Driving mechanism and energetic aspects in γ Doradus stars

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Driving mechanism and energetic aspects in γ Doradus stars

Excitation

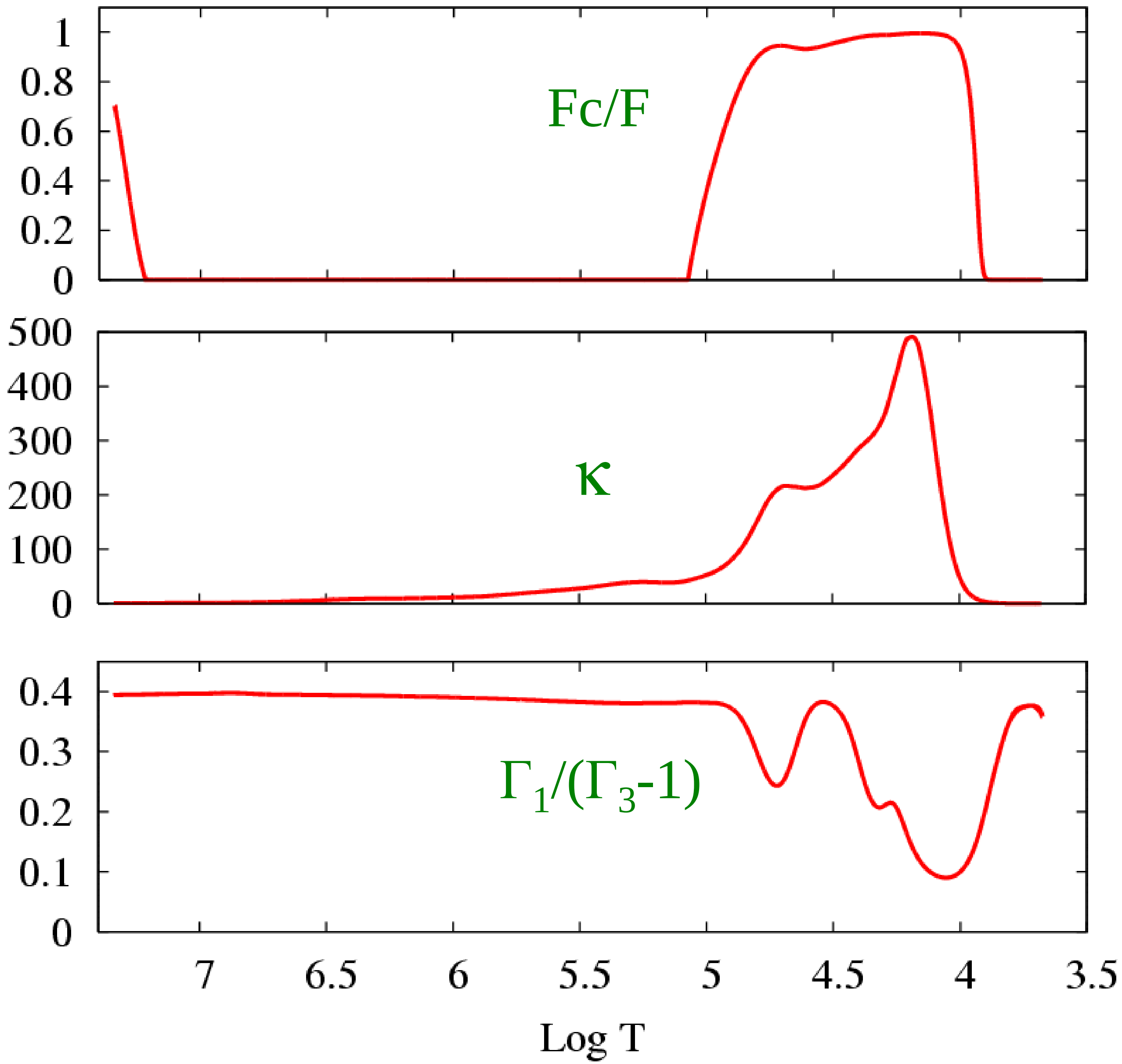
Amplitude and phases

Mode identification

Internal physics: Convection and partial ionization zones

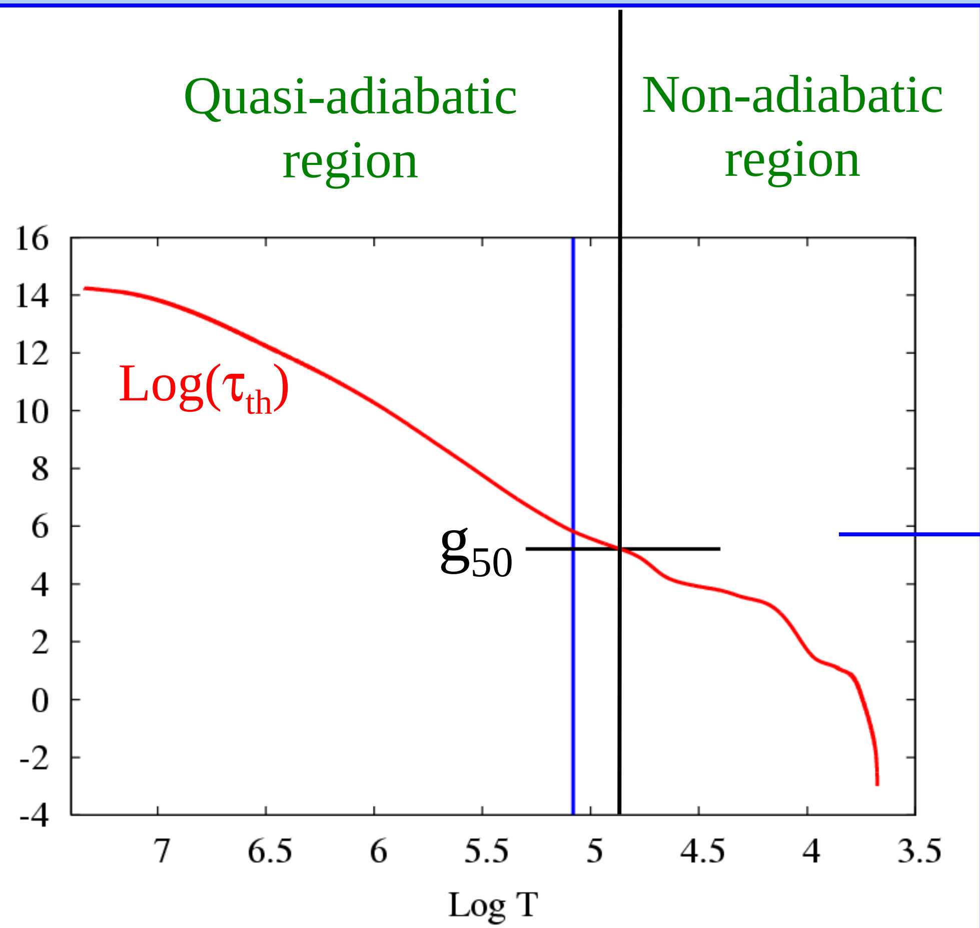
- 1 convective core
- 1 convective envelope

He an H partial ionization zones are inside the convective envelope



γ Doradus stars — Driving mechanism

Main driving occurs in the transition region where the thermal relaxation time is of the same order as the pulsation periods



For a solar calibrated mixing-length, the transition region for the g-modes is near the convective envelope bottom.

$\delta S \neq 0$

Coupling between

- the dynamical equations and
- the thermal equations

γ Doradus

Driving mechanism

Flux blocking at the base of the convective envelope

→ Motor thermodynamical cycle

$$\delta r(r,\theta,\phi,t) = \delta r(r)\, Y_l^m(\theta,\phi)\, e^{\sigma_i t}\, e^{i \sigma_r t}$$

$$\sigma_i = \frac{-1}{2\sigma_r^2} \frac{\int_0^M \frac{\delta T}{T} \frac{d\,\delta L}{d m}\, d m}{\int_0^M \delta r^2\, d m}$$

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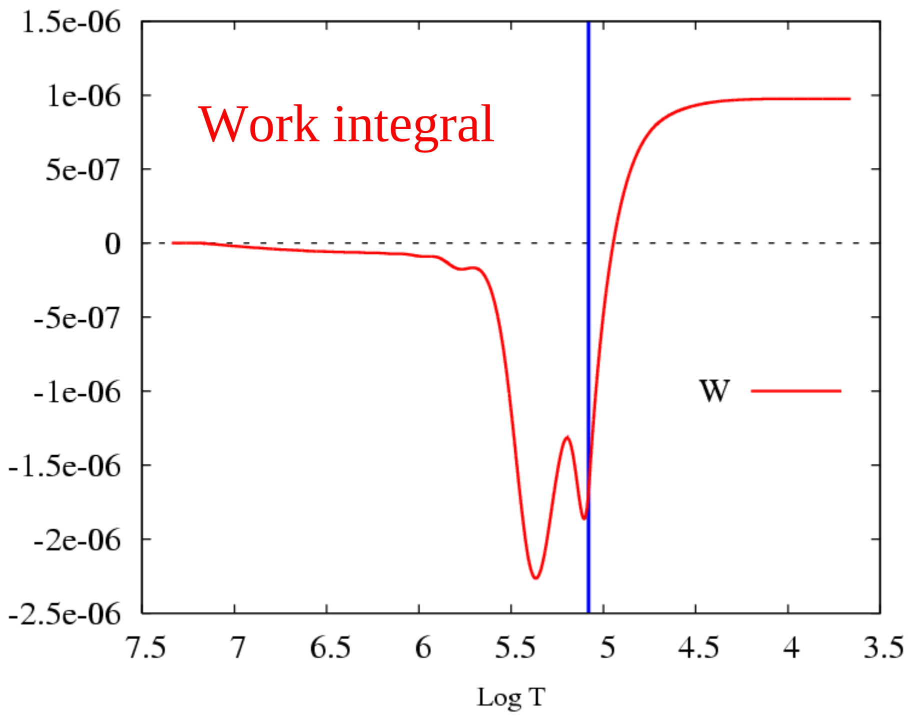
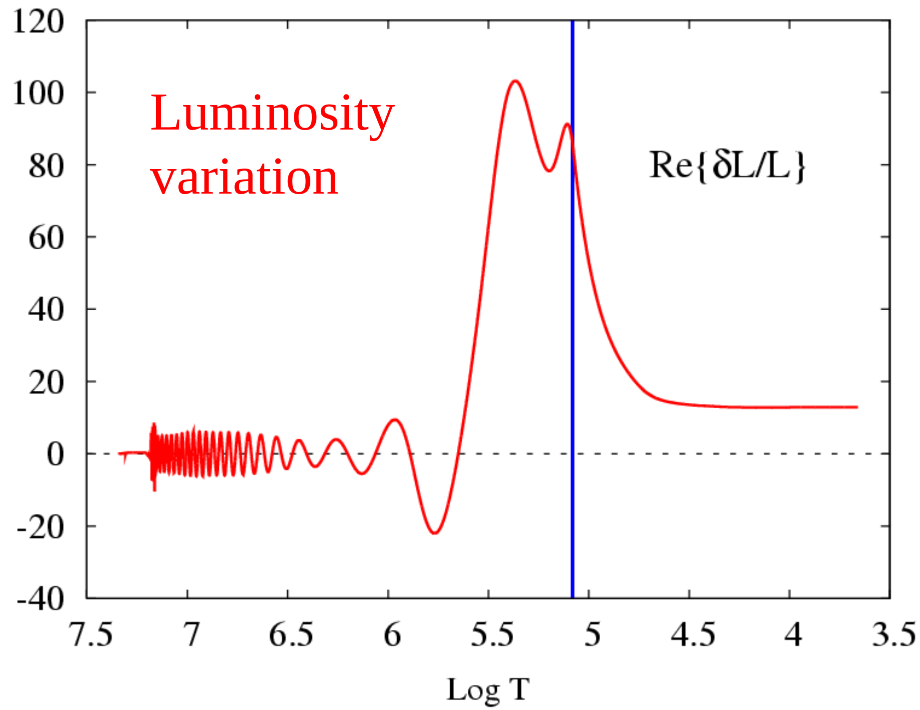
Driving mechanism

Flux blocking at the base of the convective envelope

→ Motor thermodynamical cycle





$M = 1.6\,M_0$, T_{eff} = 7000 K , $\alpha = 2$, Mode ℓ=1, g_{50}

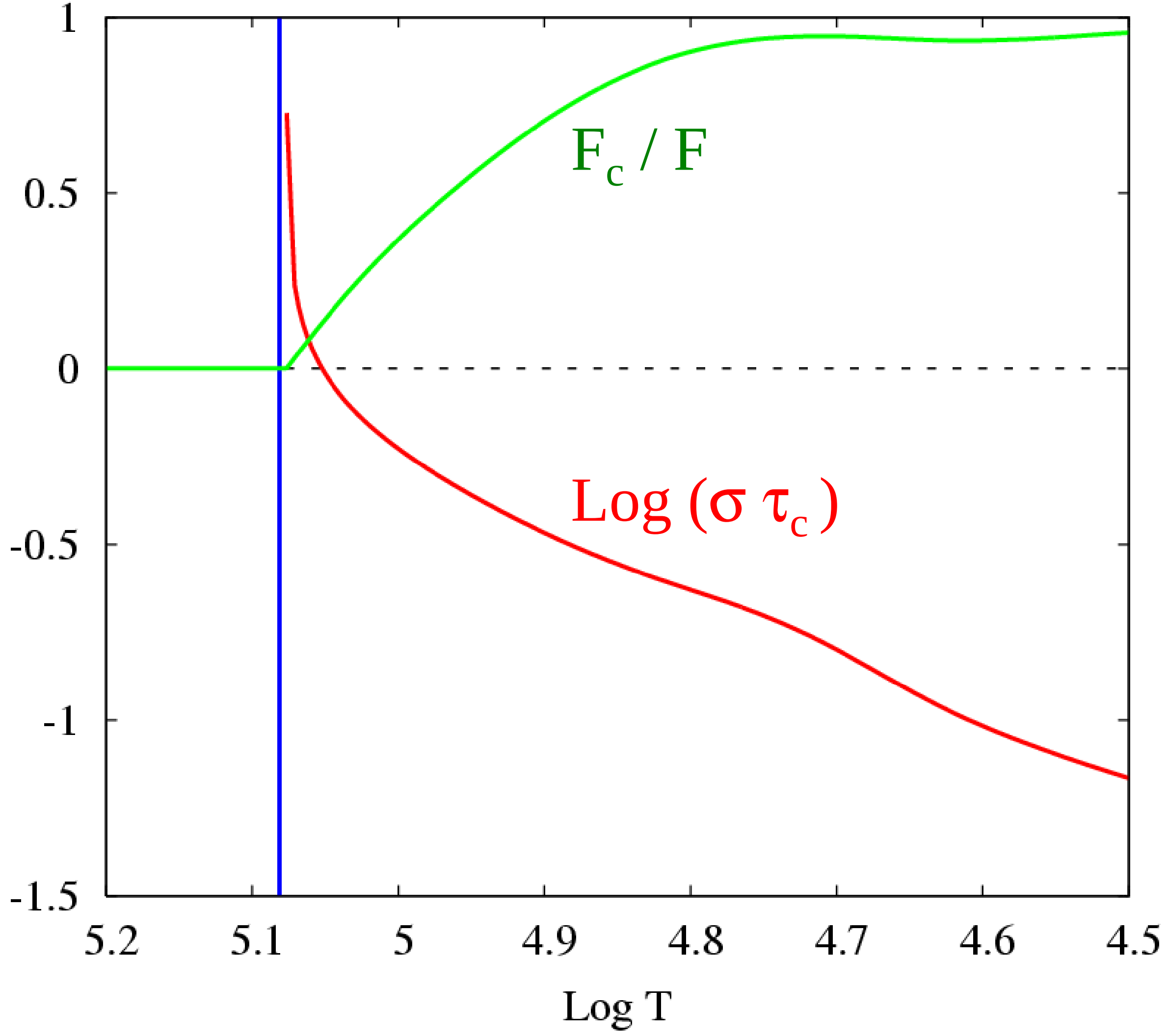
γ Doradus

Driving mechanism

$M = 1.6\ M_0$
$T_{eff} = 7000$ K
$\alpha = 2$
Mode ℓ=1, g_{50}

Role of time-dependent convection

τ_c : Life-time of convective elements
σ : Angular frequency



Convection – pulsation interaction: Work integral

Radiative luminosity

Convective luminosity

$$
\begin{aligned}
W_{\mathrm{tot}} &= -\int_0^m \Im\left\{\frac{\delta\rho^*}{\rho}\frac{\delta p}{\rho}\right\}\mathrm{d}m \\
&= -\int_0^m (\Gamma_3-1)\,\Re\left\{\frac{1}{\sigma}\frac{\delta\rho^*}{\rho}\frac{\mathrm{d}\,(\delta L_{\mathrm{R}}+\delta L_{\mathrm{c}})}{\mathrm{d}m}\right\}\mathrm{d}m \\
&\quad -\int_0^m \Im\left\{\frac{\delta\rho^*}{\rho}\frac{\delta p_{\mathrm{t}}}{\rho}\right\}\mathrm{d}m \\
&\quad +\int_0^m \frac{3}{2}(\Gamma_3-1)\Im\left\{\frac{\delta\rho^*}{\rho}\frac{\delta p_{\mathrm{t}}}{\rho}\right\}\mathrm{d}m
\end{aligned}
$$

Turbulent pressure

Turbulent kinetic energy dissipation

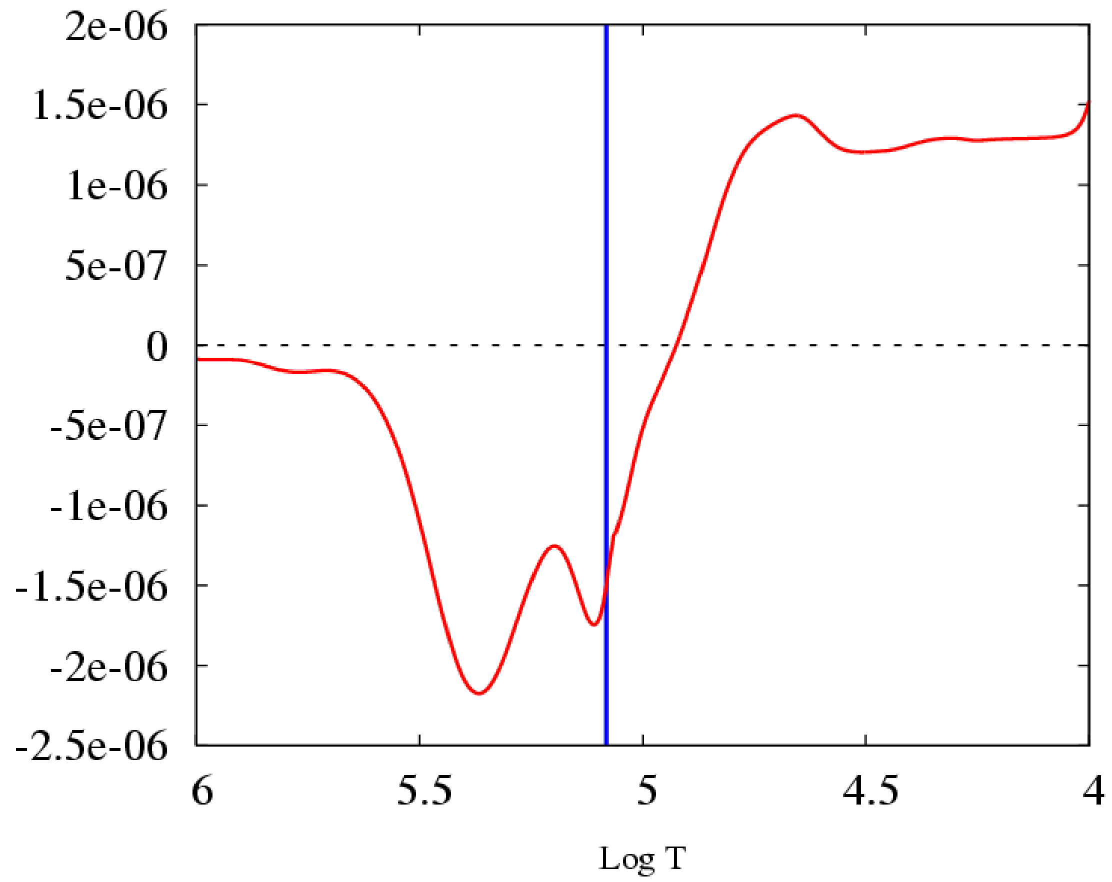
γ Doradus

Driving mechanism

$M = 1.6\ M_0$
$T_{eff} = 7000$ K
$\alpha = 2$
Mode $\ell=1$, g_{50}

W_{FRr}: Radial radiative flux term

$$W_{tot} = -\int_0^m \Im\left\{\frac{\delta\rho^*}{\rho}\frac{\delta p}{\rho}\right\}\mathrm{d}m$$
$$= -\int_0^m (\Gamma_3-1)\,\Re\left\{\frac{1}{\sigma}\frac{\delta\rho^*}{\rho}\frac{\mathrm{d}\,(\delta L_R+\delta L_c)}{\mathrm{d}m}\right\}\mathrm{d}m$$
$$-\int_0^m \Im\left\{\frac{\delta\rho^*}{\rho}\frac{\delta p_t}{\rho}\right\}\mathrm{d}m$$
$$+\int_0^m \frac{3}{2}(\Gamma_3-1)\Im\left\{\frac{\delta\rho^*}{\rho}\frac{\delta p_t}{\rho}\right\}\mathrm{d}m$$



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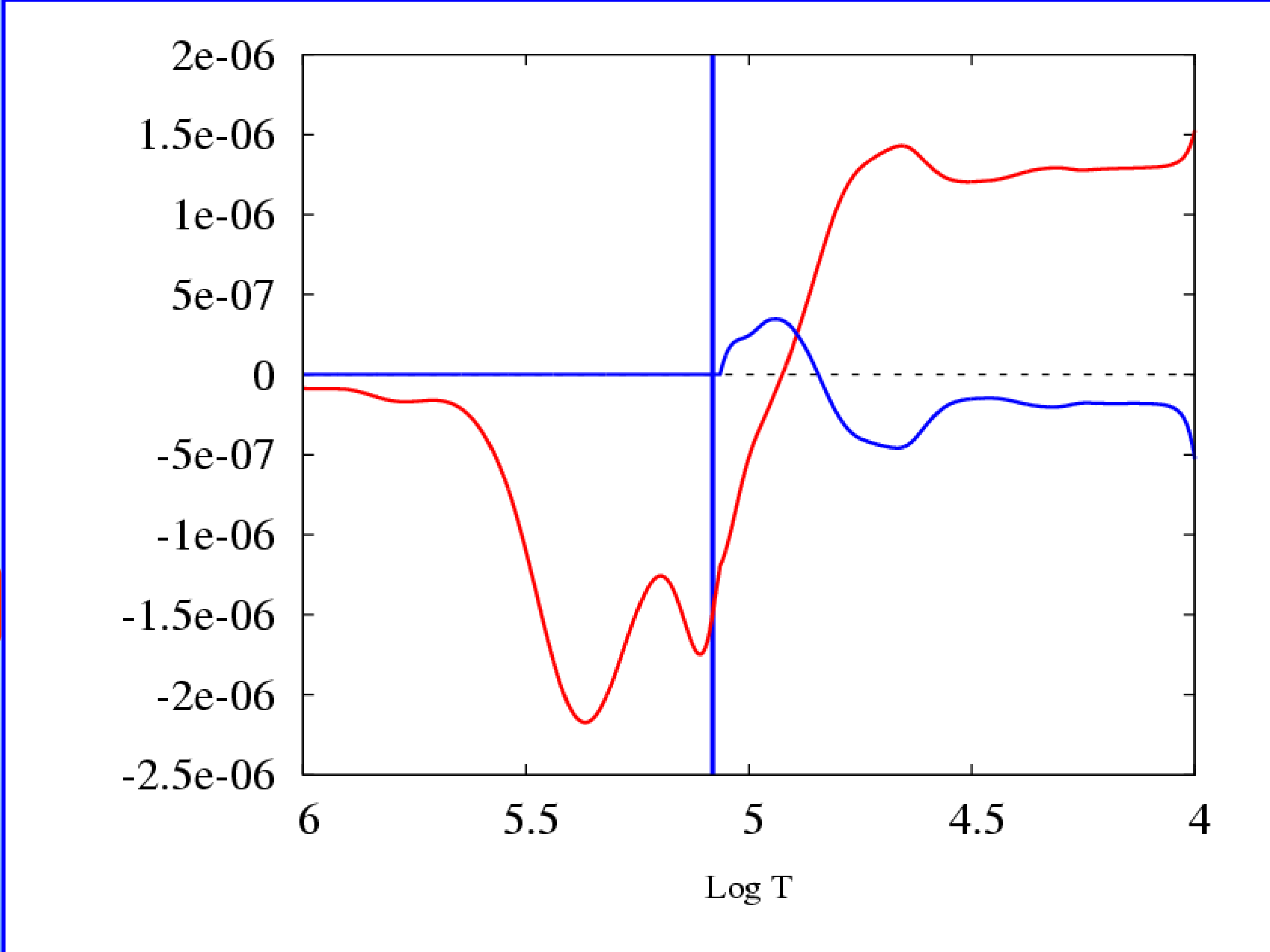
Driving mechanism

$M = 1.6\ M_0$
$T_{eff} = 7000$ K
$\alpha = 2$
Mode ℓ=1, g_{50}

W_{FRr}: Radial radiative flux term

W_{Fcr}: Radial convective flux term

$$
\begin{aligned}
W_{\rm tot} &= -\int_0^m \Im\left\{\frac{\delta\rho^*}{\rho}\frac{\delta p}{\rho}\right\}\mathrm{d}m \\
&= -\int_0^m (\Gamma_3 - 1)\,\Re\left\{\frac{1}{\sigma}\frac{\delta\rho^*}{\rho}\frac{\mathrm{d}\ (\delta L_{\rm R} + \delta L_{\rm c})}{\mathrm{d}m}\right\}\mathrm{d}m \\
&\quad -\int_0^m \Im\left\{\frac{\delta\rho^*}{\rho}\frac{\delta p_{\rm t}}{\rho}\right\}\mathrm{d}m \\
&\quad +\int_0^m \frac{3}{2}(\Gamma_3 - 1)\Im\left\{\frac{\delta\rho^*}{\rho}\frac{\delta p_{\rm t}}{\rho}\right\}\mathrm{d}m
\end{aligned}
$$



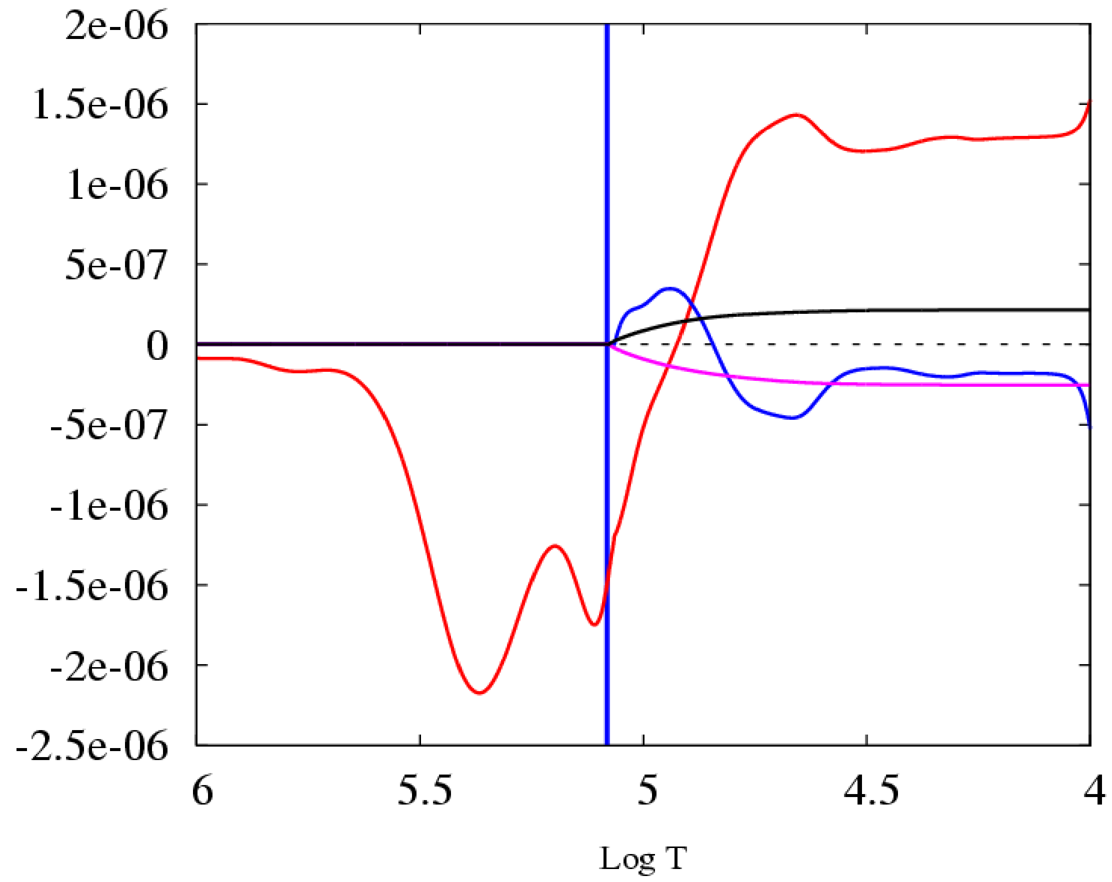
γ Doradus

Driving mechanism

$M = 1.6\ M_0$
$T_{eff} = 7000$ K
$\alpha = 2$
Mode ℓ=1, g_{50}

W_{FRr}: Radial radiative flux term
W_{Fcr}: Radial convective flux term
W_{pt}: Turbulent pressure
$W_{\varepsilon 2}$: Turbulent kinetic energy dissipation

$$\begin{aligned} W_{\rm tot} &= -\int_0^m \Im\left\{\frac{\delta\rho^*}{\rho}\frac{\delta p}{\rho}\right\} {\rm d}m \\ &= -\int_0^m (\Gamma_3-1)\,\Re\left\{\frac{1}{\sigma}\frac{\delta\rho^*}{\rho}\frac{{\rm d}\,(\delta L_{\rm R}+\delta L_{\rm c})}{{\rm d}m}\right\}{\rm d}m \\ &\quad -\int_0^m \Im\left\{\frac{\delta\rho^*}{\rho}\frac{\delta p_{\rm t}}{\rho}\right\}{\rm d}m \\ &\quad +\int_0^m \frac{3}{2}(\Gamma_3-1)\Im\left\{\frac{\delta\rho^*}{\rho}\frac{\delta p_{\rm t}}{\rho}\right\}{\rm d}m \end{aligned}$$



γ Doradus

Driving mechanism

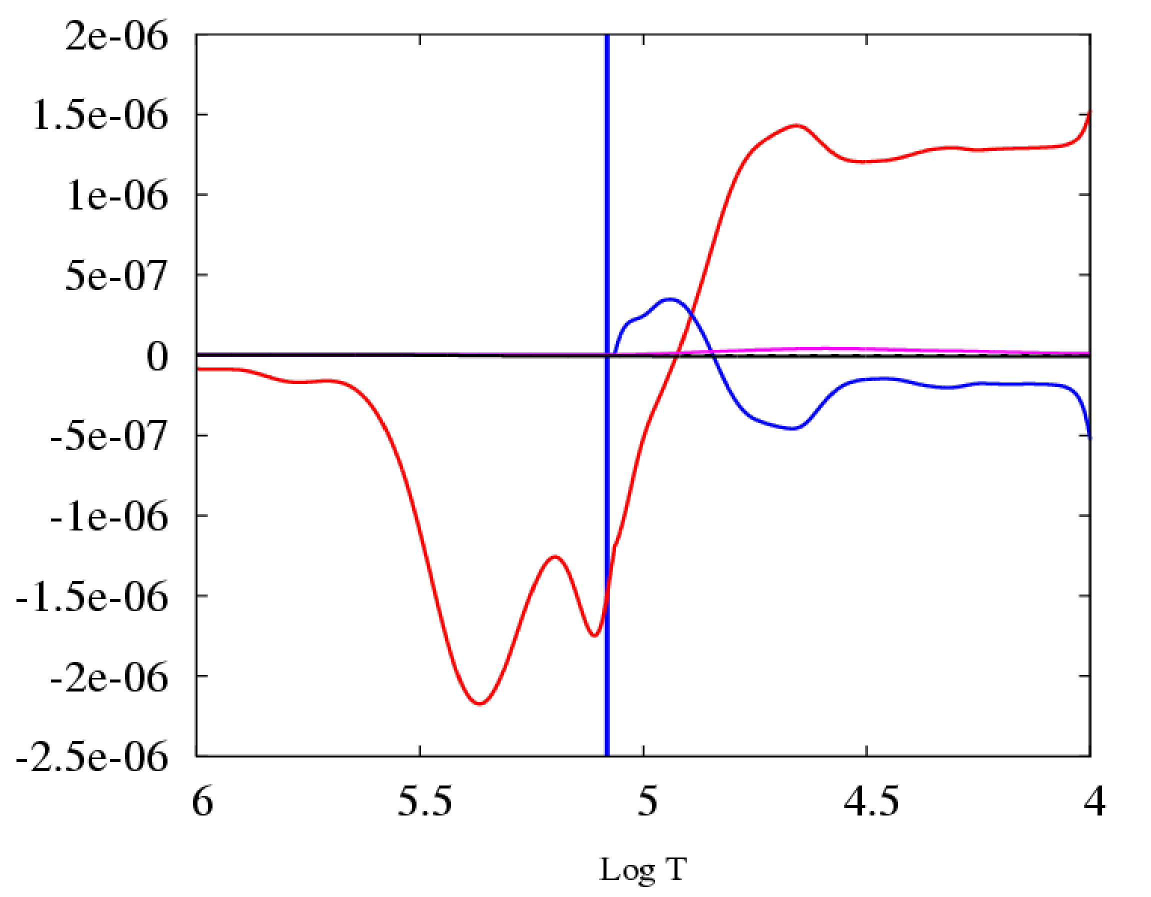
$M = 1.6\ M_0$
$T_{eff} = 7000$ K
$\alpha = 2$
Mode $\ell=1$, g_{50}

W_{FRr}: Radial radiative flux term

W_{Fcr}: Radial convective flux term

W_{Fh}: Transversal convective and radiative flux

$$
\begin{aligned}
W_{\rm tot} &= -\int_0^m \Im\left\{\frac{\delta\rho^*}{\rho}\frac{\delta p}{\rho}\right\} {\rm d}m \\
&= -\int_0^m (\Gamma_3 - 1)\,\Re\left\{\frac{1}{\sigma}\frac{\delta\rho^*}{\rho}\frac{{\rm d}\,(\delta L_{\rm R} + \delta L_{\rm c})}{{\rm d}m}\right\} {\rm d}m \\
&\quad -\int_0^m \Im\left\{\frac{\delta\rho^*}{\rho}\frac{\delta p_{\rm t}}{\rho}\right\} {\rm d}m \\
&\quad +\int_0^m \frac{3}{2}(\Gamma_3 - 1)\Im\left\{\frac{\delta\rho^*}{\rho}\frac{\delta p_{\rm t}}{\rho}\right\} {\rm d}m
\end{aligned}
$$



γ Doradus

Driving mechanism

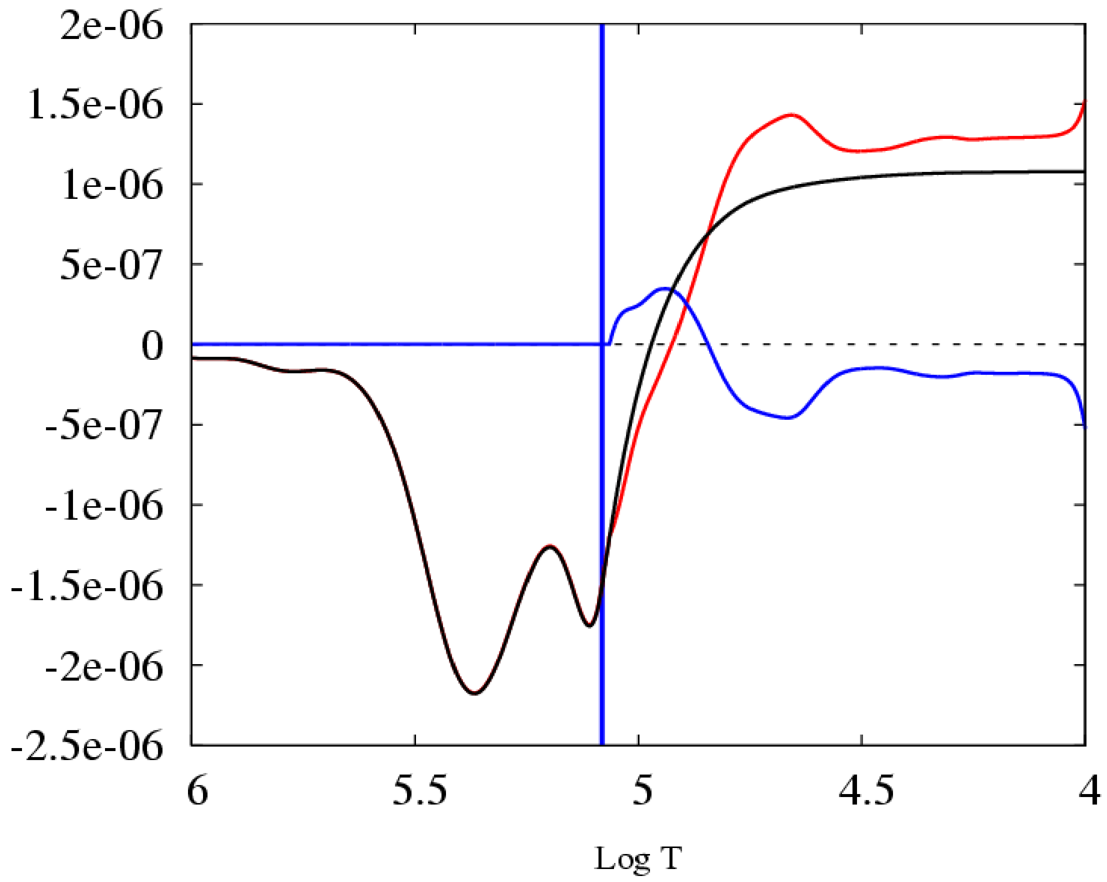
$M = 1.6\ M_0$
$T_{eff} = 7000$ K
$\alpha = 2$
Mode ℓ=1, g_{50}

W_{FRr}: Radial radiative flux term

W_{Fcr}: Radial convective flux term

W_{tot}: Total work

$$
\begin{aligned}
W_{\rm tot} &= -\int_0^m \Im\left\{\frac{\delta\rho^*}{\rho}\frac{\delta p}{\rho}\right\}\mathrm{d}m \\
&= -\int_0^m (\Gamma_3 - 1)\,\Re\left\{\frac{1}{\sigma}\frac{\delta\rho^*}{\rho}\frac{\mathrm{d}\,(\delta L_{\rm R} + \delta L_{\rm c})}{\mathrm{d}m}\right\}\mathrm{d}m \\
&\quad -\int_0^m \Im\left\{\frac{\delta\rho^*}{\rho}\frac{\delta p_{\rm t}}{\rho}\right\}\mathrm{d}m \\
&\quad +\int_0^m \frac{3}{2}(\Gamma_3 - 1)\Im\left\{\frac{\delta\rho^*}{\rho}\frac{\delta p_{\rm t}}{\rho}\right\}\mathrm{d}m
\end{aligned}
$$



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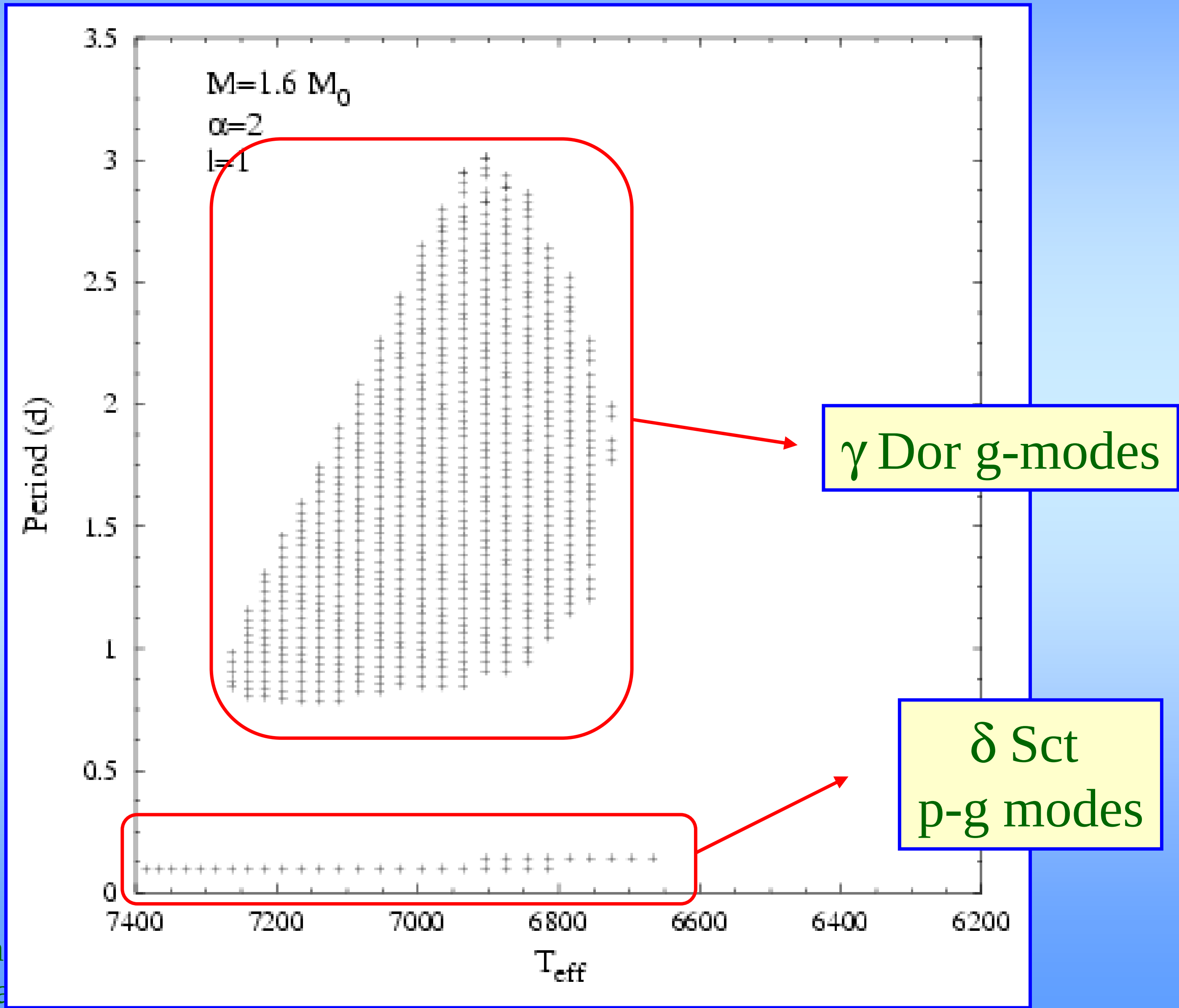
Unstable modes



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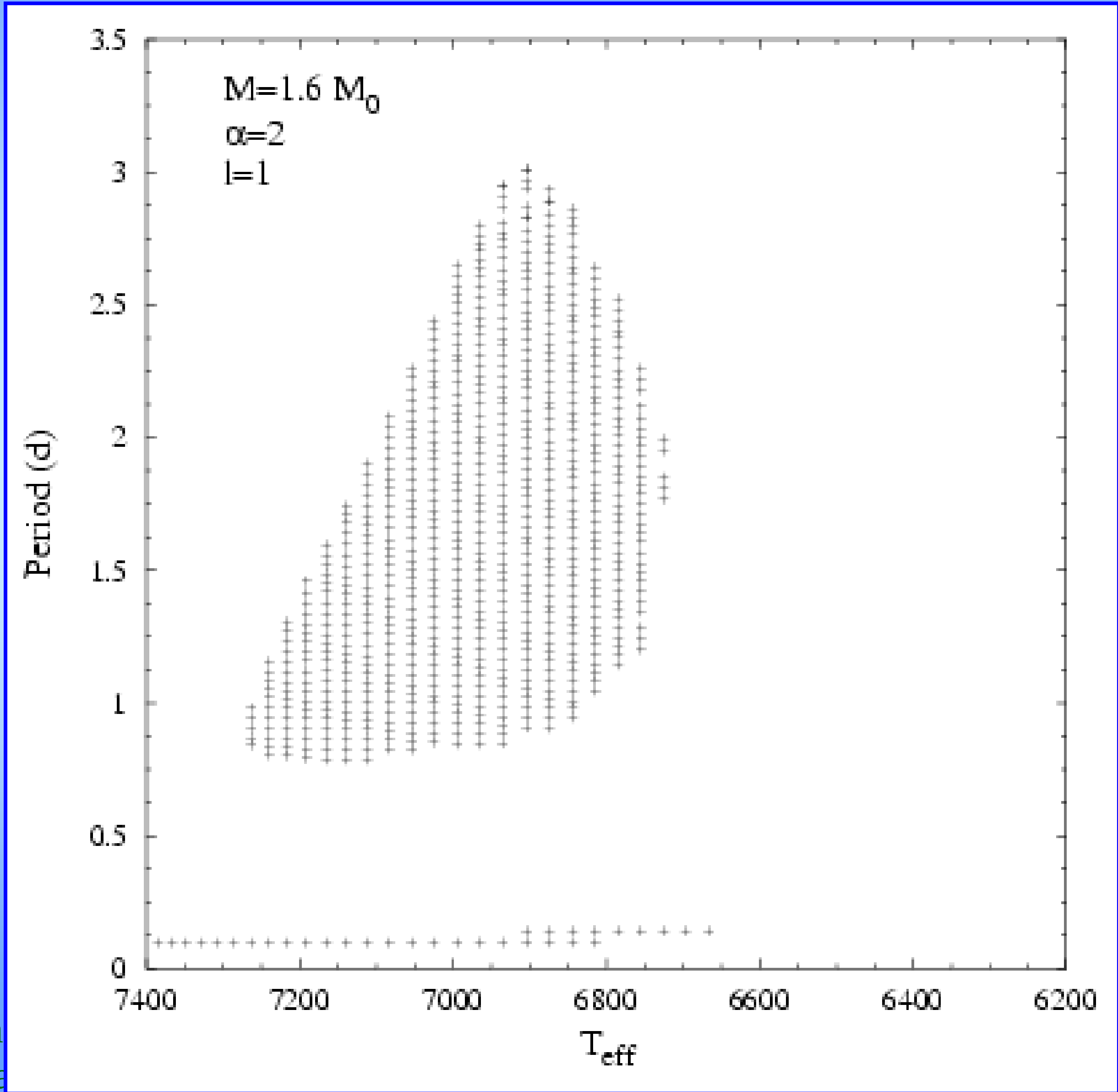
Unstable modes



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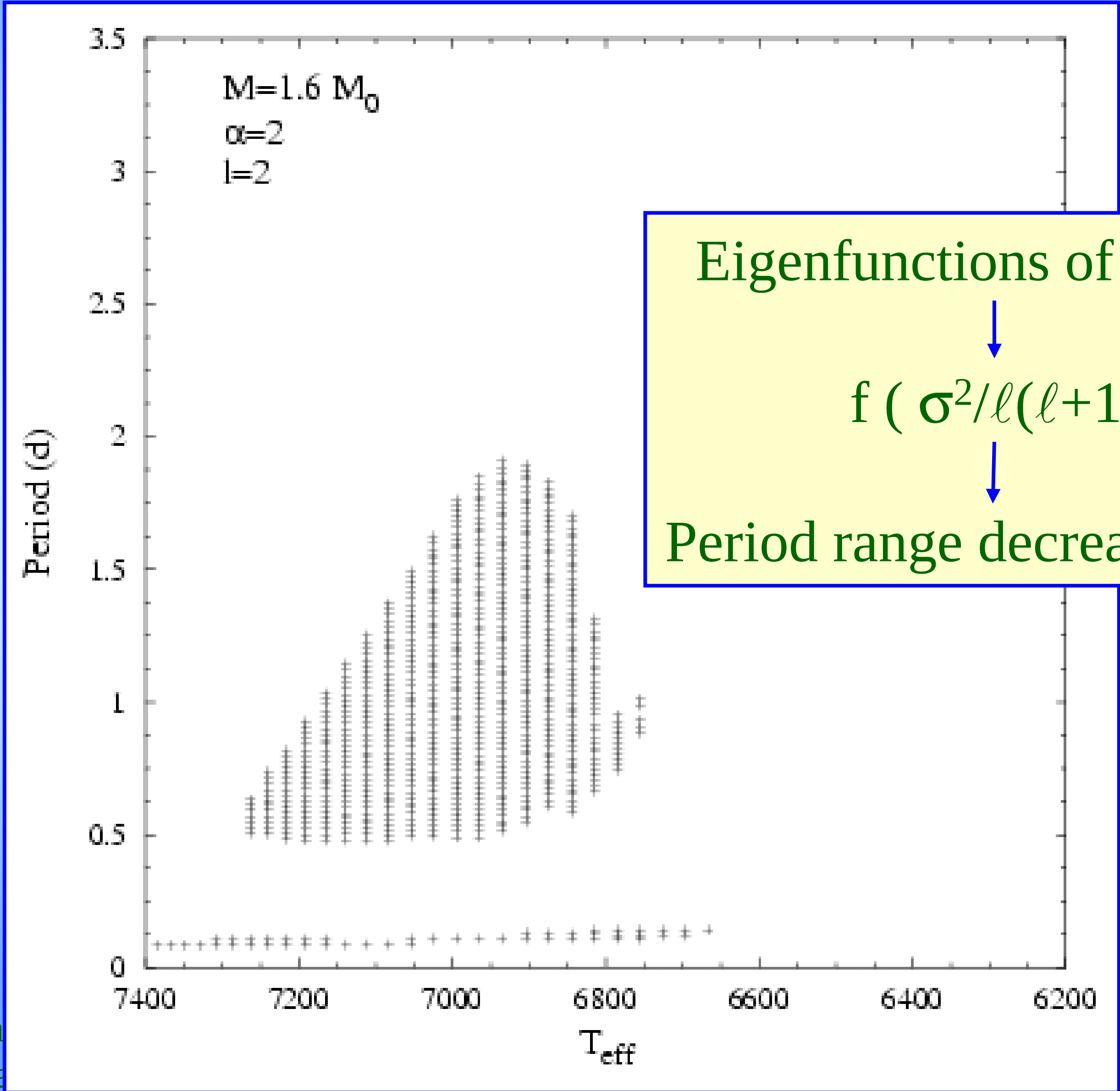
Unstable modes



Eigenfunctions of g-modes

↓

$f\ (\ \sigma^2/\ell(\ell+1)\ )$

↓

Period range decreases with ℓ

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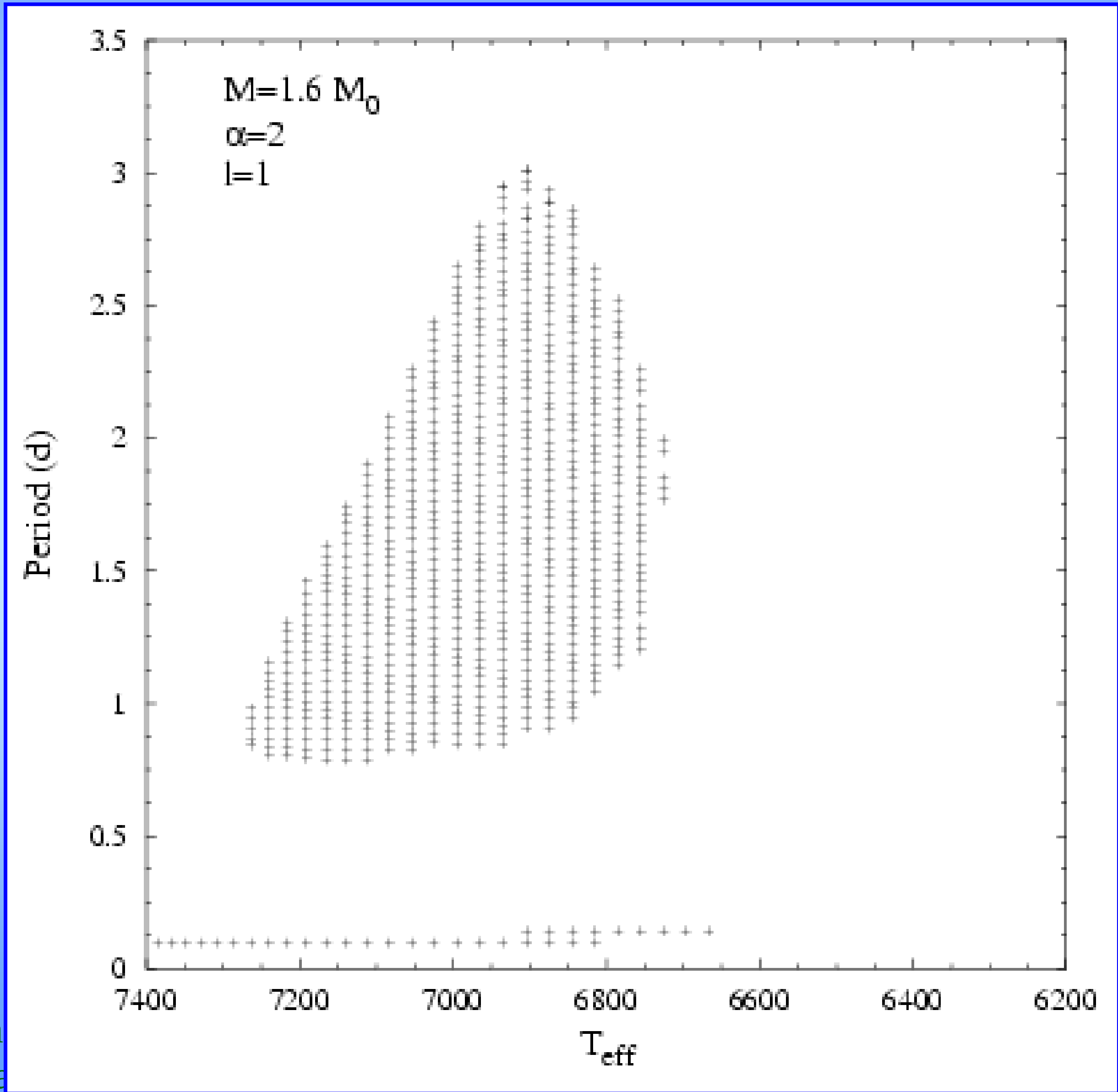
Unstable modes



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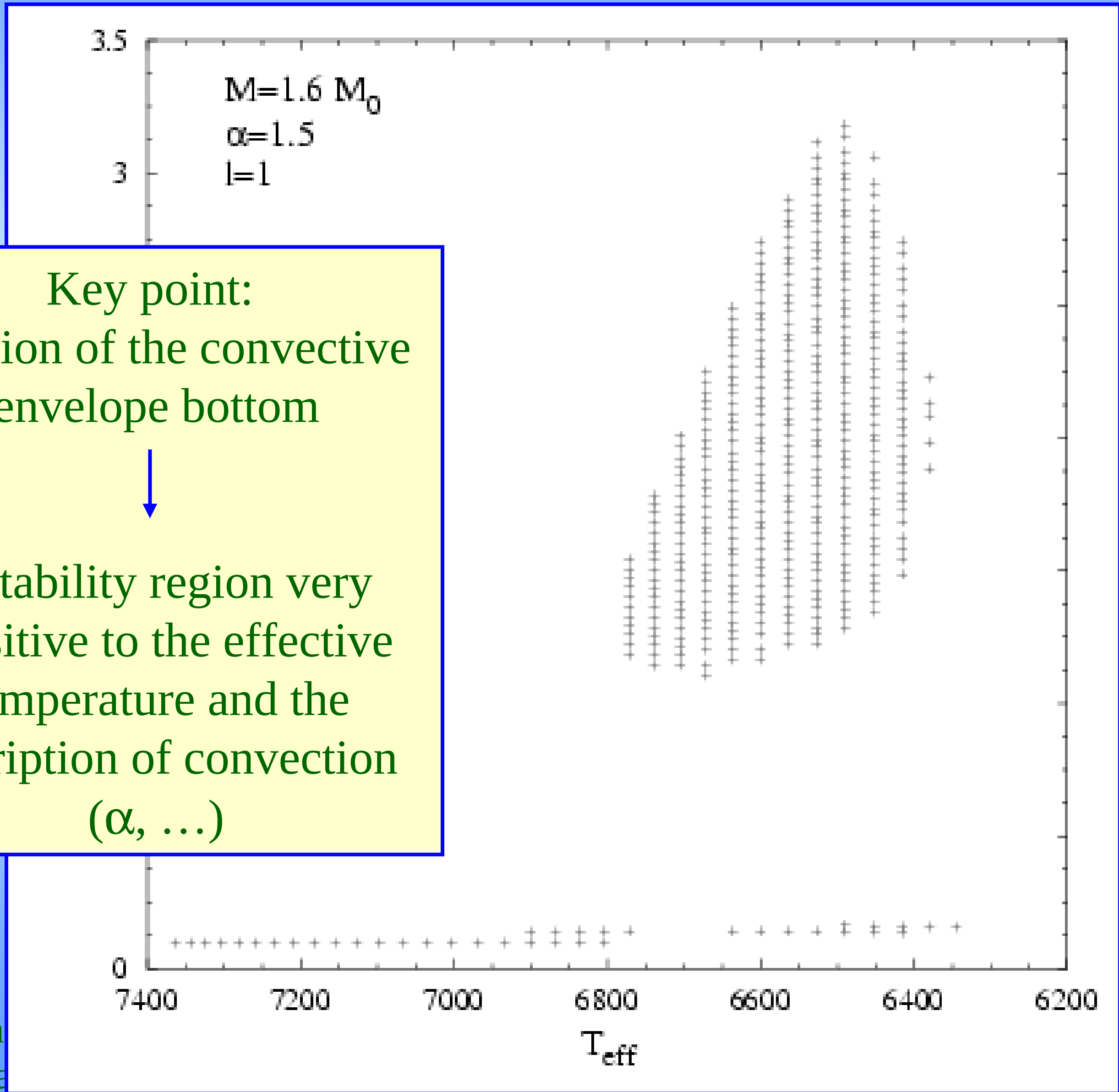
Unstable modes



Key point:
Location of the convective envelope bottom

↓

Instability region very sensitive to the effective temperature and the description of convection (α, …)

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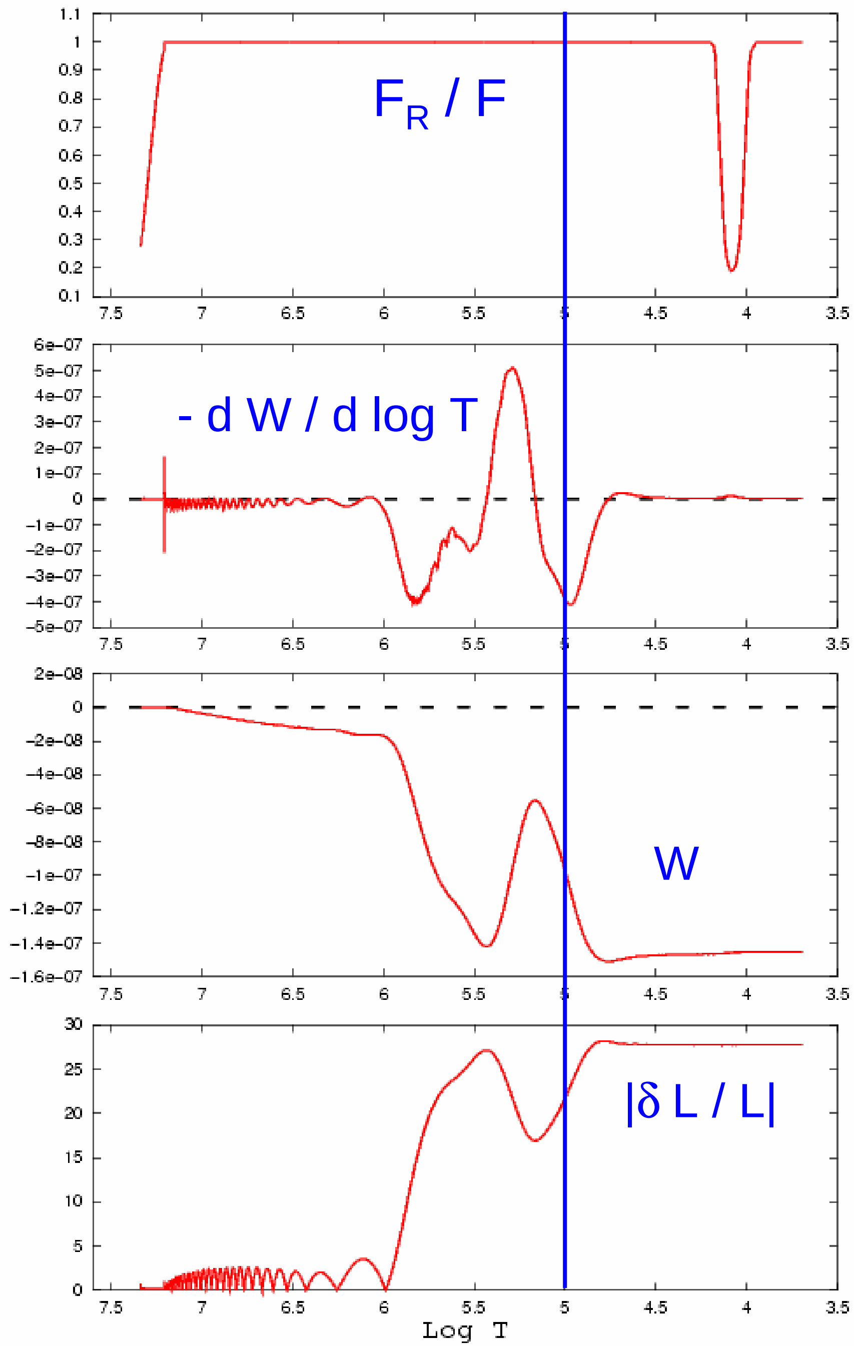
For hot or small α models:
very thin convective envelope

↓

the transition region is in the
radiative zone

↓

Small κ-driving (Fe, ~ SPBs)
compensated by
large radiative damping
below and above



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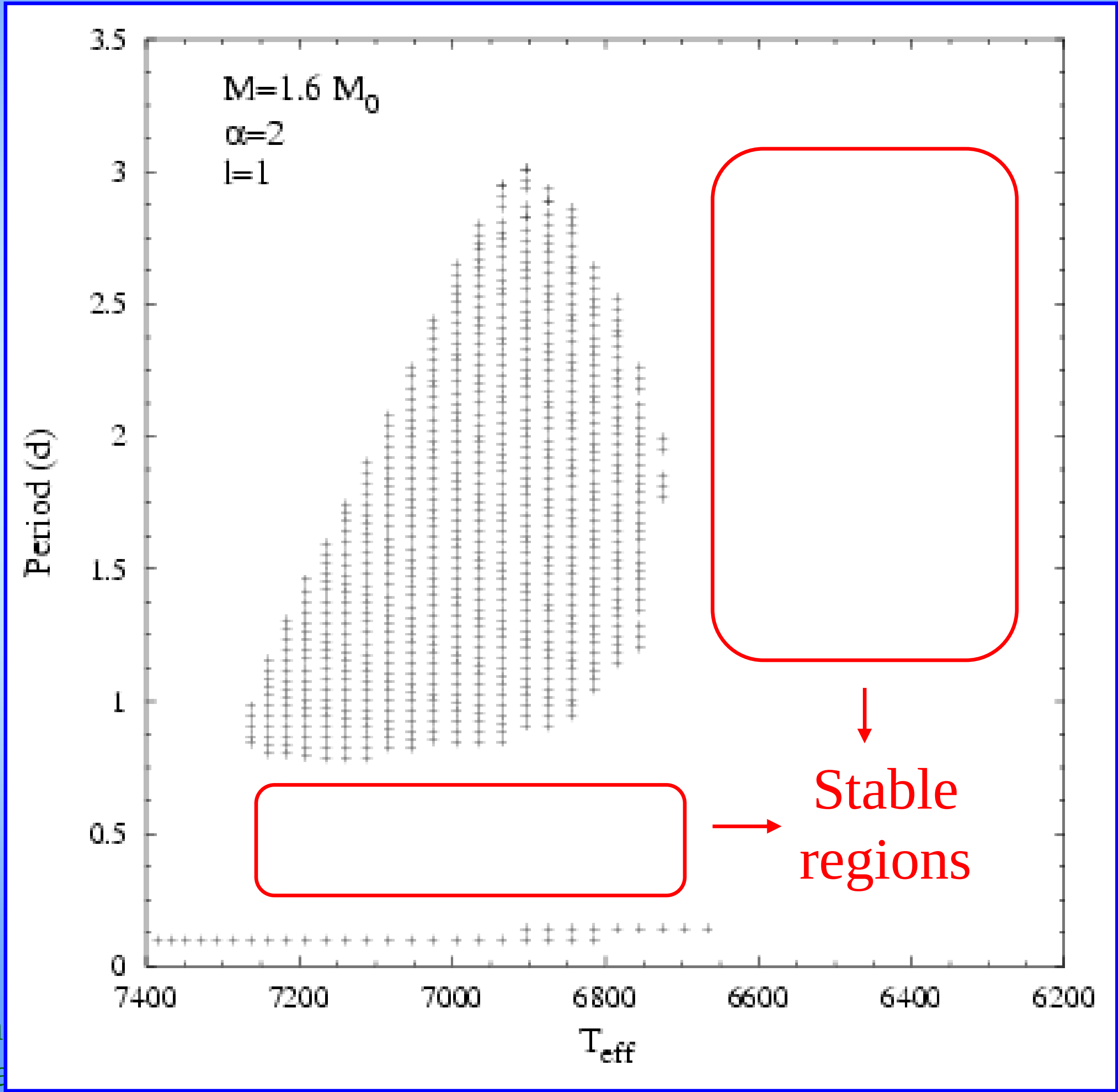
Stabilization mechanism



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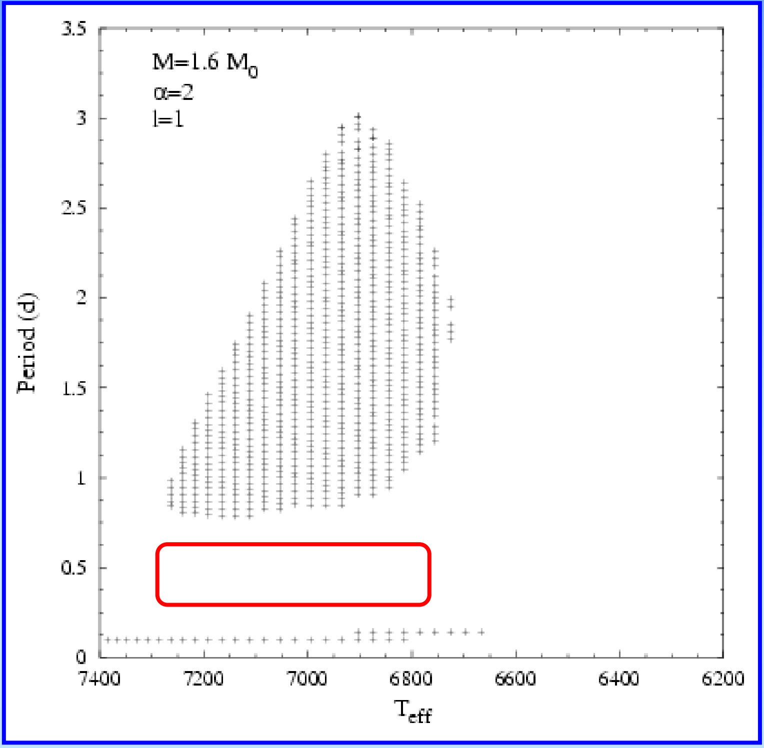
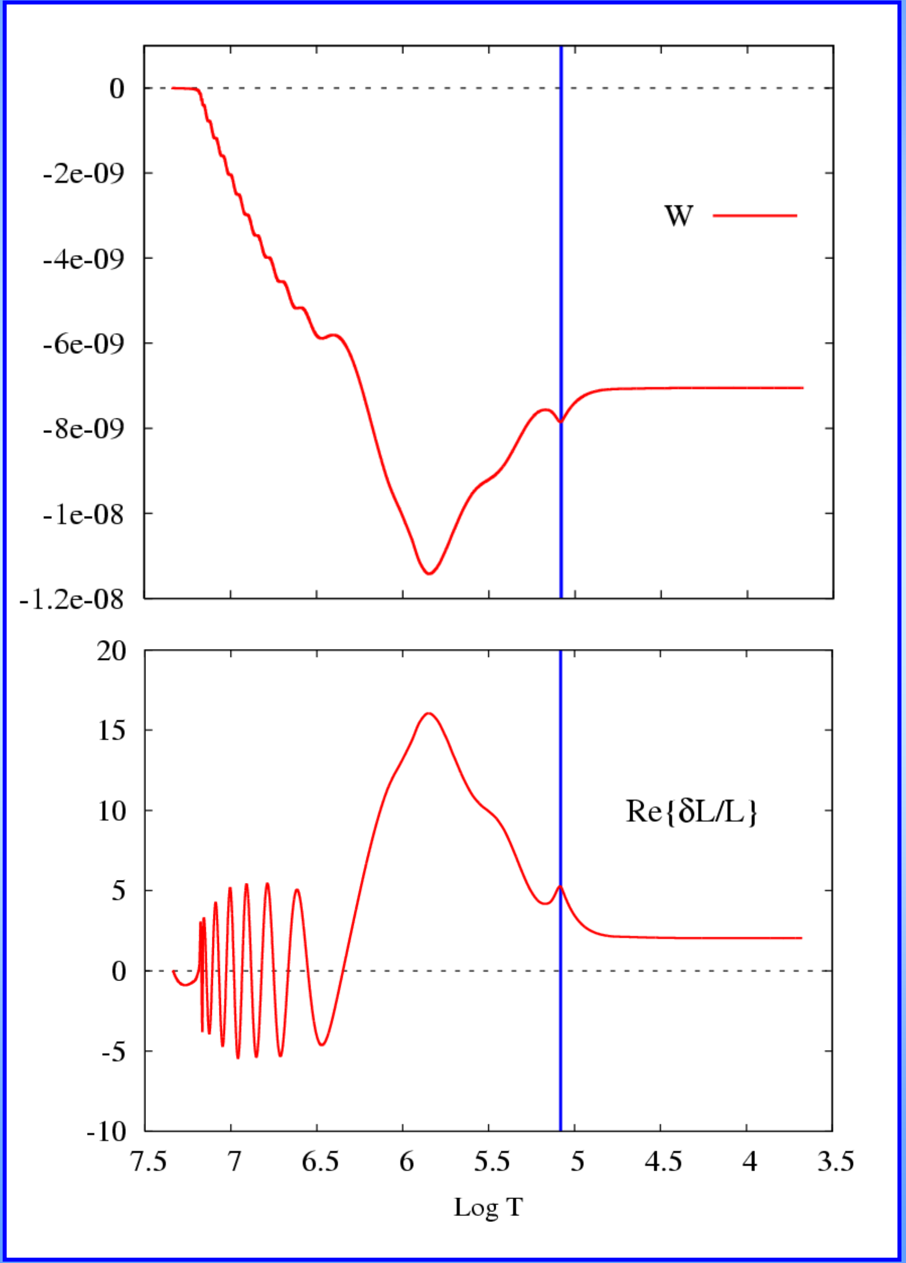
Stabilization mechanism





Radiative damping
in the g-modes cavity

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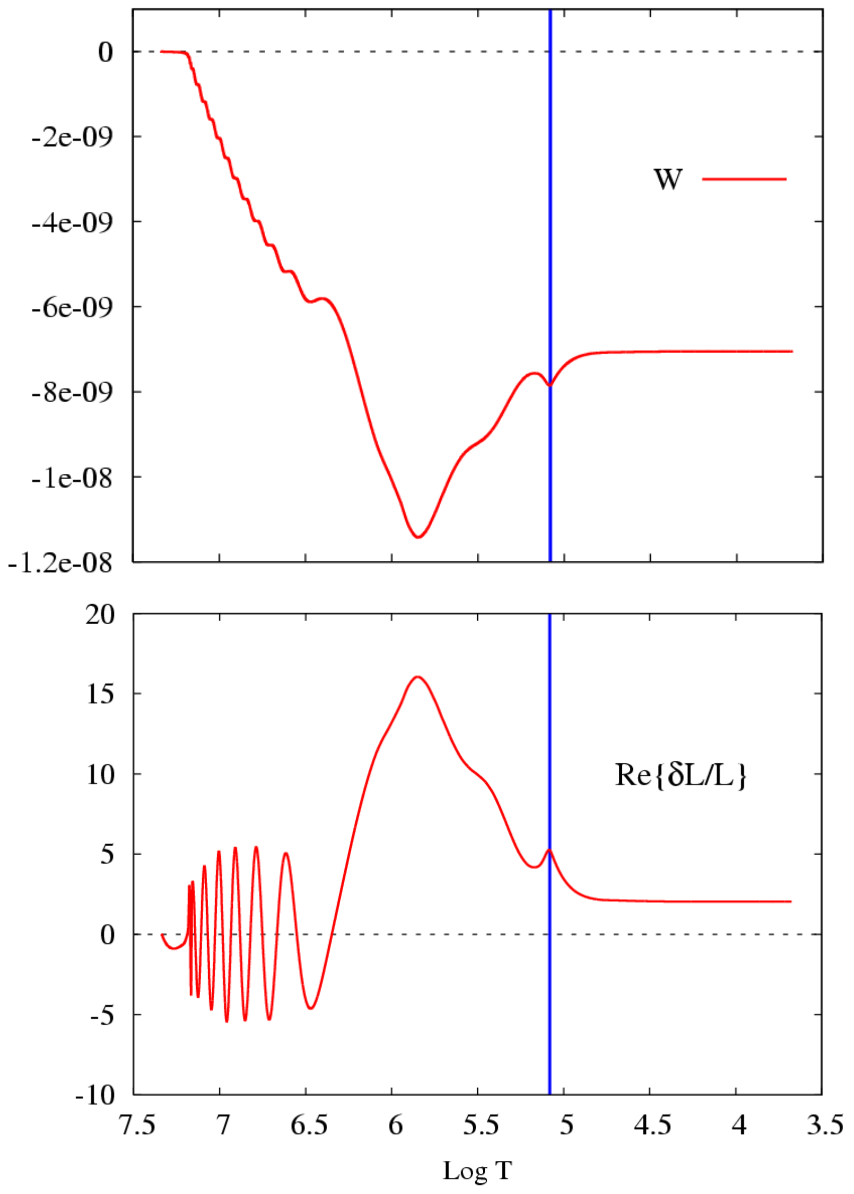
Stabilization mechanism

Radiative damping in the g-modes cavity

$$\sigma_i = \frac{-1}{2\sigma_r^2} \frac{\int_0^M \frac{\delta T}{T} \frac{d\,\delta L}{d\,m}\, d\,m}{\int_0^M \delta r^2\, d\,m}$$

$$\frac{\delta L}{L} = 2\frac{\delta r}{r} + 3\frac{\delta T}{T} - \frac{\delta\kappa}{\kappa} - \frac{\delta\rho}{\rho} + \boxed{\frac{d\,\delta T}{d\,T}} - \frac{d\,\delta r}{d\,r}$$

$$\sigma_i = \frac{\int_0^R \frac{-L}{d\ln T/dr} \frac{\delta T}{T} \frac{d^2(\delta T/T)}{d\,r^2}\, d\,r}{2\sigma_r^2 \int_0^R \delta r^2\, d\,m}$$



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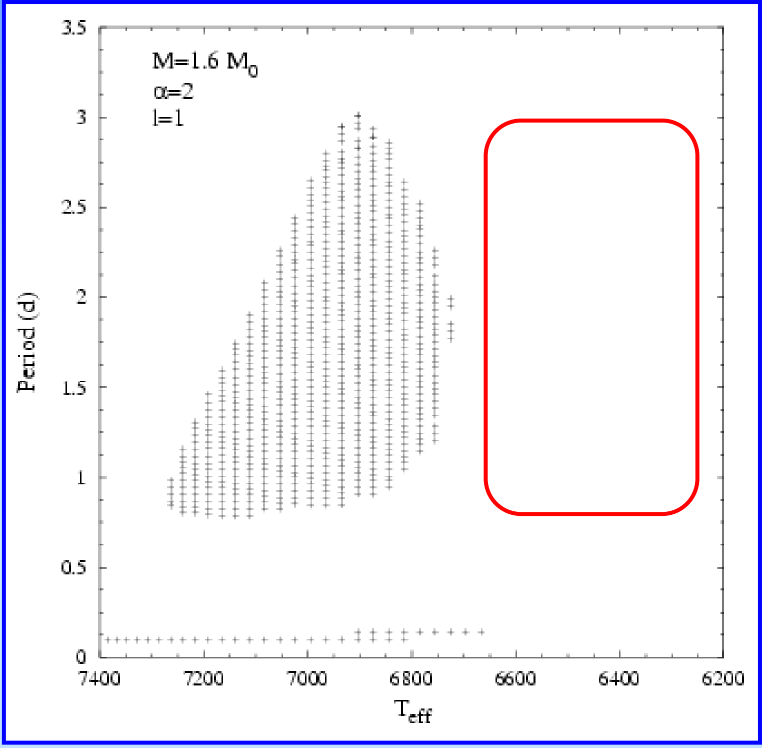
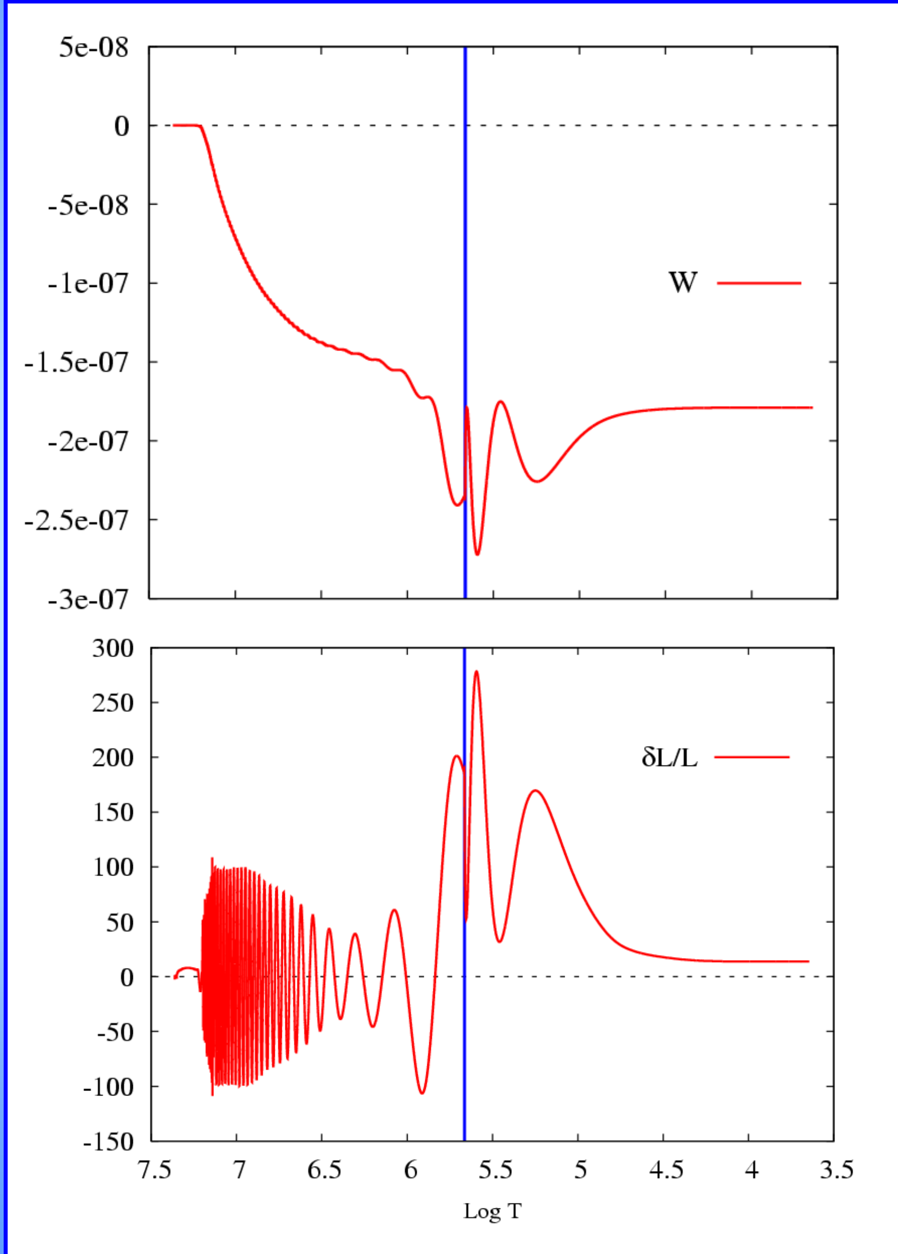
Stabilization mechanism





Radiative damping in the g-modes cavity

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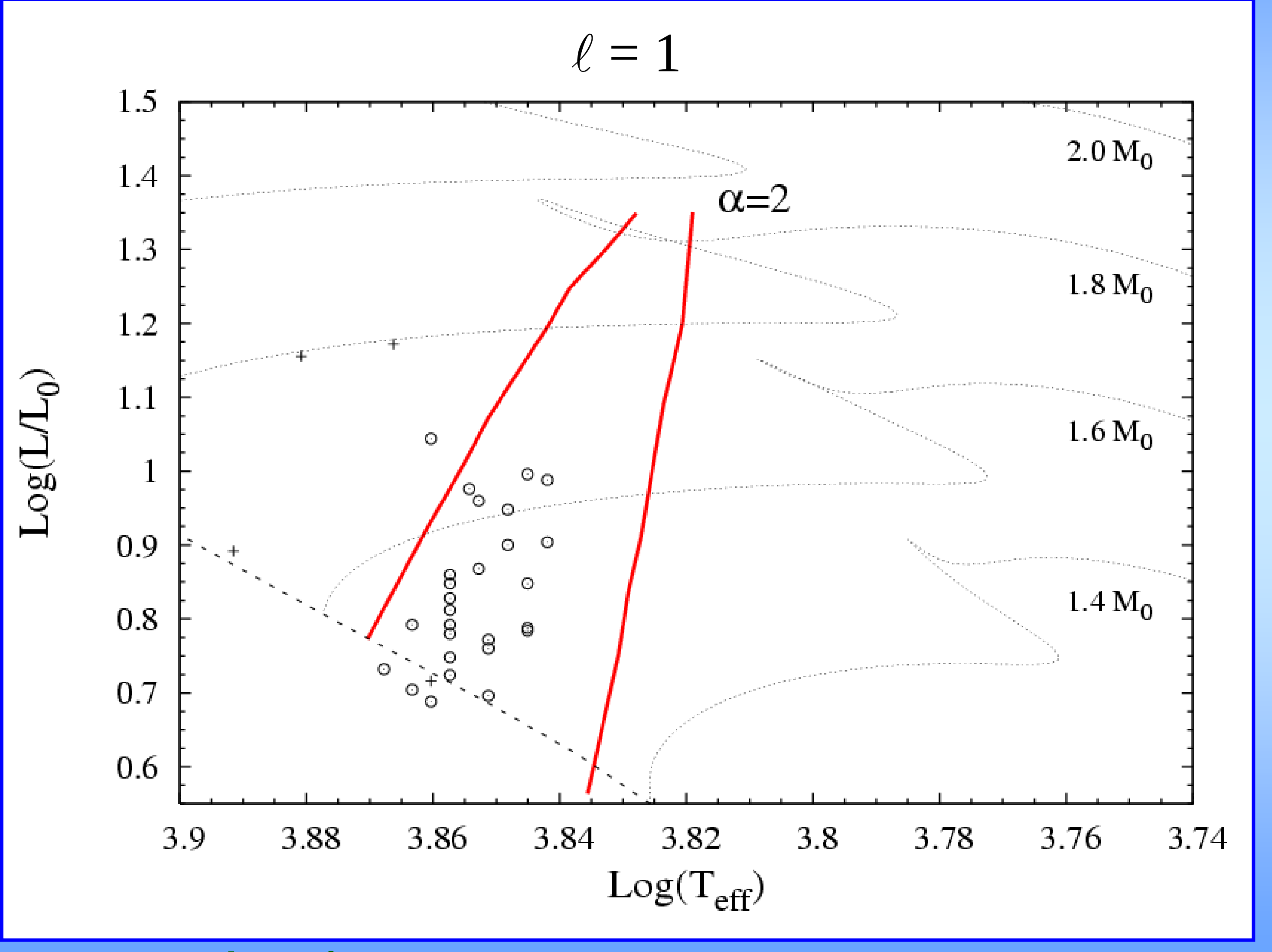
Instability strips



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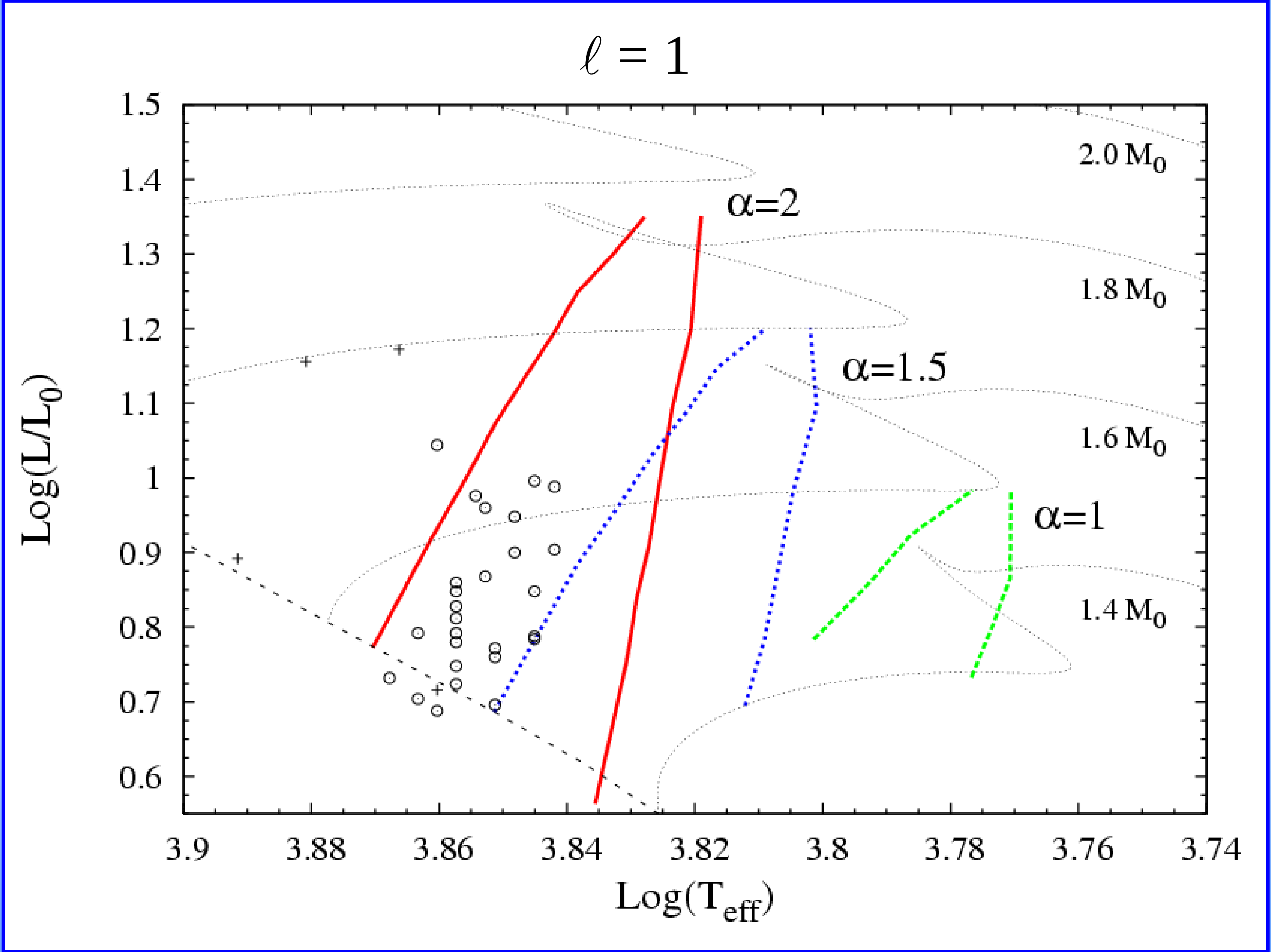
Instability strips

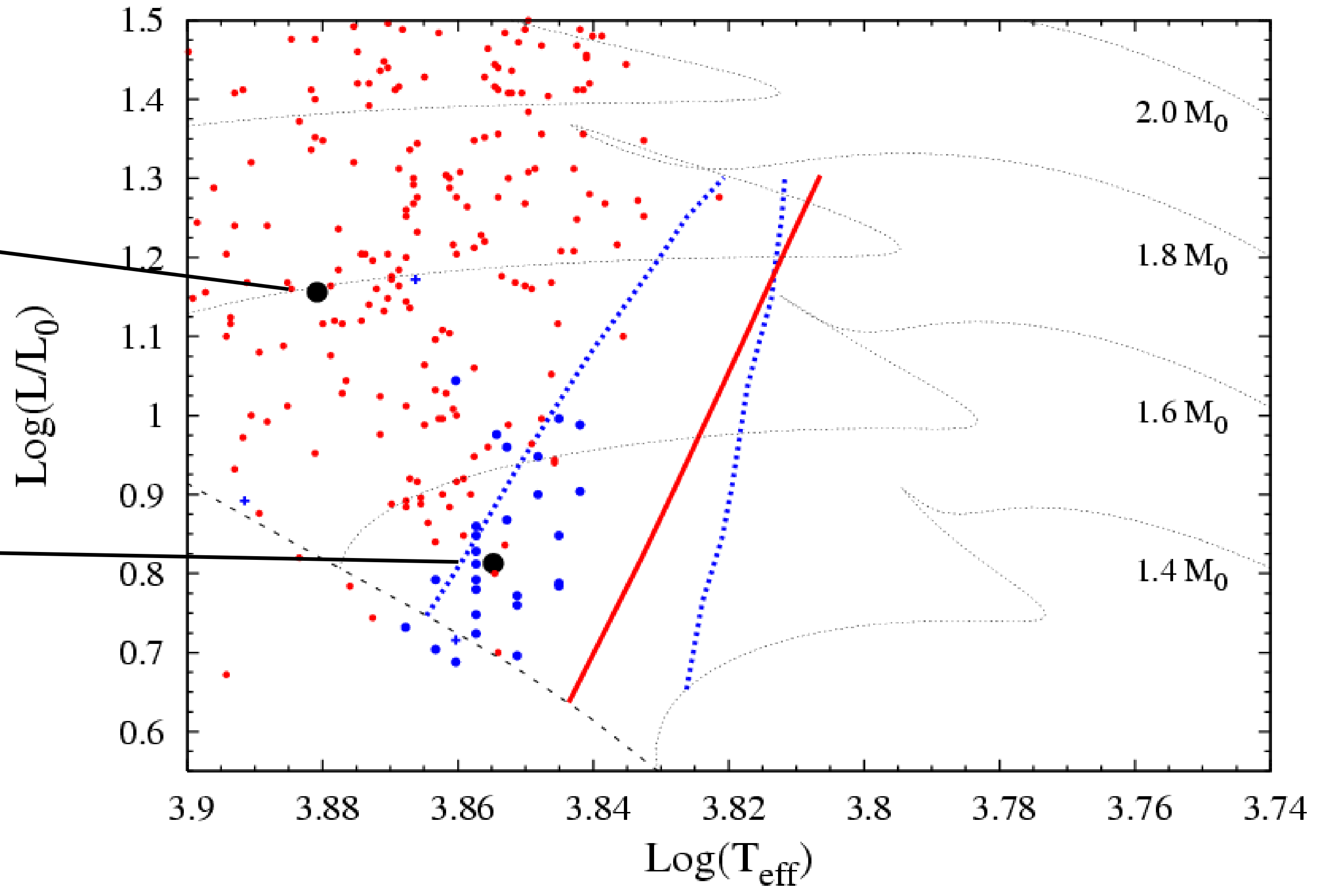


Comparison : δ Sct red edge (ℓ=0, p_1)
γ Dor instability strip (ℓ=1)

Hybrid
δ Sct – γ Dor

HD 209295
Handler et al. (2002)
Tidally excited ?

HD 8801
Henry et al. (2005)
Am star



Influence of turbulent Reynolds stress perturbation

$$\overline{\rho\vec{V}\vec{V}} = \bar{p}_T\, 1 - \bar{\beta}_T$$

$$-\delta\left(\nabla\cdot\overline{\beta_T}\right) = \Xi_r\, Y_l^m(\theta,\phi) + r\,\Xi_h\, \nabla_h Y_l^m(\theta,\phi)$$

Radial component of the equation of momentum conservation

$$\sigma^2\delta r = \frac{d\delta\Phi}{dr} - \frac{1}{\rho}\frac{d\delta p_g}{dr} - \frac{1}{\rho}\frac{d\delta p_{\mathrm{turb}}}{dr} + g\frac{\delta\rho}{\rho} + \frac{2A-1}{A}\frac{\bar{p}_T}{r\rho}\frac{\partial\delta r}{\partial r} + \frac{\Xi_r}{\rho}$$

Transversal component of the equation of momentum conservation

$$\sigma^2\delta r_H = \frac{1}{r}\left(\delta\Phi + \frac{\delta p}{\rho} + \frac{r\,\Xi_h}{\bar{\rho}} + \frac{2A-1}{A}\frac{\bar{p}_T}{\bar{\rho}}\left(\frac{\delta r}{r} - \frac{\delta r_H}{r}\right)\right)$$

σ : Angular pulsation frequency

A : Anisotropy parameter
A=1/2 for isotropic turbulence

Influence of turbulent Reynolds stress perturbation

Work integral

$$W = \int_0^M \mathrm{d}m\, \Im\left\{\frac{\delta\rho^*}{\rho}\frac{\delta p}{\rho}\right.$$

$$+ \; (1/\rho)\left(\xi_r^*\Xi_r + \ell(\ell+1)\xi_h^*\Xi_h\right)$$

$$\left. + \; \frac{2A-1}{A}\frac{p_t}{\rho}\left[\frac{\xi_r^*}{r}\frac{\mathrm{d}\xi_r}{\mathrm{d}r} + \ell(\ell+1)\frac{\xi_h^*}{r}\left(\frac{\xi_r}{r} - \frac{\xi_h}{r}\right)\right]\right\}$$

Influence of turbulent Reynolds stress perturbation

$$\Xi_\mathrm{h} = (\ldots) + \frac{1}{r^3}\frac{\mathrm{d}}{\mathrm{d}r}\left(r^3 P_\mathrm{turb} \frac{\overline{V_r \delta V_h + V_h \delta V_r}}{\overline{V_r^{\,2}}} \right)$$

$$\frac{\overline{V_r \delta V_h + V_h \delta V_r}}{\overline{V_r^{\,2}}} = \delta V V_\mathrm{h} = (\ldots) + \mathrm{C}\,\frac{\mathrm{d}\,\delta r_\mathrm{h}}{\mathrm{d}r}$$

P_{turb} ⟶ 0 and d P_{turb} / dr discontinuous

at the bottom of the convective envelope

⟶ **singularity of the equations**

⟶ **unphysical discontinuity of the eigenfunctions**

Influence of turbulent Reynolds stress perturbation

$$\Xi_{\rm h} = (\ldots) + \frac{1}{r^3}\frac{\mathrm{d}}{\mathrm{d}r}\left(r^3 P_{\rm turb} \frac{\overline{V_r \delta V_h + V_h \delta V_r}}{\overline{V_r^{\,2}}} \right)$$

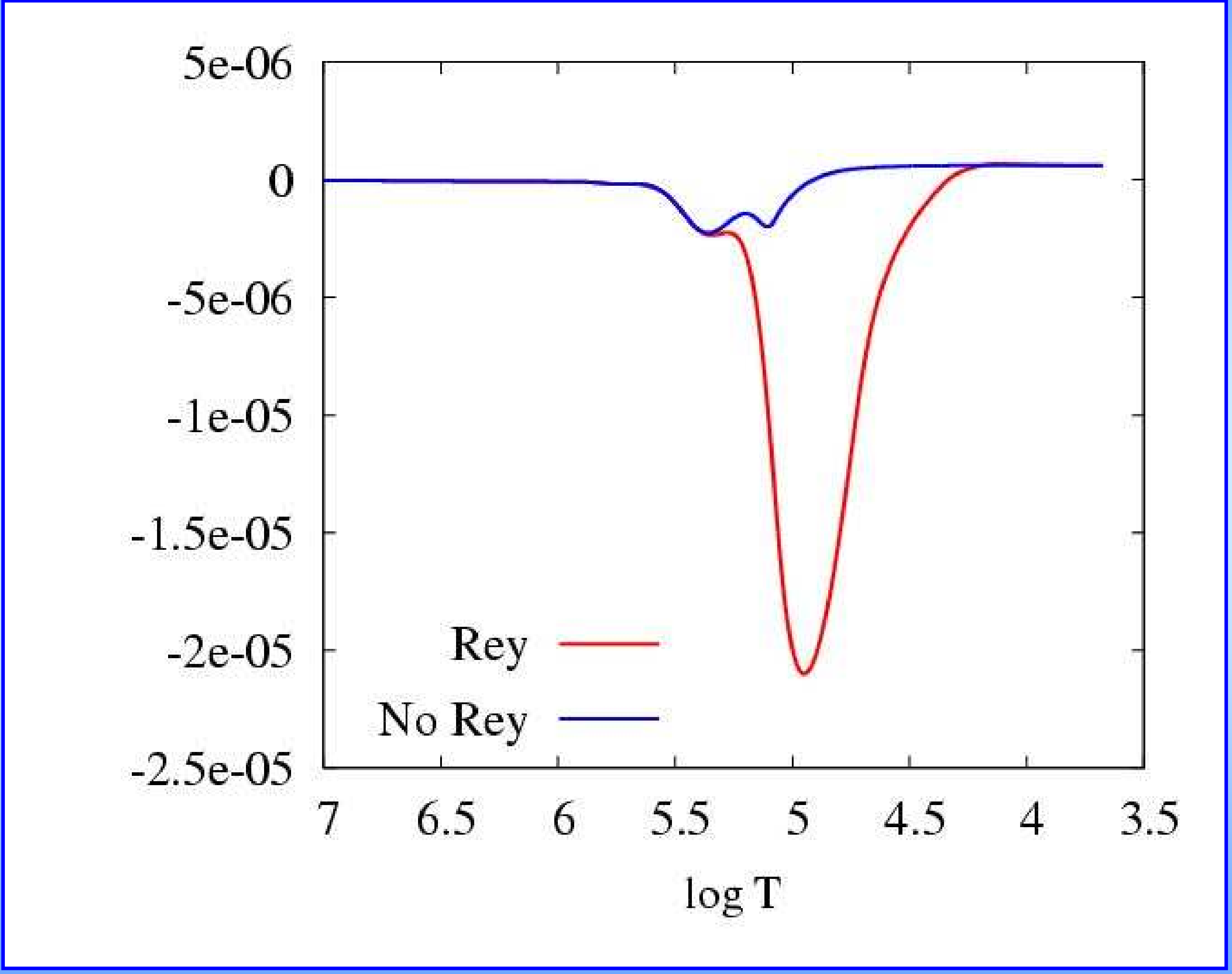
$$\frac{\overline{V_r \delta V_h + V_h \delta V_r}}{\overline{V_r^{\,2}}} = \delta VV_{\rm h} = (\ldots) + \mathrm{C}\,\frac{\mathrm{d}\,\delta r_{\rm h}}{\mathrm{d}r}$$

Non-local treatments:

$$\delta VV_{h\,\rm NL}(\zeta_0) = \int_{-\infty}^{+\infty} \delta VV_{h\,\rm L}\, e^{-b|\zeta-\zeta_0|}\,\mathrm{d}\zeta \quad ; \quad \mathrm{d}\zeta = \mathrm{d}\log P$$

Improves the things (continuity) but problem still present

Influence of Reynolds stress: Work integral



Photometric amplitudes and phases and mode identification

Hypotheses

- Lagrangian displacement → Distortion of the stellar surface

- Thermal equilibrium in the local atmosphere

  - Temperature : $$\frac{\delta T}{T} = \frac{\partial \ln T}{\partial \ln T_{eff}} \frac{\delta T_{eff}}{T_{eff}} + \frac{\partial \ln T}{\partial \ln g} \frac{\delta g_e}{g_e} + \frac{\partial \ln T}{\partial \ln \tau} \frac{\delta \tau}{\tau}$$

  - Flux : $$\frac{\delta F_\lambda}{F_\lambda} = \frac{\partial \ln F_\lambda}{\partial \ln T_{eff}} \frac{\delta T_{eff}}{T_{eff}} + \frac{\partial \ln F_\lambda}{\partial \ln g} \frac{\delta g_e}{g_e}$$

  - Limb darkening : $$\frac{\delta h_\lambda}{h_\lambda} = \frac{\partial \ln h_\lambda}{\partial \ln T_{eff}} \frac{\delta T_{eff}}{T_{eff}} + \frac{\partial \ln h_\lambda}{\partial \ln g} \frac{\delta g_e}{g_e} + \frac{\partial \ln h_\lambda}{\partial \ln \mu} \frac{\delta \mu}{\mu}$$

Monochromatic magnitude variation

Influence of the local effective temperature variations

$$\delta m_\lambda = -\frac{2.5}{\ln 10}\,\varepsilon\, P_\ell^m(\cos i)\, b_{\ell\lambda}$$

$$\left[-(\ell-1)(\ell+2)\cos(\sigma t) + \left(\frac{\partial \ln F_\lambda^+}{\partial \ln T_{\mathrm{eff}}} + \frac{\partial \ln b_{\ell\lambda}}{\partial \ln T_{\mathrm{eff}}}\right)\left|\frac{\delta T_{\mathrm{eff}}}{T_{\mathrm{eff}}}\right| \cos(\sigma t + \psi_T) - \left(\frac{\partial \ln F_\lambda^+}{\partial \ln g} + \frac{\partial \ln b_{\ell\lambda}}{\partial \ln g}\right)\left|\frac{\delta g_e}{g_e}\right| \cos(\sigma t) \right]$$

Stellar surface distortion

Equilibrium atmosphere models (Kurucz 1993)

Filters → Integration on the pass-band

Influence of the local effective gravity variations

Non - adiabatic computations

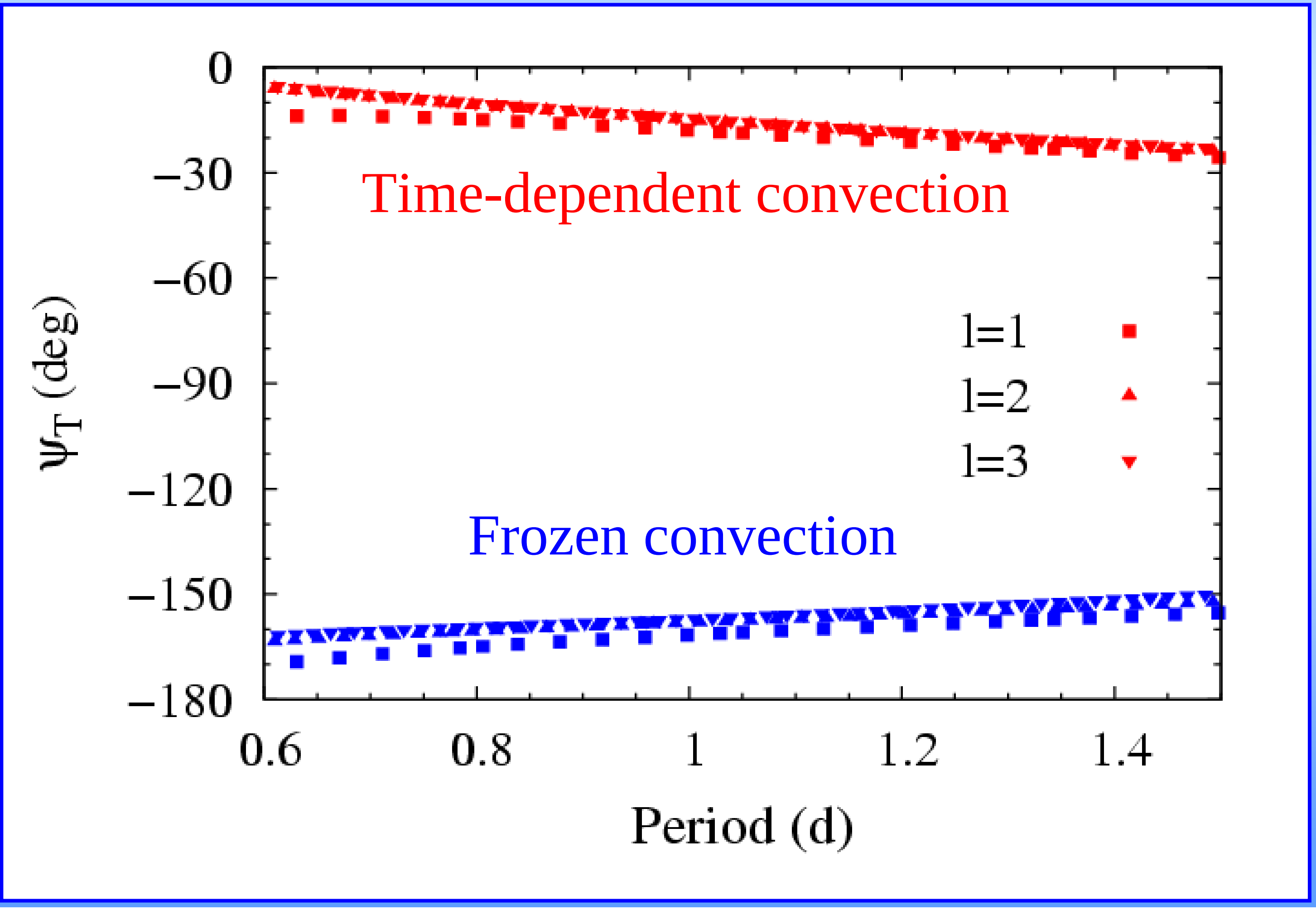
Linear computations → Amplitude ratios and phase differences

Dependence with the degree ℓ → Identification of ℓ

Spectro-photometric amplitudes and phases and mode identification

Very sensitive to the non-adiabatic treatment of convection

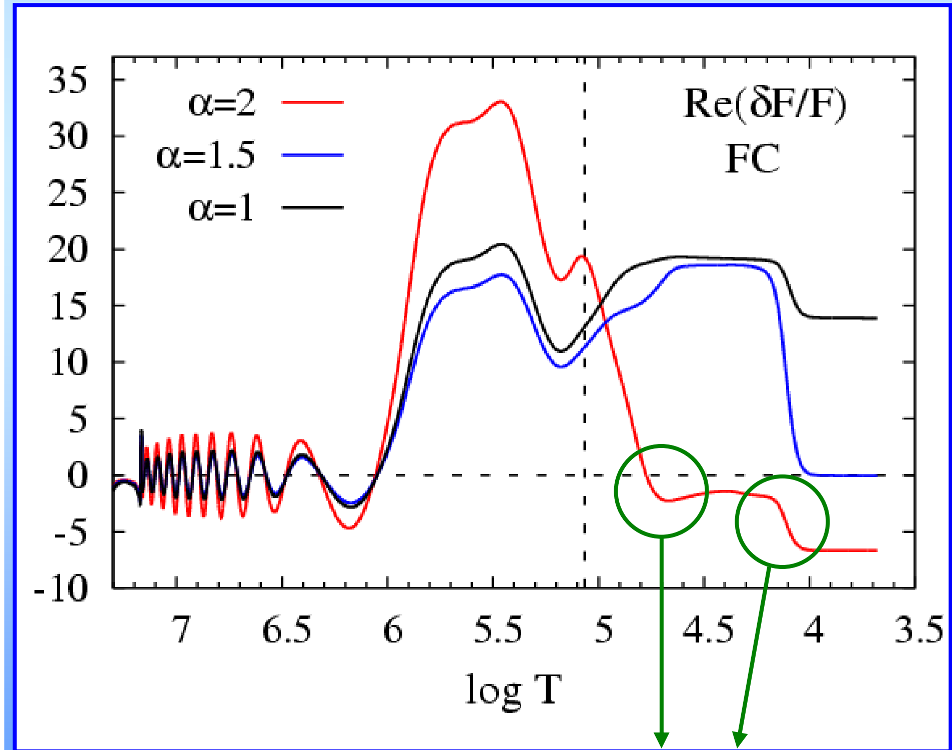
Phase-lag



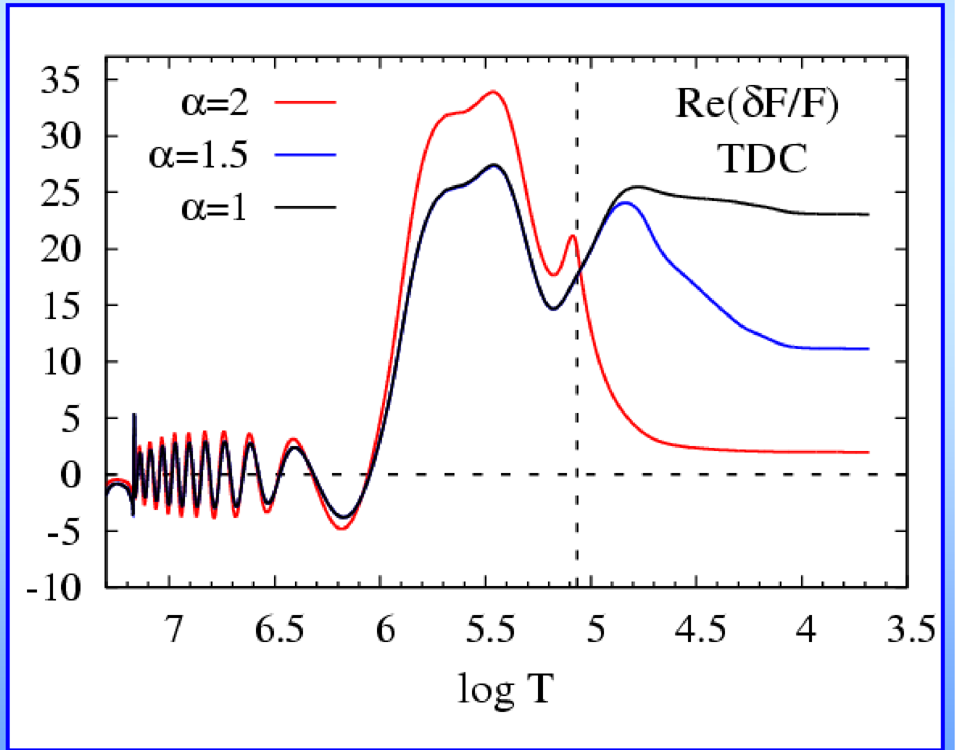
Spectro-photometric amplitudes and phases and mode identification

Very sensitive to the non-adiabatic treatment of convection

Frozen convection



Time-dependent convection



κ-mechanism → Not allowed by time-dependent convection

Spectro-photometric amplitudes and phases and mode identification

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3 frequencies: f_1=1.32098 c/d, f_2=1.36354 c/d, f_3=1.47447 c/d

Balona et al. 1994 → **Strömgren photometry**

Balona et al. 1996 → **Simultaneous photometry and spectroscopy**

→ **Spectroscopic mode identification:** $(\ell_1, m_1) = (3, 3)$,
$(\ell_2, m_2) = (1, 1)$,
$(\ell_3, m_3) = (1, 1)$

Spectro-photometric phase differences

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Balona et al. 1996 → **Simultaneous photometry and spectroscopy**

→ **Phase-lag (Vmagnitude – displacement):**

Observations: $\Delta\phi_1 = -65° \pm 5°$ $\Delta\phi_3 = -29° \pm 8°$

Theory: (α = 2)

	Time-dependent convection	Frozen convection
	$\Delta\phi = -30°$	$\Delta\phi = -165°$

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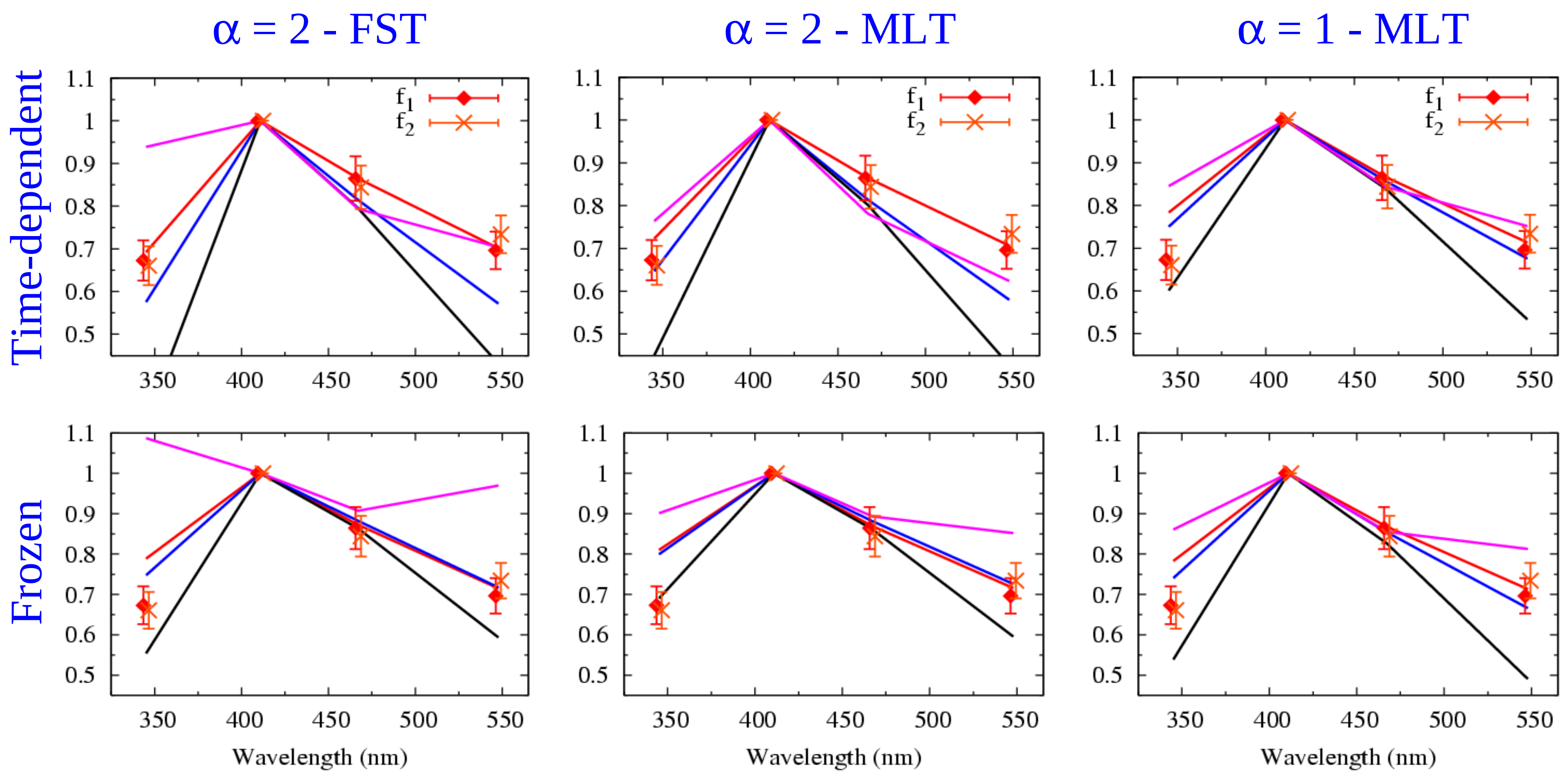
Photometric mode identification



$\ell = 1$ modes

Best models: Time-dependent convection
FST atmosphere

Spectro-photometric amplitudes and phases

9 Aurigae

3 frequencies: f_1=0.795 c/d, f_2=0.768 c/d, f_3=0.343 c/d

Zerbi et al. 1994 → **Simultaneous photometry and spectroscopy**

Spectroscopic mode id. : **$(\ell_1, |m_1|) = (3, 1)$,**
Aerts & Krisciunas (1996) **$(\ell_3, |m_3|) = (3, 1)$**

Spectro-photometric phase differences

9 Aurigae

Balona et al. 1996 → **Simultaneous photometry and spectroscopy**

→ **Phase-lag (Vmagnitude – displacement):**

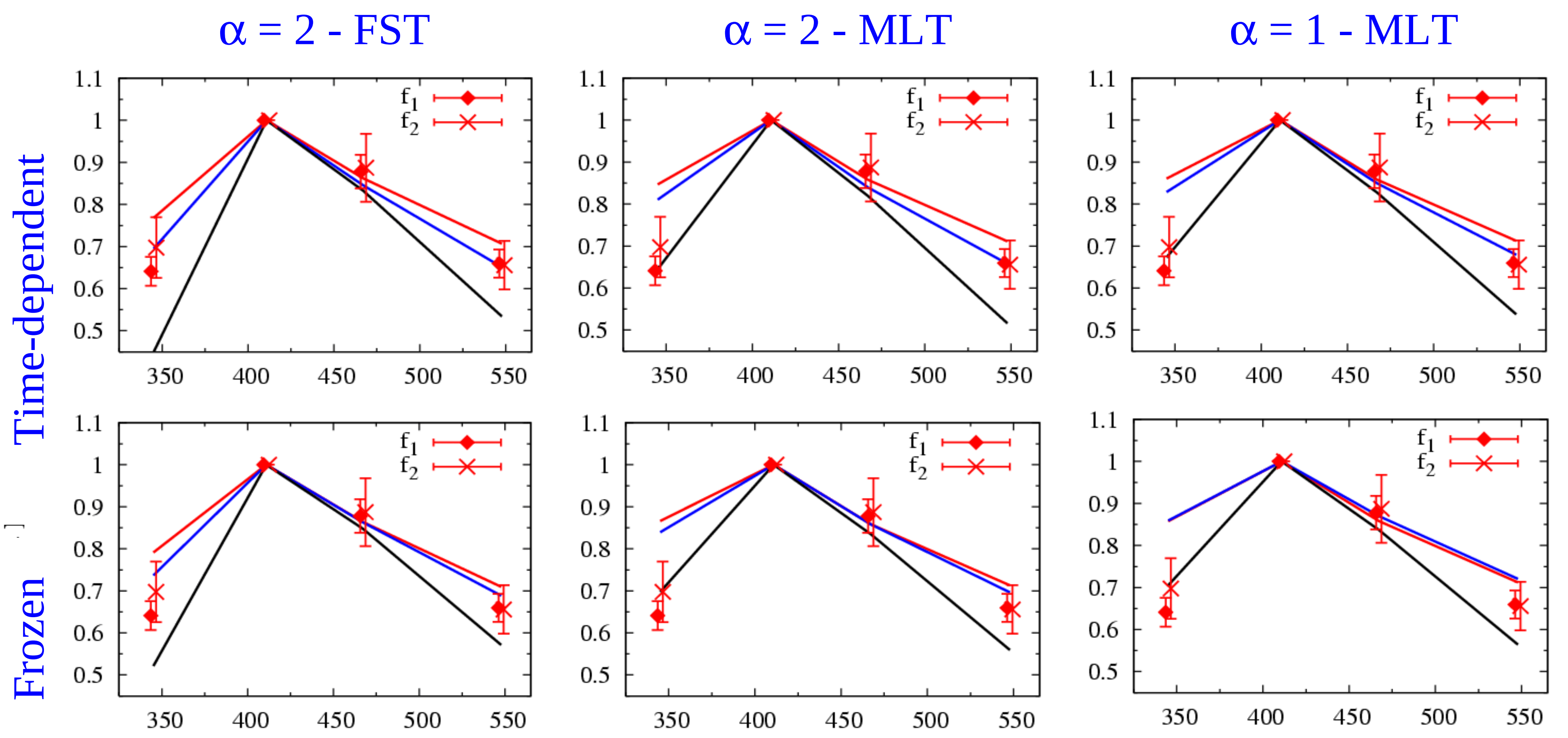
Observations: $\Delta\phi_1 = -77° \pm 12°$ $\Delta\phi_3 = -41° \pm 10°$

Theory (α = 2):

TDC	$\Delta\phi_1 = -22°$	$\Delta\phi_3 = -39°$
FC	$\Delta\phi_1 = -156°$	$\Delta\phi_3 = -140°$

9 Aurigae

Photometric mode identification



$\ell = 2$ modes

Best models: Time-dependent convection
FST atmosphere

Importance of ultraviolet observations

(bracketing the Balmer discontinuity)

Influence of the effective temperature variations

$$\delta m_\lambda = -\frac{2.5}{\ln 10}\,\varepsilon\, P_\ell^m(\cos i)\, b_{\ell\lambda}$$

$$\left[-(\ell-1)(\ell+2)\cos(\sigma t) + \left(\frac{\partial \ln F_\lambda^+}{\partial \ln T_{\rm eff}} + \frac{\partial \ln b_{\ell\lambda}}{\partial \ln T_{\rm eff}}\right)\left|\frac{\delta T_{\rm eff}}{T_{\rm eff}}\right| \cos(\sigma t + \psi_T)\right.$$

$$\left. - \left(\frac{\partial \ln F_\lambda^+}{\partial \ln g} + \frac{\partial \ln b_{\ell\lambda}}{\partial \ln g}\right)\left|\frac{\delta g_e}{g_e}\right| \cos(\sigma t)\right]$$

Influence of the effective gravity variations

Gravity derivatives vary quickly in u-v

↓

Changes the weight of T_{eff} and g_e terms

↓

Helps for the mode identification and gives constraints on $|\delta T_{eff}/T_{eff}|$

Stromgren, Geneva systems are perfects

Conclusions

Driving mechanism and energetic aspects in γ Doradus stars

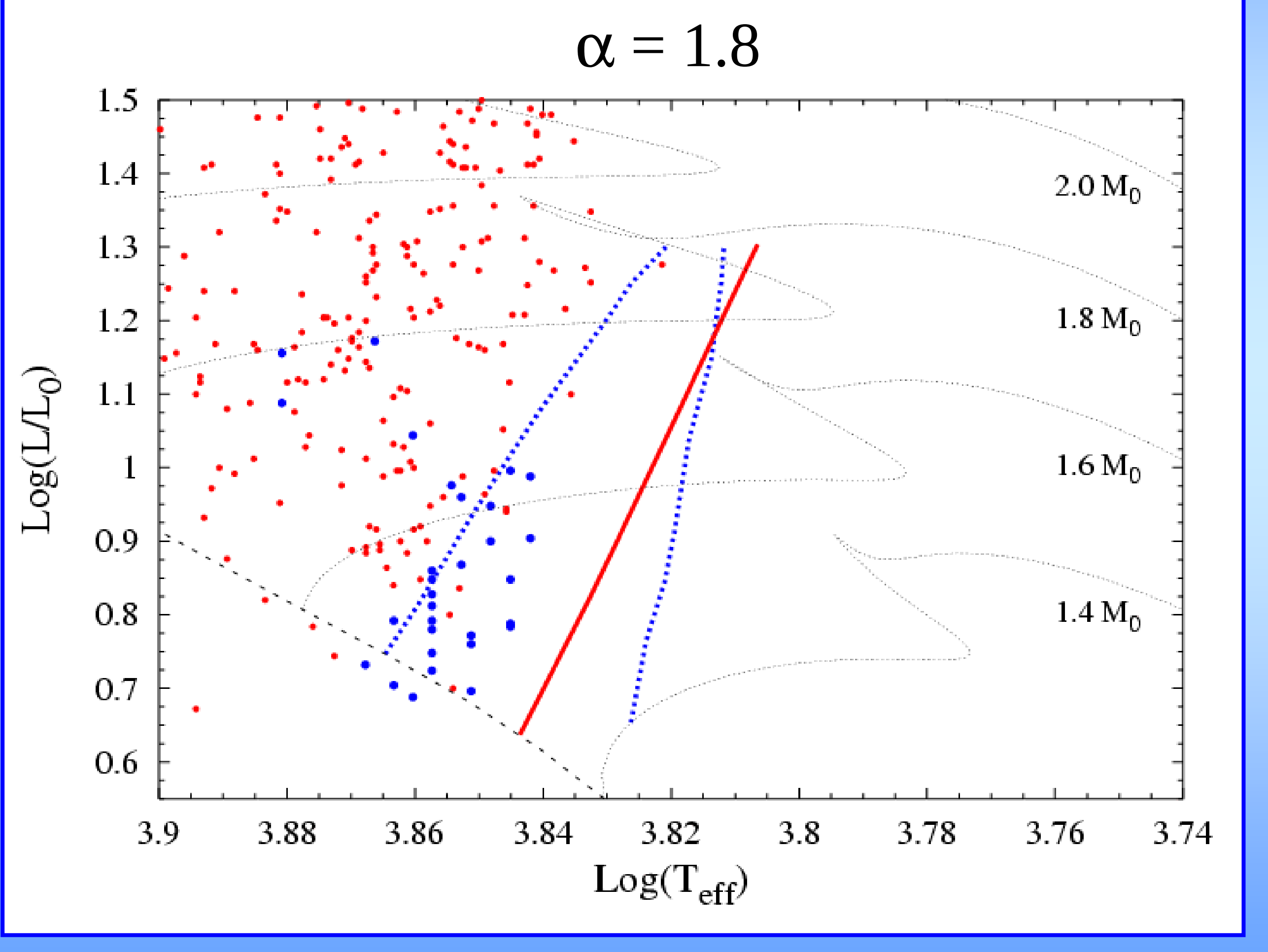
- Excitation mechanism: Convective blocking

  Time-Dependent convection does not inhibits the mechanism

- Mode identification, amplitudes and phases:

  Time-Dependent Convection required

Comparison : δ Sct red edge (ℓ=0, p_1)
γ Dor instability strip (ℓ=1)



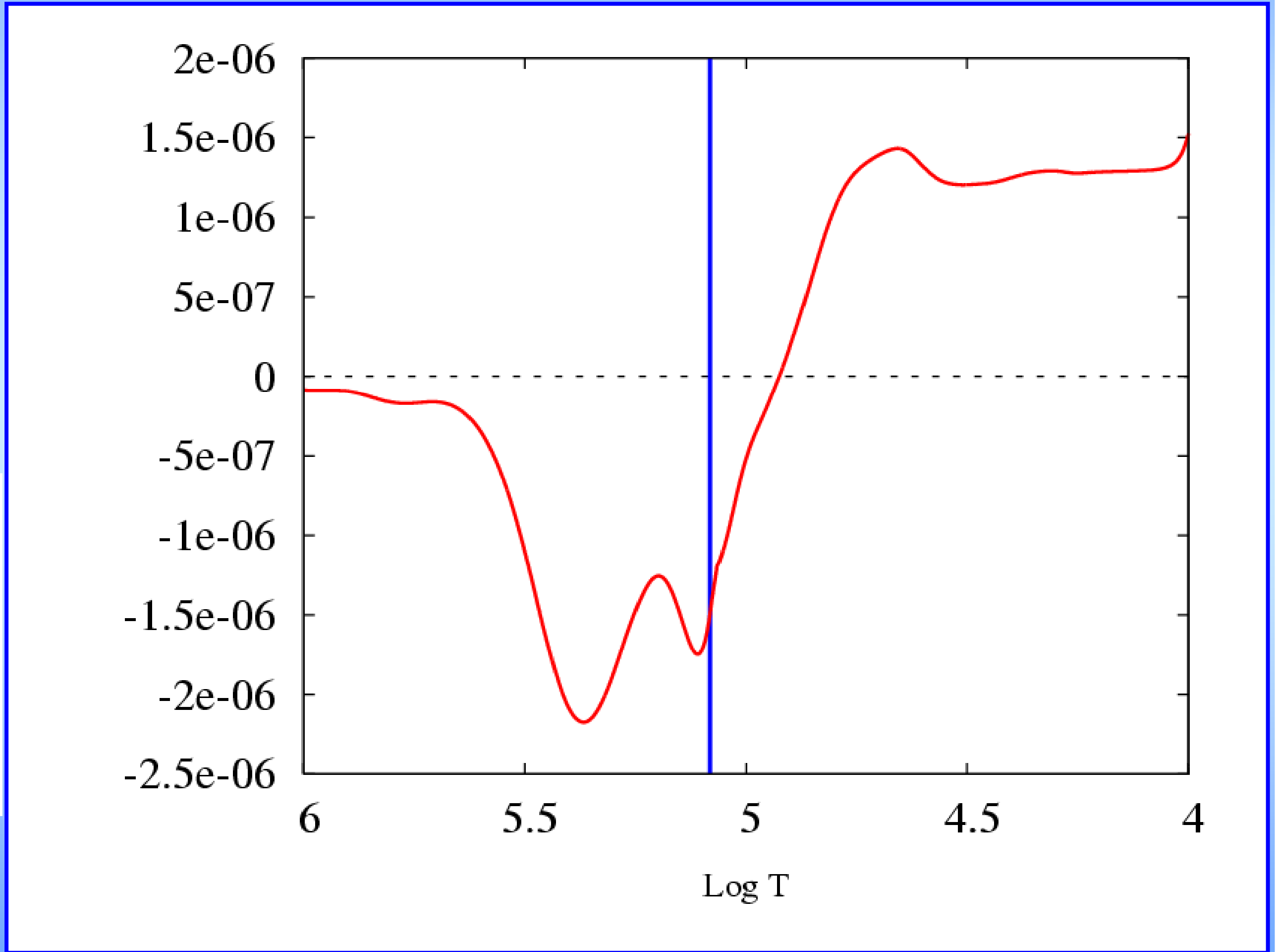
γ Doradus

Stabilization mechanism

$M = 1.6\ M_0$
$T_{eff} = 7000$ K
$\alpha = 2$
Mode $\ell=1$, g_{50}

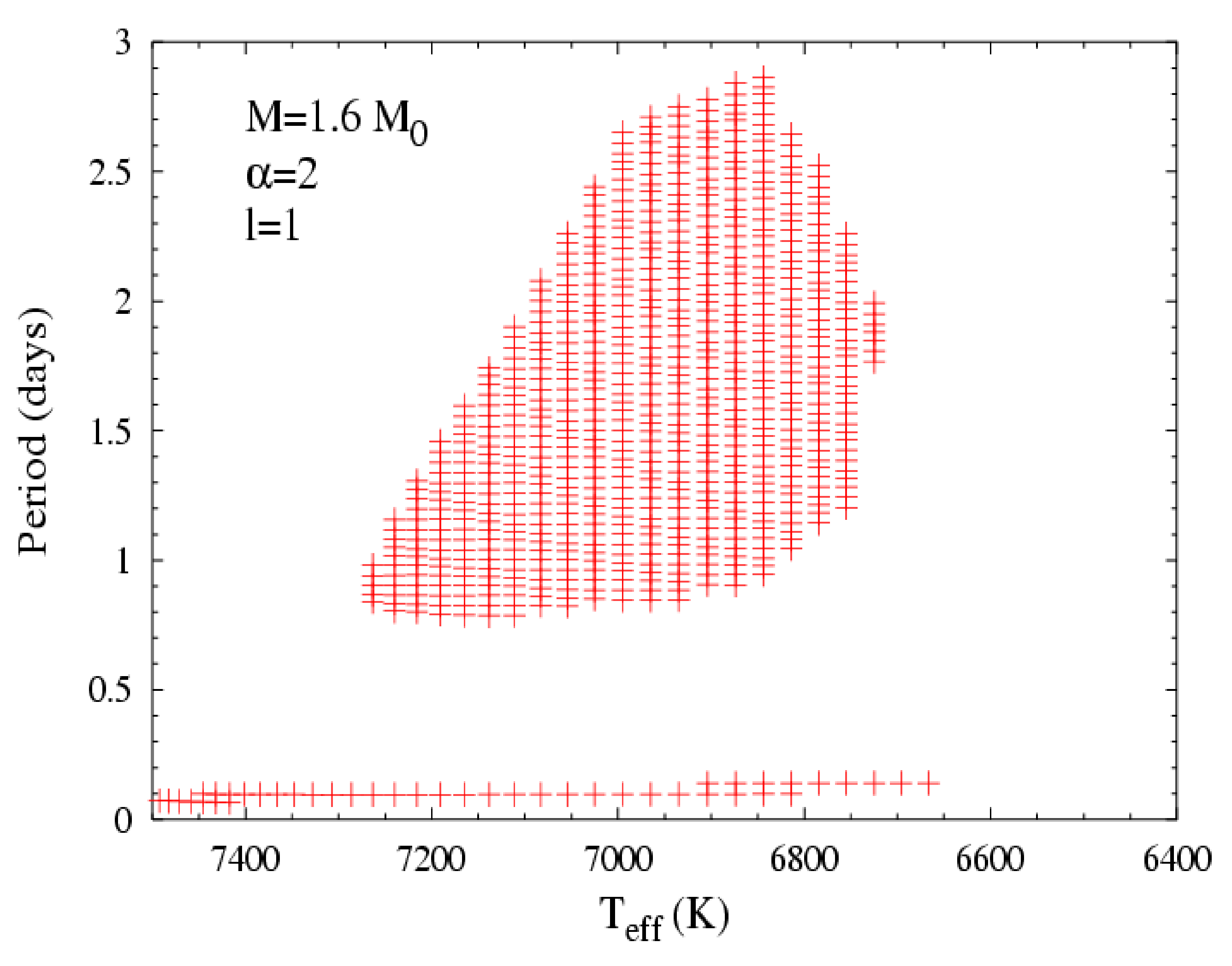
W_{FRr}: Radial radiative flux term

$$
\begin{aligned}
W_{\rm tot} &= -\int_0^m \Im\left\{\frac{\delta\rho^*}{\rho}\frac{\delta p}{\rho}\right\}\mathrm{d}m \\
&= -\int_0^m (\Gamma_3-1)\,\Re\left\{\frac{1}{\sigma}\frac{\delta\rho^*}{\rho}\frac{\mathrm{d}\ (\delta L_{\rm R}+\delta L_{\rm c})}{\mathrm{d}m}\right\}\mathrm{d}m \\
&\quad -\int_0^m \Im\left\{\frac{\delta\rho^*}{\rho}\frac{\delta p_{\rm t}}{\rho}\right\}\mathrm{d}m \\
&\quad +\int_0^m \frac{3}{2}(\Gamma_3-1)\Im\left\{\frac{\delta\rho^*}{\rho}\frac{\delta p_{\rm t}}{\rho}\right\}\mathrm{d}m
\end{aligned}
$$



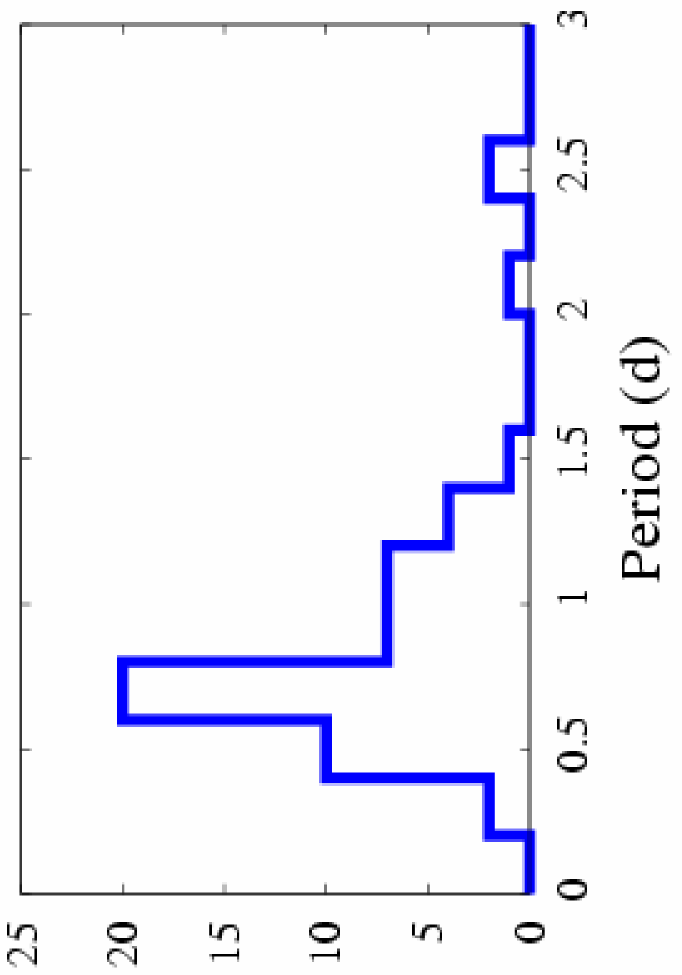
γ Doradus

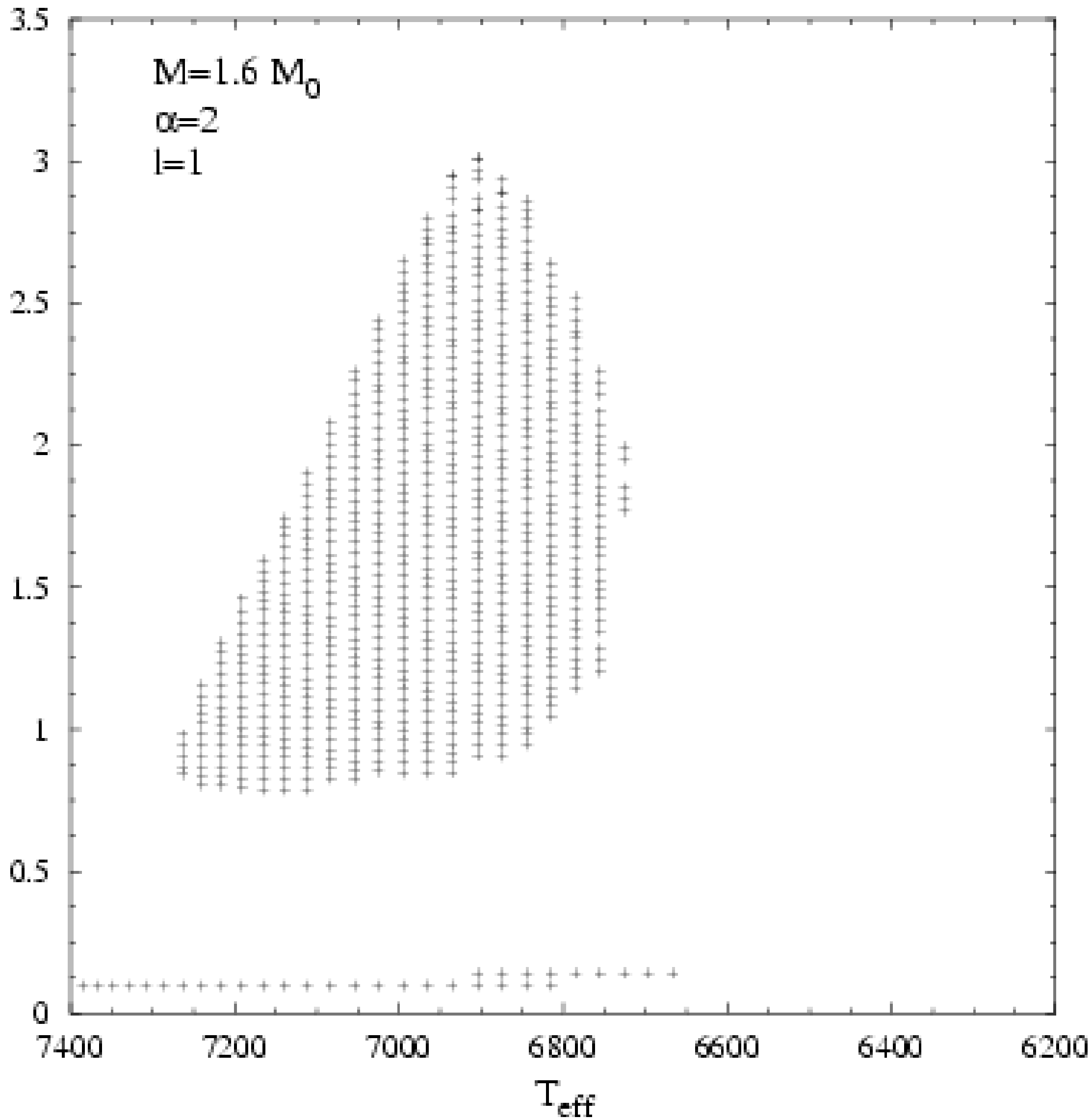
Unstable modes



γ Doradus

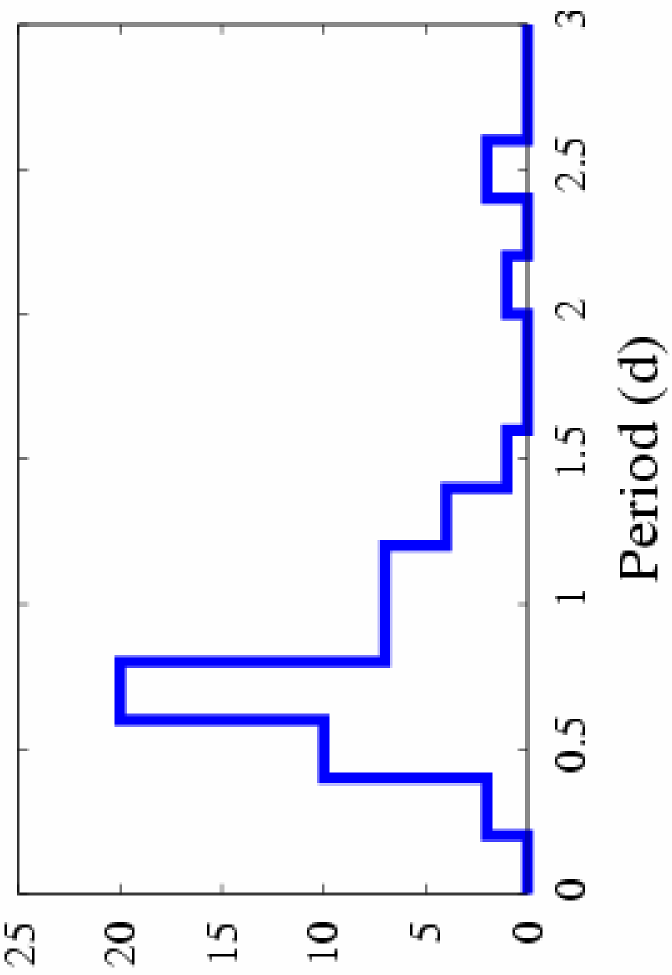
Unstable modes

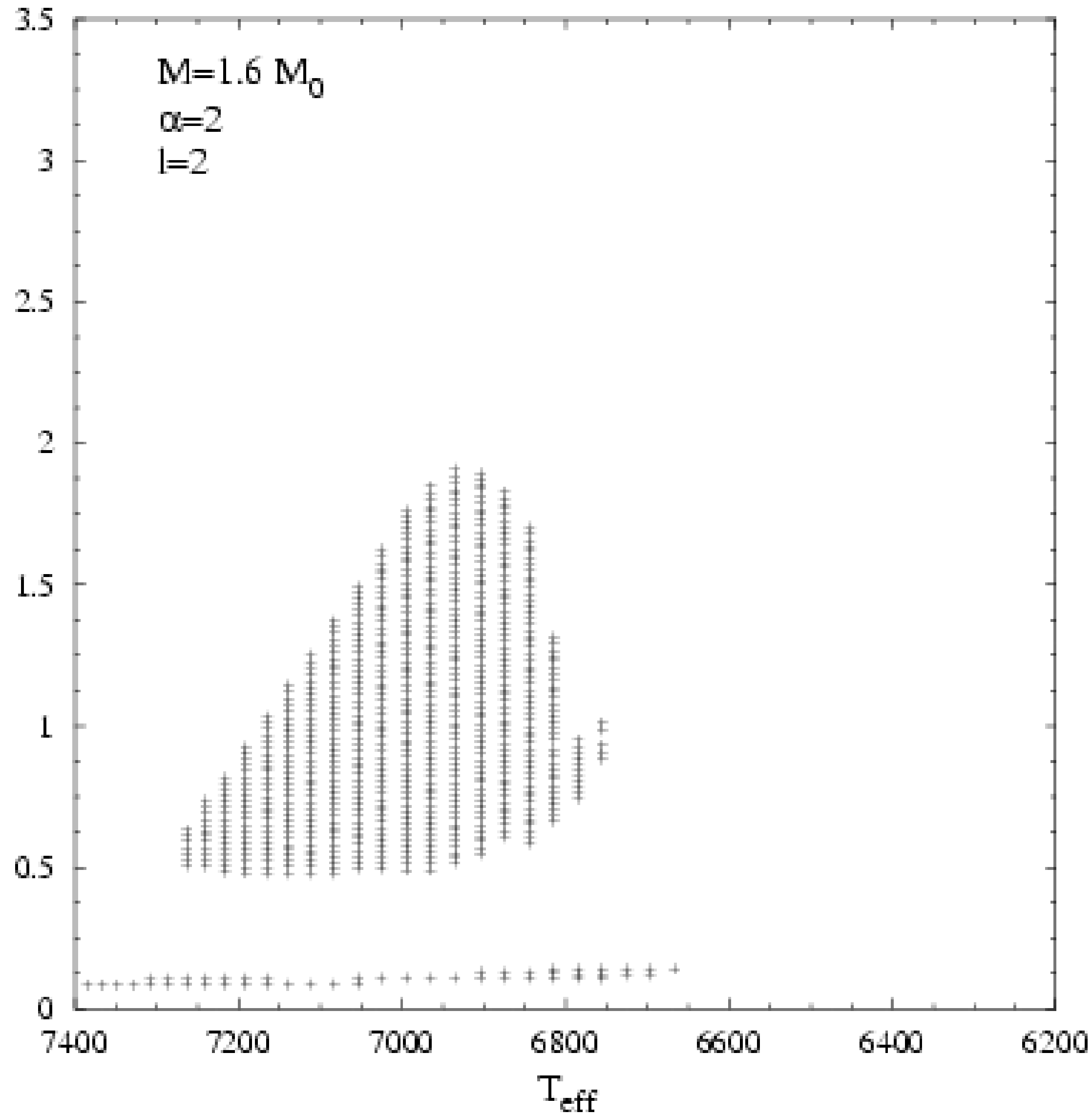




γ Doradus

Unstable modes





Non-adiabatic stellar oscillations: utility

Excitation mechanisms

Mode identification

Solar-like oscillations

Unstable modes: growth rates

Observations

Stable modes: damping rates

Line-widths in the power spectrum

Stochastic excitation models

Amplitudes

Convection – pulsation interaction

3-D hydrodynamic simulations

Perturbative approach

All motions are convective ones

In particular the p-modes (present in the solution)

Nordlund & Stein

Separation between convection and pulsation in the Fourier space of turbulence

Convective motions: short wave-lengths

Oscillations: long wave-lengths

1. Static solution without oscillations

2. Stability study of this solution

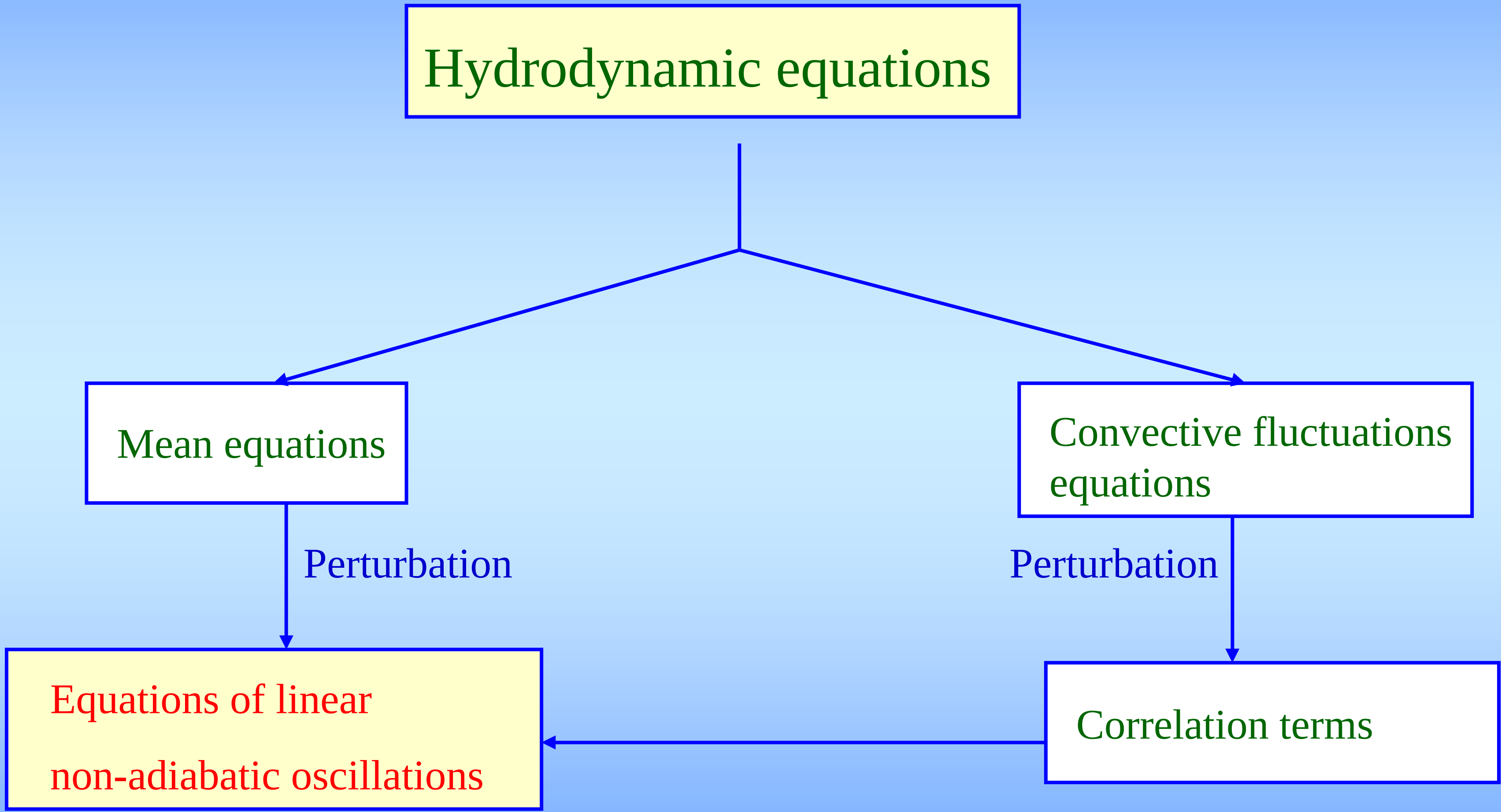
→ **Perturbation** → **Oscillations**

MLT

Gough´s theory

Gabriel´s theory

Convection – pulsation interaction: Gabriel´s theory



Convection – pulsation interaction: Gabriel´s theory

Perturbed correlation terms

- Convective flux perturbation
- Reynolds stress and turbulent pressure perturbation
- Turbulent kinetic energy dissipation perturbation

The unknown correlation terms are obtained by perturbing the convective fluctuation equations. The solutions have the form:

$$\delta(\Delta X) = \delta(\Delta X) e^{i\vec{k}\bullet\vec{r}} e^{i\sigma t}$$

Horizonthal means

Integration over k_θ, k_Φ with $k_\theta^2 + k_\Phi^2 = A k_r^2$

Separation of the variables in term of spherical harmonics → **Radial modes** / **Non-radial modes**

Convection – pulsation interaction: Work integral

Radiative luminosity

Convective luminosity

$$
\begin{aligned}
W_{\mathrm{tot}} &= -\int_0^m \Im\left\{\frac{\delta\rho^*}{\rho}\frac{\delta p}{\rho}\right\}\mathrm{d}m \\
&= -\int_0^m (\Gamma_3 - 1)\,\Re\left\{\frac{1}{\sigma}\frac{\delta\rho^*}{\rho}\frac{\mathrm{d}\,(\delta L_{\mathrm{R}} + \delta L_{\mathrm{c}})}{\mathrm{d}m}\right\}\mathrm{d}m \\
&\quad -\int_0^m \Im\left\{\frac{\delta\rho^*}{\rho}\frac{\delta p_{\mathrm{t}}}{\rho}\right\}\mathrm{d}m \\
&\quad +\int_0^m \frac{3}{2}(\Gamma_3 - 1)\Im\left\{\frac{\delta\rho^*}{\rho}\frac{\delta p_{\mathrm{t}}}{\rho}\right\}\mathrm{d}m
\end{aligned}
$$

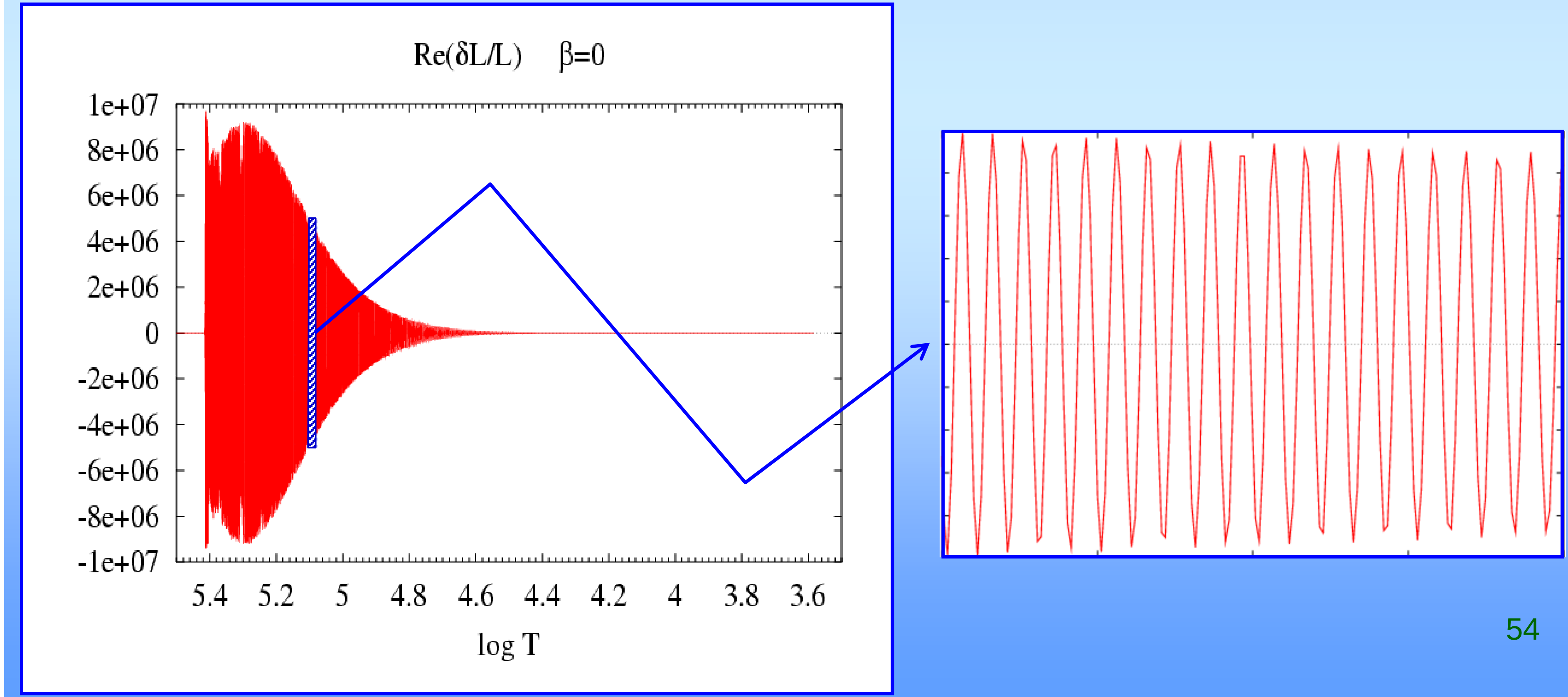
Turbulent pressure

Turbulent kinetic energy dissipation

Solar-type oscillations

Difficulties : 1. Treatment in the efficient part of convection

Local treatment → Very short wave-length oscillations of the eigenfunctions



Solar-type oscillations

Difficulties: 1. Treatment in the efficient part of convection

Origin of the problem:

$$i\sigma T\,\delta s = -\frac{d\,\delta L_C}{dm}$$

$$\delta L_C \cong \delta L_1 + \frac{L_C}{i\sigma\tau_C}\frac{d\,\delta s}{ds}$$

↘ ↙

$$\frac{l^2}{i\sigma\tau_C}\frac{d^2\delta s}{dr^2} + i\sigma\tau_C\,\delta s + (\ldots) = 0$$

↓

$$\delta s = \ldots + c_1\exp(-i\sigma\tau_c r/l) + c_2\exp(i\sigma\tau_c r/l)$$

↓

Wavelength much shorter than the mixing-length !

Solar-type oscillations

Difficulties: 1. Treatment in the efficient part of convection

Solutions

→ Non-local (Balmforth 1992)

→ Local (Gabriel 2003)

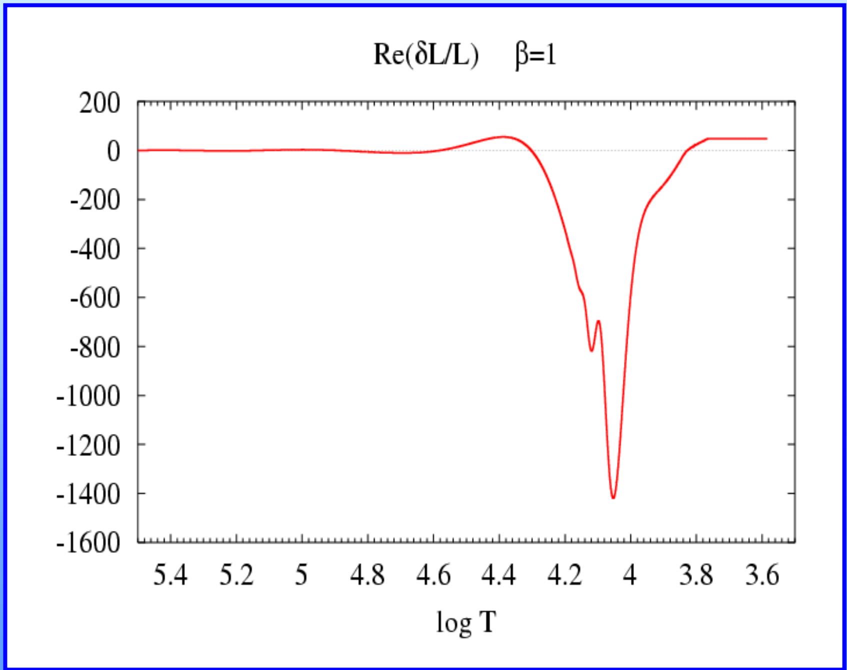
→ Introduction of new free parameters

Solar-type oscillations

Difficulties: 1. Treatment in the efficient part of convection

Solutions

Local (Gabriel 2003)



$$\frac{\Delta s}{\tau_C} = \frac{1}{\overline{\rho T}}\left[\rho\varepsilon_2 - \overline{\rho\varepsilon_2} + \rho T\nabla s \bullet \vec{V} - \overline{\rho T\nabla s \bullet \vec{V}} - \left(\nabla \bullet \vec{F}_R - \overline{\nabla \bullet \vec{F}_R}\right)\right]$$

$$\delta\left(\frac{\Delta s}{\tau_C}\right) = \frac{\Delta s}{\tau_C}\left((1+\beta\sigma\tau_C)\frac{\delta\Delta s}{\Delta s} - \frac{\delta\tau_C}{\tau_C}\right)$$

$$\frac{l^2}{(i+\beta)\sigma\tau_C}\frac{d^2\delta s}{dr^2} + i\sigma\tau_C\,\delta s + (...) = 0$$

Solar-type oscillations

Difficulties: 2. Treatment of turbulent pressure perturbation

Increases the order of the system

Very stiff problem at the boundaries

↘ ↙

Numerical instabilities

Solar-type oscillations: confrontation to observations

Models of stochastic excitation

- The Sun is a vibrationally stable oscillator.
- Excitation of the mode is due to stochastic forcing coming from turbulent convective motions.

Theory

Non-adiabatic models → Damping rate: η

Stochastic models → Acoustical noise generation rate: ***P***

$$V_s = \sqrt{\frac{P}{2\,\eta\, I}}$$

Velocity

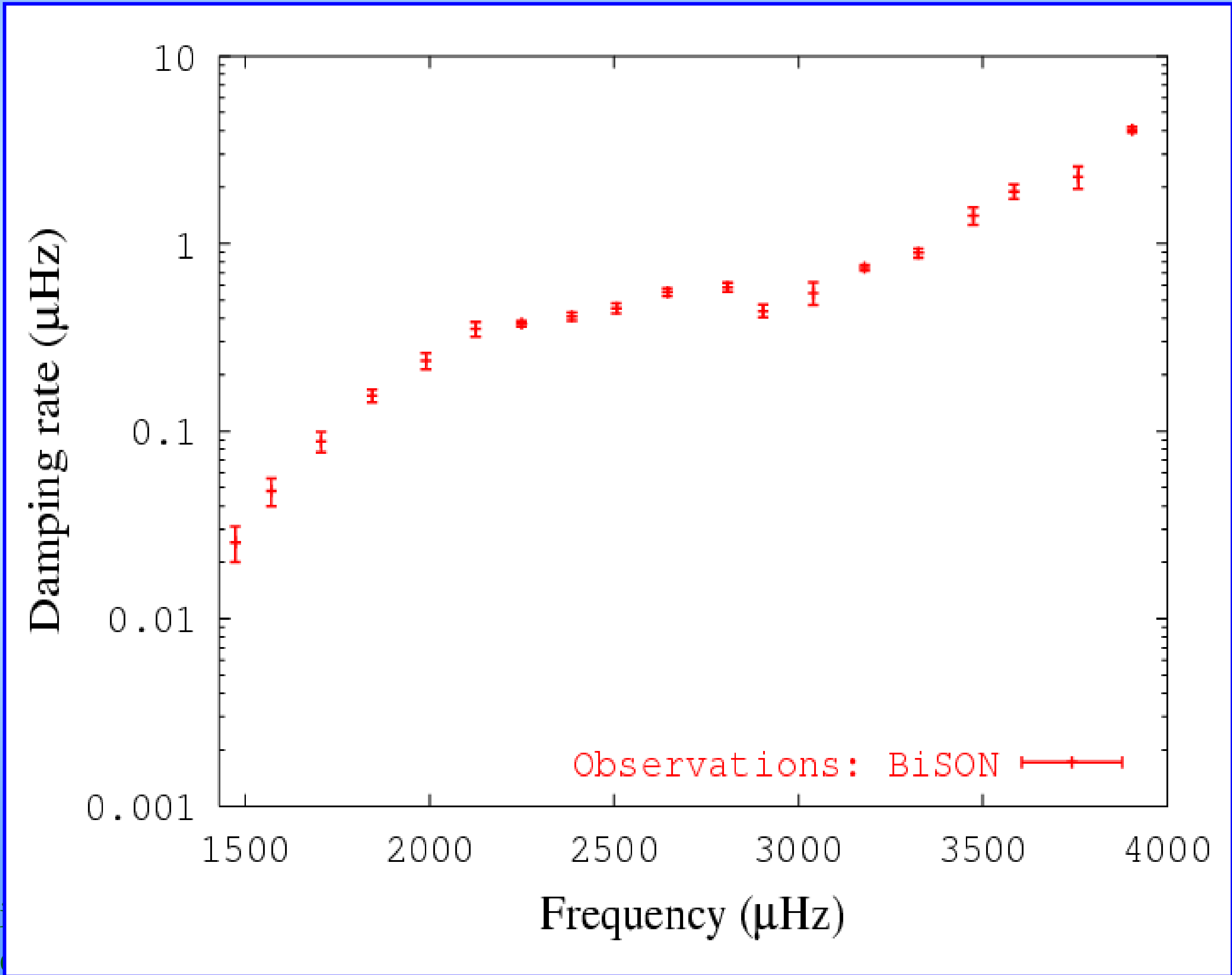
Observations

Line-widths ⇔ Damping rate: η

Observed amplitudes ⇔ V_s

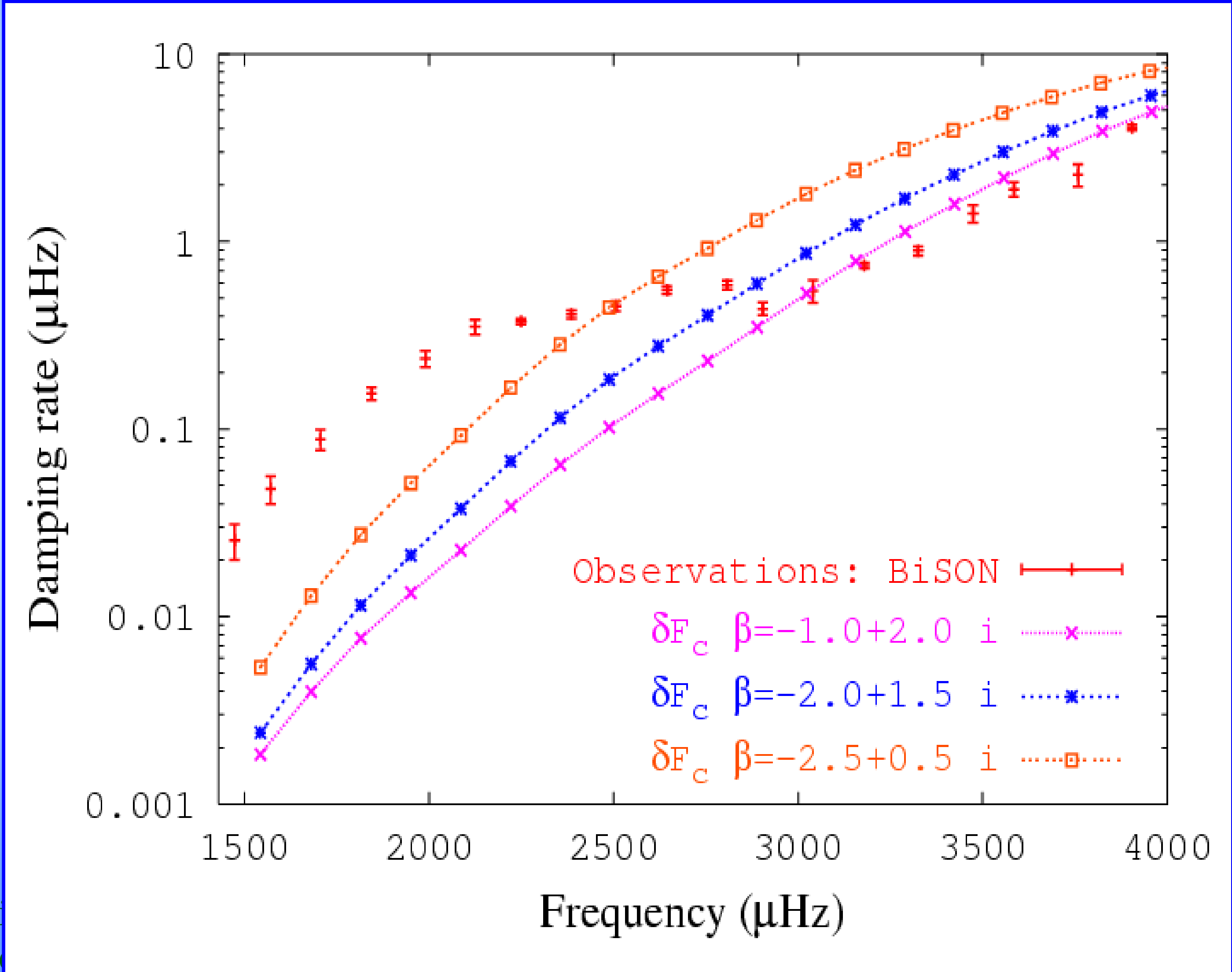
Solar-type oscillations: confrontation to observations

Theoretical damping rates ↔ line-widths observed by BiSON (Chaplin et al. 1997)



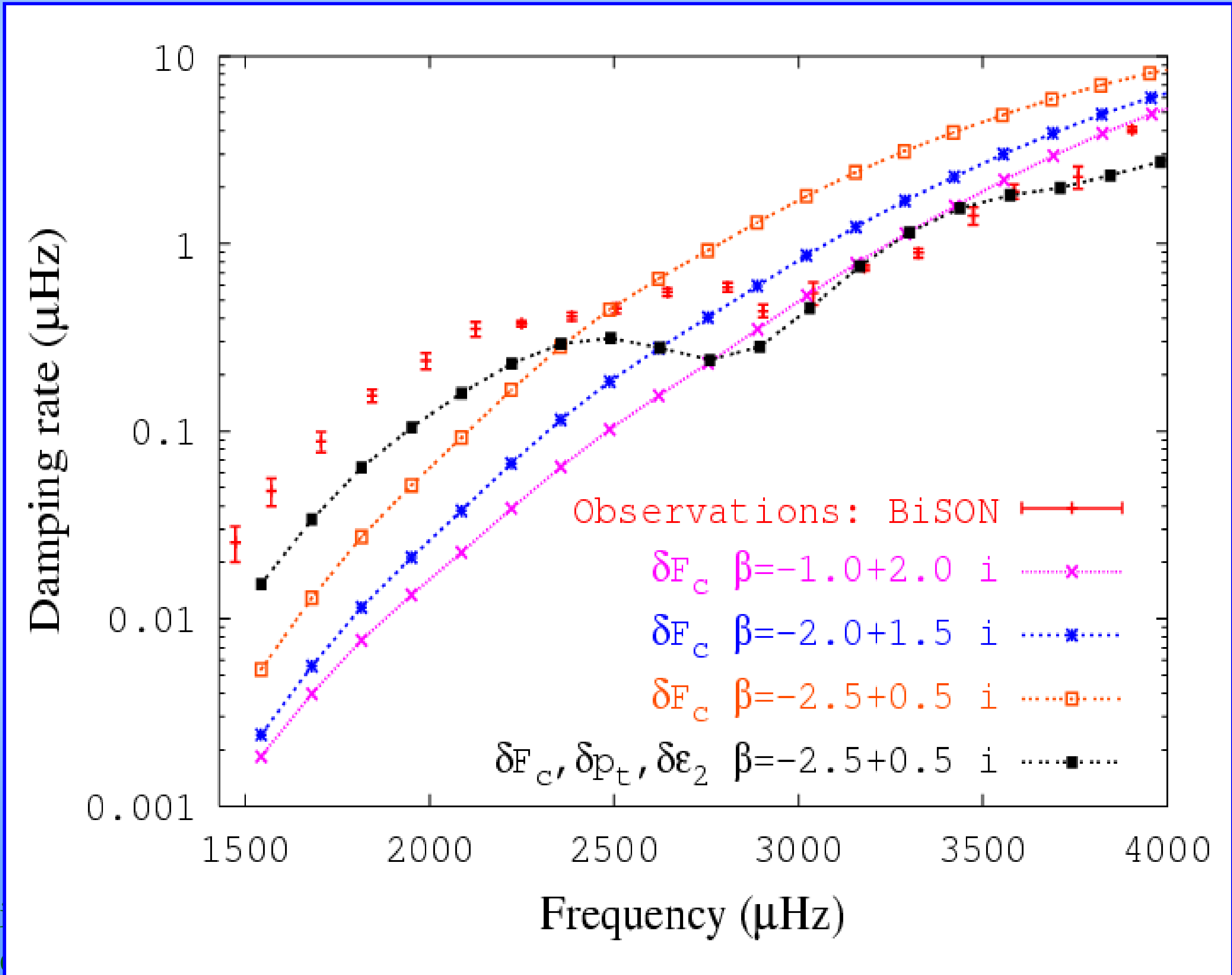
Solar-type oscillations: confrontation to observations

Theoretical damping rates ↔ line-widths observed by BiSON (Chaplin et al. 1997)



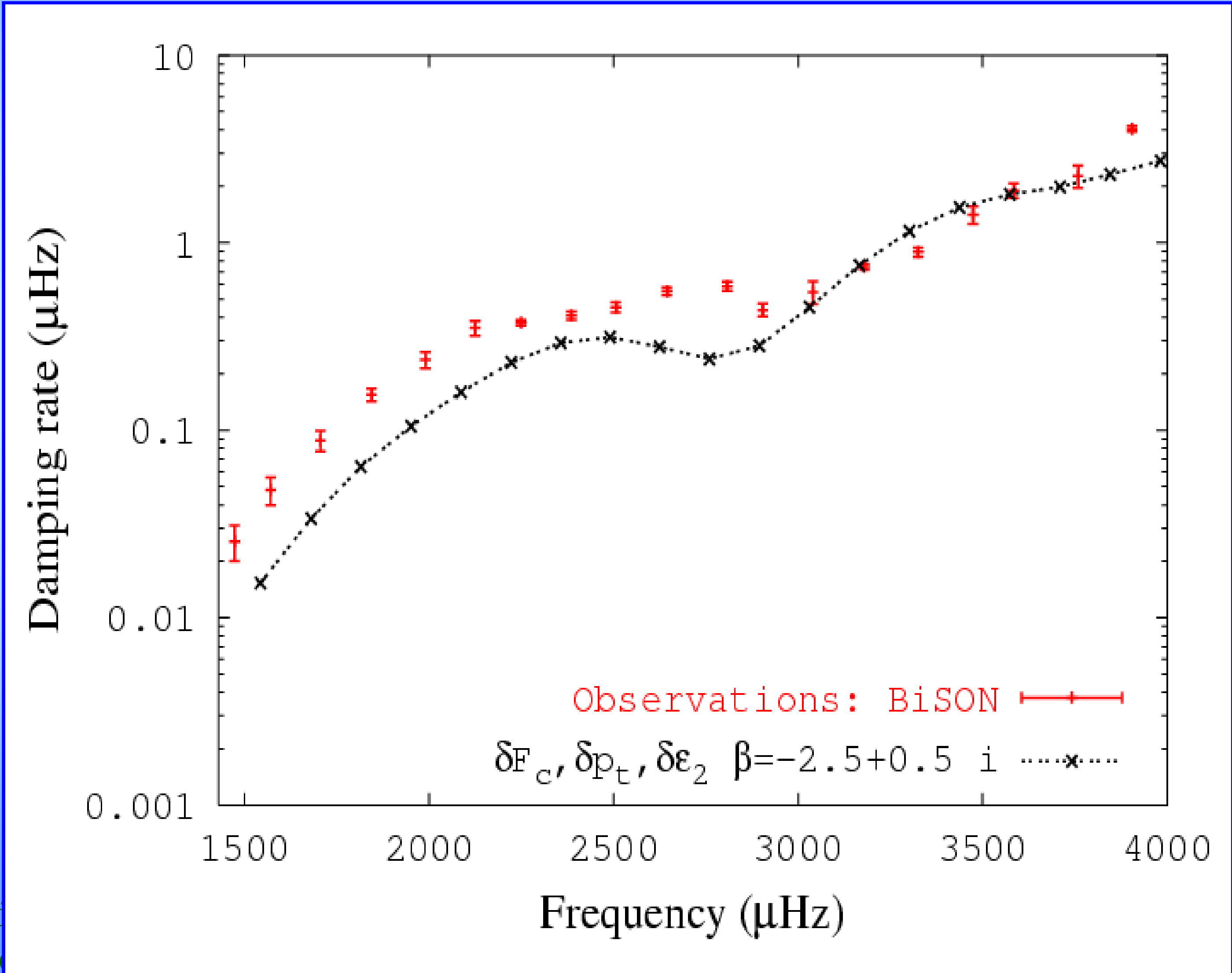
Solar-type oscillations: confrontation to observations

Theoretical damping rates ↔ line-widths observed by BiSON (Chaplin et al. 1997)



Solar-type oscillations: confrontation to observations

Theoretical damping rates ↔ line-widths observed by BiSON (Chaplin et al. 1997)

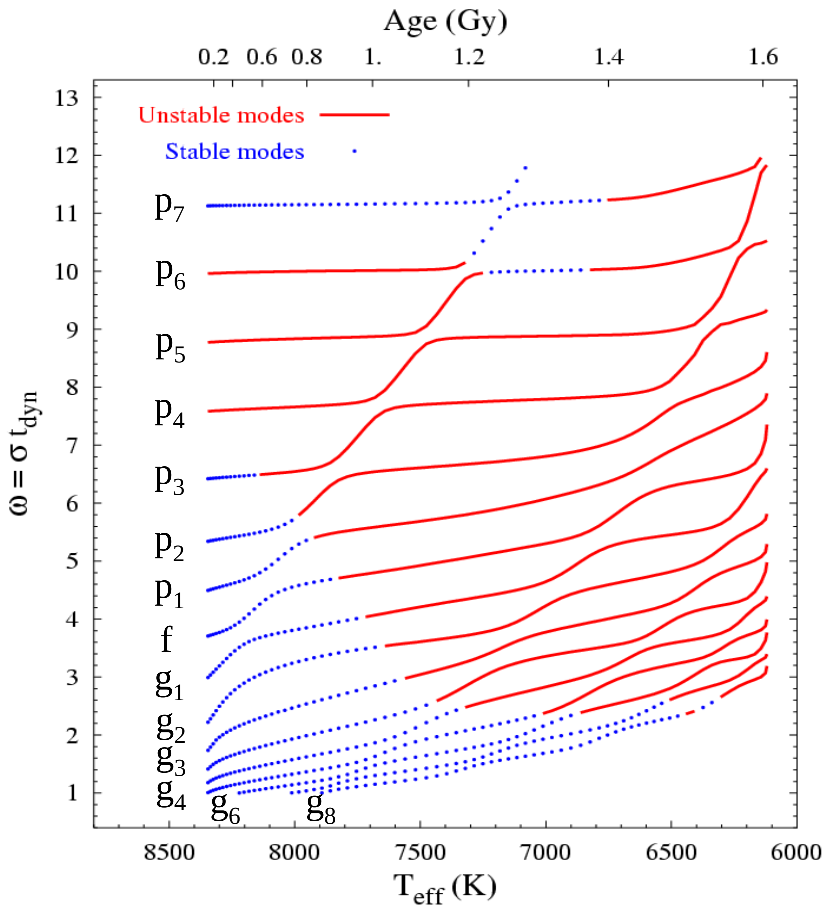


δ Scuti

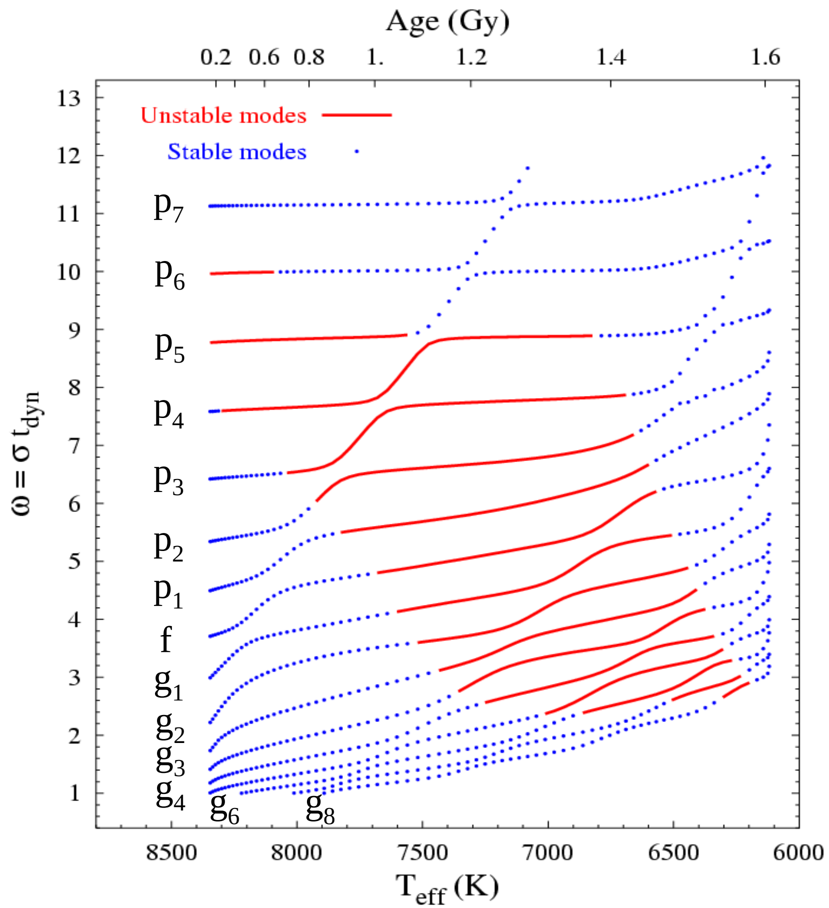
Stables and unstable modes

$\ell = 2$ - $1.8\ M_0$ - $\alpha = 1.5$

Frozen convection

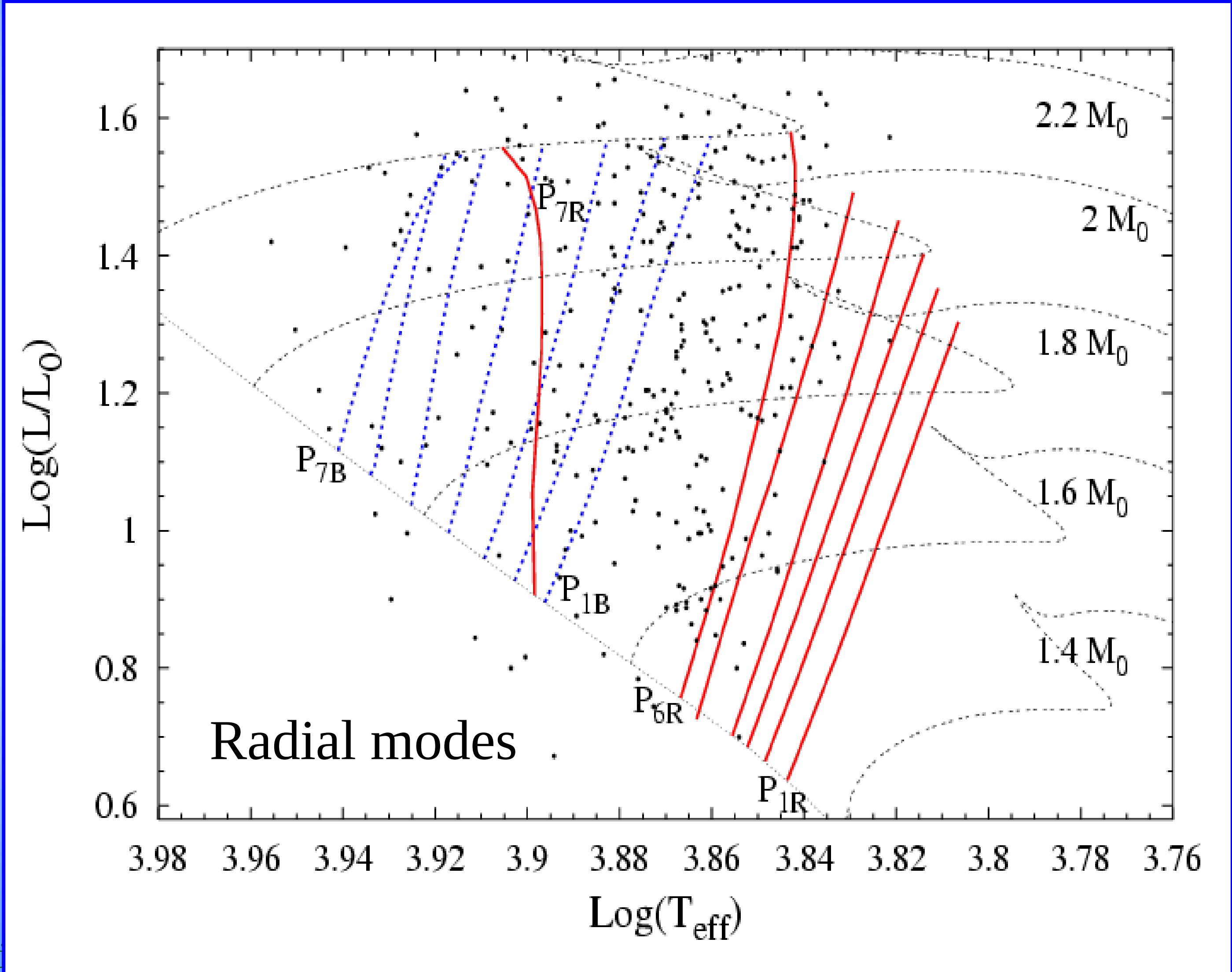


Time-dependent convection



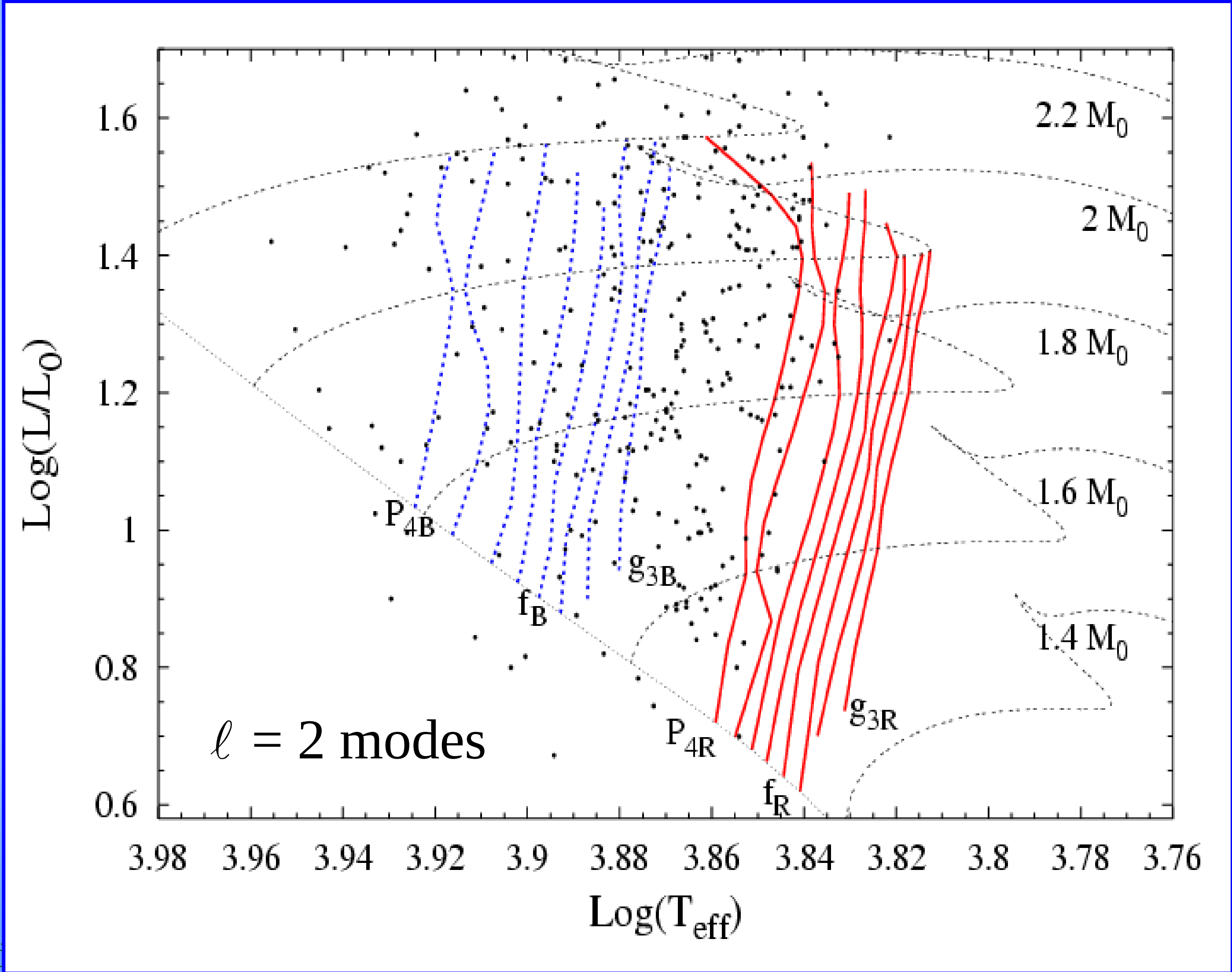
δ Scuti

Instability strips



δ Scuti

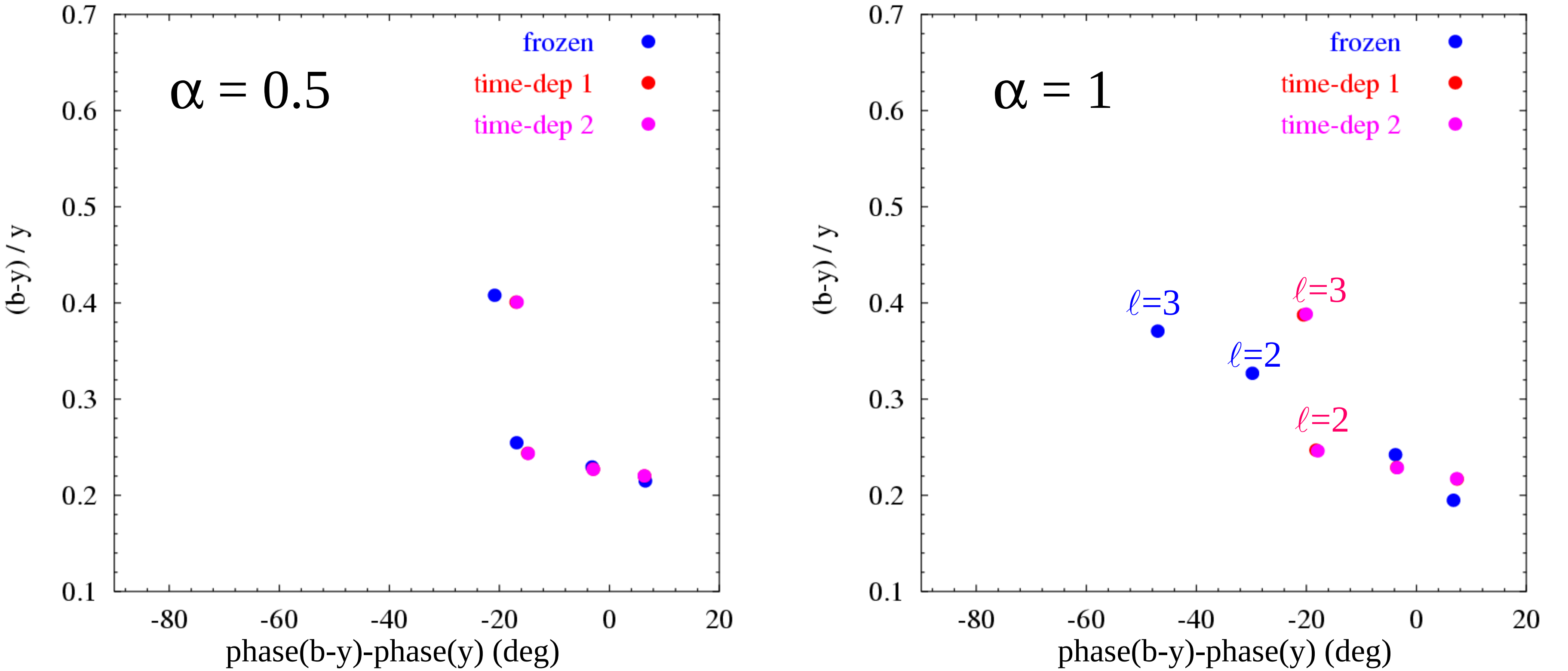
Instability strips



δ Scuti

Photometric amplitudes and phases

Amplitude ratios vs. phase difference - Stroemgren photometry



Conclusions

Convection-pulsation interaction in solar-like stars

Theoretical difficulties

Efficient part of convective envelope

Local treatment
→ Spatial oscillations of the eigenfunctions
→ Introduction of a free parameter β in the perturbation of the closure equations

Perturbation of turbulent pressure

→ Numerical instabilities

Confrontation to observations

Damping rates ⇔ Line-widths

Damping rates ⇔ Amplitudes

Stochastic excitation ⇔ Amplitudes

We found a model fitting the observed damping rates but …

Oscillations de type solaire

Mécanisme d´excitation : Excitation stochastique

→ Oscillateur vibrationellement stable
forcé stochastiquement par la convection

Taux de d´amortissement confrontables
aux observations (largeurs de raie)

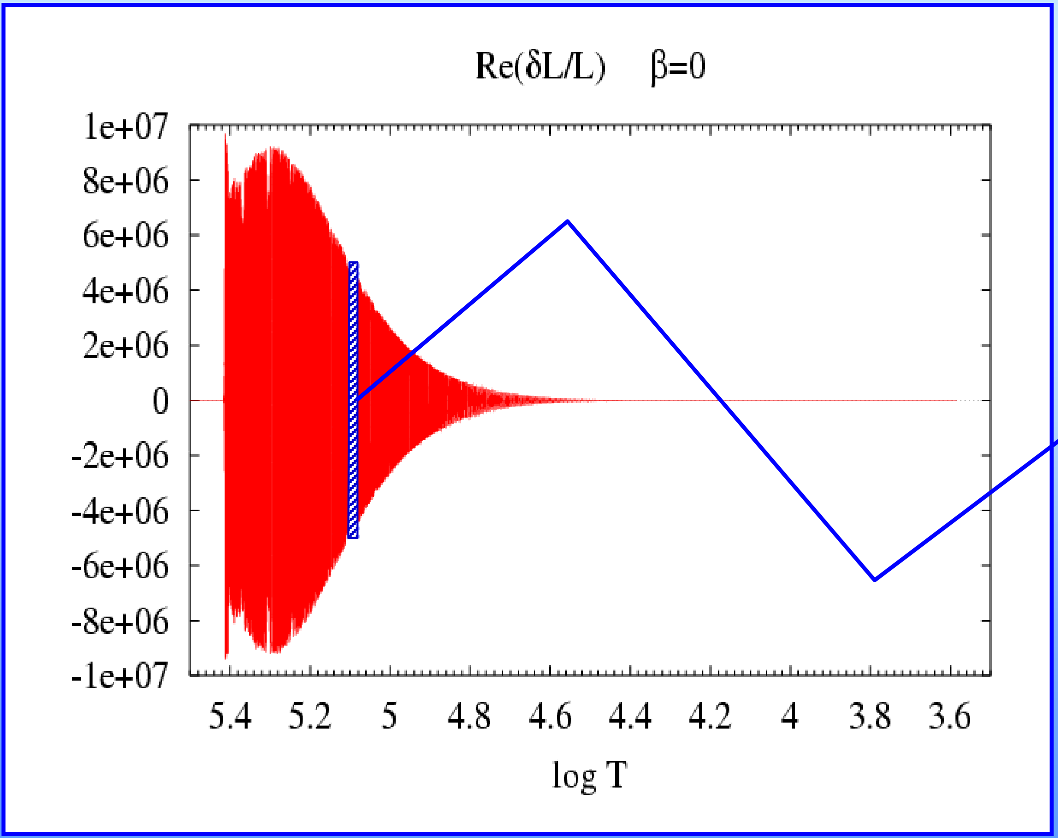
→ Contrainte sur les modèles non-adiabatiques
d´intéraction convection-oscillations

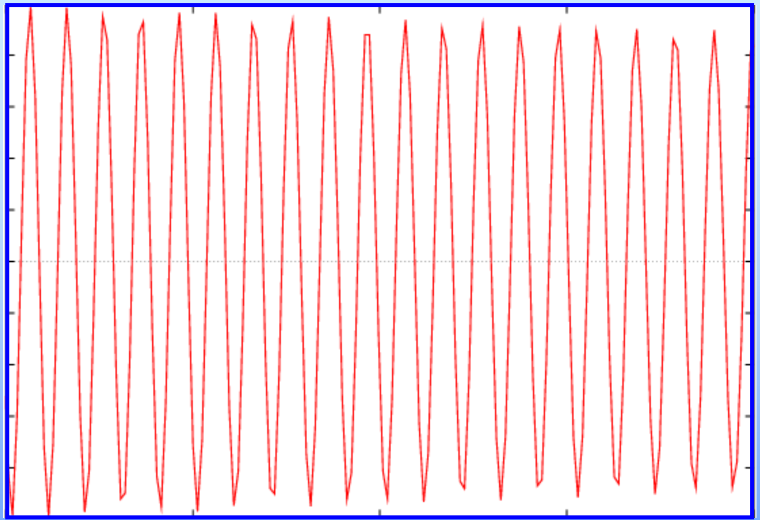
Oscillations de type solaire

Difficulté des modèles non-adiabatiques: intéraction convection-oscillations

Grande enveloppe convective
Convection efficace ($t_c >> t_p$)

→ Oscillations spatiales non-physiques des fonctions propres





Oscillations de type solaire

Difficulté des modèles non-adiabatiques: intéraction convection-oscillations

Grande enveloppe convective
Convection efficace ($t_c >> t_p$)

→ Oscillations spatiales non-physiques des fonctions propres

Solutions

- Non-locales (Balmforth 1992)
- Locales (Gabriel 2003)

→ Introduction de paramètres libres supplémentaires

Oscillations de type solaire

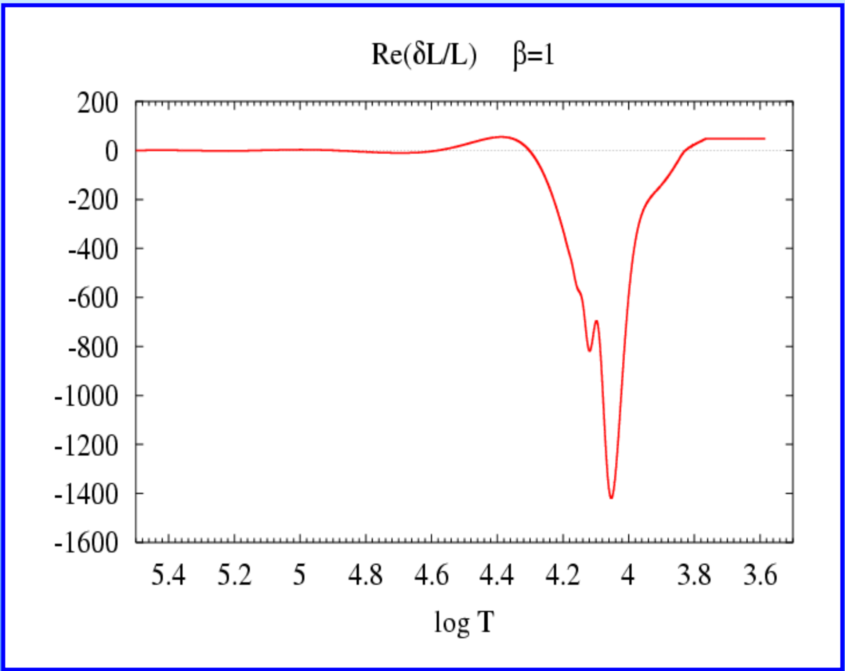
Difficulté des modèles non-adiabatiques: intéraction convection-oscillations

Grande enveloppe convective
Convection efficace ($t_c >> t_p$)

→

Oscillations spatiales non-physiques des fonctions propres

Solutions

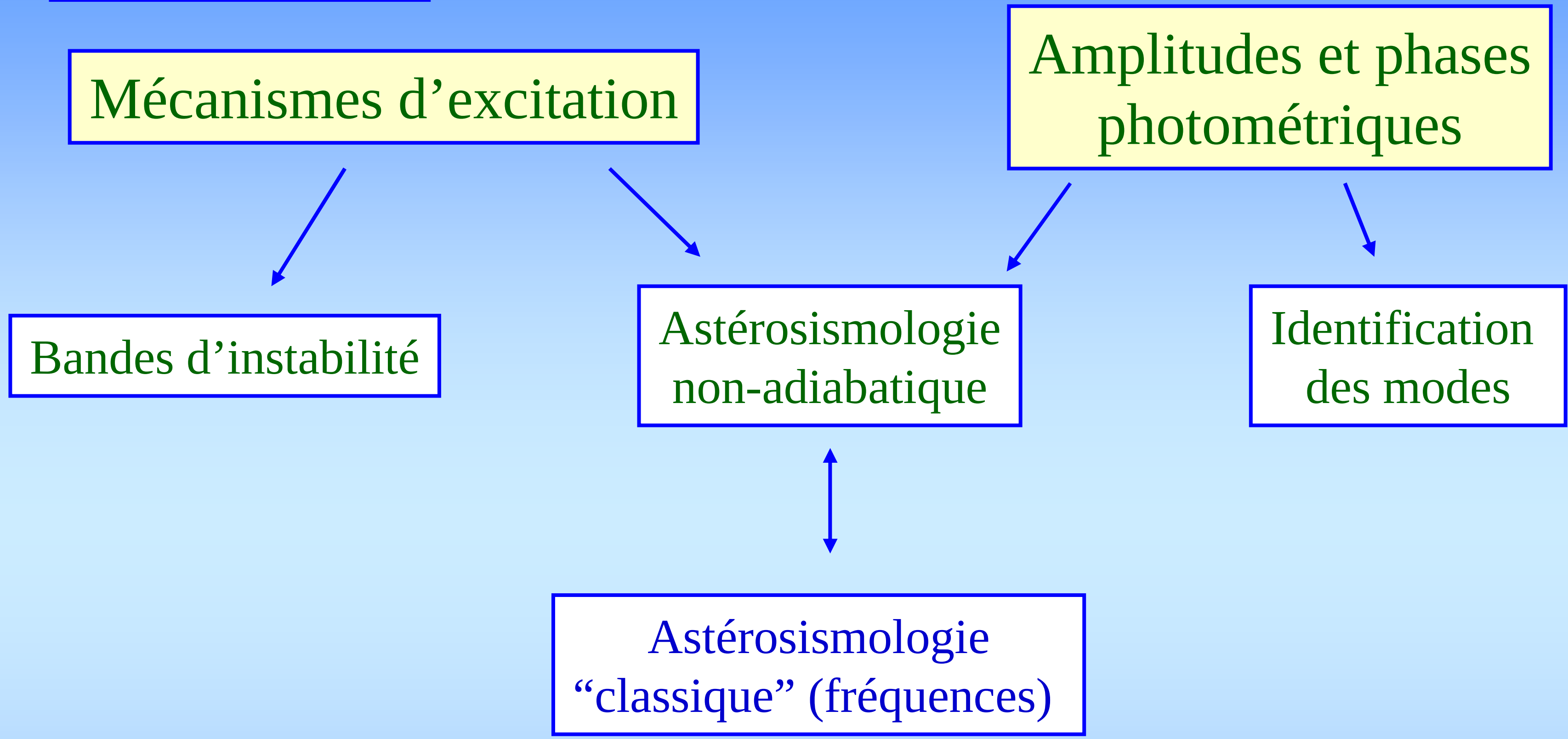


Locales (Gabriel 2003)

$$\frac{\Delta s}{\tau_C} = \frac{1}{\overline{\rho T}}\left[\rho\varepsilon_2 - \overline{\rho\varepsilon_2} + \rho T\nabla s \bullet \vec{V} - \overline{\rho T\nabla s \bullet \vec{V}} - \left(\nabla \bullet \vec{F}_R - \overline{\nabla \bullet \vec{F}_R}\right)\right]$$

$$\delta\left(\frac{\Delta s}{\tau_C}\right) = \frac{\Delta s}{\tau_C}\left((1+\beta\sigma\tau_C)\frac{\delta\Delta s}{\Delta s} - \frac{\delta\tau_C}{\tau_C}\right)$$

Conclusions



Conclusions

Mécanismes d'excitation → Bandes d'instabilité ; Astérosismologie non-adiabatique

Amplitudes et phases photométriques → Astérosismologie non-adiabatique ; Identification des modes

	Bandes d'instabilité	Astérosismologie non-adiabatique	Identification des modes
β Cephei **Modes p**	**Mécanisme κ (Fe)**	**Contraintes sur la métallicité**	**Marche très bien**
SPB **Modes g**	**Idem**	**Idem**	**OK mais effet de la rotation ?**

Conclusions

	Mécanismes d'excitation	Amplitudes et phases photométriques	
	Bandes d'instabilité	**Astérosismologie non-adiabatique**	**Identification des modes**
δ Scuti Modes p	**Frontière bleue: mécanisme κ (HeII)** **Frontière rouge: convection**	**Contraintes sur les modèles de convection et d'intéraction convection - pulsation**	**OK mais reste difficile** **Effet de la rotation ?**
γ Dor Modes g	**Bon accord avec α solaire**	**Idem**	**Nettement mieux avec l'intéraction convection-pulsation**

Mécanismes d'excitation → Bandes d'instabilité, Astérosismologie non-adiabatique

Amplitudes et phases photométriques → Astérosismologie non-adiabatique, Identification des modes

Conclusions

	Mécanismes d’excitation	Amplitudes et phases photométriques
Type solaire		
Modes p	**Excitation stochastique, modélisation difficile de l’intéraction convection – oscillations**	**Amplitudes données par les modèles d’excitation stochastique.**

Grands espoirs futurs :

Oscillations de type solaire

Difficulté des modèles non-adiabatiques:
intéraction convection-oscillations:

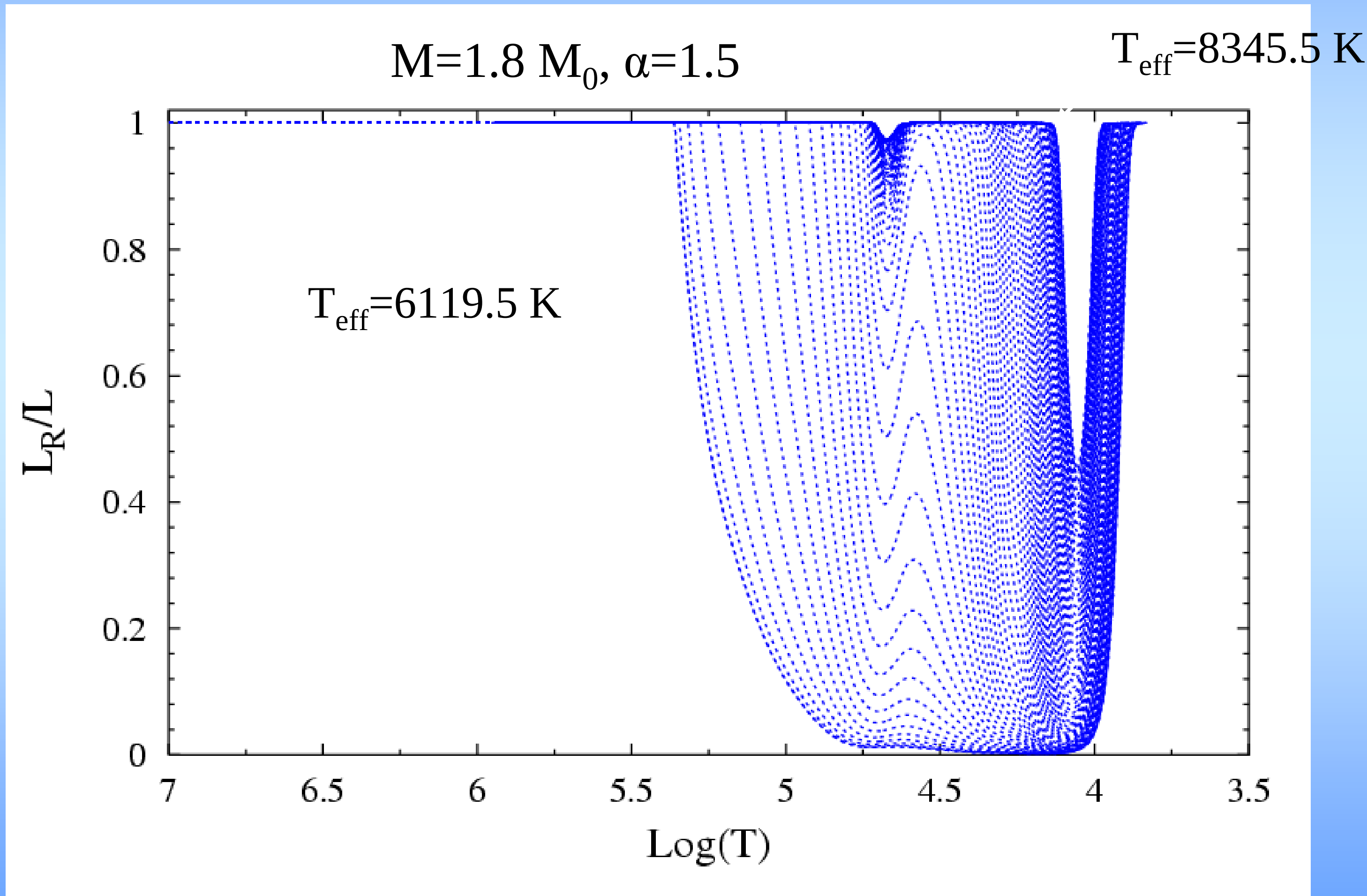
Solutions

Non-locales (Balmforth 1992)

Locales (Gabriel 2003)

δ Scuti

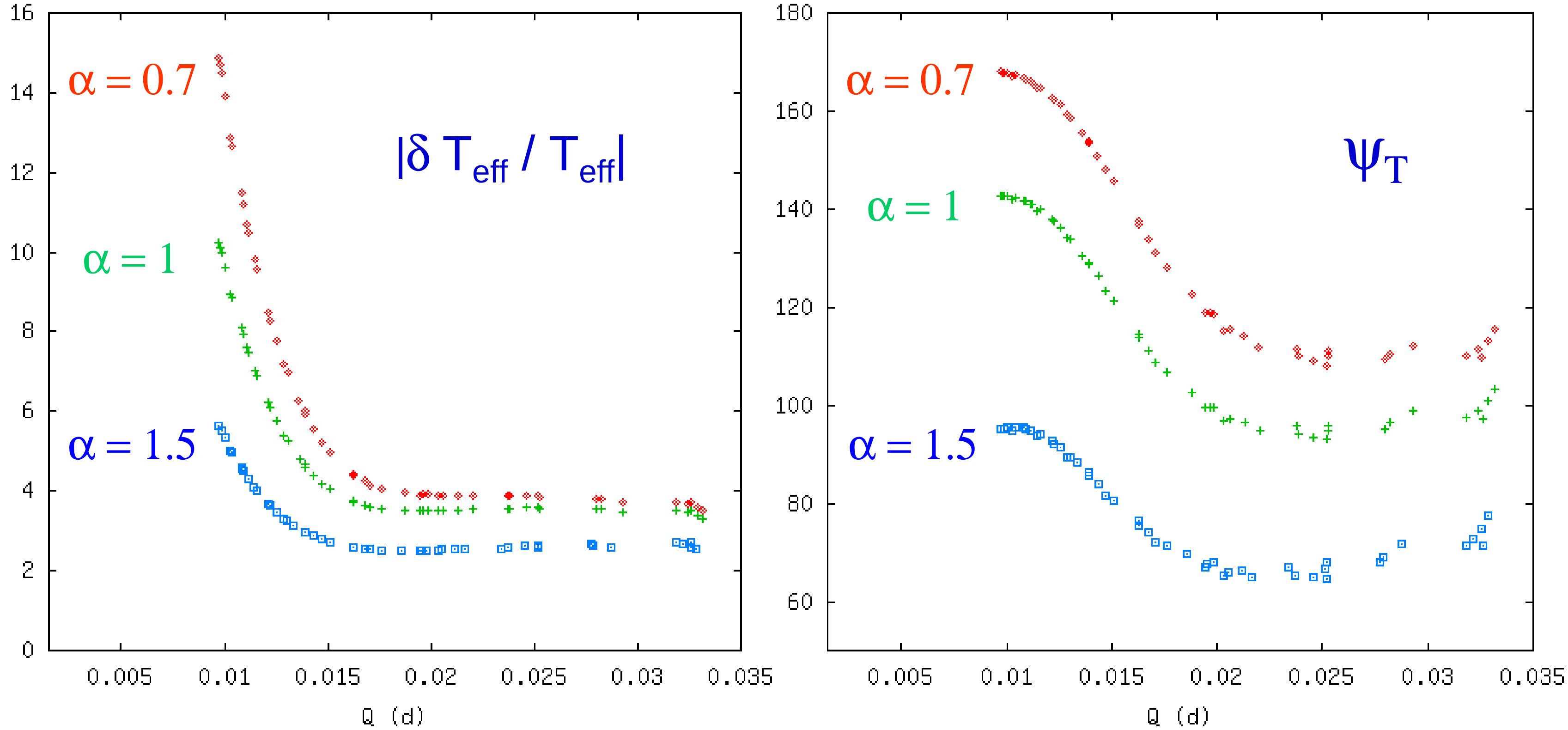
Taille de l´enveloppe convective pour différentes températures effectives



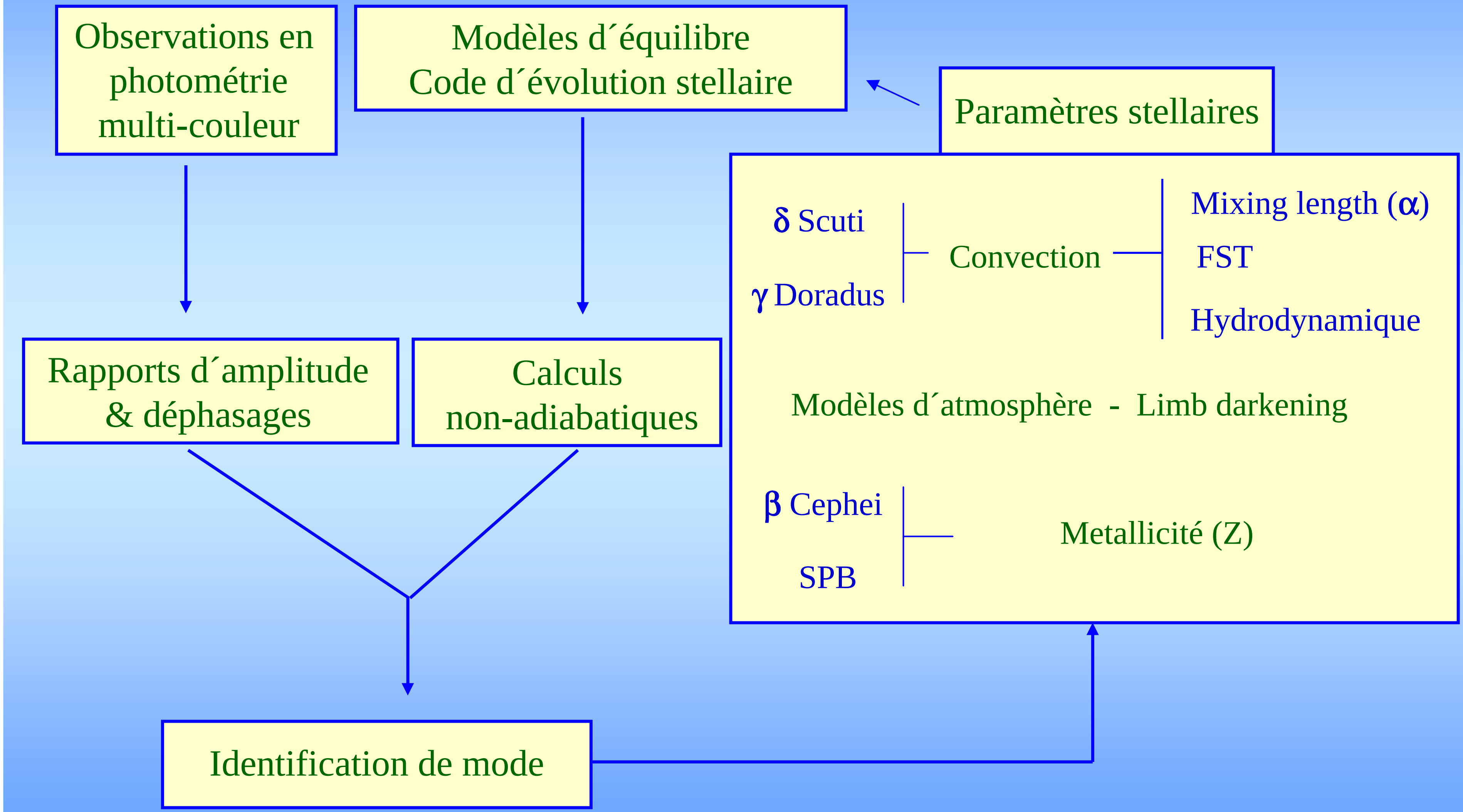
δ Scuti — Amplitudes et phases photométriques

Sensibilité à la structure de l´enveloppe convective

Longueur de mélange - différents α - convection gelée



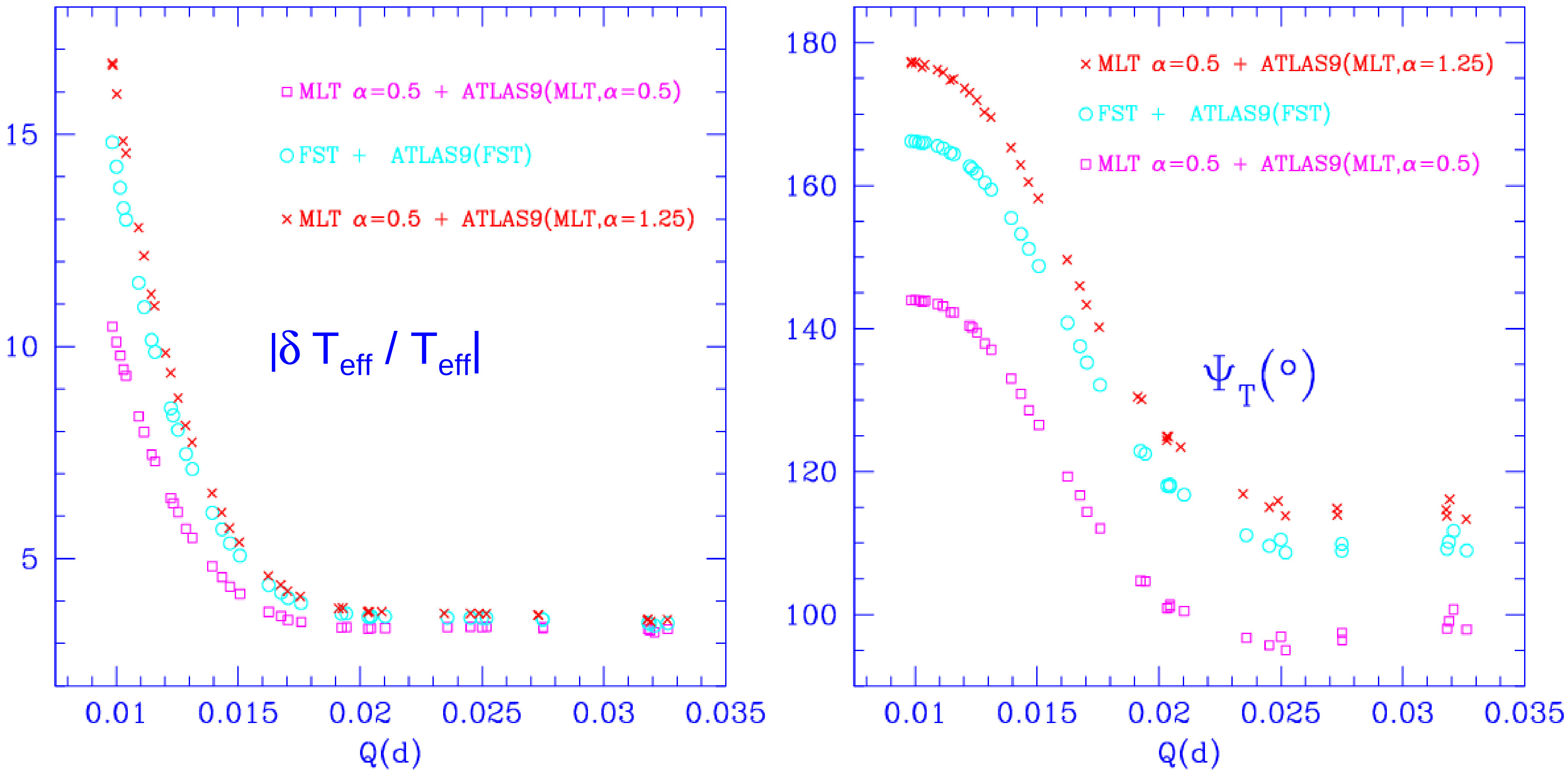
Photométrie multi-couleur et astérosismologie non - adiabatique



δ Scuti — Amplitudes et phases photométriques

Sensibilité à la structure de l´enveloppe convective

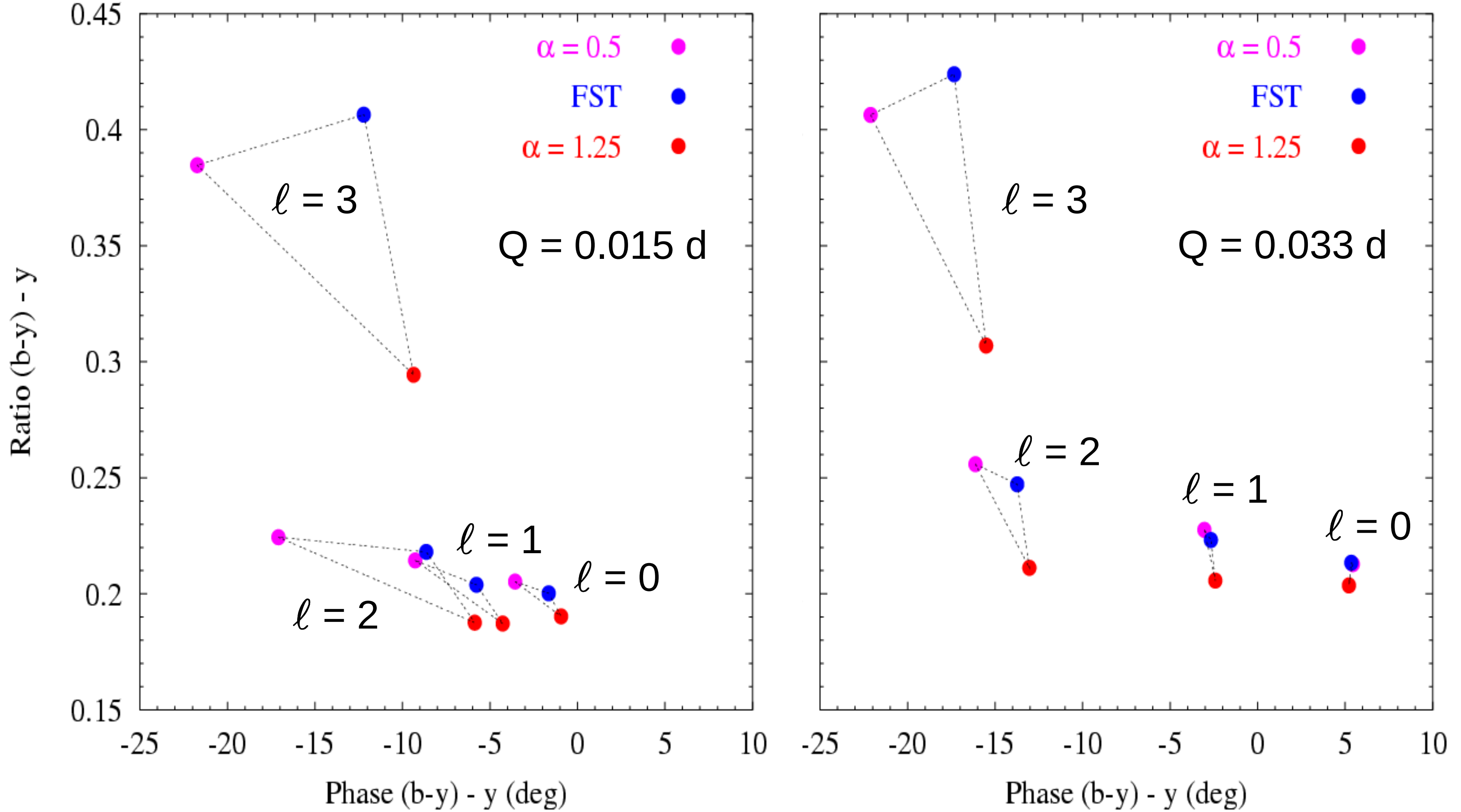
Full Spectrum of Turbulence ⟷ Longueur de mélange



δ Scuti — Amplitudes et phases photométriques

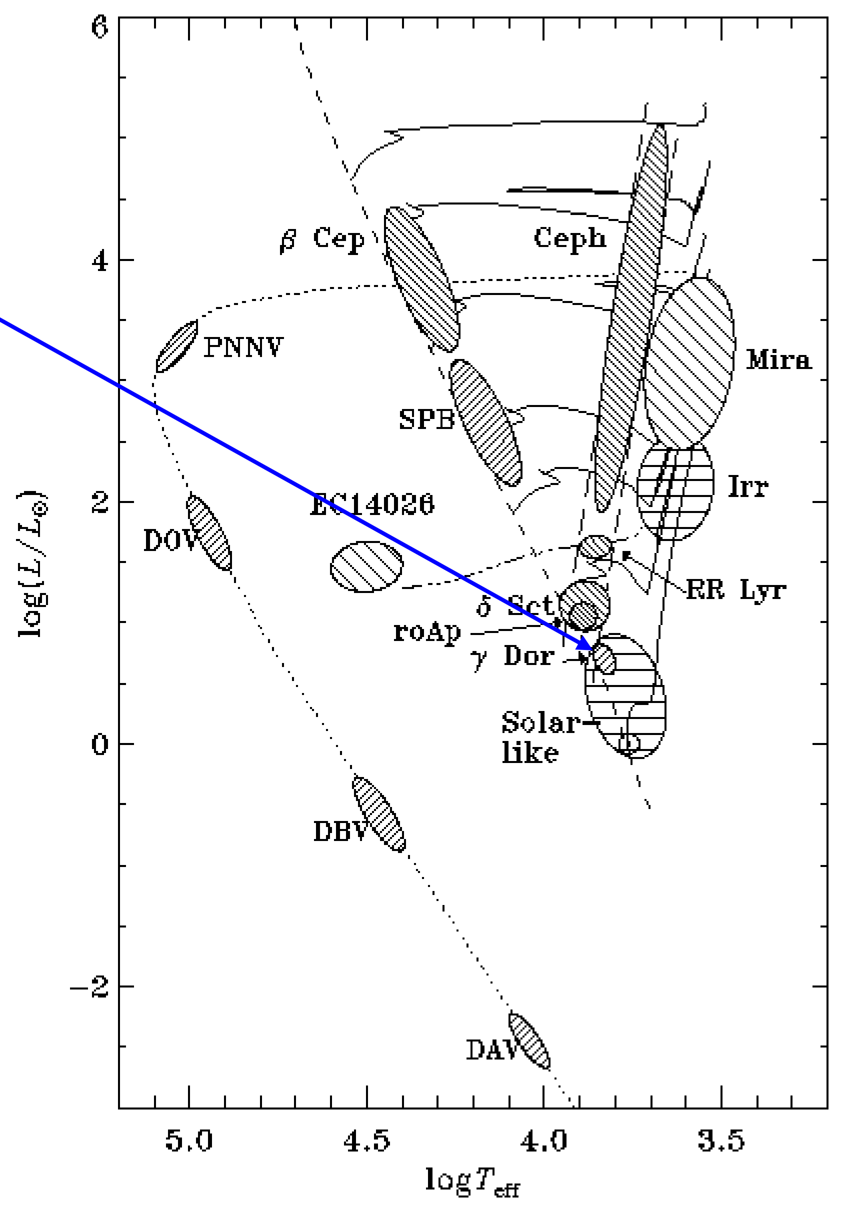
Full Spectrum of Turbulence ⟷ Longueur de mélange

Rapport d´amplitude vs. Différences de phase - photométrie Stroemgren



γ Doradus

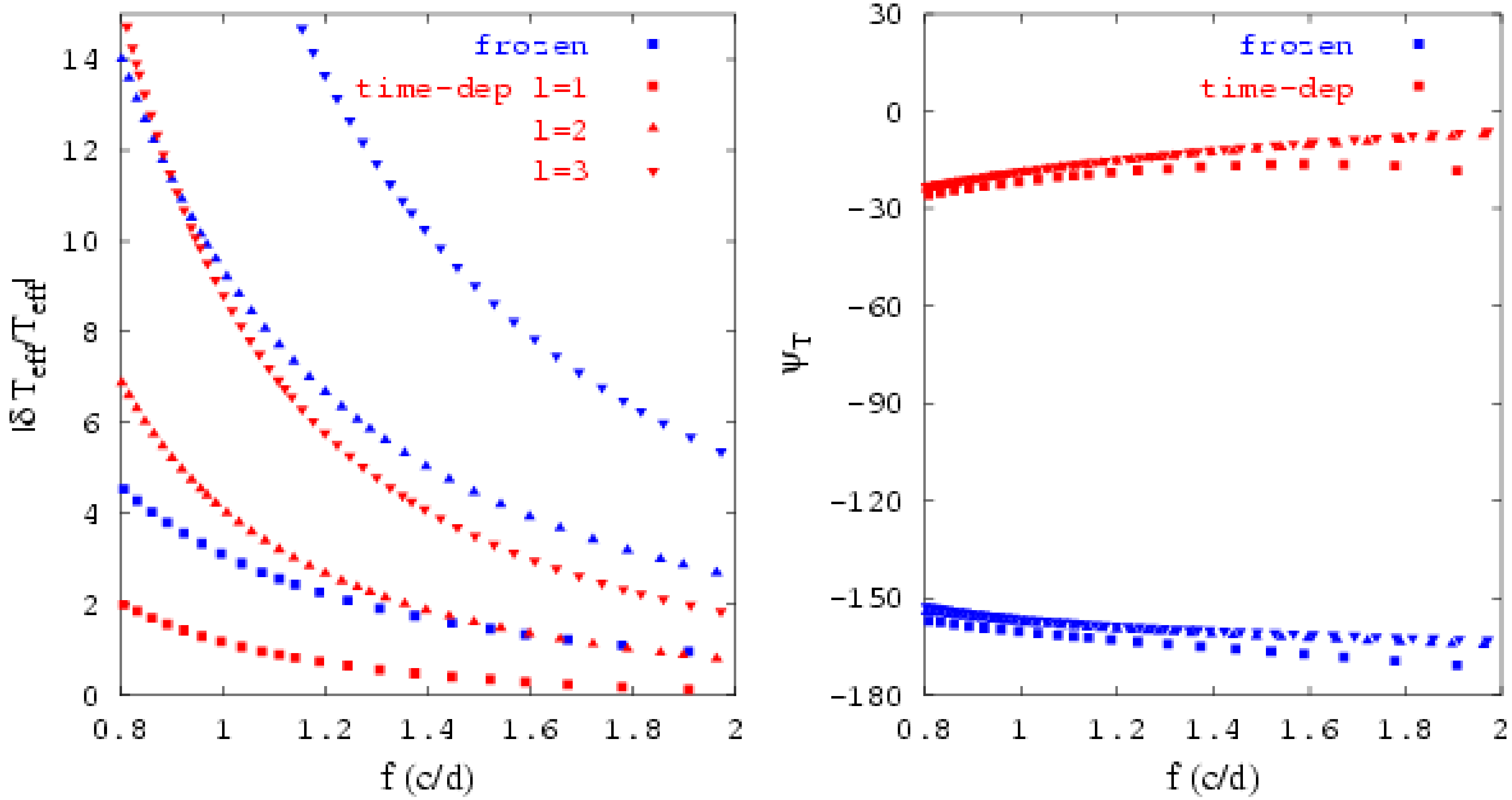
- Types spectraux
  - F
- Masses
  - +/- 1.5 M_0
- Périodes
  - 0.3 à 3 jours
  - modes g



γ Doradus | Amplitudes et phases photométriques

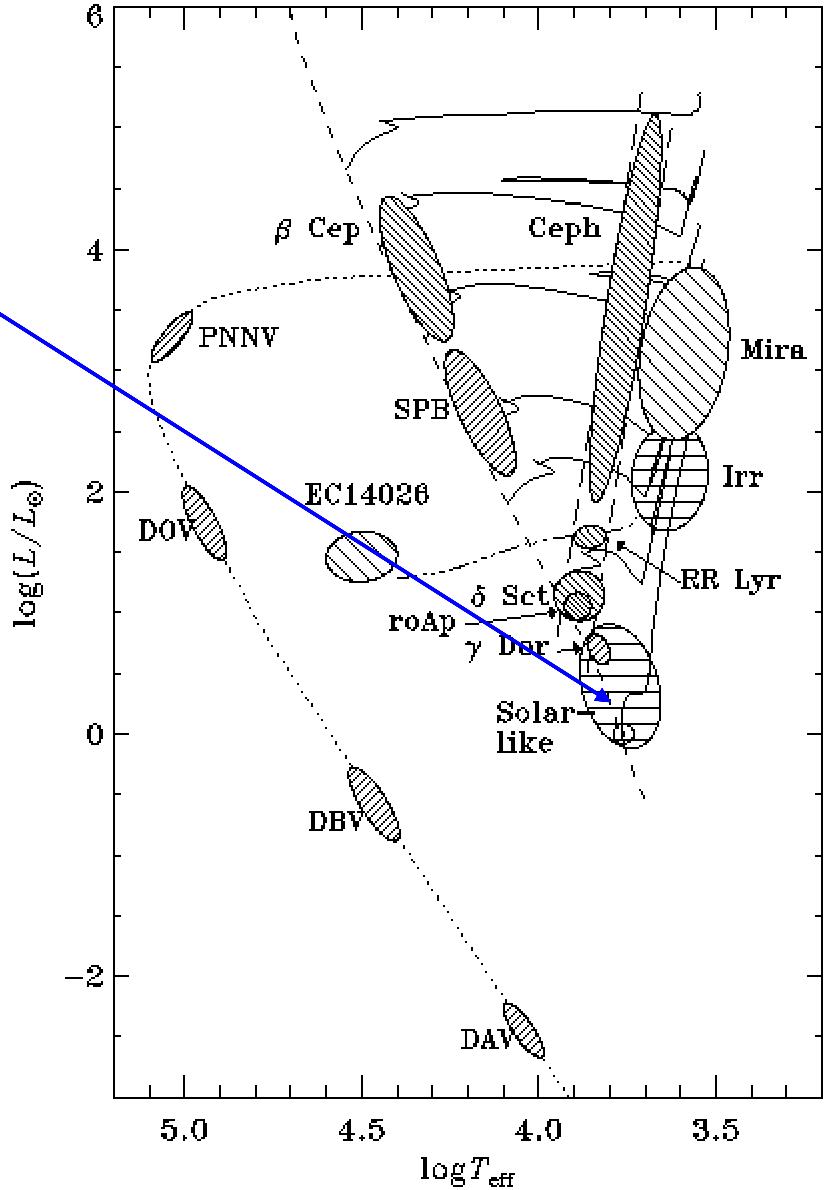
Comparaison : convection gelée
convection dépendant du temps

$M = 1.5\ M_0$ - $T_{eff} = 7000$ K - $\alpha = 1.8$



Type solaire

- Types spectraux
  - F et G
- Masses
  - 1 M_0 à 1.5 M_0
- Périodes
  - Quelques minutes
  - Modes p élevés
  - Faibles amplitudes



Utility of our non - adiabatic code

- Excitation mechanisms
- Multi-colour photometry

Photometric amplitudes
and phases in different filters

→ Identification
of the degree ℓ

→ Non - adiabatic
asteroseismology

Non adiabatic oscillations
at the photosphere

→ Need of a non - adiabatic code
for the confrontation between theory
and observations

Introduction

Stellar pulsations

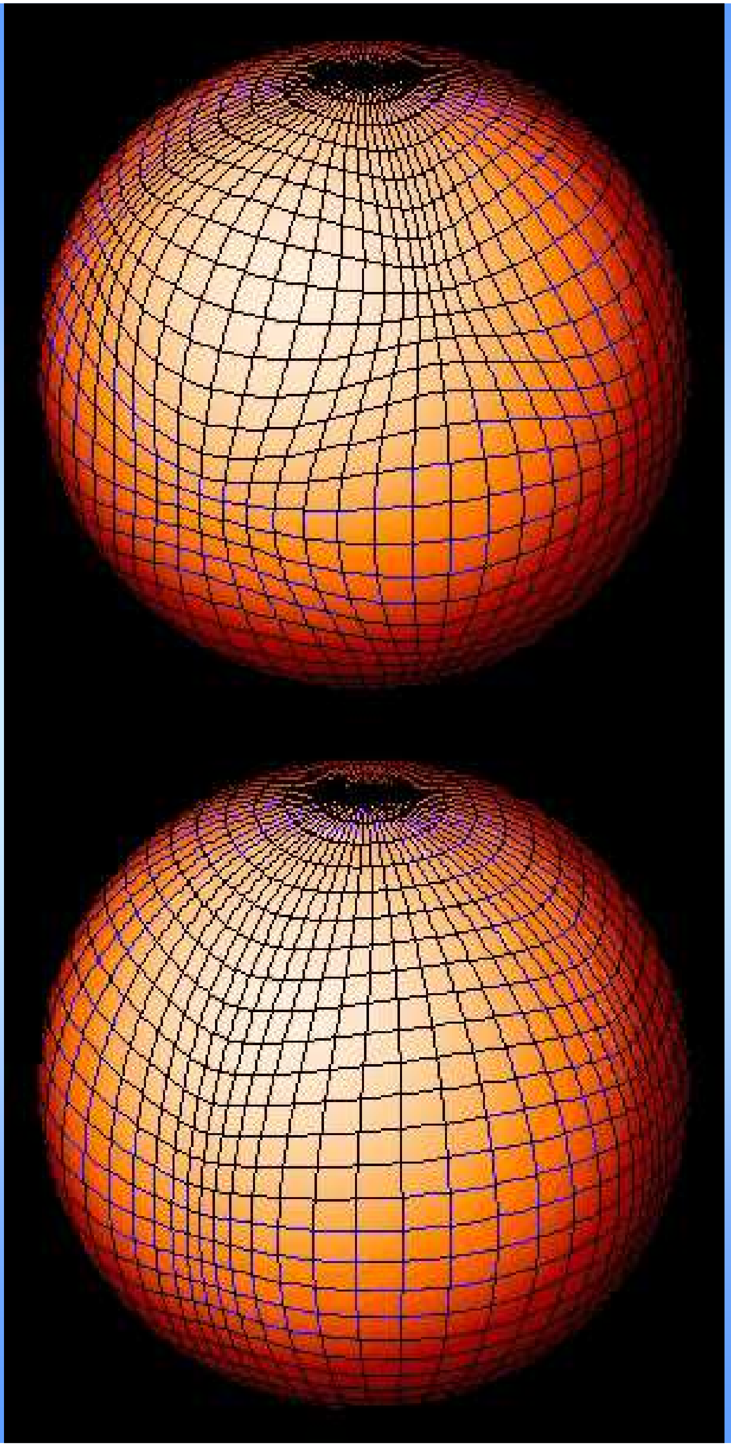
- Pressure modes

  Acoustic waves

- Gravity modes

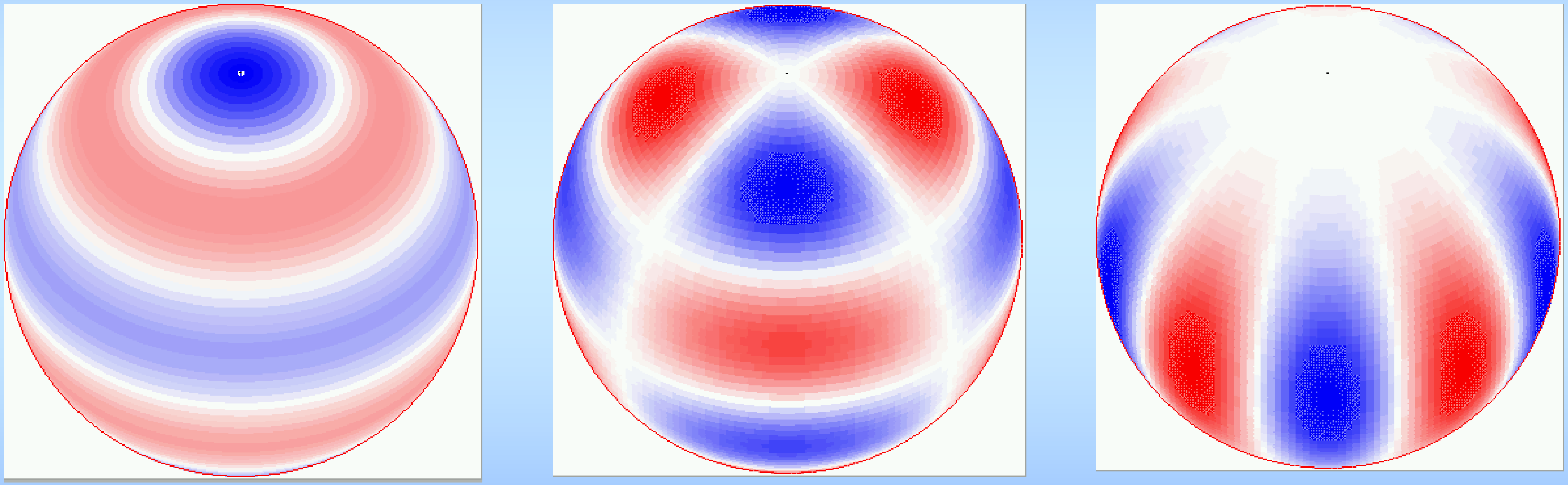
  Buoyancy force

Asteroseismology



1) Non - radial non - adiabatic stellar oscillations

Splitting in spherical harmonics



p - modes → Acoustic waves

g - modes → Buoyancy force

1) Non - radial non - adiabatic stellar oscillations

$$\delta S \neq 0$$

↓

Coupling between the dynamical and thermal equations

- Equation of momentum conservation
- Equation of mass conservation
- Poisson equation

- Equation of energy conservation
- Equations of transfer by radiation and convection

Monochromatic magnitude variation

$$\delta m_\lambda = -\frac{2.5}{\ln 10}\,\varepsilon\,P_\ell^m(\cos i)\,b_{\ell\lambda}\Bigg[-(\ell-1)(\ell+2)\cos(\sigma t) + \left(\frac{\partial \ln F_\lambda^+}{\partial \ln T_{\rm eff}} + \frac{\partial \ln b_{\ell\lambda}}{\partial \ln T_{\rm eff}}\right)\left|\frac{\delta T_{\rm eff}}{T_{\rm eff}}\right|\cos(\sigma t + \psi_T) - \left(\frac{\partial \ln F_\lambda^+}{\partial \ln g} + \frac{\partial \ln b_{\ell\lambda}}{\partial \ln g}\right)\left|\frac{\delta g_e}{g_e}\right|\cos(\sigma t)\Bigg]$$

Influence of the local effective temperature variations

Stellar surface distortion

Equilibrium atmosphere models (Kurucz 1993)

Influence of the local effective gravity variations

Non - adiabatic computations

Filters → Integration on the pass-band

Linear computations → Amplitude ratios and phase differences

Dependence with the degree ℓ → Identification of ℓ

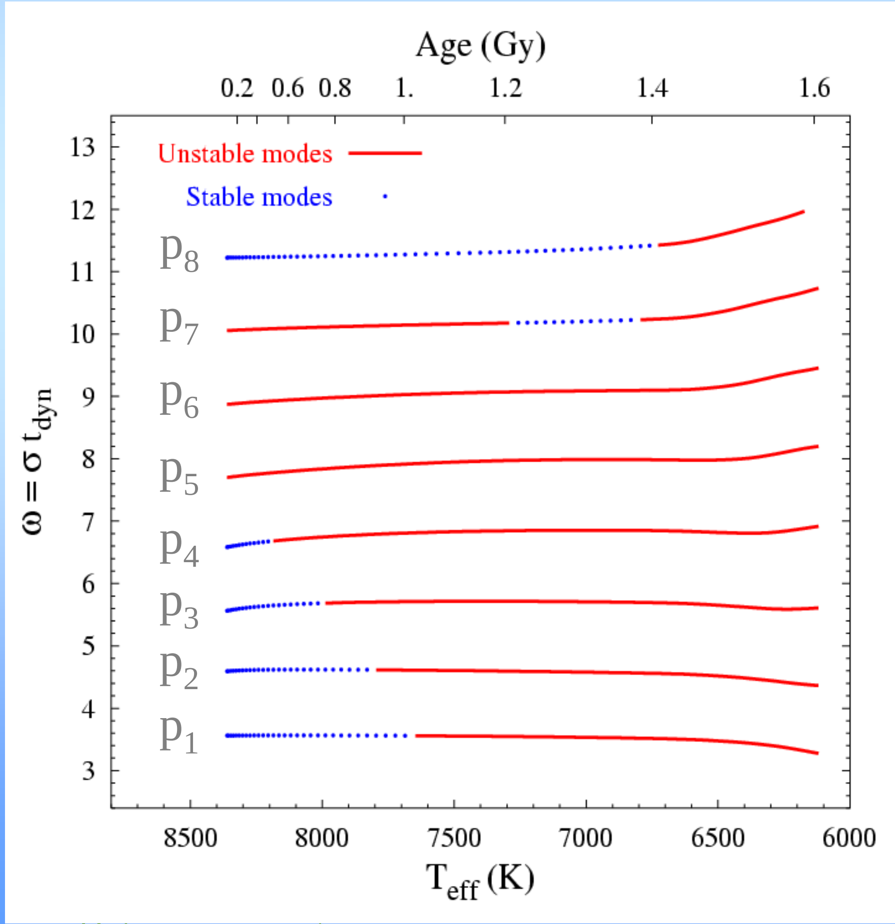
4.2 δ Scuti

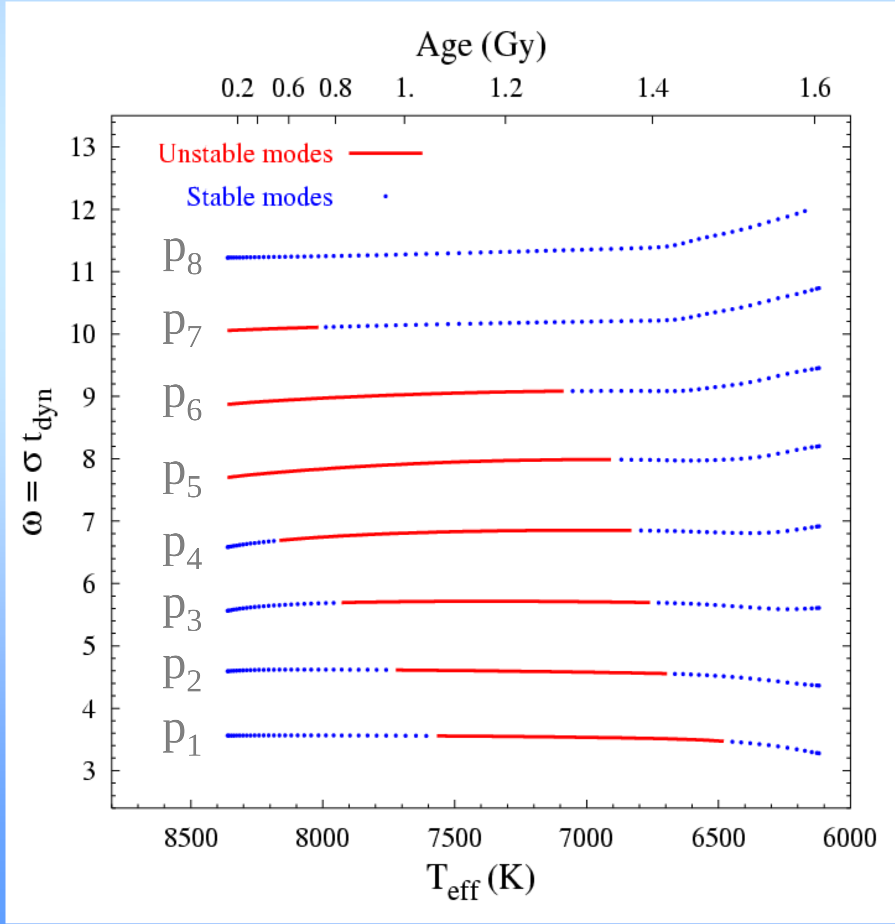
Time dependent convection - MLT
Theory of M. Gabriel

Red edge of the instability strip

Radial modes – 1.8 M_0 , α = 1.5

Frozen convection | Time-dependent convection



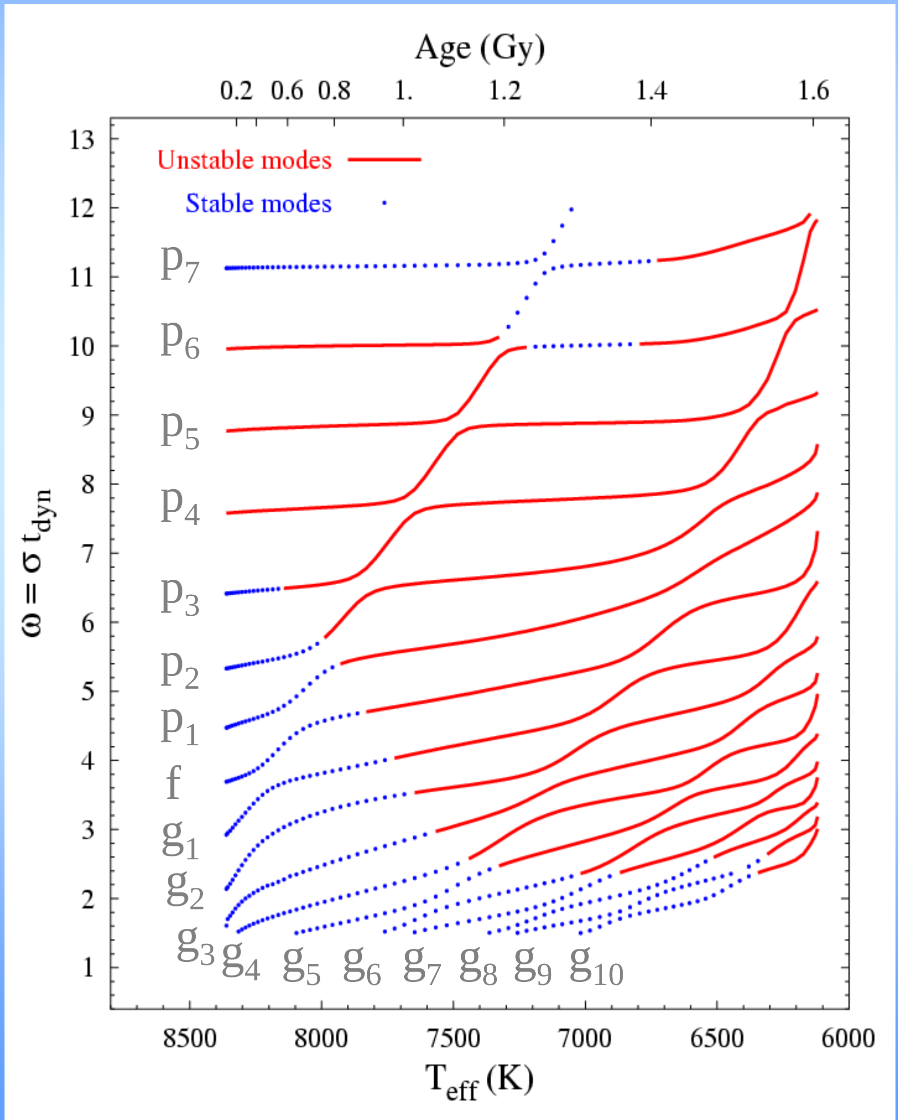


4.2 δ Scuti

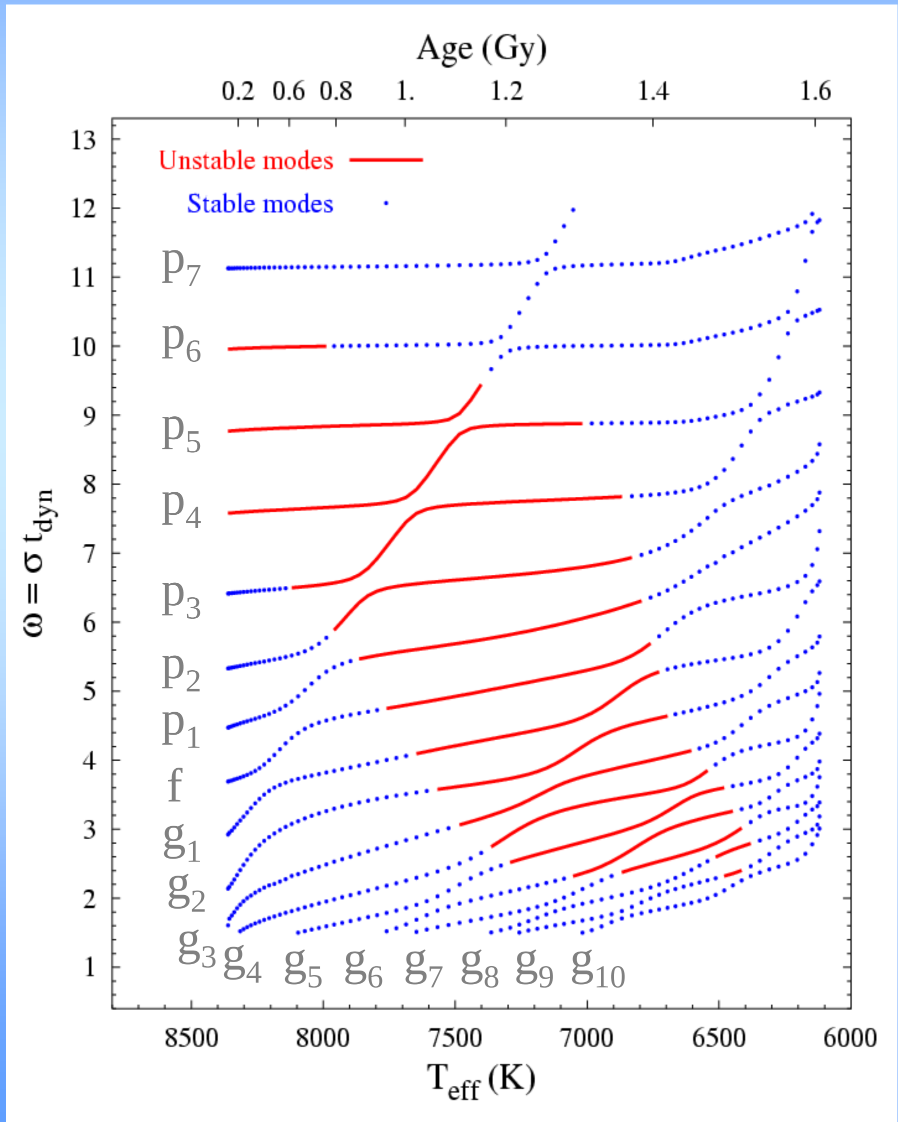
Red edge of the instability strip

ℓ = 2 modes – 1.8 M_0 , α = 1.5

Frozen convection



Time-dependent convection



Frozen Convection

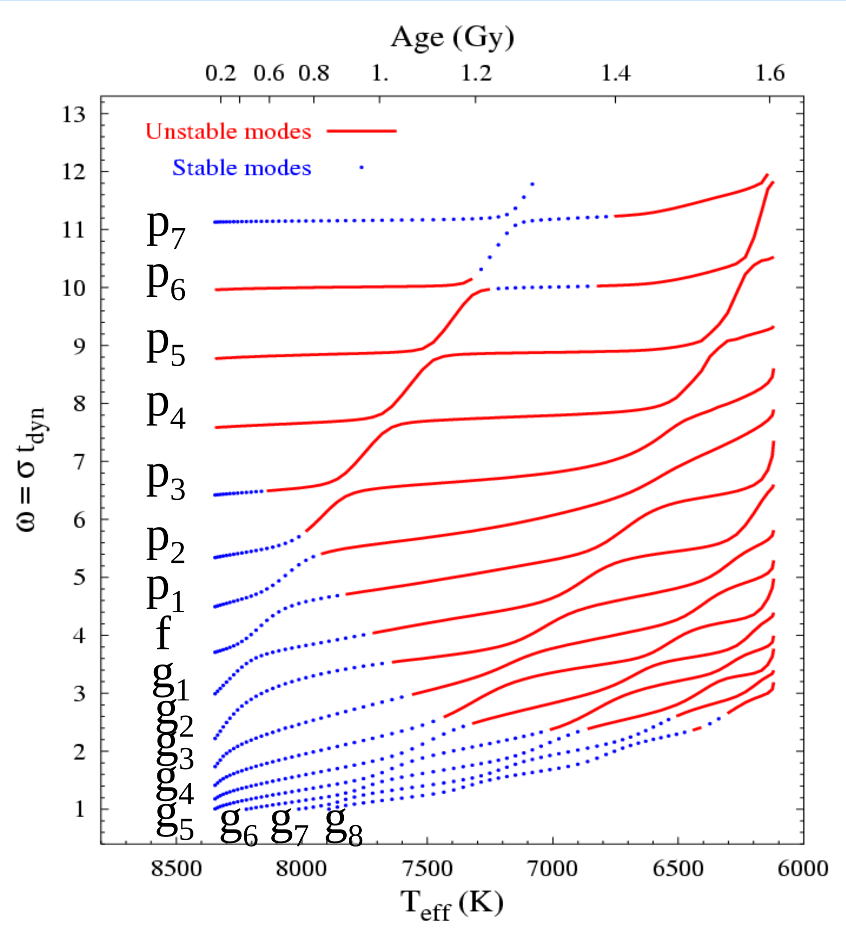


Figure 5

Time-dependent convection

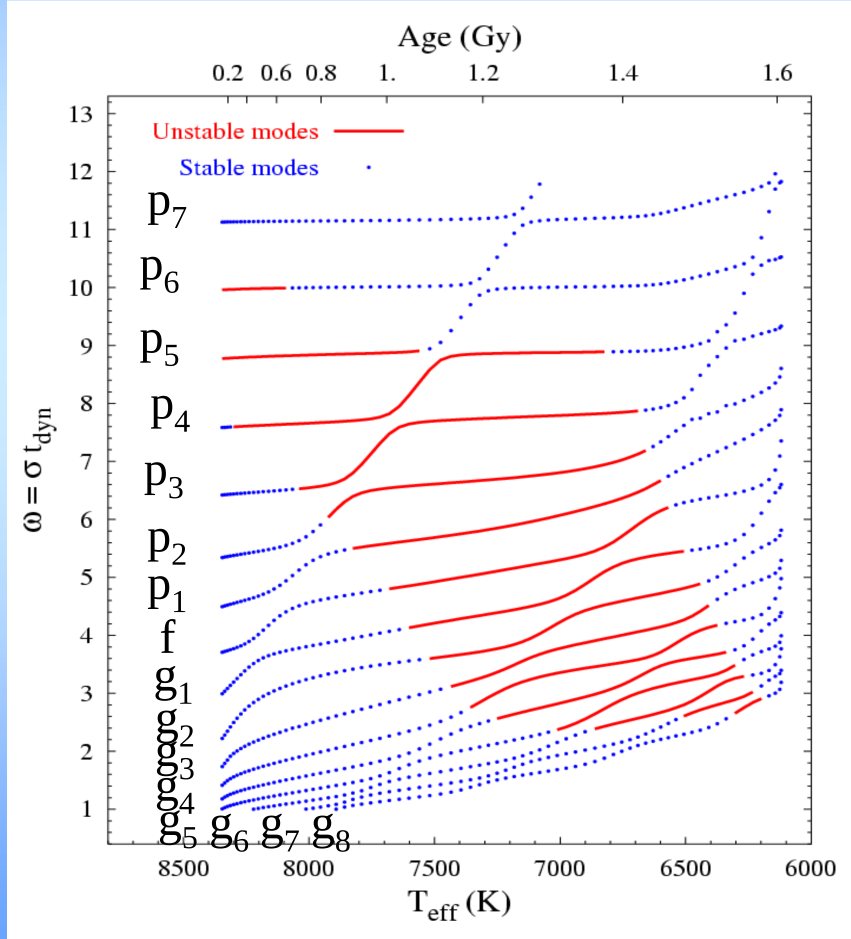
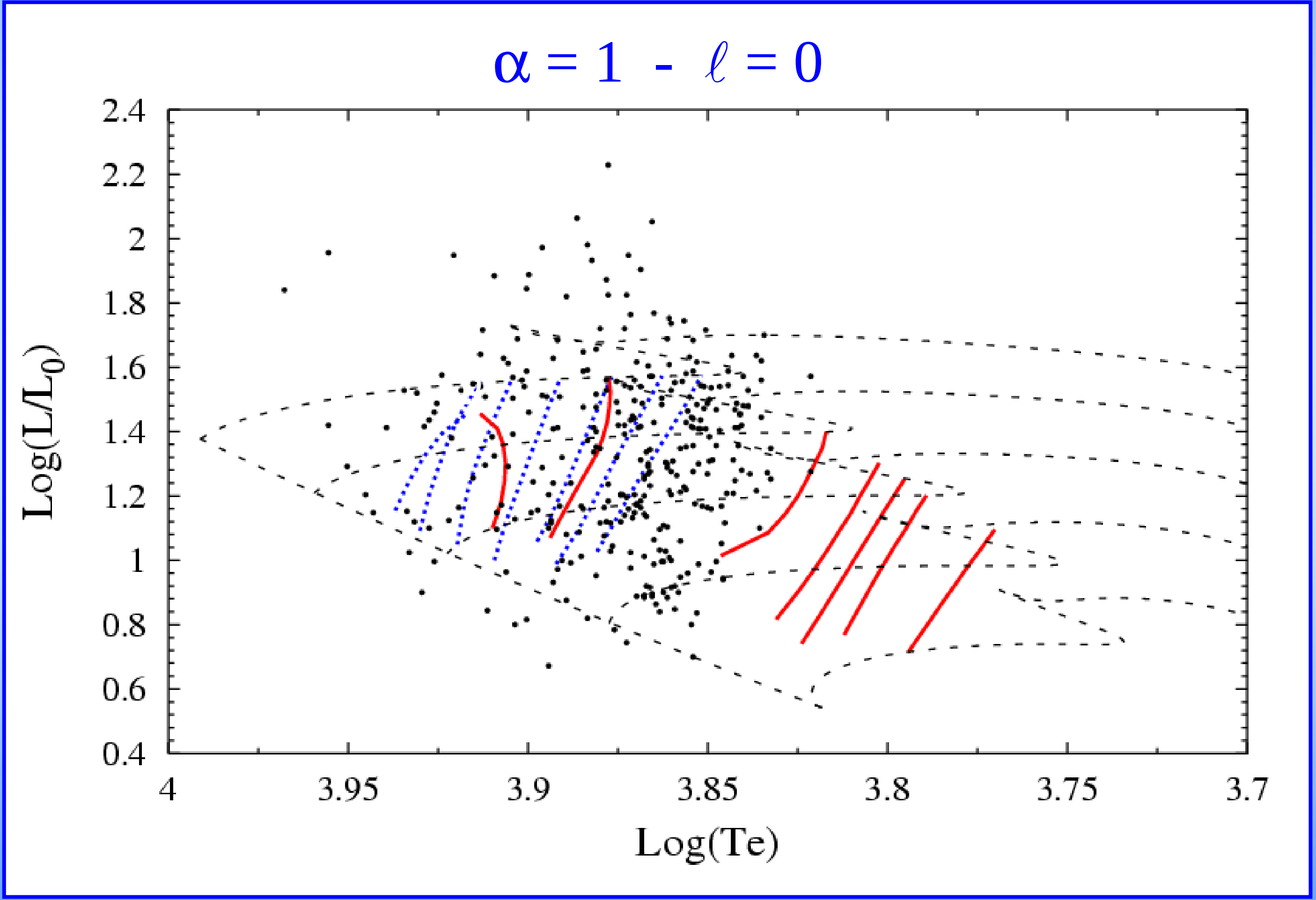


Figure 6

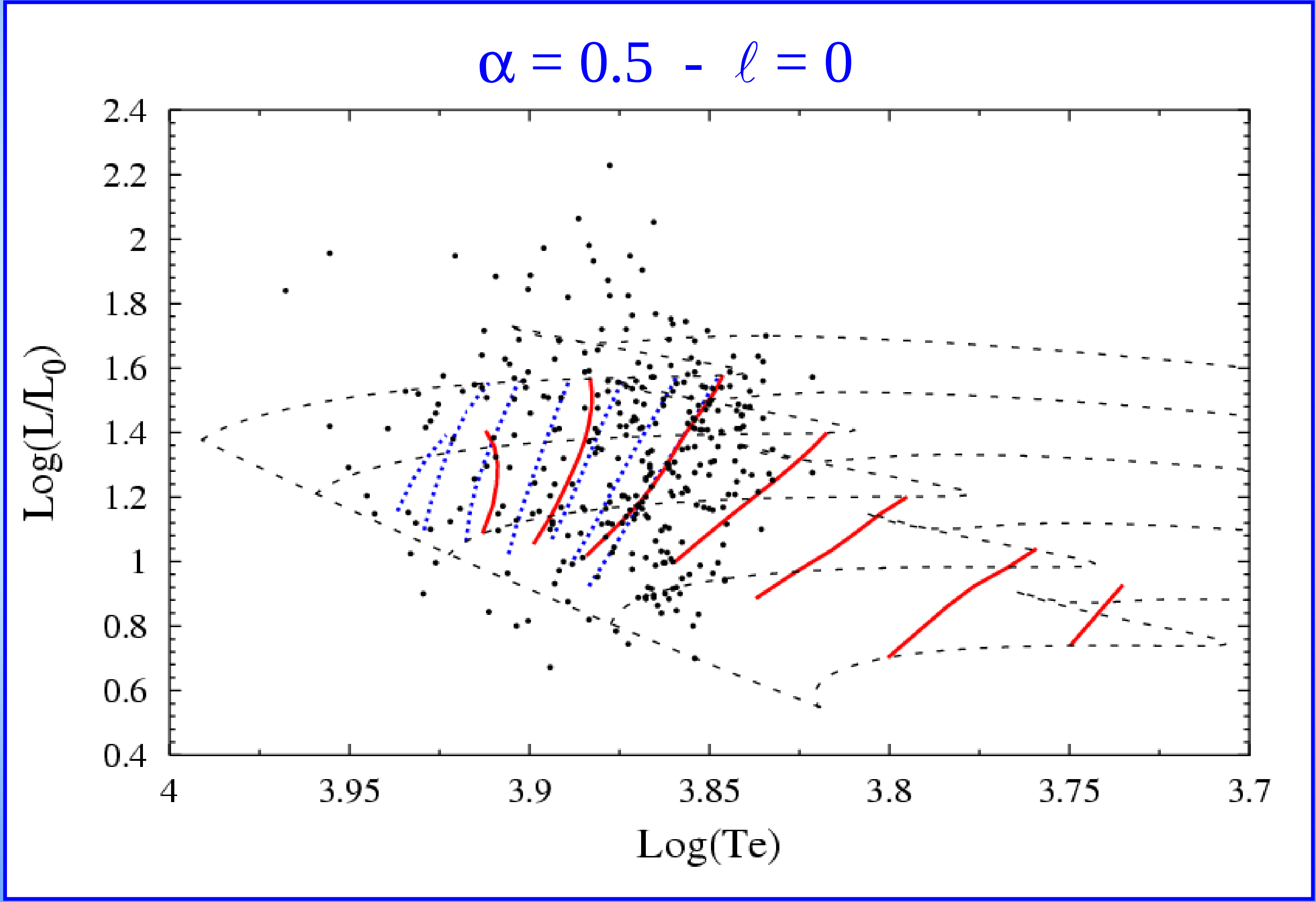
δ Scuti

Bandes d´instabilité



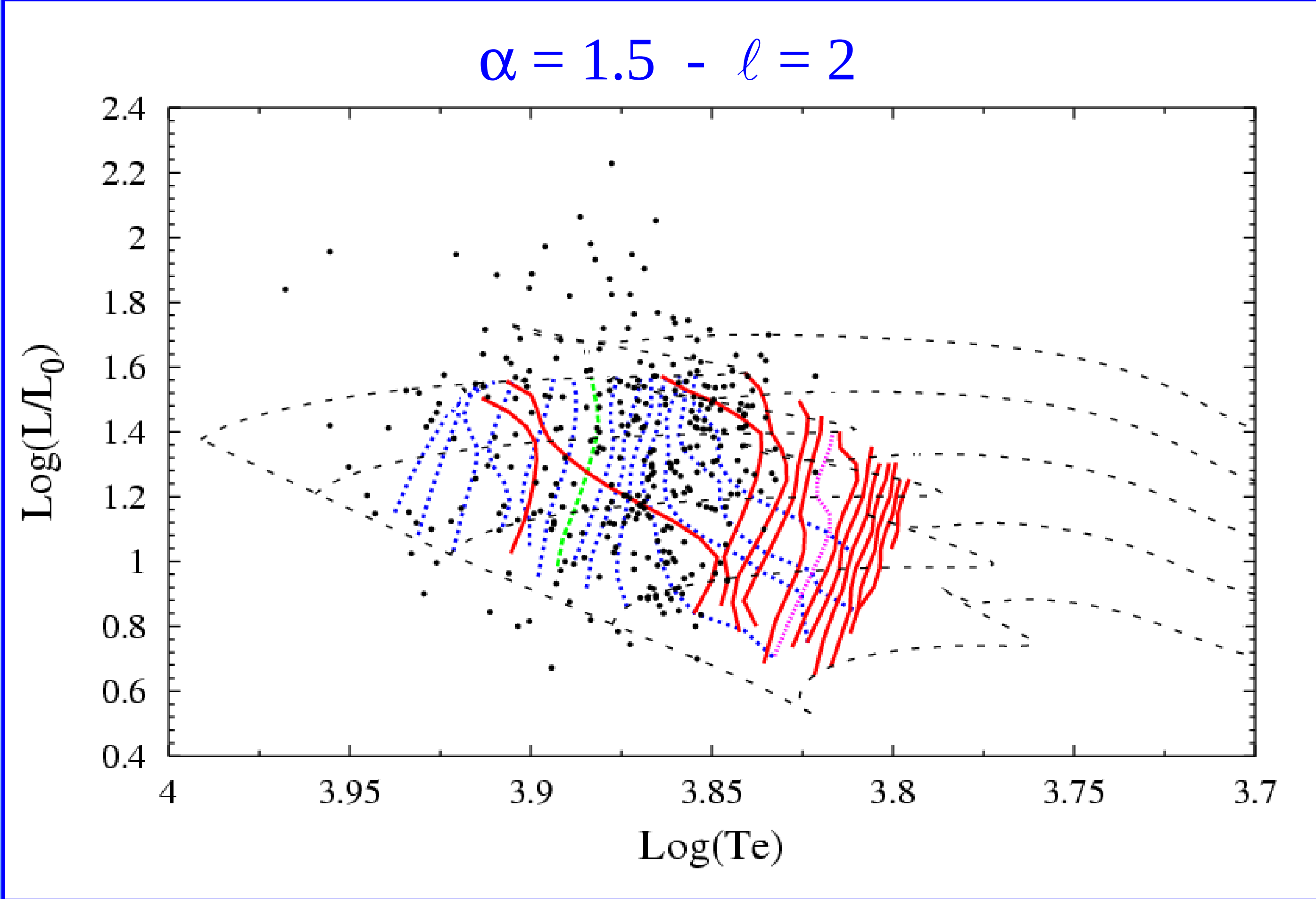
δ Scuti

Bandes d´instabilité



δ Scuti

Bandes d´instabilité



Plan de l'exposé

1. Introduction
2. Oscillations stellaires non-adiabatiques : utilité
3. Modélisation du problème
   - Atmosphère
   - Convection
4. Applications
   - β Cephei
   - Slowly Pulsating B
   - δ Scuti
   - γ Doradus
   - Type solaire
5. Conclusions

β Cephei

Multi-colour photometry

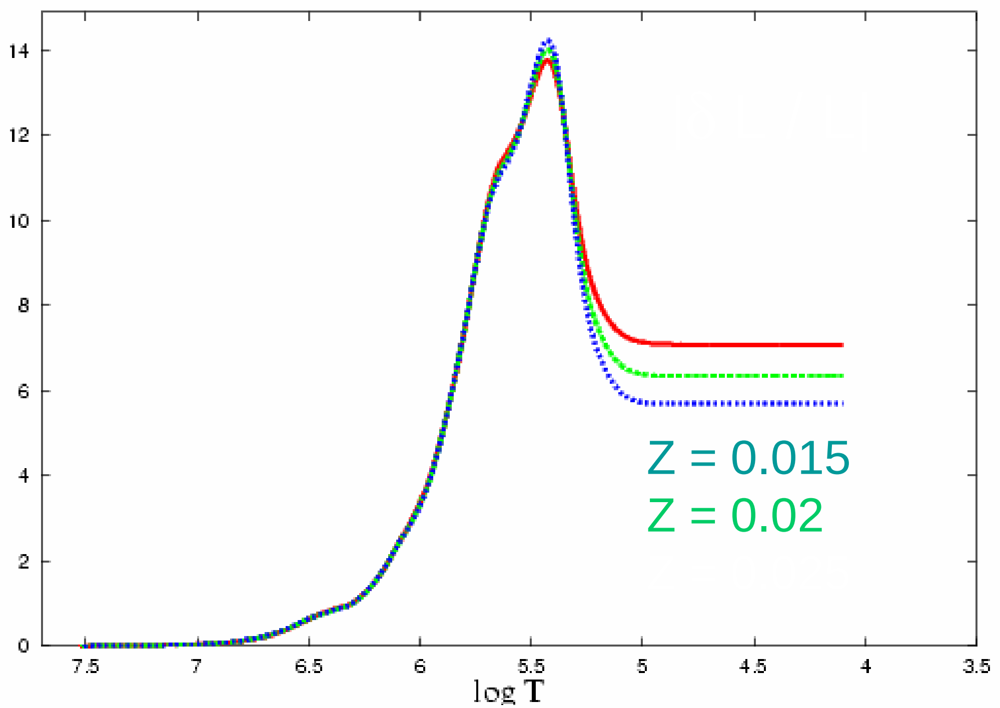
16 Lacertae

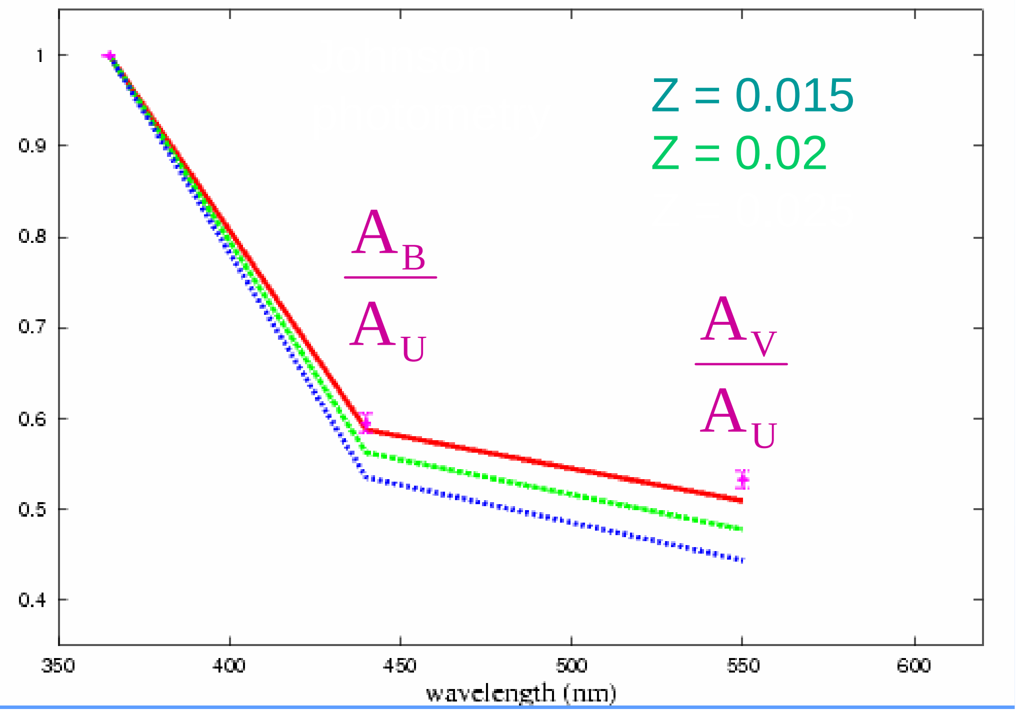
High sensitivity of the non - adiabatic results to the metallicity

Z ↗

⇩

$|\delta T_{eff} / T_{eff}|$ ↘





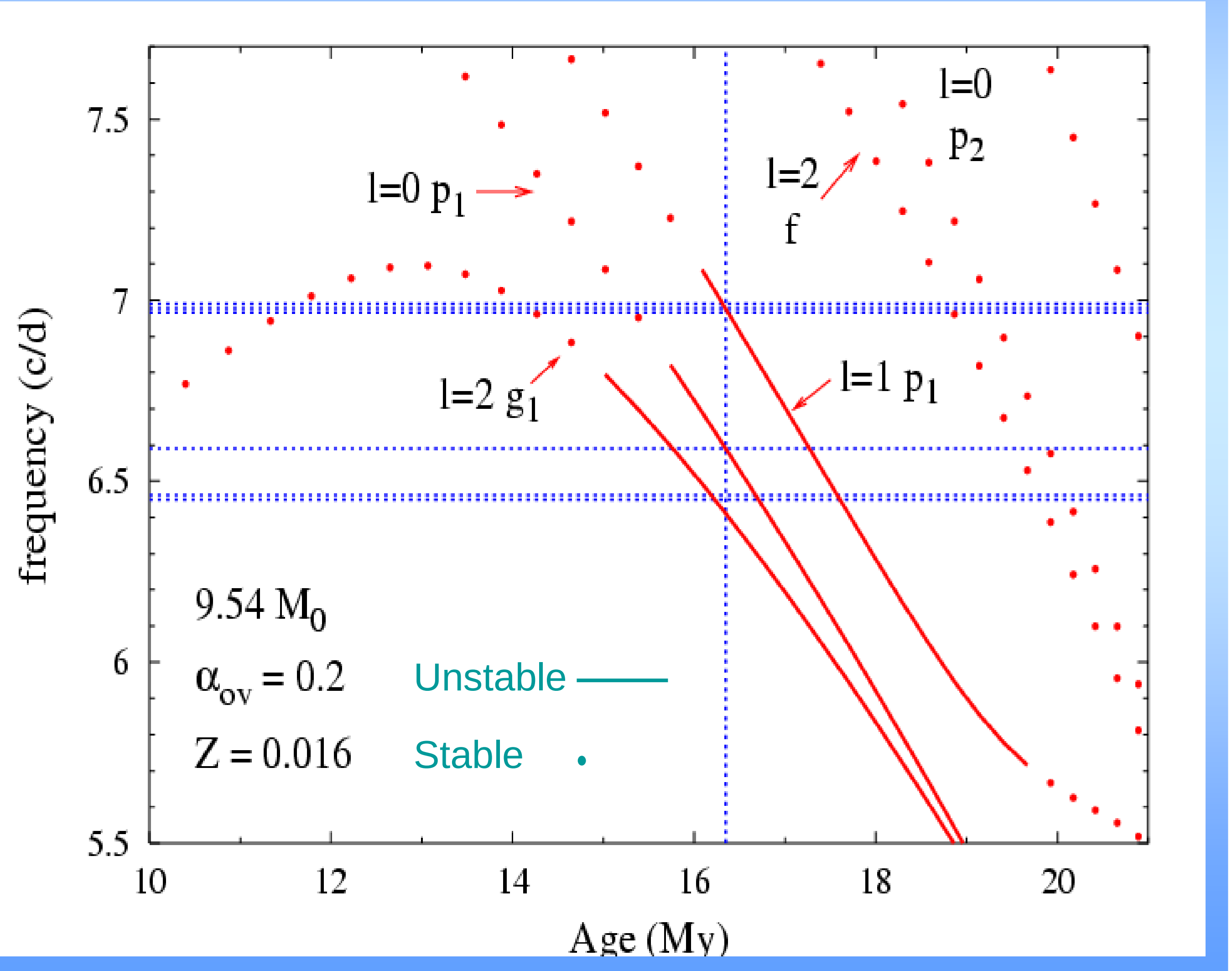
4.1 β Cephei : HD 129929

Non-adiabatic constraints on the metallicity

Modes excitation

↓

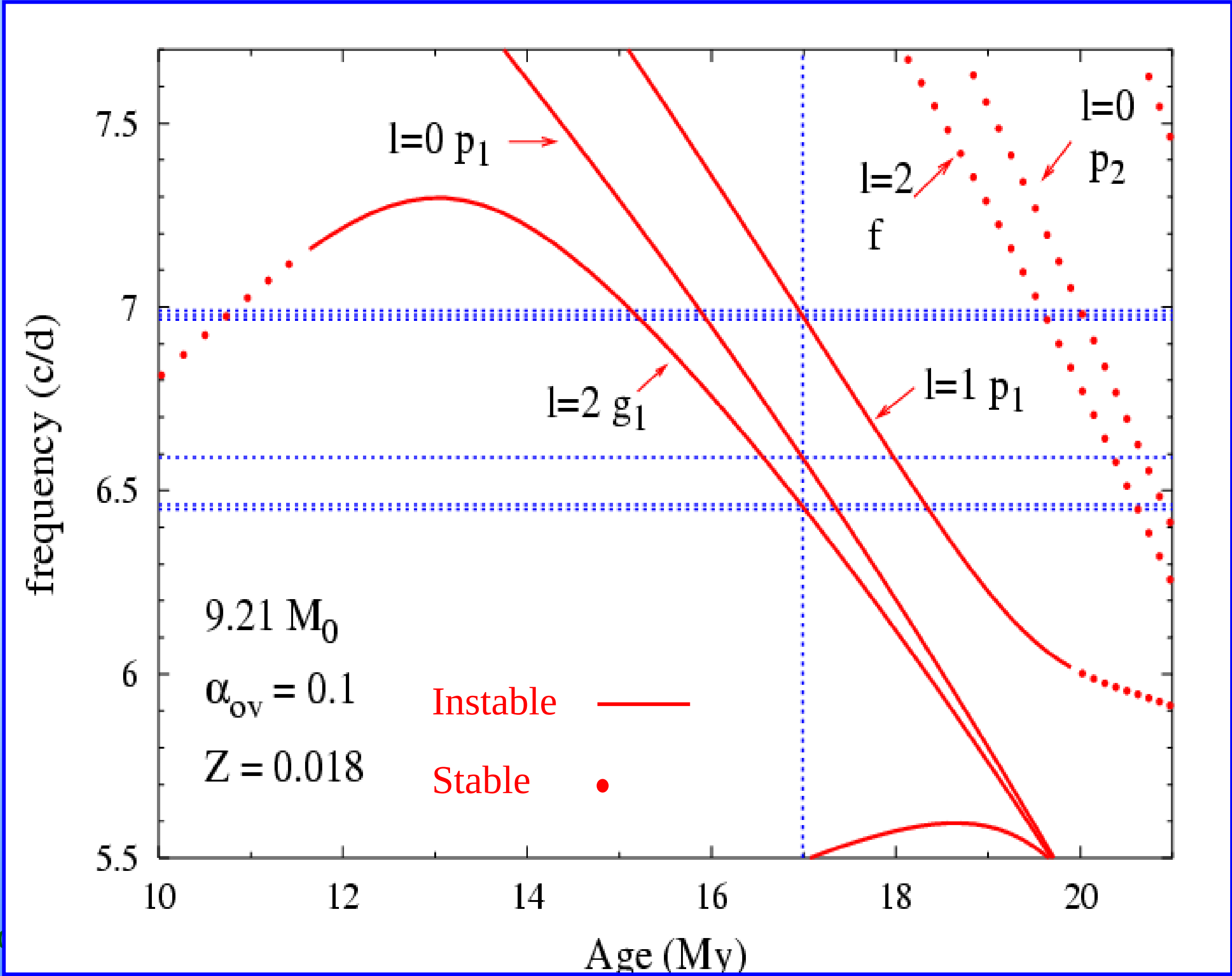
Z > 0.016



β Cephei : HD 129929

Contraintes sismiques sur l´overshooting

$\alpha_{ov} = 0.1 \pm 0.05$



Slowly Pulsating B stars

Excitation mechanism

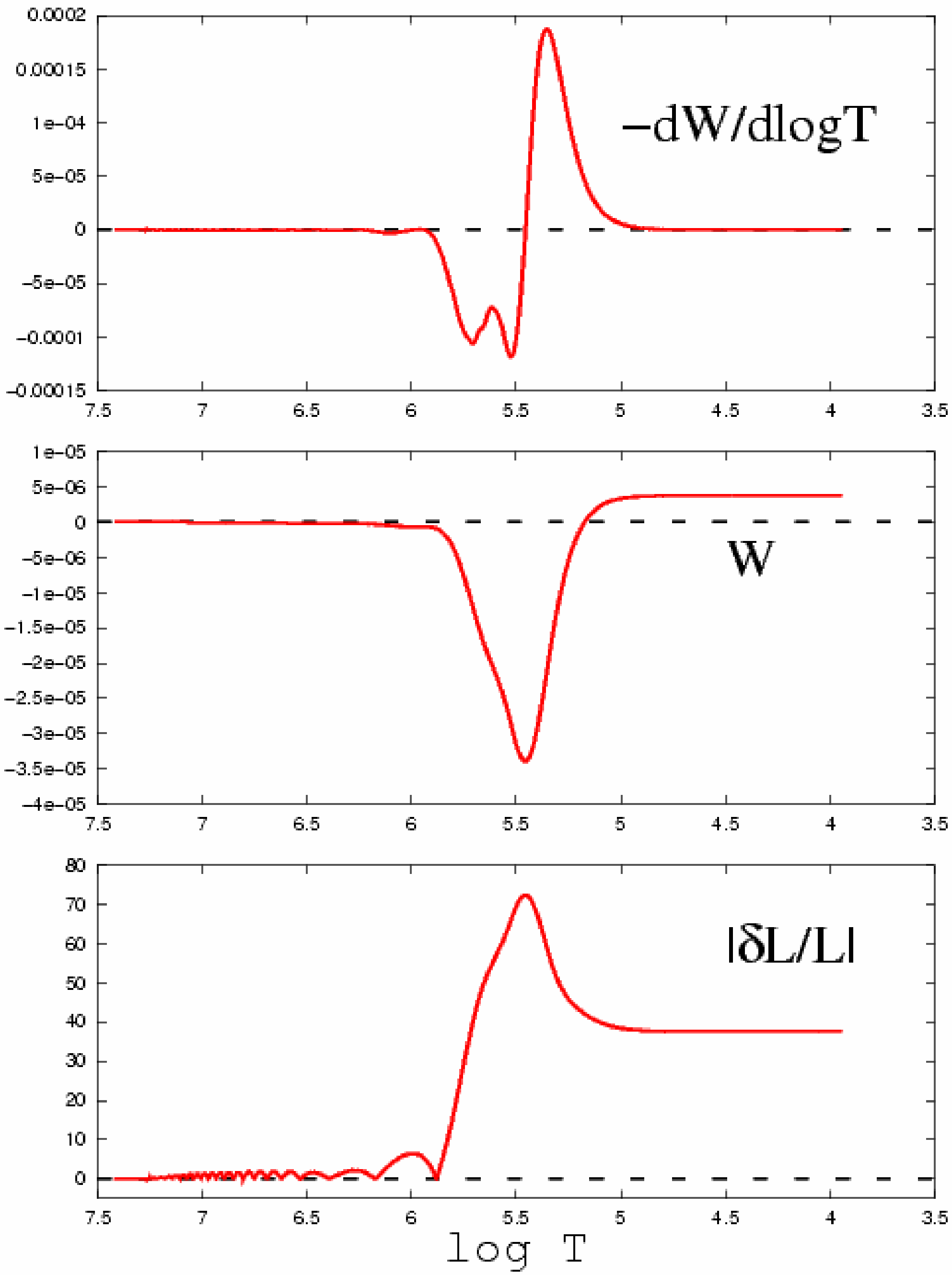
Work integral and luminosity variation from the center to the surface of the star

$M = 4\ M_0$

$T_{eff} = 13\ 955$ K

$Z = 0.02$

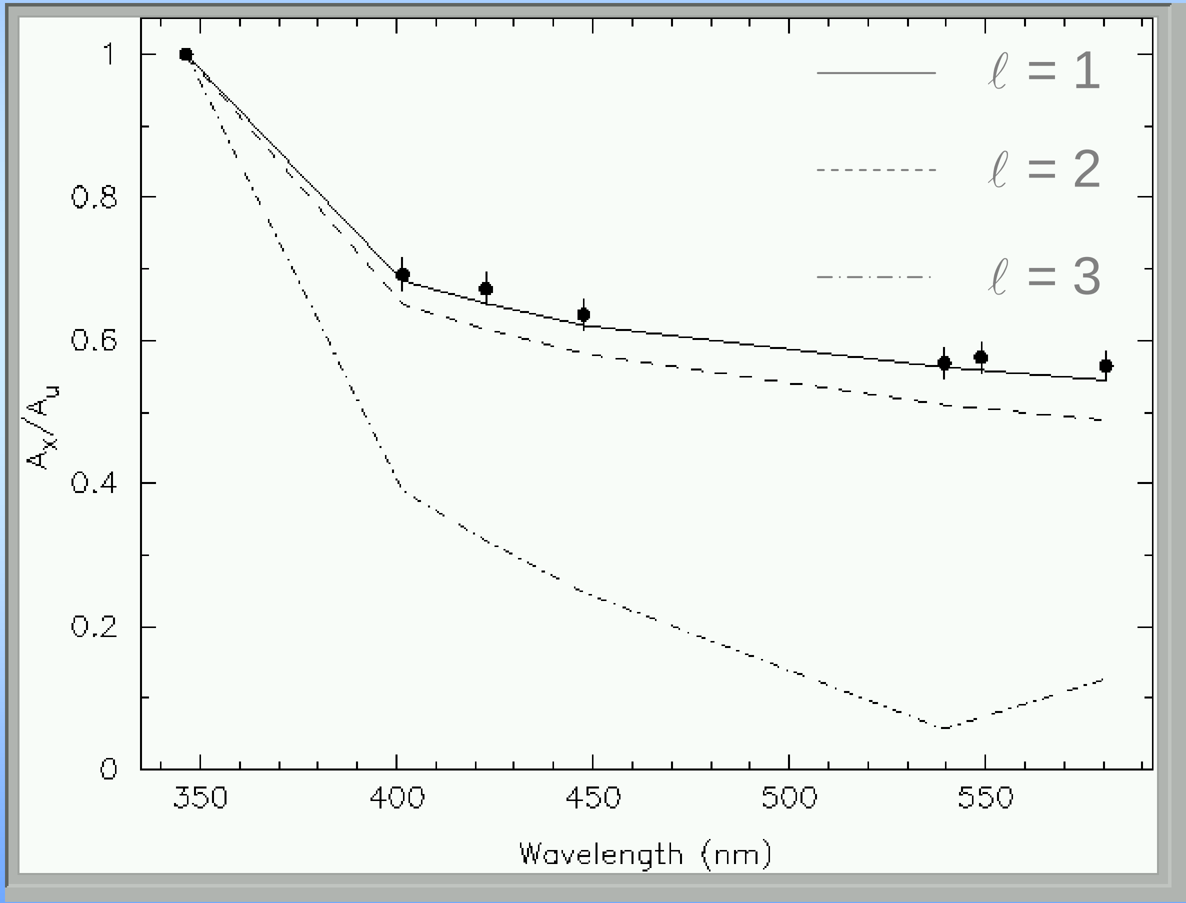
Mode $\ell = 1 \quad g_{22}$



Slowly Pulsating B stars

Identification photométrique des modes

HD 74560



δ Scuti

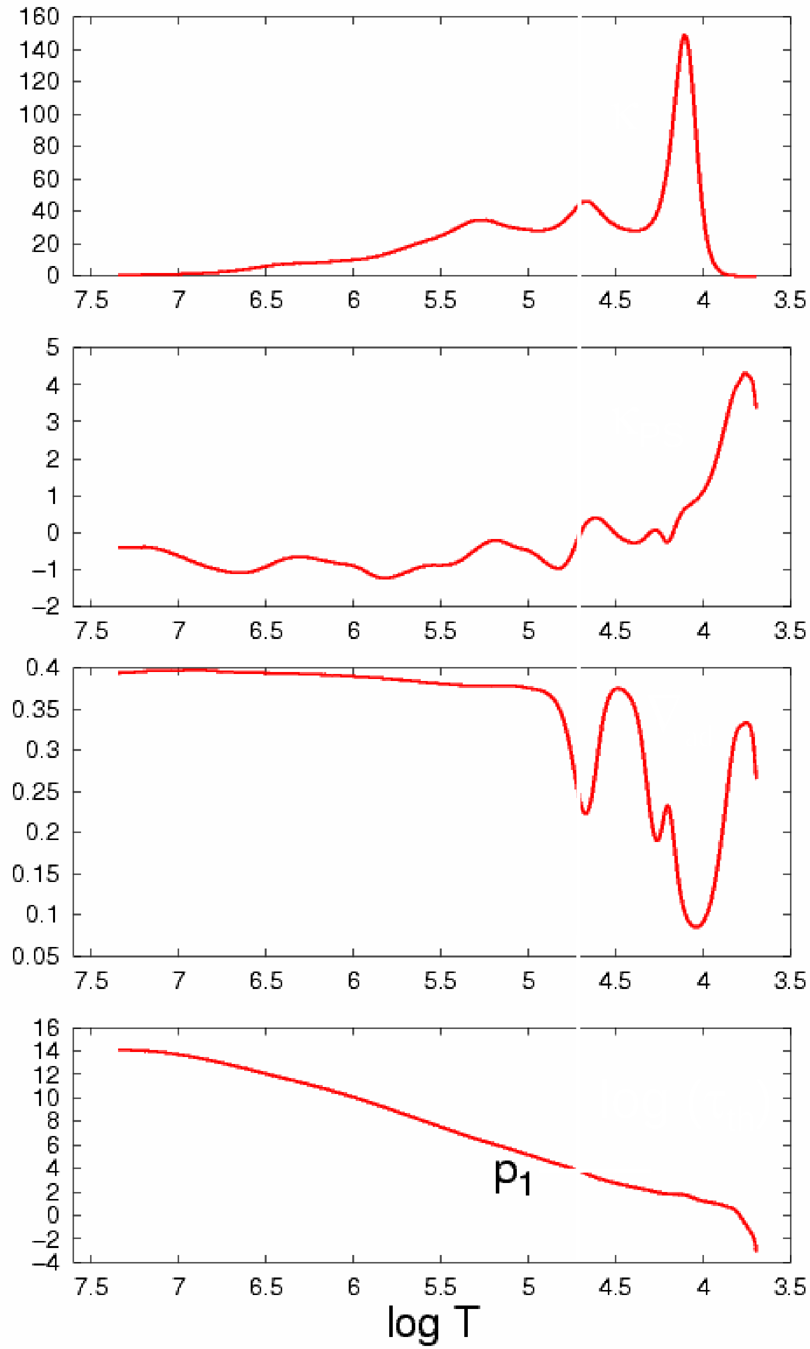
Excitation mechanism

Opacity and thermal relaxation time from the center to the surface

Partial ionization zone of Helium II = Transition zone

↓

κ–γ mechanism of excitation



BAG meeting, asteroseismology of γ Dor stars
Liège, 5th of May 2006

δ Scuti

Excitation mechanism

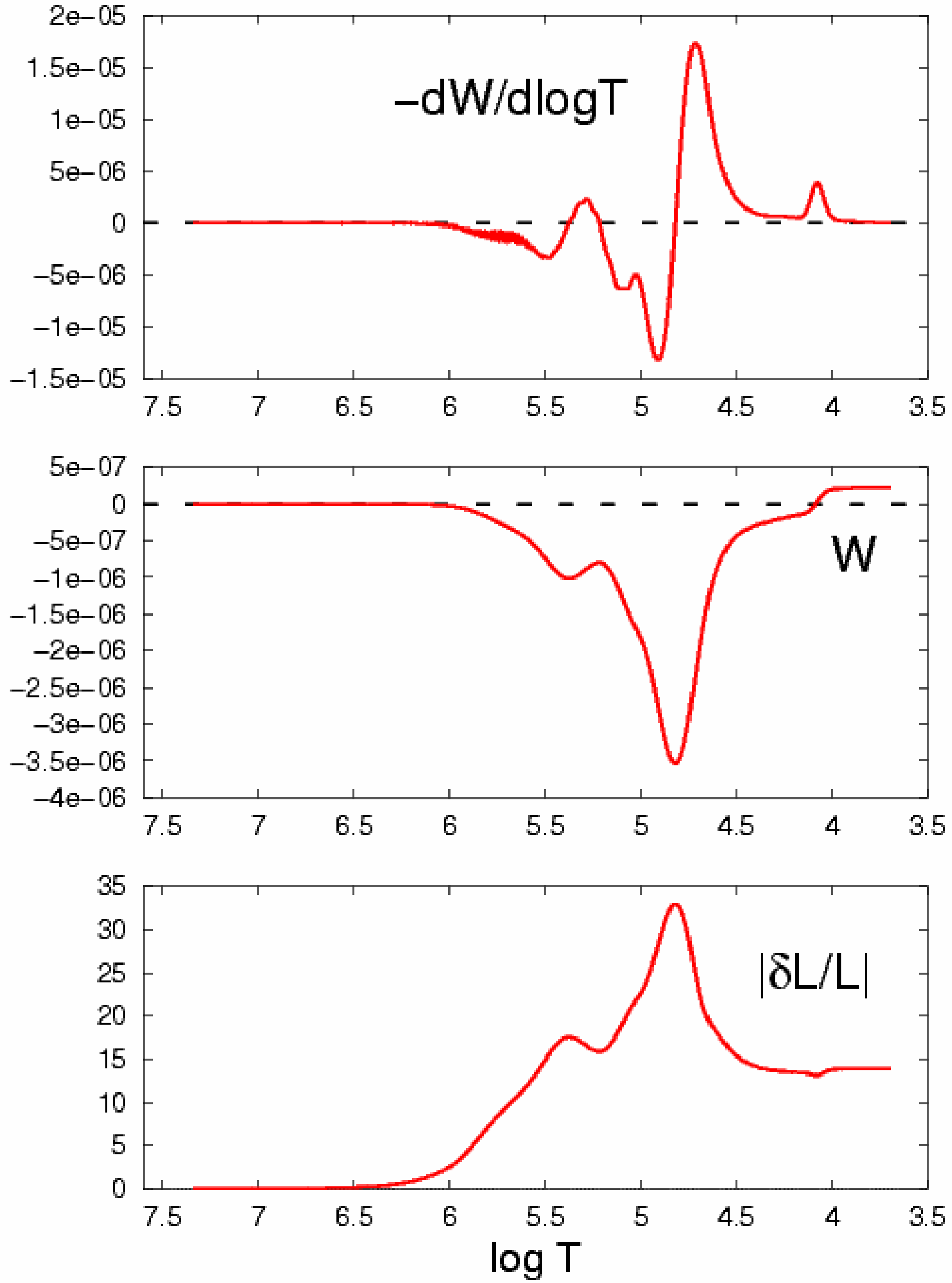
Work integral and luminosity variation from the center to the surface of the star

$M = 1.8\ M_0$

$T_{eff} = 7480$ K

$Z = 0.02$, $\alpha = 1$

Radial fundamental mode

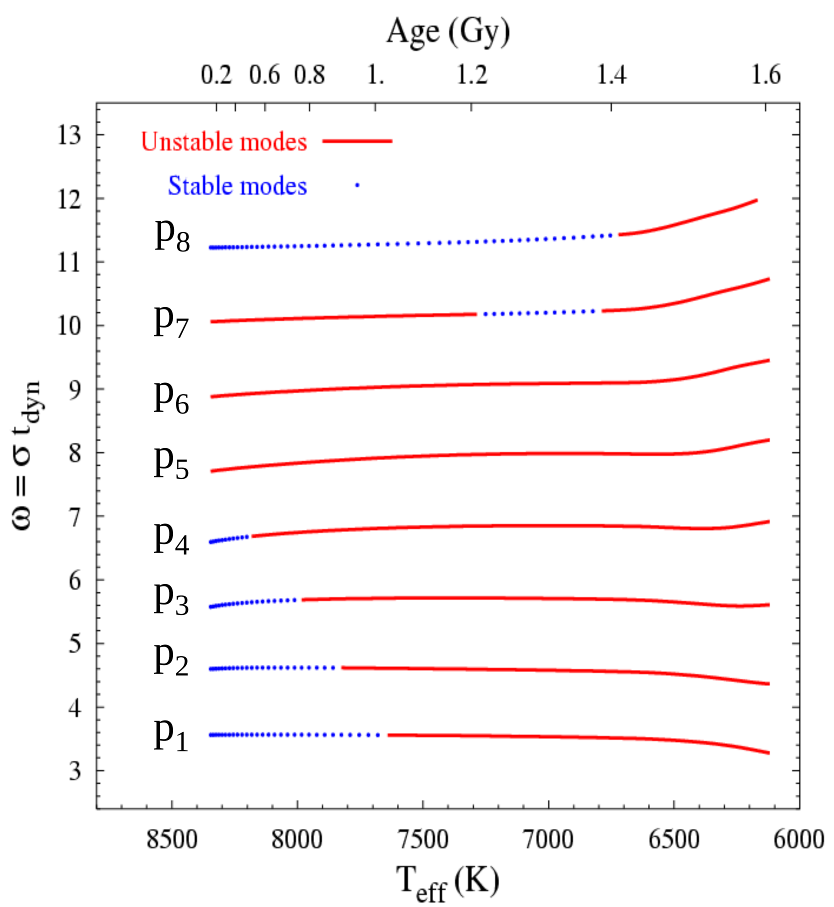


δ Scuti

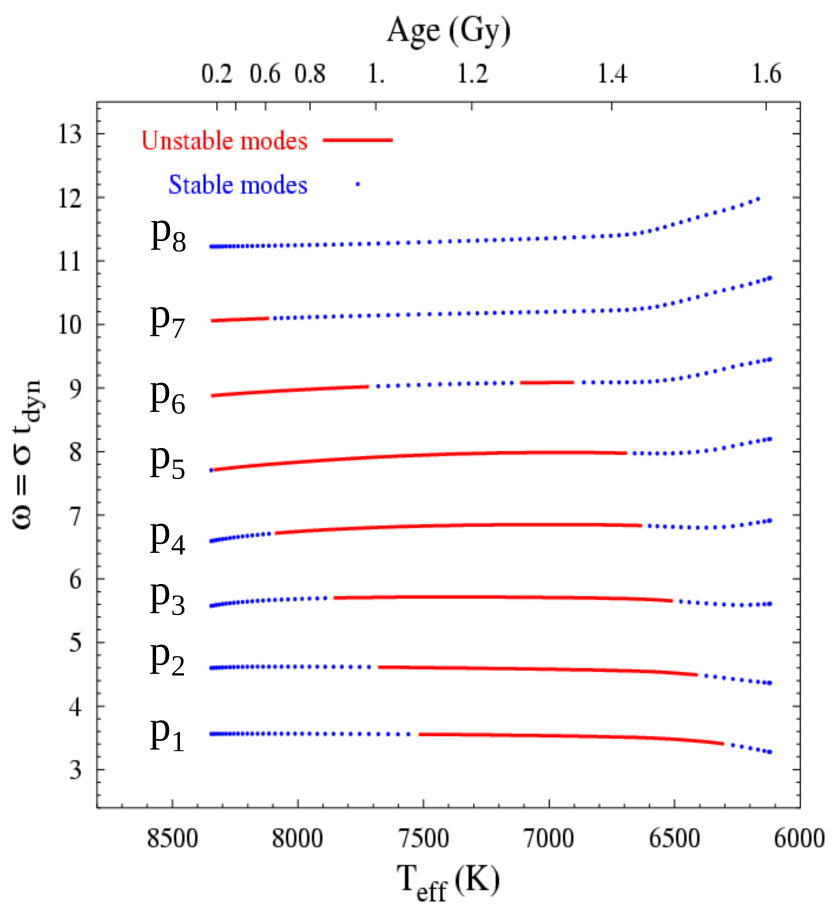
Modes stables et instables

$\ell = 0$ - $1.8\ M_0$ - $\alpha = 1.5$

Convection gelée



Convection dépendant du temps

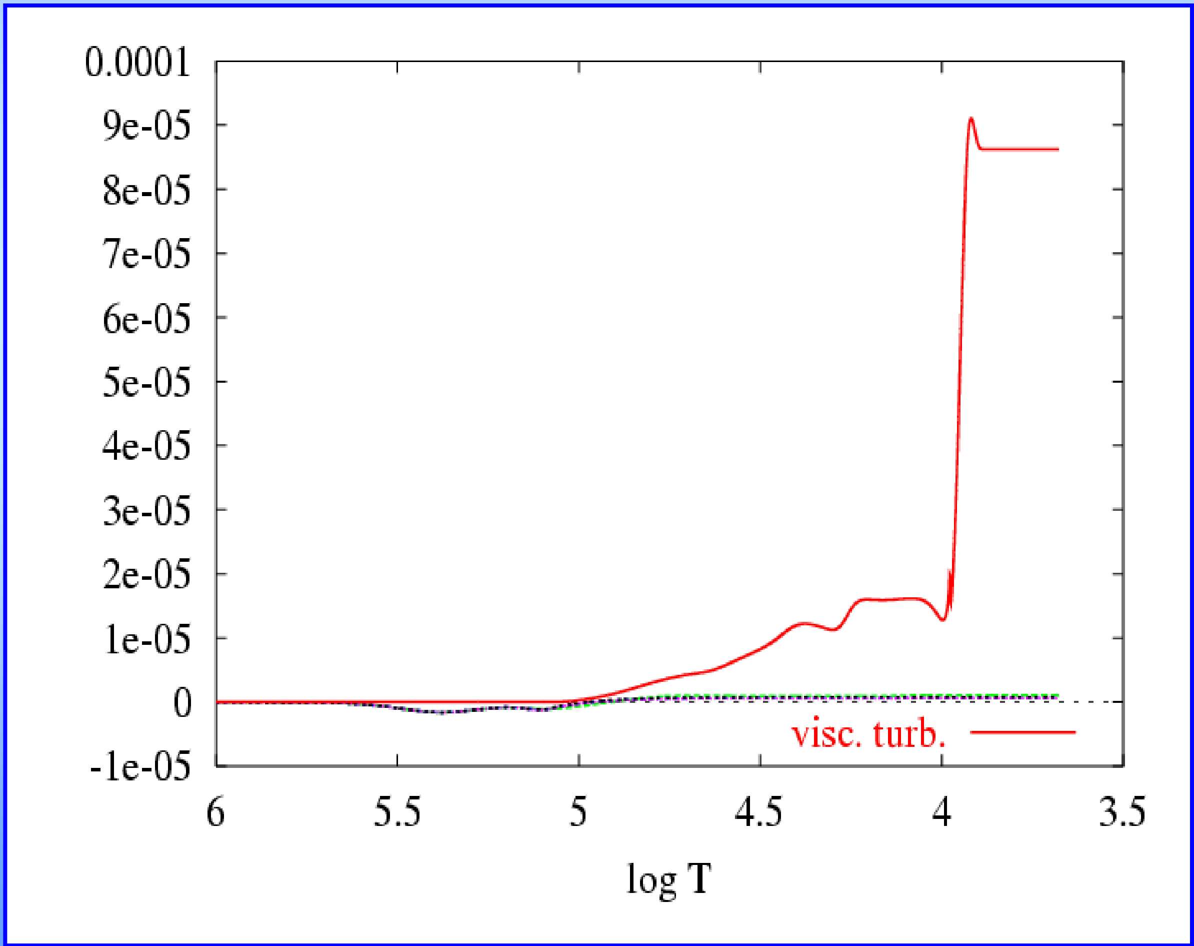


γ Doradus

Mécanisme d´excitation : → ?? Bloquage convectif ?? (Guzik et al. 2000)

Travail intégré

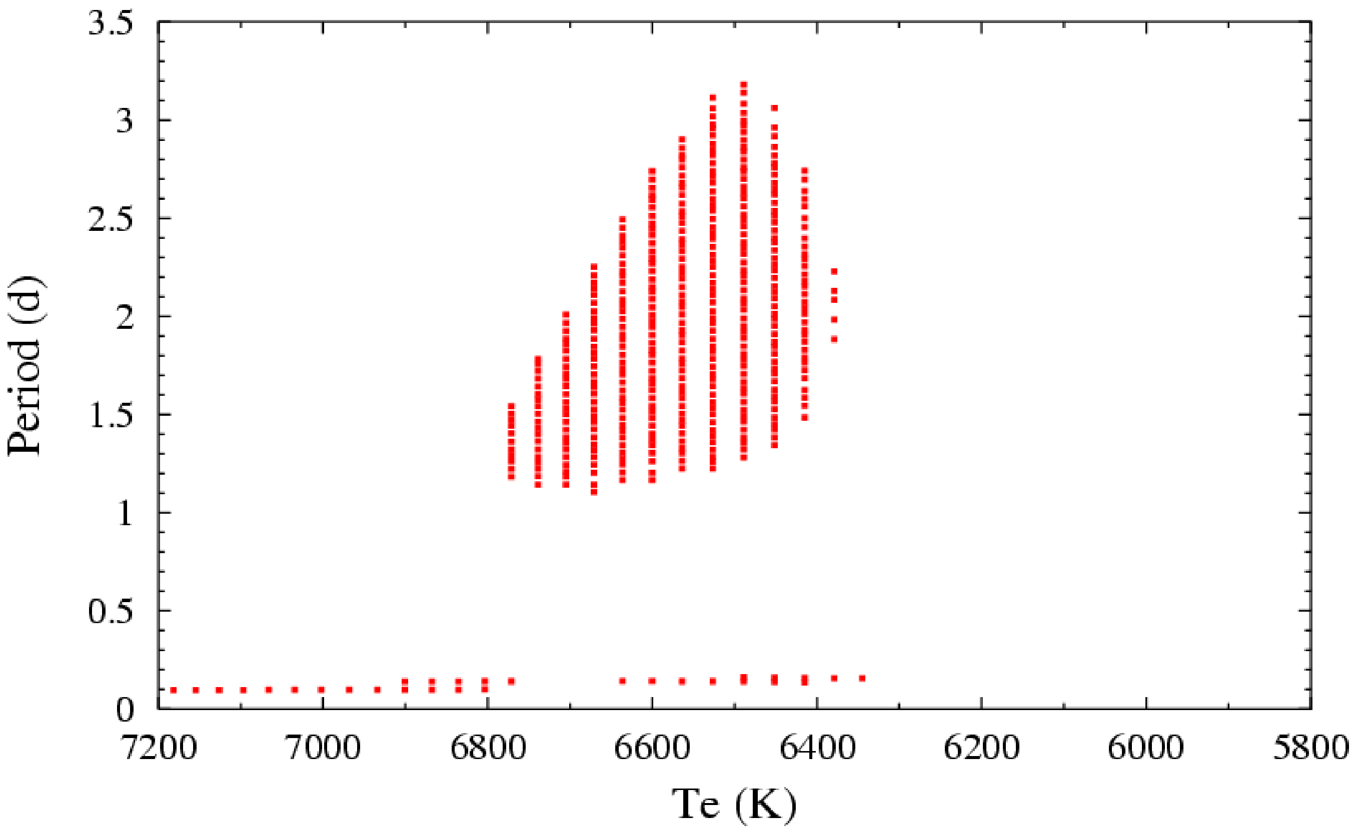
$M = 1.6\ M_0$
$T_{eff} = 7000$ K
$\alpha = 2$
Mode ℓ=1 , g_{47}



γ Doradus

Modes instables

1.6 M_0 - $\ell = 1$ - $\alpha = 1.5$



Convection – pulsation interaction: Gabriel´s theory

Hydrodynamic equations

$$\frac{\partial \rho}{\partial t} + \nabla \bullet \left(\rho \vec{v}\right) = 0$$

$$\frac{\partial (\rho \vec{v})}{\partial t} + \nabla \bullet \left(\rho \vec{v}\vec{v}\right) = -\rho \nabla \Phi + \nabla \bullet P$$

$$\frac{\partial \left(\rho U\right)}{\partial t} + \nabla \bullet \left(\rho U \; \vec{v}\right) = \rho \varepsilon_N - \nabla \bullet \vec{F}_R - P \otimes \nabla \vec{v}$$

$$P = P_G + P_R$$

$$p = p_G + p_R$$

P: Pressure tensor ; p : its diagonal component.

$$P_X = p_X \; 1 - \beta_X$$

$\vec{F}_R$ Radiative Flux

Convection – pulsation interaction: Gabriel´s theory

Mean equations

$$\frac{d\bar{\rho}}{dt} + \bar{\rho}\nabla \bullet (\vec{u}) = 0$$

$$\bar{\rho}\frac{d\vec{u}}{dt} = -\bar{\rho}\nabla\bar{\Phi} - \nabla\left(\bar{p}_G + \bar{p}_R + \underline{\underline{\bar{p}_T}}\right) + \nabla \bullet \left(\bar{\beta}_G + \bar{\beta}_R + \underline{\underline{\bar{\beta}_T}}\right)$$

$$\bar{\rho}\bar{T}\frac{d\bar{s}}{dt} = -\nabla \bullet \left(\overline{\vec{F}_R} + \underline{\underline{\overline{\vec{F}_C}}}\right) + \bar{\rho}\,\bar{\varepsilon}_N + \underline{\underline{\bar{\rho}\,\bar{\varepsilon}_2}} + \underline{\underline{\overline{\vec{V} \bullet \nabla(p_G + p_R)}}}$$

$$\underline{\underline{\bar{\rho}\frac{d}{dt}\left(\frac{1}{2}\frac{\overline{\rho V^2}}{\bar{\rho}}\right)}} = -\underline{\underline{\bar{\rho}\,\bar{\varepsilon}_2}} - \underline{\underline{\overline{\vec{V} \bullet \nabla(p_G + p_R)}}}$$

$\overline{\rho\vec{V}\vec{V}} = \bar{p}_T\, 1 - \bar{\beta}_T$	Reynolds stress tensor
$\bar{\rho}\bar{\varepsilon}_2 + \vec{V} \bullet \nabla(p_G + p_R)$	Dissipation of turbulent kinetic energy into heat
$p_T = \overline{\rho V_r^2}$	Turbulent pressure

Convection – pulsation interaction: Gabriel´s theory

Convective fluctuations equations

$$\bar{\rho}\frac{d}{dt}\left(\frac{\Delta\rho}{\bar{\rho}}\right)+\nabla\bullet\left(\rho\vec{V}\right)=0$$

$$\bar{\rho}\frac{d\vec{V}}{dt}=\frac{\Delta\rho}{\bar{\rho}}\nabla\bar{p}-\nabla\Delta p-\frac{8\rho\vec{V}}{3\tau_C}-\rho\vec{V}\bullet\nabla\vec{u}$$

$$\frac{\Delta(\rho T)}{\overline{\rho T}}\frac{d\bar{s}}{dt}+\frac{d\Delta s}{dt}+\vec{V}\bullet\nabla\bar{s}=-\frac{\Gamma^{-1}+1}{\tau_C}\Delta s$$

Approximations of Gabriel’s Theory

$$\frac{\Delta\rho}{\bar{\rho}}\nabla\bullet\left(\bar{\beta}_G+\bar{\beta}_R+\bar{\beta}_T\right)-\nabla\bullet\left(\Delta\beta_G+\Delta\beta_R+\Delta\beta_T\right)=\frac{8}{3}\frac{\rho\vec{V}}{\tau_C}$$

$$\rho\varepsilon_2-\overline{\rho\varepsilon_2}+\rho T\nabla s\bullet\vec{V}-\overline{\rho T\nabla s\bullet\vec{V}}=\frac{\left(\nabla\bullet\vec{F}_R-\overline{\nabla\bullet\vec{F}_R}\right)}{\left(\overline{\rho T}\right)}-\frac{\Delta s}{\tau_C}$$

$$\frac{\left(\nabla\bullet\vec{F}_R-\overline{\nabla\bullet\vec{F}_R}\right)}{\left(\overline{\rho T}\right)}=-\omega_R\Delta s$$

ω_R Characteristic frequency of radiative energy lost by turbulent eddies

τ_C Life time of the convective elements

$\Gamma^{-1}=\omega_R\tau_C$ Convective efficiency

In the static case, assuming constant coefficients (Hp>>l !), we have solutions which are plane waves identical to the ML solutions.

Convection – pulsation interaction: Gabriel´s theory

Perturbation of the mean equations → Linear pulsation equations

Equation of mass conservation

$$\frac{\delta\rho}{\rho}+\frac{1}{r^2}\frac{d\left(r^2\delta r\right)}{dr}-l(l+1)\frac{\delta r_H}{r}=0$$

Radial component of the equation of momentum conservation

$$\sigma^2\delta r=\frac{d\delta\Phi}{dr}-\frac{1}{\rho}\frac{d\delta p_{\mathrm{g}}}{dr}-\frac{1}{\rho}\frac{d\delta p_{\mathrm{turb}}}{dr}+g\frac{\delta\rho}{\rho}+\frac{2A-1}{A}\frac{\overline{p}_T}{r}\frac{\partial\delta r}{\partial r}-\delta\left(\nabla_j\overline{\beta_T^{r\,j}}\right)$$

Transversal component of the equation of momentum conservation

$$\sigma^2\delta r_H=\frac{1}{r}\left(\delta\Phi+\frac{\delta p}{\rho}+\frac{r\ ViscH}{\overline{\rho}}+\frac{2A-1}{A}\frac{\overline{p}_T}{\overline{\rho}}\left(\frac{\delta r}{r}-\frac{\delta r_H}{r}\right)\right)$$

σ : Angular pulsation frequency

A : Anisotropy parameter
A=1/2 for isotropic turbulence

Convection – pulsation interaction: Gabriel´s theory

Equation of Energy conservation

$$
\begin{aligned}
i\sigma T\delta s = \delta\varepsilon_N + l(l+1)\frac{\delta r_H}{r}\frac{dL}{dm} - \frac{d\delta L_R}{dm} - \frac{d\delta L_C}{dm} \\
+ \frac{l(l+1)}{4\pi r^3\rho}\left(L_R\left(\frac{\delta T}{r(dT/dr)} - \frac{\delta r}{r}\right) - L_C\frac{\delta r_H}{r}\right) \\
+ \frac{l(l+1)}{\overline{\rho} r}FCH + \delta\varepsilon_2 + \delta\left(\overline{\vec{V}\bullet\frac{\nabla(p_G + p_R)}{\overline{\rho}}}\right)
\end{aligned}
$$

FCH : Amplitude of the horizontal component of the convective flux

Convection – pulsation interaction: Gabriel´s theory

Convective flux perturbation

Convective Flux : $\vec{F}_C = \overline{\rho T \Delta s \vec{V}}$

Perturbation : $\delta\vec{F}_C = \vec{F}_C\left(\frac{\delta\rho}{\overline{\rho}} + \frac{\delta T}{\overline{T}}\right) + \overline{\rho}\overline{T}\left(\overline{\delta(\Delta s)\vec{V}} + \overline{\Delta s\,\delta\vec{V}}\right)$

$$\frac{\delta F_{C\,r}}{F_{C\,r}} = \mathrm{a}_1\frac{\delta r}{r} + \mathrm{a}_2\frac{d\,\delta r}{dr} + \mathrm{a}_3\frac{\delta r_H}{r} + \mathrm{a}_4\frac{\delta\rho}{\rho} + \mathrm{a}_5\frac{\delta s}{c_v} + \mathrm{a}_6\frac{\delta l}{l} + \mathrm{a}_7\frac{d\,\delta s}{ds}$$

$$\mathrm{a}_7 \cong \frac{\omega_\mathrm{R}\tau_\mathrm{C} + 1}{i\,\sigma\,\tau_\mathrm{C} + \omega_\mathrm{R}\tau_\mathrm{C} + 1} \cong \frac{1}{i\,\sigma\,\tau_\mathrm{C}} \quad \text{where convection is efficient}$$

Convection – pulsation interaction: Gabriel´s theory

Turbulent pressure perturbation

Turbulent pressure : $P_{\text{turb}} = \rho\, V_r^{\,2}$

Perturbation : $$\frac{\delta P_{\text{turb}}}{P_{\text{turb}}} = \frac{\delta\rho}{\rho} + 2\,\frac{\delta V_r}{V_r}$$

$$\frac{\delta V_r}{V_r} = \mathrm{b}_1 \frac{\delta r}{r} + \mathrm{b}_2 \frac{d\delta r}{dr} + \mathrm{b}_3 \frac{\delta r_H}{r} + \mathrm{b}_4 \frac{\delta\rho}{\rho} + \mathrm{b}_5 \frac{\delta s}{c_v} + \mathrm{b}_6 \frac{\delta l}{l} + \mathrm{b}_7 \frac{d\delta s}{ds}$$

$$\mathrm{b}_7 \cong \frac{\mathrm{a}_7}{i\,\sigma\,\tau_{\mathrm{C}}} \quad \text{near the surface}$$

Perturbation of the mixing-length

$$\frac{\delta l}{l} = \frac{\delta H_P}{H_P}$$

H_{p} Pressure scale height

Convection – pulsation interaction: the Solar case

Difficulties: 2. Treatment of turbulent pressure perturbation

Local analysis → $\delta X(r,t) = \delta X_0 \, e^{\lambda r + i\sigma t}$

$$\lambda\, \delta p_g/p_g + \lambda^2 \varepsilon\, \delta s/c_p = \ldots$$ → **Movement**

$$\lambda\, \delta s/c_p + \lambda\, b\, \delta p_g/p_g = \ldots$$ → **Transfer**

…

Characteristic polynomial → $\lambda^2 \varepsilon\, P_3(\lambda) + P_{40}(\lambda) = 0$

→ **New terms**

→ **ε = 0**

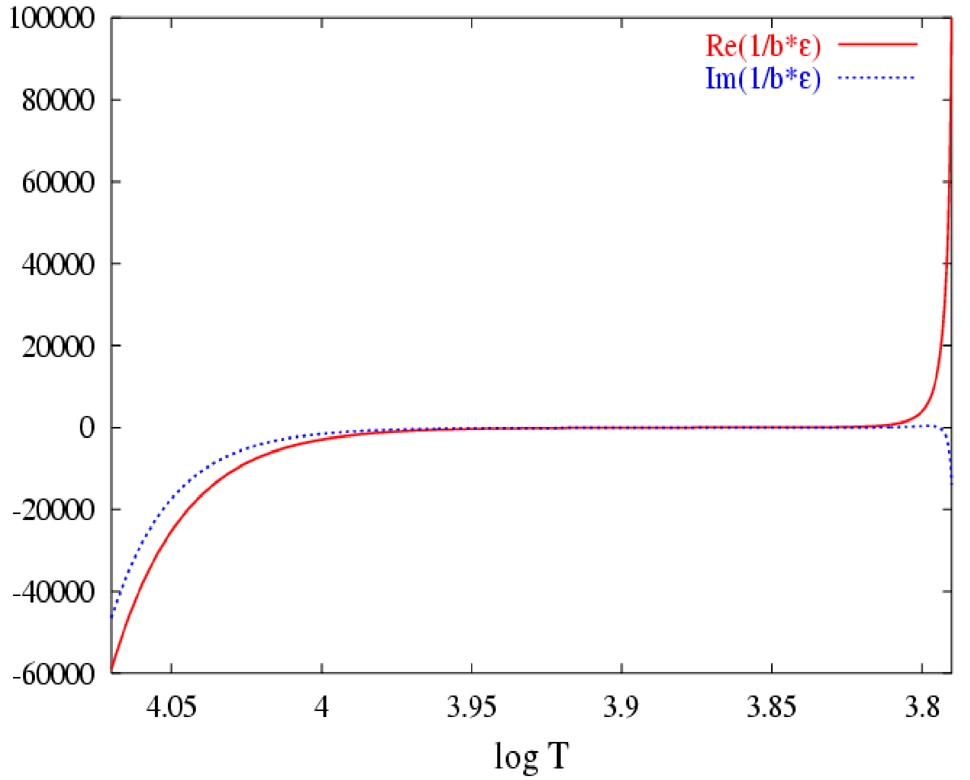
→ **New root: λ = 1/(*b* ε)** → **∞ at the convective boundaries**

The worse numerical case gives the best fits with observations

Re(1/(*b* ε)) < 0 at the left boundary
Re(1/(*b* ε)) > 0 at the right boundary

Convection – pulsation interaction: the Solar case

Difficulties: 2. Treatment of turbulent pressure perturbation



Example:

$$\frac{dz}{dx} = \frac{2x - i(1+x^2)}{(1-x^2)^2}\, z$$

$$z(x) = c \exp\left(\frac{1}{1-x^2} - i \frac{x}{1-x^2} \right)$$

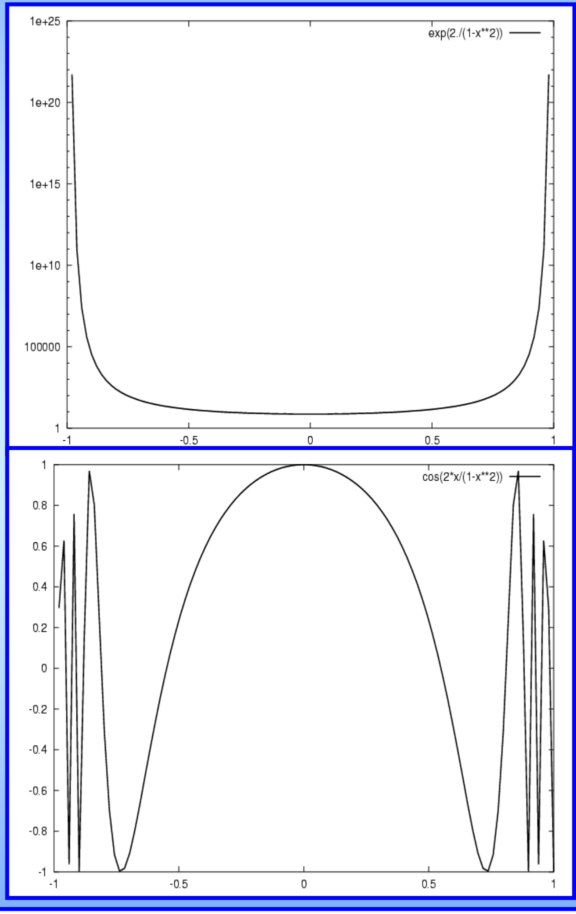
The worse numerical case gives the best fits with observations

Re(1/(b ε)) < 0 at the left boundary
Re(1/(b ε)) > 0 at the right boundary

Convection – pulsation interaction: the Solar case

Difficulties:

2. Treatment of turbulent pressure perturbation



Example:

$$\frac{dz}{dx} = \frac{2x - i(1+x^2)}{(1-x^2)^2}\, z$$

↓

$$z(x) = c \exp\left(\frac{1}{1-x^2} - i\frac{x}{1-x^2}\right)$$

The worse numerical case gives the best fits with observations

Re(1/(b ε)) < 0 at the left boundary
Re(1/(b ε)) > 0 at the right boundary

Plan of the presentation

1. Introduction

2. Convection-pulsation interaction

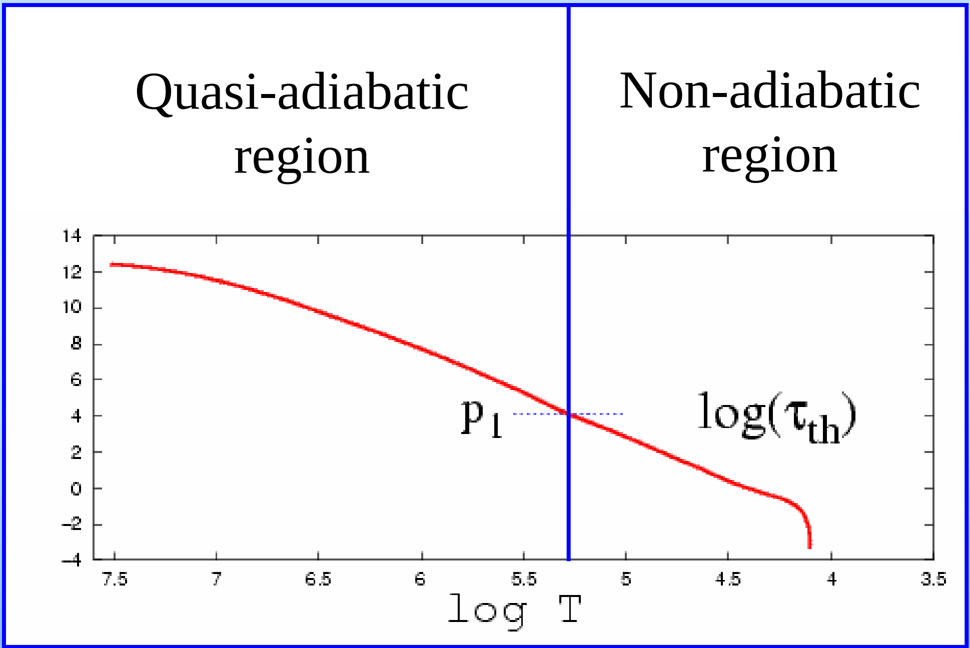
   2.1. The MLT theory of Gabriel

   2.2. The case of solar-like oscillations

3. Confrontation to observations

4. Conclusions

Non-adiabatic stellar oscillations



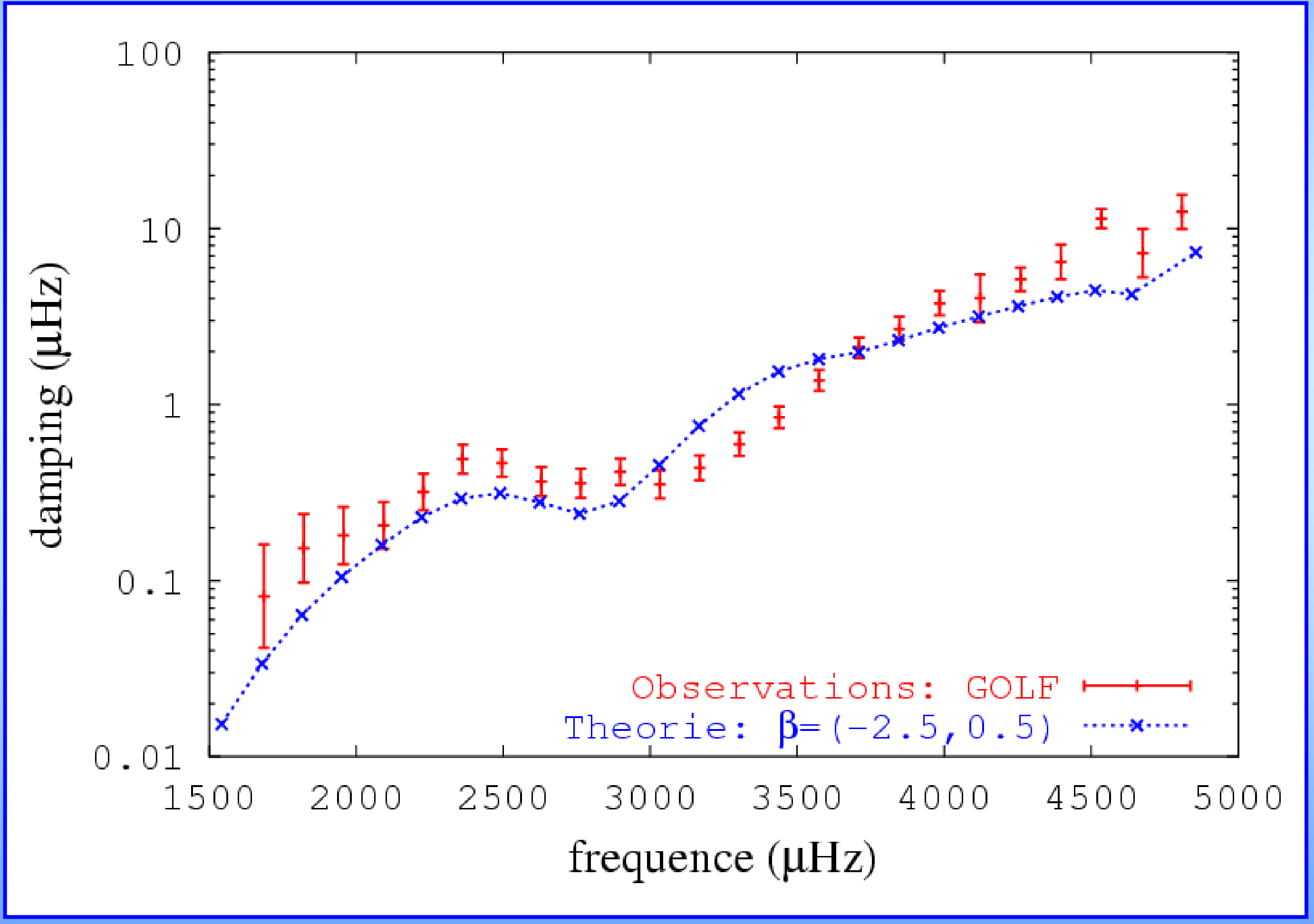
$\delta S \neq 0$

Coupling between

- the **dynamical** equations
- the **thermal** equations

Confrontation to observations

Theoretical damping rates ↔ line-widths observed by GOLF



Confrontation to observations

Theoretical damping rates ↔ line-widths observed by GOLF

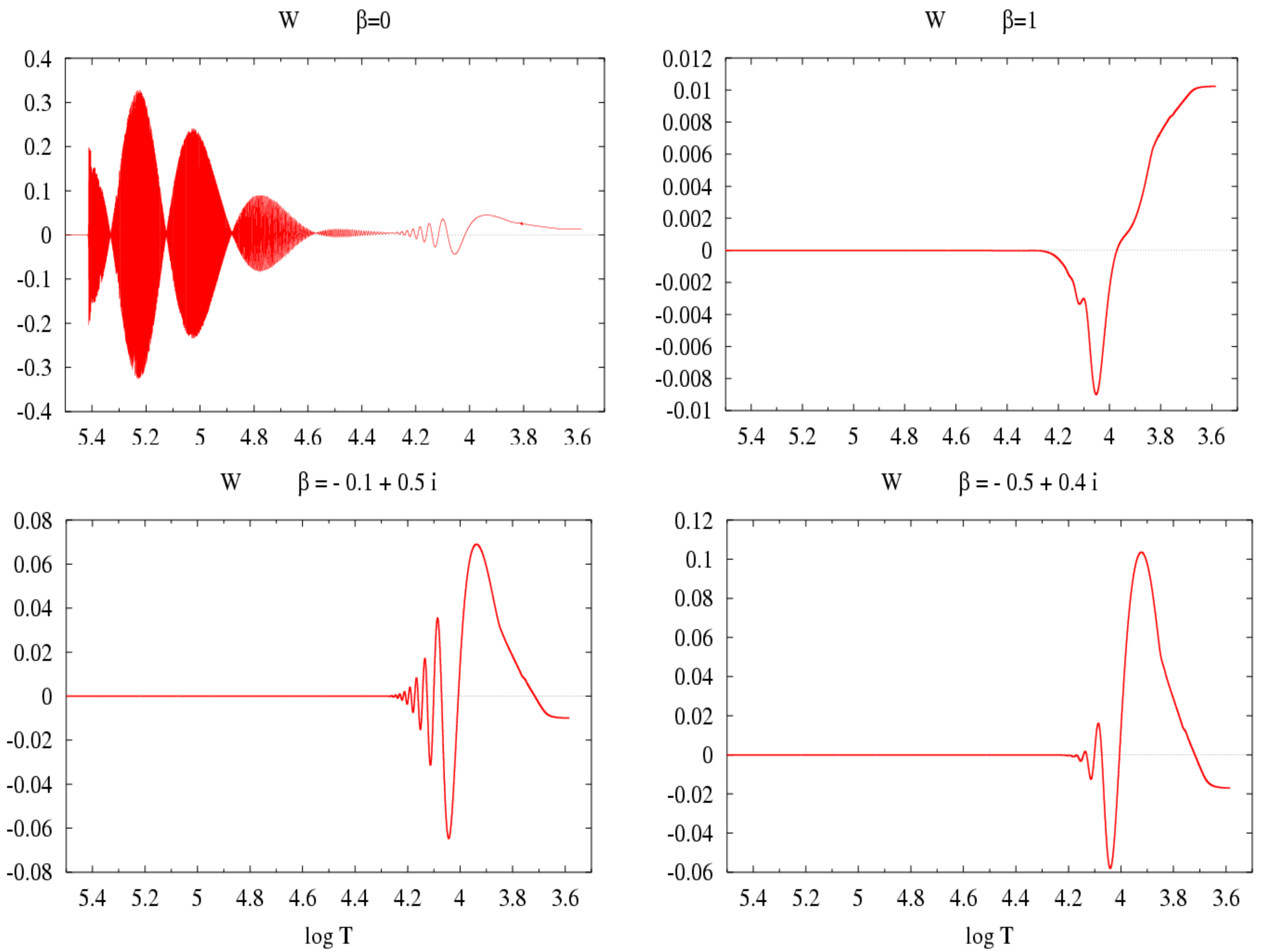
Problem:

This solution fitting very well the observations
is subject to numerical instabilities near the upper
boundary of the convective envelope.

They come from the turbulent pressure perturbation term.

Confrontation to observations

Theoretical work integrals for different β (mode l=0, p_{22})

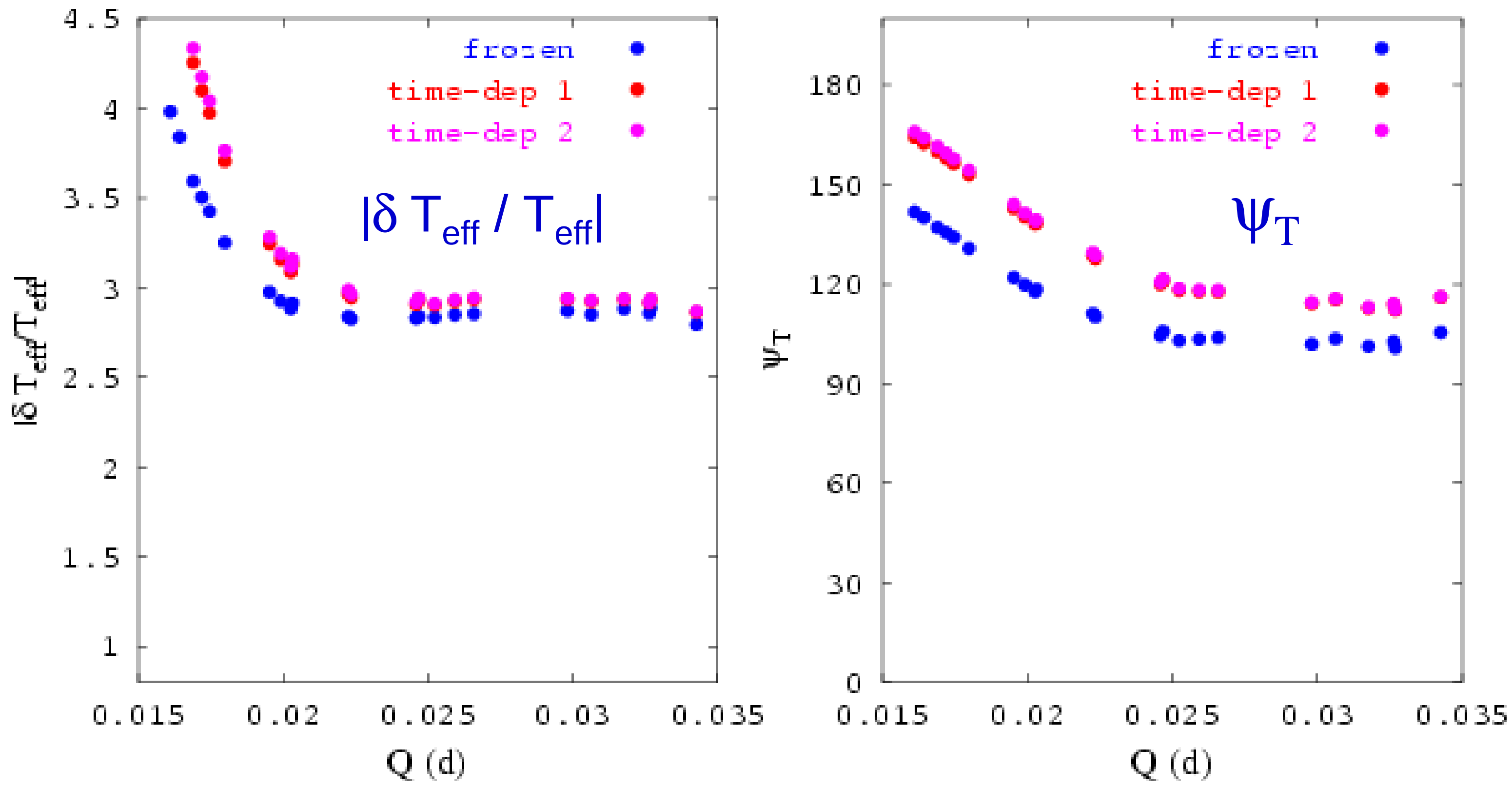


δ Scuti

Amplitudes et phases photométriques

Convection dépendant du temps

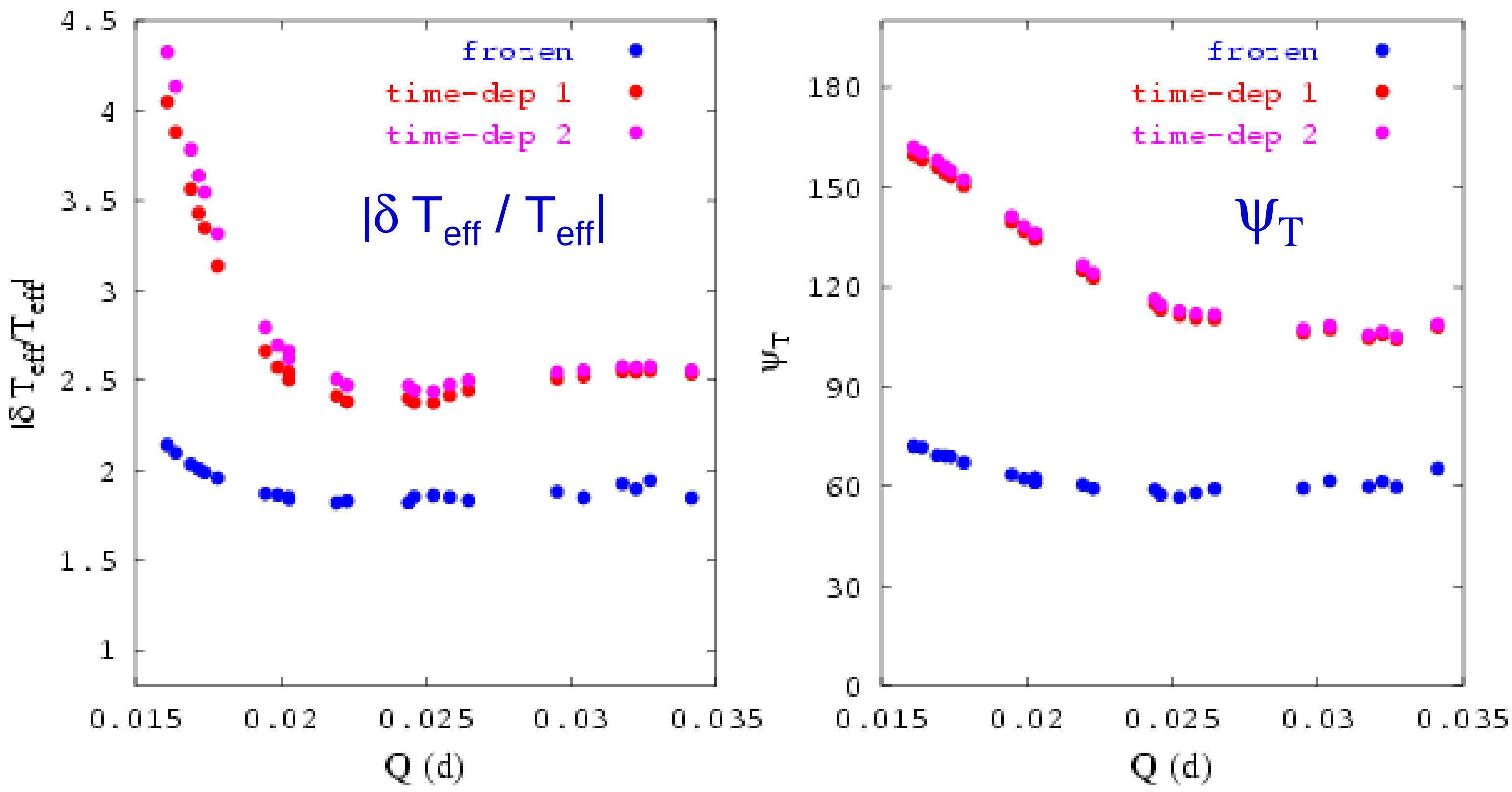
$M = 1.8\ M_0$ - $T_{eff} = 7150$ K - $\alpha = 0.5$



δ Scuti — Amplitudes et phases photométriques

Convection dépendant du temps

$M = 1.8\ M_0$ - $T_{eff} = 7130$ K - $\alpha = 1$

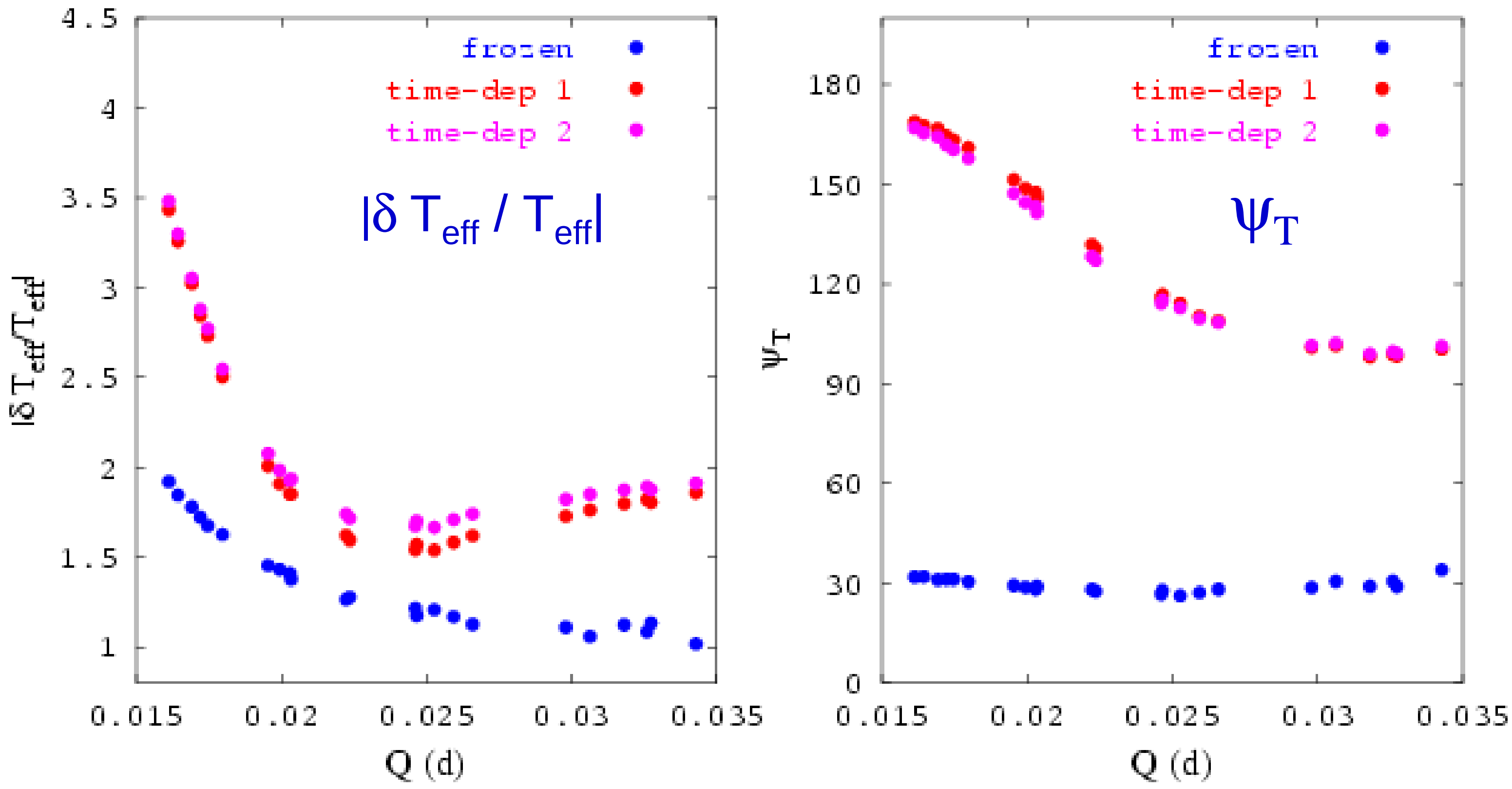


δ Scuti

Amplitudes et phases photométriques

Convection dépendant du temps

$M = 1.8\ M_0$ - $T_{eff} = 7150$ K - $\alpha = 1.5$



Internal physics: Propagation cavities g_{50}