Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique

École Doctorale d'Astronomie & Astrophysique
d'île-de-France

# *On the internal rotation of low-mass stars: effect of internal gravity waves generated by penetrative convection*

*C. Pinçon*

**2nd year PhD student**
**Supervisors :**
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# *OUTLINE*

**I- Context**

II- Excitation of IGW

III- Transport of angular momentum

# *Probing the internal rotation of the stars...*

- **...using asteroseismology**
- **Solid-body rotation observed in the solar radiative interior** ***(e.g. Garcia, 2007)***
- **Observations of evolved stars with CoRoT (2006-2014) and Kepler(2009)**

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  - … while it strongly contracts until helium fusion starts (Red Clump).

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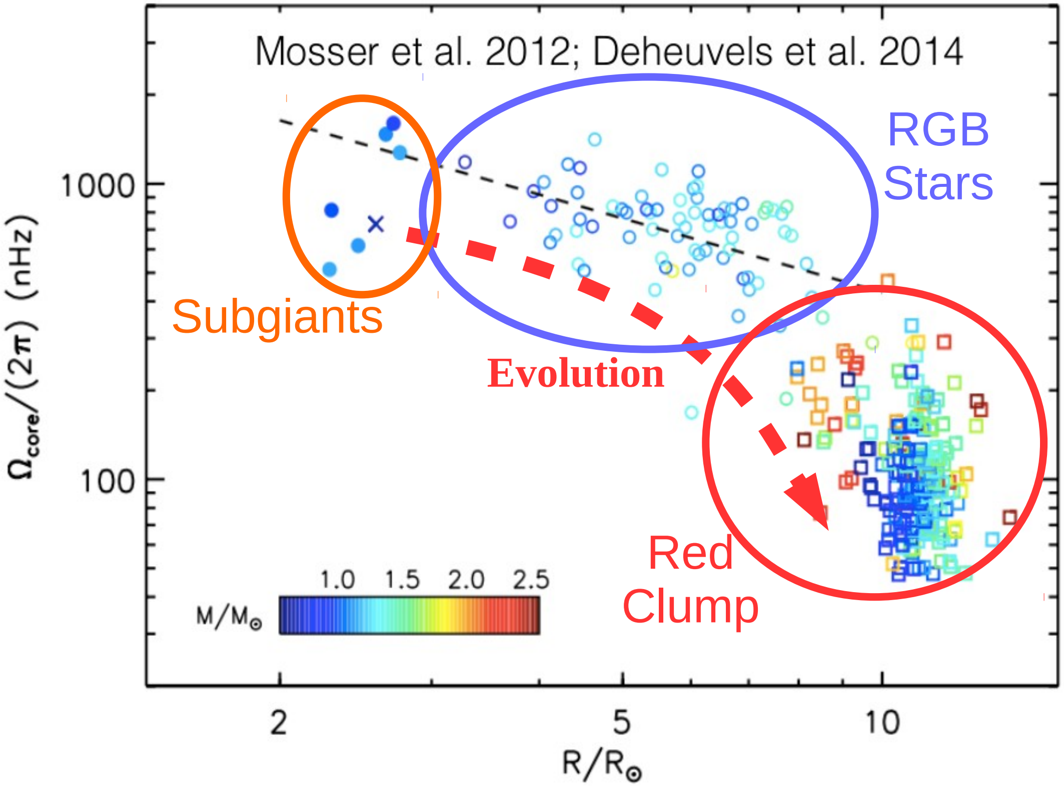

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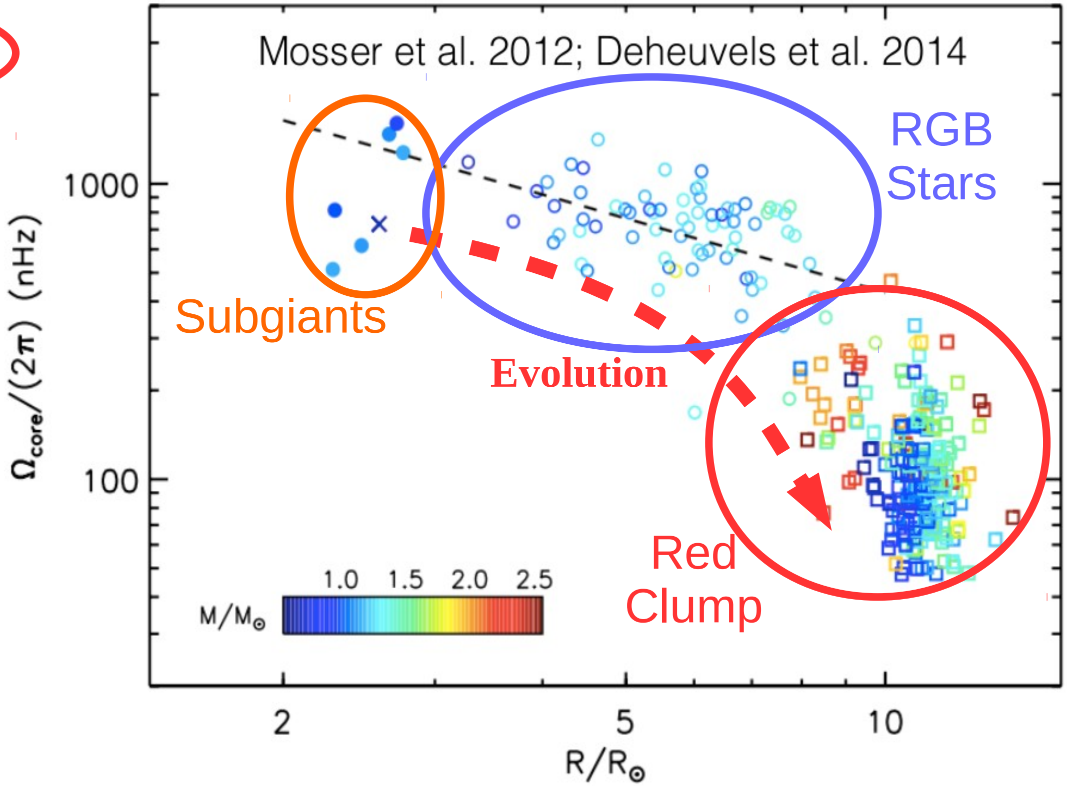
***⇒ involves angular momentum transport from the core to the envelope***



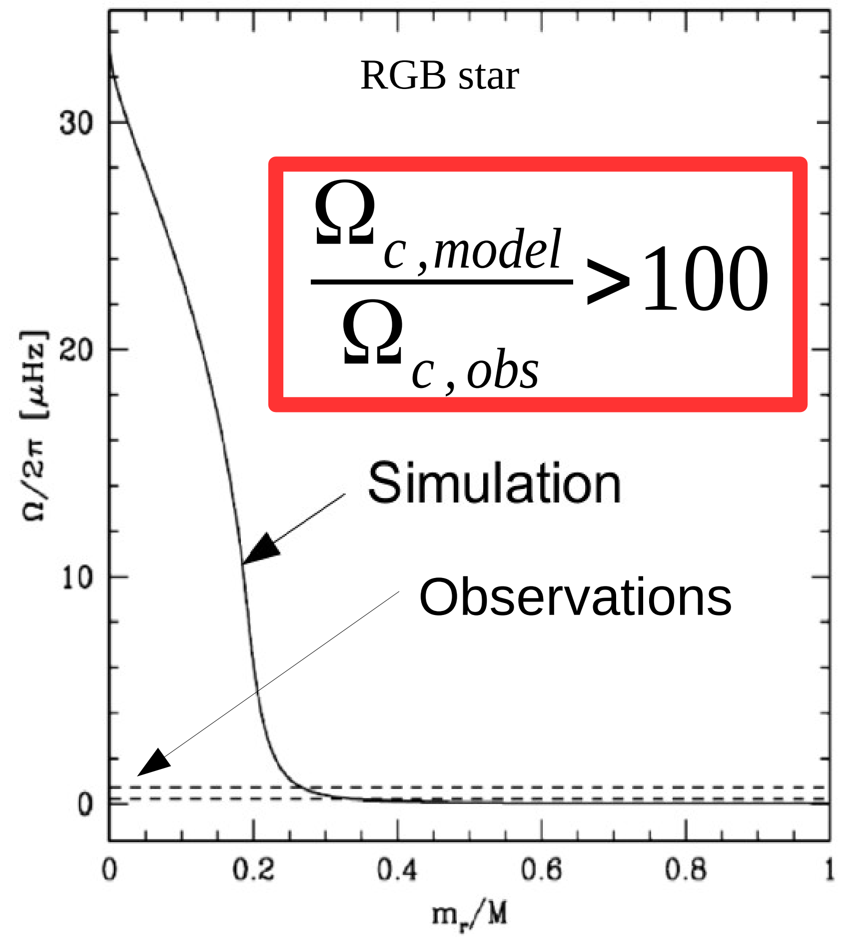
# *Are the observations predicted by stellar models ?*

- **Discrepancies between models and observations:**

- *Tranport processes in models : meridional circulation / shear-induced turbulence*
- *Model predictions 2 orders of magnitude larger than observations (Marques et al., Ceillier et al., 2013 ).*

***⇒ Insufficient to explain observations !***

- *In particular, at the beginning of the subgiant branch where the core starts contracting.*




*Result of a model for a RGB star (Ceillier et al.,2013)*

- **Solutions ?**
- *Fossil magnetic field in the core of stars ?*
- *Internal gravity waves (IGW) ?*

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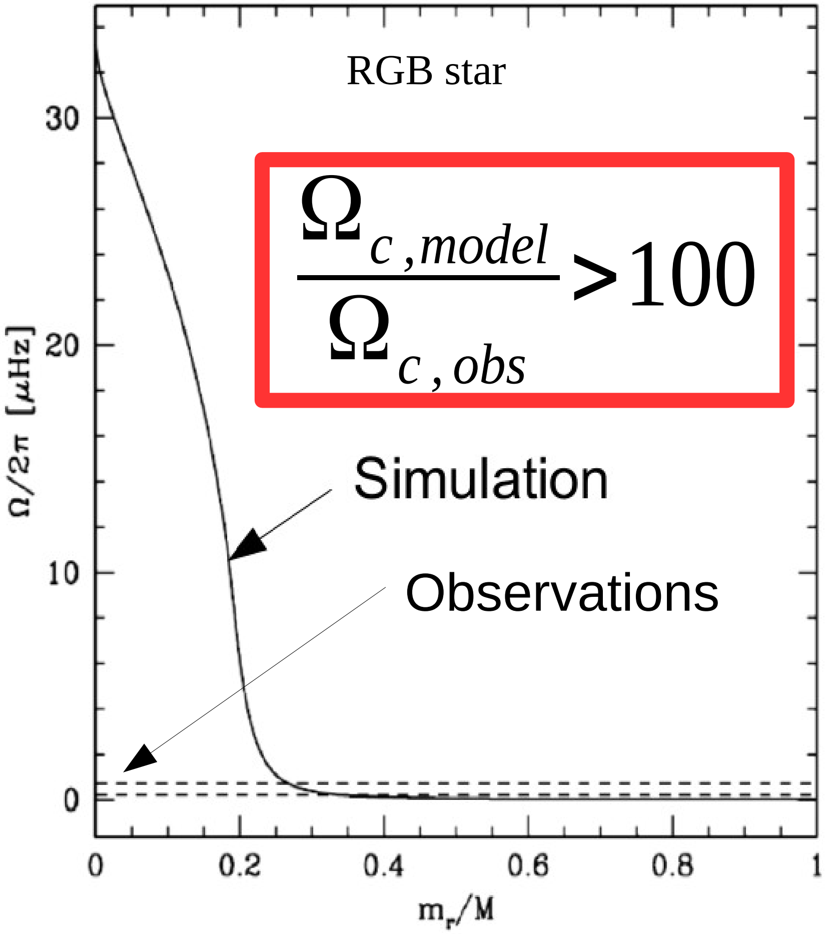
*⇒ Are the IGW able to efficiently slow down the stellar core ?*

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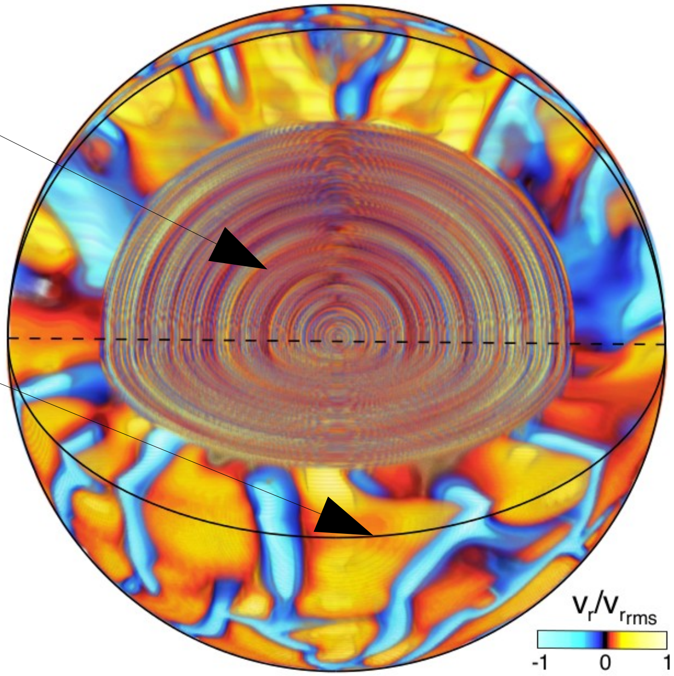
# *Mechanisms of excitation*

- **Internal Gravity Waves (IGW ):**
  - *Restoring force =buoyancy*
  - *Excited in the convective zone*
  - *Propagate in the radiative zone*

- **Efficiency of the transport by IGW**
  - *depends on the driving mechanism*

- **Difficult point** :
  - *Current simulations not realistic enough (Re, Pe numbers…)*

**⇒ *estimate by semianalytical models***

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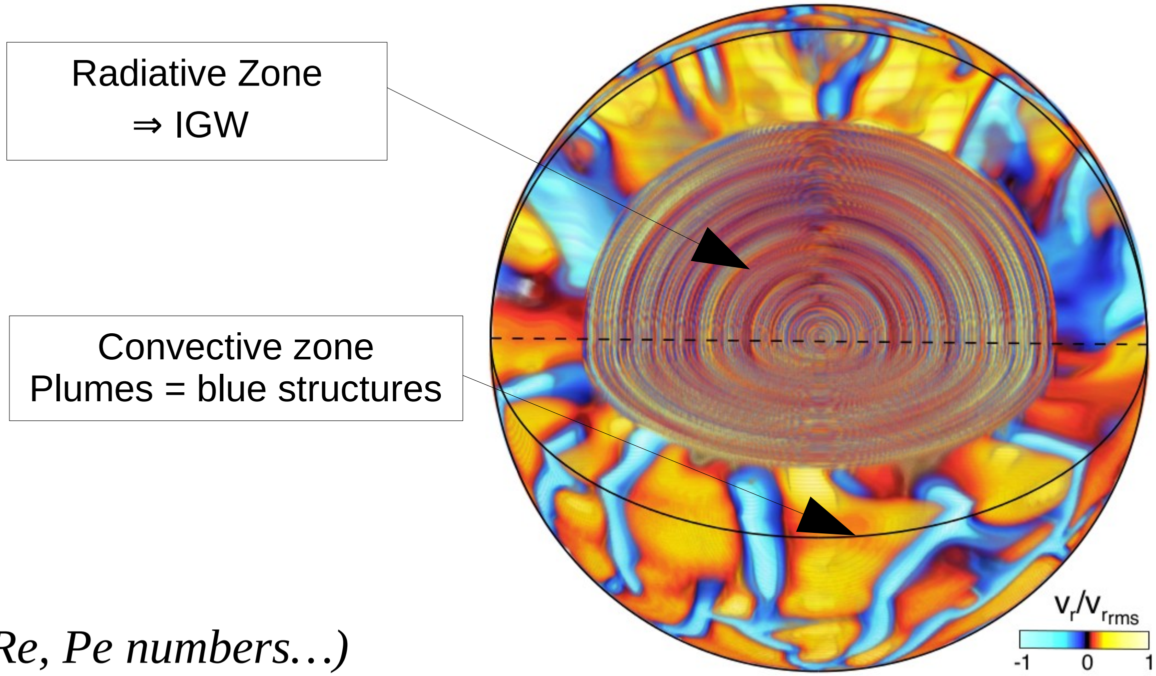


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- **Excitation by turbulent pressure**
  - *Kumar et al. (1999) ⇒ rigid solar rotation (Talon, 2002)*
    *⇒ insufficient for Subgiants and Red Giants (Fuller, 2014)*

- **Excitation by penetration of convective plumes**
  - *observed in geophysics (e.g.Townsend, 1966) and numerical simulations (e.g. Dintrans, 2005)*
  - *But a model is still missing for stellar interior*

⇒ ***Are the plume-induced waves able to play a role?***

# *Model of excitation by penetrative convection*

- **Wave equation + source term** = *pressure exerted by an ensemble of plumes in a thin region just below the base of the convective zone*

$$\frac{\partial \vec{v}}{\partial t} + \frac{1}{\rho} \vec{\nabla} p' - \frac{\rho'}{\rho} \vec{g} = -\frac{1}{\rho} \vec{\nabla} \left( \rho \vec{V}_p \otimes \vec{V}_p \right)$$

*(Pinçon, Belkacem, Goupil, 2016)*

- **Hypothesis** : *incoherent and spatially uniformly distributed plumes*

- **Plumes description in the driving region :**

➜ *Initial velocity and width (Rieutord & Zahn, 1995)*
➜ *Velocity profile (Zahn, 1991)*
➜ *Free parameters : - plume turnover lifetime (~convective time by the MLT)*
*- filling factor A ~ 0.1 (number of plumes)*

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- **Efficiency of the excitation process in the Sun**
  - *Up to 5 times more efficient than turbulent pressure in the Sun*
  - *Total wave energy flux ~ 1 % of the solar flux at the base of the convective zone*

***⇒ Ability to transport angular momentum ?***

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# *Ability to transport angular momentum in the Sun*

- **Estimate of the effect of IGW on a given rotation profile**

- *Local characteristic timescale of the process (advection-diffusion equation)*

$$T_L \sim \frac{J}{\dot{J}}$$

Local characteristic timescale on which IGW modify the rotation

Specific angular momentum $\rho r^2 \Omega$

Divergence of the wave flux

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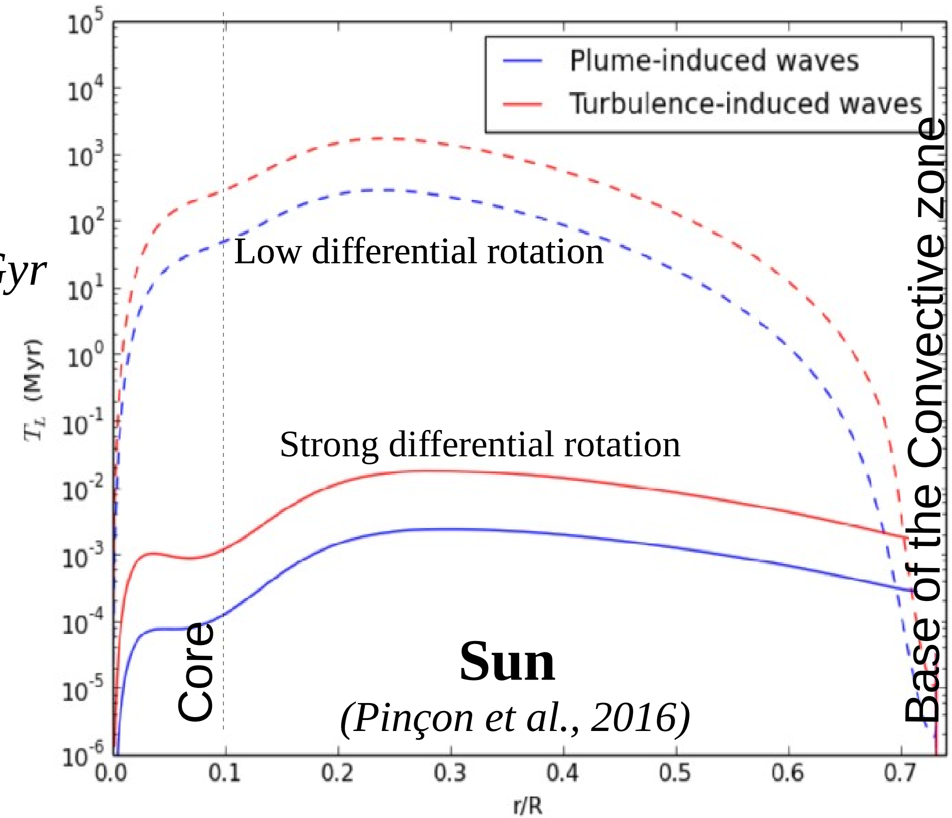
- **In the Sun, plume-induced IGW**

➜ *modify the rotation on timescales~0.1Gyr < $T_{nuc}$~10Gyr*

➜ *more efficient than Kumar et al. (1999)*

➜ *it confirms the result of Talon et al. (2002)*

***⇒ Process efficient in the Sun !***



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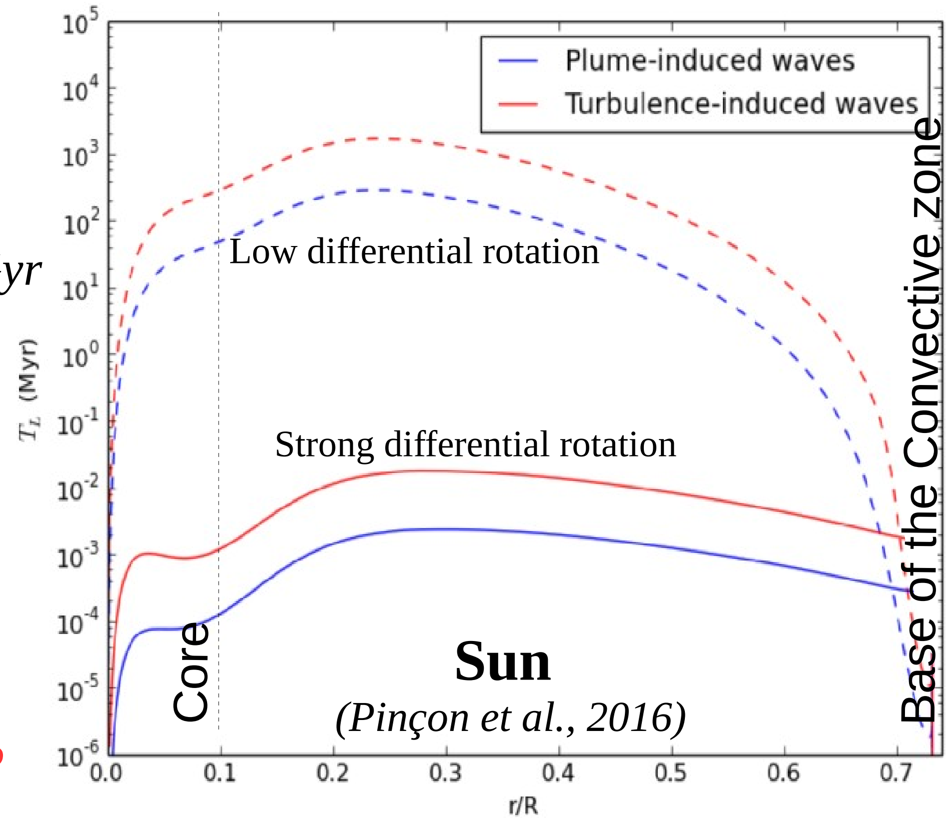


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***⇒ What about Subgiants and Red Giants ?***

# *From the subgiants branch to the ascent of the RGB*

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➡ *IGW cannot reach the core : H-burning shell ~ barrier...*
➡ *...**BUT** as for the Sun, not so simple: depends on the excitation and the differential rotation*

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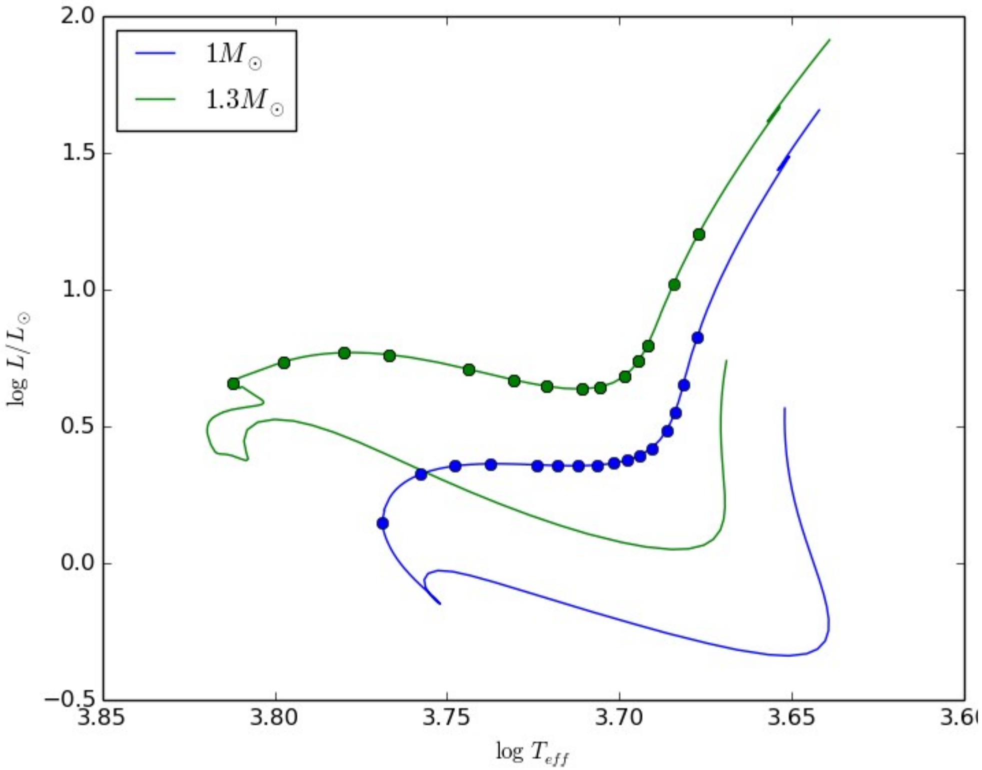

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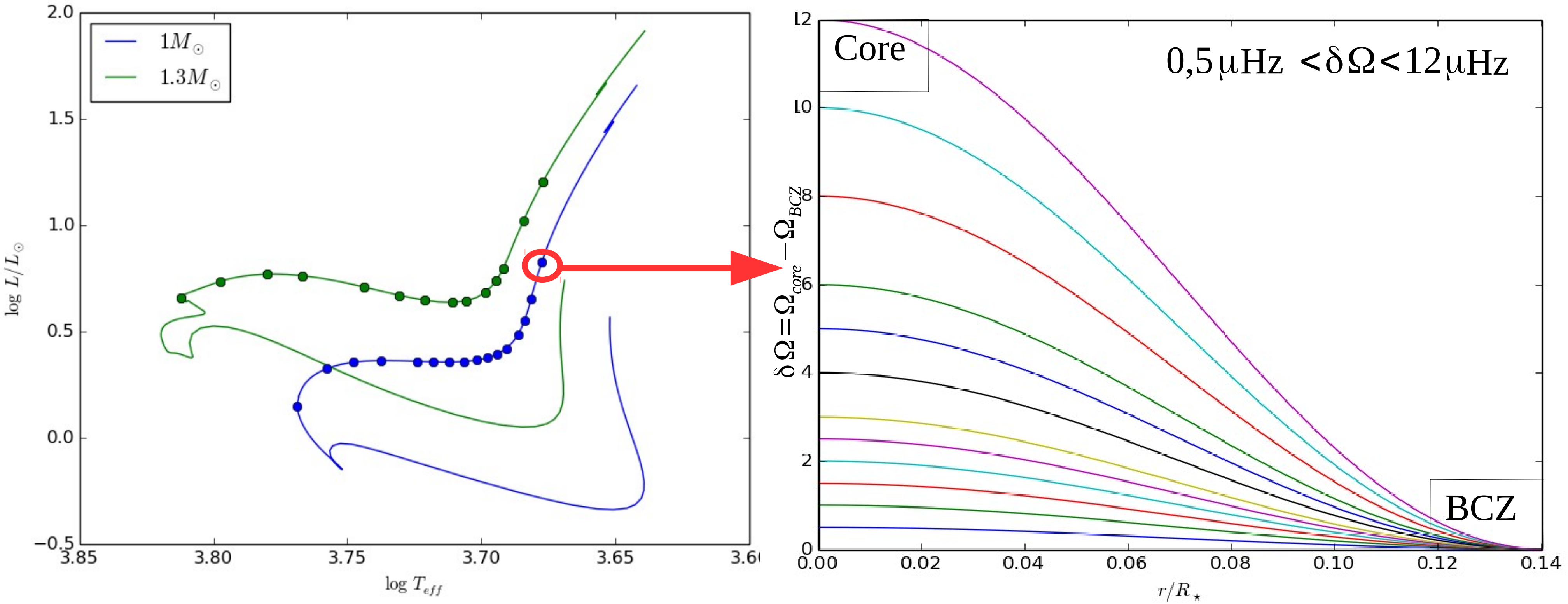
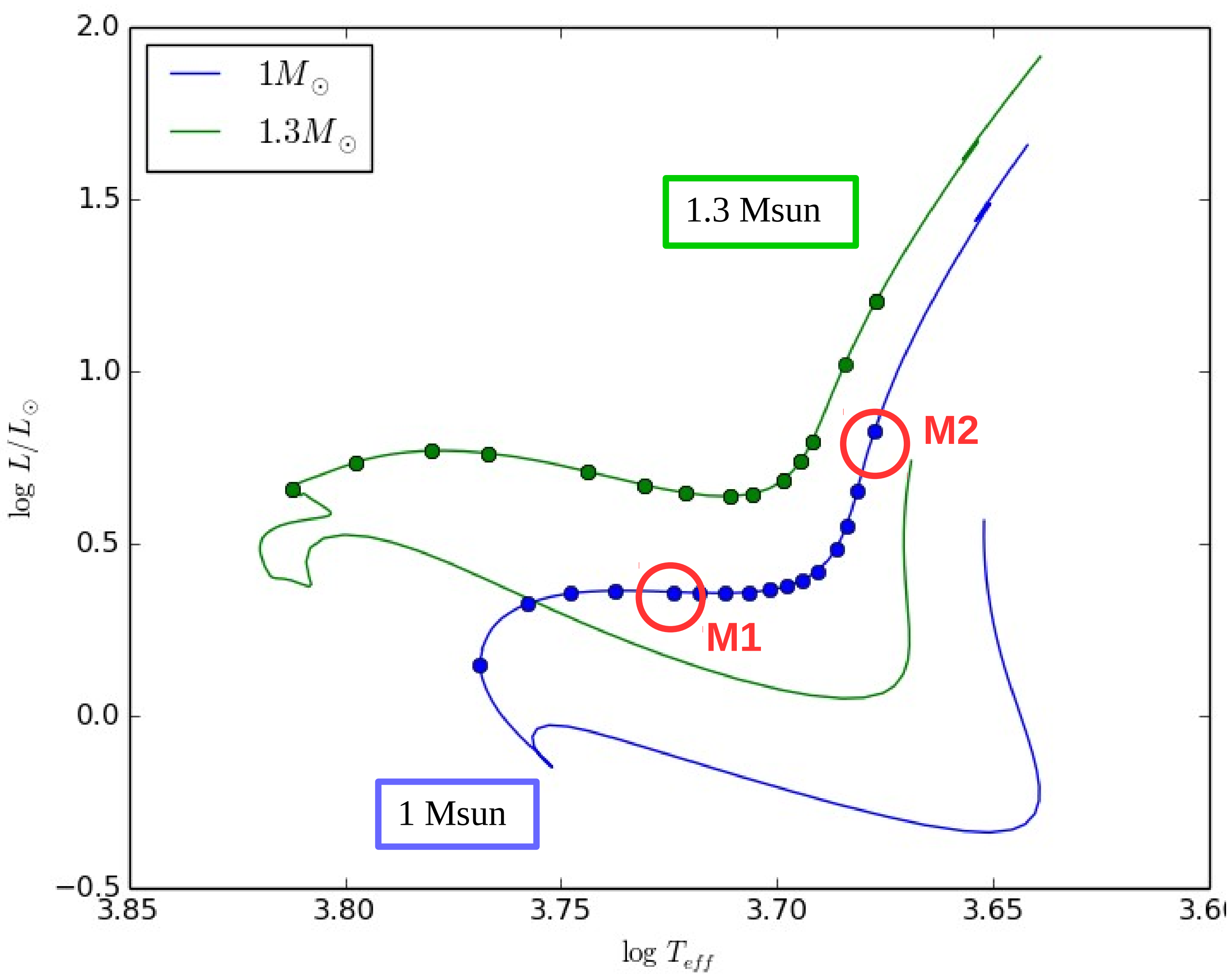
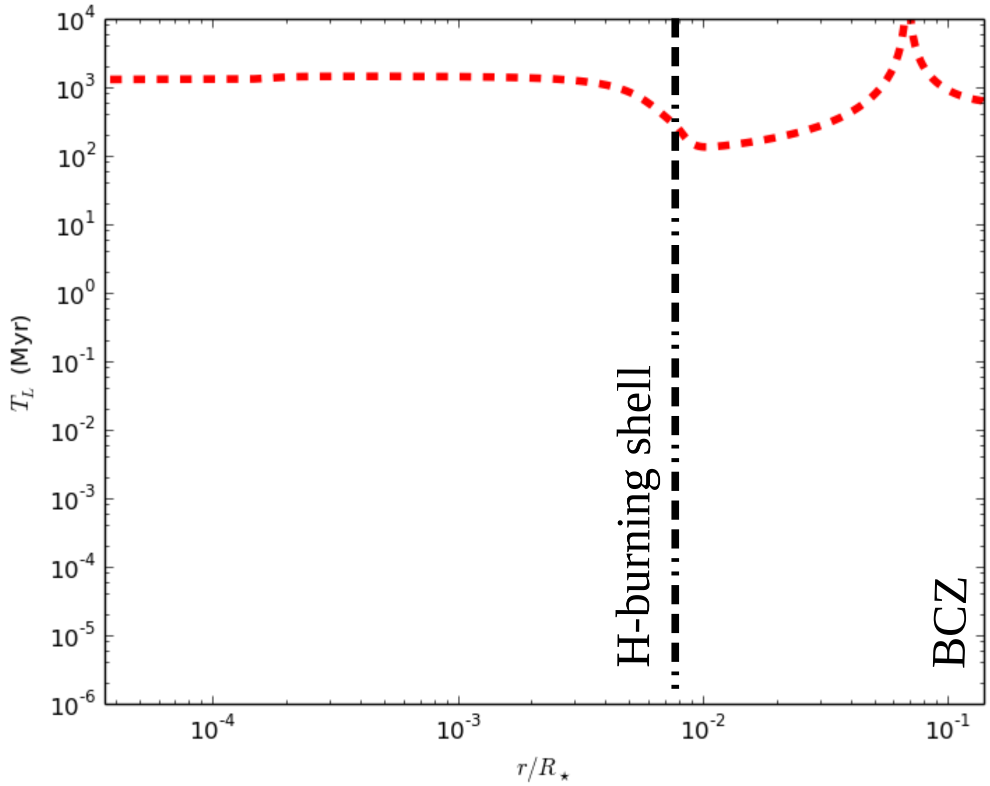
- **Rotation profile for each model :** - assumed varying as cos²
  - different amplitudes for $\delta\Omega = \Omega_{core} - \Omega_{BCZ}$

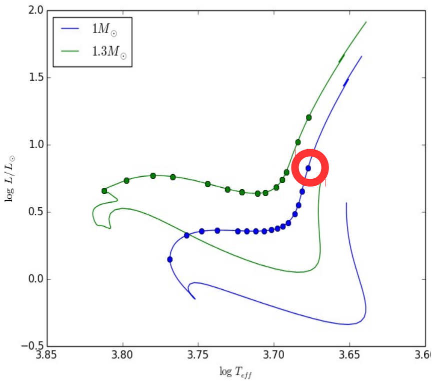


# *2 examples : models M1 and M2*



# *Red Giant (model M2)*




***Characteristic timescale of contraction***

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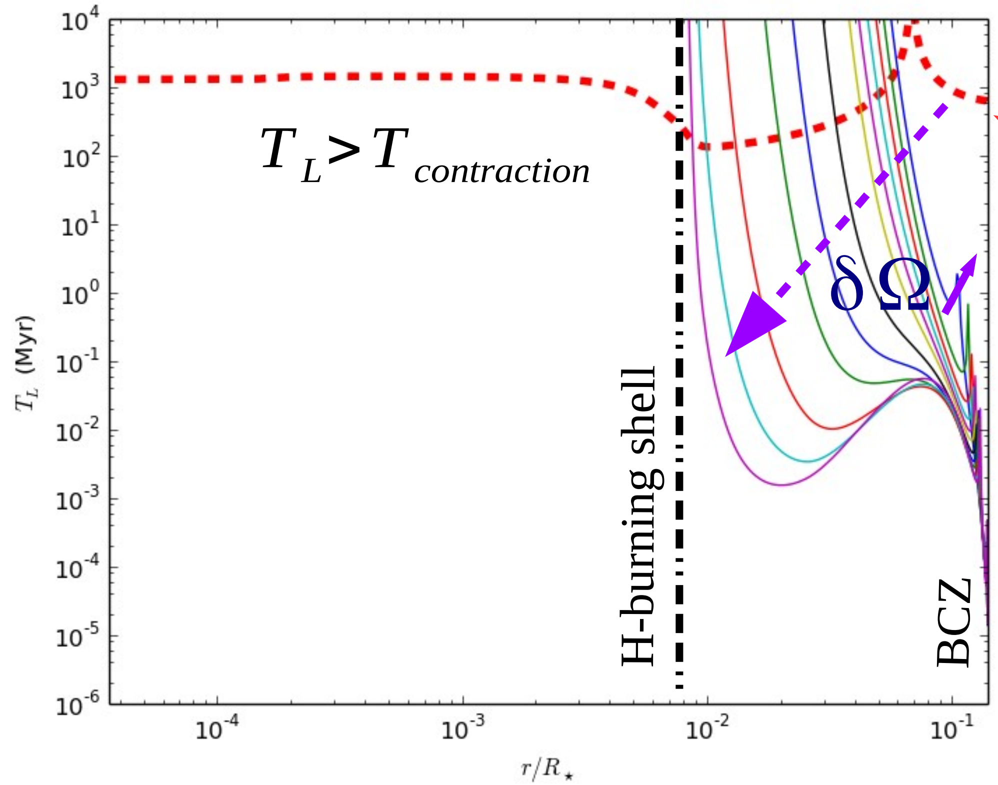


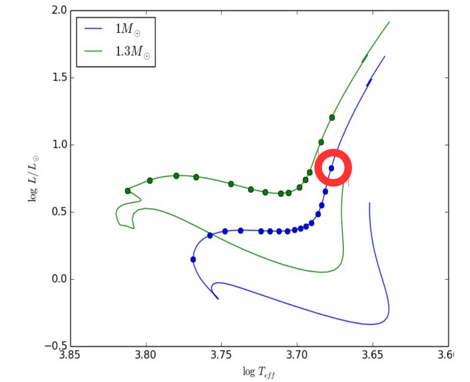


***Characteristic timescale of contraction***

- **$T_L$ increases just above the core and $T_L > T_{contraction}$ in the core for all δΩ < 12 μHz**

- *Waves strongly damped near the H-burning shell for δΩ < 12 μHz*
- *δΩ < 12 μHz in observed Red Giants (Mosser et al., 2012)*

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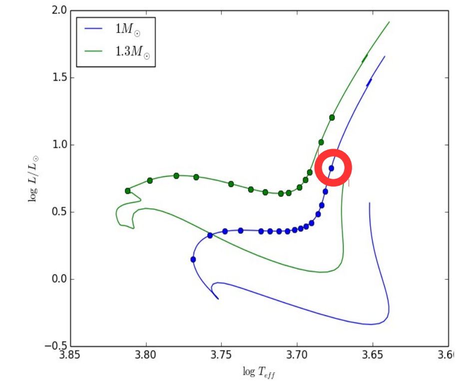


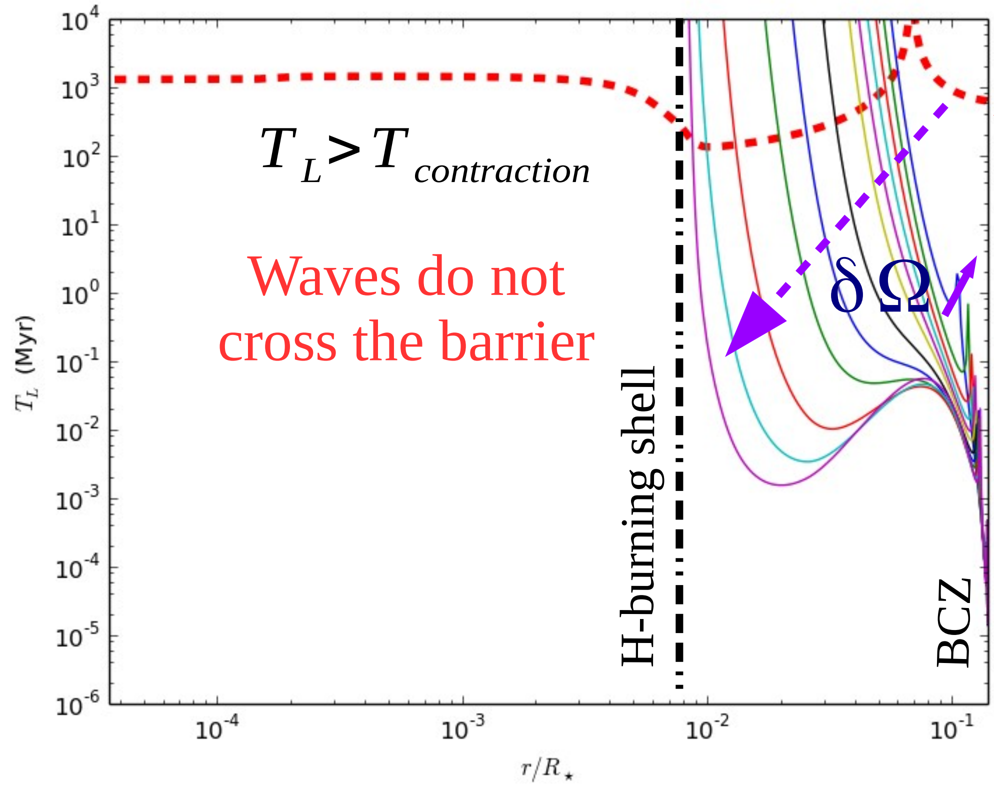


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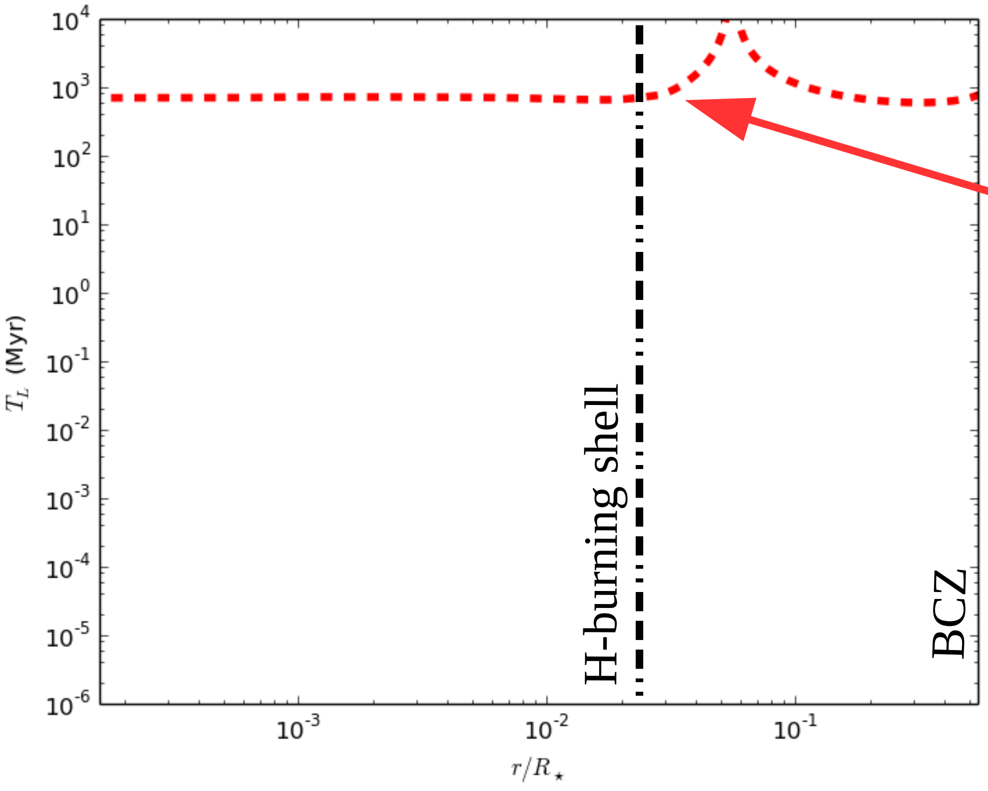
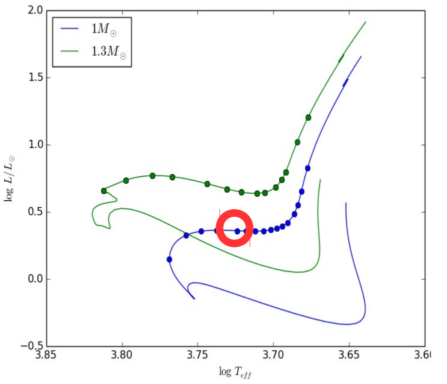
*⇒ For the RGB stars : core contraction prevents IGW from modifying the core rotation*

- **...BUT IGW damped just near the H-burning shell :**

➡ *Interaction with meridional circulation in the core ? ⇒ **need for a complete calculation***

# Subgiant (model M1)

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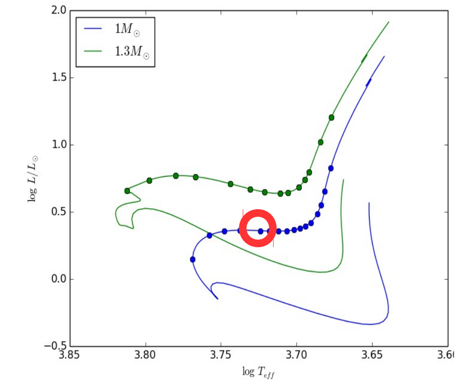
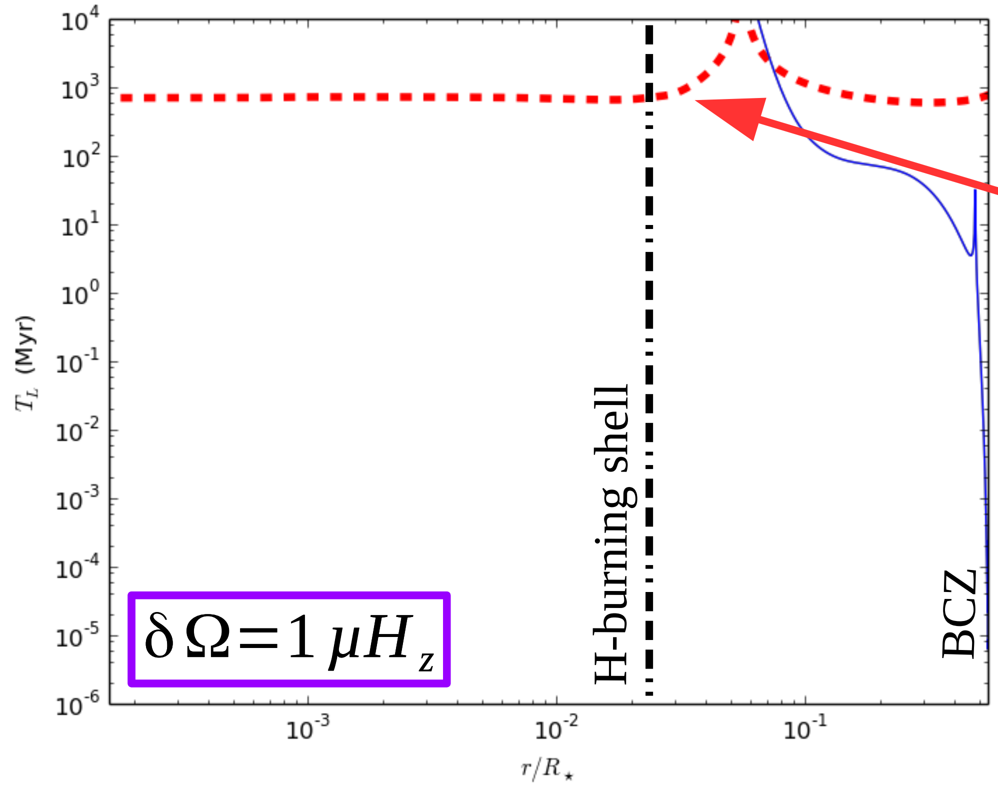



$T_L > T_{contraction}$

**Waves do not cross the barrier**

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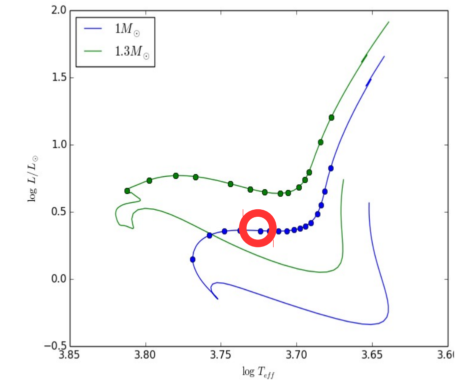


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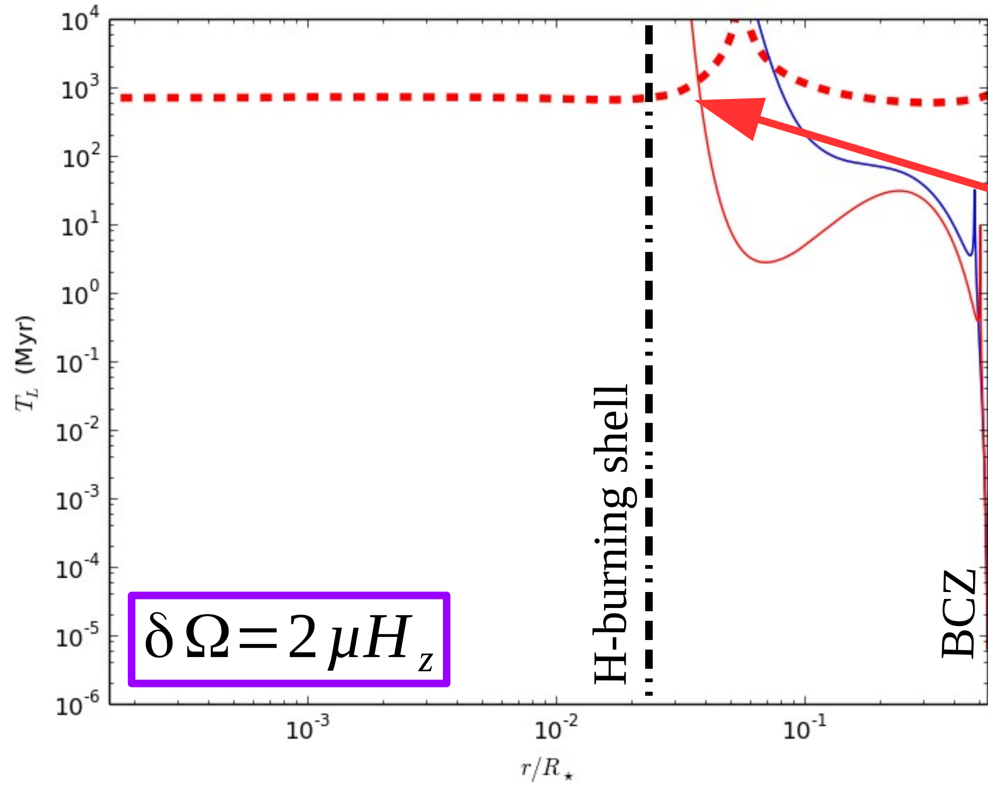


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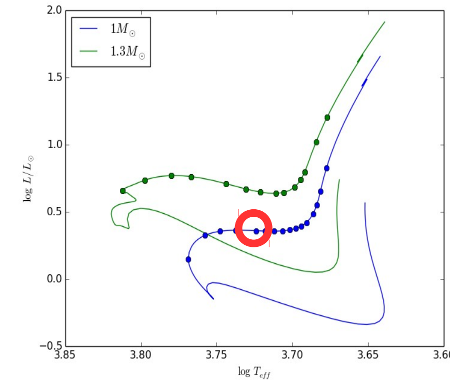


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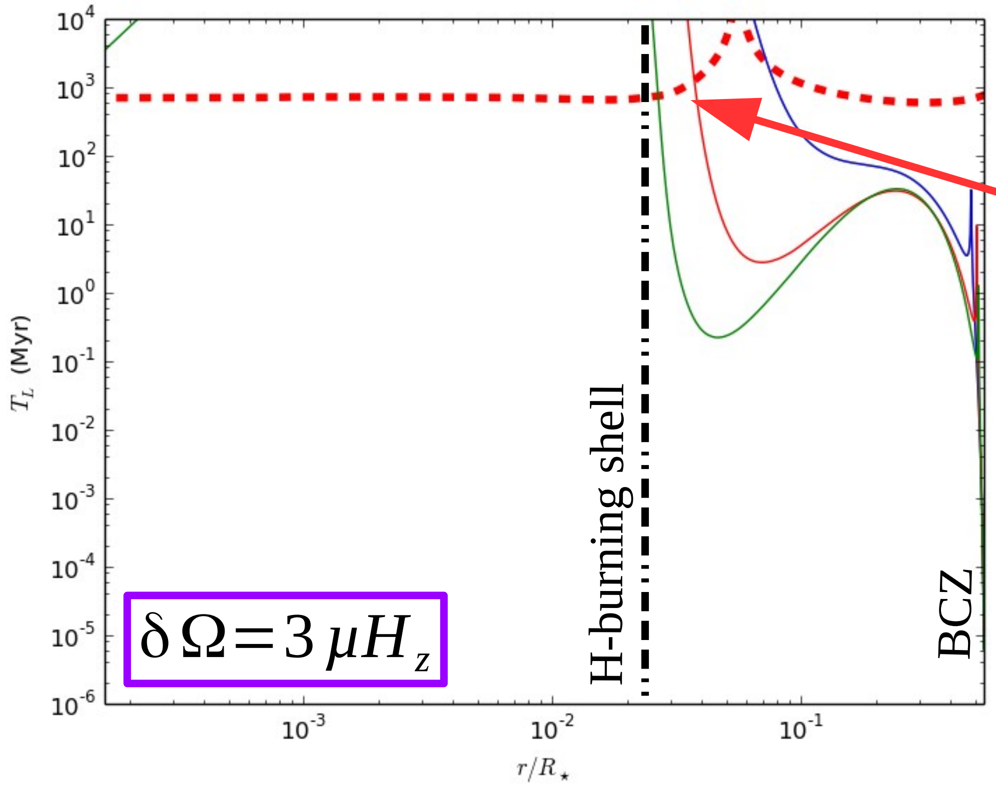


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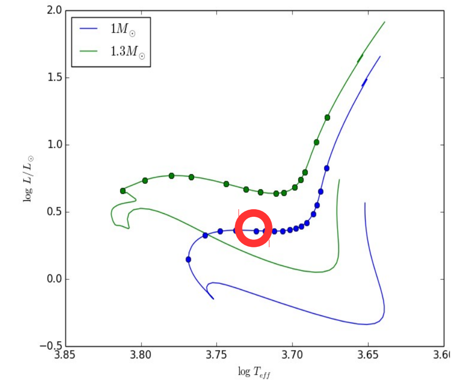


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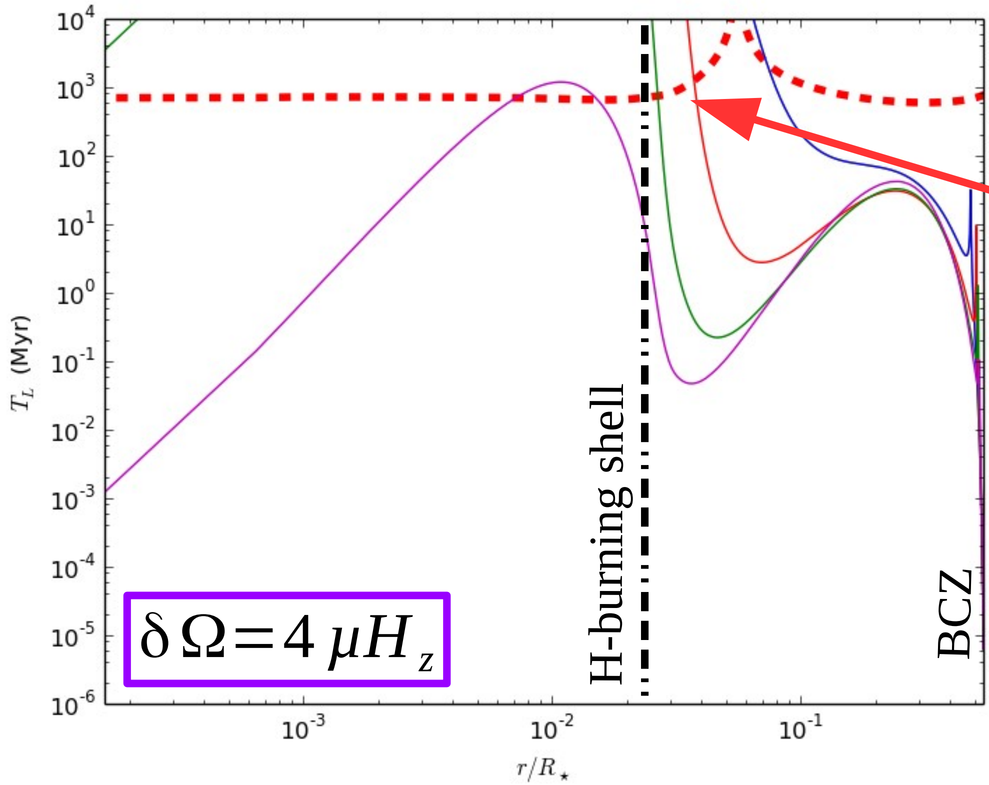


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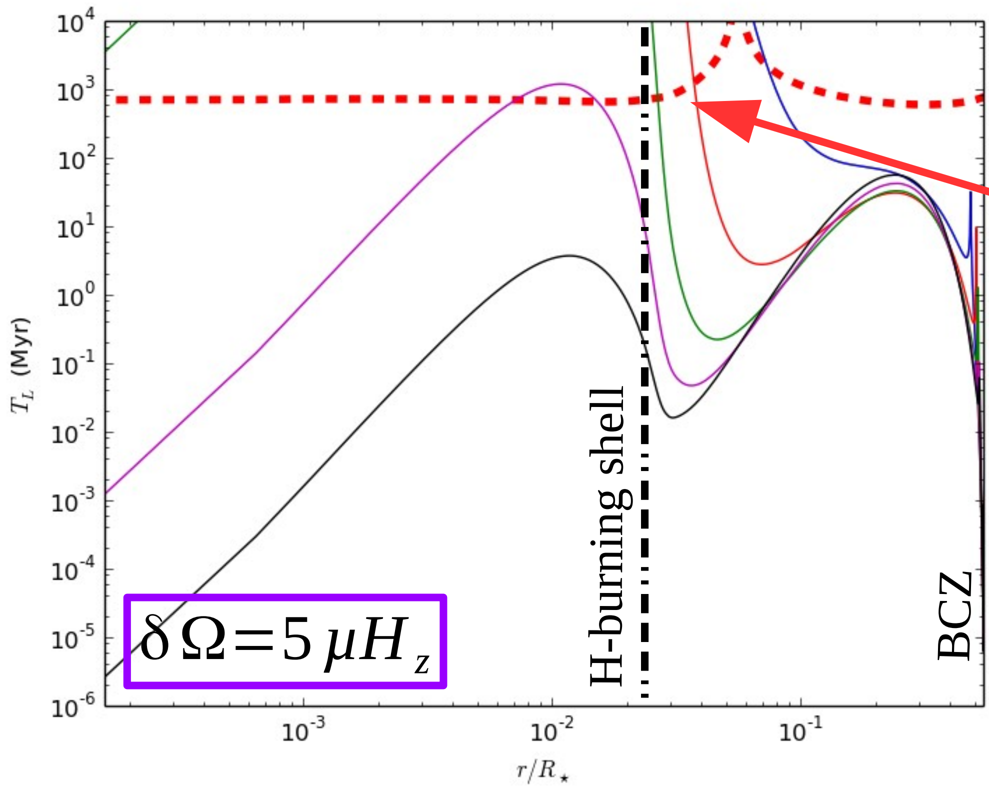


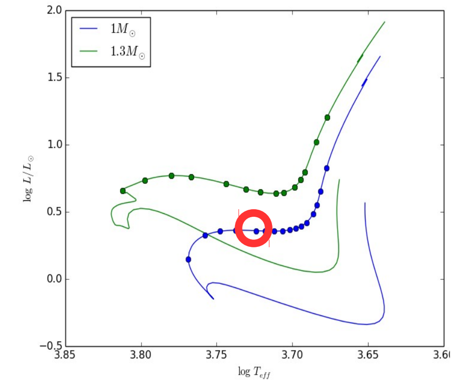


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*(Pinçon et al., 2016)*

- **Low differential rotation** ⇒ *Strong damping near the H-burning shell*
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- **Progressive increase of δΩ** ⇒ *above* $\delta\Omega > 4\,\mu Hz$*, IGW cross the barrier*
  ⇒ *cf difference between prograde and retrograde waves* ↗ *with δΩ*
  ⇒ *threshold value typical for subgiant stars (Deheuvels,2014)*

***=> It exists a threshold value for the differential rotation above which IGW can modify the core rotation !***

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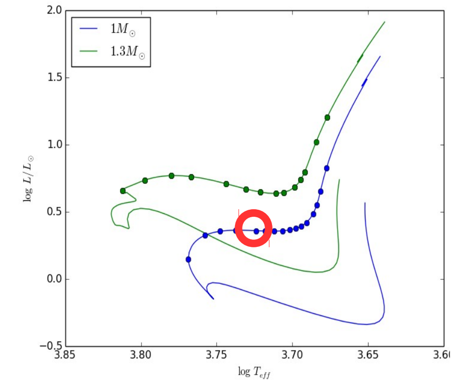


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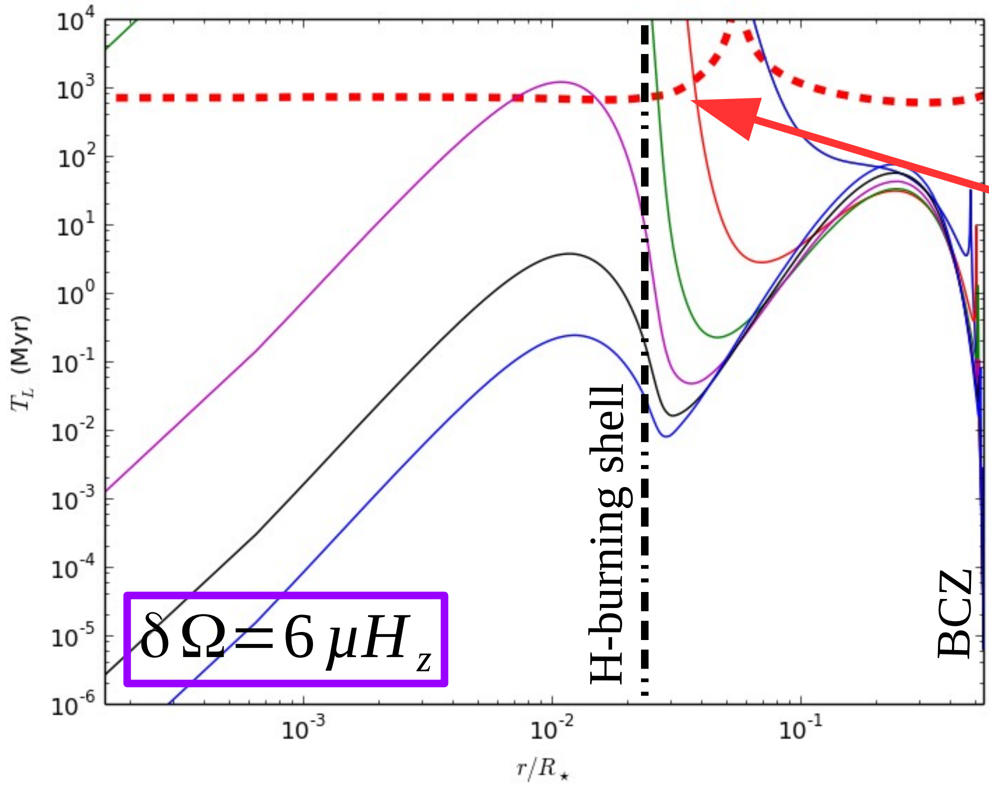


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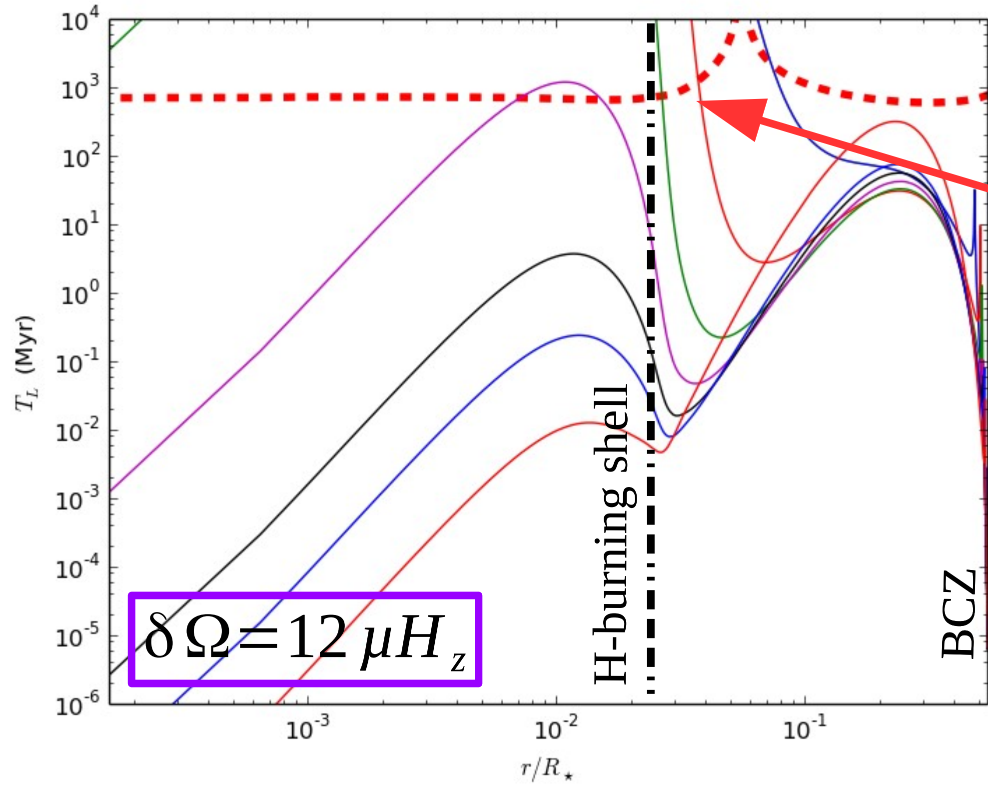


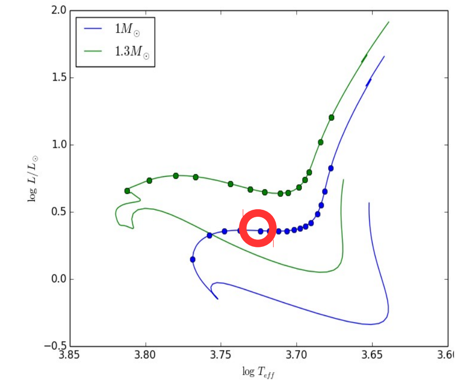


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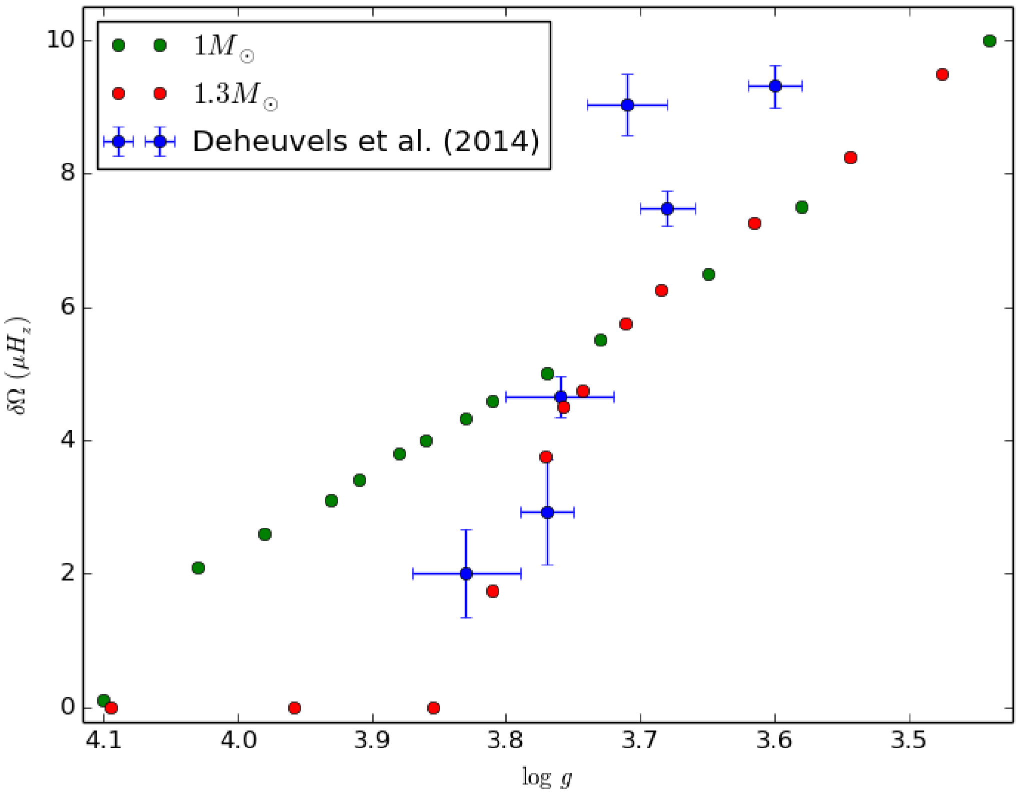
# Comparison with observations

- **Comparison :** threshold value from models VS observations in subgiants
  1Msun<M<1.5Msun (Deheuvels,2014)




*(Pinçon et al., 2016)*

- **Threshold value = $\delta\Omega_{threshold}$**

➜ *Same order of magnitude as observations*
➜ *Decreases with log g as observations*
➜ *Difference of slope : mass effect , threshold selection criterion, observed $\delta\Omega$...*

- **Possible interpretation**

➜ Core contracts
➜ $\Omega c \uparrow$
➜ $\delta\Omega > \delta\Omega_{threshold}$
➜ IGW reach the core
➜ $\Omega c \downarrow$
➜ $\delta\Omega < \delta\Omega_{threshold}$
➜ IGW can not cross the barrier

$\delta\Omega \sim \delta\Omega_{threshold}$

***⇒ Regulating effect of IGW***

# *Concluding remarks*

- **Extraction of angular momentum**:

  - *excitation model of penetrative convection ⇒ take into account the effect of plume-induced IGW on rotation*

  - *on the RGB : ⇒ IGW can not reach the core (cf Fuller et al., 2014)*
    *⇒ another process should operate (mixed-modes, Belkacem et al., 2015, etc...)*

  - *on the subgiant branch : ⇒ IGW generated by penetrative convection are a good candidate to brake the core rotation*
    *⇒ regulating effect agreeing with the seismic observations*
    *⇒ work in progress*

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- **Extraction of angular momentum**:

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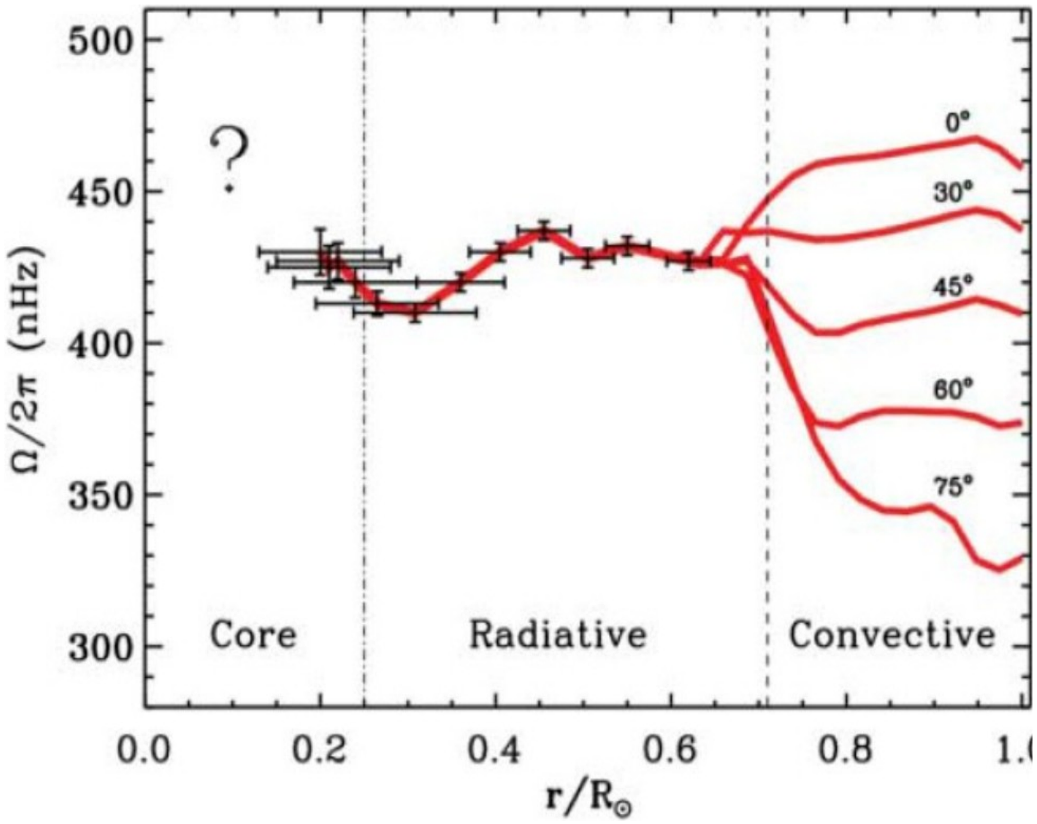
- **Next step :**

  - *role of IGW to be confirmed numerically (for example, on a static stellar model) and ...*

  - **...** *to be implemented in a stellar evolution code with the interaction with other processes (in CESTAM with the collaboration of J. Marques, IAS)*

***Thank you for your attention !***

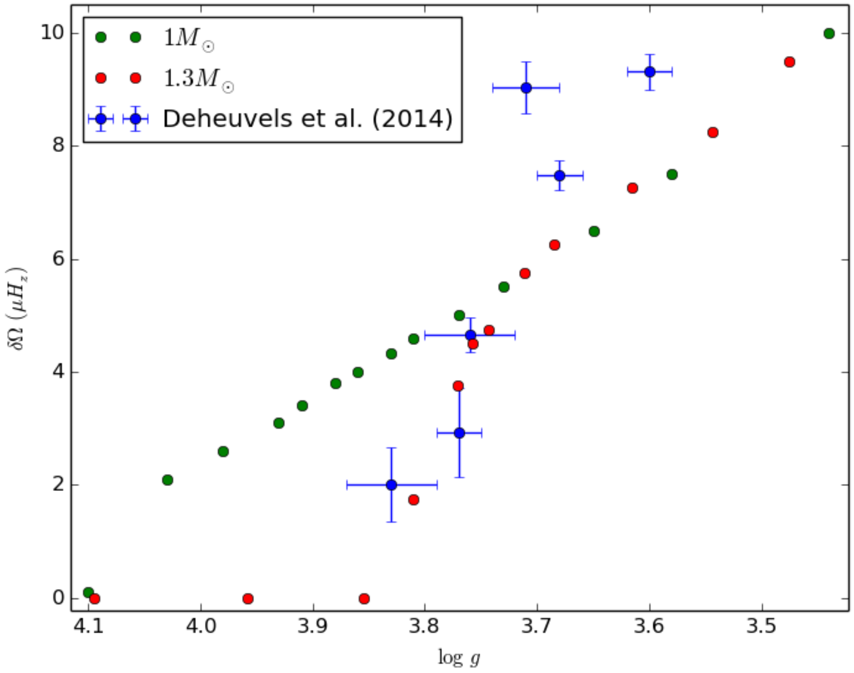
# *Internal rotation profile of the Sun*



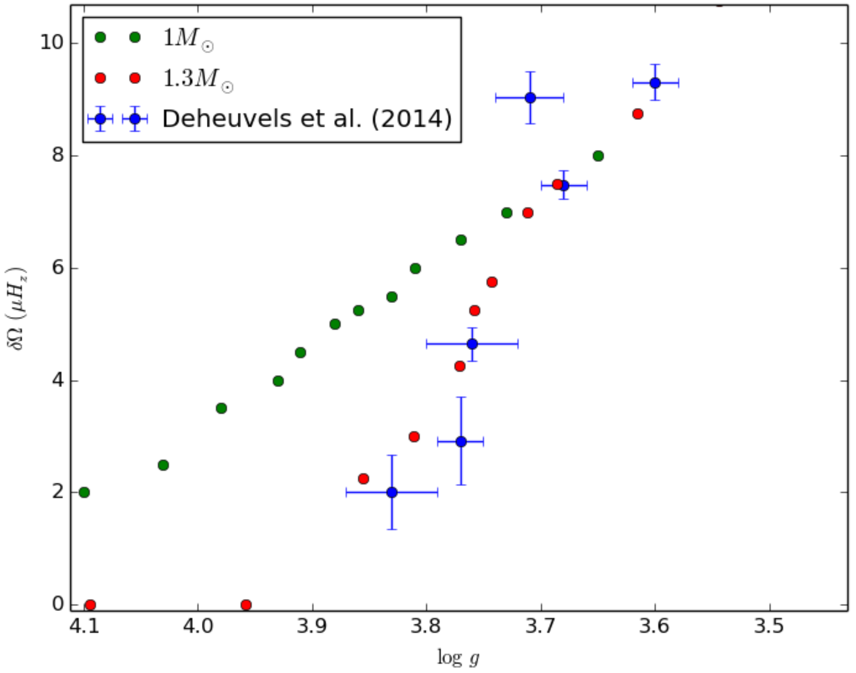

*Rotation frequency of the Sun according to data from GOLF et MDI on the SoHO satellite (Rafael A. Garcia, 2007)*

# Effect of the threshold selection criterion

**Critère 1**




**Critère 2**




***Change of criterion ~ shift in the threshold value for the differential rotation***