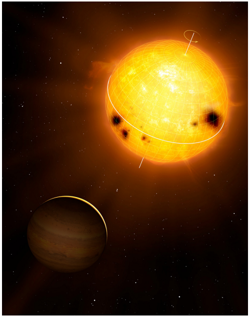

Rotation, differential rotation, and gyrochronology of active Kepler stars

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INSTITUT FÜR ASTROPHYSIK GÖTTINGEN

Rotation, differential rotation, gyrochronology

- Rotation: $P_{\rm rot} = 4.5\,{\rm d}$
- Differential Rotation: Three-spot model, beat shape
- Gyrochronology: $(T_{\rm eff}, P_{\rm rot}) \rightarrow$ age

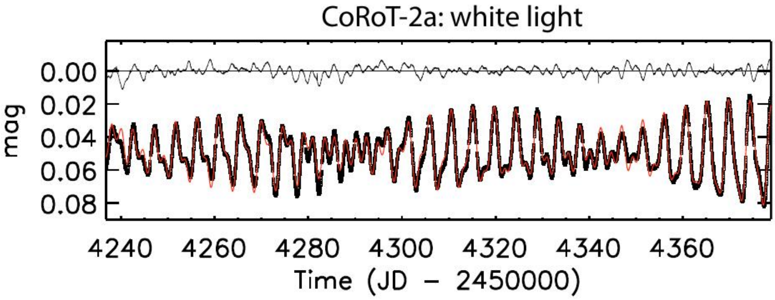


Figure 1: Three-spot model applied to CoRoT-2 (Fröhlich et al. 2009)
$\hookrightarrow$ Beat-shaped light curve reveals DR!

Lomb-Scargle periodogram

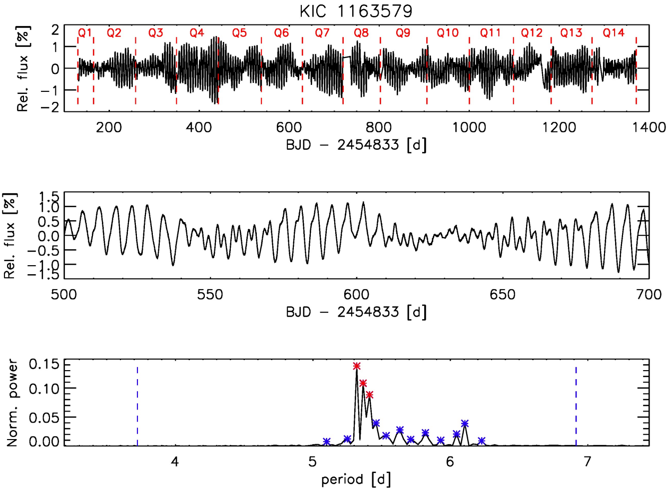


Figure 2: Fourier based methods: Power spectrum reveals periods with different power

Multiple sine fit

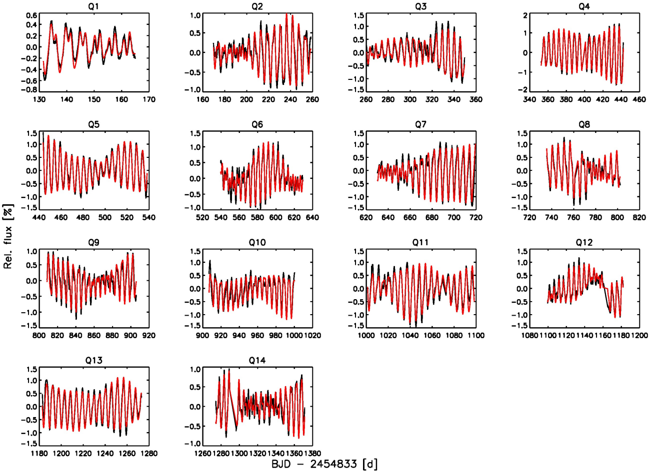


Figure 3: Fit light curves with multiple sine waves
↪ Reveal different (rotation) periods (Reinhold & Reiners 2013)

Rotation

Kepler rotation periods: old measurements

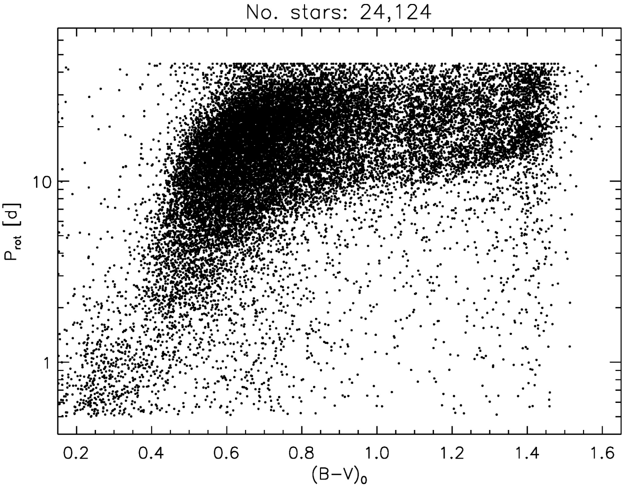


Figure 4: 24,124 rotation periods using Q3 data only.

Kepler rotation periods: revised measurements

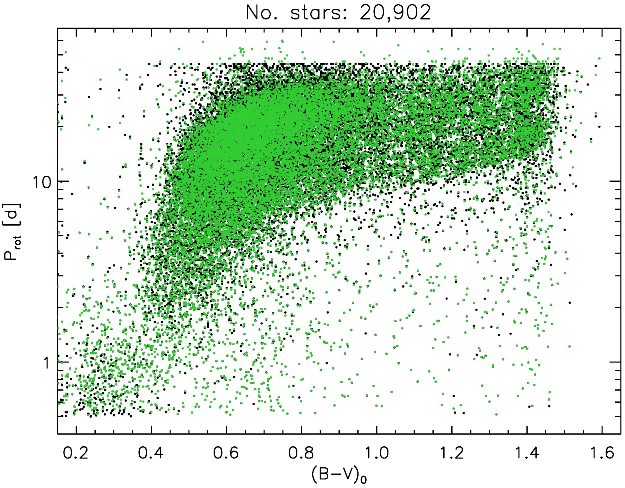


Figure 5: 20,092 revised rotation periods using all available data!

Kepler rotation periods: revised measurements

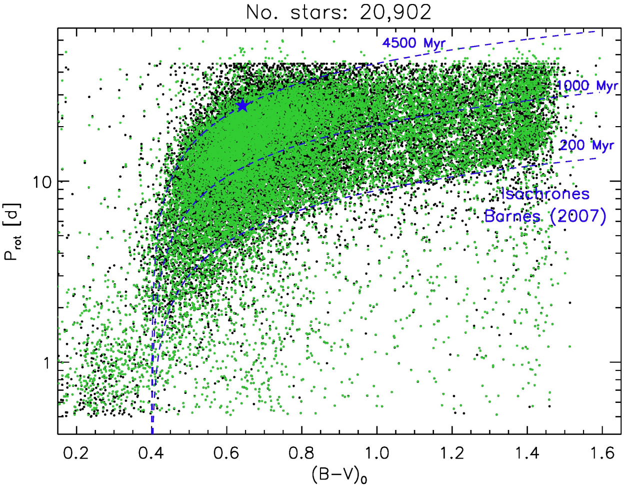


Figure 5: 20,092 revised rotation periods using all available data!

34,030 rotation periods (McQuillan et al. 2014)

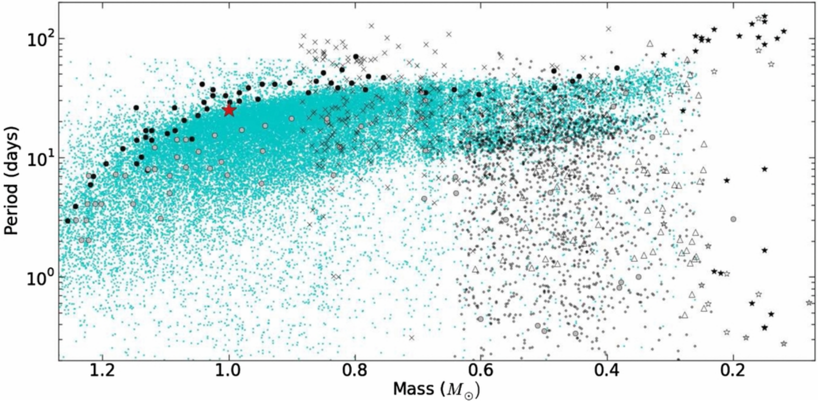


Figure 6: 34,030 rotation periods derived by Auto Correlation Function (ACF). Biggest rotation period sample so far!

AutoACF vs. Lomb-Scargle

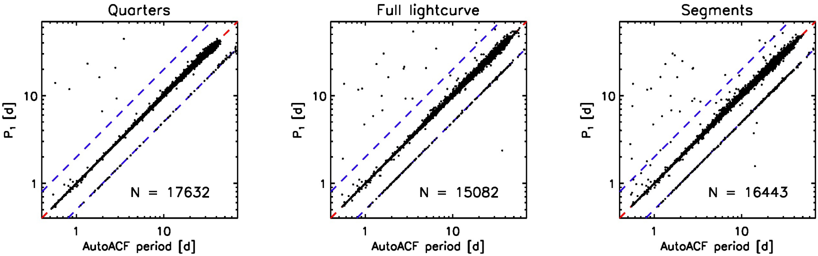


Figure 7: Comparing $\sim$ 18,000 revised rotation periods (Reinhold & Gizon 2015, submitted) to McQuillan (2014) periods: good agreement!

Bulk rotation period measurements (so far...)

- McQuillan et al. (2013a): 1570 (M dwarfs)
- Nielsen et al. (2013): 12.151 stars
- McQuillan et al. (2013b): 737 (KOIs)
- Walkowicz & Basri (2013): 950 (KOIs)
- Reinhold et al. (2013): 24.124 stars
- McQuillan et al. (2014): 34.030 stars!!!

Differential Rotation

Previous observations I: Hall 1991

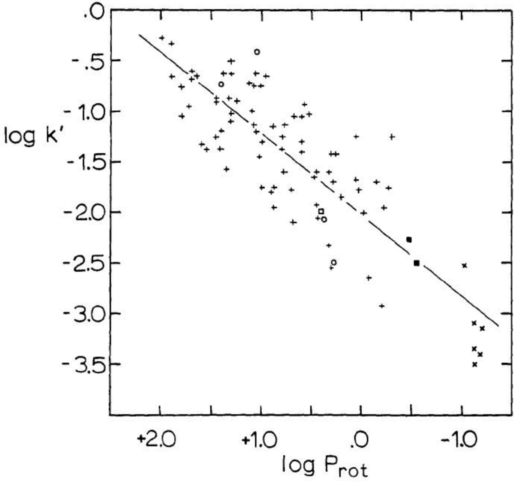


Figure 8: Relative shear k' increases with rotation period P_{rot}

Previous observations II: Donahue, Saar, & Baliunas 1996

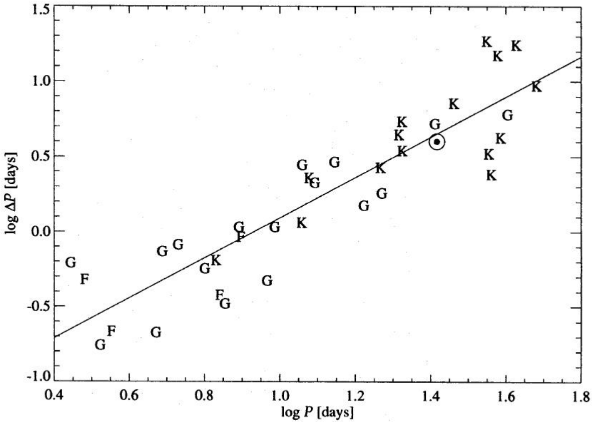


FIG. 3.—Range of observed rotation periods vs. log $\langle P \rangle$. Least-squares fit of these data yields $\Delta P \propto \langle P \rangle^{1.3 \pm 0.1}$ (correlation coefficient $r = 0.90$).

Figure 9: Period spread ΔP increases with rotation period $P_{\rm rot}$

Previous observations III: Barnes et al. 2005

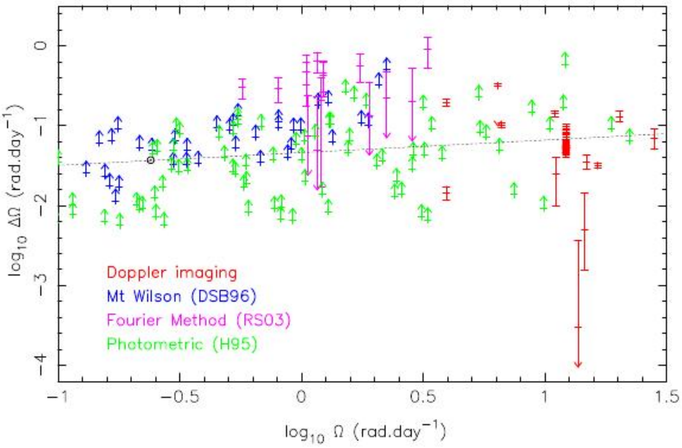


Figure 10: $\Delta\Omega$ shows weak dependence on Ω

Previous observations IV: Barnes et al. 2005

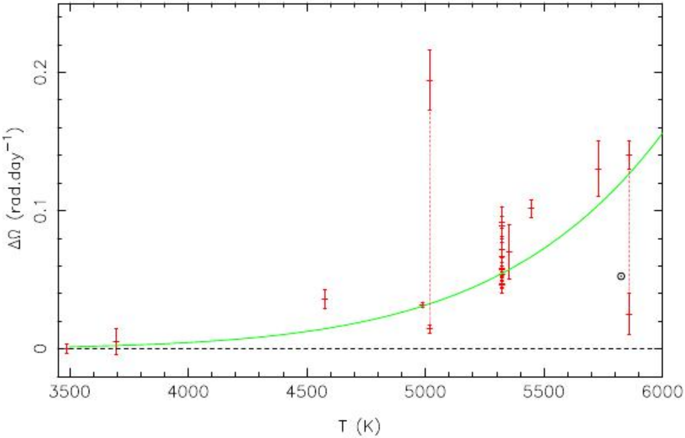


Figure 11: $\Delta\Omega$ shows strong dependence on T_{eff}

Mean field models: Küker & Rüdiger 2011

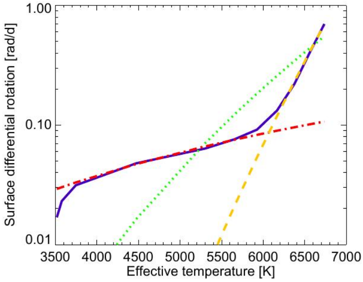


Figure 12: Two distinct temperature ranges:
$T_{\mathrm{eff}} < 6000\,K$: $\Delta\Omega \propto T_{\mathrm{eff}}^{2}$
$T_{\mathrm{eff}} > 6000\,K$: $\Delta\Omega \propto T_{\mathrm{eff}}^{20}$

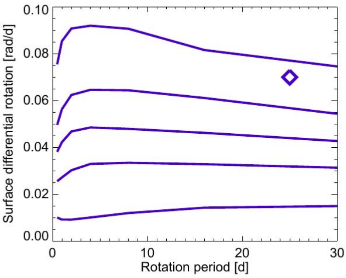


Figure 13: Weak dependence on rotation period! Models for solar masses from $1.1 - 0.3\,M_{\odot}$ (top to bottom)

Kepler observations I: $P_{\min}$ vs. α

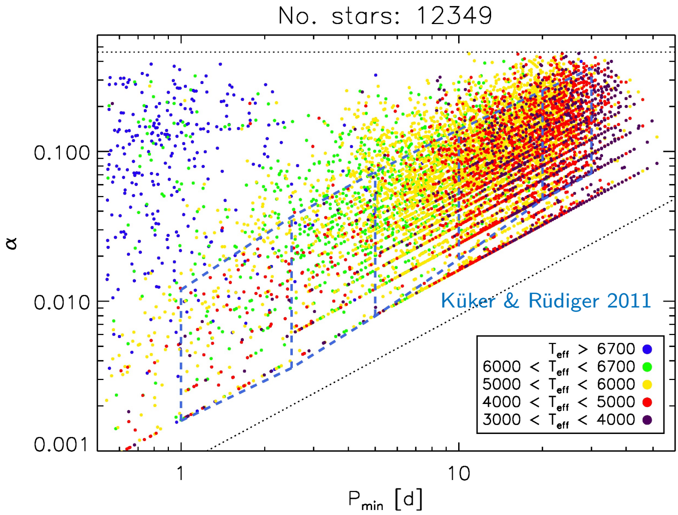


Figure 14: α strongly increases with rotation period

Kepler observations II: P_{min} vs. $\Delta\Omega$

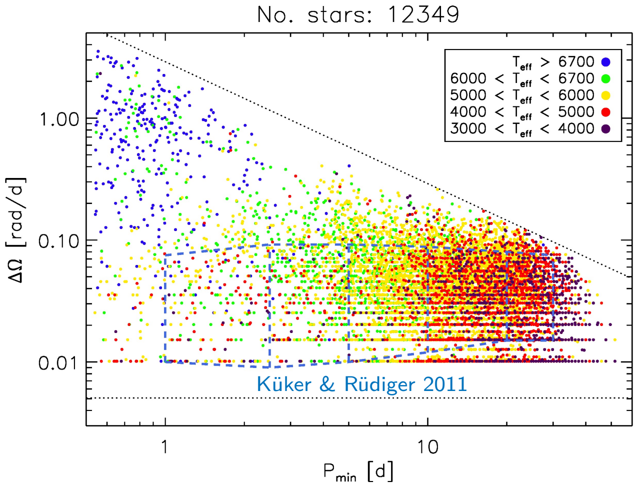


Figure 15: $\Delta\Omega$ weakly depends on rotation period. For fast rotators with $P_{\mathrm{rot}} < 2$ days, $\Delta\Omega$ shows large scatter!

Kepler observations III: $T_{\rm eff}$ vs. $\Delta\Omega$

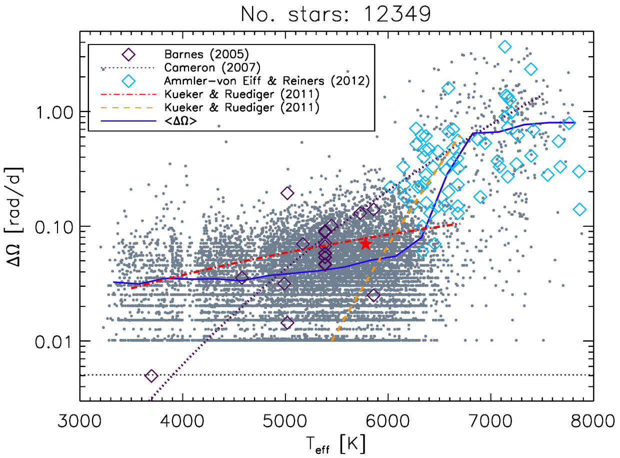


Figure 16: Distinct behavior above and below 6000 K: for $T_{\rm eff} < 6000\,$K $\Delta\Omega$ weakly depends on temperature; for $T_{\rm eff} > 6000\,$K $\Delta\Omega$ shows large scatter!

Other photometric observations I: $P_{\rm rot}$ vs. $\Delta\Omega$

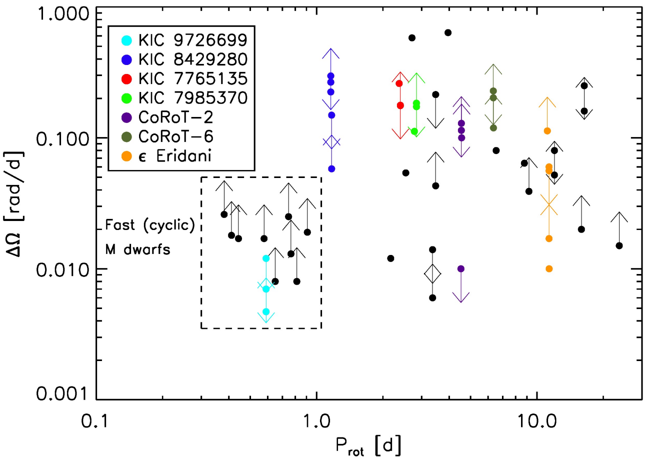


Figure 17: Large scatter, no distinct trend! Different behavior for $P_{\rm rot} < 1$ day?

Other photometric observations II: T_{eff} vs. $\Delta\Omega$

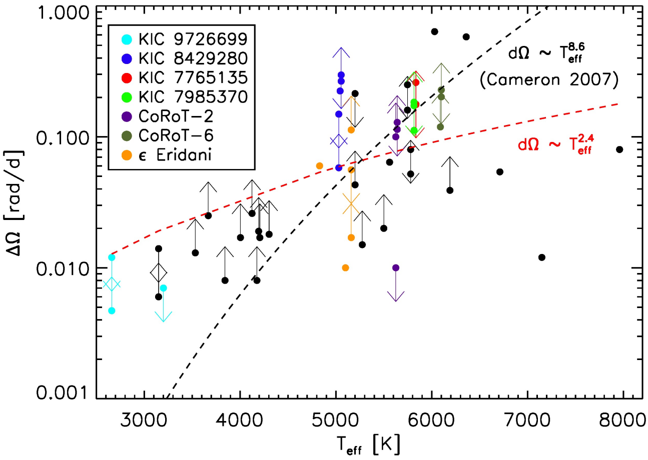


Figure 18: Large scatter; weaker dependence on temperature as predicted by Barnes (2005), Cameron (2007)!

DR from Hare & Hounds exercise (Aigrain et al. 2015)

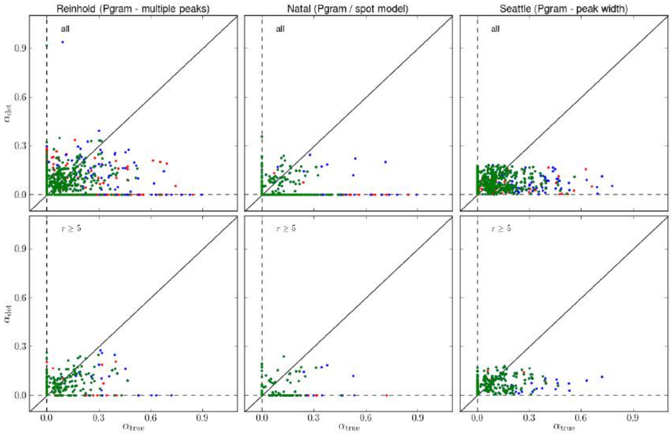


Figure 19: Bad recovery of DR! $\hookrightarrow$ Explanation: Short spot lifetimes & (much) smaller variability than in Kepler sample!

Stellar Ages

Gyrochronology
vs.
Asteroseismology

Kepler gyrochronology ages

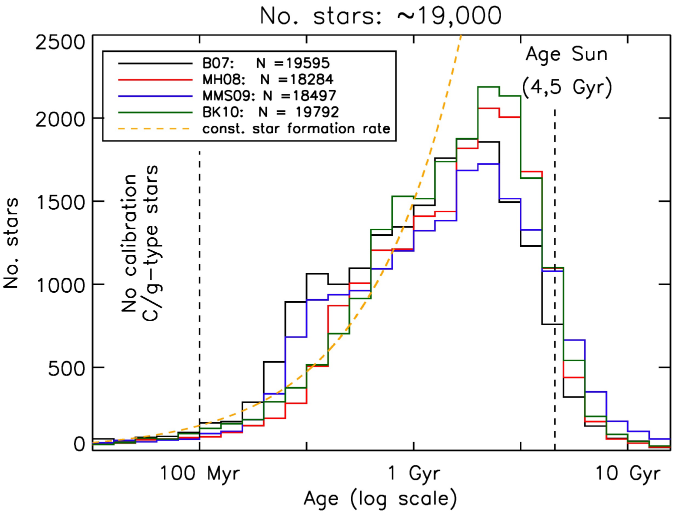


Figure 20: Kepler age distribution using different gyrochronology relations

Gyrochronology vs. asteroseismology ages

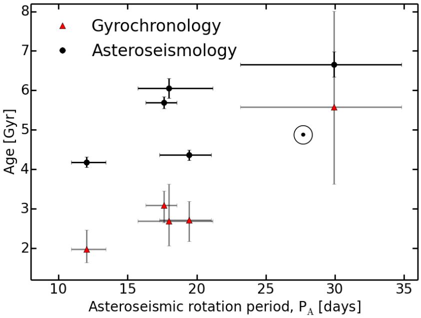
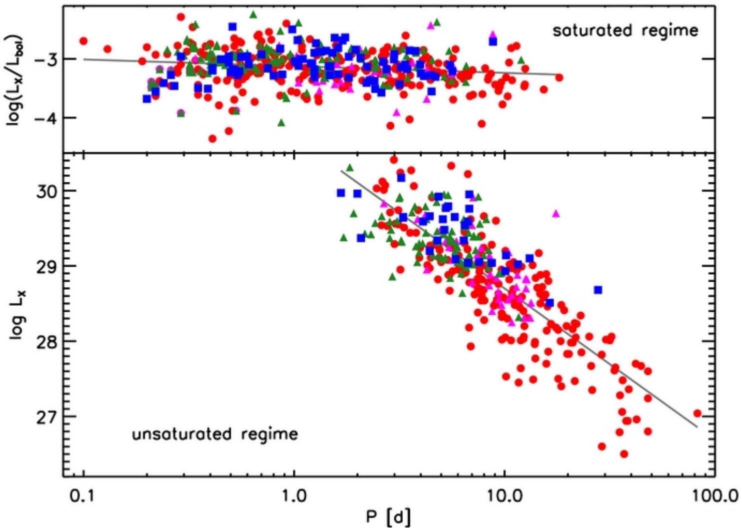


Figure 21: Gyrochronology vs. asteroseismology ages for sun-like Kepler stars (Nielsen et al. 2015, in prep.)

- Rotation period P_{A} and turnover time τ from asteroseismology
- Gyro-relation from Barnes (2010)
- Astero- and gyro-ages do not agree!
- Yet unclear which method is more accurate; both lack good calibration!

Rotation-activity relation I: Reiners et al. (2014)



Rotation-activity relation II: Variability range

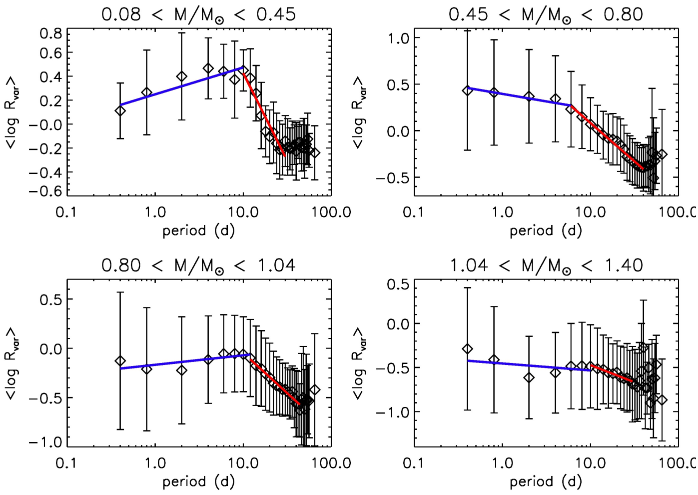


Figure 22: Light curve variability range as activity proxy. Saturated vs. unsaturated regime?

Summary

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  - Rotation Periods are well determined!
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Thank you!