Seismology of γ**Dors** as a test for **angular momentum** transport models in stars

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EX-PARROT
The Aarhus-Sydney Gamma Dor stars EXperiment on PulsAtions and RROTation

Transport mechanisms in low mass stars: A long standing problem

Zahn (1992): the first self-consistent picture...

Transport mechanisms in low mass stars: A long standing problem

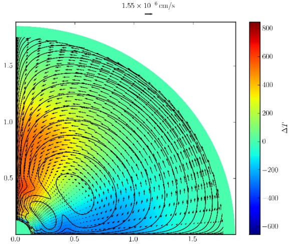
Zahn (1992): the first self-consistent picture...

- Transport of angular momentum (AM)
- Transport of chemicals

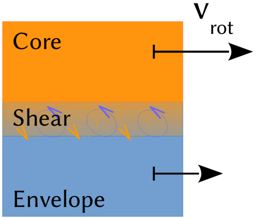
Structural evolution

Loss by magnetic winds

Meridional circulation



Shear induced turbulence



Transport mechanisms in low mass stars: A long standing problem

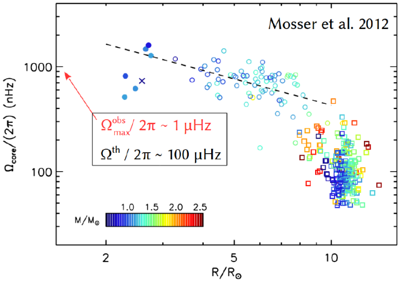
Zahn (1992): the first self-consistent picture...
Success... Until it was challenged by observations

→ Surface ^{7}Li abundances :
×No depletion !

→ Helioseismology :
Internal AM distribution
×Rigid rotation in the radiative envelope

→ Asteroseismology of red giants :
Core rotation rates
×Much too slow !

Red giants slow cores ≠ theory



⇒ Missing mechanism which counter-balances the meridional circulation and shear turbulence

A new challenge for AM transport models : Asteroseismology of γ Doradus stars

Intermediate mass 1.3 $M_\odot < M < 2\ M_\odot$

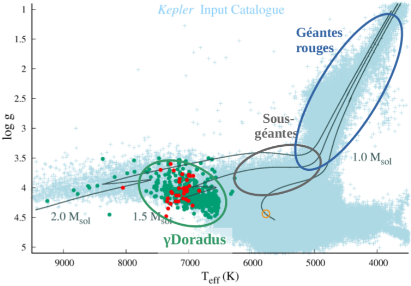
- progenitors of red giant stars

→ initial conditions for post-MS AM evolution

Spectral type: A3 → F3

- transition hot / cool stars

→ are they subject to magnetic braking ?



- A thousand of γ Doradus stars observed with *Kepler*

- **Measurement of rotation from g-modes series → Christophe et al. (2018) as test of angular momentum transport models**

Model of angular momentum transport

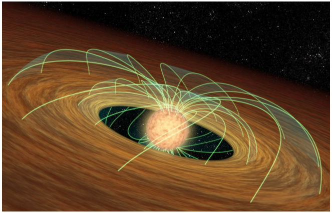
Stellar evolution models including transport of angular momentum
Based on the evolution code CESTAM (Marques et al. 2013)

Evolution of angular momentum (AM) from birthline to tip of the RGB :

1 • AM transport processes **2** • Initial AM content

$M < 2M_\odot \rightarrow$ T-Tauri stars on the PMS

Disk locking: (Bouvier et al. 1997)
star forced to corotate with the disk
at rotation period P_{disk} during time τ_{disk}



Initial angular momentum content : on the PMS

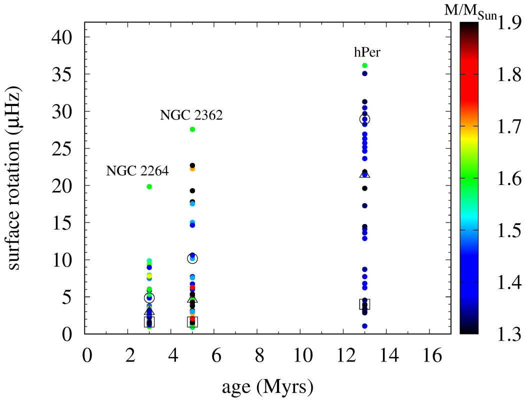
Disk locking: star forced to corotate with the disk at period P_{disk} during τ_{disk}

Initial conditions set by young clusters NGC 2264, NGC 2362 and hPer

Surface rotation

Data: Venuti+ 2017,
Irwin+ 2008, Moraux+ 2013

stars with $1.3M_{\odot} < M < 1.9M_{\odot}$



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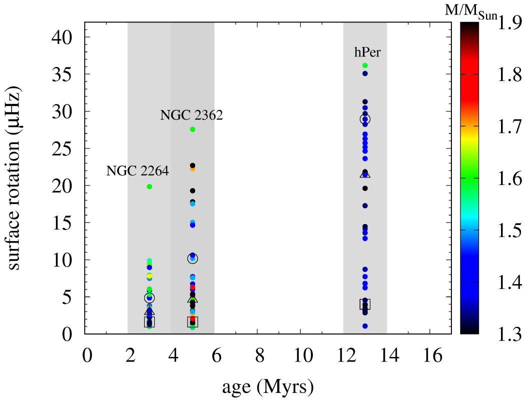

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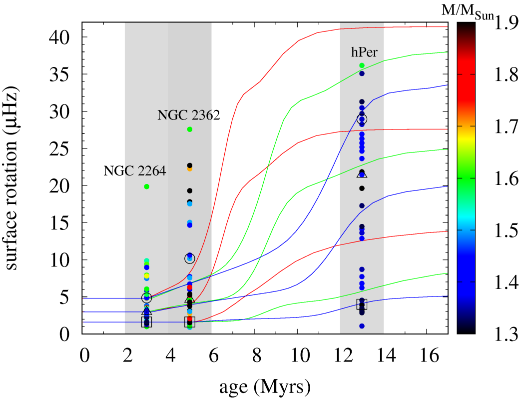
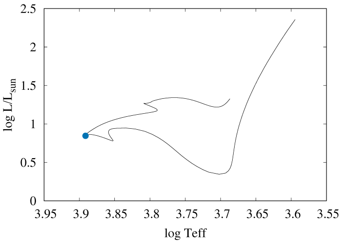
Disk locking with :
→ τ_{disk} = 3 Myrs, P_{disk} = 2.4 d
→ τ_{disk} = 3 Myrs, P_{disk} = 3.9 d
→ τ_{disk} = 5 Myrs, P_{disk} = 7.2 d

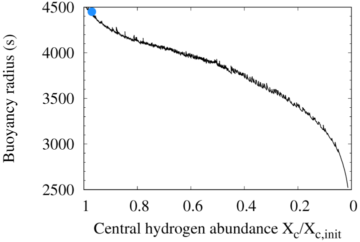


⇒ **Initial conditions compatible with surface rotation distributions in young clusters**

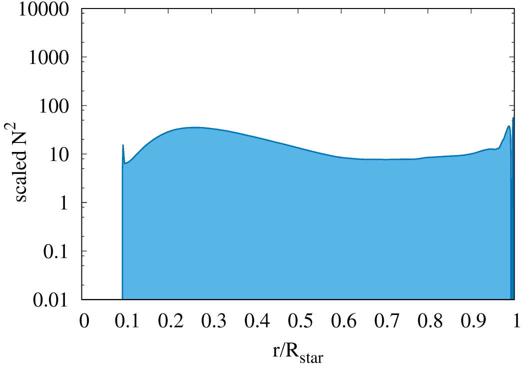
Model of angular momentum transport

Age indicator on the MS ?





The **buoyancy travel time**: $P_0 = 2\pi^2 \left(\int \frac{N}{r} dr \right)^{-1}$



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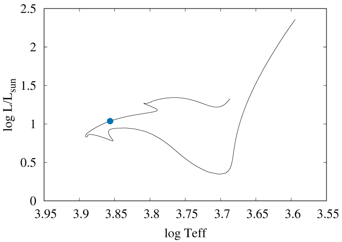

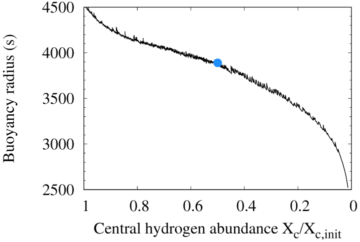

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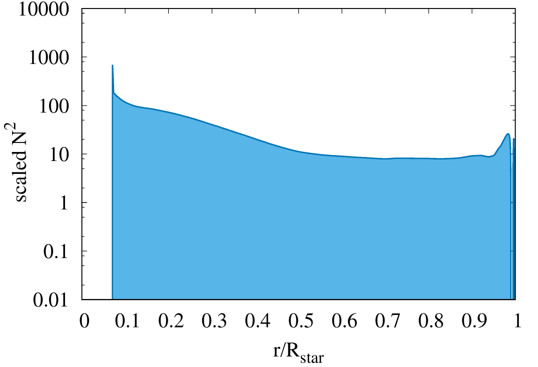

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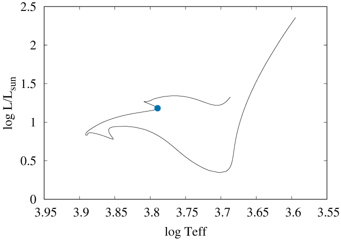

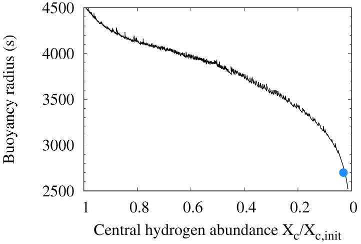

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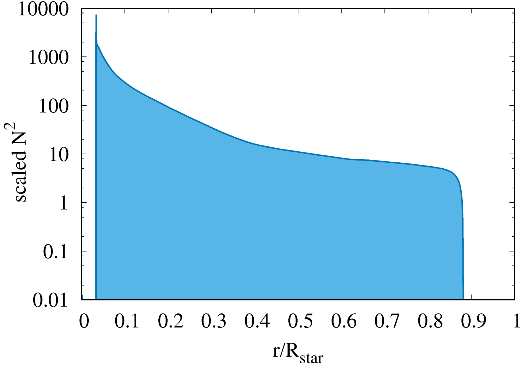
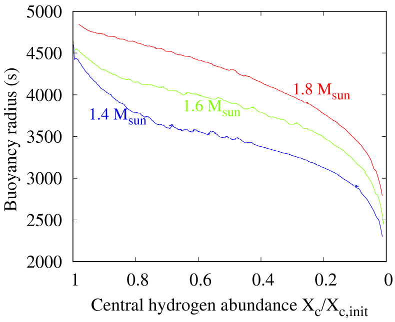


Observable P_0 monotonic decreasing function of evolution

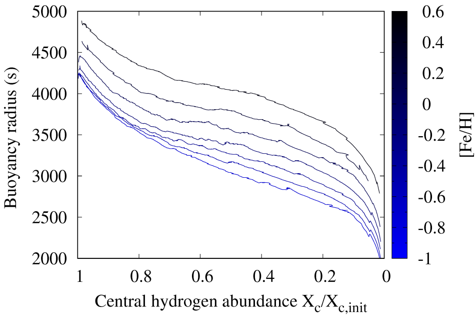
How to model the seismic observables P_0 and Ω_{rot} ?

- The buoyancy travel time : dependence on stellar parameters ?

Stellar mass



Stellar metallicity



⇒ **degeneracy between mass and metalicity to be handled carefully.**

How to model the seismic observables P_0 and Ω_{rot} ?

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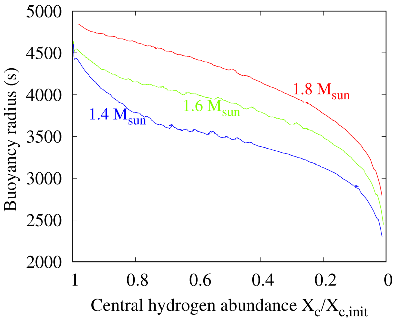
Stellar mass



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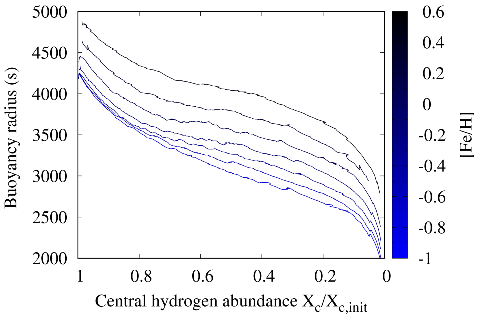
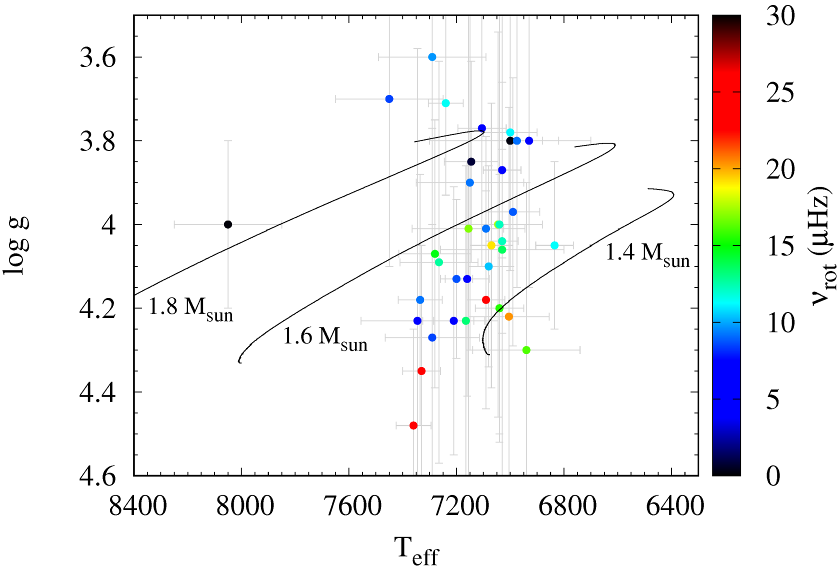


$\Rightarrow$ **degeneracy between mass and metalicity to be handled carefully.**

- Near-core rotation velocity :

$$<\Omega_{rot}> = \frac{\int_{gc} \Omega(r)\, N(r)\, \frac{dr}{r}}{\int_{gc} N(r)\, \frac{dr}{r}}.$$

Sample of observed stars



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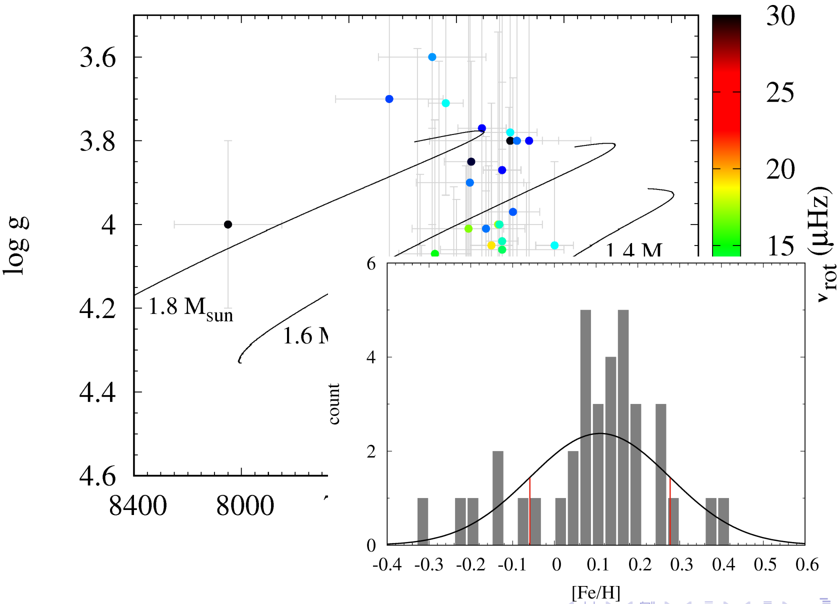

Angular momentum transport models VS observations

Transport by shear induced turbulence and meriodional circulation
Zahn (1992), Maeder & Zahn (1998), Talon + (1997), Mathis & Zahn (2004)

VS 37 γDoradus stars observed with *Kepler*

Models for :

- Metalicities: $-0.06 < [\mathrm{Fe/H}] < 0.27$
- Masses M= 1.4, 1.6, and 1.8 $M_\odot$
- Evolution from PMS up to TAMS
- Initial conditions for disk locking :

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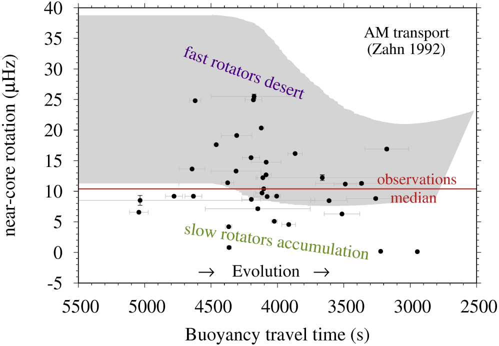

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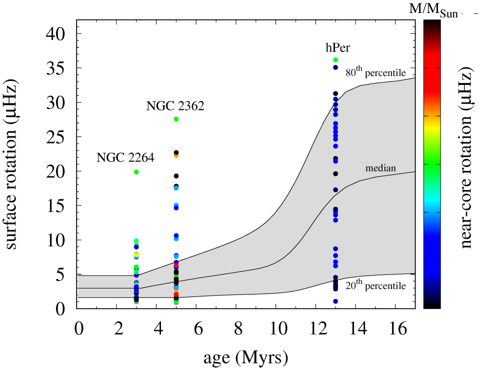

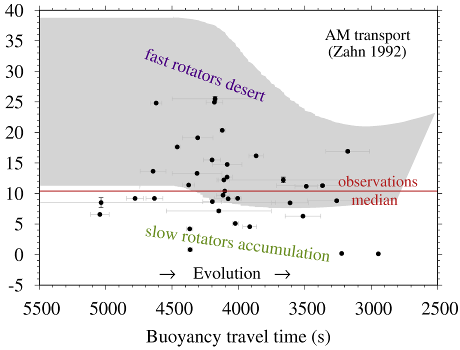

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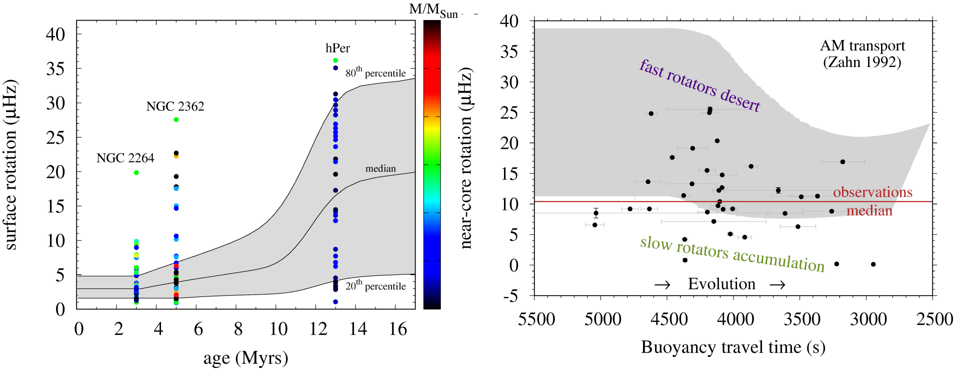


⇒ Disagreement: Observations systematically show slower rotation than models

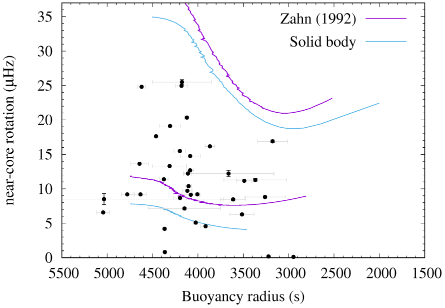
Looking for the missing AM transport process

Extremely efficient transport → enforces **solid body rotation**

VS 37 γDoradus stars observed with *Kepler*

Models for M= 1.6$M_\odot$:

- [Fe/H] = −0.06,
  and τ_{disk}= 3 Myrs, P_{disk}= 2.4 d
- [Fe/H] =0.27,
  and τ_{disk}= 5 Myrs, P_{disk}= 7.2 d



⇒ **Better agreement in the low rotation regime**

Looking for the missing AM transport process

Transport by shear induced turbulence and meriodional circulation
within Zahn (1992) but with increased **horizontal** turbulent viscosity ν_h

VS 37 γDoradus stars observed with *Kepler*

Transport with $\nu_h \times 10^2$
$\nearrow$ advection by meridional circulation

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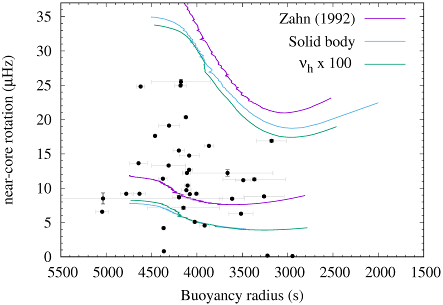

$\Rightarrow$ **Transport with $\nu_h \times 10^2$ mimicks solid rotation and agrees better**

Looking for the missing AM transport process

Transport by shear induced turbulence and meriodional circulation
+ **missing mechanism** which acts as an additional vertical turbulent viscosity $\nu_{v,add}$

VS 37 γDoradus stars observed with *Kepler*

$$\rho \frac{\mathrm{d}}{\mathrm{d}t}\left(r^2\Omega\right) = \frac{1}{5r^2}\frac{\partial}{\partial r}\left(\rho r^4 \Omega U_2\right) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho r^4 (\nu_{\mathrm{v}} + \nu_{\mathrm{v,add}} \frac{\partial \Omega}{\partial r}\right),$$

Transport with $\nu_{v,add} = 10^8 cm^2/s$
↗ diffusion of AM

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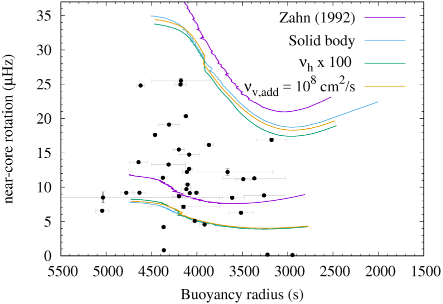

⇒ **Transport with $\nu_{v,add} = 10^8$ mimicks solid rotation and agrees better**

Questions raised and perspectives

$\mathbf{Q}_1$ Completeness of the observed sample ?
→ Few hundreds of seismic spectra un-exploited (EX-PARROT collab.)
→ Full automation of the P_0, ν_{rot} extraction method (Christophe et al. 2018)

$\mathbf{Q}_2$ Solid body can explain the measured rotation in γ Dors...
→ need seismic test of differential rotation: multiple series of g-modes

$\mathbf{Q}_3$ Can intermediate mass stars sustain a solar type dynamo and generate magnetized winds ?
→ Test different magnetic braking efficiency (Matt et al. 2015)
→ Magnetic field detection survey in γ Doradus stars (@ CFHT)

$\mathbf{Q}_4$ Can internal gravity waves transport the angular momentum ?
→ IGW generated by penetrative convection (core and envelope) in CESTAM

Observations of γ Doradus stars suggest an additional transport process which spins down their core

Ouazzani et al. (2018)

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Stellar evolution models including transport of angular momentum
Based on the evolution code CESTAM (Marques et al. 2013)

Evolution of angular momentum (AM) from birthline to tip of the RGB :

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2 • Initial AM content

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• Transport of chemicals Chaboyer & Zahn (1992) :

$$\frac{\mathrm{d}X_i}{\mathrm{d}t} = \frac{\partial}{\partial m}\left[\left(4\pi r^2 \rho\right)^2 (D_v + D_{eff}) \frac{\partial X_i}{\partial m}\right] + \left.\frac{\mathrm{d}X_i}{\mathrm{d}t}\right)_{\mathrm{nucl}} + \left.\frac{\mathrm{d}X_i}{\mathrm{d}t}\right)_{\mathrm{micro}}.$$

Prescriptions :

- meridional circulation components: Maeder & Zahn (1998)
- horizontal turbulent coefficients: Mathis & Zahn (2004)
- vertical turbulence coefficients : Talon et al. (1997)

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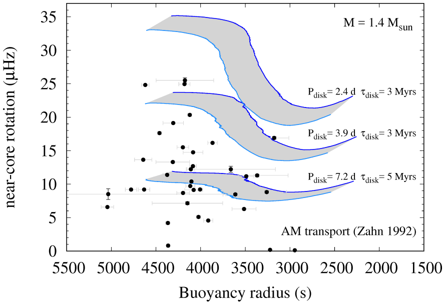

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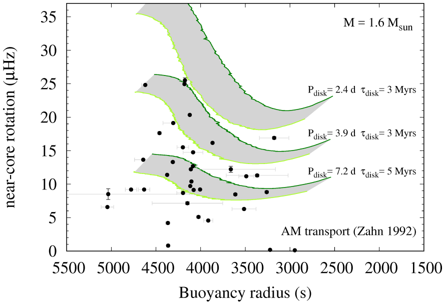

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