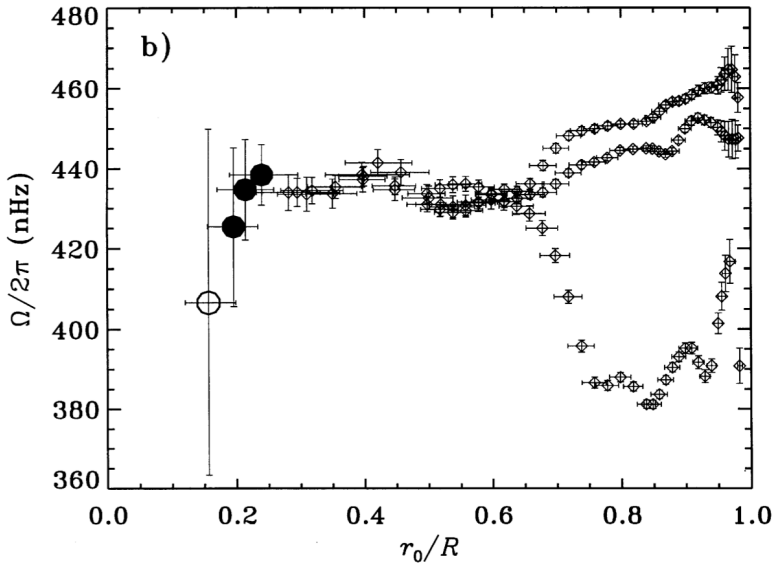
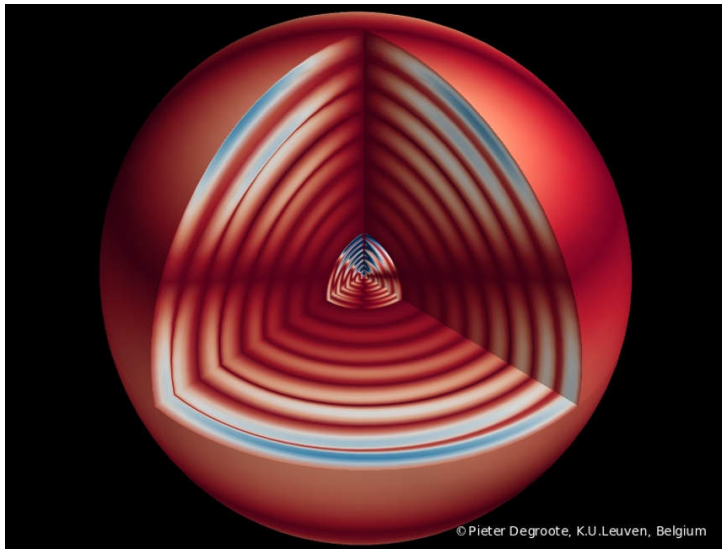
What asteroseismology is teaching us about the internal rotation of stars

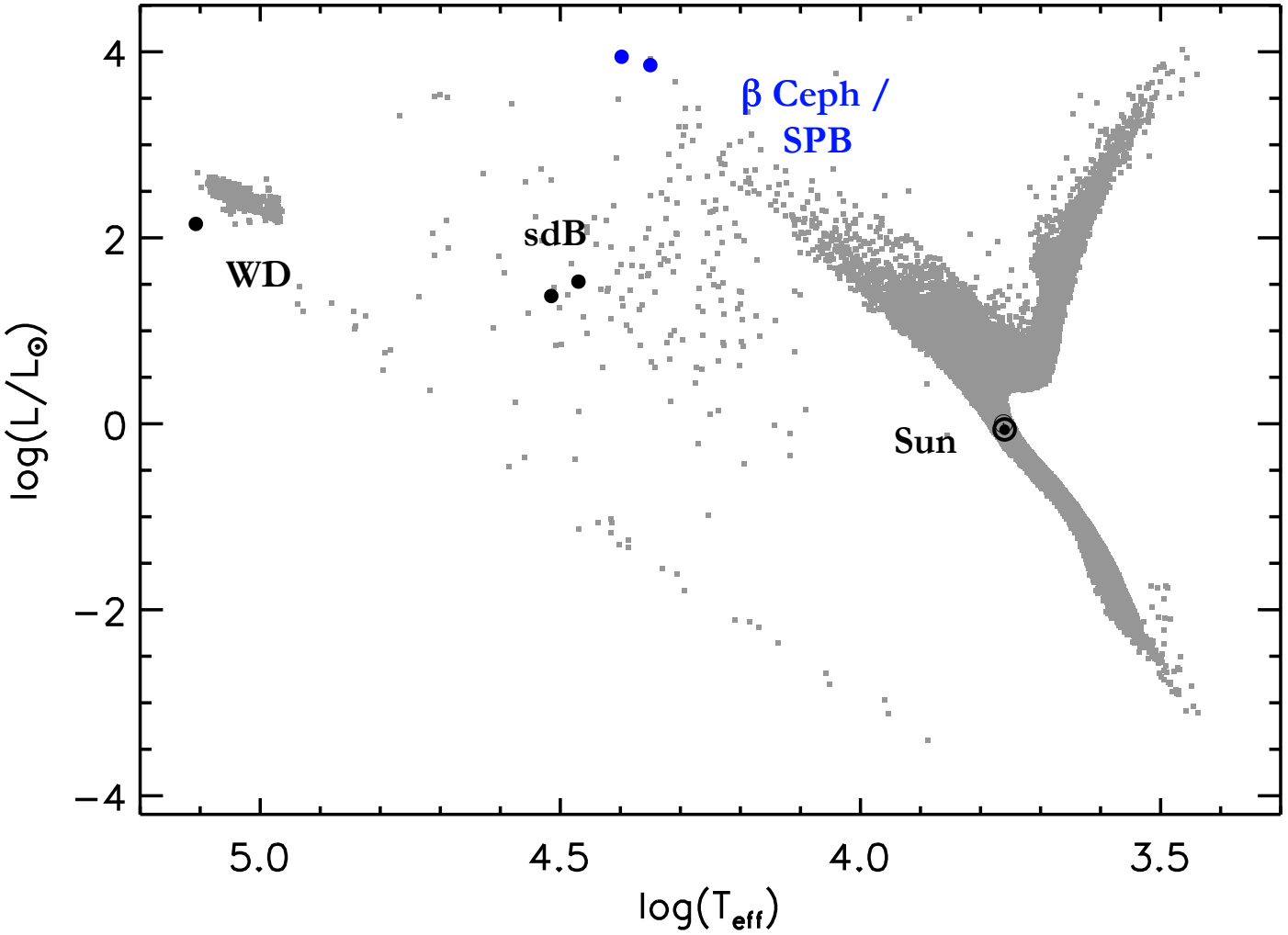
S. Deheuvels





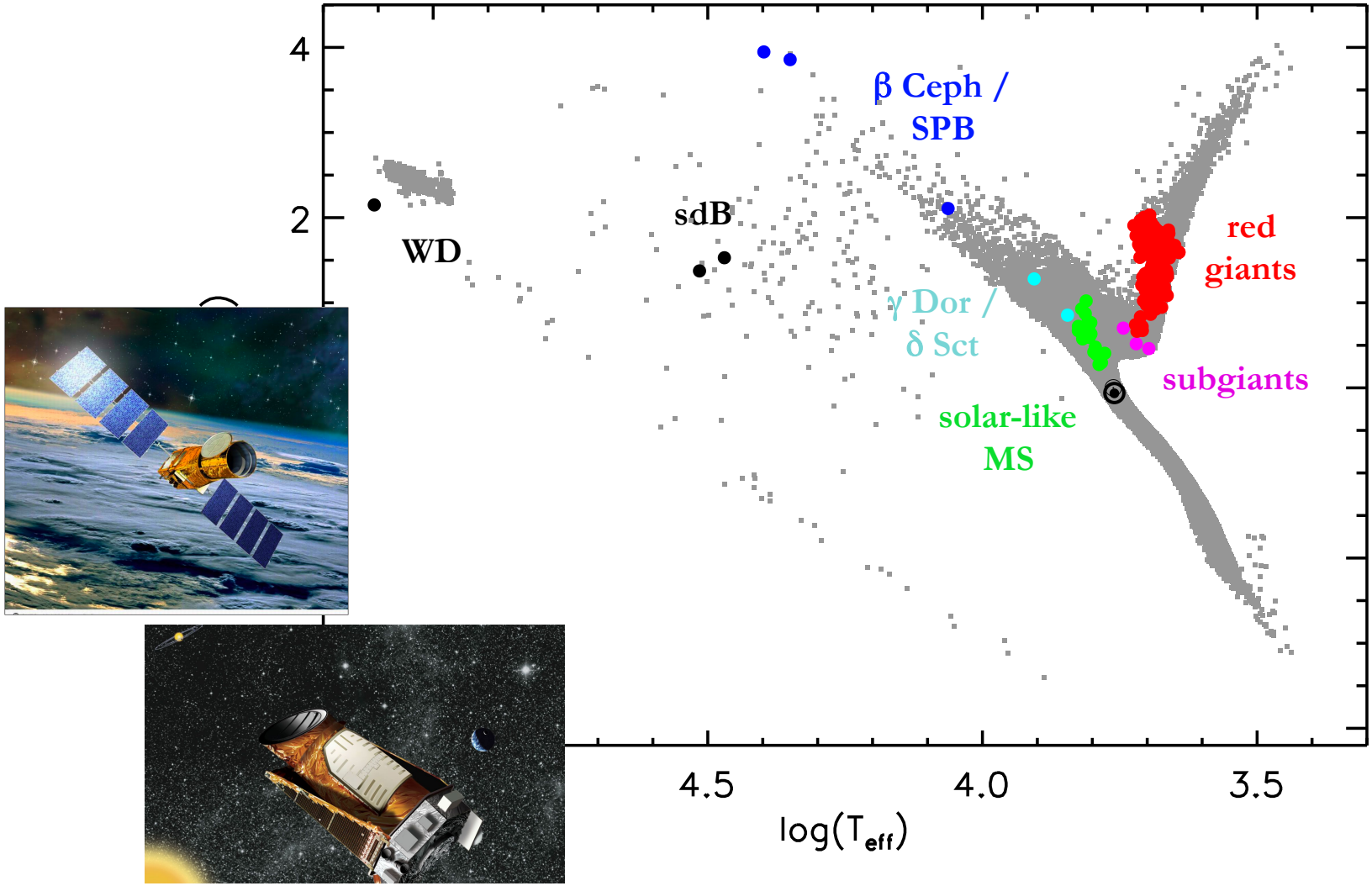
HR diagram of stars whose rotation is constrained with seismology

Pre-CoRoT/Kepler



HR diagram of stars whose rotation is constrained with seismology

Today



Probing internal rotation with seismology

- Effects of rotation on stellar oscillations
  - Geometric effects (change of coordinates from rotating to inertial frame)
  - Coriolis force
  - Centrifugal force (departure from sphericity)

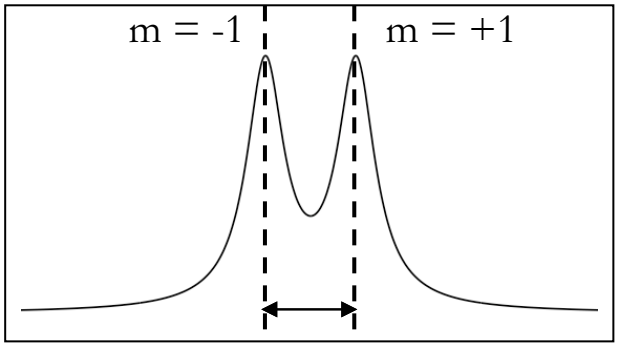
SLOW

FAST

- Slow rotators
  - Modification to the perturbed motion equation

$$-\omega^2 \rho_0 \boldsymbol{\delta r} + \underbrace{2m\omega\Omega\rho_0 \boldsymbol{\delta r}}_{\text{geometric}} - \underbrace{2i\omega\rho_0 \boldsymbol{\Omega} \times \boldsymbol{\delta r}}_{\text{Coriolis}} = -\nabla p' + \rho_0 \mathbf{g}' + \rho' \mathbf{g}_0$$

rotational splitting of $\ell = 1$ modes for high inclination



Probing internal rotation with seismology

- Rotational "splitting" of the modes (variational principle)

$$\underbrace{\delta\omega_{n,l,m}}_{\text{rotational splitting (observations)}} = m \int_0^R \int_0^\pi \underbrace{K_{n,l,m}(r,\theta)}_{\text{rotational kernels (model)}} \underbrace{\Omega(r,\theta)}_{\text{rotation rate (unknown)}} \, \mathrm{d}r\mathrm{d}\theta$$

- What do we need?
  1. Long observations (good frequency resolution)

  ⇒ **CoRoT** (2006) and **Kepler** (2009) particularly well suited!

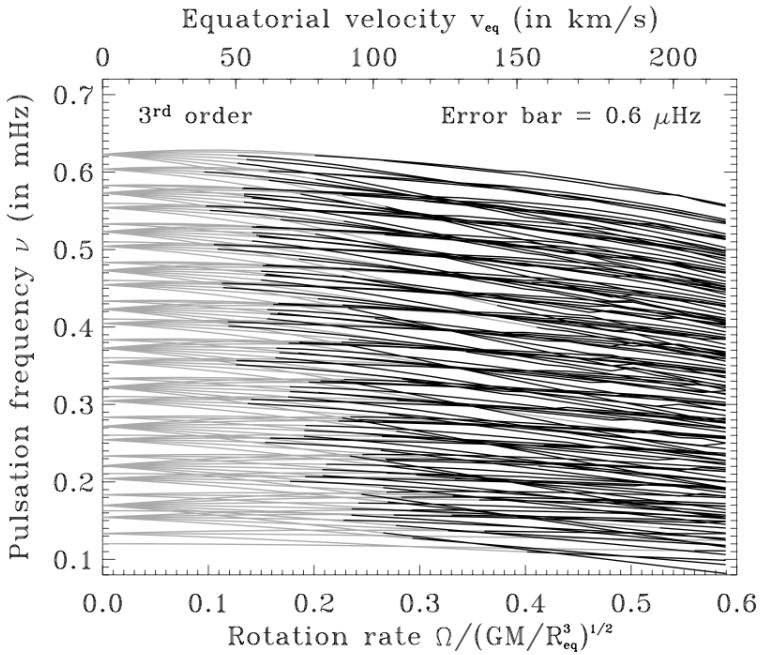
  2. Mode identification
  3. A stellar model (usually, but not necessarily)
  4. Modes that probe sufficiently distinct regions inside the star

Probing internal rotation with seismology

- Moderate rotators
  - Perturbative approach can be pushed to 2nd **(Saio 1981, Suarez et al. 2006)** or even 3rd order **(Soufi et al. 1998).**

$$\bar{\omega}^{\text{pert}}_{n,\ell,m} = \bar{\omega}^{(0)}_{n,\ell} + mC_{n,\ell}\bar{\Omega} + \left(S^1_{n,\ell} + m^2 S^2_{n,\ell}\right)\bar{\Omega}^2 + m\left(T^1_{n,\ell} + m^2 T^2_{n,\ell}\right)\bar{\Omega}^3 + O\left(\bar{\Omega}^4\right)$$

  - Validity domain for perturbative approach, ex. for acoustic modes:



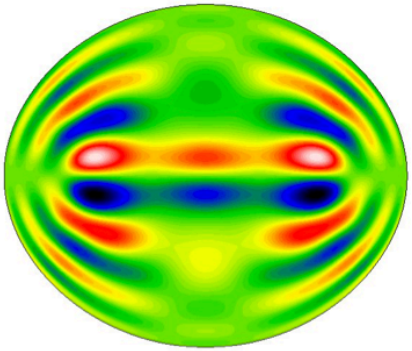
(Reese et al. 2006)

3rd-order pert. OK
complete calc. needed

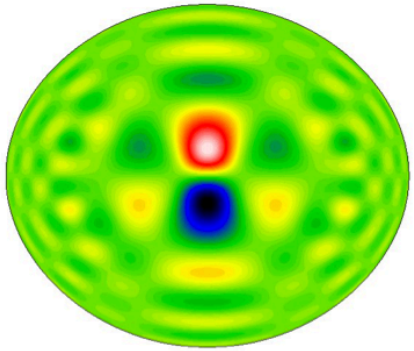
Probing internal rotation with seismology

- Fast rotators
  - Centrifugal force need to be taken into account: full 2D problem due to star distortion
  - Complete computation of 2D eigenvalue problem (requires 2D stellar models) : TOP **(Reese et al. 2006)**, ACOR **(Ouazzani et al. 2012)**.
    - **acoustic modes**

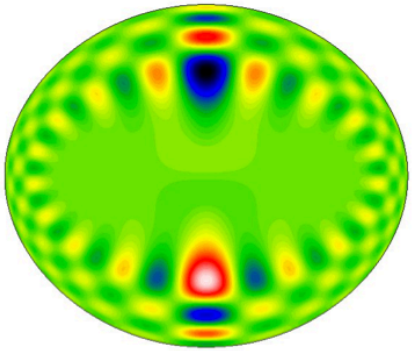
Lignières & Georgeot (2008), Reese et al. (2009)



Island modes



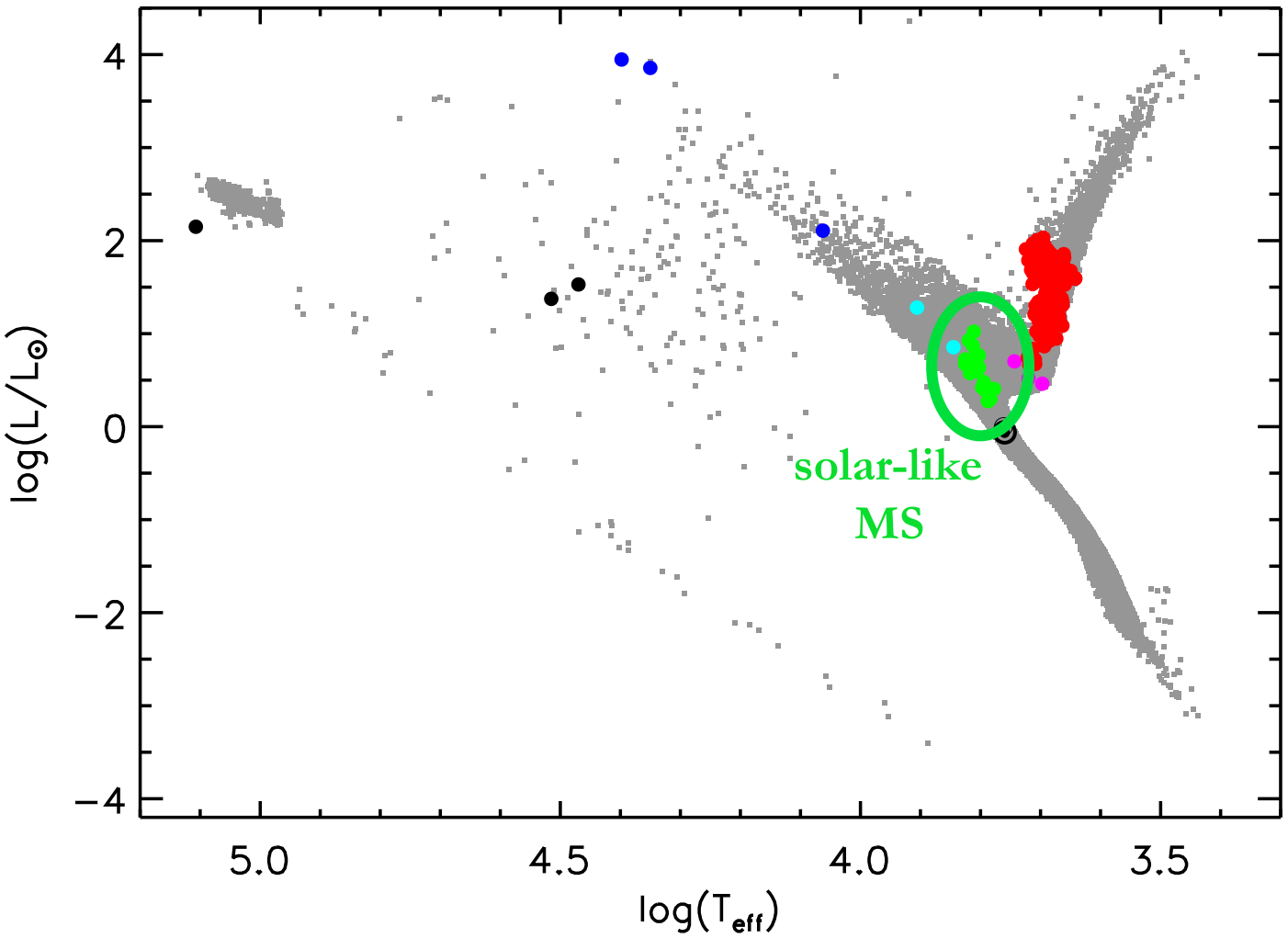
Chaotic modes



Whispering-gallery modes

    - **gravity modes** (see talk by V. Prat)
  - Link between observations and theory still not clearly made.

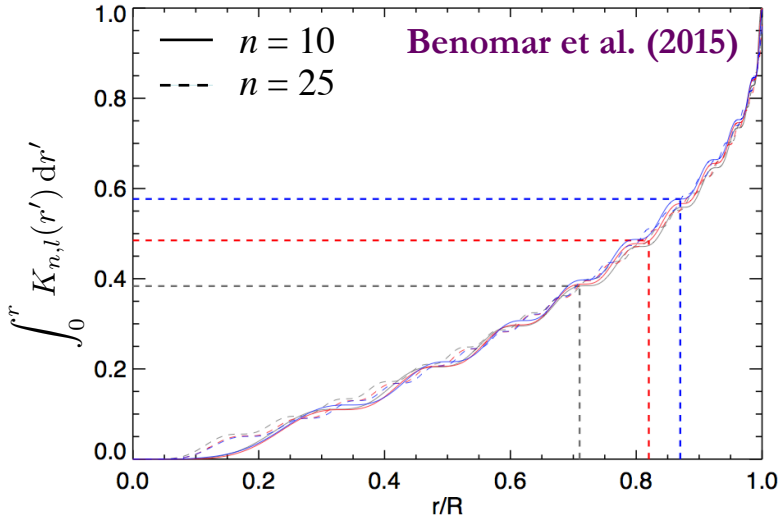
Solar-like MS stars



Solar-like MS stars

- Not the best targets to seismically probe internal rotation
  - Solar-like oscillations: high-order acoustic modes stochastically excited
  - All modes probe rather similar regions of the star (lack of high-ℓ modes)

  ⇒ only sensitive to an **average rotation in the probed cavity**

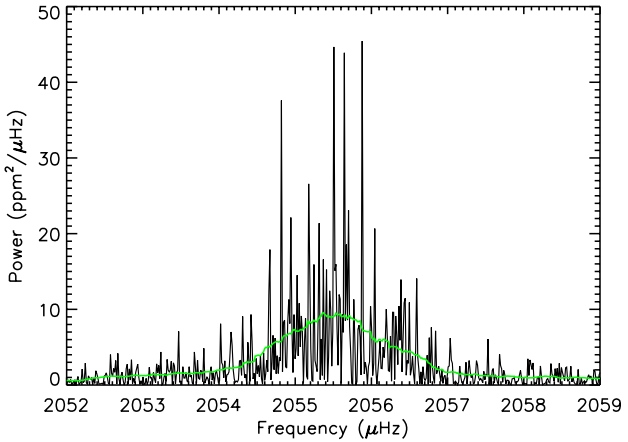


  - Modes are short-lived

  ⇒ harder to estimate the splitting

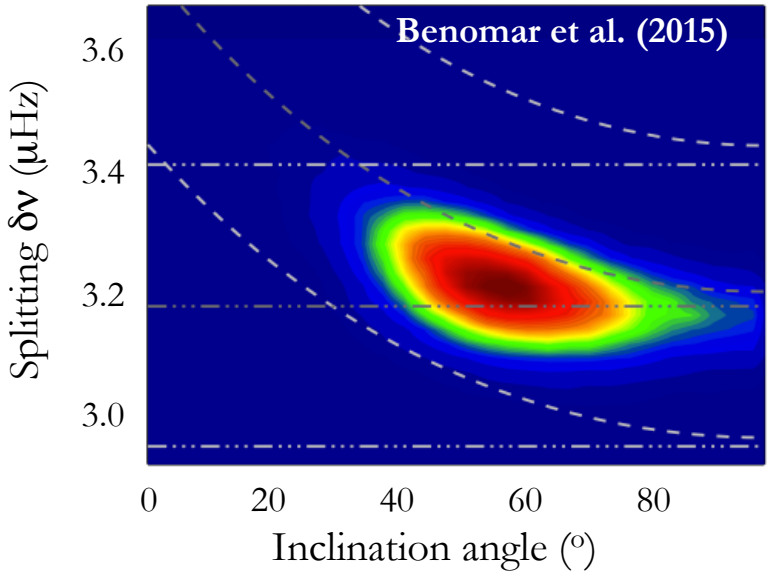
  ⇒ extraction of an average splitting for all modes

an $\ell = 1$ mode of 16 Cyg A (Kepler)



Solar-like MS stars

- Measurement of a average rotational splittings in MS stars
  - Possible in 3 CoRoT targets and ~ 20 Kepler targets

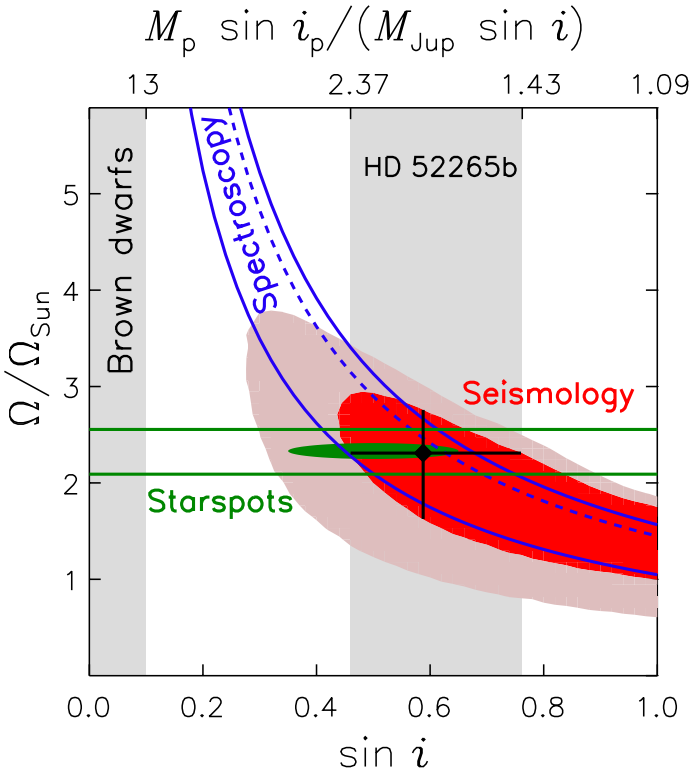


- Comparison with other measurements
  - Photometry (spot modulation)
  - Spectroscopy

$$\Omega_{\rm surf} = \frac{(v \sin i)}{R \sin i}$$

spectroscopy — model — seismology

Measurements of Ω in CoRoT target HD 52265 **(Gizon et al. (2013)**



Solar-like MS stars

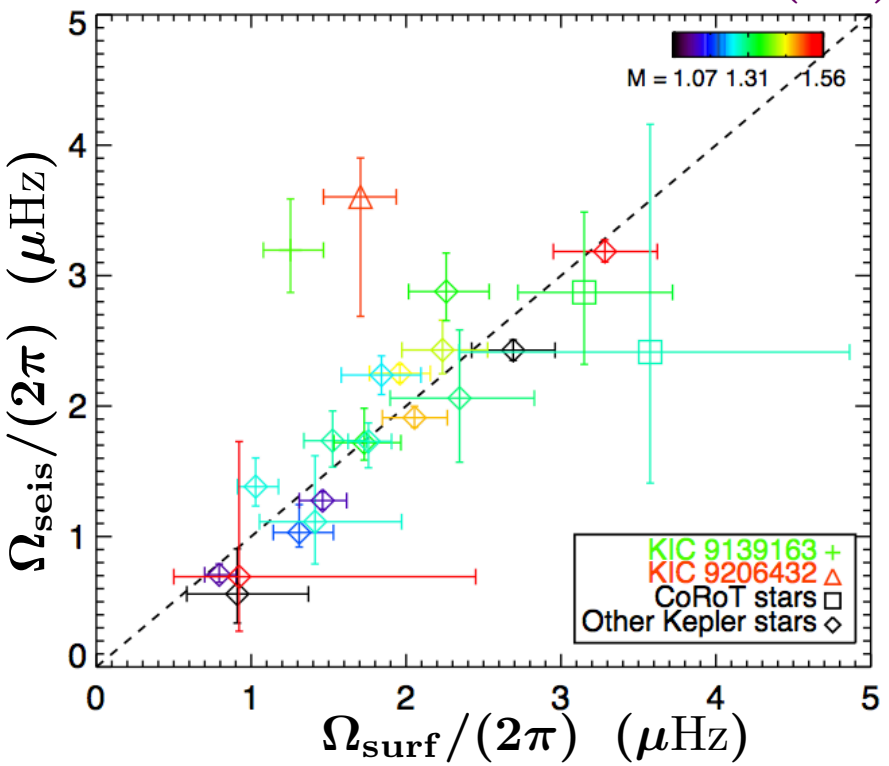
- Estimates of Ω_{seism} ($<\delta\omega>$) and Ω_{surf} (photometry & spectroscopy) for 22 solar-like pulsators from CoRoT and Kepler

- Upper limit on differential rotation (**Benomar et al. 2015**):

$$\frac{\Omega_{rad}}{\Omega_{surf}} \leqslant 2$$

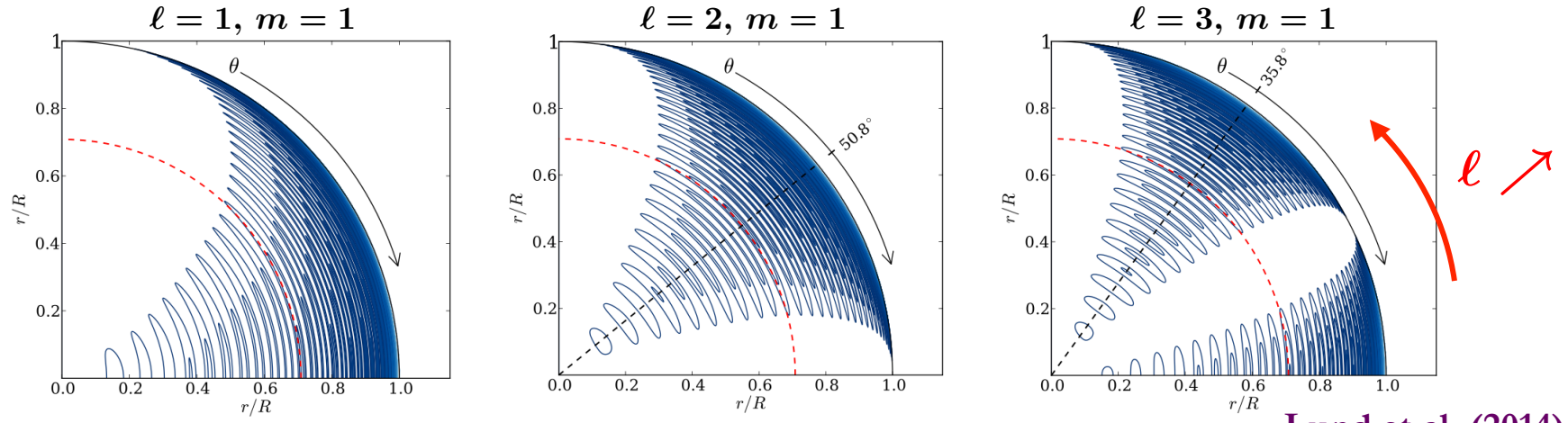
$\Rightarrow$ in line with solar rotation profile

Benomar et al. (2015)



Solar-like MS stars

- Latitudinal differential rotation
  - necessitates average splittings for different ℓ and m modes separately

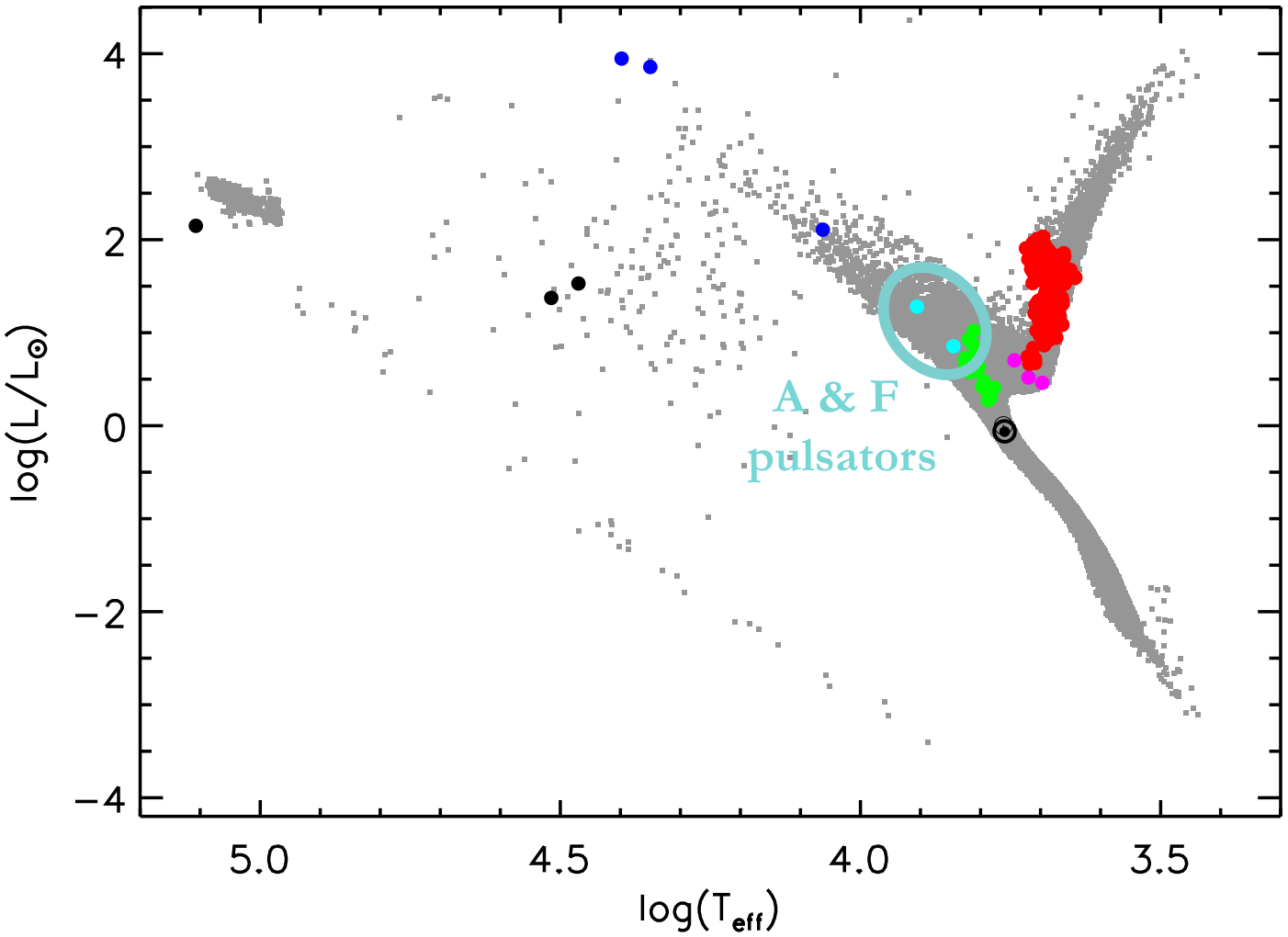


Lund et al. (2014)

  - Distinguish different scenario for latitudinal differential rotation in the envelope? **(Lund et al. 2014, Benomar et al. 2015)**

- Precise surface rotation in stars that can be seismically modeled, i.e. with precise mass and ages
  - can help calibrate **gyrochronology** **(Davies et al. 2015)**

A- & F-type pulsators



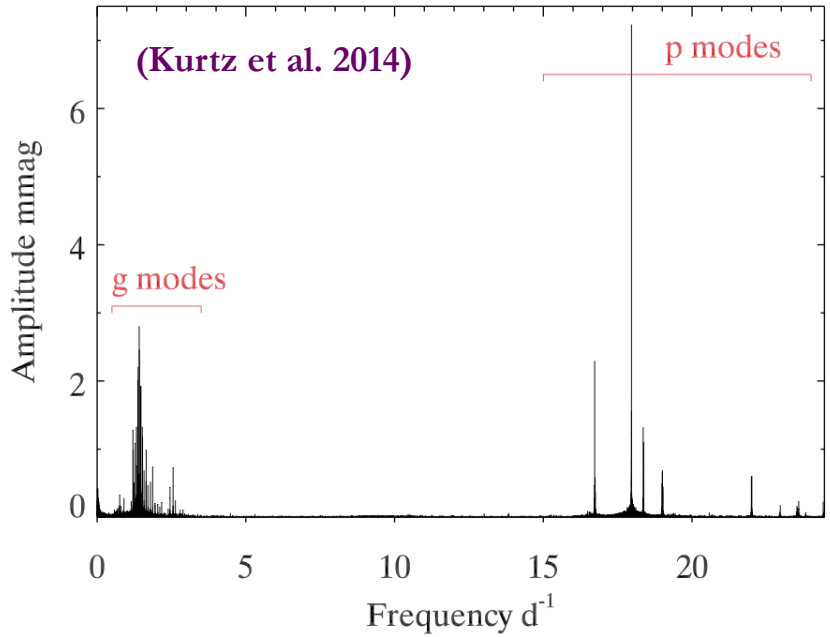
A- & F-type pulsators

- Two type of pulsators
  - **γ Dor** pulsators: high-order **g modes** excited by convective blocking
  - **δ Sct** pulsators: low-order **p modes** (potentially mixed) excited by κ-mechanism in the 2nd He ionization zone

  ⇒ + hybrid stars (probe both the p- and g-mode cavities): high potential for diagnostic!

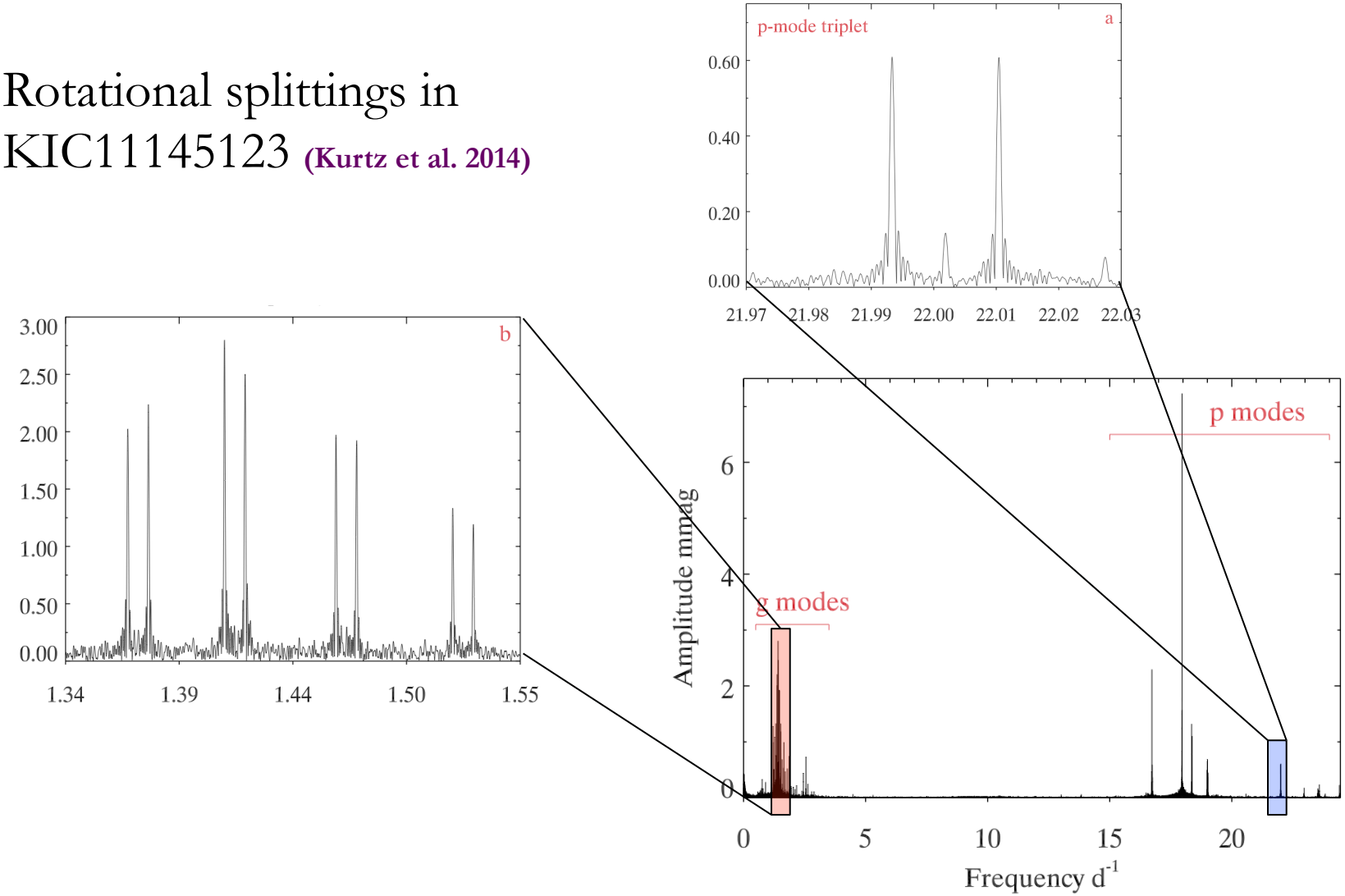
- Two hybrid γ Dor – δ Sct with split modes in Kepler data
  - KIC11145123 **(Kurtz et al. 2014)**

    15 g-mode ℓ=1 triplets, 8 p-mode multiplets
  - KIC9244992 **(Saio et al. 2015)**
  - both **slow rotators**



A- & F-type pulsators

- Rotational splittings in KIC11145123 **(Kurtz et al. 2014)**



A- & F-type pulsators

- 1st-order perturbation analysis (slow rotators):

$$\delta\omega_{n,l} = \beta_{n,l} \int_0^R \bar{K}_{n,l}(r)\,\Omega(r)\,\mathrm{d}r$$

Normalized rotational kernel

$$\beta_{n,l} \equiv \int_0^R K_{n,l}(r)\,\mathrm{d}r$$

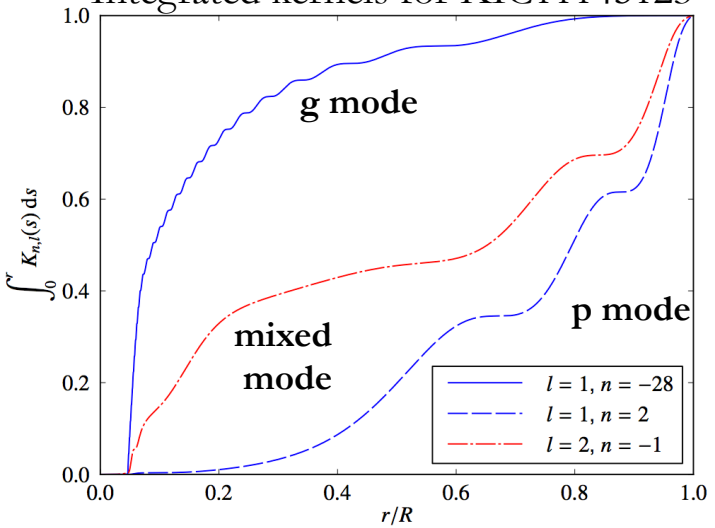
$\beta_{n,l} \leqslant 1$ for pure p modes $\Rightarrow$ $\delta\omega_\mathrm{p} = 2 \times \delta\omega_\mathrm{g}$ in case of SB rotation

$\beta_{n,l} \geqslant 1/2$ for pure g modes

- In both stars, $\delta\omega_\mathrm{p} \approx 2\,\delta\omega_\mathrm{g}$ so they are in **near-solid body rotation** (over ~ 95% of R_*)
  - For KIC11145123, $\delta\omega_\mathrm{p} > 2\,\delta\omega_\mathrm{g}$

  $\Rightarrow$ surface slightly faster than interior!

Integrated kernels for KIC11145123

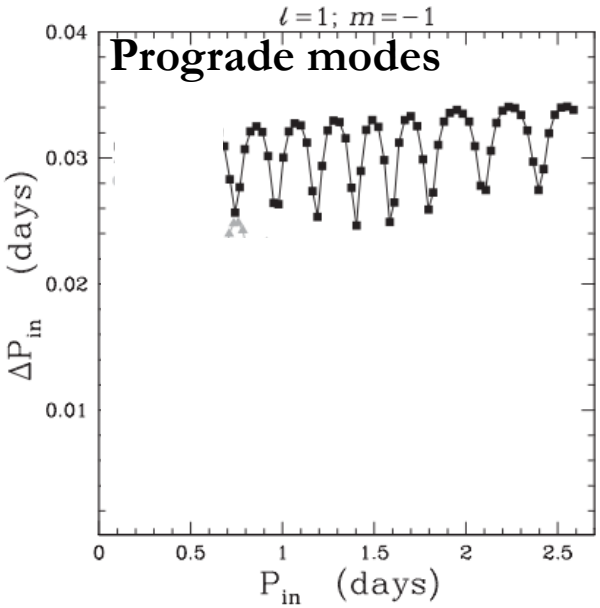


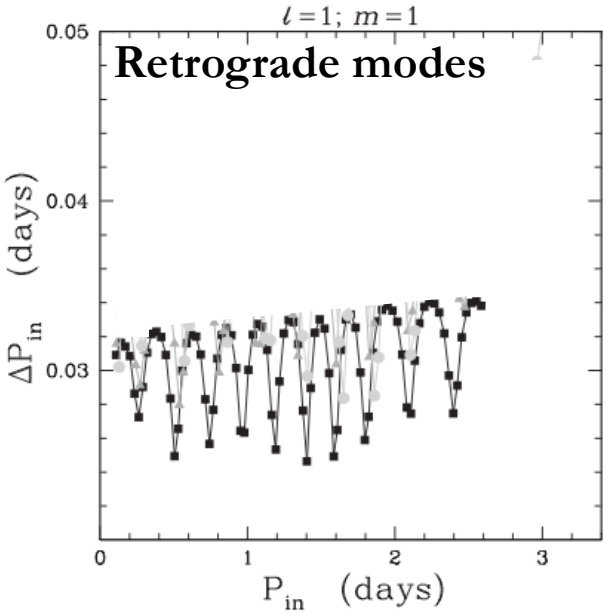
Both pulsators rotate <u>much</u> slower (v_eq ~ 1 km/s) than their counterparts!

γ Dor moderate & fast rotators

- With increasing rotation, **period spacings** of ≠ m modes behave differently

Bouabid et al. (2013)





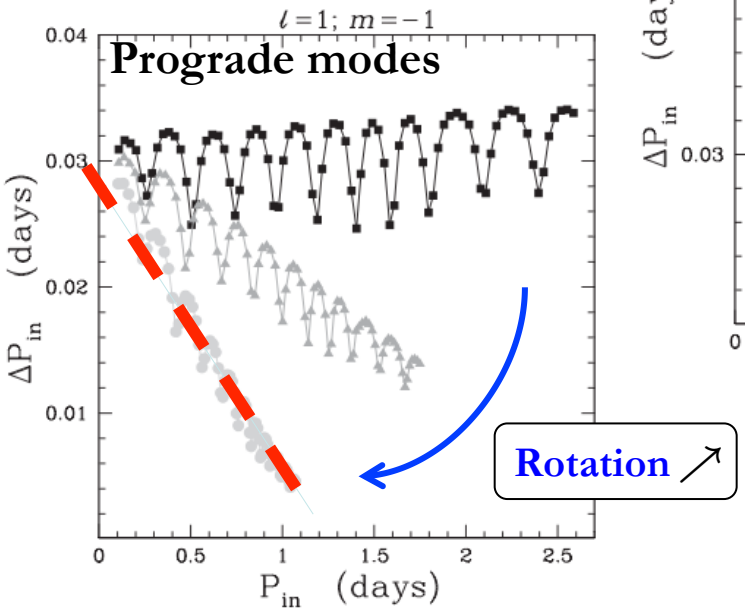
⇒ use of the slope of ΔΠ as a **tracer for differential rotation?**

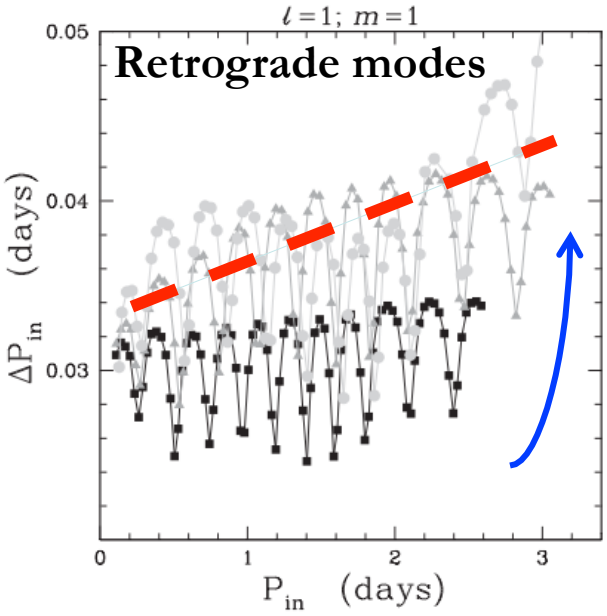
(Ouazzani et al. KASC8)

γ Dor moderate & fast rotators

- With increasing rotation, **period spacings** of ≠ m modes behave differently

Bouabid et al. (2013)



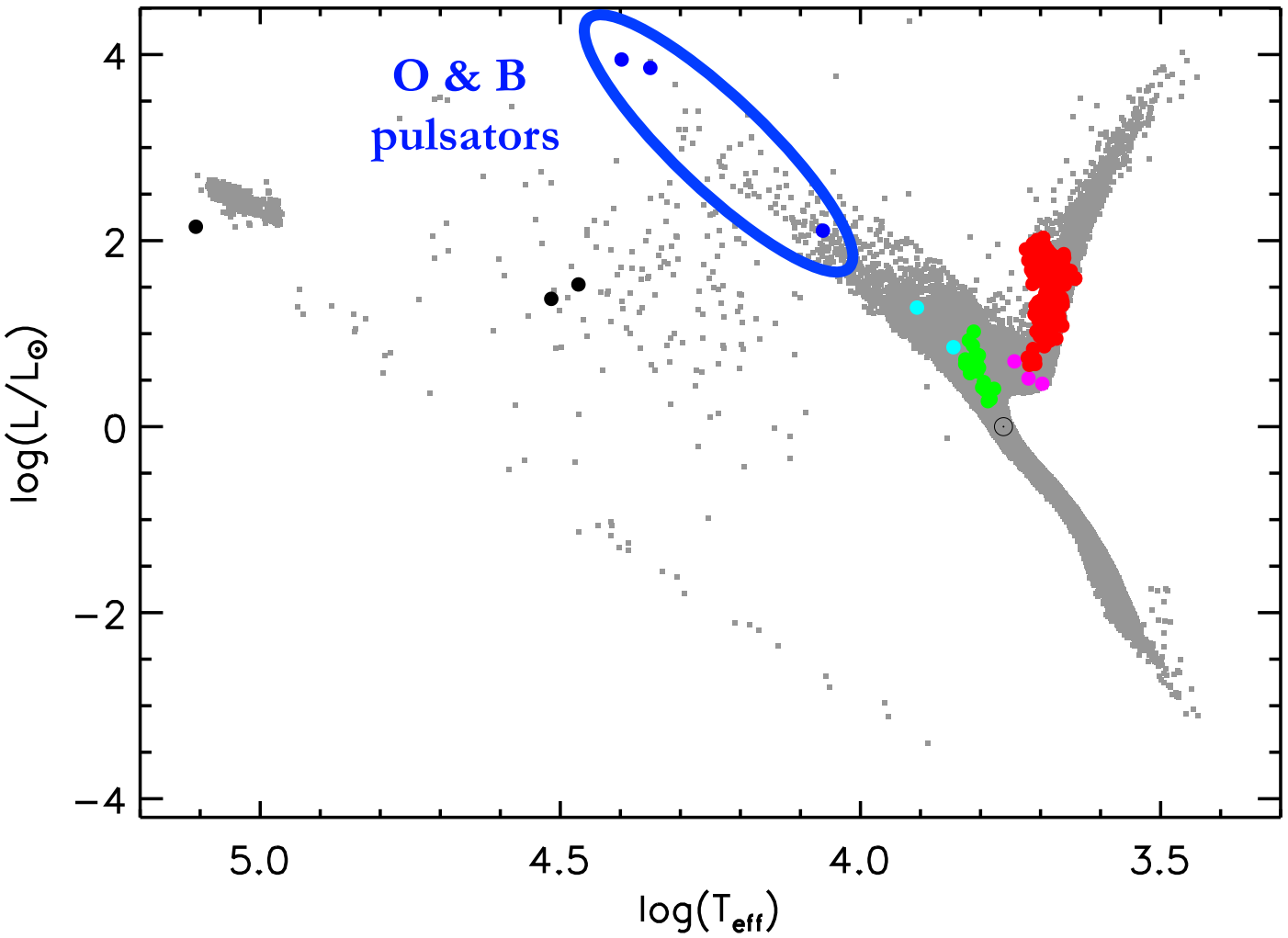


Rotation ↗

⇒ use of the slope of ΔP as a **tracer for differential rotation?**

(Ouazzani et al. KASC8)

O- & B-type pulsators



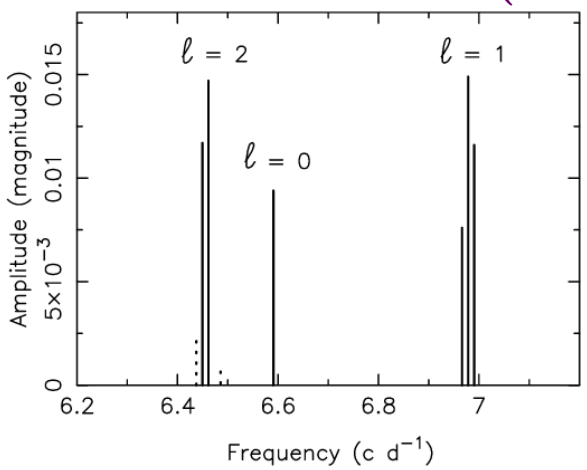
O- & B-type pulsators

- (8 - 20 $M_\odot$) stars: modes are excited by κ-mechanism in the iron partial ionization zone
  - **β Ceph** pulsations: **low-order p** (and **mixed**) **modes**
  - **SPB** pulsations: **high-order g modes**

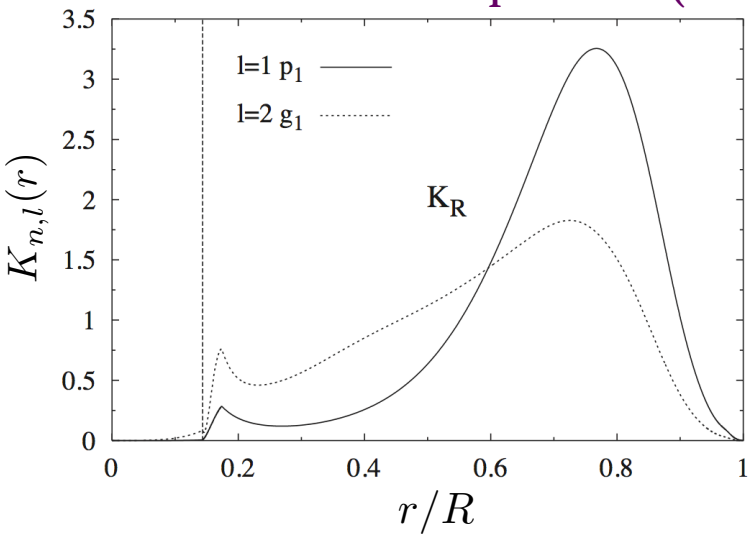
- $\ell = 1$ triplet (p_1) and $\ell = 2$ quintuplet (g_1) detected in two β Ceph pulsators observed from the ground
  - HD 129929 **(Aerts et al. 2004, Dupret et al. 2004):** core faster than envelope?
  - θ Oph **(Briquet et al. 2007)**: SB rotation?

Results depend strongly on
- Mode identification
- Modeling (mixed modes)

Aerts et al. (2004)

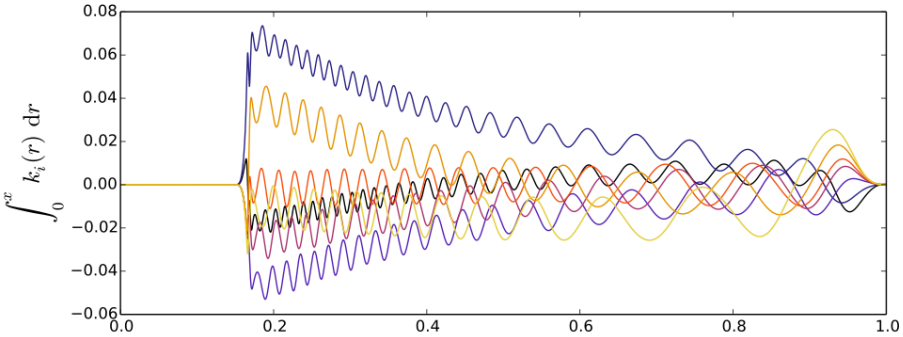


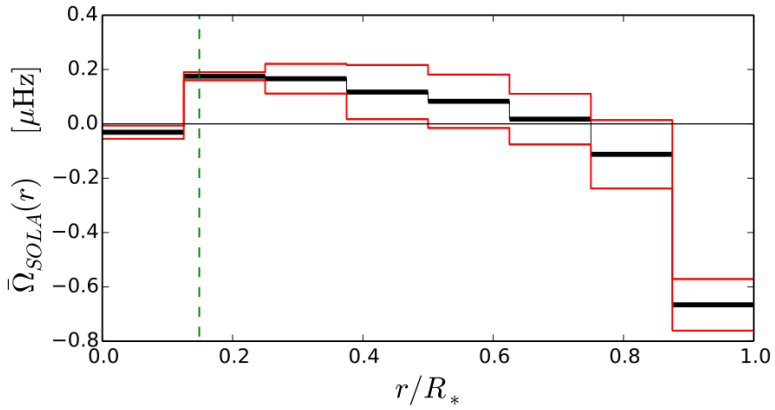
Dupret et al. (2004)



Counter-rotation in a slow-rotating SPB pulsator?

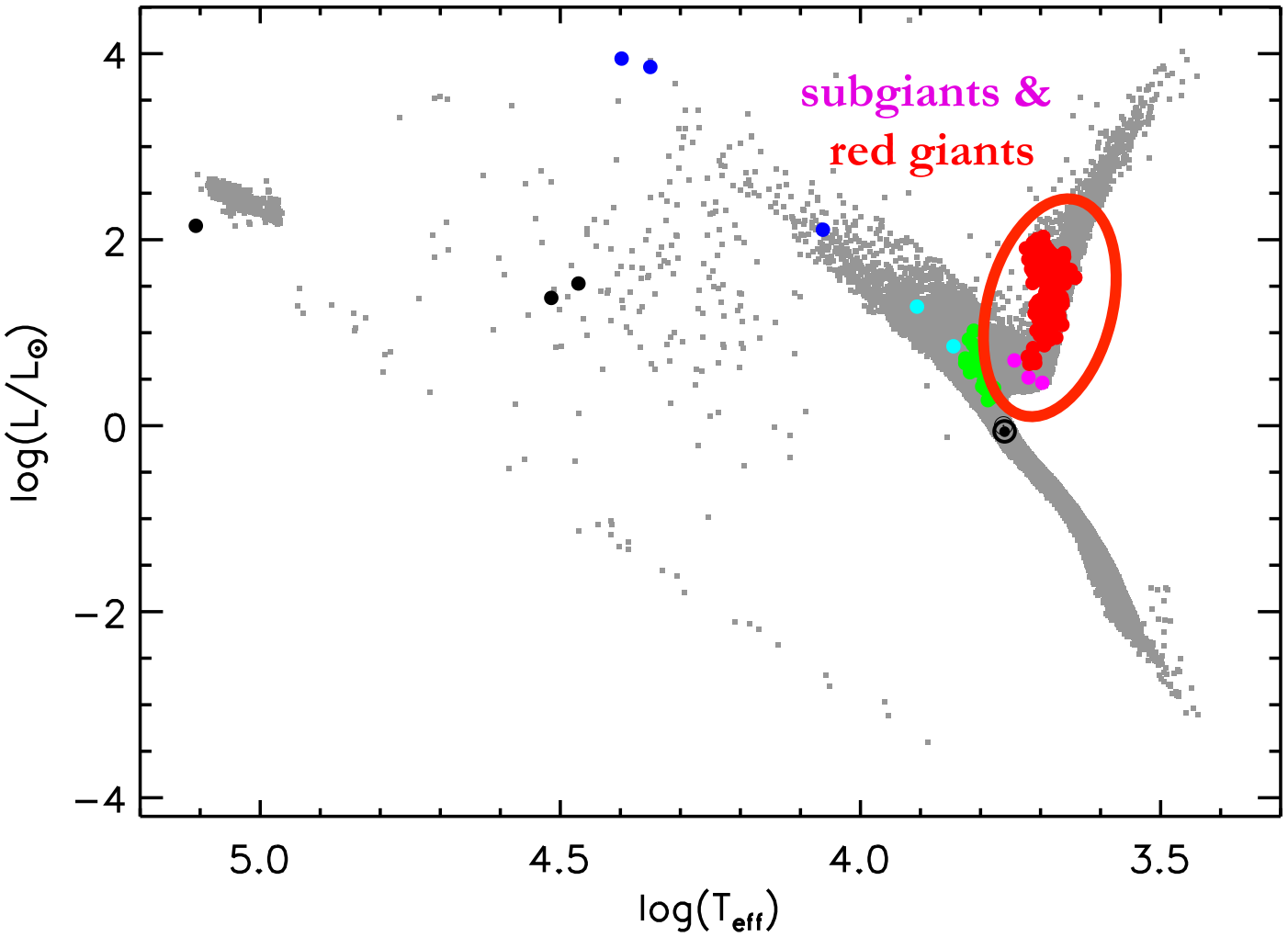
- KIC10526294 : a Kepler SPB pulsator with
  - 19 consecutive g-mode ℓ=1 triplets (n = 14 to 32)
  - Detailed modeling **(Papics et al. 2014, Moravveji et al. 2015)** => rotational kernels
- Inversion of internal rotation profile
  - Observed modes probe slightly different cavities





  - Either 2-zone model or a counter-rotating profile
  - More on this in a few minutes (S. A. Triana's talk)

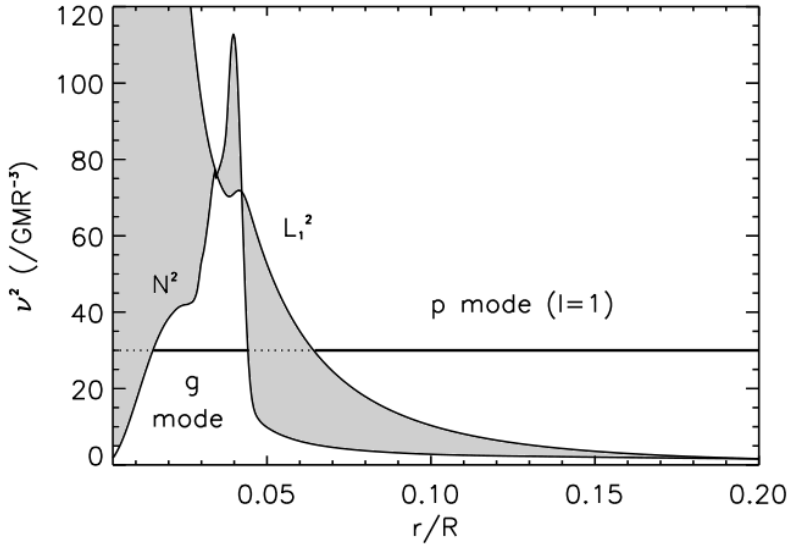
Subgiants & red giants



Sugiants & young 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**
  – behave as p modes in the envelope…
  … and as g modes in the core
  – High potential to probe radial differential rotation

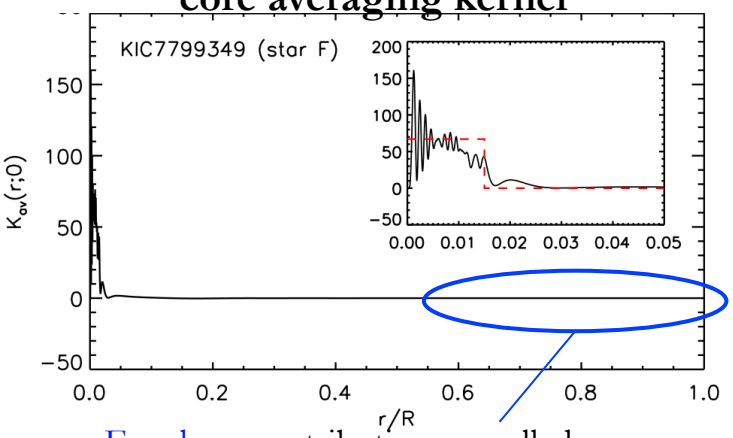


- Young subgiants
  – Few mixed modes
  – Wide modes complicate splitting estimates (as in the MS)

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



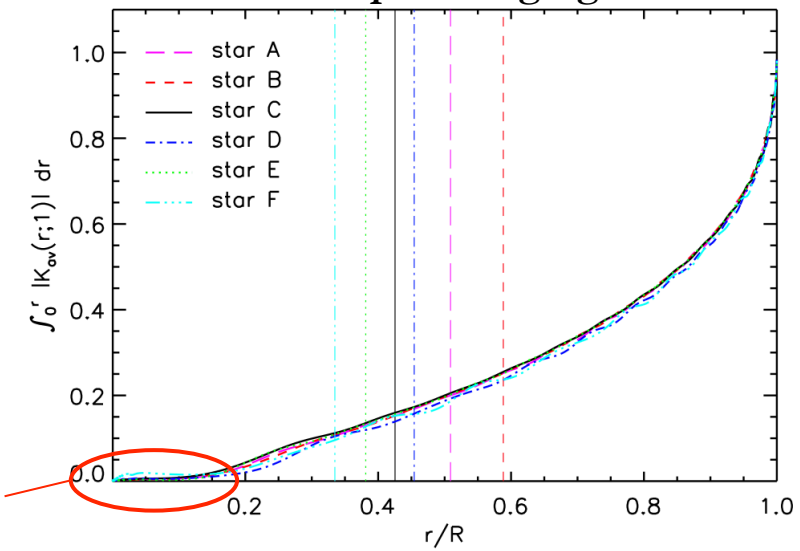
Envelope contribution cancelled

– **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

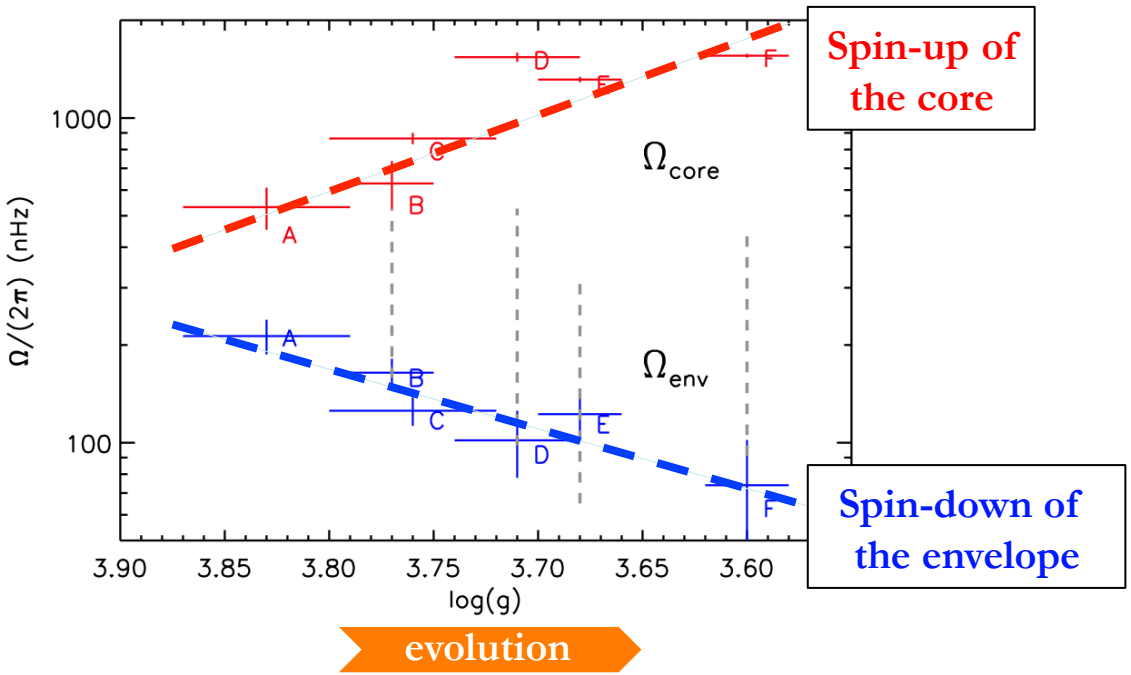
Cumulative integral of envelope averaging kernel



Core contribution cancelled

Sugiants & young red giants

- Spin-up of the core in the subgiant phase



– Qualitatively corresponds to what is expected…

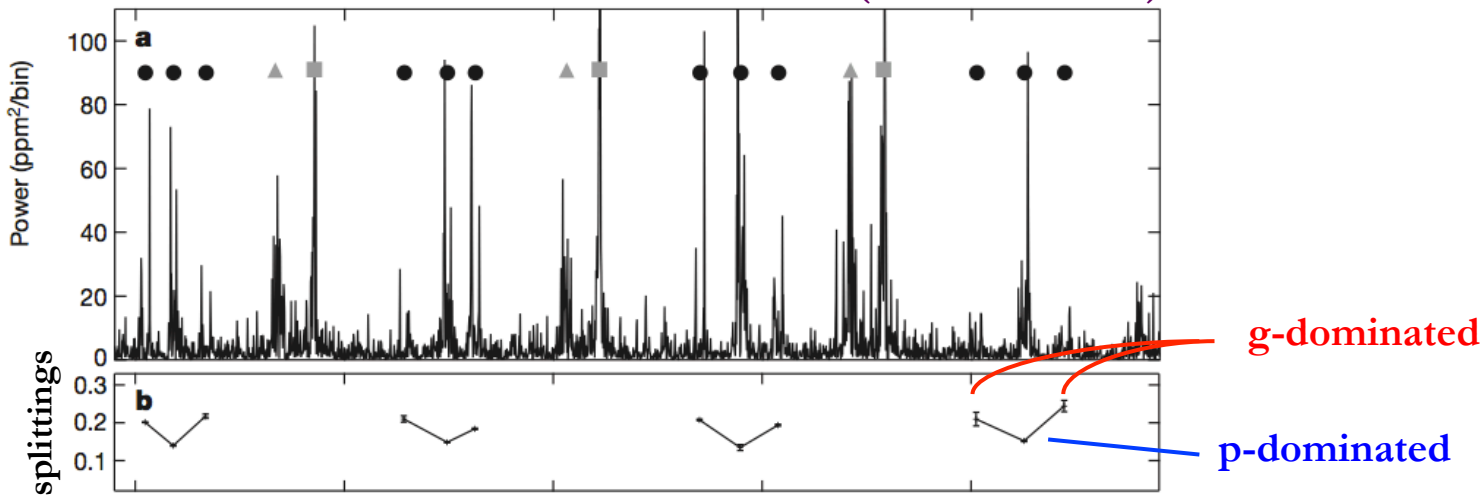
… BUT core rotation rate ~ 200 times lower than predicted **(Ceillier et al. 2013, Marques et al. 2013)**

– **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)



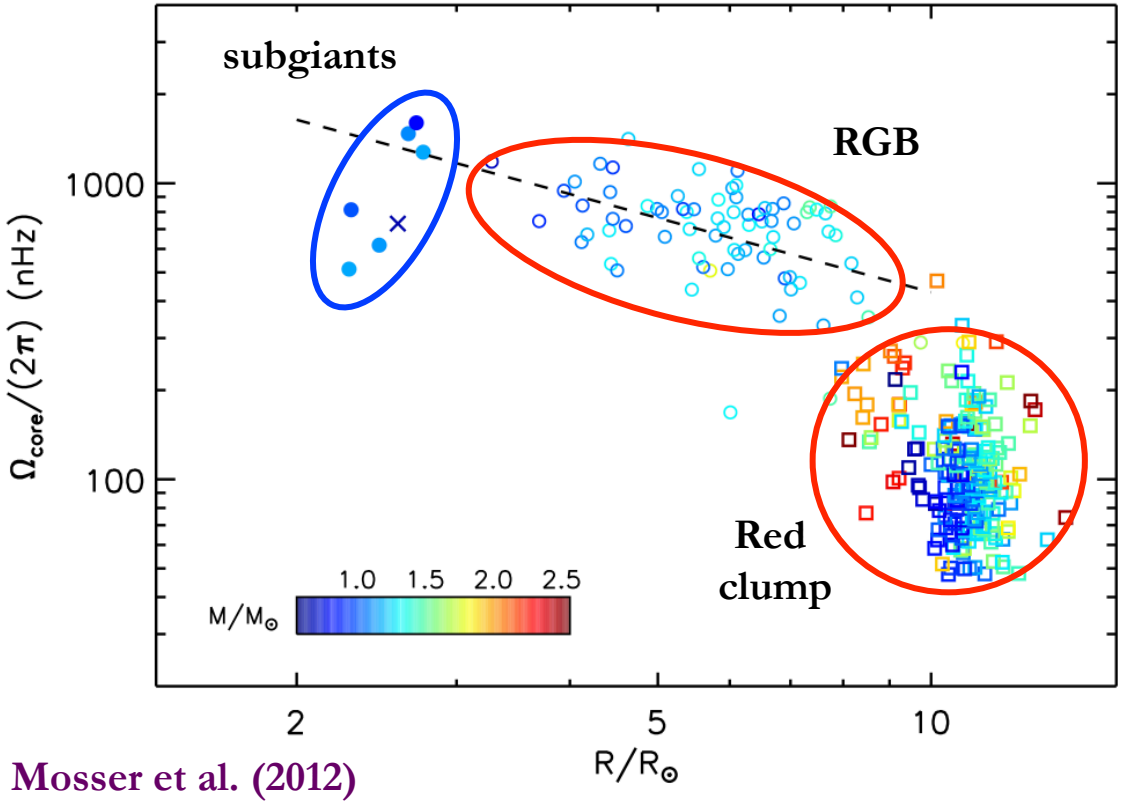
- 15,000 Kepler red giants, most of which oscillate: potential for "ensemble" measurement of internal rotation

Spin-down of the core for red giants

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

  – For gravity-dominated modes, $\beta_{\rm env} \ll \beta_{\rm core} \approx 1/2 \Rightarrow \langle \Omega_{\rm core} \rangle \approx 2\delta\omega_{\rm g}$
  so stellar model not needed to measure core rotation

Splitting of most g-like modes



Mosser et al. (2012)

- **Spin-down of the core in the RGB**

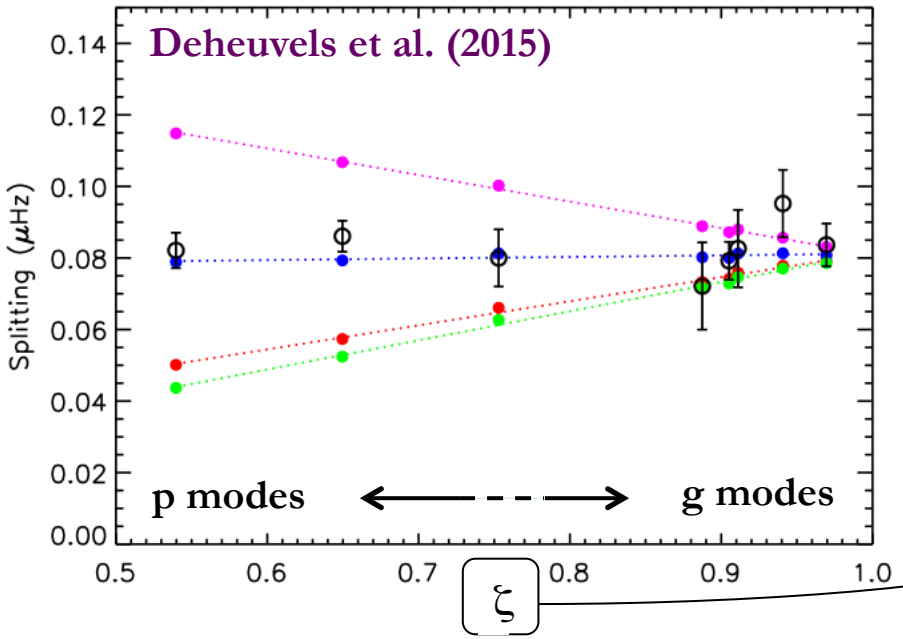
⇒ **Need for additional AM transport**

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

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

Core-He burning giants (red clump)

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



$\Omega_{core}/\Omega_{env}$ = 1 (SB rot.)
$\Omega_{core}/\Omega_{env}$ = 2
$\Omega_{core}/\Omega_{enva}$ = 10
$\Omega_{core}/\Omega_{env}$ = 100
obs. splittings

– 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)**

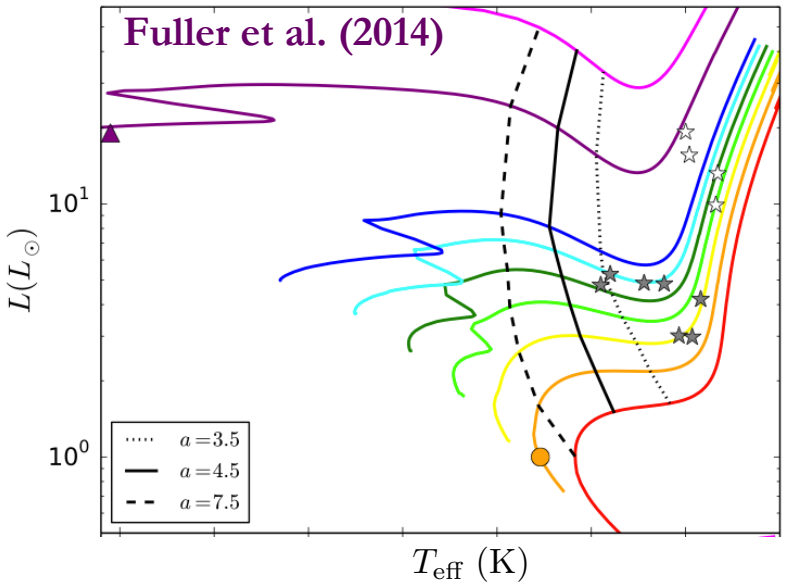
⇒ **very fast redistribution of AM** either during short-lived subgiant phase or at the beginning of core He-burning

First attempts to explain slow core rotation of red giants

- Inclusion of an **additional constant viscosity** $\nu_{add} = 3\times10^4\,cm^2/s$ can reproduce core rotation of the red giant studied by Beck et al. 2012 **(Eggenberger et al. 2012)** …

  … but a constant viscosity fails to reproduce spin-down on the RGB **(Spada et al. in prep)**

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



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

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

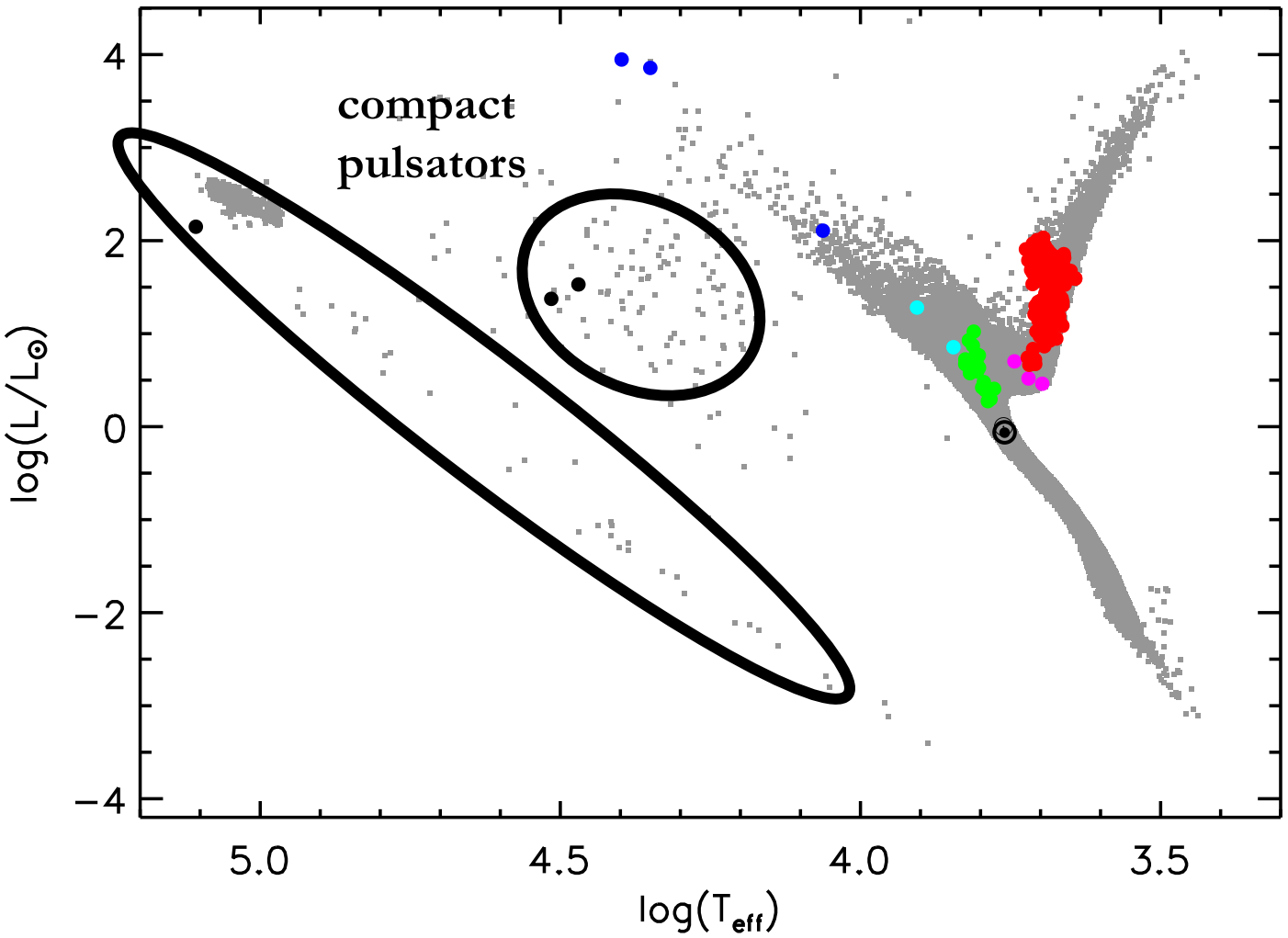
? During core-He burning **(red clump), IGW** excited by convective core might recouple?

First attempts to explain slow core rotation of red giants

- Transport of angular momentum through **magnetic fields**
  - **Fossil field** (Maeder & Meynet 2014)
  - **Taylor-Spruit dynamo**: not efficient enough (Cantiello et al. 2014)
  - Instabilities, e.g. **Azimuthal Magneto-Rotational Instability (AMRI)**: instability of a toroidal magnetic field caused by differential rotation (Rüdiger et al. 2014, Jouve et al. 2015)
    - May produce sufficient effective viscosity
    - But effects of stratification need to be considered
    - Effective viscosity depends on rotation gradient

- Extraction of angular momentum from the core by **mixed modes** themselves (Belkacem et al. 2015a,b):
  - Could explain core spin-down in evolved red giants but not the low core rotation of subgiants and young giants

Compact pulsators



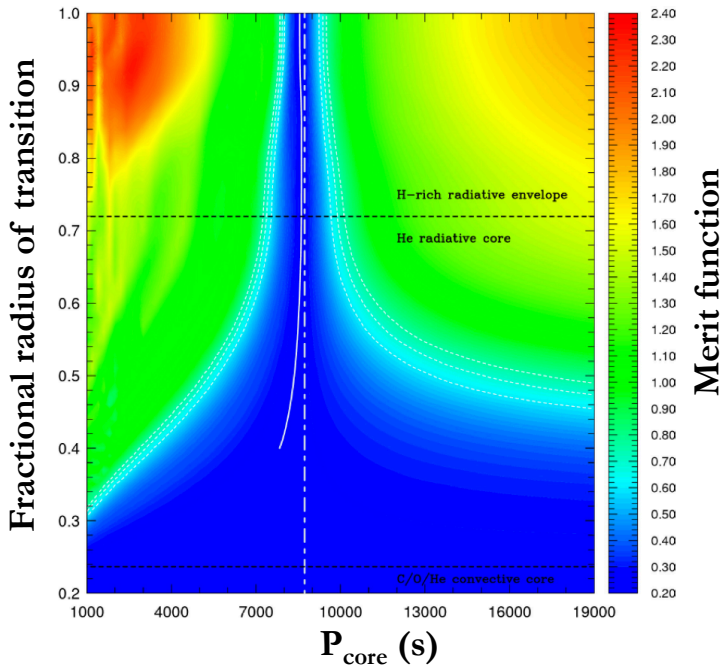
Compact pulsators

- Subdwarf B (sdB) stars: former red giants whose convective envelope has been "stripped" from the core by a yet unclear process
  - Analogous to the **core of a red clump stars**, but seen directly!
  - Modes can be trapped in different regions of the star (essentially in the H-rich envelope, **Charpinet et al. 2000**)
  - **Surface rotation ~ core rotation rates for clump stars**
  - Internal rotation probed for 3 stars

- White dwarfs: 5 stars with clear multiplets
  - **solid-body rotation** over ~ 90% of the star for all of them

More results soon

(Charpinet et al. 2008)



Conclusion

- Constraints on **internal rotation profiles** at **different masses**, **different evolutionary stages**

⇒ Tight observational constraints, which gave new momentum for studying angular momentum transport in stars!

- Current results exclusively about **slow rotators** so far, constraints on internal rotation of **moderate rotators** are expected in the near future

- Long observations are crucial to measure rotational splittings

⇒ **PLATO mission**