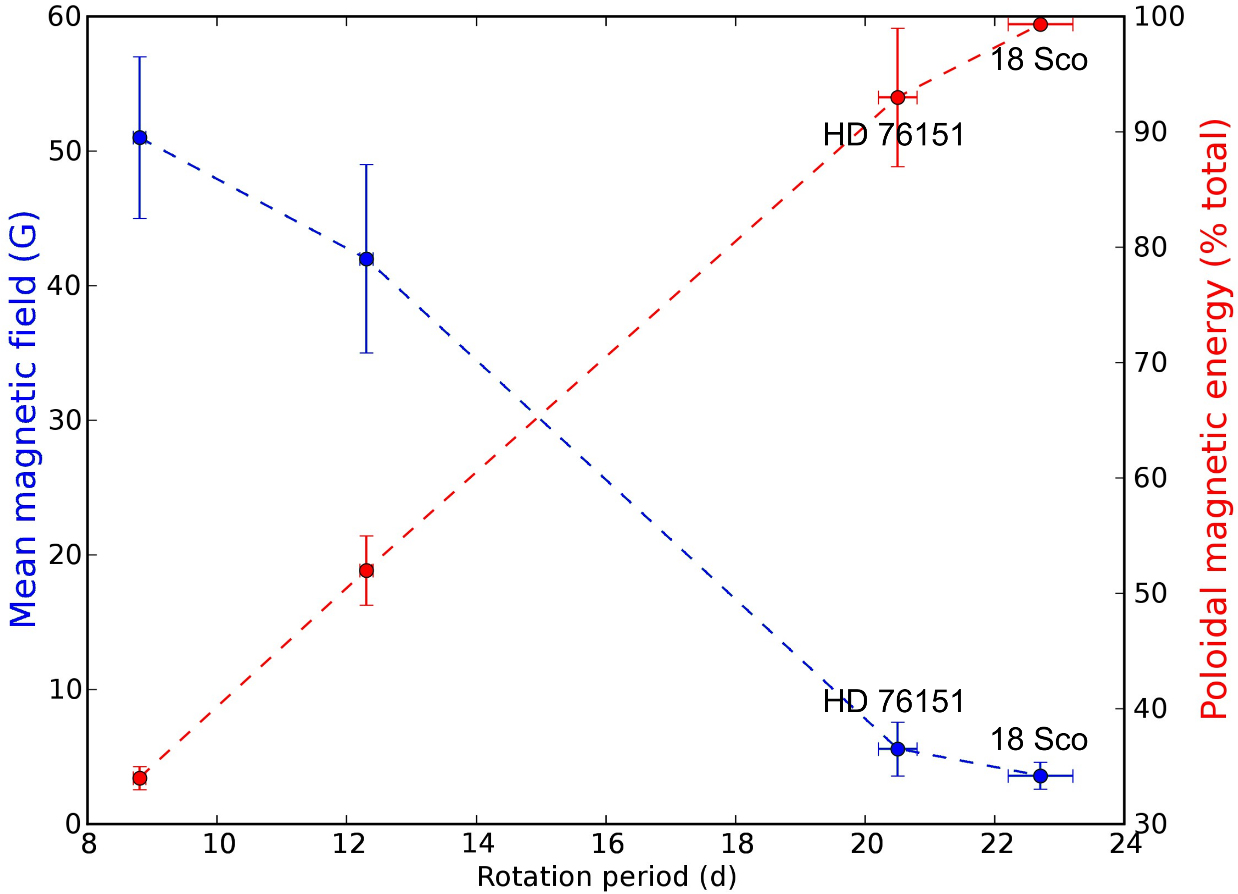
Constraints on the Magnetic Morphology of Old Sun-like Stars

Travis Metcalfe

White Dwarf Research Corp.

Collaborators: Jennifer van Saders (U.Hawaii), Ricky Egeland (NASA), & many others

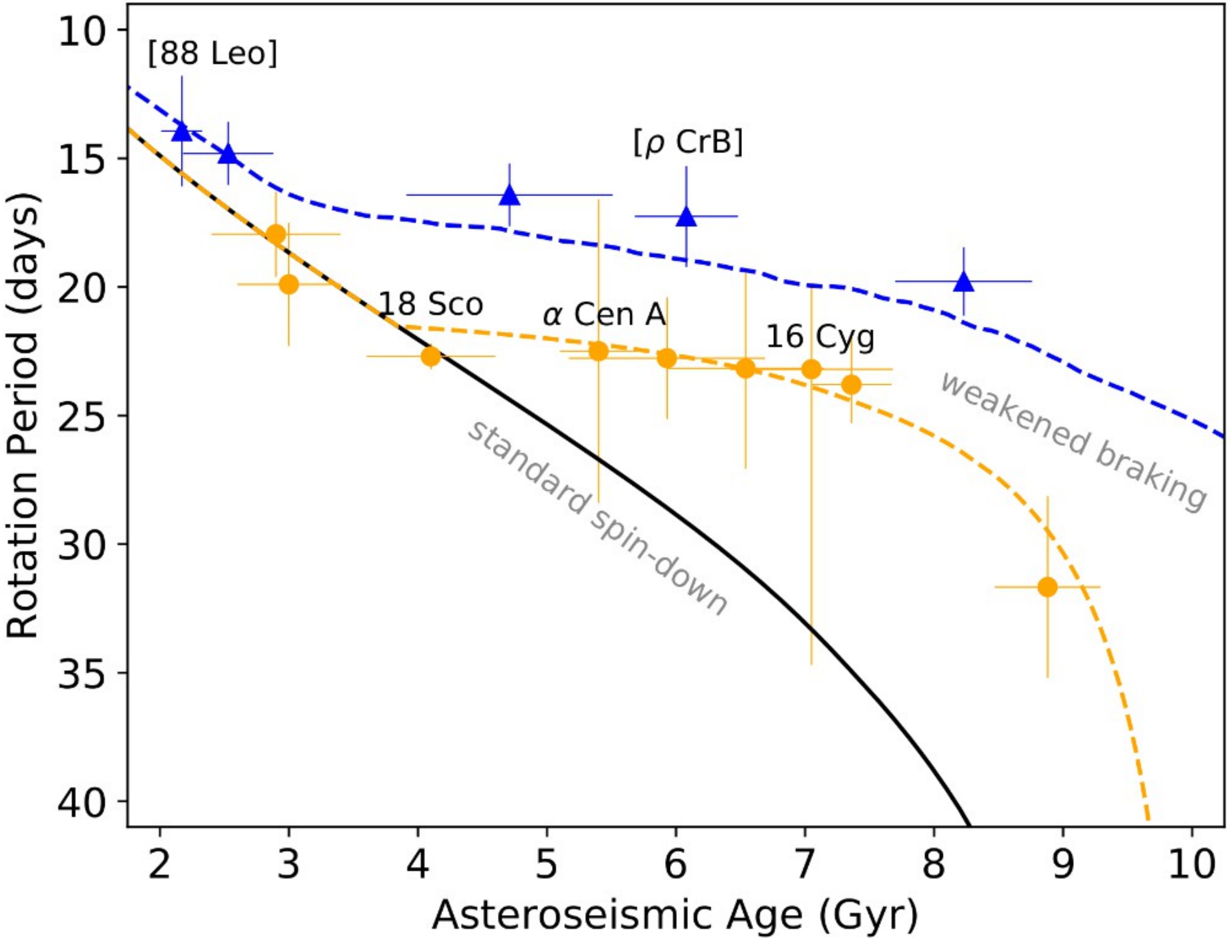
Magnetic evolution of solar analogs



- Sample of solar analogs mapped with Zeeman Doppler Imaging (ZDI)
- Mean magnetic field strength decreases as rotation rate slows
- Fraction of magnetic energy in the poloidal component increases

Petit+2008

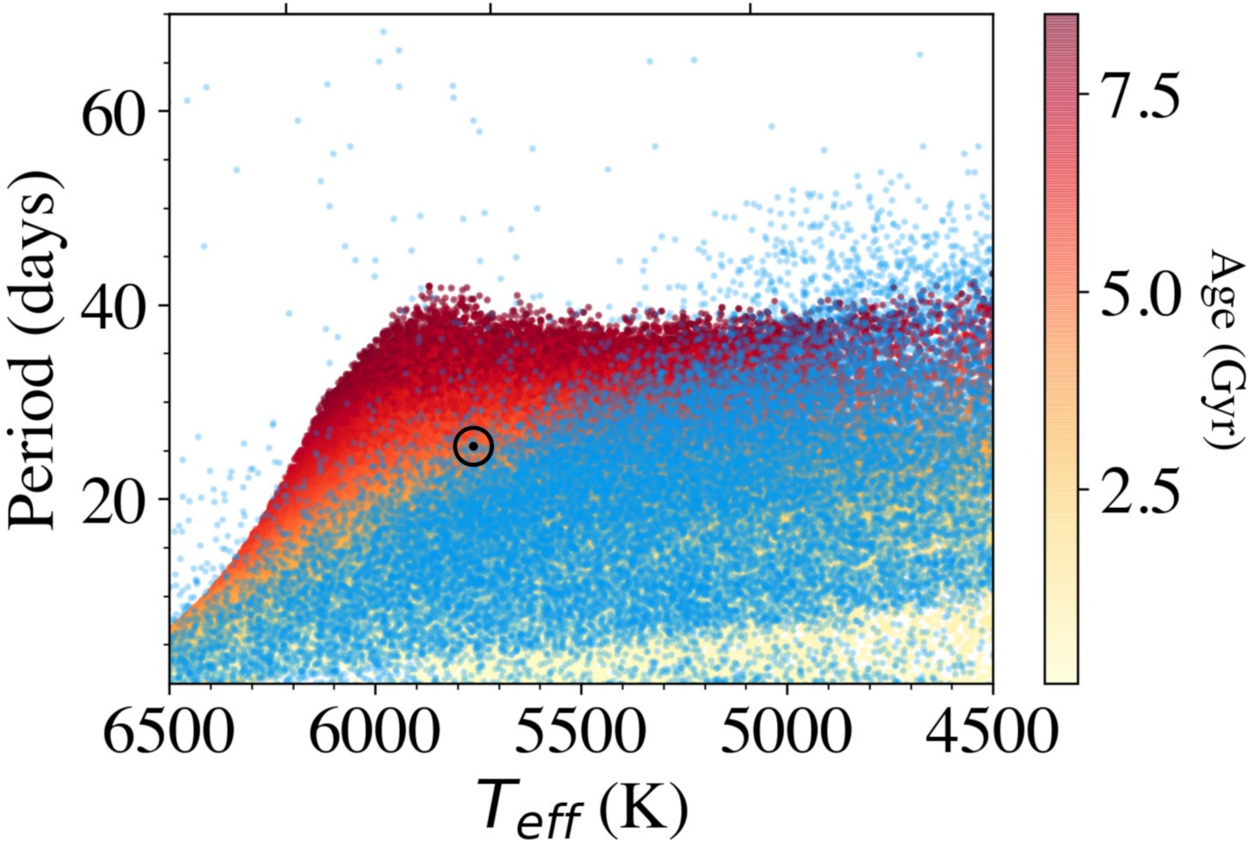
Weakened magnetic braking suspected



- Older Kepler field stars rotate more quickly than expected from theory
- Discrepancy appears at critical Rossby number, $Ro = (P_{rot} / \tau_c) \sim Ro_\odot$
- Models with weakened magnetic braking beyond $Ro_\odot$ reproduce the data

van Saders+2016

Weakened magnetic braking confirmed



- Distribution of rotation periods in the Kepler field shows long-period edge
- No detection bias: rotation from asteroseismology shows similar distribution
- Pile-up confirmed: sample with precise T_{eff} shows range of ages near edge

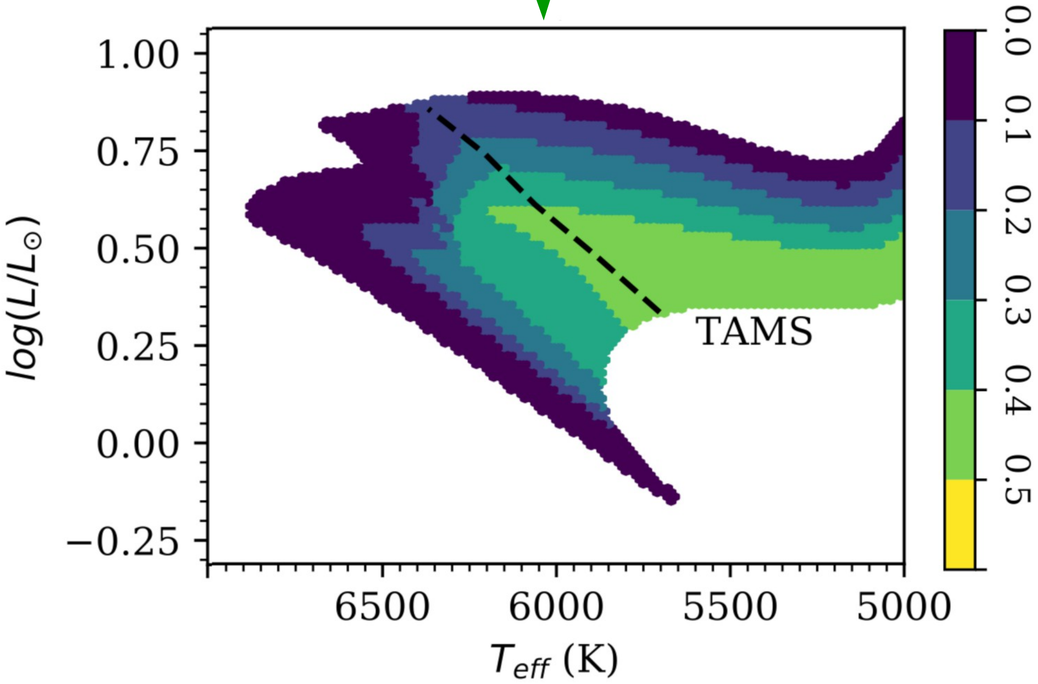
van Saders+2019, Hall+2021, David+2022

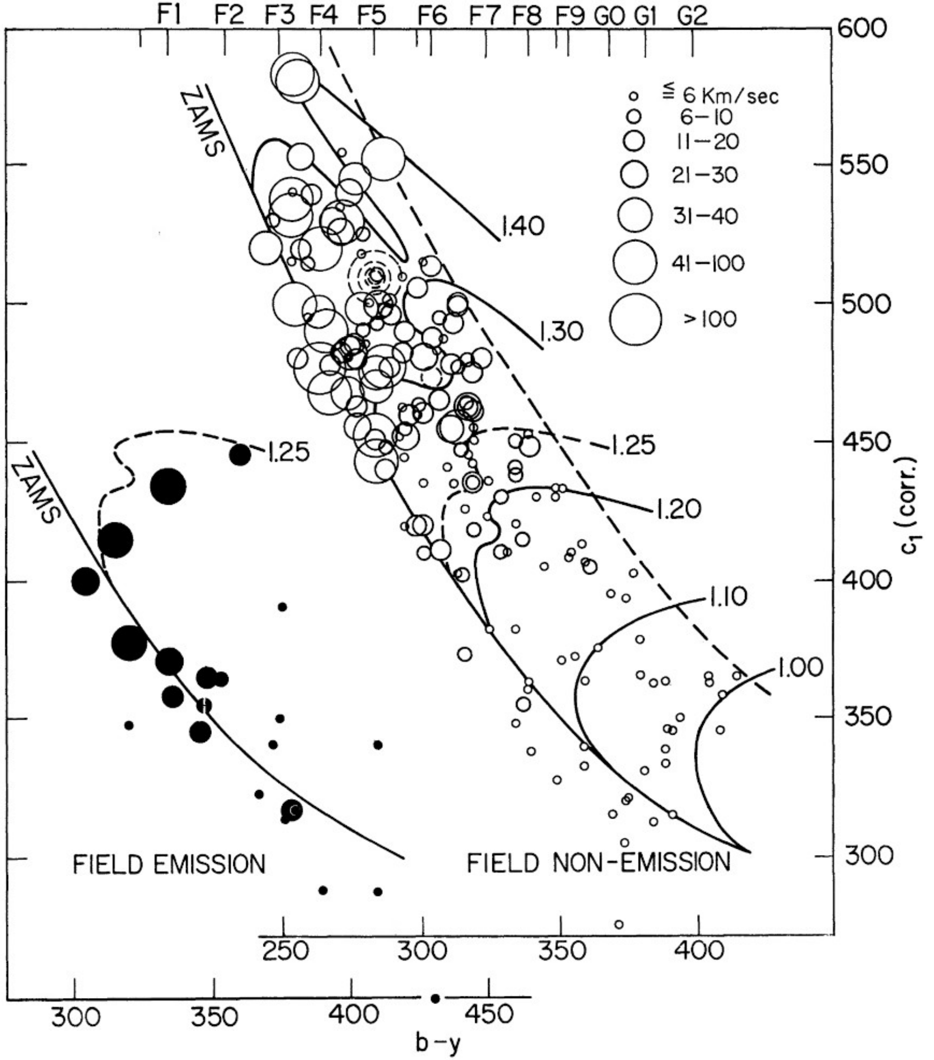
To sustain a magnetic dynamo, the Rossby number cannot be too large!

$$\mathrm{Ro} \equiv P_{rot} / \tau_c$$

too short

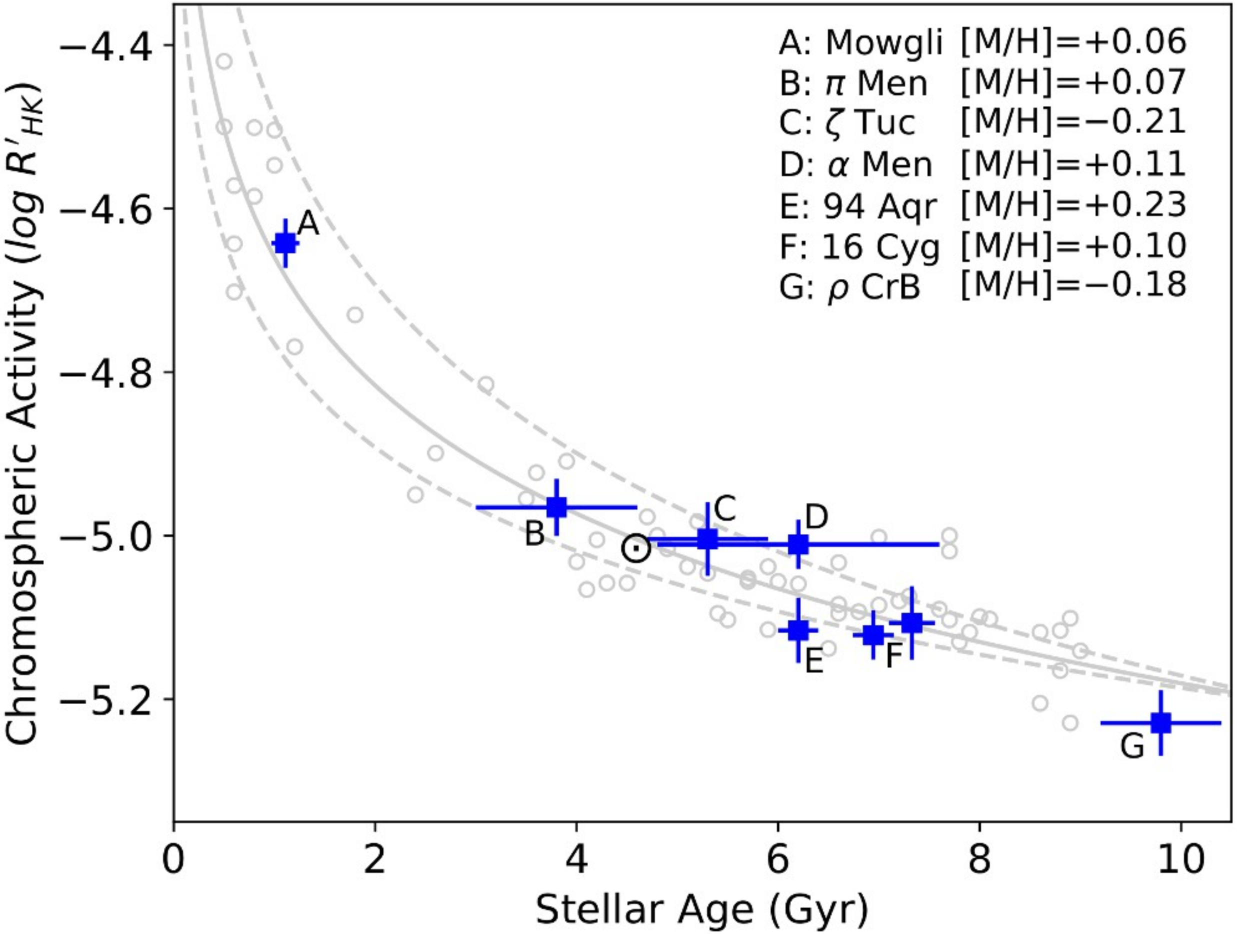
too long





Durney & Latour 1978, van Saders 2022, Kraft 1967

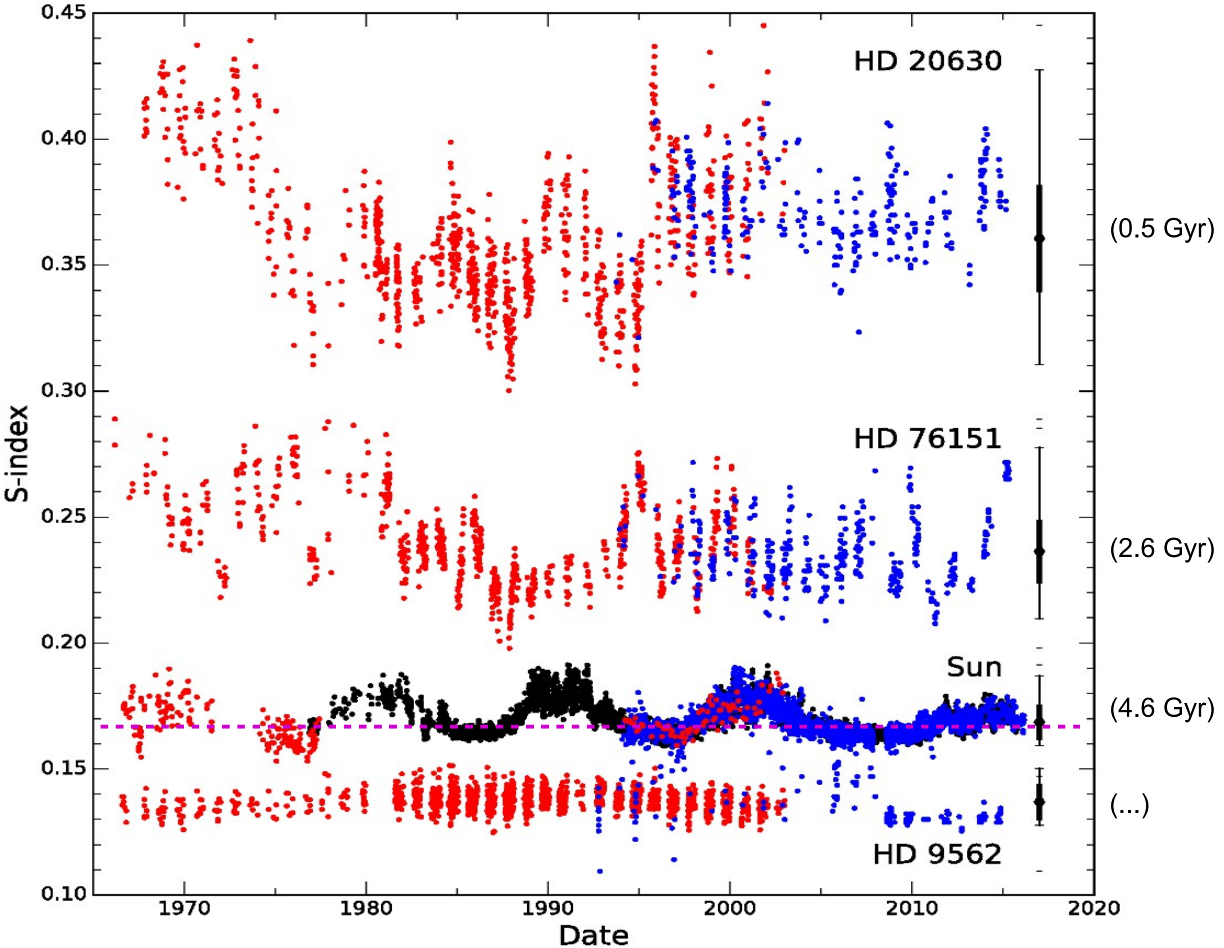
Activity level evolves continuously with age



- Activity of solar analogs and asteroseismic targets decline continuously
- Solar dipole field is ~1 G while unstructured quiet Sun has ⟨B⟩ ~170 G
- Disruption of large-scale organization is irrelevant to integrated activity level

Huber+2022

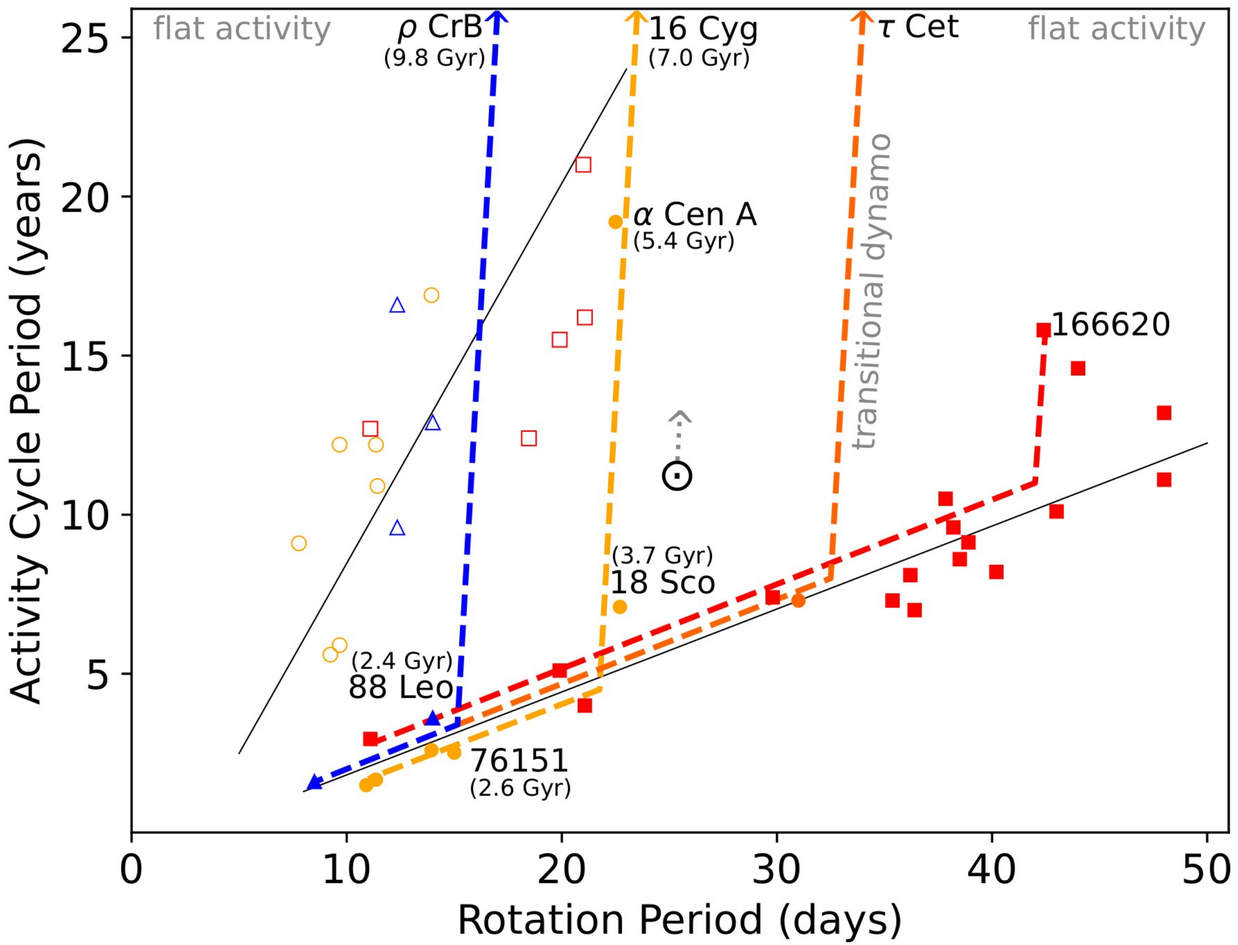
Variability is Sun-like before disappearing



- Variability in young solar analogs is multi-periodic, often appears irregular
- Sun-like cycles appear at high Rossby number, evolving to “flat activity”
- Grand minima could be intermittency as activity evolves across threshold

Egeland+2017, Tripathi+2021, Kitchatinov 2022

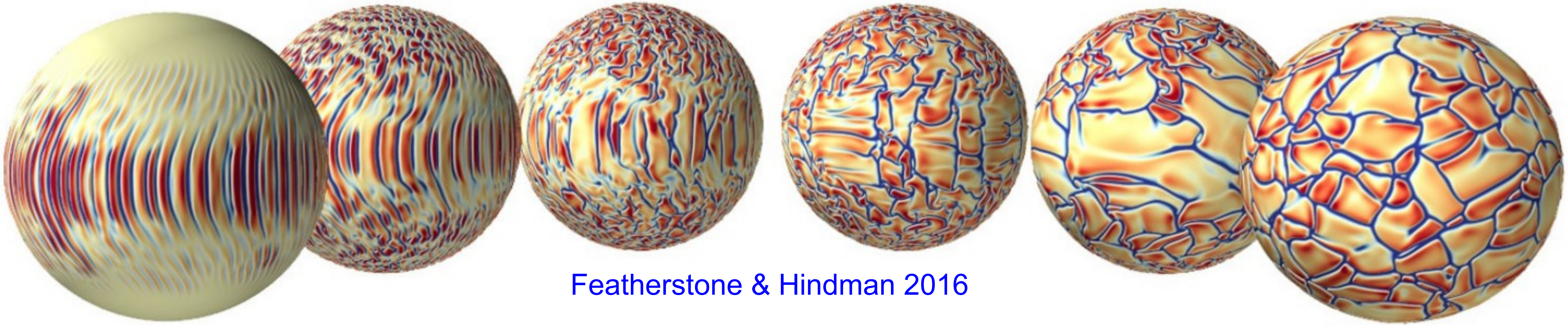
Cycles grow longer and weaker in old stars



- Stalled rotation coincides with longer activity cycles and weaker variability
- Same pattern observed in hotter and cooler stars at same Rossby number
- Position of 166620 above the lower sequence is an outlier similar to the Sun

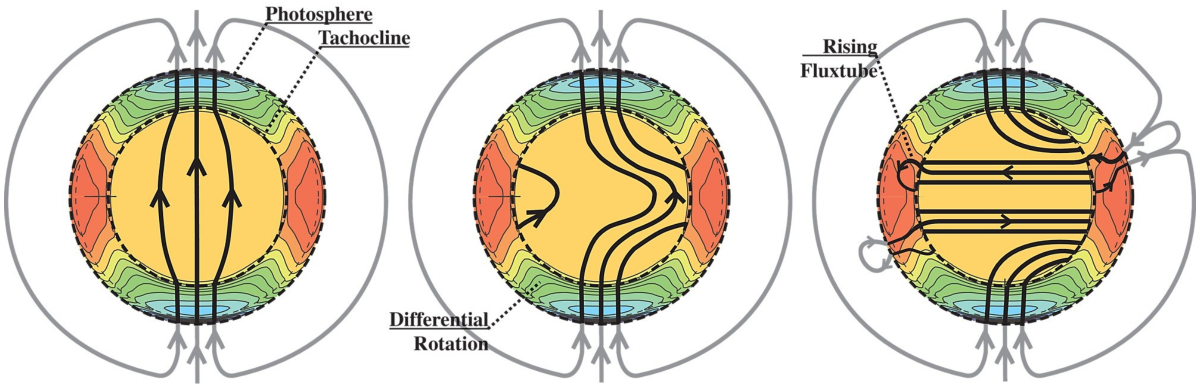
Metcalfe & van Saders 2017

1. slow rotation becomes non-differential



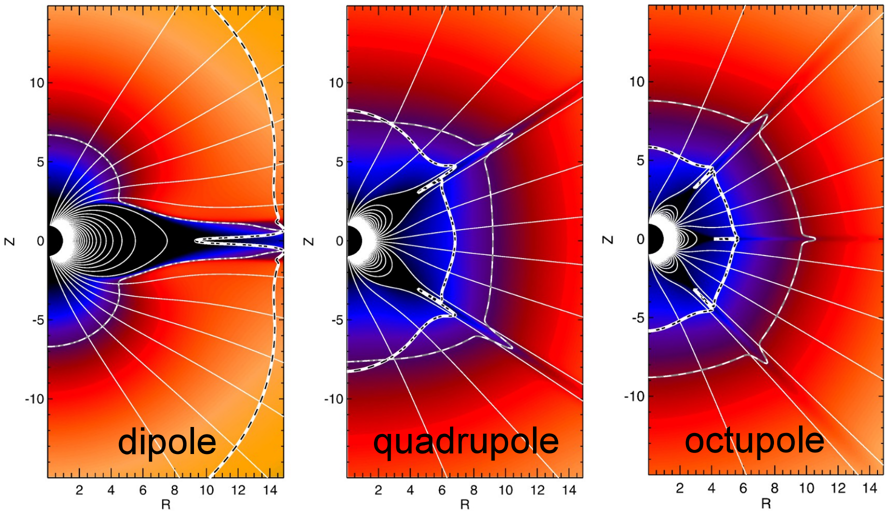
Featherstone & Hindman 2016

2. loss of shear disrupts field conversion



Ω effect (poloidal → toroidal field)

3. decaying dipole stalls braking

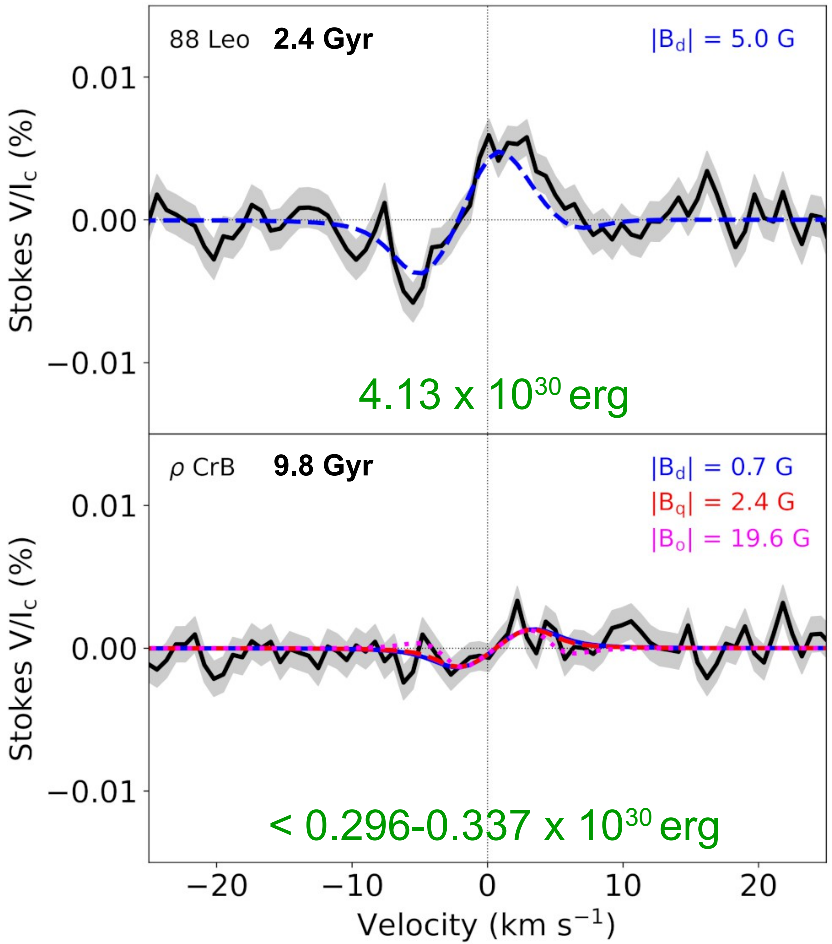


Higgins 2012

Reville+2015

Credit: NOAO

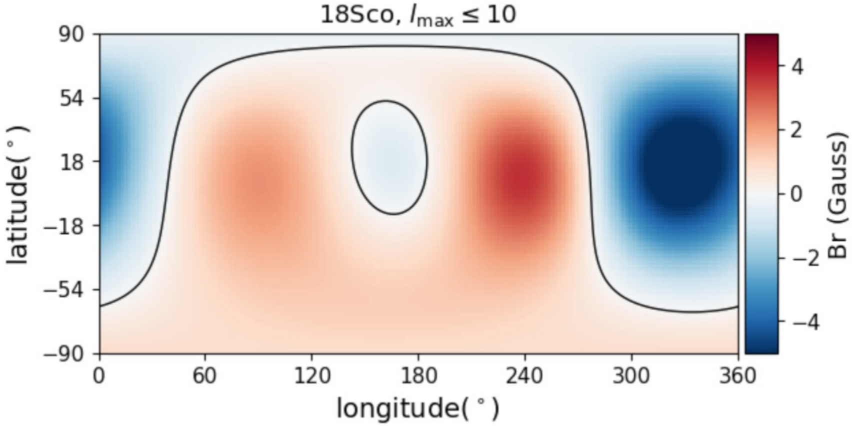
Evolutionary sequence: F-type stars



- 88 Leo: detection of large-scale field, modeled by dipole with B_d = 5.0 G
- ρ CrB: upper limits on field strength suggest a torque < 8% of 88 Leo
- Dominated by changes in field morphology, but ZDI needed for confirmation

Metcalfe+2019,2021

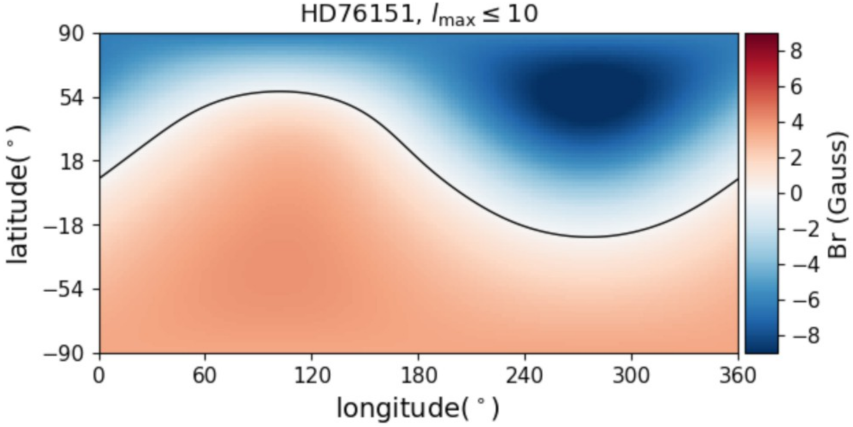
Evolutionary sequence: solar analogs



(3.7 Gyr)

B_d=1.34 G
B_q=2.01 G
B_o=0.86 G

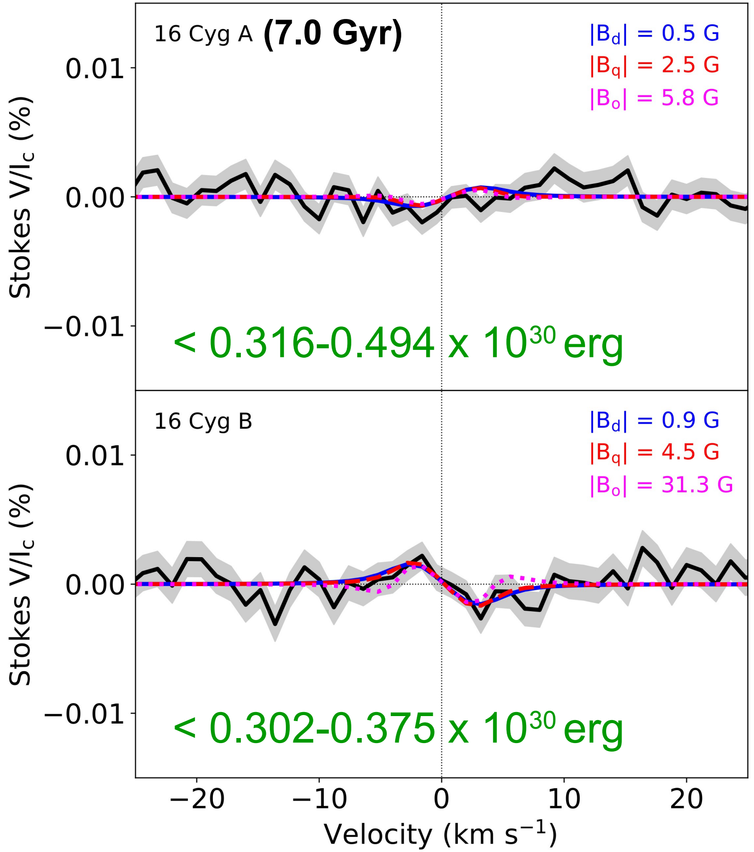
0.373 x 10^{30} erg



(2.6 Gyr)

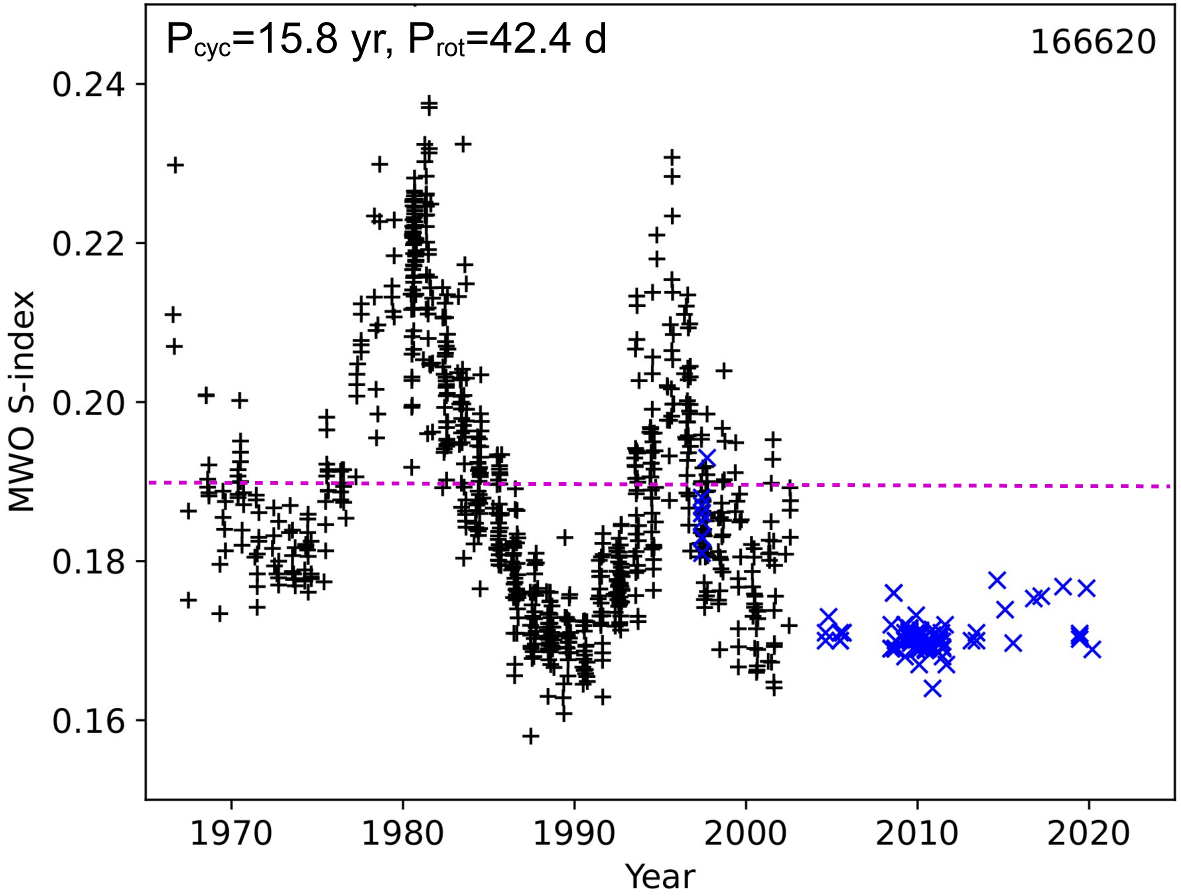
B_d=5.13 G
B_q=2.88 G
B_o=1.34 G

4.77 x 10^{30} erg



Petit+2008, Boro Saikia+2020, Metcalfe+2022

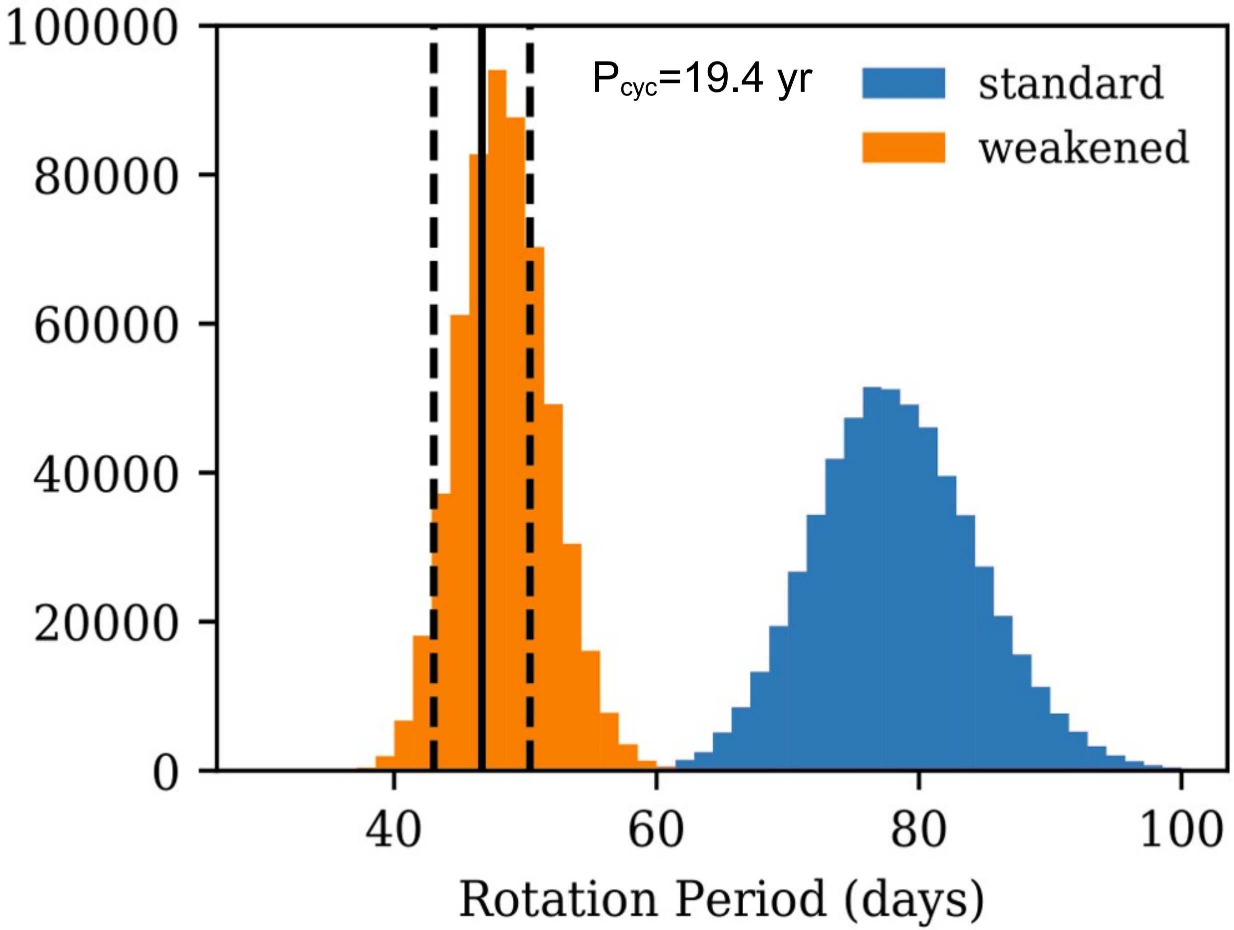
HD 166620: grand minimum



- Showed a clear Sun-like activity cycle during the Mount Wilson survey
- Keck data are consistent in the late-90s, constant activity level after 2003
- Critical Rossby number corresponds to the mean activity level during cycles

Baum+2022, Luhn+2022

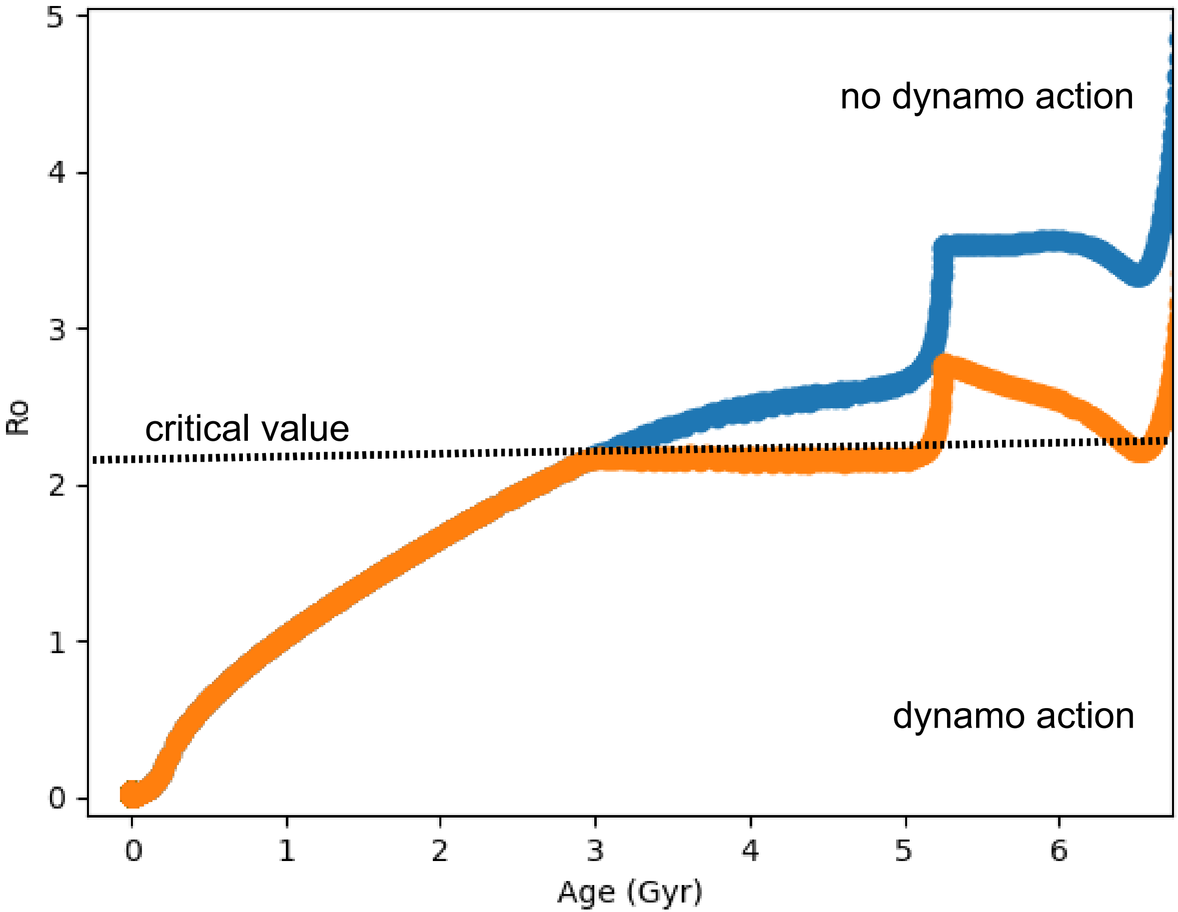
94 Aqr Aa: history of WMB



- Given stellar properties of subgiant, predict current rotation period (47 ± 4 d)
- Stalled magnetic braking beyond stellar middle-age yields: P_{rot} = 48 ± 4 days
- Standard spin-down for complete main-sequence yields: P_{rot} = 78 ± 7 days

Metcalfe+2020

94 Aqr Aa: born-again dynamo



- Subgiant mass suggests that it was an F-type star on the main-sequence
- After losing any original cycle, rotation slowed as it expanded and cooled
- Convection zone became deeper, longer timescale reinvigorated the dynamo

Metcalfe+2020

Summary of conclusions

- At a critical Rossby number comparable to the solar value, magnetic field loses large-scale organization
- At constant rotation period, the magnetic cycle grows longer and weaker on stellar evolutionary timescales
- As stars evolve below a critical activity level, cycles can become intermittent – producing grand minima
- Subgiant rotation slows further and cycles disappear, but then CZ deepens and reinvigorates the dynamo