How tides change the orbit of binaries and a new open-source code to model stellar tides

Meng Sun 孙萌 (CIERA, Northwestern University)

Rich Townsend (University of Wisconsin Madison)

Phil Arras (University of Virginia)

Nevin Weinberg (University of Texas at Arlington)

Zhao Guo (University of Cambridge)

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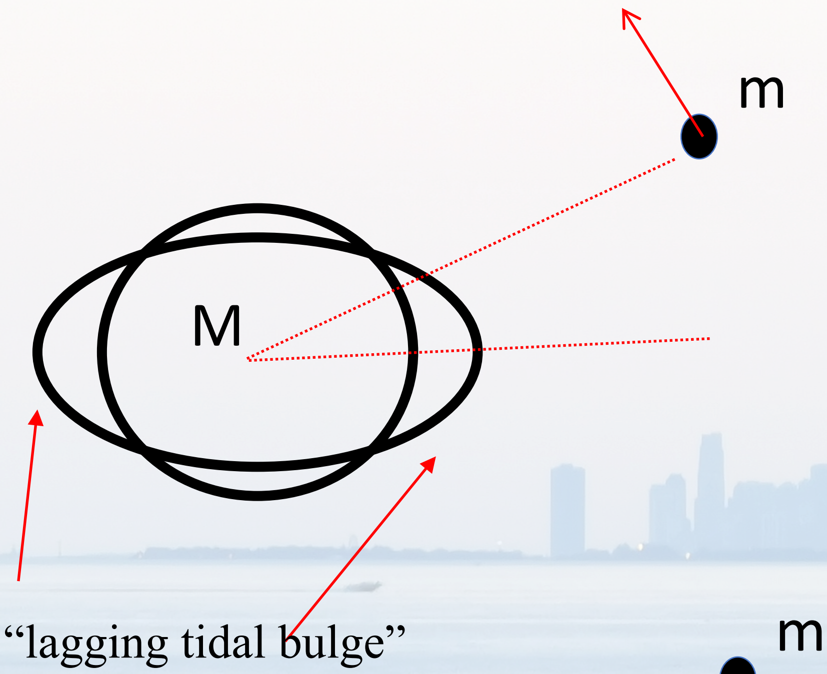
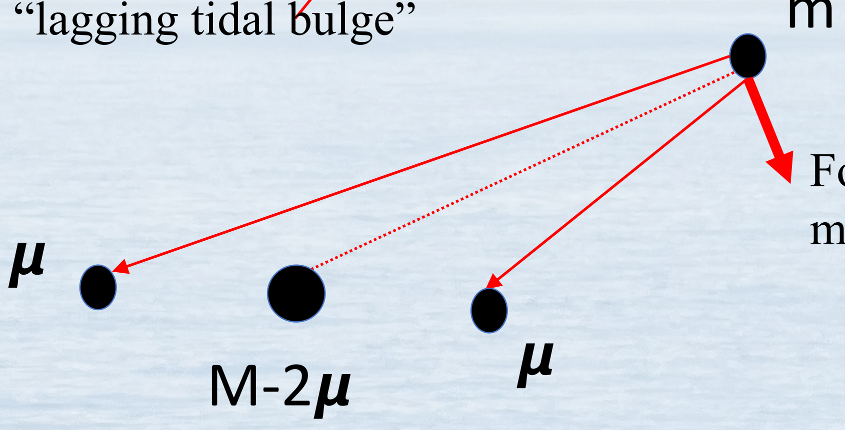
Basic Idea of How Tides Change the Orbit and the Previous Theory

G. Darwin's theory of tides: Friction causes the tidal bulge to lag behind the companion.





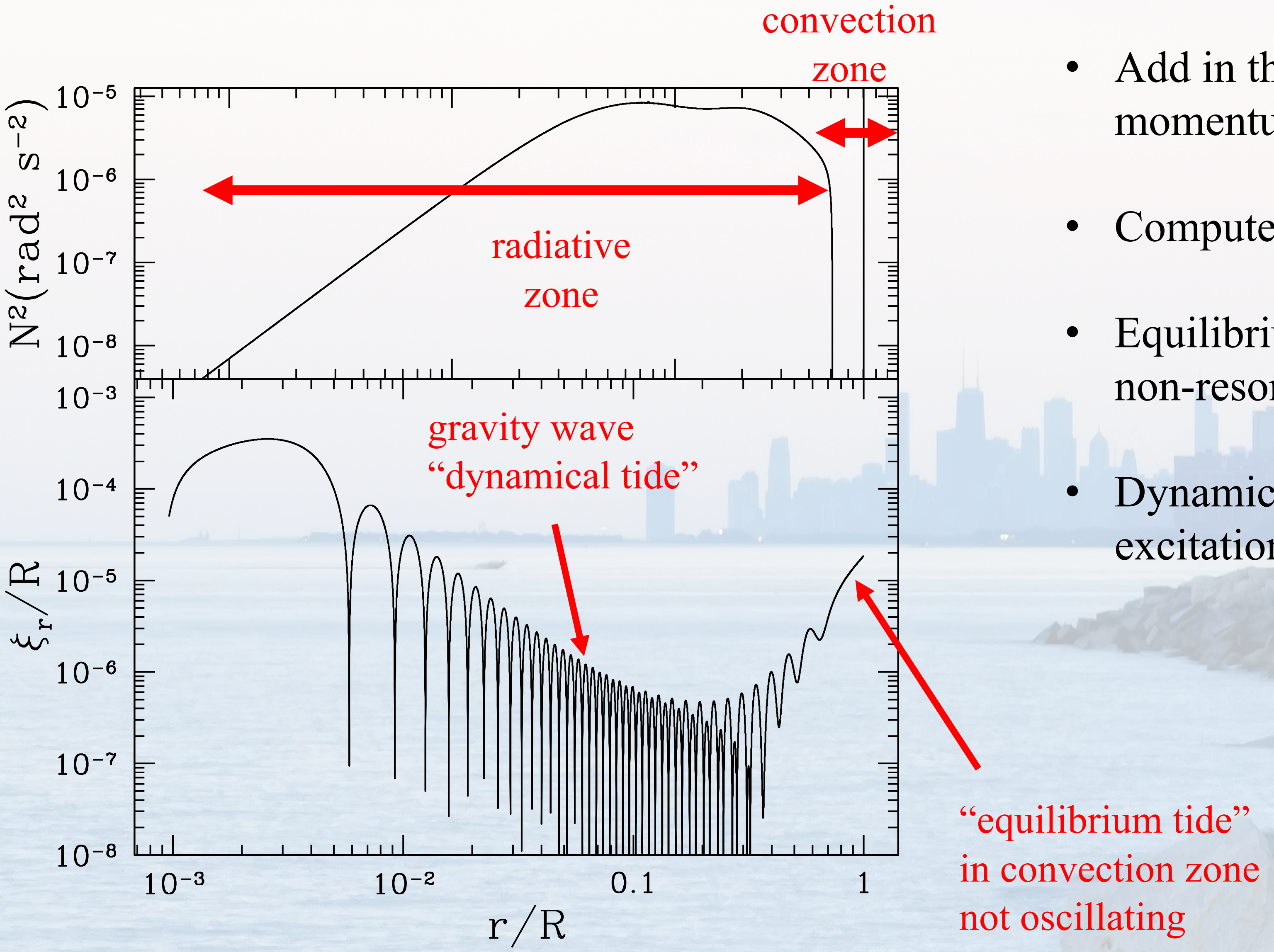
Force decreases the orbital angular momentum

- The spin angular momentum of the star increases and the orbital angular momentum decreases
- The orbit will shrink
- The lag time is a free parameter

$$\dot{a} = -\frac{a}{\tau_{\rm lag}}\left(\frac{m}{M}\right)\left(1+\frac{m}{M}\right)\left(\frac{R}{a}\right)^8\left(1-\frac{\Omega}{n}\right)$$

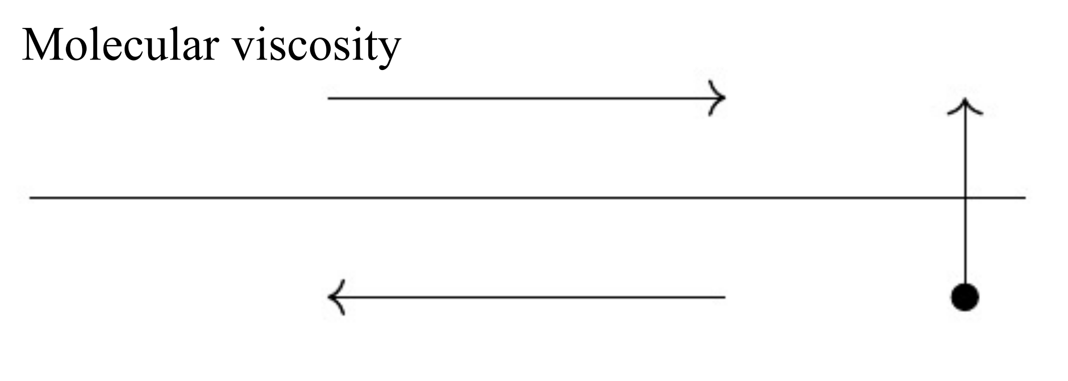
Hut (1981)

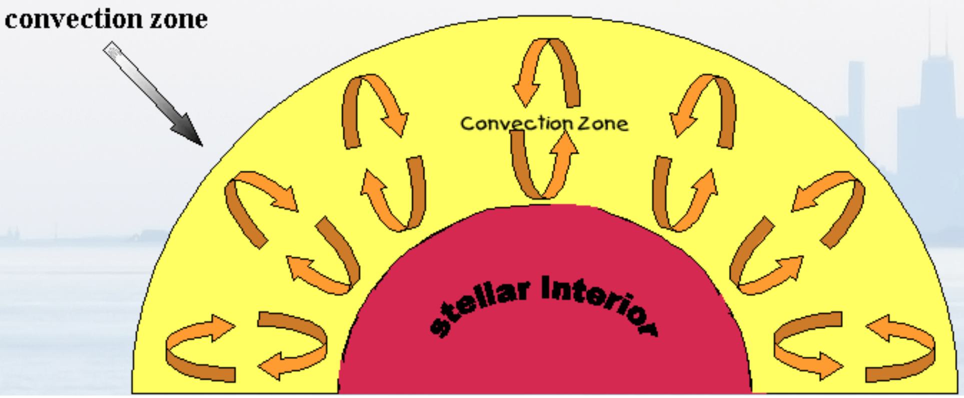
Physics of Tidal Flow

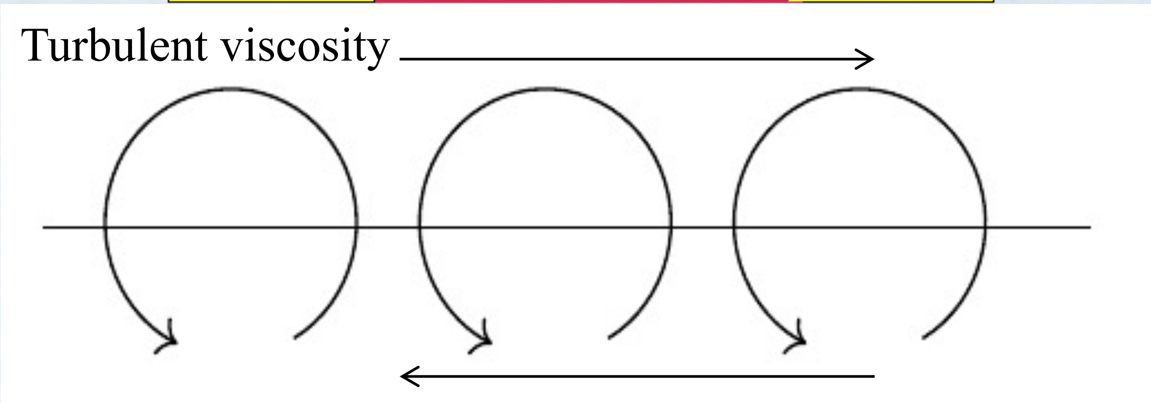


- Add in the $-\nabla U$ tidal acceleration in the momentum equation for nonadiabatic oscillations
- Compute linear response to the tidal force
- Equilibrium tide approximation: set ω=0 to get non-resonant response due to tides.
- Dynamical tide approximation: resonant excitation of internal gravity waves.

Turbulent Viscosity Damping in Convective Zones







$$\lambda = \text{mean free path}$$

$$\vec{F}_{\text{shear}} = \rho \nu_{\text{mol}} \nabla^2 \vec{v}_{\text{tide}}$$

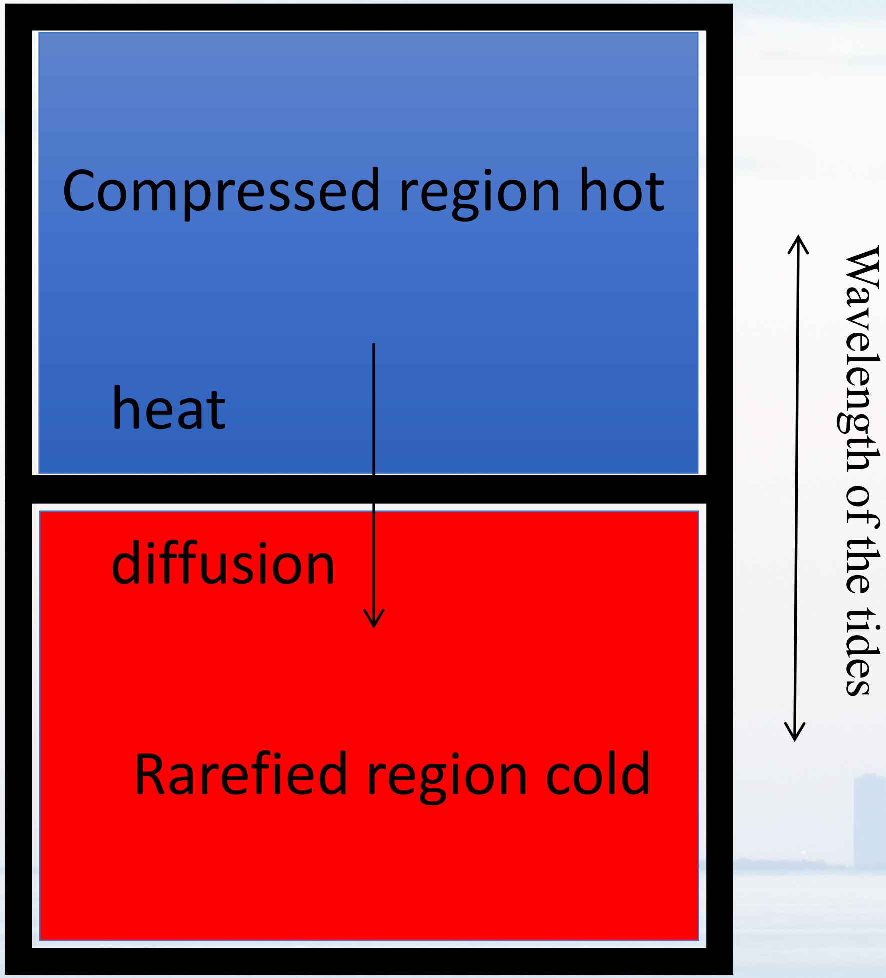
$$\nu_{\text{mol}} = \lambda v_{\text{thermal}}$$

↑ tiny!

$$\nu_{\text{turb}} = \ell_{\text{eddy}} v_{\text{eddy}}$$

$$\dot{E} \approx M \nu_{\text{turb}} |\nabla \vec{v}_{\text{tide}}|^2$$

Radiative Diffusion Damping



χ = heat diffusion coefficient

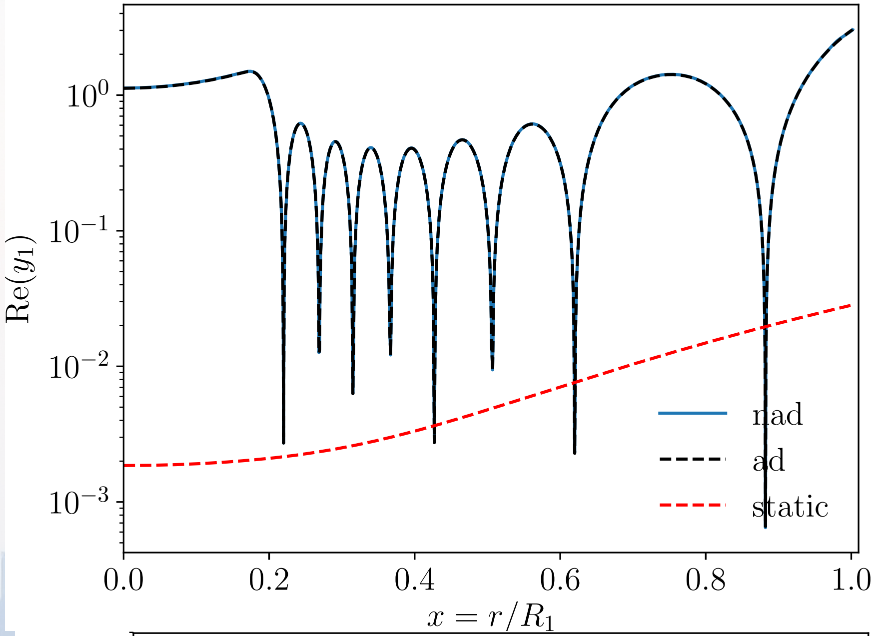
P = 2π/ω = wave period

Heat diffused distance in time P is d ≈ $(\chi P)^{1/2}$

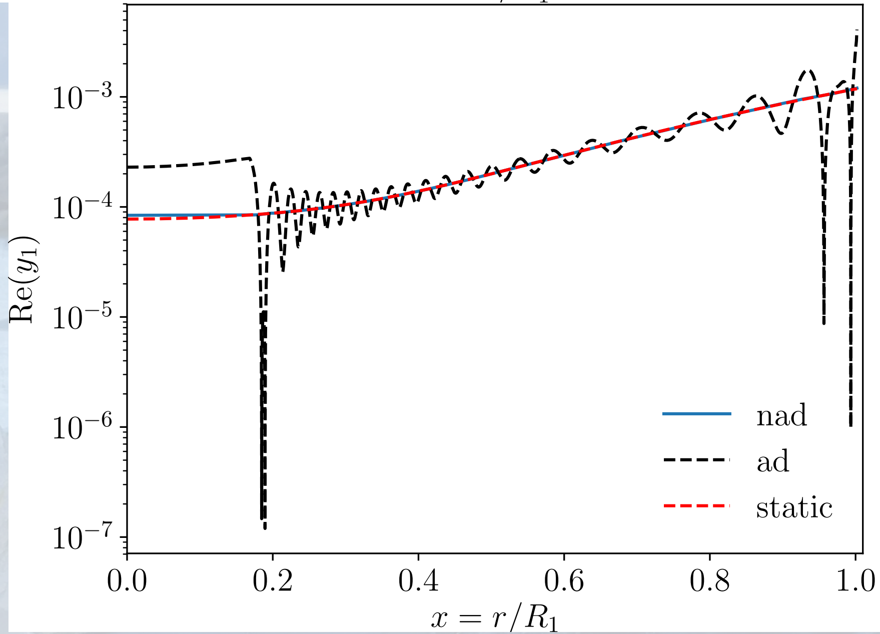
If diffusion distance d ≥ wavelength

=> the wave will be strongly damped by radiative damping

Top right:
g8 mode with no radiative damping. The nonadiabatic solution are identical with the adiabatic solution.



Bottom right:
g44 mode with strong radiative damping. The nonadiabatic solution is close to the equilibrium tide solution (no oscillatory feature).



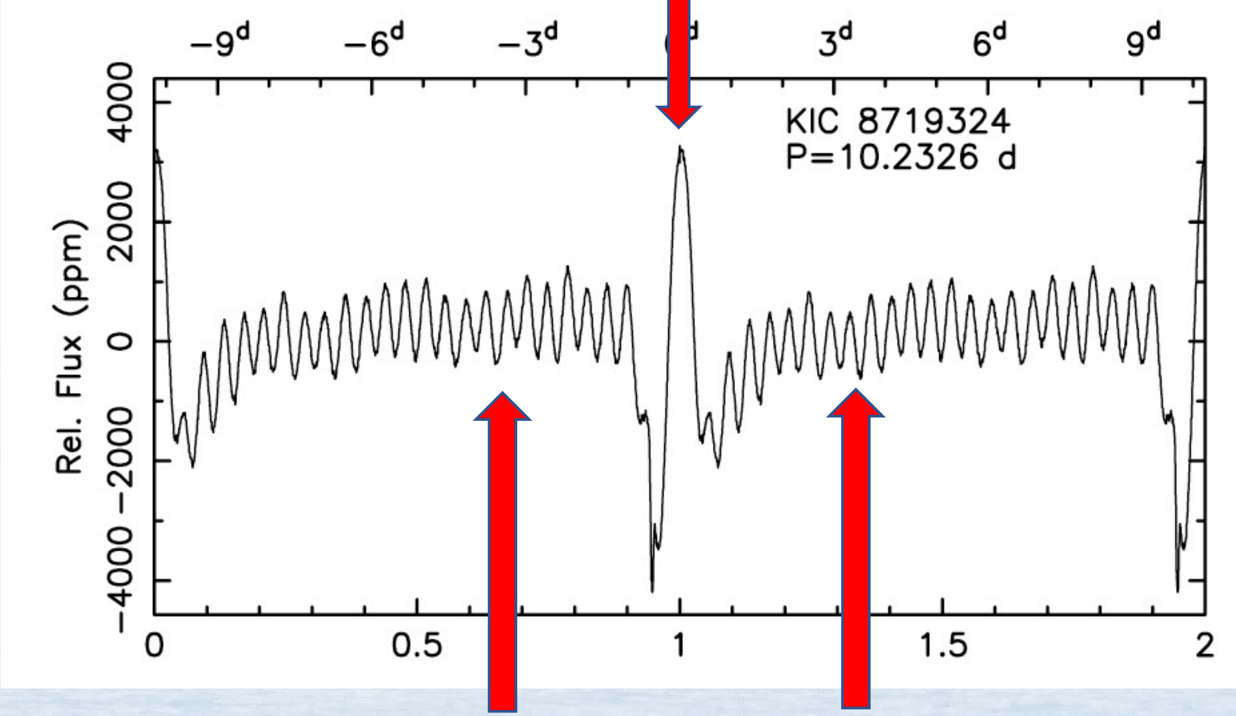
Introducing GYRE-TIDES: a New Open-Source Code to Model Stellar Tides

GYRE

Tides in Massive Stars – the Heartbeat Phenomenon

Caused by the
Equilibrium tides

Thompson et al. (2012)



Caused by the Dynamical tides

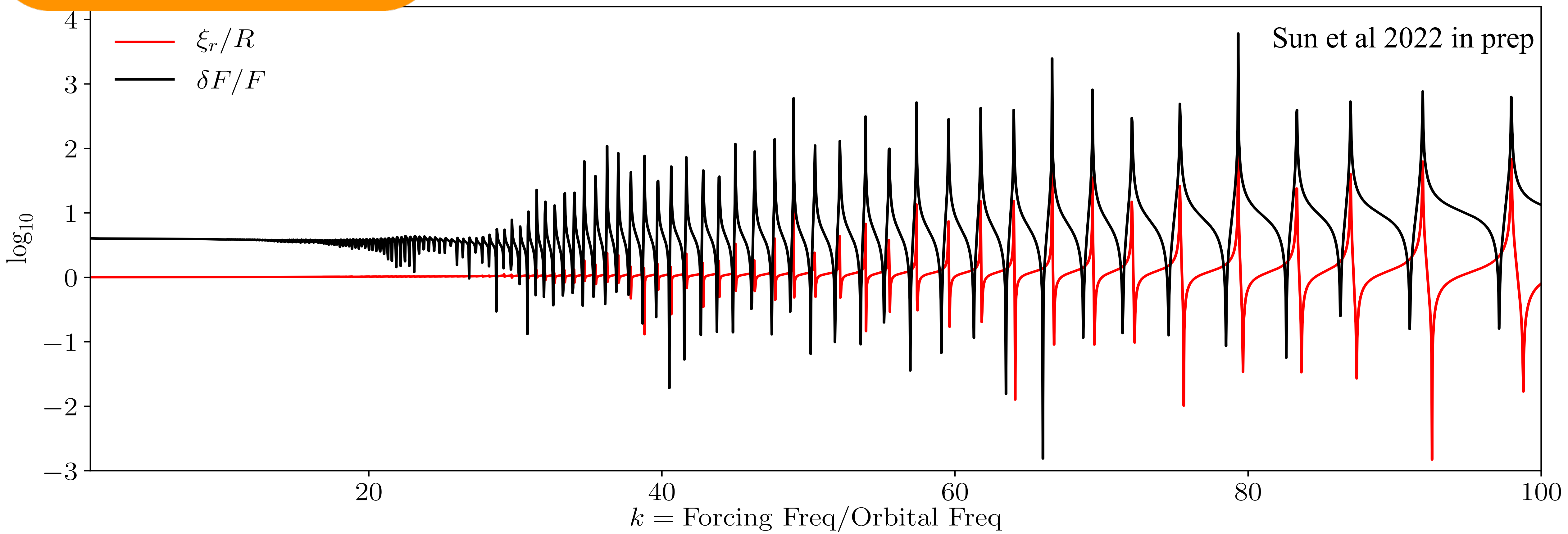
The Heartbeat features are usually observed in:

- high eccentricities binaries (0.3 < e < 0.9);
- intermediate-mass stars (1.2 Msun < M < 2.5 Msun);
- have also recently been reported in high-mass stars (up to 30 Msun).

The Kepler mission found 173 heartbeat stars (Kirk et al 2016), almost all of these stars are A- and F-type main sequence stars;

Other space and ground-base observations found heartbeat phenomenon for O and B type stars.

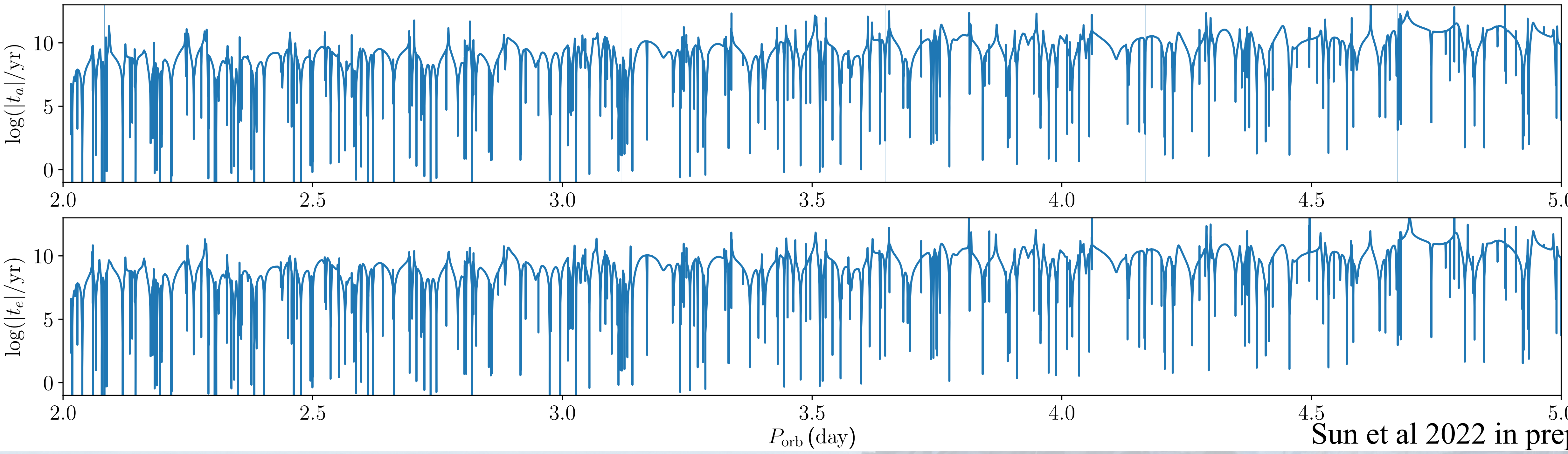
Modeling the Heartbeat Star KOI-54



↑ Surface displacement and flux versus forcing frequency for KOI-54 system, forced by a fixed-strength potential.

- The two stars in KOI-54 have similar mass, 2.32 $M_\odot$ and 2.38 $M_\odot$ with an orbital period of 42 days. The system is highly eccentric with e=0.83.
- At low forcing frequency (left of the figure), the solution is dominated by the equilibrium tides; At high forcing frequency, the spikes correspond to the excitation of the internal gravity waves (also known as the dynamical tides).

Tides in Changing the Orbital Elements of the Binary Systems

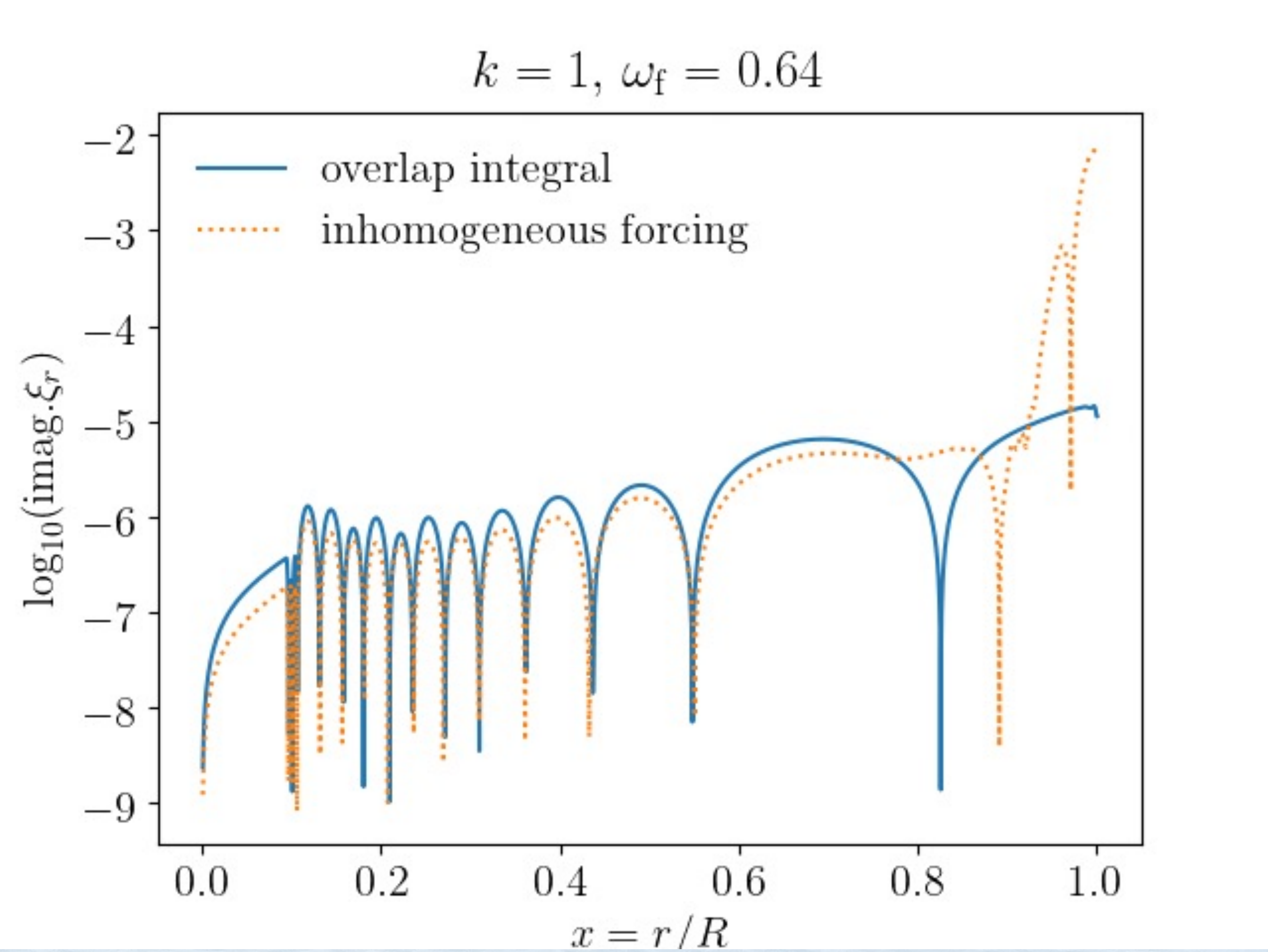


Sun et al 2022 in prep

↑ the rate-of-change in semi-major axis and eccentricity as a function of orbital period, predicted by GYRE-tide for an eccentric 1.4 solar mass neutron star raising tides on a 5 solar mass main-sequence primary.

- Generally, these timescales are smaller for short orbital periods, and larger for long periods (the strong dependence of tidal strength on orbital separation).
- The spikes can be seen where the timescales become very short (caused by dynamical tides).

Comparison between the overlap integral and the direct forcing method



Overlap integral approach: Star's response to the tidal potential is represented as a linear superposition of the adiabatic free oscillations. The amplitude of each mode is calculated by evaluating overlap integrals between the potential and the mode's eigenfunctions.

Direct forcing: the star's response is evaluated by solving the forced oscillation equations.

← The two methods disagree at:

- Superficial layers (non-adiabatic effect is strong);
- Out of resonance.