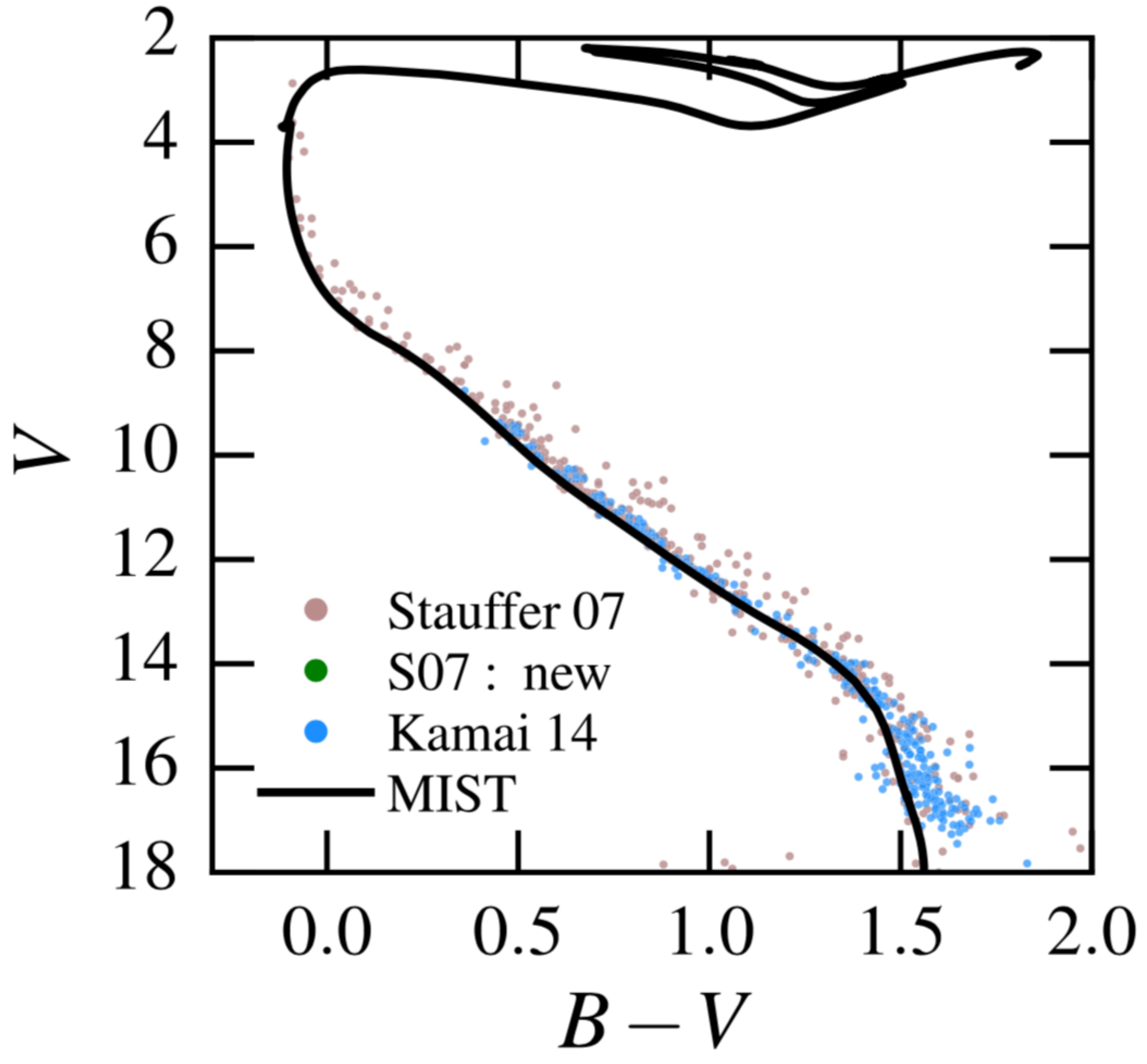
Rotation, Spindown, & Activity

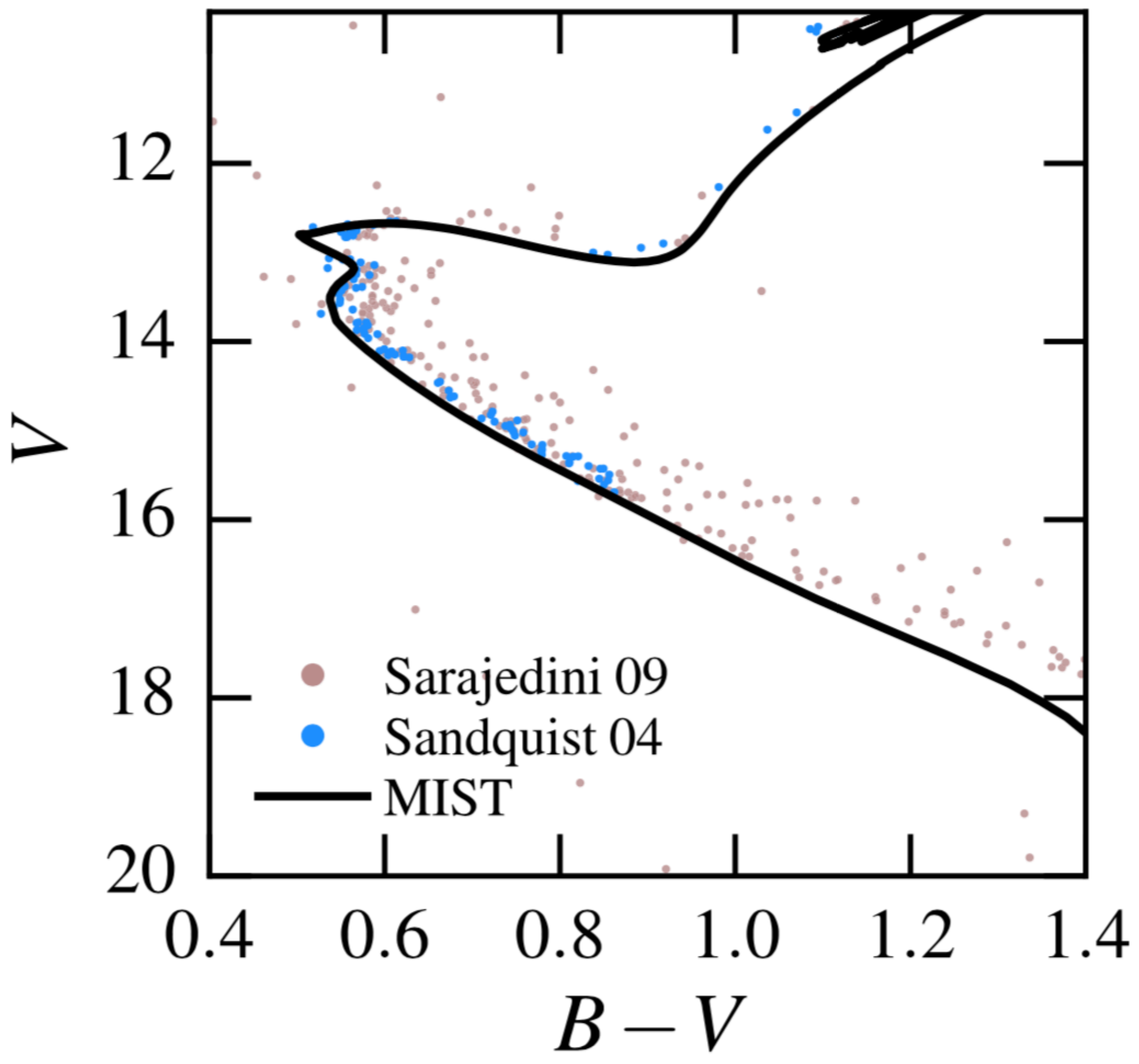
Ricky Egeland
NCAR High Altitude Observatory

NSO Solar Focus Series: "Solar-Stellar Connection"
May 8th, 2020

Stellar ages can be estimated from modeling clusters

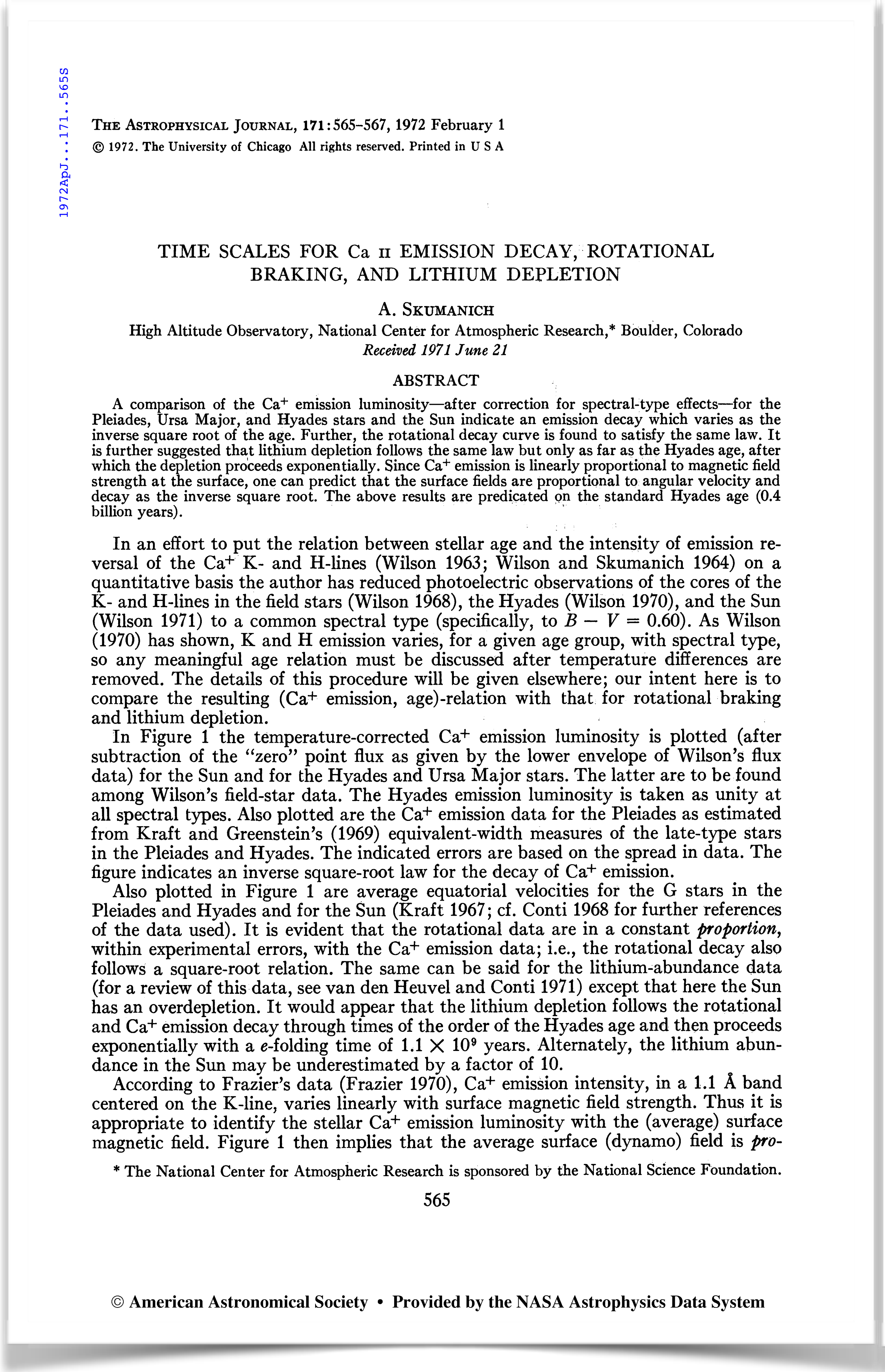


(Pleiades, 0.1 Gyr, 133 pc)



(M67, 4 Gyr, 800 pc)

Stellar rotation and magnetic activity decrease with time: "spindown"



THE ASTROPHYSICAL JOURNAL, **171**:565–567, 1972 February 1

TIME SCALES FOR Ca II EMISSION DECAY, ROTATIONAL BRAKING, AND LITHIUM DEPLETION

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ABSTRACT

A comparison of the Ca$^+$ emission luminosity—after correction for spectral-type effects—for the Pleiades, Ursa Major, and Hyades stars and the Sun indicate an emission decay which varies as the inverse square root of the age. Further, the rotational decay curve is found to satisfy the same law. It is further suggested that lithium depletion follows the same law but only as far as the Hyades age, after which the depletion proceeds exponentially. Since Ca$^+$ emission is linearly proportional to magnetic field strength at the surface, one can predict that the surface fields are proportional to angular velocity and decay as the inverse square root. The above results are predicated on the standard Hyades age (0.4 billion years).

In an effort to put the relation between stellar age and the intensity of emission reversal of the Ca$^+$ K- and H-lines (Wilson 1963; Wilson and Skumanich 1964) on a quantitative basis the author has reduced photoelectric observations of the cores of the K- and H-lines in the field stars (Wilson 1968), the Hyades (Wilson 1970), and the Sun (Wilson 1971) to a common spectral type (specifically, to $B - V = 0.60$). As Wilson (1970) has shown, K and H emission varies, for a given age group, with spectral type, so any meaningful age relation must be discussed after temperature differences are removed. The details of this procedure will be given elsewhere; our intent here is to compare the resulting (Ca$^+$ emission, age)-relation with that for rotational braking and lithium depletion.

In Figure 1 the temperature-corrected Ca$^+$ emission luminosity is plotted (after subtraction of the "zero" point flux as given by the lower envelope of Wilson's flux data) for the Sun and for the Hyades and Ursa Major stars. The latter are to be found among Wilson's field-star data. The Hyades emission luminosity is taken as unity at all spectral types. Also plotted are the Ca$^+$ emission data for the Pleiades as estimated from Kraft and Greenstein's (1969) equivalent-width measures of the late-type stars in the Pleiades and Hyades. The indicated errors are based on the spread in data. The figure indicates an inverse square-root law for the decay of Ca$^+$ emission.

Also plotted in Figure 1 are average equatorial velocities for the G stars in the Pleiades and Hyades and for the Sun (Kraft 1967; cf. Conti 1968 for further references of the data used). It is evident that the rotational data are in a constant *proportion*, within experimental errors, with the Ca$^+$ emission data; i.e., the rotational decay also follows a square-root relation. The same can be said for the lithium-abundance data (for a review of this data, see van den Heuvel and Conti 1971) except that here the Sun has an overdepletion. It would appear that the lithium depletion follows the rotational and Ca$^+$ emission decay through times of the order of the Hyades age and then proceeds exponentially with a e-folding time of 1.1×10^9 years. Alternately, the lithium abundance in the Sun may be underestimated by a factor of 10.

According to Frazier's data (Frazier 1970), Ca$^+$ emission intensity, in a 1.1 Å band centered on the K-line, varies linearly with surface magnetic field strength. Thus it is appropriate to identify the stellar Ca$^+$ emission luminosity with the (average) surface magnetic field. Figure 1 then implies that the average surface (dynamo) field is *proportional* to the rotational velocity and decays as the inverse square root of the time as the star "cooks" on the main sequence. This remarkable result has been shown to be theoretically consistent by Durney (1972) on the basis of a simple model for the stellar wind.

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* The National Center for Atmospheric Research is sponsored by the National Science Foundation.

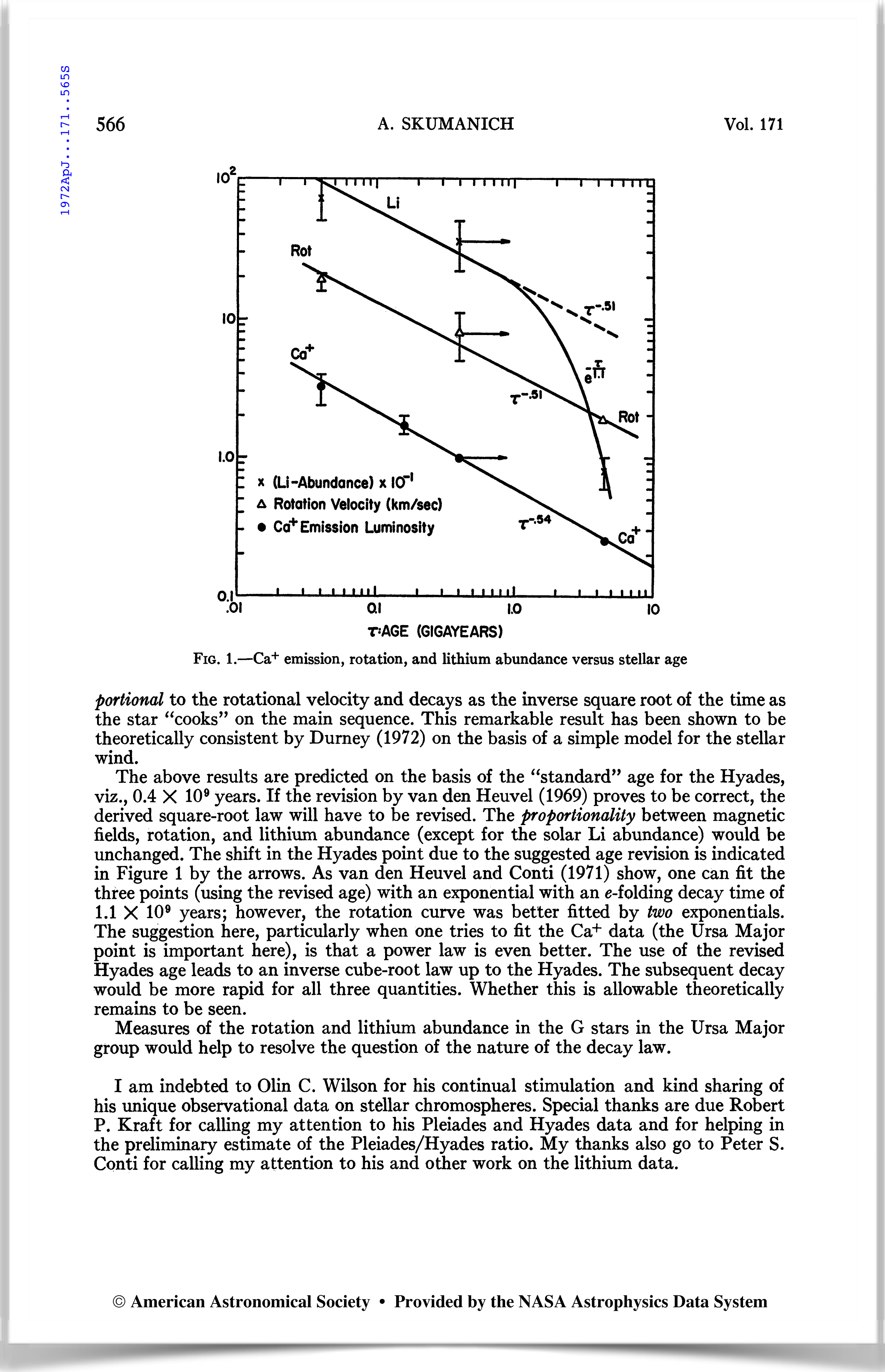
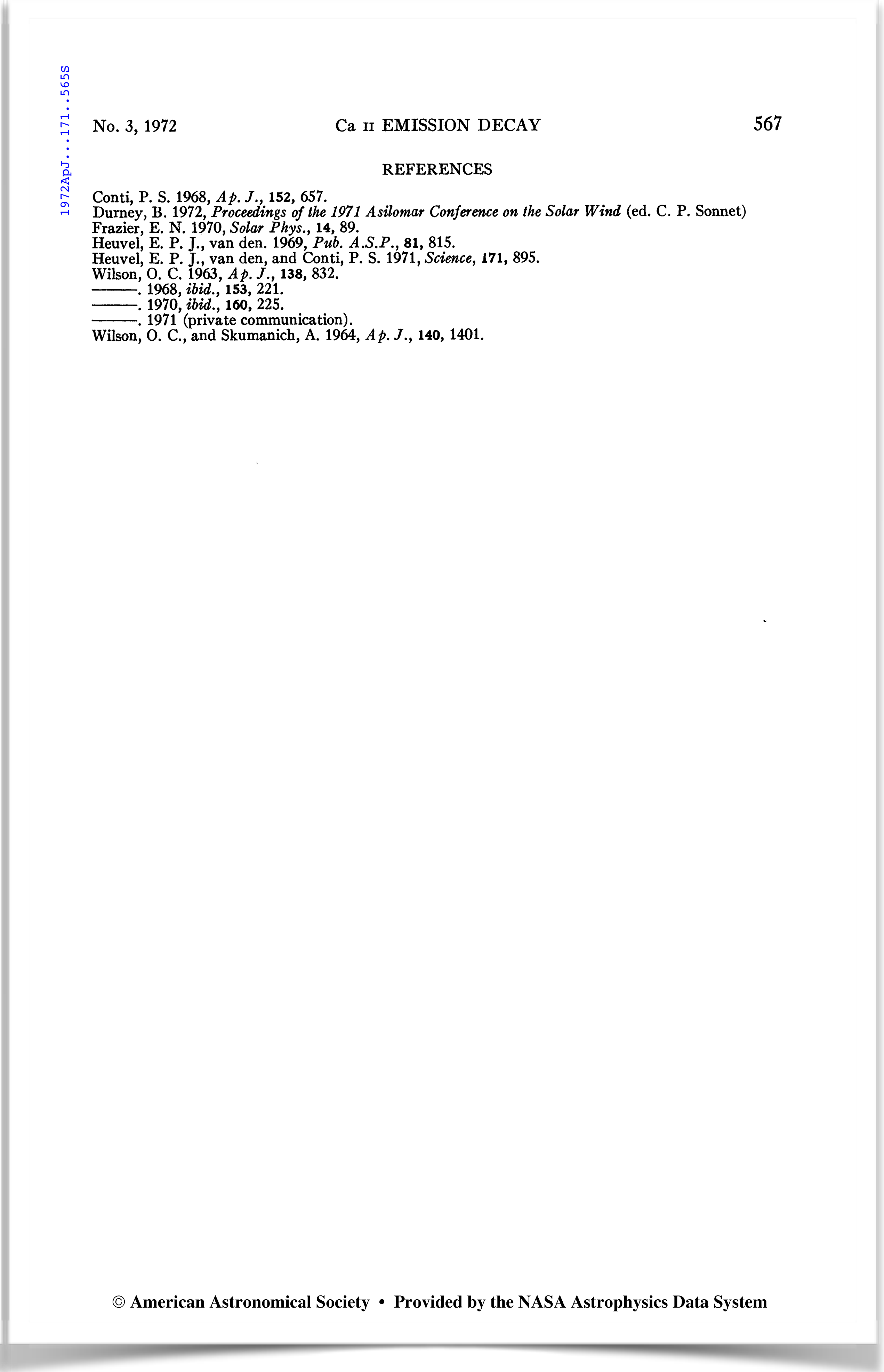


FIG. 1.—Ca$^+$ emission, rotation, and lithium abundance versus stellar age

The above results are predicted on the basis of the "standard" age for the Hyades, viz., 0.4×10^9 years. If the revision by van den Heuvel (1969) proves to be correct, the derived square-root law will have to be revised. The *proportionality* between magnetic fields, rotation, and lithium abundance (except for the solar Li abundance) would be unchanged. The shift in the Hyades point due to the suggested age revision is indicated in Figure 1 by the arrows. As van den Heuvel and Conti (1971) show, one can fit the three points (using the revised age) with an exponential with an e-folding decay time of 1.1×10^9 years; however, the rotation curve was better fitted by *two* exponentials. The suggestion here, particularly when one tries to fit the Ca$^+$ data (the Ursa Major point is important here), is that a power law is even better. The use of the revised Hyades age leads to an inverse cube-root law up to the Hyades. The subsequent decay would be more rapid for all three quantities. Whether this is allowable theoretically remains to be seen.

Measures of the rotation and lithium abundance in the G stars in the Ursa Major group would help to resolve the question of the nature of the decay law.

I am indebted to Olin C. Wilson for his continual stimulation and kind sharing of his unique observational data on stellar chromospheres. Special thanks are due Robert P. Kraft for calling my attention to his Pleiades and Hyades data and for helping in the preliminary estimate of the Pleiades/Hyades ratio. My thanks also go to Peter S. Conti for calling my attention to his and other work on the lithium data.



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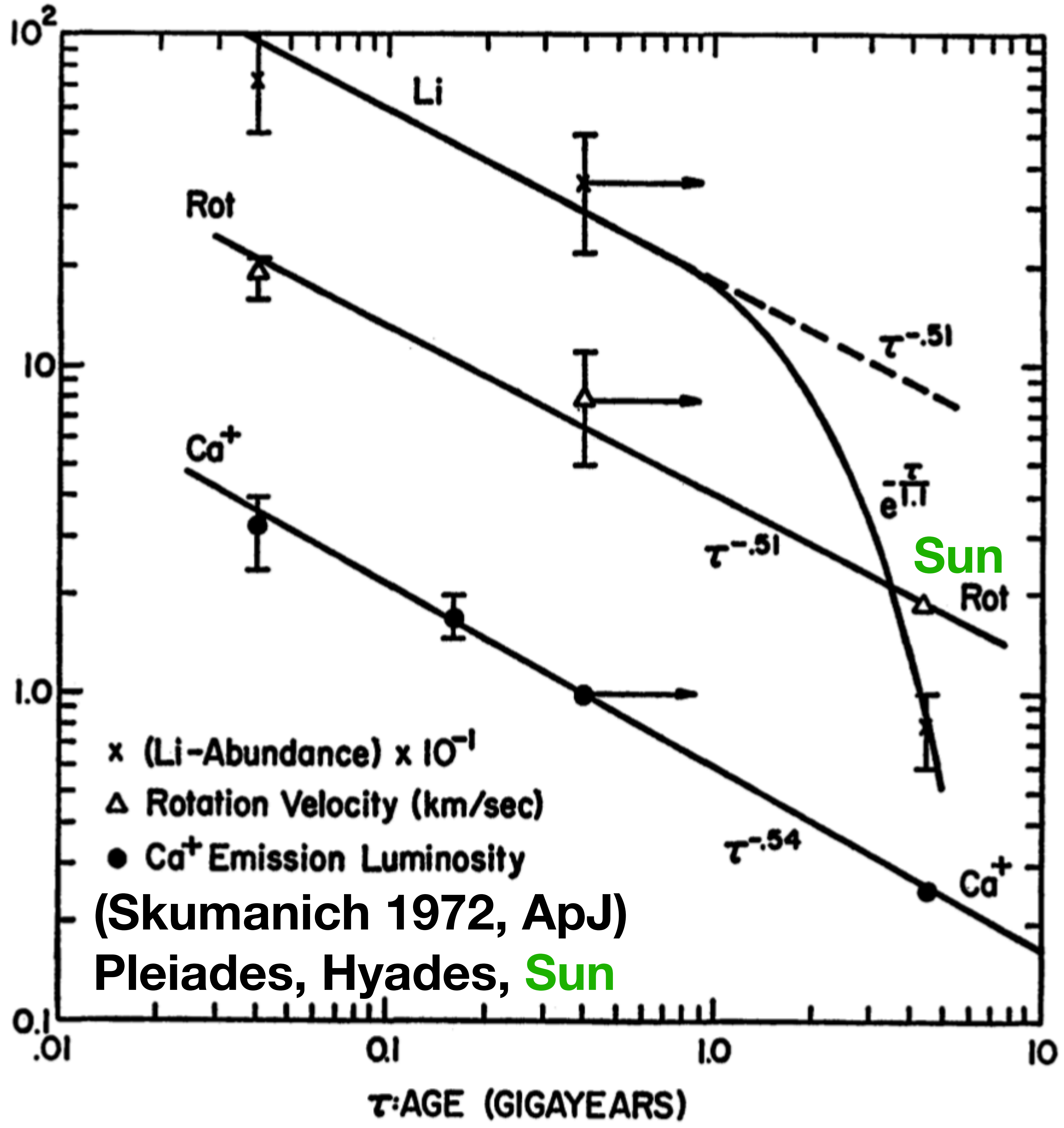
Durney, B. 1972, *Proceedings of the 1971 Asilomar Conference on the Solar Wind* (ed. C. P. Sonnet)
Frazier, E. N. 1970, *Solar Phys.*, **14**, 89.
Heuvel, E. P. J., van den. 1969, *Pub. A.S.P.*, **81**, 815.
Heuvel, E. P. J., van den, and Conti, P. S. 1971, *Science*, **171**, 895.
Wilson, O. C. 1963, *Ap. J.*, **138**, 832.
———. 1968, *ibid.*, **153**, 221.
———. 1970, *ibid.*, **160**, 225.
———. 1971 (private communication).
Wilson, O. C., and Skumanich, A. 1964, *Ap. J.*, **140**, 1401.

(Skumanich 1972, ApJ – 1364 citations*)

Stellar rotation and magnetic activity decrease with time: "spindown"



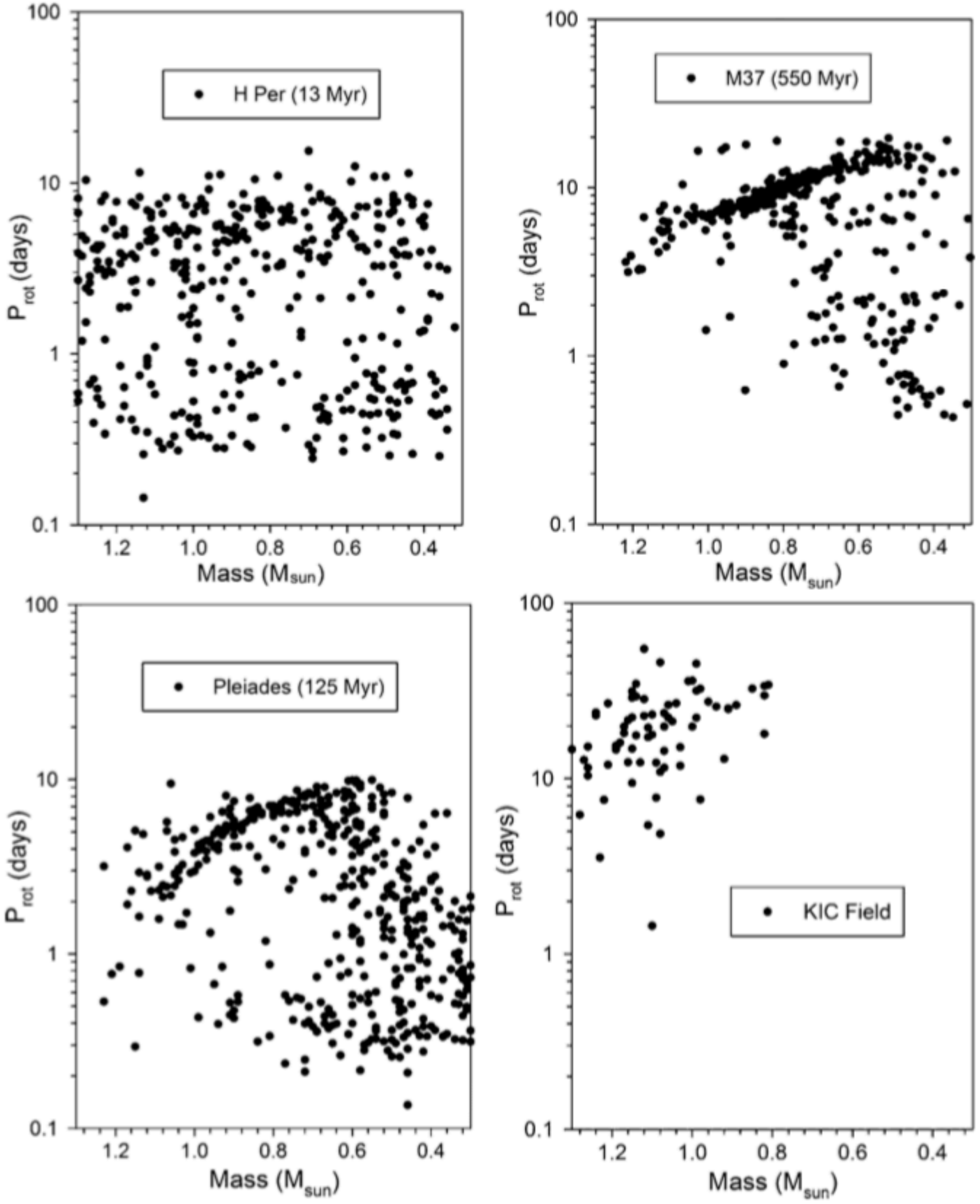
(Skumanich 1972, ApJ)
Pleiades, Hyades, Sun

FIG. 1.—Ca^+ emission, rotation, and lithium abundance versus stellar age

← Lithium abundance

← rotation period

← magnetic proxy

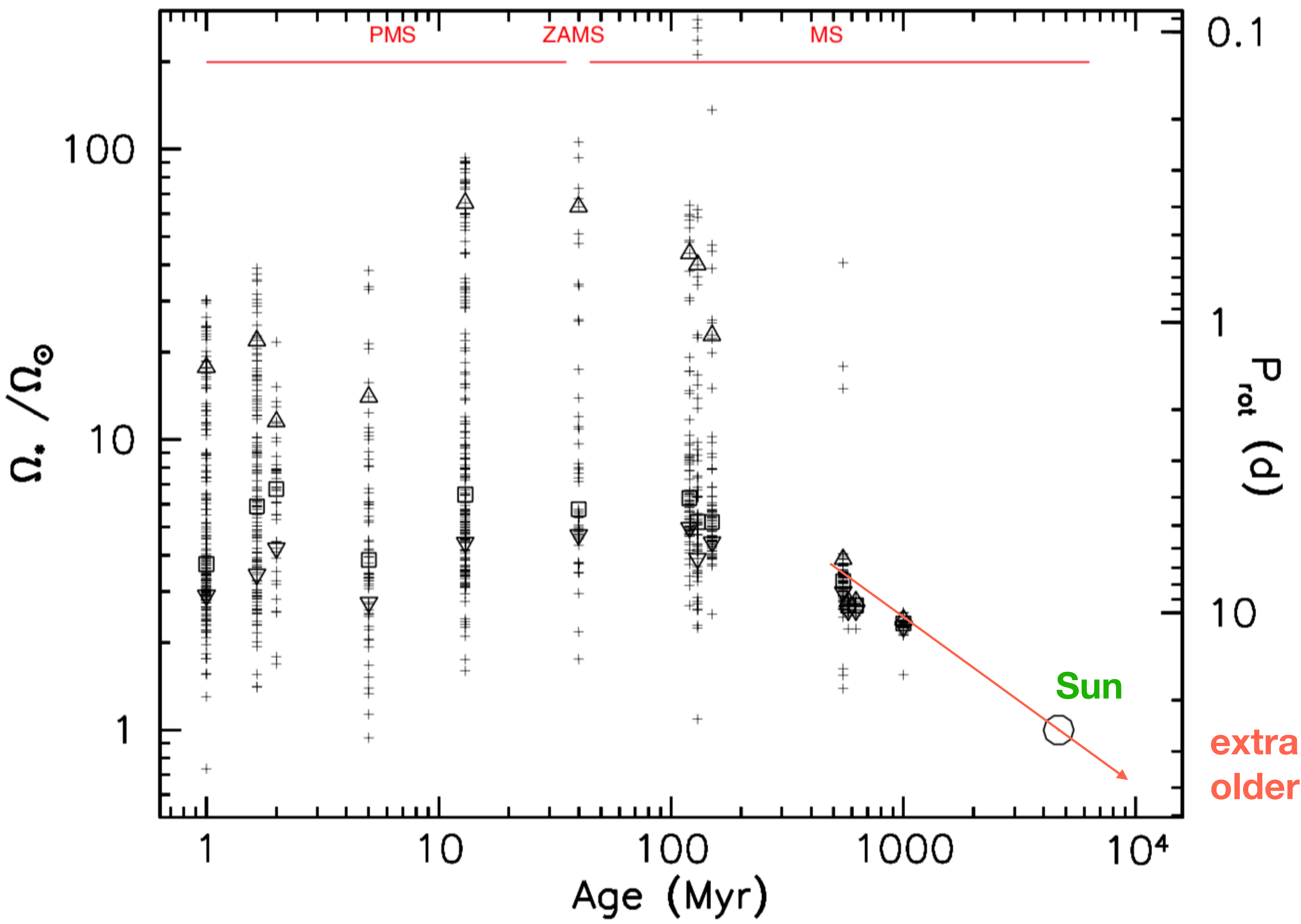


Initial Value Problem

- Wide range of rotation rates observed in youngest protostars (e.g. Rebull et al. 2006)
- Gaseous accretion disks persist fur up to 12 Myr, exchange of angular momentum
- Star-disk coupling regulates stellar rotation, preventing protostars from spinning up as they contract (Koenigl 1991; Keppens et al. 1995)
- Early angular momentum evolution of stars is a window into star and planet formation processes
- On the main sequence, surface rotation of star responds to both internal angular momentum transport and momentum loss from magnetized solar-like winds

(Brun et al. 2015, Sp. Sci. Rev.)

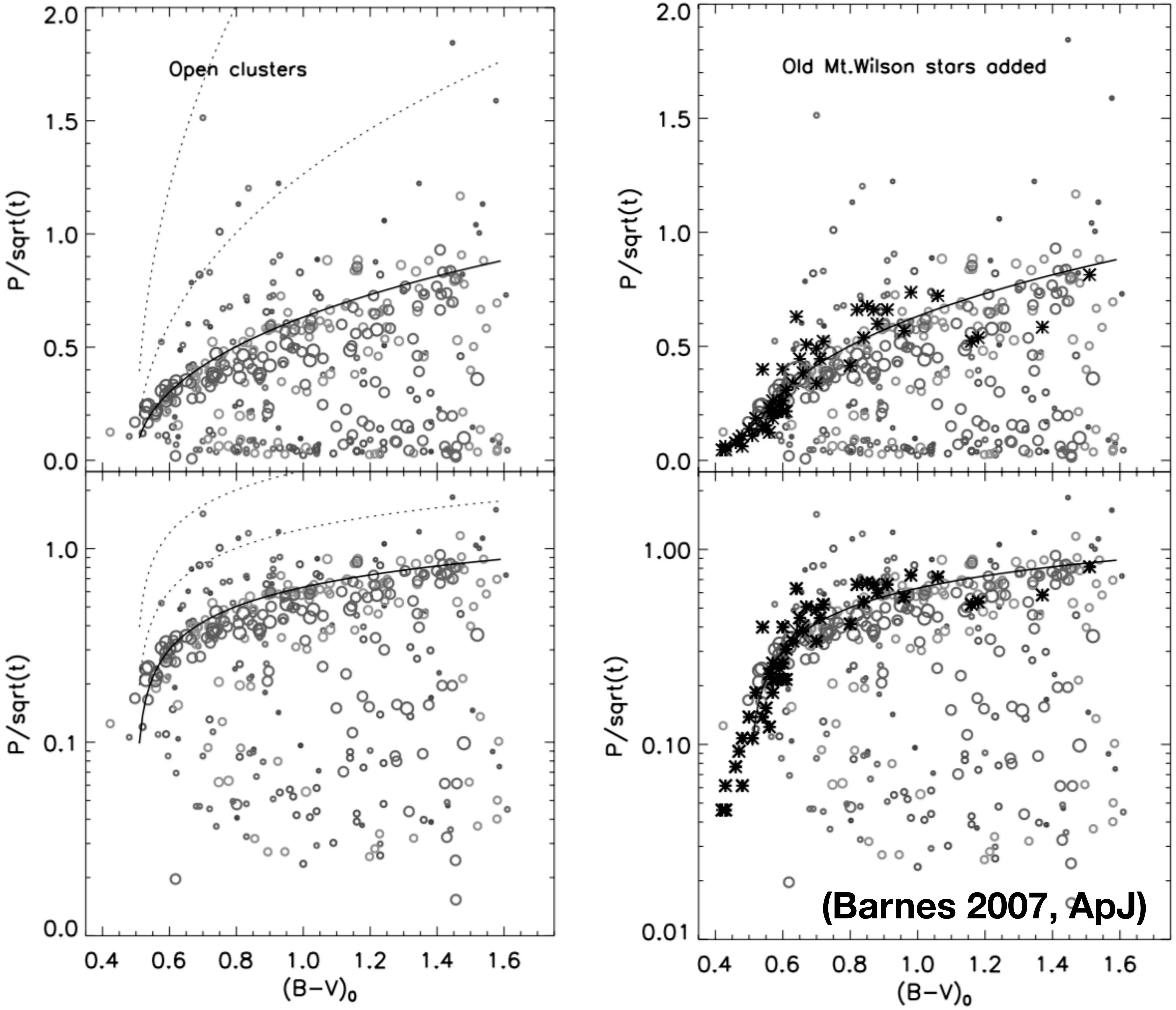
Rotational initial conditions are forgotten after ~1 Gyr



extrapolate to older ages?

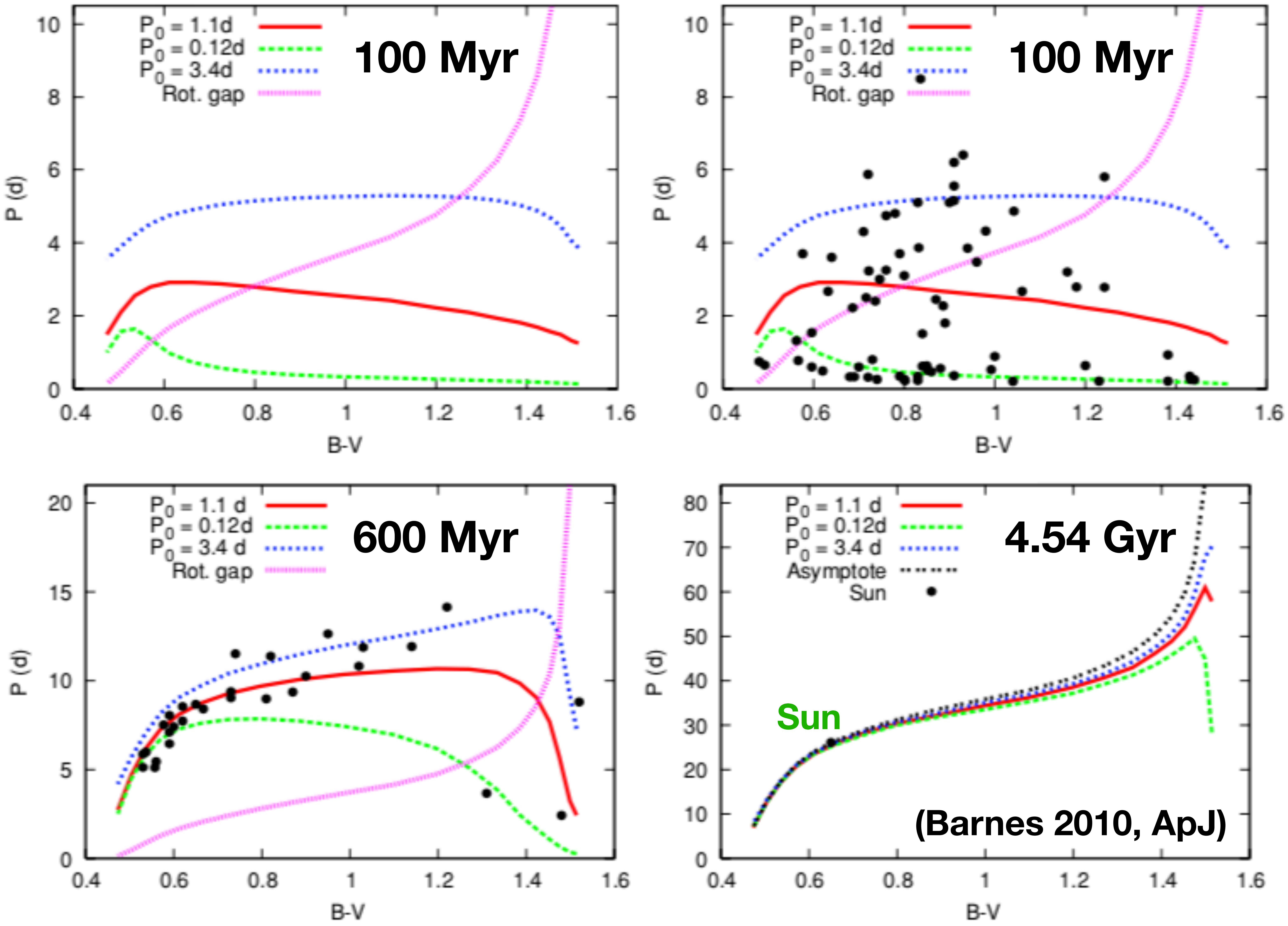
(Gallet & Bouvier 2013, A&A)

Gyrochronology



(Barnes 2007, ApJ)

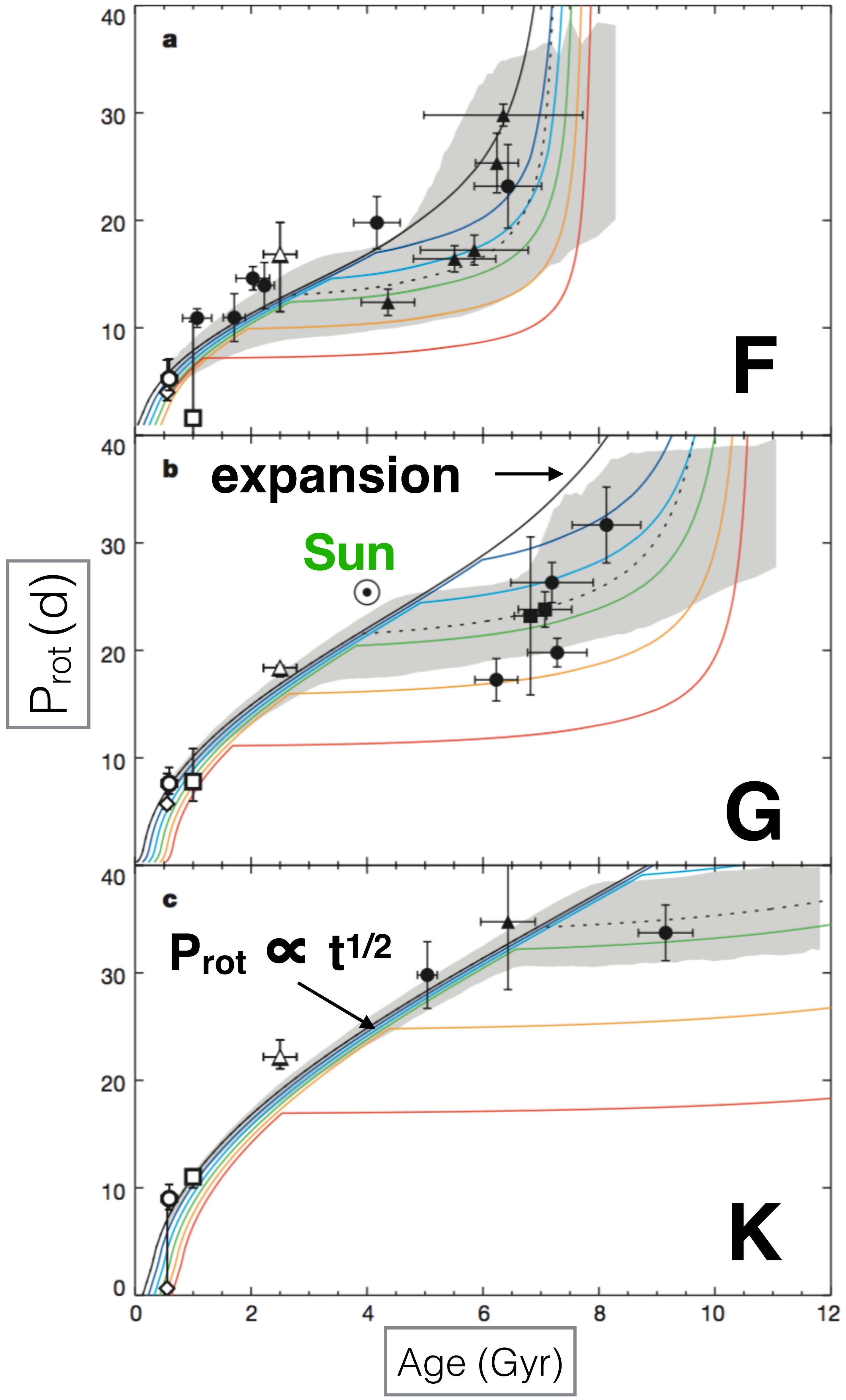
Gyrochronology



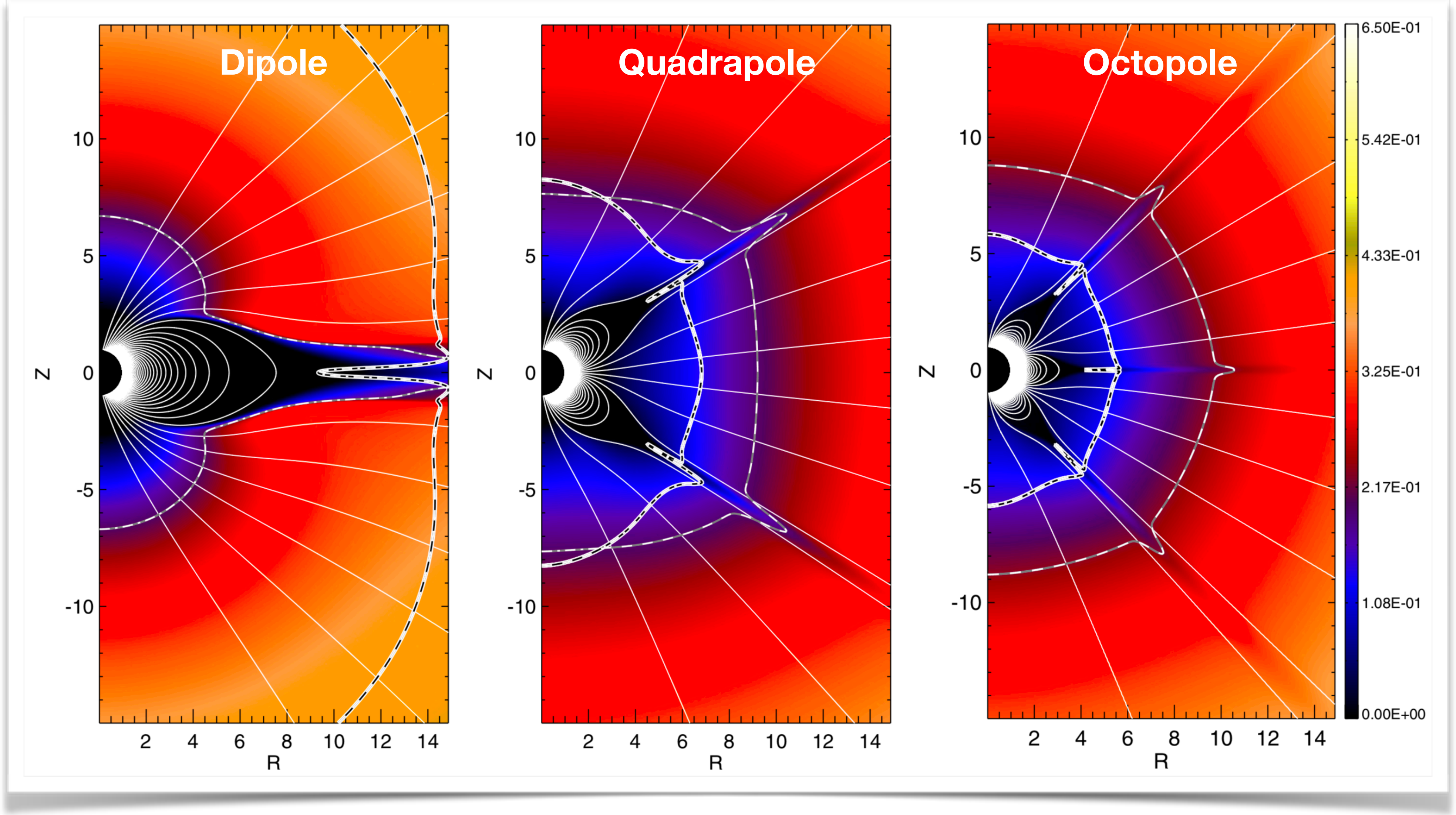
(Barnes 2010, ApJ)

Braking Breaks at a Critical Rossby Number

Van Saders et al. 2016, Nature



Réville et al. 2015

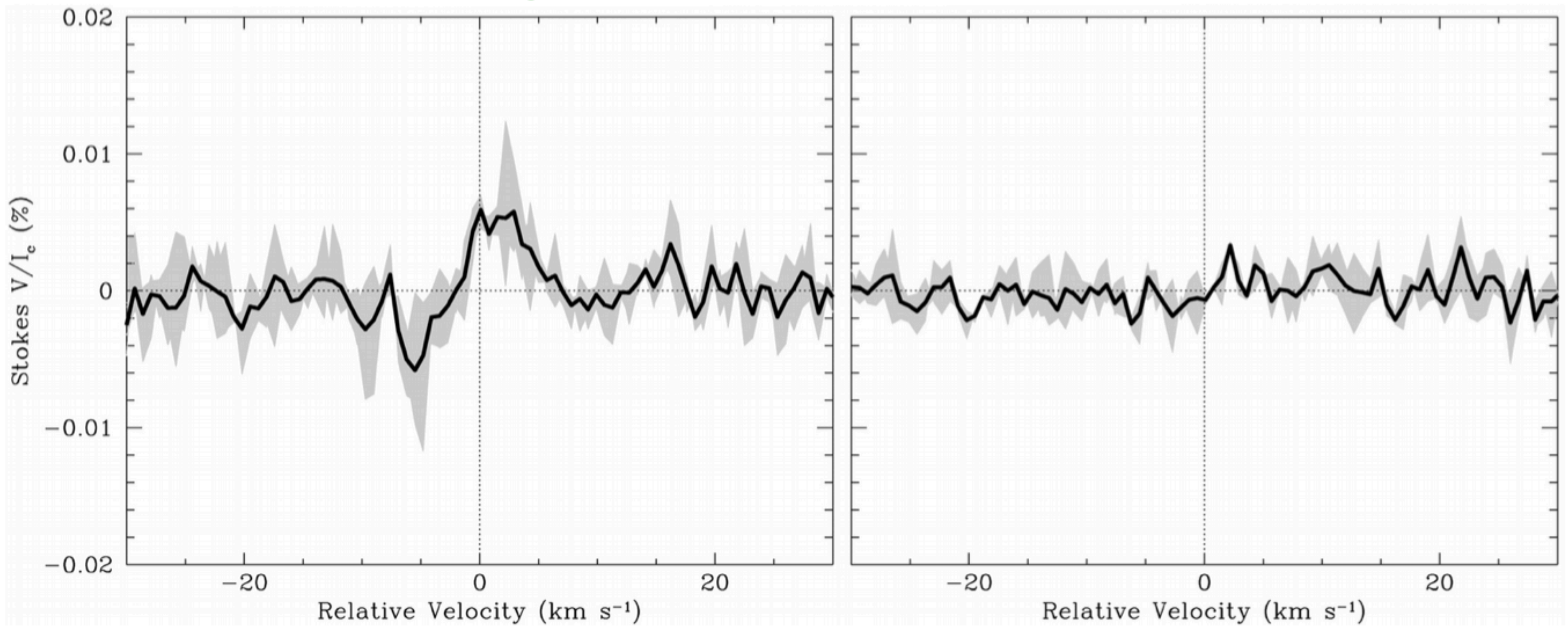


Metcalfe et al. 2019, ApJL

Evidence from PEPSI spectropolarimetry

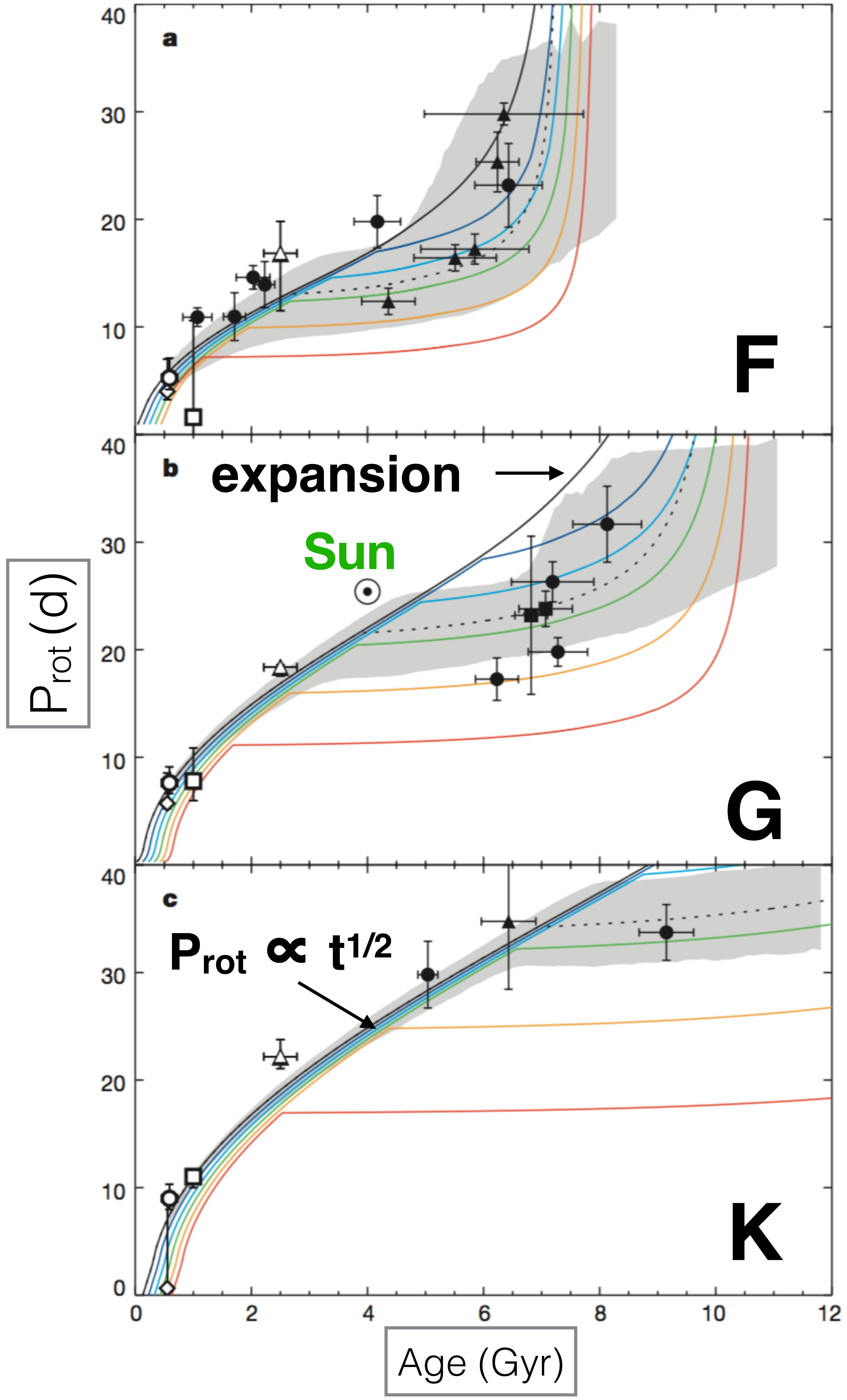
pre-transition: Prot = 14 days, short cycle **post-transition: Prot = 17 days, flat activity**

88 Leo: detect large-scale field ρ CrB: no significant detection

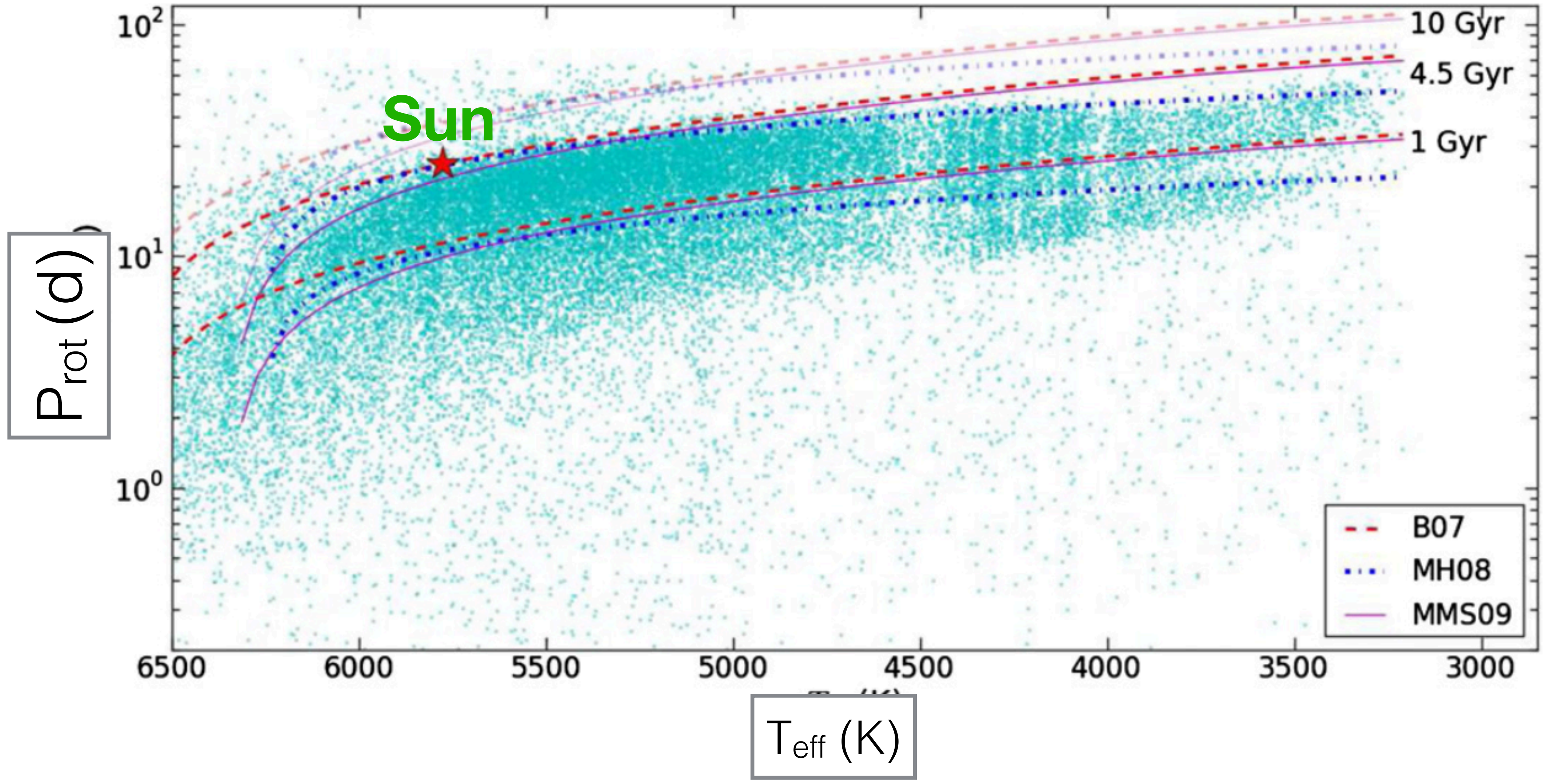


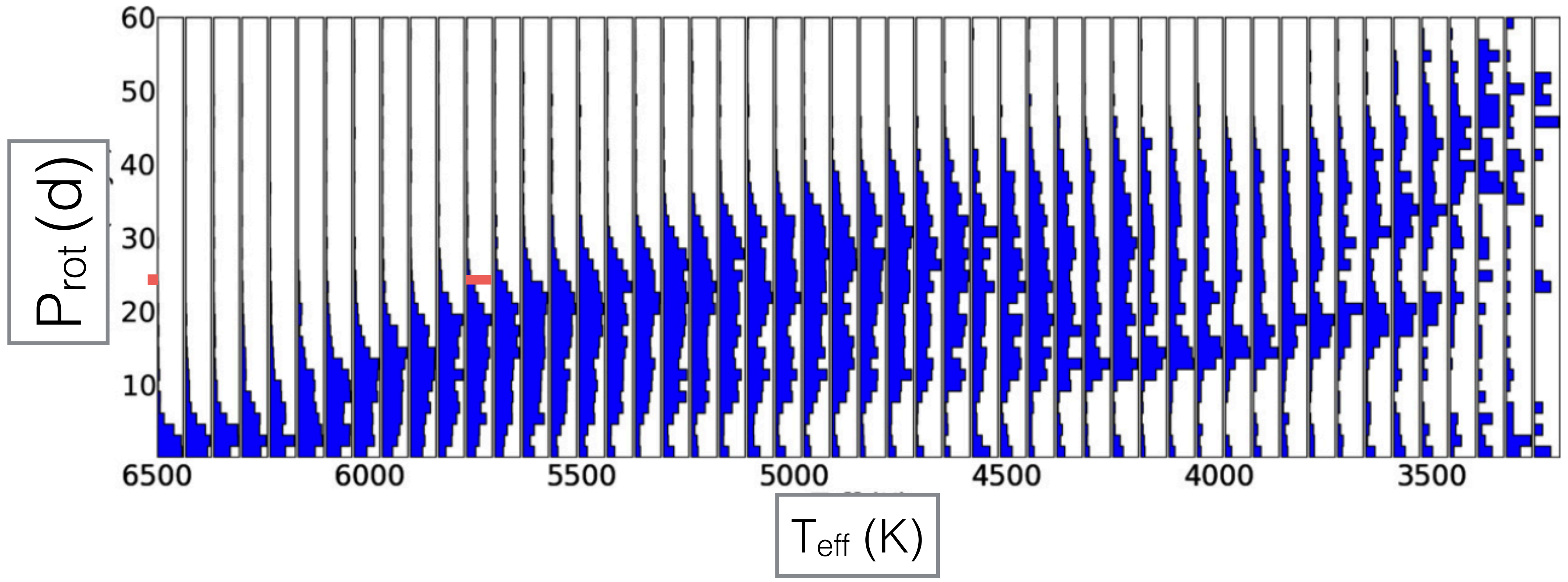
Braking Breaks at a Critical Rossby Number

Van Saders et al. 2016, Nature

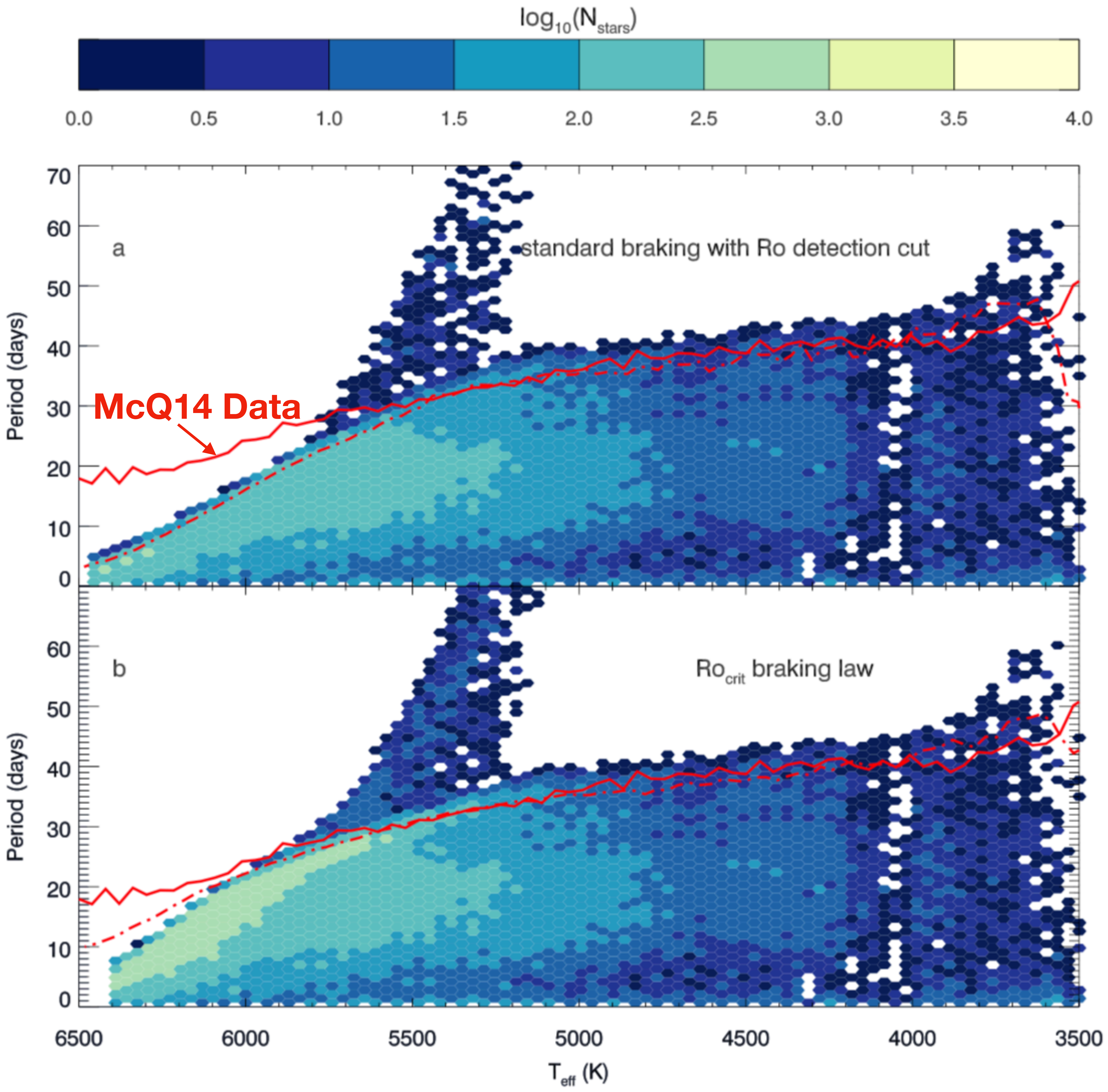


McQuillian et al. 2014, ApJS





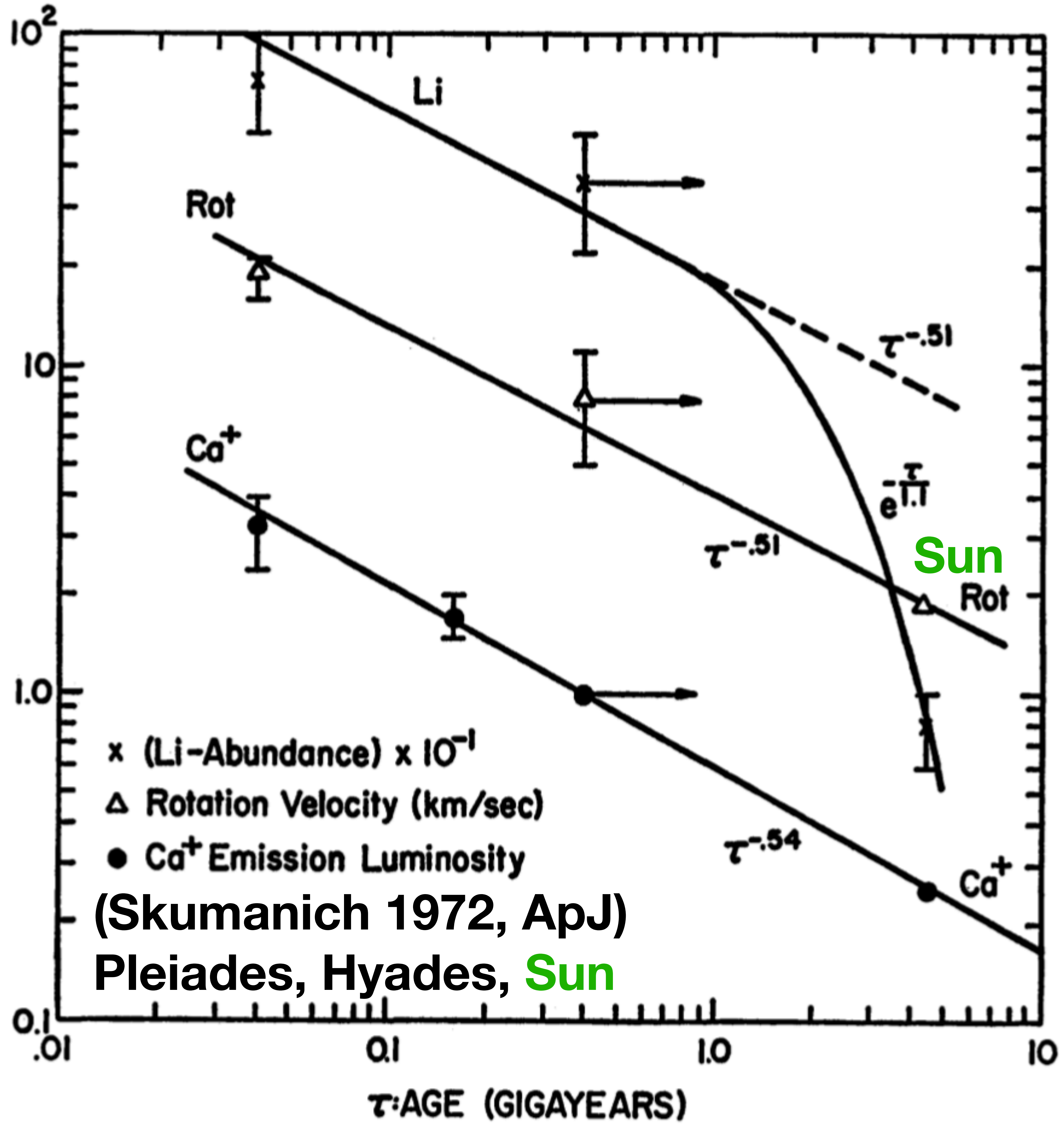
Or does it?



(Van Saders 2019, ApJ)

1. **Stars actually stop braking at a critical Rossby number due to an abrupt change in magnetic topology.**
2. **Stars actually stop braking at a critical Rossby number due to abrupt change in surface field strength.**
3. **Braking continues, but surface features diminish smoothly in a temperature dependent fashion and reach a *Kepler-specific* detection threshold.**
4. **Braking continues, but surface features diminish abruptly in a temperature-dependent fashion and impose a *universal* detection threshold.**

Stellar rotation and magnetic activity decrease with time: "magdown?"



Sun

(Skumanich 1972, ApJ)
Pleiades, Hyades, Sun

FIG. 1.—Ca^+ emission, rotation, and lithium abundance versus stellar age

← Lithium abundance

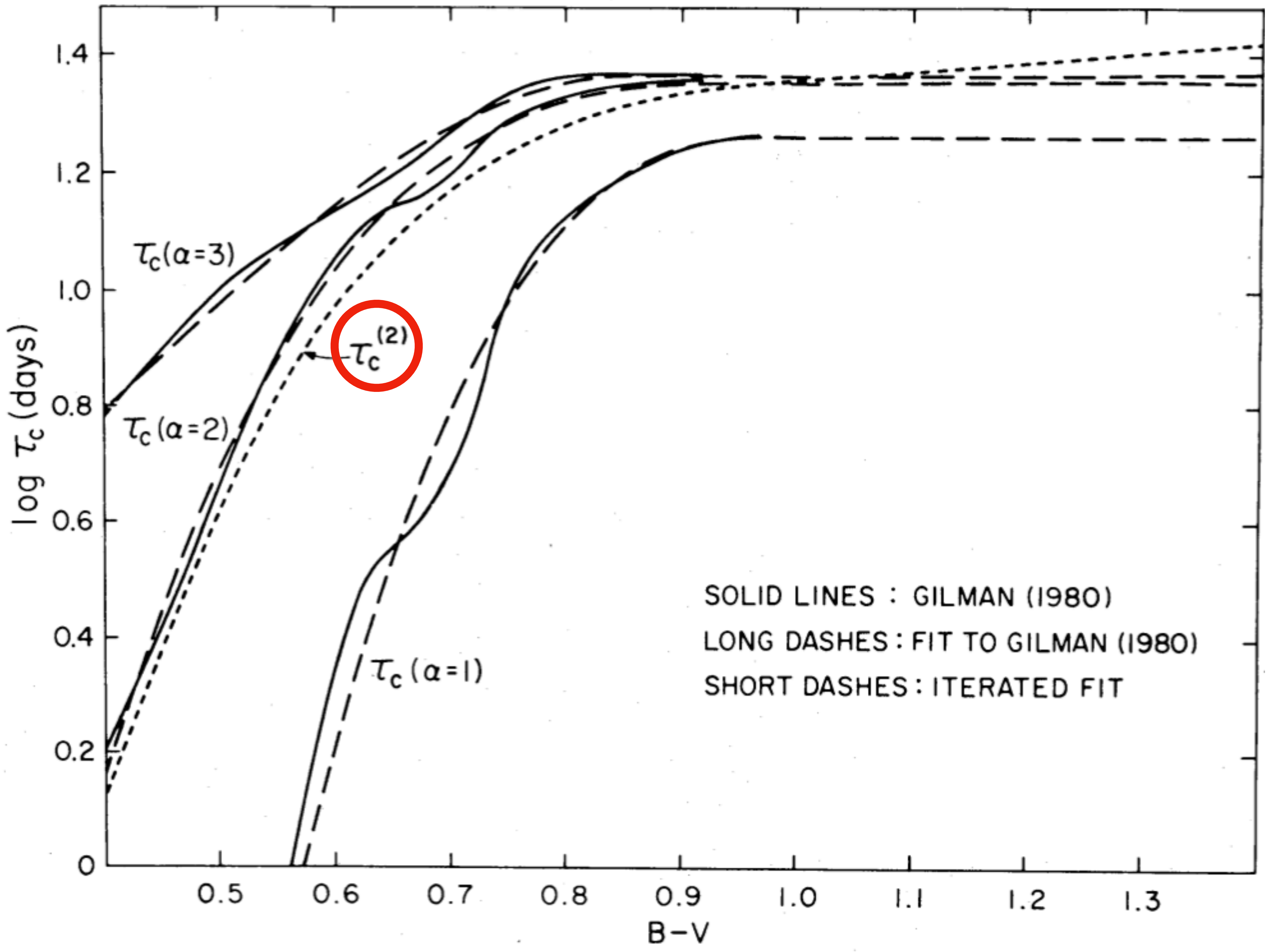
← rotation period

← magnetic proxy

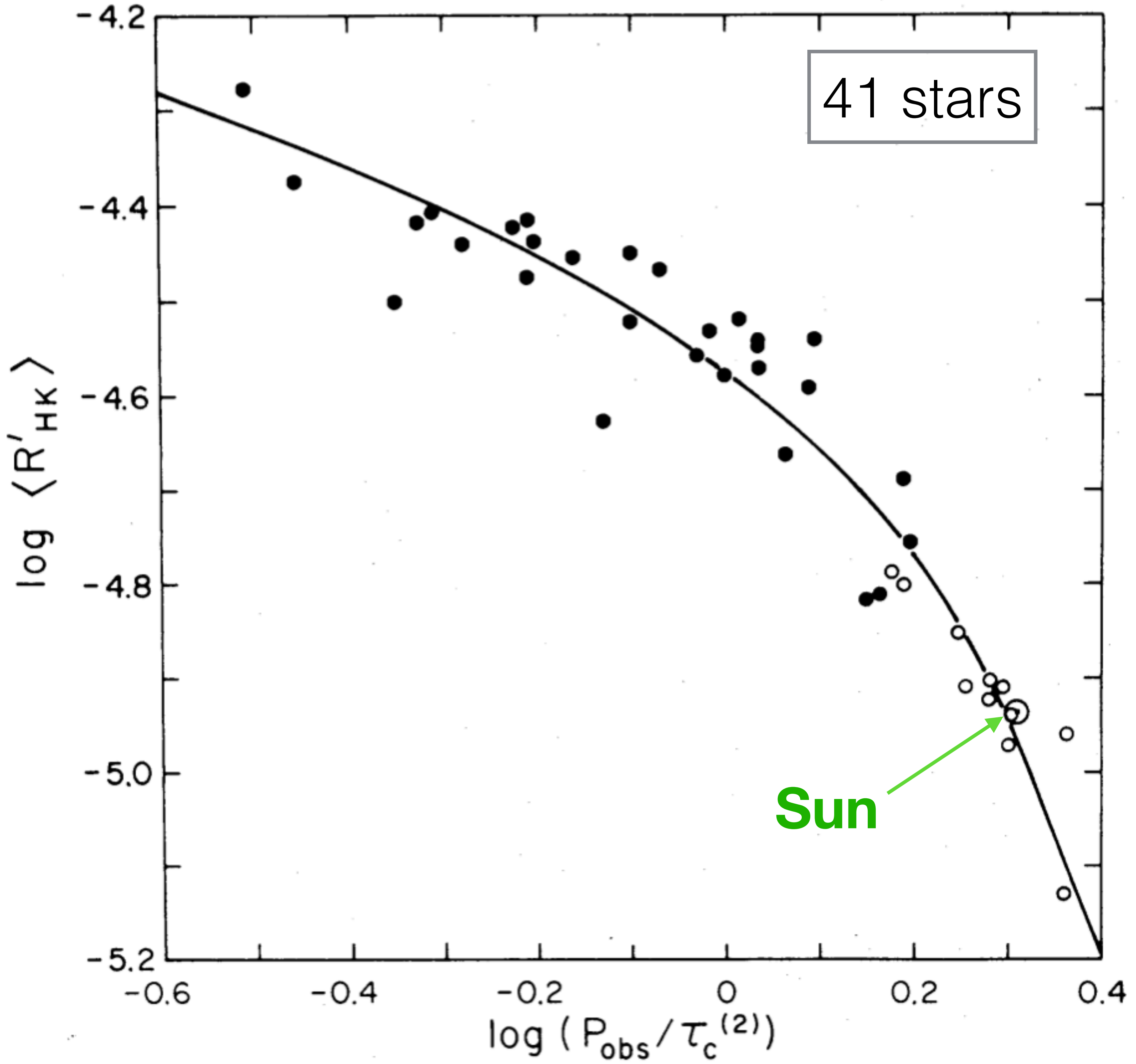
Rossby Number – useful, if nothing else

Noyes et al. 1984

Convective Turnover Time

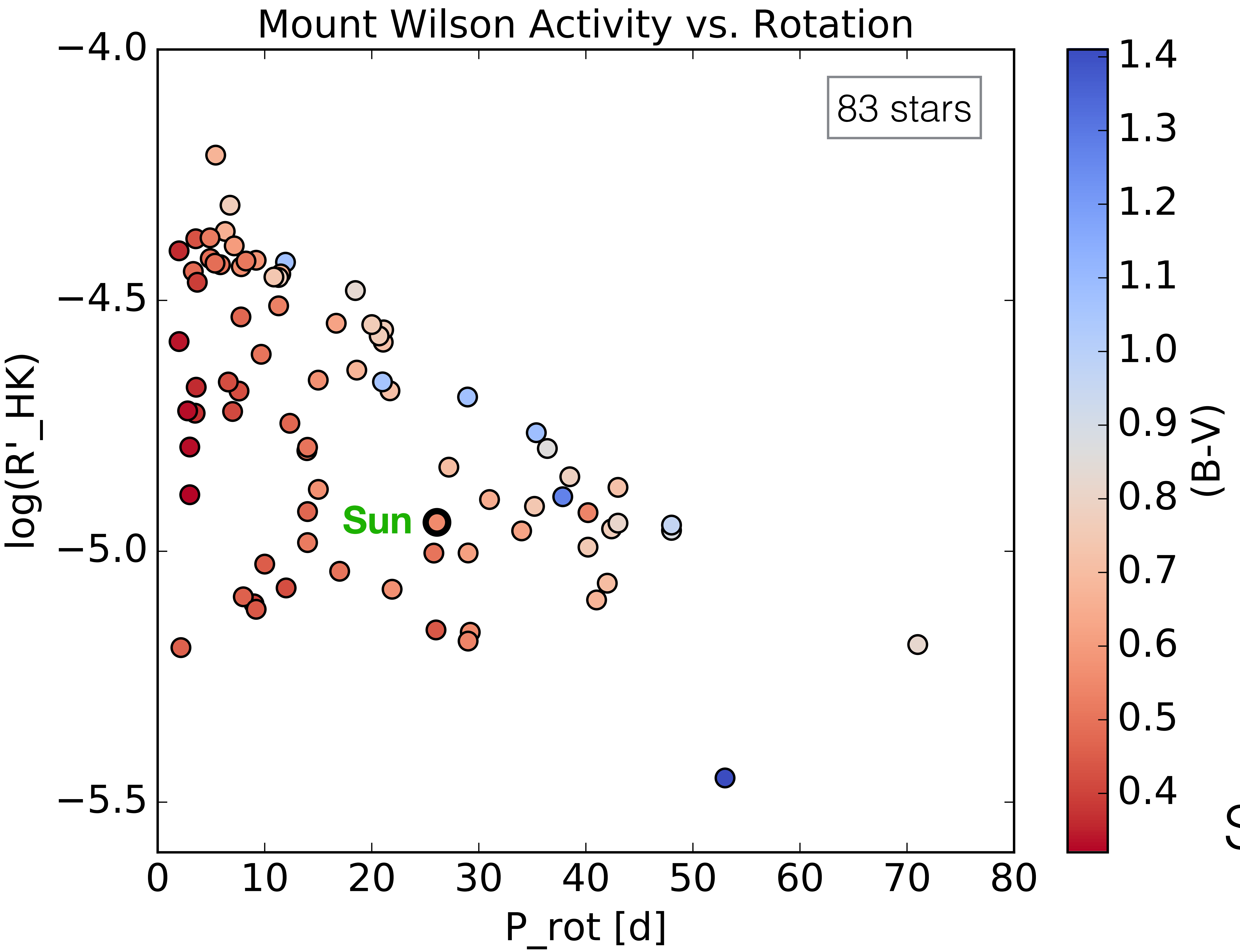


Activity vs. Rossby Number



$$Ro = \frac{P_{\rm rot}}{\tau_c}$$

Mean Activity ∝ Rotation & Mass

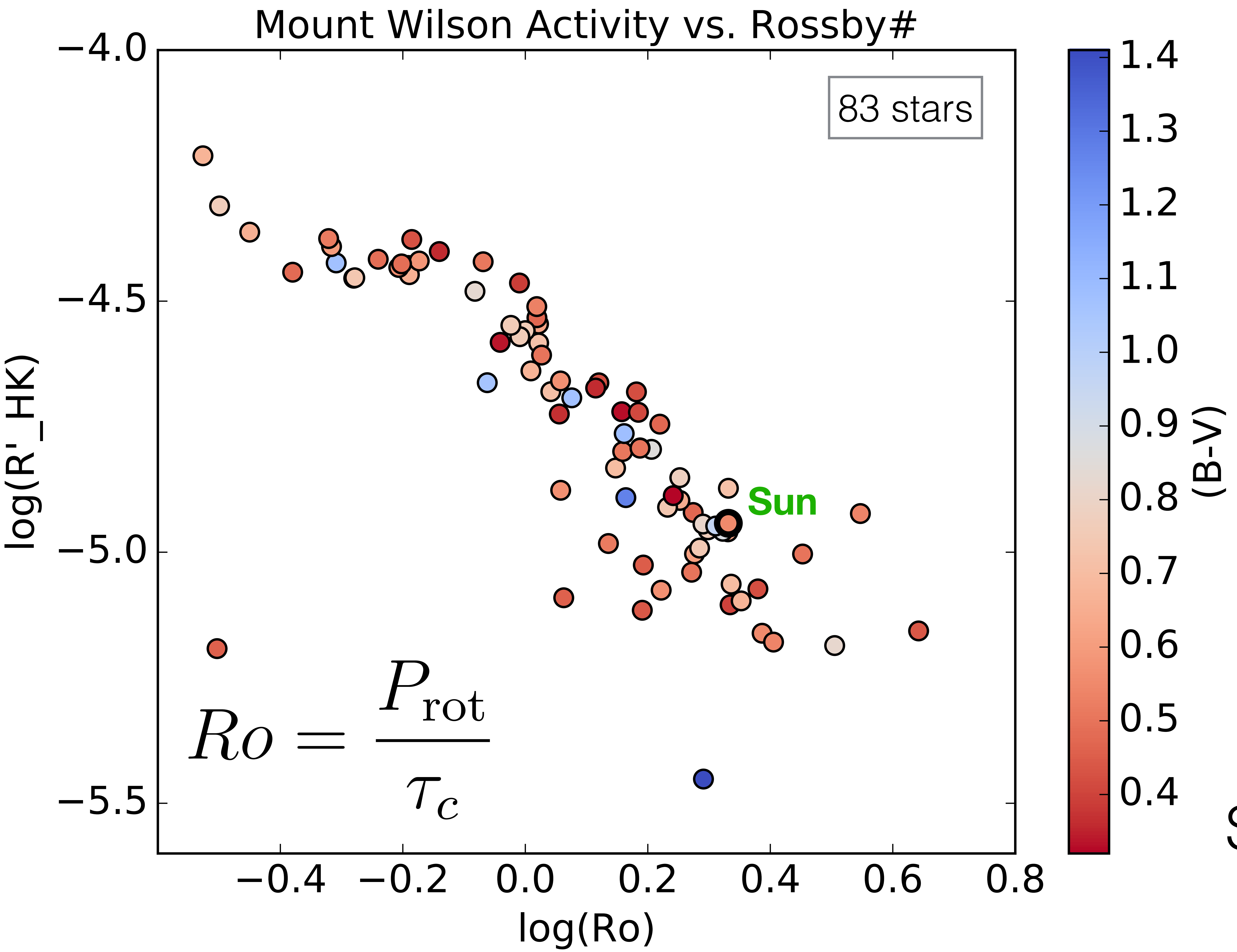


Small,
Cool,
Deep

Big,
Hot,
Shallow

(Noyes et al. 1984 + Baliunas et al. 1995 + Lit. Rotations)

Mean Activity ∝ Rossby Number



$$Ro = \frac{P_{\rm rot}}{\tau_c}$$

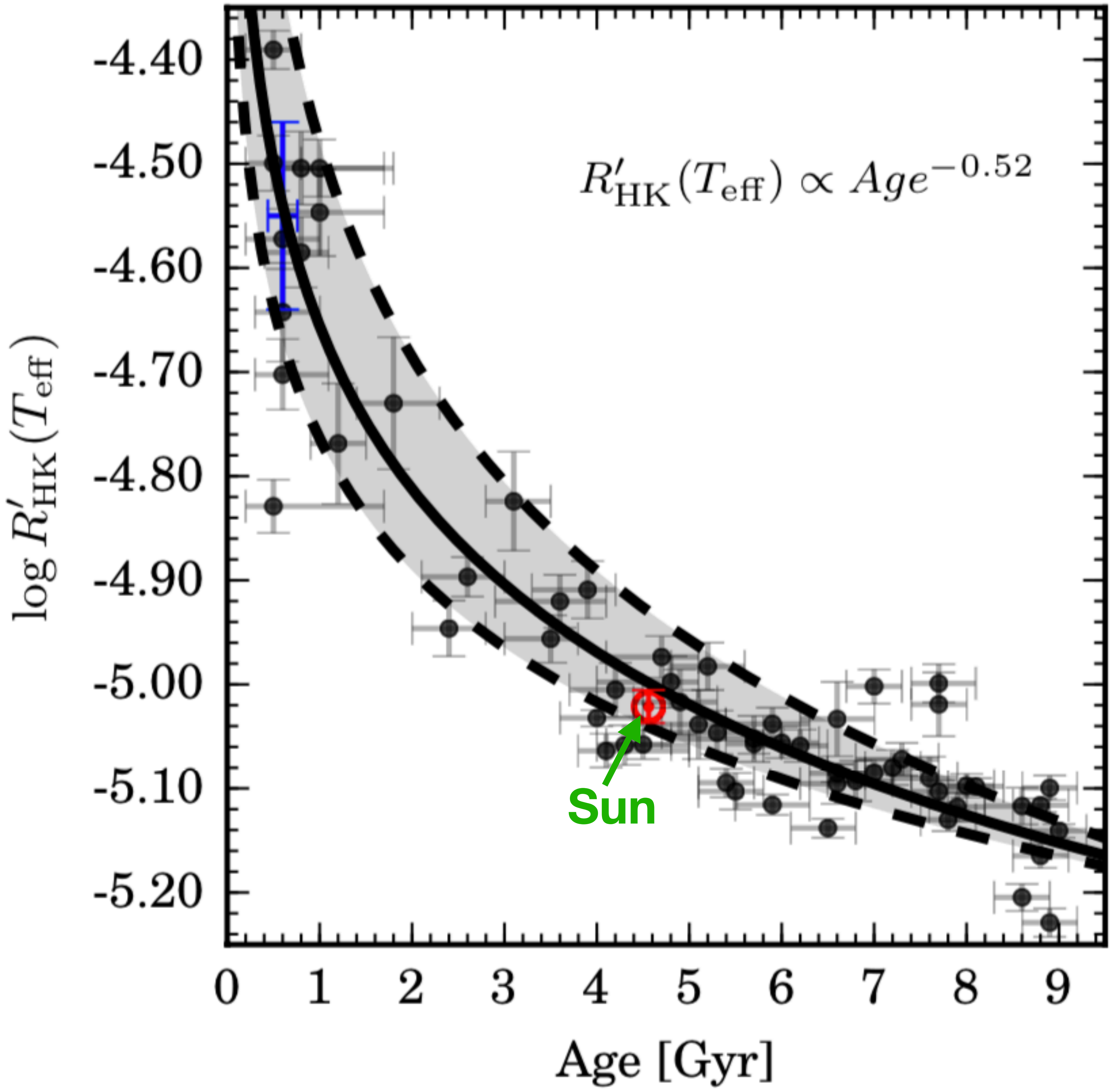
Small,
Cool,
Deep

Big,
Hot,
Shallow

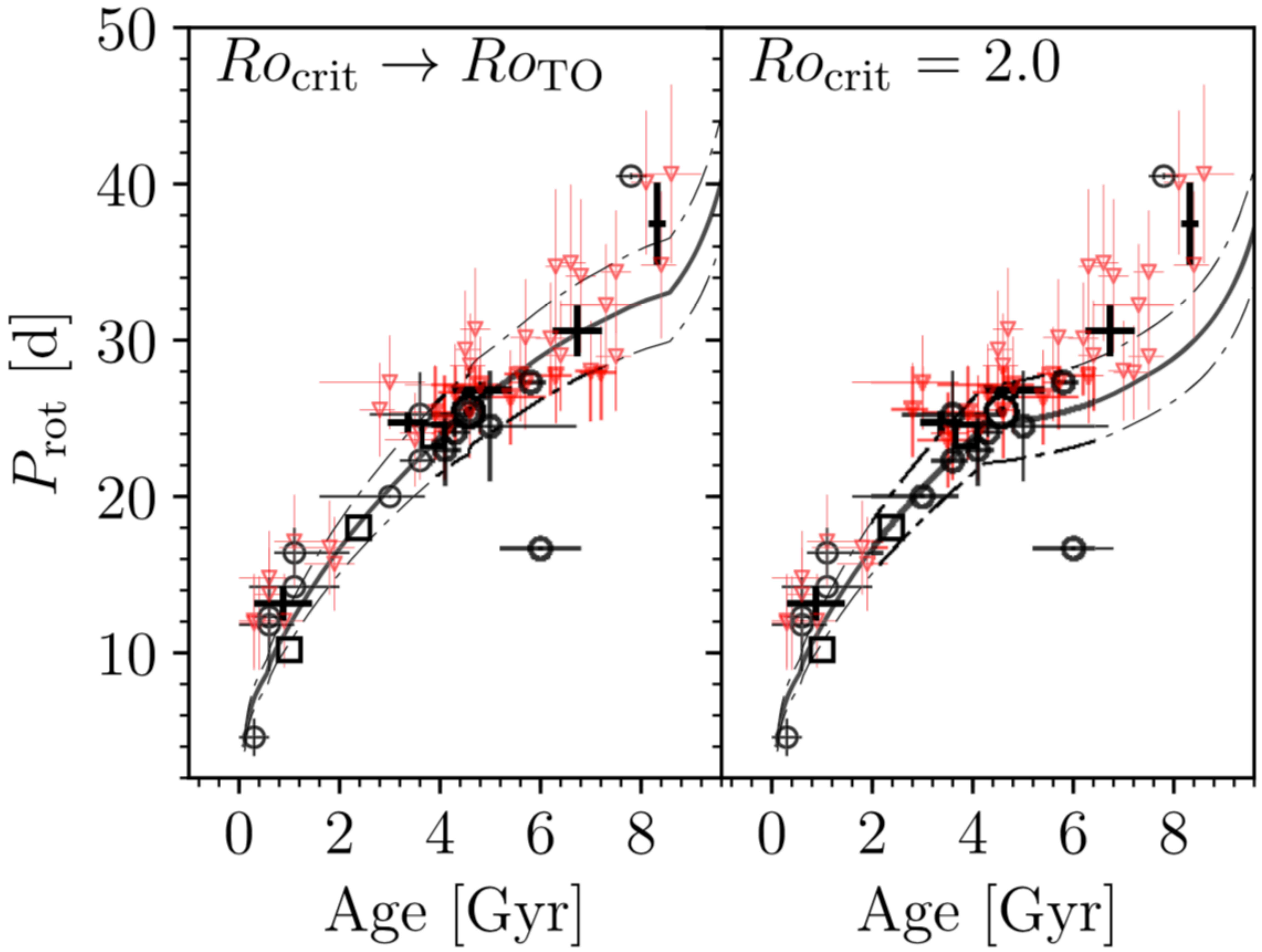
(Noyes et al. 1984 + Baliunas et al. 1995 + Lit. Rotations)

Endurance of Age-Activity, -Rotation?

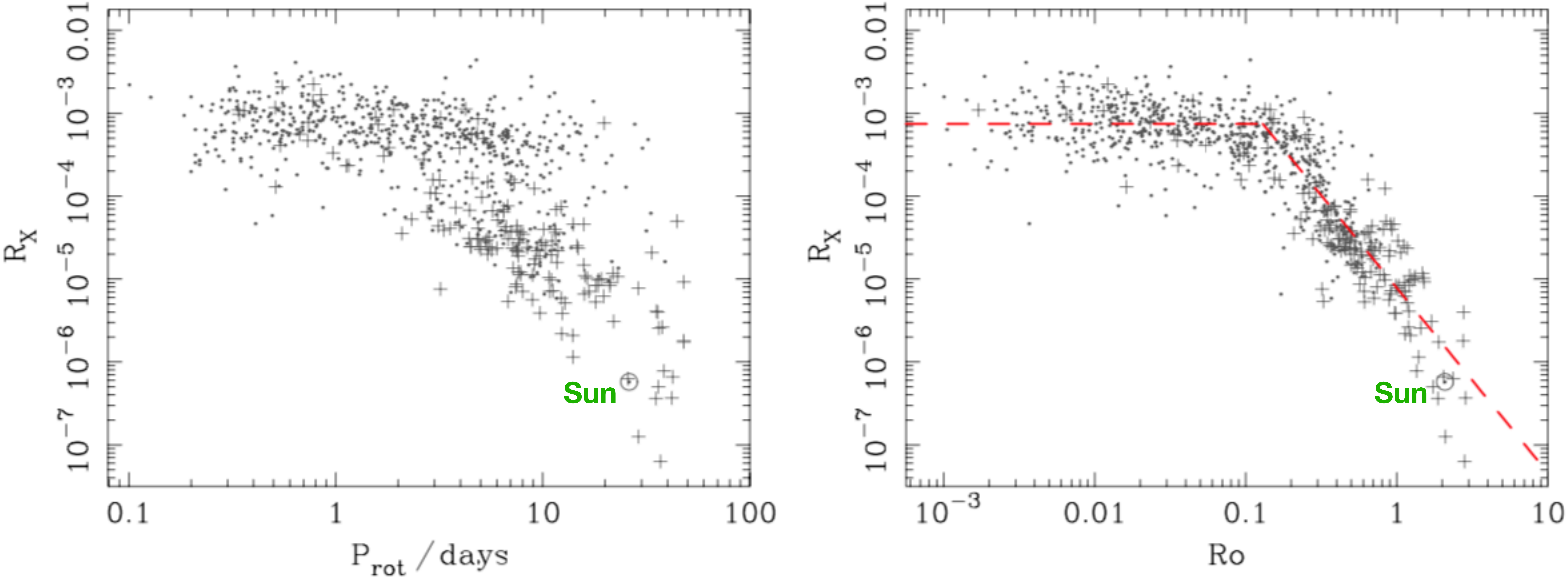
Lorenzo-Oliviera et al. 2018, A&A
"Solar Twins" Teff ±100K; logg, [Fe/H] ±0.1dex



Lorenzo-Oliviera et al. 2019, MNRAS
"Solar Twins" Teff ±100K; logg, [Fe/H] ±0.1dex



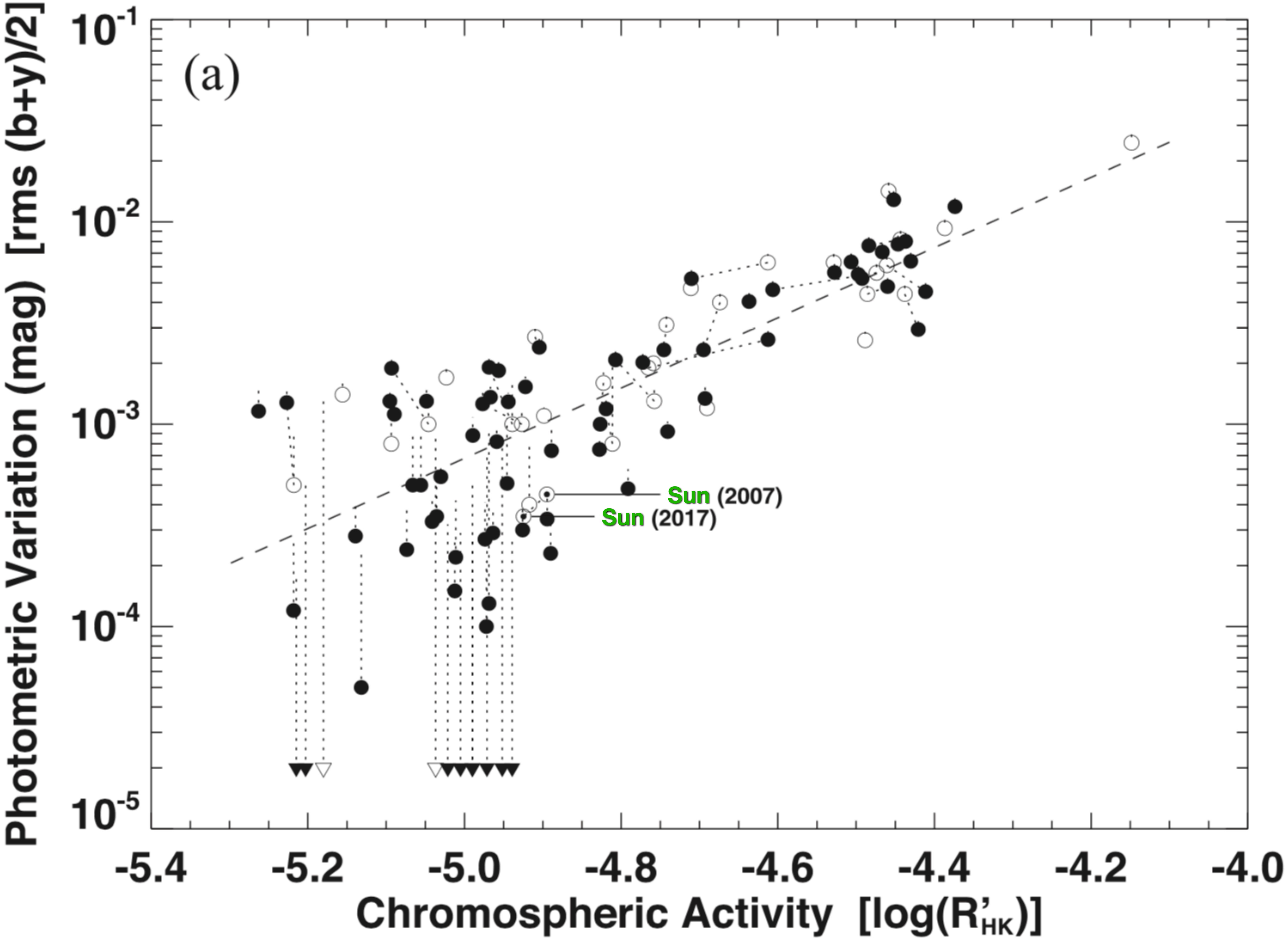
Mean Activity ∝ Rossby Number



(Wright et al. 2011)

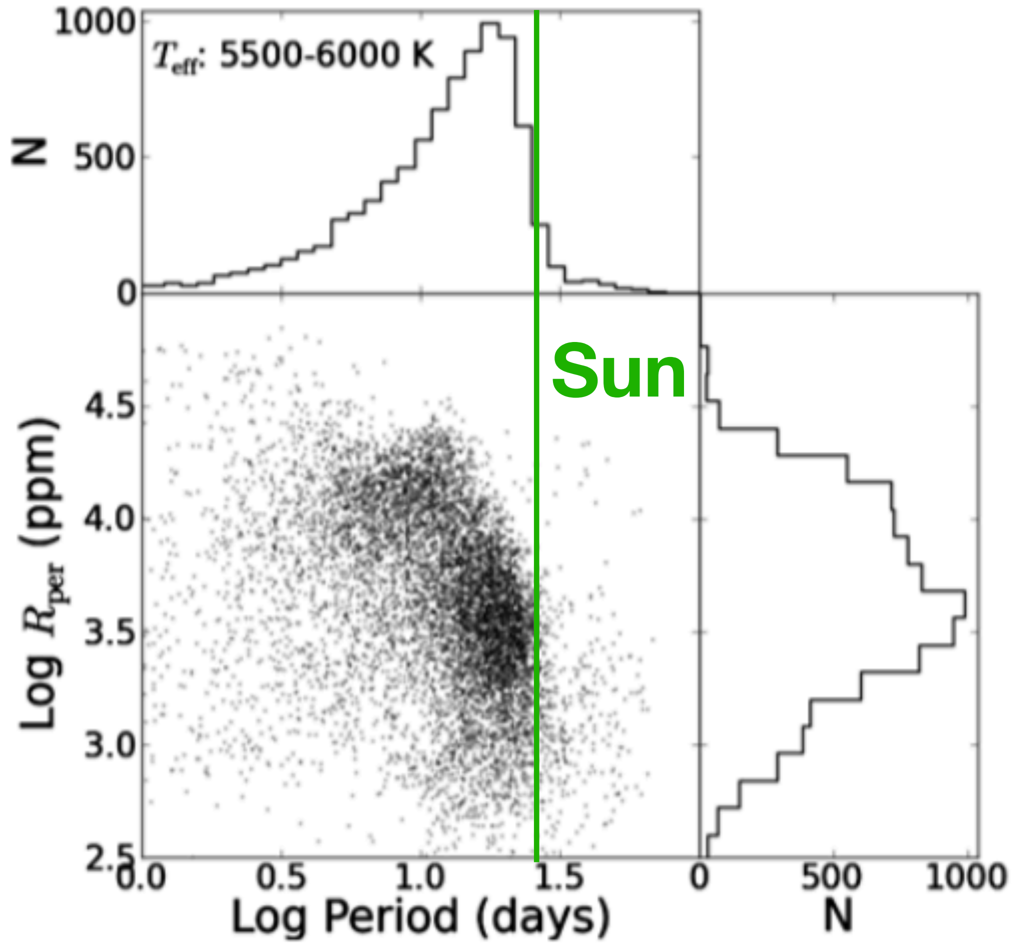
Brightness Variability as an Activity Measure

~17 years of APT observations; mostly G-type stars

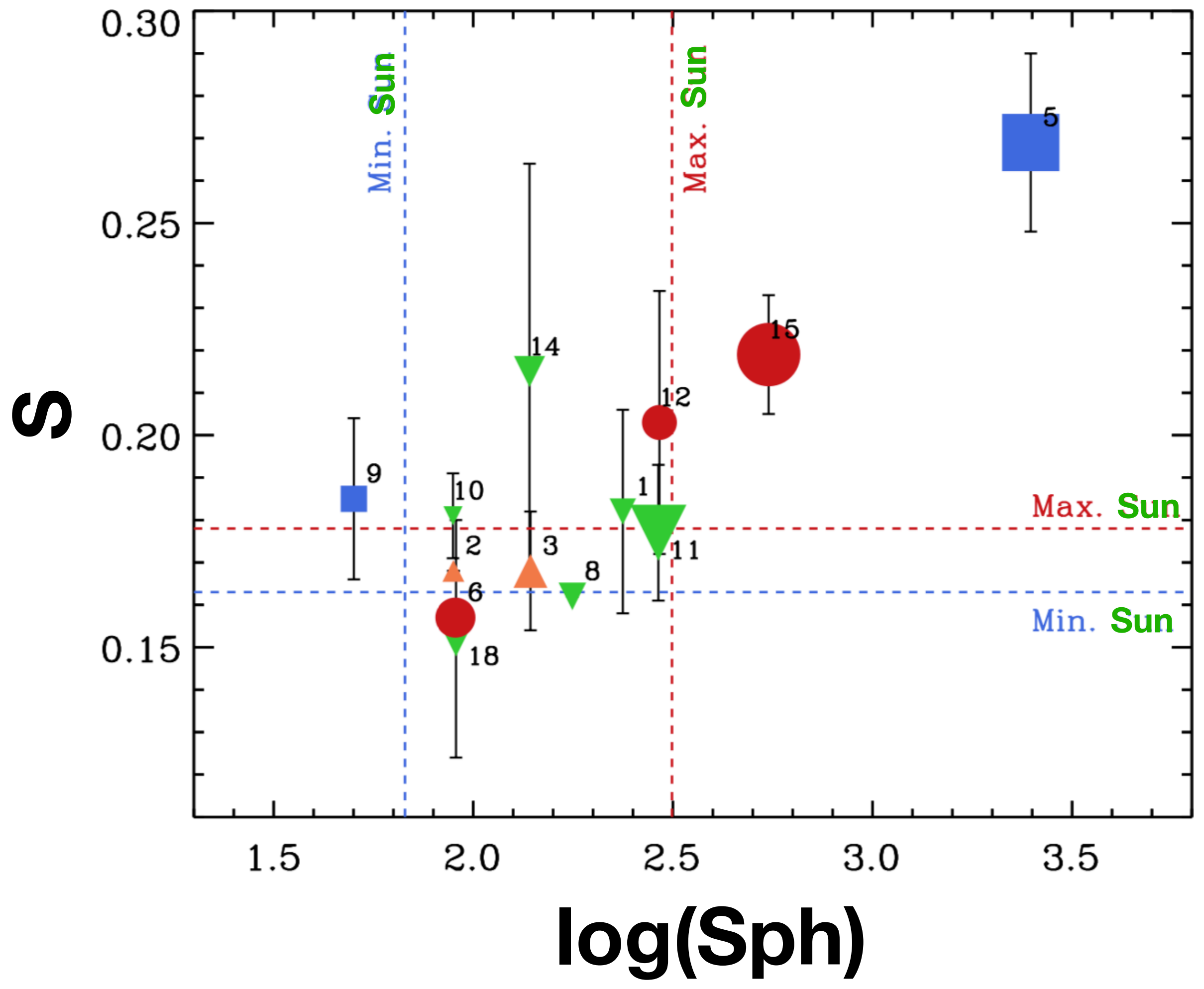


(Radick et al. 2018, ApJ)

~4 years of *Kepler* Observtions; G-type stars

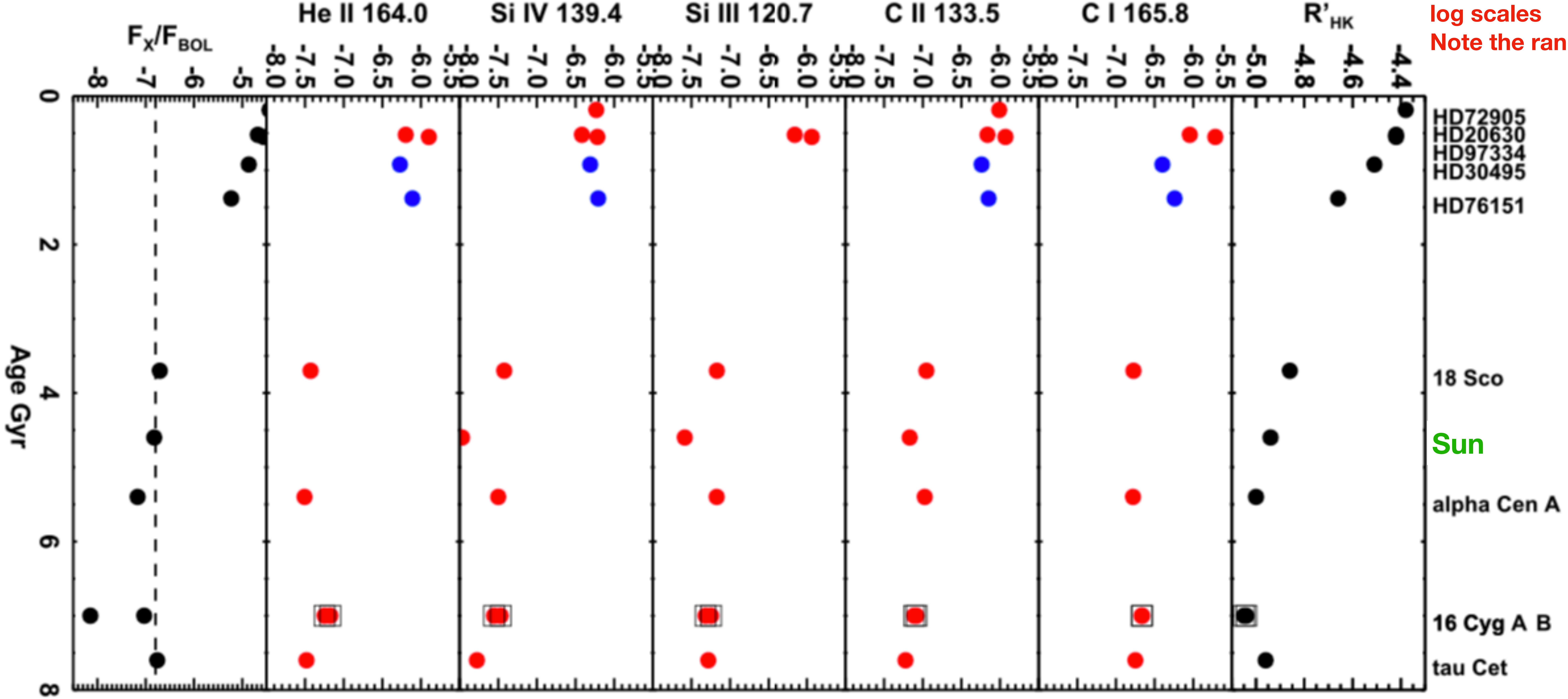


(McQuillan et al. 2015, ApJS)



(Salabert et al. 2016, A&A)

Activity Evolution in the UV



log scales
Note the range!

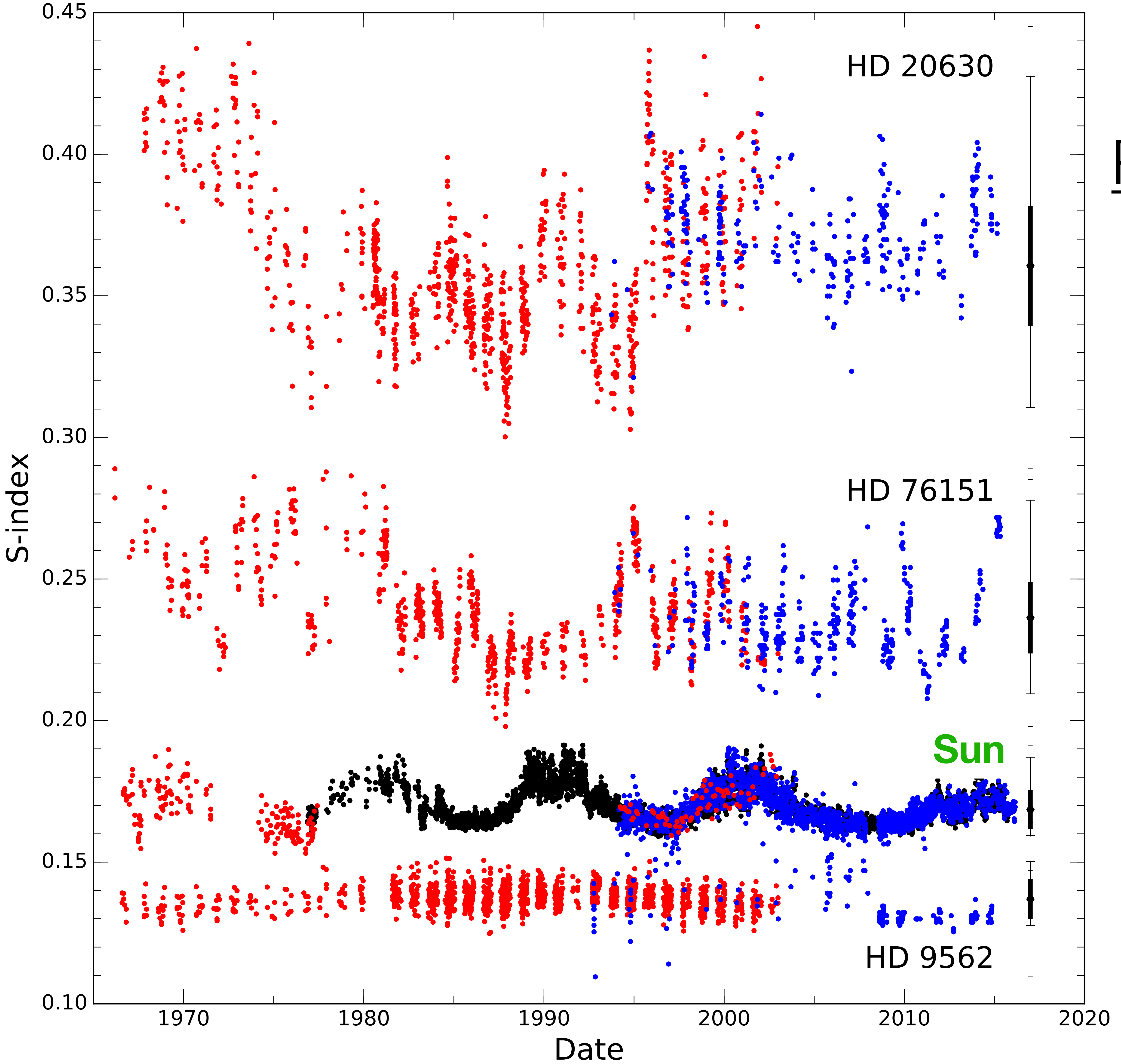
ROSAT, Chandra

IUE / Hubble

Lowell SSS

Judge et al. 2017, ApJ

Long-Term Variability Evolution



Egeland 2017

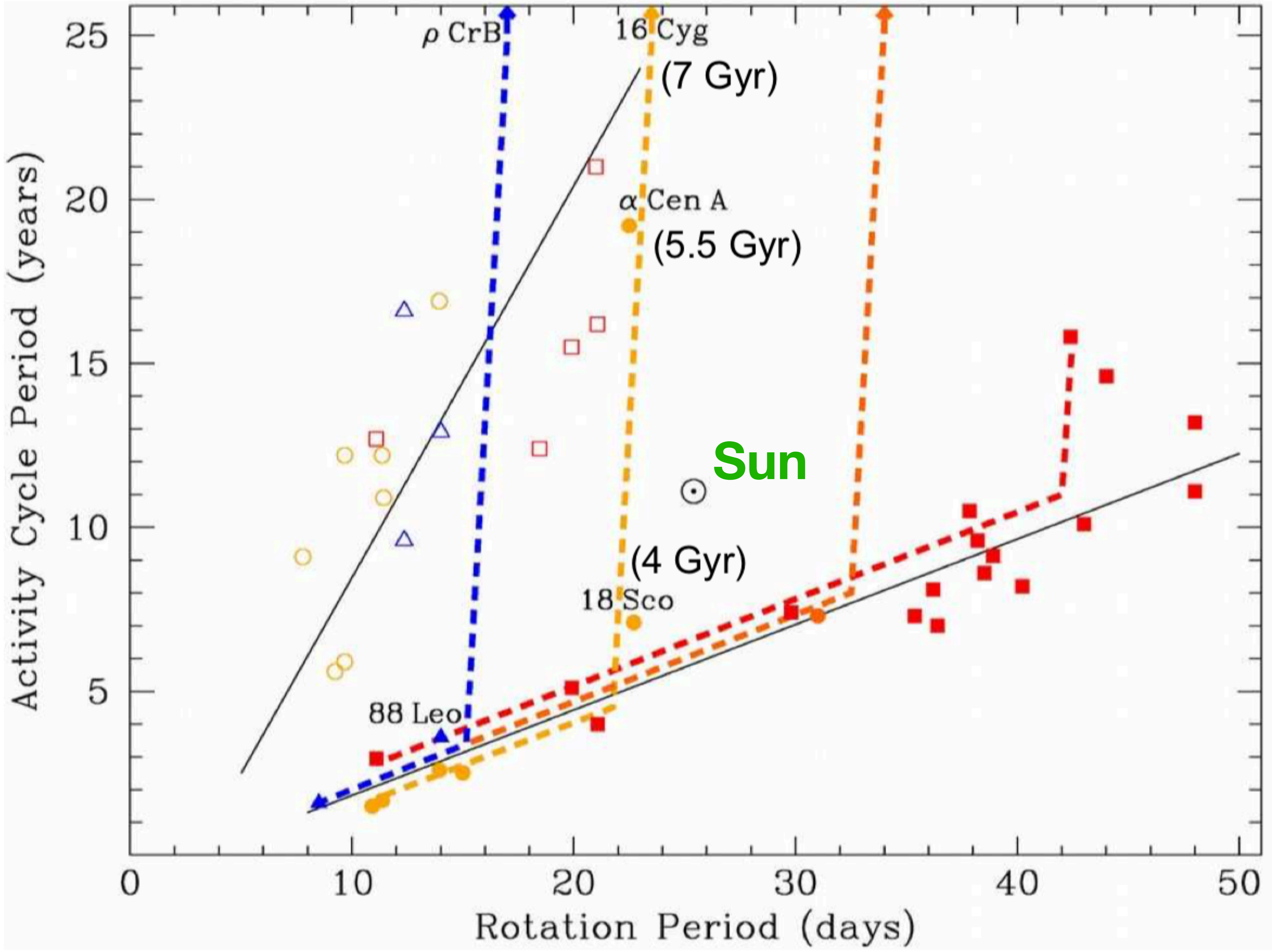
P_{rot} (d)

9.2

15.0

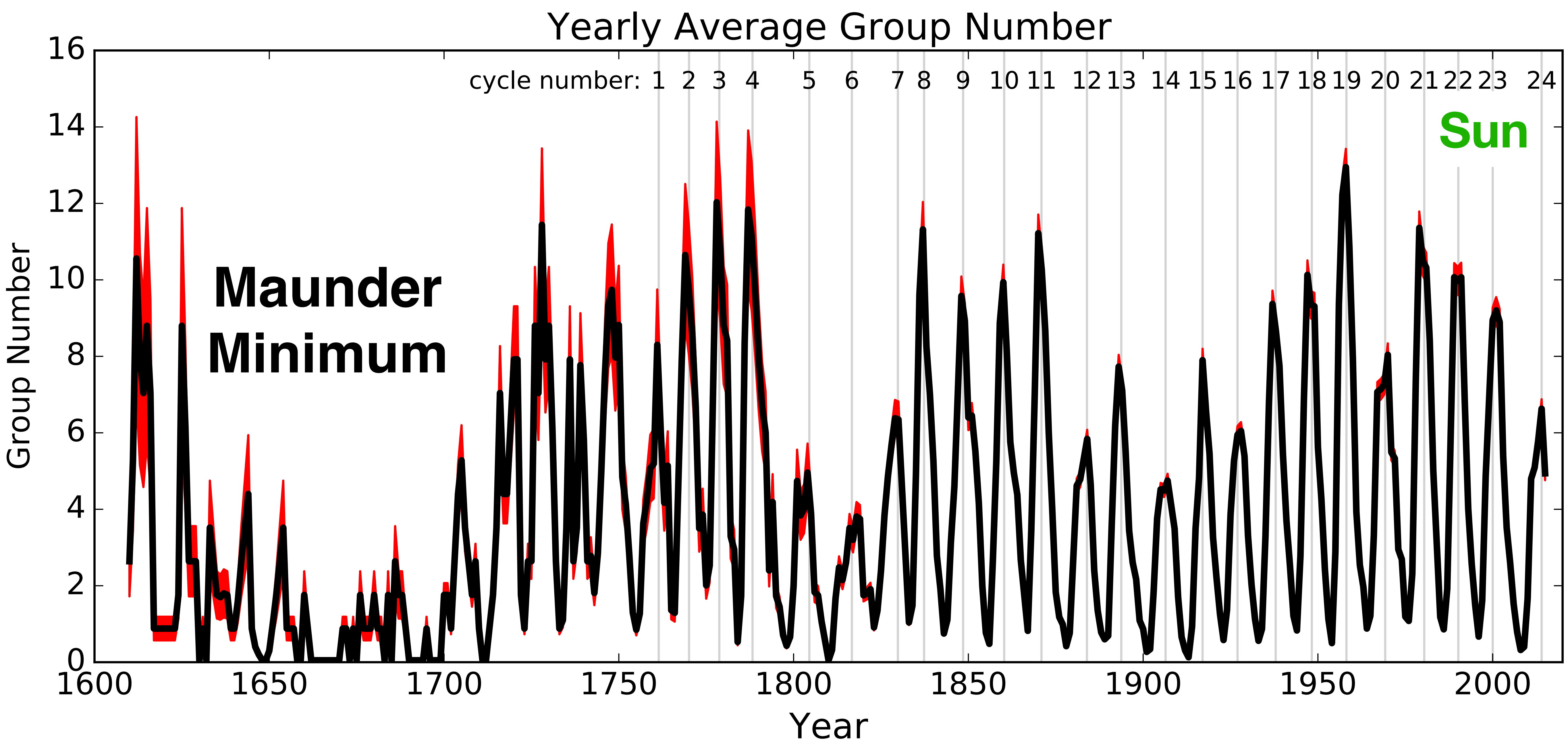
26.1

29.0*



(adapted from Metcalfe & Van Saders 2017, SoPh)

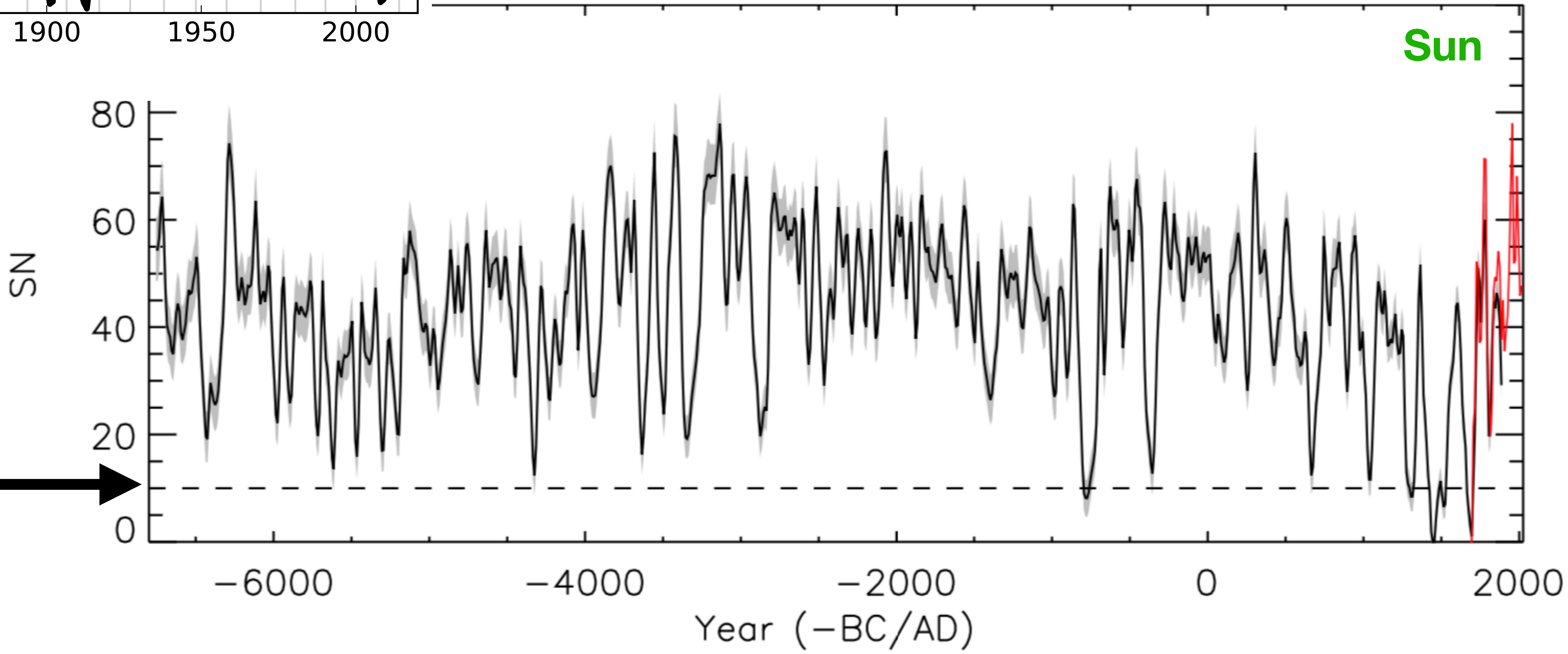
Long-Term Variability Evolution



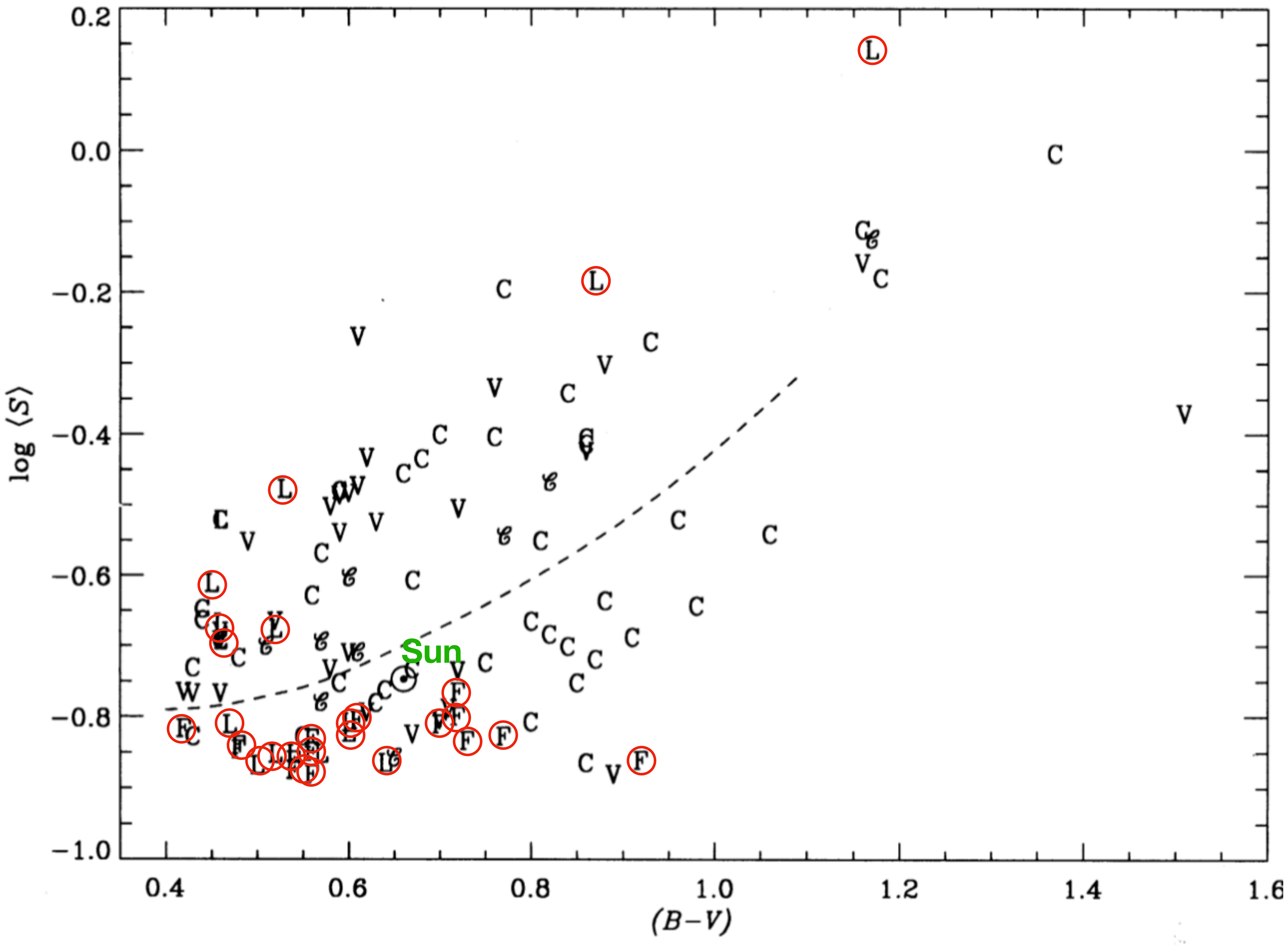
WDC-SILSO “backbone”
Svalgaard & Schatten 2015

Cosmogenic Reconstruction
Wu et al. 2019, A&A

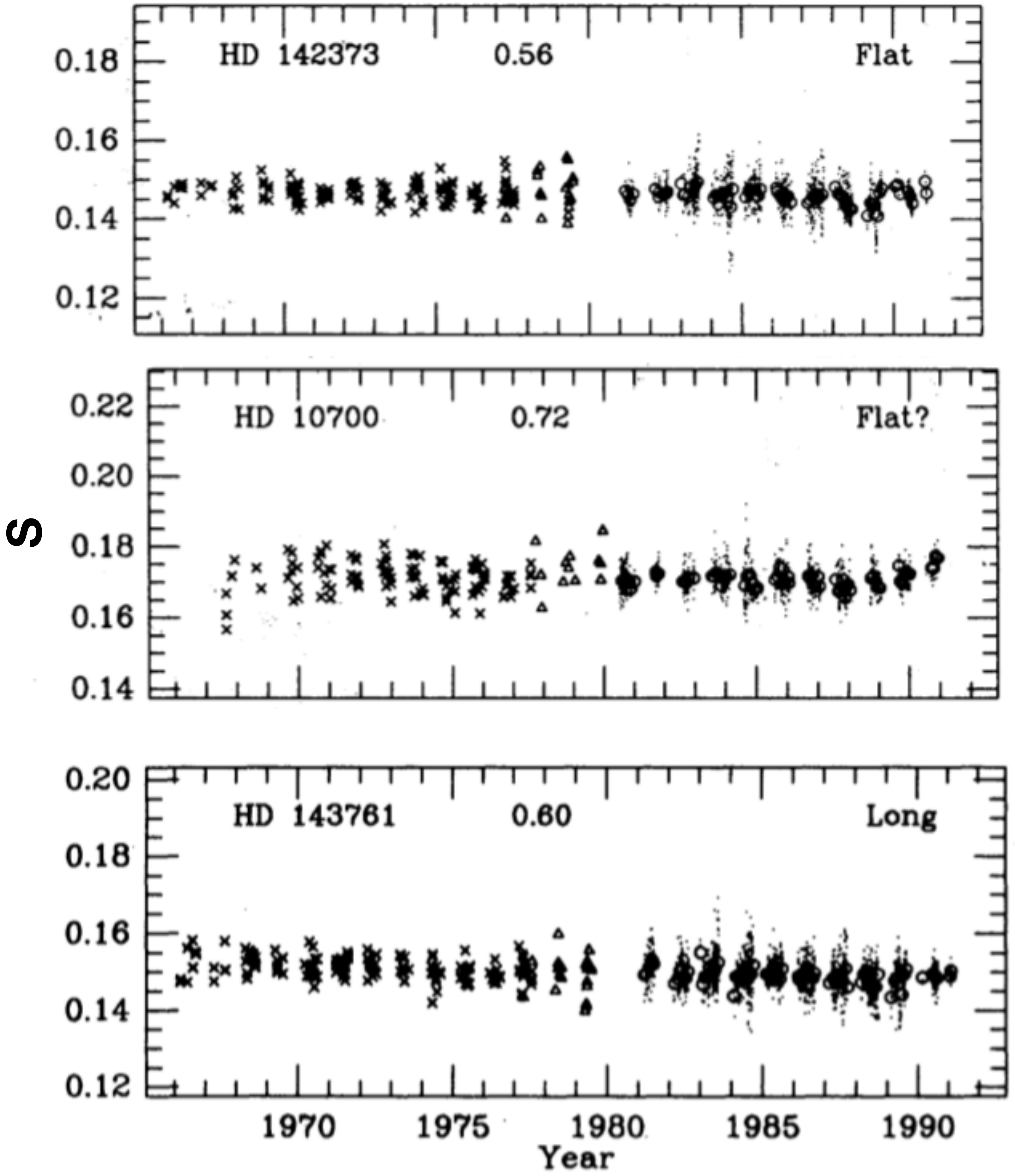
Grand Minima



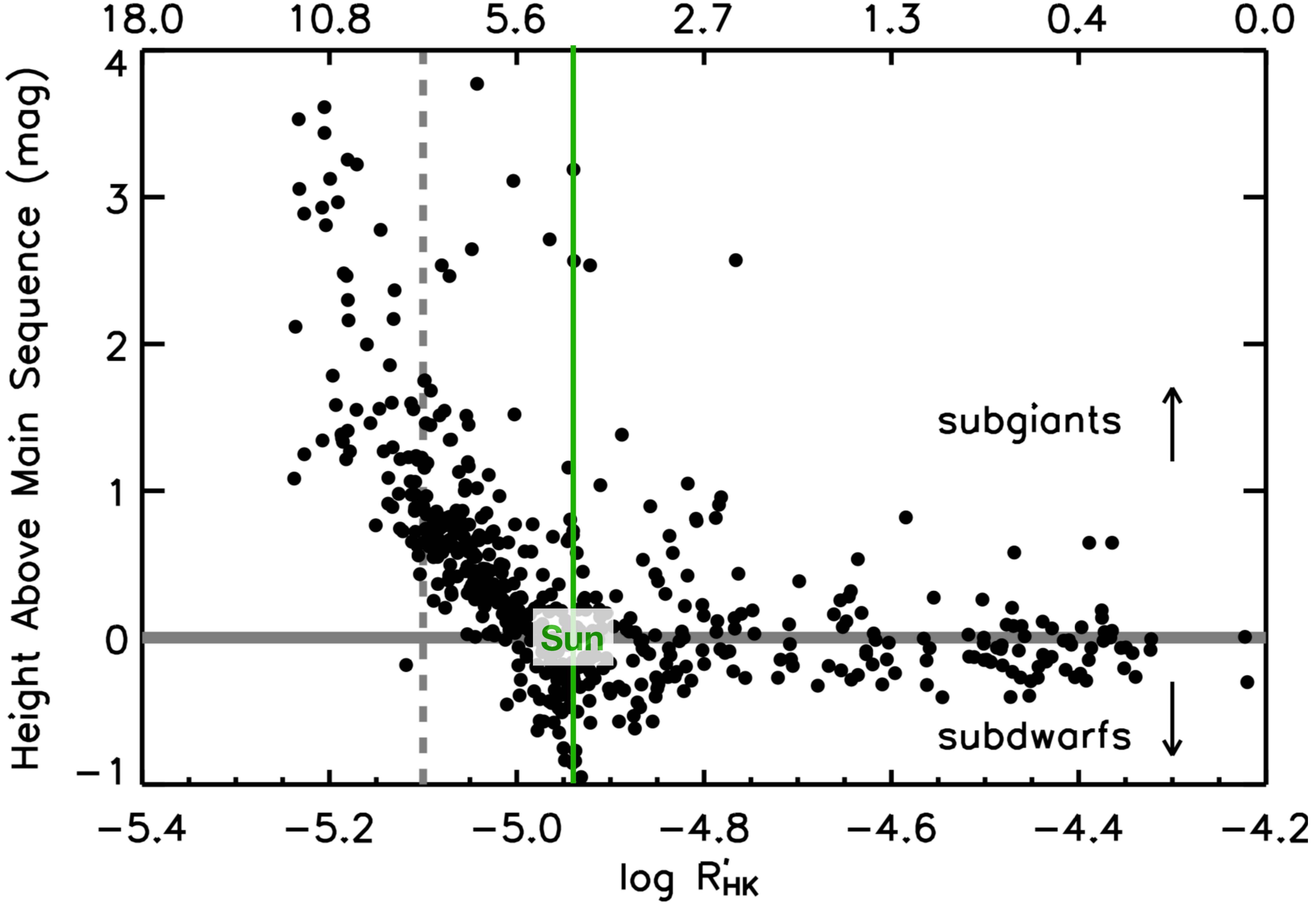
"Maunder Minimum" Stars

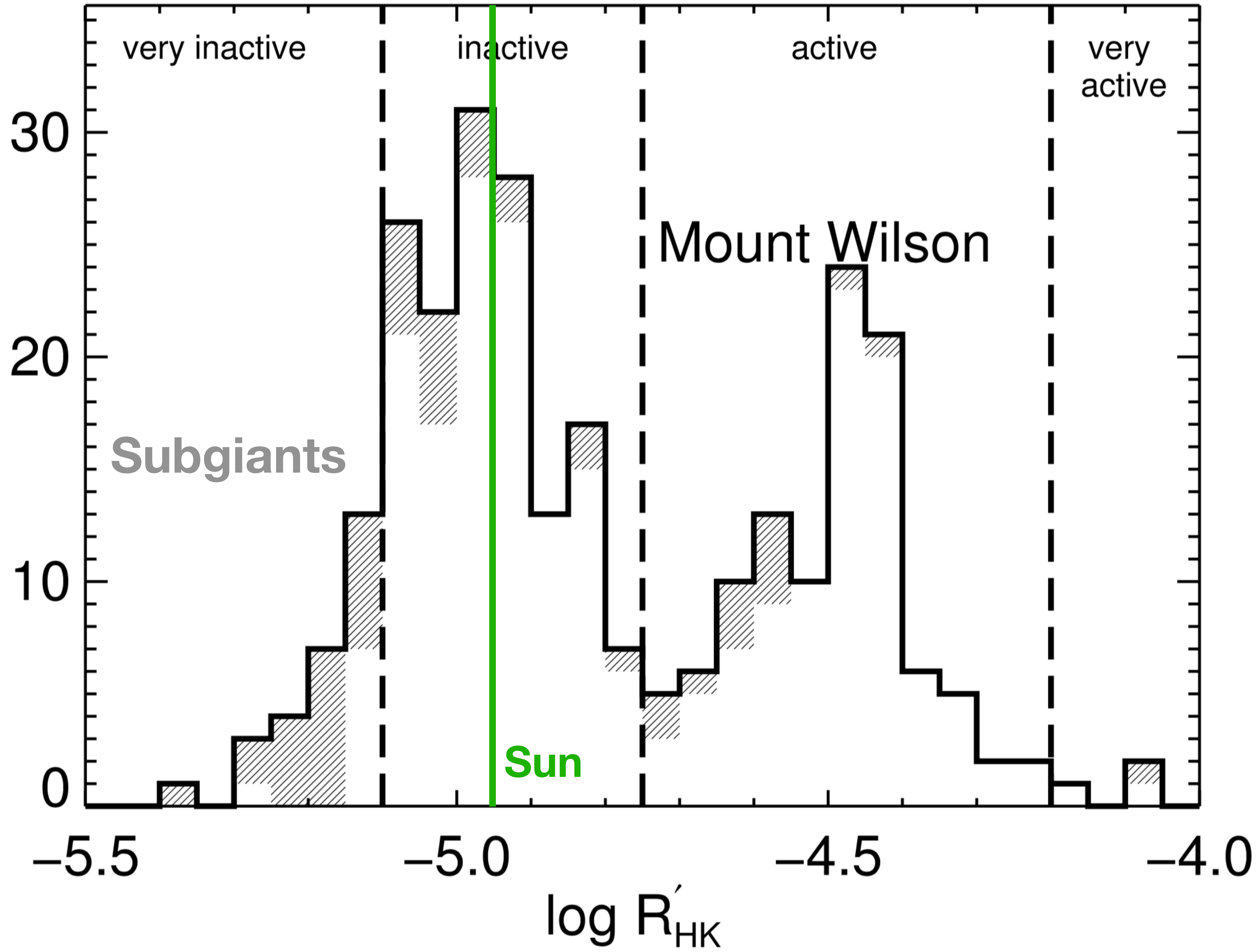


Baliunas et al. 1995



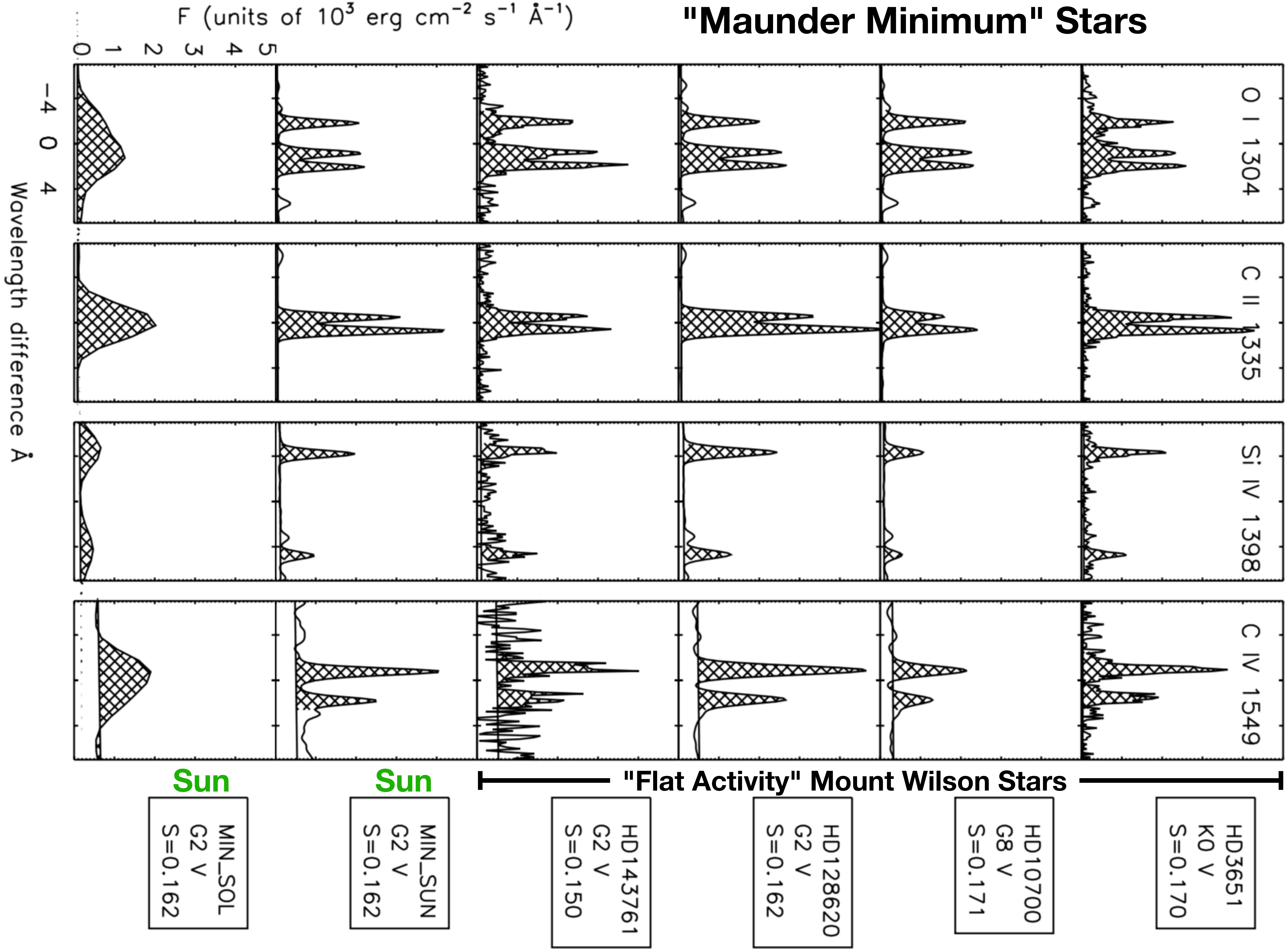
"Maunder Minimum" Stars





(Wright 2004)

"Maunder Minimum" Stars



Sun

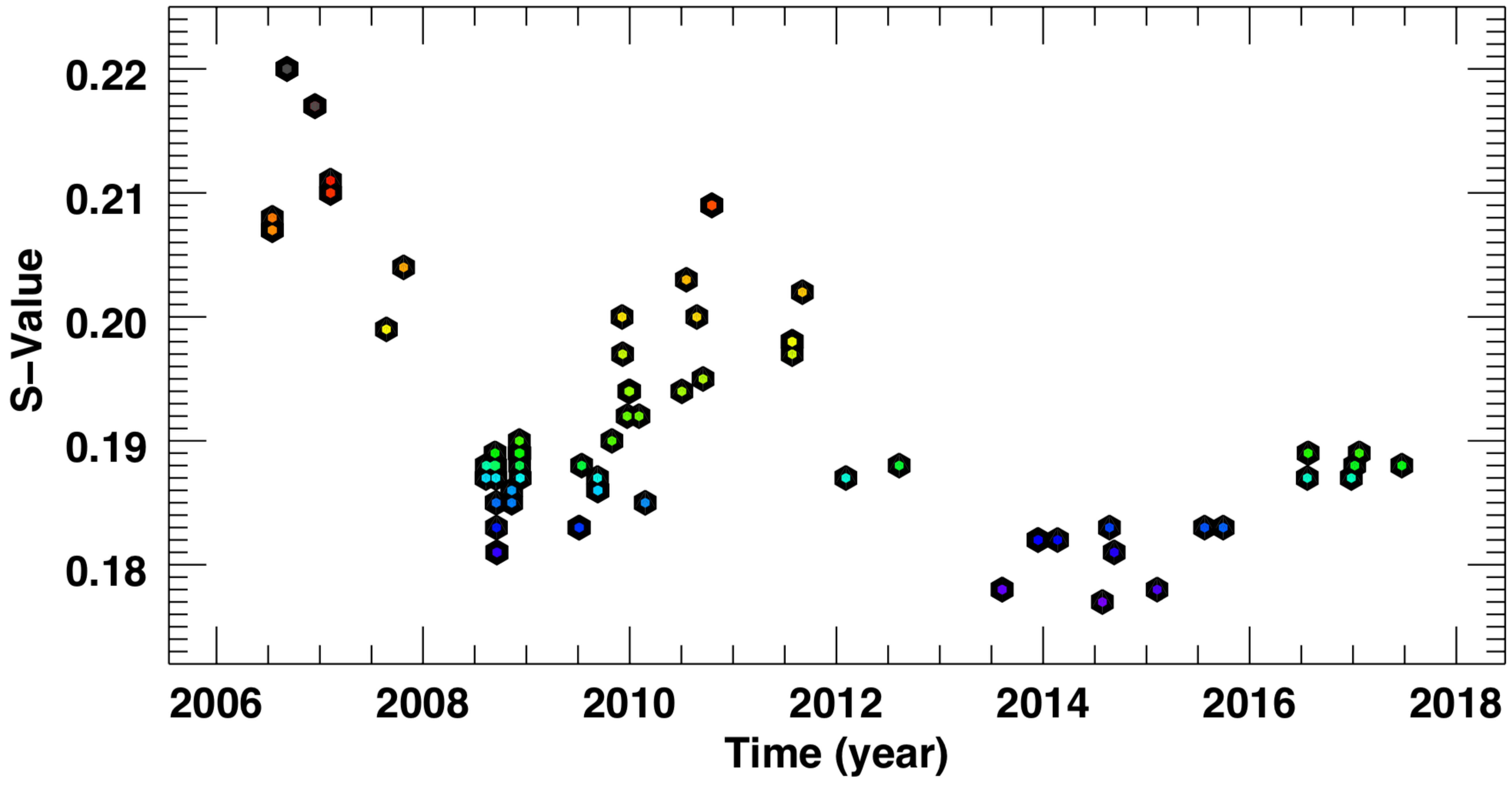
Sun

"Flat Activity" Mount Wilson Stars

Judge & Saar 2007

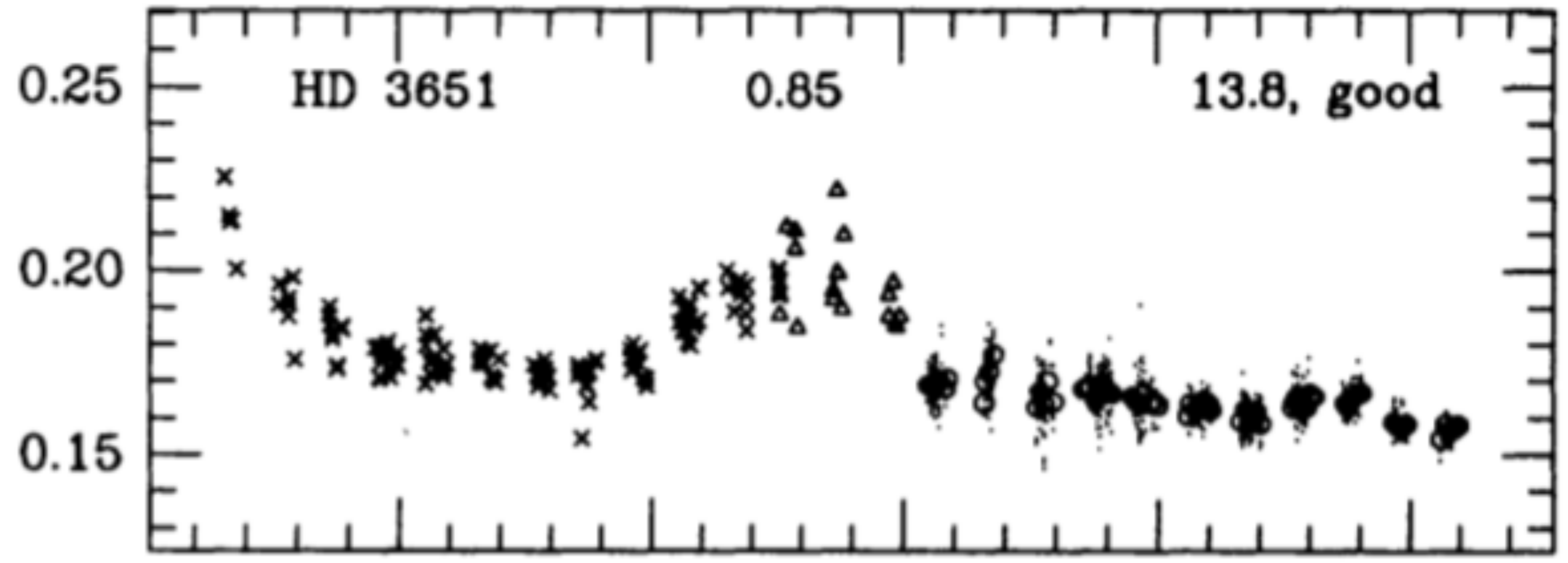
The only way to be sure?

HD 4915 (G5V)



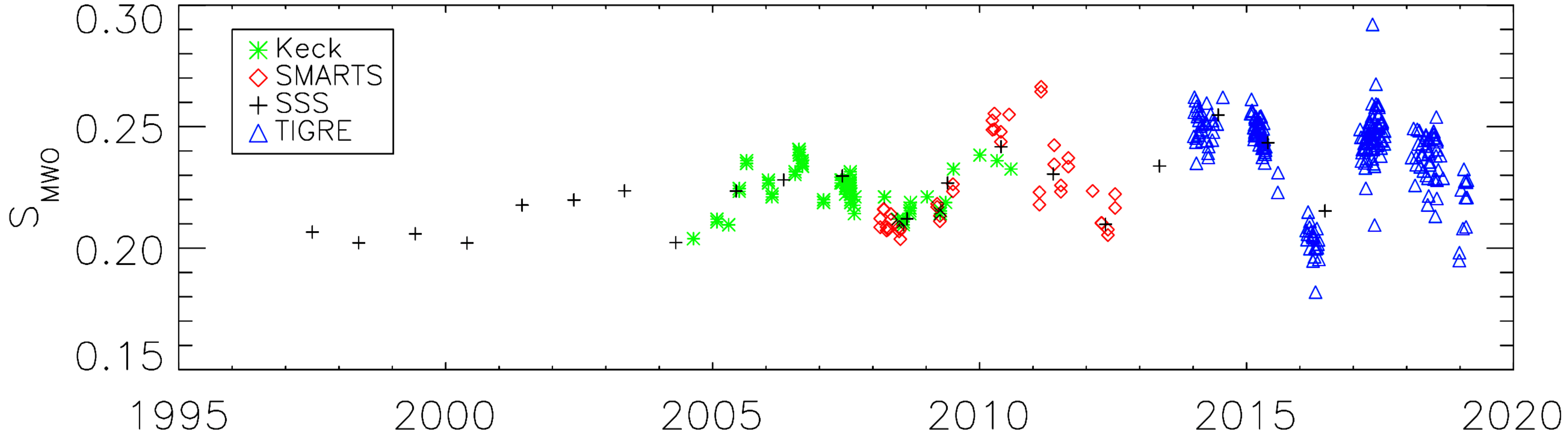
Shah et al. 2018

HD 3651 (K0V)



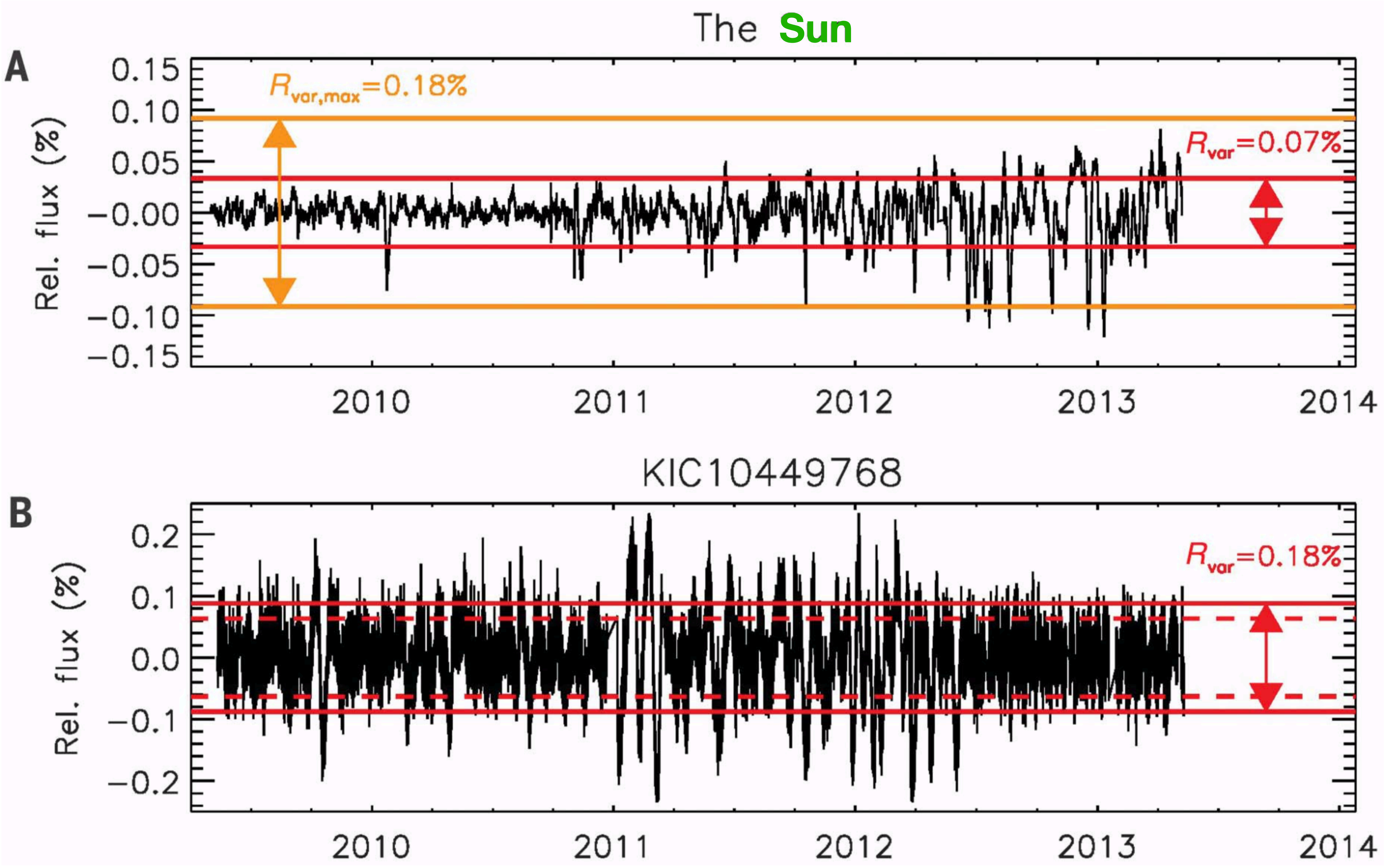
Baliunas et al. 1995; Judge & Saar 2007

HD 140538 (G2V)



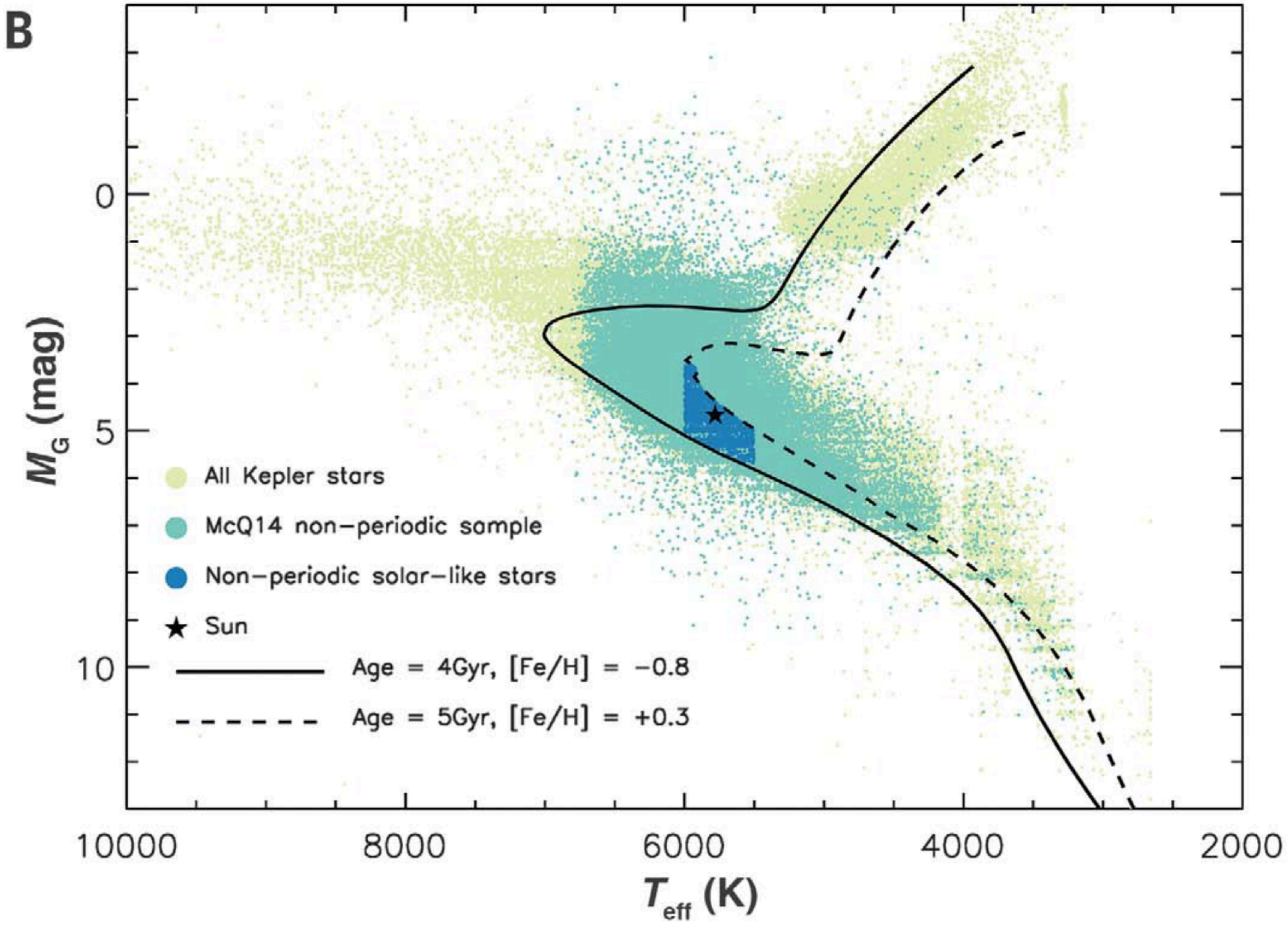
Mittag et al. 2019, A&A

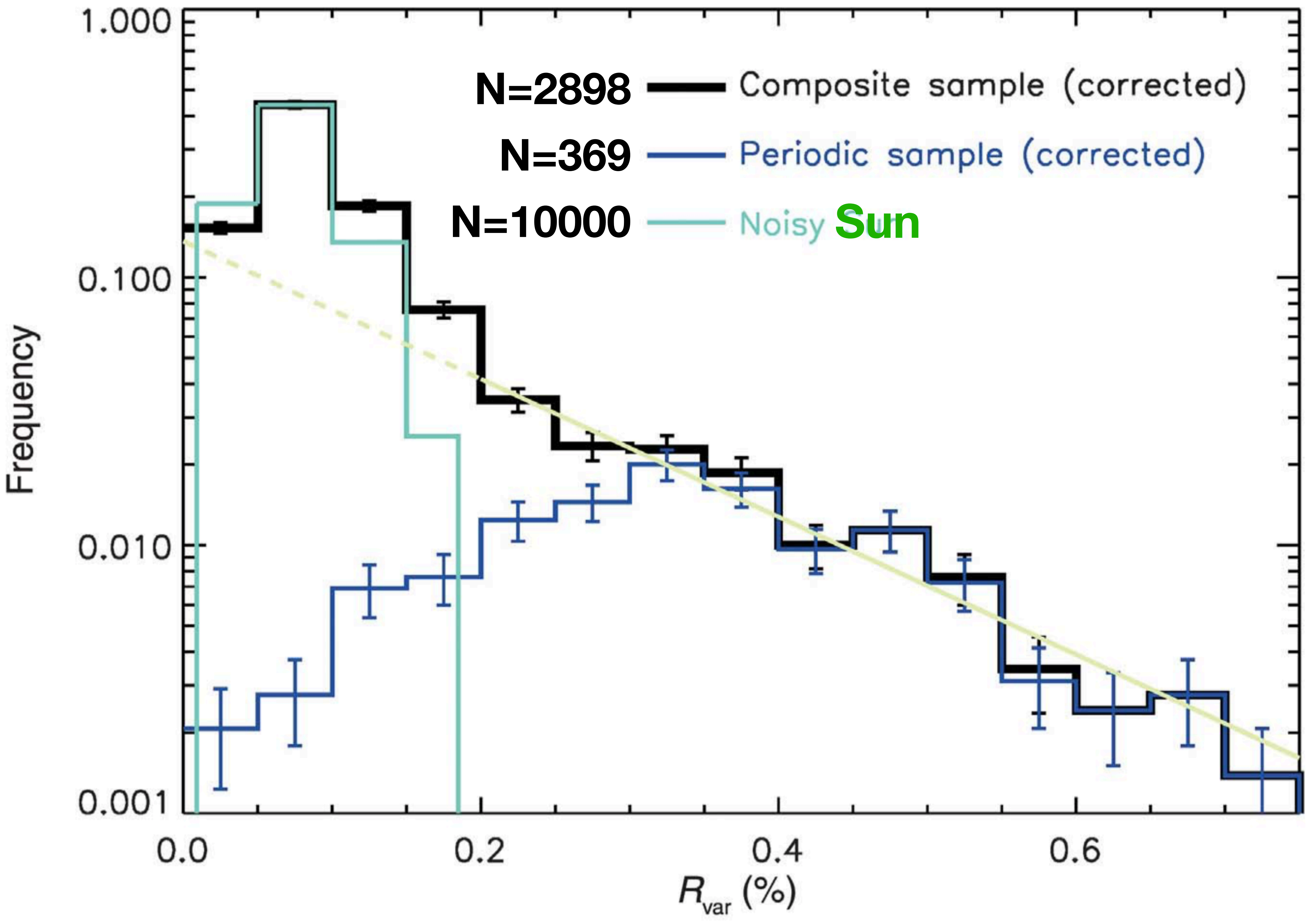
The Sun: On the way out, or ready for a comeback?



(Reinhold et al. 2020, *Science*)

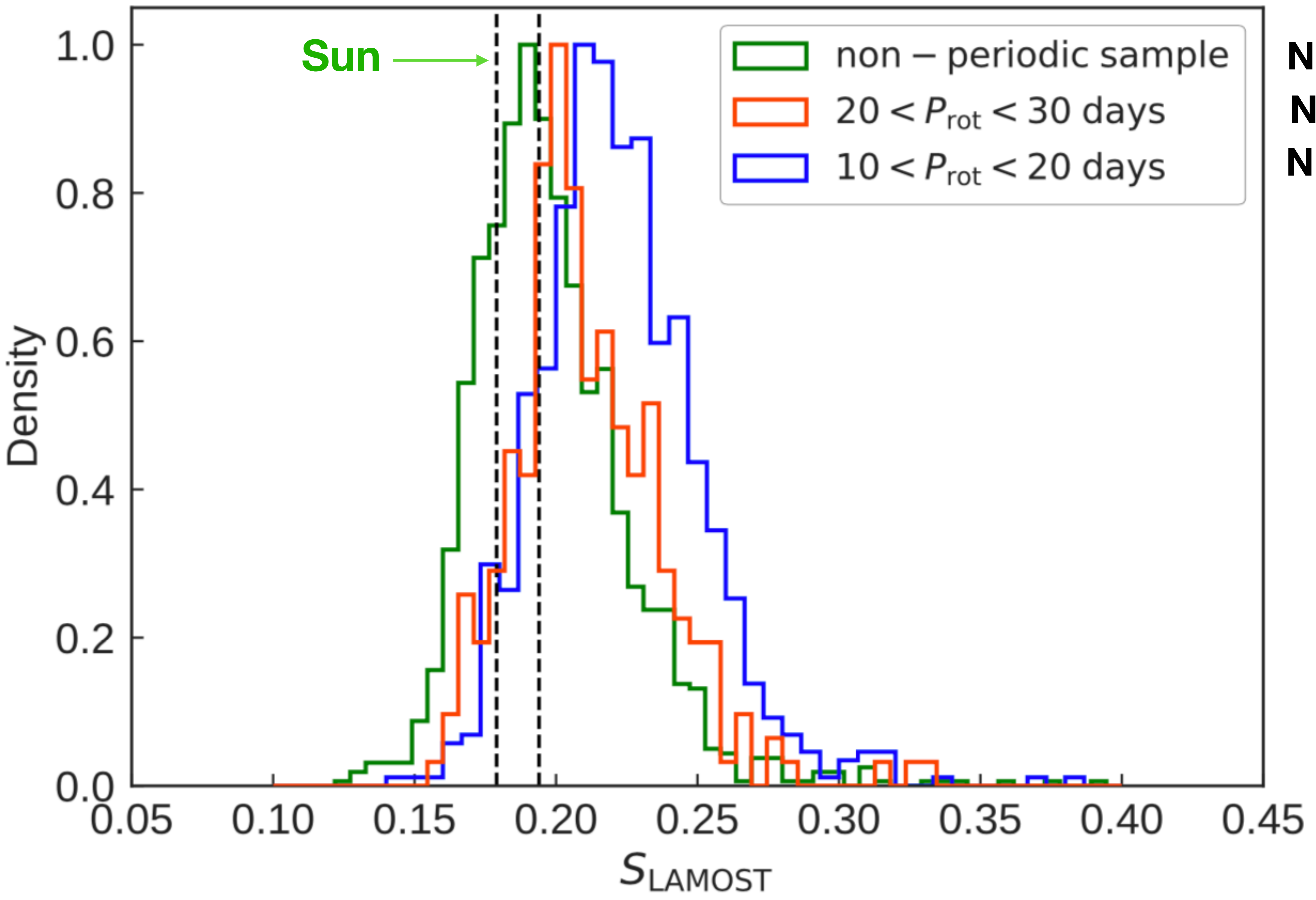
The Sun: On the way out, or ready for a comeback?





(Reinhold et al. 2020, *Science*)

The Sun: On the way out, or ready for a comeback?



N=1556
N=254
N=793

(Zhang et al. 2020, *ApJL*)

Conclusions

- Stellar observations of rotation and activity inform us about the operation of the dynamo under different conditions and give us a proxy to understand the magnetic history and future of our Sun.

- Multiple observations support the idea that angular momentum evolution stops mid-main-sequence, but this picture is still contentious. It is unclear on what timescale such a magnetic transition might take place.

- Multiple observations support the idea that the Sun is near the minimum activity attainable for a star of its mass. The location of the absolute minimum and the frequency/nature of transitions between low/high activity states is unclear.