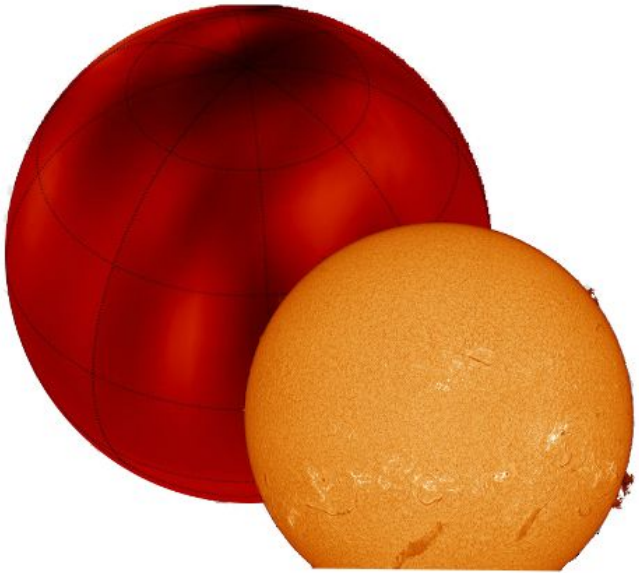
Surface differential rotation on active stars



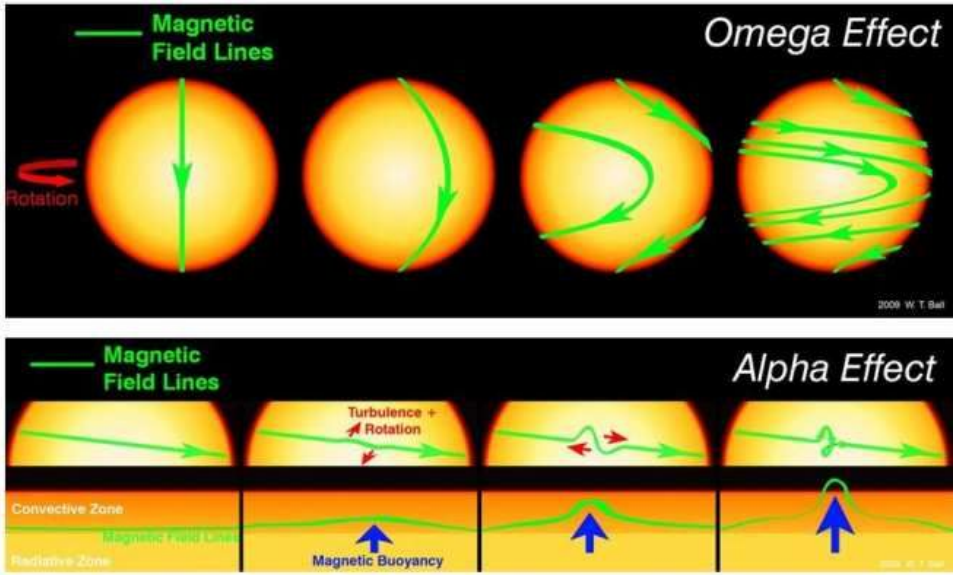
12. 11. 2025

Kriskovics, Levente

STARK@Konkoly:
Görgei, Anna
Kővári, Zsolt
Kriskovics, Levente
Oláh, Katalin
Seli, Bálint
Van-Driel Gesztelyi, Lídia
Vida, Krisztián

Dynamo, differential rotation

- Stellar dynamos in late-type (G-K-M) stars generate magnetic fields which manifest in the observables of stellar activity
- Differential rotation is of utmost importance in the regeneration of the toroidal field component during a dynamo cycle (→ Ω-effect)
- Dynamo action can differ on different types of stars



Dynamo, differential rotation

Dynamo number: $D = D_\alpha D_\Omega = \frac{\alpha_1 L}{\eta_t} \frac{\Delta\Omega L^2}{\eta_t}$

D_α, D_Ω – turbulent magnetic Reynolds-numbers

L – typical scale-length of the dynamo

η_t – scalar turbulent diffusion

α_1 – alpha-effect coeff.

$\Delta\Omega$ – difference between rotation rates

Sun: $|D_\alpha| \sim 2$, $D_\Omega \sim 10^3$ → typical for αΩ dynamo

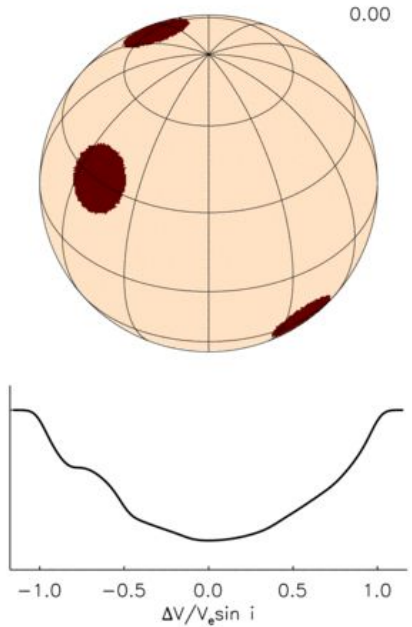
If D_α and D_Ω are in the same order of magnitude → $\alpha^2\Omega$ type dynamo, e.g. fast rotating, young MS stars

If $|D_\alpha| >> |D_\Omega|$ → α^2 type dynamo, e.g. fully convective (~ cooler than M3.5-M4) dwarfs

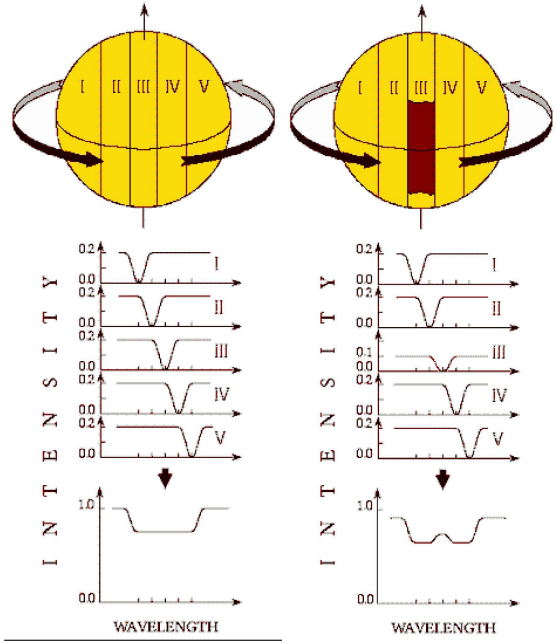
Differential rotation matters (through the Ω-effect)!

Doppler imaging

Indirect mapping method utilising high-resolution, high SNR time-series spectral data

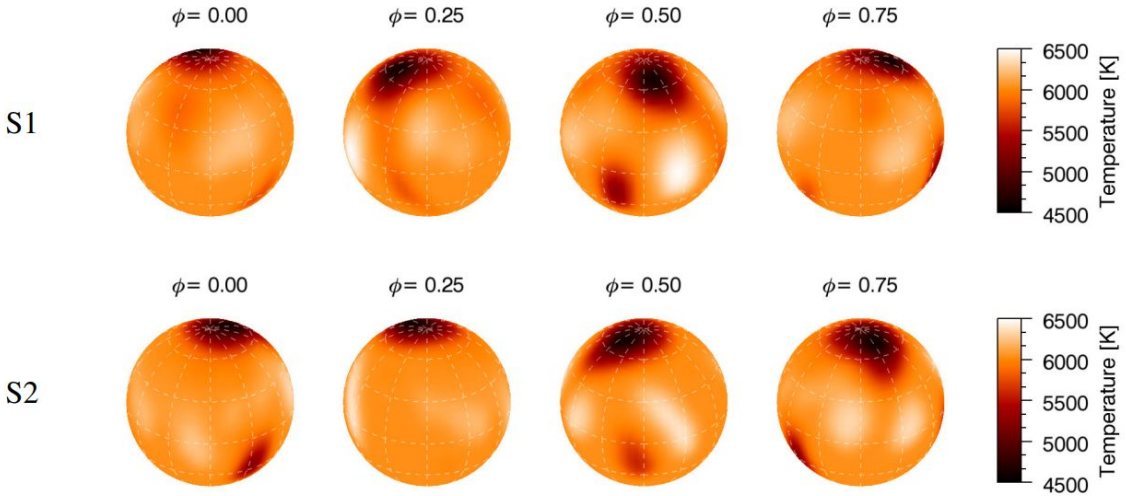


Source: O. Kochukov

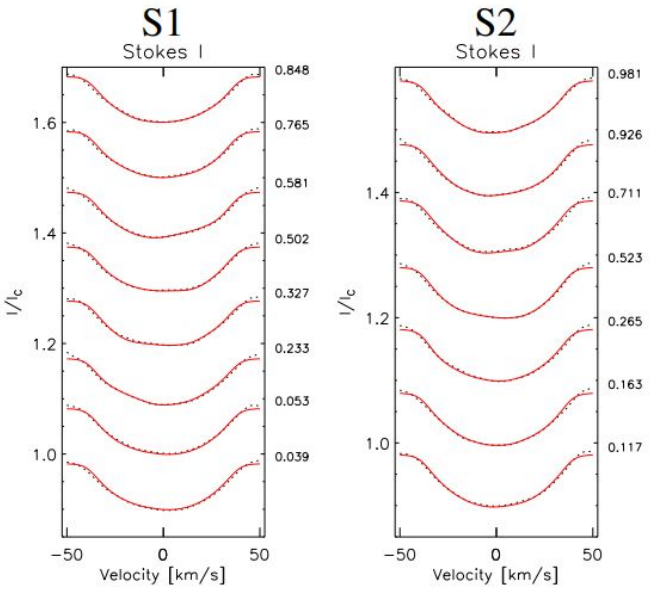


Rice+1996

Doppler imaging - iMap *(Carroll+2012)*



V1358 Ori, Kriskovics+2019



Measuring surface differential rotation

In case of stars, surface differential rotation is generally expressed in a quadratic form:

$$\Omega(\beta) = \Omega_{eq}(1 - \alpha \sin^2 \beta)$$

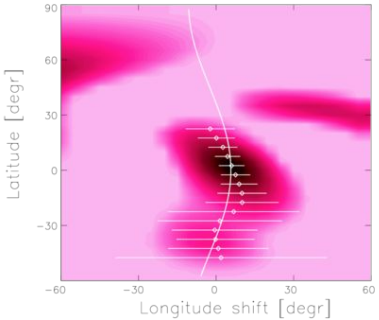
$\Omega(\beta)$: angular velocity at a given latitude β
Ω_{eq}: equatorial angular velocity
$\alpha = \Delta\Omega/\Omega = (\Omega_{eq} - \Omega_{pol})/\Omega_{eq}$: dimensionless surface shear parameter

If $\alpha > 0$: solar type differential rotation – the angular velocity is maximal at the equator
If $\alpha < 0$: anti-solar type differential rotation – the angular velocity is minimal at the equator

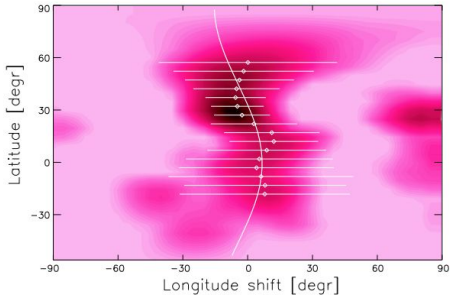
Measuring surface differential rotation – CCF

CCF (cross correlation function)-method:

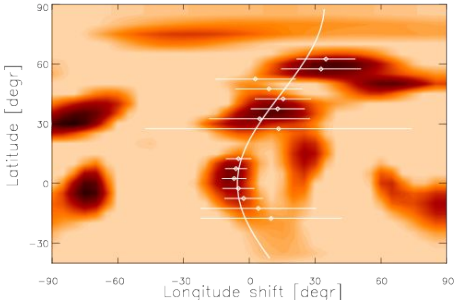
- Cross-correlation of latitude strips on consecutive Doppler-maps



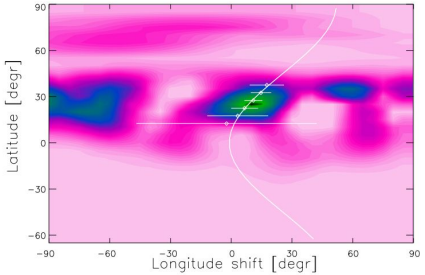
V1358 Ori, Kriskovics+2019



EI Eri, Kriskovics+2023



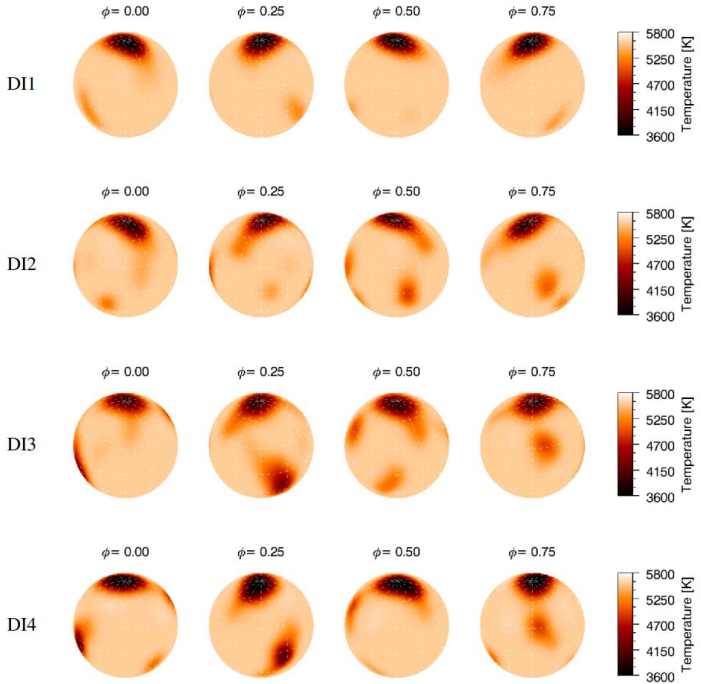
DI Psc, Kriskovics+2014



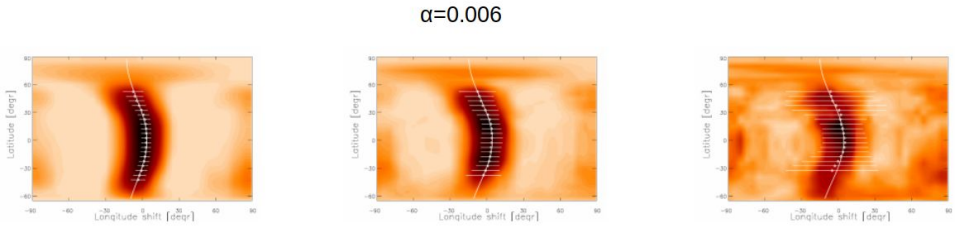
V1192 Ori, Kővári+2017

Measuring surface differential rotation – CCF

- Requires more data (more than one covered rotation) and rapid spot evolution and/or low SNR in some cases can hinder the results, but still more reliable



EI Eri, Kriskovics+2023

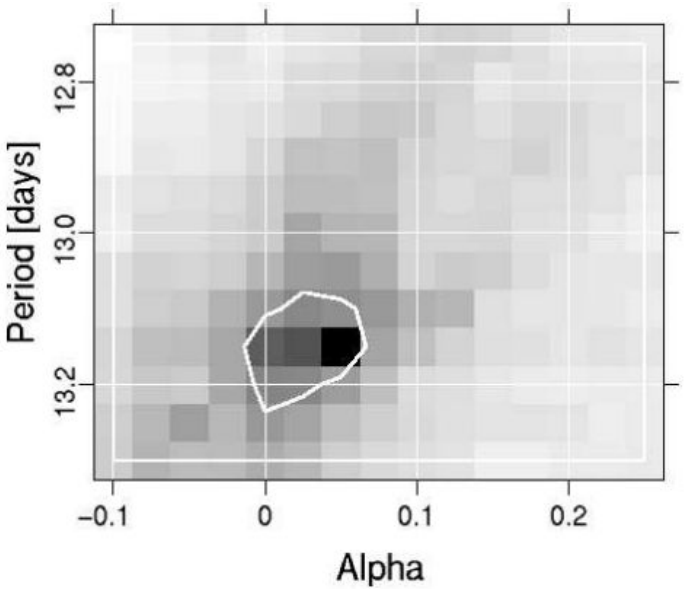


CCF results are affected by the phase coverage and signal-to-noise (Kővári+2014, Kővári+2015)

Measuring surface differential rotation – SIM

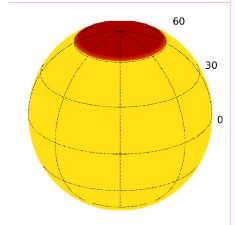
SIM (Sheared Image) method, or parametric inversion

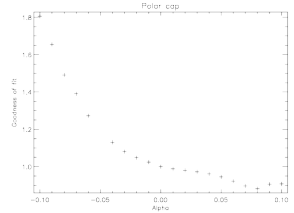
- Surface differential rotation affects the shape of the rotational profile and induces spot (profile bump) displacement
- The surface shear is an inversion parameter

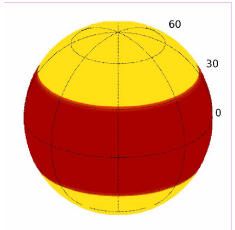


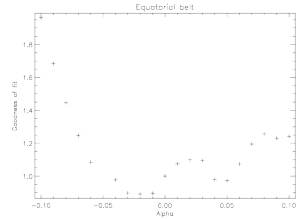
LQ Hya, Kővári+2001

SIM (and thus, measured differential rotation) could be affected by certain spot configurations? (Reiners+2002; Kővári+2014; Kriskovics, PhD thesis, 2017)









The (still expanding) sample (currently 30 stars)

CCF

Single Dwarfs
AB Dor
LQ Hya
V1358 Ori
EK Dra

Single Giants
FK Com
DP CVn
DI Psc
KU Peg
V1192 Ori
IN Com

Binary Subgiants
EI Eri
UZ Lib
HU Vir
IL Hya

Binary Dwarf
V815 Her
V471 Tau

Binary Giants
ζ And
σ Gem
V2075 Cyg

SIM

Single Dwarfs
BO Mic
LO Peg
HK Aqr
V557 Car
LQ Hya
61 Cyg A

Single Giants
V1794 Cyg

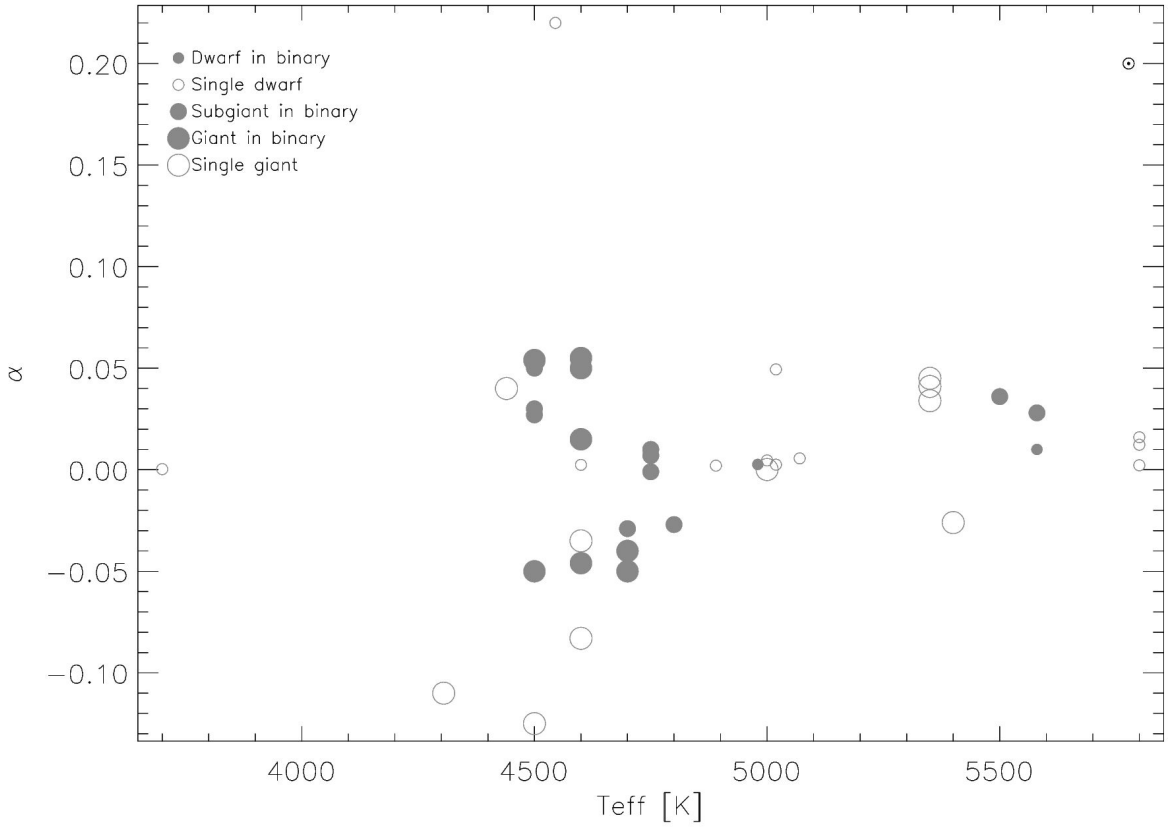
Binary subgiants
V711 Tau

Binary Giants
V2075 Cyg
HK Lac
IM Peg

Barnes+2005, Barnes+2005b, Barnes+2004, Donati+1997, Marsden+2005, Donati+2003, Petit+2004a, Kővári+2004, Kővári+2009, Korhonen+2000, Petit+2004b, Vida+2007b, Harutyunyan+2016, Kővári+2004b, Kővári+2014, Kővári+2013, Kővári+2007, Kővári et al+2012, Kriskovics+2013, Kriskovics+2014, Kővári+2015, Weber+2005, Özdarcan+2016, Kővári+2016, Marsden+2007, Strassmeier+2003, Kővári+2017, Balthasar+1986, Boro Saikia+2016,Kővári+2018, Kővári+2021, Kriskovics+2019, Kriskovics+2023, Kővári+2024, Görgei+submitted

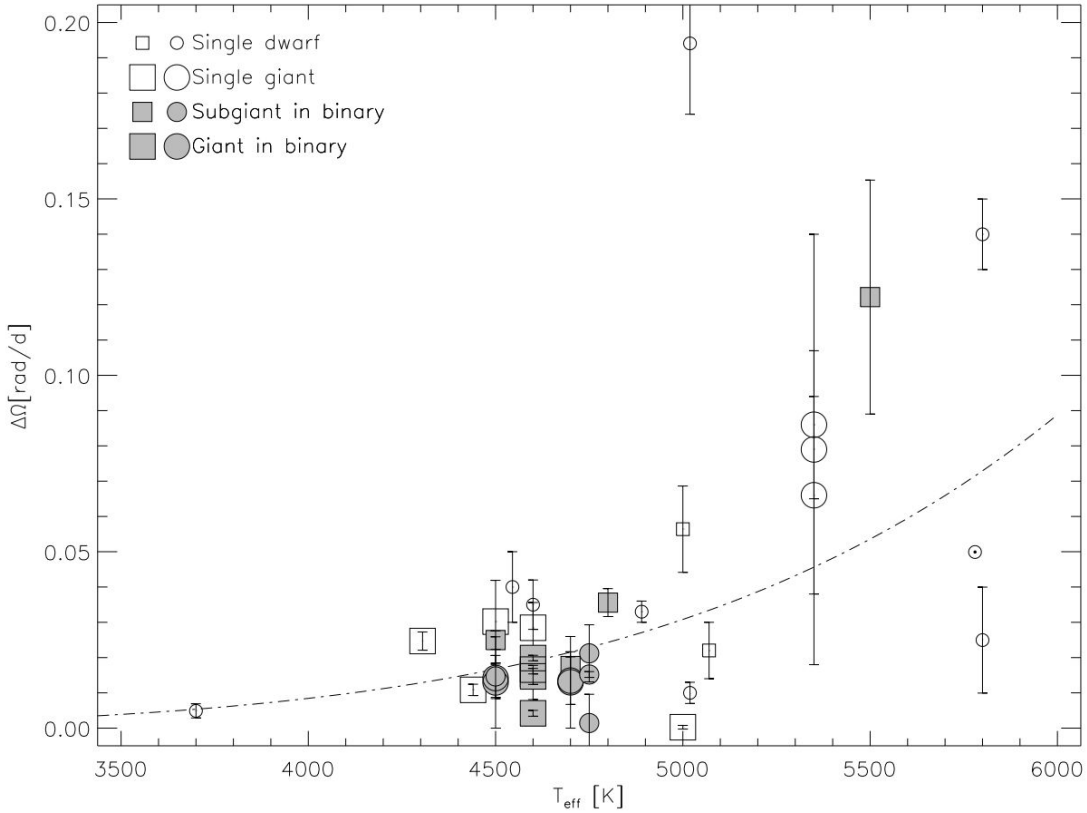
The (still expanding) sample

$\alpha=\Delta\Omega/\Omega=(\Omega_{eq}-\Omega_{pol})/\Omega$



Absolute shear vs temperature

$\alpha=\Delta\Omega/\Omega=(\Omega_{eq}-\Omega_{pol})/\Omega$

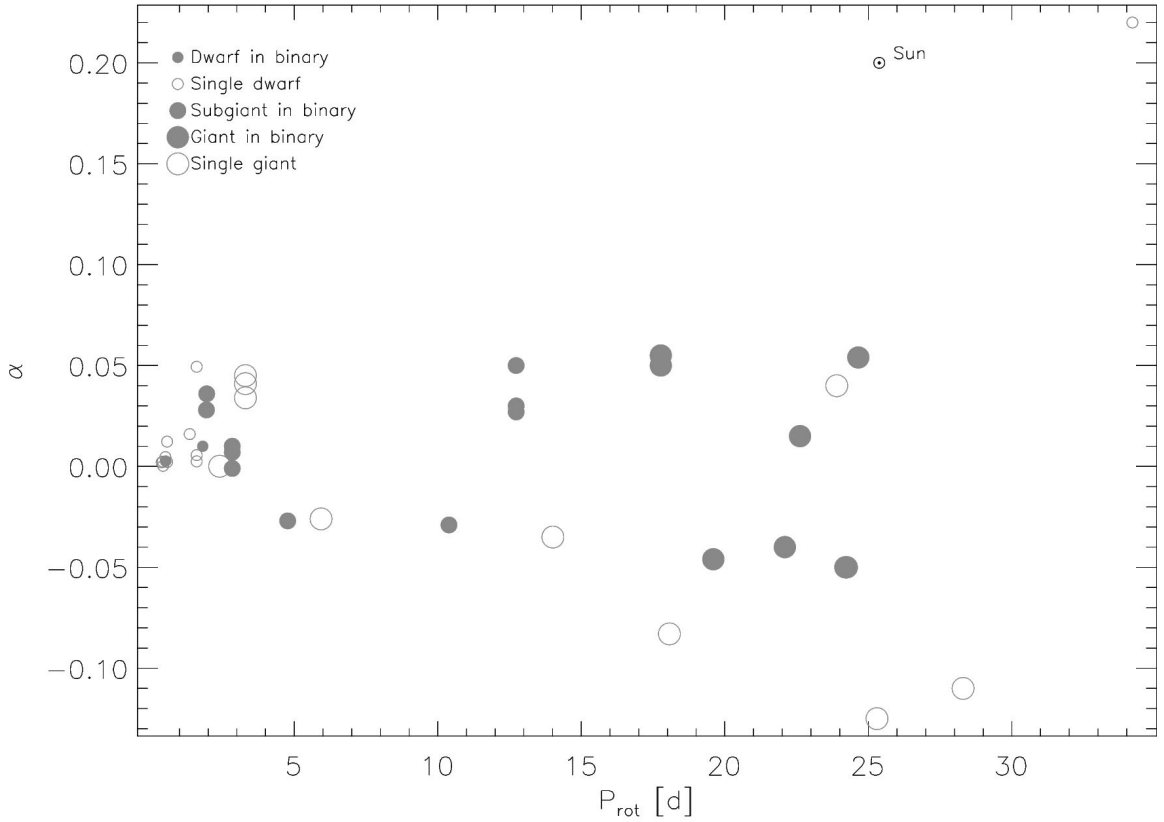


$\Delta\Omega \propto T_{eff}^{(5.8\pm1.0)}$

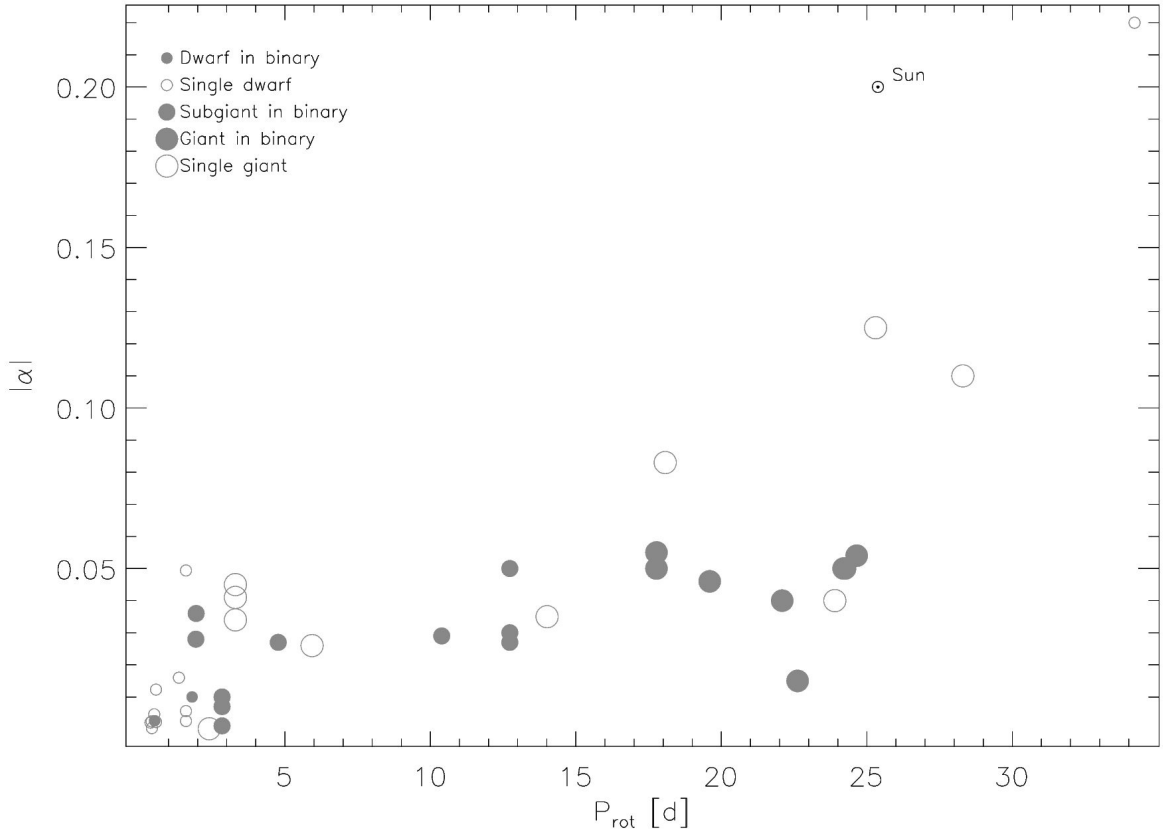
Kővári+2017

Bimodality

$\alpha=\Delta\Omega/\Omega=(\Omega_{eq}-\Omega_{pol})/\Omega$

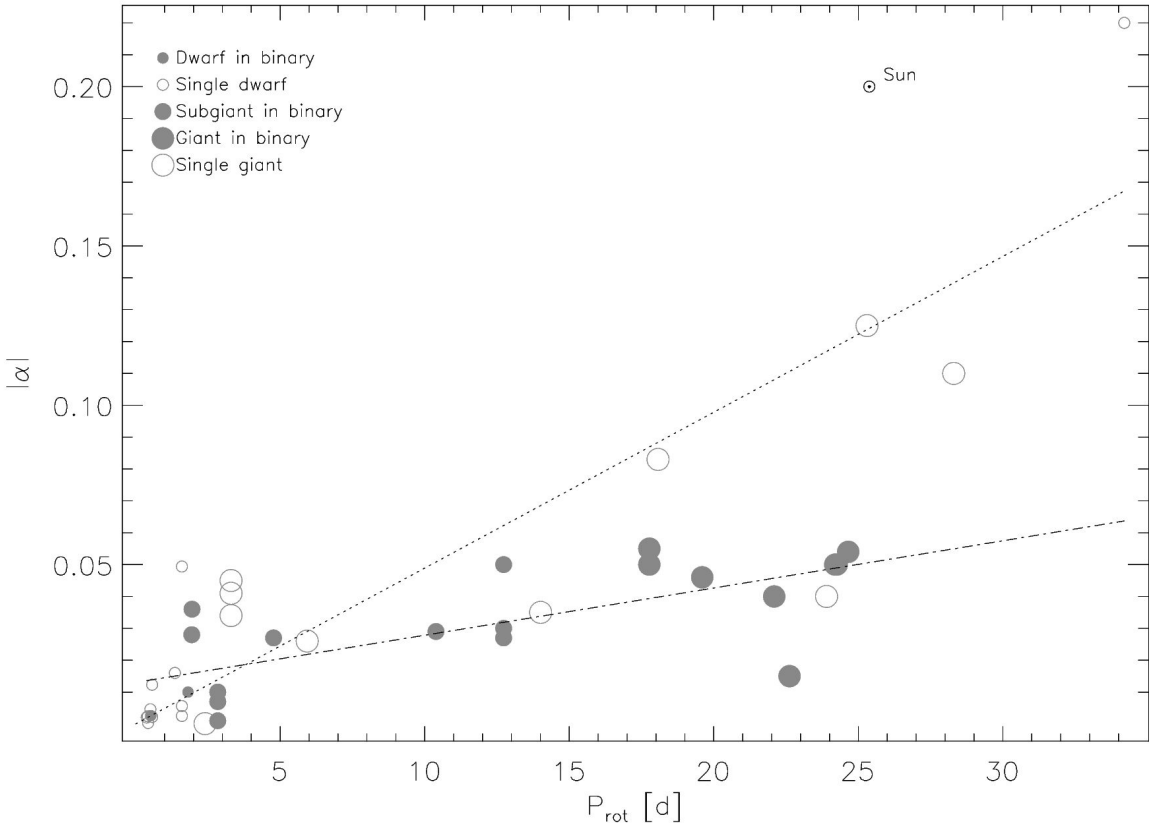


Bimodality



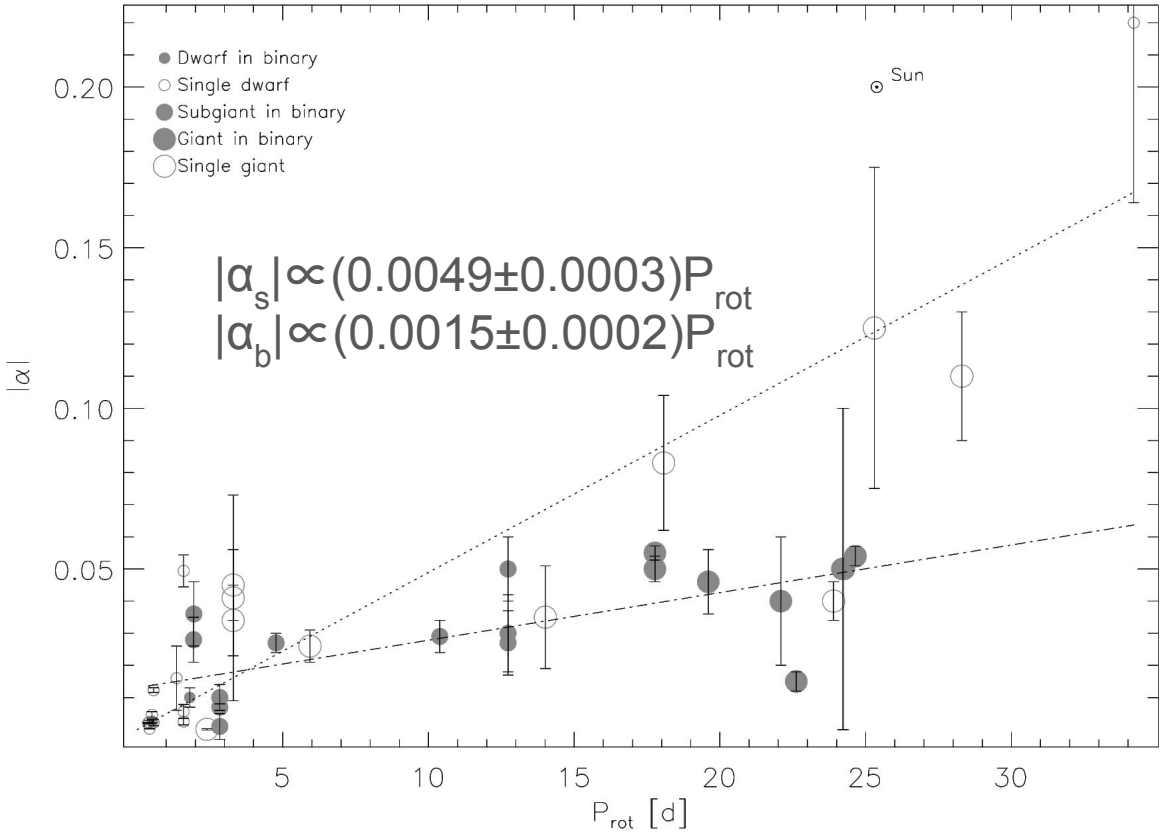
Updated plot from Kővári+2017

Bimodality



Updated plot from Kővári+2017

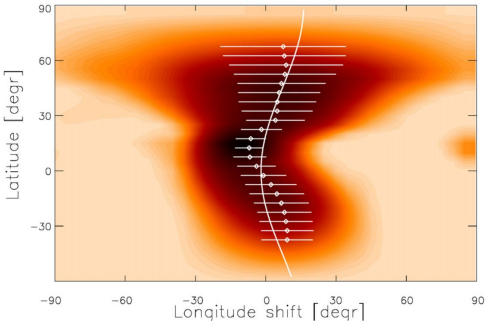
Bimodality

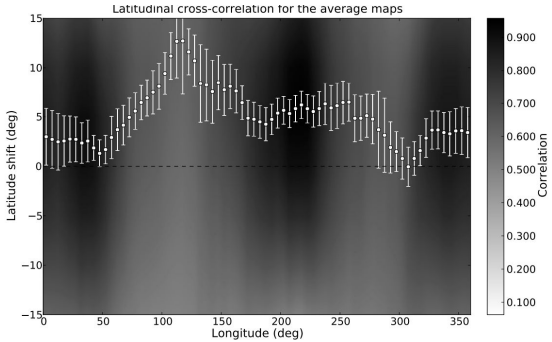


Updated plot from Kővári+2017, Kriskovics+2023, Görgei+submitted

Bimodality – Binaries

– in RS CVn binaries, tidal coupling is responsible for maintaining the fast rotation
– aspherical distortion (i.e., ellipticity, e.g. ζ And) can also cause flux emergence at “preferred” longitudes (e.g. Kővári+2012) --> this can also affect measured differential rotation
– close binaries can also exhibit corotating latitudes (Scharlemann+1982)
– tidal locking could enhance meridional circulation as well (Kitchatinov+2004) resulting in anti-solar differential rotation (e.g. sigma Gem, Kővári+2015)





--> These effects interact with the convective layer of the active components of close binaries, causing the separation between the differential rotational laws of singles and binaries

Bimodality – Binaries

– magnetic interaction between the two components?



V824 Ara, Kriskovics+2013

Dwarfs

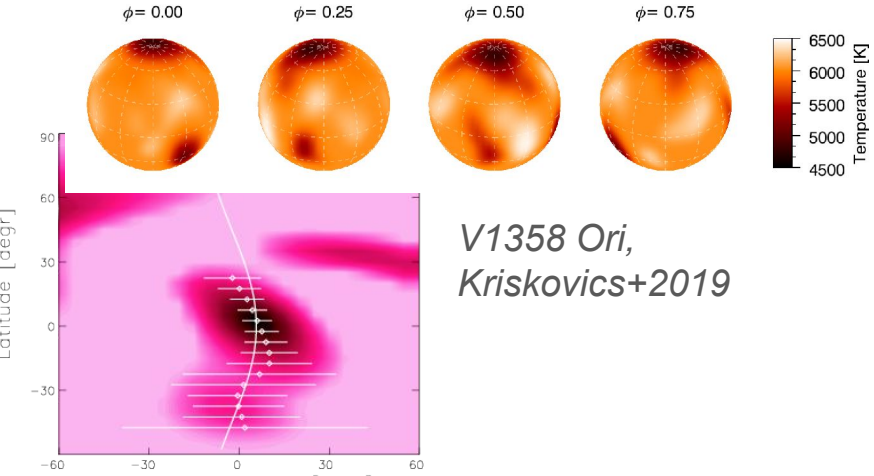
– generally low surface DR

– a strong shear could be reduced by Ω-quenching (Brun+2015) (this could be true for other luminosity classes) → $\alpha^2\Omega$?

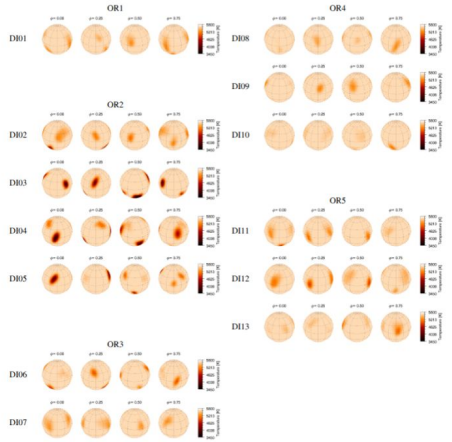
– strong toroidal field can interact with DR and suppress it

– observed differential rotations are in correlation with theory

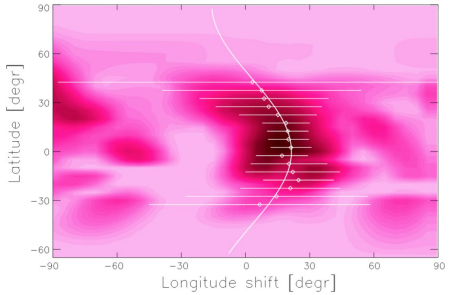
– spot configurations on single dwarfs tend to be dominated by polar structures (e.g. V889 Her, Kővári+2011; HD29165, AH Lep and V1358 Ori, Hackman+2016, EK Dra, Järvinen+2017, Görgei+submitted; V1358 Ori, Kriskovics+2019), which is in agreement with theory (e.g. Işık+2018)-- could it affect CCF?



V1358 Ori, Kriskovics+2019



EK Dra, Görgei+submitted

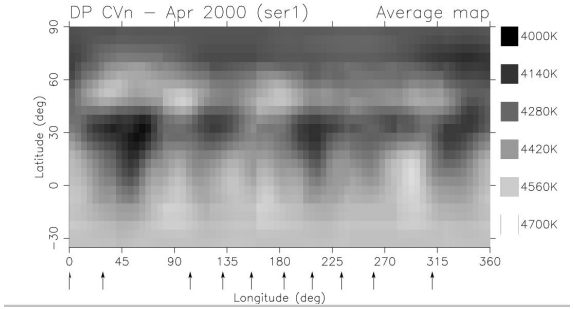


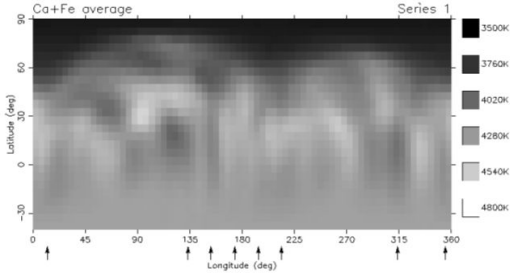
Anti-solar DR on single giants

– DP CVn, DI Psc and V1192 Ori are (the only known) single giants exhibiting anti-solar differential rotation

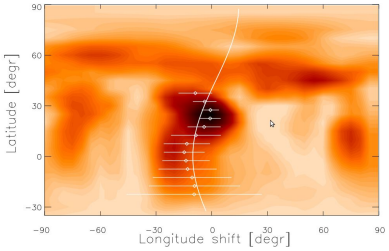
~K1III (T~4600K, logg~2.5)

Li-rich giants at their first Li dredge-up

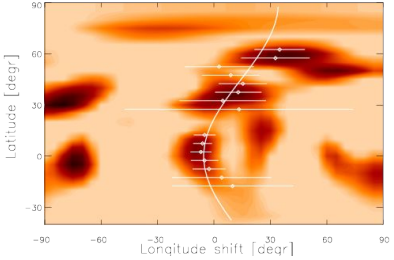




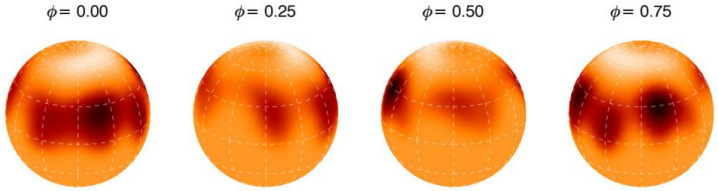
DP CVn, Kővári+2013

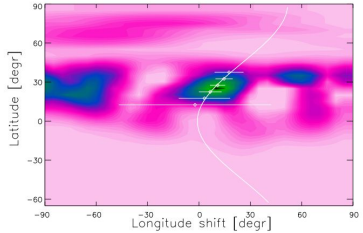


DI Psc, Kriskovics+2014



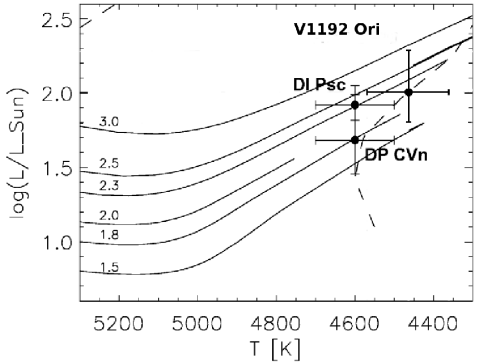
V1192 Ori, Kővári+2017





Anti-solar DR on single giants

– First dredge-up: a “quick” Li-diluting episode on the RGB
– These stars still show high Li-abundances
– The only three known single giants with anti-solar DR pattern
– suggested common origin (Charbonnel+2010, Kriskovics+2014, Kővári+2017): Li produced by the Cameron-Fowler process is transported towards the surface by strong mixing before it is destroyed
– angular momentum can be equilibrated by strong mixing resulting in anti-solar DR



Summary

– singles and binaries definitely exhibit different differential rotational (Prot-α) laws
– tidal locking in binaries affects surface differential rotation, suppressing it
– Anti-solar differential rotation can be observed in the sample on
Li-rich single giants around their first lithium dredge-up phase; a joint origin is suspected
– in close binaries, tidal locking could enhance meridional circulation resulting in anti-solar differential rotational pattern
– single dwarfs generally show low surface differential rotation
– Measured differential rotations can be affected by a few effects of artificial origin
    – SIM could be affected by certain spot configurations leading to erroneous results
    –CCF can be slightly affected by the S/N of the data and the phase coverage can CCF be affected by spot configurations dominated by polar features?
– more data is needed (but it is “expensive”). Comparison with photometric estimates?

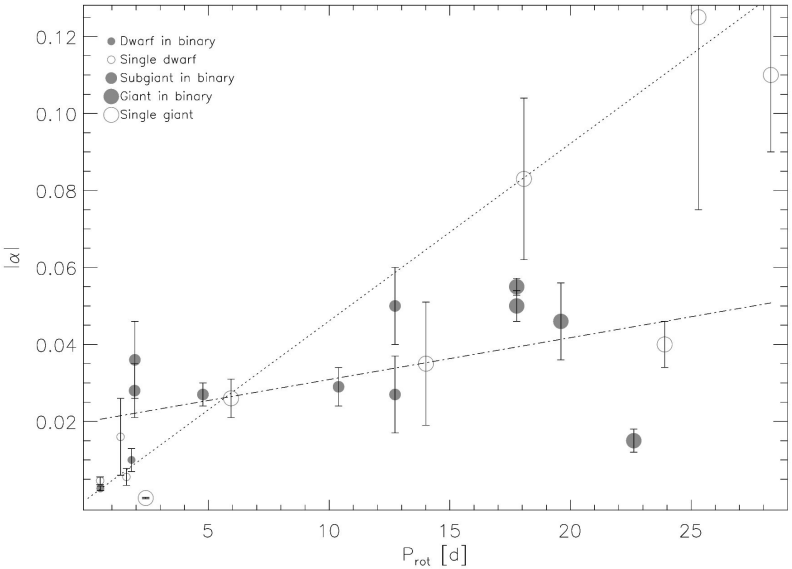
THANK YOU!

CCF vs SIM

– discrepancy between the two main methods due to the aforementioned sources of possible errors

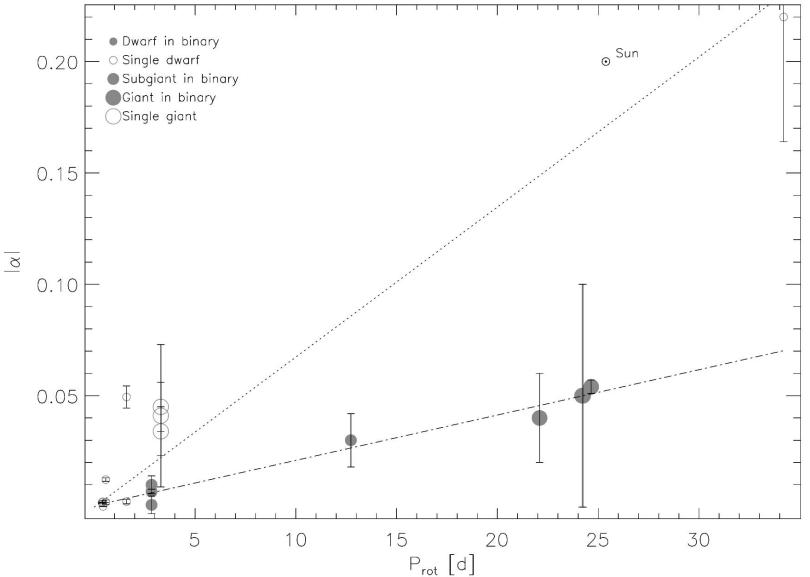
$|\alpha_s| \propto (0.005) P_{rot}$
$|\alpha_b| \propto (0.001) P_{rot}$

ccf

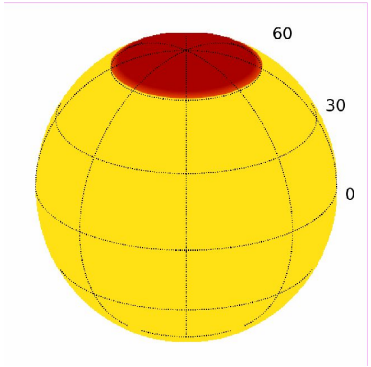


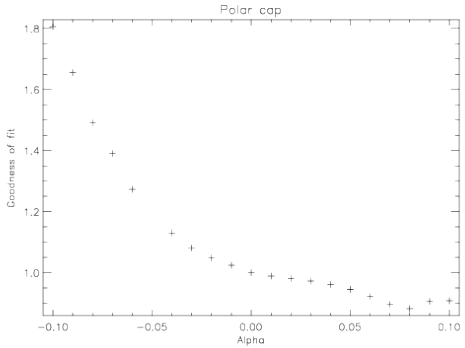
$|\alpha_s| \propto (0.007) P_{rot}$
$|\alpha_b| \propto (0.002) P_{rot}$

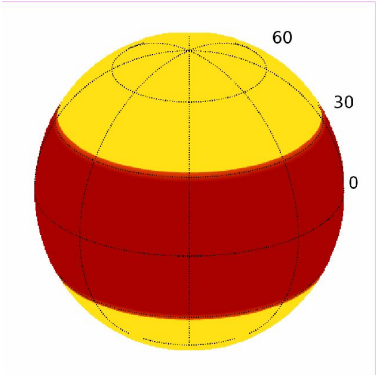
sim

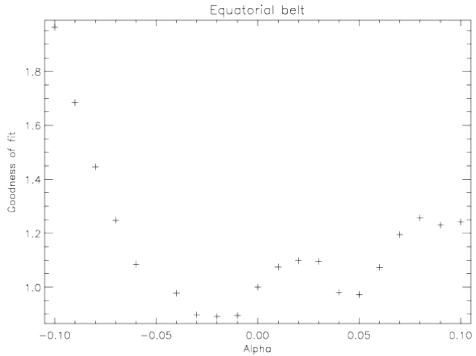


Measuring surface differential rotation – SIM









Kriskovics, PhD thesis

Absolute shear vs temperature

– theoretical predictions suggest a connection between the absolute surface shear and effective temperature (e.g. Küker+2005, Küker+2011)
– This exponent value is in rather good agreement with theory and the result of Reinhold+2015 using the extended Kepler-dataset