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# Tidal Migration of Exoplanets Around M-dwarfs: Frequency-dependent Tidal Dissipation


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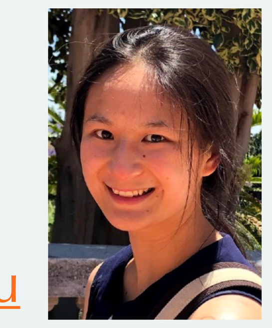
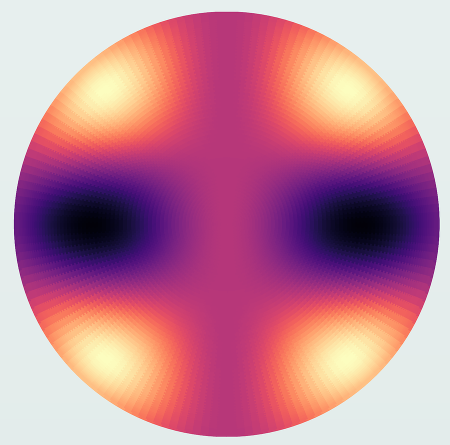


## Planets excite normal modes of oscillation in host stars via tides.

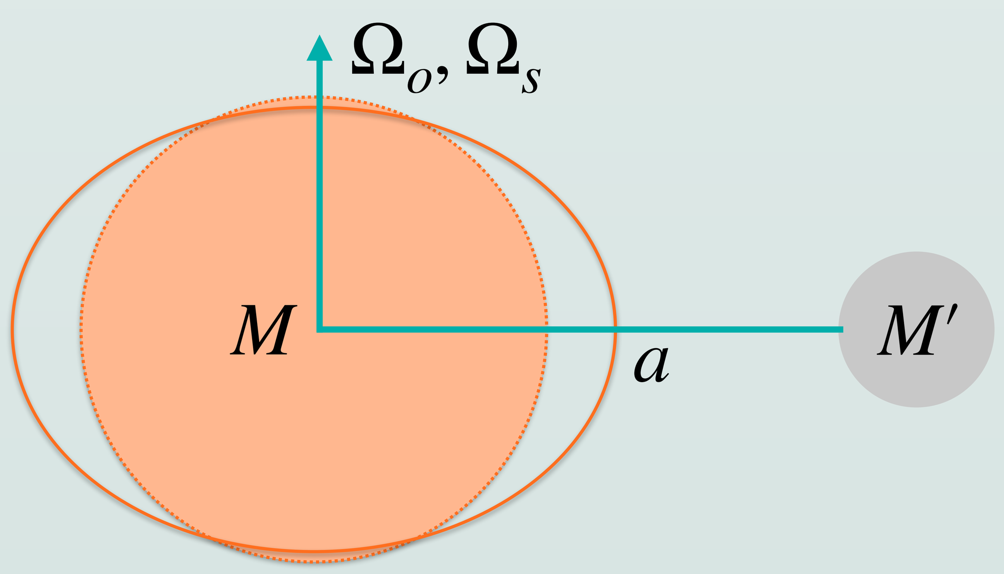
Fully convective M-dwarfs host 2 main types of modes:


f-modes are like surface gravity waves.




i-modes are restored by the Coriolis force.

- The planet's tidal potential excites the above modes and many more.
- As the modes are damped, orbital angular momentum and energy are dissipated in the star




We assume a circular and aligned orbit between a planet ($M'$) and its host star ($M$). We calculate the tidal dissipation $D$ as follows:

$$D = \int_V \mu(\delta\mathbf{S}^* : \delta\mathbf{S})dV$$

$\mu$: dynamic viscosity
$\delta\mathbf{S}$: rate of strain tensor (involves mode eigenfunctions)

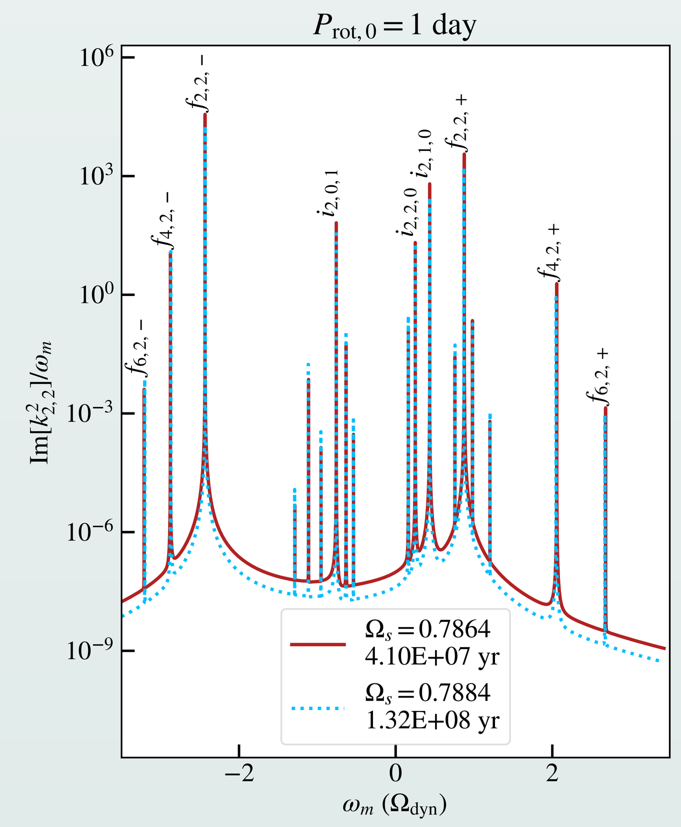
Convective turbulent viscosity is the relevant dissipative mechanism in M-dwarfs.

The imaginary part of the Love number $k_{2,2}^2$ governs orbital migration via tides. We invert the following:

$$D = \frac{5}{8\pi G} R \,|\, U_{2,2} \,|^2 \omega_m \mathrm{Im}[k_{2,2}^2]$$ dissipation

- $\omega_m = 2(\Omega_o - \Omega_s)$: tidal forcing frequency
- $\Omega_o$: orbital frequency
- $U_{2,2}$: tidal potential
- $\Omega_s$: stellar rotation rate
- $R$: stellar radius
- $m$: azimuthal wavenumber (here, $m = 2$)

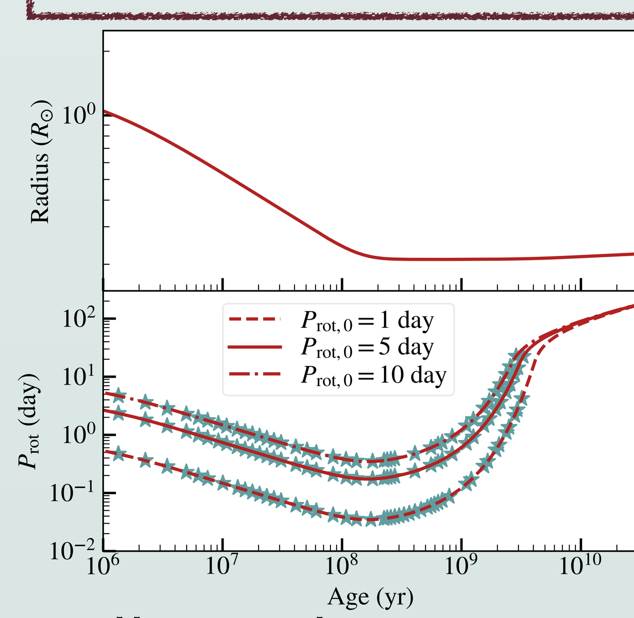
## Tidal dissipation is enhanced at resonant frequencies with modes.




The dissipation $\mathrm{Im}\left[k_{2,2}^2\right]$ peaks at the rotating-frame frequency of the star's normal modes, $\omega_m = \omega_\alpha$ .

Peaks are labeled by the relevant stellar mode that is resonantly excited by the planet's tidal potential.

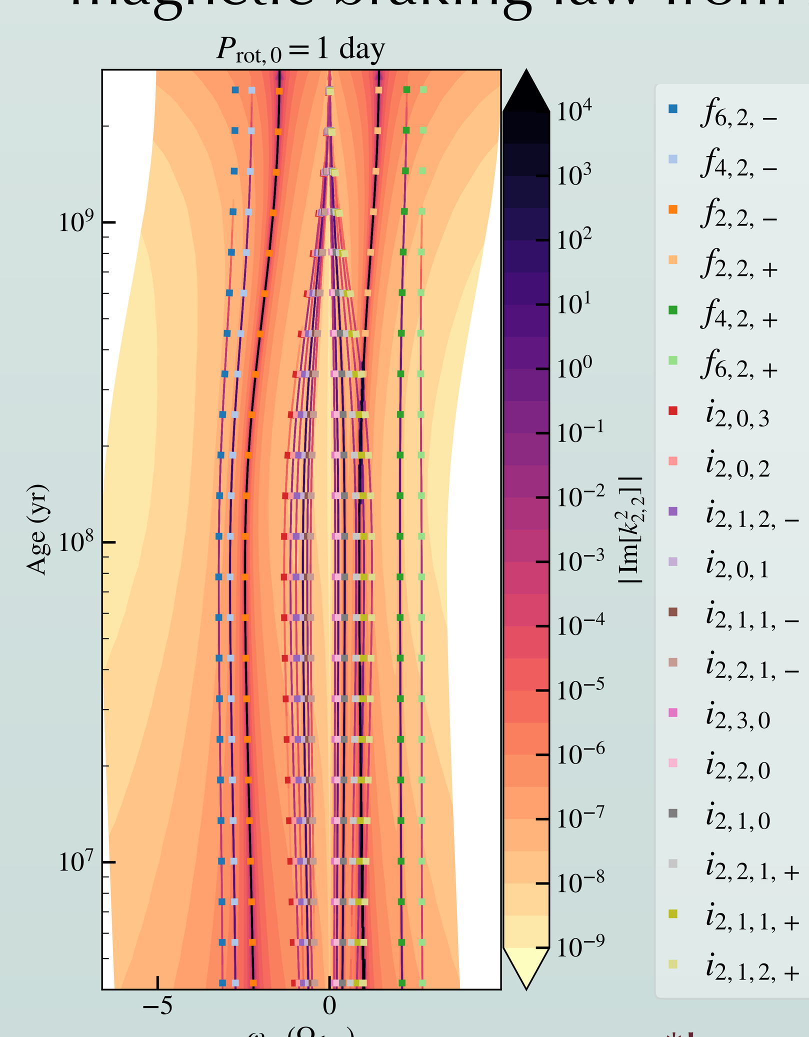
## As the star evolves, so does the spectrum of dissipation.




Model: $0.2\,M_\odot$ M-dwarf in MESA from the pre-main sequence (PMS) to the main sequence (MS) until 3 Gyr. Throughout, the star remains fully convective.

Stellar evolution:

- The star contracts from the PMS onto the MS.
- The star's rotation period evolves via a saturated magnetic braking law from Matt et al. (2015).




The legend lists each stellar mode considered in this work:
$f_{\ell,m,\pm}$ (f-modes)
$i_{m,n_1,n_2,\pm}$ (i-modes)

$\ell$: spherical harmonic degree of star's gravitational potential

$n_1, n_2$: number of nodes in roughly horizontal and vertical directions, respectively

$\pm$: prograde ($\omega_\alpha > 0$) vs. retrograde ($\omega_\alpha < 0$)

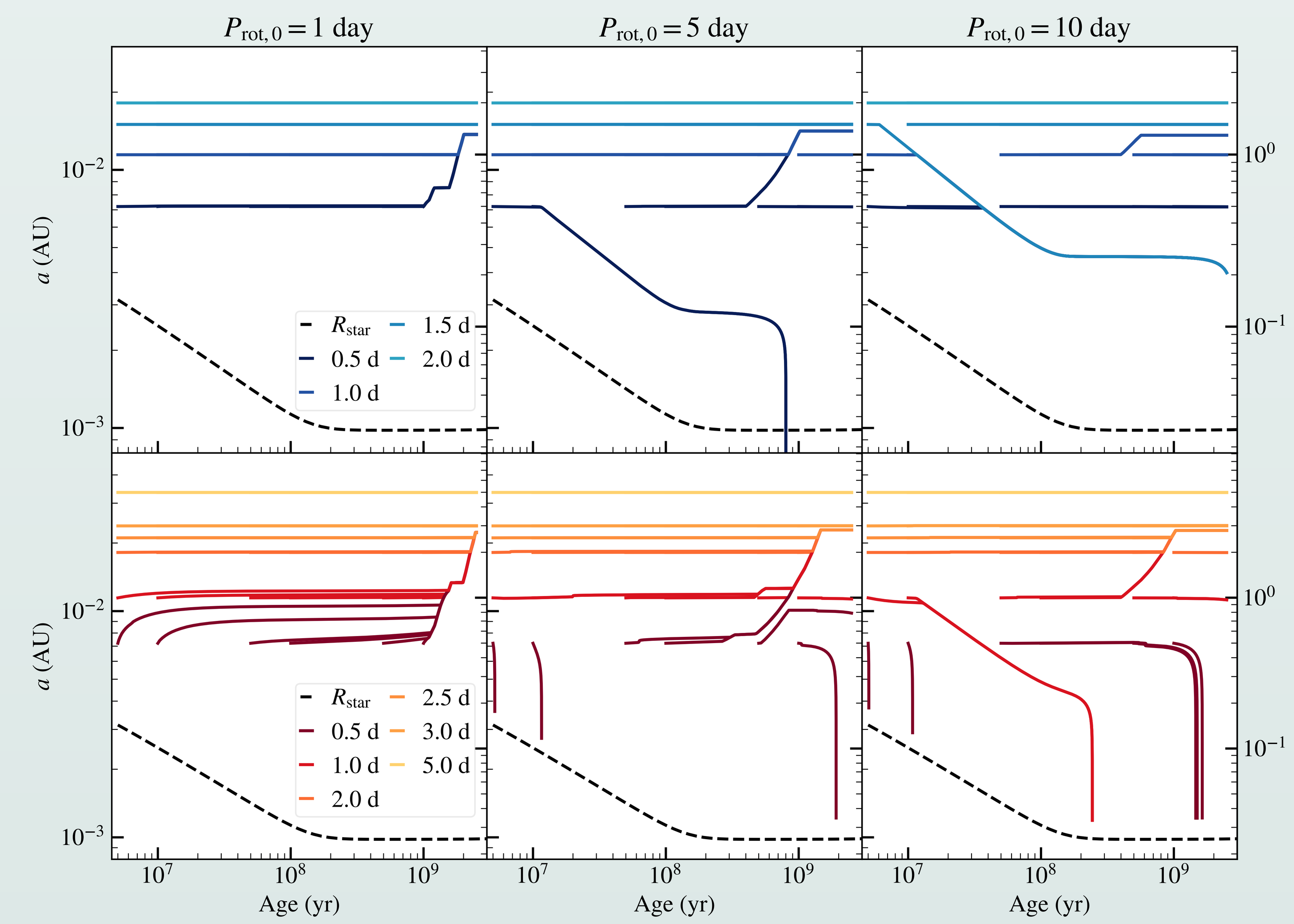
*Larger $\ell, n_1, n_2$ = shorter wavelength

- Mode frequencies trace enhanced dissipation.
- As the star and planetary orbit (e.g. age, $\omega_m$) evolve, the planet encounters varied dissipation.

## Tidal dissipation affects planetary orbits!

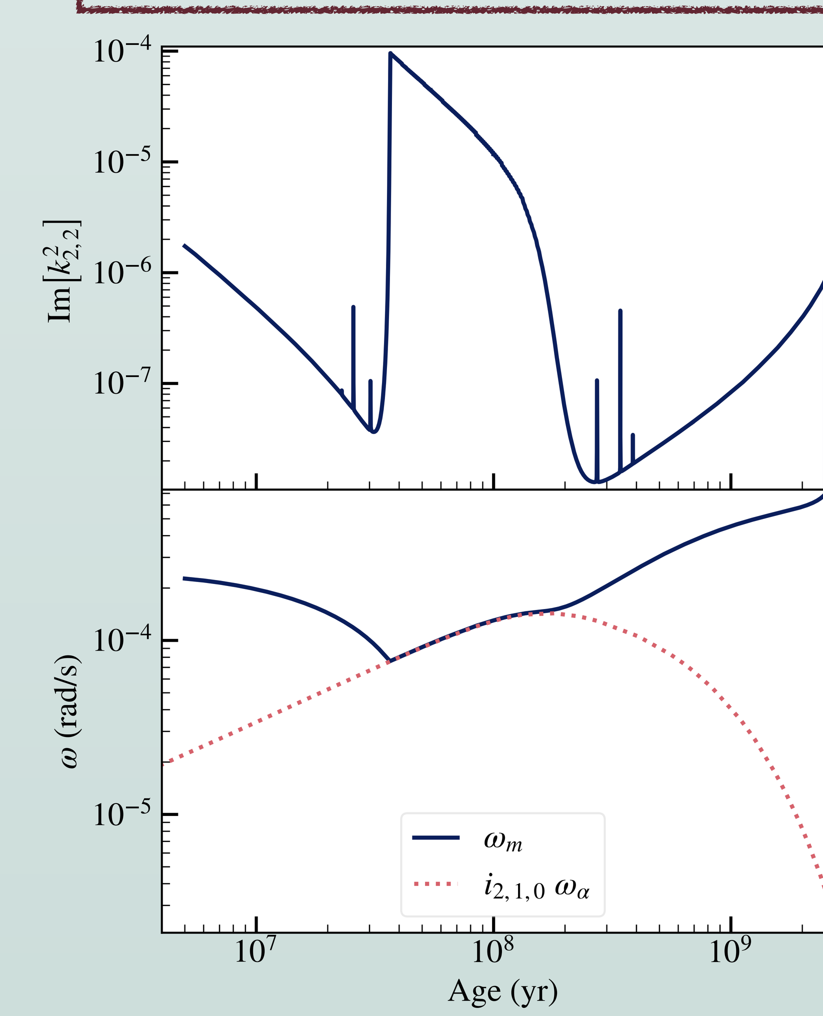
$$\frac{1}{a}\frac{da}{dt} = -3\,\mathrm{Im}\left[k_{2,2}^2\right](\omega_m)\frac{M'}{M}\left(\frac{R}{a}\right)^5 \Omega_o$$

$a$: semimajor axis  $M'/M$: mass ratio

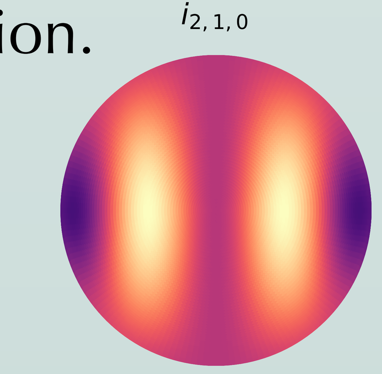



Earth-mass planets at $P_{orb,0} \lesssim 1.5$ day and Jupiter-mass planets at $P_{orb,0} \lesssim 2.5$ day experience inward and outward migration due to tidal dissipation.

## Orbital migration is driven mainly by resonance locking.




When $\omega_m = \omega_\alpha$ for the below mode, the dissipation increases by several OOM. The orbit maintains this for $\approx$ 100s of Myr, causing rapid orbital migration.




## Implications and future work:

- Possible dearth of planets within 1-2 day around low-mass M-dwarfs
- For higher mass stars, will encounter similar, but augmented results due to gravito-inertial waves.