Limits (and Strengths) of Stellar Model Physics: Rotation and Magnetism

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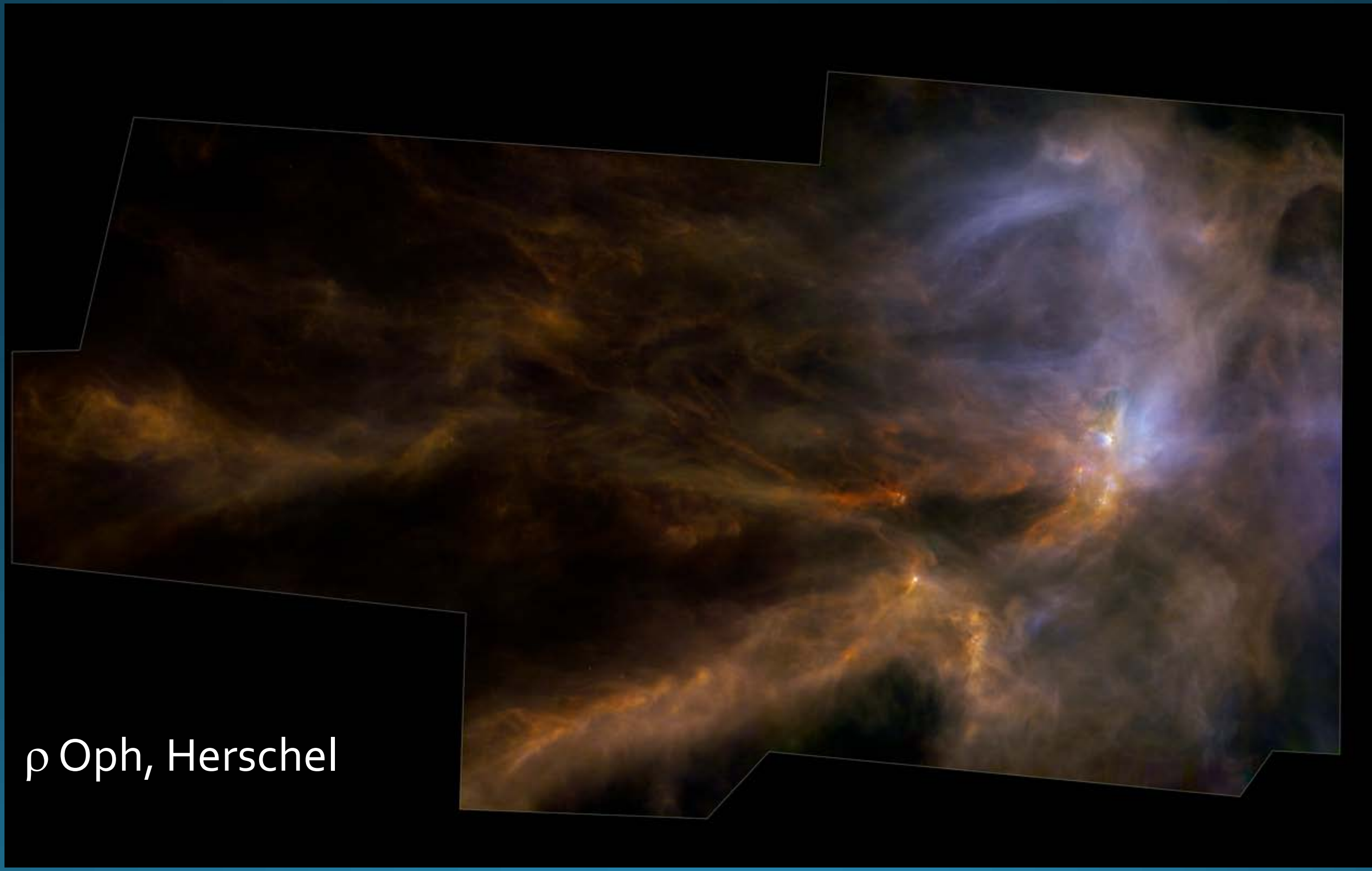
Rotation and the Star-Planet Connection

- Stellar Rotation is Intimately Linked with the Planet and Star Formation Process
- Stellar Activity Has a Dramatic Impact on Habitability, Radii, Ages and Masses of Young Stars

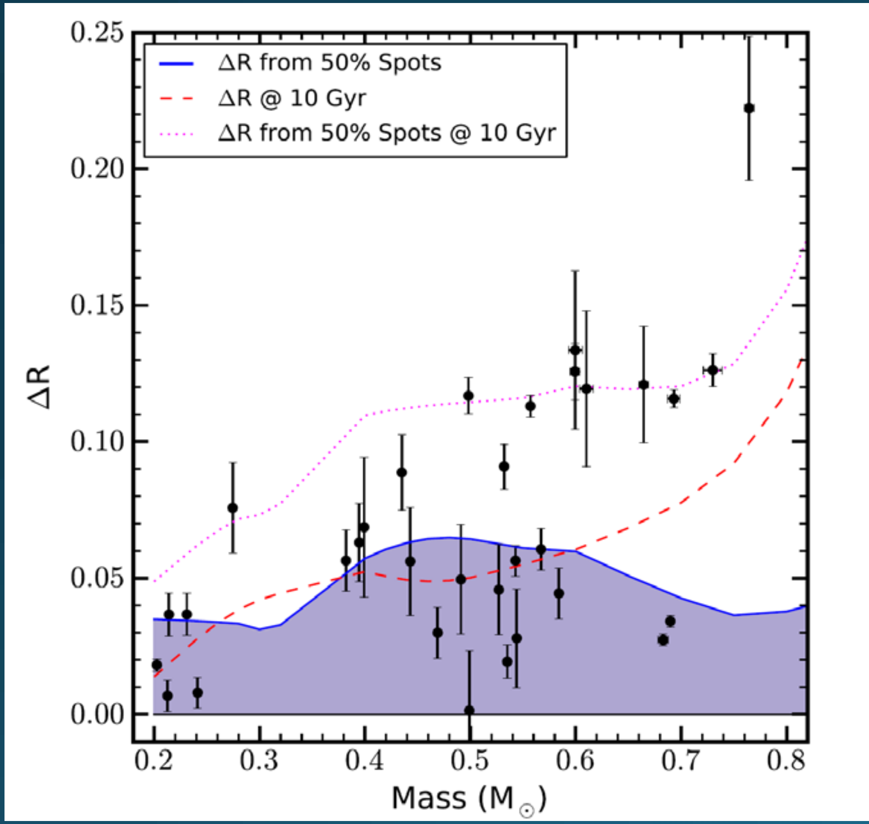
Rotation, Magnetism & Convection Are Fascinating Challenges for Stellar Theory

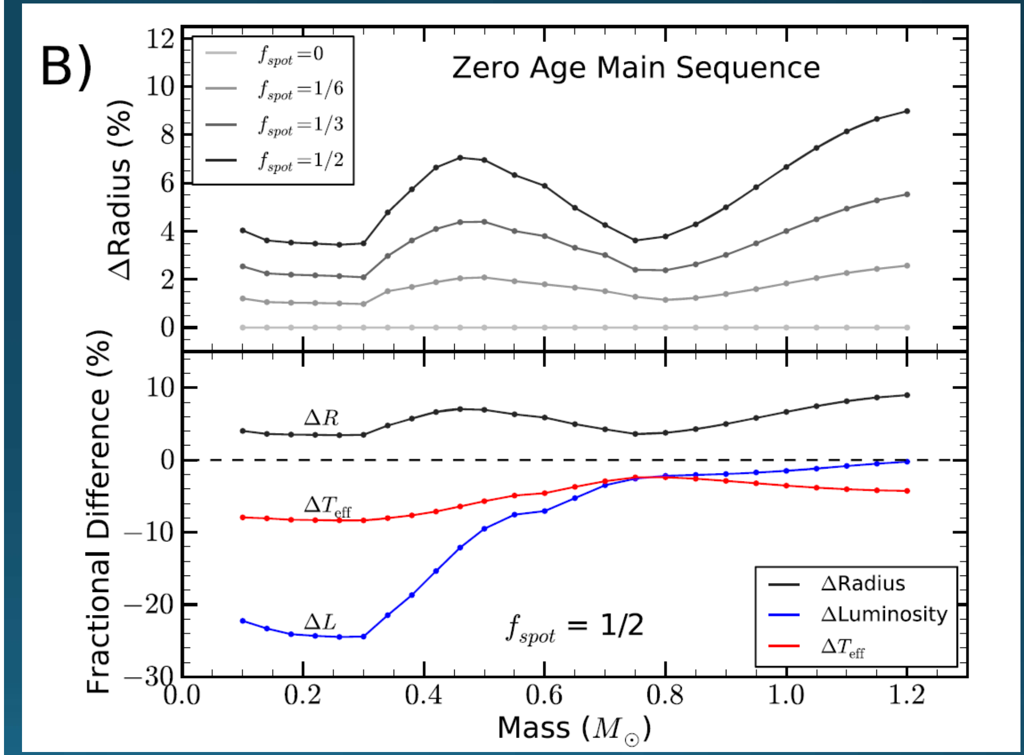


ρ Oph, Herschel

Star spots (and magnetic fields) can have a significant impact on the structure of young stars

(Feiden talk)



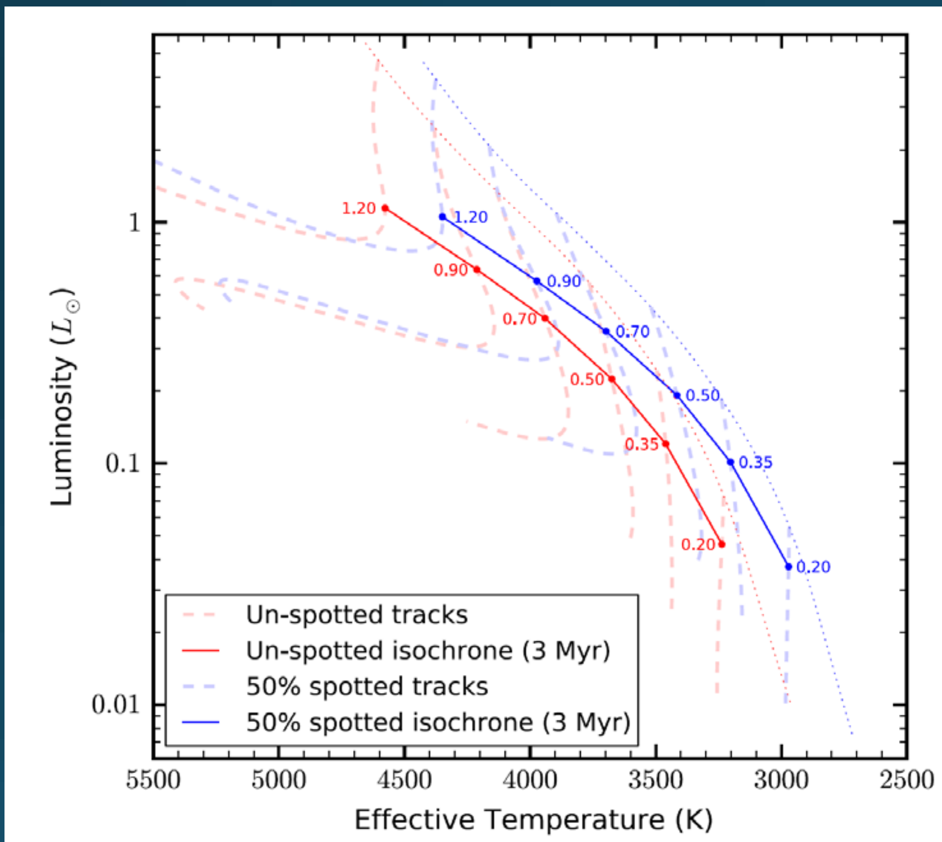


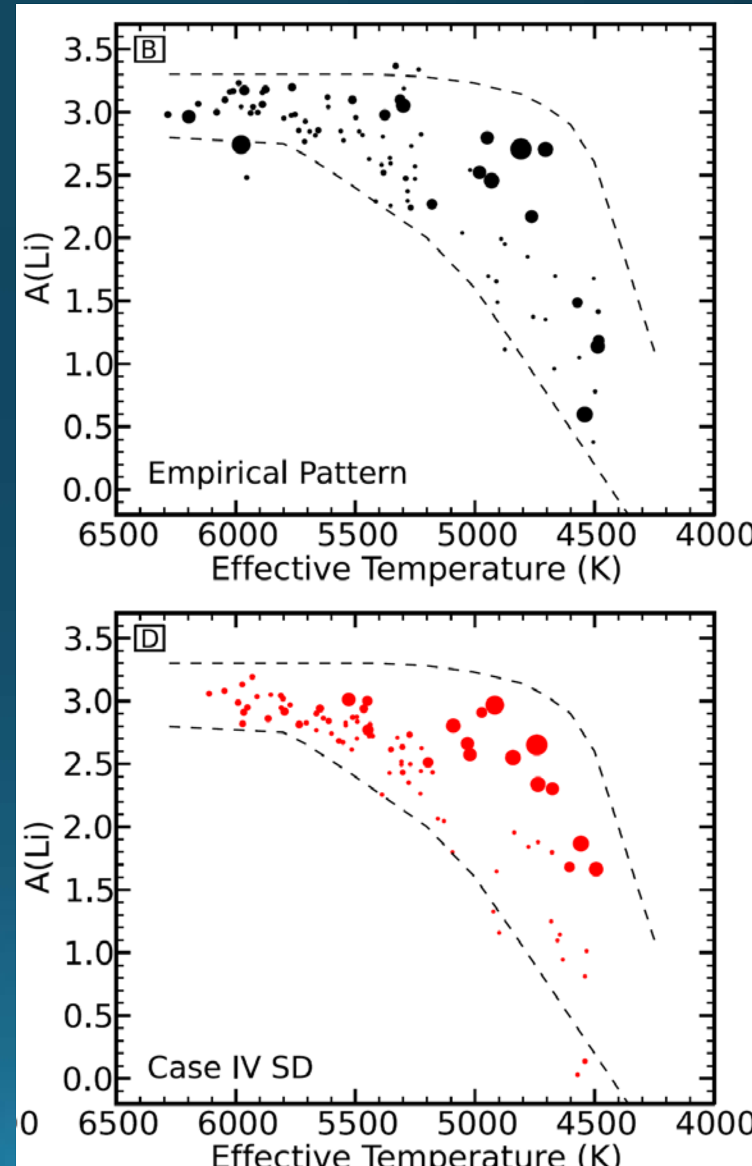
ALSO impacts observables!
(Pecaut & Mamajek 2013)

Somers & Pinsonneault (2015)

Lithium Depletion Pattern Supports Starspot Models

Somers & Pinsonneault 2016





Spotted Models Are Older and Colder
=> Longer Gas Disk Lifetimes


OLD MAN YELLS AT CLOUD

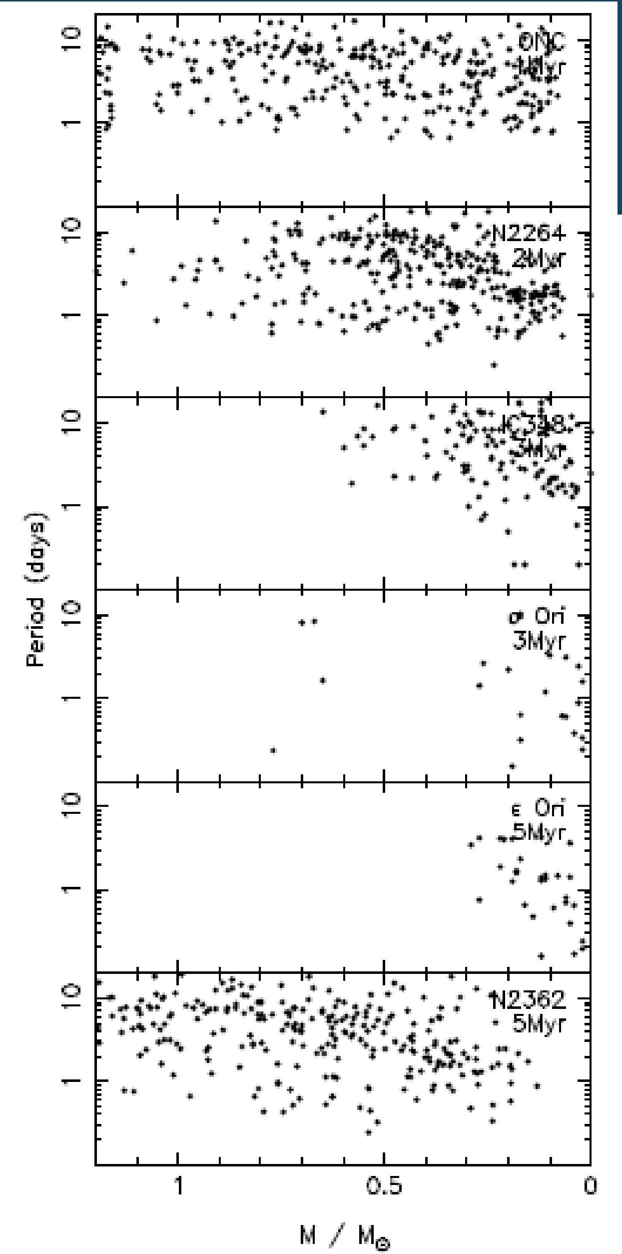
Setting the Stage: A Model of Angular Momentum Evolution in Low Mass Stars

- Basic Ingredients:
  - Initial Conditions
  - Protostar-Disk Interactions
  - Angular Momentum Loss
  - Angular Momentum Transport
- Critique and Gaps

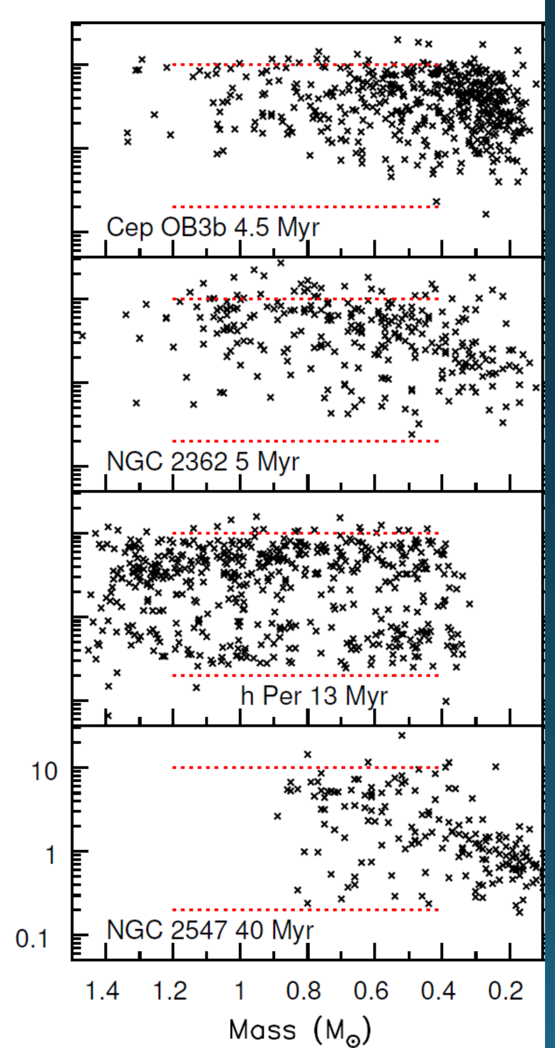
Rotation In Young Stars

Young → Old

- *Birth Rotation Much Less Than Break-Up*
- *Wide Range in Rotation Rate at Fixed Mass*
- *Weak Time Evolution Despite Rapid Contraction*



Irwin & Bouvier 2008; Moraux et al. 2013



"Standard" Model

- The initial rotation rates of stars are set in the cloud core collapse phase and regulated by protostar-disk interactions

Konigl 1991; Shu et al. 1994

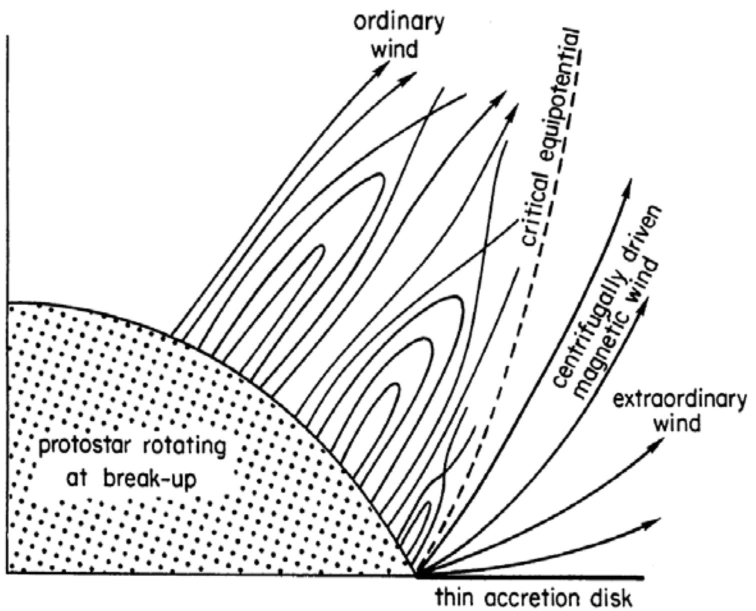


FIG. 1.—A complex geometry of open and closed field lines exists over most of the surface area of a protostar, with an ordinary wind (O-wind) blowing out along the open field lines. This wind intensifies into an extraordinary wind (X-wind) driven by magnetocentrifugal effects if open field lines protrude from the equatorial region of a star spun to breakup by heavy accretion from a thin accretion disk.

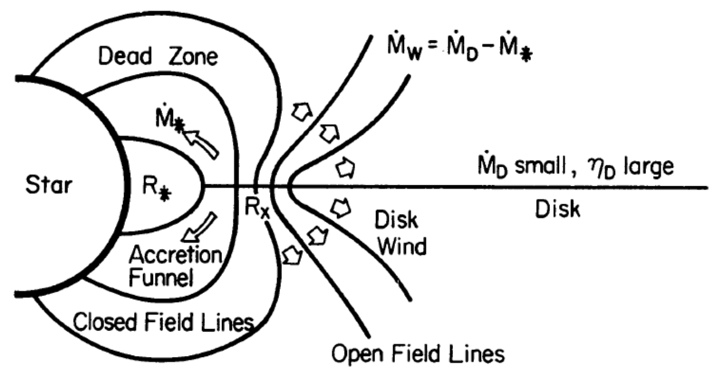


FIG. 2b

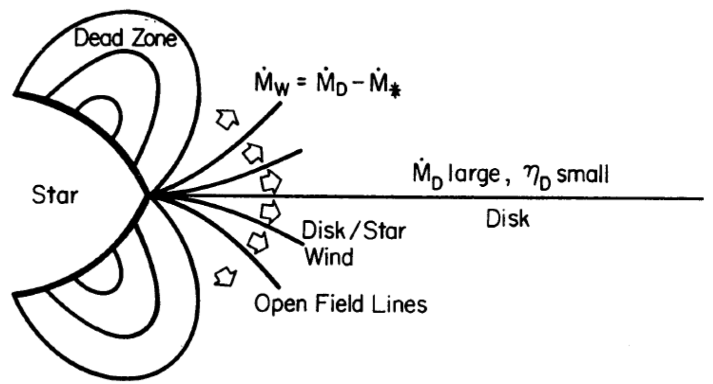


FIG. 2c

Spin Down of Solar Type Stars: History

- Kraft (1965): Late type stars are slow rotators, early type stars are not
- Sun is slower than young analogs
- Weber & Davis (1967): solar wind predicted $d\omega/dt \sim \omega^3$

  => $v \sim t^{-1/2}$, seen by Skumanich (1972) in rotation, activity, and lithium

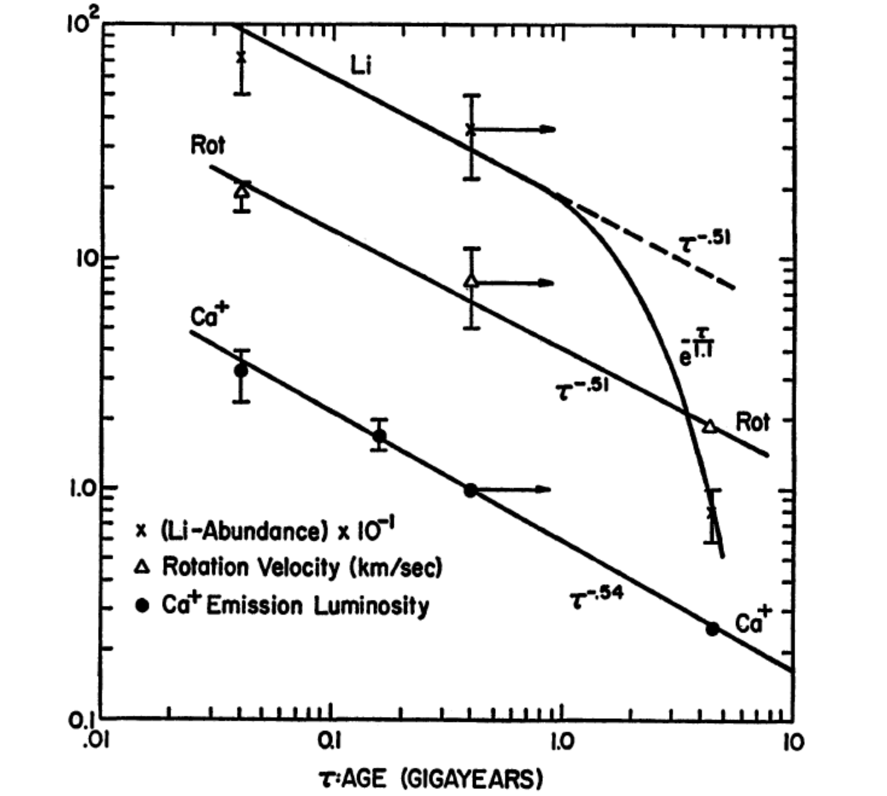
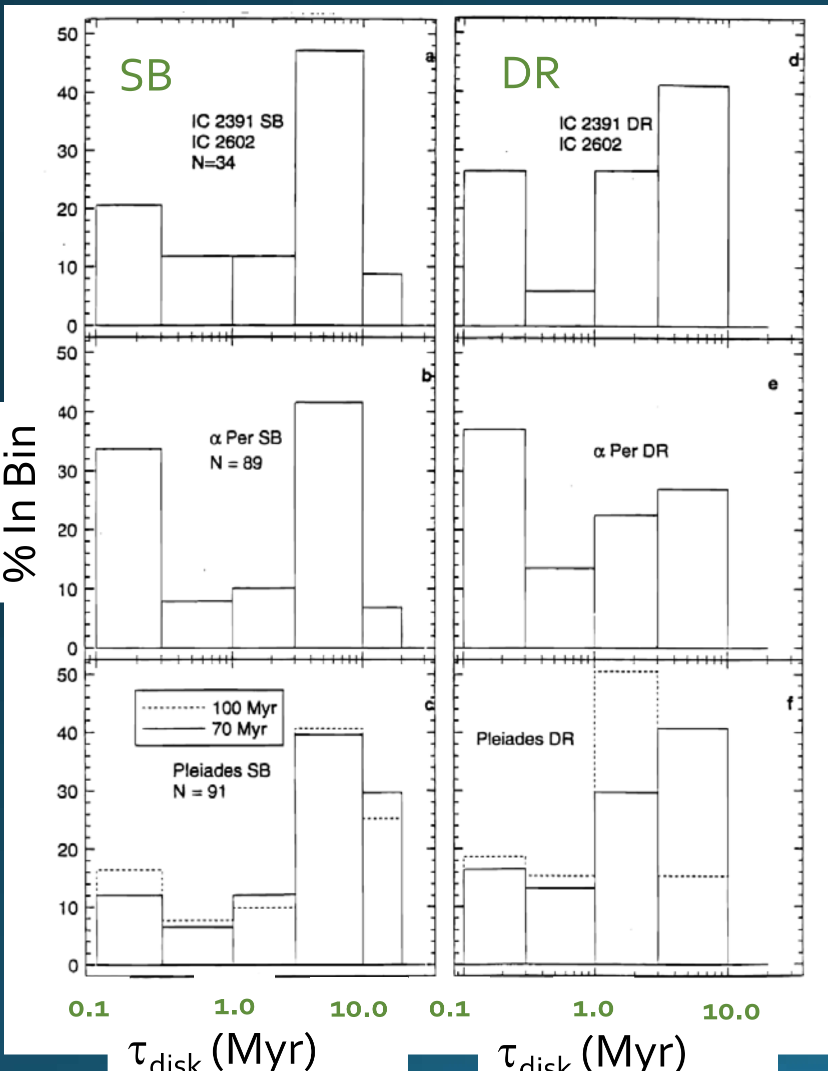


FIG. 1.—Ca^+ emission, rotation, and lithium abundance versus stellar age

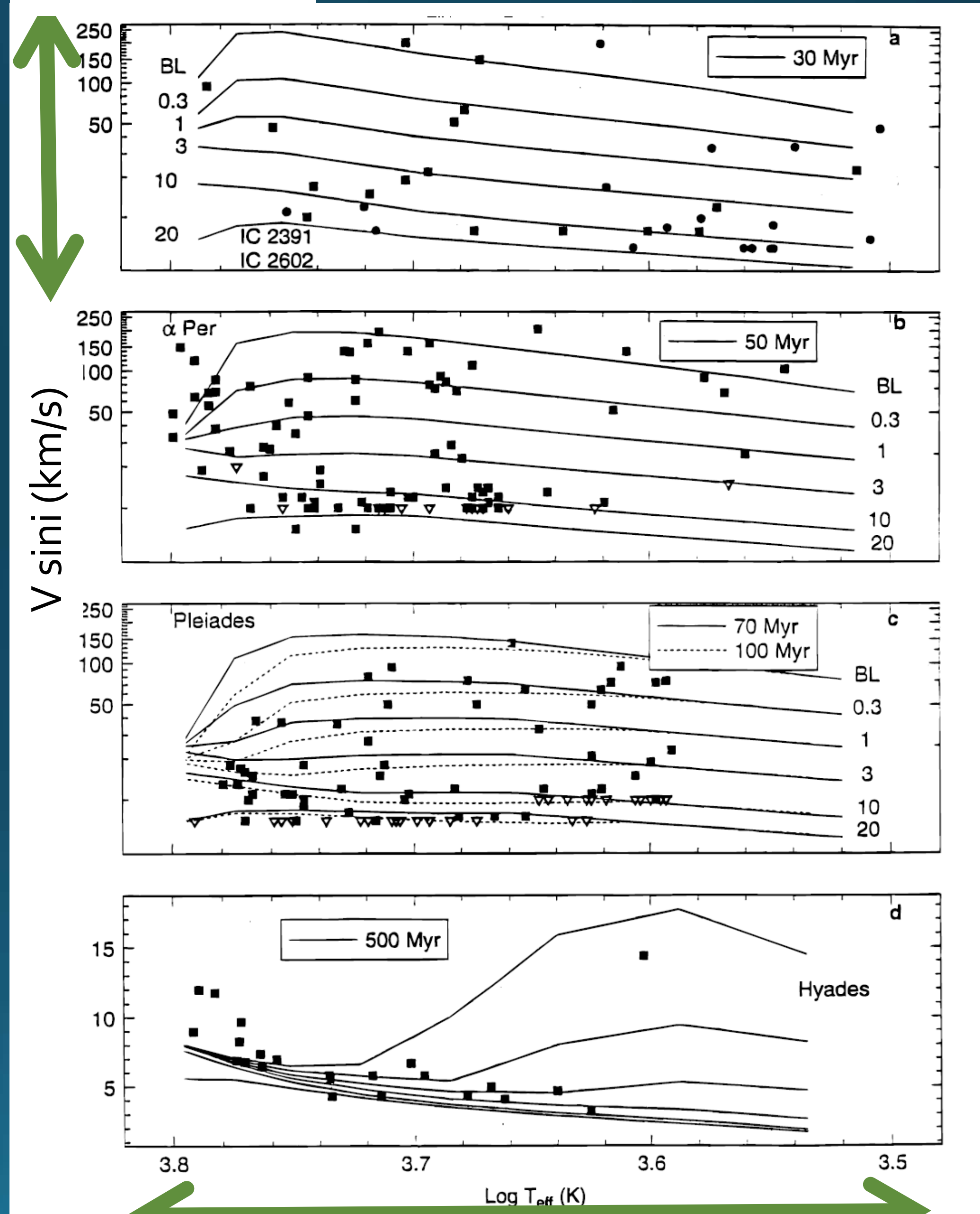
Skumanich 1972:
The first rotational clock!

Developing A Model



Consistent Disk Lifetimes, DR

Disk Lifetimes



Krishnamurthi+1997

Mass Dependent Saturation

The Spindown Pattern Decoded

- $d\omega/dt \sim (k/I)\omega^3$

$\Rightarrow$Lower mass spin slower

- $d\omega/dt \sim \omega^3$, $\omega < \omega_{crit}$

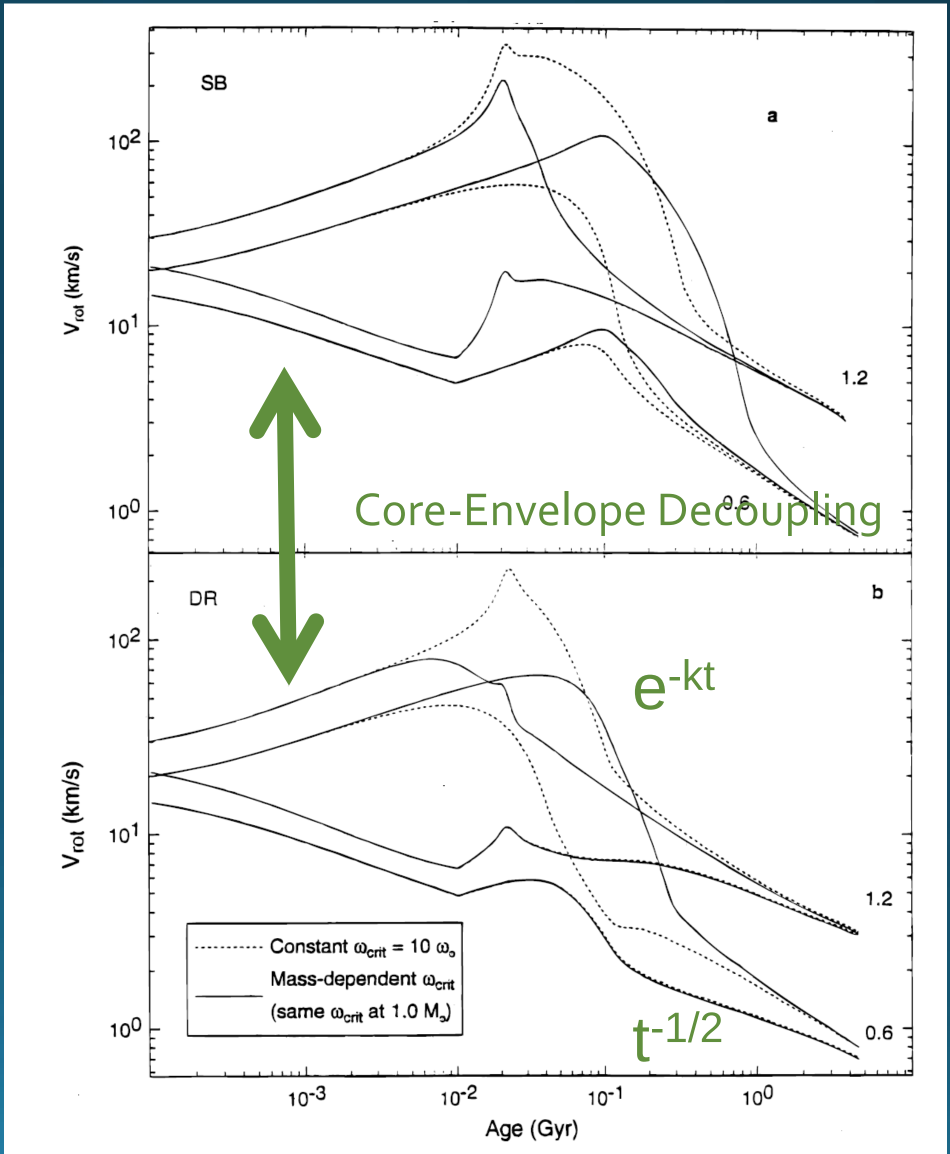
$\Rightarrow$Strong Convergence

$\Rightarrow \omega \sim t^{-1/2}$ asymptotic

- $d\omega/dt \sim \omega$, $\omega > \omega_{crit}$

$\Rightarrow \omega = \omega_o e^{-kt}$

$\Rightarrow$Self-Similar Spindown



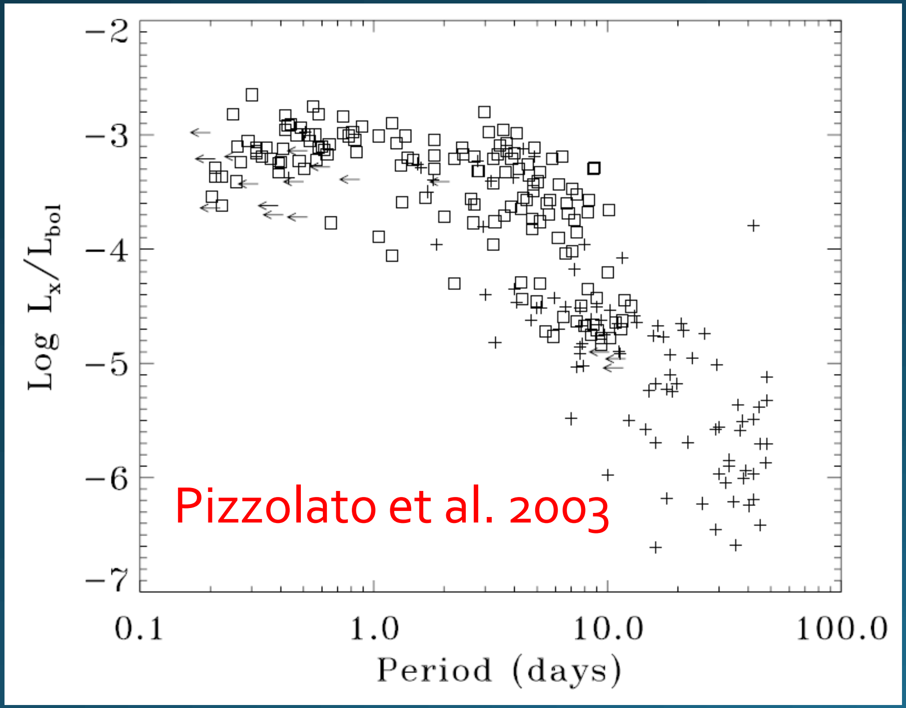
Krishnamurthi+1997

See Wright, Browning talks!

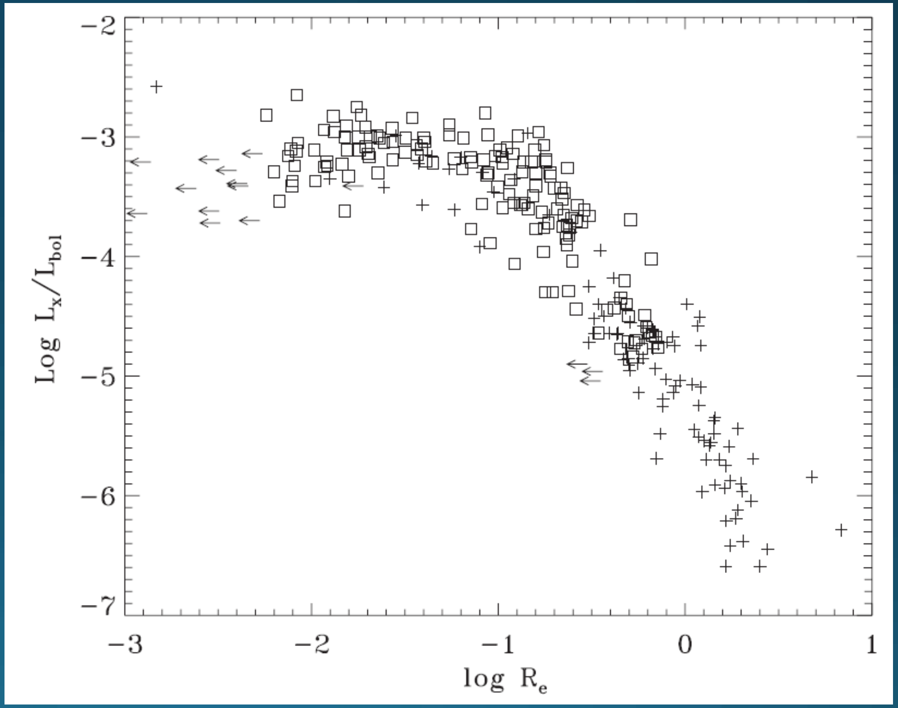
Physics of Saturation

The saturation model is empirical, not predictive!

Proxies of dipole field strength and mass loss are observed to saturate, which mirrors the torque model needed to explain data



Coronal Activity vs. Period



Coronal Activity vs. Rossby number
=> mass dependence of Lx

Three Questions

- Why are lower mass stars so heavily spotted?
  - Rotation is rapid relative to their low convective velocities even for slow rotators

- Why do they take so long to leave the saturated domain?
  - Wind Depends on B, Mdot
  - Small Mdot expected from low L, high g…

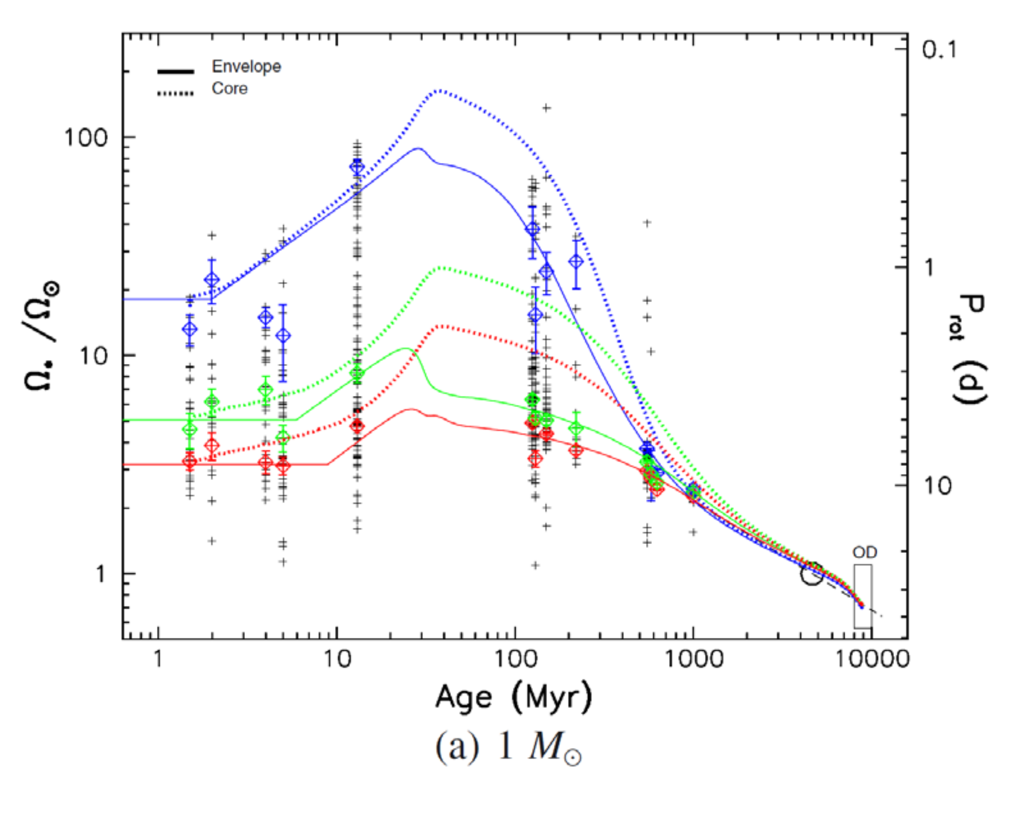
- Does the presence of a radiative core matter?

  Theorists: Yes

  Data: NO

A Consensus Model of Angular Momentum Evolution

- Range of Initial Rotation Rates
- Spin-Up (Contraction)
- Spin-Down
  - $d\omega/dt \sim \omega^3, \omega<\omega_{crit}$
  - $d\omega/dt \sim \omega\, \omega_{crit}^2, \omega > \omega_{crit}$
- Core-Envelope Decoupling



Gallet & Bouvier 2015

The Dangers of a Flexible Empirical Model

- You can fit things for the wrong reason (e.g. Brown 2014)
- Kawaler (1988) wind models fail for masses too different from the Sun
- Internal angular momentum transport still not solved (but see Fuller 2019)

Needed:
Physical models of winds, disks, internal transport…
New observational diagnosics

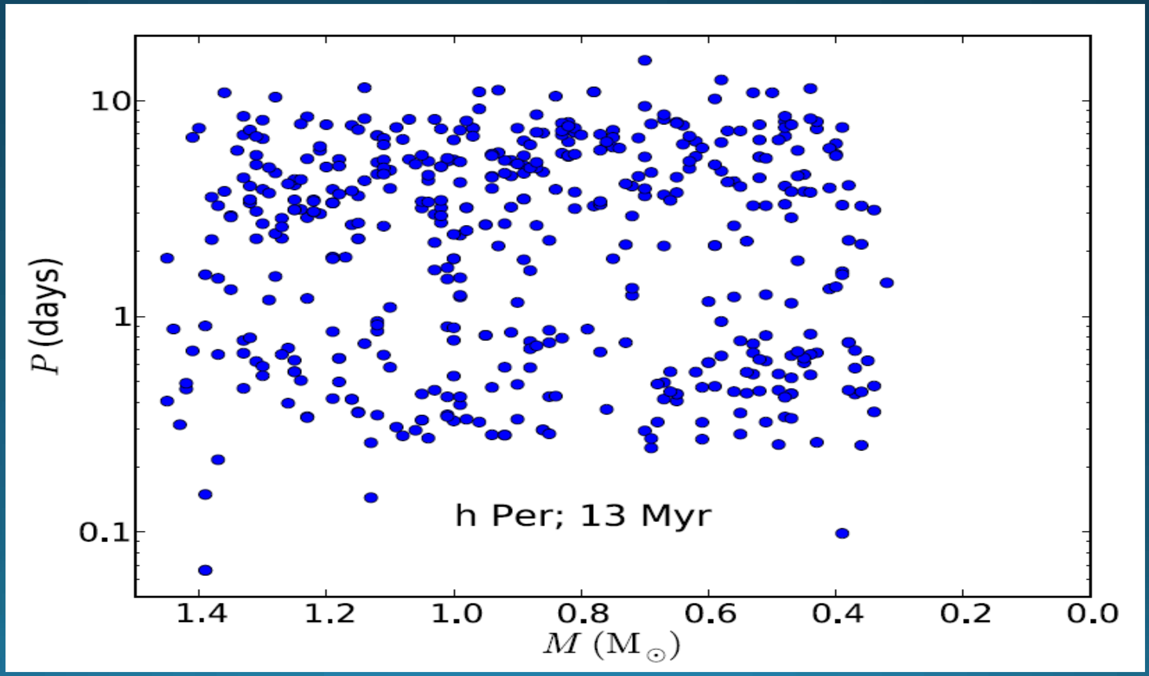
Star-Disk Interactions Are Complex

- Models of Disk-Coupling Are Suggestive
- No Detailed Link to Underlying Variables (Disk Mass, Accretion Rate, Lifetimes…

Modern Theory Bypasses This Completely, Starting With Post-Disk Stars

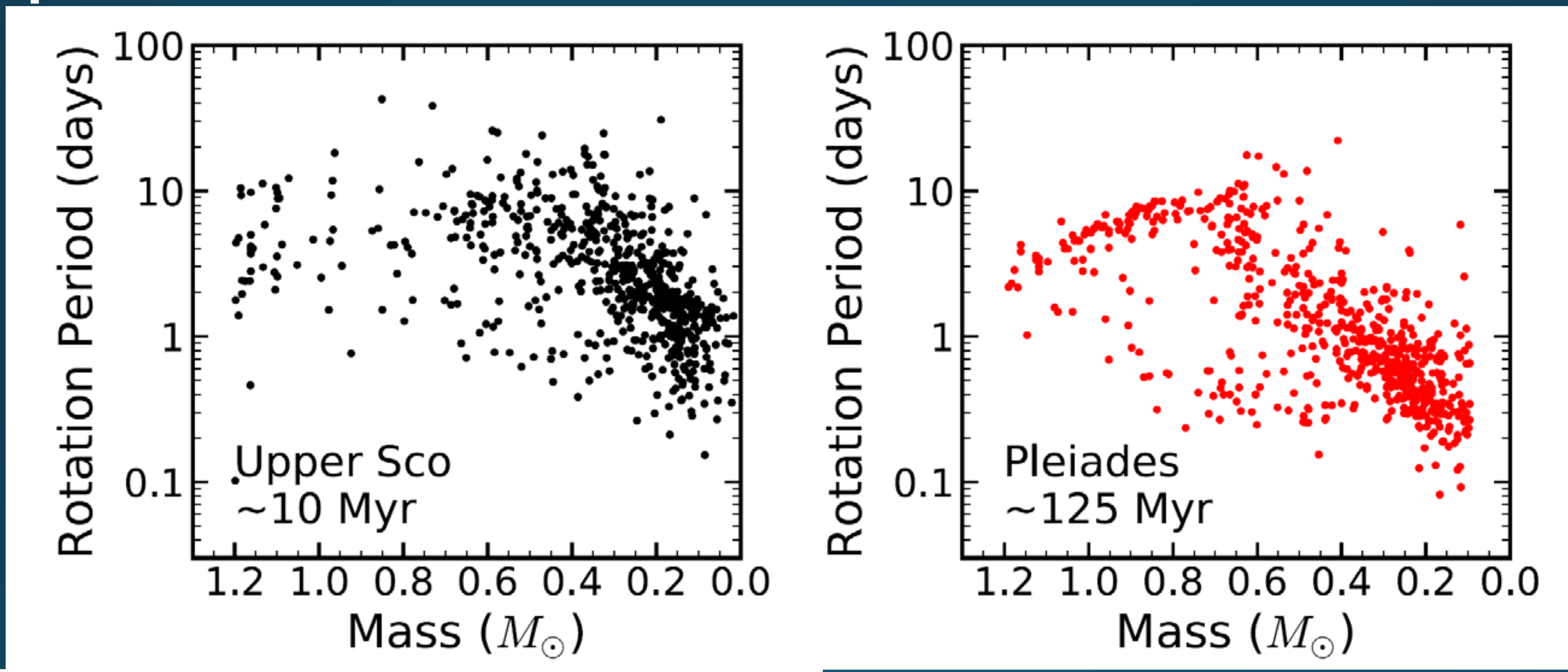
- Bi-Modal Distributions, Rotation Range Already in Place at ~13 Myr in H Per

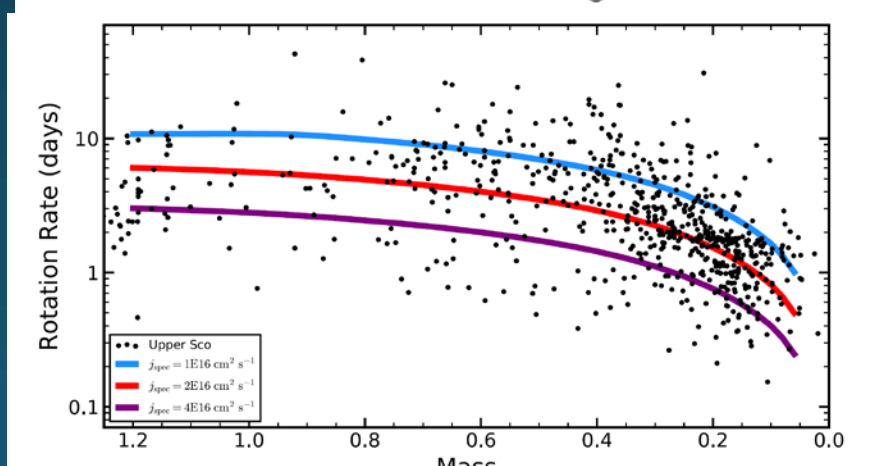
Moraux et al. 2013



Birth rotation is strongly mass-dependent

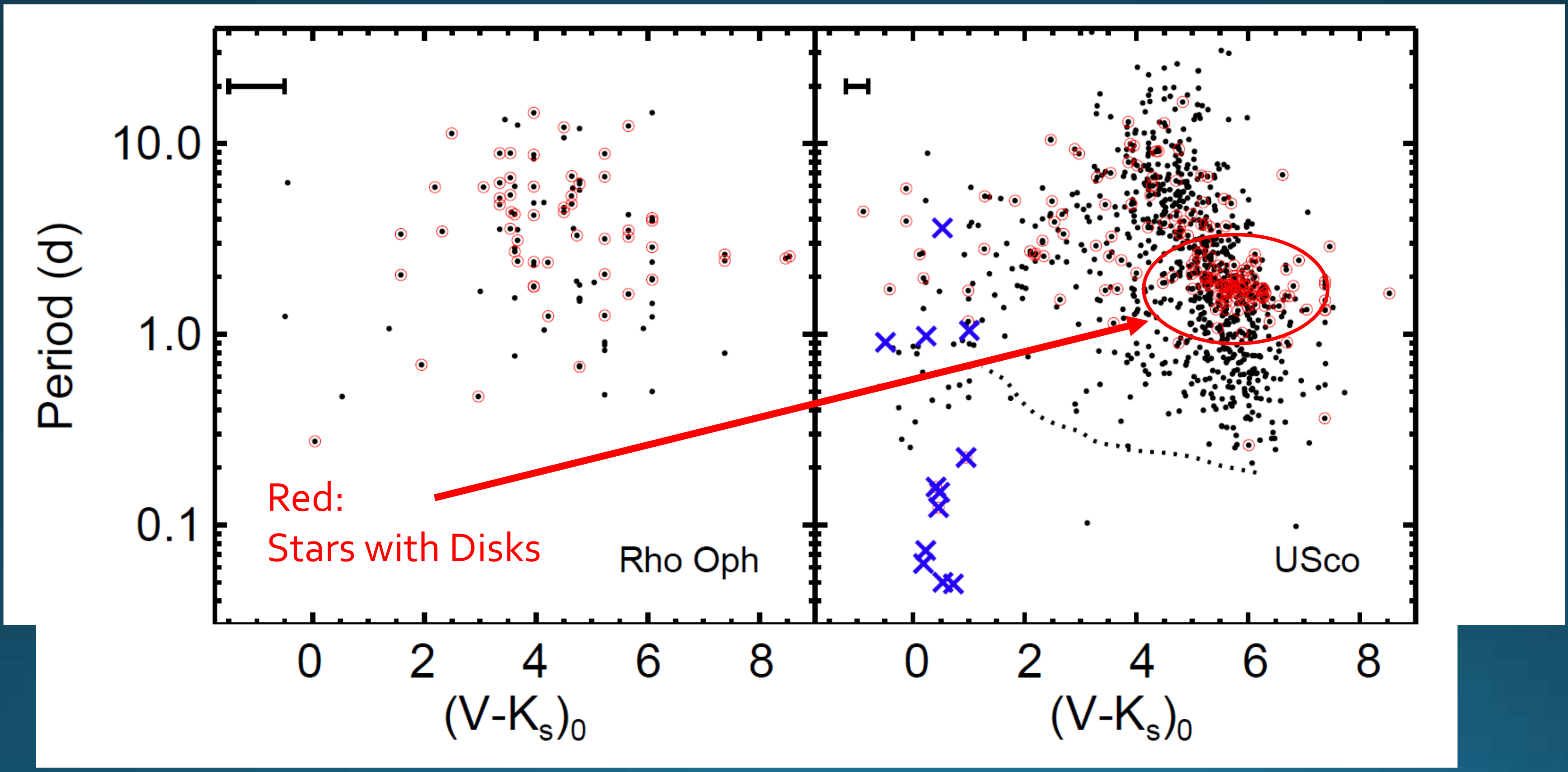
- Somers et al. 2017





=> Constant J/M (Somers et al. 2017)

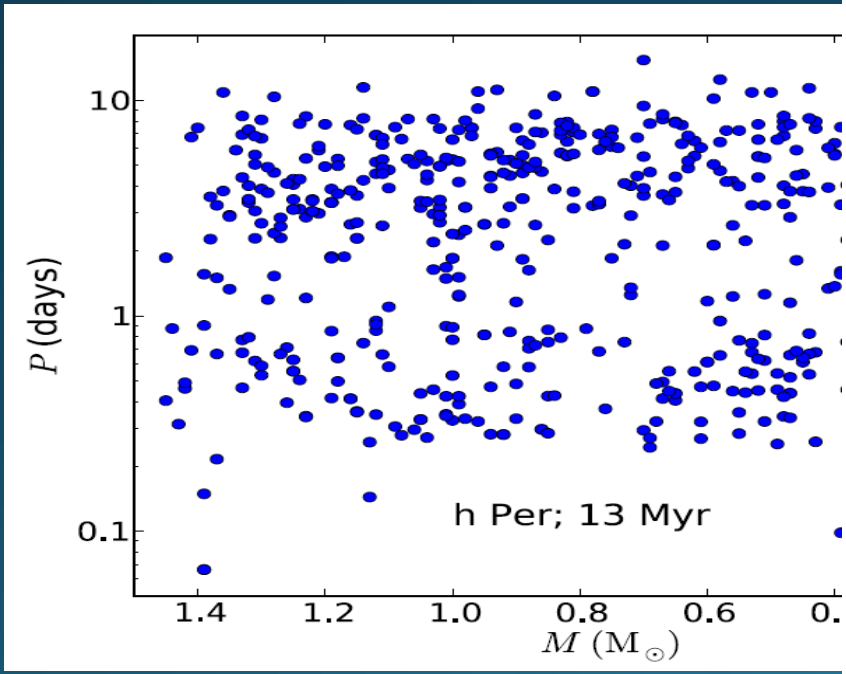
M star “disk-locking” occurs at a shorter period than for more massive stars

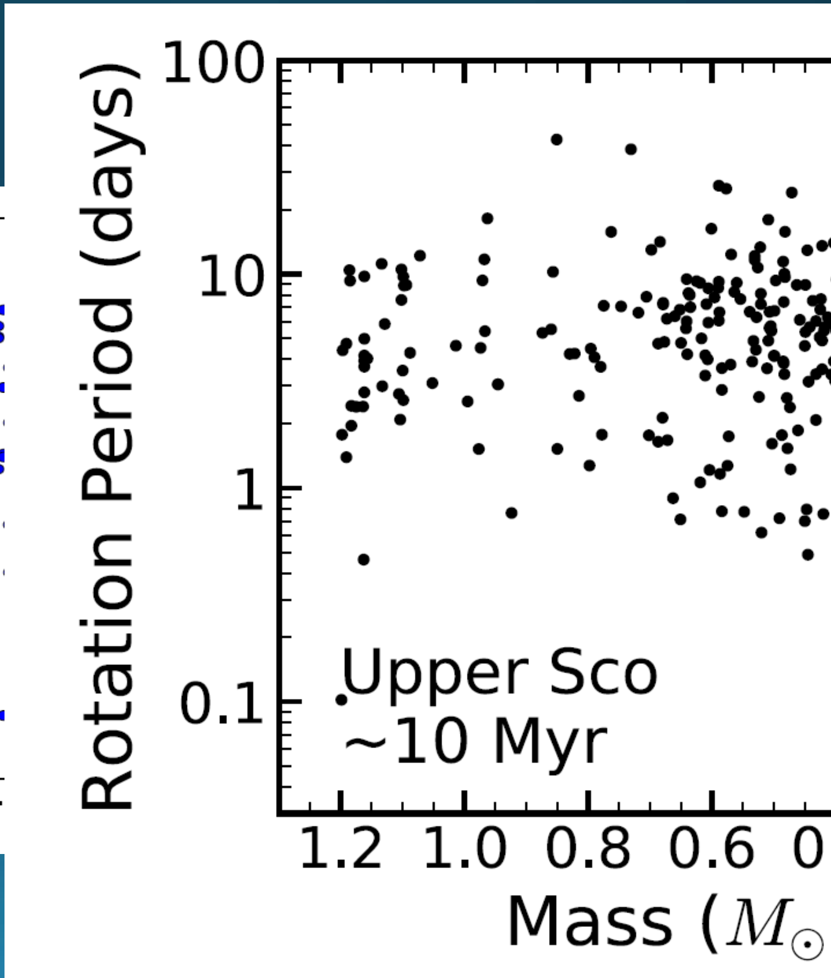


Rebull et al. 2018

Dense Cluster vs. Association: Cosmic Variance

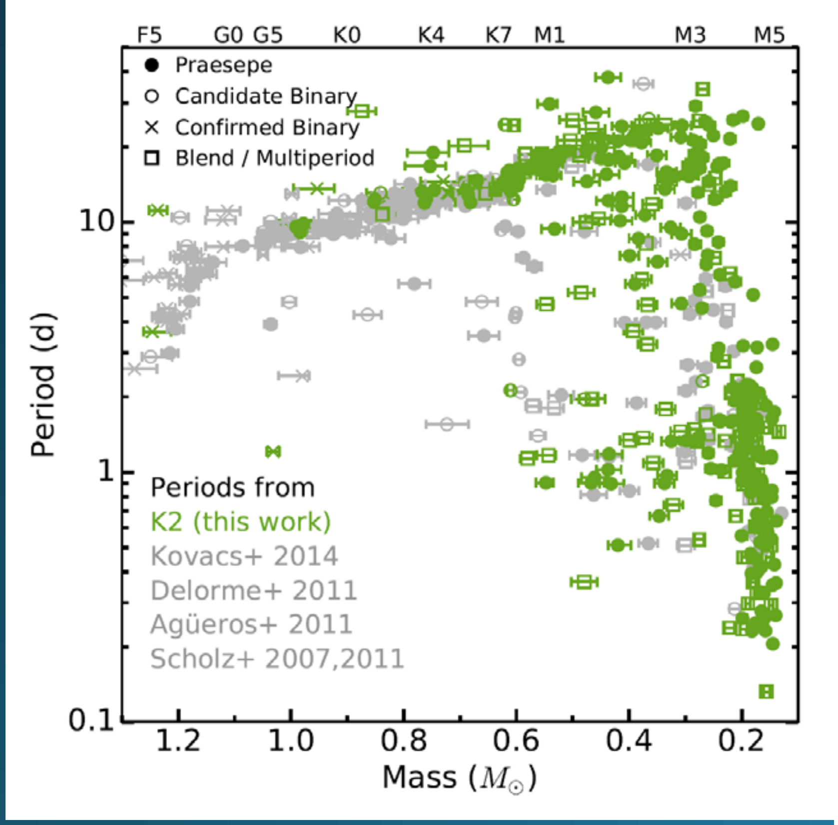
Coker+2016



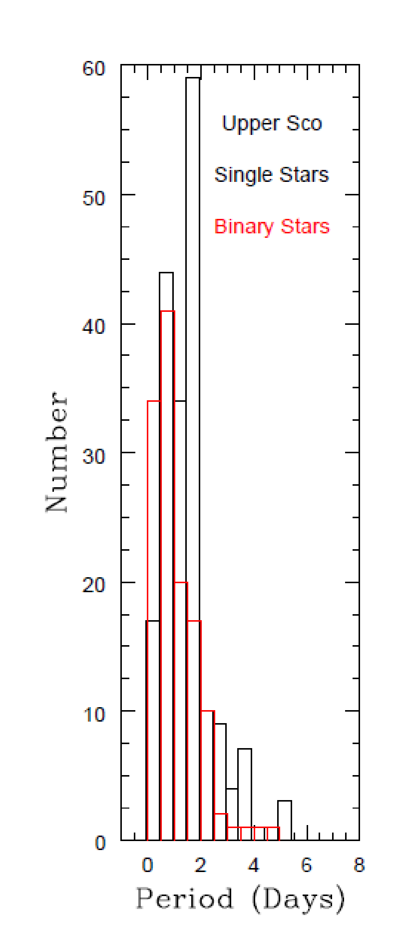


Photometric Binary Stars: Faster than Singles => Short Disk Lifetimes

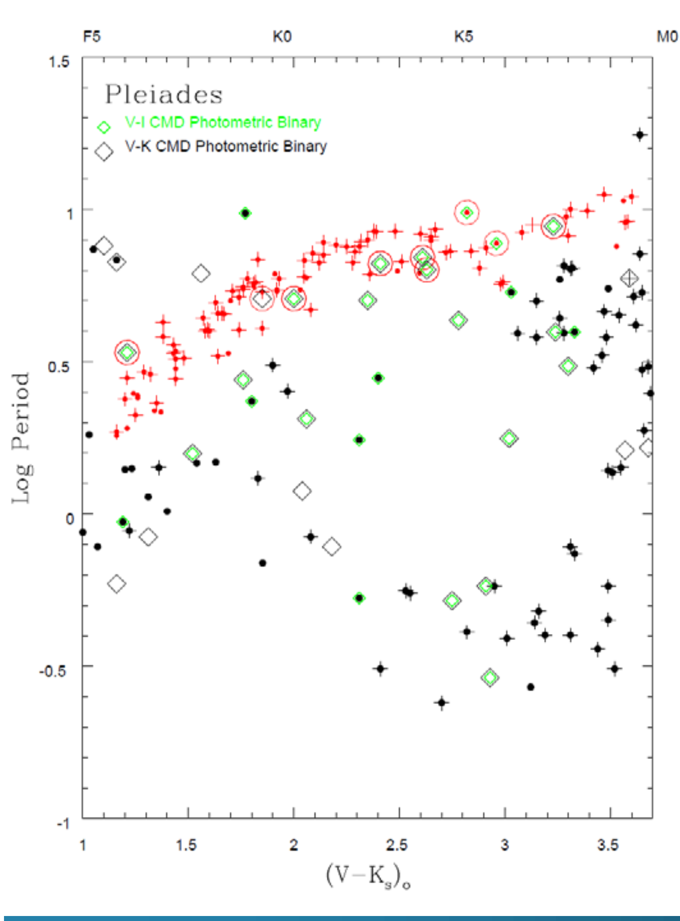
Praesepe (Douglas+2017)



Upper Sco (Stauffer+2016)



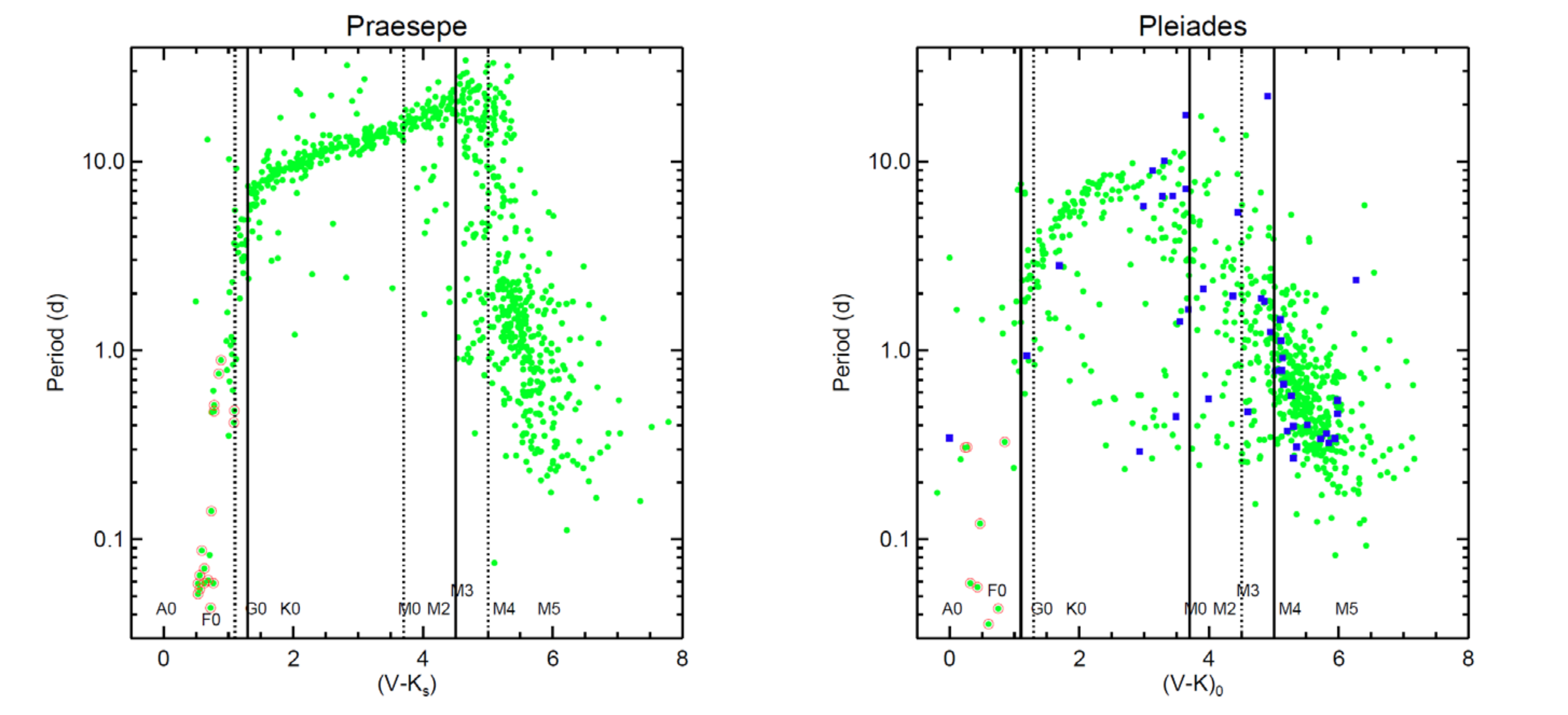
Pleiades (Stauffer+2016)



Planets and Environment

- Inner disk edge – important for migration
- General Principle: Rapid rotators arise from weak star-disk interactions and rapid mass assembly

Strongly Mass-Dependent Spindown Pattern Now Seen



Rebull et al. 2017

(Godoy-Rivera poster)

New Wind Models, New Data

See et al. (2019)

- Cranmer & Saar 2011
- Matt et al. 2012, 2015
- Van Saders & Pinsonneault 2013
- Gallet & Bouvier 2013
- Brown 2014
- Lazafame & Spada 2015
- Garraffo et al. 2018

Contrary to earlier models (Kawaler 1988), new ones predict strongly R-dependent torques.

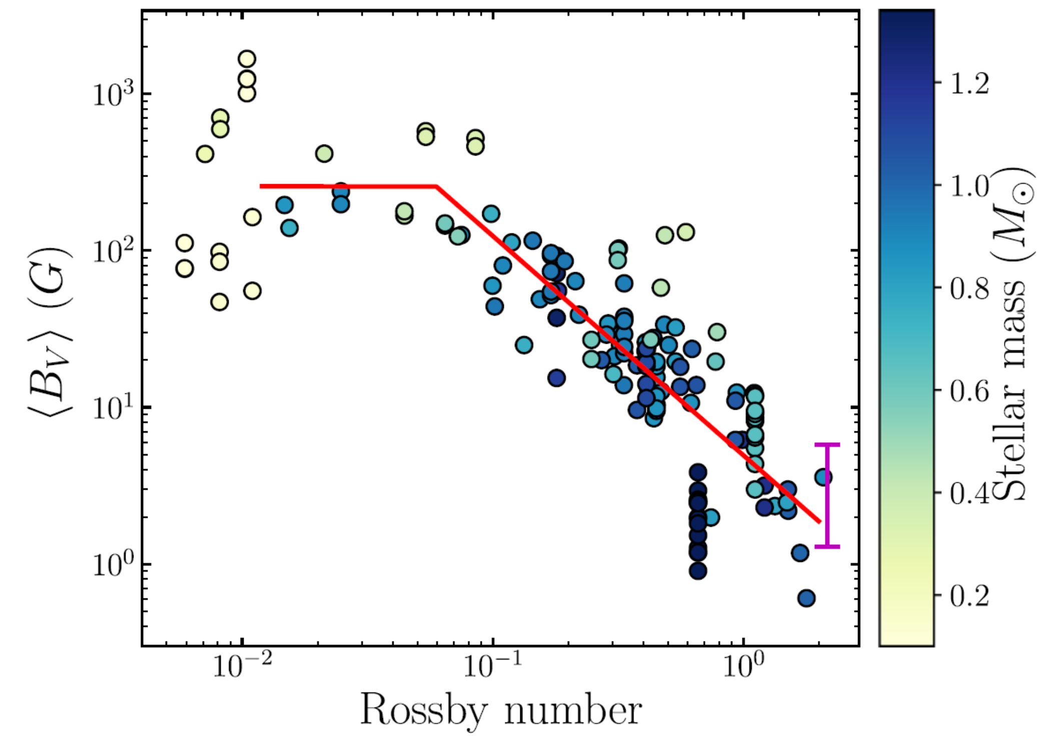
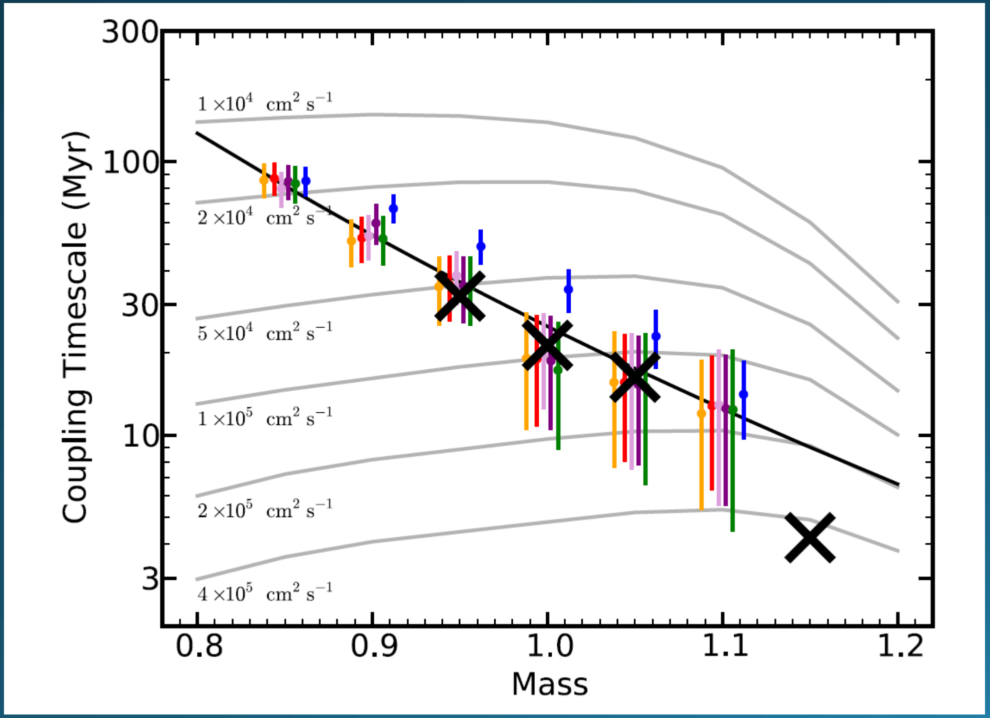
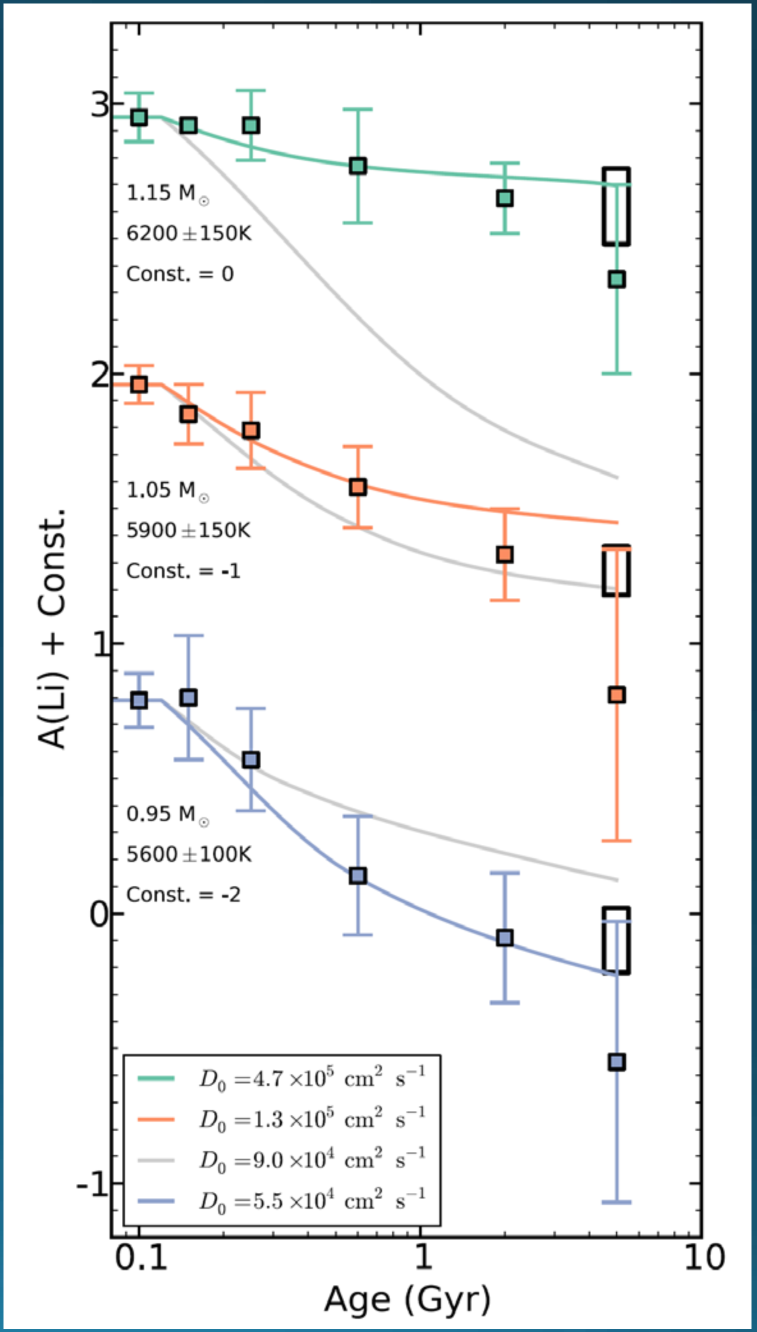


Figure 1. Average unsigned photospheric magnetic flux obtained from ZDI against Rossby number color coded by stellar mass. The three-parameter fit (solid red line) has a saturated field strength of $\langle B_V \rangle_{sat} = 257 \pm 72$ G, a critical Rossby number of $Ro_{crit} = 0.06 \pm 0.01$, and an unsaturated regime slope value of $\beta = -1.40 \pm 0.10$. The magenta strut represents the range of $\langle B_V \rangle$ values over cycle 24 (the magnetograms used to calculate this range were truncated to $\ell_{max} = 5$; see the text and Vidotto et al. (2018) for additional details).

Lithium Depletion Consistent with Angular Momentum Models

Somers & Pinsonneault 2016

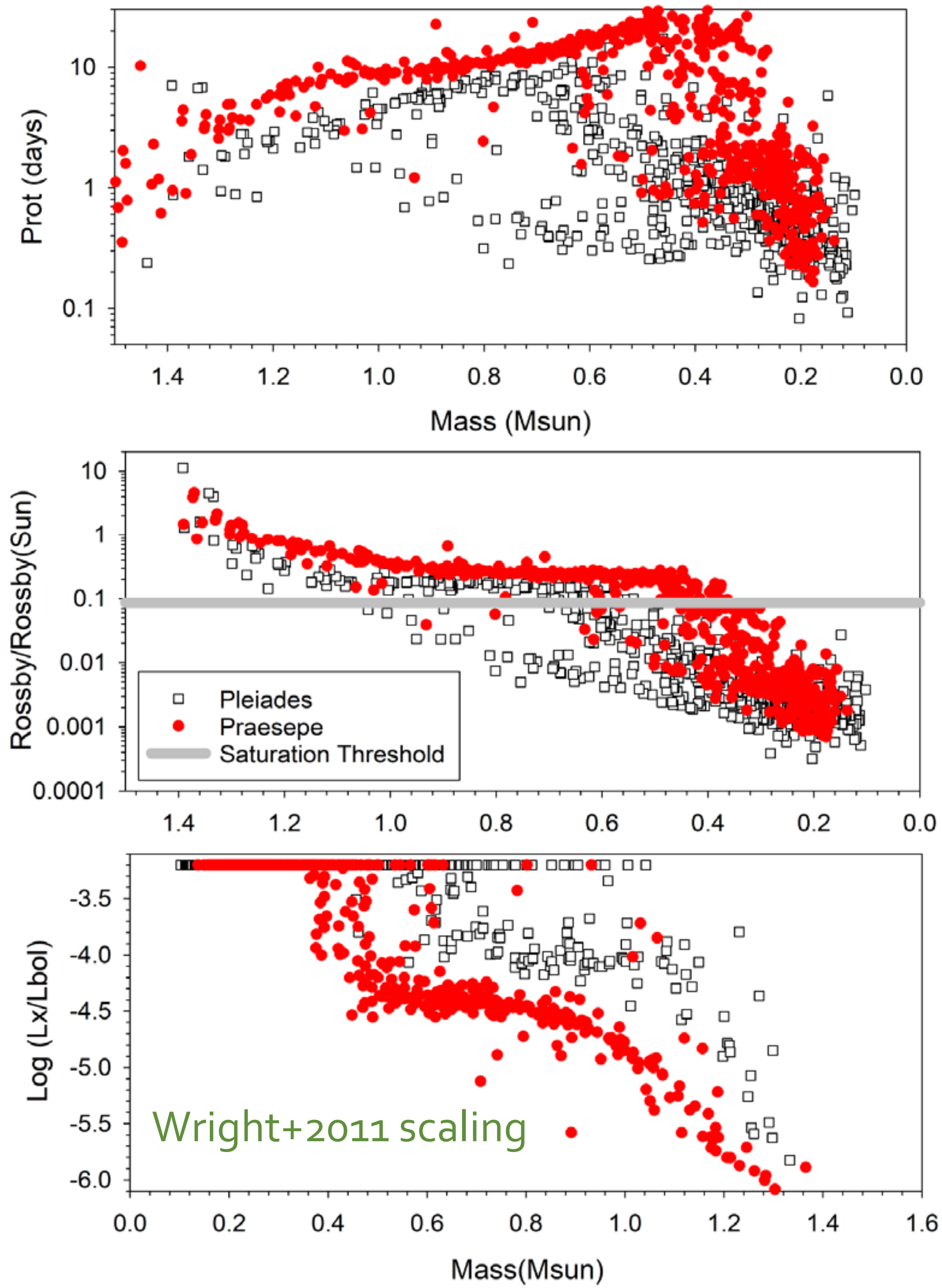




On M Dwarf Habitability

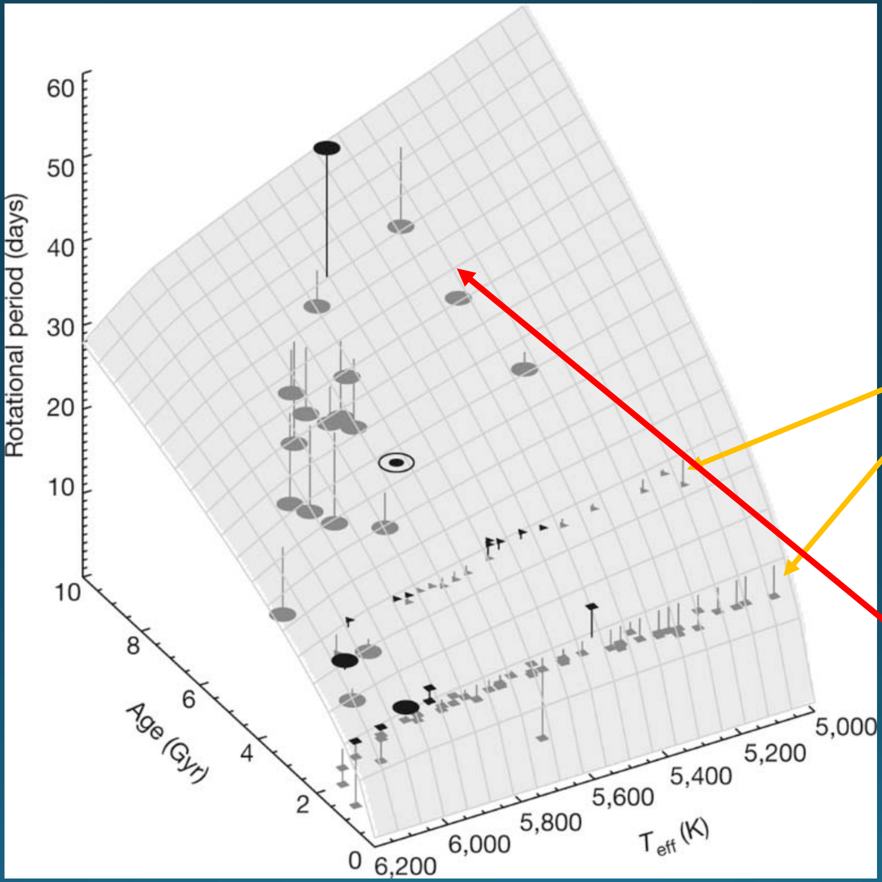
- For M > 0.7 Msun, most stars are always slow
- For M < 0.5 Msun, *all* stars are fast
- X-ray environment in late M dwarfs is intense for extended time

- "sweet spot" ~0.5 Msun



Spindown Stalls In Old Stars!

The period–age plane as predicted by gyrochronology, compared with observed periods.

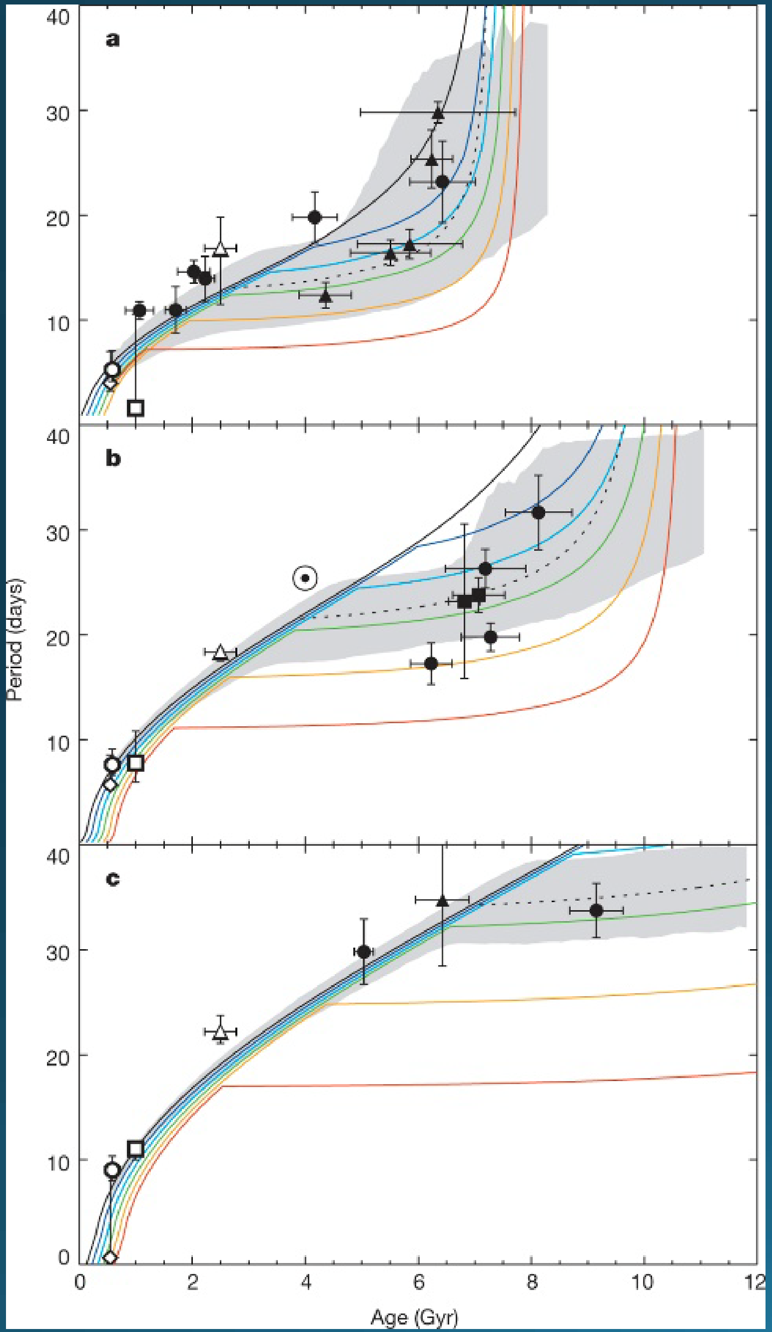


Models Calibrated On Clusters 1-2 Gyr Old…

Predict Rotation Periods Longer Than The Data

van Saders *et al.* 2016)

nature



Requires Inefficient Magnetized Torques Below The Solar Activity Level

STRONG IMPLICATION:
The Clock Stops for Stars Less Active than the Sun