Energetic properties of stellar pulsations across the HR diagram

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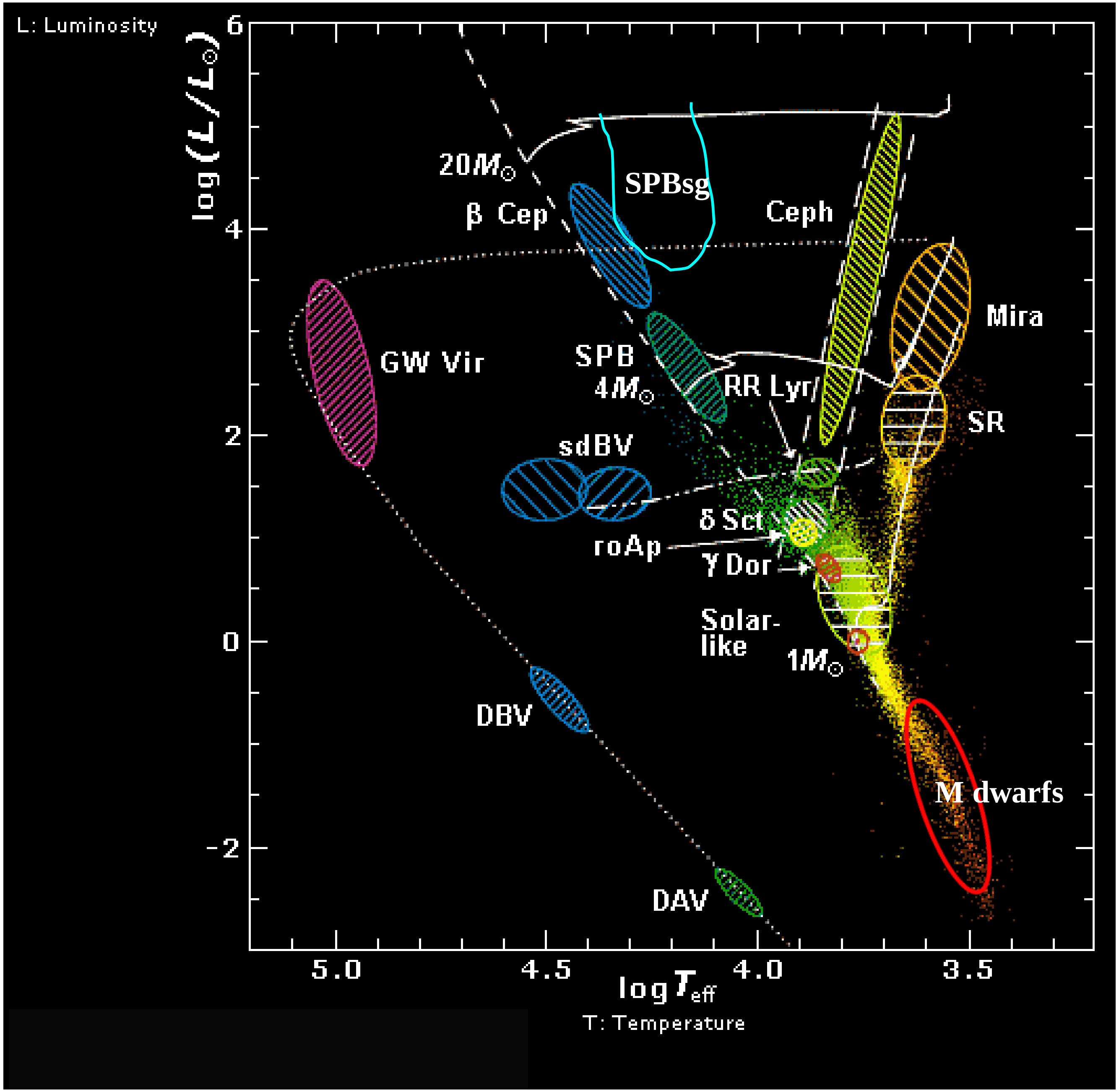


J. Christensen-Dalsgaard

Energetic properties:

EXCITATION OF PULSATIONAL MODES

KINETIC ENERGY OF A MODE

MODE AMPLITUDE, HEIGHT, LINEWIDTH

EXCITATION OF PULSATIONAL MODES

Self-excitation (heat engine) (+convection)

Convective blocking

} thermal processes

Turbulent convection

Tidal effect

} dynamical processes

SELF-EXCITATION

Work integral – the net energy gained by a mode during one cycle

$$W = \oint \frac{dE}{dt} dt = \frac{\pi}{\omega} \int_0^M \left[\frac{\delta T}{T} \delta \varepsilon_N - \frac{\delta T}{T} \delta \left(\frac{1}{\rho} \mathrm{div} \mathbf{F} \right) \right] dM_r$$

$$\mathbf{F} = \mathbf{F}_R + \mathbf{F}_C$$

$\delta\varepsilon$ - ε-mechanism

$$\int_0^M \frac{\delta T}{T}\delta\varepsilon dM_r = \int_0^M \varepsilon\left(\varepsilon_T + \frac{\varepsilon_\rho}{\Gamma_3 - 1}\right)\left(\frac{\delta T}{T}\right)^2 dM_r$$

$$\varepsilon_T = \left(\frac{\partial \ln \varepsilon}{\partial \ln T}\right)_\rho \approx 4 - 30$$

$$\varepsilon_\rho = \left(\frac{\partial \ln \varepsilon}{\partial \ln \rho}\right)_T \approx 1 - 2$$

$$\Gamma_3 - 1 \approx \frac{2}{3}$$

ε_T and ε_ρ are always positive → a positive contribution to W but usually negligible

If $\delta\varepsilon \cong 0$ and $\delta F_C \cong 0$

$$W = -\int \mathrm{d}^3x \, \nabla_{\mathrm{ad}} \oint \mathrm{d}t \, \mathrm{Re}\left[\left(\frac{\delta P}{P} \right)^* \delta \, \mathrm{div} \, \mathbf{F}_{\mathrm{R}} \right]$$

In the diffusion approximation

$$\delta \, \mathrm{div} \, \mathbf{F}_{\mathrm{R}} = \frac{1}{4\pi r^2} \frac{d \, \delta L_r}{dr}$$

$$\frac{\delta L_r}{L_r} = \frac{\mathrm{d}r}{\mathrm{d}\ln T}\frac{\mathrm{d}}{\mathrm{dr}}\left(\frac{\delta T}{T}\right) - \frac{\delta\kappa}{\kappa} + 4\left(\frac{\delta T}{T} + \frac{\delta r}{r}\right)$$

1 **Radiative dissipation**

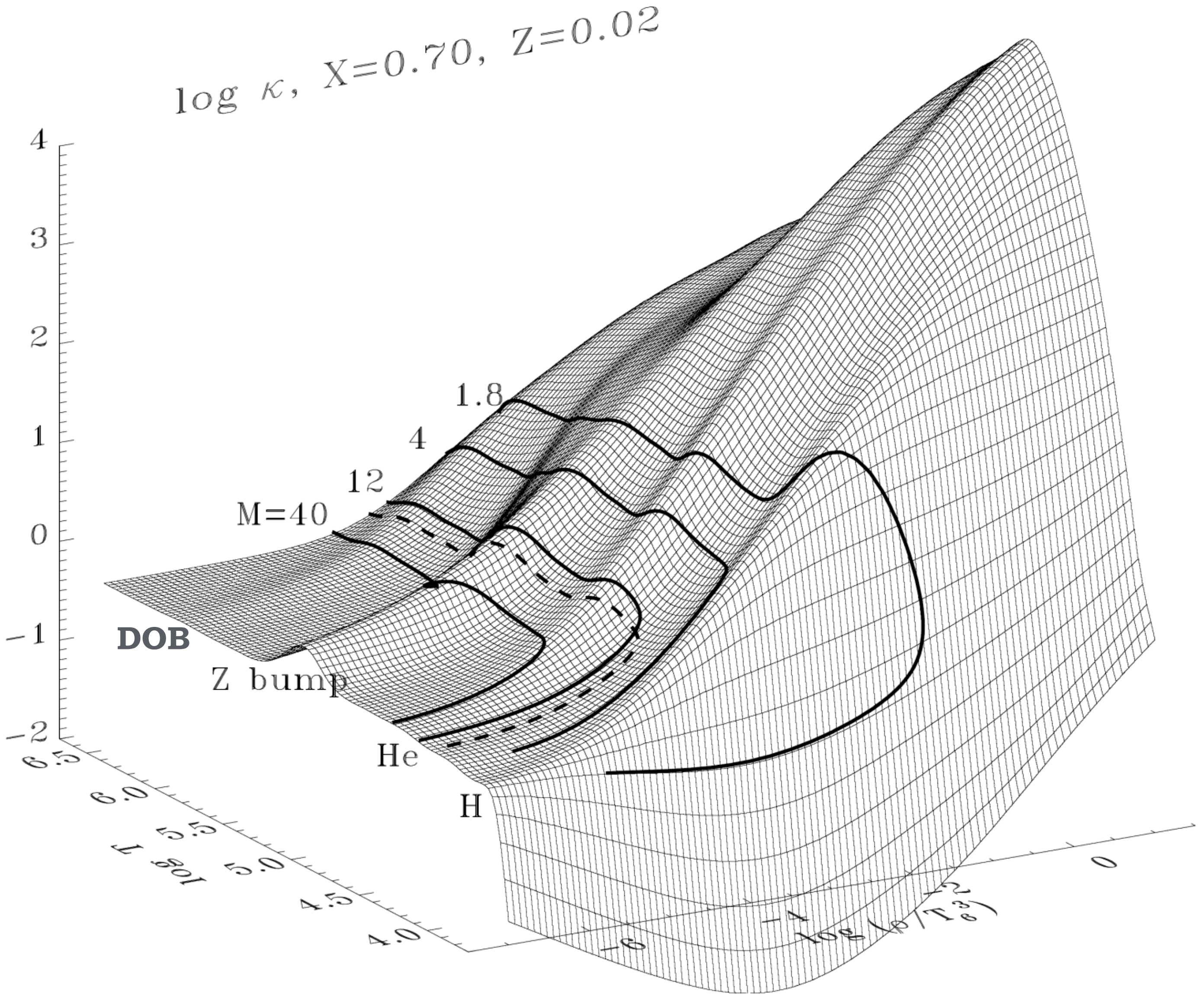
2 **κ-effect**

3 **γ-effect**

4 ***r*-effect**

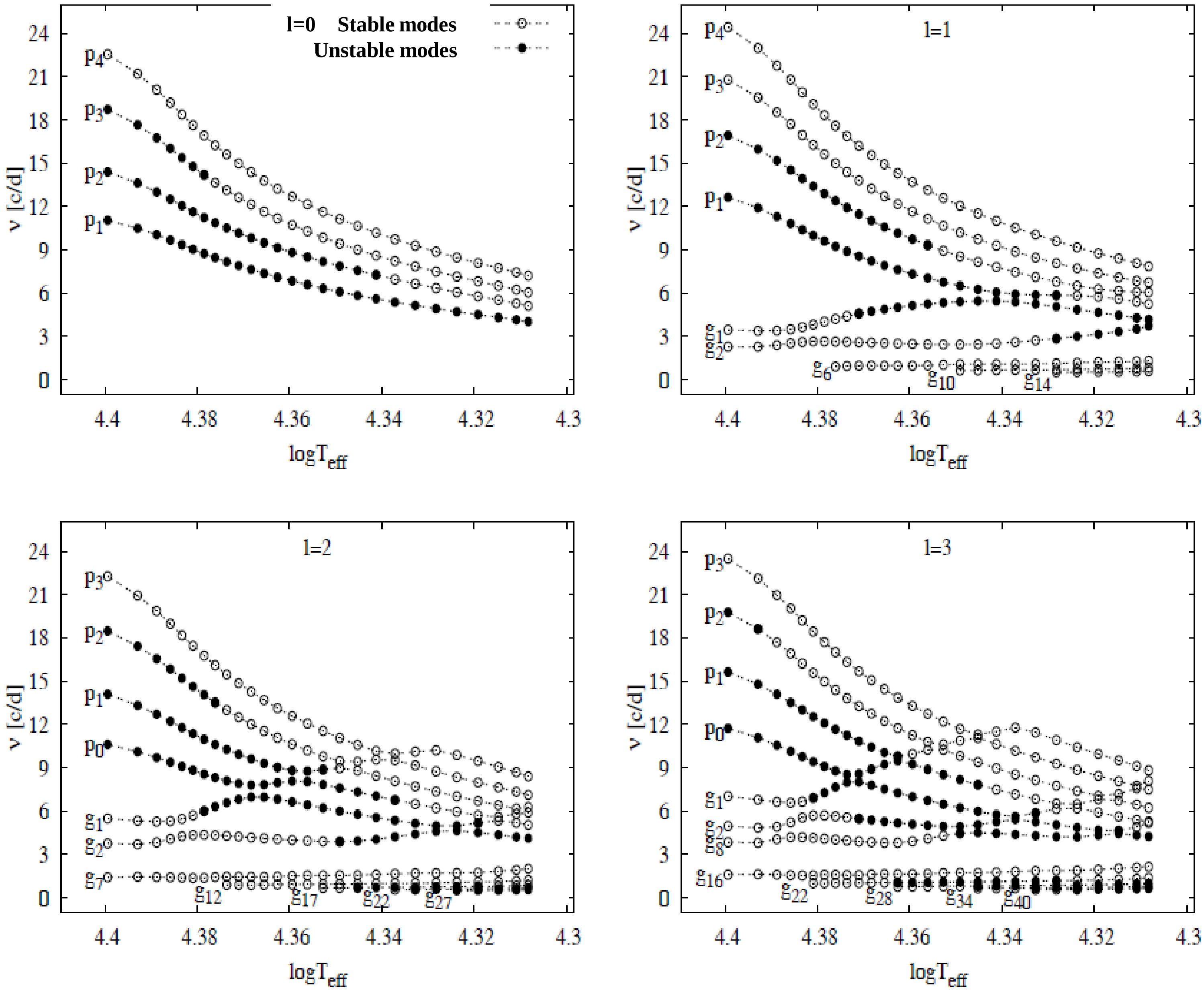
κ(+γ)-mechanism

κ(OPAL) as a function of logT and logρ/T_6^3 (T_6 =T/10^6)



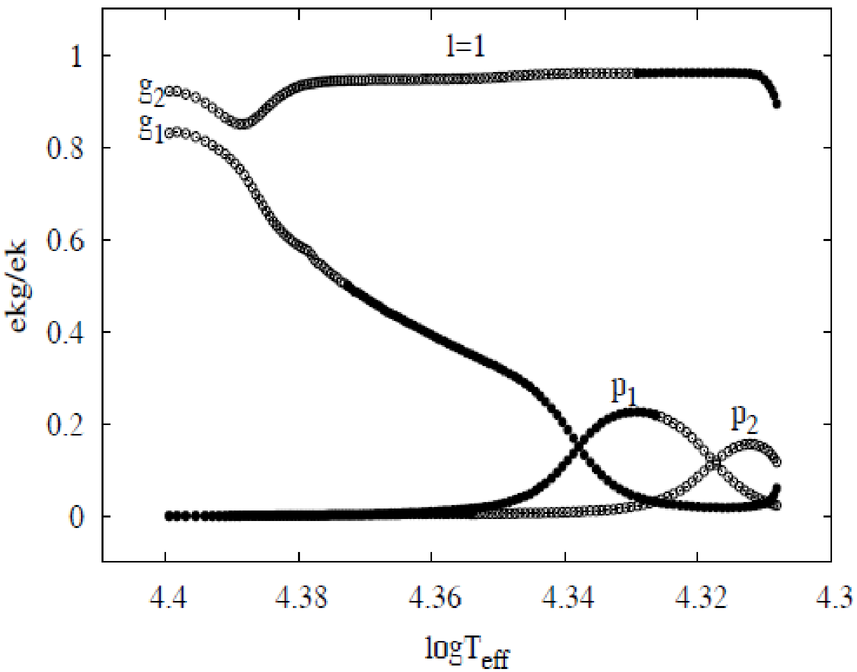
Pamyatnykh 1999

10 $M_\odot$ OP, Z=0.02

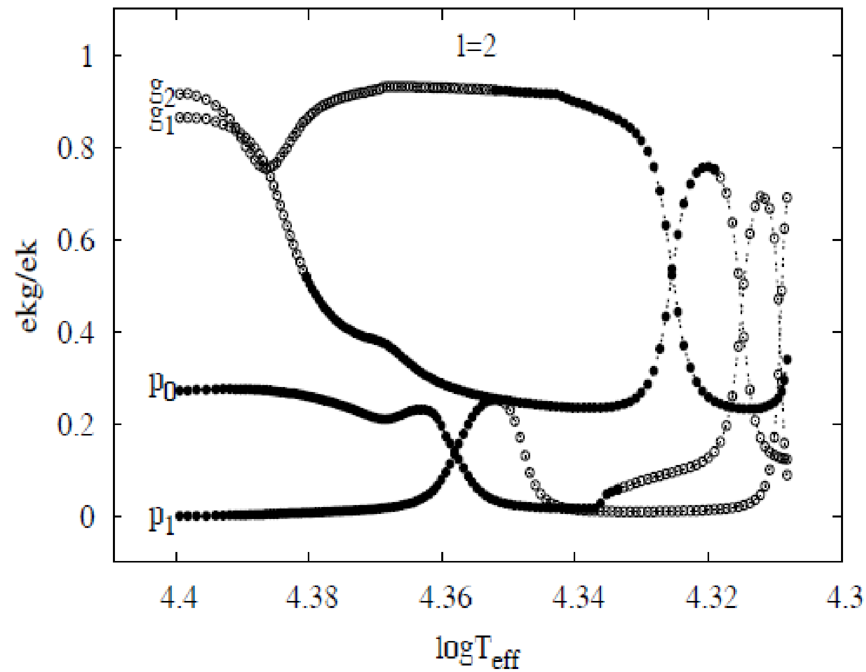


A ratio of the gravity energy to the total one for selected modes in the 10M$_\odot$ stellar model as a function of T_{eff}

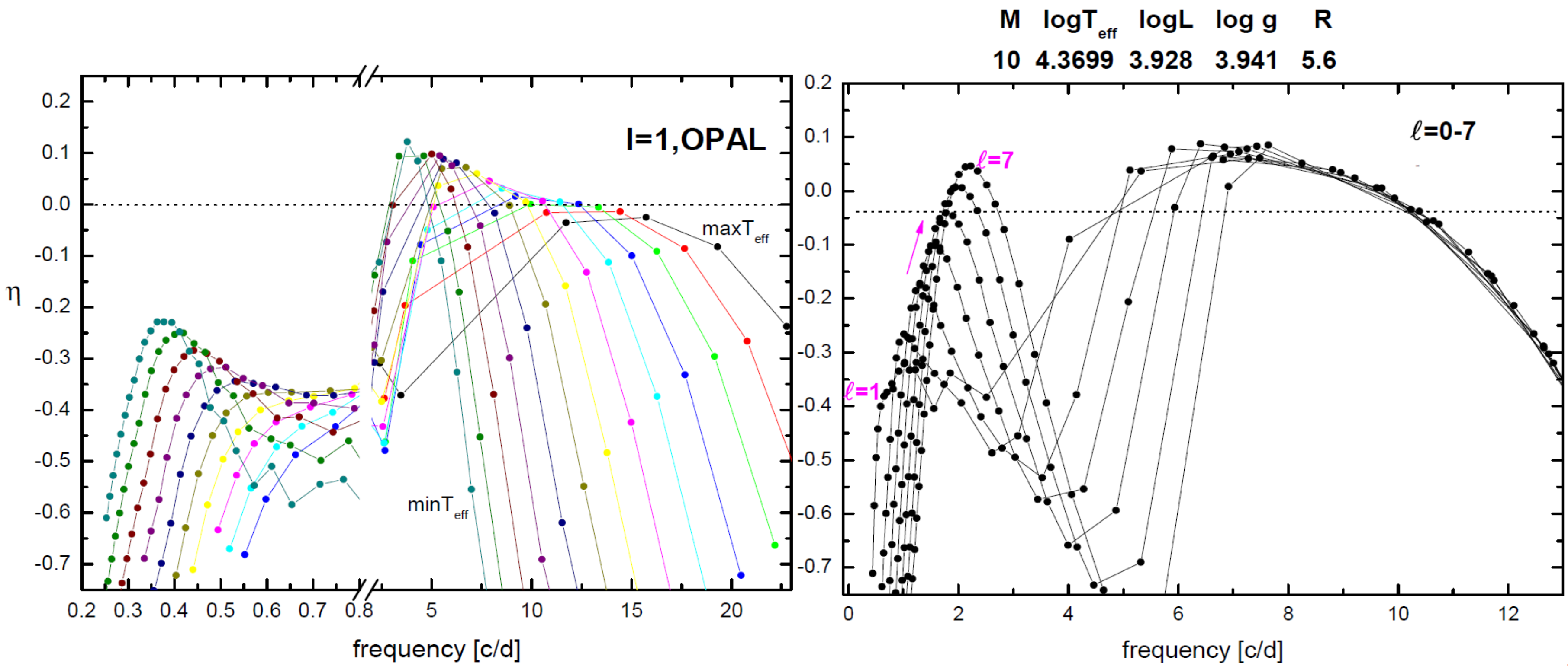
ℓ=1



ℓ=2

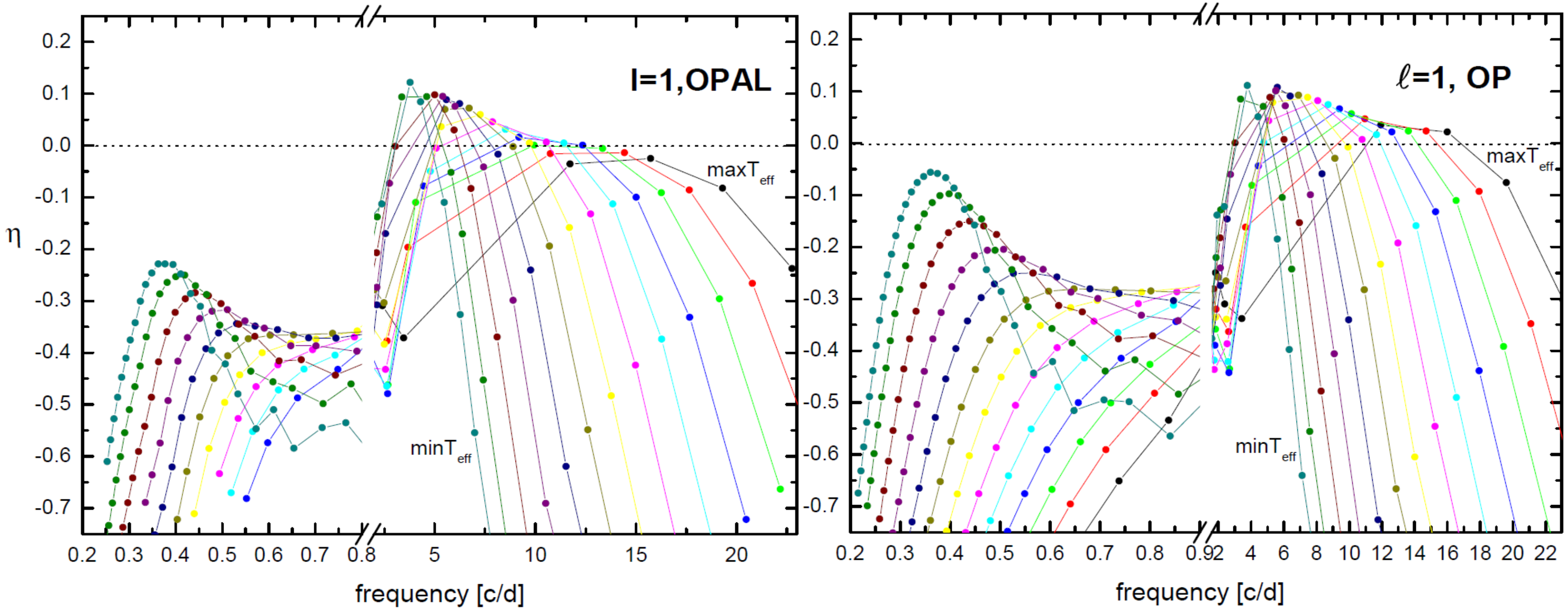


10 $M_\odot$ OPAL
η vs. frequency



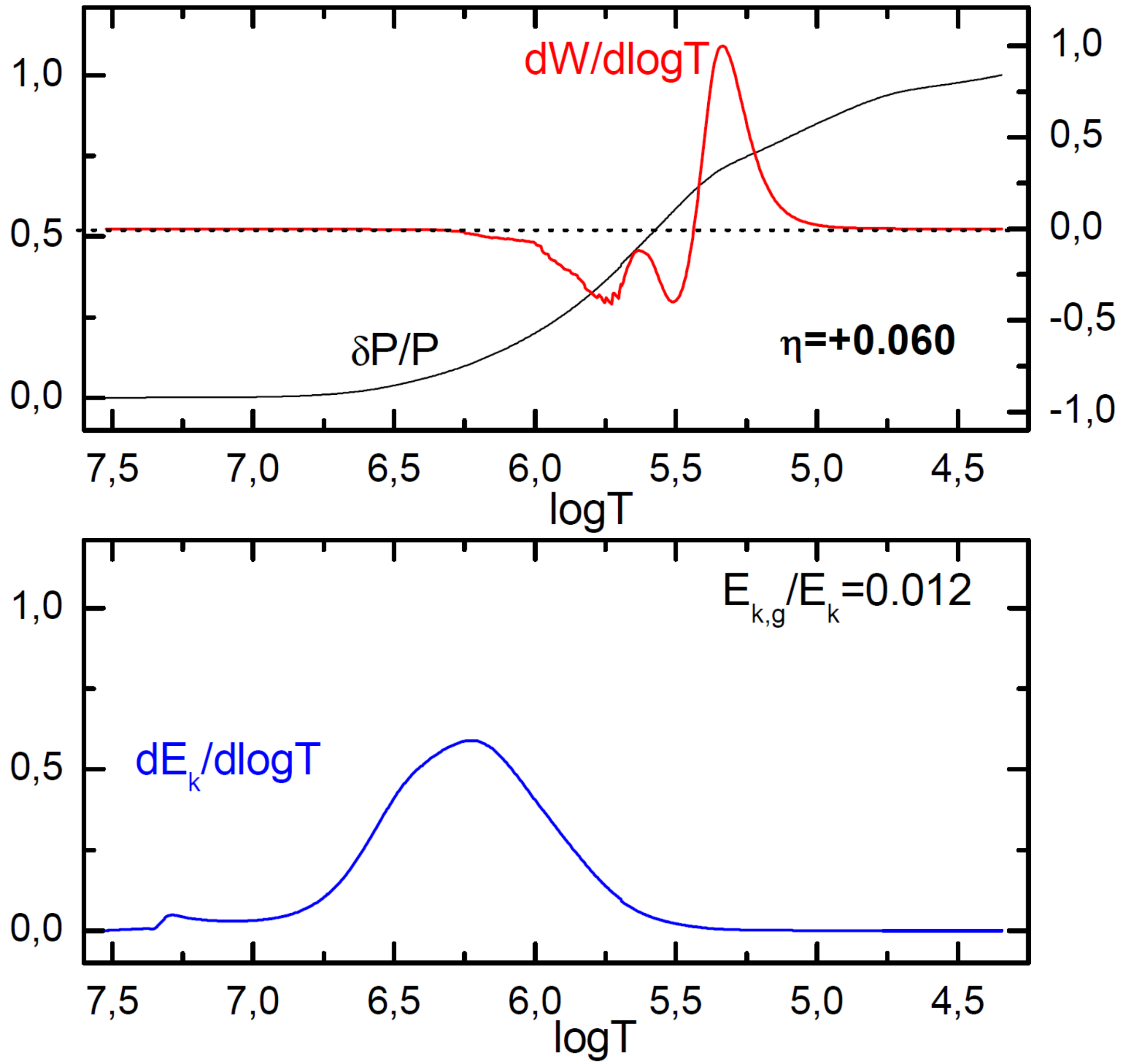
Instability up to ℓ≈30

10 $M_\odot$ OPAL vs. OP
η vs. frequency



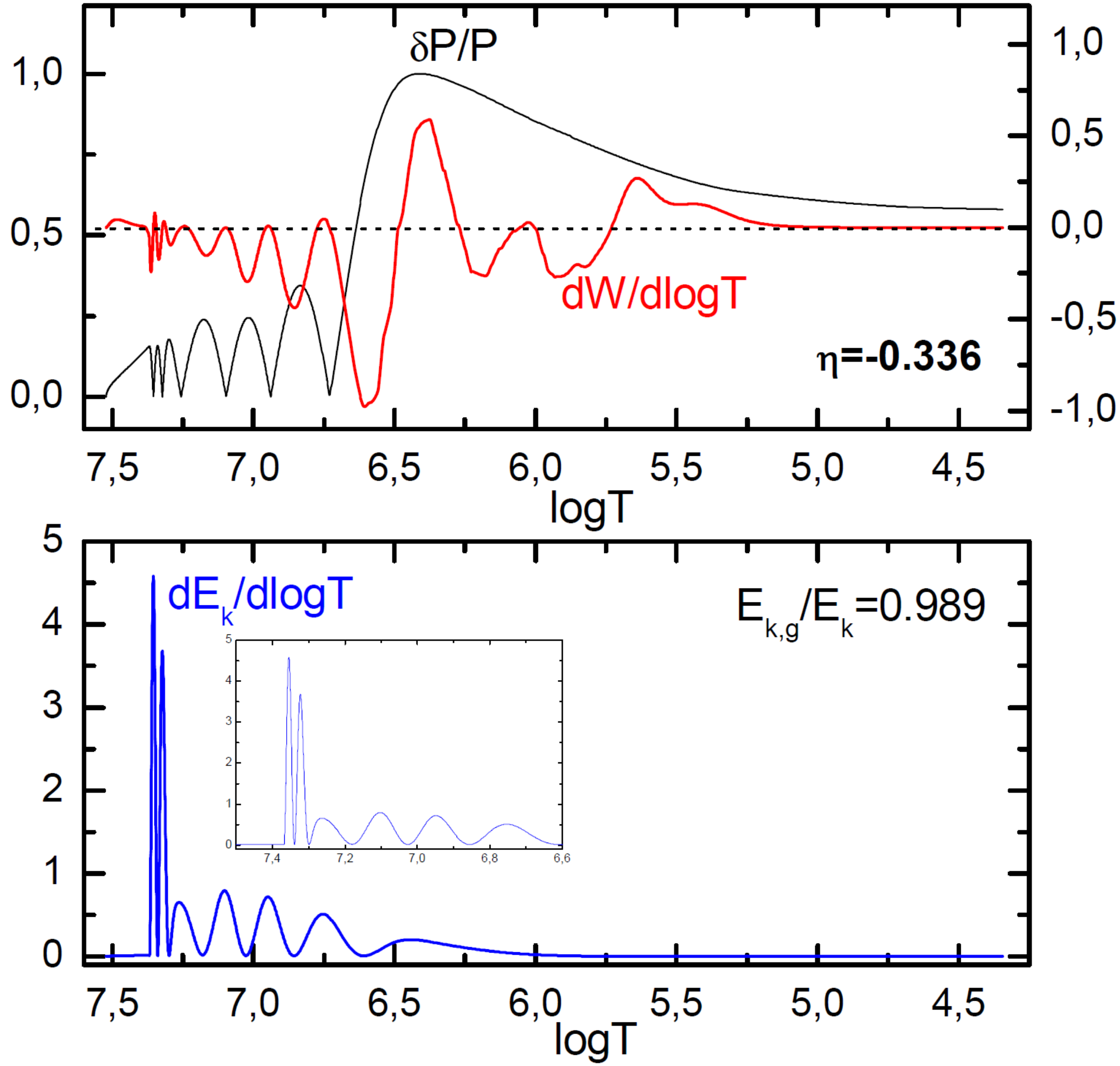
M	$\log T_{eff}$	logL	log g	R
10	4.3699	3.928	3.94	5.6

$l=1, p_1$ P=0.137 [d] ν=7.276 [c/d]



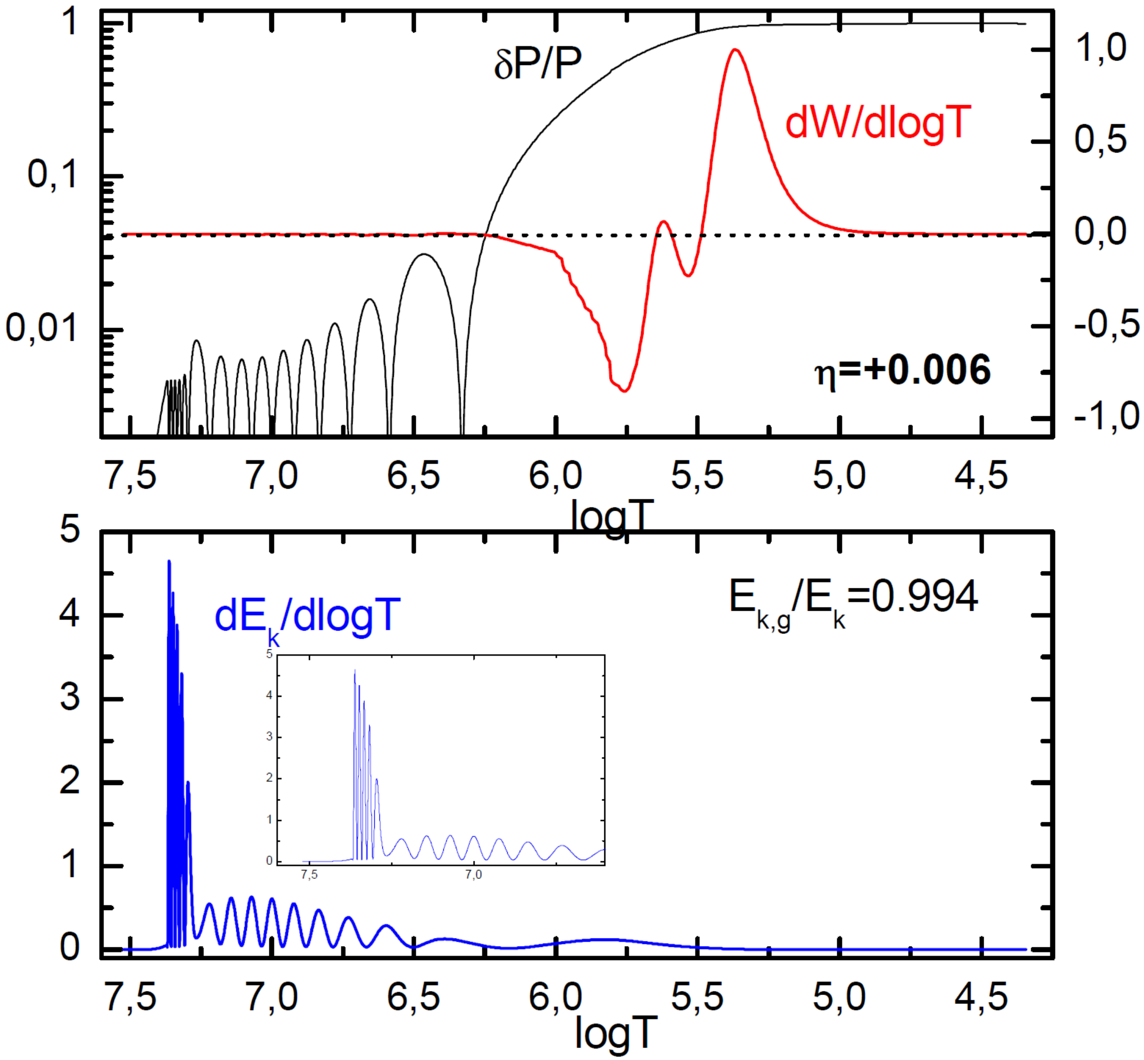
M	$\log T_{eff}$	logL	log g	R
10	4.3699	3.928	3.94	5.6

$l=1, g_7$ P=1.090 [d] ν=0.917 [c/d]

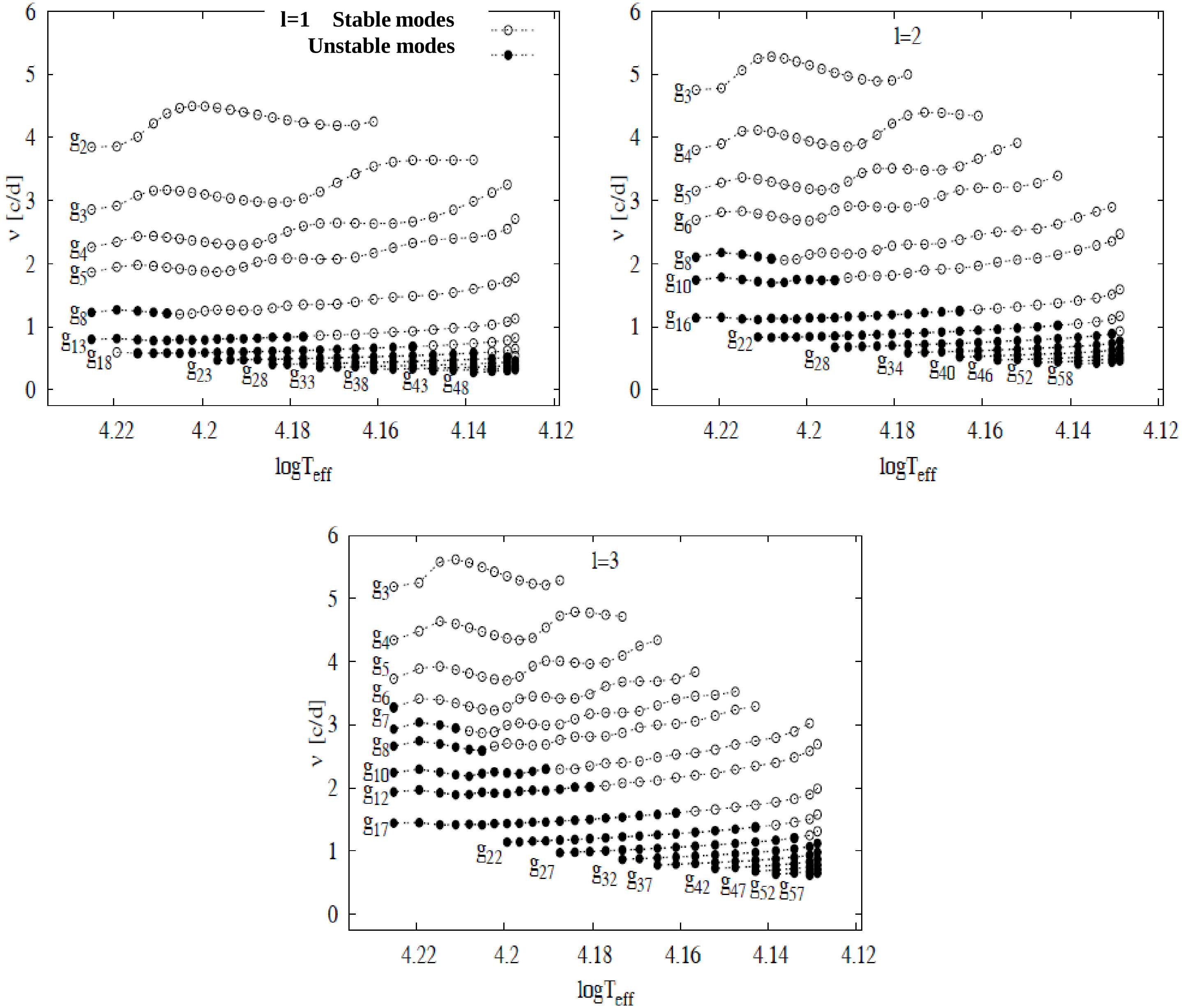


M	$\log T_{eff}$	logL	log g	R
10	4.3699	3.928	3.94	5.6

$l=6, g_{15}$ P=0.513 [d] ν=1.948 [c/d]

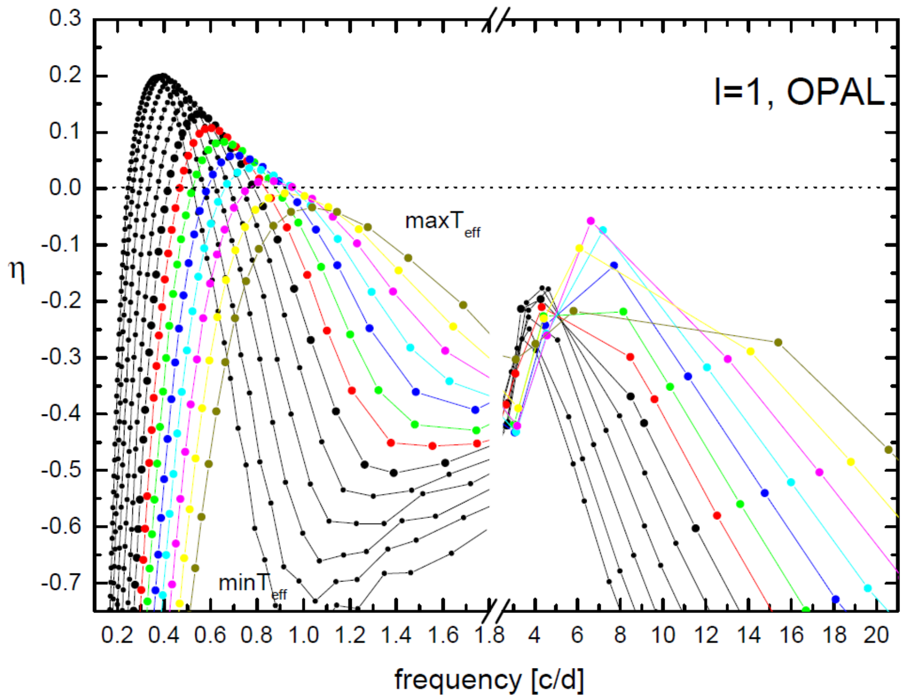


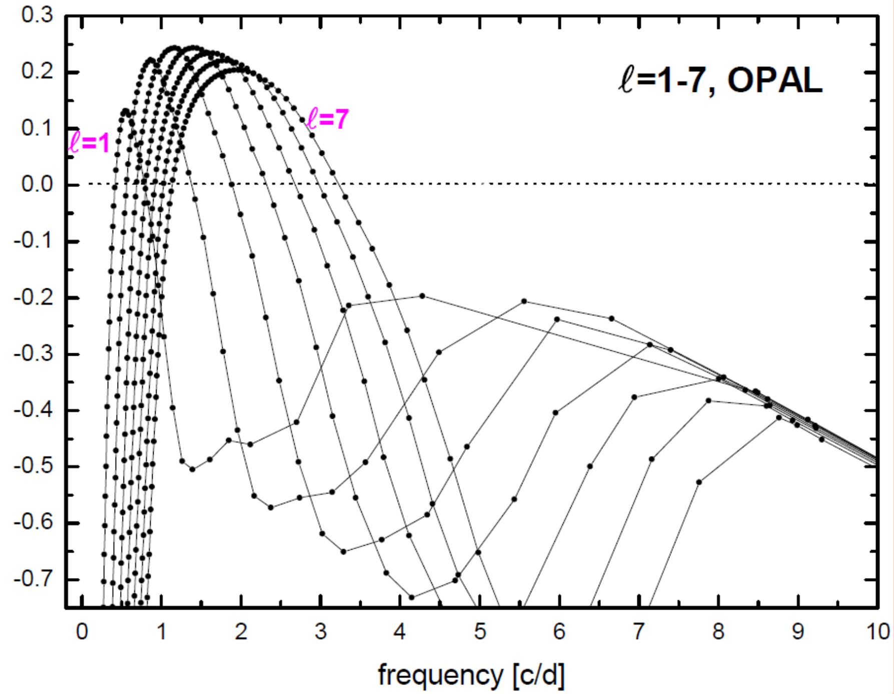
5 $M_\odot$ OP, Z=0.02



5 M$_\odot$ OPAL
η vs. frequency

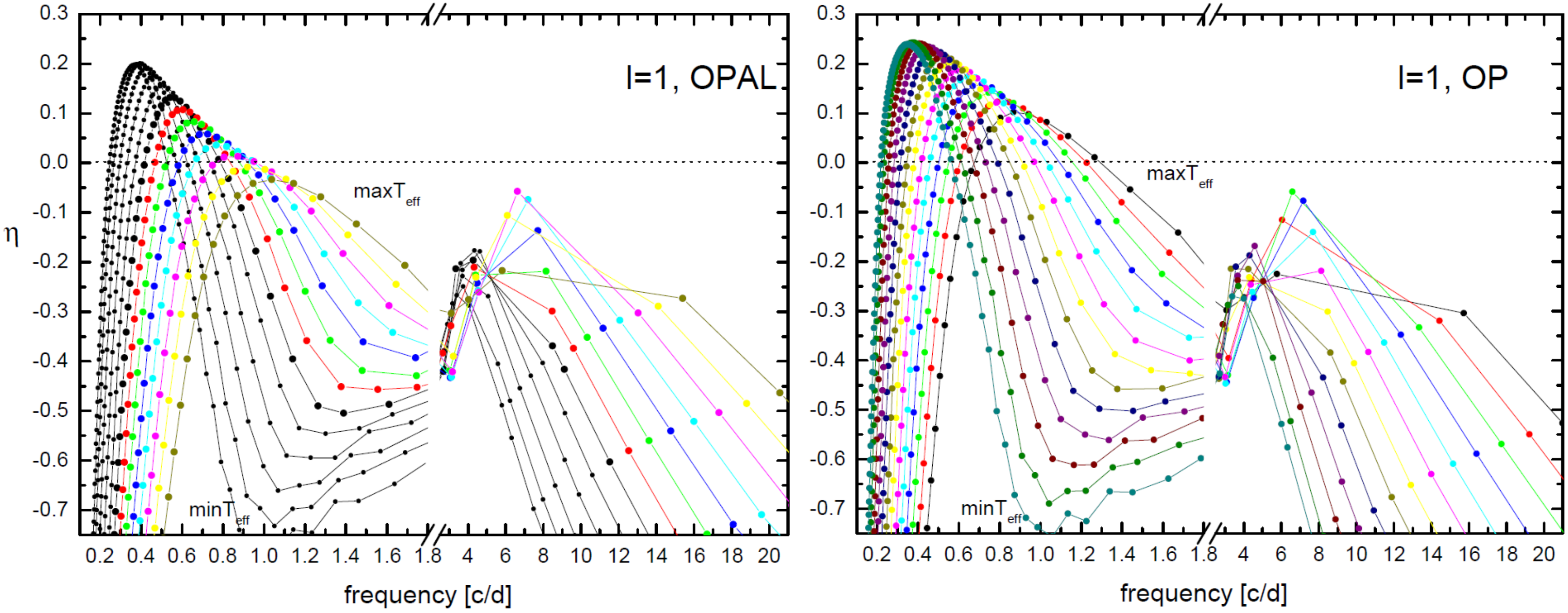
M	logT$_{eff}$	logL	log g	R
5.0	4.1886	2.906	3.937	3.98





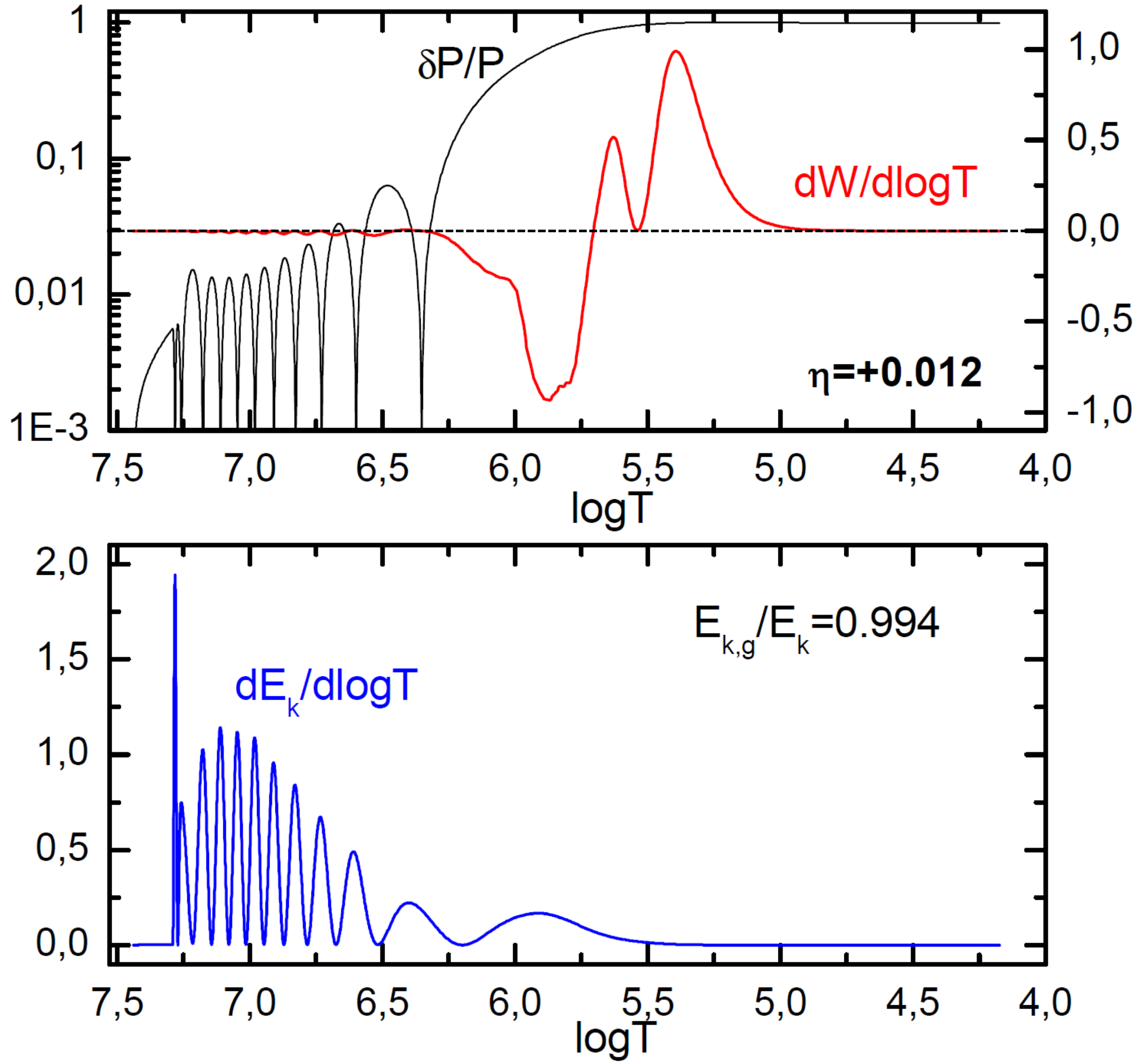
Instability up to ℓ≈17

5 $M_\odot$ OPAL vs. OP
η vs. frequency



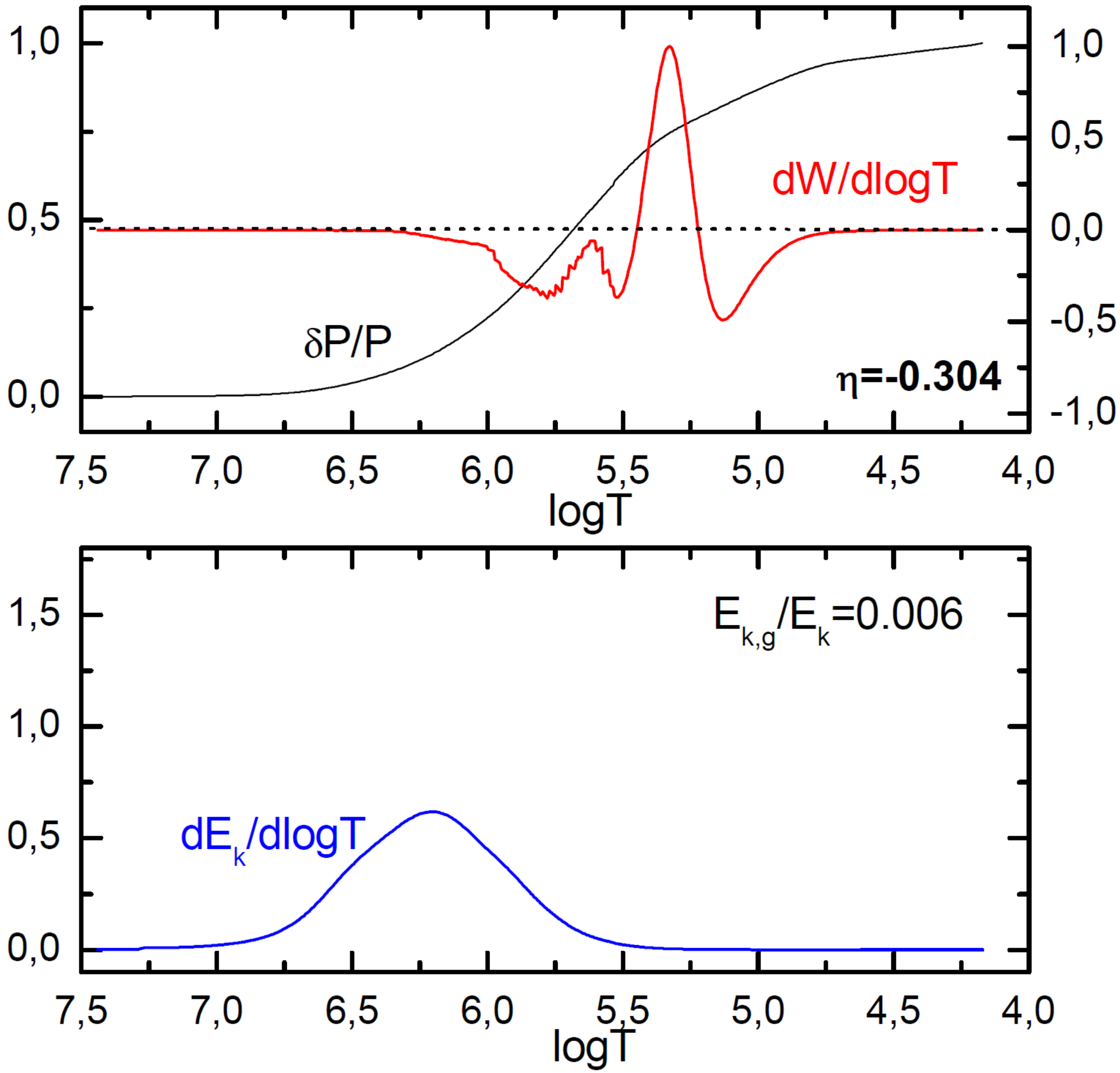
M	$\log T_{eff}$	logL	log g	R
5.0	4.2214	2.806	4.168	3.05

$l=1, g_{12}$ P=1.145 [d] ν=0.873 [c/d]



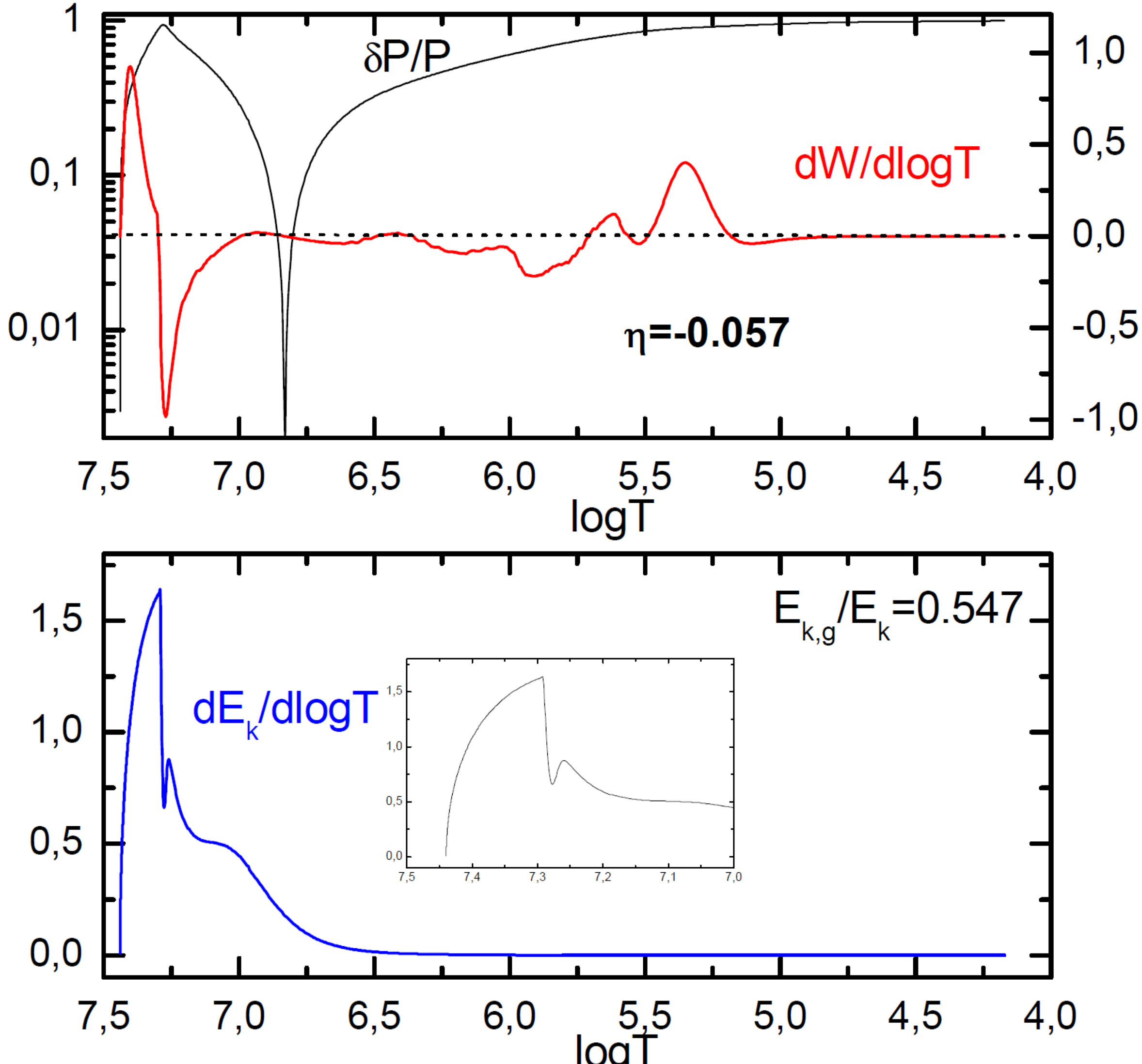
M	$\log T_{eff}$	logL	log g	R
5.0	4.2214	2.806	4.17	3.05

l=1,p_1 P=0.077 [d] ν=13.030 [c/d]

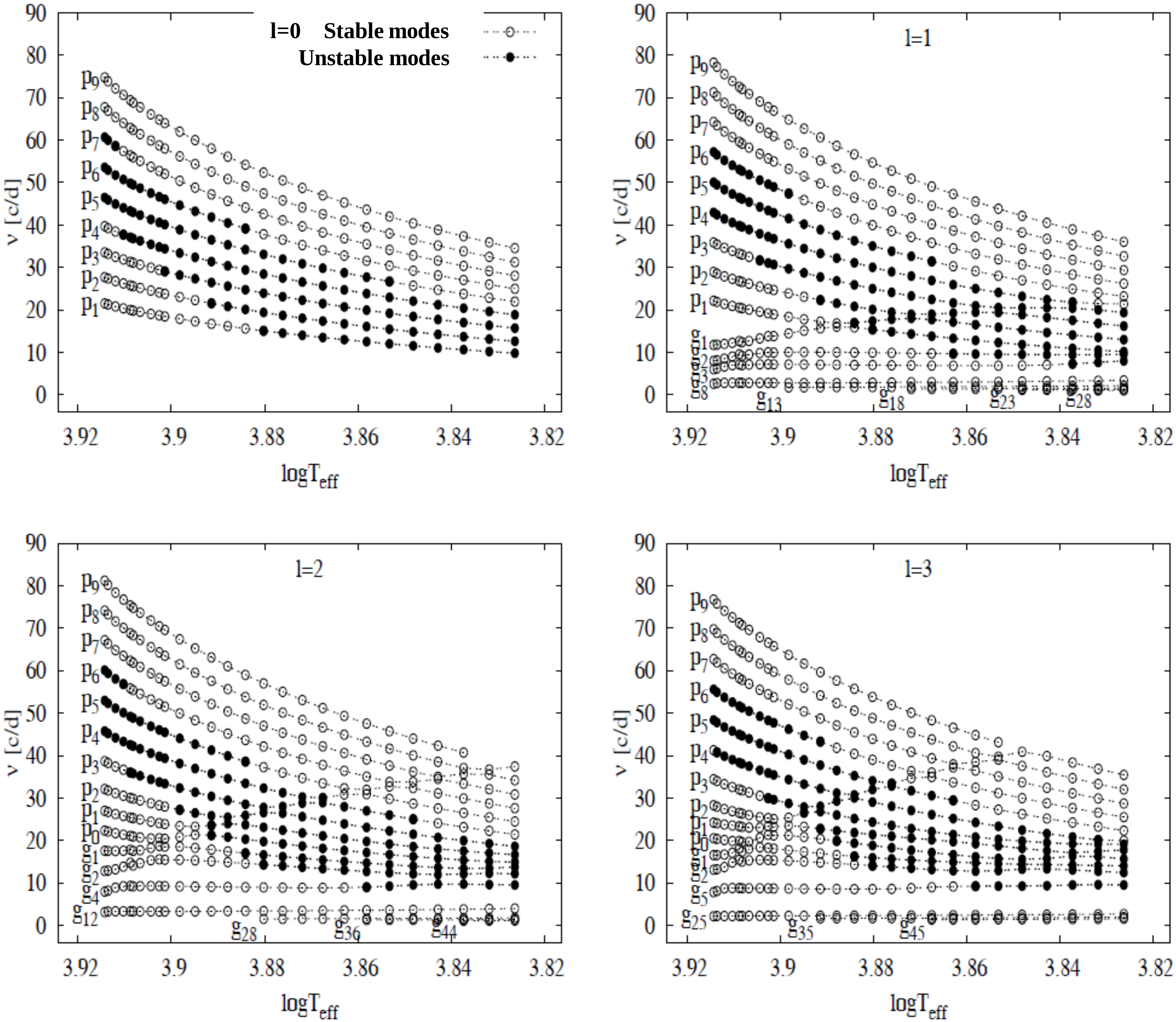


M	$\log T_{eff}$	$\log L$	$\log g$	R
5.0	4.2214	2.806	4.17	3.05

$l=1, g_1$ P=0.151 [d] ν=6.625 [c/d]

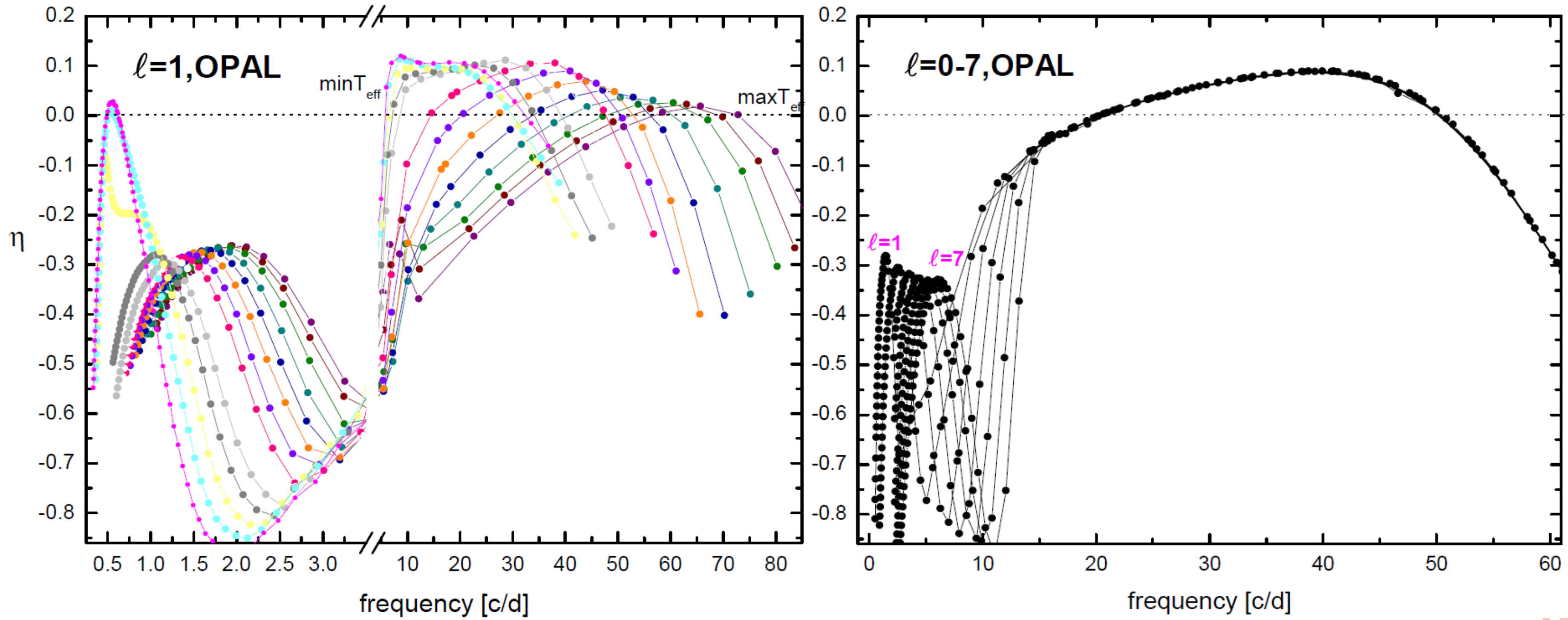


1.8 M$_\odot$ OP, Z=0.02



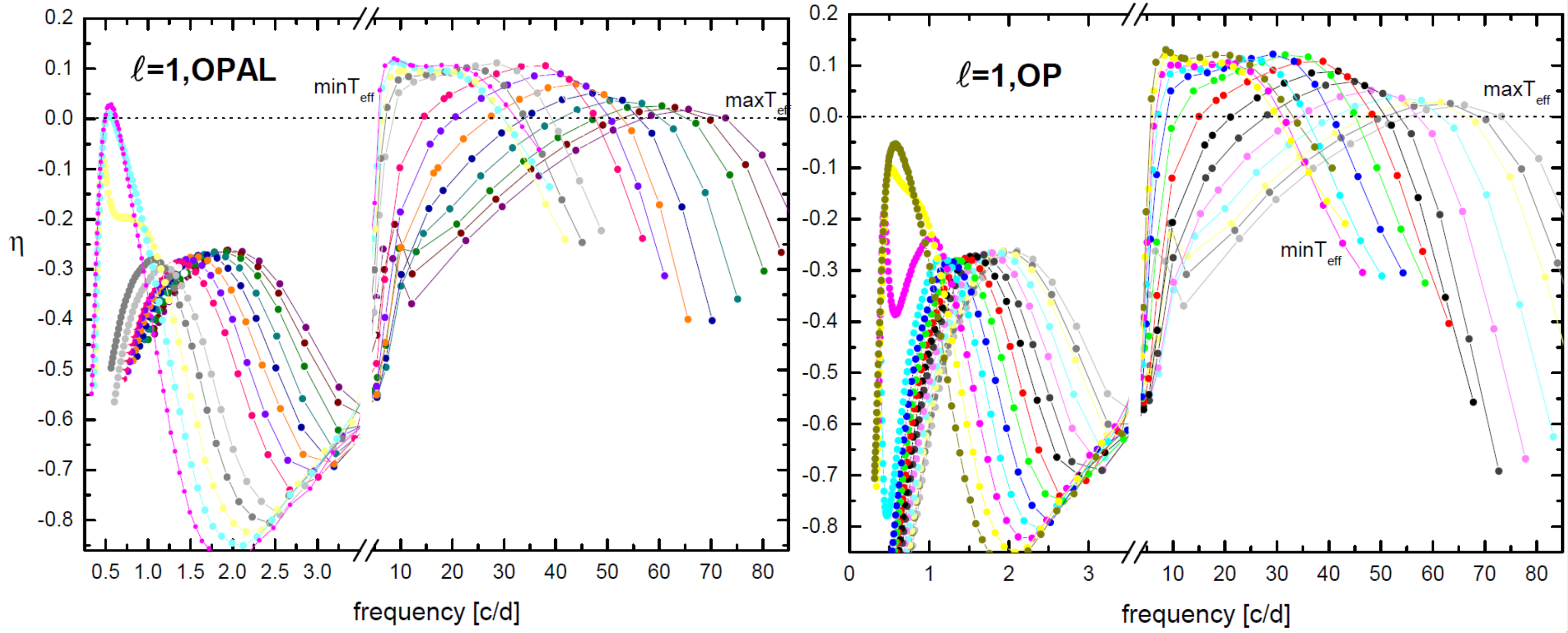
1.8 M$_\odot$ OPAL
η vs. frequency

M	logT$_{eff}$	logL	log g	R
1.8	3.9036	1.137	4.12	1.93



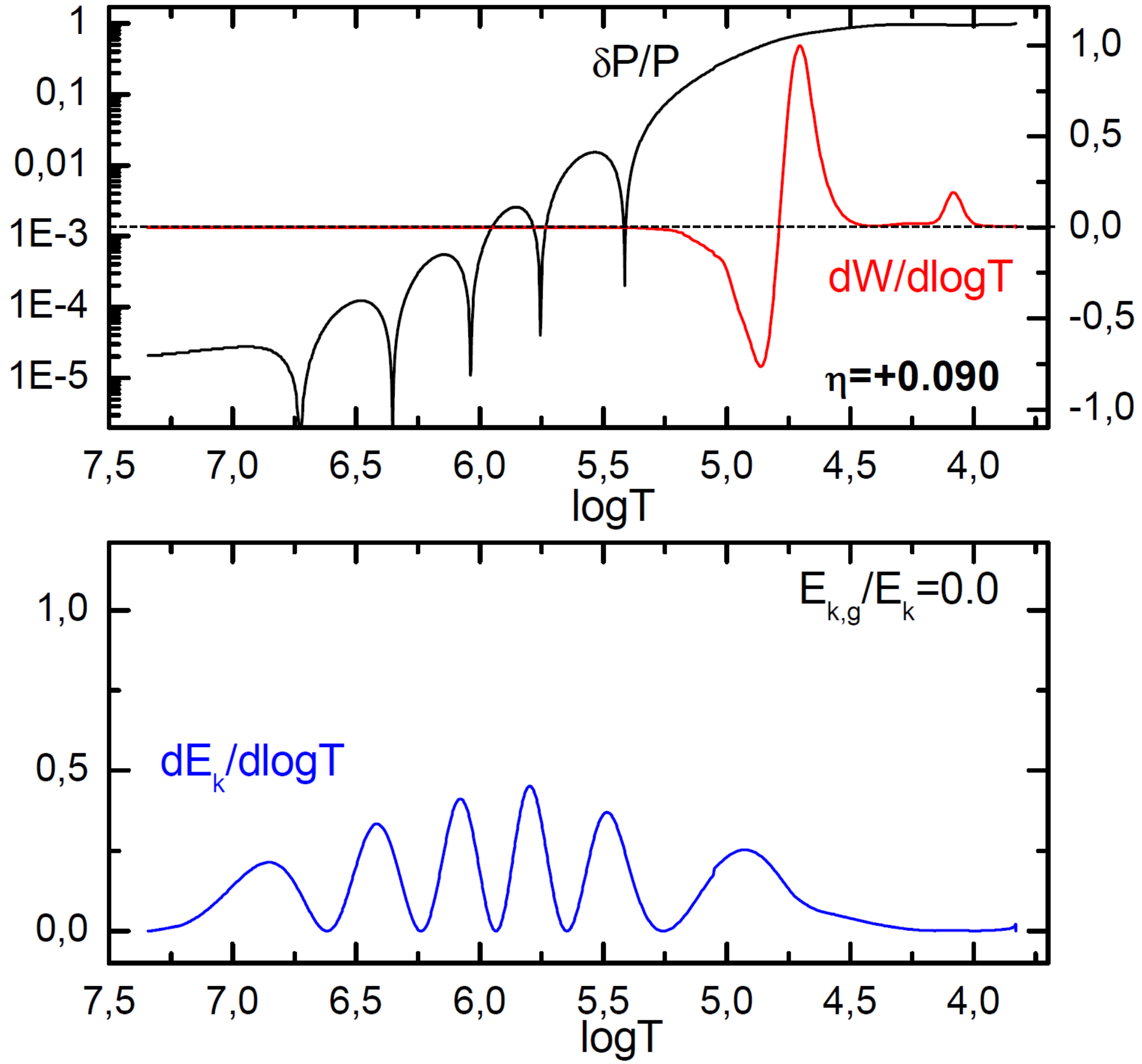
Instability up to ℓ≈60

1.8 $M_\odot$ OPAL vs. OP
η vs. frequency



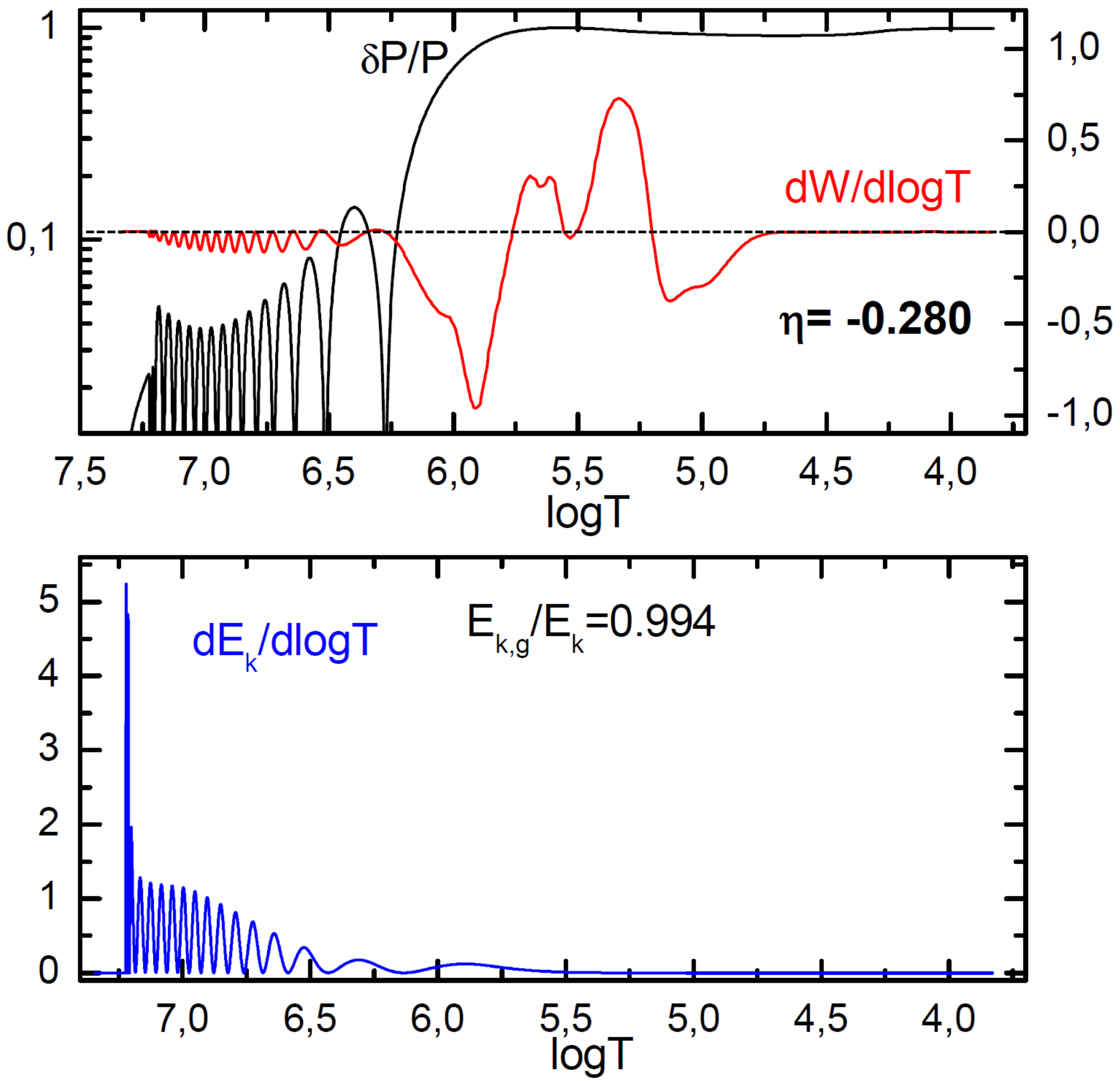
M	$\log T_{eff}$	logL	log g	R
1.8	3.9036	1.137	4.12	1.9

$l=0, p_6$ P=0.026 [d] ν=38.716 [c/d]



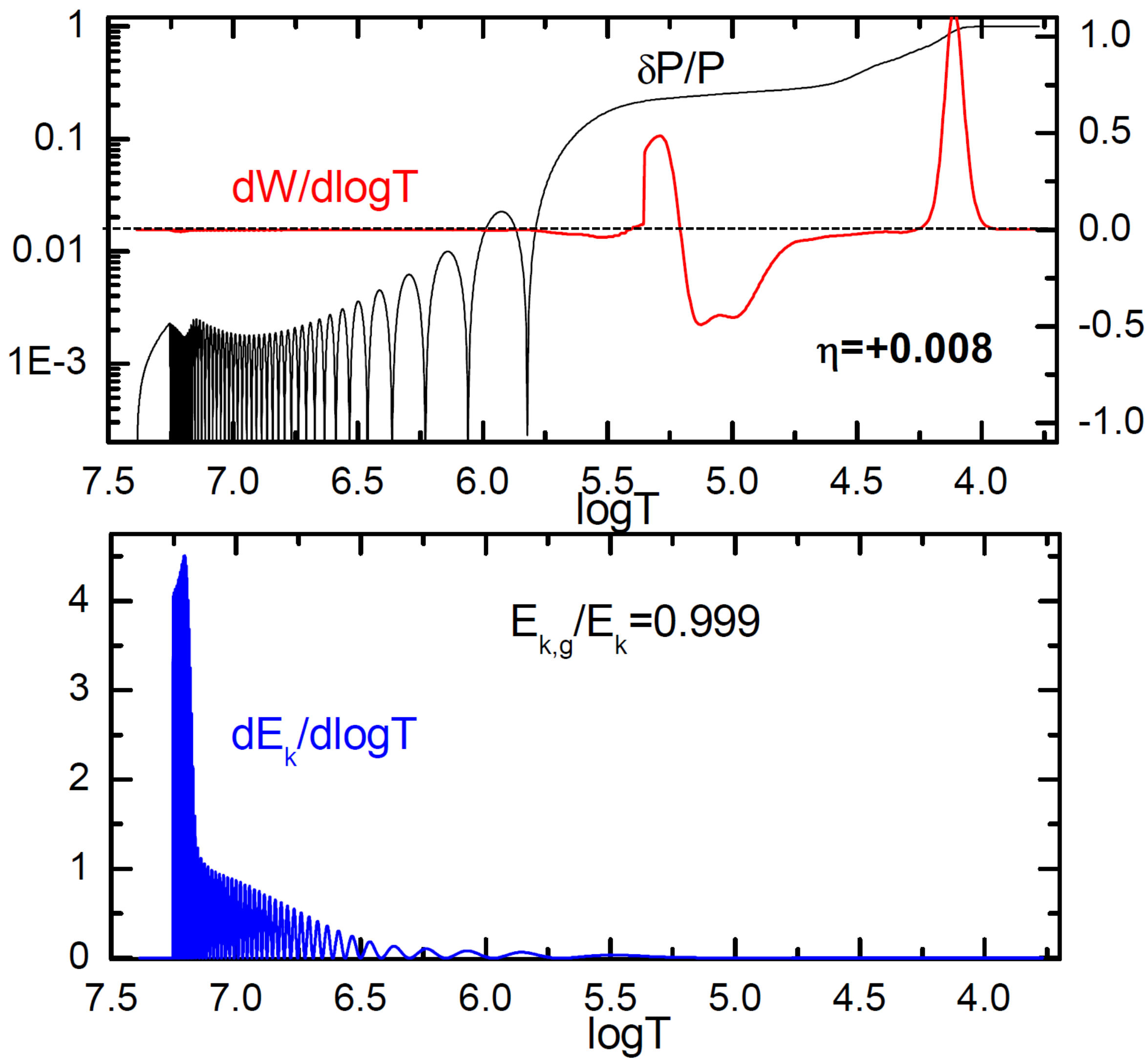
M	$\log T_{eff}$	logL	log g	R
1.8	3.9036	1.137	4.12	1.9

$l=1, g_{17}$ P=0.691 [d] ν=1.448 [c/d]



M	$\log T_{eff}$	logL	log g	R
1.8	3.8459	1.176	3.85	2.63

$l=1, g_{57}$ P=1.840 [d] ν=0.543 [c/d]



Low frequencies in *Kepler* δ Scuti stars

L. Balona 2014

convective flux blocking

(Pesnell 1987, Guzik et al. 2000)

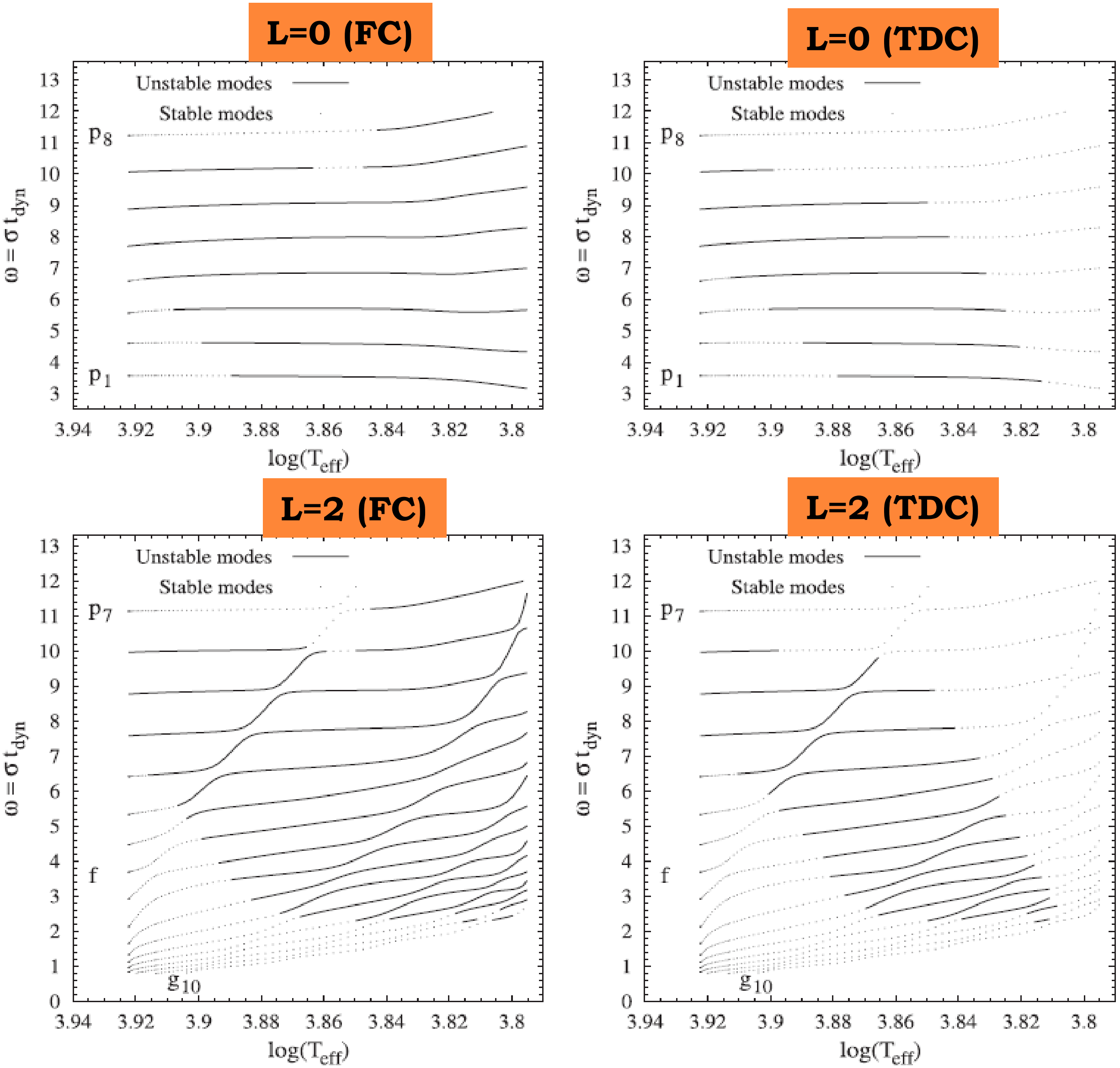
or

Opacity problem

or/and

stars near TAMS

Convection-pulsation coupling



A. Grigahcène et al. 2005
M-A. Dupert et al. 2005

OPACITY …
the neverending story

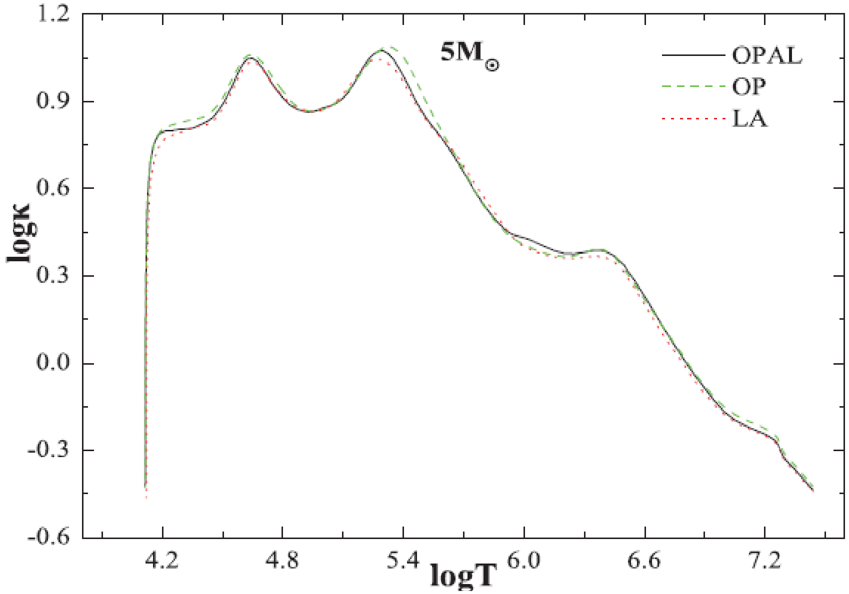
OPAL

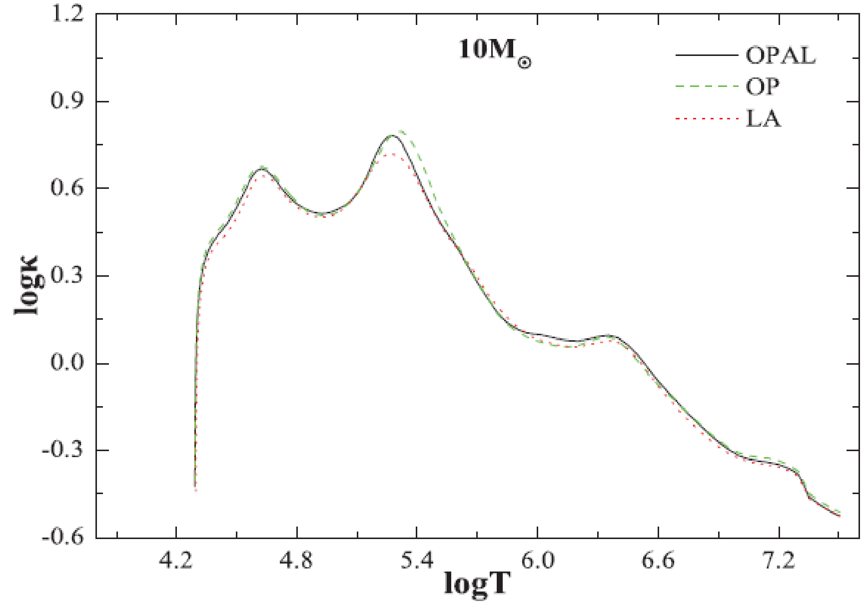
OP

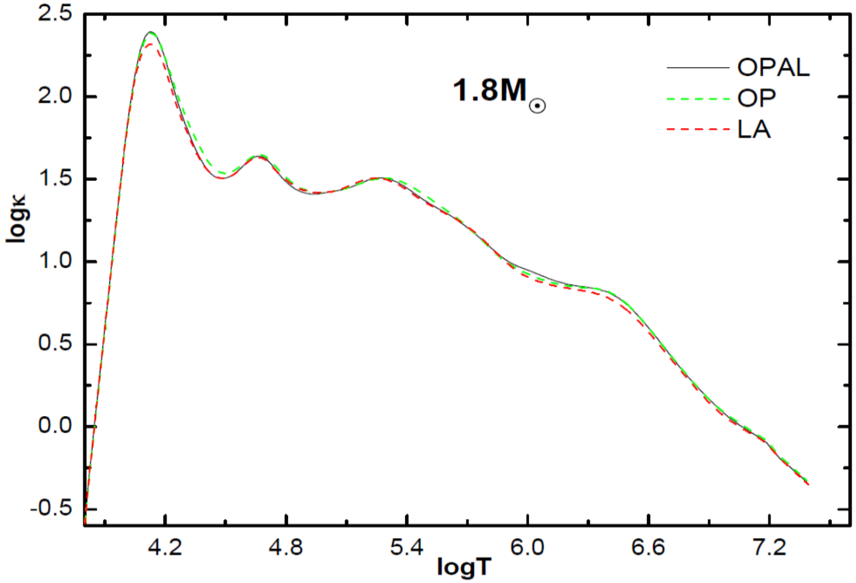
LA - reactivated

Cugier (2012,2014) – OP(OPAL)+Kurucz

The Rosseland mean opacity, κ, as a function of logT inside the stellar models with masses M=1.8, 5, 10 $M_{\odot}$ and log Teff ≅4.196, 4.373, 3.850, respectively.

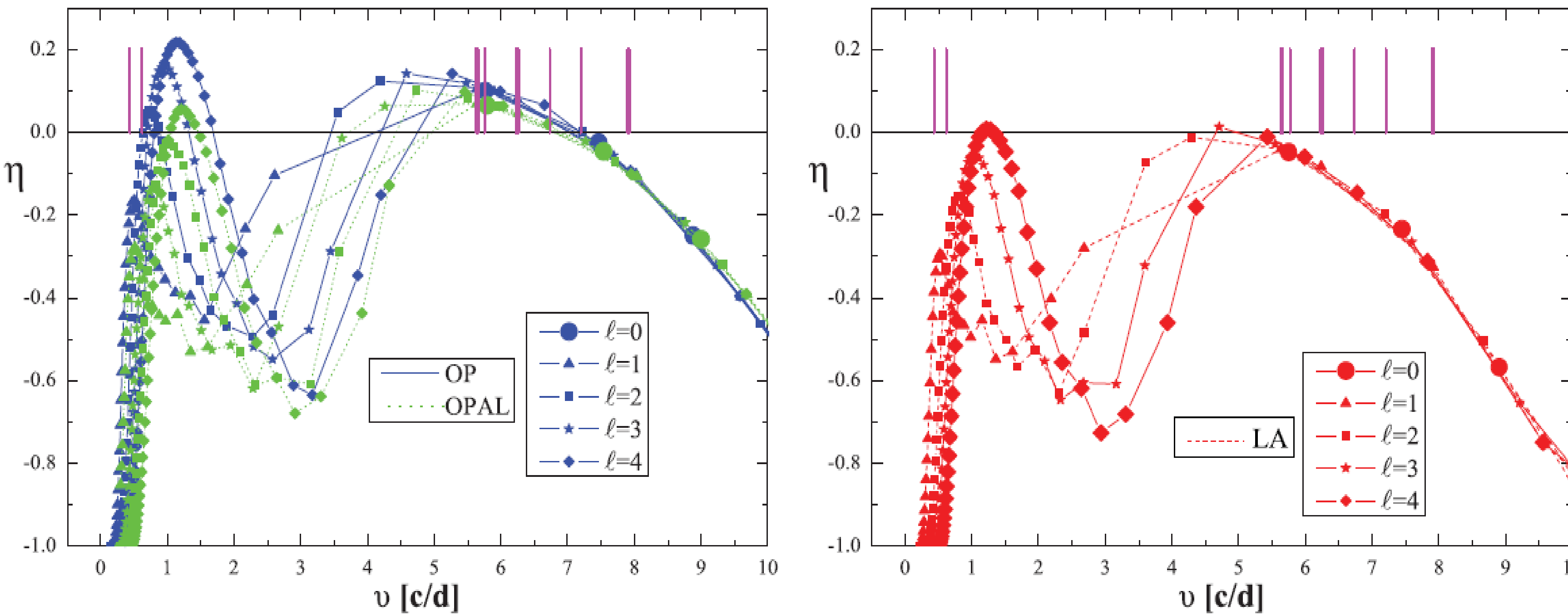






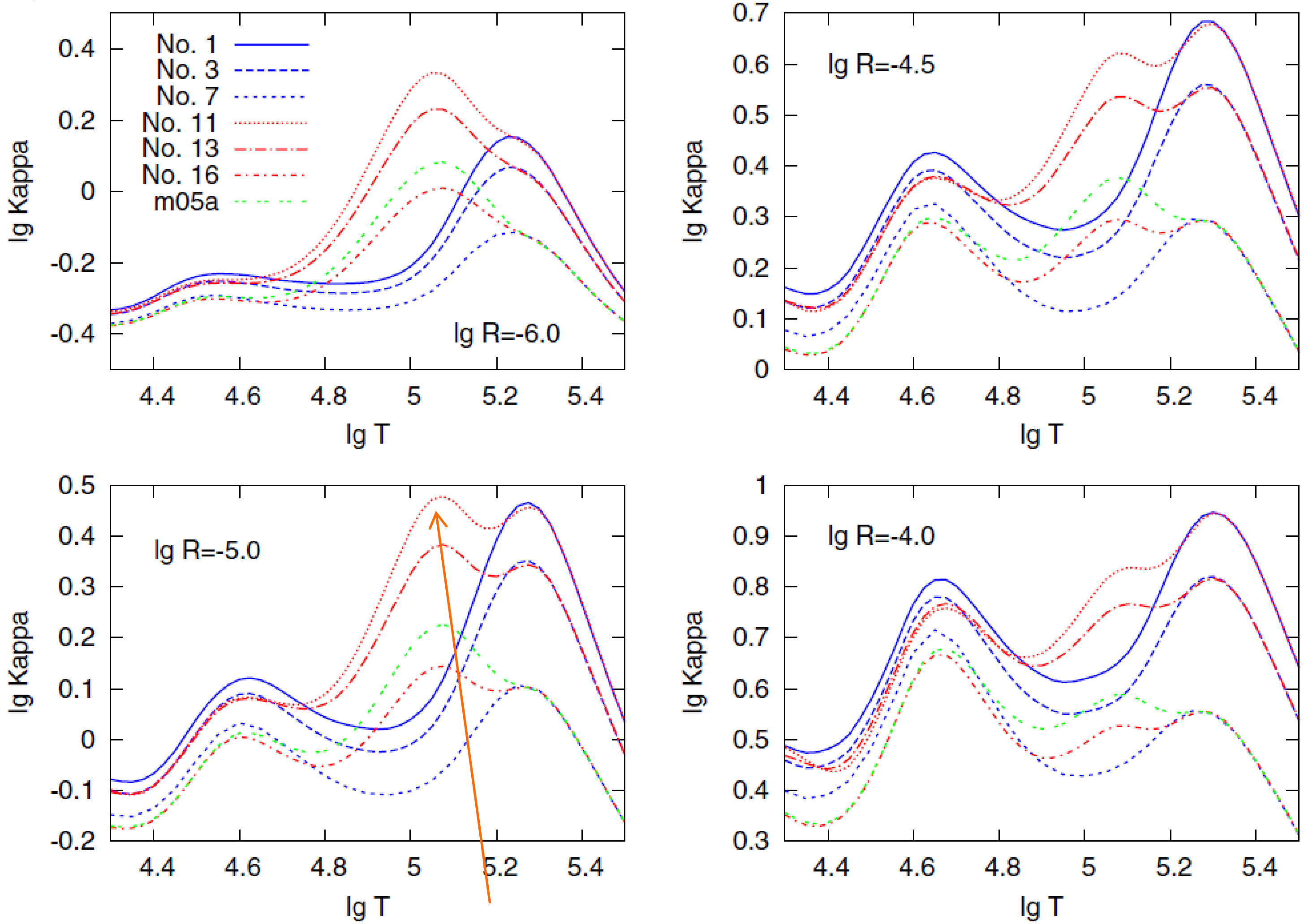
P. Walczak & J. Daszyńska-D. 2014

Instability parameter, η, as a function of the frequency for the three seismic models of ν Eri calculated with the OP, OPAL and LA opacity data.



P. Walczak & J. Daszyńska-D. 2014

Rosseland-mean opacities κ[cm^2 g^{-1}] vs. logT for lg R = −6.0, −5.0, −4.5, and −4.0. The OPAL (blue lines) and K-OPAL (red lines) data were plotted for Z = 0.0266, 0.0168 and 0.0054.



The new bump at logT=5.06

H. Cugier 2014

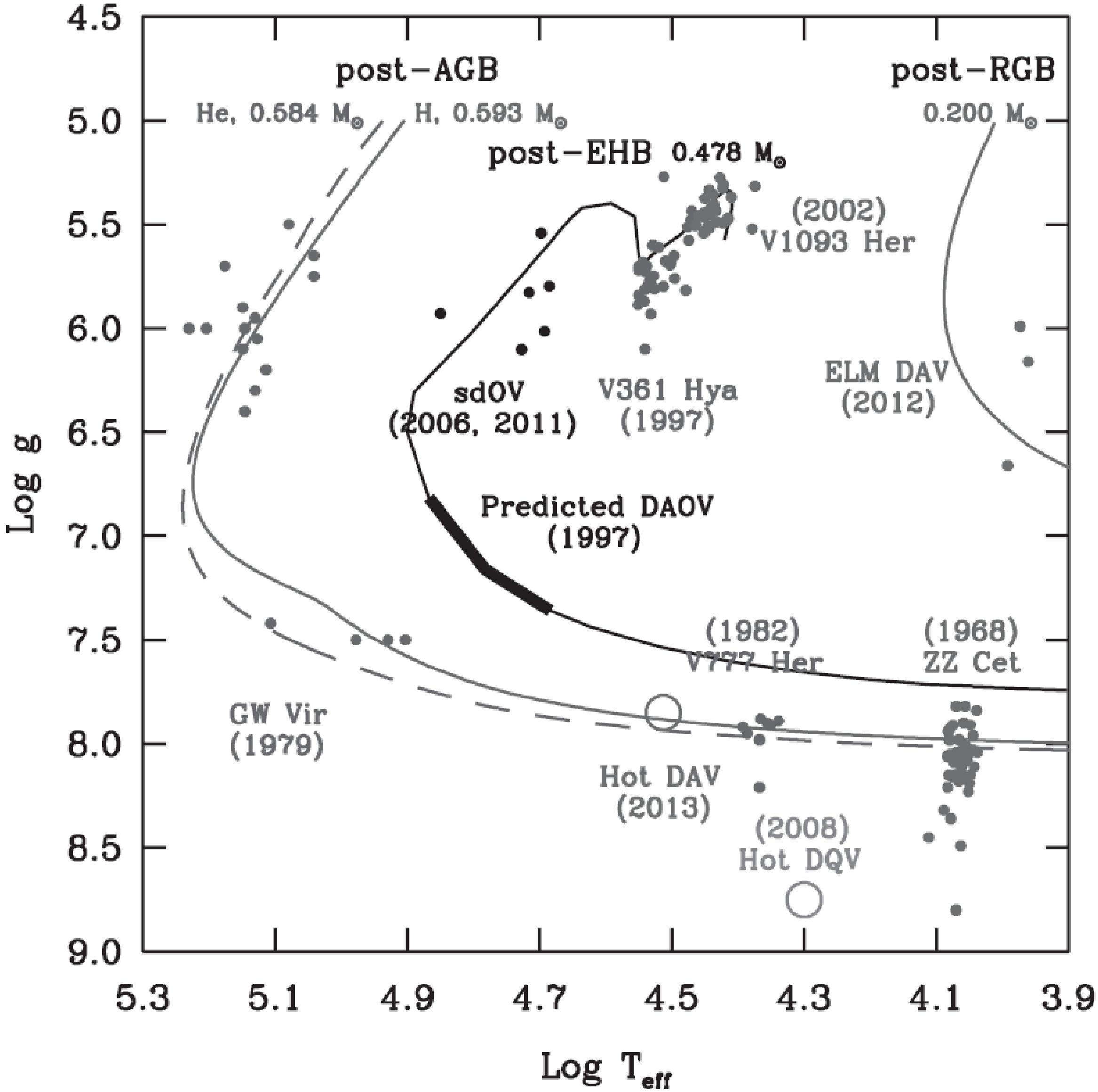
PULSATING WHITE DWARFS

Recent reviews:

G. Fontaine & P. Brassard 2008
D. E. Winget & S. O. Kepler, 2008
H. Saio 2013
G. Fontaine et al. 2014

Most stars (~97%) will end up their evolution as white dwarfs

the locus of various classes of compact pulsators



G. Fontaine 2014

1 GW Vir (PNNV + DOV) – He/C/O-atmospheres, $T_{eff} \approx 120\,000$ K

2 V777Her (DBV) – He-atmospheres, $T_{eff} \approx 25\,000$ K

3 ZZ Cet (DAV) – H-atmospheres, $T_{eff} \approx 12\,000$ K

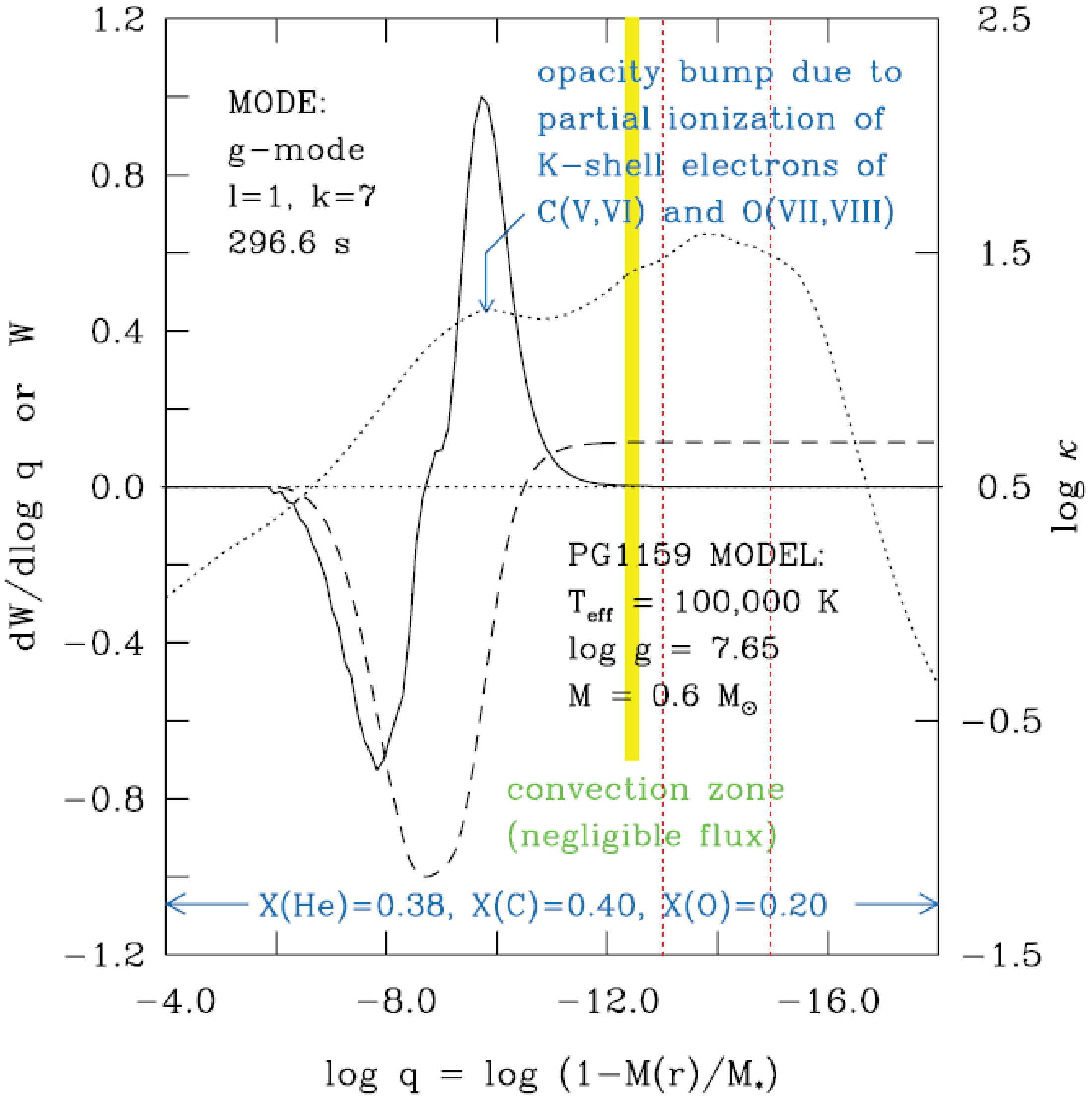
4 Hot DQV – C-atmospheres, $T_{eff} \approx 20\,000$ K
Dufour et al. 2007

5 ELM DAV – thick H-envelope, $T_{eff} < 10\,000$ K, p-modes ?
Hermes et al. 2013

6 Hot DAV – thin H-envelope, , $T_{eff} \approx 30\,000$ K
Kurtz et al. 2013

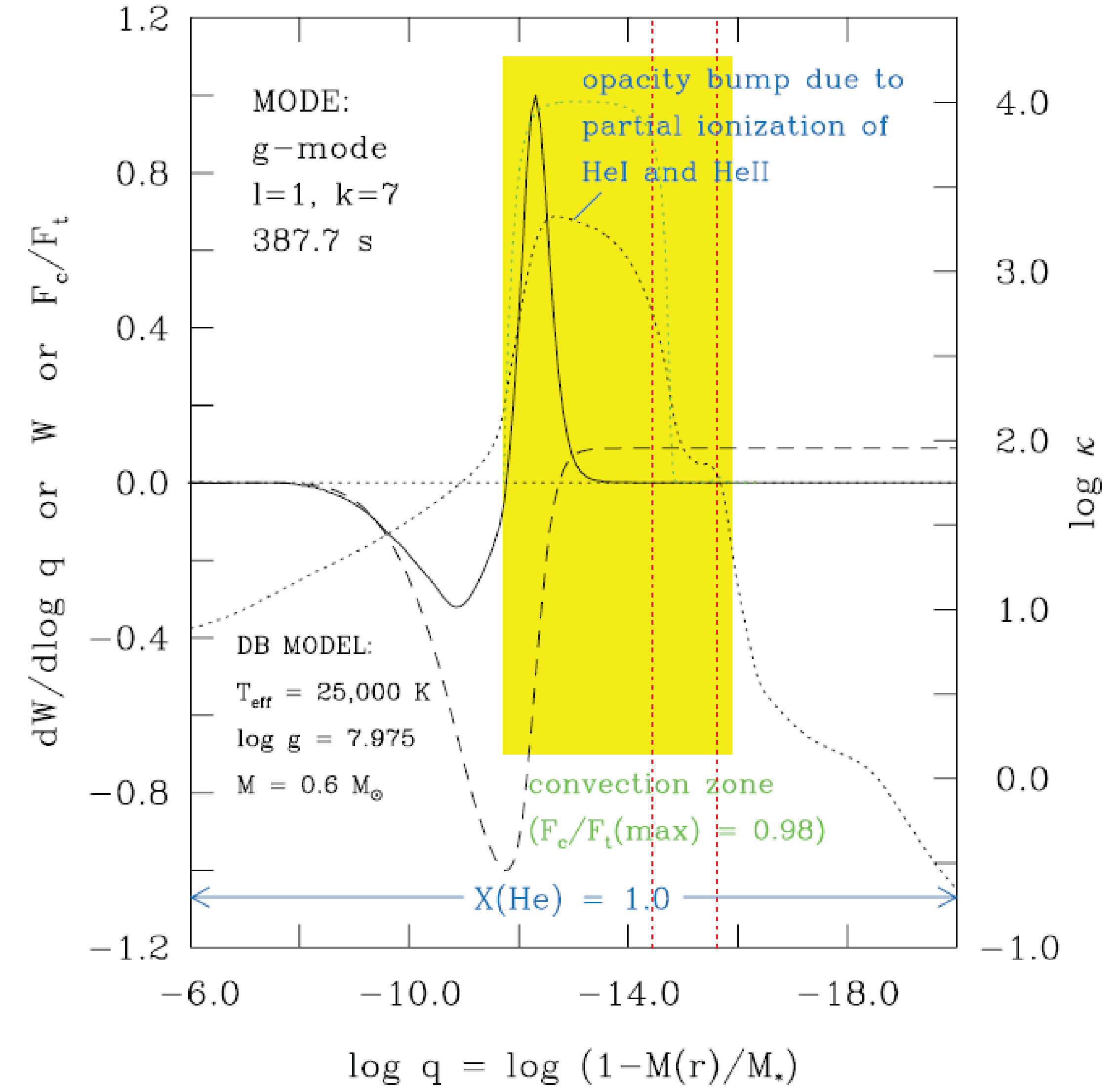
g-modes with P=100 - 2500s

Energetic properties of a typical g-mode excited in a GW Vir star model



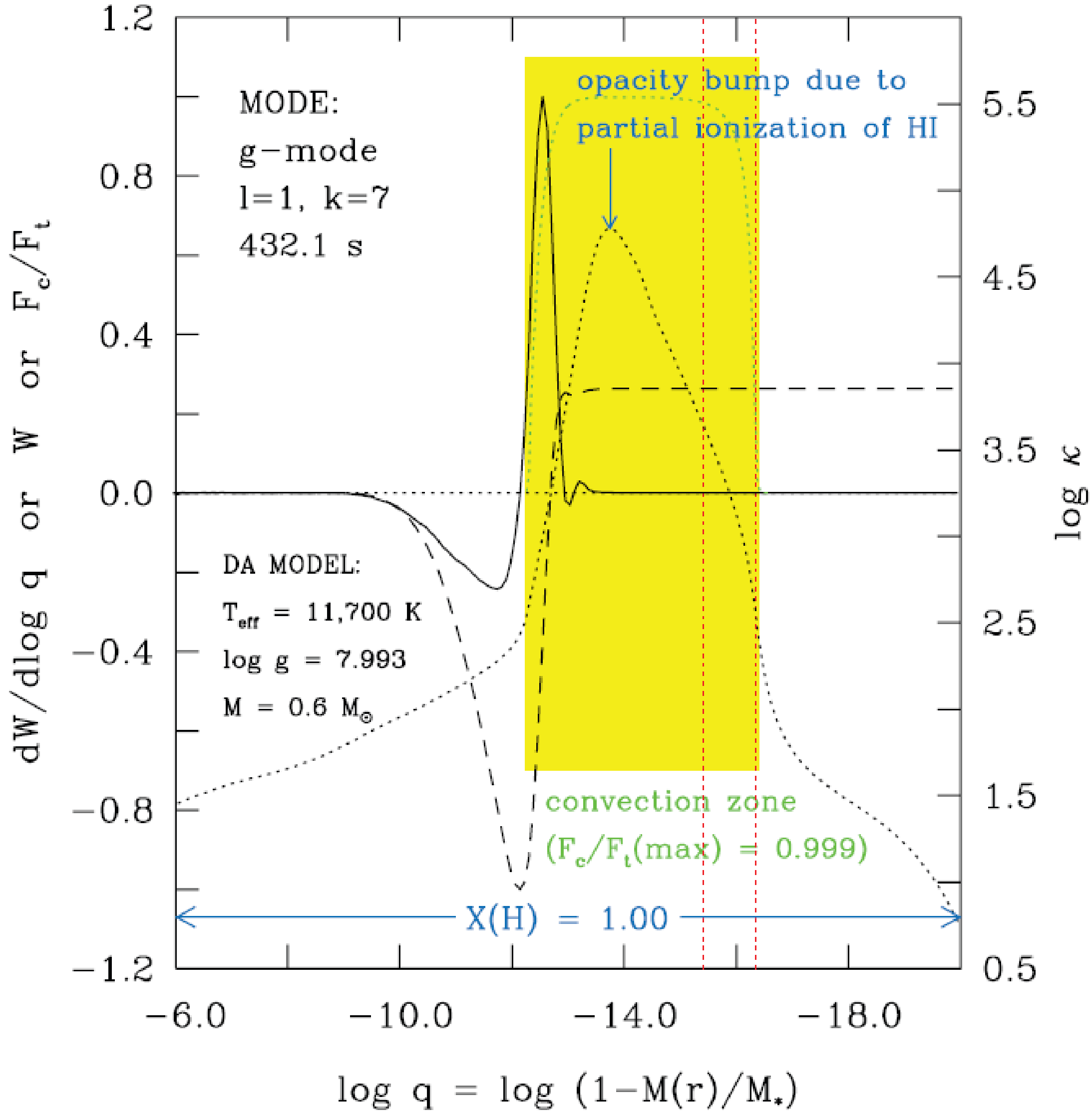
Fontaine & Brassard, 2008

Energetic properties of a typical g-mode excited in a V777 Her star model



Fontaine & Brassard, 2008

Energetic properties of a typical g-mode excited in a ZZ Cet star model



Fontaine & Brassard, 2008

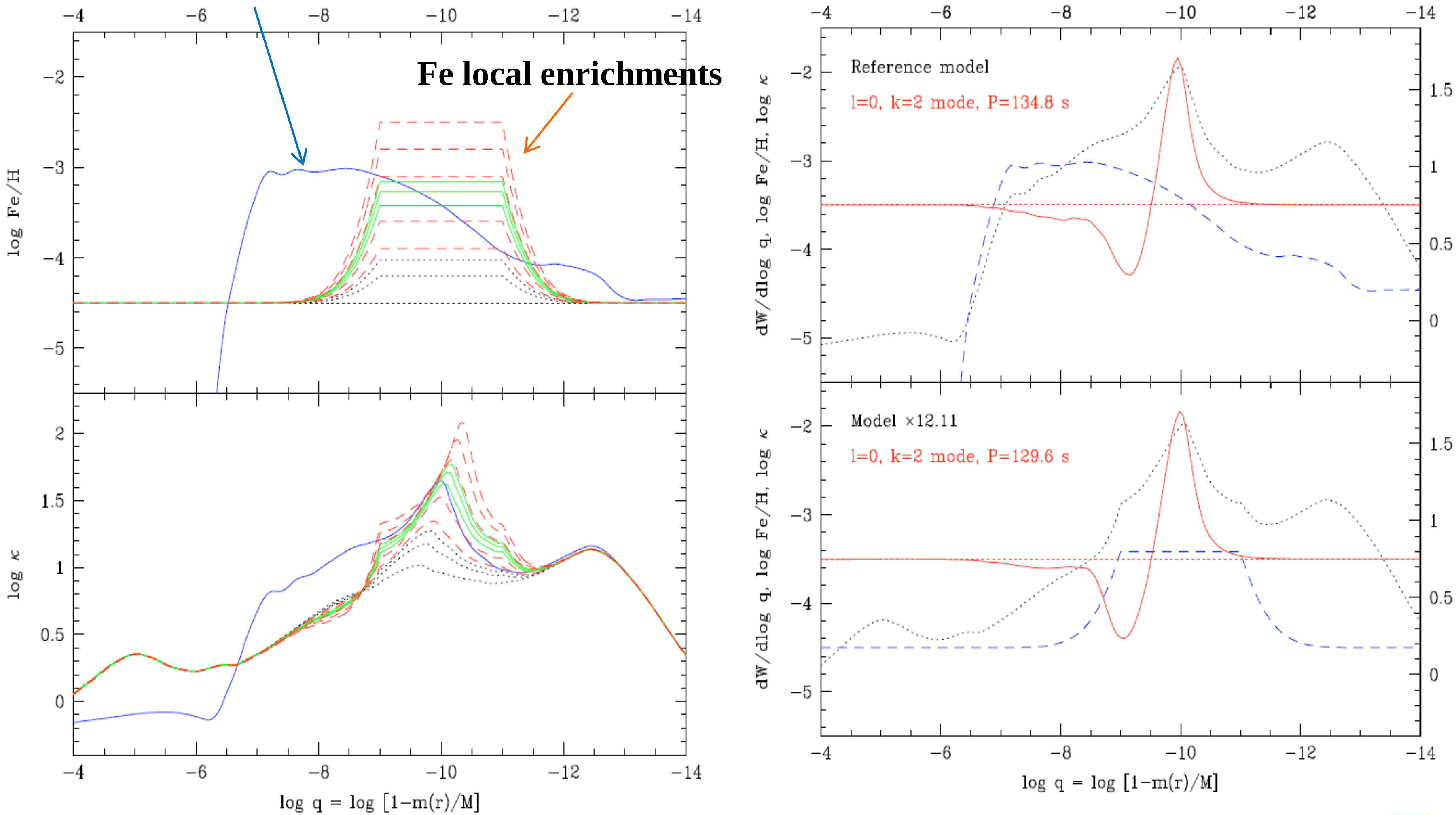
hot subdwarf stars
sdB, sdO

Recent review:

S. Randall et al. 2014

Six distinct types

the Fe profile obtained from equilibrium between gravitational settling and radiative levitation

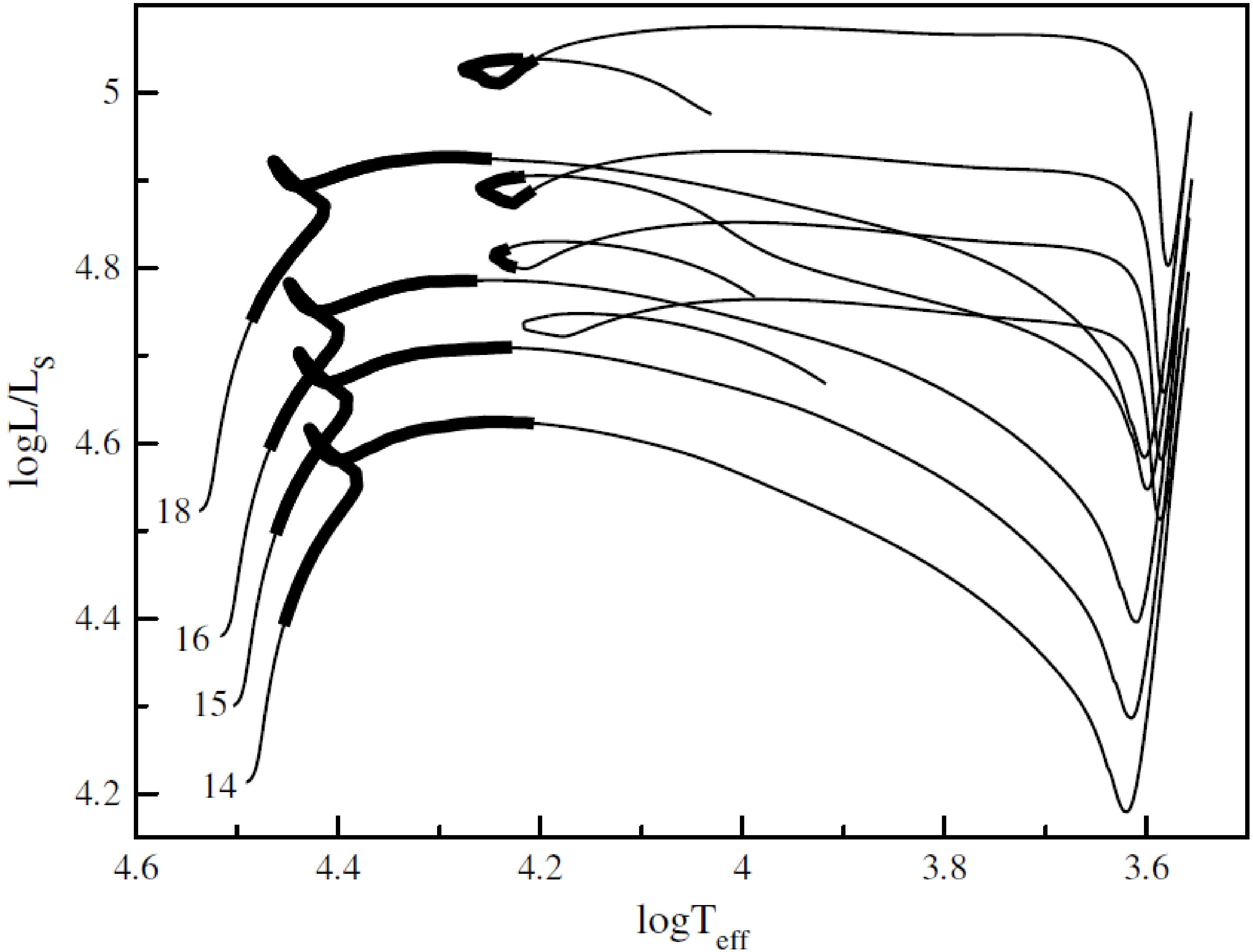


S.Charpinet, G. Fontaine & P. Brassard 2009

B-type supergiants

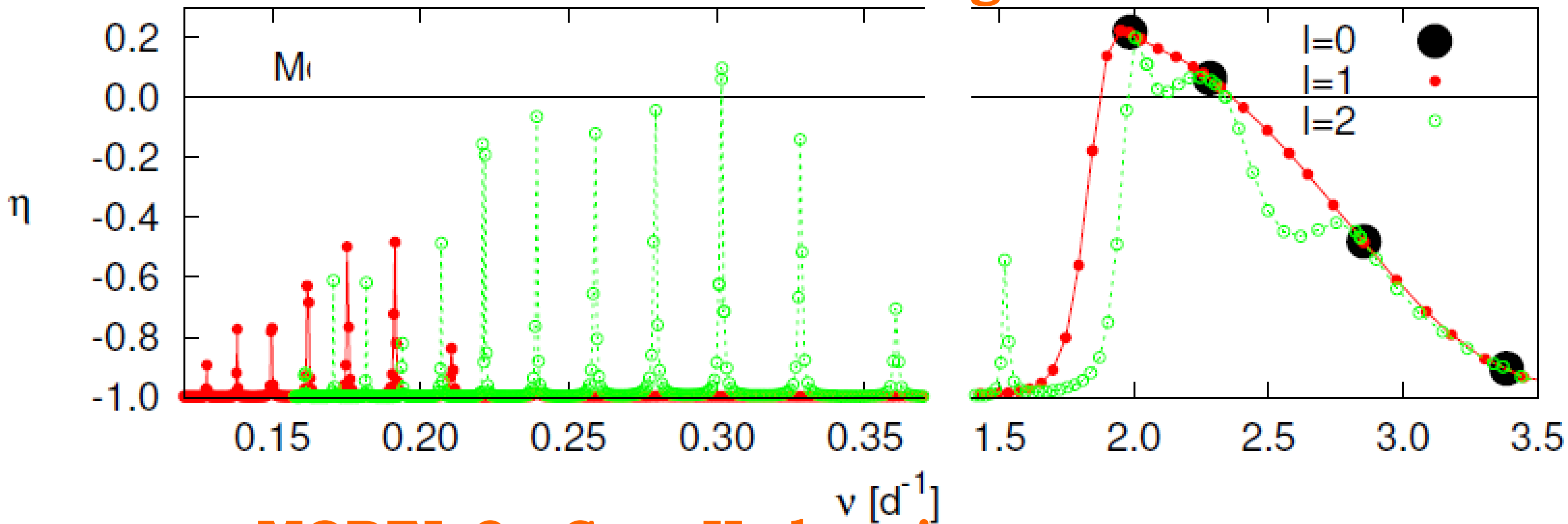
Instability domains for the modes of the degree l= 0,1,2 excited in the OPAL models with masses of 14 - 18$M_{\odot}$.

MESA code + nonadiabatic pulsational code of Dziembowski

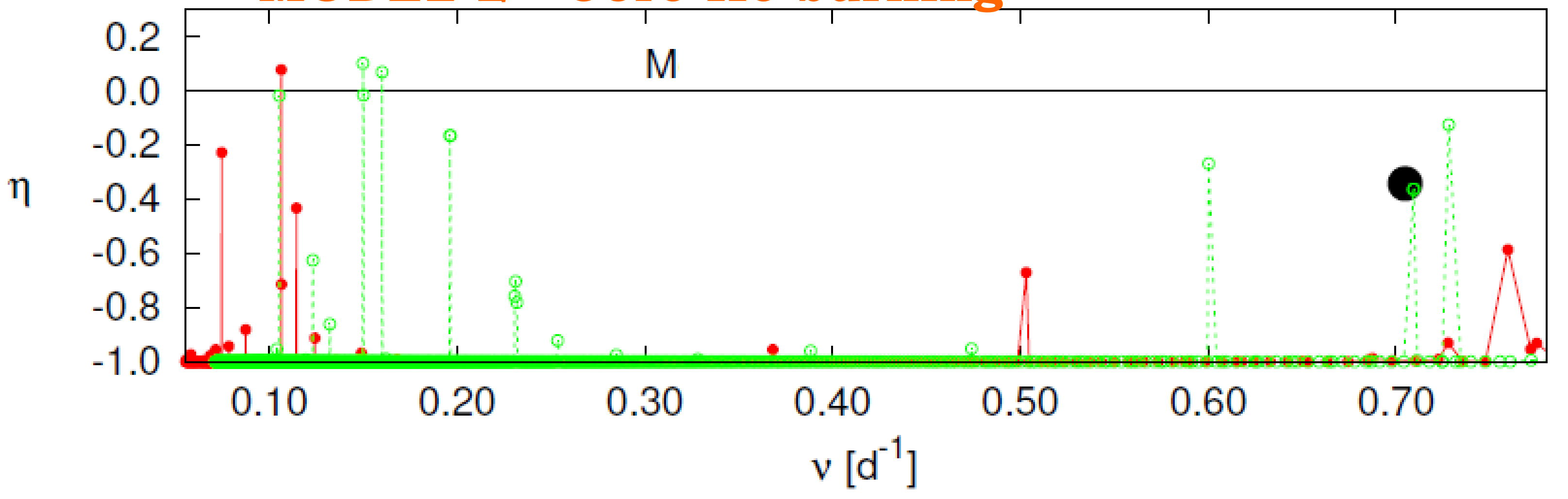


Ostrowski & Daszynska-D, 2014

MODEL 1 - H shell burning



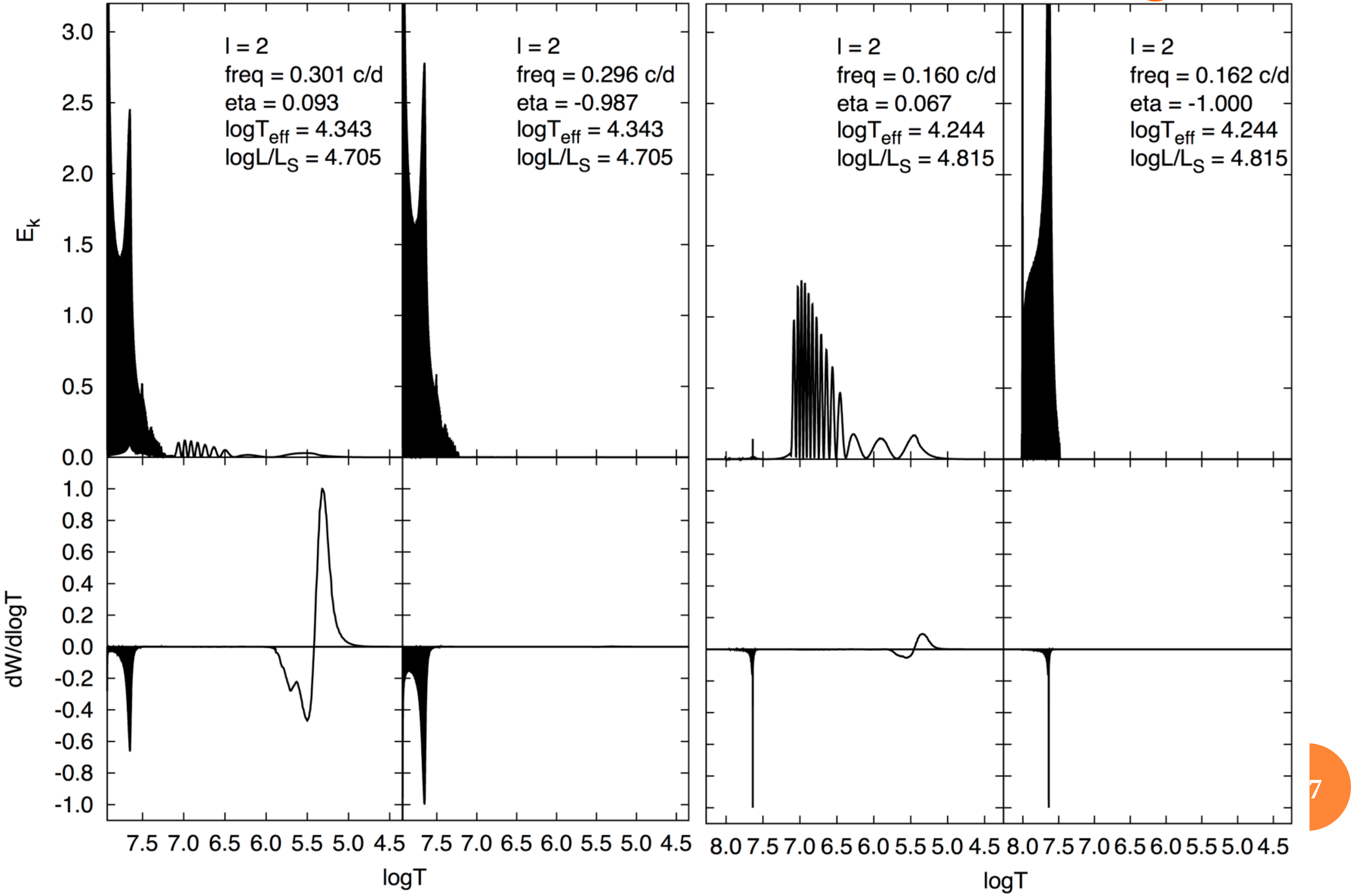
MODEL 2 - Core He burning



Ostrowski & Daszynska-D, 2014

MODEL 1
H shell burning

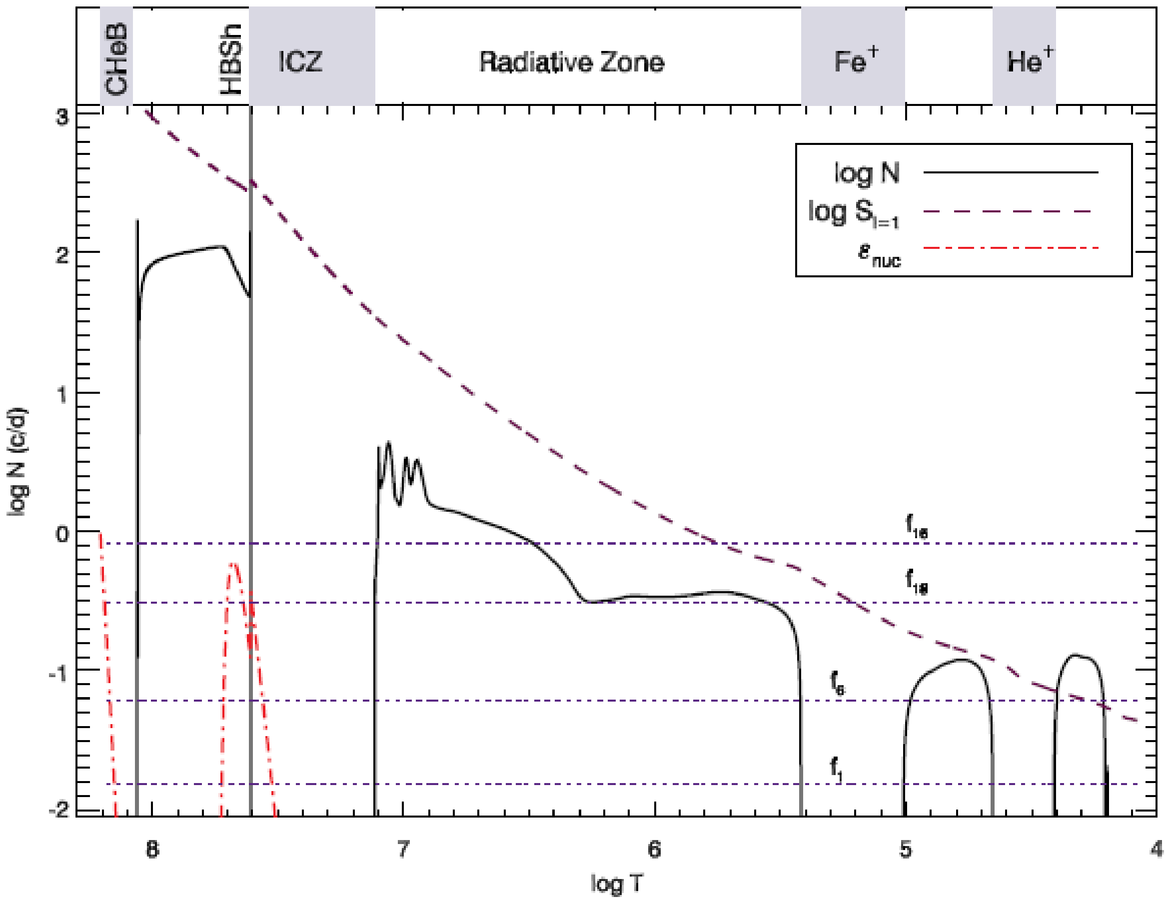
MODEL 2
Core He burning



ε-mechanism

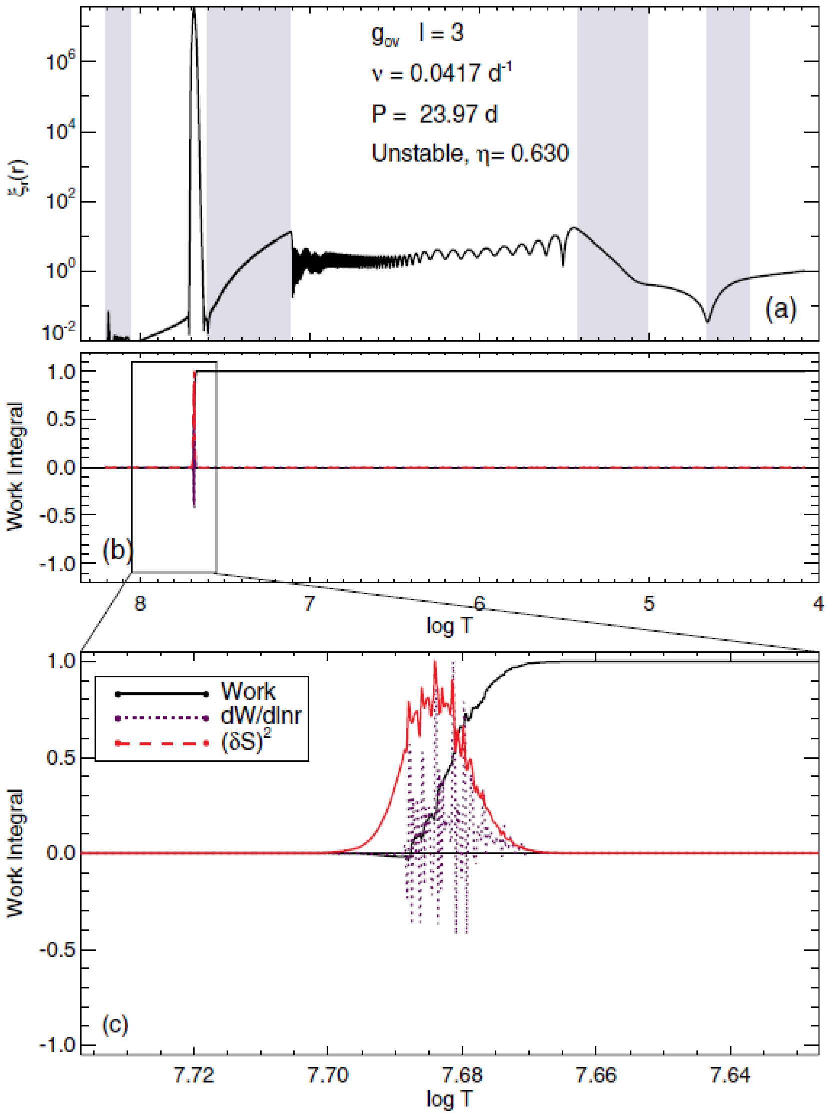
Ledoux (1941)

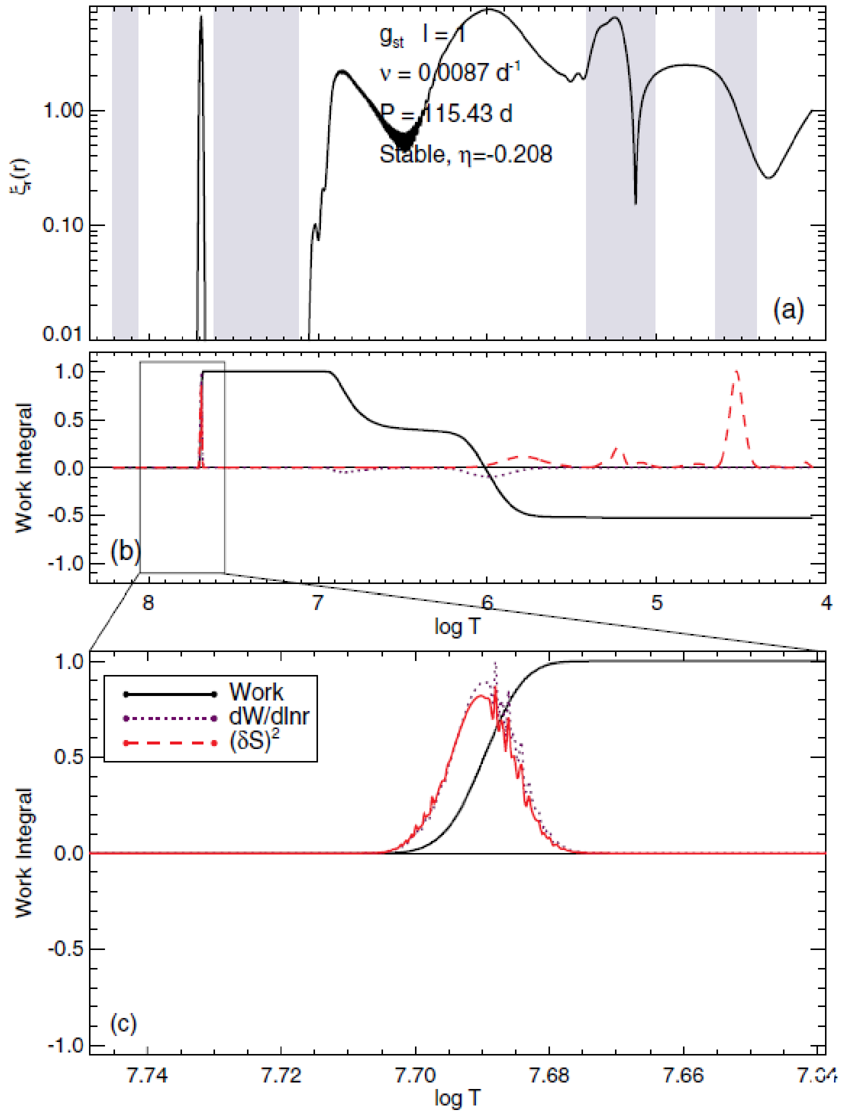
Propagation diagram for the model of Rigel (β Ori, B8 Ia)



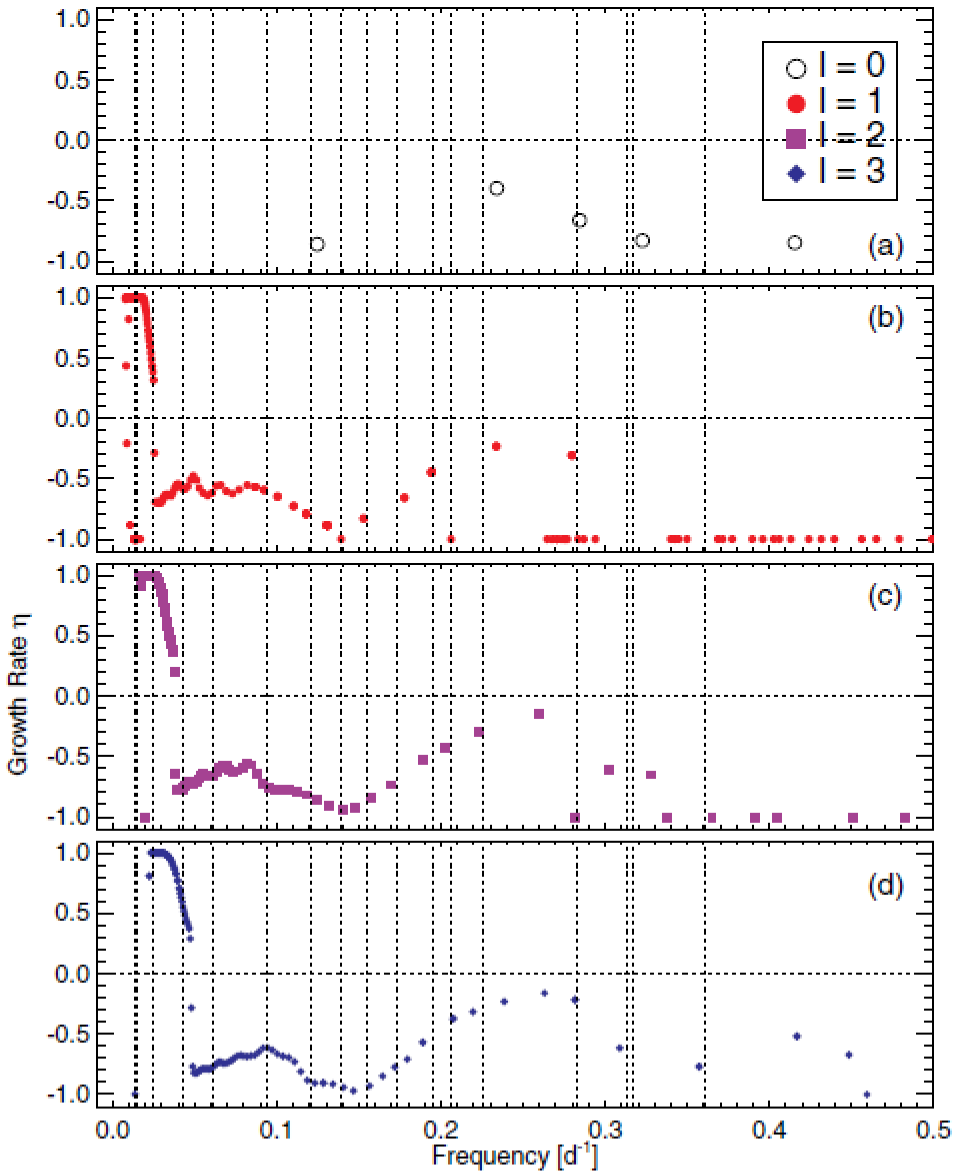
Moravveji, Moya & Guinan, 2012

Example of unstable and stable g-mode in the Rigel model





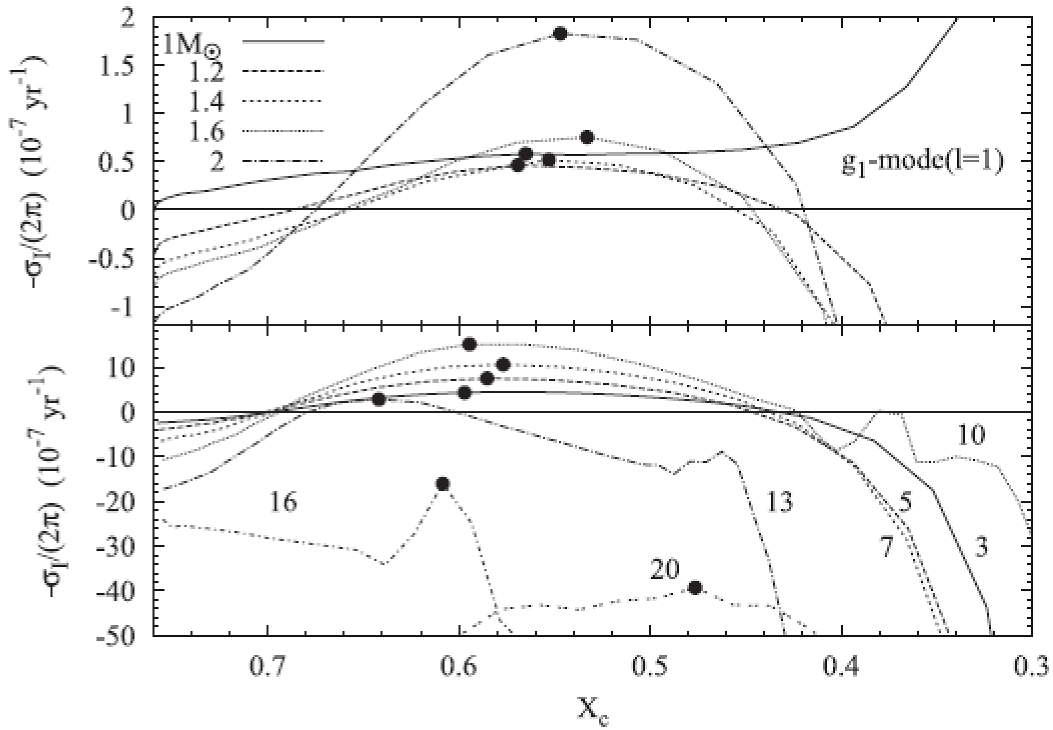
Moravveji, Moya & Guinan, 2012



Moravveji, Moya & Guinan, 2012

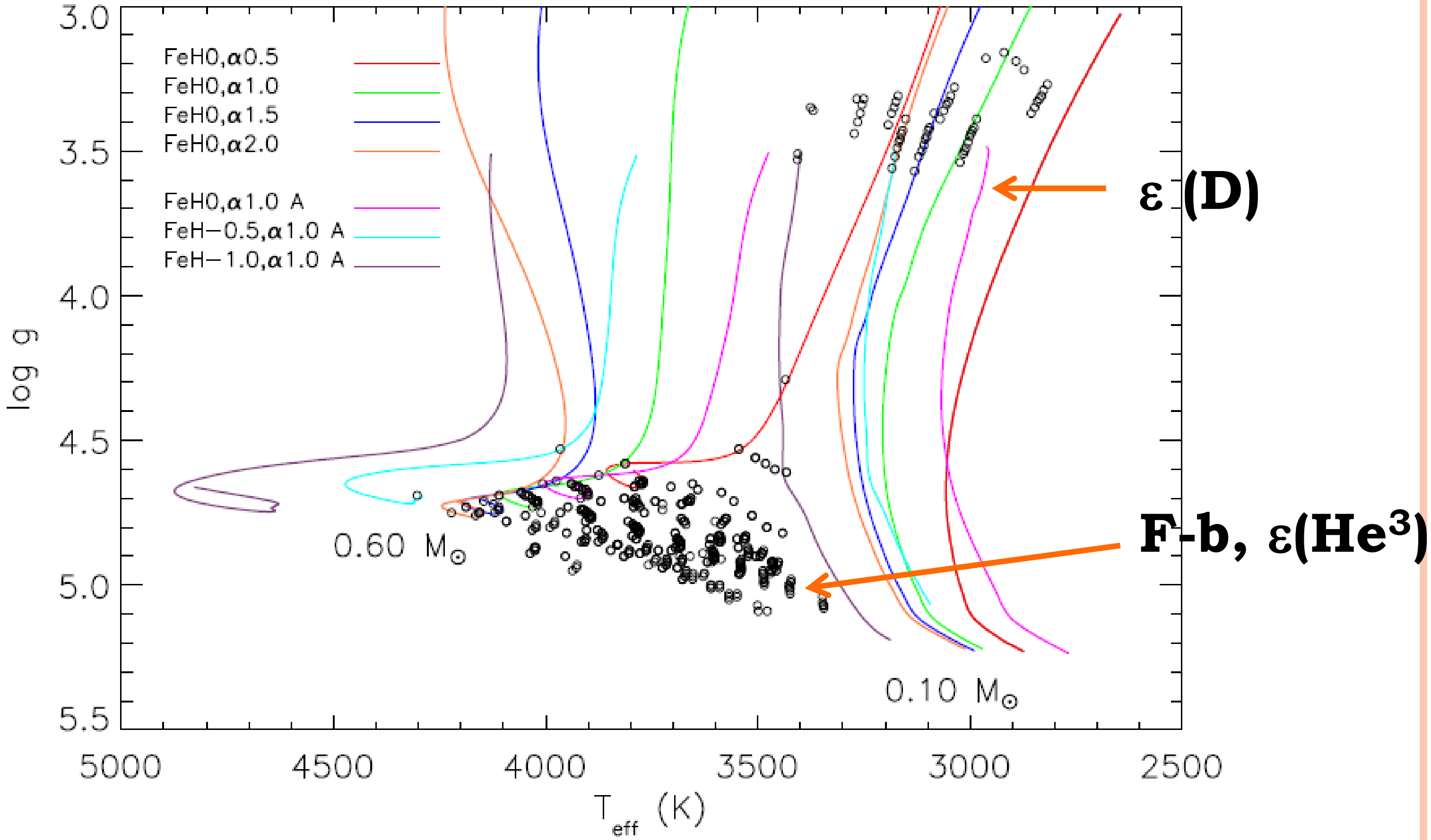
ε-Mechanism – pulsational instability of Population III Stars

„stars with M < 13M become unstable against the dipole g_1- and g_2-modes during the early evolutionary phase at which the pp-chain is still the dominant nuclear energy source"



Sonoi & Shibahashi 2011, 2012

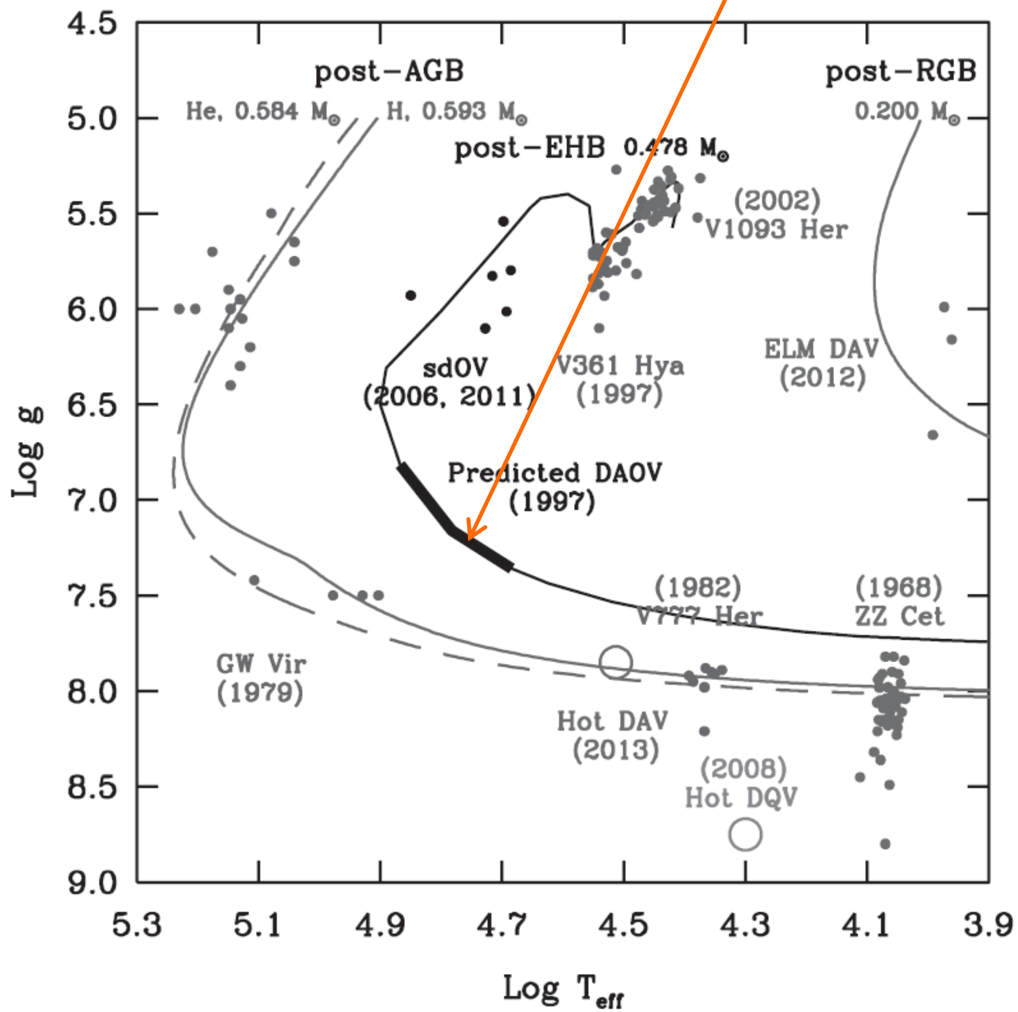
instability strip for M dwarf stars



Rodriguez-Lopez et al. 2012, 2014

post-EHB DAO white dwarfs

g-mode pulsations driven by the ε-mechanism



Charpinet et al. 1997

Effects of rotation on pulsational instability and mode properties

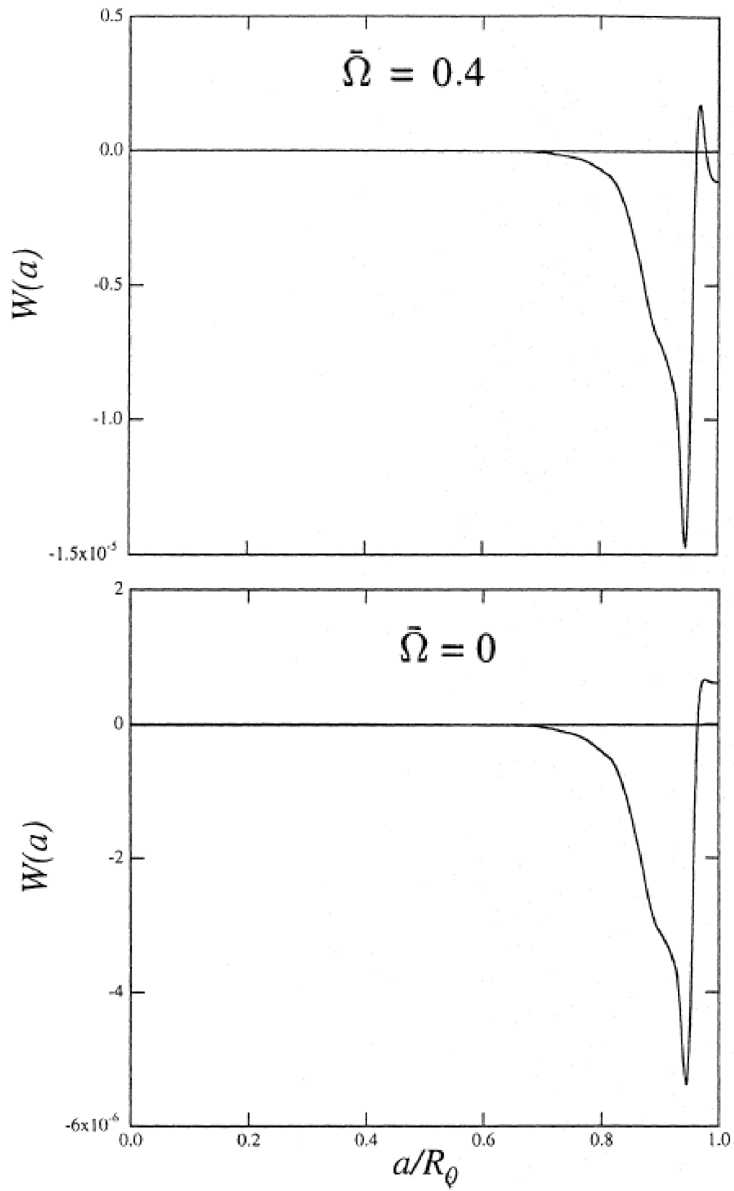
Osaki, Lee, Baraffe, Townsed, Saio, Reese, Ballot, Goupil, Savonije, Lignières, Suarez, Mathis, Neiner, …

- $\Omega \sim 0.5\Omega_{crit}$
- $\omega \sim \Omega$

$\eta(\omega, \lambda/\omega^2, \Omega)$

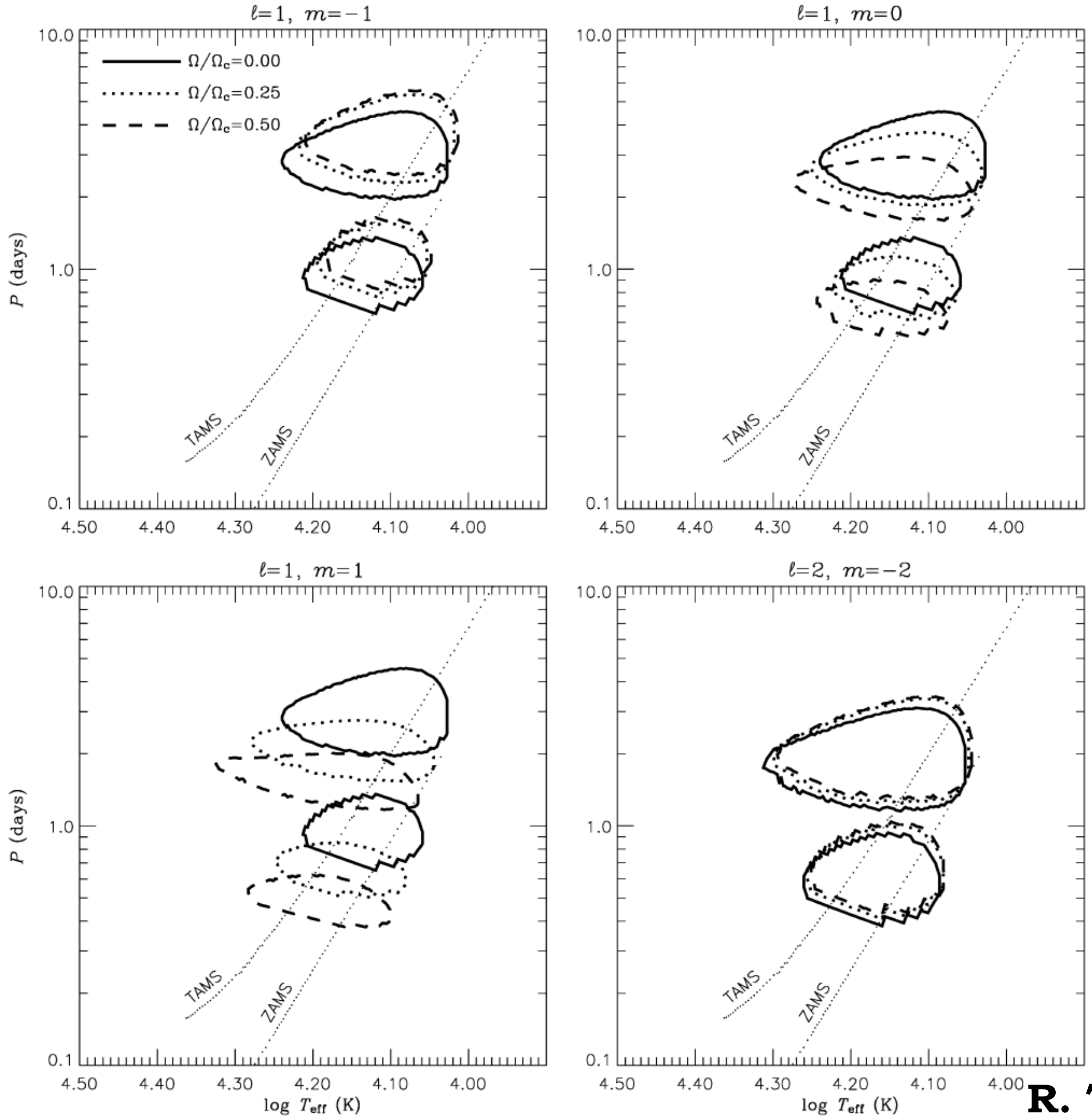
$\Omega \approx 0 \rightarrow \lambda = \ell(\ell+1)$

Cumulative W for the l=2 m=-2 p-mode of the 10 $M_\odot$ star (MS)



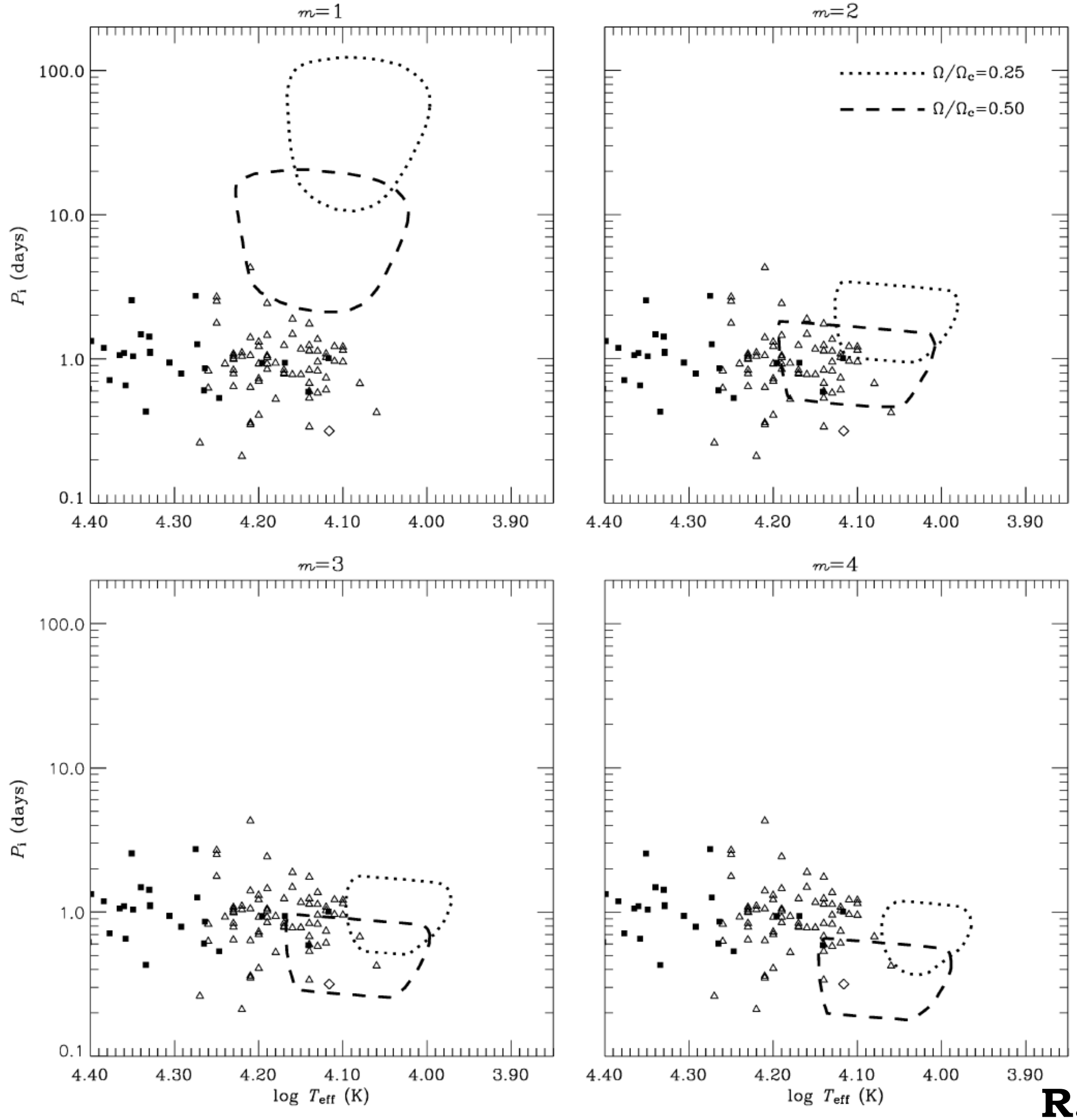
U. Lee & I. Baraffe 1995

Effect of the Coriolis force on the instability domains of SPB stars



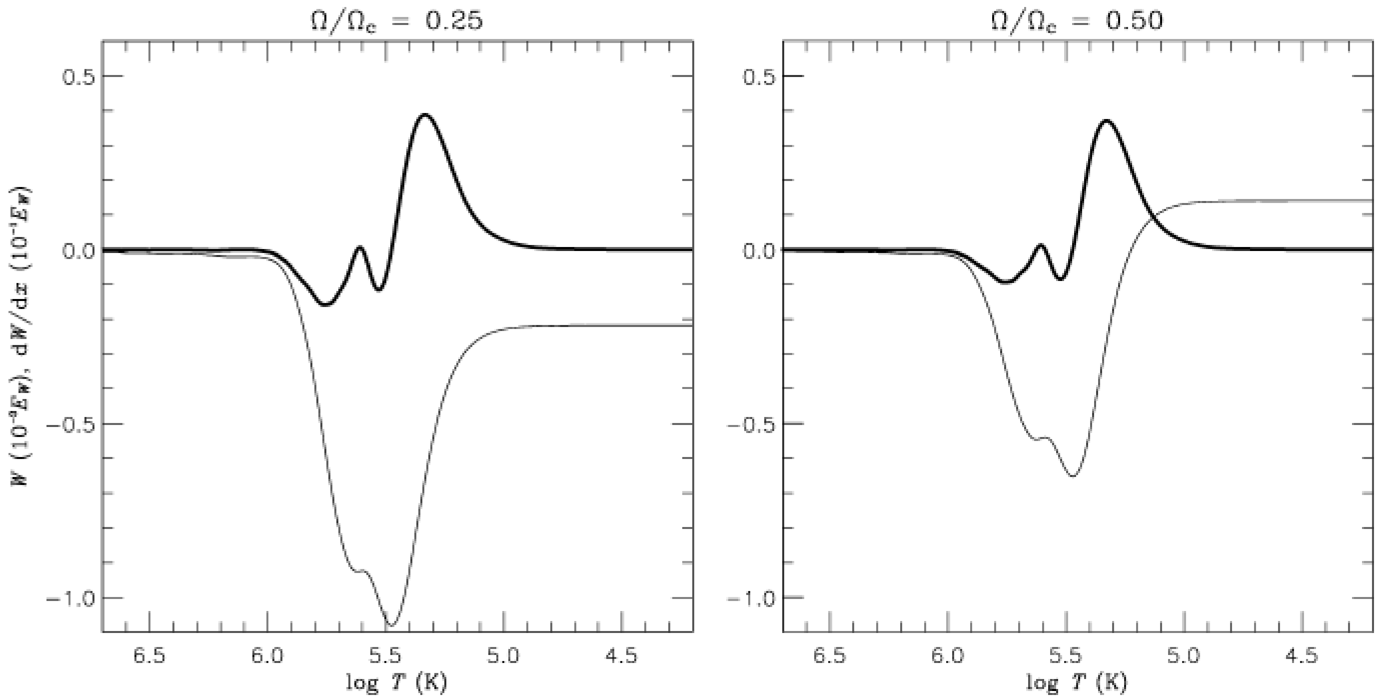
R. Townsend 2005

Instability strip of retrograde mixed modes in B-type stars



R. Townsend 2005

The cumulative and differential work integral for the m=1, n=20 mixed mode of the 53 Per model



Townsend 2005

Solar-like oscillations

Appourchaux, Basu, Baudin, Bedding, Belkacem, Chaplin, Christensen-Dalsgaard, De Ridder, Di Mauro, Dupret, Duvall, Dziembowski, Elsworth, Garcia, Goode, Gough, Goupil, Hekker, Houdek, Kjeldsen, Kosovichev, Mosser, Roxburgh, Shibahashi, Samadi, Vorontsov

…

Chaplin & Miglio, 2013, ARA&A

Solar-like oscillations

the observed amplitude of a pulsational mode changes with time

the energy distribution

$$p(E)\mathrm{d}E = \langle E\rangle^{-1}\exp(-E/\langle E\rangle)\mathrm{d}E$$

the height of a single peak

$$H = \frac{2E}{\eta I} = \frac{P}{\eta^2 I}$$

e.g. Chaplin et al. 2005, Houdek 2006

Scaling relations

Baudin et al. 2005, Chaplin et al. 2008
Belkacem et al. 2011, Kjeldsen & Bedding 2011
Mosser et al. (2011, 2012), Samadi et al. 2012,
Belkacem et al. 2013 …

the frequency of H_{max}

$$\nu_{max} \propto \nu_{ac} \propto \frac{M T_{eff}^{3.5}}{L}$$

the height

$$H = \frac{P}{2\,\eta^2\,\mathcal{M}}$$

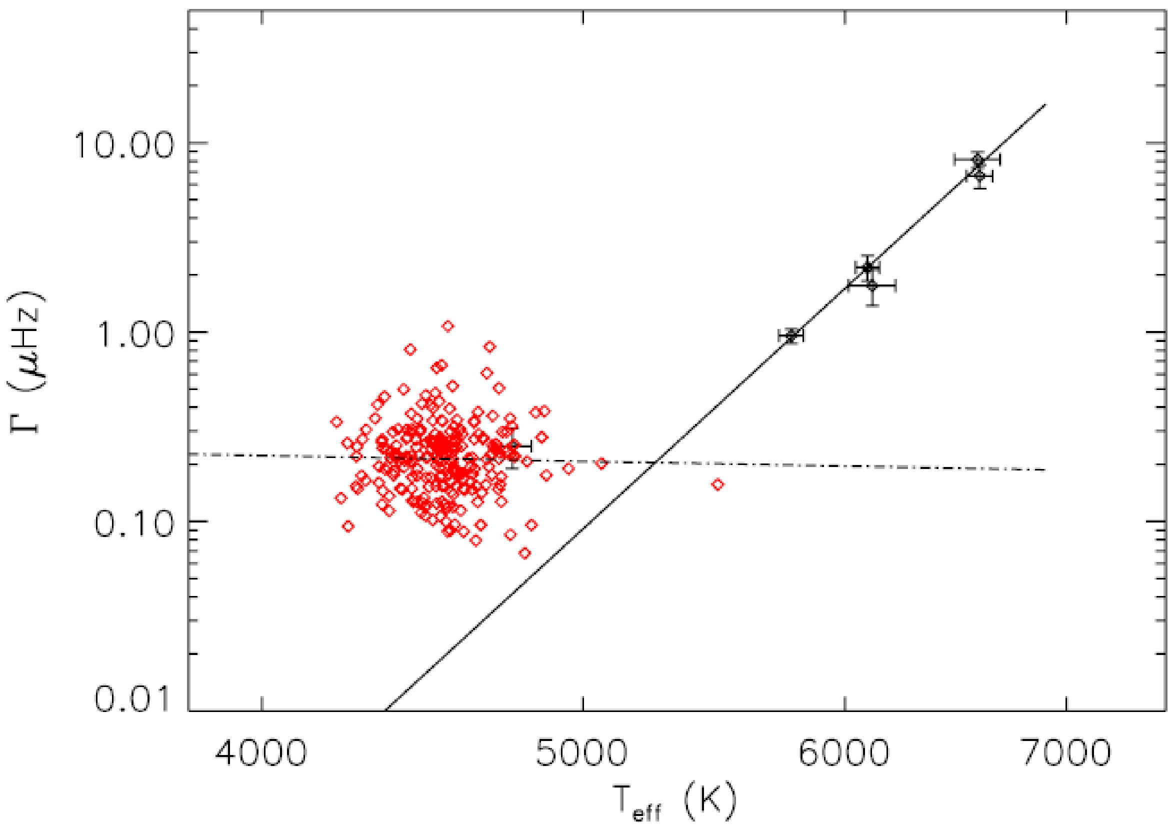
the damping rate

$$\eta \propto T_{eff}^{10.8}\; g^{-0.3}$$

the mode linewidth

$$\Gamma \propto T_{eff}^{8.75-4\beta}\, g^{\beta}$$

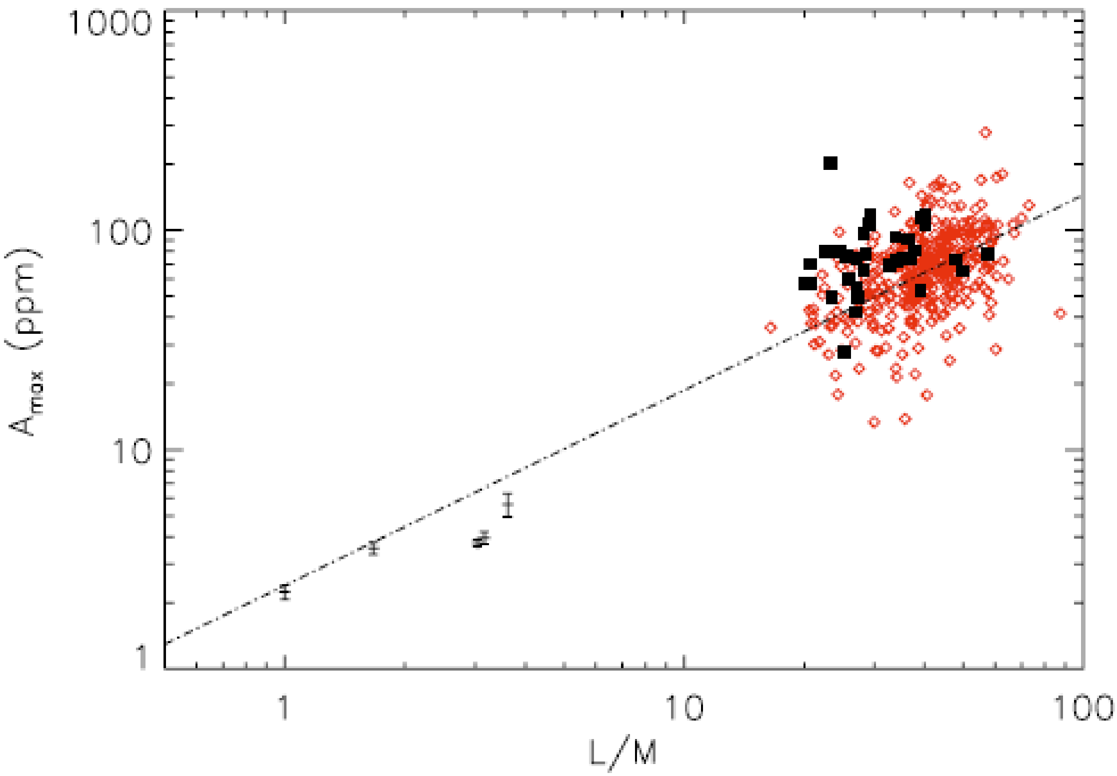
mode linewidths for the red giants (Teff < 5000K) and for the main-sequence stars (Teff > 5000 K).



$$\Gamma \propto T_{\text{eff}}^{s} \quad \text{with} \quad \begin{cases} s \approx -0.3 \pm 0.9 & \text{for RG} \\ s \approx 16 \pm 2 & \text{for MS} \end{cases}$$

Baudin et al. 2011

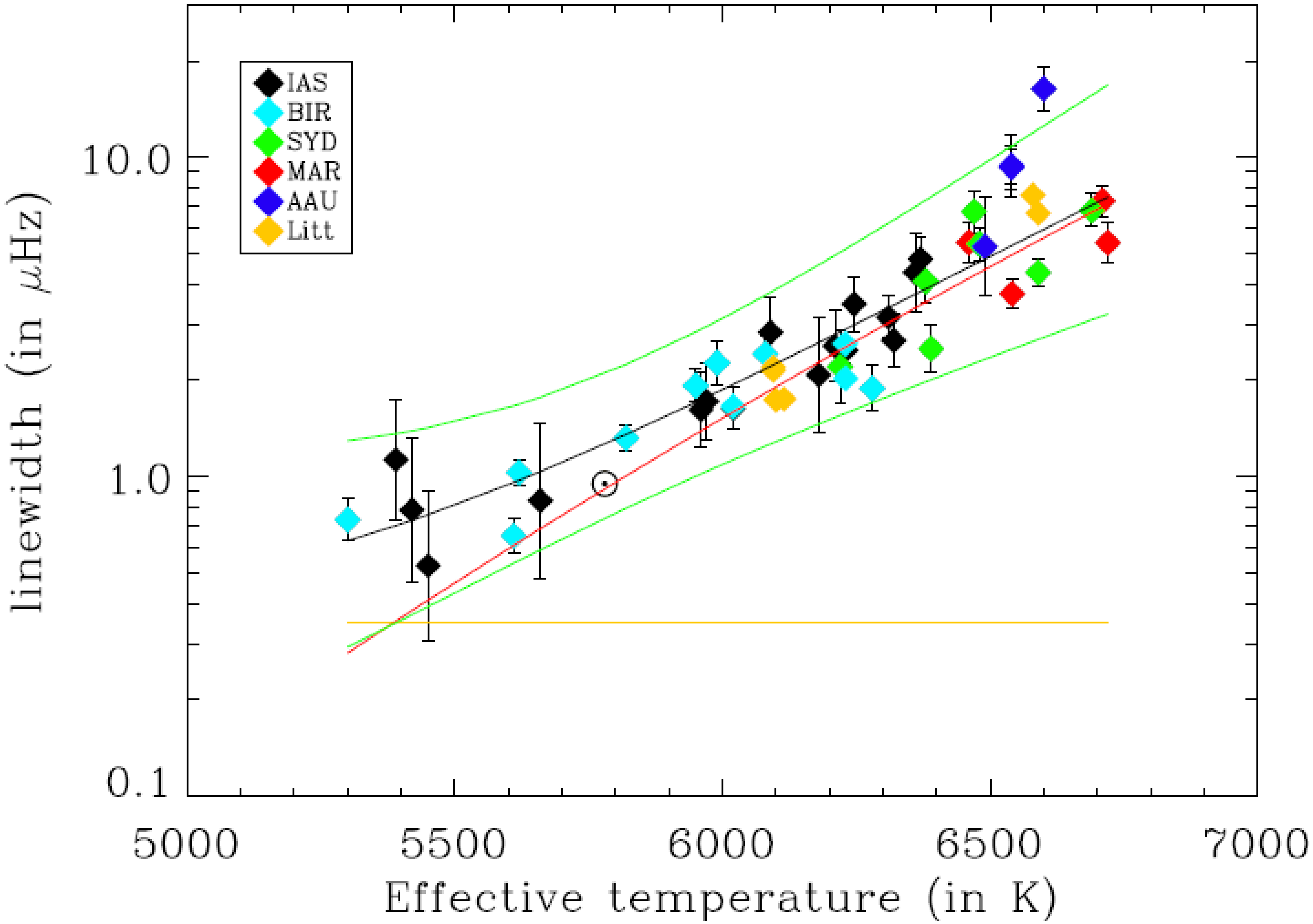
Mode amplitudes ($\propto\sqrt{H\Gamma}$) for the red giants ($L/M > 5$) and for the MS stars ($L/M < 5$)



$$A^{I}_{max} \propto \left(\frac{L}{M}\right)^{s} \text{ with } \begin{cases} s = 0.92 \pm 0.14 & \text{for RG} \\ s = 0.42 \pm 0.14 & \text{for MS} \end{cases}$$

Baudin et al. 2011

mode linewidths of MS and subgiant stars



Appourchaux et al. 2012

TIDAL EFFECTS

- Perturbation of free oscillations
- Tidally forced oscillations

Tidal perturbation of free oscillations

Fitch (1967, 1969) – some δ Sct and β Cep stars

XX Pyx – T. Arentoft et al. (2001), C. Aerts et al. 2002

DG Leo – P. Lampens et al. 2005

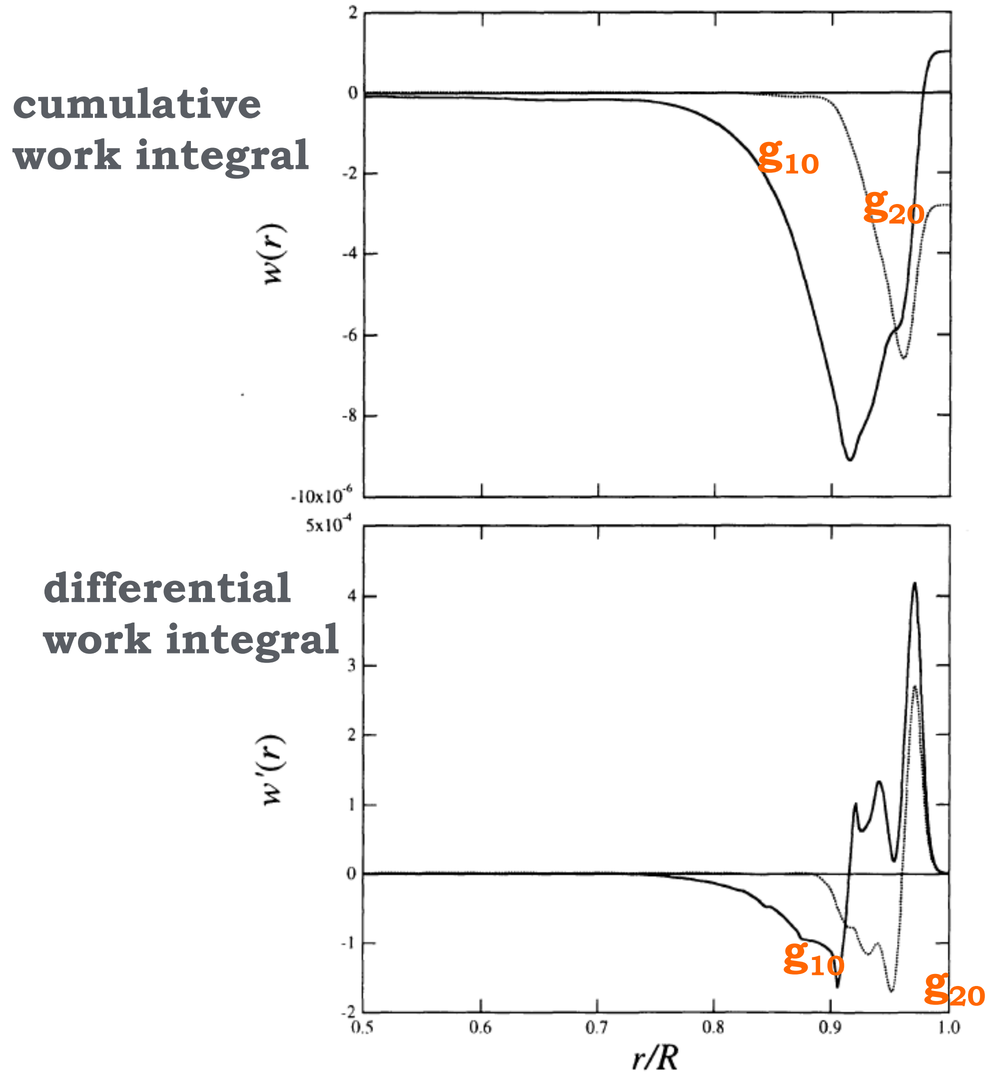
C. Aerts 2007

Tidally forced oscillations

Cowling 1941
Kato, Zahn, Savonije, Papaloizou, Witte, Lee, Shibahashi, Kurtz

δ Sct/γ Dor star HD209295 - Handler et al. 2002
the SPB star HD177863 -De Cat et al. 2000,
Willems & Aerts 2002
the Kepler SPB star - Papics et al. 2013
the Kepler δ Sct stars - K. M. Hambleton et al. 2013, C. Maceroni et al. 2014

Tidally forced oscillations in resonance with g_{10} and g_{20} quadruple mode of the 5 $M_\odot$ model



U. Lee 1993

Silvotti et al. 2014

$\nu_{puls}=3\nu^{P}_{orb}$

g-mode pulsations tidally excited by a planetary companion

CONCLUSIONS

Diversity of stellar pulsations

Seismic model → frequency + mode properties (nonadiabatic effects, convection, rotation etc.)

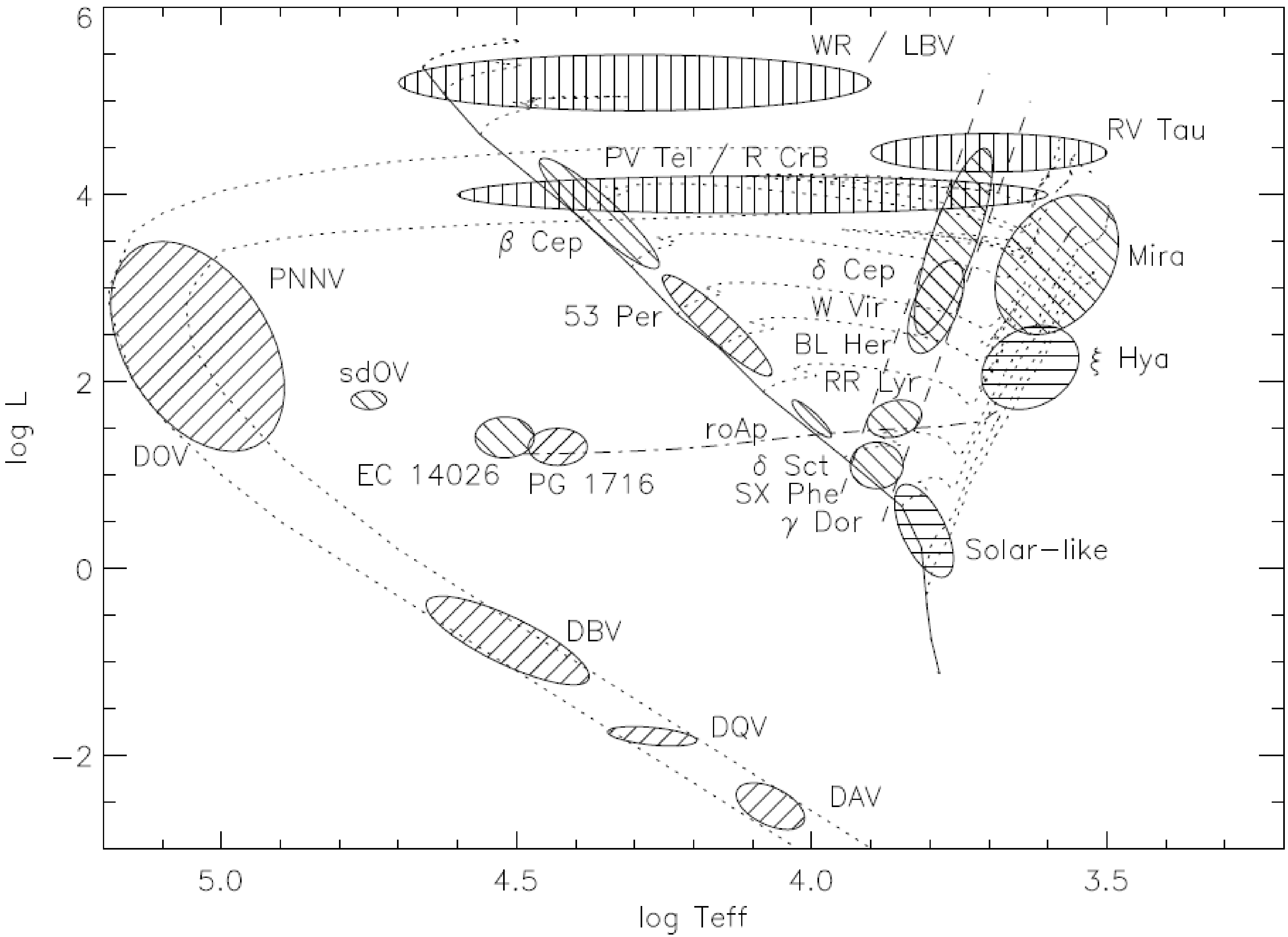
More data

better understanding ↙ ↘ **new challenges**

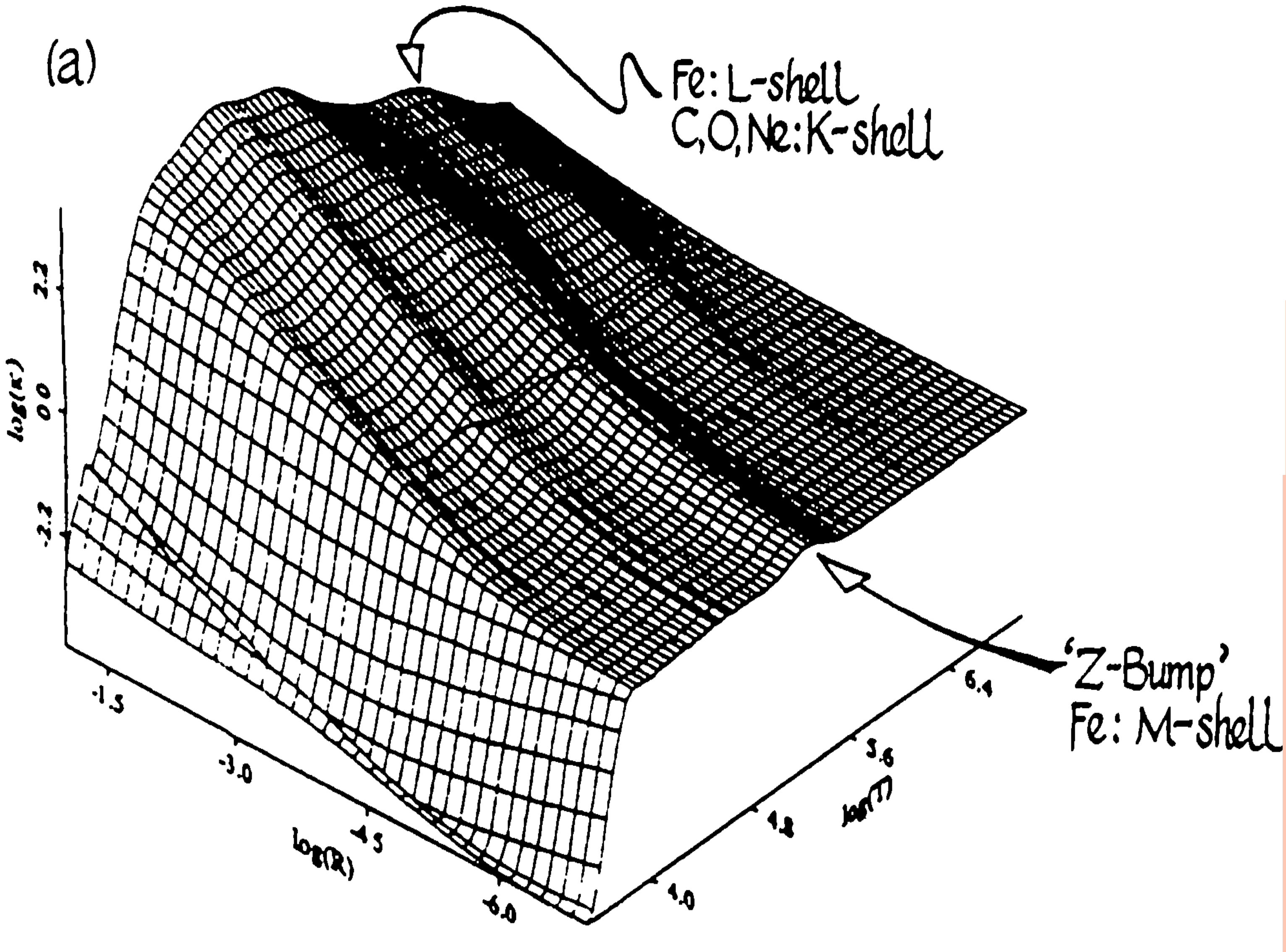
new solutions — **new problems**

Precision asteroseismology

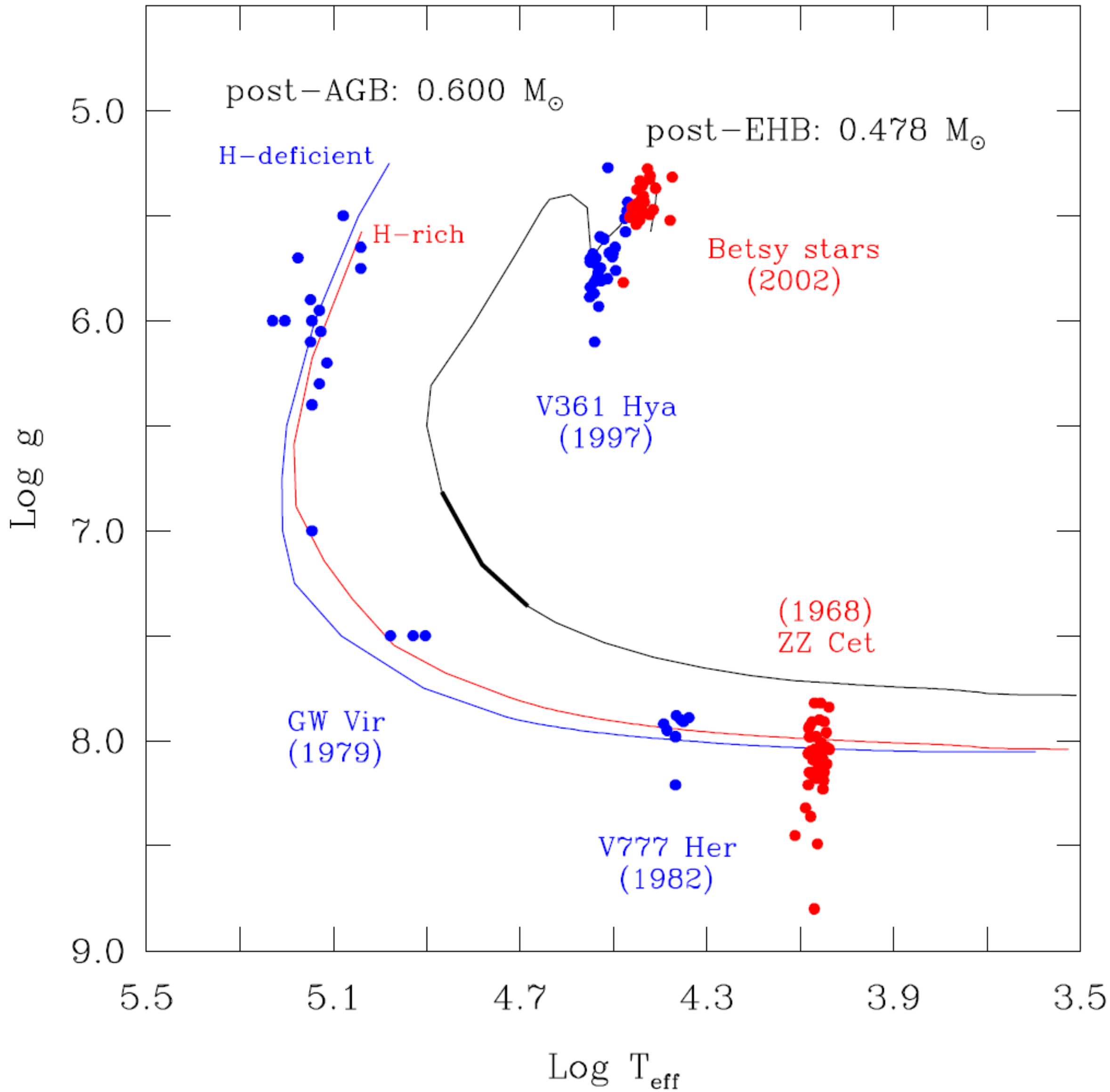

MASZYNA RÓŻNICOWA
GDZIE WASZE CIAŁA PORZUCONE
PÓŹNE LATO
ODYSEJA KOSMICZNA 2001
GROBOWCE ATUANU
SPOTKANIE POZA CZ
FANTASTYKA 50
PHILIP K. DICK
ŻUK W MROWISKU
A. Huxley NOWY WSPANIAŁY ŚWIAT
Na Srebrnym Globie
H. G. WELLS PIERWSI LUDZIE NA KSIĘŻYCU
DRUGA JESIEŃ
GENE WOLFE
C. S. FRIEDMAN
OBCY BRZEG
WIZJE ALTERNATYWNE 2
ZAMKNIĘTY ŚWIAT
BRUCE STERLING



S. Jeffery 2008



Gautschy, 1995



Fontaine & Brassard, 2008

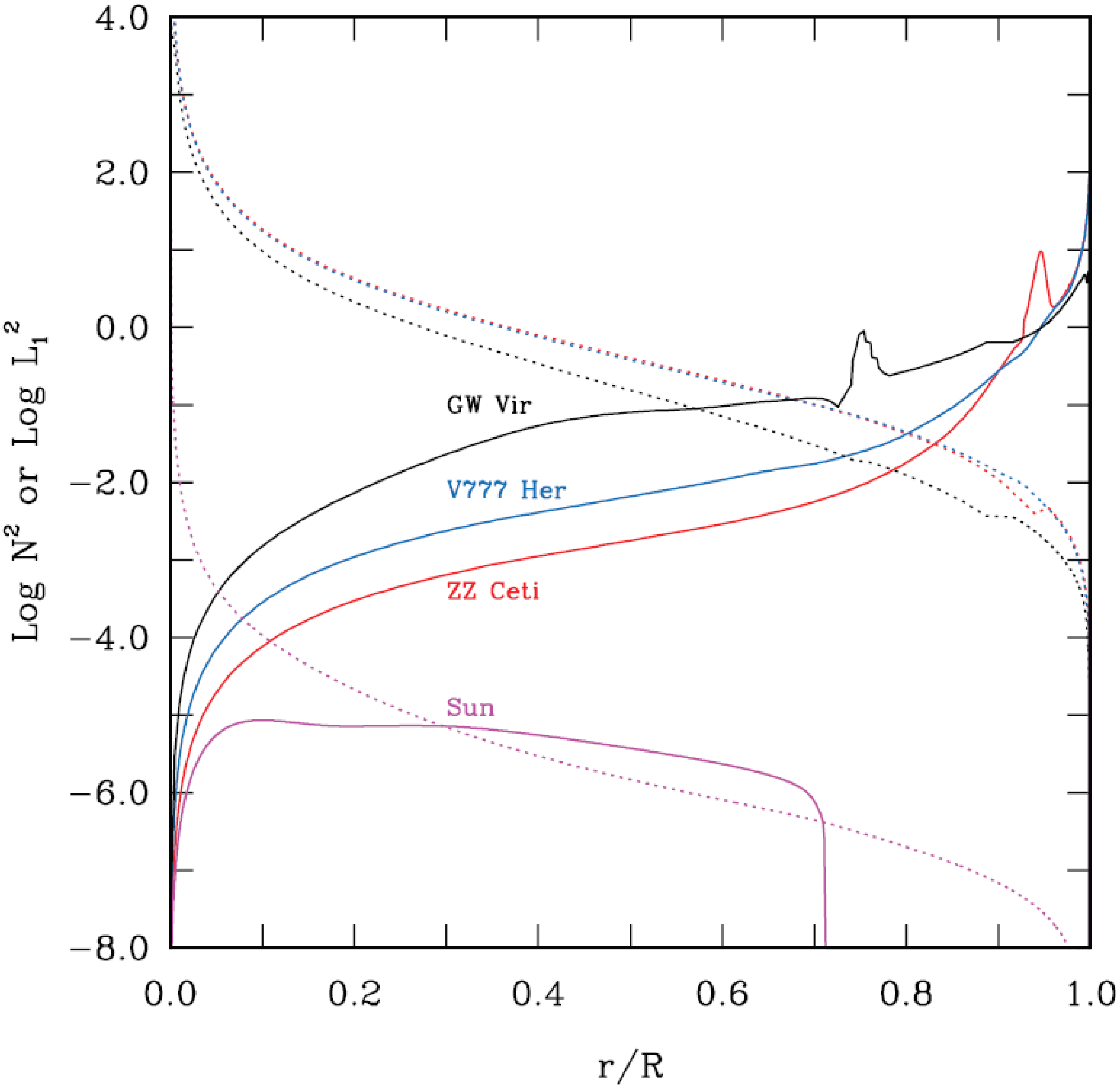
Mass ($M_\odot$)	P	Excit. mechan.	Comments
0.10 - 0.40	4 - 11 h	ϵ (D)	age $\lesssim$ 2 Myr
0.40 - 0.60	1 - 2 h	F-b	age $\leqslant$ 50 Myr
	1 - 3 h	F-b, ϵ (He^3)	g-modes
0.20 - 0.30	20 - 30 min	ϵ (He^3)	
0.35 - 0.60	20 - 60 min	F-b	

Rodriguez-Lopez et al. 2012, 2014

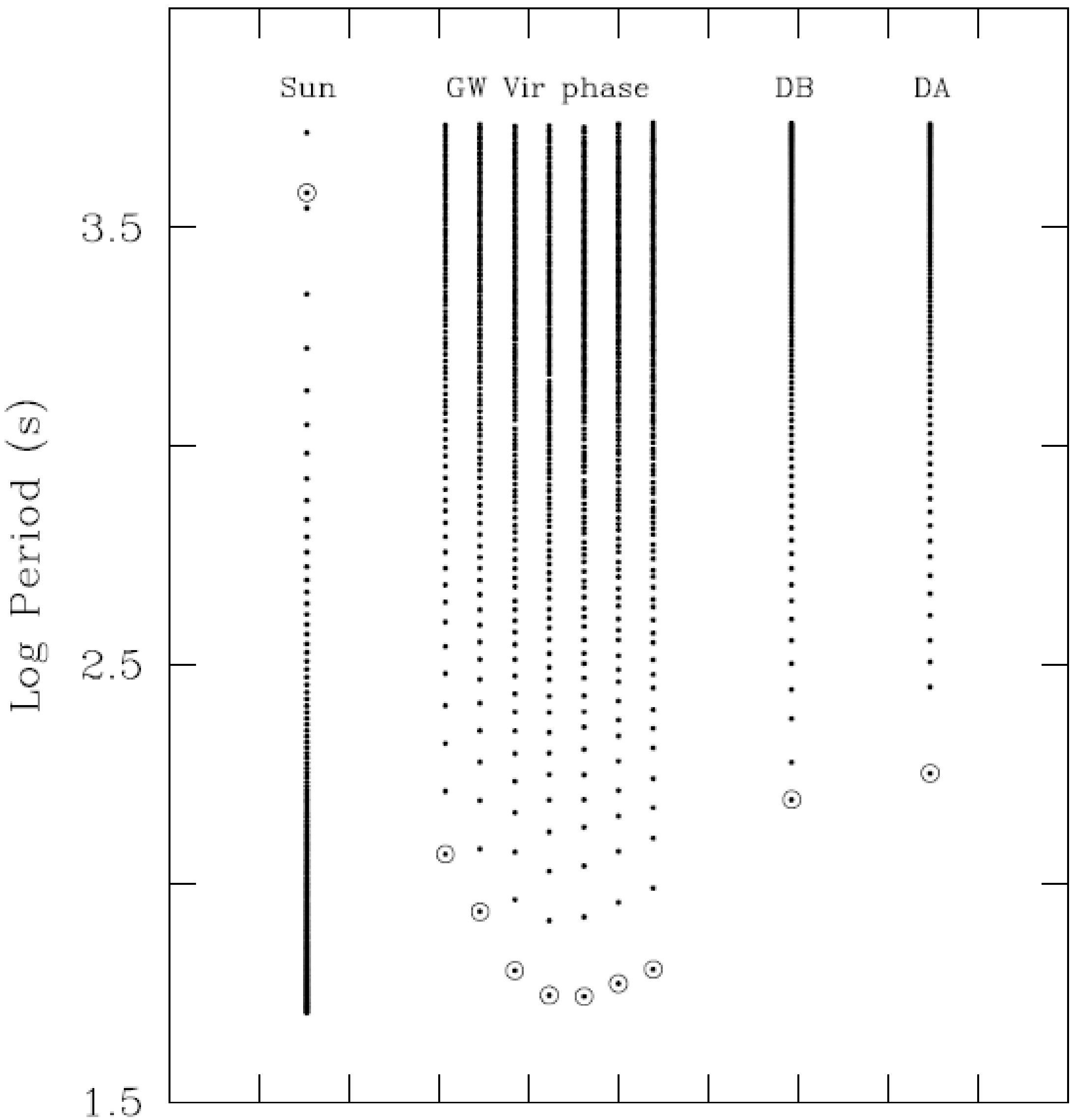
75-80 % - post-AGB with thin hydrogen envelope

~20% - post-AGB without H (born-again scenario)

2% - post-EHB, sdB



Fontaine & Brassard, 2008

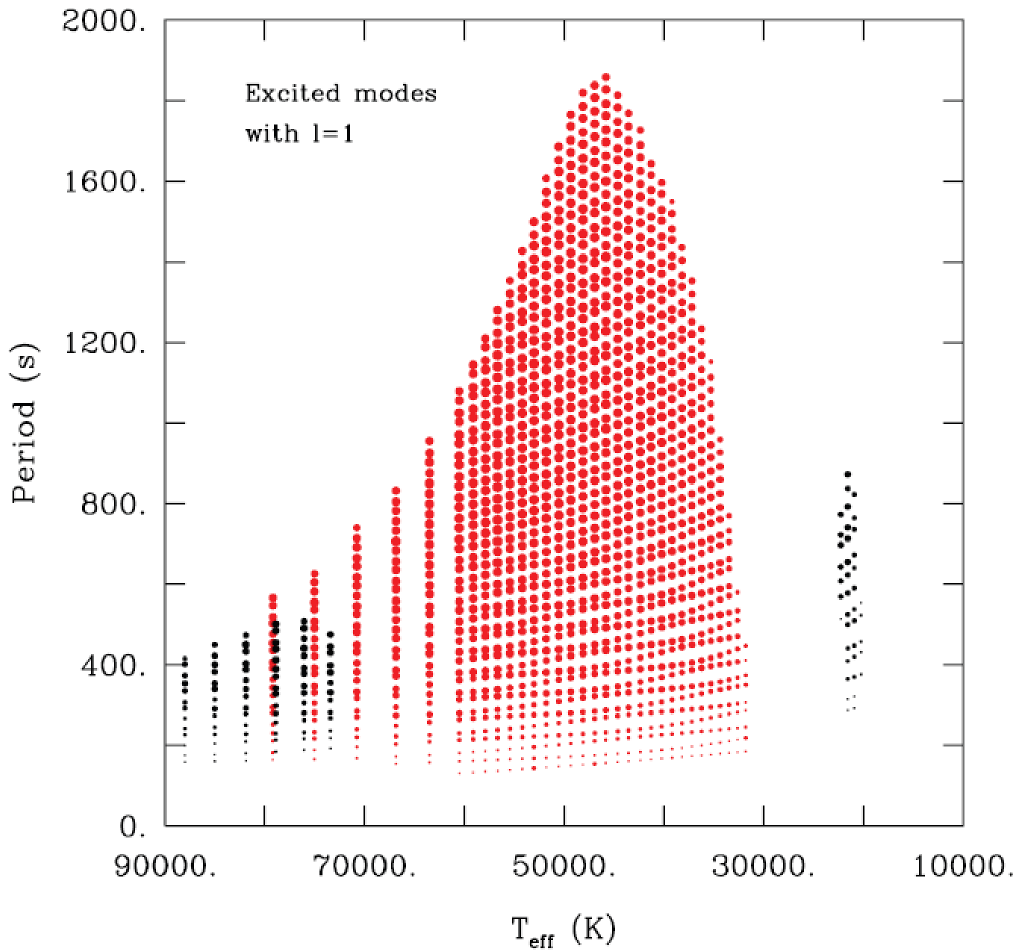


Fontaine & Brassard, 2008

Periods of unstable dipole modes in two post–PG 1159 evolutionary models:

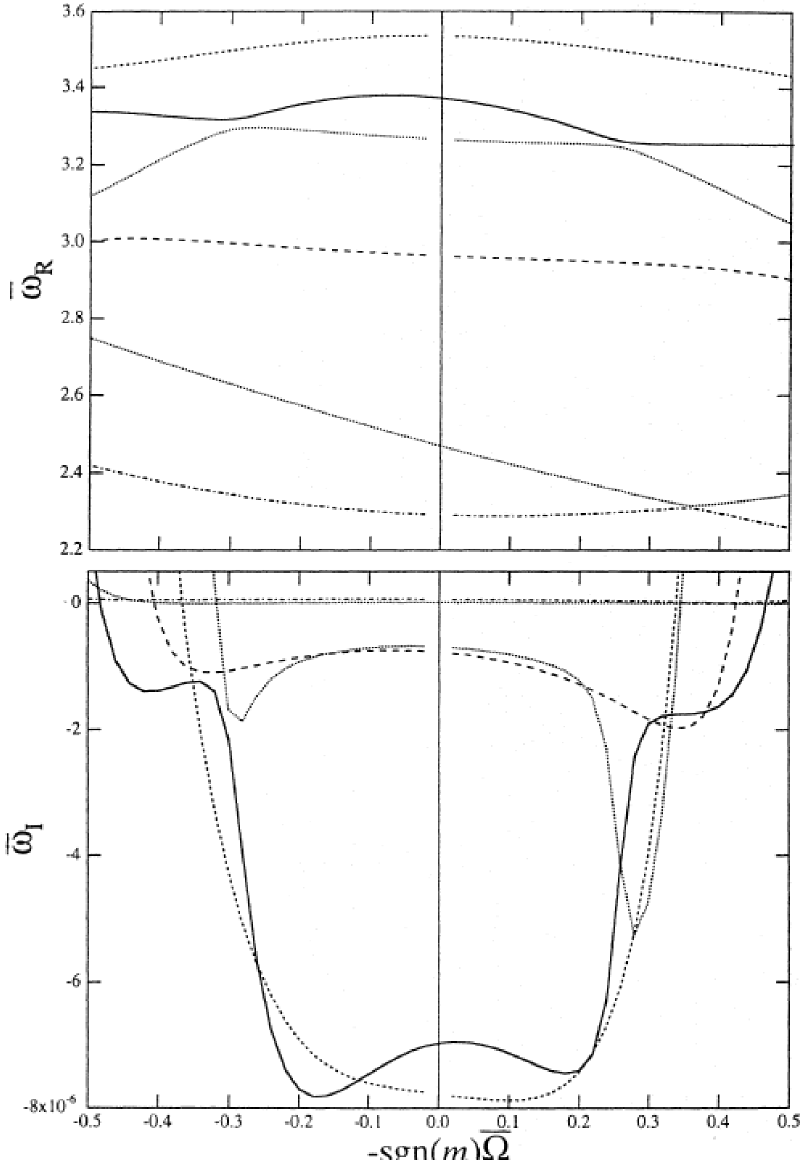
red – *M*=0.6 $M_\odot$, envelope *X(He)*=0.38, *X(C)*=0.40, *X(O)*=0.20, *Z*=0.02

black- diffusion and mass loss included



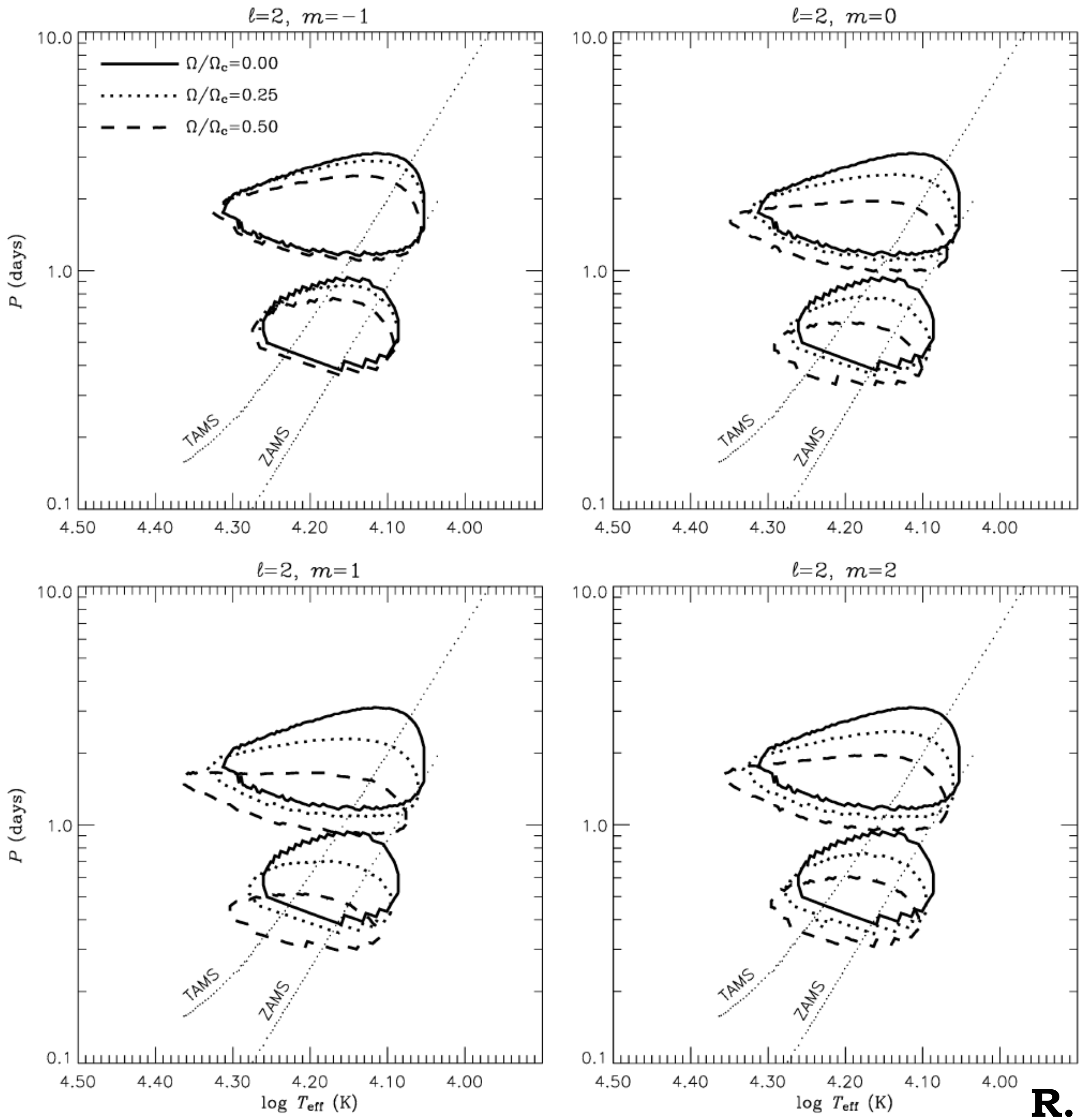
Fontaine & Brassard, 2008

Effects of rotation on frequencies of p-modes with |m|=1 for the 10 $M_\odot$ star (MS)



U. Lee & I. Baraffe 1995

Effect of the Coriolis force on the instability domains of SPB stars



R. Townsend 2005

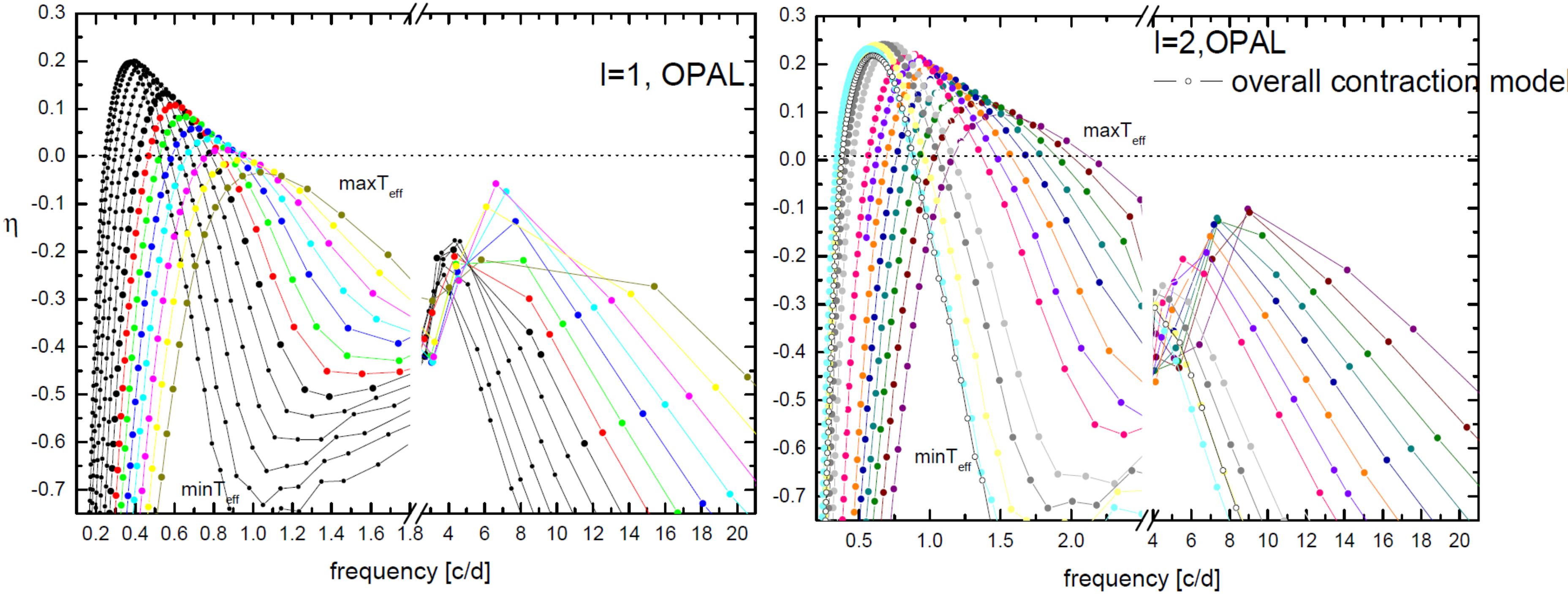
Tempo zmian okresów jest bezpośrednim pomiarem czasu chłodzenia, który zależy od składu chemicznego zdegenerowanego jądra. Jest to bezpośredni test przewidywań teorii ewolucji.

Wyznaczenie wieku białych karłów wzdłuż ciągu chłodzenia jest metodą pomiaru wieku dysku galaktycznego w okolicach Słońca.

Co możemy otrzymać z asterosejsmologii białych karłów ?

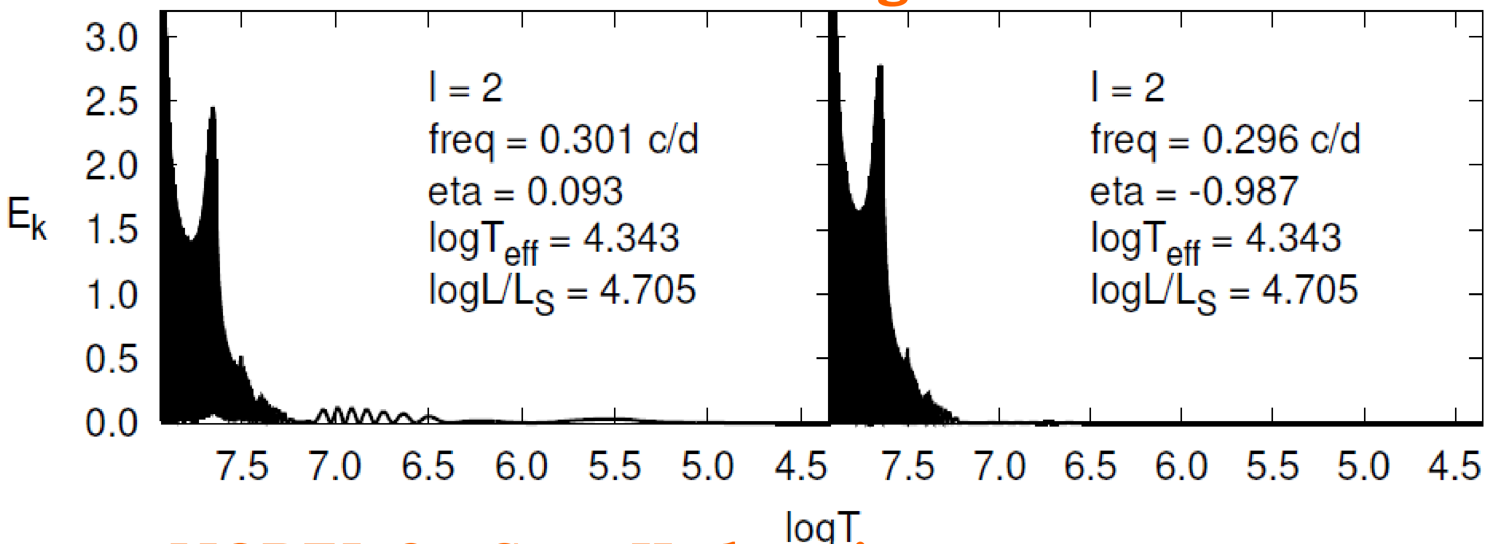
- *Całkowita masa z odstępów w okresach (reżim asymp.)*
- *Masa warstw zewnętrznych z odchyłek rozkładu okresów od regularnego, diagram ΔP vs. P*
- *Jasność gwiazdowa*
- *Okres rotacji z rozszczepienia modów*
- *Pole magnetyczne z rozszczepienia magnetycznego Pole magnetyczne rozszczepia mody na l+1 składowych, a przesunięcie w częstotliwościach jest proporcjonalne do m^2*
- *Ewolucyjną skalę czasową tempo zmian okresów → czas chłodzenia*

5 $M_\odot$ OPAL

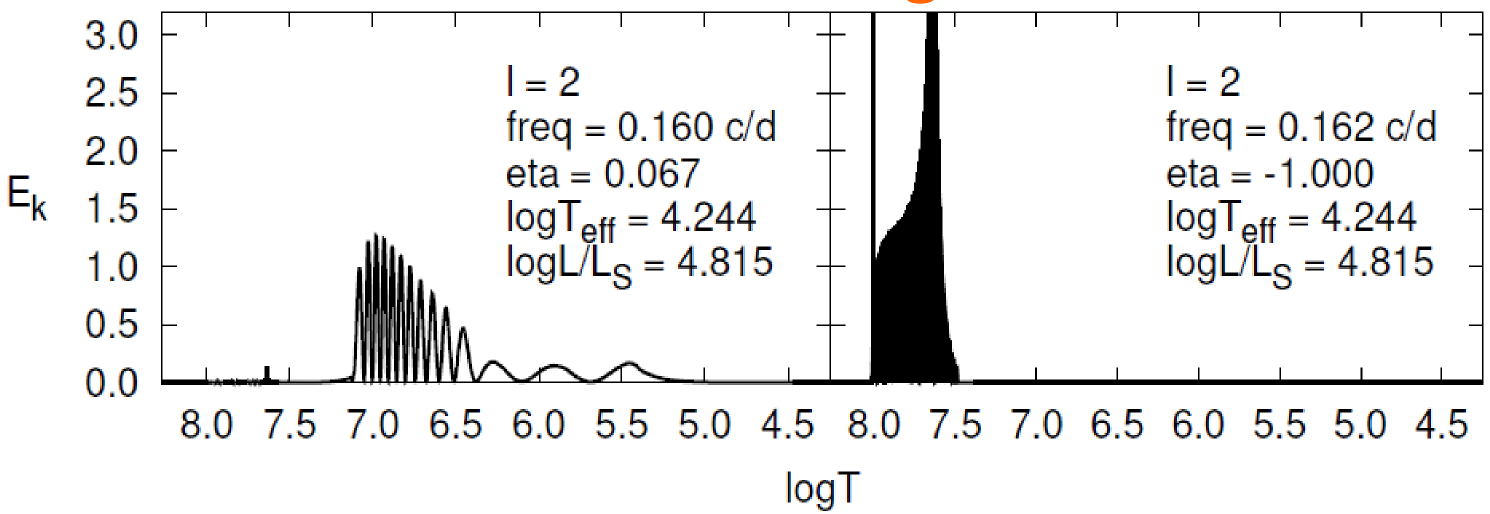


l=1, OPAL
maxT_eff
minT_eff
η
frequency [c/d]
l=2,OPAL
overall contraction model
maxT_eff
minT_eff
frequency [c/d]

MODEL 1 - H shell burning



MODEL 2 - Core He burning



Ostrowski & Daszynska-D, 2014