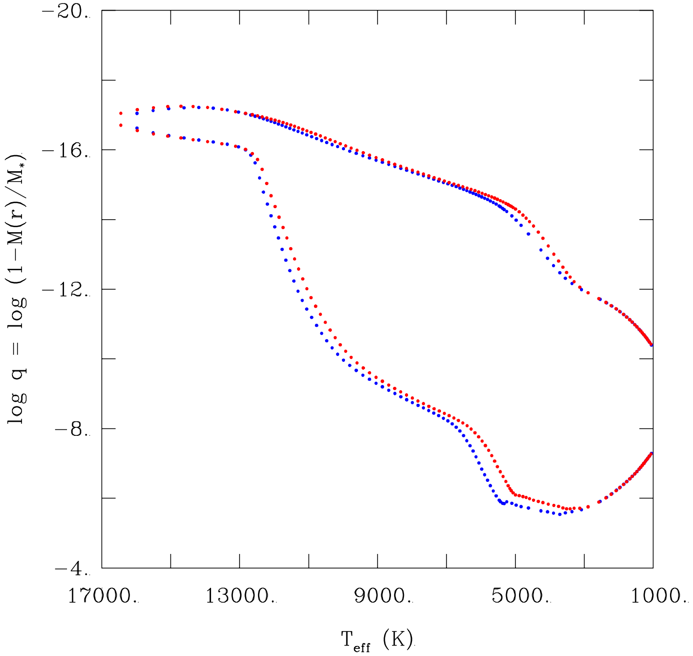
2. Evolutionary ZZ Ceti models



Superficial convection zone

Base of the atmosphere

Detailed modeling of the superficial layers



- Standard grey atmosphere
- Detailed atmosphere

Our evolutionary models have the same T stratification as the complete model atmospheres

⇒"feedback" of the convection on the global atmosphere structure

2. Evolutionary ZZ Ceti models

- Extremely Low Mass (ELM) DA white dwarf:

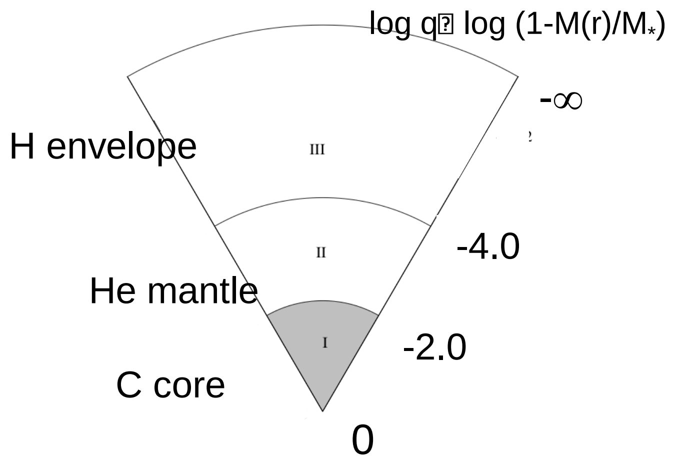
  H envelope on top of He core

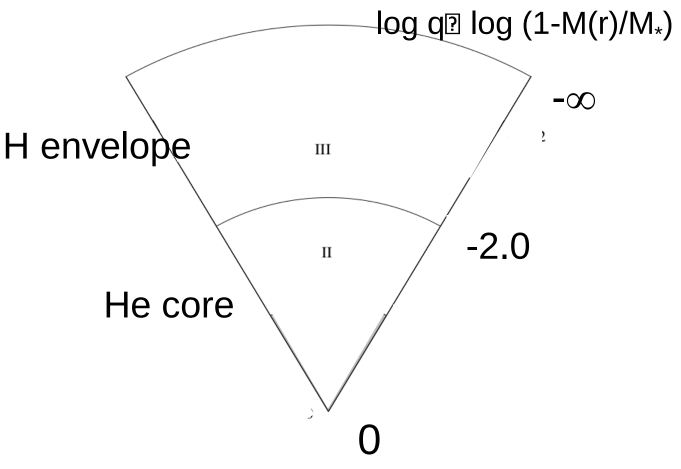
ELM white dwarfs come from stars that never experienced any He-flash, because of extreme mass loss on RGB (from binary interactions or due to high Z)

- 2 kinds of evolutionary tracks computed here:

I. Standard C core models, but for 0.125M_s and 0.15-0.4M_s (steps 0.05M_s)

II. Pure He core/H envelope models, for the same masses, but thick envelopes





Instability location in T_{eff}-log g plane ***insensitive*** *to detailed core structure and envelope layering*

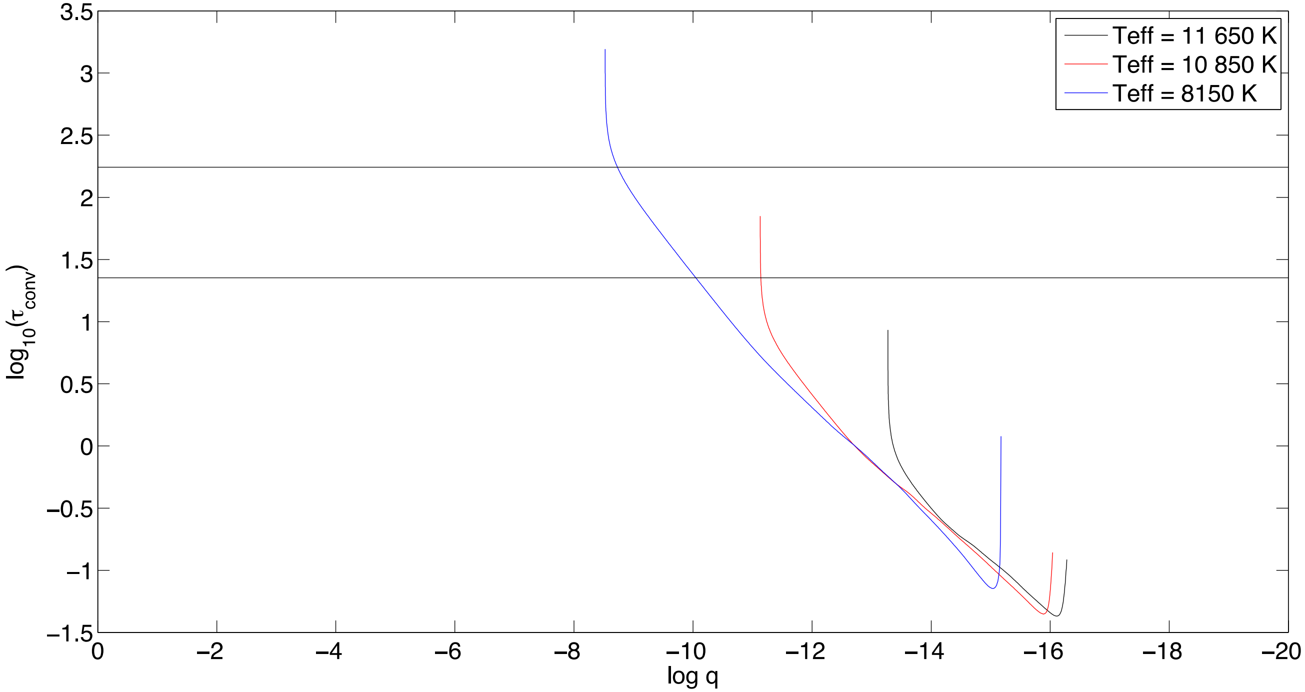
3. Time-Dependent Convection (TDC) approach

3. Time-Dependent Convection approach

For a standard $0.6M_s$ ZZ Ceti model:

- T_{eff} ~ 12,000 K: convective turnover timescale $\tau_{conv} << \sigma$ (pulsation periods)
  $\Rightarrow$ convection adapts quasi-instantaneously to the pulsations
- T_{eff} ~ 11,000 K: $\tau_{conv} \approx \sigma \Rightarrow$ NEED full Time-Dependent Convection (TDC)
- Frozen convection (FC), i.e. $\tau_{conv} >> \sigma$: NEVER justified in the ZZ Ceti T_{eff} regime

(FC is the usual assumption to study the theoretical instability strip...)



$\sigma = 1500$ s

$\sigma = 100$ s

3. Time-Dependent Convection theory

- The Liege nonadiabatic pulsation code **MAD** (Dupret 2002) is the only one to implement convenient TDC treatment
- Full development in Grigahcène et al.(2005), following the theory of M. Gabriel (1974,1996), based on ideas of Unno et al. (1967)
- The timescales of pulsations and convection are **both** taken into account
- Perturbation of the convective flux taken into account here:

$$\delta F_C = \overline{F_C}\left(\frac{\delta\rho}{\overline{\rho}} + \frac{\delta T}{\overline{T}}\right) + \overline{\rho}\,\overline{T}\left(\overline{\delta\Delta s V} + \overline{\Delta s \delta V}\right)$$

- Built within the mixing-length theory (MLT), with the adopted perturbation of the mixing-length:

$$\frac{\delta l}{l} = \frac{1}{1+(\sigma\tau_c)^2}\,\frac{\delta H_p}{H_p}$$

if $\sigma >> \tau_{\mathrm{conv}}$ (instantaneous adaption): $\delta l/l \rightarrow \delta H_p/H_p$

if $\sigma << \tau_{\mathrm{conv}}$ (frozen convection): $\delta l/l \rightarrow 0$

4. Stability survey: the theoretical instability strip

4. Results: computing the theoretical instability strip

- We applied the MAD code to all evolutionary sequences
  - “normal” C-core ZZ Ceti models, 0.4 – 1.1M_s, log q(H)=-4.0
  - ELM, C-core models: 0.125-0.4 $M_{s,}$ log q(H)=-4.0
  - ELM, He-core models: 0.125-0.4 M_s, log q(H)=-2.0
  - 0.17Ms, He-core models, “thin” envelope log q(H)=-3.7

with ML2/$\alpha = 1$, detailed atmospheric modeling, and TDC treatment

- We computed the degree $l=1$ in the range 10-5000 s (p- and g-modes)
- For the red edge (long-standing problem):

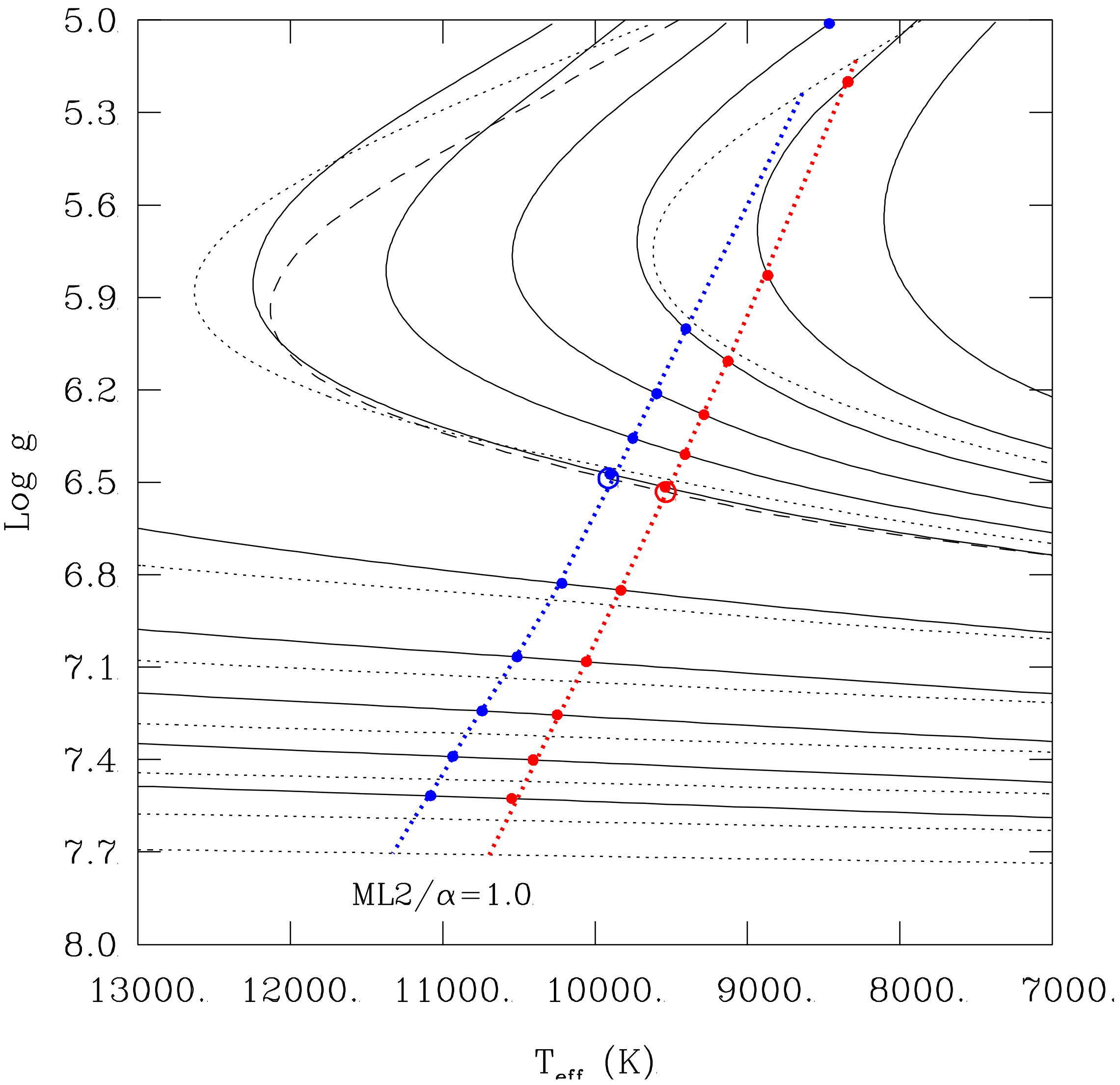
based on the idea of Hansen, Winget & Kawaler (1985): red edge arises when

$$\tau_{th} \sim P_{crit} \quad \alpha \ (l(l+1))^{-0.5}$$

(τ_{th} : thermal timescale at the base of the convection zone),

which means the mode is no longer reflected back by star’s atmosphere

Universality of the instability domain



Tracks:

Solid lines: He core, thick env.

Dotted lines: C-core, thin env.

Dashed line: 0.17M_s, thin env.

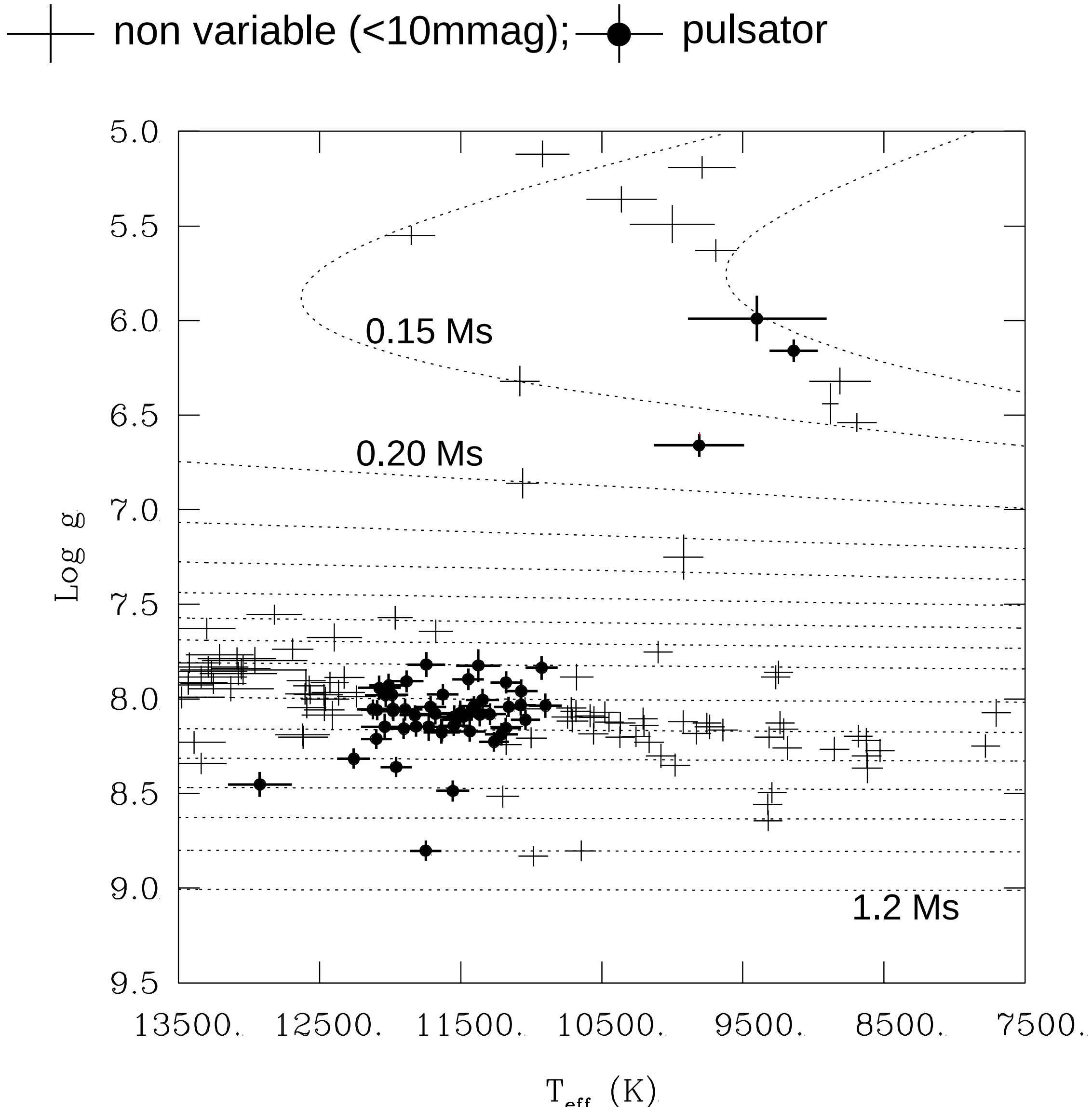
Edges:

- ··· Edges C-core tracks
- ● Edges He-core tracks
- o edges 0.17M_s track

⇓

*Instability domain is **insensitive** to the exact core structure and envelope layering for models with same T_{eff}/logg*

Empirical ZZ Ceti instability strip (2012 view)



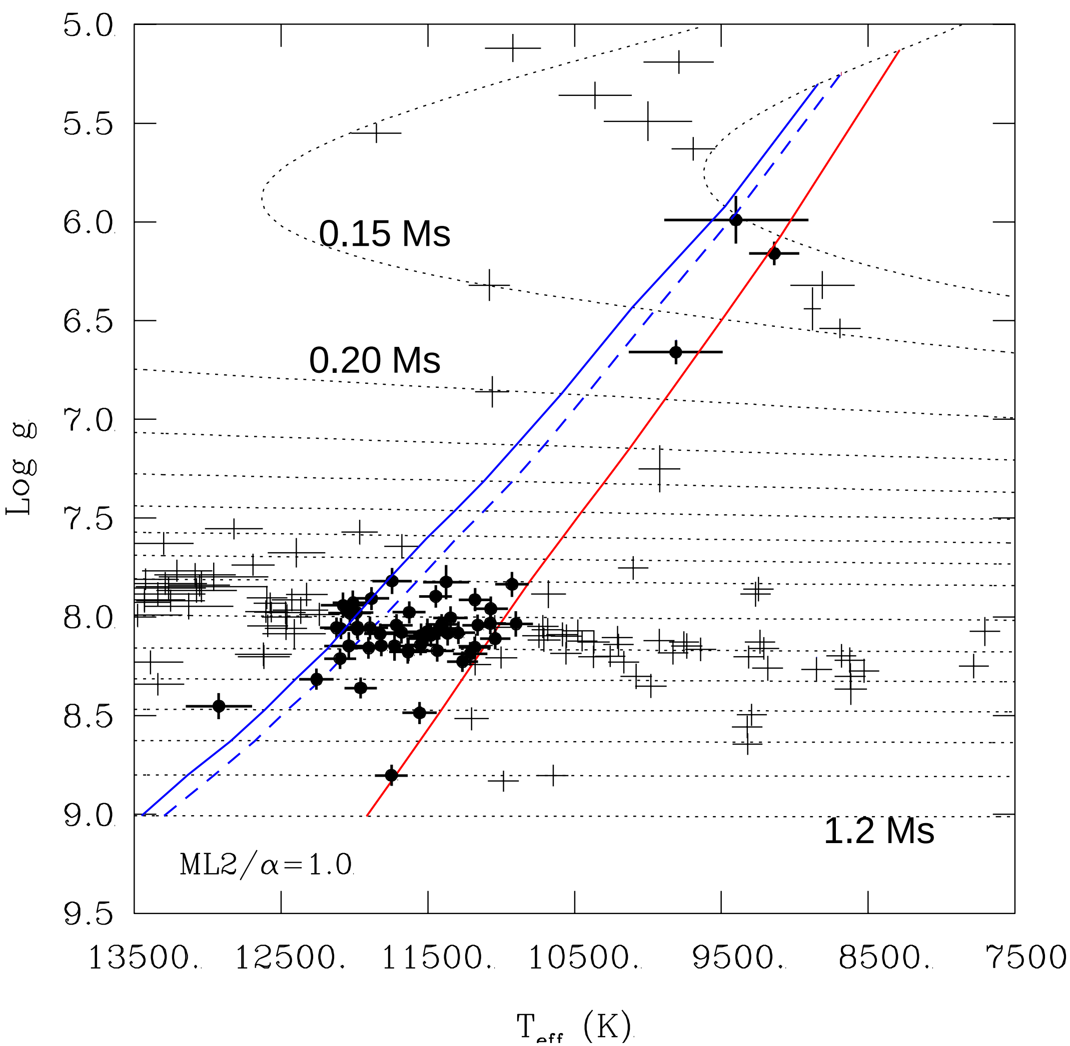
Spectroscopic estimates:

- ELM white dwarfs: D. Koester
- Standard ZZ Ceti: P. Bergeron

But both **ML2/α=0.6**

Theoretical instability strip (g-modes l=1)

┼ non variable (<10mmag); ─●─ pulsator



TDC blue edge

FC blue edge

Red edge

- Narrower strip at low masses (larger slope for the red edge)

- Evolutionary models: ML2/α = 1

  Model atmospheres: ML2/α = 0.6

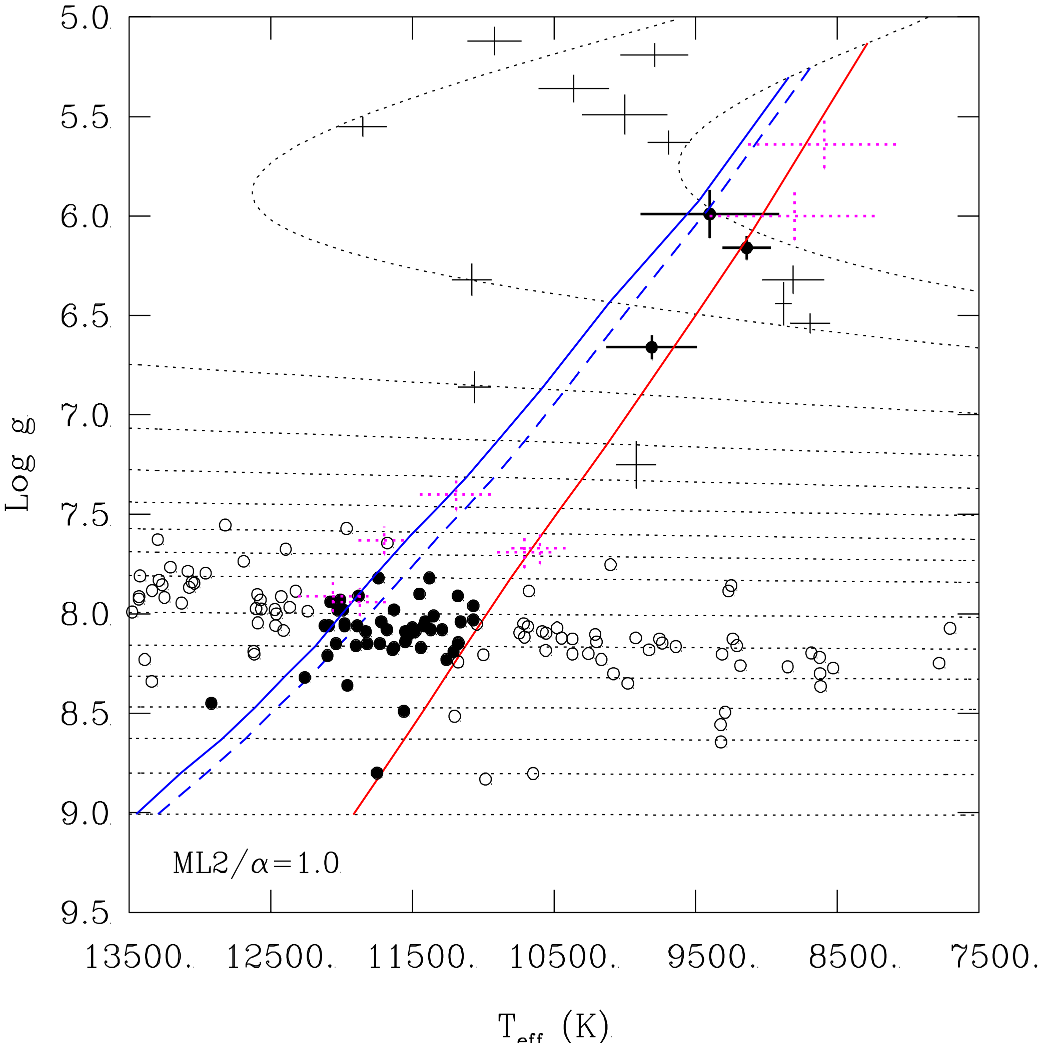
  ⇓

  Convective efficiency increases with depth?

  (consistent with hydrodynamical simulations; Ludwig et al. 1994, Tremblay & Ludwig 2012)

Other ELM/standard ZZ Ceti pulsators ?

Is the whole ZZ Ceti instability strip **pure**?



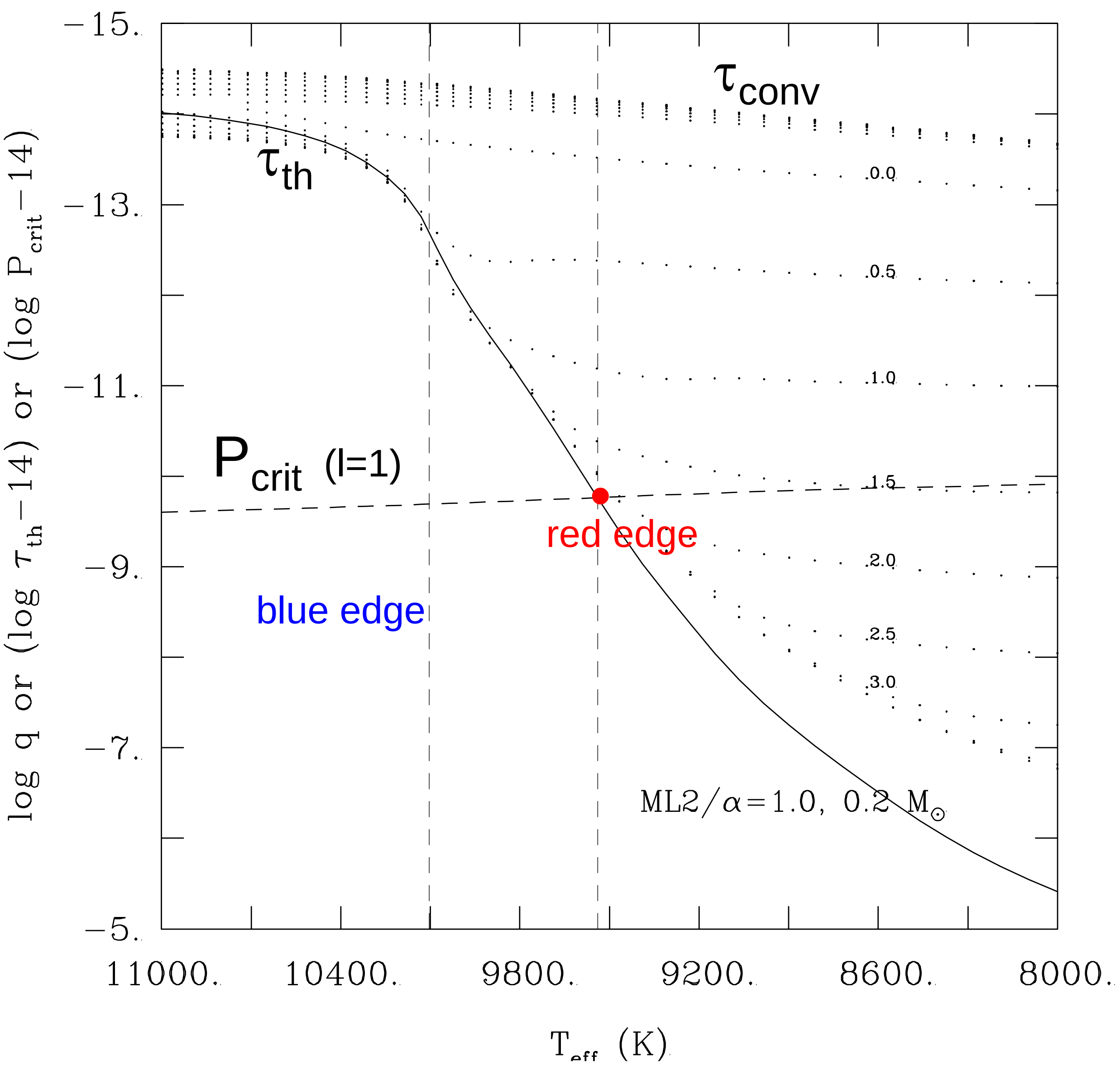
Suggestion for observations

DA white dwarfs with T_{eff}/logg close to our instability strip

Not checked for variability so far

Ex: zoom to the 0.2Ms He-core track, lq(H)=-2.0

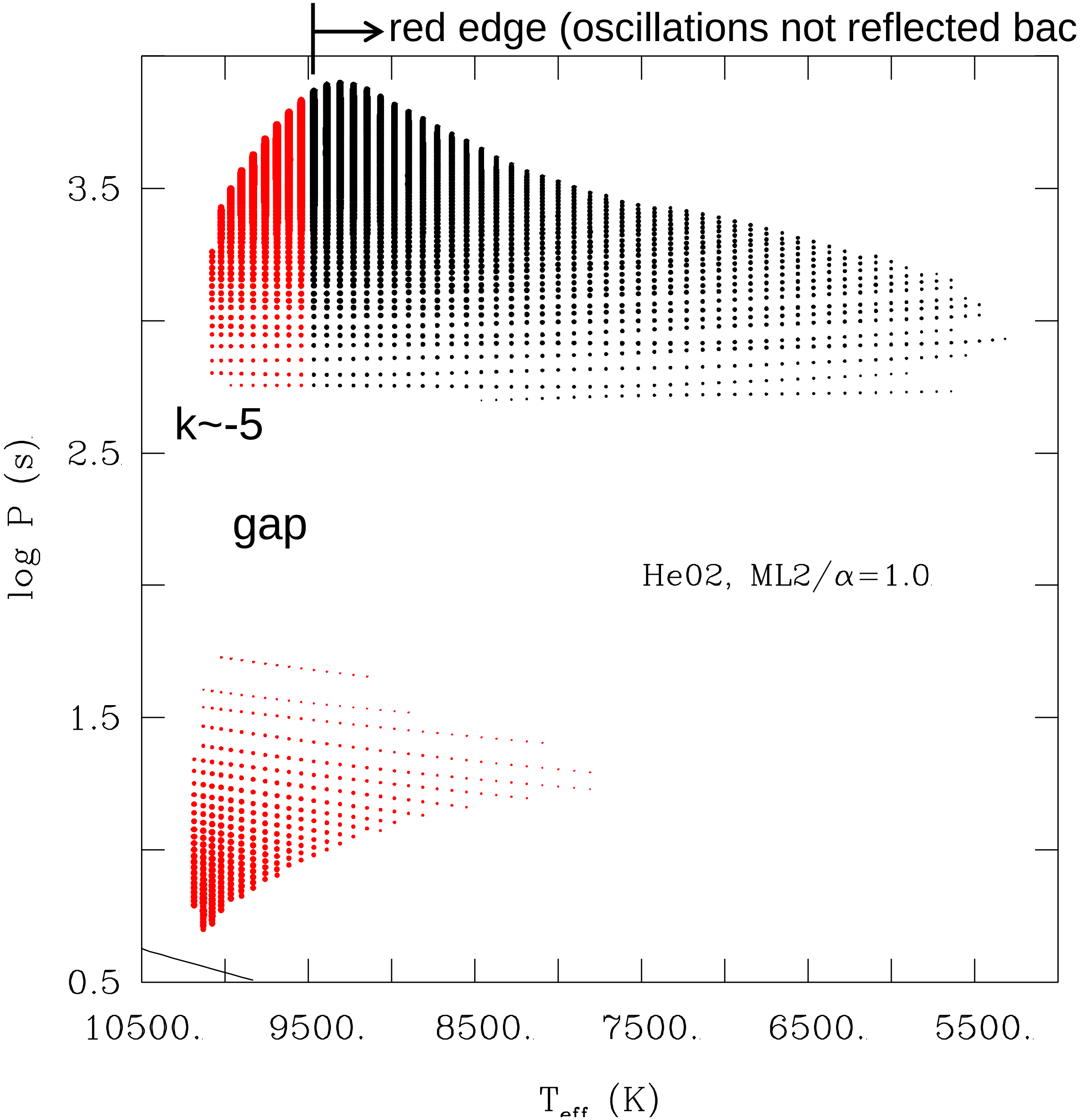
To the surface



To the core

Along the cooling track

Excited l=1 periods for the 0.2Ms He-core track



red edge (oscillations not reflected back)

k~-5

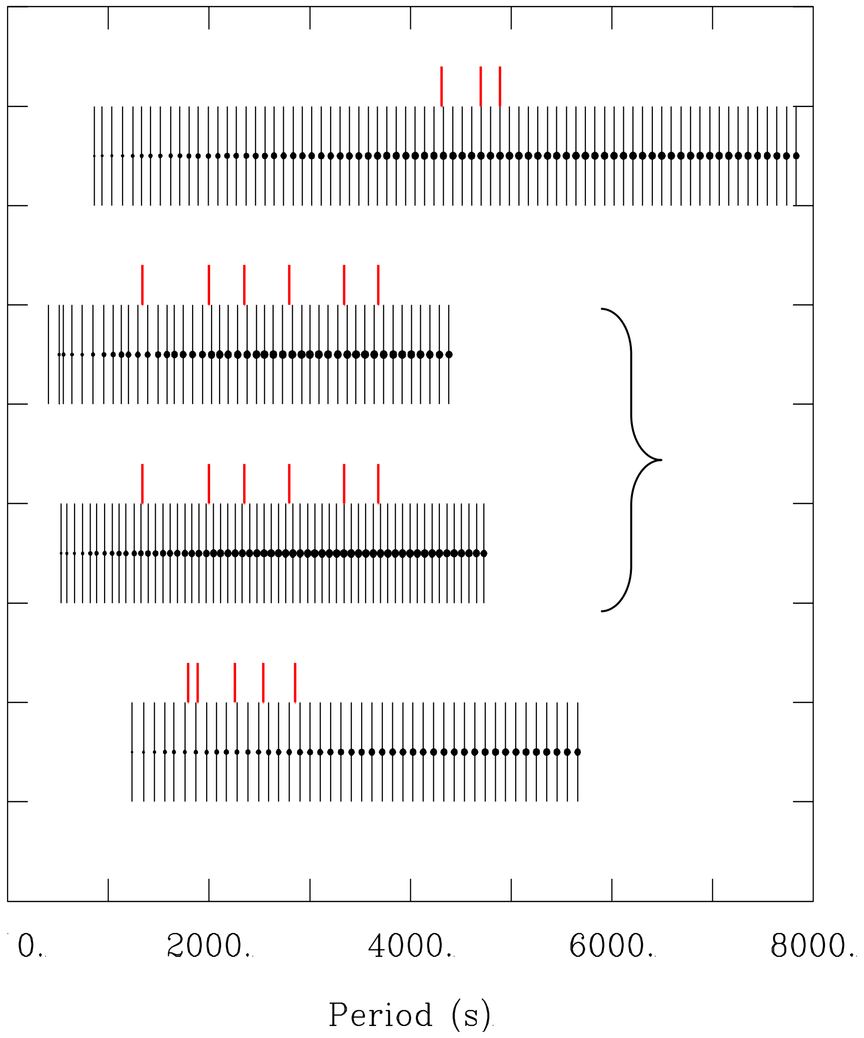
gap

g-modes

p-modes (P~50 s)

Observable?

Qualitative fit to the observed periods of the 3 ELM pulsators



SDSS J1840+6423

T_{eff}~ 9140±170 K, log*g* ~ 6.16±0.06

He-core model, log q(H)=-2.0

SDSS J1518+0658

T_{eff}~ 9810±320 K, log*g* ~ 6.66±0.06

He-core model, log q(H)=4.0 and -2.0

SDSS J1112+1117

T_{eff}~ 9400±490 K, log*g* ~ 5.99±0.12

He-core model, log q(H)=-2.0

*Adiabatic properties **are** sensitive to exact interior structure*

5. Conclusion and prospects

5. Conclusion and Prospects

Conclusions:

- ELM pulsators are low mass equivalent to standard ZZ Ceti pulsators

  ⇒ such pulsators exist from 0.15 to 1.1 M_s (log g = 5 – 9 !)

- Excellent agreement between theoretical and observed instability strip:

-Blue edge, TDC approach

-Red edge, by energy leakage through the atmosphere

- Is ML2/α=1.0 the good flavor for convection inside white dwarfs?

Related to spectroscopic calibration (ML2/α=0.6) and hydrodynamical simulations (Tremblay & Ludwig 2011,2012)

Prospects:

- Detection of p-modes in white dwarfs?
- Is the ZZ Ceti instability strip **pure**?
- Asteroseismology of ELM/standard ZZ Ceti white dwarf pulsators
  1. internal structure & fundamental parameters
  2. **age**
  3. understanding of matter under extreme conditions

Why TDC and FC blue edges are not dramatically different?

1. The difference (~250 K) is **not** negligible !

   Width of instability strip: ~1000 K at log g = 8 and ~600 K at log g = 6

2. Van Grootel et al. (2012) and Saio (2012, Liege colloquium)

eigenfunctions TDC/FC are really different, and excitation mechanisms too:

- TDC: convective driving (convective flux can be modulated)
- FC: κ-mechanism with radiative luminosity (<<L_{conv})

But both mechanisms occurs at the same layers (partial ionization zone)