Better understanding angular momentum transport in stars using the seismology of red giants

PNPS 2015-2018 (**Merci !**) + ANR proposal BEAMING

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The problem of angular momentum transport in stars

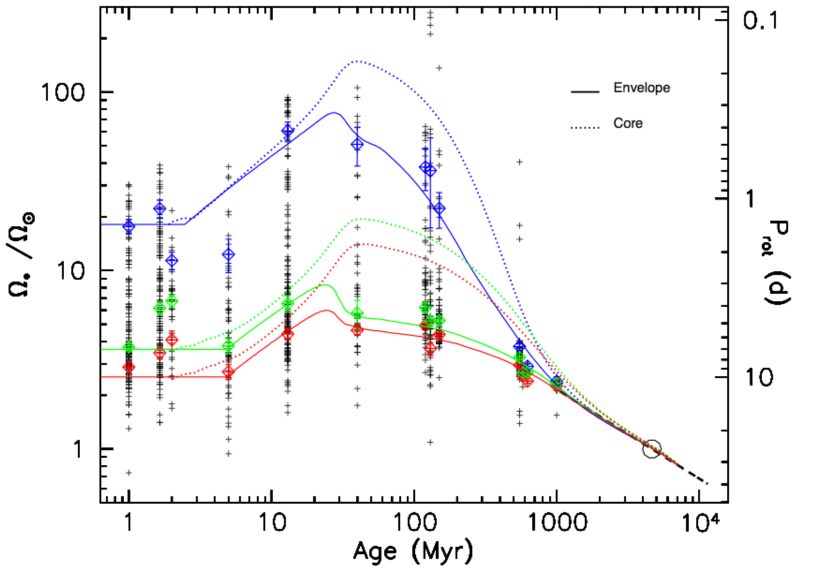
- Transport of angular momentum in stars remains uncertain
  - Several processes (rotation-induced, magnetic fields, internal waves…)

    Which ones dominate?

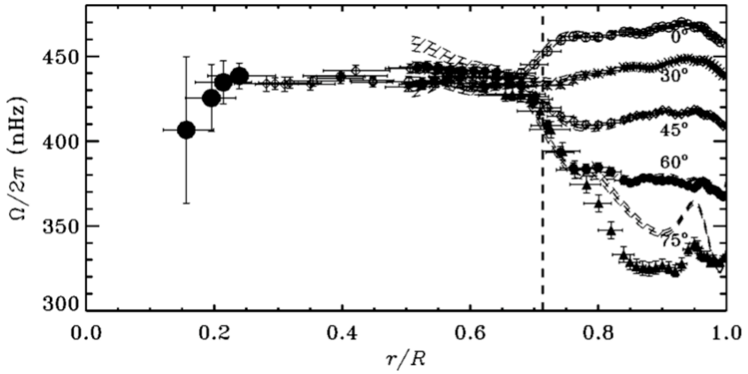
- Evidence for a missing ingredient
  - Surface rotation of young stars in clusters
  - Solar rotation profile
  - **Internal rotation of red giants**
  - Surface rotation of white dwarfs and neutron stars

⇒ All point to a more efficient transport of angular momentum in stars

Gallet et al. (2013)



Solar internal rotation **(Chaplin et al. 1999)**

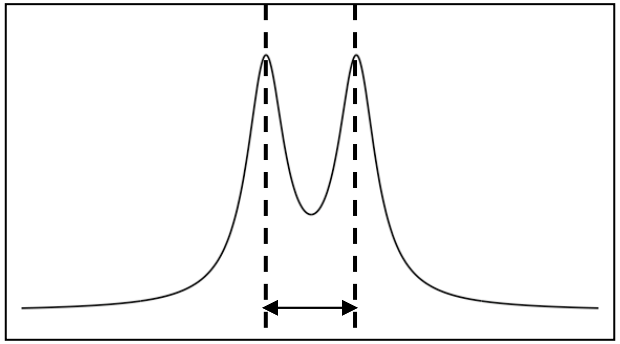


Mixed modes in red giants

- After the end of the MS: core contraction and envelope expansion
  - ⇒ The core should spin-up and the envelope spin-down in local AM is conserved
  - – Interesting phase to probe internal rotation!
- **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



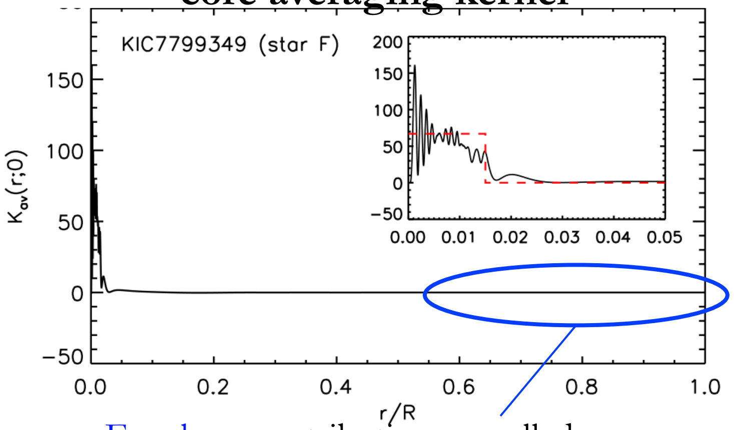
Rotational splitting

Seismic constraints obtained on the internal rotation of red giants

Sugiants & young red giants

- Detection of ~ 15 mixed modes split by rotation in 7 Kepler subgiants **(Deheuvels et al. 2012, 2014)**
- **Inversion** of rotation profile

core averaging kernel



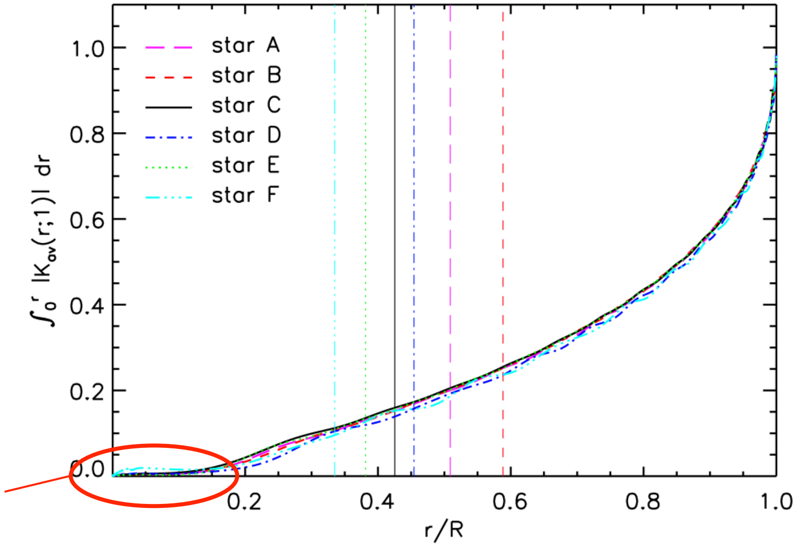
Envelope contribution cancelled

– **Core** averaging kernel well localized

⇒ precise estimate of core rotation rate in the innermost 2% of R_* (not even achieved for the Sun…)

– **Average rotation in the envelope** can be obtained

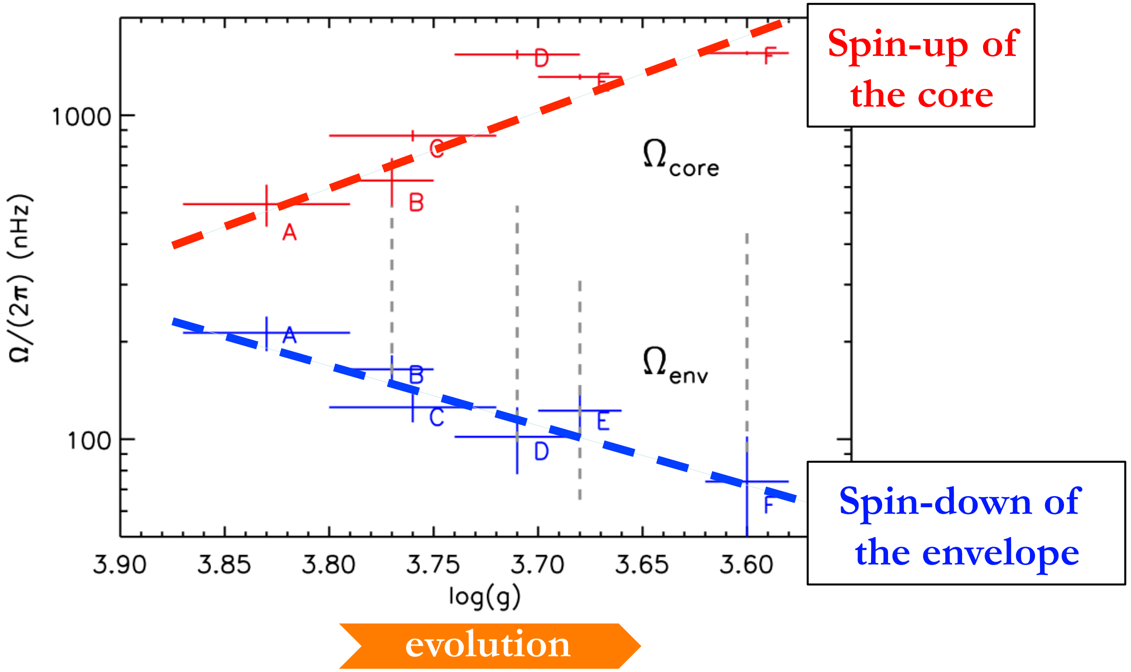
Cumulative integral of envelope averaging kernel



Core contribution cancelled

Sugiants & young red giants

- Spin-up of the core in the subgiant phase



Spin-up of the core

Spin-down of the envelope

evolution

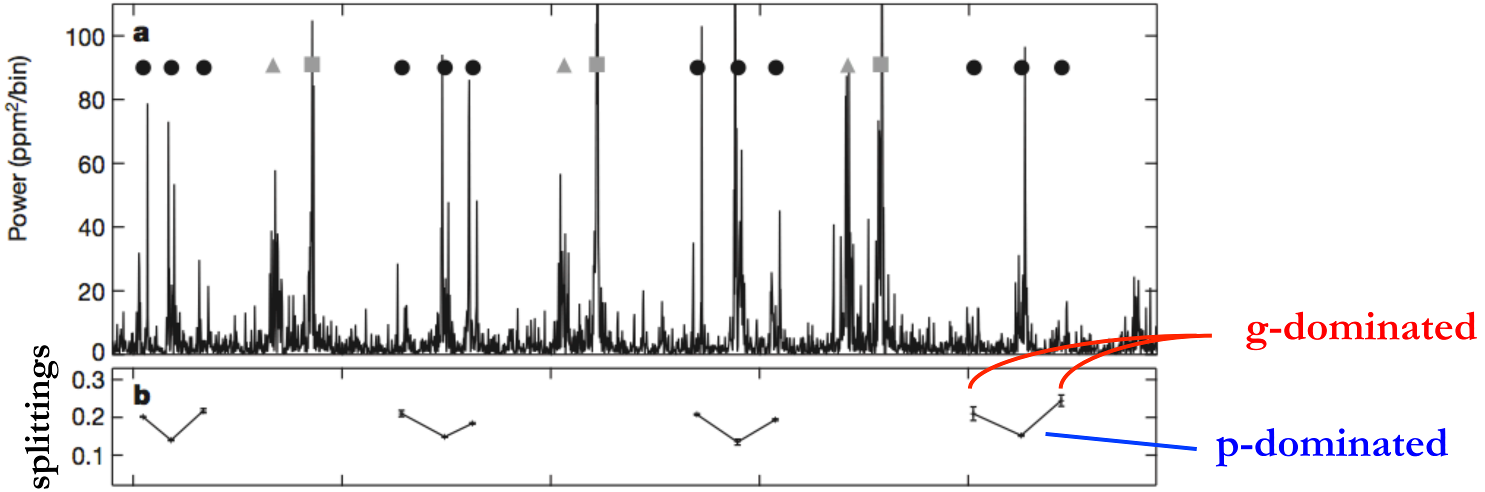
  - Qualitatively corresponds to what is expected…

    … BUT core rotation rate ~ 200 times lower than predicted **(Ceillier et al. 2013, Marques et al. 2013)**

  - **Need for an additional efficient mechanism of AM transport**

More evolved red giants

- First detection of rotationally split modes in a Kepler red giant **(Beck et al. 2012)**
  - Core spins faster than envelope



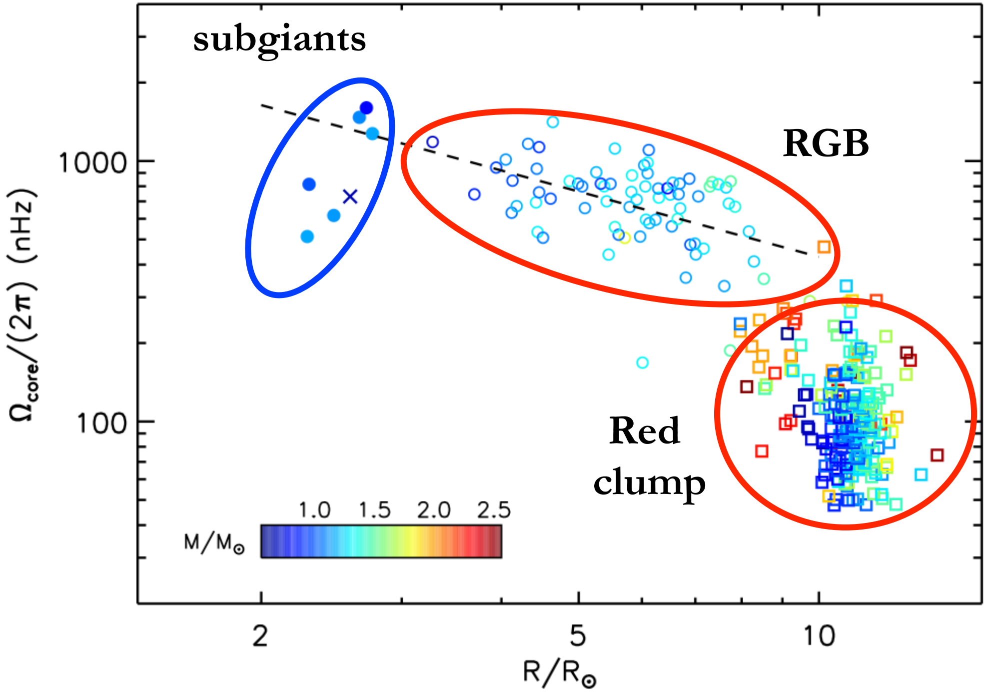
(Beck et al. 2012)

- 15,000 Kepler red giants, most of which oscillate: potential for "ensemble" measurement of internal rotation

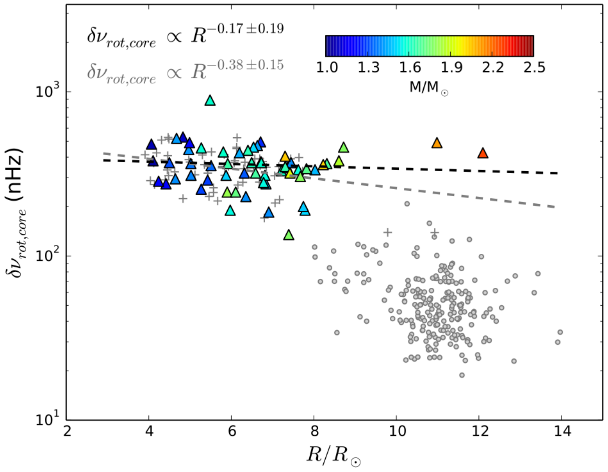
Spin-down of the core for red giants

- Extraction of rotational splittings in ~ 900 Kepler giants
  (Mosser et al. 2012, Gehan et al. 2018)

Mosser et al. (2012)



Gehan et al. (2018)



– Large core-envelope contrast on the RGB **(Goupil et al. 2013)**

⇒ Need for additional AM transport

$$\frac{\Omega_{\rm core}}{\Omega_{\rm env}} > 20$$

First attempts at interpreting the seismic rotation profiles of red giants

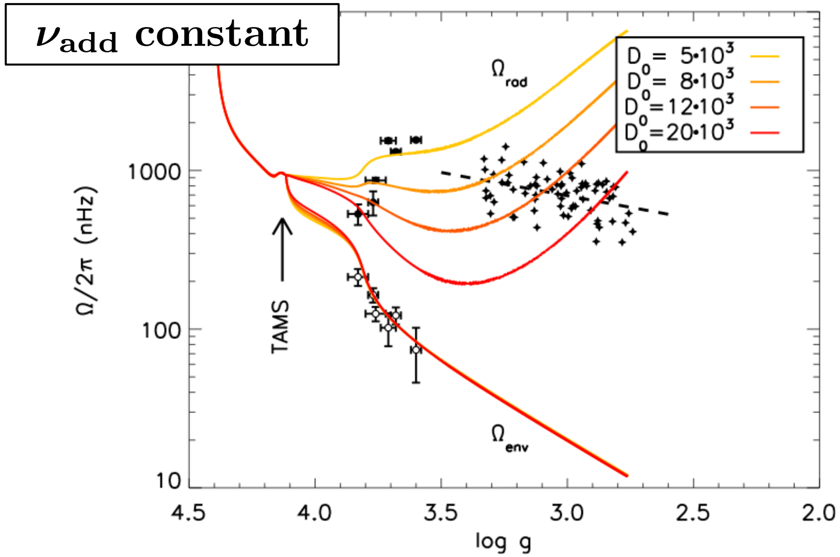
Parameterized additional transport of AM

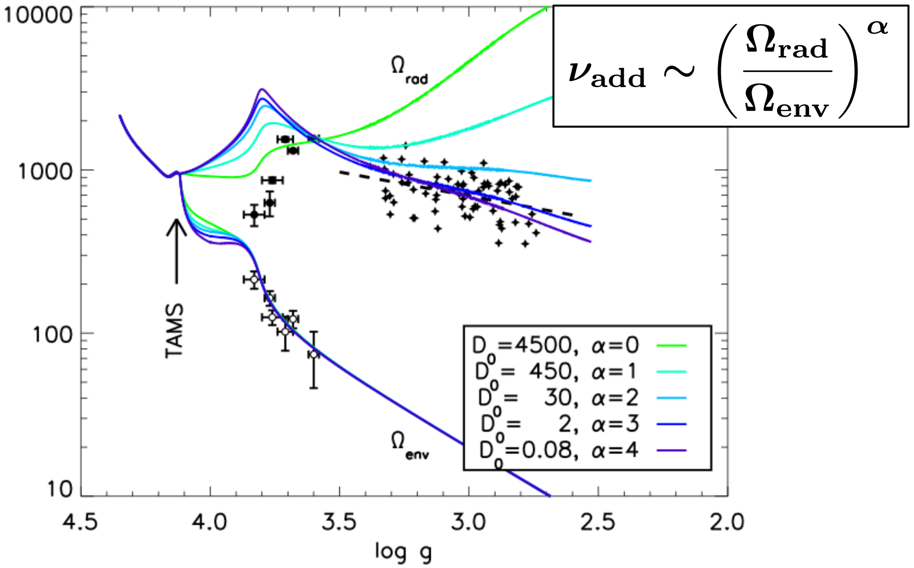
- Inclusion of an **additional constant viscosity** to match internal rotation of Kepler red giant **(Eggenberger et al. 2012, 2017)**

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

  - $\nu_{\mathrm{add}} = 3\times10^4\ \mathrm{cm}^2.\mathrm{s}^{-1}$ for red giant analyzed by **Beck et al. (2012)**
  - ν_{add} increases with stellar mass

- Dependence of ν_{add} on rotation gradient? **(Spada et al. 2016)**





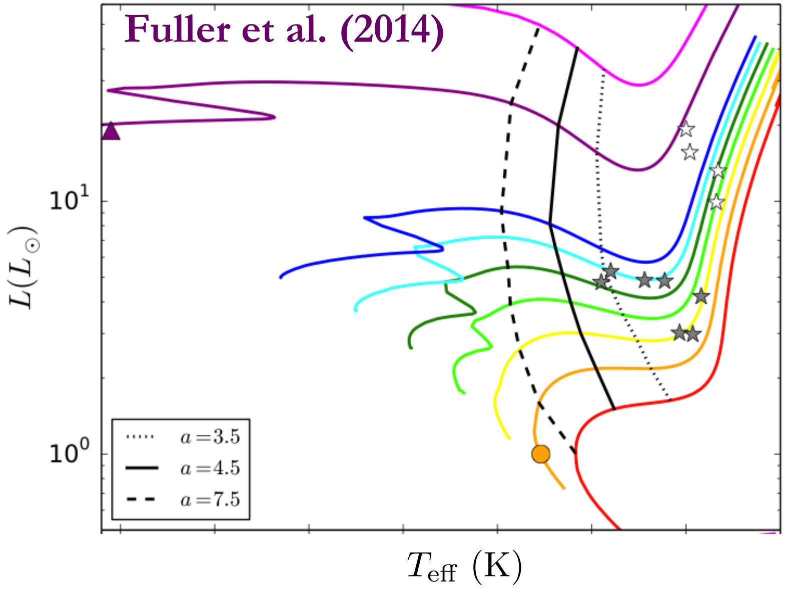
Transport of AM through IGW

- Transport of angular momentum through **internal gravity waves** excited by turbulence **(Talon & Charbonnel 2008, Fuller et al. 2014)**

✓ Might explain **core / envelope decoupling** during **subgiant phase**

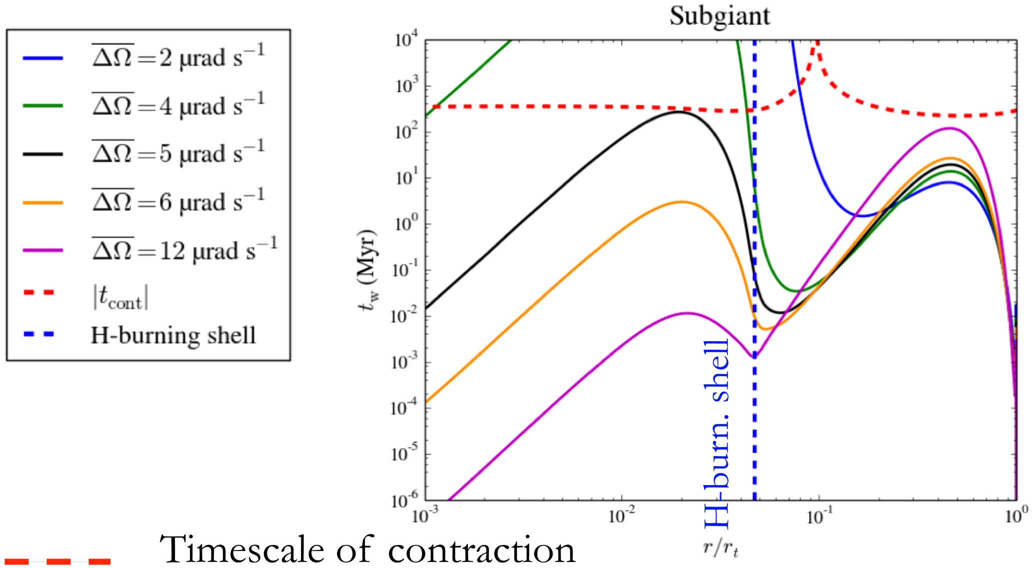
✗ But not **core spin-down** during **RGB**

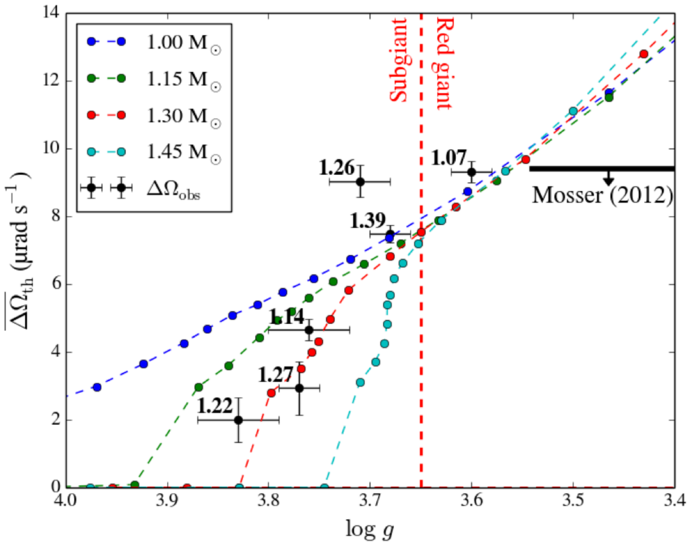
? During core-He burning **(red clump), IGW** excited by convective core might recouple?



Transport of AM through IGW

- Transport of angular momentum through **internal gravity waves** excited by penetrative convection **(Pinçon et al. 2017)**





╌ Timescale of contraction

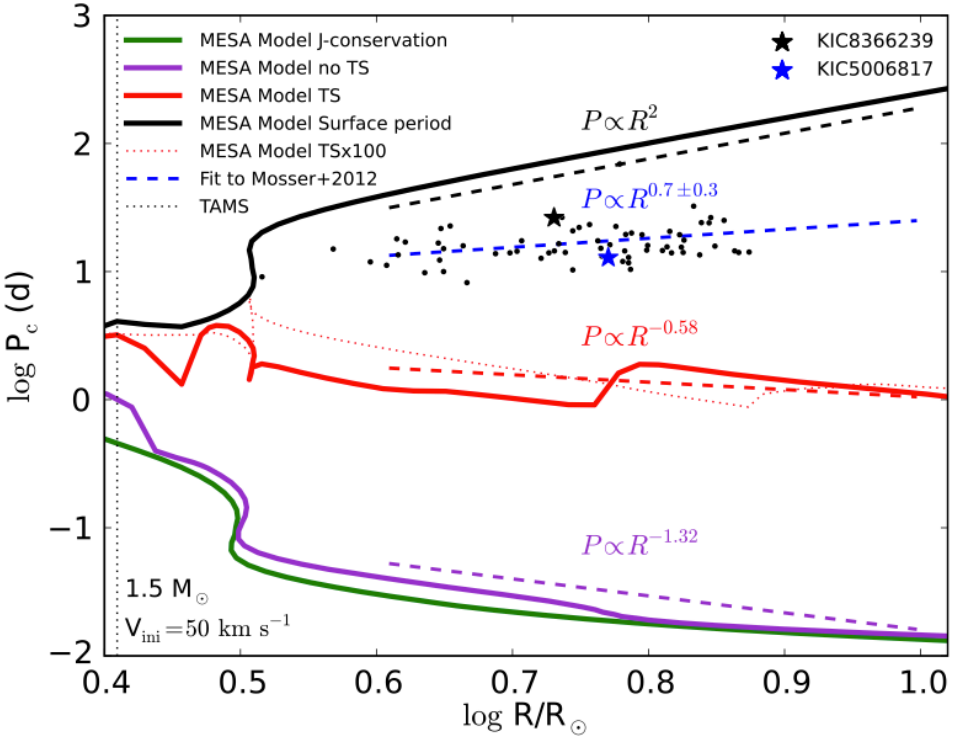
— Timescale of AM transport through IGW

⇒ **IGW could account for rotation of subgiants**

- Transport of angular momentum through **mixed modes** themselves could operate in the upper RGB **(Belkacem et al. 2015)**

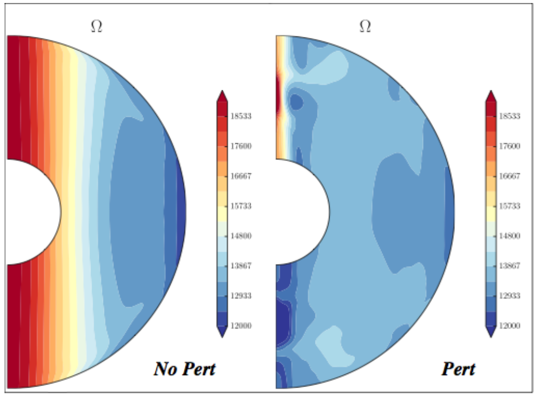
Transport of AM through magnetic fields

- Transport of angular momentum through **magnetic fields**
  - **Fossil field** **(Maeder & Meynet 2014)**
  - **Taylor-Spruit dynamo**: not efficient enough **(Cantiello et al. 2014)**



Transport of AM through magnetic fields

- Transport of angular momentum through **magnetic instabilities**
  - Poloidal magnetic field wound-up by differential rotation + perturbation => development of MHD instability, which corresponds to MRI **(Jouve et al. 2015)**



  - Transports AM on a timescale ~ Alfven time
  - Need to model the forcing of differential rotation caused by core contraction + study the impact of stratification **(Meduri et al. in prep)**

  - Unstable toroidal magnetic field prone to the AMRI **(Rüdiger et al. 2015)**
    - May produce sufficient effective viscosity (only upper limits on ν_{eff} are obtained)
    - Interesting feature: **effective viscosity depends on rotation gradient**

⇒ Main goal of ANR proposal BEAMING: to test whether MHD instabilities can be the cause of AM transport in red giants

What more information can seismology bring on the rotation profiles of giants?

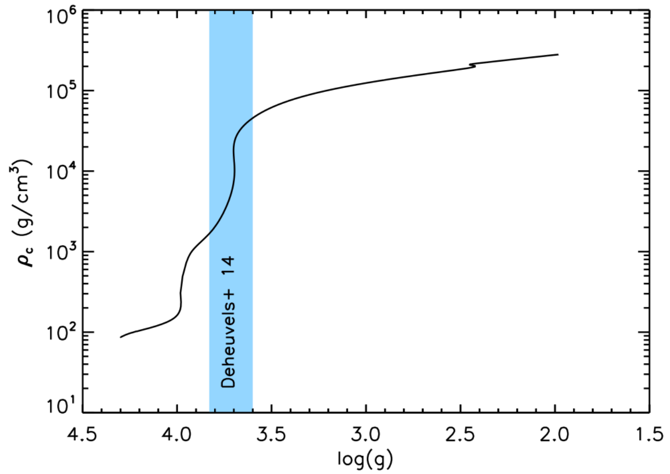
How to go further

- The *Kepler* data are far from having revealed all the information they hold on the internal rotation of red giants
  - Only a small fraction of the 15,000 *Kepler* red giants analyzed (core rotation rates for ~ 900 giants, envelope rotation for ~ 20 targets)
  - Inversion methods applied so far on datasets of at most 2 yrs (typical error bars on rotational splittings $\sigma_{\delta\nu}$ ~ 16 nHz): full *Kepler* datasets are 4 yr long ($\sigma_{\delta\nu}$ ~ 11 nHz)
  - Inversion methods directly adapted from helioseismology, not optimally suited to red giant rotation profiles (e.g., search for rotation gradients)
  - Inversions so far performed using only dipolar mixed modes (rotational splittings of quadrupolar modes ill-understood until recently)

- Upcoming space missions that will bring further constraints: TESS, **PLATO** !

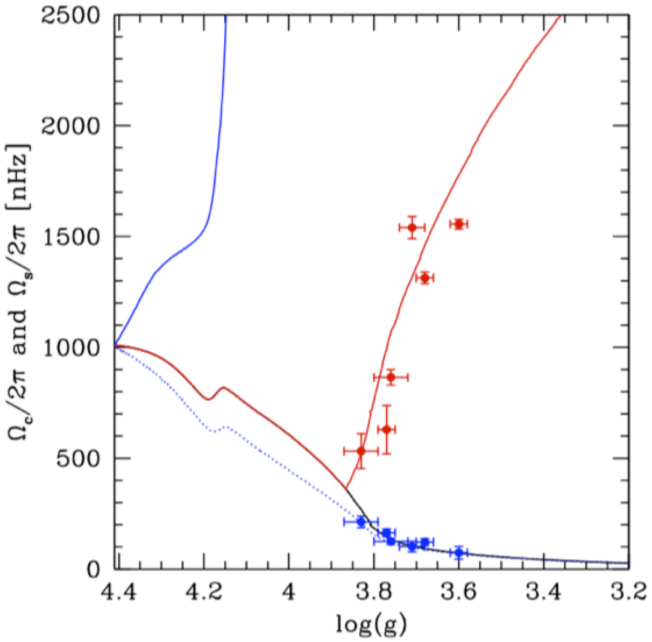
Probing Ω(r) at key stages of evolution
Young subgiants

- Precisely measure Ω(r) at key moments of the evolution can bring measurements of the efficiency of AM transport
- Good illustration: **rotation of stars immediately after MS turnoff**
  - Severe core contraction after turnoff



  - Measuring Ω(r) as close as possible to main-sequence turnoff

Credits: **P. Eggenberger**

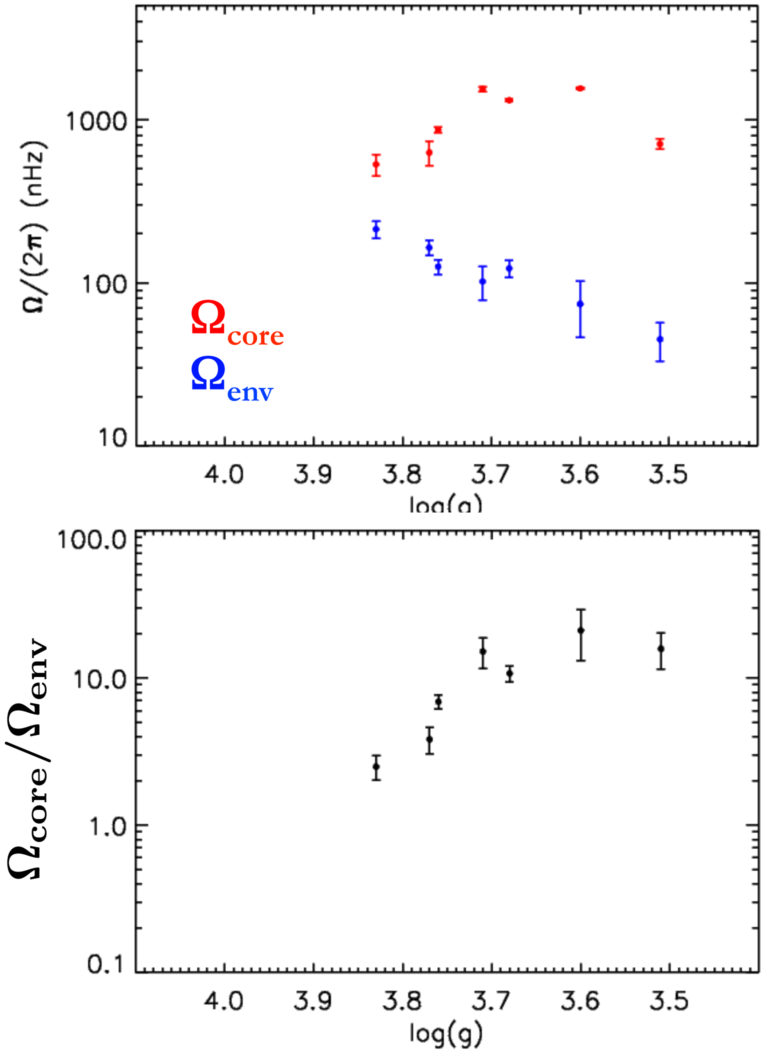


Probing the internal rotation of young subgiants

- Rotation of stars immediately after main-sequence turnoff
  - Two young Kepler subgiants **(Deheuvels et al., in prep.)**:

$M/M_\odot$	Age (Gyr)	CC in MS	(Z/X)	Y_0	$\alpha_{\rm conv}$	$R/R_\odot$	$T_{\rm eff}$ (K)	$\log g$
1.15	9.6	no	0.0293	0.24	0.60	1.82	5401	3.980
1.21	5.8	yes	0.0165	0.24	0.56	2.09	5744	3.878
1.19	6.2	no	0.0185	0.25	0.54	2.08	5644	3.874

  - Only a few mixed modes



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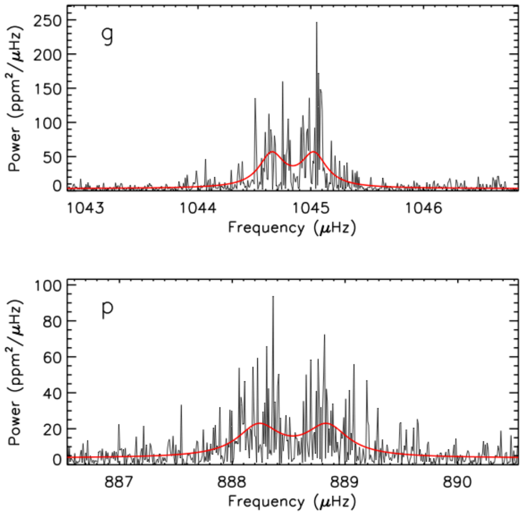
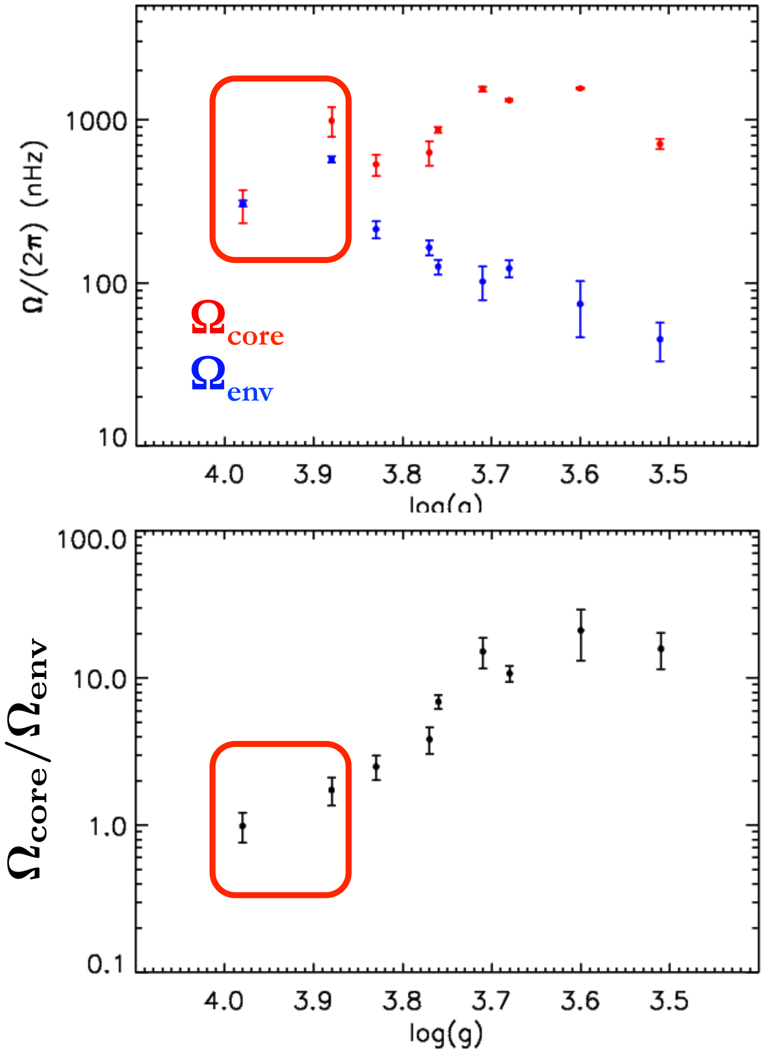


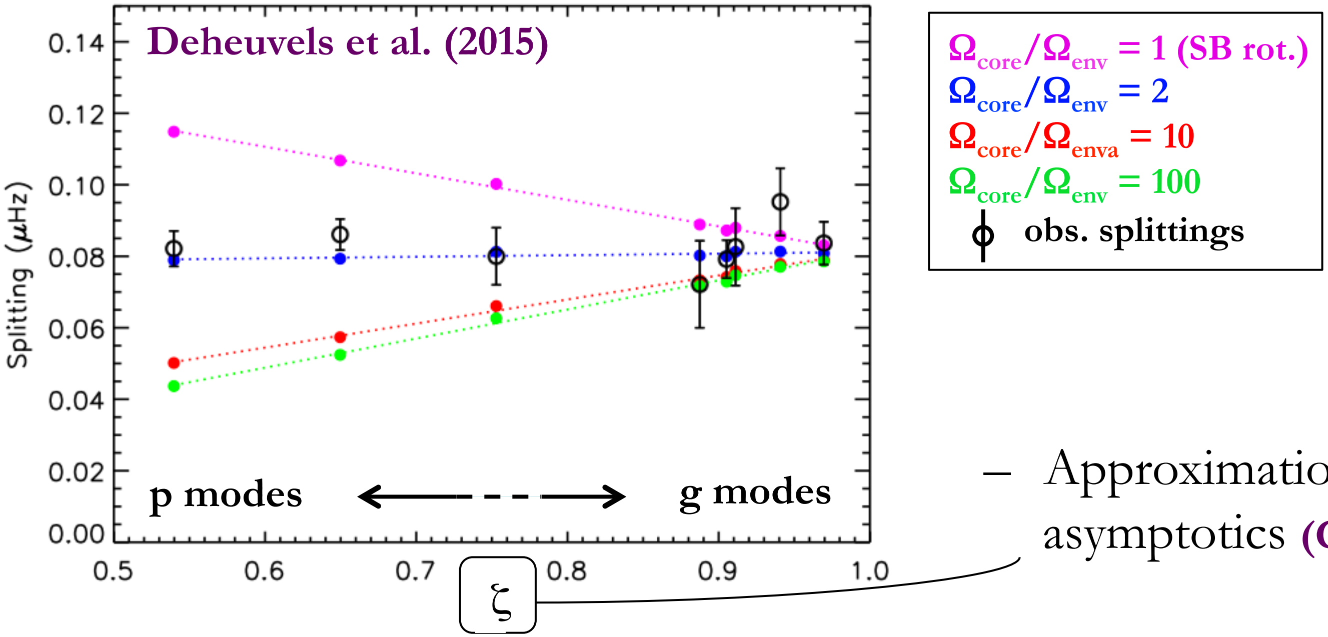
Much lower differential rotation than more evolved giants



  - Estimate of the efficiency of AM transport is under way (P. Eggenberger, F. Spada)

Probing Ω(r) at key stages of evolution
Core He burning giants

- Secondary clump stars: intermediate-mass ($M > 2.1\ M_\odot$) core He-burning stars



  - Approximation from asymptotics **(Goupil et al. 2013)**

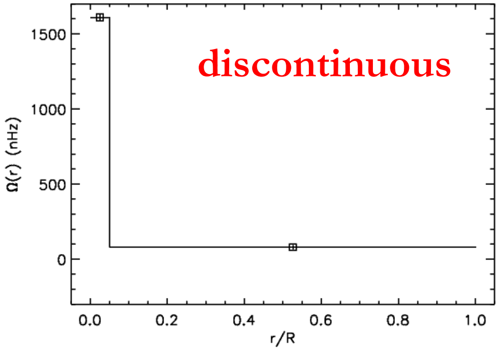
- **Weak differential rotation** $\left(1 \leqslant \frac{\Omega_{core}}{\Omega_{env}} \leqslant 3.2\right)$ for 7 Kepler clump stars
  (Deheuvels et al. 2015)

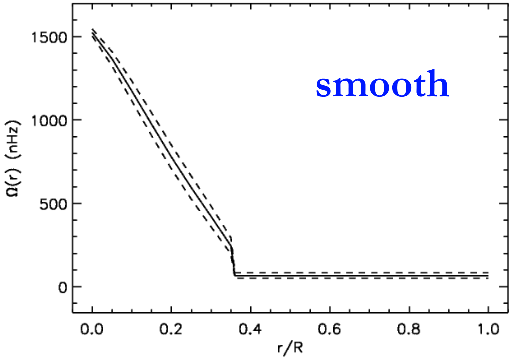
⇒ **very fast redistribution of AM** either during short-lived subgiant phase or at the beginning of core He-burning

Improving seismic inversions of rotation
Searching for rotation gradients in the core

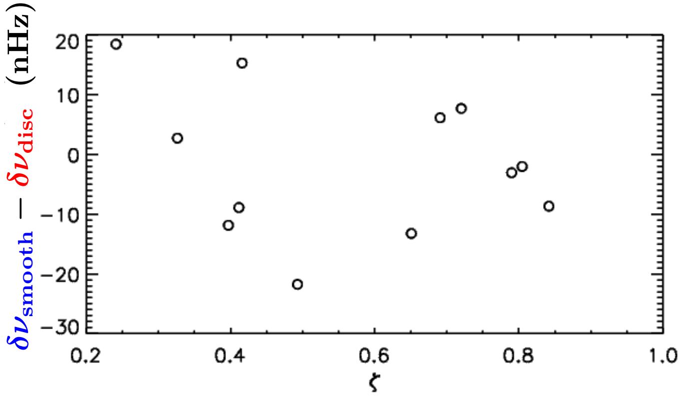
- Localized profile of Ω(r) in the core can bring decisive constraints on the mechanism that transports AM

- Tests on stellar evolution models: discontinuous vs smooth rotation profiles that generate same average core and envelope rotations





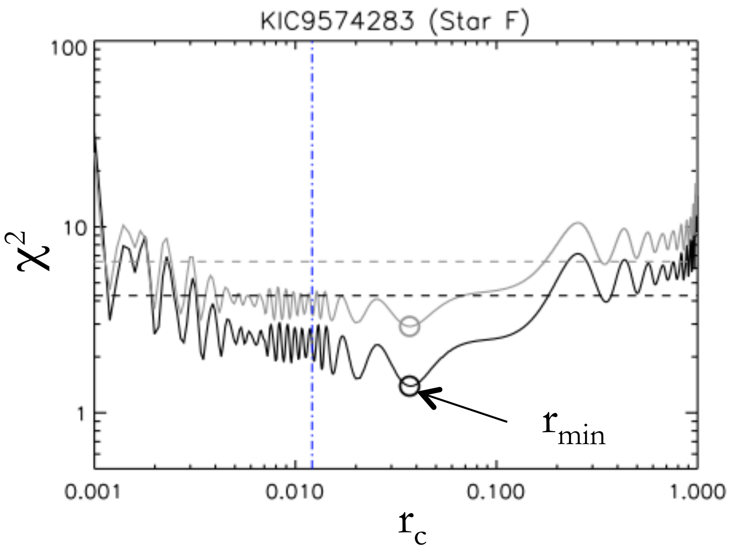
Difference btw theoretical splittings (nHz)



  - Difference of splittings ~ 20 nHz larger than typical error bars for 2 yrs (16 nHz) and 4 yrs of data (11 nHz)

Searching for rotation gradients in the core of red giants

- For two *Kepler* young giants, discontinuous rotation profiles agree better with observations than smooth profiles **(Deheuvels et al. 2014)**
  - Inversions with a discontinuous profile: for both targets, optimal depth for the discontinuity ~ H-burning shell

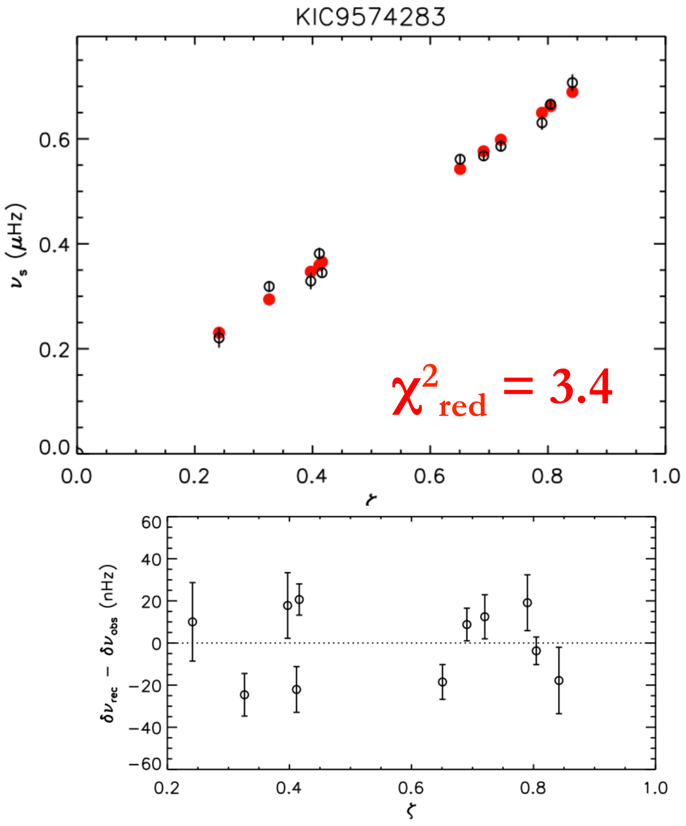


Star	Smooth		Discontinuous	
	$\chi^2_{\rm smooth}$	$\chi^2_{\rm SBenv}$	$\chi^2_{\rm disc}$	$r_{\rm min}/R_\star$
A (KIC 12508433)	1.0	1.0	0.7	0.991
B (KIC 8702606)	3.1	3.1	2.2	0.990
C (KIC 5689820)	3.3	3.2	2.1	0.998
D (KIC 8751420)	6.0	5.9	2.4	0.005
E (KIC 7799349)	1.6	1.7	1.1	0.889
F (KIC 9574283)	4.4	4.4	1.4	0.037

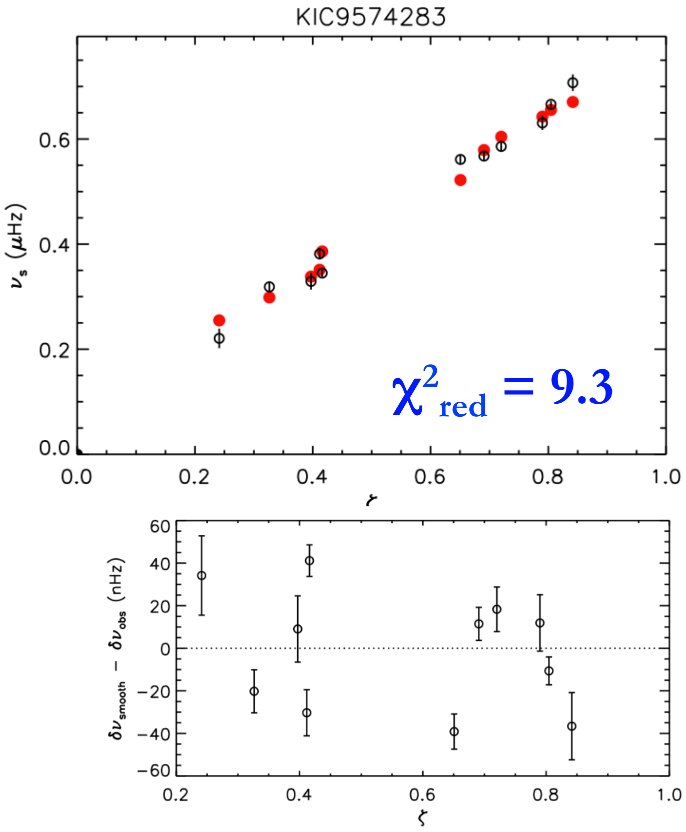
  - $\chi^2_{\rm smooth} > \chi^2_{\rm disc}$, difference of χ^2 is significant, according to statistical tests

Searching for rotation gradients in the core of red giants

- Revisiting KIC9574283 with full Kepler data (3.2 yrs of data)
  - Previous splitting estimates (1.8 yrs): mean error bar ~ 16 nHz
  - Current splitting estimates (3.2 yrs): mean error bar ~ 11 nHz



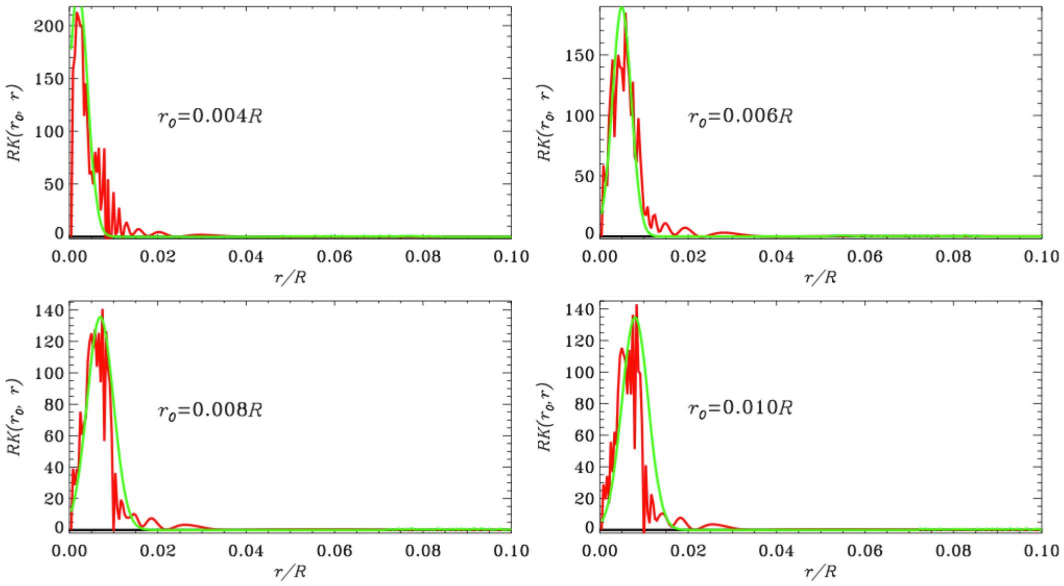
$\chi^2_{red} = 3.4$

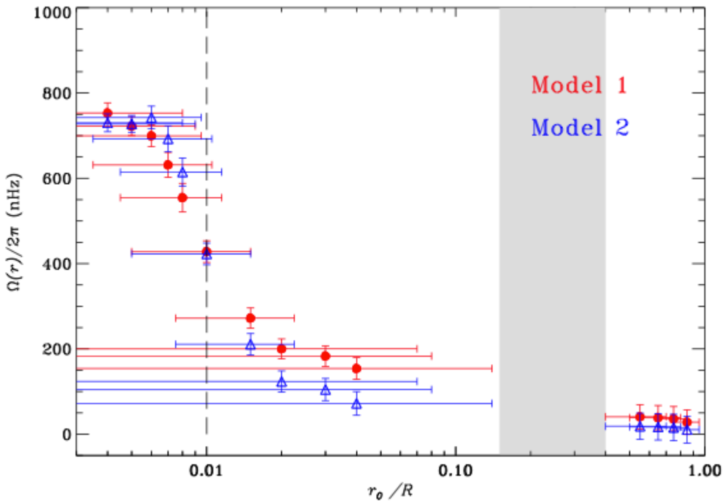


$\chi^2_{red} = 9.3$

Searching for rotation gradients in the core of red giants

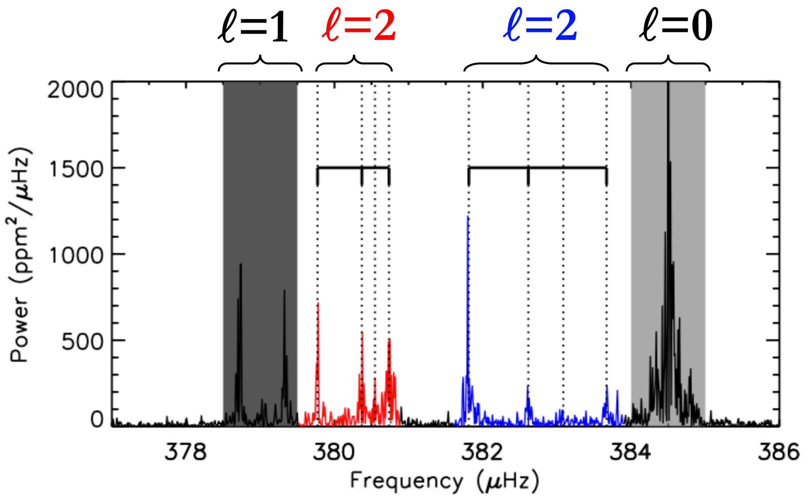
- The case of KIC4448777 **(di Mauro et al. 2016)**
  - Averaging kernels in the core well localized in different regions of the core
  - Evidence for a rotation gradient in the core





Improving seismic inversions of rotation
Using $\ell = 2$ modes

- Red giants are **slow rotators**: first-order perturbation analysis valid
  - For a spherically symmetric profile, $\omega_1 = m \int_0^R K_{n,l}(r)\Omega(r)\,\mathrm{d}r$
  - At 1st order, multiplets are expected to be **symmetric with respect to the m = 0 component**
- But, **asymmetries** reported in $\ell = 2$ mixed modes **(Deheuvels et al. 2012)**
  - Coupling between g- and p-mode cavities much weaker than for $\ell = 1$ modes
  - Only p-dominated modes are detected



- Two mixed $\ell = 2$ multiplets of KIC7341231 (Otto)

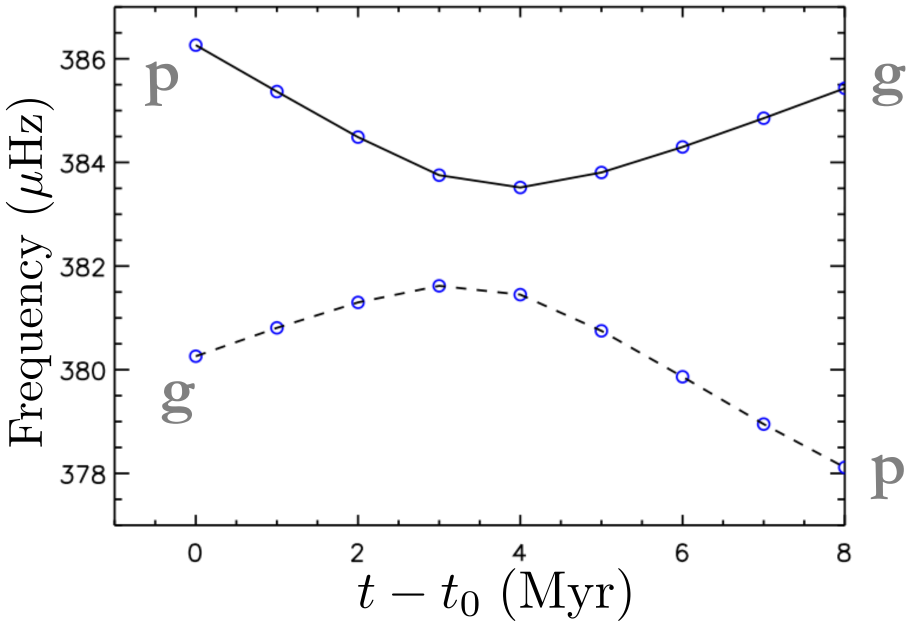
$$\delta_{\mathrm{asym}} \equiv \frac{\omega_{-m} + \omega_{+m} - 2\omega_0}{\omega_{+m} - \omega_{-m}}$$

$$\boldsymbol{\delta_{\mathrm{asym}} = -0.25 \pm 0.03}$$

$$\boldsymbol{\delta_{\mathrm{asym}} = +0.14 \pm 0.03}$$

1^{st}-order perturbation with ND effects

- Computation of perturbed frequencies for reference model of Otto
  - Sequence of models spanning the avoided crossing between $\ell = 2$ modes

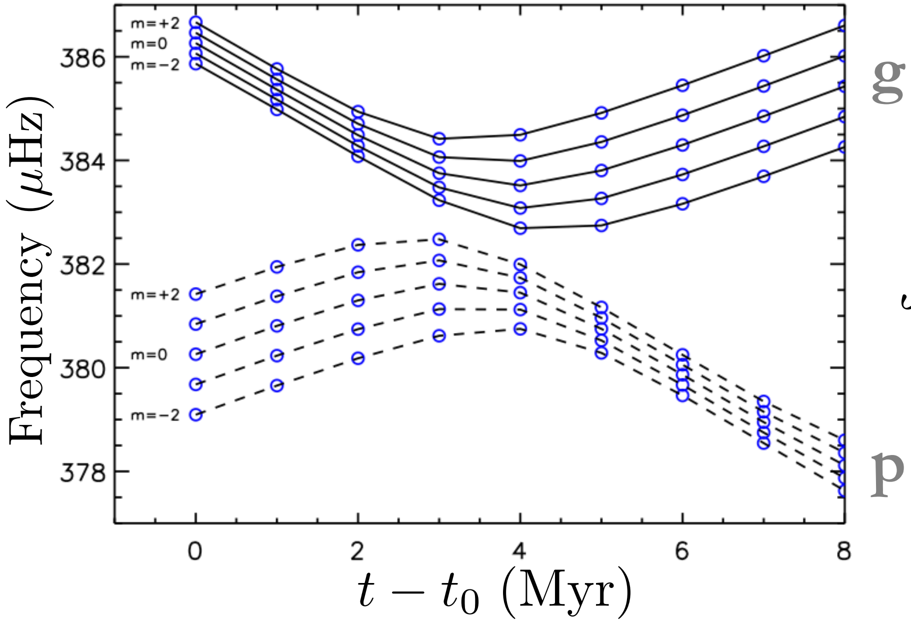


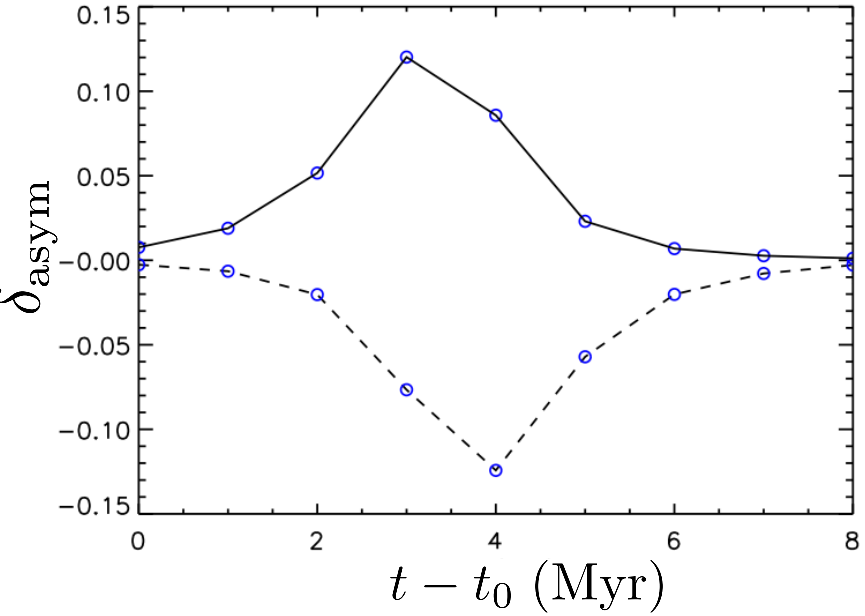
1^{st}-order perturbation with ND effects

- Computation of perturbed frequencies for reference model of Otto
  - Sequence of models spanning the avoided crossing between $\ell = 2$ modes
  - Rotation profile from $\ell = 1$ modes ($\Omega_c/2\pi = 710$ nHz, $\Omega_c/\Omega_e = 5$)

=> Excellent agreement with frequencies calculated with non-perturbative oscillation code ACOR **(R.-M. Ouazzani)**

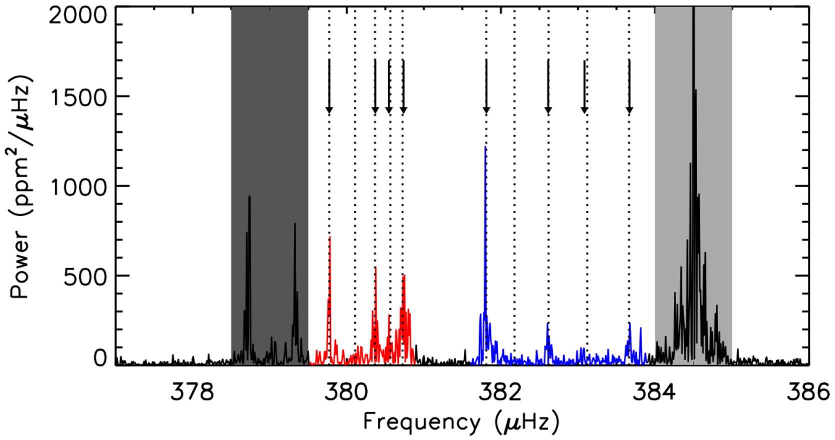
$$\delta_{\rm asym} \equiv \frac{\omega_{-m} + \omega_{+m} - 2\omega_0}{\omega_{-m} - \omega_{+m}}$$





Application to KIC7341231 (Otto)

- Iterative fit of 1st-order perturbed mode frequencies to the observed modes (8 detected components for Otto)
  - Very good agreement with observations ($\chi^2_{\mathrm{red}} = 1.6$)
  - Robust to changes in initial conditions

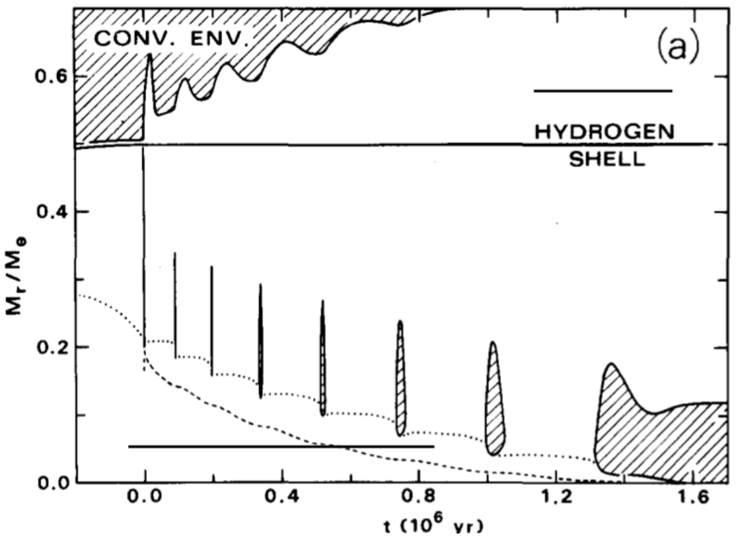


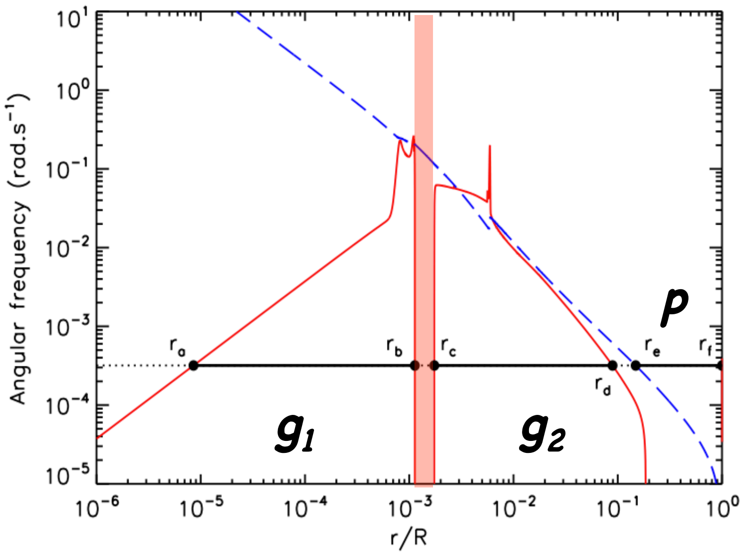
	ℓ = 2 modes	**ℓ = 1 modes**
$\langle\Omega\rangle_{\mathrm{c}}/2\pi$ (nHz)	771 ± 13	710 ± 51
$\langle\Omega\rangle_{\mathrm{e}}/2\pi$ (nHz)	45 ± 12	$< 150 \pm 19$
$\langle\Omega\rangle_{\mathrm{c}}/\langle\Omega\rangle_{\mathrm{e}}$	17 ± 5	> 5
Δt (Myr)	4.14 ± 0.02	
$\zeta_{0,a}$	0.304 ± 0.006	
$\zeta_{0,b}$	0.722 ± 0.006	

- Develop new inversion procedures taking near-degeneracy effects into account for ℓ=1 and ℓ=2 modes

Searching for He-flashing giants

Iben & Renzini (1984)





- Several 1D codes predict the He-flash to occur as a series of successive subflashes **(Thomas 1967, Iben & Renzini 1984, Bildsten et al. 2012)**

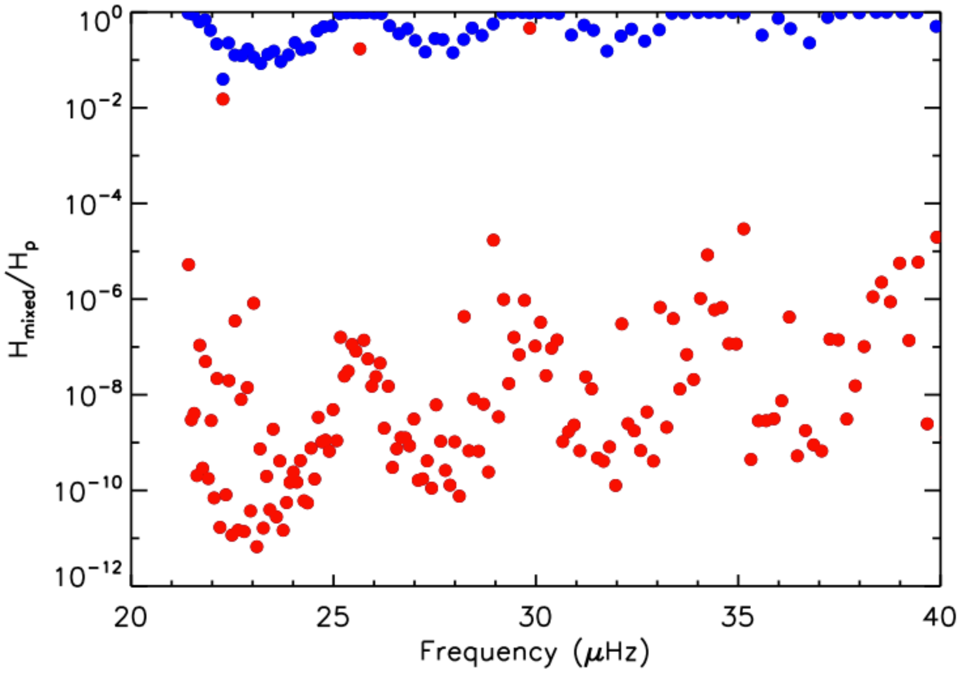
- Existence of such subflashes debated in view of 2D- and 3D- numerical computations **(Mocak et al. 2008, 2009)**

— — **Lamb for $\ell = 1$ (S_1)**

— **Brunt-Väisälä**

Searching for He-flashing giants

- Calculation of mode frequencies during a He-subflash using WKB approximation
- Comparison with numerical calculation of frequencies with ADIPLS, GYRE

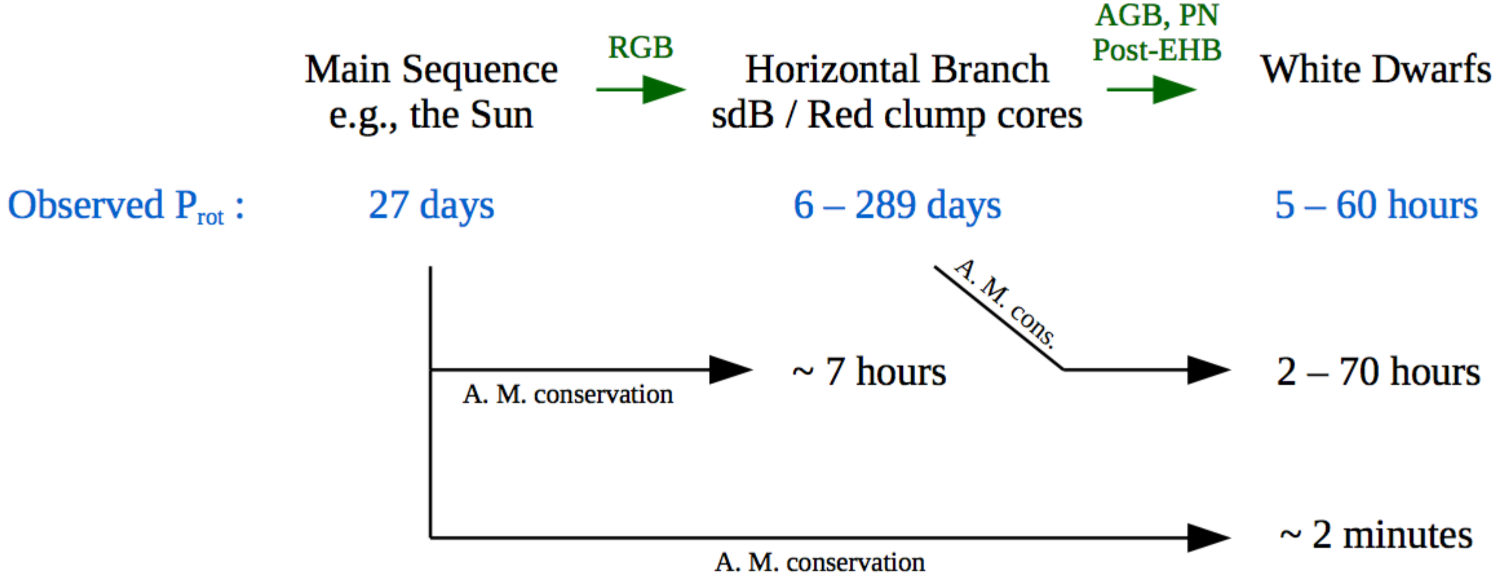


Perspectives

ANR proposal BEAMING

- Monitor the internal rotation of red giants along their evolution
  - Probe $\Omega(r)$ at key stages of the evolution
  - Link with ANR INSIDE (PI S. Charpinet): rotation of sdB and WD
  - Improve inversion techniques to obtain localized measurements of $\Omega(r)$
- Probe the internal rotation profiles of red giants hosting internal magnetic fields
  - Search for descendants of Ap stars
  - Search for magnetic splittings of oscillation modes
- Model interactions between magnetic fields and differential rotation
  - Model contraction/expansion in hydro simulations
  - Investigate the development of MHD instabilities and their efficiency to transport AM

Angular momentum evolution for low-mass stars



Main Sequence
e.g., the Sun

RGB

Horizontal Branch
sdB / Red clump cores

AGB, PN
Post-EHB

White Dwarfs

Observed P_{rot} : 27 days 6 – 289 days 5 – 60 hours

A. M. conservation

~ 7 hours

A. M. cons.

2 – 70 hours

A. M. conservation

~ 2 minutes

Star	Type	Prot (h)	**Jtot (kg.m2/s)**	**Jtot / Jsun**
Sun	Solar type	~ 648 (27 d)	**1.92×10^{41}**	**1**
PG1159-035	Pre-WD	33.7 (1.40 d)	**1.25×10^{39}**	**1/154**
KIC08626021	DB WD	46.8 (1.95 d)	**6.54×10^{38}**	**1/294**
GD165	DA WD	57.2 (2.38 d)	**4.89×10^{38}**	**1/393**
Isolated sdBs	sdB	~ 960 (40 d)	**7.60×10^{38}**	**1/253**

← Total stellar angular momentum

This suggests that angular momentum of stellar cores is globally preserved passed the RG phase and all the braking occurs during MS and/or RGB

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