Seismic evidence for a weak differential rotation in intermediate-mass He-burning giants

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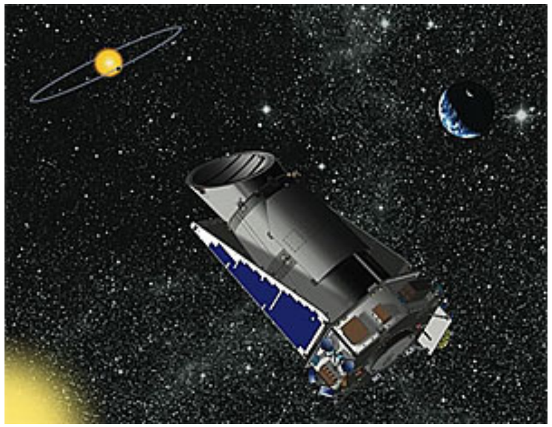
R. Ostensen, R. Garcia, M.-J. Goupil (A&A, accepted)

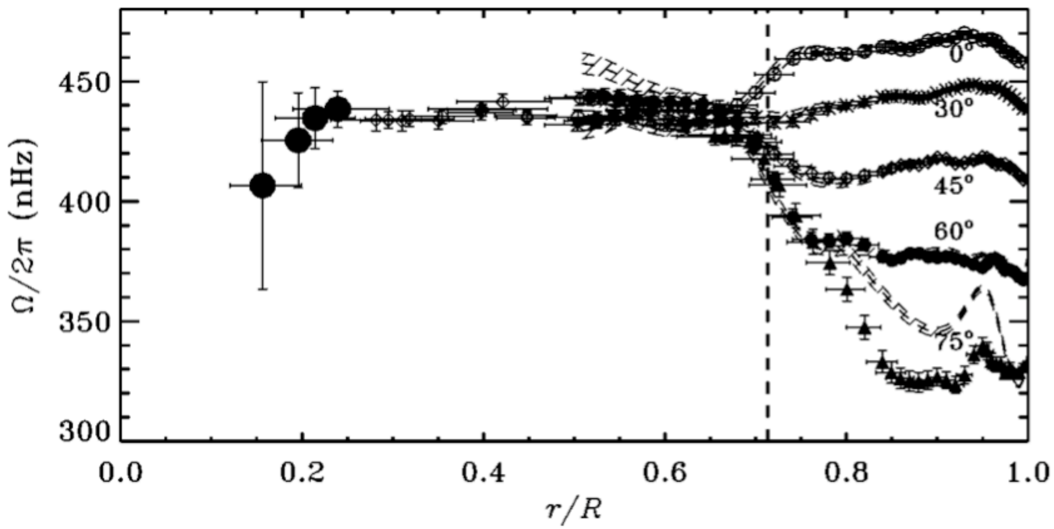


Constraining angular momentum transport in stars

- Transport of angular momentum in stars remains uncertain
  - Several processes (rotation-induced, magnetic fields, internal waves…)
    Which ones dominate?

- Lack of observational constraints
  - Surface rotation → indirect constraints
  - Helioseismology
  - **Seismology of red giants**

Solar internal rotation (Schou et al 98)

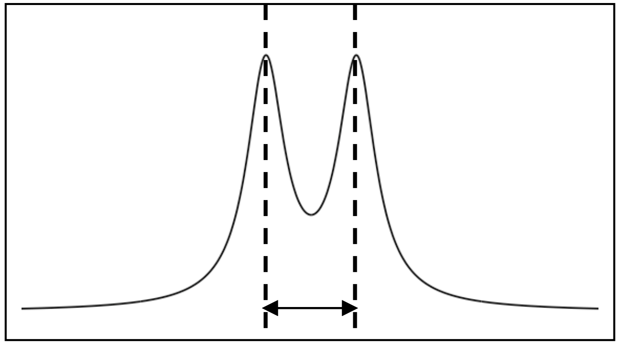


Seismology of red giants: a new piece to the puzzle

- **Large-amplitude** stochastically-excited oscillations
  - Oscillations detected in ~ **15 000 red giants** with **CoRoT** and **Kepler**
- **Mixed modes**
  - **acoustic mode** (**p-mode**) behavior in the envelope
  - **gravity mode** (**g-mode**) in the core
- **Rotation** lifts the degeneracy between $m \neq 0$ modes
  - p-dominated modes: envelope rotation
  - g-dominated modes: core rotation

$$\delta\omega_{nlm} = \int_0^R \int_0^\pi K_{nlm}(r,\theta)\Omega(r,\theta)\,\mathrm{d}r\,\mathrm{d}\theta$$

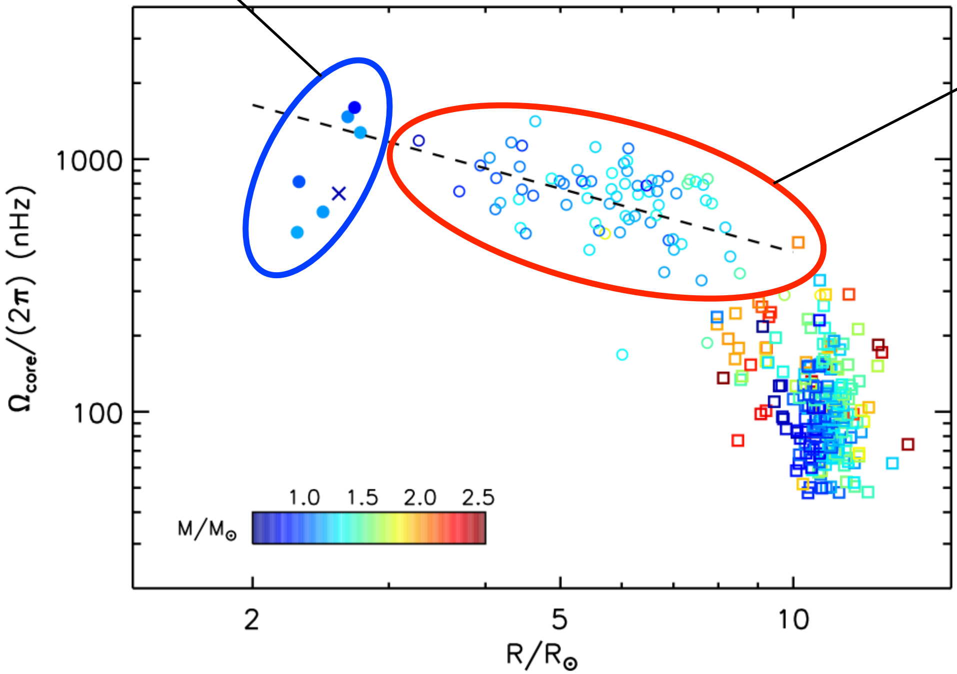
Rotational kernels



Rotational splitting

Seismology of red giants: a new piece to the puzzle

- Subgiants
  - **Spin-up** of the core **(Deheuvels et al. 2012, 2014)**
  - Ω_{core} << predicted core rotation **(Ceillier et al. 2013, Marques et al. 2013)**



- Red giants
  - Large differential rotation $\Omega_{core}/\Omega_{env} > 20$ **(Beck et al. 2012, Goupil et al. 2013)**
  - but **spin-down** of the core **(Mosser et al. 2012)**

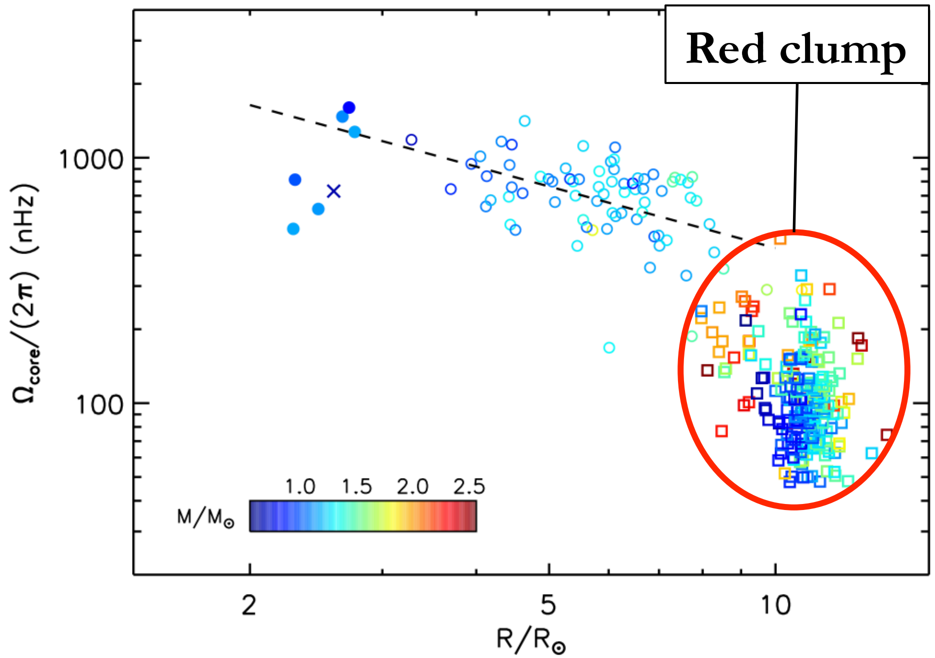
⇒ Efficient redistribution of angular momentum

« Secondary clump » stars

- Core He-burning giants (**clump stars**)
  - Post He-flash **low-mass stars** (M < 2.1 M)
  - **Intermediate-mass stars** (M > 2.1 M): **secondary clump**

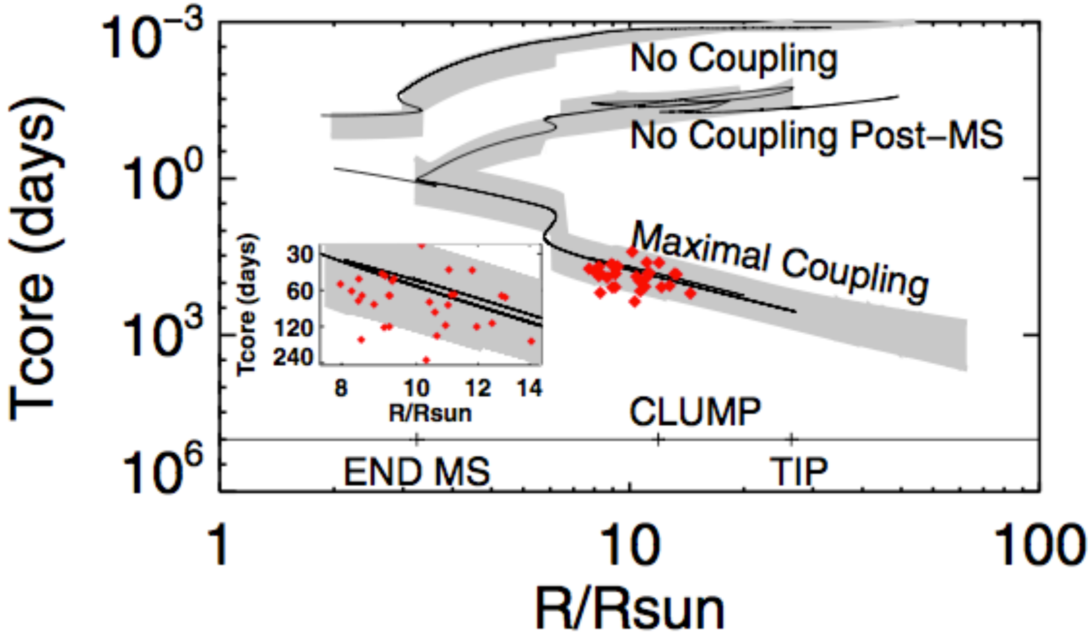
- **Secondary clump stars**
  - Fast rotation during MS (no magnetic wind)

    $V_{eq} \sim 50 - 150 \ \ km.s^{-1}$
  - Subgiant and RGB phases on a Kelvin-Helmoltz timescale



« Secondary clump » stars

- Core rotation of secondary clump stars consistent with **solid-body rotation** (Tayar & Pinsonneault 2013)



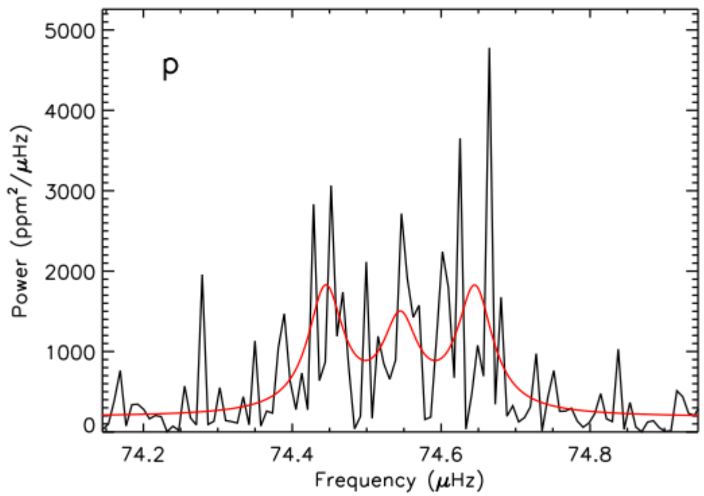
- **Objective: seismic measurement of differential rotation in secondary clump stars**

Target selection

- Measuring the internal rotation of clump stars is more difficult then on the RGB
  - **Slower core rotation**
  - **Shorter mode lifetimes** (and thus larger mode widths)

  ⇒ **(mode splitting) ~ (mode width)**

- Search for adequate targets among 1000's of Kepler giants
  - Stars seen **equator-on** favored
  - Statistical test (both **frequentist** and **Bayesian** approach) to assess significance



⇒ **7 targets with both p & g-dominated splittings**

Measurement of internal rotation Ω(r)

Inverse problem $$\delta\omega_{n,l} = \int_0^R K_{n,l}(r)\Omega(r)\,\mathrm{d}r$$

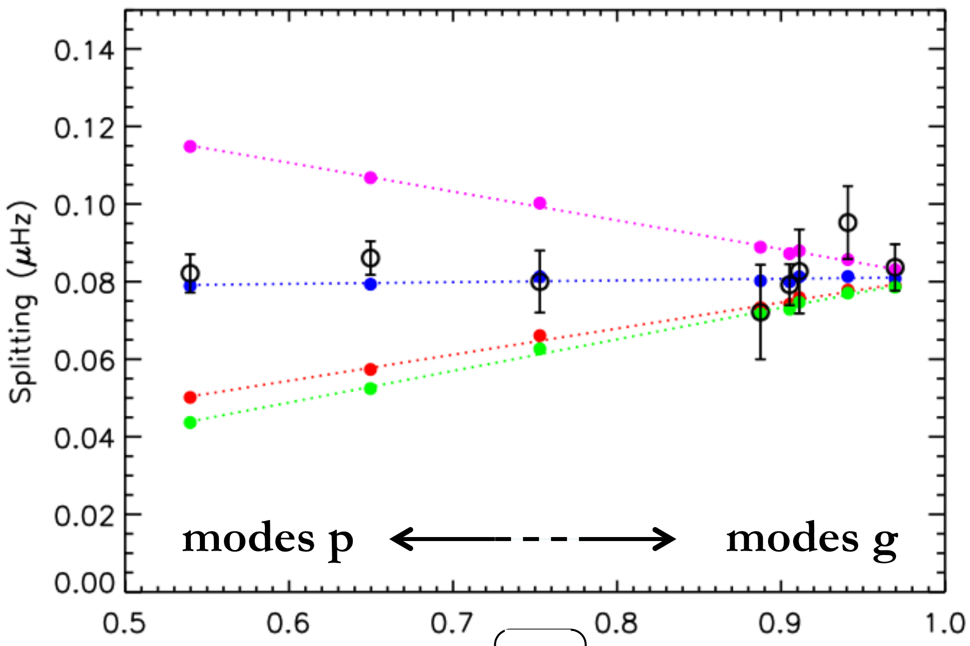
- Model-dependent approach
  1. Seismic modeling of the star
  2. Compute mode eigenfunctions and rotational kernels
  3. Apply **inversion procedures**

- Simplified approach based on asymptotics **(Goupil et al. 2013, G13)**
  1. Estimate mode **trapping** from mode **frequencies** (observed)
  2. Estimate **mean core** and **envelope rotation**

⇒ Validation of 2^{nd} approach for clump stars on the test-star KIC7581399.

Applying inversion procedures to KIC7581399

- Very precise **core rotation <Ω_c>** through OLA inversions



$\Omega_{\text{cœur}}/\Omega_{\text{env}}$ = 1 (solib-body rot.)

$\Omega_{\text{cœur}}/\Omega_{\text{env}}$ = 2

$\Omega_{\text{cœur}}/\Omega_{\text{env}}$ = 10

$\Omega_{\text{cœur}}/\Omega_{\text{env}}$ = 100

Observed splittings

ζ

Mode trapping

$$\zeta \equiv \frac{I_g}{I} = \frac{\int_{r_a}^{r_b} \rho r^2 \left[\xi_r^2 + l(l+1)\xi_h^2\right] dr}{\int_0^{R_\star} \rho r^2 \left[\xi_r^2 + l(l+1)\xi_h^2\right] dr}$$

- Estimate of the core/envelope contrast through **inversions**:

$$\langle\Omega_{\text{core}}\rangle/\langle\Omega_{\text{env}}\rangle/ = 1.6 \pm 0.4$$

Testing the simplified method of G13

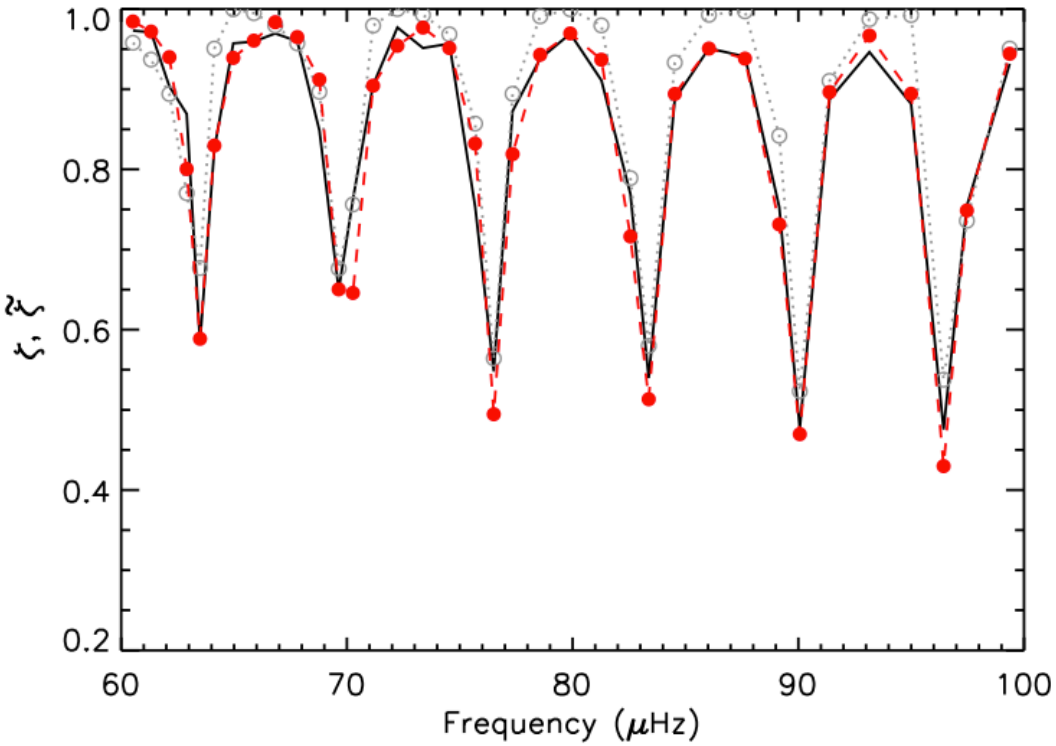
- Method of **Goupil et al. (2013)** : 2 approximations
  - Relation btw mode **trapping** ζ and mode **frequencies** (observed)
  - Linear relation btw mode splittings and ζ

  $\Rightarrow$ estimate of $<\Omega_{core}>$ and $<\Omega_{env}>$

« **true** » ζ (computed with mode eigenfunctions)

approached $\tilde{\zeta}$ (G13 formula)

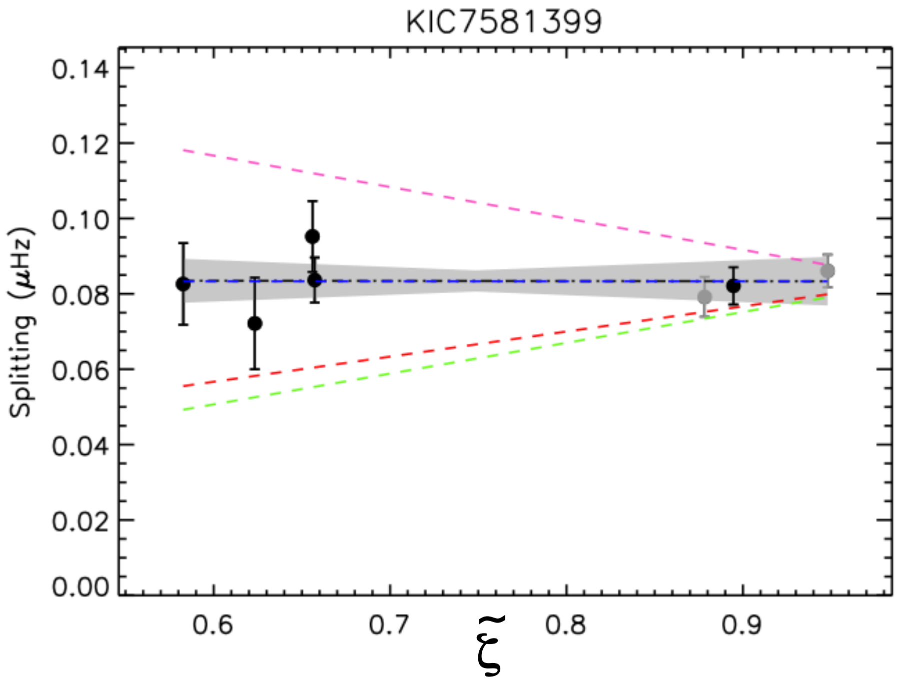
approached $\tilde{\zeta}$ (modified G13 formula, this work)



Testing the simplified method of G13

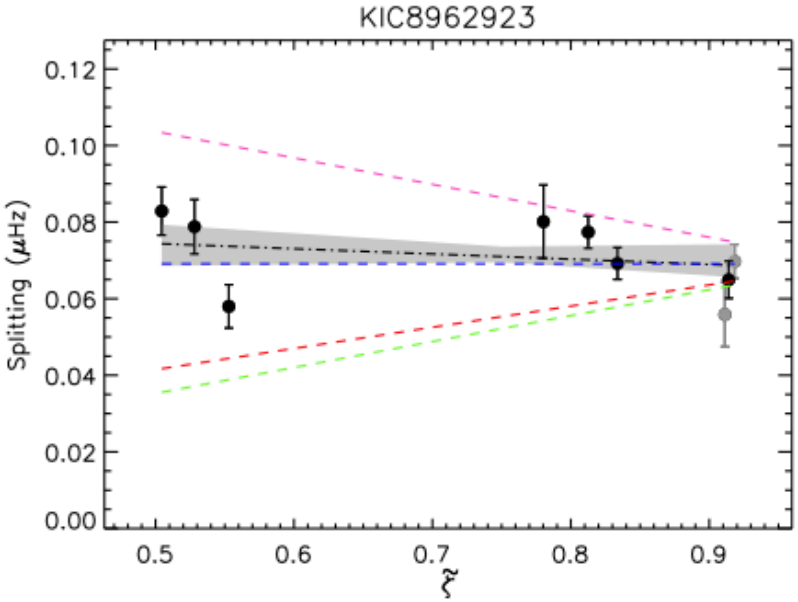
- Very good agreement with results from inversions for the test-case star KIC7581399.

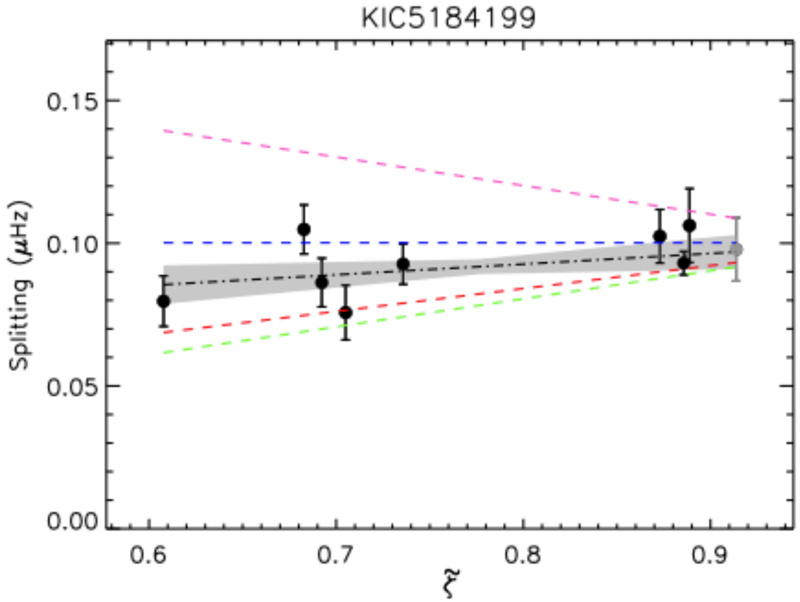
$$\langle\Omega_g\rangle/(2\pi) = 168 \pm 12 \text{ nHz}$$
$$\langle\Omega_p\rangle/(2\pi) = 88 \pm 15 \text{ nHz}$$
$$\langle\Omega_g\rangle/\langle\Omega_p\rangle = 1.9 \pm 0.4$$

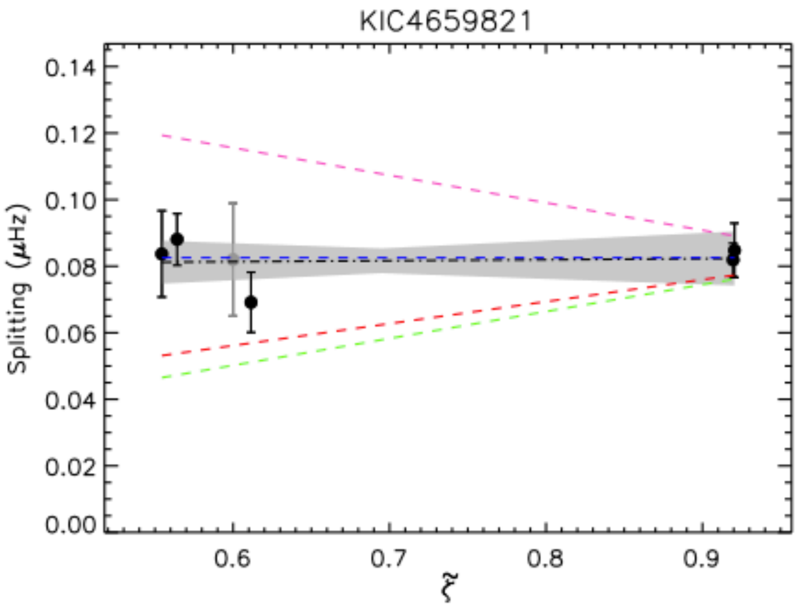


- Confirms **weak radial diffenretial rotation** of KIC7581399 (core spins only twice faster than envelope)
- **Solid-body rotation ruled out**

Results for other targets







$\Omega_{cœur}/\Omega_{env} = 1$

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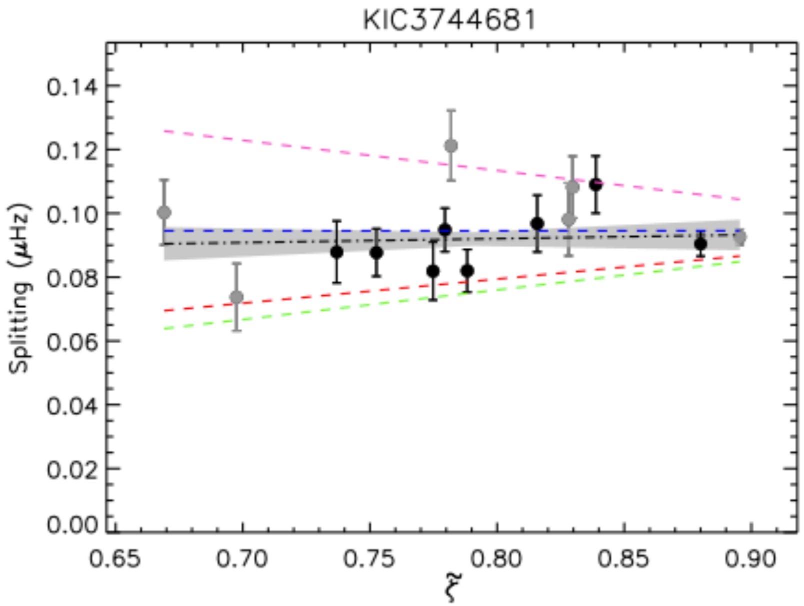
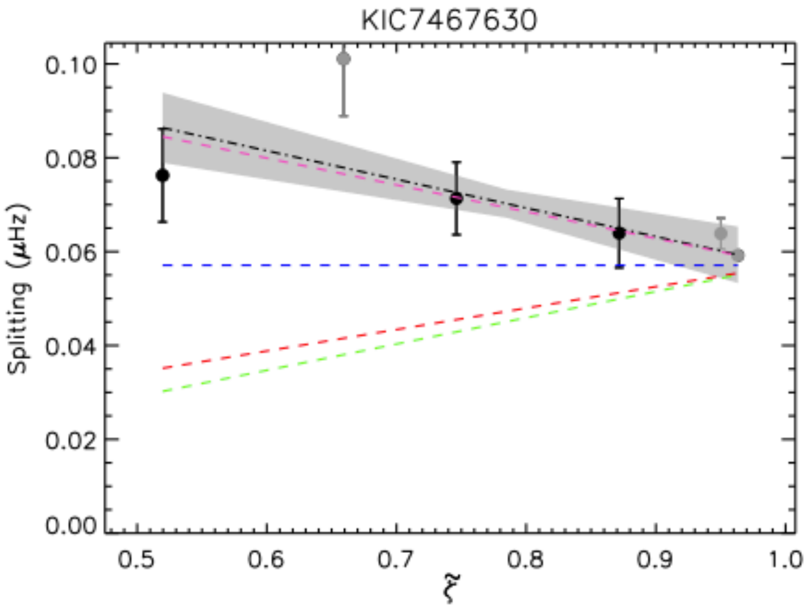
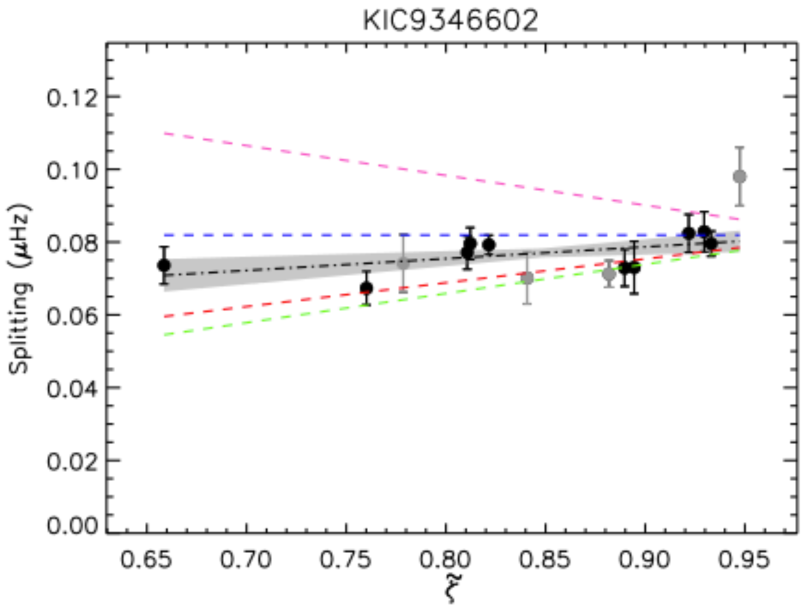






Conclusions

- **Weak differential rotation** for 6 targets ($1.8 < \Omega_g/\Omega_p < 3.2$) and consistent with solid-body rotation for 1 target.
- The redistribution of angular momentum in secondary clump stars must be **very fast**
- The two targets with the lowest core-envelope contrast are also the most evolved

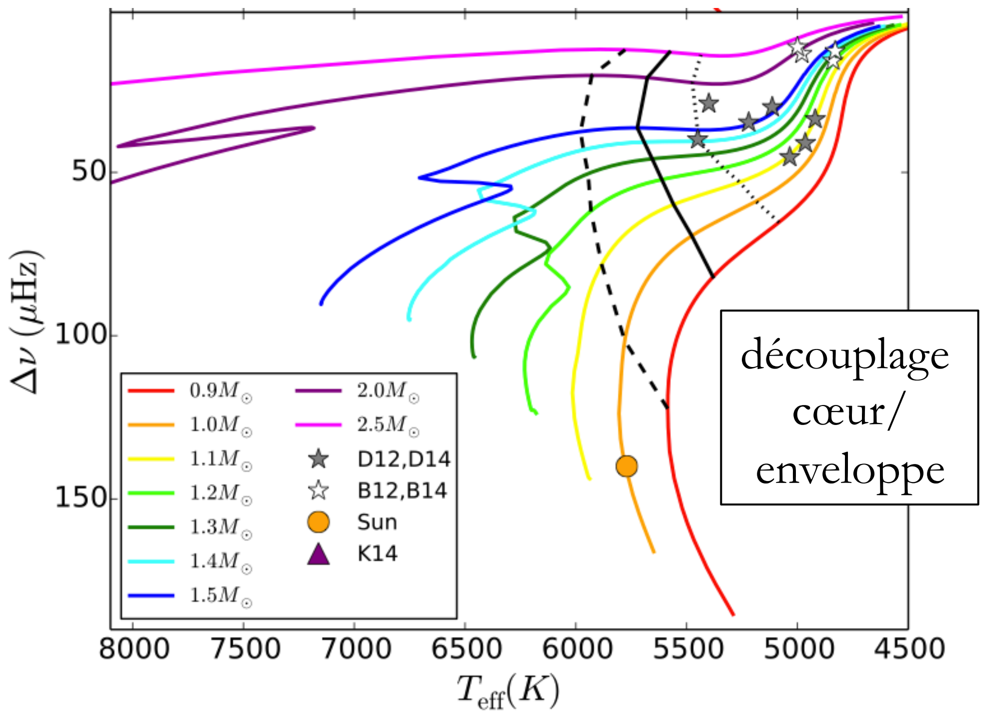
  ⇒ an evolution toward solid-body rotation in the clump?

- Potential candidates for angular momentum redistribution
  - **Internal gravity waves** (e.g. **Fuller et al. 2014**)
  - **Fossil magnetic field** (e.g. **Maeder & Meyent 2014**)
  - MHD instabilities such as **AMRI** (e.g. **Rüdiger et al. 2014**, **Jouve et al. 2015**)

Ondes de gravité internes

- Transport de moment cinétique par **ondes de gravité internes**

Fuller et al (2014)



✓ Pourrait expliquer le **découplage cœur/ enveloppe** pendant la phase de **sous-géante**

✗ Mais pas la **décélération du cœur** dans la phase **RBG**

? Dans la phase de **clump**, les **ondes venant du cœur** pourraient coupler efficacement

Champs magnétiques

- Transport de moment cinétique par **AMRI** (instabilité d'un champ magnétique toroïdal causée par la rotation différentielle) **(Rudiger et al. 2014, Jouve et al. 2015)**
  - Peut produire une viscosité effective suffisante
  - Effets de compressibilité à prendre en compte
  - la viscosité effective dépend de l'intensité de la rotation différentielle

- Transport de moment cinétique par la **dynamo de Tayler-Spruit**
  - **Pas suffisant** pour rendre compte des rotations au cœur des géantes **(Cantiello et al. 2014)**

- Transport de moment cinétique par un **champ fossile** **(Maeder & Meynet 2014)**

Dynamo de Tayler-Spruit

- Transport de moment cinétique par un **champ magnétique** généré par **dynamo** (**Tayler-Spruit**) **pas suffisant**

(Cantiello et al. 2014)