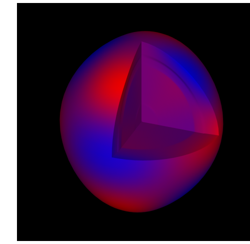
Current challenges in the physics of white dwarfs
Santa Fe, 12-16 June 2017



Pulsations in white dwarf stars

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Outline

I. What is asteroseismology ?

II. The zoo of pulsations in white dwarfs

III. What can be learned from white dwarf asteroseismology

IV. What do we need for white dwarf asteroseismology

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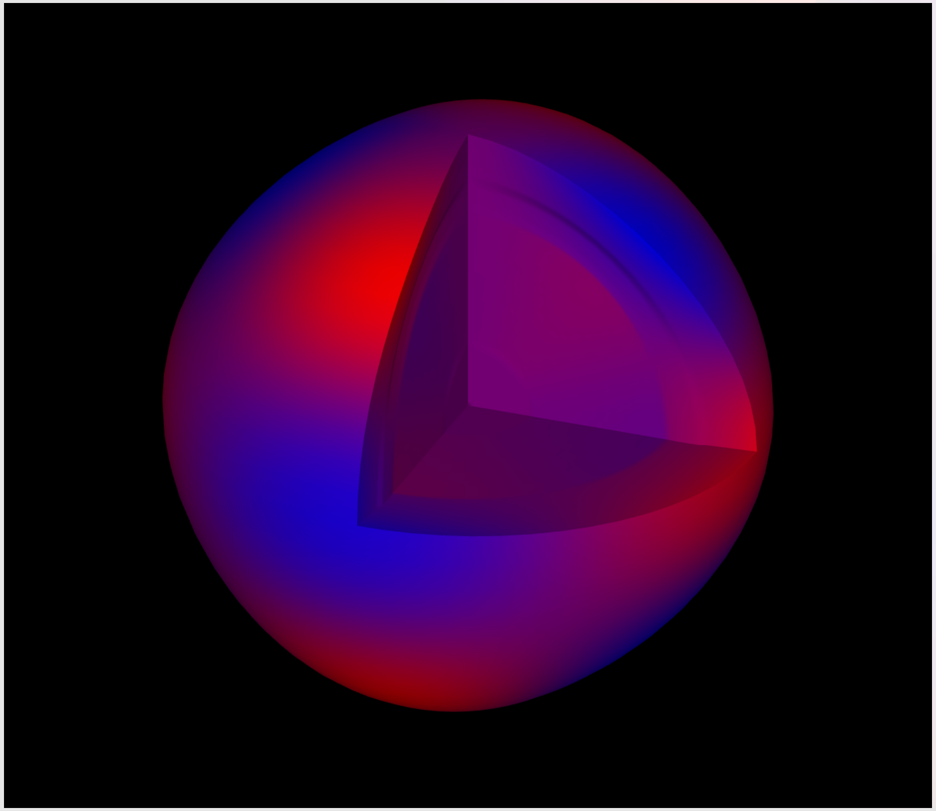
What is asteroseismology ? ("stellar seismology")

Study the interiors of stars by interpreting their pulsations

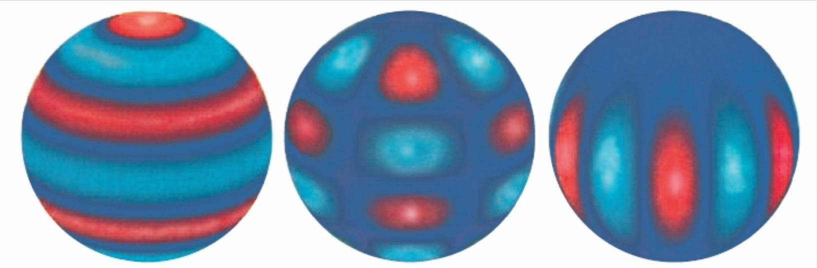
Goal: improve our knowledge of stellar interiors (stars are opaque...)

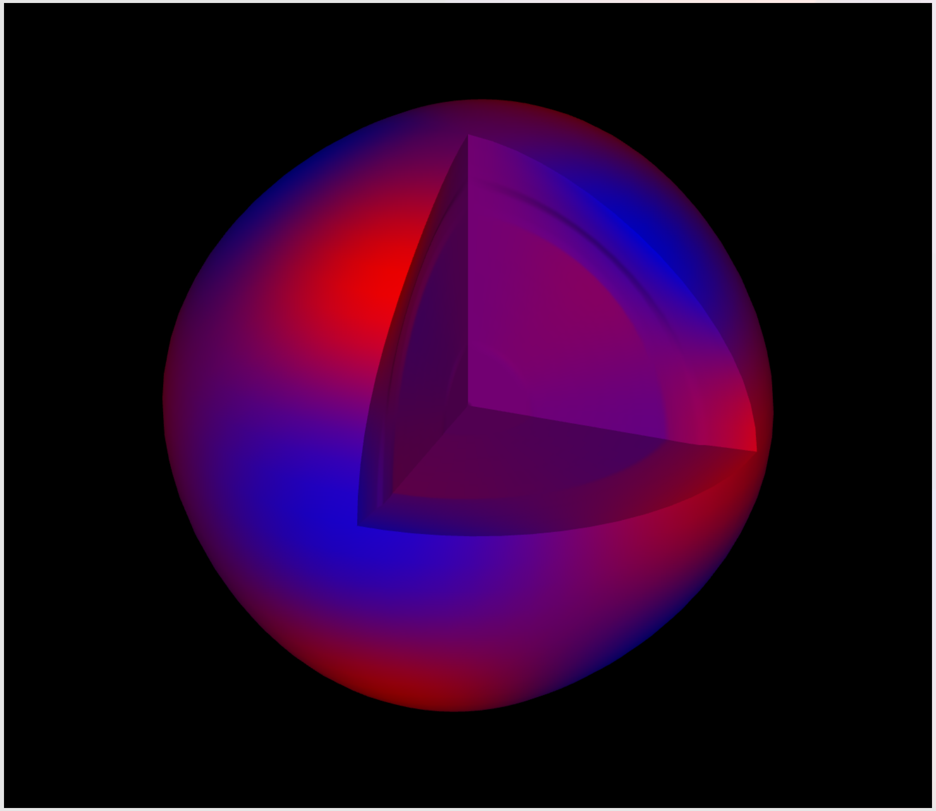


What is not well known ?

- Global properties (mass, radius,…)
- Thermonuclear fusion properties
- Microphysics (opacities)
- Convection properties (core, envelope)
- Microscopic transport (gravitational settling, radiative forces)
- Macroscopic transport (differential rotation,magnetism, etc.)
- ...

What is asteroseismology ? ("stellar seismology")



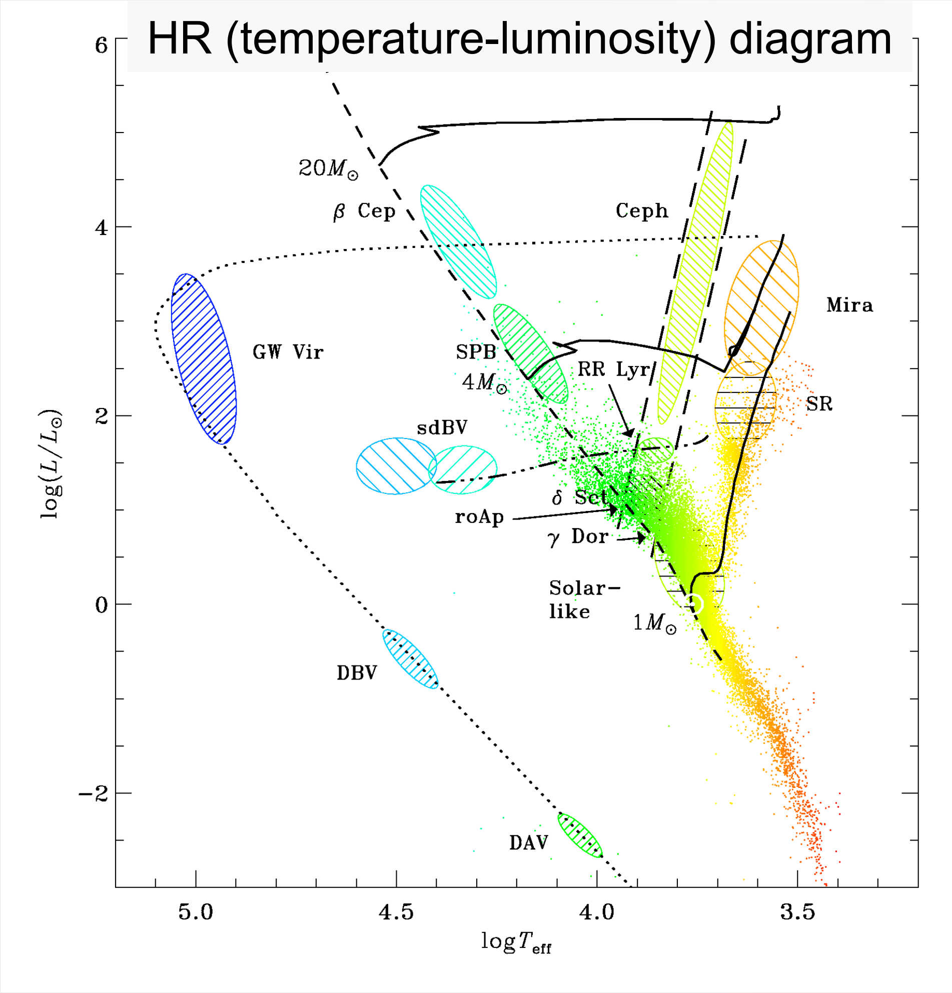


Theoretical grounds:

- Linearized equations of hydrodynamics
- Angular dependence described with spherical harmonics
- Pulsations are excited and propagate in some regions, and are evanescent in others
- In white dwarfs: gravity modes

A zoo of pulsating stars

representative of different stages of evolution (from birth to death)



<u>Main sequence stars</u>

(H-burning)

including the Sun

<u>Intermediate stages of evolution</u>

- Red Giants
- Horizontal Branch stars

(He-burning), eg. sdB stars

<u>Late stages of evolution</u>

White dwarfs (no burning)

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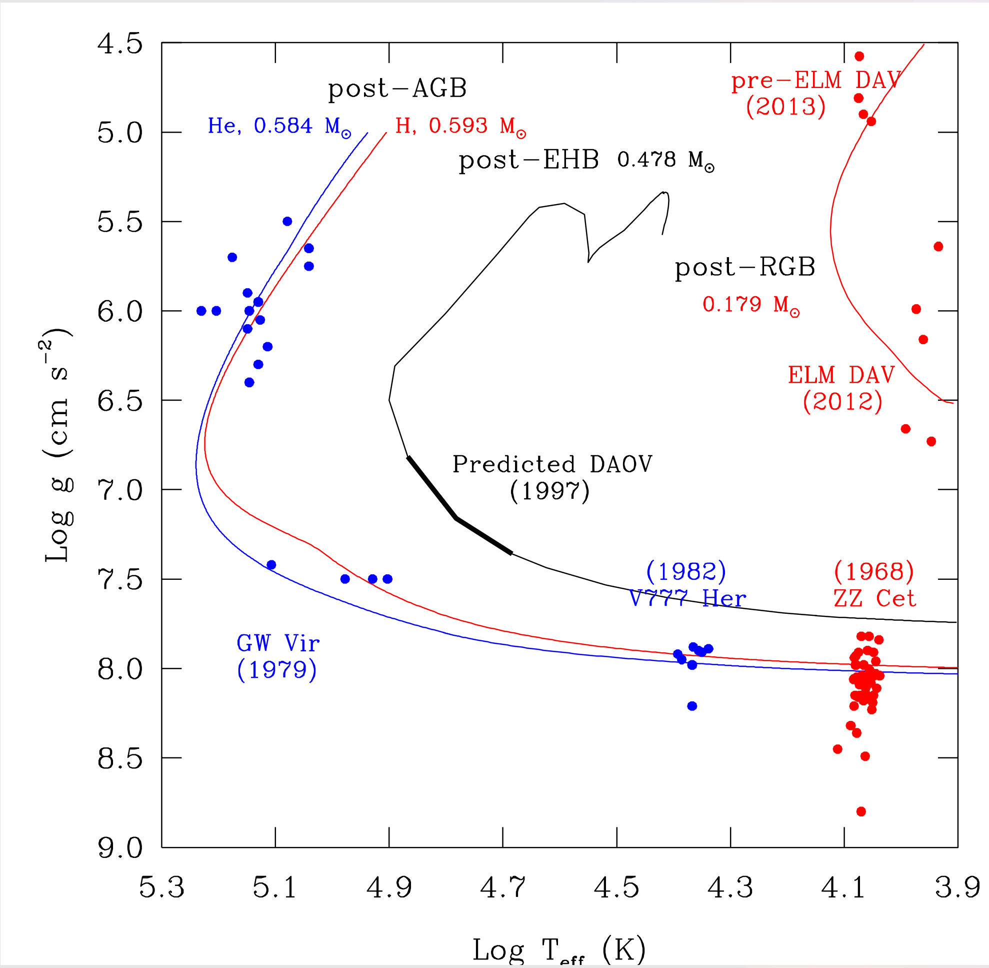
The zoo of pulsating white dwarfs

Pulsators are present at various masses and evolutionary stages



Courtesy: G. Fontaine

Classical (~0.6Ms, 0.5-1.2Ms)

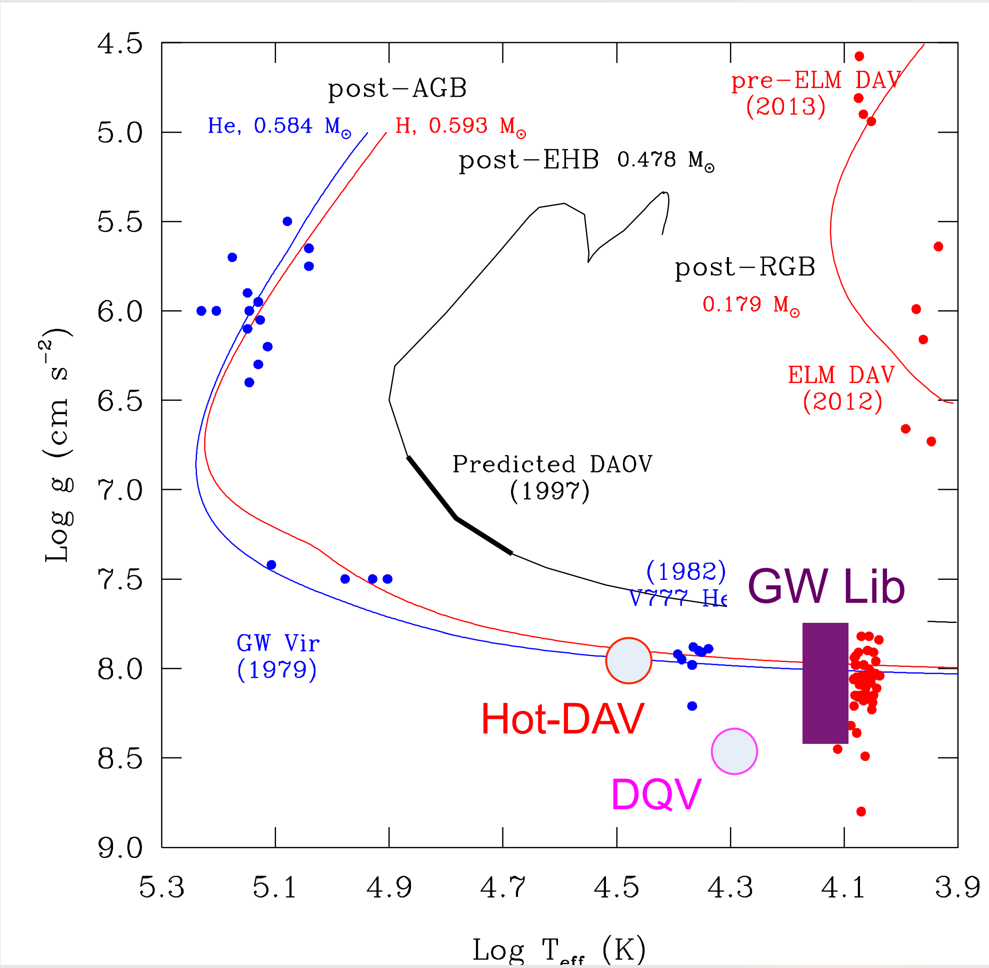
- **GW Vir or PG1159**, He-C-O atmo (~140,000-80,000 K, ~20 pulsators are known)
- **V777 Her (DBV)**, He-rich atmo (~30,000-25,000 K, ~15 known)
- **ZZ Ceti (DAV)**, H atmo (~12,000-11,000 K, ~60 known)

Extremely Low-Mass (~0.2Ms)

- **Pre-ELM,** H-He atmo, 5 known
- **ELM DAV,** H atmo, 5 known

The zoo of pulsating white dwarfs

Pulsators are present at various masses and evolutionary stages



Courtesy: G. Fontaine

Predicted

- DAOV (post-EHB)
- Hot-DAV (~30,000 K)

Exotics

- GW Lib, accreting white dwarfs, H-He atmo, ~15 known

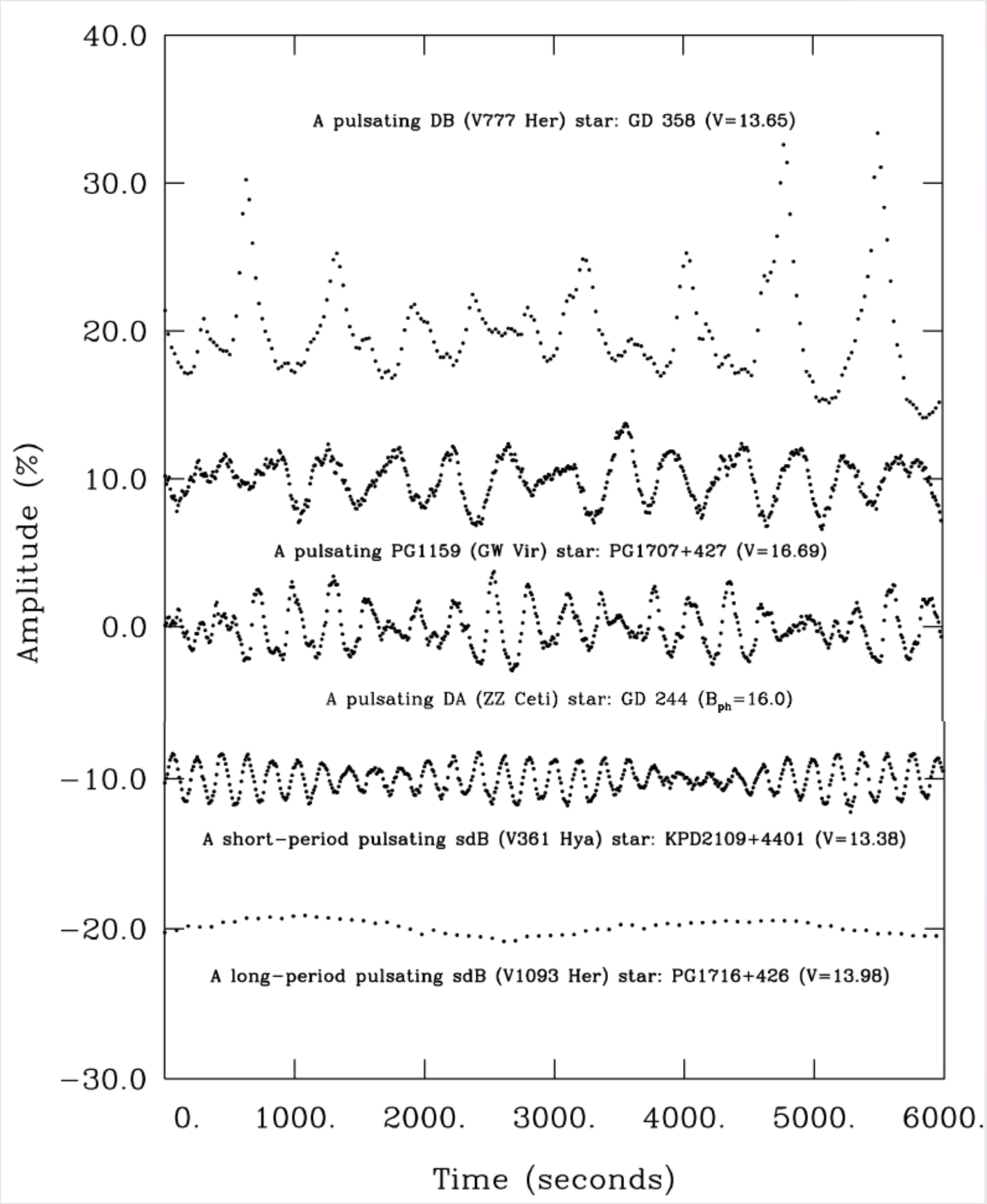
Dismissed? (as self-driven pulsator)

- DQV, C-rich atmo, ~5 known, highly magnetic (MG)

Rotation rather than pulsations?

(not multiperiodic + theoretical works)

The zoo of pulsating white dwarfs



Multiperiodic pulsators (V ~ 15 - 20)

- GW Vir stars: 500-5000 s
- V777 Her stars: 150 - 1000 s
- ZZ Ceti stars: 100 - 1000 s
- Pre-ELM white dwarfs: 300-1000 s
- ELM white dwarfs: 1500-5000 s

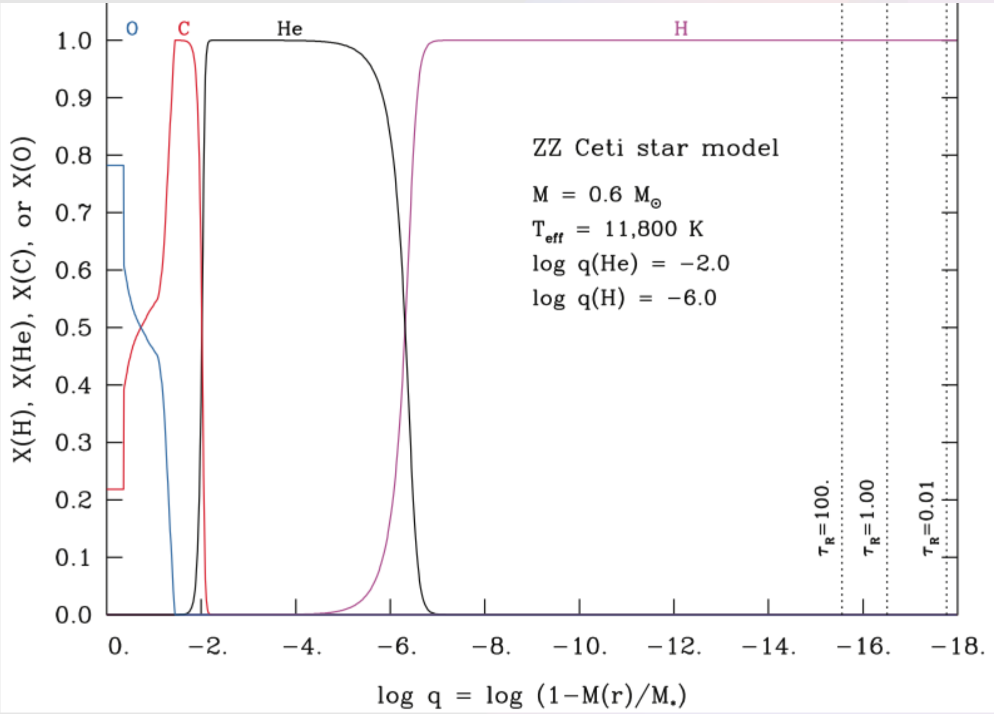
← short-period pulsating sdB

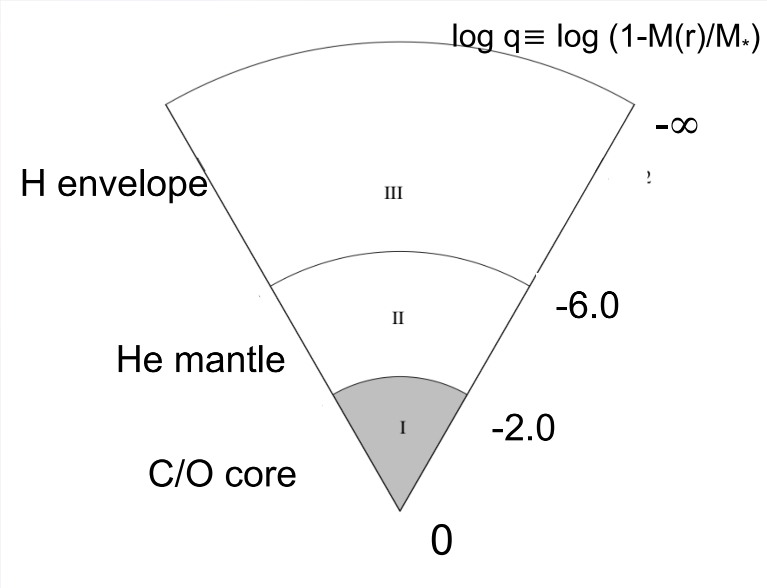
← long-period pulsating sdB

Typical internal structure of a white dwarf

Here: ZZ Ceti model, 0.6Ms, T_{eff}=11,800 K

"onion-like" stratification





ELM: He-core

Very massive: Ne-Mg core

Internal stratification and core composition not well known !

(reflects uncertainties on the previous phases of stellar evolution: $^{12}C(\alpha,\gamma)^{16}O$ rate, various mixing processes, thermal pulses on AGB, etc)

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1. "Quantitative asteroseismology" (P_{obs} ⇔ P_{theo})

Search the stellar model(s) whose theoretical periods best fit all the observed ones, in order to minimize

$$S^2(a_1, a_2, ..., a_N) = \sum_{i=1}^{N_{\rm obs}} (P_{\rm obs}^{(i)} - P_{\rm th}^{(i)})^2$$

> **Models**: Parametrized/static models (*<u>independent</u> of stellar evolution)*, or grids of fully evolutionary models

N parameters: T_{eff}, logg, envelope layering, core composition, convection efficiency

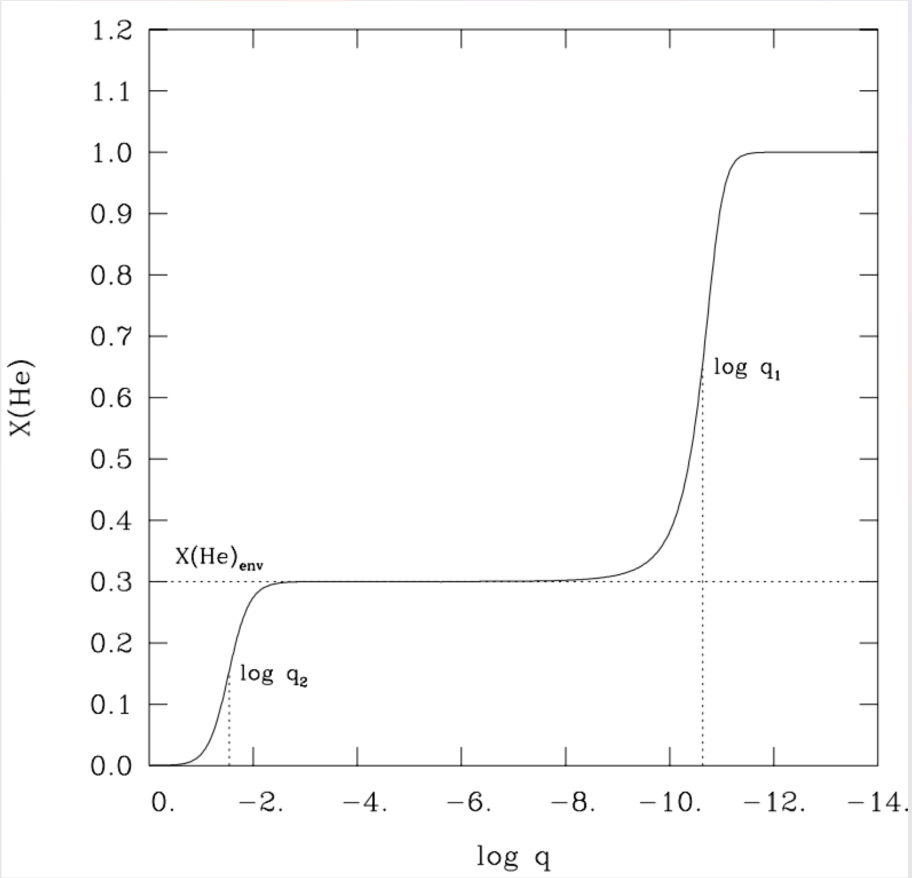
> **Optimization procedure**: Efficient optimization codes (based on *Genetic Algorithms*) to thoroughly explore the parameter space and find the minima of S^2

Under *external* constraints from spectroscopy + mode identification (if available)

> **Results**: structural and core parameters of the star (M_*, M_{env}, M_{core}, etc.), internal chemical stratification (elements profiles)

The example of the V777Her star KIC08626021 (Giammichele et al.)

- 23 months of *Kepler* high-precision observations (0.6 nHz)
- 8 observed independent modes, 143-376 s
- Spectroscopy: T_{eff}=29,360±780 K, logg=7.89±0.05
- Parametrized models for DB stars: ex. He profile parametrization:

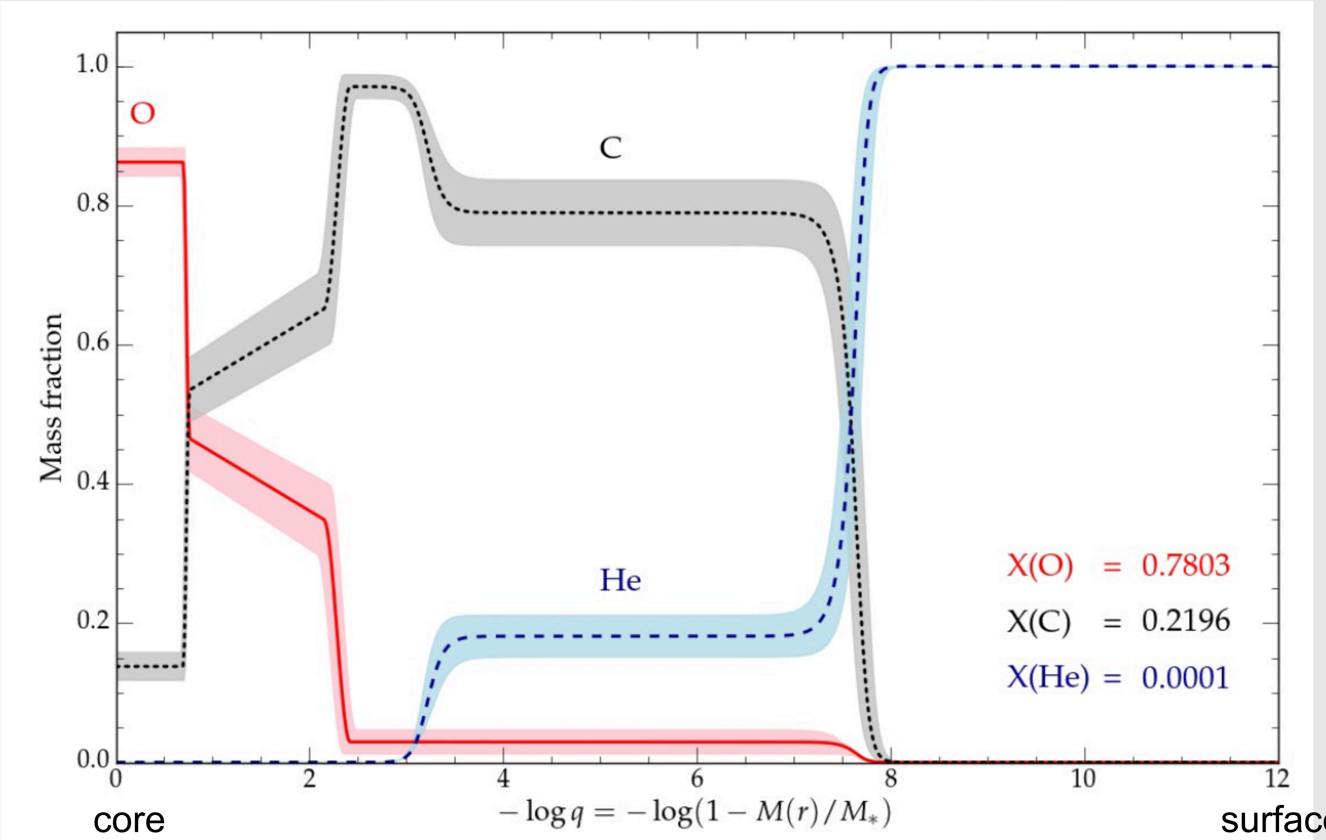


Giammichele et al.

core ← → surface

The example of the V777Her star KIC08626021 (Giammichele et al.)

- Fit to the 8 periods *at the precision of the observations* ($S^2 \sim 10^{-15}$)
- Inferred chemical profile:



Giammichele et al. (submitted)

Higher central and total O abundance and bigger core than predicted from stellar evolution

See also poster of N. Giammichele

The example of the V777Her star KIC08626021 (Giammichele et al.)

Table 1 | Derived properties of KIC08626021

Quantity	Estimated value
$\log g$ (cm s^{-2})	7.917 ± 0.009
T_{eff} (K)	29,968 ± 150
$X(He)_{env}$	0.18 ± 0.03
$\log q_1$	-7.63 ±0.09
$\log q_2$	-3.23 ± 0.05
$X(O)_{center}$	0.86 ± 0.02
$\log q_3$	-0.72 ± 0.01
$M(He)/M_*$	0.0113 ± 0.0006%
$M(C)/M_*$	21.96 ± 2.7%
$M(O)/M_*$	78.03 ± 2.7%
$M_*/M_\odot$	0.570 ± 0.004
$R_*/R_\odot$	0.0138 ± 0.0001
$L_*/L_\odot$	0.137 ± 0.005
M_r[a]	10.28 ± 0.03
d (pc)[b]	422 ± 45
P_{rot} (h)	46.3 ± 2.5
V_{eq} (km s^{-1})	0.36 ± 0.02
J (kg m^2 s^{-1})[c]	$6.59 \pm 0.38 \times 10^{38}$
$J/J_\odot$	1/291
dP/dt_{197} (s/s)[d]	14.4 or 2.8×10^{-14}
dP/dt_{232} (s/s)[d]	15.1 or 2.8×10^{-14}
dP/dt_{271} (s/s)[d]	15.5 or 3.0×10^{-14}

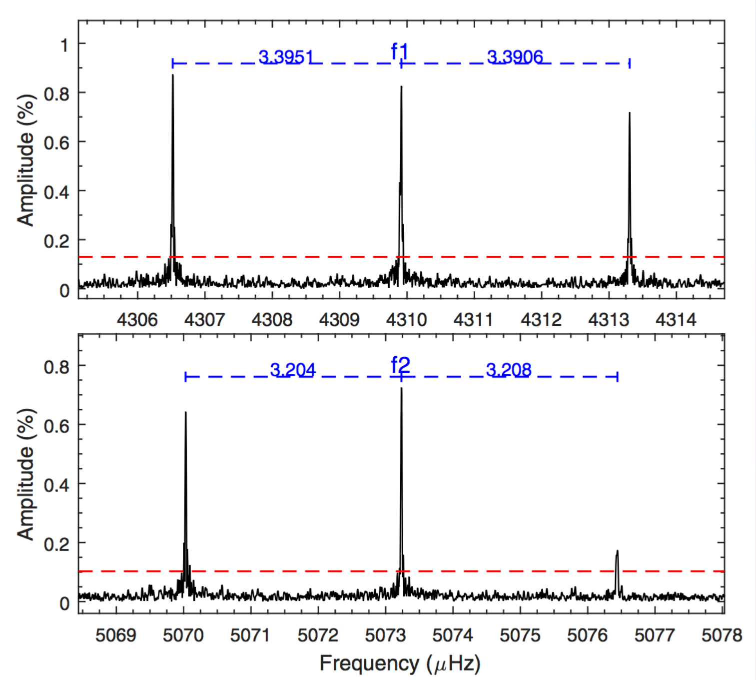
Access to stellar radius, mass, luminosity, distance,…

Asteroseismic results important for:

- Constraints for stellar evolution
- WD cosmochronology (GAIA)
  - C/O content
  - « insulating » envelope

Internal rotation profile in white dwarfs

By exploiting the fine structure of modes, interpreted as *rotational splitting*
(rotation lifts the (2l+1)-fold degeneracy of pulsation modes)



KIC08626021
(Zong et al. 2016)

How to compute pulsation periods in presence of rotation is a whole field of asteroseismology, but, if Pmodes << Prot:

$$\sigma_{klm} = \sigma_{kl} - m \int_0^R \Omega(r) K_{kl}(r) dr$$

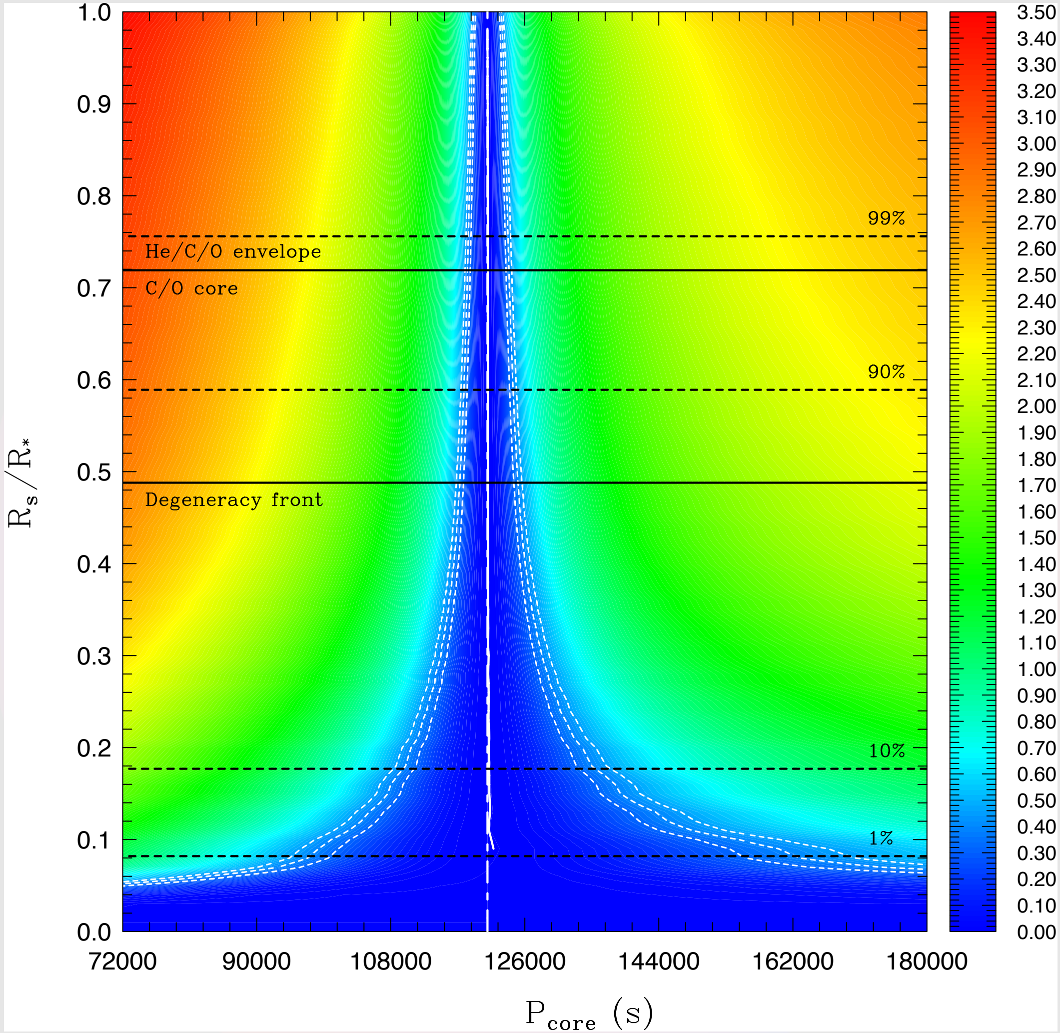
$$K_{kl}(r) = \frac{\xi_r^2 - [l(l+1) - 1]\xi_h^2 - 2\xi_r\xi_h}{\int_0^R [\xi_r^2 + l(l+1)\xi_h^2]\rho r^2 dr} \rho r^2$$

ξ_r,ξ_h:eigenfunctions

Internal rotation profile in white dwarfs: PG 1159-035 (=GW Vir)

Charpinet et al. (2009), Nature

12+5 multiplets



Solid-body rotation over 99% of the stellar mass; P_{rot}=33.67±0.24h

A pre-WD has already lost all of its angular momentum

2. “Non-adiabatic asteroseismology”

Understanding how pulsations are excited, trying to reproduce observed instability strips

General picture: opacity-driven mechanism:

- Don Winget (1981) for ZZ Ceti:

H ionization/recomb. around T_{eff}~12,000 K

⇒ envelope opacity increase

⇒ strangle the flow of radiation, convection zone develops

⇒ g-modes instabilities

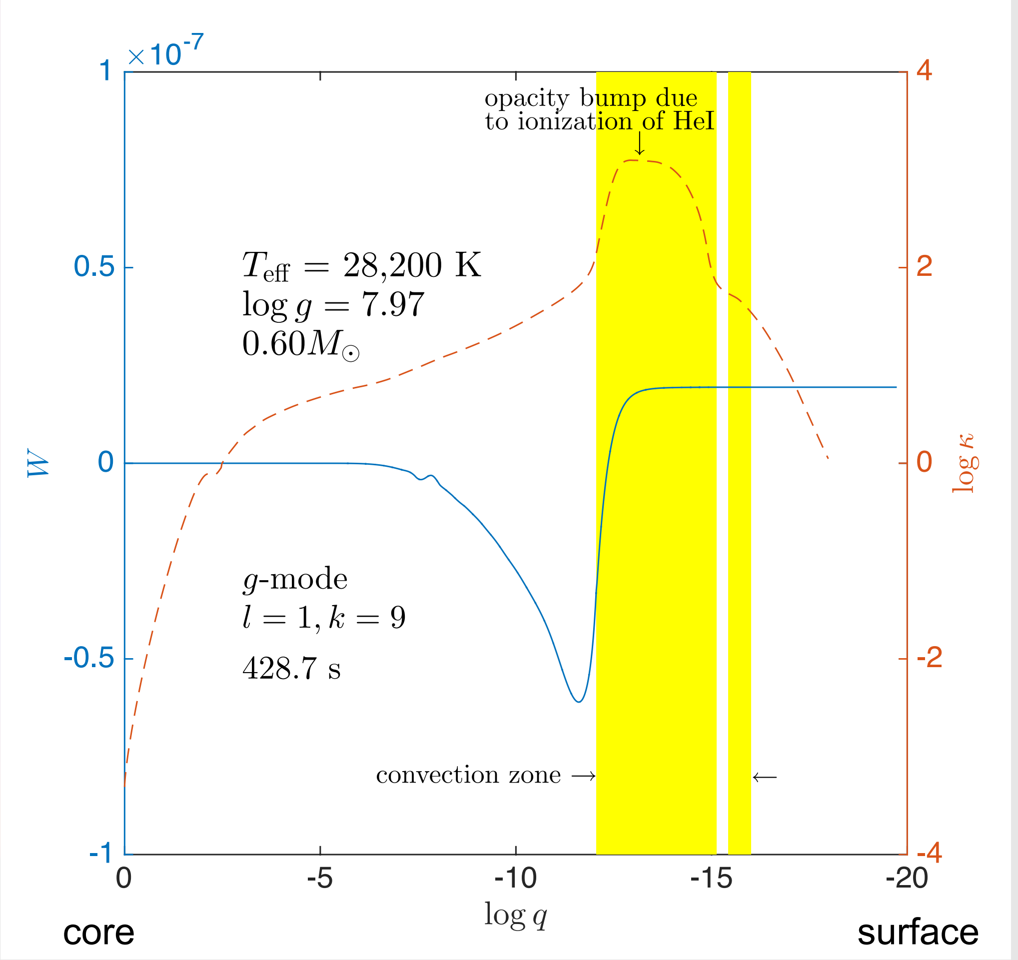
// ELM pulsators (H atmo)

- By analogy, Winget proposed pulsating He-rich, V777 Her white dwarfs:

HeII partial ionization around T_{eff}~30,000 K

// pre-ELM pulsators (H-He atmo)

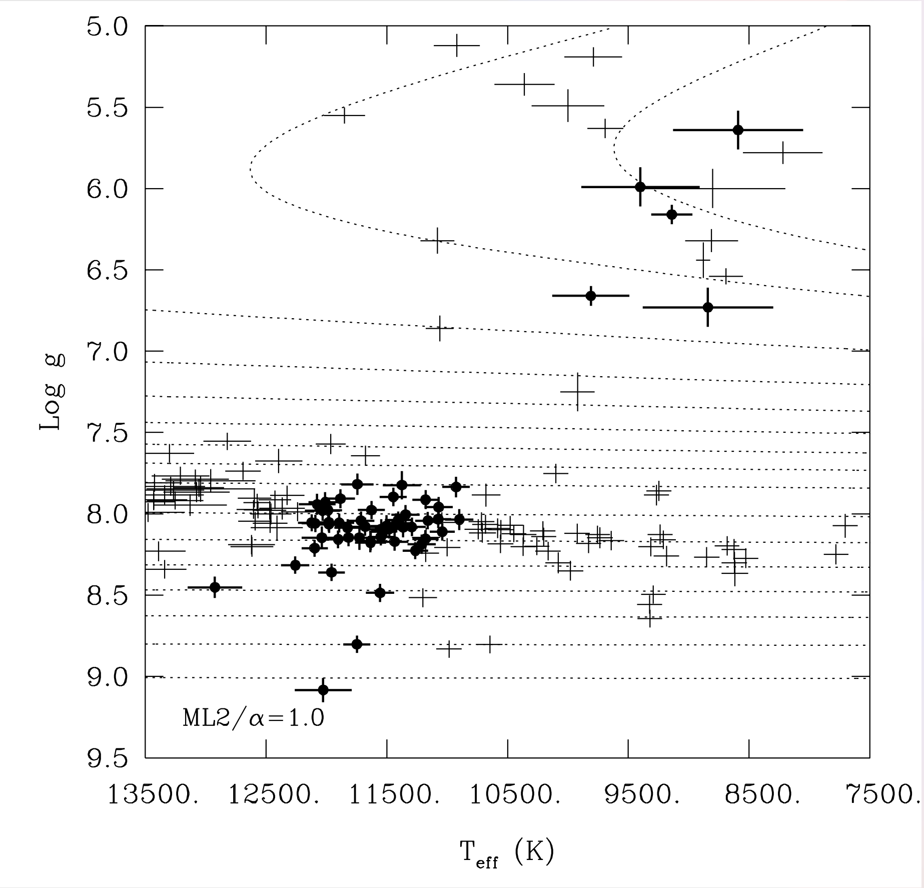
- Partial ionization of K-shell e^- of C and O for GW Vir, no convection development (κ-mechanism)



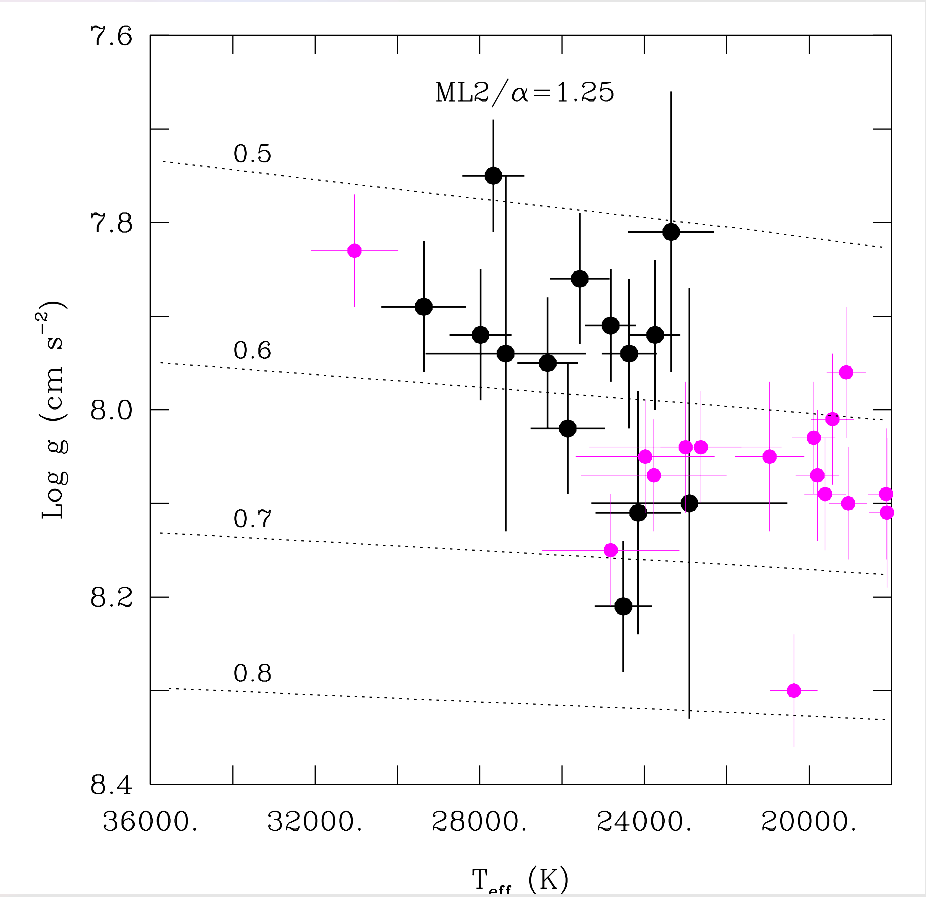
2. "Non-adiabatic asteroseismology"

Understanding how pulsations are excited, trying to reproduce observed instability strips

ZZ Ceti & ELM (H-atmo)



V777 Her (He-rich atmo)



What can be learned: convection in WDs (depth, efficiency)

2. "Non-adiabatic asteroseismology"

Understanding how pulsations are excited, trying to reproduce observed instability strips

Empirical strips (e.g. group of P. Bergeron, WET collaboration):

- Decades of work to reach a homogeneous view of the empirical strips (high-quality photometric & spectroscopic observations + high-quality model atmospheres)
- In both cases: most likely a **pure** strip
- Efficiency of convection in *atmospheres*: α/MLT=0.6 (ZZ Ceti) and α/MLT=1.25 (V777Her)

Theoretical strips (e.g. Van Grootel et al.):

- T_{conv} << Periods of pulsations (blue edge), or T_{conv} <~ Periods (later in cooling)

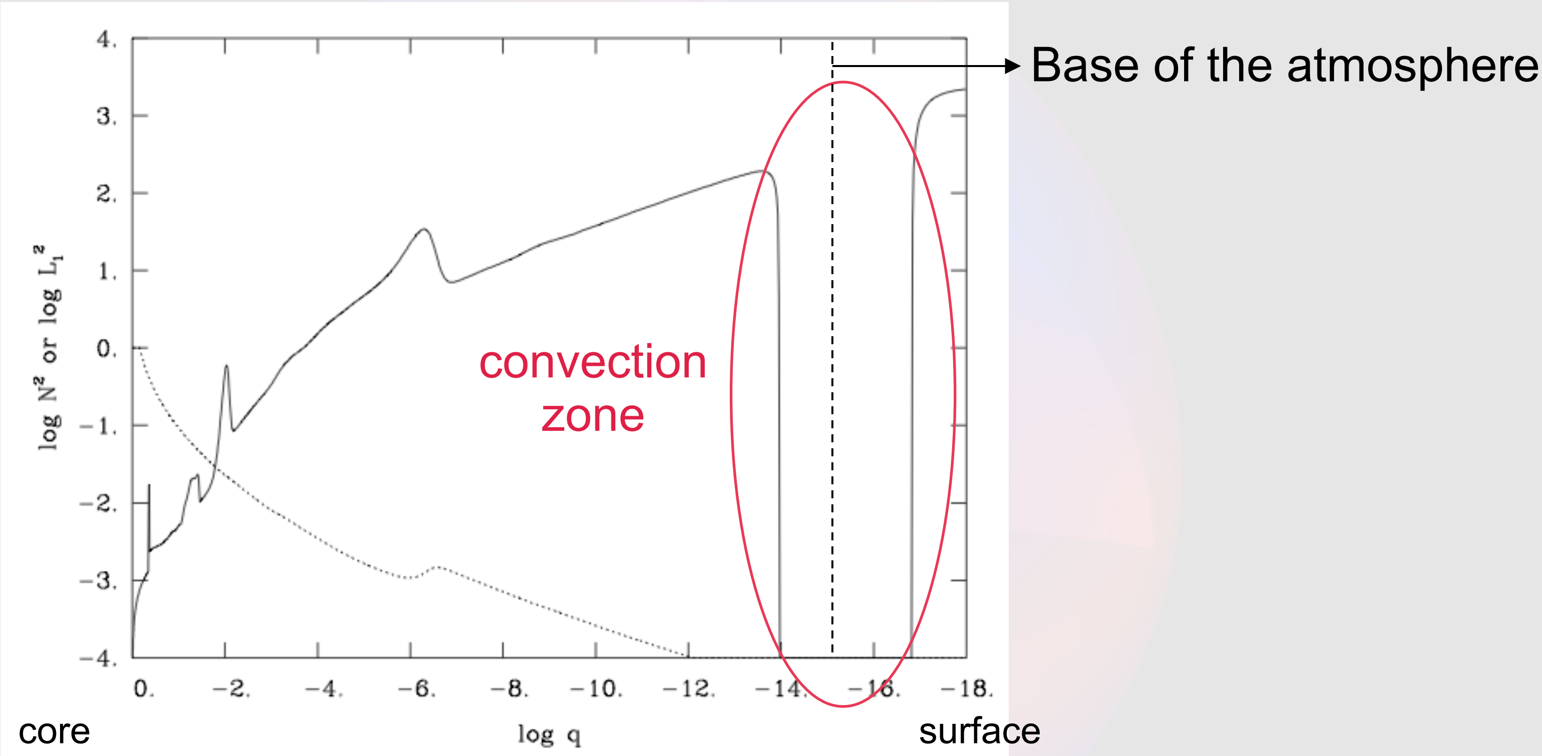
⇒ need of **Time-Dependent Convection (TDC),** as in MAD code (Dupret, Liège)

- TDC still fails to reproduce the red edge: energy leakage argument (mode are no longer reflected back by the atmosphere)

- **1D** stellar models with, for upper layers, same T stratification than full 1D model atmospheres

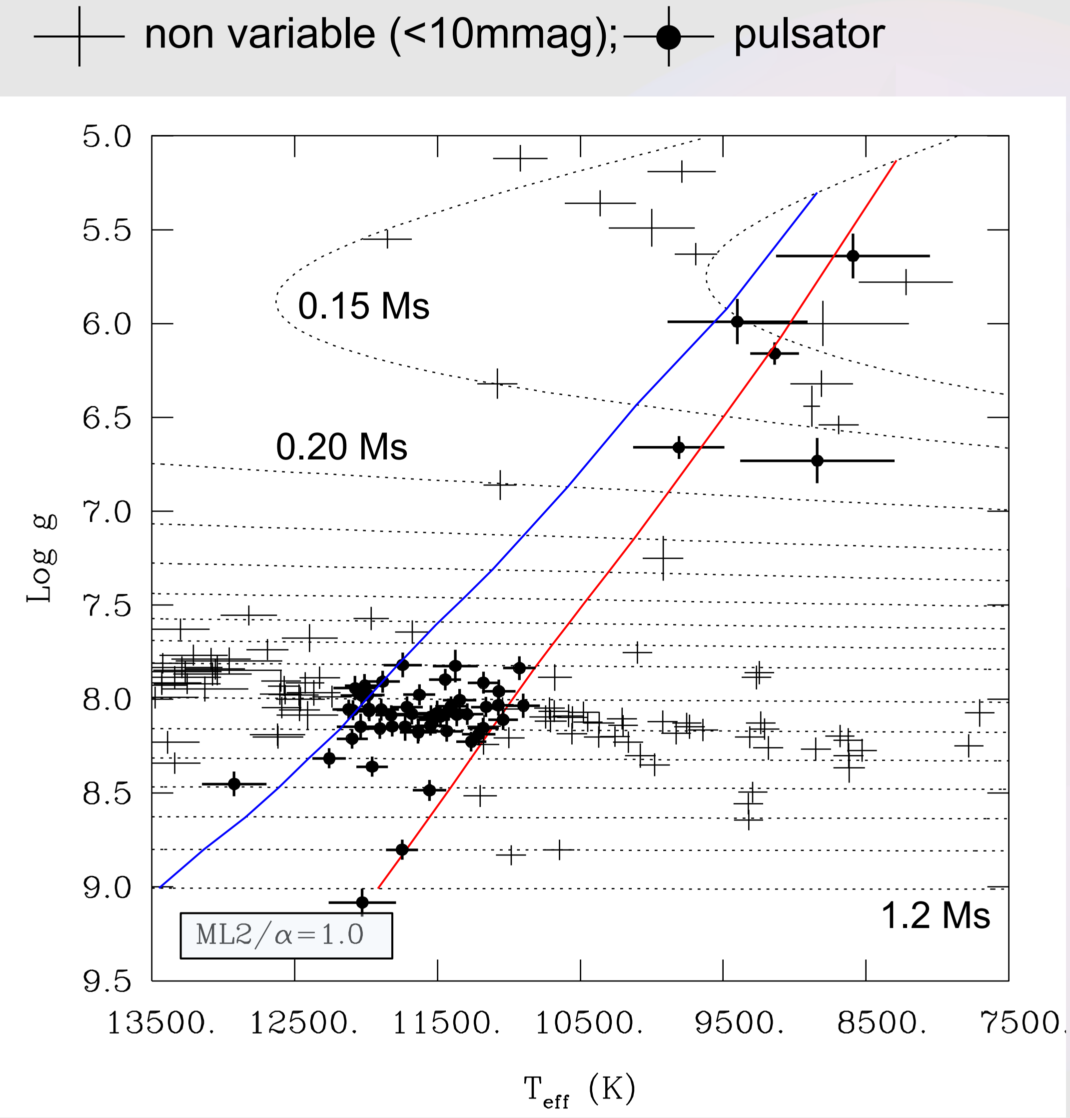
Modeling details

Detailed modeling of the superficial layers:



Our structure models have the same T stratification as the complete (1D) model atmospheres
⇒"feedback" of the convection on the global atmosphere structure

Theoretical instability strip for ZZ Ceti and ELM DA pulsators



Van Grootel et al. (2013)

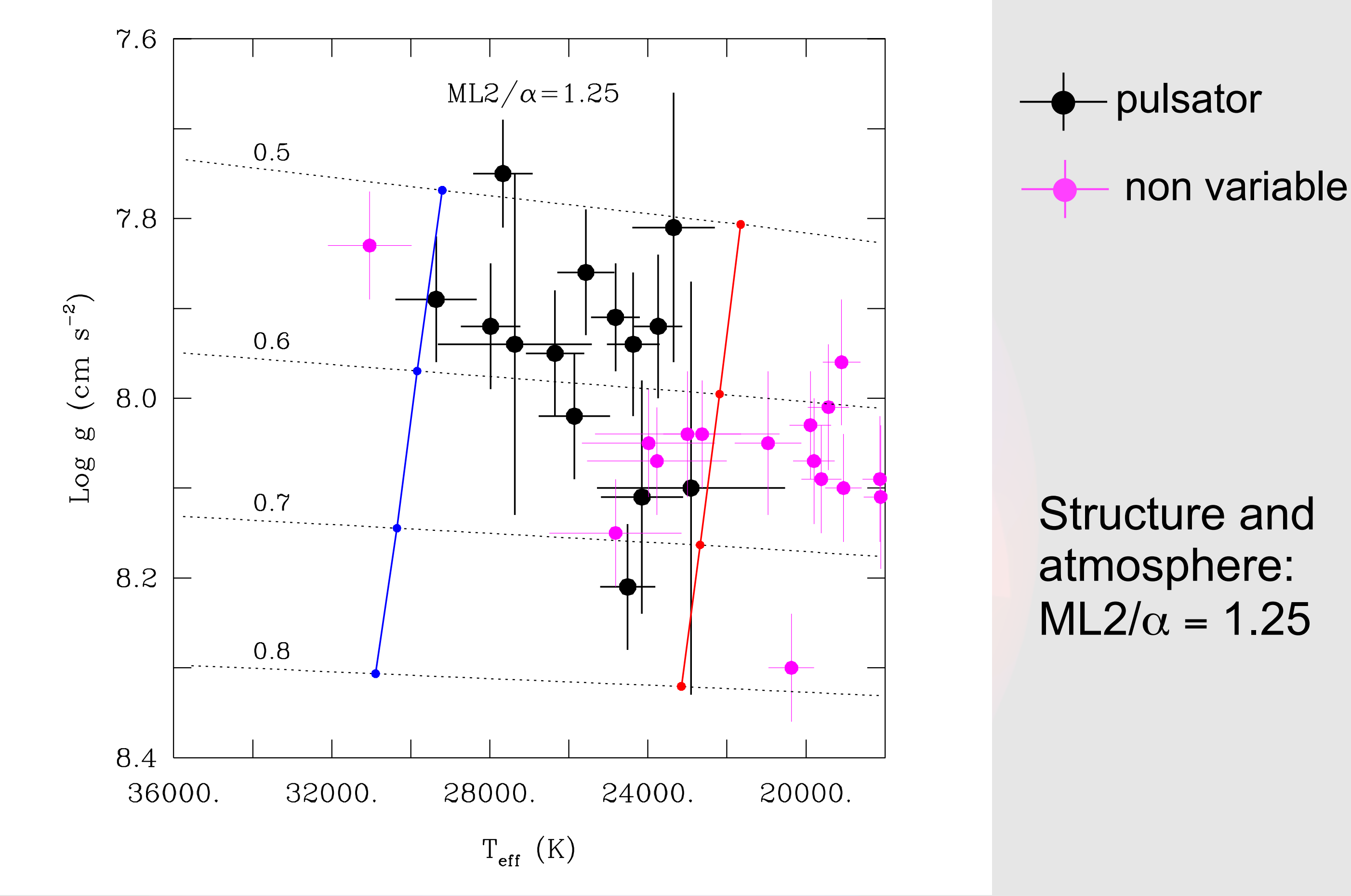
TDC blue edge

Red edge (energy leakage)

Homogeneous atmospheric parameters (here ML2/α = 0.6)

Structure (ML2/α = 1.0) and atmospheric (ML2/α = 0.6) MLT calibrations are dependent

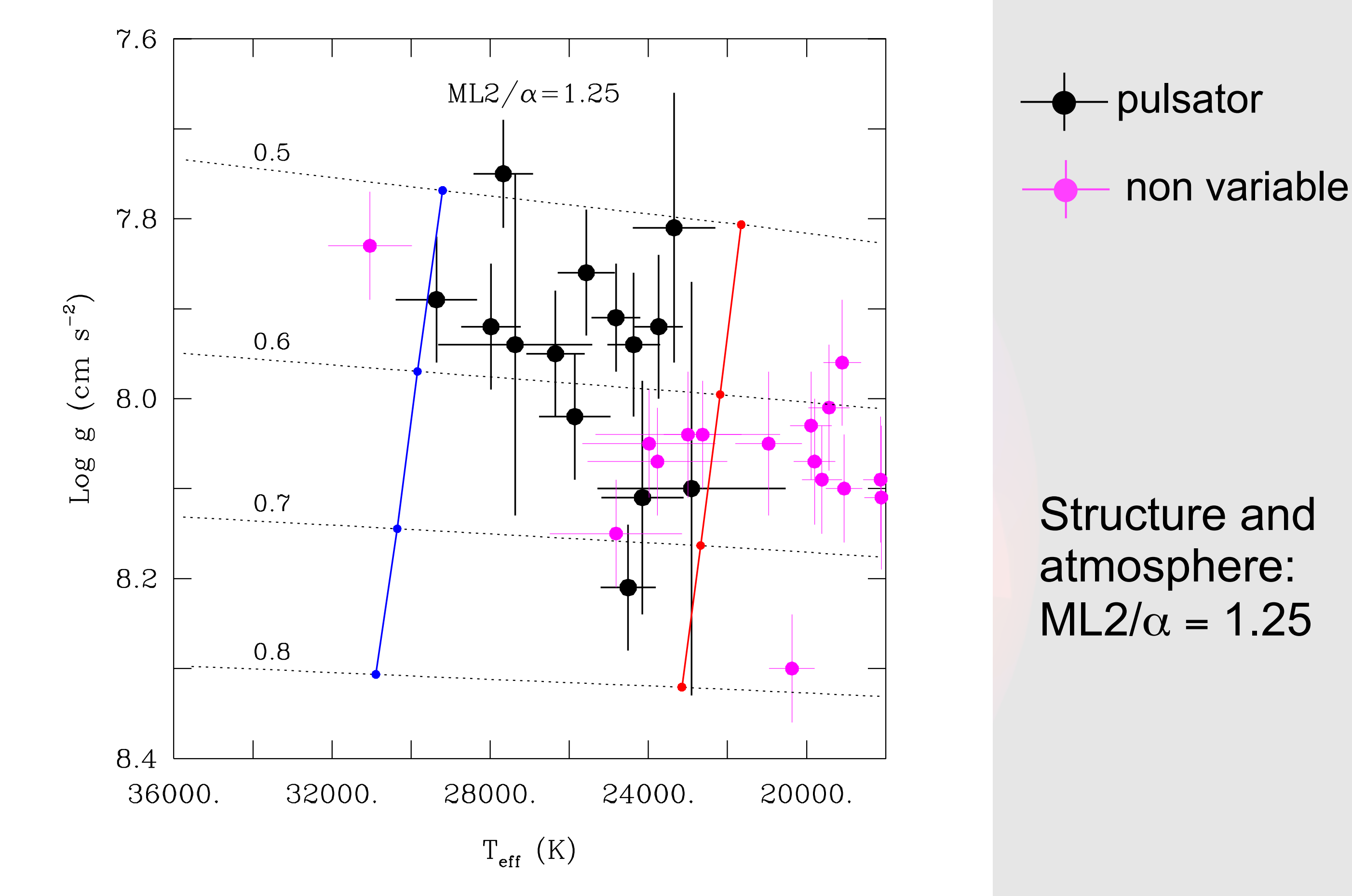
Theoretical instability strip for V777Her stars



Van Grootel et al. (2017)

Structure and atmosphere: ML2/α = 1.25

Theoretical instability strip for V777Her stars



Structure and atmosphere: ML2/α = 1.25

Van Grootel et al. (2017)

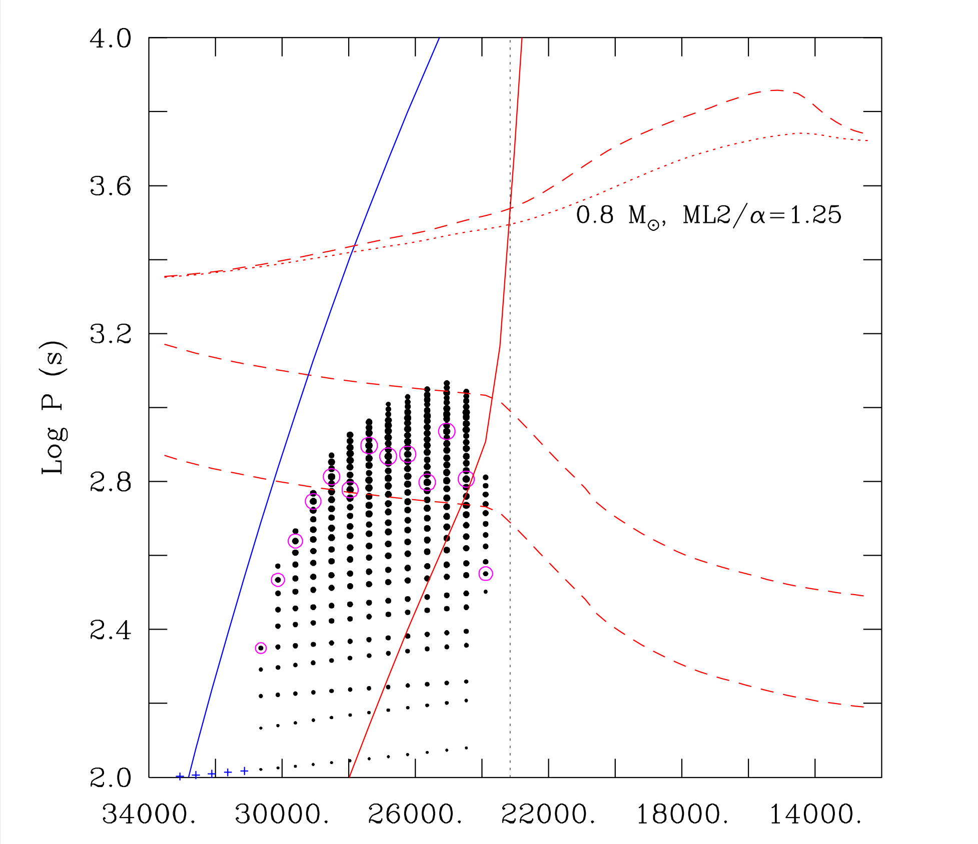
BUT:
- Red edge leakage *slightly* too cool (?)
- Kepler observartions: 2 pulsators hotter than blue edge !

Possibilities for improvement ?

- TDC **with** turbulent pressure perturbations

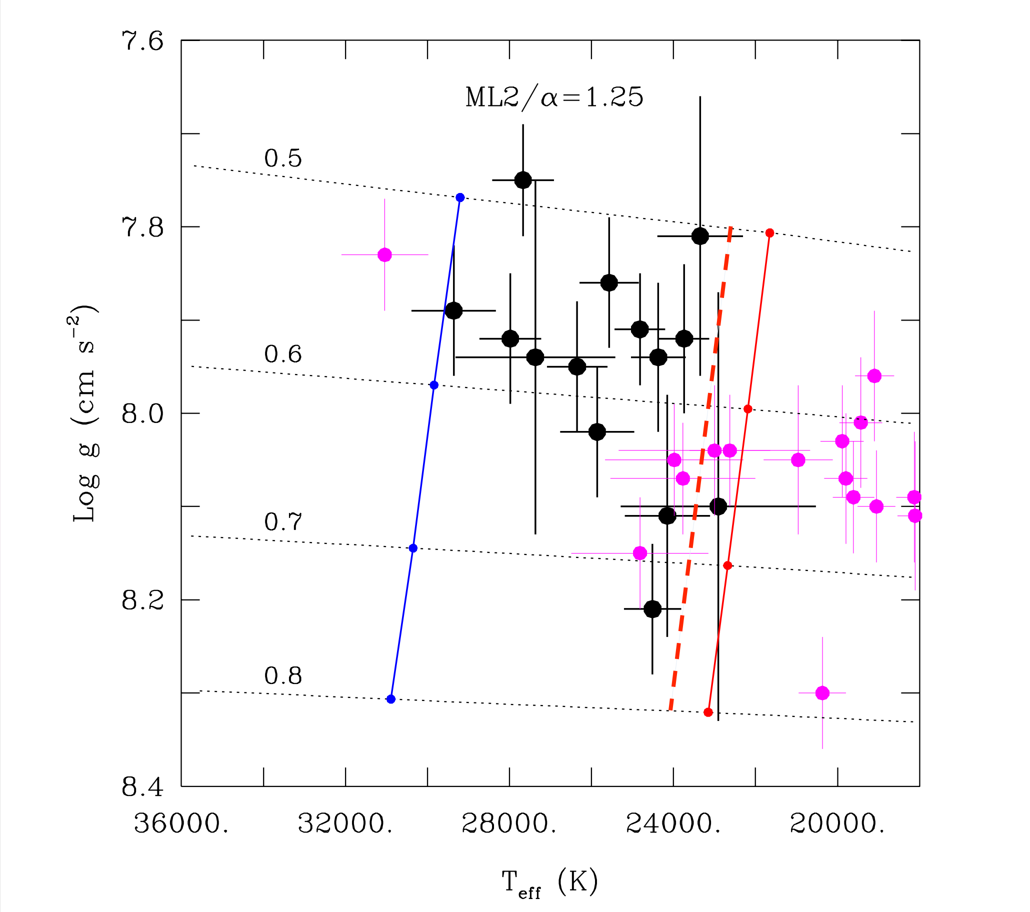
$$\frac{\delta P_t}{P_t} = \frac{\delta \rho}{\rho} + 2\frac{\overline{\delta V_r}}{V_r}$$

- With δPt=3:



Teff (K)

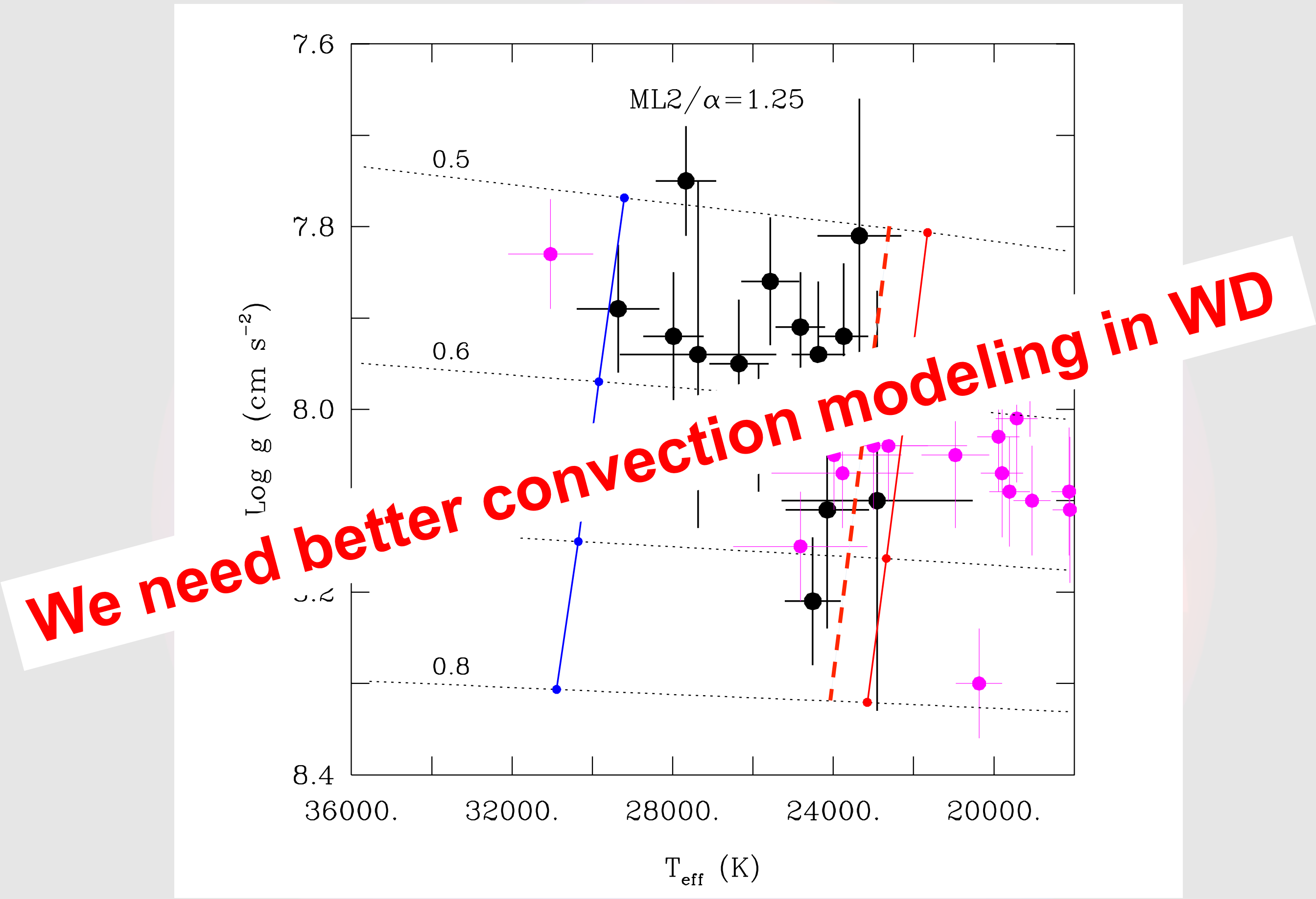
Theoretical instability strip for V777Her stars



Red edge « with turbulent pressure »: ~500 K hotter than red edge leakage

But 3δPt is not physically realistic. Mimic other components of the Reynolds stress tensor (Pt = *rr* component), i.e. **turbulent viscosity** ?

Theoretical instability strip for V777Her stars



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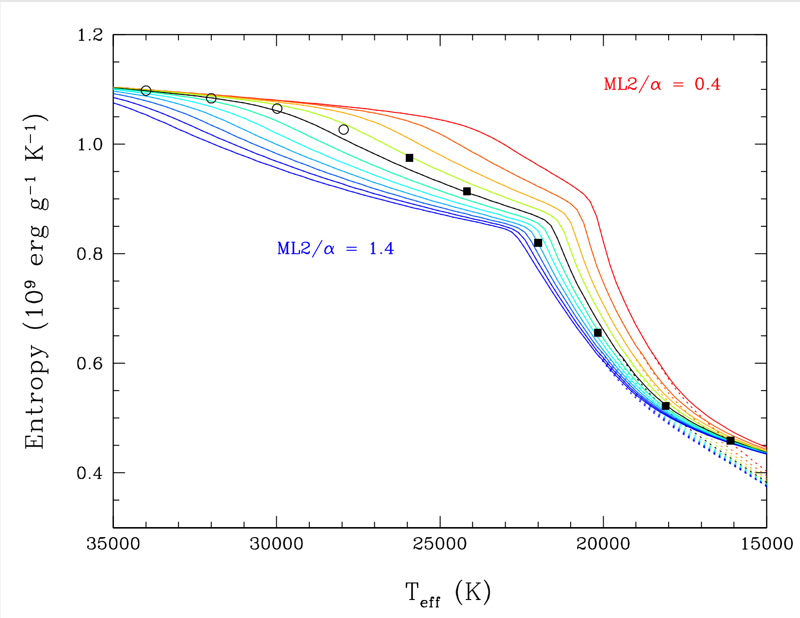
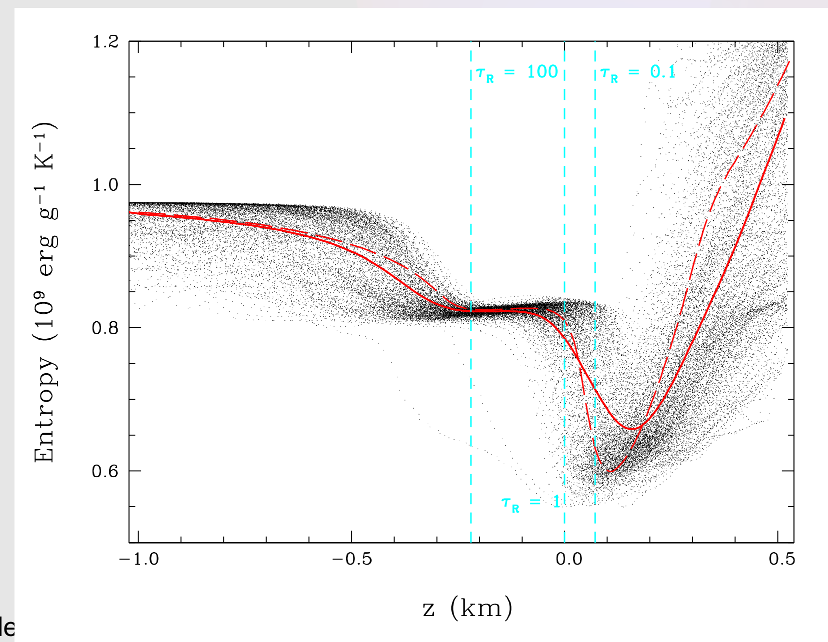
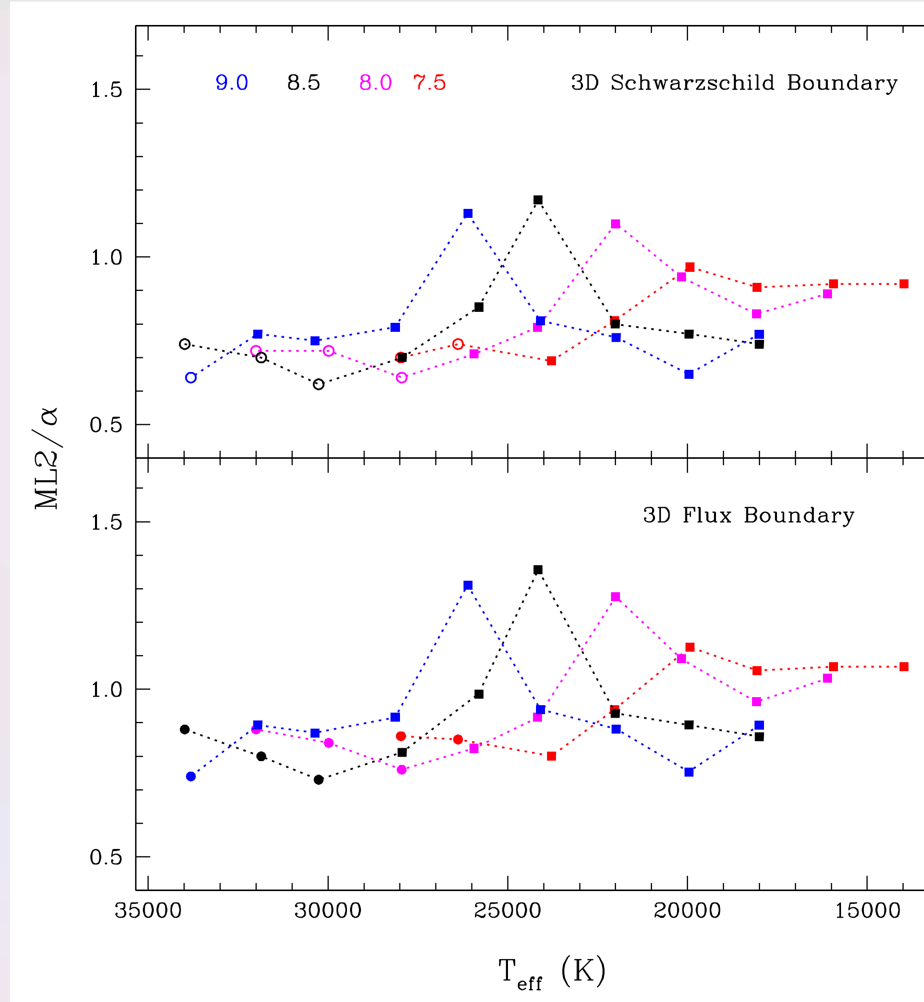
3D simulations for DA and DB white dwarfs (P.E. Tremblay)





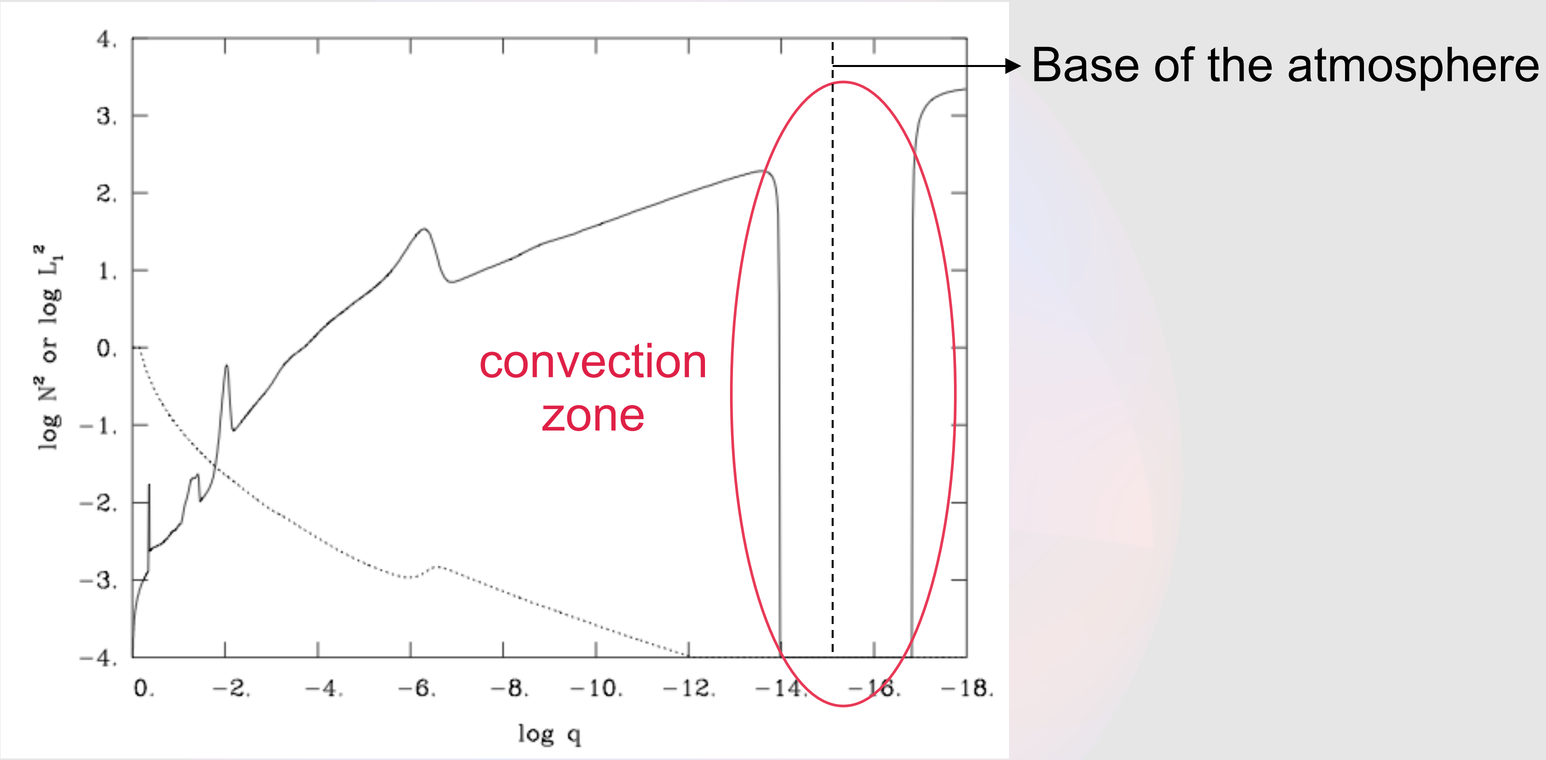


Vale

See also poster of E. Cukanovaite

Modeling details

Detailed modeling of the superficial layers:



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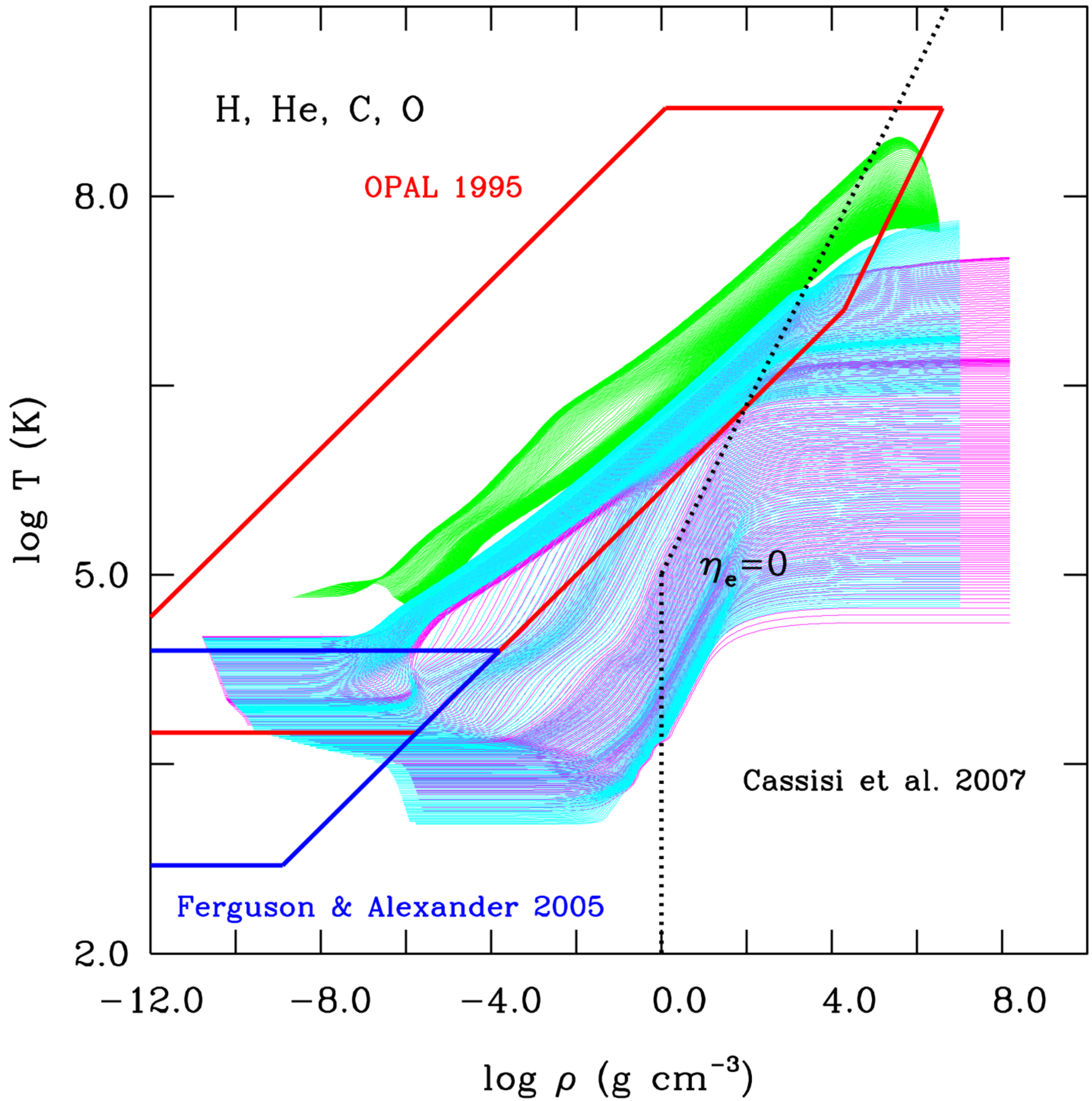
To improve further equilibrium structures used for asteroseismology, including for WD cosmochronology:

- Extended EOS
- Radiative & conductive opacities

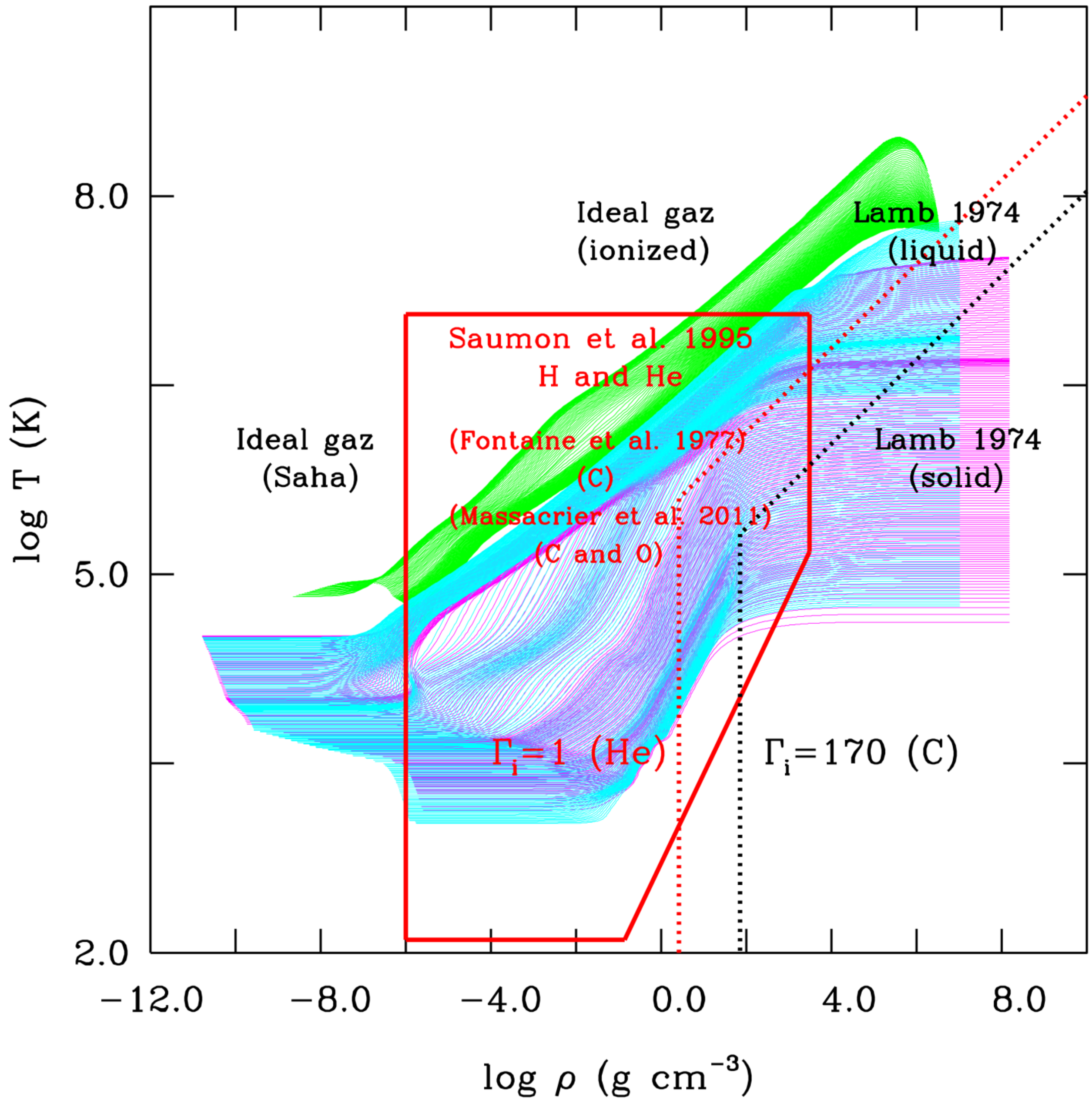
To understand better driving/damping pulsations in WDs:

- Patched 1D models + improved treatment for interaction between convection and pulsations by including turbulent viscosity (work in progress)

Radiative and conductive opacities



Equation of state



Conclusions

What we can learned from WD seismology:

- **Quantitative asteroseismology:**
  - Global parameters
  - Internal layering and chemical stratification
  - Internal rotation profile
- **Non-adiabatic asteroseismology:**
  - how pulsations are driven
  - how convection behaves in WD

What do we need from WD seismology:

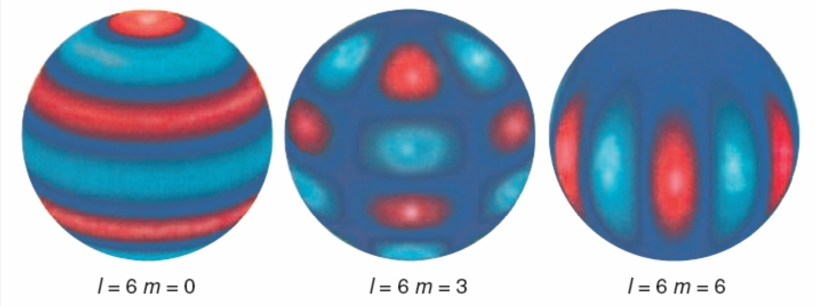
- About physics: EOS & opacities
- Patched 1D models + improved treatment for interaction between convection and pulsations (work in progress)

Theoretical grounds of asteroseismology

•From the linearized equations of hydrodynamics (small perturbations to equilibrium):

$$f'_{klm}(r,\theta,\phi,t) = f'_{kl}(r) Y_l^m(\theta,\phi) e^{i\sigma_{kl} t}$$

(f' = p, v, T, ...)



- eigenfunction f'(r) (radial dependence)
- oscillation eigenfrequency σ_{kl} (temporal dep.)
- spherical harmonics Y_l^m (angular dep.)

•Lamb and Brunt-Väisälä frequency

$$L_l^2 = \frac{l(l+1)c_s^2}{r^2}$$

$$N^2 = \frac{g^2\rho}{p}\frac{\chi_T}{\chi_\rho}(\nabla_{\rm ad} - \nabla + B)$$

Oscillations are excited and propagate in some regions, and are evanescent in others

- if $\sigma^2 > L_l^2, N^2$: p-modes (restoring force : pressure), acoustic waves
- if $\sigma^2 < L_l^2, N^2$: g-modes (restoring force : buoyancy), gravity waves

Driving and damping of pulsations in GW Vir white dwarf

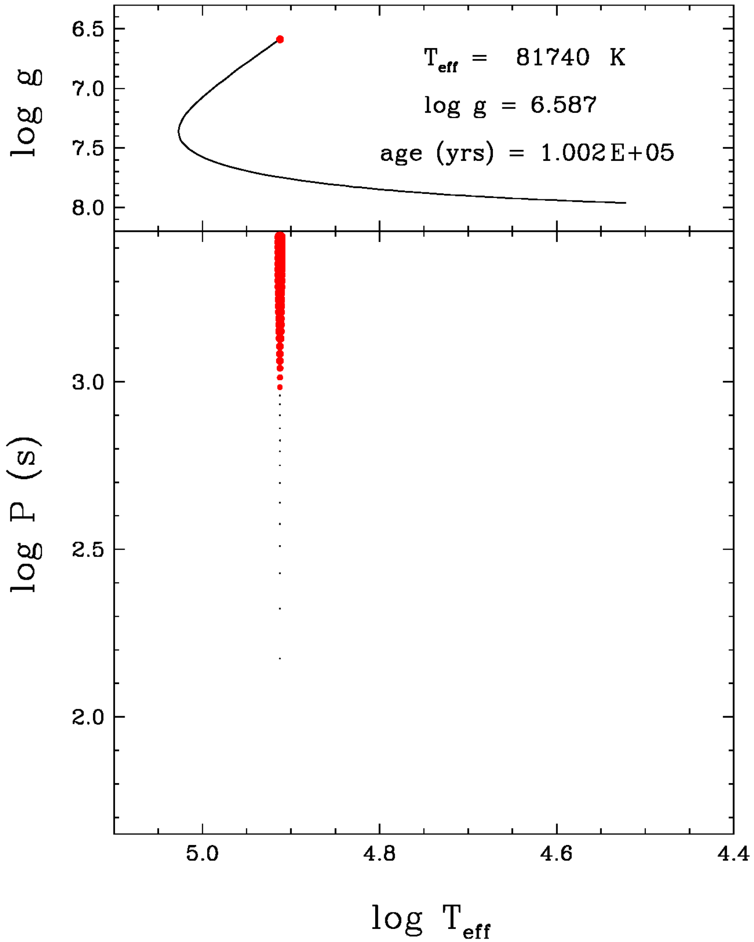
Courtesy: G. Fontaine

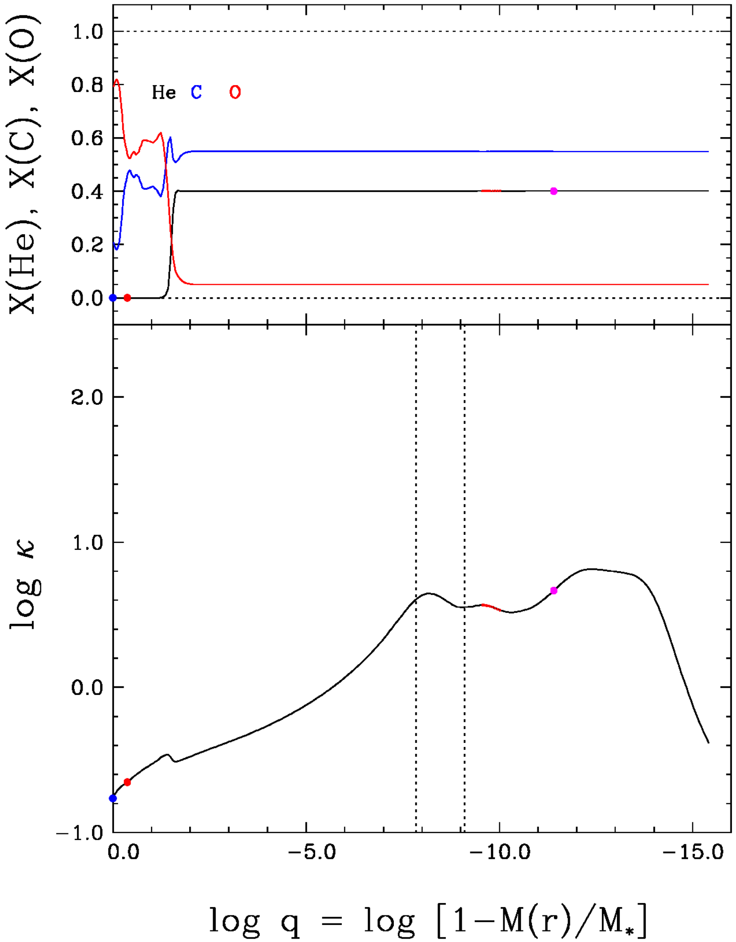
Bipping: pulsations are driven

convection zone

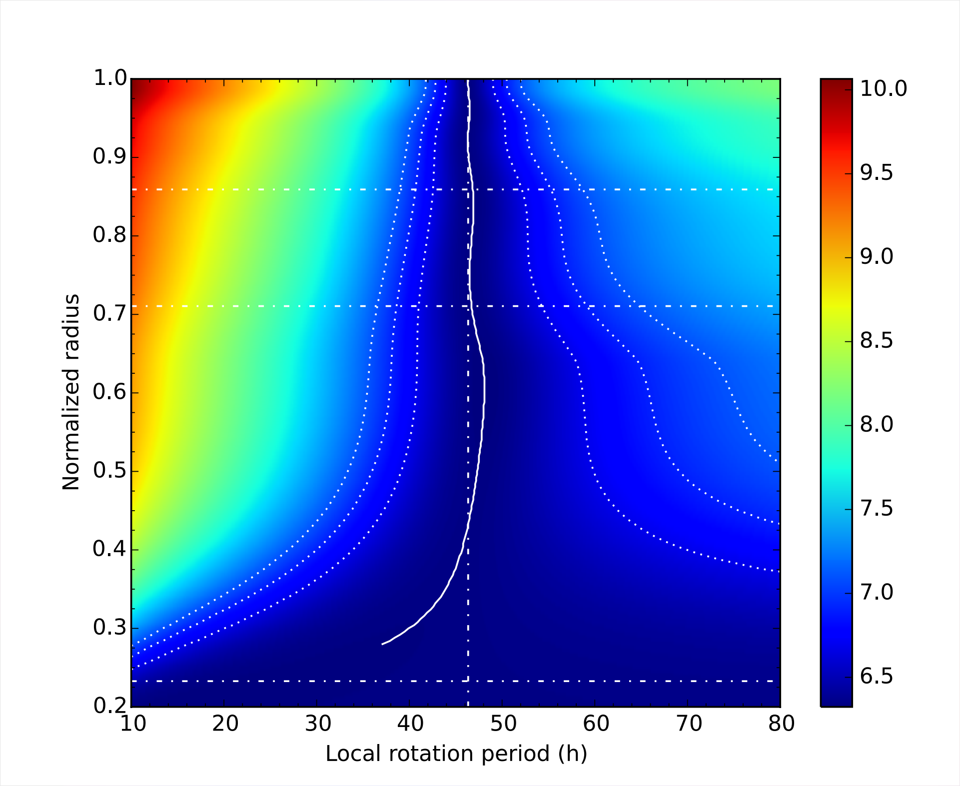
Base of the photosphere

Degeneracy boundary





Internal rotation profile in white dwarfs: KIC08626021



(Giammichele et al.)

Pulsation modes probe ~70% of the stellar radius (81% of the stellar mass)

Solid-body rotation down to 0.3 R_*, Prot=46.34±2.54 h

Driving mechanism for pulsations

Common point: opacity-driven mechanism

- Don Winget (1981) for ZZ Ceti:

H ionization/recomb. around T_{eff}~12,000 K

⇒ envelope opacity increase

⇒ strangle the flow of radiation, convection zone develops

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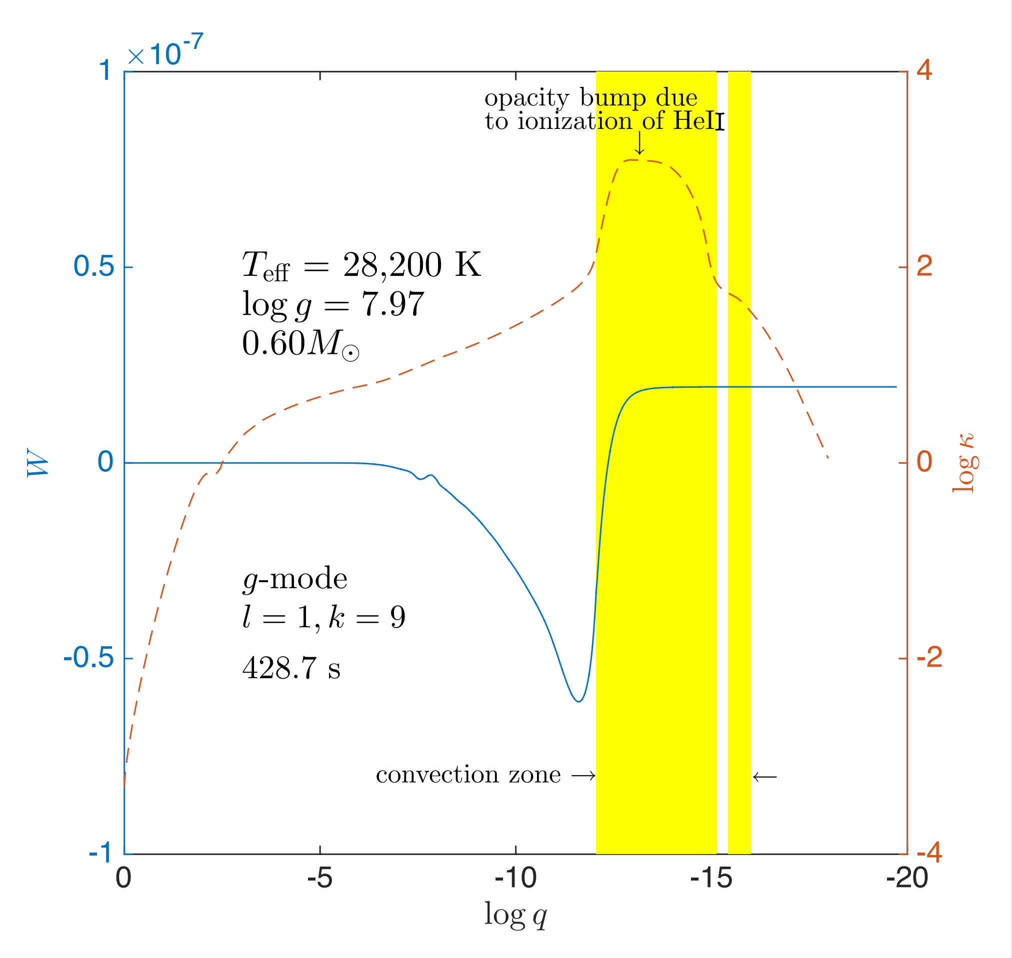

Modeling details

Energy leakage argument

- 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