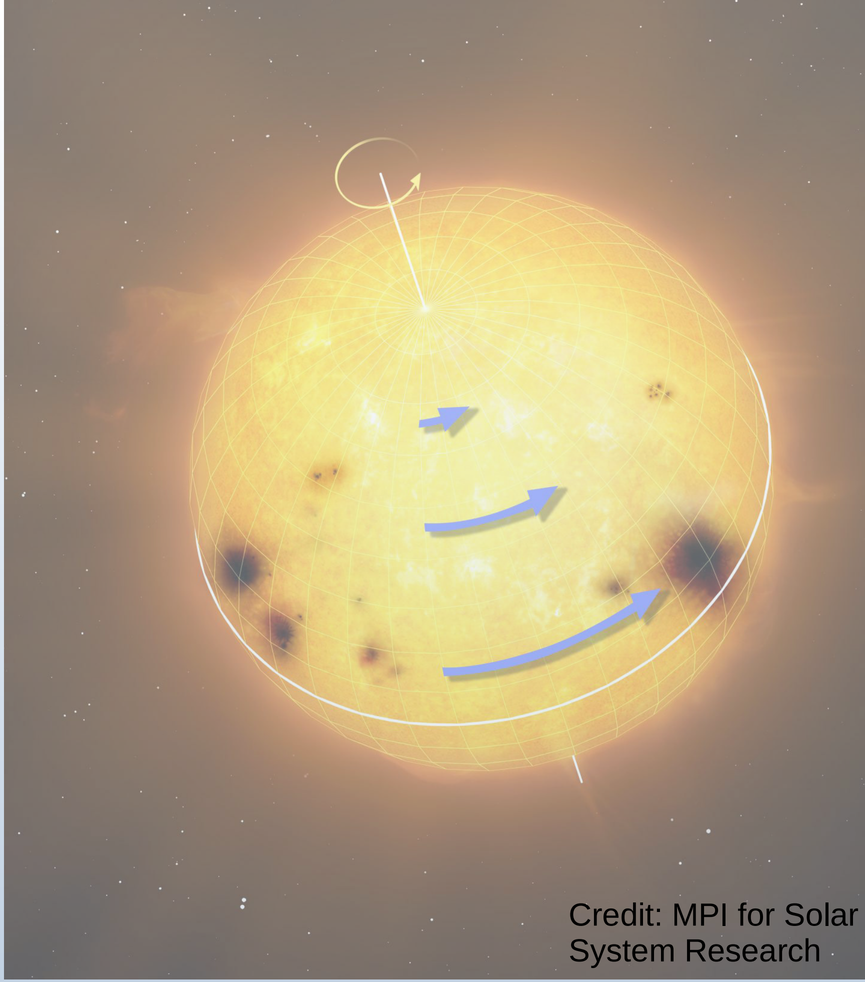
Transport by internal magnetic fields through stellar evolution

Moyano, Facundo D.

Eggenberger, Patrick
Meynet, Georges

University of Geneva, Switzerland



Credit: MPI for Solar System Research

European Research Council
Established by the European Commission

Geneva stellar evolution code (GENEC)

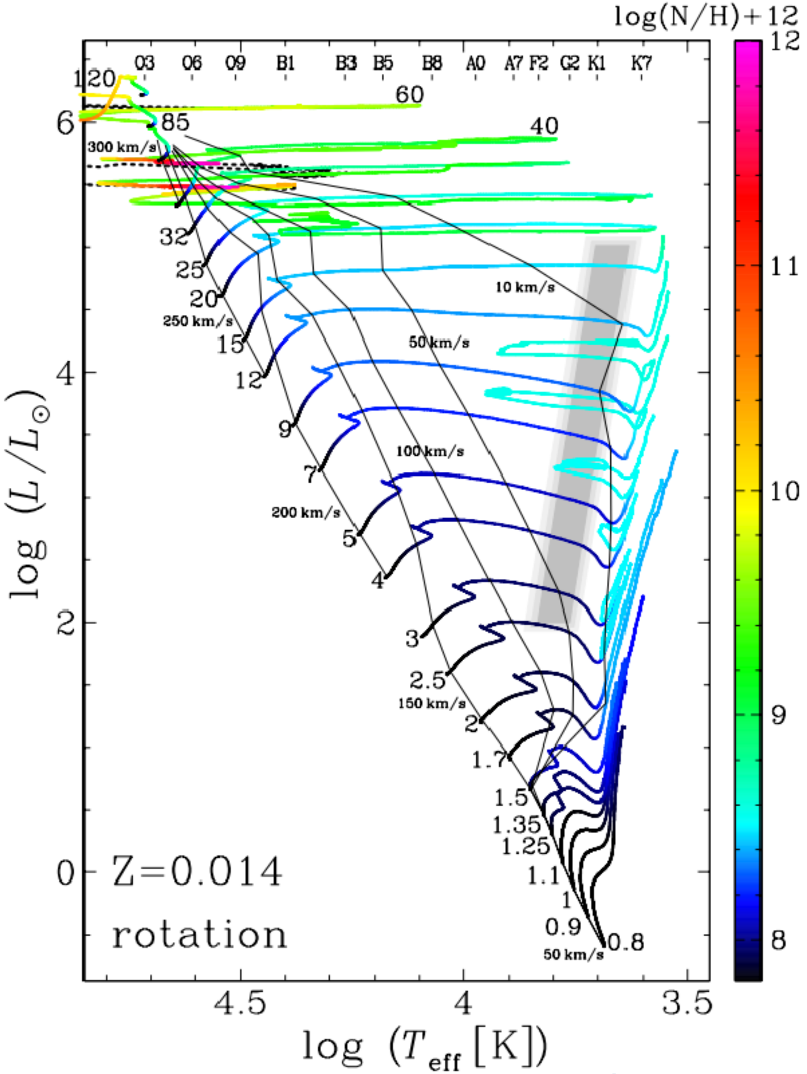
- Able to follow the evolution until: tip of the RGB, beginning of TP-AGB, end of C burning

- Used to compute extensive grids of models (Schaller+1992, Ekstrom+2012, Georgy+2013, Eggenberger+2021, Yusof+2022)

- Extensive sets of physics: rotation, chemical mixing, mass-loss, loss of angular momentum, etc (see Eggenberger+2008).

- Modular code, written entirely in FORTRAN90.

- Available upon request (regularly updated github repository)



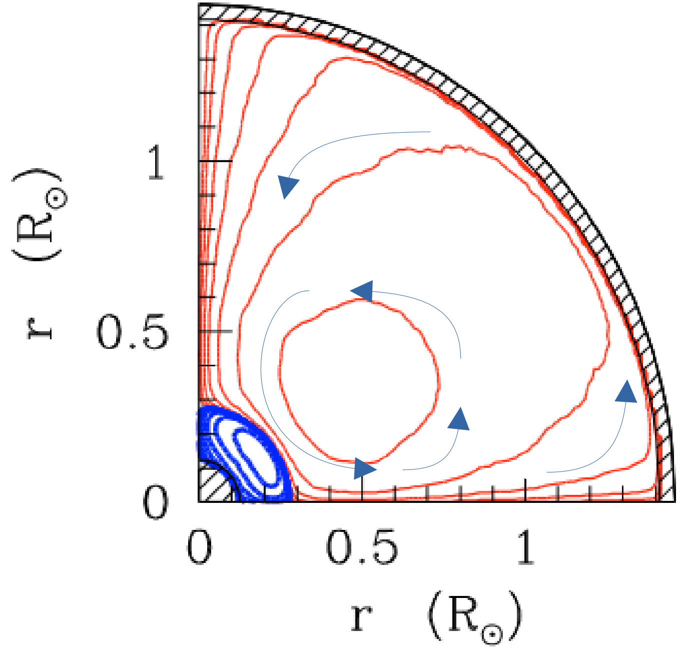
Ekstrom+2012

Geneva stellar evolution code (GENEC)

- Rotation is modified by meridional circulation and diffusive processes (Zahn, 1992)

- Meridional currents advect angular momentum and can transport chemical elements in a diffusive way (see Maeder & Meynet, 2000)

- Shear instabilities diffuse angular momentum. Several prescriptions available (e.g. Maeder+1997; Talon & Zahn, 1997)

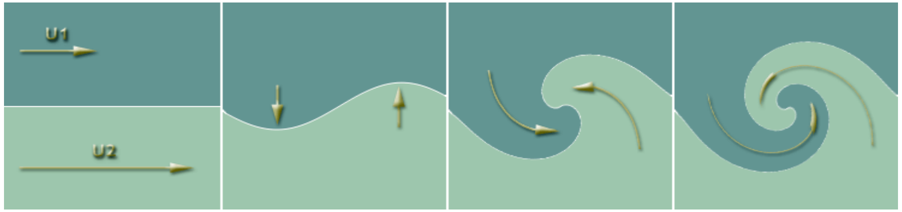


Adapted from Decressin+2009

$$\rho \frac{\mathrm{d}}{\mathrm{d}t}\left(r^2\Omega\right)_{M_r} = \frac{1}{5r^2}\frac{\partial}{\partial r}\left(\rho r^4 \Omega U(r)\right) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho D r^4 \frac{\partial \Omega}{\partial r}\right),$$

Advection

Diffusion



Internal magnetic fields:
I. Tayler-Spruit dynamo

I) Winding up of initial radial magnetic field by differential rotation amplifies azimuthal component so $B_\phi >> B_\mathrm{r}$

ii) Tayler instability on the azimuthal field generates new radial component (Tayler, 1973; Spruit,1999)

Iii) New radial components are stretched into azimuthal components by radial differential rotation → amplification of magnetic fields (Spruit+2002, Fuller+2019)

Properties:
- activated only by differential rotation
- efficient transport of angular momentum

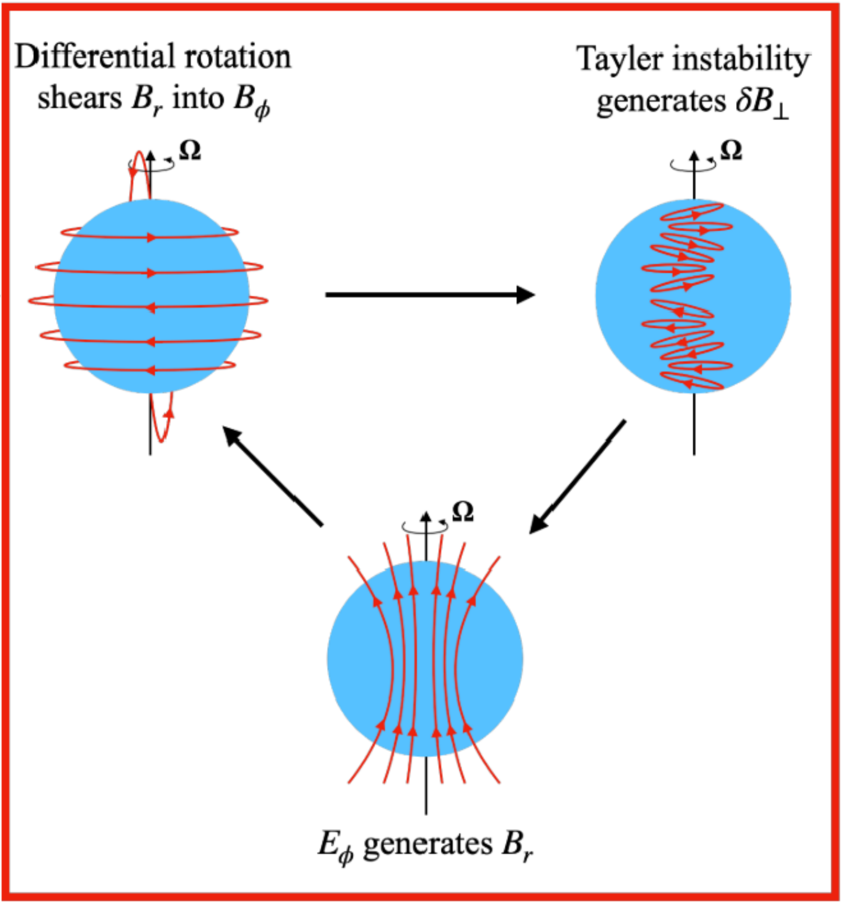


Image taken from Barrere+2022

See also Denissenkov & Pinsonneault, 2007

Internal magnetic fields: I. Tayler-Spruit dynamo

- Instability is triggered when there is enough differential rotation

$$q > q_{\min}$$

Shear
parameter

$$q = \frac{\partial \ln \Omega}{\partial \ln \mathrm{r}}$$

$$\Omega(r) \propto r^{-q}$$

- Chemical gradients strongly inhibit the instabilities, thermal stratification plays a minor role

$$q_{\min,\mathrm{T}} = C_{\mathrm{T}}^{-1} \left(\frac{N_{\mathrm{eff}}}{\Omega}\right)^{(n+2)/2} \left(\frac{\eta}{r^2 \Omega}\right)^{n/4}$$

$$N_{\mathrm{eff}}^2 = \frac{\eta}{K} N_T^2 + N_\mu^2$$

Thermal Chemical

$$N_\mu^2 = \frac{g\phi}{H_{\mathrm{p}}} \nabla_\mu$$

- Transport of angular momentum is very efficient, but inefficient for chemicals

$$\rho \frac{\mathrm{d}}{\mathrm{d}t}(r^2 \Omega)_{M_r} = \frac{1}{5r^2} \frac{\partial}{\partial r}\left(\rho r^4 \Omega U(r)\right) + \frac{1}{r^2} \frac{\partial}{\partial r}\left(\rho D r^4 \frac{\partial \Omega}{\partial r}\right),$$

Advection

Diffusion

$$\nu_{\mathrm{T}} = \frac{\Omega\, r^2}{q} \left(C_{\mathrm{T}}\, q \frac{\Omega}{N_{\mathrm{eff}}}\right)^{3/n} \left(\frac{\Omega}{N_{\mathrm{eff}}}\right).$$

$$D = D_{\mathrm{shear}} + \nu_T$$

Spruit+2002; Fuller+2019; Eggenberger+submitted

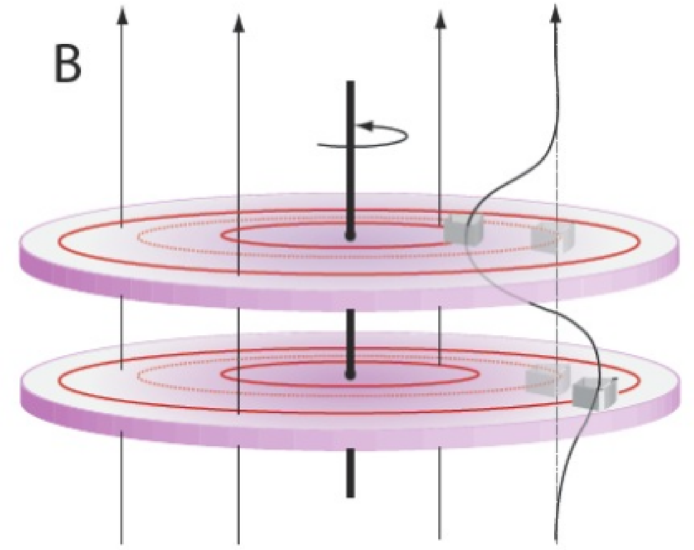
Internal magnetic fields:
II. Magneto-rotational instability

- Studied in the context of accretion disks (Balbus & Hawley, 1991), stellar radiative zones (Balbus & Hawley, 1998)

- Vertical magnetic fields try to enforce uniform rotation in a differentially rotating medium. Produces instability as outwardly displaced elements are forced to rotate too fast

- Very efficient at transporting both angular momentum and chemical elements (Wheeler+2015)

- Triggered when differential rotation is strong enough, strongly inhibited by thermal and chemical gradients



$$q_{\min,\mathrm{MRI}} = \frac{\frac{\eta}{K} N_T^2 + N_\mu^2}{2\Omega^2}$$

$$D_{\mathrm{MRI}} = 0.02 |q| \Omega r^2$$

Structure of a post-main sequence star

- A hydrogen-burning shell develops after the main sequence

- A chemical gradient barrier separates the inert helium core and the hydrogen -rich envelope

- Chemical gradients inhibit the instability

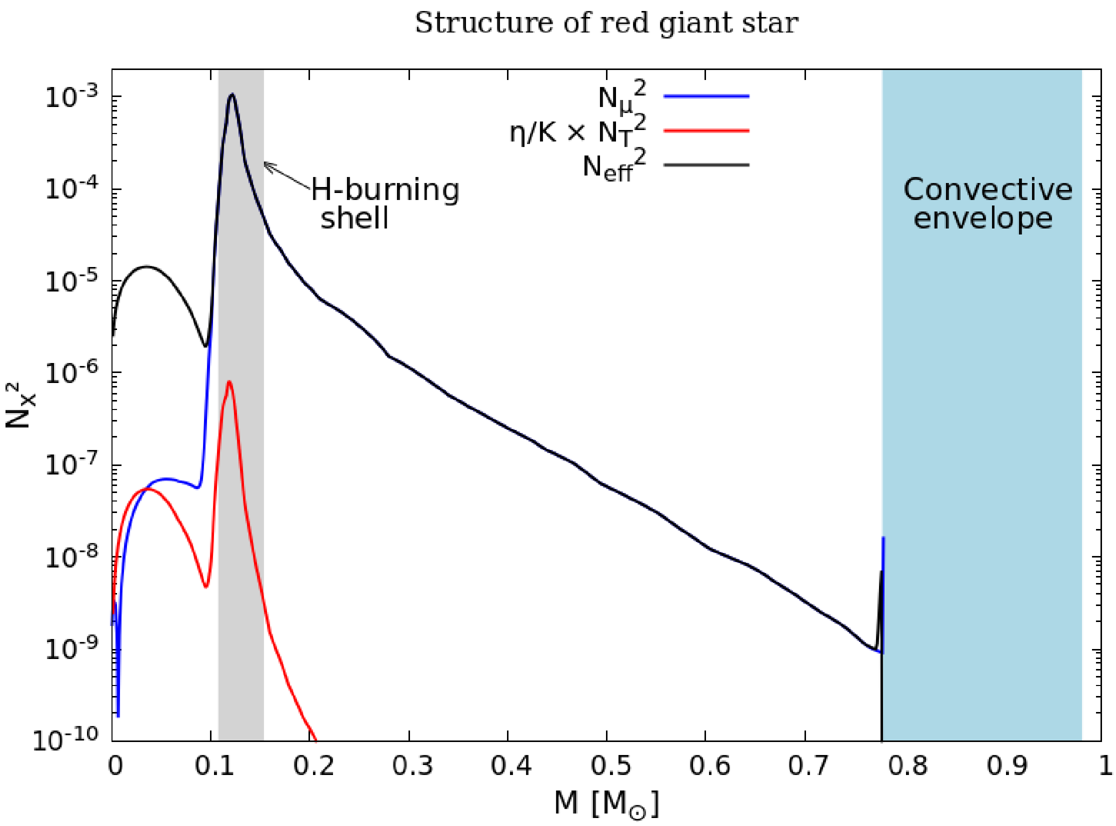
MRI

$$q_{\rm min,MRI} = \frac{\frac{\eta}{K}N_T^2 + N_\mu^2}{2\Omega^2}$$

TS dynamo

$$q_{\rm min,T} = C_{\rm T}^{-1}\left(\frac{N_{\rm eff}}{\Omega}\right)^{(n+2)/2}\left(\frac{\eta}{r^2\Omega}\right)^{n/4}$$

$$N_\mu^2 = \frac{g\phi}{H_{\rm p}}\nabla_\mu$$

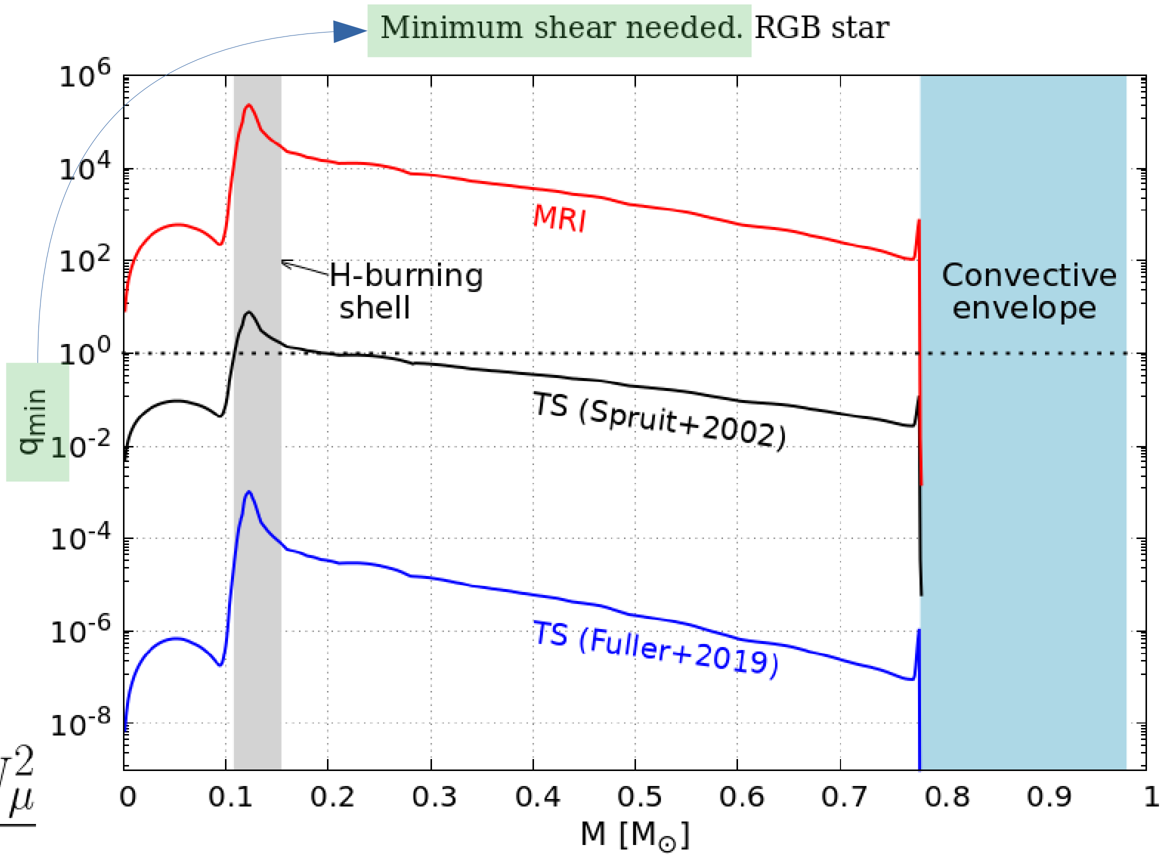


Minimum shear needed

- Chemical stratification is the most important ingredient to determine if a physical process is relevant or not through evolution

- In faster rotating stars, magnetic instabilities are more easily triggered

- The minimum shear required dictates how easily a given process is triggered and shapes the rotation profile



$$\Omega(r) = \frac{\Omega_{\rm surf}}{r}$$

$$q_{\rm min,MRI} = \frac{\frac{\eta}{K} N_T^2 + N_\mu^2}{2\Omega^2}$$

$$q_{\rm min,T} = C_{\rm T}^{-1} \left(\frac{N_{\rm eff}}{\Omega}\right)^{(n+2)/2} \left(\frac{\eta}{r^2\Omega}\right)^{n/4}$$

Minimum shear needed

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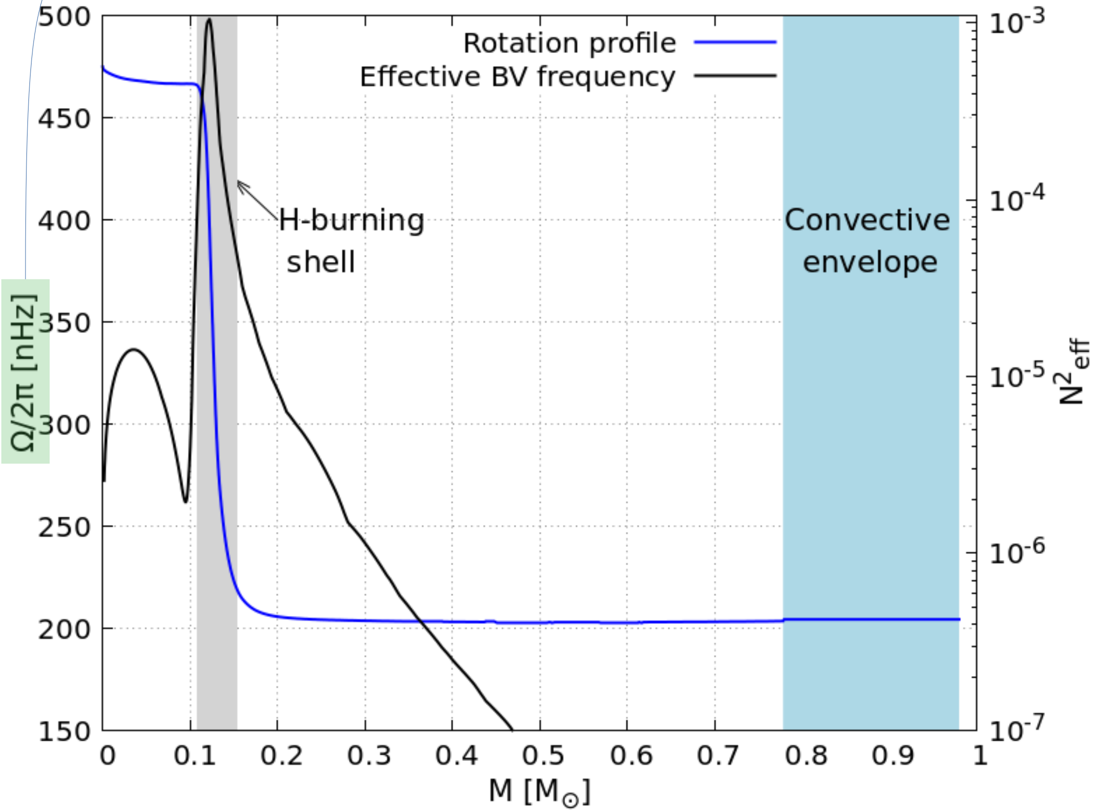
Rotation rate



$$\Omega(r) = \frac{\Omega_{\rm surf}}{r}$$

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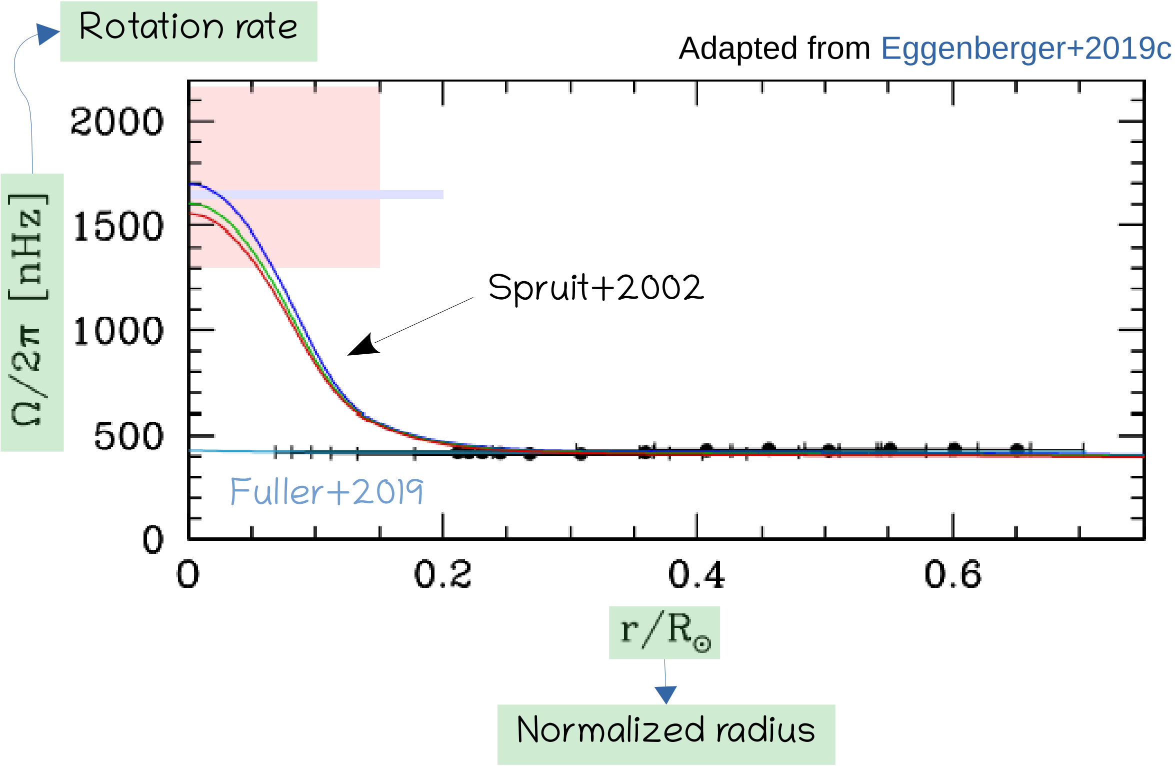
TS dynamo: I. Solar rotation profile

- Internal rotation profile of the sun constrained down to ~ 20 % of radius by helioseismology (Couvidat+2003)

- Core rotation rate hard to reliably constrain (Appourchaux+2010; Schunker+2018)*

- TS dynamo produce flat rotation profiles in the external part of the radiative interior (Eggenberger+2005,2019c) and can account for surface composition (Eggenberger+2022)



*See also Garcia+2007; Fossat+2017; Scherrer+2019; Apporchaux & Corbard, 2019

TS dynamo:
II. Beta Cephei stars

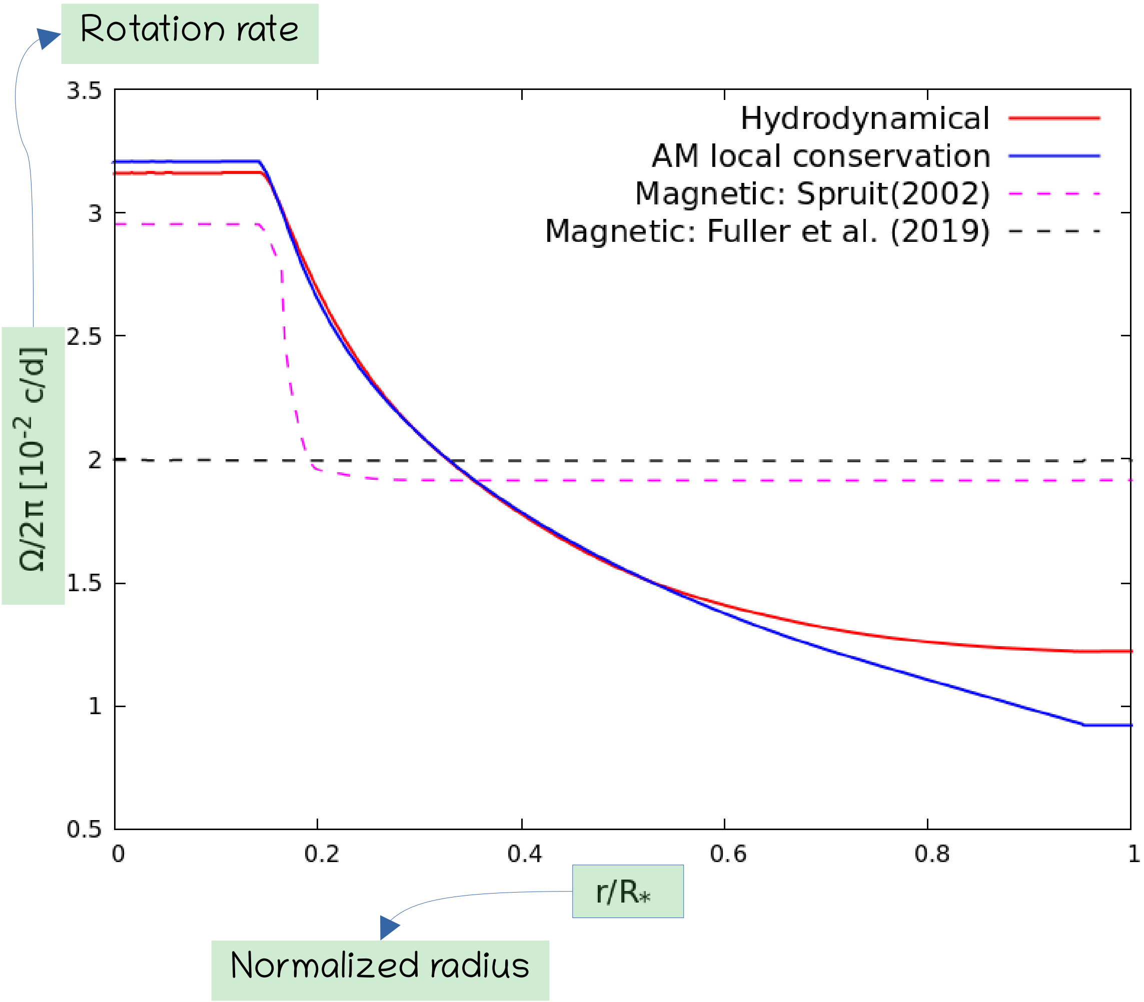
- B3V Beta Cephei HD12992: internal differential rotation (Aerts+2004; Dupret+2004)

- $M \sim 9.3\ M_{sun}$ main sequence star ($X_c \sim 0.35$)
- Slow rotator ($V_{surf} \sim 2$ km/s)
- **Core rotates ~3.6 times faster than surface**

- Internal magnetic fields are too efficient, even at low rotational velocities.

- Local conservation or hydrodynamic processes are preferred.

- Possibility to constrain **the initial differential rotation**: $(\Omega_{core}/\Omega_{surf})_{ZAMS} \sim 1.7$



Rotation rate

Normalized radius

Salmon, Moyano, Eggenberger + submitted

TS dynamo:
III. Evolution of massive stars

- Rotation can transport chemical elements by hydrodynamical processes (non-magnetic):

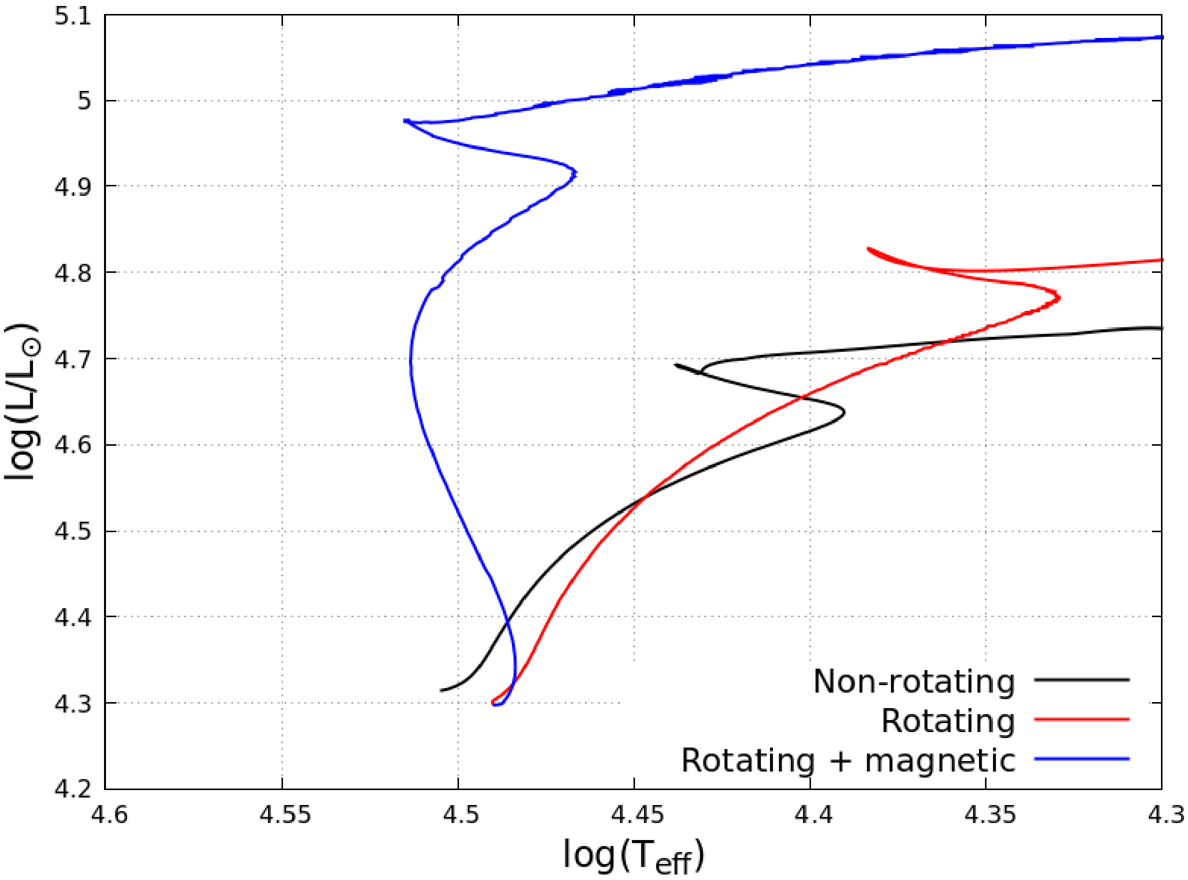
i) Meridional circulation ~ U(r) ~ Ω^2
ii) Shear instabilities ~ $(d\Omega/dr)^2$

-Internal magnetic fields can enforce rigid rotation (Spruit+2002; Fuller+2019)

- Meridional currents can be enhanced

- Quasi-homogeneous evolution can occur (e.g. Yoon+2012)

HR diagram of a 15 M⊙ star during the main sequence



See Maeder & Meynet(2003,2004,2005); Brott+2011; Yoon+2012

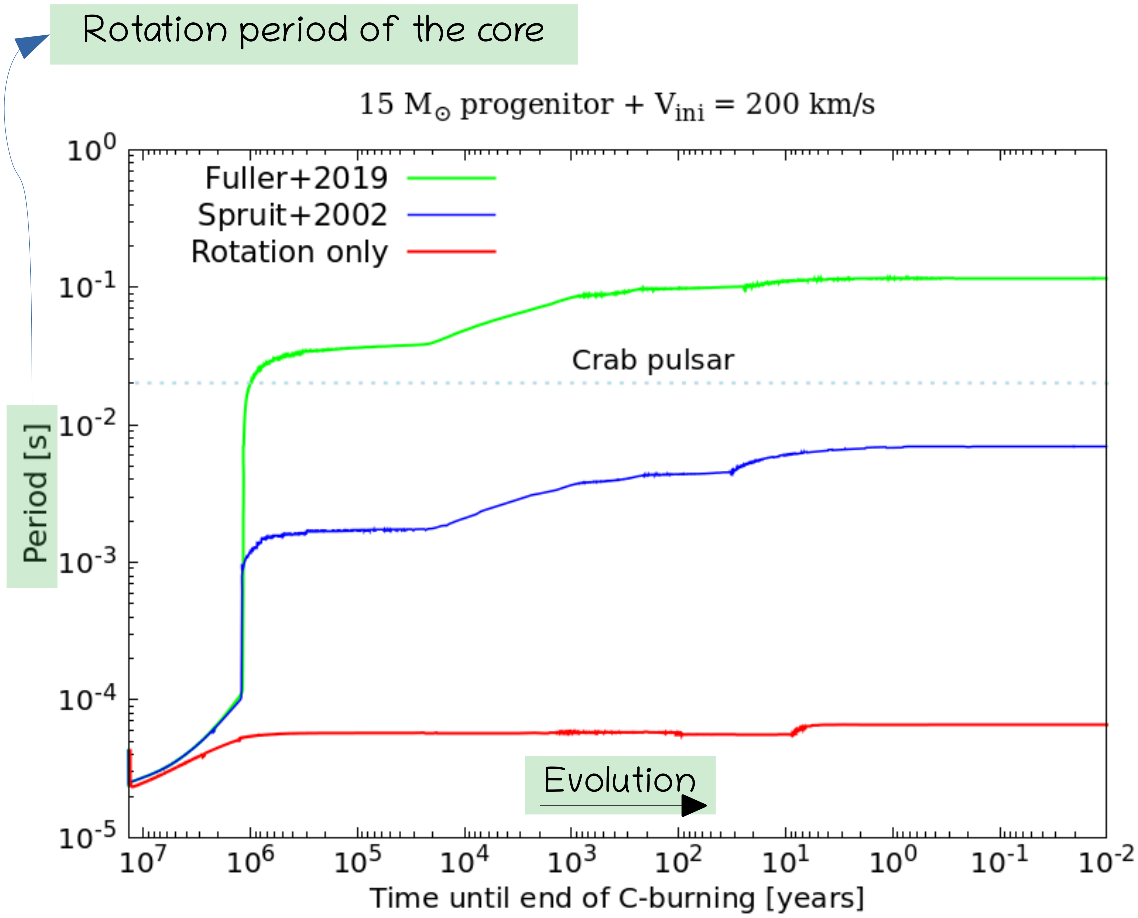
TS dynamo:
IV. Periods of remnants

- Rotation can transport chemical elements by hydrodynamical processes (non-magnetic):

  i) Meridional circulation ~ U(r) ~ Ω^2
  ii) Shear instabilities ~ $(d\Omega/dr)^2$

- Internal magnetic fields can enforce rigid rotation (Spruit+2002; Fuller+2019)

- Periods of compact objects are increased (Heger+2005; Suijs+2008; Ma & Fuller, 2019; den Hartogh+2019)


Rotation period of the core

Evolution

See Maeder & Meynet(2003,2004,2005); Brott+2011; Yoon+2012

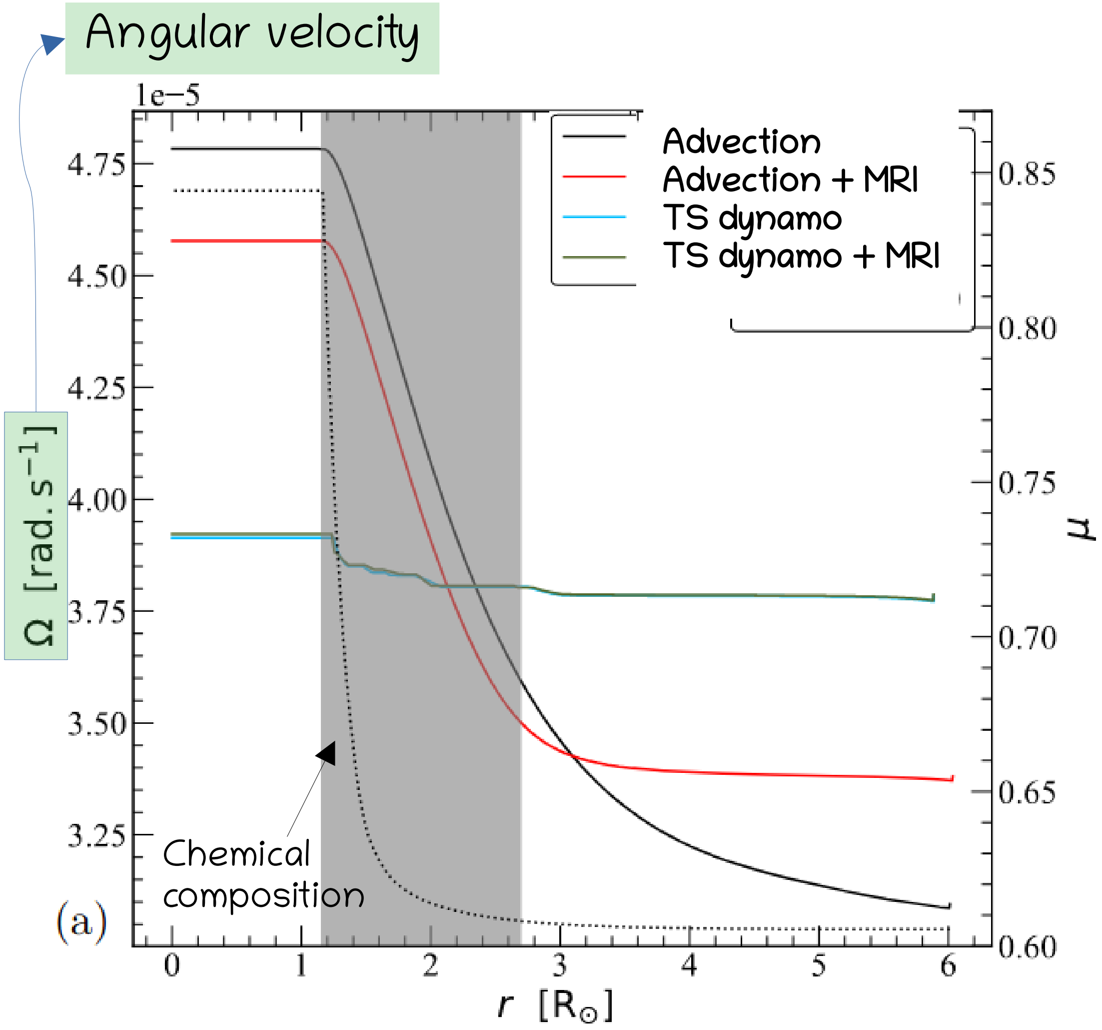
Magneto-rotational instability: Interplay with meridional circulation

- MRI activates during the evolution, and can trigger strong chemical mixing in local regions (Wheeler+2015)

- Meridional currents can create shear due to their advective nature

- MRI can be enhanced by the regeneration of shear (Griffiths+ submitted)

- Tayler-Spruit dynamo dominates over MRI



Adapted from Griffiths+ submitted

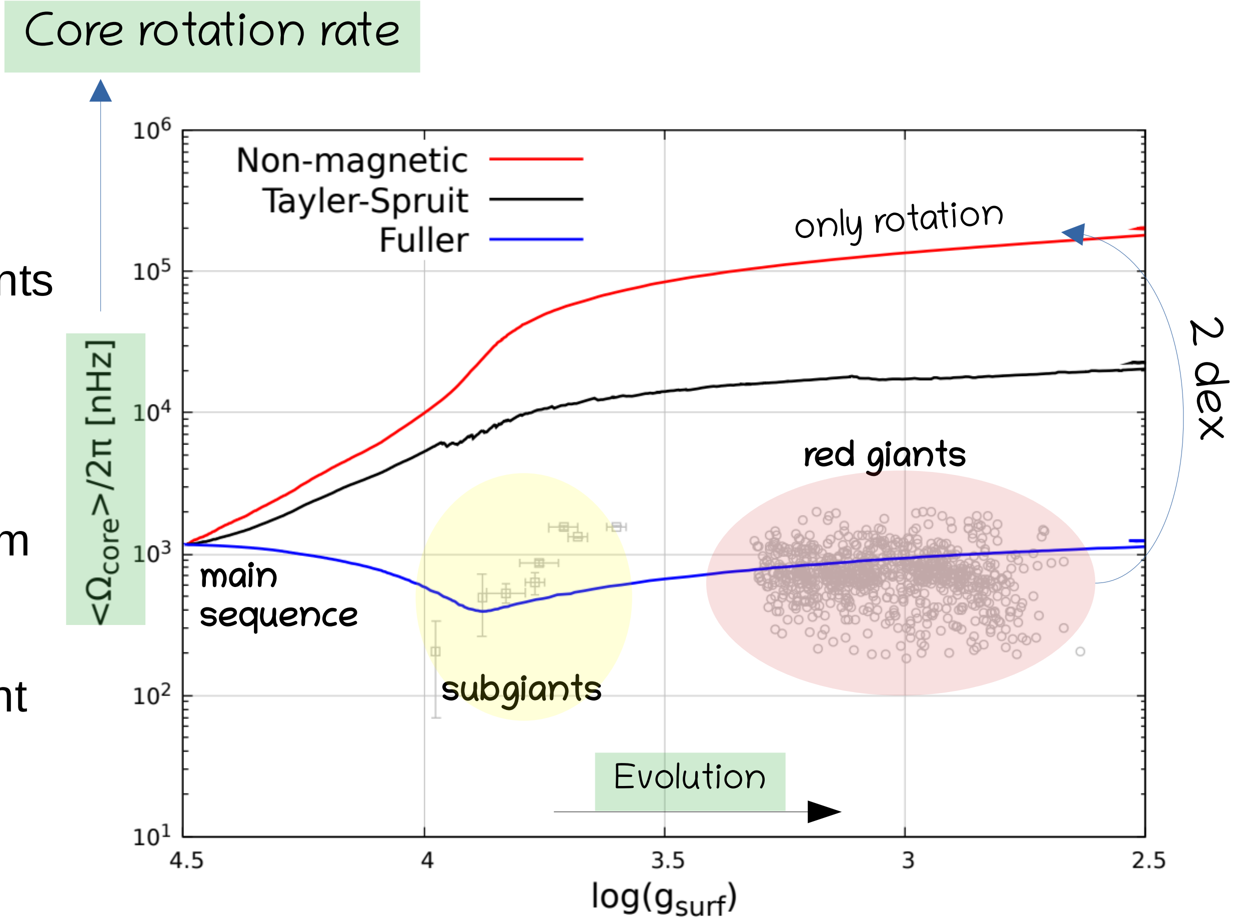
Late phases: subgiants and red giants

- Core rotation rates for +800 red giants (Mosser+2012, Triana+2017, Gehan+2018, Beck+2018) and 8 subgiants (Deheuvels+2014,2020)

- Internal magnetic fields (e.g. Spruit+1999,2002) fed by differential rotation, can transport angular momentum efficiently

- Original Tayler-Spruit dynamo is efficient but not enough for red giants (Cantiello+2014)

- Revised prescription by Fuller+2019 gives better global agreement with red giants



Summary

- GENEC is a stellar evolution code with extensive physical ingredients

- A detailed treatment of redistribution of angular momentum by internal magnetic fields is included, which can affect strongly the evolution of fast rotators and the redistribution of angular momentum

- The interplay with non-diffusive processes and chemical mixing is fundamental to correctly interpret the models

- A triggering condition is essential to study objectively the physical processes through evolutionary timescales

- Other physical processes need to be explored with a detailed numerical treatment:

i) Mixed modes (Belkacem+2015)
ii) Internal gravity waves (e.g. Talon & Charbonnel, 2005; Fuller+2014 Pincon+2016,2017)
Iii) Other magnetic instabilities (e.g. AMRI; Spada+2016)