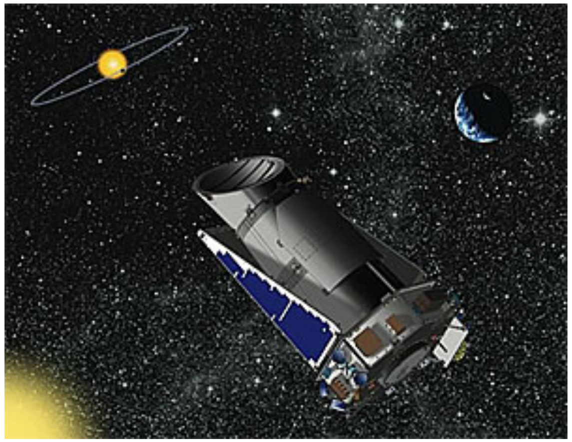
What the seismology of red giants is teaching us about stellar physics

S. Deheuvels



Introduction

- Red giant phase is **a tumultuous stage of stellar evolution**

  ⇒ evolution of red giants critically depends on several ill-understood physical processes (**mixing of chemical elements, transport of angular momentum, rotation**…)

  ⇒ powerful tools to better understand these processes!

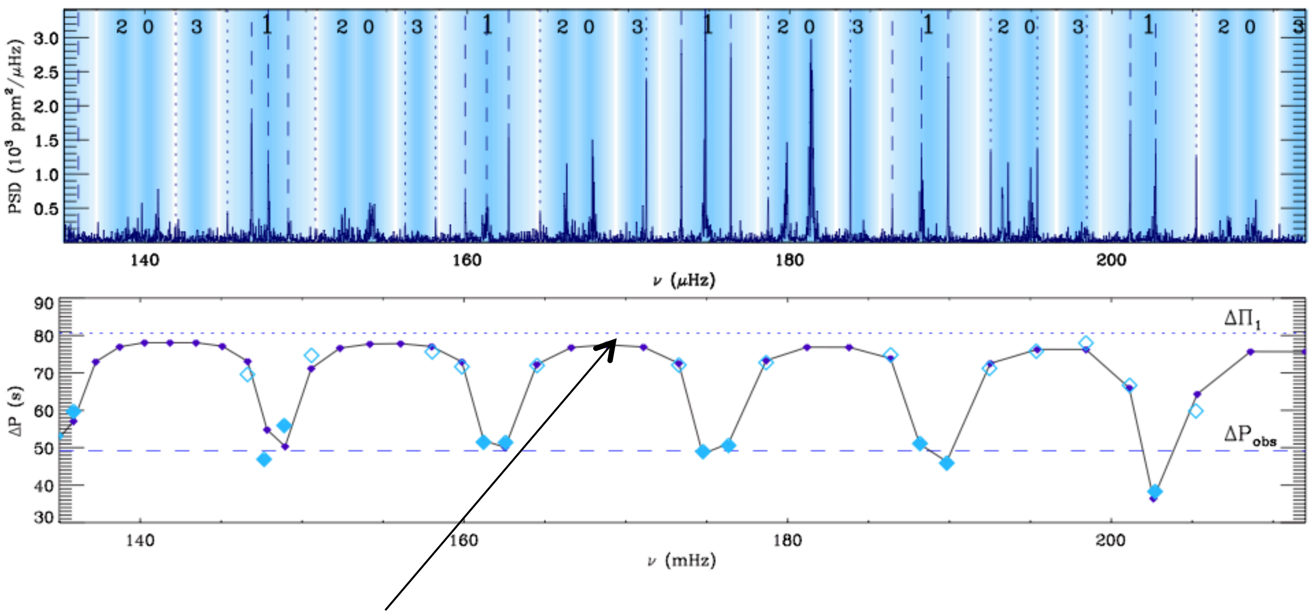
- **Seismology of red giants**
  - Detection of non-radial modes in red giants **(de Ridder et al. 2009)**
  - Stochastically-excited modes detected in ~ 20,000 red giants (CoRoT + Kepler)
  - Large diagnostic potential of mixed modes

Outline

- Understanding the oscillation spectra of giants
- Probing the convective cores of core-He-burning giants
- Monitoring stellar evolution using mixed modes
- Toward a better understanding of angular momentum transport in stars

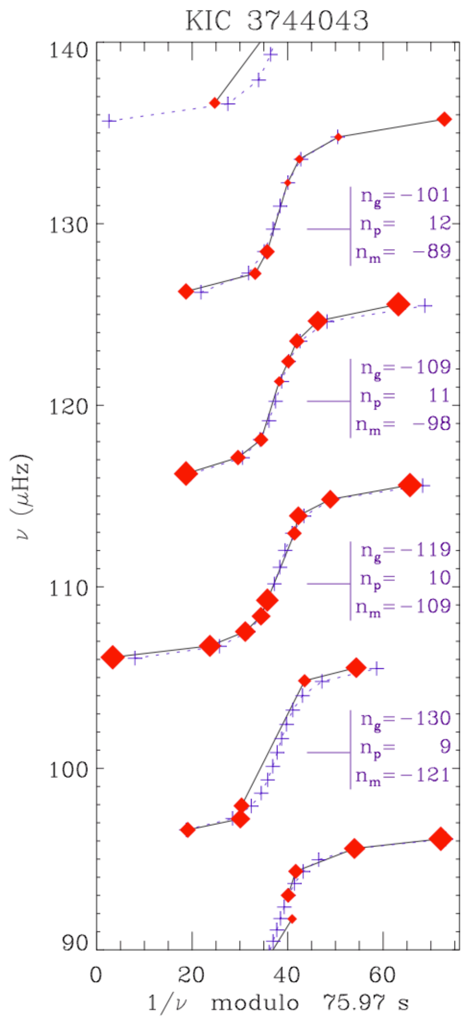
Understanding red giant oscillation spectra

Mosser et al. (2012)



$$\Delta\Pi_1 = \frac{2\pi^2}{\sqrt{2}} \left[\int_{\text{core}} \frac{N_{\text{BV}}}{r} \, \text{d}r \right]^{-1} \qquad N^2 = \frac{g}{H_P} \left(\nabla_{\text{ad}} - \nabla + \nabla_\mu \right)$$

Period échelle diagram



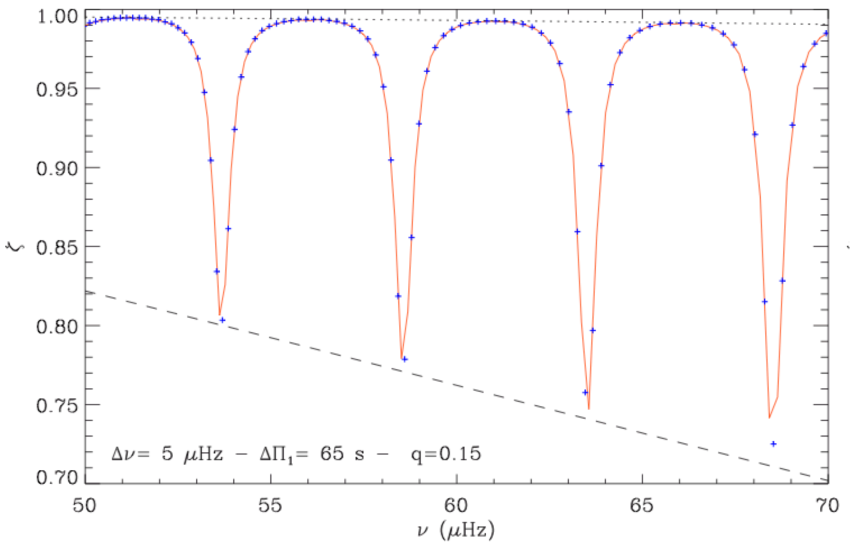
- Several methods to estimate $\Delta\Pi_1$ (Mosser et al. 2012, Datta et al. 2015, Vrard et al. 2016)

"Stretched" period échelle diagrams

- Ratios of inertia $\zeta \equiv \frac{I_g}{I} = \frac{\int_{\text{g-cav}} |\boldsymbol{\xi}|^2 \, \mathrm{d}m}{\int_0^M |\boldsymbol{\xi}|^2 \, \mathrm{d}m}$

- Approximate expression for ζ from WKB analysis **(Goupil et al. 2013, Deheuvels et al. 2015)**

$$\tilde{\zeta} = \left\{ 1 + \frac{1}{q} \frac{\cos^2\left[\pi\left(\frac{1}{\nu\Delta\Pi_1} - \varepsilon_g\right)\right]}{\cos^2\left[\pi\frac{(\nu-\nu_p)}{\Delta\nu}\right]} \frac{\nu^2\Delta\Pi_1}{\Delta\nu} \right\}^{-1}$$



- Idea: introduce a "modified" period **τ** to force a regular spacing of modes in period **(Mosser et al. 2015)**

$$\mathrm{d}\tau = \frac{\mathrm{d}P}{\zeta}$$

"Stretched" period échelle diagrams

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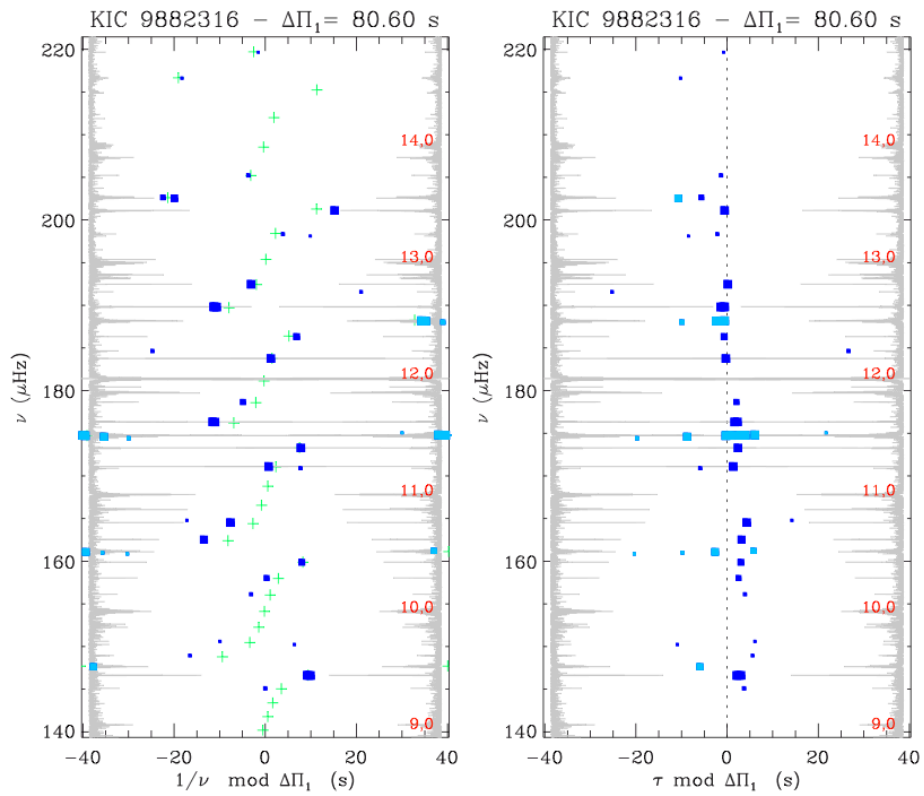
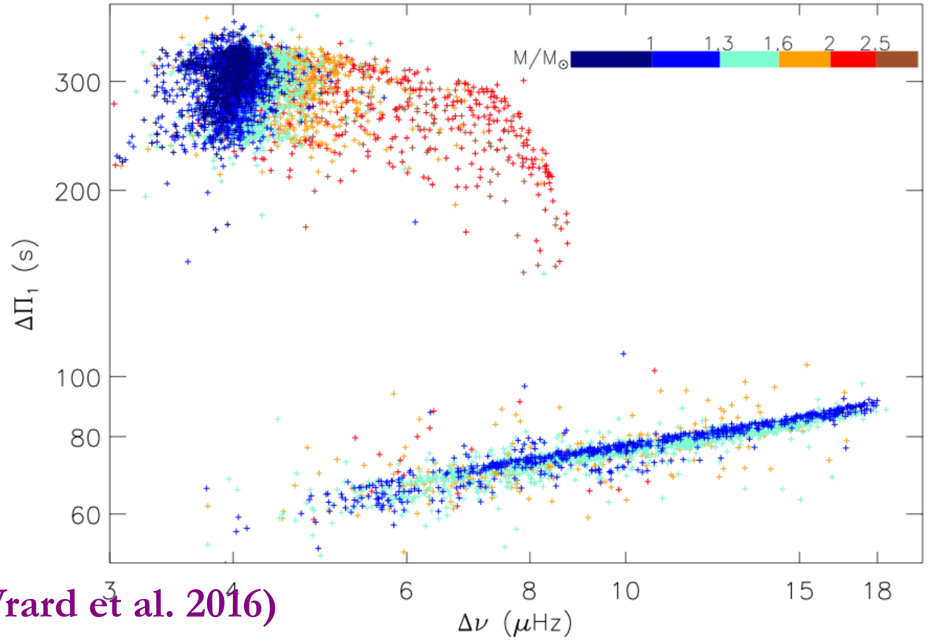


- Opened the way for **automated measurements of $\Delta\Pi_1$**

Measuring $\Delta\Pi_1$ for Kepler giants

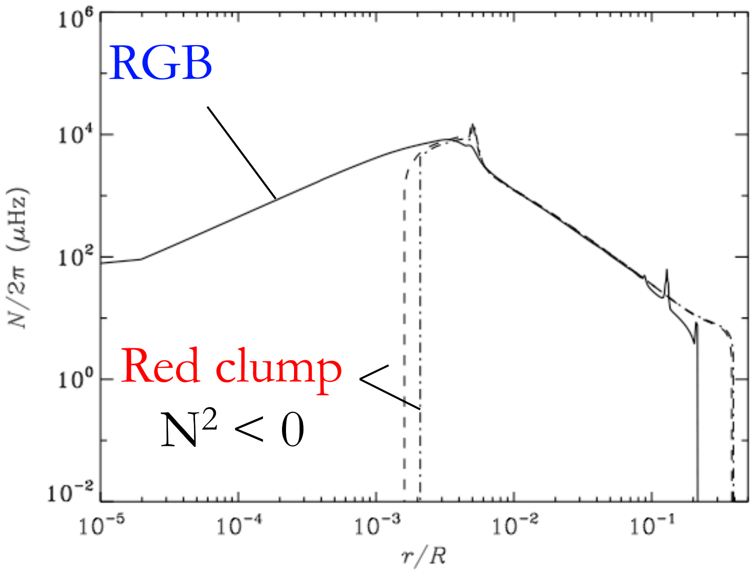
- Automated measurements of $\Delta\Pi_1$ for ~ 6100 giants **(Vrard et al. 2016)**
  - Becomes impossible for the brighter part of RGB and AGB (radiative damping, **Grosjean et al. 2014**)
  - Analysis made tricky in the presence of "glitches"

$$\Delta\Pi_1 = \frac{\sqrt{2}\pi^2}{\int_g \frac{N_{BV}}{r}\,dr}$$



(Vrard et al. 2016)

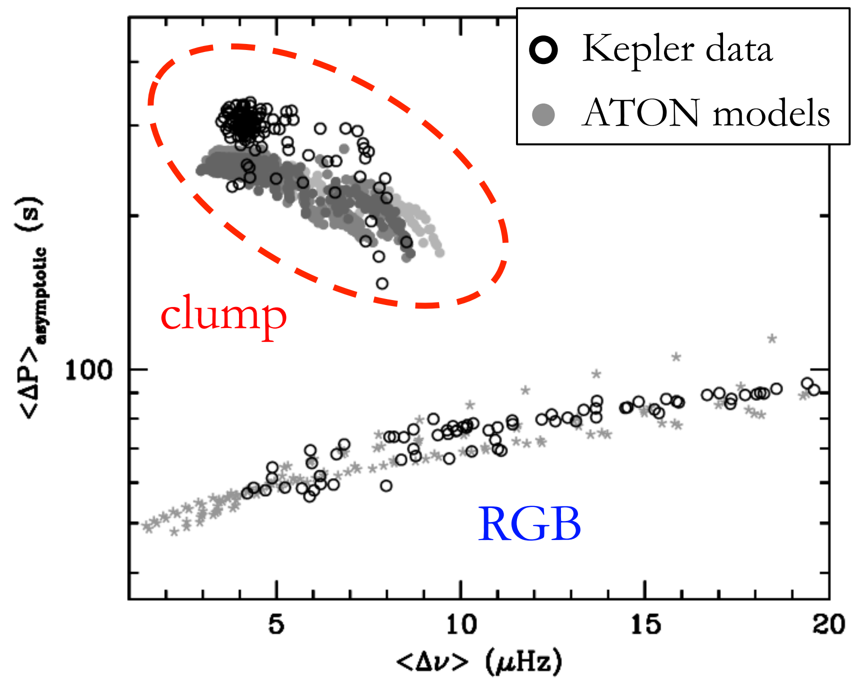
(Christensen-Dalsgaard et al. 2011)



- Disentangling RGB from clump giants! **(Bedding et al. 2011)**

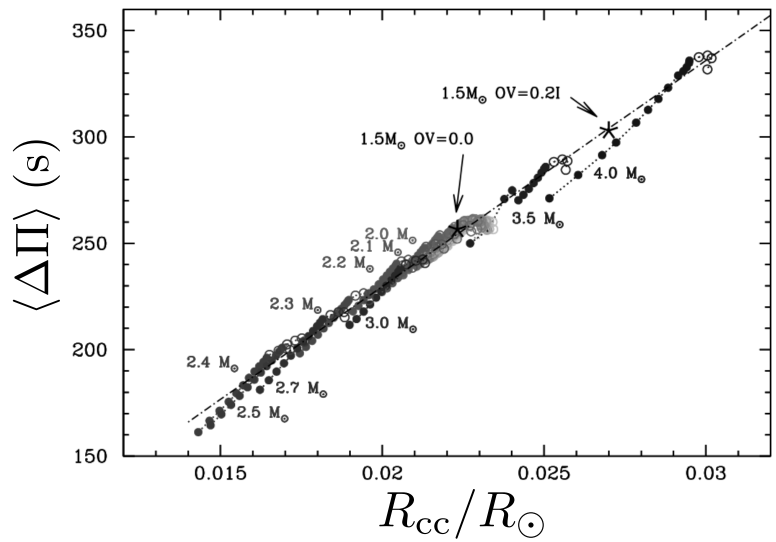
Need for an extended convective core in CHeB stars

- Discrepancy btw observed and theoretical $\Delta\Pi_1$ from models
  - Robust: obtained with several different evolutionary codes (e.g. MESA, ATON, MONSTAR)
  - Uncertainties on microphysics (EOS, reaction rates, opacities…) not sufficient to account for this difference **(Campbell's talk in KASC6, Constantino et al. 2015)**



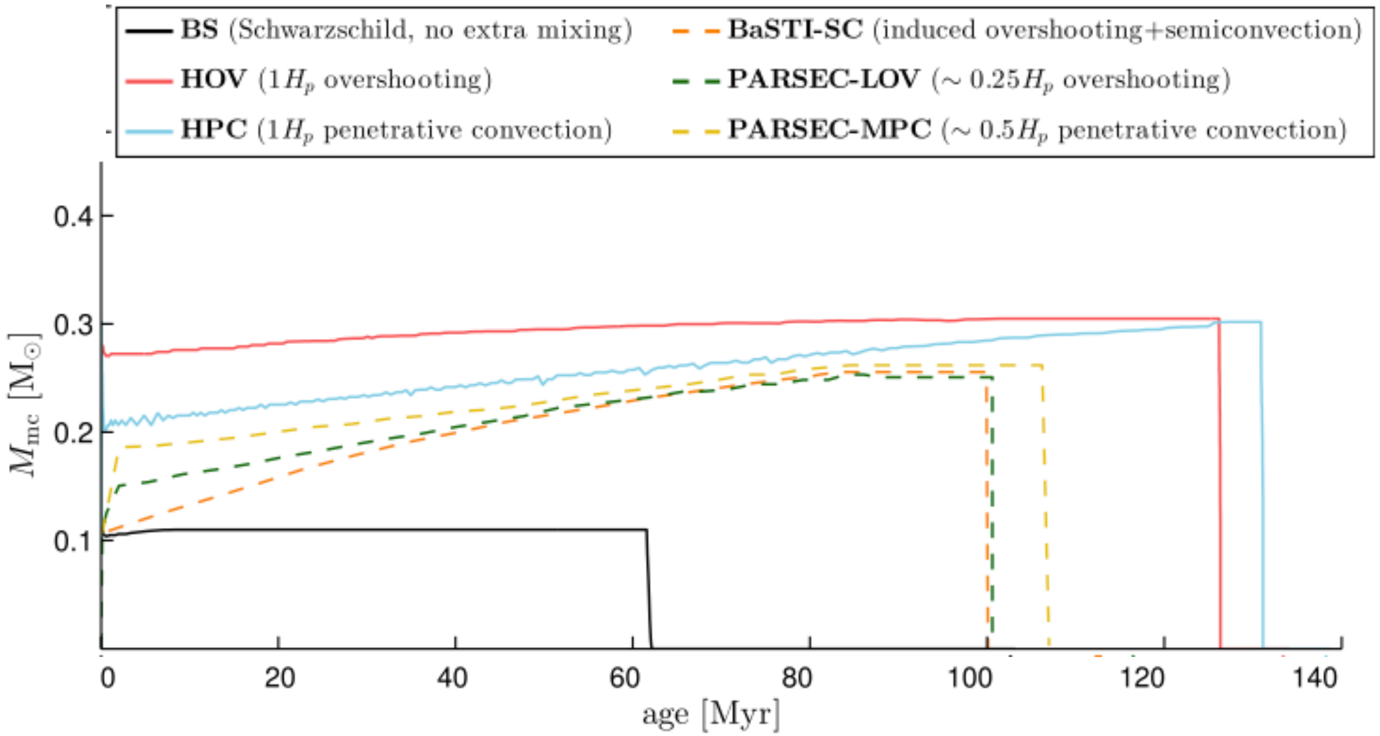
(Montalban et al. 2013)

- Linear relation between size of the convective core and $\Delta\Pi_1$ **(Montalban et al. 2013)**



Extent of mixed core in CHeB giants

- Uncertainties in the extent of mixed core in core-He-burning giants
  - Size of He core when reaching the clump **(Catelan et al. 1996)**
  - **Mixing processes** at the edge of the core **(Constantino et al. 2015, Bossini et al. 2015)**



Bossini et al. (2015)

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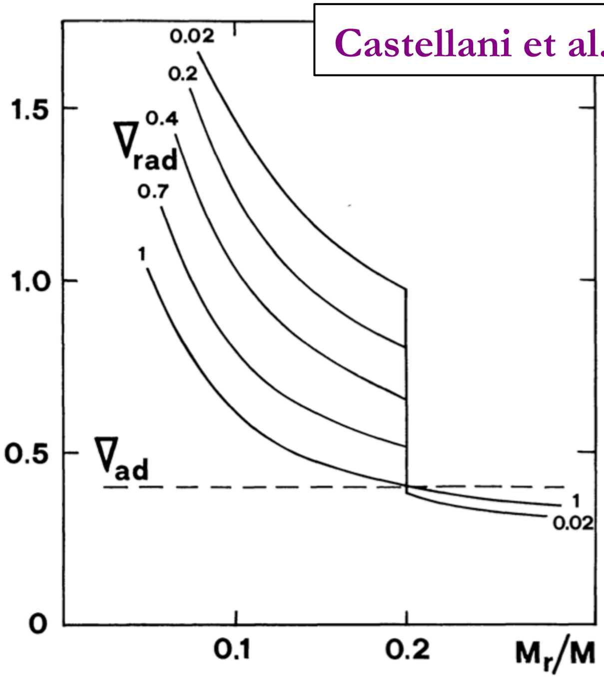
  - Size of He core when reaching the clump **(Catelan et al. 1996)**
  - **Mixing processes** at the edge of the core **(Constantino et al. 2015, Bossini et al. 2015)**
- Common (and yet erroneous) numerical procedure to search for boundary of convective cores $\nabla_{\rm rad}^{\rm ext} = \nabla_{\rm ad}^{\rm ext}$



Castellani et al. (1971)

- $\nabla_{\rm rad}$ increases in the core due to increasing κ (accumulation of C,O)

$\Rightarrow$ $\nabla_{\rm rad} \neq \nabla_{\rm ad}$ at the core boundary, which is unphysical

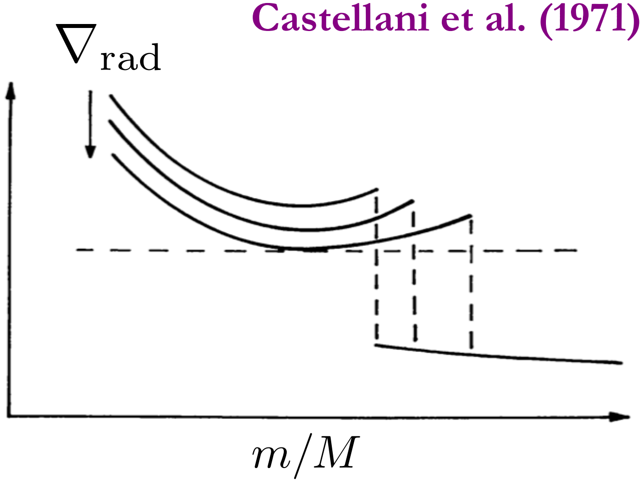
(Schwarzschild 1958, Gabriel et al. 2014)

- produces **spuriously small convective cores**

Extent of mixed core in CHeB giants

Castellani et al. (1971)

- "Induced" **core overshooting**
  - Boundary of the mixed core goes back and forth
  - Overshooting ($\nabla = \nabla_{\rm rad}$ in mixed zone) or convective penetration ($\nabla = \nabla_{\rm ad}$)?



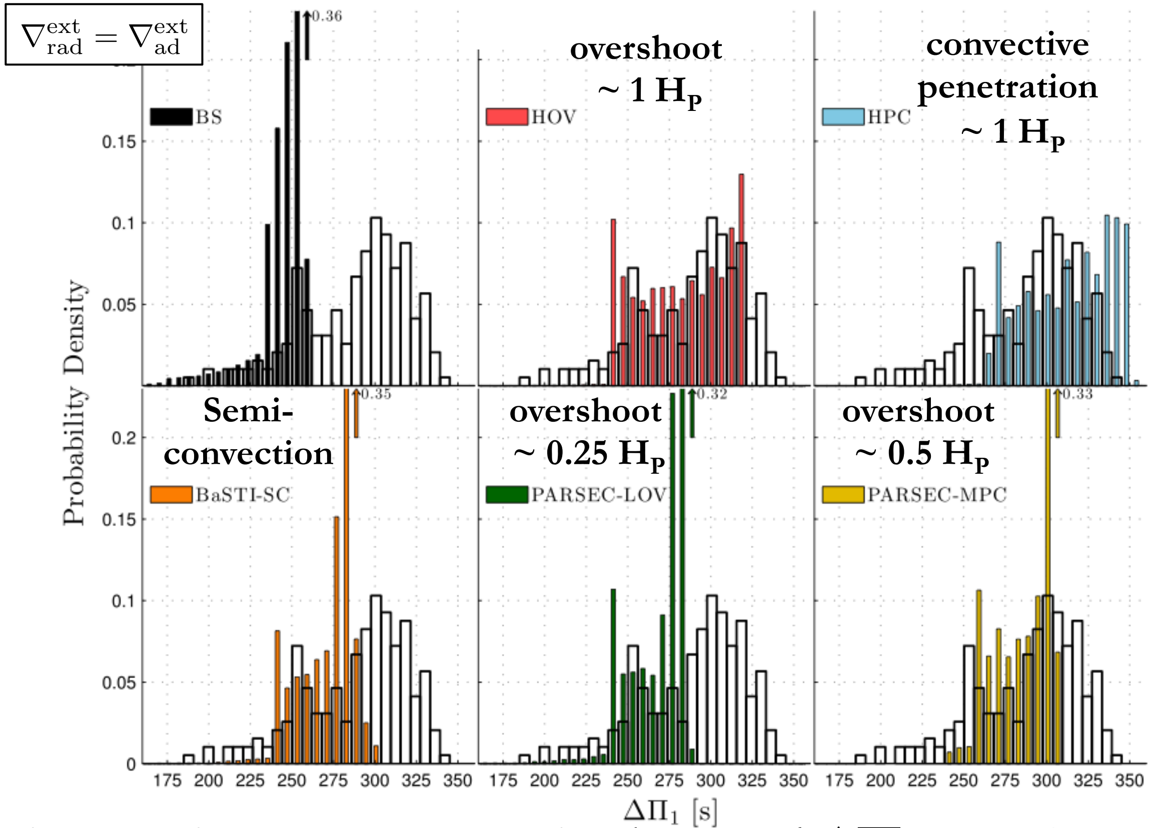
- **Semi-convection**
  - Convective core expending into He-rich layers => stabilizing ∇_μ
  - Semi-convection triggered when $[He]_c \sim 0.7$ => partial mixing

produce a different effect on $\Delta\Pi_1$

- Waves evanescent in the mixed region (convective penetration) => **higher $\Delta\Pi_1$**
- Propagation of waves inside the mixed region (overshooting, semi-convection) => **lower $\Delta\Pi_1$**

Extent of mixed core in CHeB giants

- Comparison of the distribution in $\Delta\Pi_1$ between observations and models with different mixing schemes **(Bossini et al. 2015, Constantino et al. 2015)**



- Need for high overshooting to match observed $\Delta\Pi_1$ (similar conclusion by **Constantino et al. 2015)**

Extent of mixed core in CHeB giants

- Evidence of **large mixed cores in CHeB giants** from other sources of observations
  - Time spent in core-He-burning vs time spent on AGB: star counts in globular clusters favor **large mixed cores** **(**e.g. **Constantino et al. 2016)**
  - Seismic measurements of mixed core sizes in subdwarf-B stars **(van Grootel et al. 2010a, 2010b, Charpinet et al. 2011)**
    - Extend between 0.22 and 0.28 $M_\odot$ (~ 50% total mass)
    - Need for large overshoot (~ 0.8 H_P) to account for such large cores **(Schindler et al. 2015)**

(Jan-Torge Schindler's talk)

- Body of evidence in favor of extended mixed cores in the interior of CHeB giants

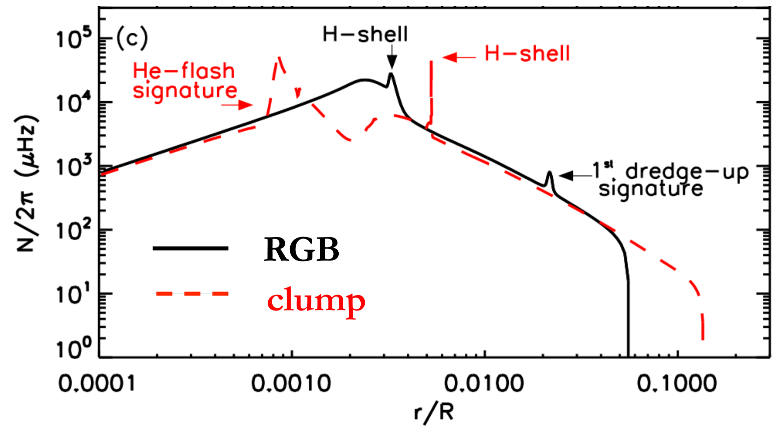
⇒ Clump stars are now good laboratories to test mixing beyond cores

“Buoyancy” glitches

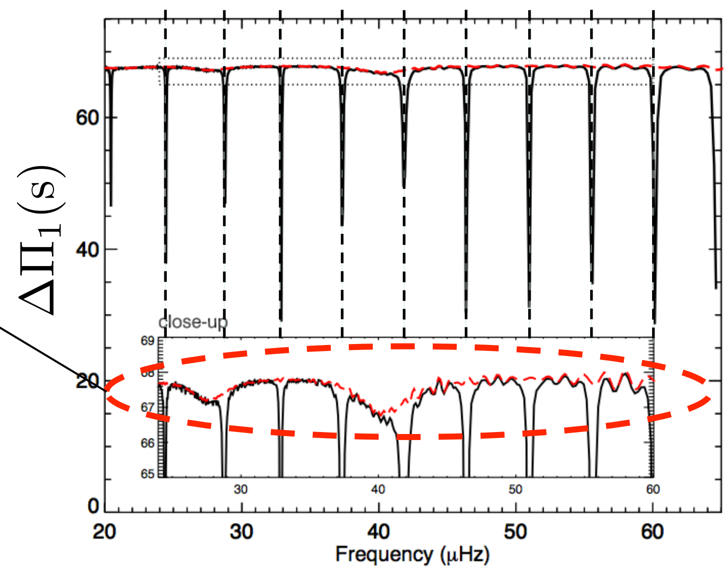
- **Glitches**: variations in equilibrium quantities (e.g. the Brunt-Väisälä profile) over length scales ~ mode wavelength
  - Buoyancy glitches arise due to
    - 1st dredge-up
    - H-shell
    - He-flash signature…
  - Cause periodic modulation in the mode periods (and thus in $\Delta\Pi_1$)

$$\Delta n = \frac{\Pi_{\rm glitch}}{\Pi_{\rm g\text{-}cav}} = \frac{\int_{r_{\rm i}}^{r_0} \frac{N}{r}\,{\rm d}r}{\int_{r_{\rm i}}^{r_{\rm glitch}} \frac{N}{r}\,{\rm d}r}$$

Cunha et al. (2015)



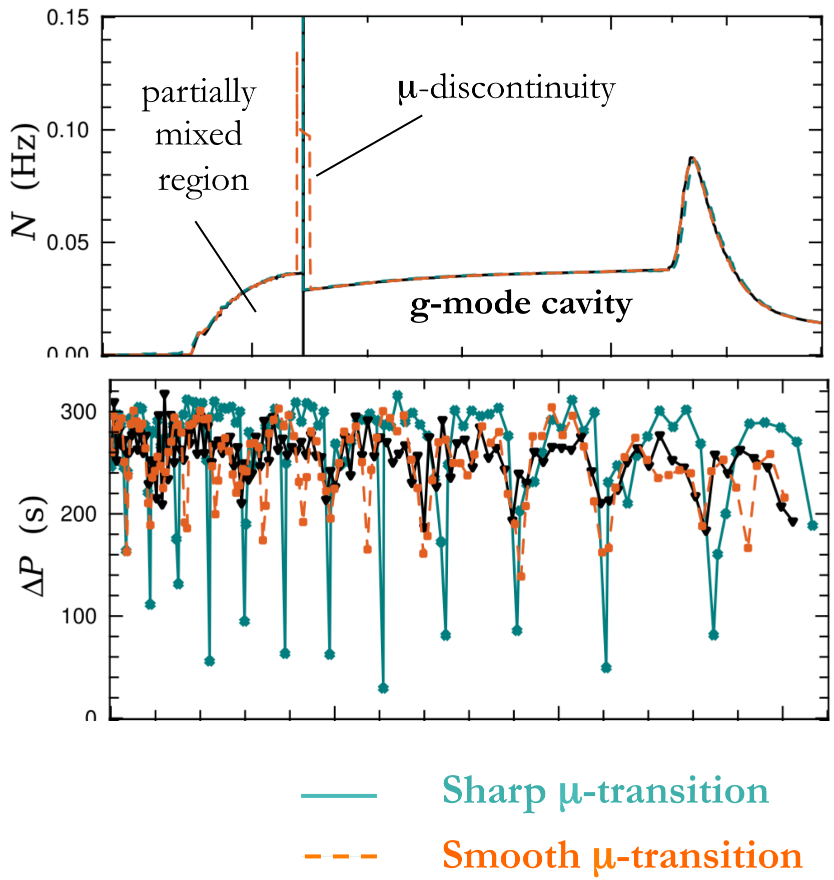
p-modes

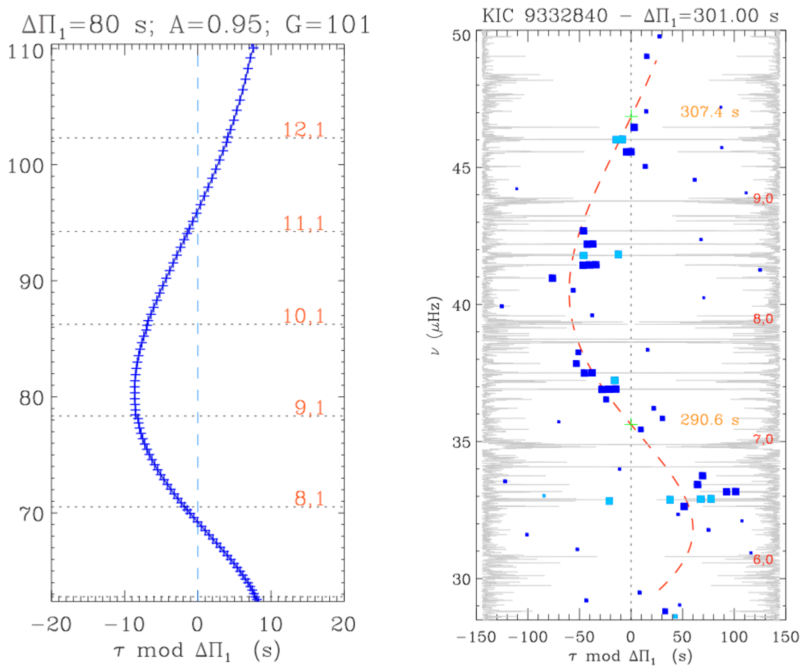


“Buoyancy” glitches

- Glitch at boundary of mixed core
  - Could increase $\Delta\Pi_1$ with semi-convection **(Constantino et al. 2015)**

- Detection of buoyancy glitches
  - Stretched échelle diagrams



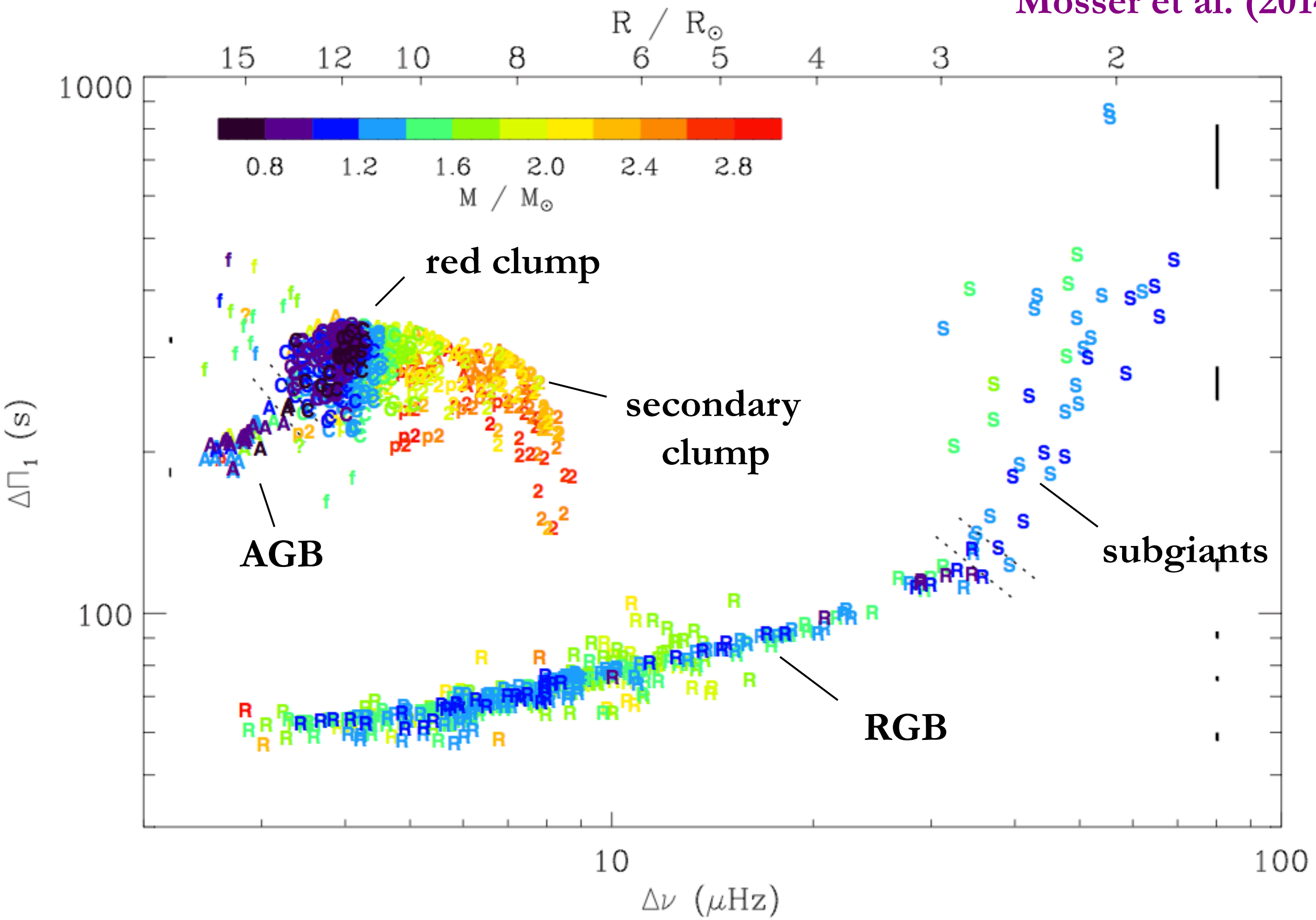


(Mosser et al. 2015)

A window on stellar evolution

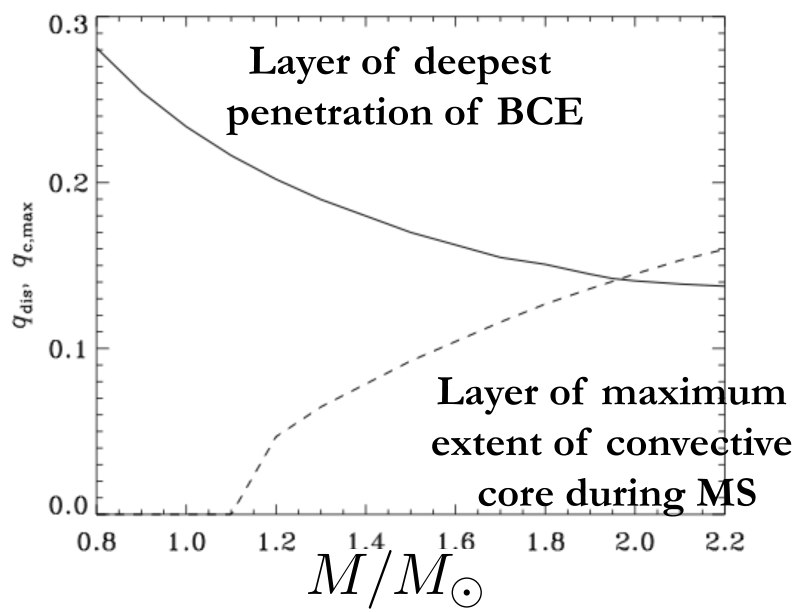
- The $\Delta\Pi_1$-$\Delta\nu$ diagram

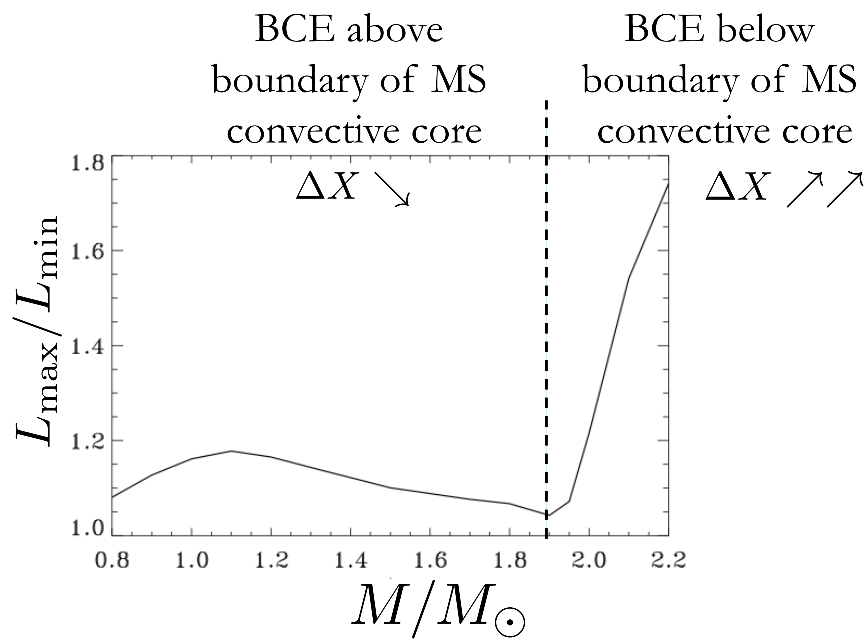
Mosser et al. (2014)



Luminosity bump

- Using **luminosity bump** as an observational constraint **(Christensen-Dalsgaard et al. 2015)**
  - L_{max}/L_{min} depends mainly on ΔX above H-shell



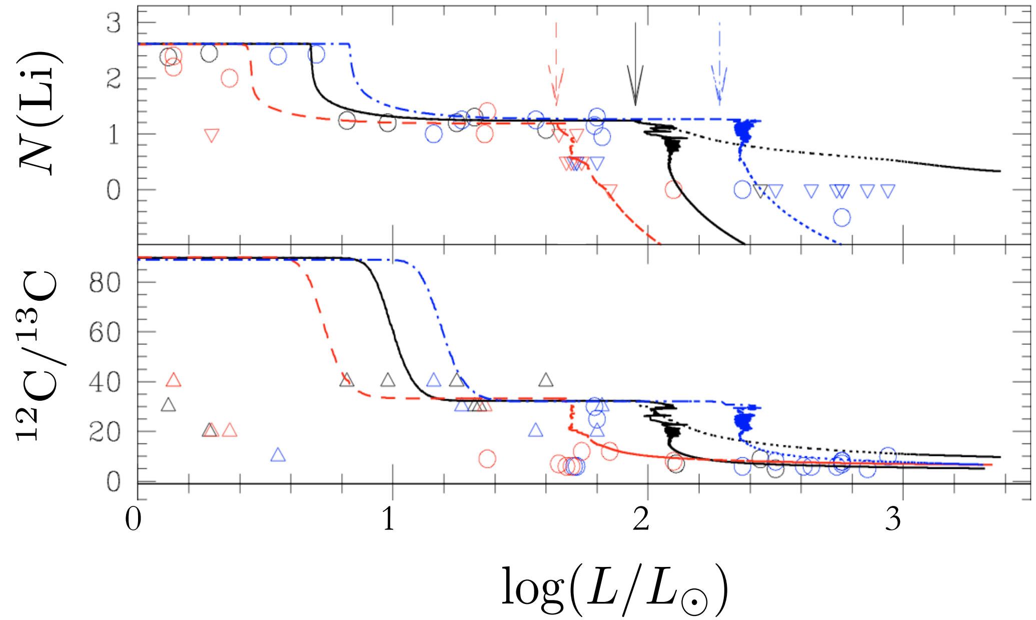


  - Potential probe of **the extension of convective regions** (needs to be further tested)

Luminosity bump

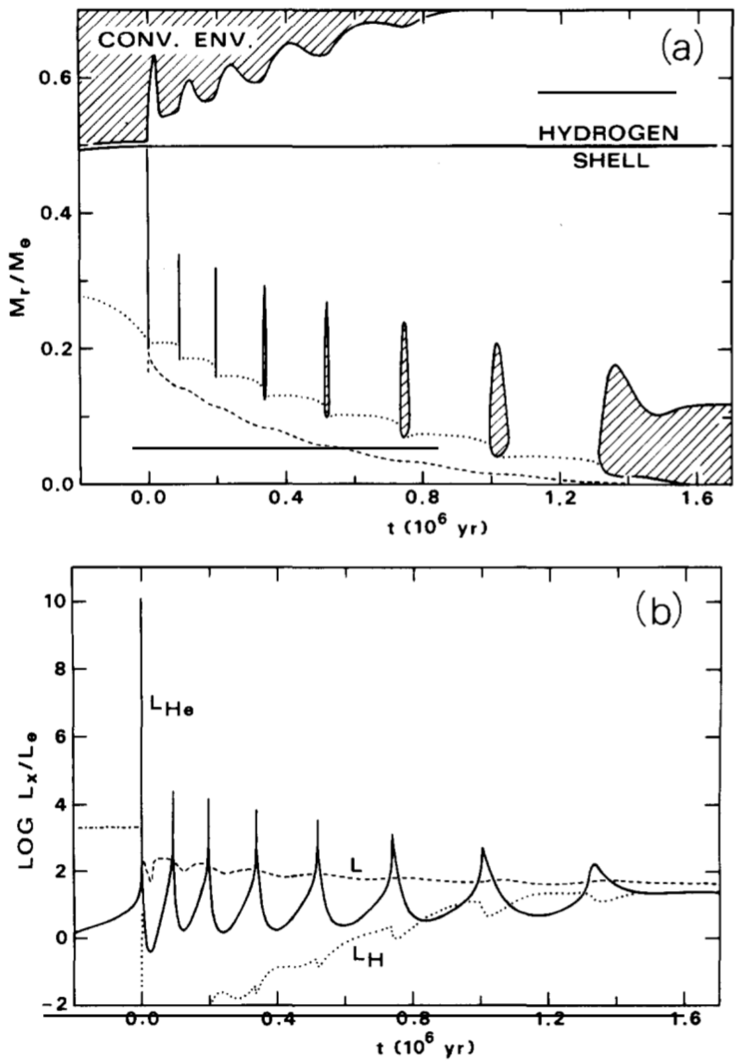
- **Mixing in radiative interiors** after luminosity bump
  - After luminosity bump, ^{3}He burning above the H-shell
  - ⇒ Inverse μ-gradient, which triggers **thermohaline convection**

    (Charbonnel & Zahn 2007)
  - Combine asteroseismology with spectroscopic measurements **(Lagarde et al. 2015)** + **APOKASC** data



(Charbonnel & Zahn 2007)

Searching for giants undergoing the He-flash



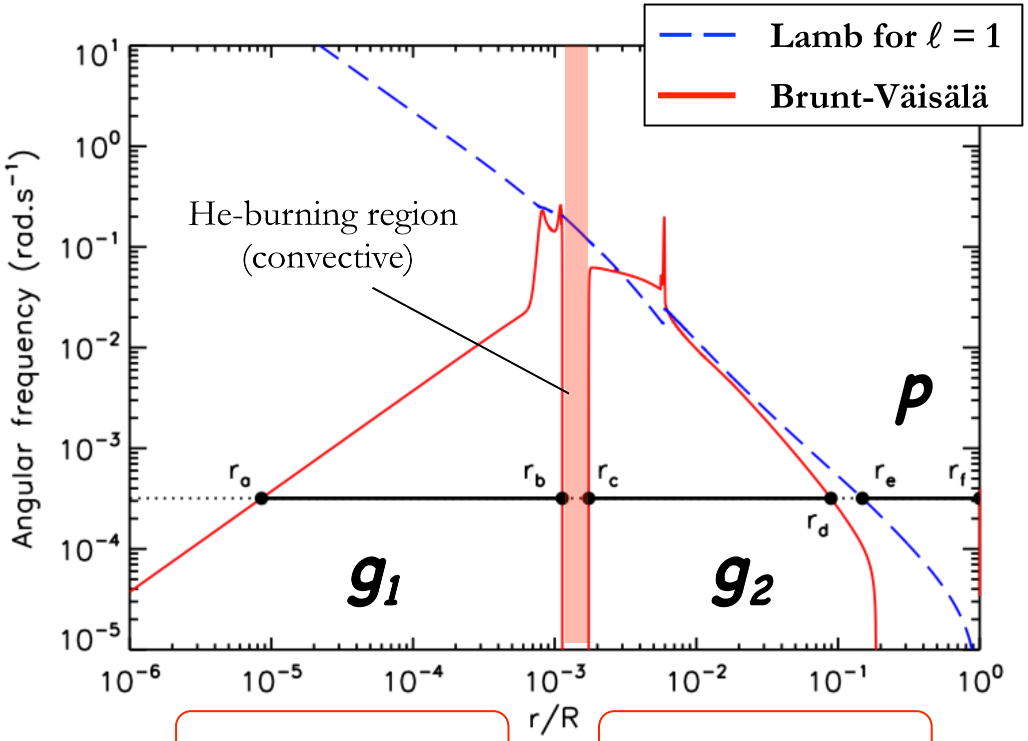
- Several 1D codes predict the He-flash to occur as a series of successive subflashes **(Thomas 1967, Iben & Renzini 1984, Bildsten et al. 2012)**

- Existence of such subflashes debated in view of 2D- and 3D- numerical computations **(Mocak et al. 2008, 2009)**
  - Fast extension of inner and outer convective region caused by He-burning
  - Would suppress the He-subflashes

Iben & Renzini (1984)

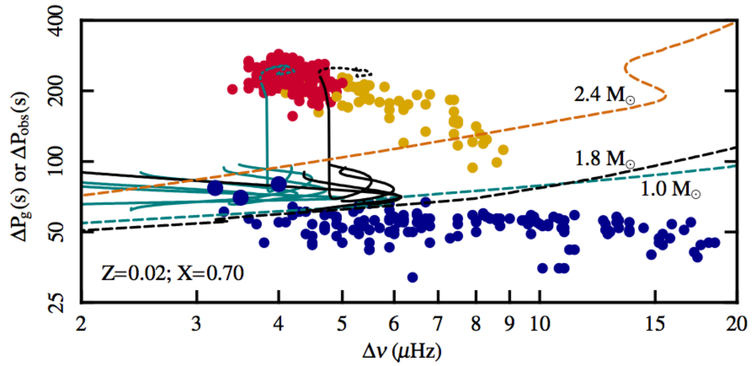
Searching for He-flashing giants among *Kepler* data

- What is the influence on the oscillation spectrum?



$\Delta\Pi_{g_1} = 137$ s $\Delta\Pi_{g_2} = 171$ s

  - Decrease of the period spacing of the outer g-mode cavity (g_2) **(Bildsten et al. 2012)**



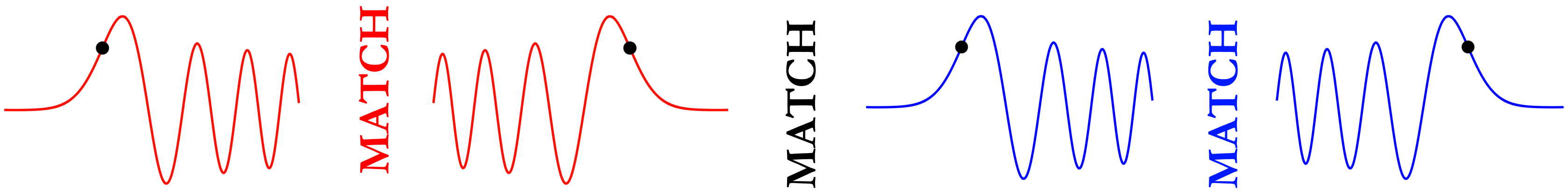
- Propagation of waves in 3 cavities (g_1, g_2, p):
  What impact on the mode frequencies?

WKB approximation applied to 2 cavities (mixed modes)

- Equations of **non-radial stellar oscillations** (adiabatic, Cowling approximation) can be expressed as turning-point (TP) equations **(Unno 1989)**

$$\begin{cases} \dfrac{\mathrm{d}^2 v}{\mathrm{d}r^2} + k_r^2 v & = 0 \\ \dfrac{\mathrm{d}^2 w}{\mathrm{d}r^2} + k_r^2 w & = 0 \end{cases} \quad \text{with} \quad \begin{aligned} v &\equiv \rho^{1/2} c r \left| 1 - \frac{S_l^2}{\omega^2} \right|^{-1/2} \xi_r \\ w &\equiv \rho^{-1/2} r \left| N^2 - \omega^2 \right|^{-1/2} p' \end{aligned}$$

- For two cavities, i.e. **mixed modes**



g cavity **p cavity**

$$\cot(\theta_\mathrm{g}) \tan(\theta_\mathrm{p}) = q$$

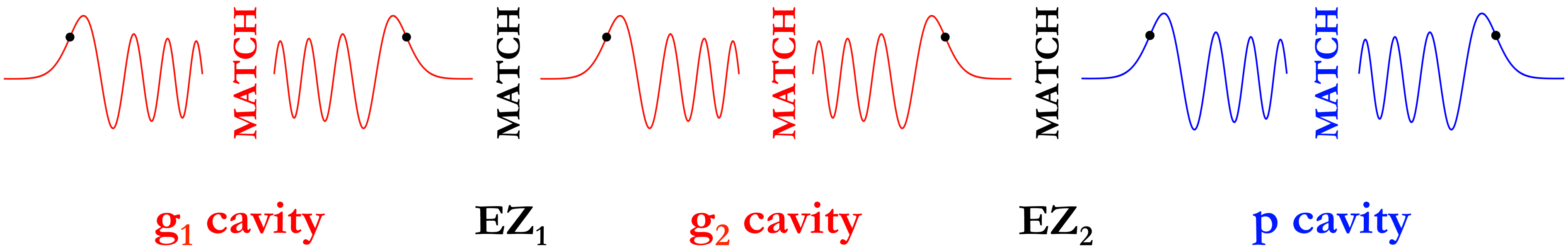
$\theta_\mathrm{g}(\omega, \Delta\Pi_1, \varepsilon_\mathrm{g}, \ldots)$ $\theta_\mathrm{p}(\omega, \Delta\nu, \varepsilon_\mathrm{p}, \ldots)$

coupling term

$$q = \frac{1}{4} \exp\left(-2 \int_\mathrm{EZ} |k_r| \mathrm{d}r \right)$$

WKB approximation applied to 3 cavities (He subflash)

- Extension to the case of three cavities (two g-mode cavities + p-mode cavity)



$$\boxed{\cot\theta_{g_1}\cot\theta_{g_2}\tan\theta_p - q_2\cot\theta_{g_1} - q_1\tan\theta_p - q_1 q_2\cot\theta_{g_2} = 0}$$

- Limiting case where $q_1 = 0$

$$\begin{cases} \cot(\theta_{g_1}) = 0 & \text{— } g_1 \text{ pure mode} \\ \cot(\theta_{g_2})\tan(\theta_p) = q_2 & \text{— } p/g_2 \text{ mixed mode} \end{cases}$$

- Coupling intensities

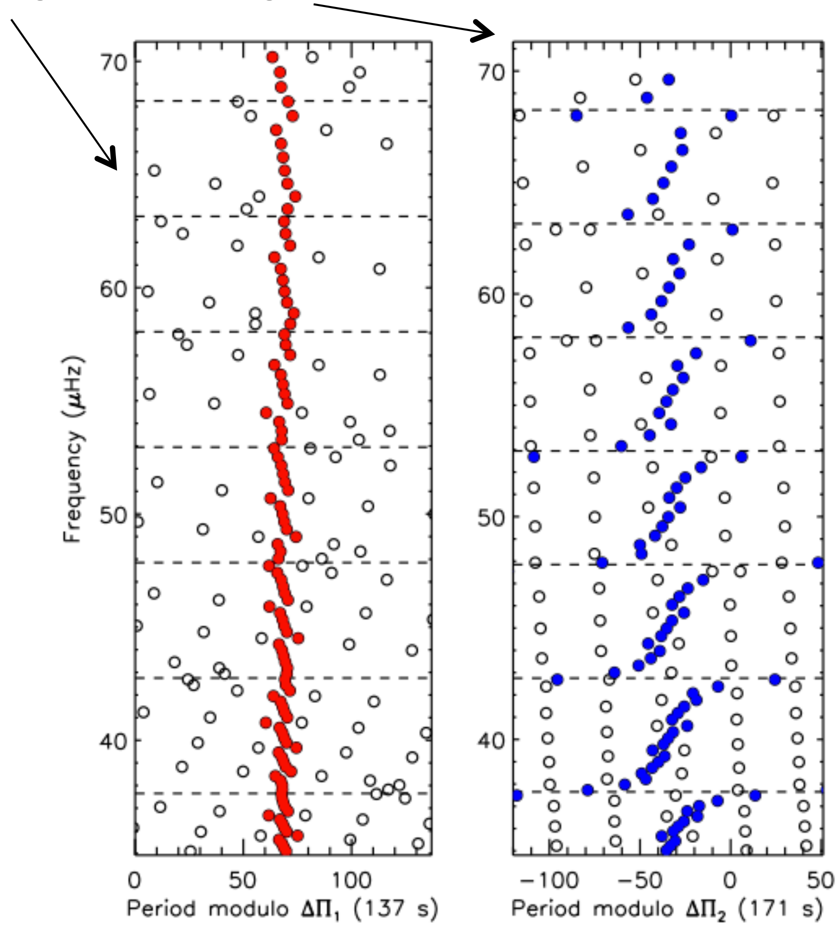
MESA model

$$q_1 = \frac{1}{4}\exp\left(-2\int_{EZ_1}|k_r|dr\right) \quad \text{—} \quad \boldsymbol{q_1 \approx 0.03}$$

$$q_2 = \frac{1}{4}\exp\left(-2\int_{EZ_2}|k_r|dr\right) \quad \text{—} \quad \boldsymbol{q_2 = 0.13}$$

WKB approximation applied to 3 cavities
(He subflash)

- Period échelle diagrams of asymptotic oscillation spectrum, folded with $\Delta\Pi_{g1}$ and $\Delta\Pi_{g2}$, respectively

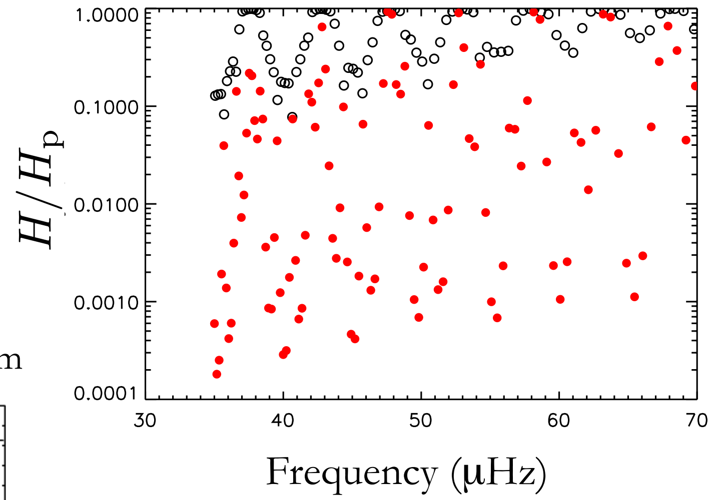


- modes trapped mainly in p and g_2 cavities
- modes trapped mainly in g_1 cavities

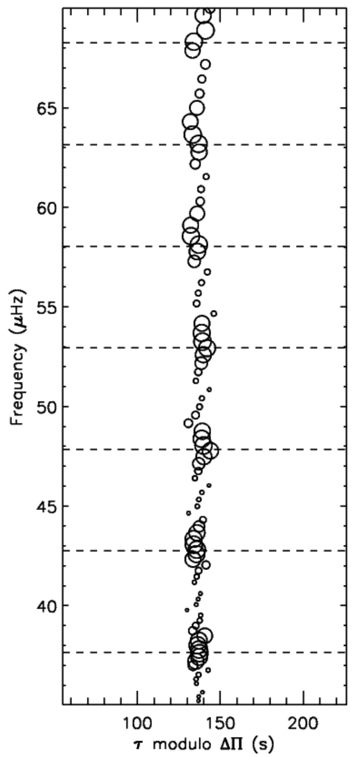
WKB approximation applied to 3 cavities (He subflash)

- Mode heights in the power spectrum
  - Ratios of inertia I_p/I derived from WKB analysis (based on **Goupil et al. 2013**)
  - Effects of radiative damping (based on **Godart et al. 2009**)

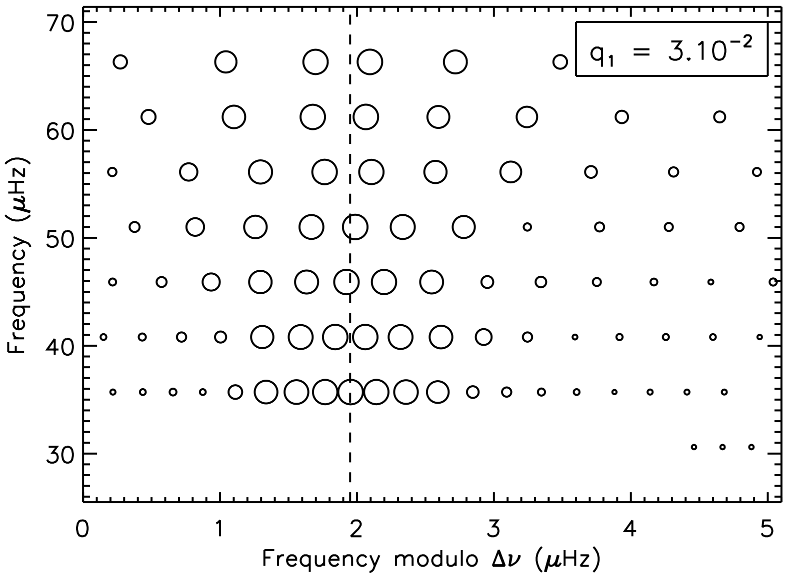
$$\eta_{\mathrm{g}} = -\frac{W_{\mathrm{g}_1} + W_{\mathrm{g}_2} + W_{\mathrm{e}}}{2\omega^2 I}$$



Stretched échelle diagram



Frequency échelle diagram



○ modes trapped mainly in p & g_2 cavities

● modes trapped mainly in g_1 cavity

WKB approximation applied to 3 cavities (He subflash)

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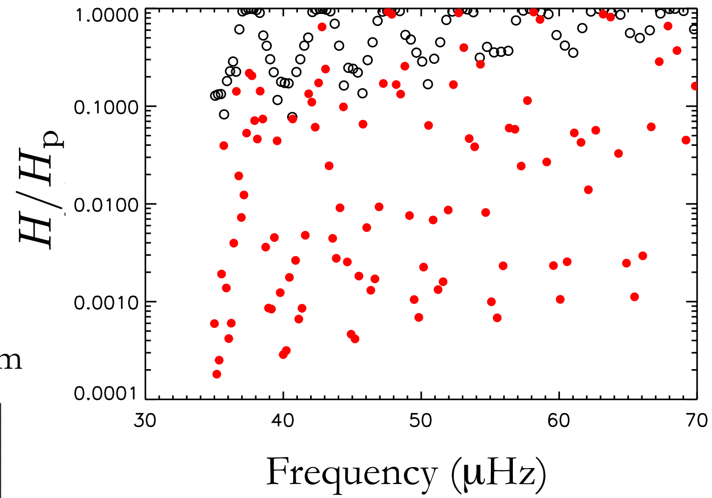
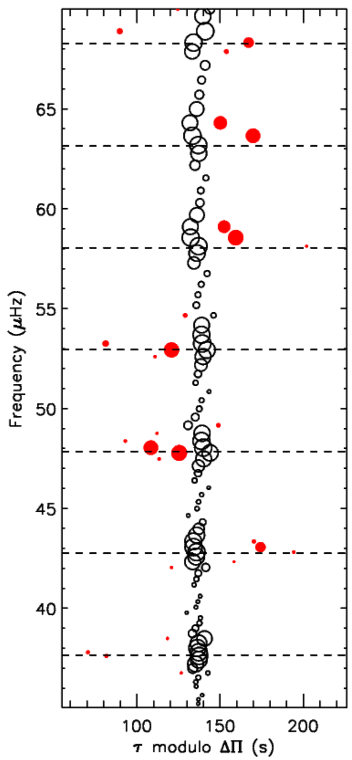


Stretched échelle diagram



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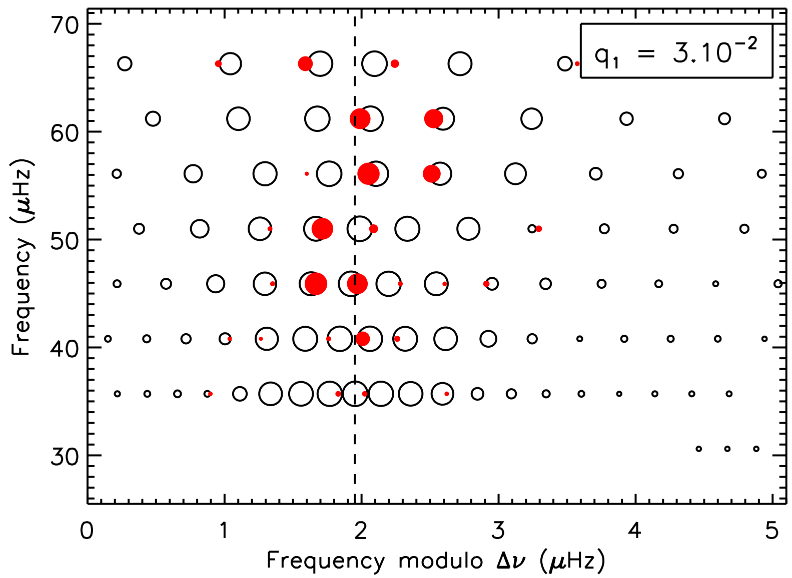


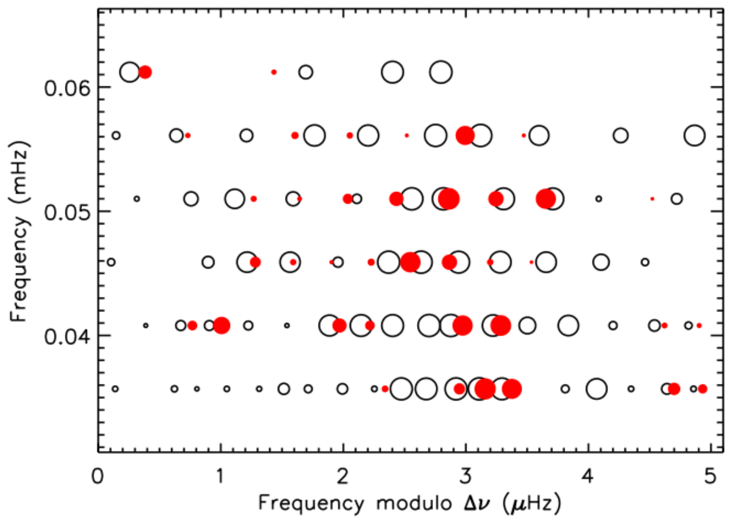
○ modes trapped mainly in p & g_2 cavities

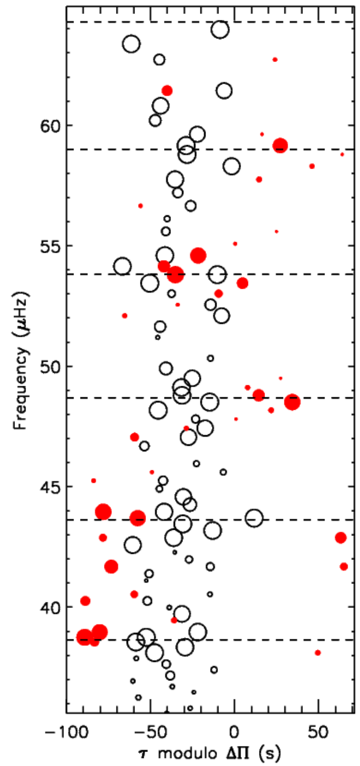
● modes trapped mainly in g_1 cavity

Additional detectable modes in the vicinity of pure p modes

Comparison with full numerical solutions

- MESA model (1.7 $M_\odot$) during a He-subflash
  - Mode frequencies extracted with LOSC **(Scuflaire et al. 2008)** taking care to resolve rapidly varying eigenfunctions near the core
  - Ratios of inertia + effects of radiative damping estimated based on eigenfunctions





○ modes trapped mainly in p & g_2 cavities

● modes trapped mainly in g_1 cavity

- Confirms presence of additional detectable modes
- Search for candidates among Kepler targets (in collaboration with M. Vrard and B. Mosser)

Constraining angular momentum transport in stars

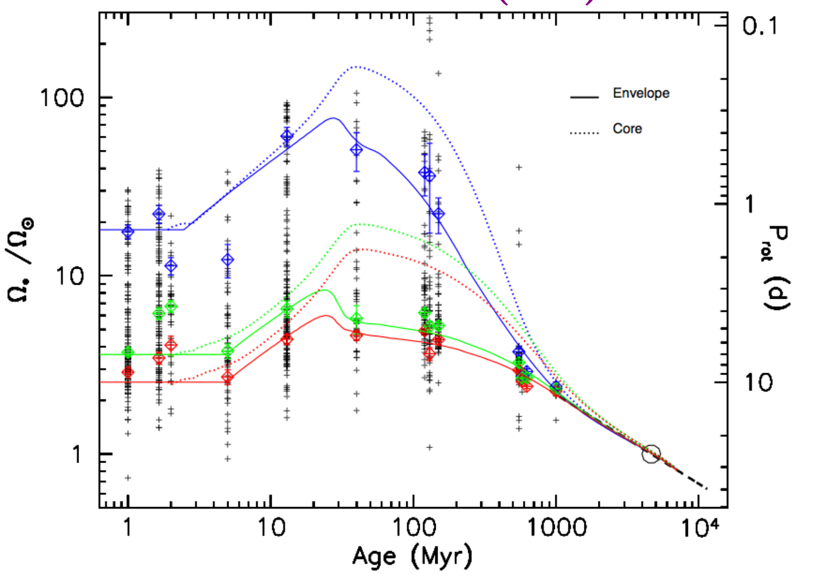
- Transport of angular momentum in stars remains uncertain
  - Several processes (rotation-induced, magnetic fields, internal waves…)

    Which ones dominate?

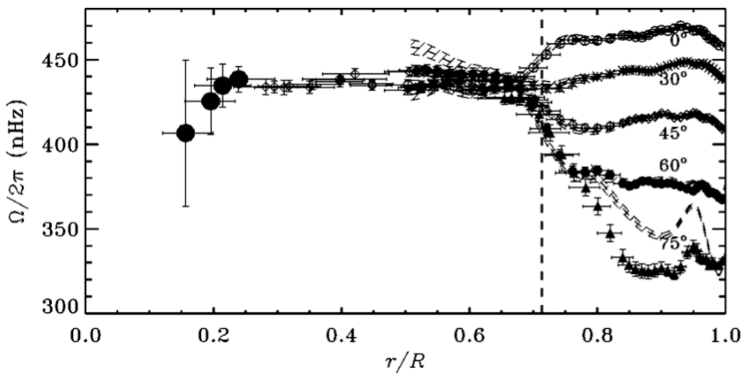
- Evidence for a missing ingredient
  - Surface rotation of young stars in clusters
  - Solar rotation profile
  - **Internal rotation of red giants**
  - Surface rotation of white dwarfs and neutron stars

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

Gallet et al. (2013)

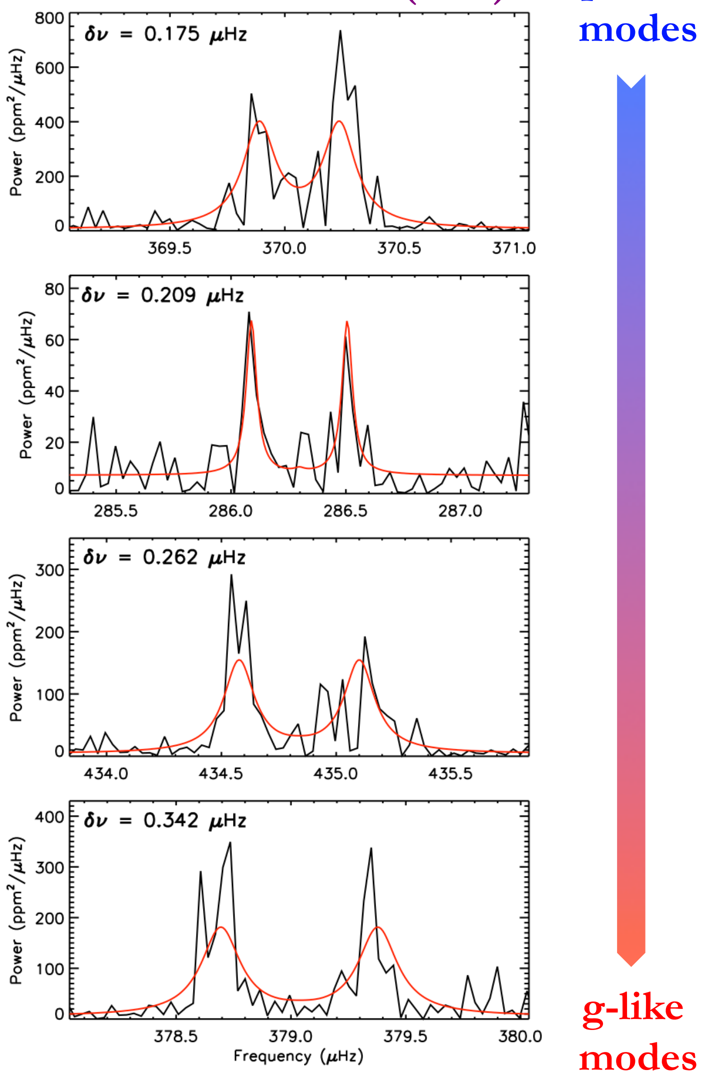


Solar internal rotation **(Chaplin et al. 1999)**



Seismology of red giants: a new piece to the puzzle

Deheuvels et al. (2012)

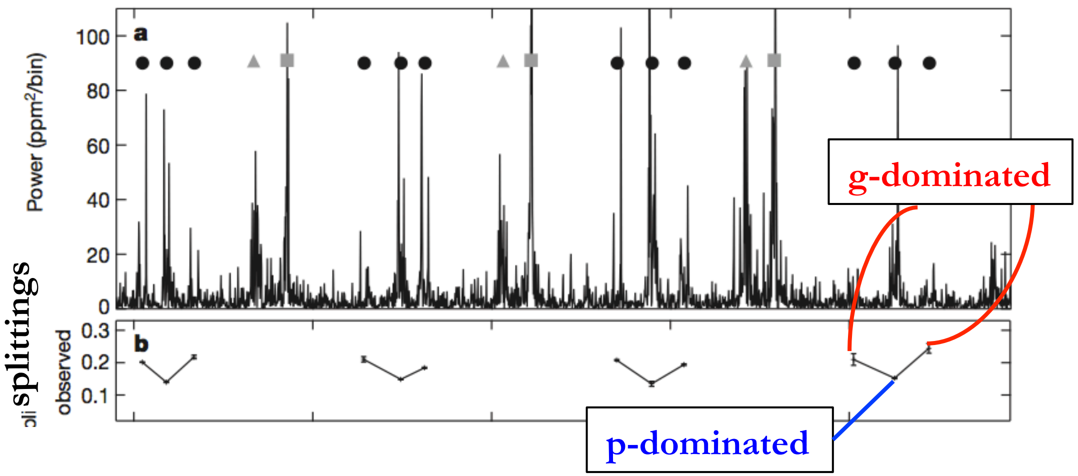


- **Rotation** lifts the degeneracy between m ≠ 0 modes

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

Rotational kernels

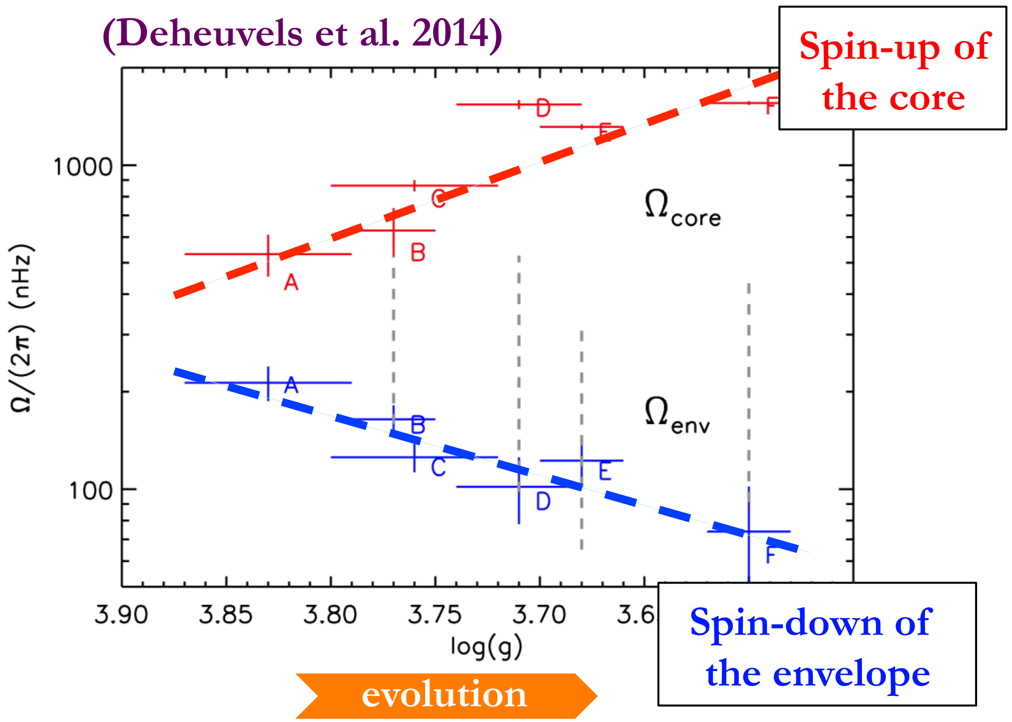
(Beck et al. 2012)

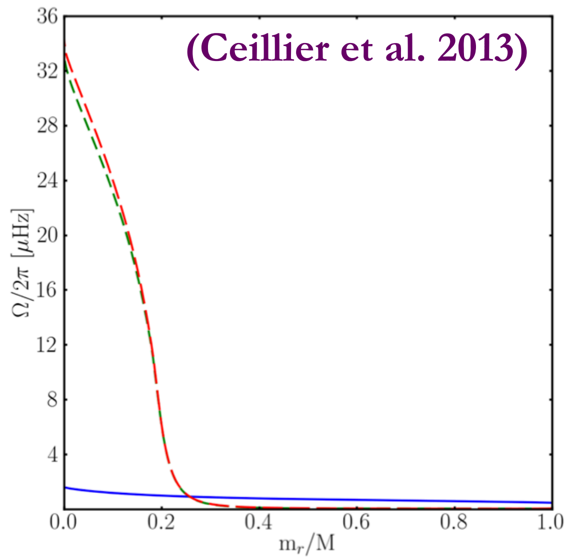


⇒ **Core rotates faster than envelope in young red giants**

Subgiants & young red giants

- **Spin-up** of the core in subgiants & young red giants



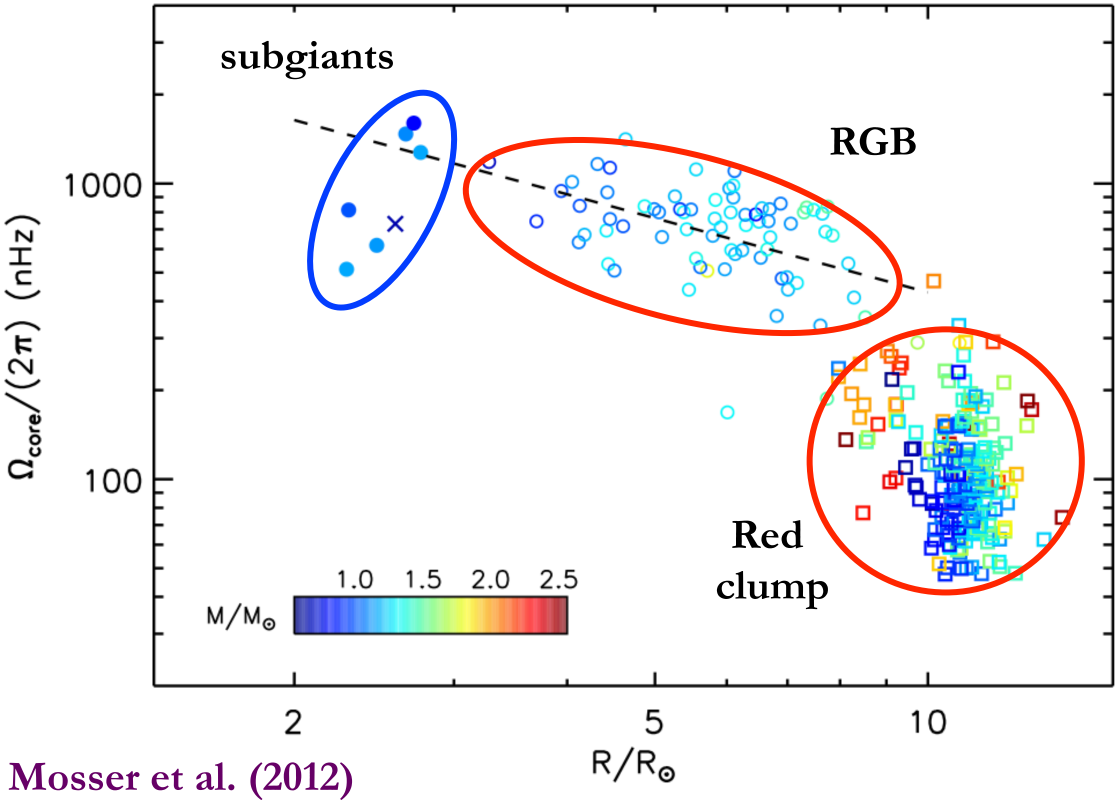


Need for an additional efficient mechanism of AM transport

AM transport including shear + circulation à la Zahn et al. (1992) predict **much faster core** rotation **(Ceillier et al. 2013, Marques et al. 2013)**

Spin-down of the core for red giants

- Extraction of rotational splittings in ~ 300 Kepler giants
  (Mosser et al. 2012)



Mosser et al. (2012)

Spin-down of the core in the RGB

⇒ Need for additional AM transport

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

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

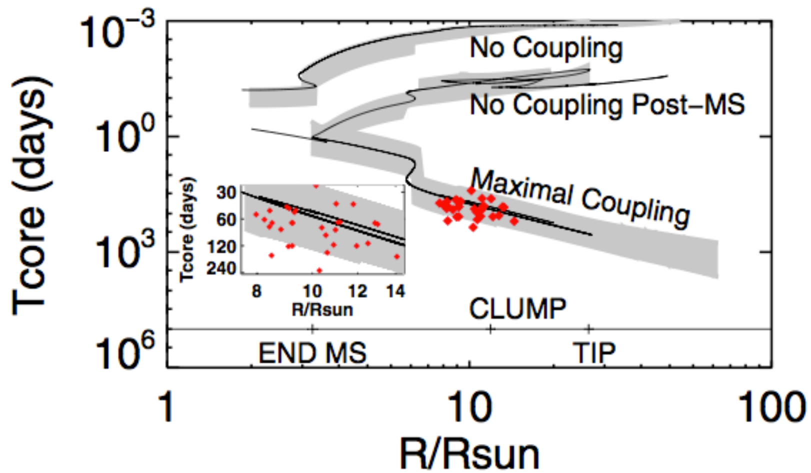
Intermediate-mass clump stars

- Evolution of intermediate-mass stars ($M > 2.1\ M_\odot$)
  - experience **similar structural changes** as low-mass stars with similar radius…
  - BUT on much smaller timescales since **subgiant & RGB phases are short-lived** (on a thermal timescale)
  - Non-degenerate core => no He flash

$\Rightarrow$ **AM transport must act on shorter timescales**

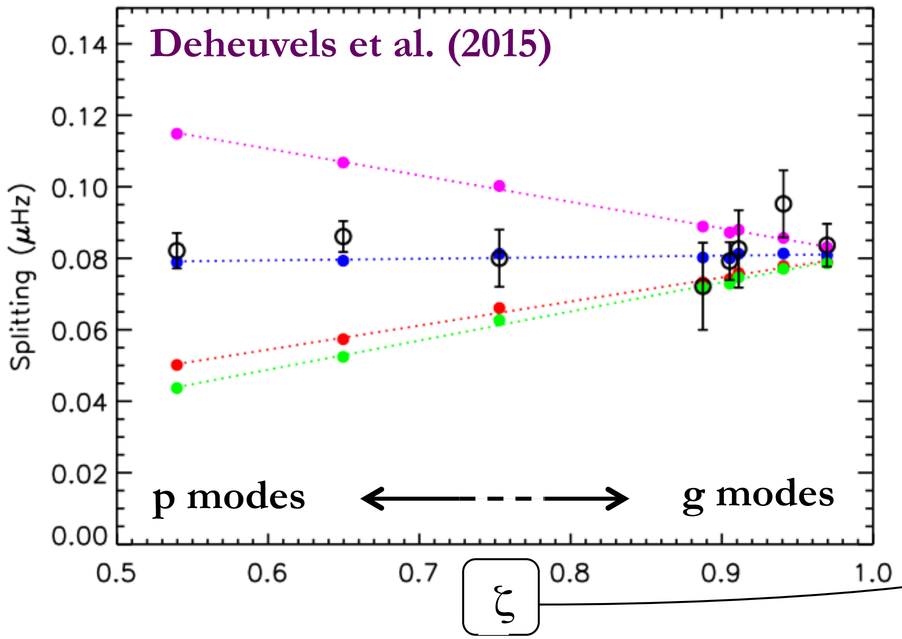
- Core rotation roughly compatible with solid-body rotation

(Tayar & Pinsonneault 2013)



Core-He burning giants (red clump)

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



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

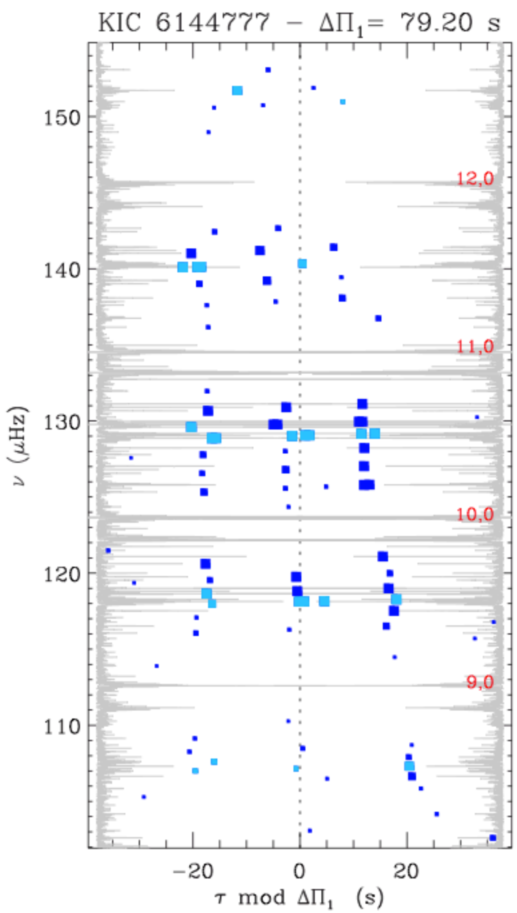
- **Weak differential rotation** $\left(1 \leqslant \frac{\Omega_{core}}{\Omega_{env}} \leqslant 3.2\right)$ for 7 Kepler clump stars **(Deheuvels et al. 2015)**

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

What more can we expect from seismology about rotation?

- Automatic measurement of core rotation in *Kepler* giants (Charlotte Gehan's poster S10.48)
- Inversion of rotation profiles for stars at particular stages of evolution or which have peculiarities ("fast" rotators, stars showing large surface magnetic fields…)
- More precise/localized information about rotation profiles
  - Potential existence of strong rotational gradients in the vicinity of the H-shell in young giants **(Deheuvels et al. 2014)**
- Future missions with long observations: TESS (1-yr observations), PLATO!

(Mosser et al. 2015)



Mechanisms that could efficiently AM transport

- Purely hydrodynamical processes (shear, meridional circulation)
  - By far not efficient enough **Füller et al (2014)**
  - But **Mathis et al. 2016**?
- Internal gravity waves (Charlie Pinçon & Tamara Rogers' talks)

✓ Might account for **core/ envelope decoupling** during **subgiant** phase

+ role of differential rotation for plume-induced IGW **(Pincon et al. 2016)**

✗ But not for **core spin down** during **RBG**

? During core-He burning (**clump**), **waves excited at the core edge** might efficiently couple

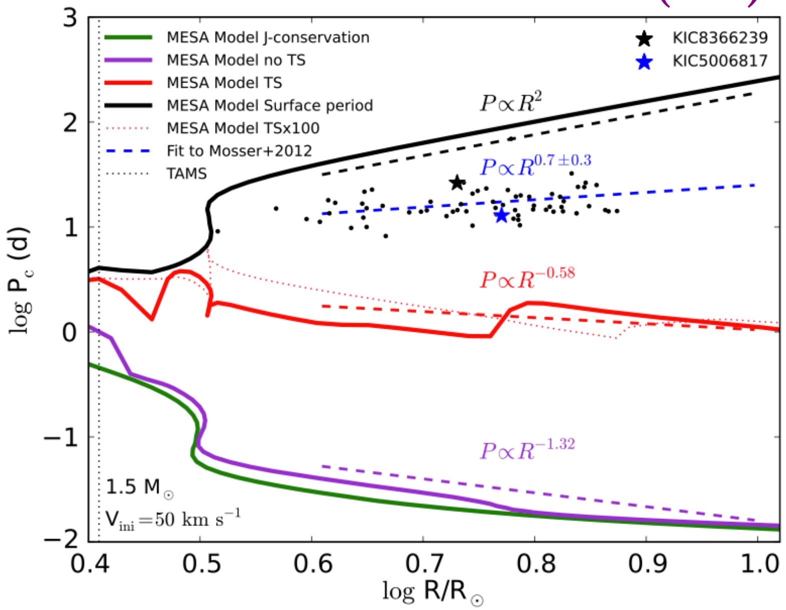
- Transport by mixed modes **(Belkacem et al. 2015a,b)**
  - Efficient in the upper part of the RGB, but not at the subgiant/young giant phase

Magnetic fields

- Transport of angular momentum through **a fossil field** **(Maeder & Meynet 2014)**
  – order-or-magnitude calculations of the extension of a dipolar fossil magnetic field in core-He-burning stars
  – Coupling between core and convective envelope very unlikely
  – Coupling between core and intermediate radiative regions is "easy"

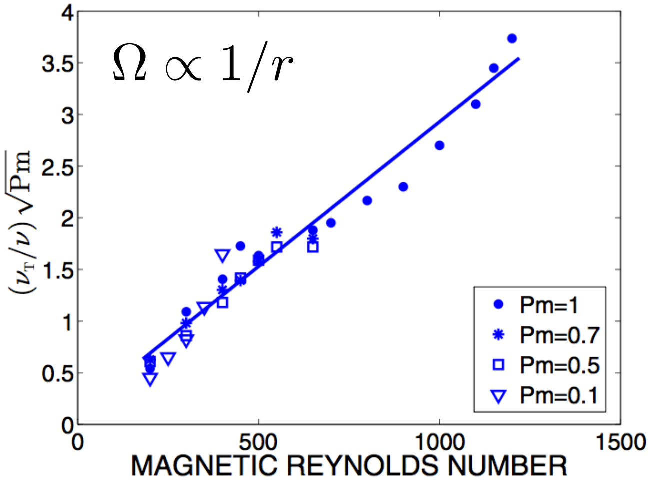
- **Tayler-Spruit dynamo** (amplification of toroidal magnetic field due to the combined effect of Tayler instability and differential rotation)
  – Existence debated **(Zahn et al. 1997, Braithwaite et al. 2006)**
  – Not efficient enough to account for core rotation of giants **(Cantiello et al. 2014)**

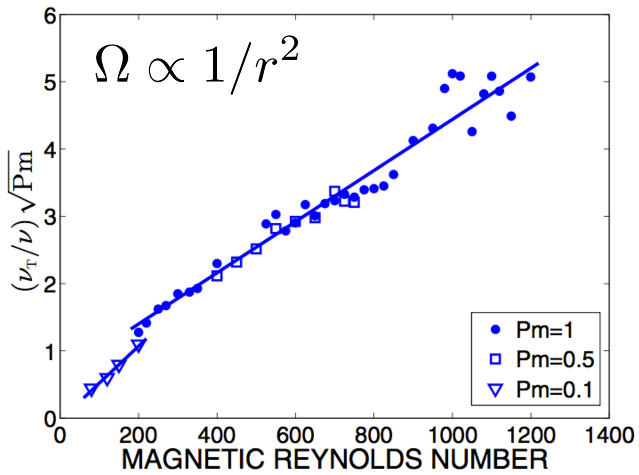
Cantiello et al. (2014)



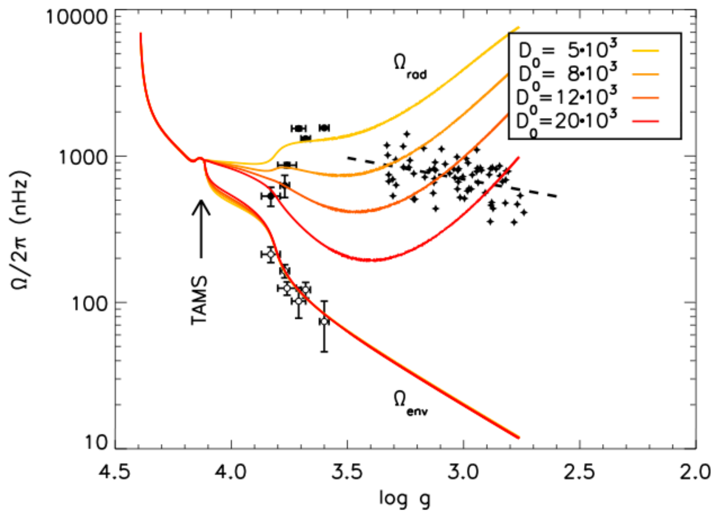
Magnetic fields

- Transport of angular momentum through **(A)MRI**: instability of a magnetic field induced by differential rotation)
  - Numerical simulations with different setups (**Rüdiger et al. 2015, Jouve et al. 2015**)
  - Development of (A)MRI **over τ ~ rotation period << evolution timescale**
  - **Efficient AM transport**: effective viscosity >> ν_{add} required by **Eggenberger et al. 2012** to account for core rotation of young giants **(Rüdiger et al. 2015)**
  - Only an **upper limit** (effects of stratification are ignored)
  - **Efficiency of AM transport depends on the intensity of the shear**





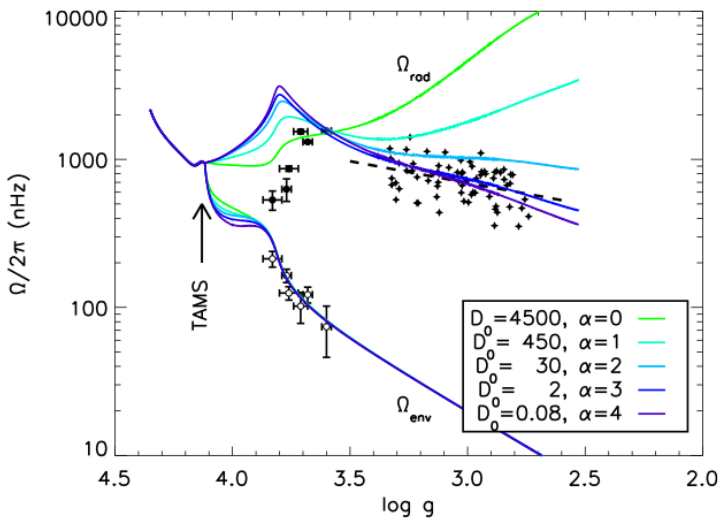
Magnetic fields

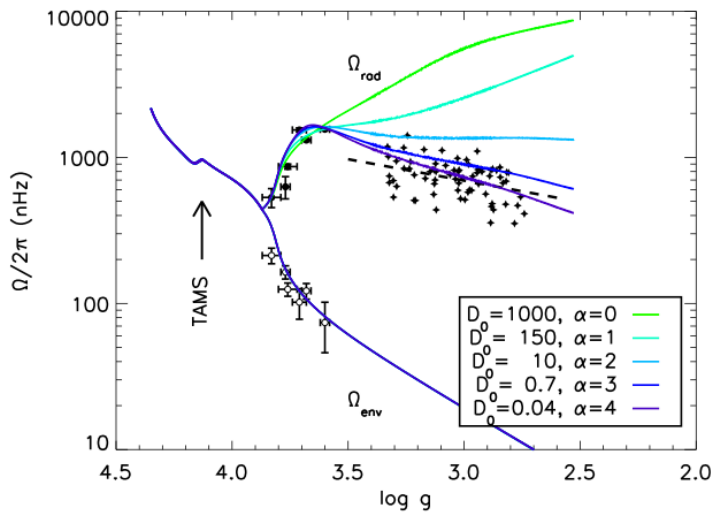


- Modeling additional AM transport as an ad hoc diffusion process **(Spada et al. 2016)**

$$\rho r^4 \frac{\partial \Omega}{\partial t} = \frac{\partial}{\partial r}\left[\rho r^4 D \frac{\partial \Omega}{\partial r}\right]$$

$$D = D_0 \left(\frac{\Omega_{\rm rad}}{\Omega_{\rm env}}\right)^{\alpha}$$



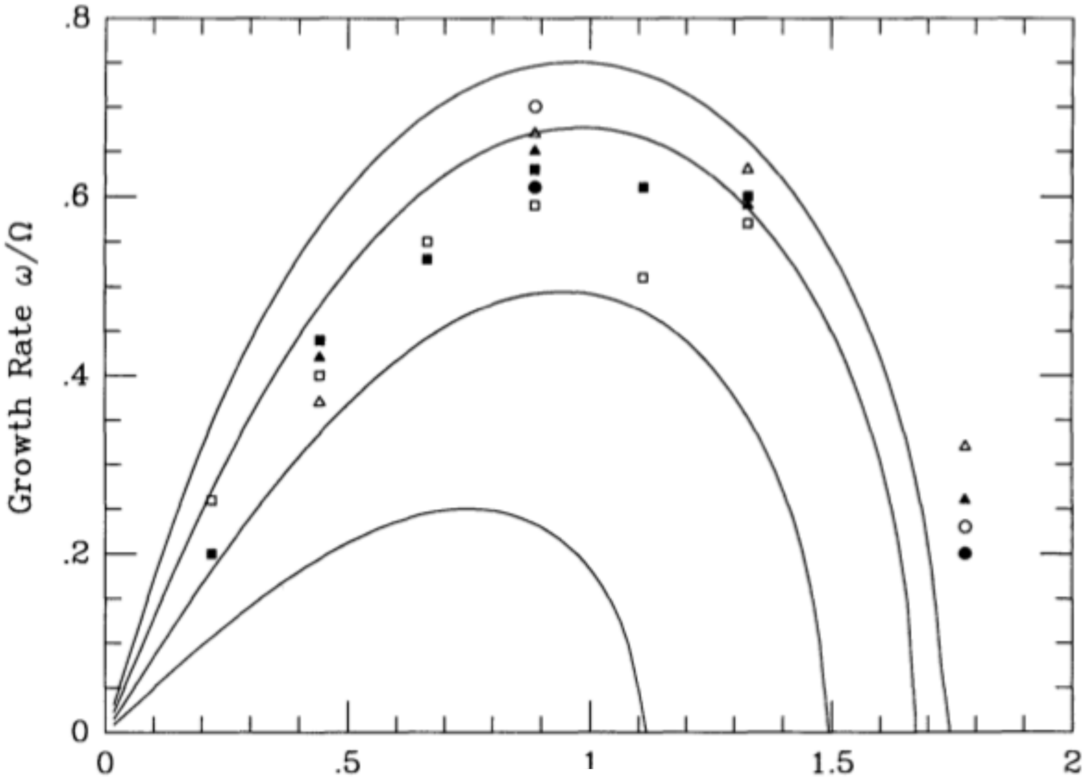


Conclusions

- Combination of observations, particularly interesting to test theory
  - Mass, radius, surface gravity (scaling relations)
  - Core (+envelope) rotation (rotational splittings)
  - Surface abundances (spectroscopic follow-up, APOKASC)
  - Luminosities (GAIA)
- Many other exciting results!
  - Potential signature of magnetic fields in the core of red giants from giants with $\ell=1$ depressed modes (Denis Stello and Matteo Cantiello's talk)
  - 1st detection of a Li-rich giant of a core-He burning giant **(Silva Aguirre et al. 2014)**
  - Mass loss using clusters **(Miglio et al. 2012)**
  - Acoustic glitches **(Miglio et al. 2010, Vrard et al. 2015)**
  - Using mixed modes in subgiants to measure MS convective cores **(Deheuvels et al. 2011)**
  - Detection of non-radial oscillation in M-giants **(Stello et al. 2014)**

AMRI

(Hawley & Balbus 1991)



$q_i = k_i v_A / \Omega$

$\lambda \sim 1\%$ of core for $B = 10^5 - 10^6$ G