Rotation in Low-mass stars: Physics, Patterns, and Puzzles

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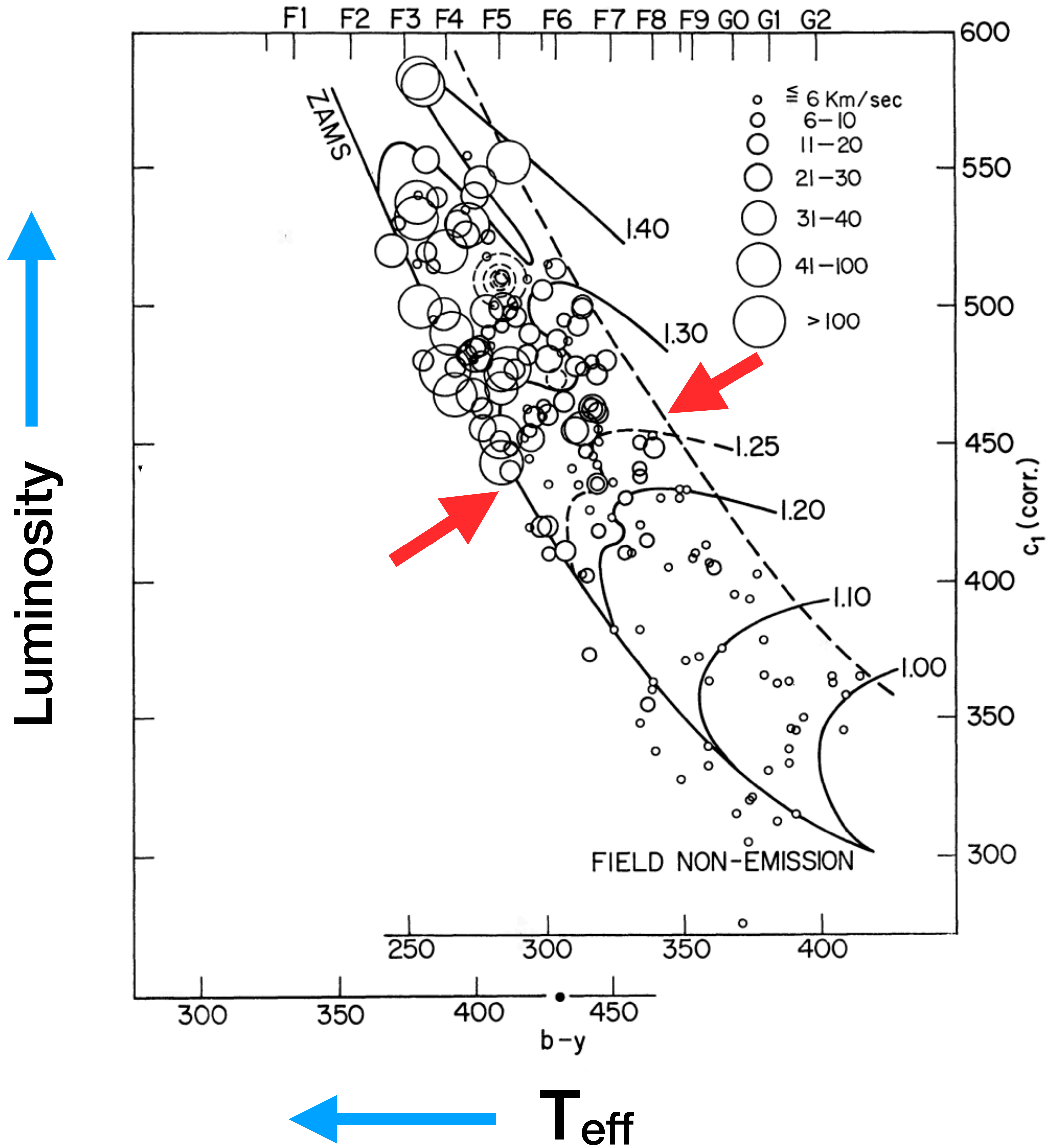
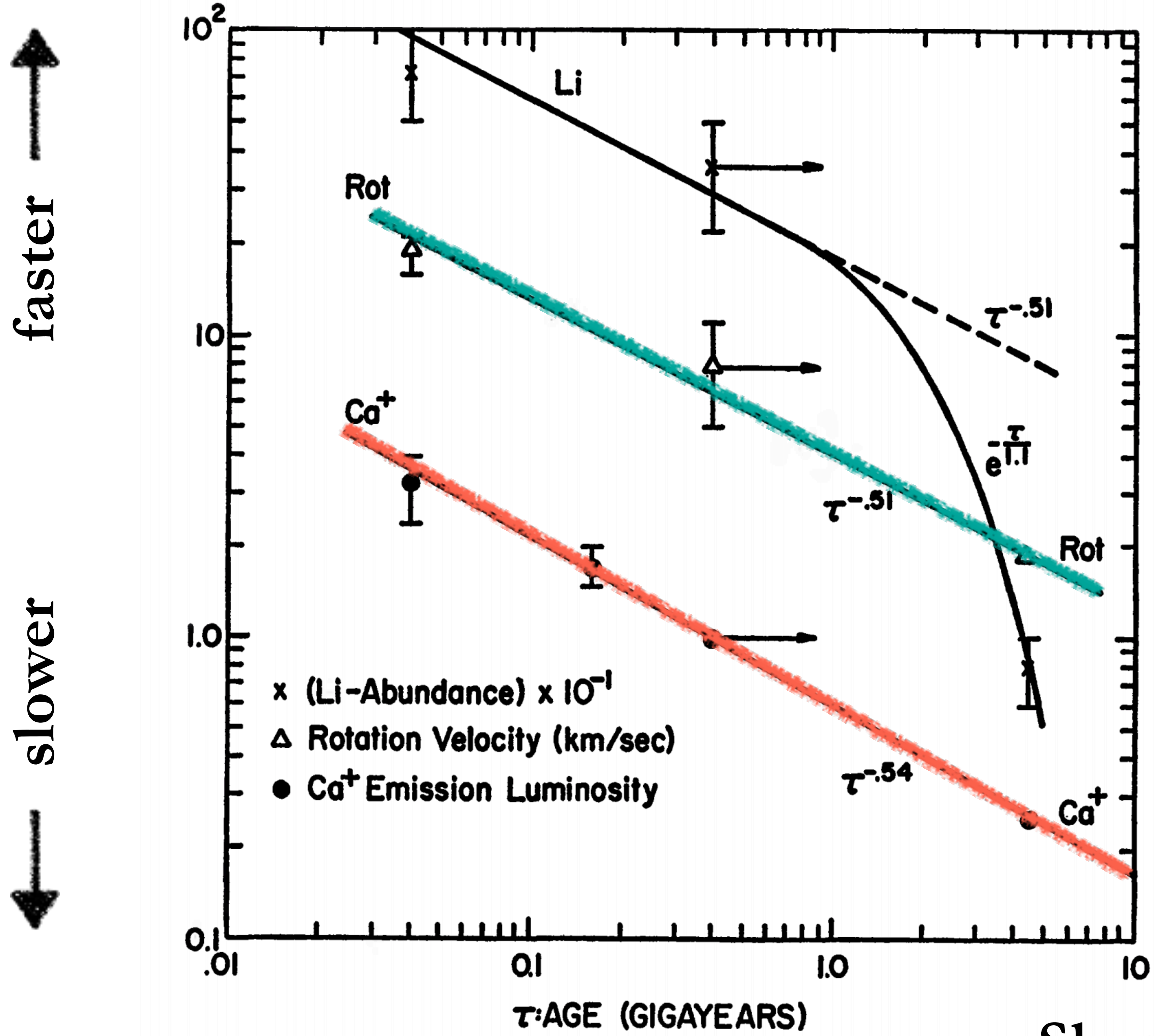


F1 F2 F3 F4 F5 F6 F7 F8 F9 G0 G1 G2
ZAMS
≦ 6 Km/sec
6–10
11–20
21–30
31–40
41–100
> 100
1.40
1.30
1.25
1.20
1.10
1.00
FIELD NON-EMISSION
600
550
500
450
400
350
300
c1 (corr.)
250 300 350 400
300 350 400 450
b – y
Luminosity
Teff

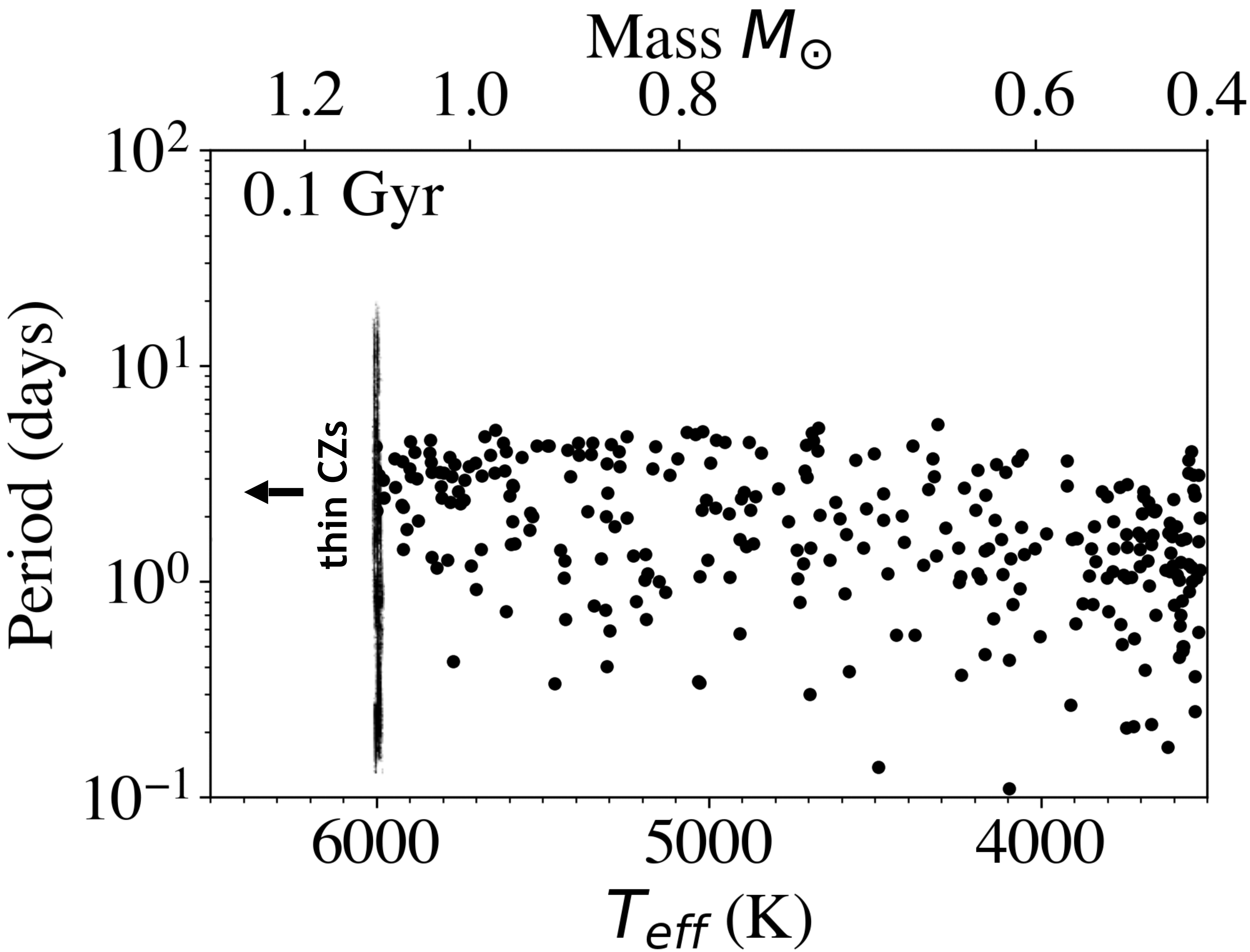
Skumanich laws

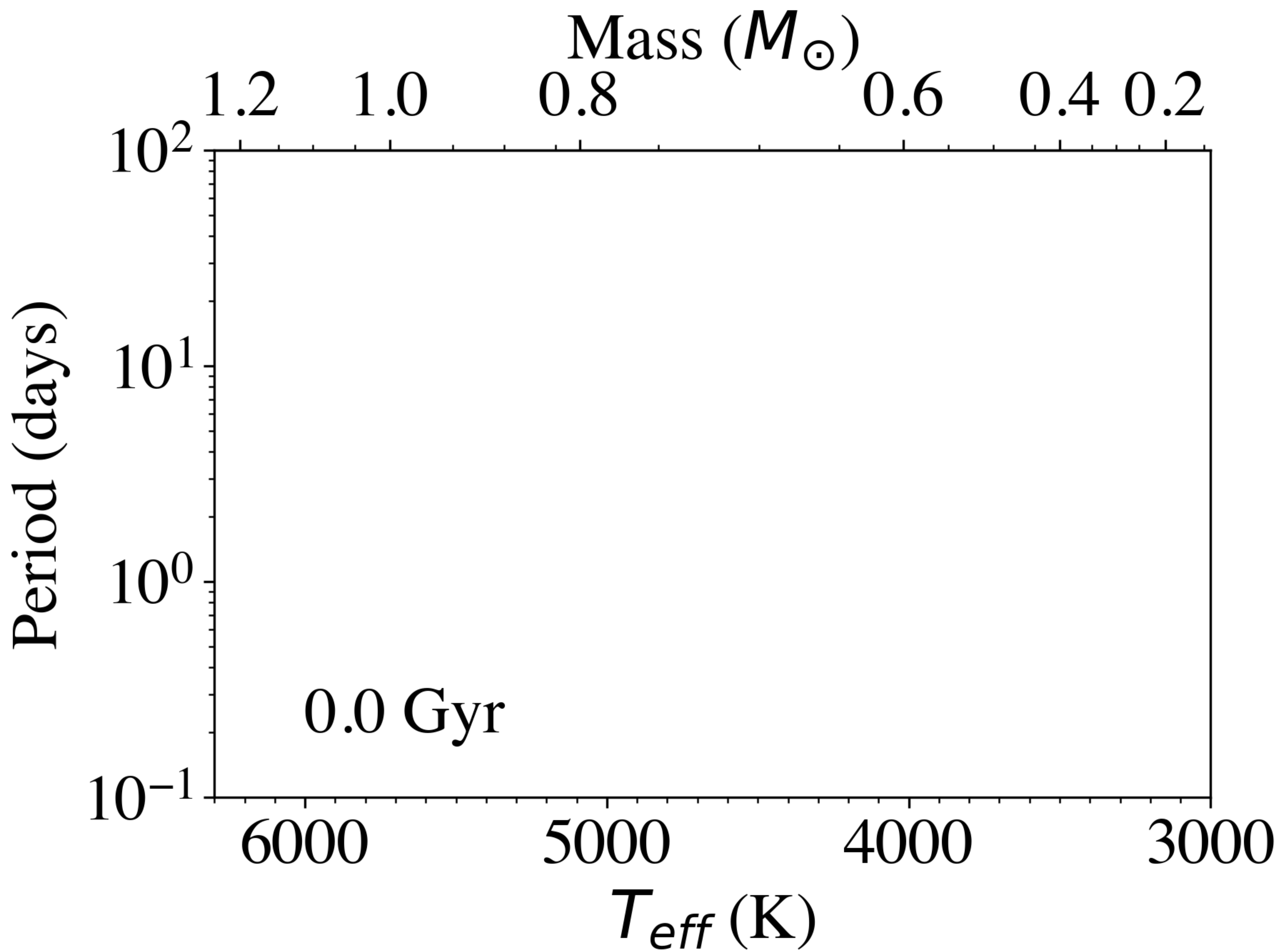


$$\Longrightarrow \frac{dJ}{dt} \propto \Omega^3$$

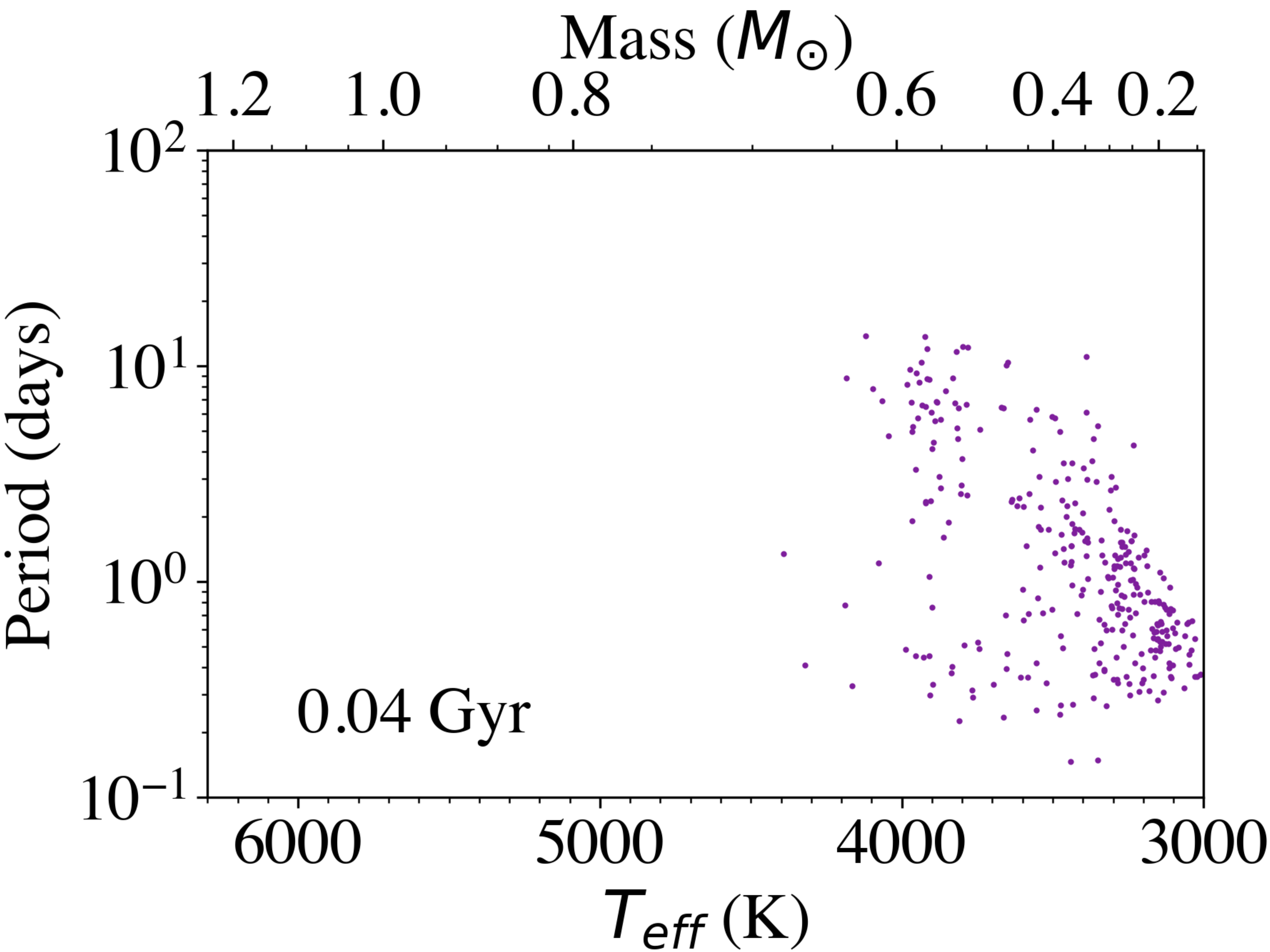
Skumanich 1972

A model of stellar spin down





NGC2547 (Irwin et al. 2008), Pleiades (Rebull et al. 2016), M50 (Irwin et al. 2009), M37 (Hartman et al. 2009, Praesepe (Rebull et al. 2017), NGC 6811 (Curtis et al. 2019, Meibom et al. 2011), NGC 6819 (Meibom et al. 2015), Rup147 (Curtis et al. 2020), M67 (Barnes et al. 2016, Esselstein 2016)



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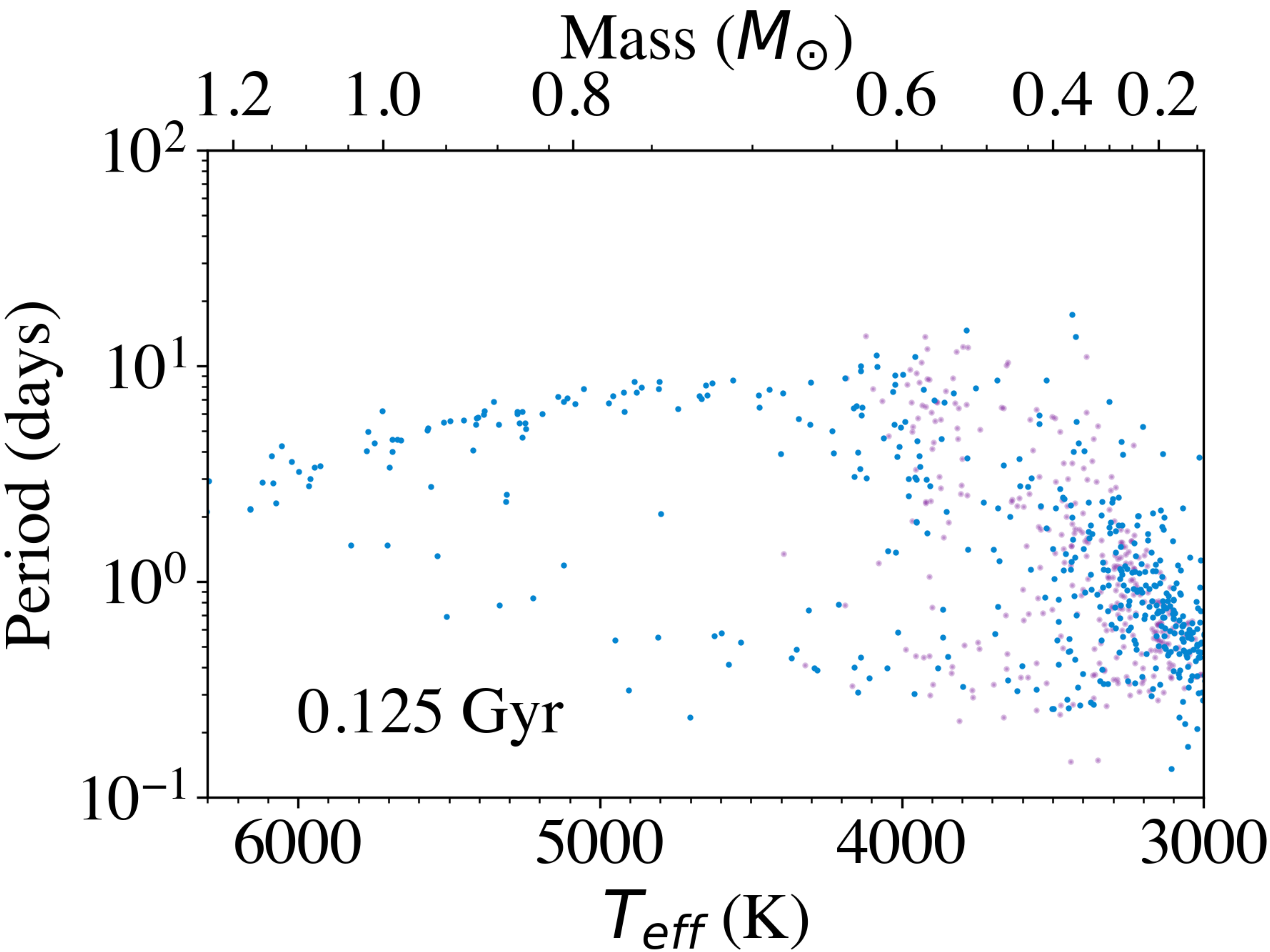

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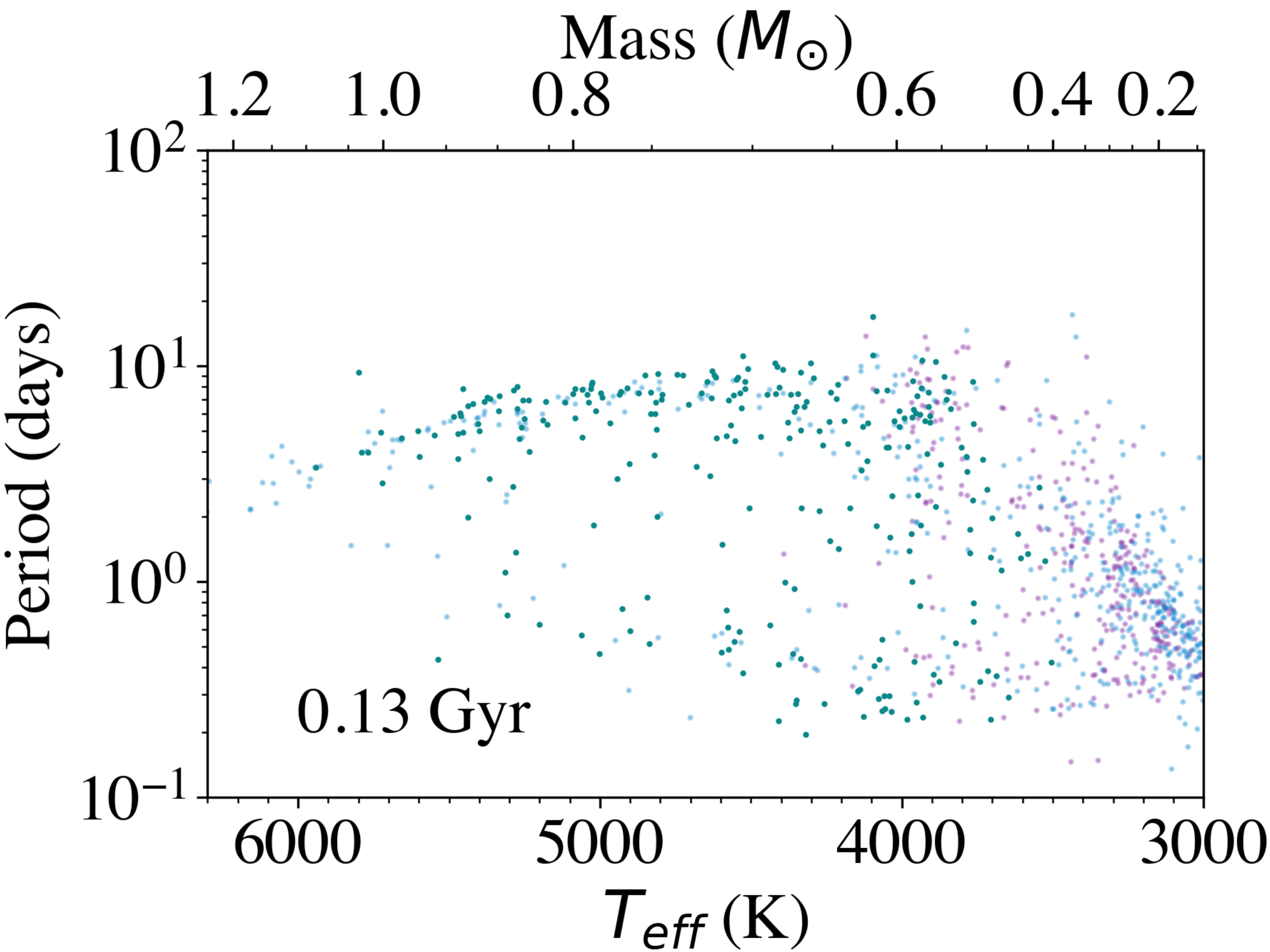

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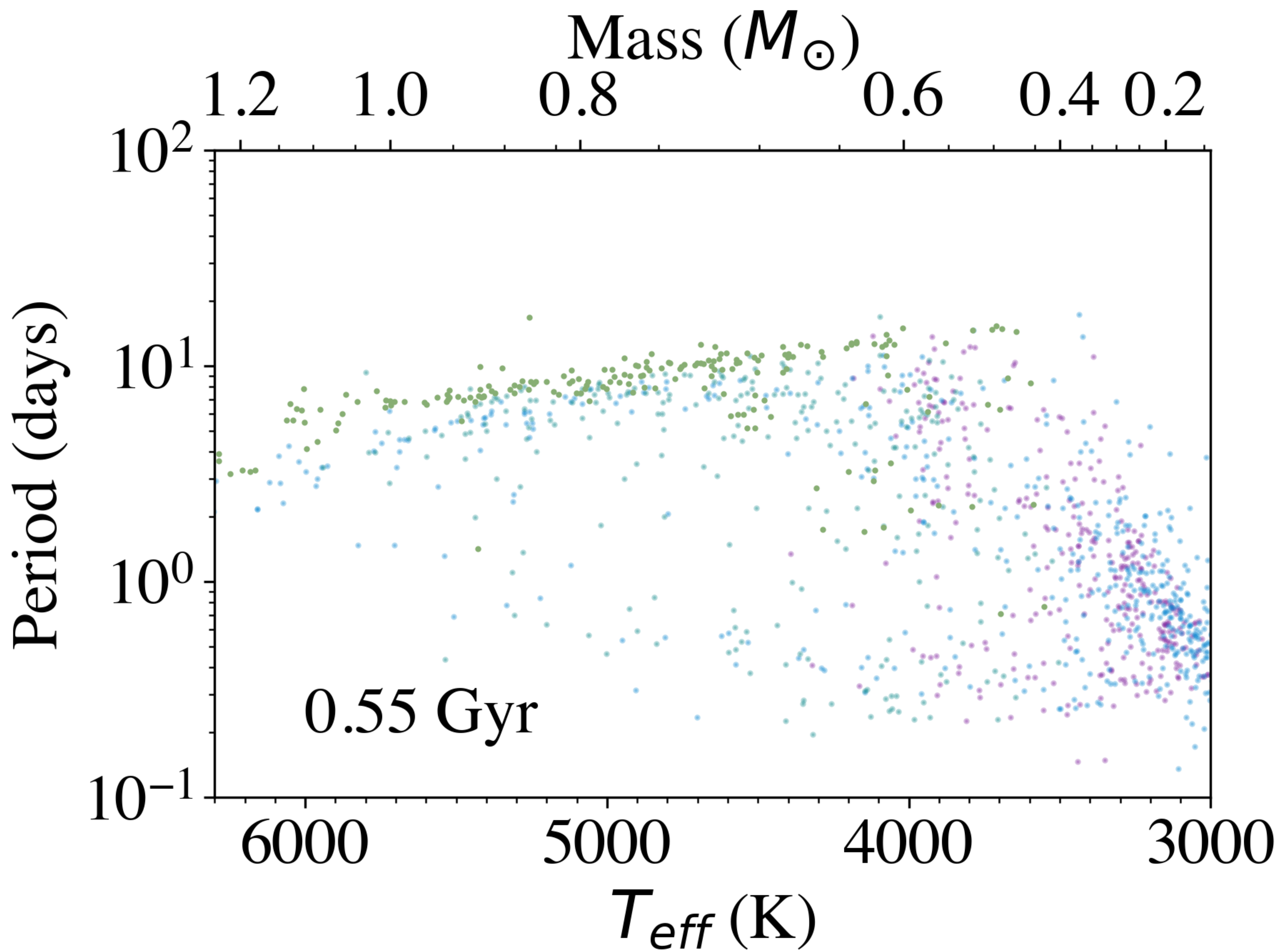

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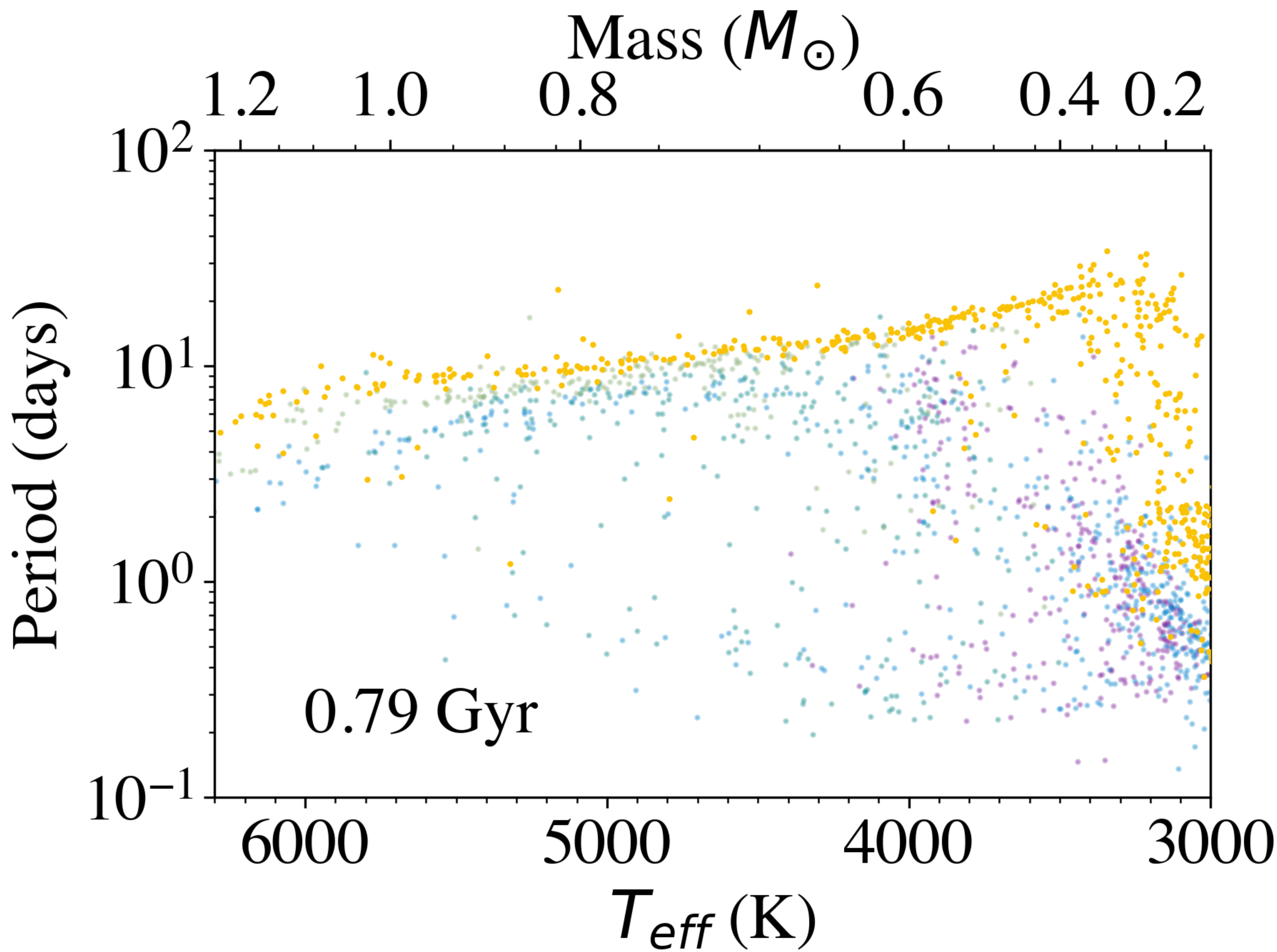

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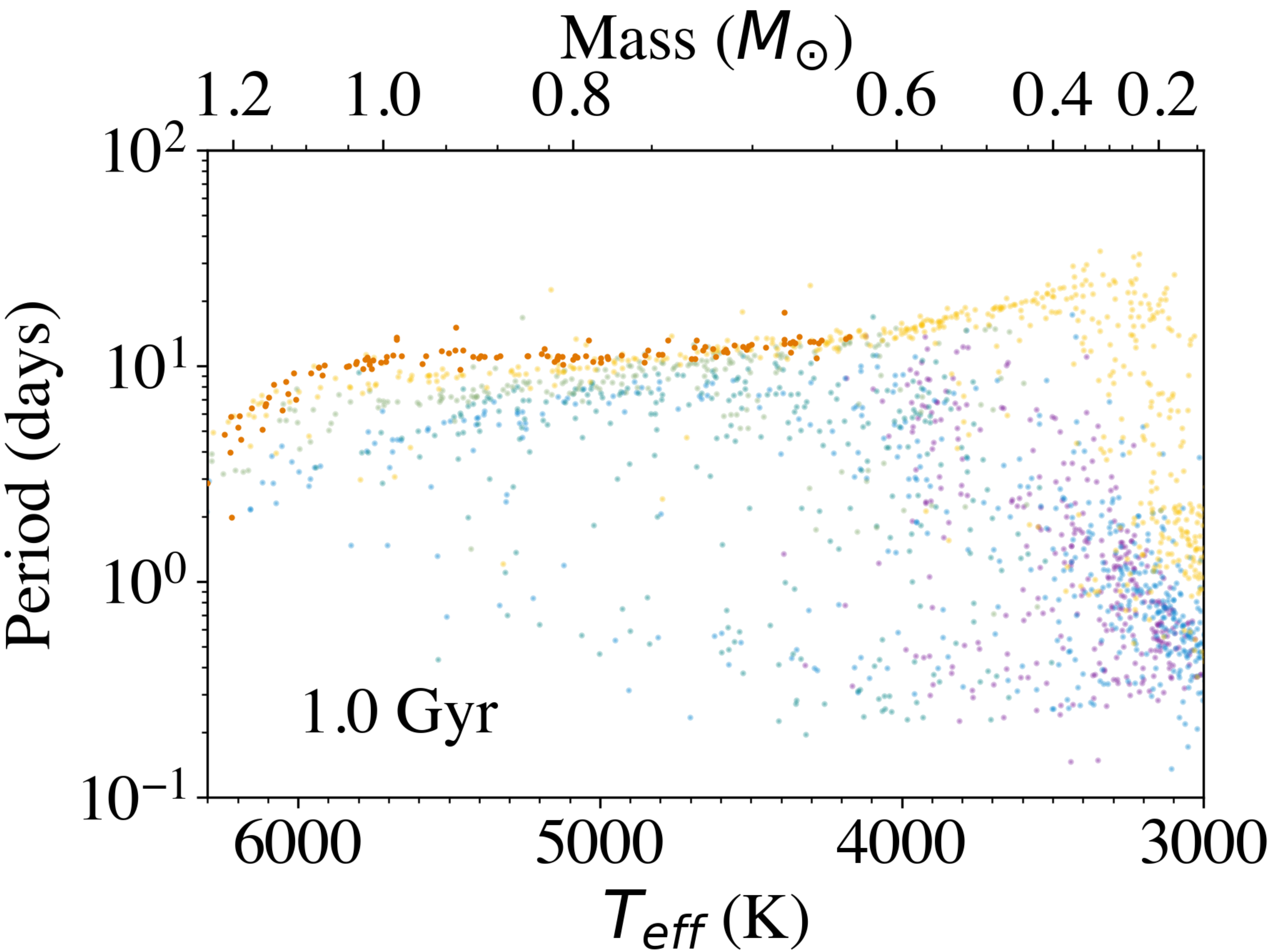

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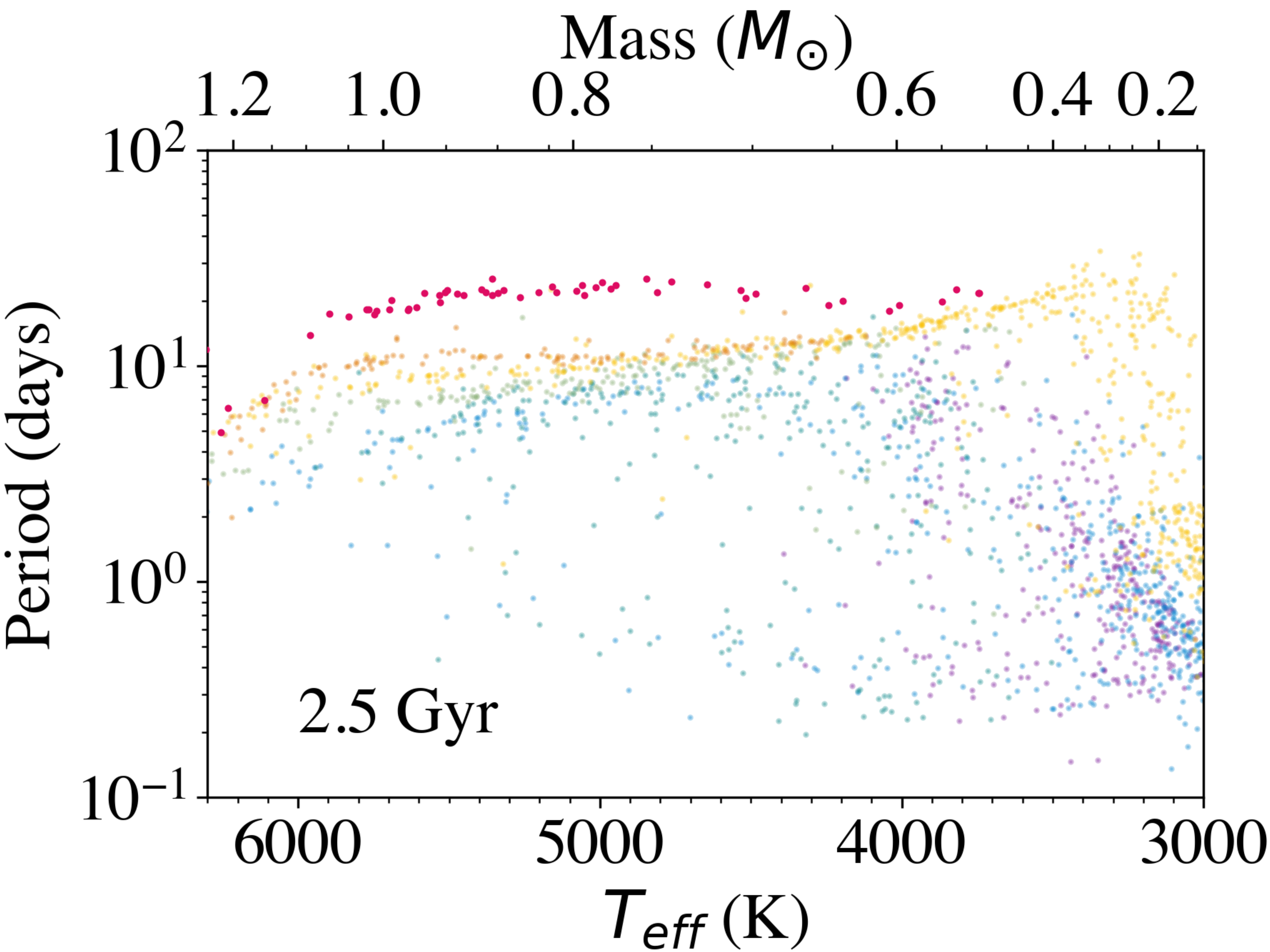

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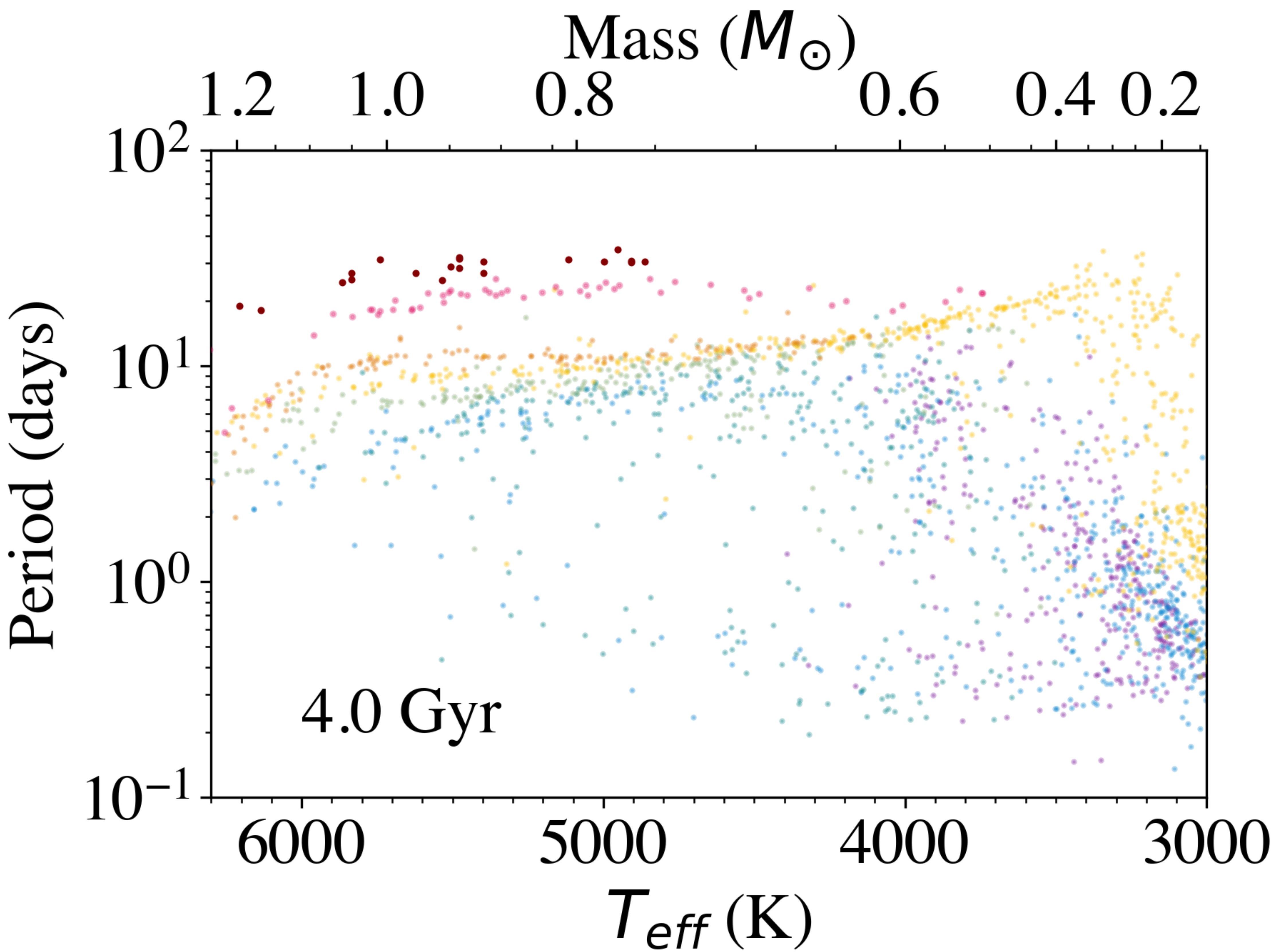

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Model Ingredients

1.) A description of initial conditions

2.) A description of magnetic braking at the stellar surface

3.) A description interior angular momentum transport

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Very young stars display a wide range of initial rotation periods

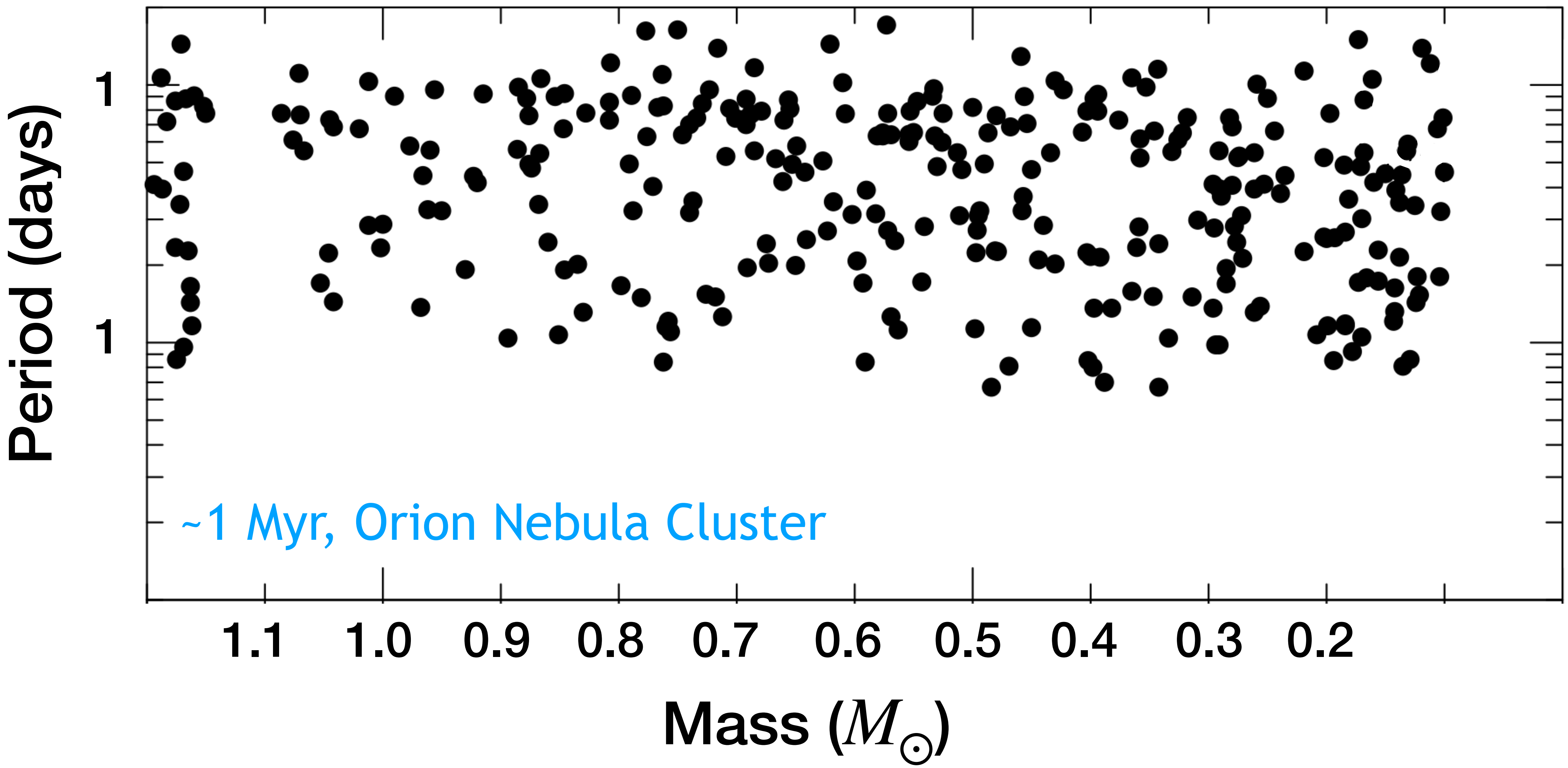


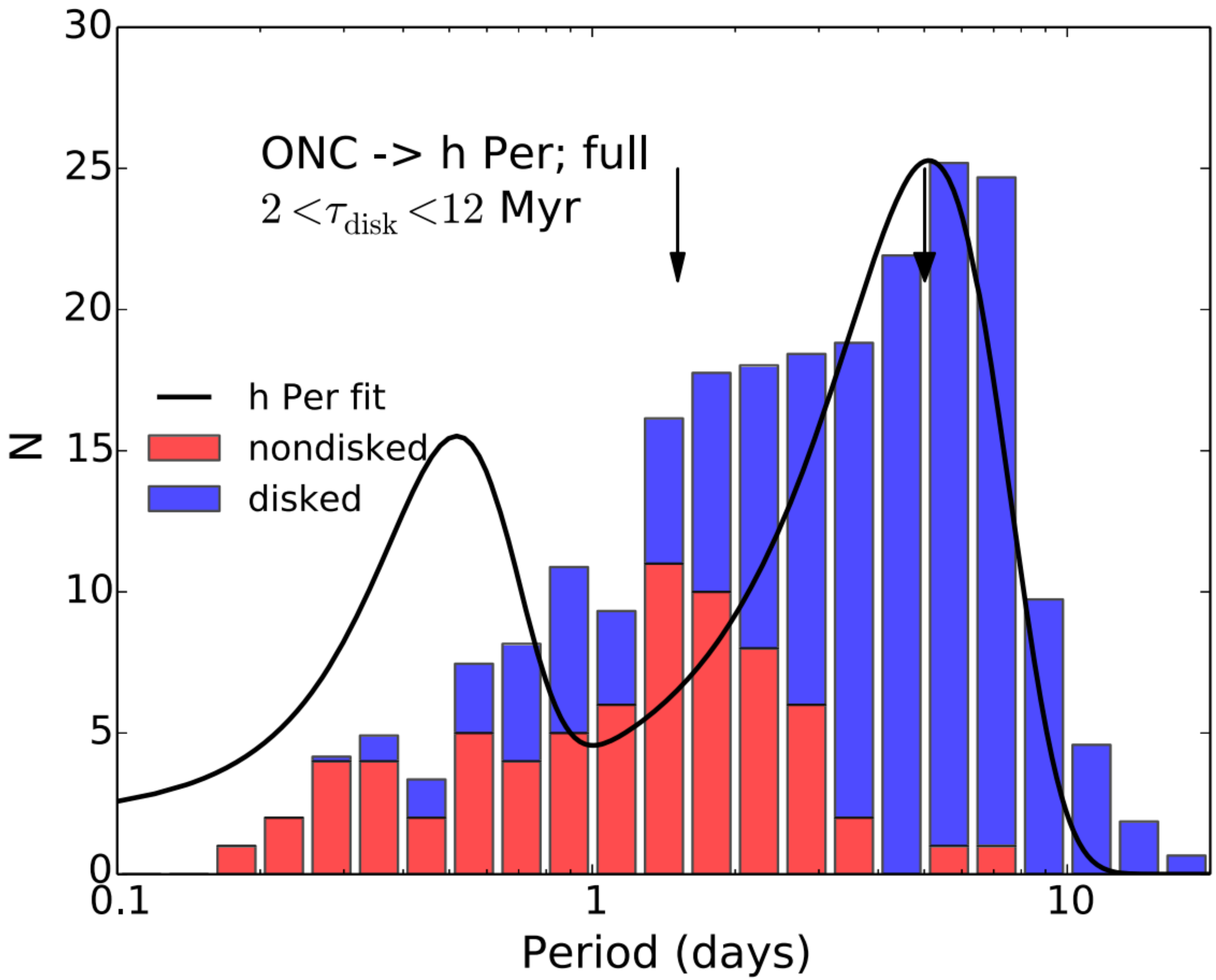
Fig from Bouvier et al. 2013
Data from Herbst et al. 2000

Problem #1

There may be real variance in the starting distributions of rotation periods that depends on environment

Assuming clusters at different ages represent an evolutionary sequence may not be safe

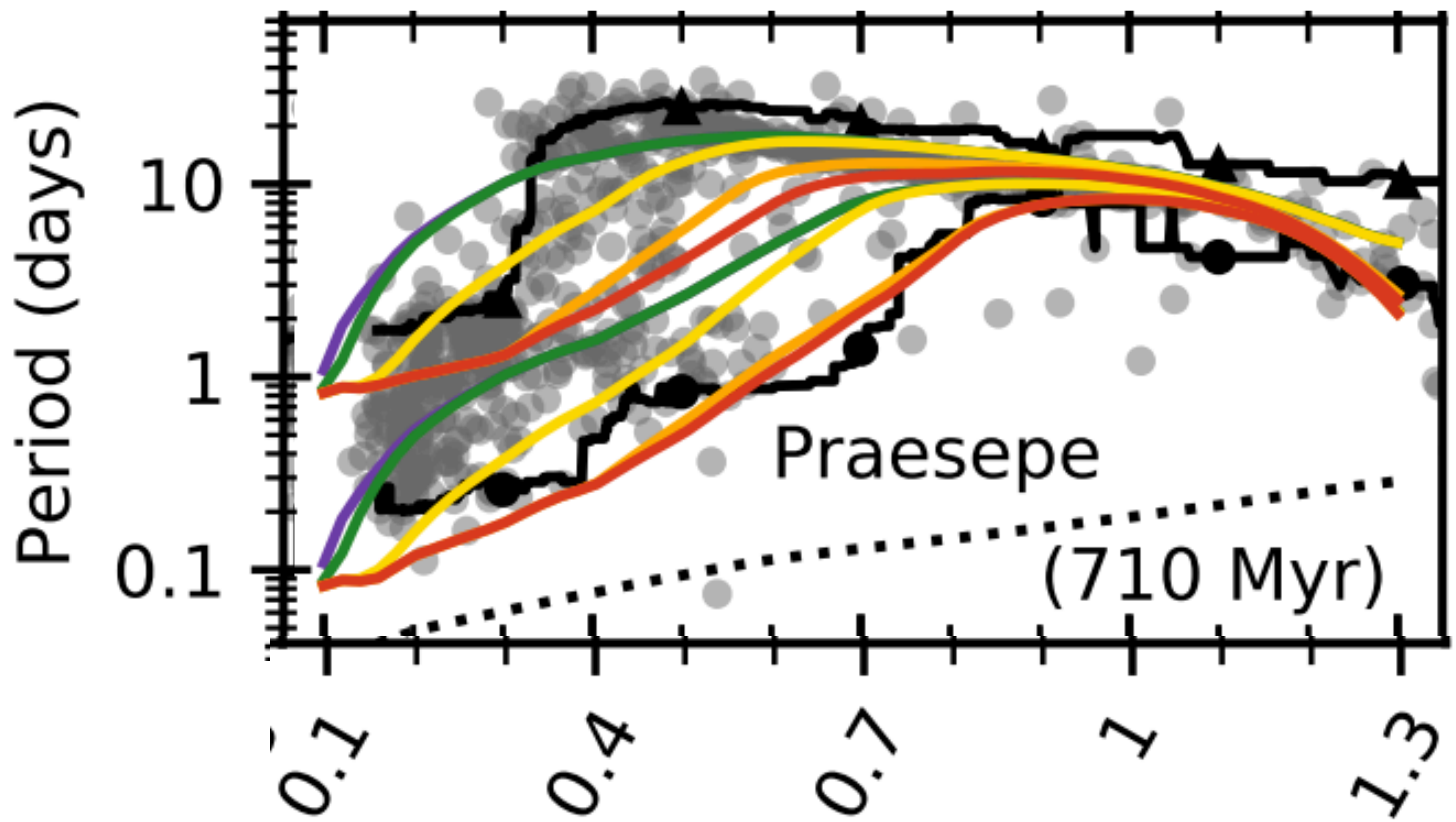
Example: the problem of h Per



Coker, Pinsonneault & Terndrup 2016

Stronger FUV exposure

Weaker FUV exposure



Roquette et al. 2021

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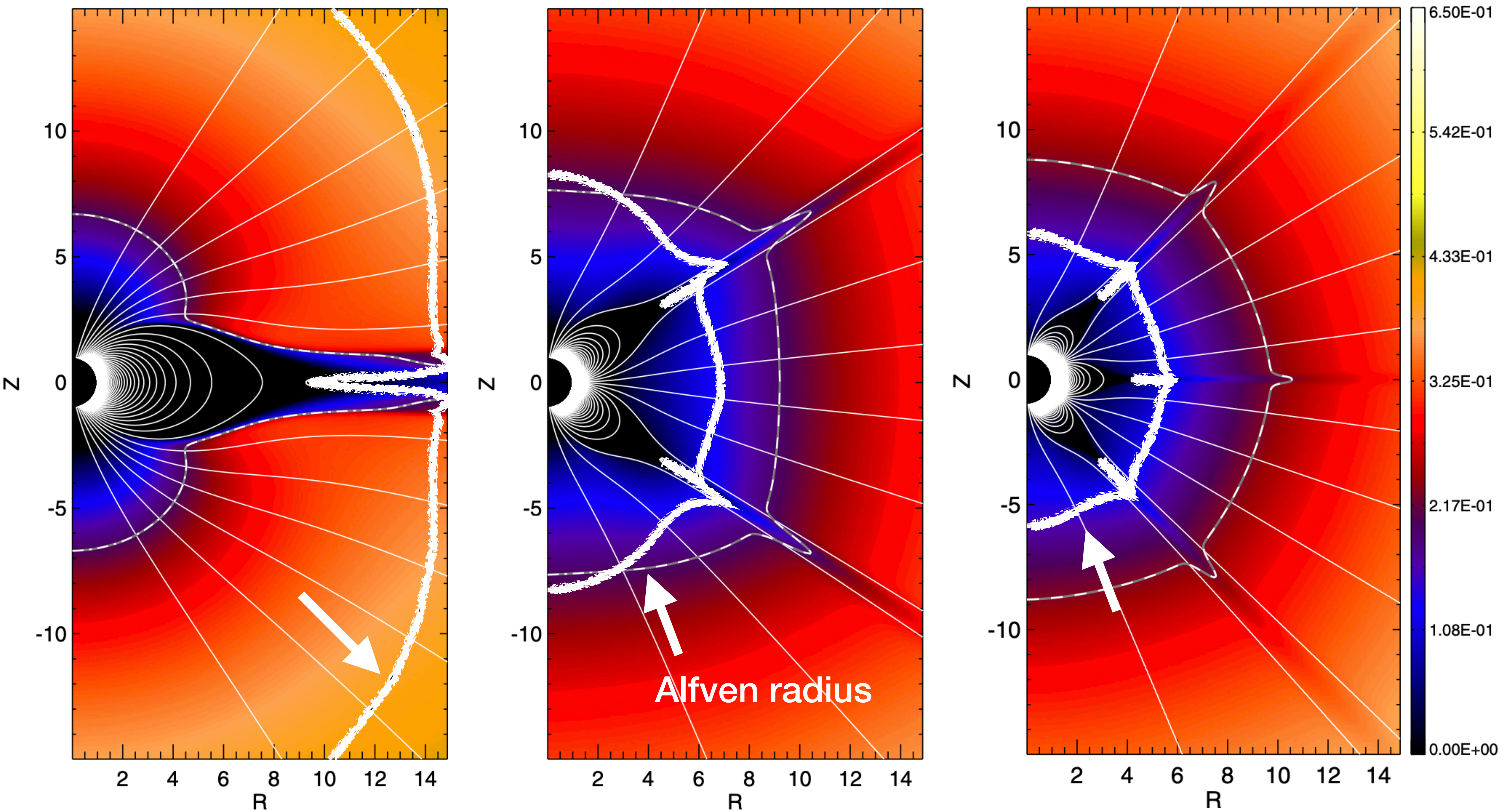
Magnetic braking prescriptions

$$\frac{dJ}{dt} \propto \dot{M}\Omega R_\star^2 \left(\frac{r_A}{R_\star}\right)^2$$

Magnetic field strength and morphology matter



$r_A \uparrow$ as $B \uparrow$, $r_A \downarrow$ with increasing field order

Reville et al. 2015, see also Garraffo et al. 2015, 2016, Finley & Matt 2018, See et al. 2019

Magnetic braking prescriptions

$$\frac{dJ}{dt} = -K\left(\frac{M_\star}{M_\odot}\right)^{-m}\left(\frac{R_\star}{R_\odot}\right)^{5m+2}\left(\frac{B_\star}{B_\odot}\right)^{4m}\left(\frac{\dot{M}_\star}{\dot{M}_\odot}\right)^{1-2m}\left(\frac{\Omega_\star}{\Omega_\odot}\right)$$

Matt et al. 2012
Matt et al. 2015
van Saders & Pinsonneault 2013

Magnetic braking prescriptions

Set by field morphology, wind acceleration

$$\frac{dJ}{dt} = -K\left(\frac{M_\star}{M_\odot}\right)^{-m}\left(\frac{R_\star}{R_\odot}\right)^{5m+2}\left(\frac{B_\star}{B_\odot}\right)^{4m}\left(\frac{\dot{M}_\star}{\dot{M}_\odot}\right)^{1-2m}\left(\frac{\Omega_\star}{\Omega_\odot}\right)$$

Normalization constant

Matt et al. 2012
Matt et al. 2015
van Saders & Pinsonneault 2013

Magnetic braking prescriptions

$$\frac{dJ}{dt} = -K \left(\frac{M_\star}{M_\odot}\right)^{-m} \left(\frac{R_\star}{R_\odot}\right)^{5m+2} \left(\frac{B_\star}{B_\odot}\right)^{4m} \left(\frac{\dot{M}_\star}{\dot{M}_\odot}\right)^{1-2m} \left(\frac{\Omega_\star}{\Omega_\odot}\right)$$

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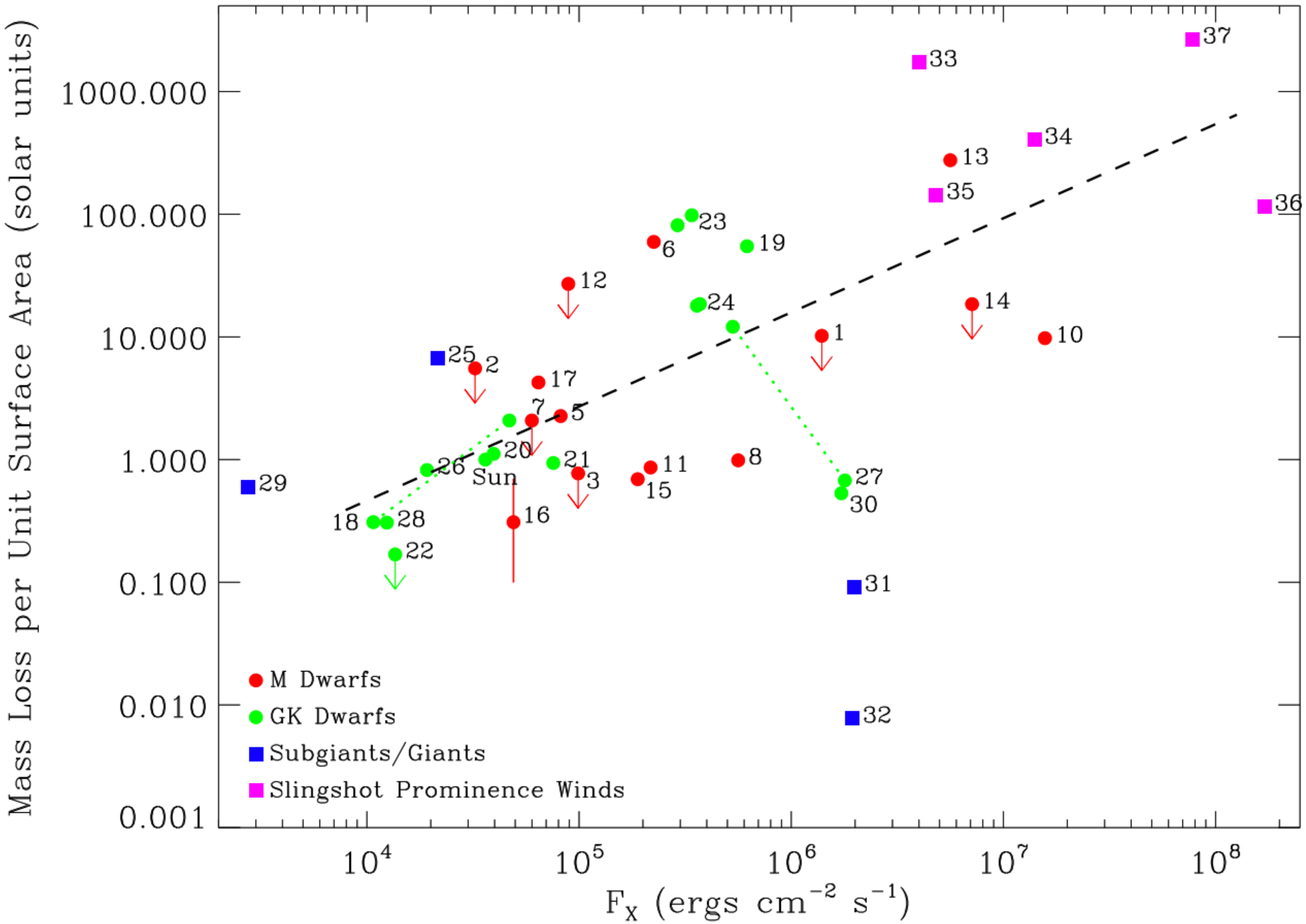
Measurements of mass loss rates for dwarfs exist, but they are few.



Wood et al. 2021

Magnetic braking prescriptions

$$\frac{dJ}{dt} = -K \left(\frac{M_\star}{M_\odot}\right)^{-m} \left(\frac{R_\star}{R_\odot}\right)^{5m+2} \left(\frac{B_\star}{B_\odot}\right)^{4m} \left(\frac{\dot{M}_\star}{\dot{M}_\odot}\right)^{1-2m} \left(\frac{\Omega_\star}{\Omega_\odot}\right)$$

Magnetic braking prescriptions

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First, assume a dipole*

Magnetic braking prescriptions

$$\frac{dJ}{dt} = -K\left(\frac{M_\star}{M_\odot}\right)^{-m}\left(\frac{R_\star}{R_\odot}\right)^{5m+2}\left(\frac{B_\star}{B_\odot}\right)^{4m}\left(\frac{\dot{M}_\star}{\dot{M}_\odot}\right)^{1-2m}\left(\frac{\Omega_\star}{\Omega_\odot}\right)$$

First, assume a dipole*
Second, assume a Rossby scaling*

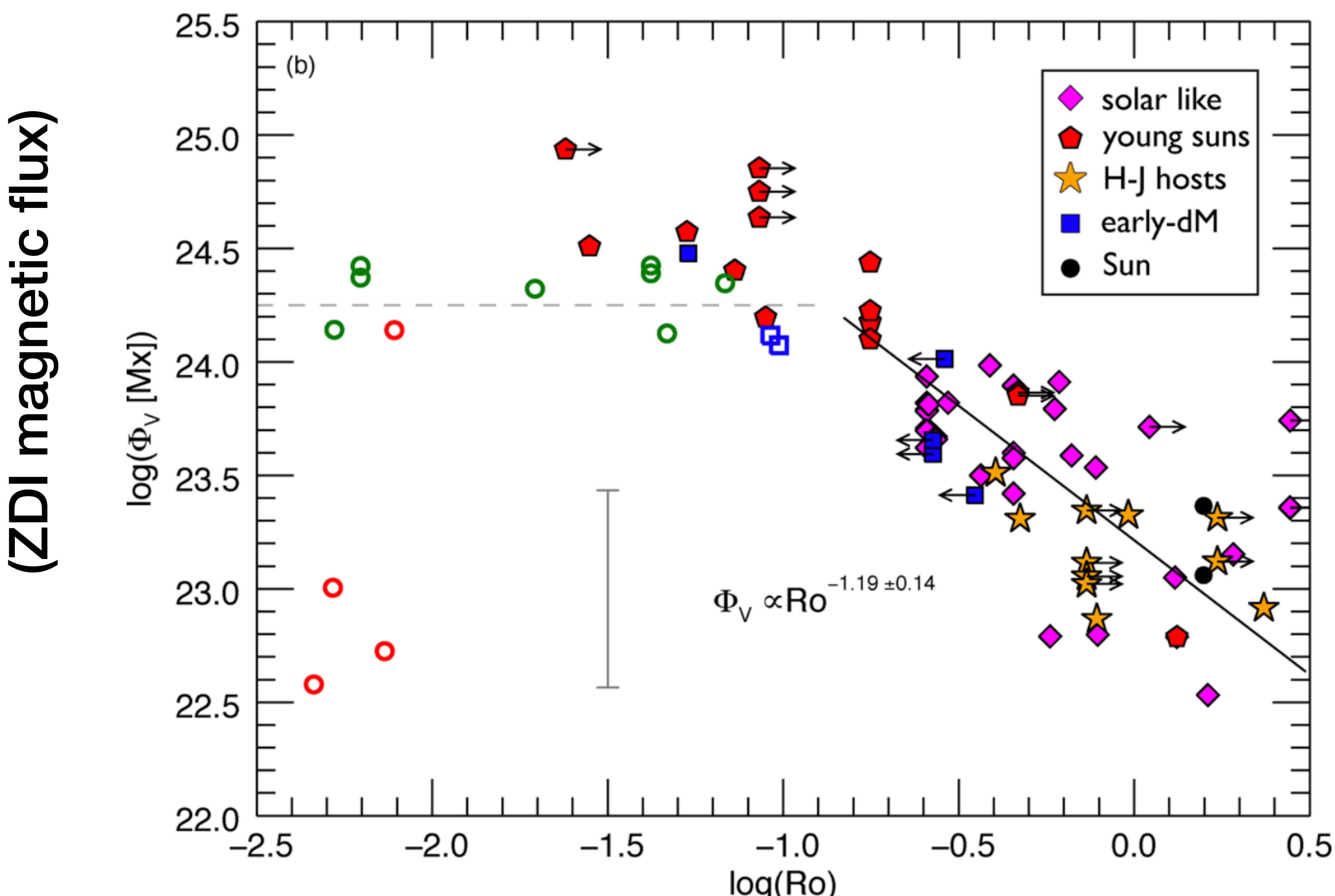
Magnetic phenomena (appear to) depend on the Rossby number

$$\mathrm{Ro} = \frac{P_{rot}}{\tau_{cz}}$$

increases as the star spins down with time

Roughly constant during the main sequence, but a strong function of mass

Objects with lower Rossby numbers are more active, with stronger fields



Vidotto et al. 2014

Magnetic braking prescriptions

$$\frac{dJ}{dt} = -K\left(\frac{M_\star}{M_\odot}\right)^{-m}\left(\frac{R_\star}{R_\odot}\right)^{5m+2}\left(\frac{B_\star}{B_\odot}\right)^{4m}\left(\frac{\dot{M}_\star}{\dot{M}_\odot}\right)^{1-2m}\left(\frac{\Omega_\star}{\Omega_\odot}\right)$$

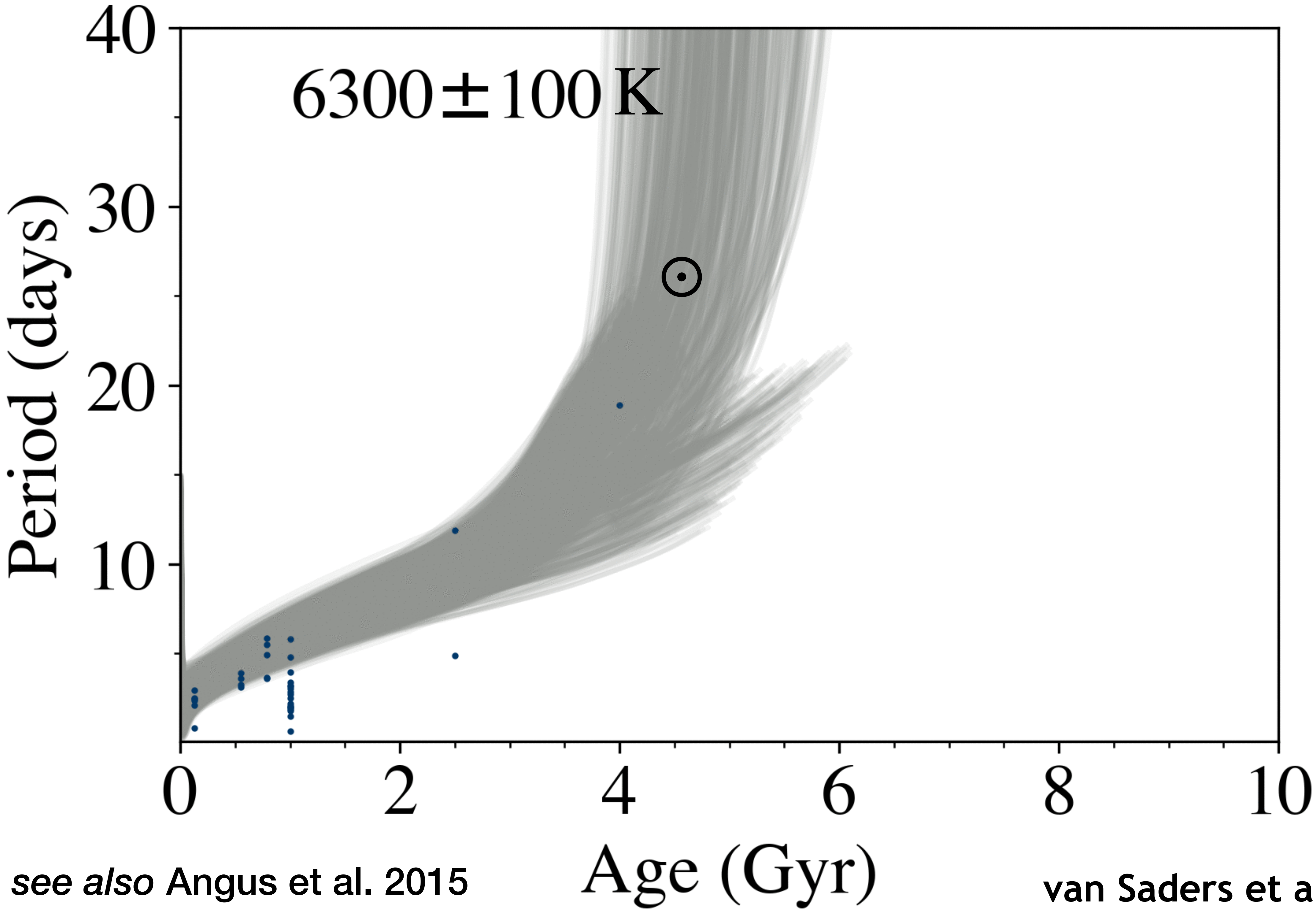
Generally:

$$\frac{dJ}{dt} \propto \Omega^3$$

To reproduce the observed time dependence of spin down

dJ/dt is a strong function of mass (or Teff, or color) of the star

A standard spin-down model

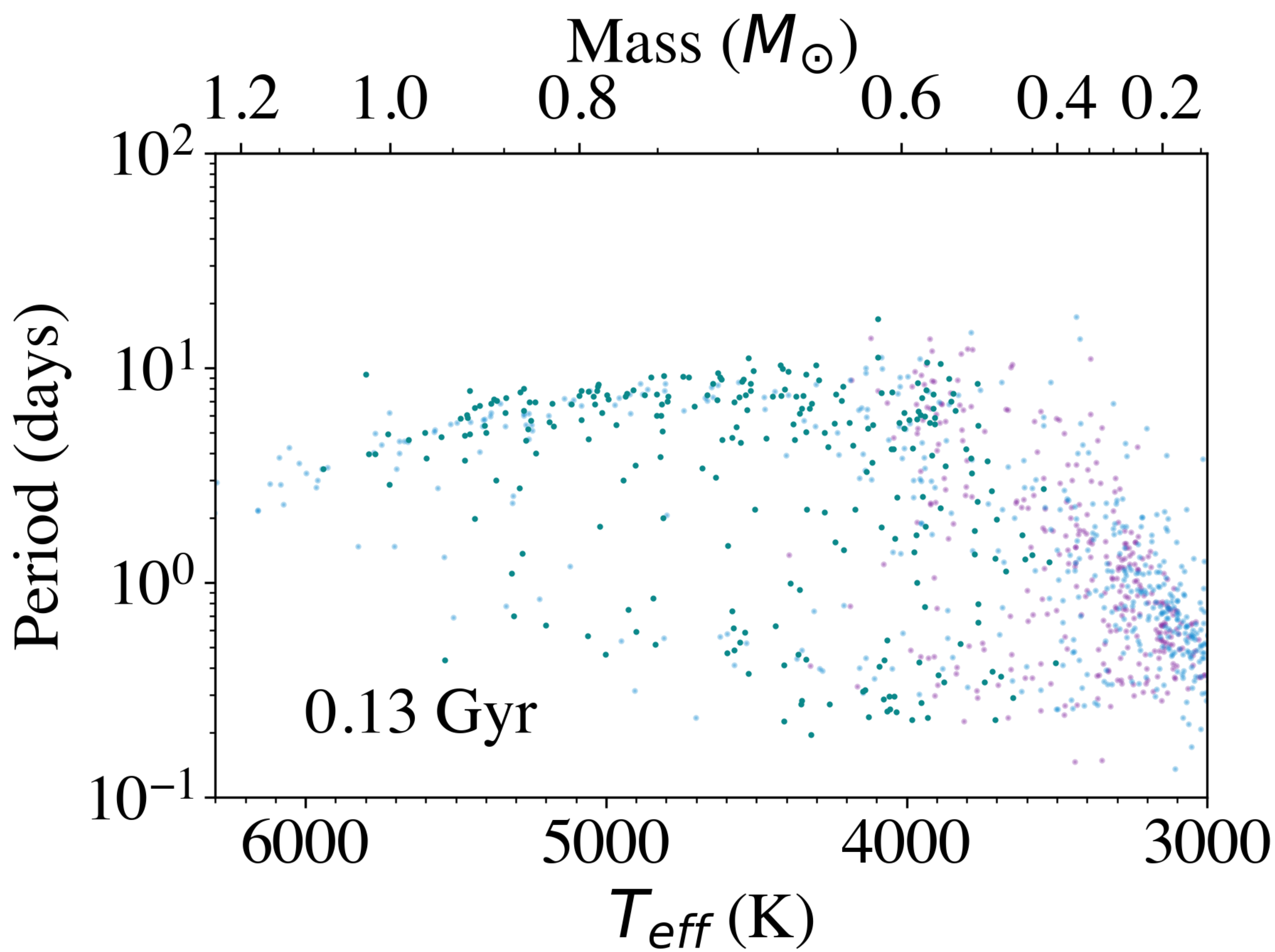


see also Angus et al. 2015

van Saders et al. 2016
Hall et al. 2021

Problem #2

Rapid rotators cannot survive to their observed ages with Ω^3 spin down



Problem #2

Rapid rotators cannot survive to their observed ages with Ω^3 spin down

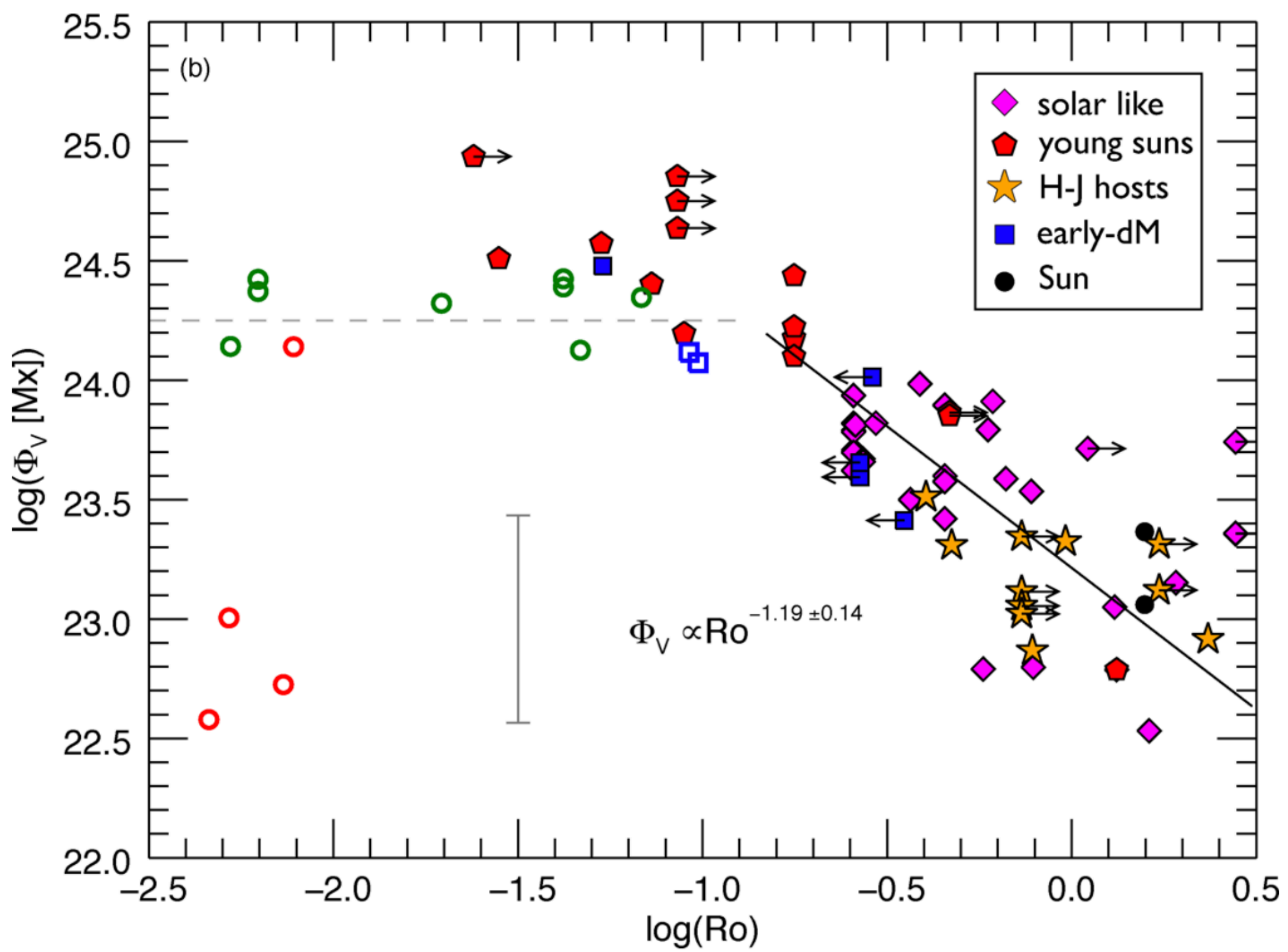
$$\frac{dJ}{dt} \propto \Omega^3, \Omega < \Omega_{crit}$$

$$\frac{dJ}{dt} \propto \Omega, \Omega > \Omega_{crit}$$

“Saturation”: At some Ω_{crit}, spinning the star faster does not yield a stronger field, thus you do not have stronger braking

Problem #2

Rapid rotators cannot survive to their observed ages with Ω^3 spin down



Vidotto et al. 2014

Problem #2

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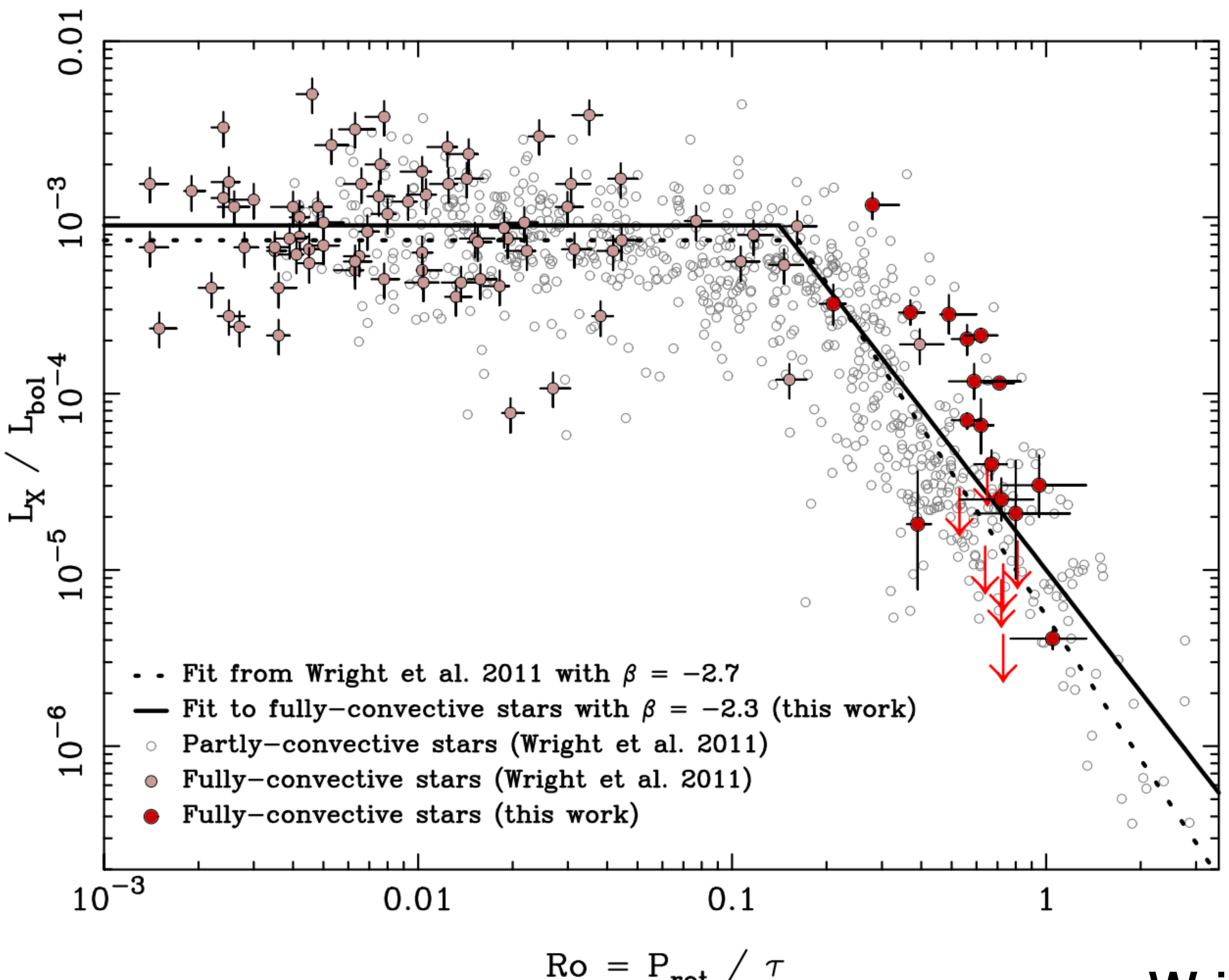
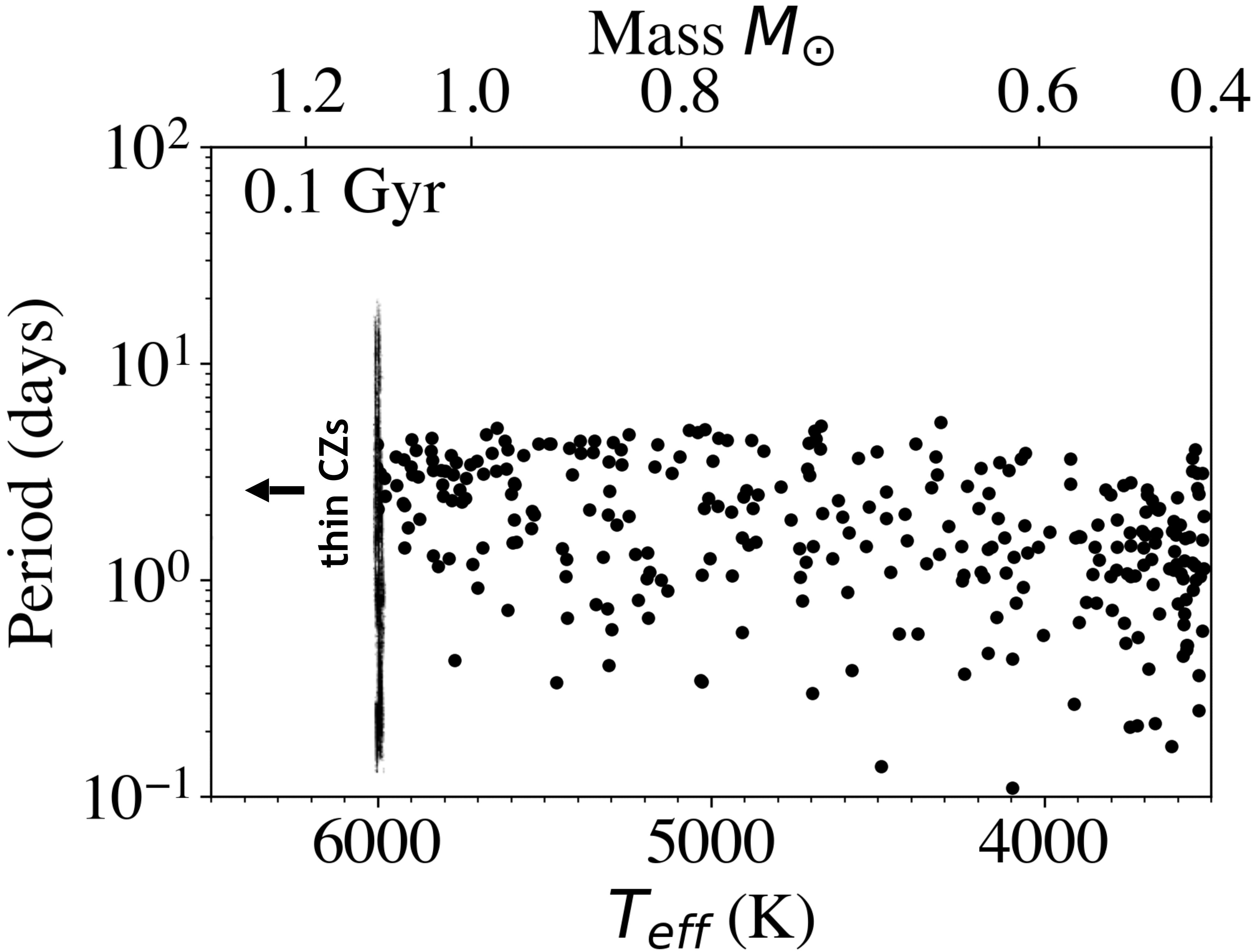


Wright et al. 2018

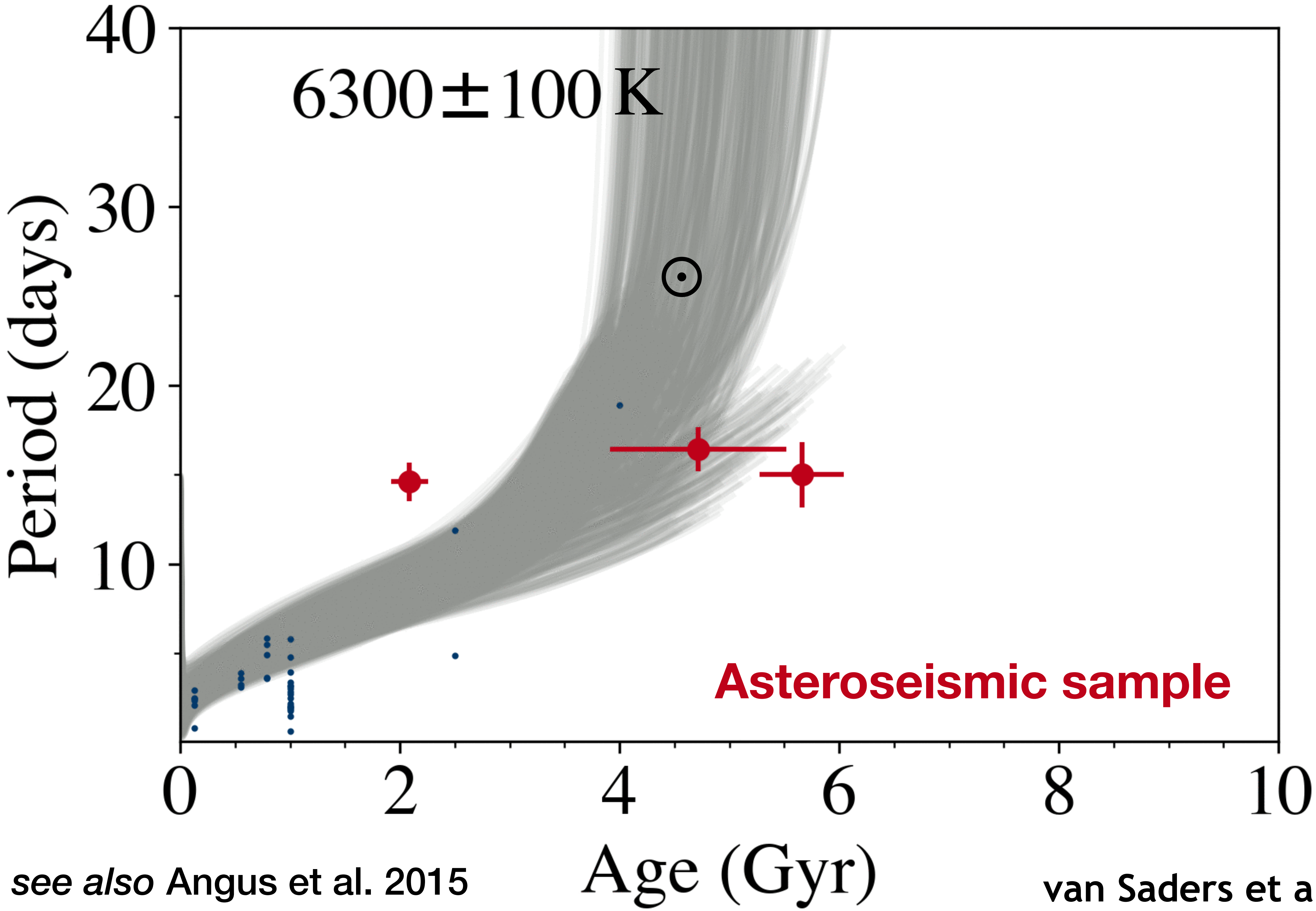
A model of stellar spin down



Problem #3

Old stars appear to stop losing angular momentum at Rossby numbers larger than solar

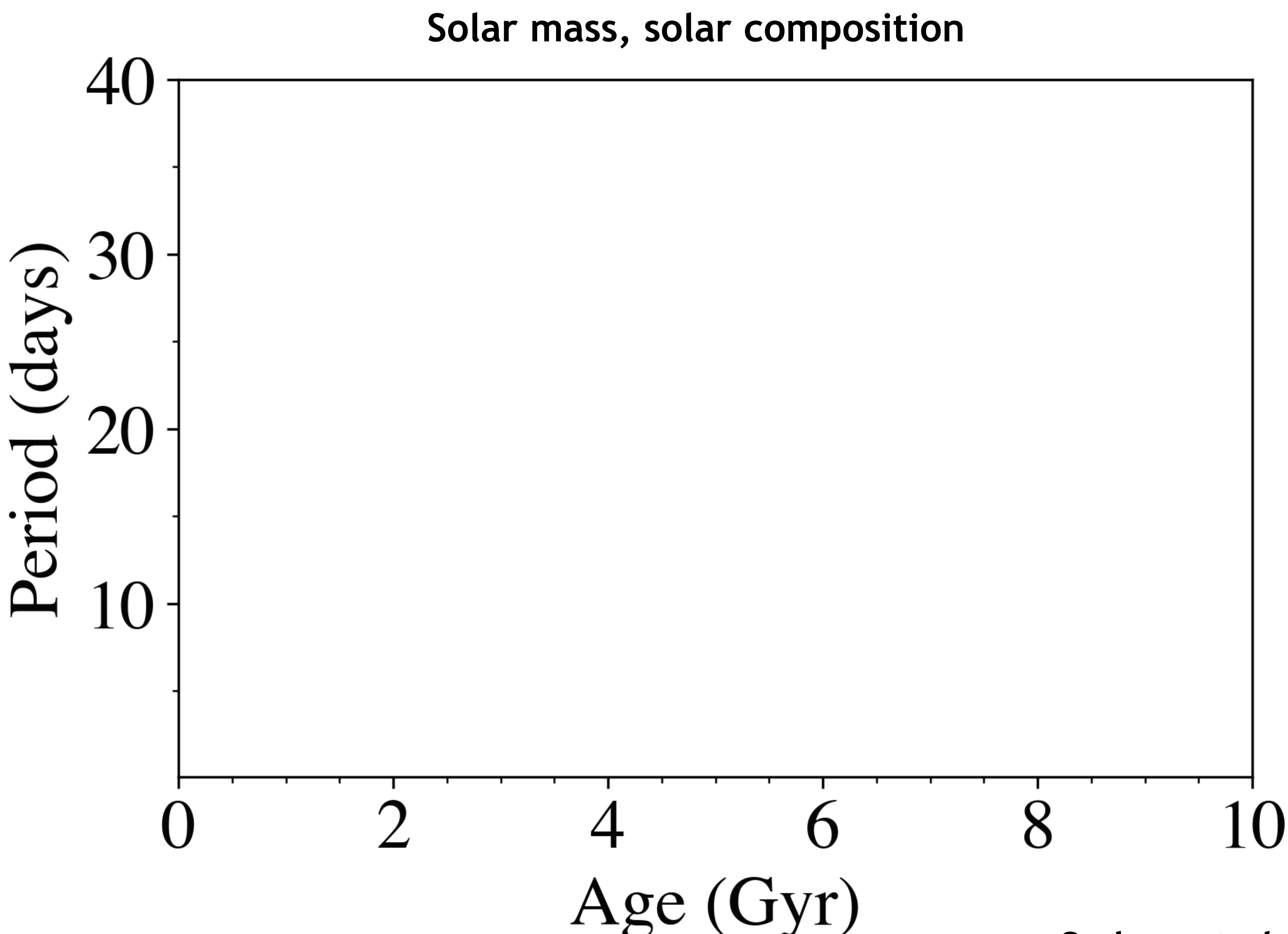
A standard spin-down model



see also Angus et al. 2015

van Saders et al. 2016
Hall et al. 2021

Weakened magnetic braking



van Saders et al. 2016

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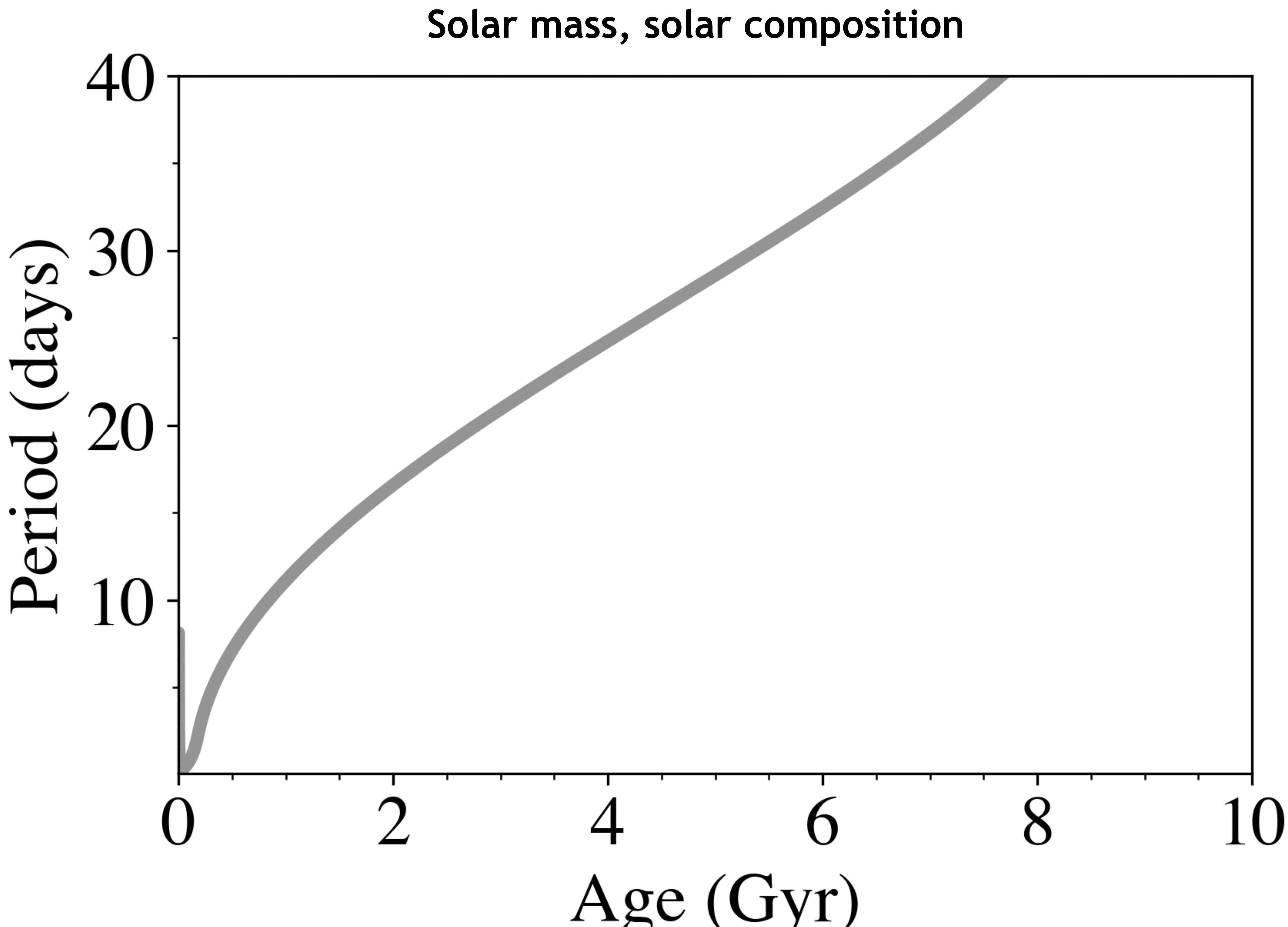

van Saders et al. 2016

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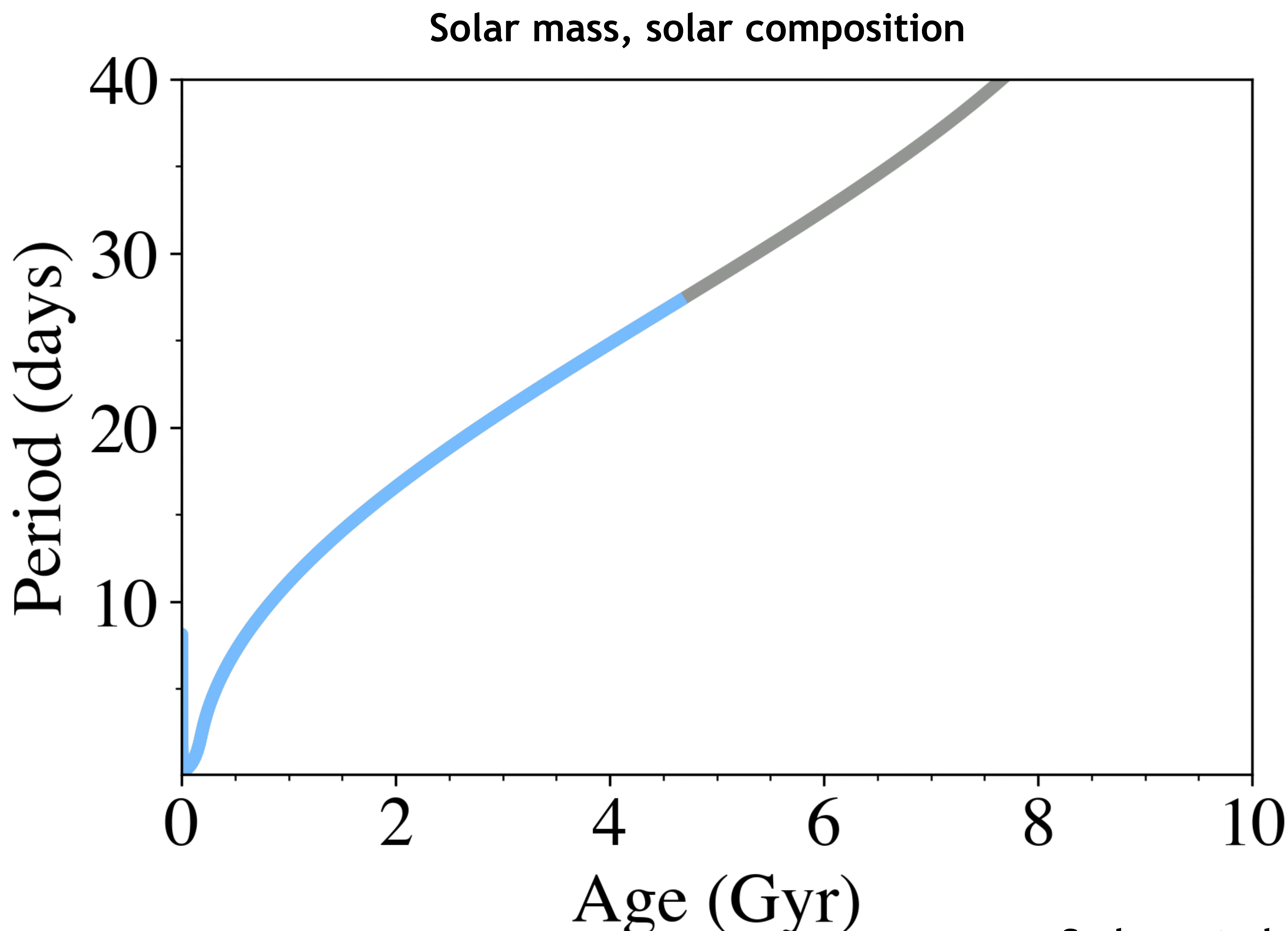

van Saders et al. 2016

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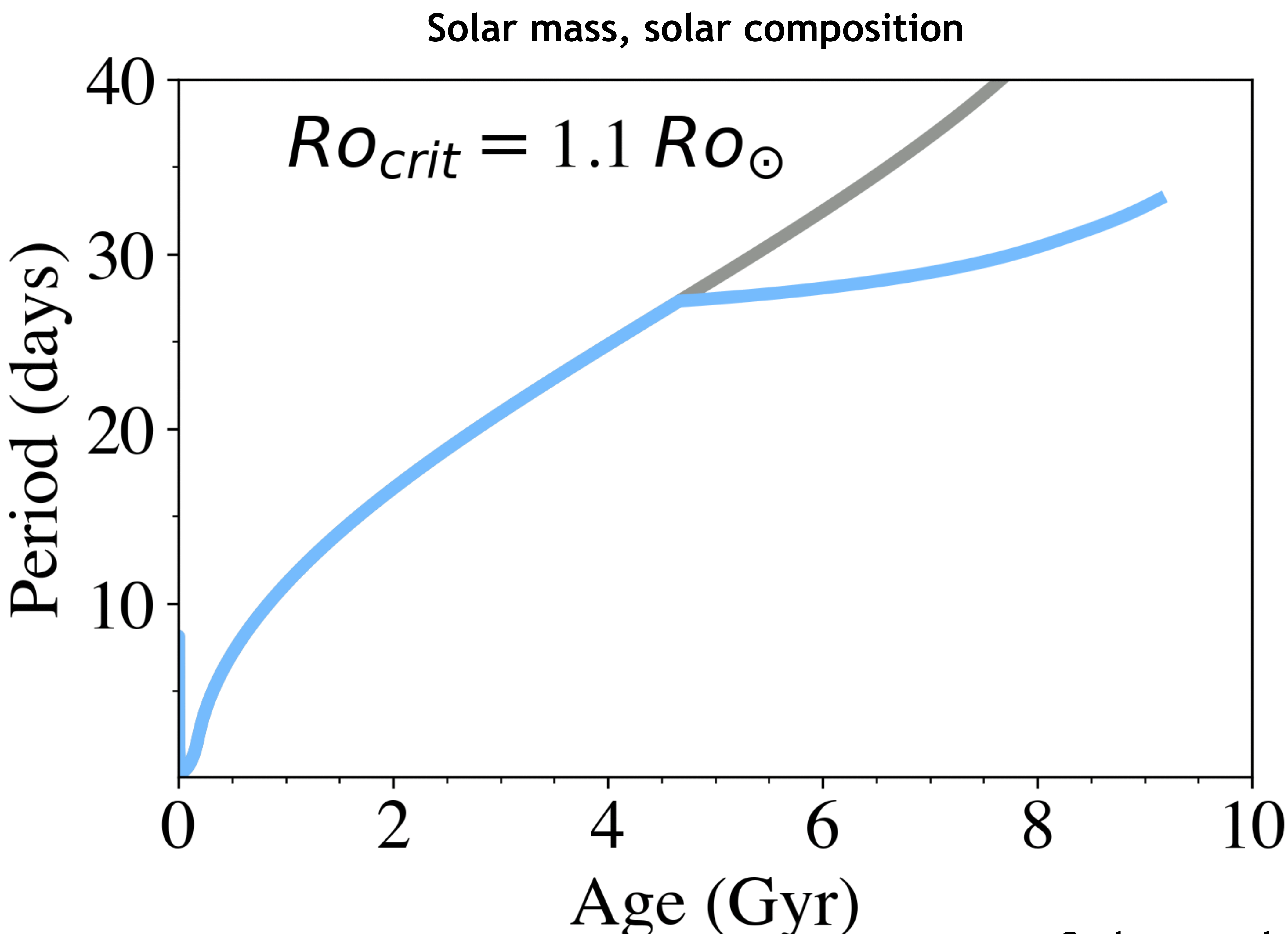
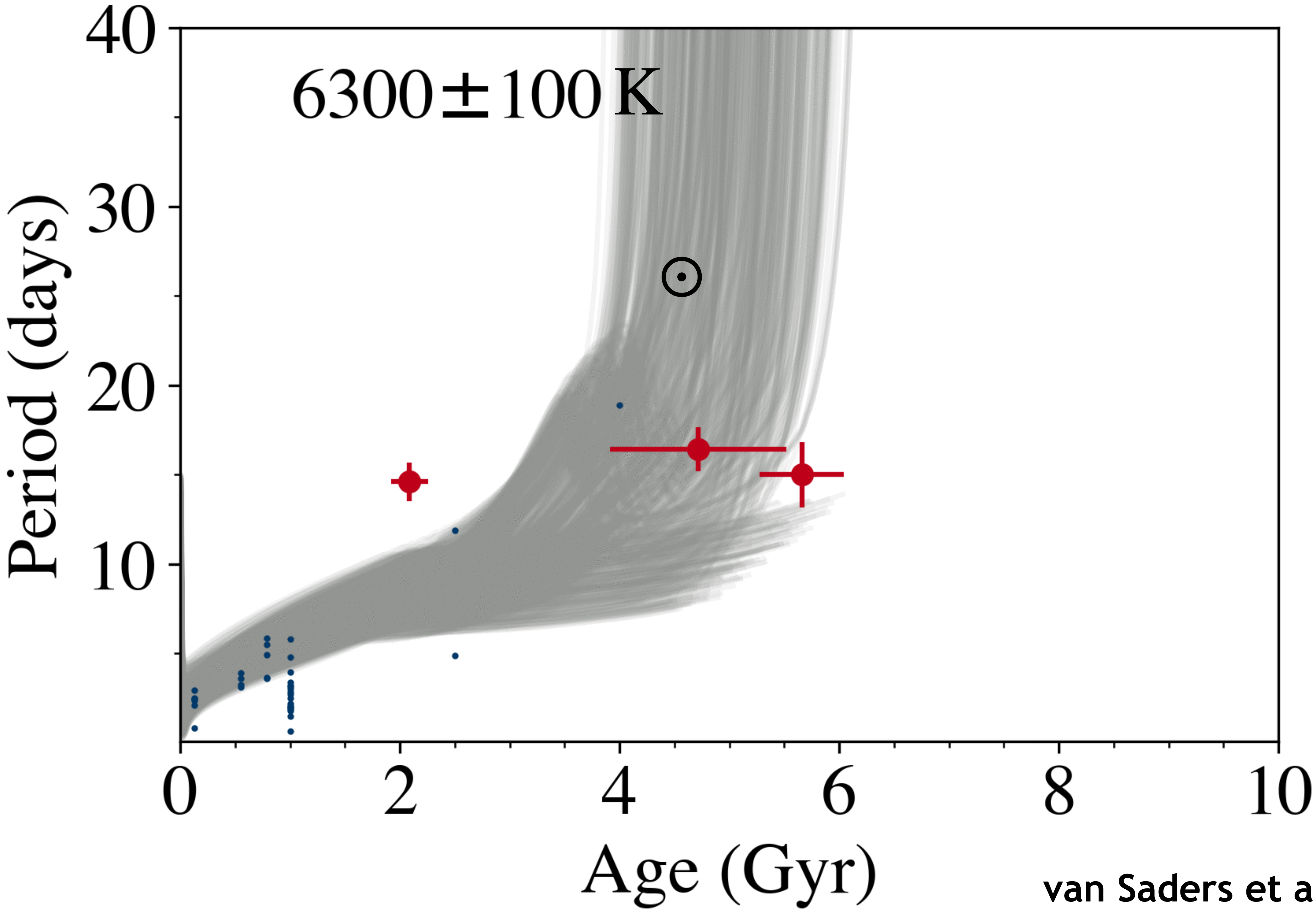


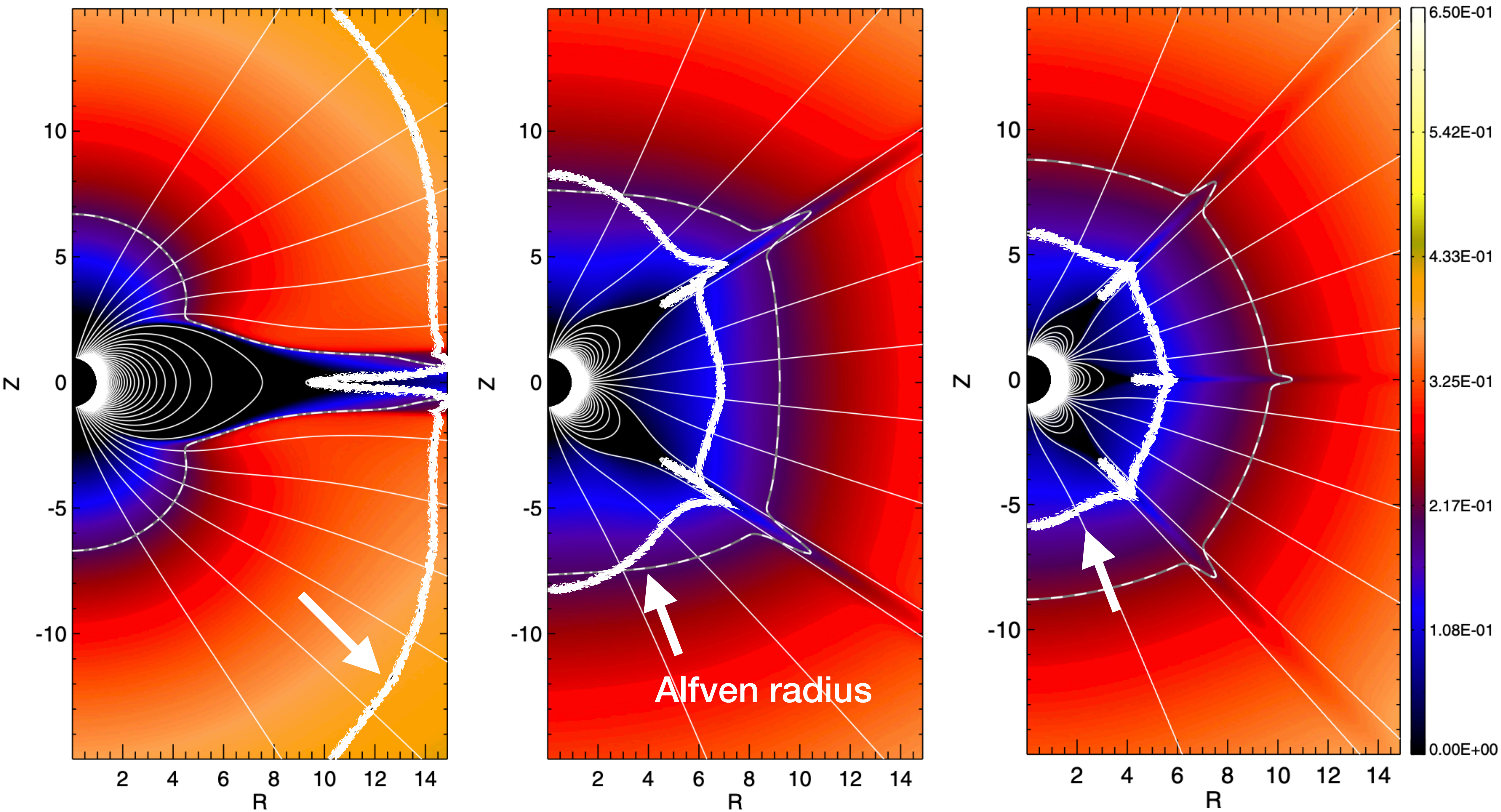
van Saders et al. 2016

Halt spin-down past a critical Rossby number



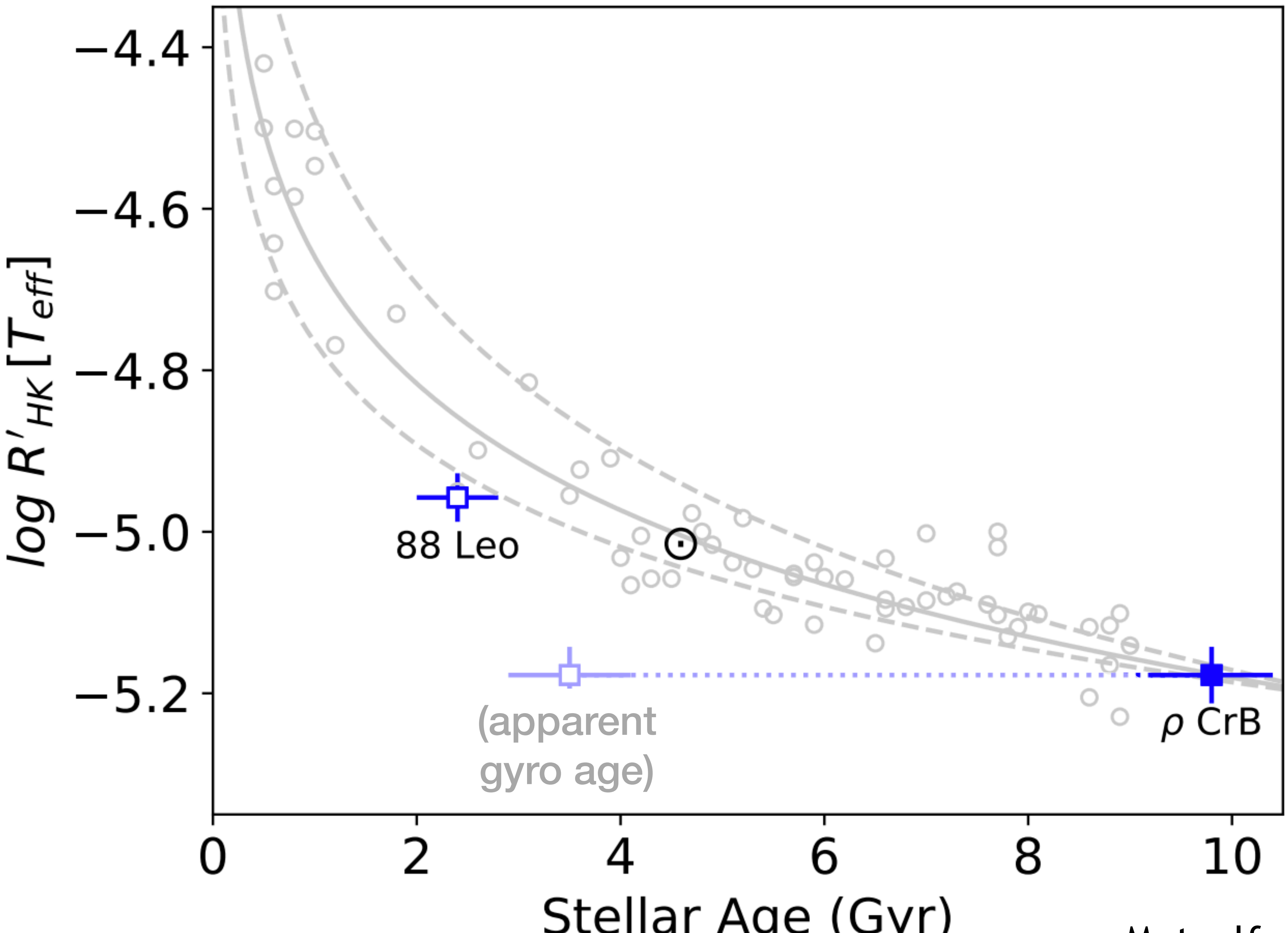
van Saders et al. 2016
Hall et al. 2021

Magnetic field strength and morphology matter



Reville et al. 2015, see also Garraffo et al. 2015, 2016, Finley & Matt 2018, See et al. 2019

A shift in magnetic field morphology?



Metcalfe et al. 2021

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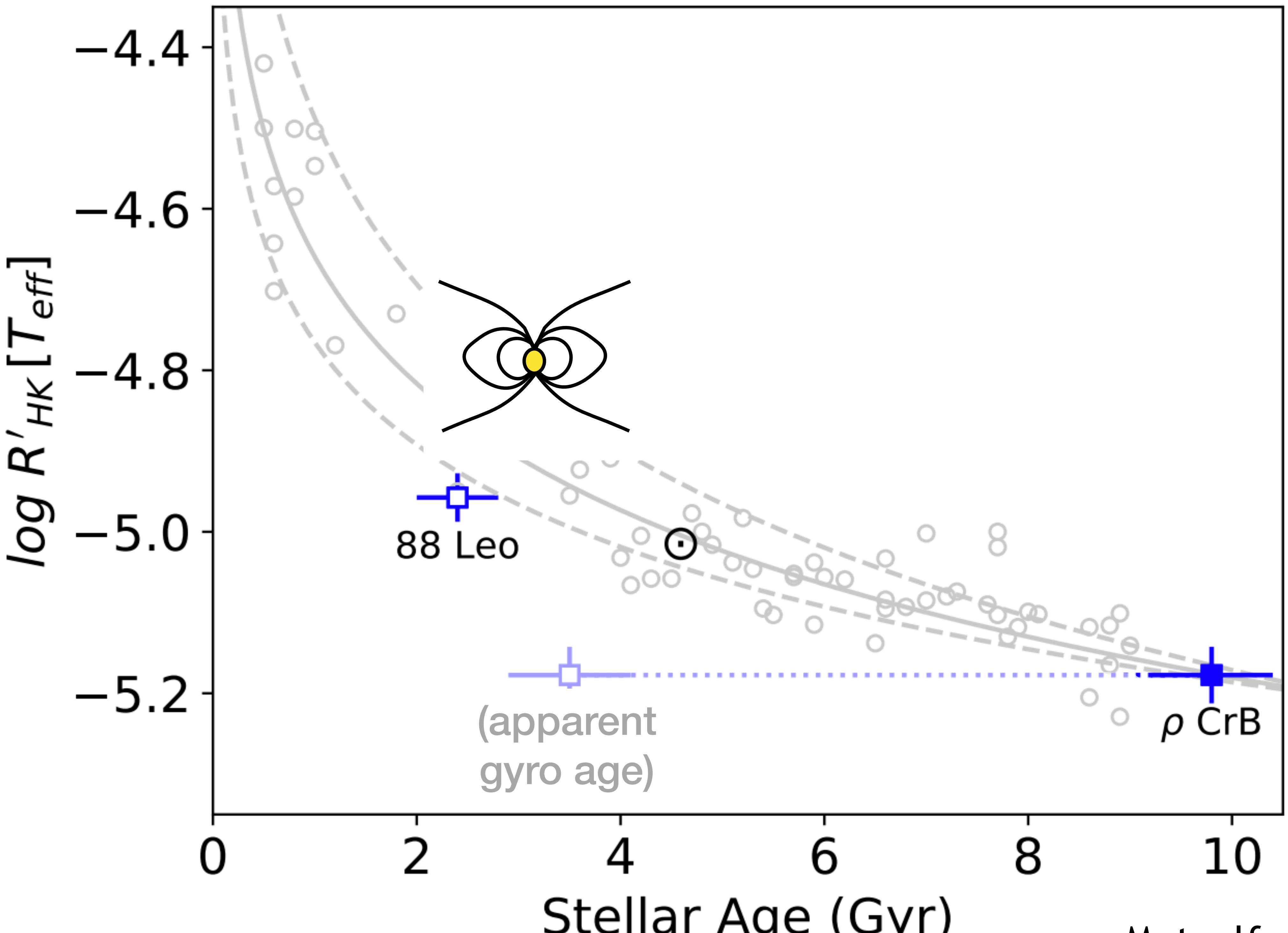

Metcalfe et al. 2021

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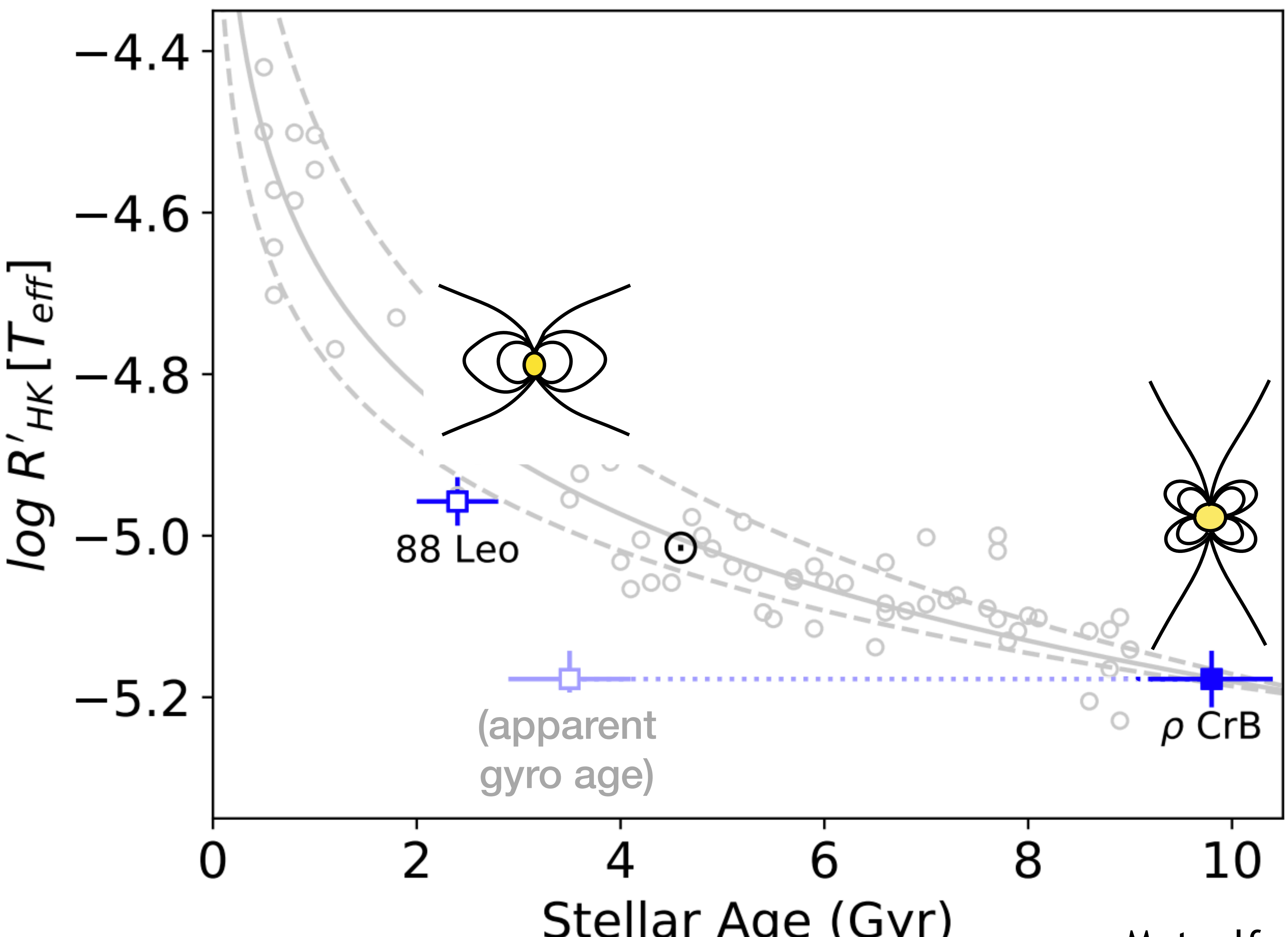

Metcalfe et al. 2021

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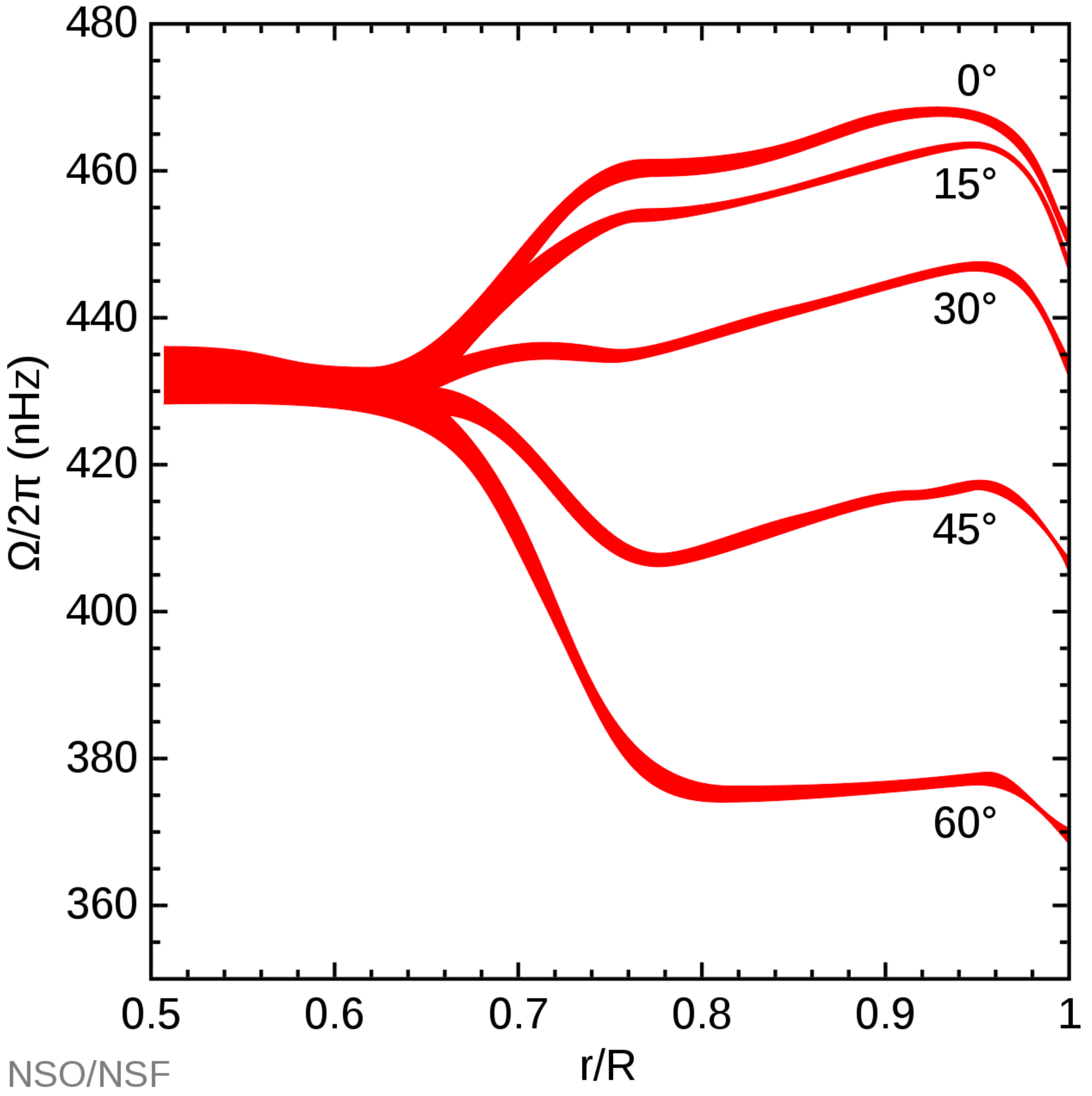
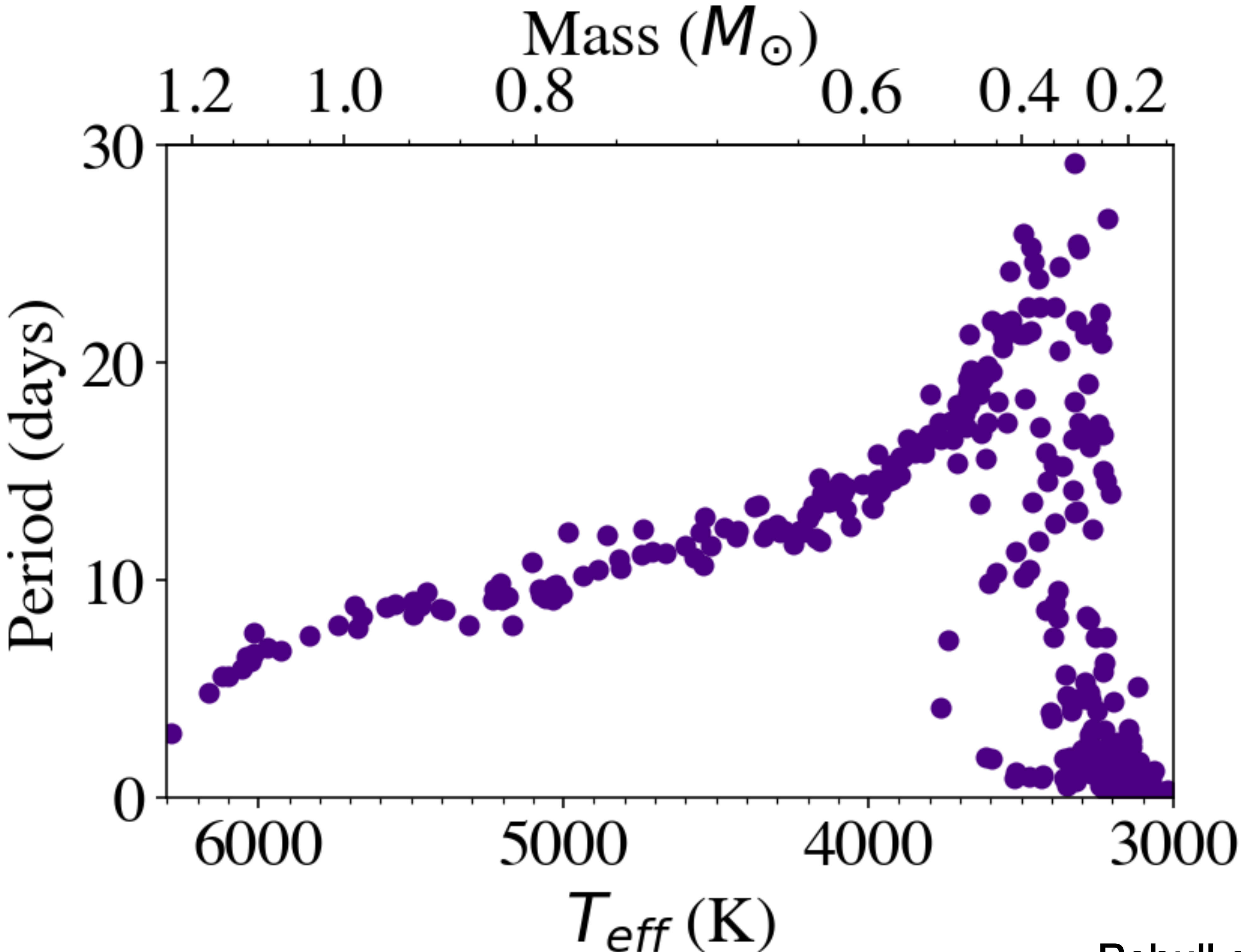
The Sun is not far from a solid body

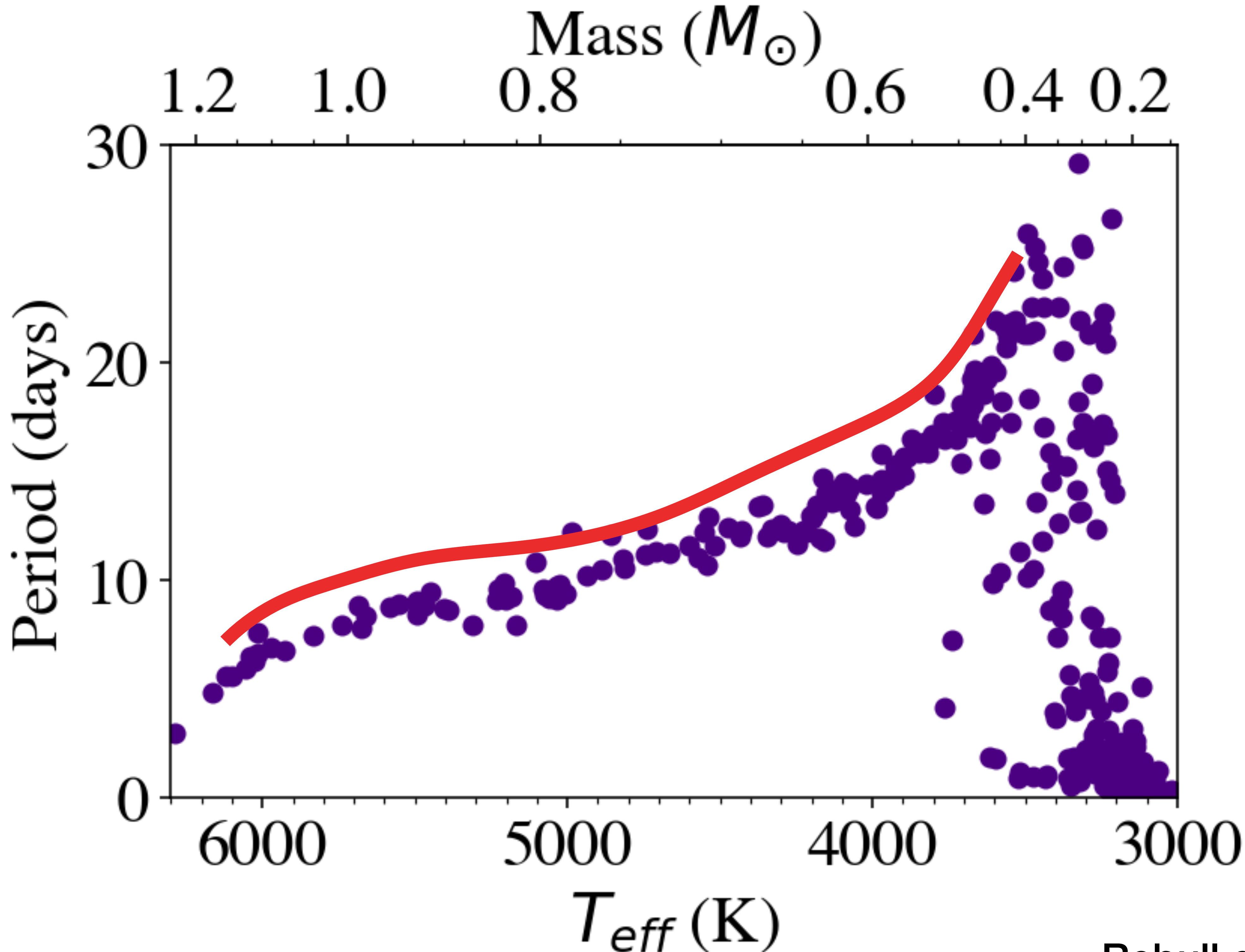


Problem #4



Rebull et al. 2016

Problem #4



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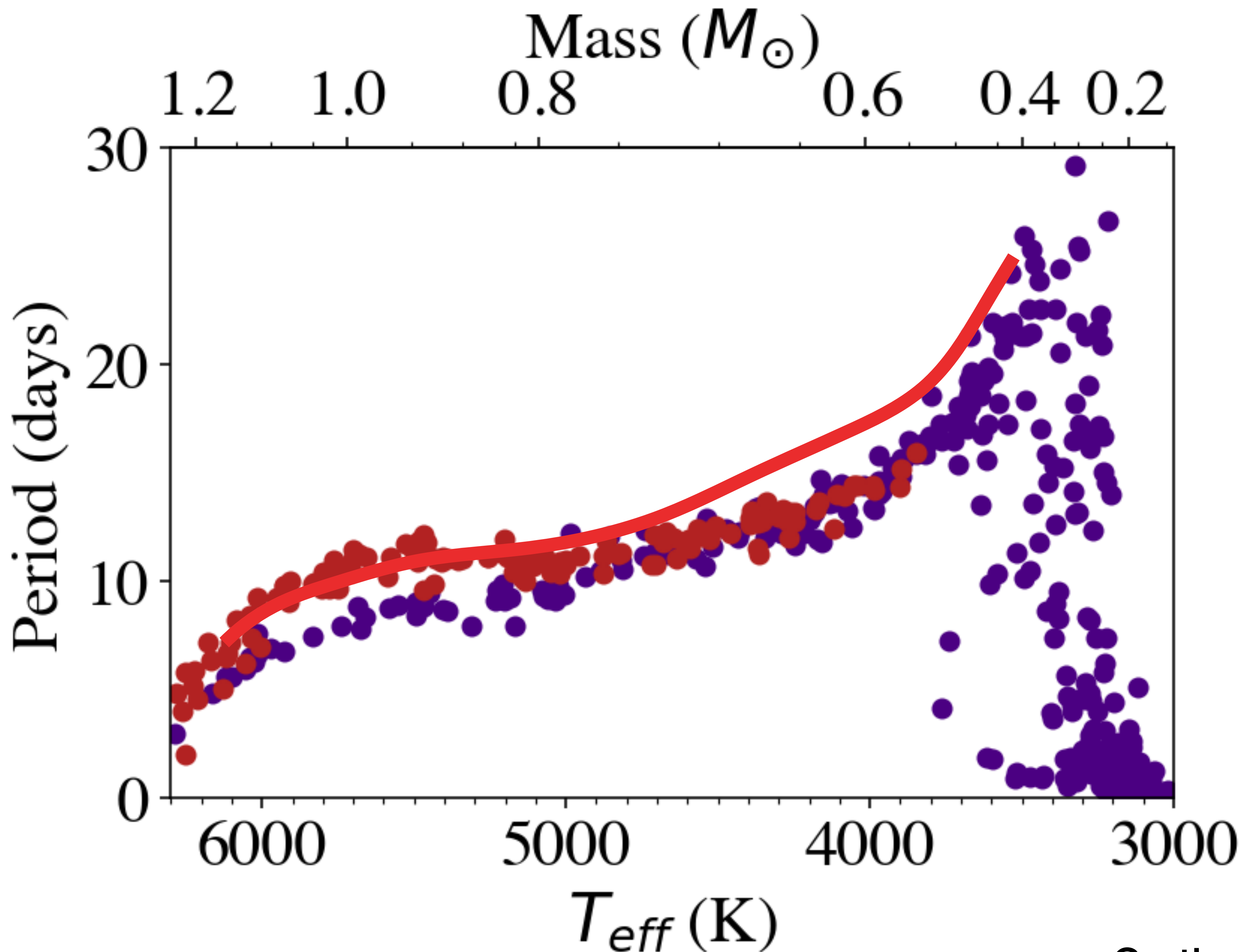
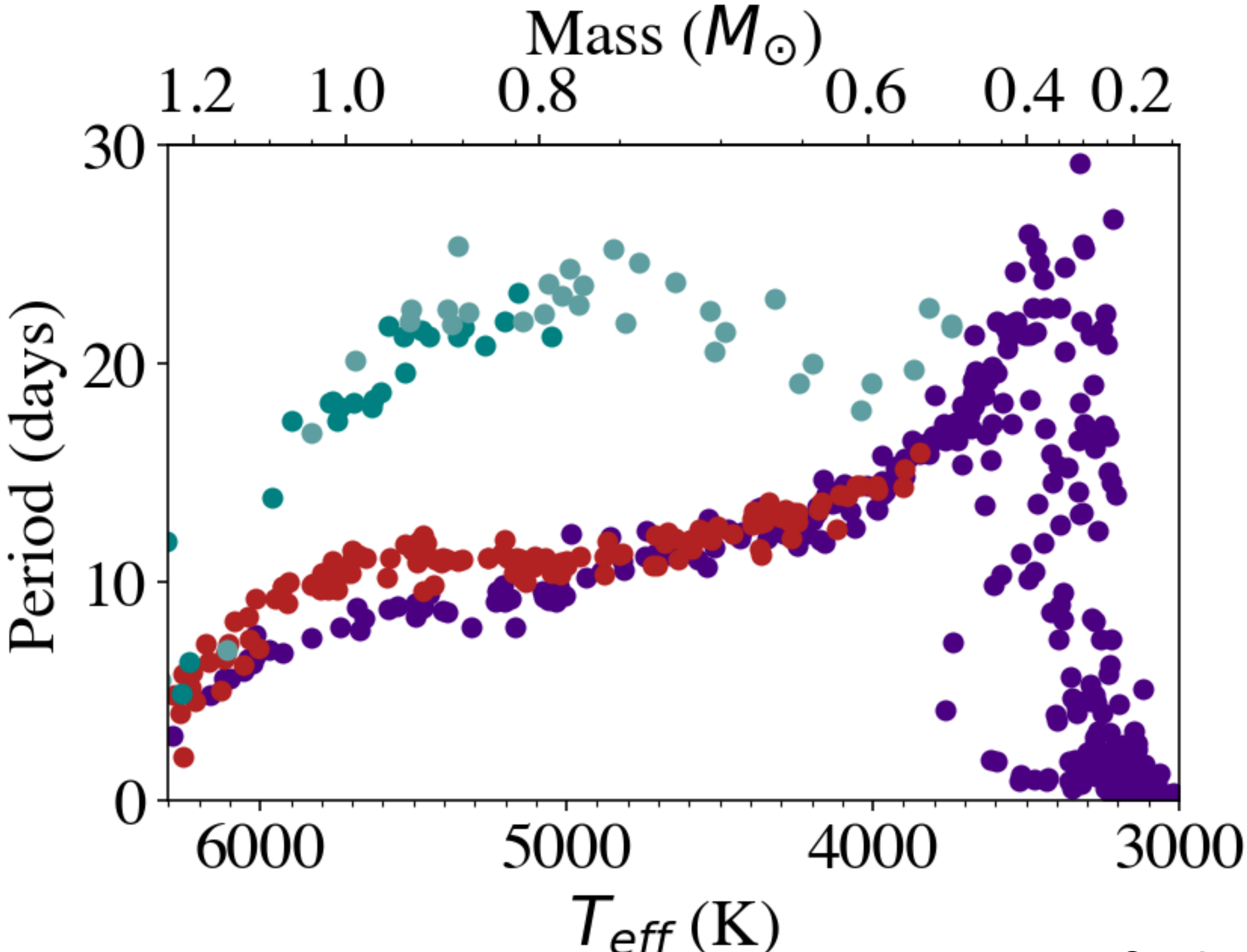


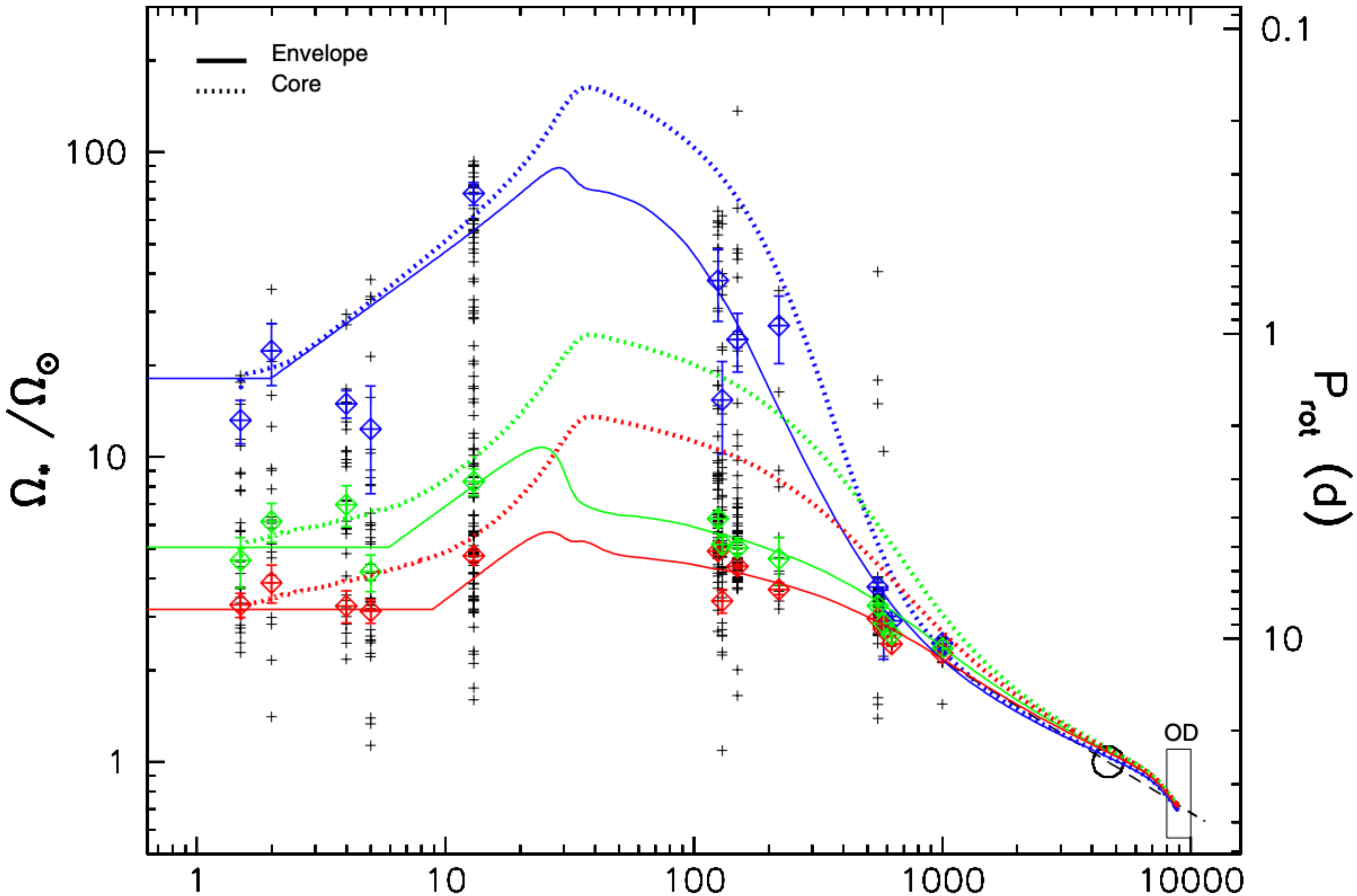
Curtis et al. 2020

Problem #4



Curtis et al. 2020

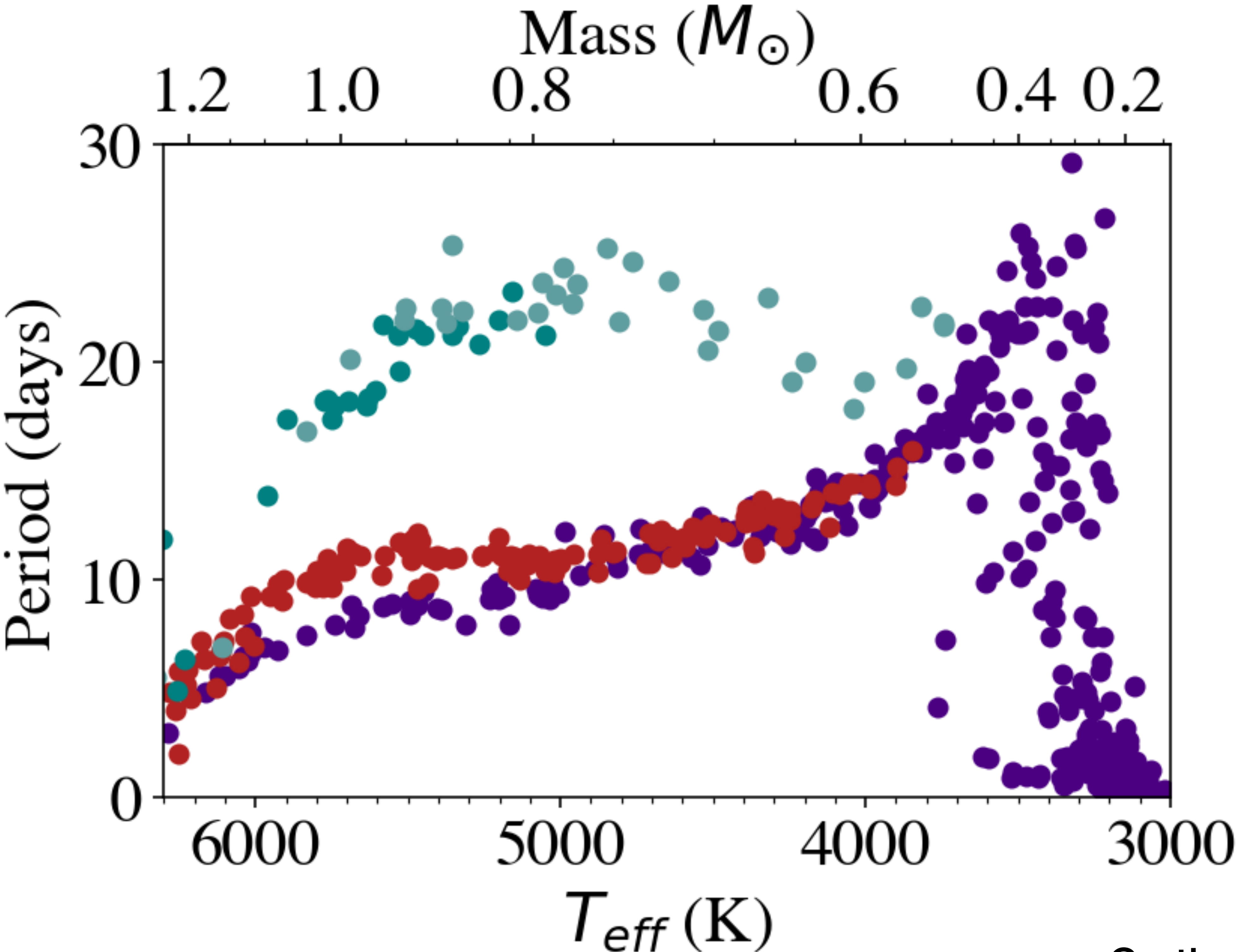
Allow envelopes and cores to “decouple”



(a) 1 $M_\odot$

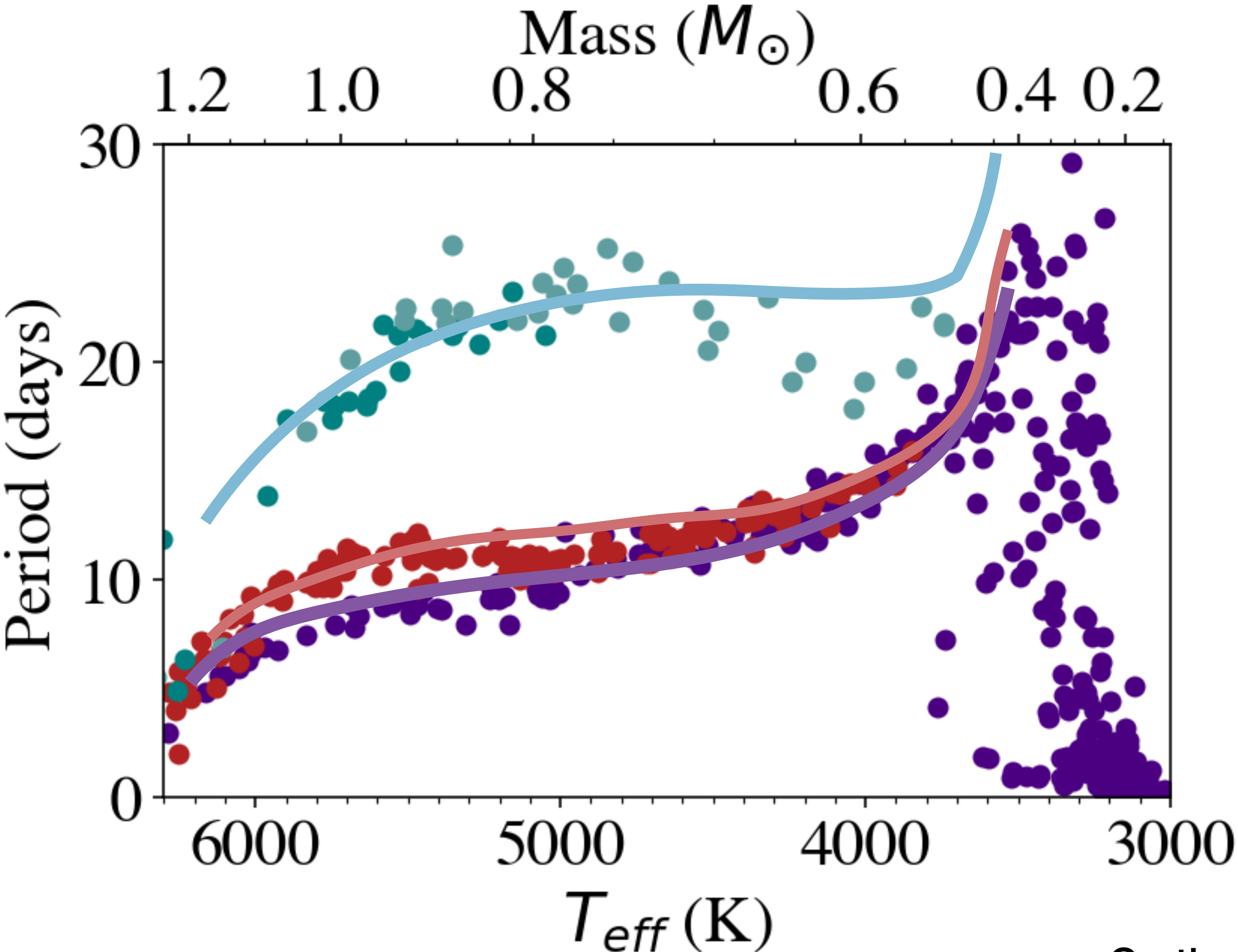
MacGregor & Brenner 1991, Krishnamurthi et al. 1997, **Gallet & Bouvier 2015,** Denissenkov & Pinsonneault 2010, Spada & Lanzafame 2020

Problem #4



Curtis et al. 2020

Problem #4



Curtis et al. 2020

Rotation cares about the things you care about: internal transport, magnetic field generation, convection zone properties, stellar structure