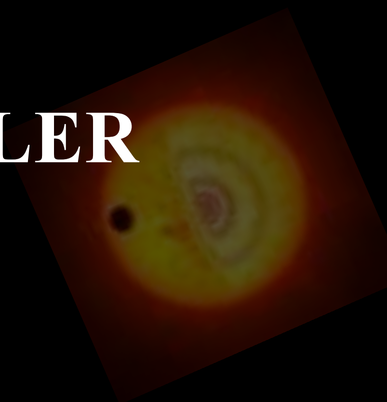
STELLAR ROTATION, ACTIVITY, AND DYNAMOS

RESULTS FROM COROT AND KEPLER



Rafael A. García

Service d'Astrophysique, CEA-Saclay, France

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GENERAL OUTLINE

- I- Introduction
  - What can High precision photometry offer to the study of stellar dynamics?
- II- Stellar Dynamics
  - Rotation
  - Stellar variability
- III- Surface magnetic activity proxy
  - Definition photospheric magnetic proxy: Sph
    - Based on reliable surface rotation rates
    - Surface magnetic activity of solar analogs
- IV- Stellar magnetic cycles
  - F-stars: Fast rotating, shorter cycles
  - Using seismology

I-Introduction

I-INTRODUCTION

- What can offer high-precision photometry (HPP) to better understand stellar dynamics, magnetism & dynamos ?
  - HPP observations can potentially give access to:
    - Surface (differential?) rotation of hundred to thousand stars [e.g. McQuillan et al. 2013, 2014; Nielsen et al. 2013; Reinhold & Reiners 2013, 2015; García et al. 2014]
    - Internal (differential?) rotation through seismology [e.g. Beck et al. 2012; Deheuvels et al. 2012,2014; Mosser et al. 2012 Deheuvels et al. sub., Benomar et al. sub. Pia di Mauro et al. sub. Nielsen et al. 2014 & Poster]
  - Convection properties
    - Characteristic time scale of convection (granulation) [e.g. Mathur et al. 2011; Kallinger et al. 2014]
      - other scales:
        - e.g. Faculae in active stars [e.g. Karoff et al. 2013]
  - Internal structure (through seismology)
    - Size of the convective envelope (through seismology (+ modelling)) [e.g. Mathur et al. 2012; Mazumdar et al. 2014; Metcalfe et al. 2014,…]
    - Constraining deep internal magnetic fields & convective core dynamos [Fuller et al. sub.; Stello et al sub.]
  - Activity cycles & surface magnetism
    - Through the analysis of long time series (activity proxies) [e.g. García et al. 2010; Mathur et al. 2013, 2014]
      - Or asteroseismology [e.g. García et al. 2010; Régulo et al. submitted]

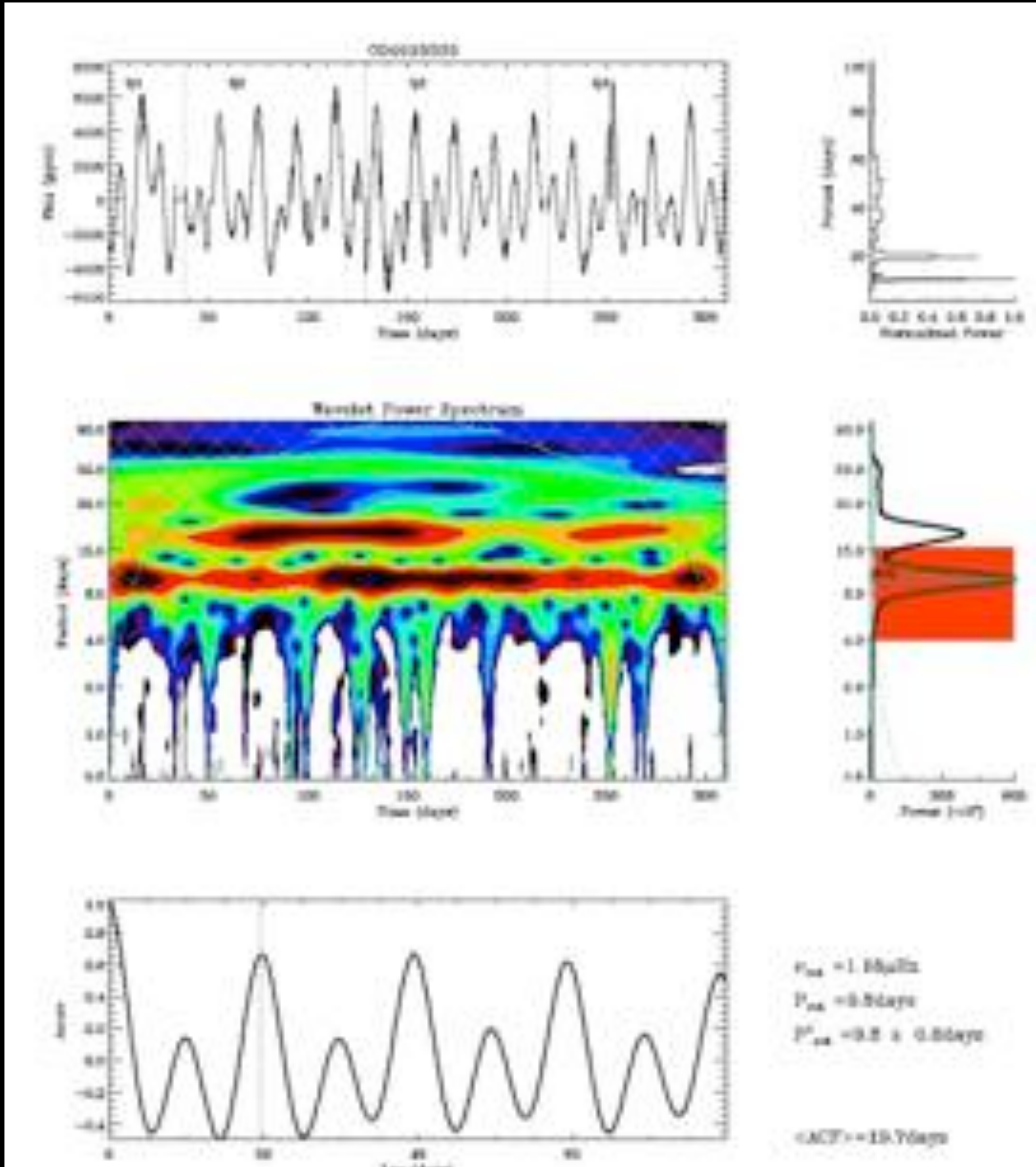
IIa-Stellar Dynamics:

Rotation

II-SURFACE ROTATION

- Techniques based on the analysis of the low-frequency part of the Periodogram
- Periodogram analysis:
  - Possible problem
    - 2nd > 1st harmonic
    - Check half of P_{rot}
- Autocorrelation
  - Powerful for capturing the correct P_{rot}
    - When there are two well defined
      - active longitudes
- Time frequency analysis
  - Flag instrumental problems
- Spot modelling
  - Robust estimation of:
    - Average rotation
    - Spot lifetime
  - More uncertain estimation of:
    - Size and distribution of spots
    - Inclination of the star
    - Differential rotation
  - Extremely slow

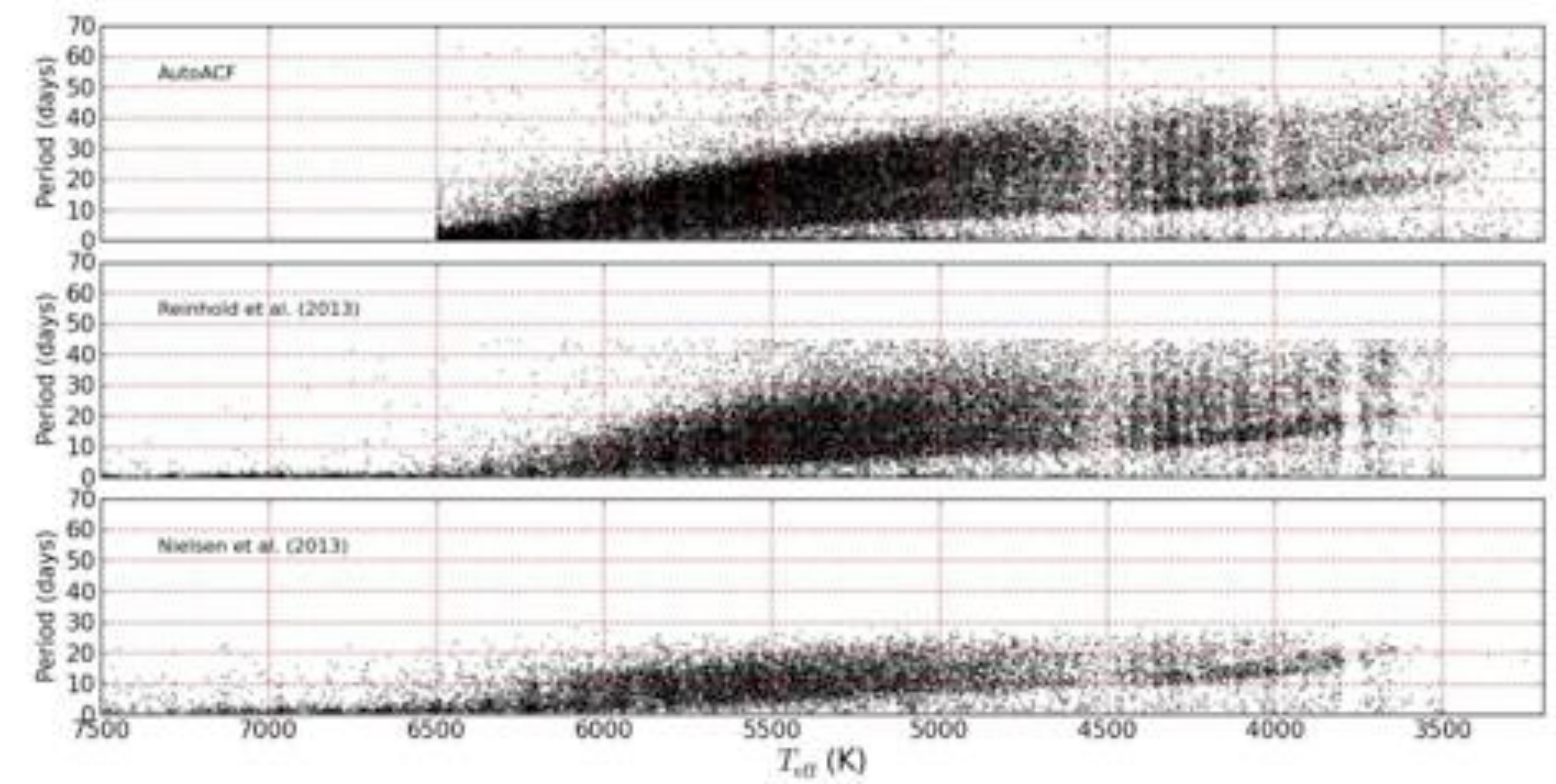
[e.g. Mosser et al. 2009; Frohlich et al. 2012; Lanza et al.2014, Bonano et al. 2015]



[KIC4918333 from McQuillan et al. 2013]

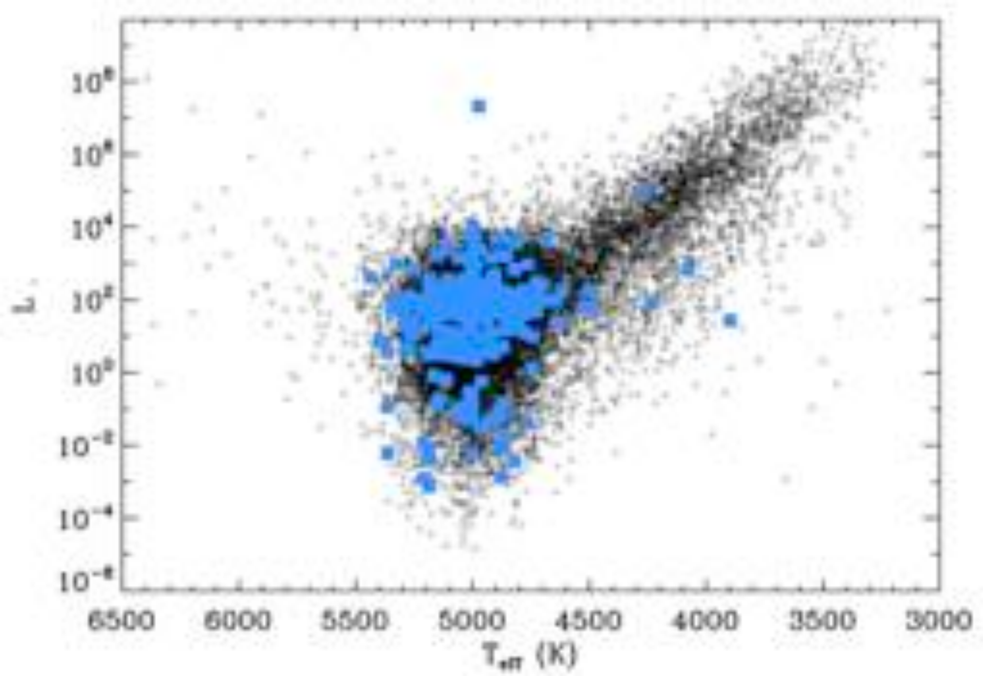
II-SURFACE ROTATION

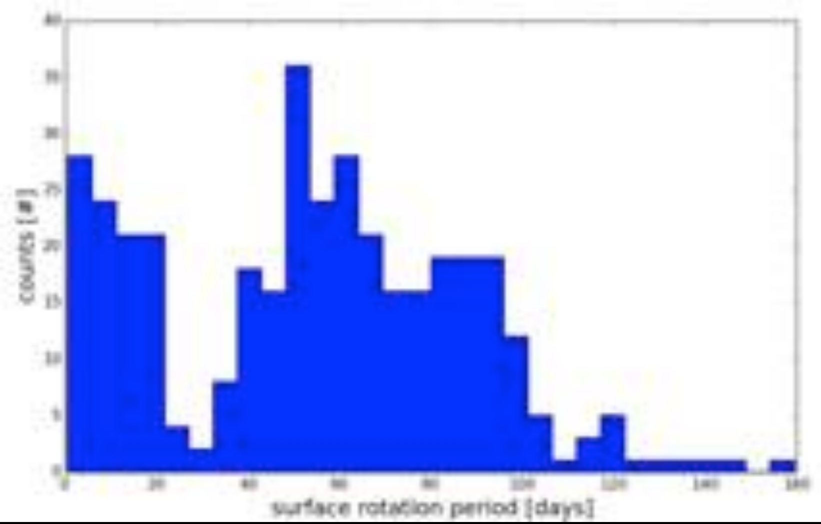
	AutoACF	Reinhold et al. (2013)	Nielsen et al. (2013)
Total Number	34,030	24,124	12,515
AND AutoACF	–	20,009	10,381
AND Reinhold et al. (2013)	20,009	–	9,292
AND Nielsen et al. (2013)	10,381	9,292	–



[McQuillan et al. 2014]

II-SURFACE ROTATION (RGB-RC)



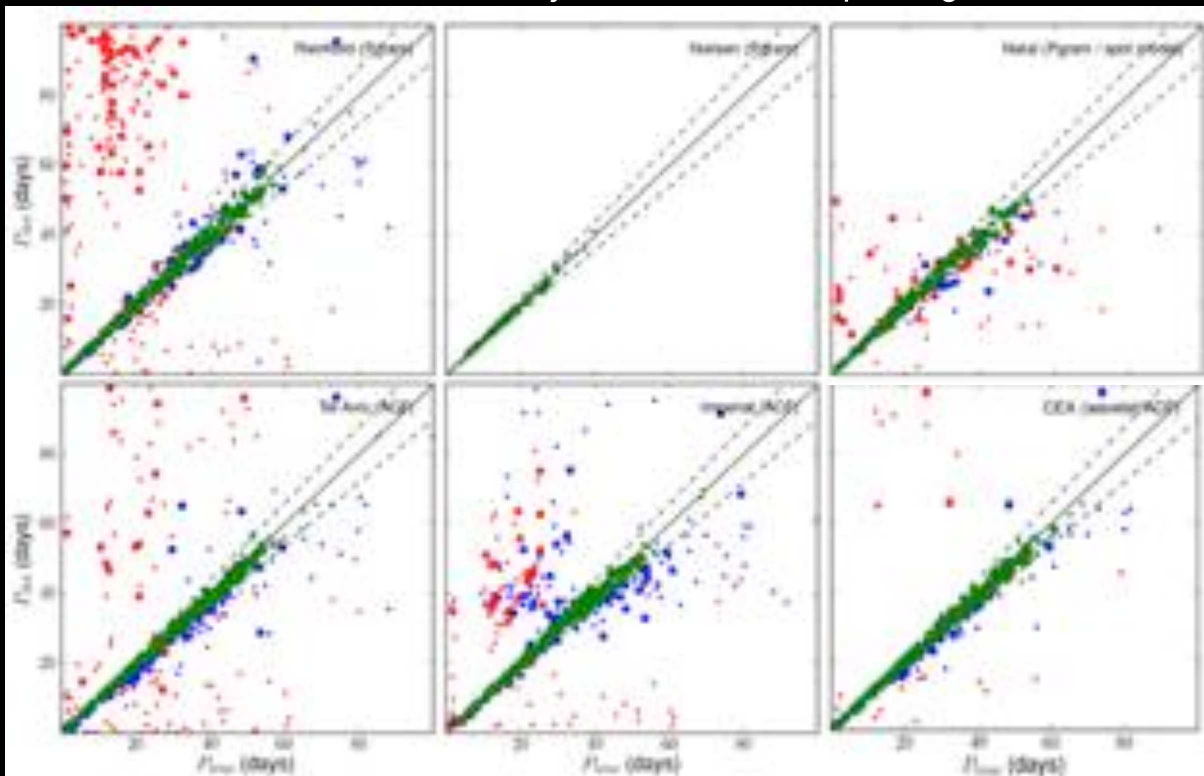


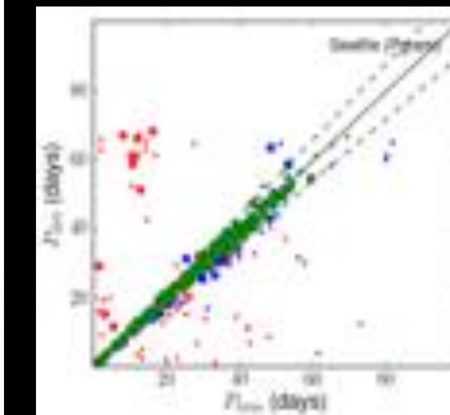
- Ensemble analysis of 17,000 Kepler pulsating RGs, only ~400 shows reliable surface rotation
- As expected
  - Most are RC stars
  - Some possible mergers detected
    - Still tracing false positives

[Ceillier, et al. in preparation]

II-VALIDATING P_{ROT}

- Through Simulations:
  - 1000 simulated stars injected on real *Kepler* light curves



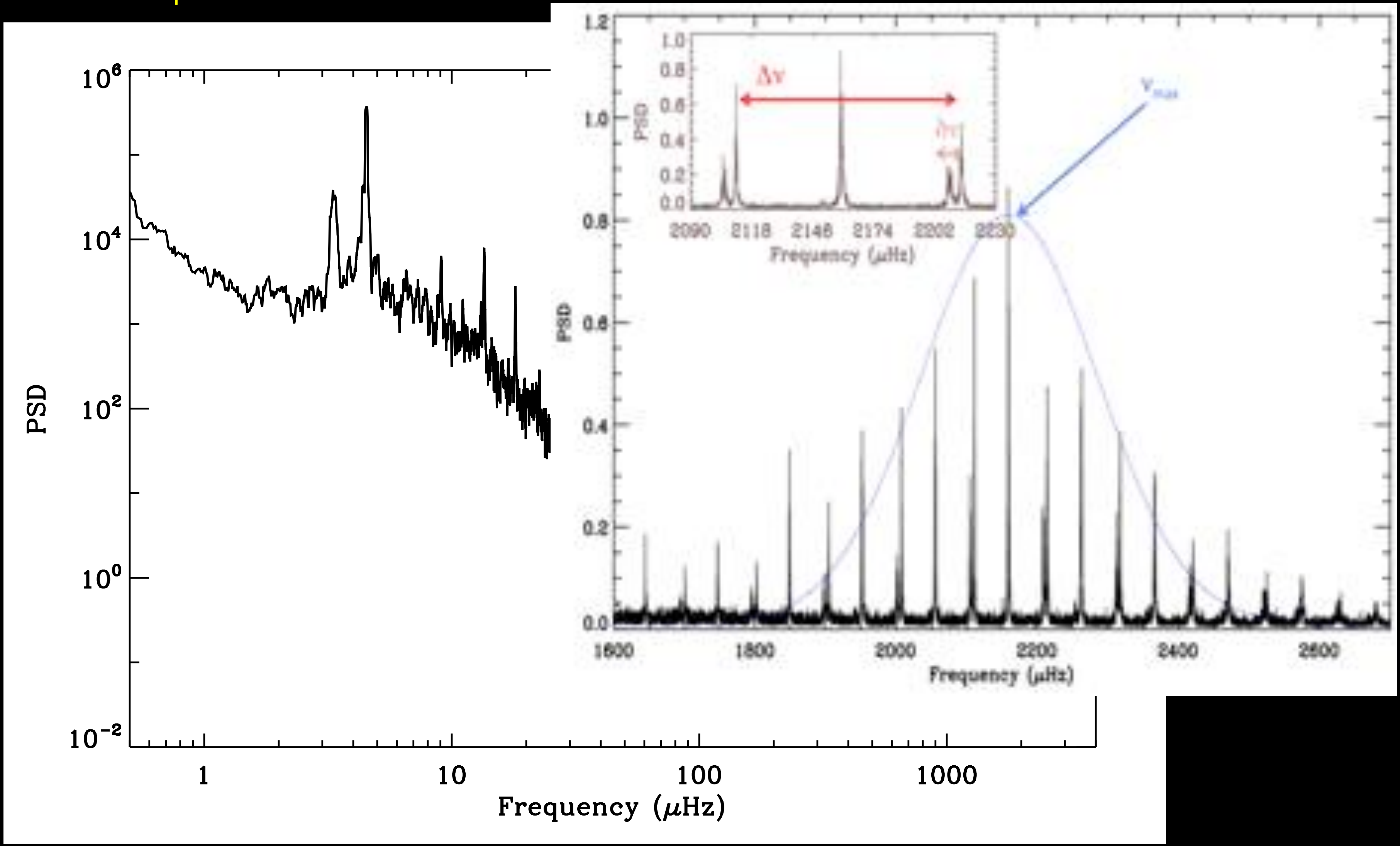


[Aigrain et al. 2015.]

Method	Noisy			Noise-free			solar	
	% det	% good	% ok	% det	% good	% ok	No. det	No. ok
Blind teams								
Reinhold (Periodogram)	82	67	76	87	65	77	4	2
Nielsen (Periodogram)	16	100	100	15	100	100	0	0
Natal (Periodogram / spot model)	27	69	76	72	80	85	5	2
Tel Aviv (ACF)	100	68	80	100	75	90	5	4
Imperial (ACF)	95	71	87	98	73	88	5	4
Non-blind teams								
Seattle (Periodogram)	68	81	88	75	84	90	0	0
CEA (Wavelets / ACF)	78	88	95	82	92	99	2	2

II-GLOBAL SEISMIC PARAMETERS

- Example of the PSD of a Solar-Like star



II-GLOBAL SEISMIC PARAMETERS

- Mean large frequency separation $\Delta\nu$

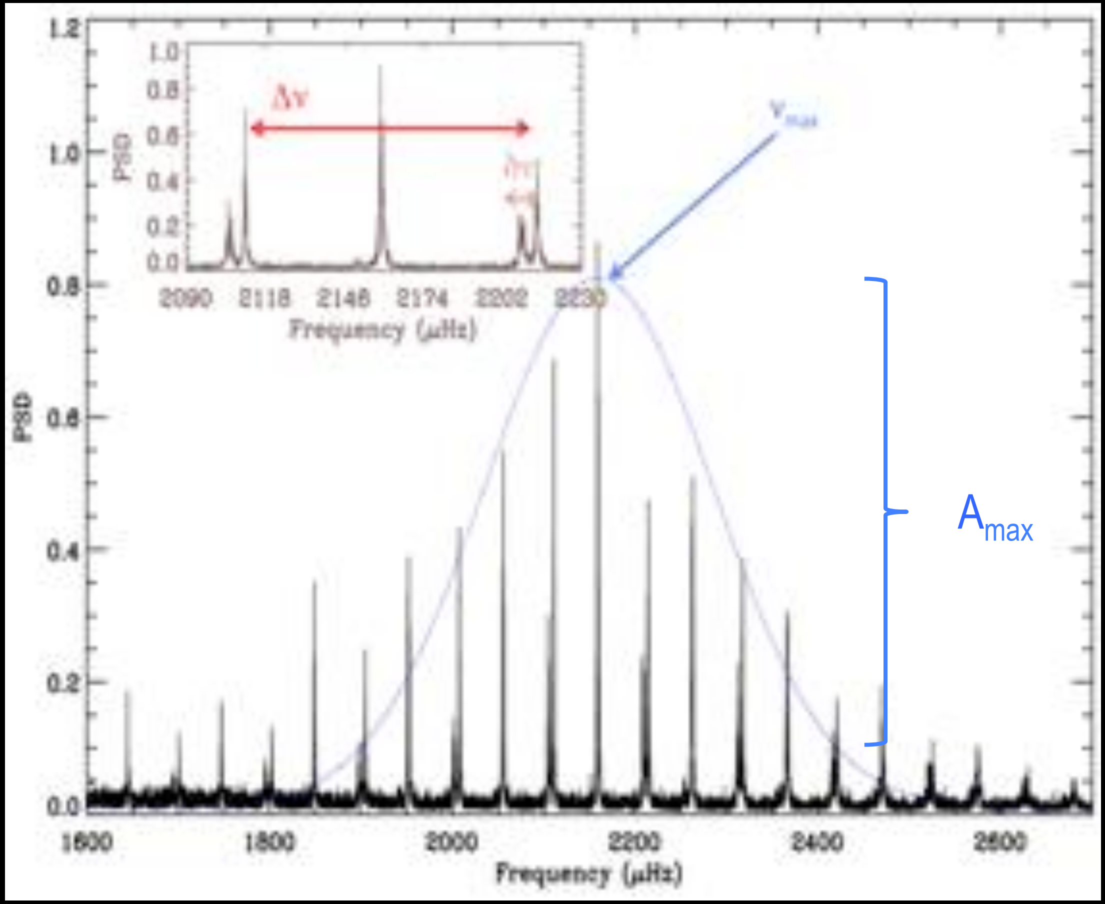
$$\Delta\nu = \left(\frac{M}{M_\odot}\right)^{1/2} \cdot \left(\frac{R}{R_\odot}\right)^{-3/2} \cdot 135\,\mu\mathrm{Hz}.$$

- Frequency at maximum power ν_{max}

$$\nu_{\max} = \frac{M/M_\odot}{(R/R_\odot)^2 \cdot \sqrt{\frac{T_{\mathrm{eff}}}{5777}}} \cdot 3050\,\mu\mathrm{Hz}.$$

- Maximum amplitude A_{max}

$$A_{\max} = \left(\frac{\mathrm{d}L}{L}\right)_{\max} = \left(\frac{L/L_\odot}{M/M_\odot}\right)^{0.7} \cdot \sqrt{\frac{5777}{T_{\mathrm{eff}}}} \cdot A_{\odot\max}.$$



- Combination of T_{eff}, $\Delta\nu$, and ν_{max}: 1st determination of R and M

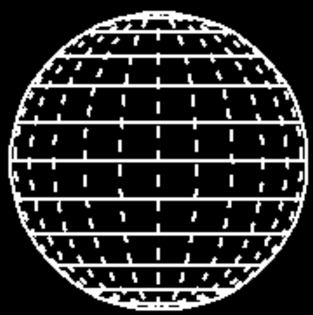
II-GLOBAL SEISMIC PARAMETERS

- Acoustic (p) modes:
  - Restoring force:
    - Pressure
    - High frequencies
    - Equidistant in frequency

- Gravity (g) modes:
  - Restoring force:
    - Buoyancy
  - Low-freqeuncies
  - Evanescents in the convective zone
  - Equidistant in period

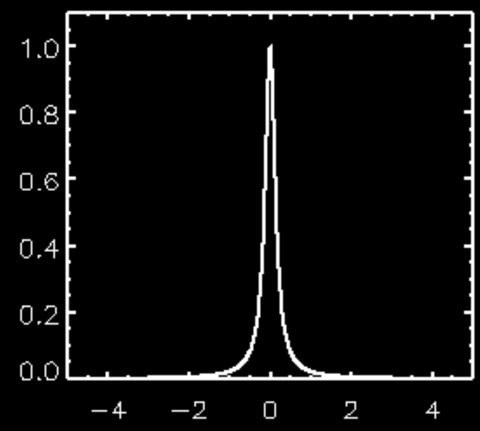
II-INTERNAL ROTATION

$\Omega = 0{,}0$

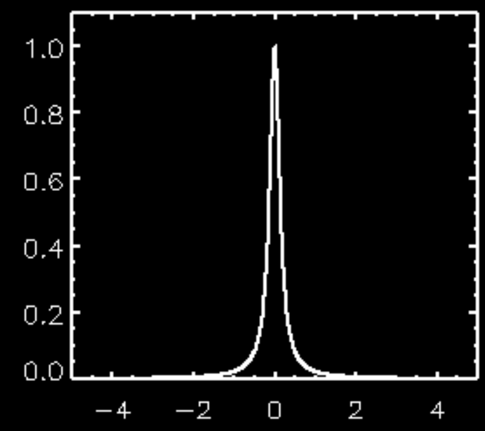


$i = 90°$

ℓ=1 mode



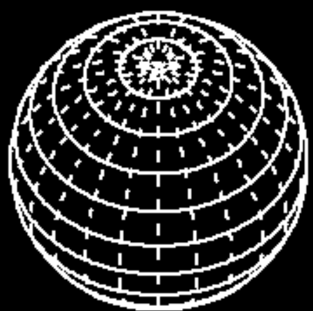
ℓ=2 mode



[Adapted from J. Ballot 2010]

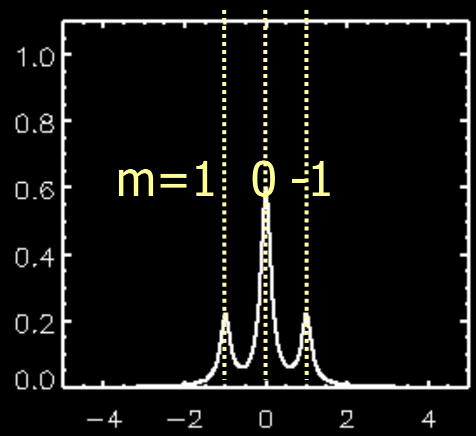
II-INTERNAL ROTATION

$\Omega = 1{,}0$

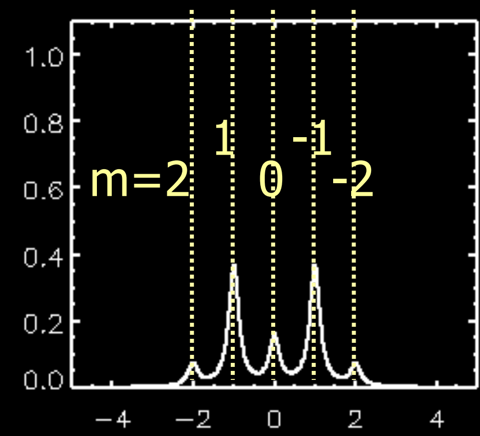


$i = 40°$

ℓ=1 mode

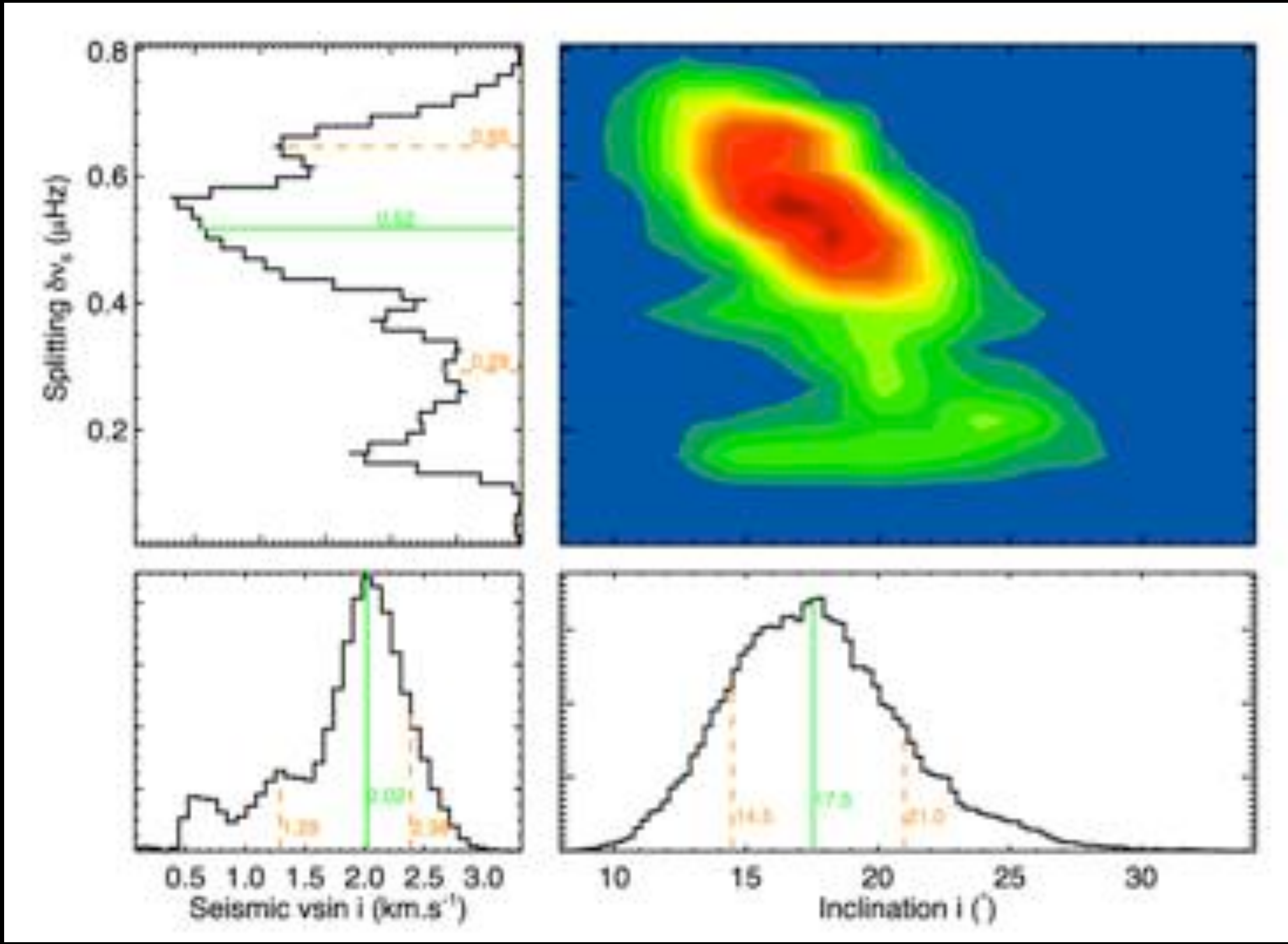


ℓ=2 mode



[Adapted from J. Ballot 2010]

II-SEISMIC ROTATION (MS)



[e.g. García et al. 2014; see also Gizon et al. 2013; Nielsen et al. 2014; Davies et al. 2015, Benomar et al. submitted]

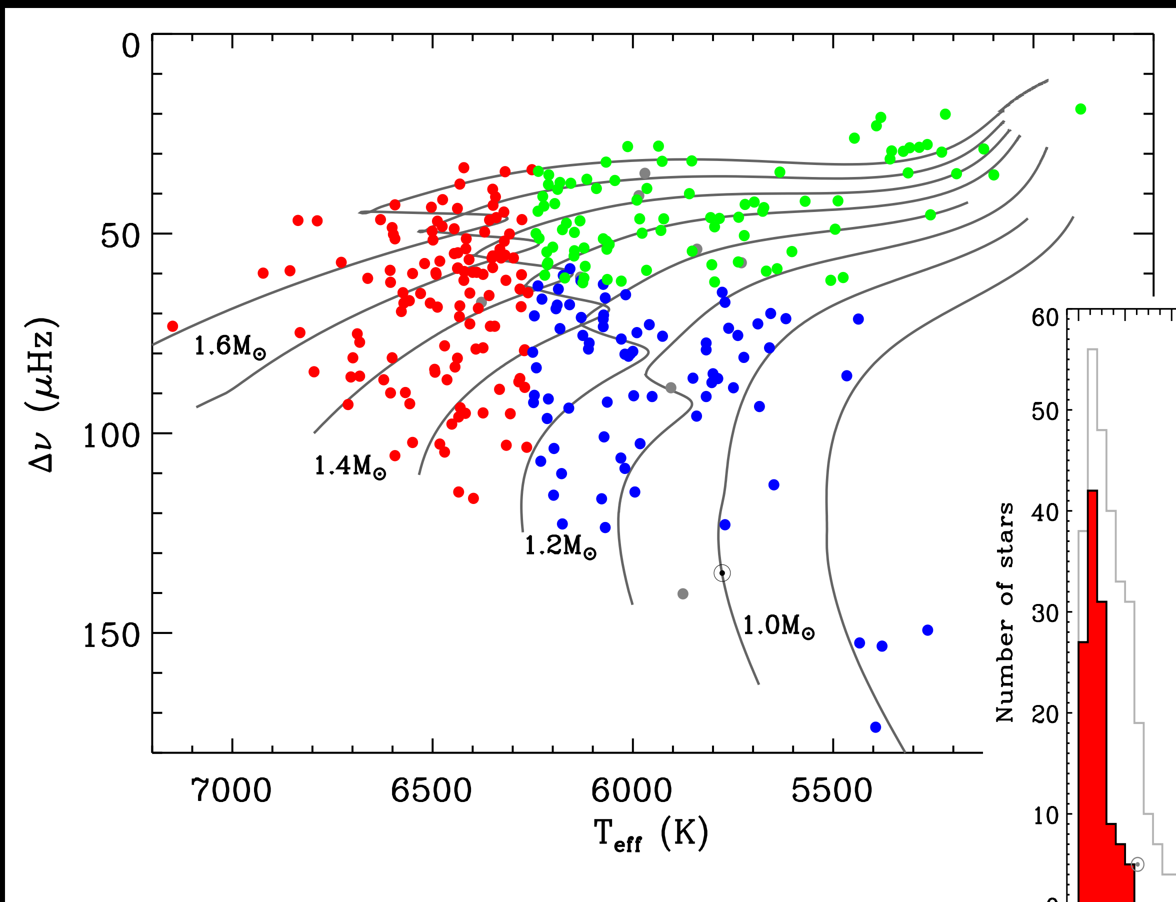
Asteroseismic inclinations put constraints on star-planet systems dynamics

[Chaplin et al. 2013 for some Kepler results on Kepler-50 and Kepler-65; Huber et al. 2013 for Kepler-56]

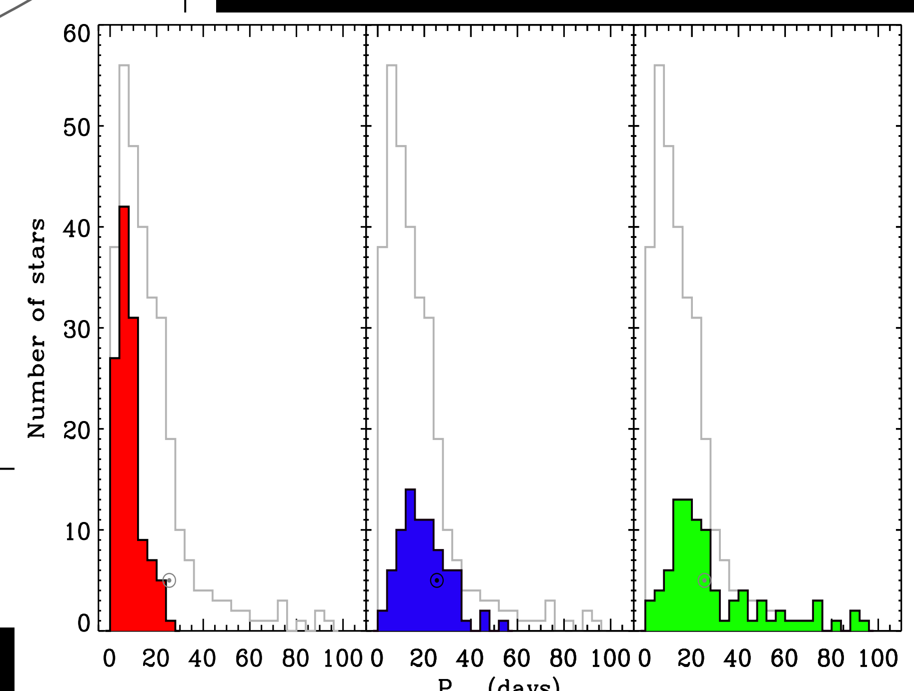
II-SURFACE ROTATION (M-S & SUB-RG)

- ~540 solar-like stars showing p-mode oscillations have been measured (1 month) [Chaplin et al. 2014]
  - Reliable surface rotation rates and photospheric magnetic index obtained for 310 stars
- Stars in which pulsations are measured => Low surface activity (biased sample)

[Garcia et al. 2010; Chaplin et al. 2011]



[García et al 2014]

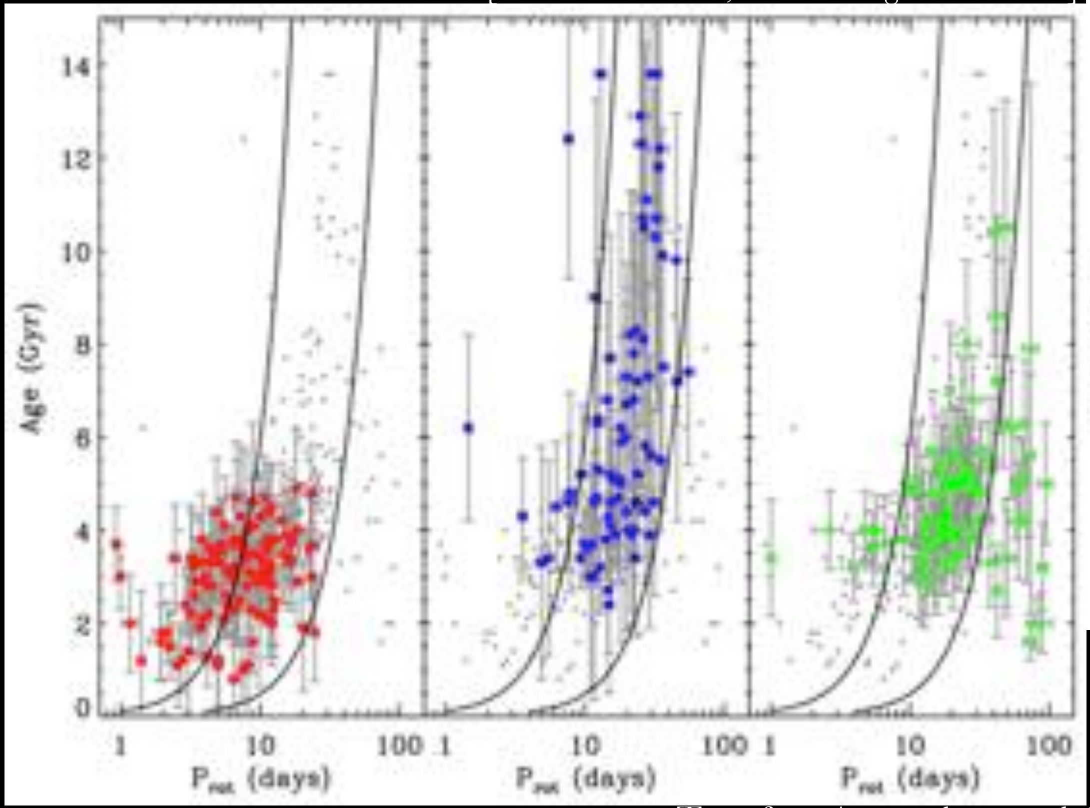


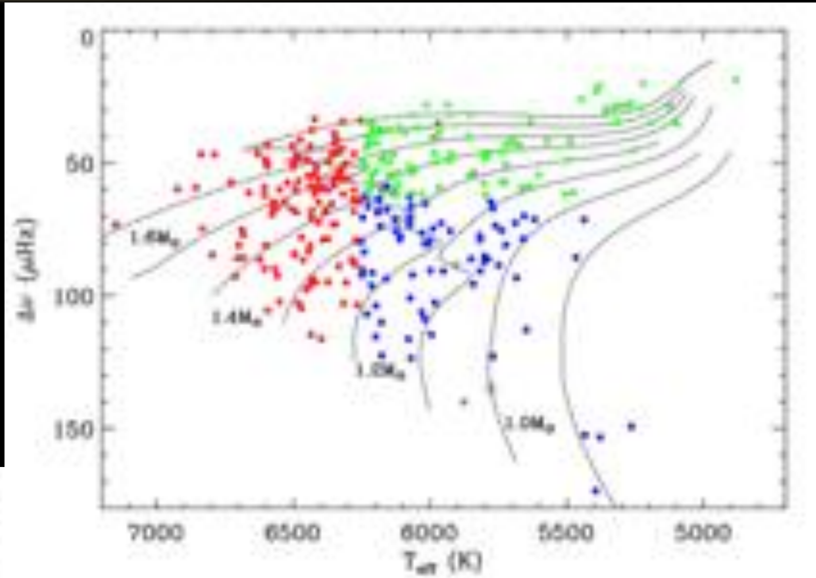
II-SURFACE ROTATION

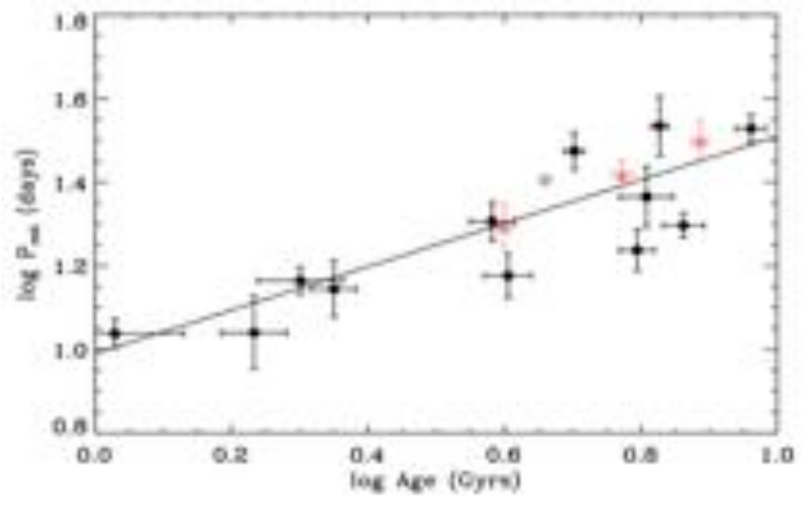
- Gyrochronology
  - must be calibrated using stars of known age
  - published relations mostly employ open cluster stars and the Sun.
  - Until now, gyrochronology has simply extrapolated these trends to stars older than the Sun."

- Towards asteroseismically calibrated Gyrochronology of field stars

[García et al. 2014; see also Angus et al. 2015]







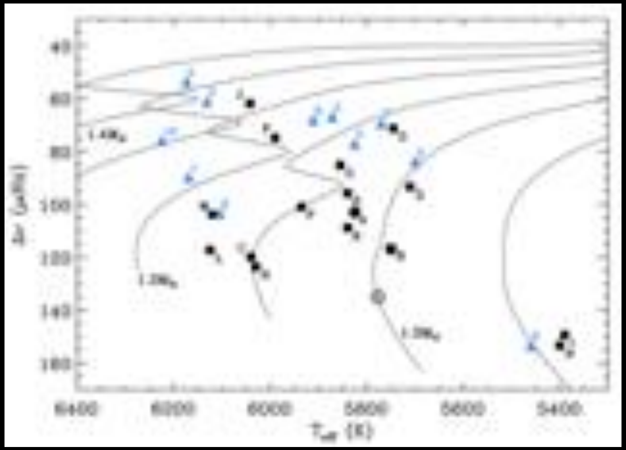
$$\log P_{rot} = (0.52 \pm 0.06)\log(t) + (0.99 \pm 0.04).$$

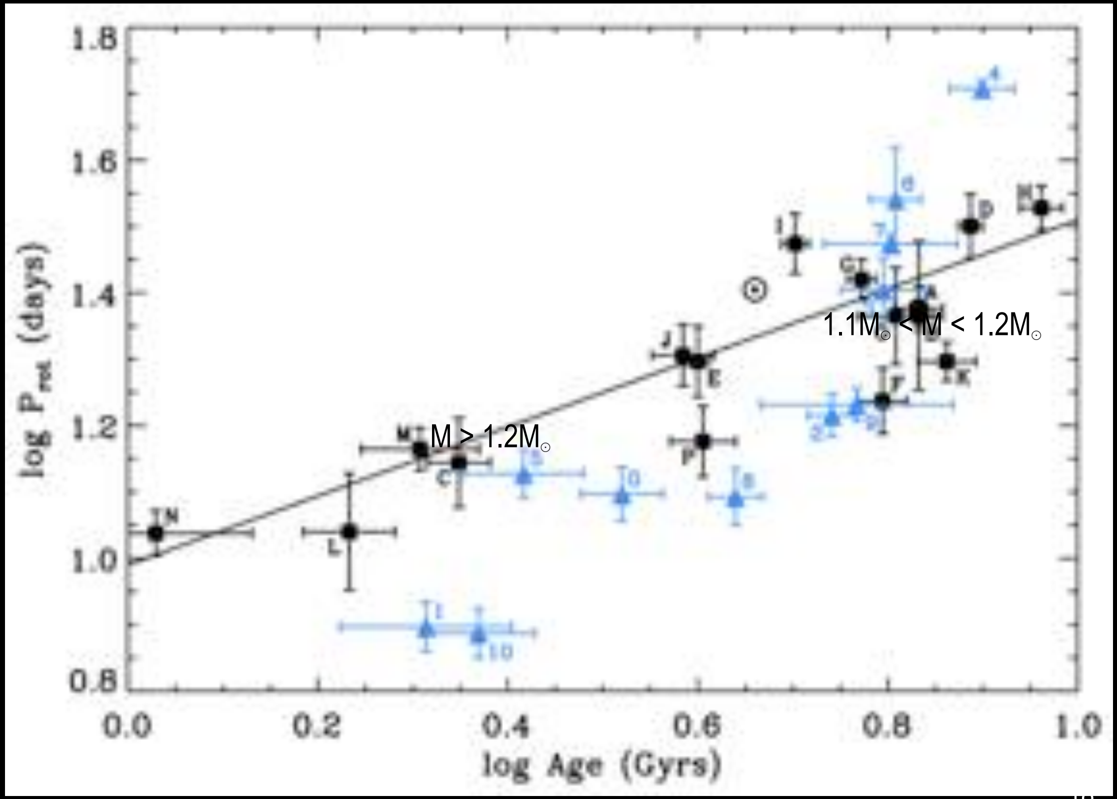
[Freqs from Appourchaux et al. 2012, models from Mathur et al. 2012 & Metcalfe et al. 2014]

II-SURFACE ROTATION OF (SEISMIC) KOIs

- Comparing with confirmed stars holding planets
  - Small planets in the range 0.7 to 3.94 $R_{\oplus}$
  - semi-major axes range from 0.035 to 0.392 AU
  - Differences are due to a difference mass distribution

[Ceillier et al. Submitted]





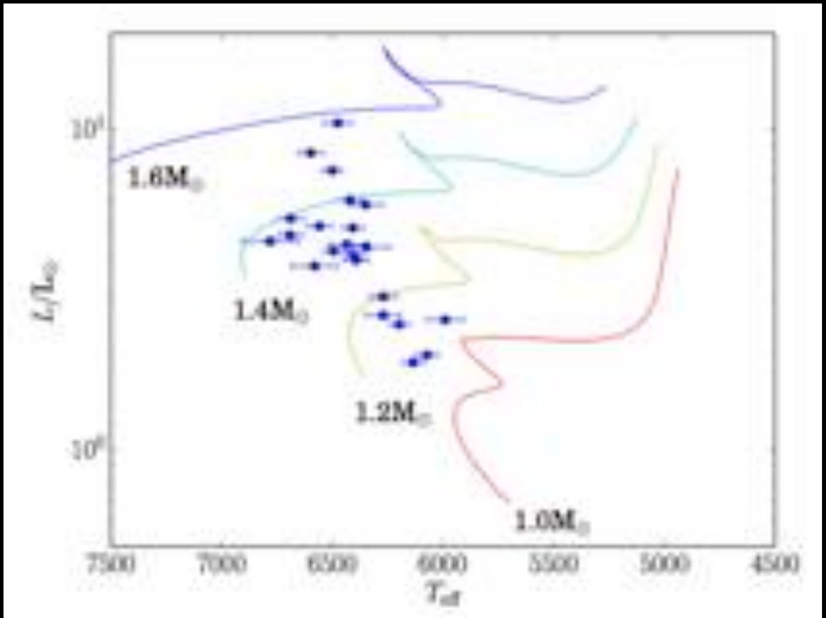
[see also Paz-Chinchón et al. 2015]

II-INTERNAL ROTATION (M-S)

- Analysis of 22 main-sequence stars with masses between 1.0 and 1.6 $M_\odot$
  - Combining seismic analysis of *Kepler* and CoRoT data with spectroscopic Vsini

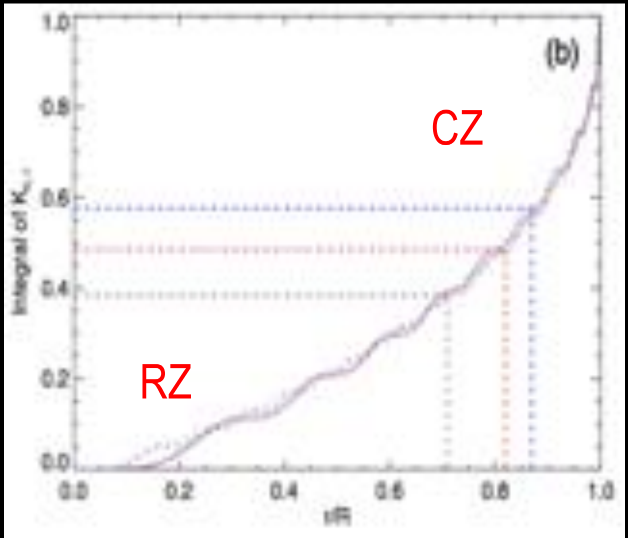
$$\delta\nu_{n,l} \simeq I_{\rm rad} f_{\rm rad} + I_{\rm conv} f_{\rm conv},$$

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



- Assuming:
  - the two zones rotate uniformly with different rates (about the same axis)
  - f_{conv} is equal to the surface rotation (as in the solar case)
  - Rotational splittings remain nearly constant over the observed ranges of n and l,

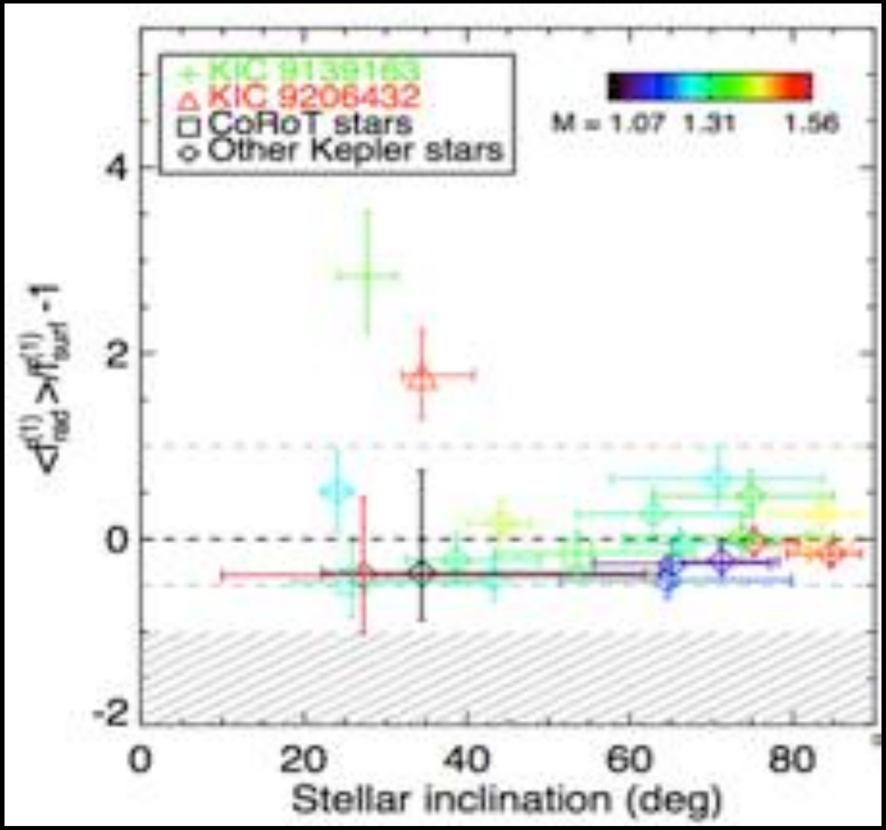
$$\langle f_{\rm rad}\rangle = f_{\rm surf} + \langle I_{\rm rad}\rangle^{-1}(f_{\rm seis} - f_{\rm surf}).$$



[Benomar et al. submitted]

II-INTERNAL ROTATION (M-S)

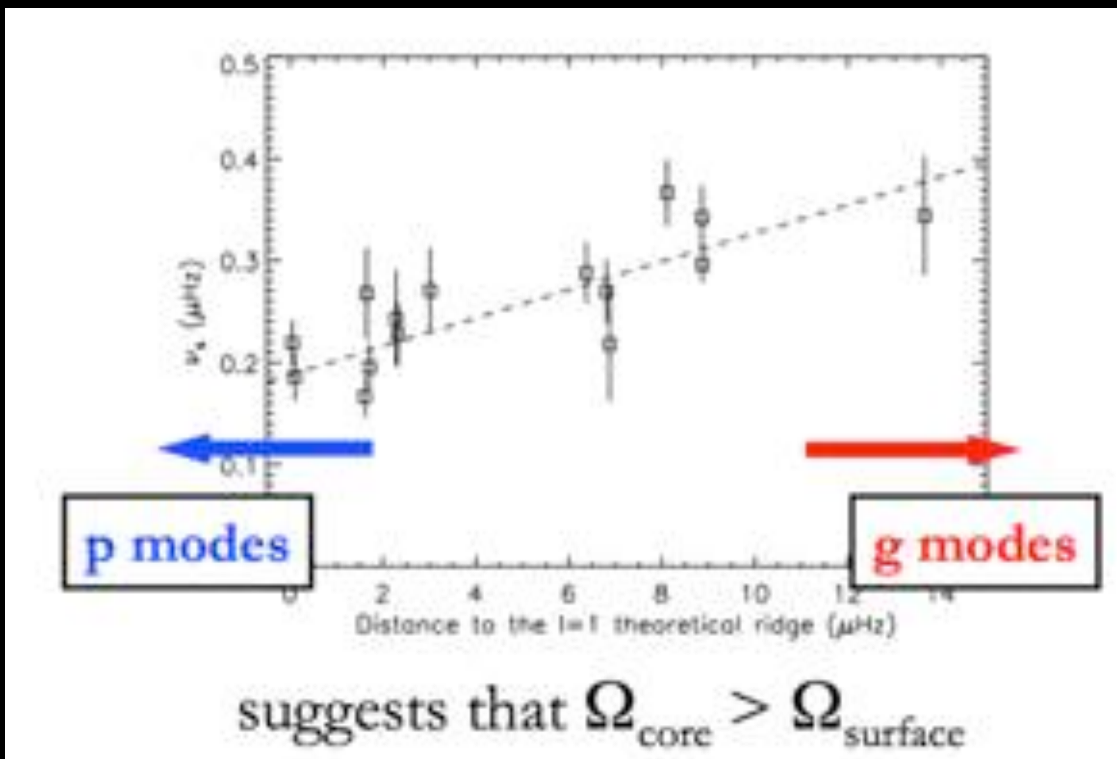
- The rotation rates between the radiative interior and the outer convective zone/surface
  - is no more than a factor of two in most of the stars independently of their ages.
  - This suggests that an efficient process of angular momentum transport operates during and/or before the main-sequence stage of stars.

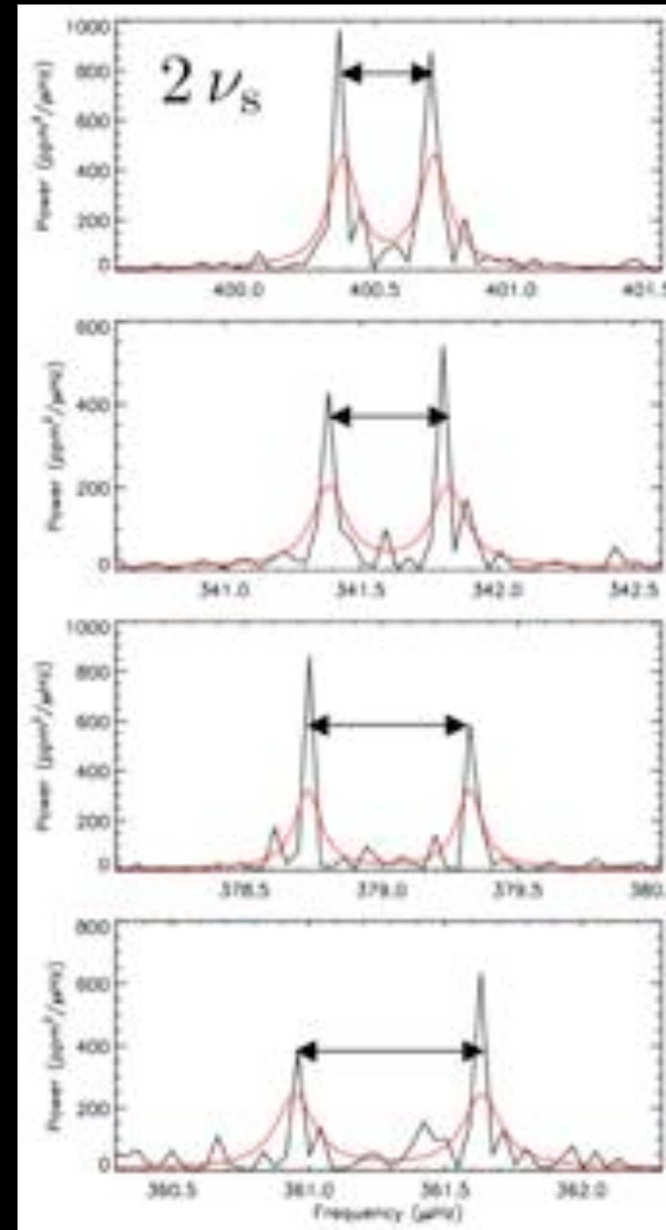


[Benomar, et al. submitted]

II-INTERNAL ROTATION

- Mixed modes allow us to study the internal dynamics
  - g-dominated mixed modes:
    - Sensitive to the deep radiative interior
  - P-dominated modes
    - Sensibility weighted towards the outer layers



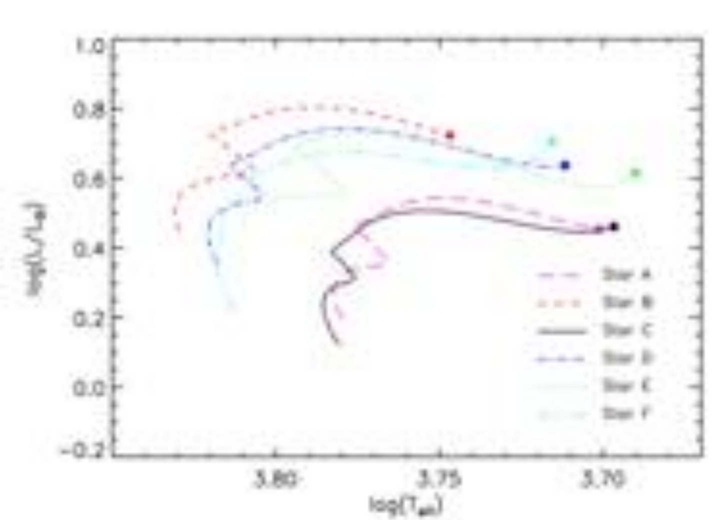


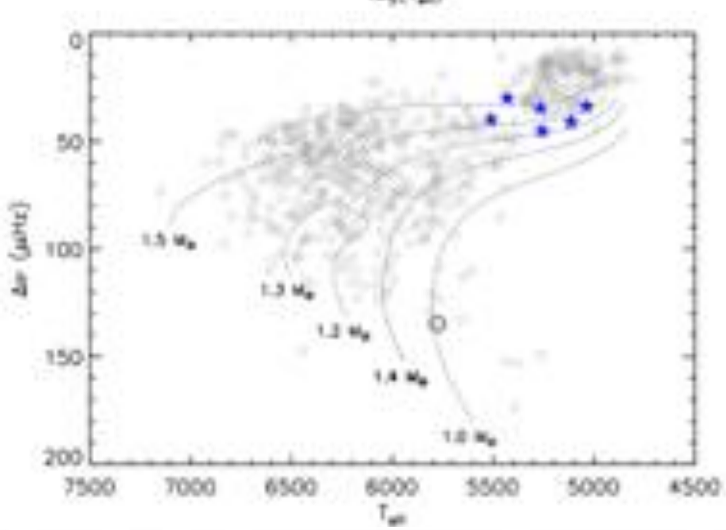
[Deheuvels, Garcia, et al. 2012

see also Beck et al. 2012

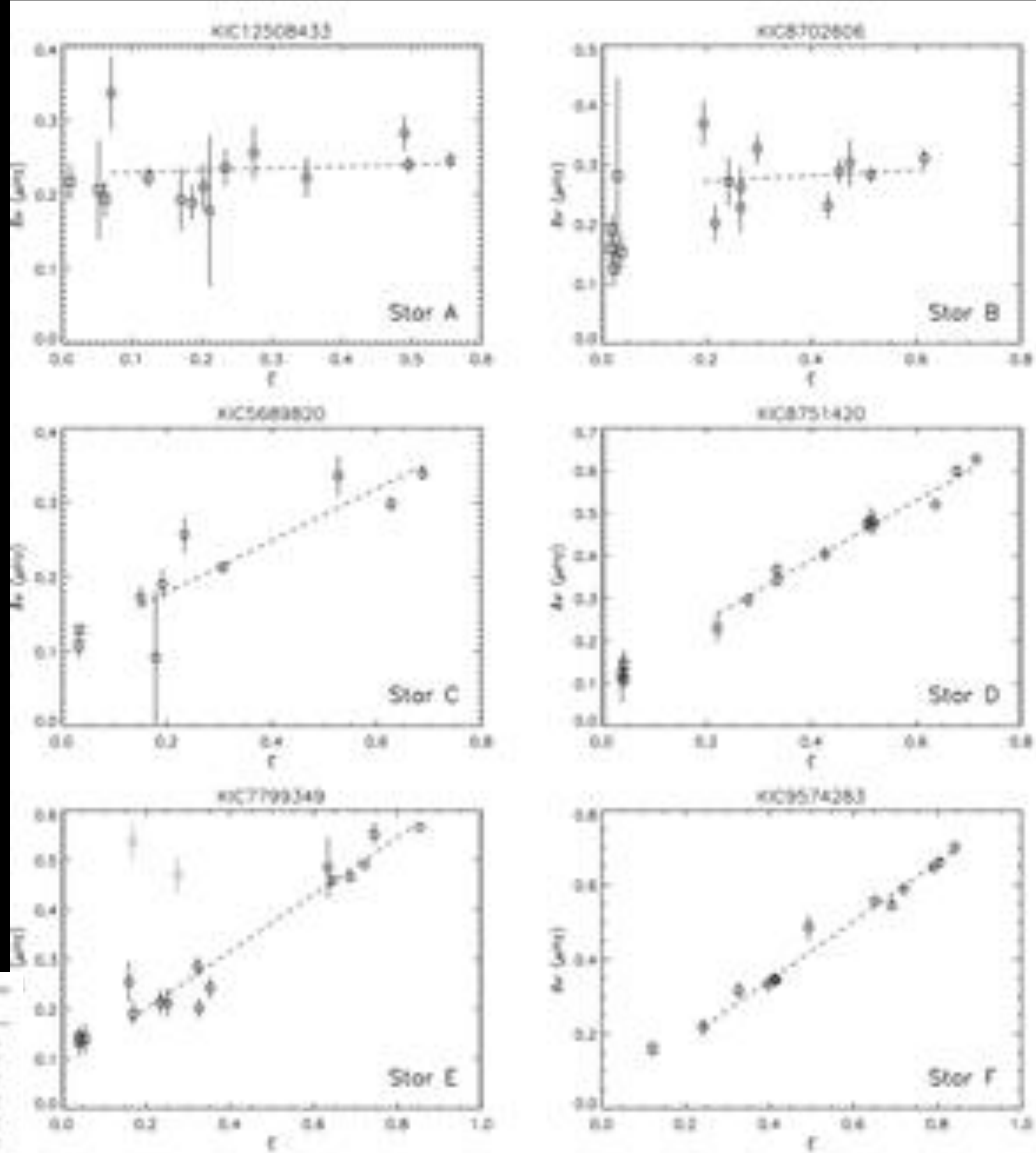
- 6 Subgiant/early RGBs

[Deheuvels et al. 2014]





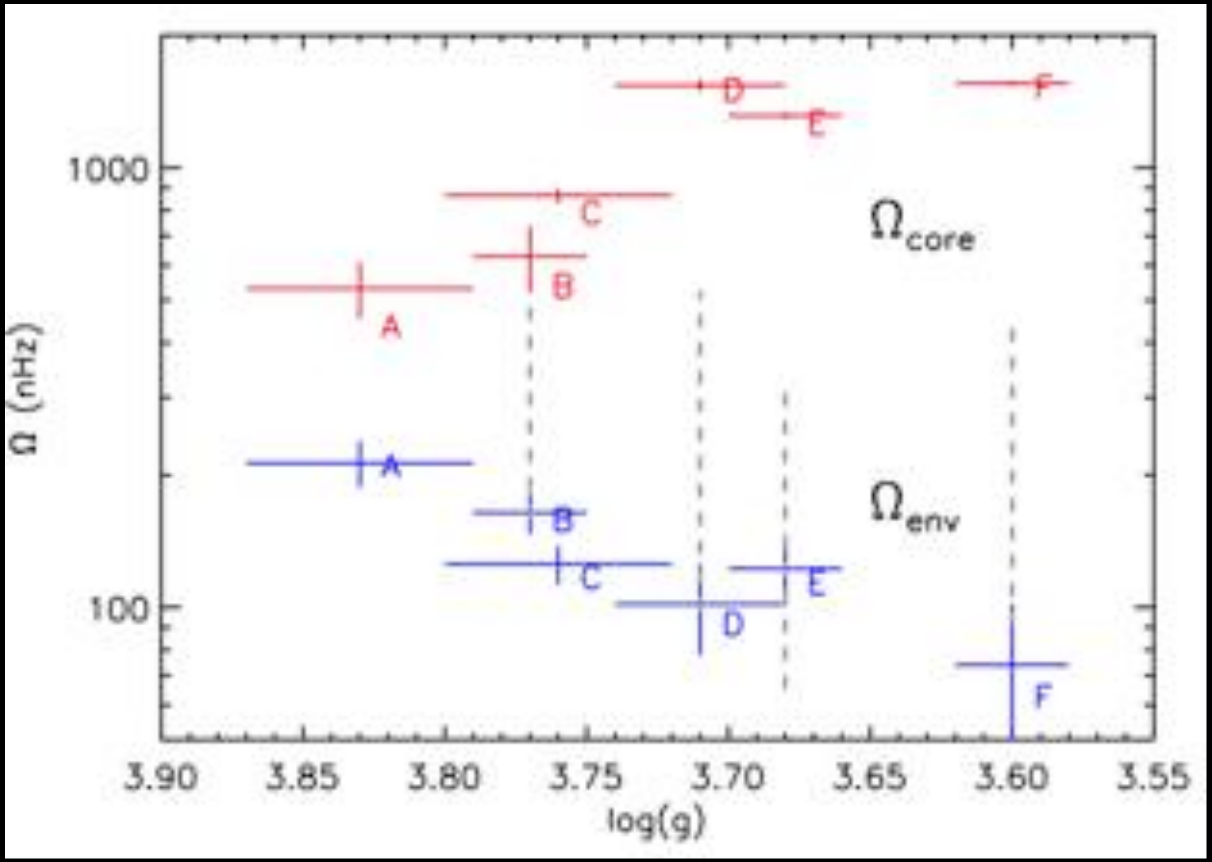
Star	Ref. letter	$\Delta\nu$ (μHz)	ν_{max} (μHz)	M	R	$\log g$
KIC12508433	A	45.3 ± 0.2	790 ± 21	1.20 ± 0.16	2.20 ± 0.10	3.83 ± 0.04
KIC8702606	B	39.9 ± 0.4	664 ± 14	1.27 ± 0.15	2.44 ± 0.11	3.77 ± 0.02
KIC5689820	C	41.0 ± 0.3	690 ± 15	1.11 ± 0.16	2.29 ± 0.12	3.78 ± 0.04
KIC8751420	D	34.7 ± 0.4	598 ± 14	1.30 ± 0.20	2.83 ± 0.13	3.71 ± 0.03
KIC7799349	E	33.7 ± 0.4	561 ± 8	1.32 ± 0.14	2.77 ± 0.12	3.68 ± 0.02
KIC9574283	F	30.0 ± 0.5	455 ± 8	1.24 ± 0.17	2.92 ± 0.17	3.60 ± 0.02



II-INTERNAL ROTATION (SUBGIANTS)

- 6 Subgiant/early RGBs

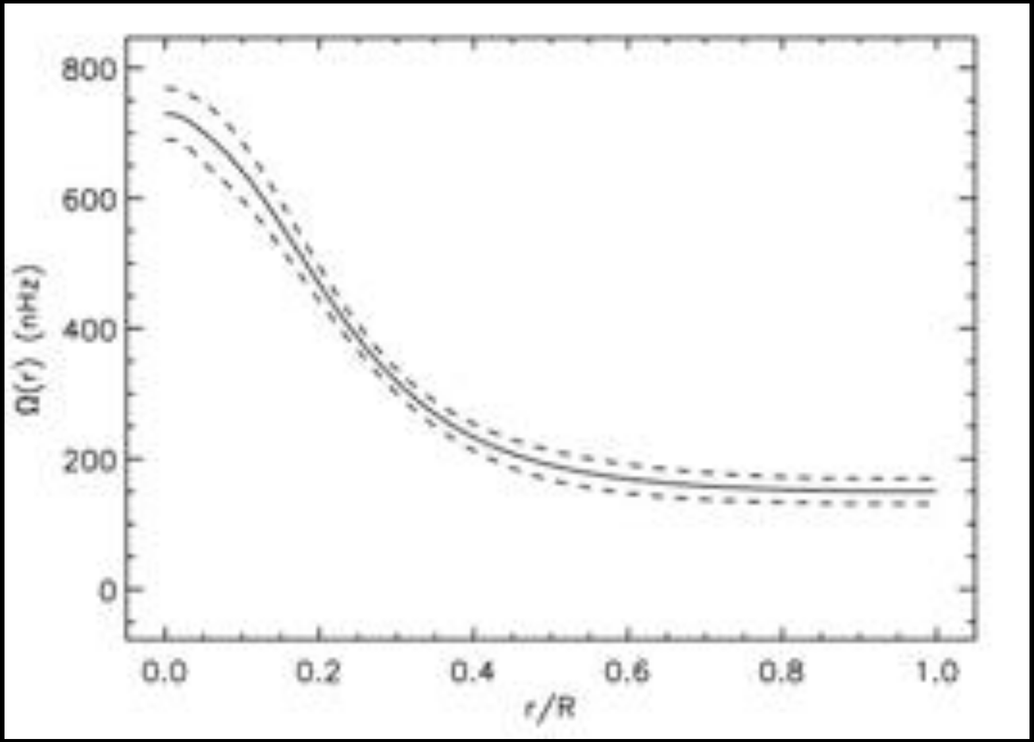
[Deheuvels et al. 2014]



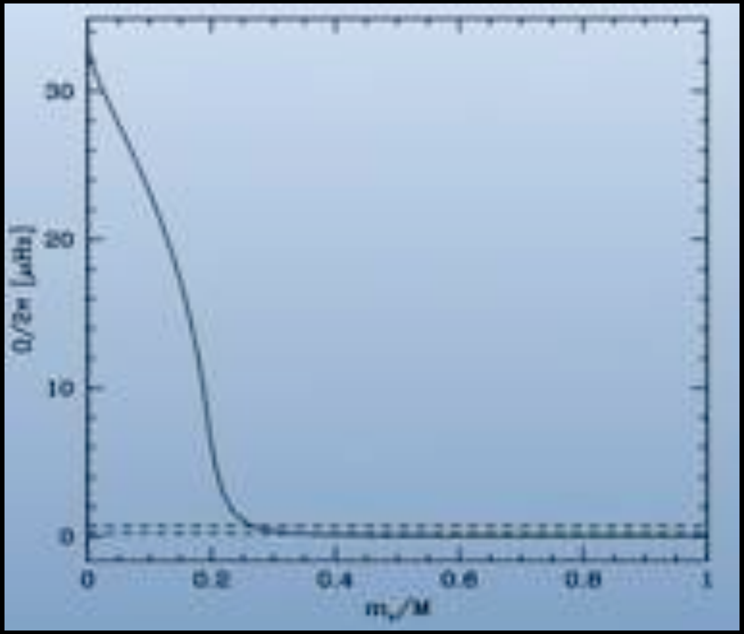
The trend with the seismic logg suggests that the core spins up in the subgiant phase

II-INTERNAL ROTATION (SUBGIANTS)

- Mixed modes allow us to study the internal dynamics
  - g-dominated mixed modes:
    - Sensitive to the deep radiative interior
  - P-dominated modes
    - Sensibility weighted towards the outer layers

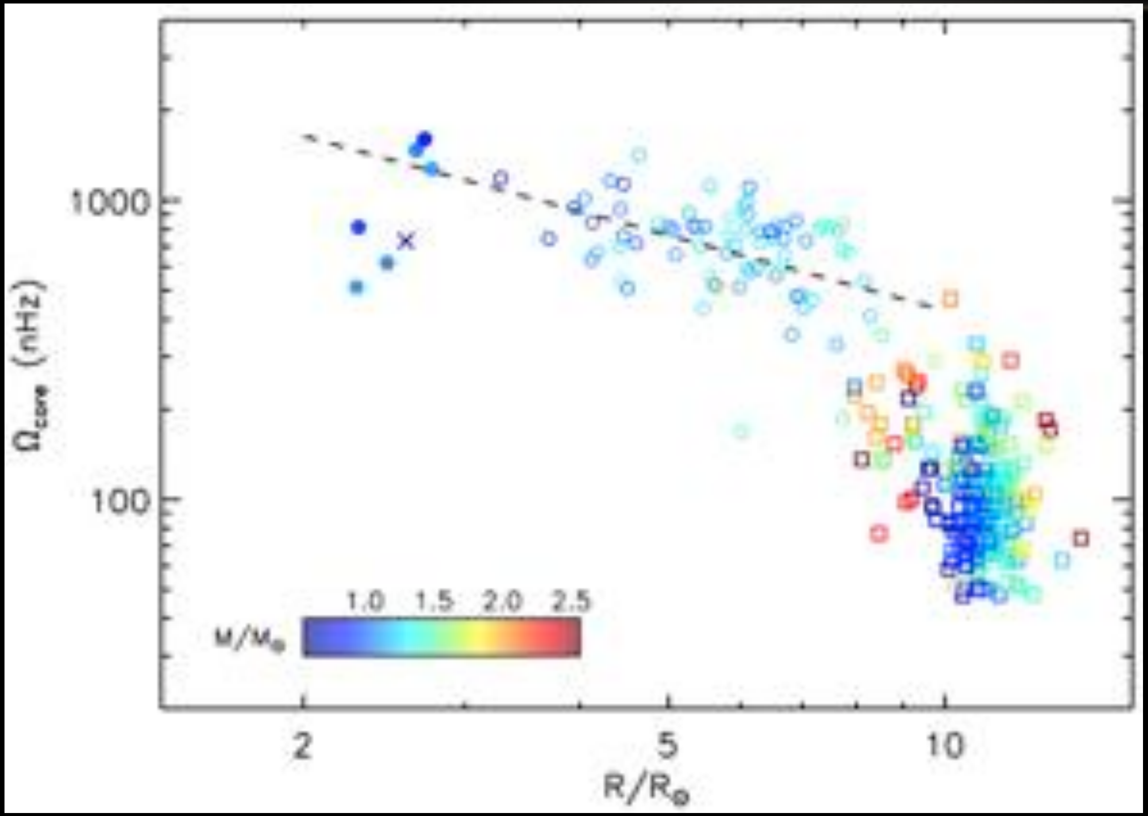


[Deheuvels, Garcia et al. 2012]



[Ceillier, Eggenberger, García & Mathis 2013]

II-INTERNAL ROTATION (RGB-RC)



[Mosser et al. 2012
Filled circles from Deheuvels et al. 2014]

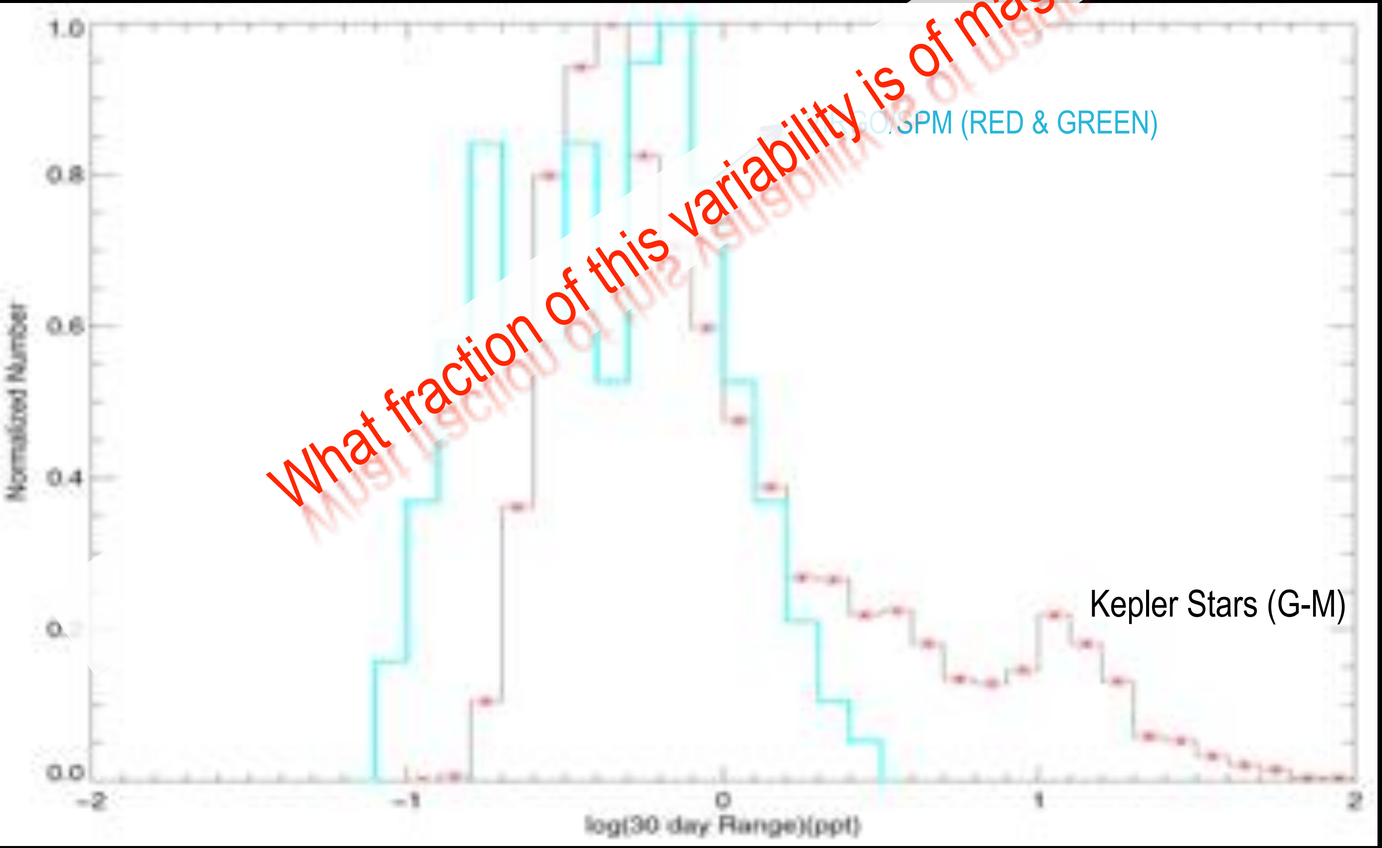
- Ensemble analysis used to obtain a proxy of the rotation rate of the deep radiative interior
- During RGB (circles):
  - The core of the stars during RGB spins down during evolution!
  - Efficient AM transport to counterbalance the core contraction and not efficeint during subgiant phase
- Change from RGB to the clump (squares) can be related to the expansion of the non-degenerate helium burning core.
  - It can not explain all the reduction [Iben 1971; Sills & Pinsonneault 2000]
    - significant transfer of internal angular momentum from the inner to the outer layers.
- New results coming on the 2nd clump stars [Deheuvels et al. Sub.]

IIb-Stellar Dynamics:

Magnetic variability

II-STELLAR VARIABILITY

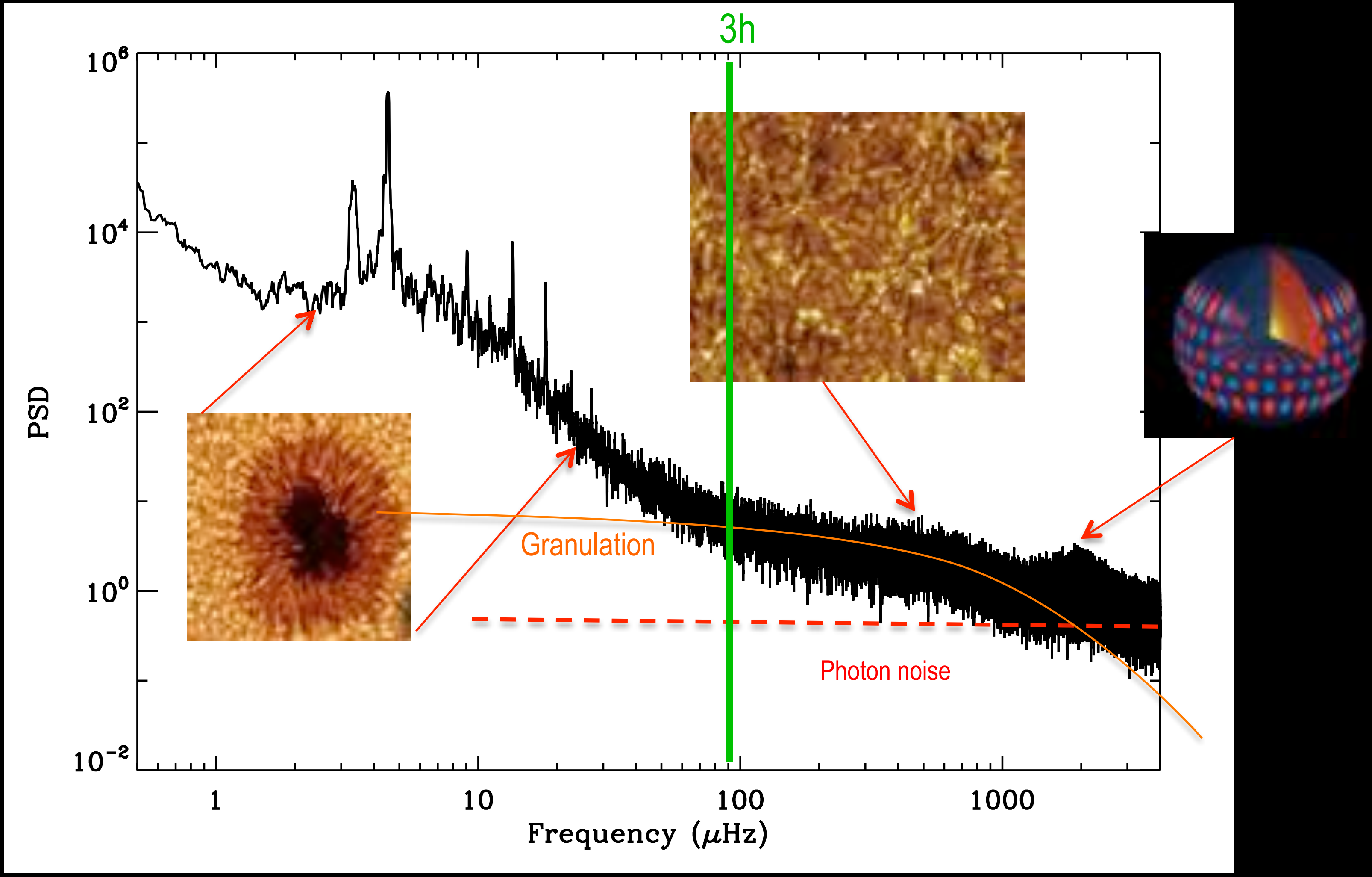
- To study the photometric variability of a star:
  - It is common to parameterize it at a given time
    - E.g. MDV (t_{bin}) (Median Differential Variability), Range, etc
      - Median of the bin-to-bin variability for bins of a given timescale t_{bin}
    - This methodology is good to compare variability of stars at different timescales



[Basri et al. 2013]

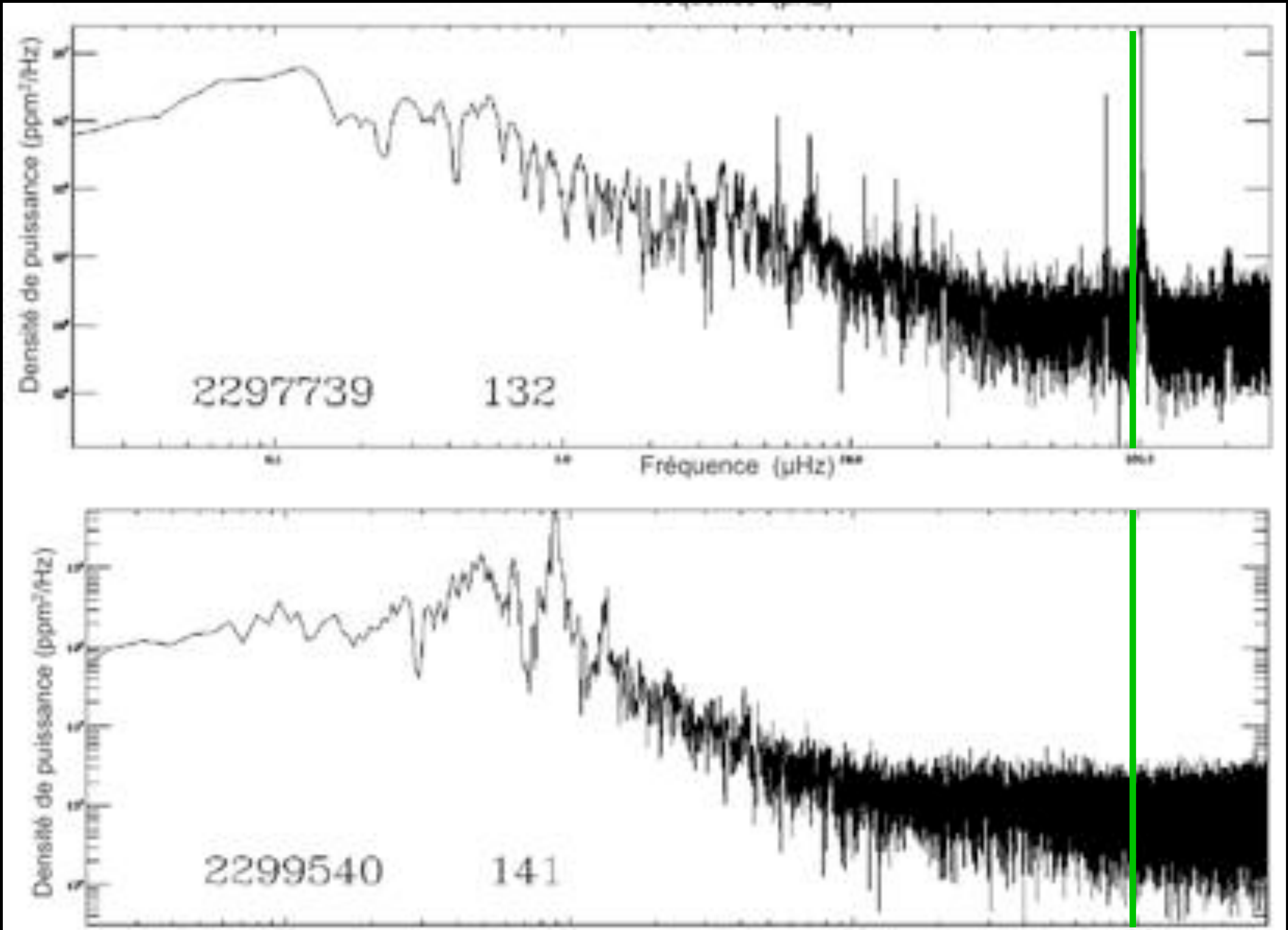
II-STELLAR VARIABILITY

- Example of the PSD of a Solar-Like star



II-STELLAR VARIABILITY

- Example of other type of pulsators (F, M)

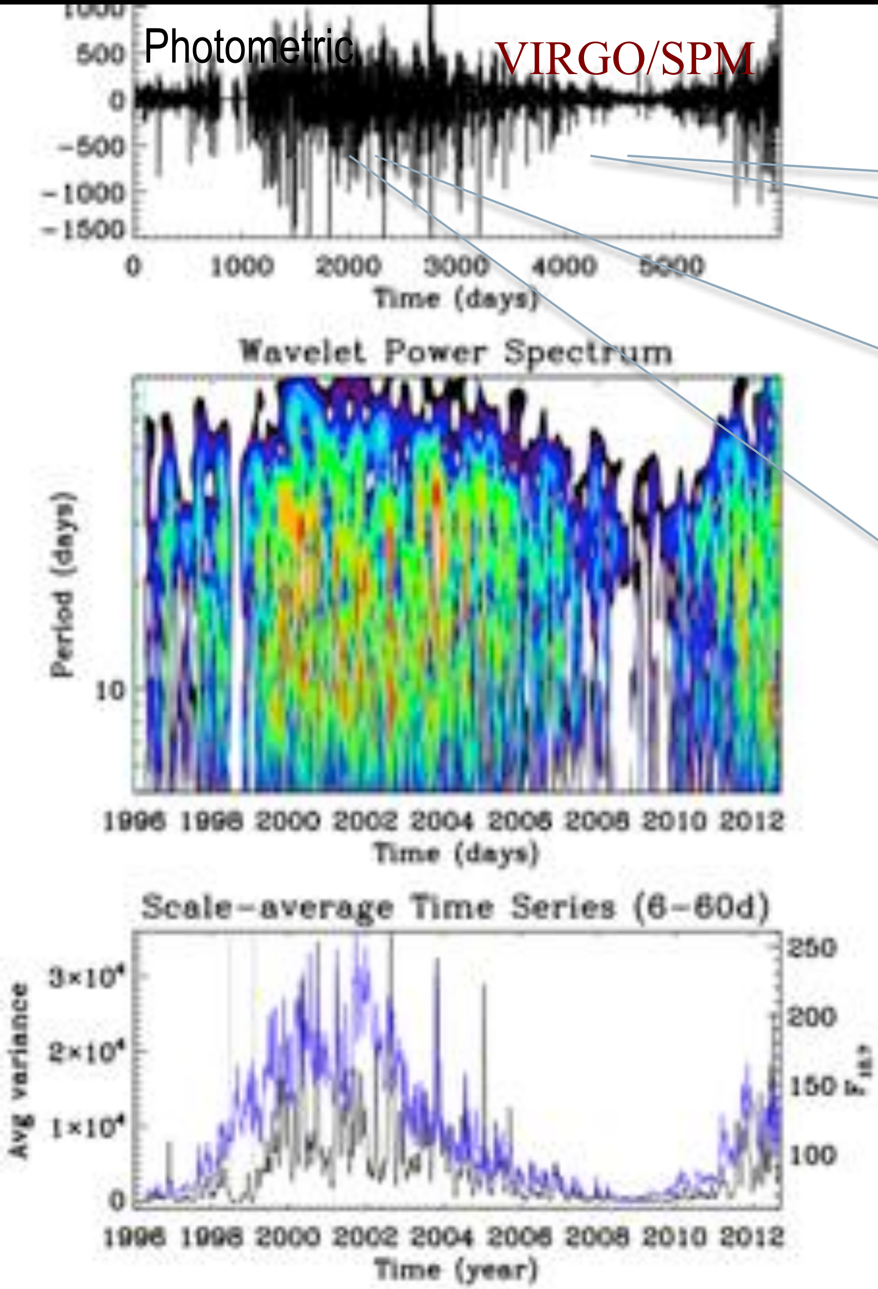


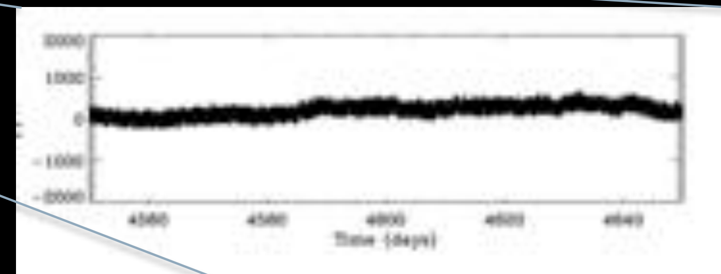
[Houmani, Stage M1, 2014]

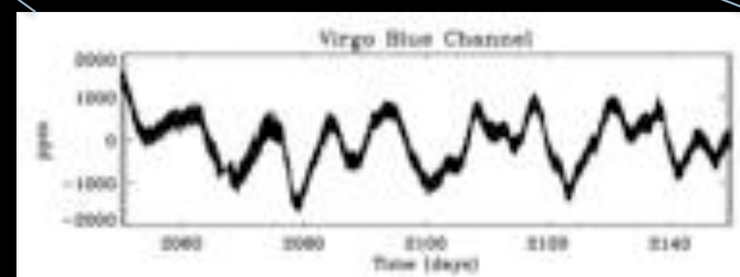
III-Surface Magnetic Activity

proxy

II-MAGNETIC ACTIVITY & ROTATION



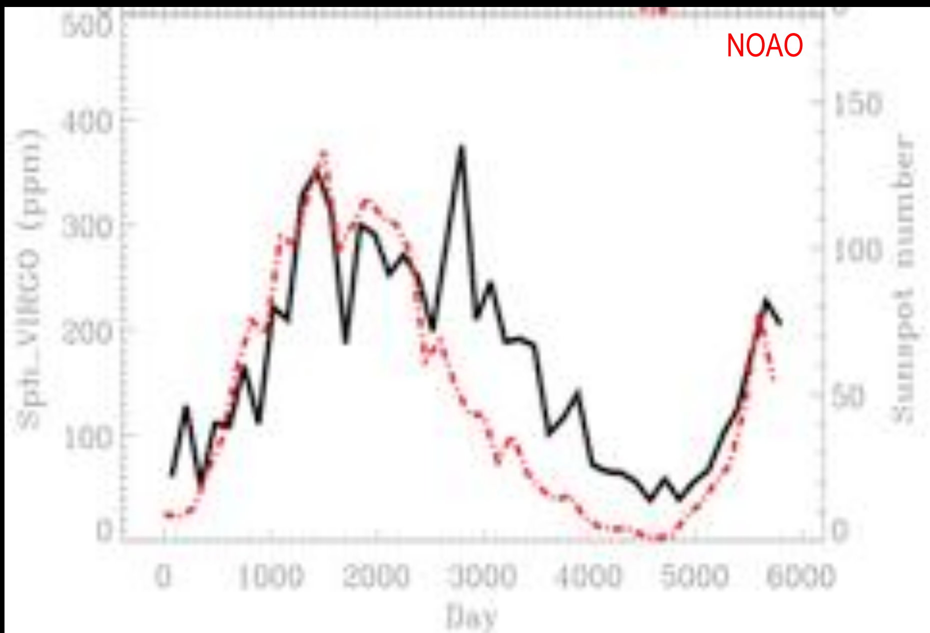


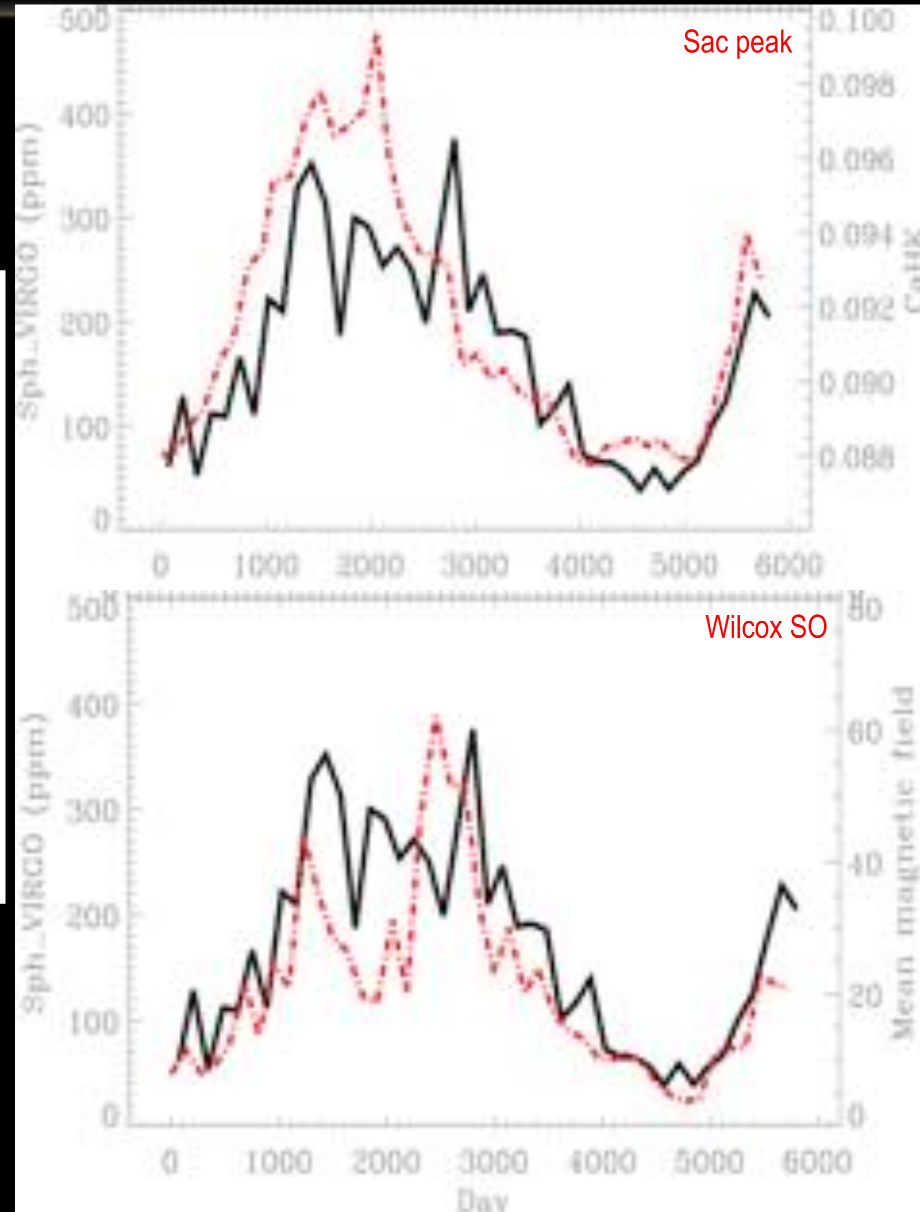


[García, Salabert, Mathur et al. 2013]

III-SURFACE MAGNETIC ACTIVITY PROXY

- Solar S_{ph} (VIRGO/SPM)
  - Comparison with other solar indexes



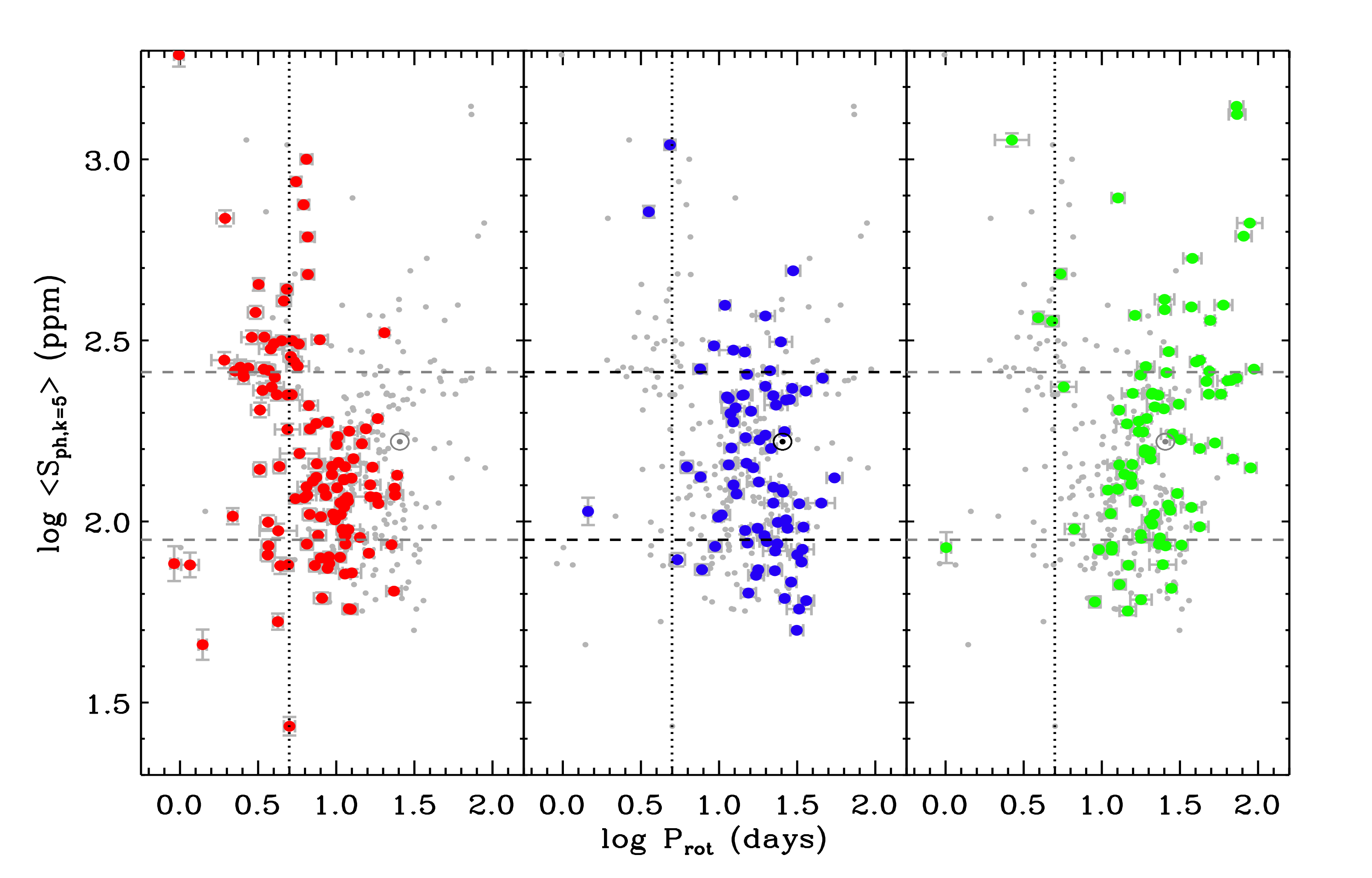


GOLF proxy also available

[Salabert, García, Roth, et al. in prep]

http://www.spaceinn.eu/data-access/photospheric-solar-activity-index-virgospm-sph/

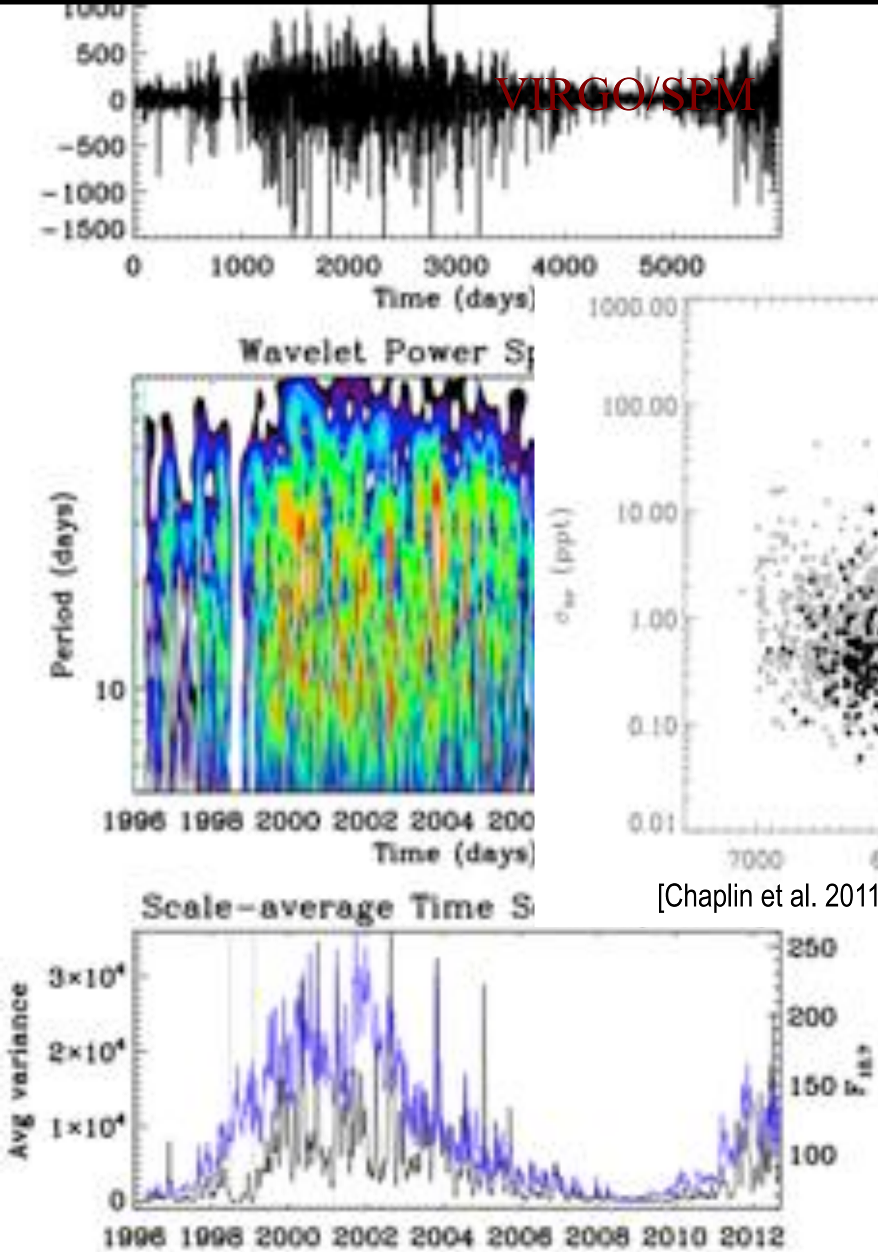
III-SURFACE MAGNETIC ACTIVITY S-L STARS



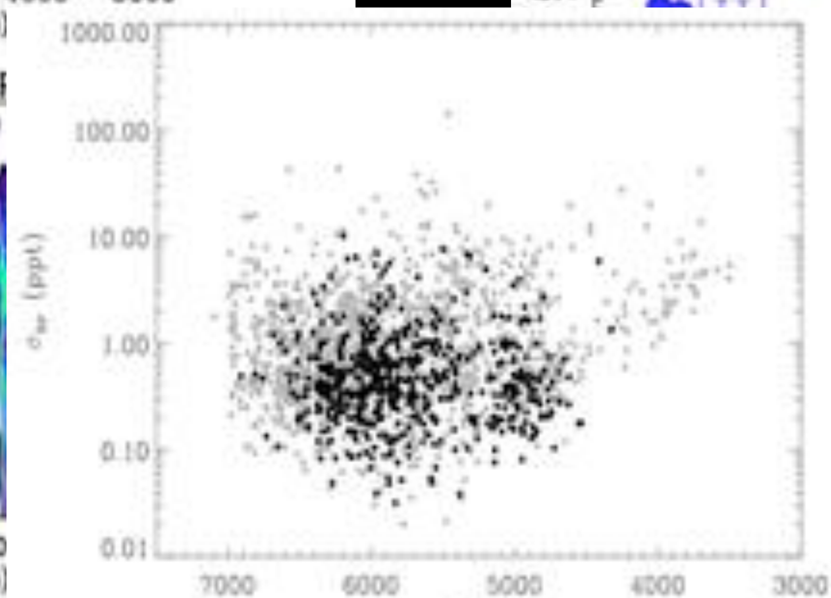
[García et al. 2014]

- The photospheric magnetic activity of the pulsating solar-like stars
  - Compatible with the solar magnetic activity during the solar cycle (61.5%)
  - But large range of inclination angles and position in an on-going long activity cycle

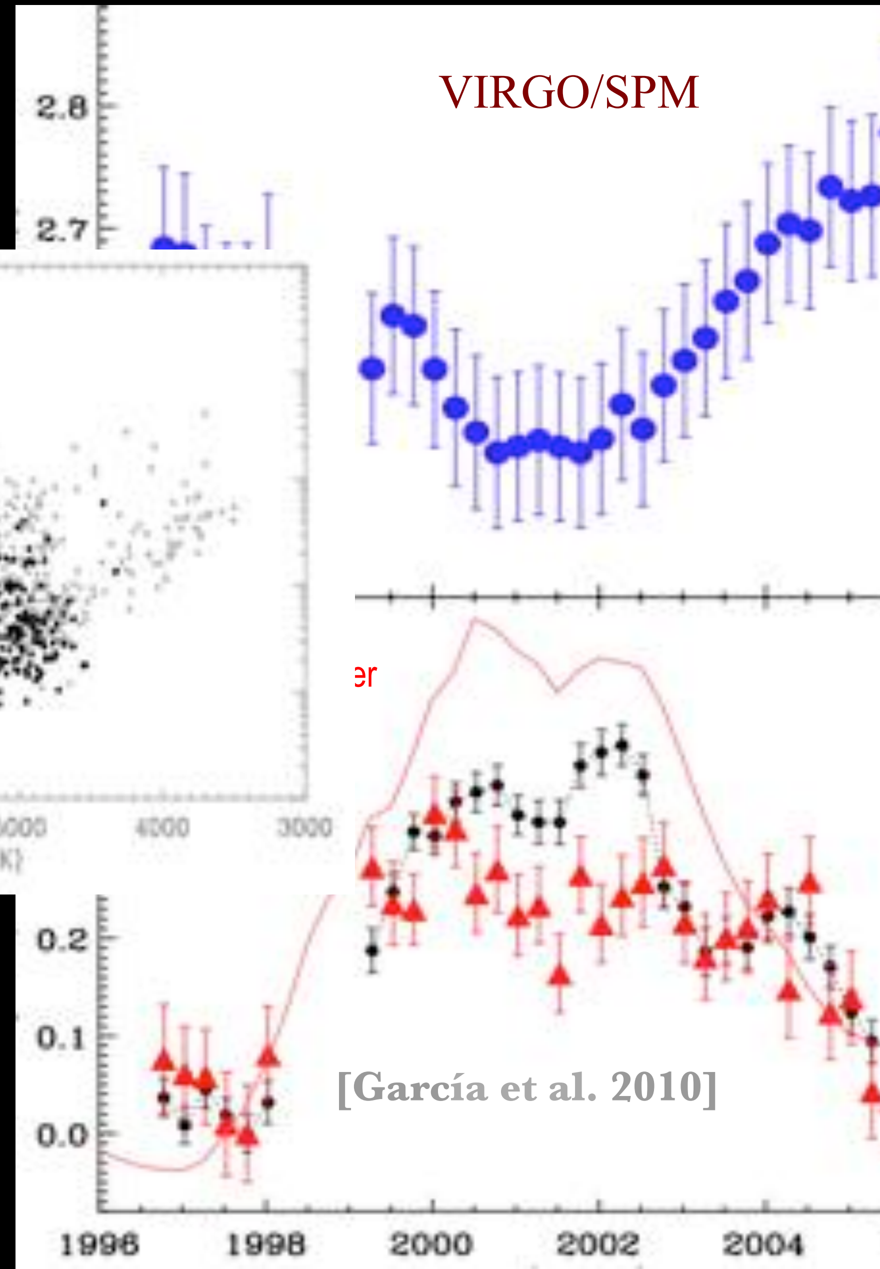
III-BIASED SAMPLE: SEISMOLOGY



[Garcia et al. 2013]



[Chaplin et al. 2011]



[García et al. 2010]

IV-Stellar magnetic cycles

IV-STELLAR MAGNETIC CYCLES

- Activity cycles are the consequence of:
  - Interaction between
    - Rotation, convection & magnetic fields
- There is a relation between:

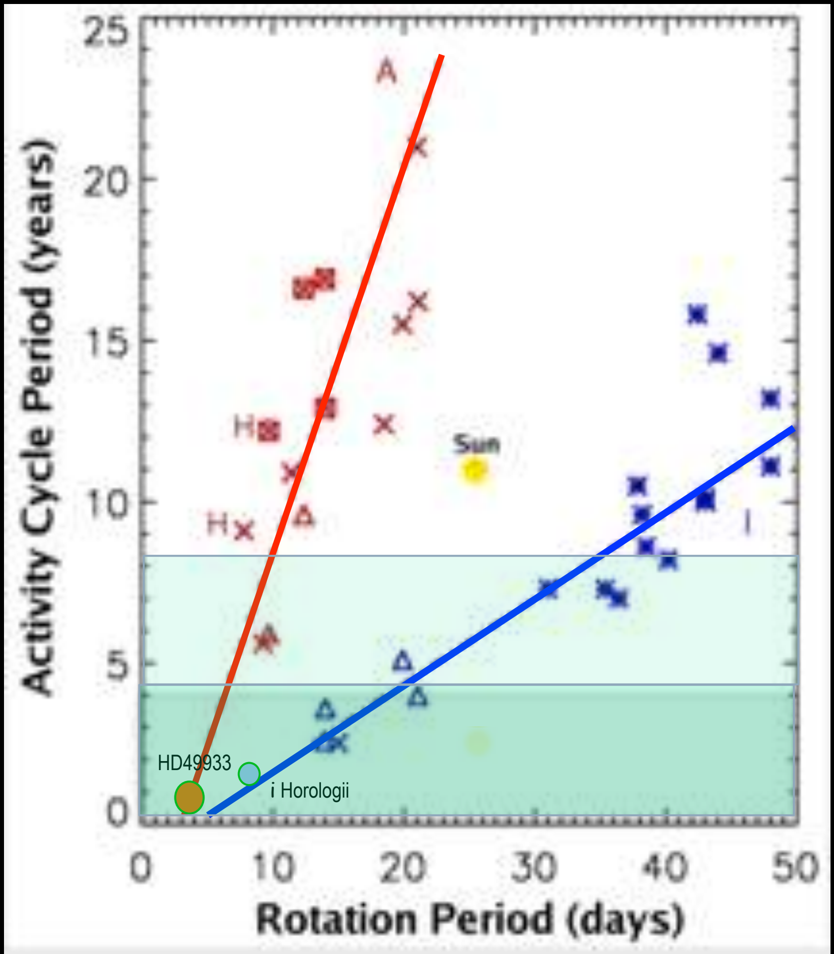
$$P_{cyc}/P_{rot} = \Omega/\ \Omega_{cyc} = CRo^q$$

[e.g. Thomas & Weiss 2008]

  - with $Ro = P_{rot}/\tau_c$, the Rosby number
  - τ_c the convective turnover time
  - q changing from 0.25 to 1

[e.g. Ossendrijver 1997; Saar 2002; Jouve et al. 2010]

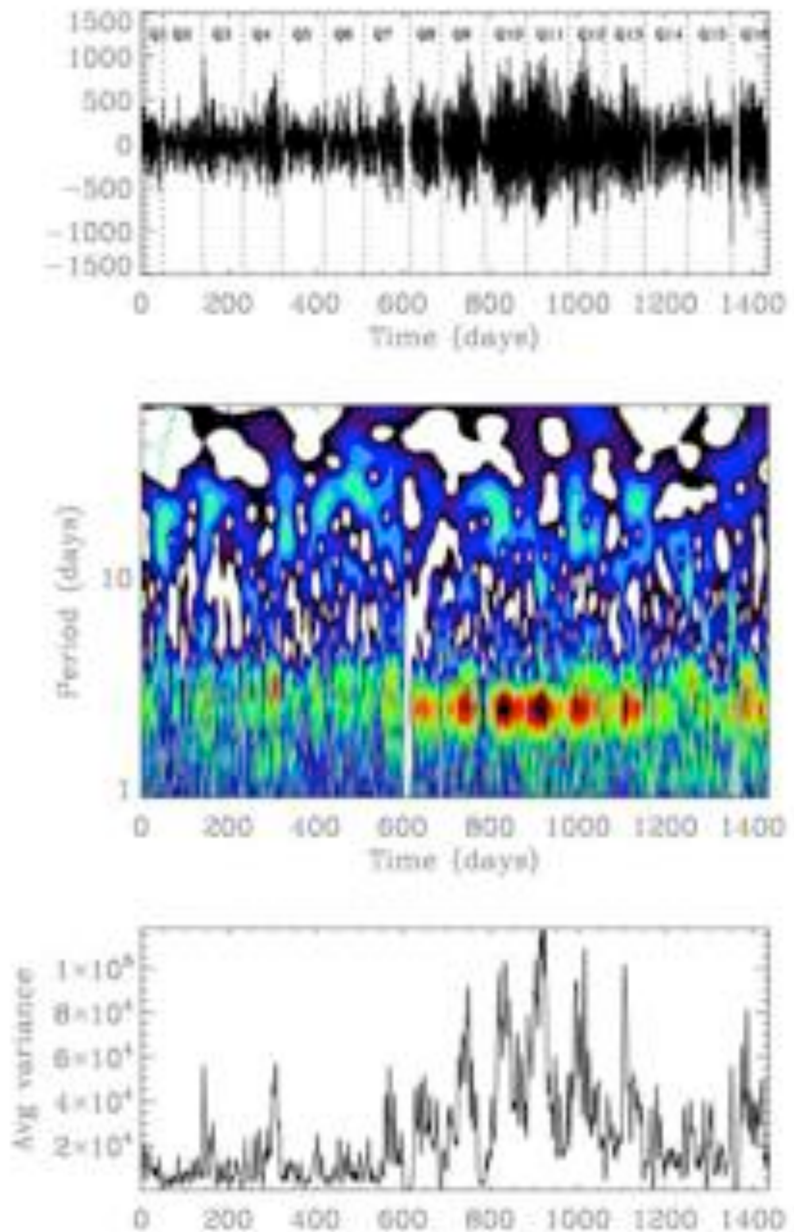
- Stellar activity cycles:
  - Two branches
  - The position of the Sun
    - Between both branches
- Faster rotators
  - Stronger magnetic activity amplitudes
  - Rarely have regular cycles



[Adapted from Bohm-Vitense, 2007
Based on Brandenbourg, Saar & Turpin 1998]

[Benevolenskaya 1995, Fletcher et al. 2010]

IV-STELLAR MAGNETIC CYCLES



[Mathur, Garcia, et al. 2014]

KIC3733735

P_{rot}=2.5d

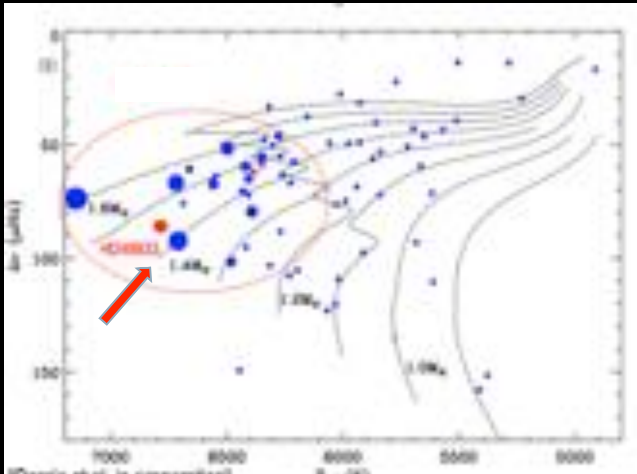
$<S_{ph}>$ = 250 ppm

i ~30^o

Asteroseismology:

M~1.4$M_\odot$

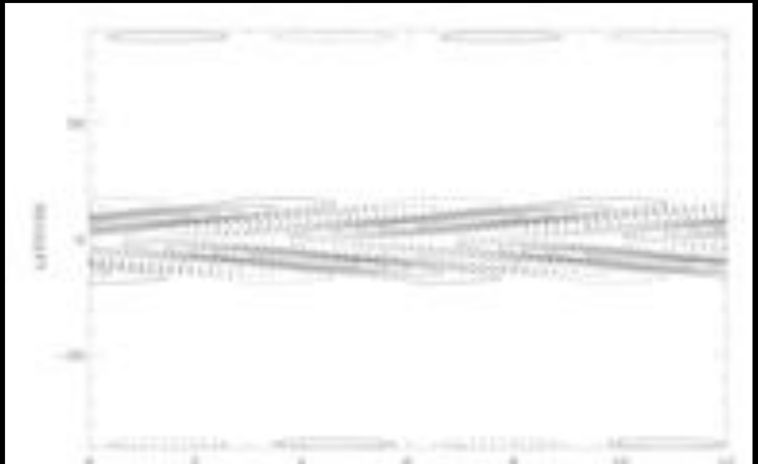
DCZ~1%



[Garcia et al. in preparation]

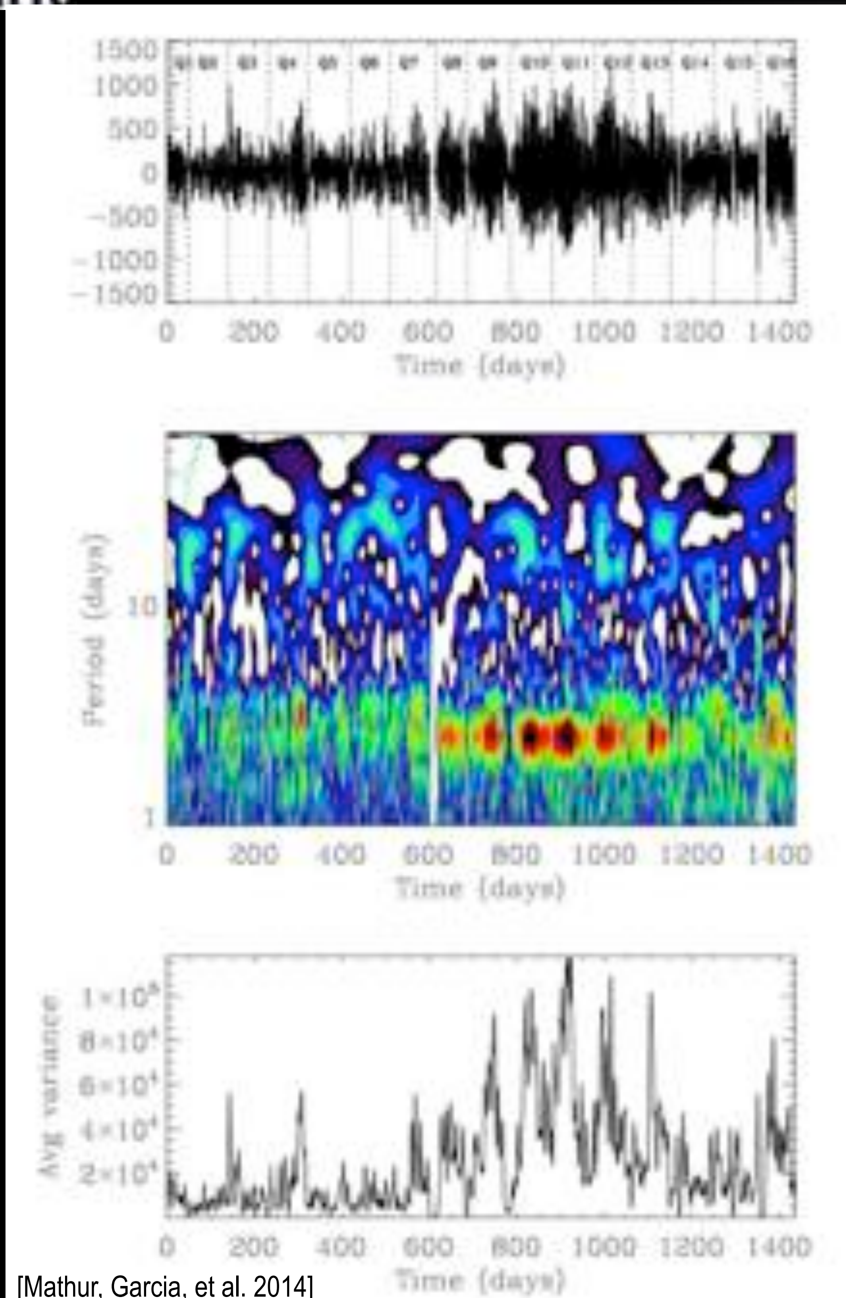
We observe:

- Magnetic Cycle like behaviour
- Presence of Active longitudes during maximum activity
- Mean field advection dominated model:



[Bonanno priv. comm.]

IV-STELLAR MAGNETIC CYCLES



[Mathur, Garcia, et al. 2014]

P_{rot}=2

<S_{ph}>

i ~30

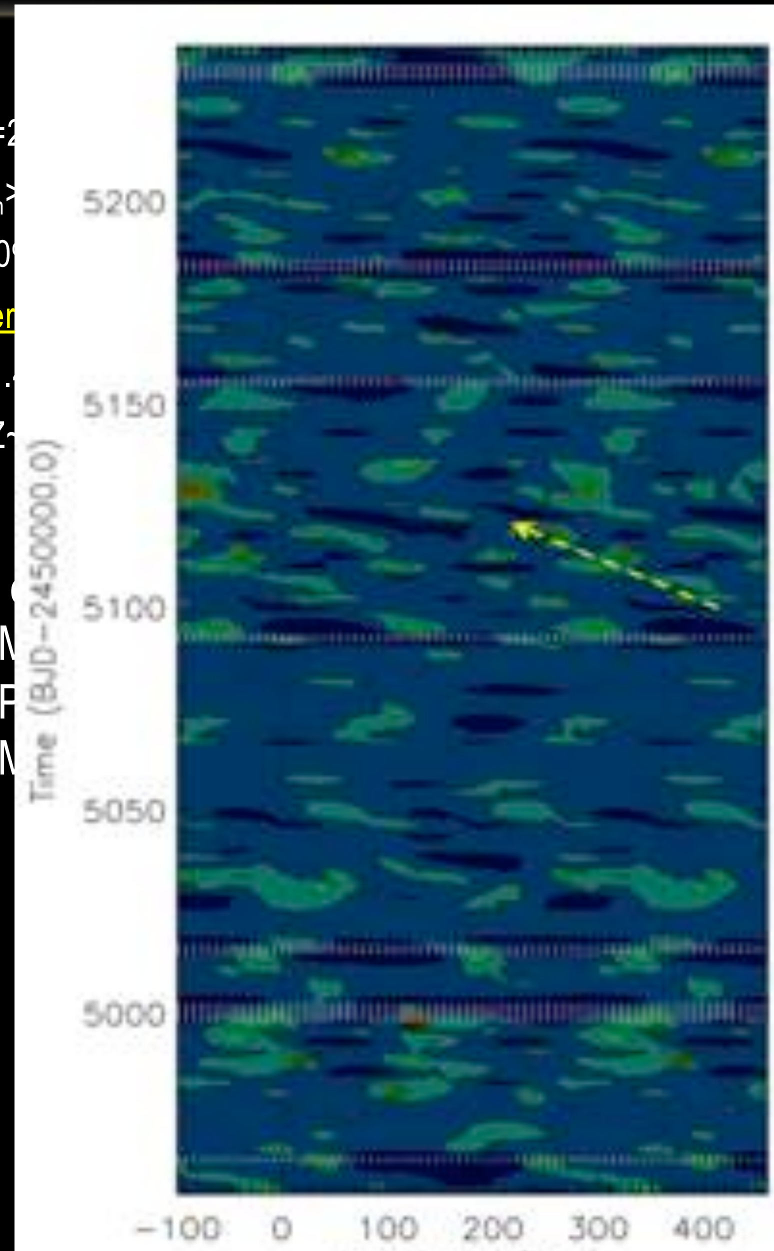
Aster

M~1.

DCZ~

We

- M
- P
- M

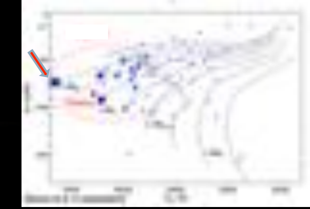


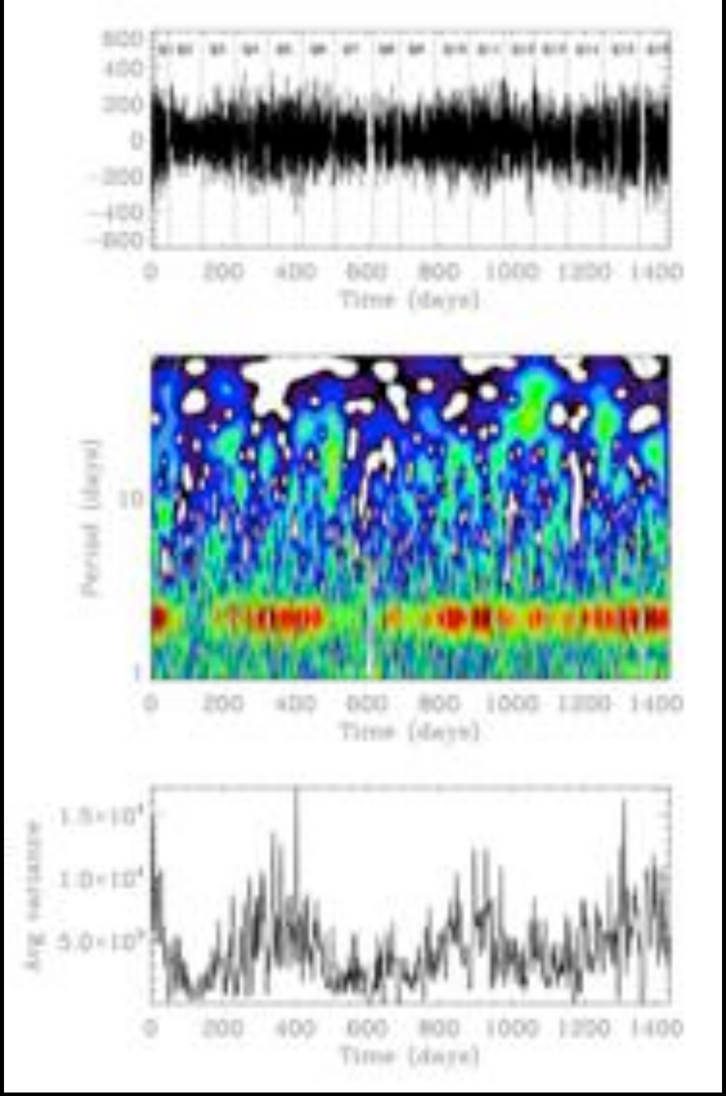
[Lanza priv. comm.]

m activity

nm.]

IV-STELLAR MAGNETIC CYCLES





KIC9226926

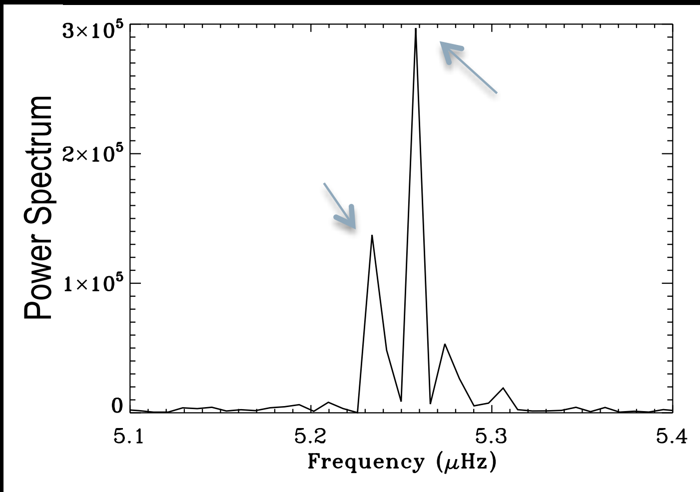
P_{rot}=2.2d

$<S_{ph}>$ = 104 ppm

Asteroseismology:

M~1.4$M_\odot$

DCZ~1%

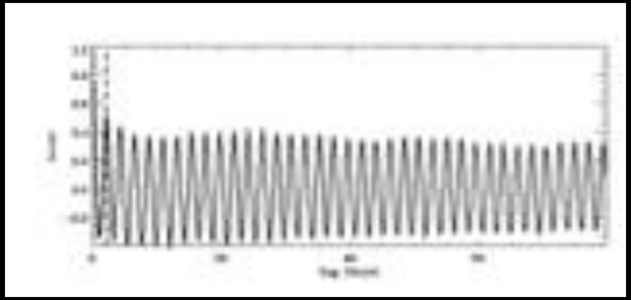


Two close frequencies (5.223 and 5.259 μHz)

→ Beating effect with a period of ~540 days

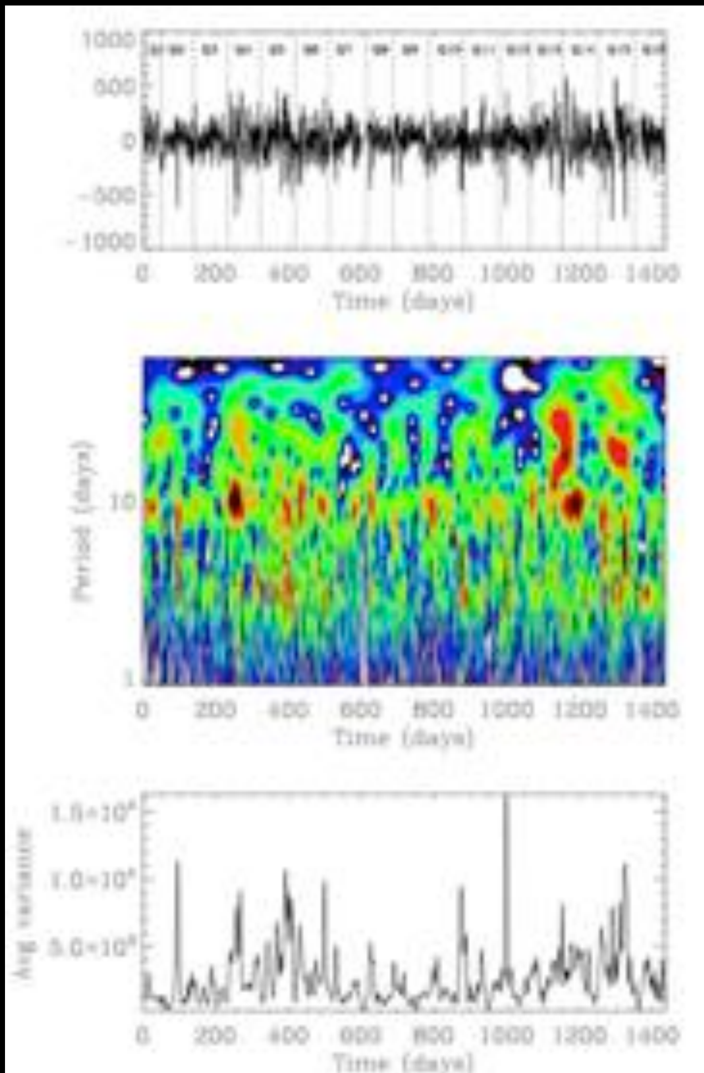
Not a cycle but signature of long lived magnetic structures:

→ Active longitudes

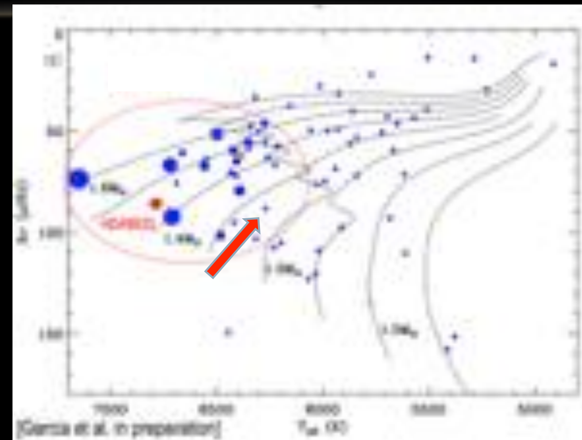


[Mathur, Garcia, et al. ApJ, 2014]

IV-STELLAR MAGNETIC CYCLES

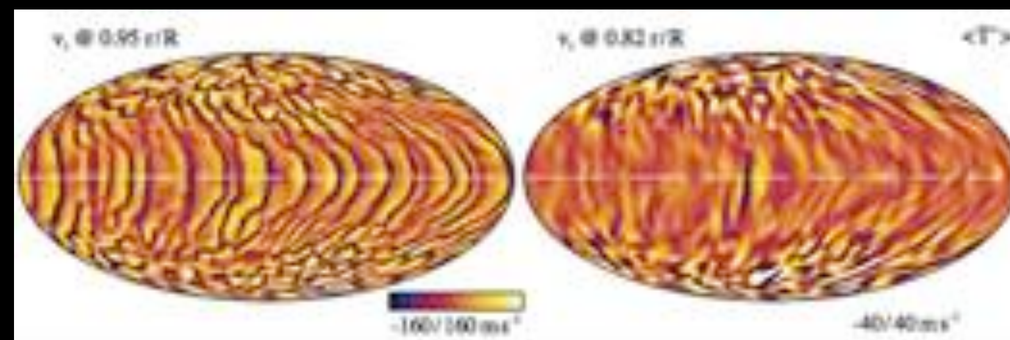


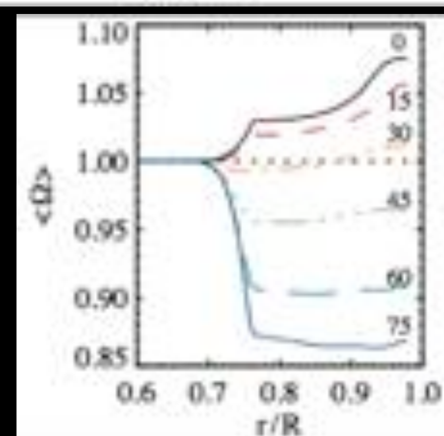
[Mathur, Garcia, et al. ApJ, 2014]



- KIC12009504
- 1D Seismic model
- 3D Model by ASH

Hydrodynamic models

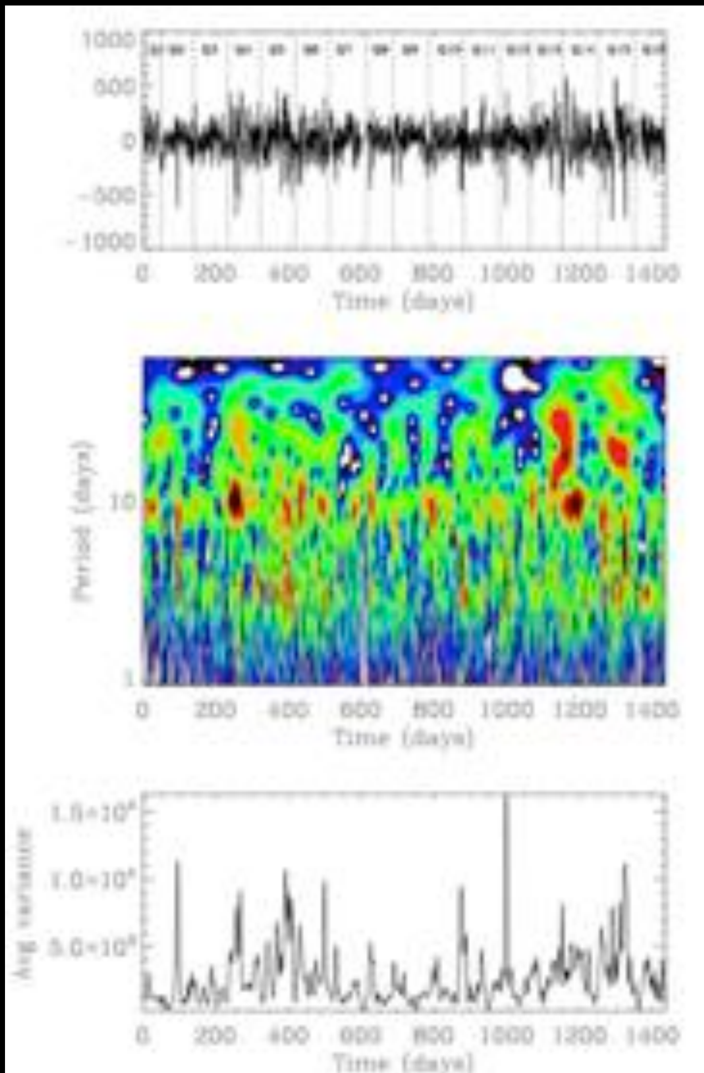




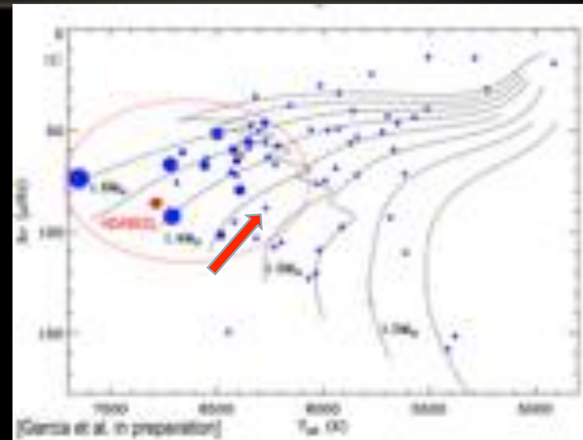
[Augustson, Mathur, Brun et al. in prep.]

P_{rot}=9.5d; M~1.12$M_{\odot}$; $<S_{ph}>$ = 167.1 ppm; DCZ 0.8 R

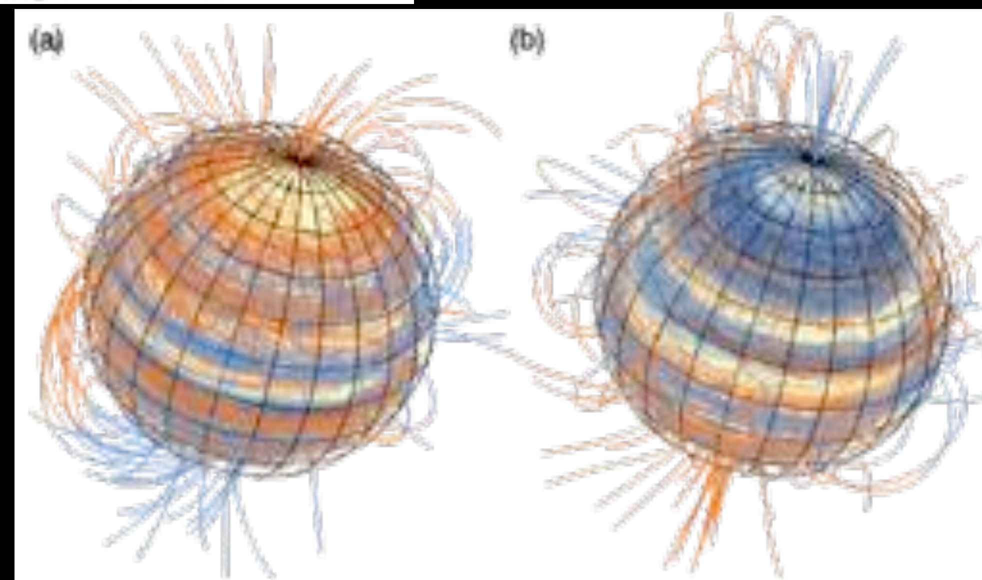
IV-STELLAR MAGNETIC CYCLES



[Mathur, Garcia, et al. ApJ, 2014]



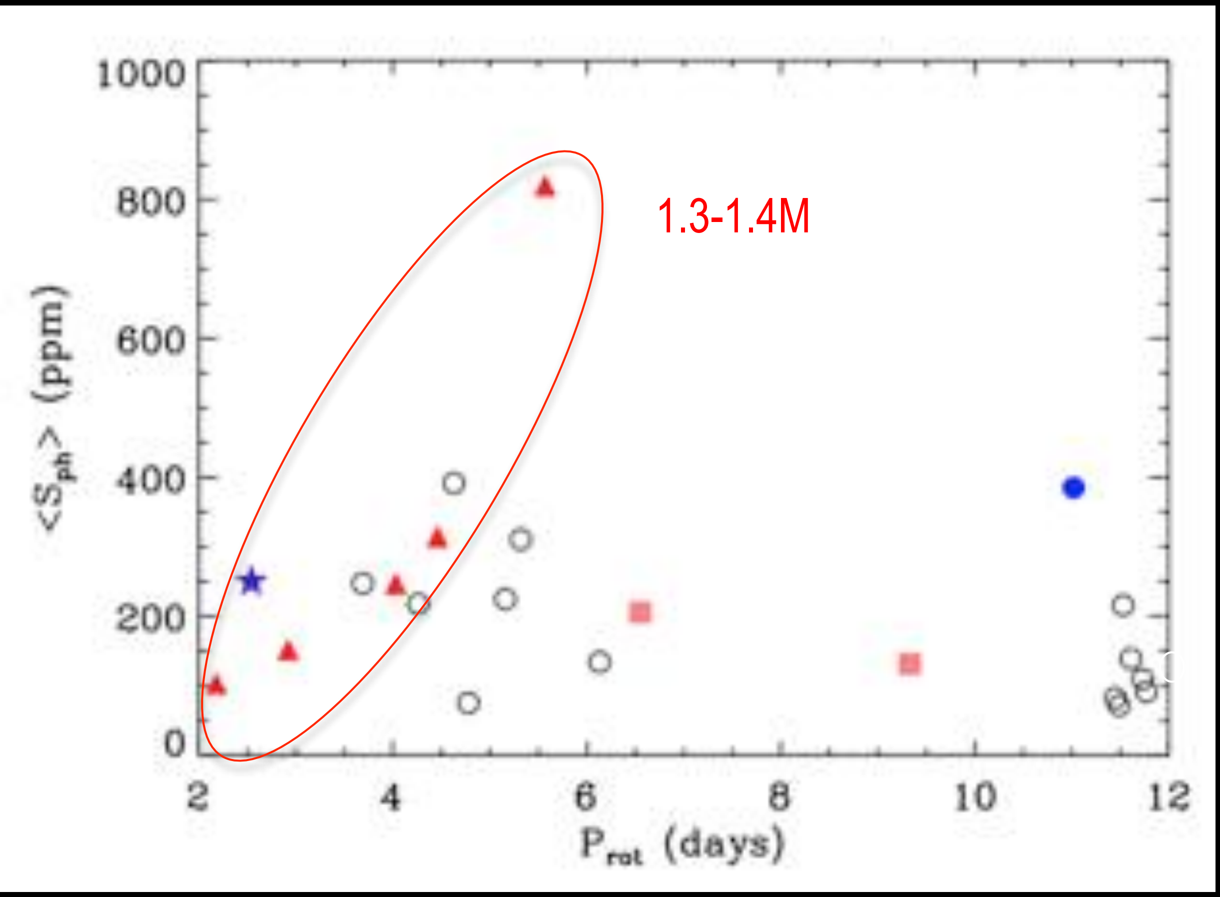
- KIC12009504
- 1D Seismic model
- 3D Model by ASH



[Augustson, Mathur, Brun et al. in prep.]

P_{rot}=9.5d; M~1.12$M_{\odot}$; $<S_{ph}>$ = 167.1 ppm; DCZ~20%

IV-STELLAR MAGNETIC CYCLES



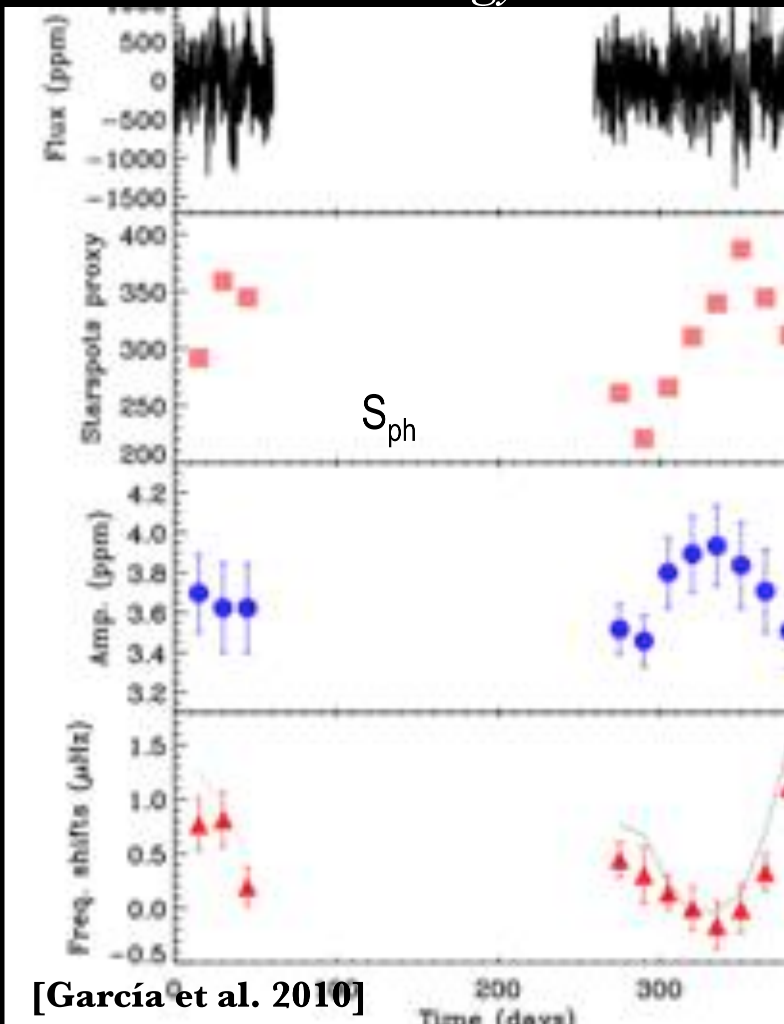
▲ Long-lived active longitudes
■ Trends
● Cycle

[Mathur, Garcia, et al. ApJ, 2014]

HINTS OF A MAGNETIC-ACTIVITY CYCLE

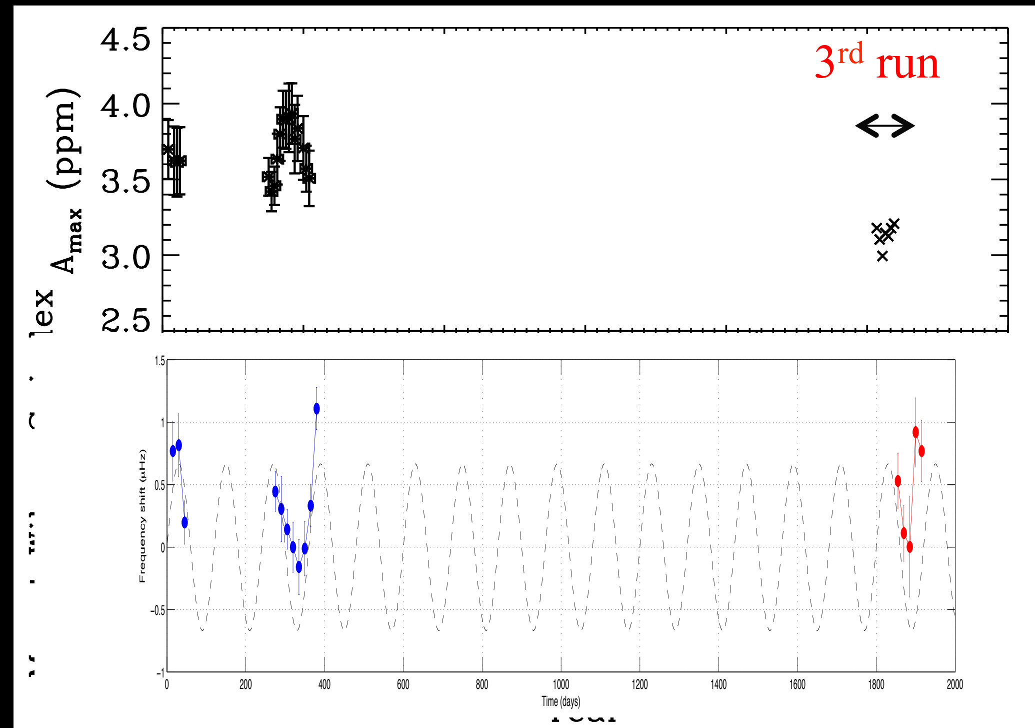
Seismology

CoRoT



[García et al. 2010]

HD49933



Anticorrelation between amplitude variation and frequency shifts

P_{cyc}>120days

- Complementary observations
  - ✓ Ca HK: Mount Wilson index of 0.31
    Active star

Modified S_{ph} also used by Chaplin et al. 2011
Campante et al. 2014

CONCLUSIONS

Understand stellar dynamics and magnetism

Is required

To properly model stellar interiors

To better constraint geometry of exoplanetary systems

To properly interpret exoplanet atmospheres

Characterization of Habitable zones (development of life)

Studying many solar-like stars will help

to better understand The Solar magnetism

TESS