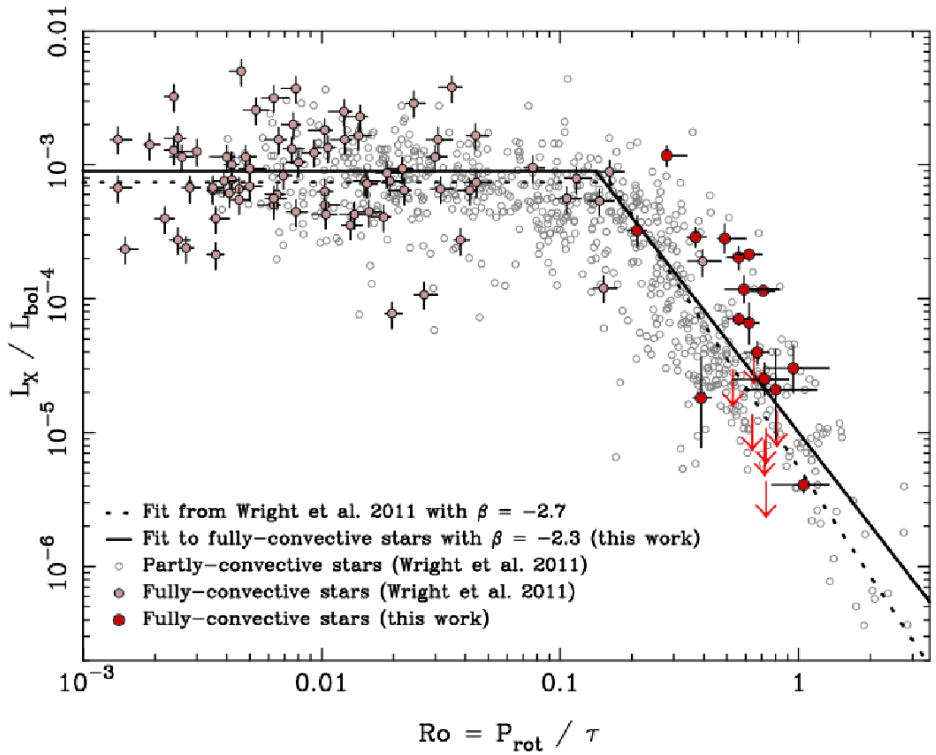
Common dynamo scaling in slowly rotating young and evolved stars

Jyri J. Lehtinen

Federico Spada, Maarit J. Käpylä, Nigul Olspert, Petri J. Käpylä

30 March 2020

Rotation–activity relation in MS and beyond



Wright et al. (2018)

- Extending the rotation–activity relation beyond MS:

Lehtinen et al. (2020), *Nature Astronomy*,
DOI: 10.1038/s41550-020-1039-x

Activity levels of evolved stars

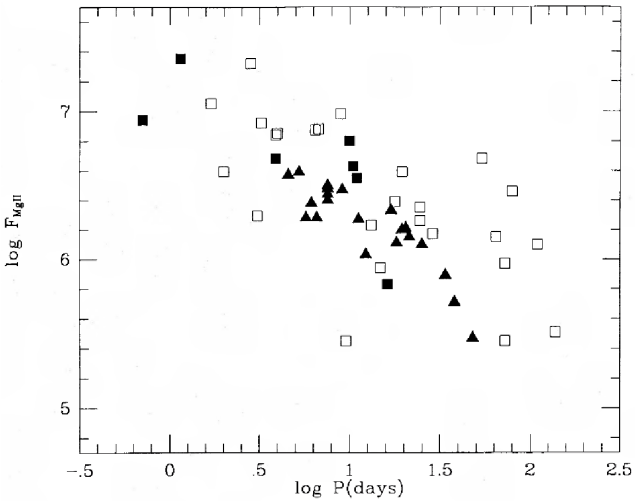


FIG. 6a

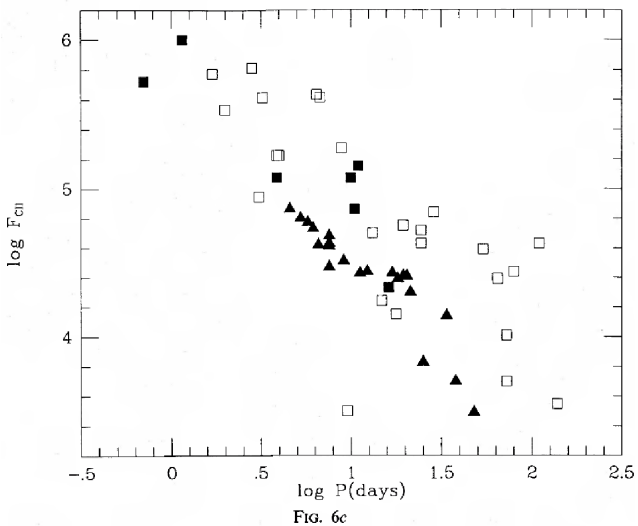
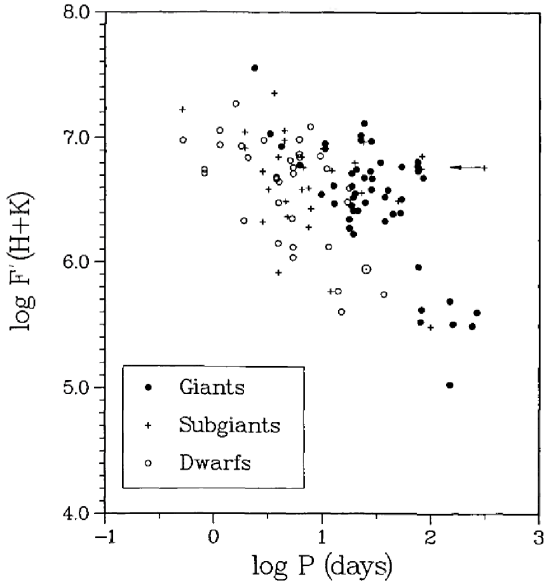
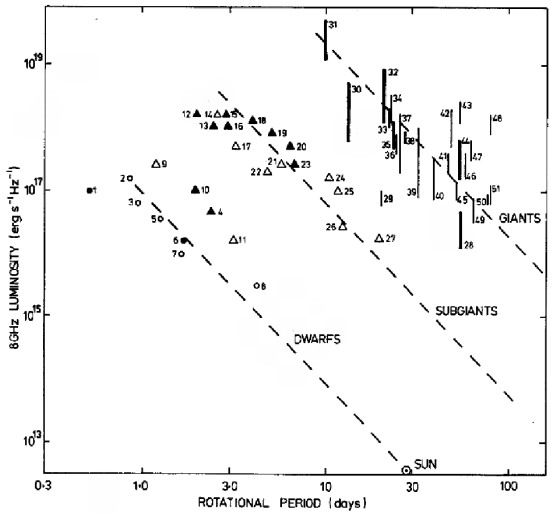


FIG. 6c

Basri (1987)



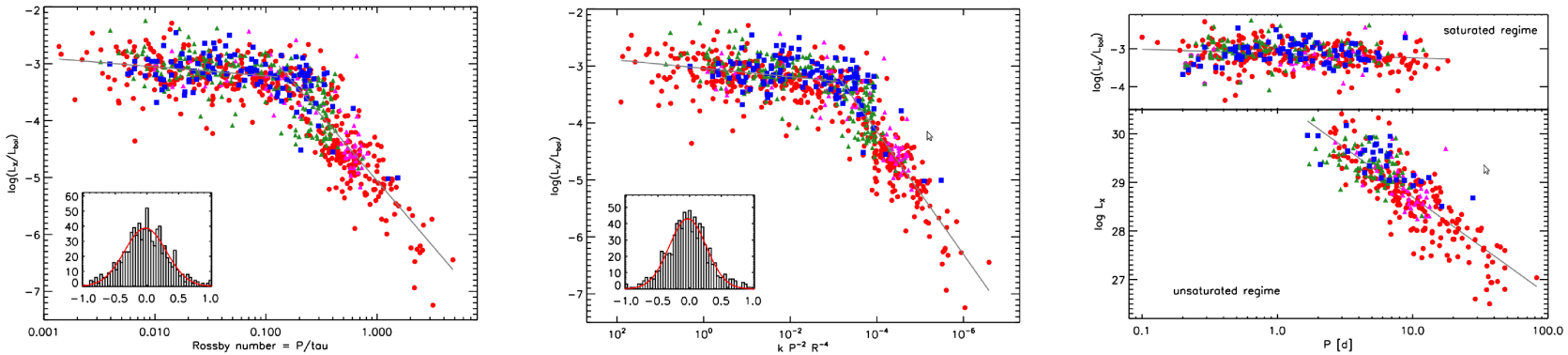
Strassmeier et al. (1990)



Stewart et al. (1988)

Is Rossby required?

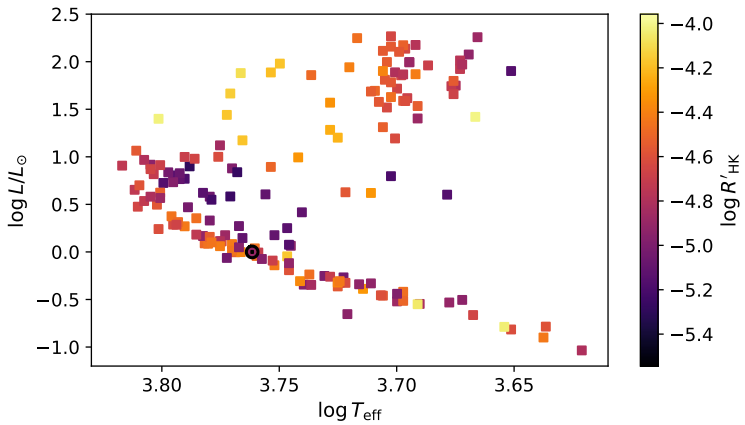
- Within MS relating activity to $\mathrm{Ro} = P_\mathrm{rot}/\tau_\mathrm{c}$ instead or P_rot gives a tighter rotation–activity relation (Noyes et al. 1984).
- Commonly used empirical $\tau_\mathrm{e}(B-V)$ scalings have been criticised, though.
  - $\tau_\mathrm{e}(B-V)$ designed to minimise scatter
  - Actual τ_c not directly observable
- $L_\mathrm{X} \propto P_\mathrm{rot}^{-2}$ and $R_\mathrm{X} \propto P_\mathrm{rot}^{-2} R^{-4}$ have been suggested as better options (Pizzolato et al. 2003, Reiners et al. 2014).
  - Post-MS stars not considered

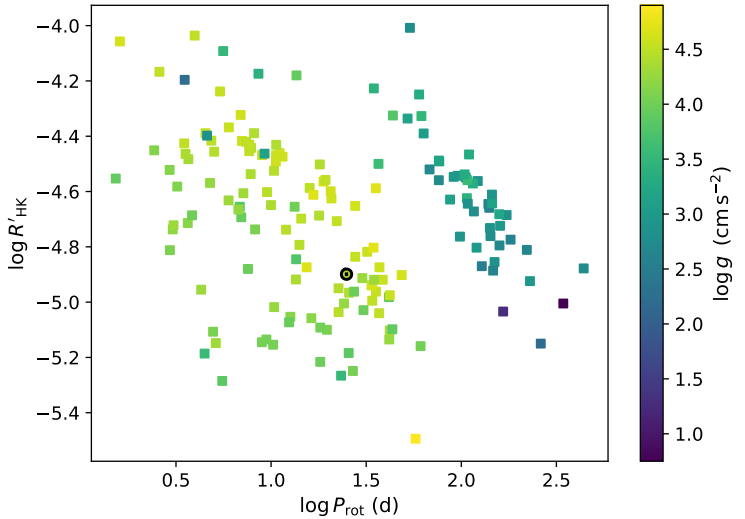


Reiners et al. (2014)

Mt. Wilson rotation–activity relation

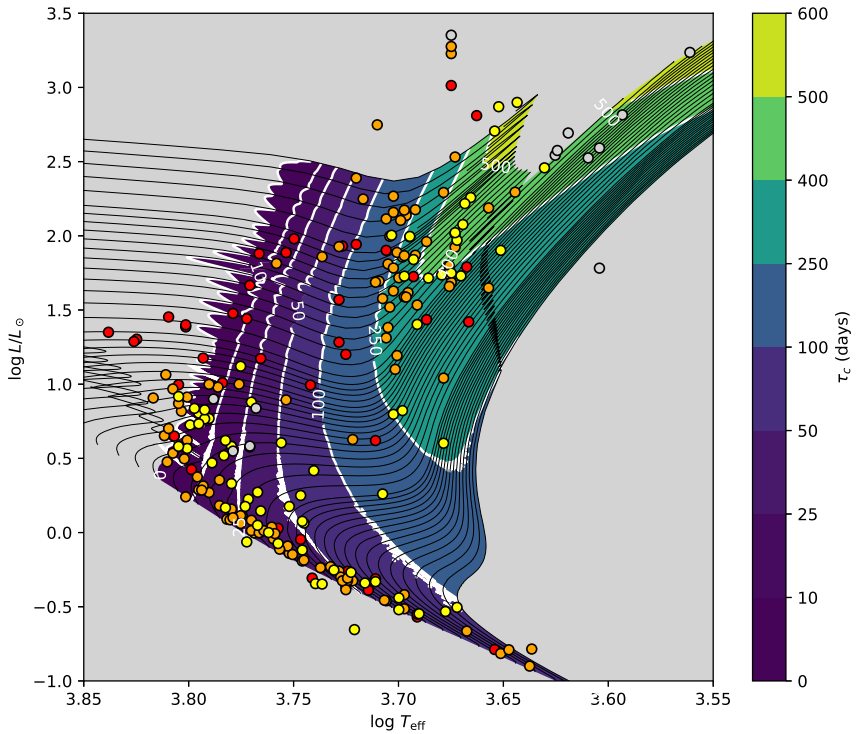
- MWO CaII HK Project
  - Sub-sample with ≥ 4 seasons of data spanning ≥ 5 yr
  - 81 MS (incl. Sun) and 143 post-MS stars
- Derived from the MWO time series:
  - Mean $S_{\mathrm{MW}} \Rightarrow \log R'_{\mathrm{HK}}$
  - P_{rot} (found for 169 stars)
- 5 Supplementary MS stars:
  - MWO $\log R'_{\mathrm{HK}}$
  - photometric P_{rot} (Lehtinen et al. 2016)



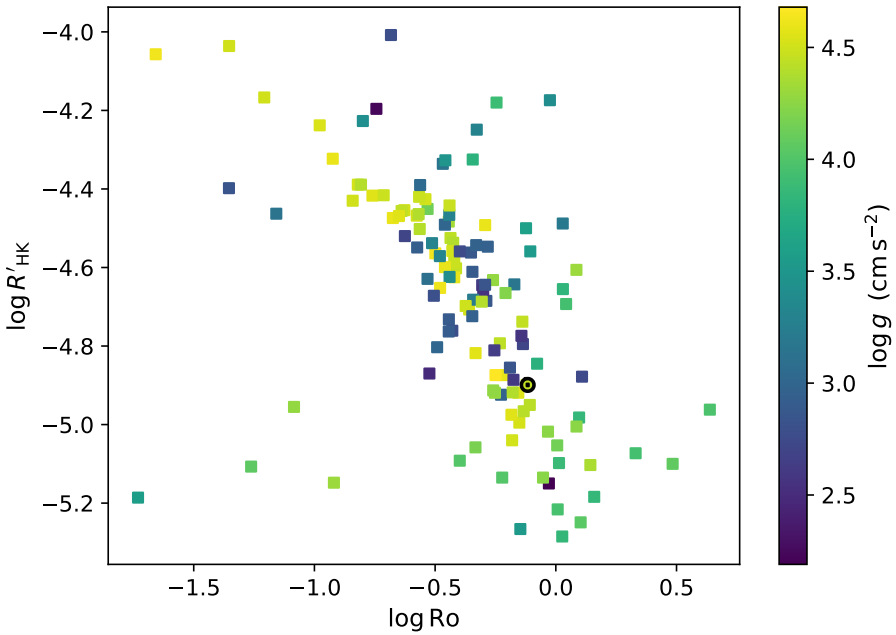


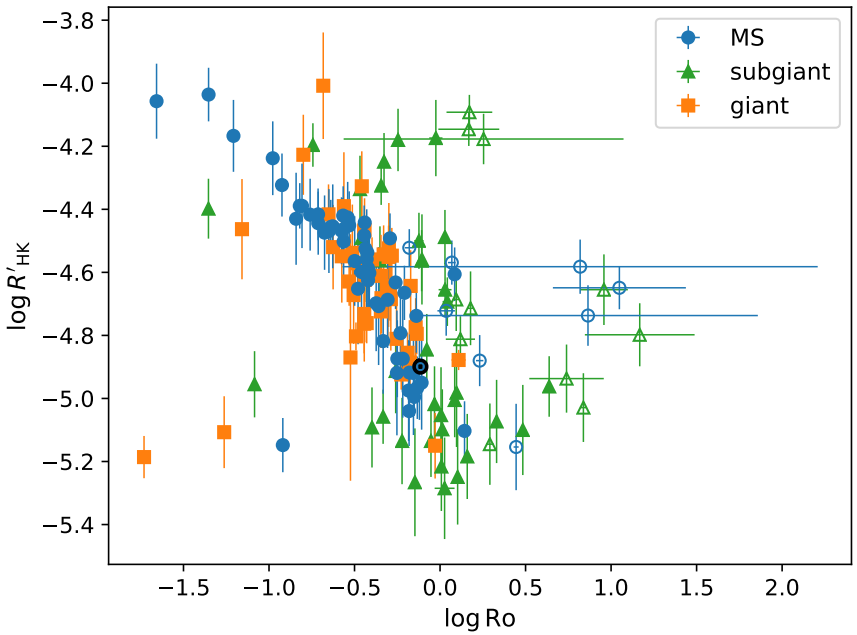
Deriving Rossby from models

- Giants have vastly expanded convective envelopes.
  - $\Rightarrow$ Increased convective turnover times τ_c and reduced Ro $= P_{rot}/\tau_c$
- Empirical $\tau_e(B-V)$ models fail post-MS.
  - τ_c derived from stellar structure model fits (Yale-Potsdam Stellar Isochrones, Spada et al. 2017)



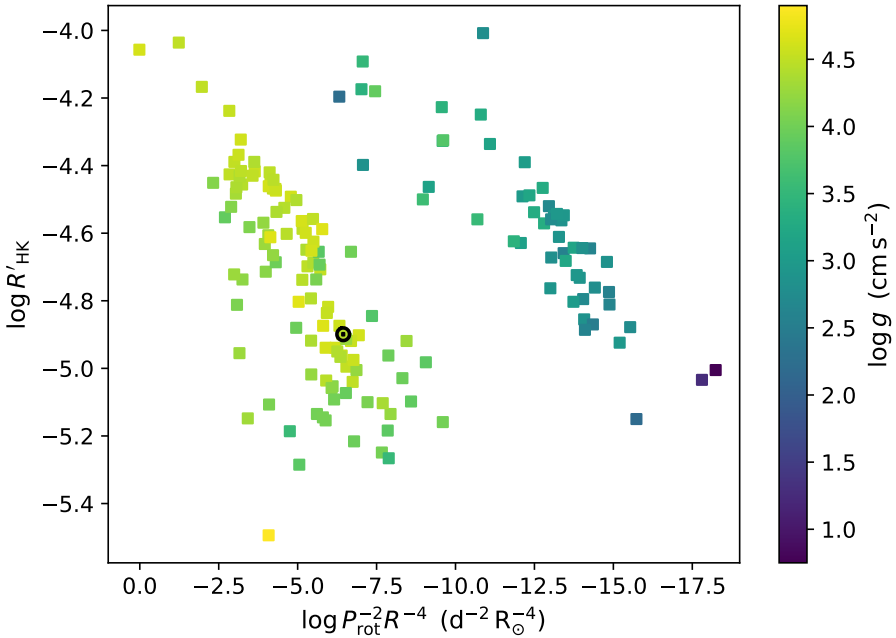
R'_{HK} vs. Ro relation



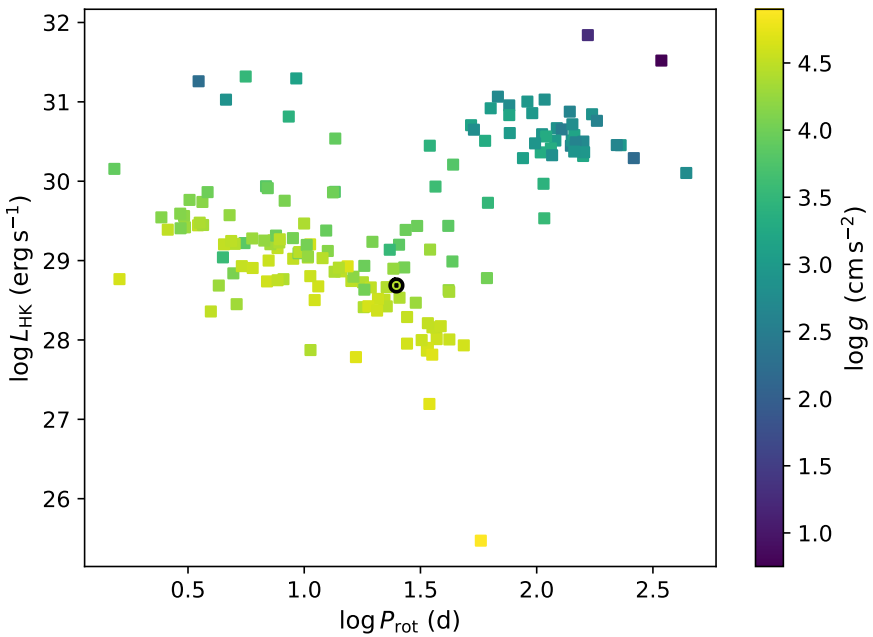


- Model based Ro removes the MS–giant gap completely.
- Remaining scatter due to model fitting uncertainties
  - Most noticeable for $\tau_{\mathrm{c}} < 5$ d and stars identified as subgiants

Alternate non-Rossby based relations



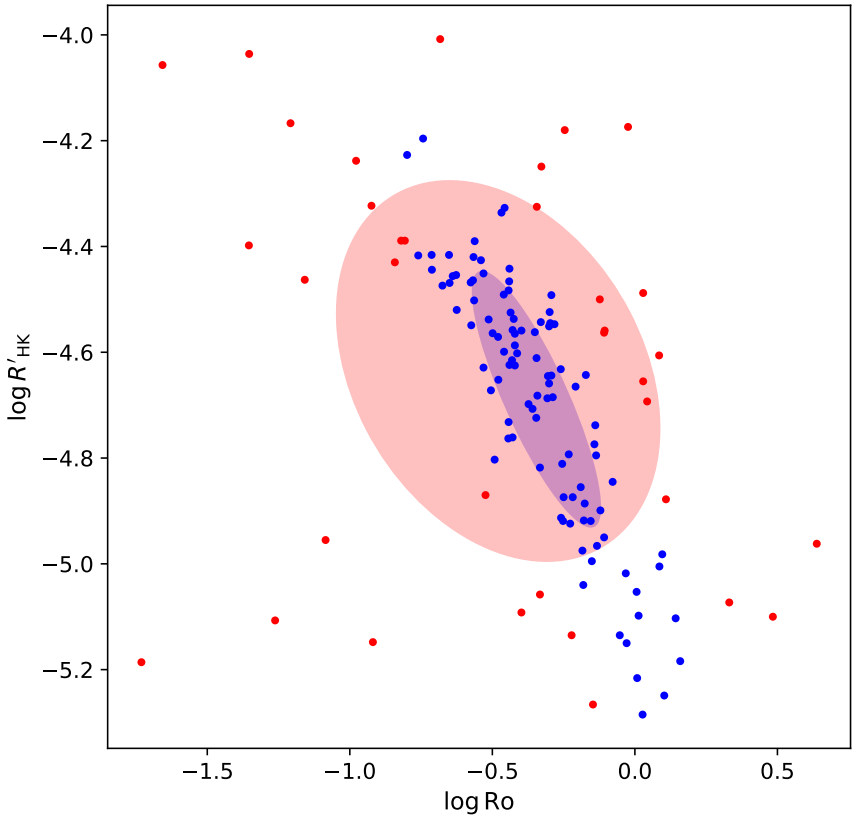
R'_{HK} vs. $P_{rot}^{-2} R^{-4}$



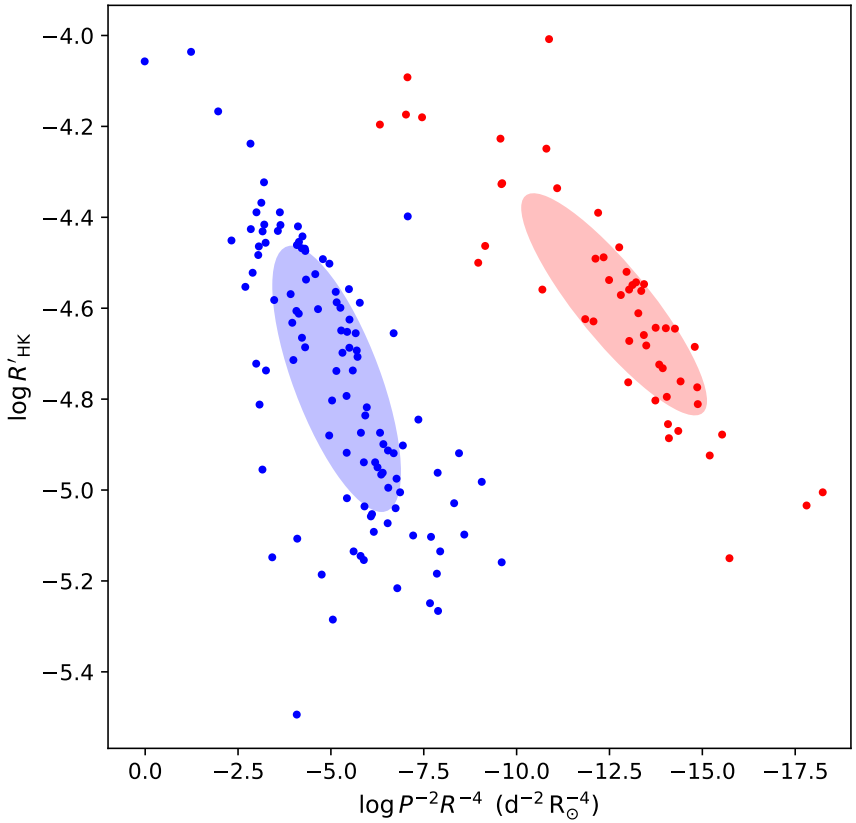
L_{HK} vs. P_{rot}

- Proposed alternates for Rossby do not unify the sequence.

Gaussian clustering



R'_{HK} vs. Ro



R'_{HK} vs. $P_{rot}^{-2}R^{-4}$

Alternate non-Rossby based relations

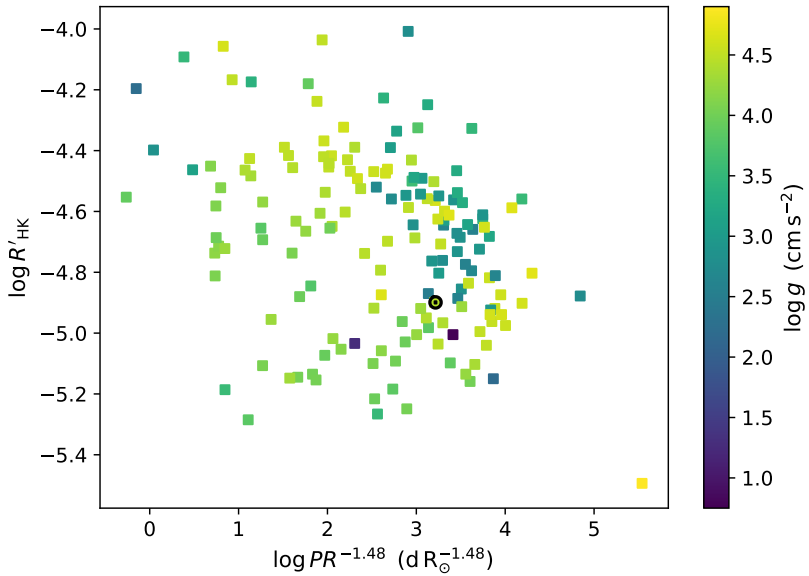
- In fact, we find that

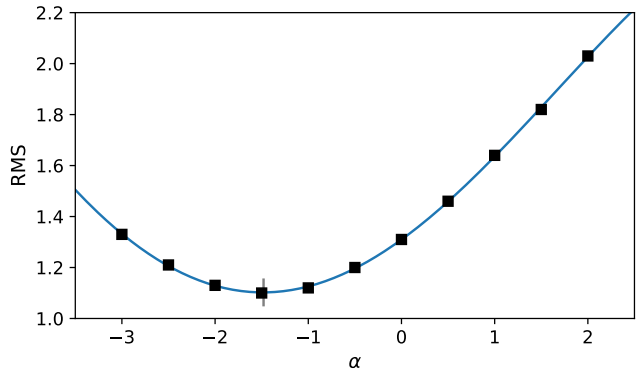
  $\mathrm{Ro} = P_{\mathrm{rot}}/\tau_{\mathrm{c}} \neq P_{\mathrm{rot}} R^{\alpha}$

  holds for any simple stellar parameter R (not just radius).

  $\Rightarrow$ No non-Rossby relations

- This follows from the non-trivial dependence of τ_{c} from the other stellar parameters.
  - In our models $\tau_{\mathrm{c}} = \tau_{\mathrm{c}}(T_{\mathrm{eff}}, L, [\mathrm{Fe/H}])$





What about the slope?

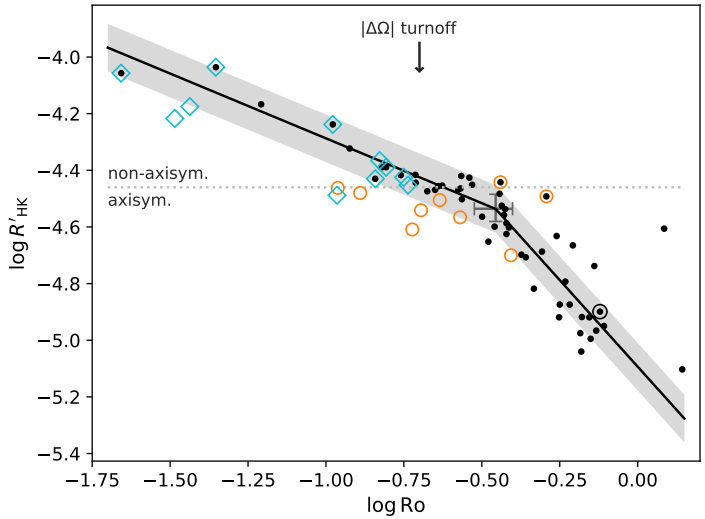
- Not much consensus exists between activity vs. Ro slopes:

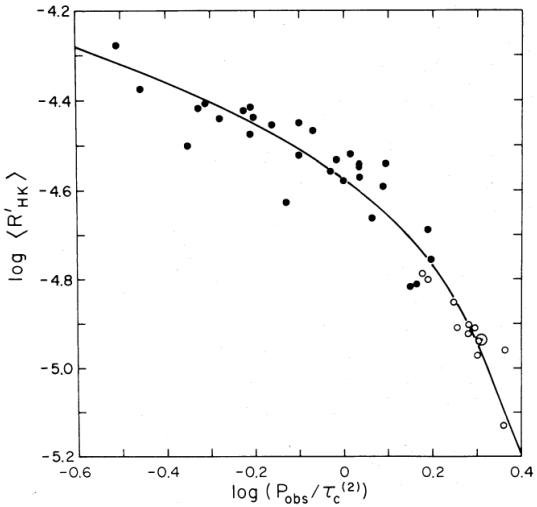
$R_X \propto \mathrm{Ro}^{-2}$	$R'_{HK} \propto \mathrm{Ro}^{-1.5}$	$R_{H\alpha} \propto \mathrm{Ro}^{-0.7}$	$B \propto \mathrm{Ro}^{-1.2}$
Pizzolato et al. (2003)	Astudillo-Defru et al. (2017)	Douglas et al. (2014)	Saar (2001)
$R_X \propto \mathrm{Ro}^{-2.3}$	$R'_{HK} \propto \mathrm{Ro}^{-1.0}$	$R_{H\alpha} \propto \mathrm{Ro}^{-1.7}$	$B \propto \mathrm{Ro}^{-1.4}$
Wright et al. (2018)	our work (simple fit)	Newton et al. (2017)	Vidotto et al. (2014)

- The steeper X-ray slopes may be explained by differences in the emission processes.
  - $R^{+}_{HK} \propto R^{0.4}_{X}$ (Mittag et al. 2018)
- At least R'_{HK} appears to be a fair proxy for total $\langle B \rangle$
  - $\langle B \rangle \propto {R'_{HK}}^{1.09 \pm 0.12}$ (Kochukhov et al. 2020)

A bend in the R'_{HK} slope

- At least in the MS the activity scaling has a bend at $\log R'_{HK} \approx -4.5$.
  - Already noted by Noyes et al. (1984)
- Fits a two-piece powerlaw:
  - $\beta_{upper} = -0.5$, $\beta_{lower} = -1.2$
- Maybe related to the onset of non-axisymmetric activity at $\log R'_{HK} = -4.45$ seen in time series photometry (Lehtinen et al. 2016)

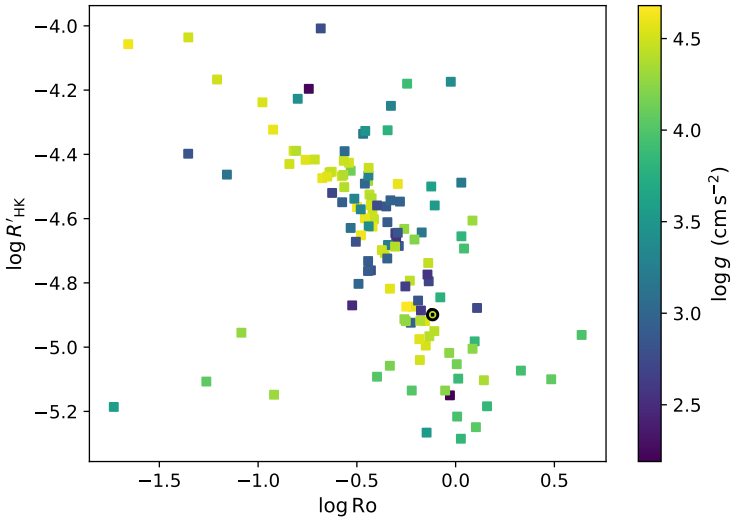




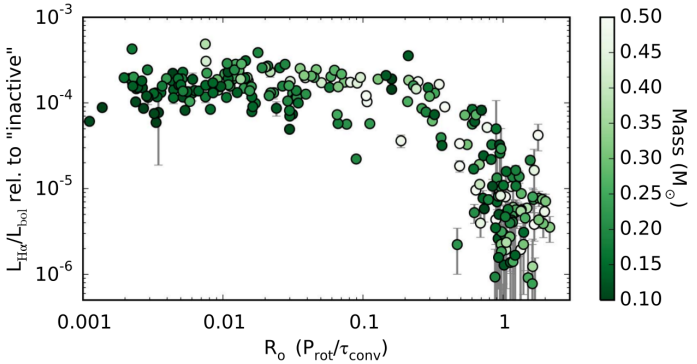
Noyes et al. (1984)

Conclusions

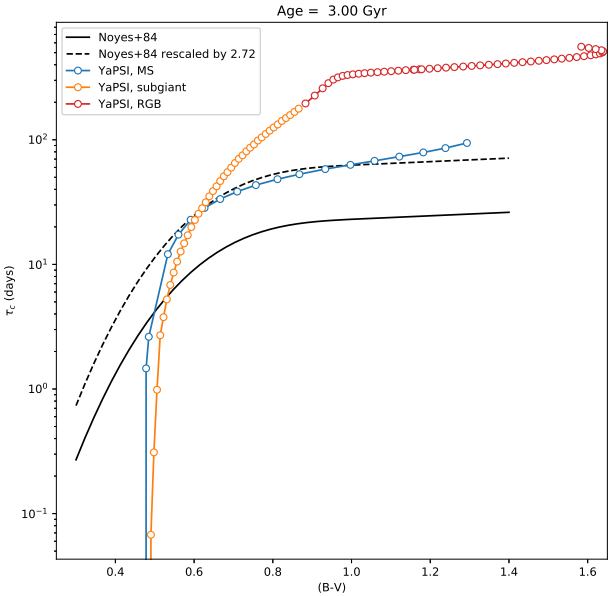
- Ro-scaling qualitatively unifies the rotation–activity relation from lower MS to red giants.
  - Only one dynamo type necessary
- Turbulence has to be parametrised in the relation.
  - Indicates turbulent dynamo.
- The exact slope and shape need further study.

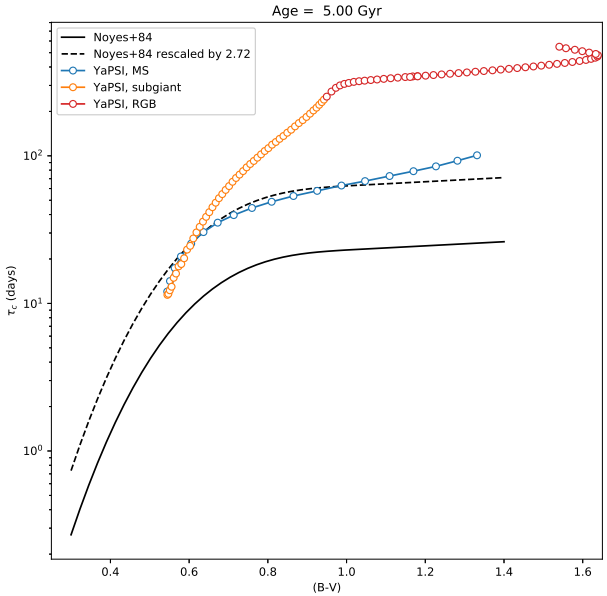


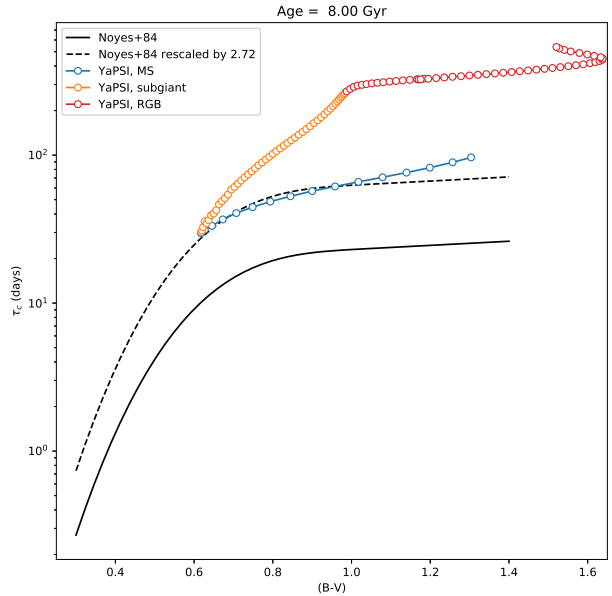
MS and evolved stars

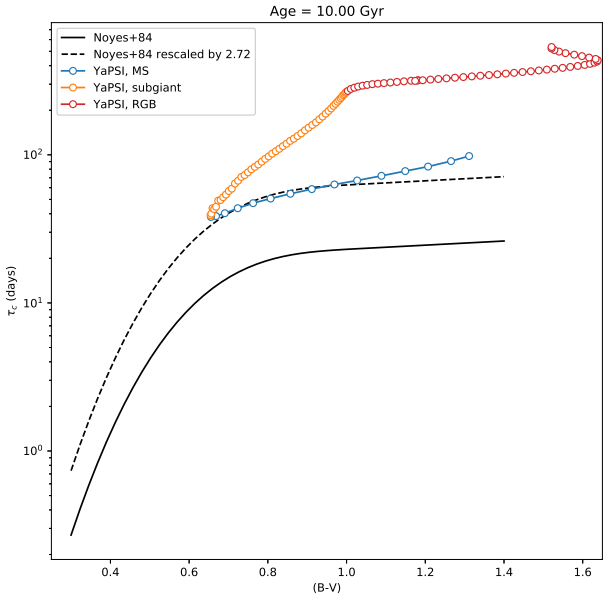


Newton et al. (2017),
partially and fully convective MS


Age = 3.00 Gyr
Noyes+84
Noyes+84 rescaled by 2.72
YaPSI, MS
YaPSI, subgiant
YaPSI, RGB
τ_c (days)
(B-V)


Age = 5.00 Gyr
Noyes+84
Noyes+84 rescaled by 2.72
YaPSI, MS
YaPSI, subgiant
YaPSI, RGB
τ_c (days)
(B-V)


Age = 8.00 Gyr
Noyes+84
Noyes+84 rescaled by 2.72
YaPSI, MS
YaPSI, subgiant
YaPSI, RGB
τ_c (days)
(B-V)


Age = 10.00 Gyr
Noyes+84
Noyes+84 rescaled by 2.72
YaPSI, MS
YaPSI, subgiant
YaPSI, RGB
τ_c (days)
(B-V)