Interior Rotation from Red Giants

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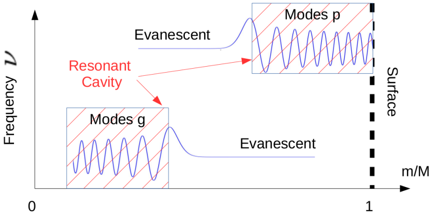
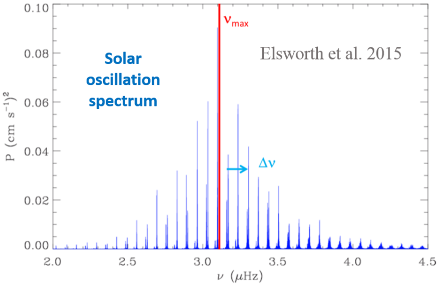
Solar-type pulsators on the main-sequence: pressure modes

- Solar-like pulsators → stable oscillations, excited in a stochastic way by turbulent convection in the external envelope.
- On the MS → only pressure modes essentially visible, gravity modes confined in the core.

→ **No information on the core of solar-like pulsators on the MS.**



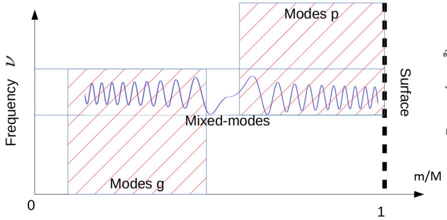


Credits: C. Pinçon

Red giant stars: mixed-modes probing the core

- Coupling between pressure waves in the convective envelope and gravity waves in the radiative interior → mixed-modes, rich oscillation spectrum.
- Mixed-modes → probe the red giant (RG) core.

→ **Unique opportunity to derive observational constraints on the rotation of stellar cores with RG.**



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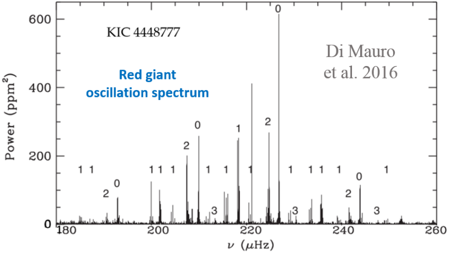
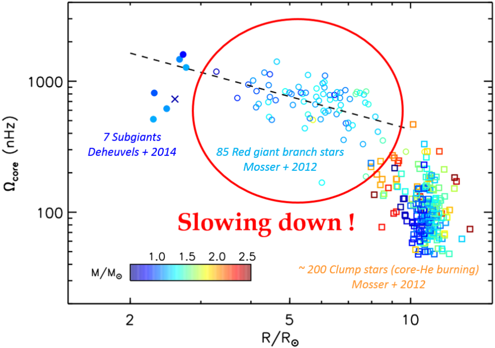


Core rotation measurements: 2012

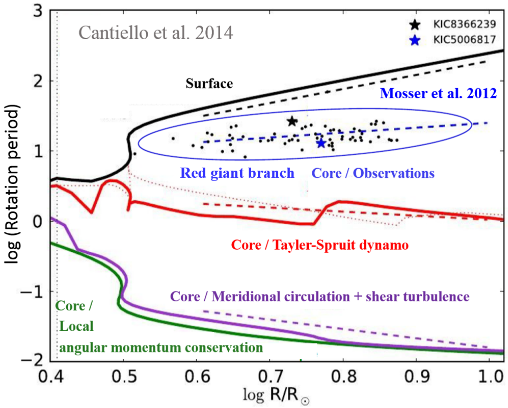
- Slow down of the core rotation on the red giant branch (Mosser et al. 2012): paradox → the core is contracting!
- Important extraction of angular momentum from the core → we need to identify the physical processes at work.



Source: Mosser et al. 2012, Deheuvels et al. 2014

Angular momentum transport problem: physical prescriptions

- Models based on physical prescriptions for the angular momentum transport → still predict too fast core rotation rates.
- Major discrepancy between models and measurements → we don't yet fully understand the physical mechanisms transporting angular momentum in red giants.



Eggenberger et al. (2012)
Marques et al. (2013)
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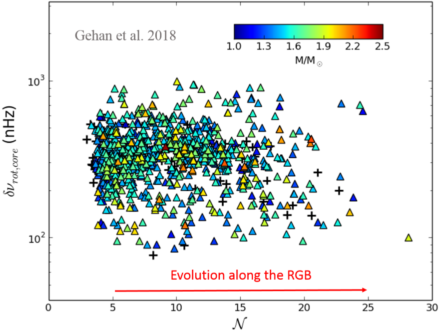
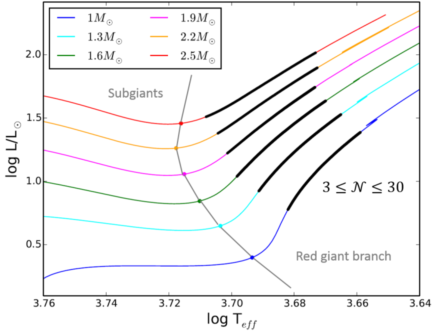
Fuller et al. (2014)
Rüdiger et al. (2015)
Belkacem et al. (2015a, b)
Fuller et al. (2015)
Pinçon et al. (2017)

Core rotation measurements: 2018

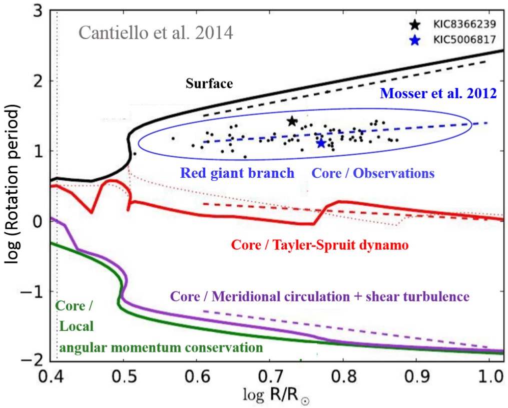
- Gehan et al. (2018) $\rightarrow$ mean core rotation measurements for 875 RGB stars.
- Mixed-mode density $\mathcal{N} = \frac{\Delta\nu}{\Delta\Pi_1\ \nu_{\max}^2}$ $\rightarrow$ proxy of stellar evolution on the RGB.
- Refinement of Mosser et al. (2012) diagnosis $\rightarrow$ constant rotation with evolution on the RGB instead of slowing down.
- Measurements $\rightarrow$ low RGB below the bump.





Angular momentum transport problem: physical prescriptions

- Measurements of Gehan et al. (2018) for a sample 10 times larger → confirm that we still need to identify the physical mechanism(s) slowing down the red giant core rotation.



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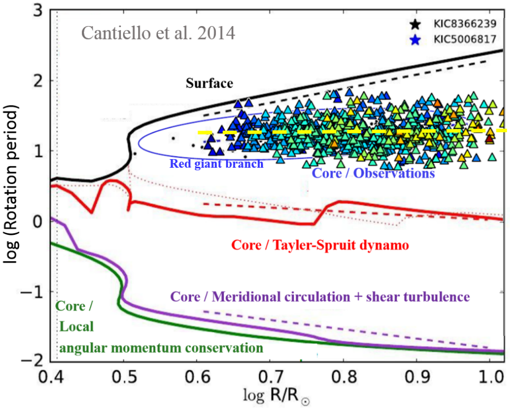

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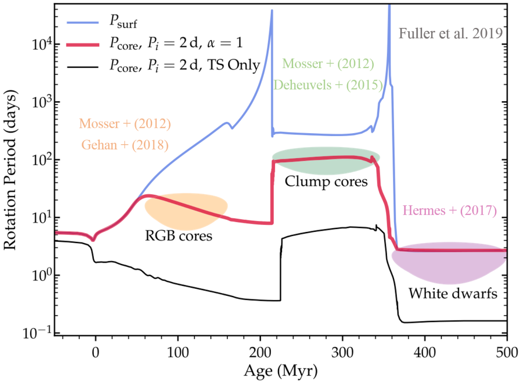
Pinçon et al. (2017)

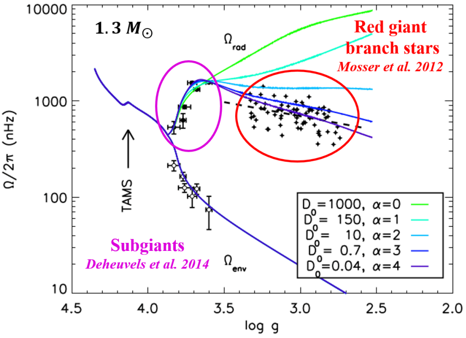
Angular momentum transport problem: physical prescriptions

- Fuller et al. (2019) → roughly reproduce core rotation measurements for red giants and white dwarfs.
- Problem → prediction of a spin-down for subgiants instead of a spin-up, and a spin-up on the RGB instead of a constant evolution.
- Encouraging result to predict effective core rotation rates along stellar evolution → but still a lot to understand to solve the angular momentum transport problem.



Angular momentum transport problem: parameterization

- Spada et al. (2016) $\rightarrow$ parametrize the efficiency of the angular momentum transport using a diffusion coefficient $D = D_0 \left(\frac{\Omega_{\rm rad}}{\Omega_{\rm env}}\right)^{\alpha}$.
- Reproduce both subgiant and RGB measurements $\rightarrow$ need to enforce a rigid rotation not only during the MS but also during the early subgiant phase.
- Allows to put constraints on the unknown mechanism transporting angular momentum $\rightarrow$ but this/these mechanism(s) still need to be identified!



Source: Spada et al. 2016

Conclusions

- With a correct angular momentum transport, we can constrain stellar evolution from the main-sequence to the red giant phase, including the subgiant phase.
- Evolution of the core rotation of red giants $\rightarrow$ still not correctly predicted by models including angular momentum transport.
- Additional observational constraints from a larger sample with PLATO $\rightarrow$ crucial to solve the angular momentum transport problem.

$\rightarrow$ **All we learn on red giants allows us to constrain the evolution of main-sequence stars, for which the core cannot be probed.**

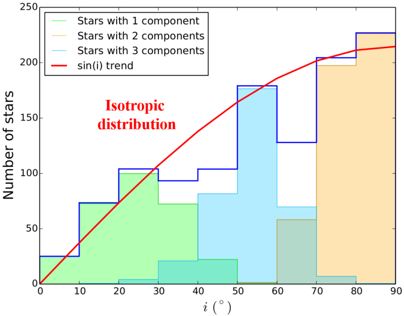
$\rightarrow$ **Red giants are key to unravel the internal rotation of exoplanet host stars on the main-sequence.**

Perspectives: Planet host red giants

- Measurement of the mean core rotation → possible to derive measurements of the stellar inclination angle of the rotation axis.

- Large-scale measurements of inclinations for ∼ 1200 red giants (Gehan et al. in prep) → catalogue of red giants with large *i* to look for exoplanetary transits.

→ **Perspective to have a direct constraint on the core rotation of planet host stars.**



Planets around evolved stars:

Johnson et al. 2010, 2011

Hirano et al. 2015

Lillo-Box et al. 2014

Jones et al. 2015

Lee et al. 2015

Quinn et al. 2015

Lillo-Box et al. 2016

Hrudková et al. 2017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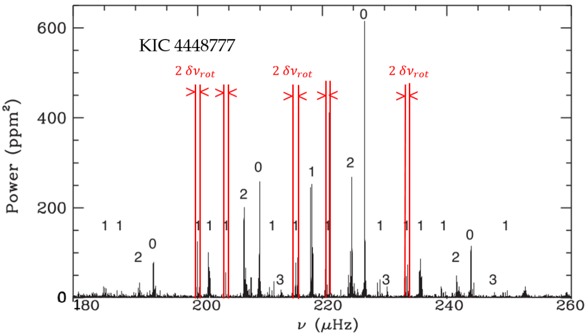
Rotational signature in oscillation spectra

- Rotation $\rightarrow$ similar to the Zeeman effect on modes of same radial order and angular degree but different azimuthal orders.
- Rotational splitting of gravity-dominated dipole modes $\rightarrow$ mean core rotation rate (Mosser et al. 2012, Goupil et al. 2013):

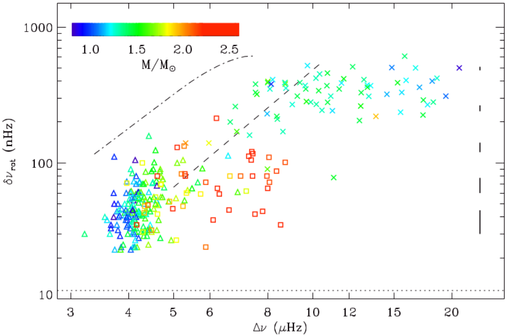
$$\delta\nu_{\mathrm{rot,core}} \simeq \frac{1}{2}\left\langle \frac{\Omega}{2\pi} \right\rangle_{\mathrm{core}}$$

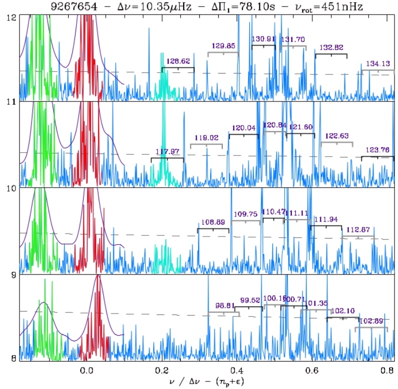


Source: Di Mauro et al. 2016

Red giant branch: complicated cases

- Confusion limit between rotational splittings and mixed-mode spacings → more likely reached when stars evolve along the red giant branch.
- Consequence → overlapping $\delta\nu_{\rm rot}$ and mixed-mode frequency spacings at low frequency.



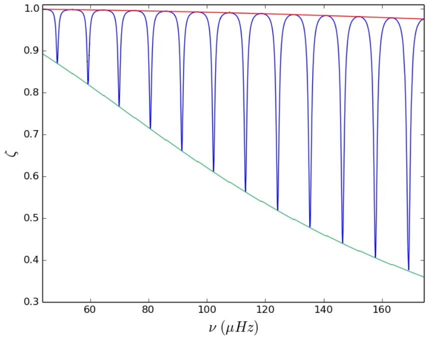


Source: *Mosser et al. (2012)*

Stretching the spectra: the ζ function

- The ζ function characterizes the different nature of $\ell = 1$ p-m and g-m modes:

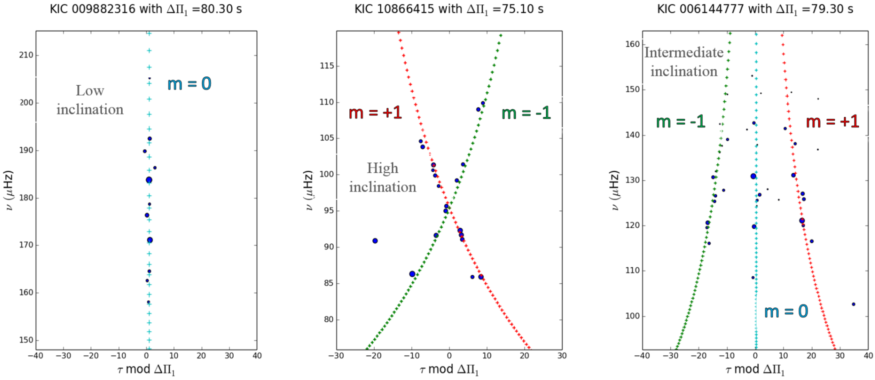
$$\zeta = \frac{I_{\rm core}}{I_{\rm env} + I_{\rm core}} = \left[1 + \frac{\nu^2}{q} \frac{\Delta\Pi_1}{\Delta\nu_{\rm p}} \frac{1}{\frac{1}{q^2} \sin^2\left(\pi \frac{\nu - \nu_{\rm p}}{\Delta\nu_{\rm p}}\right) + \cos^2\left(\pi \frac{\nu - \nu_{\rm p}}{\Delta\nu_{\rm p}}\right)} \right]^{-1} \simeq \frac{\Delta P}{\Delta\Pi_1}$$



Source: Gehan et al. (2018)

Automatic identification of the rotational components

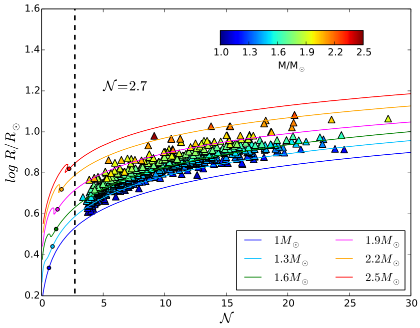
- Correlation of the observed spectrum with a synthetic spectrum.
- The stellar inclination impacts the number of visible rotationally split components: three components $m = \{-1, 0, +1\}$ for dipole mixed-modes.

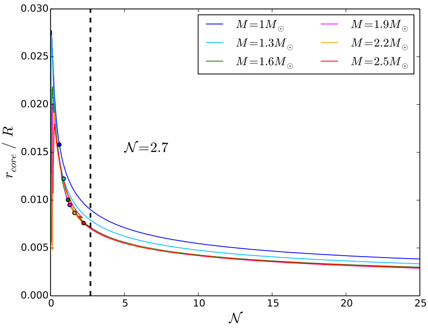


Gehan et al. (2018)

The choice of the mixed-mode density as a proxy of stellar evolution

- Stars enter the red giant branch with a radius depending dramatically on the stellar mass.
- Mixed-mode density $\rightarrow$ remarkably monitors the fraction of the stellar radius occupied by the inert helium core along the red giant branch.



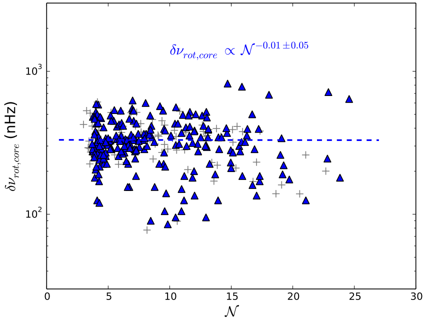


Source: Gehan et al. (2018)

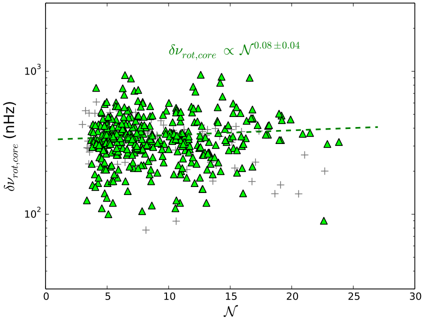
Does the slow-down rate of the core rotation depend on stellar mass?

- Selection of different mass ranges.

$M \leq 1.4 M_\odot$



$1.4 < M \leq 1.6 M_\odot$



Source: Gehan et al. (2018)

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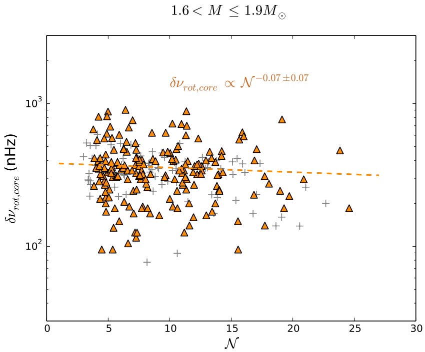
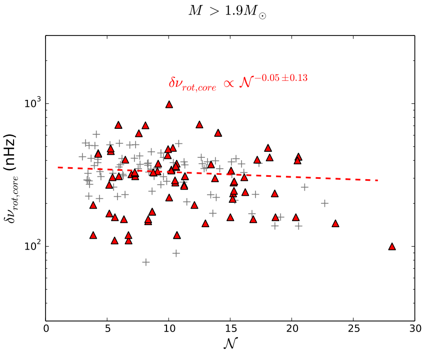
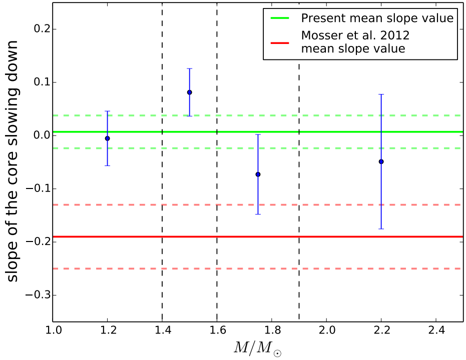




Source: Gehan et al. (2018)

Evolution of the core rotation as a function of the stellar mass

- Evolution of the core rotation on the red giant branch → independent of the stellar mass.
- Refinement of the diagnostic of Mosser et al. (2012) → the core rotation is almost constant on the red giant branch instead of slightly slowing down.



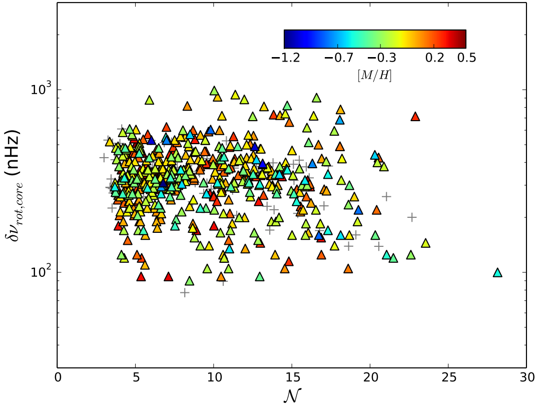
$a = 0.01 \pm 0.03$

$a_{2012} = -0.19 \pm 0.06$

Source: Gehan et al. (2018)

Effect of metallicity on the core rotation

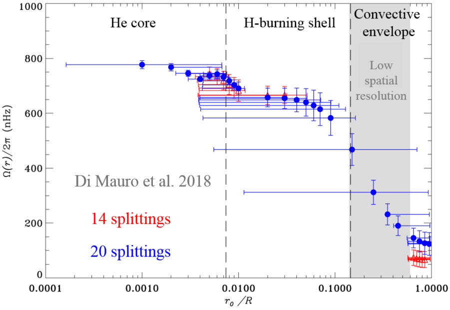
- Measured rotational splittings and their evolution $\rightarrow$ no apparent dependence with metallicity.



Source: Gehan et al. (2018)

Internal rotation profile: stellar inversion techniques

- We cannot firmly constrain the shape of the rotation profile.
- Studies → the core rotates 5 to 10 faster than the envelope.
- Di Mauro et al. (2018) → constant core rotation in the He core, differential rotation starts in the H-burning shell.
- Deheuvels et al. (2015) → core-envelope rotation gradient much milder for secondary clump stars, more efficient angular momentum redistribution.



Beck et al. (2012)
Deheuvels et al. (2012)
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Triana et al. (2017)
Di Mauro et al. (2018)