Asteroseismology and transport processes in stellar interiors

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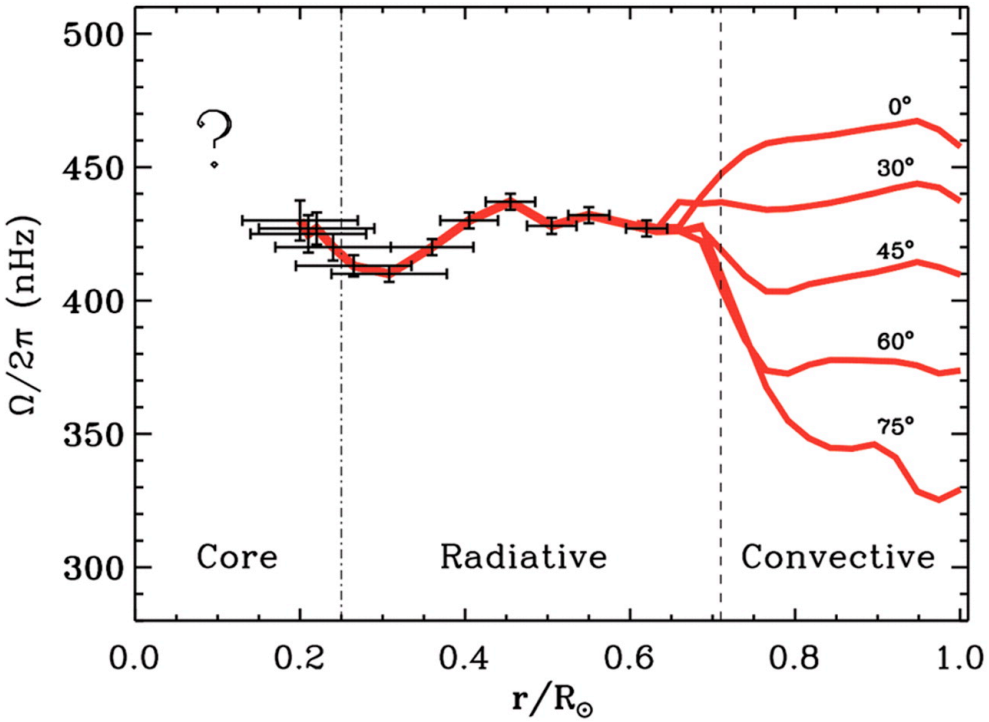
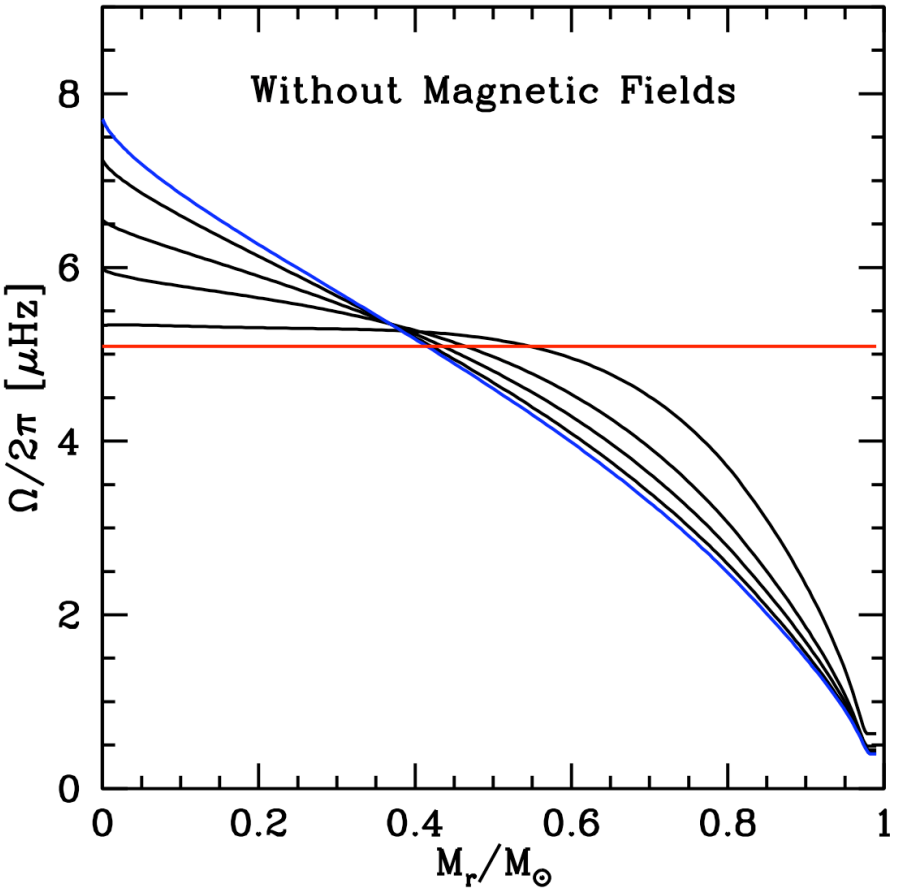
FACULTÉ DES SCIENCES

Asteroseismology of MS stars

- The solar rotation profile
  - Helioseismic measurements



Garcia et al. 2007, Science, 316, 1591

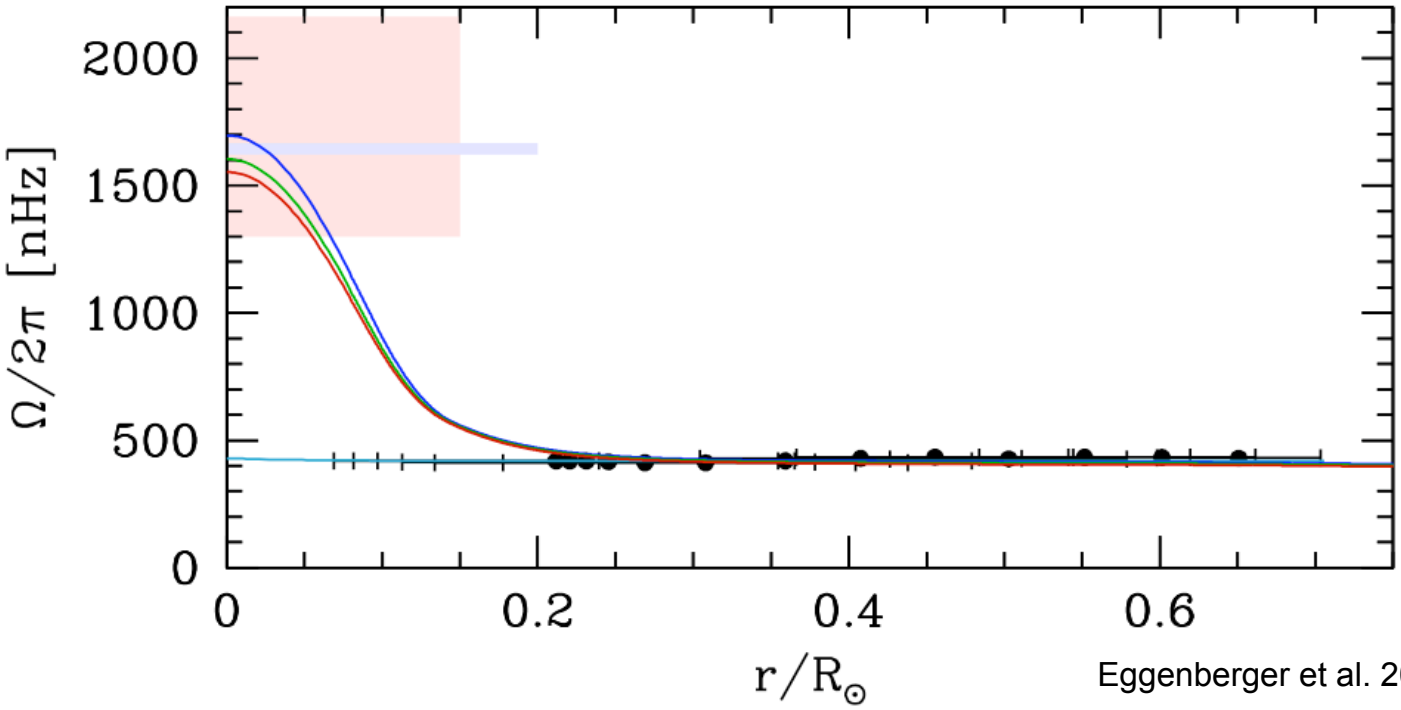


  - Inefficient transport by hydrodynamic processes

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

Asteroseismology of MS stars

- The solar rotation profile: magnetic fields
  - Steady internal field in radiative zones ?
    - issue: mechanical coupling to the convective zone
  - Small-scale dynamos in radiative zones ?
    - Tayler-Spruit: ✓ Braithwaite (2006); ✖ Zahn et al. (2007)
    - MRI (strong shears): Arlt et al. (2003); Rüdiger et al. (2014, 2015); Jouve et al. (2015)

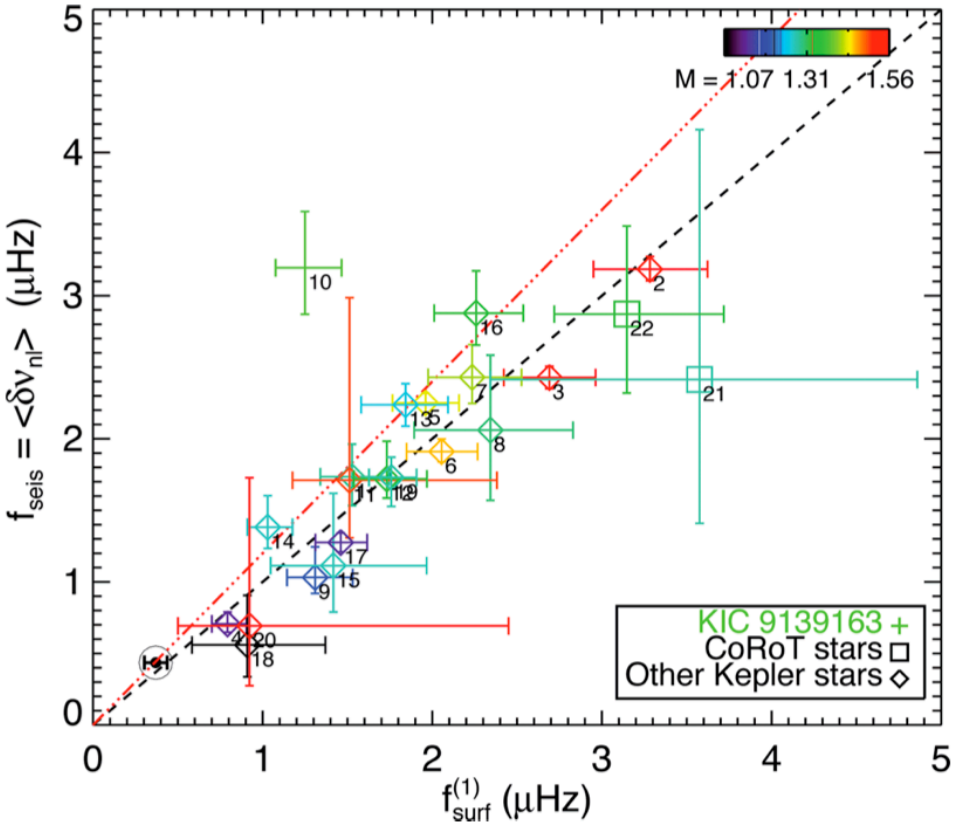


Eggenberger et al. 2019a, A&A, 626, L1

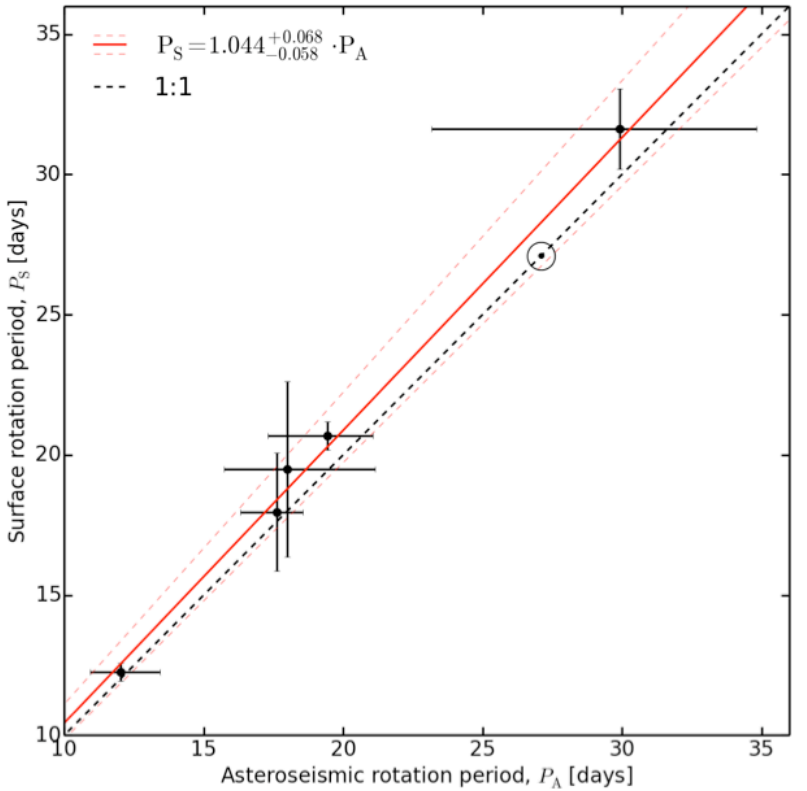
Asteroseismology of MS stars

- Solar-like oscillations in MS stars

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



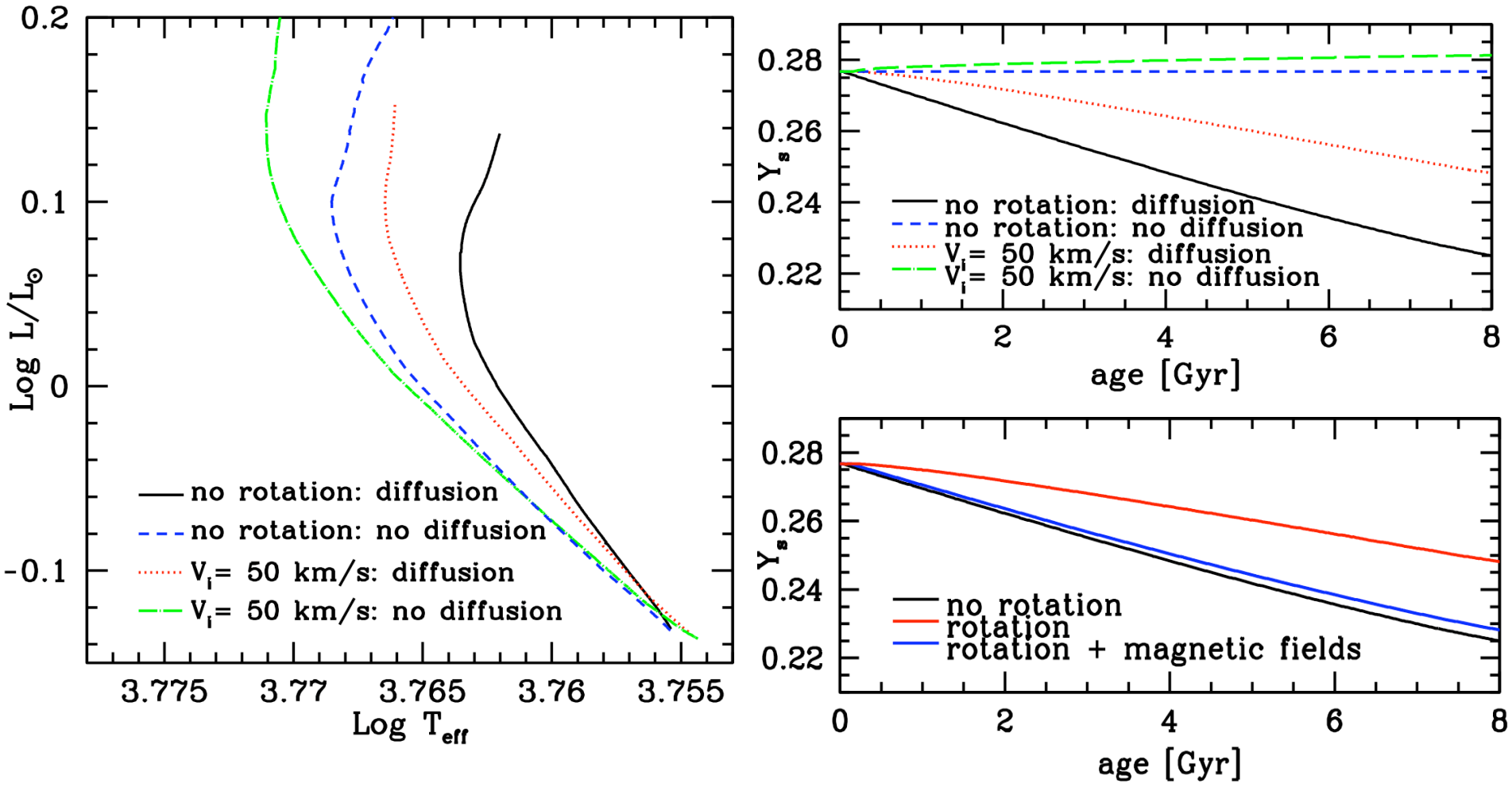
Benomar et al. 2015, MNRAS, 452, 2654



Nielsen et al. 2015, A&A, 582, A10

Asteroseismology of MS stars

- Impact of an efficient AM transport on rotating MS models



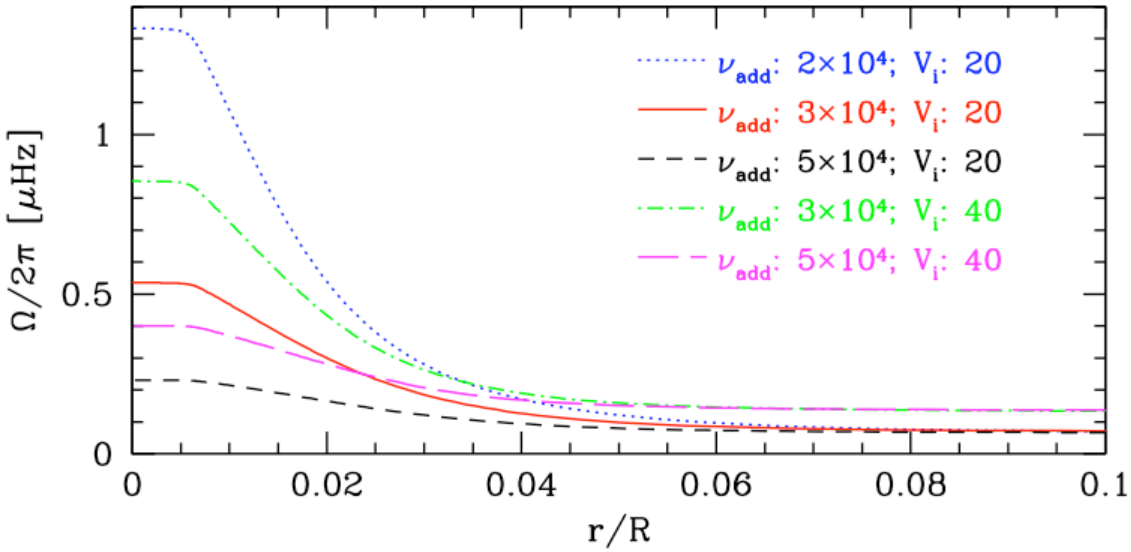
Eggenberger et al. 2010, A&A, 519, A116

Asteroseismology of red giants

- Mixed modes in the 1.5 $M_\odot$ red giant KIC 8366239 (Beck et al. 2012)
  - Inefficient AM transport by hydrodynamic processes
  - Efficiency of the needed additional mechanism can be precisely determined thanks to seismic constraints (Eggenberger et al. 2012)

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

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



Eggenberger et al. 2012, A&A, 544, L4

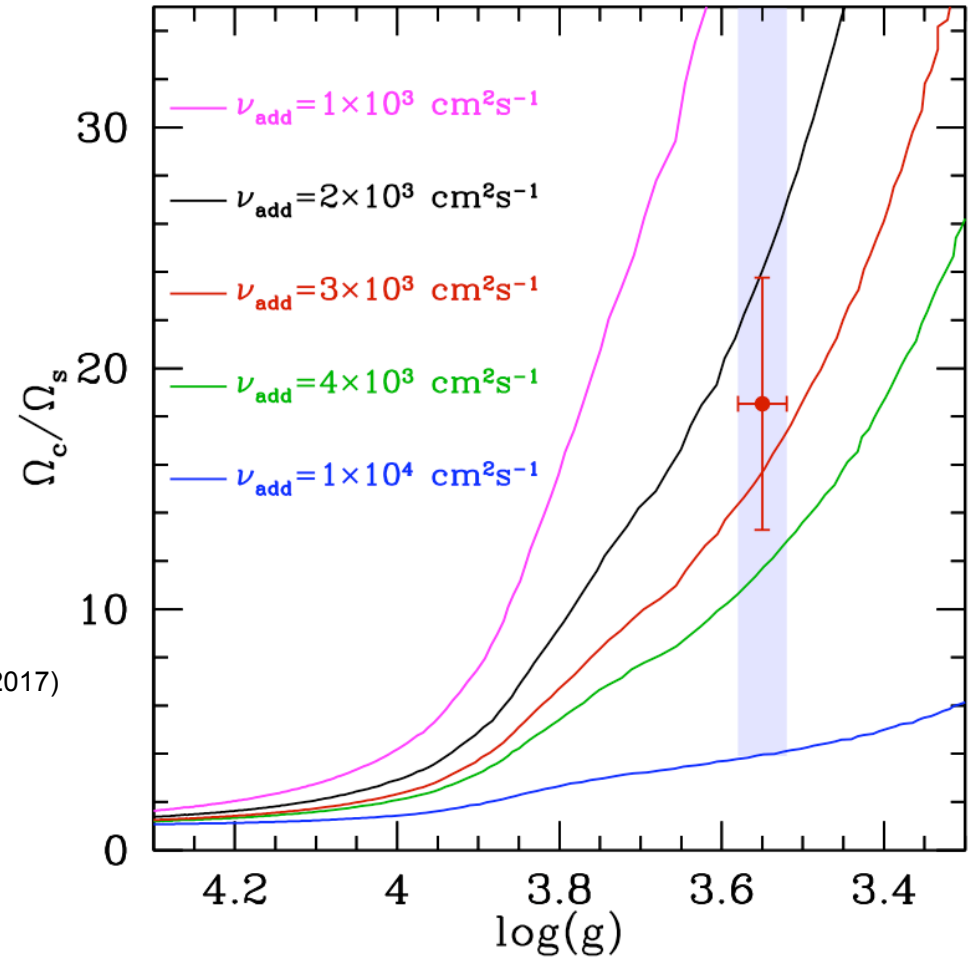
Asteroseismology of red giants

- KIC 7341231: a low-mass (0.84 $M_\odot$) red giant (Deheuvels et al. 2012, 2017)

Additional transport mechanism also needed for a star with a radiative core on the main sequence

$\nu_{add}=2\cdot10^3\text{-}4\cdot10^3\ cm^2\ s^{-1}$

ν_{add} ↘ *when M* ↘ (Eggenberger et al. 2017)

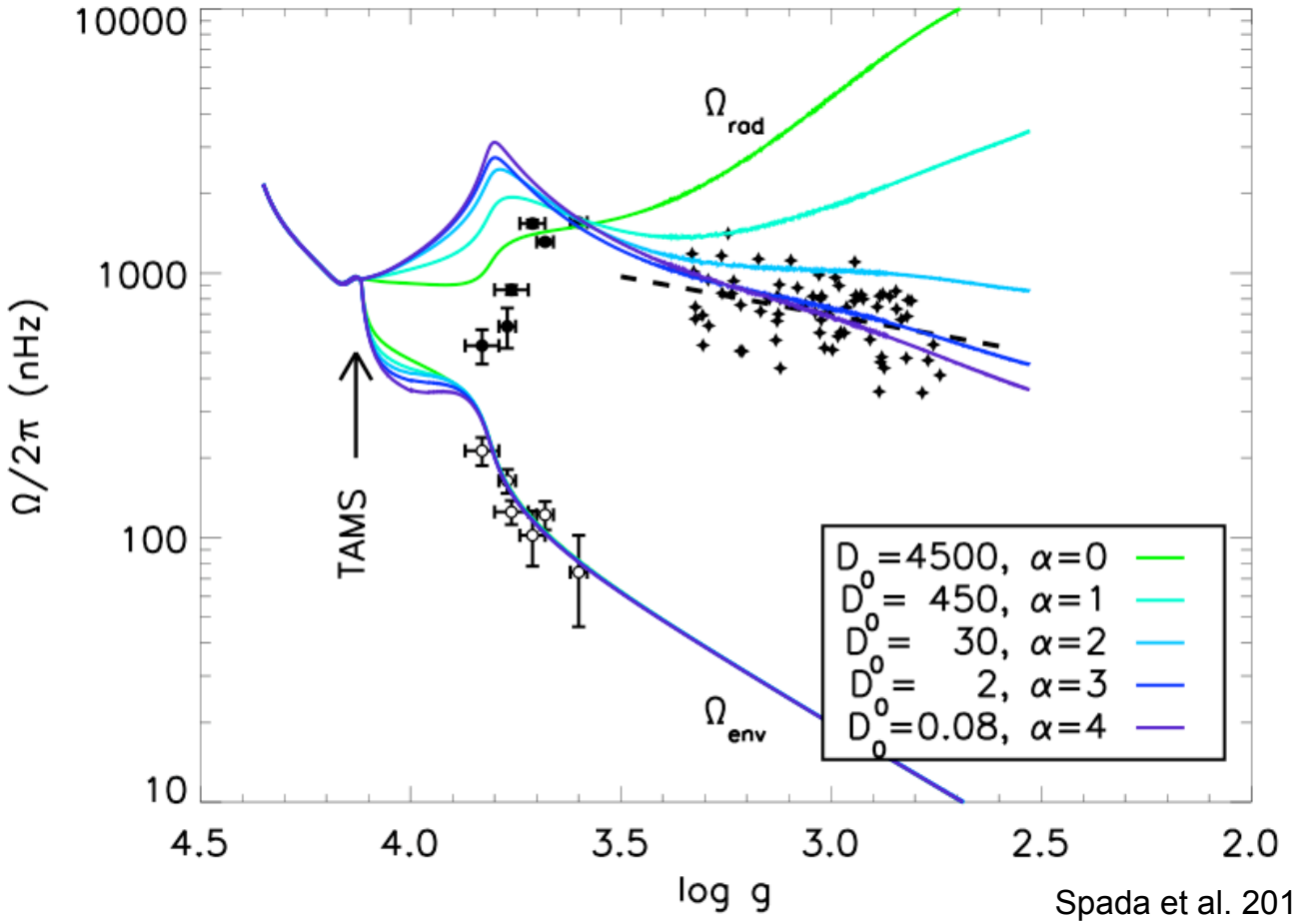


Asteroseismology of red giants

- Core rotation rates for a large number of evolved stars

Asteroseismic measurements: Mosser et al. (2012); Gehan et al. (2018)

ν_{add} increases with the evolution on the red-giant branch

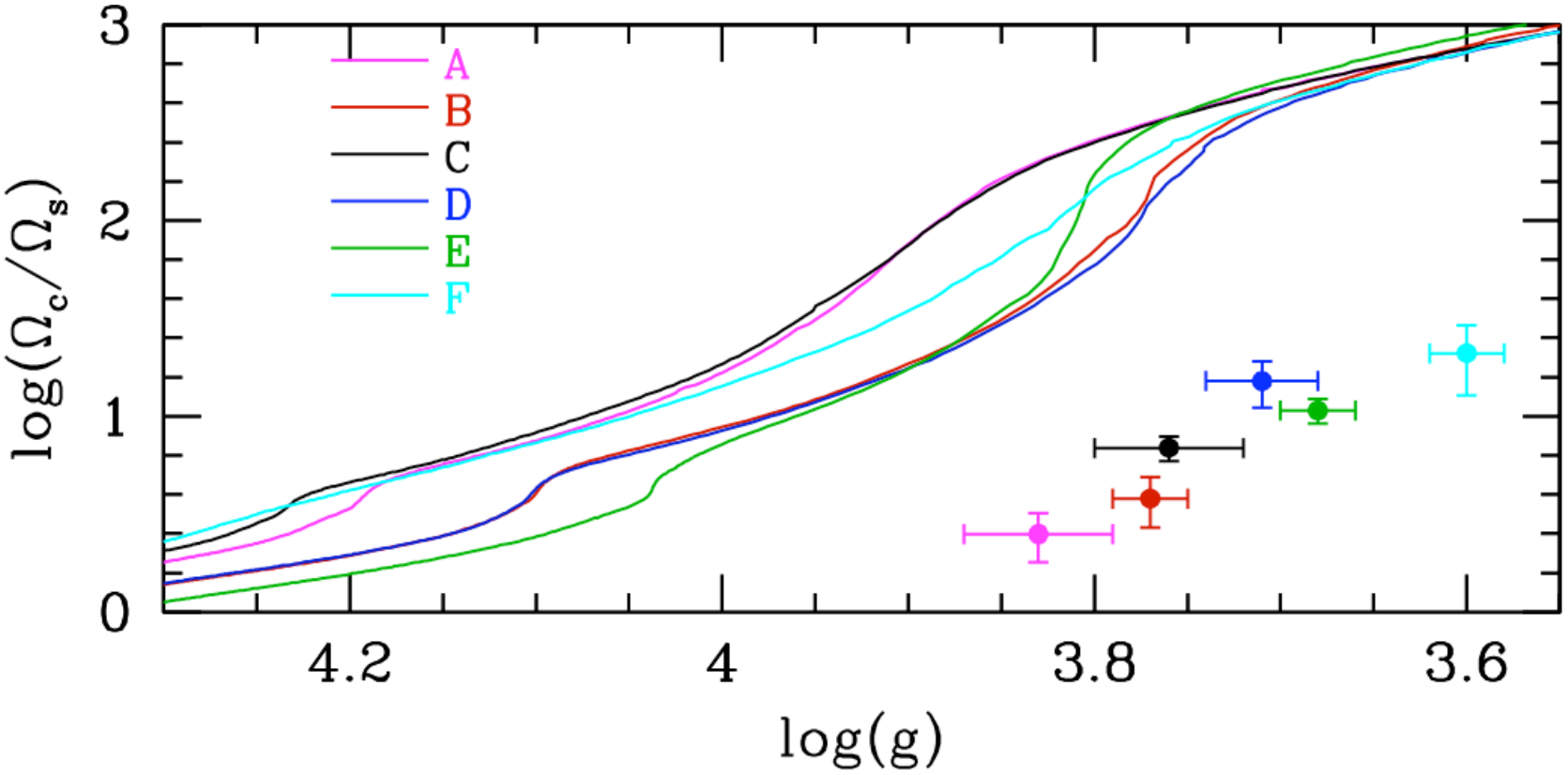


$$D = D_0 \left(\frac{\Omega_{rad}}{\Omega_{env}} \right)^{\alpha}$$

Spada et al. 2016, A&A, 589, A23

Asteroseismology of red giants

- Rotational splittings for 6 *Kepler* subgiants and young rgs
  - Additional transport also needed during the subgiant phase

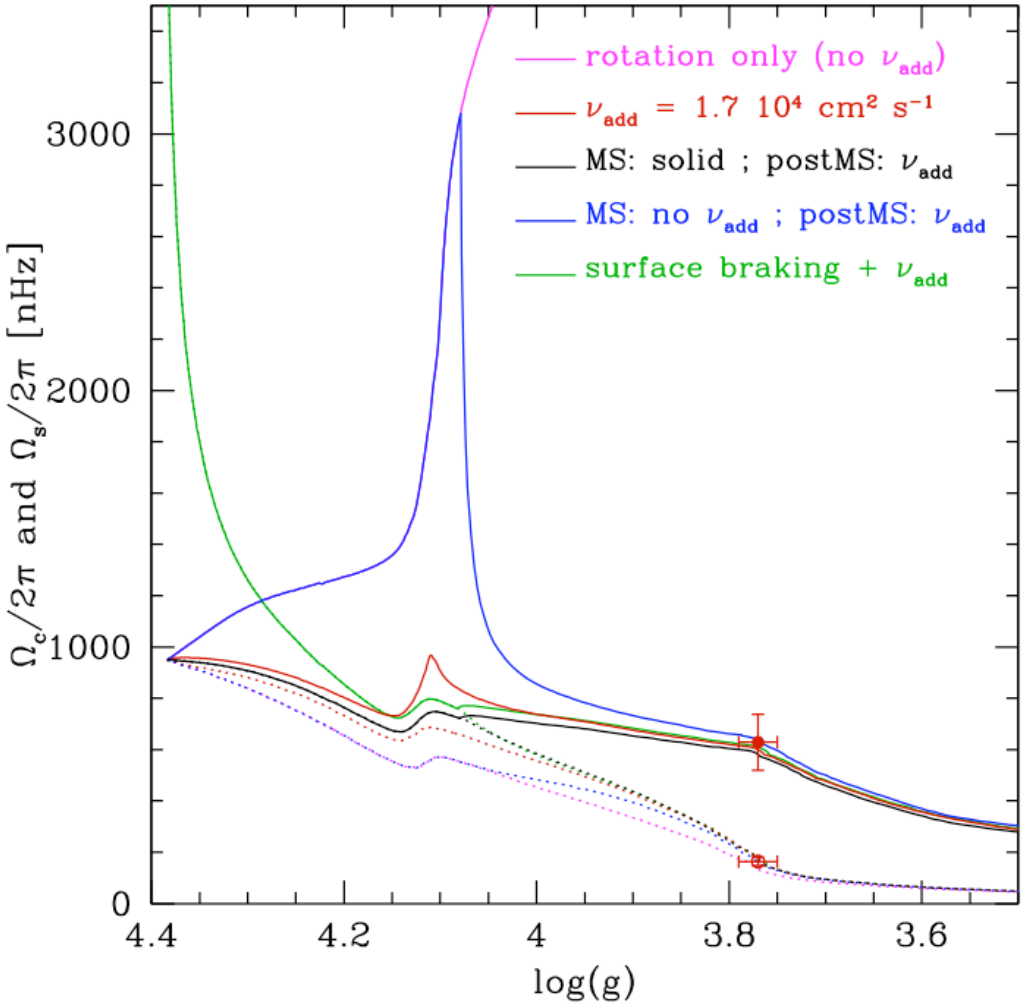


Eggenberger et al. 2019, A&A, 621, A66

Asteroseismology of red giants

- Rotational splittings for 6 *Kepler* subgiants and young rgs

Efficiency of the additional transport process during the subgiant phase is not sensitive to the rotational history of the star



Eggenberger et al. 2019, A&A, 621, A66

Asteroseismology of red giants

- Rotational splittings for 6 *Kepler* subgiants and young rgs

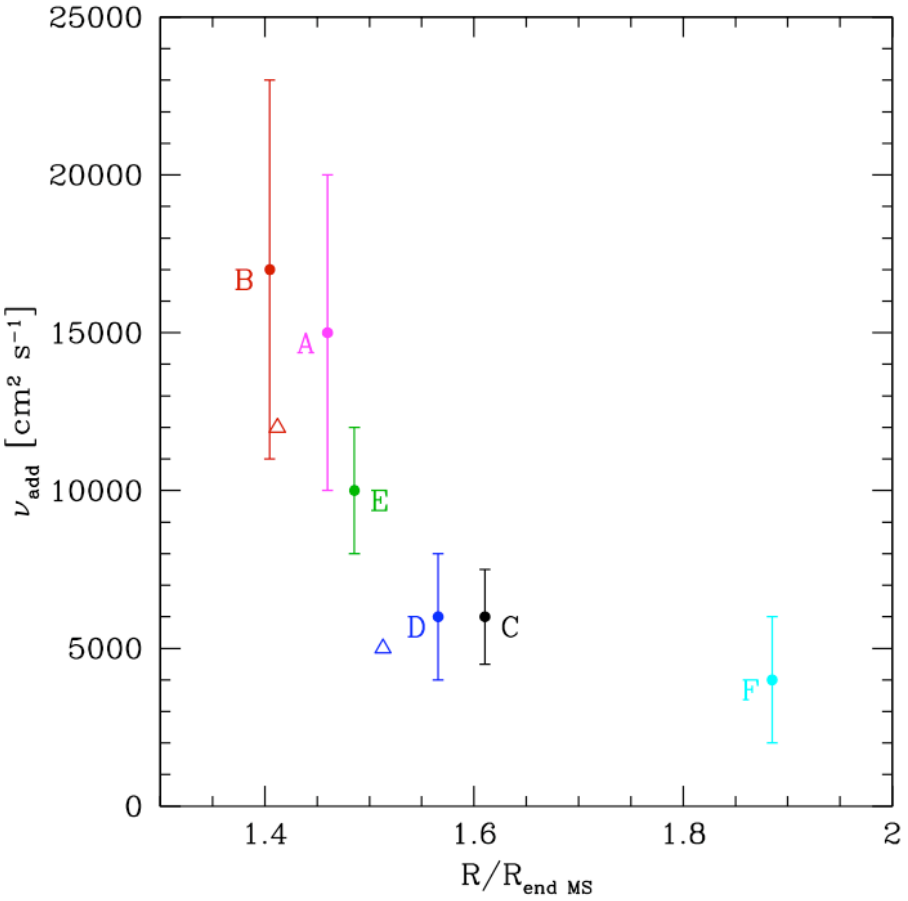
  Asteroseismic determination of AM transport efficiency:

Subgiants: ν_{add} ↗ with mass

and ↘ with evolutionary state

Red giants: ν_{add} ↗ with mass

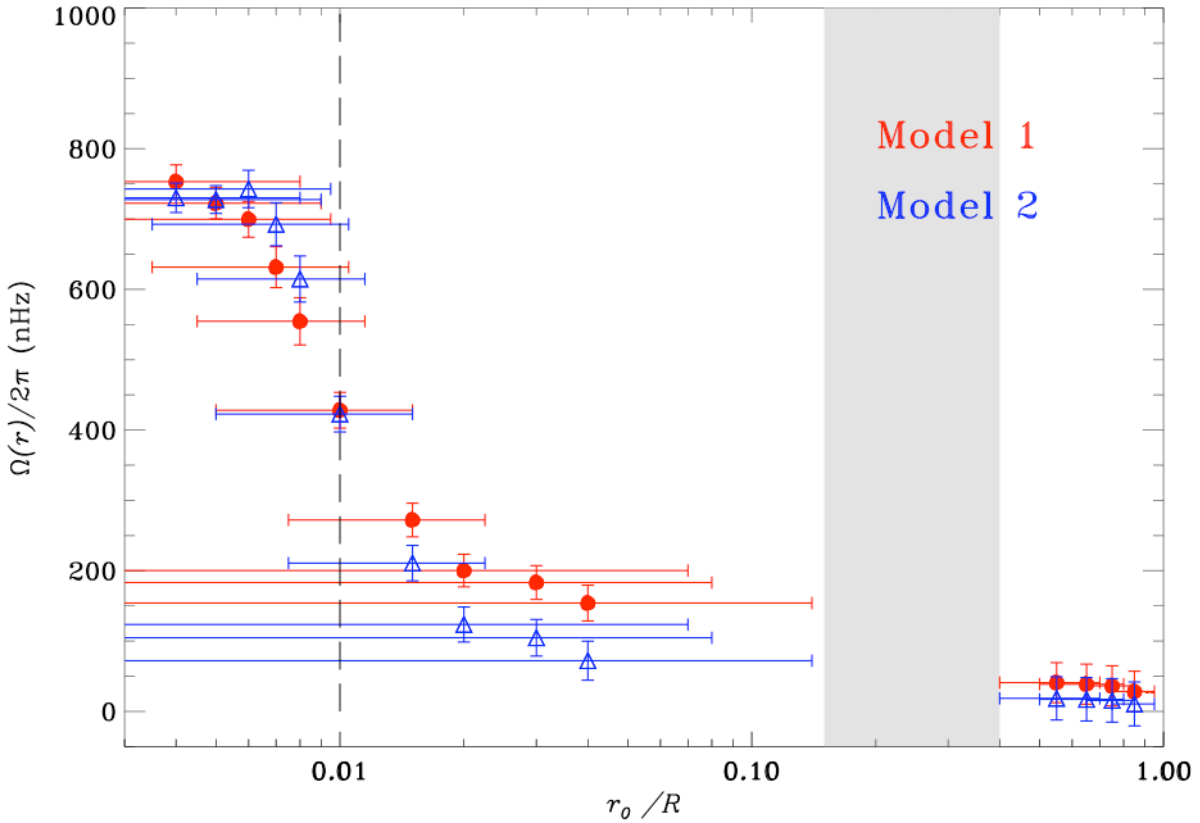
and ↗ with evolutionary state



Eggenberger et al. 2019, A&A, 621, A66

Asteroseismology of red giants

- Sharp discontinity in the rotation profiles of evolved stars
  - red giant KIC 4448777 (Di Mauro et al. 2016, 2018) + 2 subgiants (Deheuvels et al. 2014)



Di Mauro et al. 2018, ApJ, 862, 9

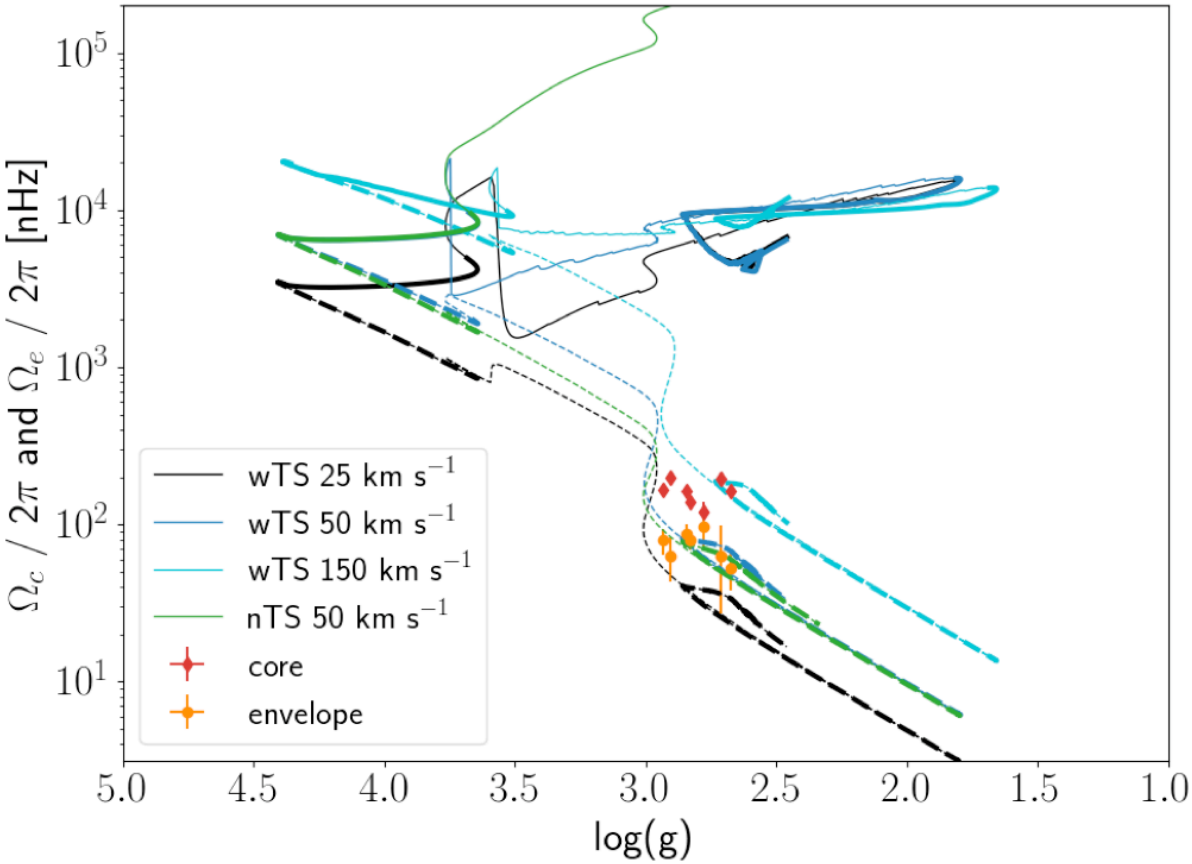
transport process with reduced efficiency when $\nabla_\mu \nearrow$?

Asteroseismology of red giants

- Physical nature of the missing transport mechanism

  Tayler-Spruit dynamo: not efficient enough (Cantiello et al. 2014; den Hartogh et al. 2019)

  For evolved 2.5 $M_\odot$ stars : $\nu_{add} \sim 10^7\ cm^2\ s^{-1}$

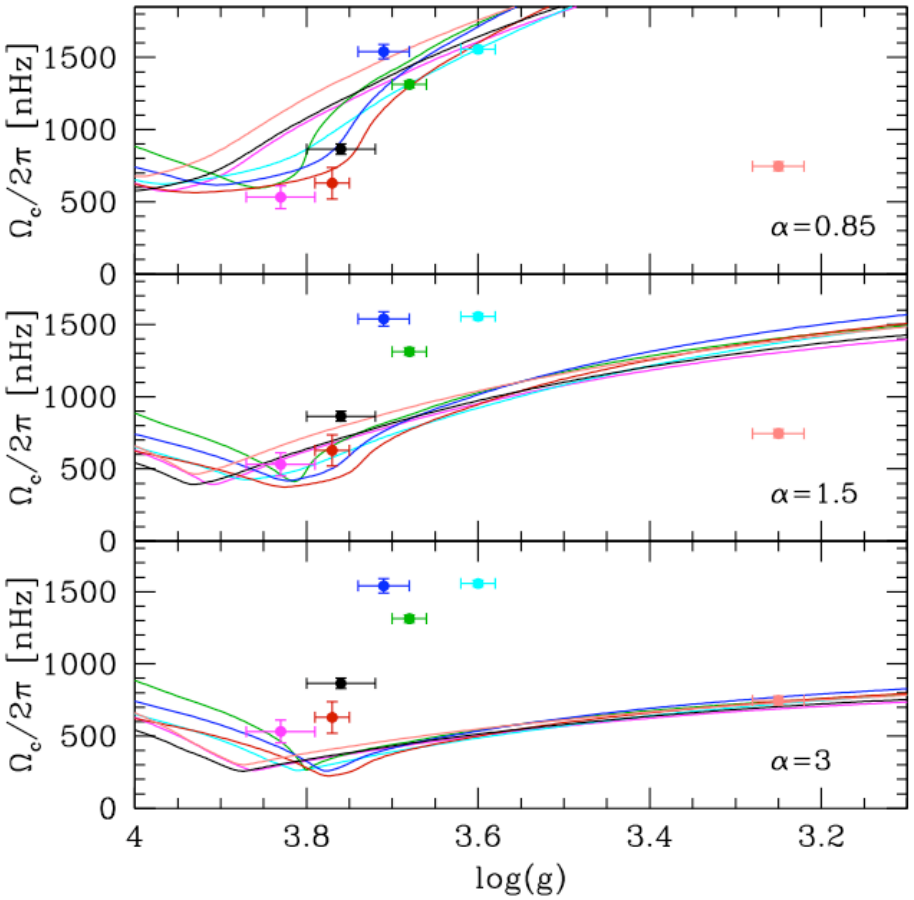


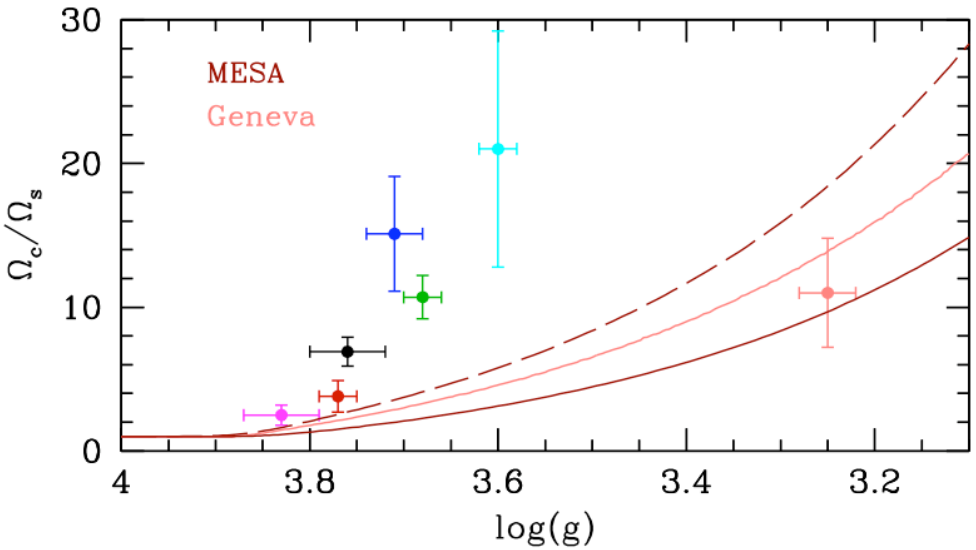
den Hartogh et al. 2019, A&A, 622, A187

Asteroseismology of red giants

- Physical nature of the missing transport mechanism

  Revised transport by the magnetic Tayler instability (Fuller et al. 2019)

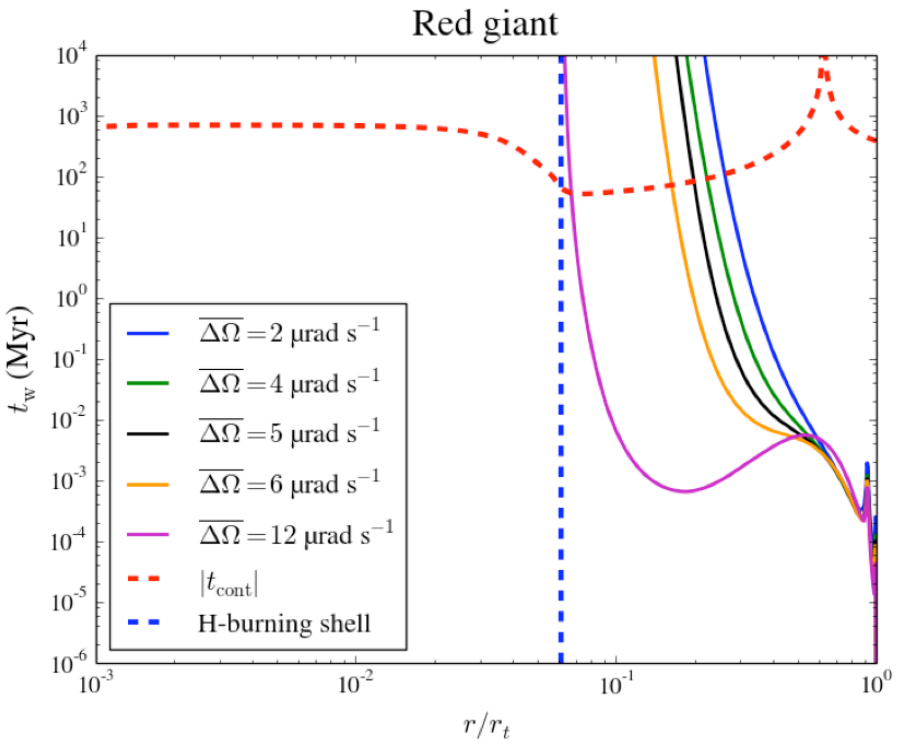


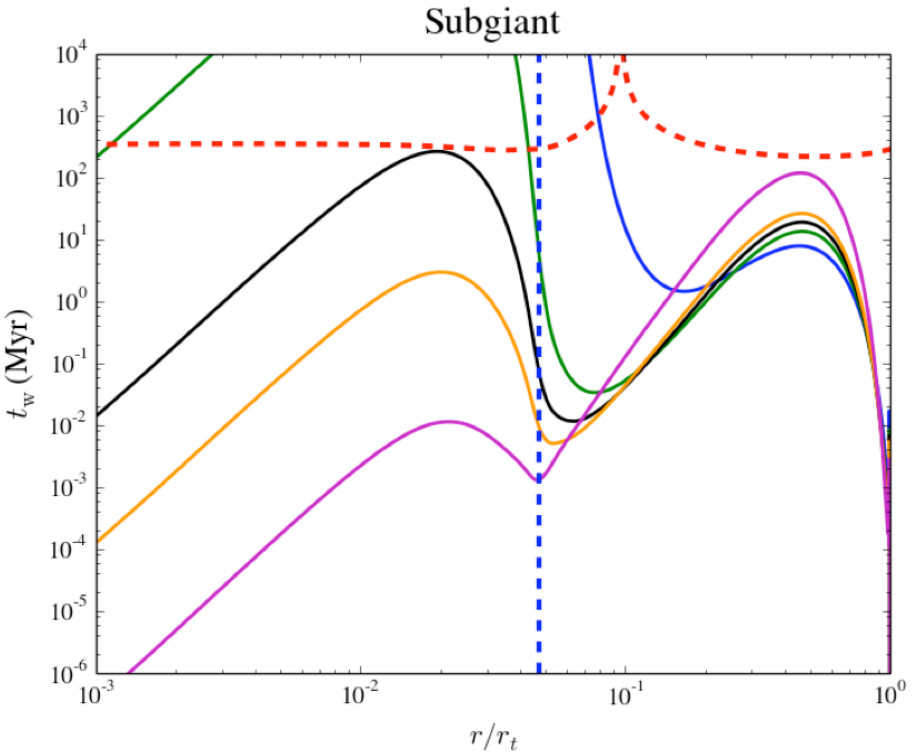


Eggenberger et al. 2019, A&A submitted

Asteroseismology of red giants

- Physical nature of the missing transport mechanism
  - 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)

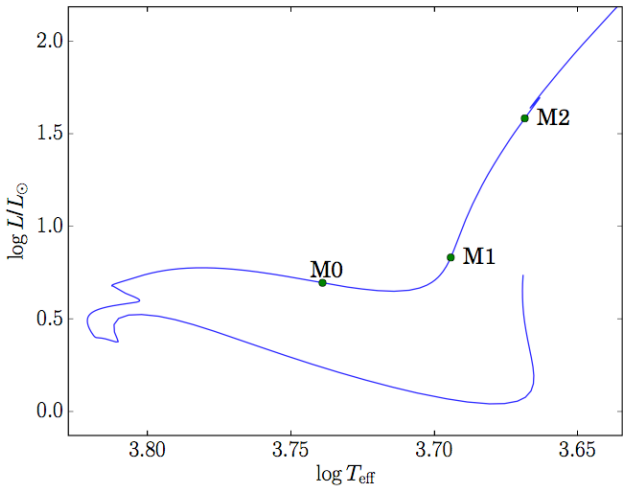


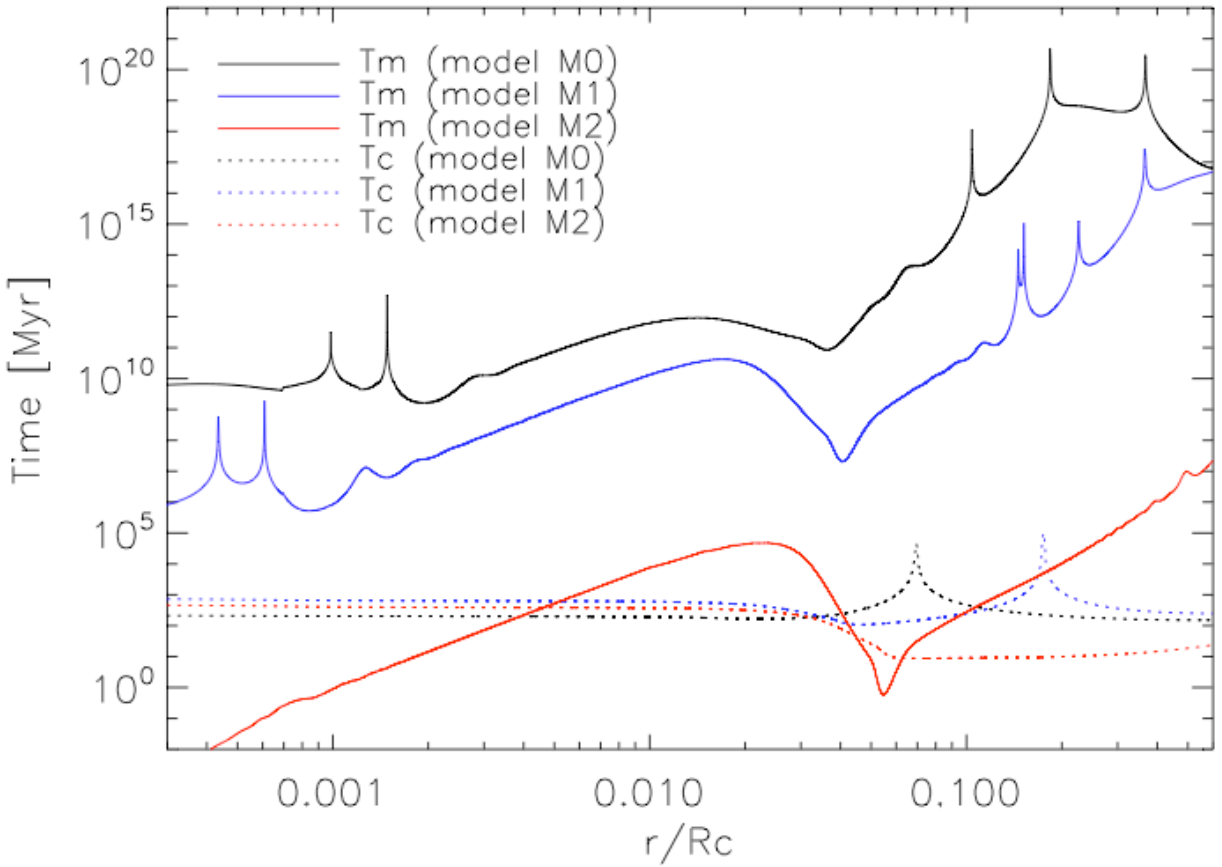


Pinçon et al. 2017, A&A, 605, A31

Asteroseismology of red giants

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





Belkacem et al. 2015, A&A, 579, A31

Summary

- Inefficient transport by hydrodynamic processes: an additional transport process is needed for the Sun, MS and post-MS stars
- The solar rotation profile: compatible with Tayler-Spruit dynamo
- Impact of an efficient AM transport on chemicals:
  - low-mass stars: chemical mixing is reduced
  - massive stars: efficient mixing possible: role of meridional circulation
- Red giants: ν_{add} ↗ with M and evolution: magnetic instabilities ?
- Subgiants: ν_{add} ↗ with M but ↘ with evolution: different transport processes during the MS and the post-MS phase ?