Slowing the Spins of Stellar Cores

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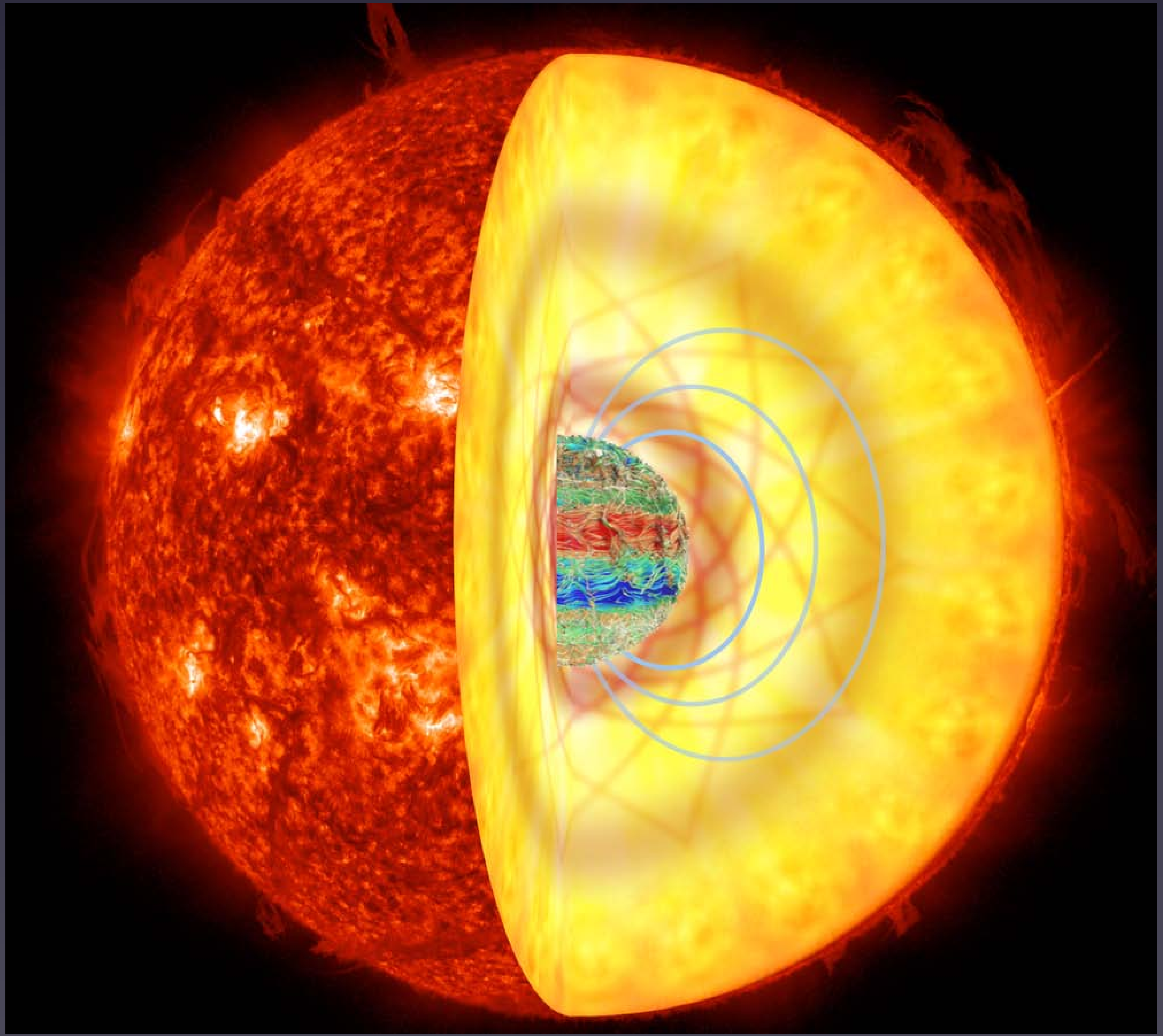
Caltech



The Spin of Stellar Cores

- Cores contract and spin up, generating shear
- MHD Instabilities transport angular momentum, slowing rotation of the core
- Determines spins of compact objects



Asteroseismology to the Rescue

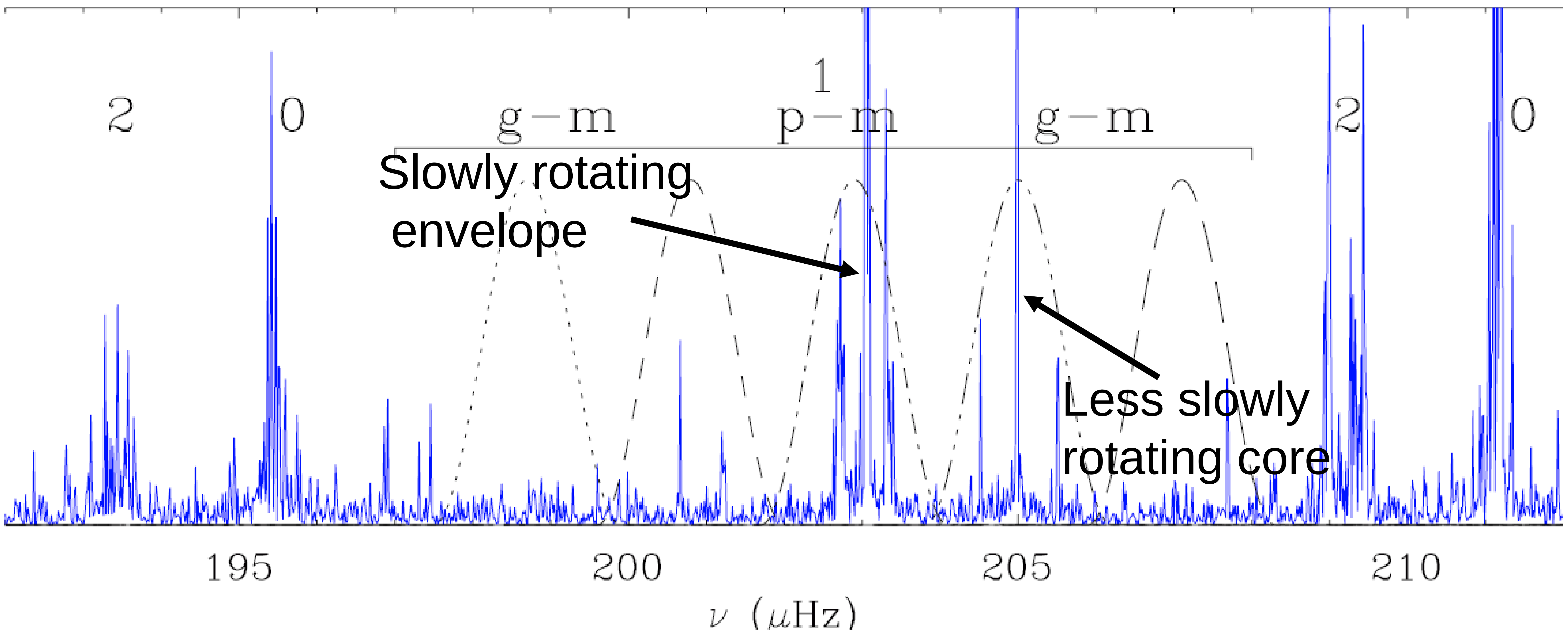
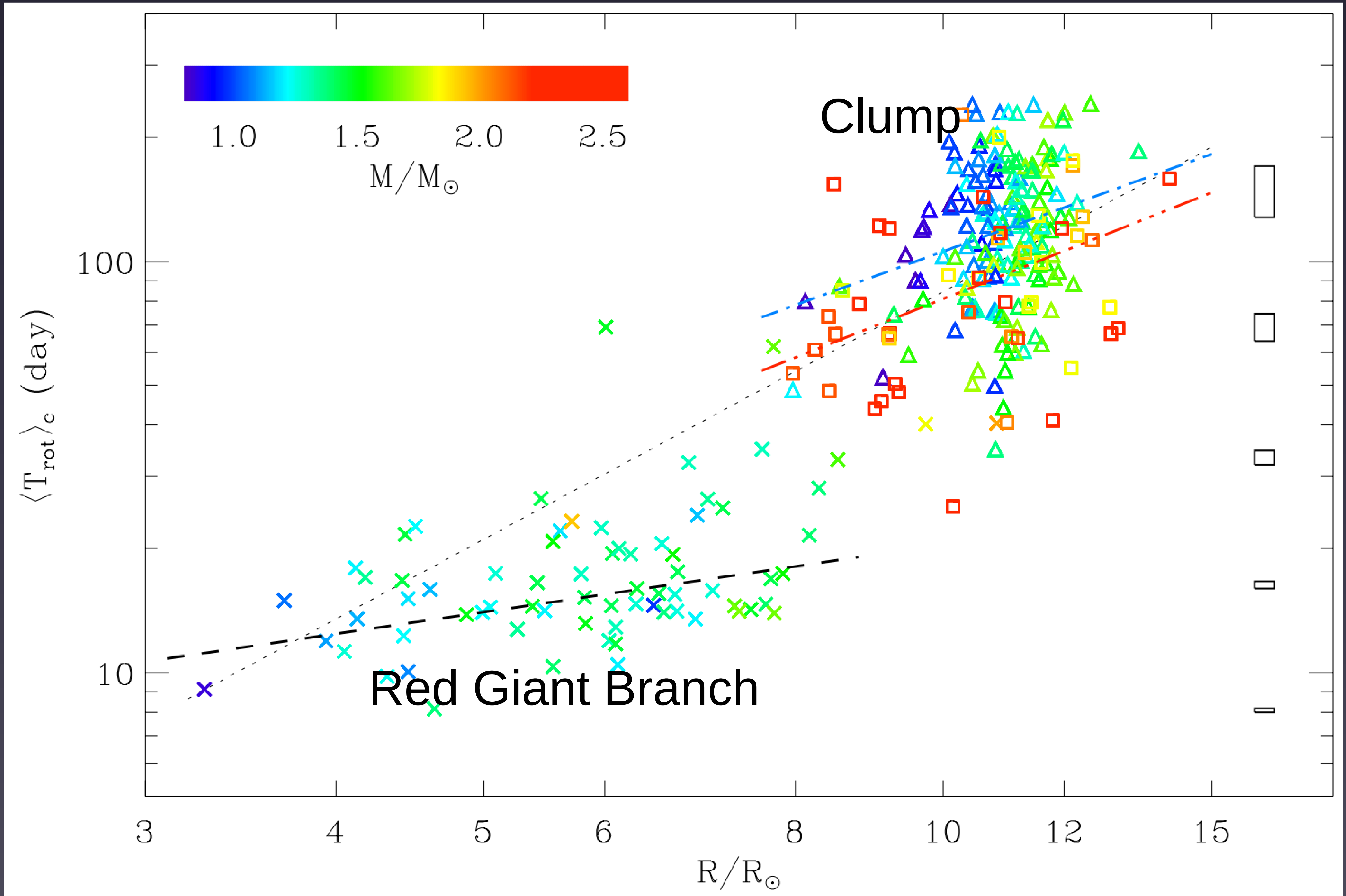


Fig. 3. Zoom on the oscillation spectrum of the target KIC 10777816. Different narrow filters centered in the $\ell = 1$ mixed mode range, indicated with different line styles, allow us to measure a local rotational splitting in each filter. For clarity, only those filters centered on possible multiplets have been represented.

Mosser et al. 2012

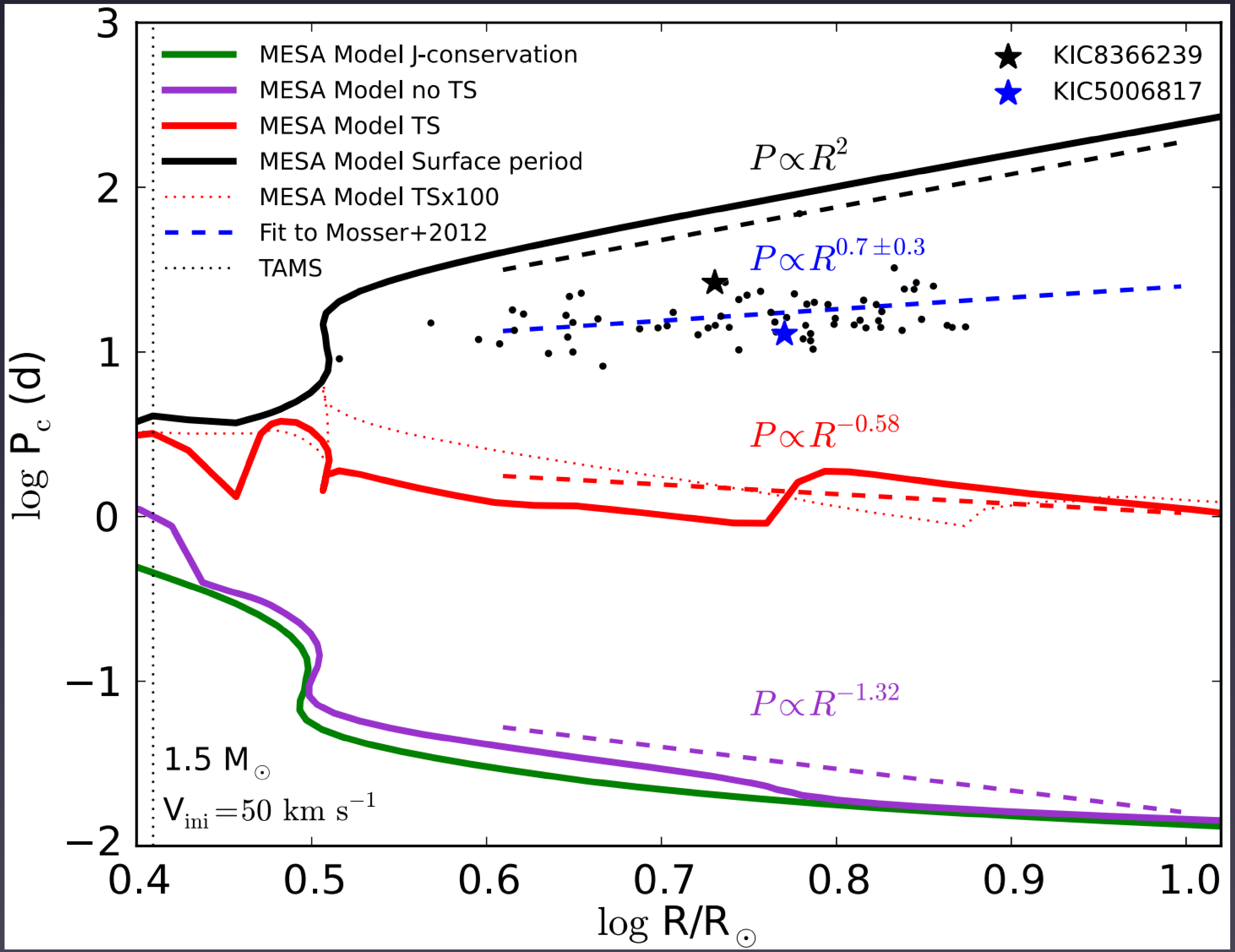
Asteroseismic Spin Rates



Mosser et al. 2012

AM transport: failure of theory

- Hydrodynamic instabilities hopeless
- MRI suppressed by stable stratification
- Tayler-Spruit dynamo provides most AM transport, but is suppressed by composition gradients



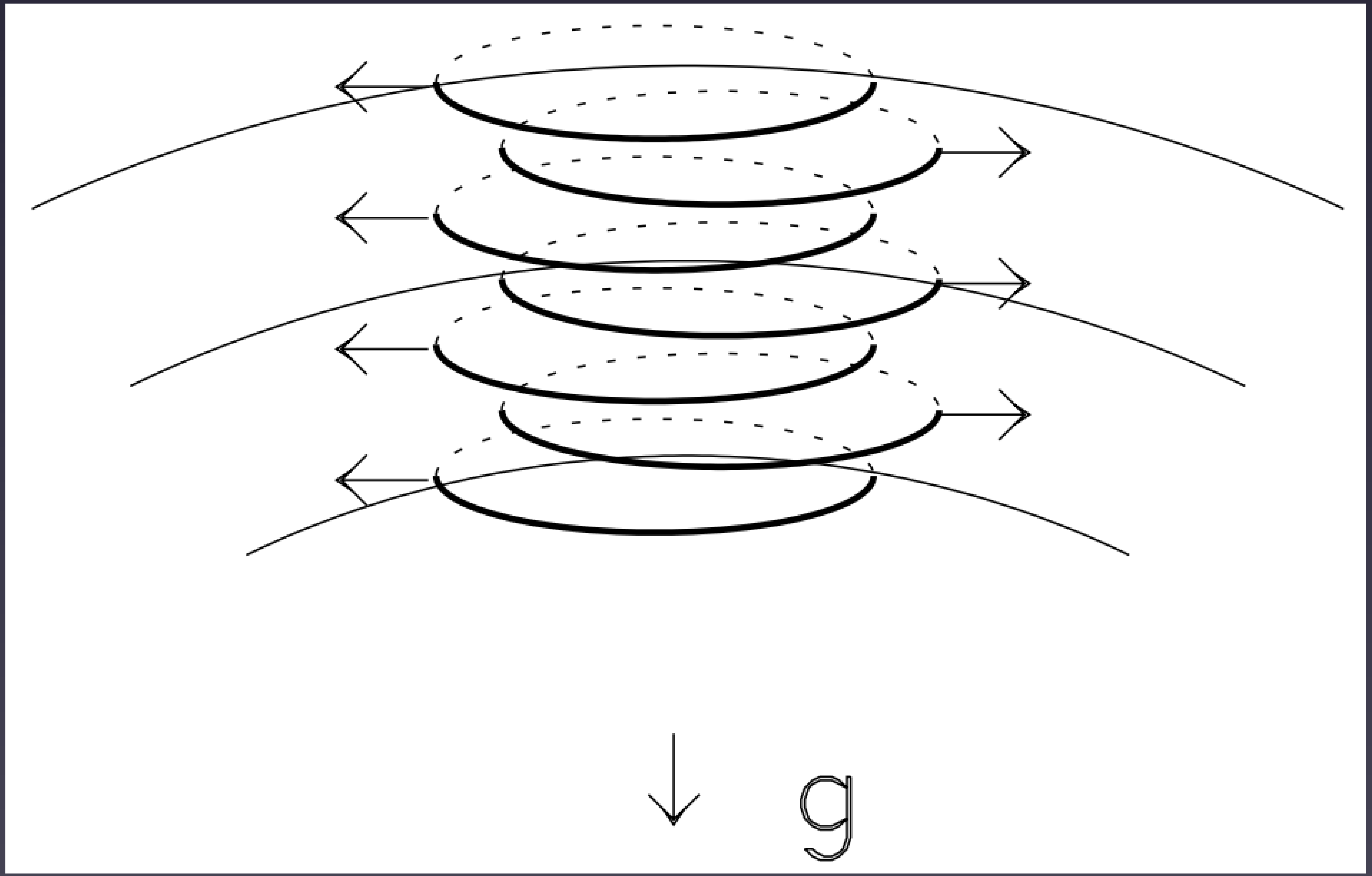
Cantiello et al. 2014

Tayler-Spruit Dynamo

- Weak radial magnetic field wound up by differential rotation
- Toroidal field unstable to Tayler instability, magnetic loops slip sideways, regenerate radial field
- According to Spruit 2002, instability creates net torque

$$S_0 \approx \frac{B_{r0} B_{\phi 0}}{4\pi} = \rho \Omega^2 r^2 q^3 \left(\frac{\Omega}{N} \right)^4$$

$$N_{\rm eff}^2 = N_\mu^2 + N_{\rm T}^2 / (1 + \tau / \tau_{\rm T})$$



Spruit 1999

How does Tayler instability saturate?

- Growth rate = Non-linear damping rate

$$\frac{\omega_{\rm A}^2}{\Omega} \sim \gamma$$

Spruit's picture

- Energy input = Energy output

$$q\Omega B_r B_\phi \sim \gamma B_\phi^2$$

- Poloidal to Toroidal field strength ratio

$$\frac{B_r}{B_\phi} \sim \frac{\omega_{\rm A}}{N_{\rm eff}}$$

How does Tayler instability saturate?

Our picture

- Growth rate = Non-linear damping rate

$$\frac{\omega_{\mathrm{A}}^2}{\Omega} \sim \frac{\delta v_{\mathrm{A}}}{r}$$

- Energy input = Energy output

$$q\Omega B_\phi B_r \sim \frac{\omega_{\mathrm{A}}^2}{\Omega} |\delta B_\perp|^2$$

- Poloidal to Toroidal field strength ratio

$$\frac{B_r}{B_\phi} \sim \frac{\omega_{\mathrm{A}}}{N_{\mathrm{eff}}}$$

TS++ Dynamo

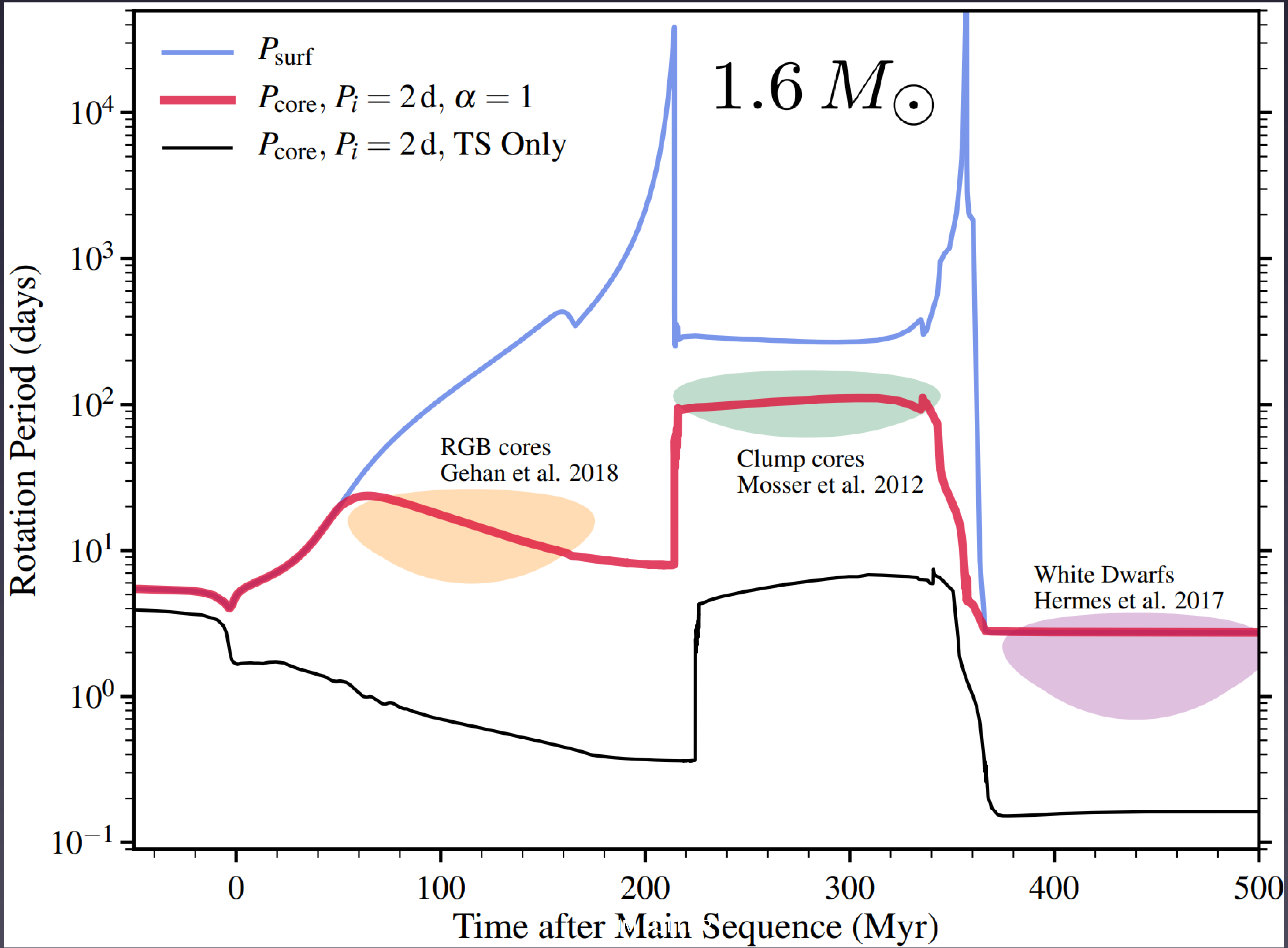
- Combination of radial/azimuthal field creates a Maxwell stress

$$T = B_r B_\phi \sim 4\pi q \rho r^2 \Omega^2 \left(\frac{\Omega}{N_{\rm eff}} \right)^2$$

- With corresponding AM diffusivity

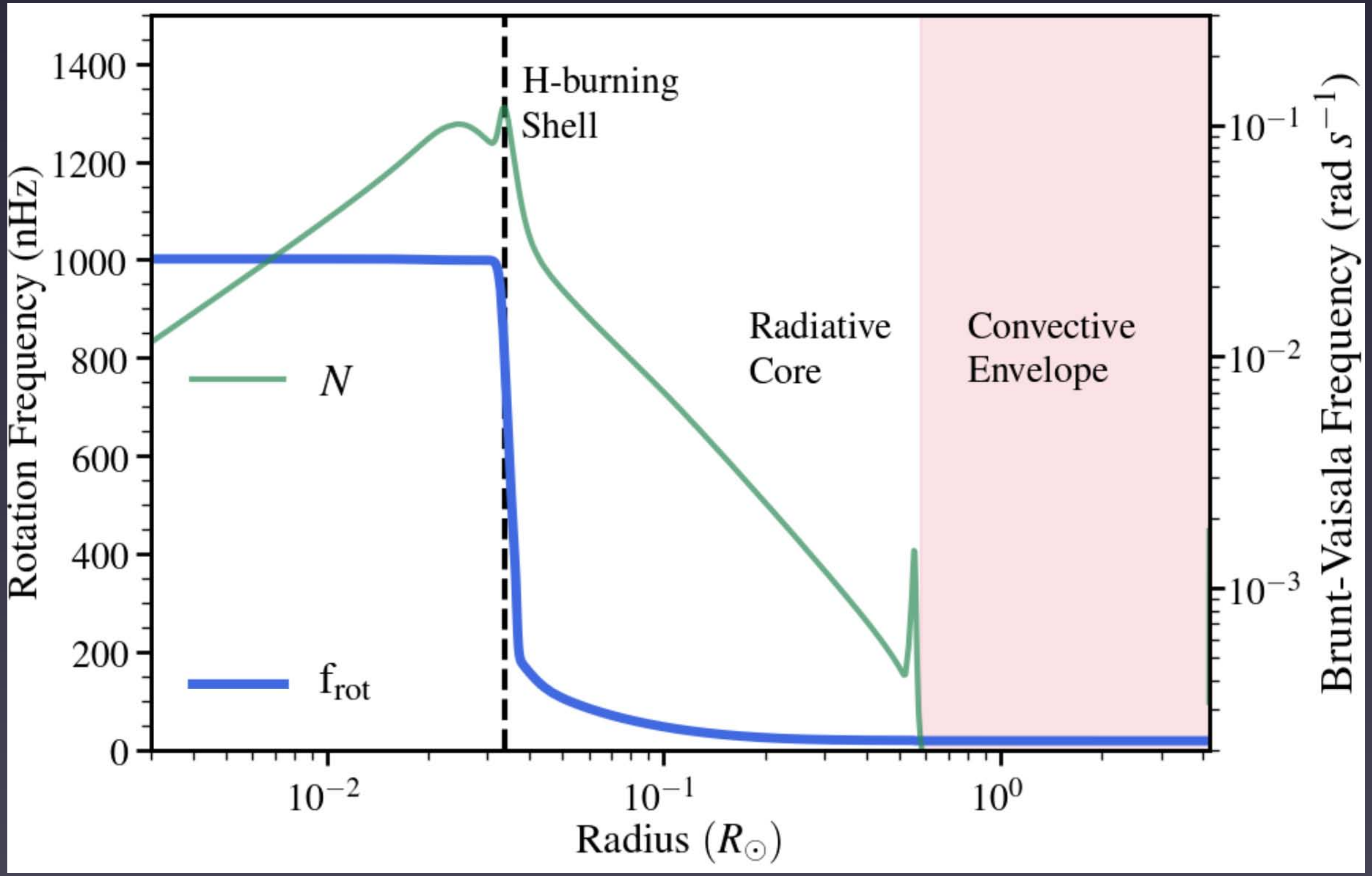
$$\nu_{\rm AM} = \frac{T}{4\pi \rho q \Omega} \sim r^2 \Omega \left(\frac{\Omega}{N_{\rm eff}} \right)^2$$

Rotational Evolution

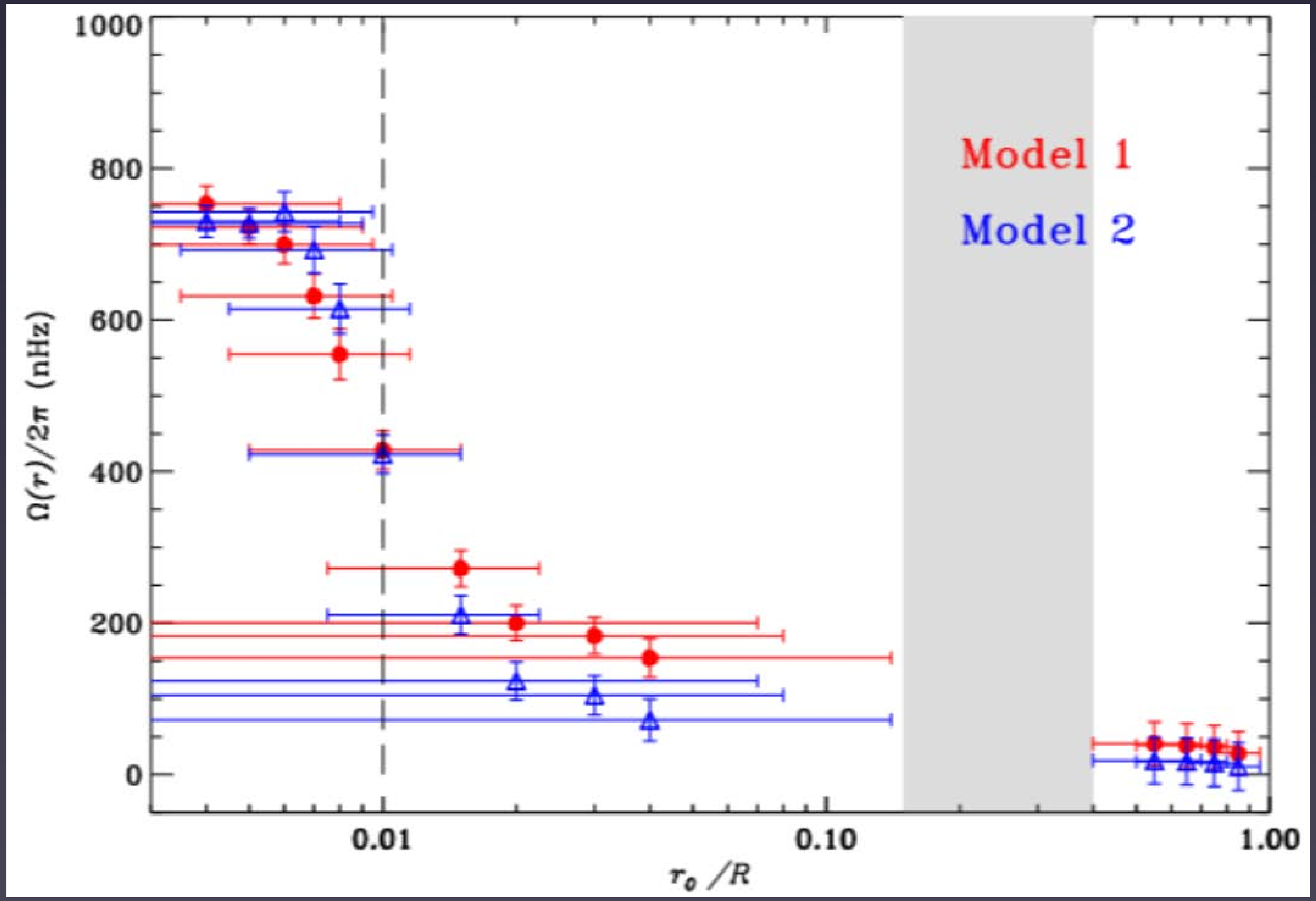


Fuller+ 2019

Rotation Profile



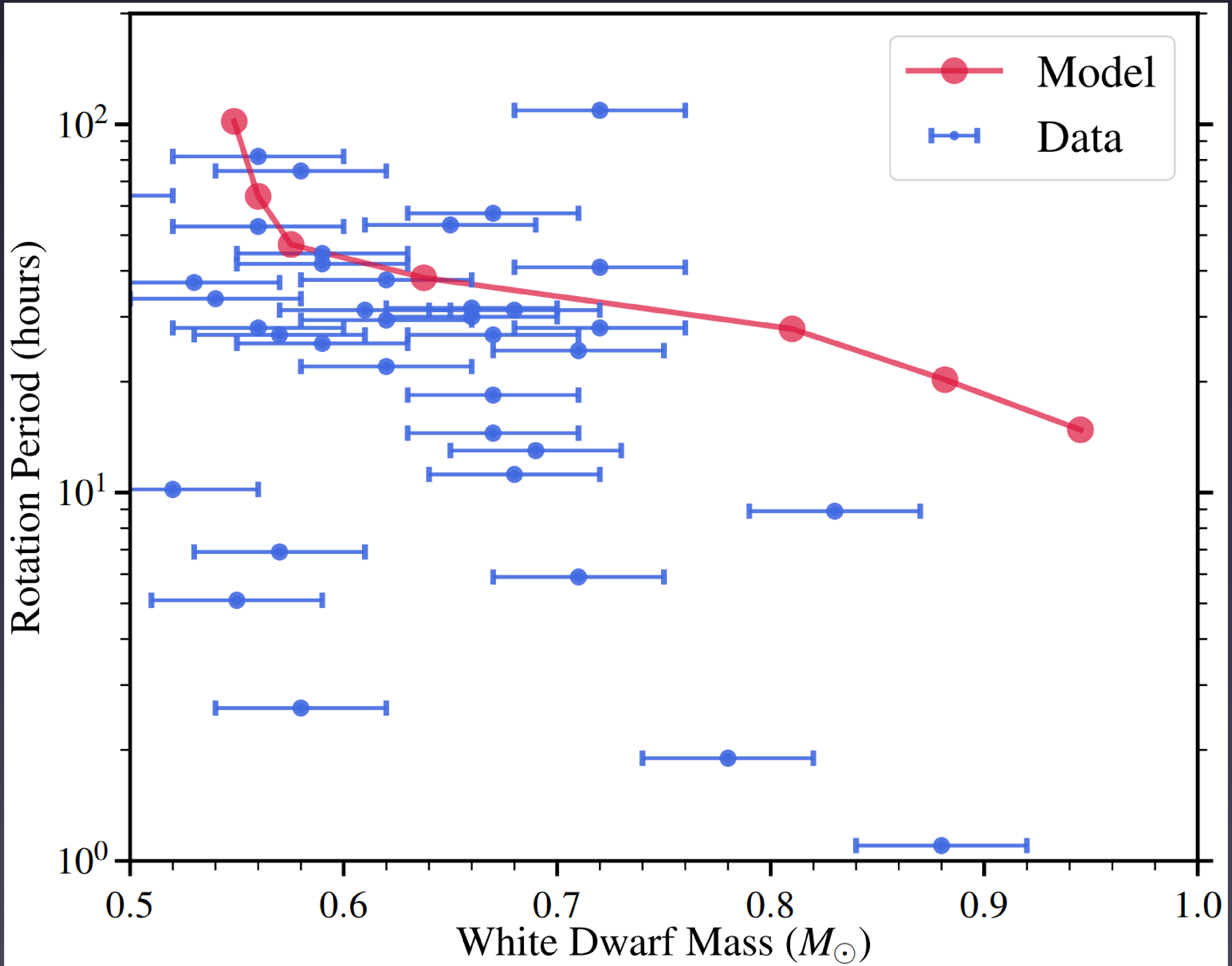
Fuller+ 2019



Di Mauro et al. 2017

White Dwarfs

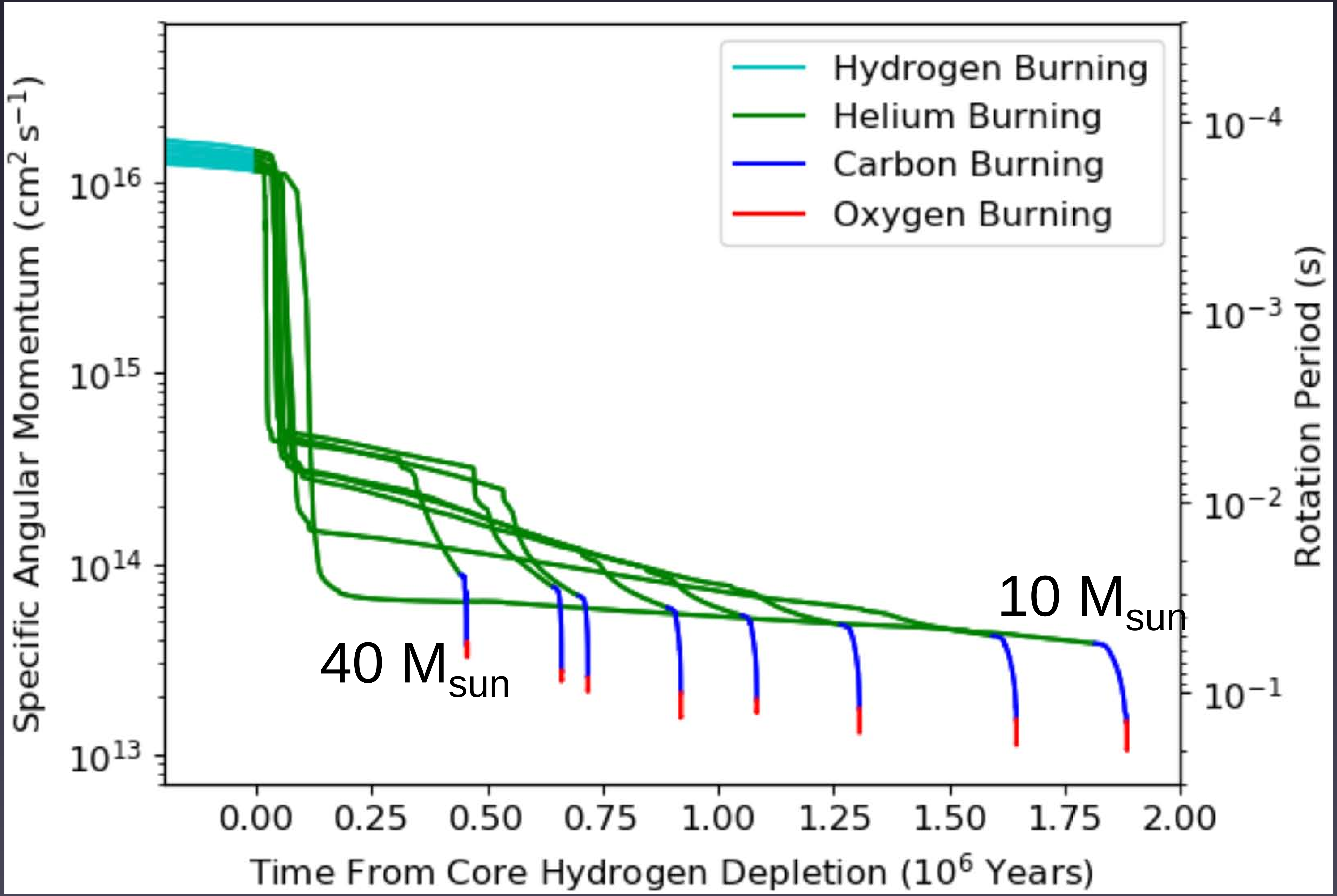
- WD rotation rates previously unexplained
- Massive WDs appear to rotate faster



Fuller+ 2019

Massive Stars

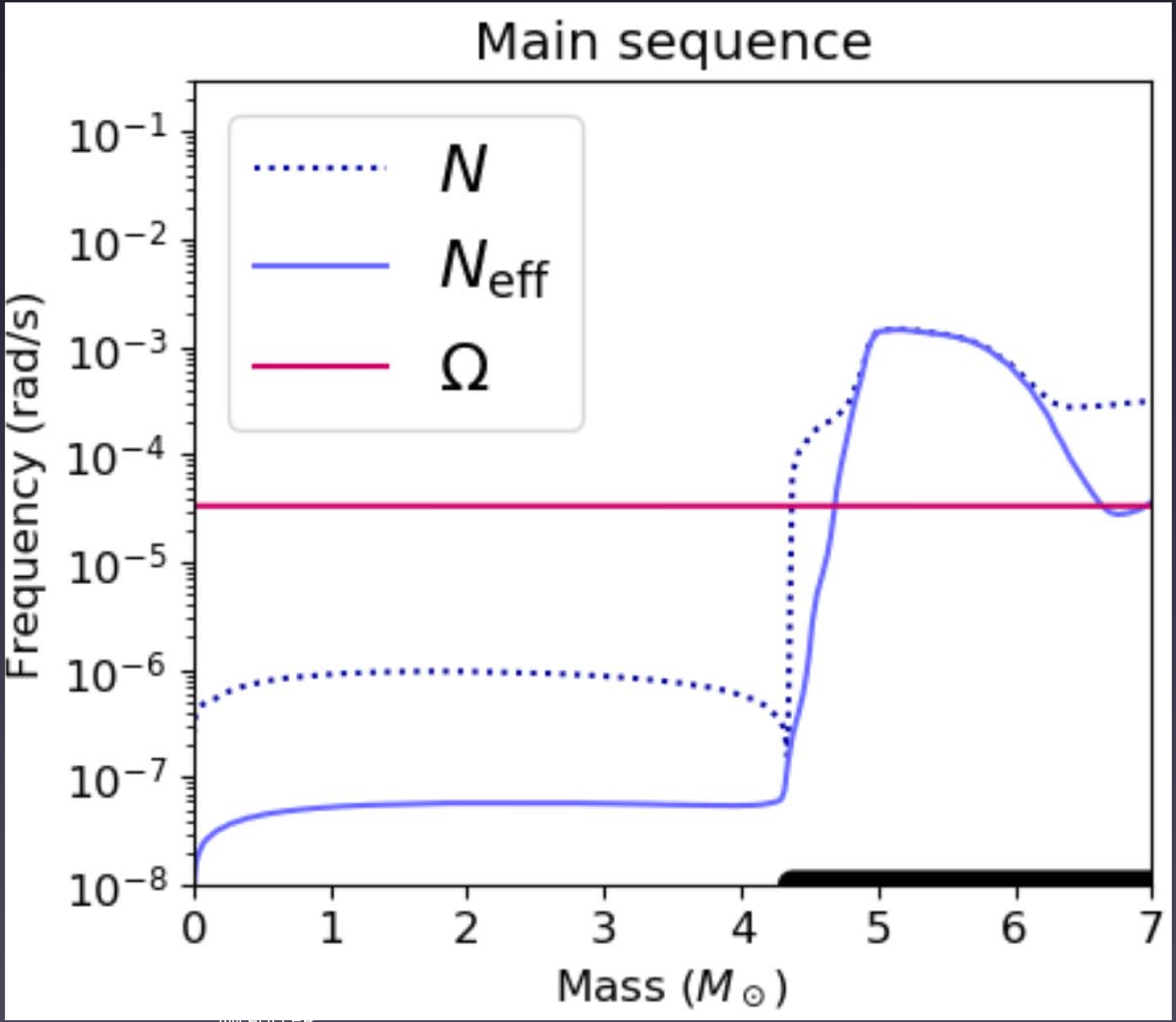
- AM of inner core lost upon He core contraction after main sequence



Ma & Fuller, in prep

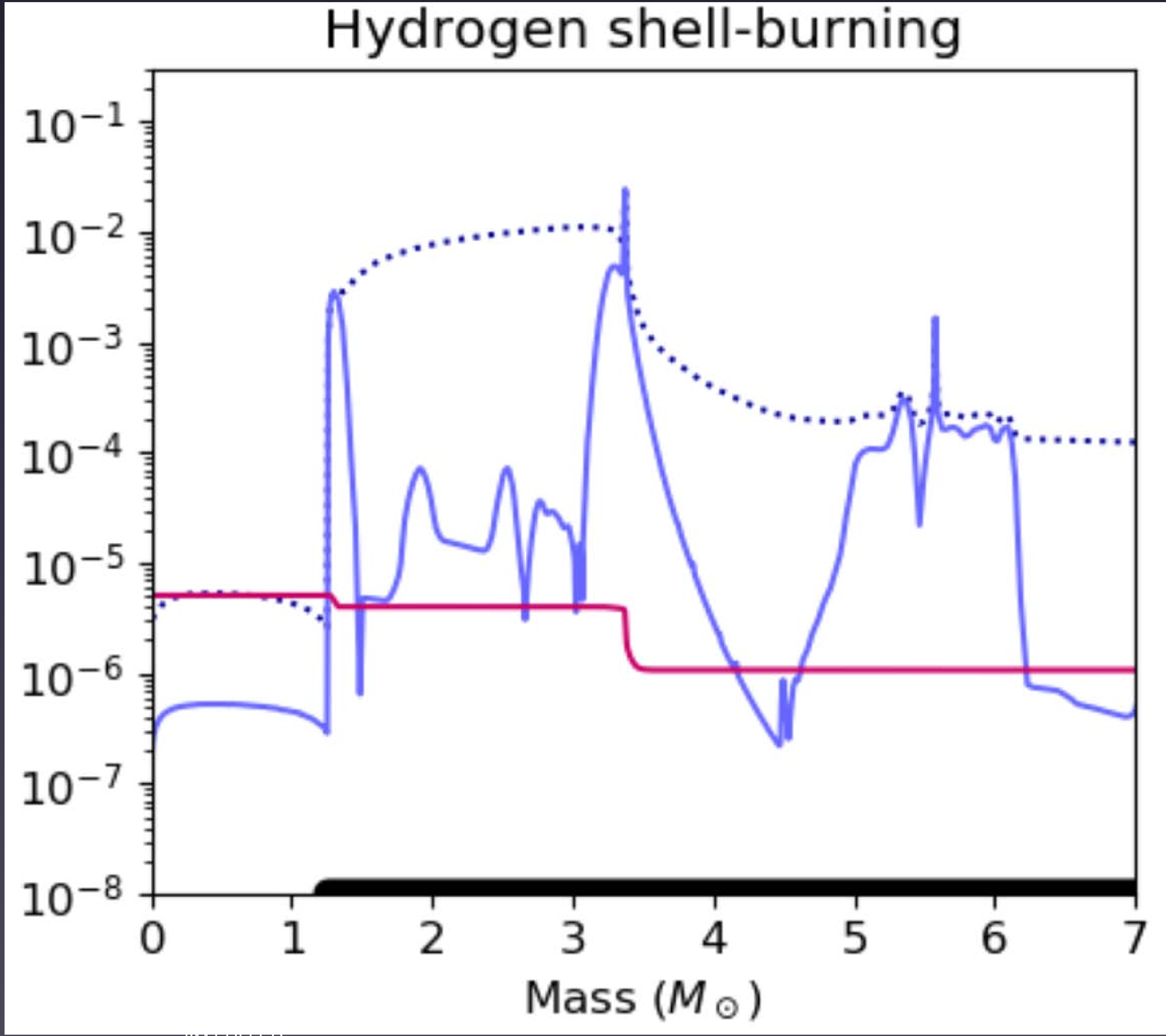
Angular Momentum Extraction

- Core/envelope tightly coupled on main sequence



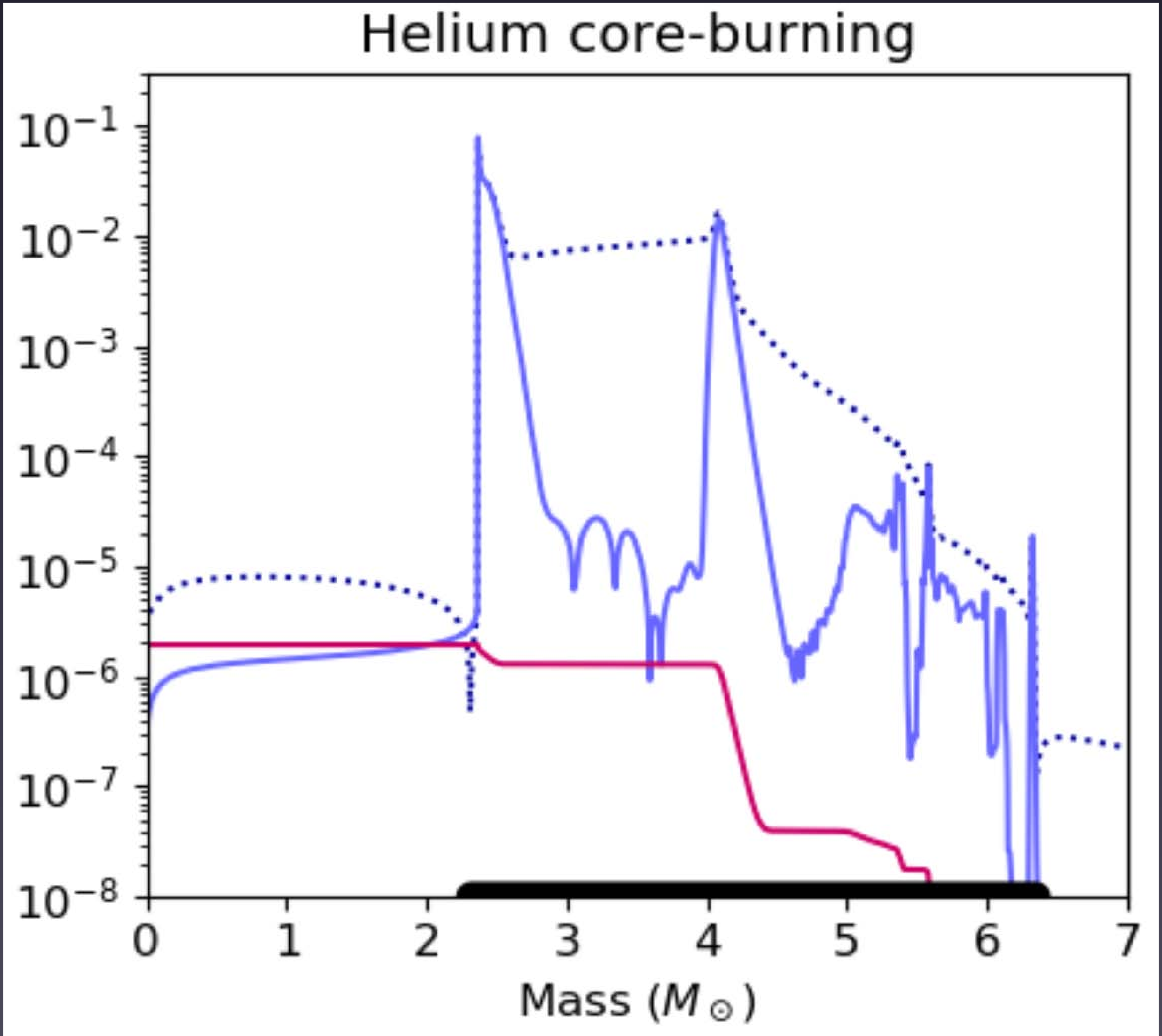
Angular Momentum Extraction

- AM extracted from contracting core after main sequence

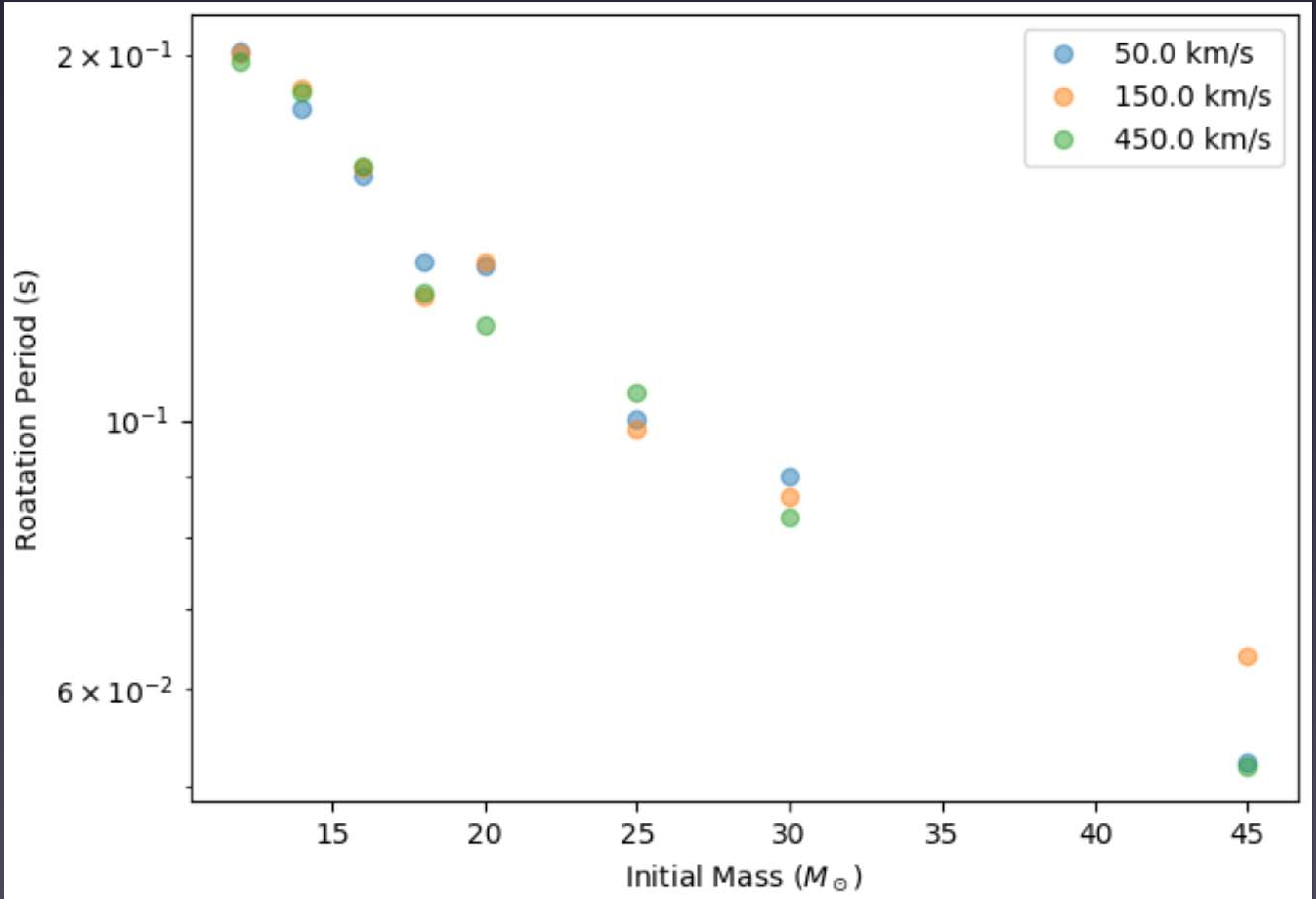


Angular Momentum Extraction

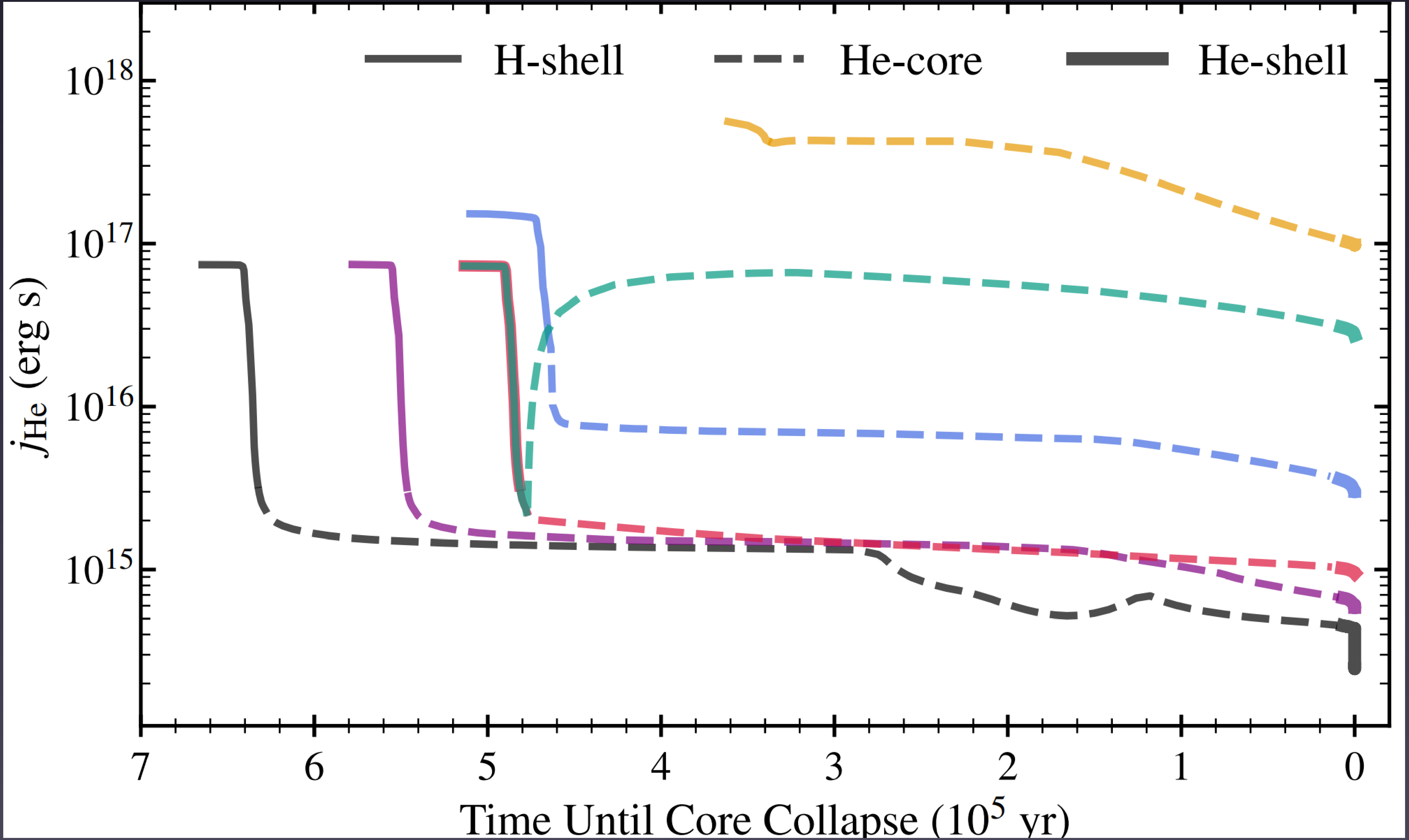
- H-burning shell prevents perfect coupling during He-burning and beyond



Neutron Stars Slowly Rotating

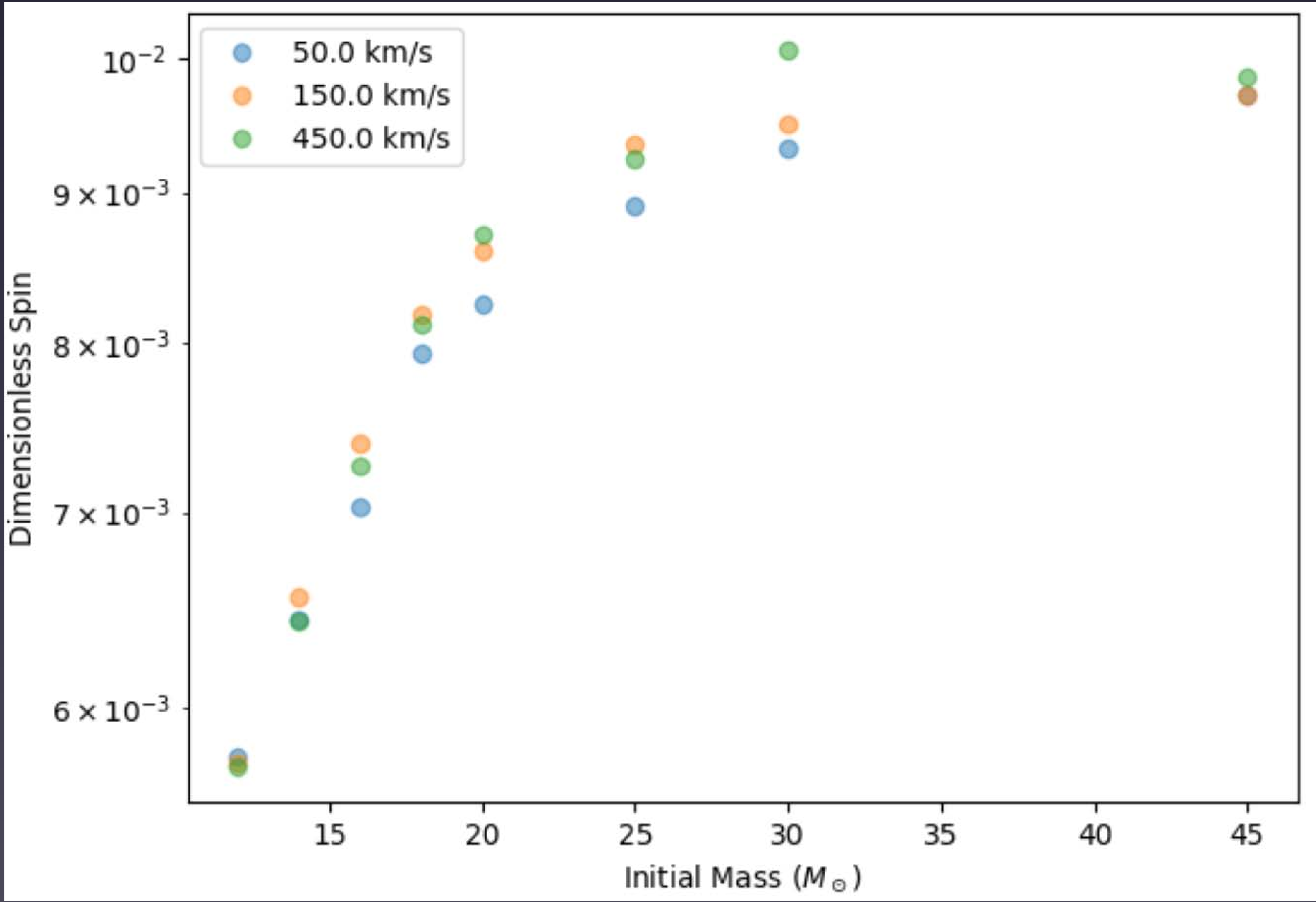


Ma & Fuller, In prep



Fuller & Ma, in prep

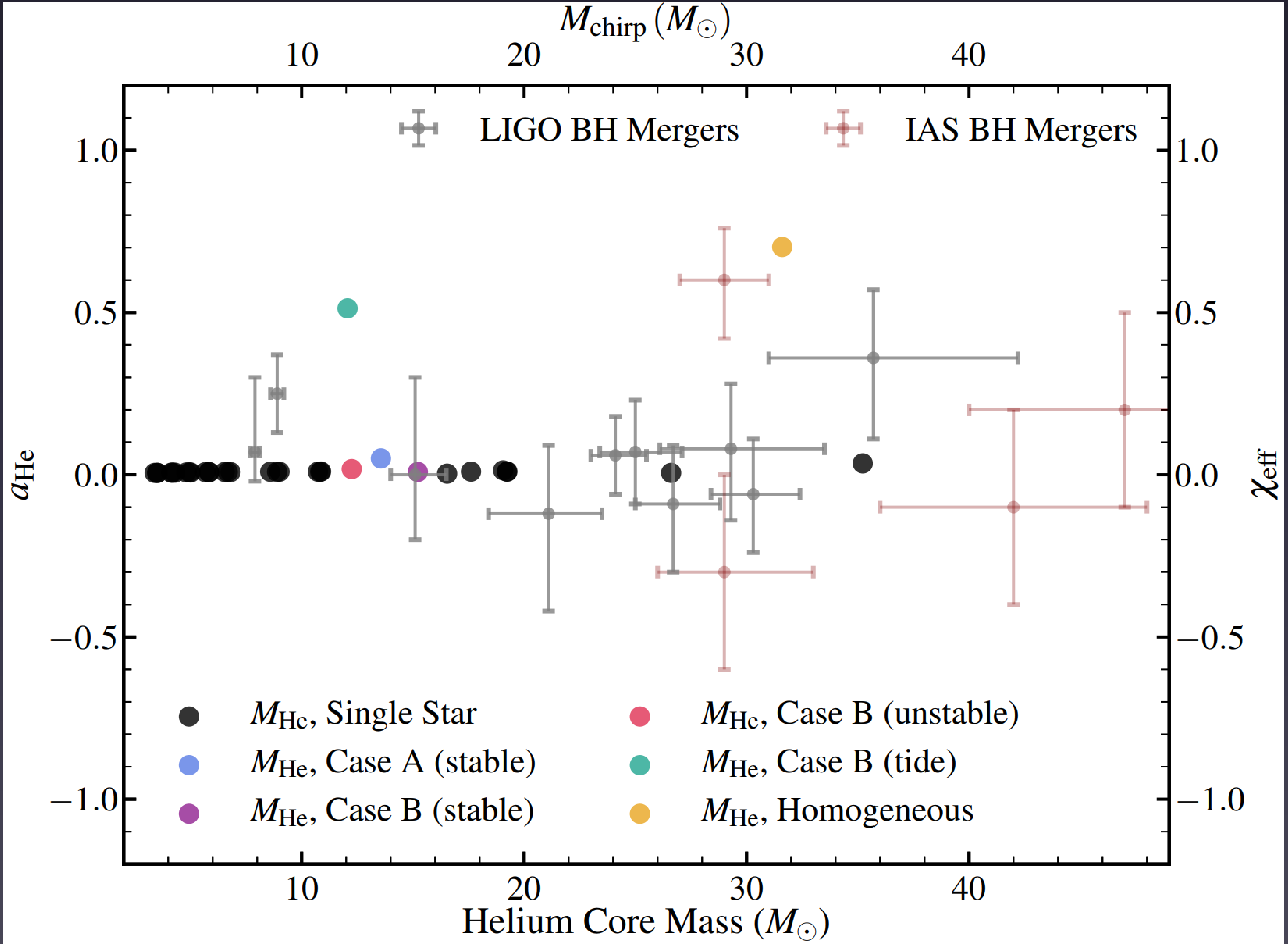
Black Holes Slowly Rotating



Ma & Fuller,
In prep

Compact Objects

- Black holes detected by LIGO appear to rotate slowly
- Binary scenarios with tidal spin-up can produce rapidly rotating BHs



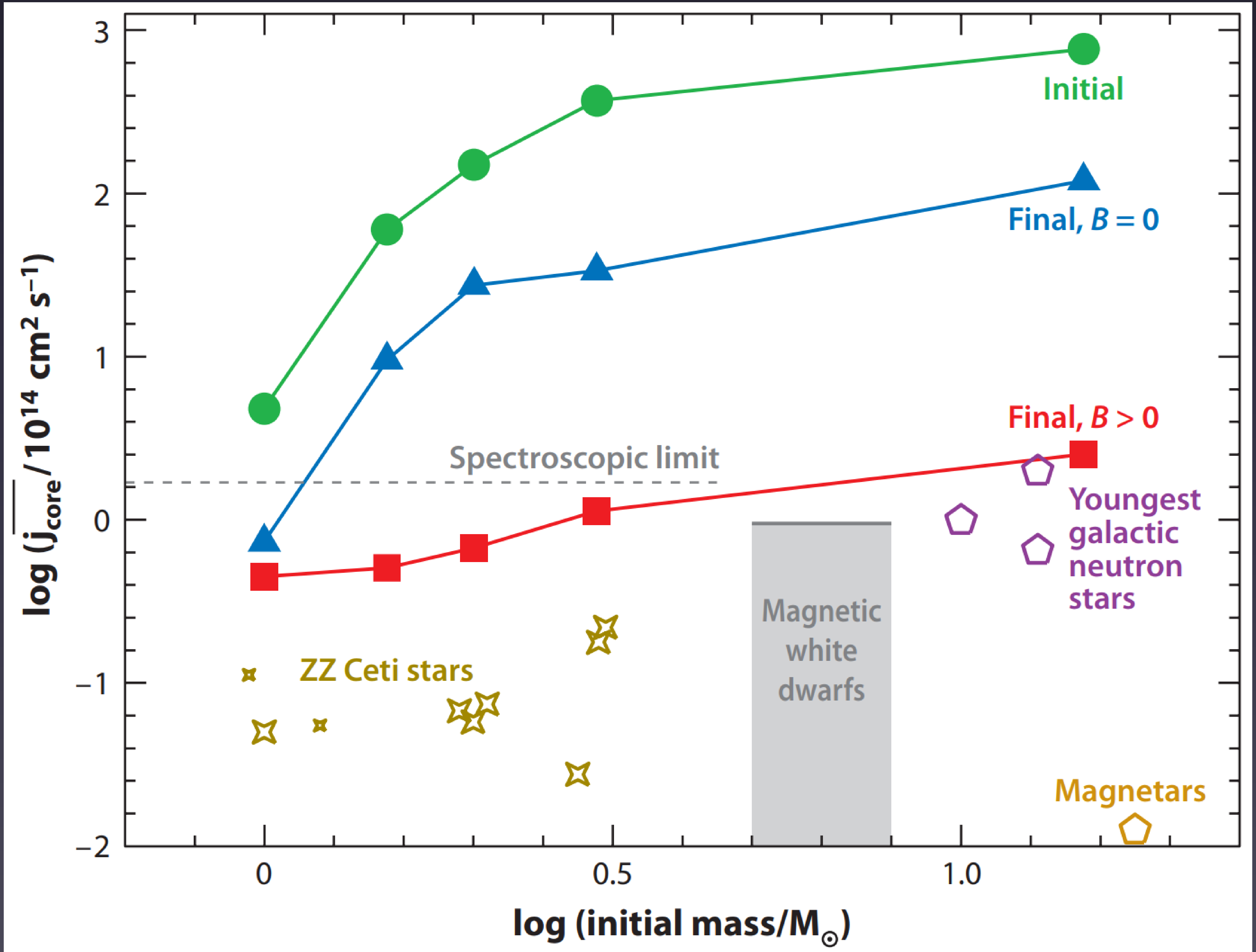
Fuller & Ma, in prep

Postdictions

- White dwarfs rotate extremely slowly ($\sim 10^{-4}$ breakup)
- Black holes and neutron stars rotate very slowly ($\sim 10^{-2}$ breakup)
- Rapidly rotating magnetars and black holes mostly originate from tidally spun up binaries

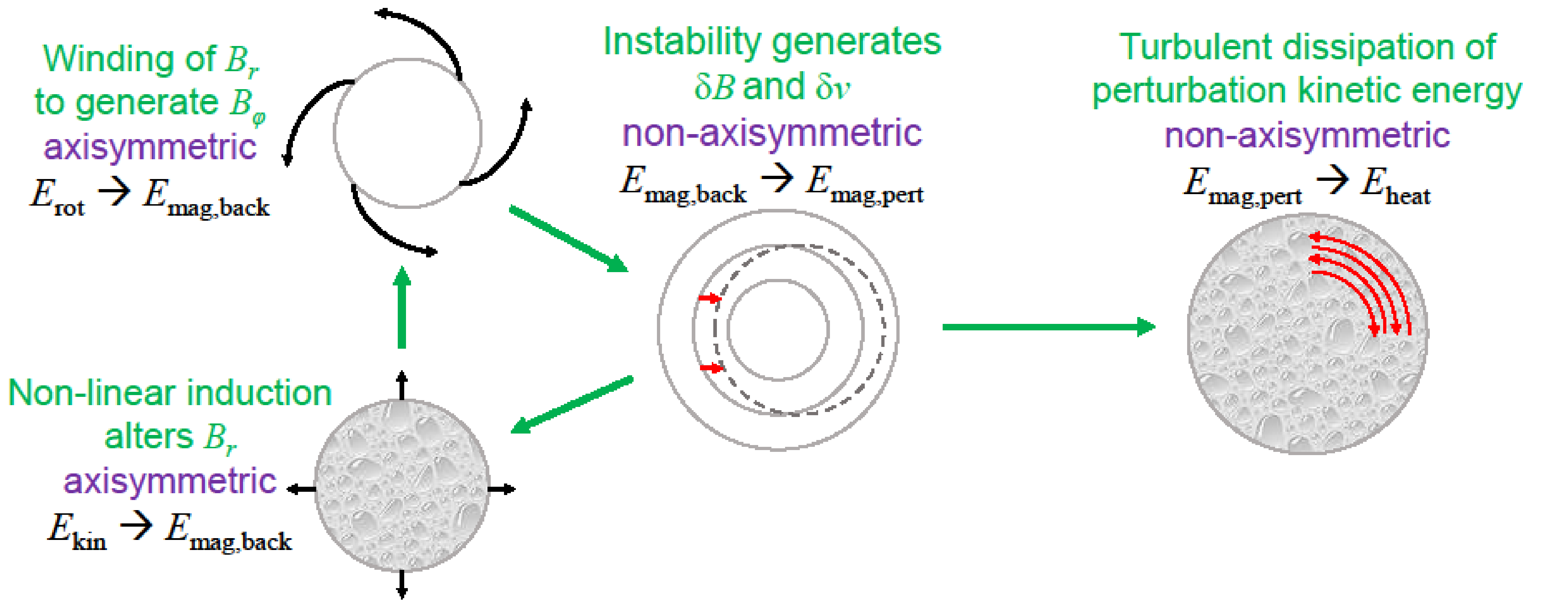
How do we make rapidly rotating central engines?

- Tidal torques in helium star progenitors in compact binaries
  - Might only spin up iron core if M_{He} > 20 Msun
- Tidal torques in ultracompact ultrastripped binaries?
- Collapse of blue supergiant?
- Homogeneous evolution?

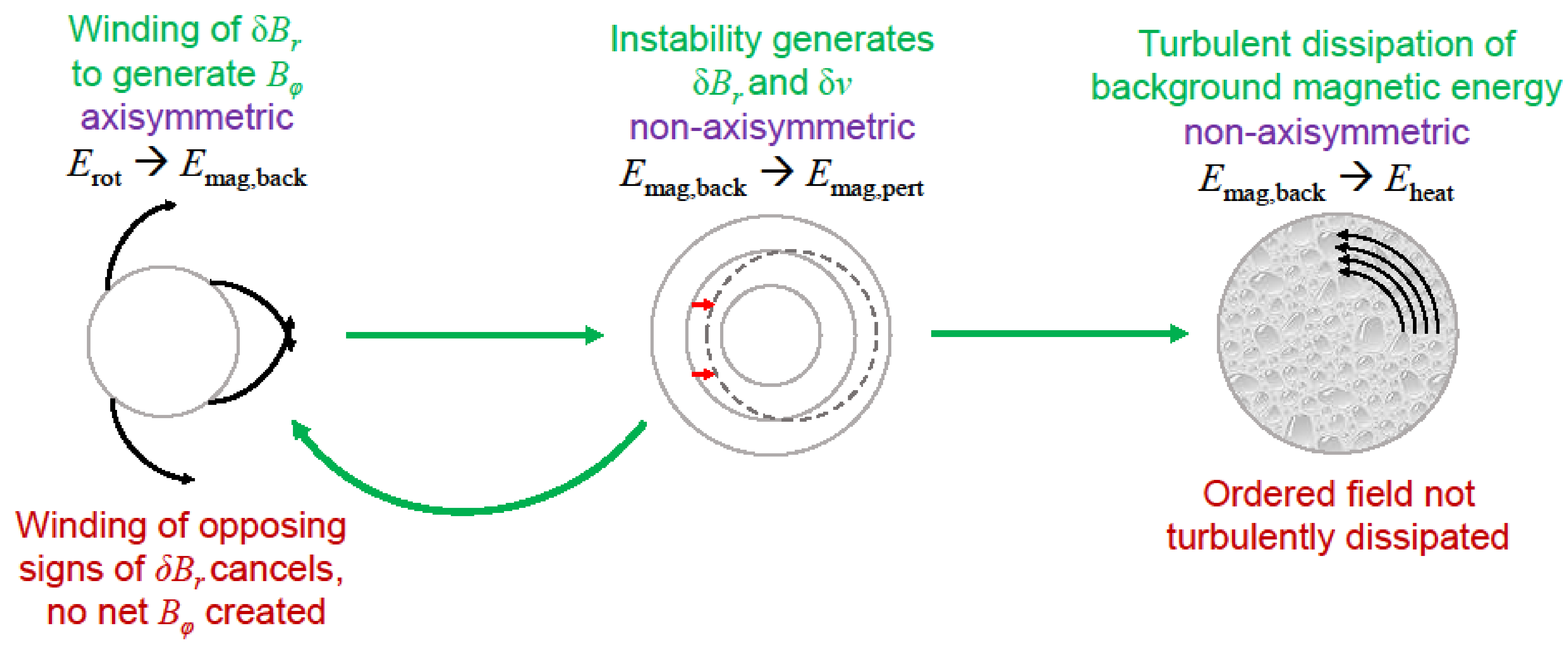


Initial
Final, B = 0
Final, B > 0
Spectroscopic limit
Youngest galactic neutron stars
Magnetic white dwarfs
ZZ Ceti stars
Magnetars
log (j_core/10^14 cm^2 s^−1)
log (initial mass/M_⊙)
3
2
1
0
−1
−2
0
0.5
1.0

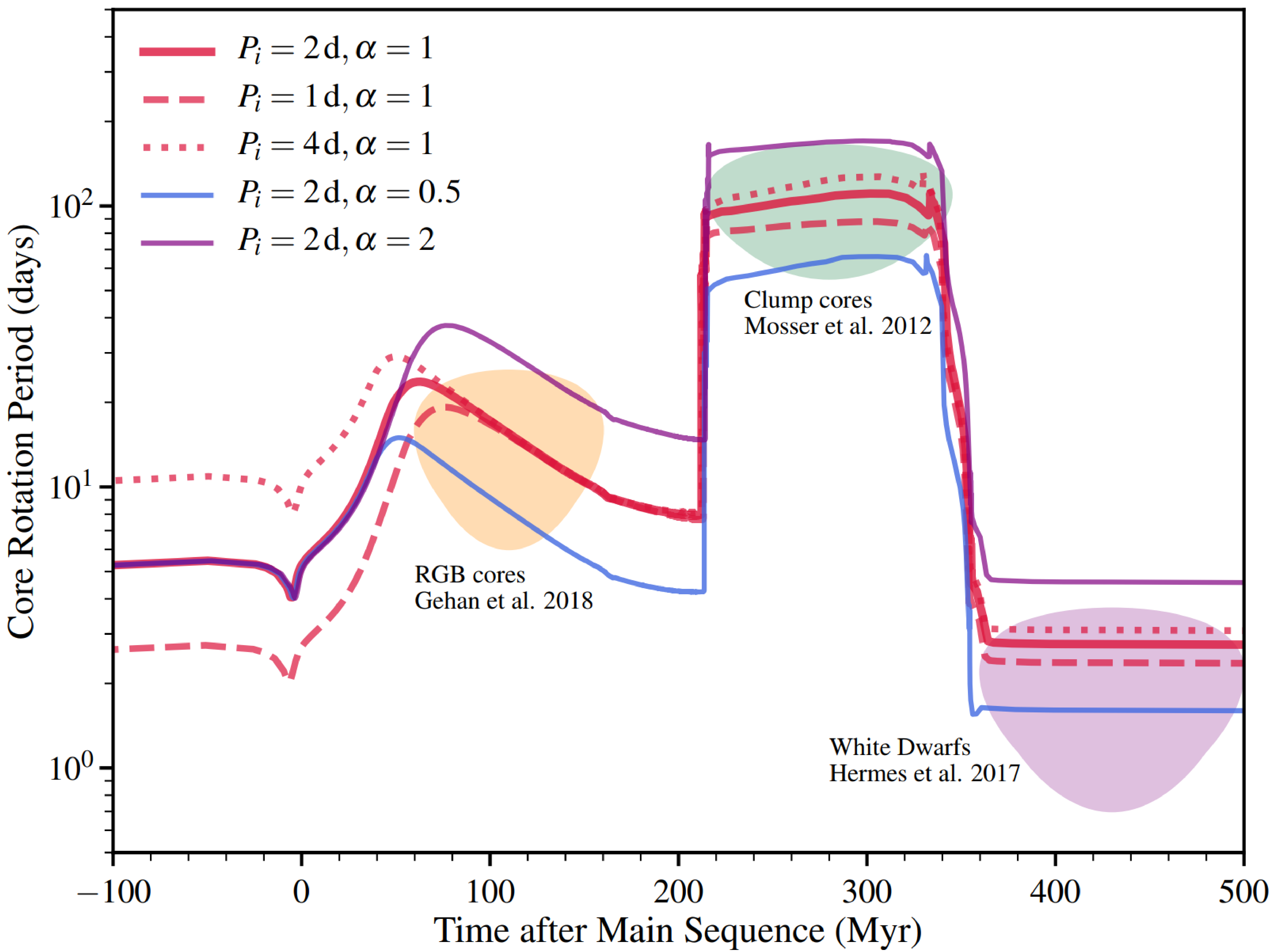
Our Picture

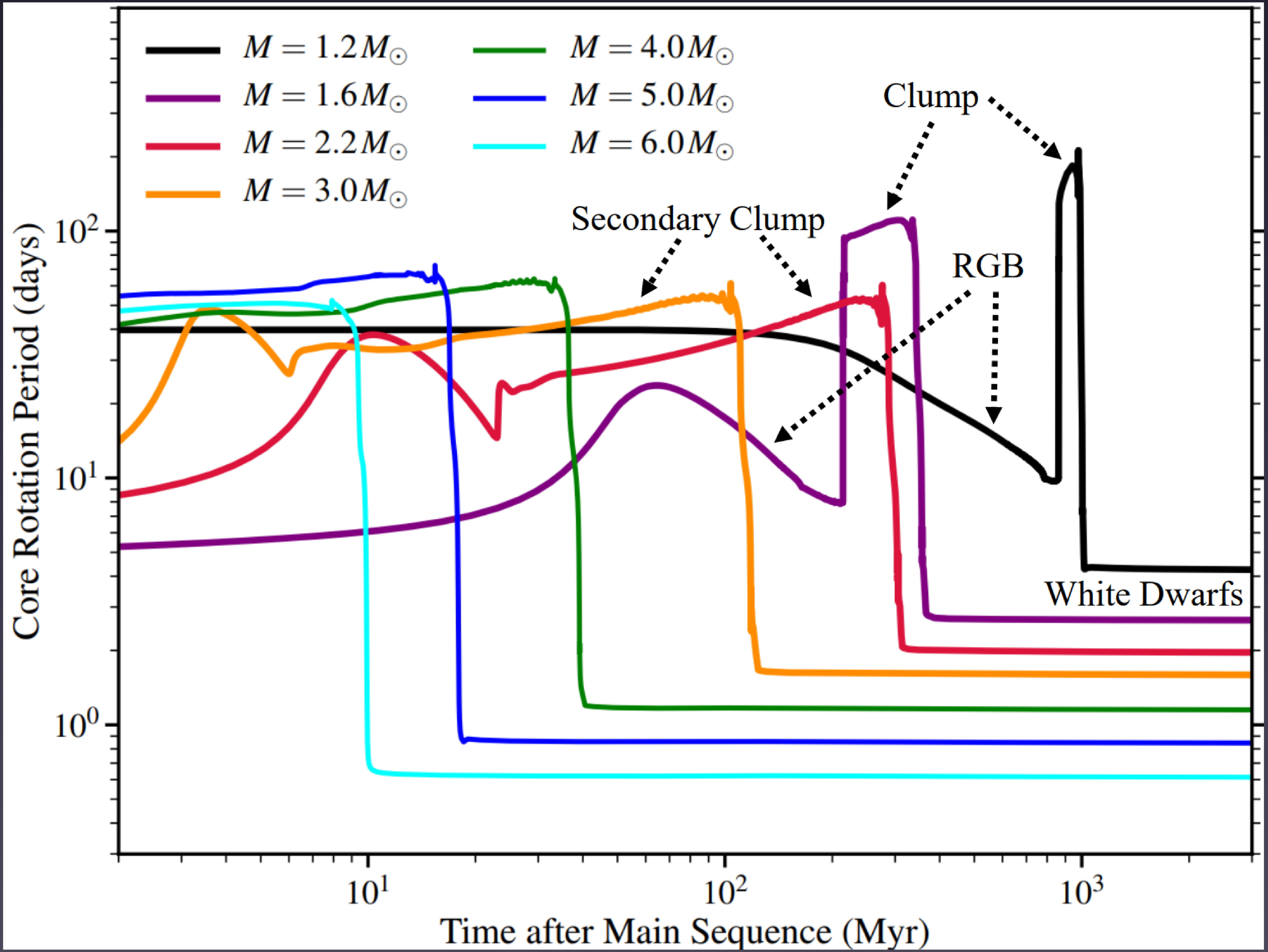


Spruit's Picture

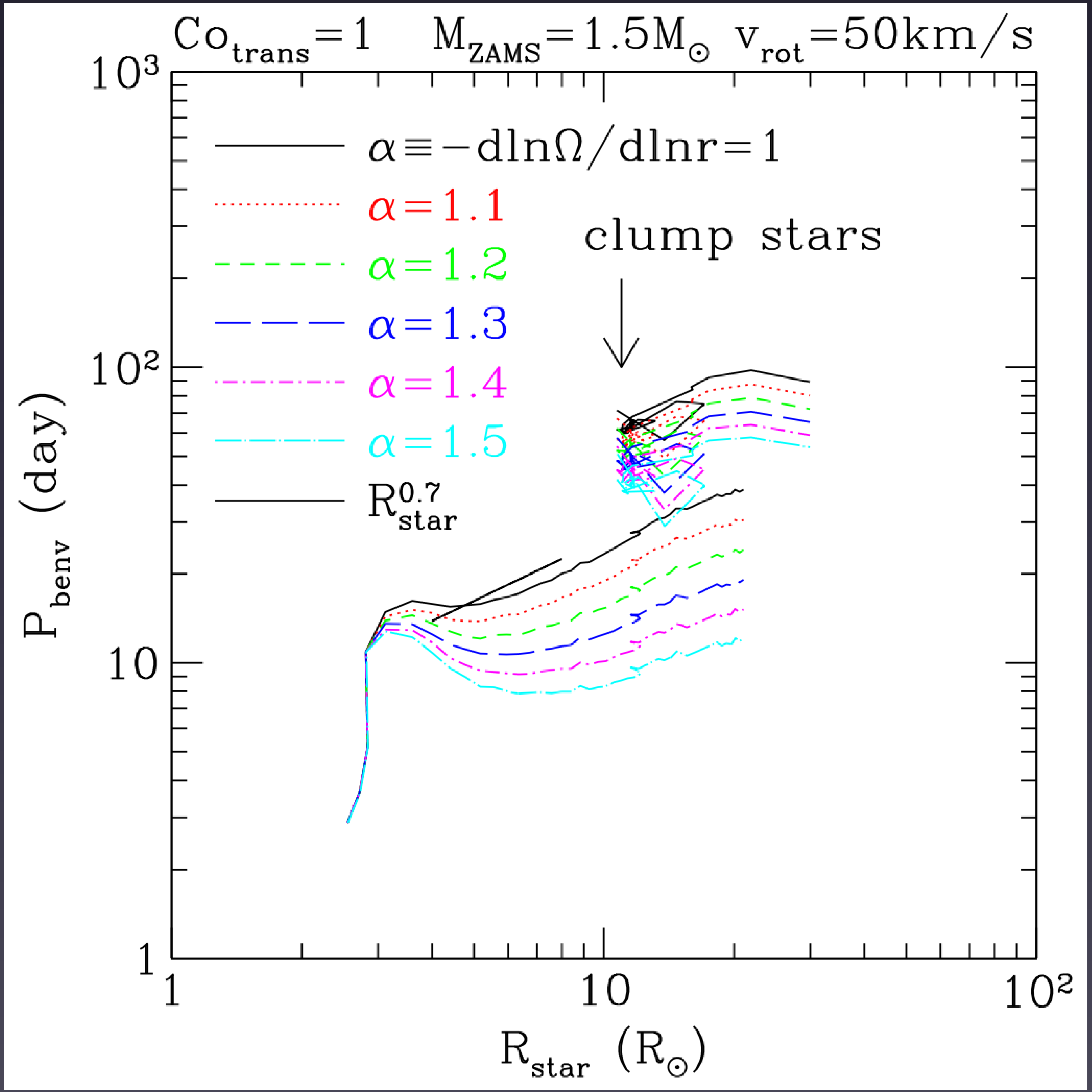


- Relatively insensitive to initial conditions
- Slight dependence on parameter α

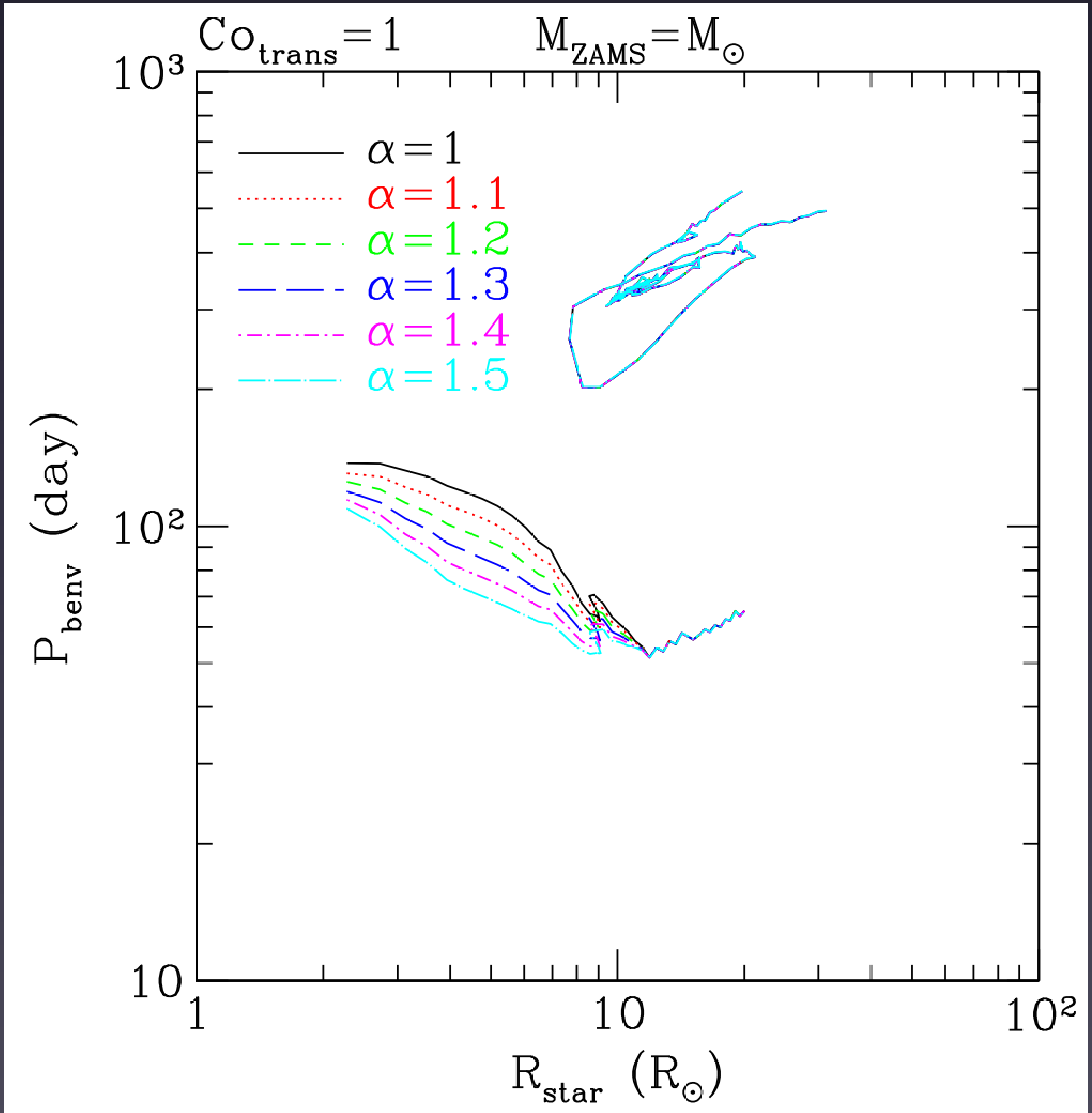




$M = 1.2 M_\odot$
$M = 1.6 M_\odot$
$M = 2.2 M_\odot$
$M = 3.0 M_\odot$
$M = 4.0 M_\odot$
$M = 5.0 M_\odot$
$M = 6.0 M_\odot$
Clump
Secondary Clump
RGB
White Dwarfs
Core Rotation Period (days)
10^2
10^1
10^0
10^1
10^2
10^3
Time after Main Sequence (Myr)



Kissin & Thompson 2015



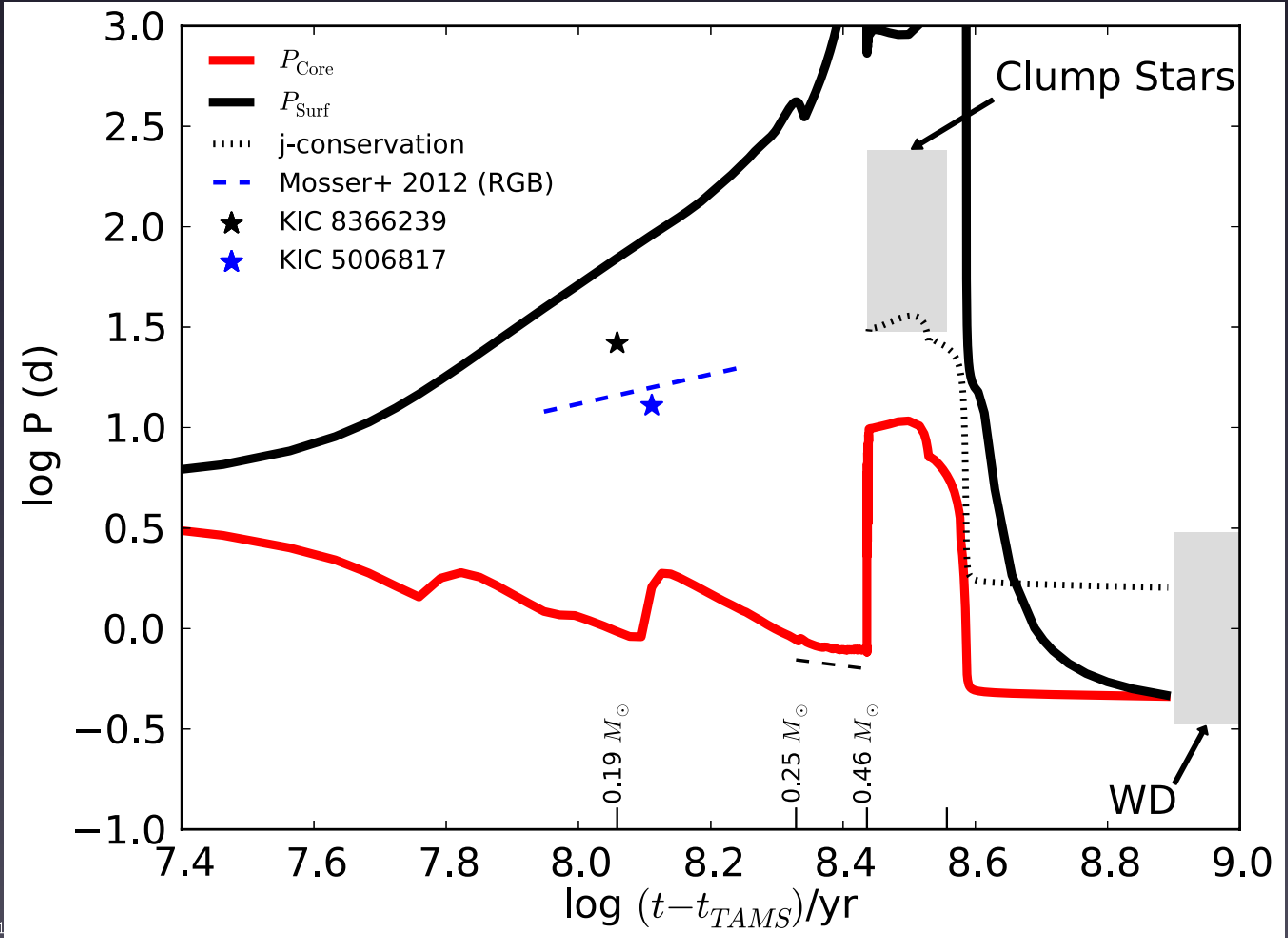
Kissin & Thompson 2015

TABLE 3

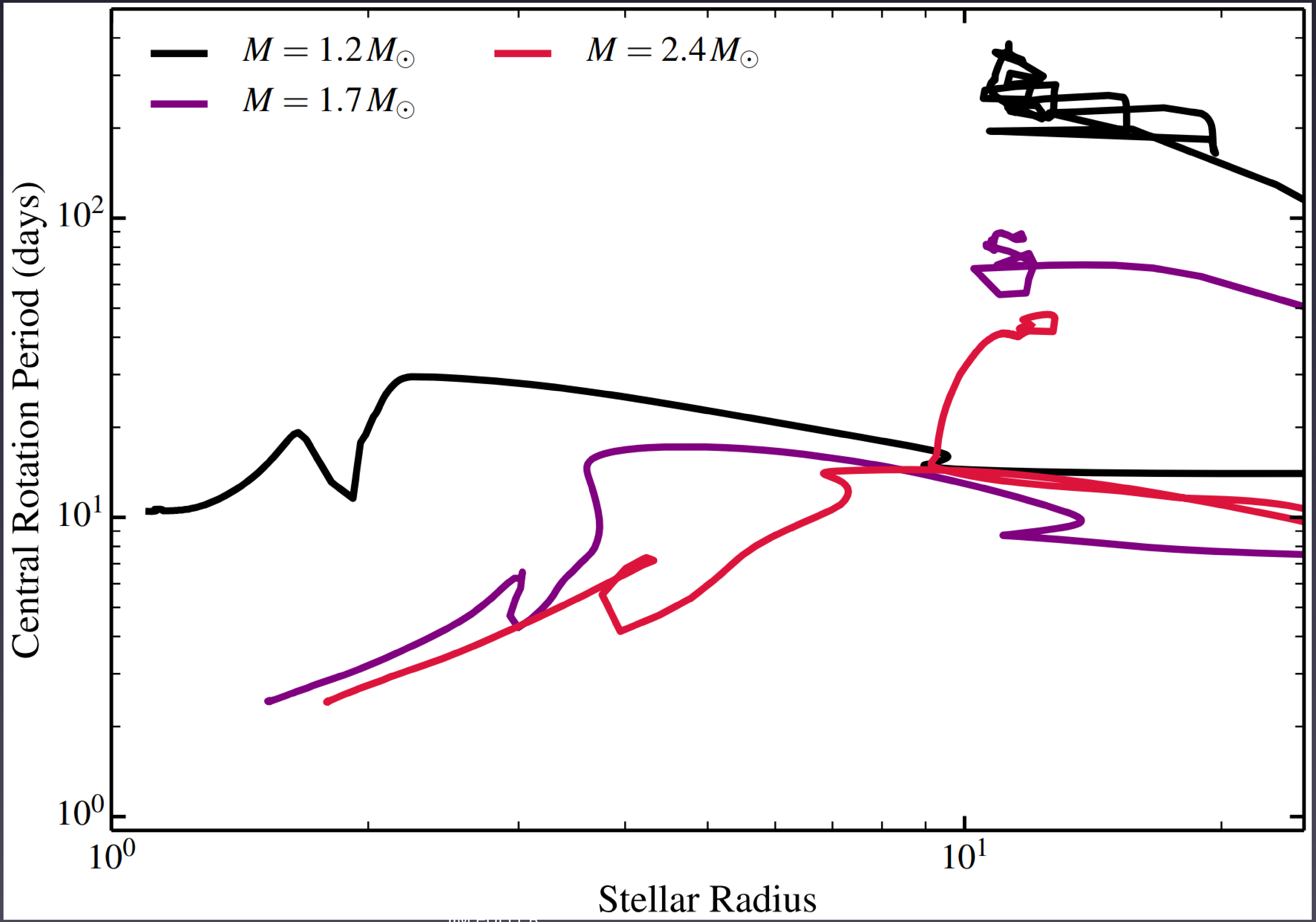
PULSAR ROTATION RATE DEPENDENCE ON DYNAMO MODEL PARAMETERS[a]

Initial Mass ($M_\odot$)	Std.	N_μ^2 0.1	N_μ^2 10	N_T^2 0.1	N_T^2 10	$B_\phi B_r$ 0.1	$B_\phi B_r$ 10	Ω_{ZAMS} 0.5	Ω_{ZAMS} 1.5	$B = 0$
	Period (ms)									
12	9.9	...	...	...	...	...	...	...	...	...
15	11	24	4.4	12	10	5.7	21	9.8	10	0.20
20	6.9	14	3.2	8.4	6.4	3.3	11	7.2	6.5[b]	0.21
25	6.8	13	3.1	7.3	4.9	2.6	13	7.1	4.3[b]	0.22
35	4.4[b]	...	...	...	...	...	...	...	...	...

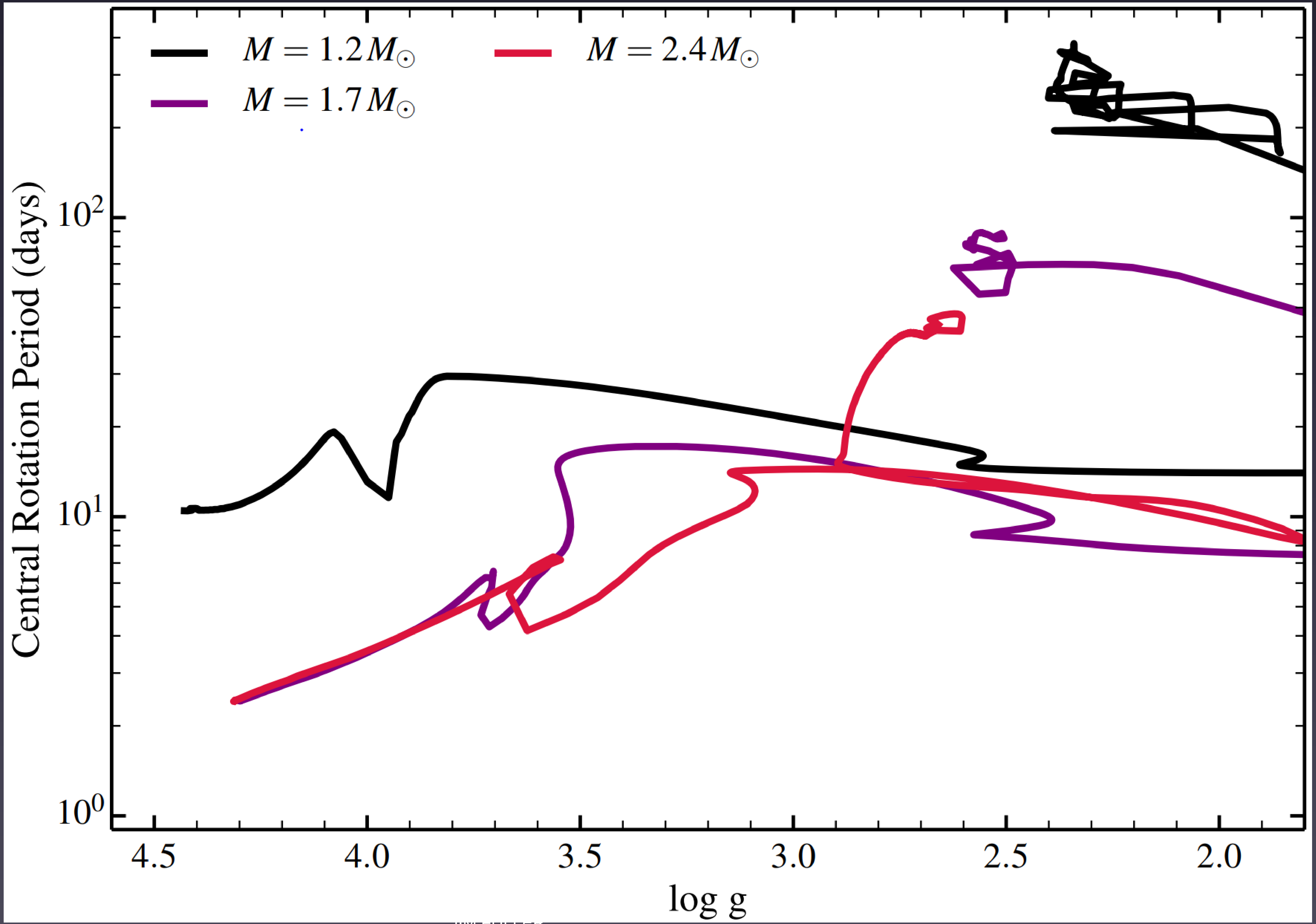
[a] All numbers here can be multiplied by 1.2–1.3 to account for the angular momentum carried away by neutrinos.
[b] Became a Wolf-Rayet star during helium burning.

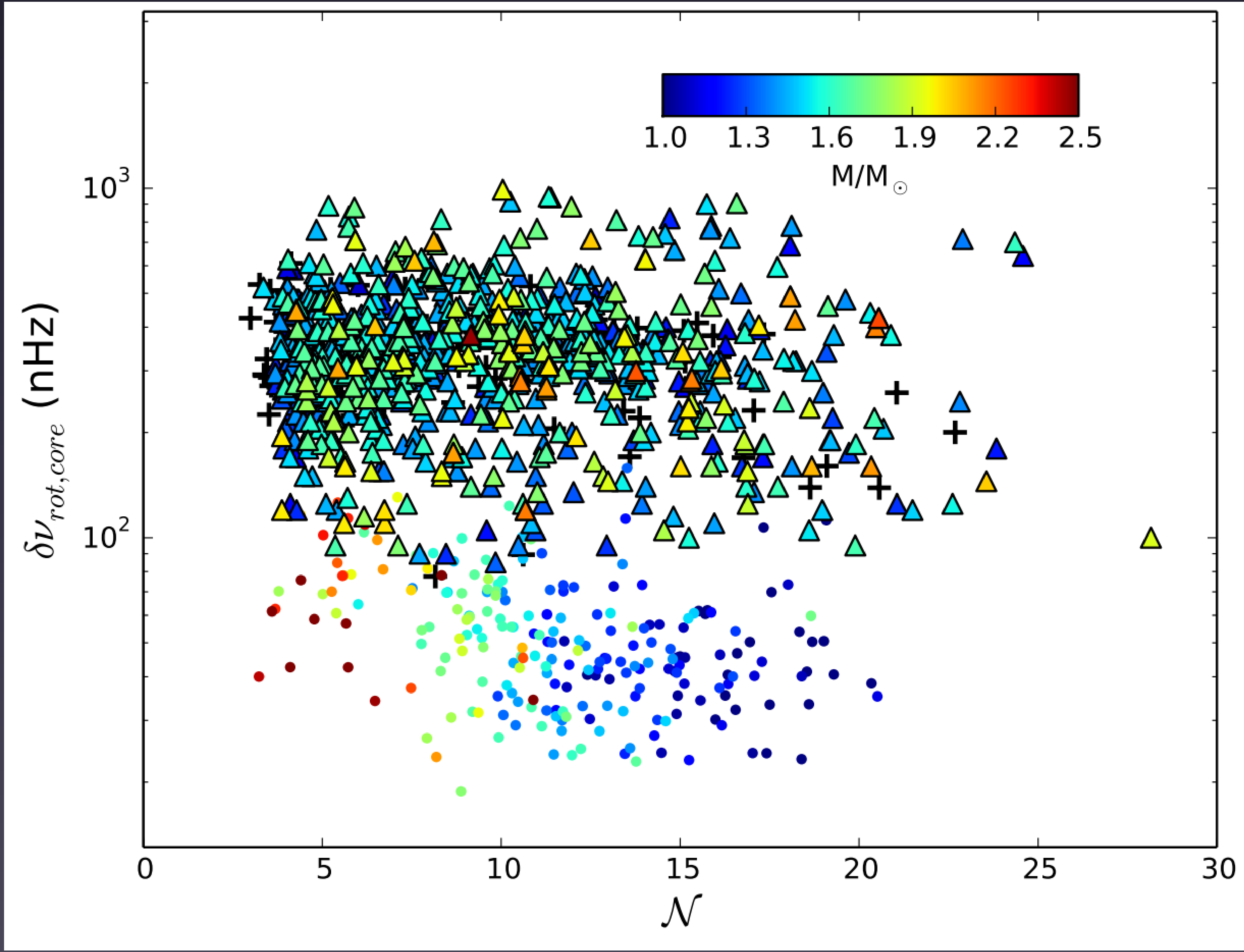


P_{Core}
P_{Surf}
j-conservation
Mosser+ 2012 (RGB)
KIC 8366239
KIC 5006817
Clump Stars
WD
0.19 $M_\odot$
0.25 $M_\odot$
0.46 $M_\odot$
log P (d)
log $(t - t_{TAMS})$/yr
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
7.4
7.6
7.8
8.0
8.2
8.4
8.6
8.8
9.0

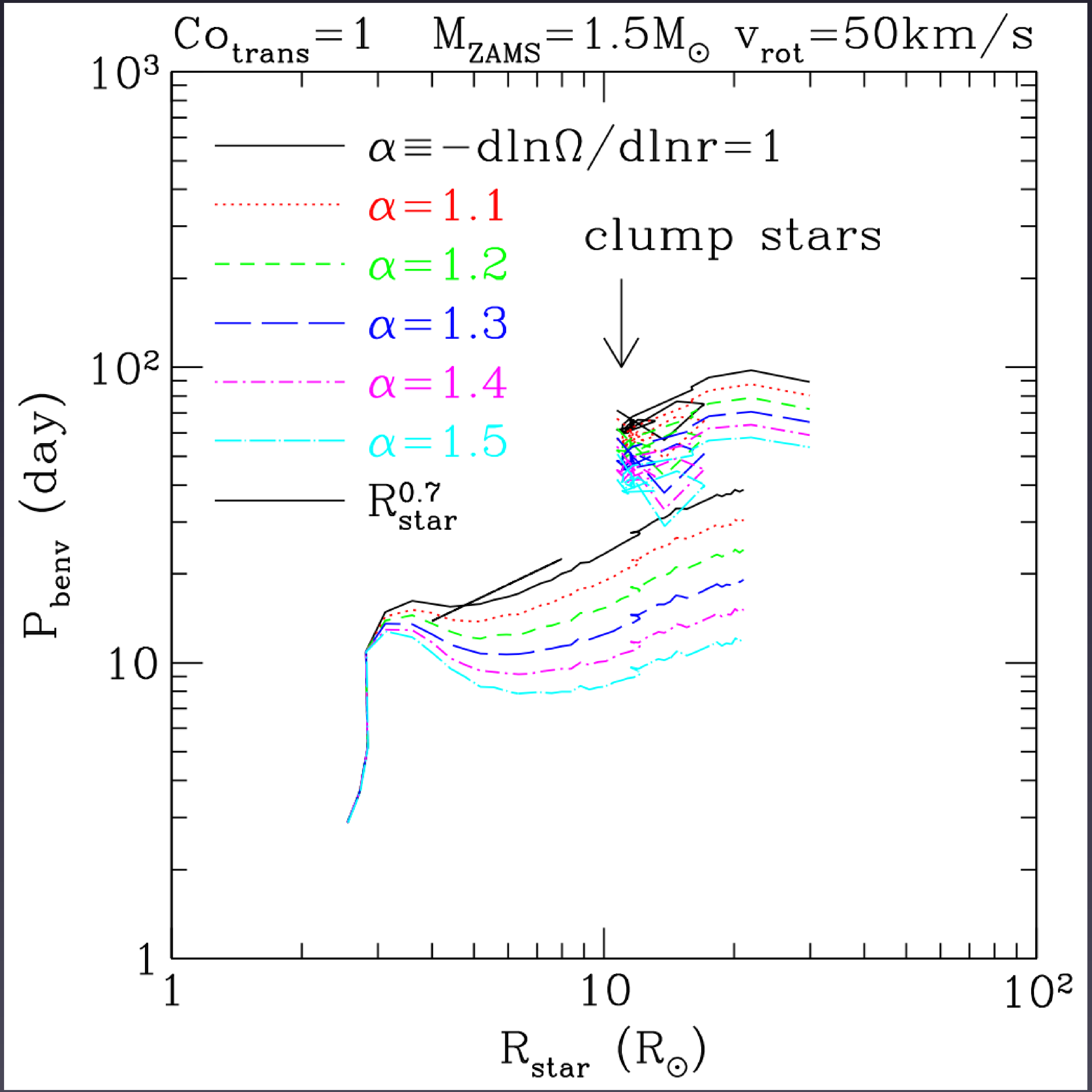


$M = 1.2 M_\odot$
$M = 1.7 M_\odot$
$M = 2.4 M_\odot$
Central Rotation Period (days)
10^2
10^1
10^0
10^0
10^1
Stellar Radius

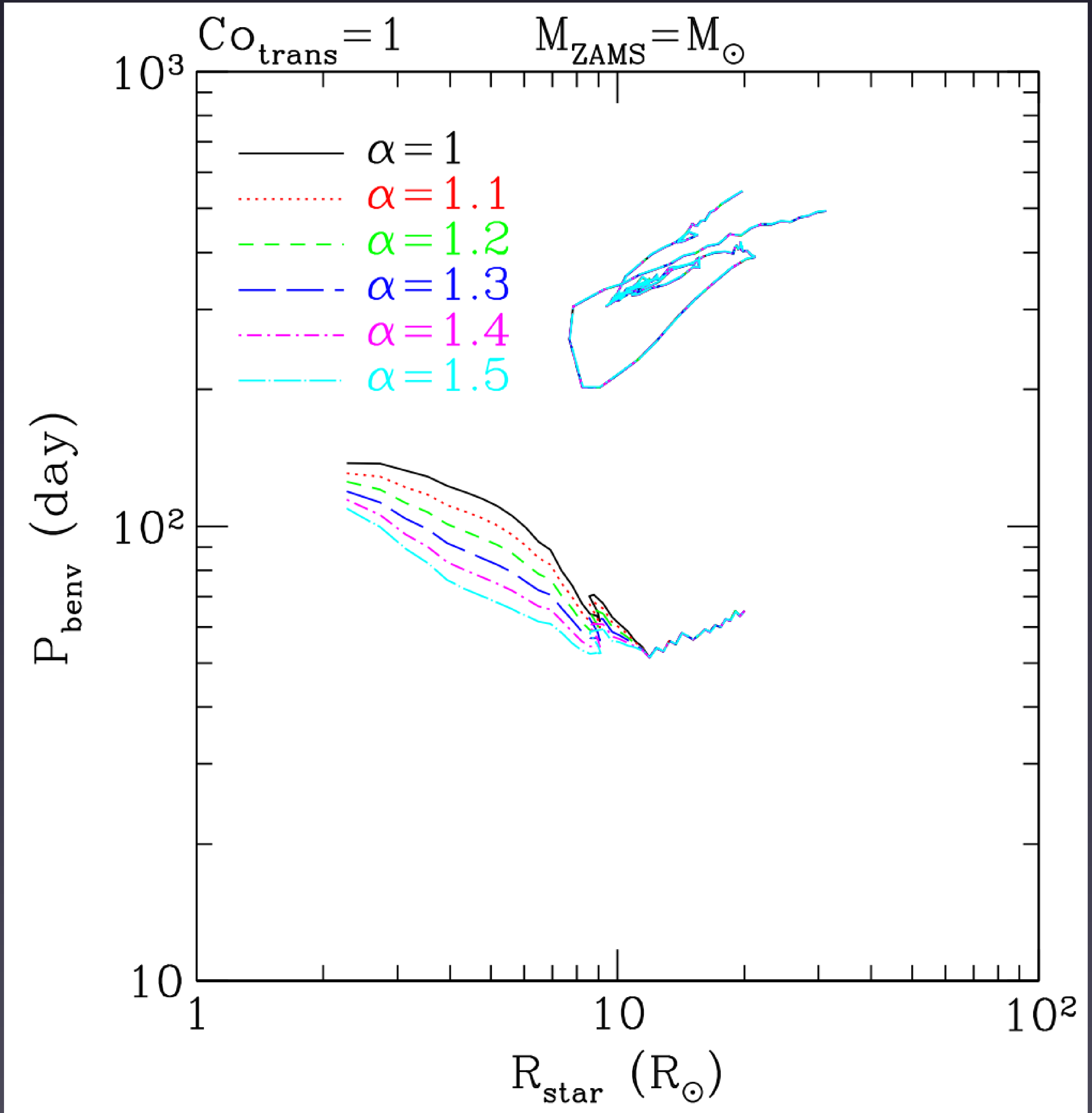

$M = 1.2M_\odot$
$M = 1.7M_\odot$
$M = 2.4M_\odot$
Central Rotation Period (days)
10^0
10^1
10^2
4.5
4.0
3.5
3.0
2.5
2.0
log g



Gehan et al. 2018



Kissin & Thompson 2015



Kissin & Thompson 2015