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The instability strip of ZZ Ceti white dwarfs

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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. 2013, ApJ, 762, 57

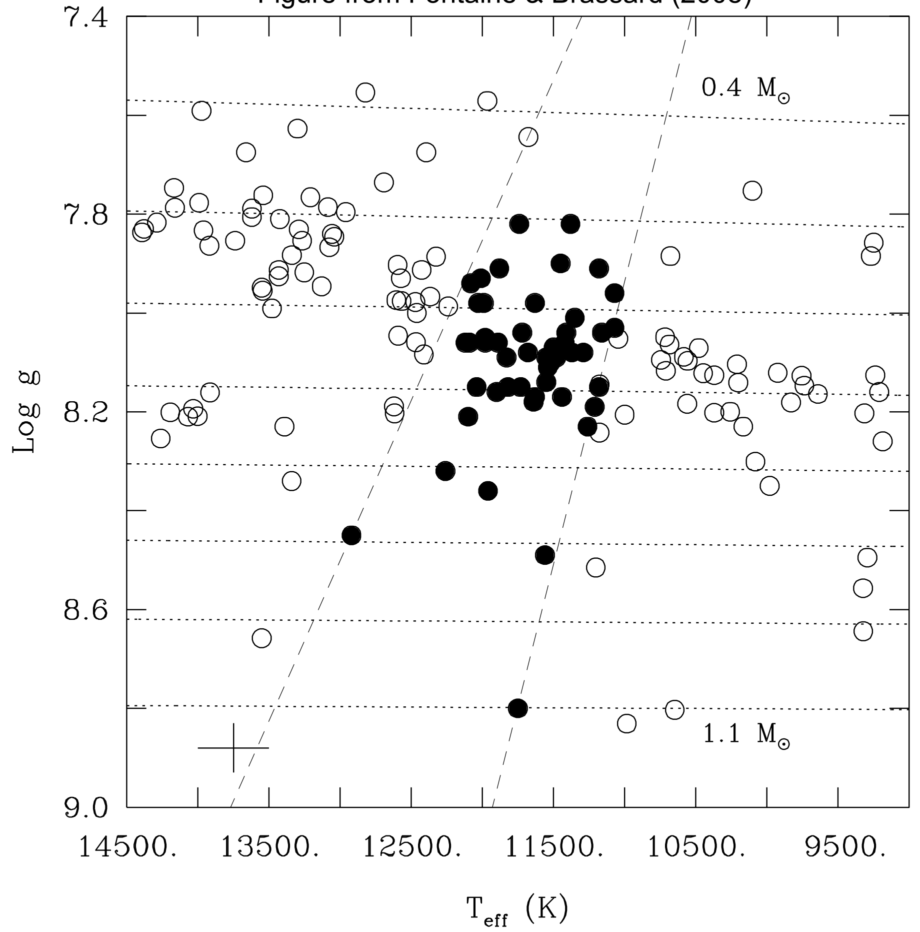
Pulsations in DA white dwarfs

Pulsating DA white dwarfs

Empirical ZZ Ceti instability strip (classic view)

● Observed pulsator ; O non-variable DA white dwarf

Figure from Fontaine & Brassard (2008)

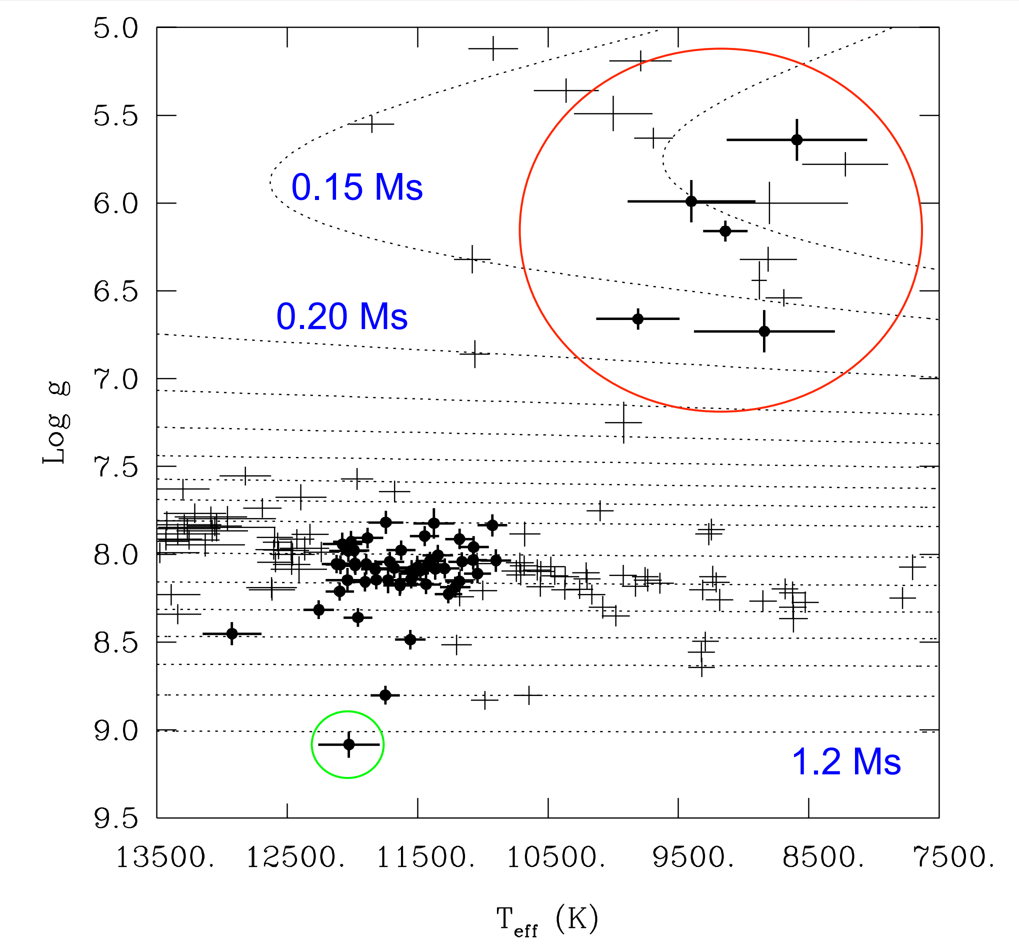


- Multiperiodic pulsators, observed period range: 100-1500 s (g-modes)
- Reliable atmospheric parameters: work of Bergeron et al., Gianninas et al., here with ML2/α=0.6
- (most probably) a **pure** strip
- log g/T_{eff} correlation (with a more pronounced slope for red edge): the lower log g, the lower edge T_{eff}

Pulsating DA white dwarfs

Empirical ZZ Ceti instability strip (2014 view)

┼ non variable (<10mmag); ●┼ pulsator



Hermes et al. (2012, 2013a,b):

5 ELM pulsators

(SDSS J1840, J1112, J1518, J1614, J2228)

Multiperiodic pulsators, 1500-6000 s

Hermes et al. (2013c):

1 UHM pulsator

(GD 518)

Multiperiodic pulsator, 425-595 s

Pulsating DA white dwarfs

Excitation mechanism of ZZ Ceti stars (general picture)

- Don Winget (1981):

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

⇒ envelope opacity increase

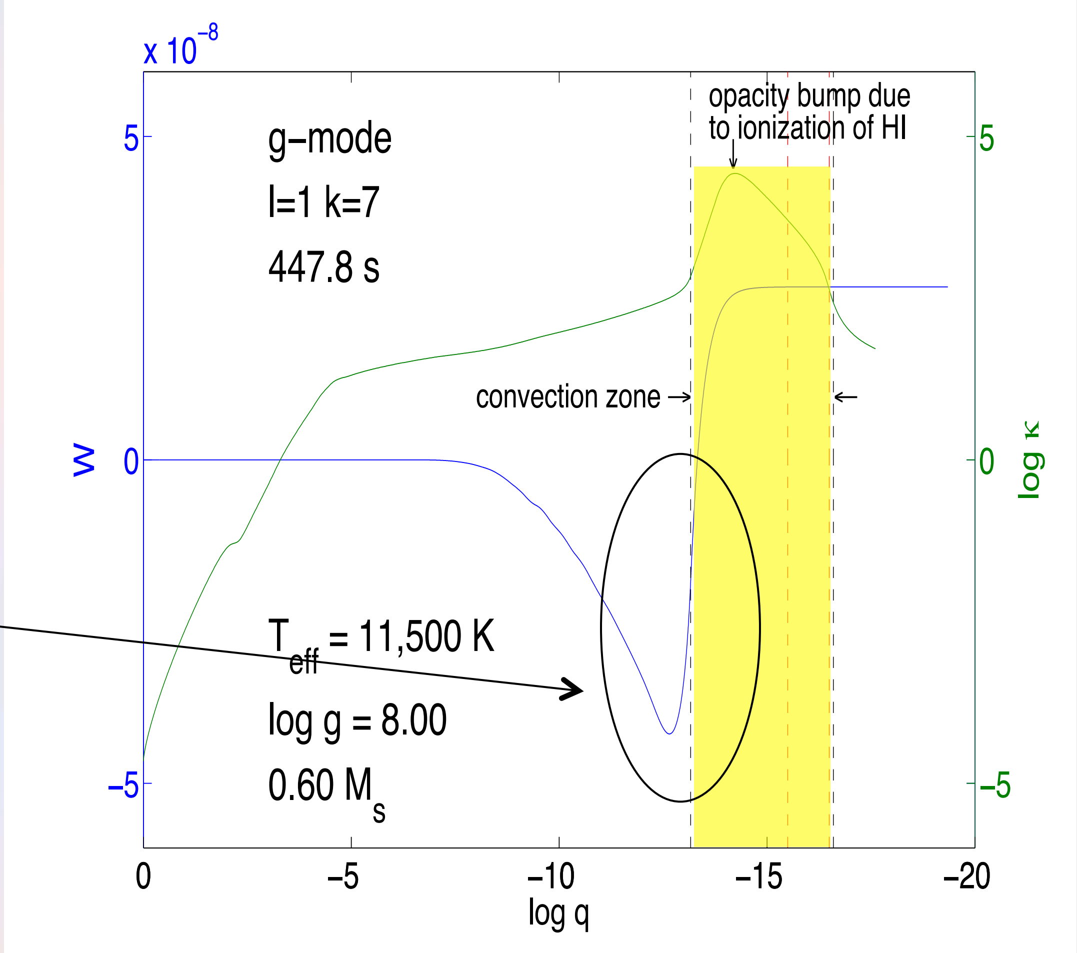
⇒ strangle the flow of radiation

⇒ modes instabilities

- Pulsations are destabilized at the base of the convection zone

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

“convective driving”



$\log q \equiv \log(1-M(r)/M_*)$

Pulsations are driven when the convection zone is sufficiently deep and developed

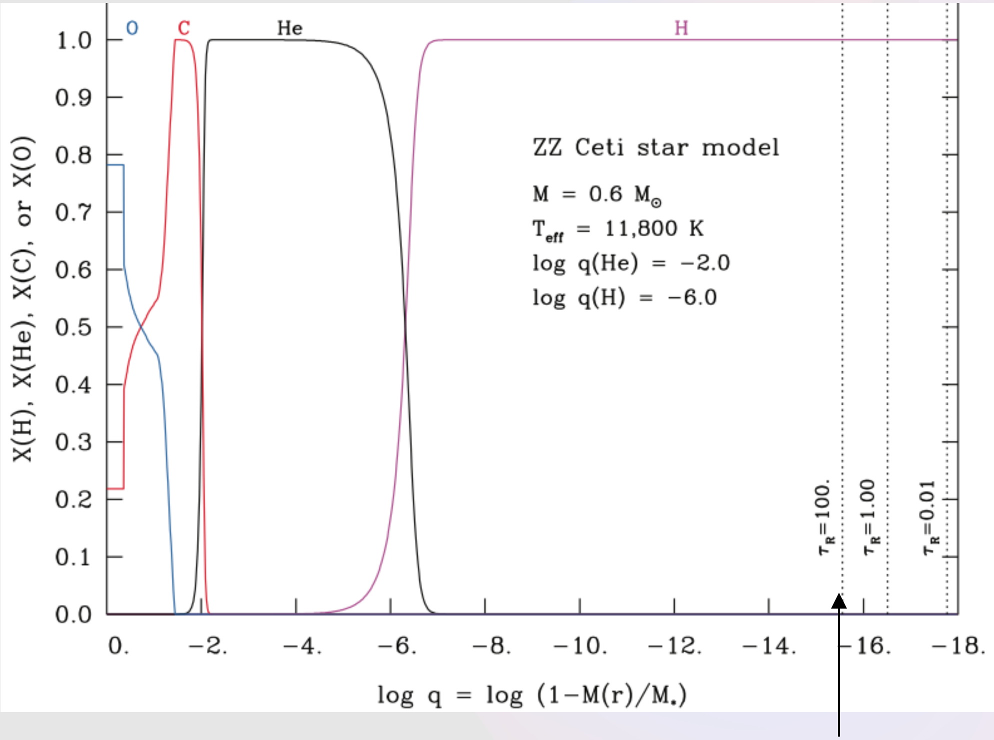
The theoretical instability strip

- Evolutionary DA White Dwarf Models

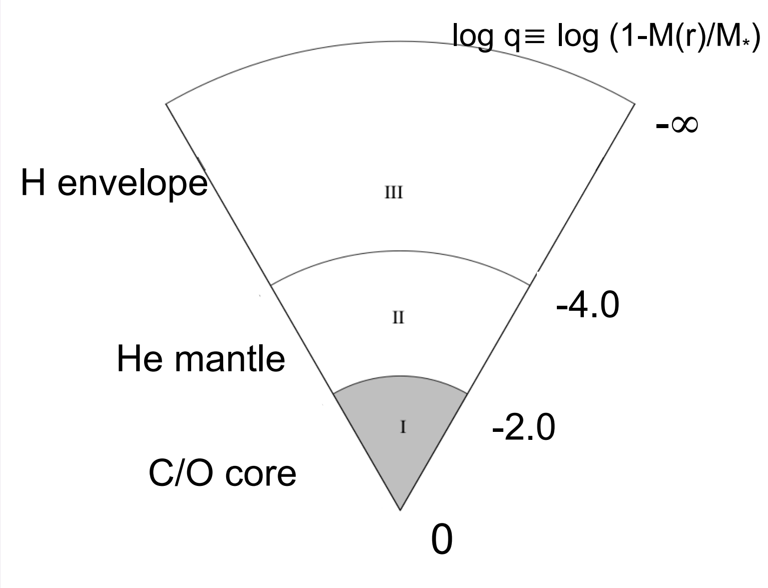
Evolutionary DA models

- A standard DA white dwarf structure model (C/O core)

"onion-like" stratification



Base of the atmosphere


log q≡ log (1-M(r)/M$_*$)

-∞

H envelope

III

-4.0

II

He mantle

-2.0

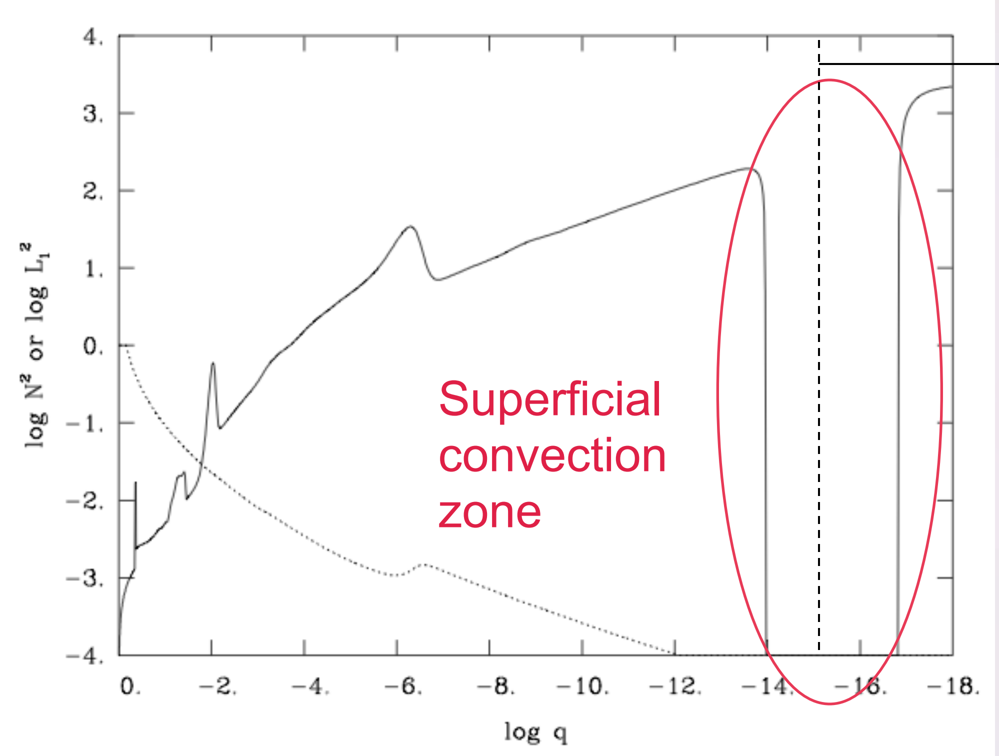
I

C/O core

0

- Evolutionary tracks computed for $0.4M_s$ to $1.2M_s$ ($0.1M_s$ step)
- from T_{eff}=35,000 K to 2,000 K (~150 models)
- with ML2 version (a=1,b=2,c=16); α = 1 (ie *l* = *Hp*)

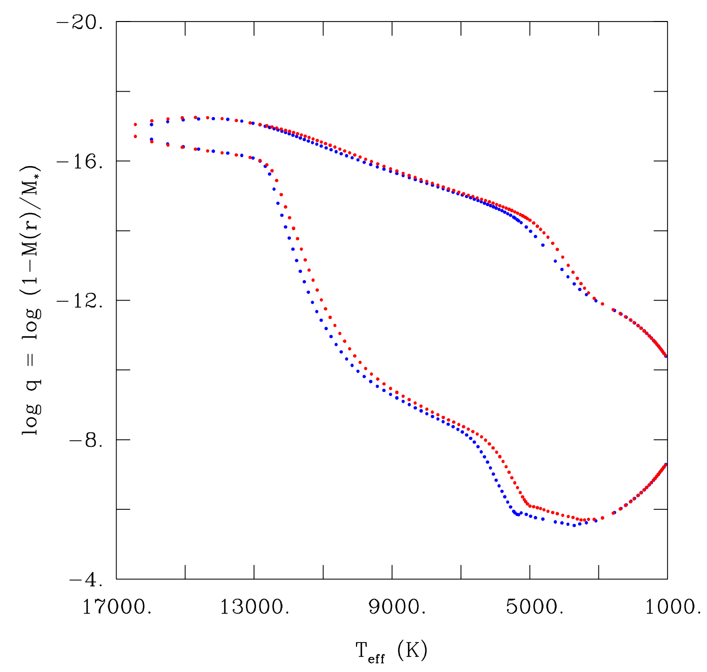
Evolutionary DA models



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 (1D) model atmospheres

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

Evolutionary DA models

- Extremely Low Mass (ELM) DA white dwarf:

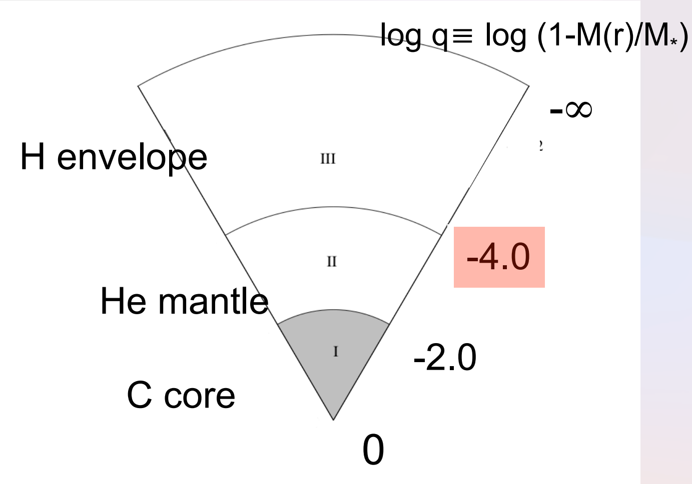
H envelope on top of He core

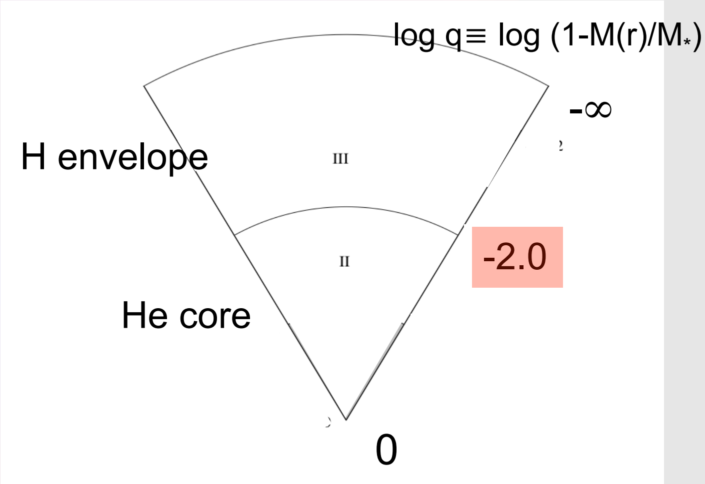
ELM white dwarfs come from stars that never experienced any He-flash, because of extreme mass loss on RGB (from binary interactions or due to high Z)

- 2 kinds of evolutionary tracks computed here:

I. Standard C core models, but for $0.125M_s$ and $0.15\text{-}0.4M_s$ (steps $0.05M_s$)

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





*Instability strip location in T_{eff}-log g plane **insensitive** to detailed core composition and envelope thickness*

The theoretical instability strip

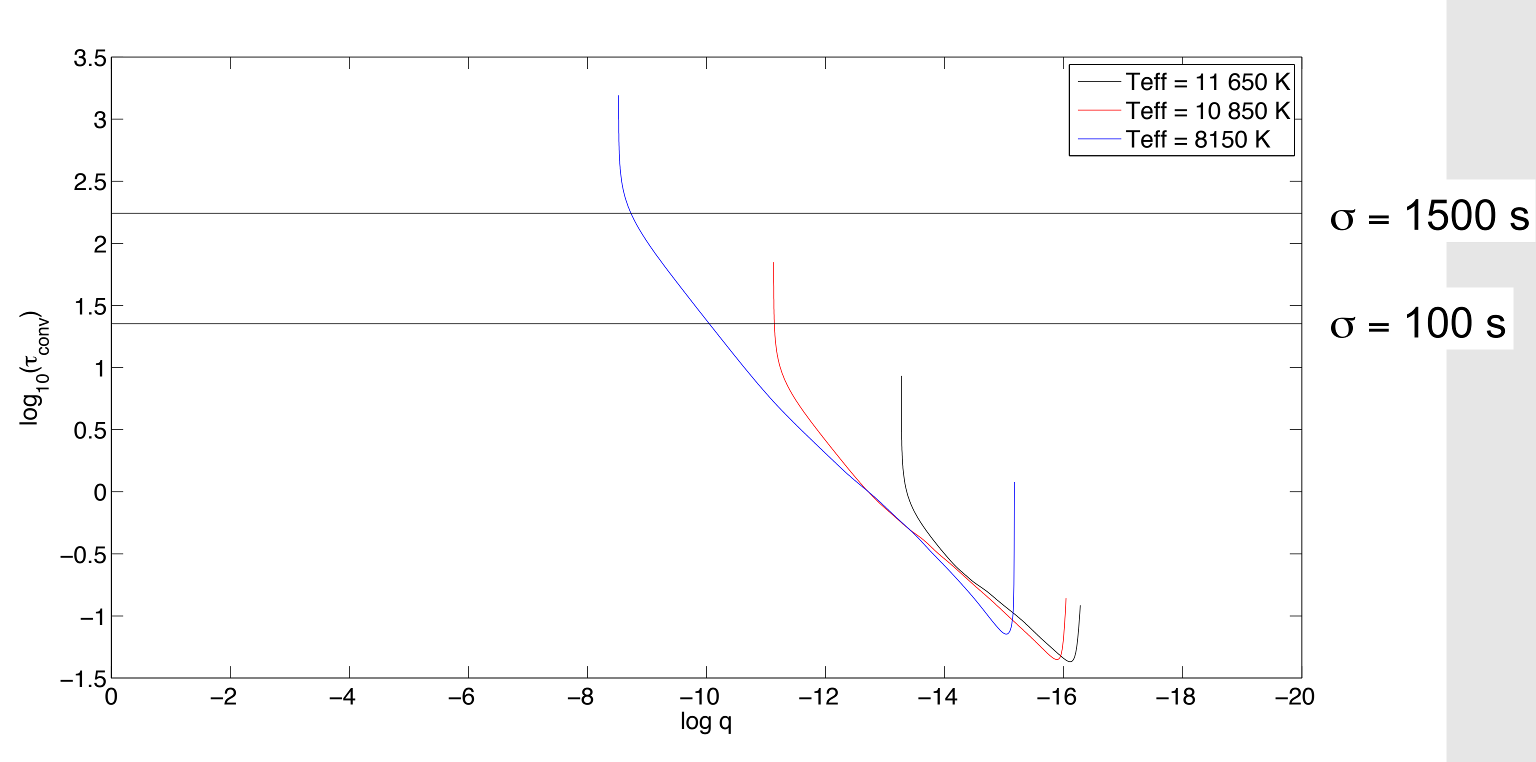
- Evolutionary DA White Dwarf Models
- Time-Dependent Convection (TDC) Approach

The Time-Dependent Convection approach

For a standard $0.6M_s$ DA 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)



The Time-Dependent Convection theory

- Full development in Grigahcène et al.(2005), following the theory of M. Gabriel (1974,1996), based on ideas of Unno et al. (1967)
- The Liege nonadiabatic pulsation code **MAD** (Dupret 2002) is the only one to implement convenient TDC treatment

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

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

The theoretical instability strip

- Evolutionary DA White Dwarf Models
- Time-Dependent Convection (TDC) Approach
- Results

Results: computing the theoretical instability strip

- We applied the MAD code to all evolutionary sequences
  - "normal" CO-core DA models, 0.4 – 1.2M_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/α = 1, detailed atmospheric modeling, and TDC treatment

- We computed the degree l=1 in the range 10-7000 s (p- and g-modes)
- For the red edge (long-standing problem):

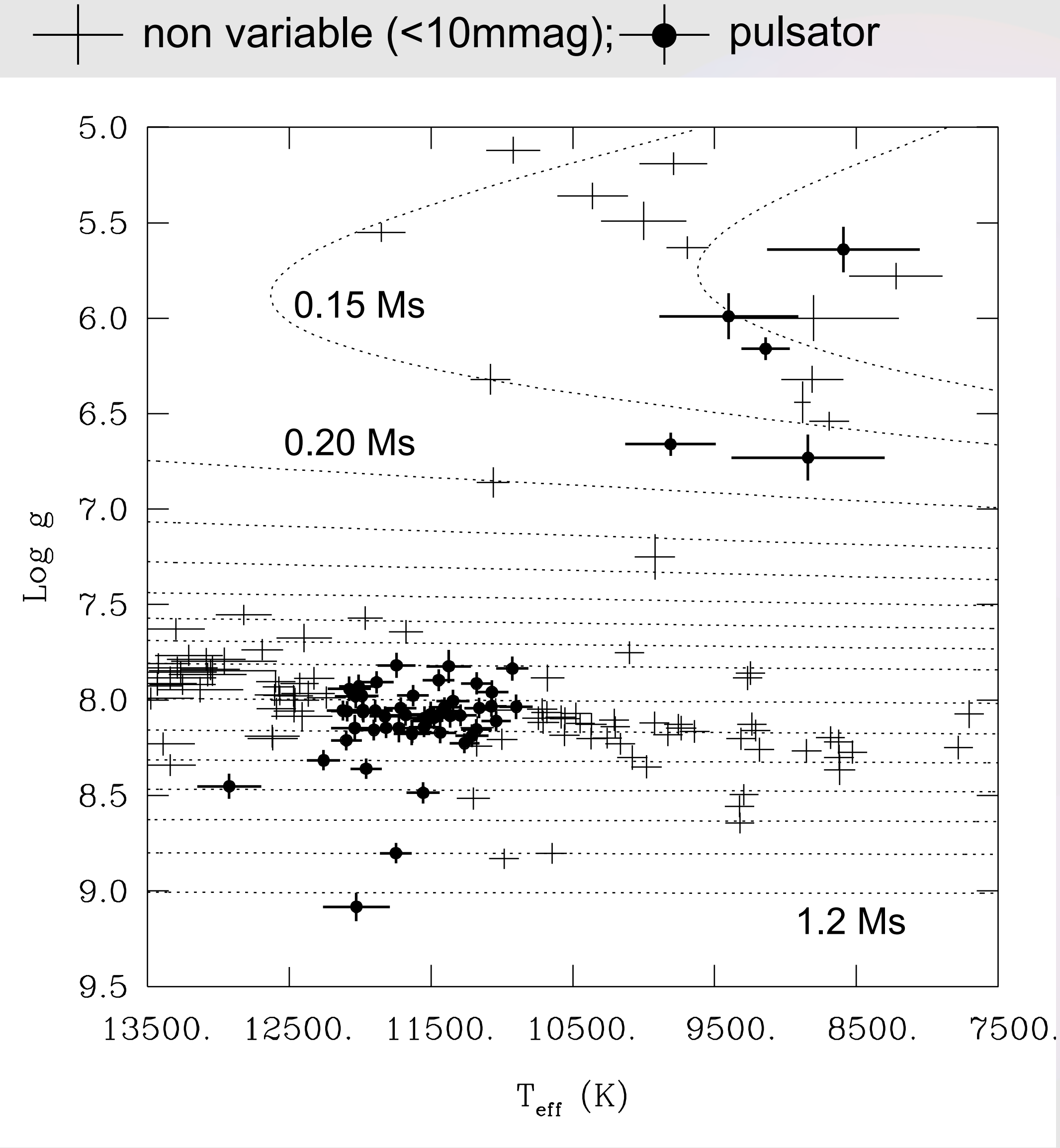
based on the idea of Hansen, Winget & Kawaler (1985): red edge arises when

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

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

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

Empirical ZZ Ceti instability strip (2014 view)



Spectroscopic estimates:

- ELM white dwarfs: D. Koester models (Brown et al. 2012)
- UHM white dwarf: Gianninas et al. (2011)
- Standard ZZ Ceti: P. Bergeron et al.

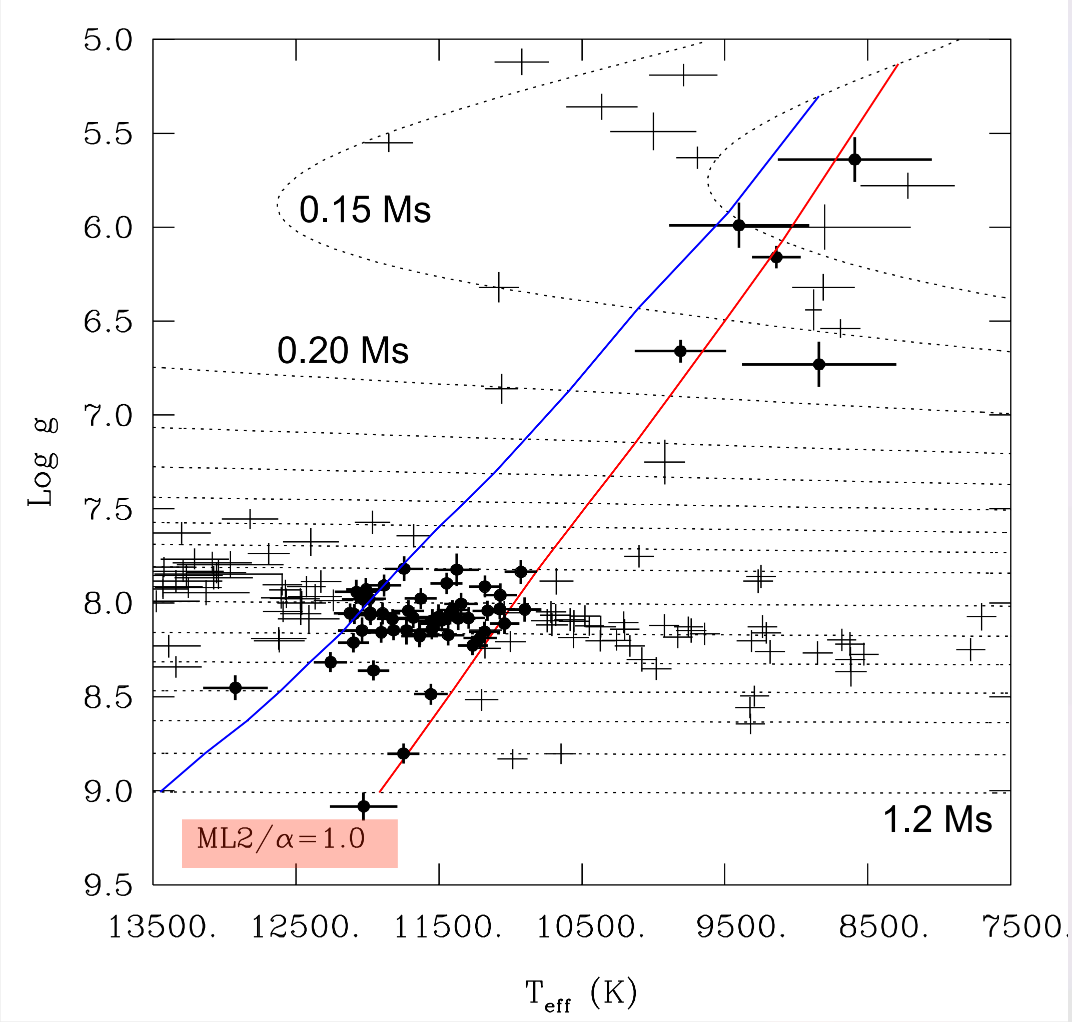
But all **ML2/α=0.6**

(must be consistent)

+ standard ZZCeti: spectroscopic observations gathered during several cycles of pulsations

Theoretical instability strip (g-modes l=1)

+ non variable (<10mmag); ● pulsator



TDC blue edge

Red edge

- Narrower strip at low masses

(larger slope for the red edge)

- Structure models:

ML2/α = 1

Model atmospheres:

ML2/α = 0.6

$\Downarrow$

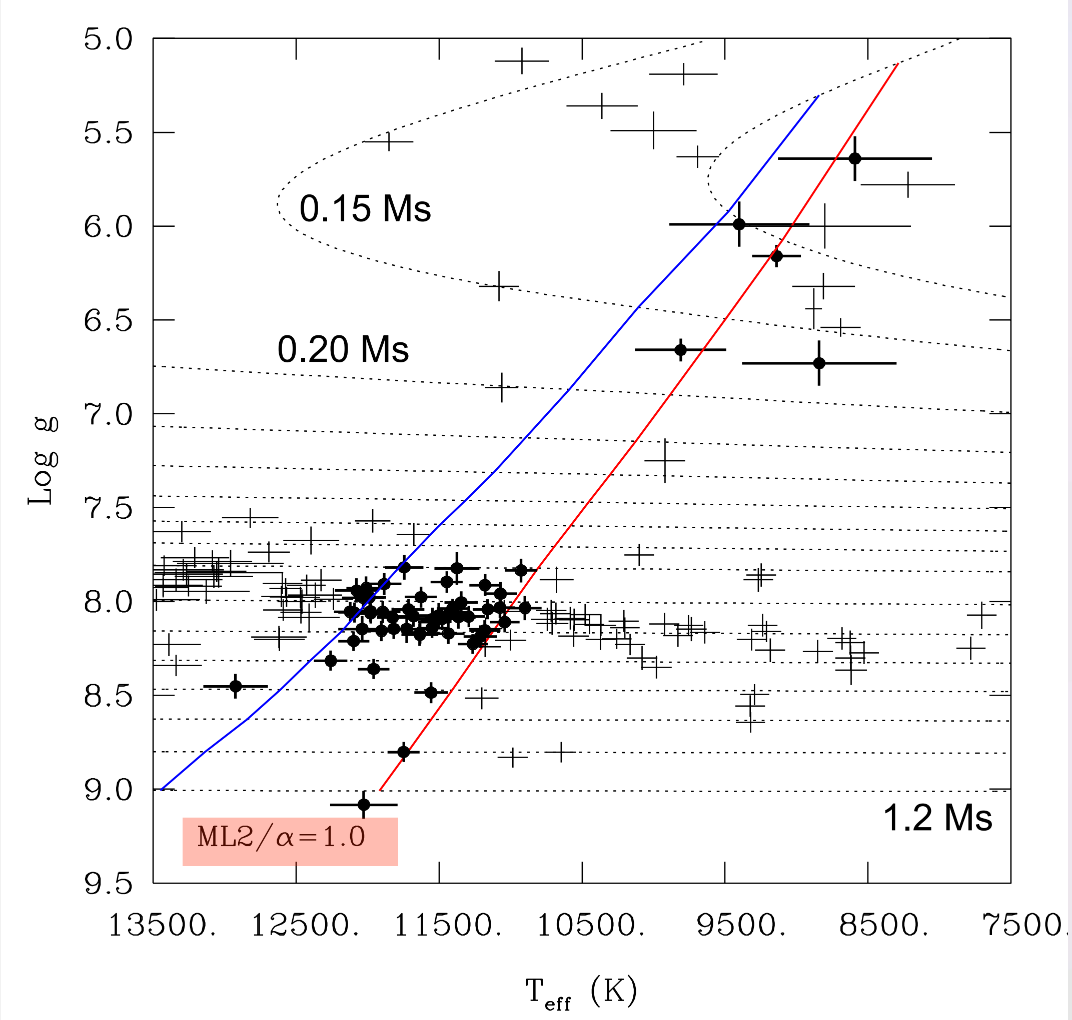
Convective efficiency increases with depth?

(consistent with hydrodynamical simulations; Ludwig et al. 1994, Tremblay & Ludwig 2011)

NB: evolutionary and atmospheric MLT calibrations are dependent

Theoretical instability strip (g-modes l=1)

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



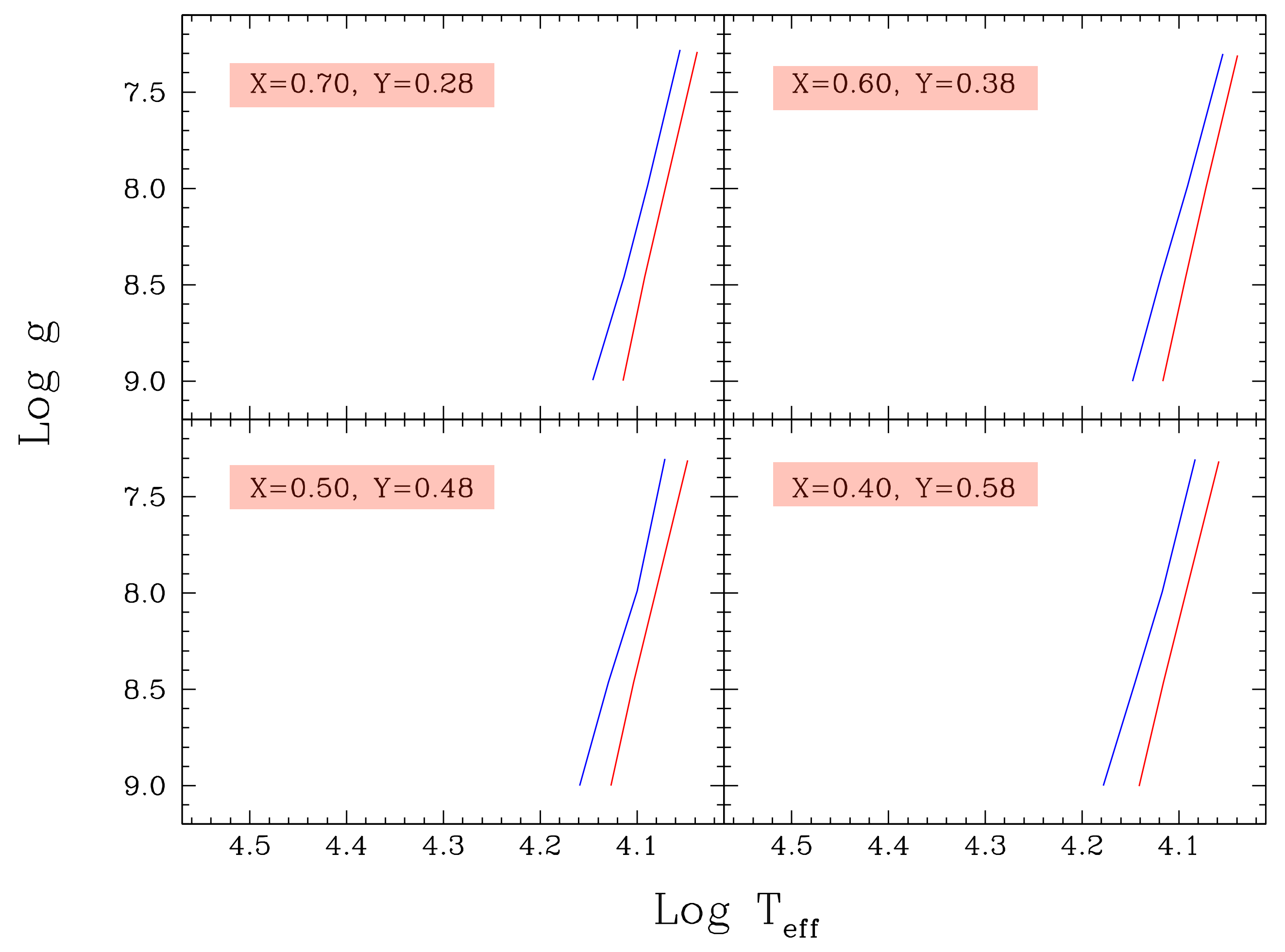
YES

- Need only small fine-tuning
- J2228 is a little bit tricky
- Consistency between ML calibrations atmospheres ⇔ structure models
- Spectra must cover a few pulsational cycles !

BUT

- Are all ELM pure H (DA) white dwarfs or with traces of He ?

Instability strips of WDs with H/He atmospheres



The instability strip is dependent of the amount of H and He

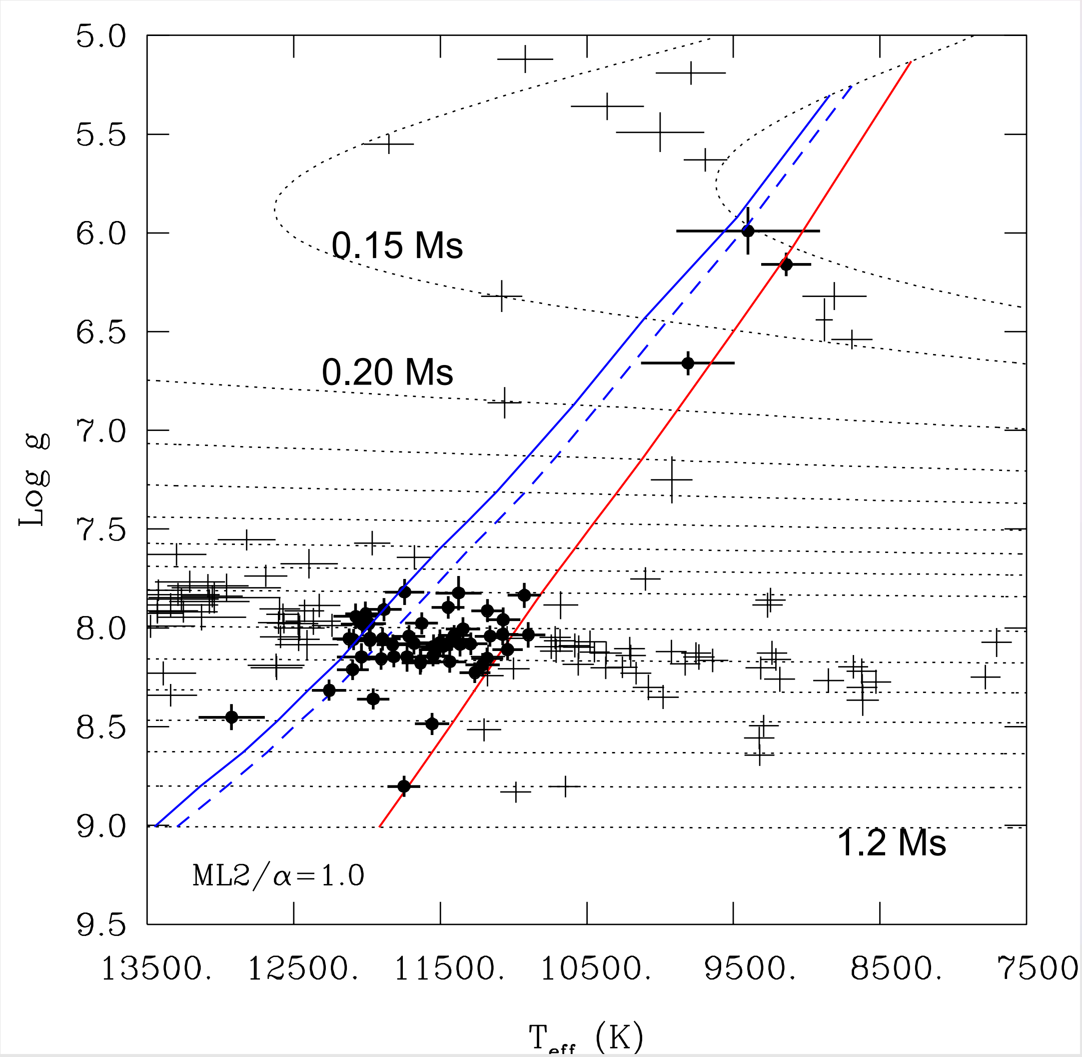
Details in poster of Van Grootel et al.

The theoretical instability strip

- Evolutionary DA White Dwarf Models
- Time-Dependent Convection (TDC) Approach
- Results
- Convective Driving

Theoretical instability strip (g-modes l=1)

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



TDC blue edge

FC blue edge

Red edge

Van Grootel et al. (2013)

A last remark

Convective Driving (≠ κ-mecanism or convective blocking)

TDC and FC blue edges are not dramatically different, but:

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

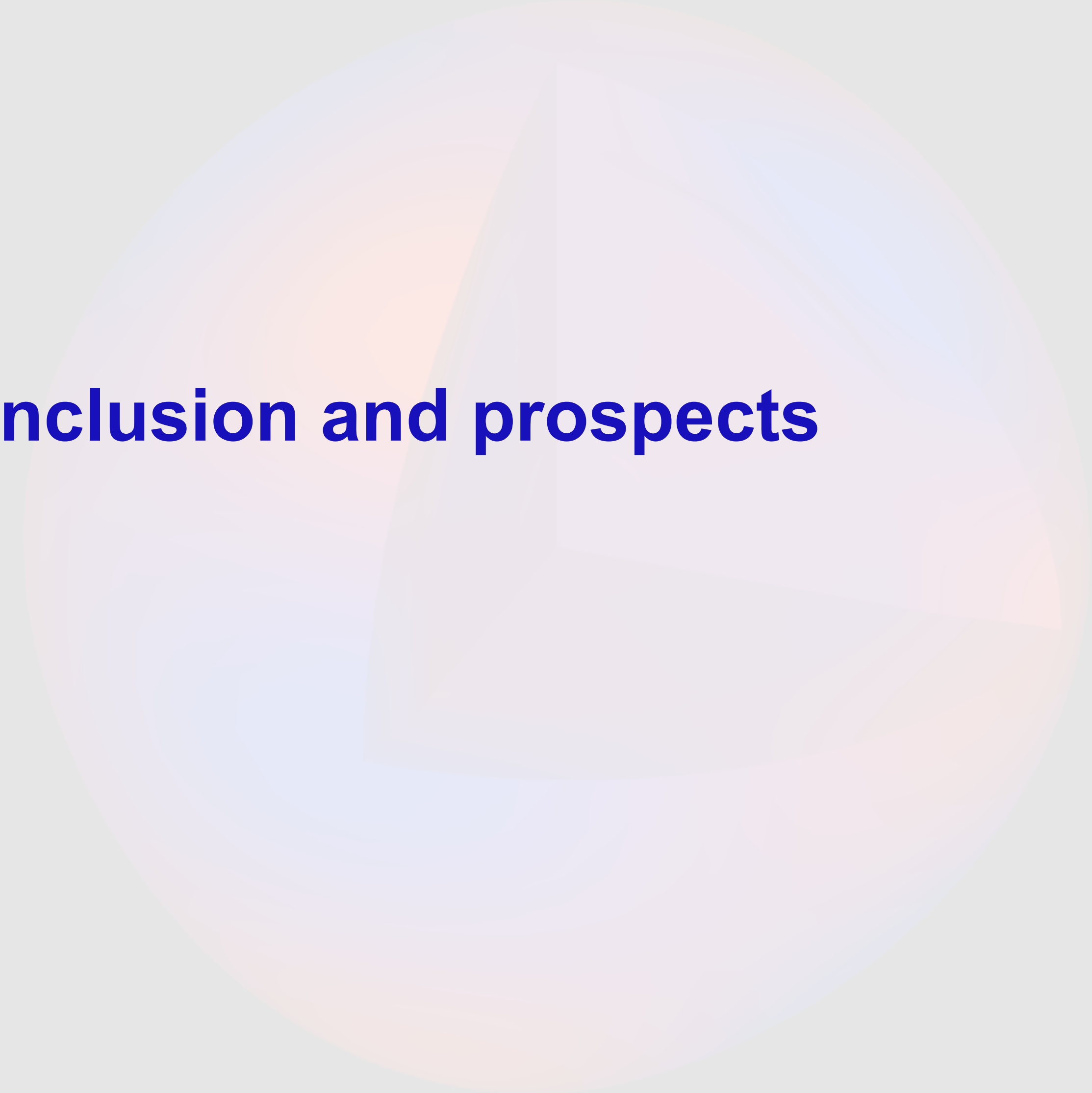
Width of instability strip: ~1000 K at log g = 8 and ~600 K at log g = 6

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 ($\ll L_{conv}$)

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



Conclusion and prospects

Conclusion and Prospects

Conclusions:

- **Excellent agreement** between theoretical and observed instability strip:
  - Blue edge, TDC approach
  - Red edge, by energy leakage through the atmosphere
- ELM pulsators are low mass equivalent to standard ZZ Ceti pulsators excited by **convective driving**

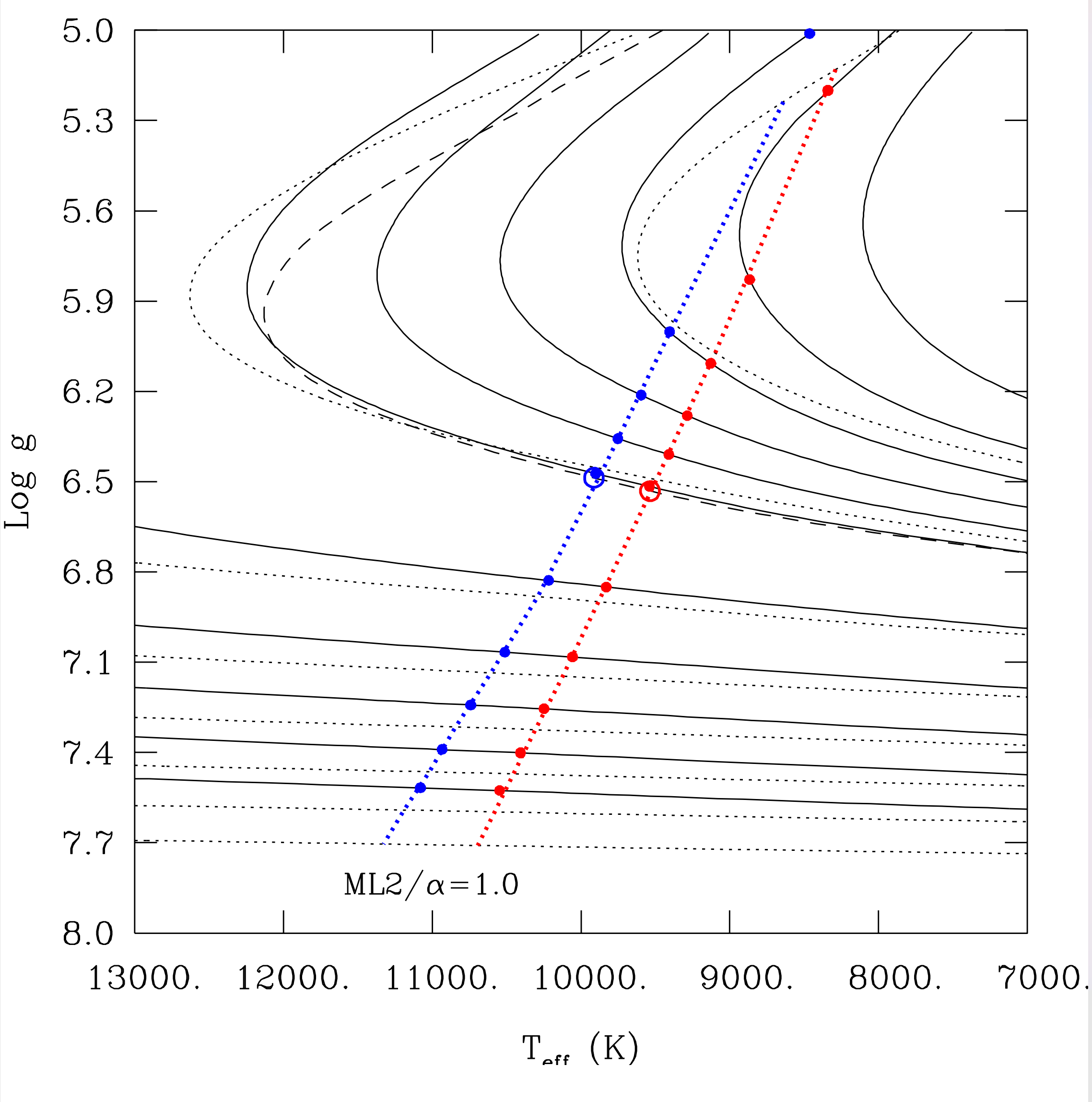
  ⇒ such pulsators exist from 0.15 to 1.2 M_s (log g = 5 – 9 !)
- Is **ML2/α=1.0** the good flavor for convection inside white dwarfs?
  Related to spectroscopic calibration (here ML2/α=0.6) and 3D hydrodynamical simulations (Tremblay et al. 2011,2012, this conference)

Prospects:

- Is the ZZ Ceti instability strip **pure**? Traces of He in ELM white dwarfs?
- Instability strip with structure models including 3D atmospheres?
- Asteroseismology of ELM/standard/UHM ZZ Ceti white dwarf pulsators

Supp. Slides

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.

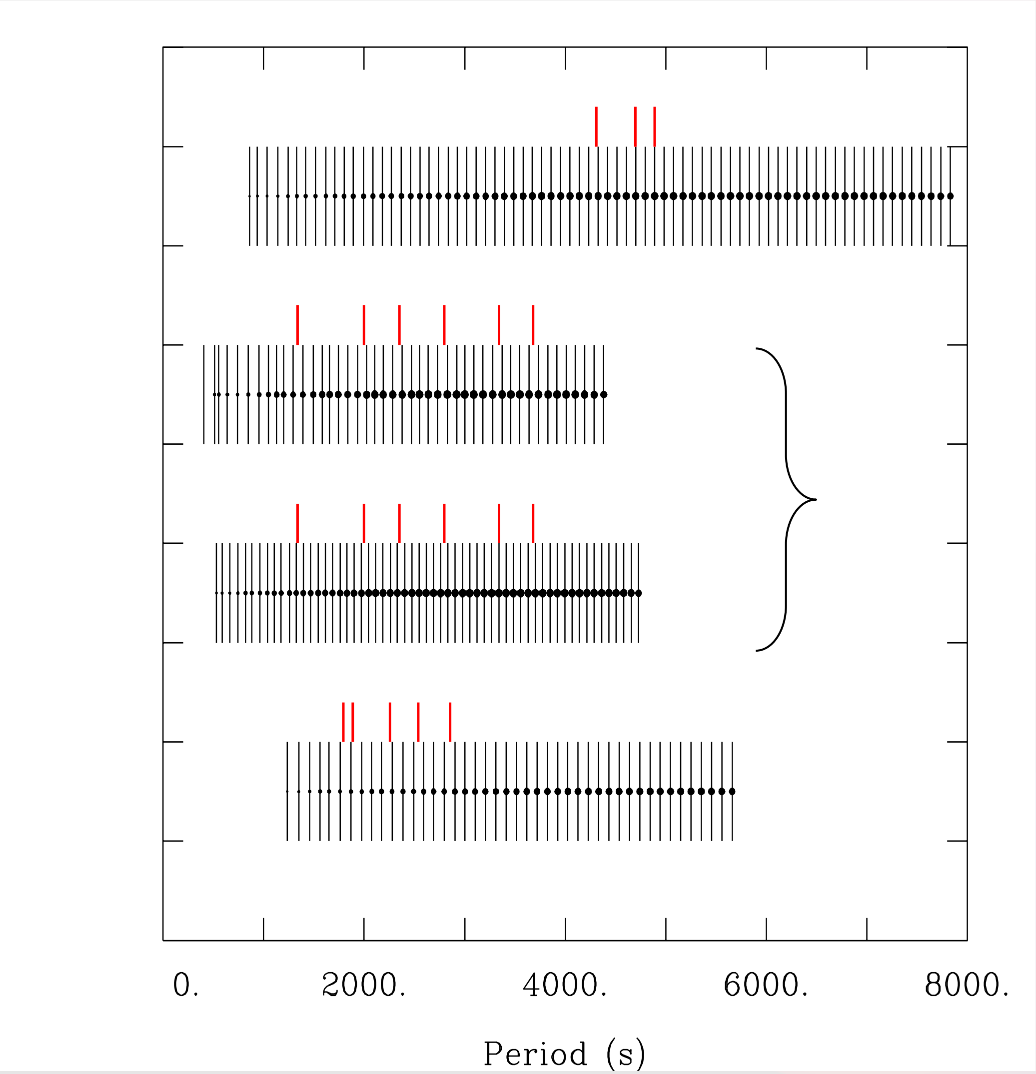
Edges:

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

⇓

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

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*