# Solar-like pulsations across the HR diagram

**PHOST 03/09/2018**

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New york university Abu Dhabi

# A (biased) perspective on solar-like pulsation of MS stars

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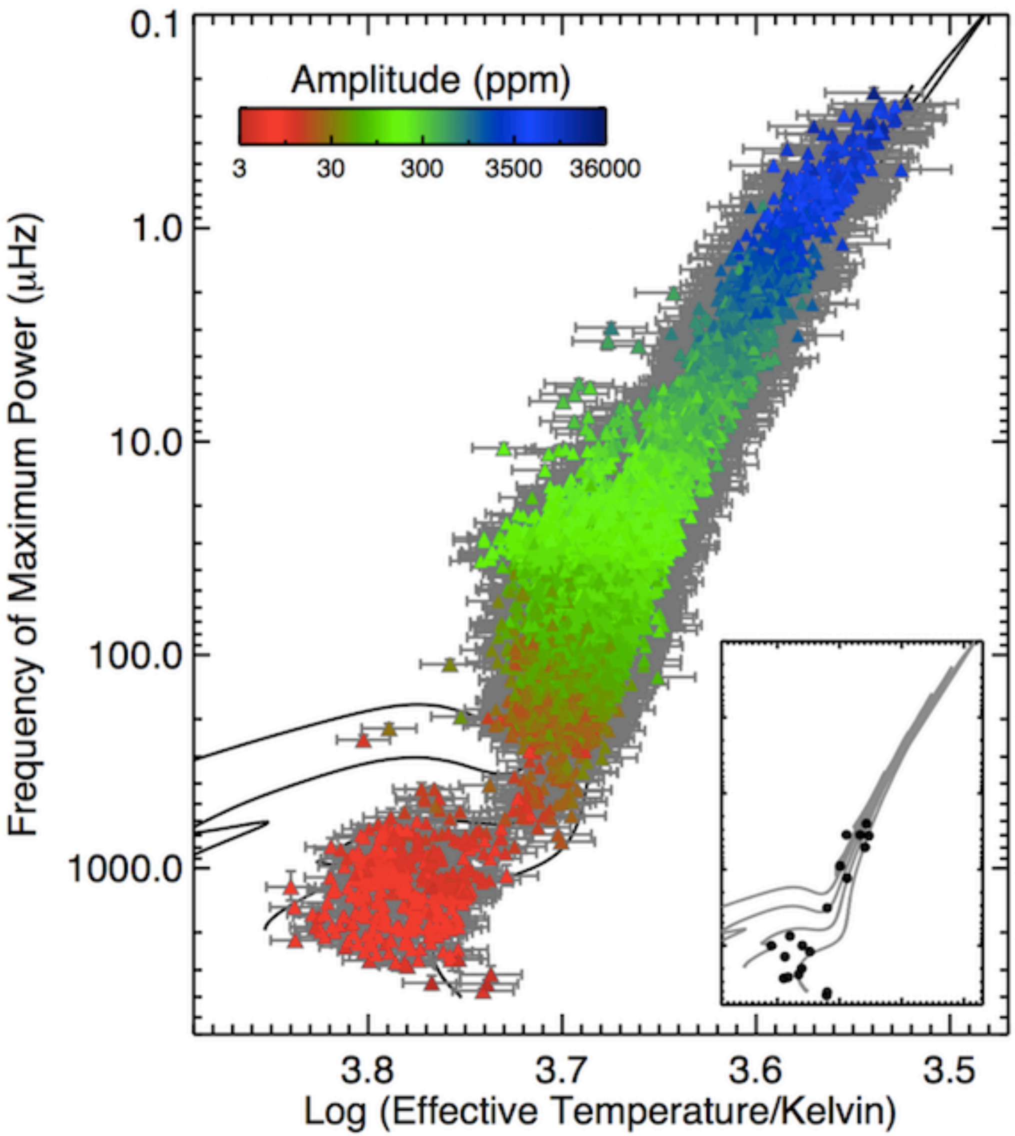
# Before CoRoT / After Kepler




<u>Before CoRoT (2008):</u>
A handful of stars with detected pulsations

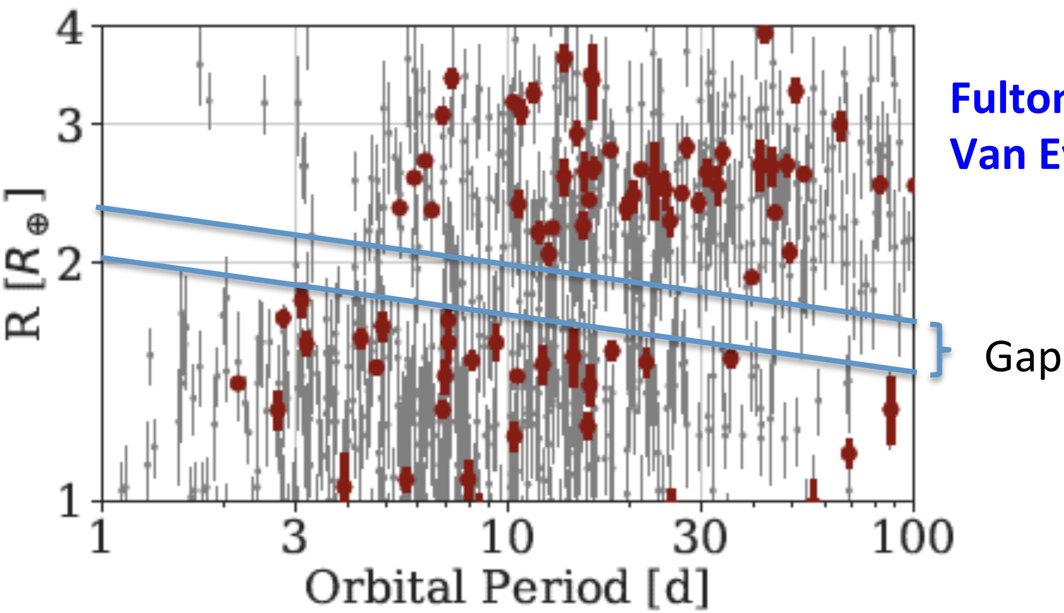
<u>Nowadays:</u>

RGB: ~ 15000 detections

MS: ~200 detections

Credit: Daniel Huber

# Example of importance of seismology for exoplanets



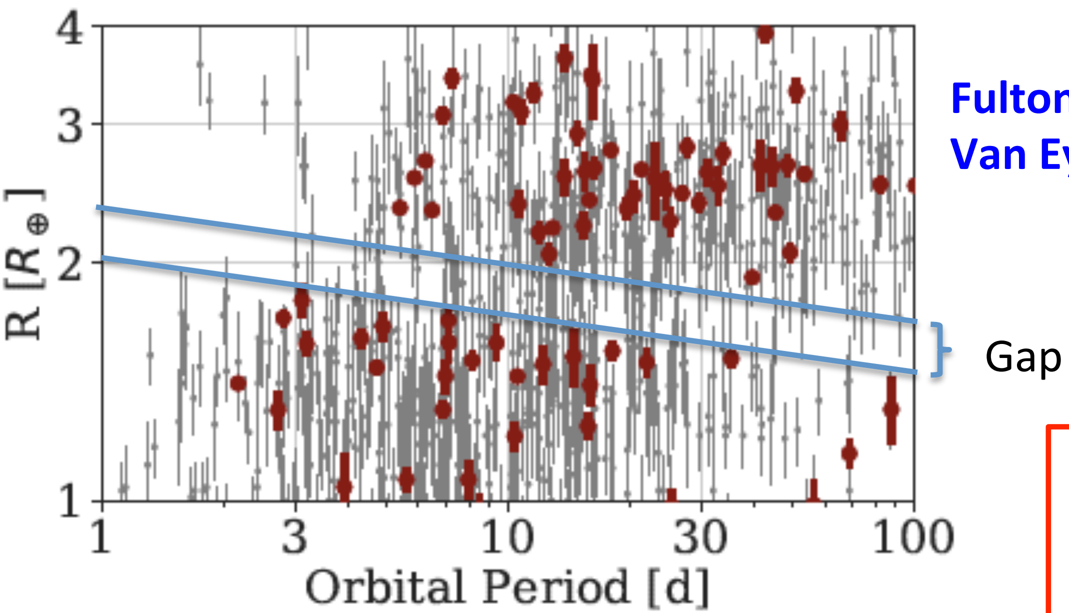

**Fulton+2017**: Spectroscopy only (gray)
**Van Eylen+2018**: Spectroscopy + seismology (red)

Seismology increases the level of details:

- ➢ Clear gap
- ➢ Gap position decreases with orbital period

A gap requires rocky cores (**Owen+2017, Jin+2018**)
A decrease of the gap position is likely due to photo-evaporation and rules out other scenarii

# Example of importance of seismology for exoplanets

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Seismology increases the level of details:

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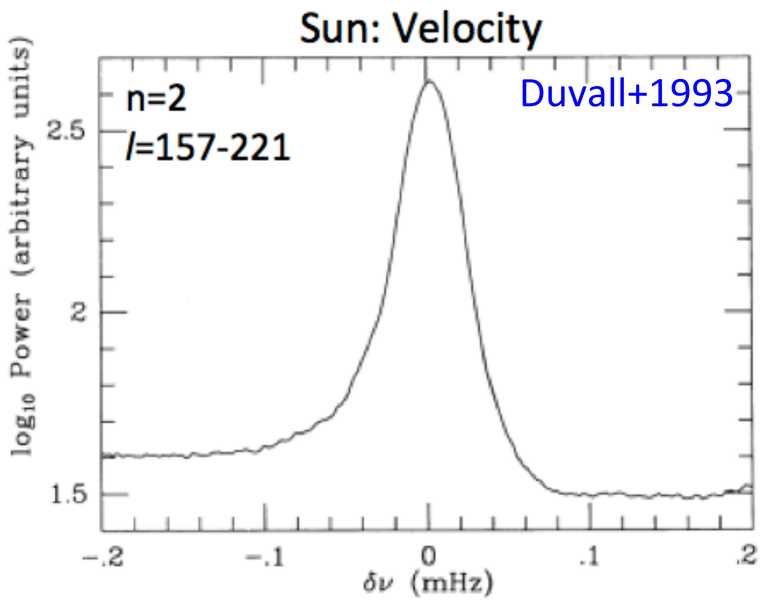
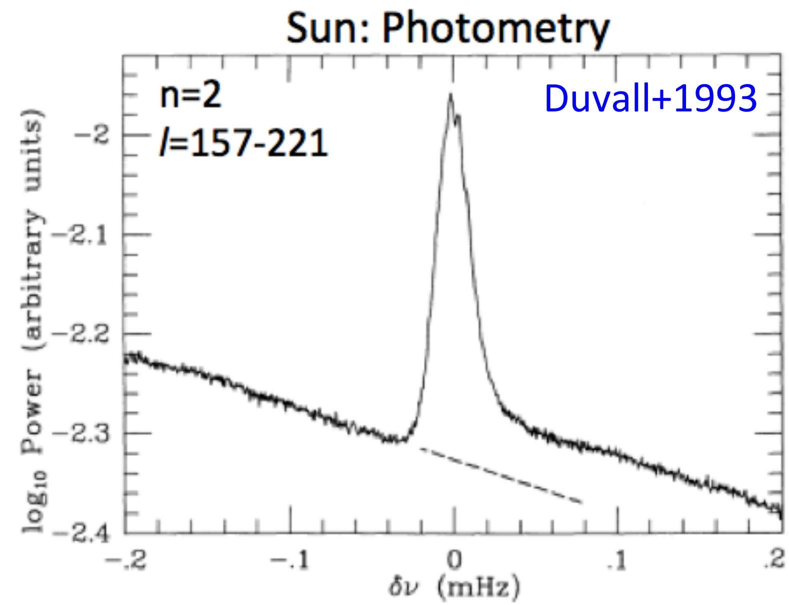
More on Friday about
Planets – Seismo synergies by:
A. Wolszczan
T. Campante

A gap requires rocky cores (**Owen+2017, Jin+2018**)
A decrease of the gap position is likely due to photo-evaporation and rules out other scenarii

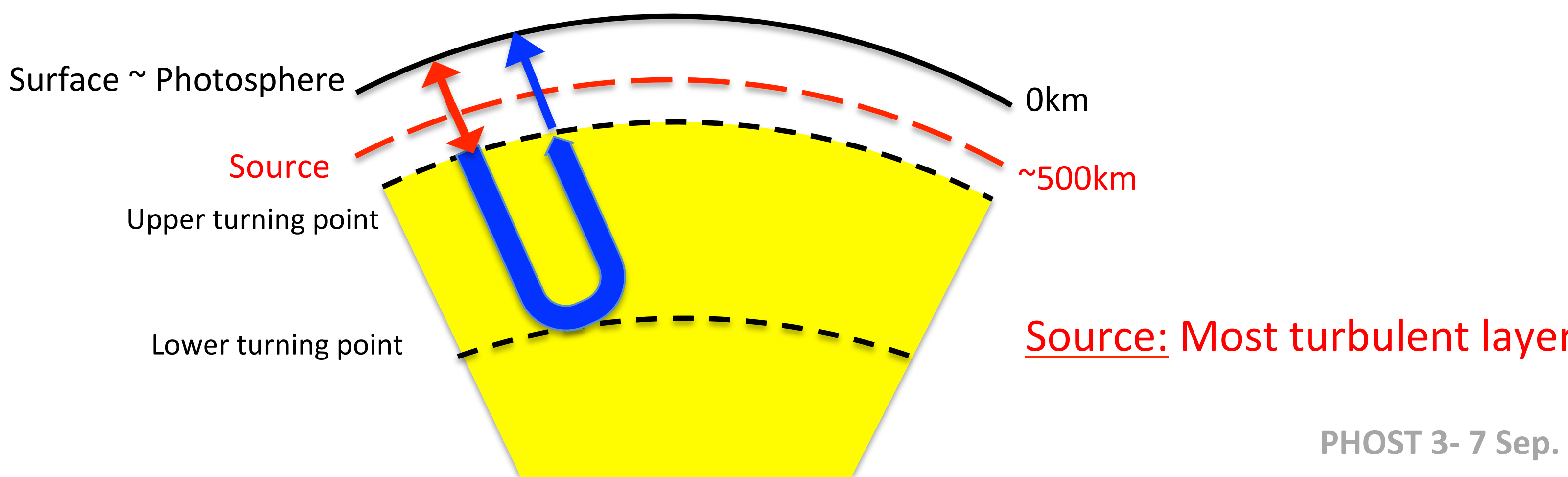
# Mode asymmetry for the Sun




<u>Duvall's interpretation for asymmetry:</u> Interference of inward with outward waves near the surface and with a source located outside the mode cavity

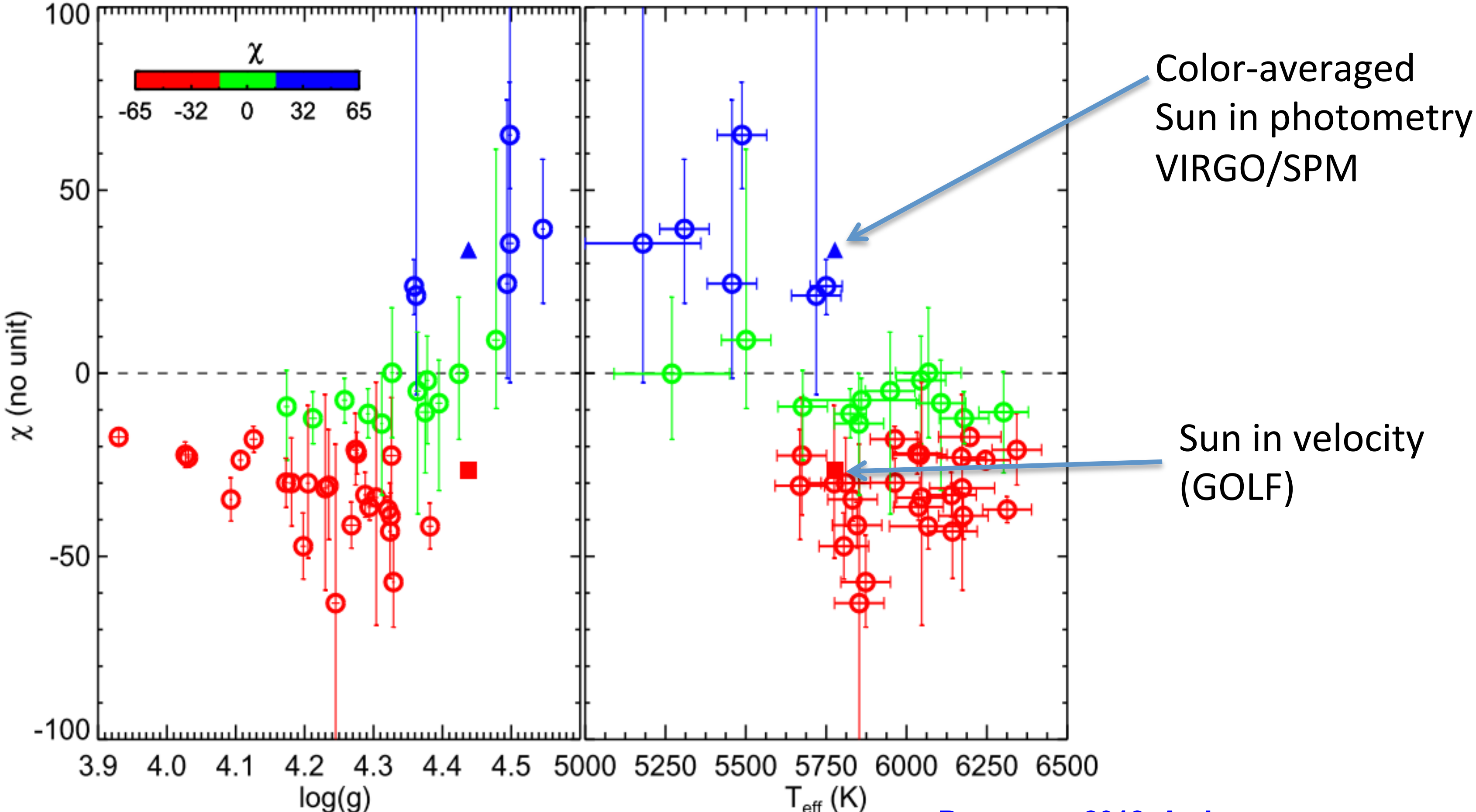
<u>Sign reversal:</u> Favoured hypothesis Noise−Waves correlation Roxburgh+1997, Nigam+1998



# Mode asymmetry for solar-like stars

Sample: 43 Legacy stars with clear *l*=0,2

log(g) / $T_{eff}$ from spectroscopy summarized in Creevey+2017 or Silva-Aguirre+2017

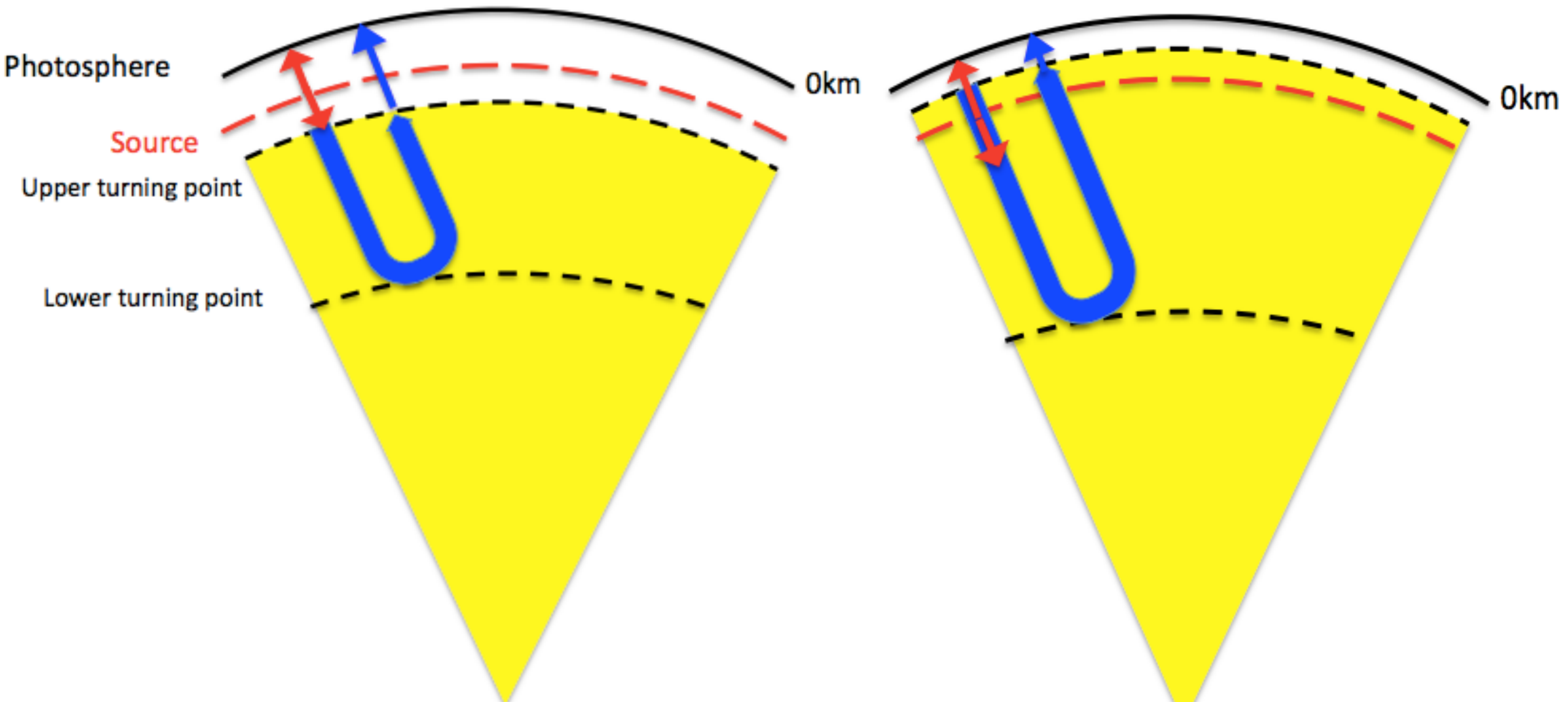



Benomar+ 2018, ApJ

# Mode asymmetry for solar-like stars

## Implications/Interpretation

Relative depth of the excitation source



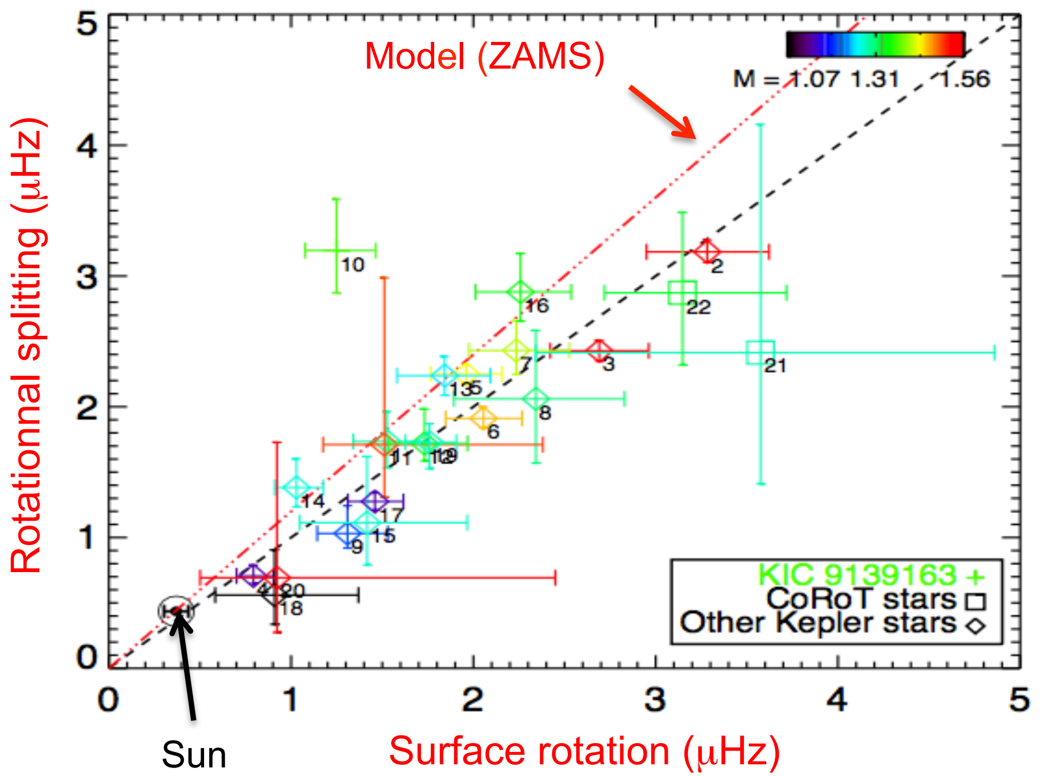

Cool stars (e.g. Sun):
- Source below photosphere
- Upper turning point below source

Hotter stars (e.g. F type stars):
- Source near or above the photosphere
- Upper turning point above source

Constraints on the dynamic of upper layers of solar-like stars

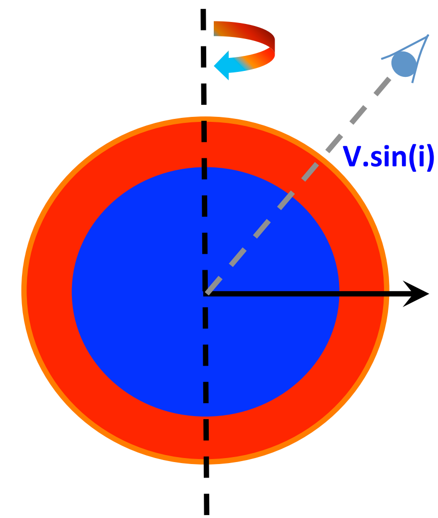
# Radial differential rotation in the MS

Benomar+ 2015, MNRAS




ZAMS model hypothesis:

- Total AM conserved (e.g. no mass loss)
- Local AM conserved in radiative zone
- Constant rotation in convective zone




→ Nearly uniform rotation

→ Consistent with Nielsen+2017

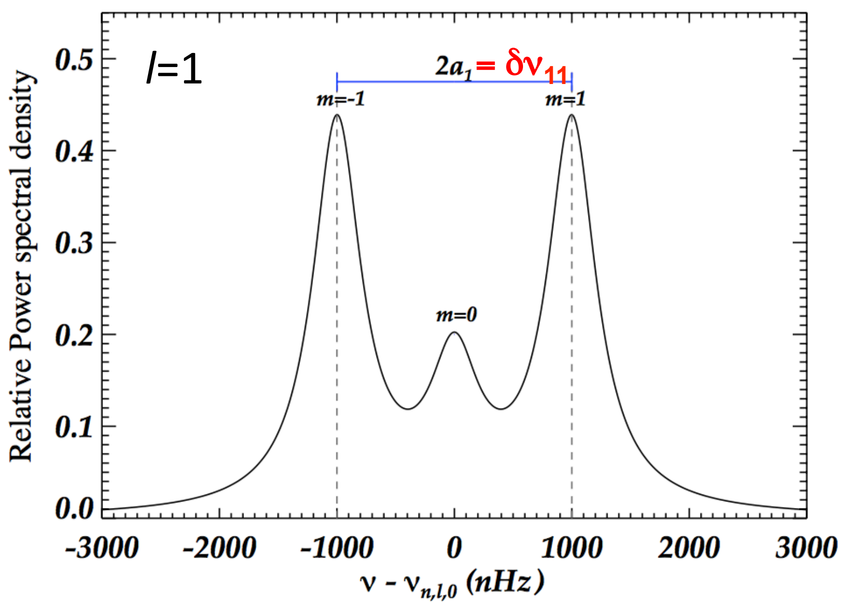
Angular momentum transport in main-sequence solar-like stars

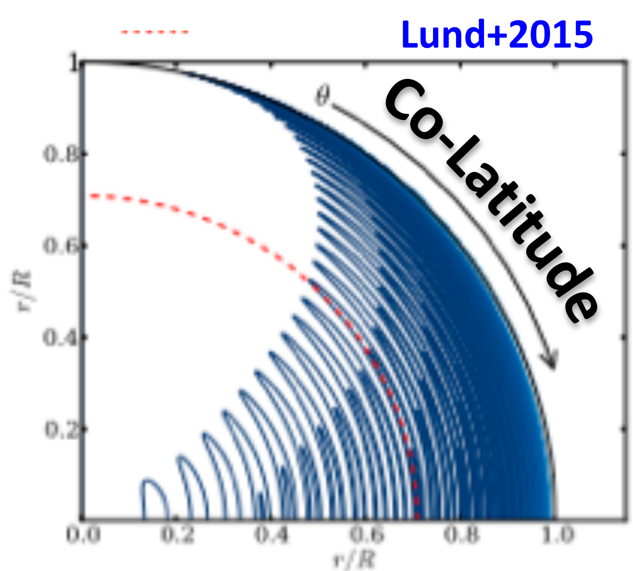
# Latitudinal differential rotation in the MS

**Benomar+ 2018, accepted to Science (Embargo until 21 September 2018)**

**a-coefficients:** Parametrisation of the frequency splittings such that they form an orthogonal basis (**Ritzwoller & Lavely, 1991**) with:

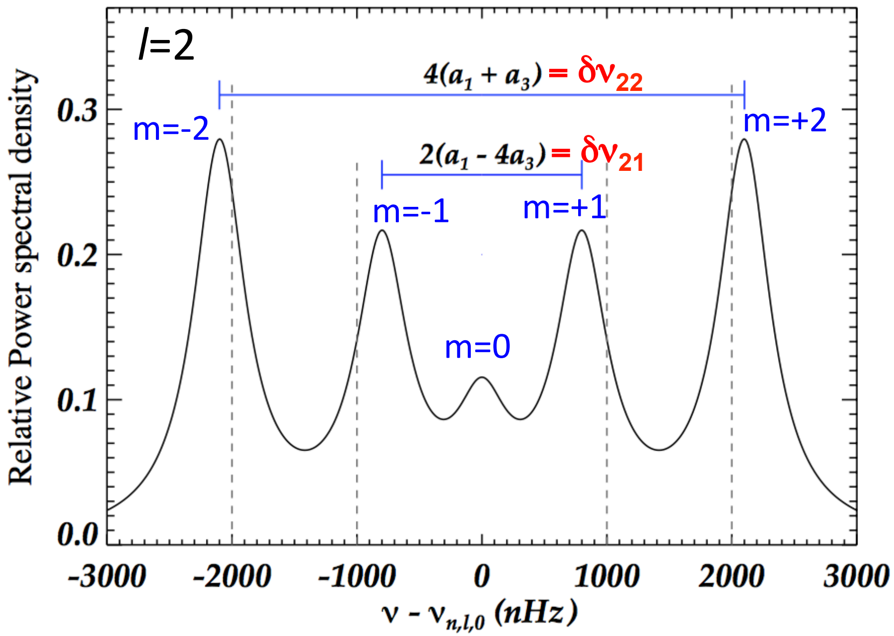
- Even coefficients: depend only on the shape of the star
- Odds coefficients: depend only on the rotation profile $\Omega(r,\theta)$



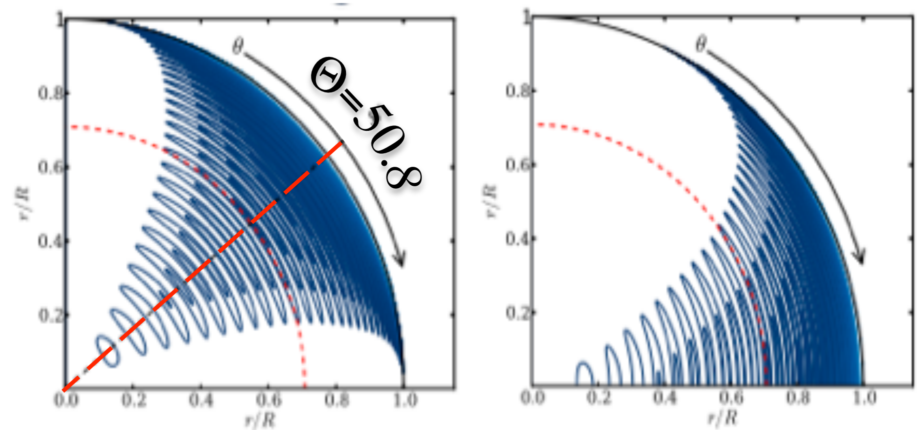




l=1, m=+/-1

# Latitudinal differential rotation in the MS




Lund+2015




*l*=2, m=+/-1

*l*=2, m=+/-2

<u>Properties of $a_3$:</u>

$a_3>0$: solar-like rotation
$a_3<0$: anti solar rotation

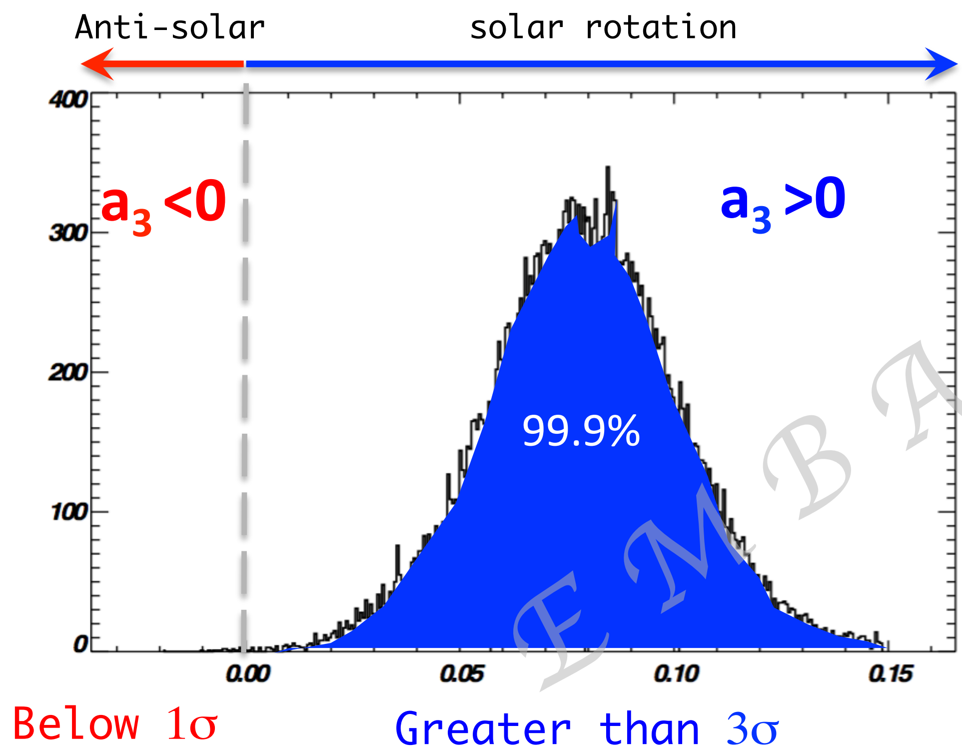
<u>For the Sun:</u>
$a_1$~ 400 nHz
$a_3$~ 5 nHz

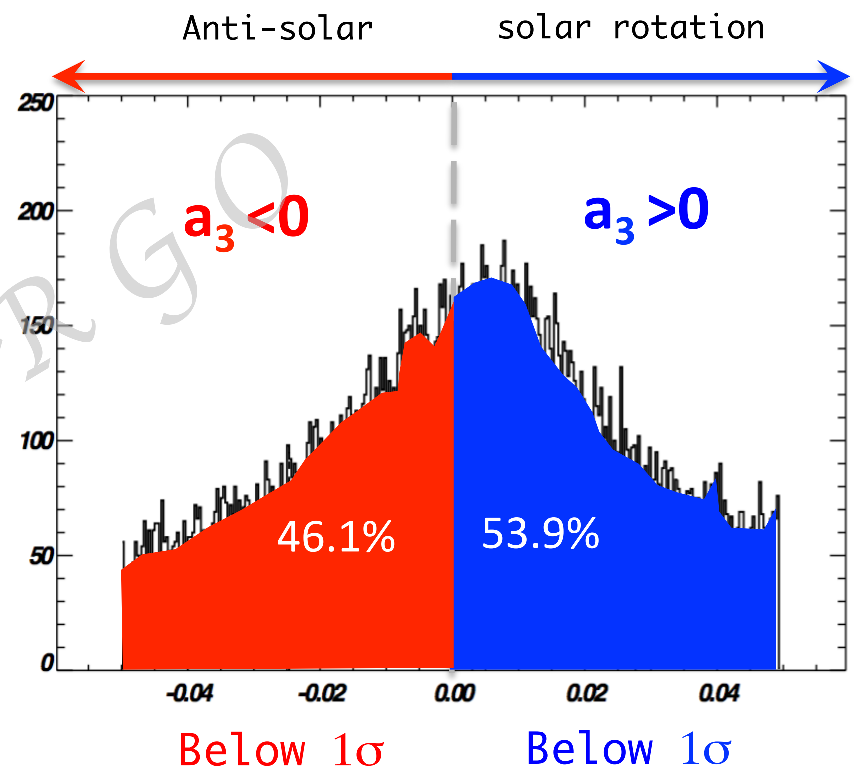
- ➔ Need year-long observations
- ➔ Need clear l=0, 1, 2 modes

Legacy sample excluding F stars

# Latitudinal differential rotation in the MS

## anti-solar vs. solar-like rotation



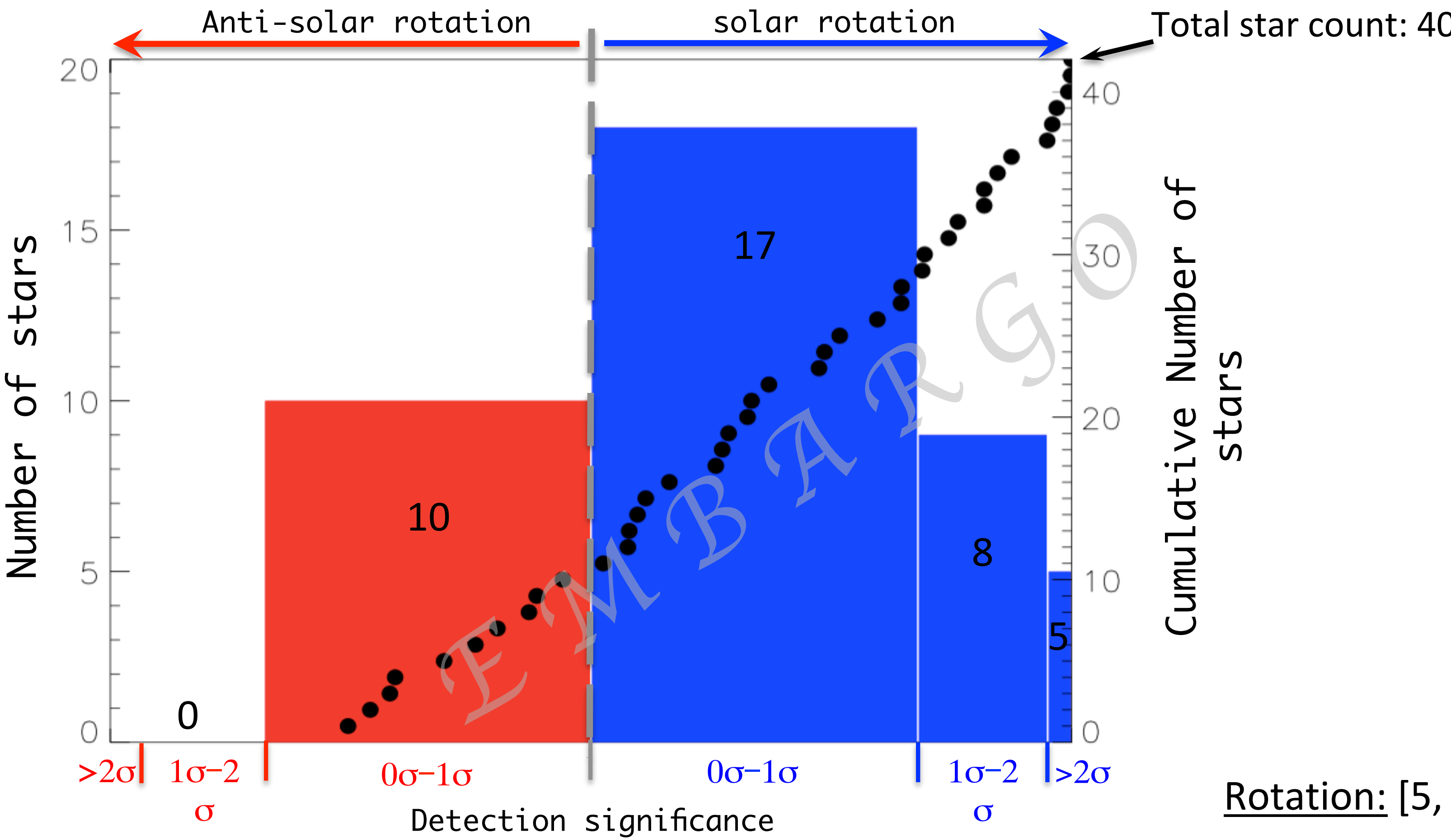




Detection of solar-like rotation
Significant at more than 3σ

No detection

# Latitudinal differential rotation in the MS

## anti-solar vs. solar-like rotation

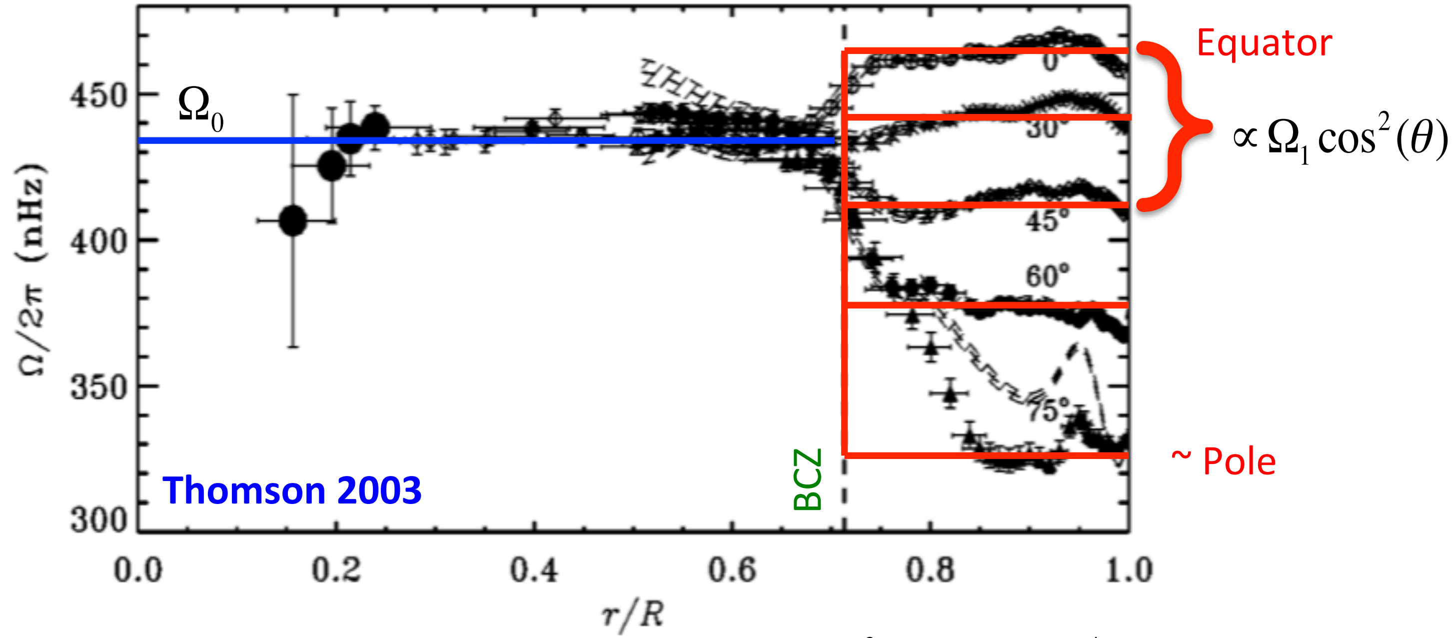



Rotation: [5, 50] days

Mass: [0.8, 1.3] $M_{sun}$

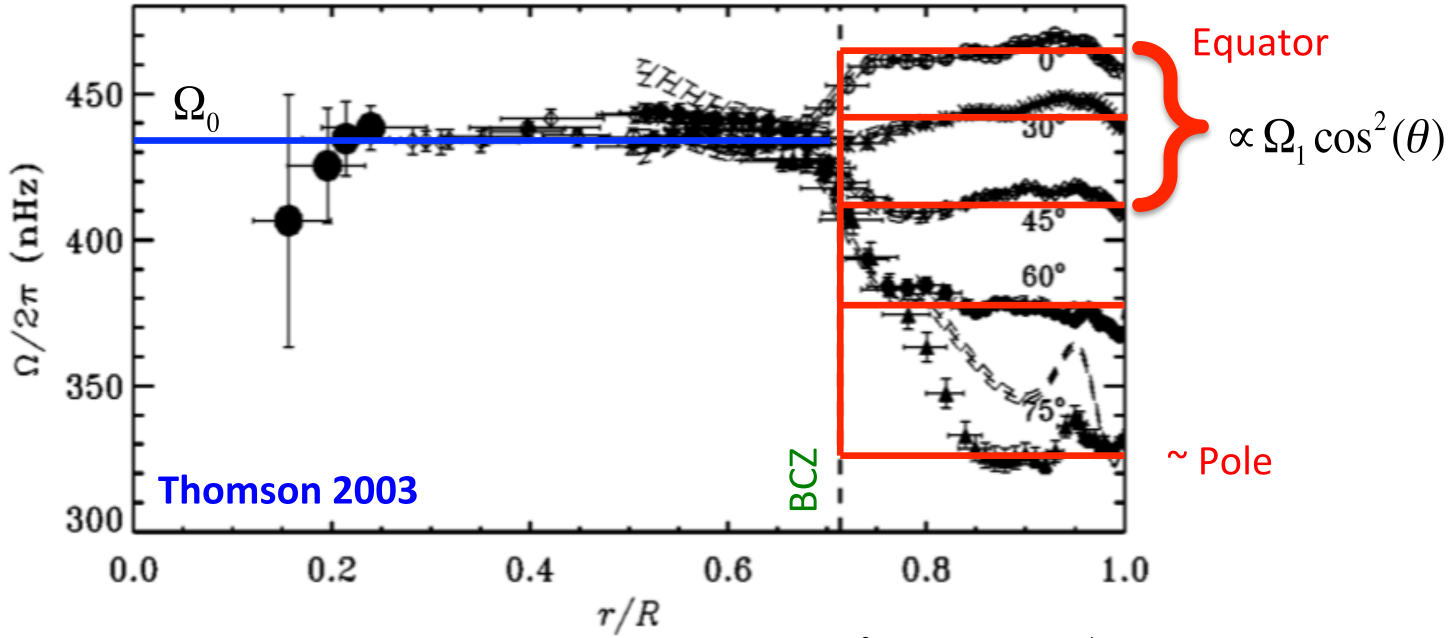
Radius: [0.8, 2.0] $R_{sun}$

# Inversion of the differential rotation profile




- Solar-like profile in the convective zone : $\propto \Omega_1 \cos^2(\theta) + \Omega_2 \cos^4(\theta)$
- Two observables ($a_1$, $a_3$) ➔ Two-zone model only :
  - Average rotation : $\Omega_0$
  - Convective zone: $\propto \Omega_1 \cos^2(\theta)$

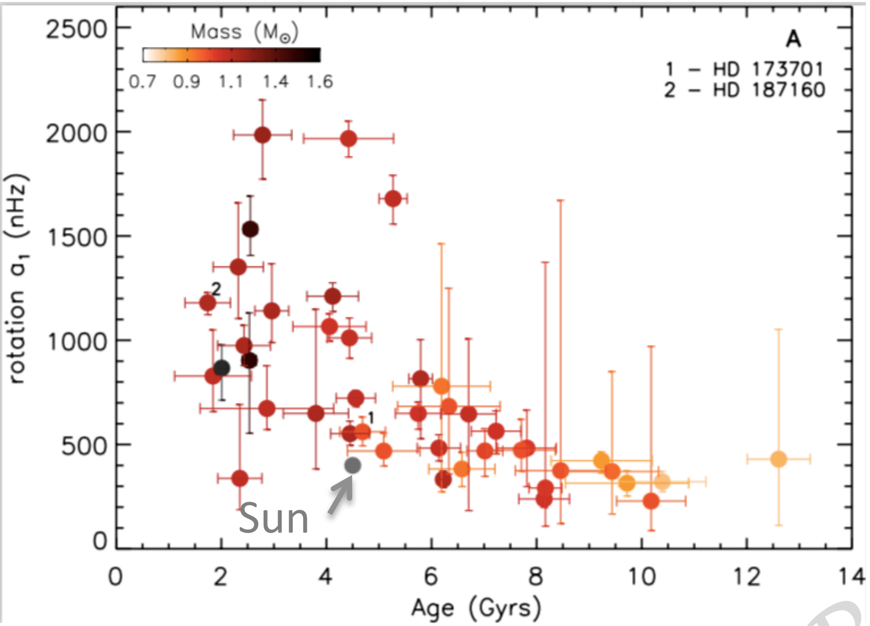
# Inversion of the differential rotation profile

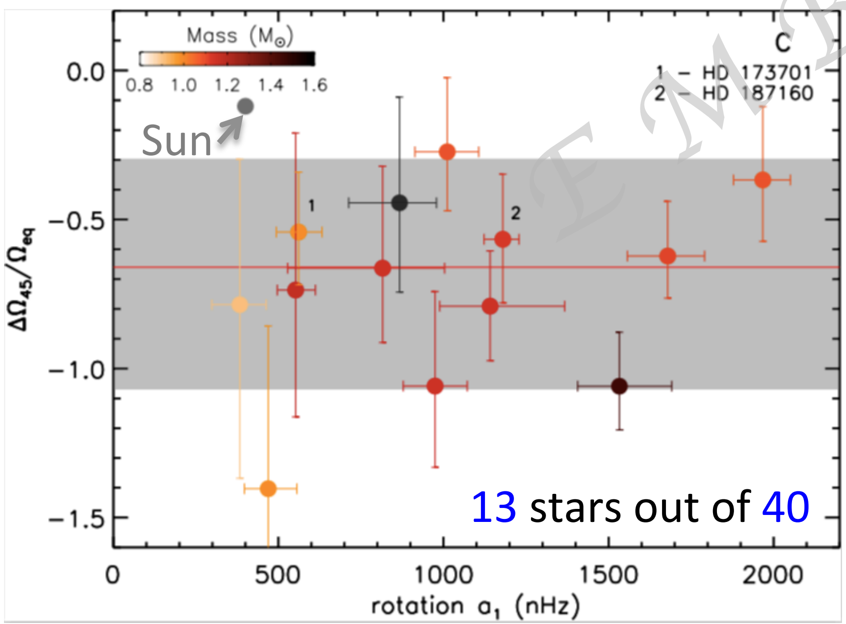



- Solar-like profile in the convective zone : $\propto \Omega_1 \cos^2(\theta) + \Omega_2 \cos^4(\theta)$
- Two observables ($a_1$, $a_3$) ➔ Two-zone model only : Gizon+2004
  - Average rotation : $\Omega_0$
  - Convective zone: $\propto \Omega_1 \cos^2(\theta)$
- Orthonormal basis implies one-to-one relations: $a_1 = \kappa_0 \Omega_0$ $a_3 = \kappa_1 \Omega_1$ (Integrals of Rotational Kernels)
- In the Sun this approximation is accurate for latitudes lower than 45 degrees

For Slow rotators, the latitudinal differential rotation can be reliably measured for latitude lower than 45 degrees…
(If the Sun is an accurate prototype of solar-like star)

# Inversion of the differential rotation profile




Ages: Silva Aguirre+2017

$a_1$ vs age: The well-established Age-rotation relation is evident

- Significant detections: strong latitudinal differential rotation: ~2 -5 times the Sun
- Others:
  - Weaker differential rotation
  - Too slow rotators to detect it
- Strong AM transport from pole to equator: Weak large scale magnetic field + strong small scale field?

*Thank you*

# Sensitivity to stellar interior rotation

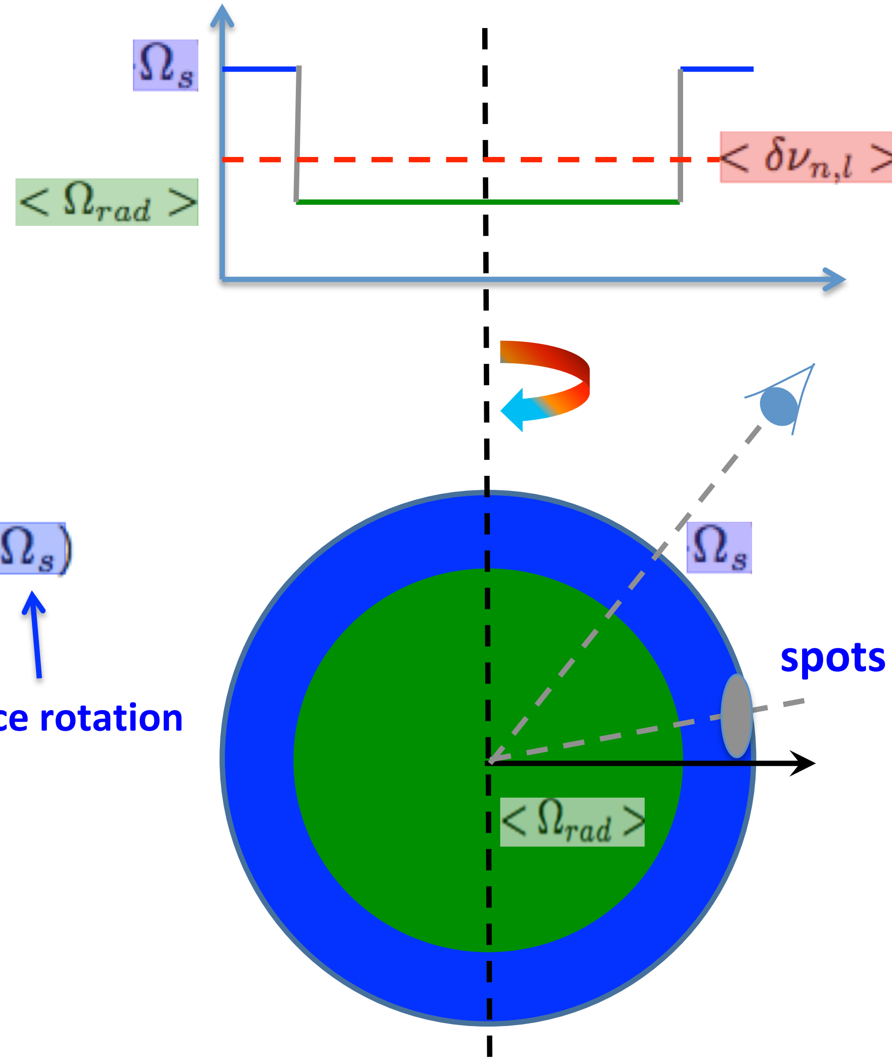
How to take advantage of the large sensitivity on the radiative zone?

**Comparing surface rotation with radiative zone rotation**

2 zone model:

$$I_{conv} + I_{rad} = 1,$$

$$\delta\nu_{n,l} \simeq I_{rad}\,\Omega_{rad} + I_{conv}\,\Omega_{conv}$$




Integral of Kernel in radiative zone

$$< \Omega_{rad} > = \Omega_s + < I_{rad}^{-1} > (< \delta\nu_{n,l} > - \Omega_s)$$

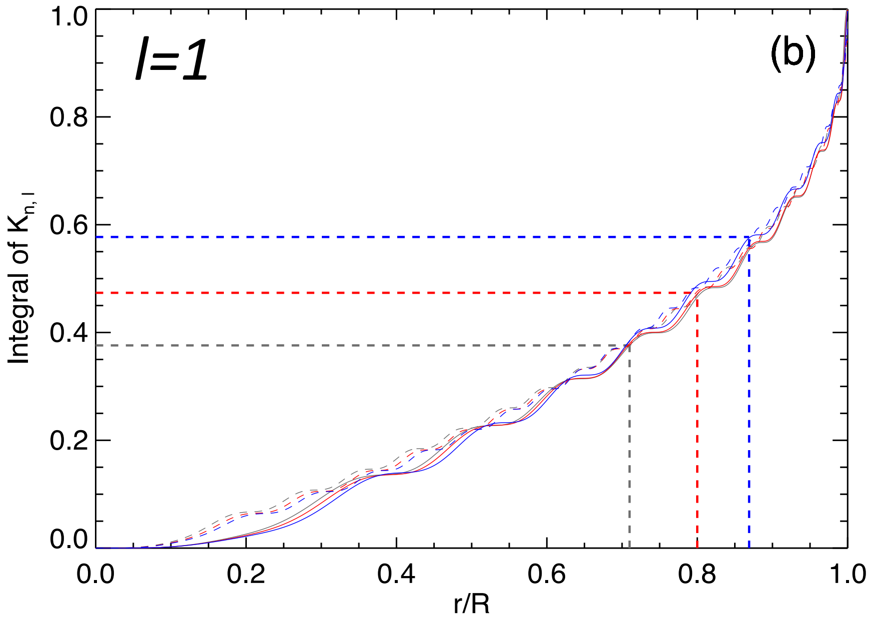
Average rotation in the radiative zone

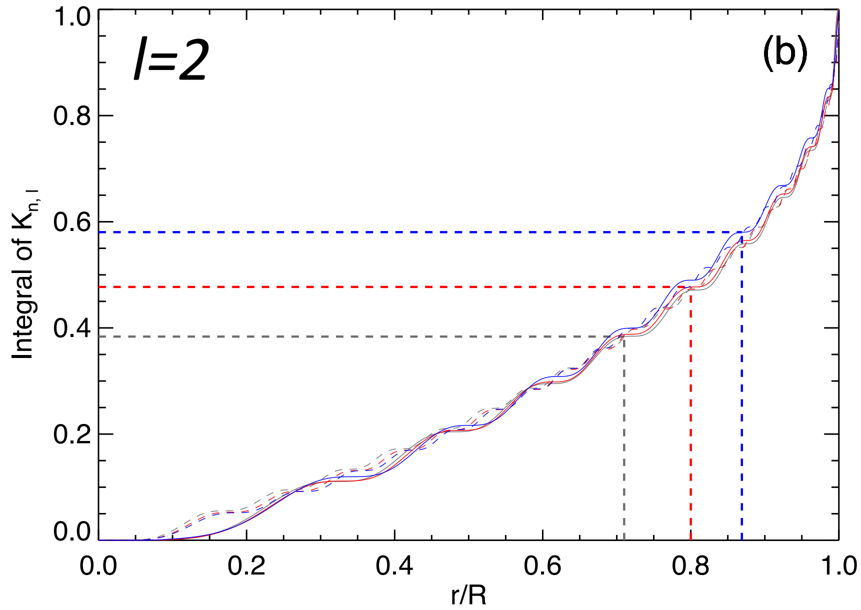
Average splitting

Surface rotation

**Surface rotation:** Measured either by using vsin(i) or surface spot

# Sensitivity to stellar interior rotation




**Rotational splitting :** weighted average of internal rotation

**Kernel integral (Sensitivity):** weight for a mode (n,l)

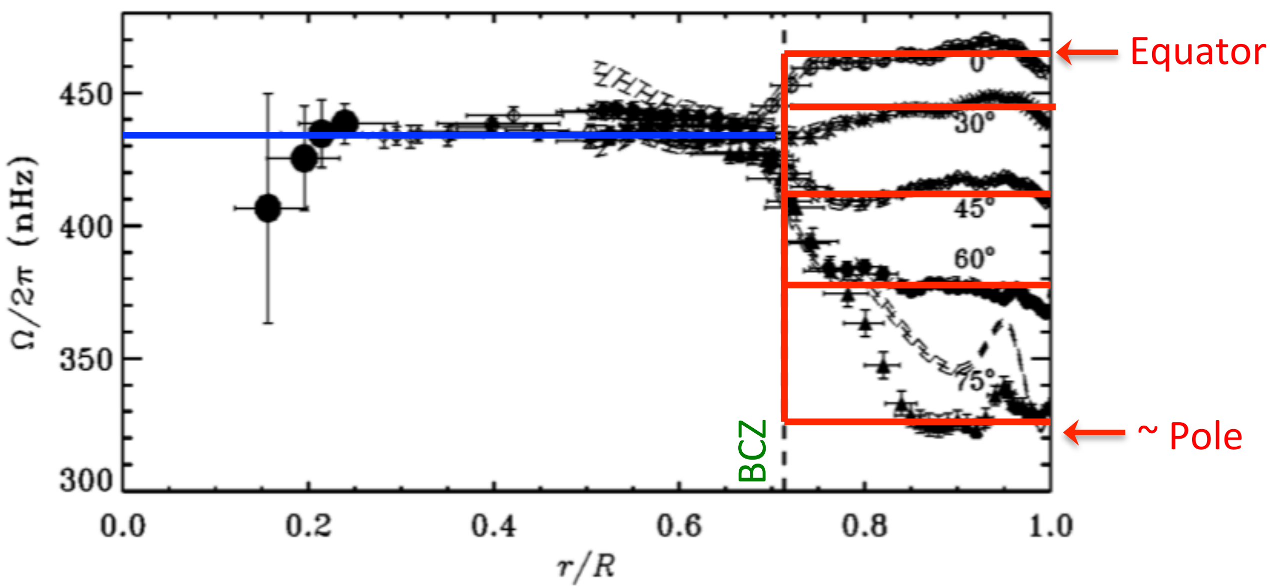
Mode penetrate deep enough to be sensitive to the radiative zone

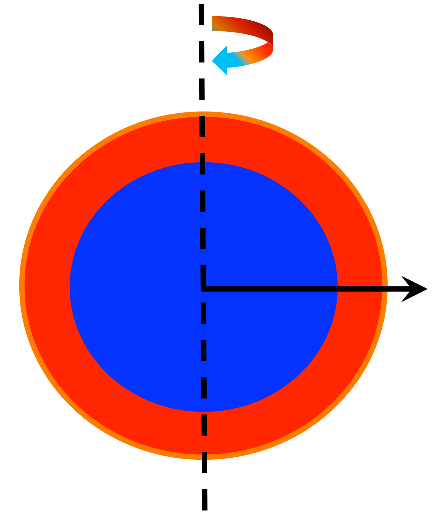
~ 50% of the rotational splitting value is due to the rotation within the radiative zone

Thin convective zone ➔ Greater sensitivity to radiative zone

If differential rotation between radiative/convective zone ➔ Splitting must be different than surface rotation

# Inversion of the latitudinal differential rotation



$$\Omega(r,\theta) = \Omega_0(r)\psi_0(\theta) + \Omega_1(r)\psi_1(\theta)$$

$$\psi_0(\theta) = 1,$$

$$\psi_1(\theta) = \frac{3}{2}(5\cos^2\theta - 1)$$

$$2\pi\, a_1 = \tilde{\Omega}_0 \int_0^{\pi} \int_0^{R_\star} K_{2,2}(r,\theta) r dr d\theta$$

$$2\pi\, a_3 = \frac{\tilde{\Omega}_1}{5} \int_0^{\pi} \int_{r_c}^{R_\star} (K_{2,2}(r,\theta) - K_{2,1}(r,\theta))\psi_1(\theta) r dr d\theta$$

# Modes of different l,m probe different region of the star (radialy and latitudinally)

Lund+2015, ApJ

Jeorgen Christensen-Dalsgaard Lecture Notes

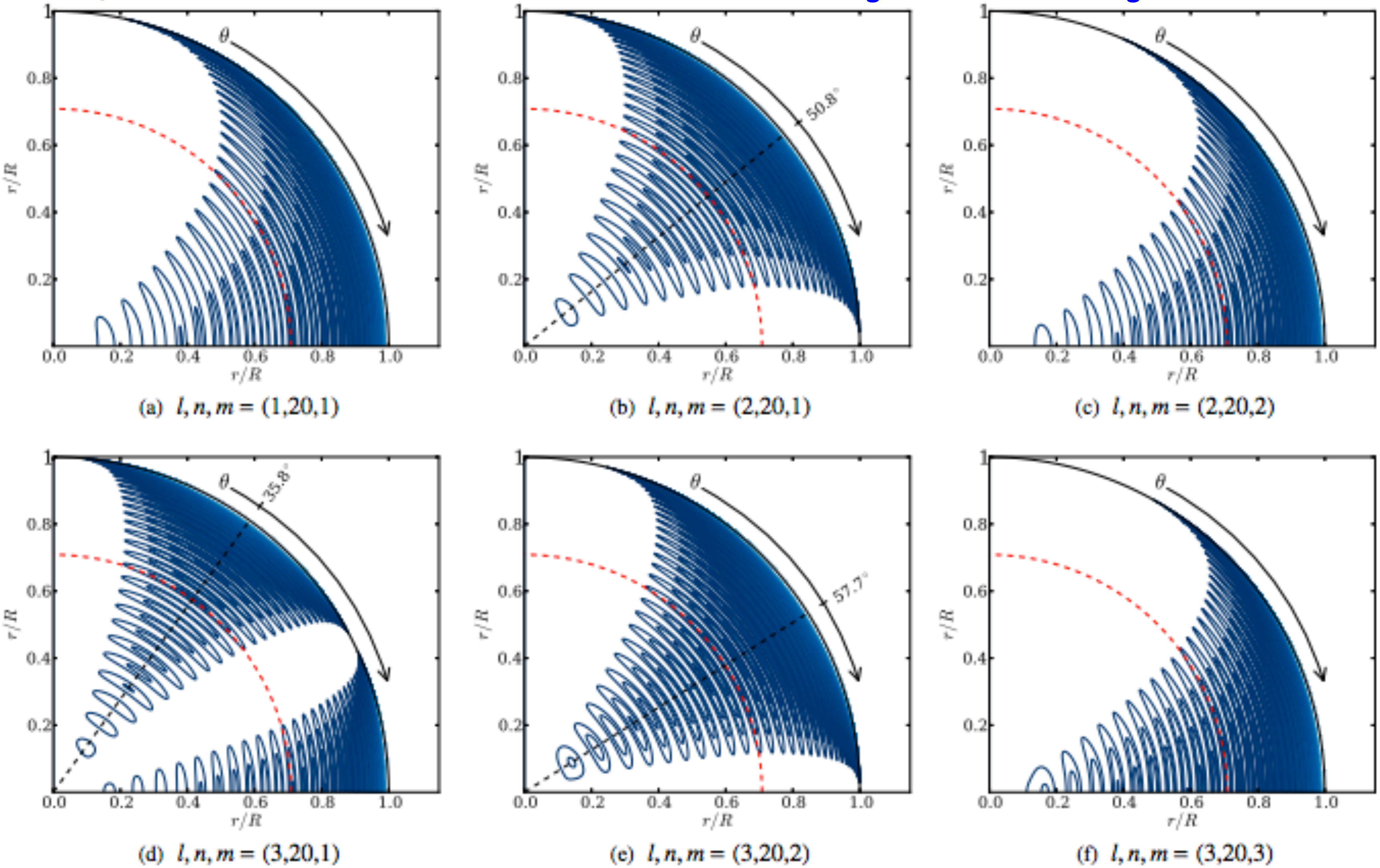



**Figure 1.** Contour plots of the rotation kernels for modes of degree $l = 1, 2, 3$, all with radial order $n = 20$. Only one quadrant of the star is shown and in units of the stellar radius. The displayed kernel may by mirrored in both axes. The dashed red circle indicates the base of the convection zone, $r_{bcz}$, for the model considered. For kernels where the maximum in latitude is different from the equator ($\theta = 90°$), a dashed line indicates the co-latitude of kernel maximum.

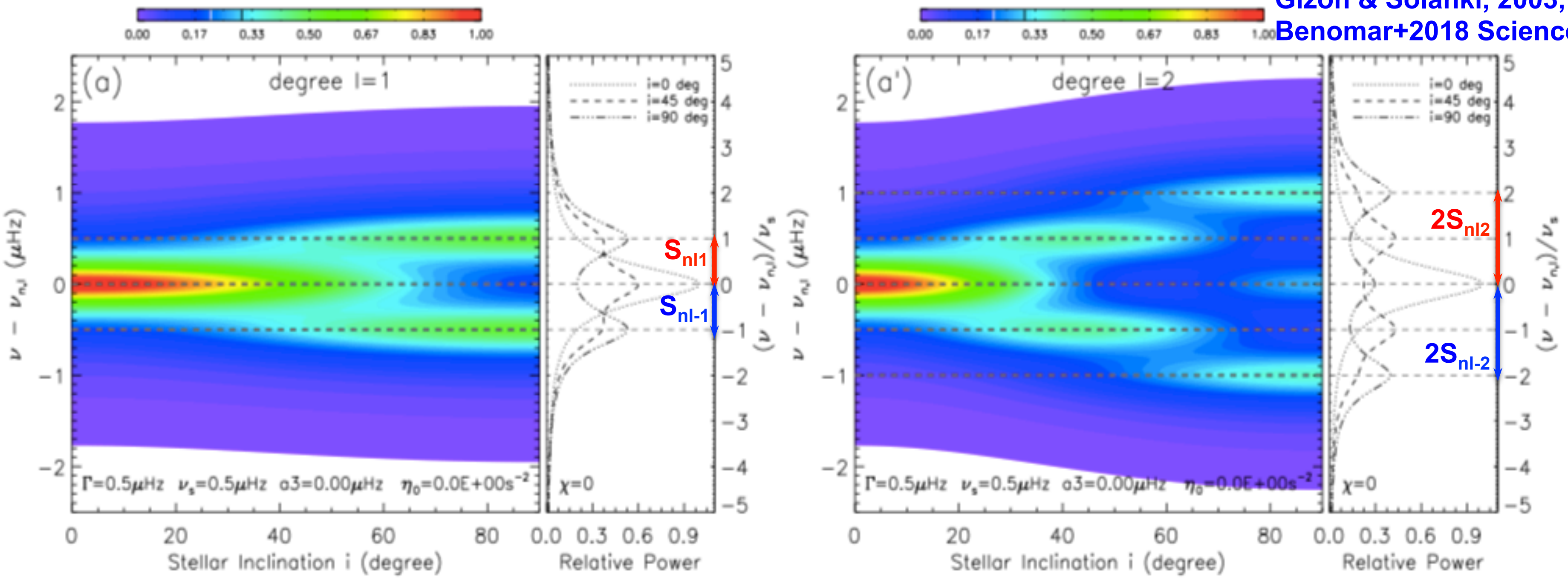
(A color version of this figure is available in the online journal.)

# Rotation: Main sequence solar-like stars

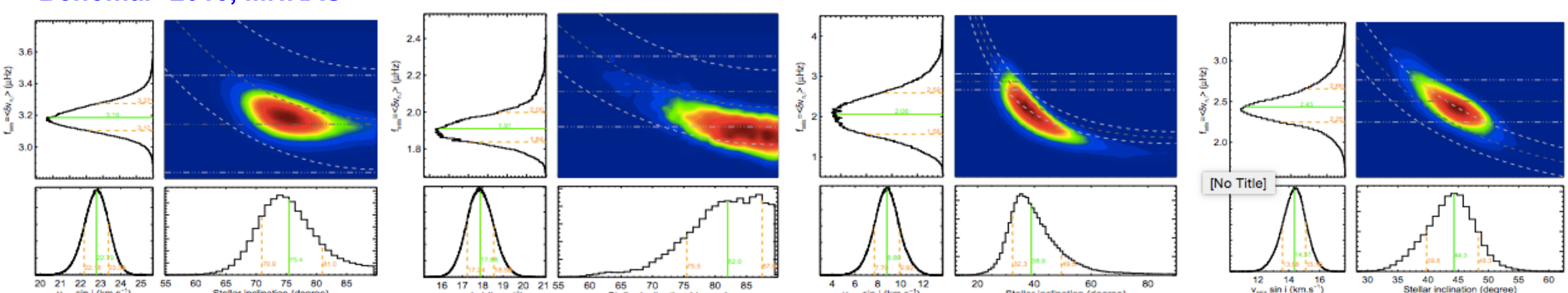
In case of a solid-body rotation of a sphere: $S_{nlm} = S_{nl-m} = \delta\nu_s$

$\delta\nu_s$ is the average rotation rate of the star

**Gizon & Solanki, 2003, ApJ**
**Benomar+2018 Science**




**Benomar+2015, MNRAS**




(2) KIC 2837475 (6) KIC 6679371 (8) KIC 7206837 (7) KIC 7103006

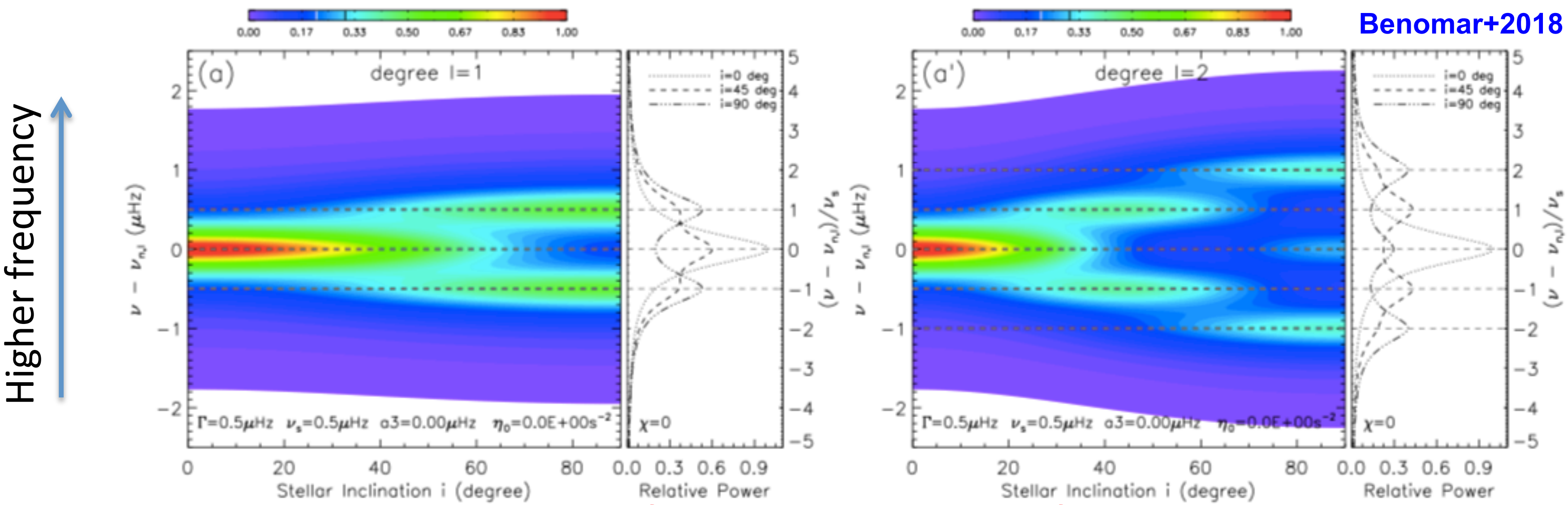
# Rotation: Asphericity and latitudinal rotation effects

**Schou+ 1994, ApJ**

In case of a solid-body rotation of a sphere: $S_{nlm} = S_{nl-m} = \delta\nu_s$

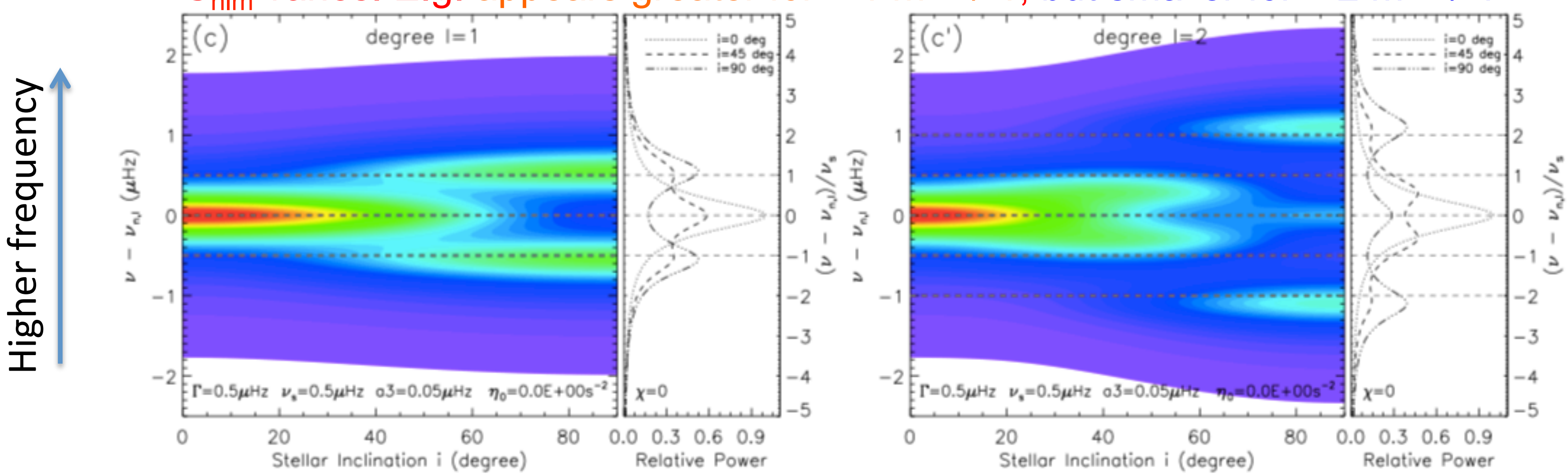
$\delta\nu_s$ is the average rotation rate of the star

**Benomar+2018 Science**




In case of a latitudinal rotation of a sphere

$S_{nlm}$ varies. E.g. appears greater for l=1 m=+/-1, but smaller for l=2 m=+/-1



# Rotation: Asphericity and latitudinal rotation effects

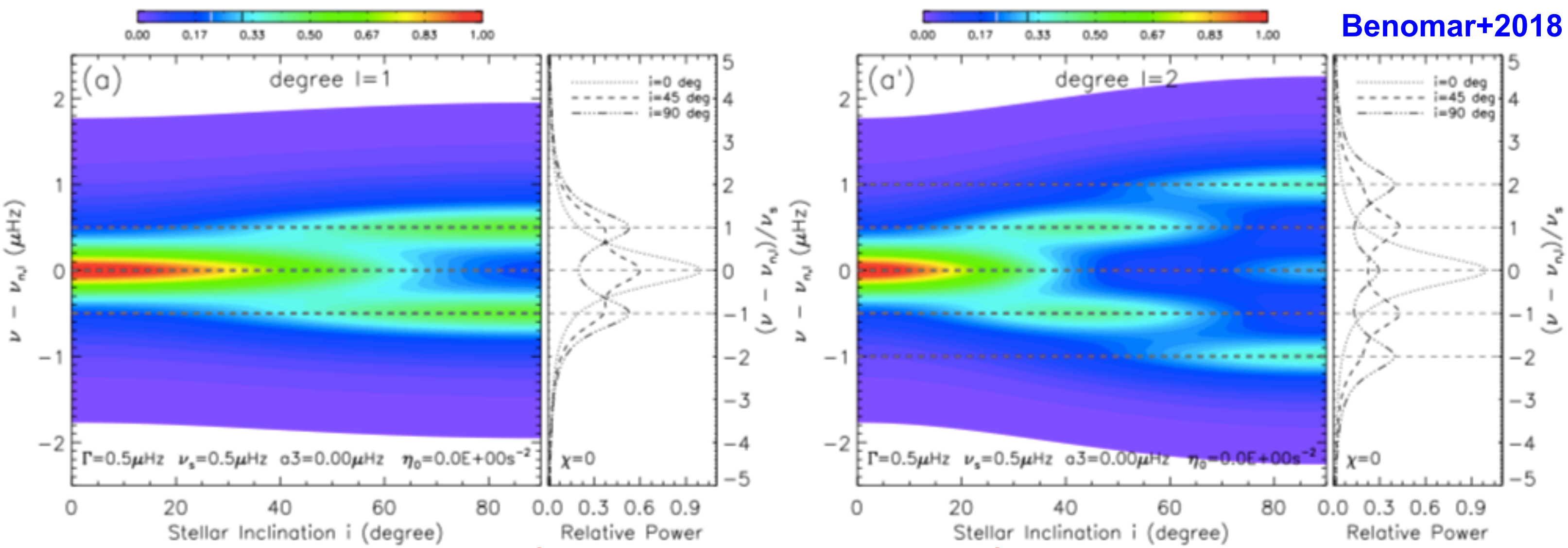
**Schou+ 1994, ApJ**

In case of a solid-body rotation of a sphere: $S_{nlm} = S_{nl-m} = \delta\nu_s$

$\delta\nu_s$ is the average rotation rate of the star

**Benomar+2018 Science**

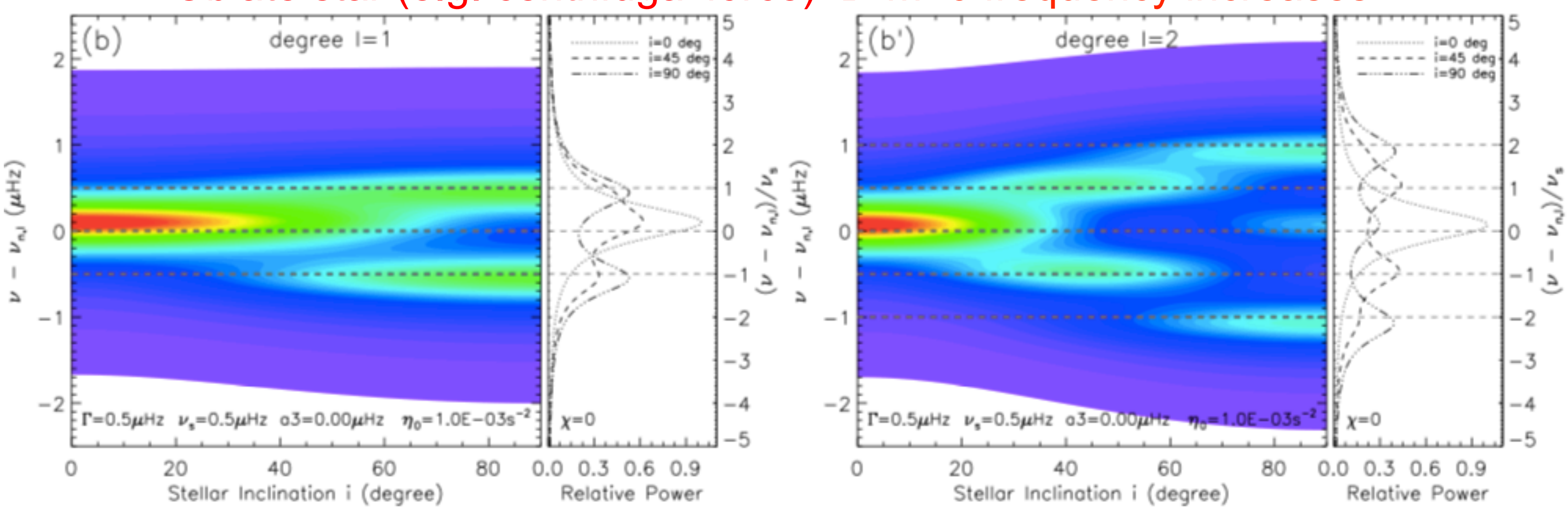
Higher frequency




In case of a solid-body rotation of a spheroid

Oblate star (e.g. centrifugal force) ➔ m=0 frequency increases

Higher frequency



# Rotation: Evolved solar-like stars

**Rotation in evolved stars: Subgiants and (low-mass) early red giants**

Observed splitting

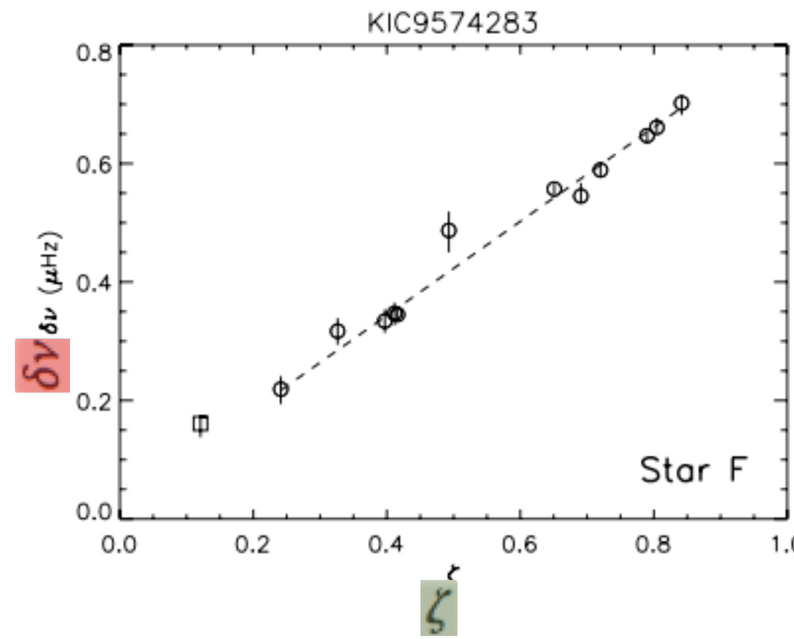
Core (g-cavity)

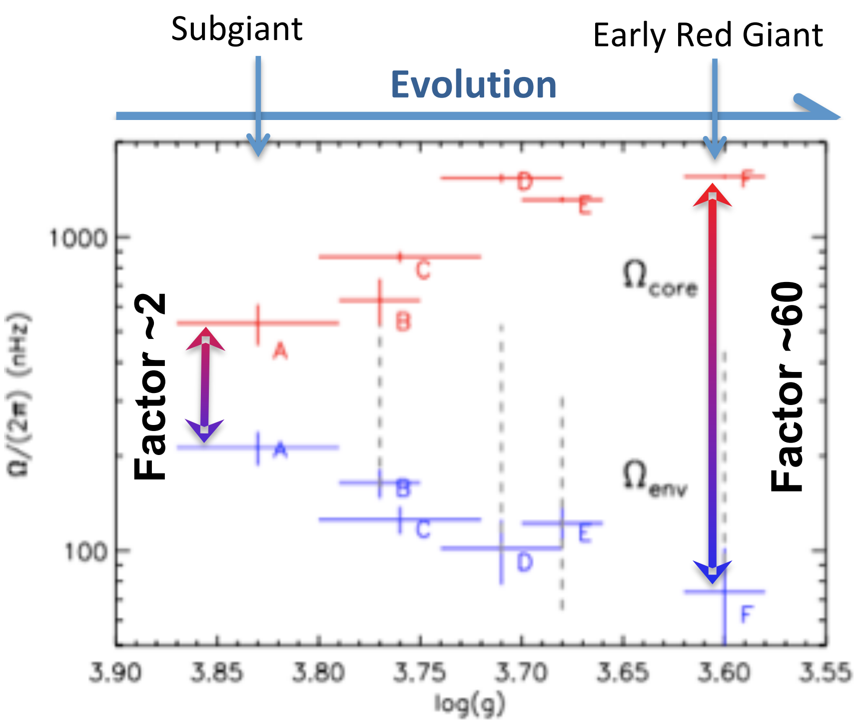
Outer layers (p-cavity)

$$\delta\nu = \zeta\left(\frac{1}{2}\left\langle\frac{\Omega_g}{2\pi}\right\rangle - \left\langle\frac{\Omega_p}{2\pi}\right\rangle\right) + \left\langle\frac{\Omega_p}{2\pi}\right\rangle$$

Kinetic energy in the core/Total kinetic energy (from model or theory)

**Goupil+ 2013, A&A**



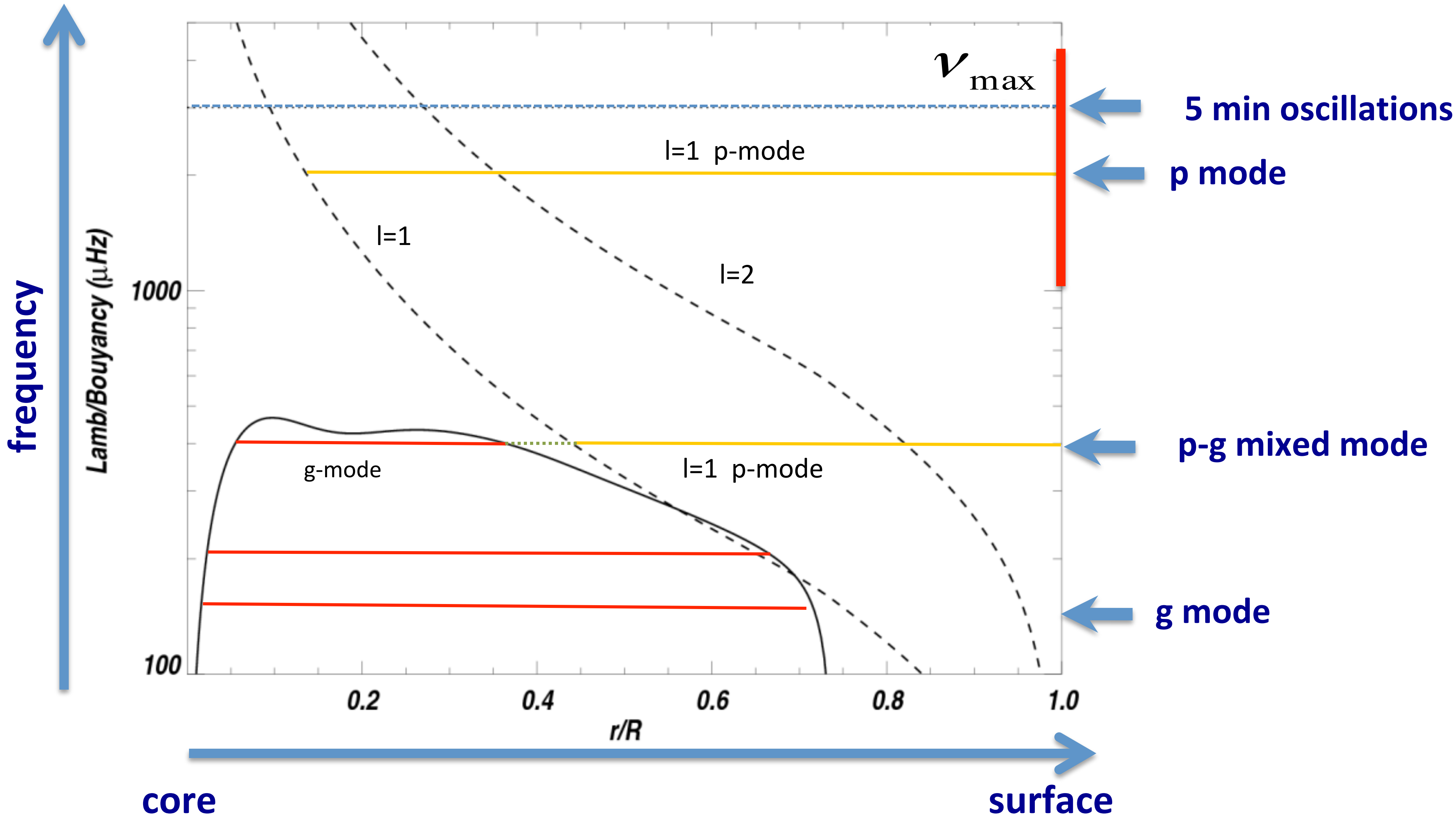




<u>During the subgiant/early red giant phase:</u>

- ✧ Spin-up of the core (core contraction)
- ✧ Spin-down of the envelope (envelope expansion)

**Deheuvels+ 2014, A&A**

# Propagation diagram of the Sun

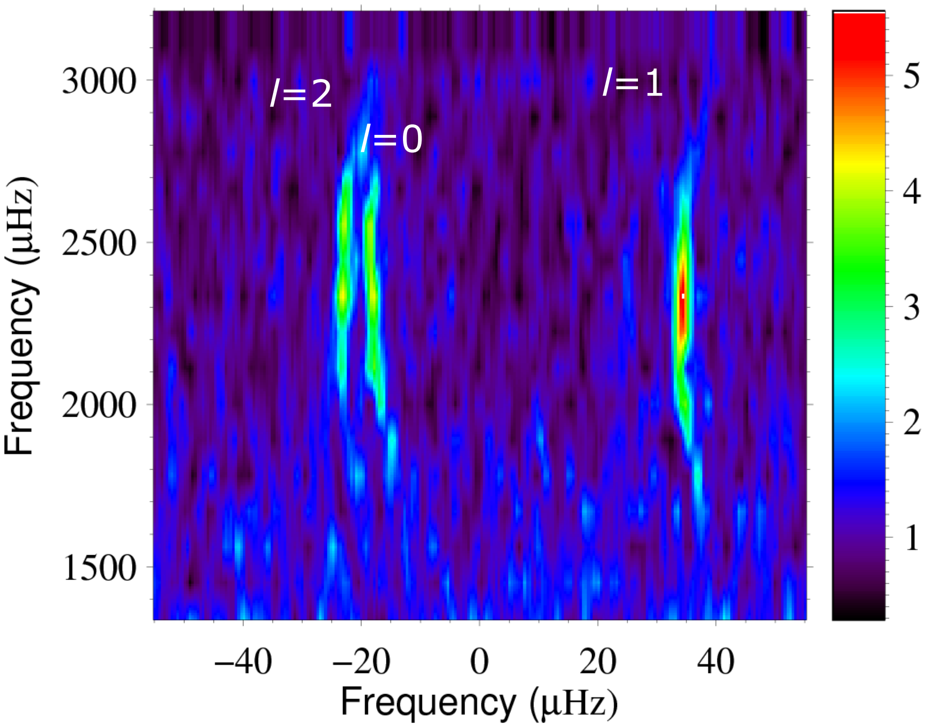



<u>Lamb frequency:</u> delimits the p modes cavities

<u>Brunt Vaisala frequency:</u> delimits the g modes cavity

# Space-based seismology reveals details on core structure

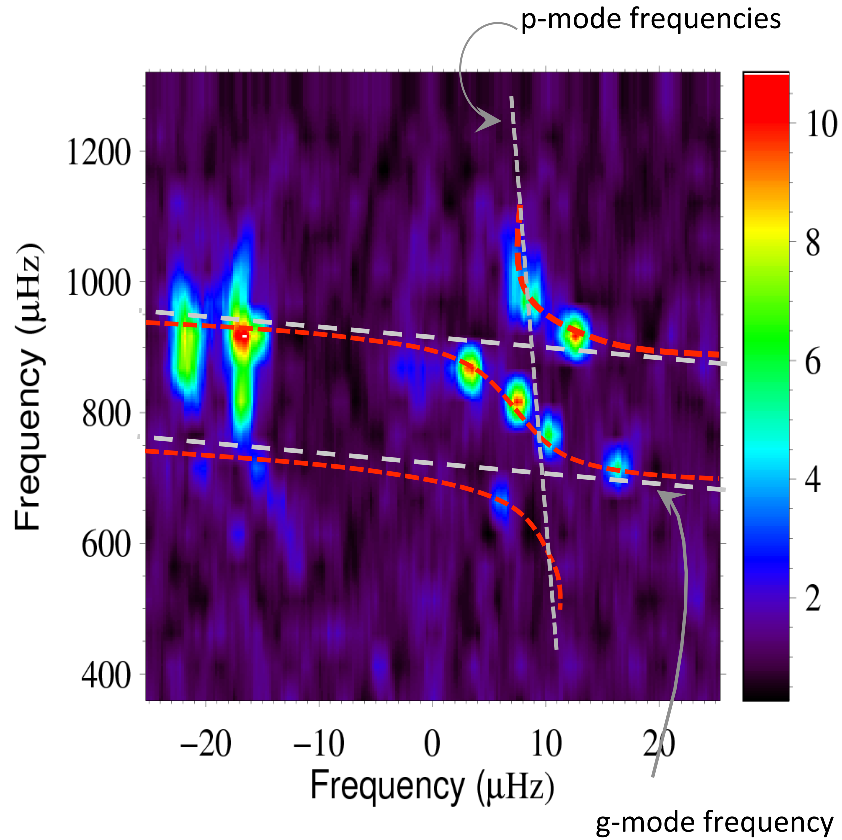
## Saxo (KIC 6603624)




*l*=0 & 2: Equally spaced by ~Δν

*l*=1: Equally spaced by ~Δν

## Gemma (KIC 11026764)

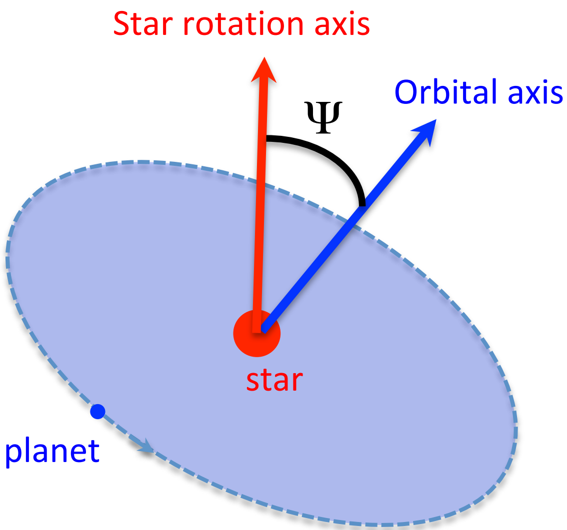



*l*=0 & 2: Equally spaced by ~Δν

*l*=1: Not equally spaced

*l*=1 (and *l*=2) are mixed modes

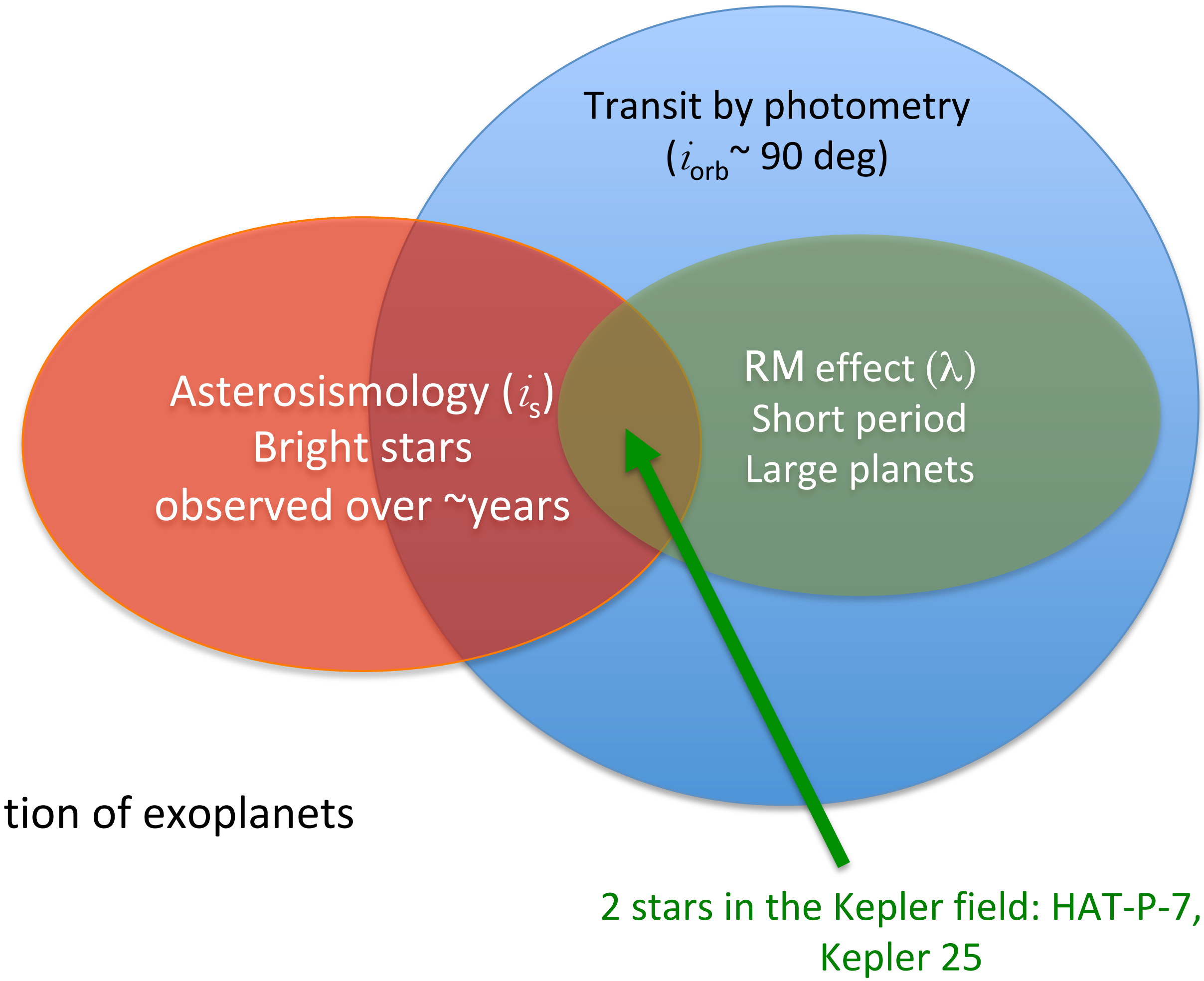
# Measure of the spin-orbit angle




$\Psi(\lambda, i_{orb}, i_s)$: spin-orbit angle

Indicator of formation and evolution of exoplanets

$\Psi_{SUN}$ = 7 deg.




- 3D spin-orbit angle is difficult to measure
- Use instead other indicators

Benomar+2014, Campante+2016:

Kepler-25: possibly aligned

HAT-P-7: Confirmed misalignement