Tidal interactions between planets and stars

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Science & Technology Facilities Council

https://arxiv.org/abs/2008.03262.pdf
see also
https://arxiv.org/pdf/2007.12624.pdf
https://arxiv.org/pdf/2007.13392.pdf

Tides in stars: orbital decay of hot Jupiters

- Gravitational tidal interactions drive spin and orbital evolution in planetary systems with close-in planets (e.g. hot Jupiters) and binary stars

- First tentative evidence for tidally-driven orbital decay for the hot Jupiter WASP-12 b (Maciejewski et al. 2016; Patra et al. 2017; Yee et al. 2020)

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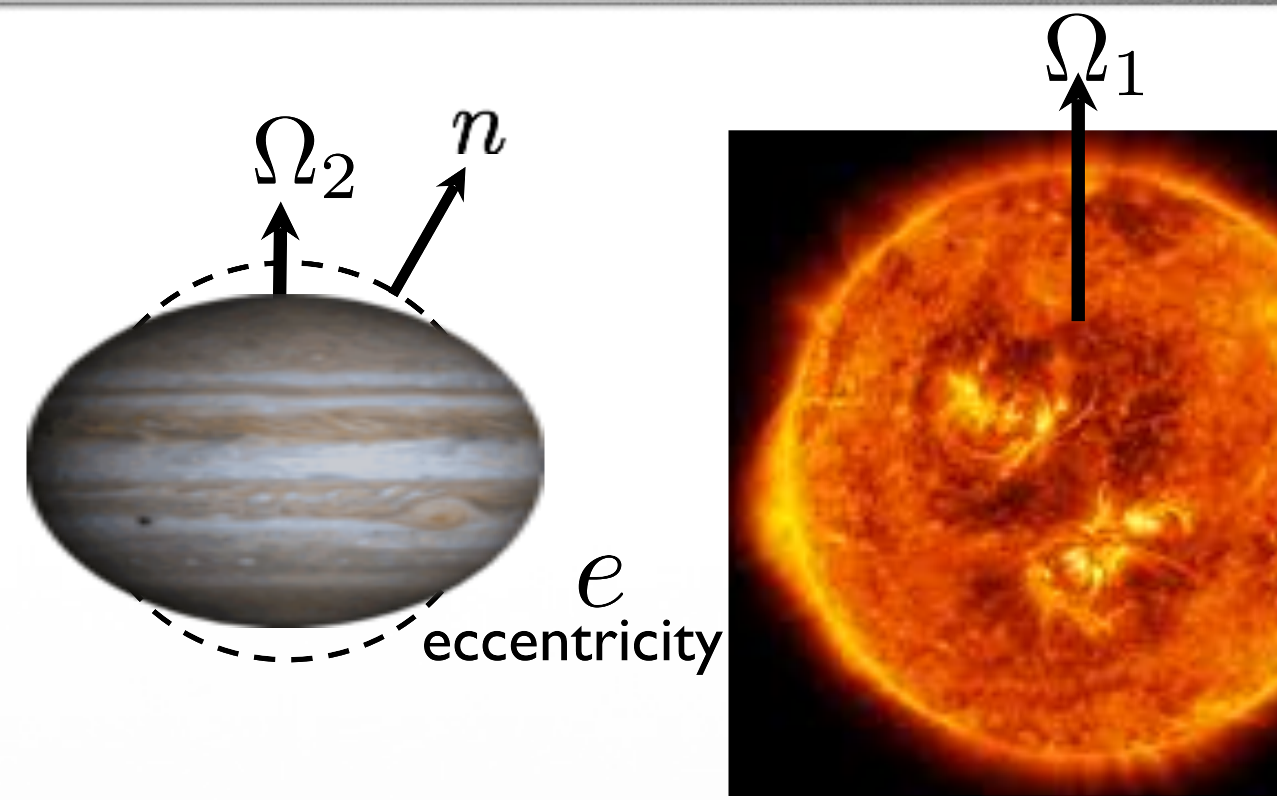
- Evidence against rapid orbital decay for WASP-18 b (Wilkins et al. 2017)

- Tidally-driven orbital decay of hot Jupiters due to dissipation in the star => *what mechanisms are responsible?*



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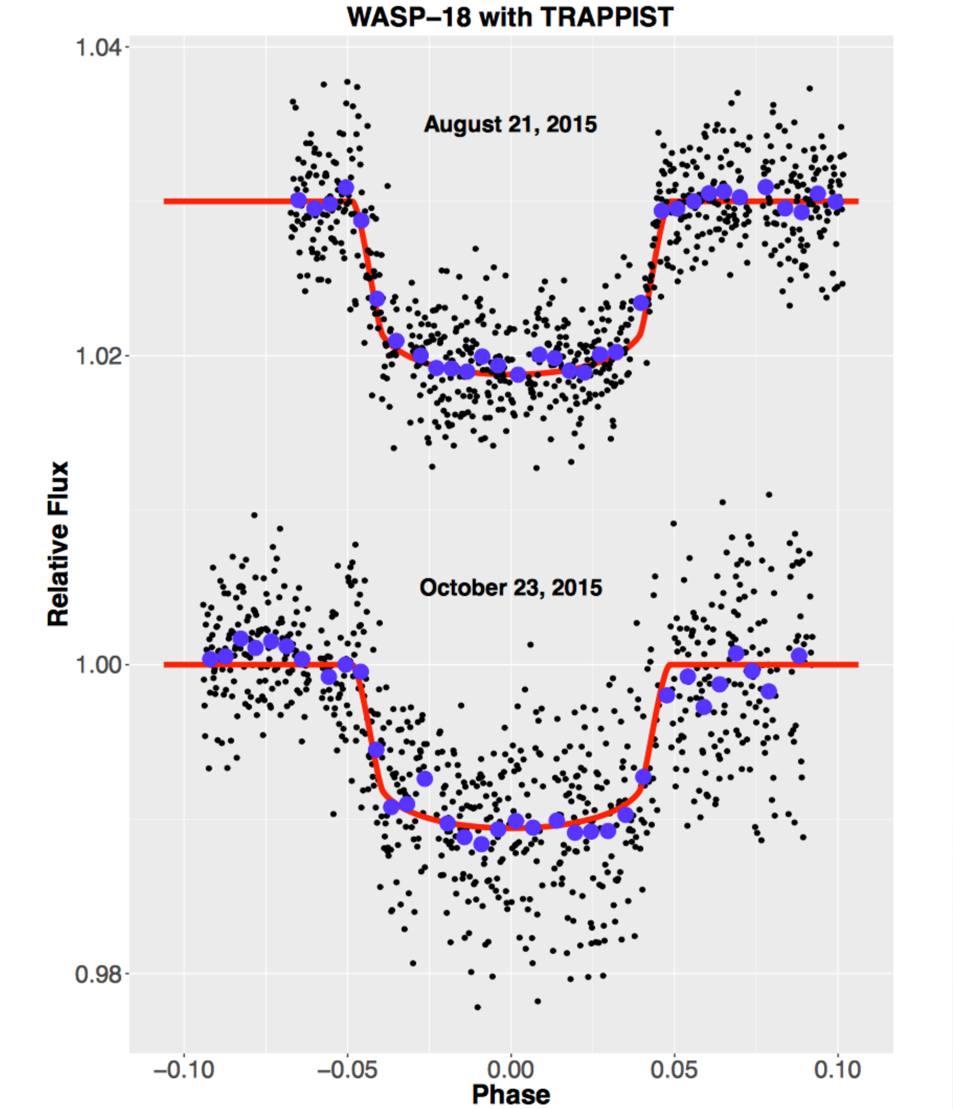
Wilkins, Delrez, Barker et al. (2017)

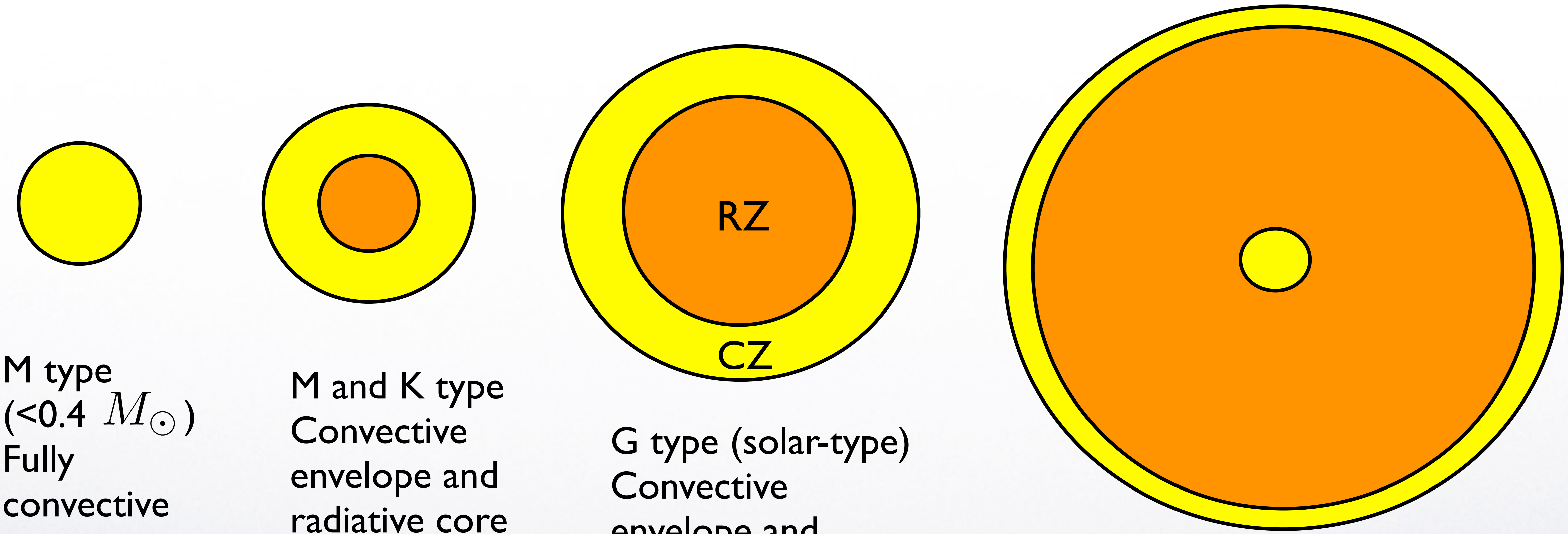


$$T_{shift} = -\left(\frac{27}{8}\right)\left(\frac{M_p}{M_*}\right)\left(\frac{R_*}{a}\right)^5\left(\frac{2\pi}{P}\right)\left(\frac{1}{Q_*'}\right)T^2$$

Dimensionless inverse measure of the efficiency of tidal dissipation

Tides in stars

- I will present theoretical calculations of tidal dissipation in stars with masses ranging from 0.1 to 1.6 $M_\odot$ throughout their pre-main sequence (PMS) and main sequence (MS) evolution



M type
(<0.4 $M_\odot$)
Fully
convective

M and K type
Convective
envelope and
radiative core

G type (solar-type)
Convective
envelope and
radiative core

F type
>1.1 $M_\odot$ (<1.6)
Convective core and
envelope

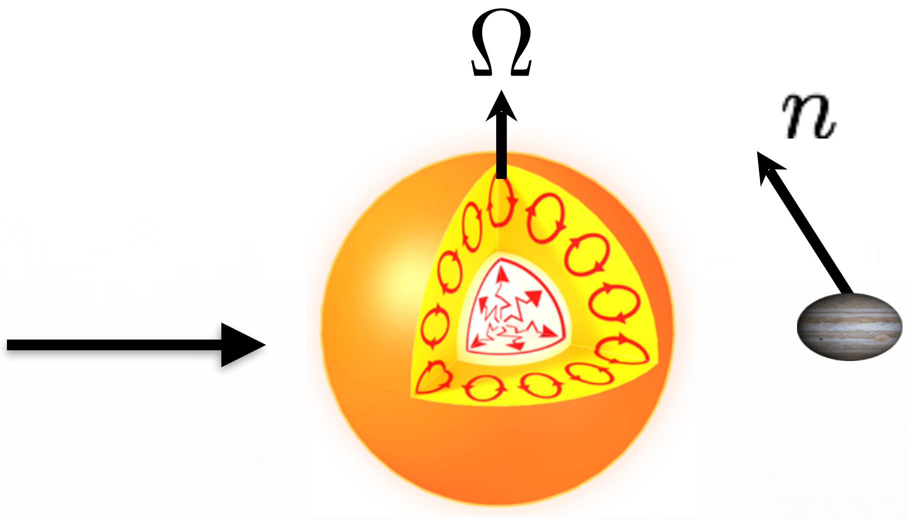
Tides in stars: mechanisms

- The tidal response is usually decomposed into two components: an **equilibrium** and **dynamical** tide.

1. **Equilibrium (non-wavelike) tides**: large-scale quasi-hydrostatic deformation of the body, with associated flow. This flow is dissipated by:

 a) interaction with turbulent convection, which can act as an effective viscosity (e.g. Zahn 1966/1989; Goldreich & Nicholson 1977; Goodman & Oh 1997; Ogilvie & Lesur 2012; Braviner 2015; Duguid et al. 2020a,b; Vidal & Barker 2020a,b; Terquem 2021)

 b) "nonlinear tidal effects" such as the elliptical instability (e.g. Kerswell 2002; Rieutord 2004; Le Bars et al. 2010; Barker & Lithwick 2013; Barker 2016; Le Reun et al. 2017…)



2. Dynamical (wave-like) tides: waves restored by Coriolis or buoyancy (or Lorentz?) forces. Dissipated by viscosity/diffusion/ turbulent viscosity (?) /nonlinear interactions.

 a) Internal gravity waves in radiative regions (e.g. Cowling 1941; Zahn 1977; Goodman & Dickson 1998; Ogilvie & Lin 2007; Barker & Ogilvie 2010; Barker 2011; Weinberg et al. 2012; Chernov et al. 2017…)

 b) Inertial waves in convective regions (e.g. Wu 2005; Ogilvie & Lin 2007; Ivanov & Papaloizou 2007; Goodman & Lackner 2009; Rieutord & Valdettaro 2010; Favier, Barker et al. 2014; Gallet et al. 2017; Astoul & Barker, in prep…)

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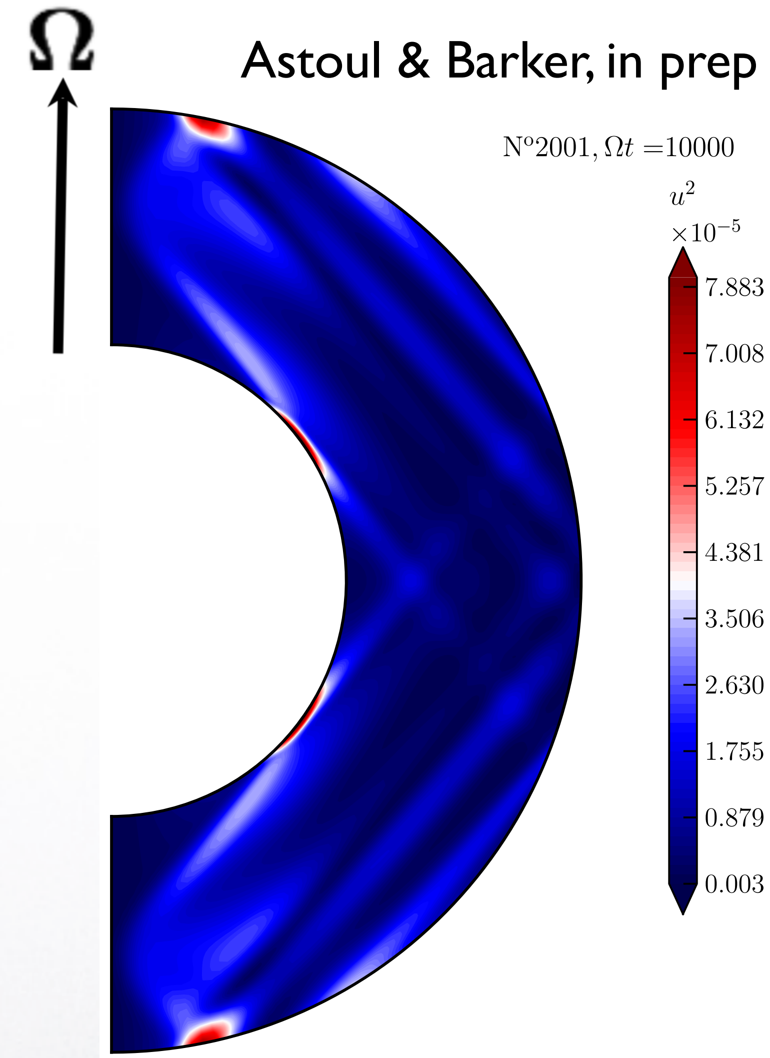

Probably important in rapidly rotating young stars, but most HJ hosts rotate too slowly for this to operate *at the present day*. Probably dominant for binary star tidal evolution.

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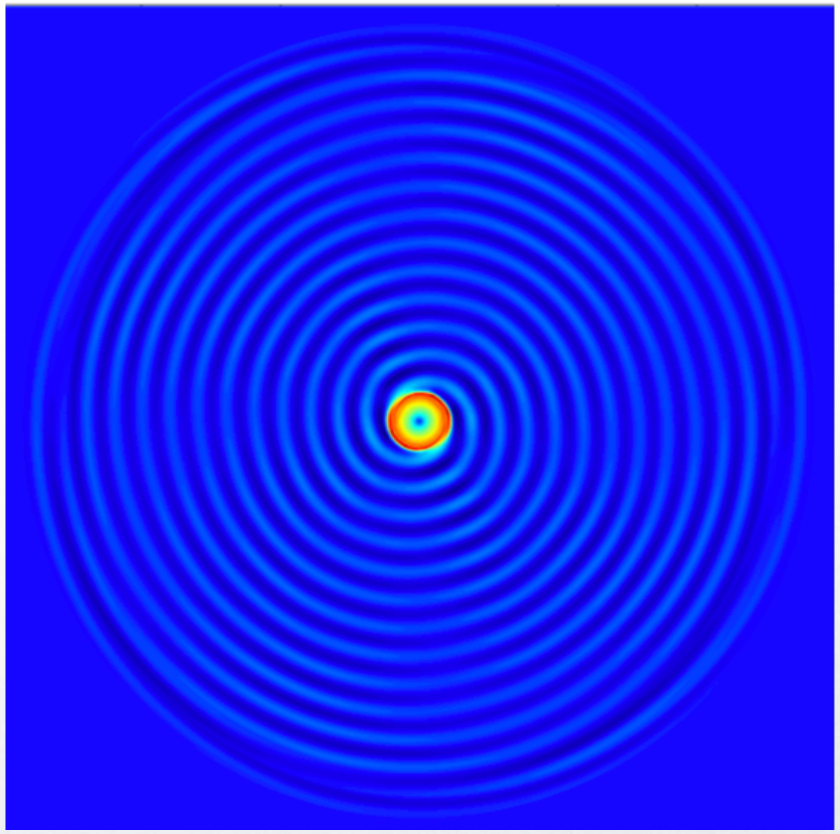


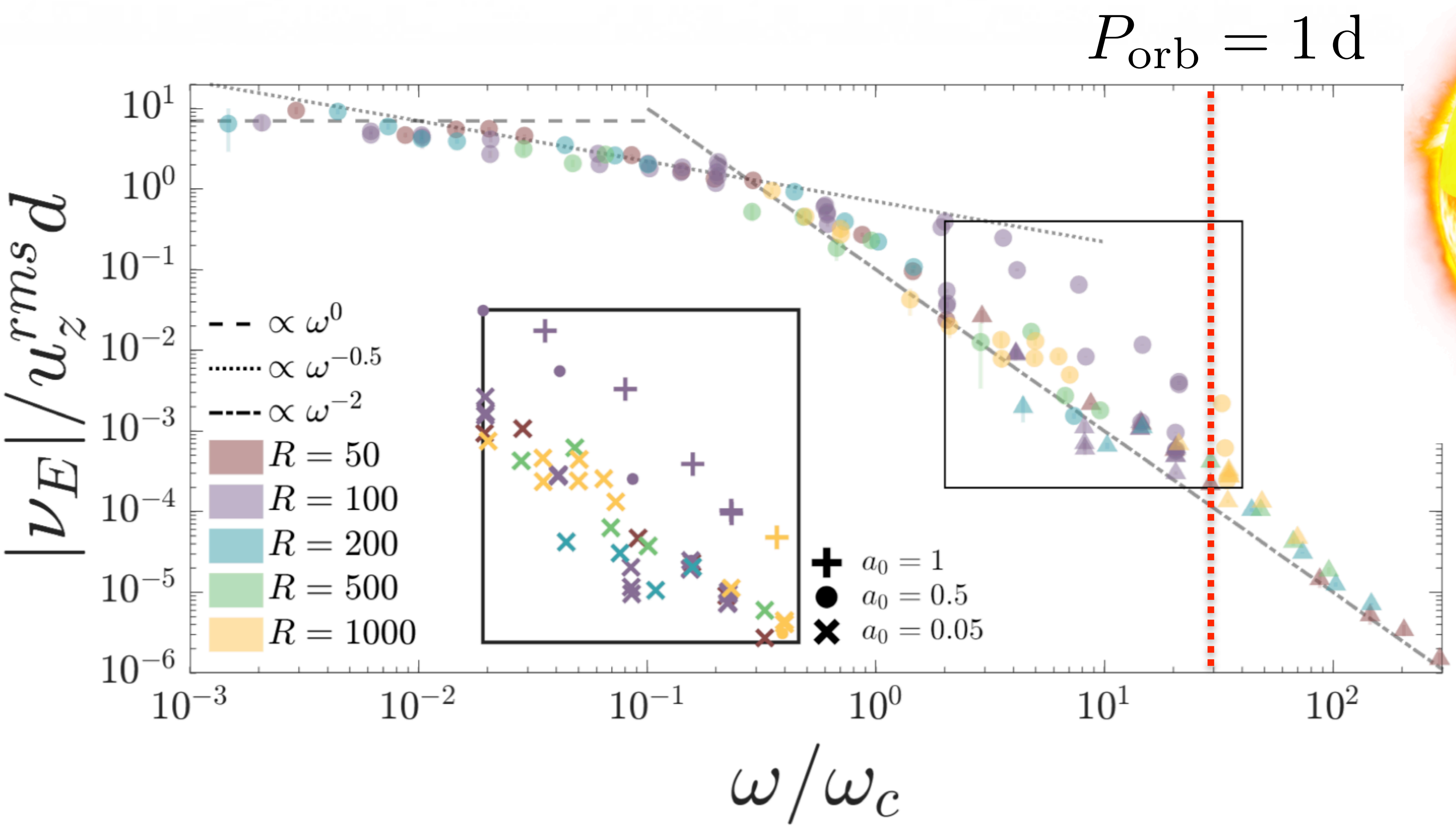
Barker & Ogilvie 2010

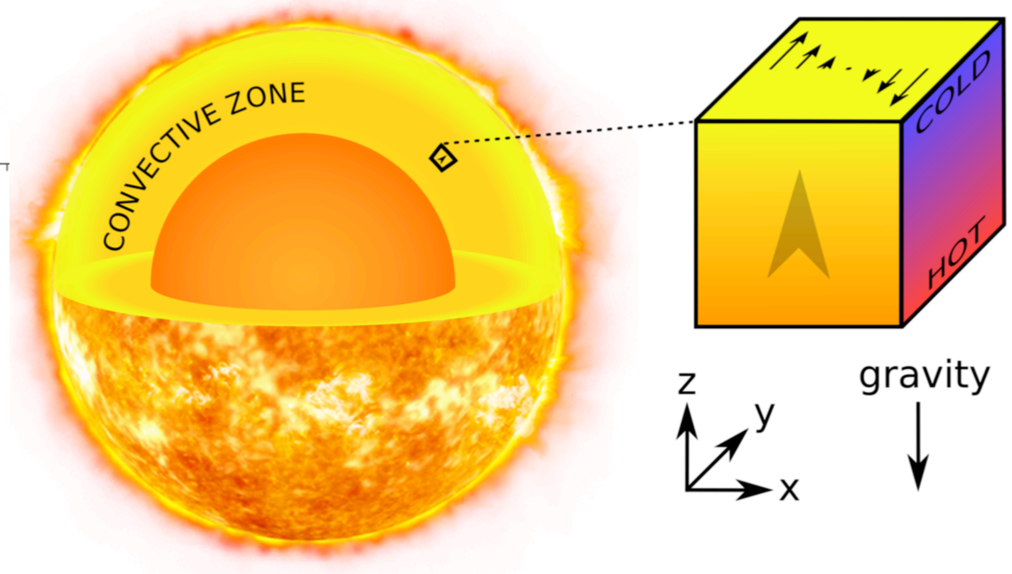
Equilibrium tides in CZs

- Equilibrium tide damping is theoretically uncertain, but recent simulations have shed light on this mechanism.

> To summarize, the main weaknesses of the tidal theory, when applied to stars with a convective envelope, reside in our limited knowledge of the dynamics of the convective motions and of their interaction with the tidal flow. (Zahn 1989)

- Turbulent convection can act as an effective viscosity in damping equilibrium tides… Less efficient for rapidly orbiting planets (large ratios of tidal/convective frequencies)…

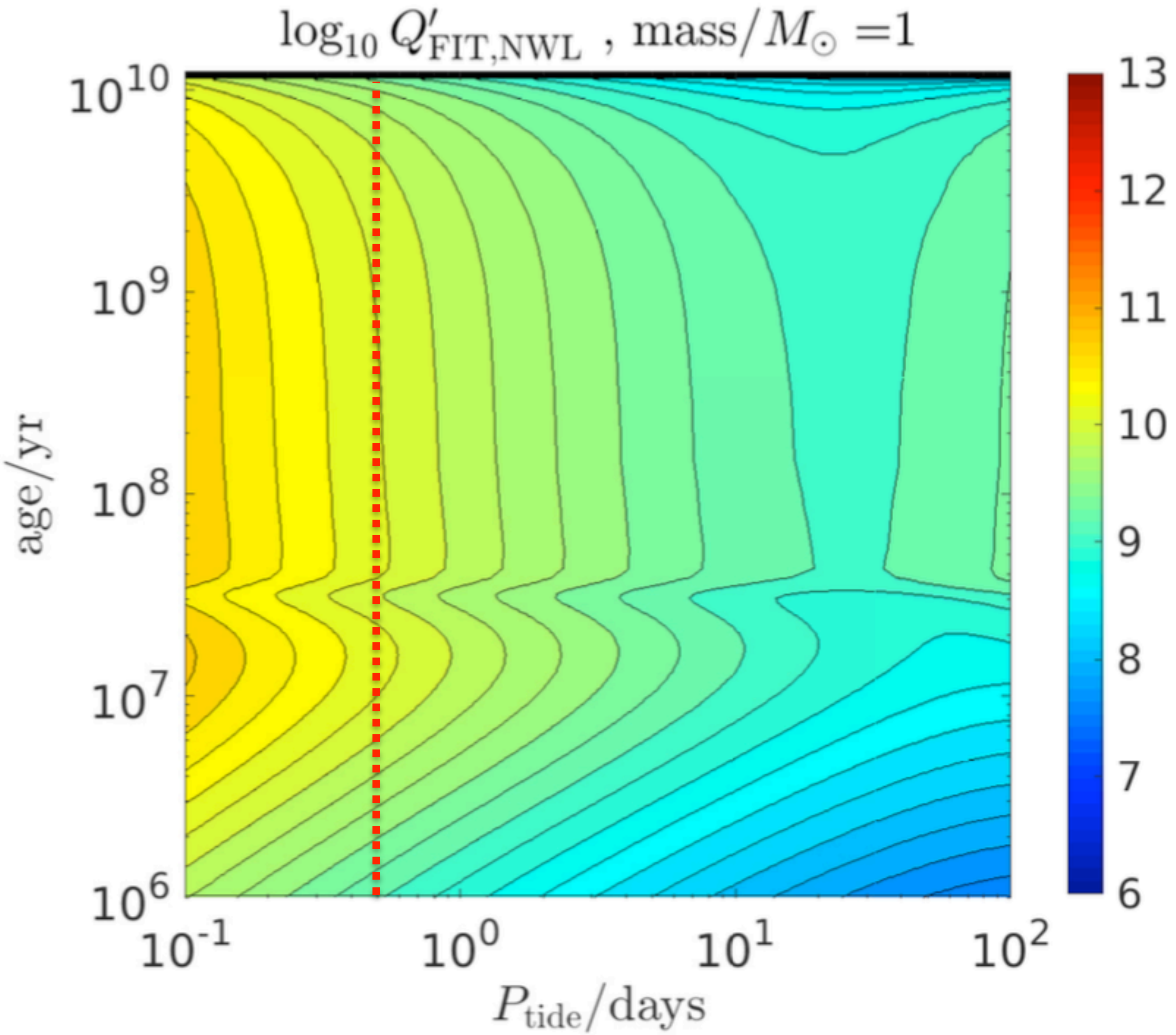




Duguid, Barker & Jones, 2020, MNRAS, 491, 923
Duguid, Barker & Jones, 2020, MNRAS, 497, 3400
Vidal & Barker, 2020, MNRAS, 497, 4472
Vidal & Barker, 2020, ApJL, 888, L31

1.

Equilibrium tides in CZs



$$Q'_{\rm eq} \sim 10^{10}$$

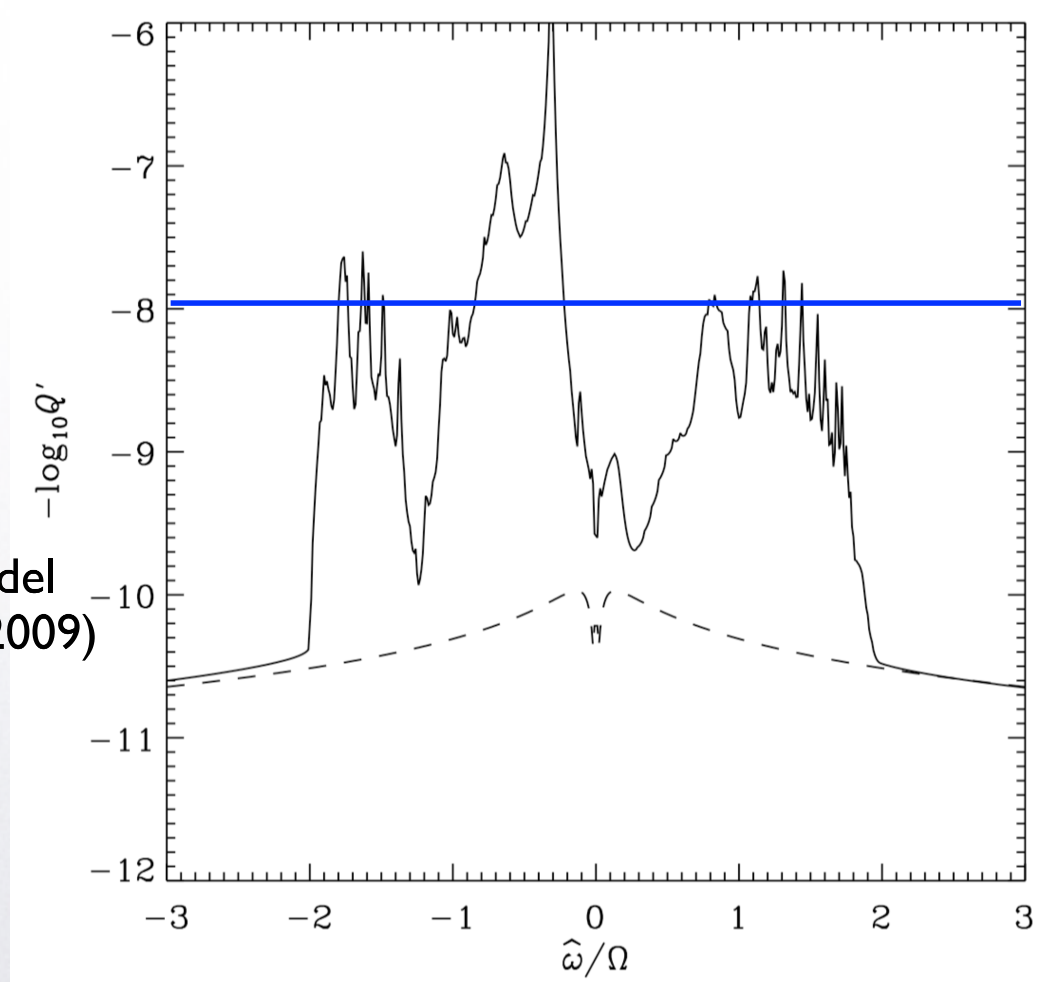
for planets on ~ day orbital periods => *orbital decay timescales much longer than MS lifetime (>100 Gyr)*

Equilibrium tide dissipation in CZs is probably unimportant for tidal dissipation in PMS and MS stars but is probably dominant for giant stars

Barker (2020, MNRAS, 498, 2270) https://arxiv.org/abs/2008.03262.pdf

Dynamical tides: inertial waves in CZs

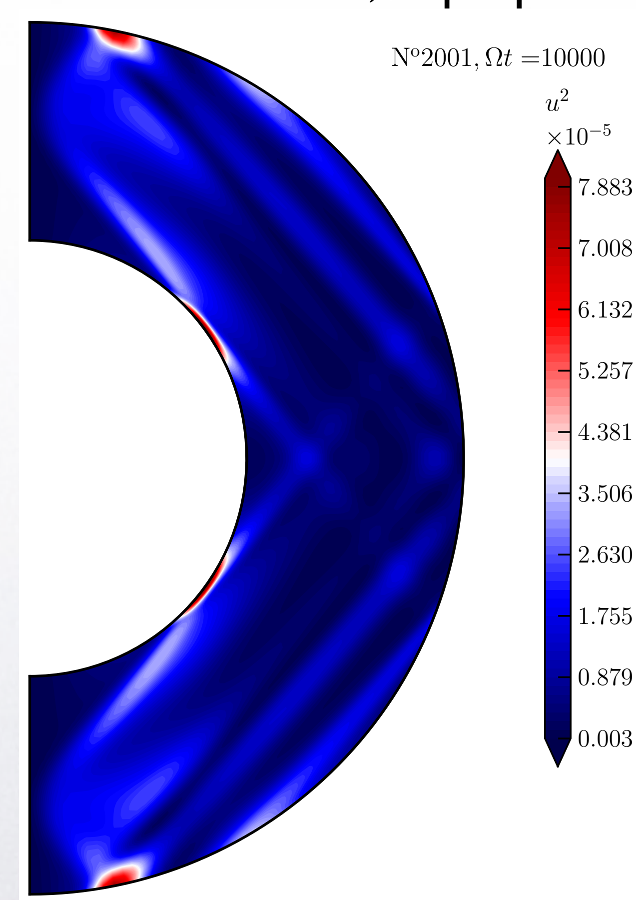
- Tidal forcing excites inertial waves in CZs of rotating stars if the tidal frequency is less than twice the stellar spin frequency i.e. $P_{\rm rot} < 2P_{\rm tide}$ (not satisfied for most HJs currently!)
- I compute dissipation due to inertial waves using a frequency-averaged formalism building upon Ogilvie (2013) & Mathis (2015), Gallet et al. 2017+ *but accounting for the realistic stellar structure*



$\langle Q'_{\rm IW} \rangle$

1.2 $M_\odot$ F star model
Barker & Ogilvie (2009)

Astoul & Barker, in prep



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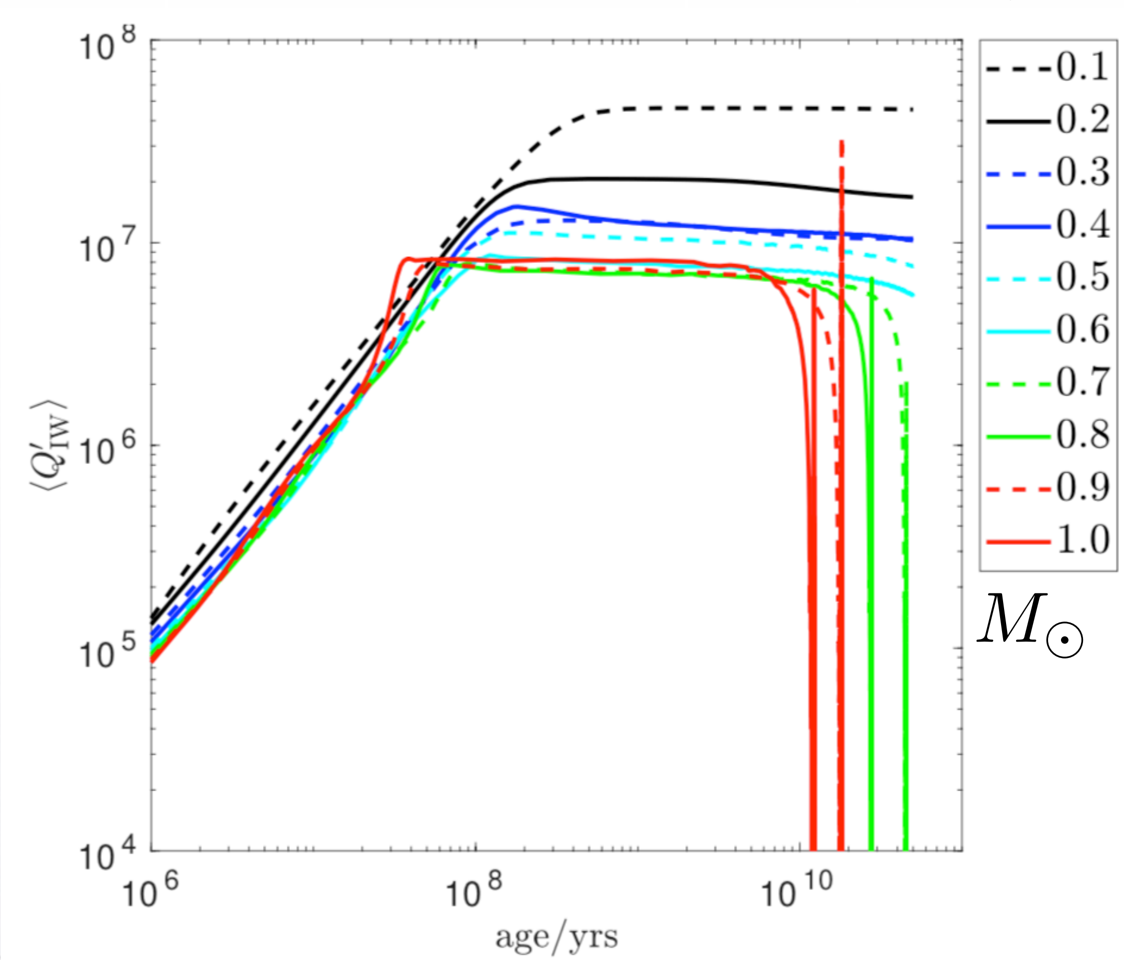
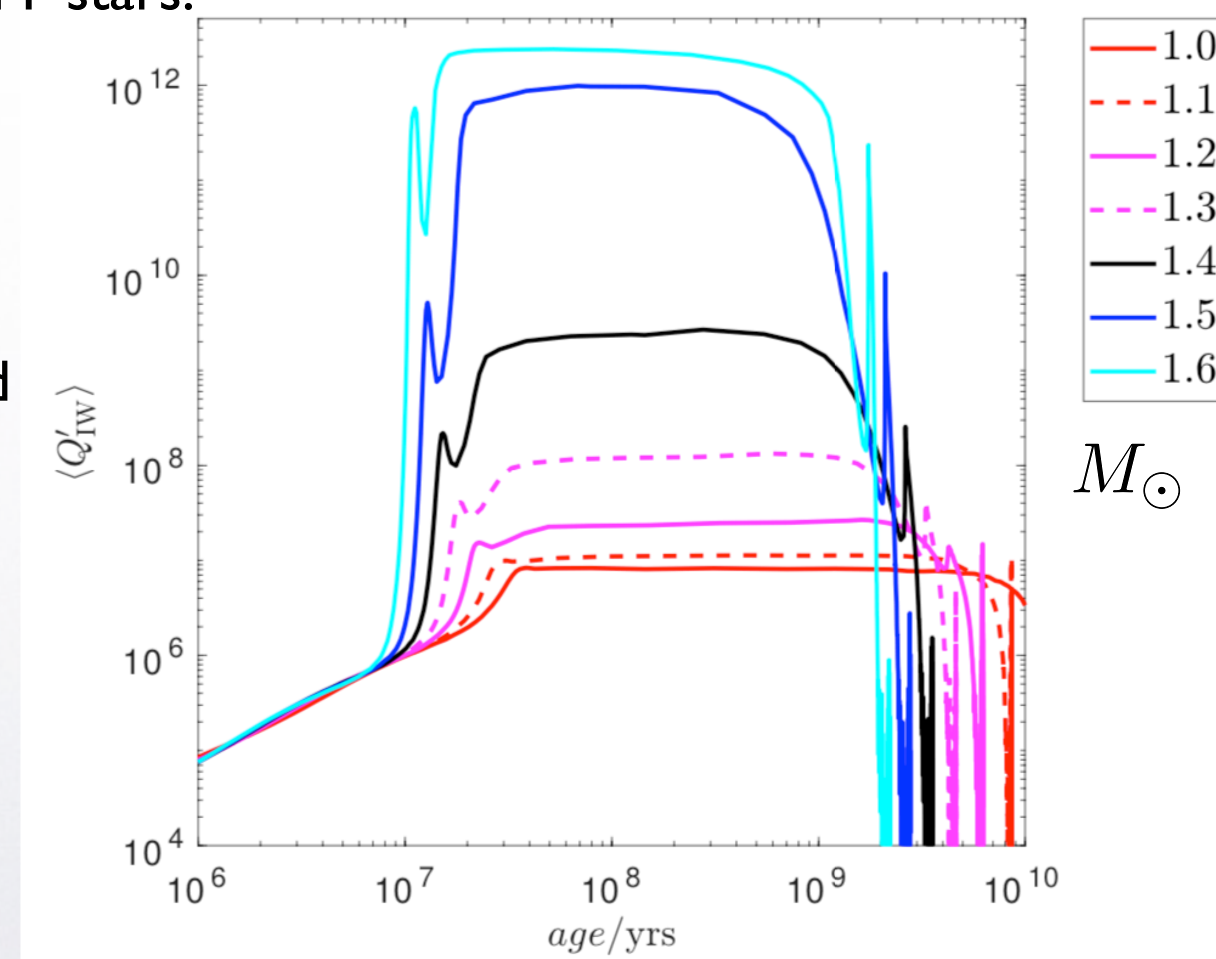
- I compute dissipation due to inertial waves using a frequency-averaged formalism building upon Ogilvie (2013) & Mathis (2015) *but accounting for the realistic stellar structure*

- Solar-like stars have $\langle Q'_{\rm IW}\rangle \approx 10^7\,(P_{\rm rot}/10{\rm d})^2$ on the MS *when these waves are excited.* Consistent with statistical analysis of observations by Collier Cameron & Jardine (2018)

- Dominant tidal mechanism in PMS stars… Less dissipative in F stars.



Shown for fixed
$P_{\rm rot} = 10{\rm d}$



Barker (2020, MNRAS, 498, 2270) https://arxiv.org/abs/2008.03262.pdf

3. Dynamical tides: internal gravity waves in RZs

- Tidal forcing excites internal gravity waves in the RZ that propagate towards the centres of solar-type stars

- If waves are weakly damped, obtain global standing modes (g-modes), with efficient dissipation only for narrow (resonant) ranges of tidal frequencies.

- If waves are fully damped (e.g. by wave breaking), we obtain efficient dissipation:

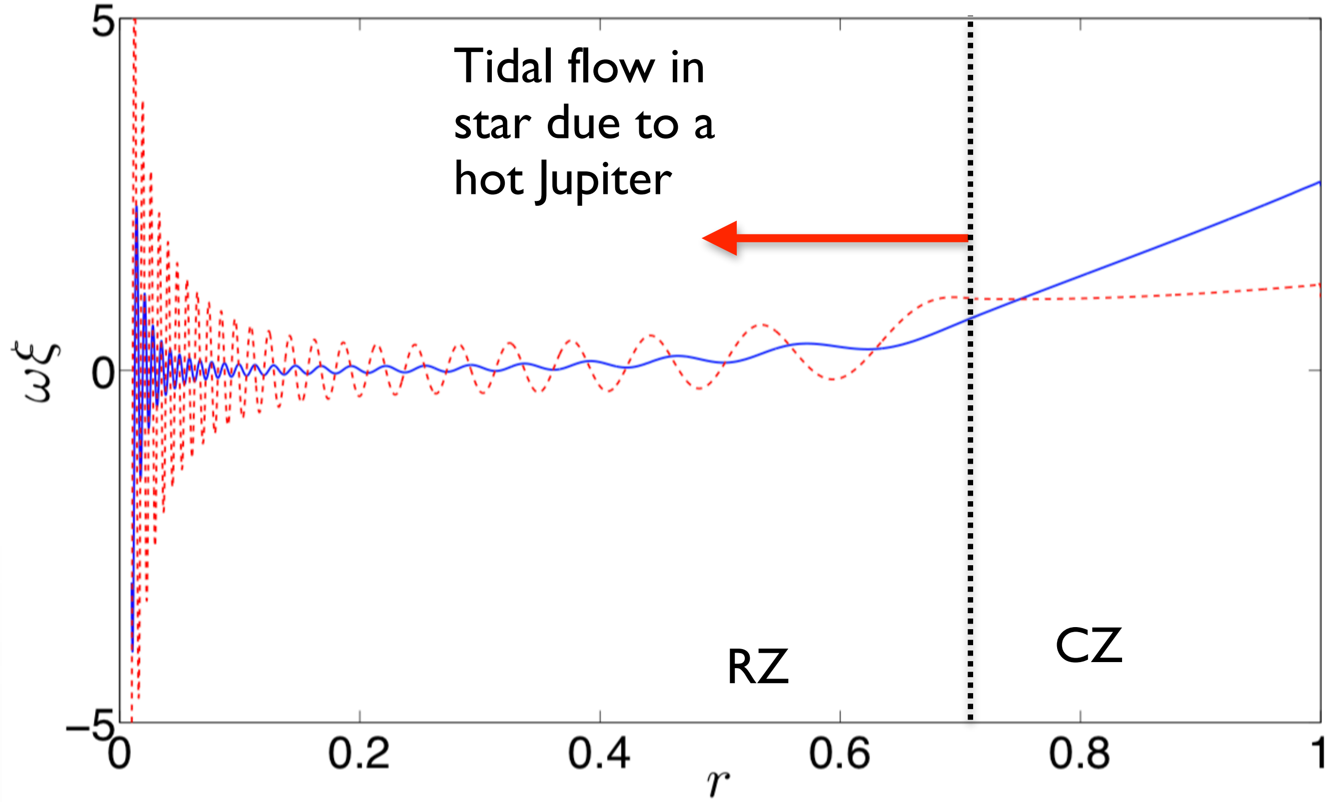
$$Q'_{\rm IGW} \approx 10^5 \left(\frac{P_{\rm orb}}{1\rm d}\right)^{\frac{8}{3}}$$

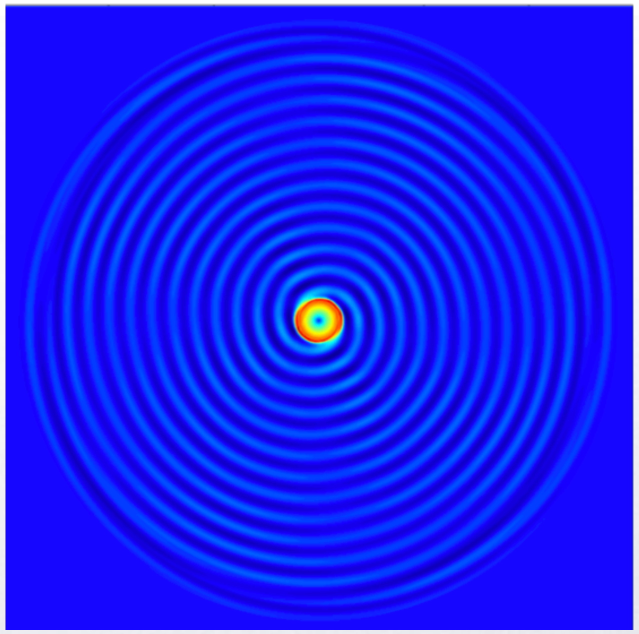
- Drives hot Jupiter orbital decay on the timescale

$$\tau_a \approx 2\,{\rm Myr}\left(\frac{M_J}{M_p}\right)\left(\frac{P}{1\rm d}\right)^7$$

- This mechanism may explain the observed orbital decay of e.g. WASP-12 b and the absence of decay in WASP-18 b…

However: *should the waves be fully damped in WASP-12 b? Depends on stellar model…*





Wave breaking can lead to efficient wave damping

Barker & Ogilvie 2010

Barker (2020, MNRAS, 498, 2270) https://arxiv.org/abs/2008.03262.pdf

3. Dynamical tides: internal gravity waves in RZs

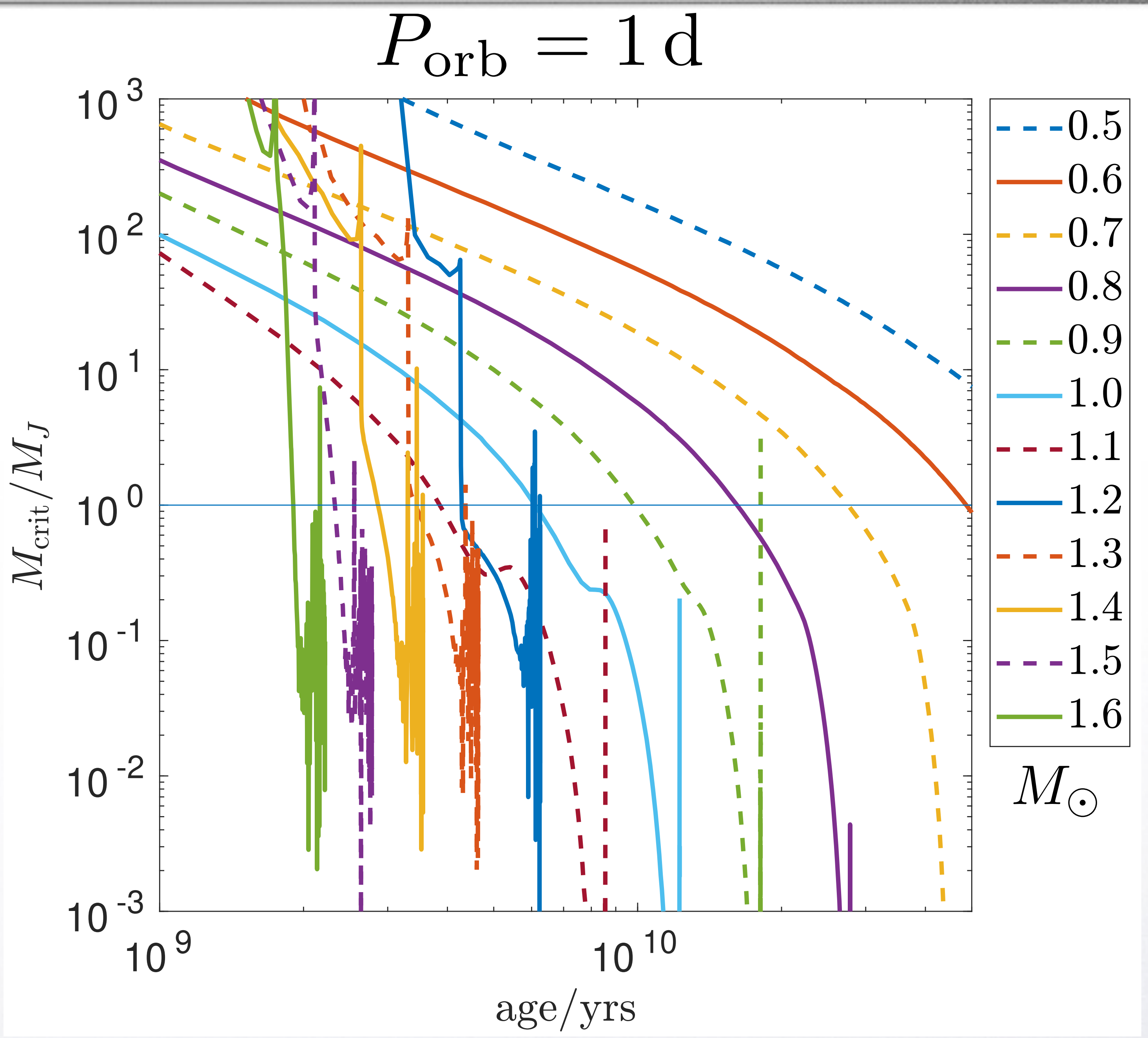
- Wave breaking predicted if planetary mass exceeds $M_{\rm crit}$, *which depends strongly on mass and age*

- For the *current Sun + 1day orbit*, we predict

$$M_{\rm crit} \approx 3.3 M_J \left(\frac{\mathcal{G}_\odot}{\mathcal{G}}\right)^{\frac{1}{2}} \left(\frac{C_\odot}{C}\right)^{\frac{5}{2}}$$

- Wave breaking predicted for lower mass planets as the star evolves

- Many short-period hot Jupiters can be destroyed by this mechanism near the end of the MS.
  Consistent with observational results from Hamer & Schlaufman (2019, 2020) and Mustill et al. 2021



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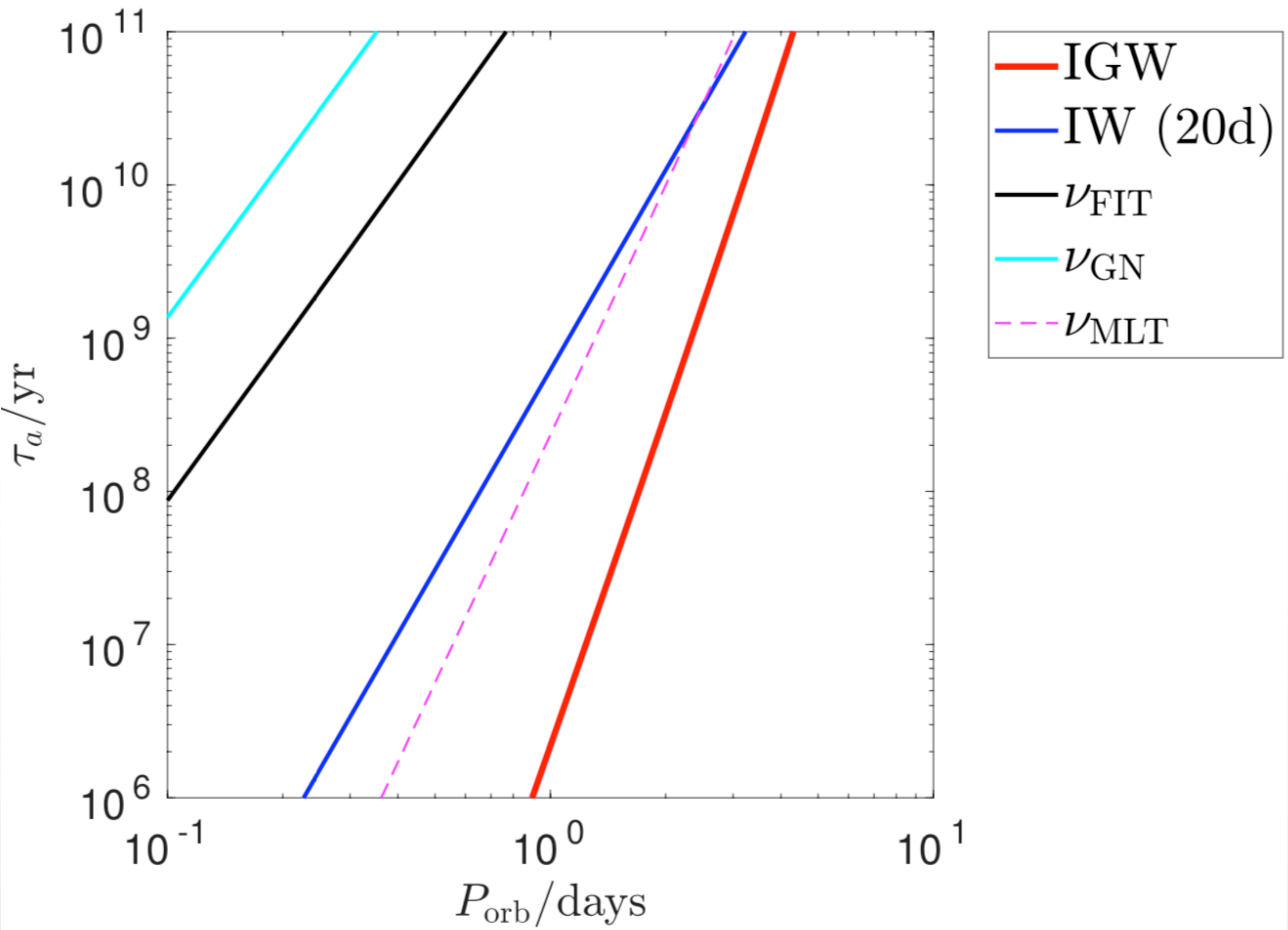
Summary: orbital decay timescales for HJs



(c) $M/M_\odot = 1$, age/yr $= 4.70 \times 10^9$

- Hot Jupiter orbital decay slowly rotating stars is primarily due to internal gravity waves in RZs — if these waves are efficiently damped (e.g. by wave breaking)
- Inertial waves in CZs are important around rapidly rotating young stars
- Equilibrium tides are probably unimportant on the PMS and MS, *though is probably the dominant mechanism of tidal dissipation in giant stars*

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Summary: predictions for orbital decay

Name	M_p/M_J	$P_{\rm orb}/{\rm d}$	$M/M_\odot$	$R/R_\odot$	Z_{init}	T_{eff}	$P_{\rm rot}/{\rm d}$	age/Gyr	$Q'_{\rm obs}$	$Q'_{\rm IGW}$	$\tau_a/{\rm Myr}$	$T_{\rm shift}/s$
WASP-4b	1.2	1.34	0.93	0.9	0.02	5542	23	5.8	$4.5 - 8.5 \times 10^4$	$3.3 - 3.8 \times 10^5$	$14 - 17$	13-15
WASP-12b (MS1)	1.47	1.09	1.43	1.68	0.03	6376	38	1.62	2×10^5	4.5×10^6	11	20.5
WASP-12b (MS2)	1.47	1.09	1.32	1.69	0.025	6072	38	3.1	2×10^5	2.2×10^5	0.42	522
WASP-12b (SG)	1.47	1.09	1.24	1.69	0.023	6126	38	4.1	2×10^5	2.7×10^5	0.58	384
WASP-18b	11.4	0.94	1.24	1.29	0.02	6306	6	1.37	$> 1.3 \times 10^6$	2.6×10^6	1.2	200
WASP-19b	1.14	0.79	0.94	1.01	0.02	5624	13	9.28	$3.5 - 7.5 \times 10^5$	$0.6 - 0.8 \times 10^5$	$0.13 - 0.3$	675-1000
WASP-43b	2.03	0.81	0.72	0.67	0.02	4462	6	5.03	$> 0.7 - 3.5 \times 10^5$	1.3×10^5	0.98	230
WASP-72b	1.55	2.22	1.39	2.01	0.01	6876?	17	2.3	$> 2.1 \times 10^3$	$> 10^{12}$		
WASP-103b	1.51	0.93	1.21	1.43	0.02	6115	7	3.48	$> 1.1 \times 10^5$	4×10^5	0.68	322
WASP-114b	1.77	1.55	1.29	1.42	0.03	6206	12	2.12		3×10^6	48	4.7
WASP-121b	1.18	1.27	1.353	1.49	0.025	6429	5.5	1.42		2.4×10^7	225	1
WASP-122b	1.284	1.71	1.24	1.50	0.04	5895	23	4.2		3.5×10^5	8.4	27
WASP-128b	37.2	2.21	1.16	1.16	0.02	6108	3	1.57		1.7×10^8	1400	0.2
NGTS-6b	1.33	0.88	0.787	0.74	0.025	4774		9.01		$> 0.99 \times 10^5$	1.2	182
NGTS-7Ab	62.0	0.676	0.48?	0.645	0.02	3736	sync?	0.0055		$> 0.9 \times 10^5$		
NGTS-10b	2.16	0.77	0.696	0.68	0.02	4428	8.8	10.06		0.99×10^5	0.5	440
HAT-P-23b	2.09	1.21	1.13	1.22	0.03	5916	7.5	4.3	$> 4.5 \times 10^5$	3.5×10^5	2.5	91
HATS-18b	1.98	0.84	1.04	1.03	0.03	5735	8.3	4.26		1.1×10^5	0.33	686
KELT-16b	2.75	0.97	1.21	1.38	0.02	6180	9	2.97	$> 0.7 \times 10^5$	7×10^5	0.98	228
TRES-3b	1.91	1.306	0.924	0.845	0.009	5699	27	1.23	1.1×10^5	6.1×10^5	23.6	9.5
OGLE-TR-56b	1.39	1.21	1.23	1.38	0.02	6235	23	2.53	$> 5 \times 10^5$	1.8×10^6	14	16.5
WTS-2b	1.12	1.018	0.82	0.74	0.02	4761	17	0.43		1.9×10^5	6.4	35

- For further details please see the paper below or ask me!

Barker (2020, MNRAS, 498, 2270) https://arxiv.org/abs/2008.03262.pdf

Conclusions

- Tidal dissipation in stars drives orbital decay of hot Jupiters, as well as orbital circularization & spin synchronization in stellar binaries.

- I have presented theoretical calculations of tidal dissipation in stars with masses $0.1 \leq M/M_{\odot} \leq 1.6$ following their evolution

- Dominant tidal mechanism for planetary orbital decay around slowly rotating stars is internal gravity waves in RZs if waves are efficiently damped (e.g. by wave breaking)

- Dominant tidal mechanism for tidal evolution around rapidly rotating young MS and PMS stars is inertial waves in CZs

- Equilibrium tides are probably unimportant on the PMS and MS, *but are expected to be the dominant mechanism in giant stars*

- For further details and for predictions for planetary orbital decay for current hot Jupiters, see: Barker (2020, MNRAS, 498, 2270) https://arxiv.org/abs/2008.03262.pdf

- Further work is required to study:

1. Direct simulations of turbulent convection & tidal flows in realistic stellar models
2. Direct simulations of tidal dissipation due to inertial waves in realistic stellar models