The physics of red-giant oscillations

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The impact of asteroseismology across stellar astrophysics
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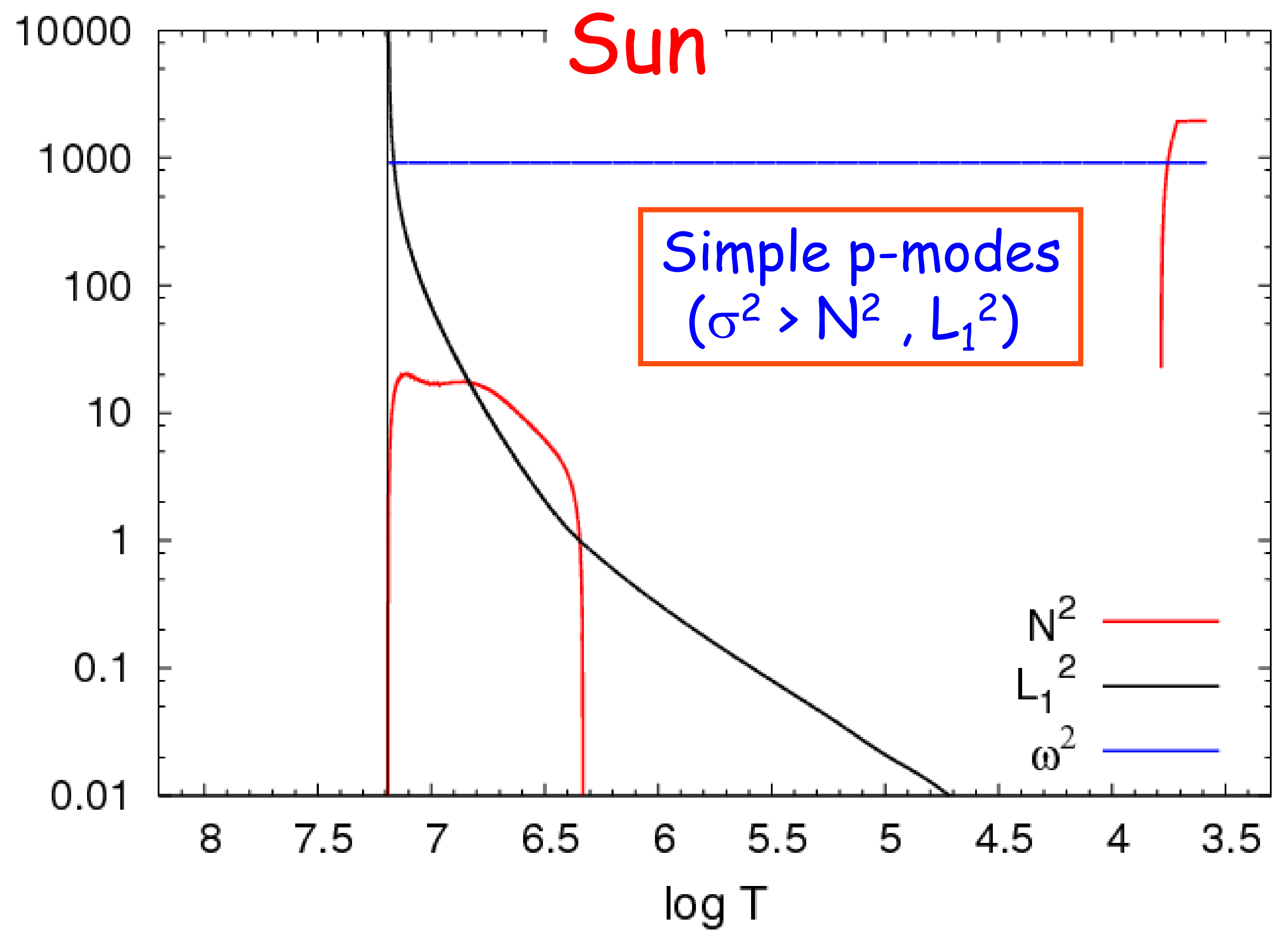
Plan of the presentation

- Dynamical aspects (adiabatic analysis)
  - Acoustic structure of red giants and mode trapping
  - Seismic diagnostics from p-like modes
  - Seismic diagnostics from g-like modes

- Energetic aspects (non-adiabatic analysis)
  - Stochastic excitation
  - Convective and radiative damping
  - Predictions for different models

How red giants differ from the Sun from an acoustic point of view ?

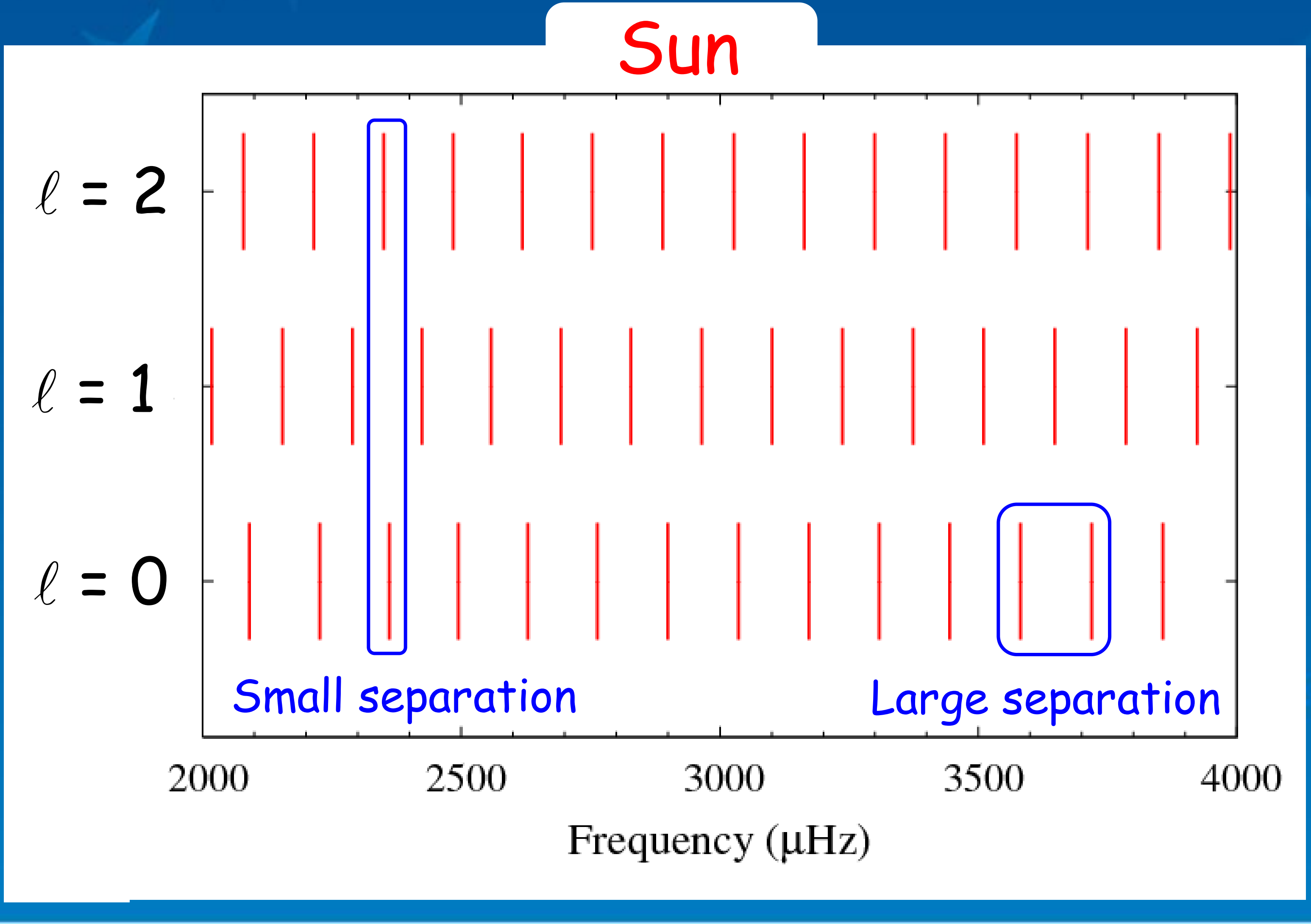


Simple p-modes

($\sigma^2 > N^2$, L_1^2)

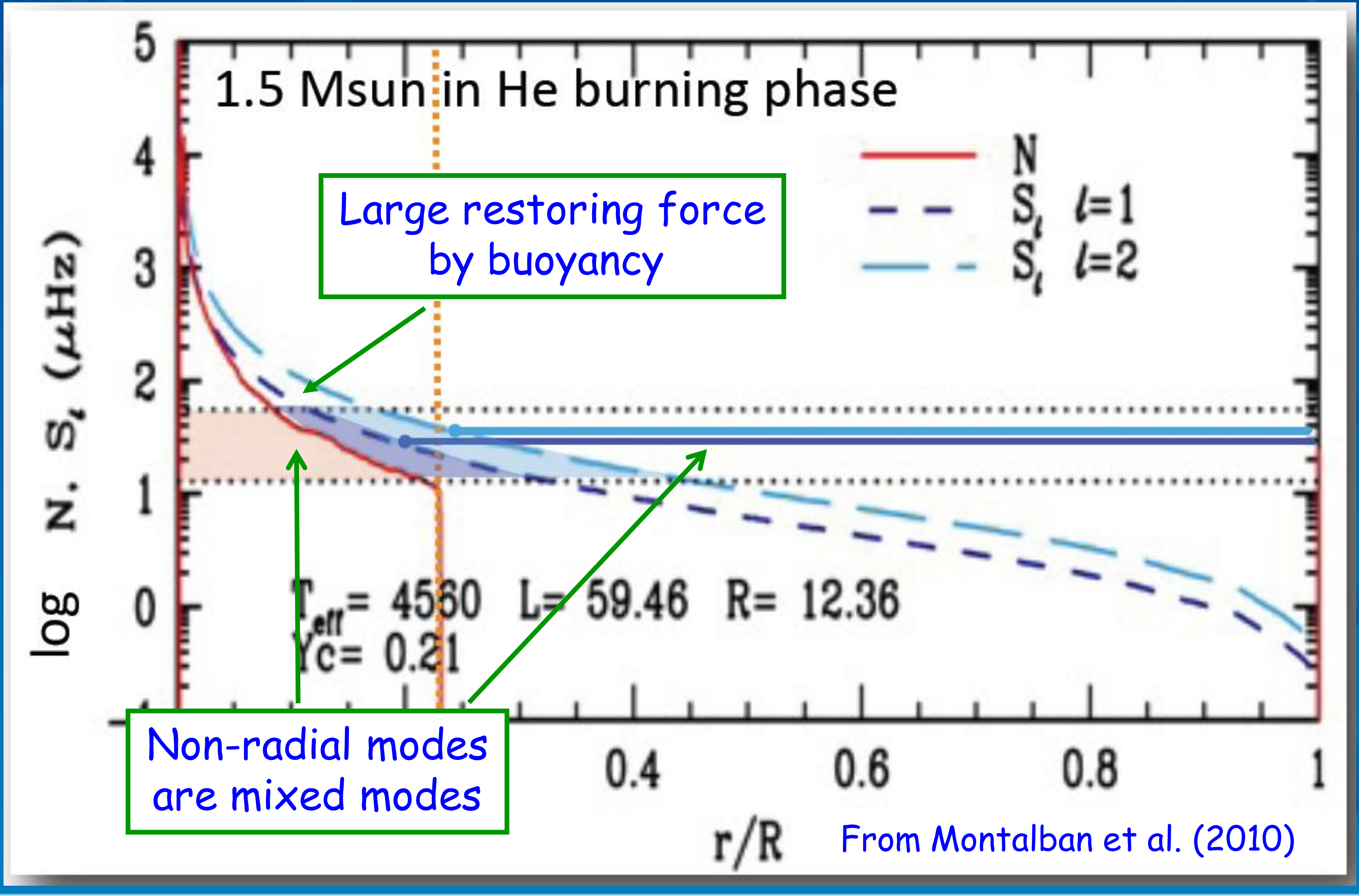
How red giants differ from the Sun ?

Regular frequency pattern ~ Asymptotic



Acoustic structure of red giants and mode trapping

Large core-envelope density contrast in red giants



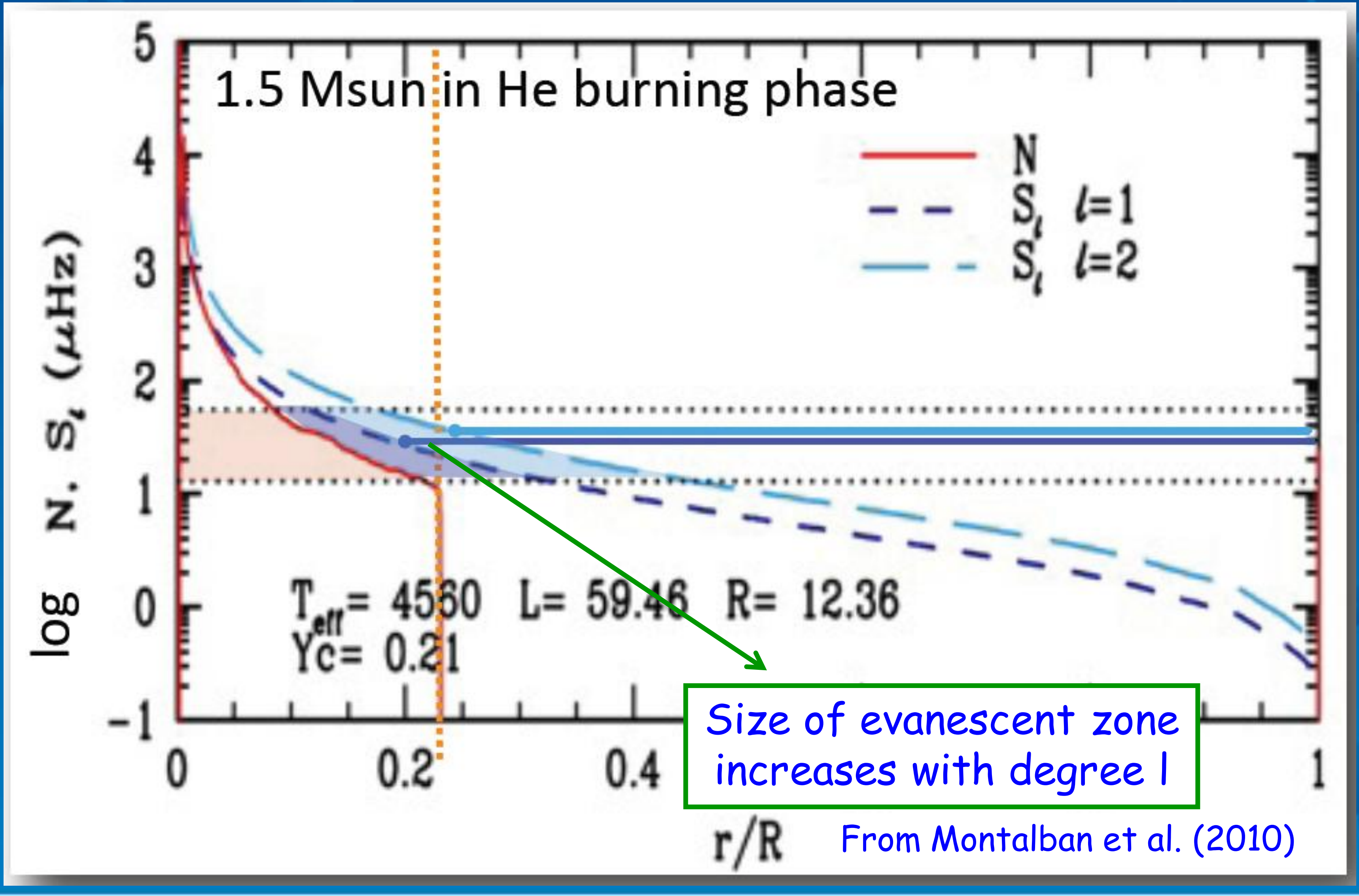
Large restoring force by buoyancy

Non-radial modes are mixed modes

From Montalban et al. (2010)

Acoustic structure of red giants and mode trapping

Large core-envelope density contrast in red giants



Size of evanescent zone increases with degree l

From Montalban et al. (2010)

Acoustic structure of red giants and mode trapping

Dipolar modes physics (Takata, 2005, 2006)

First integral (center of mass motion)

Rigorous 2nd order oscillation equations :

$$\frac{d\mathcal{Y}_1}{dr} = F_1(r;\sigma^2)\mathcal{Y}_2 \qquad F_1(r;\sigma^2) = \frac{r^2u^2}{c^2}\left[\frac{L_1^2}{\sigma^2}\left(1-\frac{\rho}{\rho_{\mathrm{av}}}\right)^2 - 1\right]$$

$$\frac{d\mathcal{Y}_2}{dr} = F_2(r;\sigma^2)\mathcal{Y}_1 \qquad F_2(r;\sigma^2) = \frac{1}{r^2u^2}\left[\sigma^2 - N^2\left(1-\frac{\rho}{\rho_{\mathrm{av}}}\right)^{-2}\right]$$

$$\rho_{\mathrm{av}} = \frac{3M_r}{4\pi r^3}$$

New critical frequencies :

$$\tilde{L}_1^2 = L_1^2\left(1-\frac{\rho}{\rho_{\mathrm{av}}}\right)^2$$

$$\tilde{N}^2 = N^2\left(1-\frac{\rho}{\rho_{\mathrm{av}}}\right)^{-2}$$

This should affect the size and location of the cavities

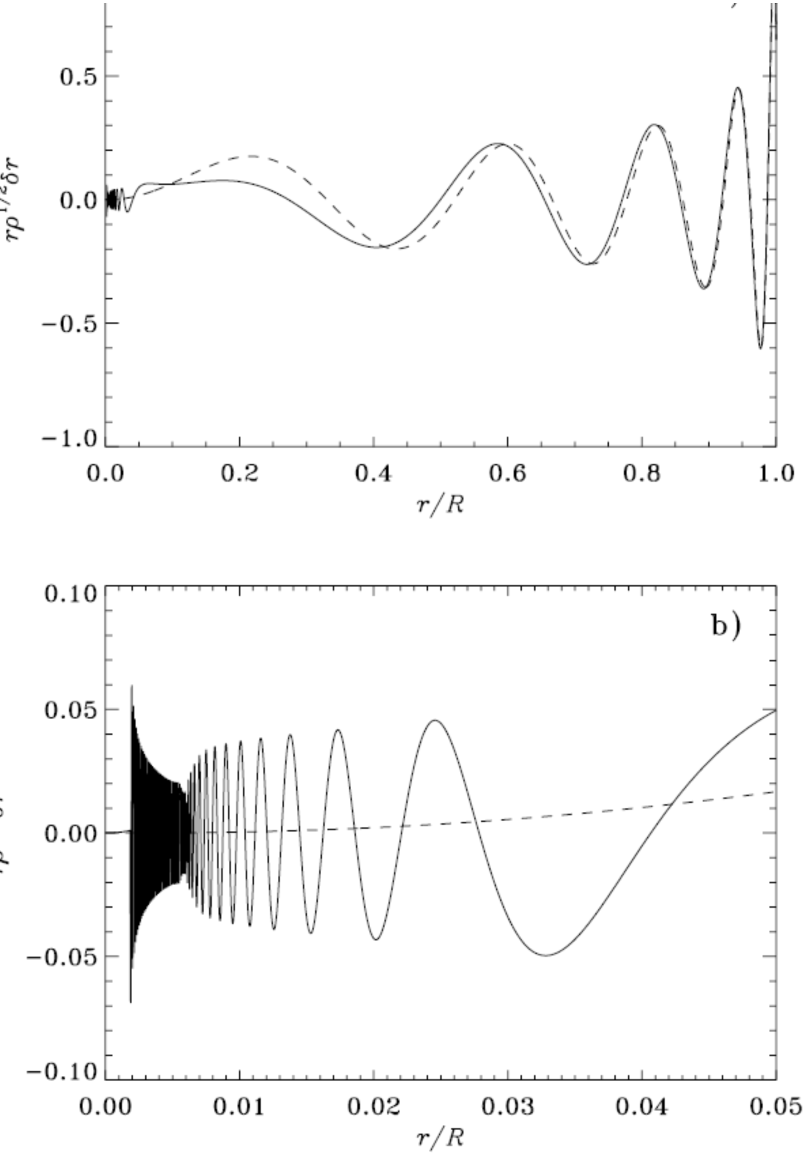
Acoustic structure of red giants and mode trapping

Eigenfunctions similar to classical p-modes in the envelope

Huge number of nodes in the core

$$n_g \propto (\ell(\ell+1))^{1/2} \int \frac{N}{r} dr.$$

From Christensen-Dalsgaard (2004)



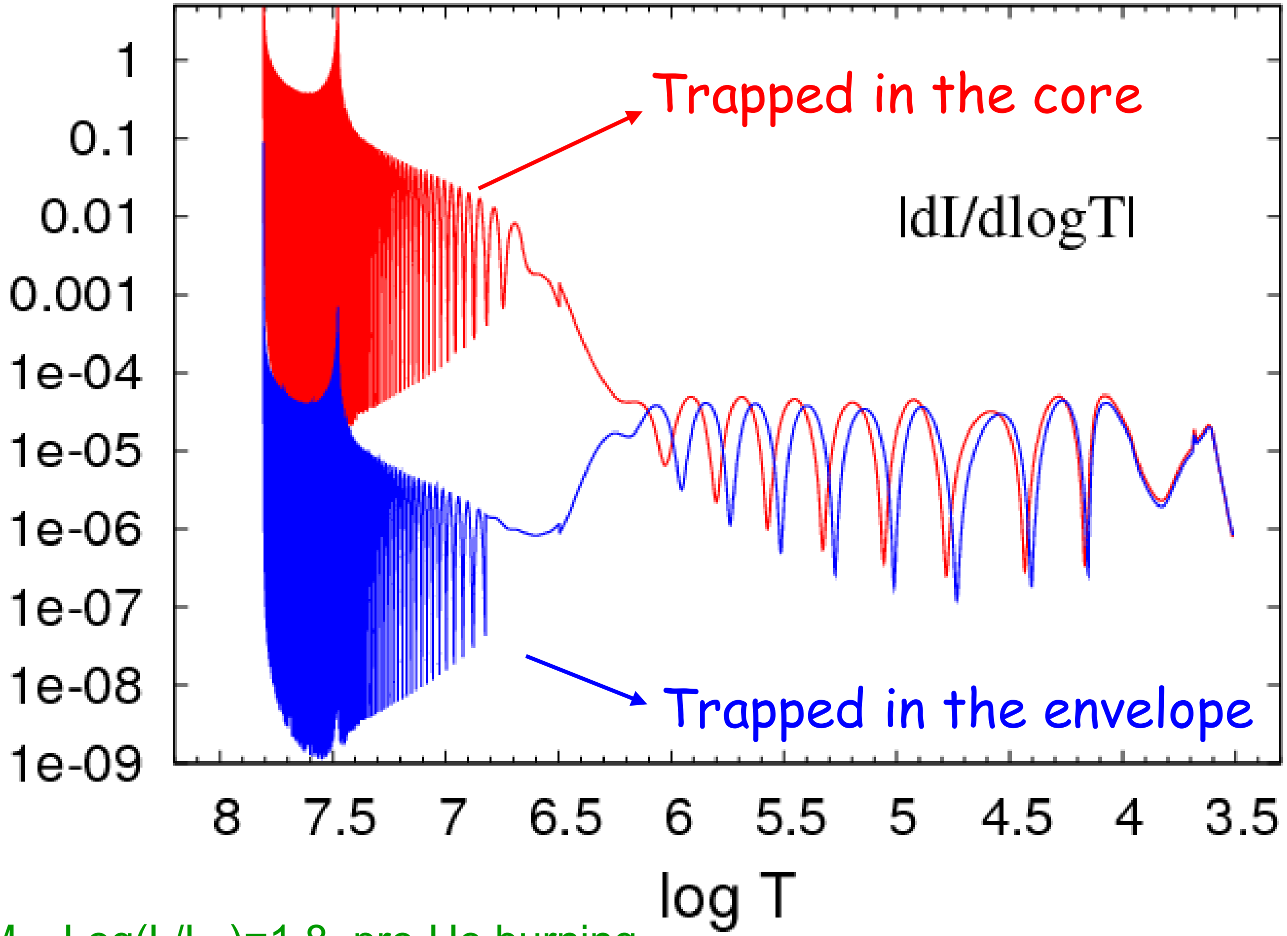
Acoustic structure of red giants and mode trapping

Mode trapping

See also Dziembowski et al. (2001)
Christensen-Dalsgaard (2004)

ENERGY density

$$\text{Inertia} = \int_0^M |\,\delta\vec{r}\,|^2\, dm = \int \boxed{(\mathrm{d}I/\mathrm{d}\log T)}\, \mathrm{d}\log T$$



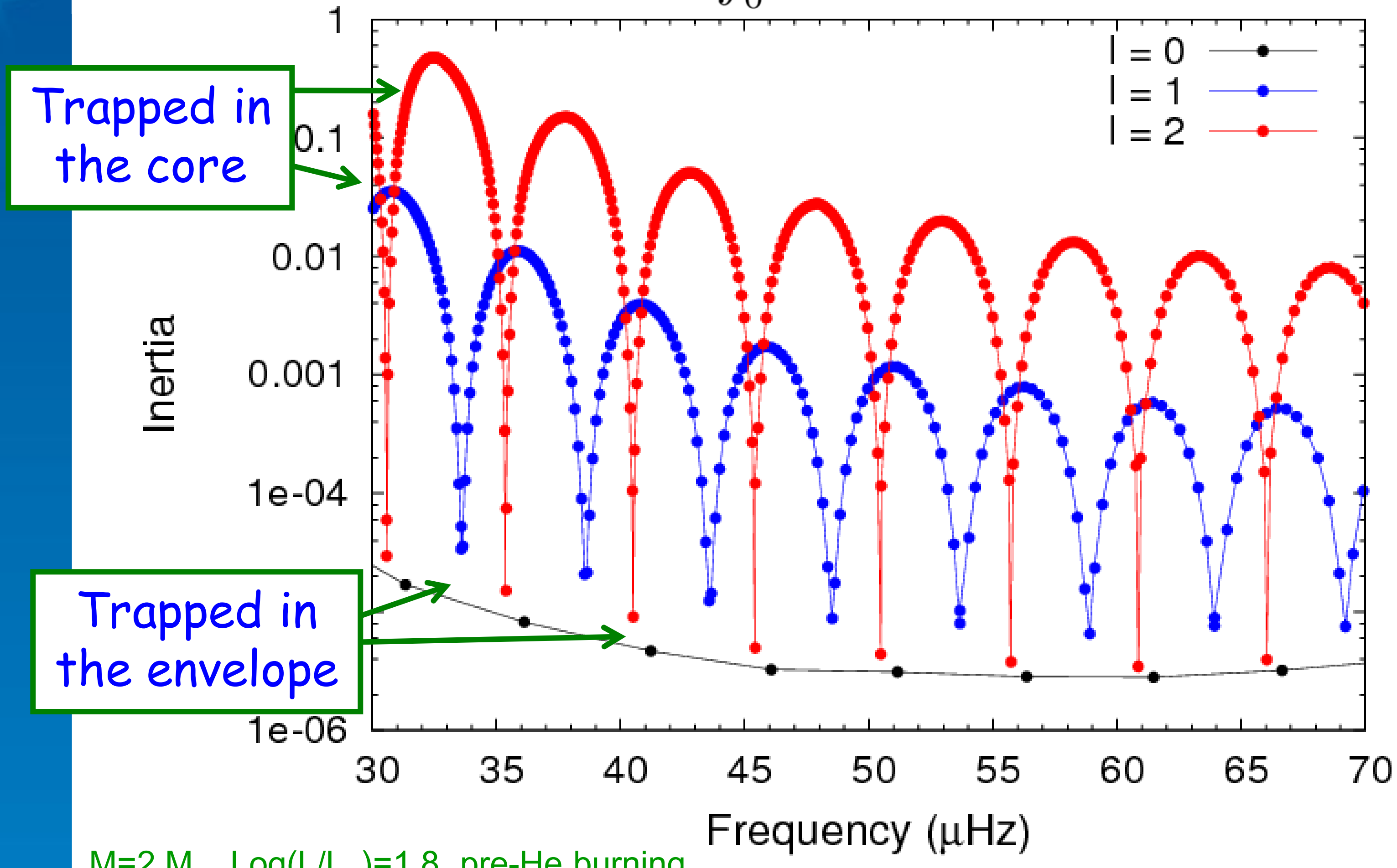
M=2 $M_\odot$, Log($L/L_\odot$)=1.8, pre-He burning

Acoustic structure of red giants and mode trapping

Mode trapping

See also Dziembowski et al. (2001)
Christensen-Dalsgaard (2004)

$$\text{Inertia} = \int_0^M |\,\vec{\delta r}\,|^2 \; dm$$



M=2 $M_\odot$, Log($L/L_\odot$)=1.8, pre-He burning

Seismic diagnostics from modes trapped in the **envelope**

Same diagnostics as in main sequence solar-like stars

1) Large separation

In the asymptotic limit :

$$< \Delta\nu > \simeq \left(\int_0^R dr/c \right)^{-1}$$

Homologous reasoning :

$$\propto (M/R^3)^{1/2}$$

Mean density

But : surface effects (non-adiabaticity, …)

But : red giants are not homologous …

Seismic diagnostics from modes trapped in the **envelope**

2) Acoustic glitches

Sharp features in sound speed

↓

Deviations from constant $\Delta\nu$ as oscillatory components

$$\delta\nu = A(\nu)\cos\left(4\pi\tau_0\nu + \phi\right)$$

$$\tau_0 = \int_{r_0}^{R} \frac{\mathrm{d}r}{c}$$

See e.g. Gough (1990)

In red giants : - Signature of He_{II} ionization zone

→ access to envelope He abundance

Miglio et al. (2010)

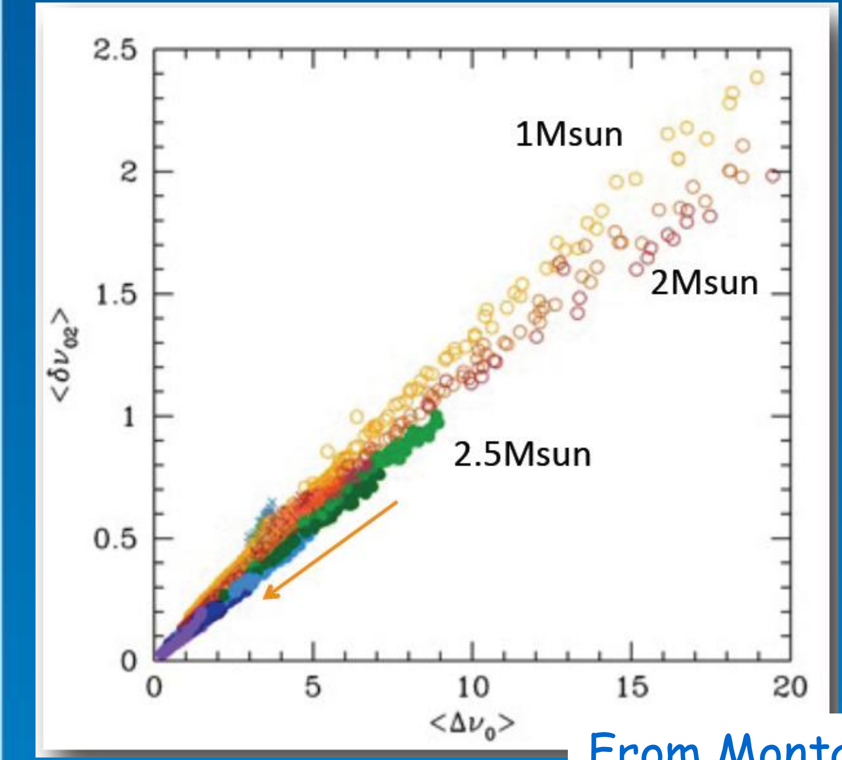
- No signatures of the base of convective envelope because too large acoustic depth

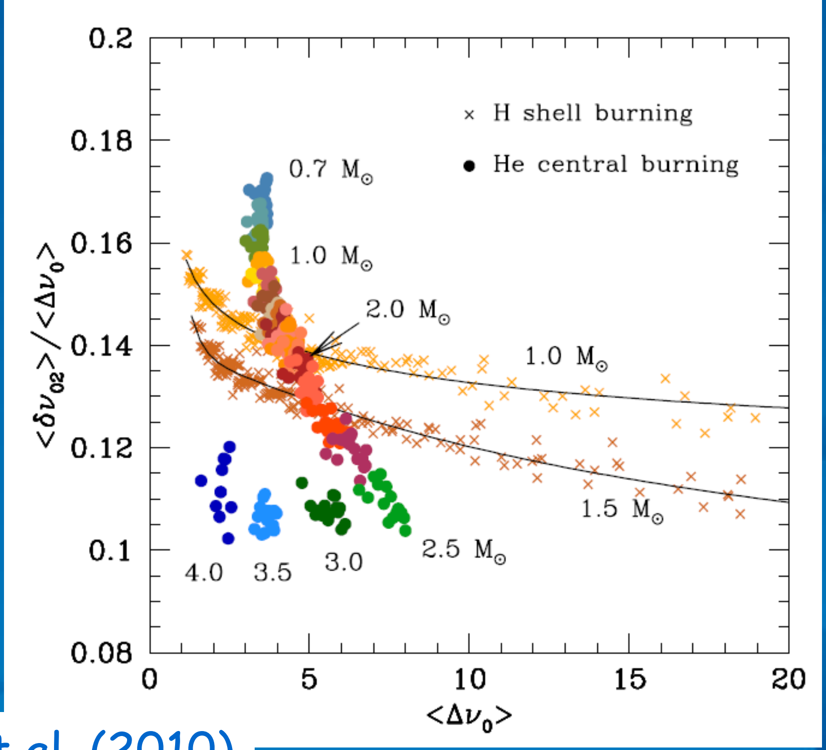
Seismic diagnostics from modes trapped in the **envelope**

3) Small separation

$\delta\nu_{02}$ - $\Delta\nu_0$ degeneracy

$\delta\nu_{02}$ depends mainly on mass and radius





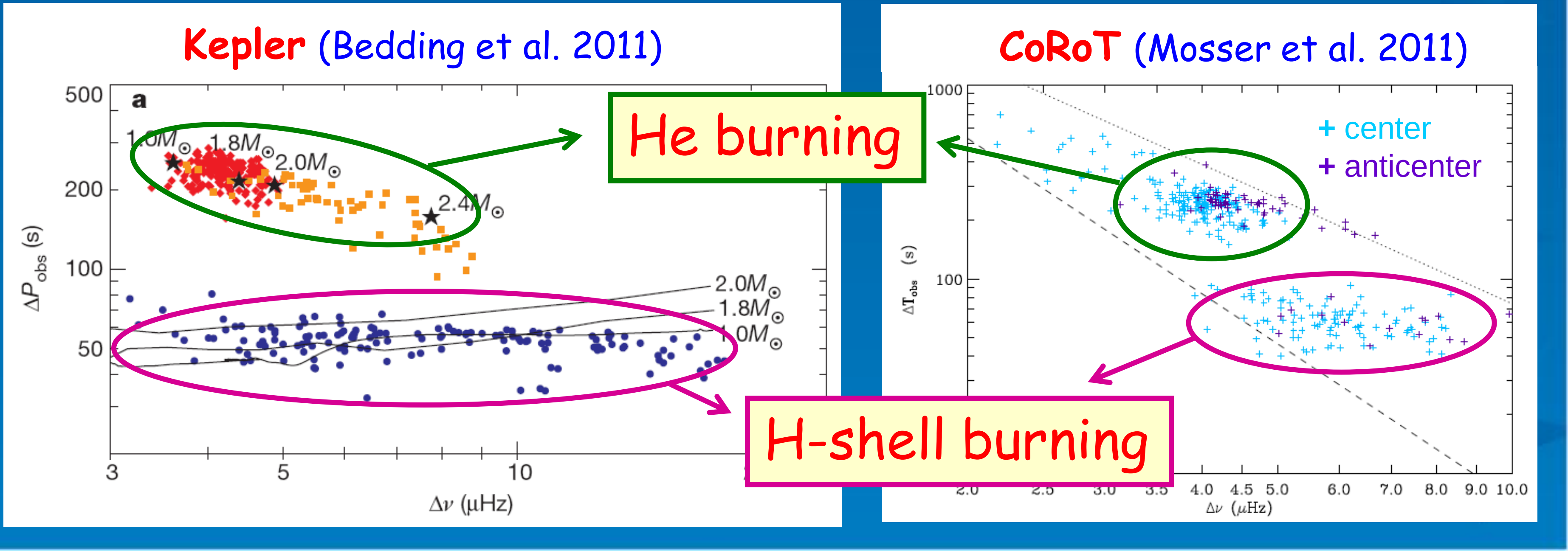
From Montalban et al. (2010)

Seismic diagnostics from modes trapped in the **core**

Period spacing : $\Delta P = P_{k,\ell} - P_{k-1,\ell} \approx \frac{2\pi^2}{\sqrt{\ell(\ell+1)}} \left(\int_{g_{cavity}} \frac{N}{r}\,\mathrm{d}r\right)^{-1}$

Huge potential to probe the deepest layers :

- Determination of the evolutionary stage
- Measure of the He core mass (Montalban et al. 2012)
- Signatures of the μ-gradient in the core ?



Kepler (Bedding et al. 2011)

CoRoT (Mosser et al. 2011)

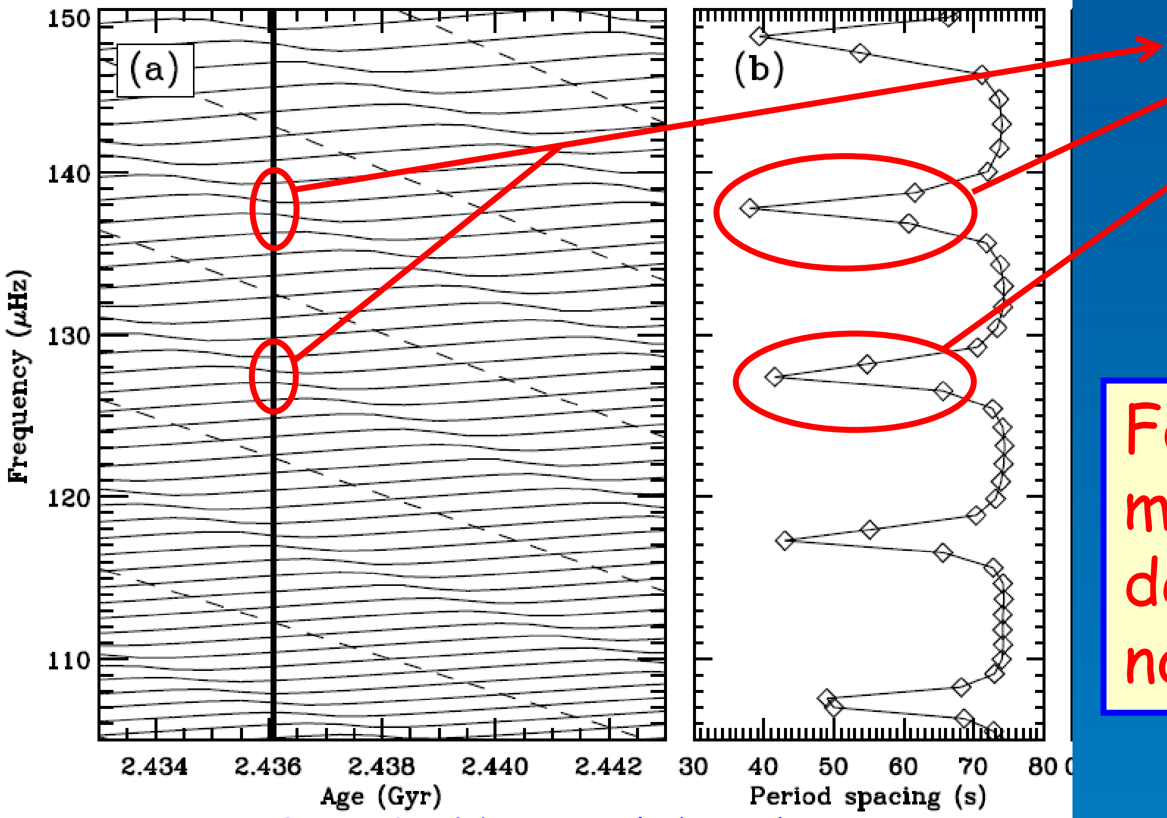
He burning

H-shell burning

Seismic diagnostics from modes trapped in the core

Period spacing : $\Delta P = P_{k,\ell} - P_{k-1,\ell} \approx \frac{2\pi^2}{\sqrt{\ell(\ell+1)}} \left(\int_{g_{cavity}} \frac{N}{r} \mathrm{d}r \right)^{-1}$

l=1 p-g modes avoided crossings



From Bedding et al. (2011)

For a precise seismic modelling, we have to deal with these strong non-linearities …

Energetic aspects of mode physics

Stochastic excitation (top of the convective envelope)

Samadi et al. (2003, …) Belkacem et al. (2006, …) Houdek et al.

Amplitude (velocity)

$$V^2(R) = \frac{P}{2\,\eta\ I}$$

Stochastic power

Inertia

Damping rate

Stochastic excitation model

$$P = p\,I^{-1}$$

Outermost part of the convective envelope

Two types of terms :

- Reynolds stress
- Entropy

Main uncertainties : Injection length scale, kinetic energy spectrum

Energetic aspects of mode physics

Damping of the modes

$$\eta = \tau^{-1} = -W/(2\sigma I)$$

Convective damping in the envelope

See e.g. Gabriel (1996), Grigahcène et al. (2005),
Gough (1977), Balmforth et al. (1992), Houdek et al.

Coherent interaction convection-oscillations

Very complex because : Convective time-scale
~ thermal time-scale
~ oscillation periods

➡ Large uncertainties but … only depend on mode physics in the outermost part of the convective envelope

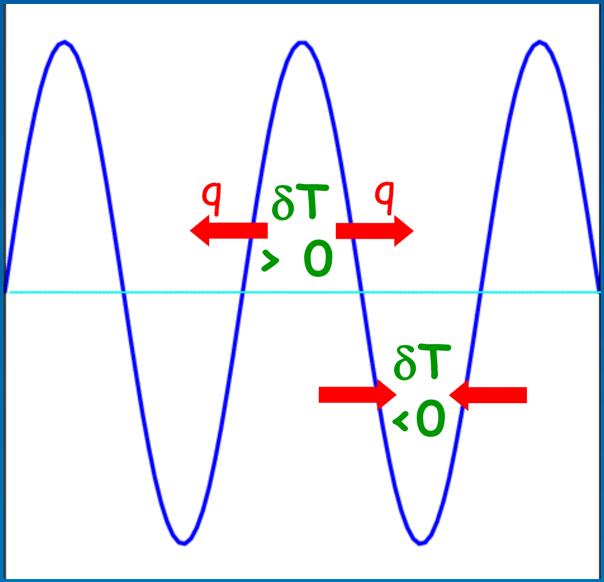
➡ Not affected by mode trapping

How to improve ? : use of 3D simulations, fitting of mode life times

Energetic aspects of mode physics

Radiative damping in the core

In a cavity with short wavelength oscillations :



Large variations of the temperature gradient

⬇

Large radiative damping

Affected by mode trapping

Significant for models with huge N^2 in the core

⇔ huge core-envelope density contrast

Energetic aspects of mode physics

Mode profiles in the power spectrum

If the modes are resolved :

$\mathrm{life-time} \ll T_{obs}$

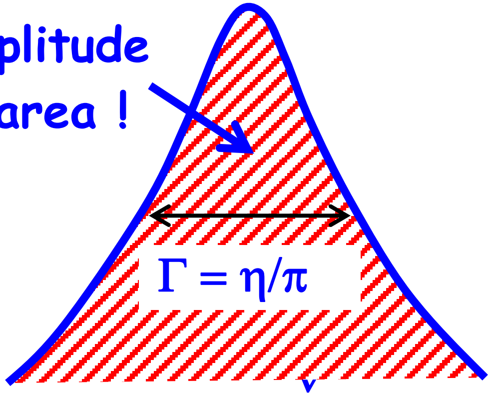
Height in the power spectrum

$$H = \frac{p}{2\,\eta^2\,I^2}$$

If $\eta \propto I^{-1}$: $H \propto p$

Similar heights for radial and resolved non-radial modes

Mode profile



Amplitude = area !

If the modes are not resolved :

$T_{obs} \ll \mathrm{life-time}$

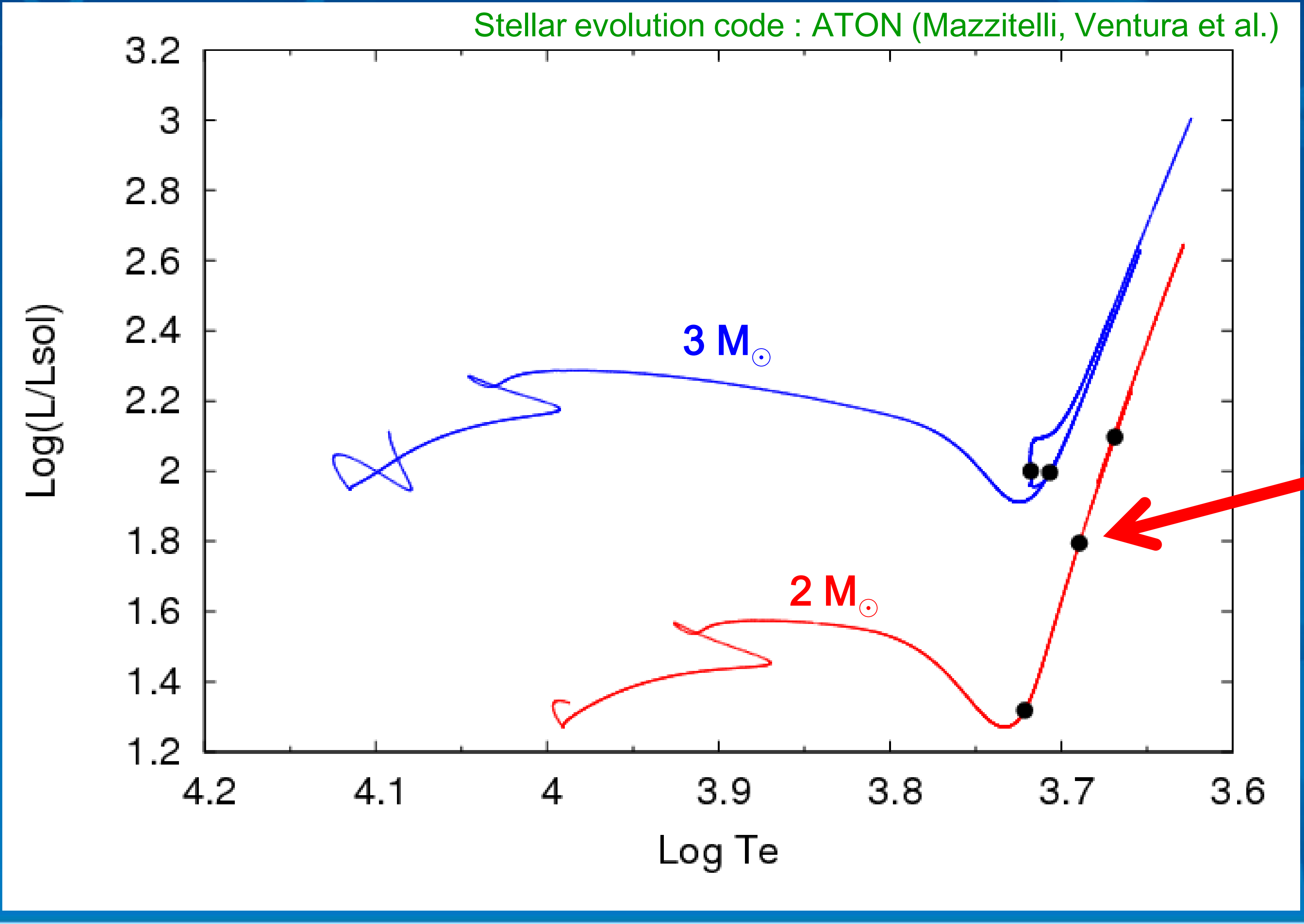
$$H = \frac{T_{obs}\,p}{4\,\eta\,I^2}$$

If $\eta \propto I^{-1}$:

$$\begin{aligned} H &\propto T_{obs}/\tau \\ &\propto I^{-1} \end{aligned}$$

Smaller heights for very long lifetime unresolved modes !

Some predictions : typical model in red giant branch

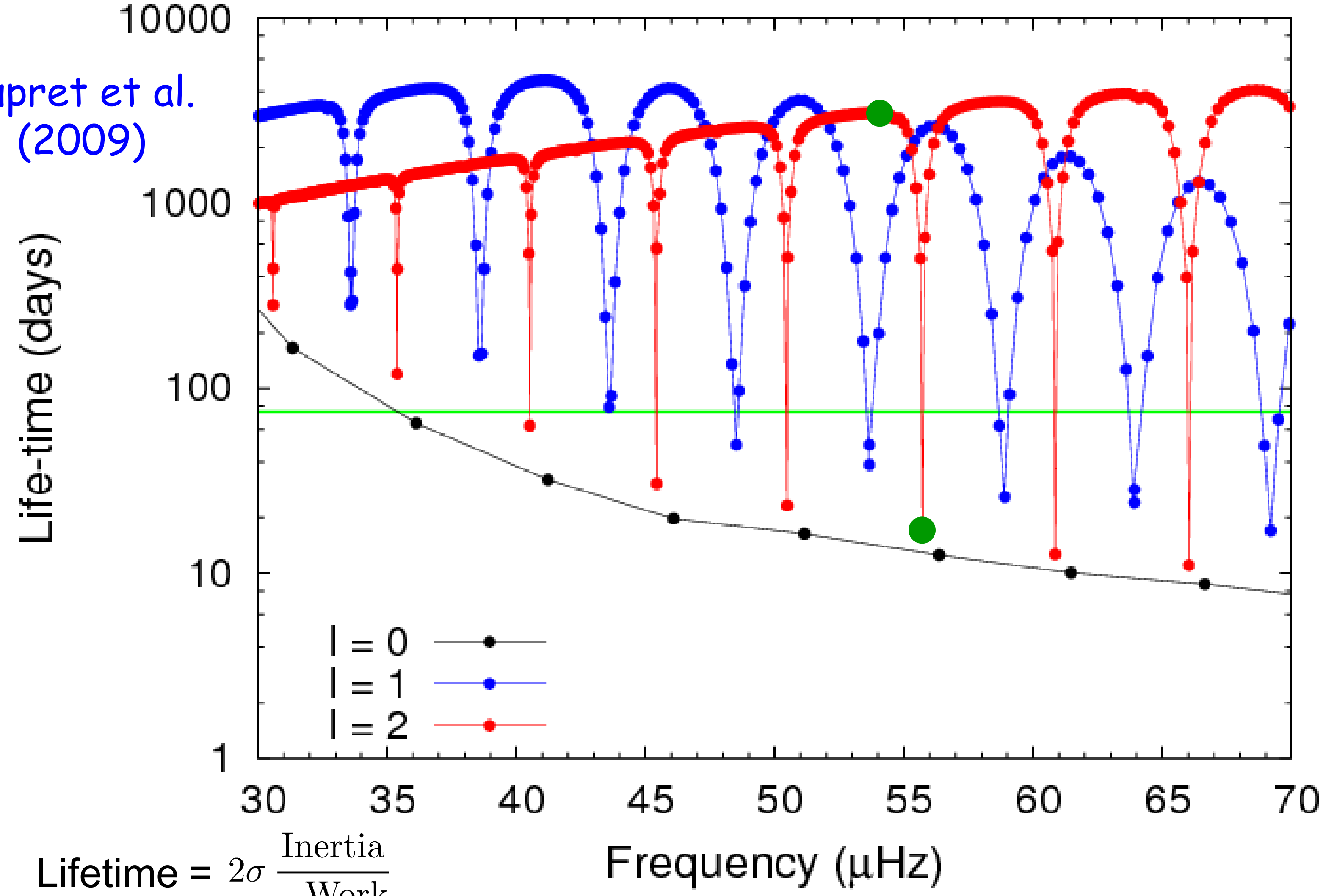


Some predictions : typical model in red giant branch

Lifetimes

M=2 $M_\odot$, Log($L/L_\odot$)=1.8, pre-He burning

Dupret et al. (2009)

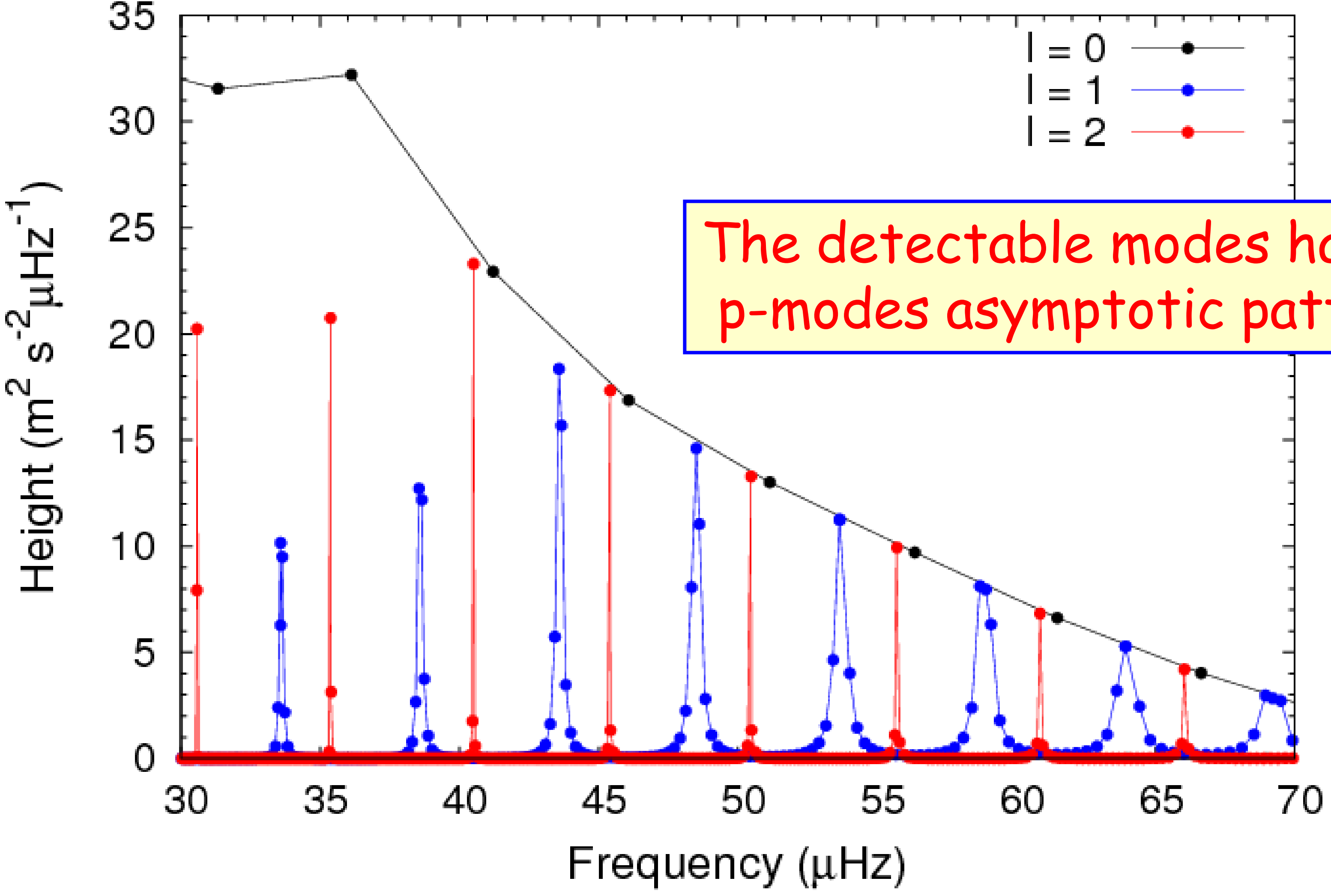


Lifetime = $2\sigma \frac{\text{Inertia}}{-\text{Work}}$

Some predictions : typical model in red giant branch

Height in PS

M=2 $M_\odot$, Log($L/L_\odot$)=1.8, pre-He burning



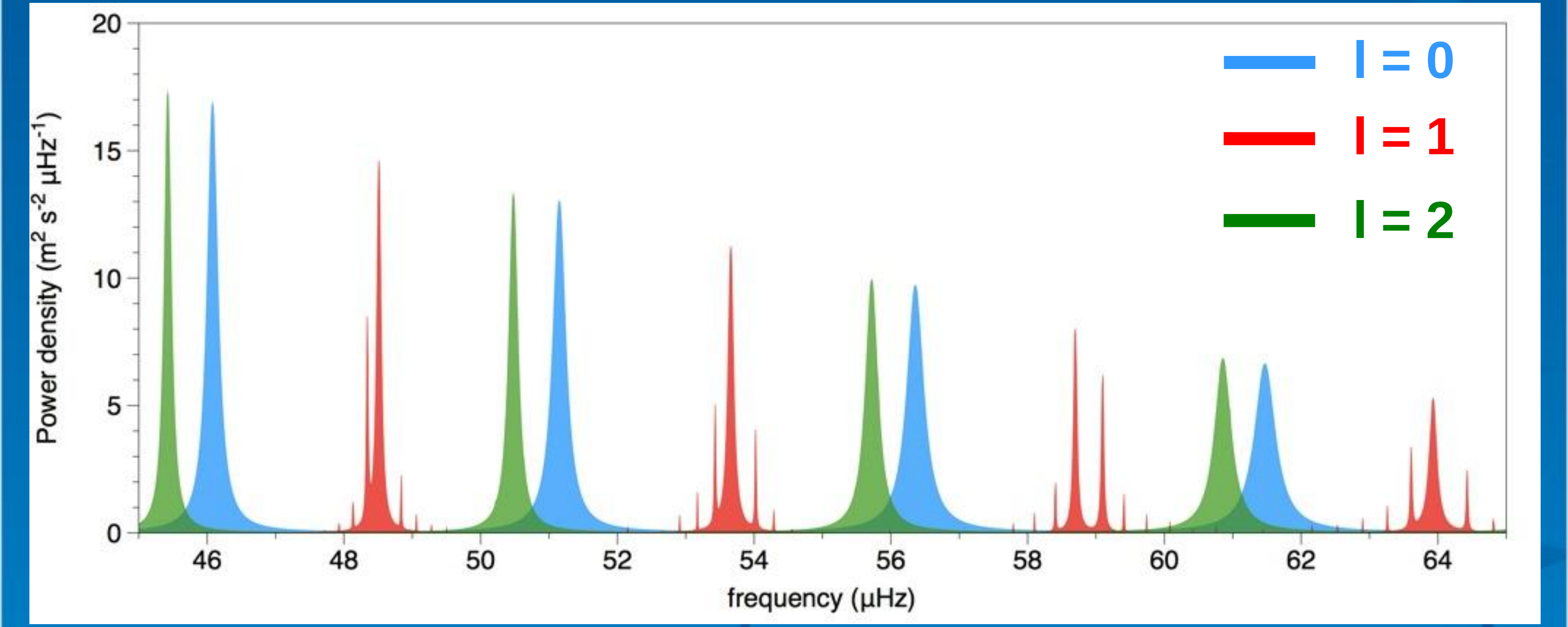
The detectable modes have p-modes asymptotic pattern

Some predictions : typical model in red giant branch

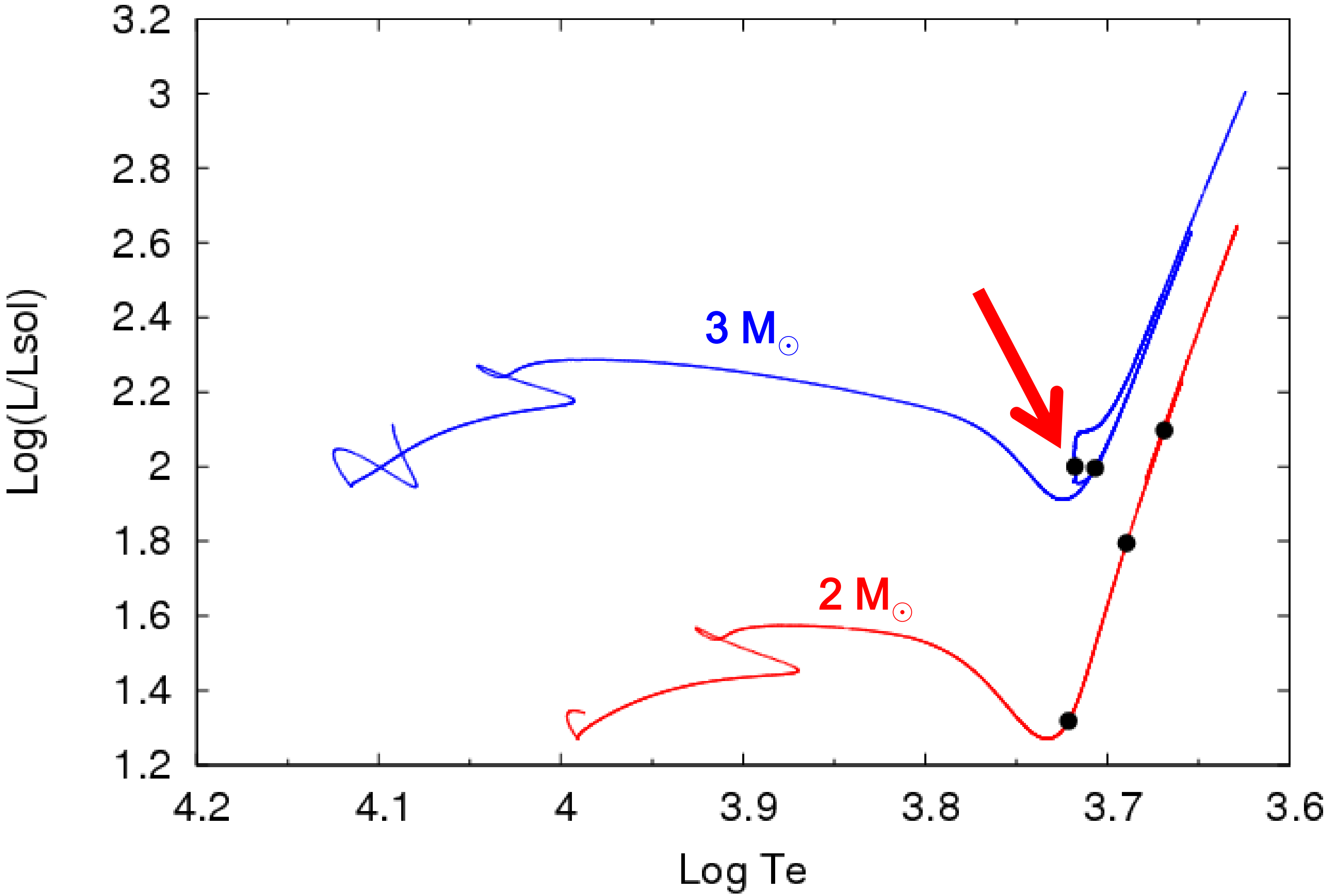
Predicted power spectrum

Regular for l=0 and 2

« Fine structures » of l=1 mixed modes



An Helium burning model



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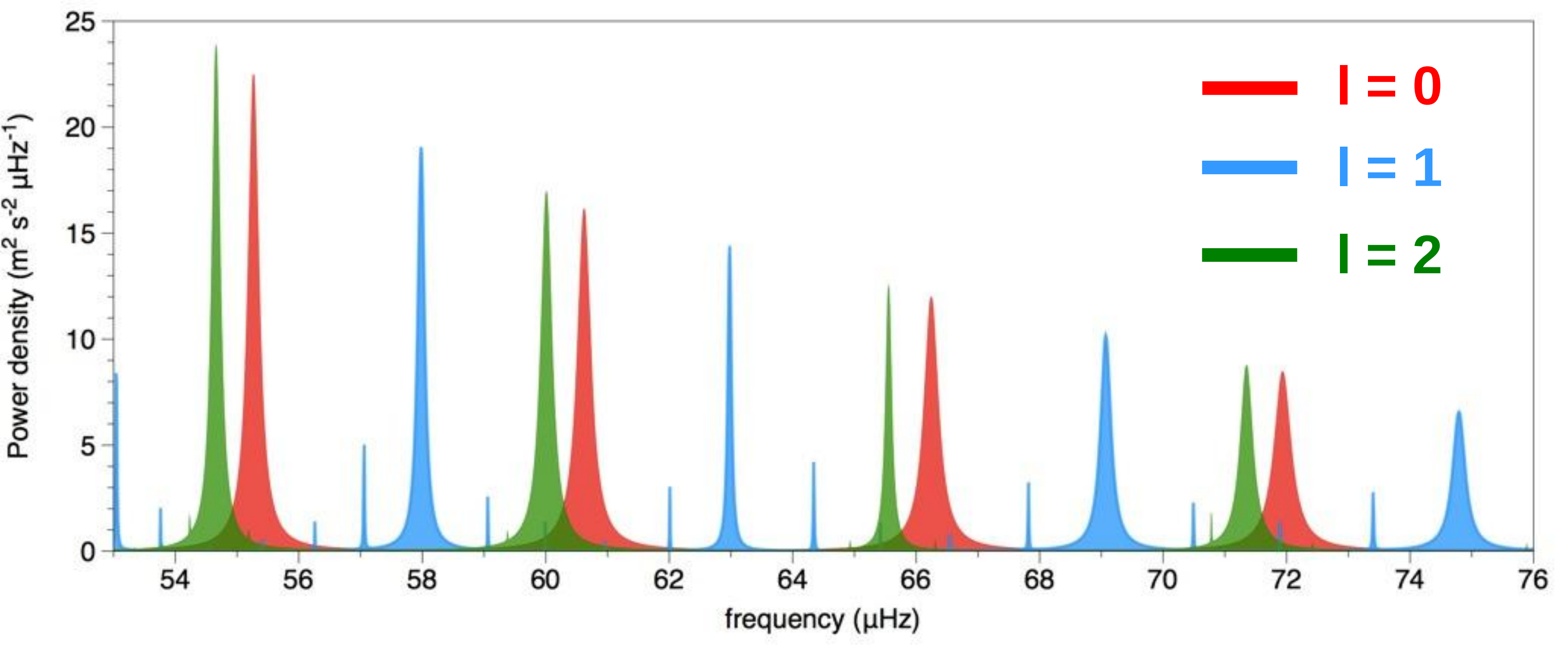
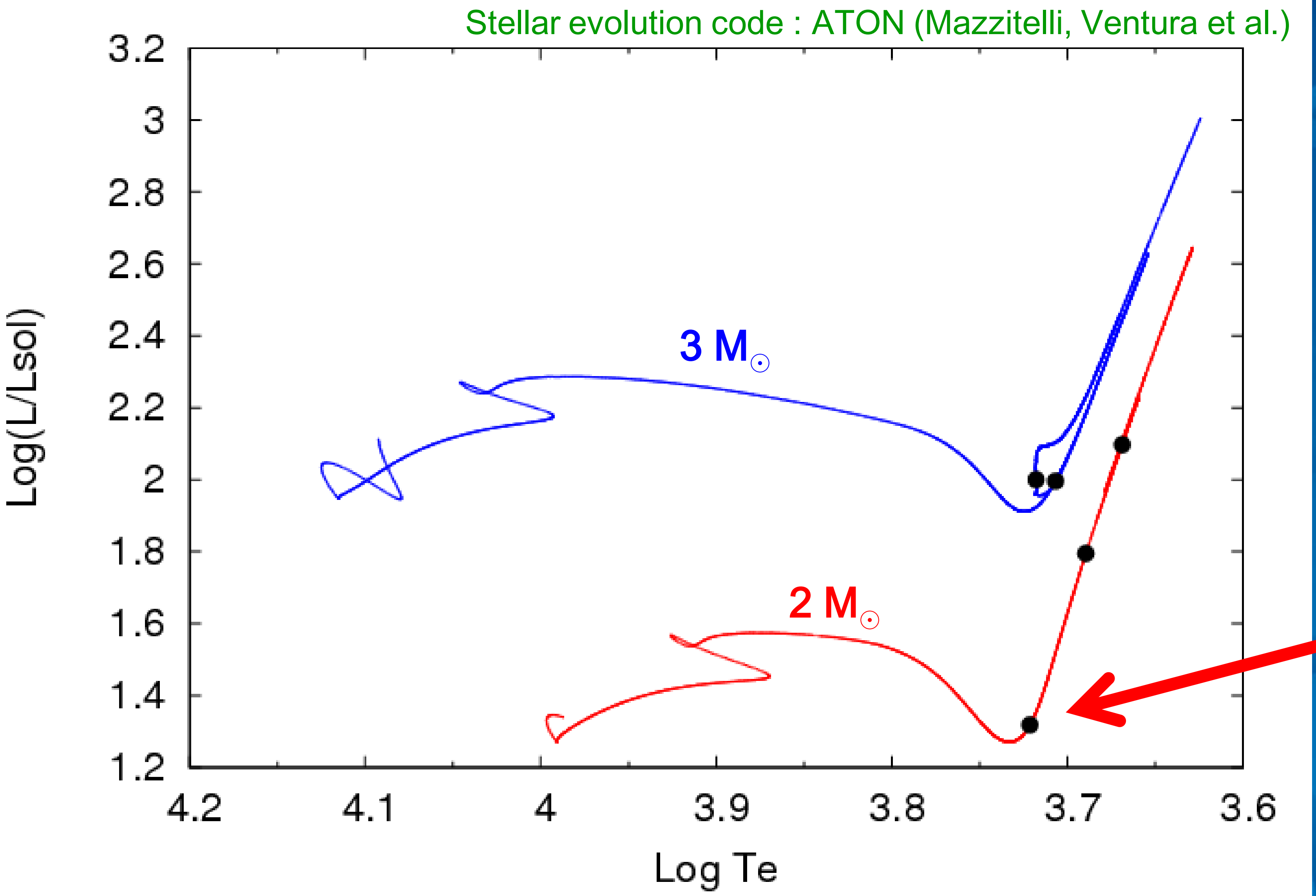


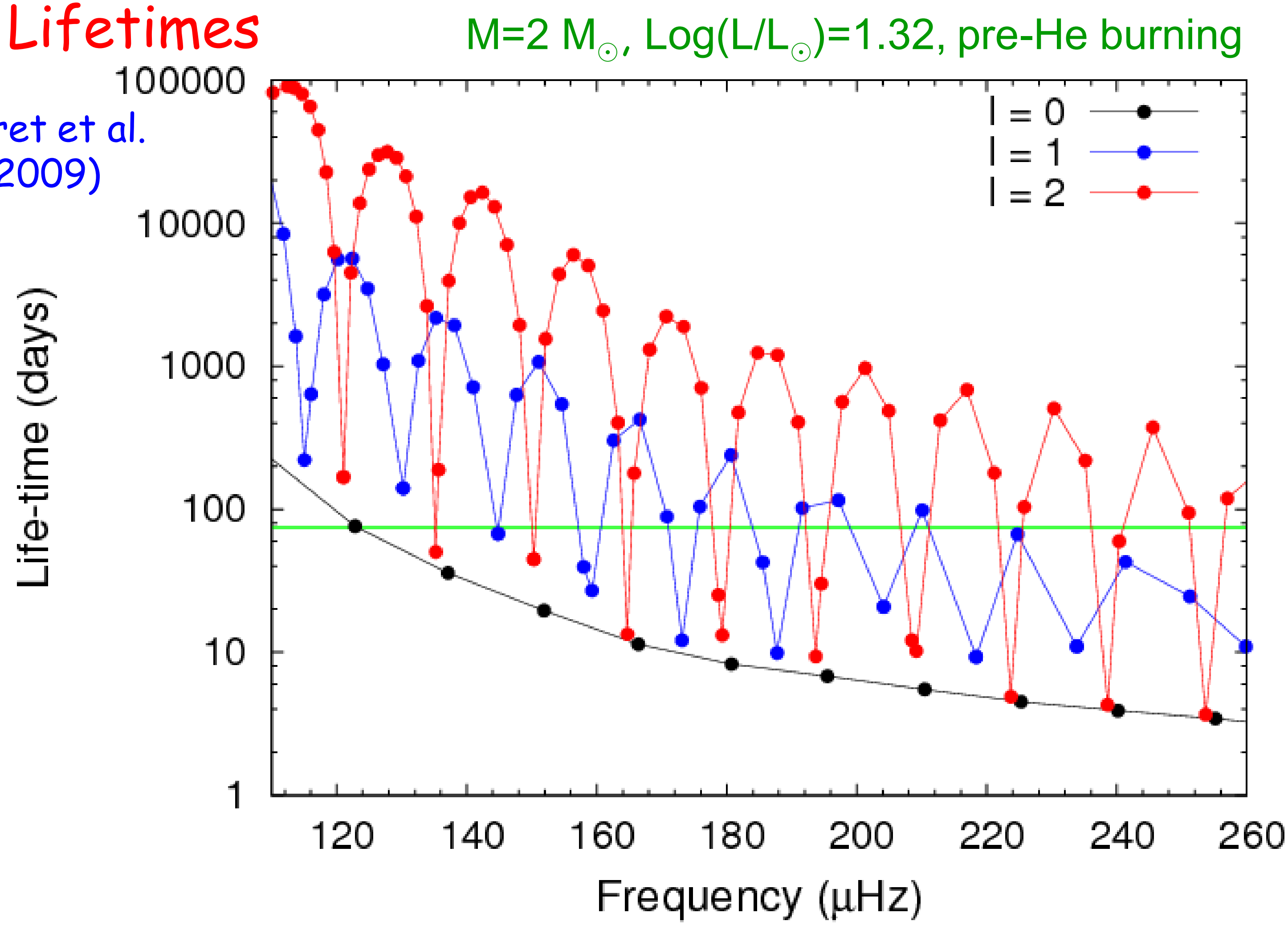
Some predictions : subgiants



Some predictions : subgiants

Lifetimes

Dupret et al. (2009)



$$\text{Lifetime} = 2\sigma \frac{\boxed{\text{Inertia}}}{-\text{Work}}$$

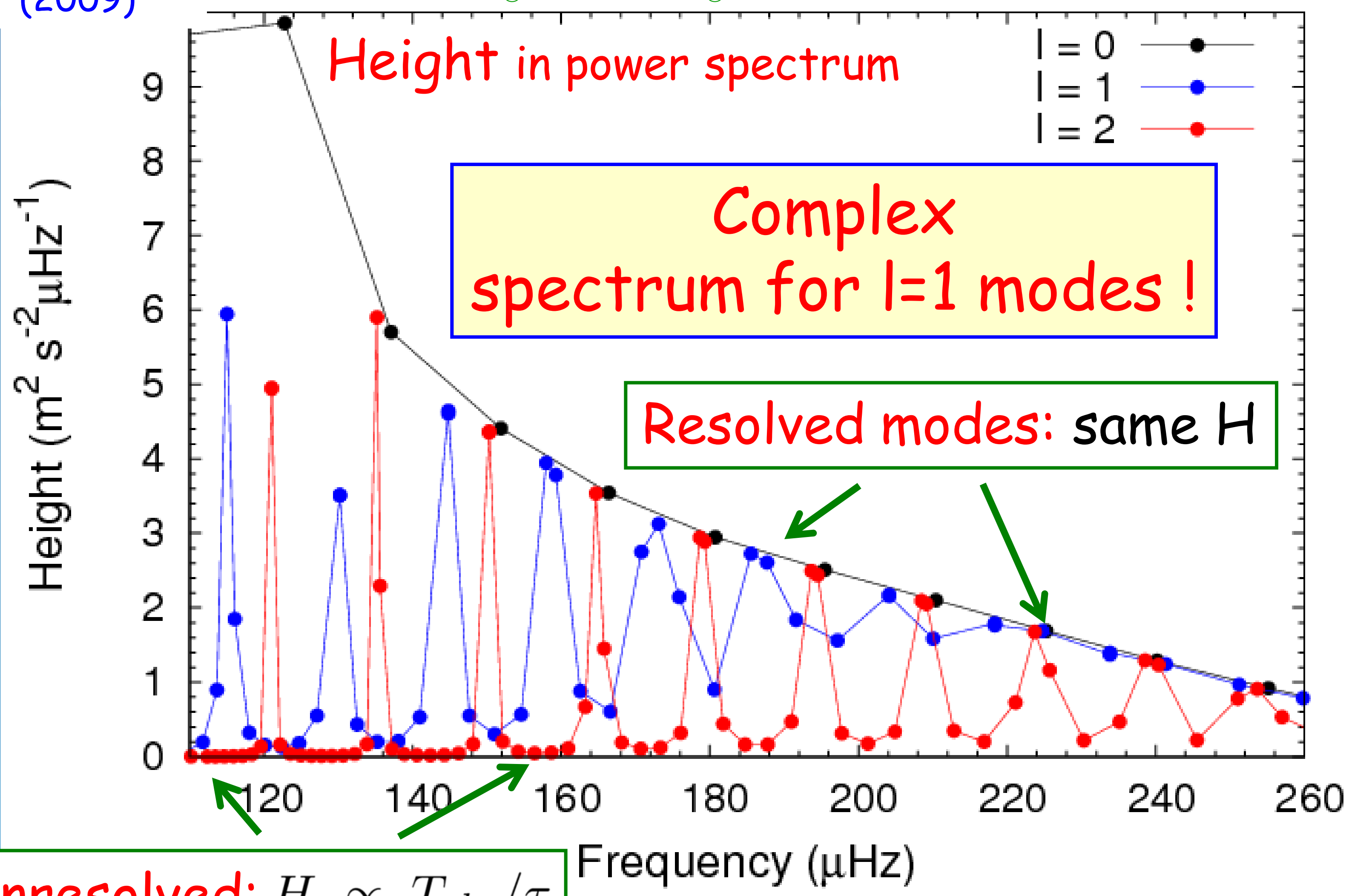
Oscillatory behaviour due to mode trapping

No radiative damping

Some predictions : subgiants

Dupret et al.
(2009)

M=2 $M_\odot$, Log($L/L_\odot$)=1.32, pre-He burning



Height in power spectrum

Complex
spectrum for l=1 modes !

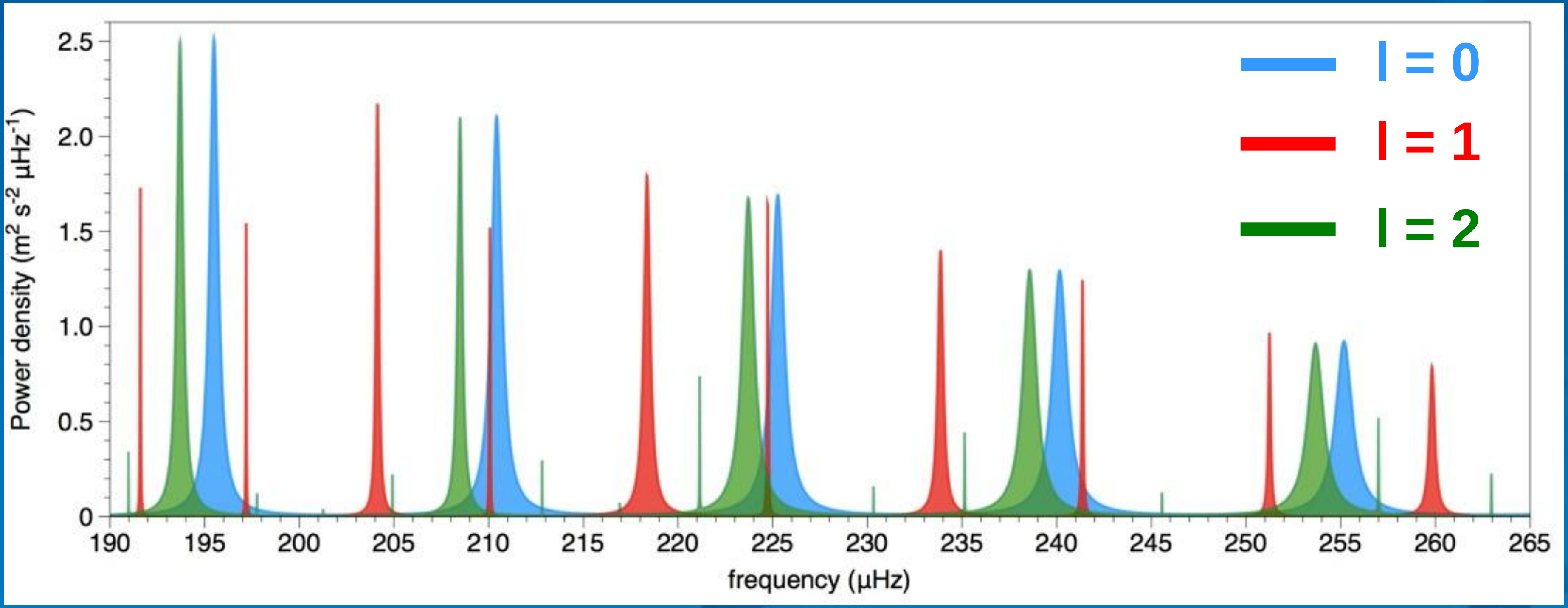
Resolved modes: same H

Unresolved: $H \propto T_{obs}/\tau$

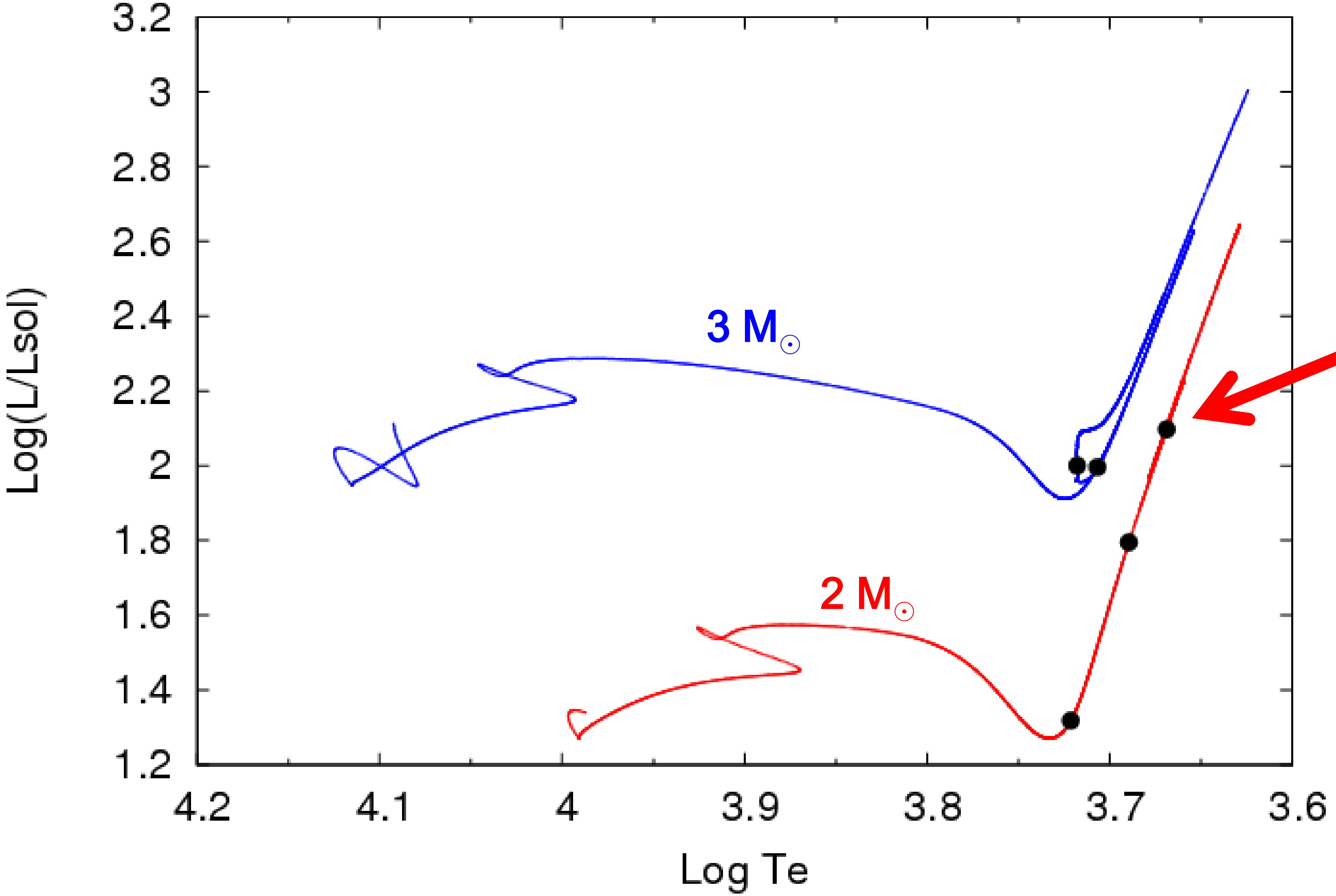
Some predictions : subgiants

Predicted power spectrum

Complex spectrum for l=1 modes !



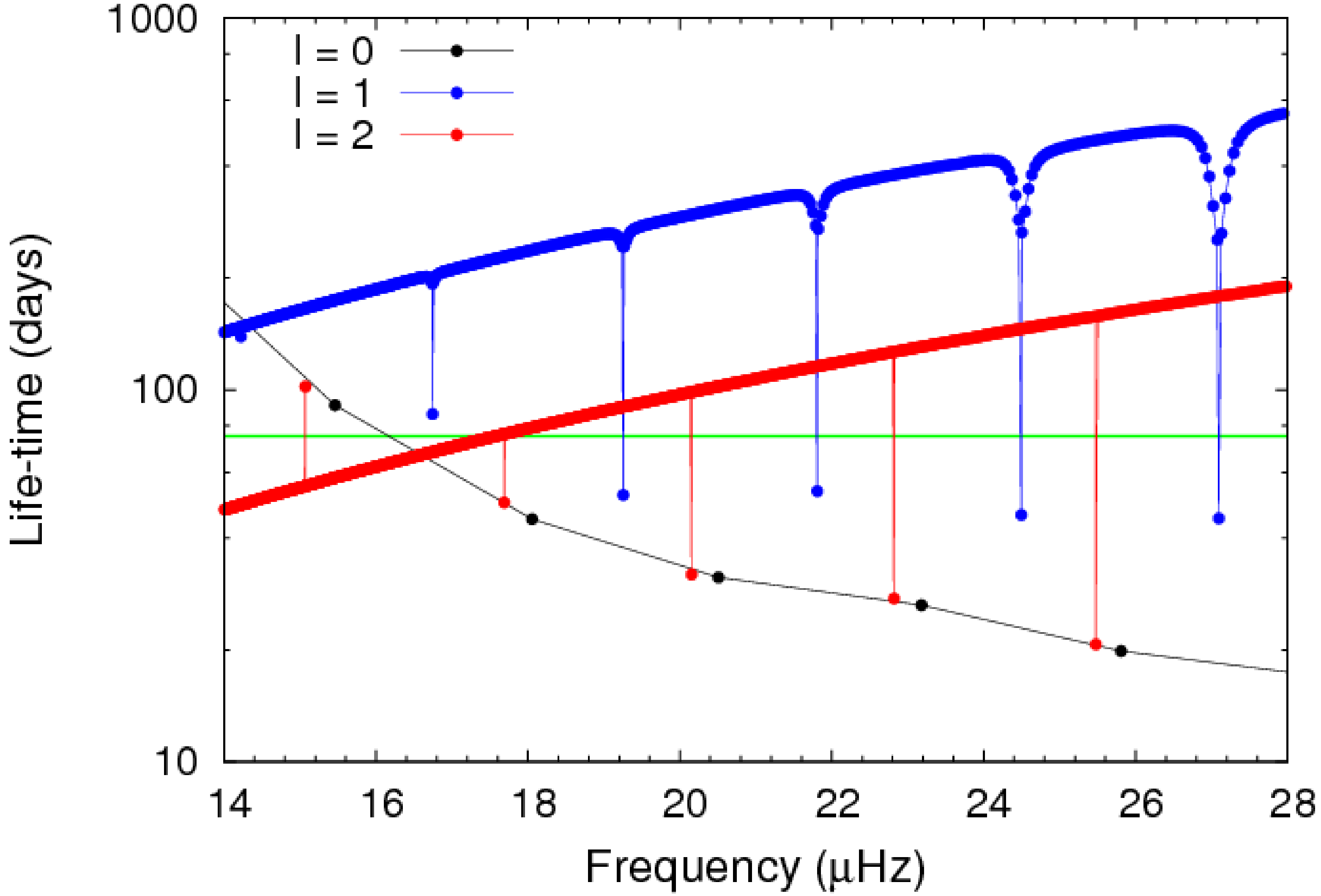
High luminosity model in the red giant branch



High luminosity model in the red giant branch

Lifetimes

$M=2\ M_\odot$, $\mathrm{Log}(L/L_\odot)=2.1$, pre-He burning



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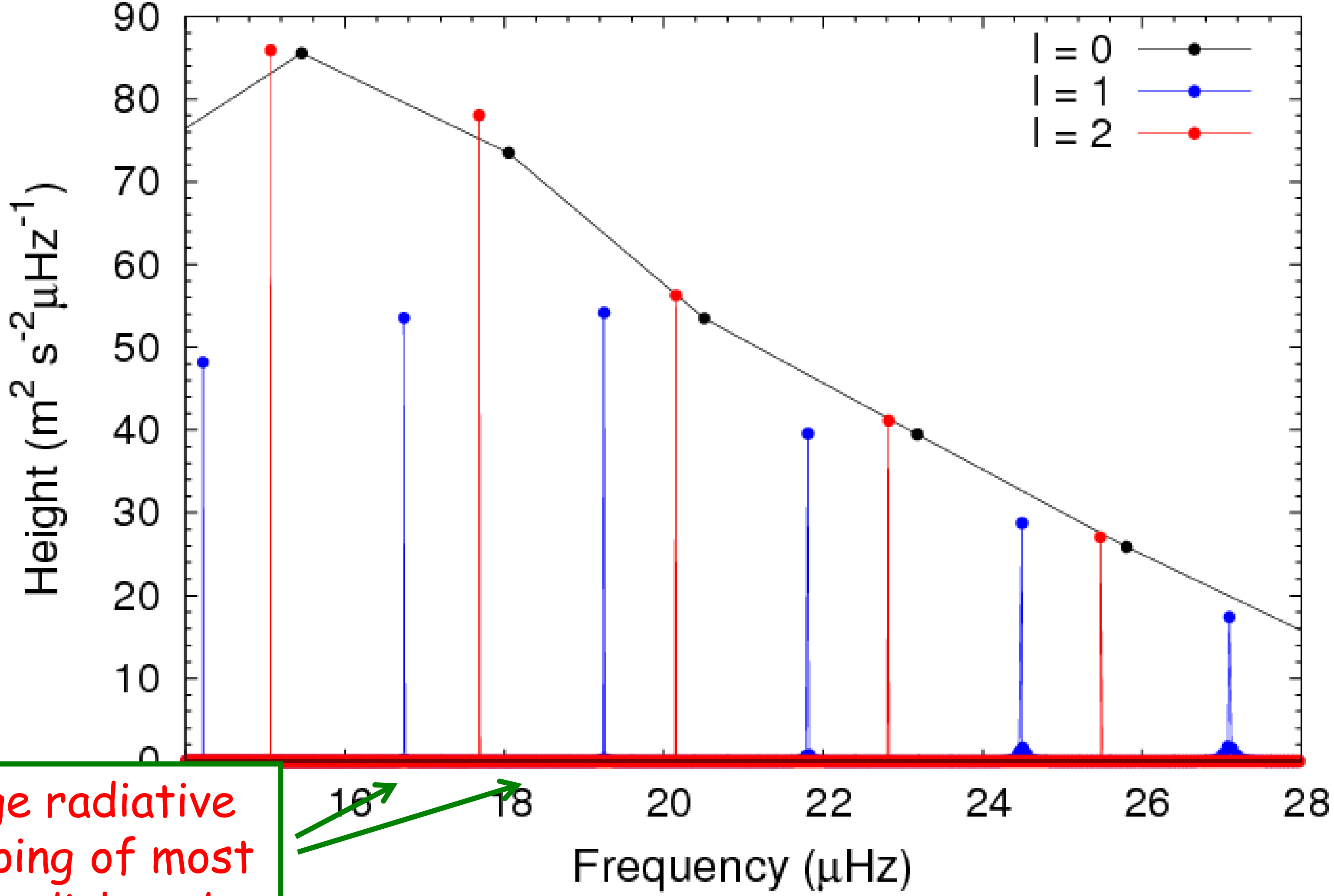


Height in PS

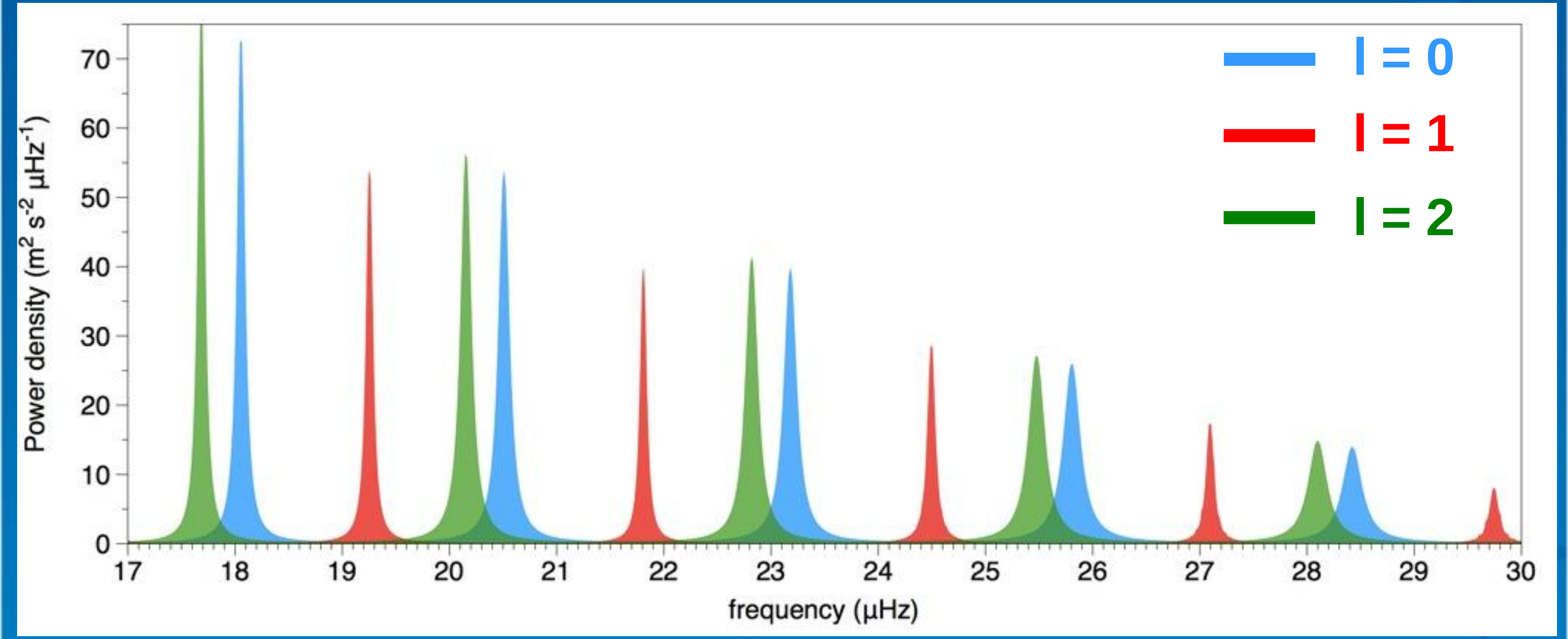
M=2 $M_\odot$, Log($L/L_\odot$)=2.1, pre-He burning

Huge radiative damping of most non-radial modes

High luminosity model in the red giant branch

Predicted power spectrum

Regular spectrum
similar to main sequence stars

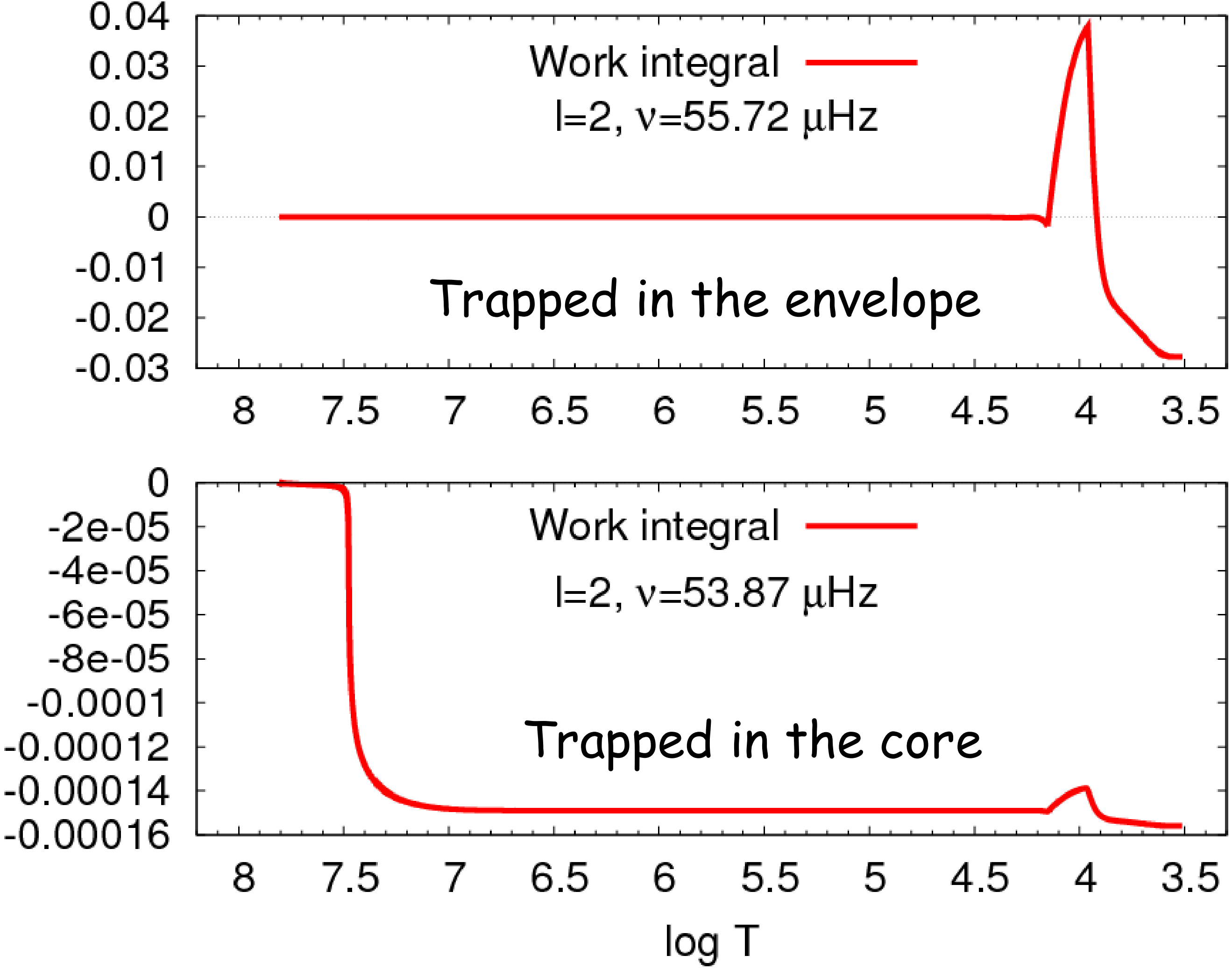


Thank you !

Some predictions : typical model in red giant branch

Work integrals

$M=2\,M_\odot$, $\mathrm{Log}(L/L_\odot)=1.8$, pre-He burning



Trapped in the envelope

Trapped in the core

Convective damping near the surface

Radiative damping in the core