Service d'Astrophysique
Laboratoire AIM

STELLAR ROTATION & ACTIVITY

FROM THE SURFACE TO THE INTERIOR MEASURED BY COROT AND *KEPLER*

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Special thanks to:

K. Auguston, J. Ballot, A. Bonanno , A.S. Brun, T. Ceillier, A. Lanza, S. Mathur, T. Metcalfe, J. van Saders, D. Salabert & J. Tayar

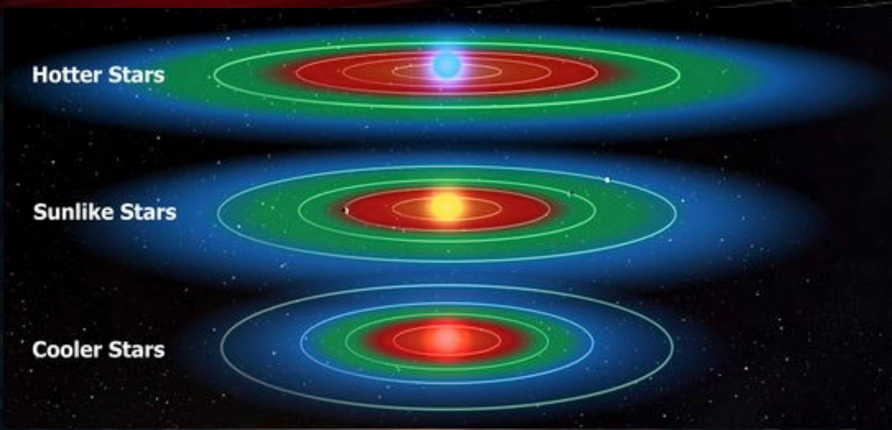
GENERAL OUTLINE

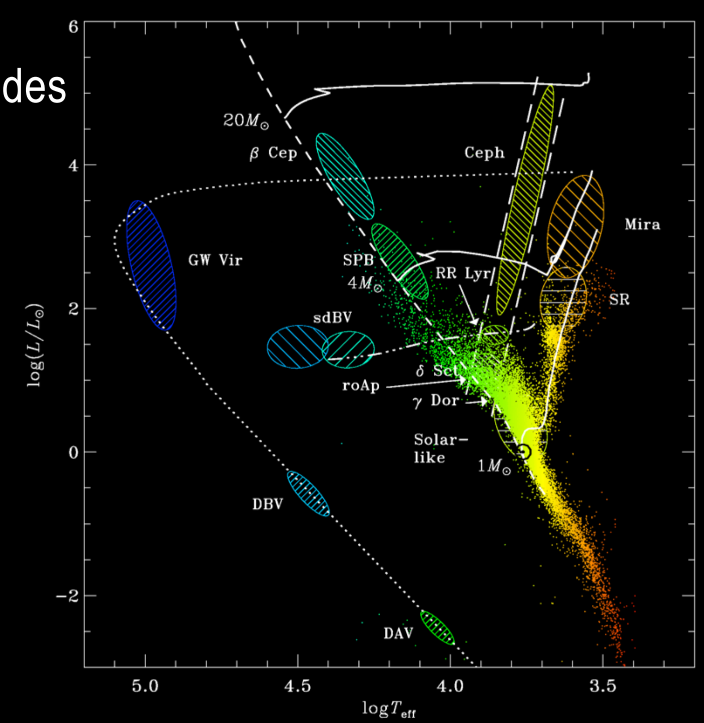
- I- Introduction
  - Why study the dynamics of other stars and their magnetism?
    - Closer look to solar-like stars
    - Using long time series high-precision photometry from space
- II- Stellar Dynamics
  - Rotation
  - Magnetism
- III- Surface magnetic activity proxy
  - Definition photospheric 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

- Why study the dynamics of other stars and their magnetism?
  - Are the dynamics of the Sun particular or its properties are common?
  - Put the Sun in a broader, evolutionary context
  - Solar-stellar connection
  - Star-planet interaction: Habitability
  - Validate gyrochronology
  - Dynamical stellar evolution codes





I-INTRODUCTION

➢ What can offer high-precision photometry (HPP) to better understand stellar dynamics & magnetism ?

- 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 Pia di Mauro et al. subm.]
- Convection properties
  - Characteristic time scale and velocities 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 [e.g. Mathur et al. 2012; Mazumdar et al. 2014; Metcalfe et al. 2014]
  - Probing (or not) the existence of internal magnetic fields
- Activity cycles
  - 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:

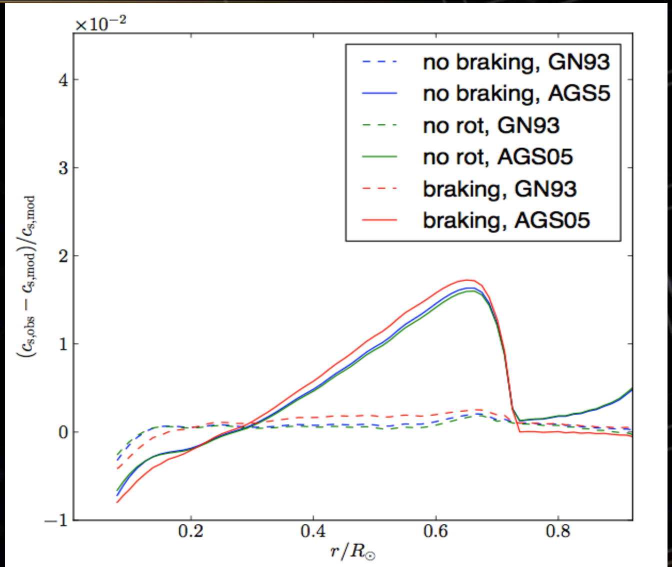
Rotation

II-EFFECTS OF INTERNAL ROTATION

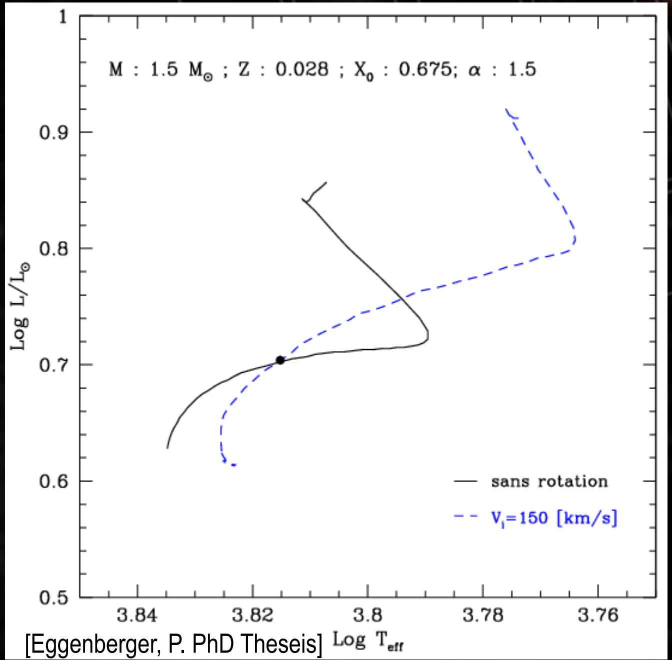
- Why studying the rotation of stars?
  - It changes stellar evolution:
    - Angular momentum transfer
    - Mixing
  - It also changes seismic variables:

	Model no rotation	V_i = 150 km s-1
$\Delta\nu$	70.40 μHz	69.94 μHz
$\delta\nu_{02}$	5.07 μHz	5.76 μHz

  - When rotation is considered in models:
    - Modify p-mode frequencies
    - high orders (surface effects?)



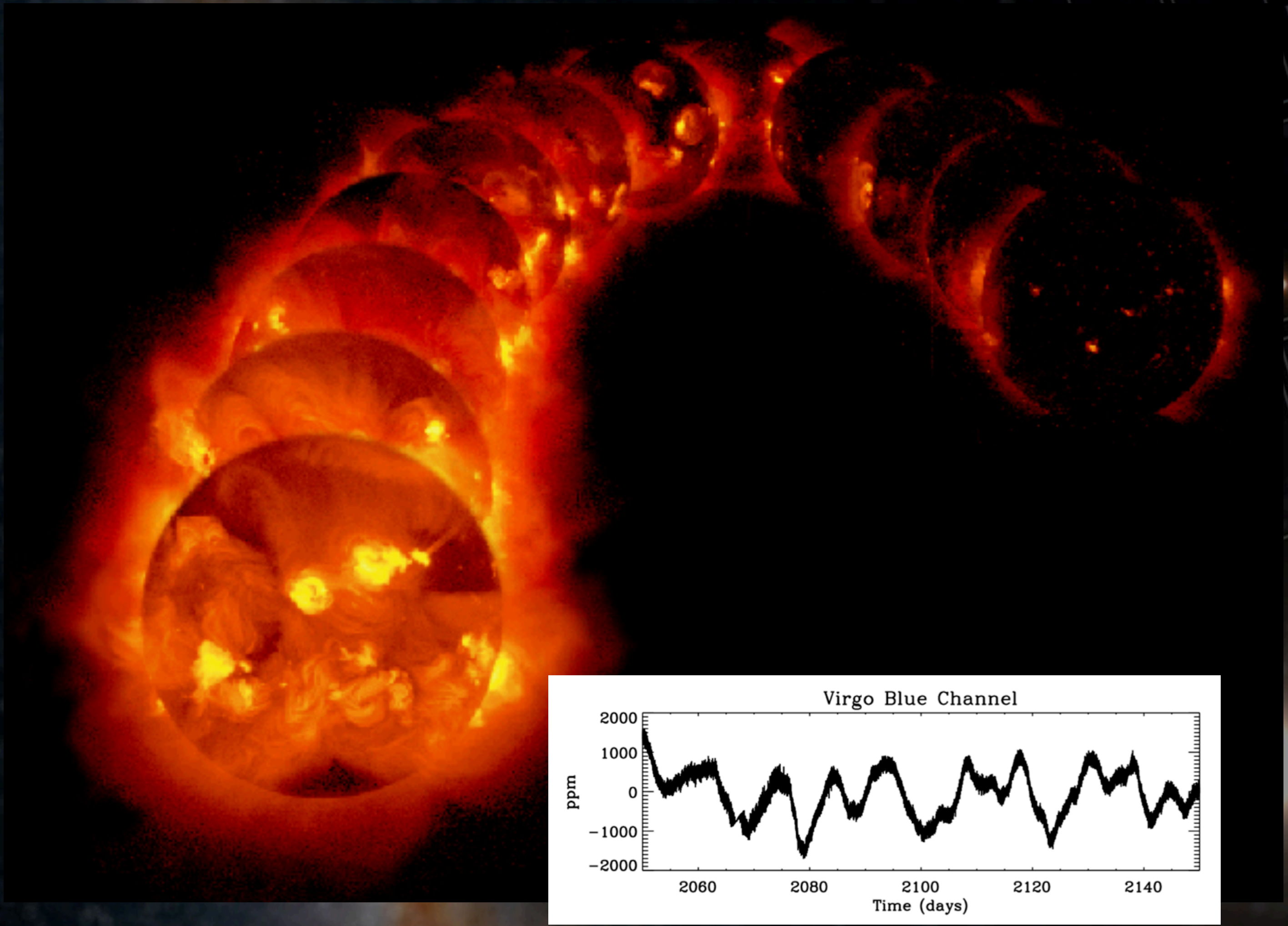
[Marques, et al. 2012; Turck-Chièze et al. (2010)…]



[Eggenberger, P. PhD Theseis]

II-MAGNETIC VARIABILITY & ROTATION

- When a star is magnetically active
  - Starspots crossing the visible disk of stars induce a modulation in the light curve



Solar Activity Maximum

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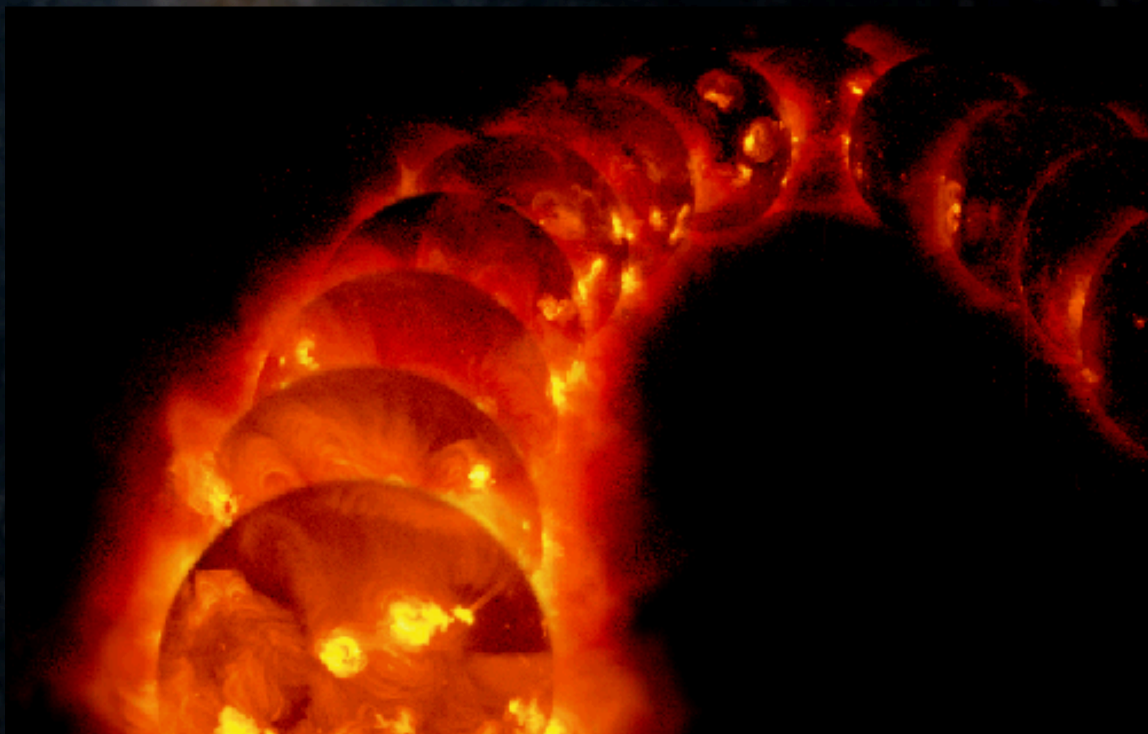
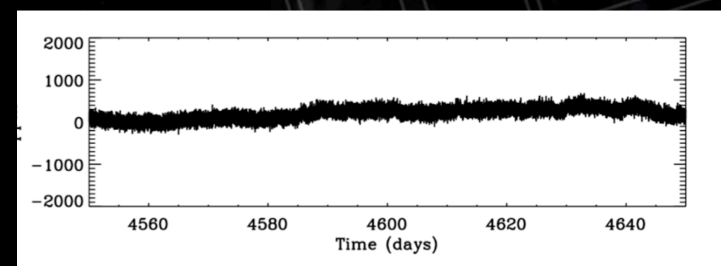
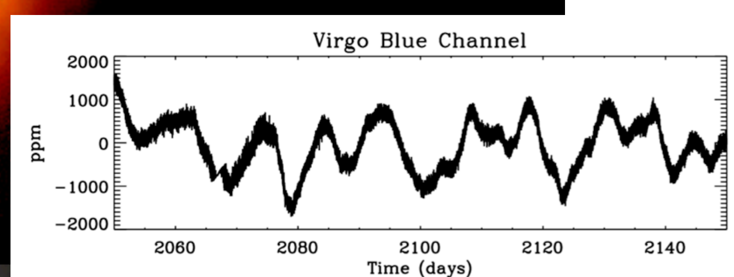




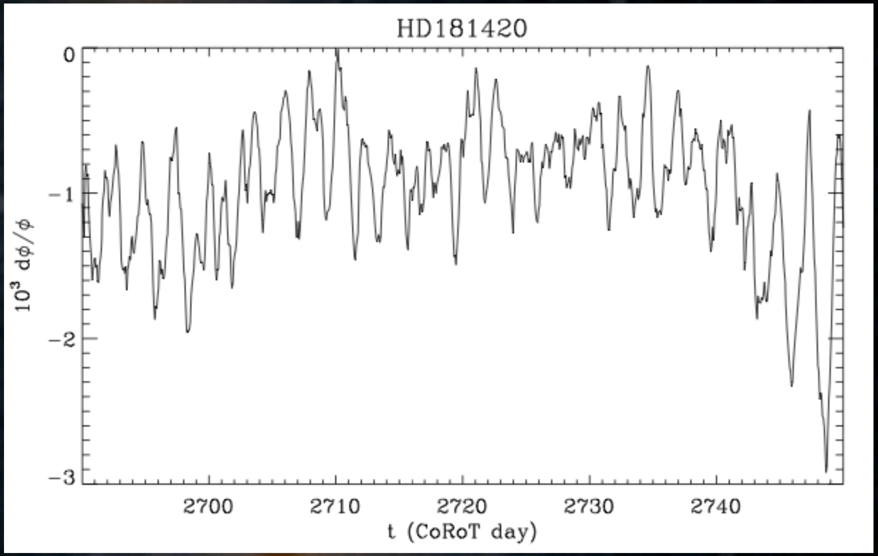
Solar Activity Minimum

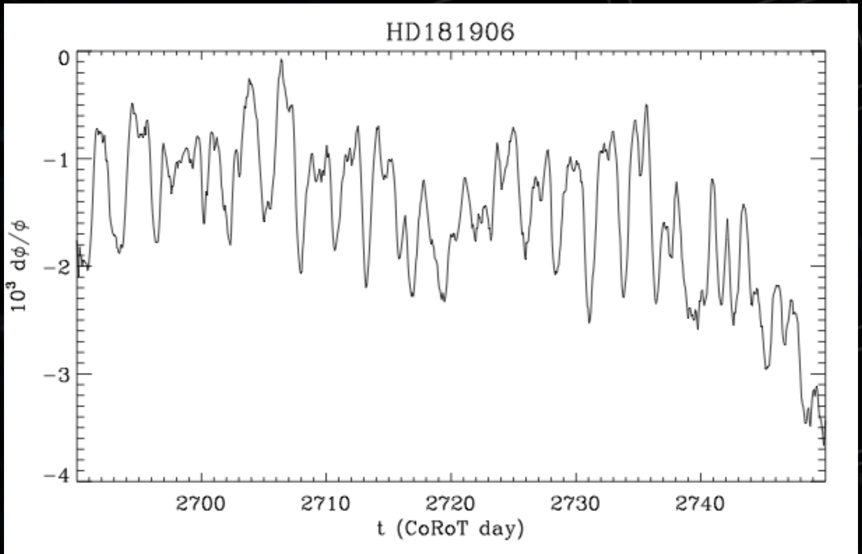


Solar Activity Maximum

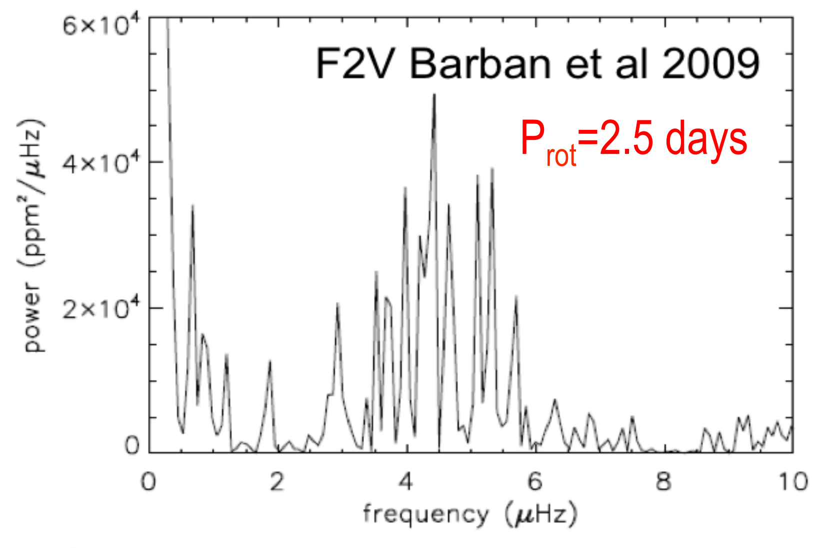
II-SURFACE ROTATION

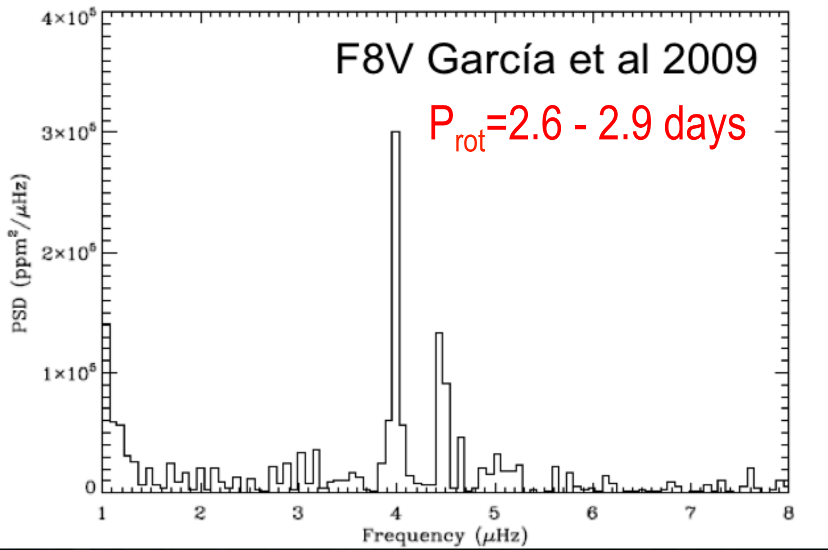
- Examples of two CoRoT F Stars





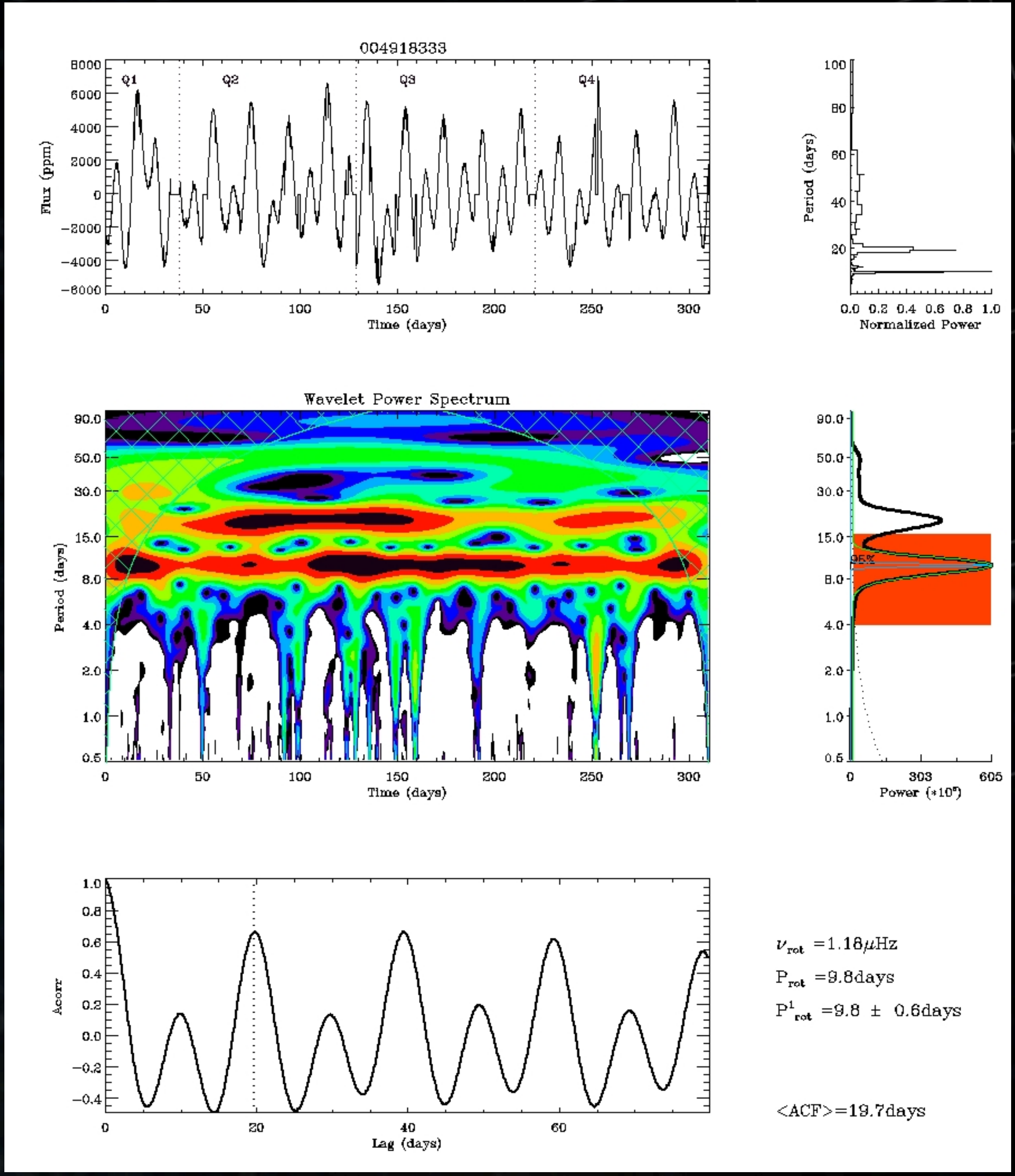
- Analysis of the low-frequency range of the periodogram





II-SURFACE ROTATION

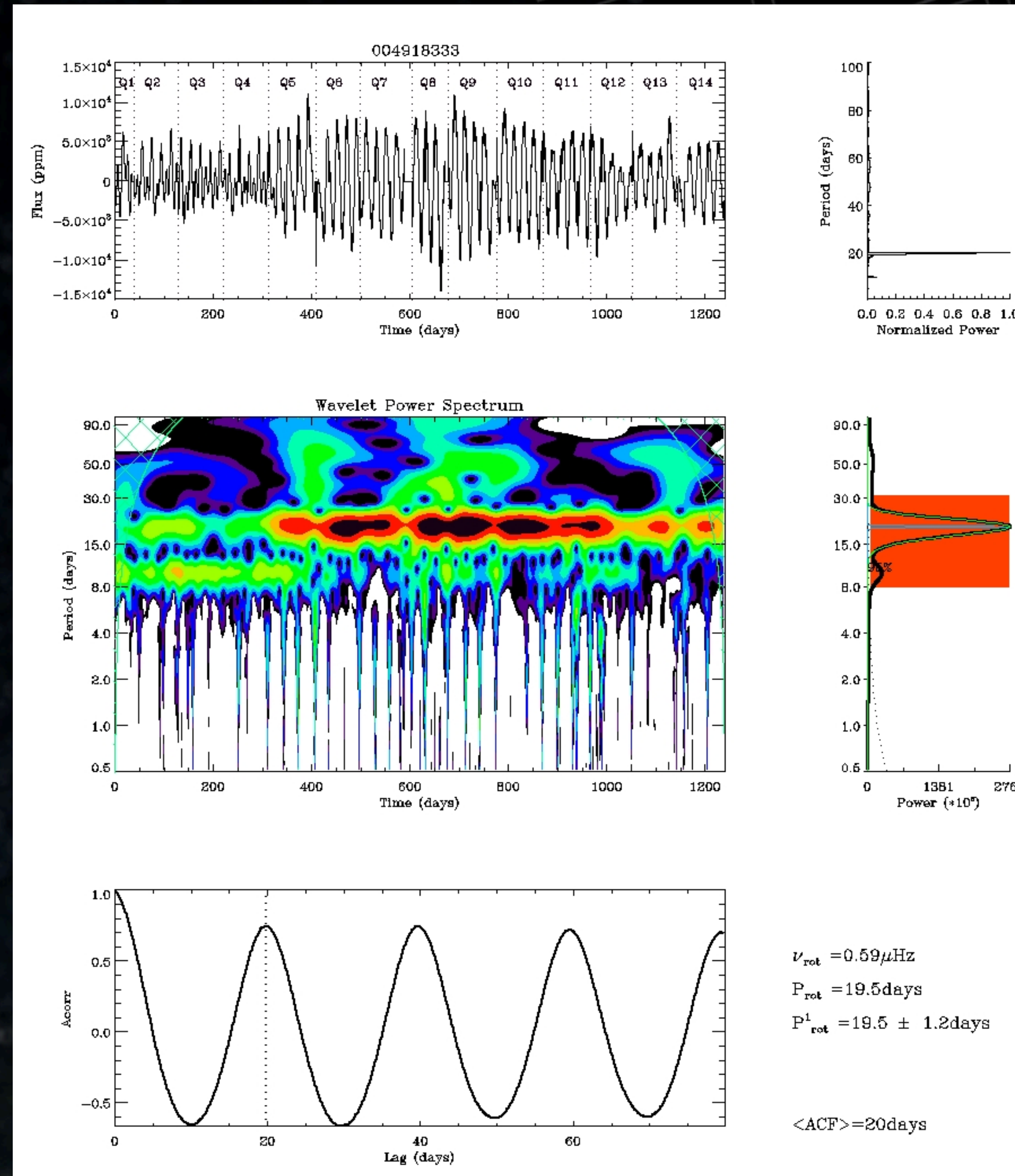
- Techniques based on the analysis of the low-frequency part of the Periodogram
  - Problem:
    - 2^{nd} > 1^{st} harmonic
    - Check half of P_{rot}
- Autocorrelation
  - Powerful for capturing the correct P_{rot}
    - When there are two well defined
      - active longitudes



[KIC4918333 from McQuillan et al. 2013]

II-SURFACE ROTATION

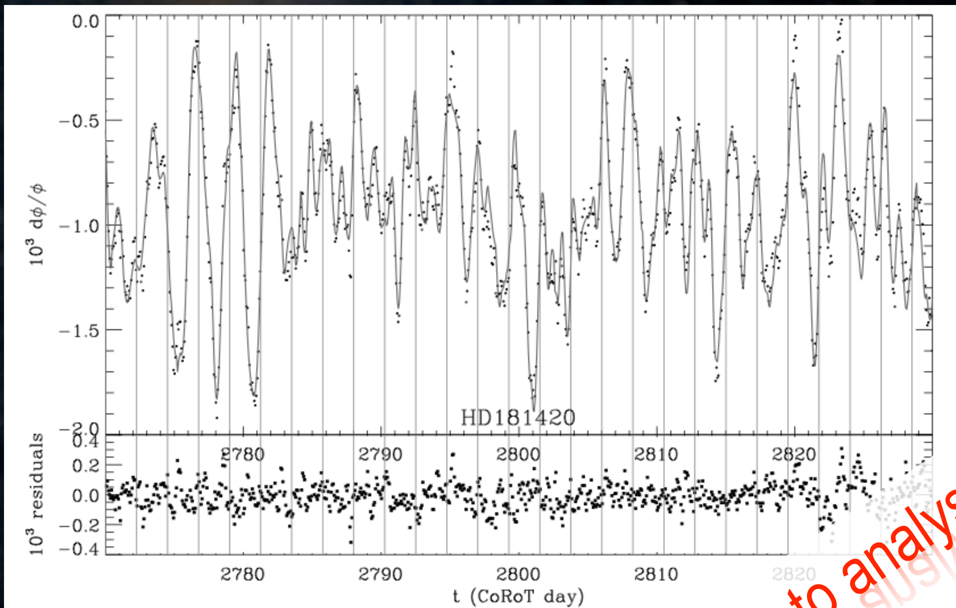
- Techniques based on the analysis of the low-frequency part of the Periodogram
  - Problem:
    - 2nd > 1st harmonic
    - Check half of P_{rot}
  - Using all the available data
    - Could solve it !!
- Autocorrelation
  - Powerful for capturing the correct P_{rot}
    - When there are two well defined
      - active longitudes



[KIC4918333 from McQuillan et al. 2013]

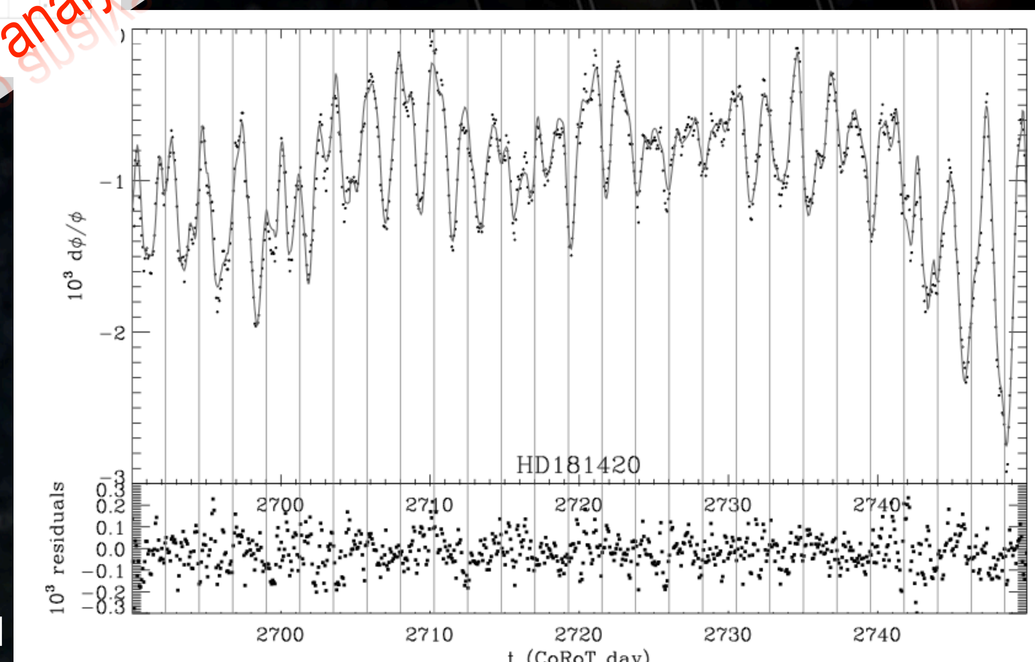
II-SURFACE ROTATION

- Spot modelling
  - Robust estimation of:
    - Average rotation
    - Spot lifetime
  - More uncertain estimation of:
    - Size and distribution of spots
    - Inclination of the star
    - Differential rotation



[Mosser et al. 2009]

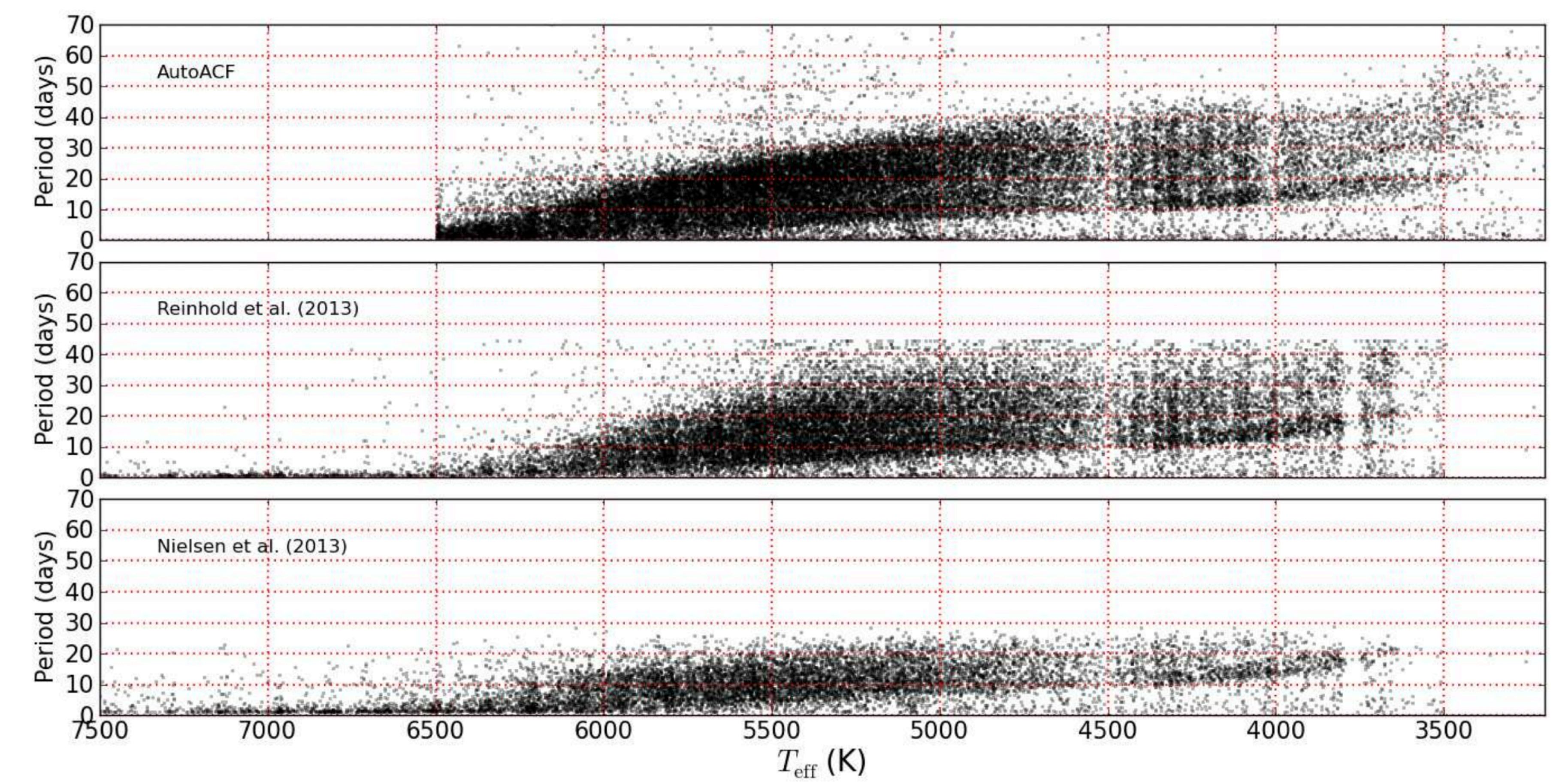
Very time consuming to analyse hundred to thousand stars



[see also e.g. Frohlich et al. 2012; Lanza et al.2014, Bonano et al. 2015]

II-SURFACE ROTATION

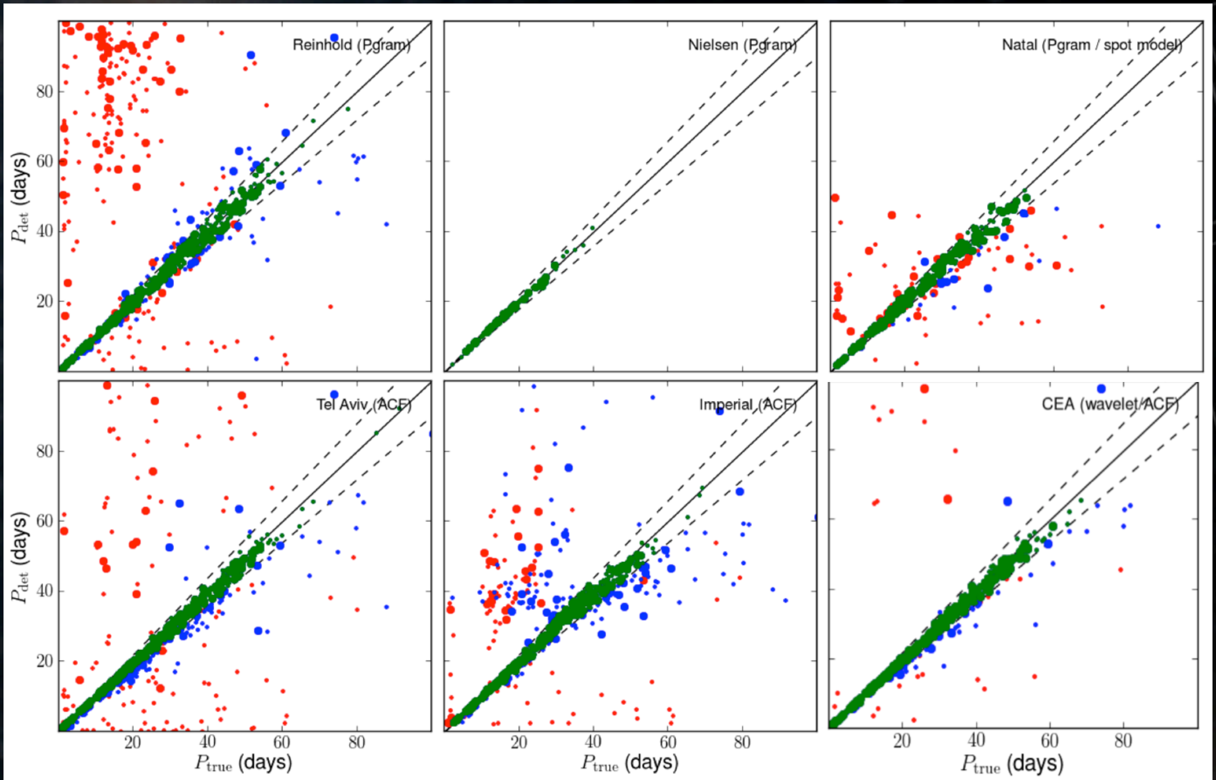
	AutoACF	Reinhold et al. (2013)	Nielsen et al. (2013)
Total Number	34,030	24,124	12,515
AND AutoACF	–	20,009	10,381
AND Reinhold et al. (2013)	20,009	–	9,292
AND Nielsen et al. (2013)	10,381	9,292	–

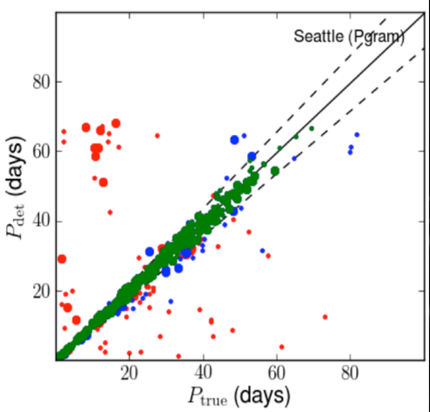


[McQuillan et al. 2014]

II-VALIDATING P_{ROT}

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



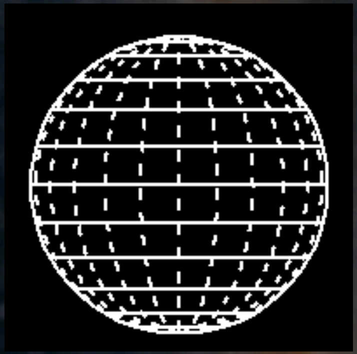


[Aigrain et al. Subm.]

Method	Noisy % det	Noisy % good	Noisy % ok	Noise-free % det	Noise-free % good	Noise-free % ok	solar No. det	solar 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-INTERNAL ROTATION

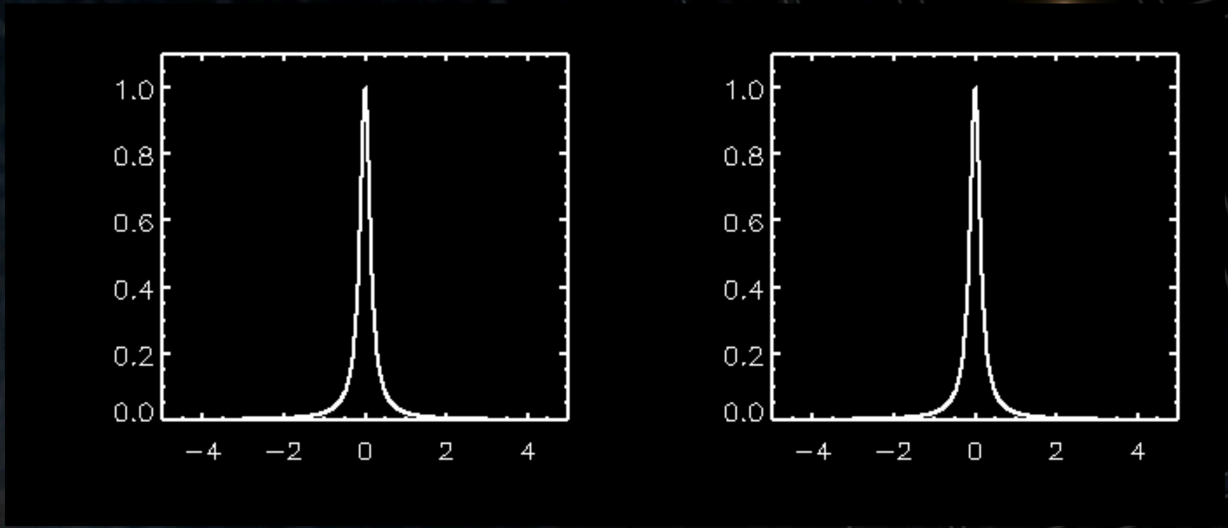
Ω = 0,0



i = 90°

ℓ=1 mode

ℓ=2 mode



[Adapted from J. Ballot 2010]

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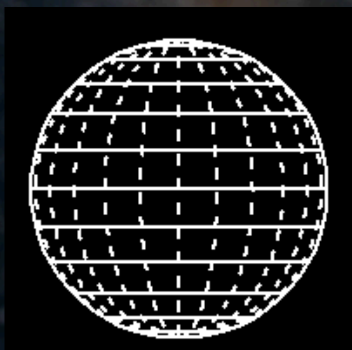

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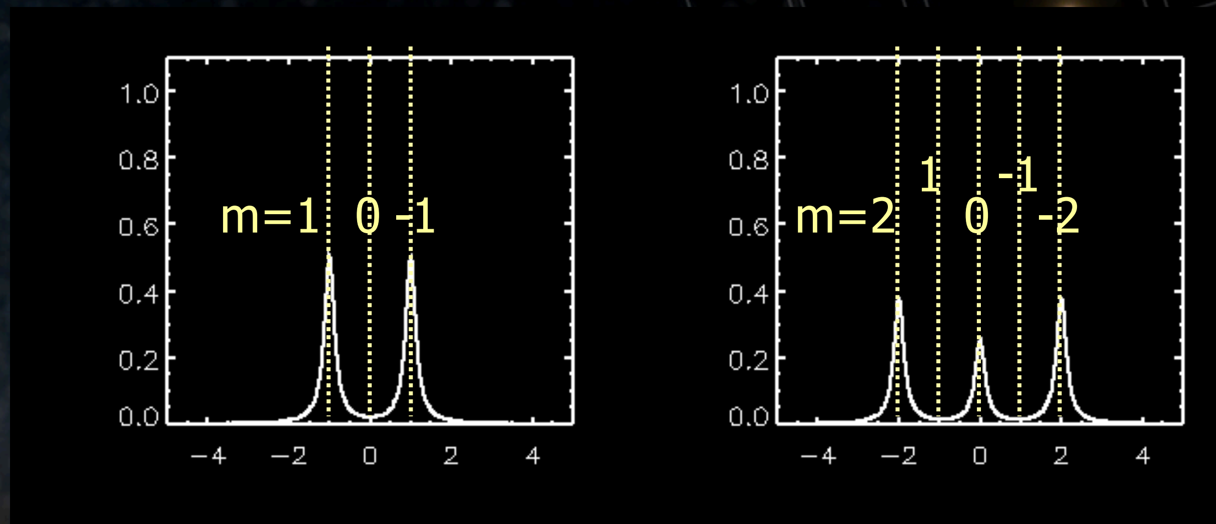

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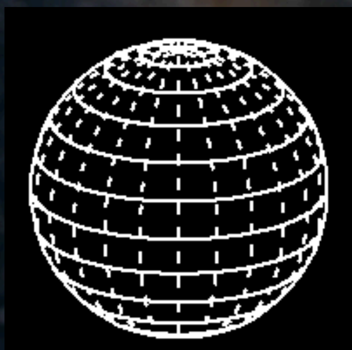
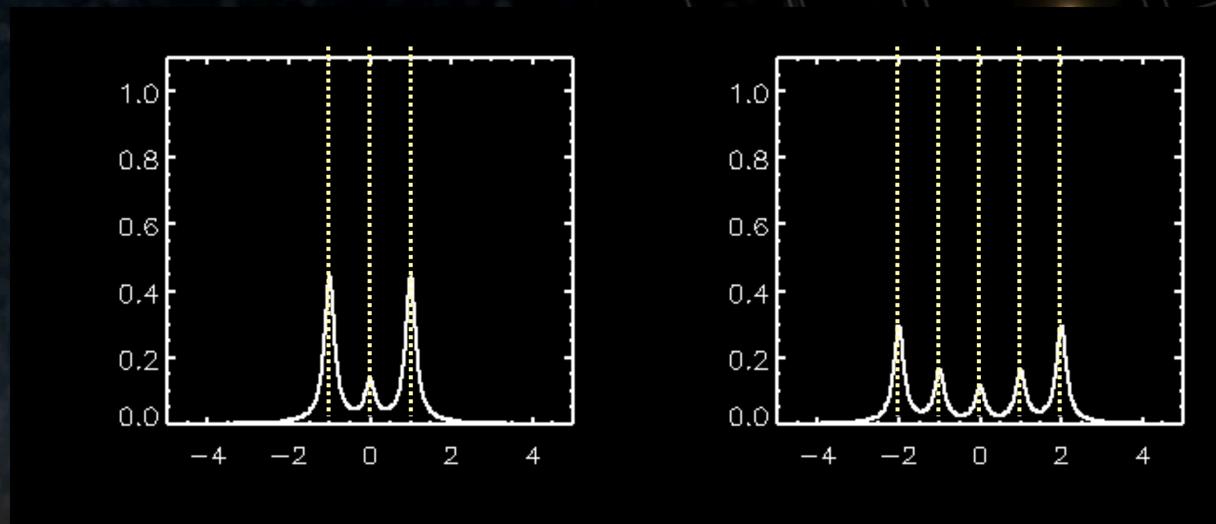


i = 70°

ℓ=1 mode

ℓ=2 mode



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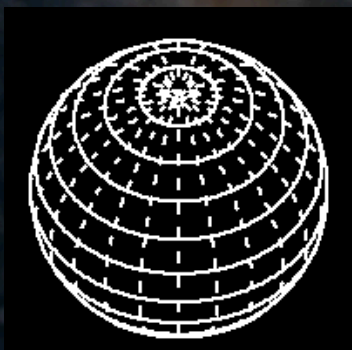
II-INTERNAL ROTATION

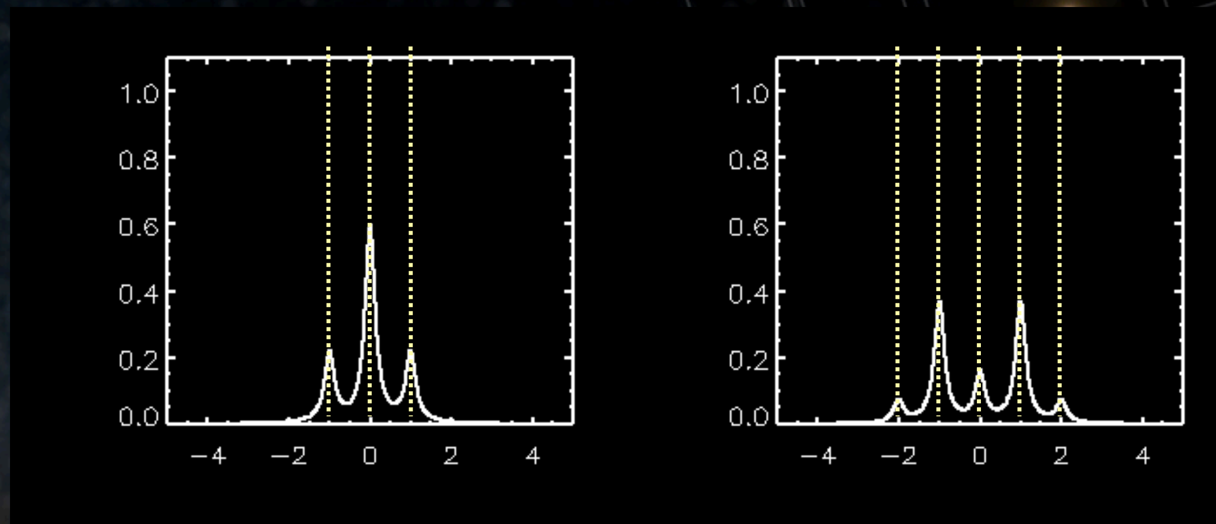
Ω = 1,0



i = 40°

ℓ=1 mode

ℓ=2 mode



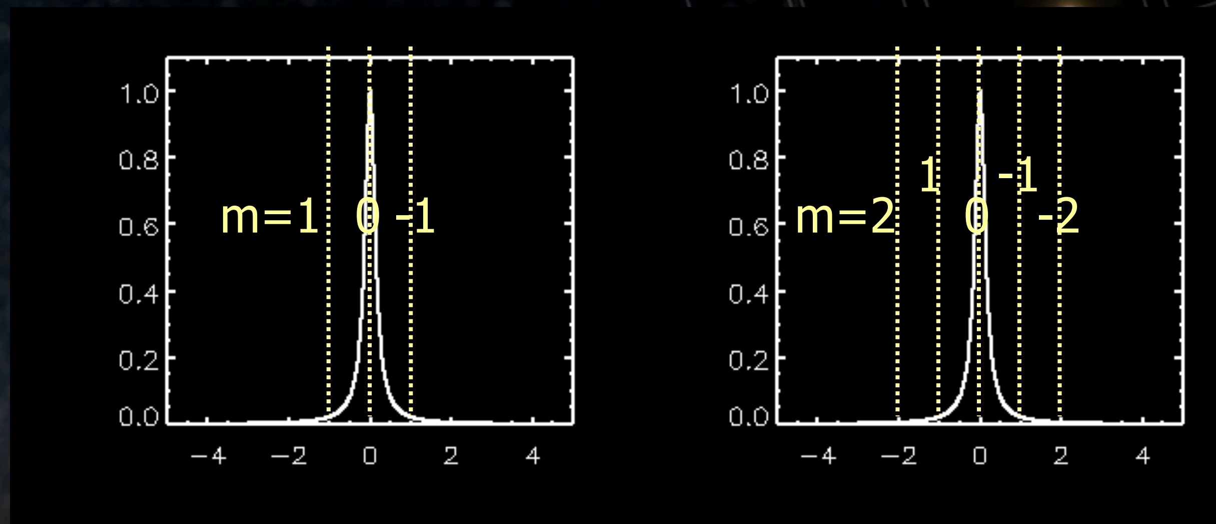
[Adapted from J. Ballot 2010]

II-INTERNAL ROTATION

Ω = 1,0

i = 0°

ℓ=1 mode ℓ=2 mode

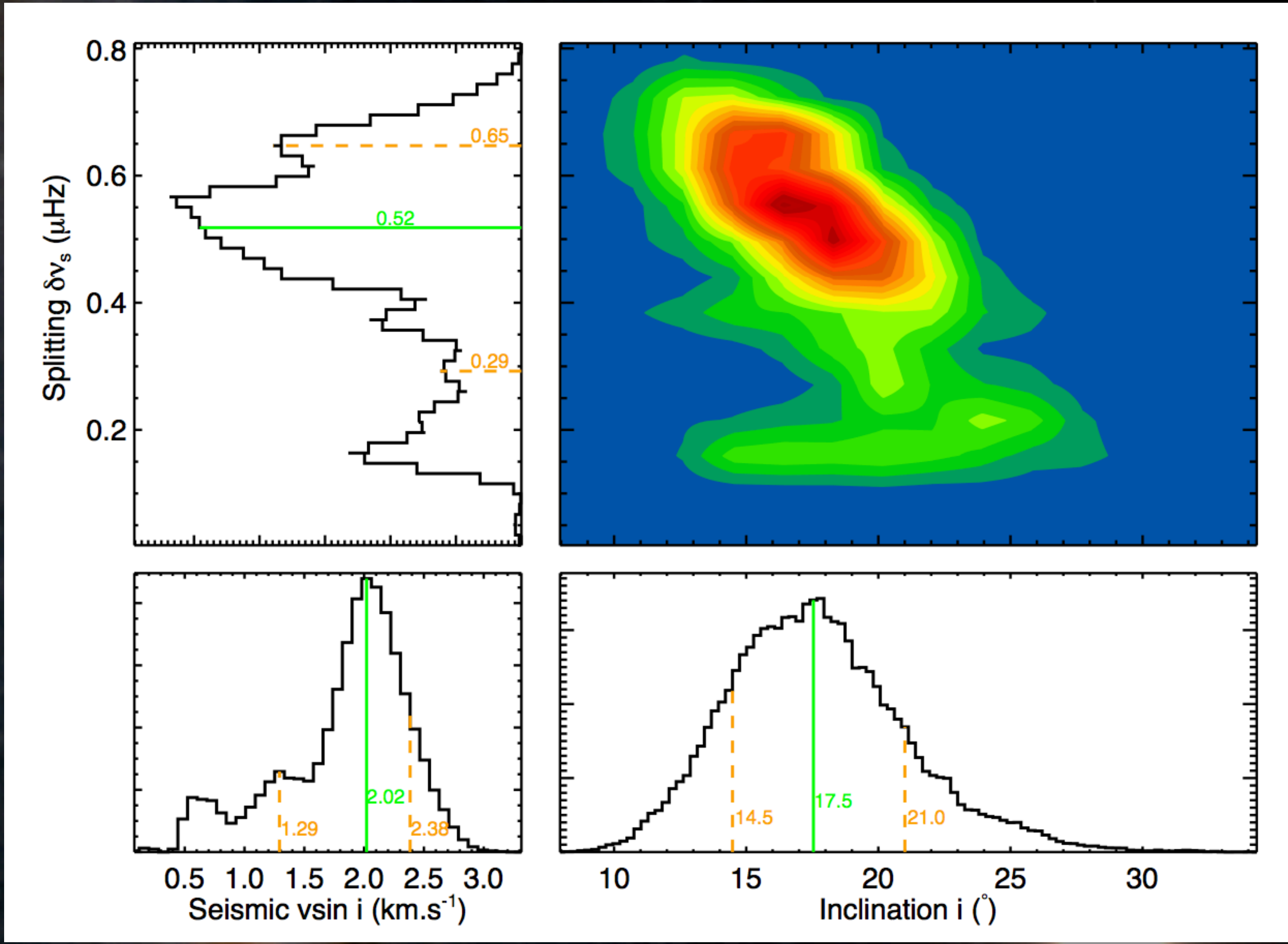


- Strong correlation between angle and splitting
  - We need to fit the stellar inclination angle and the rotational splitting together

[Ballot et al. 2006]

[Adapted from J. Ballot 2010]

II-INTERNAL ROTATION (MS)



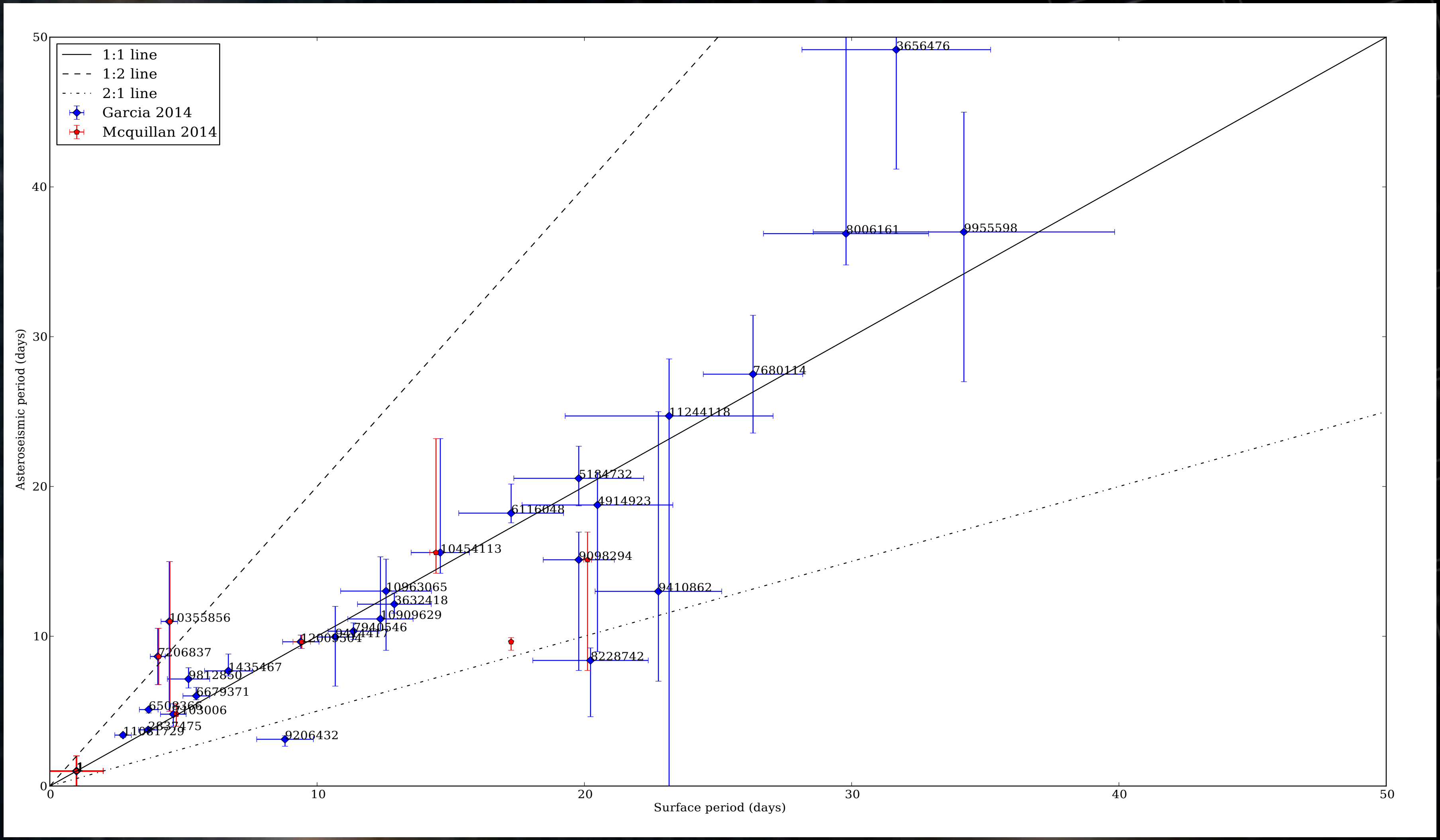
[García et al. 2014; see also Gizon et al. 2013; Davies et al. 2015, Benomar et al. submitted]

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]

III-VALIDATING P_{ROT}

- Using seismic inferences



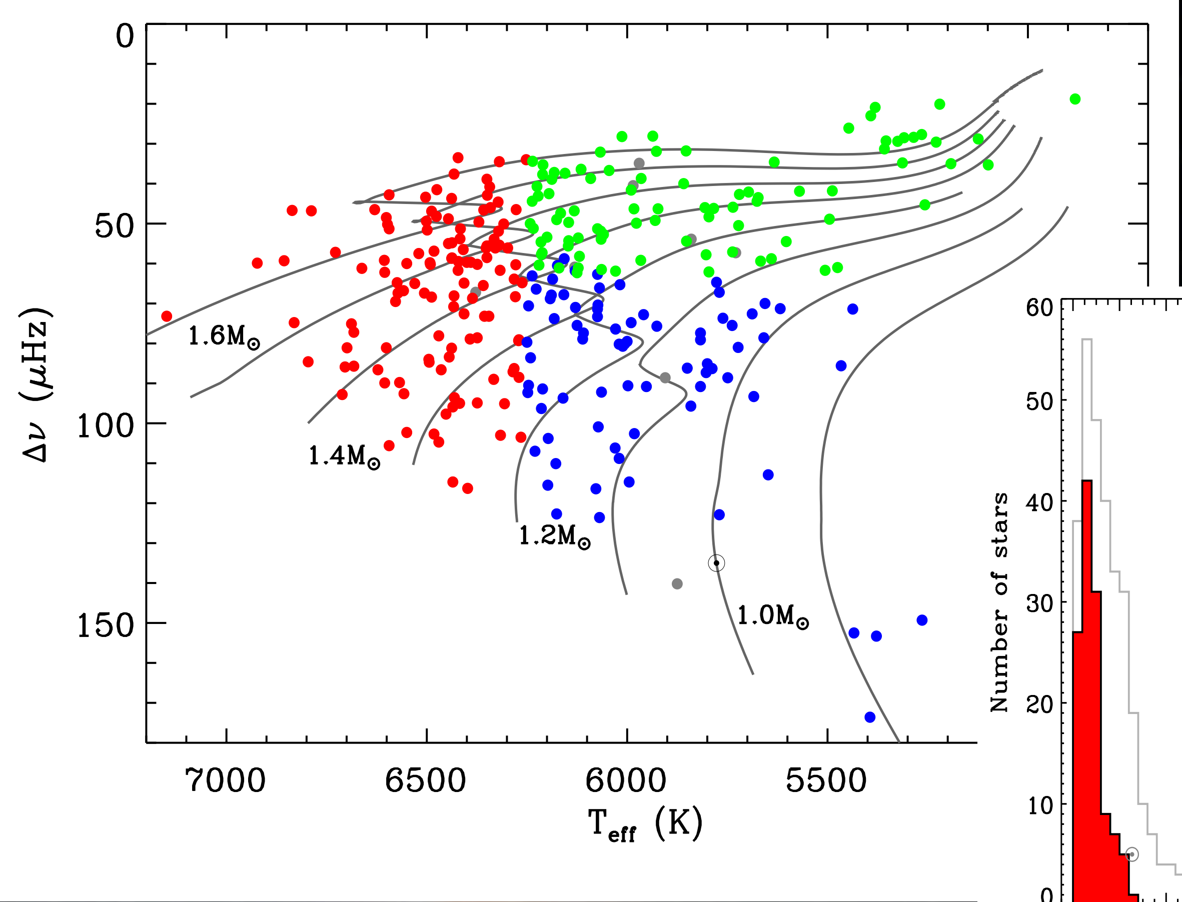
- Inferred p-mode rotational splittings are a good proxy of surface rotation
  - Both inferences agree inside the error bars for most of the stars

[Davies, Garcia et al. in preparation]

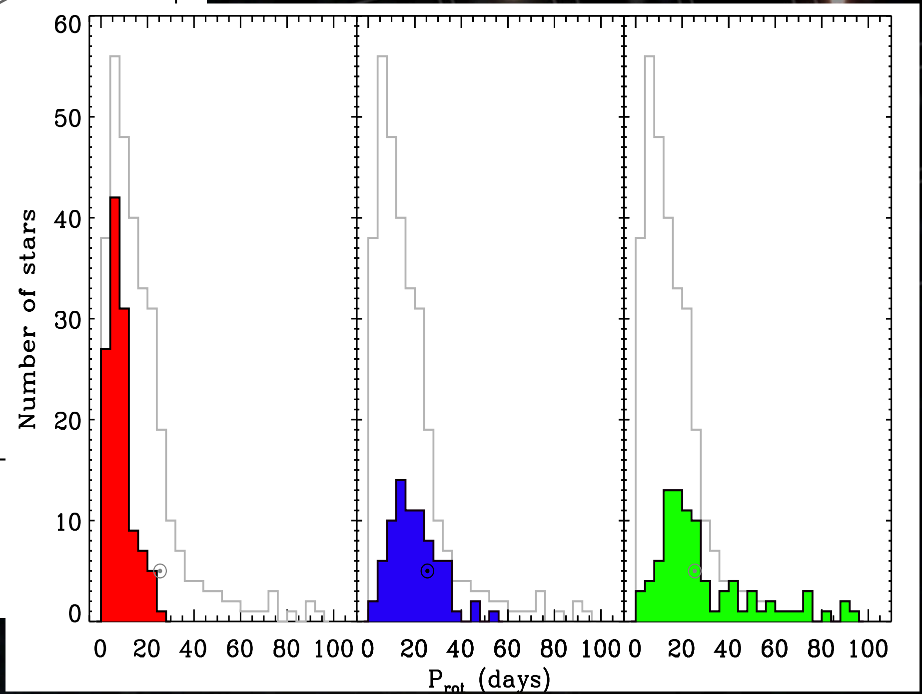
[Lund et al. 2015; Benomar et al. in preparation]

II-SURFACE ROTATION (S-L STARS)

- ~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]



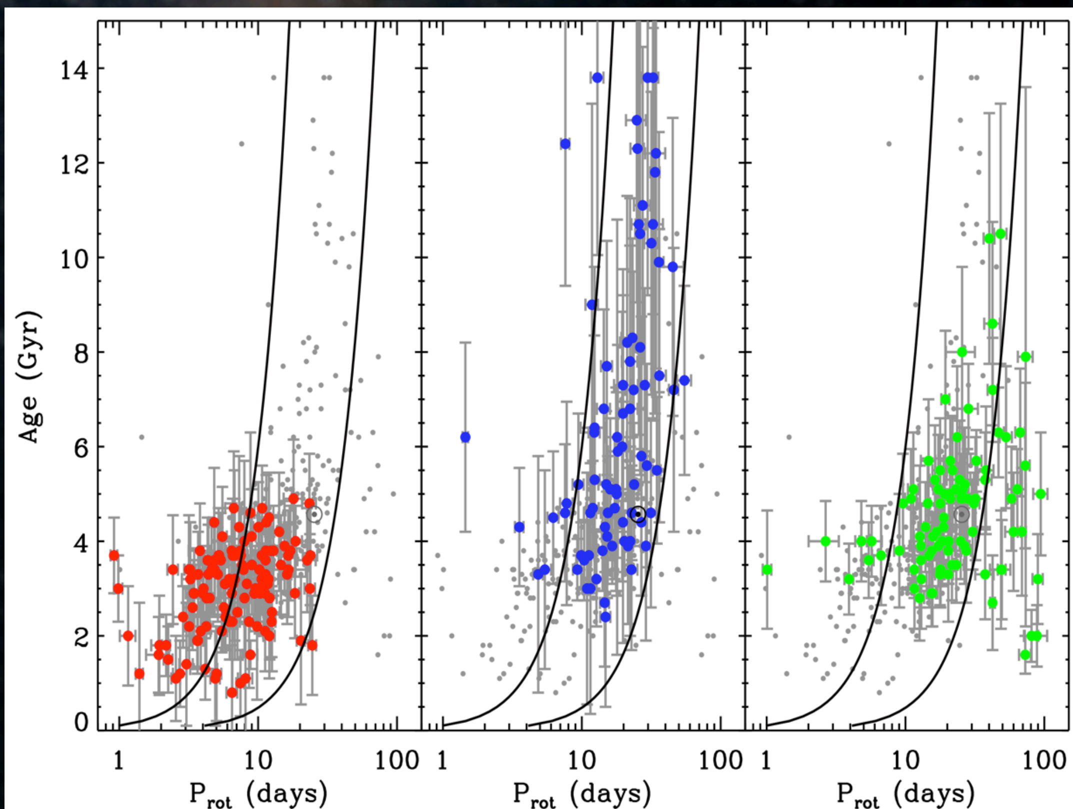
[García et al 2014]

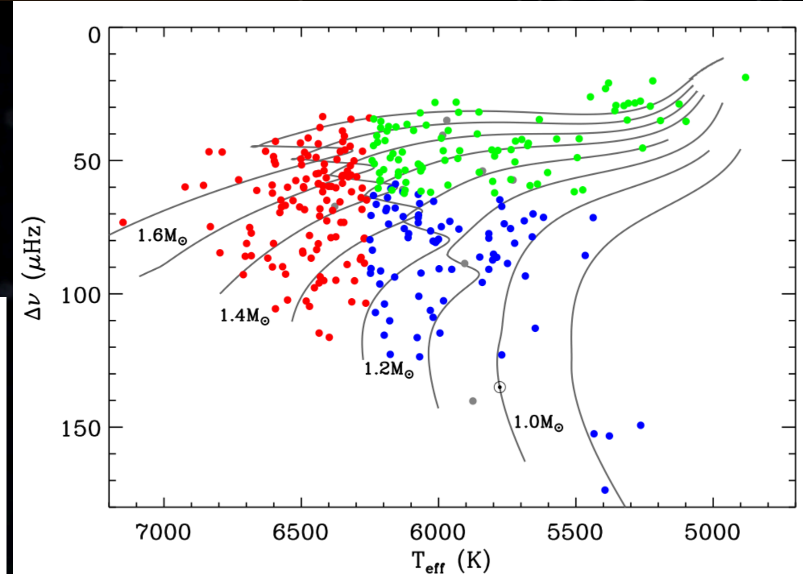


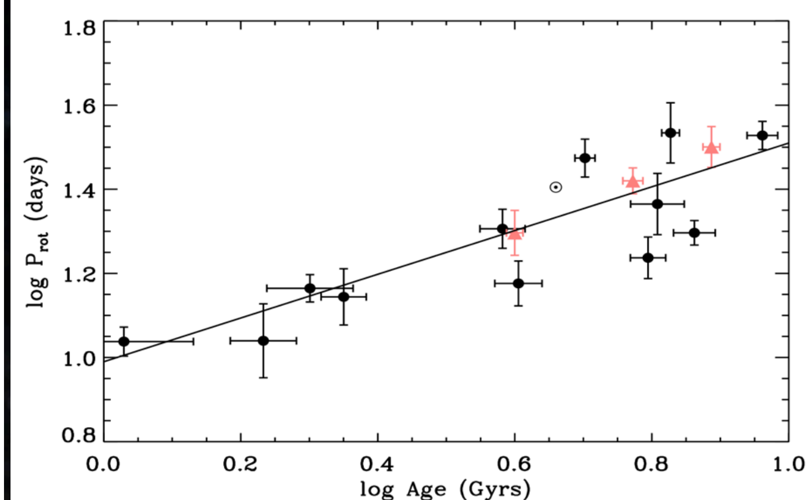
II-SURFACE ROTATION

- Towards asteroseismically calibrated age-rotation relations. Gyrochronology of field stars
  - Biased sample

[García et al. 2014]





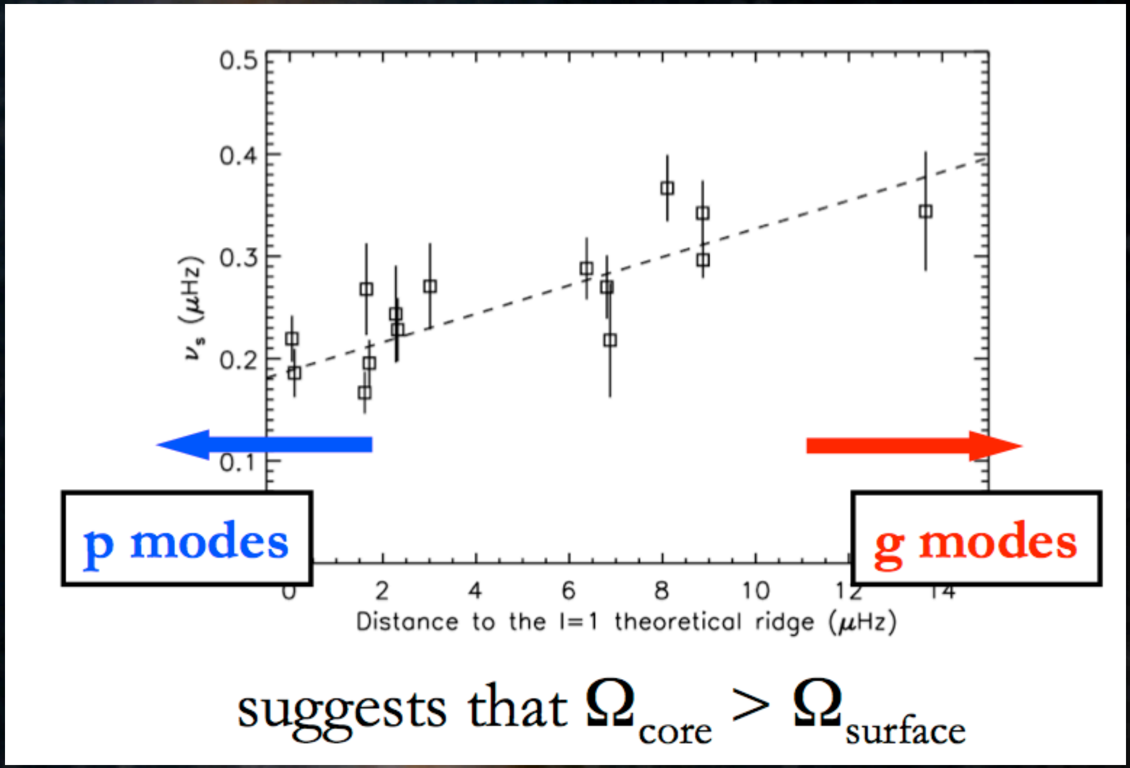


$$\log P_{\rm rot} = (0.52 \pm 0.06) \log(t) + (0.99 \pm 0.04).$$

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

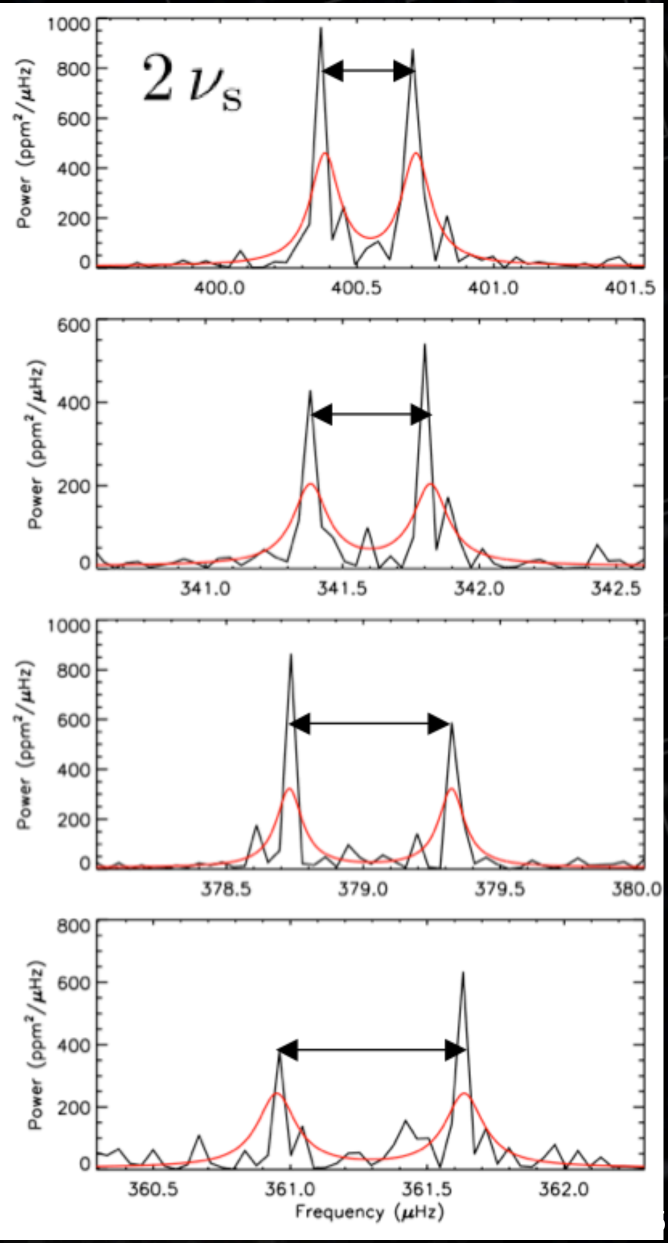
II-INTERNAL ROTATION

- 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



II-INTERNAL ROTATION (SUBGIANTS)

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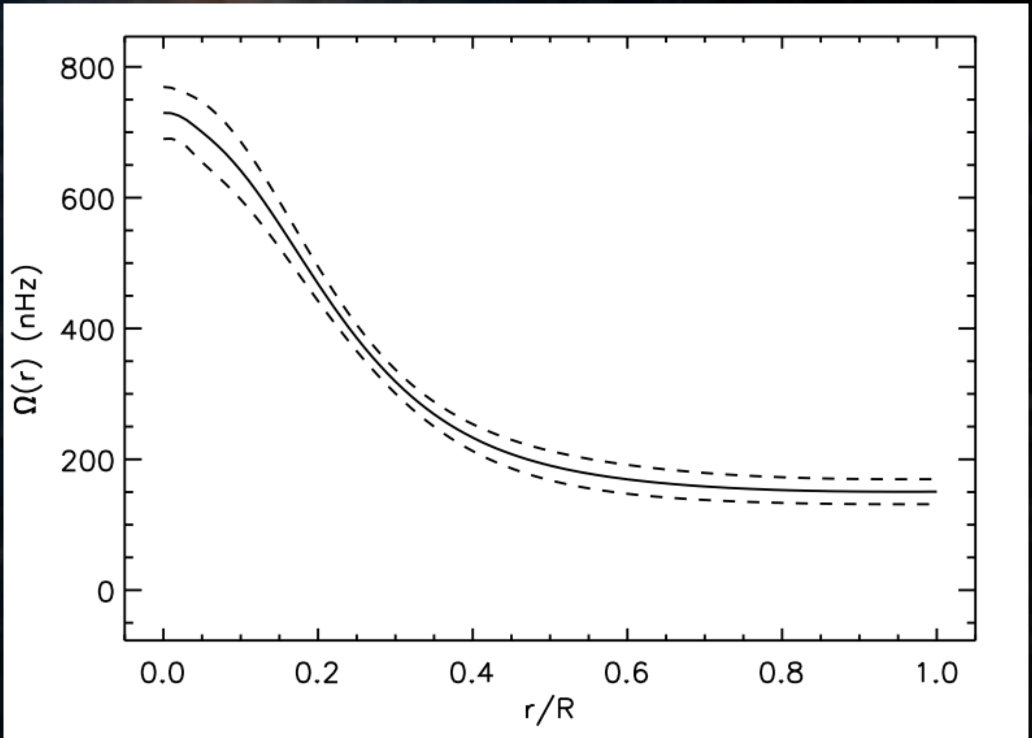

[Deheuvels, Garcia et al. 2012]

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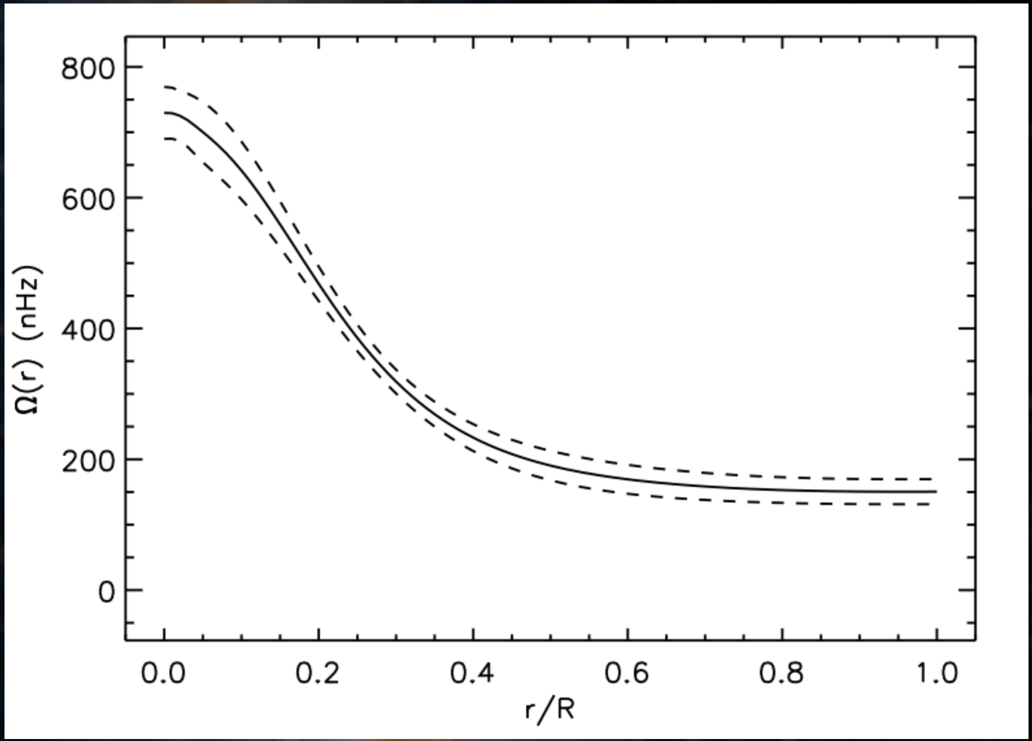
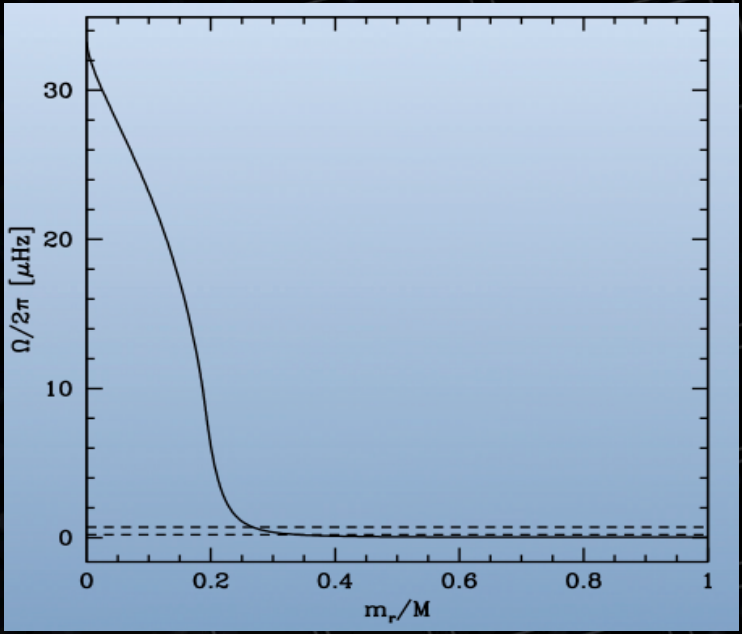


[Deheuvels, Garcia et al. 2012]



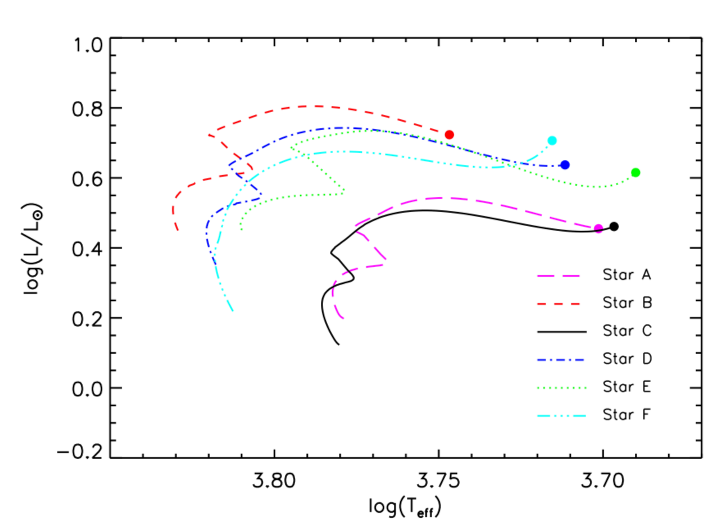
[Ceillier et al. 2013]

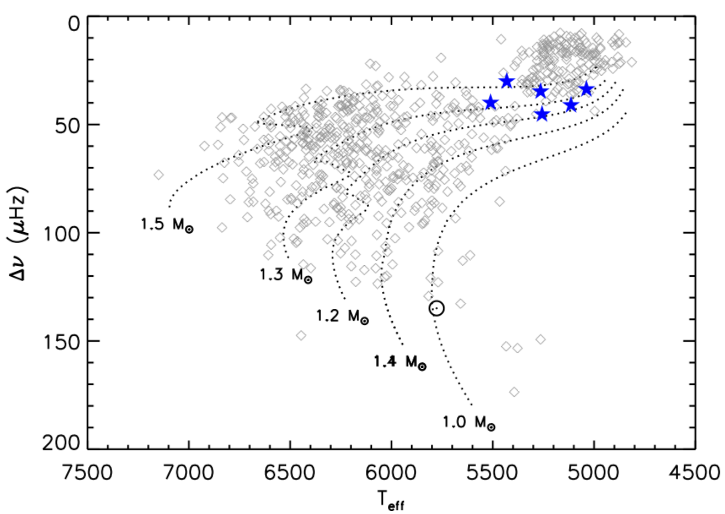
See also Eggenberger et al. 2012; Marques et al. 2013

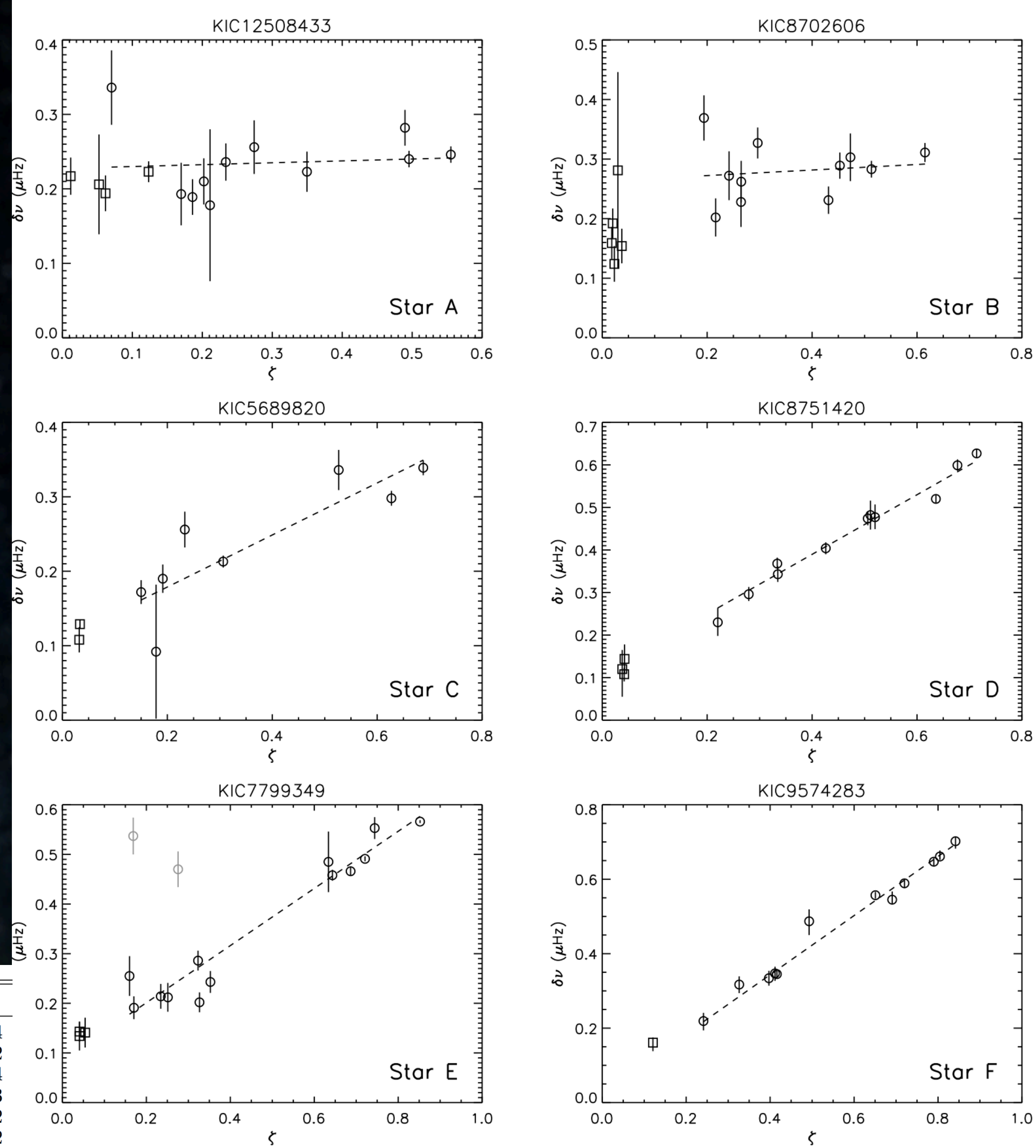
II-INTERNAL ROTATION (SUBGIANTS)

- 6 Subgiant/early RGBs

[Deheuvels et al. 2014]





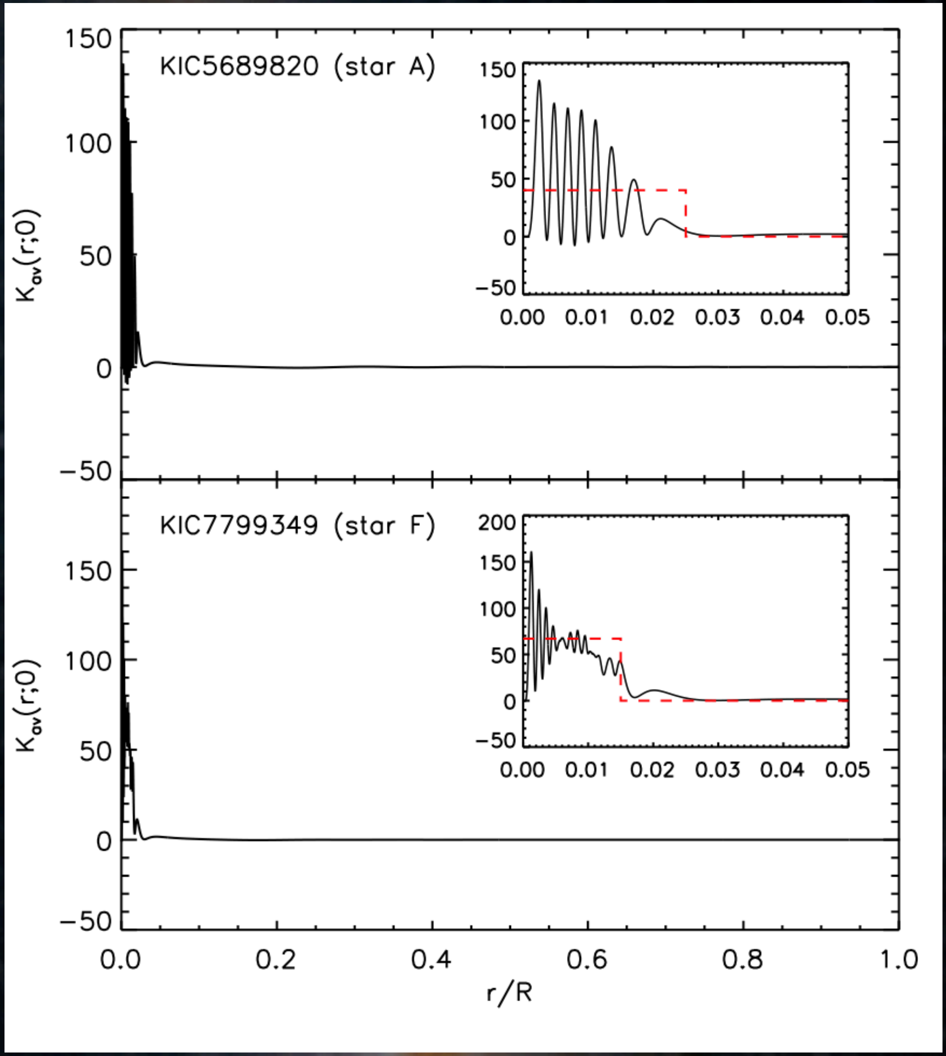


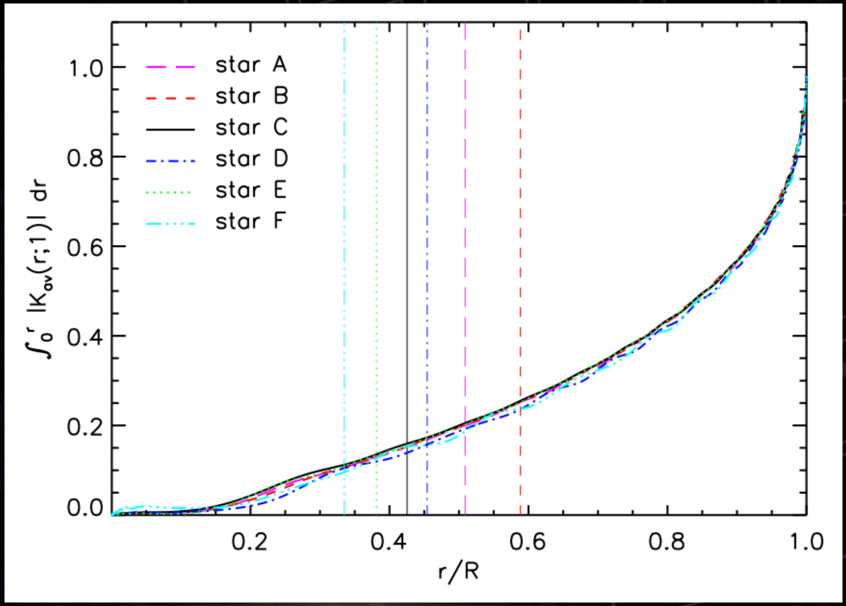
Star	Ref. letter	$\Delta\nu$ (μHz)	$\nu_{\max}$ (μHz)	M	R	$\log g$
KIC12508433	A	45.3 ± 0.2	793 ± 21	1.20 ± 0.16	2.20 ± 0.10	3.83 ± 0.04
KIC8702606	B	39.9 ± 0.4	664 ± 14	1.27 ± 0.15	2.44 ± 0.11	3.77 ± 0.02
KIC5689820	C	41.0 ± 0.3	695 ± 15	1.11 ± 0.16	2.29 ± 0.12	3.76 ± 0.04
KIC8751420	D	34.7 ± 0.4	598 ± 14	1.50 ± 0.20	2.83 ± 0.15	3.71 ± 0.03
KIC7799349	E	33.7 ± 0.4	561 ± 8	1.33 ± 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]





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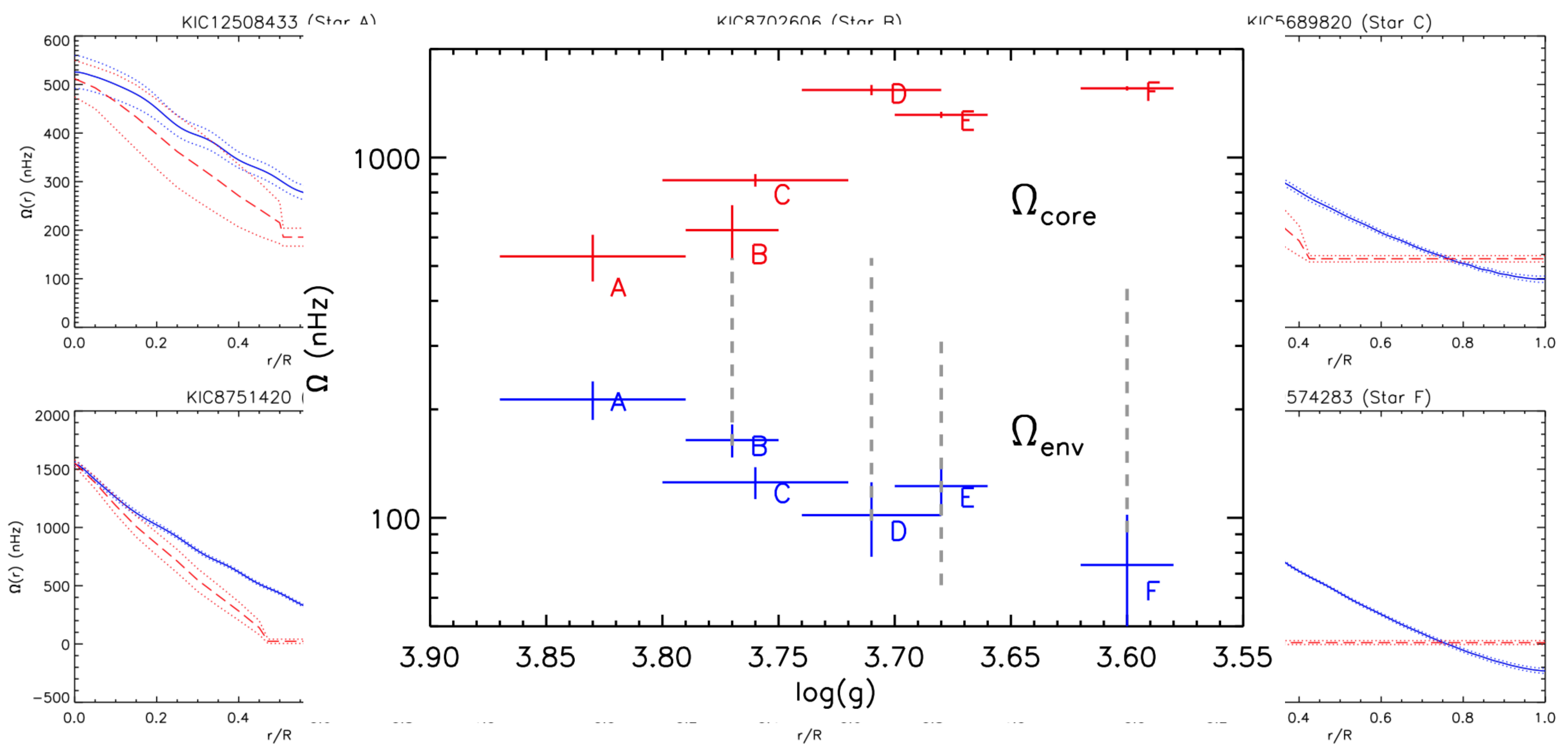
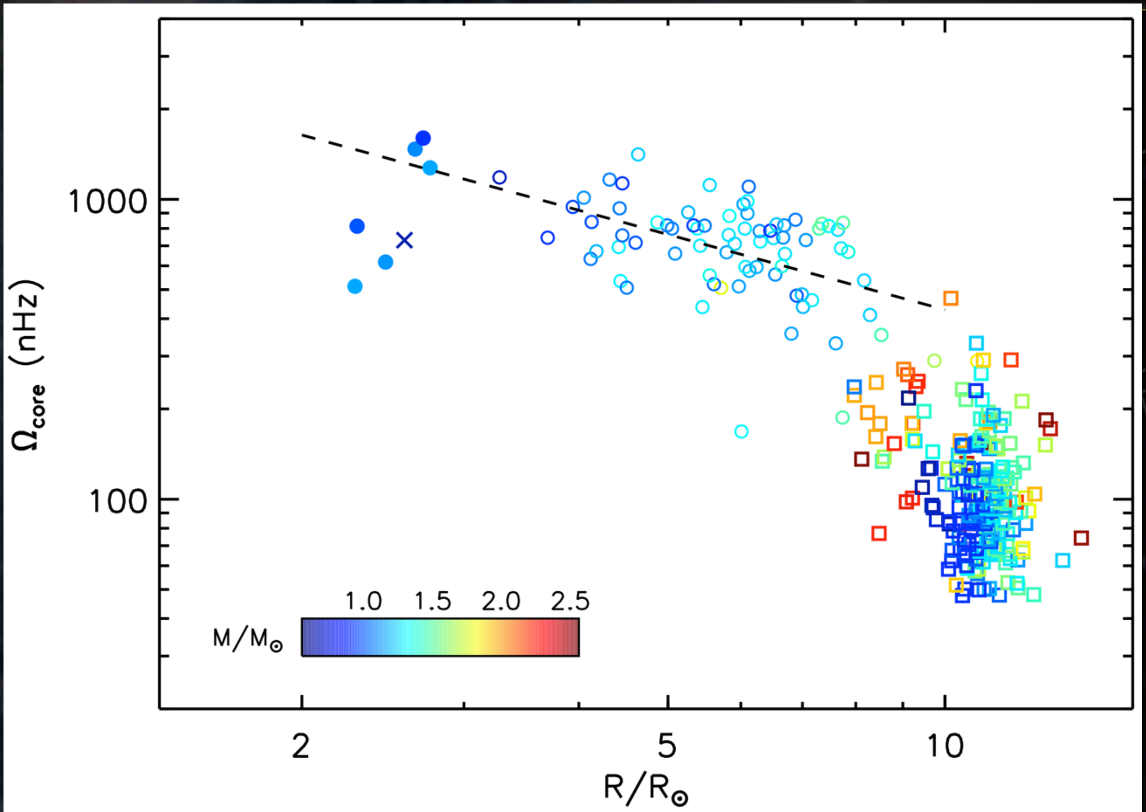


The trend with the seismic logg suggests that the core spins in the subgiant phase

II-INTERNAL ROTATION



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

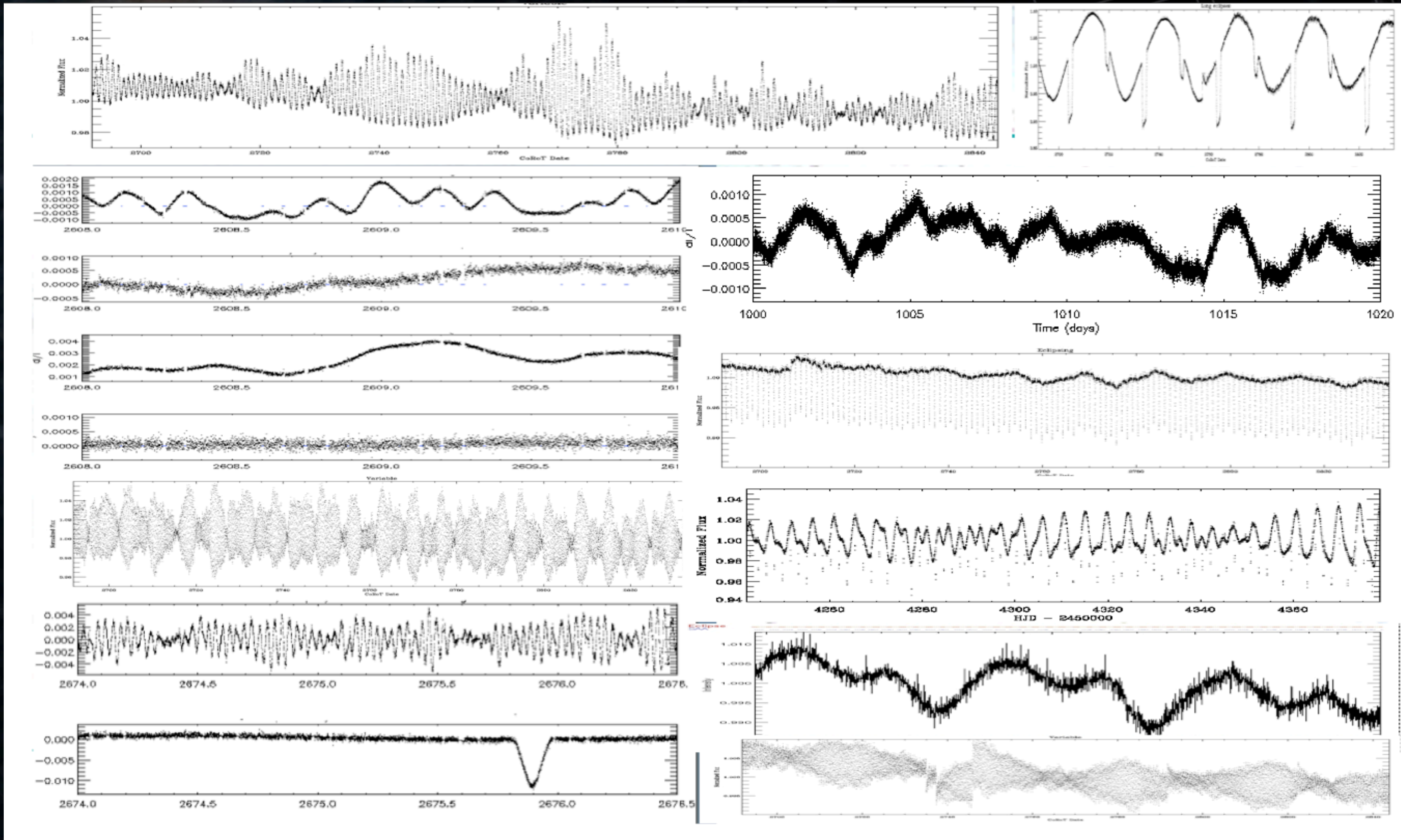
- Ensemble analysis used to obtain a proxy of the rotation rate of the deep radiative interior
- During RGB (circles):
  - The core of the stars during RGB spins down!
  - Efficient AM transport to counterbalance the core contraction and not efficeint during subgiant phase
- Change from RGB to the clump (squares) can be related to the expansion of the non-degenerate helium burning core.
  - It can not explain all the reduction
    - significant transfer of internal angular momentum from the inner to the outer layers.

[Iben 1971; Sills & Pinsonneault 2000]

IIb-Stellar Dynamics:

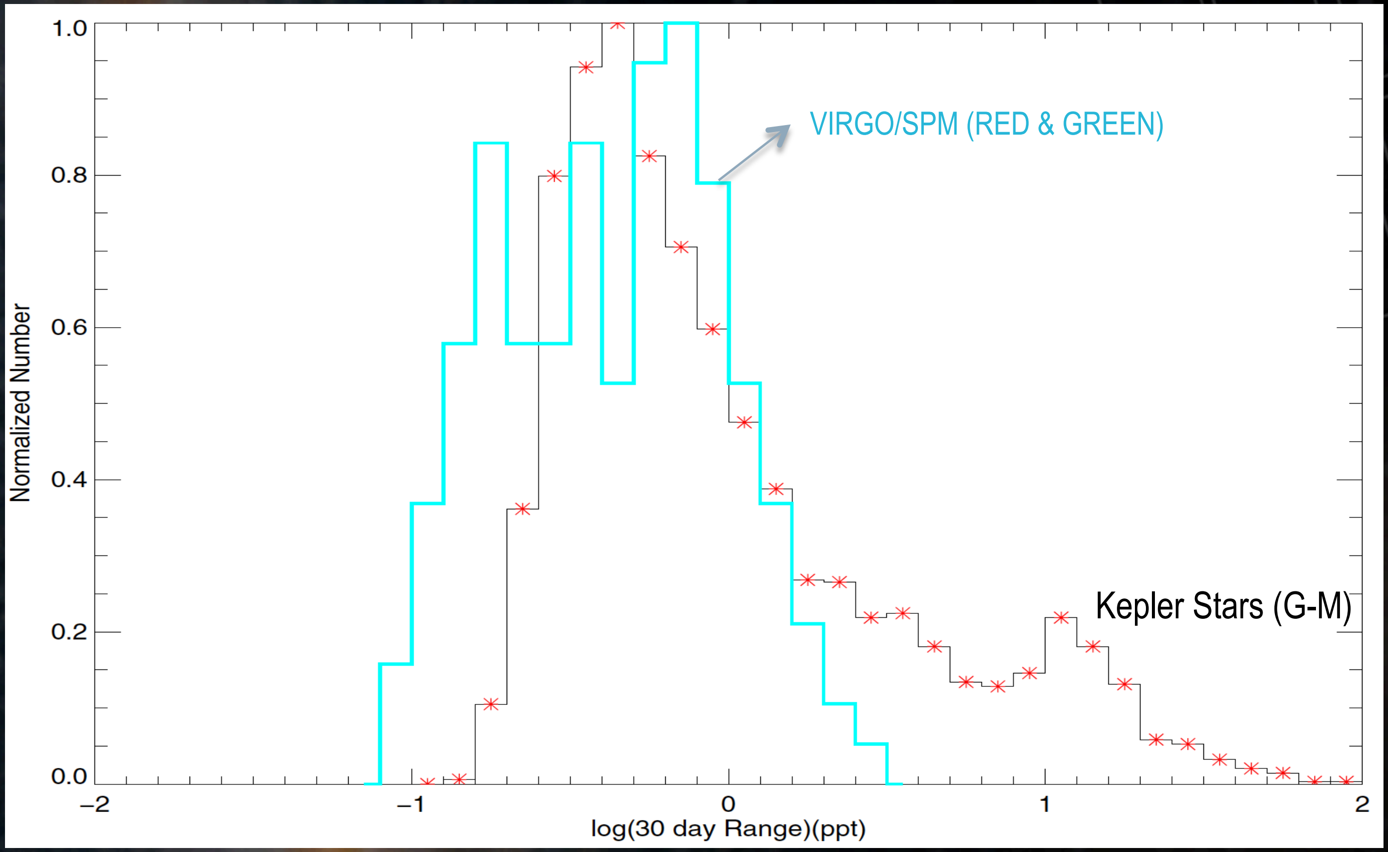
Magnetic variability

II-STELLAR 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]

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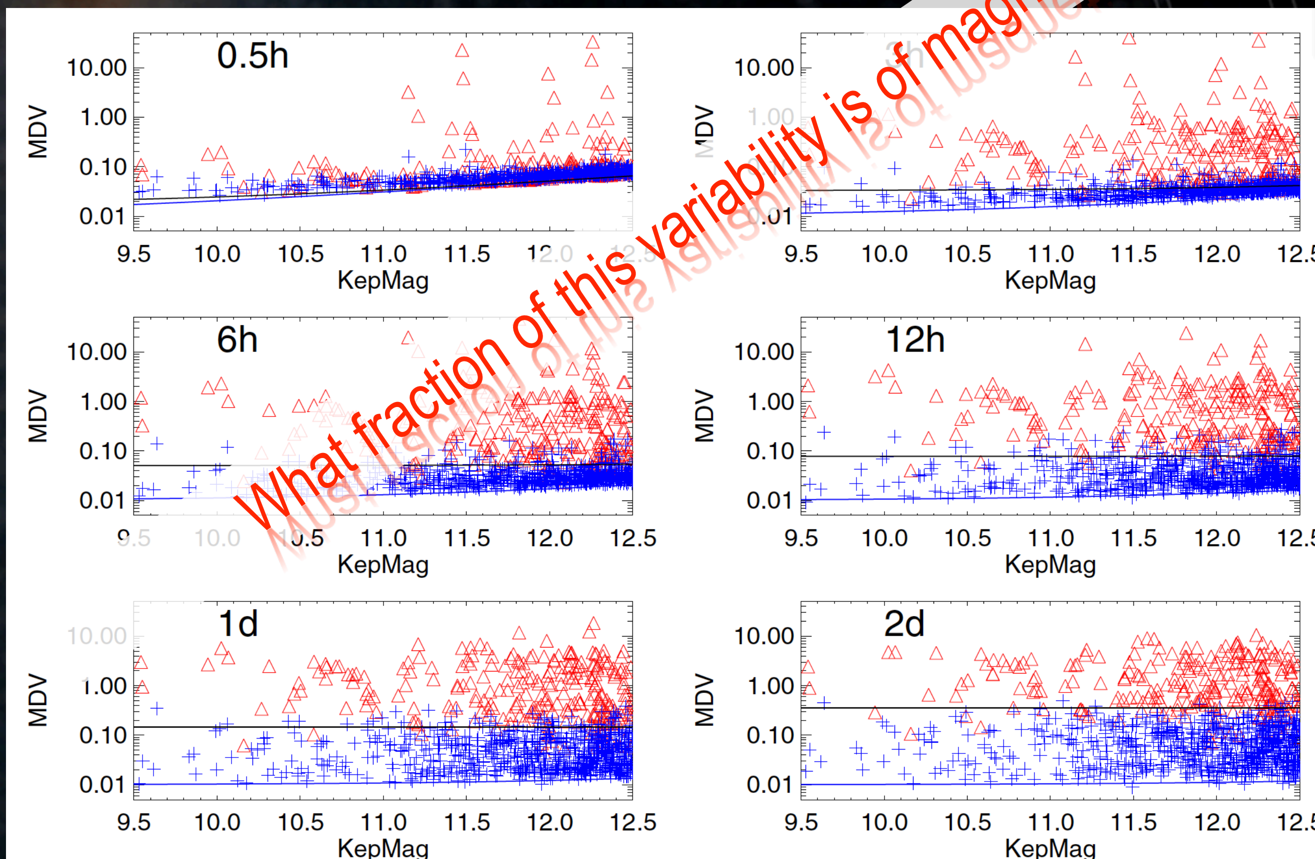
    - This methodology is good to compare variability of stars at different timescales

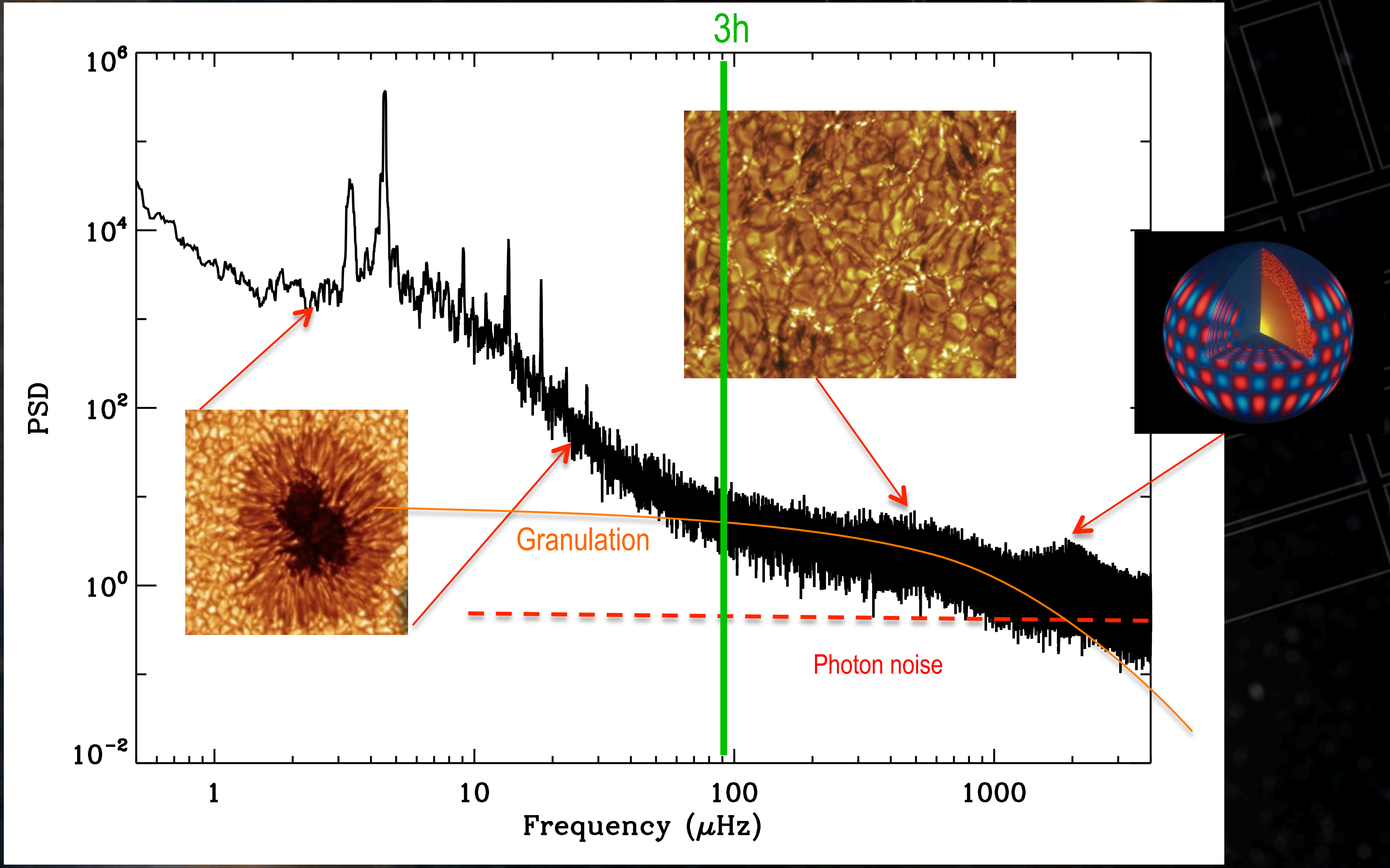
What fraction of this variability is of magnetic origin?



[Basri et al. 2013]

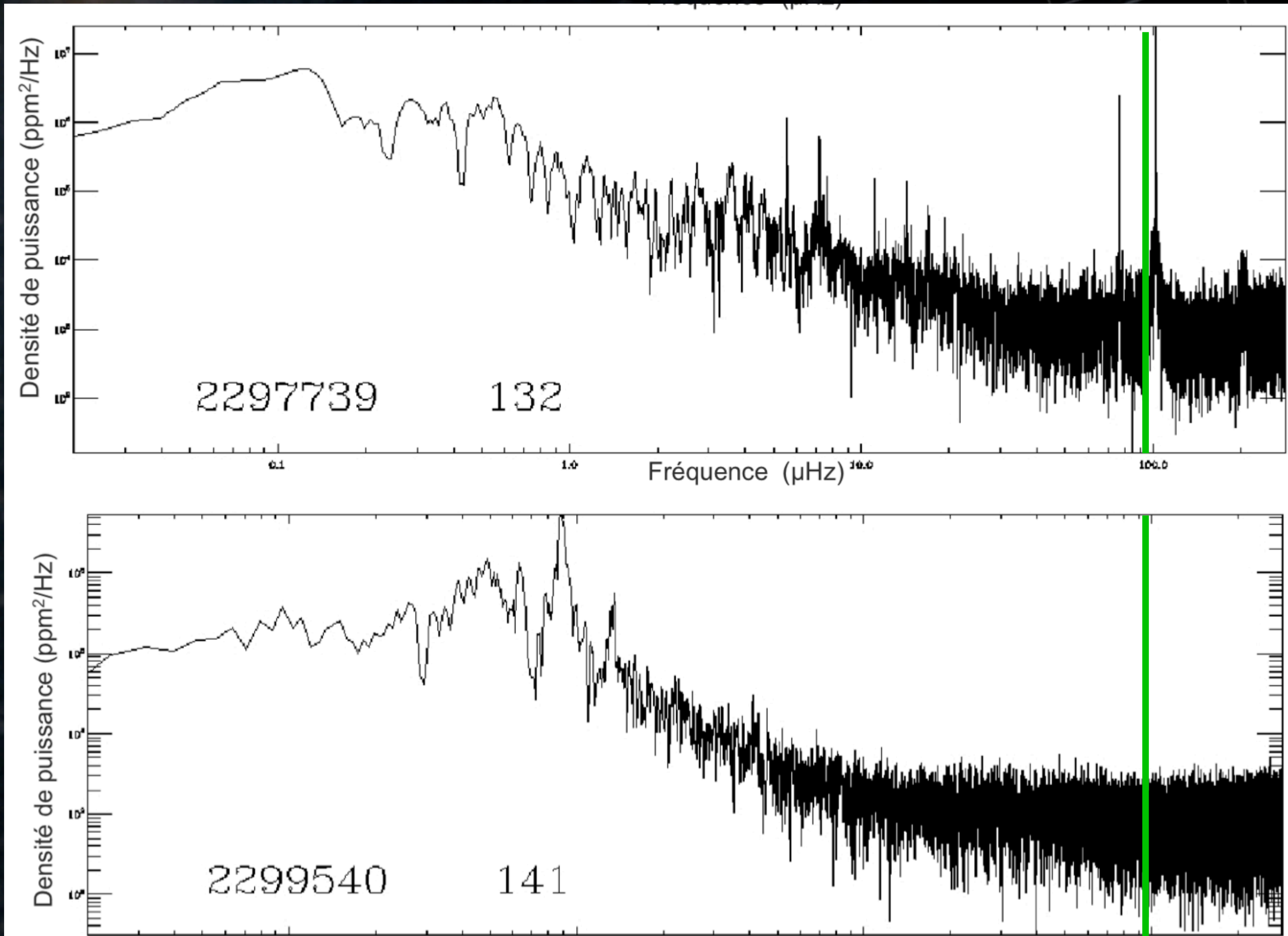
II-STELLAR VARIABILITY

➢ Example of the PSD of a Solar-Like star



II-STELLAR VARIABILITY

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

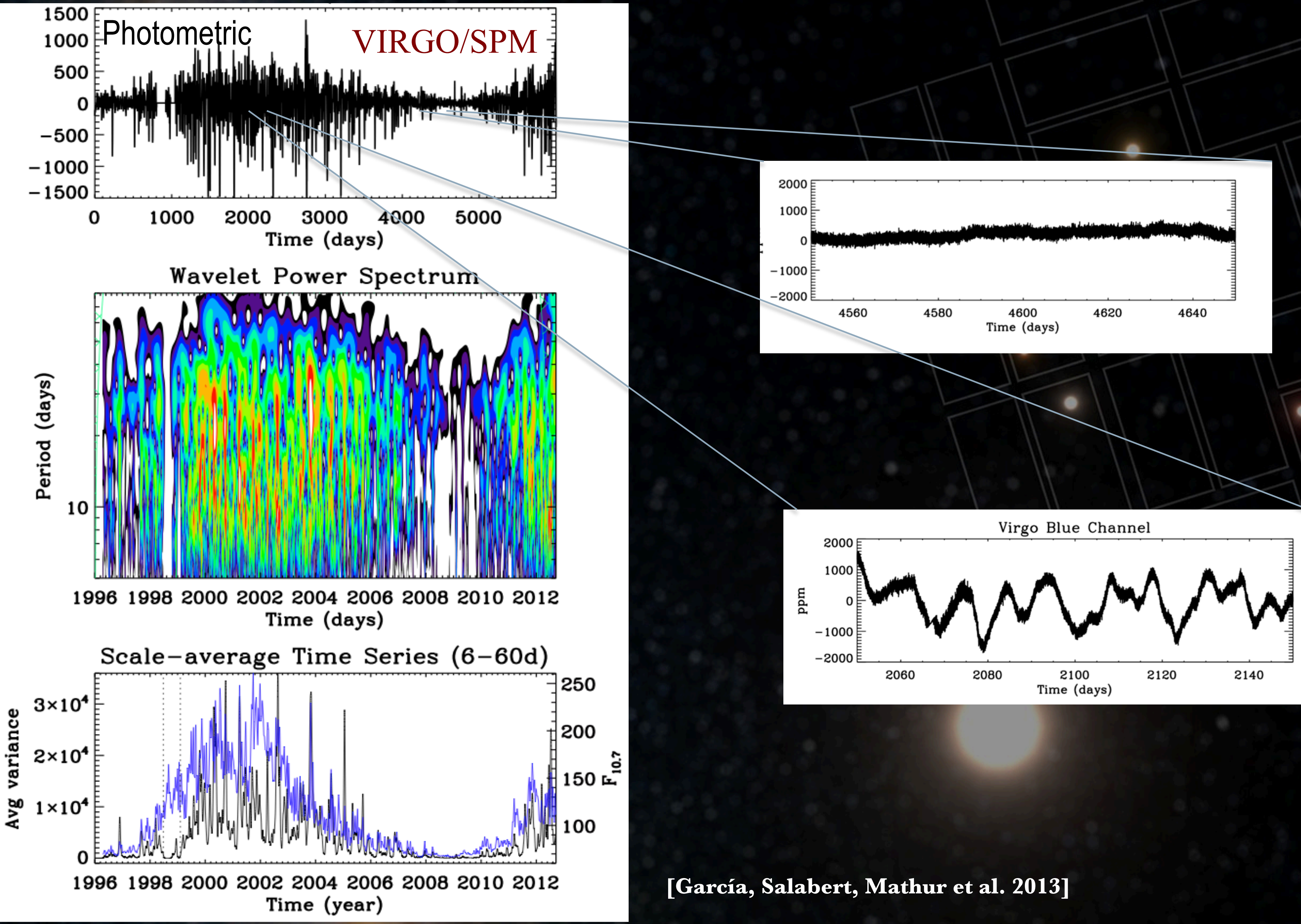


[Houmani, Stage M1, 2014]

III-Surface Magnetic Activity

proxy

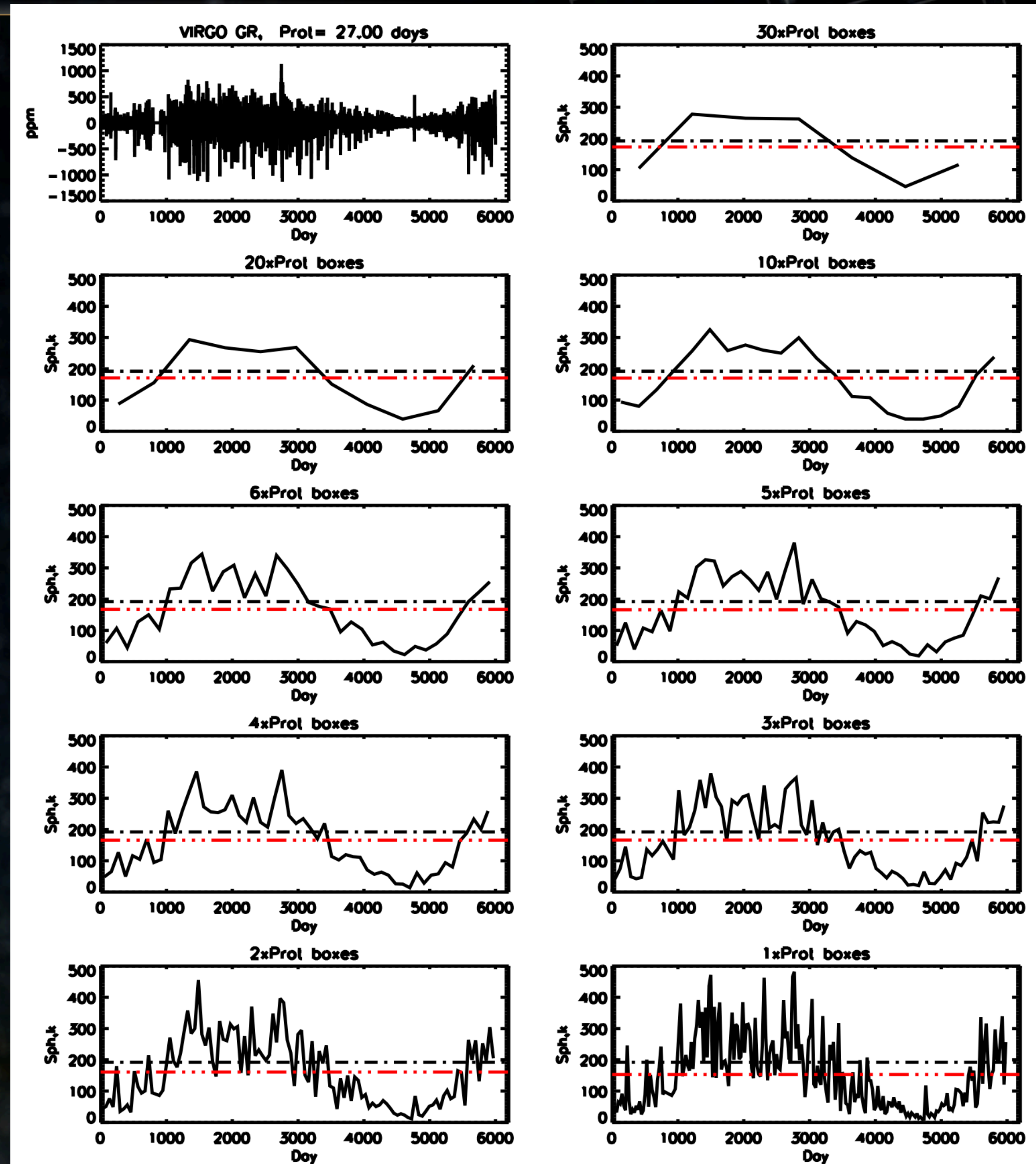
II-MAGNETIC ACTIVITY & ROTATION



[García, Salabert, Mathur et al. 2013]

III-SURFACE MAGNETIC ACTIVITY PROXY

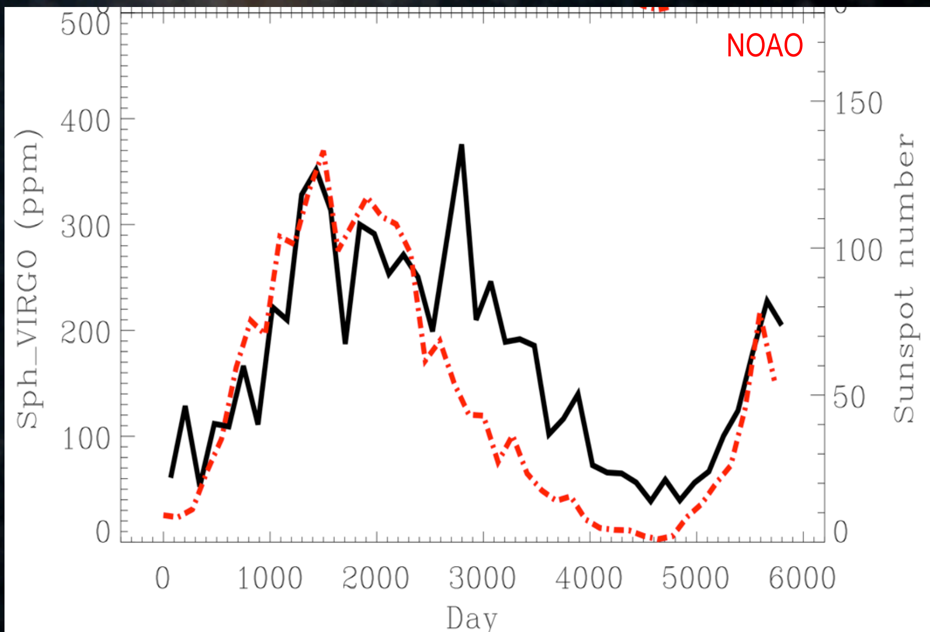
- S_{ph}
  - Standard deviation of the light curve
    [García et al. 2010; Chaplin et al. 2011; Campante et al. 2013]
  - K x P_{rot}
    - In general k=5

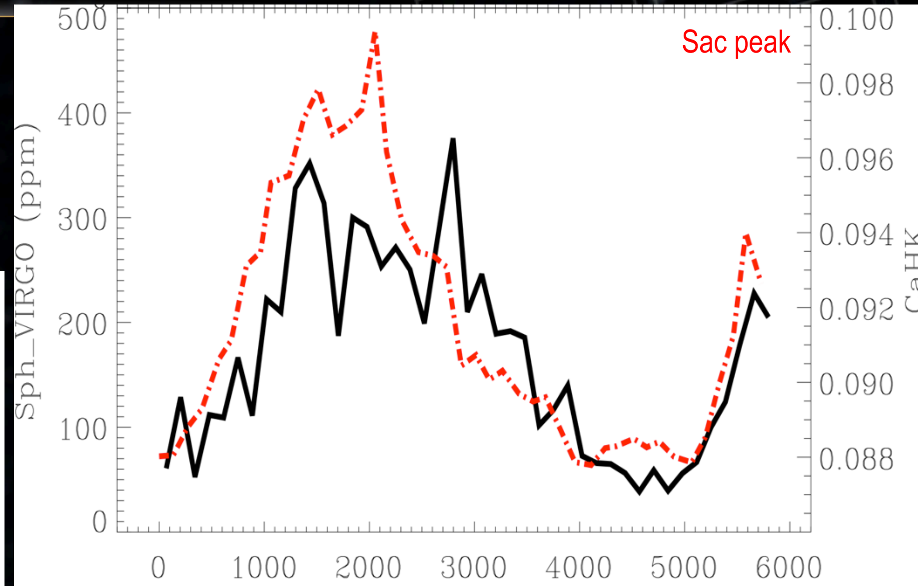


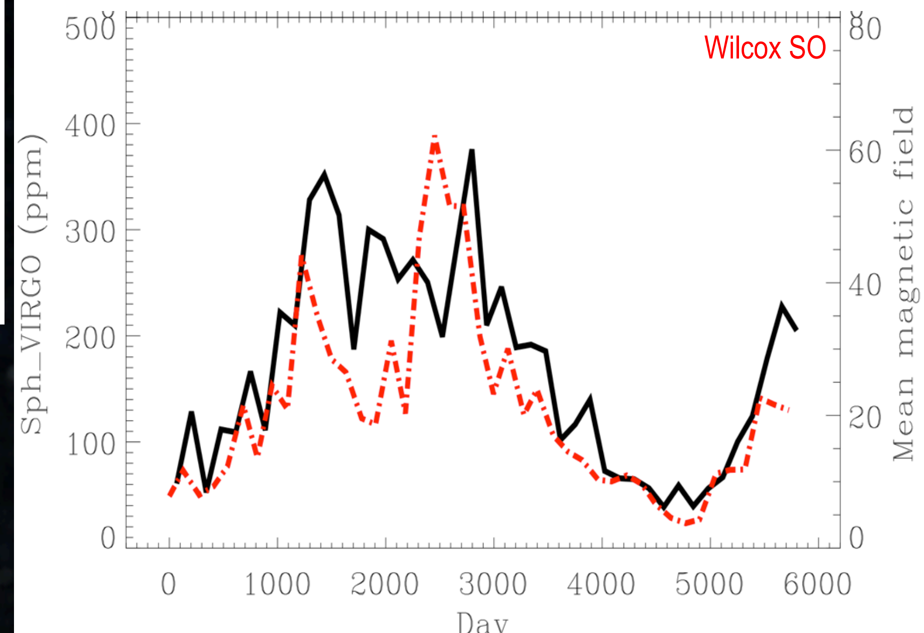
[Mathur, Salabert, García, et al. 2014]

III-SURFACE MAGNETIC ACTIVITY PROXY

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





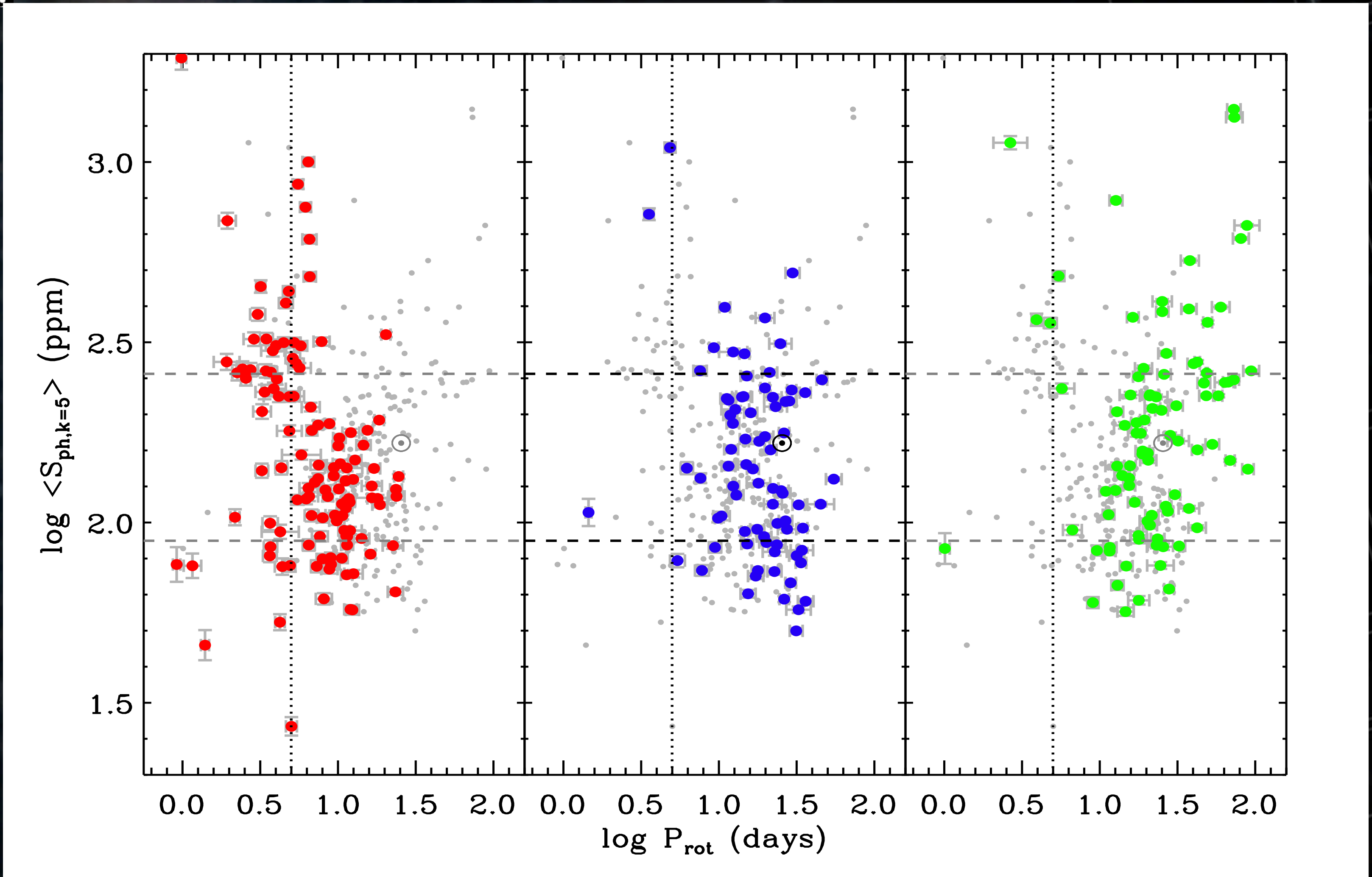


GOLF proxy also available

[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

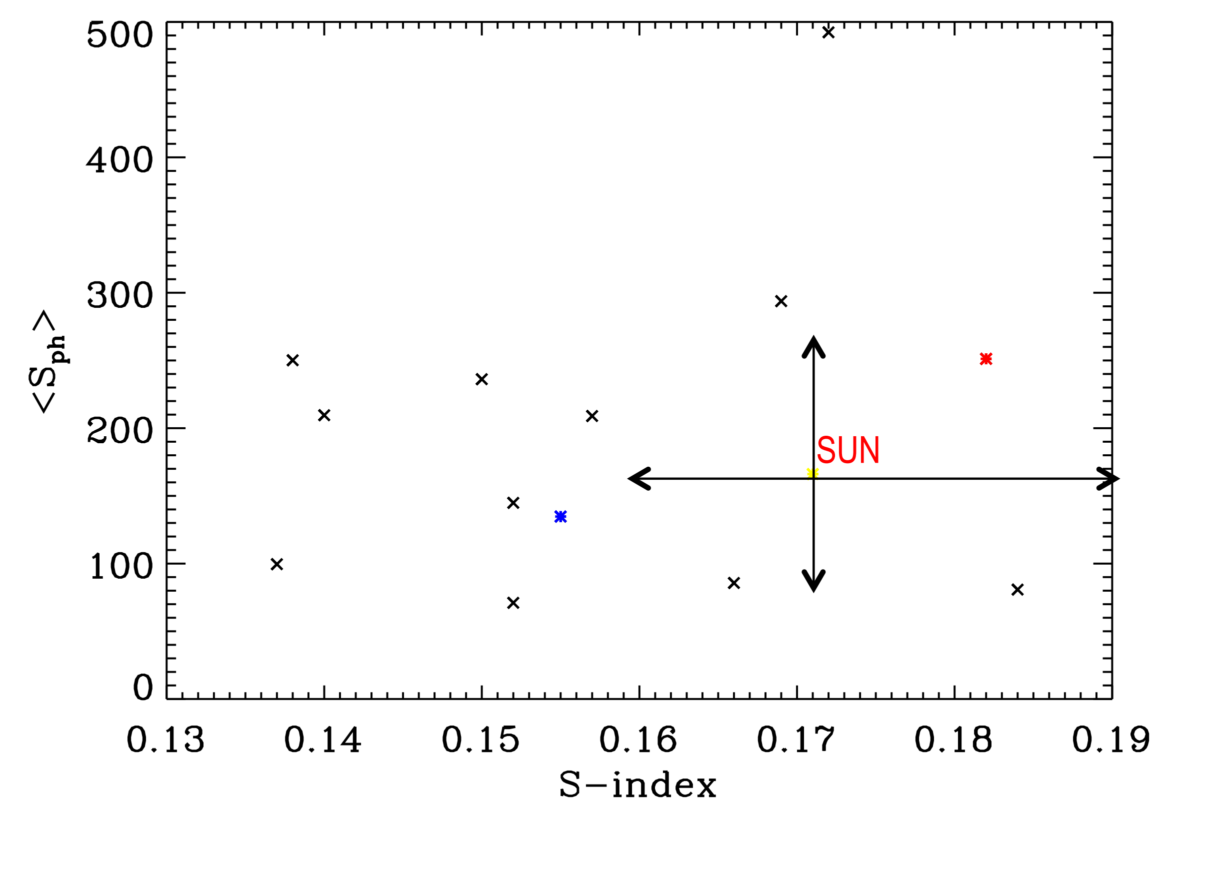


- The photospheric magnetic activity of the pulsating solar-like stars
  - Compatible with the solar magnetic activity during the solar cycle (61.5%)

[García et al. 2014]

III-SURFACE MAGNETIC ACTIVITY S-L STARS

- S-index from NOT (Karoff et al. 2013) observations in 2009, 2010, and 2011
  - S_{ph} and Ca HK covering different periods of time
  - S_{ph} sensible to the stellar inclination angle
  - S_{ph} underestimate maximum activity in comparison to Ca HK



[Mathur et al. 2014]

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:

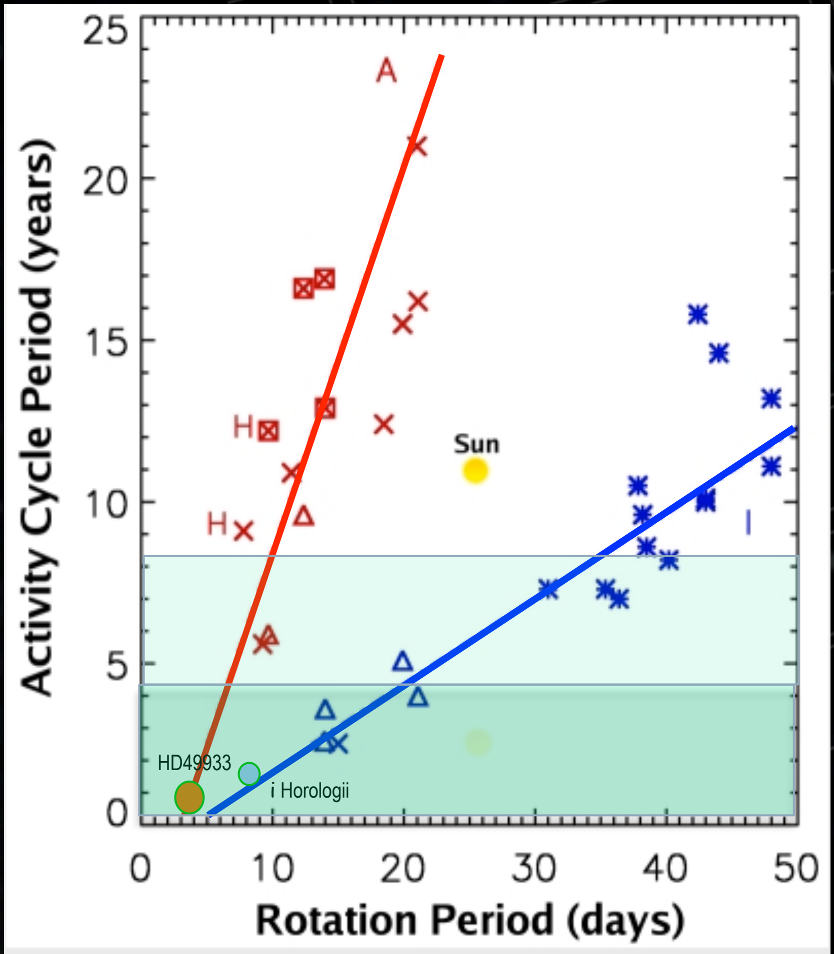
$$P_{cyc}/P_{rot} = \Omega/\ \Omega_{cyc} = CRo^q$$

[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]

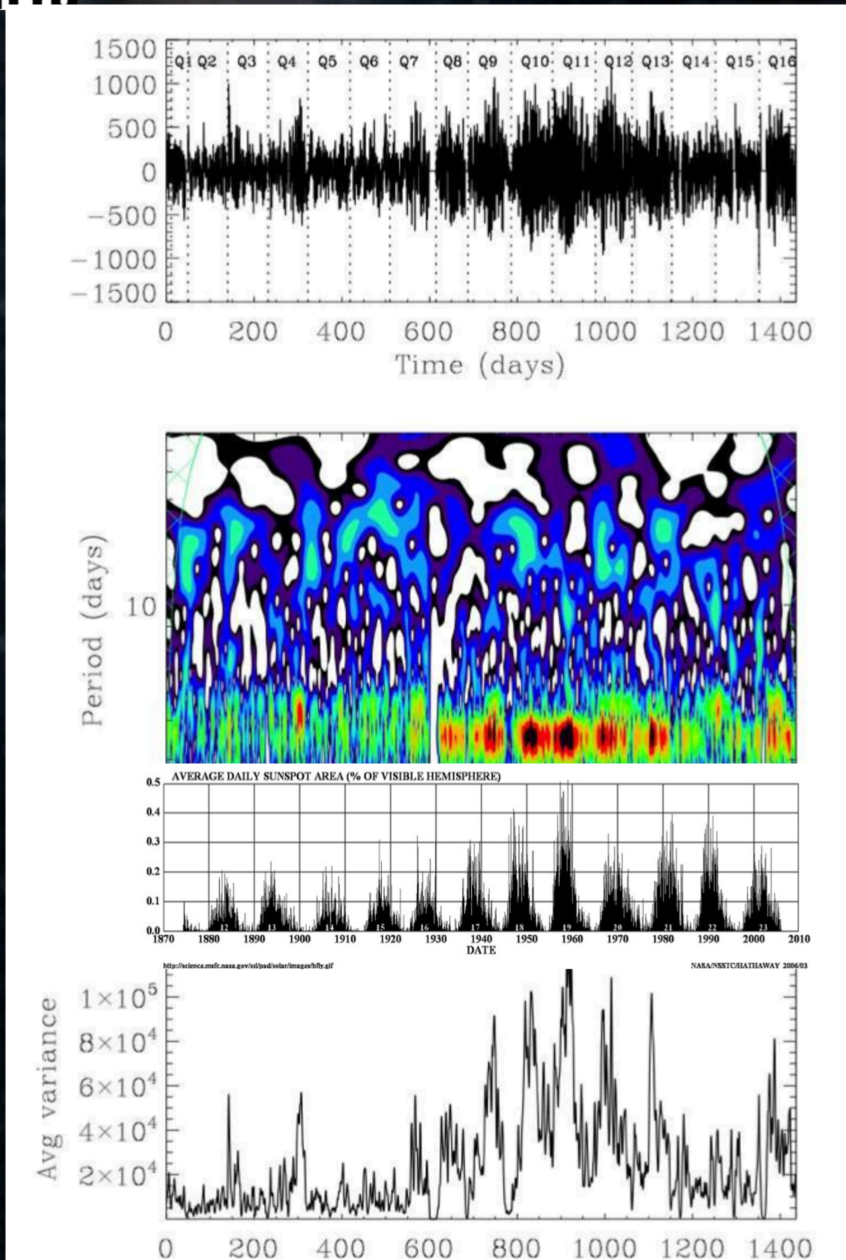
- Stellar activity cycles:
  - Two branches
  - The position of the Sun
    - Between both branches
- Faster rotators
  - Stronger magnetic activity amplitudes
  - Rarely have regular cycles



[Adapted from Bohm-Vitense, 2007]

[Benevolenskaya 1995, Fletcher et al. 2010]

IV-STELLAR MAGNETIC CYCLES



[Mathur, Garcia, et al. 2014]

KIC3733735

P_{rot}=2.5d

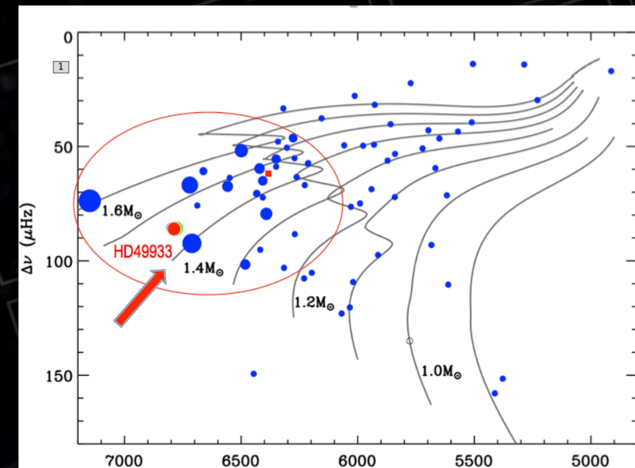
$\langle S_{ph} \rangle$ = 250 ppm

i ~30^o

<u>Asteroseismology:</u>

M~1.4$M_\odot$

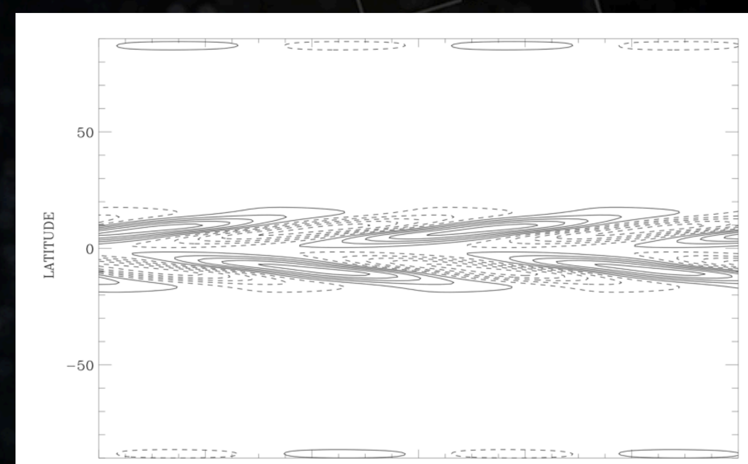
DCZ~1%



[Garcia et al. in preparation]

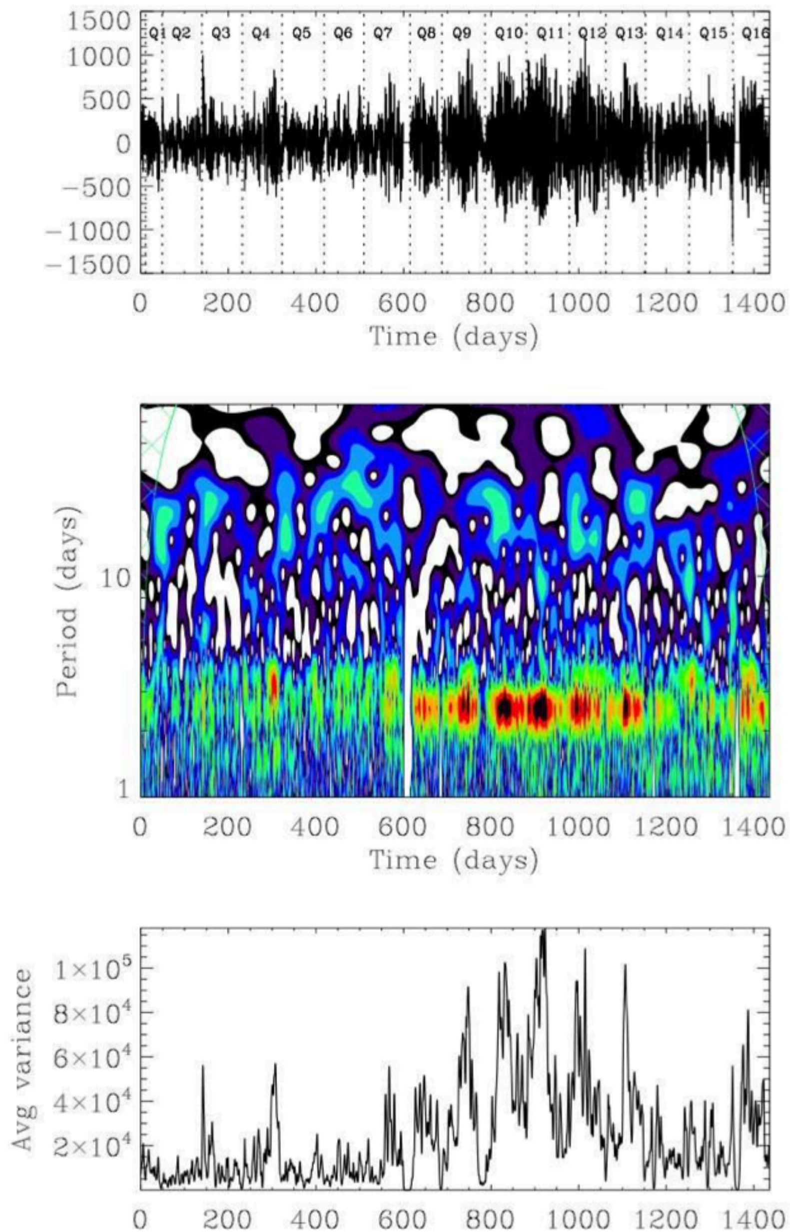
We observe:

- Magnetic Cycle like behavior
- 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

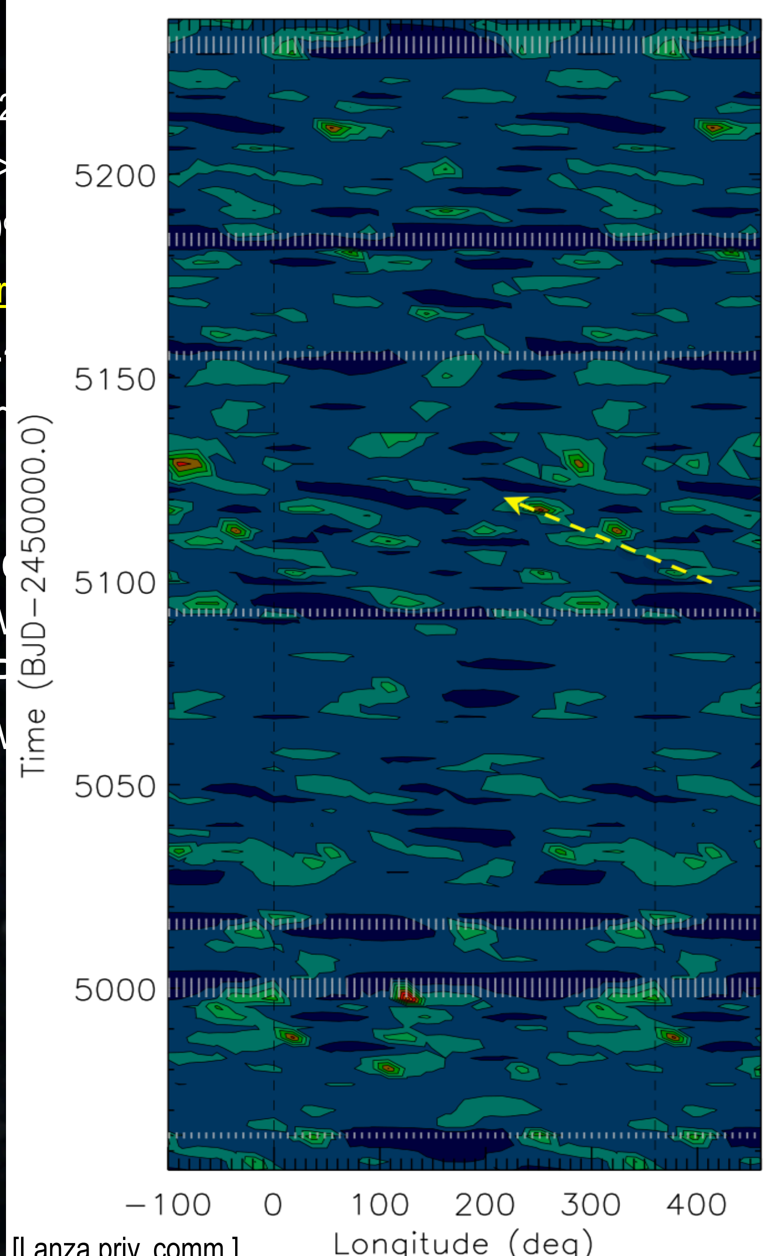
M~1.

DCZ~

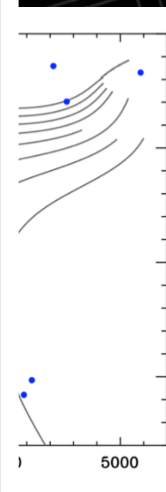
We

- M
- F
- M

m activity

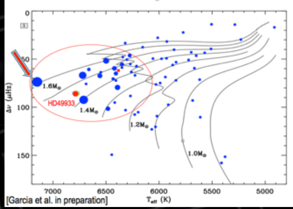


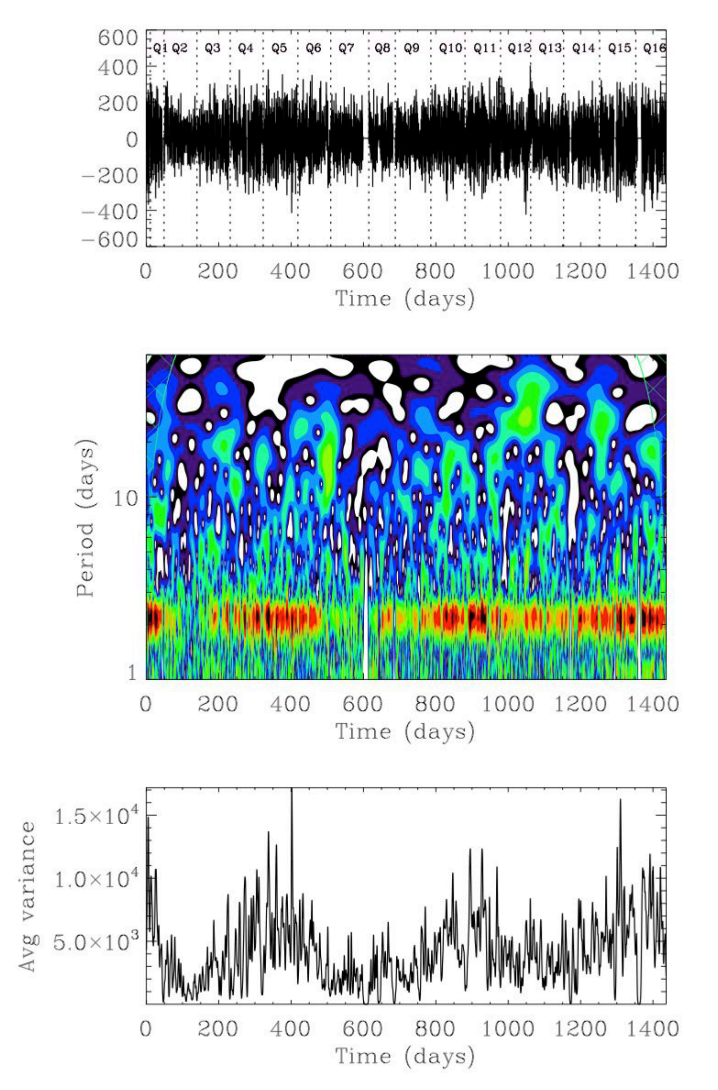
[Lanza priv. comm.]



nm.]

IV-STELLAR MAGNETIC CYCLES





KIC9226926

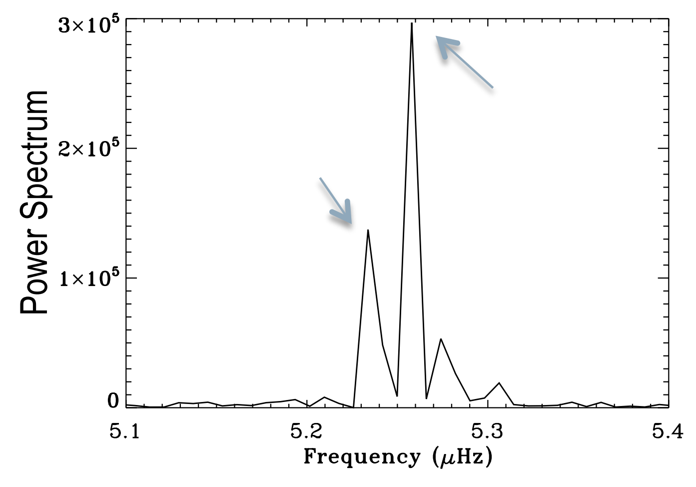
P_{rot}=2.2d

$<S_{ph}>$ = 104 ppm

<u>Asteroseismology</u>:

M~1.4$M_\odot$

DCZ~1%

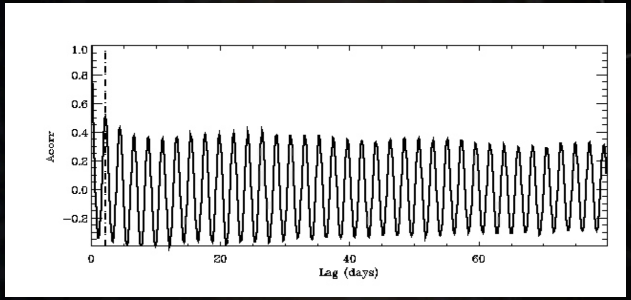


Two close frequencies (5.223 and 5.259 μHz)

→ Beating effect with a period of ~540 days

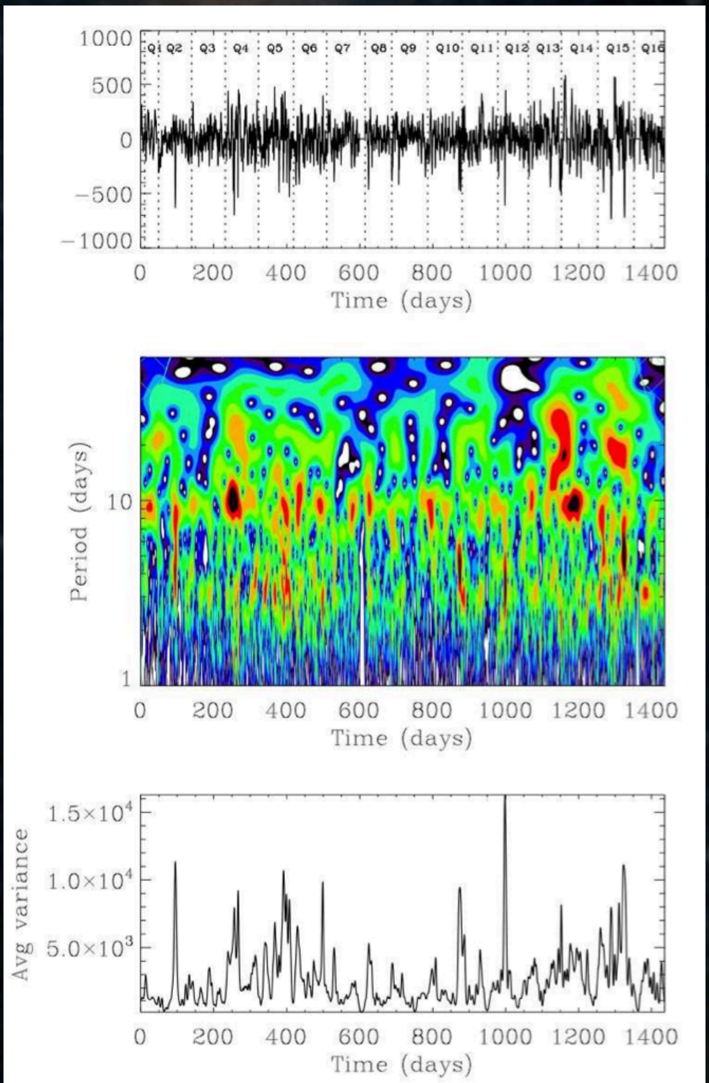
Not a cycle but signature of long lived magnetic structures:

→ Active longitudes

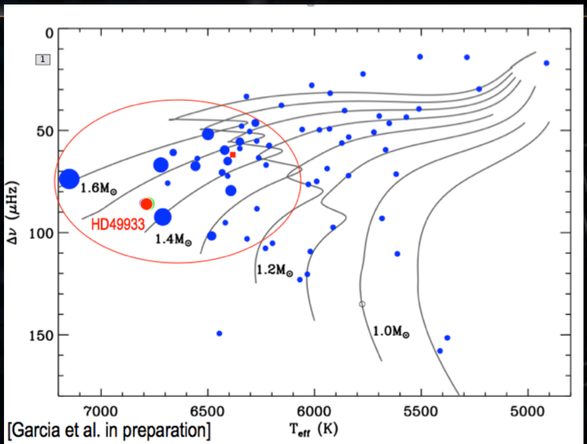


[Mathur, Garcia, et al. ApJ, 2014]

IV-STELLAR MAGNETIC CYCLES

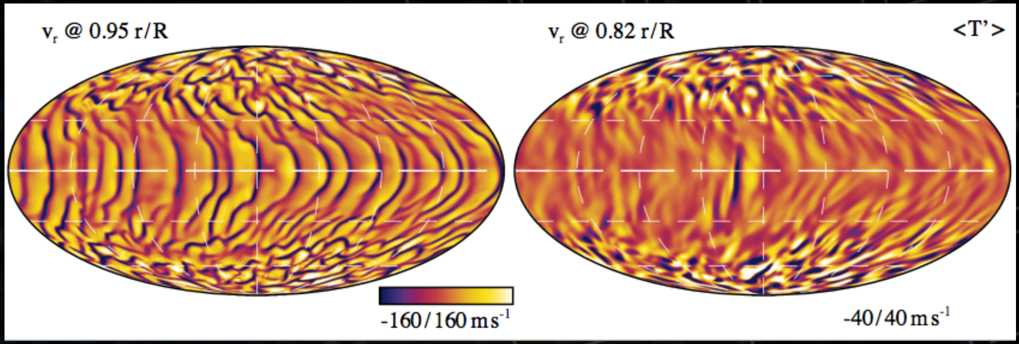


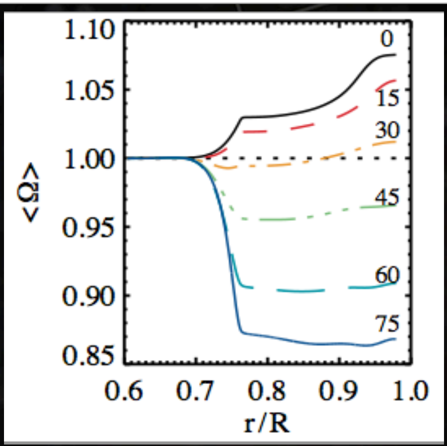
[Mathur, Garcia, et al. ApJ, 2014]



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

Hydrodynamic models

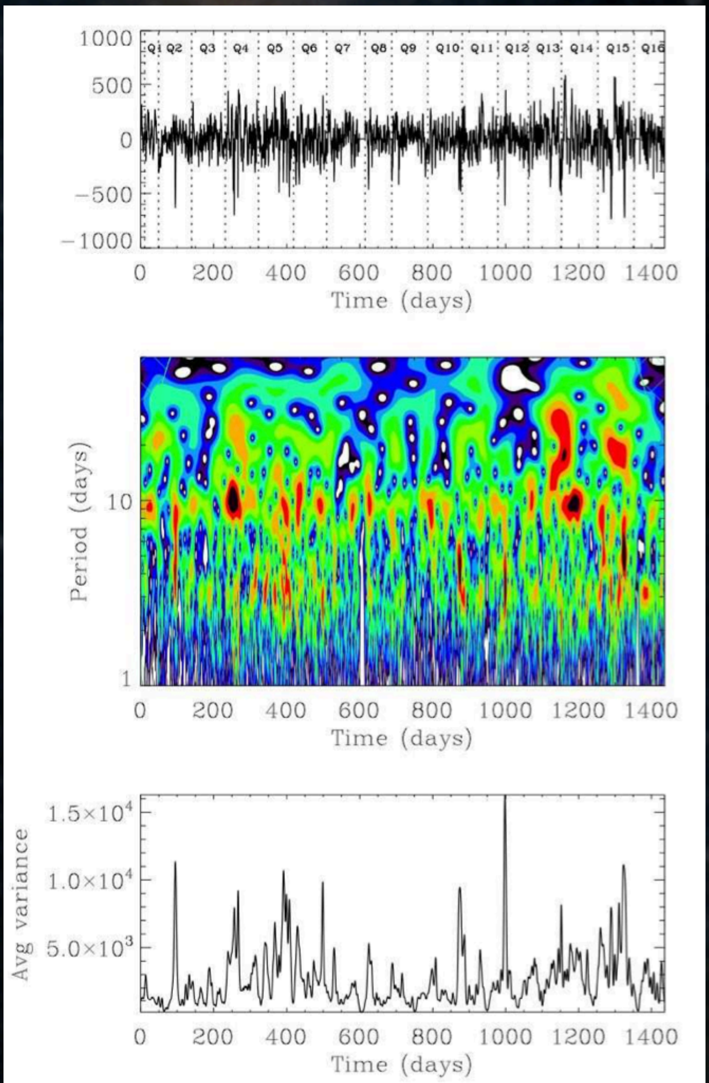




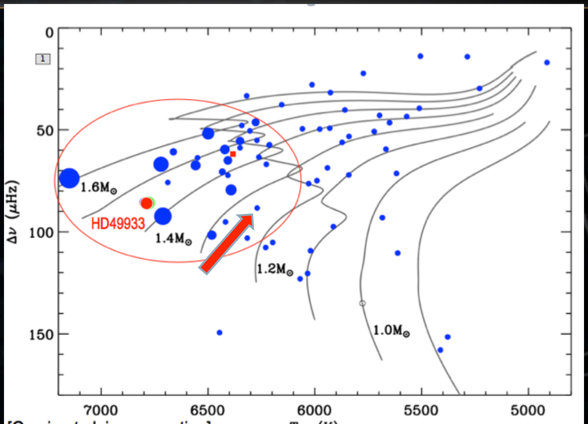
[Augustson, Mathur, Brun et al. in prep.]

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]



[Garcia et al. in preparation]

- KIC12009504
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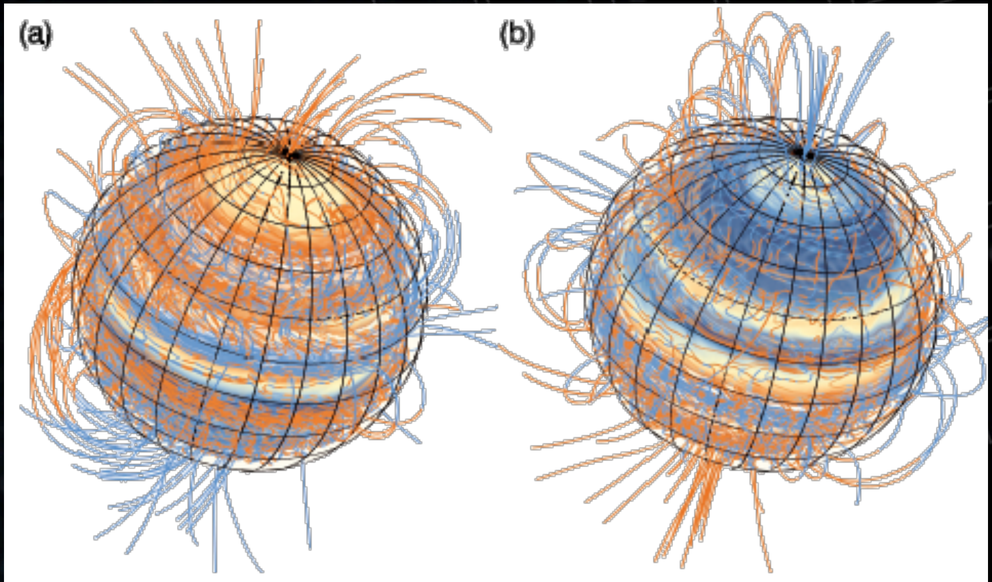
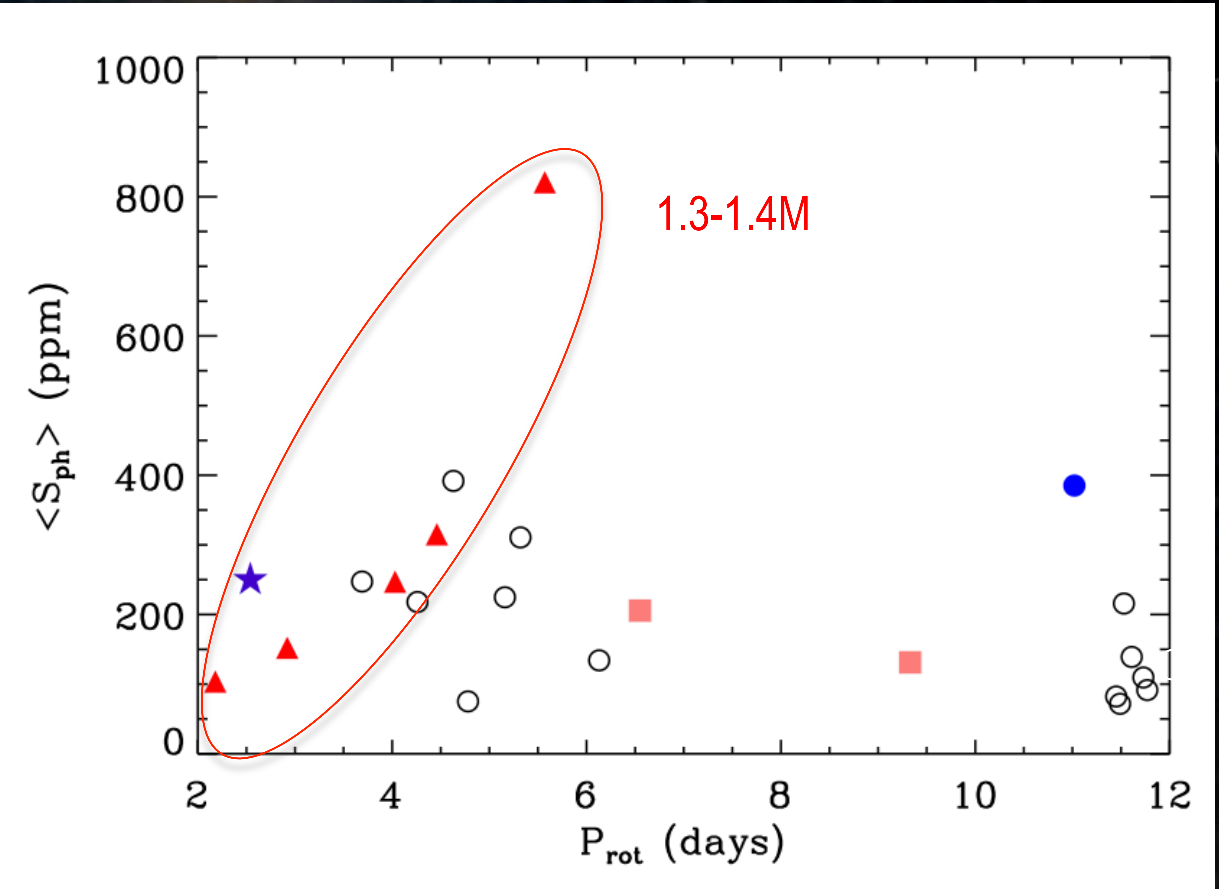


[Augustson, Mathur, Brun et al. in prep.]

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

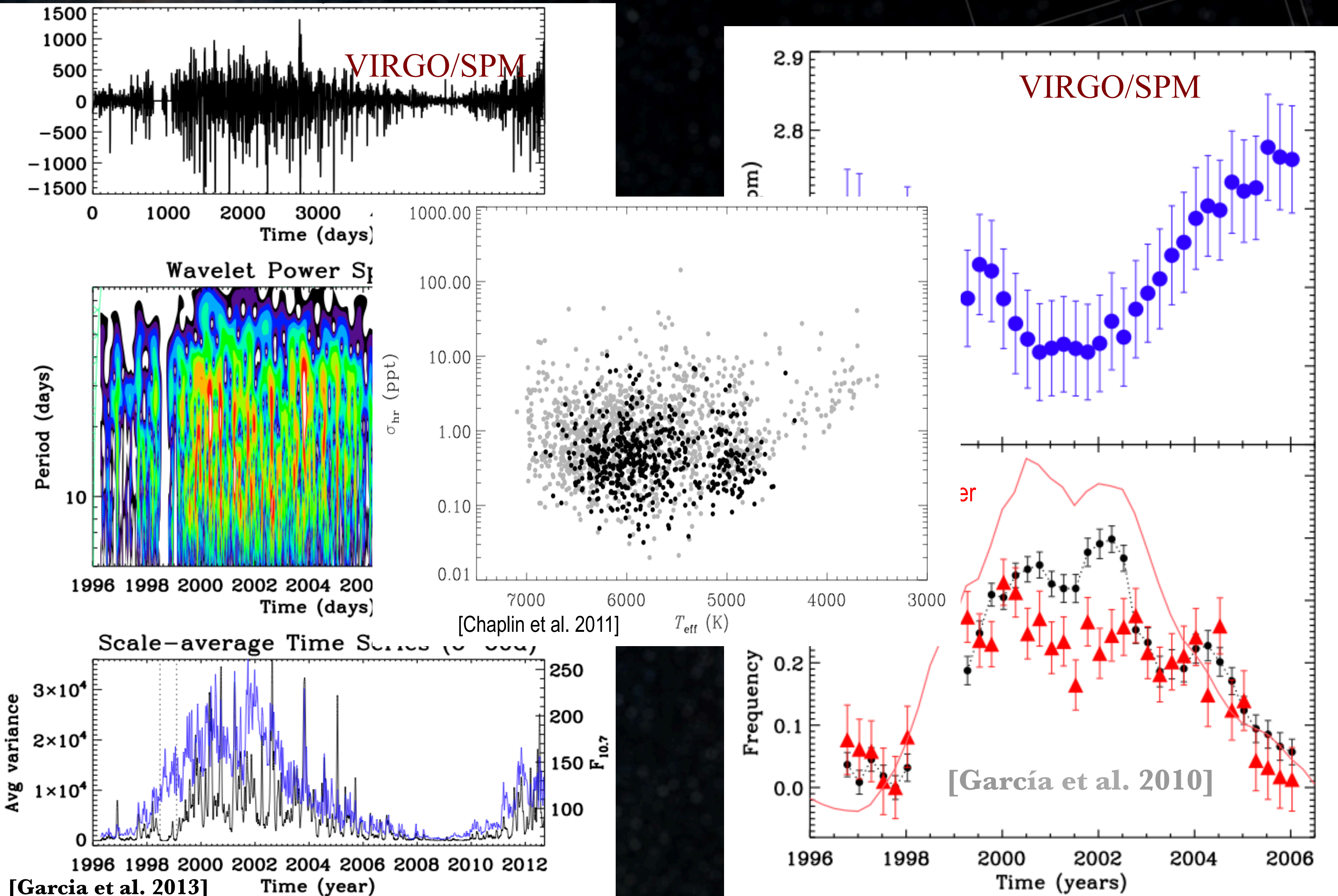
IV-STELLAR MAGNETIC CYCLES



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

Long-lived active longitudes
Trends
Cycle

IV-MAGNETIC ACTIVITY: SEISMOLOGY



[Garcia et al. 2013]

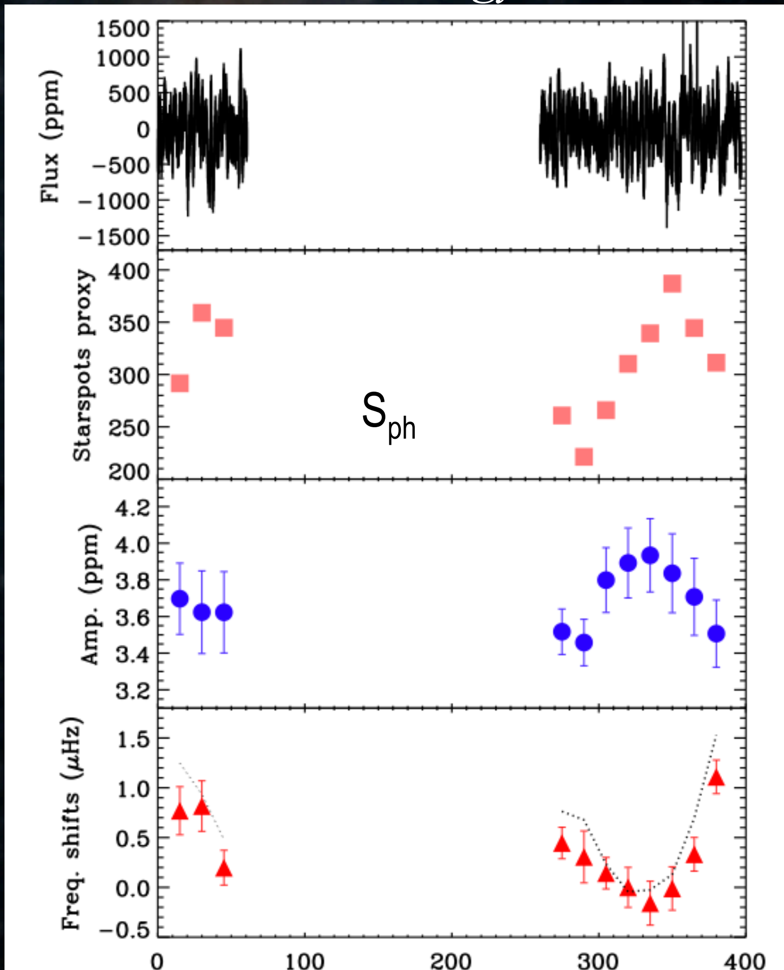
[Chaplin et al. 2011]

[García et al. 2010]

HINTS OF A MAGNETIC-ACTIVITY CYCLE

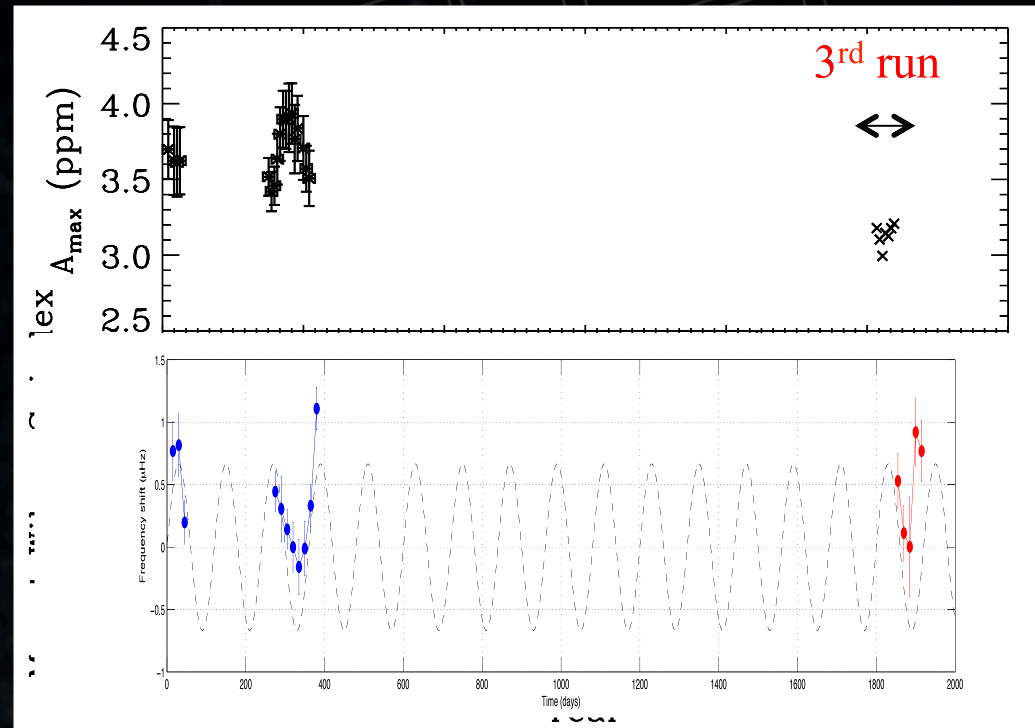
Seismology

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

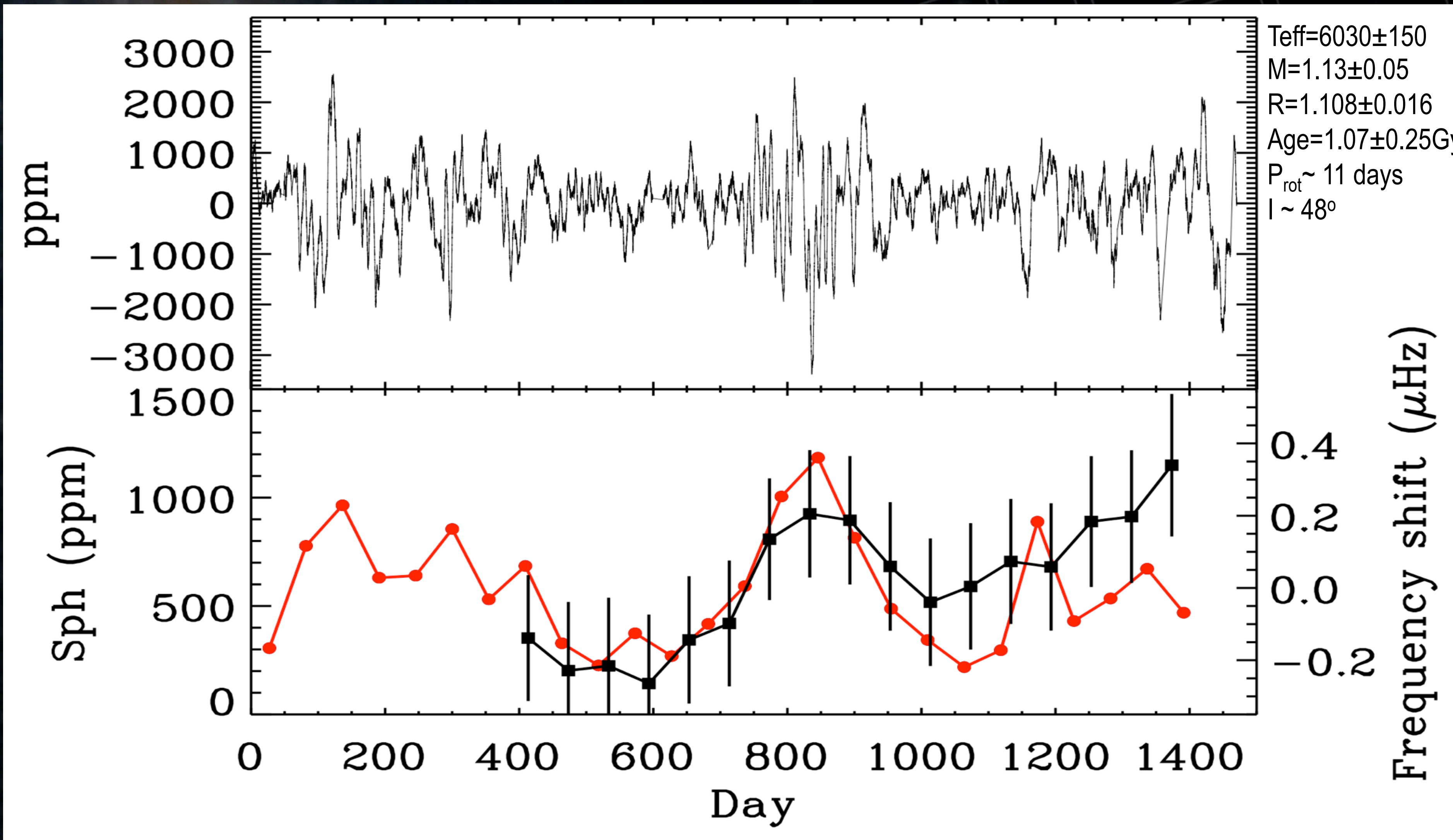
Campante et al. 2014

HINTS OF A MAGNETIC-ACTIVITY CYCLE

- ≈Solar analog
  - Correlation between S_{ph} and p-mode frequency shifts

Kepler

[Bruntt et al. 2012; Metcalfe et al. 2014; García et al. 2014]



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

CONCLUSIONS

K2
Extending Kepler's Power to the Ecliptic

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

PLATO