Transport of angular momentum within stars

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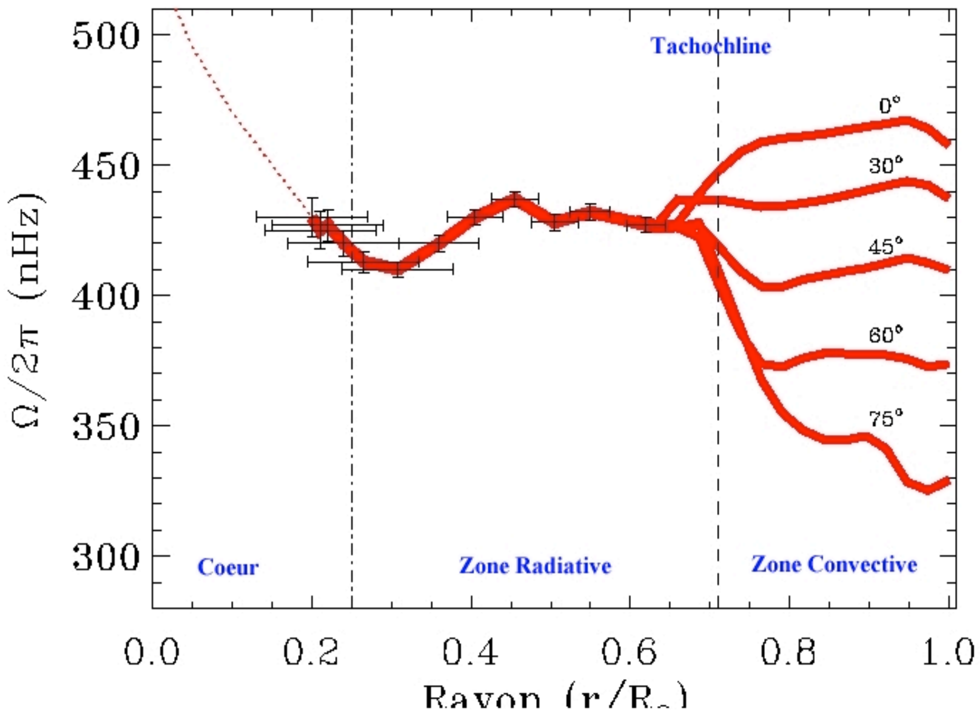
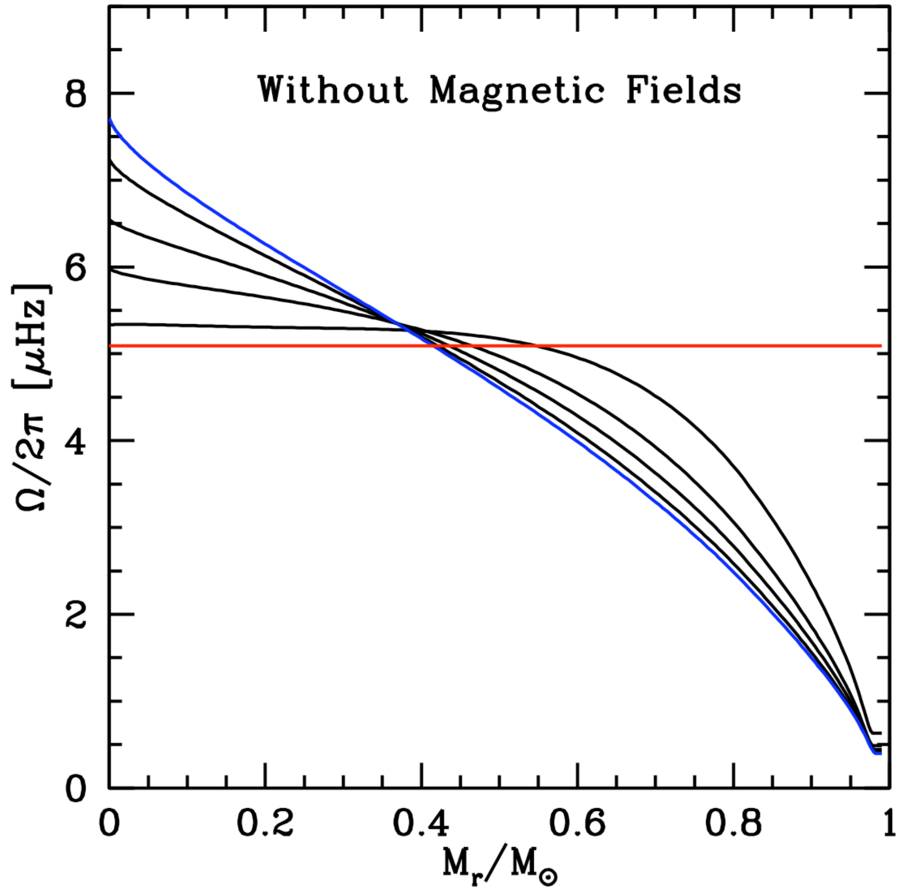
The solar rotation profile

- Helioseismic measurements



Garcia et al. 2007

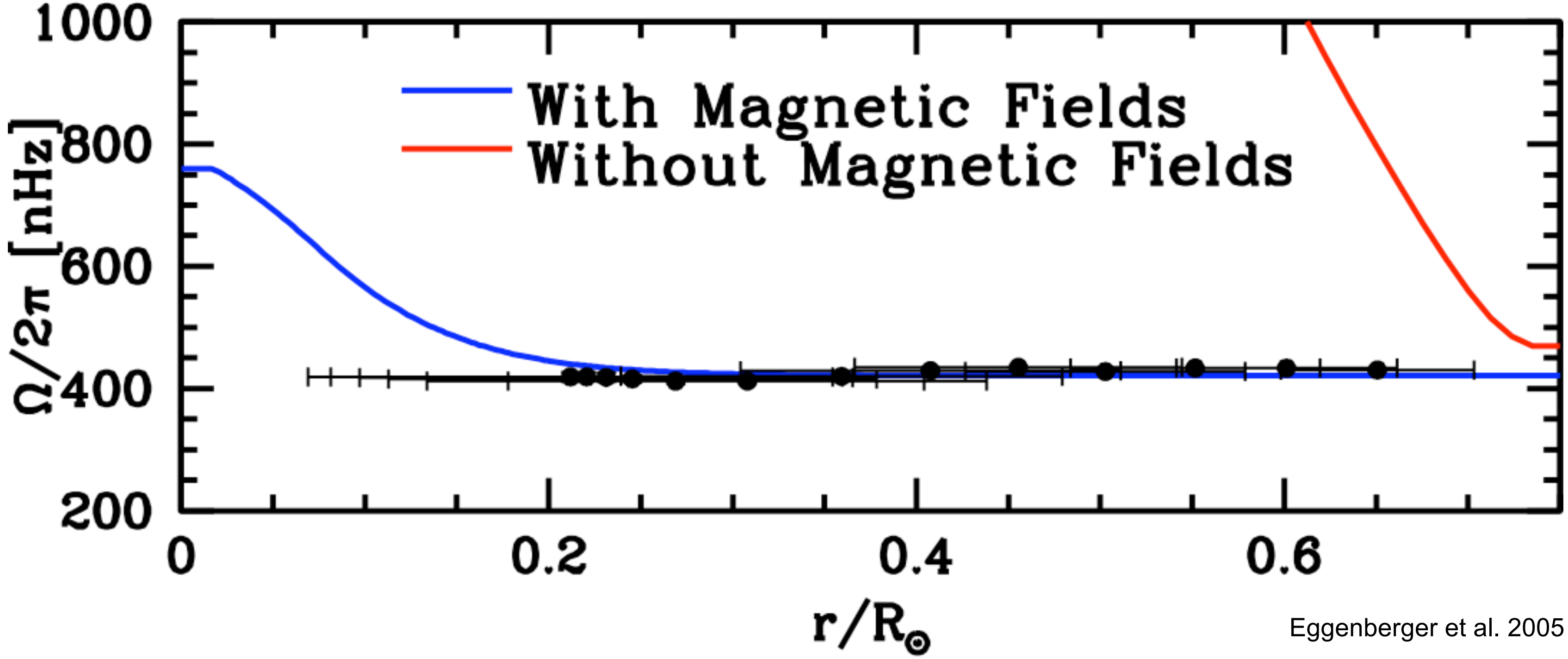


  – Problem with shellular rotation

    Pinsonneault et al. 1989; Chaboyer et al. 1995; Talon et al. 1997; Eggenberger et al. 2005; Turck-Chièze et al. 2010

The solar rotation profile

- Effects of magnetic fields

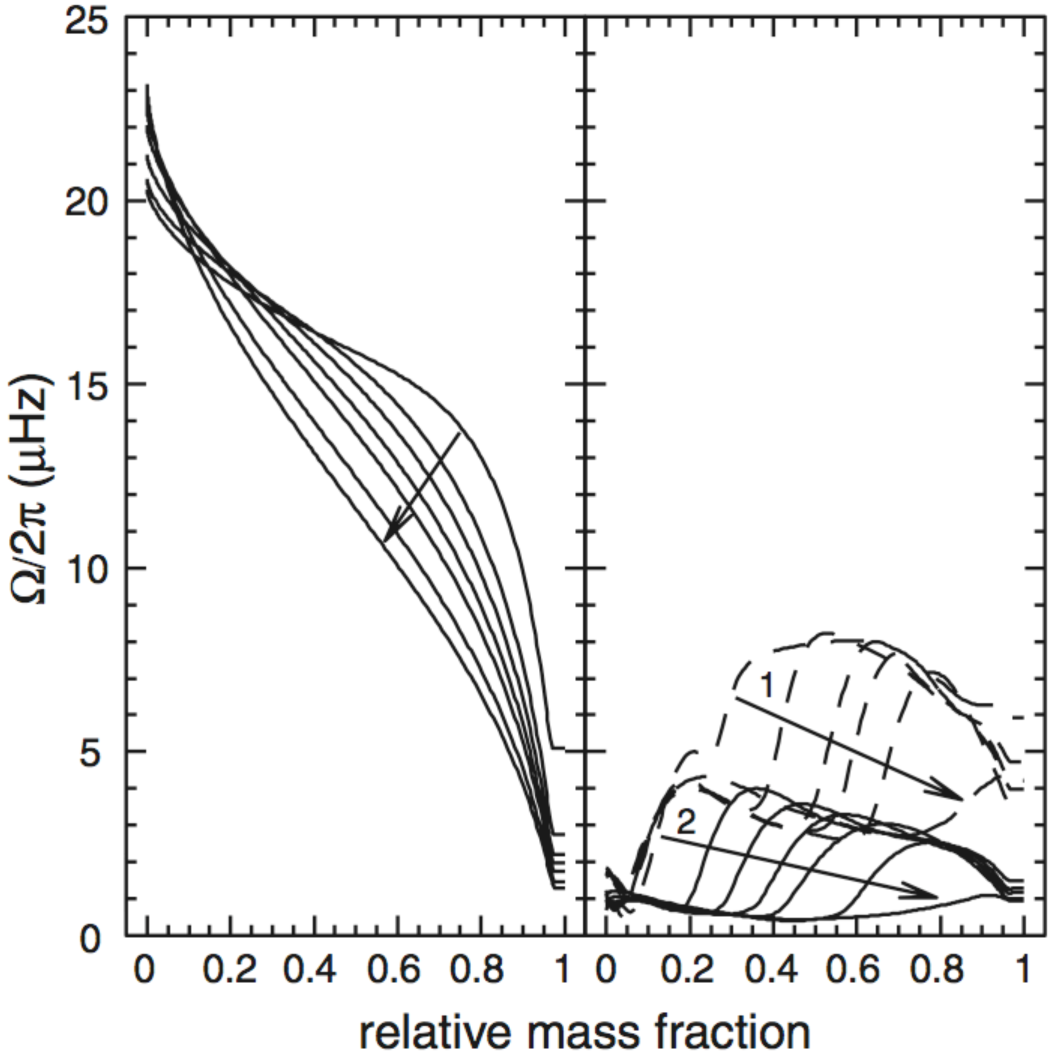


Eggenberger et al. 2005

$$\rho \frac{\mathrm{d}}{\mathrm{d}t}\left[r^2\Omega\right] = \frac{1}{5r^2}\frac{\partial}{\partial r}\left[\rho r^4 \Omega U\right] + \frac{1}{r^2}\frac{\partial}{\partial r}\left[\rho(D_{\mathrm{shear}} + \nu_{\mathrm{magn}}) r^4 \frac{\partial \Omega}{\partial r}\right]$$

The solar rotation profile

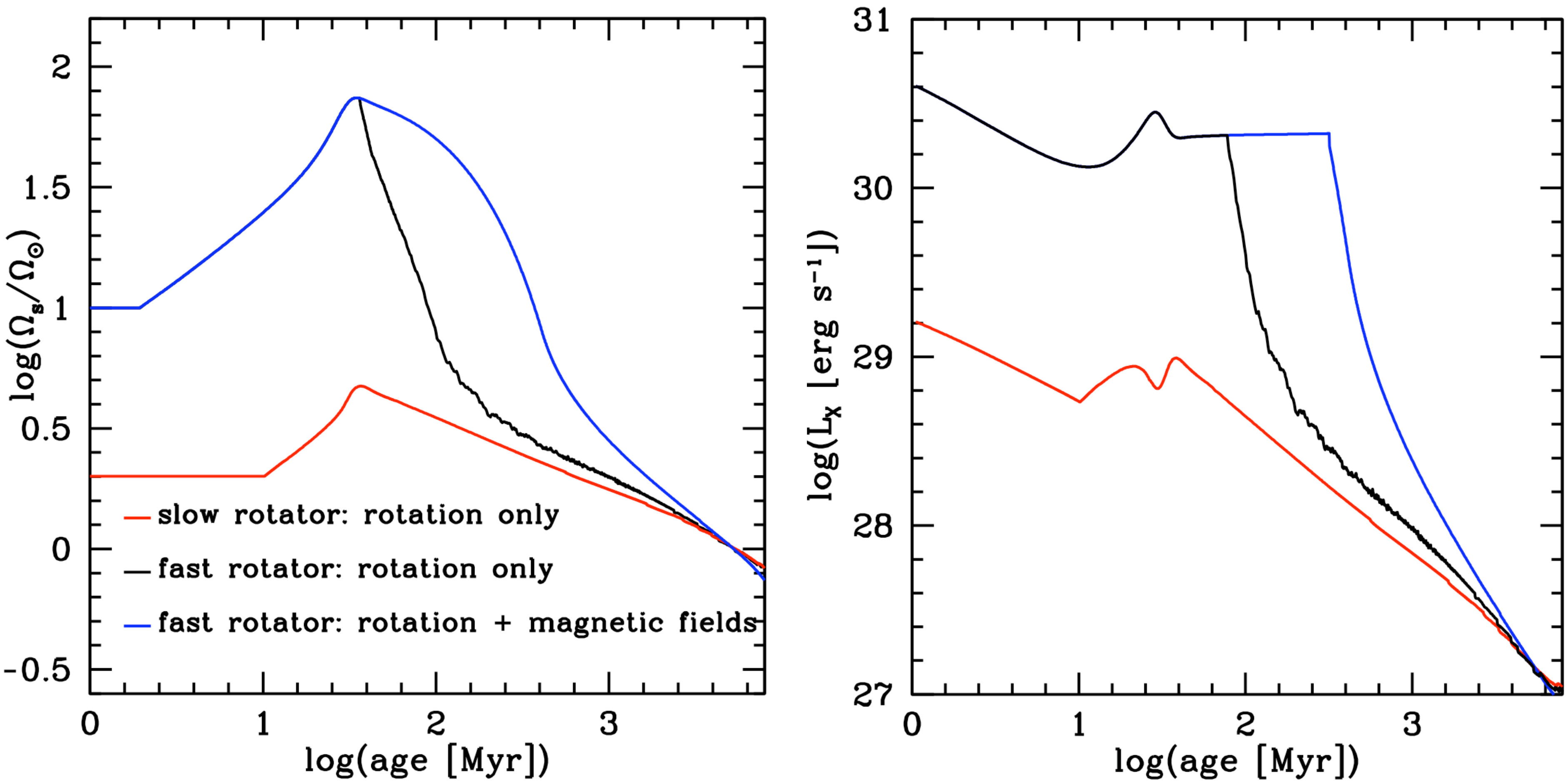
- Effects of internal gravity waves



Charbonnel & Talon 2005

Asteroseismology of MS stars

- Impact of MS angular momentum transport on exoplanets

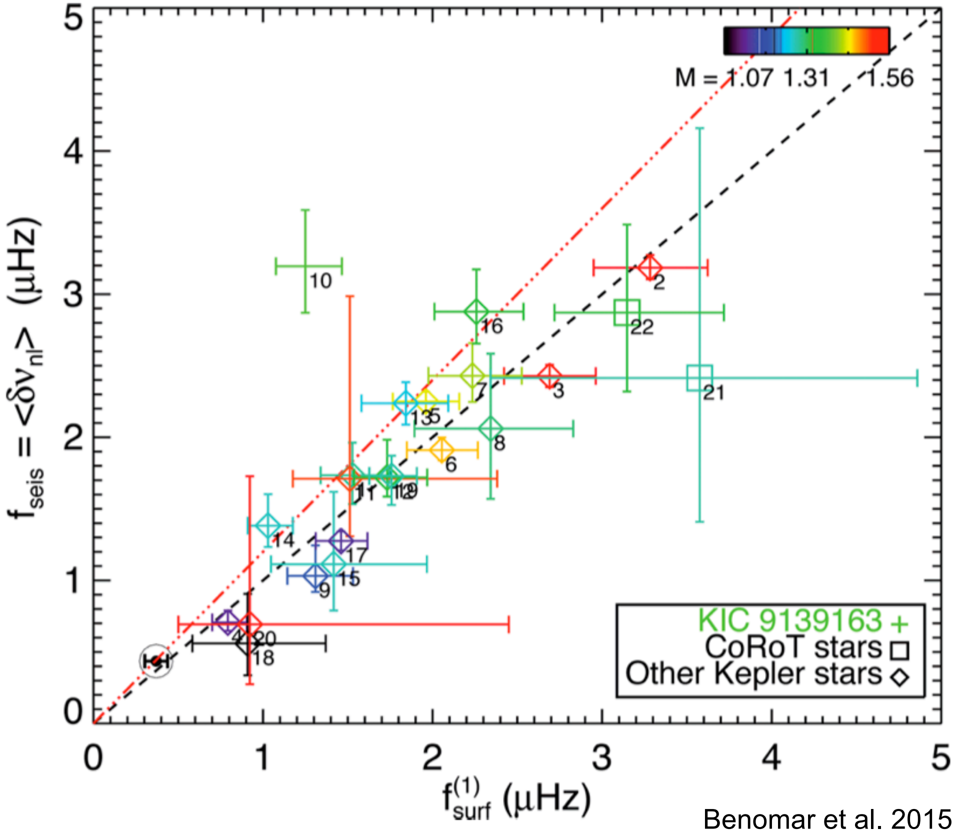


Eggenberger et al. 2010

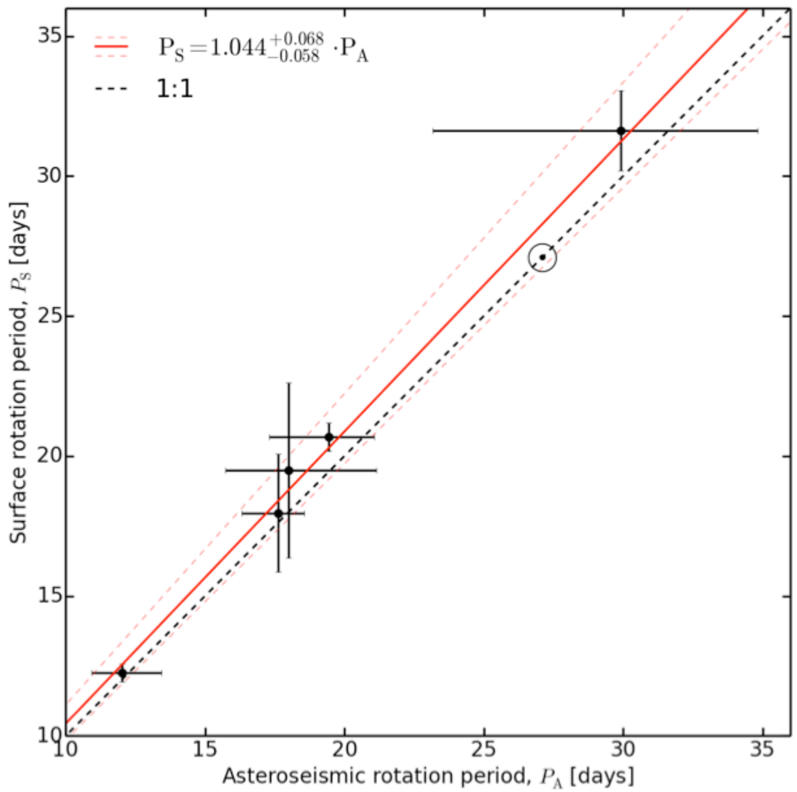
Asteroseismology of MS stars

- Solar-like oscillations in MS stars

mean internal rotation from rotational splittings +
independent measurements of surface rotation rates



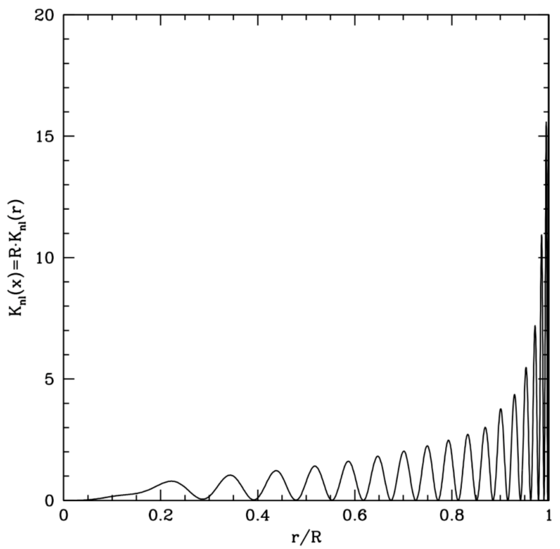
Benomar et al. 2015

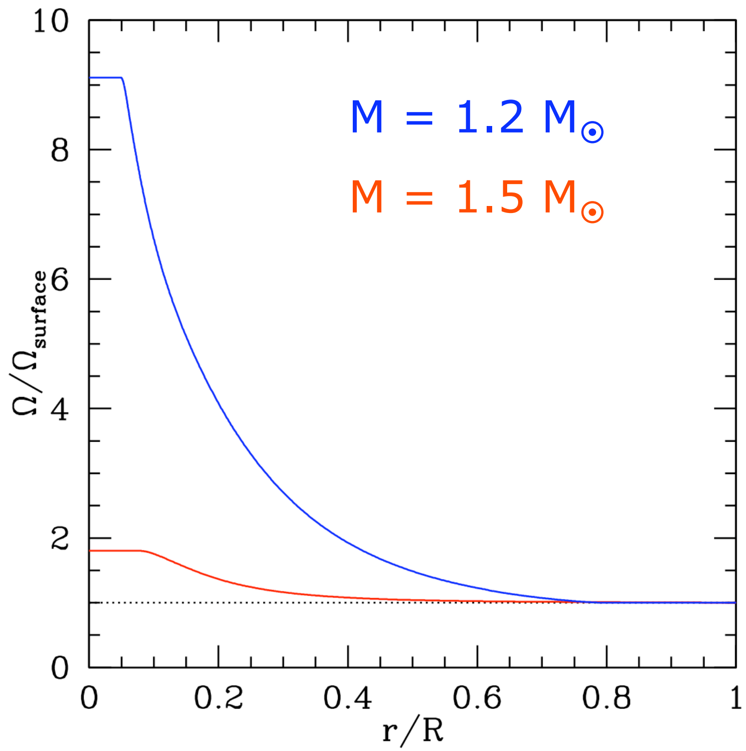


Nielsen et al. 2015

Asteroseismology of MS stars

- More massive MS stars





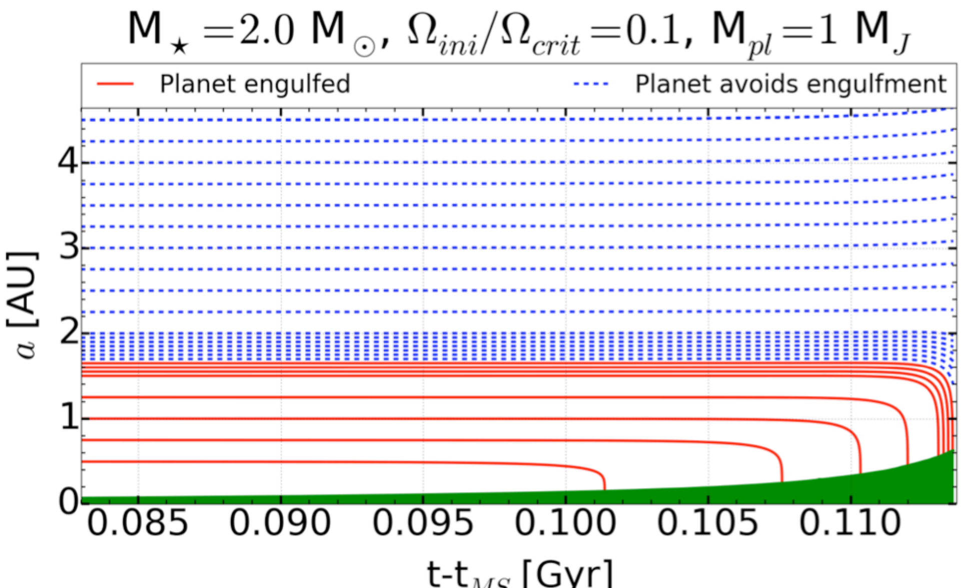
- Slowly rotating δ Scuti/γ Dor and SPB stars : ~ SB rotation (Kurtz et al. 2014; Saio et al. 2015; Schmid et al. 2015; Murphy et al. 2016; Triana et al. 2015; Kallinger et al. 2017)
- SB rotation also for faster rotating MS stars? (Van Reeth et al. 2016; Ouazzani et al. 2017)
- β Ceph stars : non-rigid rotation with $\Omega_{core} \sim 3\ \Omega_{env}$ (Aerts et al. 2003; Dupret et al. 2004; Ausseloos et al. 2004; Pamyatnykh et al. 2004) or compatible with SB rotation (Briquet et al. 2007)

Asteroseismology of red giants

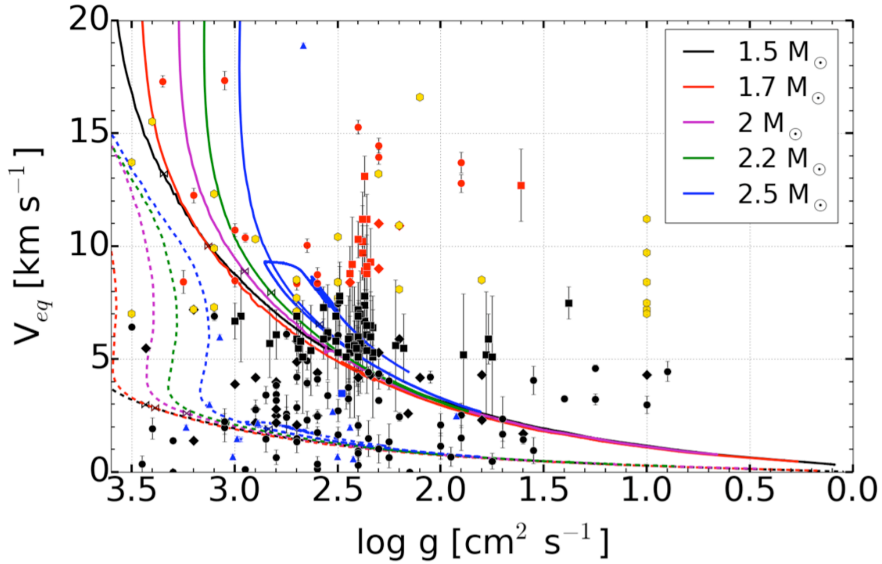
- Impact of post-MS angular momentum transport on planet engulfment

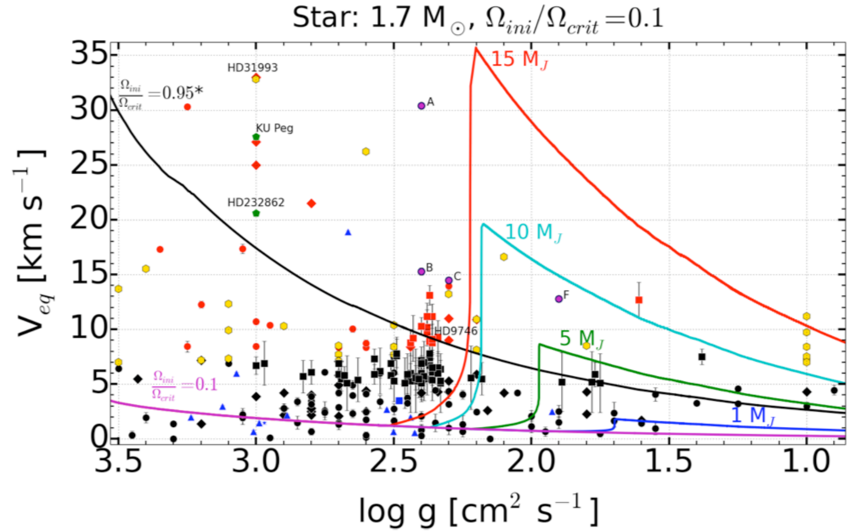
AM exchange with the planet

+ internal transport of AM



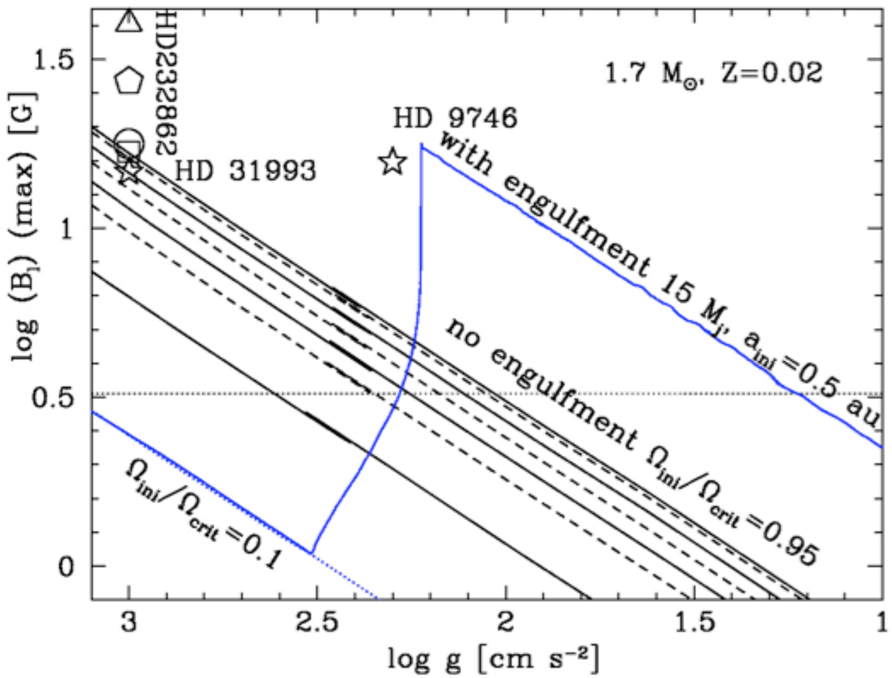
Privitera et al. 2016

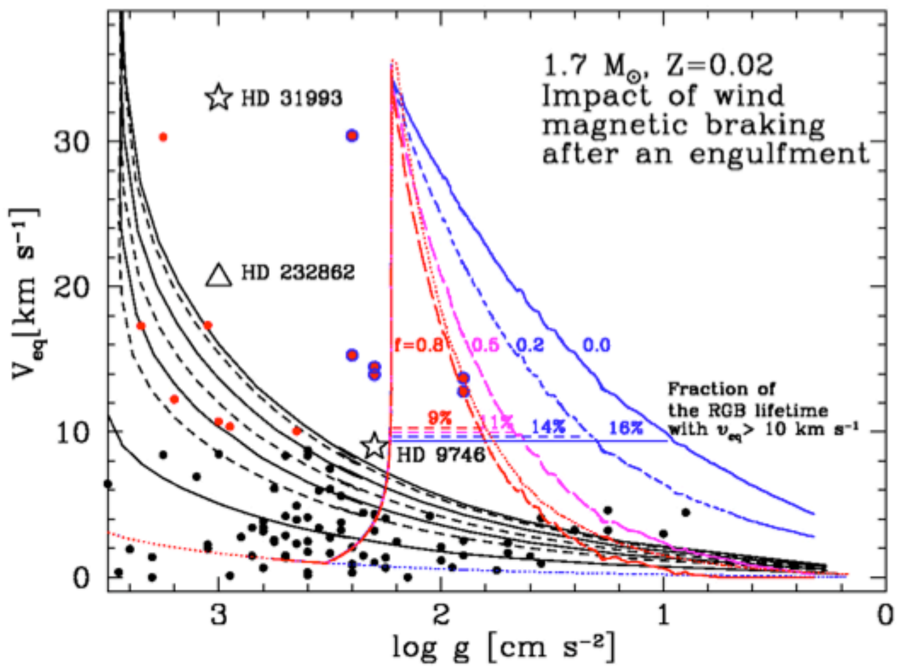




- Impact of post-MS angular momentum transport on planet engulfment

High surface magnetic fields + impact of magnetic braking

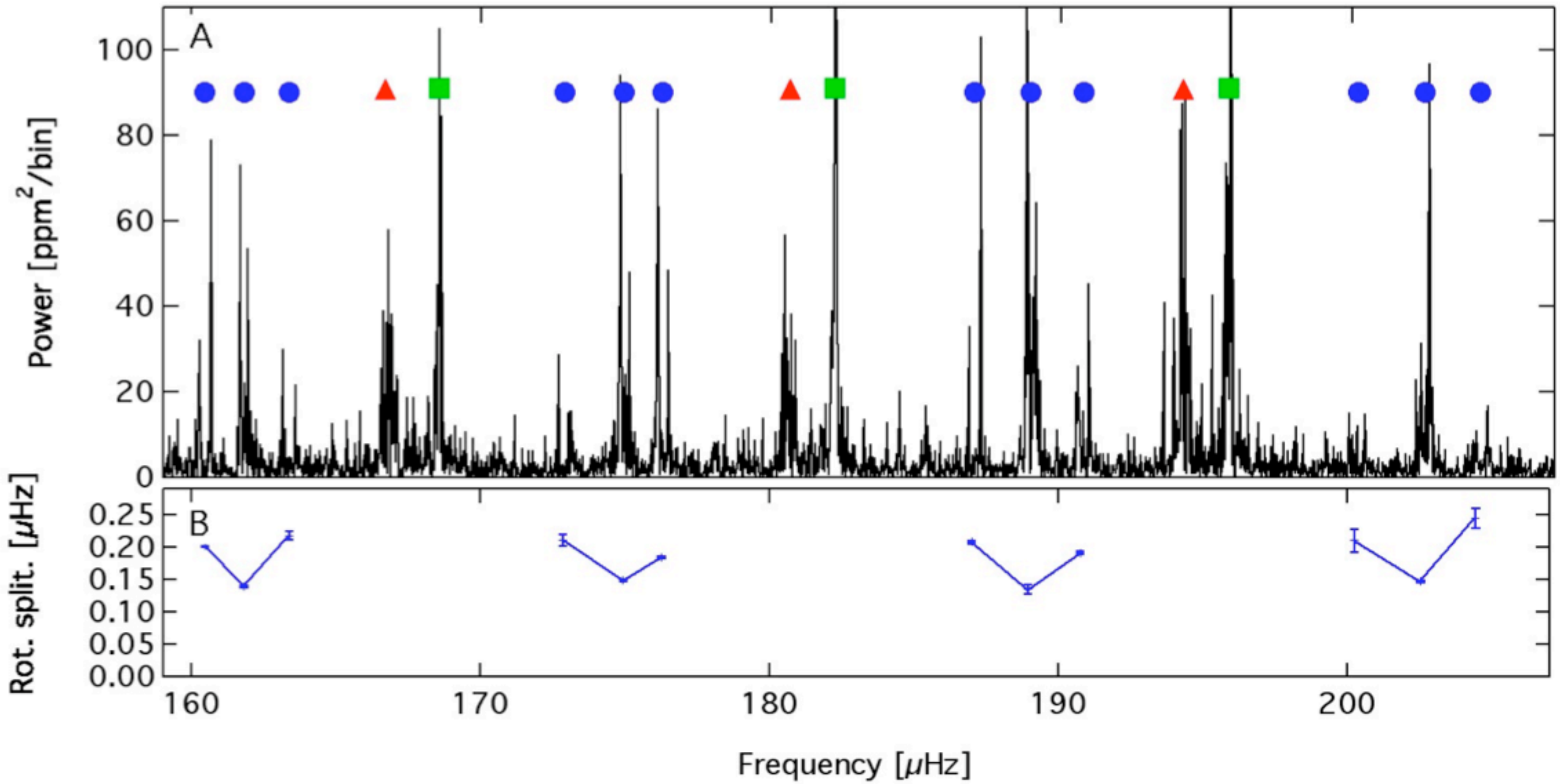




Privitera et al. 2016

Asteroseismology of red giants

- Rotational splittings for solar-like oscillations in red giants



Beck et al. 2012

- Mixed modes in KIC 8366239 (Beck et al. 2012): 1.5 $M_\odot$ with $Z_\odot$

Asteroseismology of red giants

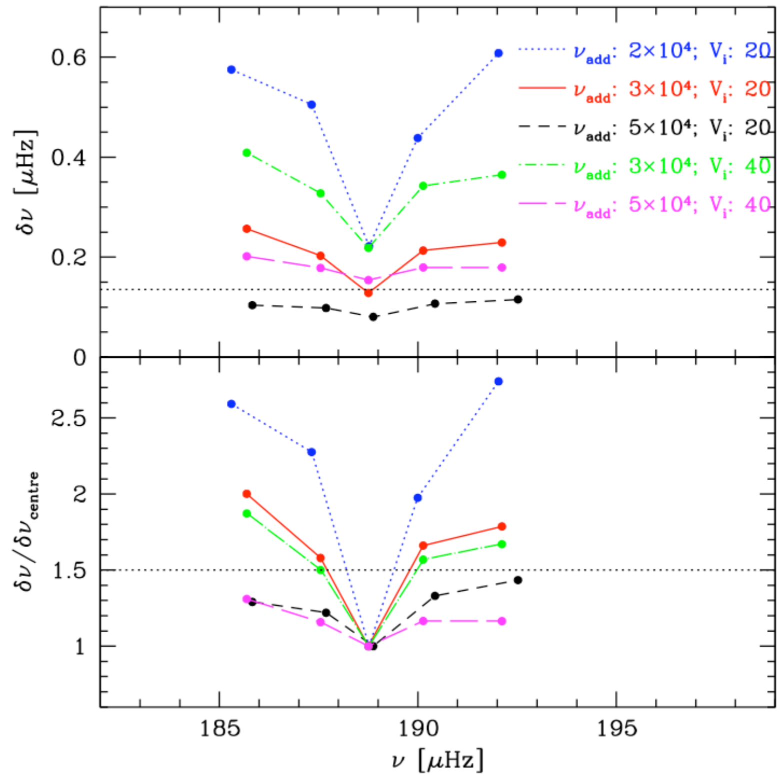
- Mixed modes in the red giant KIC 8366239
  - Additional mechanism for the transport of angular momentum:

$$\rho \frac{\mathrm{d}}{\mathrm{d}t}\left[r^2\Omega\right] = \frac{1}{5r^2}\frac{\partial}{\partial r}\left[\rho r^4 \Omega U\right] + \frac{1}{r^2}\frac{\partial}{\partial r}\left[\rho (D_{\mathrm{shear}} + \nu_{\mathrm{add}}) r^4 \frac{\partial \Omega}{\partial r}\right]$$

$\delta\nu_{rot}^{wings}/\delta\nu_{rot}^{centre} = 1.5$

$\Rightarrow \nu_{add} = 3\cdot 10^4\ cm^2\ s^{-1}$

see study by Goupil et al. (2013)



Eggenberger et al. 2012

Asteroseismology of red giants

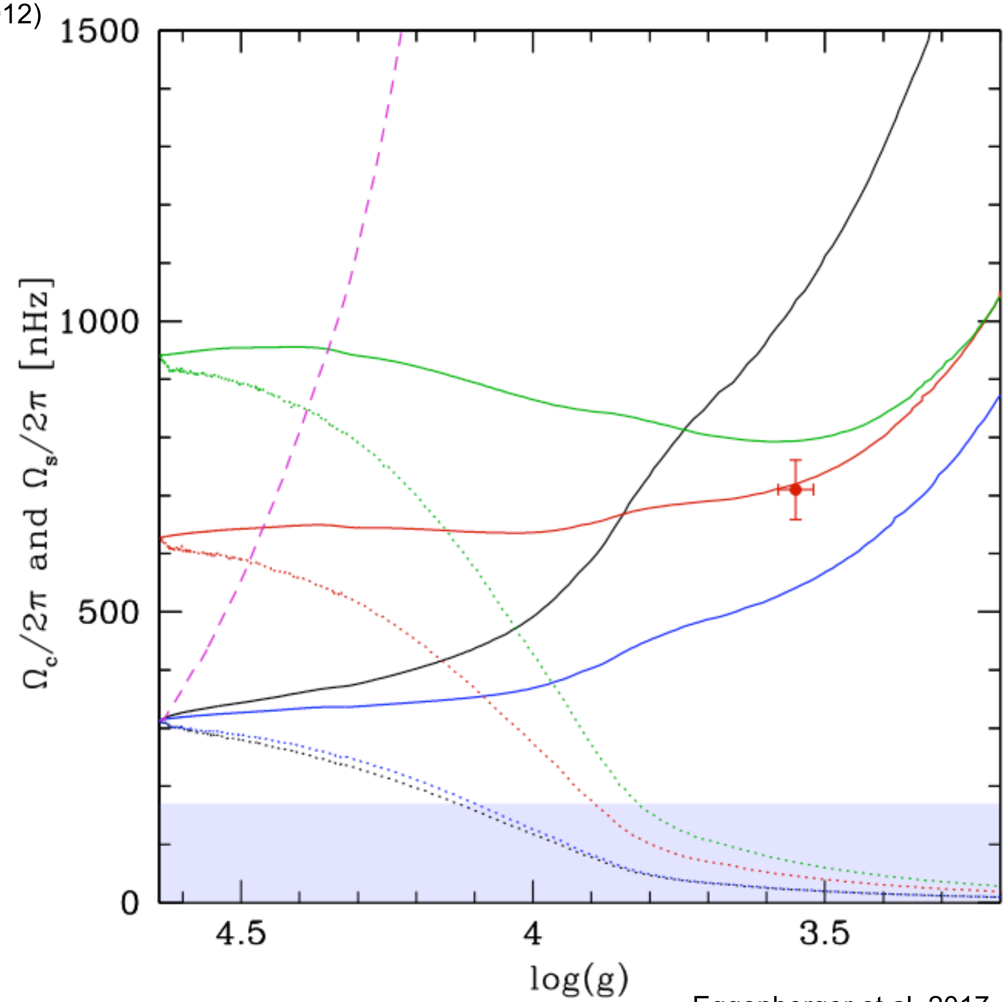
- KIC 7341231: a low-mass red giant
  - Internal rotation (Deheuvels et al. 2012)

    $\Omega_c = 710 \pm 51$ nHz

    $\Omega_s < 150 \pm 19$ nHz

  - Negligible impact of the rotational history on ν_{add} (AM transport and surface braking by magnetized winds during MS and PMS):

    $\nu_{add} = 1 \cdot 10^3 - 1.3 \cdot 10^4 \; cm^2 \; s^{-1}$

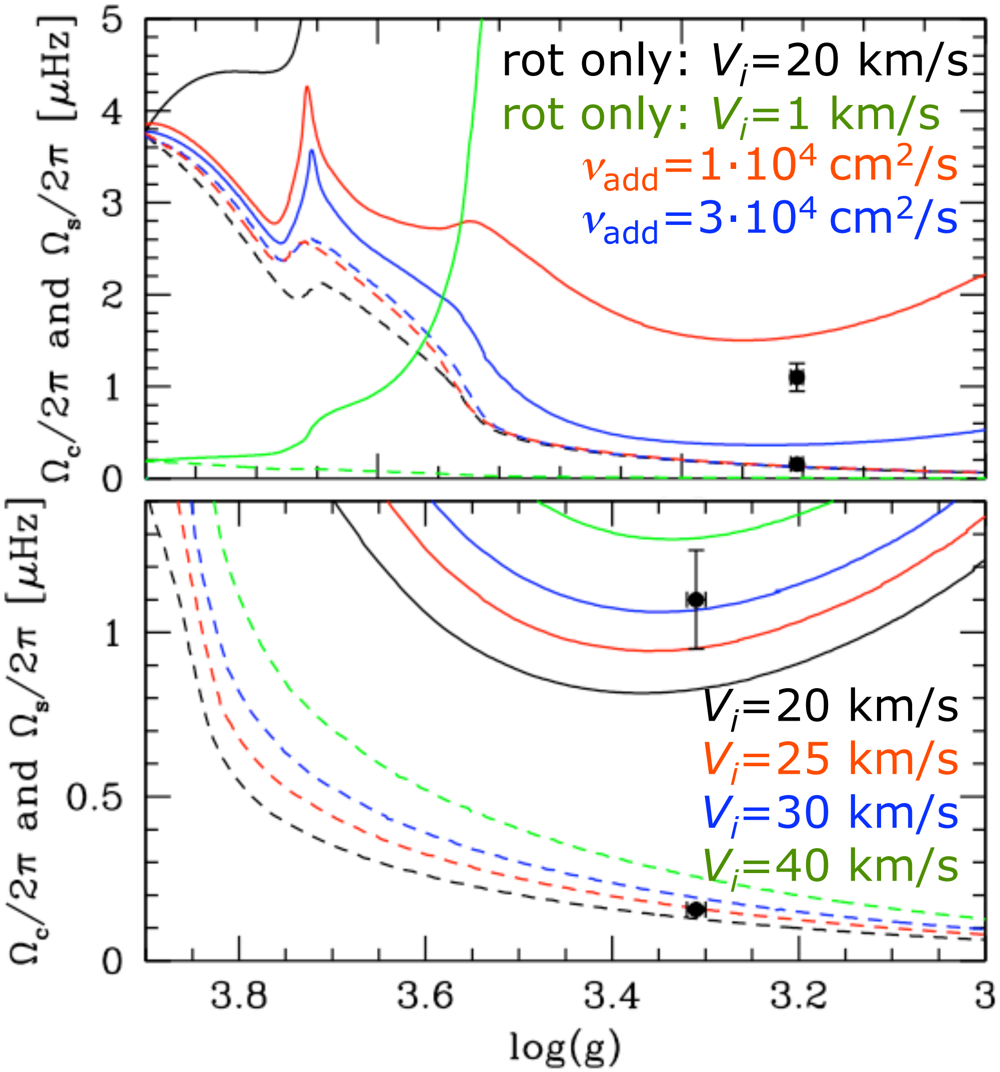


Eggenberger et al. 2017

- Kepler-56
  - Precise estimates of both core and surface rotation rates (Huber et al. 2013)

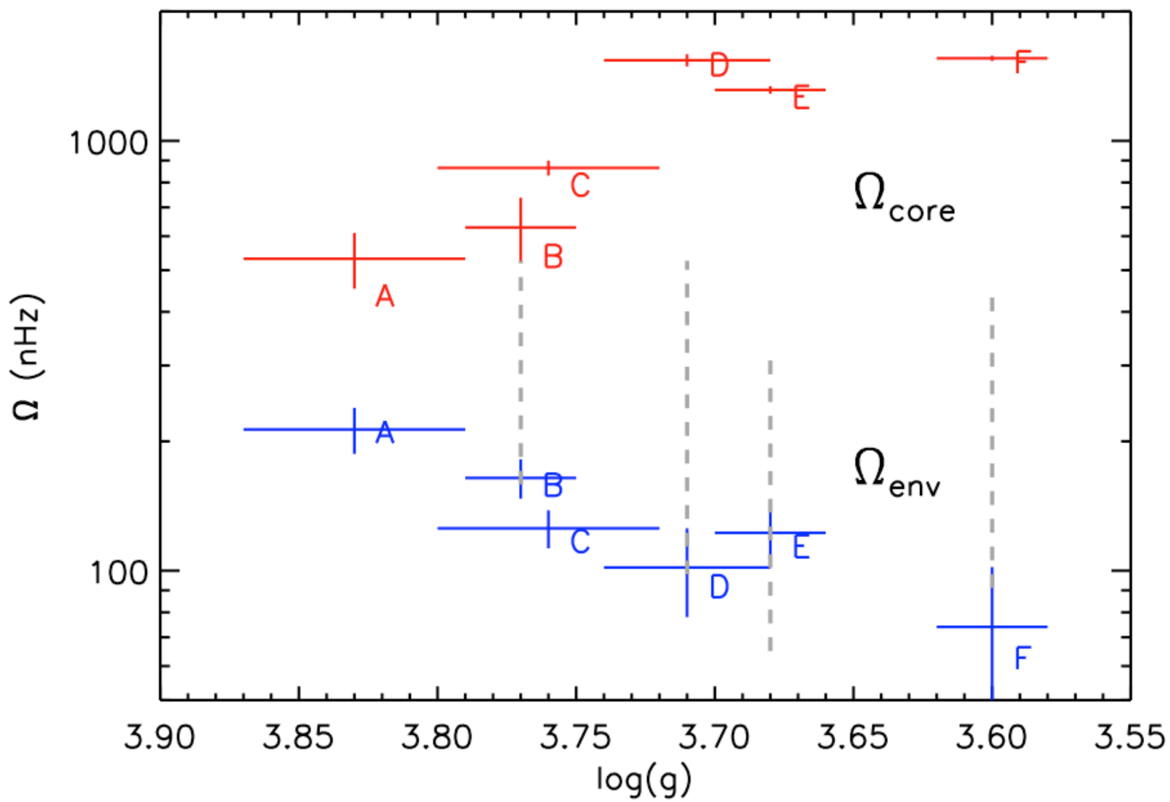
$\nu_{add} = 1.4 \pm 0.1 \cdot 10^4\ cm^2\ s^{-1}$

ν_{add} ↘ *when M* ↘



Asteroseismology of red giants

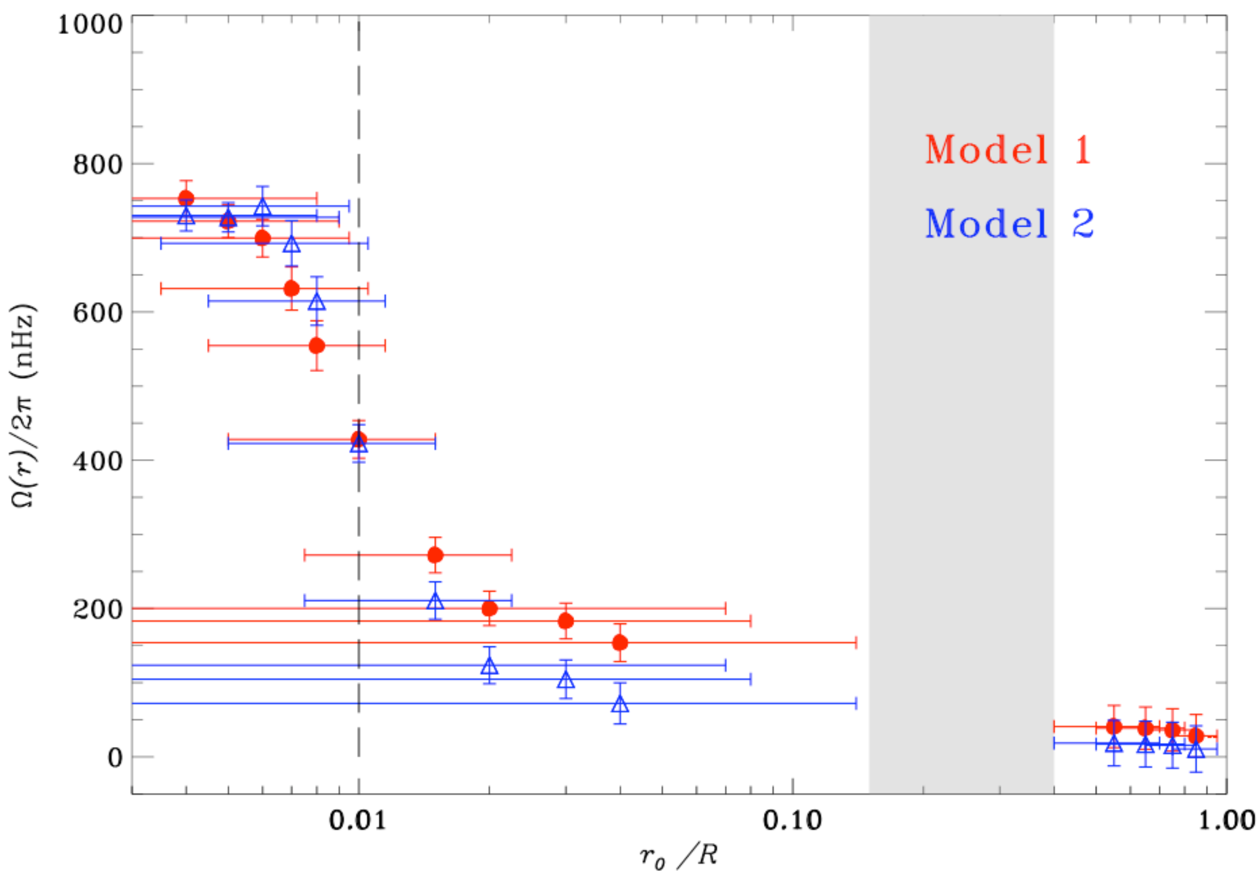
- Rotational splittings for 6 *Kepler* subgiants and young RGs
  - Core and surface rotation rates precisely determined
  - Increase of differential rotation when evolution proceeds?



Deheuvels et al. 2014

Asteroseismology of red giants

- Location of the angular velocity gradient
  - KIC 4448777 (Di Mauro et al. 2016) + 2 subgiants (Deheuvels et al. 2014)

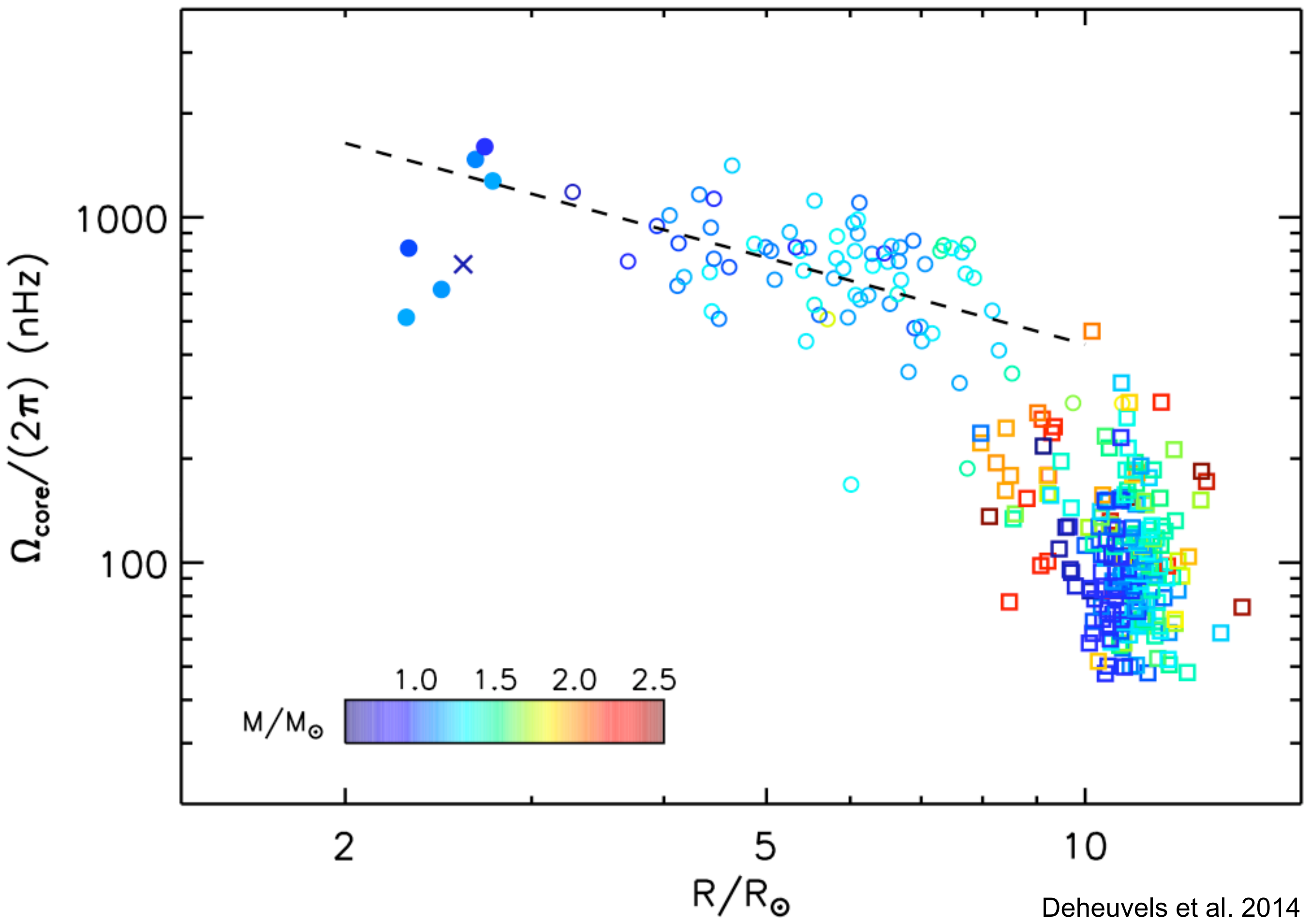


Di Mauro et al. 2016

  - $\delta\nu/\delta\nu_{max}$: differential rotation in the radiative zone (Klion & Quataert 2017)

Asteroseismology of red giants

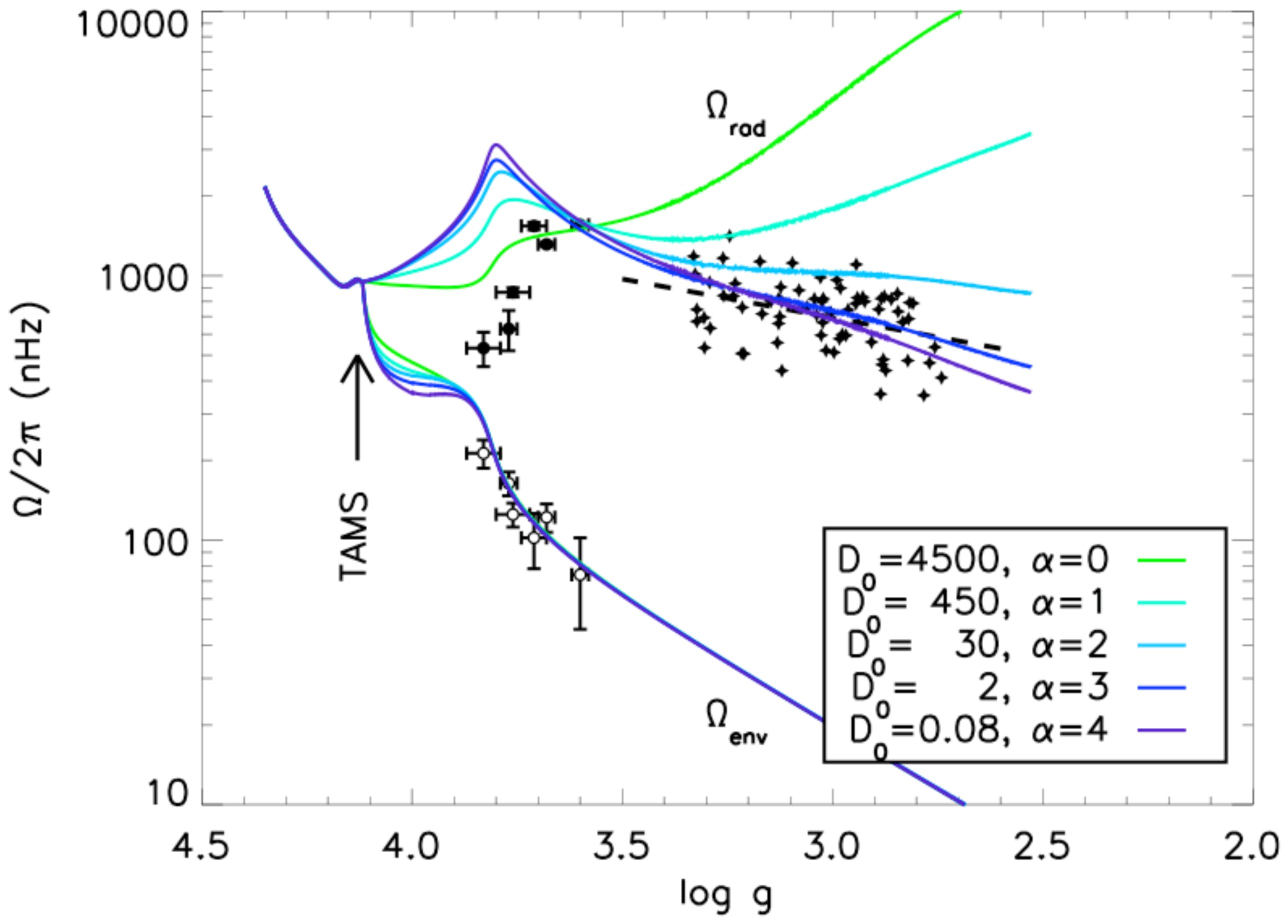
- Core rotation rates for a large number of evolved stars
  - Sample of Mosser et al. (2012) + Deheuvels et al. (2014)



Deheuvels et al. 2014

Asteroseismology of red giants

- Core rotation rates for a large number of evolved stars
  - Evolution of core rotation rates: red giants

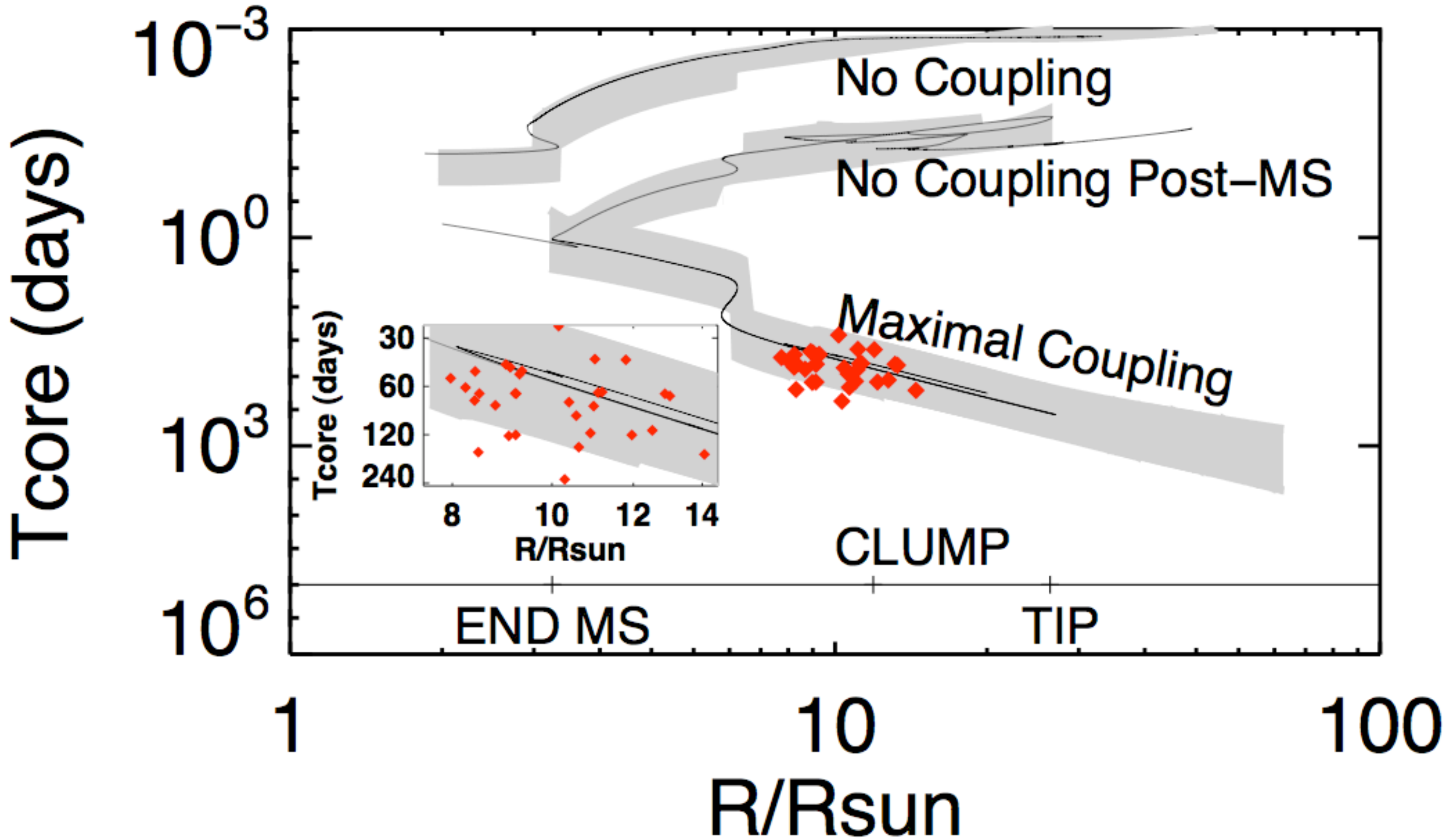


$$D = D_0 \left(\frac{\Omega_{rad}}{\Omega_{env}} \right)^{\alpha}$$

Spada et al. 2016

Asteroseismology of red giants

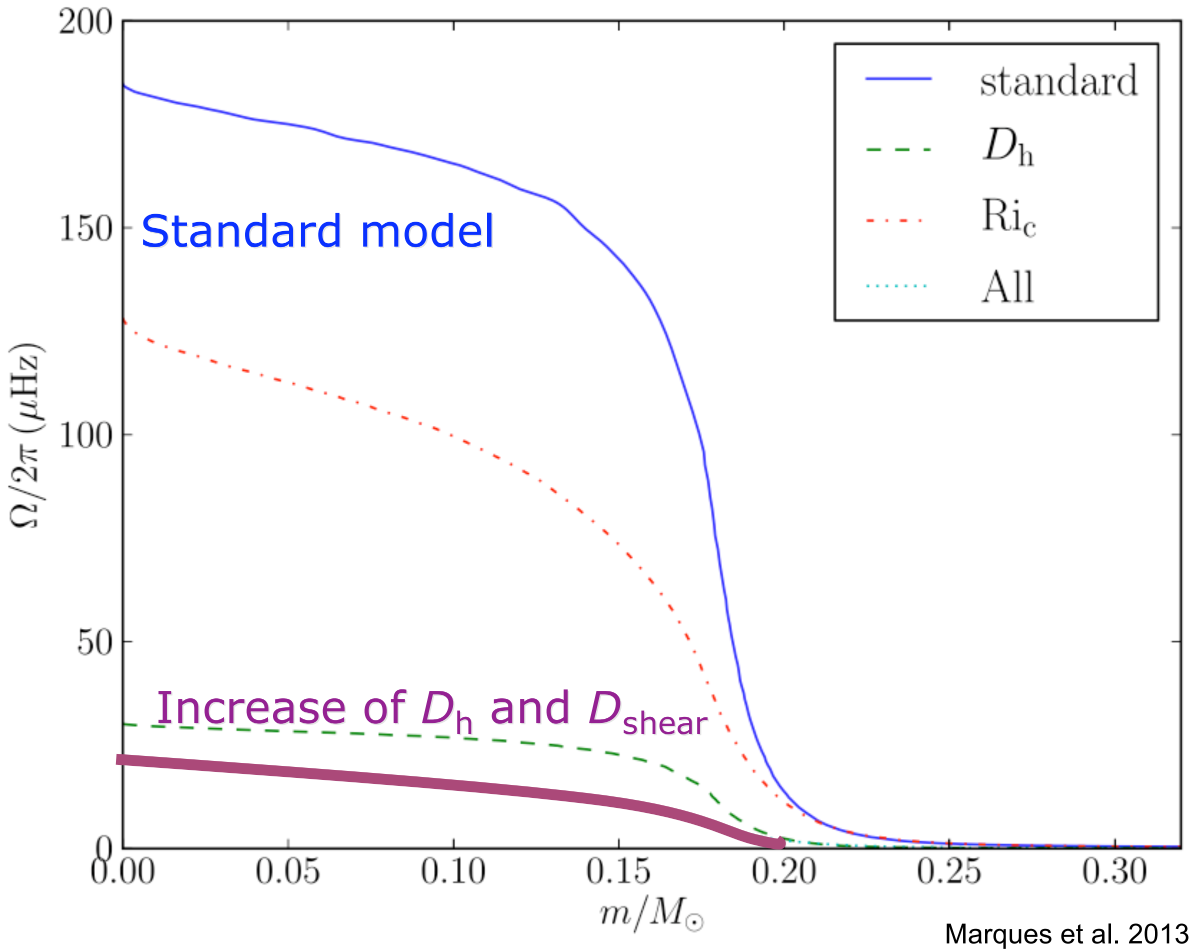
- Core rotation rates for a large number of evolved stars
  - Red giants burning helium in non-degenerate conditions



Tayar & Pinsonneault 2013

Asteroseismology of red giants

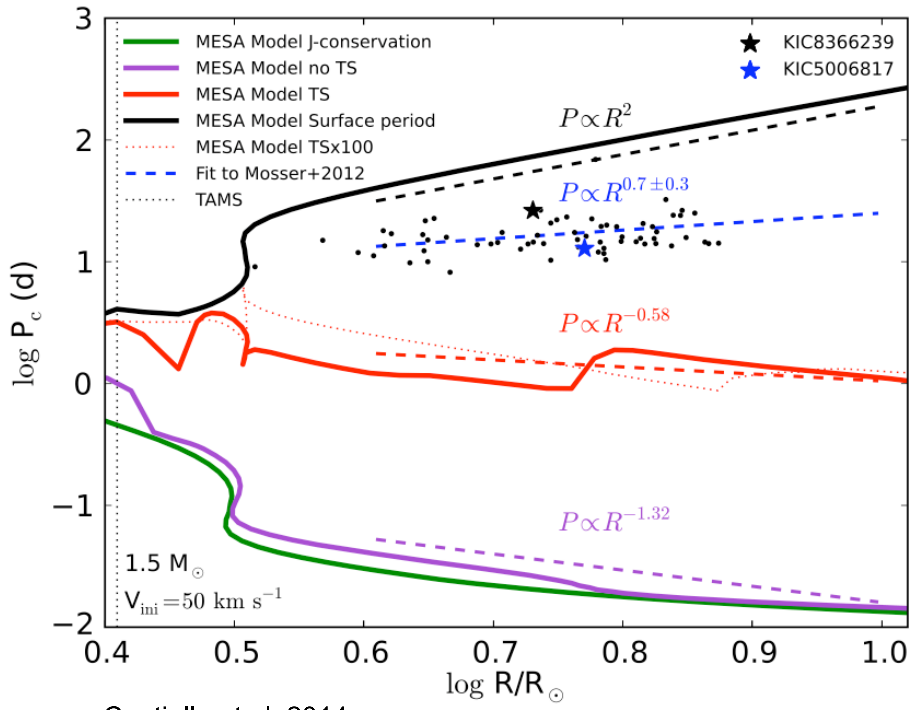
- Physical nature of the missing transport mechanism
  - Modelling of turbulence (Marques et al. 2013)



Marques et al. 2013

Asteroseismology of red giants

- Physical nature of the missing transport mechanism
  - Tayler-Spruit dynamo: predicted transport not efficient enough (Cantiello et al. 2014)

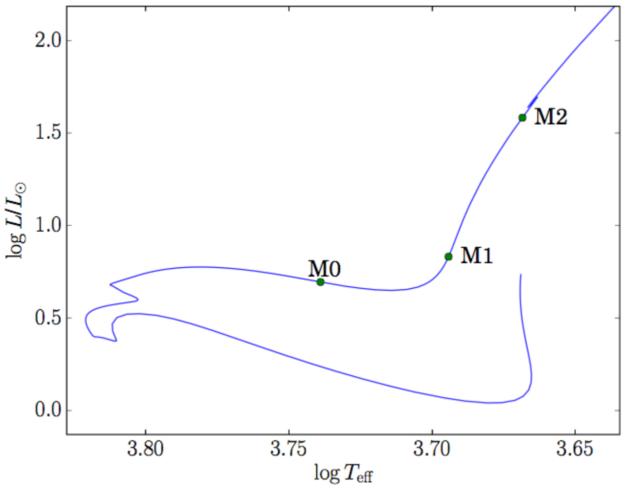


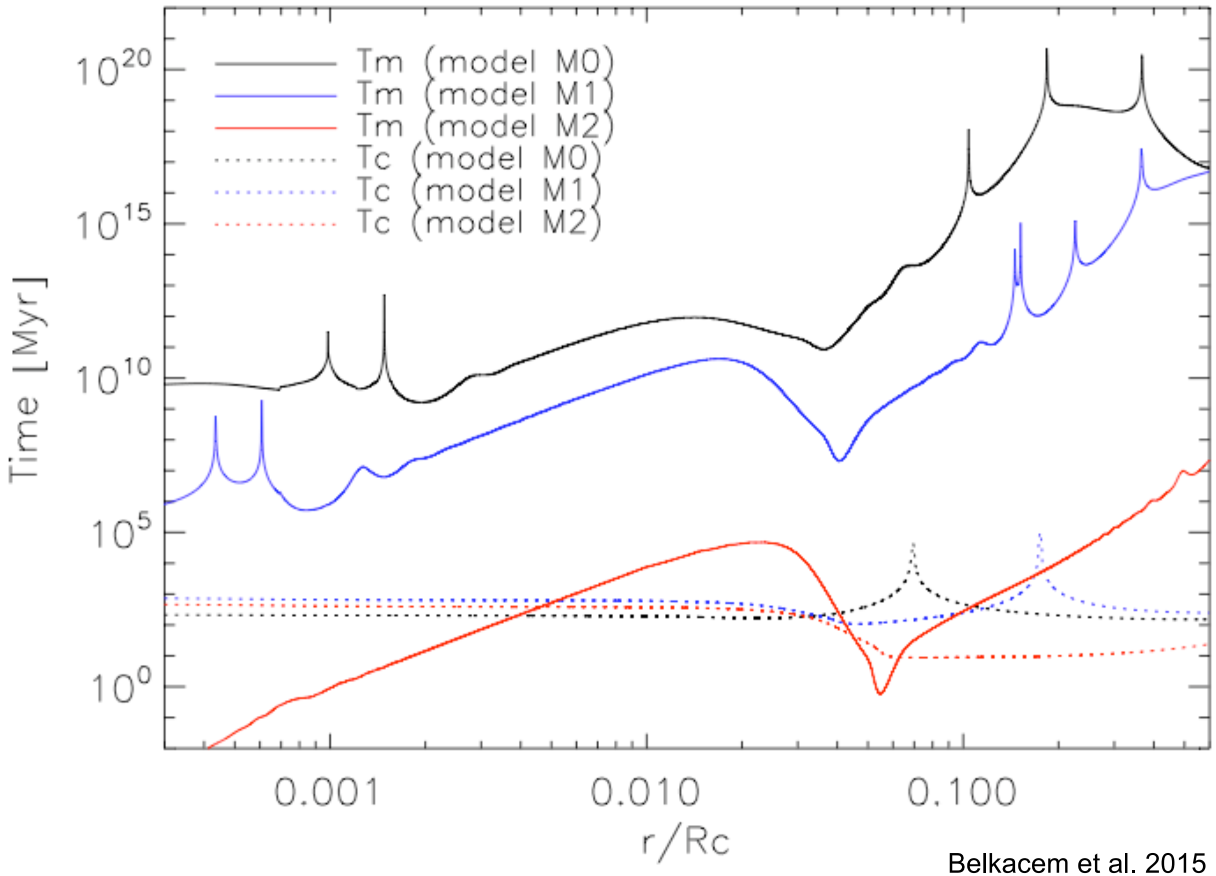
Cantiello et al. 2014

  - IGW generated by turbulent pressure: not efficient (Fuller et al. 2014)
  - IGW generated by penetrative convection: not efficient for red giants but efficient for subgiants (Pinçon et al. 2017)

Asteroseismology of red giants

- Physical nature of the missing transport mechanism
  - Transport of angular momentum by mixed modes





Belkacem et al. 2015

Summary

- Additional mechanism for the transport of angular momentum
  - Needed for the Sun and slowly rotating low-mass MS stars.
    Also needed for more massive/faster rotating MS stars?
  - Needed for subgiants and red giants

- Efficiency and physical nature of the additional mechanism
  - For subgiants and red giants: ν_{add} can be precisely determined
  - Red giants: ν_{add} ↗ with mass and evolutionary state
  - Magnetic fields: fossil fields? MHD instabilities: ν_{add} ok with AMRI
  - IGW: not for red giants. subgiants: penetrative convection
  - Mixed modes: efficient for evolved red giants