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

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

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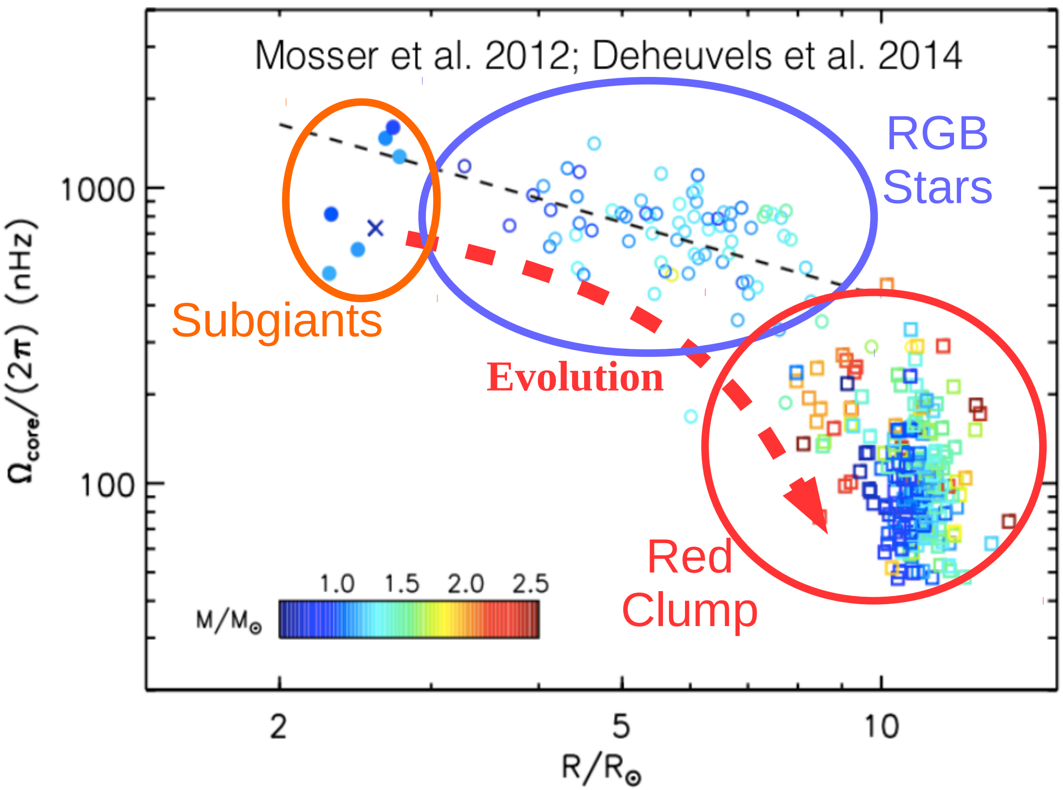
- **In agreement with low rotation rates observed in white dwarfs (Kawaler et al., 1999).**



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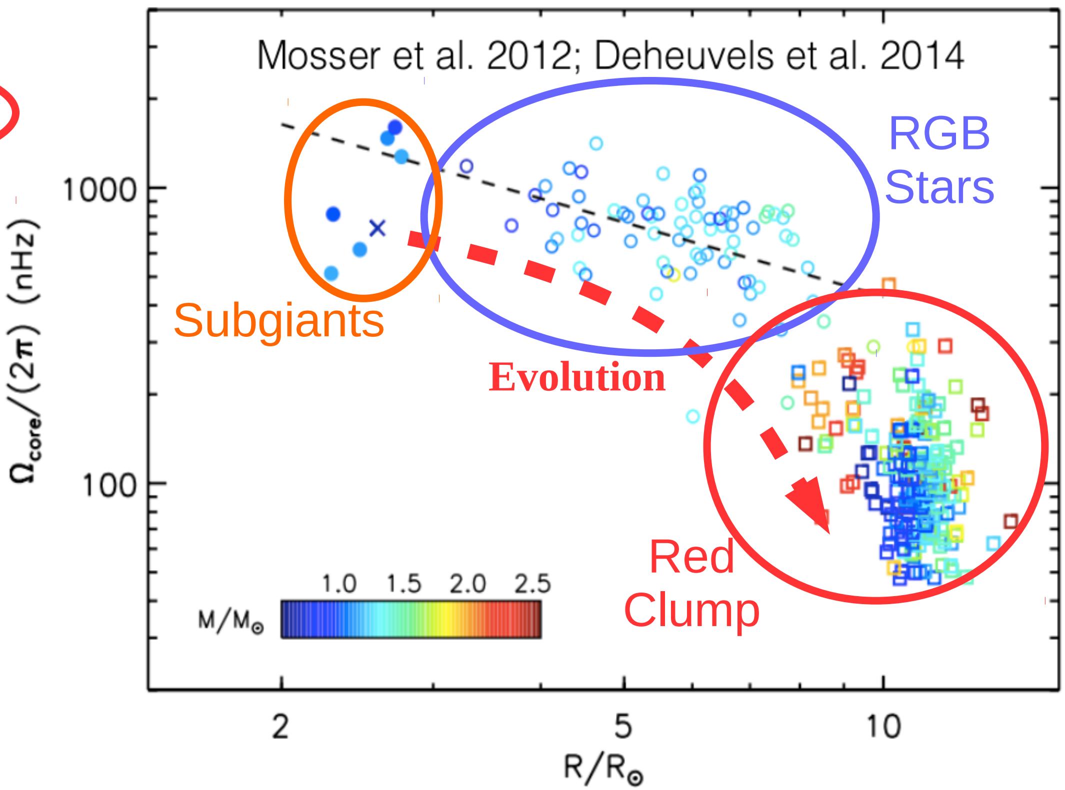

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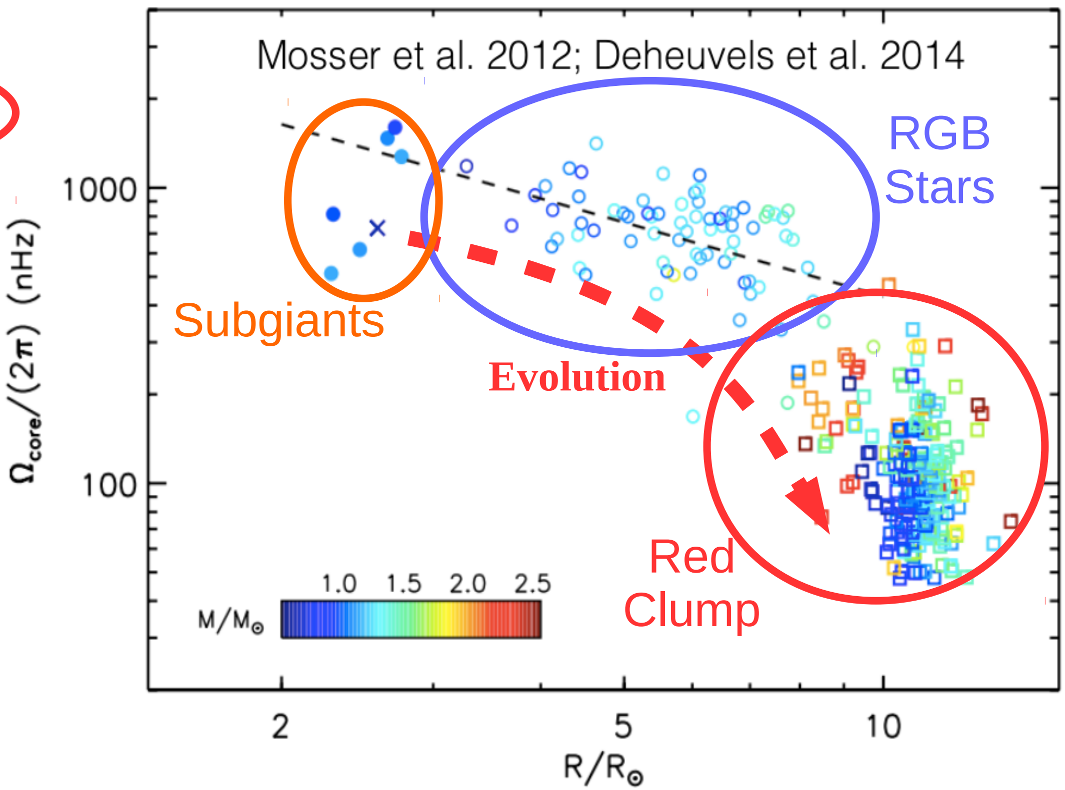

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⇒ Problem : current stellar models do not reproduce the observations…

Internal gravity waves

- **Internal Gravity Waves (IGW):**

  - *Restoring force =buoyancy*
  - *Excited in the convective zone*
  - *Propagate in the radiative zone*

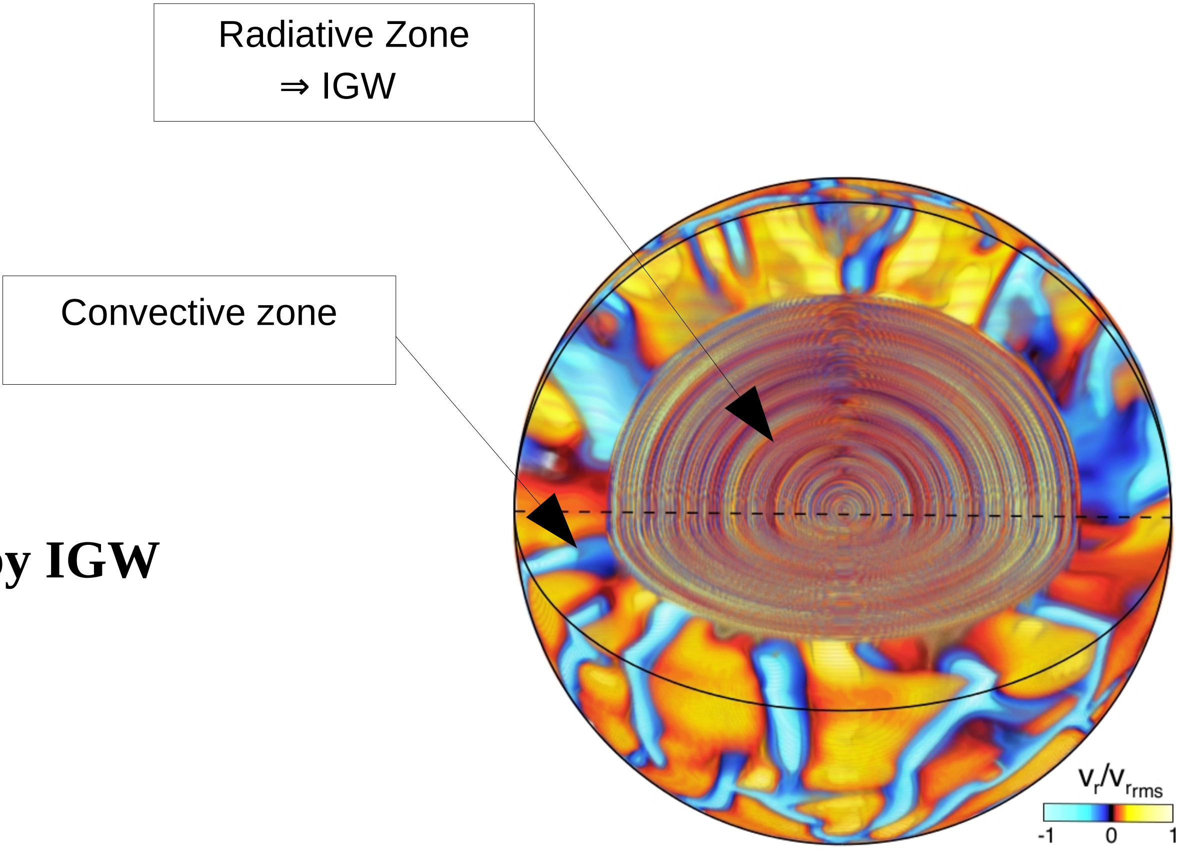
- **Efficiency of the transport of AM by IGW**

  - *depends on the driving mechanism*

- **Difficult point :**

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

⇒ Estimate by semianalytical models



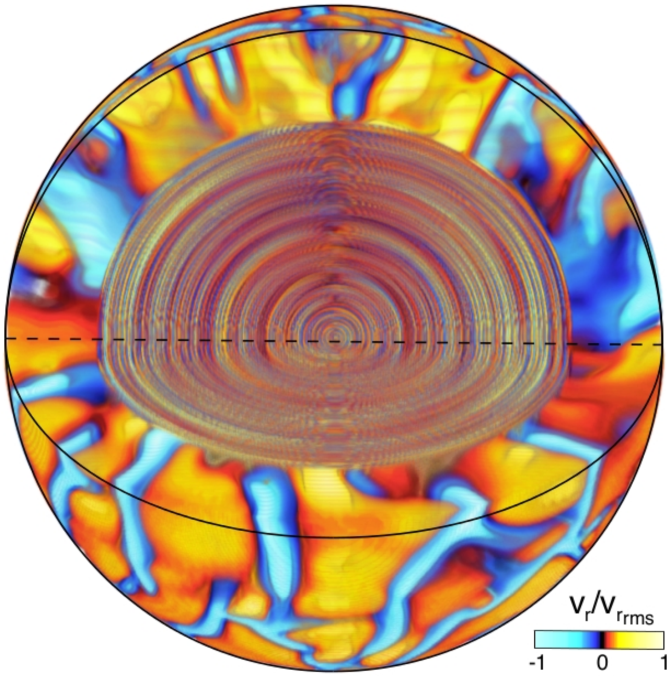
3-D Simulations of the Sun (Alvan et al., 2014)

Excitation mechanisms

- **2 kinds of excitation mechanisms**

- **Excitation by turbulent pressure in the convective bulk**

➨ *Kumar et al. (1999) ⇒ rigid solar rotation (Talon, 2002)*
⇒ insufficient for Red Giants (Fuller, 2014)



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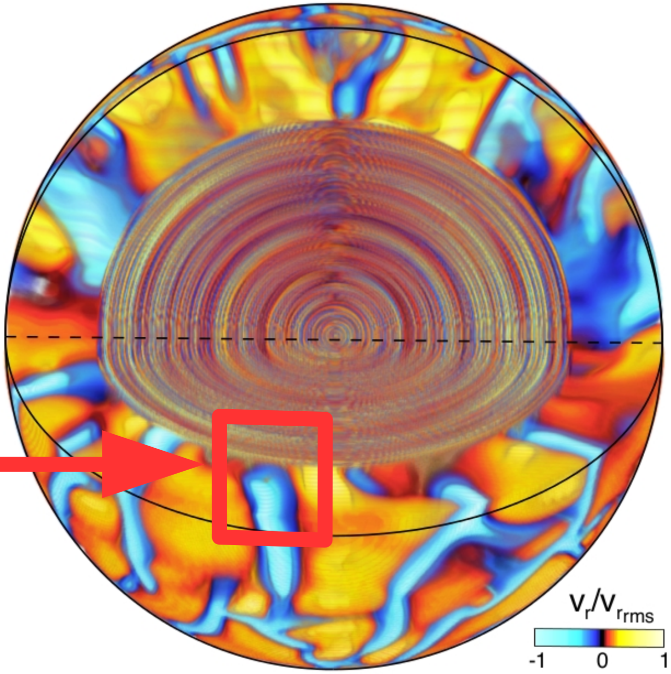
- **Excitation by penetration of convective plumes**

➡ *observed in geophysics (e.g.Townsend, 1966) and numerical simulations (e.g. Dintrans, 2005)*
➡ *But a model is still missing for stellar interior*



3-D Simulations of the Sun (Alvan et al., 2014)

⇒ Are the plume-induced waves able to play a role and to be included in stellar models ?

Excitation model by penetrative convection

- **Wave equation + source term** = *pressure exerted by an ensemble of incoherent and spatially uniformly distributed plumes at the base of the convective zone*

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

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

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

(Pinçon, Belkacem, Goupil, 2016a)

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- **Excitation process in the Sun** *(Pinçon, Belkacem, Goupil, 2016a)*

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

⇒ Ability to transport angular momentum ?

Ability to transport angular momentum in the Sun

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

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

Local characteristic timescale on which IGW modify the rotation

Density of angular momentum $\rho r^2 \Omega$

Divergence of the radiatively damped wave flux

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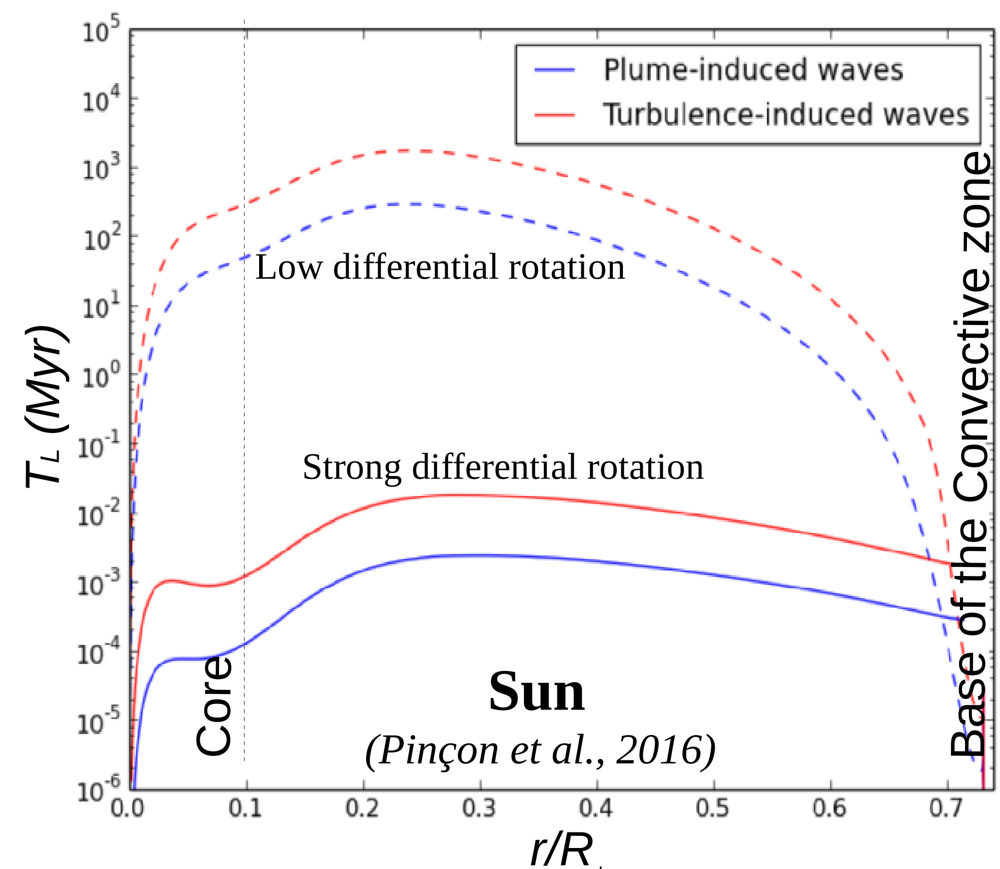

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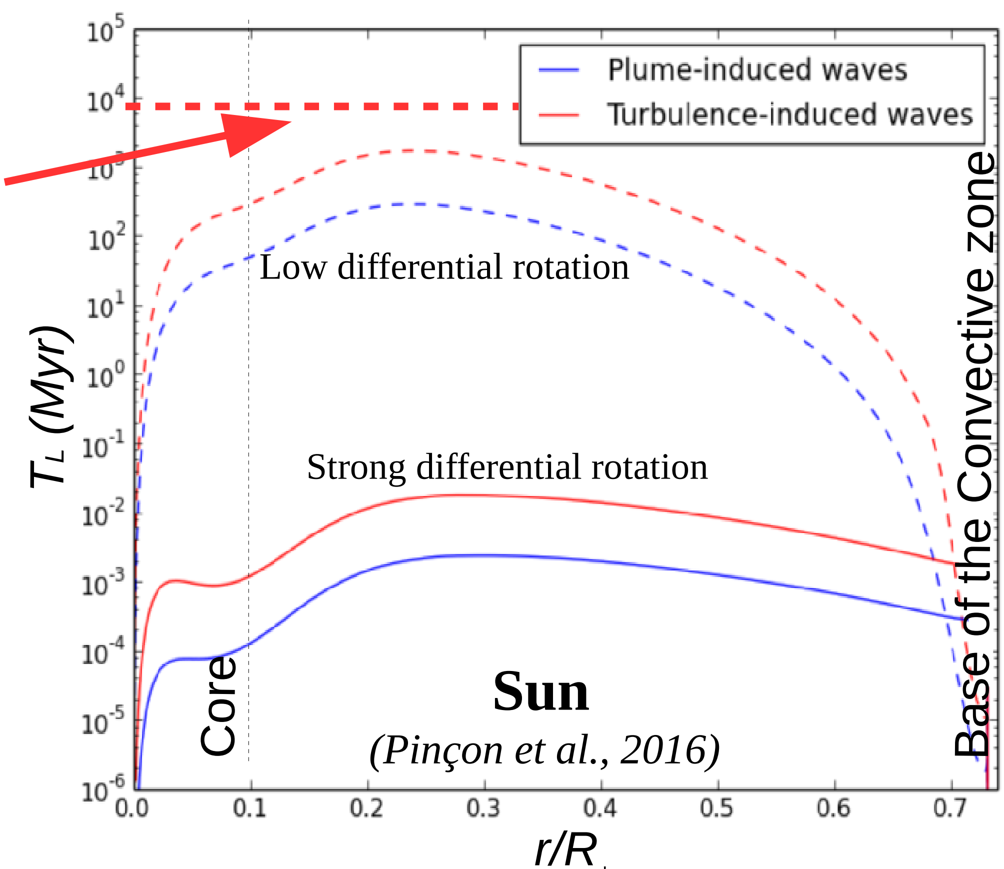
➡ *modify the rotation on timescales $T_L < T_{nuc}$~10Gyr*

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

➡ *the higher the differential rotation, the more efficient the transport*



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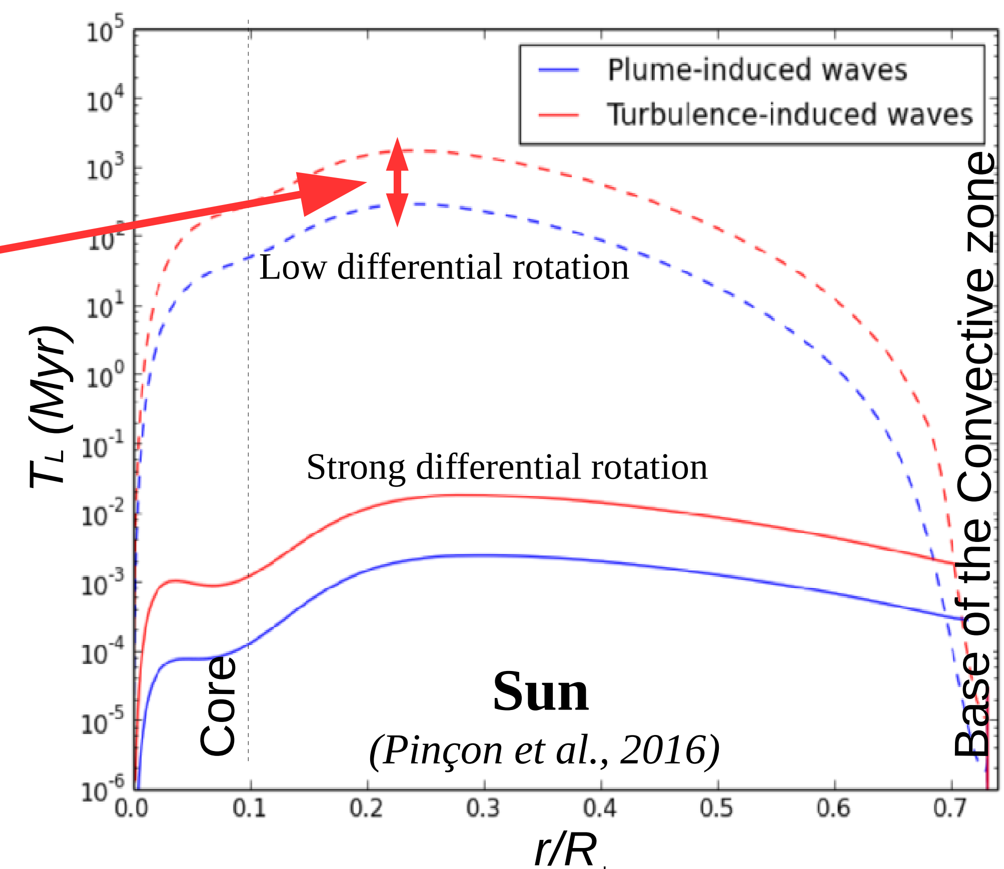

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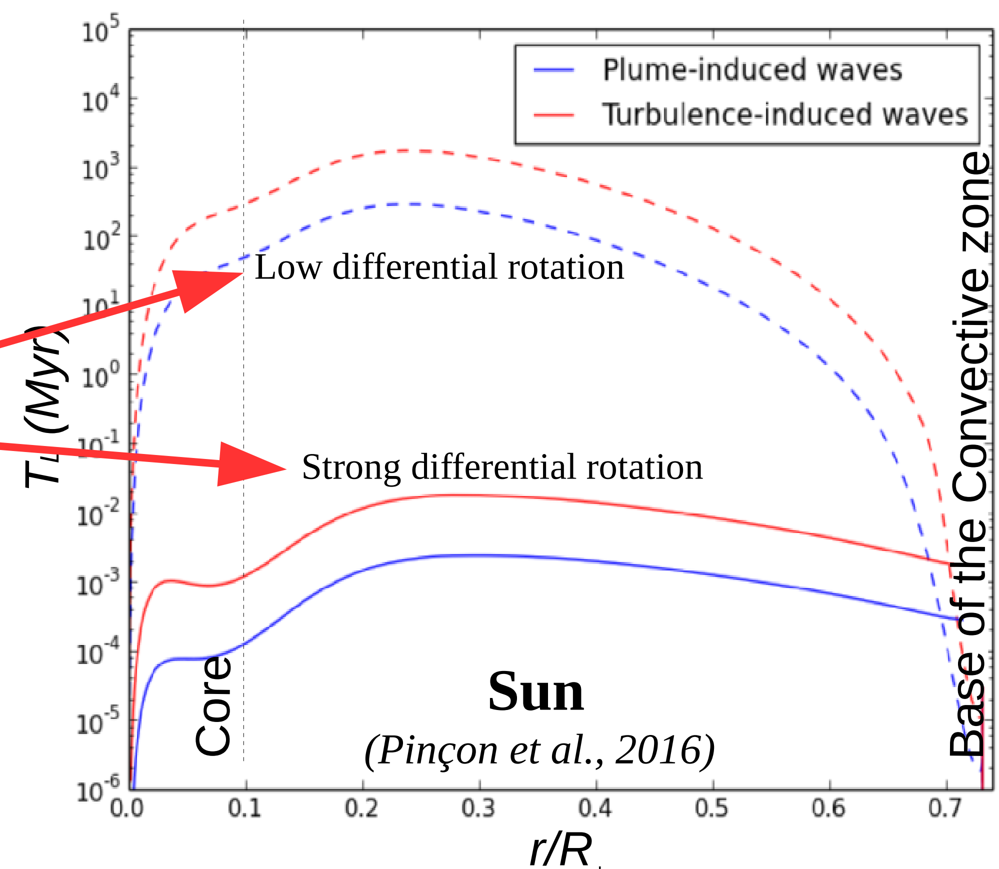

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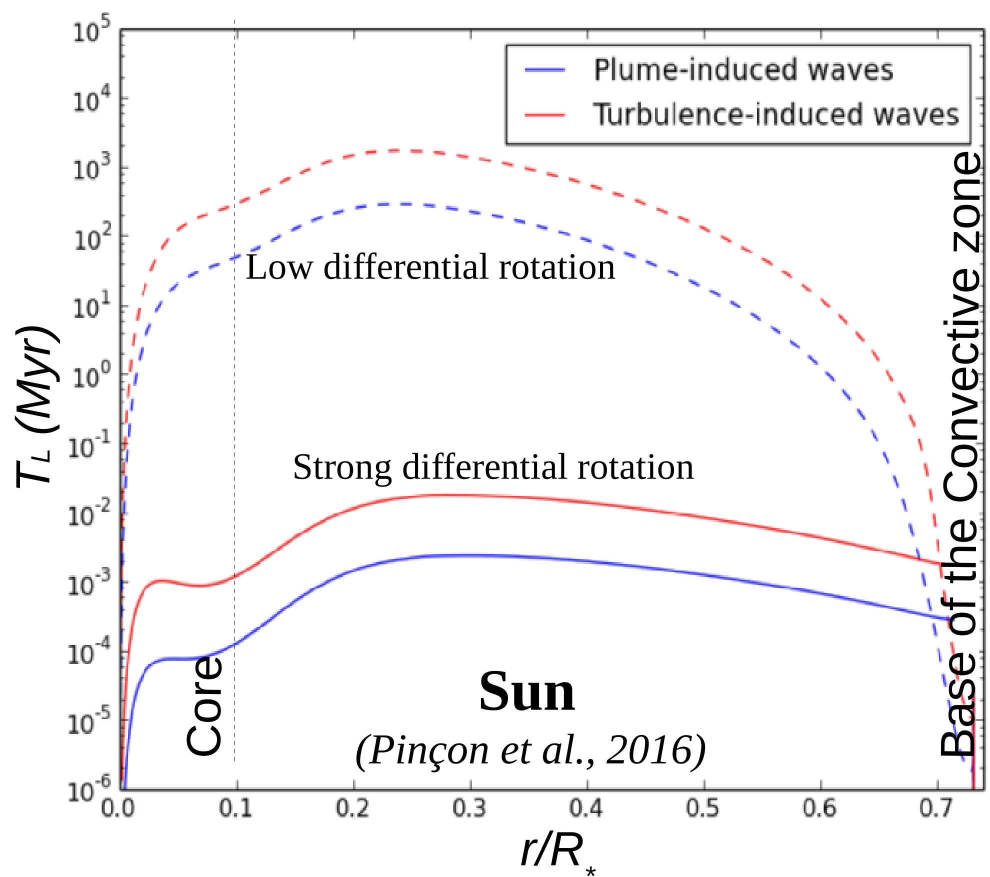
⇒ Process efficient in the Sun !
What about Subgiants and Red Giants ?



From the subgiants branch to the ascent of the RGB

- **Fuller et al. (2014)**

➨ *IGW cannot reach the core : strong radiative damping near the H-burning shell...*
➨ *...**BUT** as for the Sun, not so simple: depends on excitation and differential rotation (via damping)*

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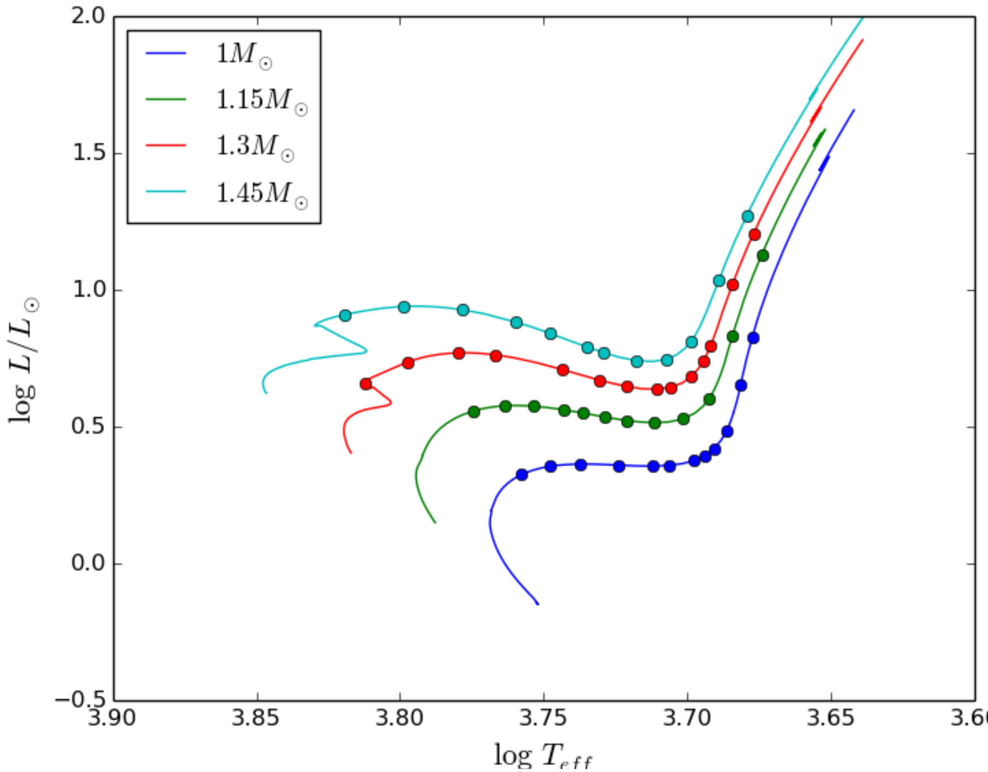
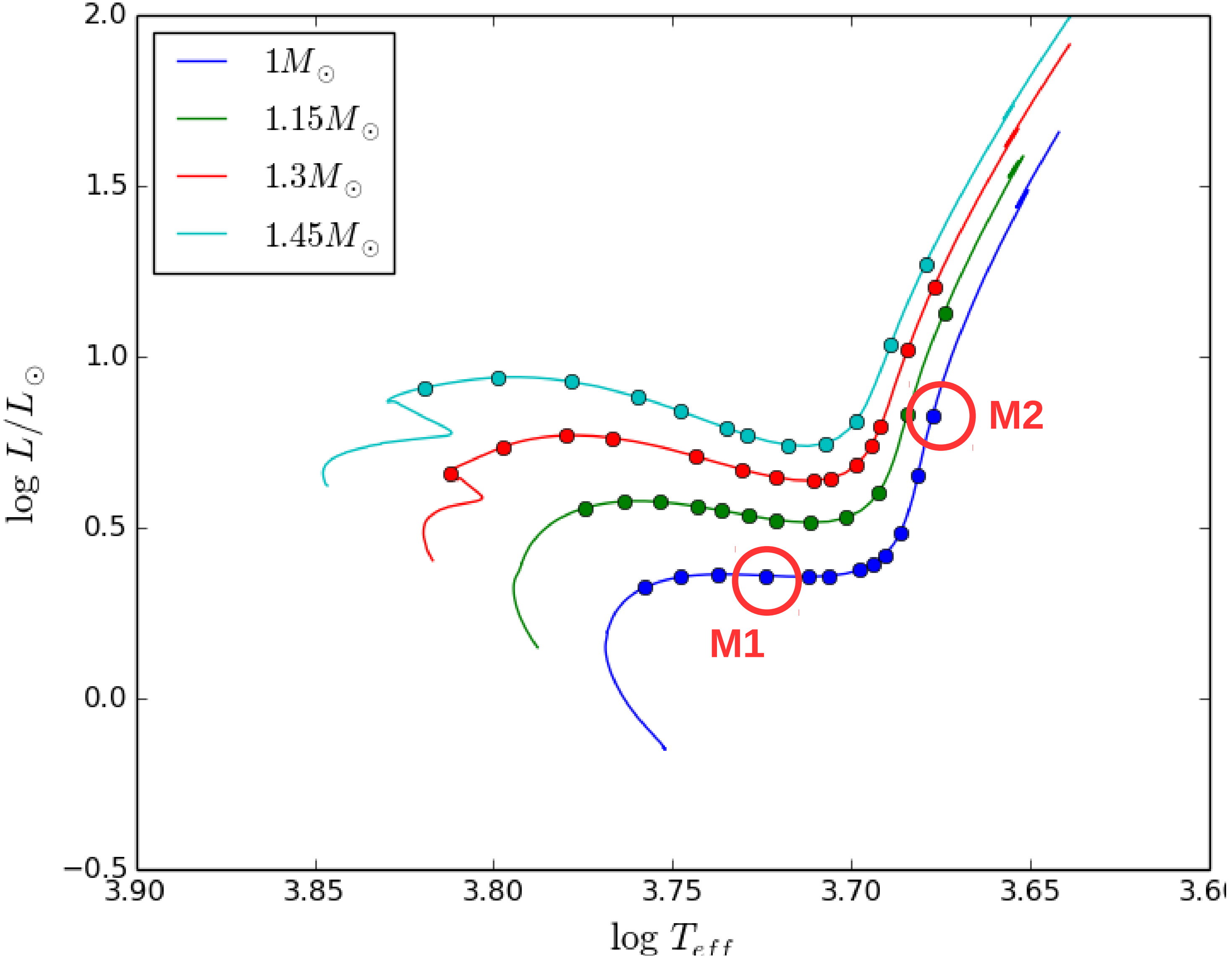
- **Calculations for several models on the subgiant and redgiant branches with IGW excited by penetrative convection**

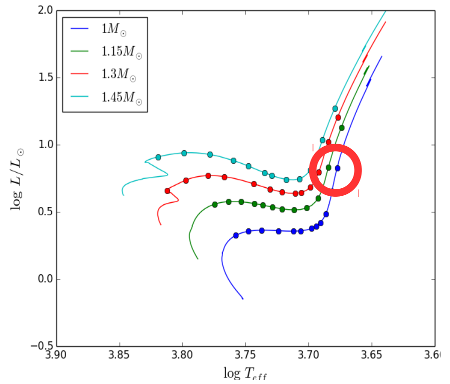
- **Rotation profile for each model :** - *assumed smooth*
  - *different amplitudes for* $\delta\Omega = \Omega_{core} - \Omega_{BCZ}$



2 examples : models M1 and M2



Red Giant (model M2)



The Red Giant case in a nutshell :

- **Considering $0 < \delta\Omega < 12$ µrad s^{-1} as in observed Red Giants (Mosser et al., 2012)**

- **$T_L > T_{contraction}$ in the core (below the H-burning shell)**

➜ *Strong radiative damping near the H-burning shell (peak of the Brunt-Väisälä frequency)*

⇒ For the RGB stars : strong radiative damping prevents IGW from modifying the core rotation, confirms Fuller et al.'s result

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

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

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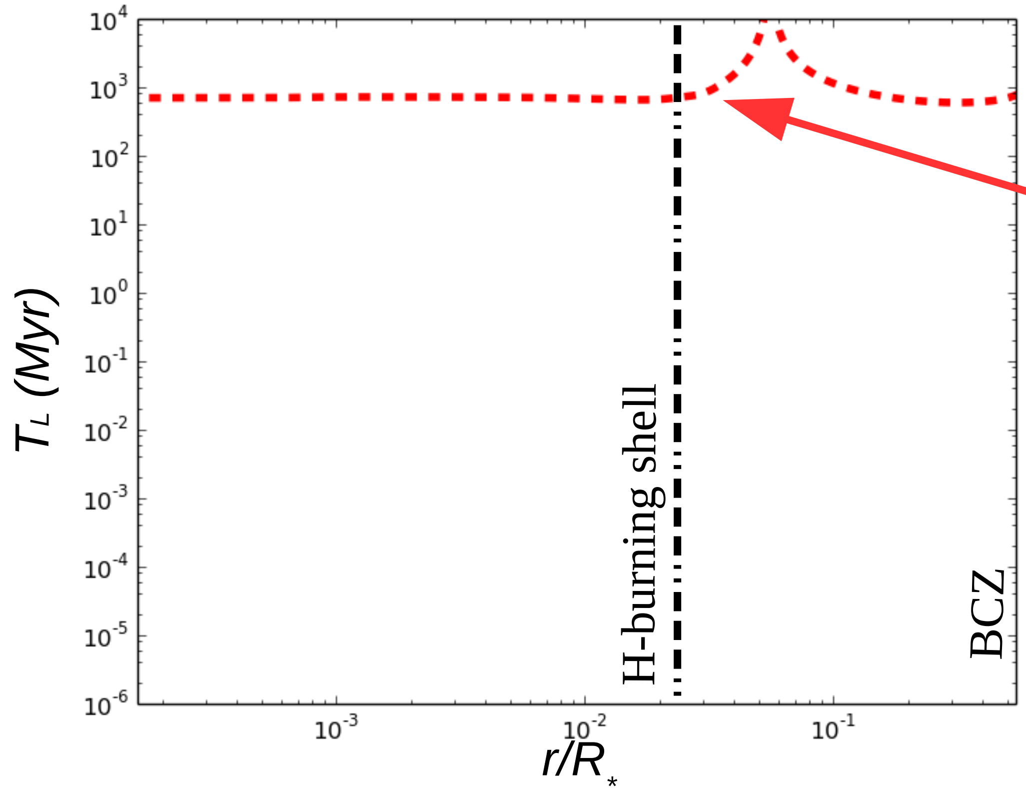
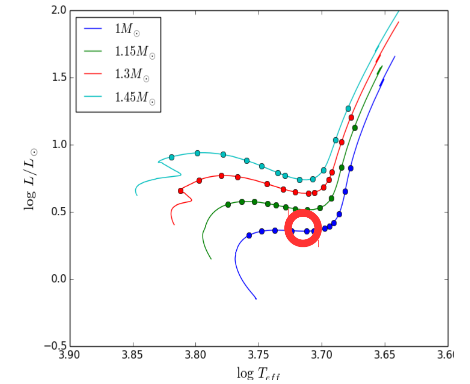




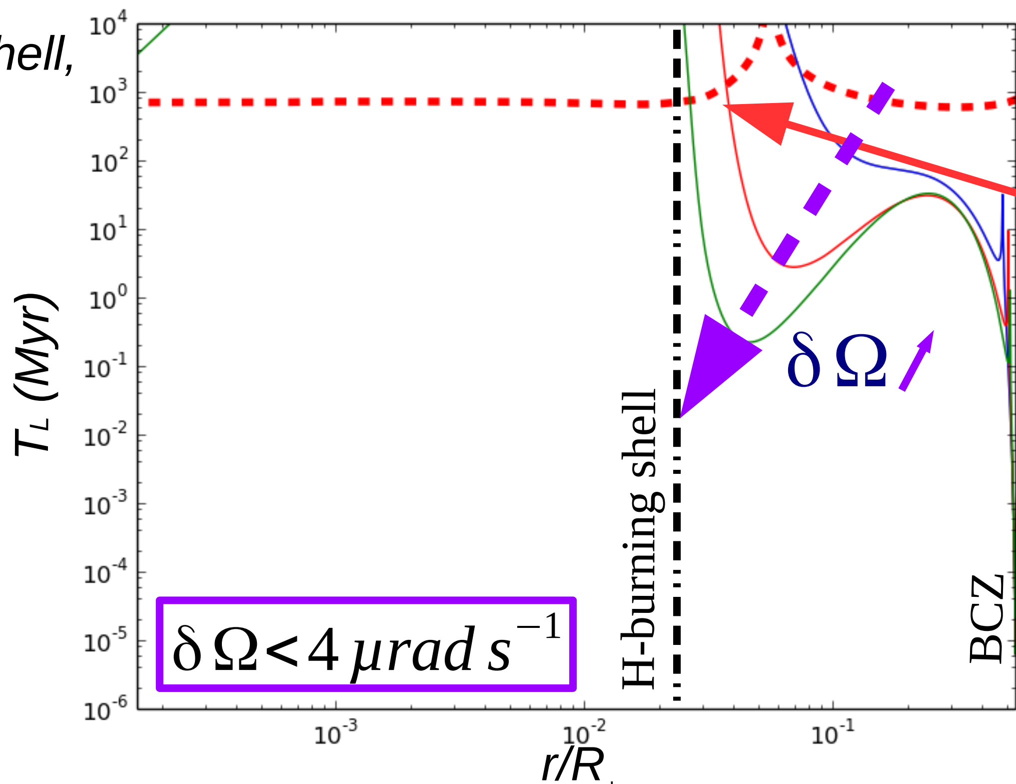
Characteristic timescale of contraction

Subgiant (model M1)

Below the H-burning shell,

$$T_L > T_{contraction}$$

Waves do not cross the barrier



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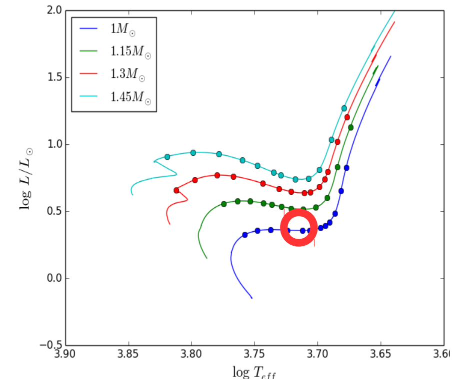

- **Low differential rotation** ⇒ *Strong damping before the H-burning shell*
  ⇒ *IGW cannot overcome the « barrier »*

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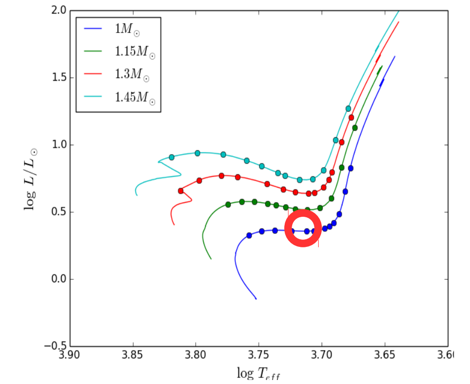

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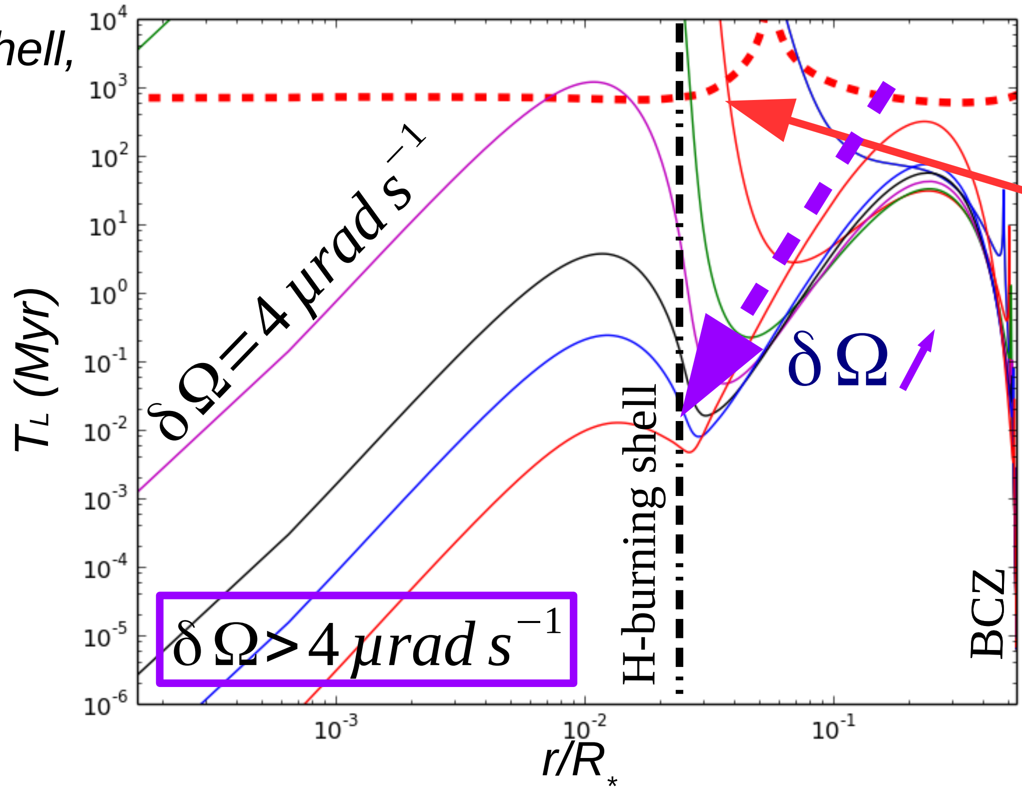

Characteristic timescale of contraction

(Pinçon et al., 2016)

- **Low differential rotation** ⇒ *Strong damping before the H-burning shell*
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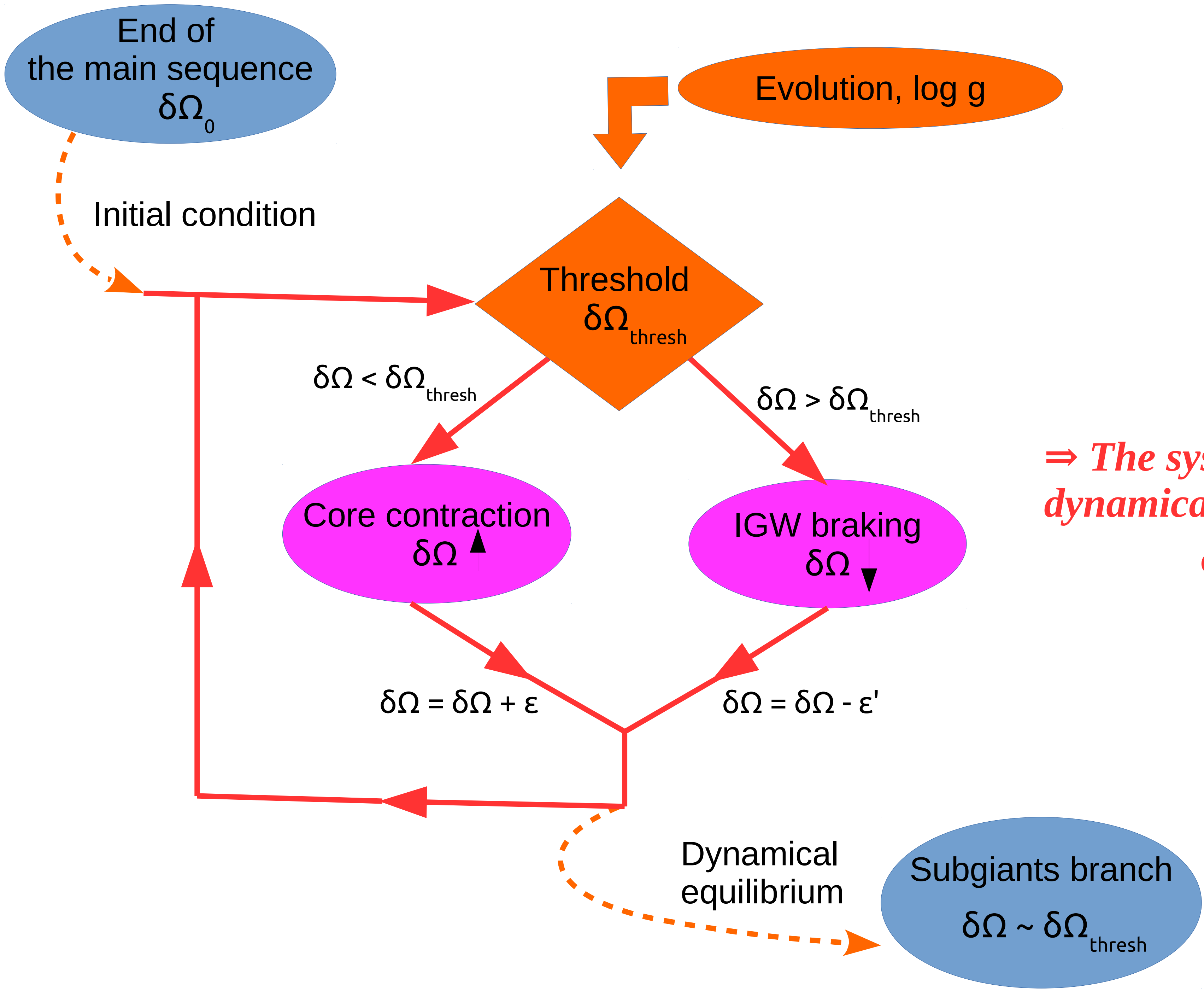
- **Progressive increase of δΩ** ⇒ *above δΩ > 4 μrad s^{-1} , IGW cross the « barrier »*
  ⇒ *cf difference between prograde and retrograde waves ↗ with δΩ*

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

A possible regulation loop in Subgiants

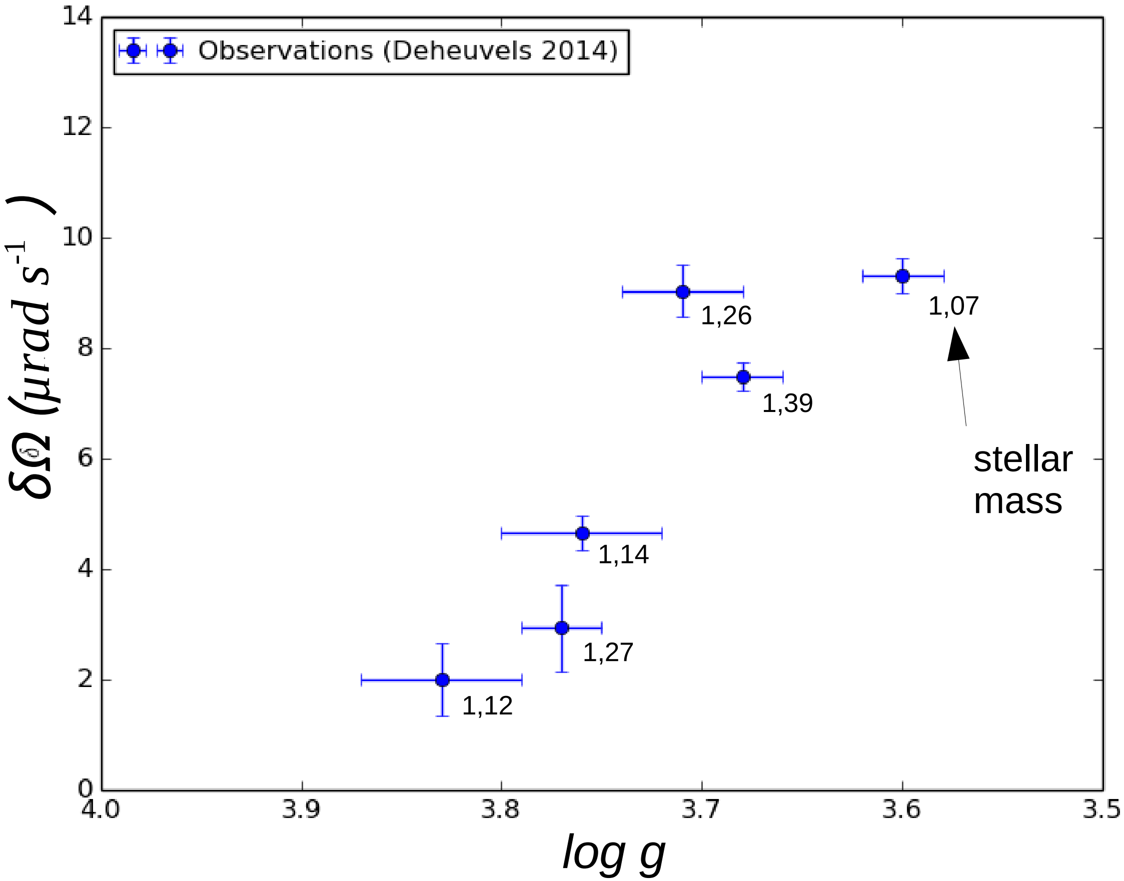


⇒ The system reaches a dynamical equilibrium :

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

A threshold close to the observations

- Observations of 6 subgiants 1Msun<M<1.45Msun (Deheuvels et al., 2014)
- Comparison with the threshold $\delta\Omega_{threshold}$ derived from stellar models ?



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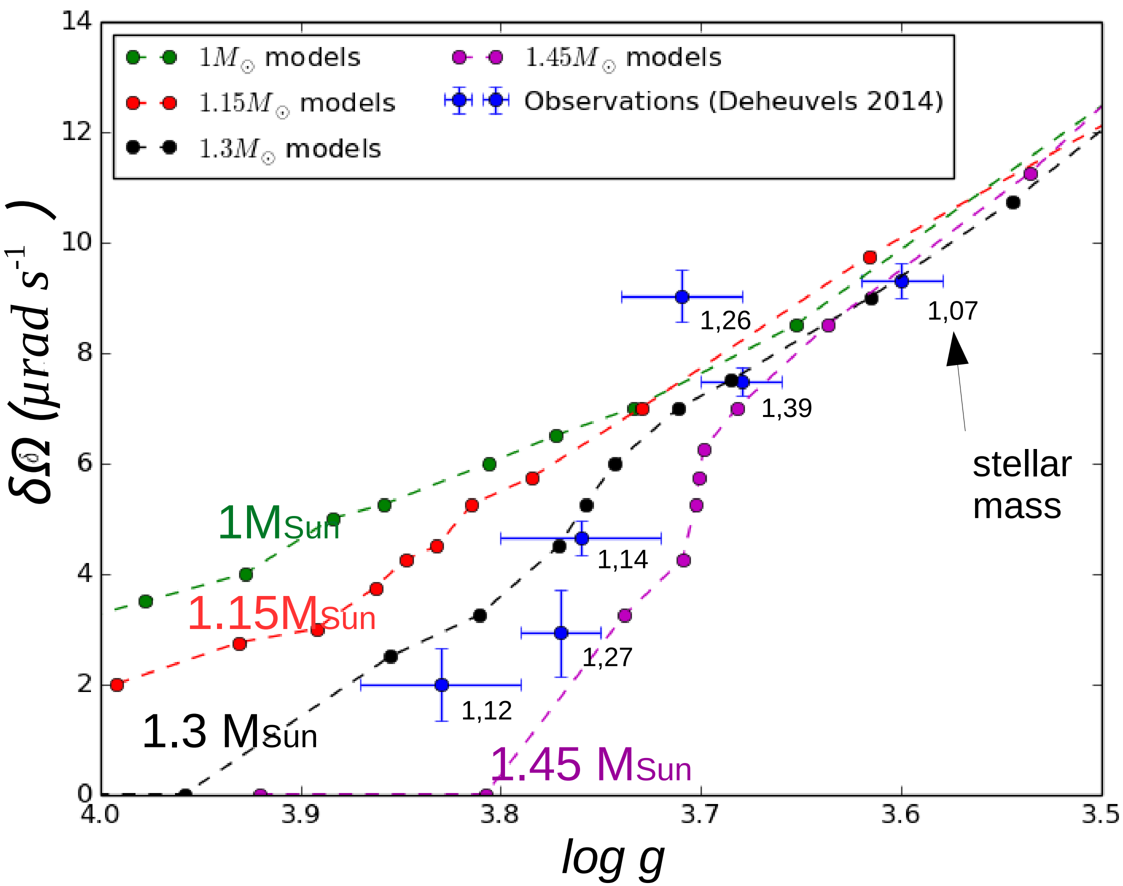

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- **Amazing similarities between both**

  - *Same typical values*
  - *Decrease with log g*

⇒ observations in agreement with a regulation effect coming from IGW

- *Some discrepancies: mass effect, assumed rotation profile, threshold selection criterion, meaning of the mean observed $\delta\Omega$ (rotational splittings)...*

Concluding remarks

- **New excitation model of IGW by penetrative convection…**
- **… with consequences for the extraction of angular momentum :**

  - *on the RGB : ⇒ IGW can not reach the core (cf Fuller et al.)*

  - ***on the subgiant branch : ⇒ IGW generated by penetrative convection are a good candidate to regulate the core rotation***

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- **Next steps :**

  - regulation in subgiants ⇒ promising and in progress (conservative?)

  - role of IGW to be confirmed by means of a numerical resolution for the angular momentum transport (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 !

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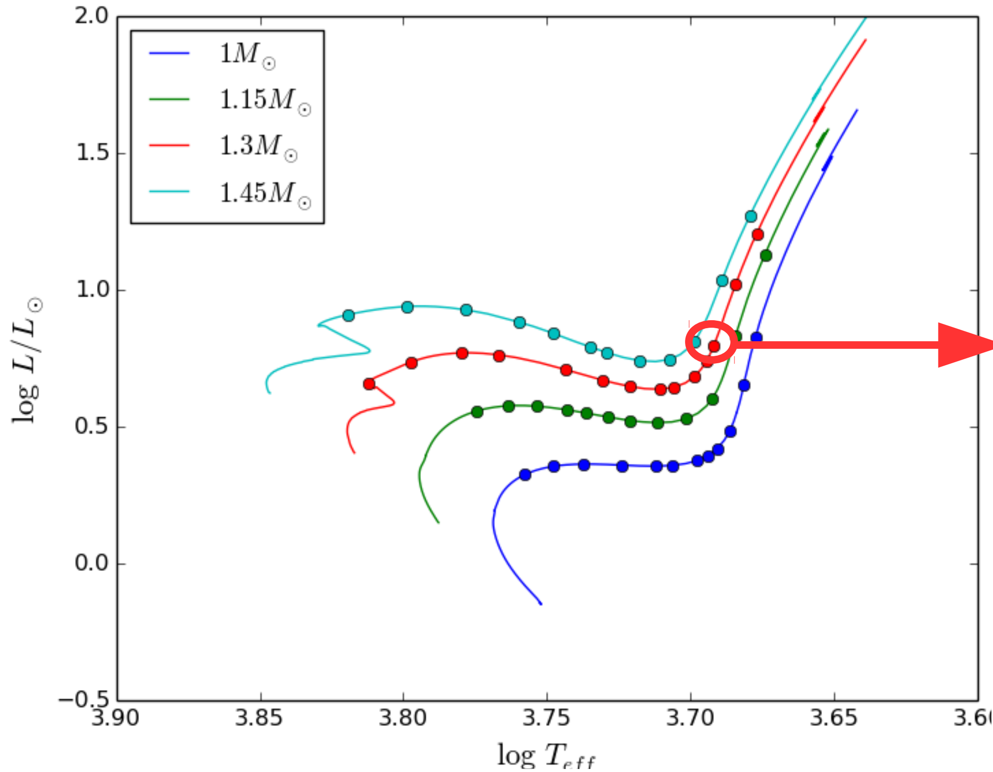

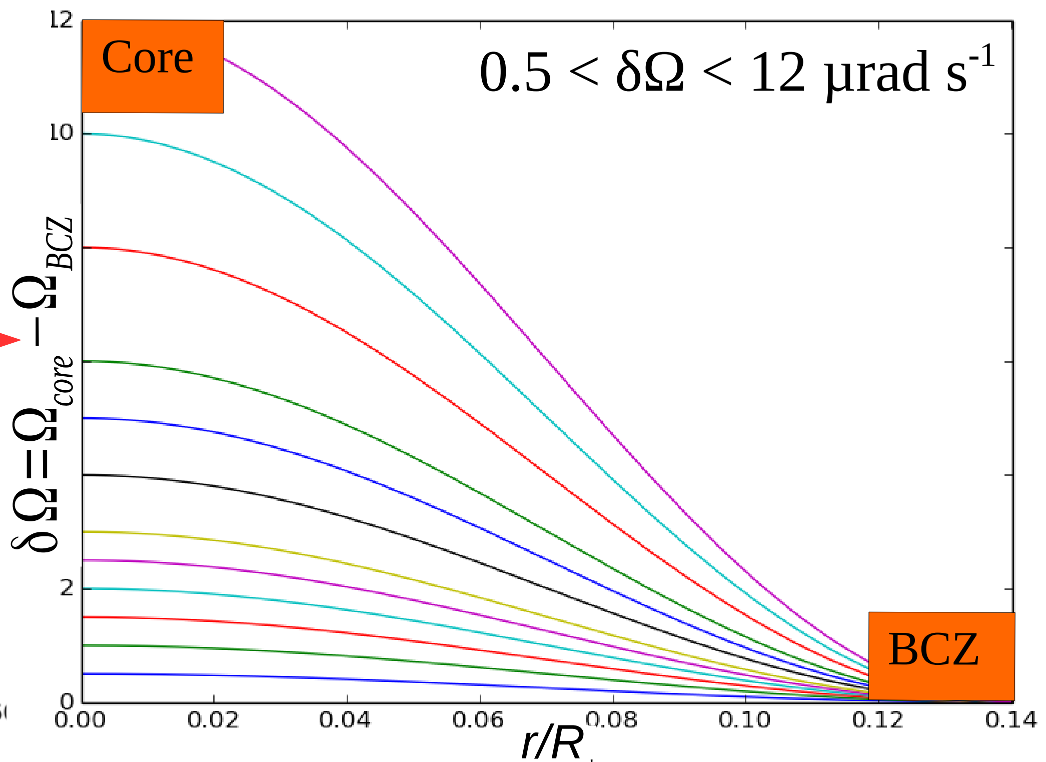

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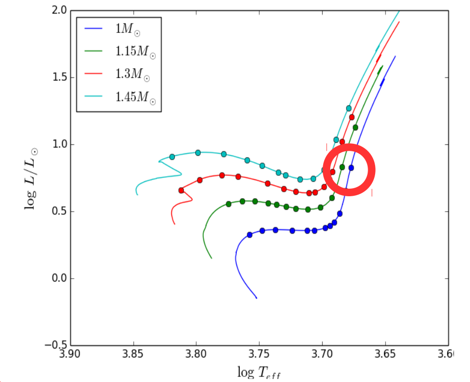

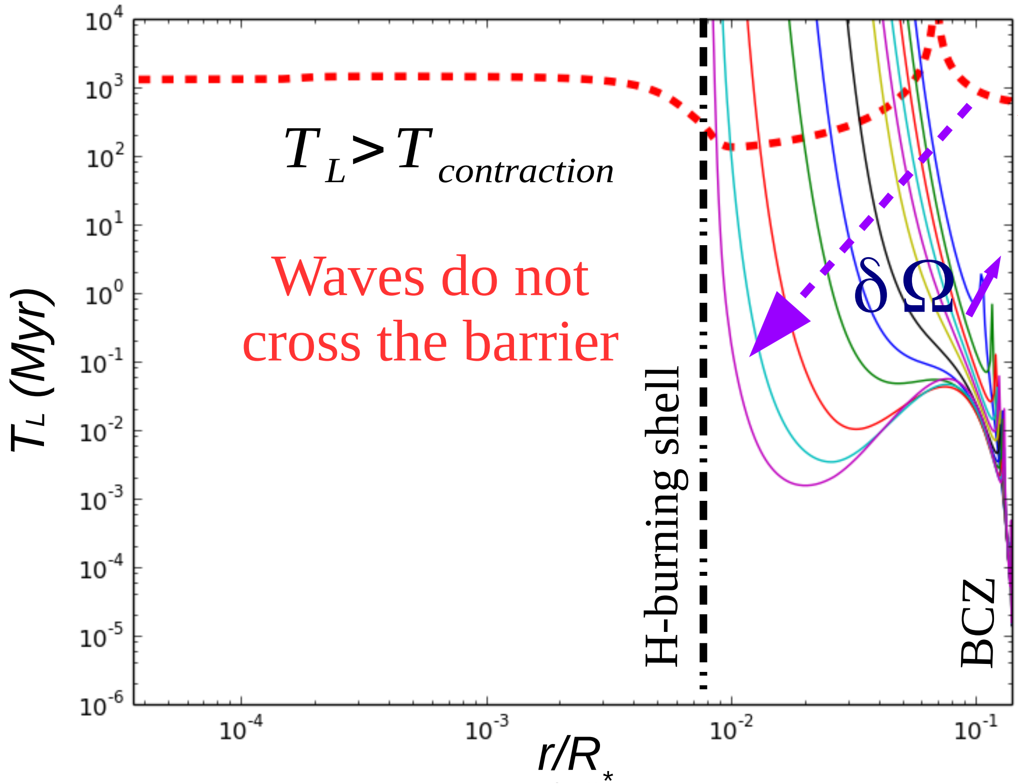

Characteristic timescale of contraction

- ✓ **T_L increases going deeper and $T_L > T_{contraction}$ in the core for all δΩ < 12 µrad s^{-1}**
  - *Waves strongly damped near the H-burning shell (peak of the Brunt-Väisälä frequency)*
  - *δΩ < 12 µrad s^{-1} in observed Red Giants (Mosser et al., 2012)*

    ⇒ For the RGB stars : radiative damping prevents IGW from modifying the core rotation

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