Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique

# Excitation mechanisms (Sun, subgiants, & red giants)

K. Belkacem

- P-modes in the Sun and main-sequence stars
- G-modes in the Sun
- Mixed-modes in sub giants and red giants

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# Energetics of solar-like oscillations

- Solar-like oscillations are damped and forced oscillations $$\frac{\mathrm{d}}{\mathrm{d}t}A^2 \propto \mathcal{P} - \eta A^2$$

Stationarity $\longrightarrow$ $A^2 \propto \dfrac{\mathcal{P}}{\eta}$ mode amplitudes = balance between damping and driving

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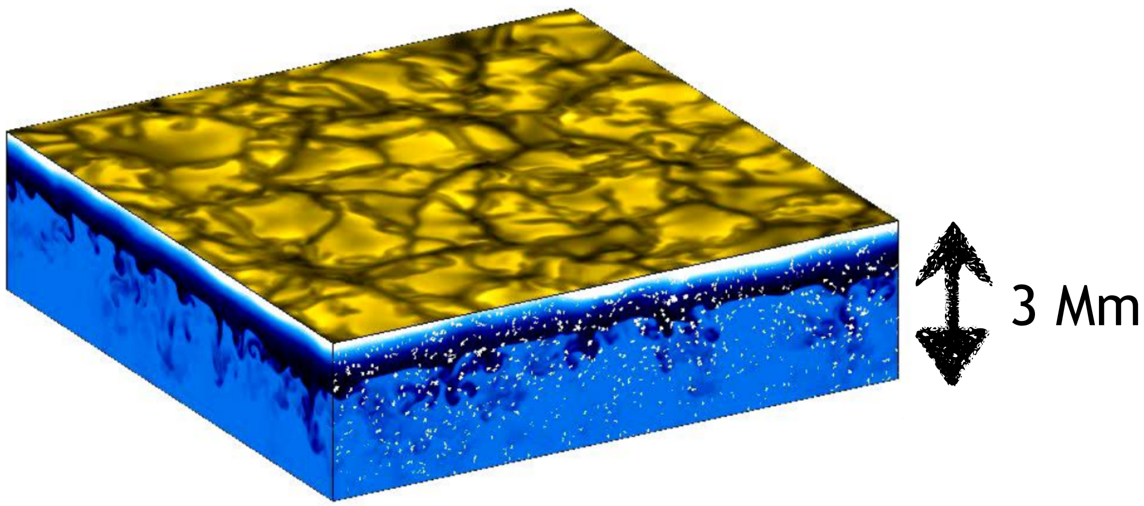
Driving ($P$):
"Stochastic excitation" by turbulent eddies

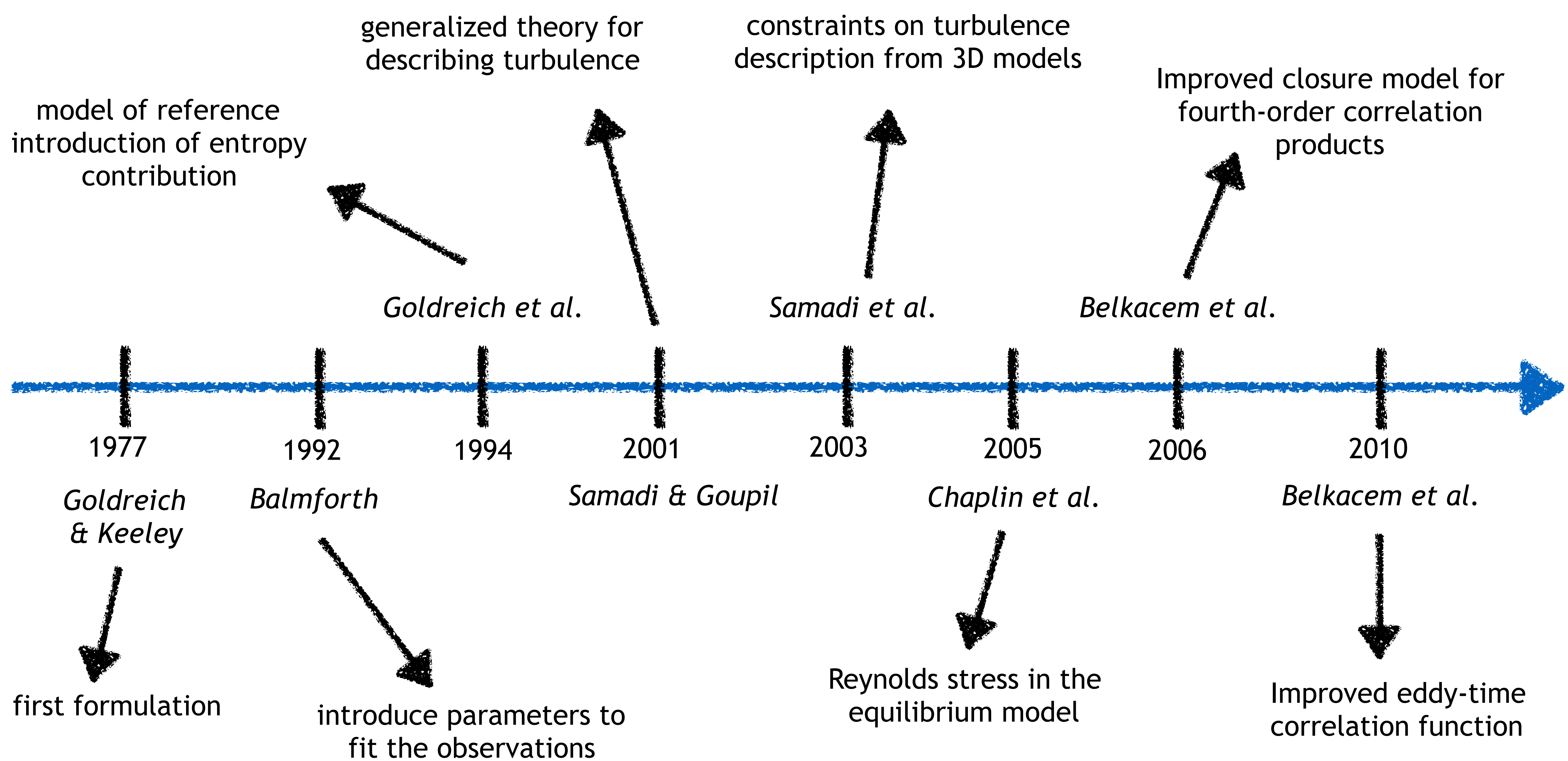



- eddies drive « randomly » the normal modes
- modes are excited in the upper-most layers of stars where turbulence is important
- typically a region of 3 Mm depth for the Sun

# Energetics of solar-like oscillations: mode driving

$$A^2 \propto \frac{\mathcal{P}}{\eta}$$

- For the Sun, the modeling of mode driving was a long process



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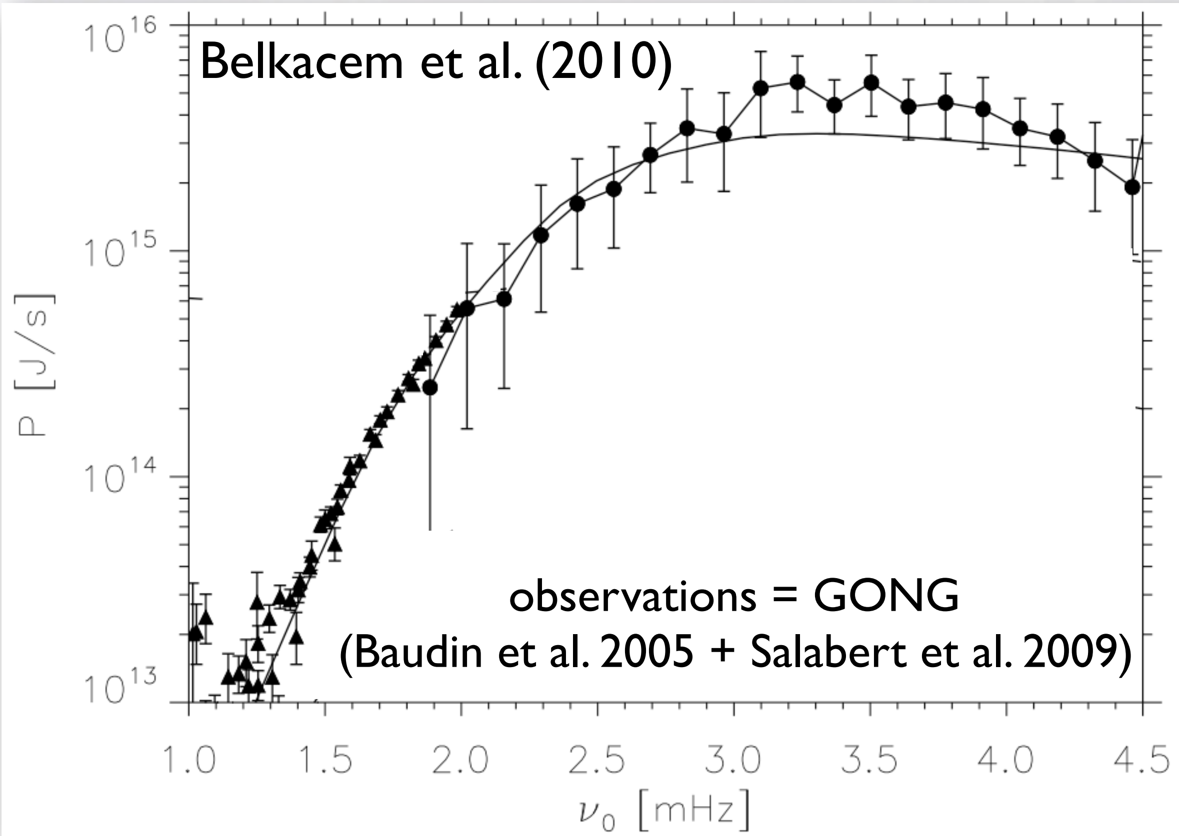


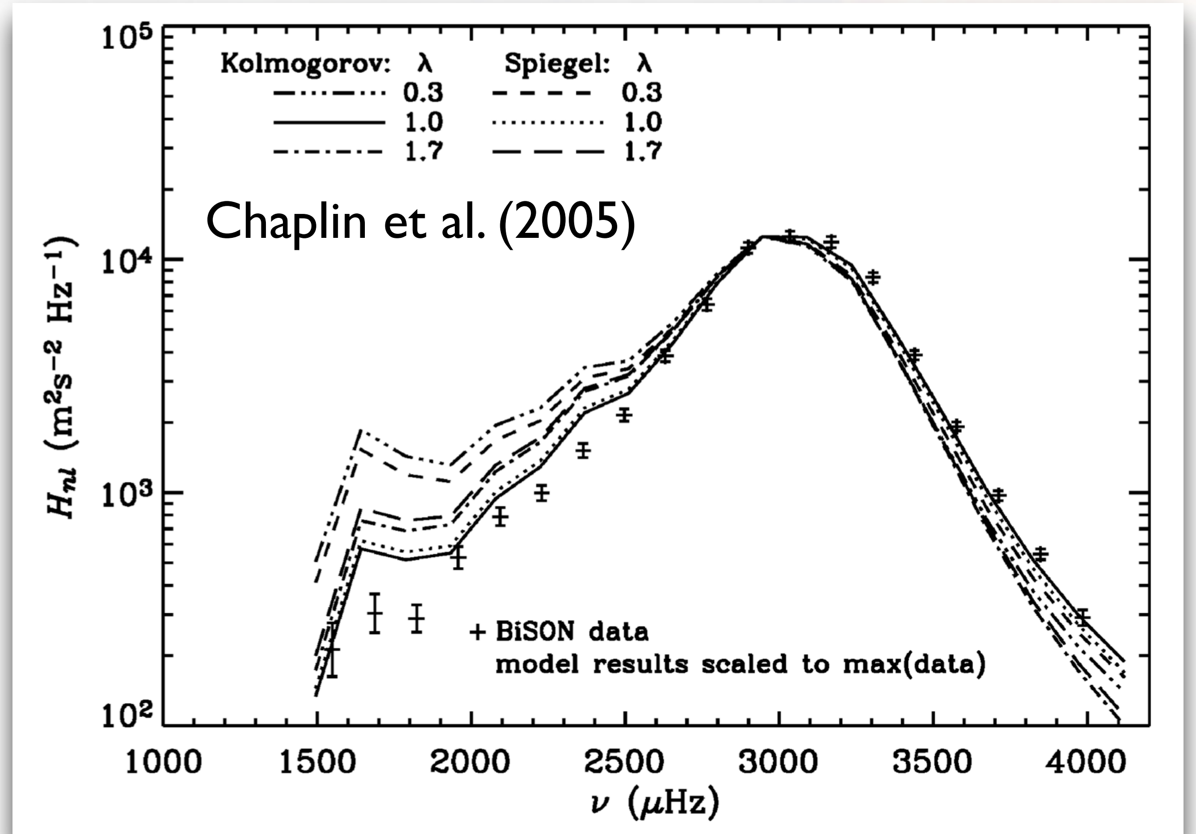


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- The dominant forcing is due to the Reynolds stresses

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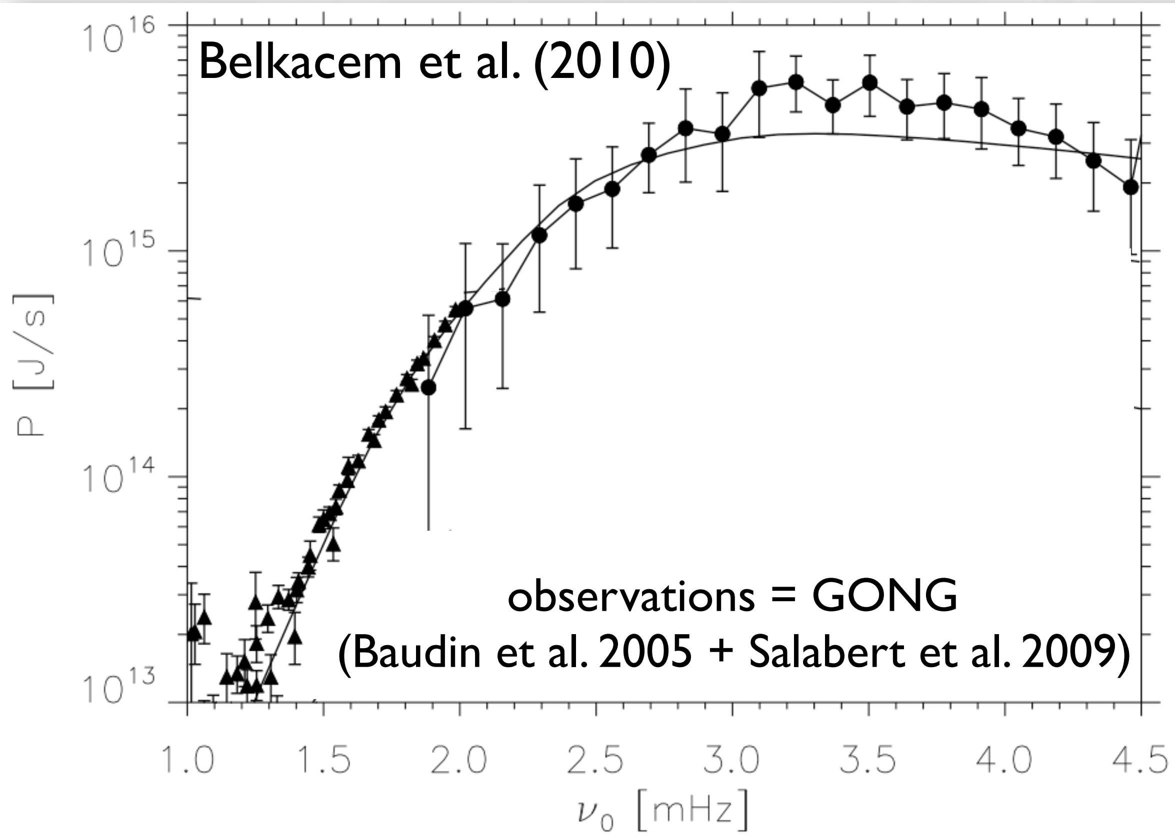


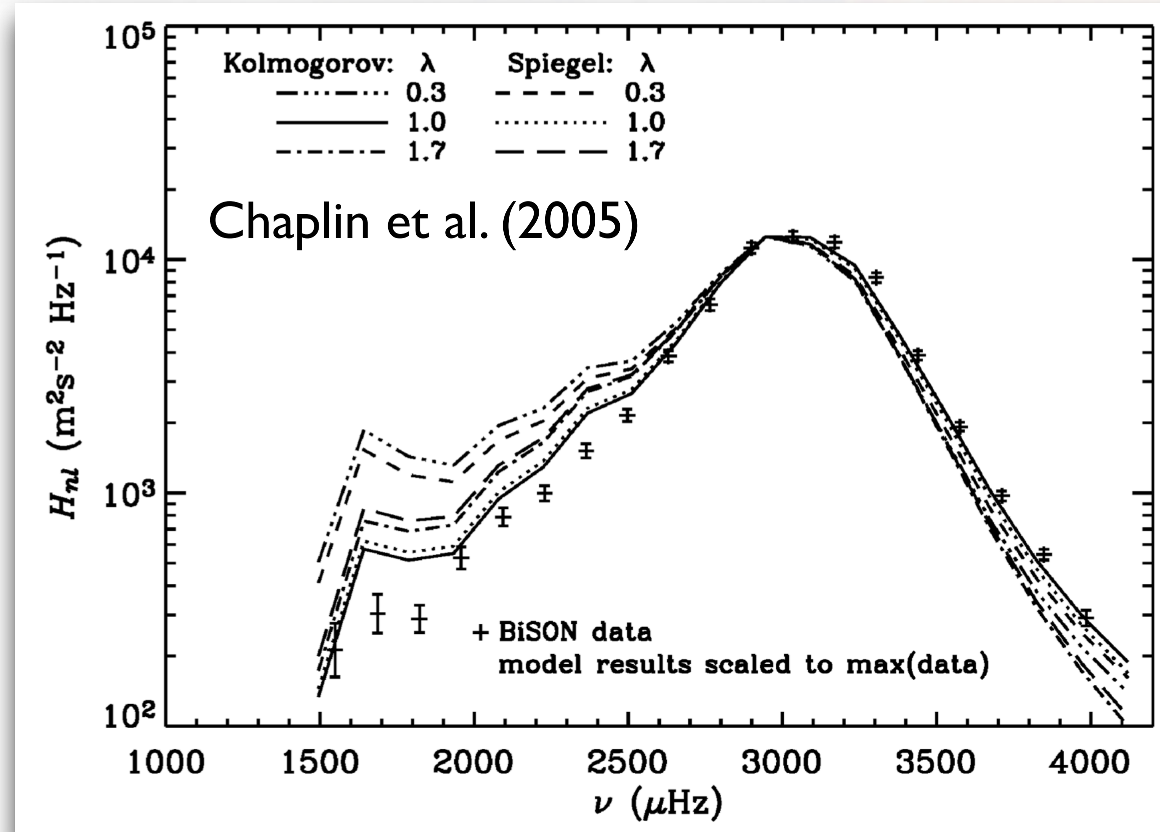


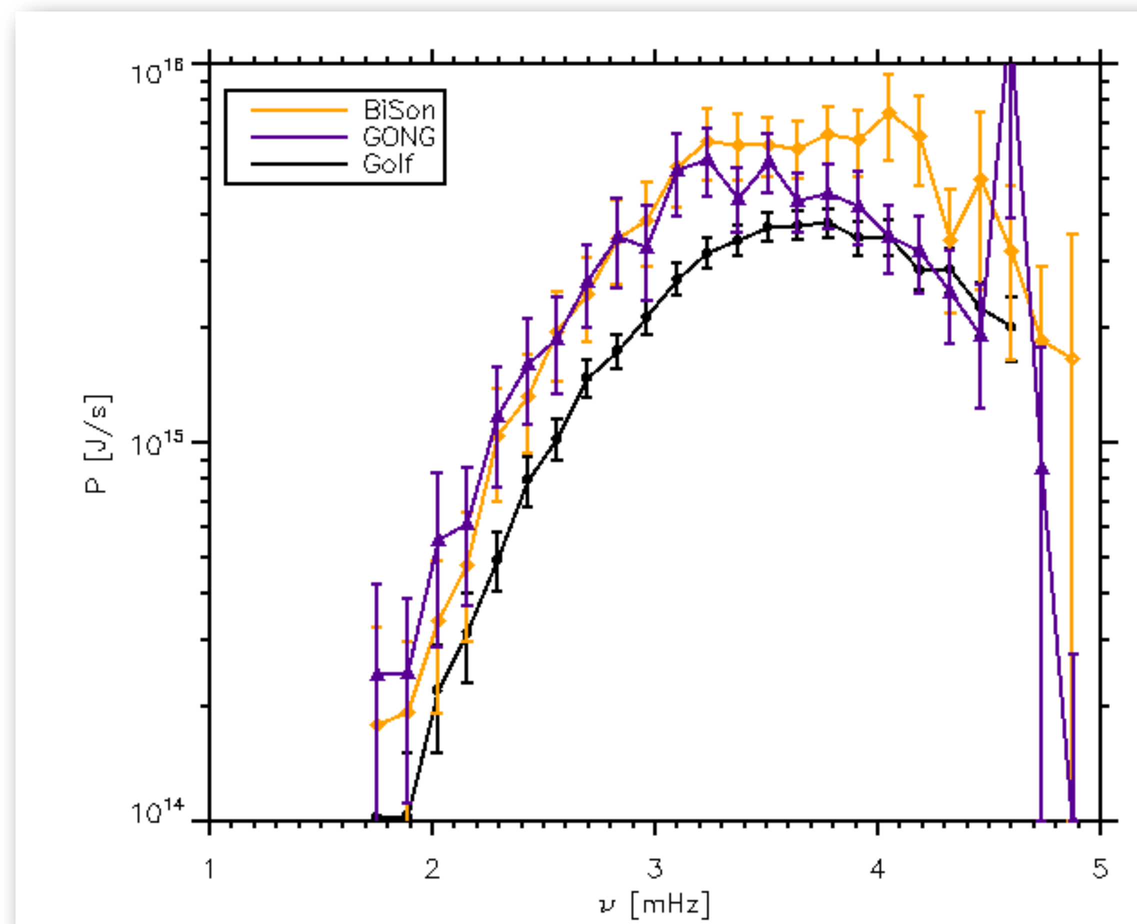


- The main physics for p-mode driving is grasped
- The dominant forcing is due to the Reynolds stresses
- Still some problems:

  *- at high frequencies, mainly related to the separation of scales assumption*

  *- treatment of non-isotropic turbulence*

  *- need to improve the observational constraints !*

# Energetics of solar-like oscillations

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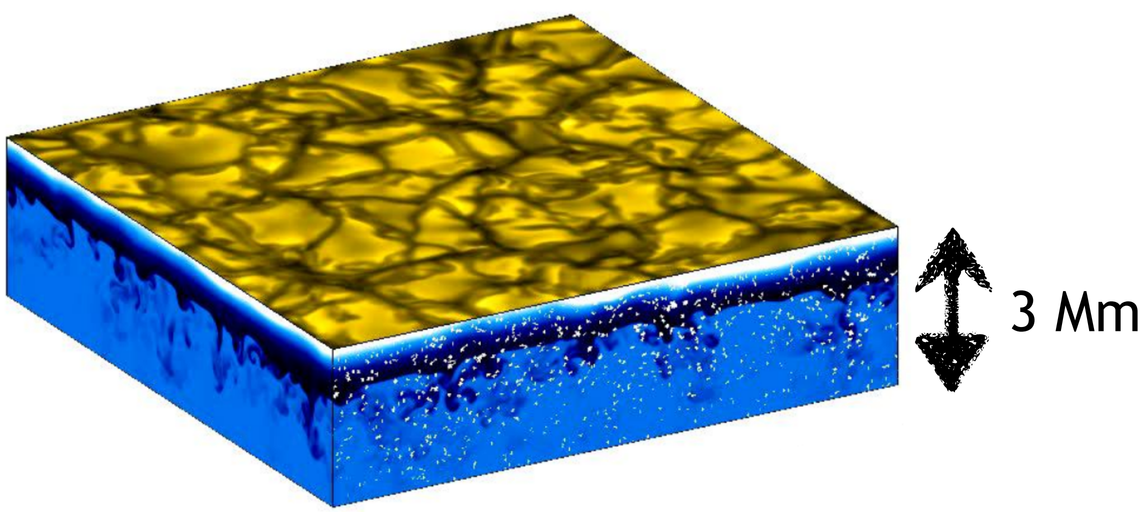
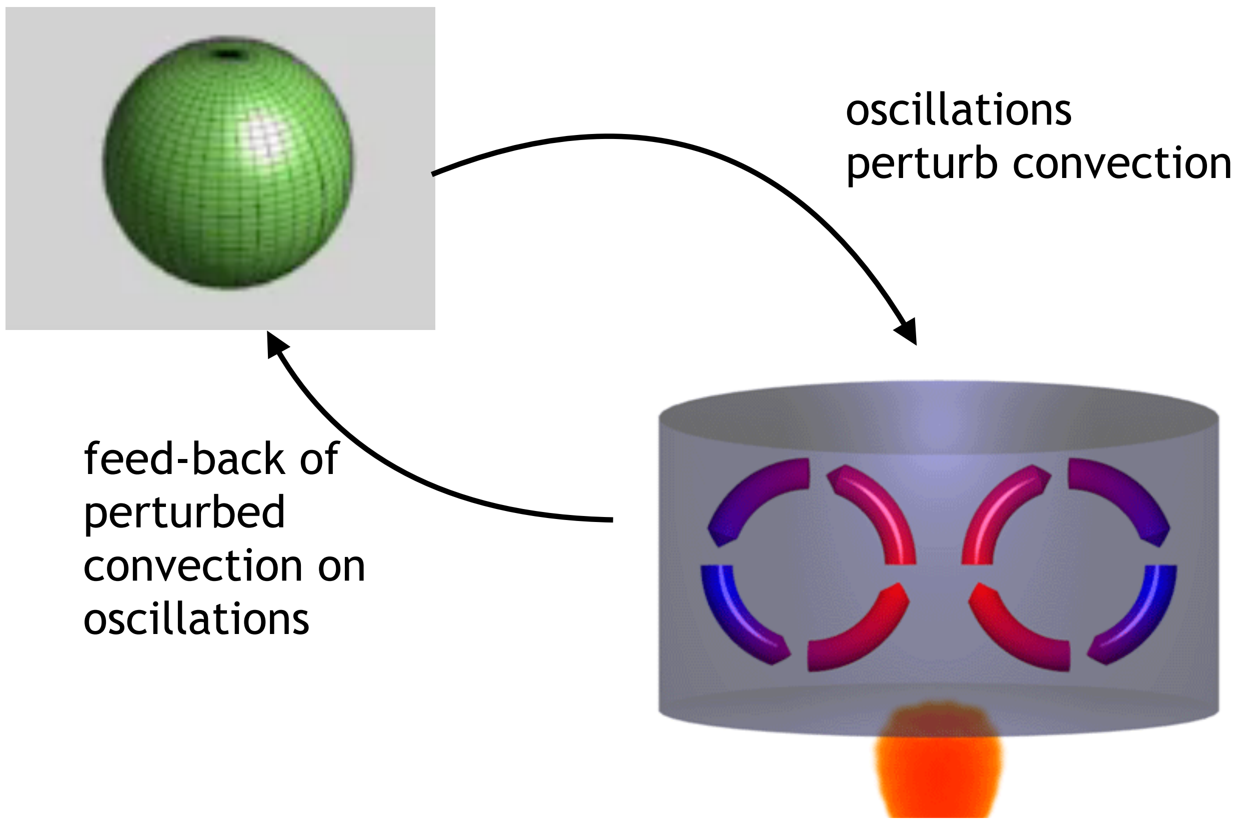
Driving ($P$):
"Stochastic excitation" by turbulent eddies

Damping (η): phase lag introduced by the oscillation/convection coupling




- eddies drive « randomly » the normal modes
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# Energetics of solar-like oscillations: mode damping

$$A^2 \propto \frac{\mathcal{P}}{\eta}$$

Computation of mode damping is a difficult task:

→ need to account for convection and its perturbation by the oscillations

→ the relevant timescales are comparable

- modal period

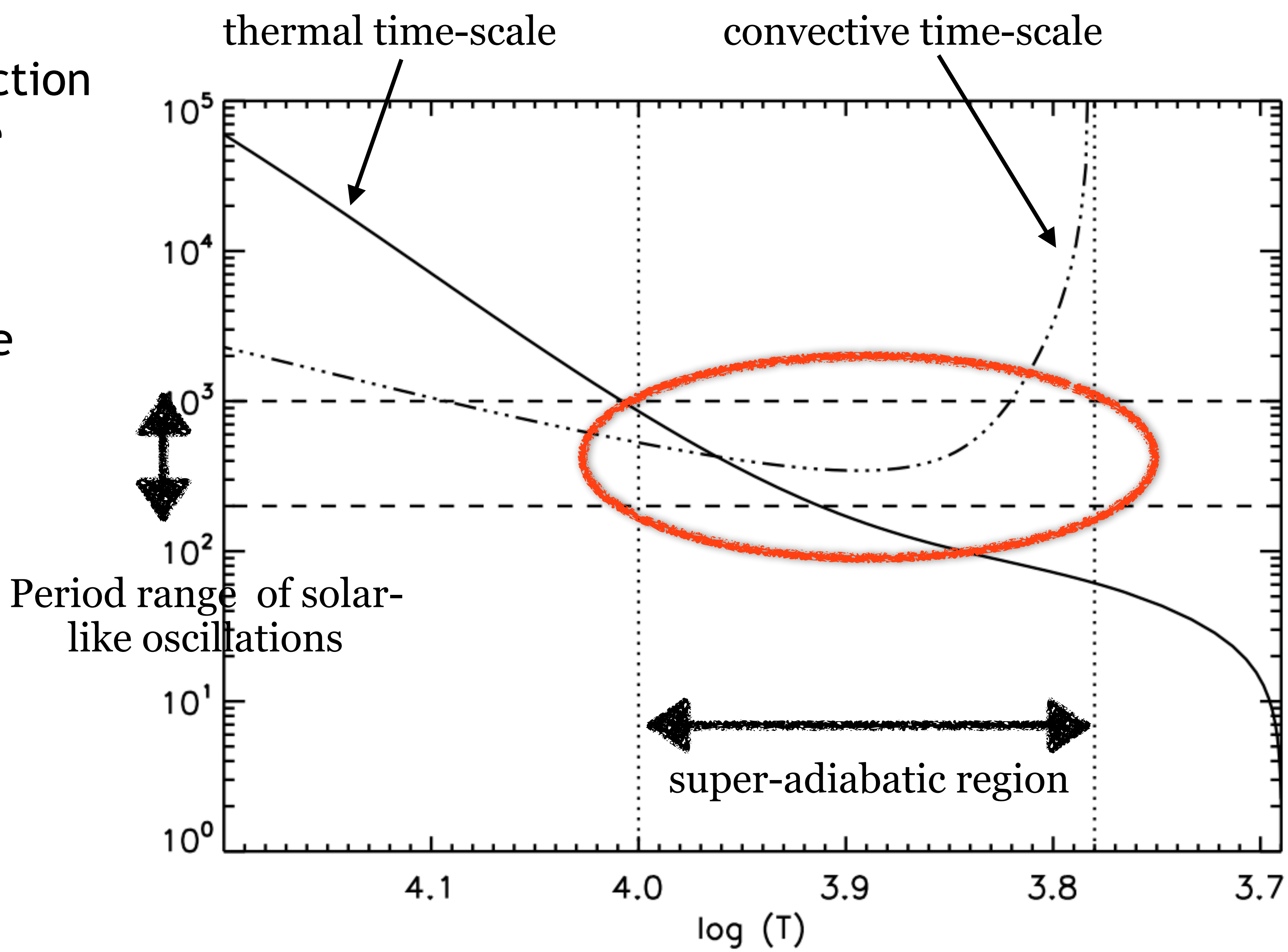
$$P_0 \in [200; 1000] \text{ seconds}$$

- convective time-scale

$$\tau_{\rm conv} = \Lambda / v_{\rm conv}$$

- thermal time-scale

$$\tau_{\rm thermal} = \frac{4\pi r^2 \rho c_p T H_p}{L}$$




$$\boxed{P_0 \simeq \tau_{\rm conv} \simeq \tau_{\rm thermal}}$$

# Energetics of solar-like oscillations: mode damping

$$A^2 \propto \frac{\mathcal{P}}{\eta}$$

It remains an open problem:

I) Reynolds stress approach for modeling convection (Xiong et al. 1977,1989,2000,2010, …) $\longrightarrow$

- unstable intermediate degree p-modes are found
- most of the problems arise from the closures

# Energetics of solar-like oscillations: mode damping

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I) Reynolds stress approach for modeling convection (Xiong et al. 1977,1989,2000,2010, …) →
- unstable intermediate degree p-modes are found
- most of the problems arise from the closures

II) Non-local mixing-length formalisms with time-dependent treatment of convection

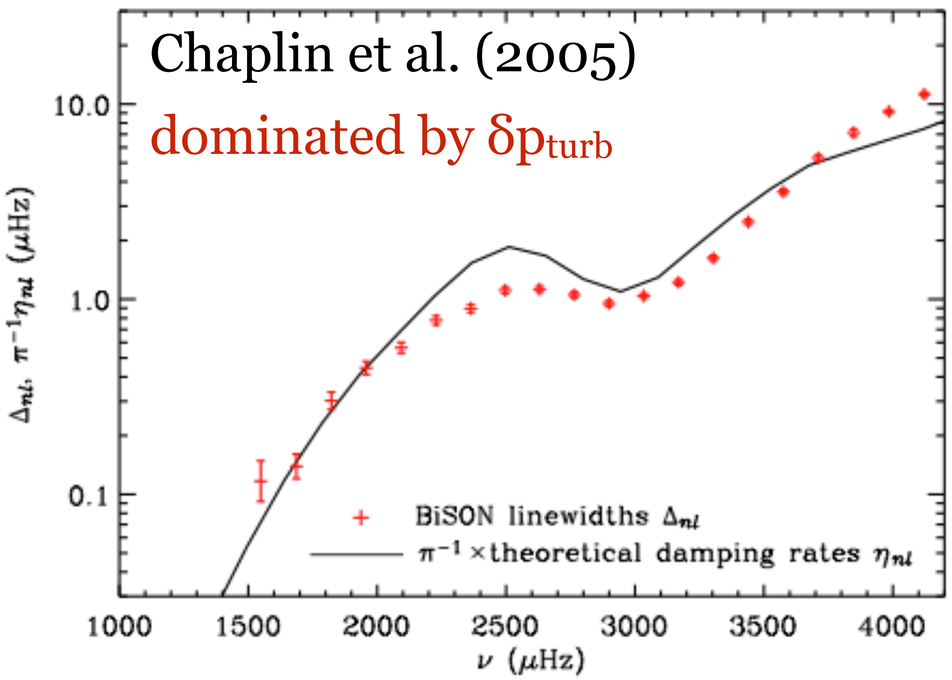
- Balmforth (1992); Houdek et al. (1999); Chaplin et al. (2005) based on Gough's theory of convection →
  - all modes are found stable
  - stabilisation: perturbation of turbulent pressure

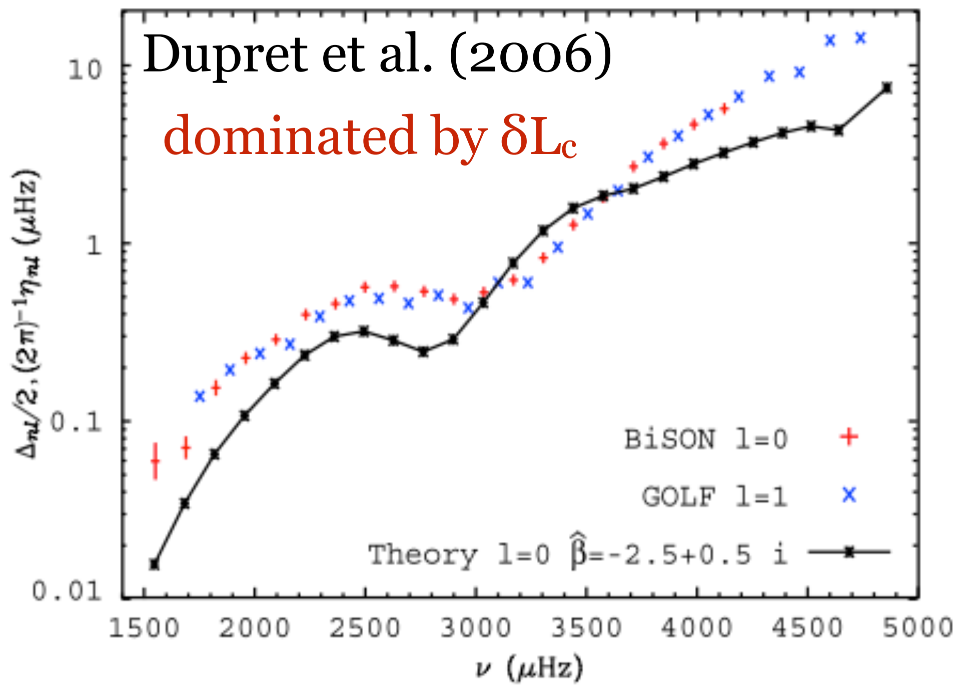
- Grigahcène et al. (2005); Dupret et al. (2006) based on Unno's theory of convection →
  - all modes are found stable
  - stabilisation: perturbation of convective flux

# Energetics of solar-like oscillations: mode damping

$$A^2 \propto \frac{\mathcal{P}}{\eta}$$

- Thus, the firsts attempts to confront theoretical computations and observations … were not very convincing




Disagreement on the dominant contribution to the dampings

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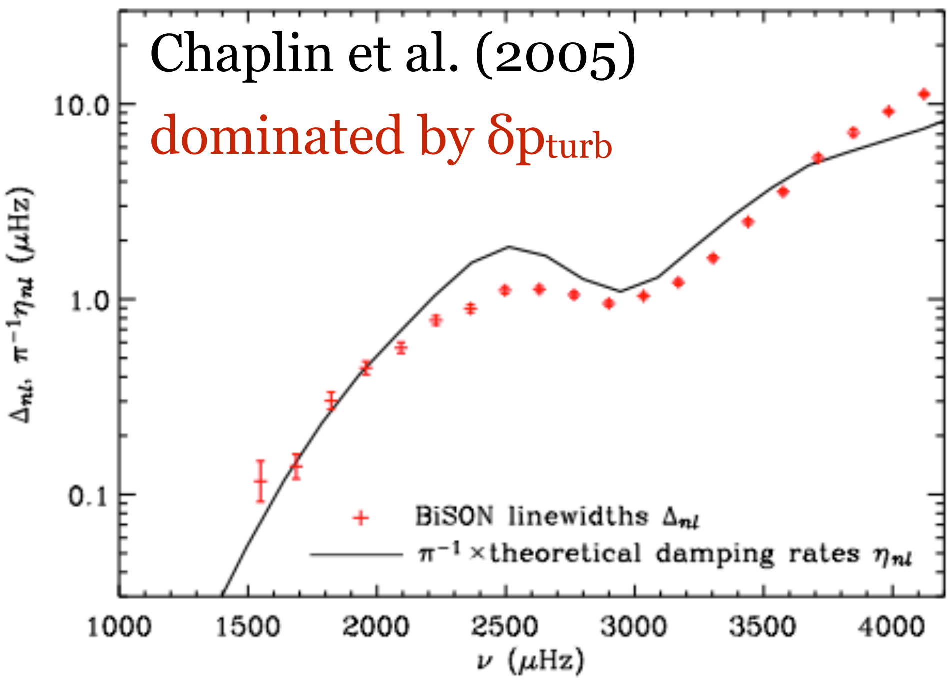
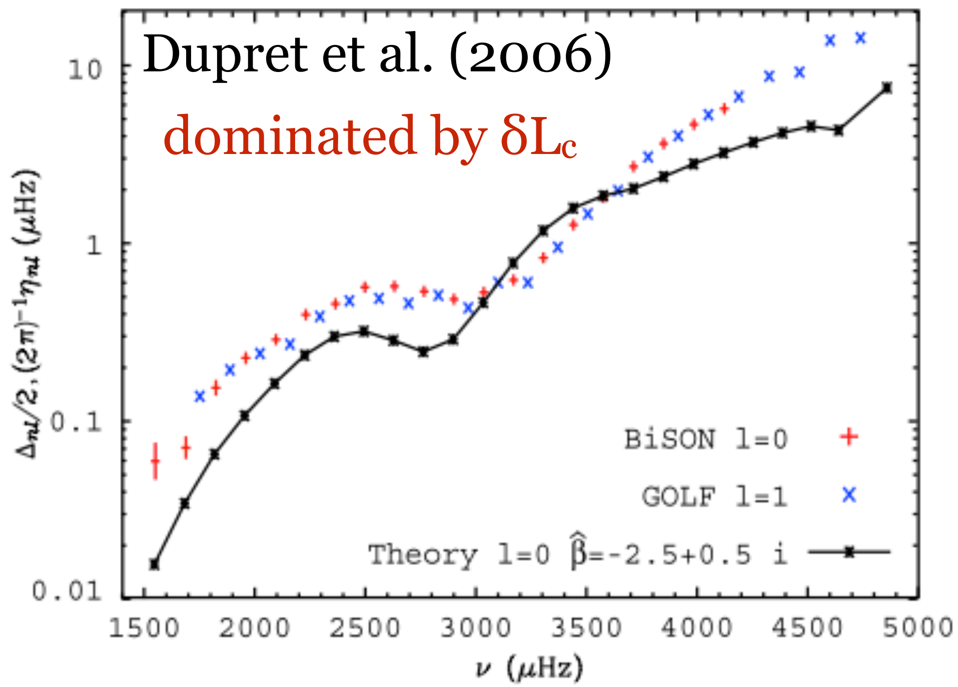
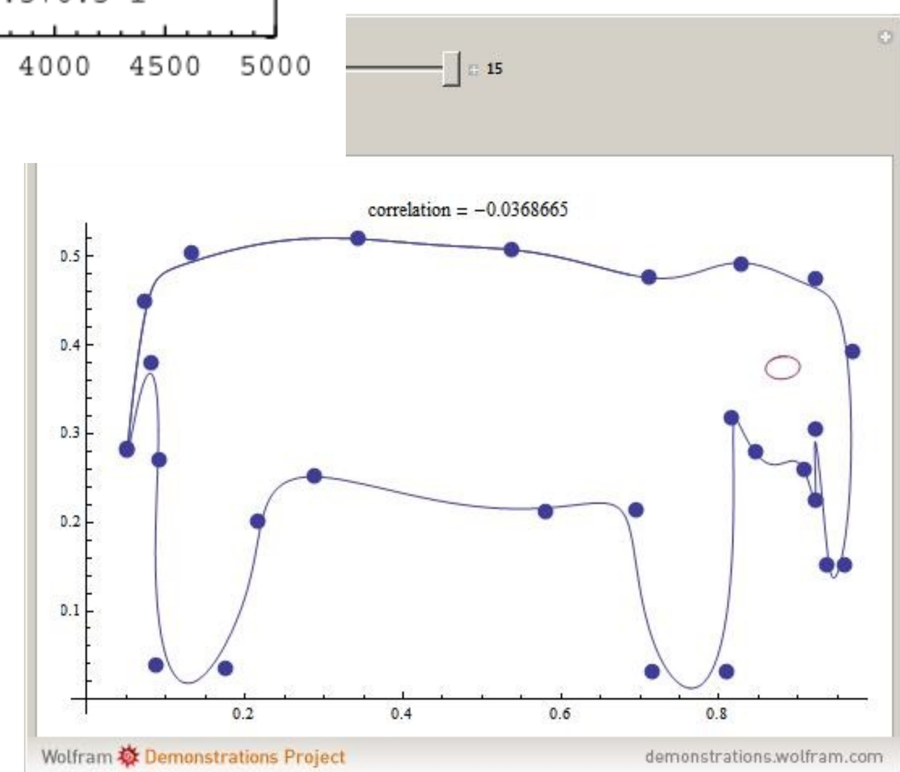



Disagreement on the dominant contribution to the dampings

The theories contain too many free parameters…

To improve the results there is a need of constraints



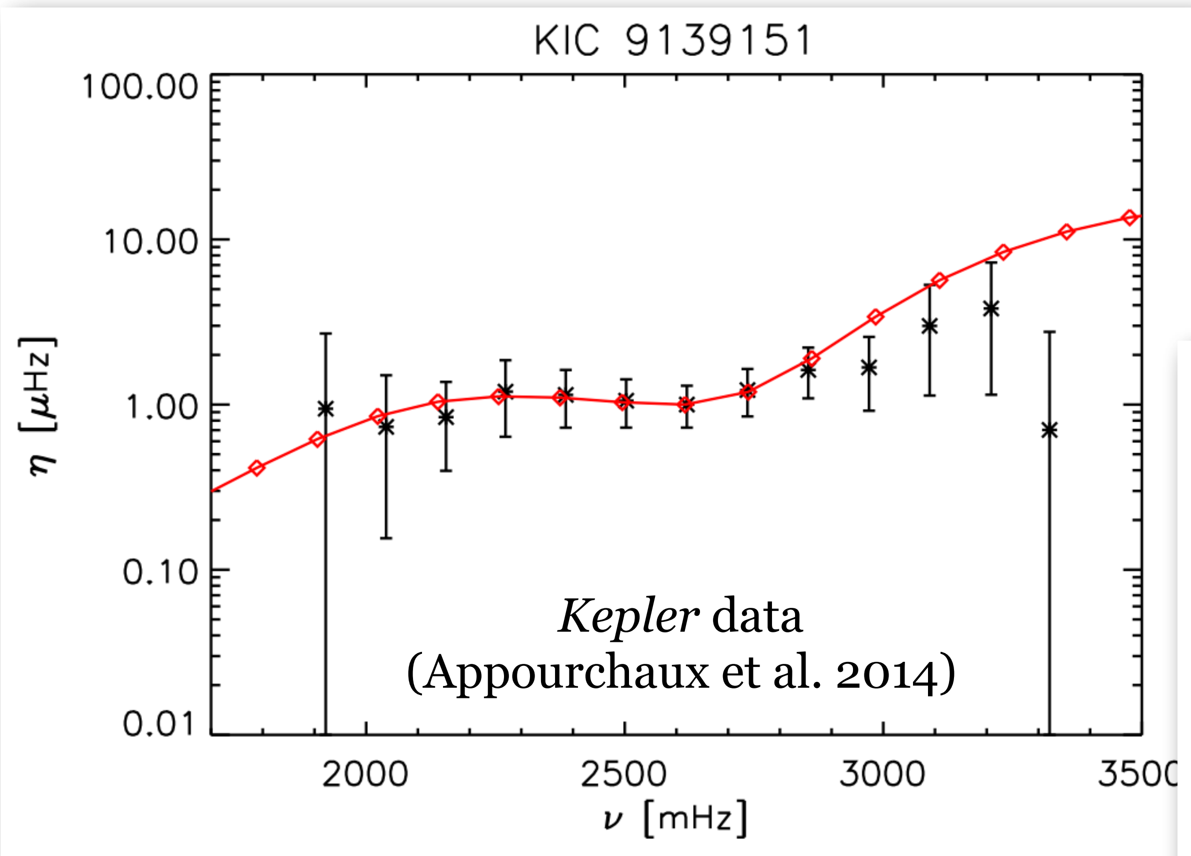

*« With four parameters I can fit an elephant and with five I can make him wiggle his trunk. »*
John von Neumann

# Energetics of solar-like oscillations: mode damping

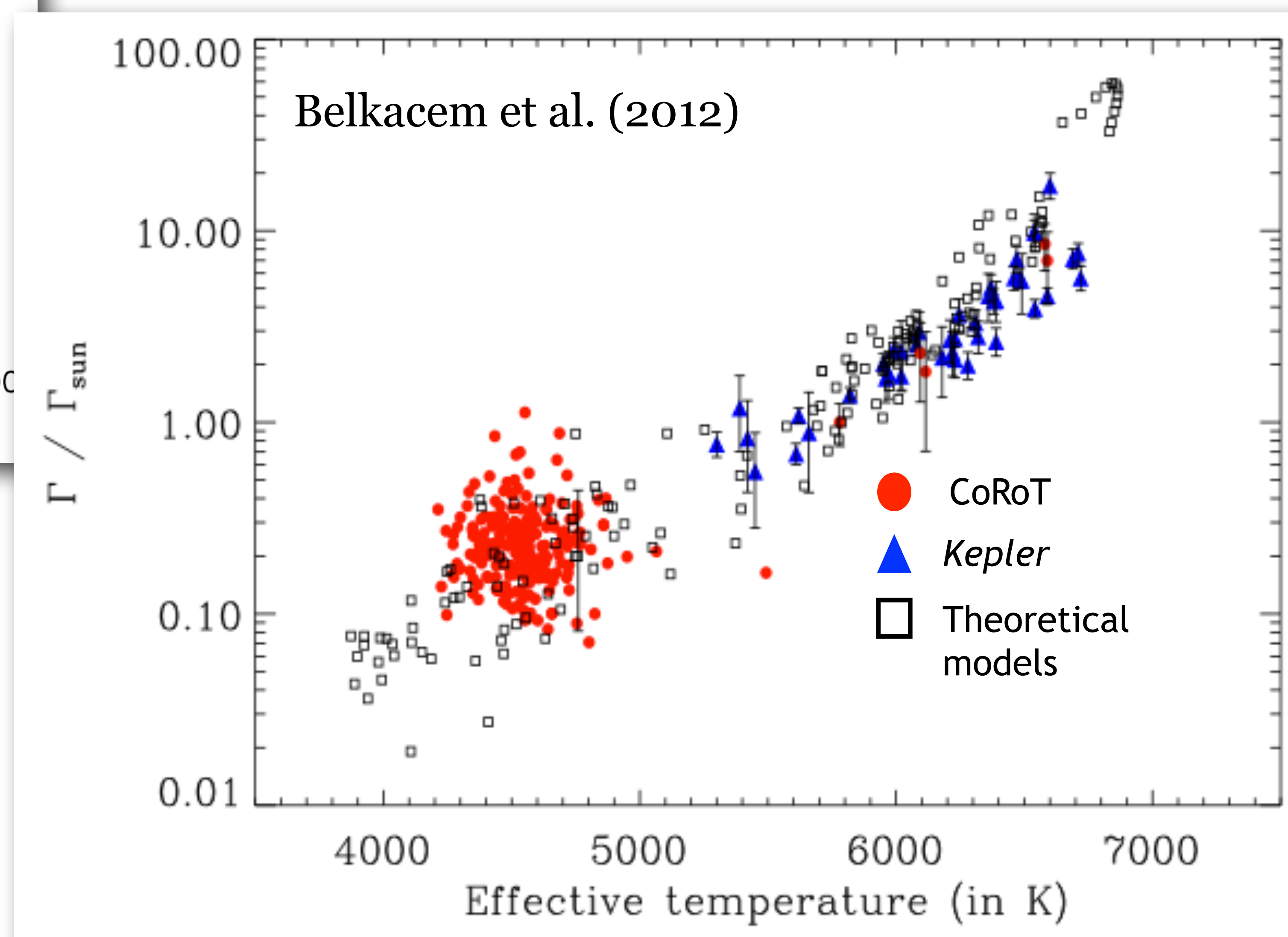
$A^2 \propto \frac{\mathcal{P}}{\eta}$

- To get some clues on the free parameters, several approaches are possible

✓ free parameters are constrained: non-local parameters with 3D models & closure parameter with the observed scaling relations (Belkacem et al. 2012)




Modeling using a non-local and time-dependent treatment of convection (MAD code)




- Good agreement between theoretical models and observations

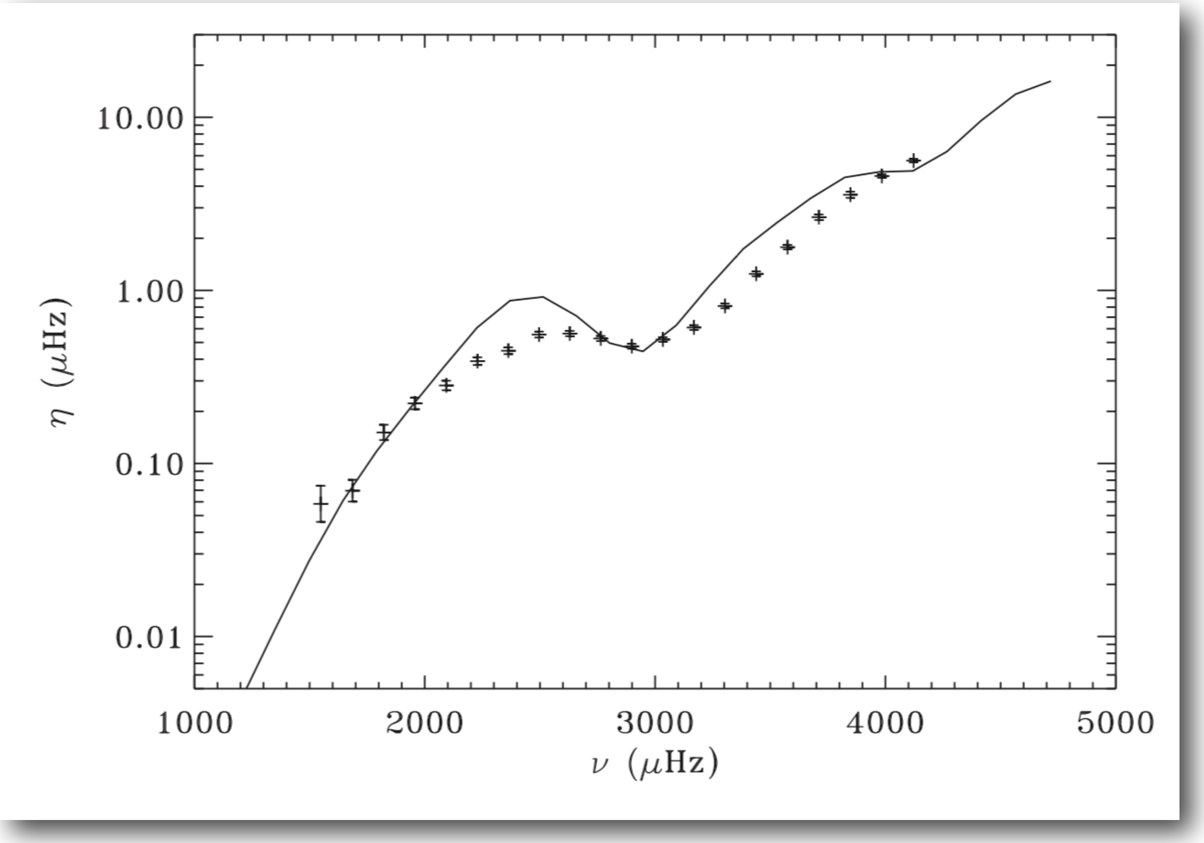
- Good agreement between theoretical models and observations

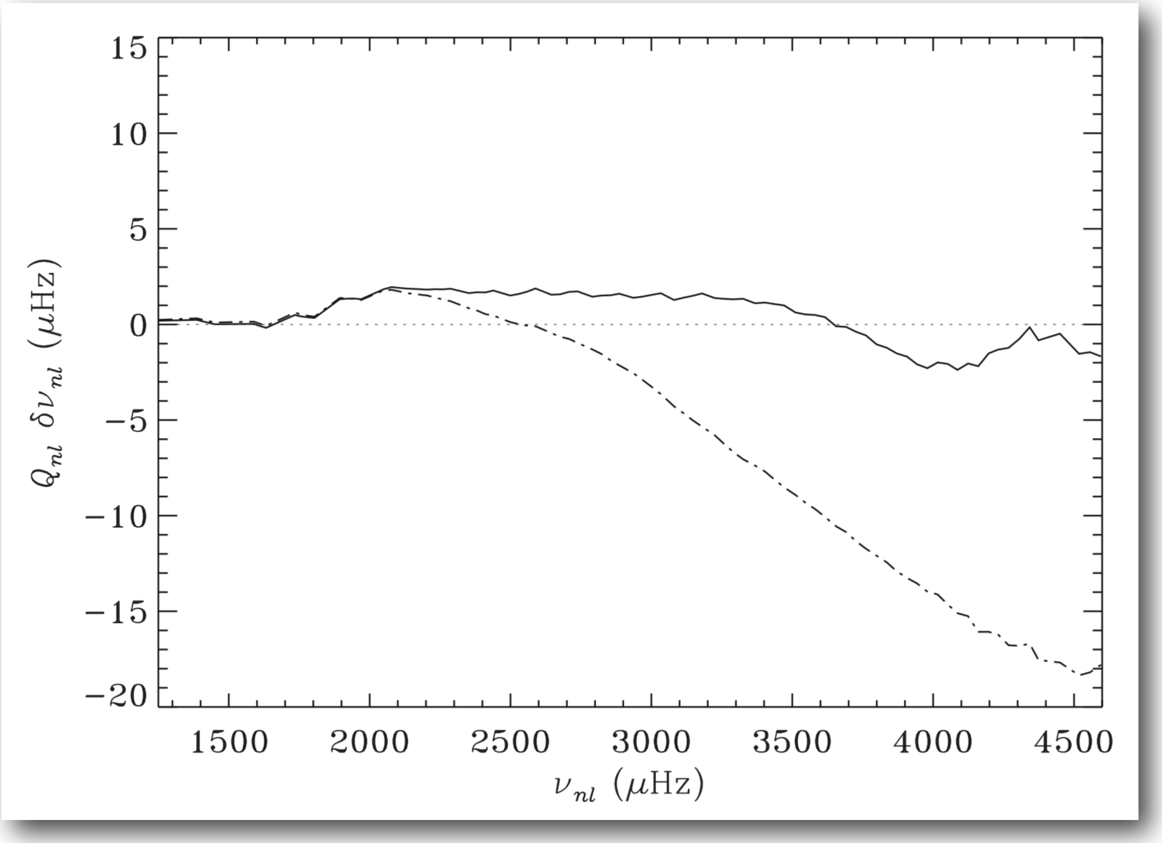
# Energetics of solar-like oscillations: mode damping

$$A^2 \propto \frac{\mathcal{P}}{\eta}$$

- To get some clues on the free parameters, several approaches are possible

✓ free parameters are constrained: 3D structure (turbulent pressure, etc…) & turbulent anisotropy (Houdek et al. 2017)




The problem is that some parameters (non-local parameters) are not fitted to the 3D models → Since they have unrealistic values, they « engulf » all the problems of the theory

When all free parameters are constrained with the 3D simulation = no solution ! (Sonoi, private comm) → Quite obvious because you try to reproduce a very complex physics with a very simple model…

# Energetics of solar-like oscillations: mode damping

$$A^2 \propto \frac{\mathcal{P}}{\eta}$$

- Is the main physical «picture» grasped ?

→ Not obvious, certainly the main actors are identified but their relative contributions remain to be properly determined

- Need to go beyond 1D models (even if constrained using 3D models)

→ New approaches are needed

- For g modes and especially for low-order ones, damping is thus very uncertain because extrapolation from p-modes would be dangerous

- P-modes in the Sun and main-sequence stars
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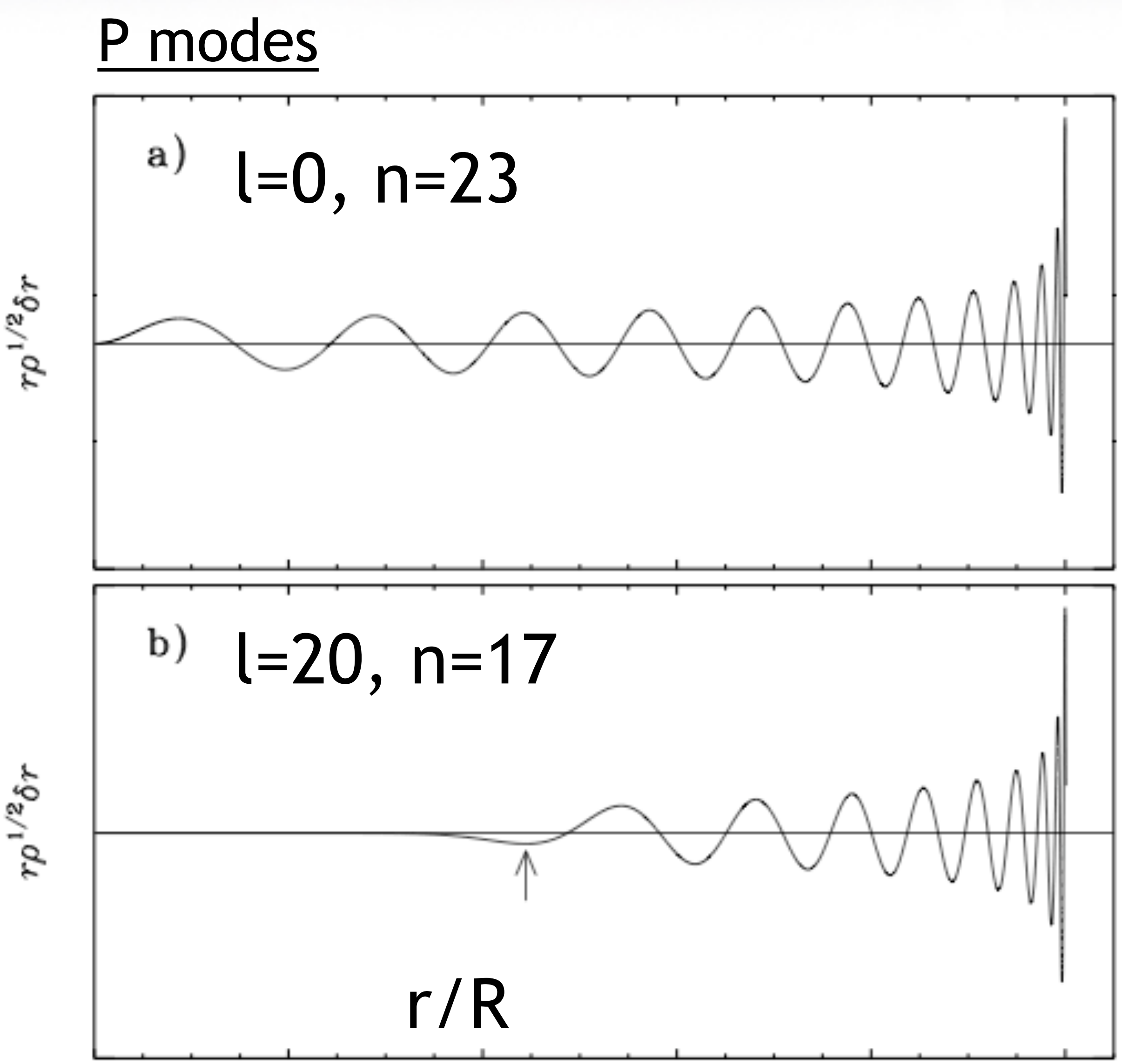
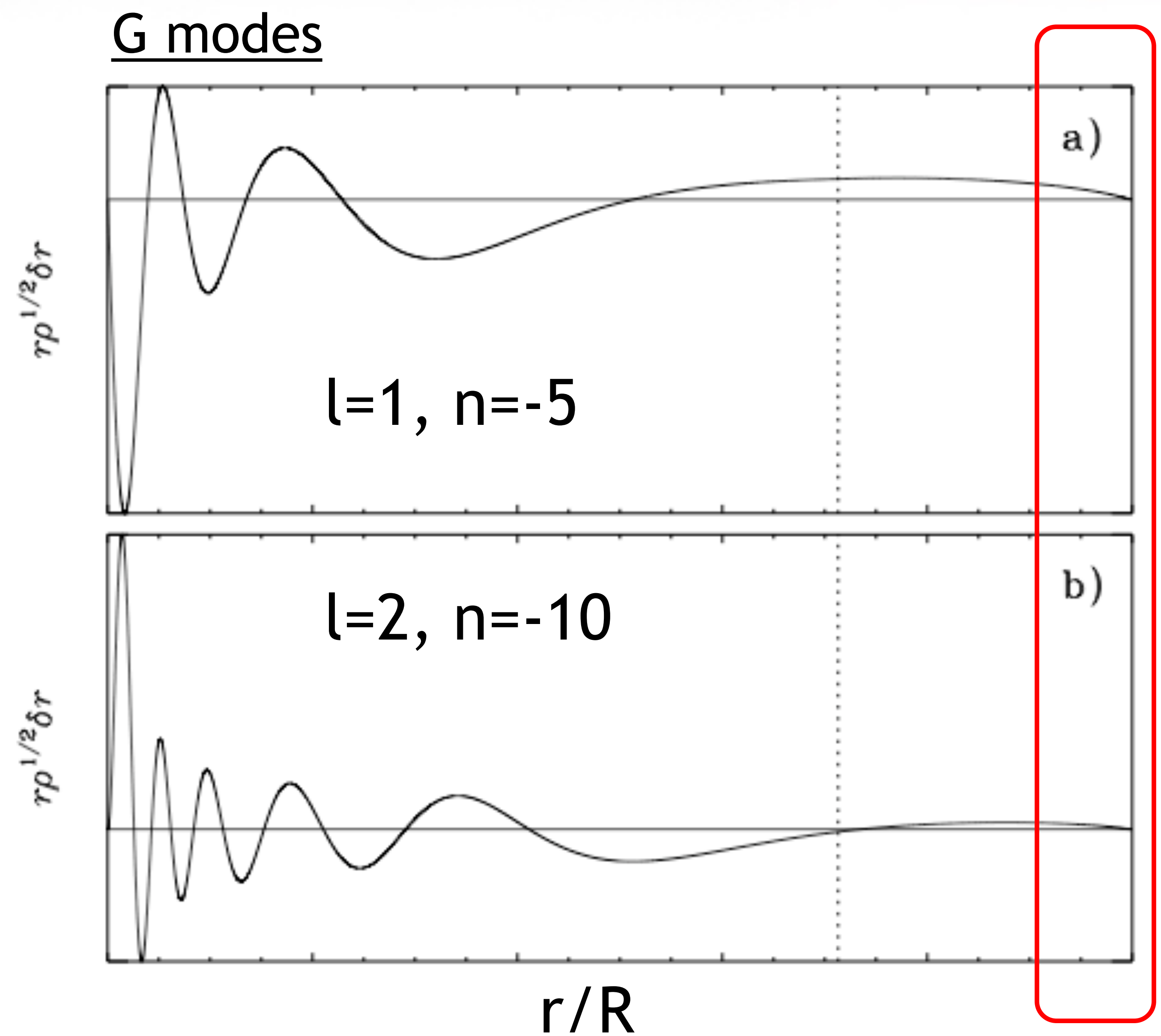
# G modes : why it is so difficult to detect them ?




Credit: J. Christensen-Dalsgaard

- G modes are evanescent in the convective region
- Driving is related to mode compressibility $\frac{\delta\rho}{\rho} \propto \frac{\partial \xi_r}{\partial r}$

## G mode amplitudes: what are the expected excitation mechanisms ?

There are mainly two candidates

- ✓ Excitation by penetrative convection at the base of the convective zone
- ✓ Excitation, as for p modes, by turbulent convection

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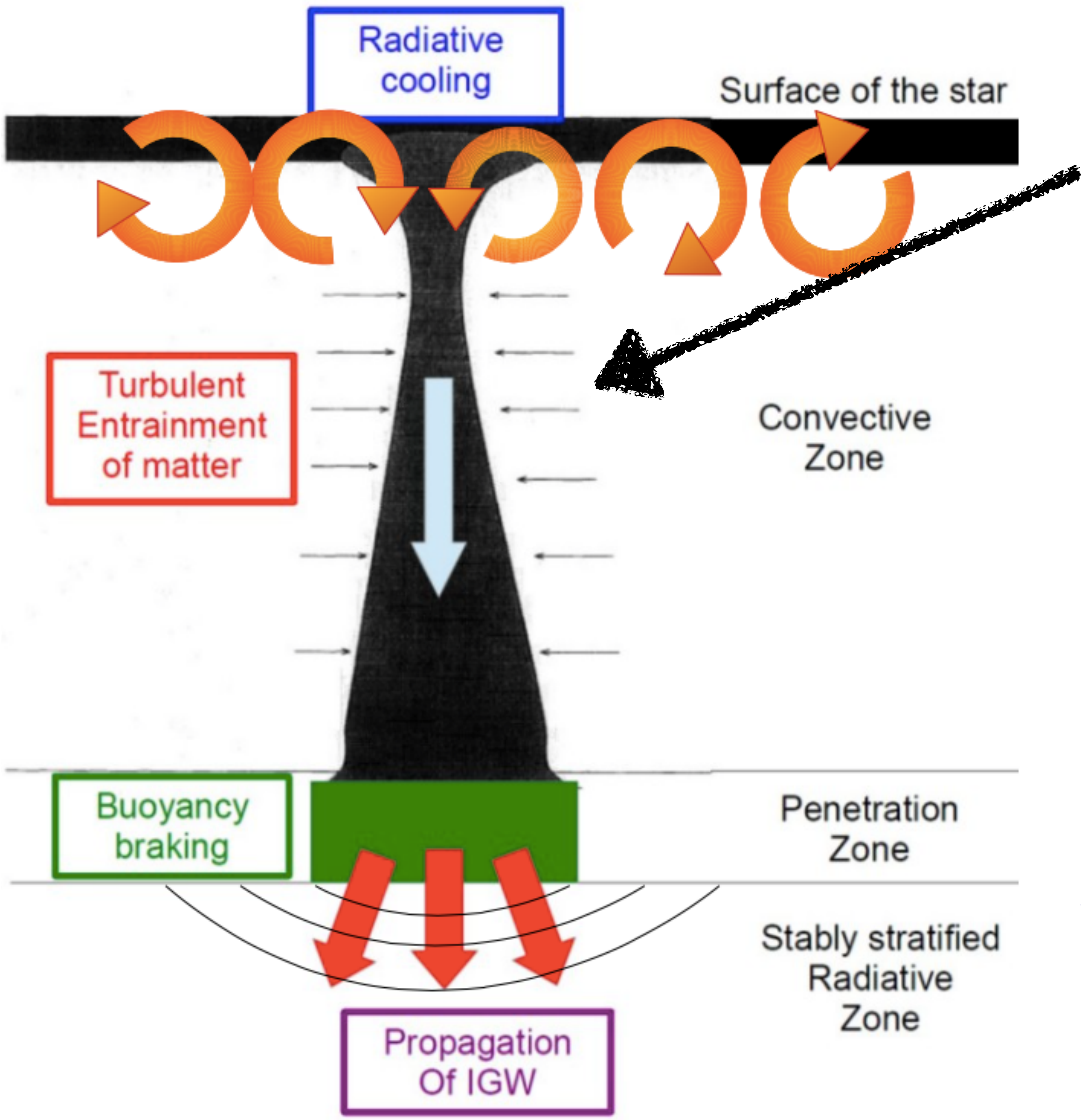
# G mode amplitudes: excitation by penetrative convection

Schematic picture of penetrative convection




Turbulent downflow
= plume

Entrainment: turbulence inside the downflow entrains matter from the environment

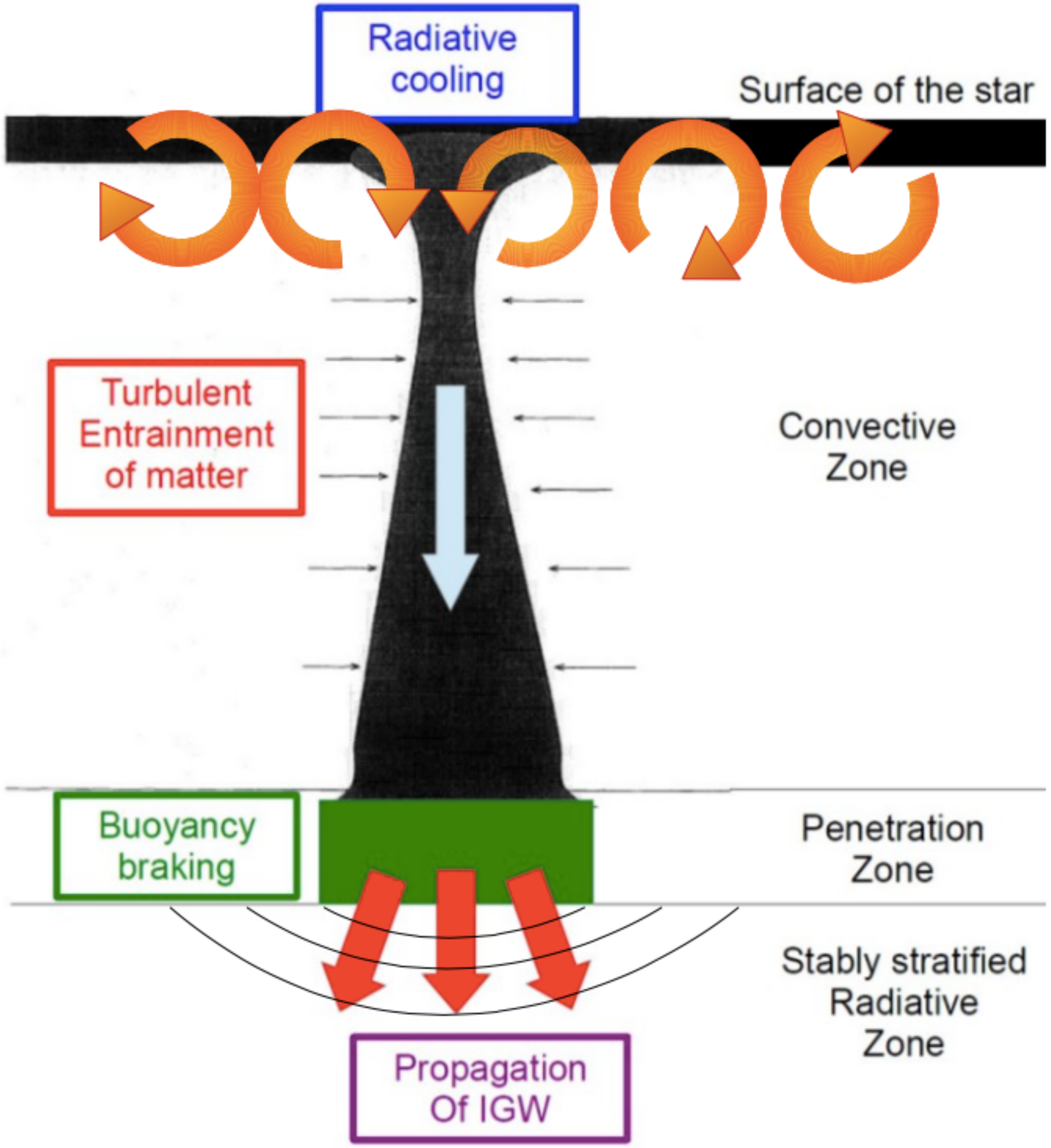
Penetration: the downflow penetrates into the radiative region

Waves generation: part of the plume kinetic energy is supplied to the waves

Waves (progressive and/or stationnary)

# G mode amplitudes: excitation by penetrative convection

Some numbers




The Reynolds number: defined as the ratio between inertia forces and viscous forces

velocity length-scale

$$R_e = \frac{U\,L}{\nu}$$

viscosity

At the top of the CZ: $R_e \sim 10^{13}$

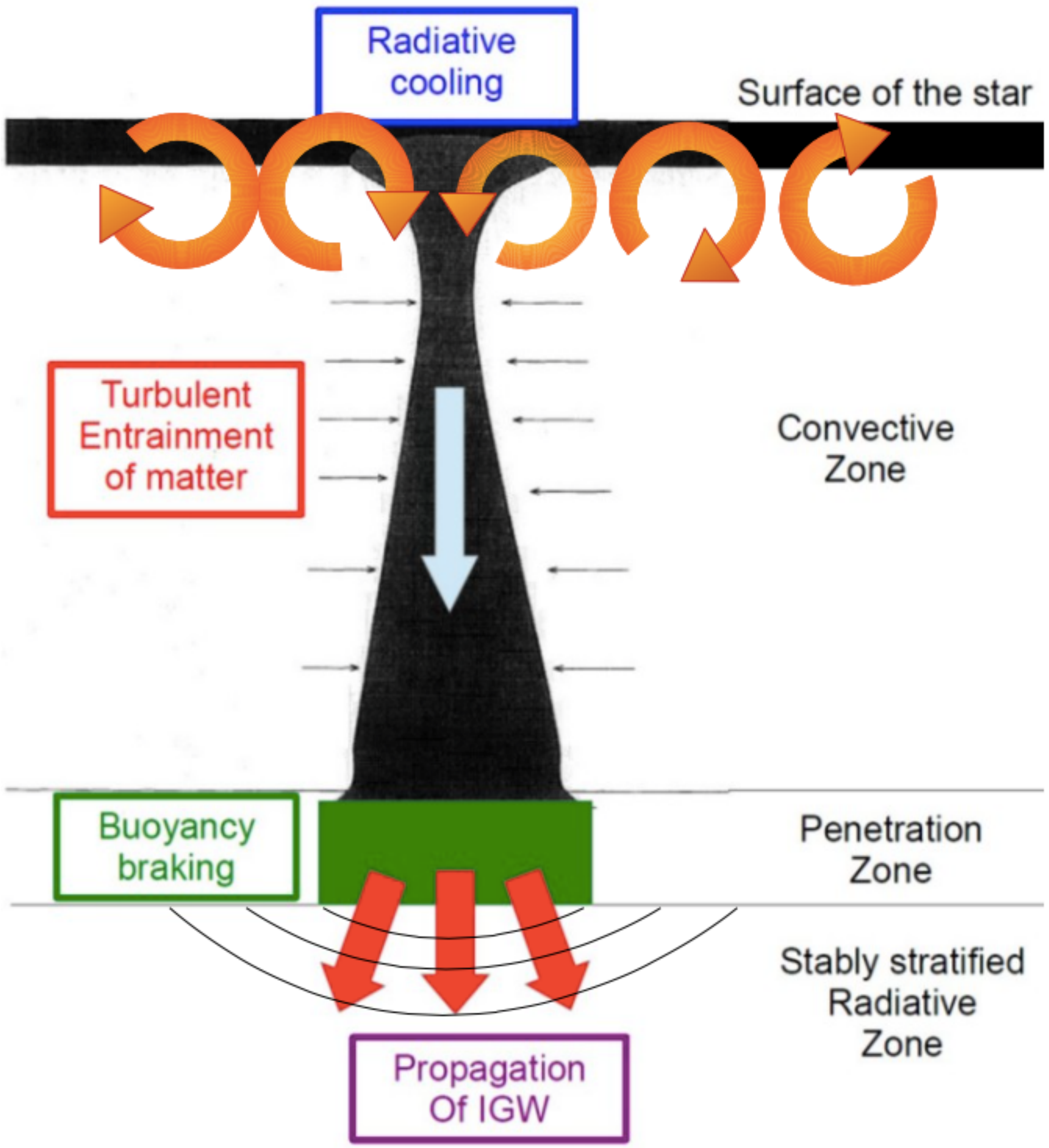
At the bottom of the CZ: $R_e \sim 10^{10}$

→ Plumes are highly turbulent structures

Waves (progressive and/or stationary)

# G mode amplitudes: excitation by penetrative convection

Some numbers




The Péclet number: defined as the ratio between inertia and radiative losses

$$P_e = \frac{U\,L}{\kappa}$$

Thermal diffusivity

$P_e \leq 1$: overshoot regime, i.e. plumes penetrate into RZ, thermally adjust to the environment and go on under the action of their inertia

Regime obtained in most of numerical simulations

$P_e >> 1$: penetration regime, i.e. plumes penetrate into RZ, remain quasi-adiabatic. Hence, plumes are strongly slowed down

Regime in the Sun, $P_e \sim 10^7$ at the bottom of the CZ

Waves (progressive and/or stationary)

# G mode amplitudes: excitation by penetrative convection

## Historical overview

Well known in geophysical flows (Townsend 1966, Stull 1970 etc…)

Dintrans (2005)

Andersen (1992,1994,1996)

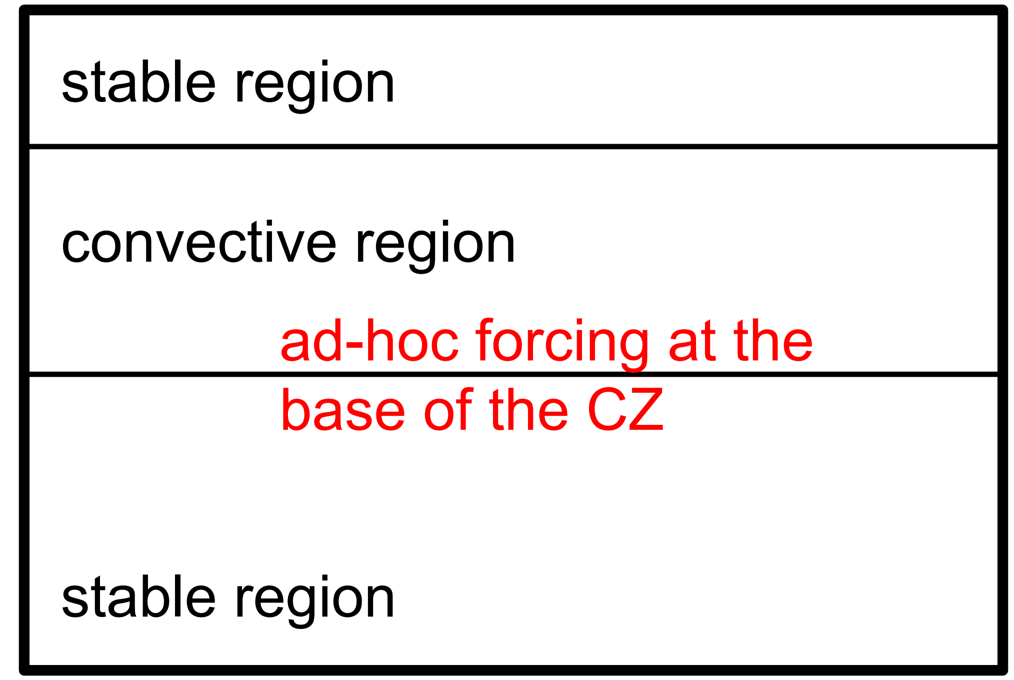
Rogers et al. (2005,2006)

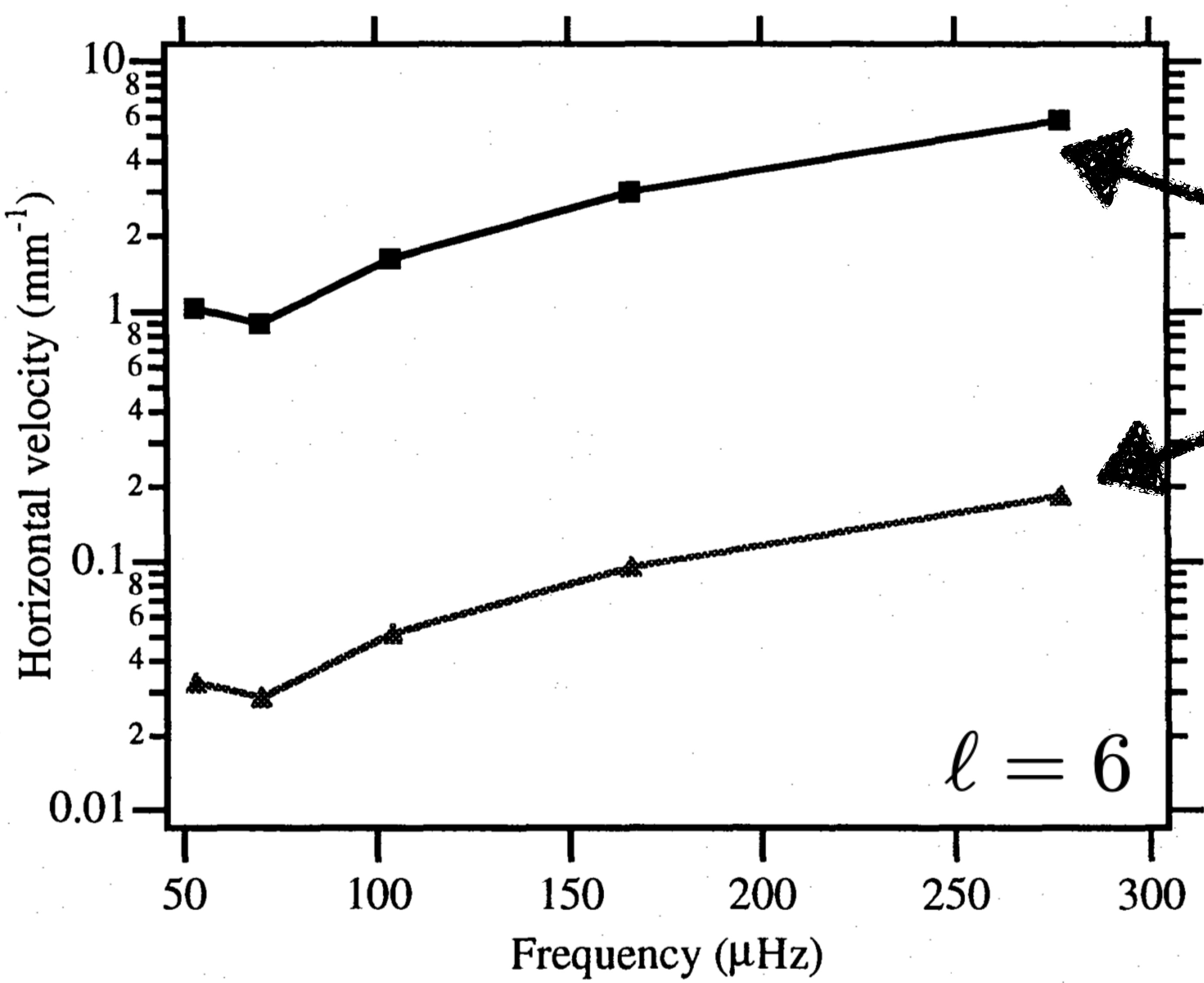
estimation of the mode surface velocity

# G mode amplitudes: excitation by penetrative convection

Work by Andersen (1992,1994,1996)

- 2D cartesian numerical simulations
- Investigate the amplitude ratios between the two stable regions



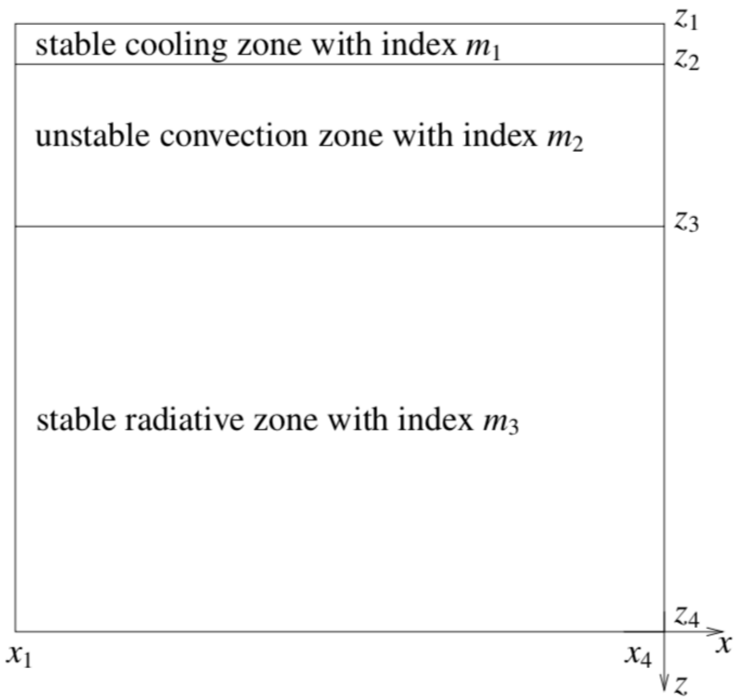

Assuming 1 mode excited

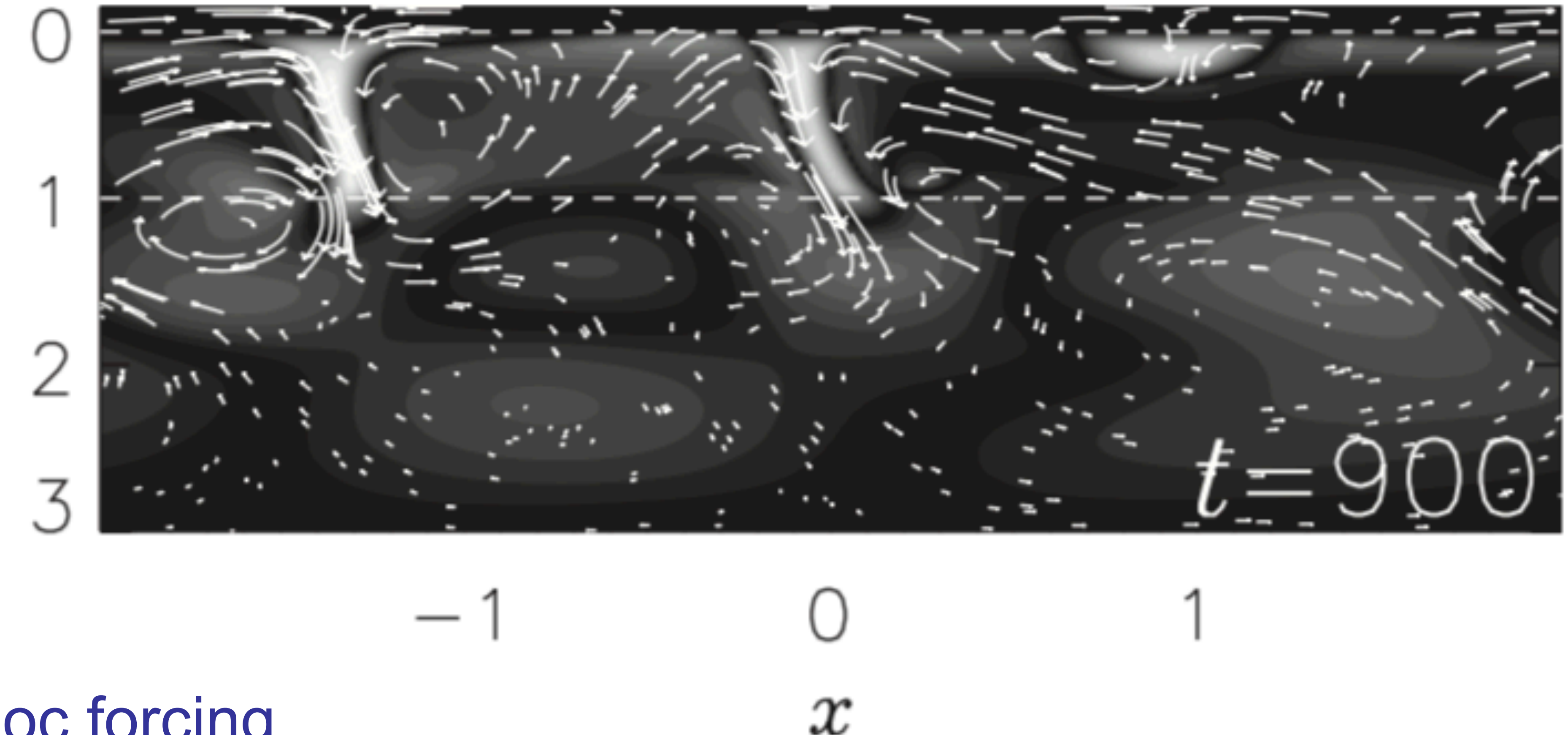
Assuming 1000 modes excited

$$\boxed{V \approx 0.01 - 5\ \mathrm{mm.s}^{-1}}$$

# G mode amplitudes: excitation by penetrative convection

Dintrans et al. (2005)




No more ad-hoc forcing

Up to 40% of the kinetic energy can be supplied to the modes

Life-time of modes ~ 2 periods

# G mode amplitudes: excitation by penetrative convection

- Rogers et al. (2006)

  2D numerical simulations with a realistic stratification

  IGW were found in the radiative region but it was unclear if g-modes were excited

# G mode amplitudes: excitation by penetrative convection

- Rogers et al. (2006)

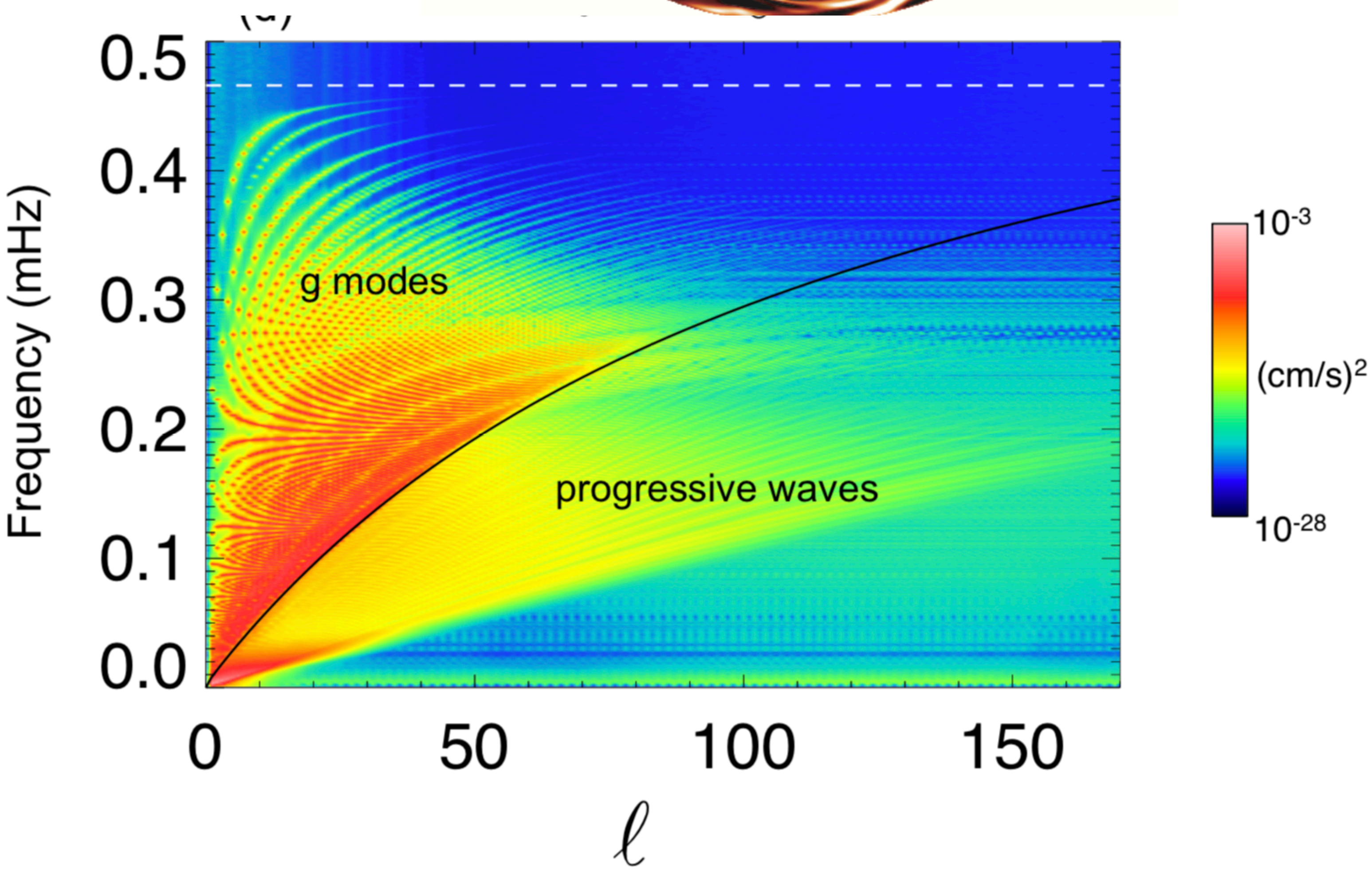
  2D numerical simulations with a realistic stratification

  IGW were found in the radiative region but it was unclear if g-modes were excited

- Alvan et al. (2015)

  3D numerical simulations using the ASH code

  G-modes seem to be efficiently excited but it is unclear if it is due to the turbulent convection or penetrative convection



# G mode amplitudes: excitation by penetrative convection

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- To be thermally relaxed (and not only dynamically): no choice than to use some tricks

e.g. Rogers & Glatzmaier (2005) radiative diffusivity is tuned to allow for computable time-scales → *The obtained convective flux is $10^5$ higher than the solar one!!*

# G mode amplitudes: excitation by penetrative convection

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e.g. Rogers & Glatzmaier (2005) radiative diffusivity is tuned to allow for computable time-scales → *The obtained convective flux is $10^5$ higher than the solar one!!*

- Last but not least: inner boundary conditions

Due to the artificially low radiative diffusivity, internal gravity waves are hardly dissipated → Part of the energy is then « catched » into g modes

*So, simulations are useful but are still models and do not (yet?) provide an answer concerning excitation of g modes*

# G mode amplitudes: what are the expected excitation mechanisms ?

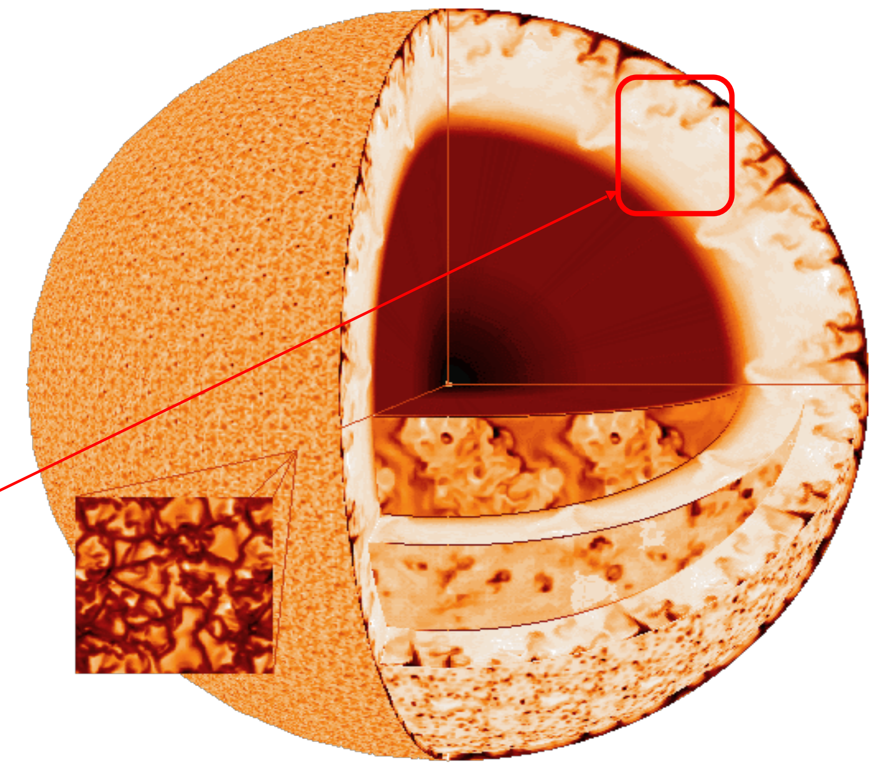
There are mainly two candidates

- ✓ Excitation by penetrative convection at the base of the convective zone
- ✓ Excitation, as for p modes, by turbulent convection

# G mode amplitudes: excitation turbulent convection

As for p modes: stochastic excitation by turbulent convection

- Turbulent eddies excite randomly the modes
- for *g* modes excitation takes place in the deep convective layers



Historical overview

Berthomieu & Provost (1990)

Belkacem et al. (2009)

Gough (1985)

Kumar et al. (1996)

# G mode amplitudes: excitation turbulent convection

## Equipartition “principle”

Used by Gough (1985) (see also Berthomieu & Provost 1990)

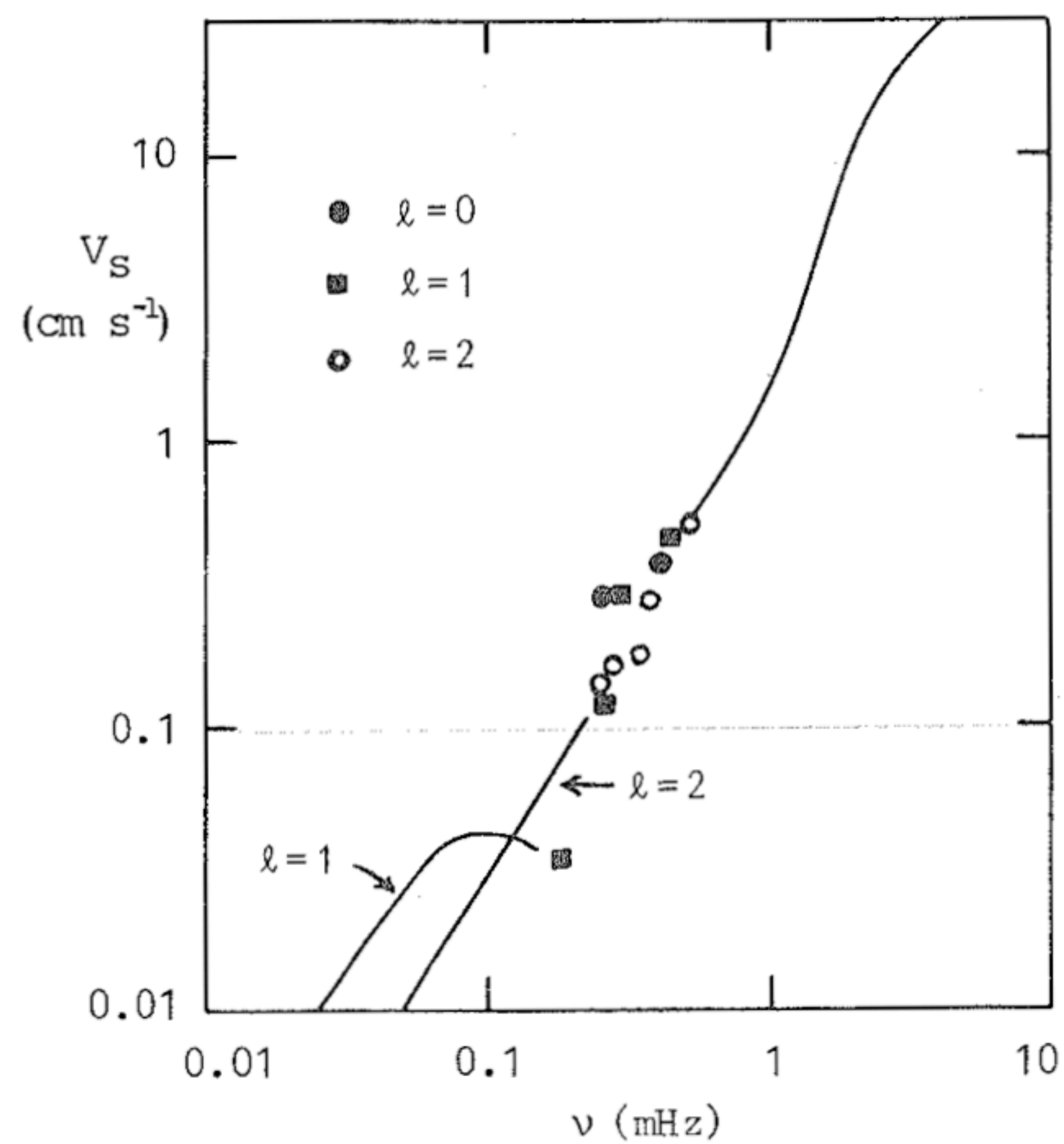
$$V^2 \propto \frac{P}{\eta} = E_{\rm osc}$$

equipartition = equipartition of kinetic energy between an acoustic mode and the resonant eddy

This assumption permits to avoid the computation of P and η

***Pb***: demonstrated by Goldreich & Keeley (1977b) for p modes under the assumption that damping is dominated by turbulent viscosity

- *No evidence it works for g modes, No evidence the damping is dominated by turbulent viscosity (very unlikely for p modes !!)*



# G mode amplitudes: excitation turbulent convection

First full calculation (i.e. excitation + damping): Kumar et al. (1996)

*Mode excitation*

Adapted from the modeling of *p* modes (Goldreich et al., 1994)

Turbulent kinetic energy spectrum: distribution of energy in the turbulent eddies → They use a Kolmogorov spectrum

Eddy-time correlation function → They use a Gaussian function

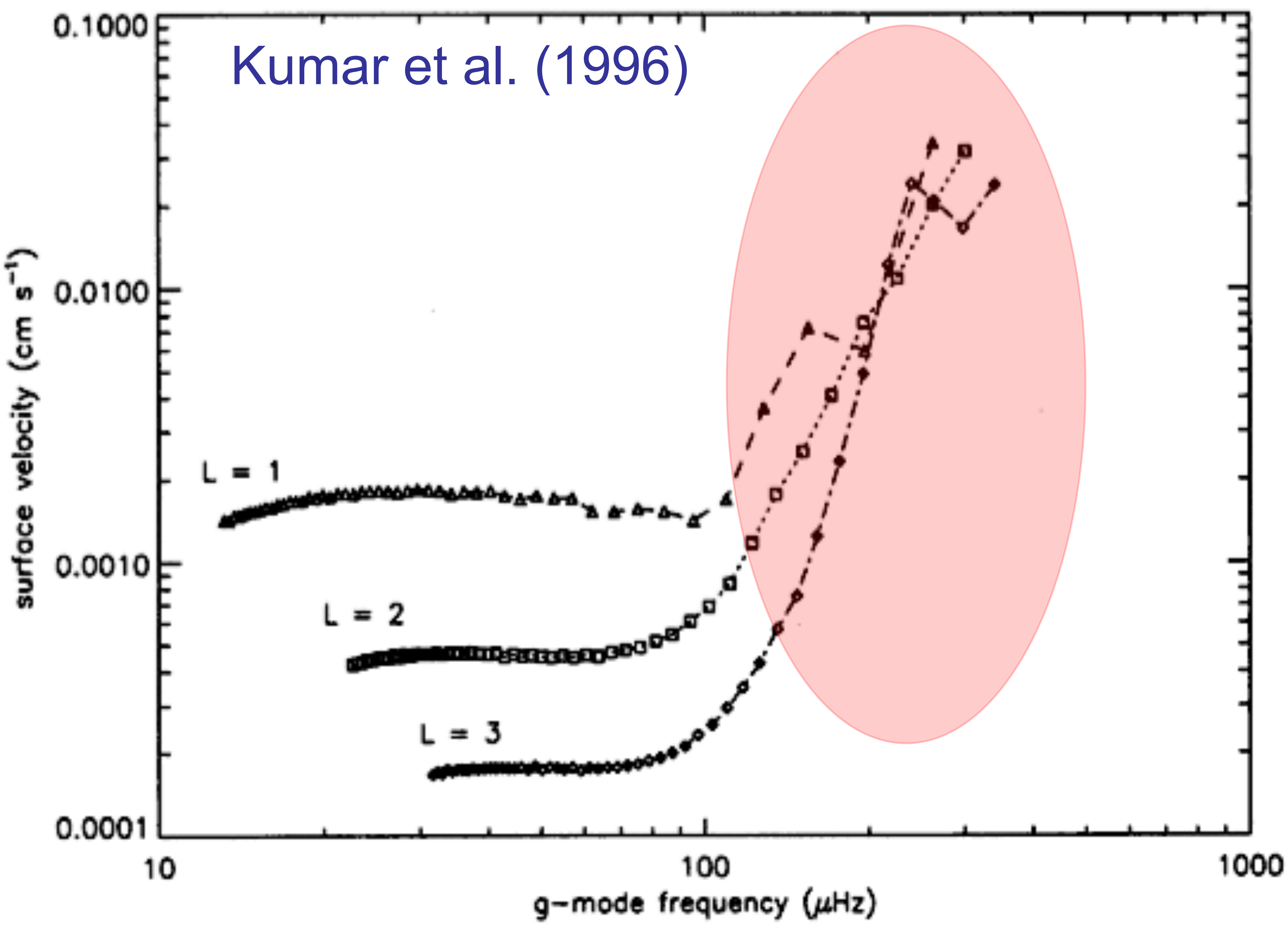
*Mode damping*

Adaptation of the Goldreich & Kumar (1991) formalism

- ✓ Radiative damping
- ✓Turbulent viscosity: analogy with molecular viscosity, small-scale eddies (compared to the mode wave-length) generate an effective viscosity for modes

# G mode amplitudes: excitation turbulent convection

First full calculation (i.e. excitation + damping)

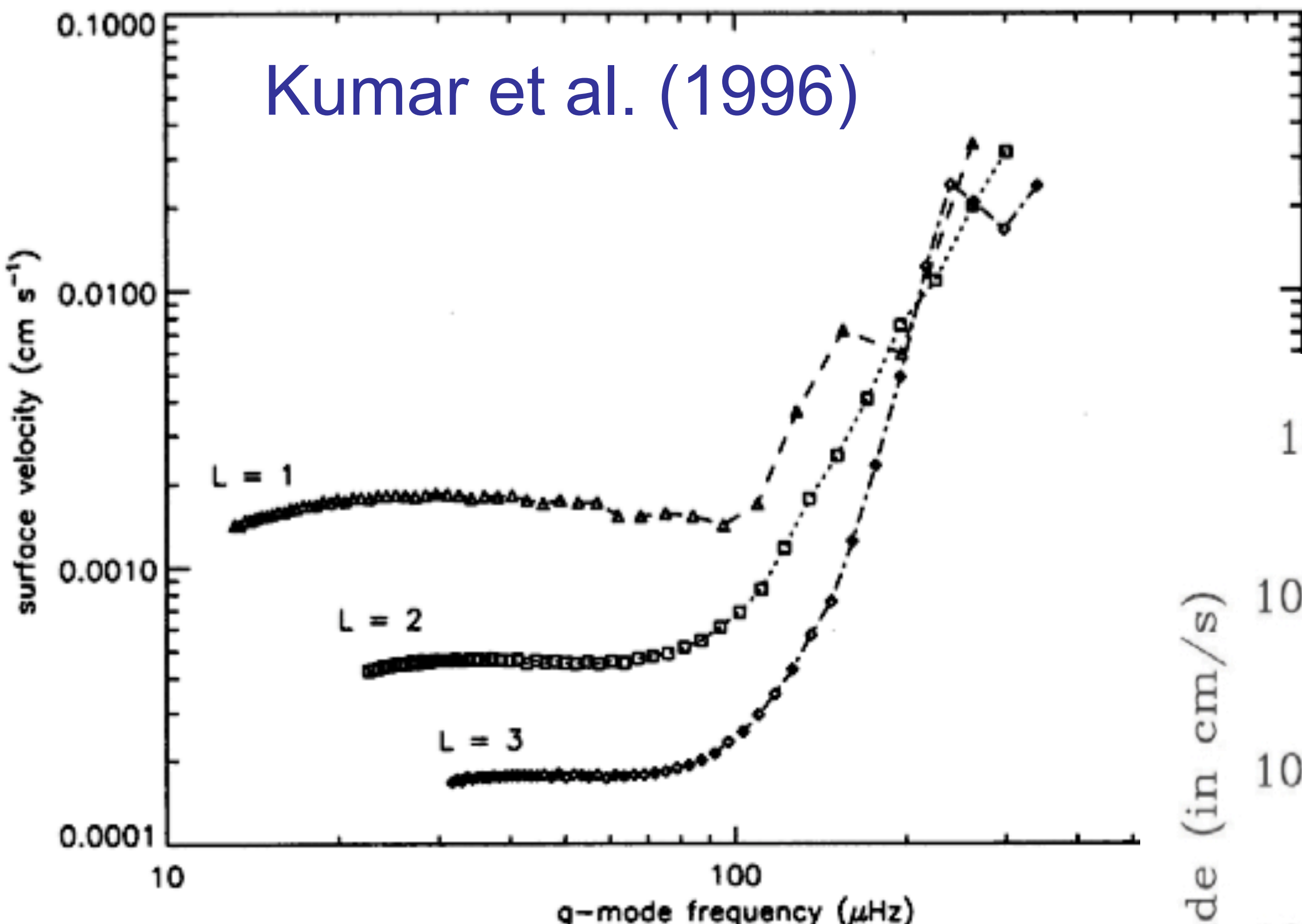



Tends to favor low-order g modes

Had motivated most of the observational efforts to focus on low-order g modes

# G mode amplitudes: excitation turbulent convection

First full calculation (i.e. excitation + damping)

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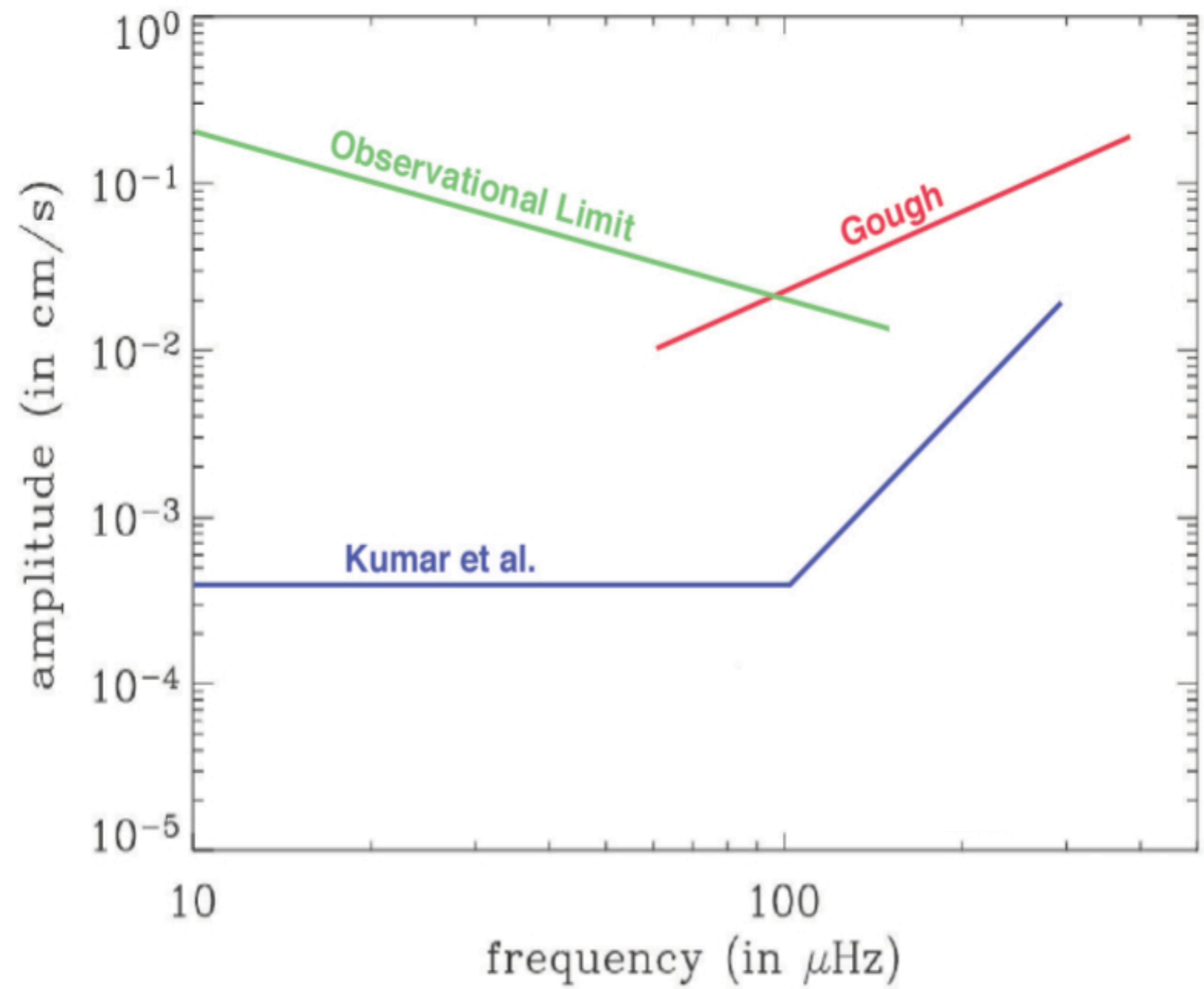


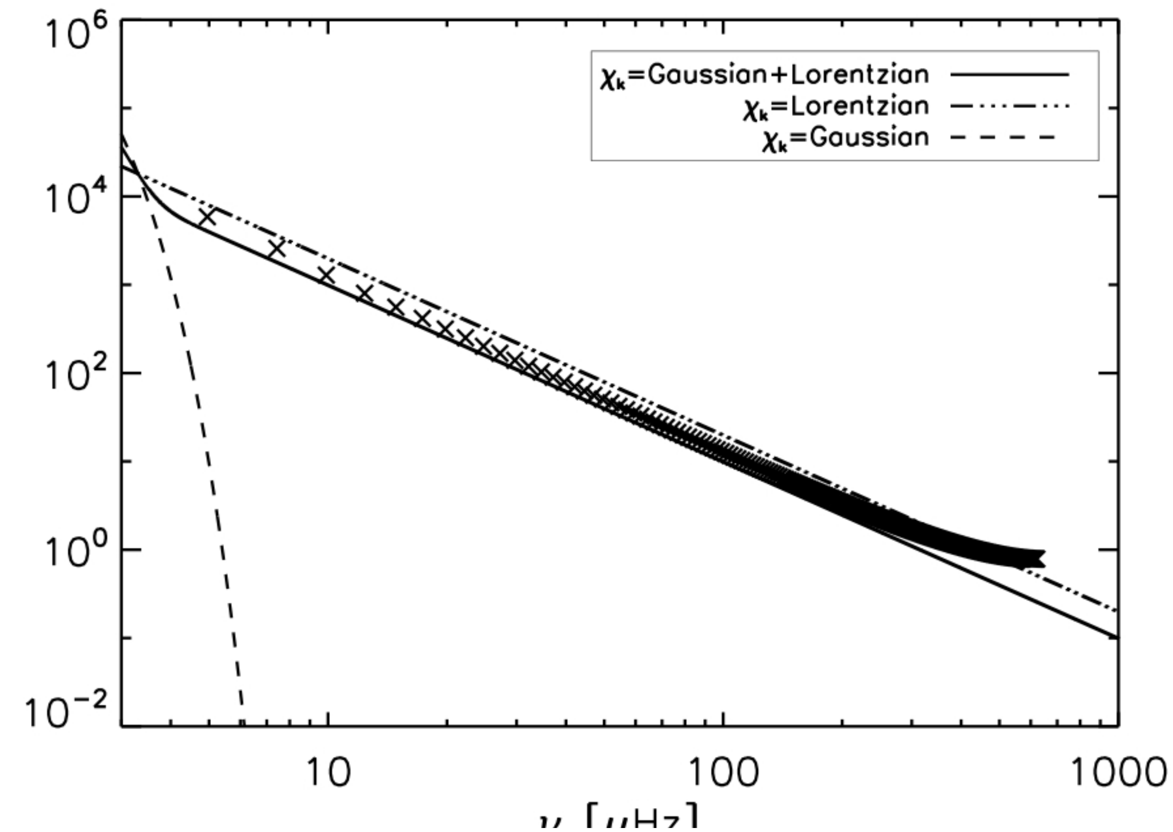

→ But the results are widely dispersed

# G mode amplitudes: excitation turbulent convection

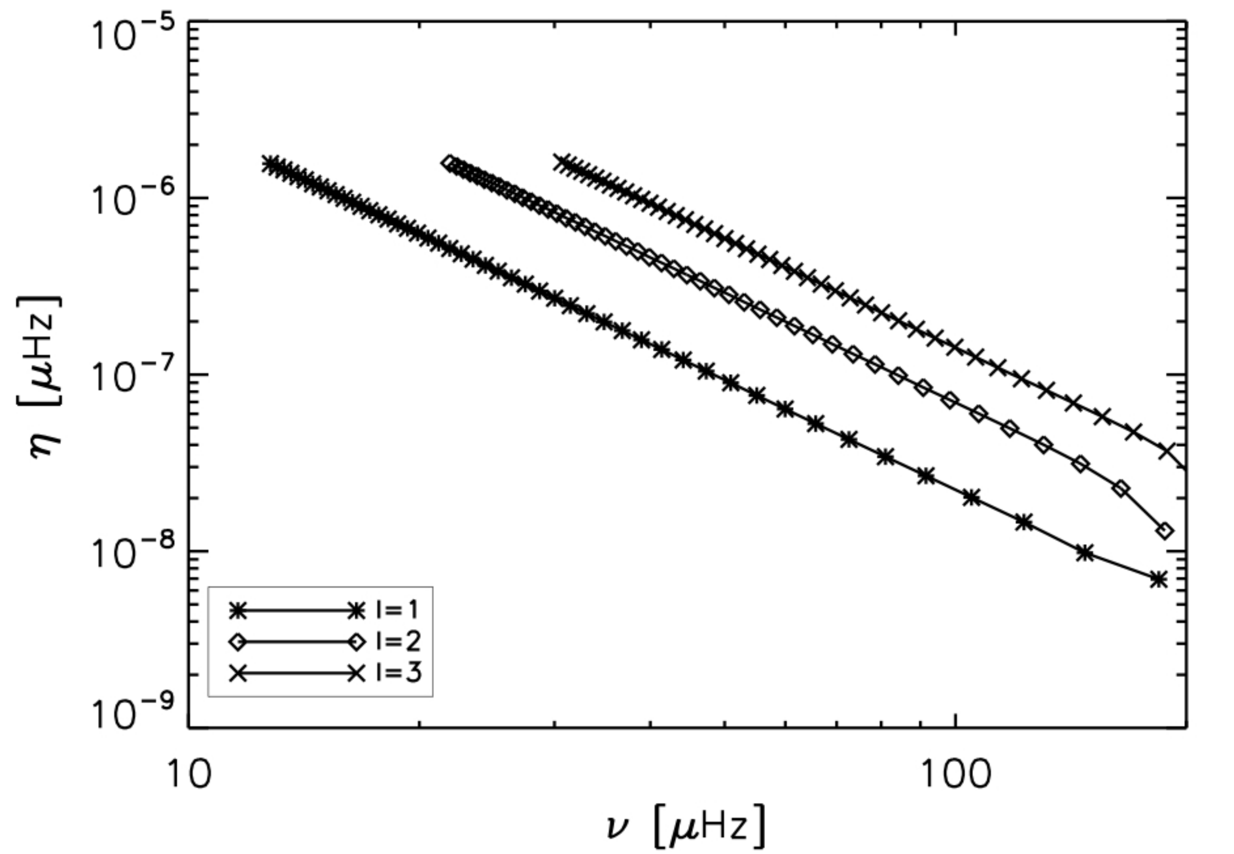
<u>Belkacem et al. (2009)</u>

- For the excitation

➡ determination of turbulent properties using the ASH code (in particular Lorentzian eddy-time correlation function)




- Full non-radial computation is performed but only for asymptotic g-modes




➡ to get rid of the uncertainties linked to the treatment of convection, turbulent pressure etc…

➡ to avoid any extrapolation from the observed p modes

➡ Damping dominated by radiative losses

# G mode amplitudes: excitation turbulent convection

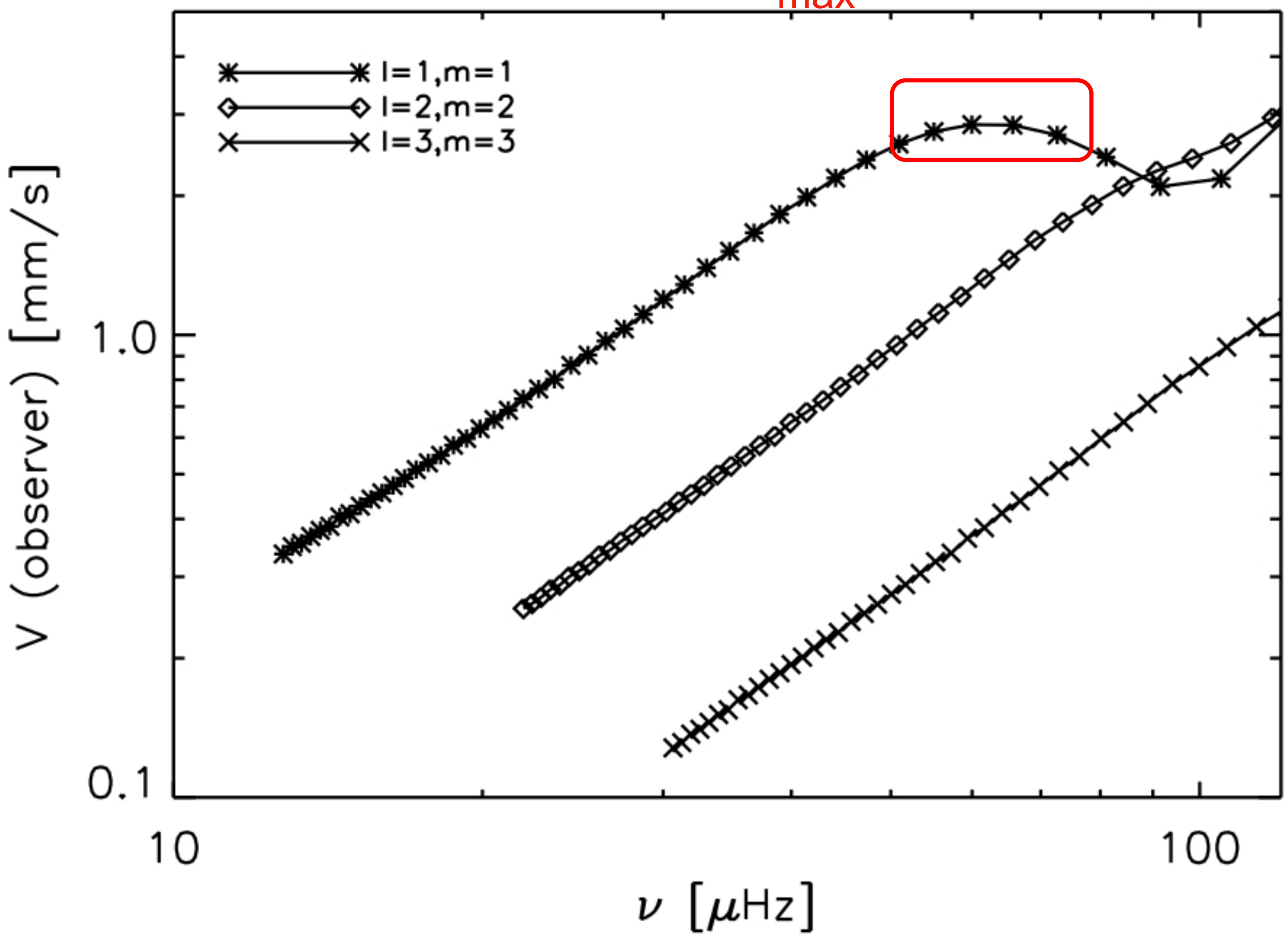
Belkacem et al. (2009)

- Taking into account visibility factors as well as limb darkening

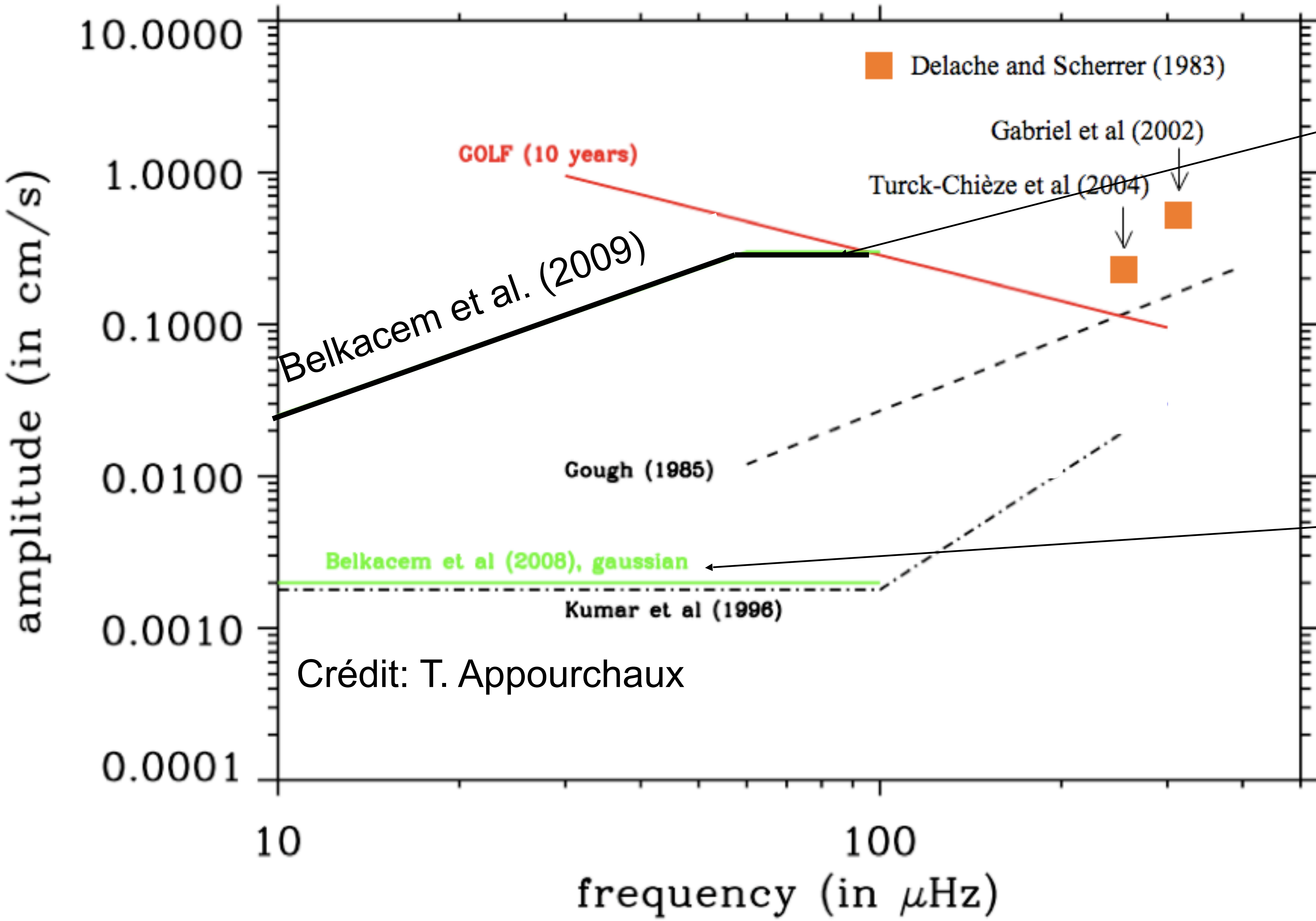
➡l > 3 highly damped, detection unlikely ($\eta \propto l^2$)

➡Still some uncertainties, mainly related to the turbulent velocities at the base of the convective zone

$V_{max}$~ 3 mm/s



# G mode amplitudes: excitation turbulent convection




Velocities around 3 mm/s

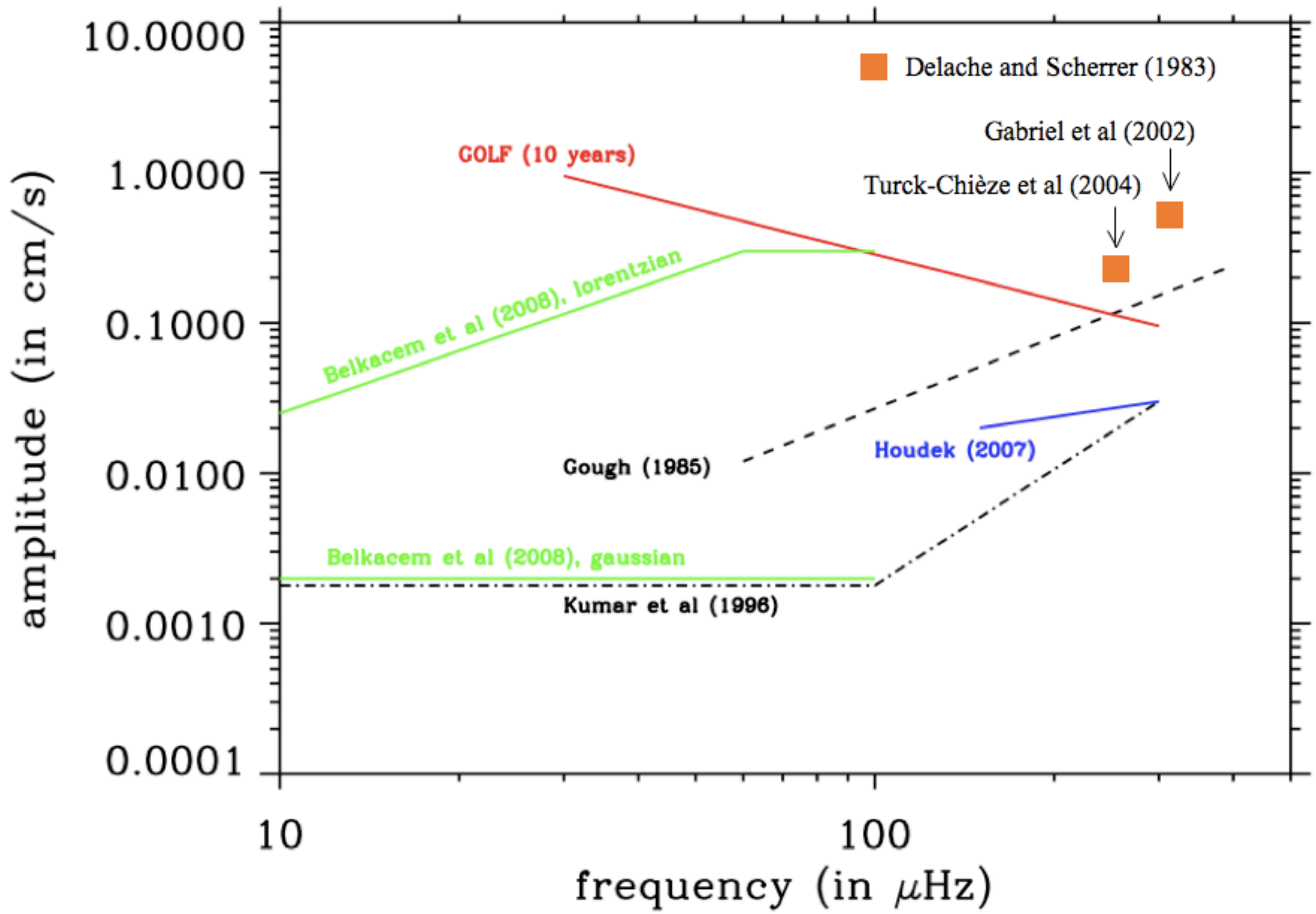
Near the detection threshold

Disagreement with Kumar et al (1996) comes from the choice of $\chi_k$

# Some concluding remarks about g-mode excitation models…

« Essentially, all models are wrong, but some are useful. »

George E. P. Box, *Empirical Model-Building and Response Surfaces*, 1987



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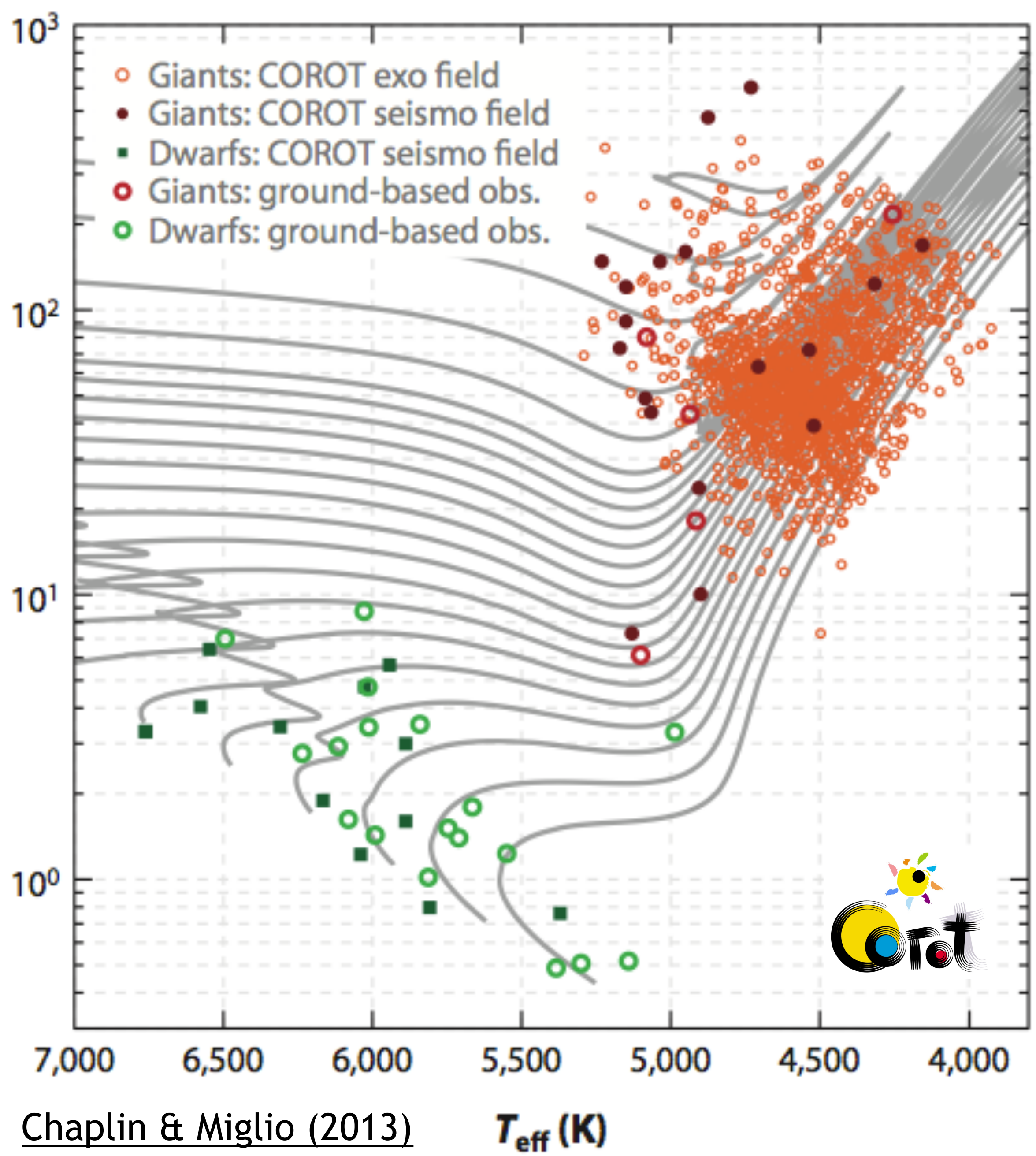
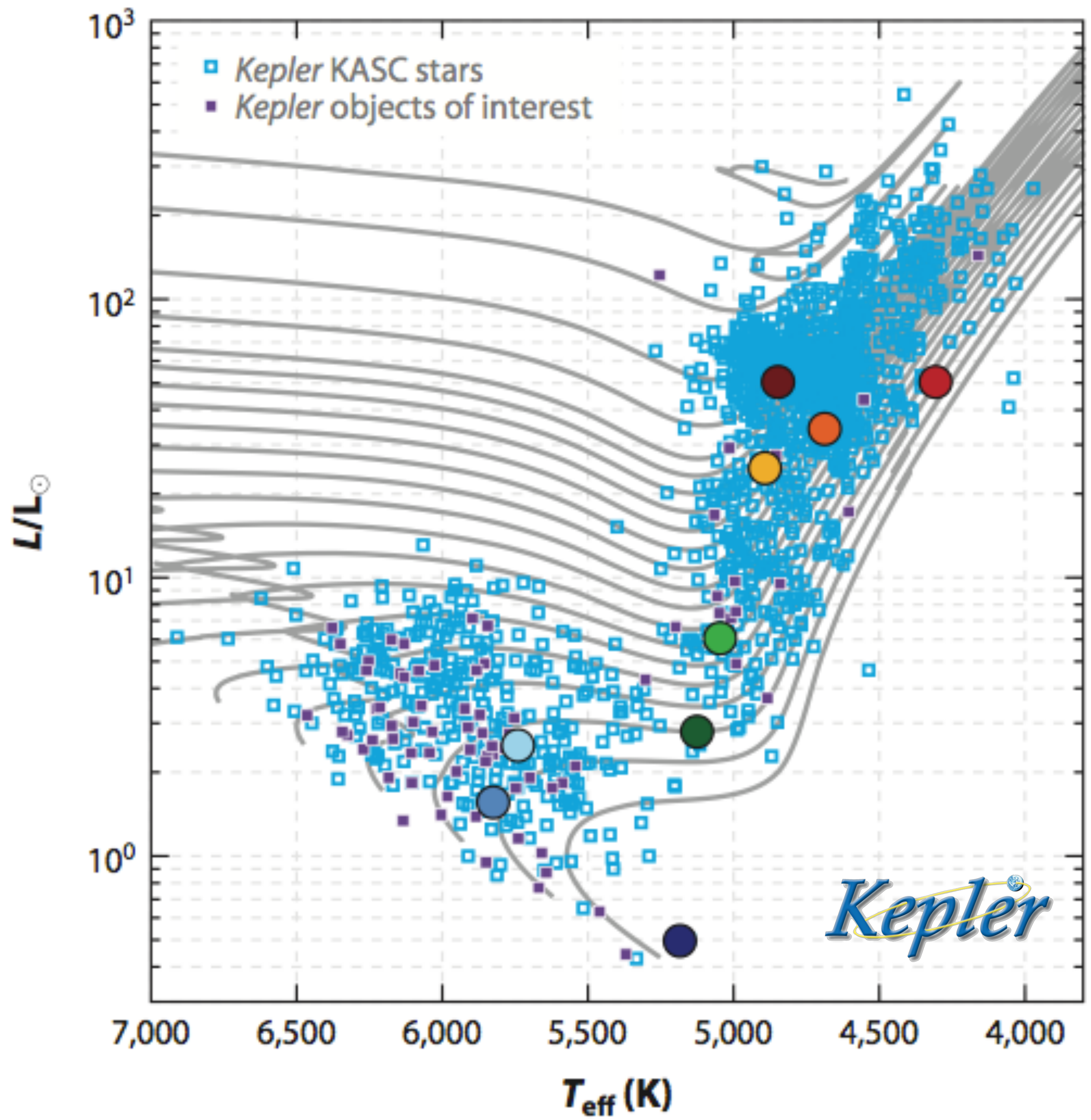
- Mixed-modes in sub giants and red giants

# From scarcity to abundance: evolved stars

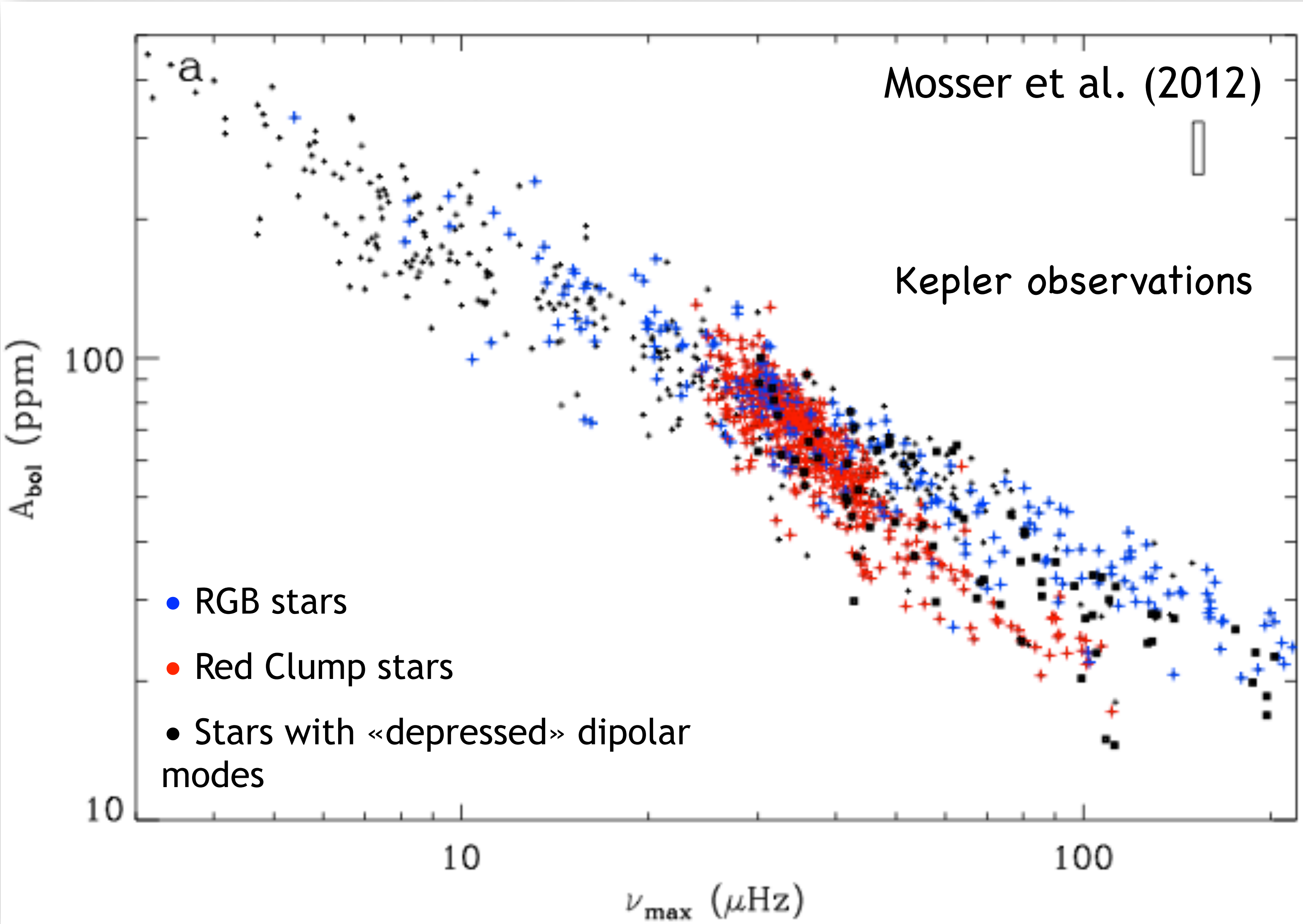



Chaplin & Miglio (2013)

- hundreds of oscillating MS stars and thousands of RG stars
- highly accurate measurements of individual mode properties

# From scarcity to abundance: evolved stars

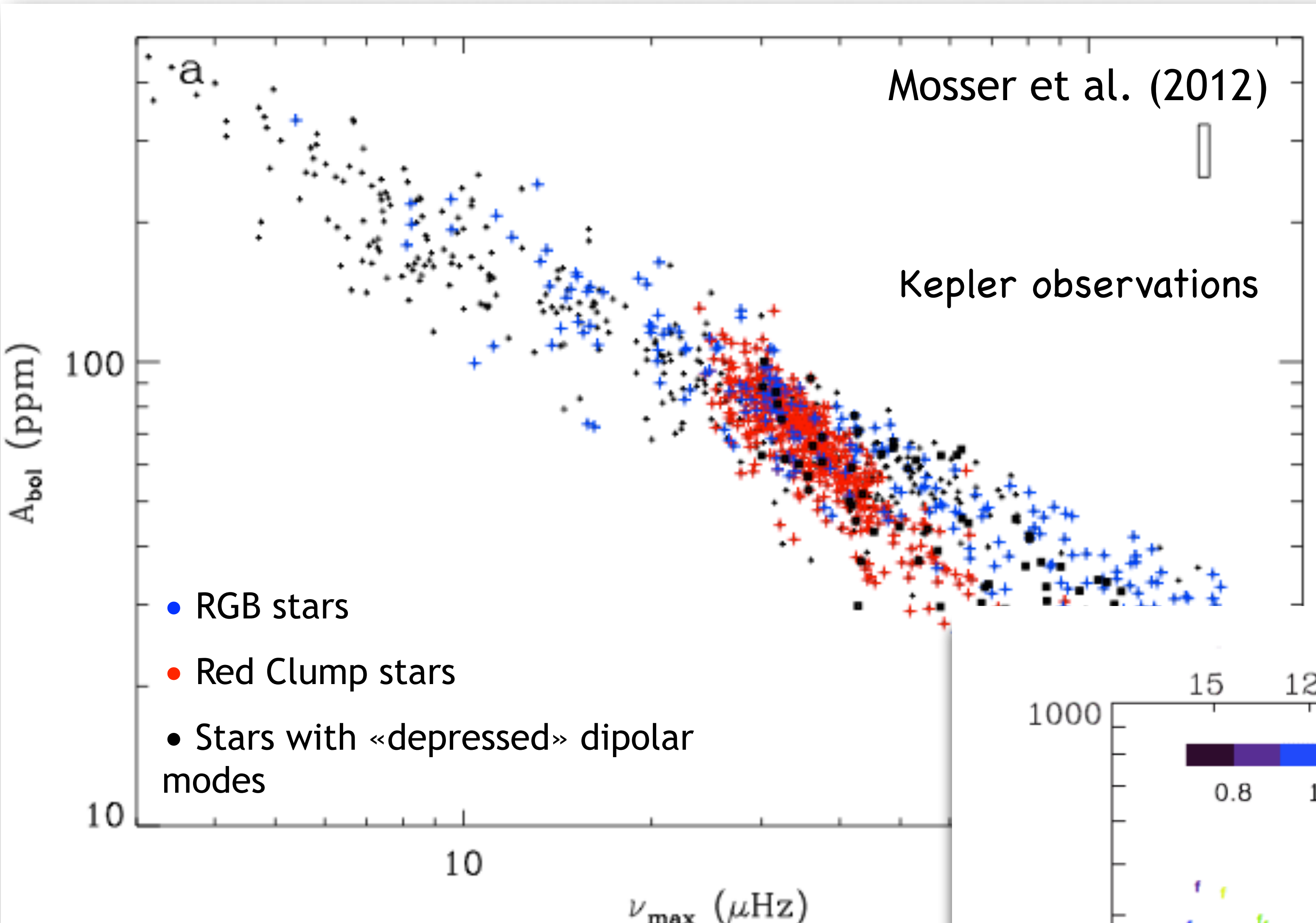



- The slope is understood (Samadi et al. 2012)

$$\left(\frac{\delta L}{L}\right) \propto T_{\rm eff}^{0.1}\, \nu_{\rm max}^{-0.65}$$

The more the star is evolved the higher is the amplitude

# From scarcity to abundance: evolved stars

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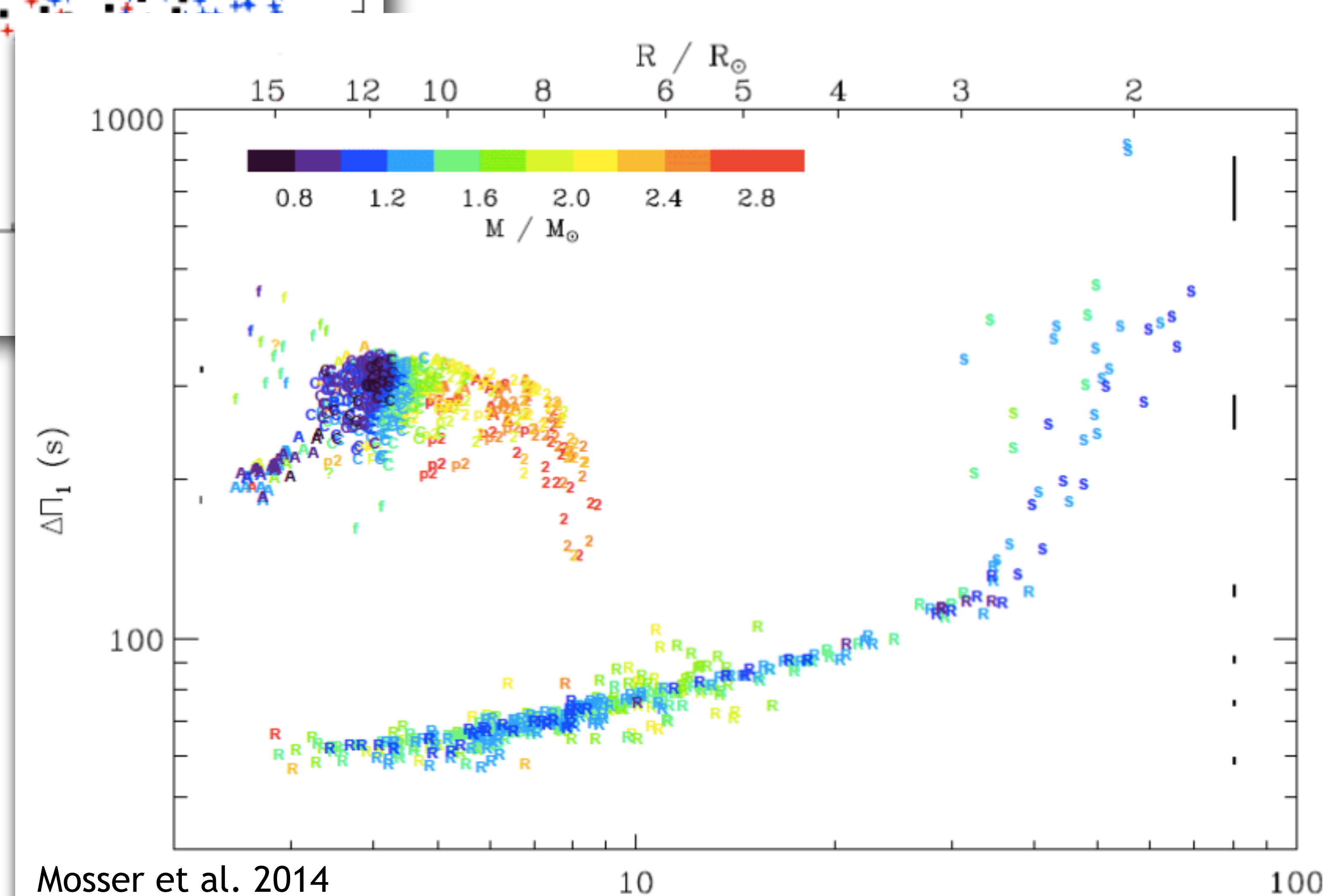
- More importantly, we detect mixed modes and then have access to the inner layers



# Mixed modes in evolved stars

- The oscillations of red-giants differ significantly from main-sequence stars

→ the power spectrum of sub-giants and red-giants is largely modified by *mixed modes*

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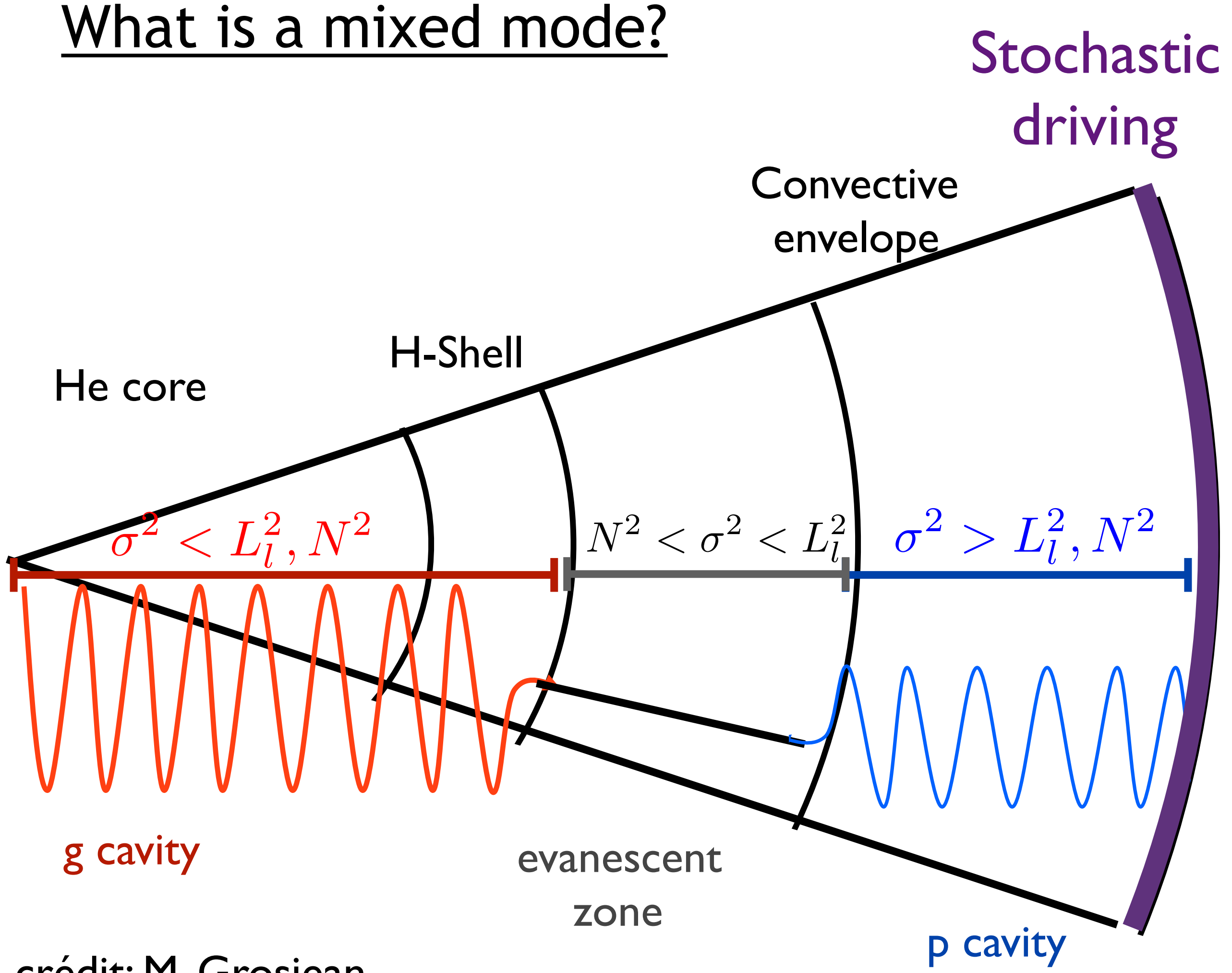


crédit: M. Grosjean

✓ upper cavity in which acoustic modes can exist

the restoring force is dominated by the pressure gradient

✓ inner cavity in which gravity modes can exist

the dominant restoring force is the buoyancy

✓ intermediate region, in which modes are evanescent, couples the cavities

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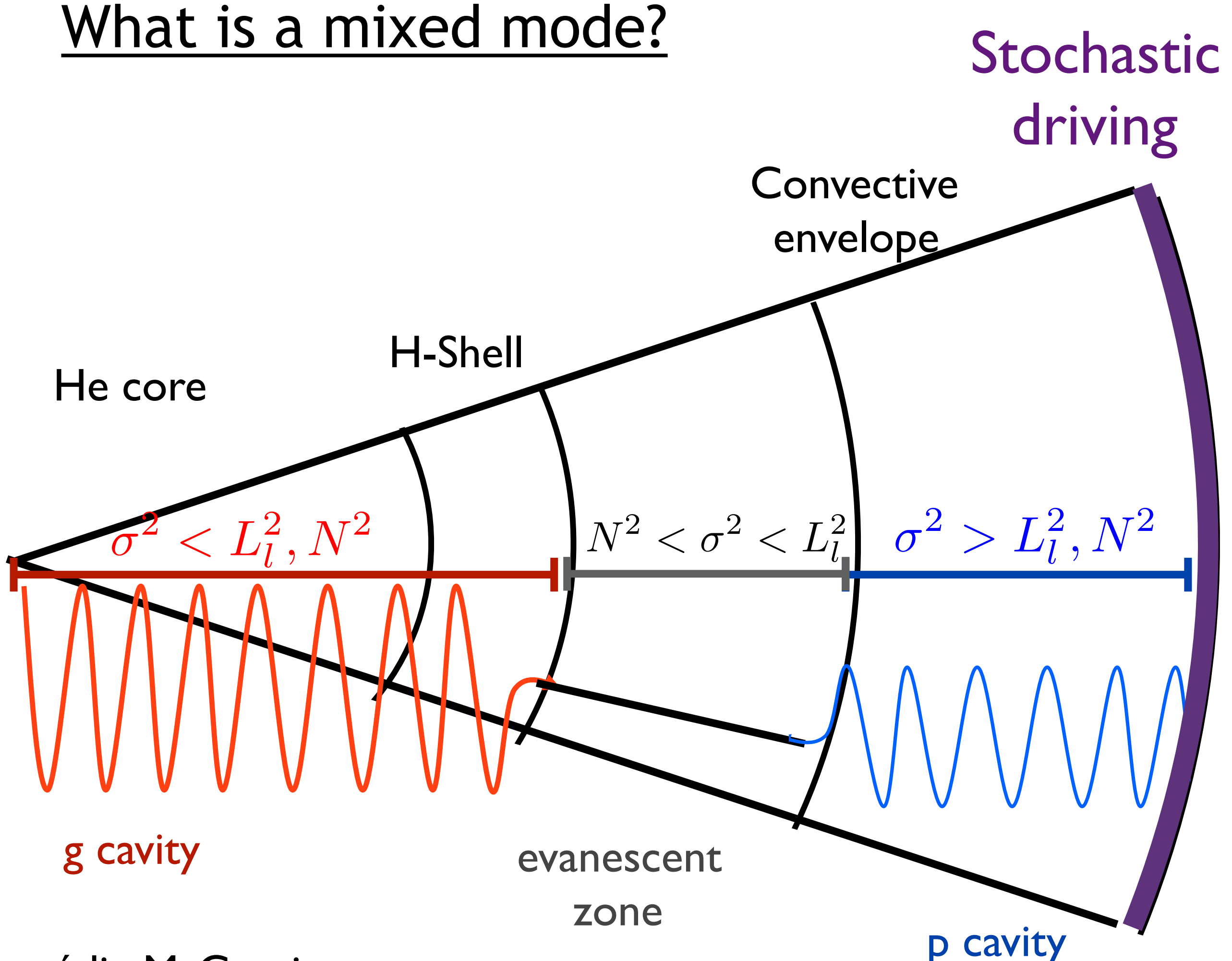


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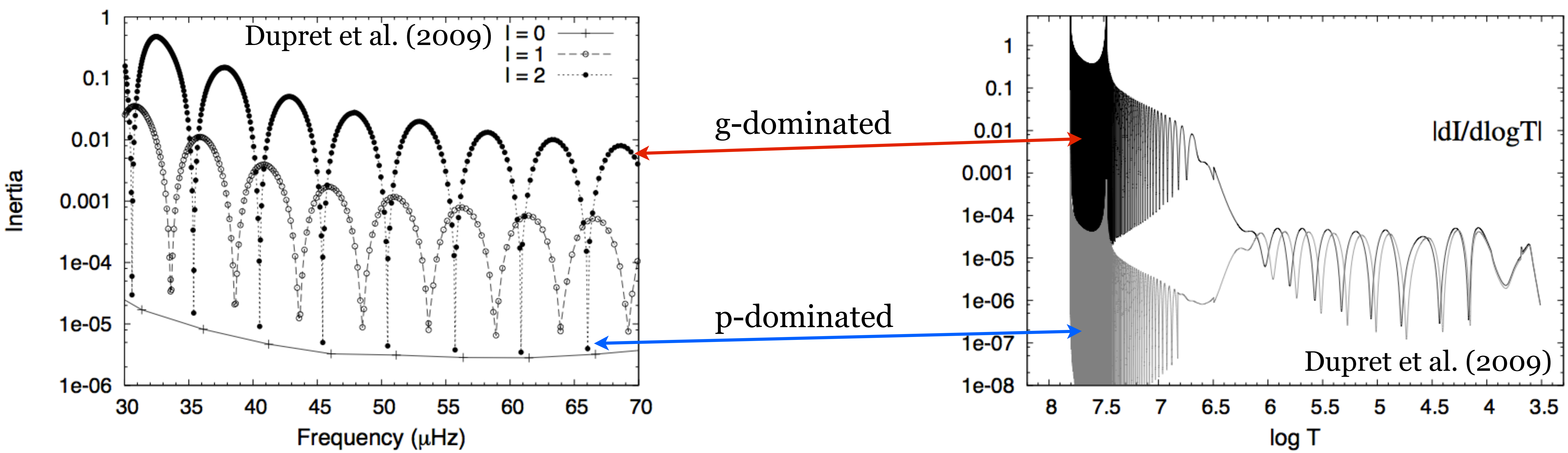
- Mixed modes have amplitude in the enveloppe and in the core → can be used to probe the innermost layers

# Mixed modes in evolved stars

- How mixed modes modify the power spectrum?

The first ingredient is the mode inertia $I = \int_0^M \left|\vec{\xi}\right|^2 \mathrm{d}m$




The second ingredient is the radiative damping in the core

As the star evolves, the radiative damping of g-dominated modes increases

$$\eta_{\mathrm{rad}} \propto \frac{LR}{GM^2}\left(\frac{R}{r_{\mathrm{core}}}\right)^2$$

# Mixed modes in evolved stars

Non-adiabatic non-radial calculation including a time-dependent treatment of convection

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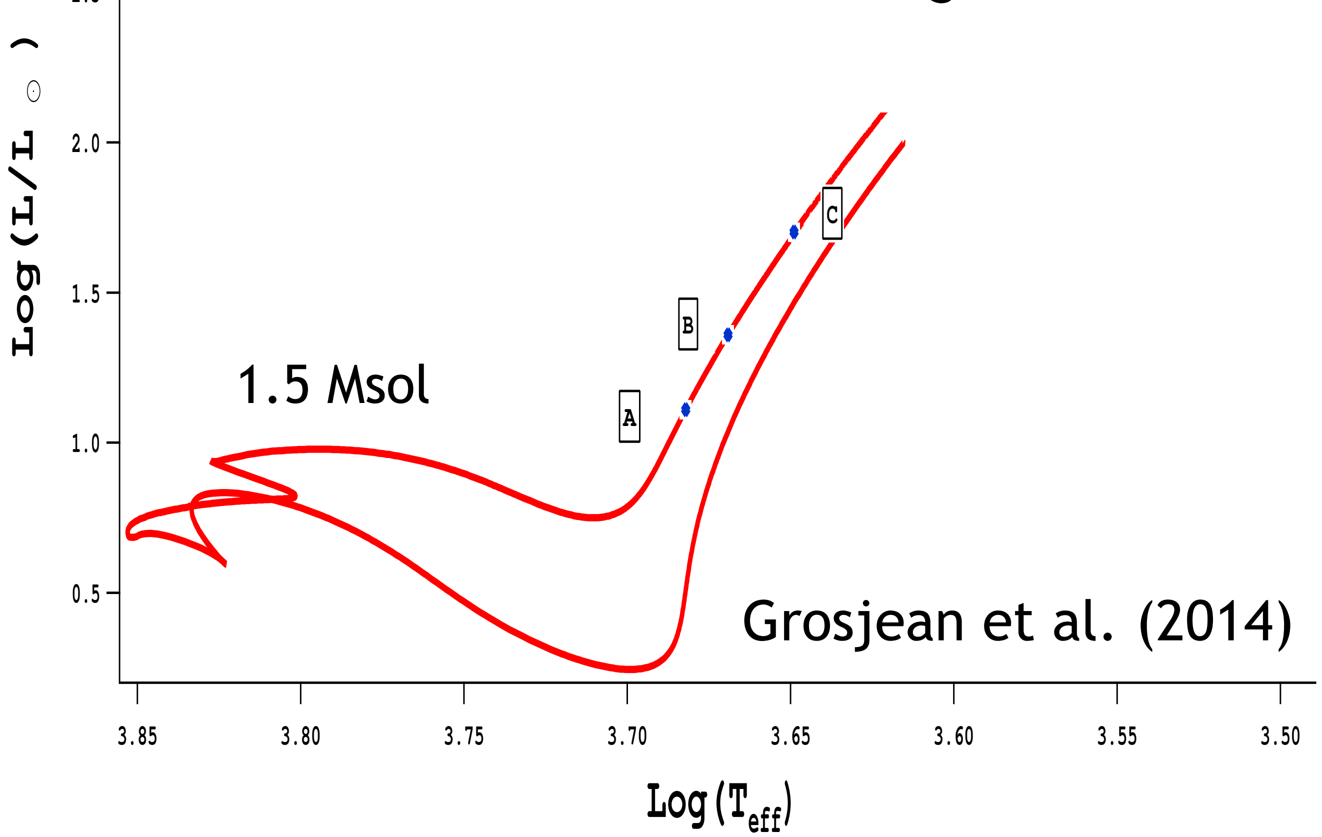
Calculation of stochastic driving

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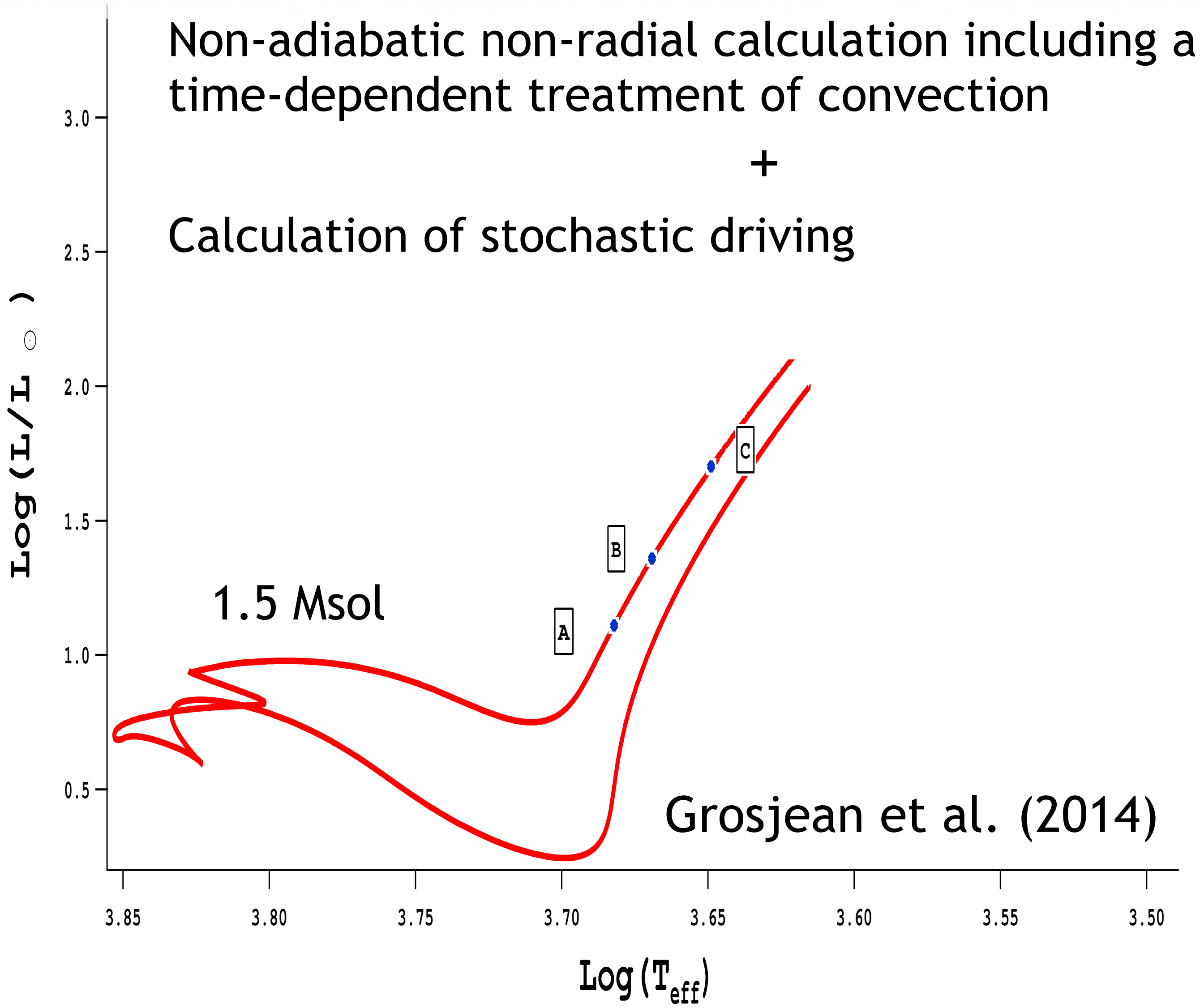


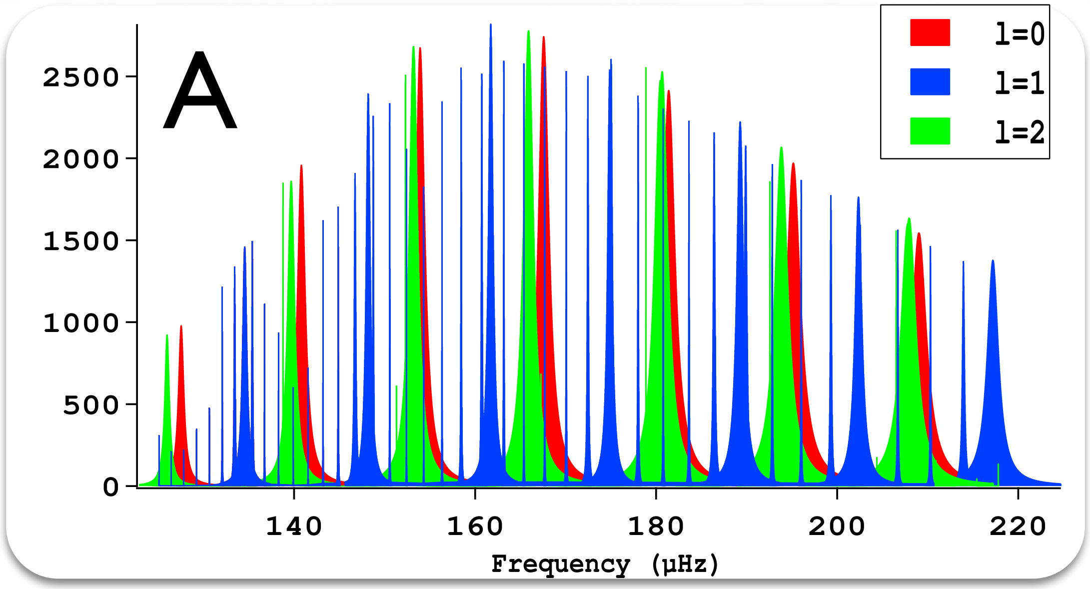


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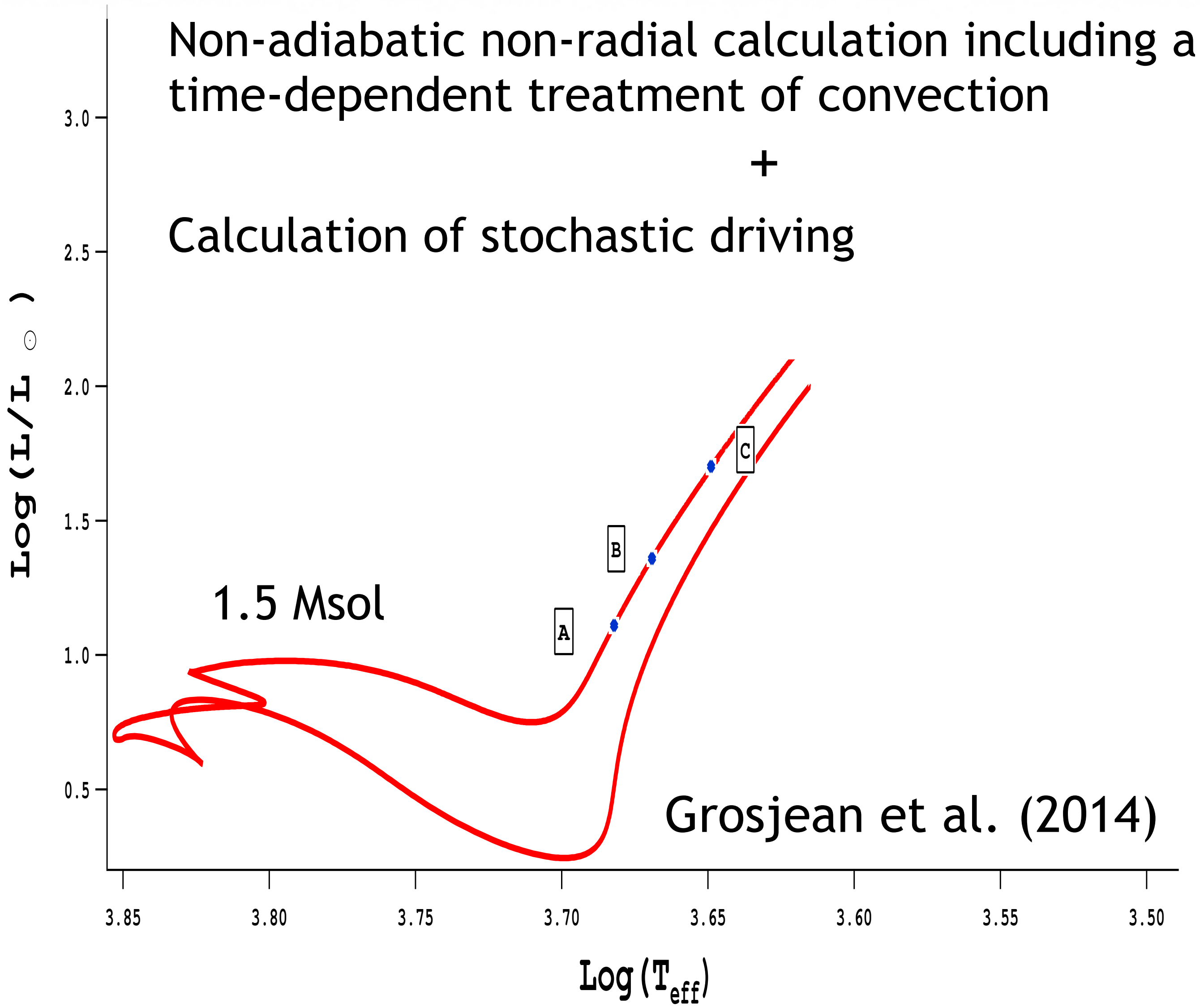


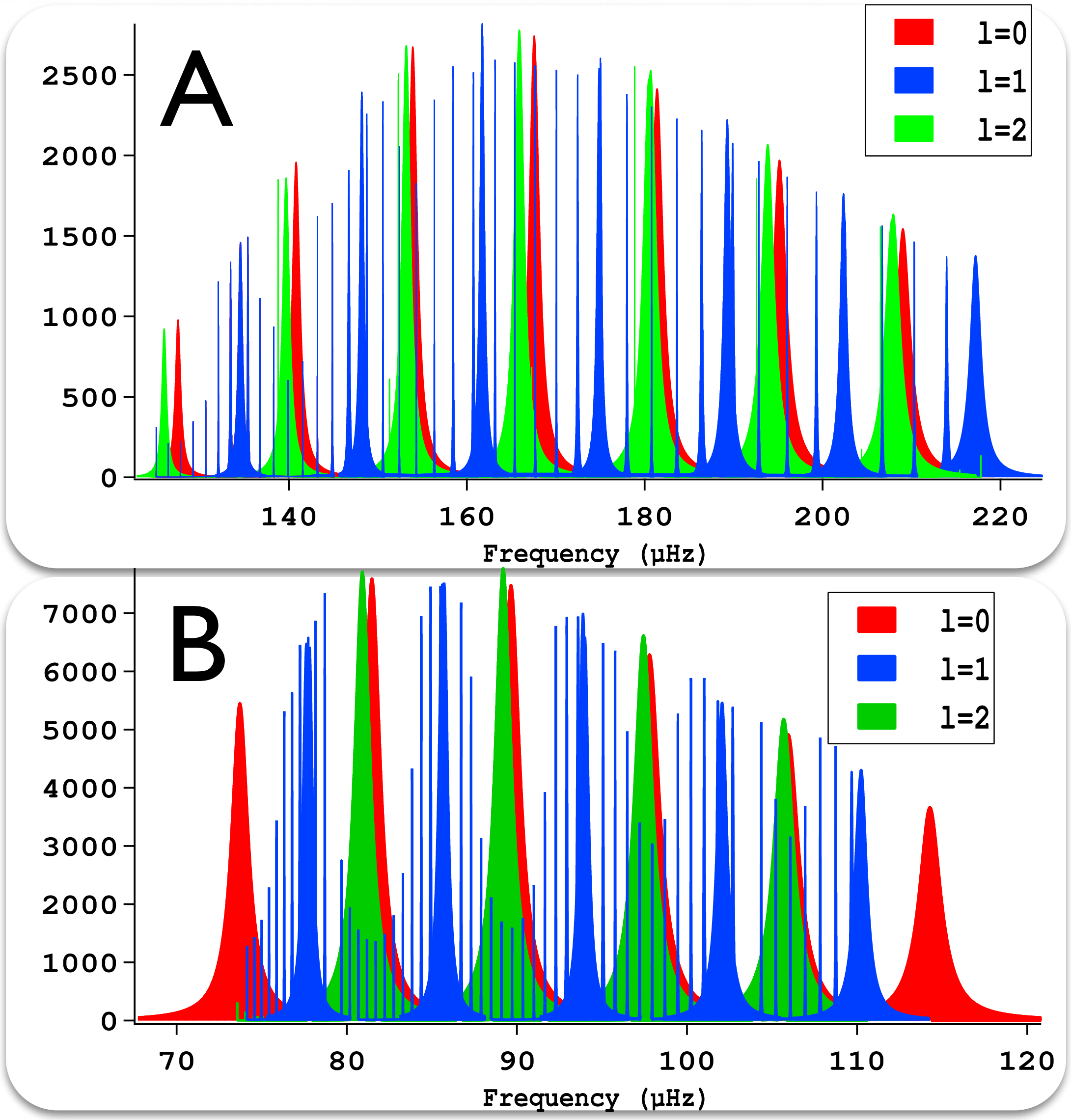


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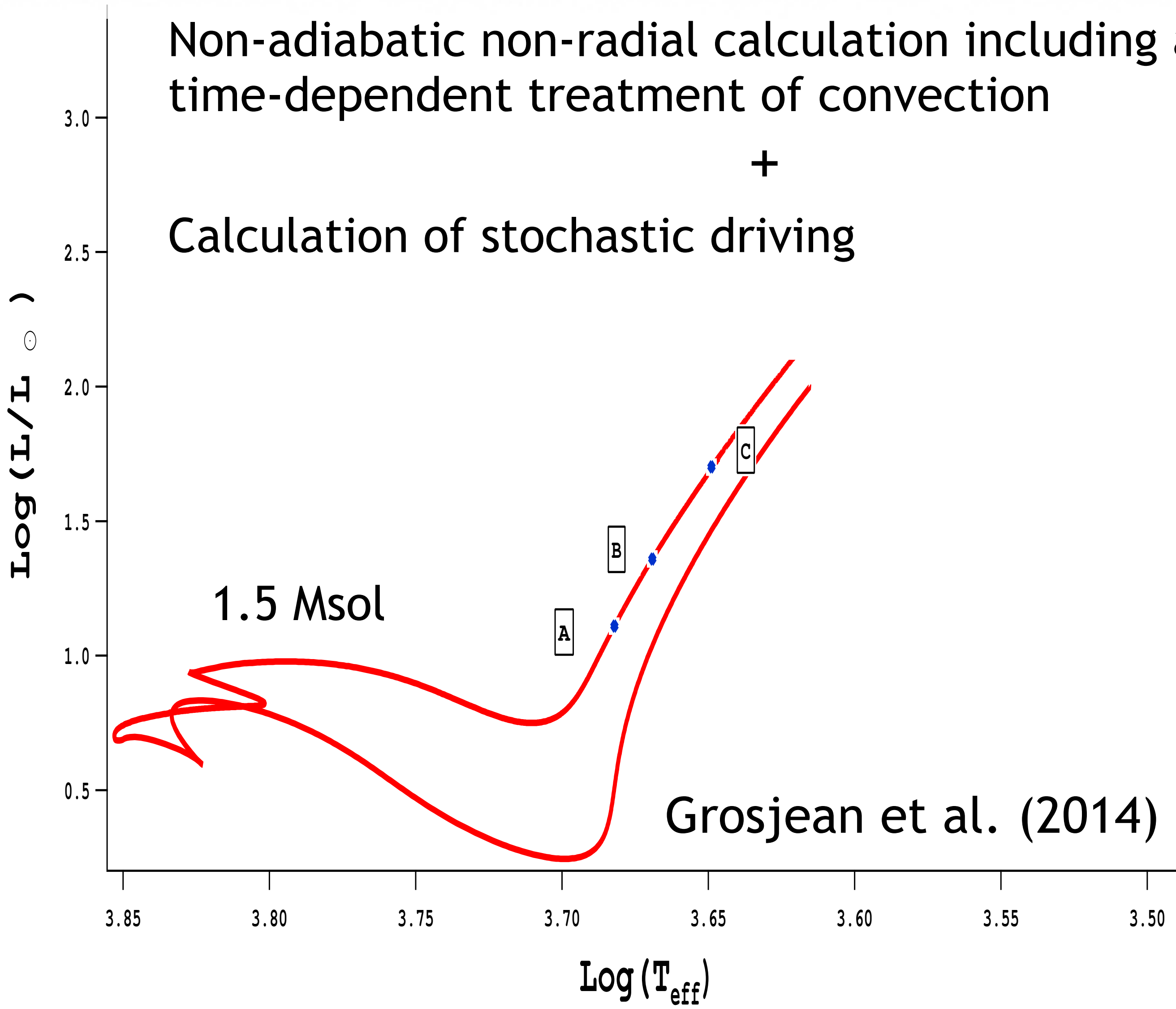


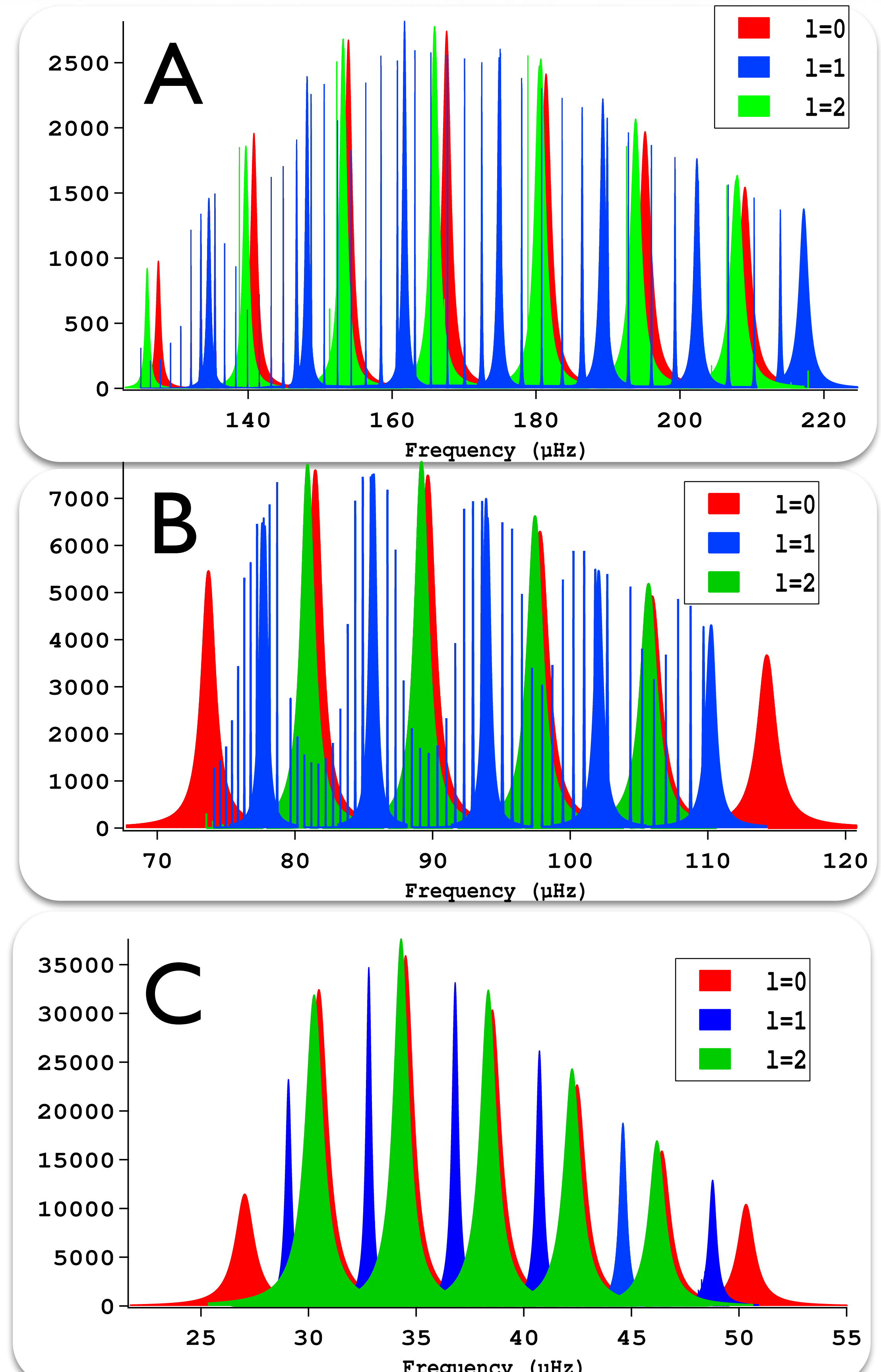


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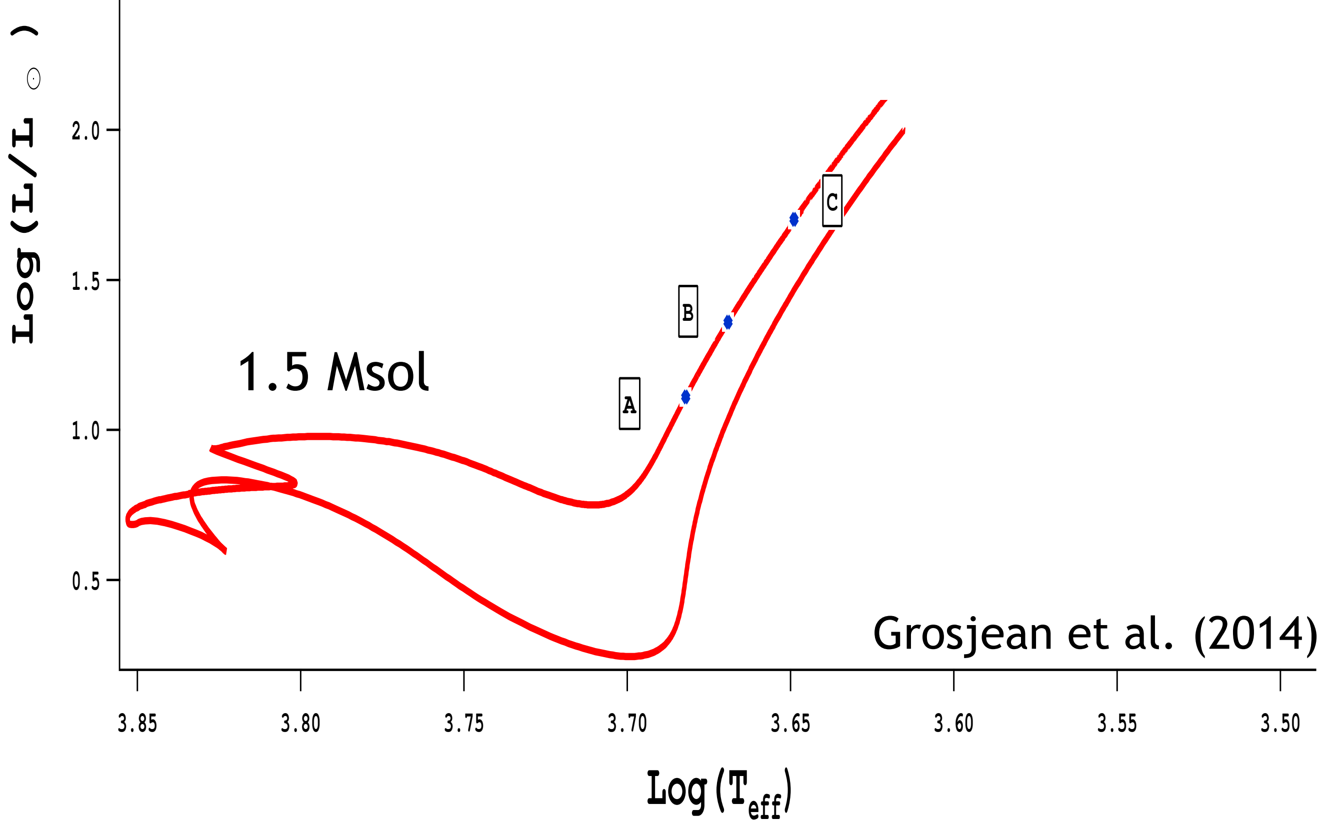


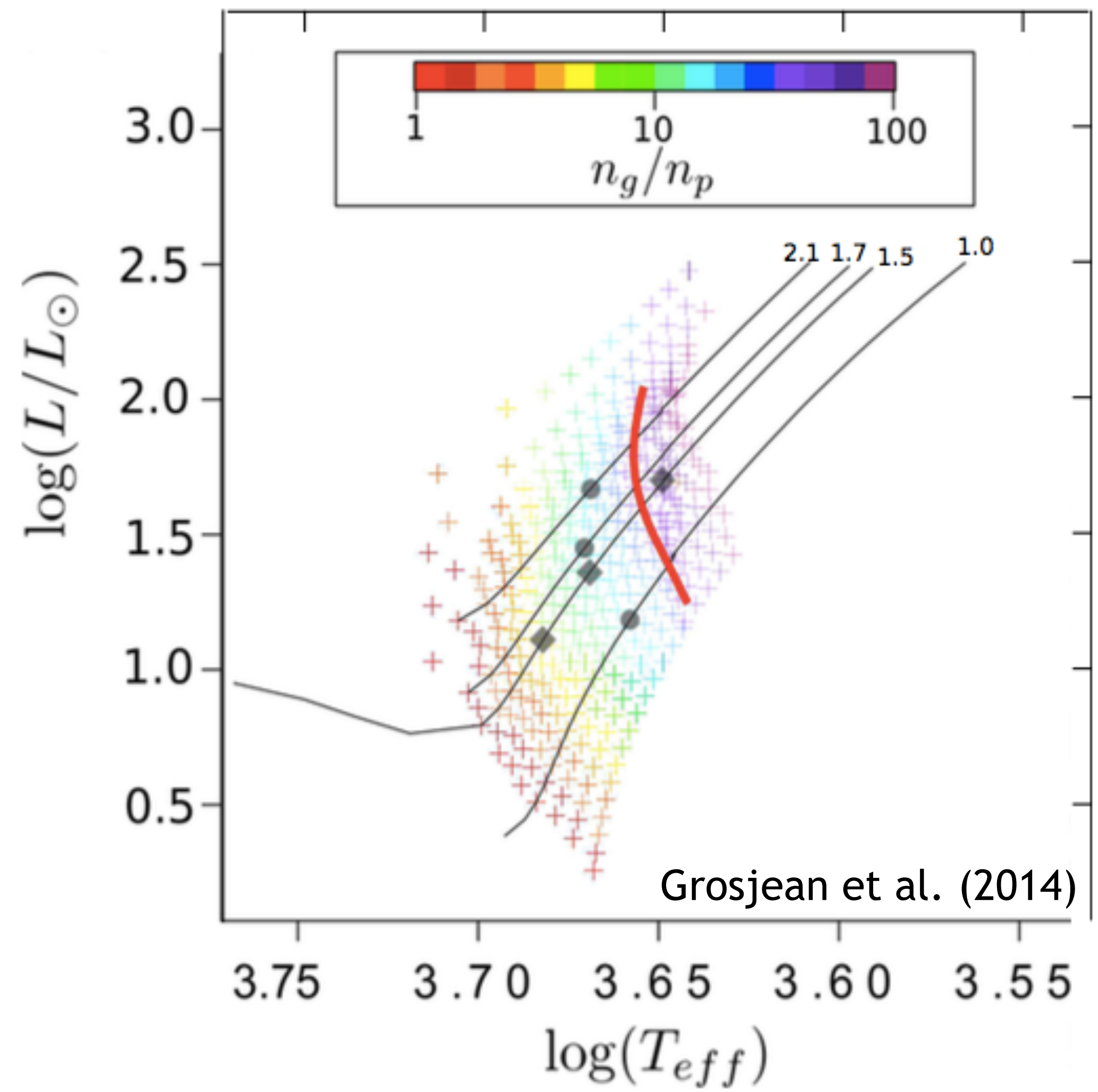


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- *for more evolved red giants, radiative damping begins to reduce mixed mode amplitudes (model B)*
- *for highly evolved stars radiative damping prevent mixed modes from being observed (model C)*
- *similar behaviors for the same number of mixed modes by large separation*

$$\frac{n_g}{n_p} \approx \frac{\Delta\nu}{\Delta\Pi\,\nu_{\max}^2}$$

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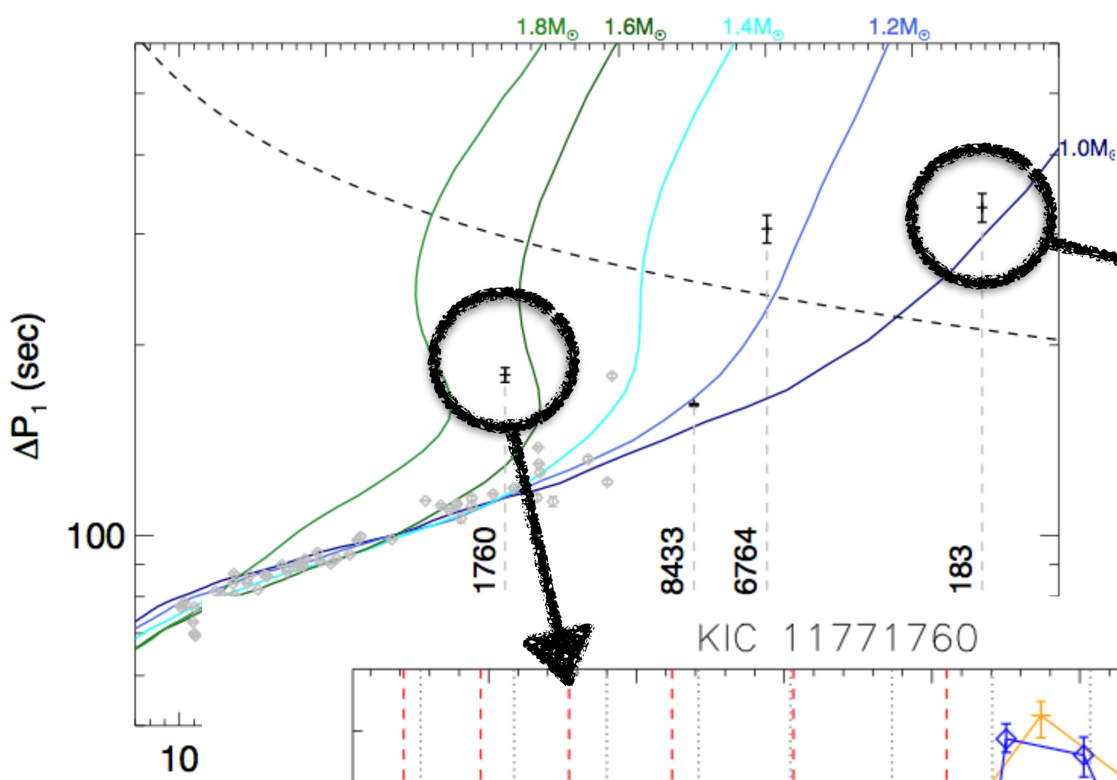
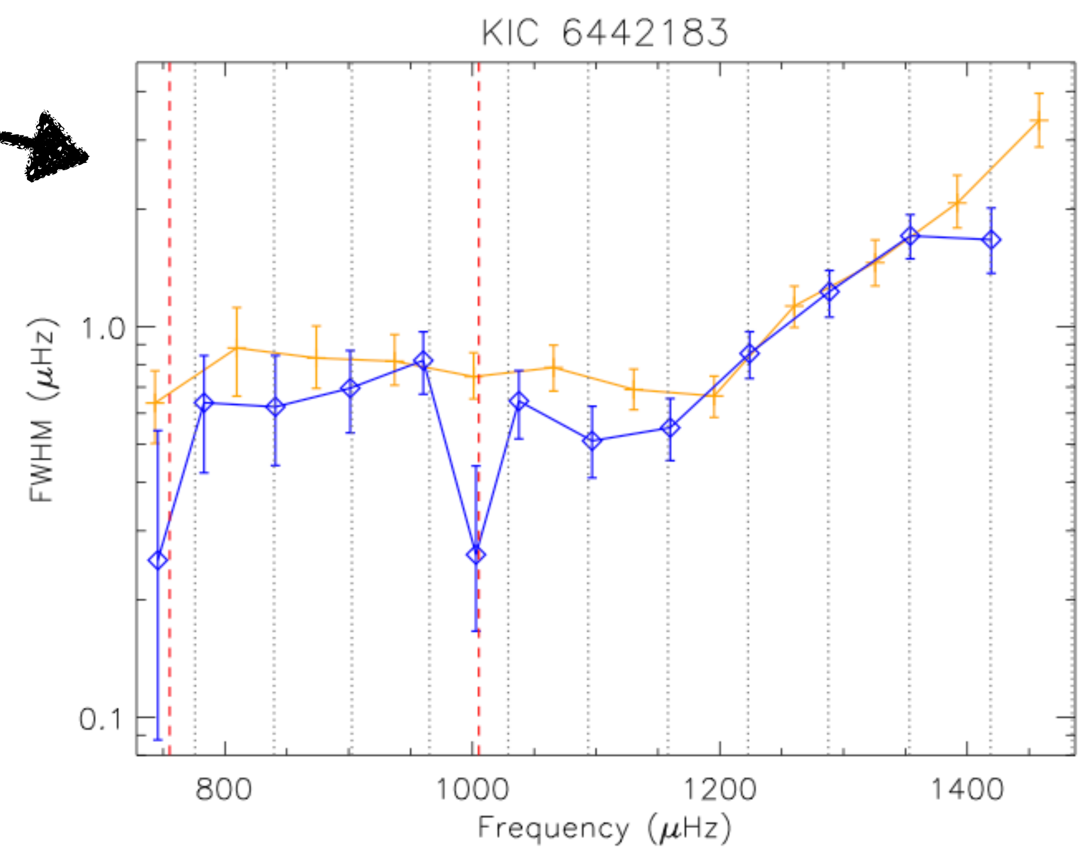
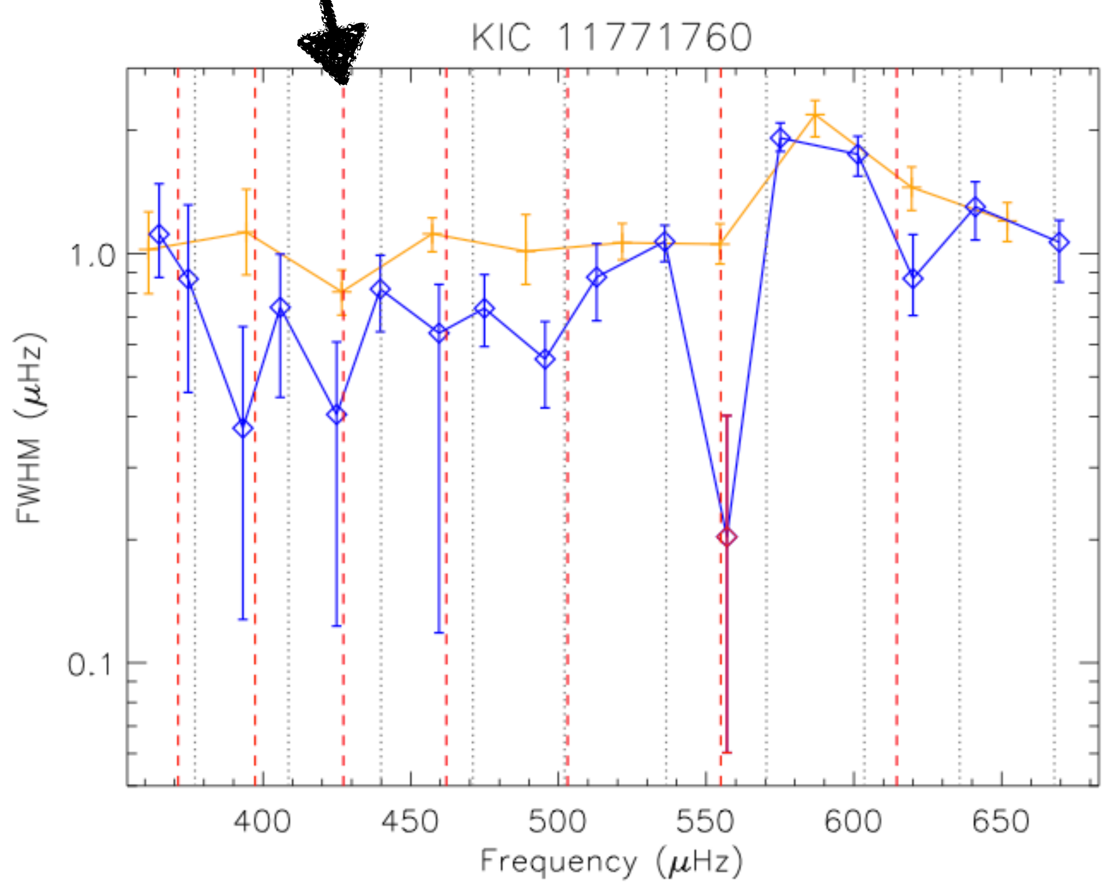
# Mixed modes in evolved stars

- for red-giants, there are not (at least yet) precise measurements of linewidth of mixed modes




- for sub-giants, only a few measurements by Benomar et al. (2013)




✓ the main behavior of mixed-modes linewidths is in agreement with expectations

✓ effect of mode inertia and radiative damping can then be probed inside sub giants (Grosjean et al. 2014)

# Mixed modes in evolved stars

Application: inferring mode inertias (from Benomar et al. 2014)

- Mode height reads $H = \dfrac{\mathcal{P}}{2\eta^2 \mathcal{M}}$

- Consider two modes at roughly the same frequency, namely a p-dominated and g-dominated

$$\frac{H_p}{H_g} = \left(\frac{\mathcal{P}_p}{\mathcal{P}_g}\right)\left(\frac{\mathcal{M}_g}{\mathcal{M}_p}\right)\left(\frac{\eta_g}{\eta_p}\right)$$

- Since the two modes have the same shape at the surface

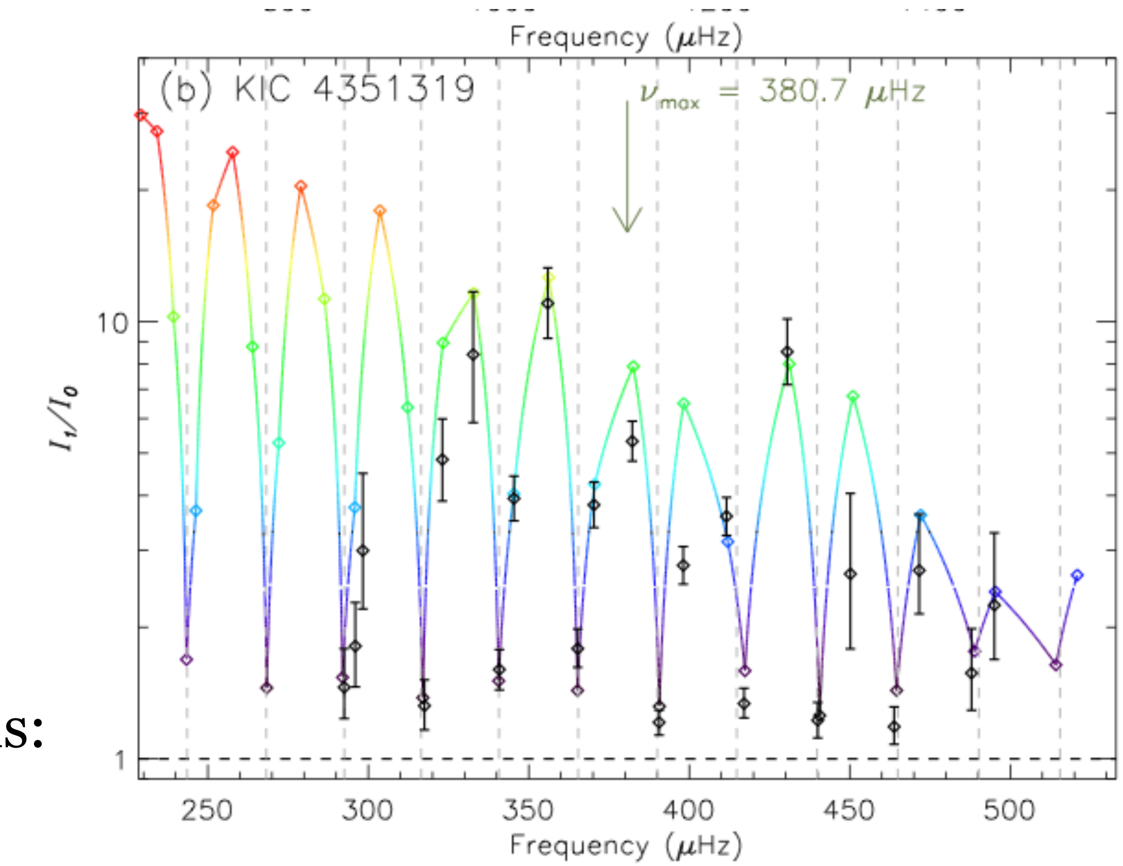
$$\mathcal{P}_i \propto \frac{1}{\mathcal{M}_i} \int \mathrm{d}W \longrightarrow \mathcal{P}_p \mathcal{M}_p \approx \mathcal{P}_g \mathcal{M}_g$$

modes experience the same work at the surface

- Finally,

$$\boxed{\frac{\mathcal{M}_g}{\mathcal{M}_p}} \approx \boxed{\sqrt{\frac{H_p}{H_g}\frac{\eta_p}{\eta_g}}}$$

inferred quantities measured quantities




mode inertia ratio is derived from the observations: new constraint for theoretical models