UNIVERSITÉ DE GRENOBLE

UNIVERSITÉ DE GENÈVE

Florian Gallet & Jérôme Bouvier

Angular momentum evolution model

: exploring the mass dependence

4 June 2015 - SF2A - Toulouse

UNIVERSITÉ DE GRENOBLE

UNIVERSITÉ DE GENÈVE

Florian Gallet & Jérôme Bouvier

Angular momentum evolution model

: exploring the mass dependence

OBSERVATOIRE DE GENÈVE FONDÉ EN 1772

TOUPIES TOwards Understanding the sPIn Evolution of Stars

SF2A SOCIÉTÉ FRANÇAISE D'ASTRONOMIE & D'ASTROPHYSIQUE

IPAG Institut de Planétologie et d'Astrophysique de Grenoble

4 June 2015 - SF2A - Toulouse

Studying angular momentum evolution? Why?

Study and understand stellar physics

1- wind braking

2- internal redistribution of AM

3- environmental interactions

Sun : the angular moment paradox

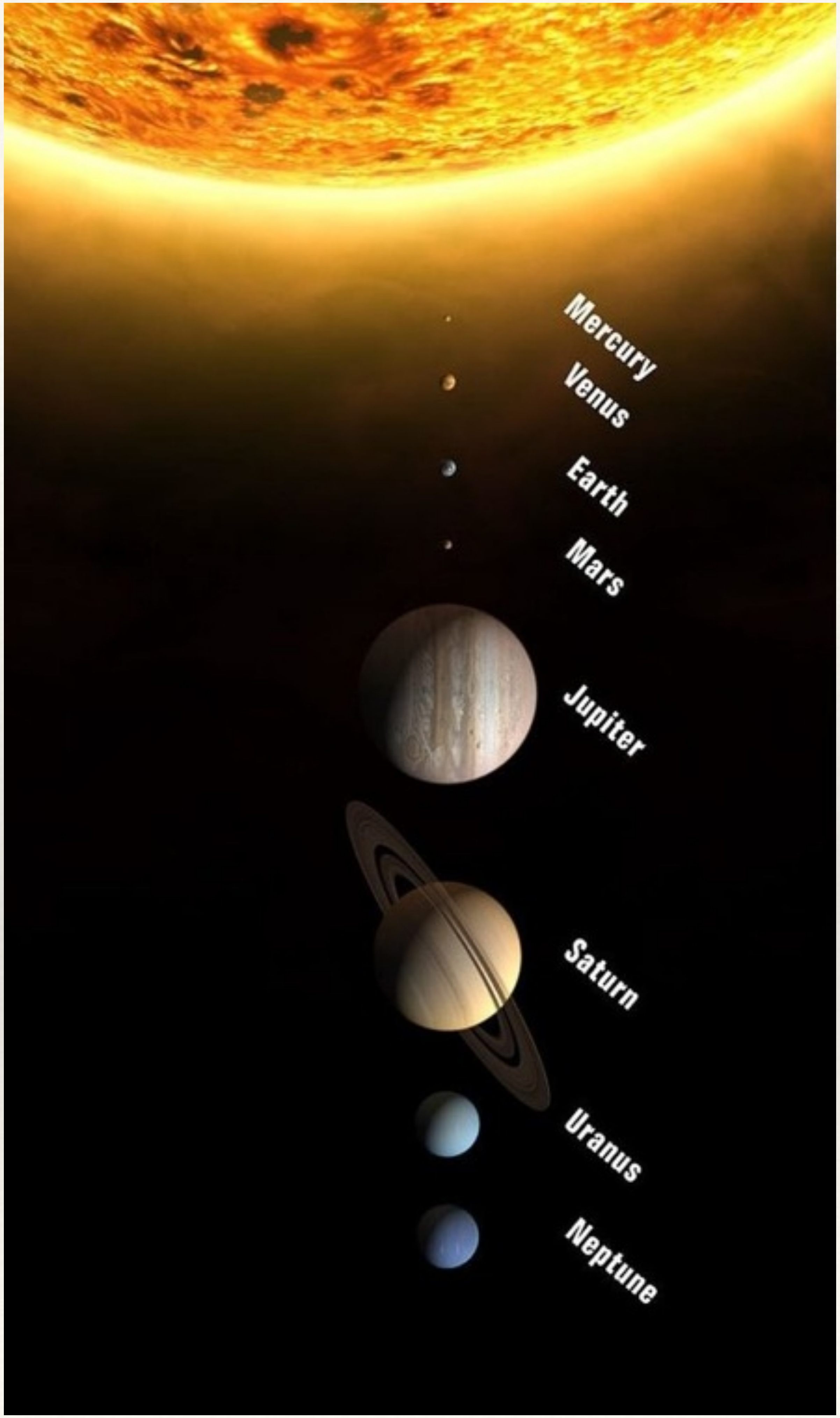
Mass of the Sun = 99% mass of the solar system

BUT

Angular momentum of the Sun = few % of total angular momentum (70% in **Jupiter**!!!!)

$J_\odot$ (1 Myr) = 100-1000 $J_\odot$ (4.6 Gyr)

Why Sun's angular momentum so low? Physical mechanisms responsible for these huge losses between 1 Myr and 4.6 Gyr?



Outline

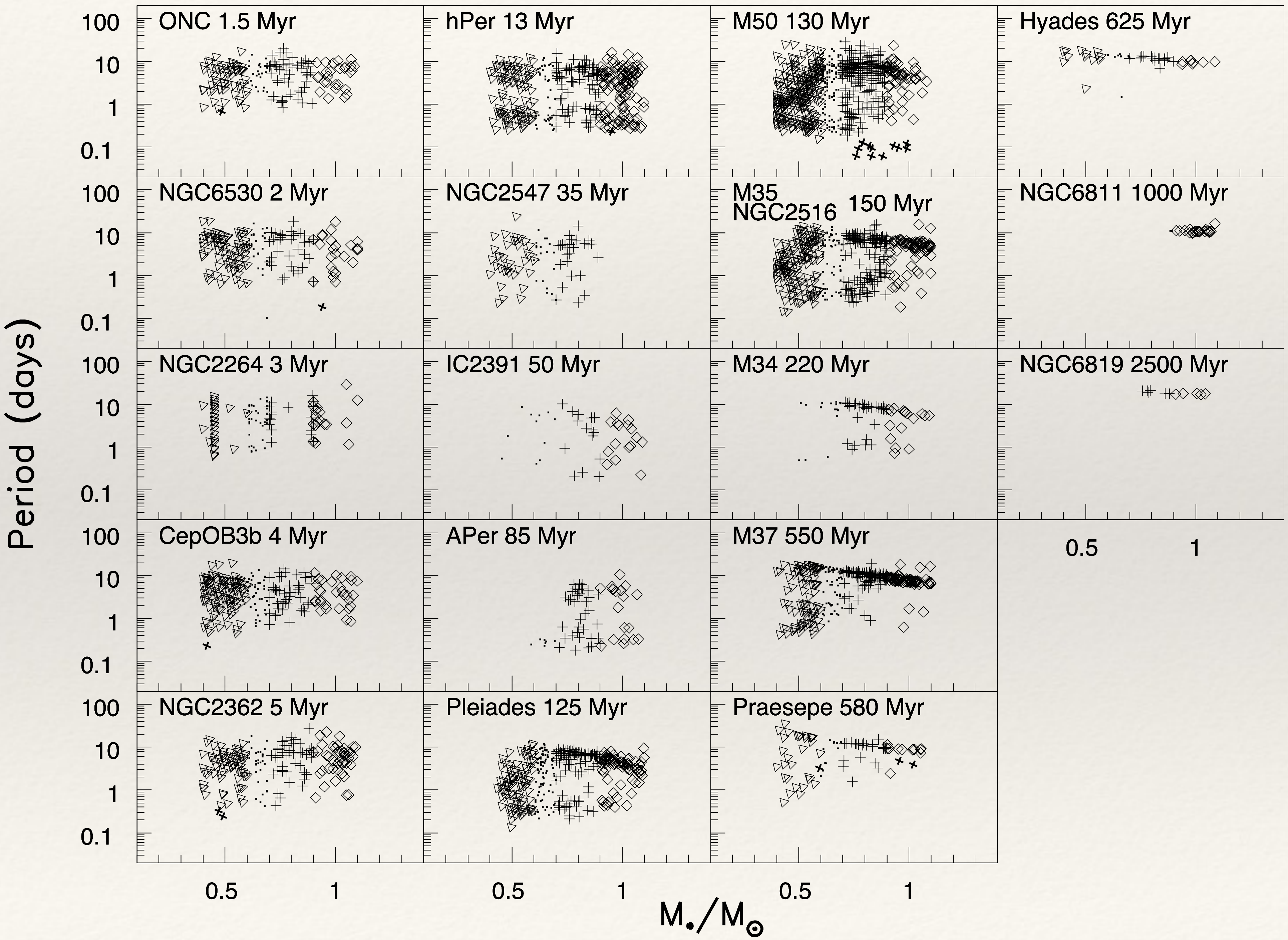
- Observational context
  - Observed rotational evolution
- Numerical models
  - Parametric model
- Rotational evolution
  - Solar type stars : 1 $M_\odot$
  - Low mass stars : 0.5 and 0.8 $M_\odot$
  - Implication for stellar physics
- Conclusion and perspectives

I - Observational context

- Observed rotational evolution

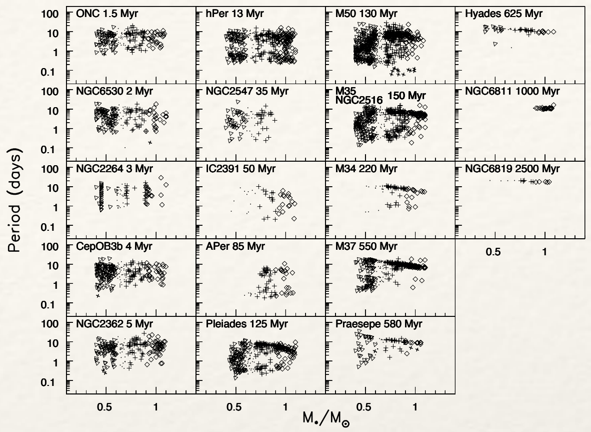
Observed rotational evolution

Evolution as a function of time



Observed rotational evolution

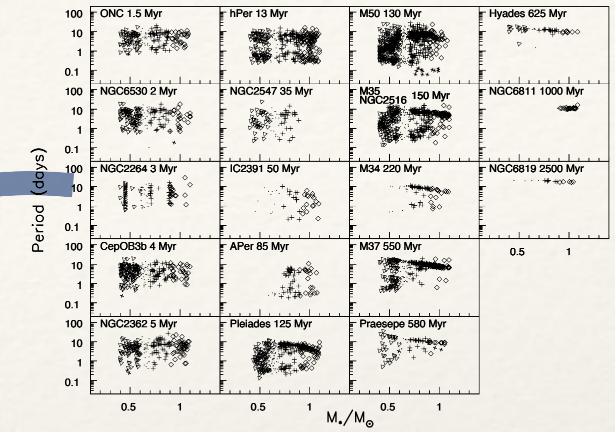
Evolution as a function of time

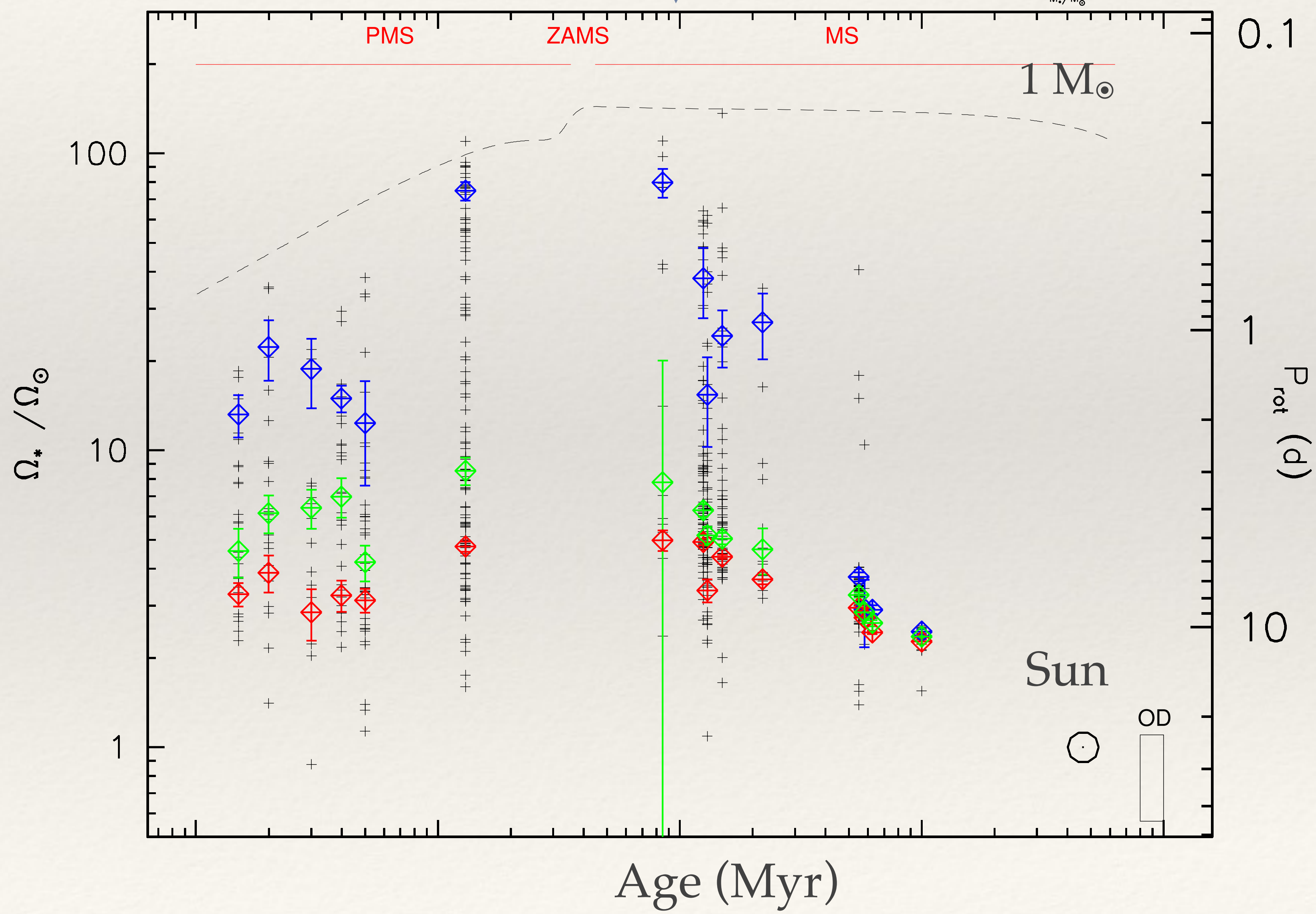


Observed rotational evolution

Evolution as a function of time

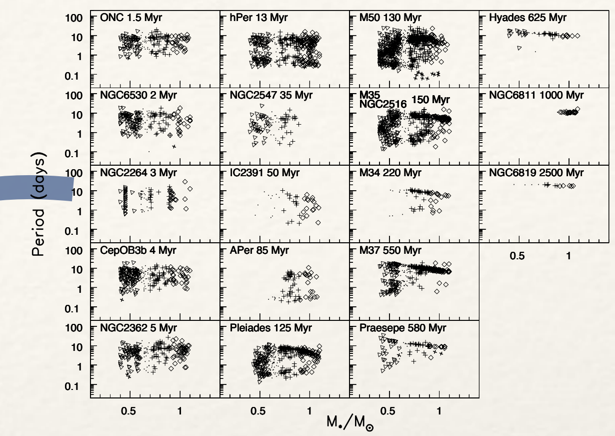
0.9 - 1.1 $M_{\odot}$ mass bin





Observed rotational evolution

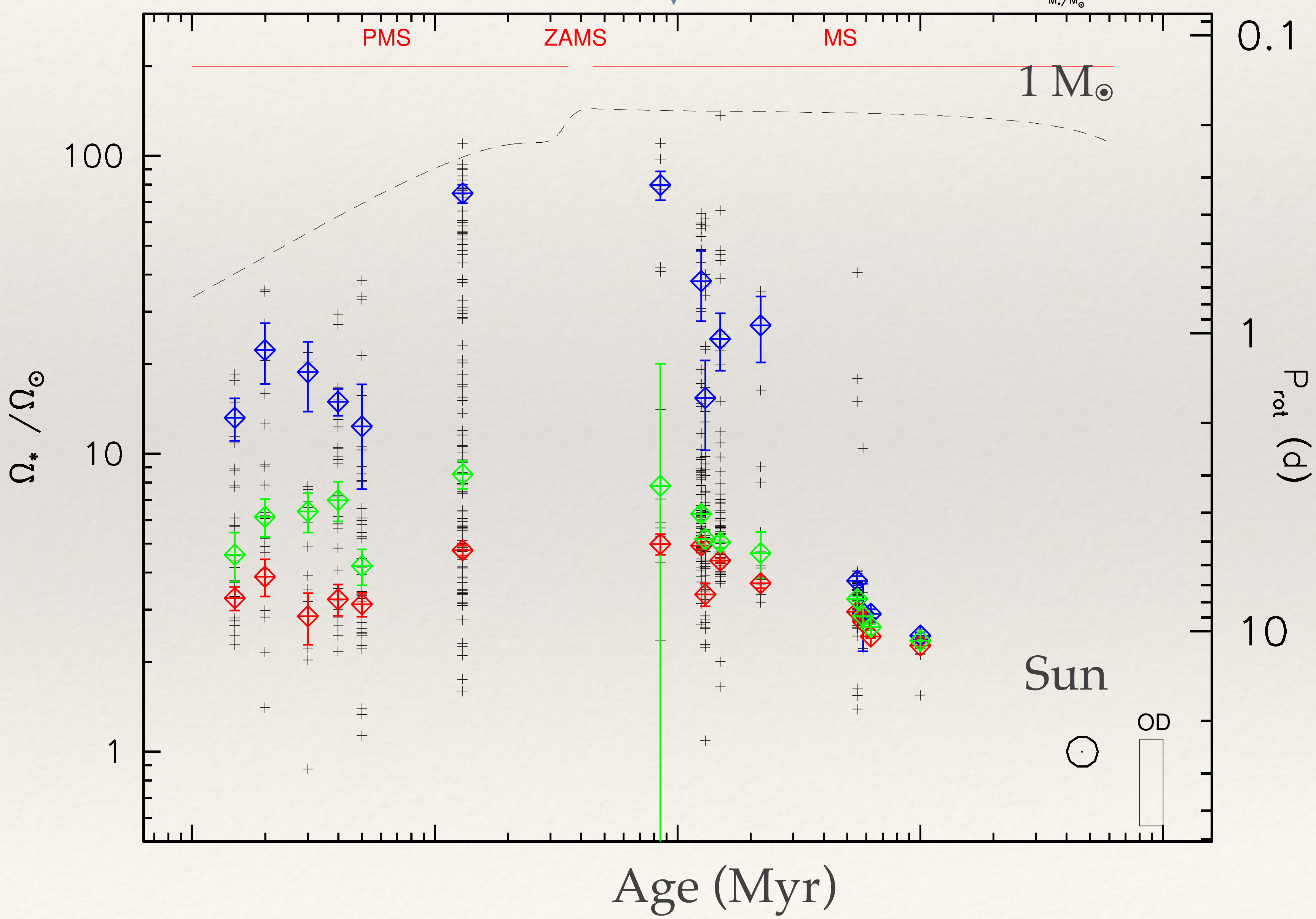
Evolution as a function of time



0.9 - 1.1 M⊙ mass bin

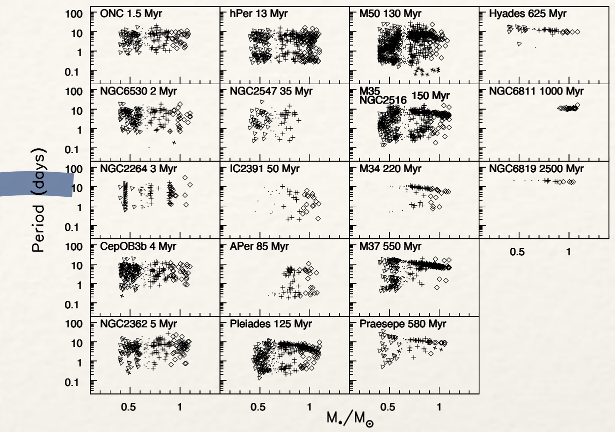
- 1st, 2nd and 3rd quartiles
  - 25th
  - median
  - 90th

  } of each distribution



Observed rotational evolution

Evolution as a function of time

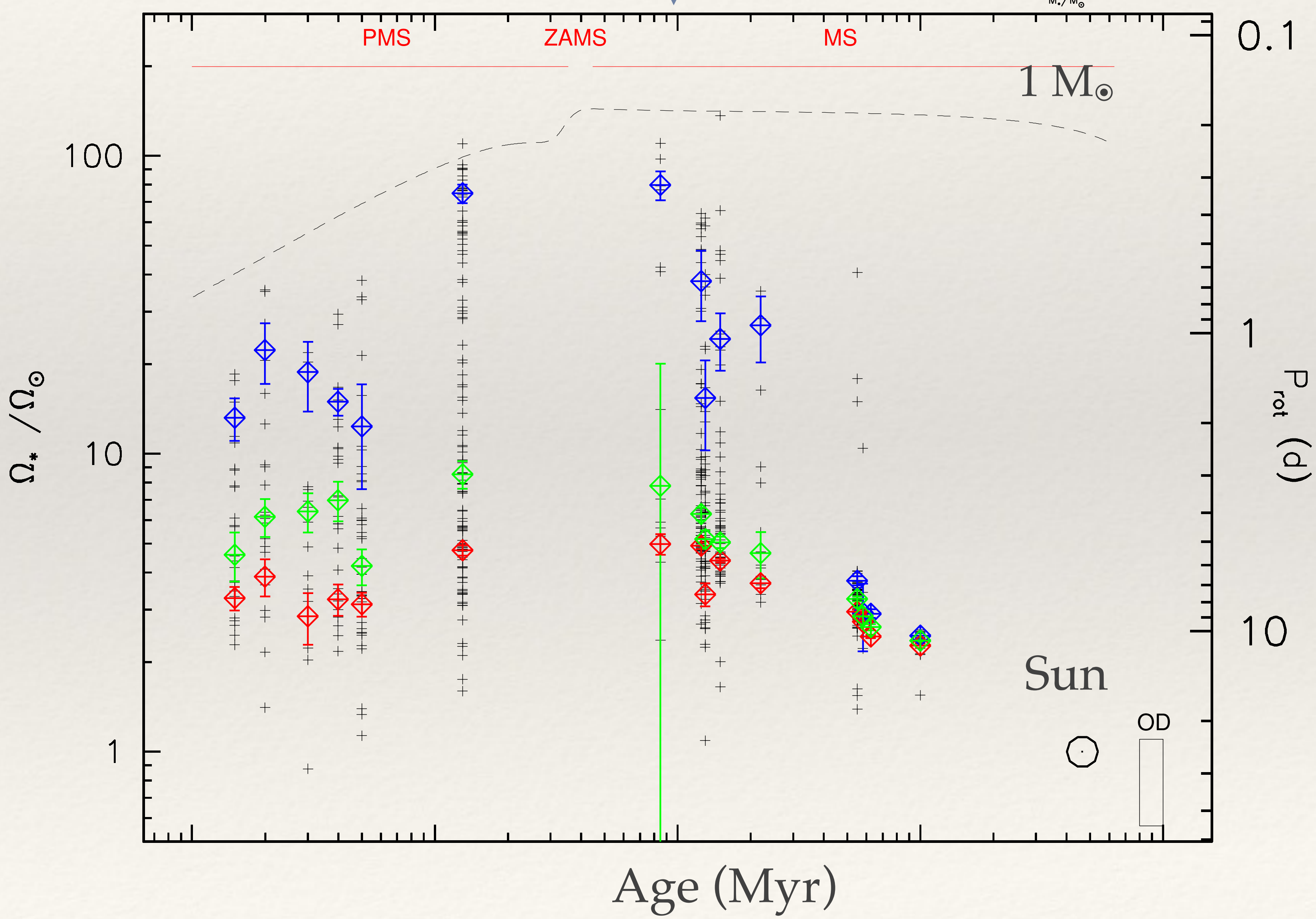


0.9 - 1.1 M⊙ mass bin

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

  } of each distribution

- PMS
  - Early PMS : rotation period ≈ constant
  - Late PMS : spin-up due to contraction (up to 200 km/s)



Observed rotational evolution

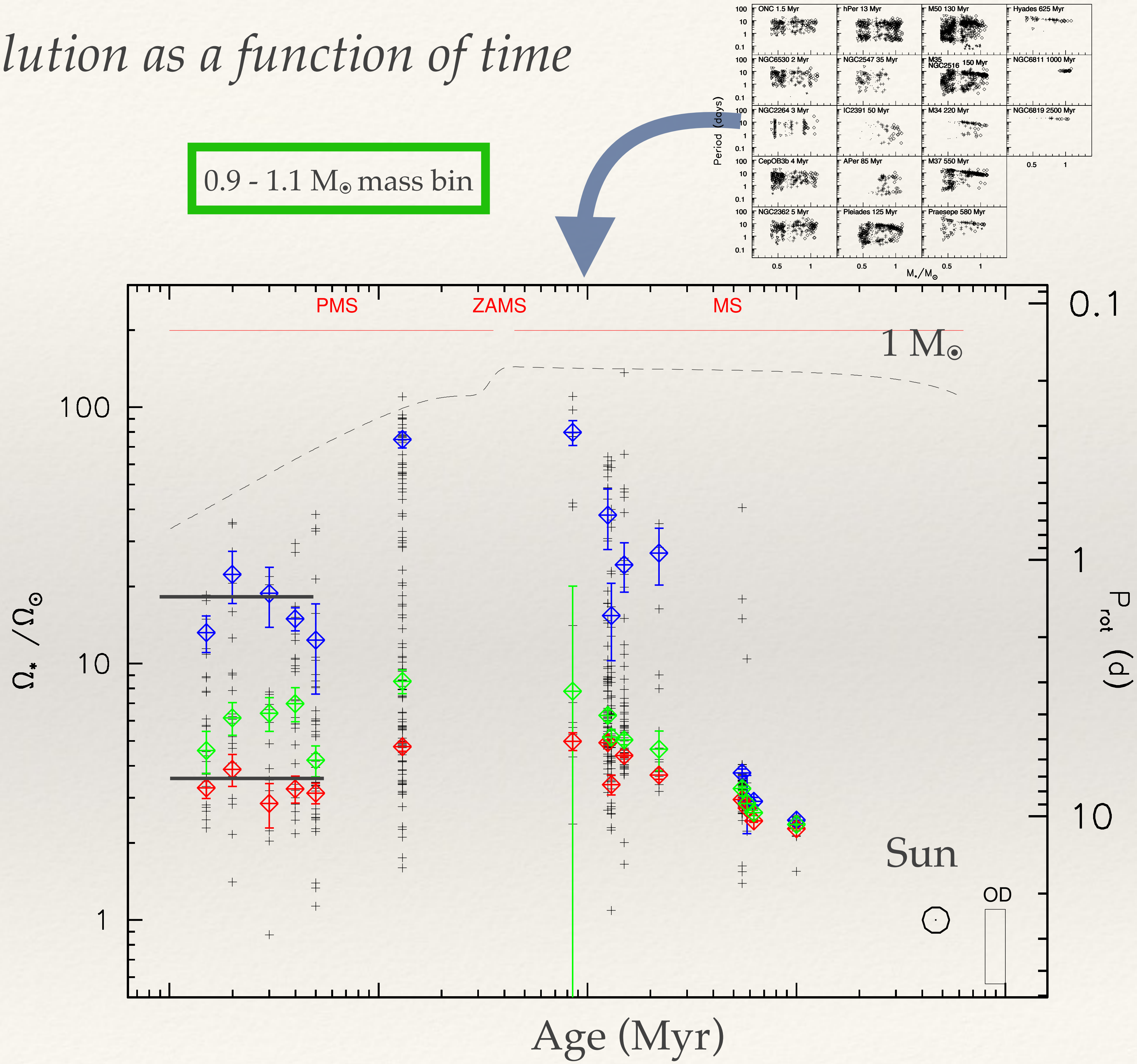
Evolution as a function of time

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

  } of each distribution

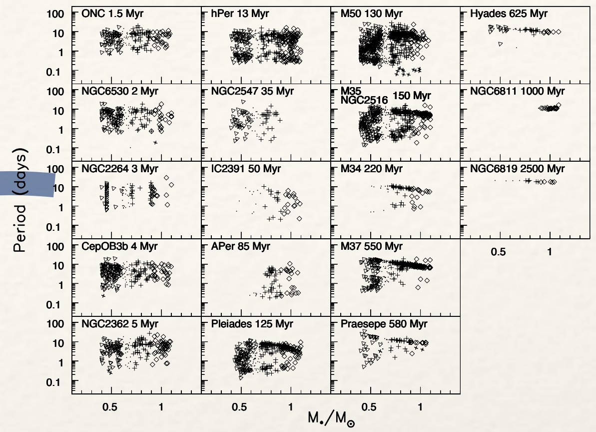
- PMS
  - Early PMS : rotation period ≈ constant
  - Late PMS : spin-up due to contraction (up to 200 km/s)

0.9 - 1.1 $M_\odot$ mass bin



Observed rotational evolution

Evolution as a function of time

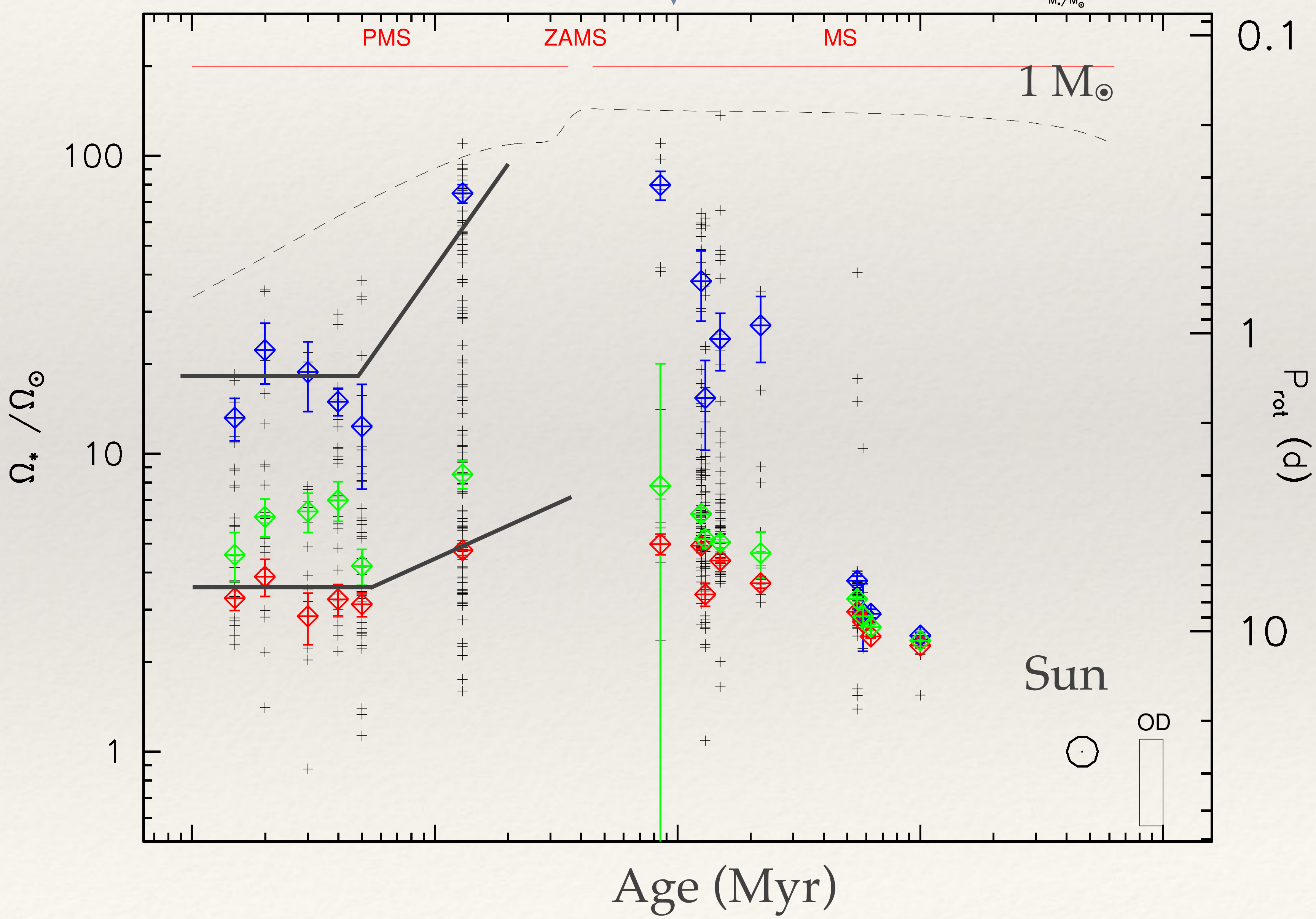


0.9 - 1.1 $M_\odot$ mass bin

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

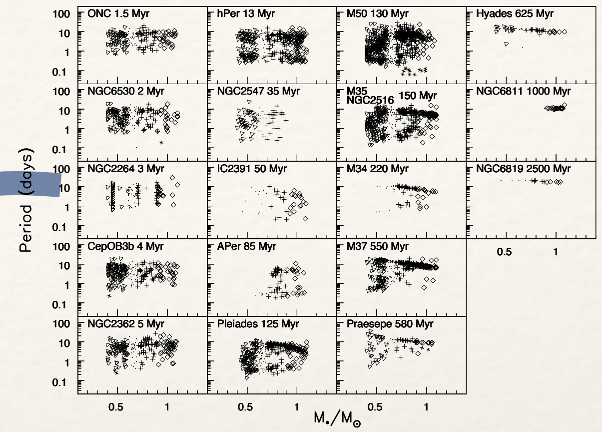
  } of each distribution

- PMS
  - Early PMS : rotation period ≈ constant
  - Late PMS : spin-up due to contraction (up to 200 km/s)



Observed rotational evolution

Evolution as a function of time



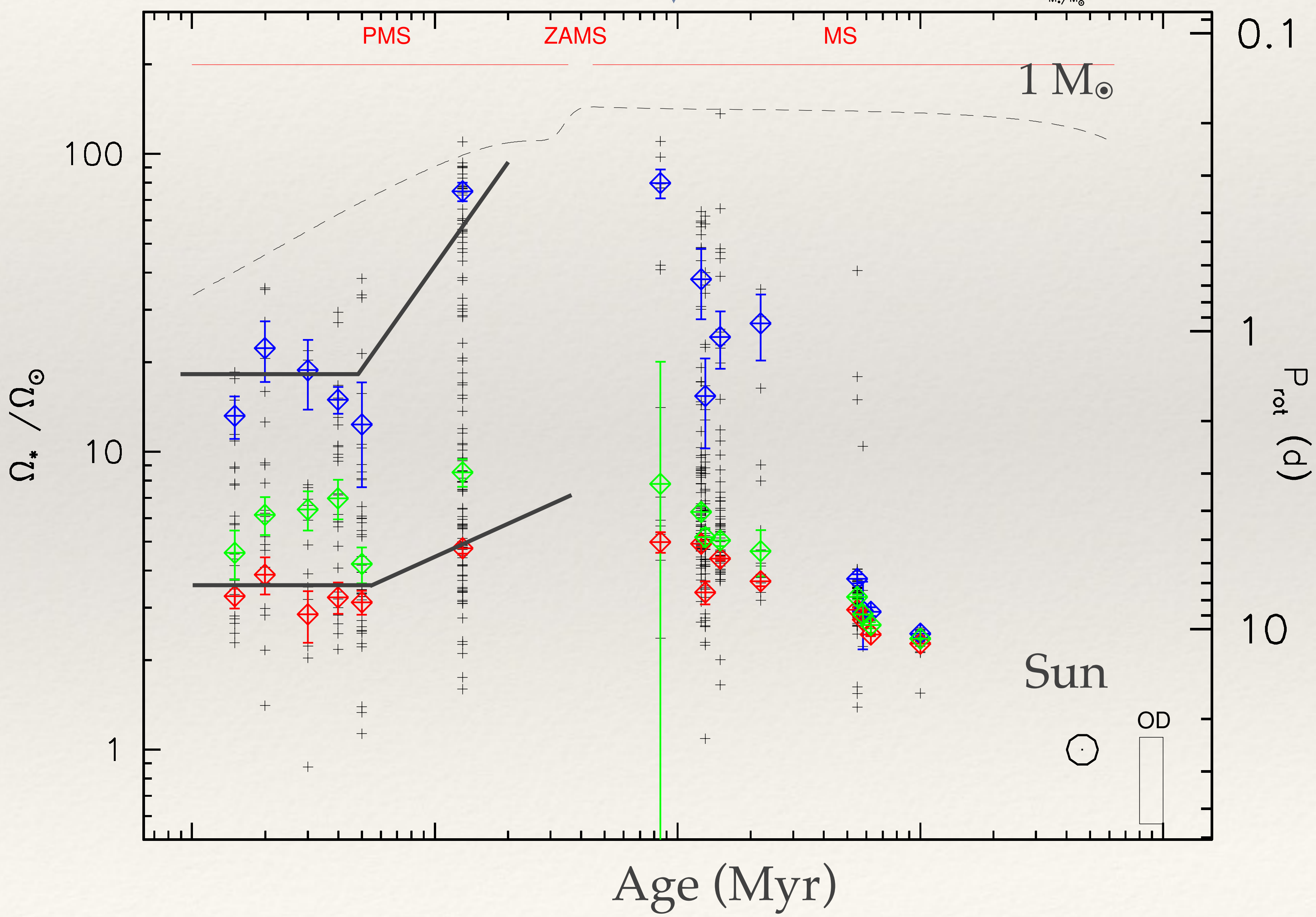
0.9 - 1.1 M⊙ mass bin

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

  } of each distribution

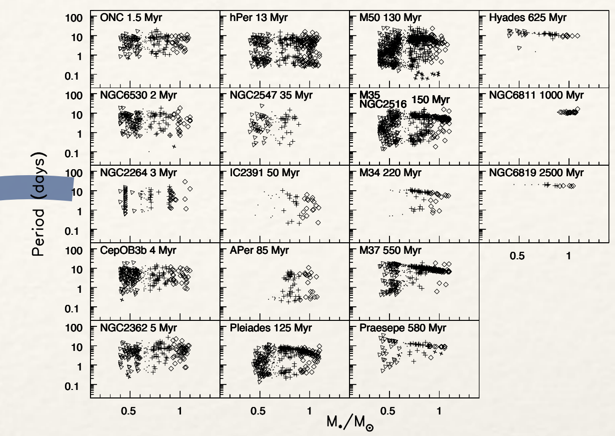
- PMS
  - Early PMS : rotation period ≈ constant
  - Late PMS : spin-up due to contraction (up to 200 km/s)

- ZAMS
  - Stabilisation of the stellar structure



Observed rotational evolution

Evolution as a function of time



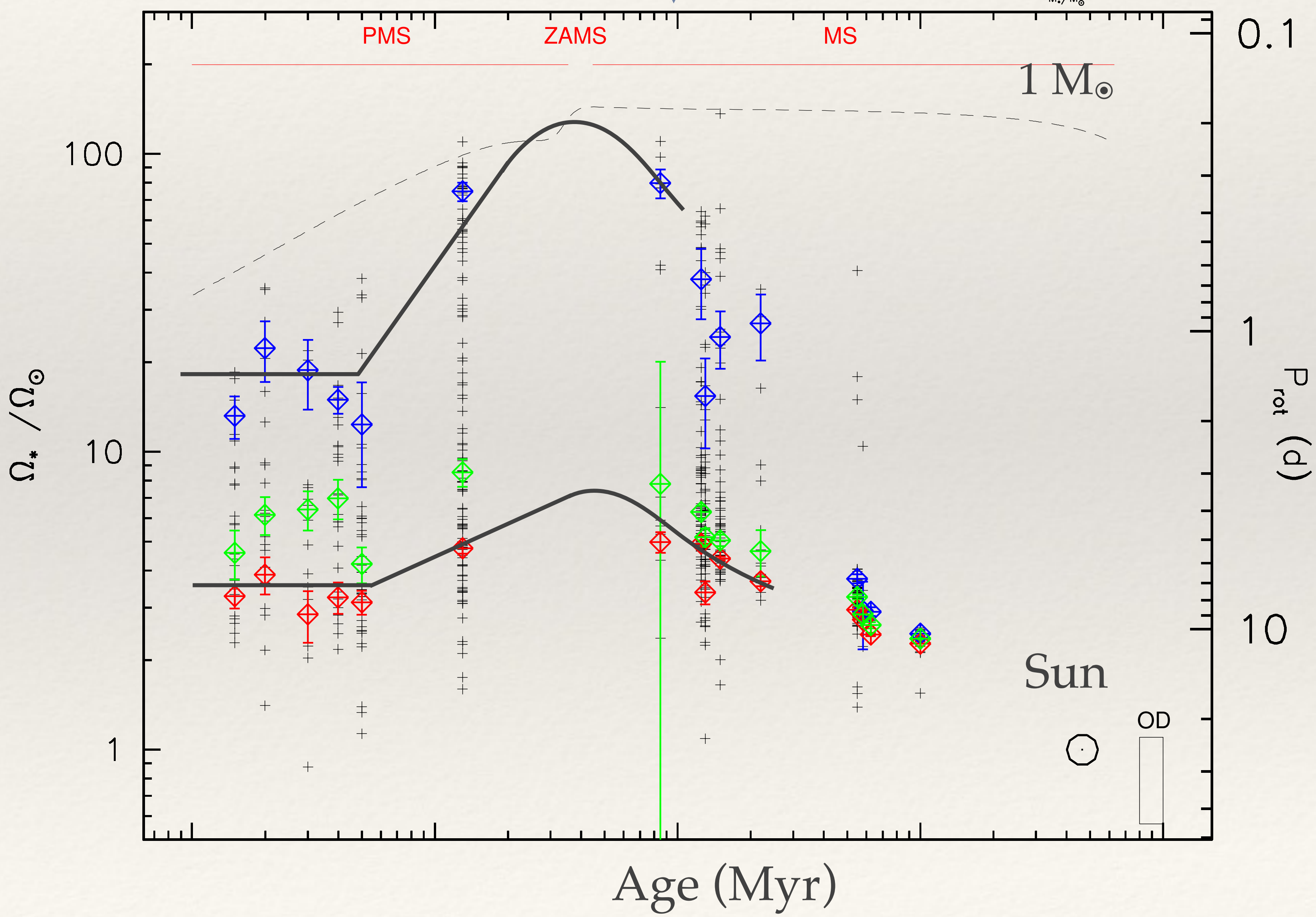
0.9 - 1.1 $M_\odot$ mass bin

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

  of each distribution

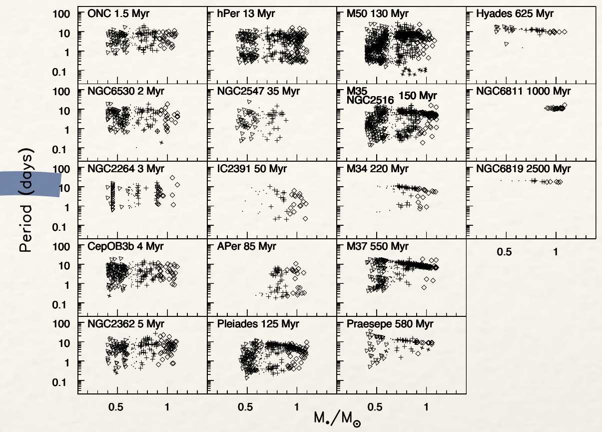
- PMS
  - Early PMS : rotation period ≈ constant
  - Late PMS : spin-up due to contraction (up to 200 km/s)

- ZAMS
  - Stabilisation of the stellar structure



Observed rotational evolution

Evolution as a function of time

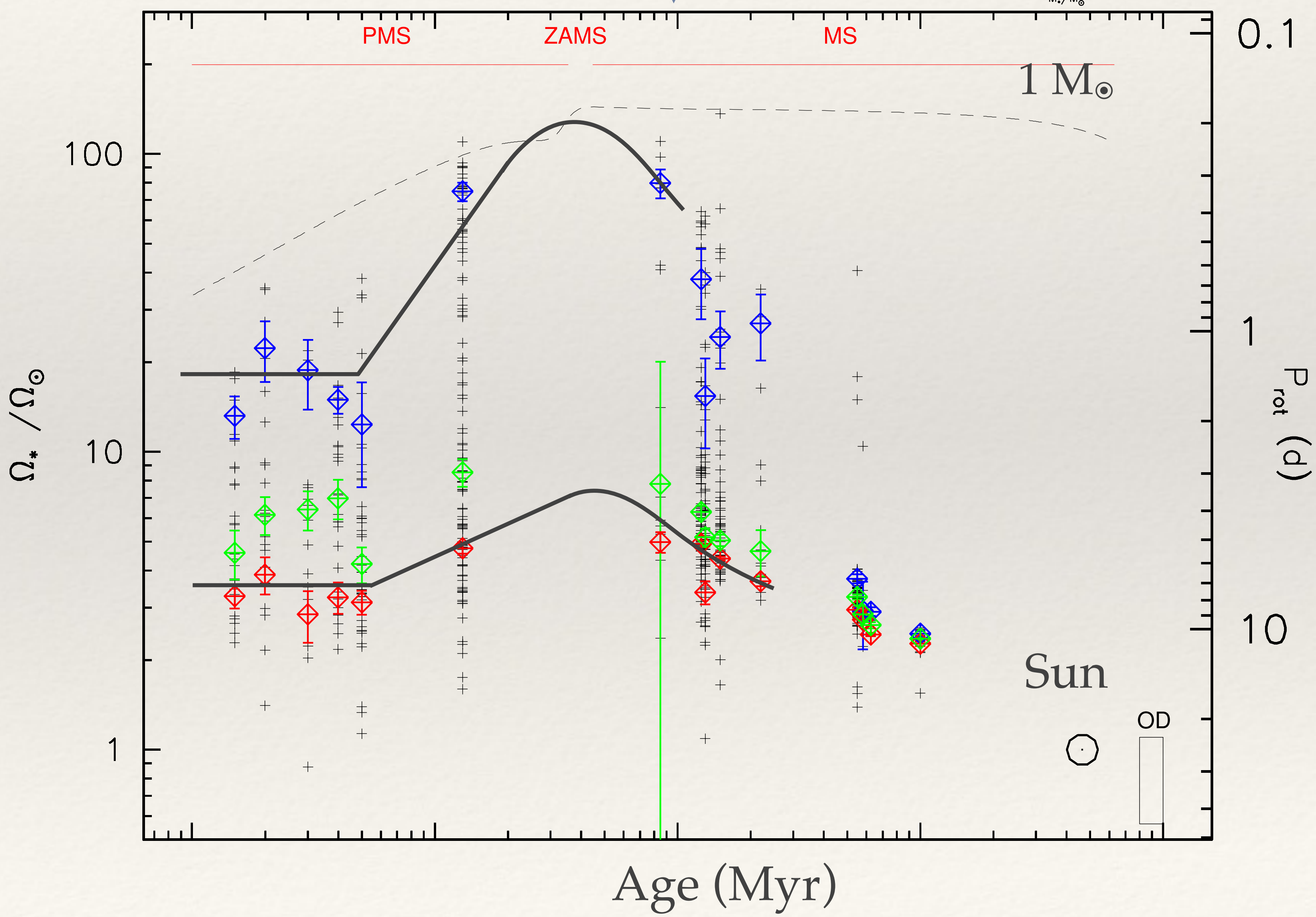


0.9 - 1.1 $M_\odot$ mass bin

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

  } of each distribution

- PMS
  - Early PMS : rotation period ≈ constant
  - Late PMS : spin-up due to contraction (up to 200 km/s)
- ZAMS
  - Stabilisation of the stellar structure
- MS
  - Rotational convergence

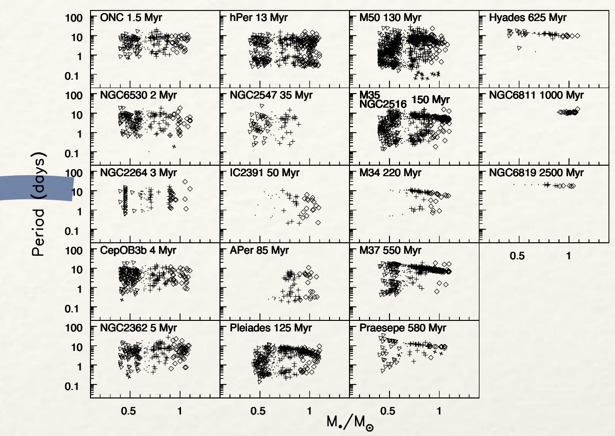


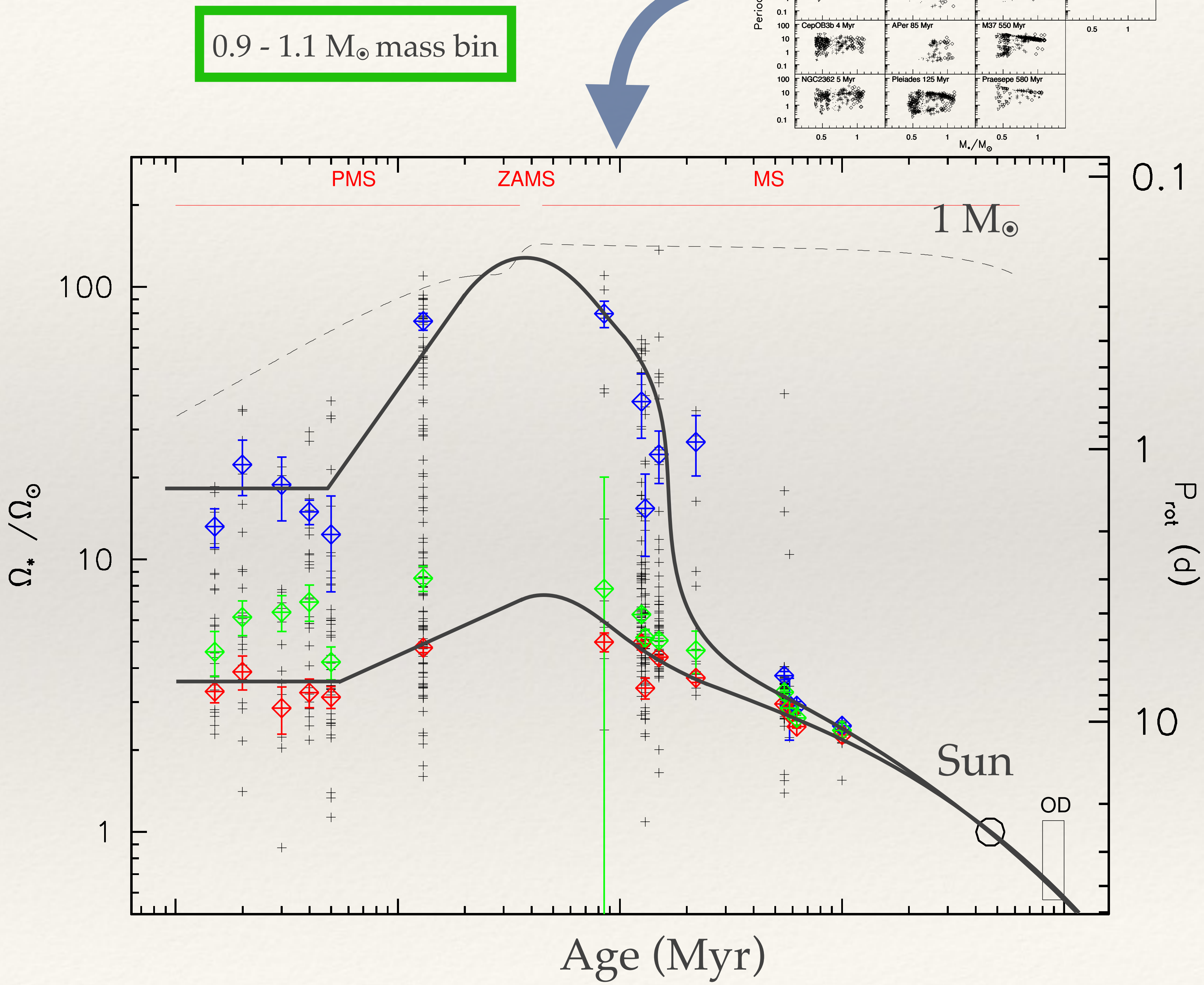
Observed rotational evolution

Evolution as a function of time

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

  } of each distribution

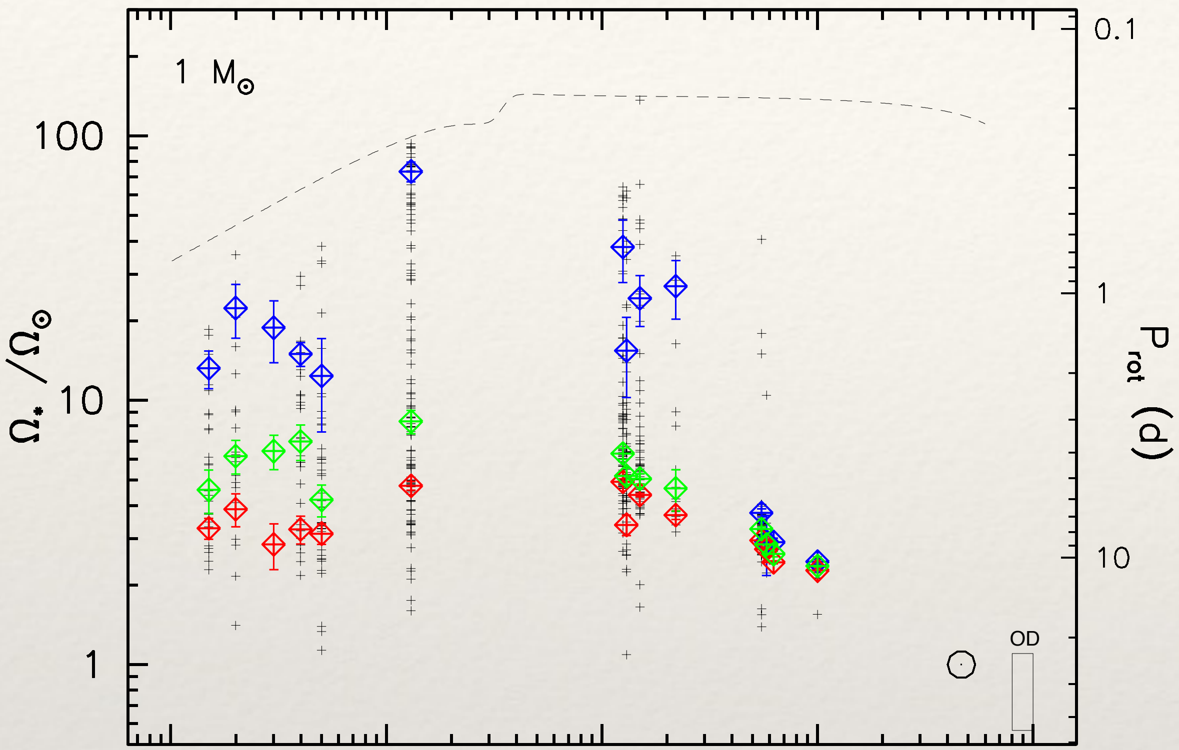


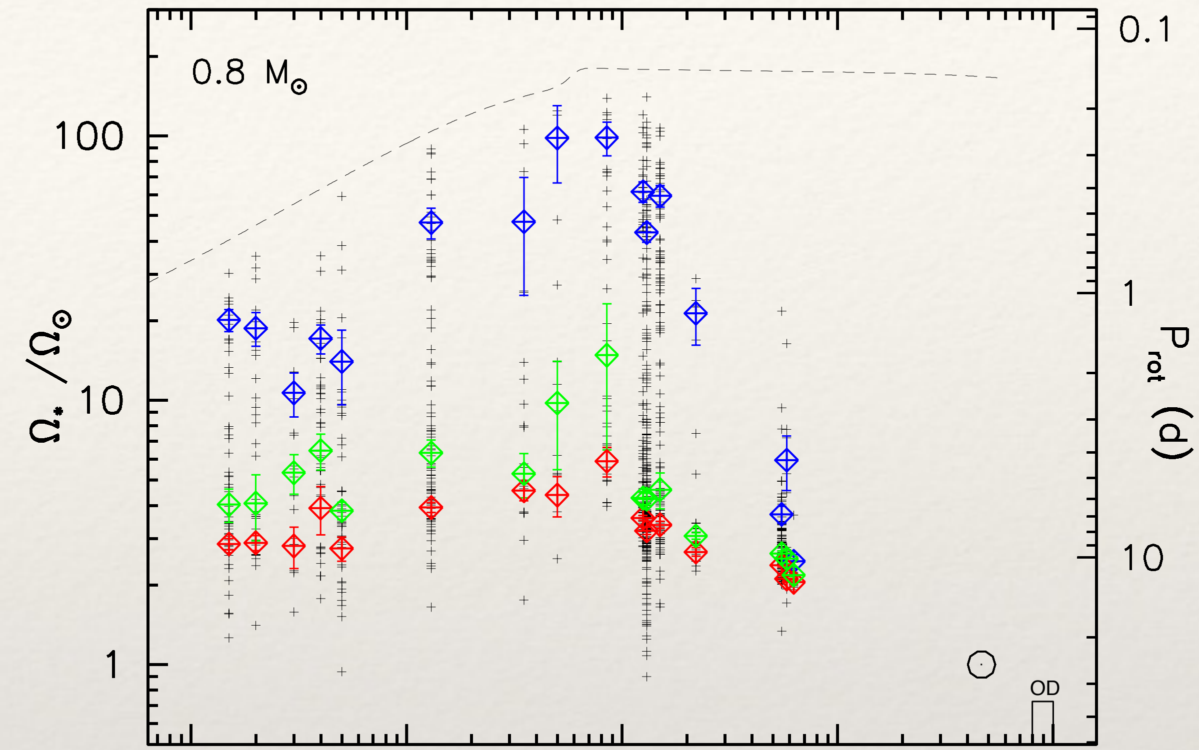


- PMS
  - Early PMS : rotation period ≈ constant
  - Late PMS : spin-up due to contraction (up to 200 km/s)
- ZAMS
  - Stabilisation of the stellar structure
- MS
  - Rotational convergence

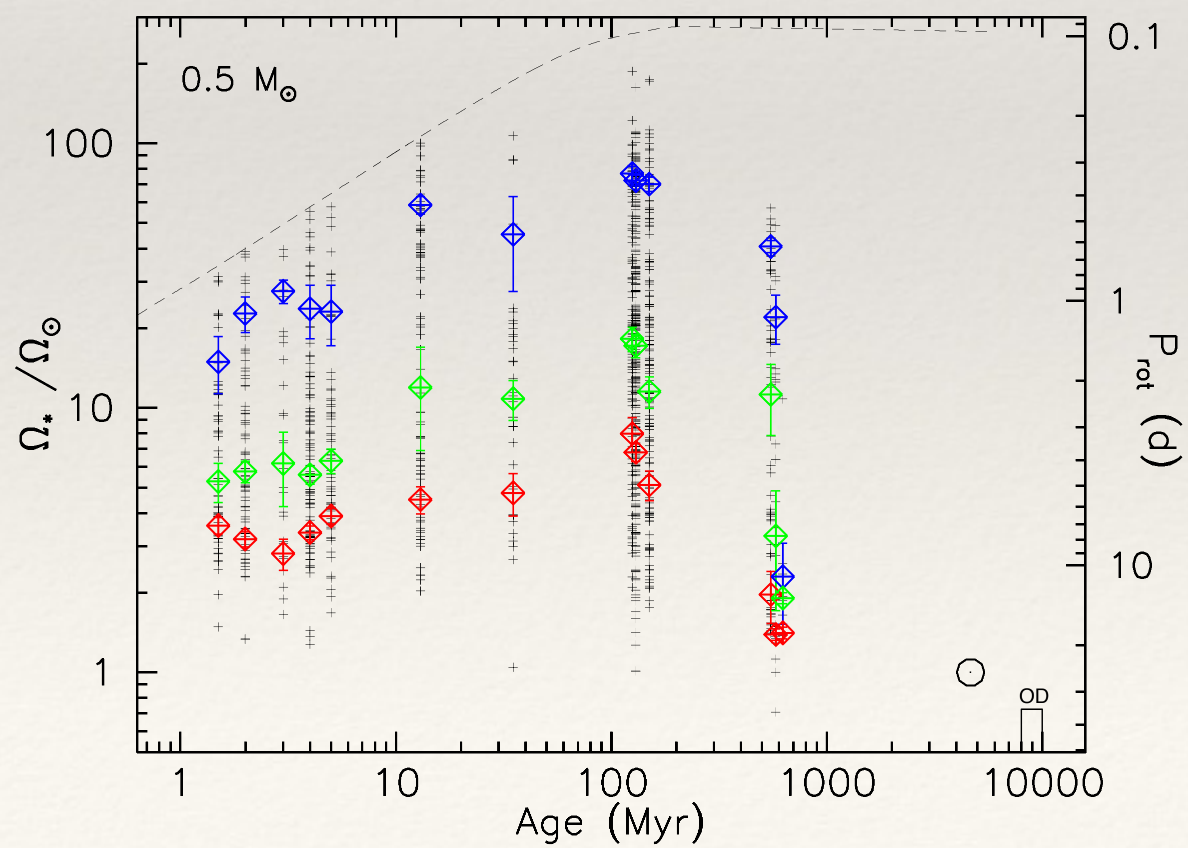
Observed rotational evolution

Evolution as a function of mass





Gallet & Bouvier (2015)



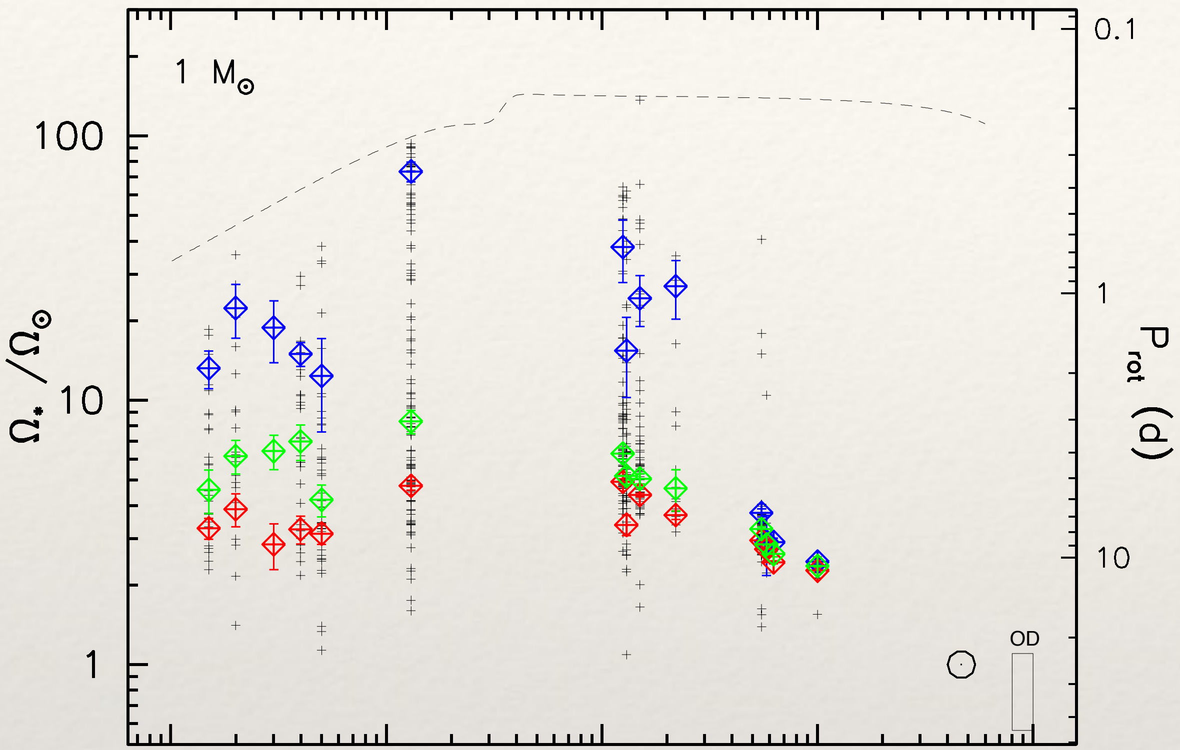
Same evolution

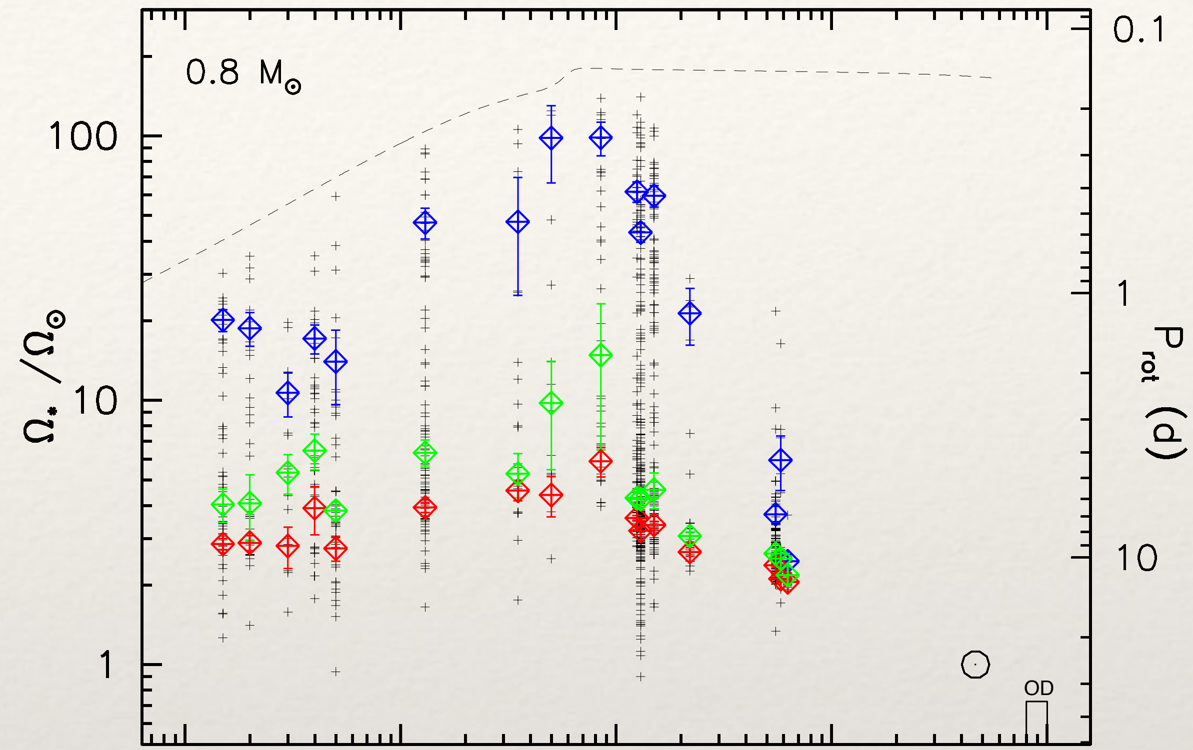
but

Longer convergence for lower mass stars

Observed rotational evolution

Evolution as a function of mass

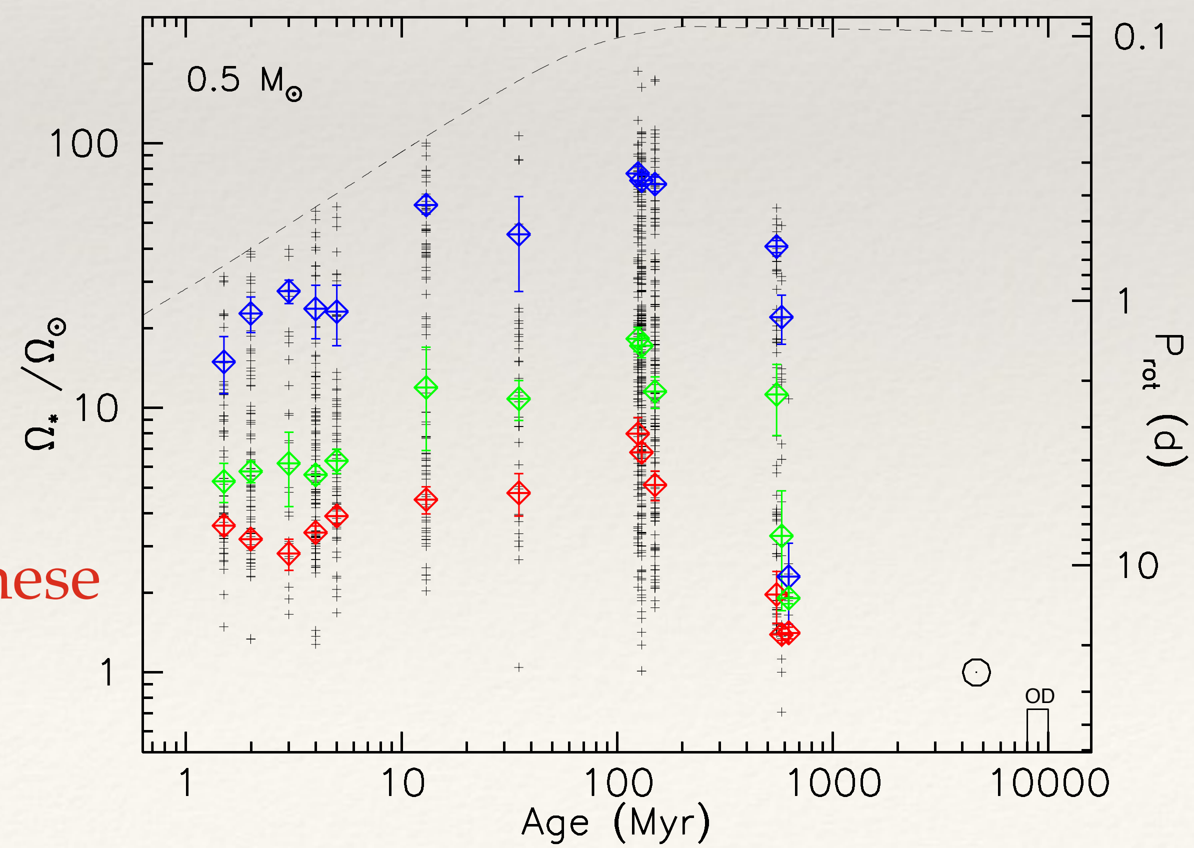




Gallet & Bouvier (2015)

⇩

Model must reproduce these observations



Same evolution

but

Longer convergence for lower mass stars

II - Numerical models

- Parametric model

Parametric model

Physical mechanisms

- **wind braking**
- **core/envelope decoupling**
- **star/disk interaction**

Parametric model => free parameters adjusted from observations

Parametric model

Physical mechanisms

Weber & Davis (1967)

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

- **core/envelope decoupling**

- **star/disk interaction**

Parametric model => free parameters adjusted from observations

Parametric model

Physical mechanisms

Weber & Davis (1967)

Matt et al. (2012a)

- **wind braking**

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

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

$K_1 = 1.3$
$K_2 = 0.0506$
$m = 0.22$

- **core/envelope decoupling**

- **star/disk interaction**

Parametric model => free parameters adjusted from observations

Parametric model

Physical mechanisms

Weber & Davis (1967)

Matt et al. (2012a)

- **wind braking**

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

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

$K_1 = 1.3$
$K_2 = 0.0506$
$m = 0.22$

K_1 (free parameter)

- **core/envelope decoupling**

- **star/disk interaction**

Parametric model => free parameters adjusted from observations

Parametric model

Physical mechanisms

Weber & Davis (1967)

Matt et al. (2012a)

- **wind braking**

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

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

$K_1 = 1.3$
$K_2 = 0.0506$
$m = 0.22$

K_1 (free parameter)

Two unknown => B_p and $\dot{M}_{wind}$ ⇨ Cranmer & Saar (2011) BOREAS routine

- **core/envelope decoupling**

- **star/disk interaction**

Parametric model => free parameters adjusted from observations

Parametric model

Physical mechanisms

Weber & Davis (1967)

Matt et al. (2012a)

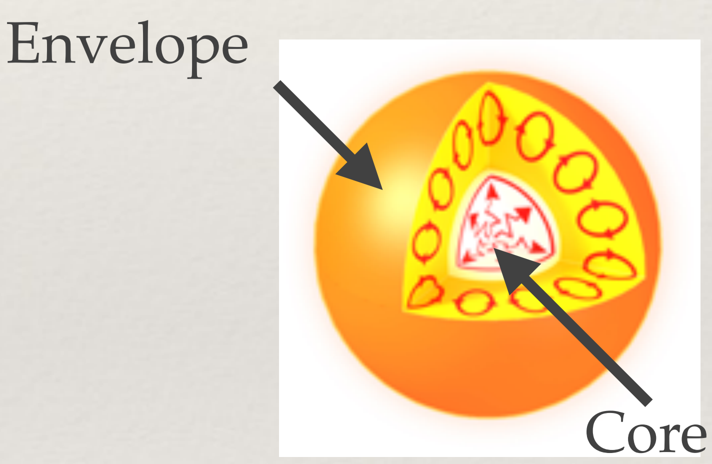
- **wind braking** $\left.\frac{dJ}{dt}\right|_{wind} \approx \Omega_* \dot{M}_{wind} r_A^2$ $\quad r_A = K_1 \left[\frac{B_p^2 R_*^2}{\dot{M}_{wind}\sqrt{K_2^2 v_{esc}^2 + \Omega_*^2 R_*^2}} \right]^m R_*$

$K_1 = 1.3$
$K_2 = 0.0506$
$m = 0.22$

K_1 (free parameter)

Two unknown => B_p and $\dot{M}_{wind}$ ⇨ Cranmer & Saar (2011) BOREAS routine

- **core/envelope decoupling**



- **star/disk interaction**

Parametric model => free parameters adjusted from observations

Parametric model

Physical mechanisms

Weber & Davis (1967)

Matt et al. (2012a)

- **wind braking**

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

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

$K_1 = 1.3$
$K_2 = 0.0506$
$m = 0.22$

K_1 (free parameter)

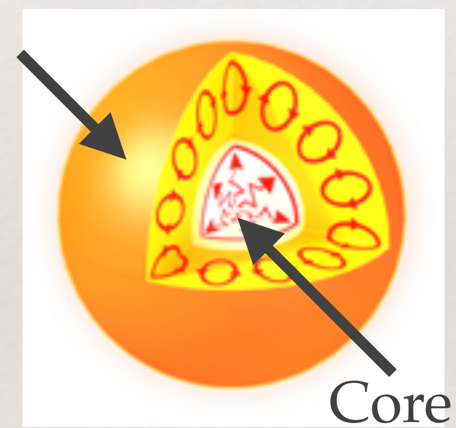
Two unknown => B_p and $\dot{M}_{wind}$ ⇨ Cranmer & Saar (2011) BOREAS routine

- **core/envelope decoupling**

MacGregor & Brenner (1991)

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

=> τ_{c-e} (free parameter)



- **star/disk interaction**

Parametric model => free parameters adjusted from observations

Parametric model

Physical mechanisms

Weber & Davis (1967)

Matt et al. (2012a)

- **wind braking**

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

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

$K_1 = 1.3$
$K_2 = 0.0506$
$m = 0.22$

K_1 (free parameter)

Two unknown => B_p and $\dot{M}_{wind}$ ⇨ Cranmer & Saar (2011) BOREAS routine

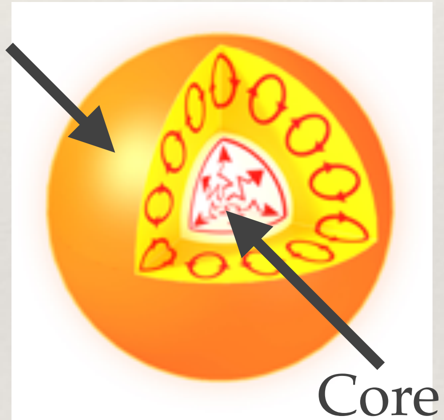
- **core/envelope decoupling**

MacGregor & Brenner (1991)

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

=> τ_{c-e} (free parameter) $\quad \tau_{c-e} = cst|_{model}$

(Allain 1998; Irwin & Bouvier 2009)



- **star/disk interaction**

Parametric model => free parameters adjusted from observations

Parametric model

Physical mechanisms

Weber & Davis (1967) Matt et al. (2012a)

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

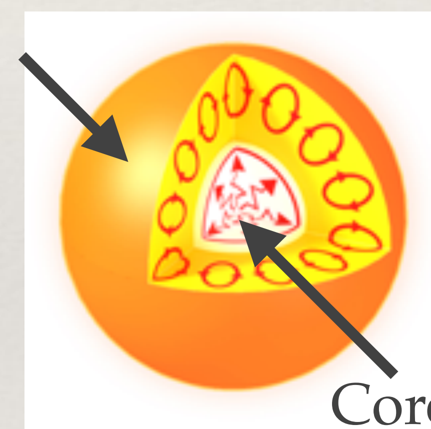
$$r_A = K_1 \left[\frac{B_p^2 R_*^2}{\dot{M}_{wind} \sqrt{K_2^2 v_{esc}^2 + \Omega_*^2 R_*^2}} \right]^m R_*$$

$K_1 = 1.3$
$K_2 = 0.0506$
$m = 0.22$

K_1 (free parameter)

Two unknown => B_p and $\dot{M}_{wind}$ ⇨ Cranmer & Saar (2011) BOREAS routine

- **core/envelope decoupling**



MacGregor & Brenner (1991)

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

=> τ_{c-e} (free parameter) $\left.\tau_{c-e} = cst\right|_{model}$

(Allain 1998; Irwin & Bouvier 2009)

- **star/disk interaction**

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

=> τ_{disk} (free parameter)

Parametric model => free parameters adjusted from observations

III - Rotational evolution

- Solar type stars : 1 $M_{\odot}$
- Low mass stars : 0.5 and 0.8 $M_{\odot}$
- Implication for stellar physics

Solar type stars

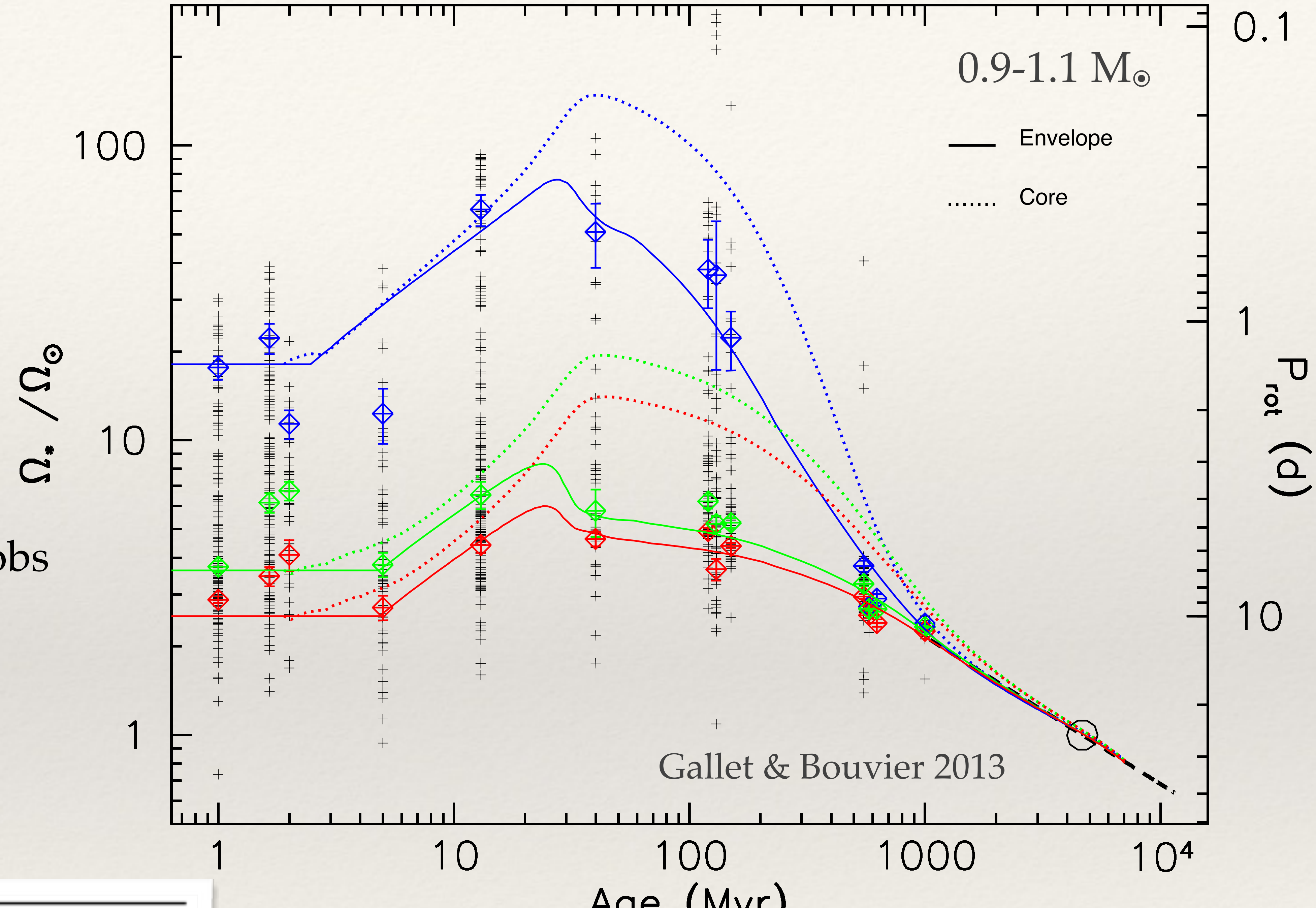
<u>4 free parameters</u>:

P_{init} => obs

τ_{disk} => obs

τ_{c-e} => obs

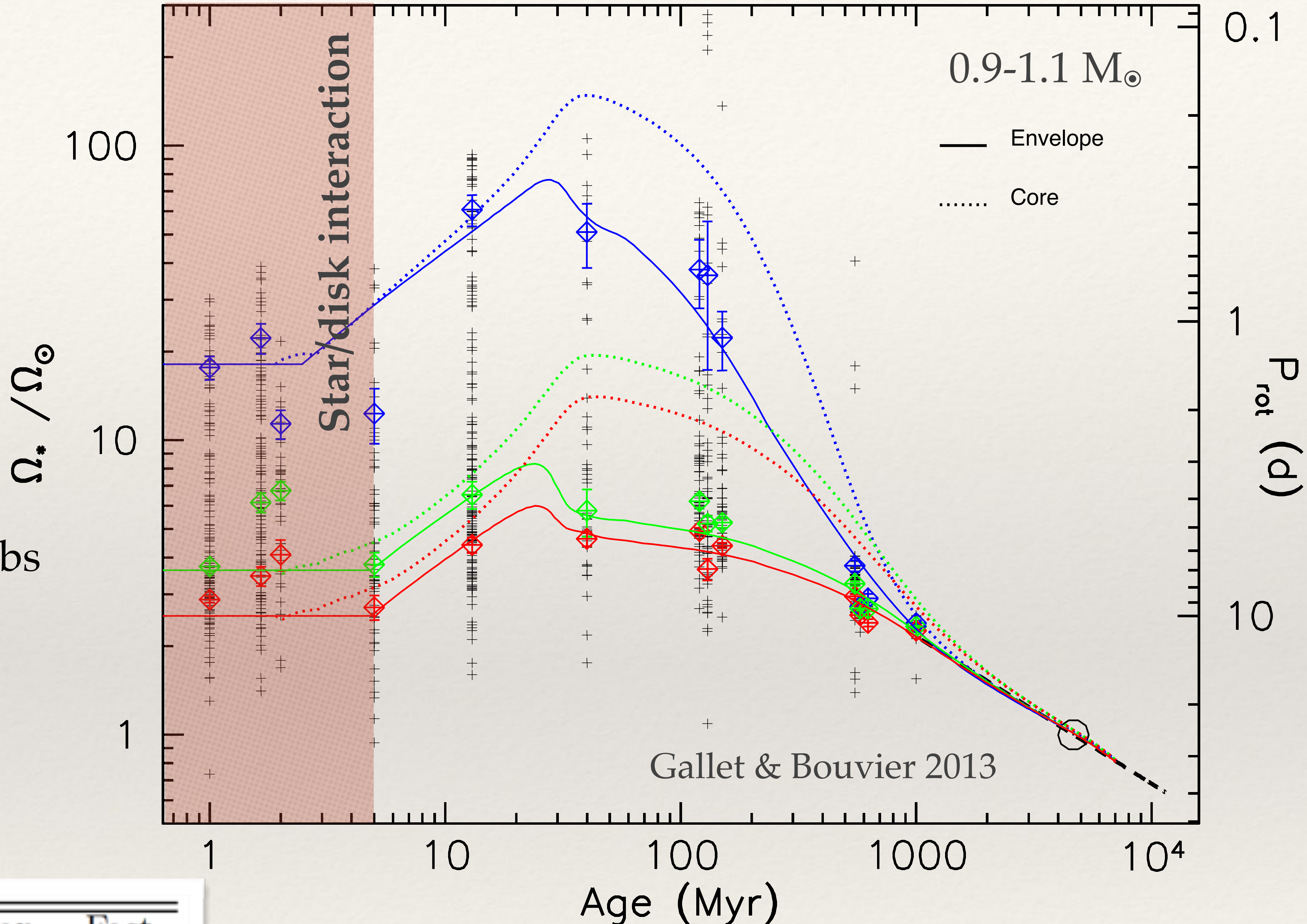
K_1(dJ/dt) => numerical+obs



Parameter	Slow	Median	Fast
P_{init} (days)	10	7	1.4
τ_{c-e} (Myr)	30	28	12
τ_{disk} (Myr)	5	5	2.5
K_1	1.8	1.8	1.7

<u>Stellar structure evolution model</u> : Baraffe et al. (1998)

Solar type stars



4 free parameters:

P_{init} => obs

τ_{disk} => obs

τ_{c-e} => obs

K_1(dJ/dt) => numerical+obs

Parameter	Slow	Median	Fast
P_{init} (days)	10	7	1.4
τ_{c-e} (Myr)	30	28	12
τ_{disk} (Myr)	5	5	2.5
K_1	1.8	1.8	1.7

Stellar structure evolution model : Baraffe et al. (1998)

Solar type stars

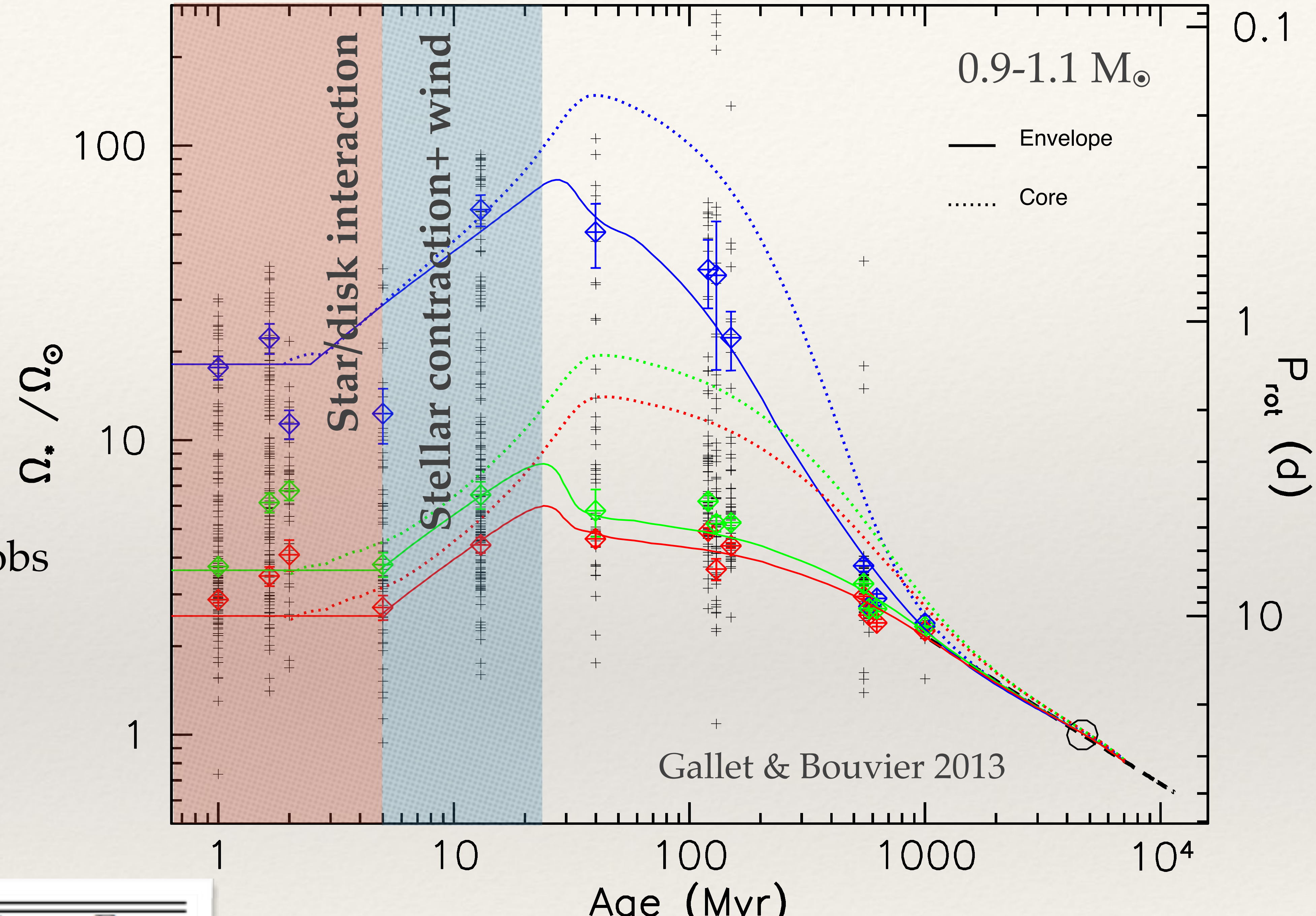
<u>4 free parameters</u>:

P_{init} => obs

τ_{disk} => obs

τ_{c-e} => obs

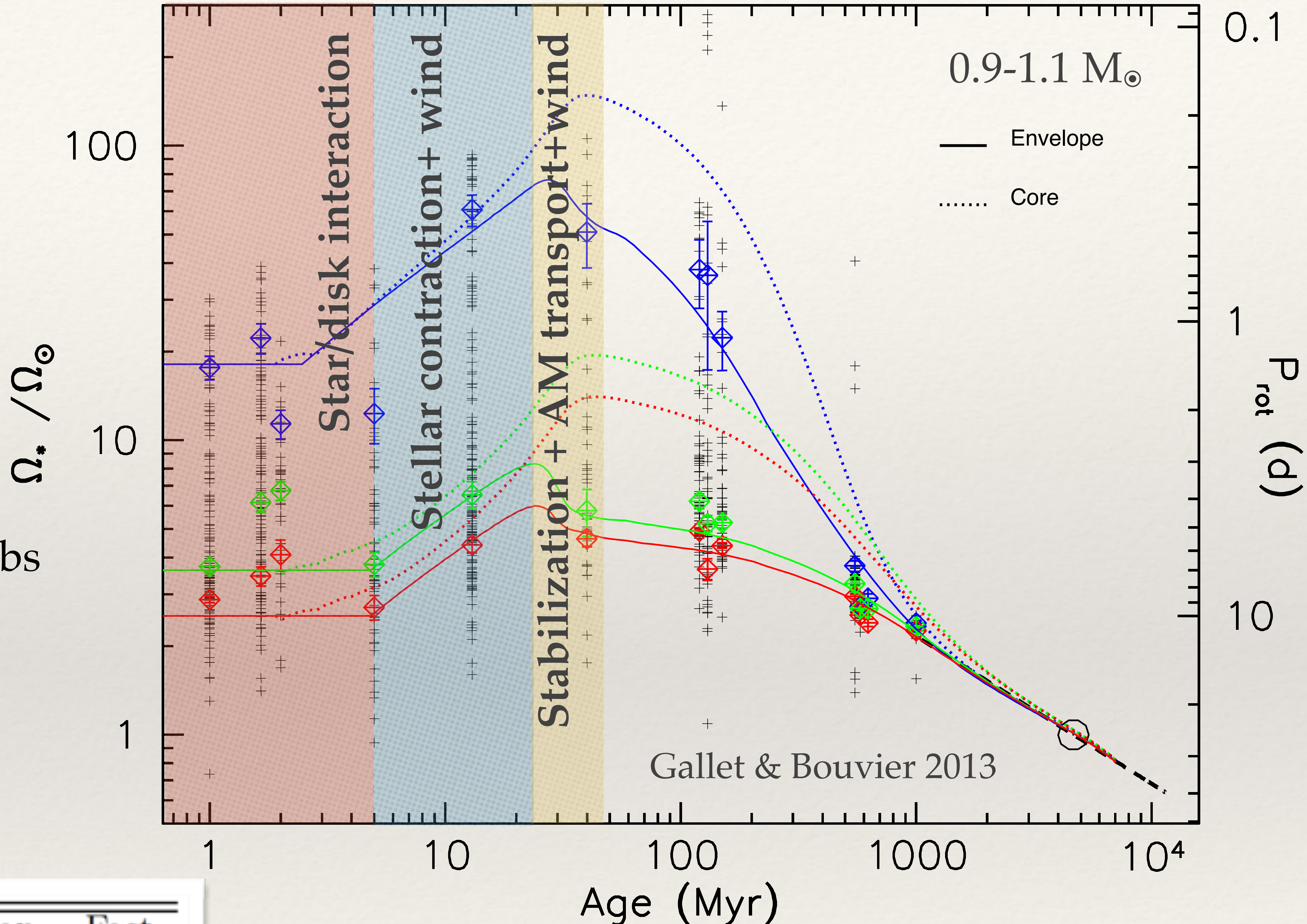
K_1(dJ/dt) => numerical+obs



Parameter	Slow	Median	Fast
P_{init} (days)	10	7	1.4
τ_{c-e} (Myr)	30	28	12
τ_{disk} (Myr)	5	5	2.5
K_1	1.8	1.8	1.7

<u>Stellar structure evolution model</u> : Baraffe et al. (1998)

Solar type stars



<u>4 free parameters</u>:

P_{init} => obs

τ_{disk} => obs

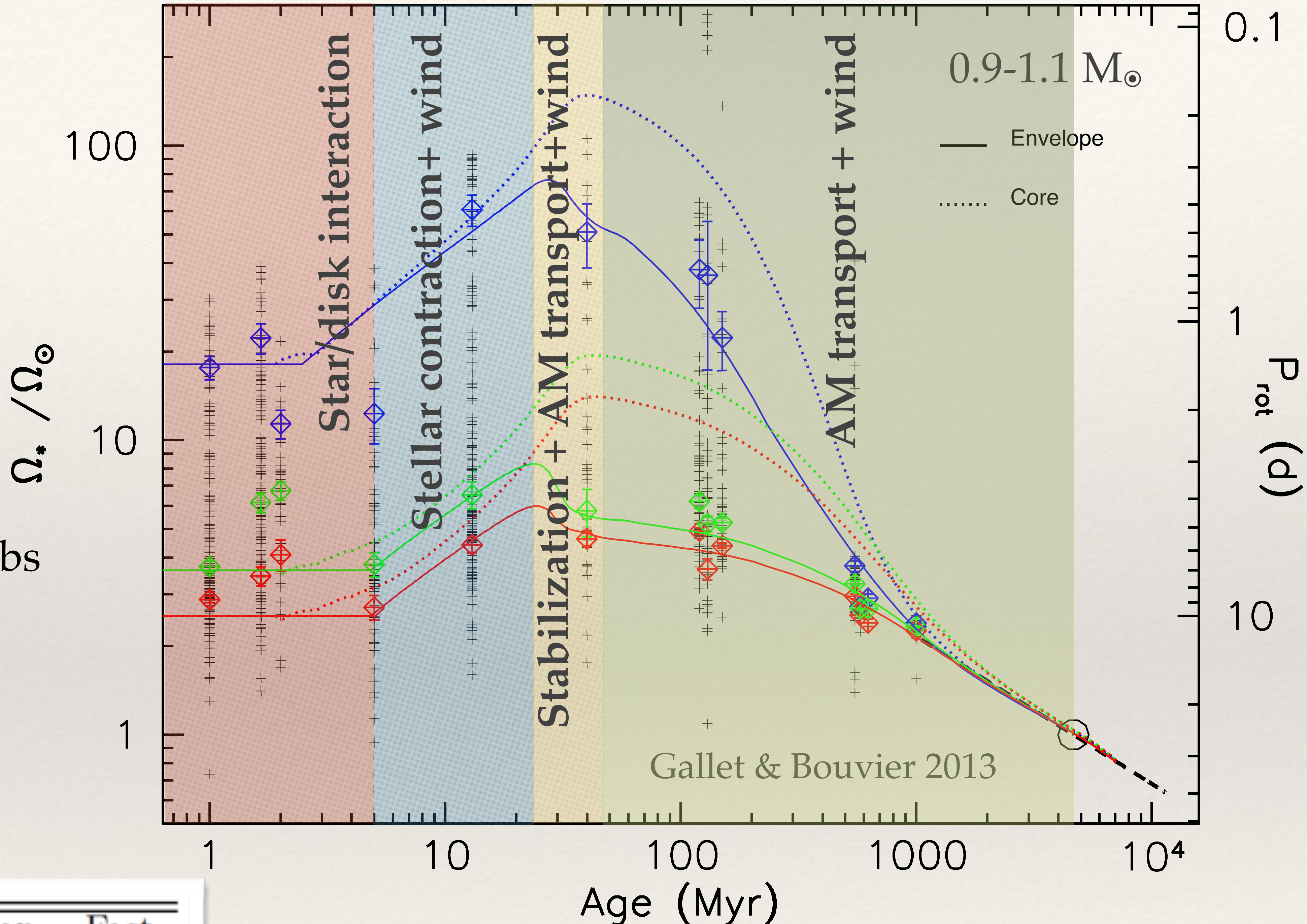
τ_{c-e} => obs

$K_1(dJ/dt)$ => numerical+obs

Parameter	Slow	Median	Fast
P_{init} (days)	10	7	1.4
τ_{c-e} (Myr)	30	28	12
τ_{disk} (Myr)	5	5	2.5
K_1	1.8	1.8	1.7

<u>Stellar structure evolution model</u> : Baraffe et al. (1998)

Solar type stars



4 free parameters:

P_{init} => obs

$\tau_{\mathbf{disk}}$ => obs

$\tau_{\mathbf{c\text{-}e}}$ => obs

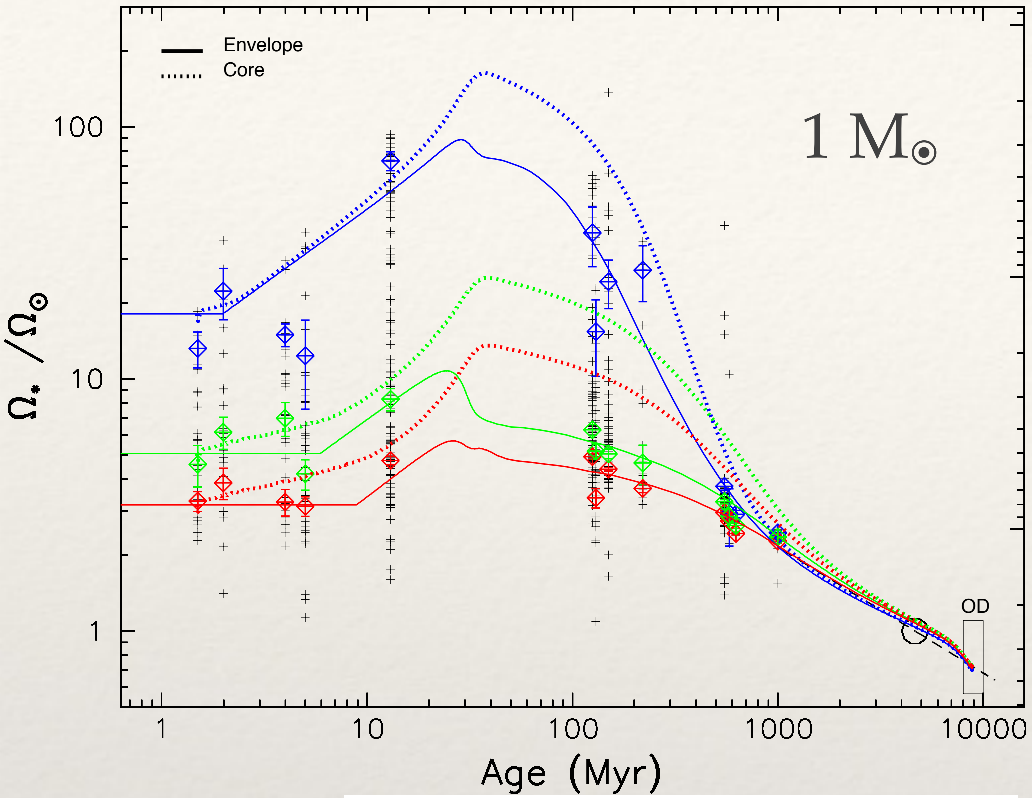
K_1(dJ/dt) => numerical+obs

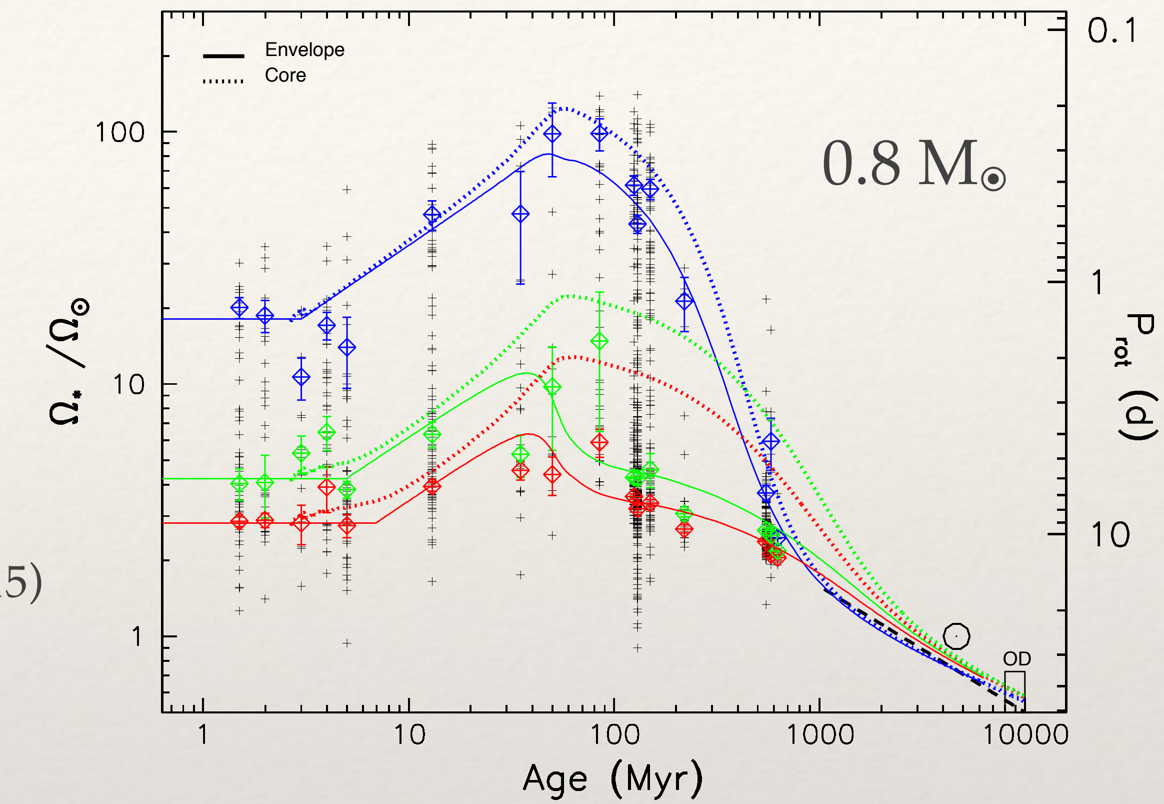
Parameter	Slow	Median	Fast
P_{init} (days)	10	7	1.4
τ_{c-e} (Myr)	30	28	12
τ_{disk} (Myr)	5	5	2.5
K_1	1.8	1.8	1.7

Stellar structure evolution model : Baraffe et al. (1998)

Low mass stars

The mass dependance





Gallet & Bouvier (2015)

$M_* = 1\ M_\odot$

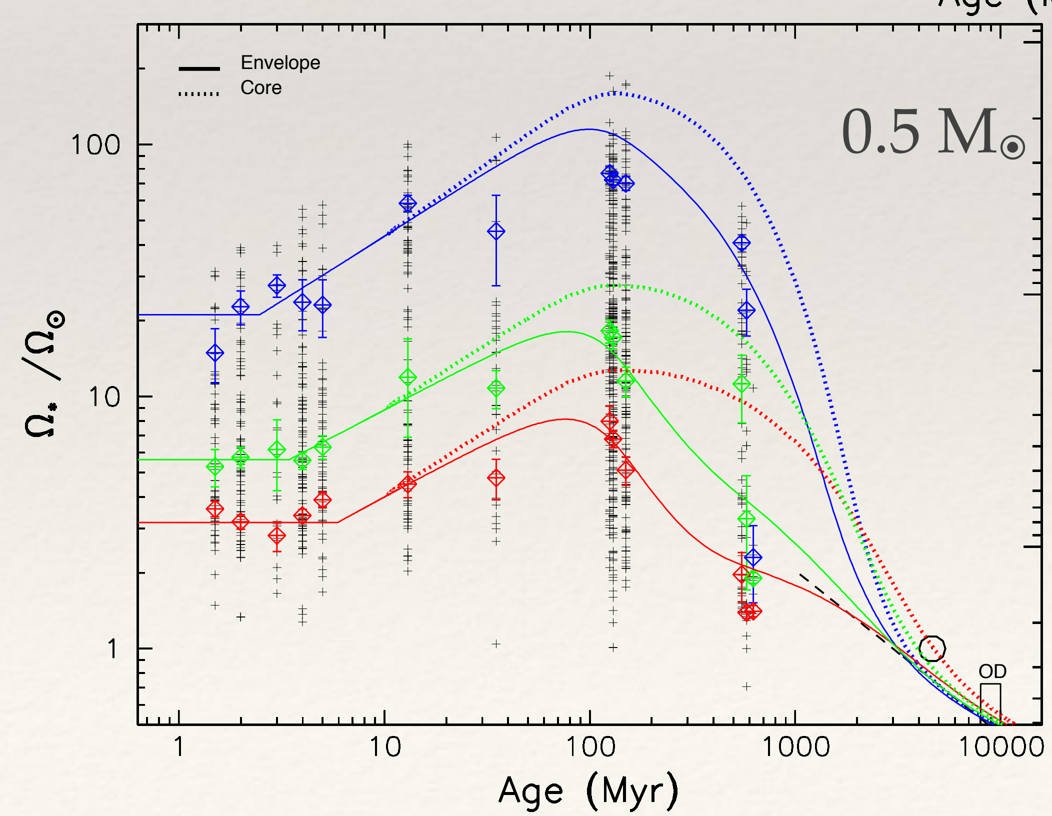
Paramètre	Lent	Médian	Rapide
P_{init} (jours)	8	5	1.4
τ_{c-e} (Myr)	30	28	10
τ_{disque} (Myr)	9	6	2
K_1	1.7	1.7	1.7

$M_* = 0.8\ M_\odot$

Paramètre	Lent	Médian	Rapide
P_{init} (jours)	9	6	1.4
τ_{c-e} (Myr)	80	80	15
τ_{disque} (Myr)	7	5	3
K_1	3	3	3

$M_* = 0.5\ M_\odot$

Paramètre	Lent	Médian	Rapide
P_{init} (jours)	8	4.5	1.2
τ_{c-e} (Myr)	500	300	150
τ_{disque} (Myr)	6	3.5	2.5
K_1	8.5	8.5	8.5



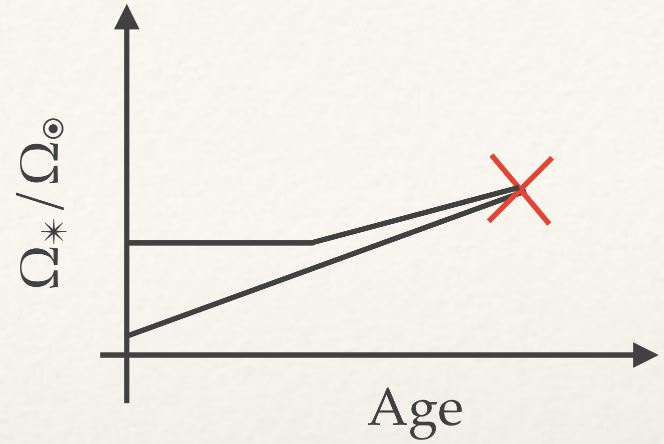
Implication for stellar physics

Implication for stellar physics

- (P_{init}, τ_{disk})
  - crucial to reproduce wide dispersion at ZAMS
  - degeneracy lifted using young SFR
  - need to be correlated (c.f. Gallet & Bouvier 2013)
  - fixed by observations

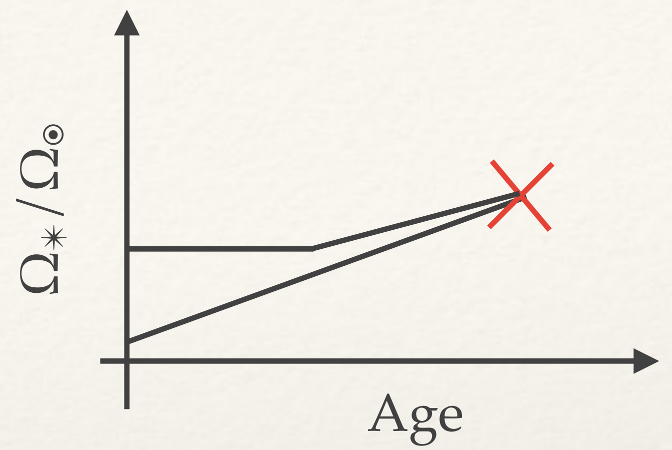
Implication for stellar physics

- (P_{init}, τ_{disk})
  - crucial to reproduce wide dispersion at ZAMS
  - degeneracy lifted using young SFR
  - need to be correlated (c.f. Gallet & Bouvier 2013)
  - fixed by observations



Implication for stellar physics

- (P_{init}, τ_{disk})
  - crucial to reproduce wide dispersion at ZAMS
  - degeneracy lifted using young SFR
  - need to be correlated (c.f. Gallet & Bouvier 2013)
  - fixed by observations

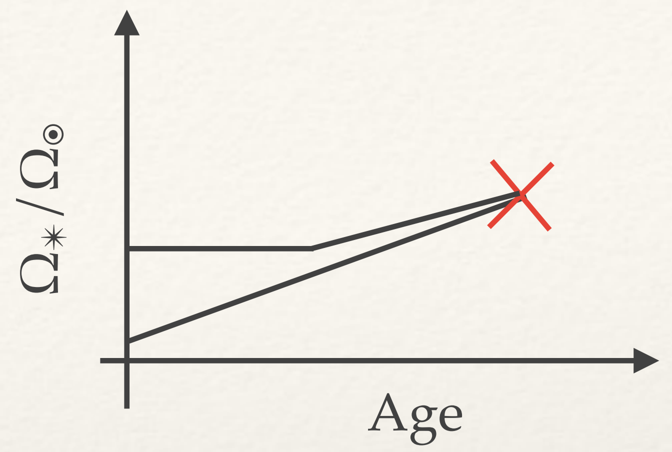


Gallet & Bouvier (2013) possible explanation :
slowest rotators = massive proto-stellar disk and strong star/disk interaction in embedded phase (Ferreira et al. 2000)

Implication for stellar physics

- (P_{init}, τ_{disk})
  - crucial to reproduce wide dispersion at ZAMS
  - degeneracy lifted using young SFR
  - need to be correlated (c.f. Gallet & Bouvier 2013)
  - fixed by observations

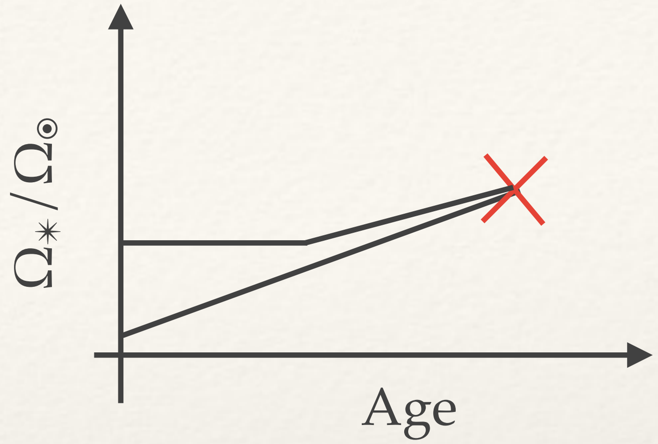
Need star/disk interaction during embedded phase!?



Gallet & Bouvier (2013) possible explanation : slowest rotators = massive proto-stellar disk and strong star/disk interaction in embedded phase (Ferreira et al. 2000)

Implication for stellar physics

- (P_{init}, τ_{disk})
  - crucial to reproduce wide dispersion at ZAMS
  - degeneracy lifted using young SFR
  - need to be correlated (c.f. Gallet & Bouvier 2013)
  - fixed by observations



Need star/disk interaction during embedded phase!?

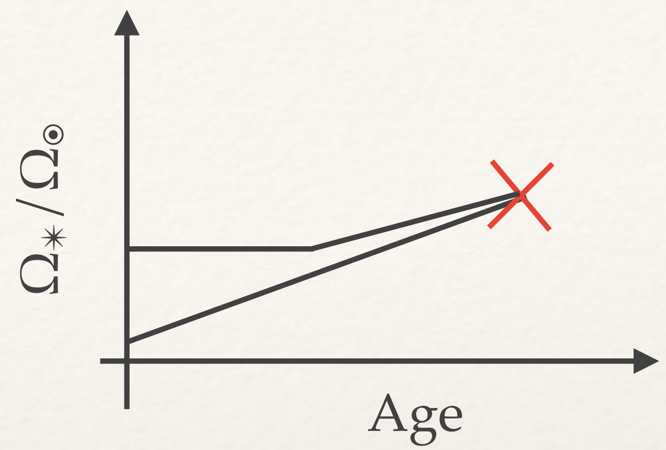
- $\tau_{c\text{-}e}$
  - increases toward low mass stars and slow rotators
  - consistent with Irwin et al. (2007) and Denissenkov et al. (2010)

Gallet & Bouvier (2013) possible explanation : slowest rotators = massive proto-stellar disk and strong star/disk interaction in embedded phase (Ferreira et al. 2000)

⇨ $\tau_{c\text{-}e}$ = 500 and 55±25 Myr for 1 $M_\odot$
$\tau_{c\text{-}e}$ = 1 Gyr and 175±25 Myr for 0.8 $M_\odot$

Implication for stellar physics

- (P_{init}, τ_{disk})
  - crucial to reproduce wide dispersion at ZAMS
  - degeneracy lifted using young SFR
  - need to be correlated (c.f. Gallet & Bouvier 2013)
  - fixed by observations



Need star/disk interaction during embedded phase!?

Gallet & Bouvier (2013) possible explanation : slowest rotators = massive proto-stellar disk and strong star/disk interaction in embedded phase (Ferreira et al. 2000)

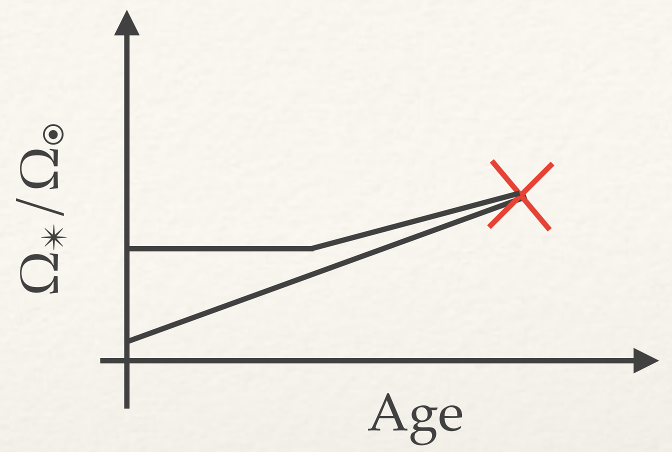
- $\tau_{c\text{-}e}$
  - increases toward low mass stars and slow rotators
  - consistent with Irwin et al. (2007) and Denissenkov et al. (2010)

⇨ $\tau_{c\text{-}e}$ = 500 and 55±25 Myr for 1 $M_\odot$
$\tau_{c\text{-}e}$ = 1 Gyr and 175±25 Myr for 0.8 $M_\odot$

Physical mechanism must vary with both spin rate and mass

Implication for stellar physics

- (P_{init}, τ_{disk})
  - crucial to reproduce wide dispersion at ZAMS
  - degeneracy lifted using young SFR
  - need to be correlated (c.f. Gallet & Bouvier 2013)
  - fixed by observations



Need star/disk interaction during embedded phase!?

Gallet & Bouvier (2013) possible explanation : slowest rotators = massive proto-stellar disk and strong star/disk interaction in embedded phase (Ferreira et al. 2000)

- $\tau_{c\text{-}e}$
  - increases toward low mass stars and slow rotators
  - consistent with Irwin et al. (2007) and Denissenkov et al. (2010)

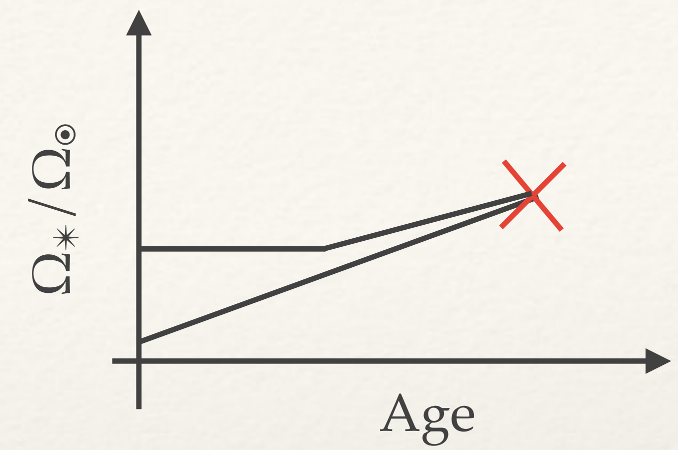
⇨ $\tau_{c\text{-}e}$ = 500 and 55±25 Myr for 1 $M_\odot$
$\tau_{c\text{-}e}$ = 1 Gyr and 175±25 Myr for 0.8 $M_\odot$

Physical mechanism must vary with both spin rate and mass

- is K_1 need to be rescaled?
  - K_1 = 1.7, 3.0, 8.5 but m = cst
  - change in the magnetic field topology? => dipolar
  - braking law prescriptions still do not properly account for mass and/or radius dependence (e.g. mass loss rate)?

Implication for stellar physics

- (P_{init}, τ_{disk})
  - crucial to reproduce wide dispersion at ZAMS
  - degeneracy lifted using young SFR
  - need to be correlated (c.f. Gallet & Bouvier 2013)
  - fixed by observations



Need star/disk interaction during embedded phase!?

Gallet & Bouvier (2013) possible explanation : slowest rotators = massive proto-stellar disk and strong star/disk interaction in embedded phase (Ferreira et al. 2000)

- $\tau_{c\text{-}e}$
  - increases toward low mass stars and slow rotators
  - consistent with Irwin et al. (2007) and Denissenkov et al. (2010)

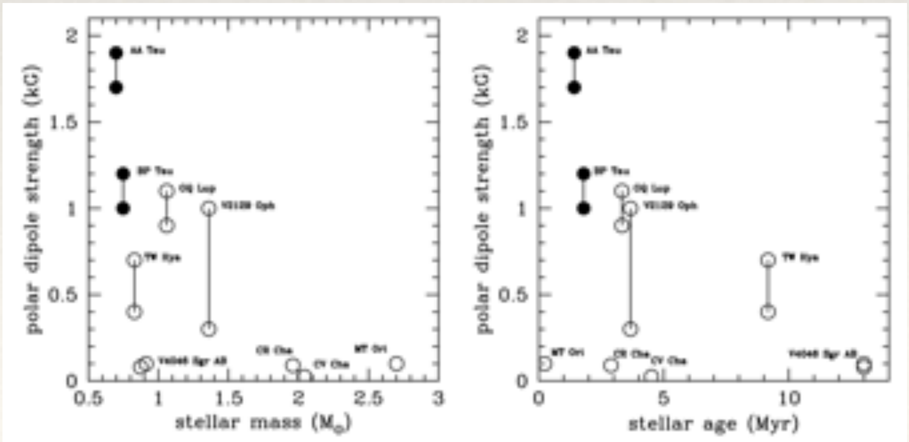
⇨ $\tau_{c\text{-}e}$ = 500 and 55±25 Myr for 1 $M_\odot$

$\tau_{c\text{-}e}$ = 1 Gyr and 175±25 Myr for 0.8 $M_\odot$

Physical mechanism must vary with both spin rate and mass

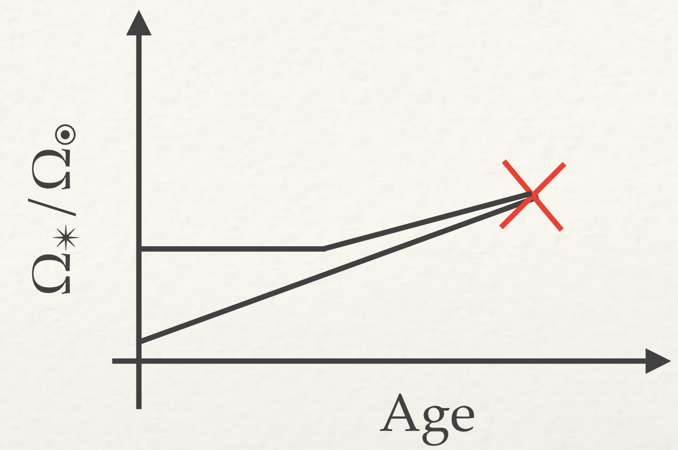
- is K_1 need to be rescaled?
  - K_1 = 1.7, 3.0, 8.5 but m = cst
  - change in the magnetic field topology? => dipolar
  - braking law prescriptions still do not properly account for mass and/or radius dependence (e.g. mass loss rate)?

Gregory et al. (2012)



Implication for stellar physics

- (P_{init}, τ_{disk})
  - crucial to reproduce wide dispersion at ZAMS
  - degeneracy lifted using young SFR
  - need to be correlated (c.f. Gallet & Bouvier 2013)
  - fixed by observations



Need star/disk interaction during embedded phase!?

Gallet & Bouvier (2013) possible explanation : slowest rotators = massive proto-stellar disk and strong star/disk interaction in embedded phase (Ferreira et al. 2000)

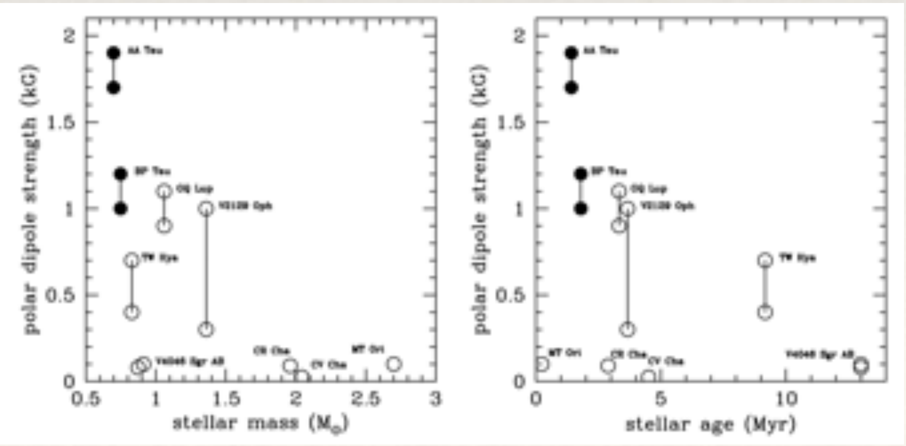
- $\tau_{c\text{-}e}$
  - increases toward low mass stars and slow rotators
  - consistent with Irwin et al. (2007) and Denissenkov et al. (2010)

⇨ $\tau_{c\text{-}e}$ = 500 and 55±25 Myr for 1 $M_\odot$
$\tau_{c\text{-}e}$ = 1 Gyr and 175±25 Myr for 0.8 $M_\odot$

Physical mechanism must vary with both spin rate and mass

- is K_1 need to be rescaled?
  - K_1 = 1.7, 3.0, 8.5 but m = cst
  - change in the magnetic field topology? => dipolar
  - braking law prescriptions still do not properly account for mass and/or radius dependence (e.g. mass loss rate)?

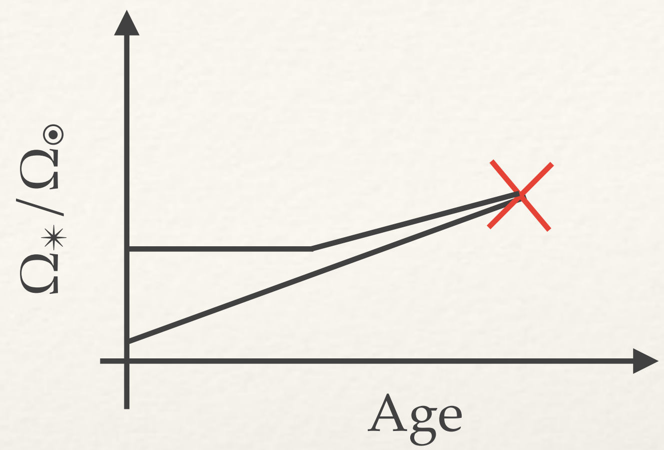
Gregory et al. (2012)



Change in the magnetic topology?

Implication for stellar physics

- (P_{init}, τ_{disk})
  - crucial to reproduce wide dispersion at ZAMS
  - degeneracy lifted using young SFR
  - need to be correlated (c.f. Gallet & Bouvier 2013)
  - fixed by observations



Need star/disk interaction during embedded phase!?

Gallet & Bouvier (2013) possible explanation : slowest rotators = massive proto-stellar disk and strong star/disk interaction in embedded phase (Ferreira et al. 2000)

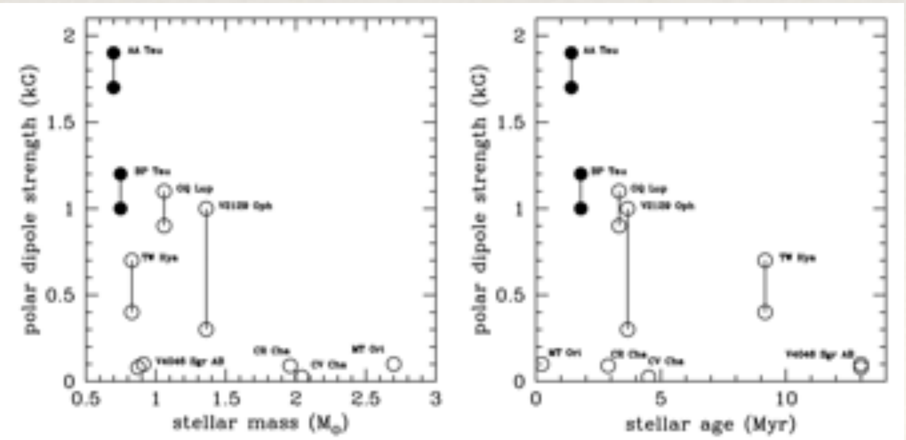
- $\tau_{c\text{-}e}$
  - increases toward low mass stars and slow rotators
  - consistent with Irwin et al. (2007) and Denissenkov et al. (2010)

⇨ $\tau_{c\text{-}e}$ = 500 and 55±25 Myr for 1 $M_\odot$
$\tau_{c\text{-}e}$ = 1 Gyr and 175±25 Myr for 0.8 $M_\odot$

Physical mechanism must vary with both spin rate and mass

- is K_1 need to be rescaled?
  - K_1 = 1.7, 3.0, 8.5 but m = cst
  - change in the magnetic field topology? => dipolar
  - braking law prescriptions still do not properly account for mass and/or radius dependence (e.g. mass loss rate)?

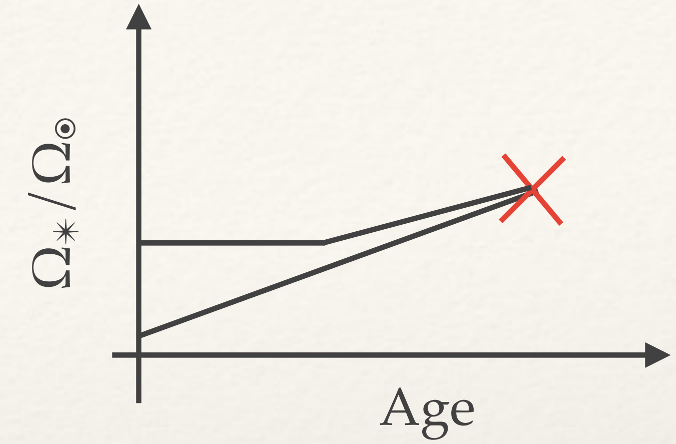
Gregory et al. (2012)



Change in the magnetic topology?

Implication for stellar physics

- (P_{init}, τ_{disk})
    - crucial to reproduce wide dispersion at ZAMS
    - degeneracy lifted using young SFR
    - need to be correlated (c.f. Gallet & Bouvier 2013)
    - fixed by observations



Need star/disk interaction during embedded phase!?

Gallet & Bouvier (2013) possible explanation : slowest rotators = massive proto-stellar disk and strong star/disk interaction in embedded phase (Ferreira et al. 2000)

- $\tau_{c\text{-}e}$
    - increases toward low mass stars and slow rotators
    - consistent with Irwin et al. (2007) and Denissenkov et al. (2010)

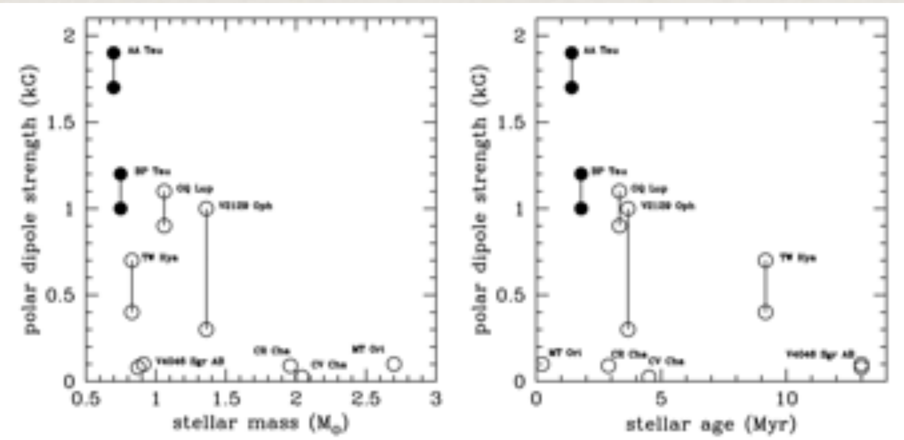
⇨ $\tau_{c\text{-}e}$ = 500 and 55±25 Myr for 1 $M_\odot$

$\tau_{c\text{-}e}$ = 1 Gyr and 175±25 Myr for 0.8 $M_\odot$

Physical mechanism must vary with both spin rate and mass

- is K_1 need to be rescaled?
    - K_1 = 1.7, 3.0, 8.5 but m = cst
    - change in the magnetic field topology? => dipolar
    - braking law prescriptions still do not properly account for mass and/or radius dependence (e.g. mass loss rate)?

Gregory et al. (2012)



Change in the magnetic topology? not sure…

IV - Conclusion and perspectives

Summary

New angular momentum evolution model…

Summary

New angular momentum evolution model…

- New theoretical and observational constraints
  - star/disk interaction
    - ME and APSW => kG intensity and high mass accretion rate (Gallet & Zanni, in prep.)
  - internal redistribution of AM
    - vary with both spin rate and mass
  - magnetic braking
    - new braking law (Matt et al. 2012a) (more physics)

Summary

New angular momentum evolution model…

- New theoretical and observational constraints
  - star/disk interaction
    - ME and APSW => kG intensity and high mass accretion rate (Gallet & Zanni, in prep.)
  - internal redistribution of AM
    - vary with both spin rate and mass
  - magnetic braking
    - new braking law (Matt et al. 2012a) (more physics)

Current models grasp the main observed trends of AM evolution for low-mass stars.

They can serve as a guide to further theoretical developments on rotation-related processes (e.g., Lithium depletion, AM transport, stellar dynamos, wind models, etc.).

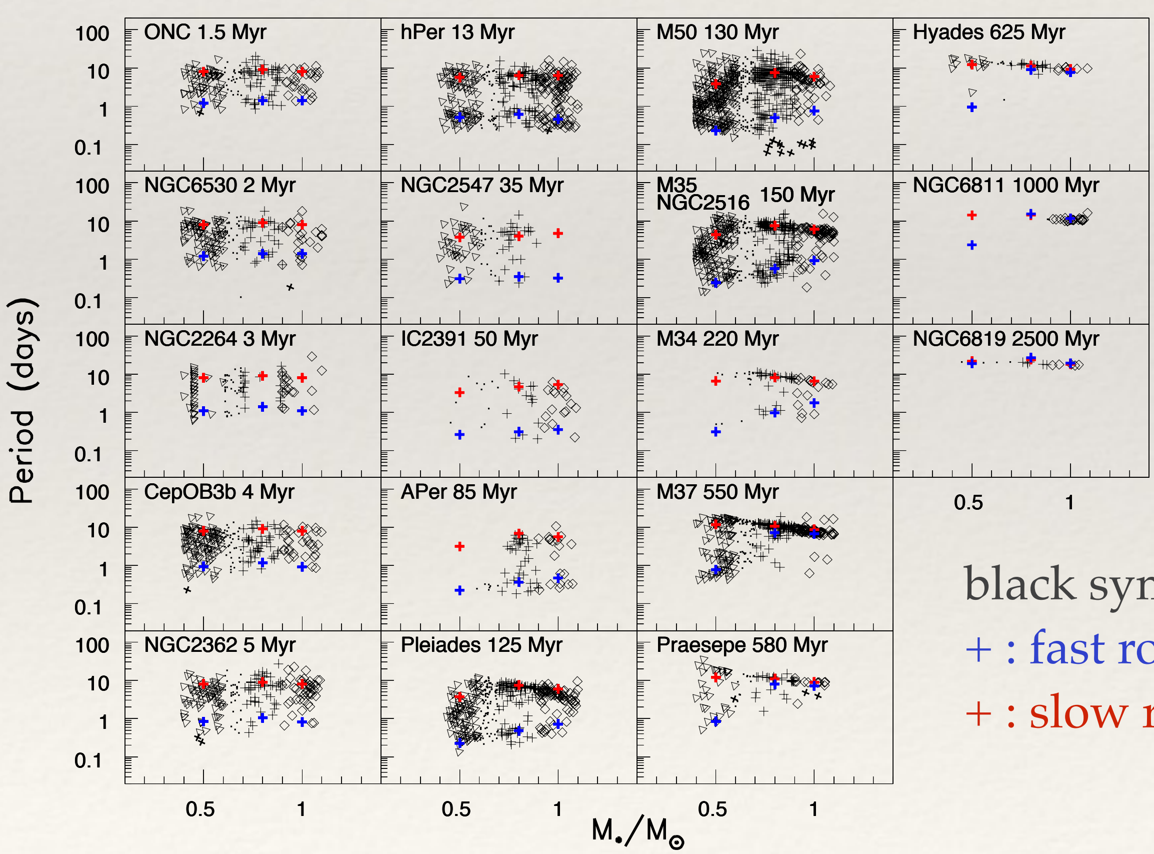
Summary

New angular momentum evolution model…

- New theoretical and observational constraints
  - star / disk interaction
    - ME and APSW => kG intensity and high mass accretion rate (Gallet & Zanni, in prep.)
  - internal redistribution of AM
    - vary with both spin rate and mass
  - magnetic braking
    - new braking law (Matt et al. 2012a) (more physics)

Current models grasp the main observed trends of AM evolution for low-mass stars.

They can serve as a guide to further theoretical developments on rotation-related processes (e.g., Lithium depletion, AM transport, stellar dynamos, wind models, etc.).



black symbols : obs

+ : fast rotators

+ : slow rotators

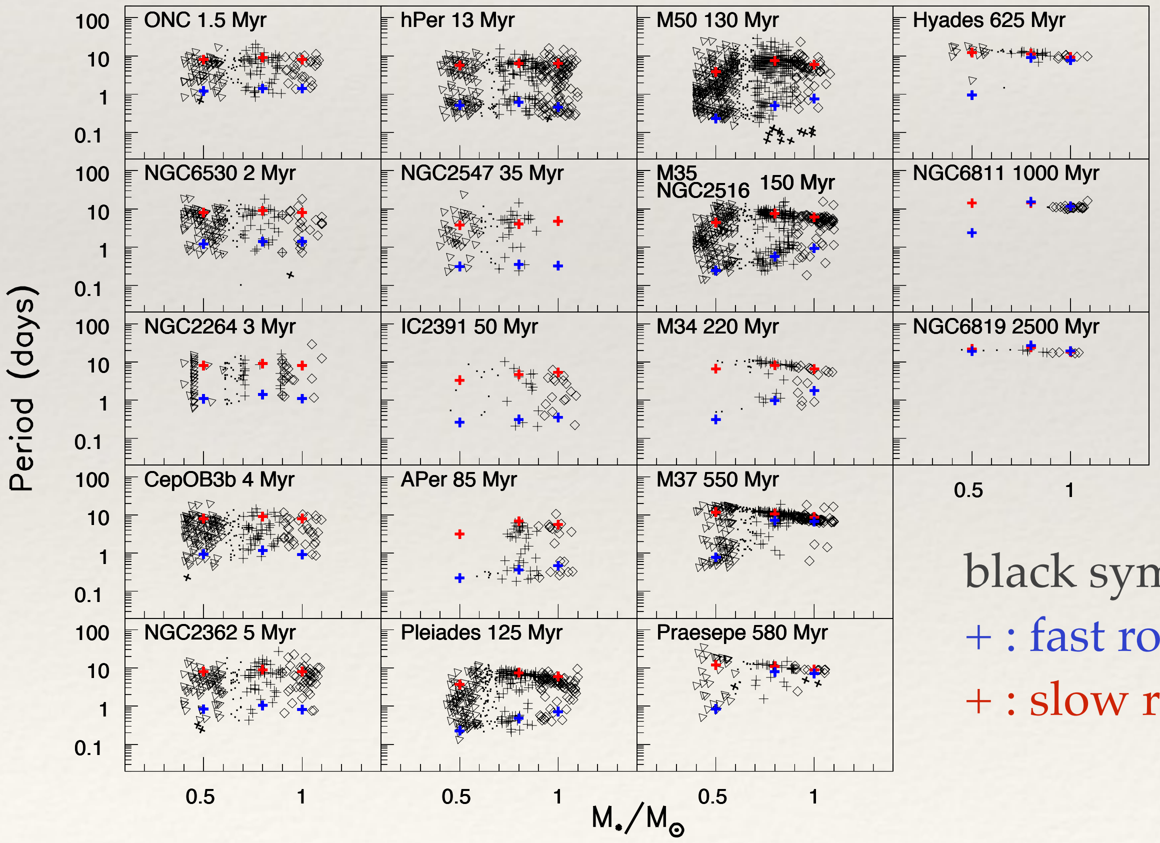
Summary

New angular momentum evolution model…

- New theoretical and observational constraints
  - <u>star/disk interaction</u>
    - ME and APSW => kG intensity and high mass accretion rate (Gallet & Zanni, in prep.)
  - <u>internal redistribution of AM</u>
    - vary with both spin rate and mass
  - <u>magnetic braking</u>
    - new braking law (Matt et al. 2012a) (more physics)

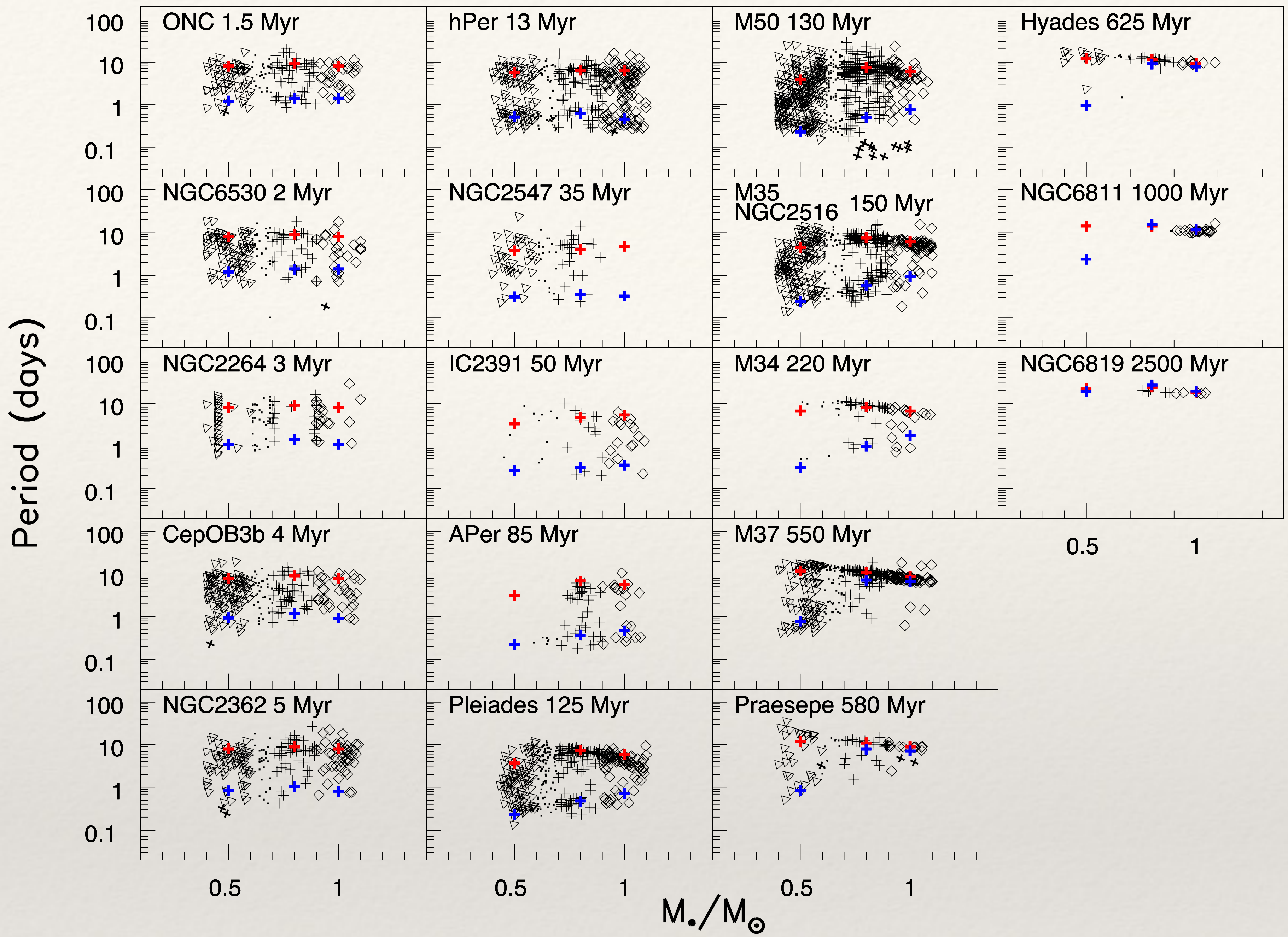
Current models grasp the main observed trends of AM evolution for low-mass stars.

They can serve as a guide to further theoretical developments on rotation-related processes (e.g., Lithium depletion, AM transport, stellar dynamos, wind models, etc.).



black symbols : obs
+ : fast rotators
+ : slow rotators

- … but still limited (obs+theoretical constraints) = **ongoing** research



«That's all folks! »

ANR 2011 Blanc SIMI5-6 020 01 ``Toupies: Towards understanding the spin evolution of stars'' (\url{http://ipag.osug.fr/Anr_Toupies/})