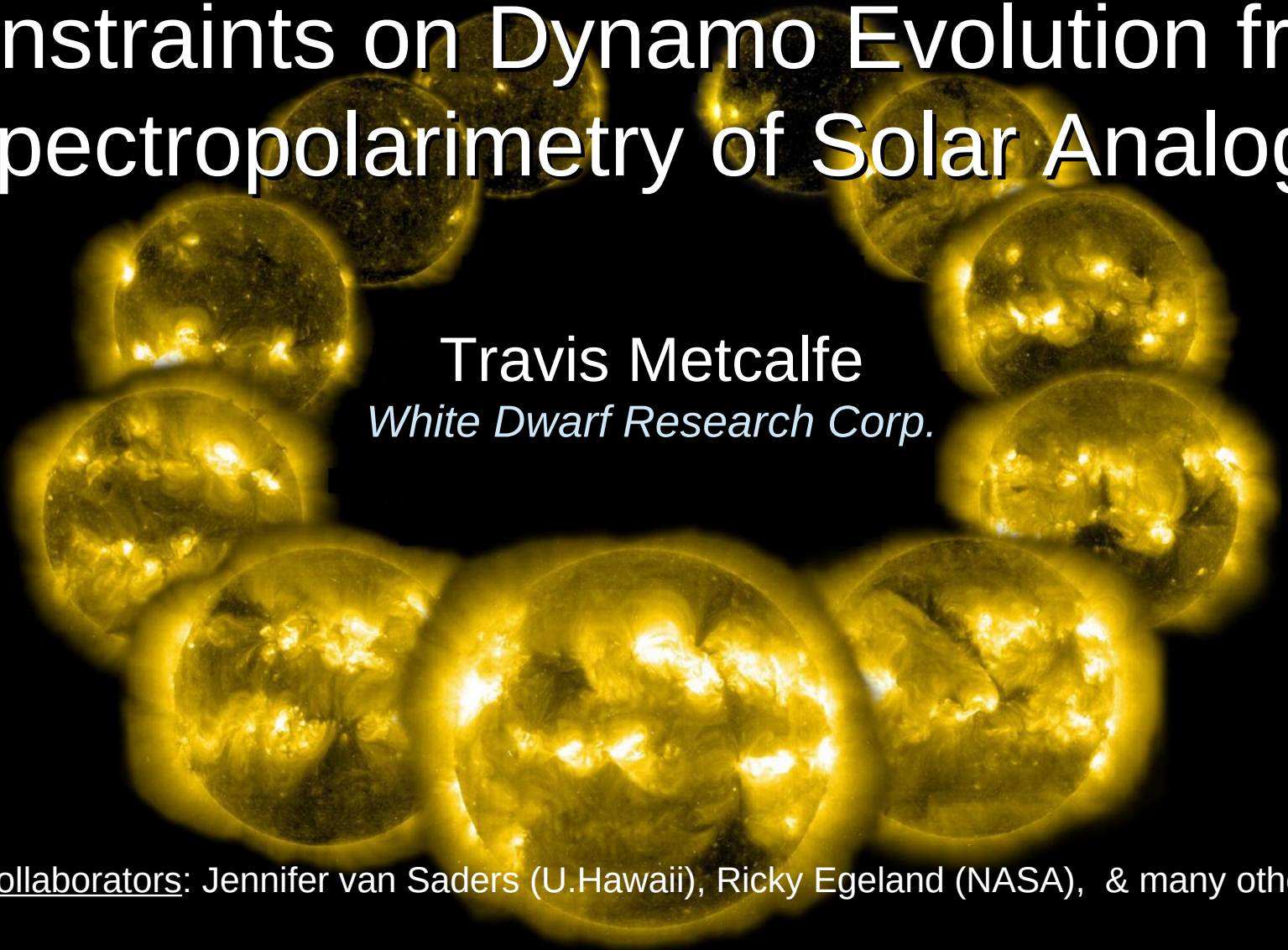
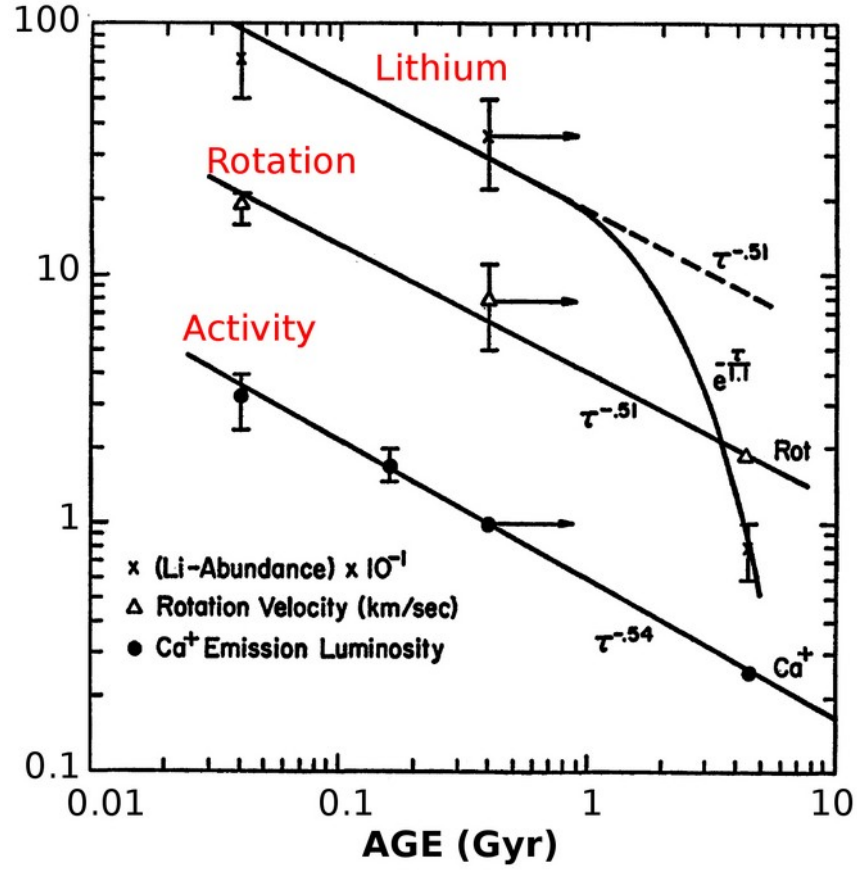
Constraints on Dynamo Evolution from Spectropolarimetry of Solar Analogs

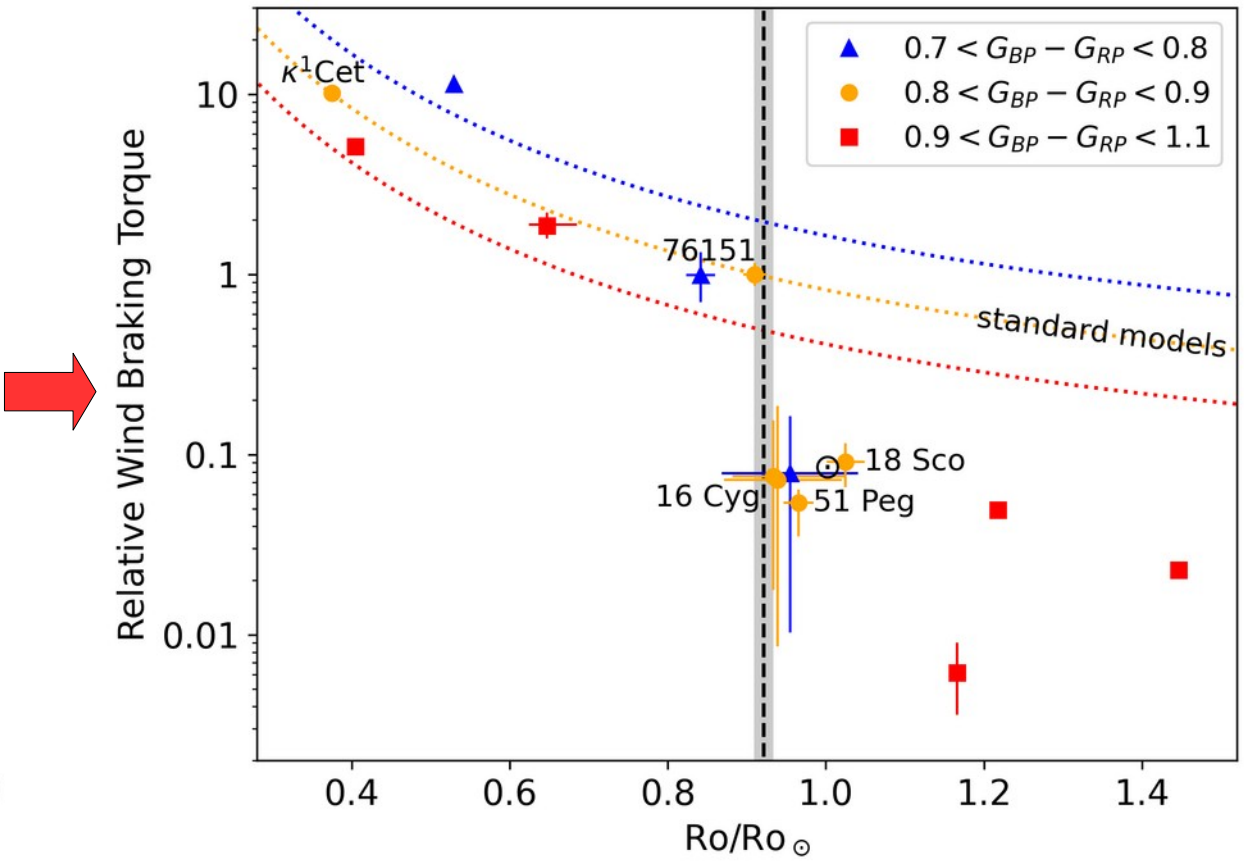


Travis Metcalfe
White Dwarf Research Corp.

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

A paradigm shift for magnetic evolution

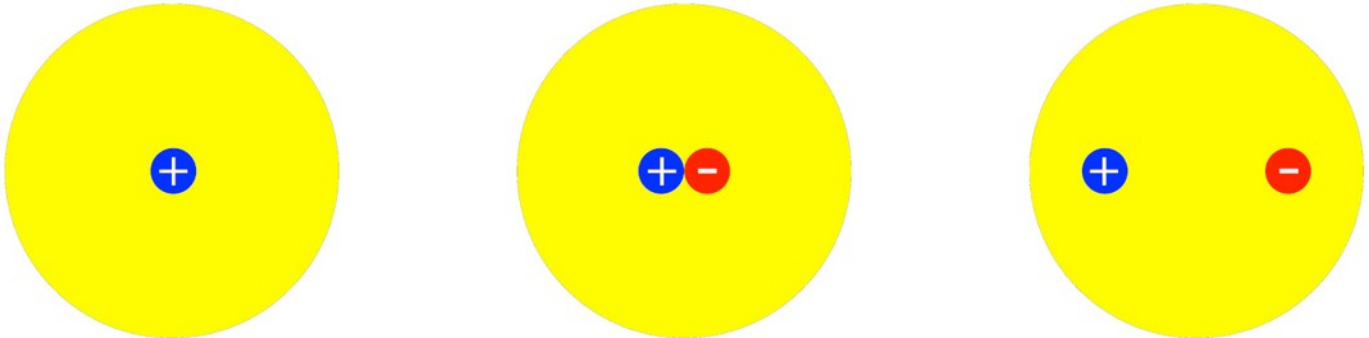




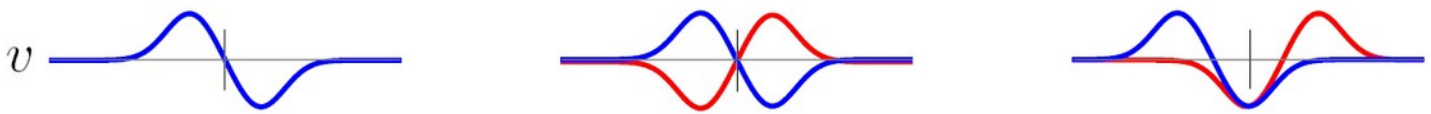
Skumanich 1972

Metcalfe+2023

Geometry

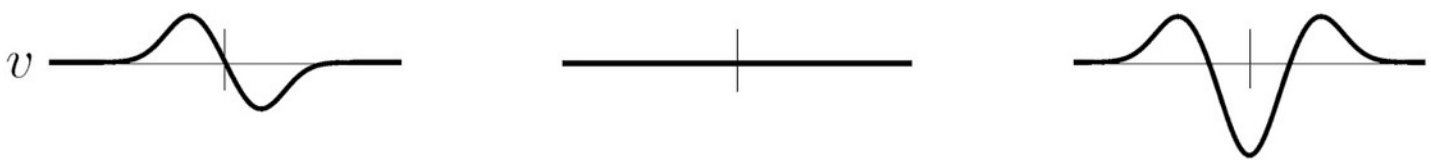


Stokes V signal (components)



Signals doppler shifted due to rotation

Stokes V signal (net)



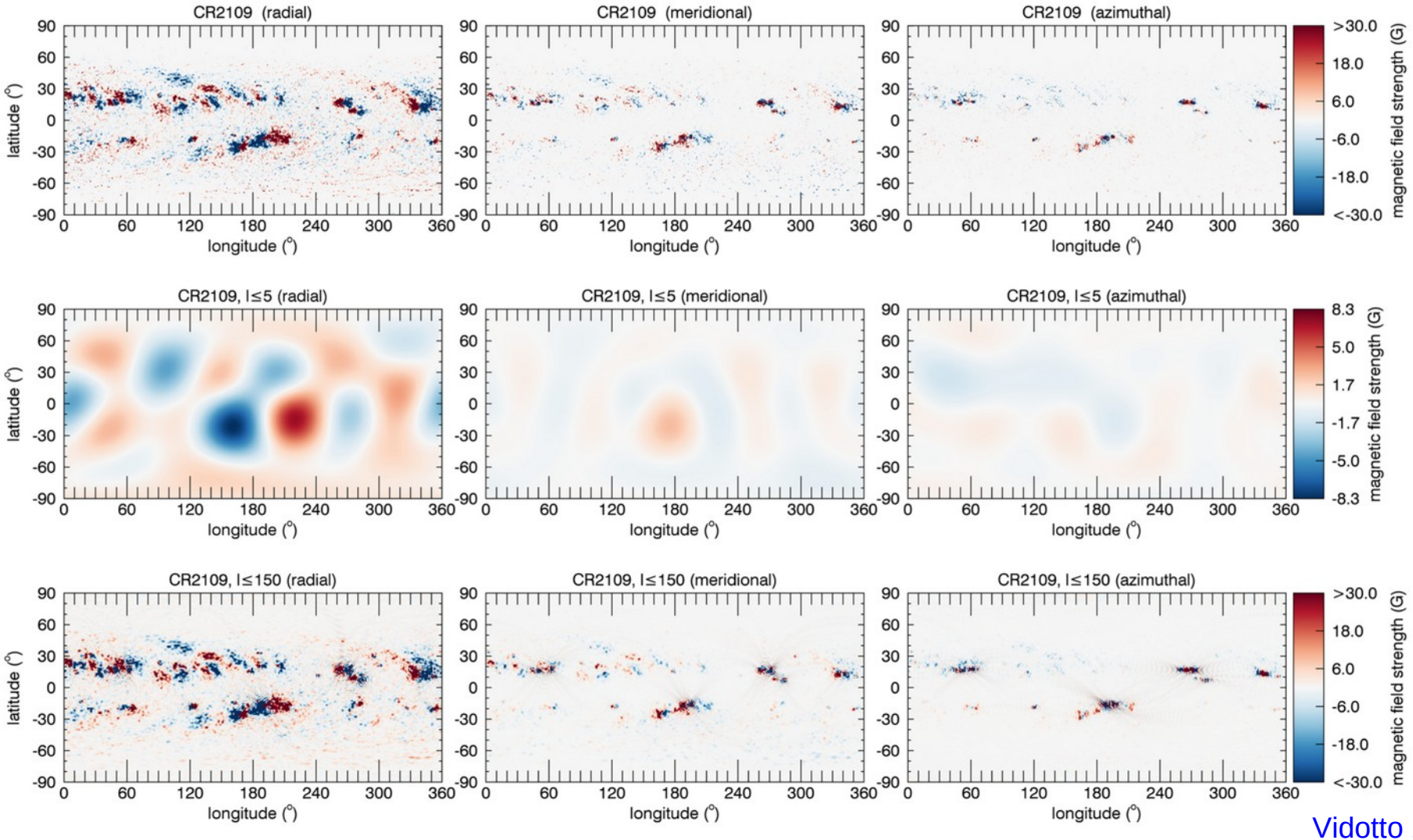
slide: Victor See

radial meridional (N-S) azimuthal (E-W)

obs

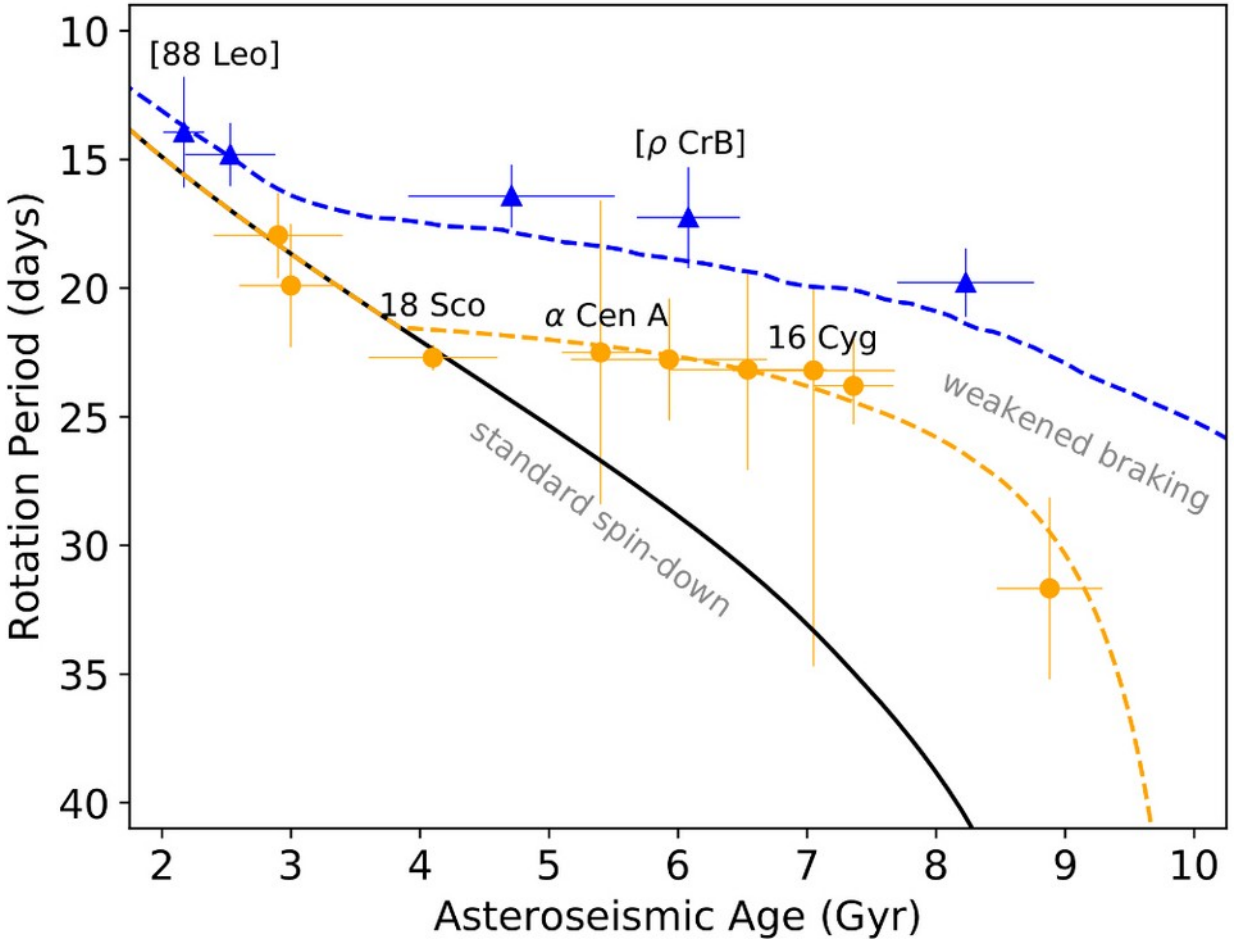
ℓ<5

ℓ<150



Vidotto 2016

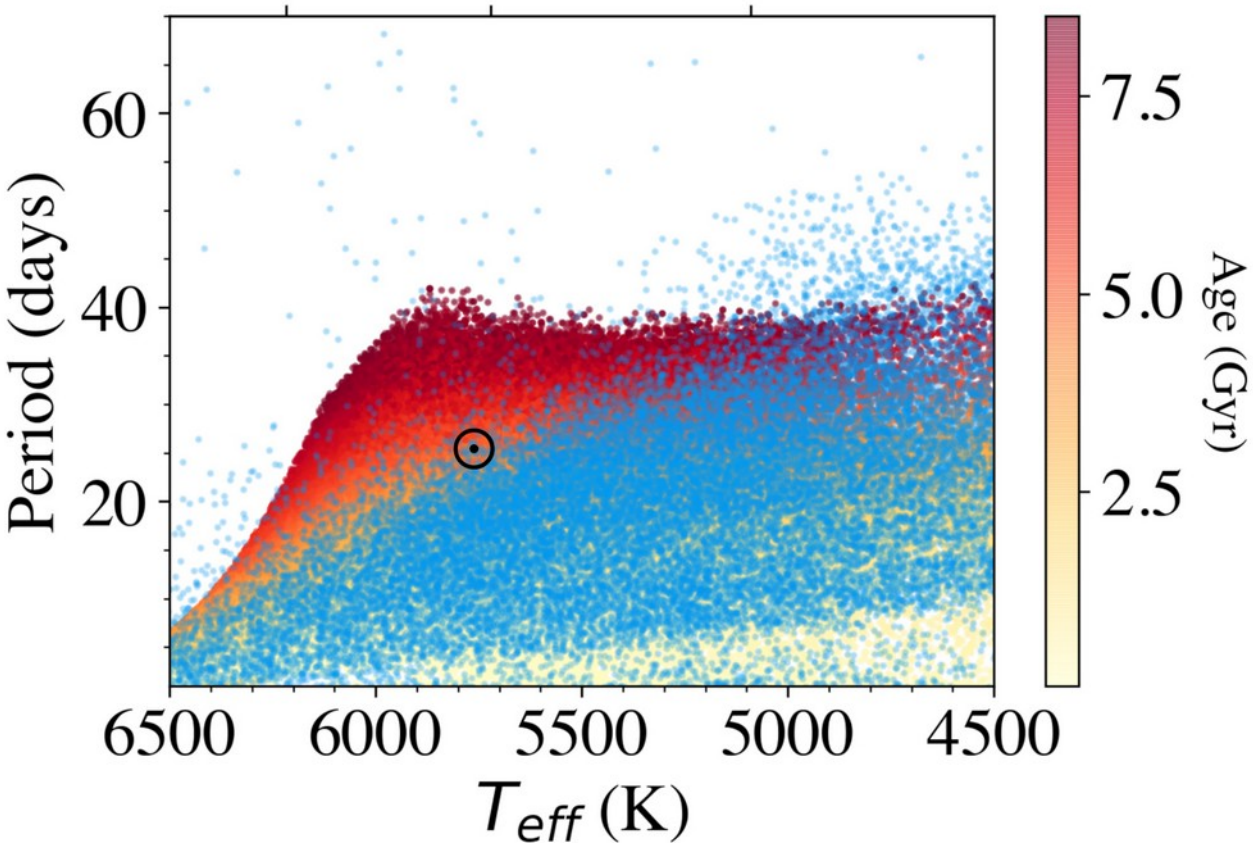
Weakened magnetic braking suspected



- 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

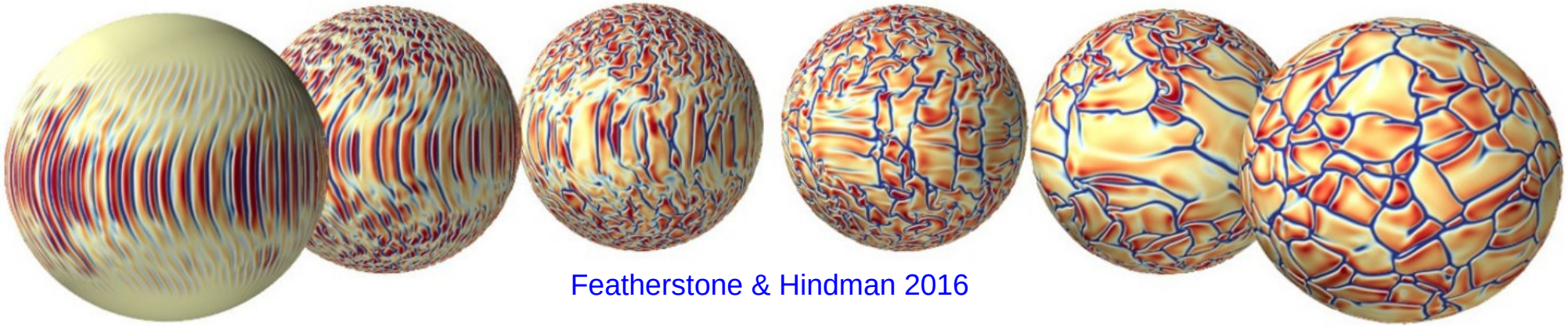
Weakened magnetic braking confirmed



- 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

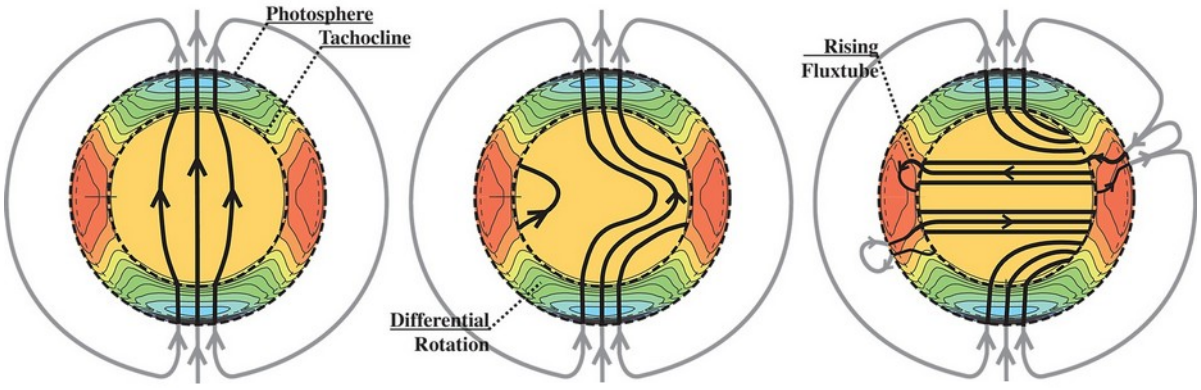
van Saders+2019, Hall+2021, David+2022

1. slow rotation becomes non-differential



Featherstone & Hindman 2016

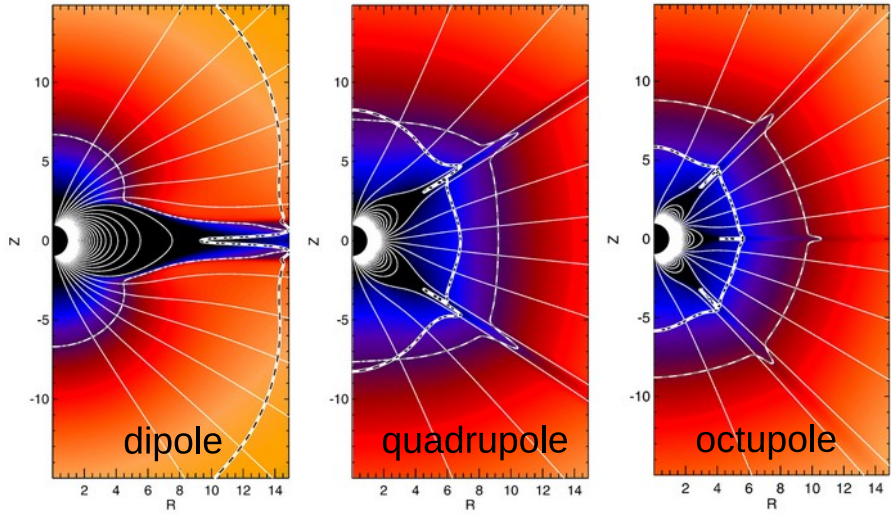
2. loss of shear disrupts field conversion



Ω effect (poloidal → toroidal field)

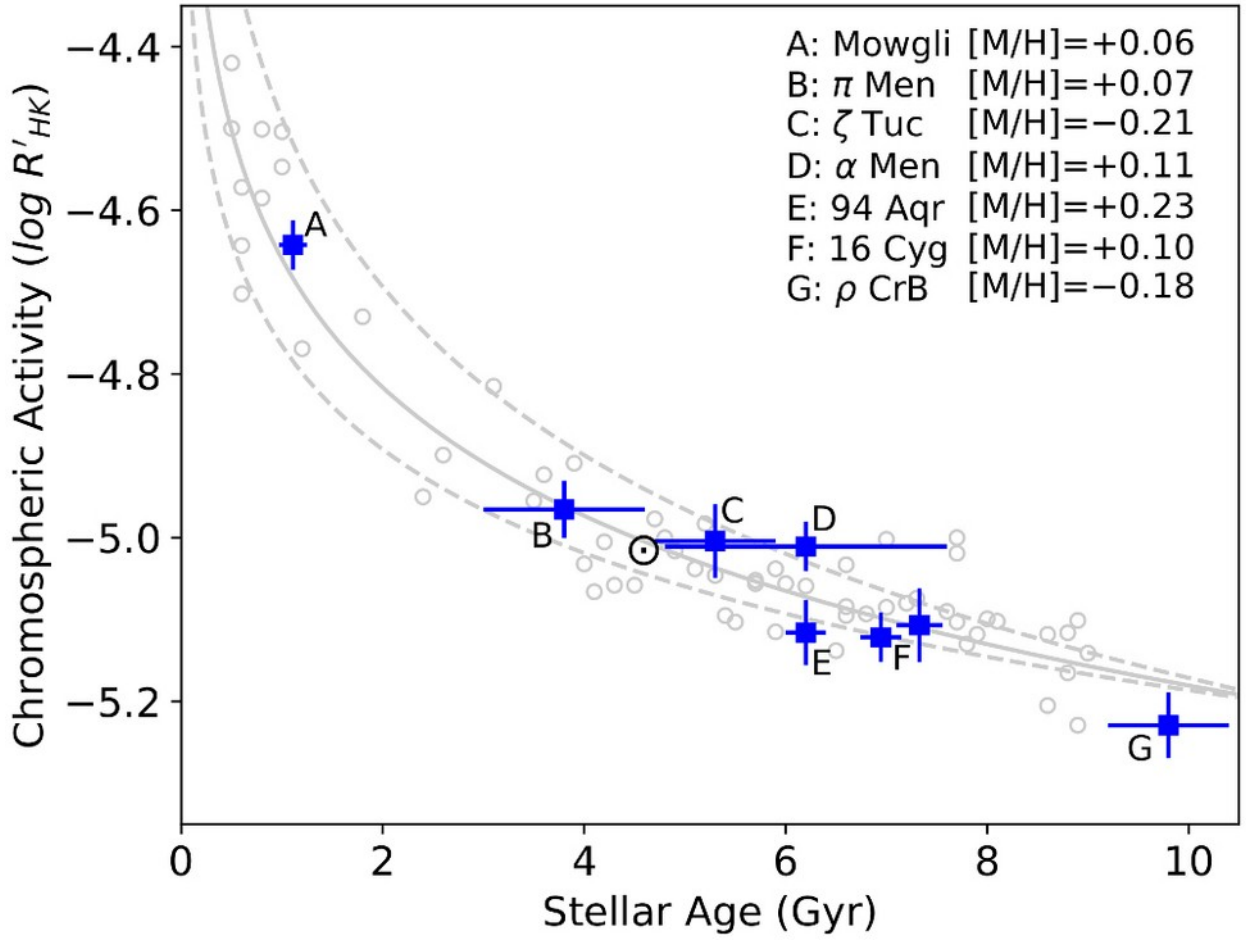
Higgins 2012

3. decaying dipole stalls braking



Reville+2015

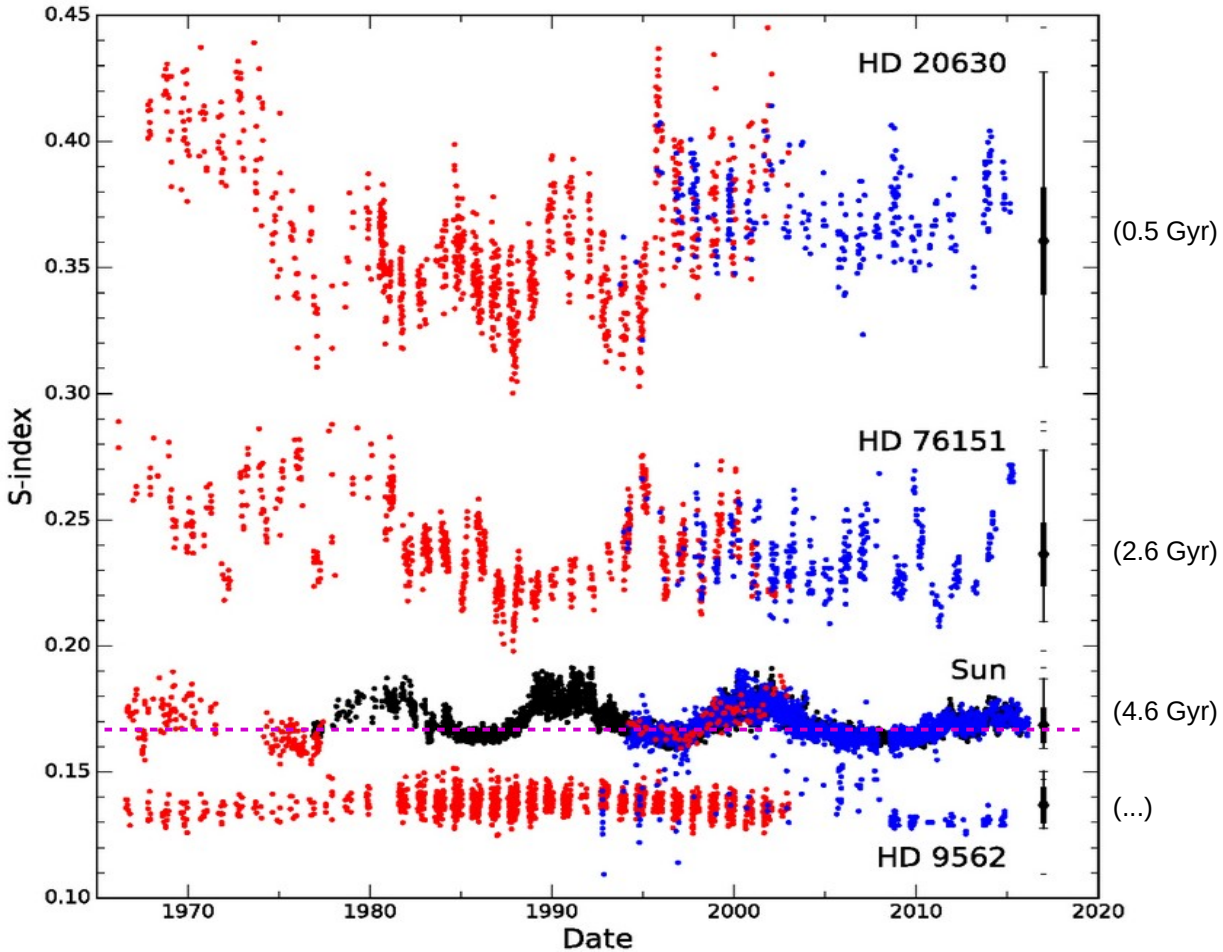
Activity level evolves continuously with age



- 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

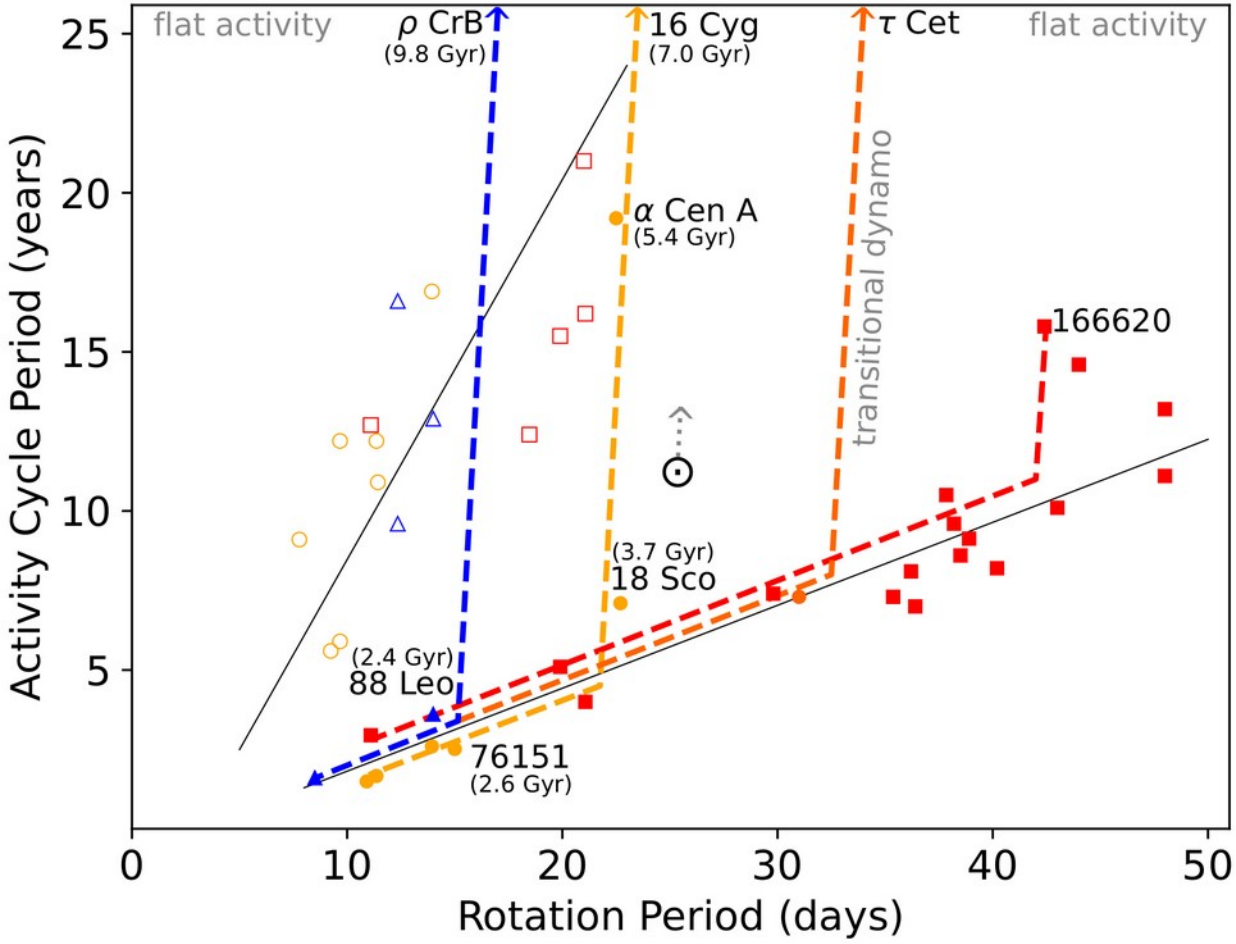
Variability is Sun-like before disappearing



- 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

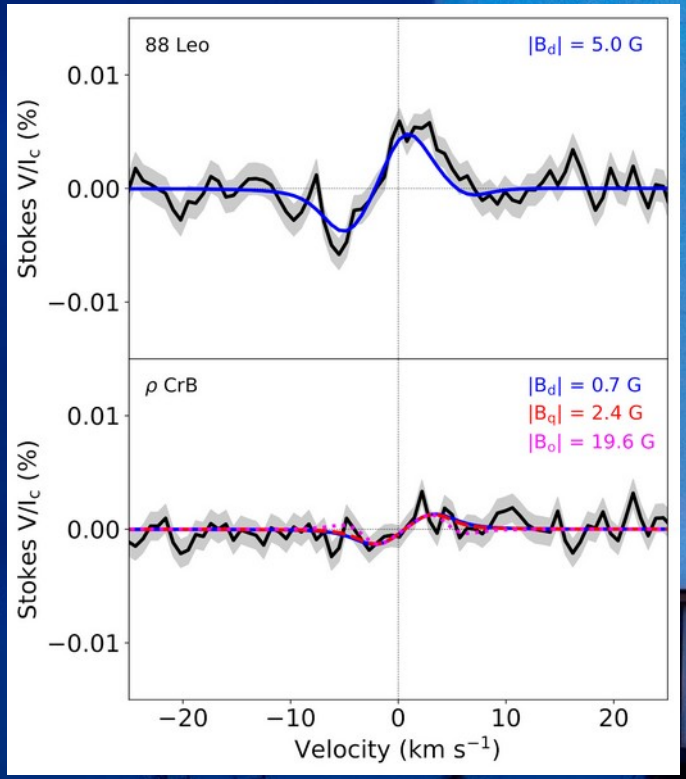
Cycles grow longer and weaker in old stars

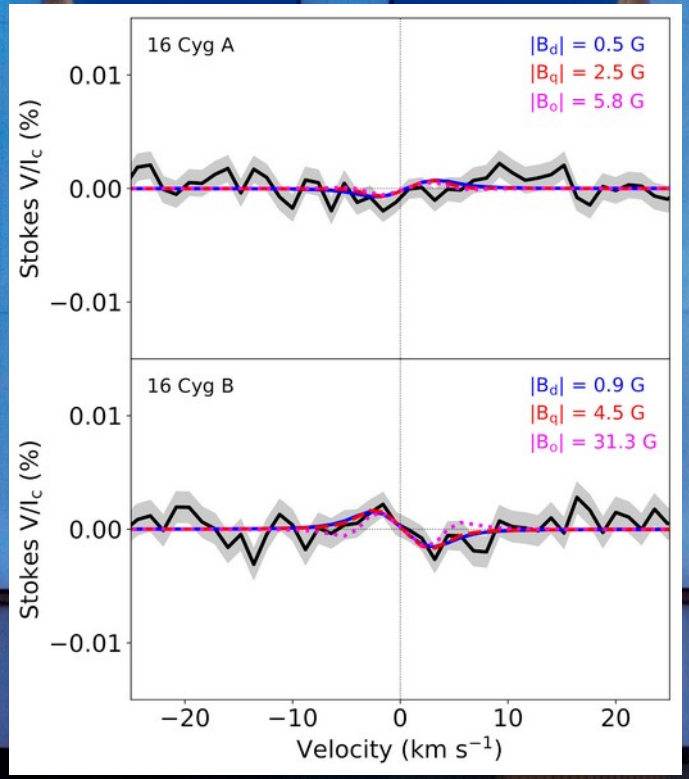


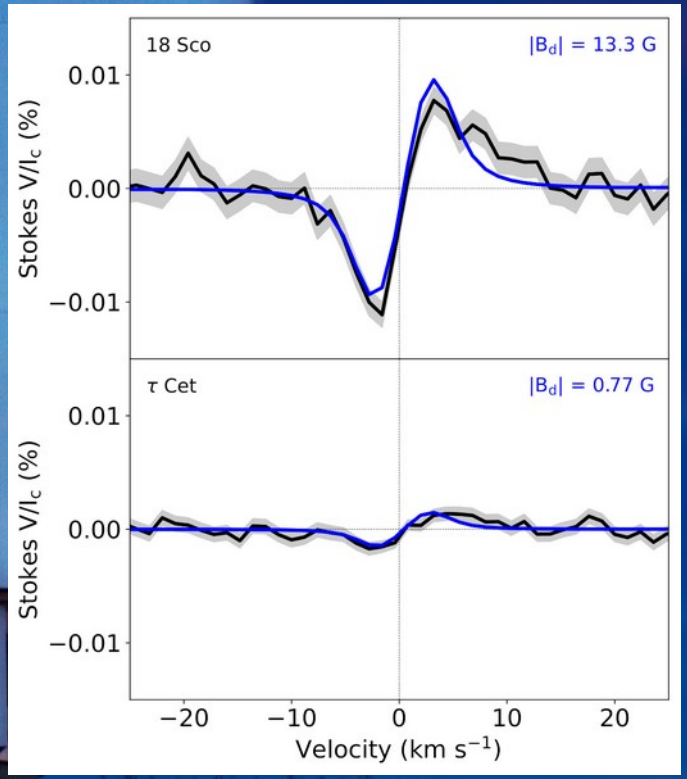
- Stalled rotation coincides with longer activity cycles and weaker variability
- Same pattern observed in hotter and cooler stars at same Rossby number
- Solar cycle appears to be in the transition, and may disappear in a few Gyr

Metcalfe & van Saders 2017, Metcalfe+2019


Credit: NOAO


88 Leo
$|B_d|$ = 5.0 G
ρ CrB
$|B_d|$ = 0.7 G
$|B_q|$ = 2.4 G
$|B_o|$ = 19.6 G
Stokes V/I$_c$ (%)
0.01
0.00
−0.01
−20
−10
0
10
20
Velocity (km s^{-1})


16 Cyg A
$|B_d|$ = 0.5 G
$|B_q|$ = 2.5 G
$|B_o|$ = 5.8 G
16 Cyg B
$|B_d|$ = 0.9 G
$|B_q|$ = 4.5 G
$|B_o|$ = 31.3 G
Stokes V/I$_c$ (%)
0.01
0.00
−0.01
−20
−10
0
10
20
Velocity (km s^{-1})


18 Sco
$|B_d|$ = 13.3 G
τ Cet
$|B_d|$ = 0.77 G
Stokes V/I$_c$ (%)
0.01
0.00
−0.01
−20
−10
0
10
20
Velocity (km s^{-1})

Credit: NOAO

The Astrophysical Journal, 921:122 (10pp), 2021 November 10 https://doi.org/10.3847/1538-4357/ac1f19

Magnetic and Rotational Evolution of ρ CrB from Asteroseismology with TESS

Travis S. Metcalfe[1,2], Jennifer L. van Saders[3], Sarbani Basu[4], Derek Buzasi[5], Jeremy J. Drake[6], Ricky Egeland[7], Daniel Huber[3], Steven H. Saar[6], Keivan G. Stassun[8], Warrick H. Ball[9,10], Tiago L. Campante[11,12], Adam J. Finley[13], Oleg Kochukhov[14], Savita Mathur[15,16], Timo Reinhold[17], Victor See[18], Sallie Baliunas[6], and Willie Soon[6]

The Astrophysical Journal Letters, 933:L17 (6pp), 2022 July 1 https://doi.org/10.3847/2041-8213/ac794d

The Origin of Weakened Magnetic Braking in Old Solar Analogs

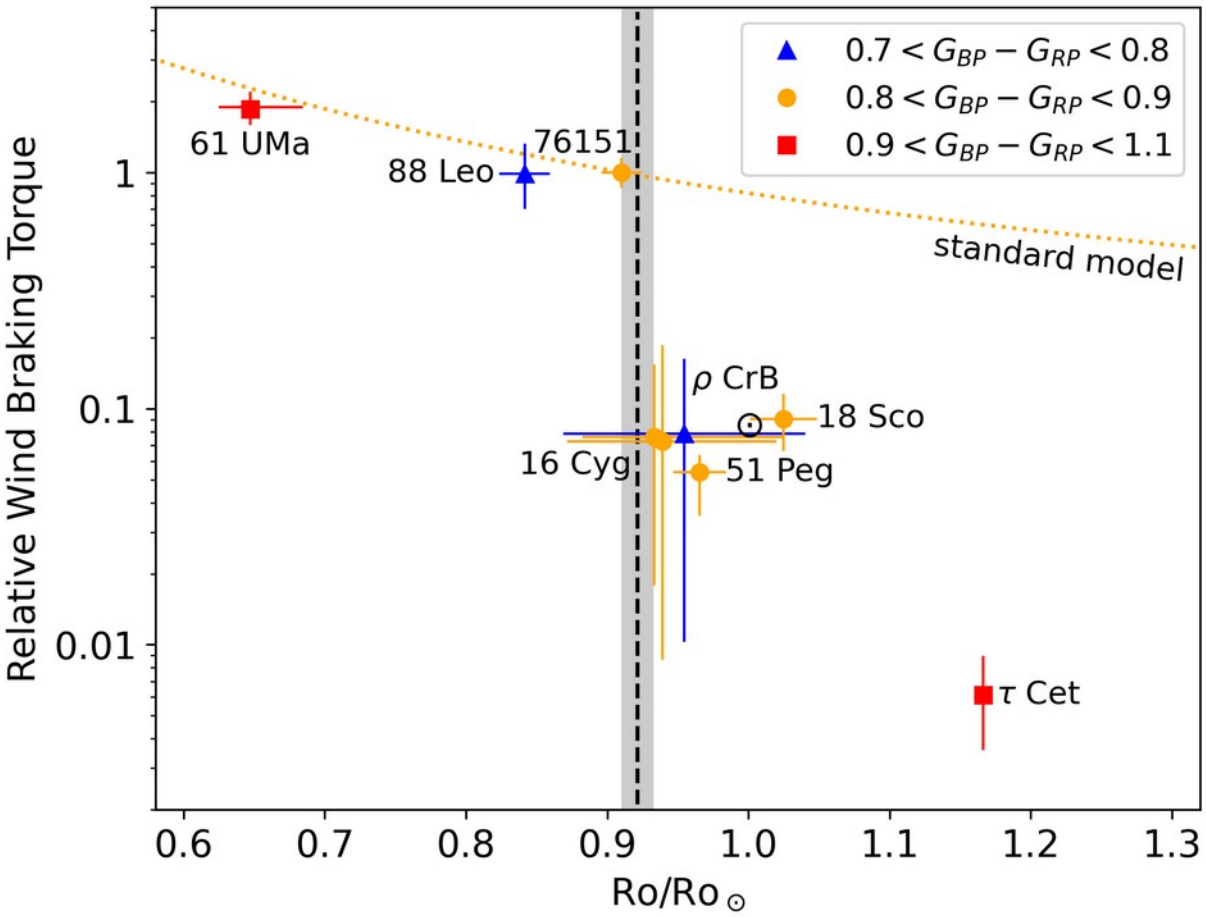
Travis S. Metcalfe[1], Adam J. Finley[2], Oleg Kochukhov[3], Victor See[4], Thomas R. Ayres[5], Keivan G. Stassun[6], Jennifer L. van Saders[7], Catherine A. Clark[8,9], Diego Godoy-Rivera[10,11,12], Ilya V. Ilyin[13], Marc H. Pinsonneault[10], Klaus G. Strassmeier[13], and Pascal Petit[14]

The Astrophysical Journal Letters, 948:L6 (5pp), 2023 May 1 https://doi.org/10.3847/2041-8213/acce38

Constraints on Magnetic Braking from the G8 Dwarf Stars 61 UMa and τ Cet

Travis S. Metcalfe[1], Klaus G. Strassmeier[2], Ilya V. Ilyin[2], Jennifer L. van Saders[3], Thomas R. Ayres[4], Adam J. Finley[5], Oleg Kochukhov[6], Pascal Petit[7], Victor See[8], Keivan G. Stassun[9], Sandra V. Jeffers[10], Stephen C. Marsden[11], Julien Morin[12], and Aline A. Vidotto[13]

Direct estimates of wind braking torque



- Braking torque weakens by ~300x between Ro of 61 UMa and τ Cet
- Empirical value of critical Ro (shaded) constrained by HD 76151 and 16 Cyg
- Larger uncertainties when we only have upper limits on the large-scale field

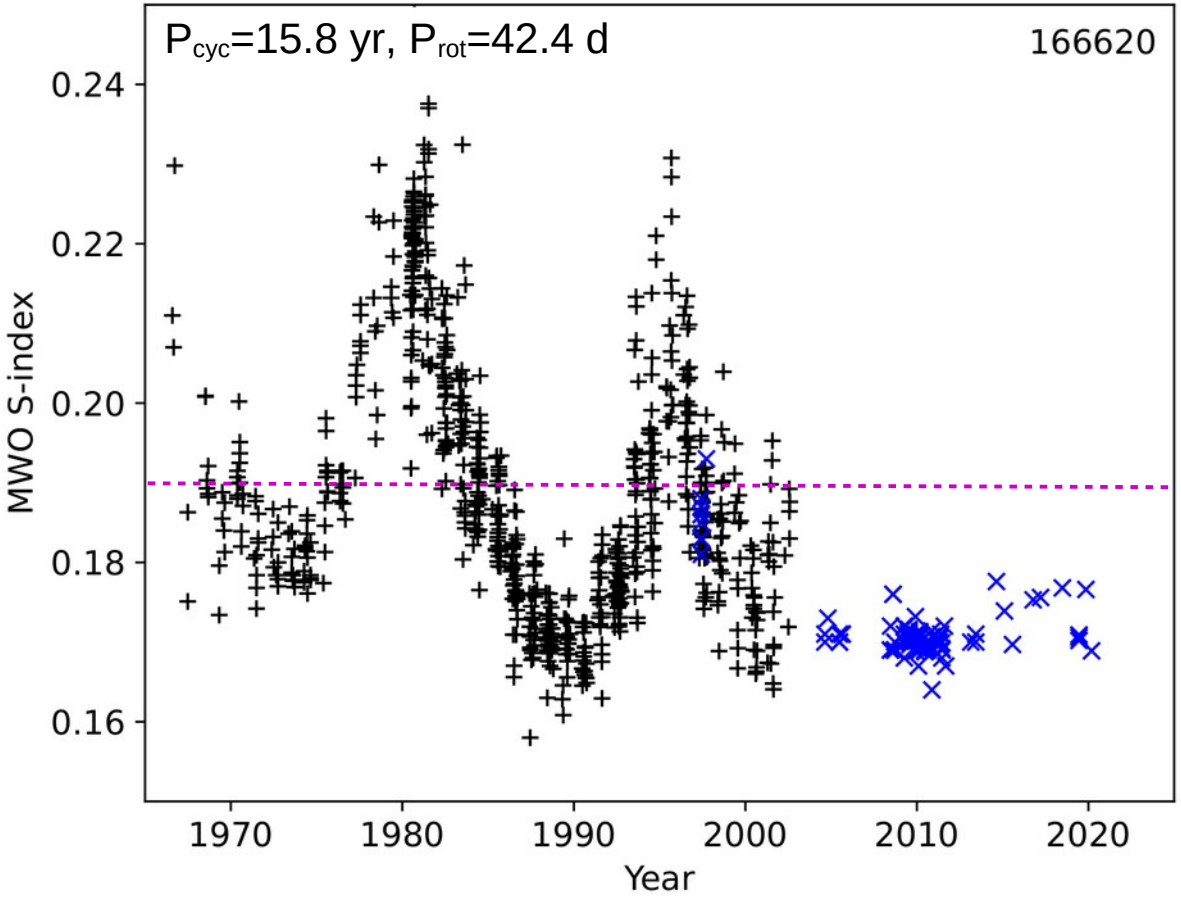
Metcalfe+2023

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

SCOSTEP
Scientific Committee on Solar-Terrestrial Physics

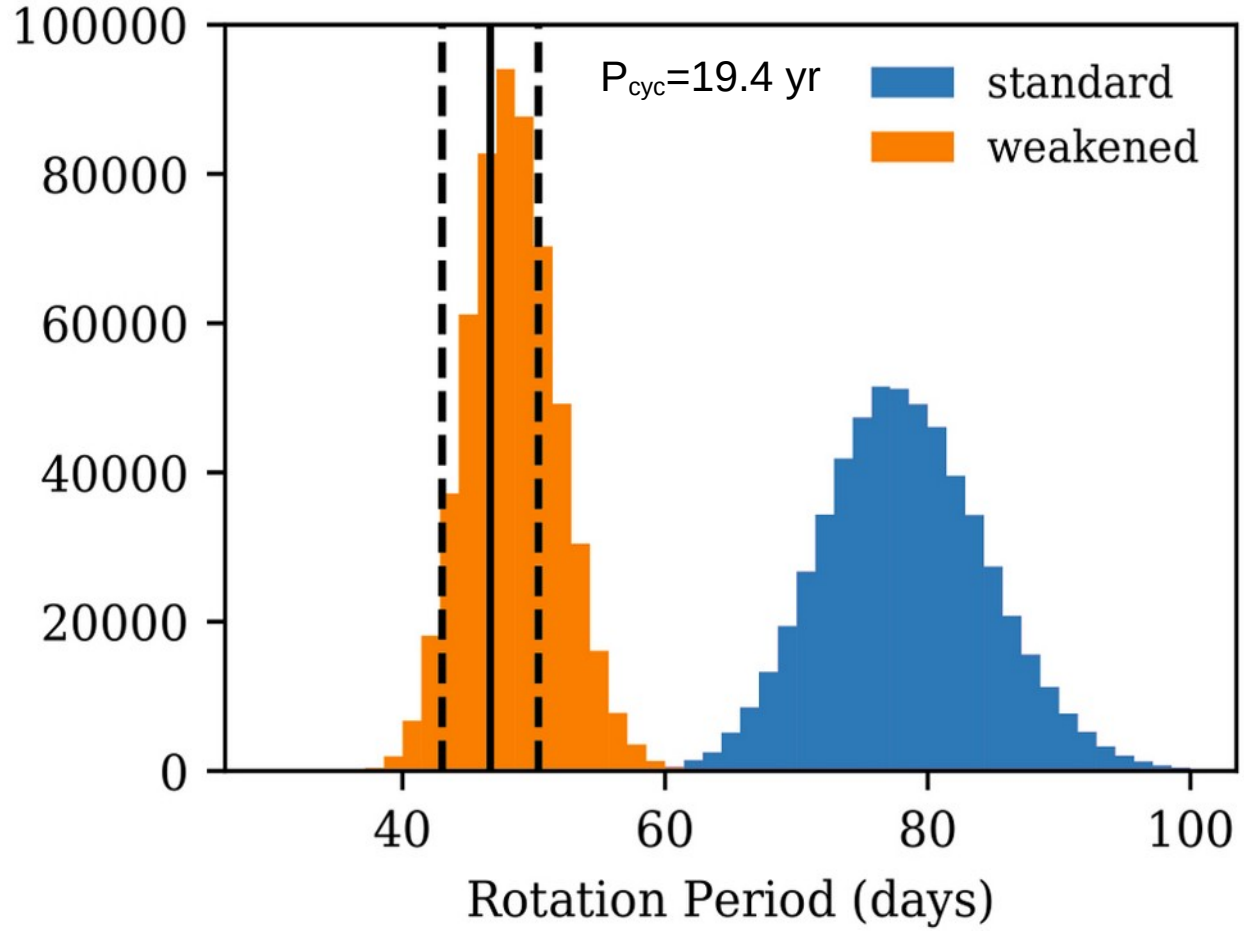
HD 166620: grand minimum



- 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

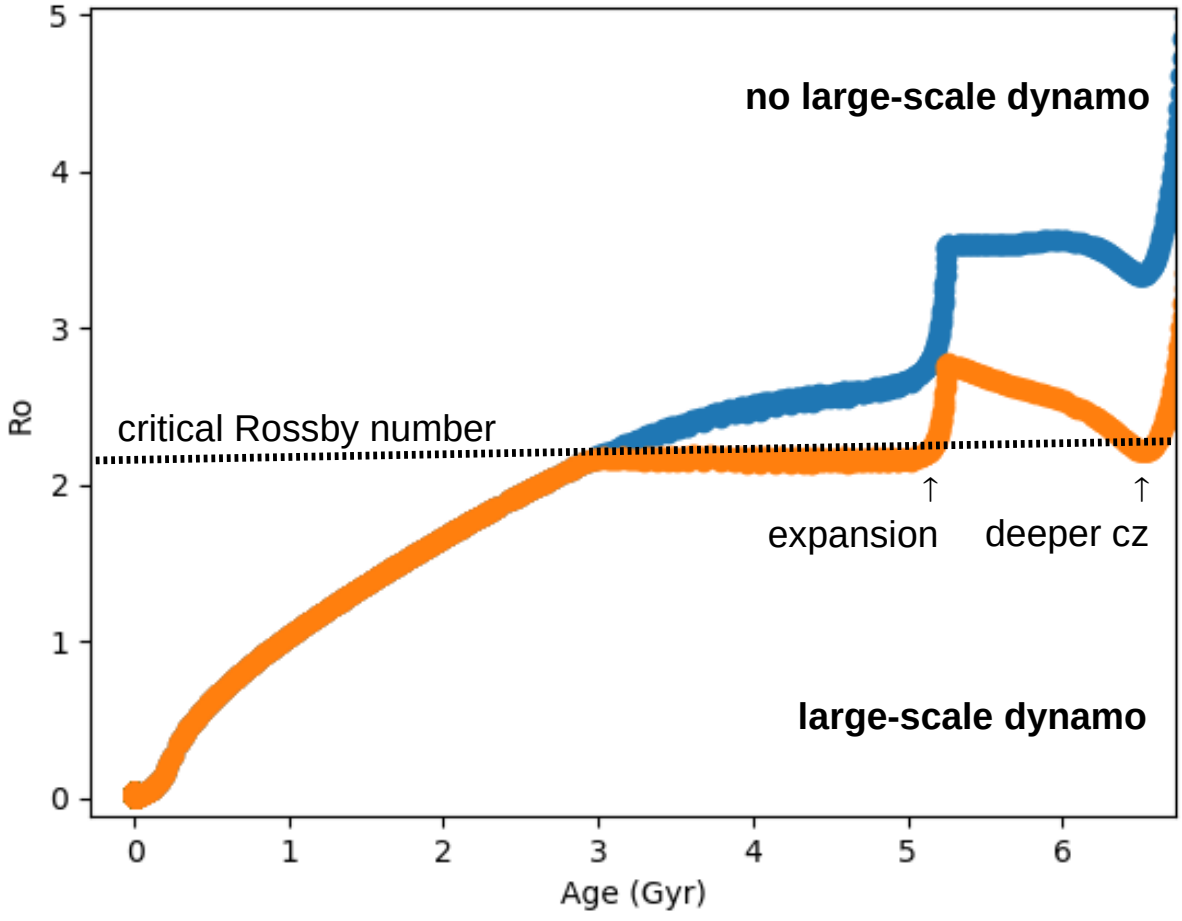
94 Aqr Aa: history of WMB



- Given stellar properties of subgiant, predict current rotation period (47 ± 4 d)
- Weakened magnetic braking after 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