The Importance of Accretion and Outflows for Young Star Spins

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I will discuss theoretical models of angular momentum transport, due to both accretion and outflows, highlighting how they are helping us to understand the observed spin rates of pre-main-sequence and young stars.

Subject :	:	oral
Topics	:	Astrophysics

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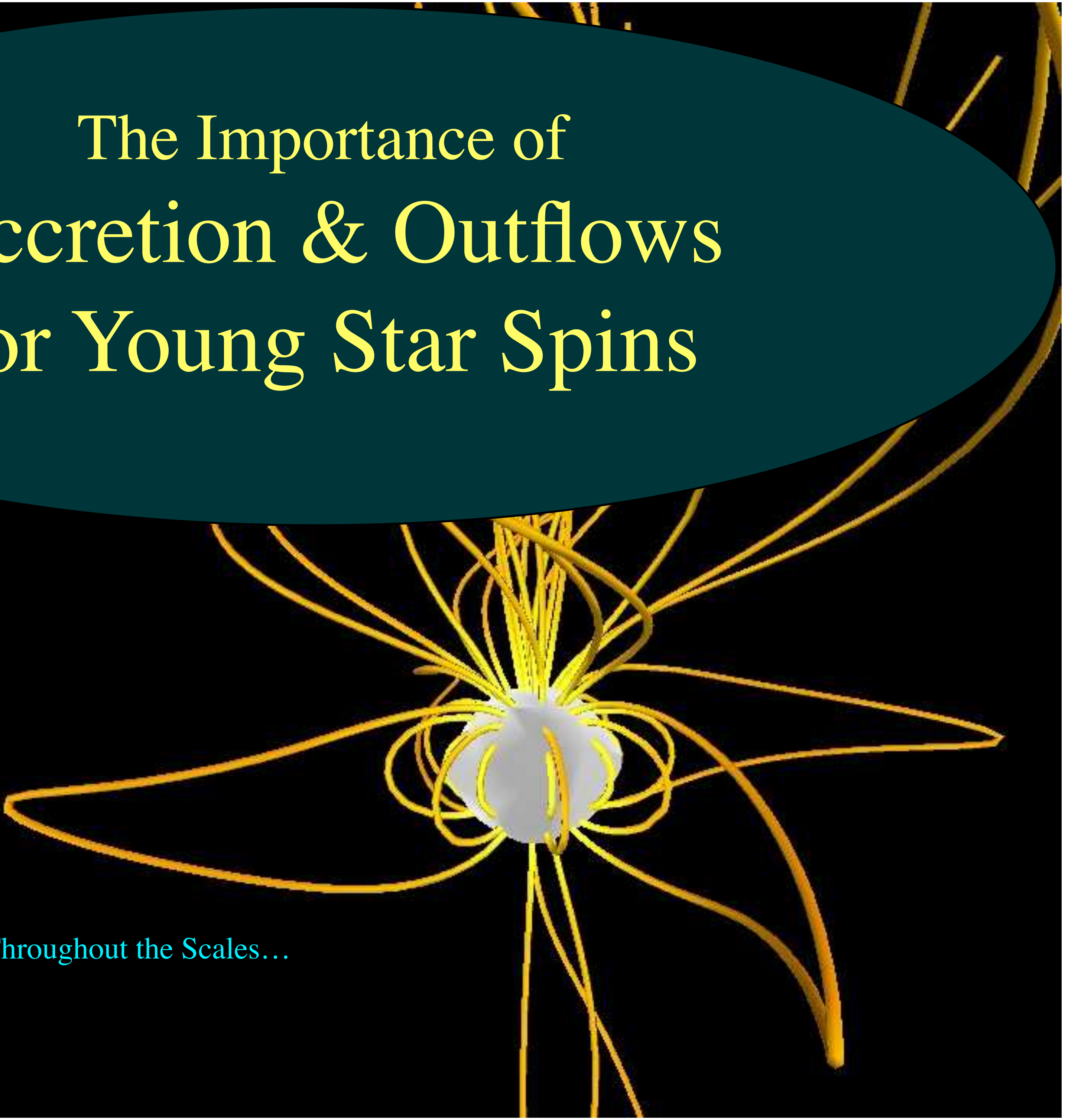
UNIVERSITY OF EXETER



Accretion & Outflows Throughout the Scales…

Lyon, France

October 1, 2014

Focus of Talk

- Accretion and outflows transport angular momentum

- Sun-like stars (<1.3 M_{sun}; GKM stars)

Matching models and observations of spin rates gives us new information about accretion and outflow histories and the magnetic properties of the central object.

Outline

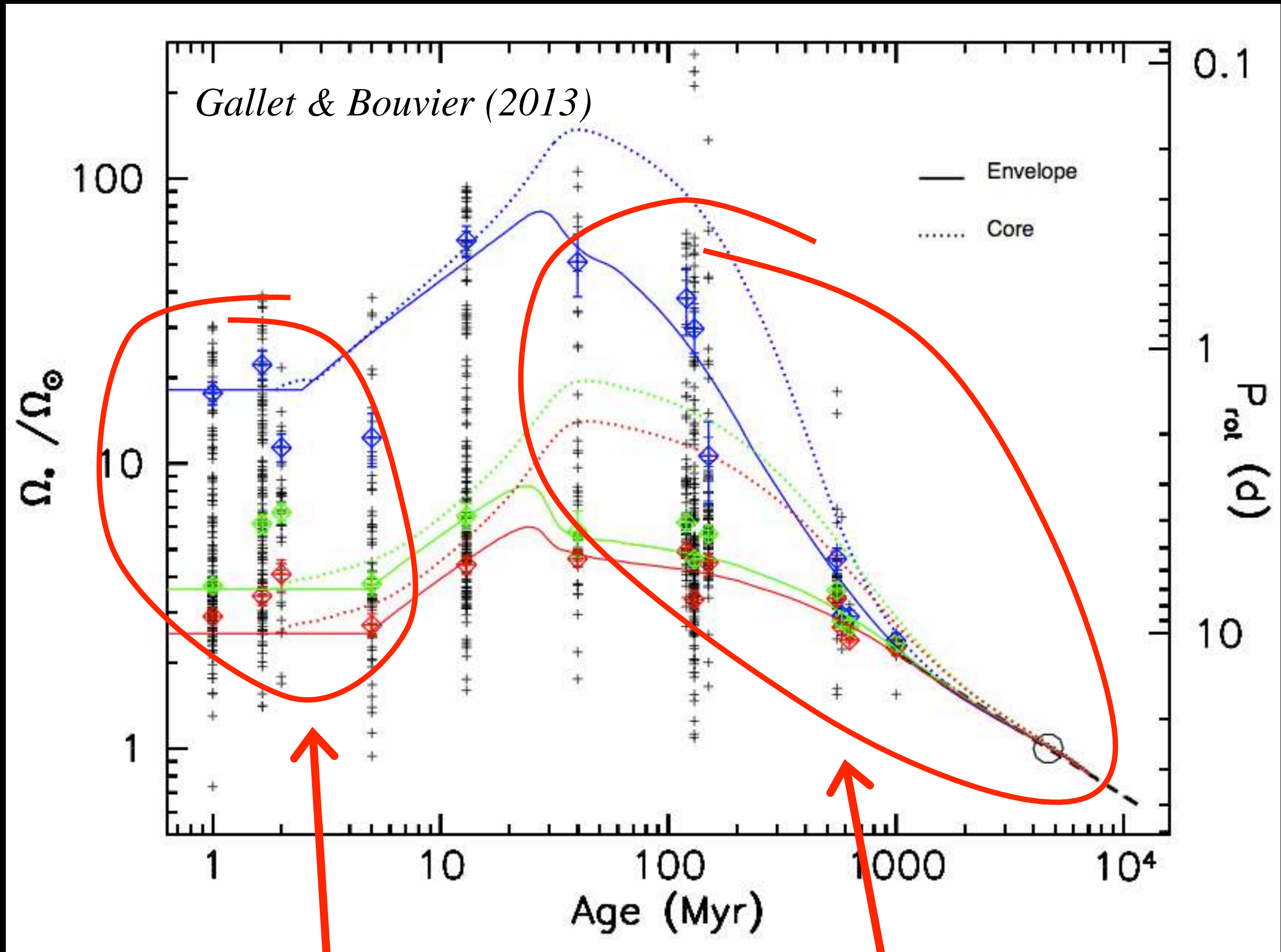
1. Rotation & Magnetic Activity

2. Post-Accretion Phase & Wind Torque

3. Accretion Phase & Star-Disk Interaction

4. Conclusion

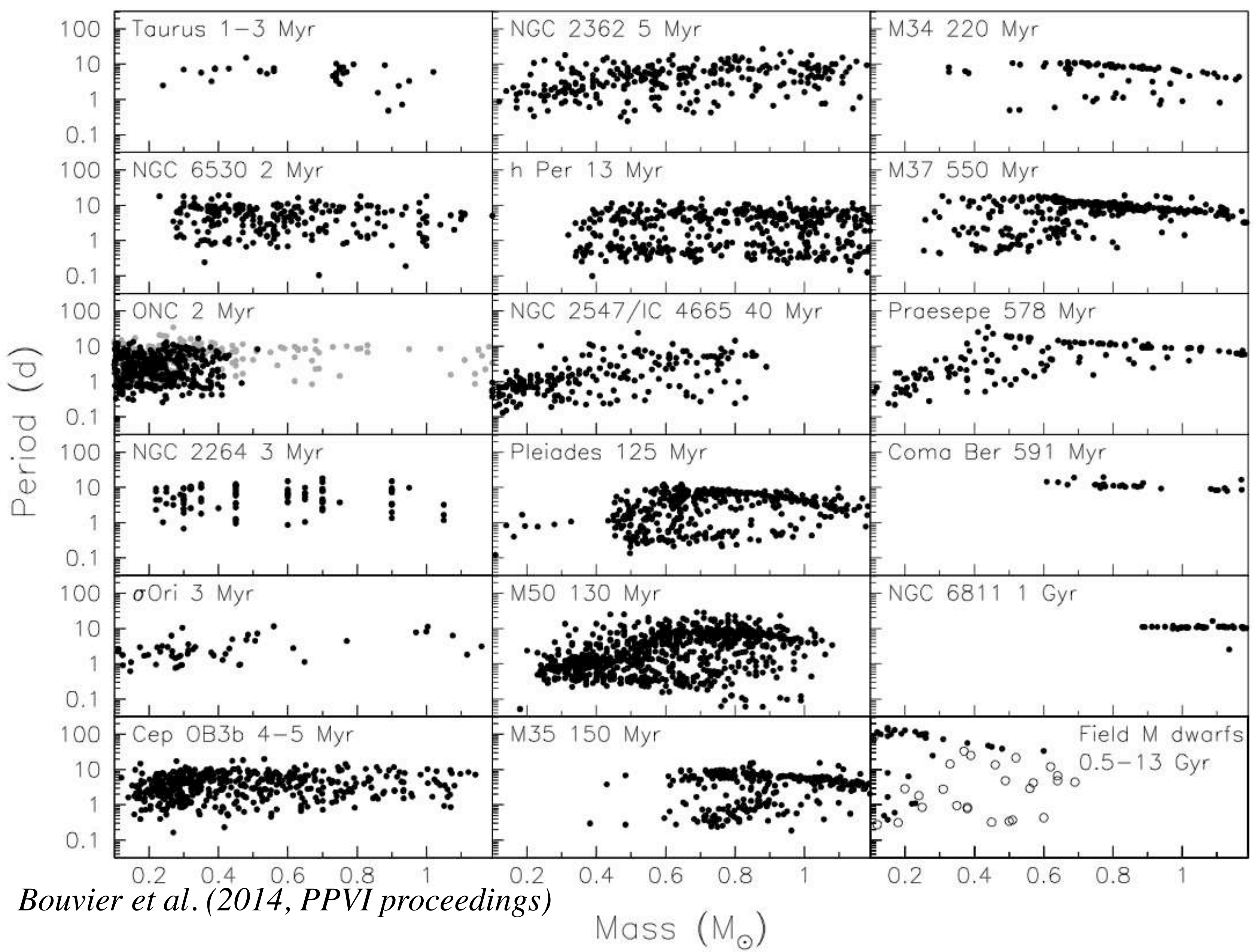
Spin Evolution of Solar Mass Star



Accretion phase:
"Initial" distribution?
Slow rotation?

Skumanich (1972) relationship:
spin rate, $\Omega_* \propto t^{-1/2}$

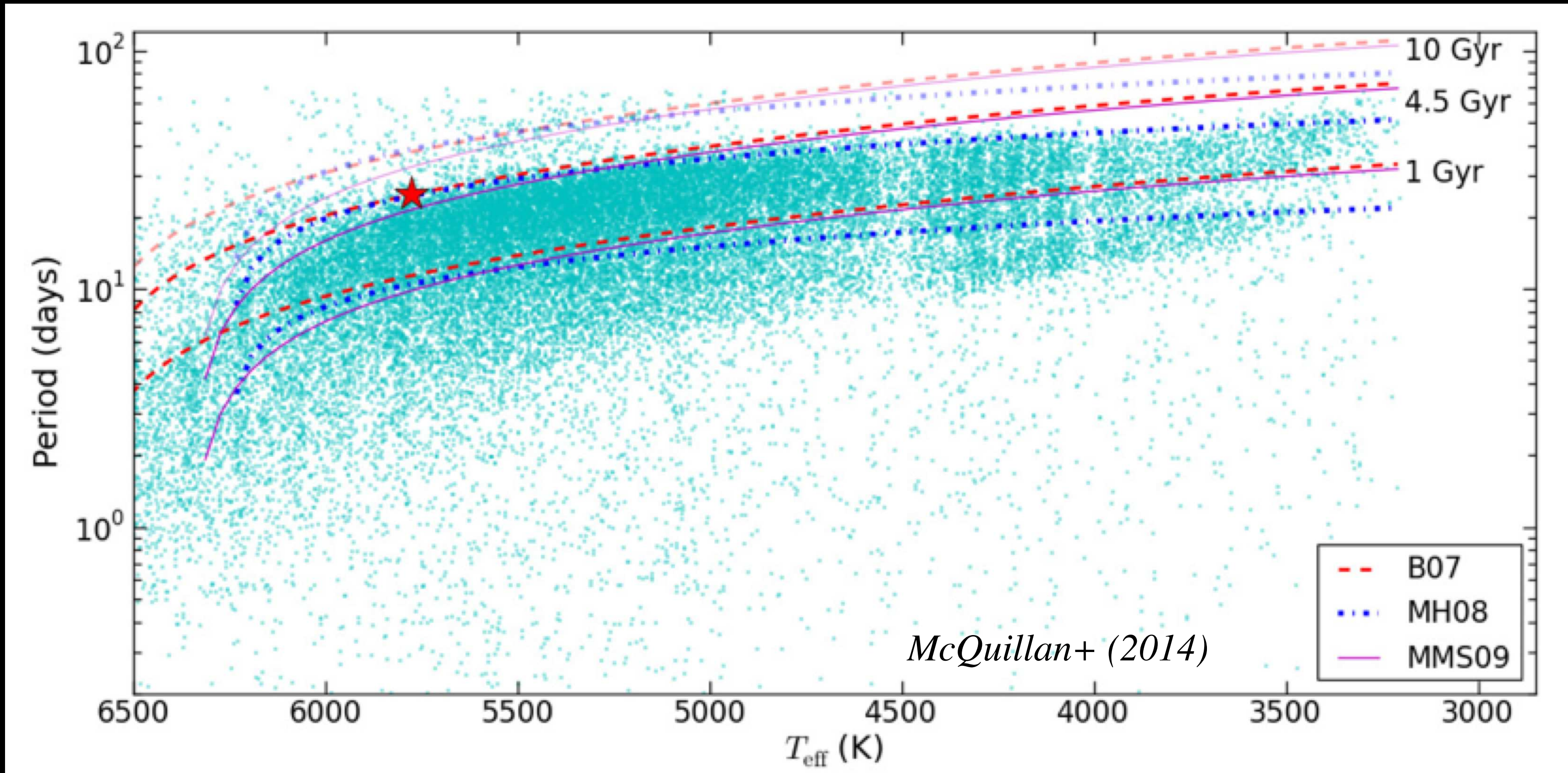
Observations of Stellar Rotation



Bouvier et al. (2014, PPVI proceedings)

~5000 new photometric periods since 2007 (in ~30 publications)

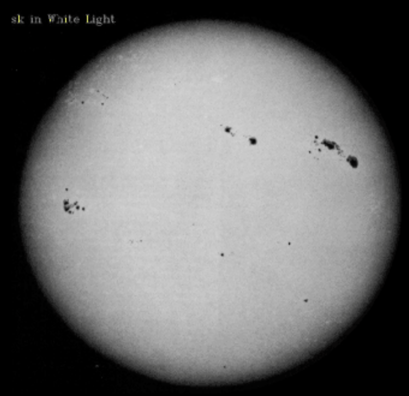
Field Stars & Gyrochronology

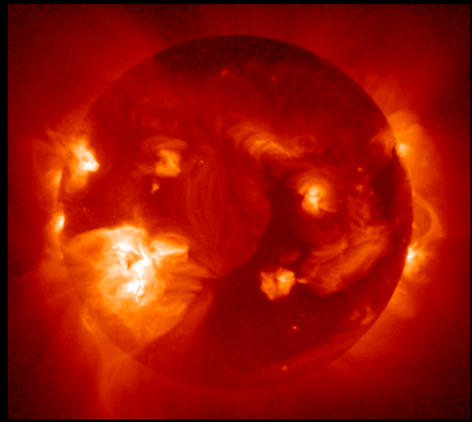


~34000 rotation periods from Kepler field stars.

Rotation & convection produces magnetic activity

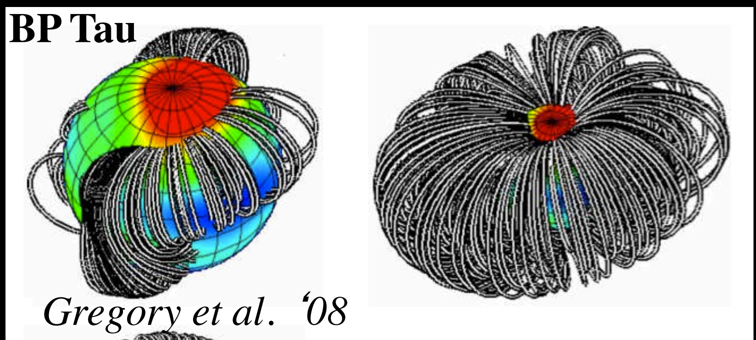
magnetic fields, spots, high energy radiation, winds…





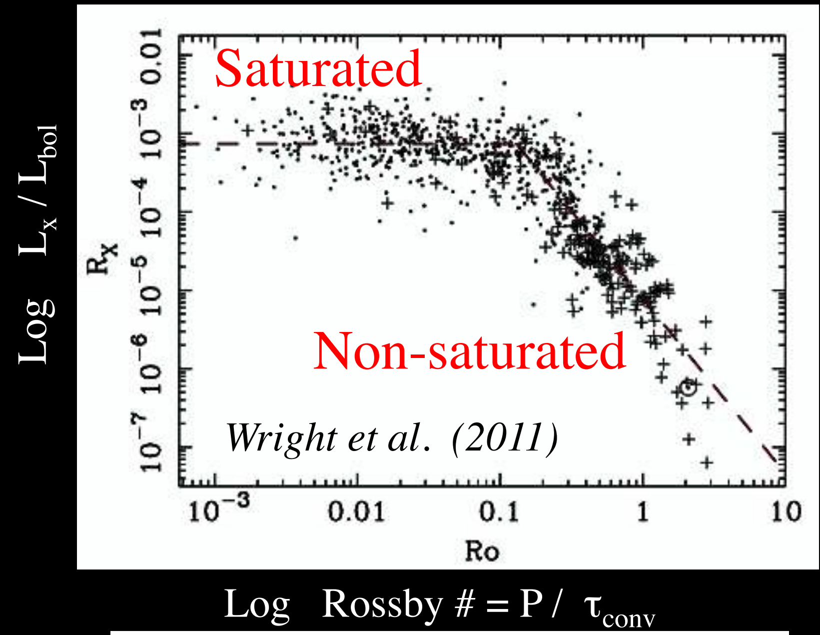
Dynamo models...

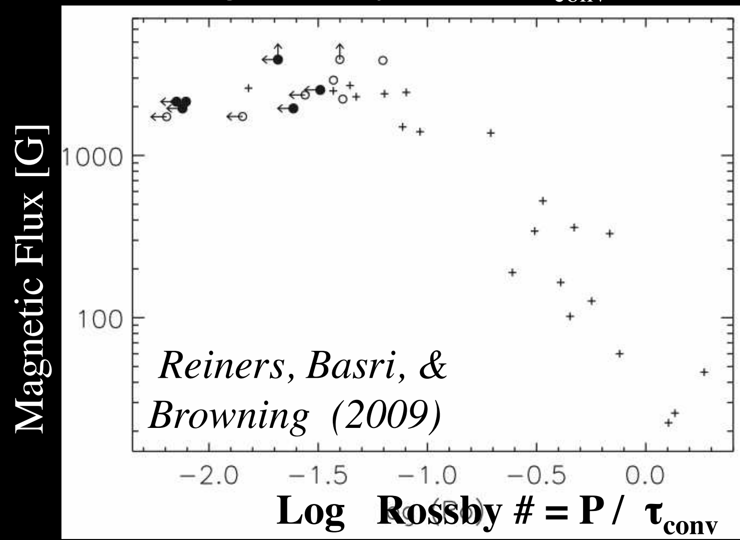
Magnetic field measurements
(e.g., Johns-Krull 07; Donati & Landstreet 09; Gregory+ 10; Morin+ 11)



Magnetic properties depend on mass, rotation, & age.

Rotation-activity relationship



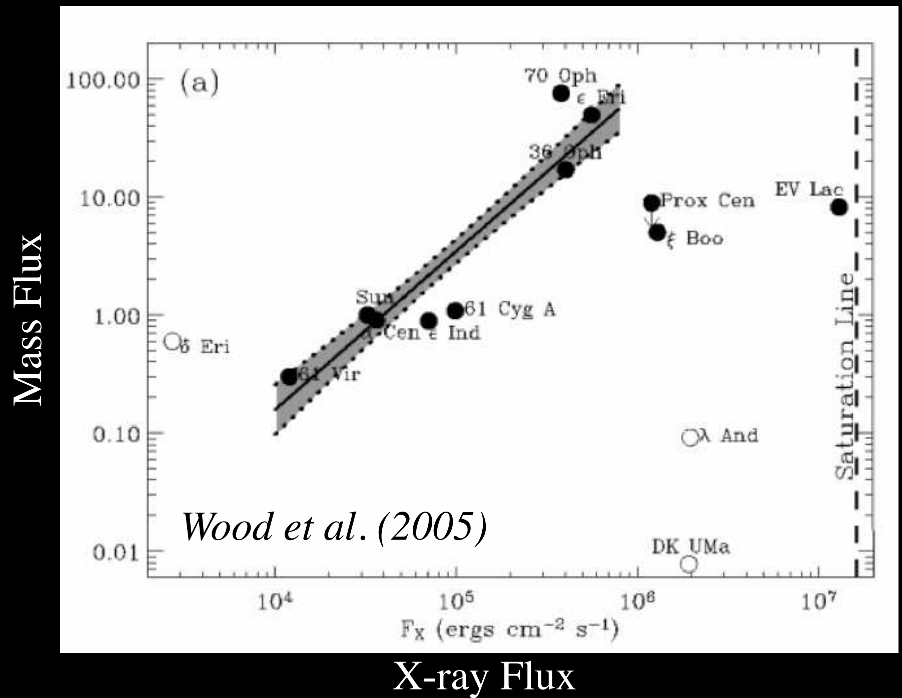


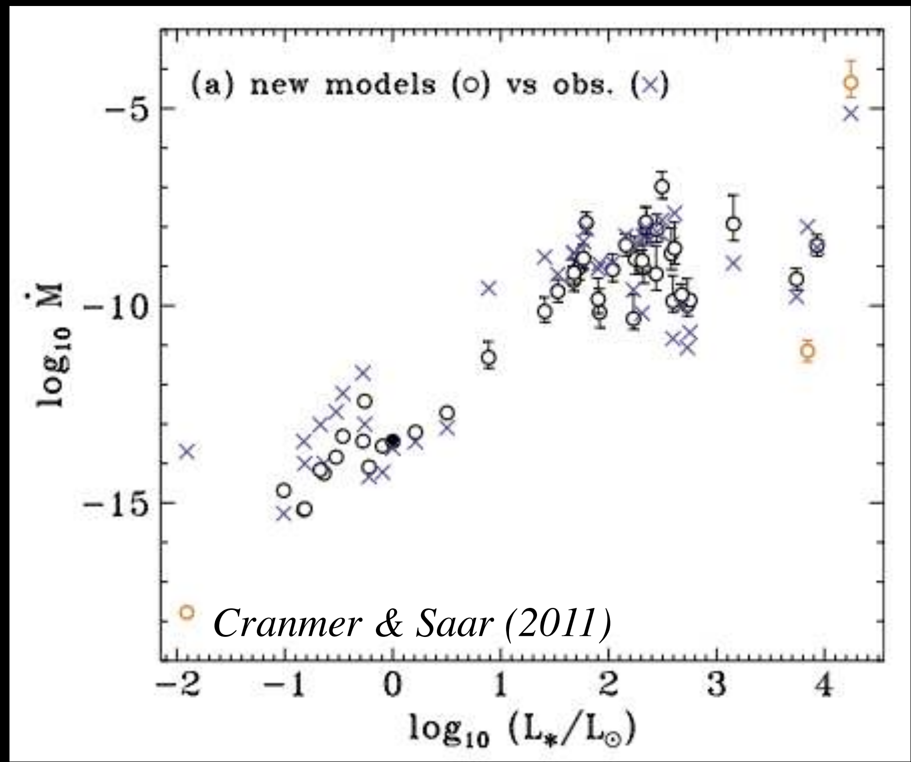
Convection & B-field produces stellar winds

Solar wind *(Parker 1958)* $\dot{M}_w \sim 3 \times 10^{-14}\ M_{sun}/yr$

- Observations of $\dot{M}_w$
  (e.g., Wood et al. 2002, 2005)

- Theoretical predictions of $\dot{M}_w$
  (e.g., Cranmer & Saar 2011; Suzuki et al. 2013)





- CME $\dot{M}_w$ inferred from flares *(Aarnio+ 12; Drake+ 12)*

Saturation of mass loss rate?

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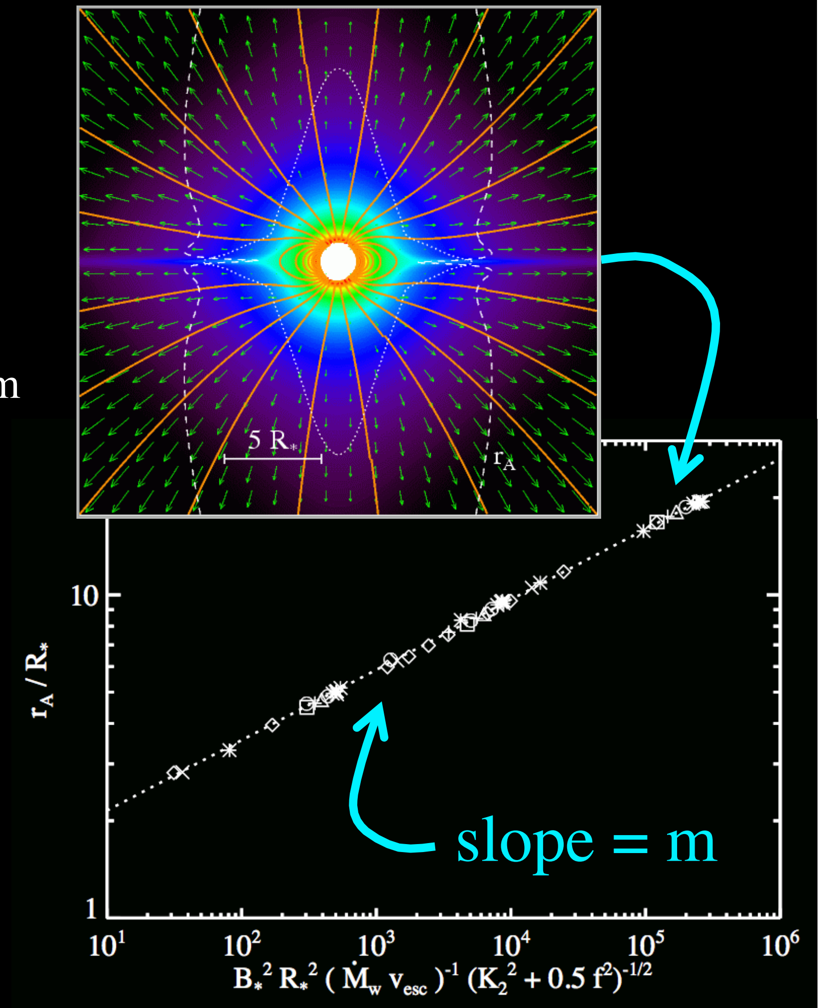
Stellar Wind Torque

$$T_w = K \; (2GM_*)^{-m} \; R_*^{5m+2} \; \dot{M}_w^{1-2m} \; B_*^{4m} \; \Omega_*$$

Fit to simulations w/ dipole field:

(Matt & Pudritz 08; Matt+ 12, Ud-Doula+ 09; Pinto+ 11)

$m \approx 0.22$ & $K \approx 6.2 \; [1 + (f/0.072)^2]^{-m}$



Unanticipated by analytic work (e.g.):

Kawaler (1988): $m = 0.5$

Reiners & Mohanty (2012): $m = 2/3$

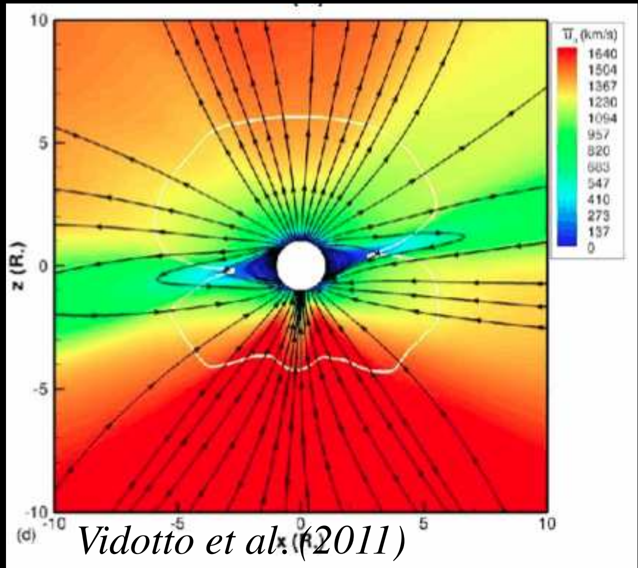
(see also Mestel 84)

Matt et al. (2008, 2012)

Stellar Wind Torque, More Progress

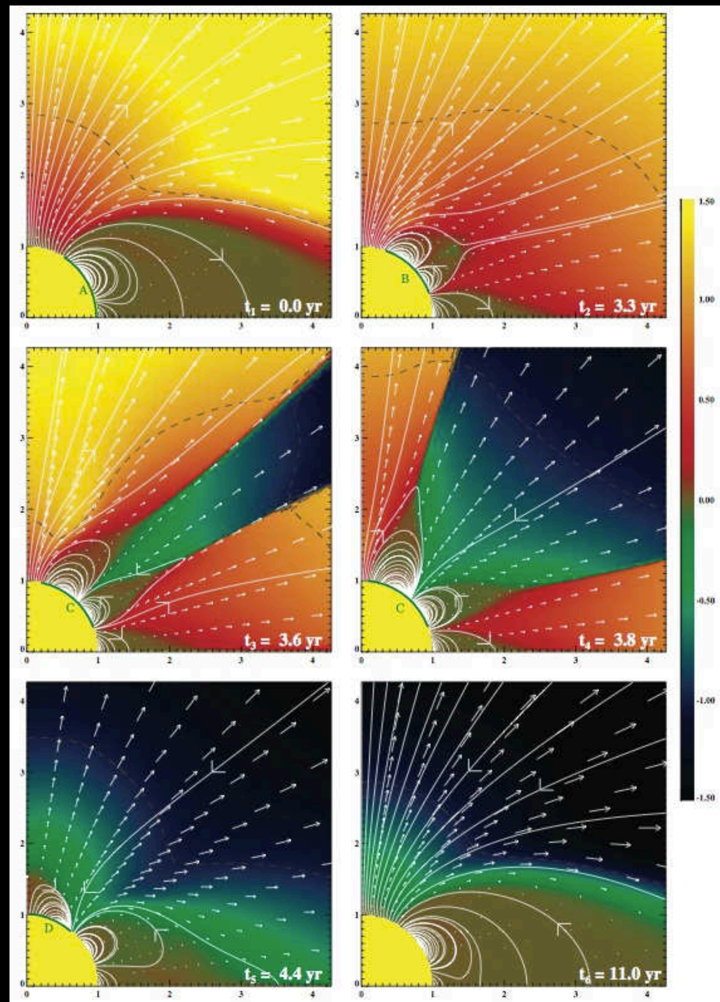
Realistic (observed) B-fields

(e.g., Matt & Pudtirz 08, Cohen + 09, Vidotto+ 10, 11)



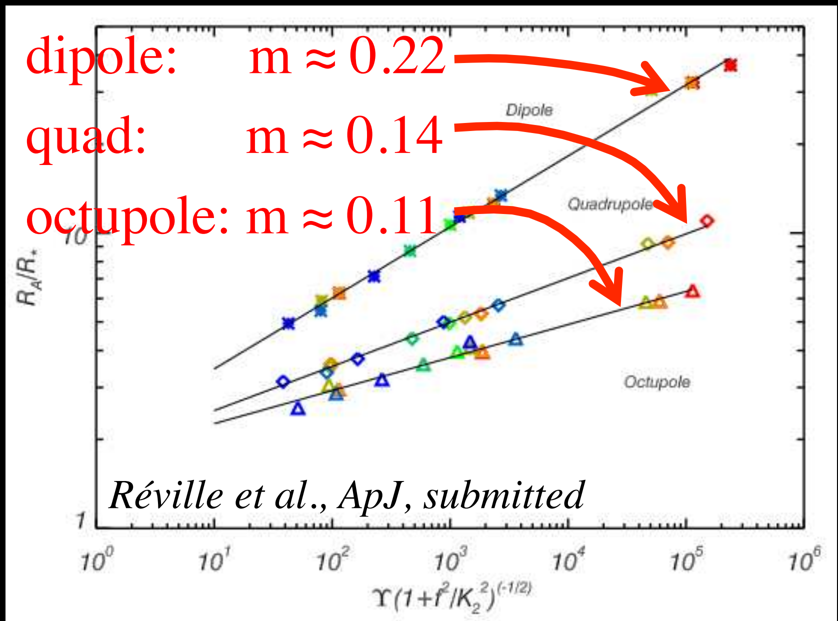
Vidotto et al. (2011)

Time-variability (e.g., solar cycle)



Pinto et al. (2011)

Systematic Study



Réville et al., ApJ, submitted

Evolution of Stellar Spin Rate

$$d\Omega_*/dt \;=\; T_w / I_* \;-\; \Omega_* / I_* \;\; dI_*/dt$$

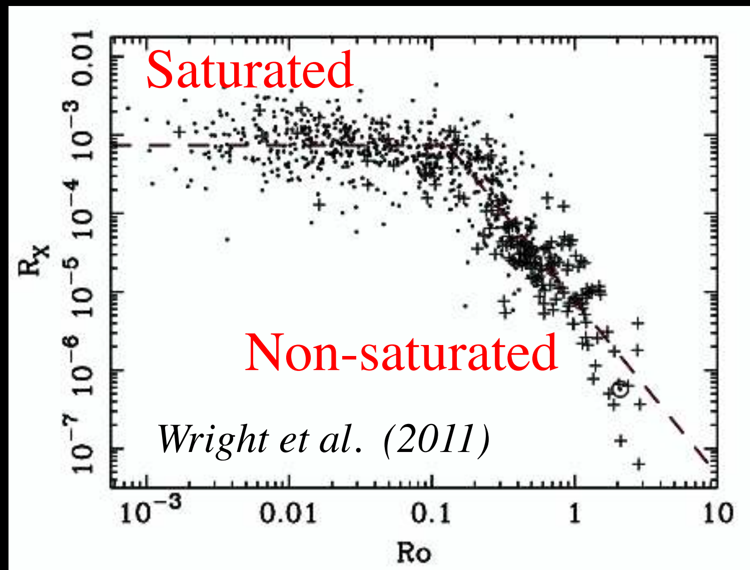
$$T_w \;=\; K \;\; (2GM_*)^{-m} \;\; R_*^{5m+2} \;\; \dot{M}_w^{1-2m} \;\; B_*^{4m} \;\; \Omega_*$$

- Physical torque relates spin, B_*, and $\dot{M}_w$ *(Matt et al. '08, '12)*

To explain observations, e.g.:
(Matt et al. 2014, ApJL, submitted)

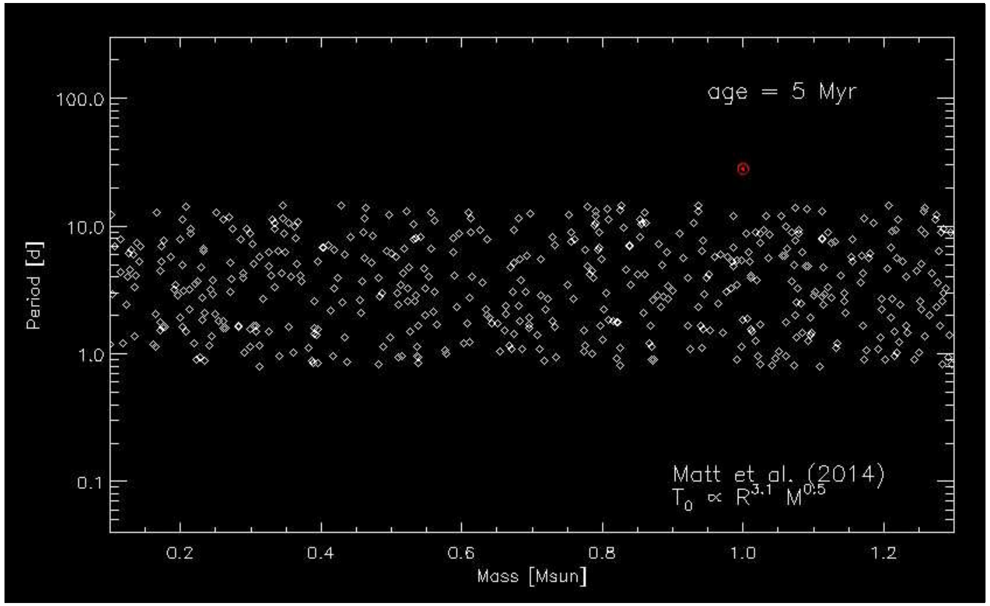
$$B_* \;\propto\; R_o^{-1}$$
$$\dot{M}_w \propto \;\; M_*^{1.3} \;\; R_o^{-2}$$

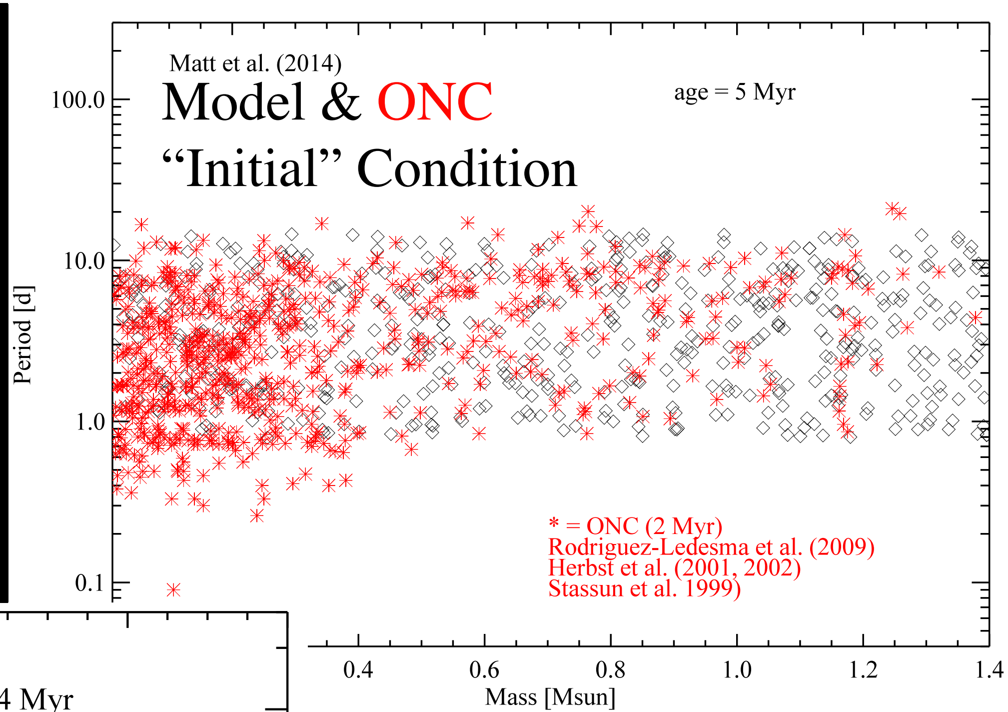
+ Saturation at 10 x solar R_o
+ Dipole field (m = 0.22)

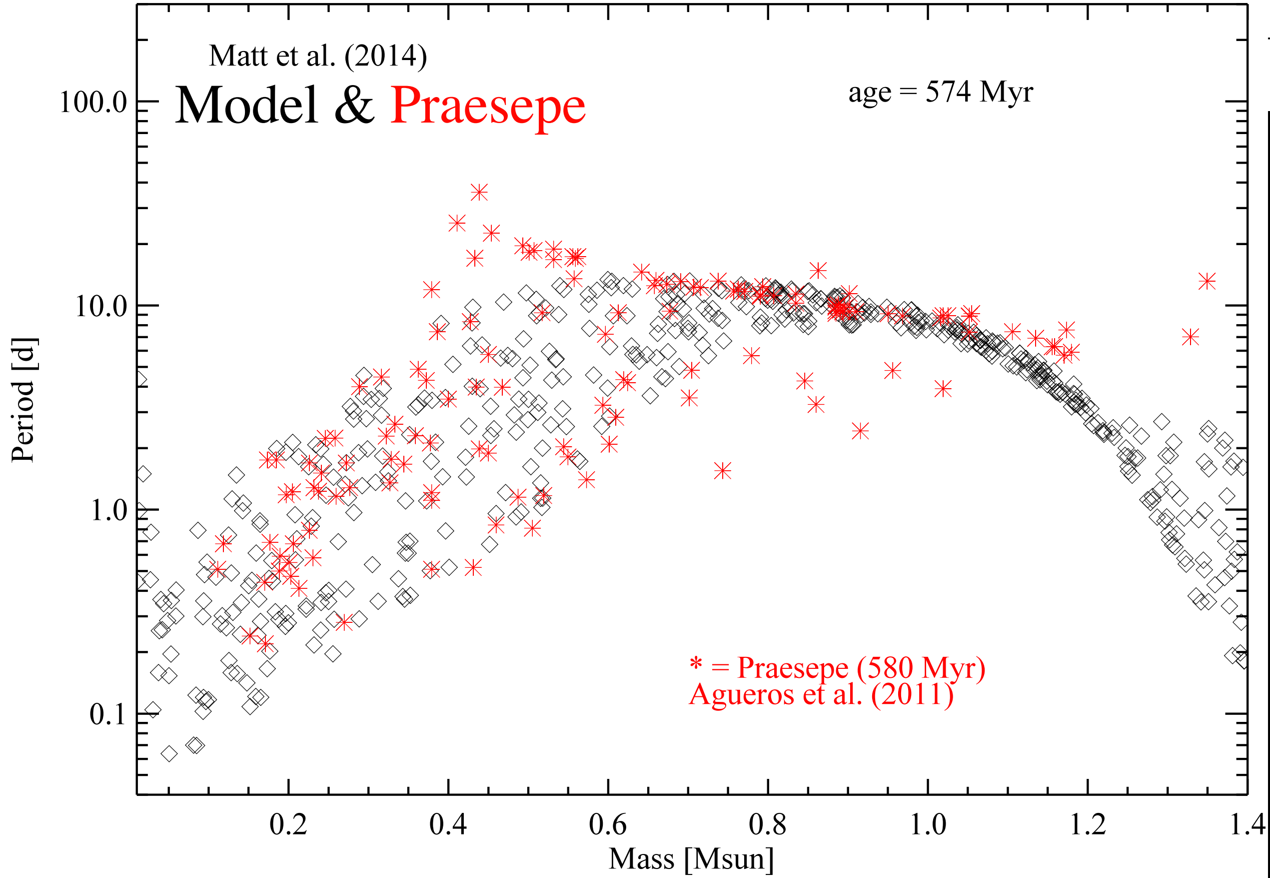


Log L_x / L_{bol}

Log $R_o\# = (\Omega_*\, \tau_{conv})^{-1}$







Assumes:

(Matt et al. 2014, ApJL, submitted)

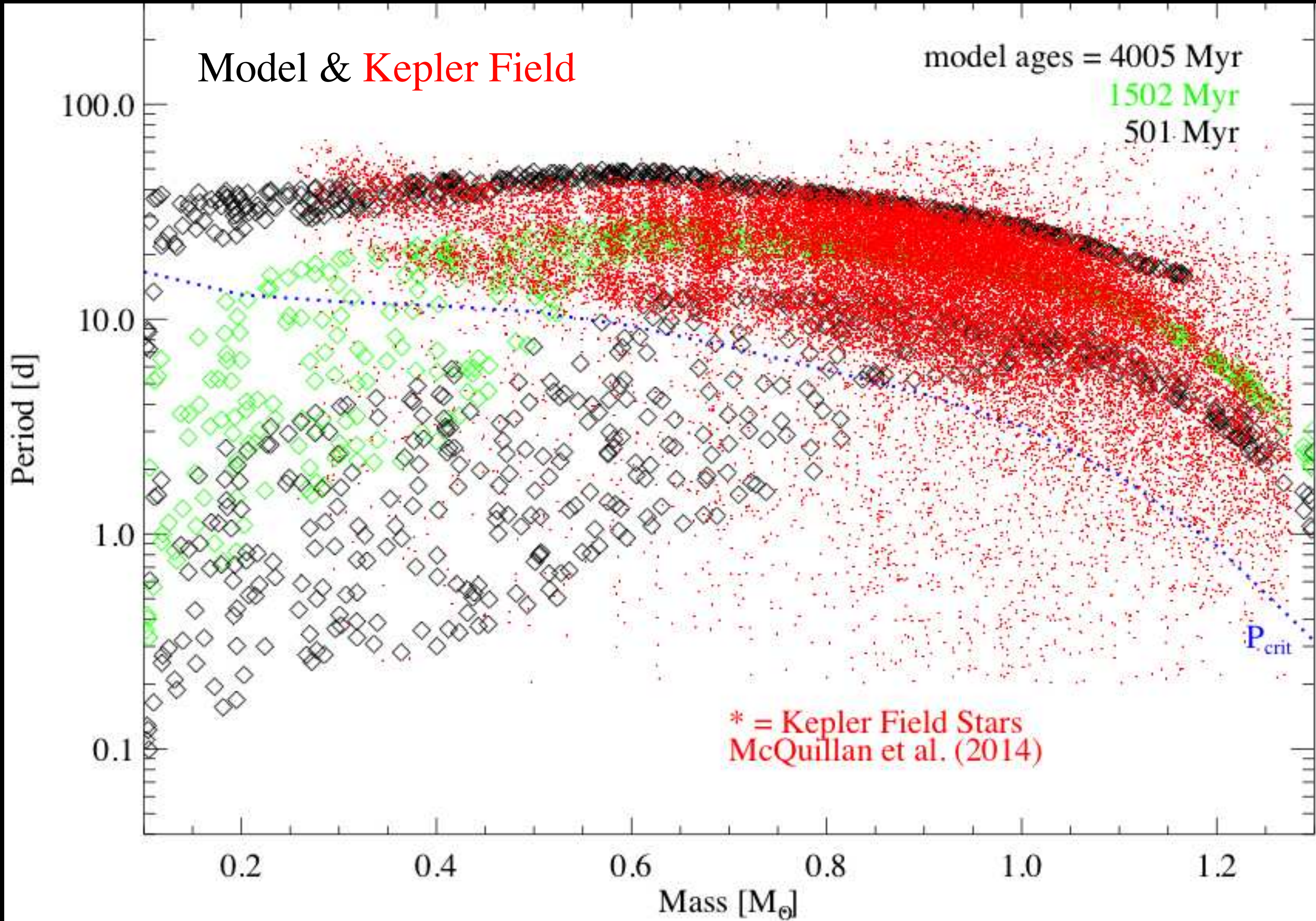
$B_* \propto R_o^{-1}$

$\dot{M}_w \propto M_*^{1.3}\ R_o^{-2}$

+ Saturation

+ Dipole field

Solid-body rotation



Model & Kepler Field
model ages = 4005 Myr
1502 Myr
501 Myr
100.0
10.0
1.0
0.1
Period [d]
P_{crit}
* = Kepler Field Stars
McQuillan et al. (2014)
0.2
0.4
0.6
0.8
1.0
1.2
Mass [$M_\odot$]

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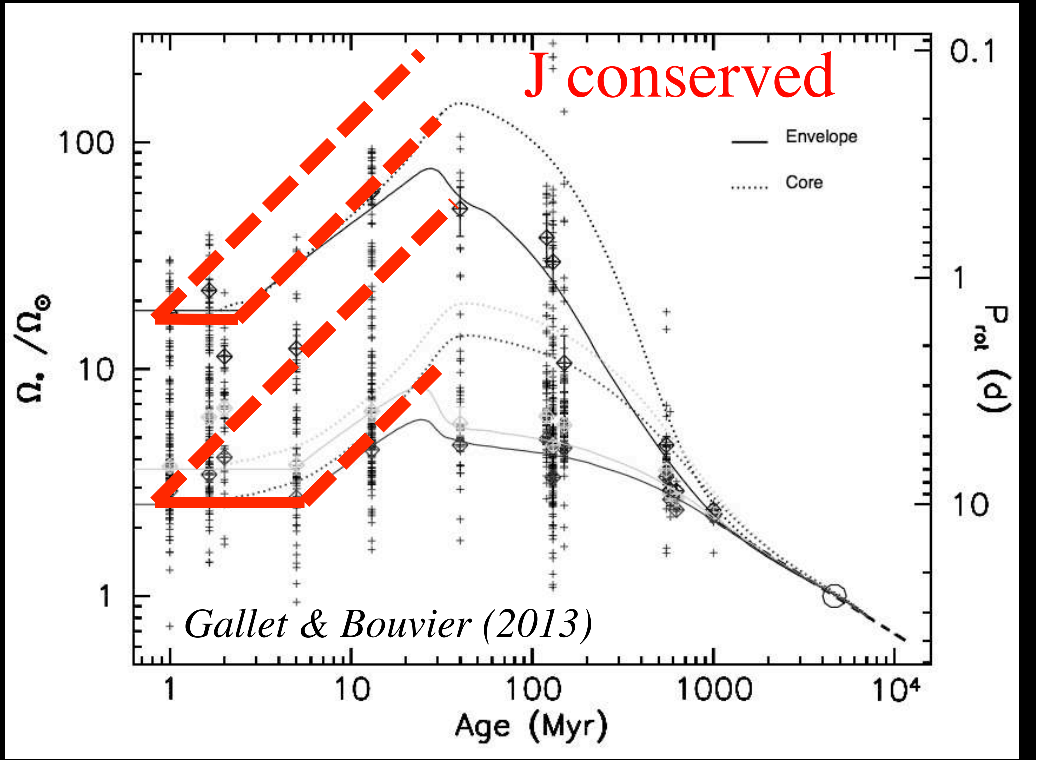
Earliest Stage

During early PMS:

To counteract contraction & accretion, $\tau_a = \dot{M}_a \sqrt{G M_* R_t}$

need ~10^6 × solar wind torque

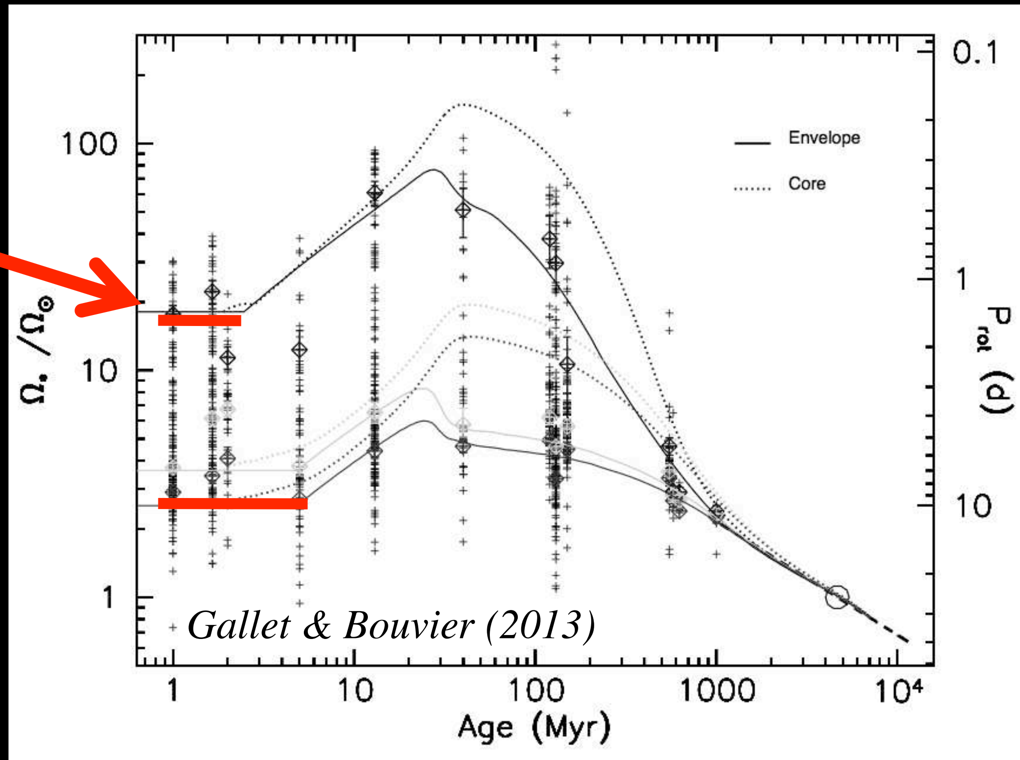


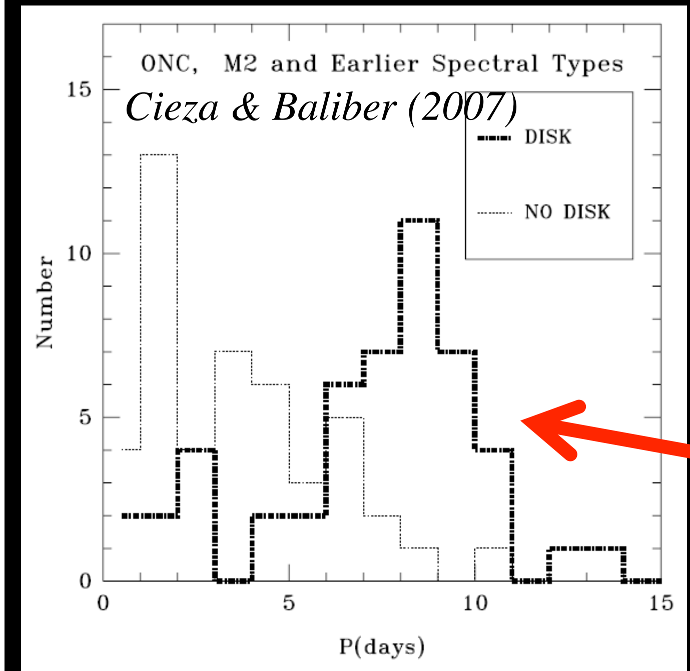
1. Can the star-disk interaction provide these torques? (tentative answer: Yes)
2. What happens before ~1 Myr?

Accreting Phase

Three flavors of "Disk Locking"

1. Constant rotation rate?
(e.g., Bouvier 95; Krishnamurthi+ 97; Rebull+ 04; Irwin+ 07; Denissenkov+ 10)





2. Correlation between accretion and rotation?
(Edwards+ 93; Bouvier+ 93; Choi & Herbst 96; Mohanty+ 05; Rebull 06; Cieza & Baliber 07; Littlefair+ 10; Henderson & Stassun 12; Affer+ 13)

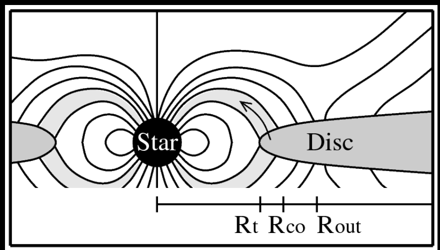
3. Star-Disk interaction models predict "equilibrium" spin rate.
(Konigl 91; Shu+ 94; Cameron & Campbell 93)

Accreting Phase

Accretion-Powered Stellar Winds

(*Hartmann & Stauffer 89; Matt & Pudritz 05*)

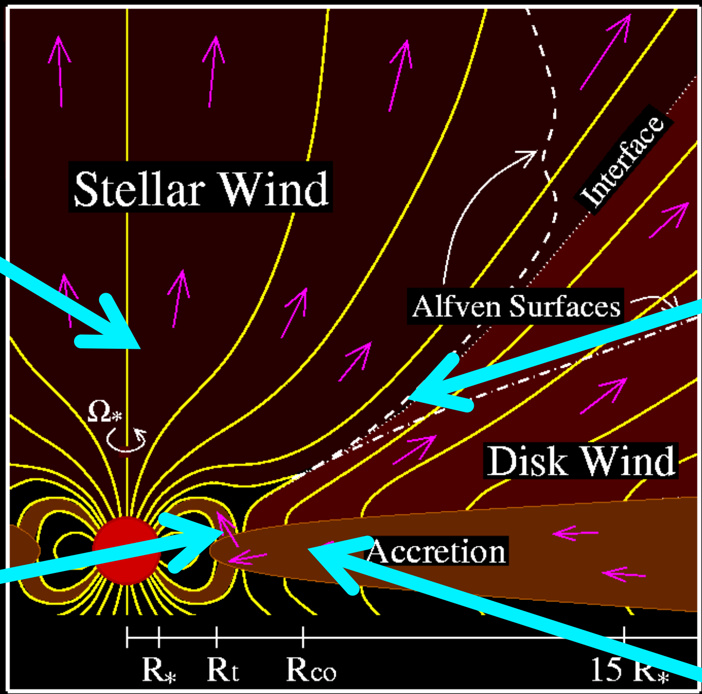
Magnetic Star-Disk Connection



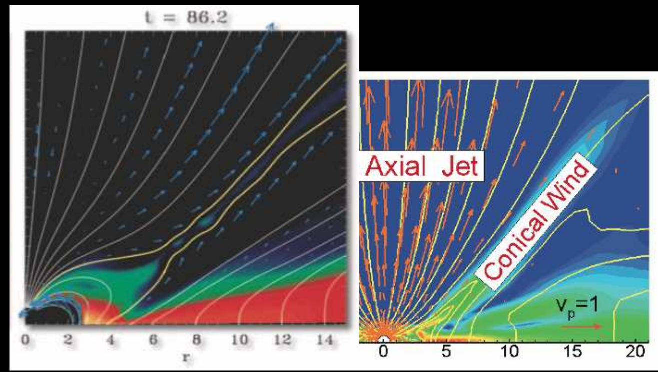
Ghosh & Lamb (78); Matt & Pudritz (05)

"propeller" regime?

D'Angelo & Spruit (11); Romanova et al. (09); Zanni & Ferreira (13)



Magnetospheric Ejections, Conical Winds



Zanni & Ferreira (13); Romanova et al. (09)

Disk "Viscosity"

(*Popham & Narayan 91*)

Gravitational Torques

(*Lin+ 11*)

Torques depend on:

M_* , R_* , Ω_*

B-field (& geometry)

accretion rate (& outflow rate)

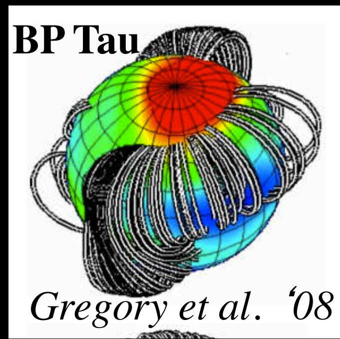
Star-Disk Interaction, More Progress

(still exploring mechanisms)

- APSW development *(Meliani+ 06; Matt & Pudritz 07, 08a,b; Cranmer 08, 09; Fendt 09; Zanni & Ferreira 11; Sauty+ 11; Matt+ 12)*

- New mechanism, MEs *(Zanni & Ferreira 13)*

- Effects of non-dipole fields:
  - disk truncation *(Gregory+ 08)*
  - MHD simulations *(Romanova+ 11; Long+ 07, 08, 09, 11)*

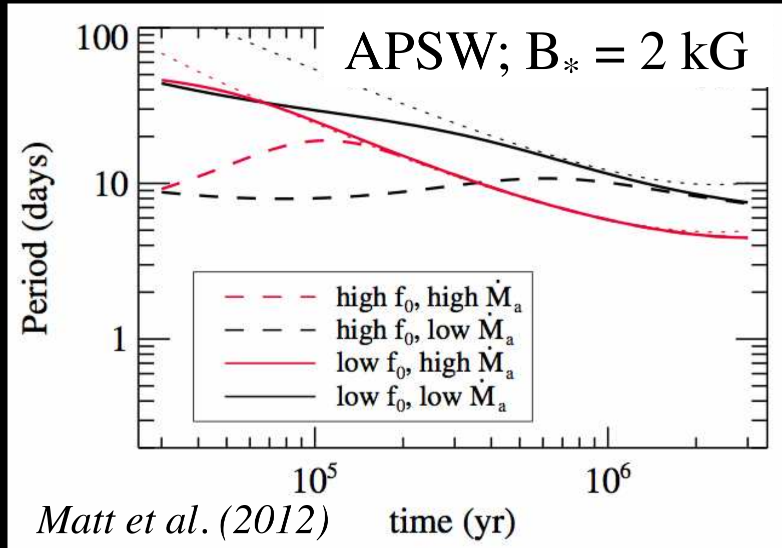


- Need torques calculated from simulations

- Obs. probes: e.g., Radiative transfer/high-res spectroscopy *(Kurosawa+ 06, 11, 12; Bouvier+ 07; Kwan+ 07; Fisher+ 08; Alencar+ 12)*

Accreting Phase, Spin Evolution

<u>Spin evolution models</u> (need more!)
(few since Armitage & Clarke 96: Matt+ 10, 12; Foucart & Lai 10; Lai 11; Campbell 11; Rosen & Krumholz 12)



Matt et al. (2012)

Ingredients:
- Stellar model
- Accretion history
- Magnetic properties
- S-D interaction model
- Include embedded phase

Q: Does "disk locking" work?
→ We don't know yet.

Q: Which mechanisms are most important?

→ A lot more work to do.

Conclusions

After accretion phase: A self-consistent picture

- Simulations give wind torques
- Spin models/obs. constrain mass loss and B_*
- Next: internal angular momentum transport

Accretion phase is more challenging

- Need better understanding of torque mechanism(s)
- Need realistic torque calculations
- Spin models/obs. will constrain accretion/outflow history and B_*