Angular momentum evolution of late-type stars

Florian Gallet

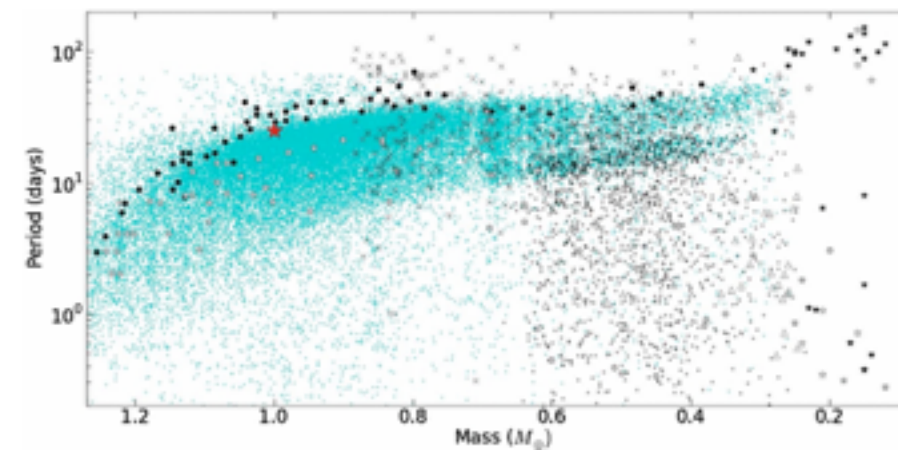
PLATO Barcelona 21/11/2019

Jérôme Bouvier (IPAG), Corinne Charbonnel (Geneva), Louis Amard (Exeter), Stephane Mathis (AIM Paris-Saclay), Emeline Bolmont (Geneva), Ana Palacios (LUPM)

Context

- Late-type stars = 0.3 - 1.2 M_{sun}
- Lots of rotational period measurements
  - CoRoT, Kepler, K2
  - Gaia DR2 (DR3/DR4)
  - Future => PLATO, JWST
- Strong observational constraints
- Two ways to model P_{rot}
  - Stellar model (ab-initio modeling)
  - Parametric model

Kepler MS field stars (34000+)



McQuillan et al. (2014)

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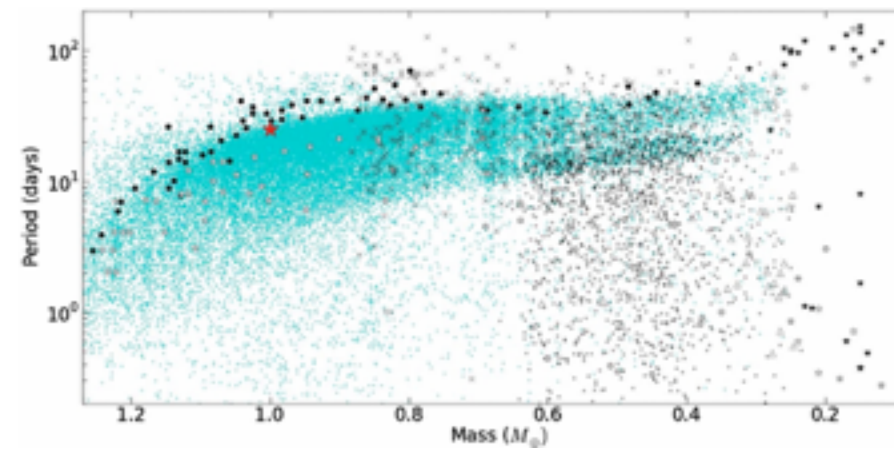

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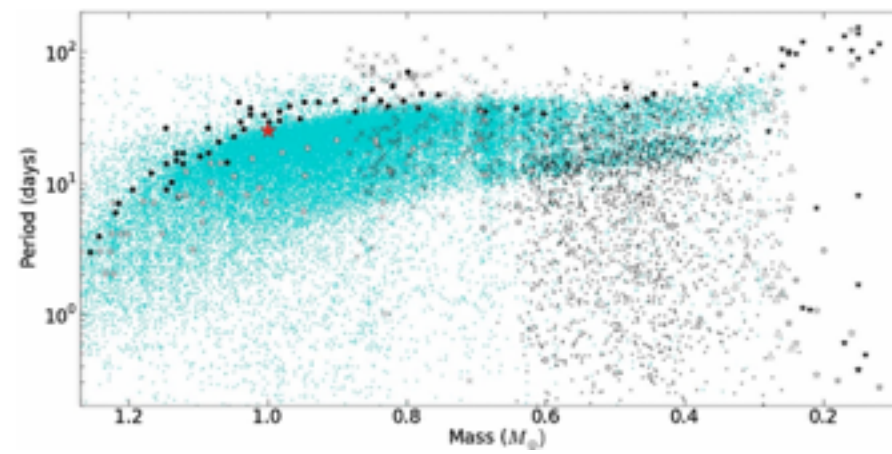

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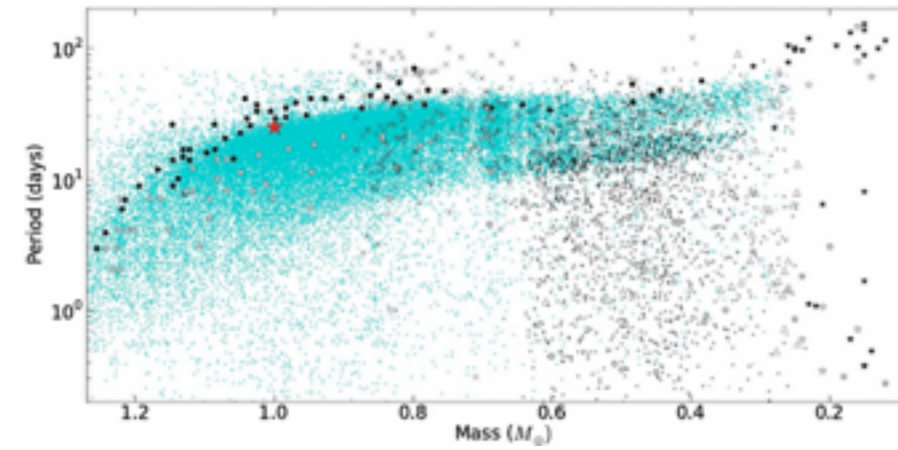

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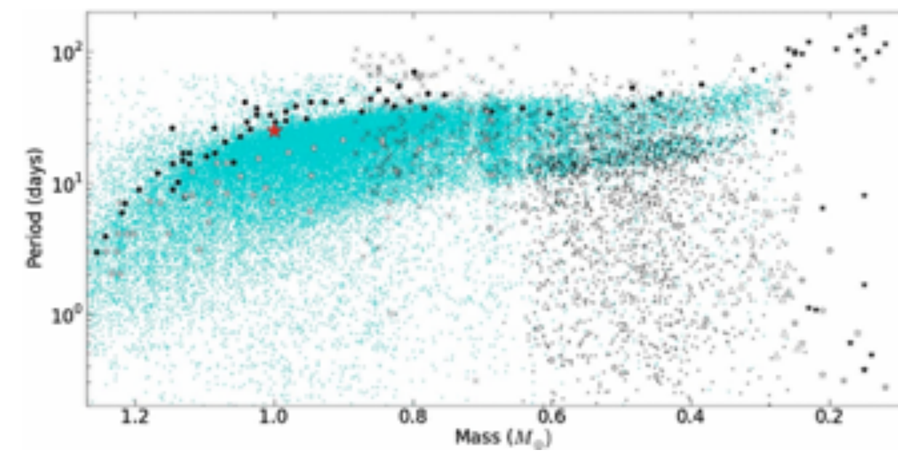

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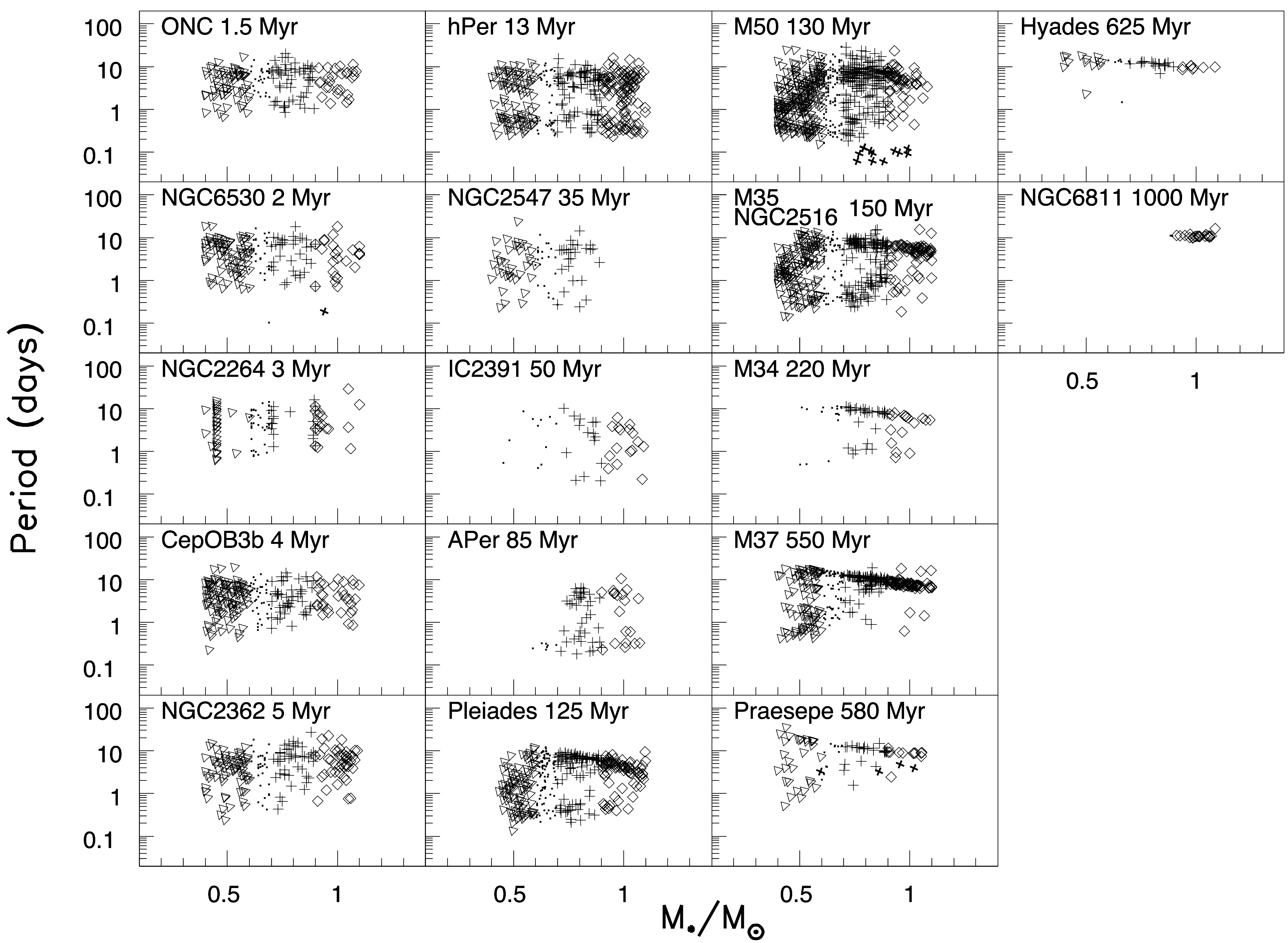
<u>Goal</u>

Use these observations to understand the general mechanisms involve in the AM evolution

Observed rotational evolution

Solar mass stars



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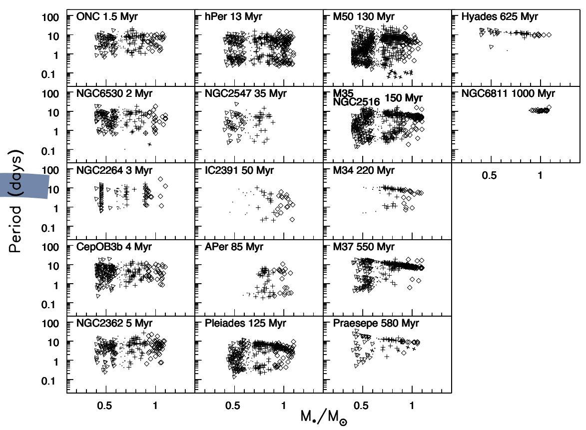
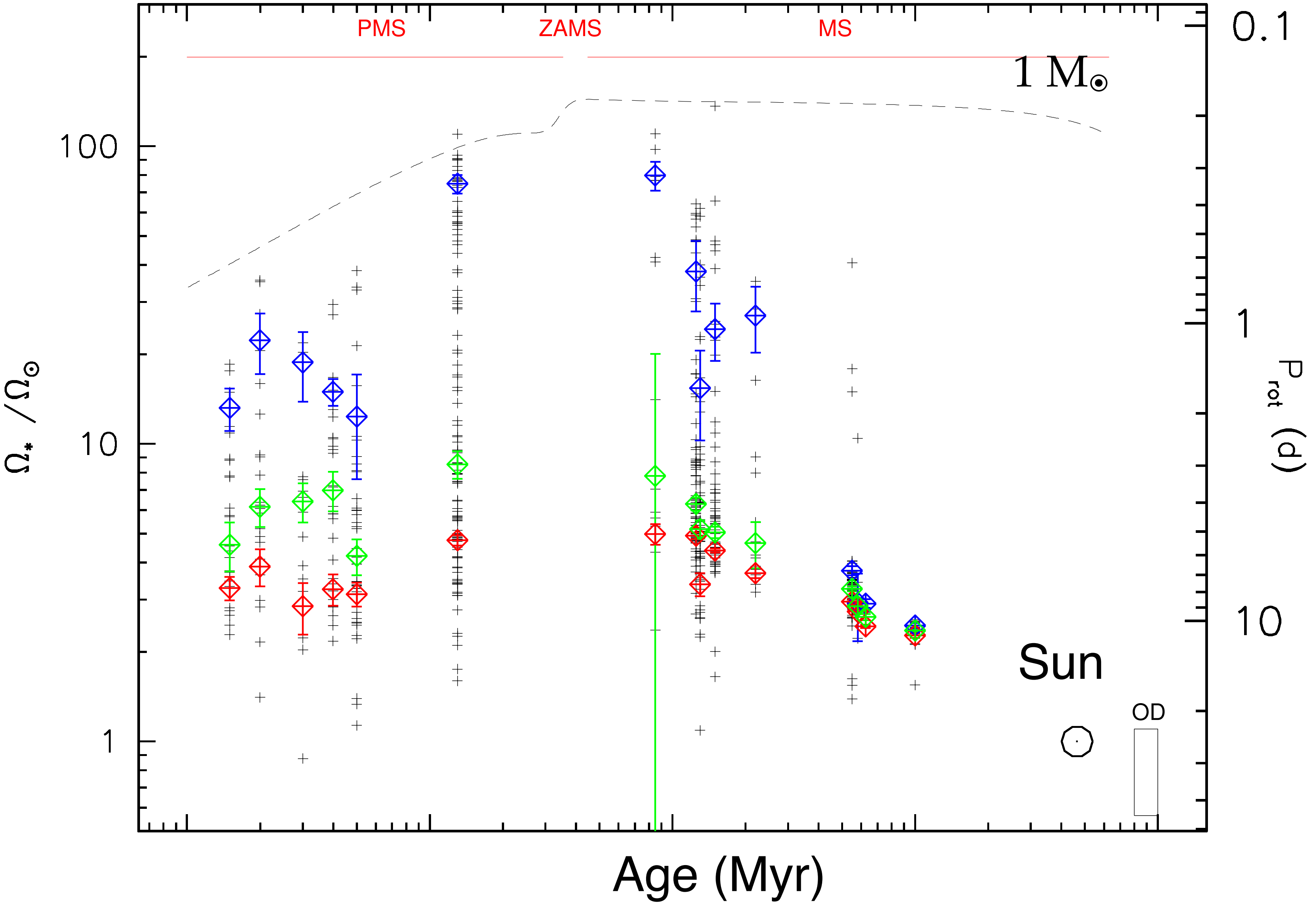
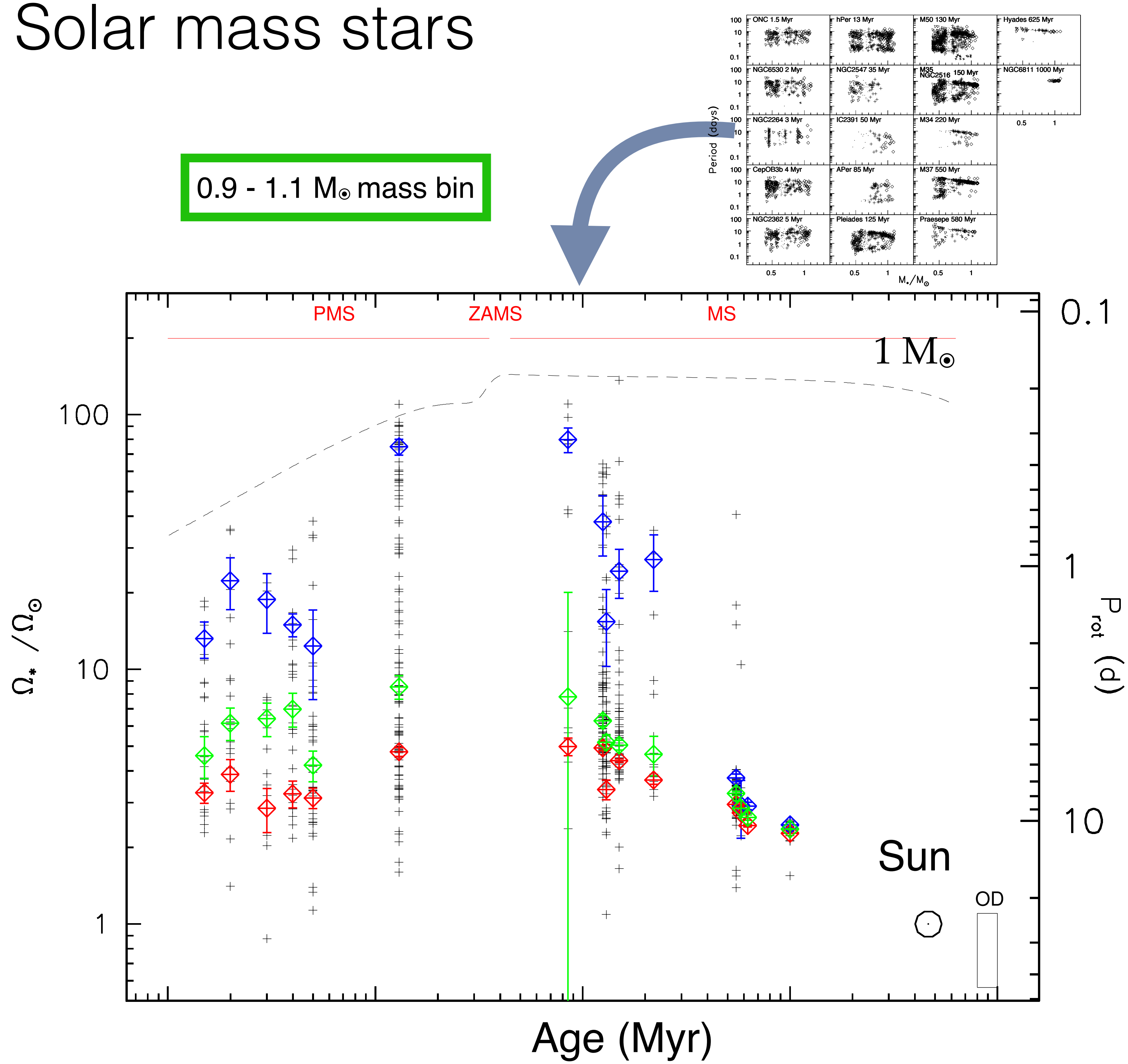




Observed rotational evolution

Solar mass stars

- 1st, 2nd and 3rd quartiles
  - 25th
  - median
  - 90th



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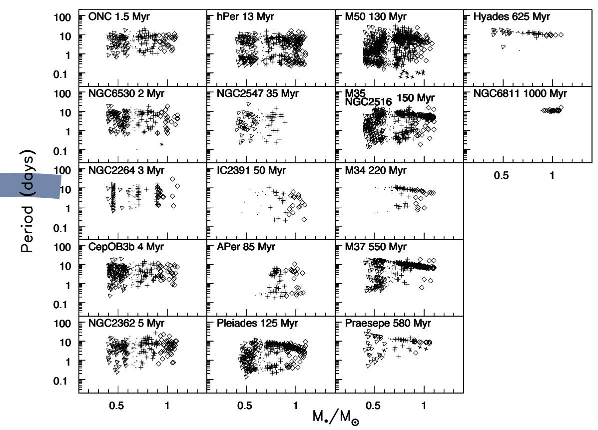
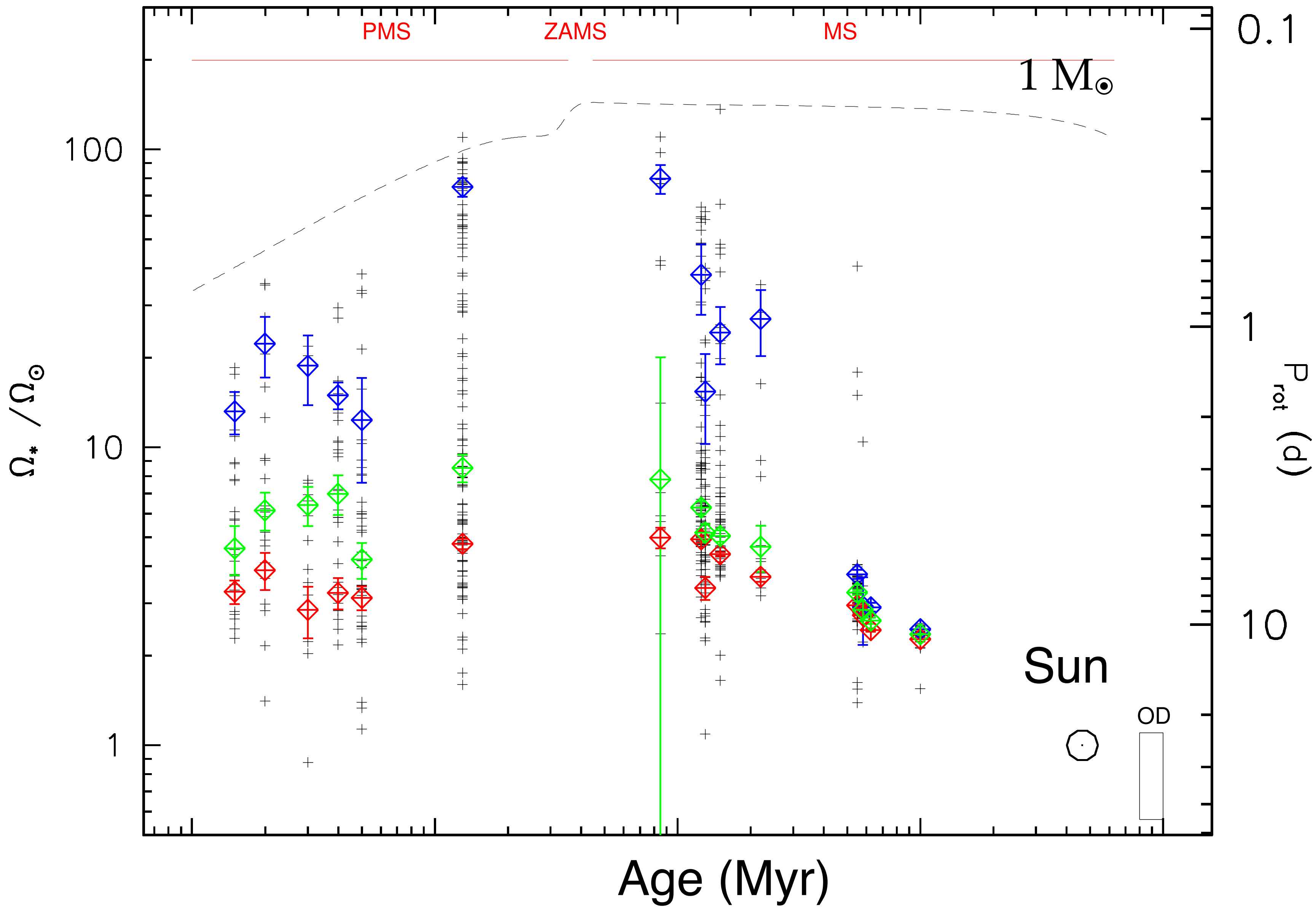
of each distribution

0.9 - 1.1 $M_\odot$ mass bin





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  - Early PMS : rotation period ≈ constant
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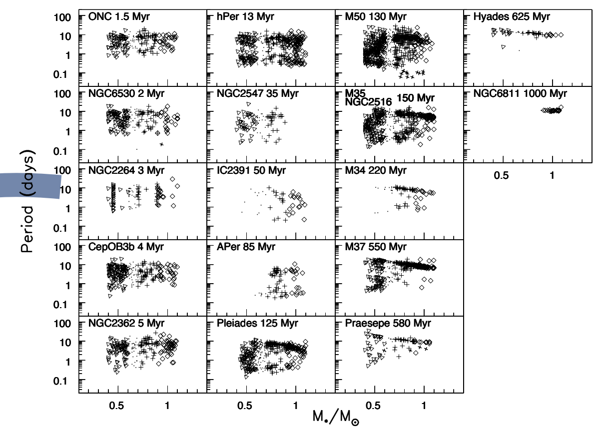

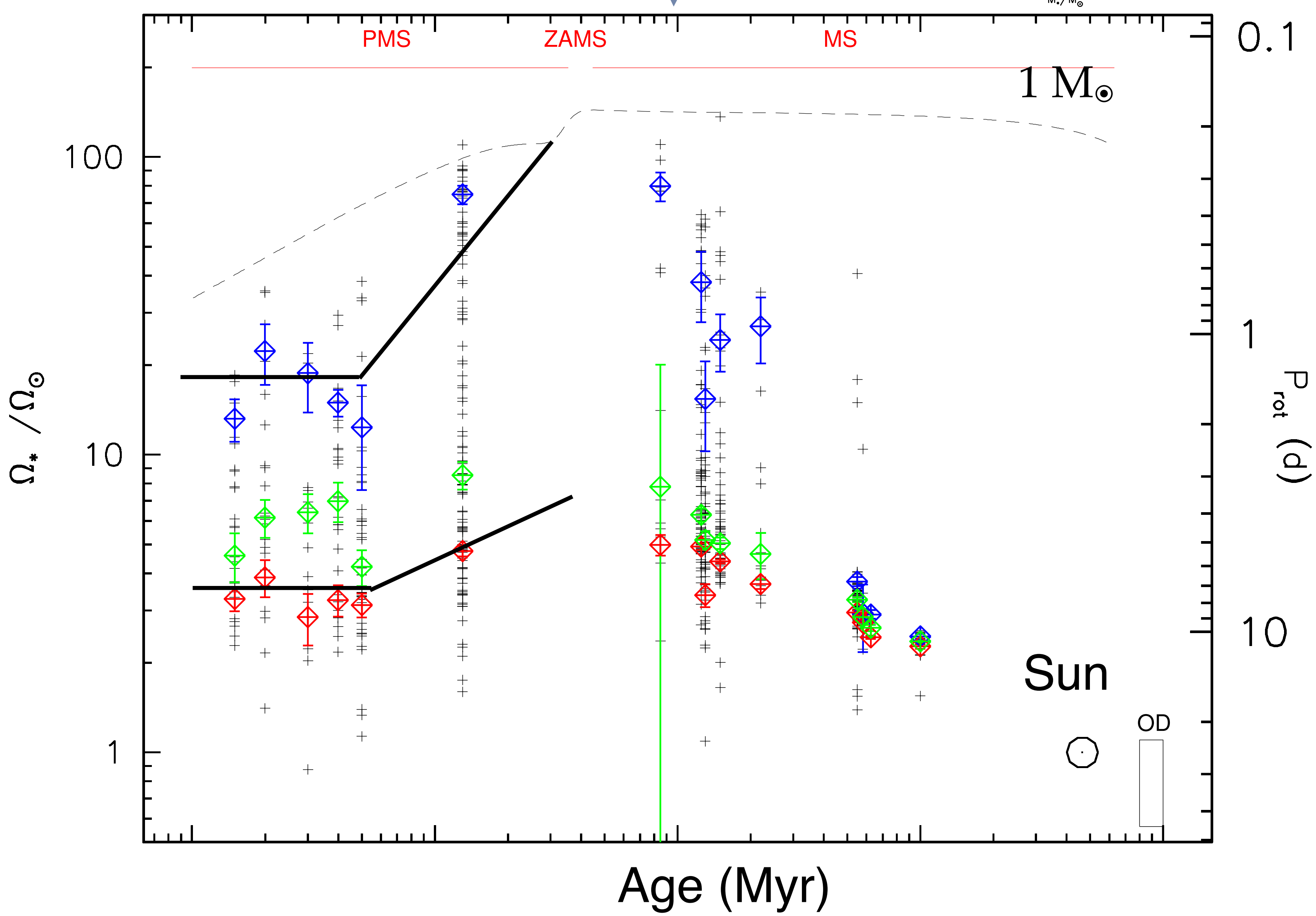

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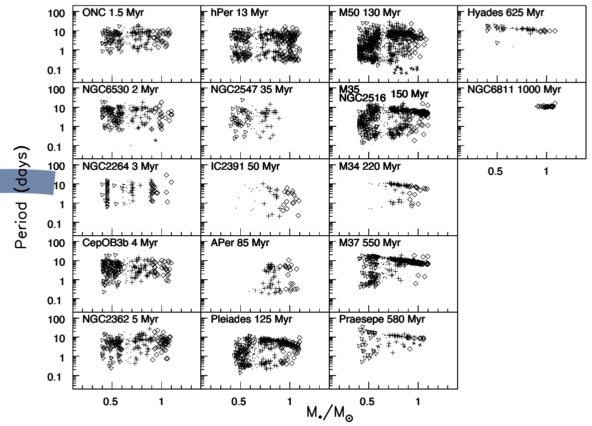

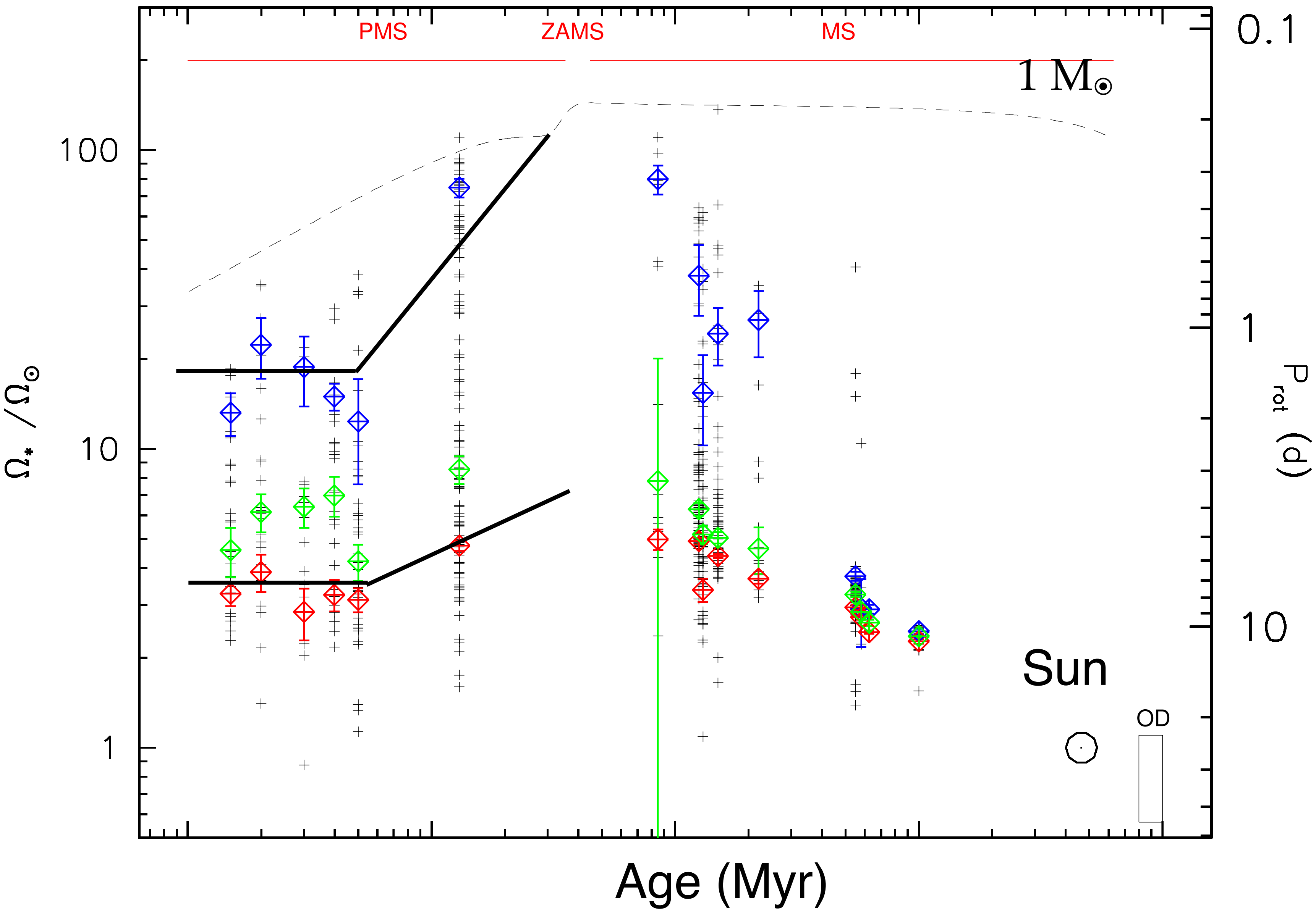

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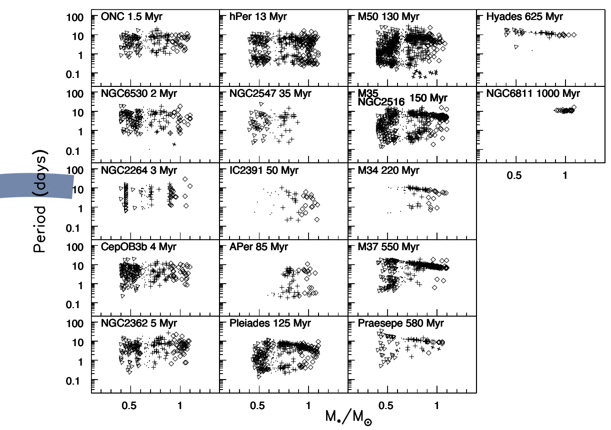

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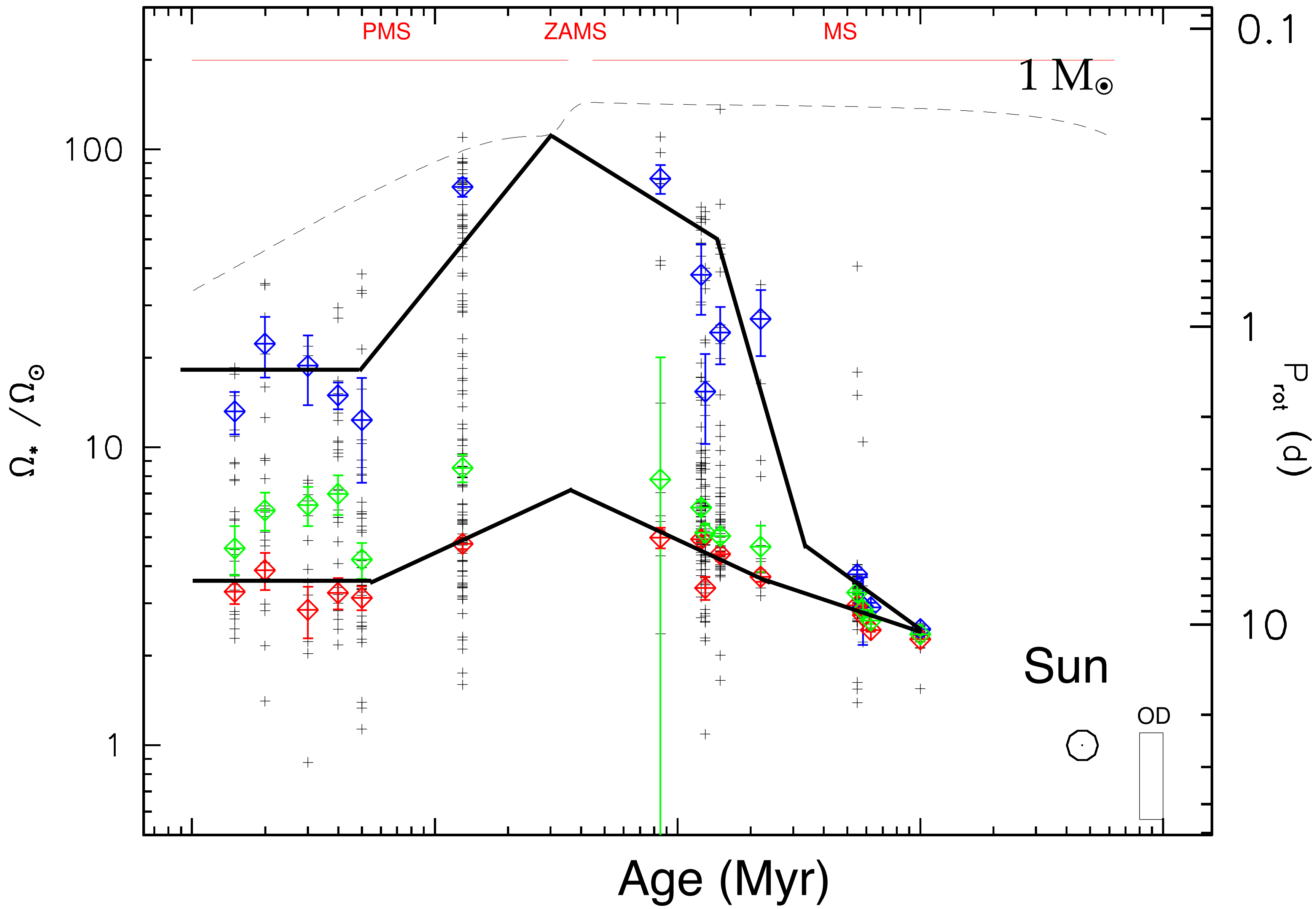

- PMS
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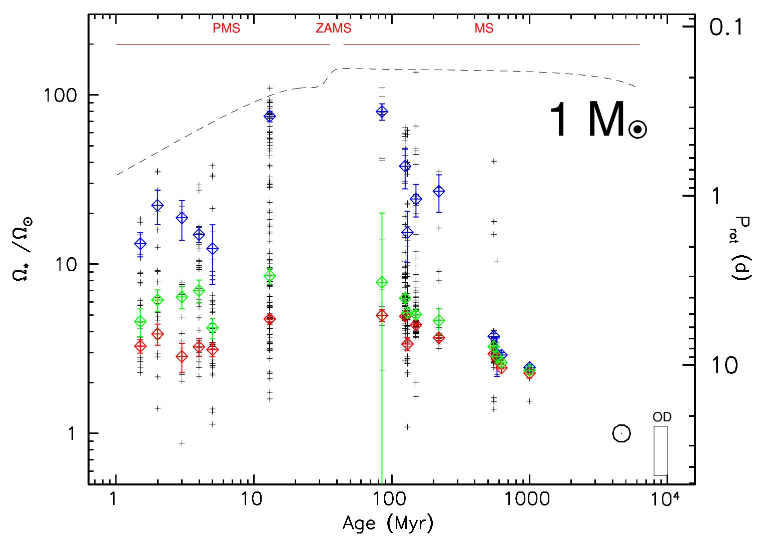
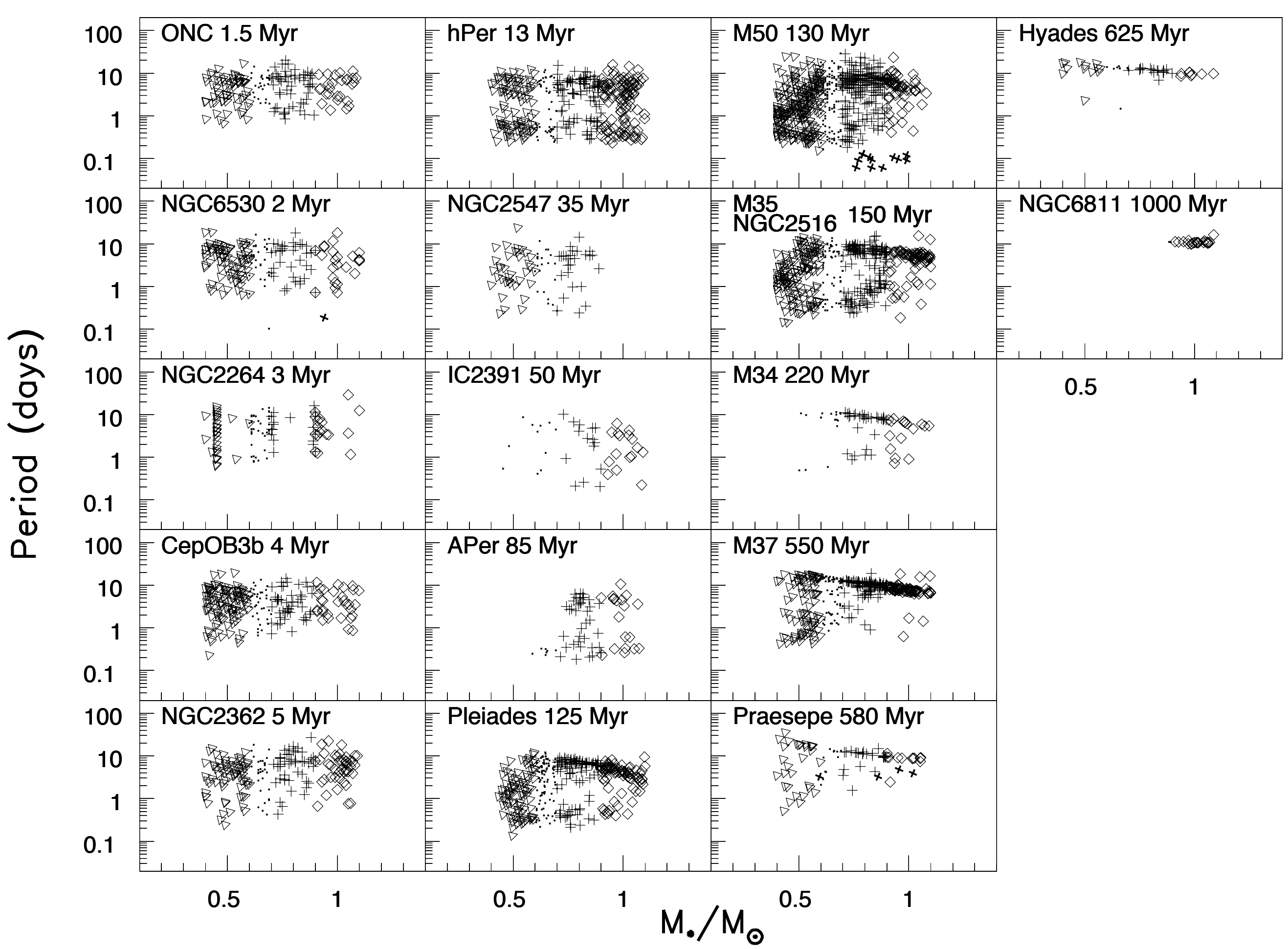
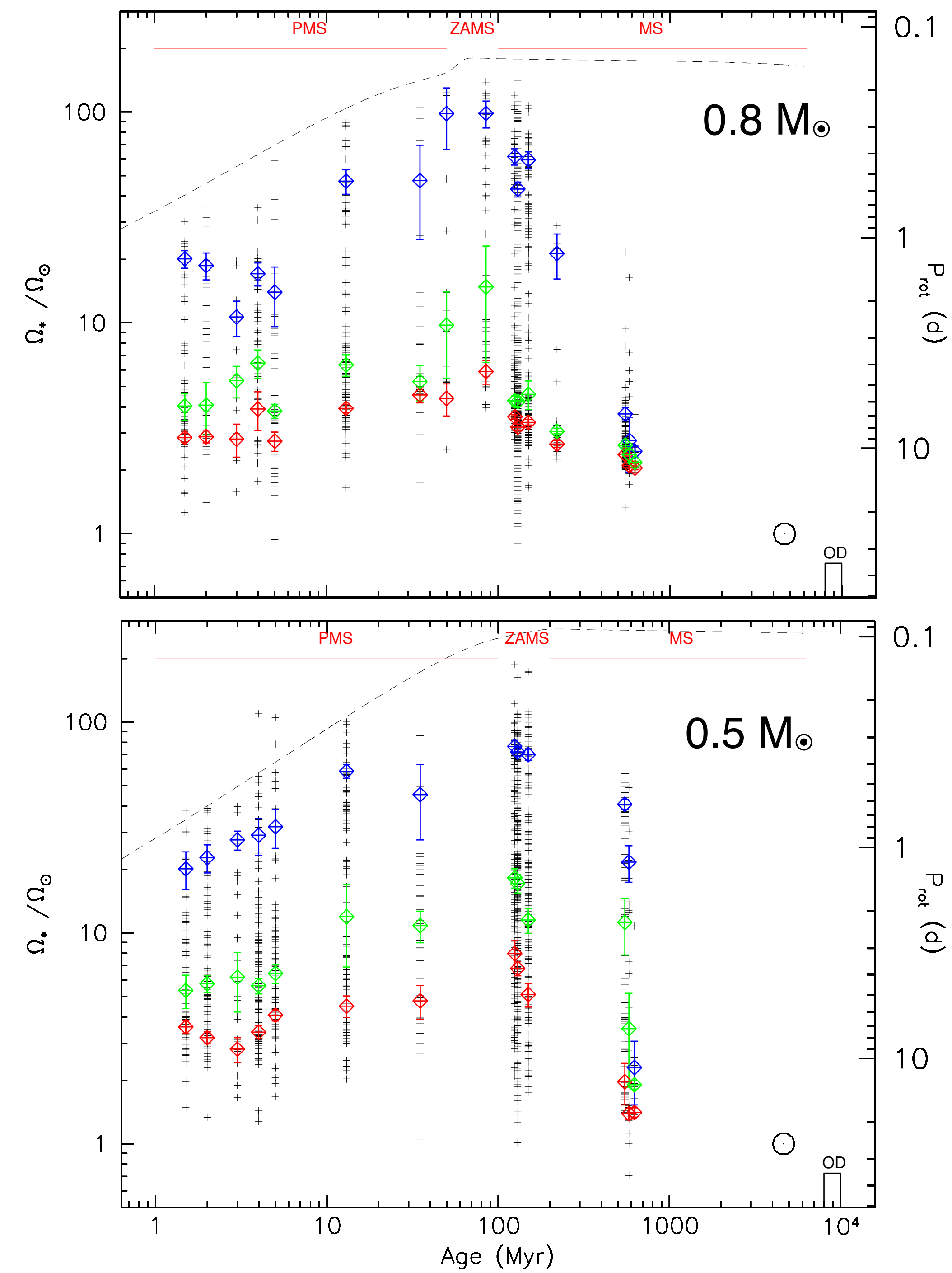
- MS
  - Rotational convergence

Observed rotational evolution

Low mass stars







⇨ AM evolution models must reproduce these observations

Physical ingredients

- **Stellar angular momentum:** $J_* = \Omega_* I_*$

See also Keppens+95, Krishnamurthi+97, Somers & Pinsonneault15, Lanzafame & Spada15, Sadeghi Ardestani+16, …

AM evolution model = **Stelar evolution model + AM evolution mechanisms**

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Weber & Davis (1967)

$$\left.\frac{dJ}{dt}\right|_{\rm wind} \approx \Omega_* \dot{M}_{\rm wind} r_A^2$$

-ideal MHD
-spherical symmetry

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  - mass-loss rate?
  - magnetic field?
  - open flux?
  - rossby number?

See also Matt+12,15, Reiners&Mohanty12, VanSaders+13 Réville+15 Finley & Matt17, See+17,19, …

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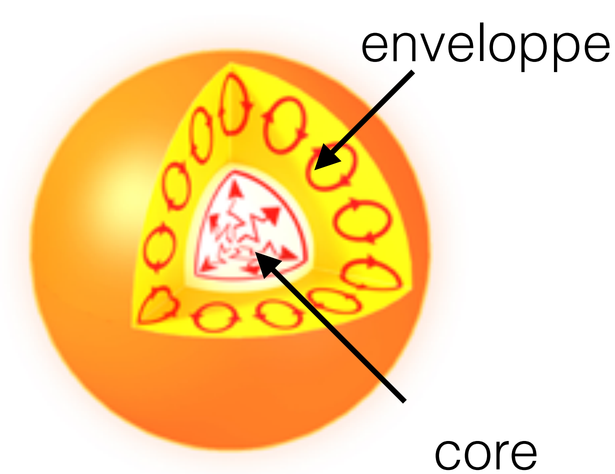

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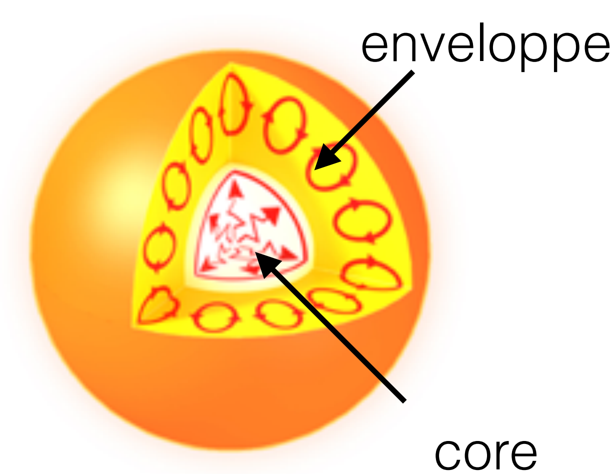

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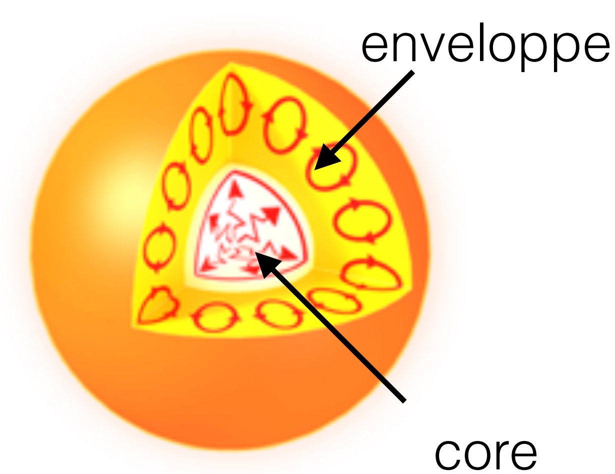


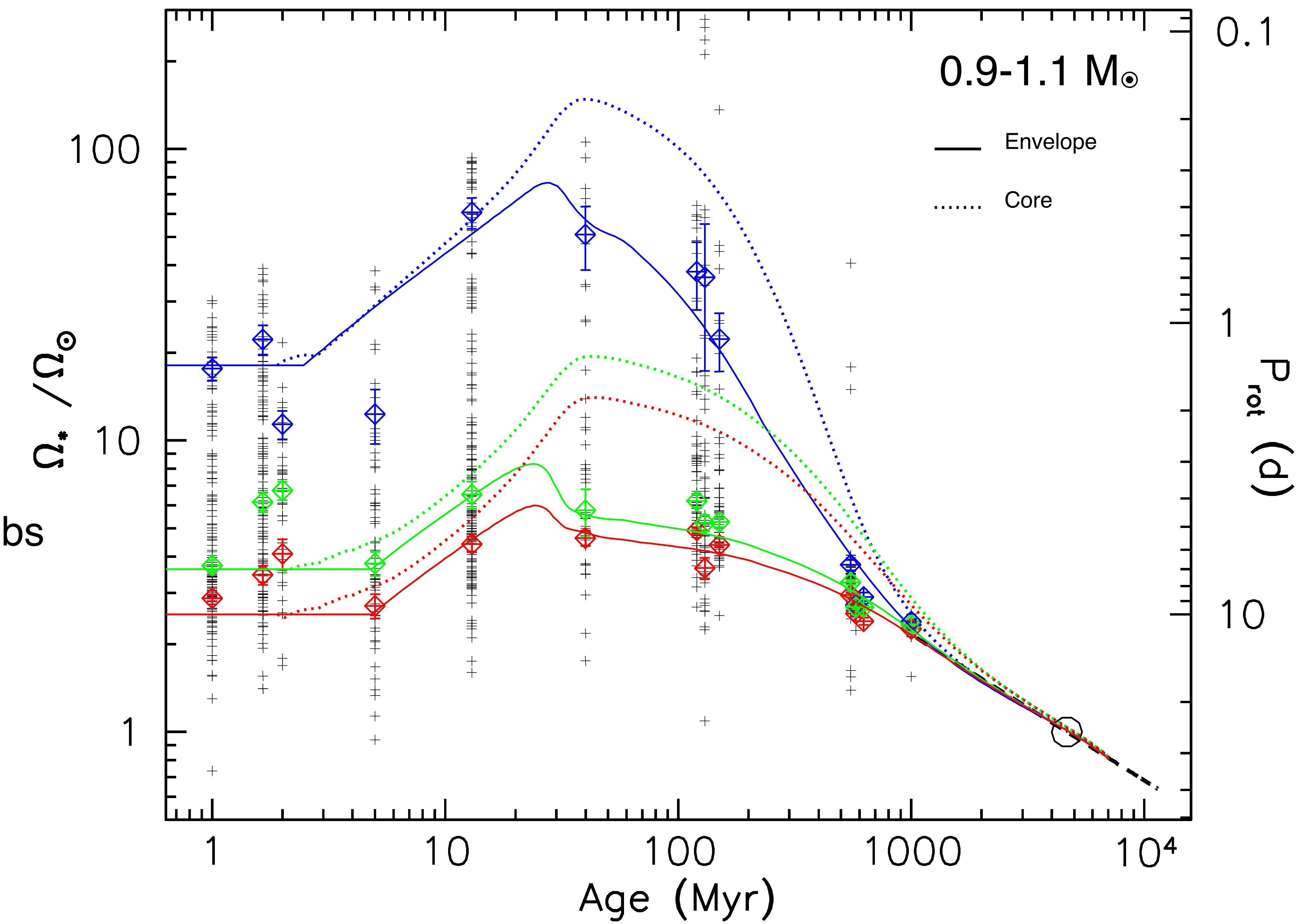
- **Environment (extra):** Disk + Planet ?

- tidal and magnetic star-(massive) planet interaction?
- star-disk magnetic interaction?

See Matt&Pudritz08,Ogilvie&Lin13, Zanni&Ferreira13,Lanza&Mathis16, Bolmont&Mathis16,Strugarek+18,19, Gallet+19a,b, …

Modeling

Gallet & Bouvier (2013)



4 free parameters:

Initial: P_{init} → obs

Environment: τ_{disk} → obs

Internal: $\tau_{c\text{-}e}$ → obs

Wind: K_1(dJ/dt) → num+obs

No tidal interaction

$$r_A = K_1 \left[\frac{B_p^2 R_*^2 (\dot{M}_{wind} v_{esc})^{-1}}{\sqrt{K_2^2 + \Omega_*^2 R_*^2 v_{esc}^{-2}}} \right]^m R_*$$

Matt et al. (2012a)

$$\Delta J = \frac{I_{env} J_{core} - I_{core} J_{env}}{I_{core} + I_{env}}$$

MacGregor & Brenner (1991)

$$\Omega_{conv} = \Omega_{init} = 2\pi / P_{init} = cst$$

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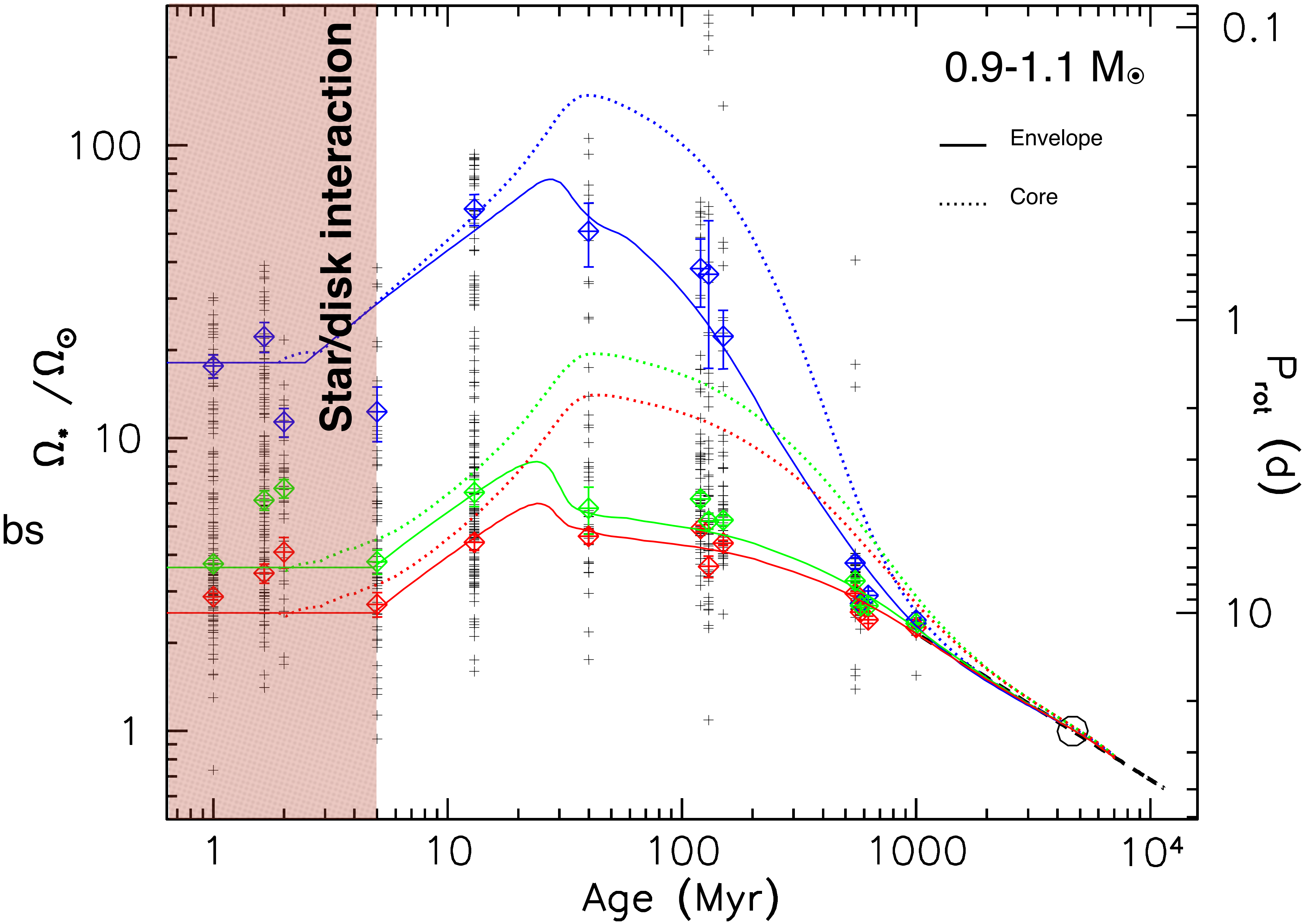

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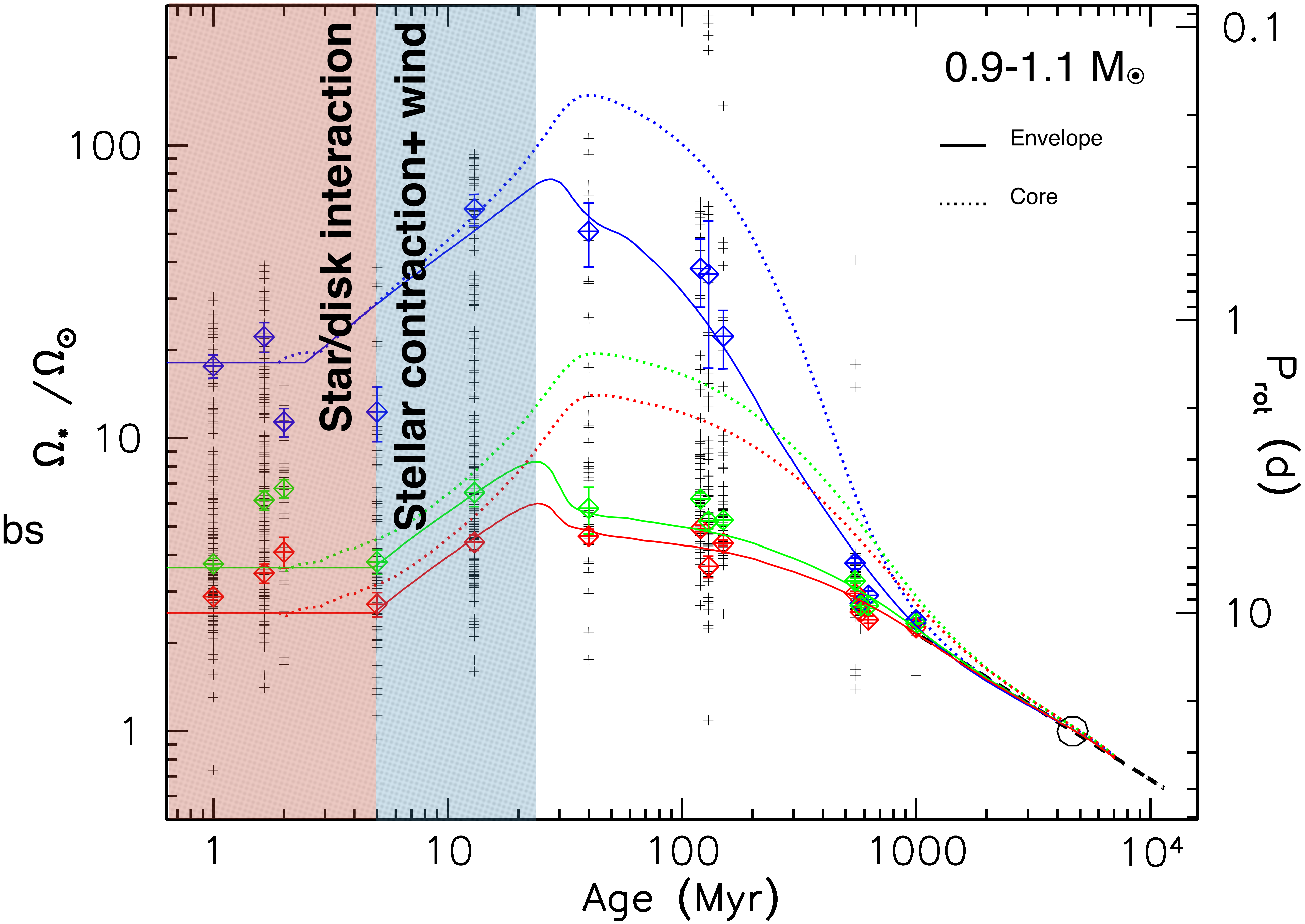

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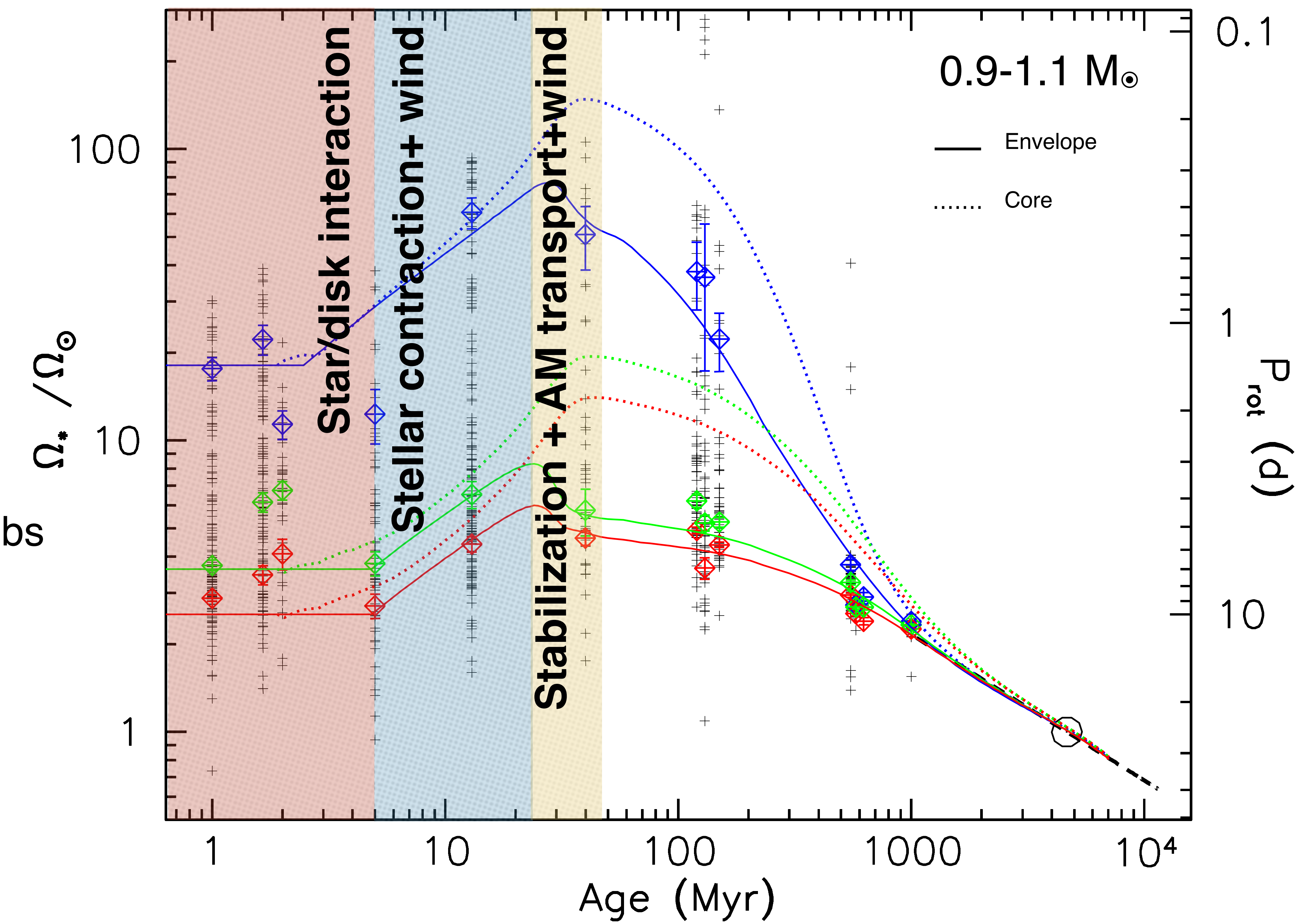

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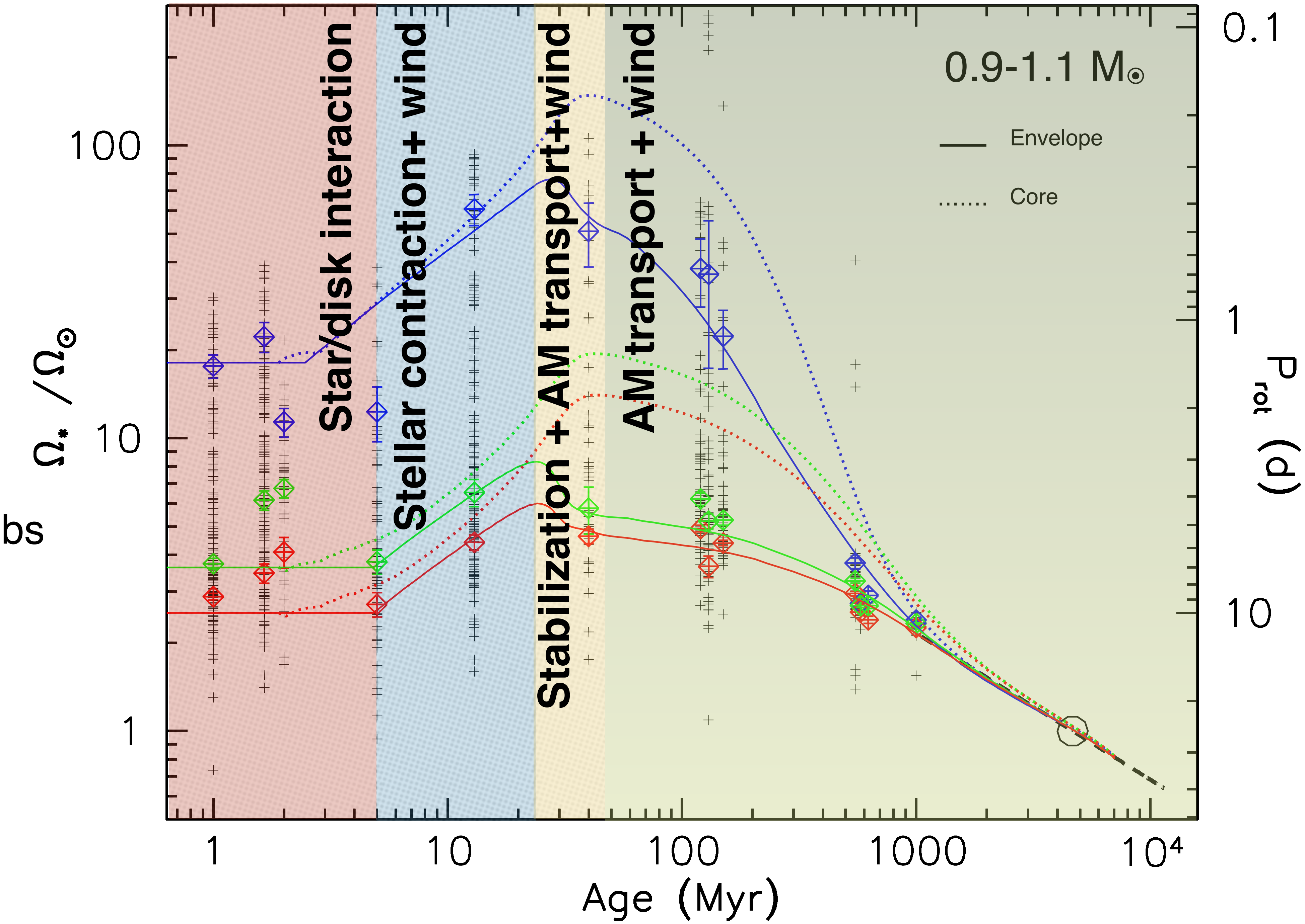

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Models in literature

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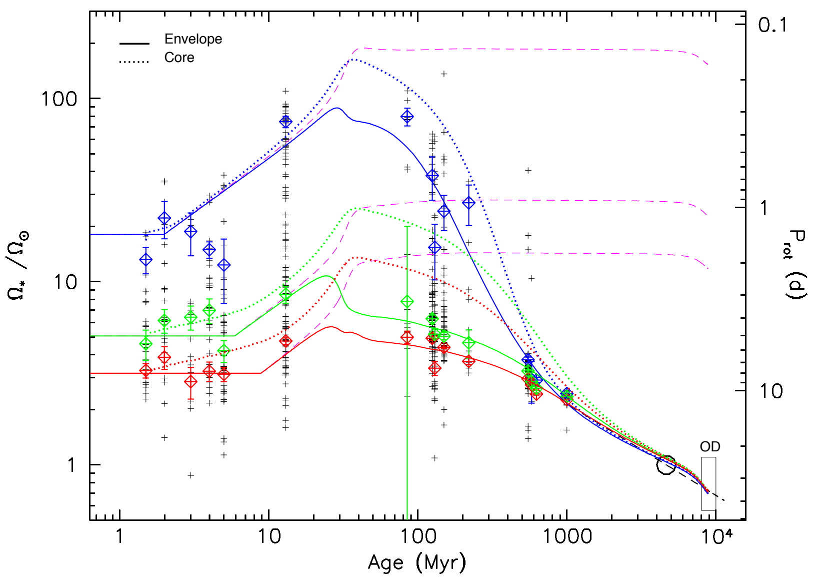
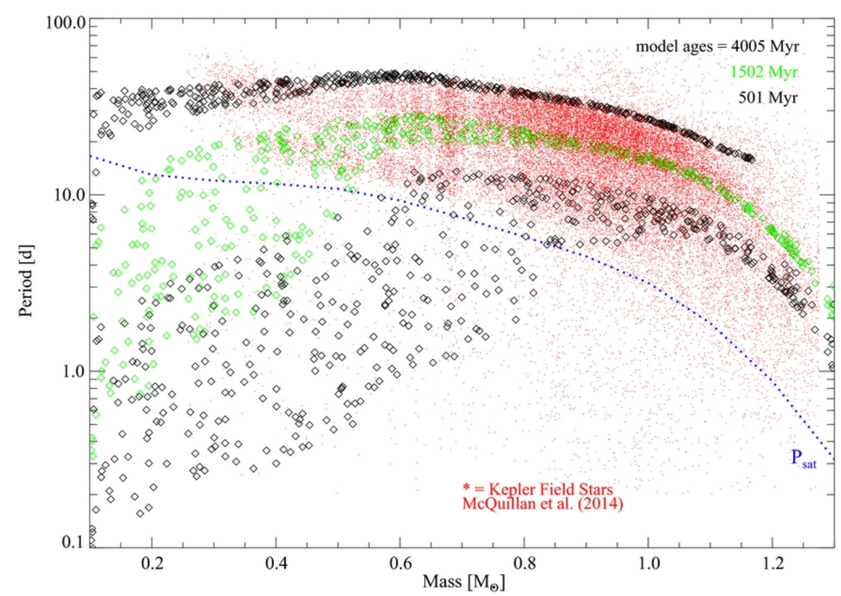
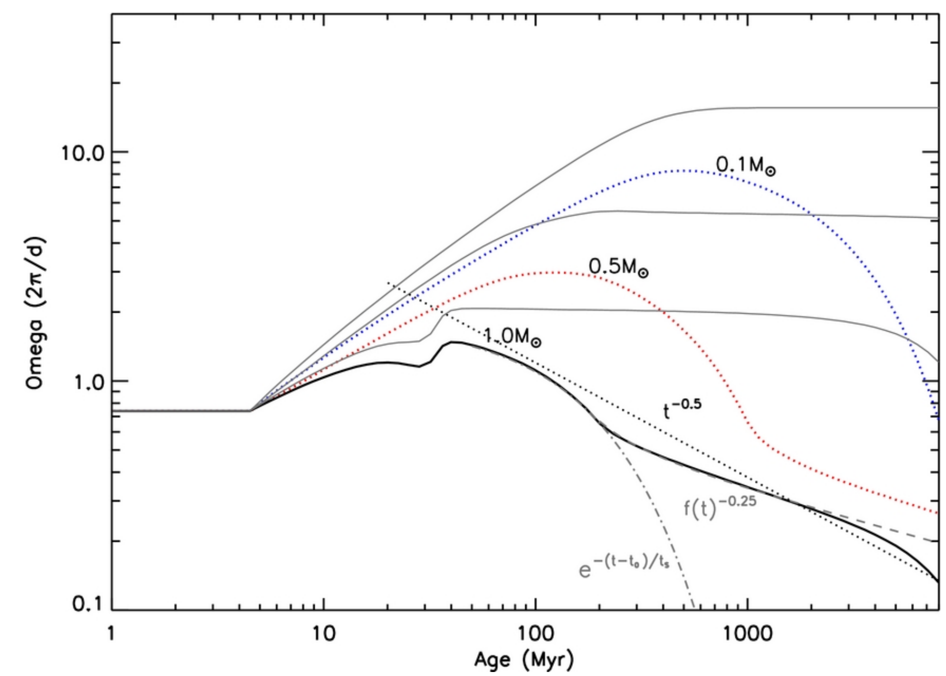


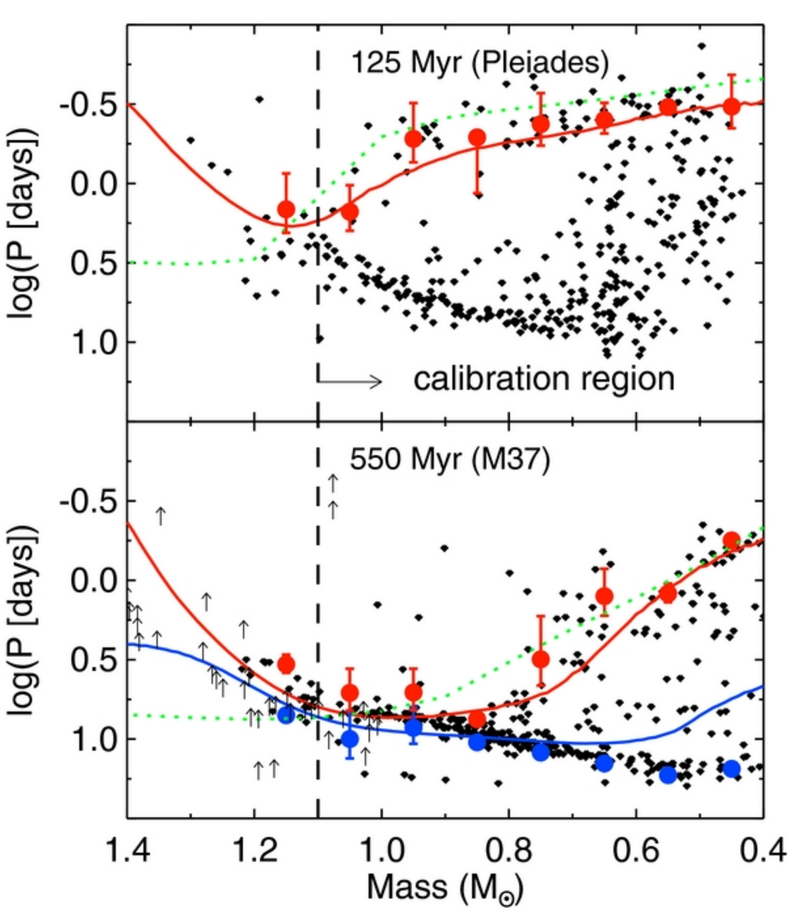
Matt+15



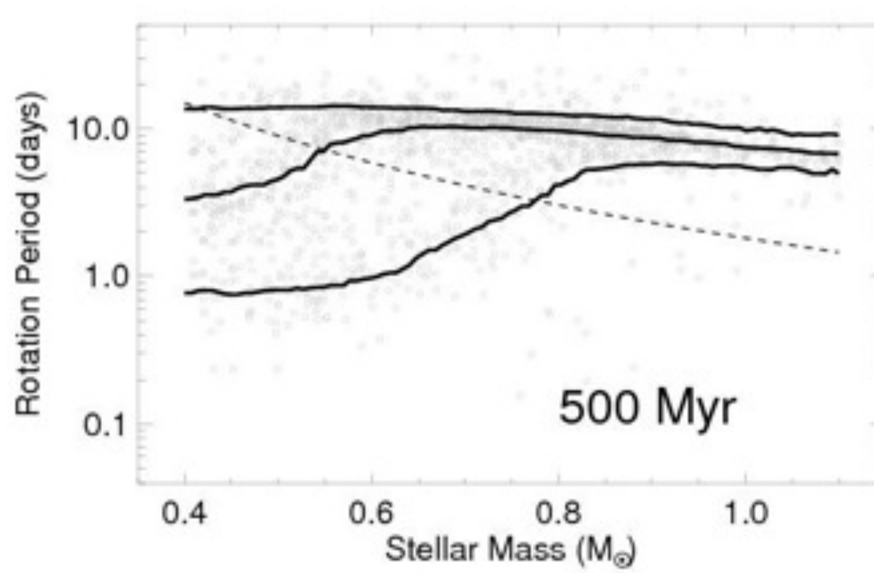
Reiners & Monhanty (2012)



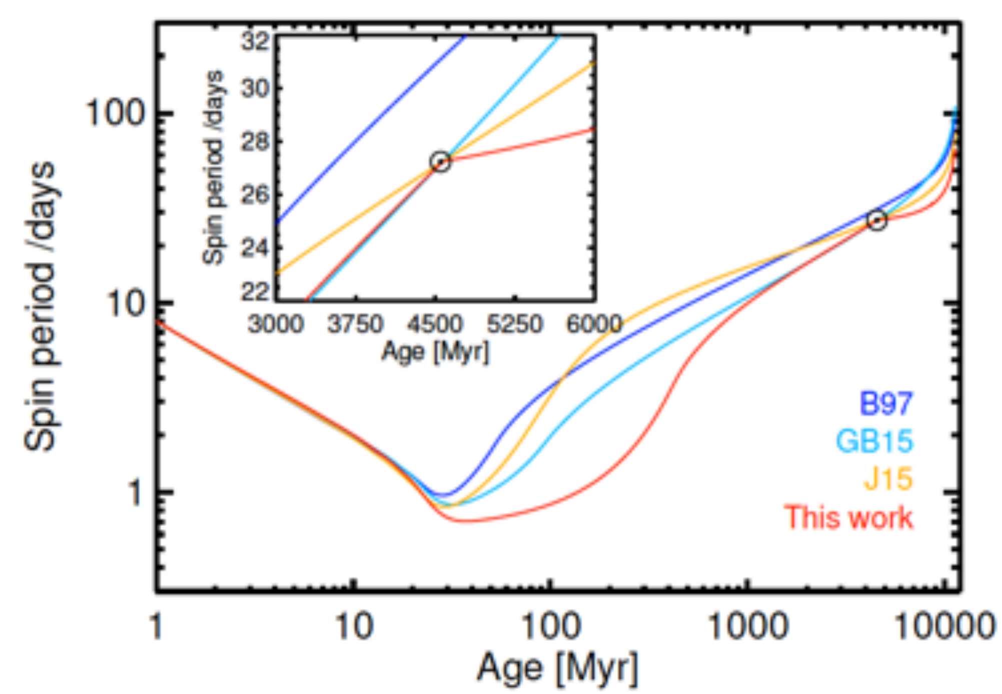
Van Saders & Pinsonneault (2013)



Johnstone+15



Sadeghi Ardestani+16



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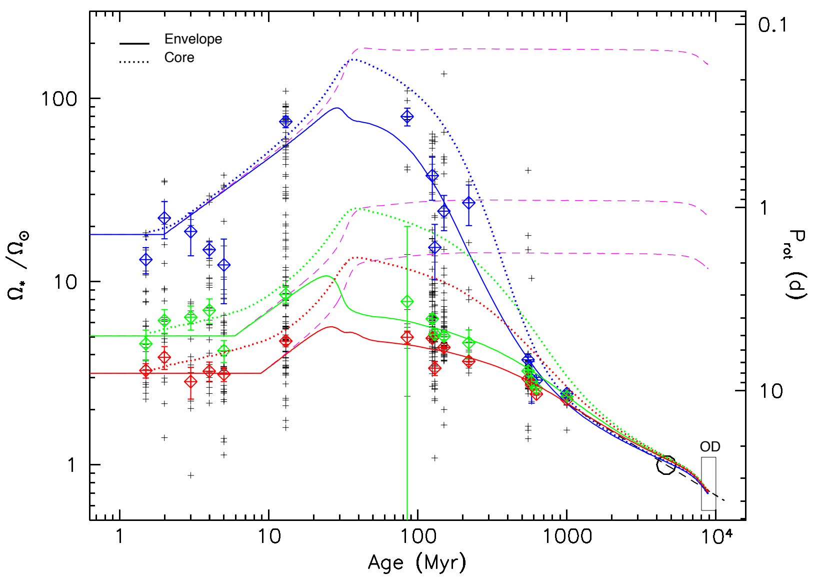
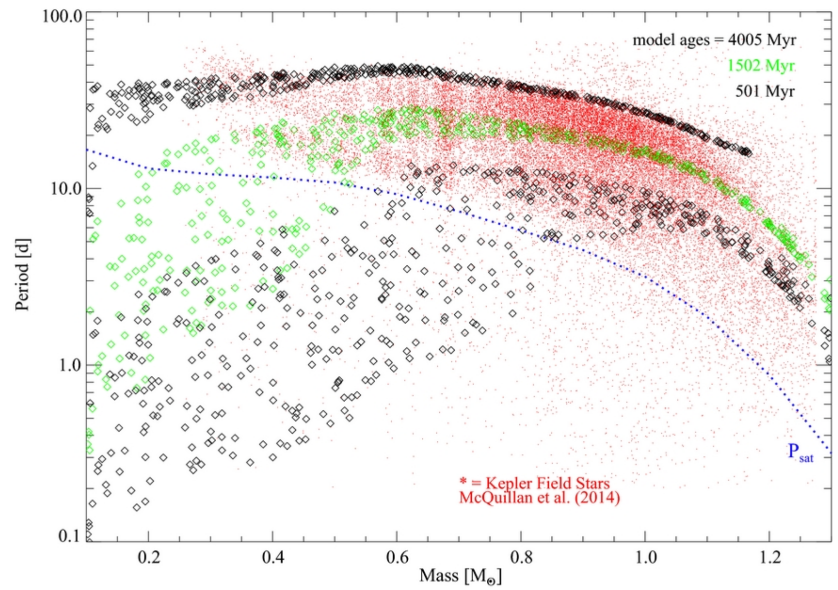
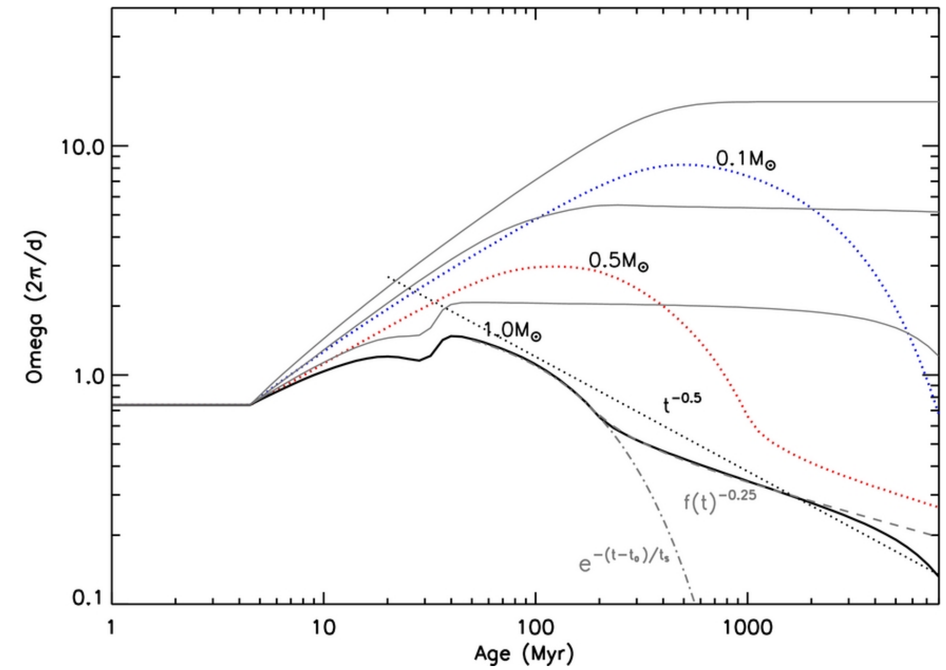


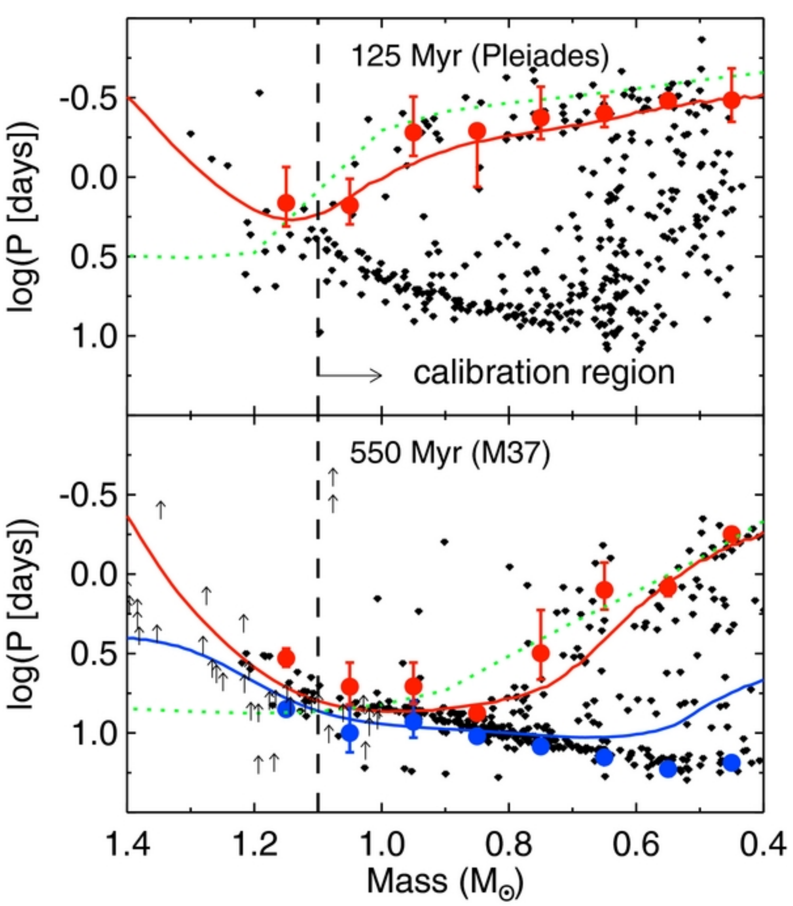
Matt+15



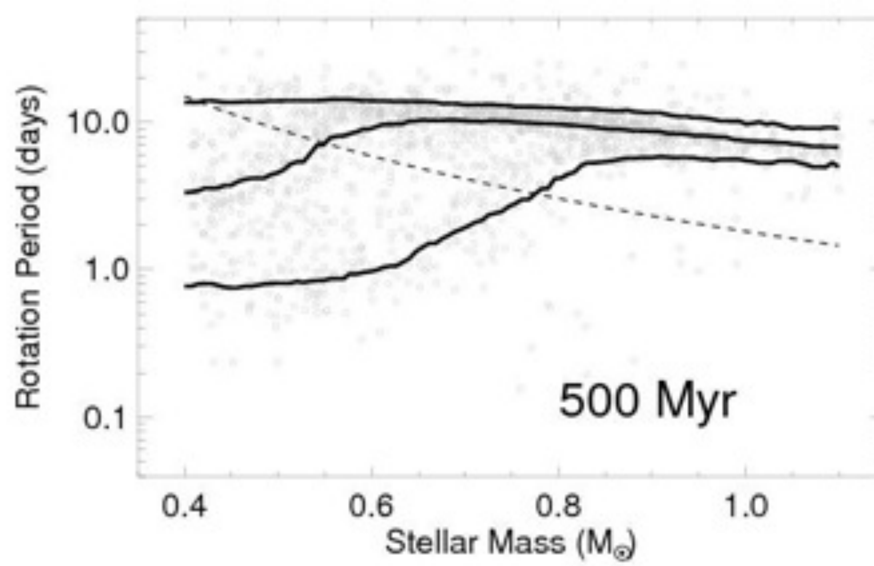
Reiners & Monhanty (2012)



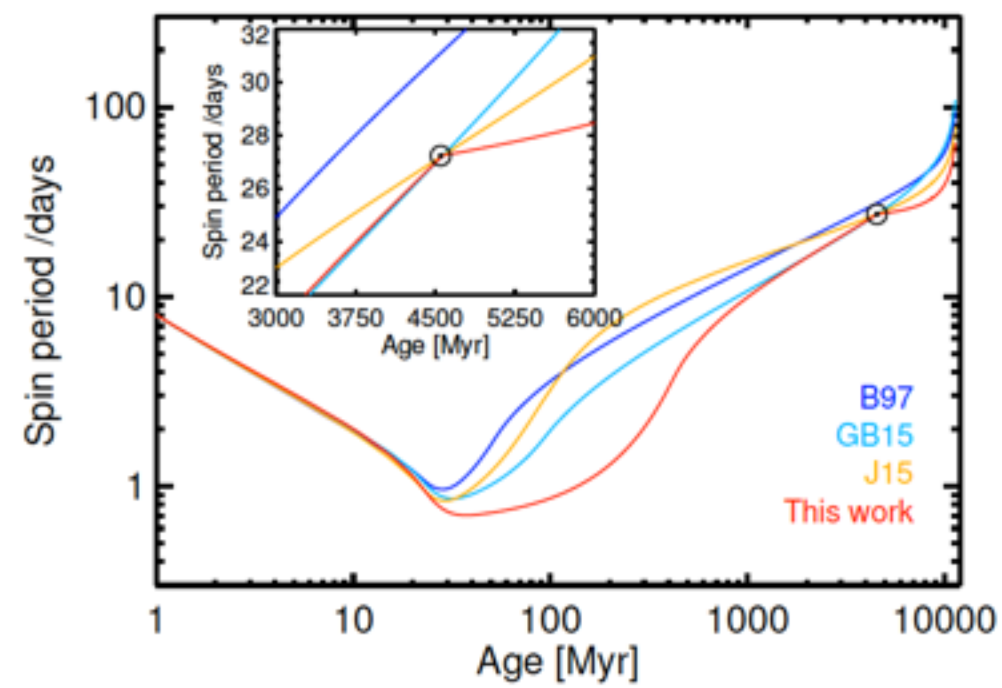
Van Saders & Pinsonneault (2013)



Johnstone+15



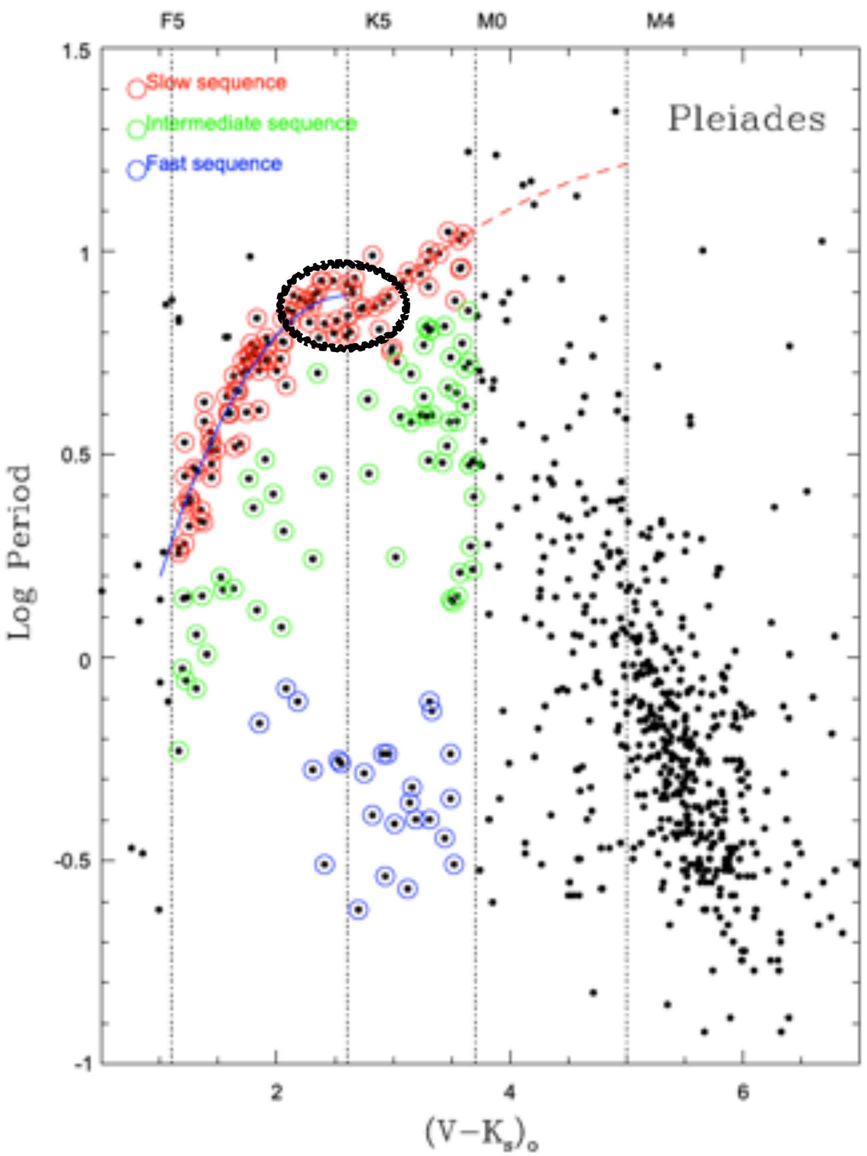
Sadeghi Ardestani+16



Observations quite well reproduced!

What's next?

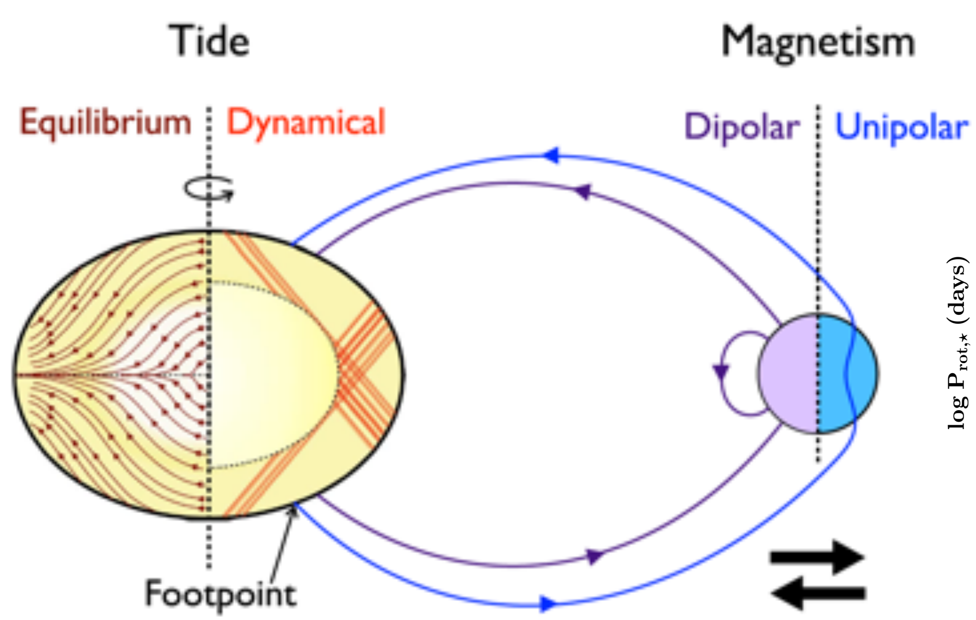
K2



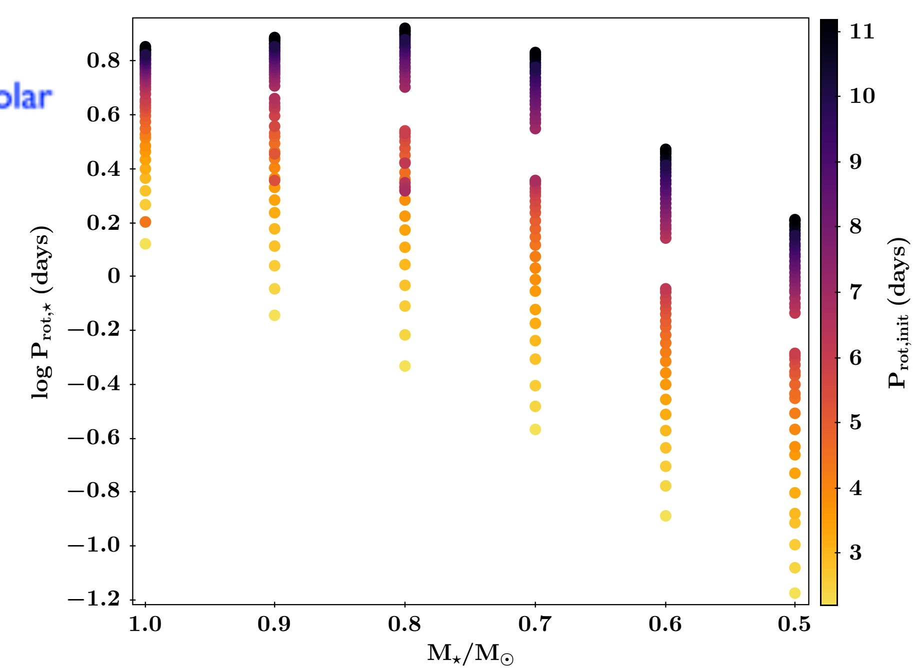
Stauffer et al. (2016)

=> footprint of interaction between a star and companion (massive planet or star)?

- not clear yet
- but seems to be probable/possible
- magnetic and/or tidal interactions

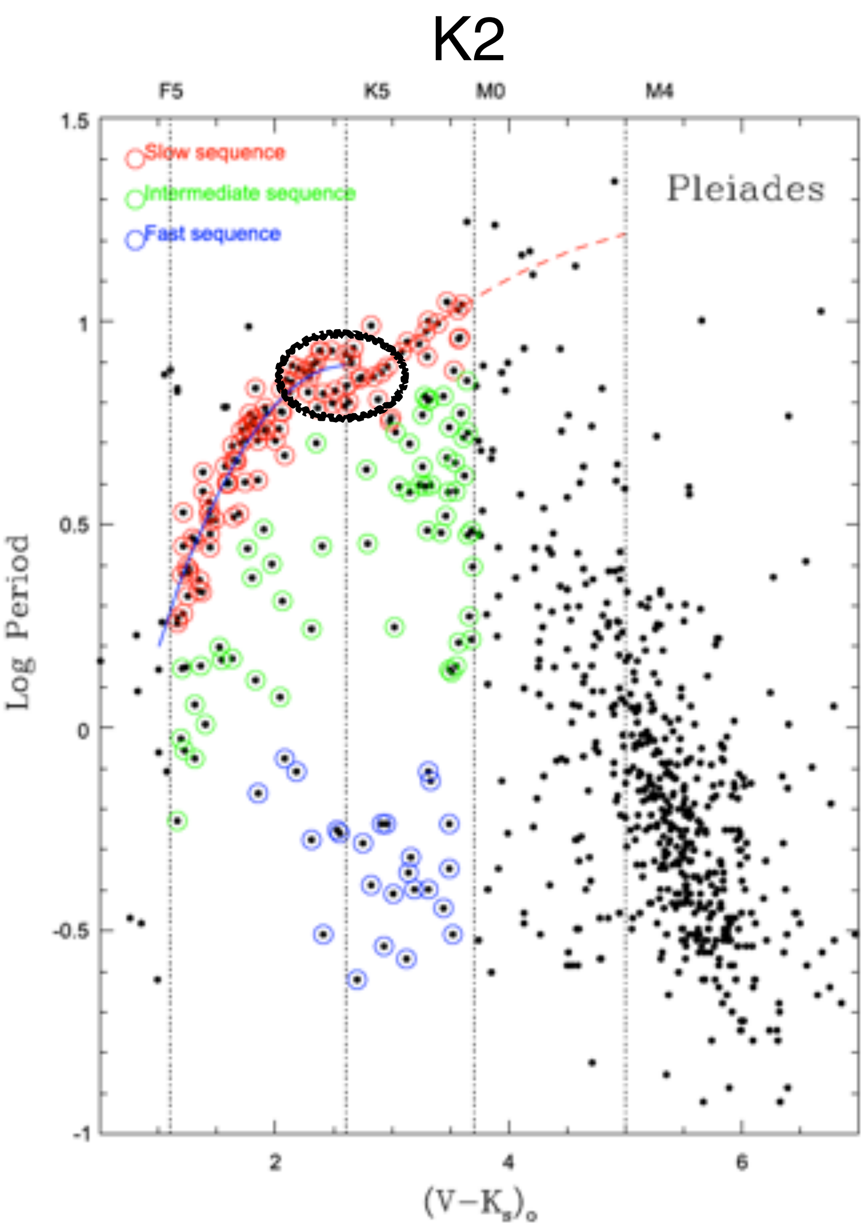


Stugarek et al. (2016)



Gallet et al. (2018)

What's next?



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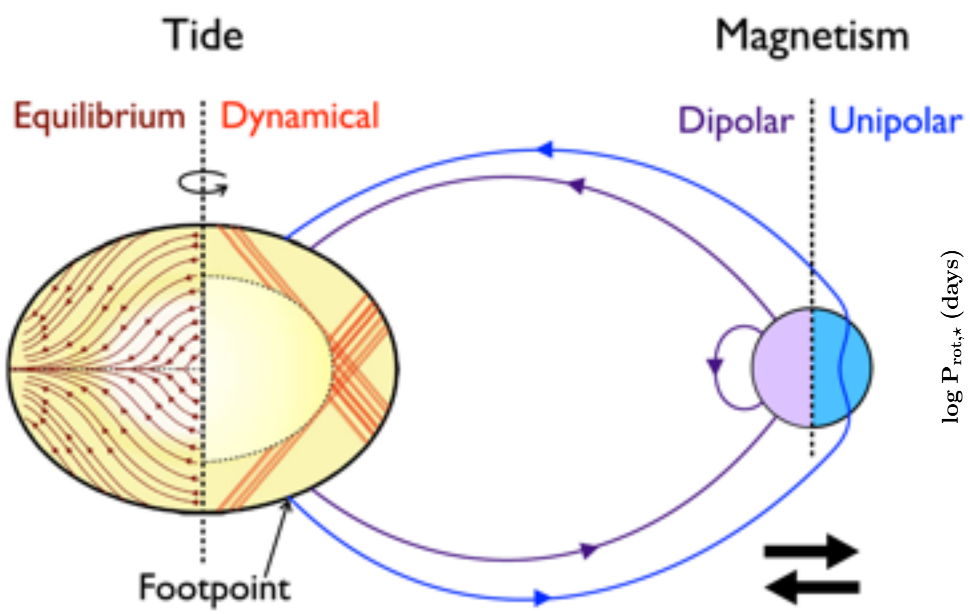
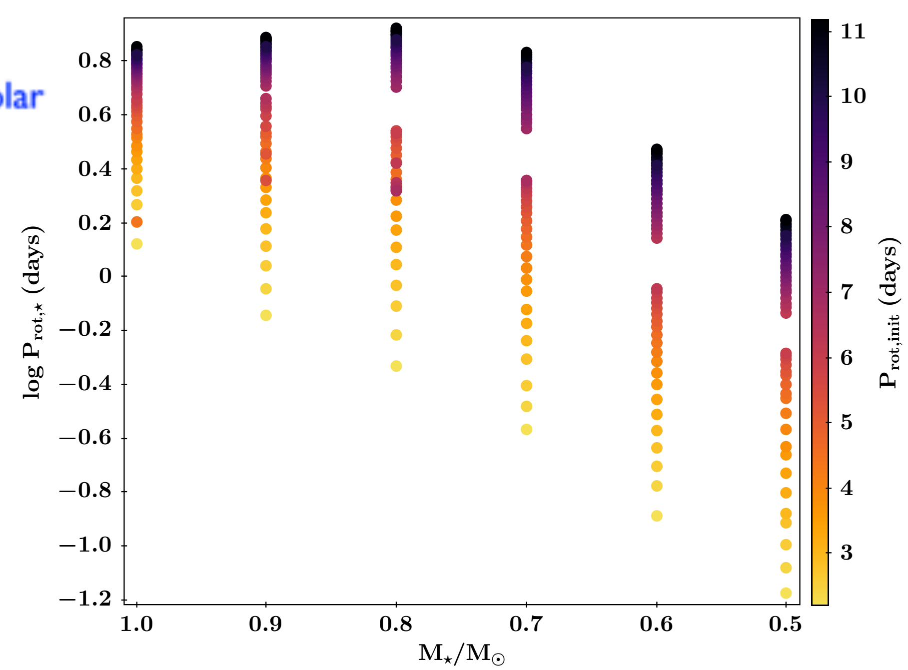


Stugarek et al. (2016)

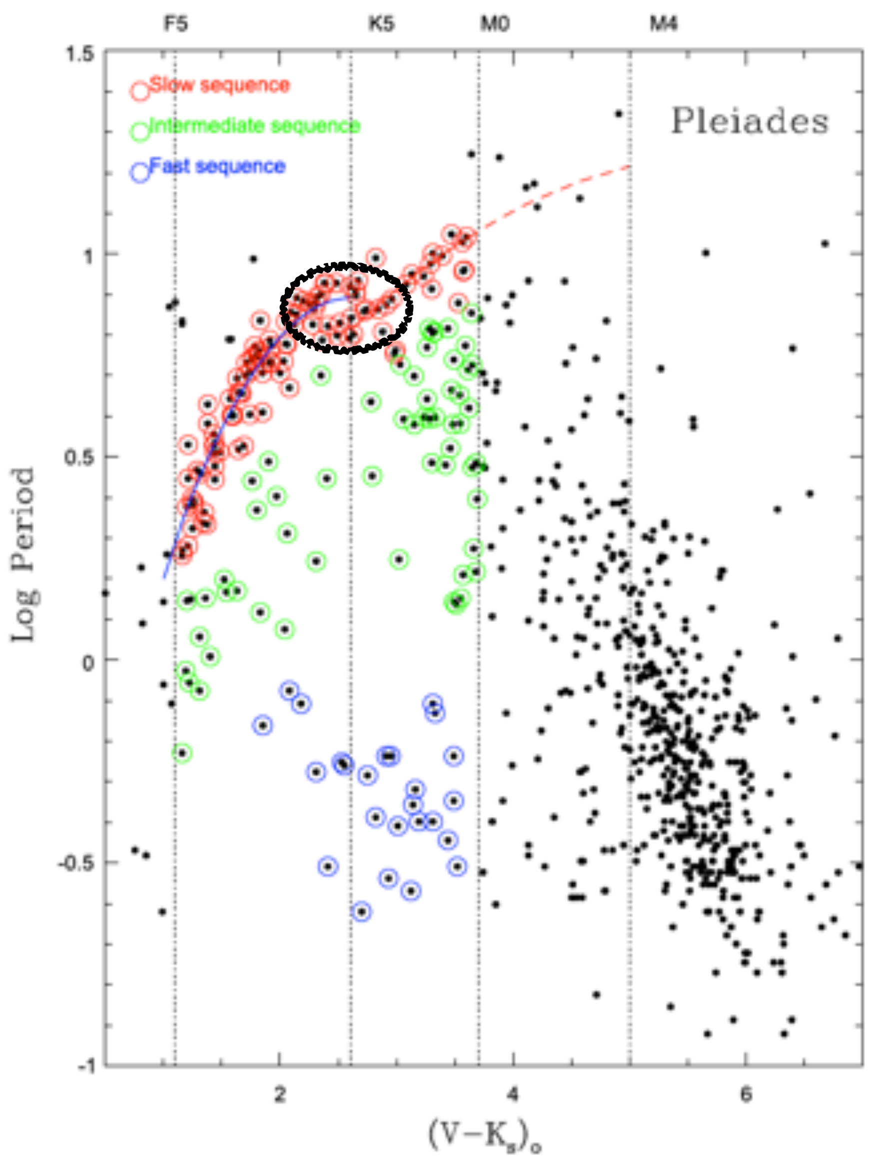


Gallet et al. (2018)

Next step in AM modeling?
To prepare PLATO (+ Gaia DR3/DR4) data: yes!

What's next?

K2



Stauffer et al. (2016)

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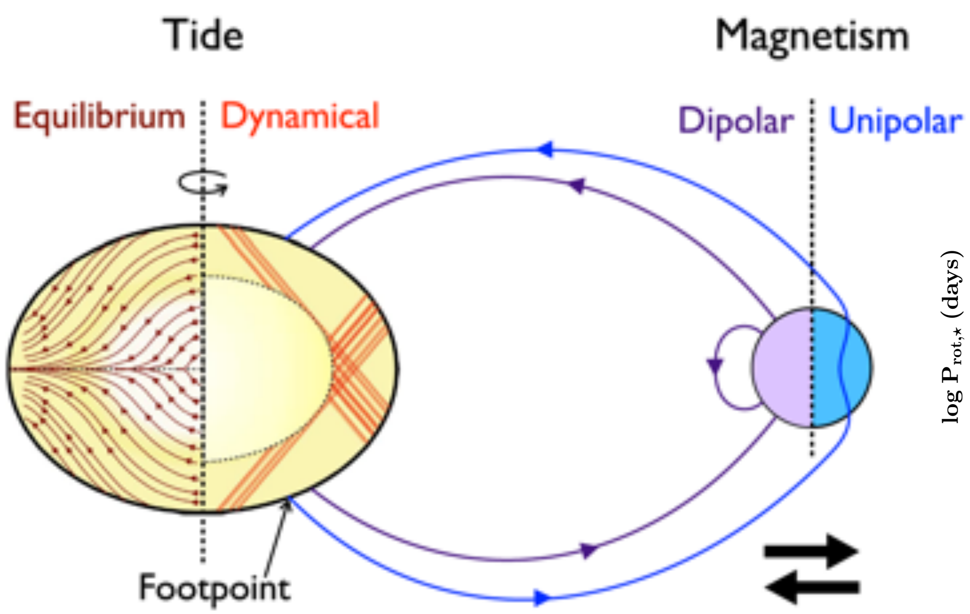
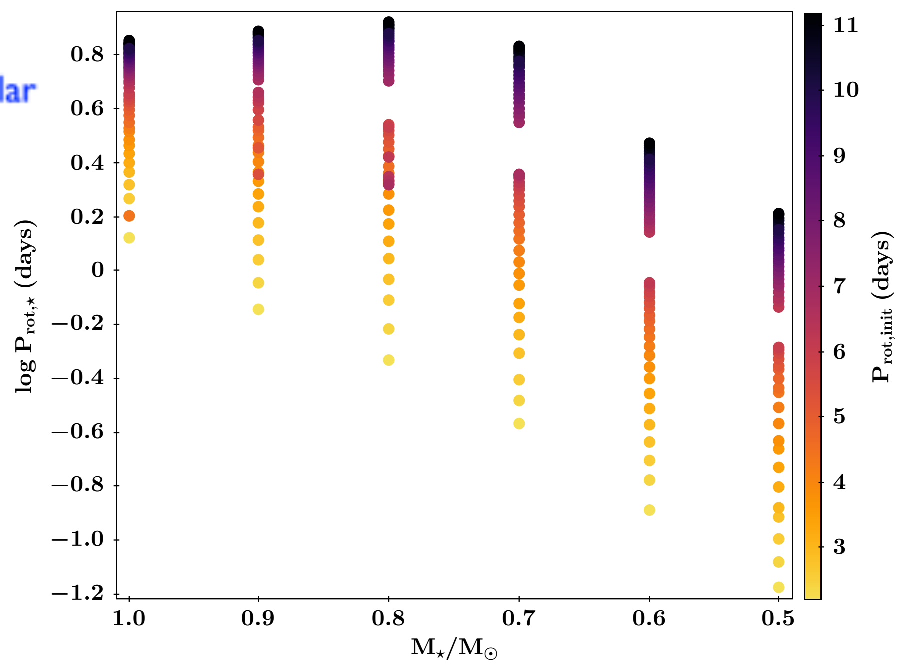




Stugarek et al. (2016)

Gallet et al. (2018)

Next step in AM modeling?
To prepare PLATO (+ Gaia DR3/DR4) data: yes!

On going work ✓

Conclusion

1. **Parametric models grasp the main trends of AM evolution**

   - fast, robust and simple: perfect for large exploration of initial conditions
   - strong complementarity with stellar models
   - choose model according to the mix of ingredients

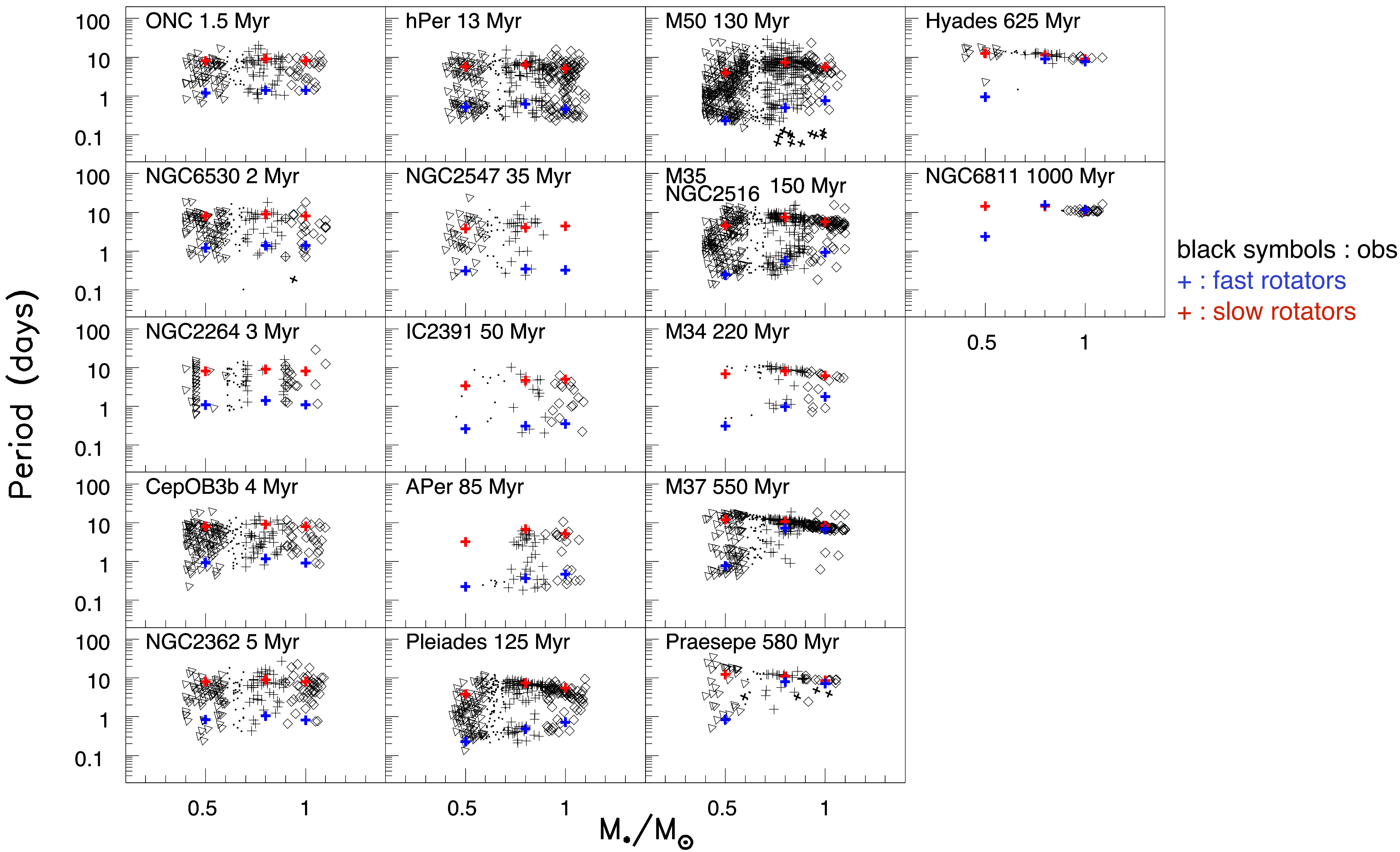
2. **Some obs. suggest the need for an additional ingredient**

   - add tidal interaction (star-companion)?
   - probably yes!

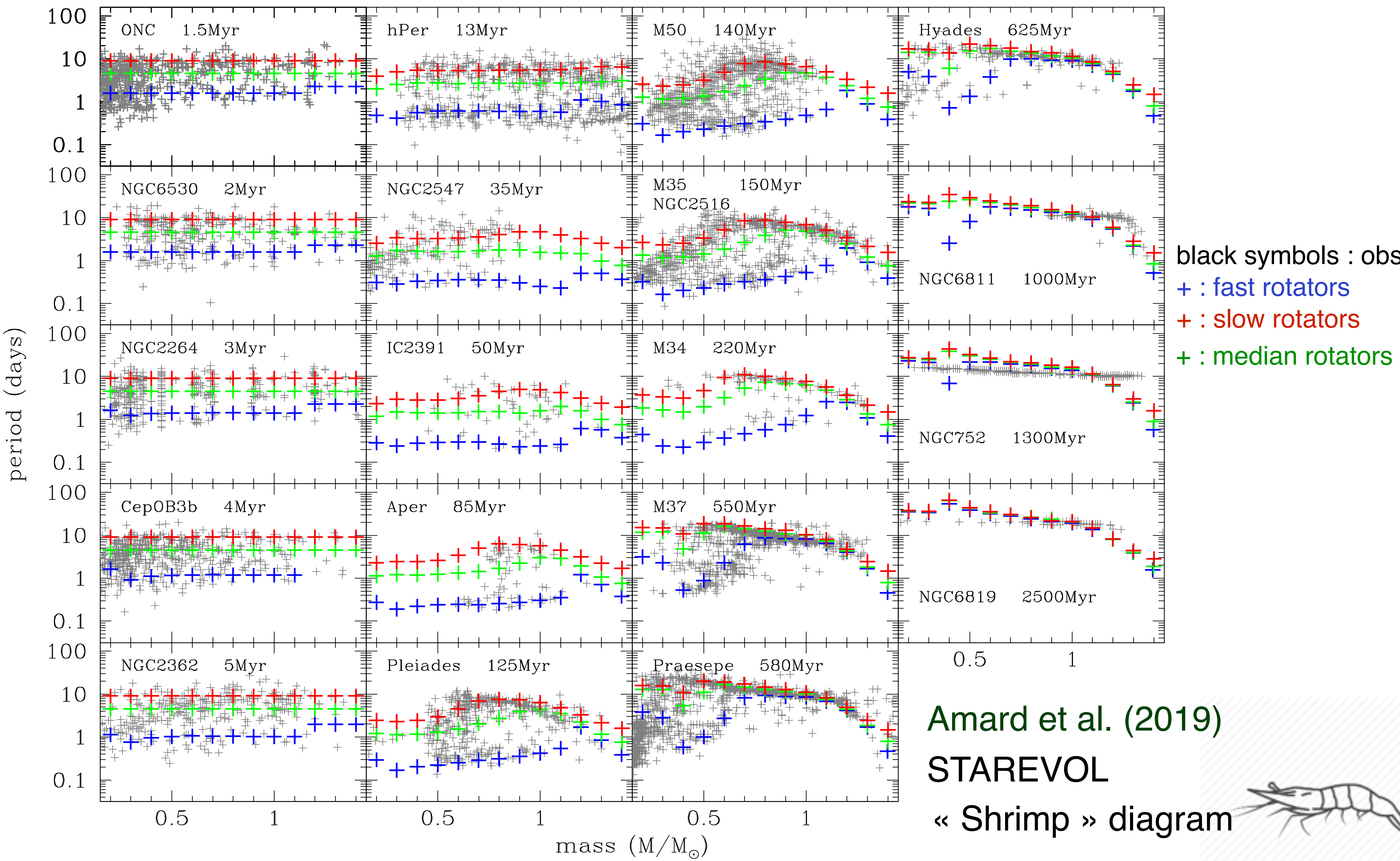
3. **Open questions?**

   - star-disk interaction: what mechanism?
   - magnetic braking: what quantity?
   - internal transport of AM: magnetic field? internal gravity waves?

Modeling clusters



Modeling clusters



Amard et al. (2019)

STAREVOL

« Shrimp » diagram