

Resonance Locking and Hot Jupiters

Know Thy Star, Know Thy Planet 2
February 6, 2025

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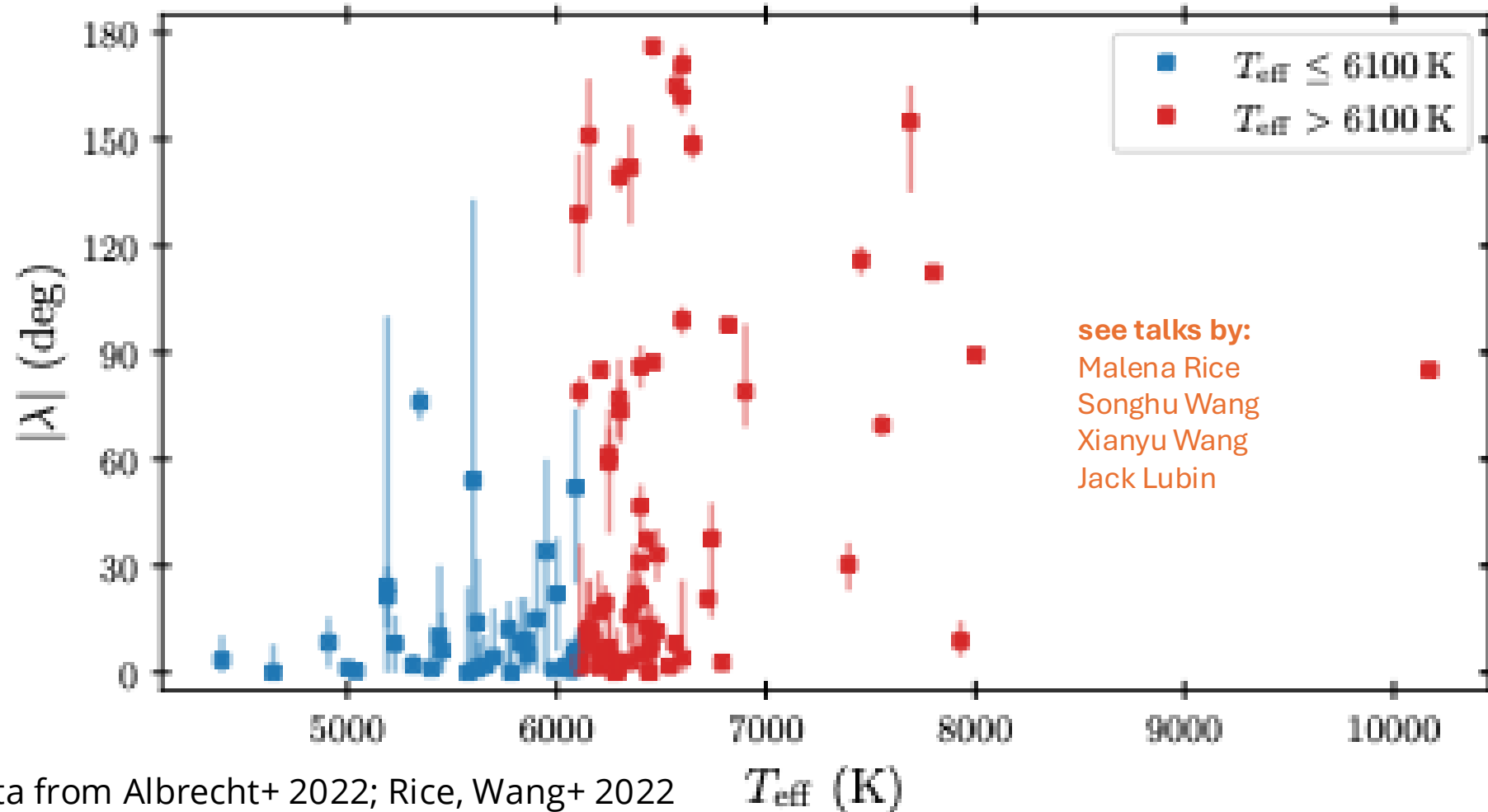


51 Pegasi b
Fellowship in Planetary Astronomy

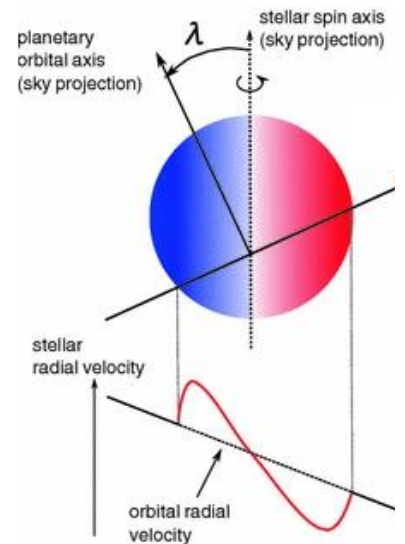


HEISING-SIMONS
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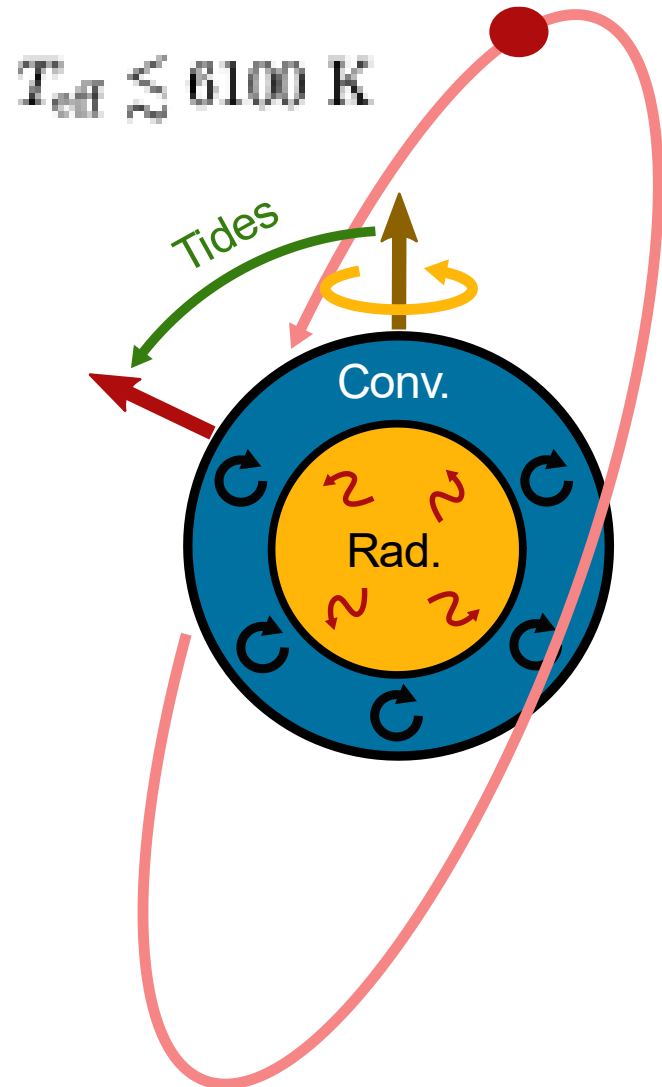
Cool Hosts are Aligned, Hot Hosts are Not



RM Effect
Masuda 2018



Can Tidal Dissipation Align Cool Stars?



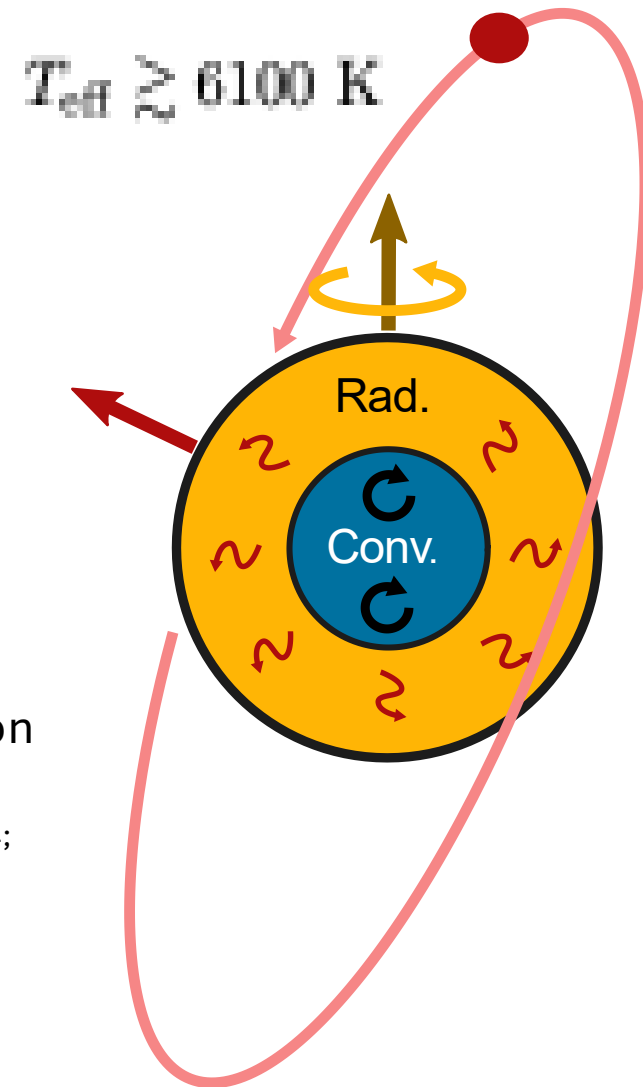
Convective Envelopes can not Dissipate Tidal Flow

Equilibrium Tides

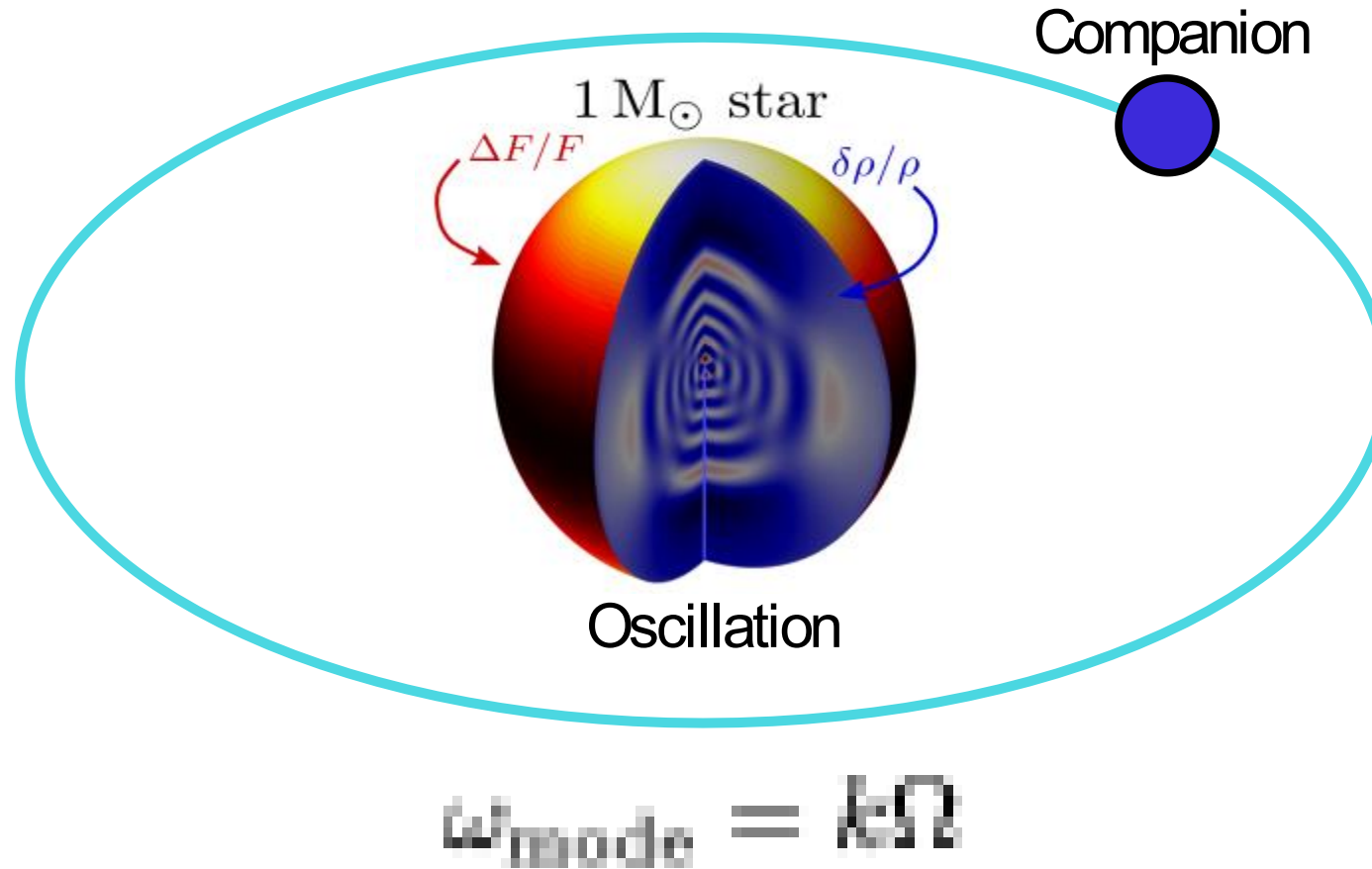
e.g. Barker & Ogilvie 2009;
Winn, Fabrycky+ 2010;
Dawson 2014

Inertial Wave Dissipation

e.g. Lai 2012; Rogers & Lin 2013;
Valsecchi & Rasio 2014; Xue+ 2014;
Li & Winn 2016; Lin & Ogilvie 2017;
Anderson+ 2021; Spalding & Winn 2022

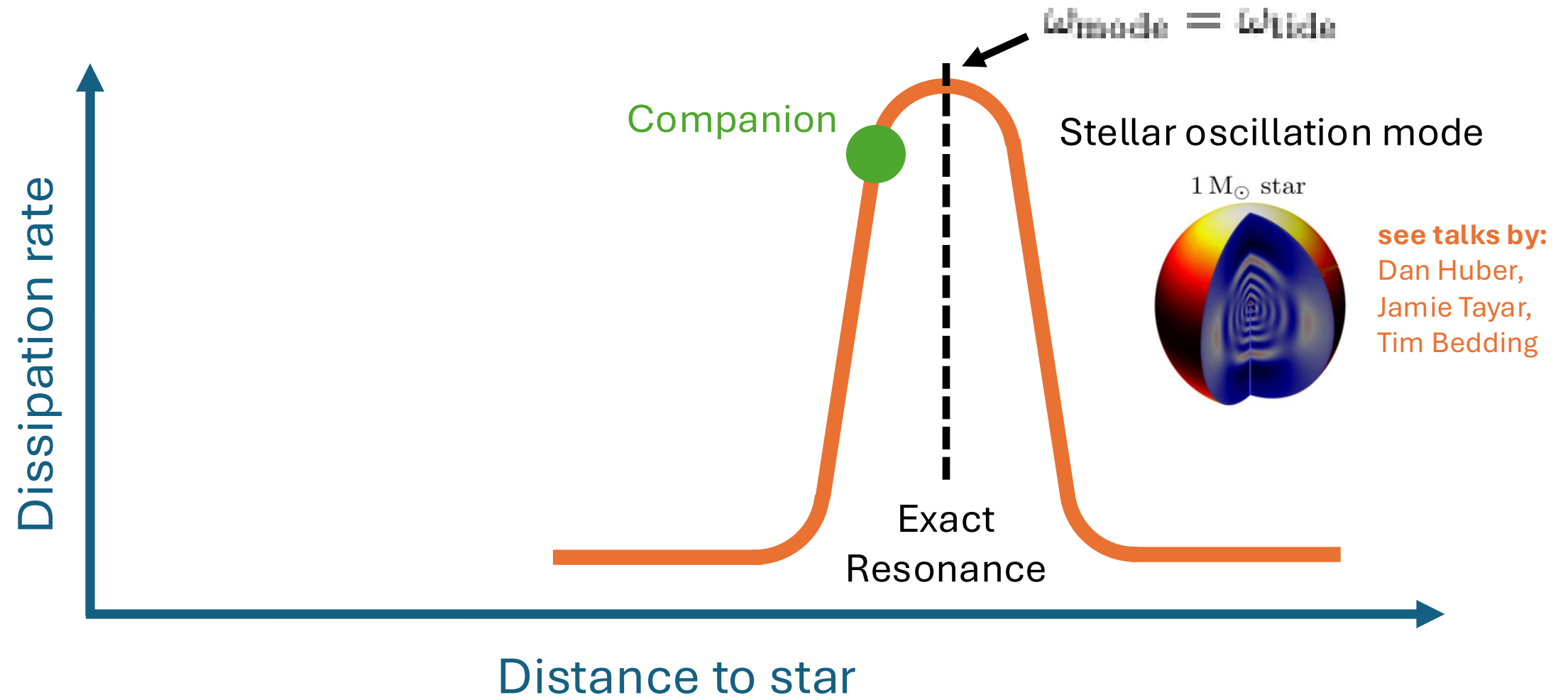


Resonance Locking: Orbit Coupled to Oscillation

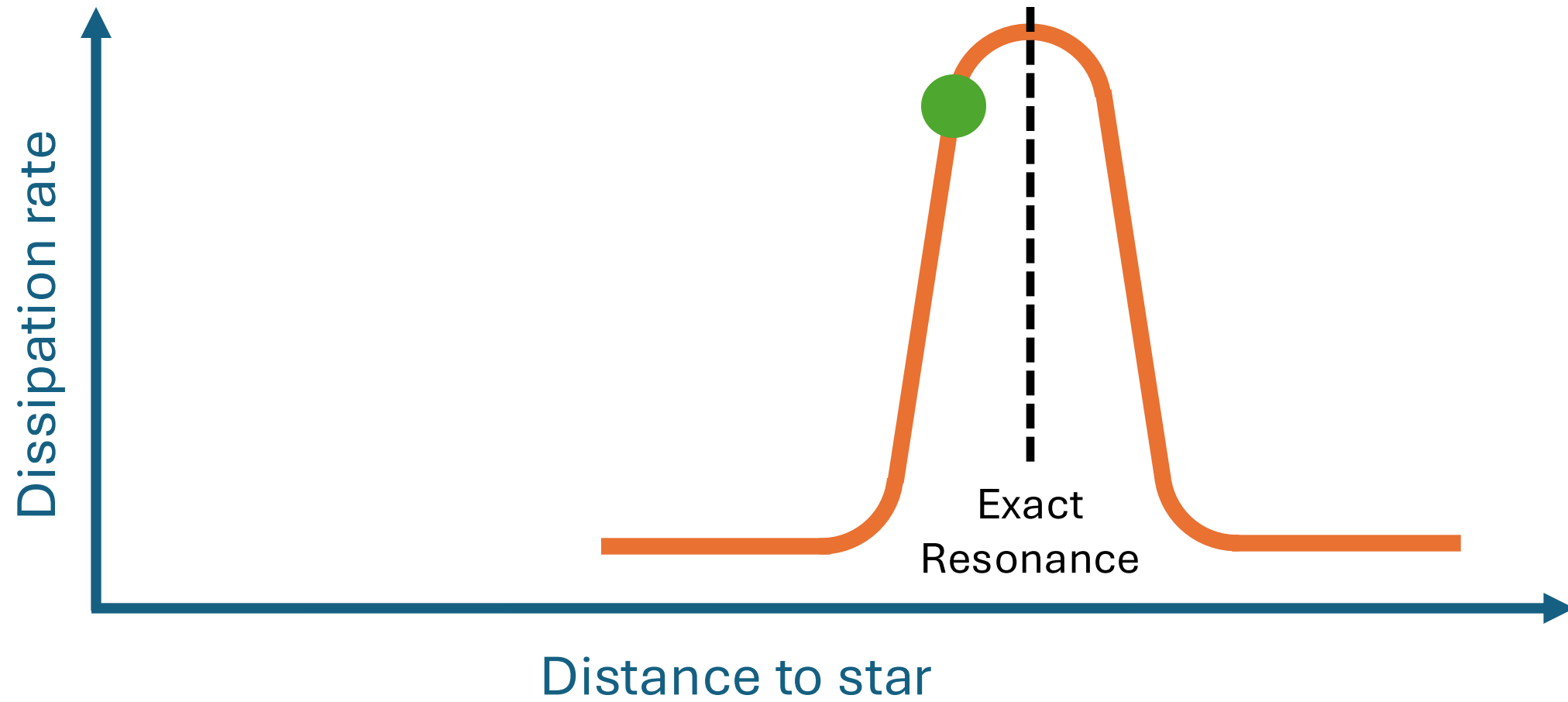


e.g. Witte & Savonije 1999, 2001; Burkart+ 2012;
Fuller 2017; Zanazzi & Wu 2021; Ma & Fuller 2021

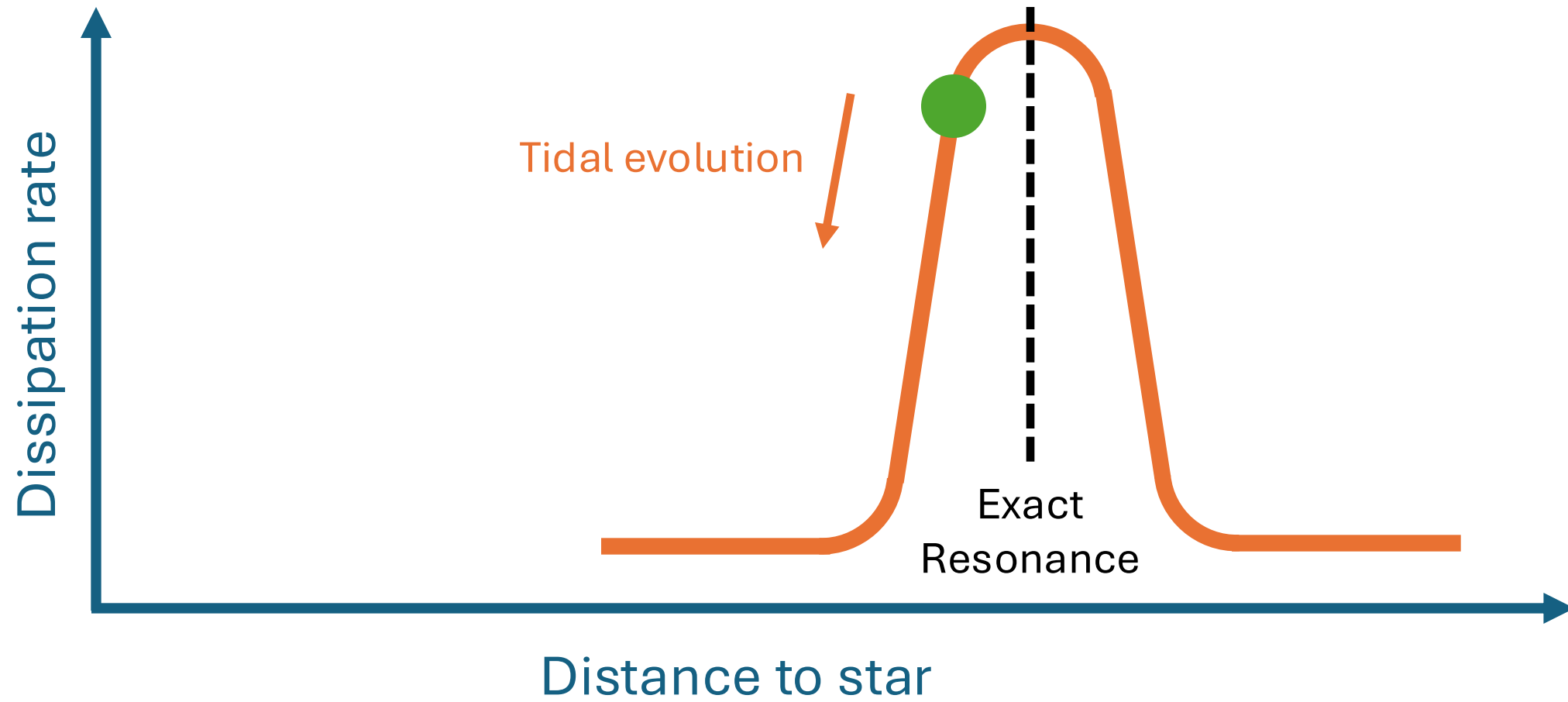
Physics of Resonance Locking



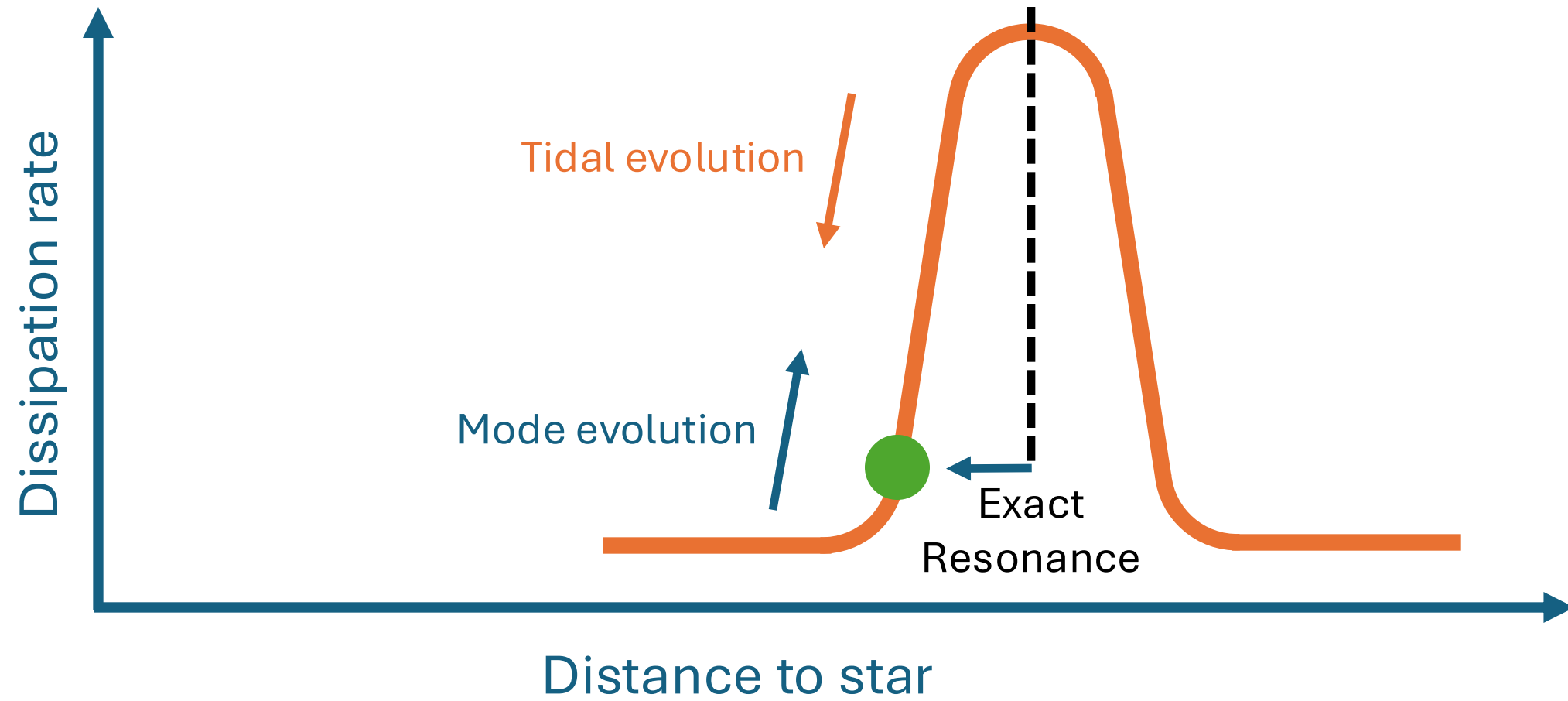
Physics of Resonance Locking



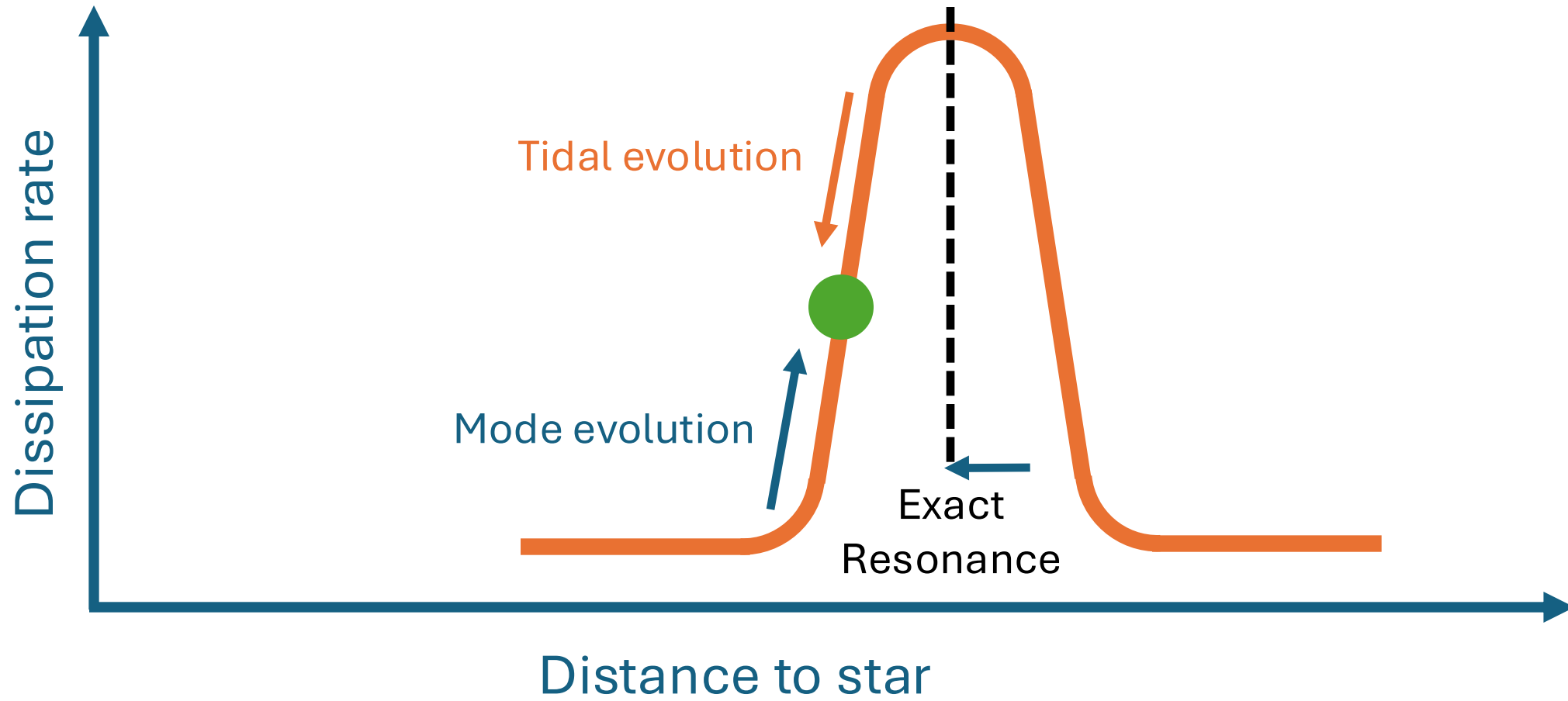
Physics of Resonance Locking



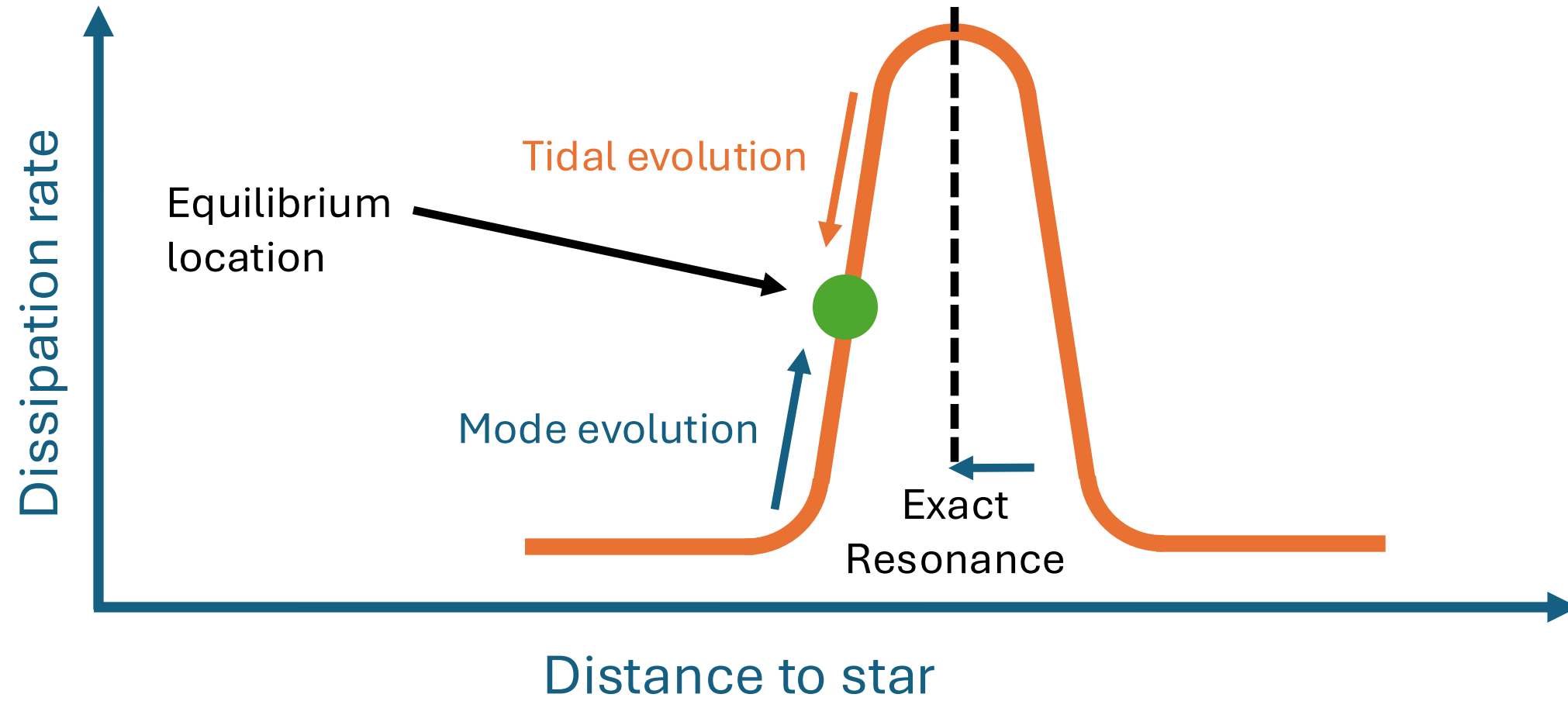
Physics of Resonance Locking



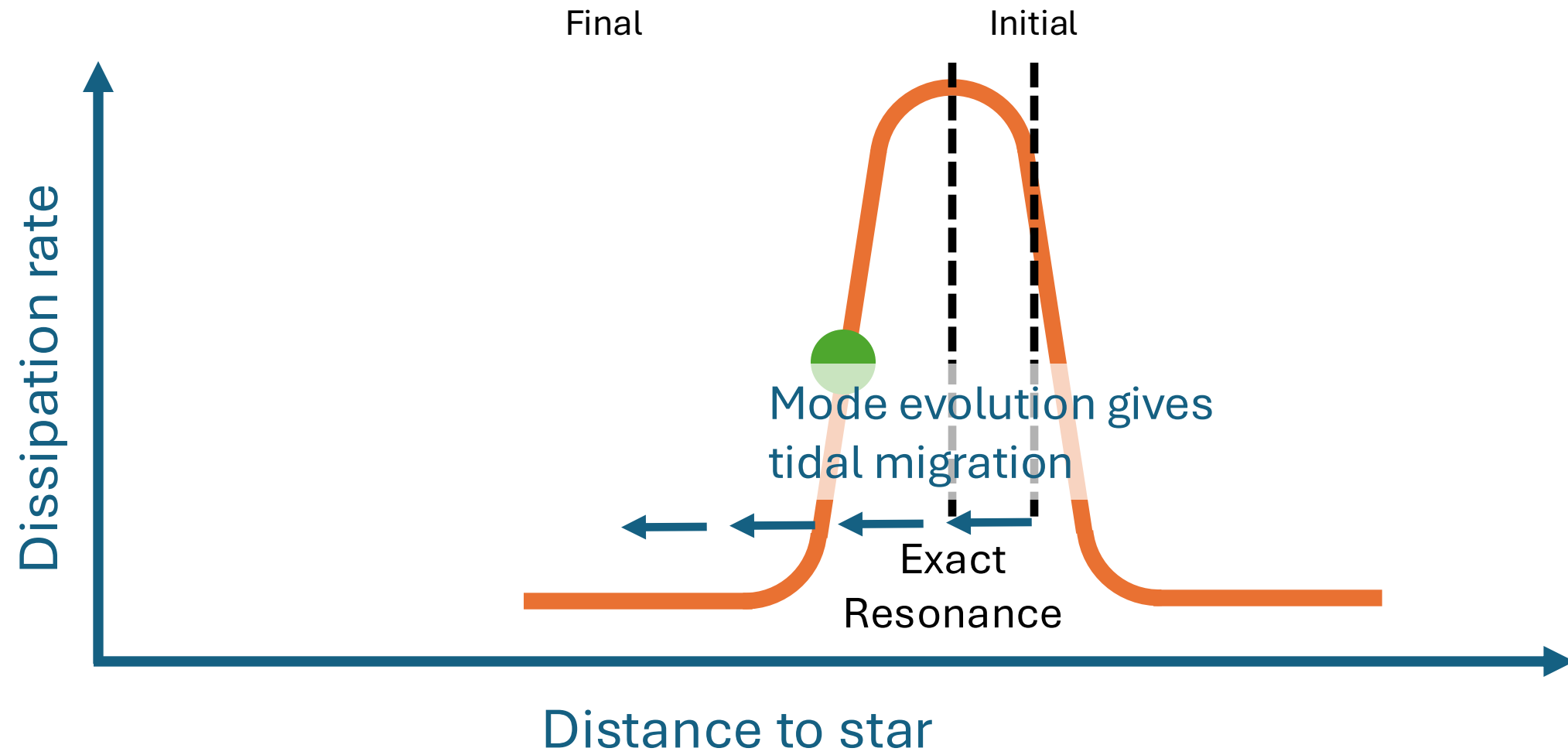
Physics of Resonance Locking



Physics of Resonance Locking

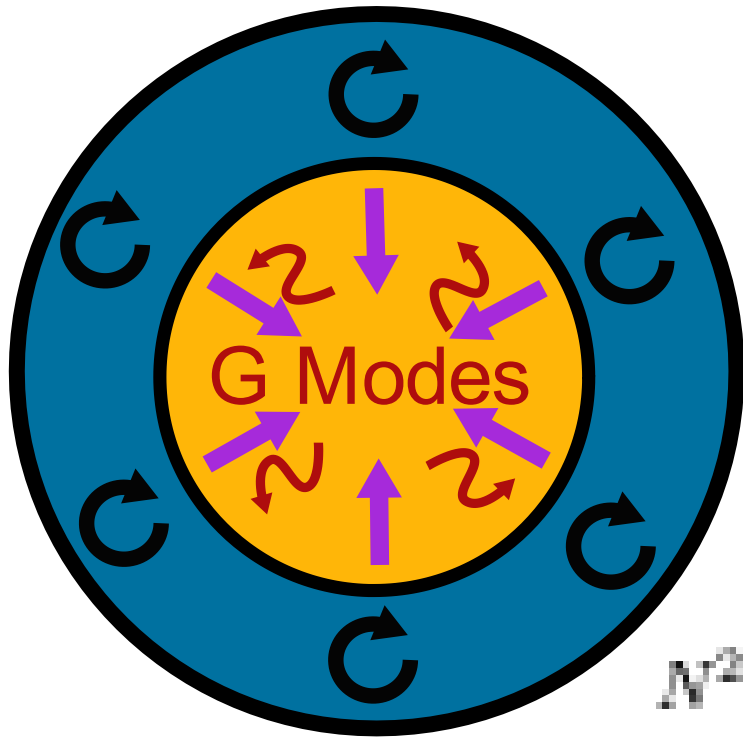


Physics of Resonance Locking



Core G Modes Affected, Envelope G Modes are Not

$T_{\text{eff}} \lesssim 6100 \text{ K}$



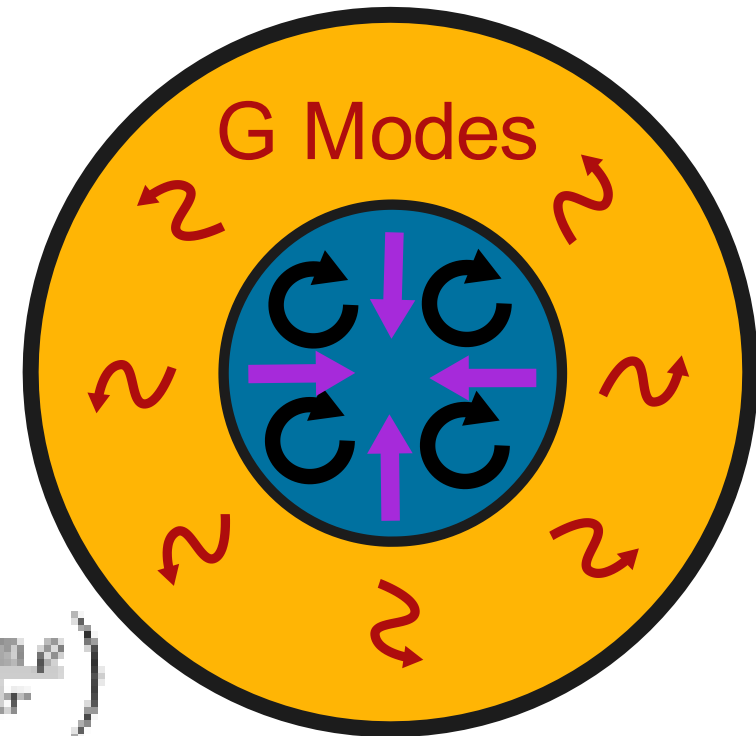
$\omega \propto N$ increases

Main-sequence
nuclear burning,
core contraction

Zanazzi, Dewberry,
& Chiang 2024

$$N^2 = g \left(\frac{1}{r_1} \frac{d \ln g}{dr} - \frac{d \ln \rho}{dr} \right)$$

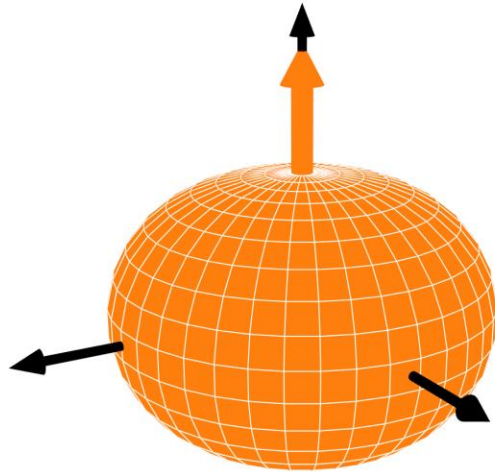
$T_{\text{eff}} \gtrsim 6100 \text{ K}$



$\omega \propto N \approx \text{constant}$

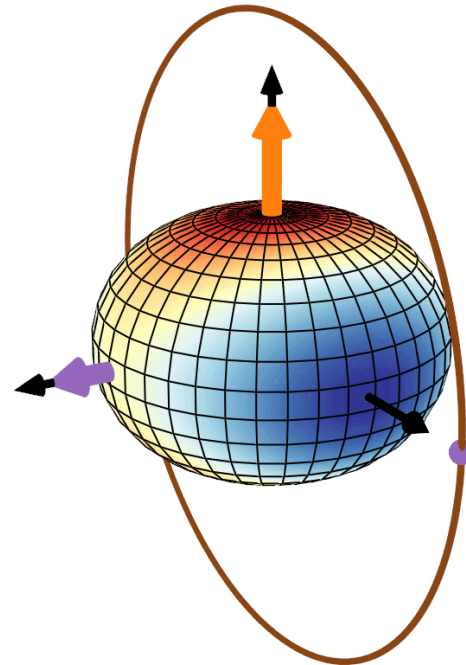
Resonance Locking affects Stellar Obliquities

Stellar oscillation

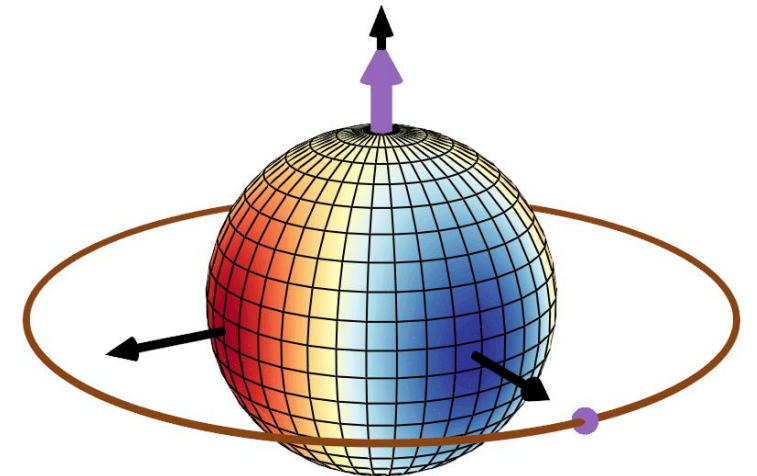


Zanazzi, Dewberry,
& Chiang 2024

Obliquity damping

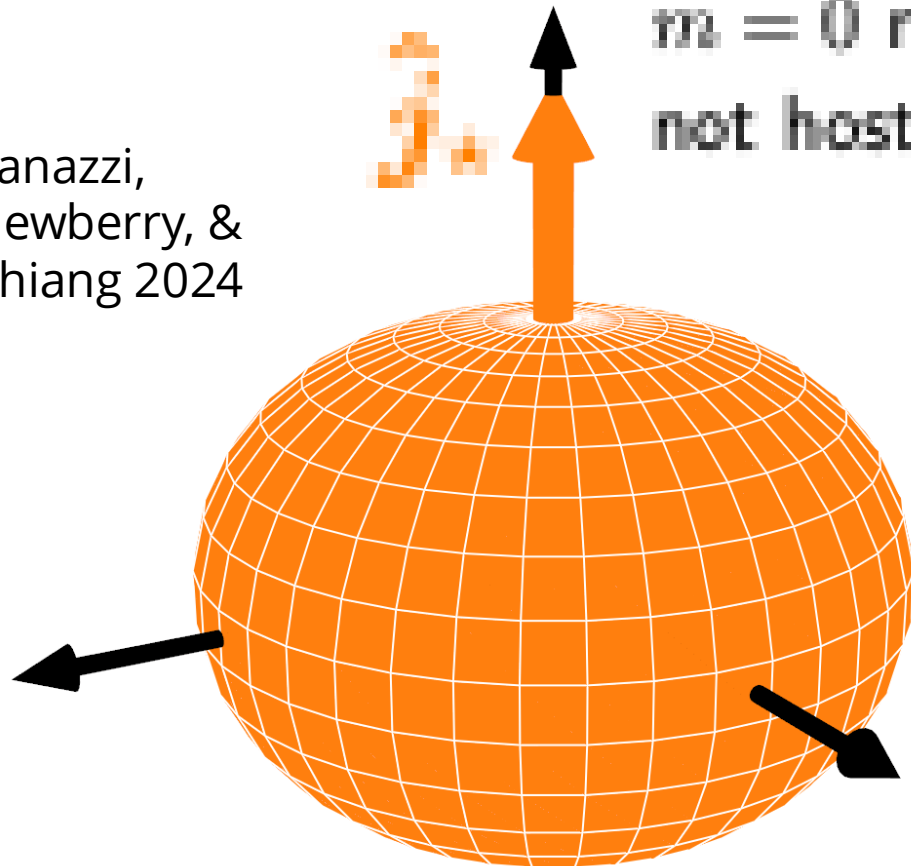


Companion forcing



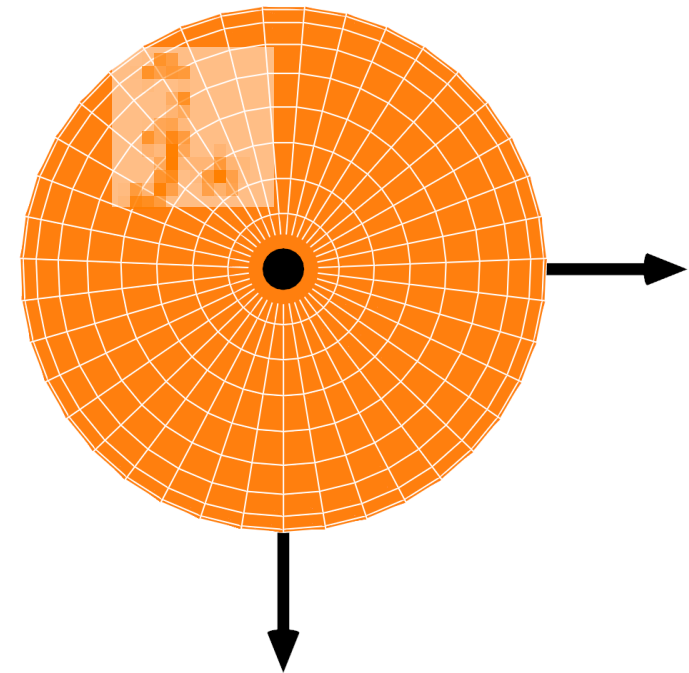
Axisymmetric Oscillation

Zanazzi,
Dewberry, &
Chiang 2024



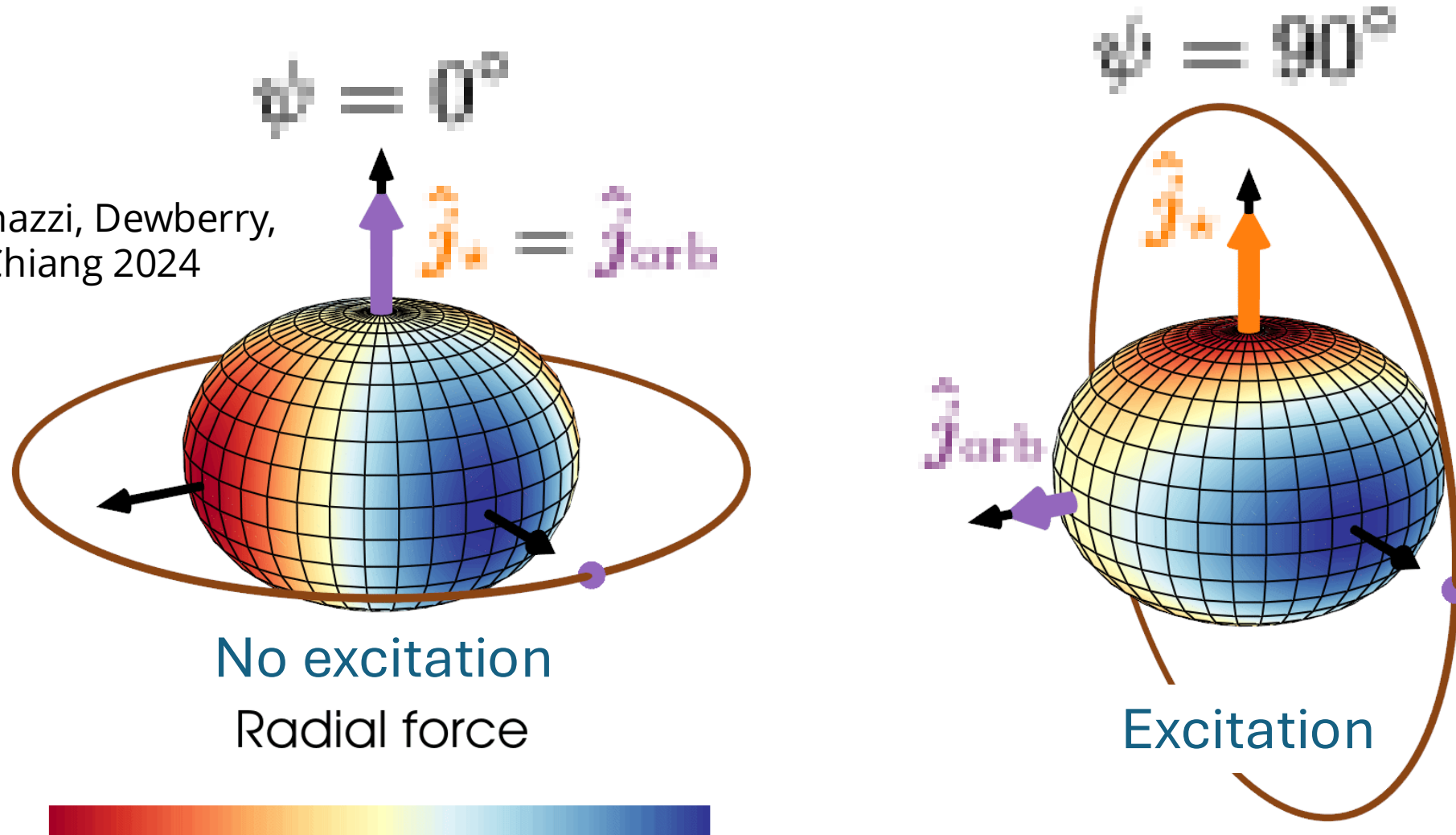
$m = 0$ mode evolves orbit,
not host's spin

Azimuthal number $m = 0$

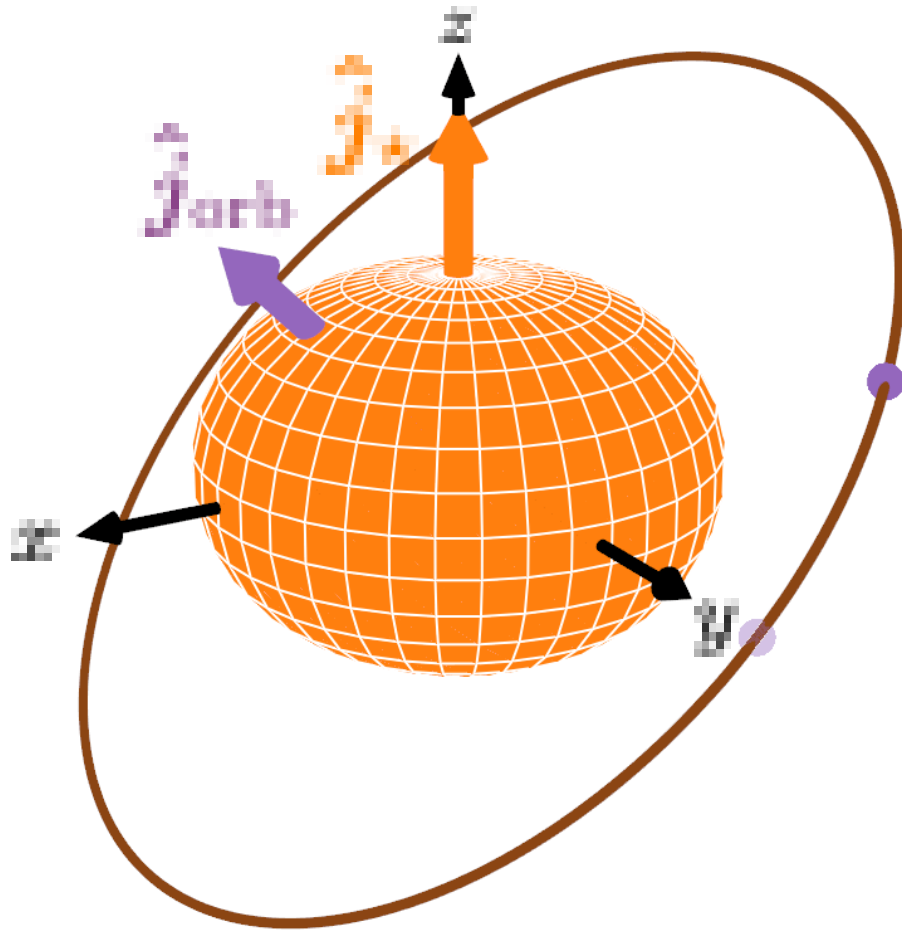


Inclined planet excites axisymmetric modes

Zanazzi, Dewberry,
& Chiang 2024



Tidal Lag and Torques



Oscillation bulge (light purple)

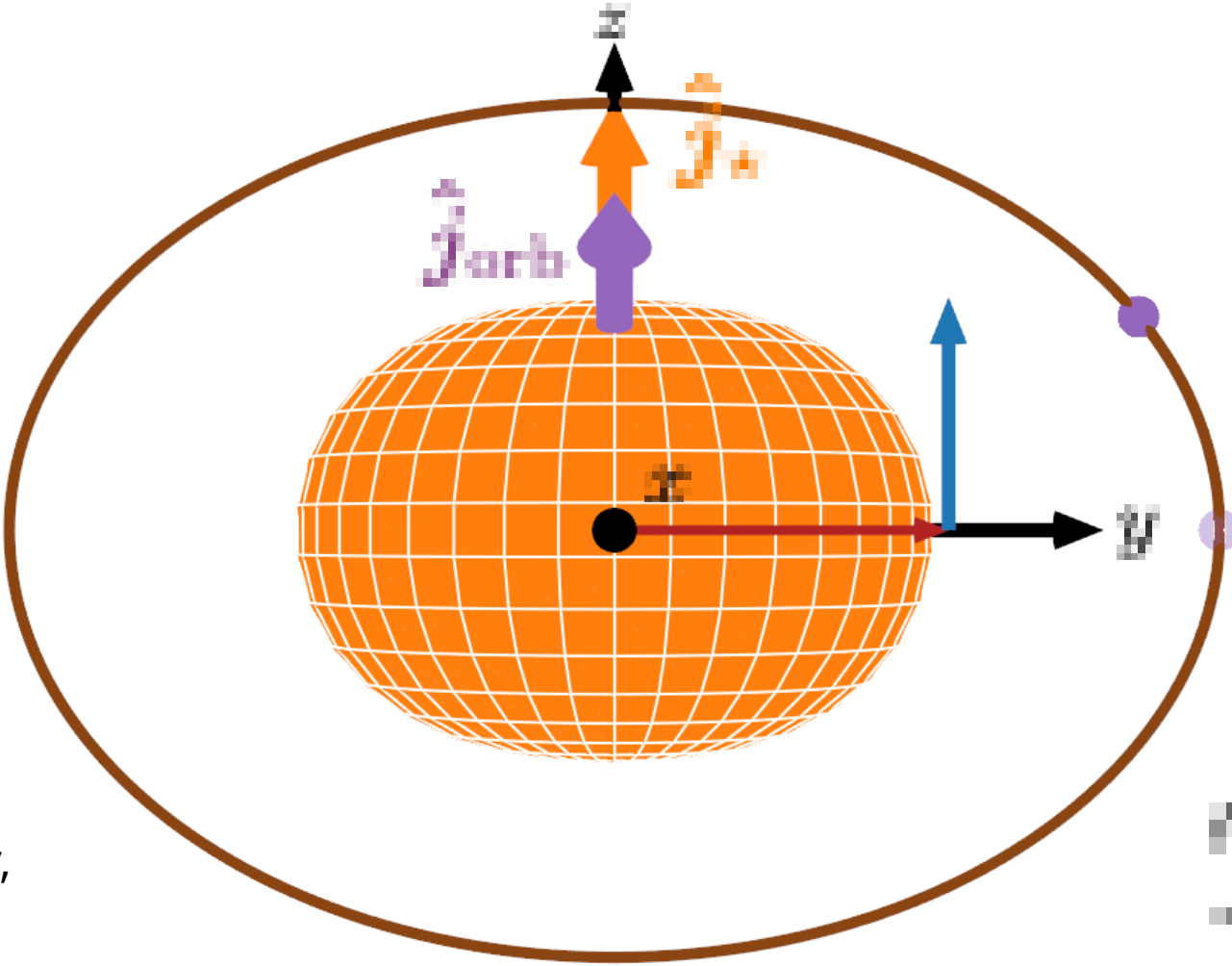
lags

planet location (dark purple)

due to dissipation

Zanazzi, Dewberry, & Chiang 2024

Alignment Torque



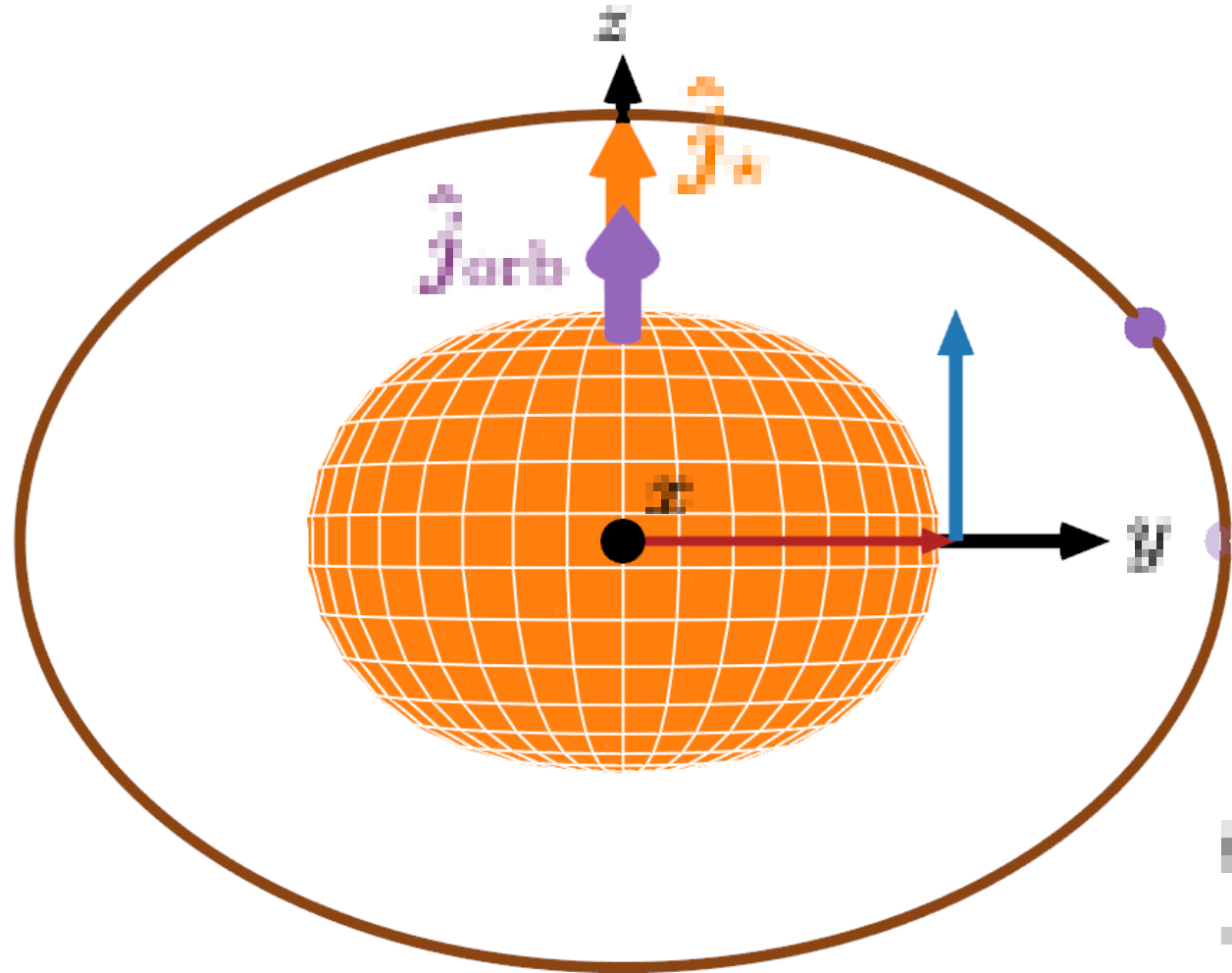
\mathbf{r} = position of oscillation bulge

\mathbf{F} = tidal force

$$\mathbf{T} \geq 0$$

Zanazzi, Dewberry,
& Chiang 2024

Alignment Torque



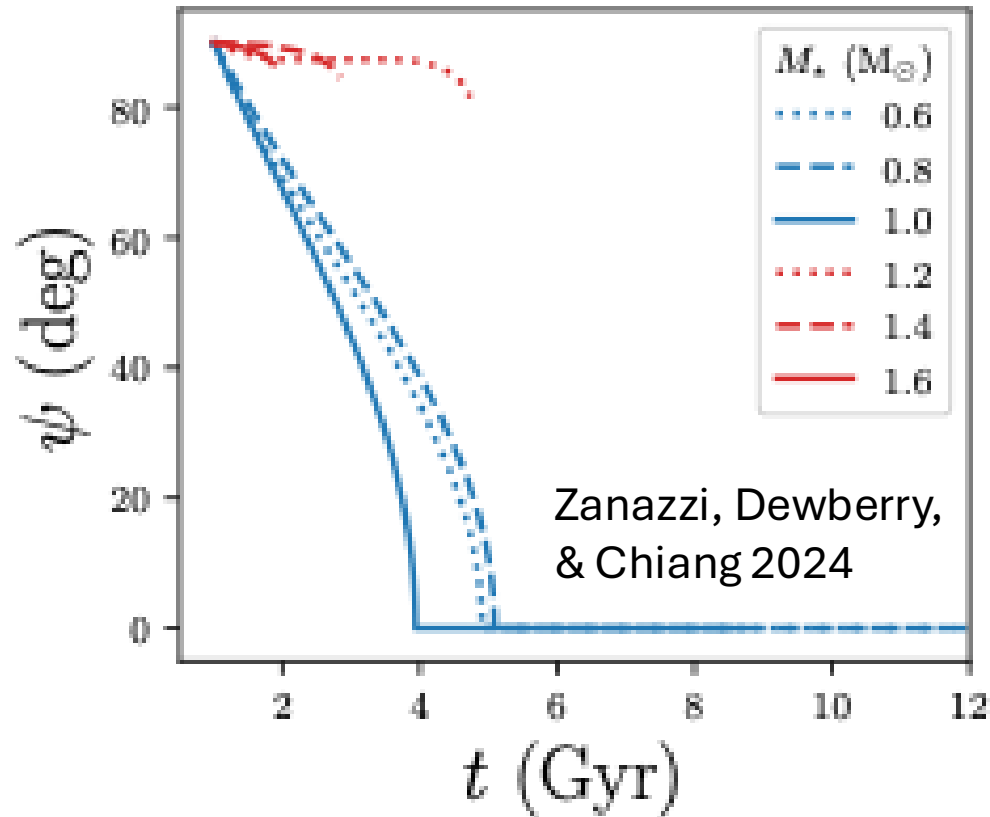
\mathbf{r} = position of oscillation bulge

\mathbf{F} = tidal force

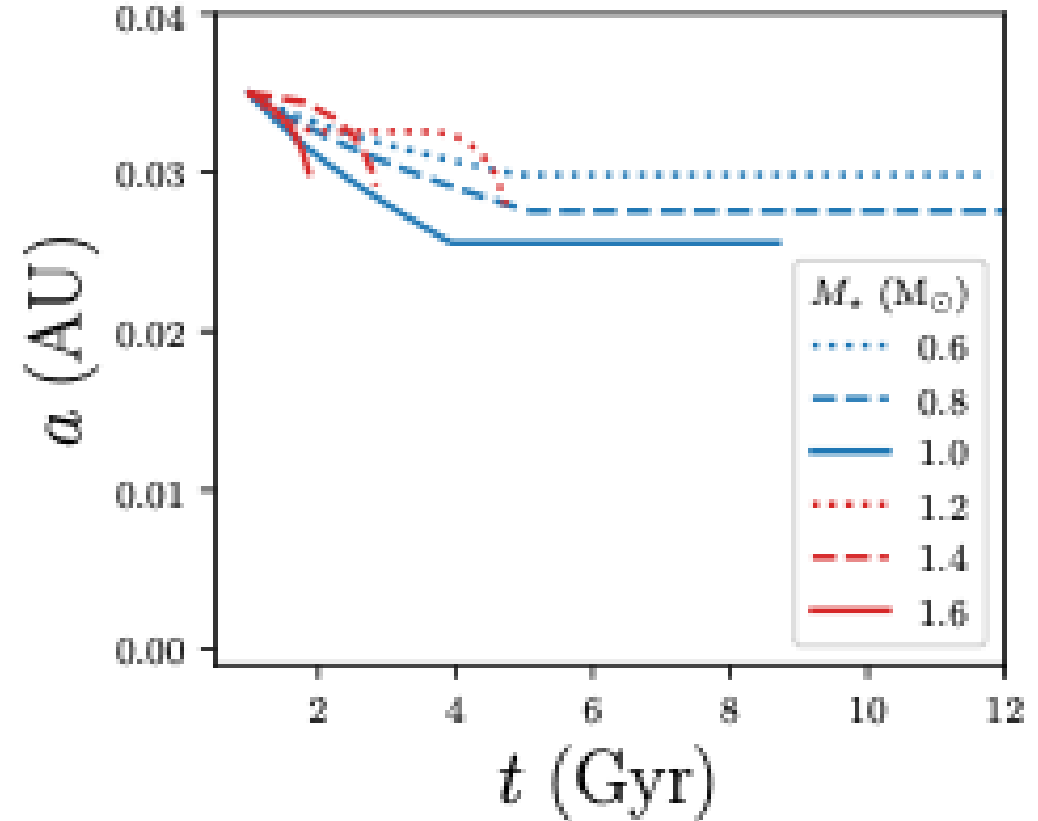
$$\mathbf{T}_g \geq 0$$

Zanazzi, Dewberry,
& Chiang 2024

Cool Stars Align, Hot Stay Misaligned



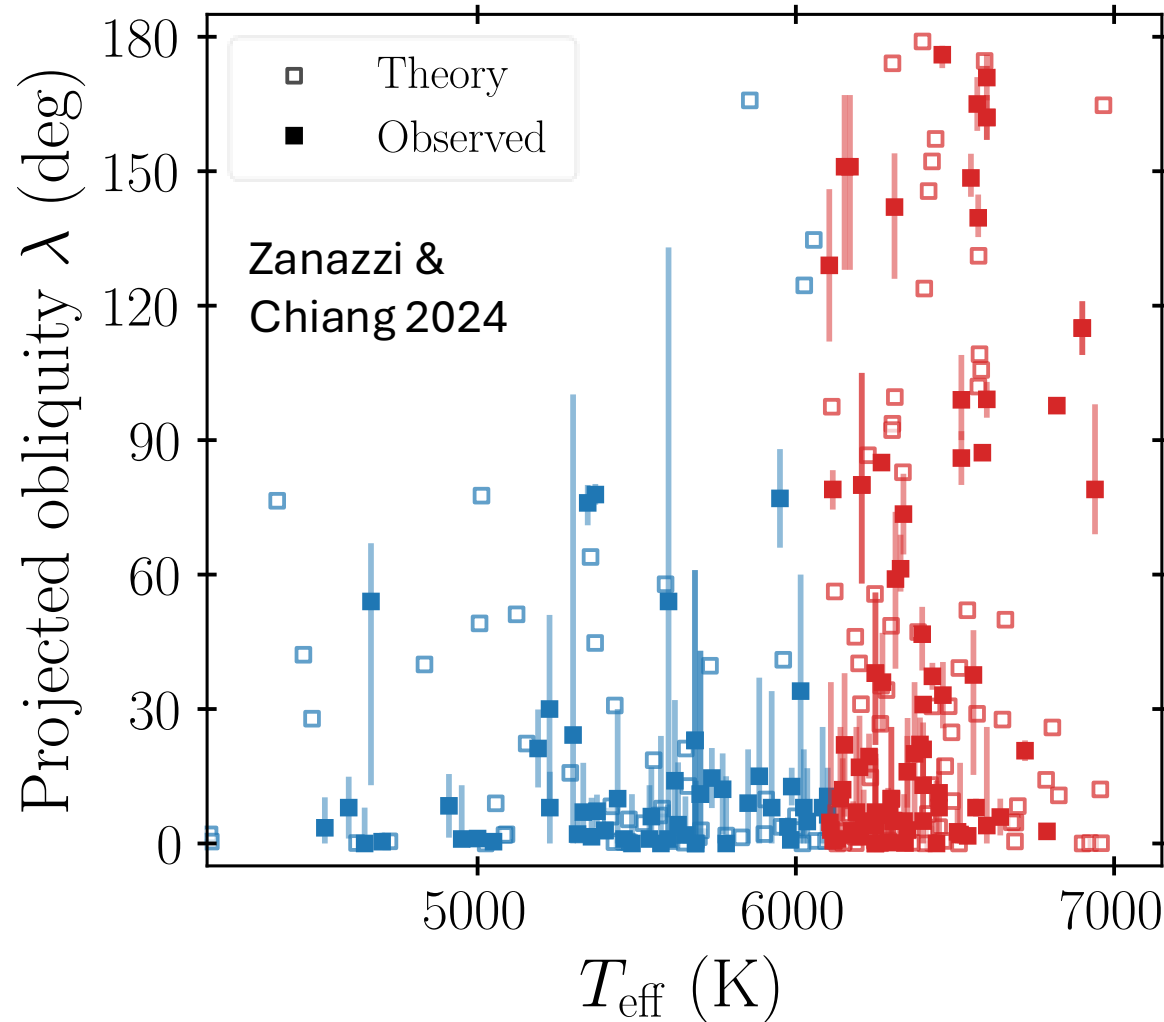
Cool stars align...



but don't engulf

Jupiter mass planet, $t_0 = 1$ Gyr, $t_{\text{end}} = \min(t_{\text{MS}}, 12)$ Gyr

Resonance Locks Damp Cool Obliquities



Population synthesis:

$\cos \psi_0 \sim \text{hot stars}$

$M_p \sim M_{p,\text{obs}}, t_0 = 0.1 \text{ Gyr},$

$t_{\text{max}} = \min(t_{\text{MS}}, 12 \text{ Gyr}),$

$a_0/R \sim \mathcal{N}(13, 3.5)$

Data: HJs with $\frac{a}{R} < 12$

Albrecht+ 2022; Rice, Wang+ 2022;

Knudstrup+ 2024 incl. Zanazzi; Wang, Rice, Wang+ 2024

Conclusions

Resonance locking preferentially damps the obliquities of cool stars, which can explain their low obliquities

Zanazzi & Chiang 2024, arXiv:2410.10943

Zanazzi, Dewberry & Chiang 2024, ApJL, 967, L29

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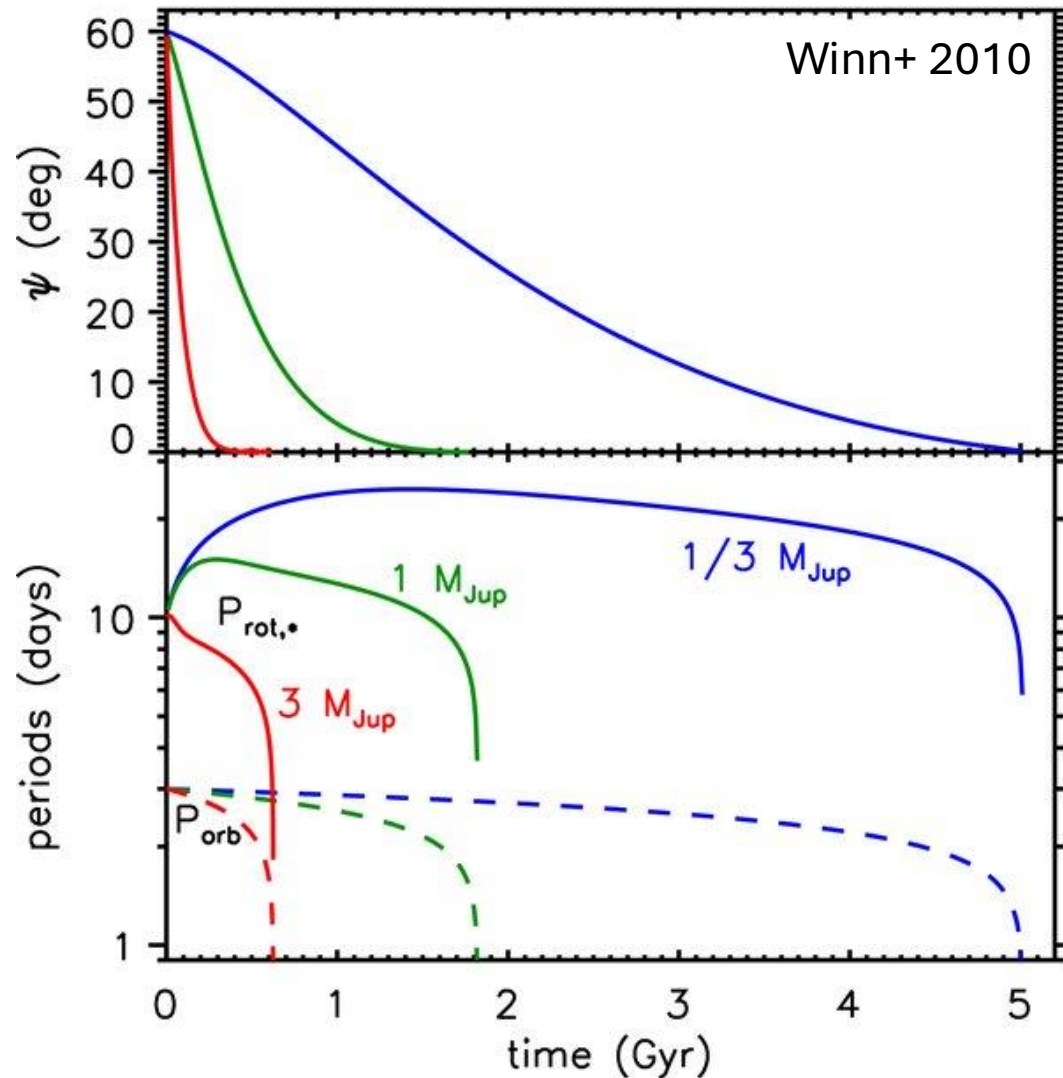
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Equilibrium Tides Engulf Hot Jupiters

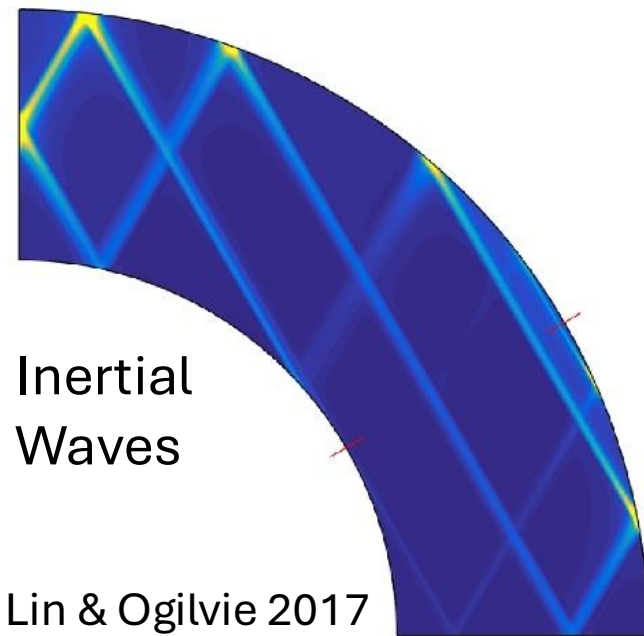


Equilibrium tides align...

but also engulf

e.g. Barker & Ogilvie 2009;
Winn+ 2010; Dawson 2014

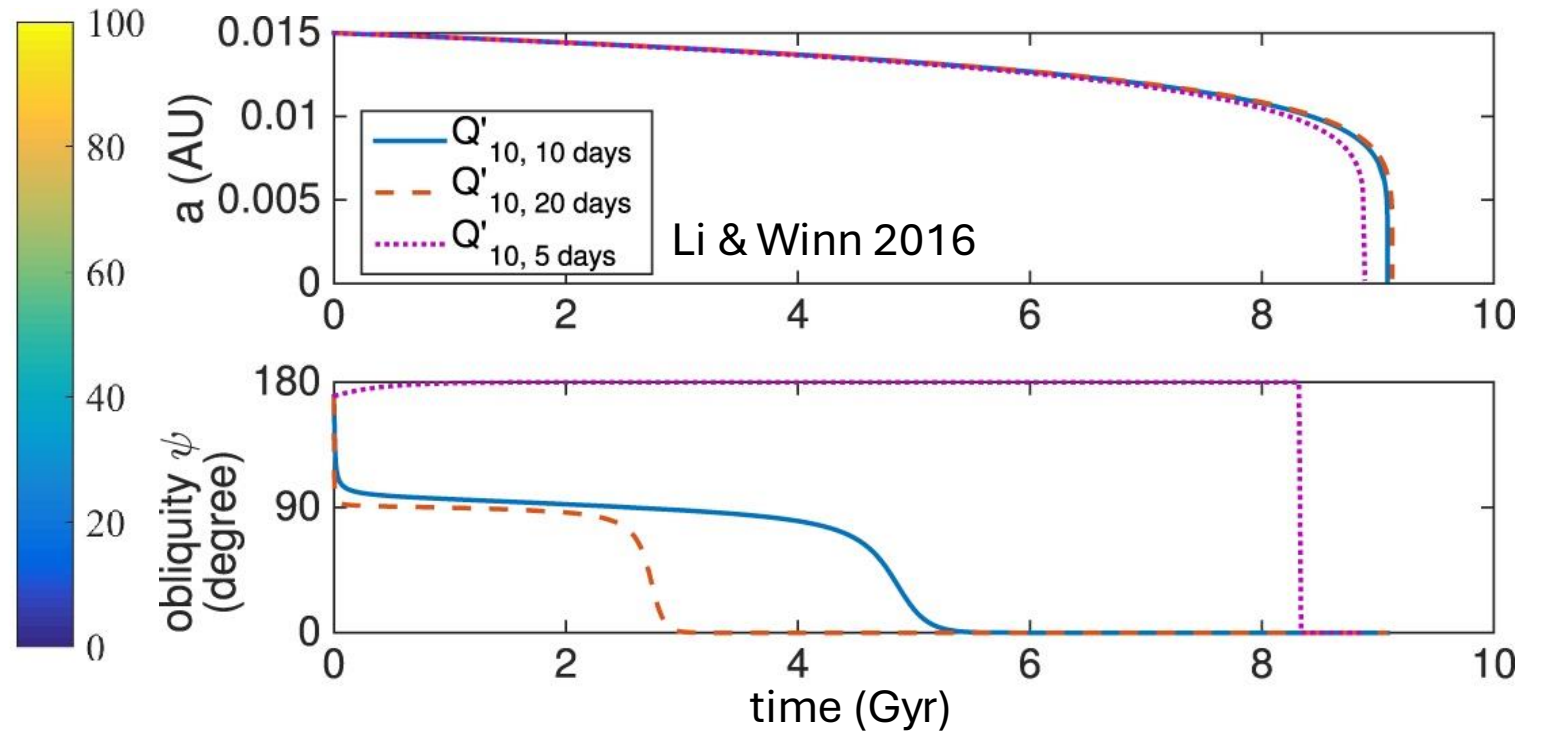
Inertial Waves Damp Obliquities without Engulfment...



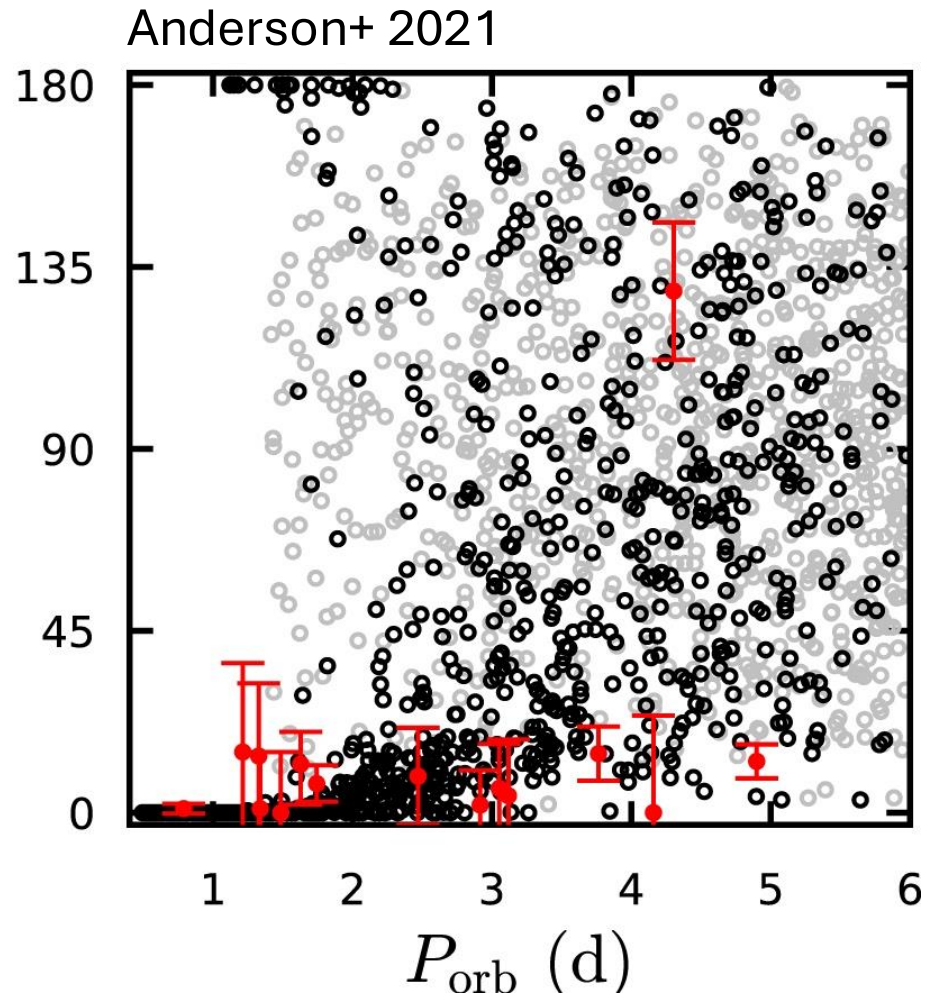
see also e.g. Ogilvie & Lin 2004, 2007; Wu 2005 a,b; Dewberry 2024

Inertial waves align while fixing a

Lai 2012



... but Obliquities are not Damped Enough



Black dots: True obliquities with inertial waves & equilibrium tides

Red dots: Projected obliquities

see also e.g. Lai 2012; Rogers & Lin 2013; Valsecchi & Rasio 2014; Xue+ 2014; Li & Winn 2016; Lin & Ogilvie 2017; Penev+ 2018; Spalding & Winn 2022

Obliquity Evolution from Resonance Locks

Zanazzi, Dewberry, & Chiang 2024

$$\frac{1}{a} \frac{da}{dt} = -\frac{1}{\eta t_{ev}},$$

$$\frac{dJ_s}{dt} = \frac{m}{2k\sqrt{1-e^2}} \frac{J_{orb}}{\eta t_{ev}},$$

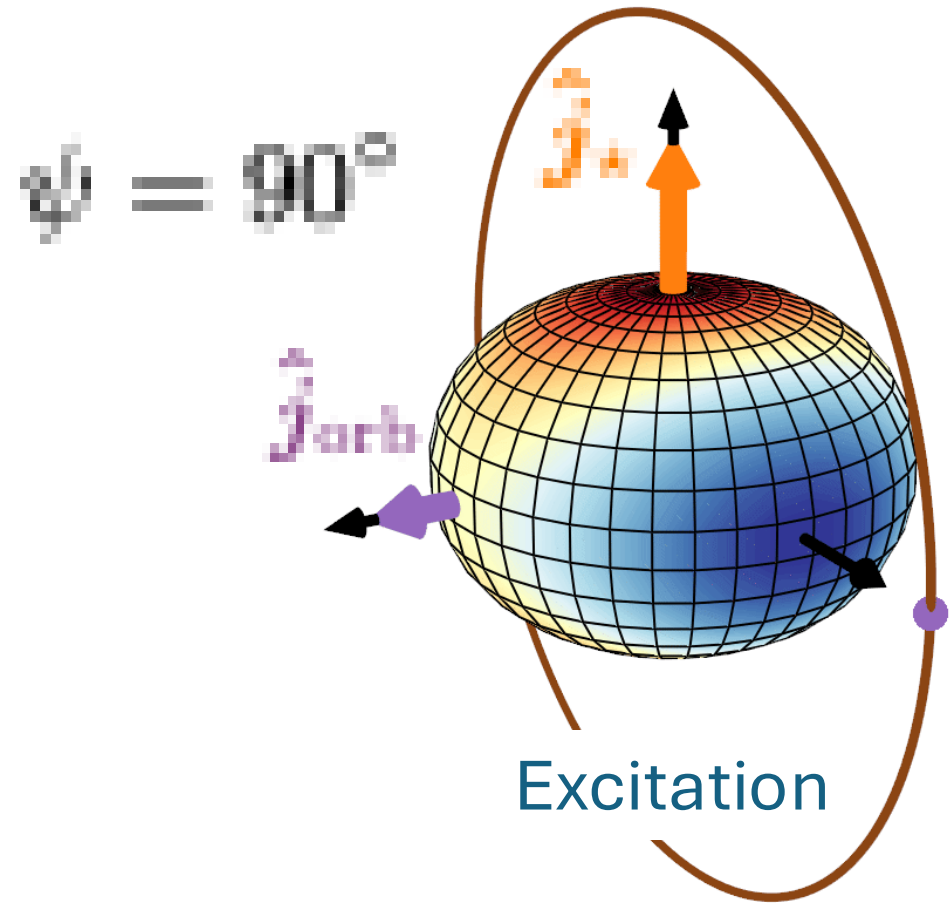
$$\frac{de}{dt} = -\frac{1-e^2}{2e} \left[1 - \frac{1}{k\sqrt{1-e^2}} (\tau_m \sin \psi + m \cos \psi) \right] \frac{1}{\eta t_{ev}},$$

$$\frac{d\psi}{dt} = -\frac{1}{2k\sqrt{1-e^2}} \left[\tau_m \left(\frac{J_{orb}}{J_s} + \cos \psi \right) - m \sin \psi \right] \frac{1}{\eta t_{ev}},$$

where $t_{ev} = \omega/\dot{\omega}$, $\tau_m = k\Omega T_{z,m}/\dot{E}_m$.

Inclined planet excites $m < 2$ modes

$$Y_{\ell m_{\text{orb}}}(\theta_{\text{orb}}, \varphi_{\text{orb}}) = \sum_{m=-\ell}^{\ell} D_{m m_{\text{orb}}}^{\ell}(-\Omega_{\text{orb}} t, \psi, \omega_p + \pi/2) Y_{\ell m}(\theta, \varphi)$$



Future Work: Dissipation of G-Modes

Line: Linear Radiative Diffusion

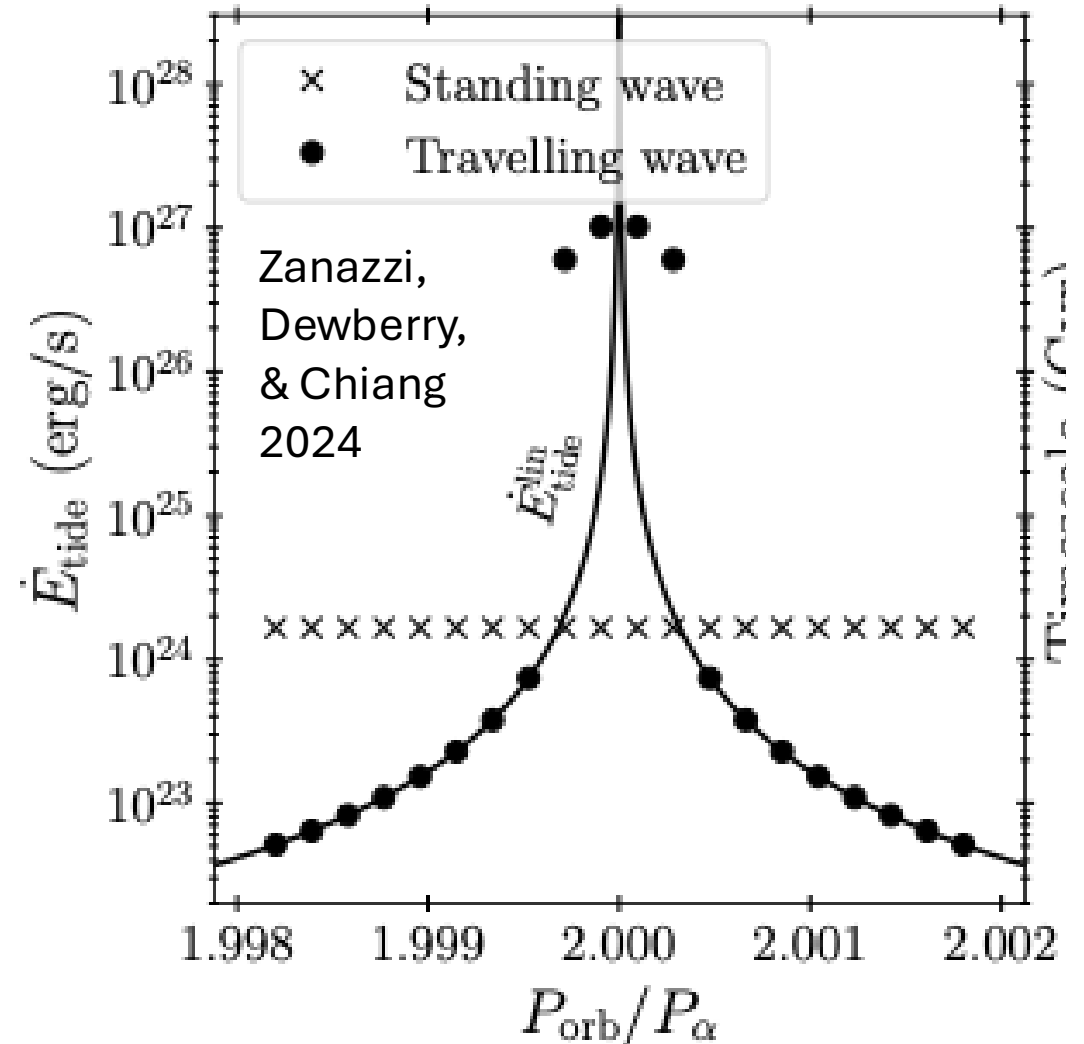
e.g. Fuller+ 2017; Zanazzi & Wu 2021

Crosses: Non-linear dissipation, child standing waves

e.g. Essick & Weinberg 2016

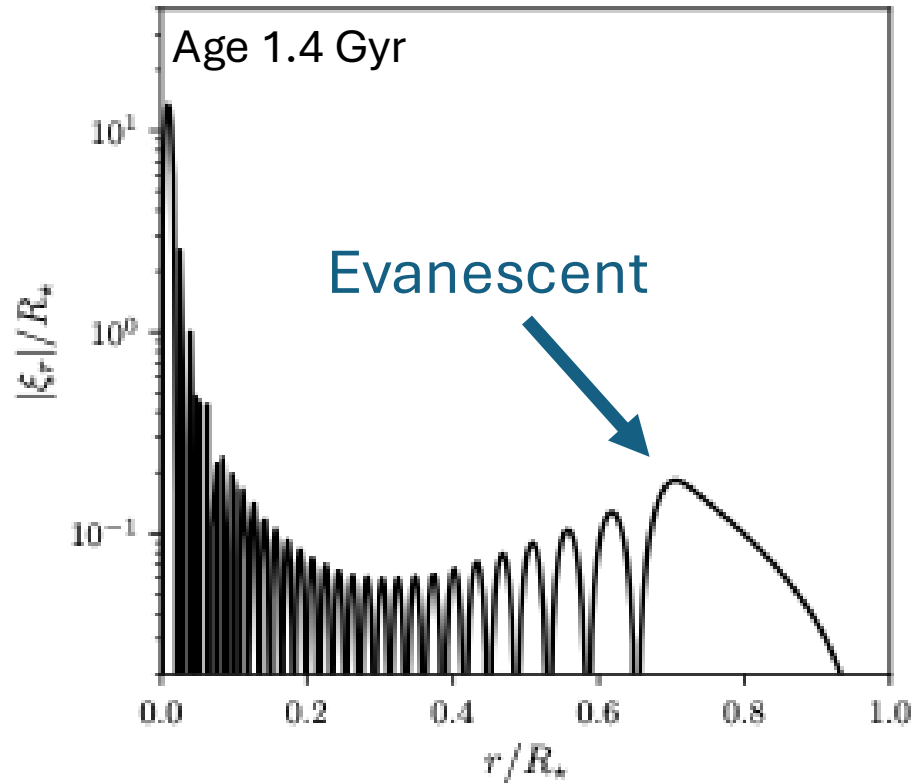
Dots: Non-linear dissipation, child traveling waves

Wu & Goldreich 2001; Weinberg+ 2012;
Zanazzi, Dewberry, & Chiang 2024



Future work: Post-Main-Sequence Locks

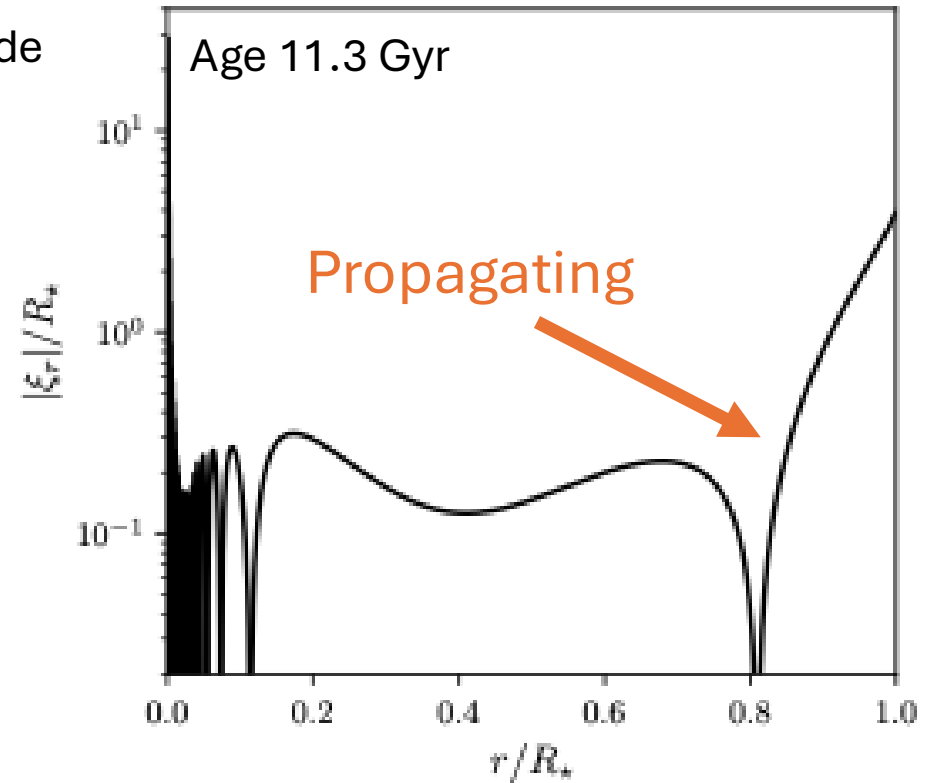
Main-sequence g-mode



Locked, trapped main-sequence modes...

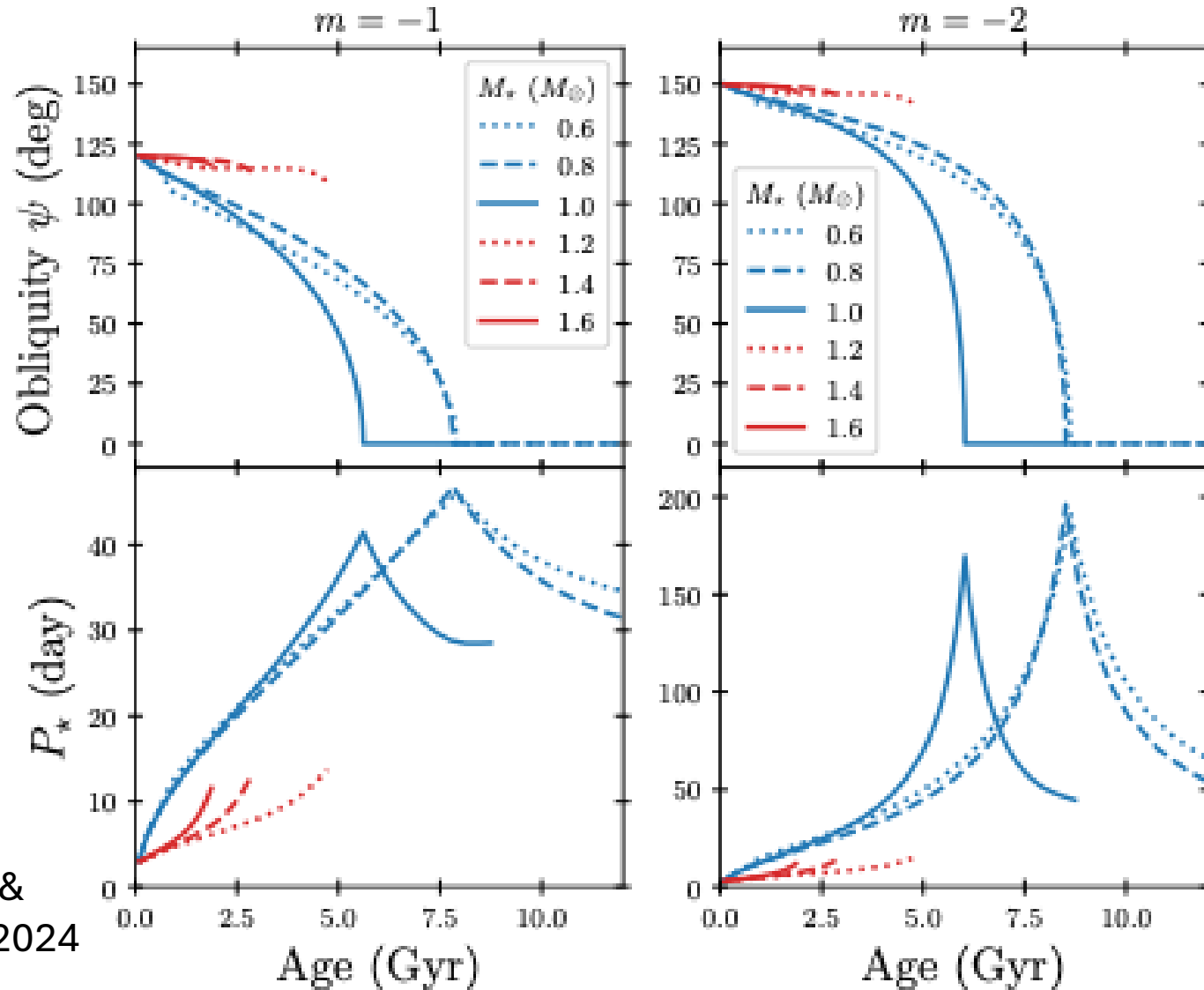
$n = -30$ mode
for solar star

Subgiant mixed-mode



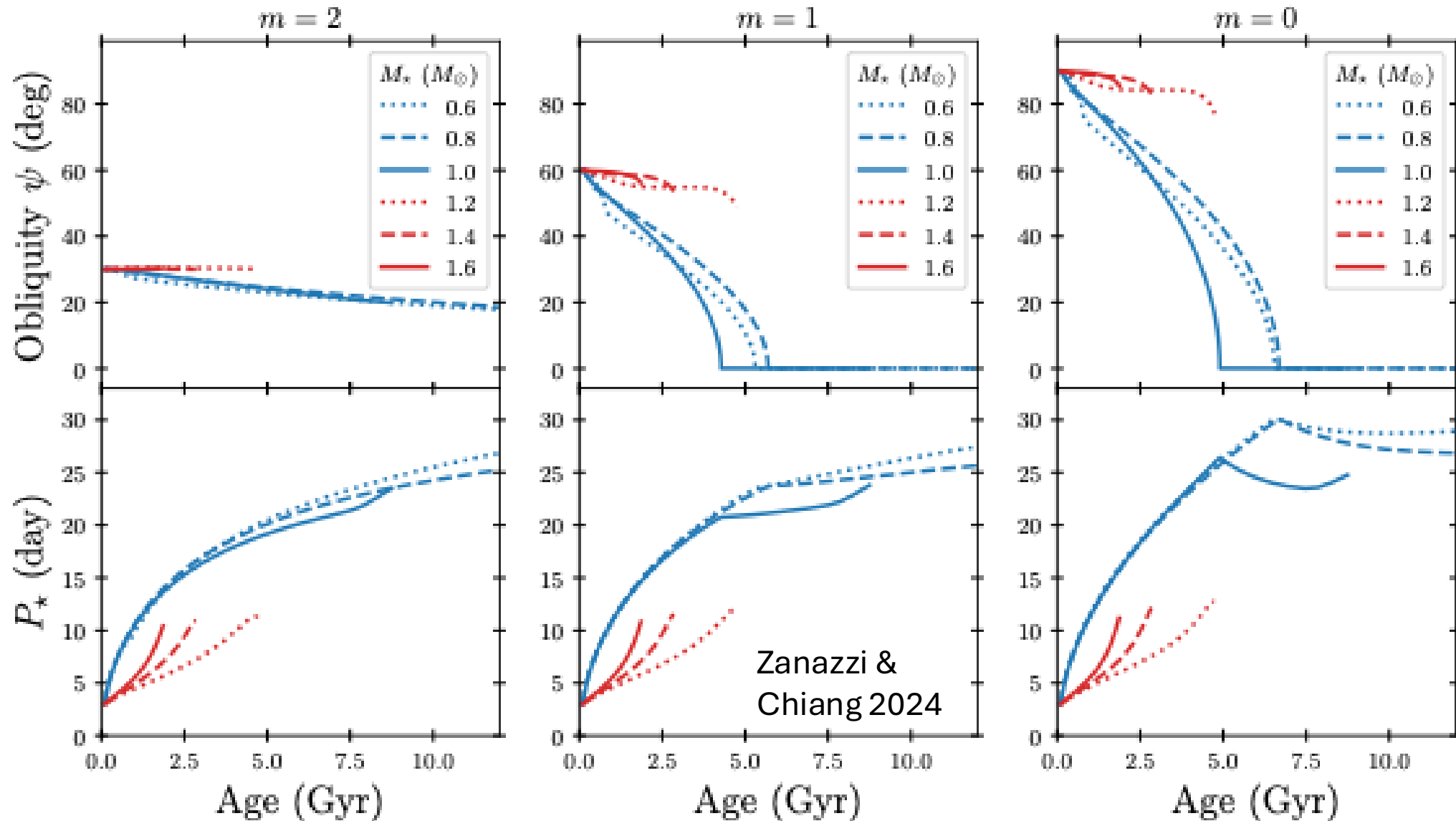
...become visible on the post-main-sequence

Retrograde Obliquities Damp

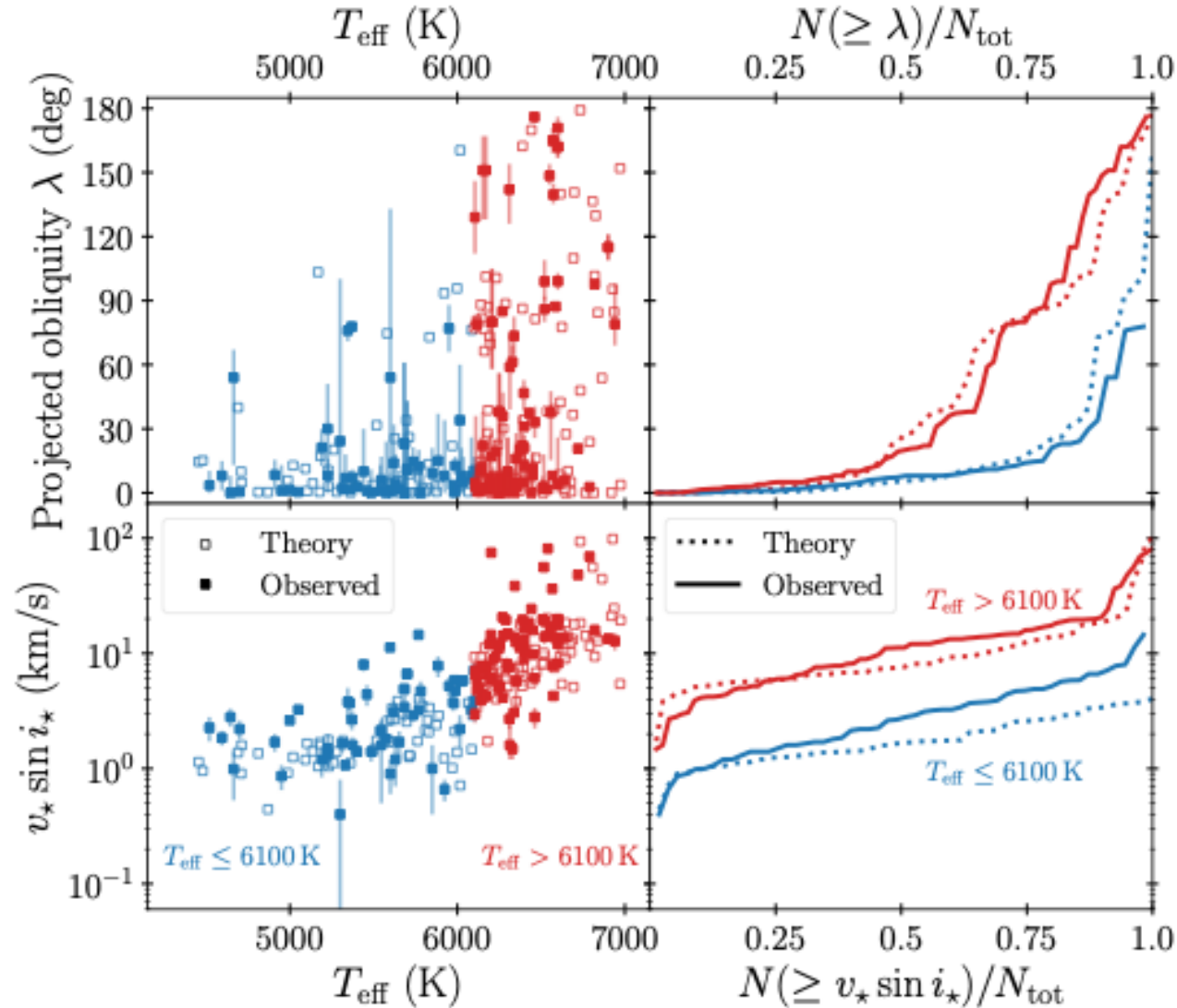


Zanazzi &
Chiang 2024

Prograde Obliquities Damp

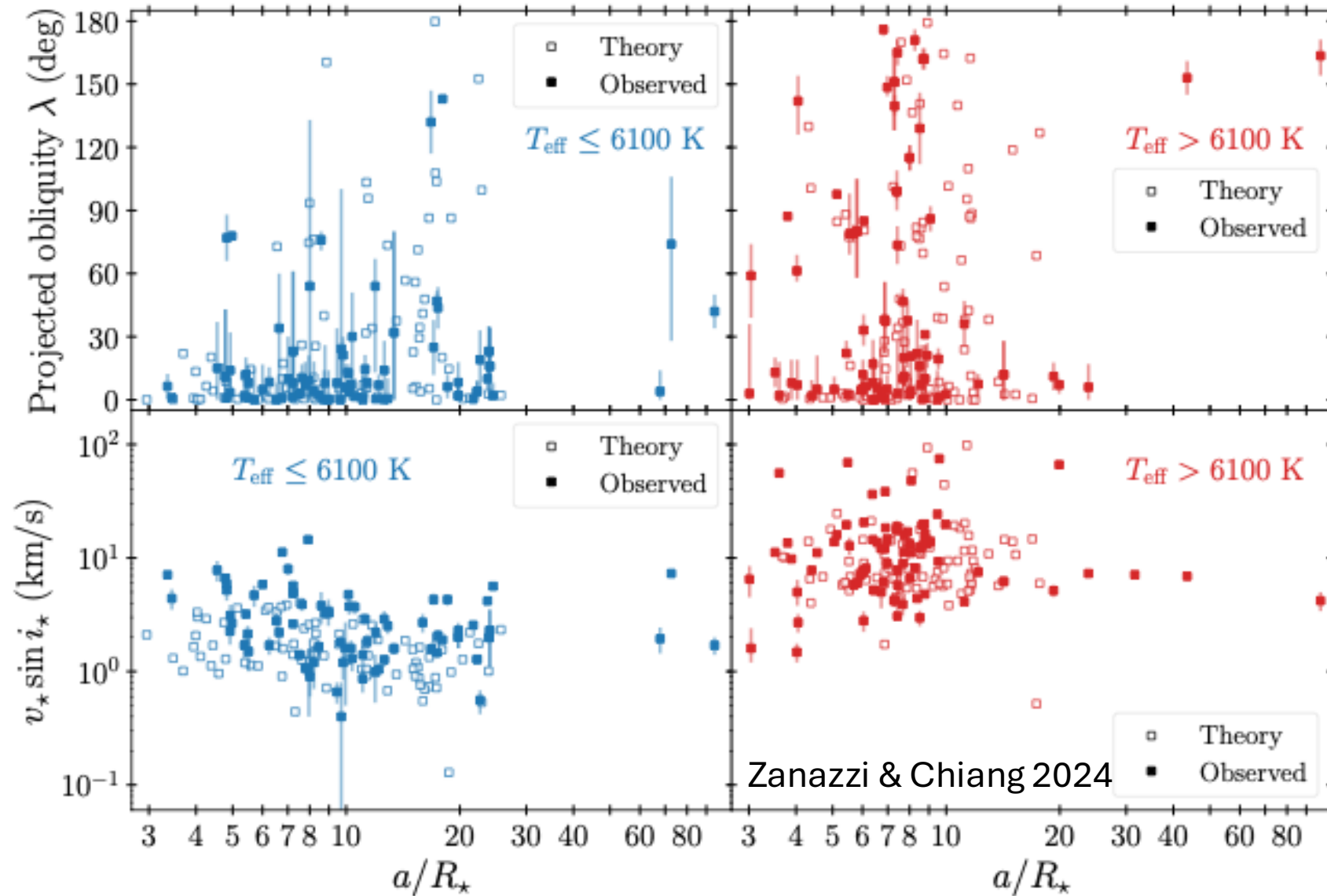


HJ Spin and Obliquity Distributions agree with Resonance Locks

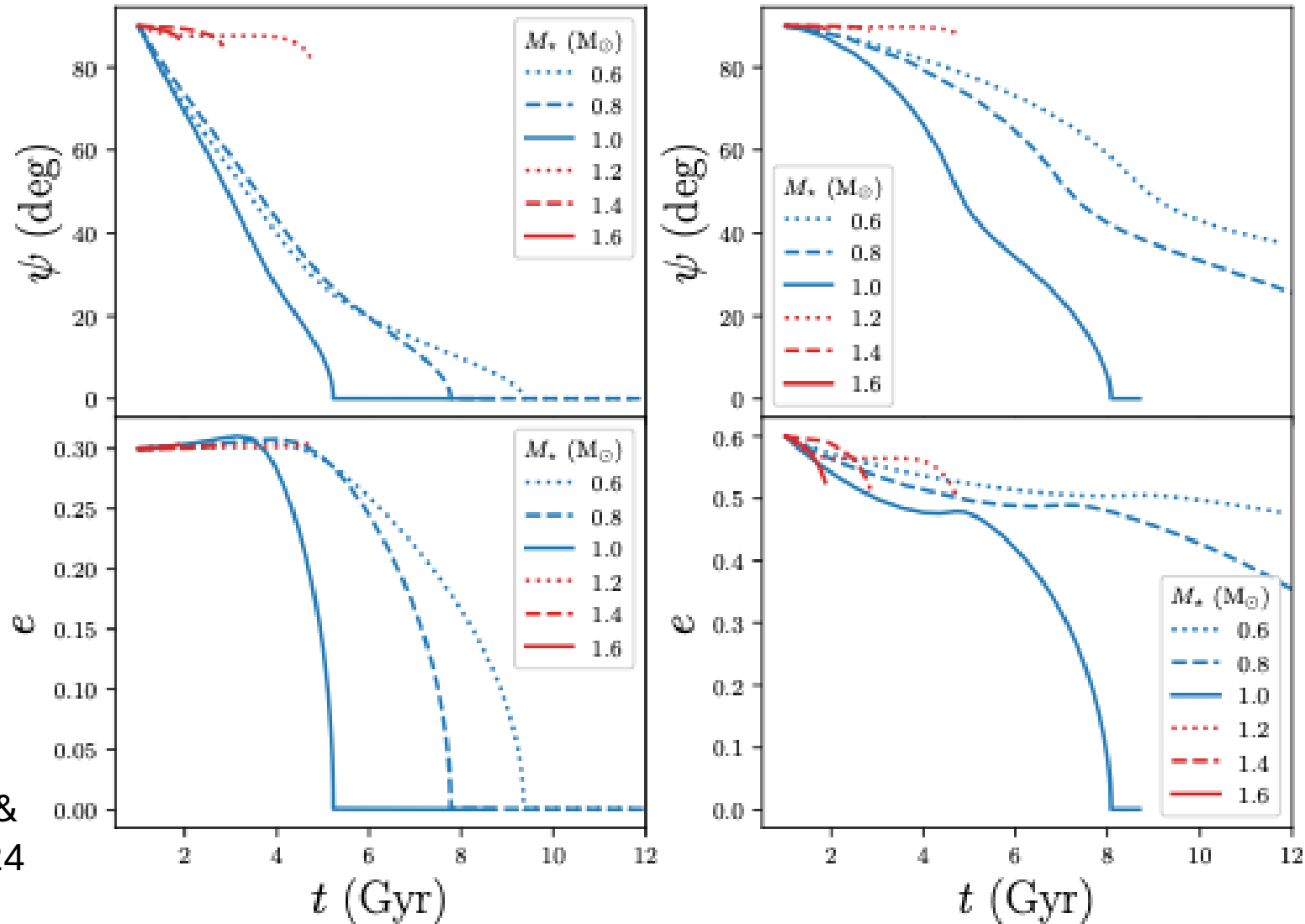


Zanazzi & Chiang 2024

Resonance Locks and a/R

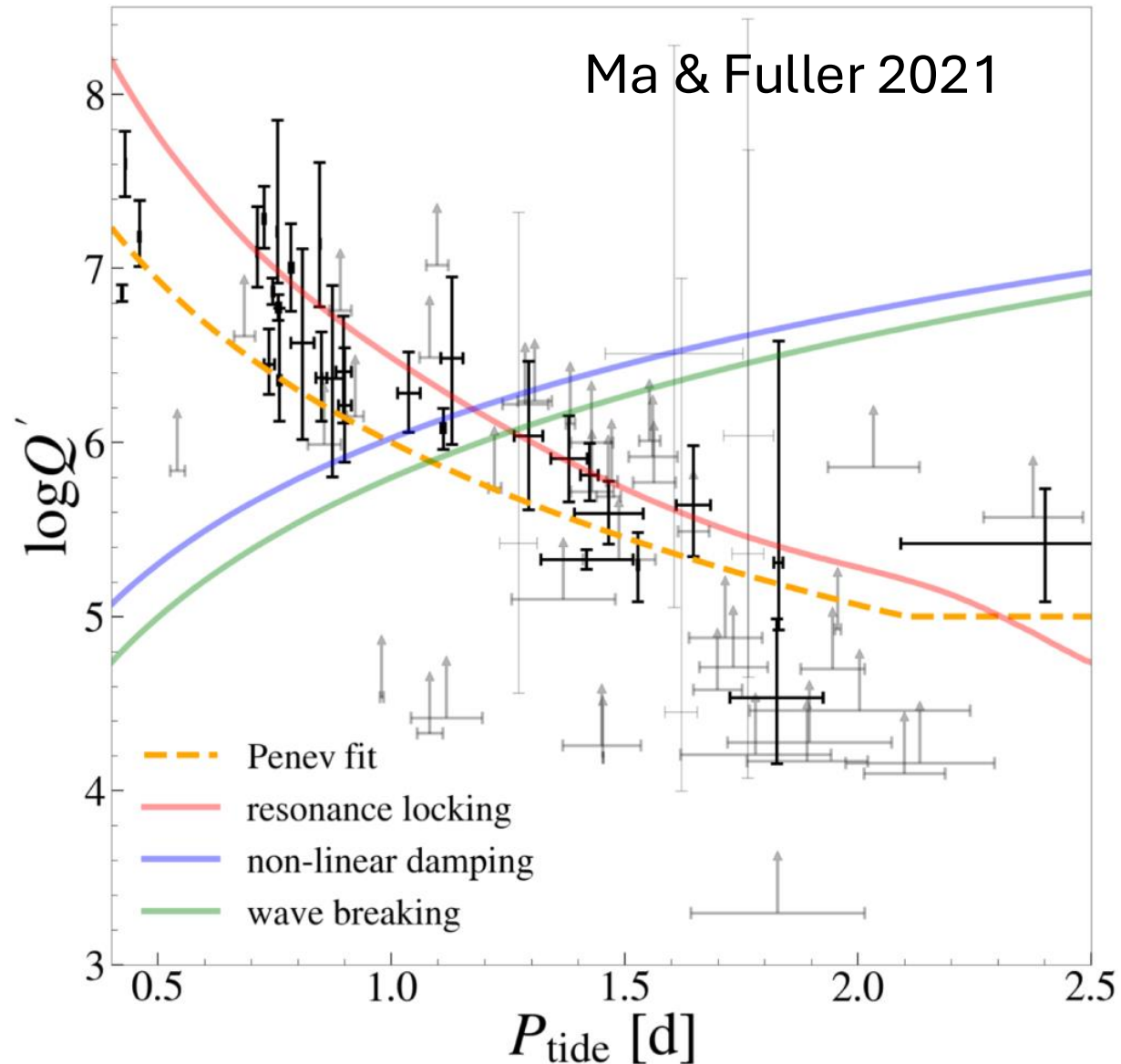


Eccentricities and Obliquities Damp



Zanazzi,
Dewberry, &
Chiang 2024

Tidal Q from Spin-Up Supports Resonance Locks



Orange: Empirical fit to hot Jupiter host stars

Penev+ 2018

Red: Resonance locking

Ma & Fuller 2021

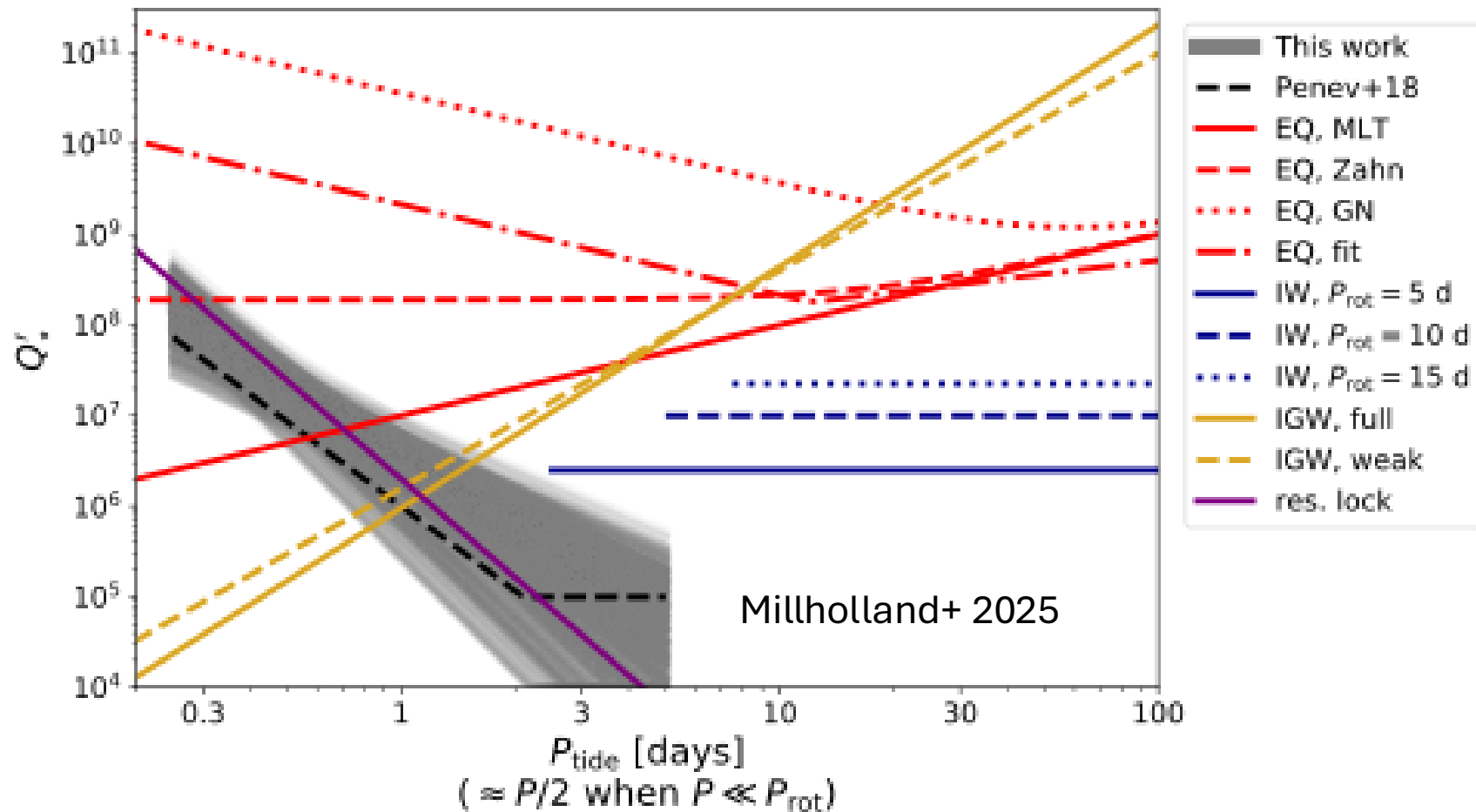
Blue: Non-linear damping

Essick & Weinberg 2016

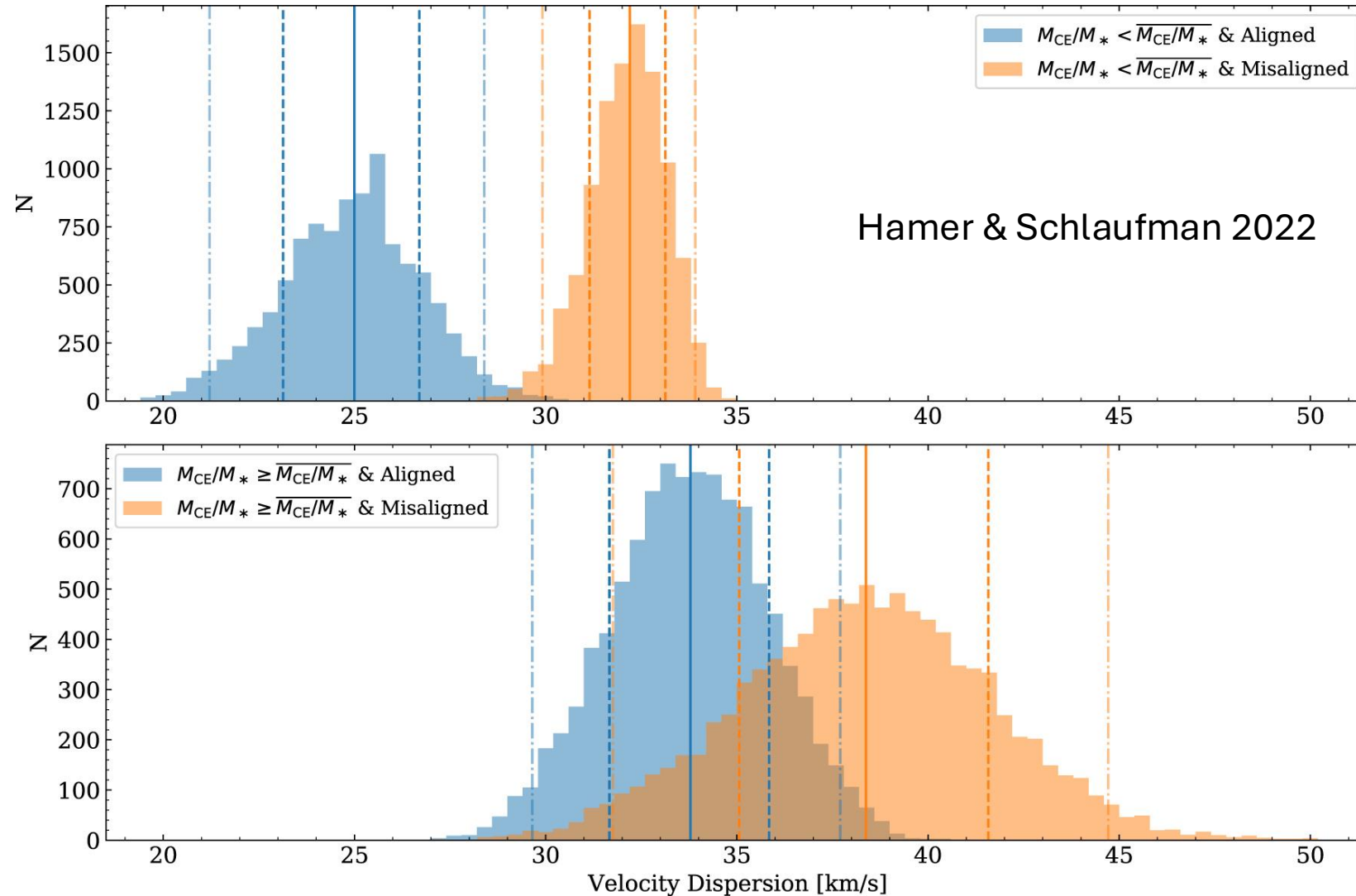
Green: Wave breaking

Goodman & Dickson 1998; Barker & Ogilvie 2010

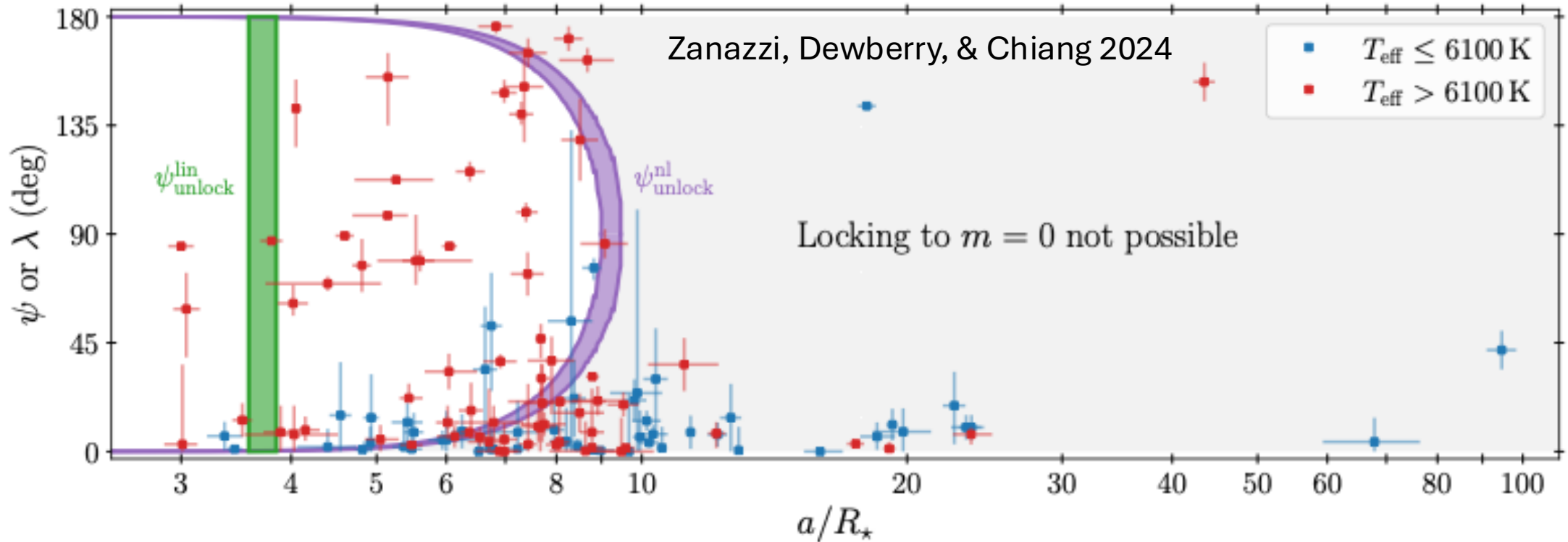
Resonance Locks Reproduce Hot Jupiter Period Distribution



Misaligned Hot Stars Older than Aligned Hot Stars



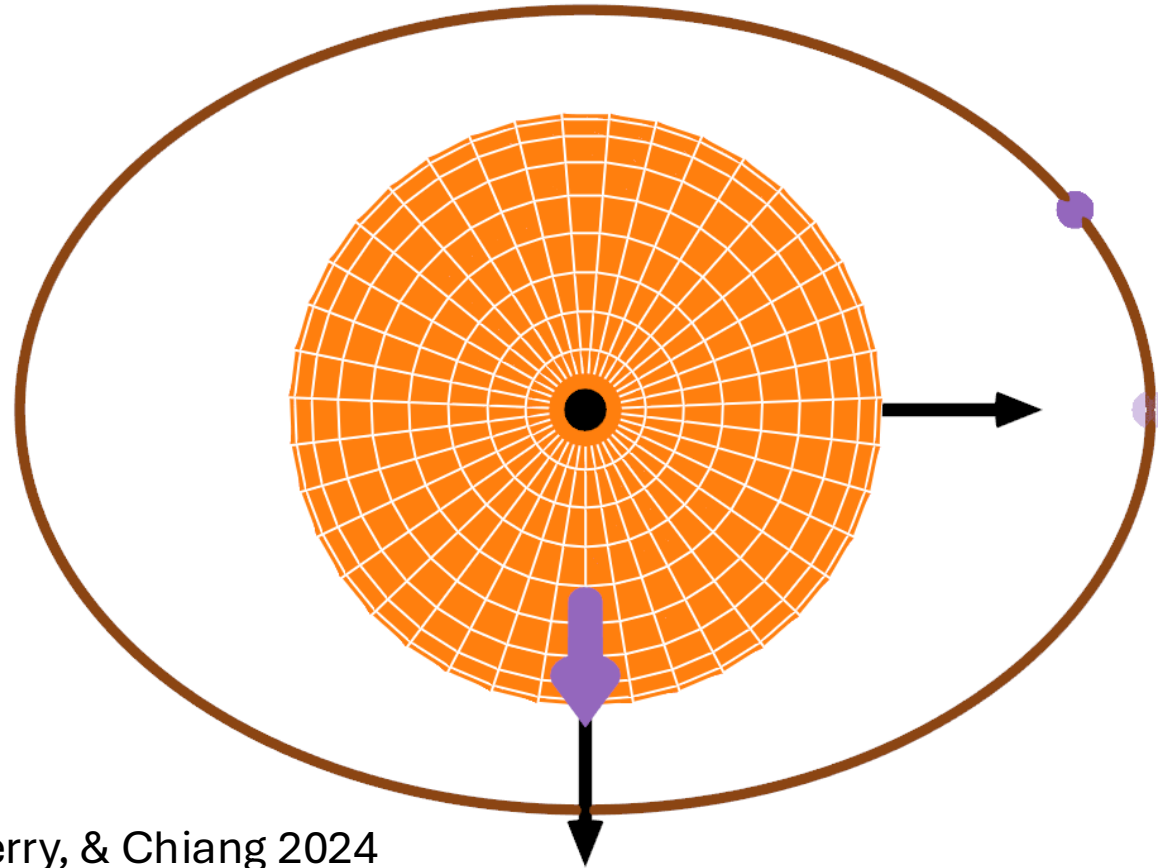
Tidal Alignment and a/R



Resonances unlock when $t_{\text{diss}} = |E_{\text{orb}}|/|\dot{E}_{\text{tide}}| > 3t_{\text{ev}}/2$

Obliquities damp to $a/R_* \sim 8 - 10$ from NL dissipation

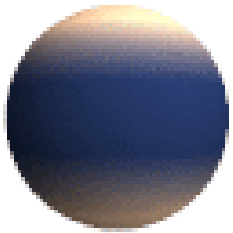
No Spin-Up from Axisymmetric Mode



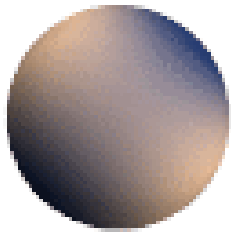
Zanazzi, Dewberry, & Chiang 2024

Mode Energy for Different m

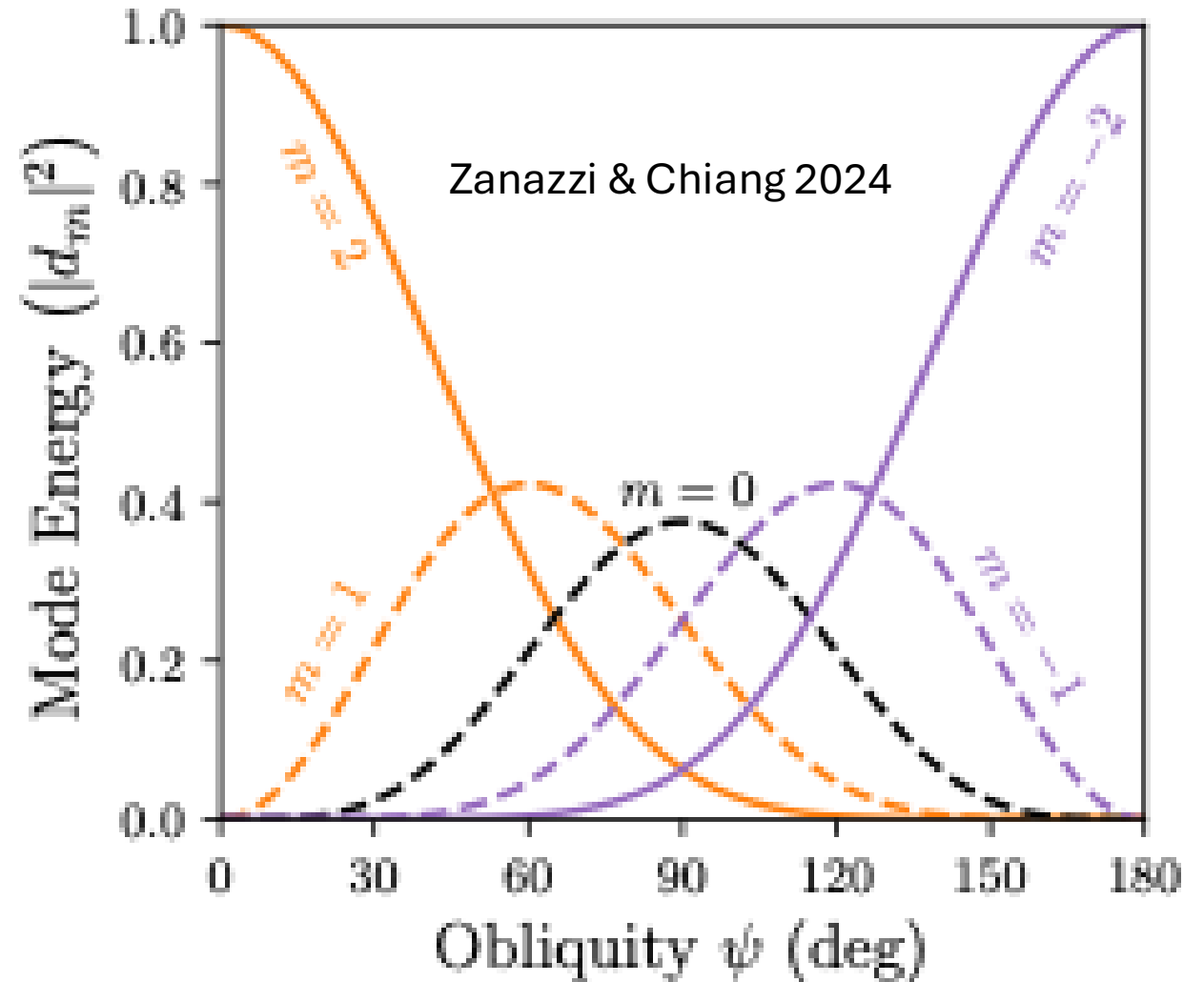
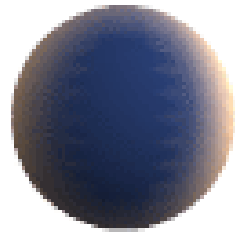
$m = 0$



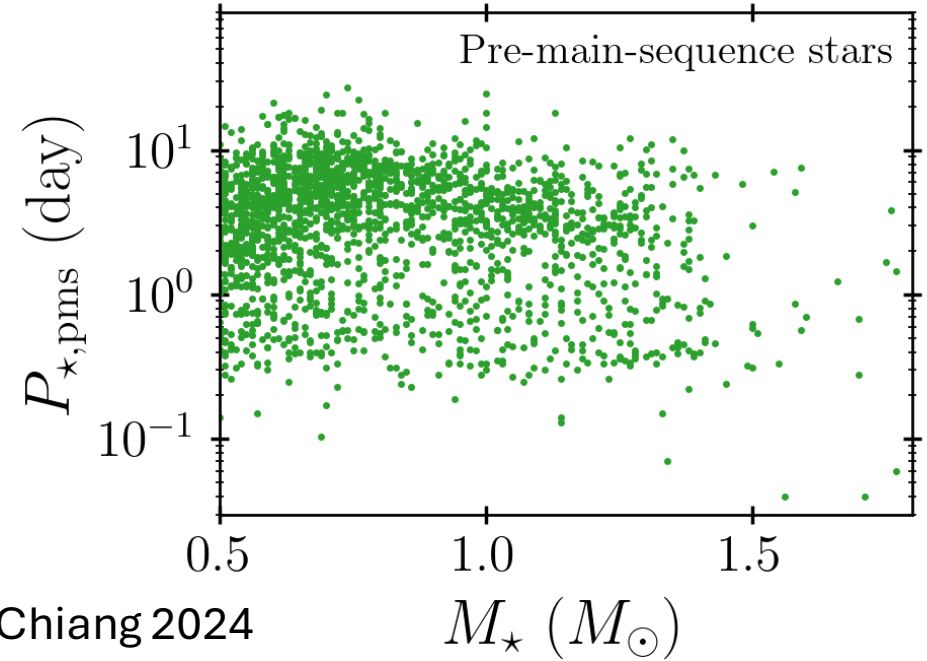
$m = 1$



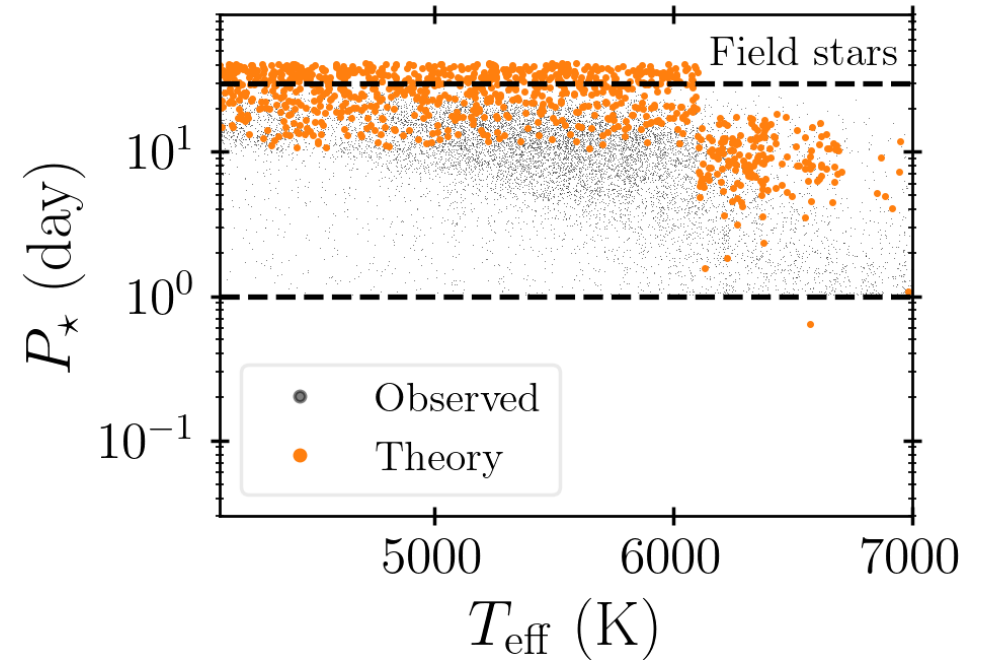
$m = 2$



Spin-Down from Magnetic Braking

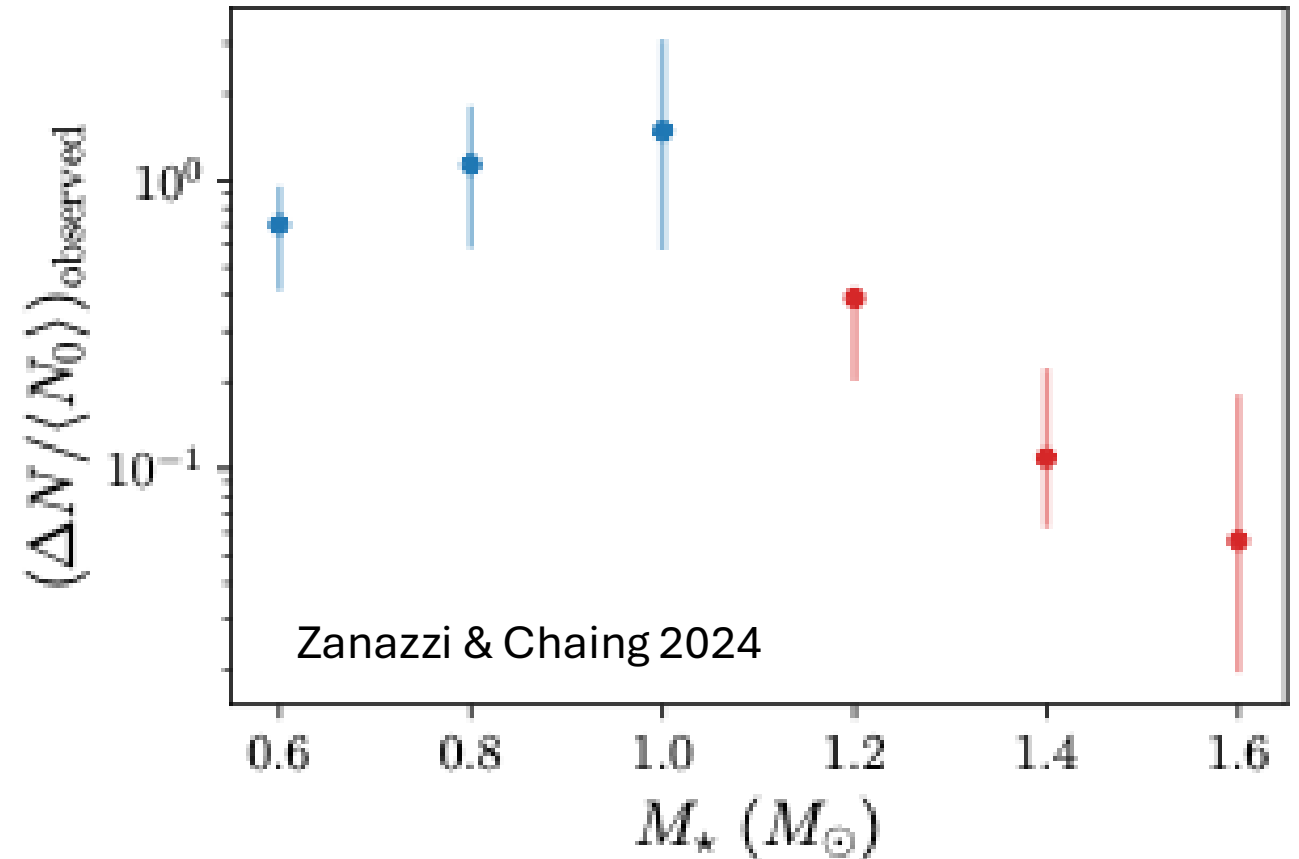


Zanazzi & Chiang 2024



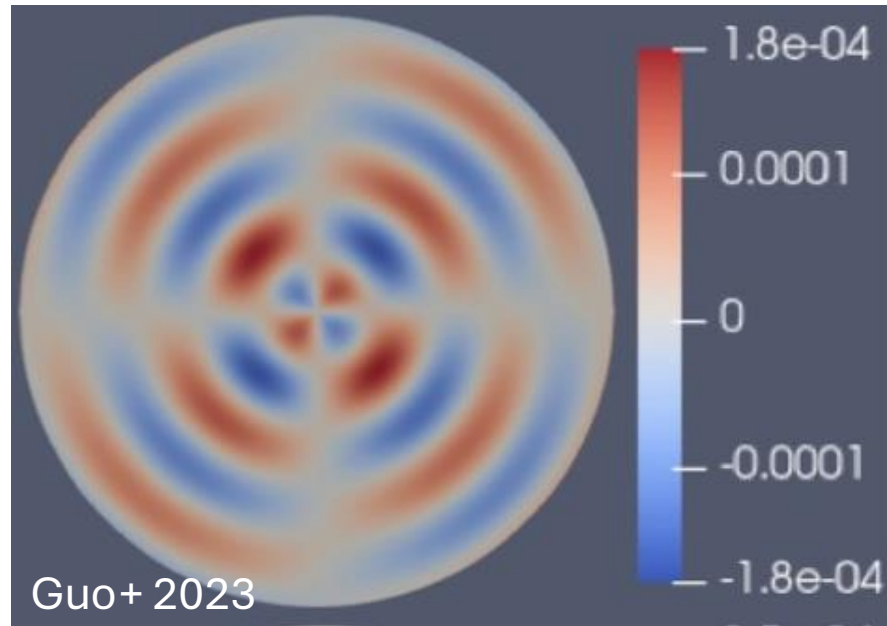
Planets around Cool Hosts Evolve their Orbits More

$$\frac{\Delta a}{a_0} \propto - \frac{\Delta N}{\langle N_0 \rangle}$$

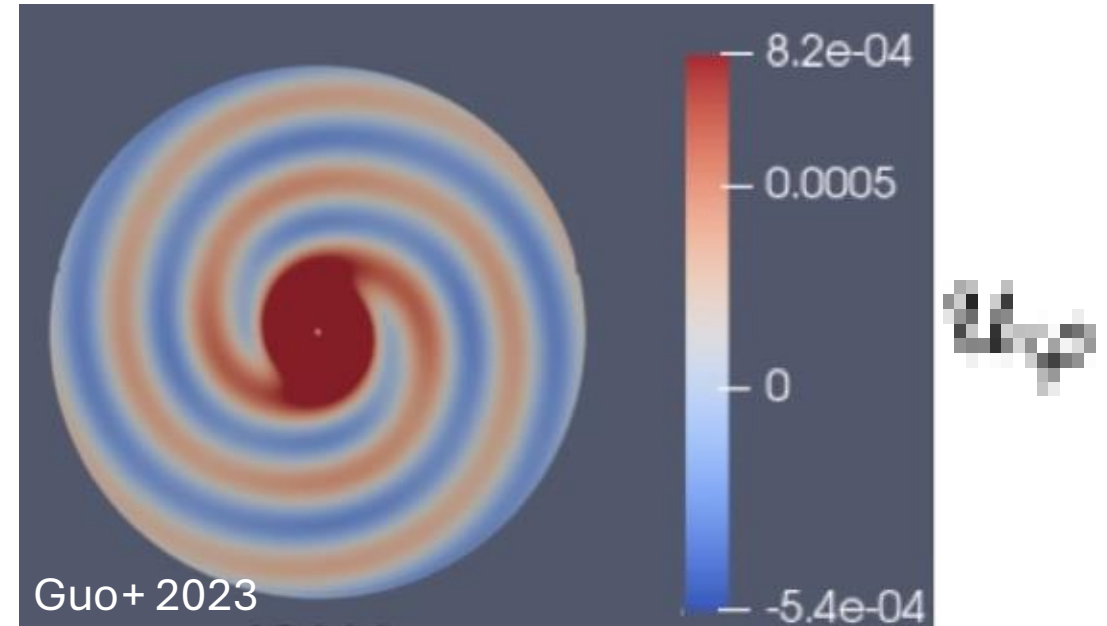


Future Work: G-Mode Dissipation in Stellar Cores

Standing wave



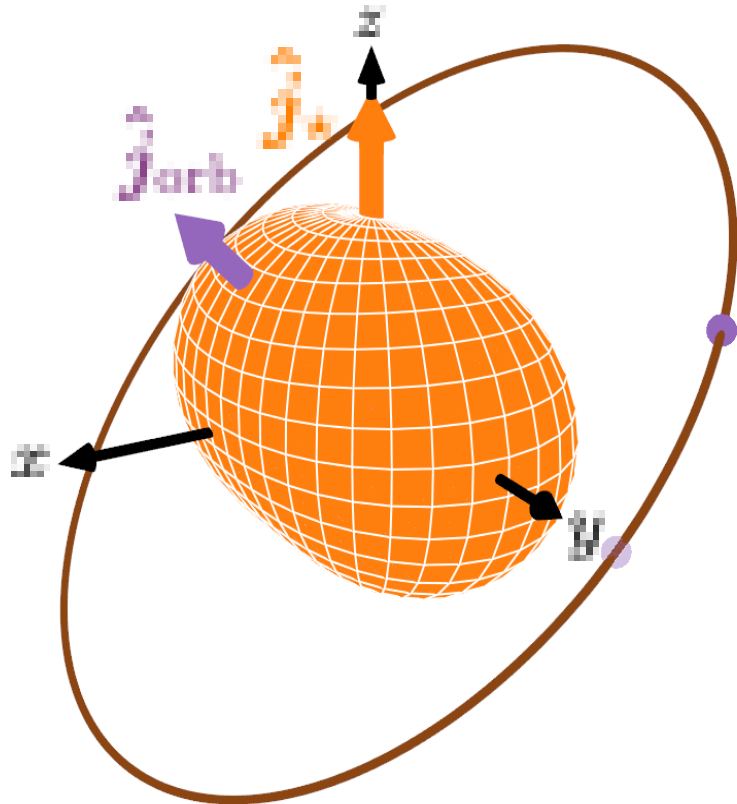
Travelling wave



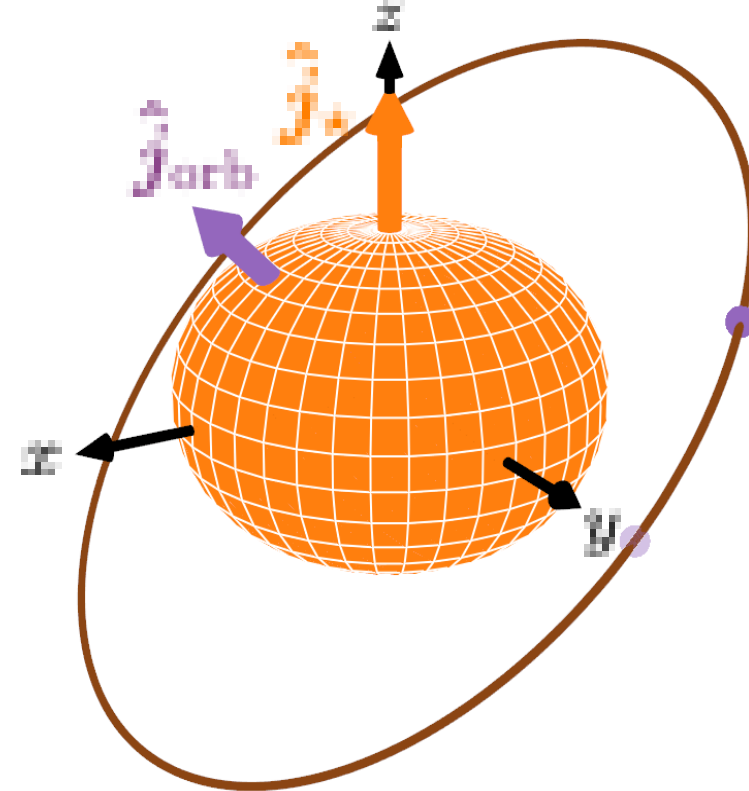
Standing vs. travelling wave large difference in dissipation,
hydrodynamical simulations needed to address

Strong Obliquity Damping from Oscillations

Equilibrium bulge

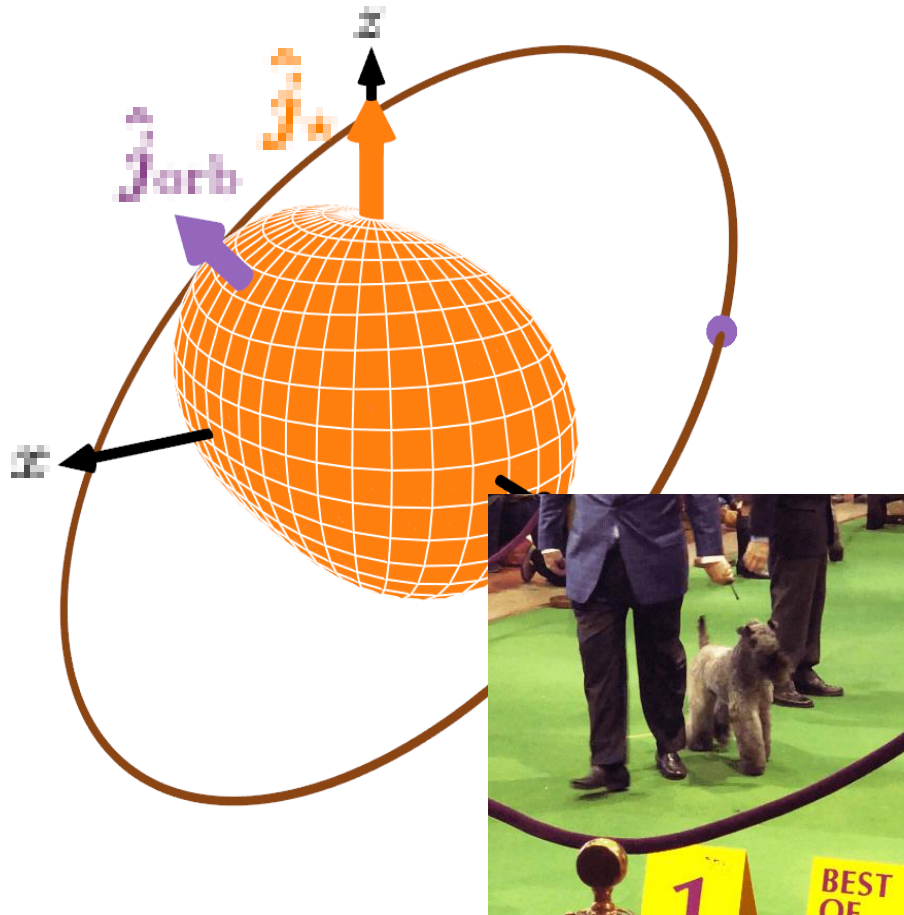


$m = 0$ bulge

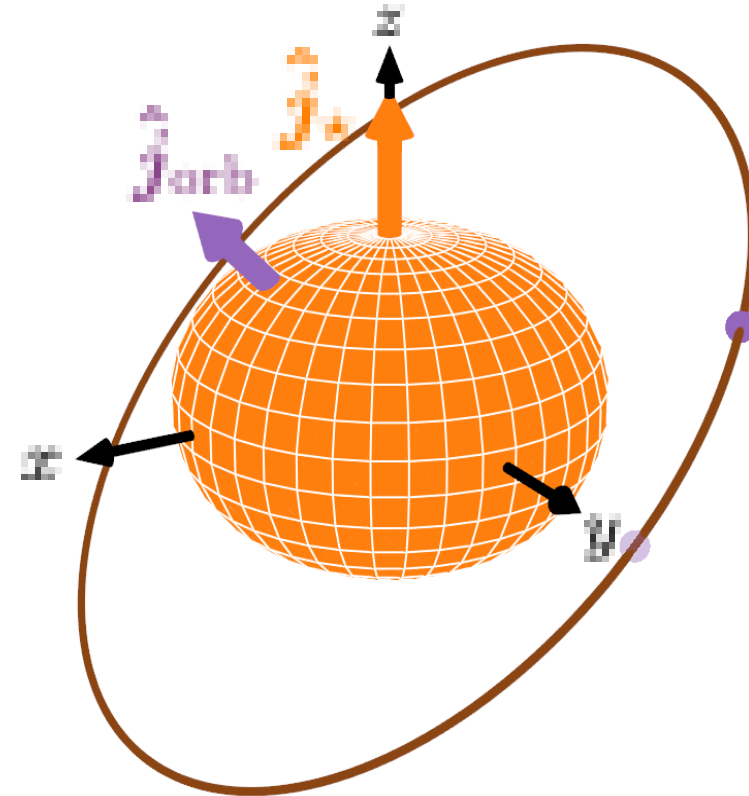


Strong Obliquity Damping from Oscillations

Equilibrium bulge

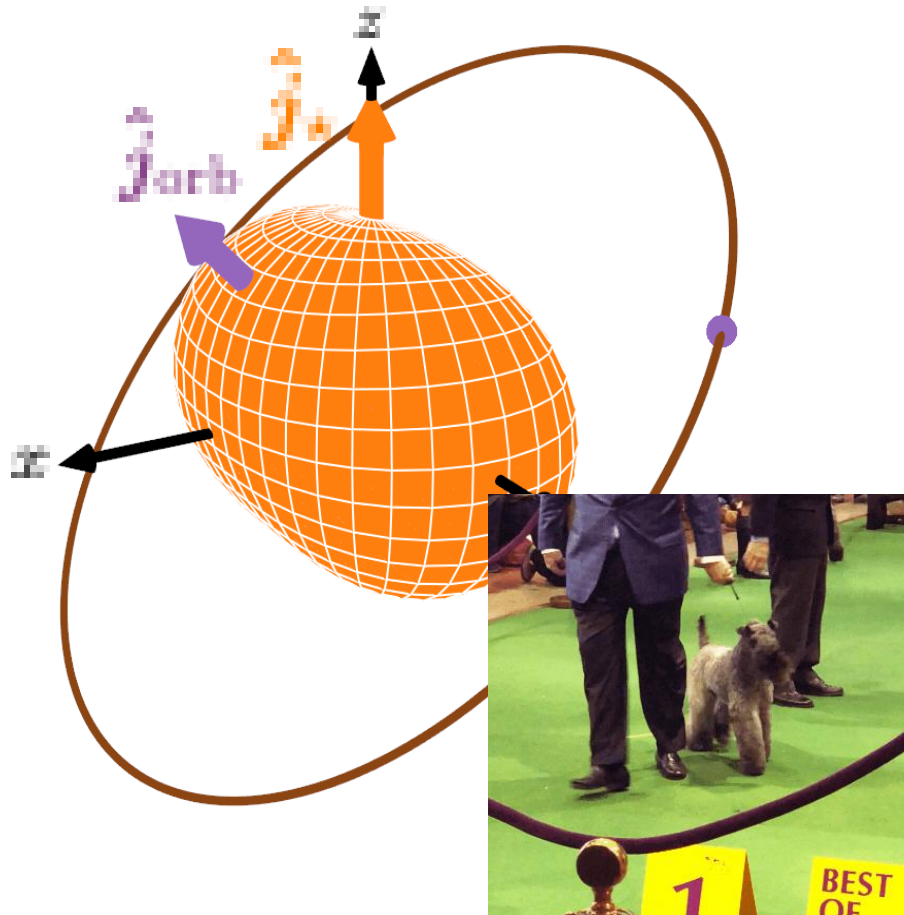


$m = 0$ bulge



Strong Obliquity Damping from Oscillations

Equilibrium bulge



$m = 0$ bulge

