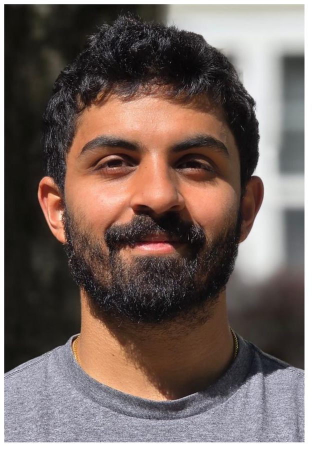

Modeling the early stages of post-main sequence evolution of Hot and Warm Jupiters

Sricharan Balaji[1*], Samuel Grunblatt[1], Tiger Lu[2]

1. Department of Physics and Astronomy, University of Alabama, 2. Center for Computational Astrophysics, Flatiron Institute

*sbalaji1@crimson.ua.edu

How do post-MS planetary systems evolve?

A balance between star-planet and planet-planet interactions

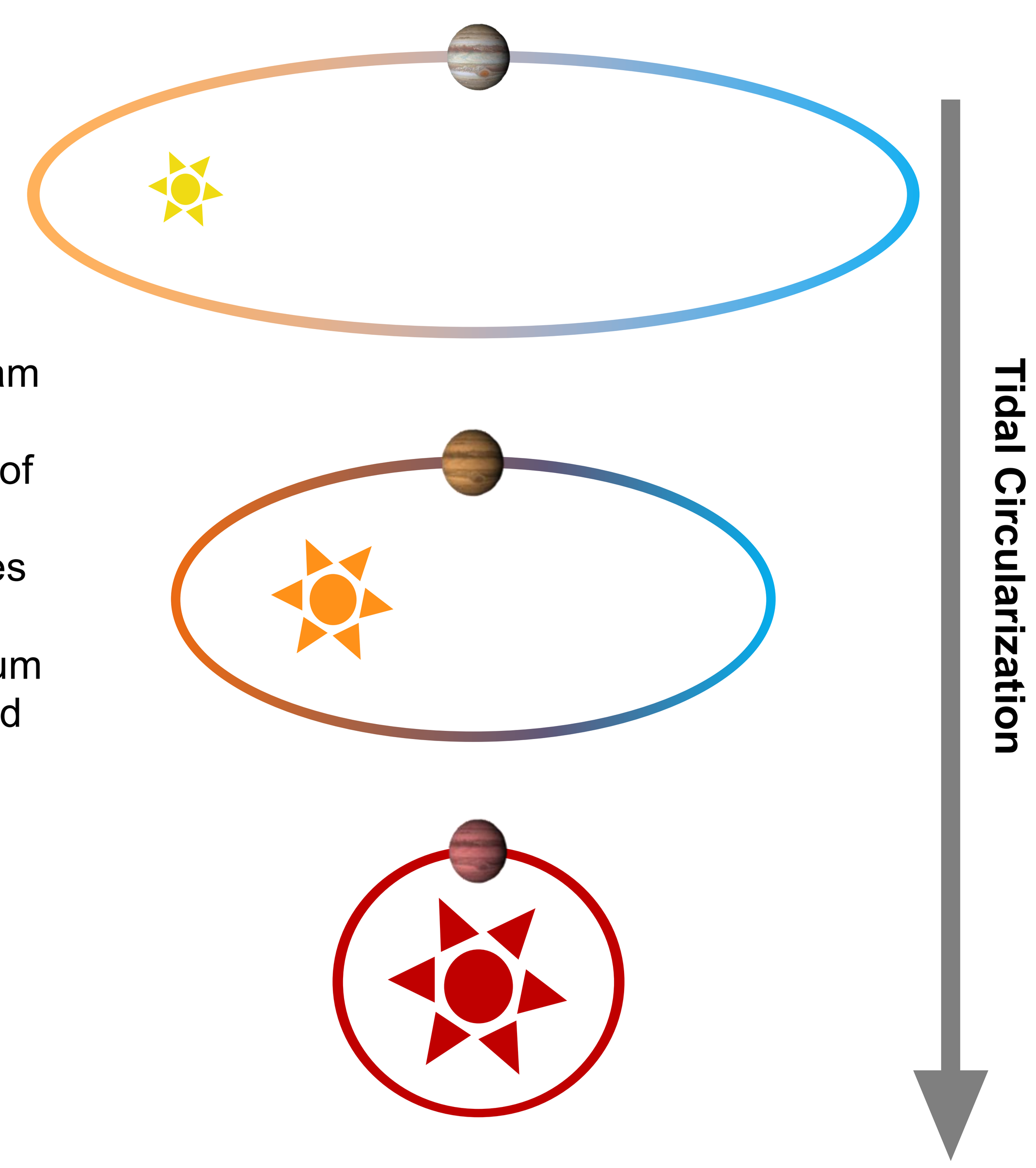

Figure 1: A schematic diagram showing the effect of equilibrium tides on the orbit of a Jupiter-like planet with an evolving star. Equilibrium tides dissipate energy and redistribute angular momentum causing planet to **inspiral** and their orbits to **circularize.**

- ❖Equilibriums tides drive **orbital decay** (inspiral) and **circularization,** causing massive planets to evolve into Warm and/or Hot Jupiters around post-MS stars [1,2](see Figure 1)
- ❖However, planet-planet scattering events can produce Warm/Hot Jupiters at all evolutionary stages [1,4]

By modeling both of these effects, we may be able to reproduce the observed Warm and Hot Jupiter populations around post-MS stars.

The period-eccentricity relationship for Hot Jupiters around post-MS stars

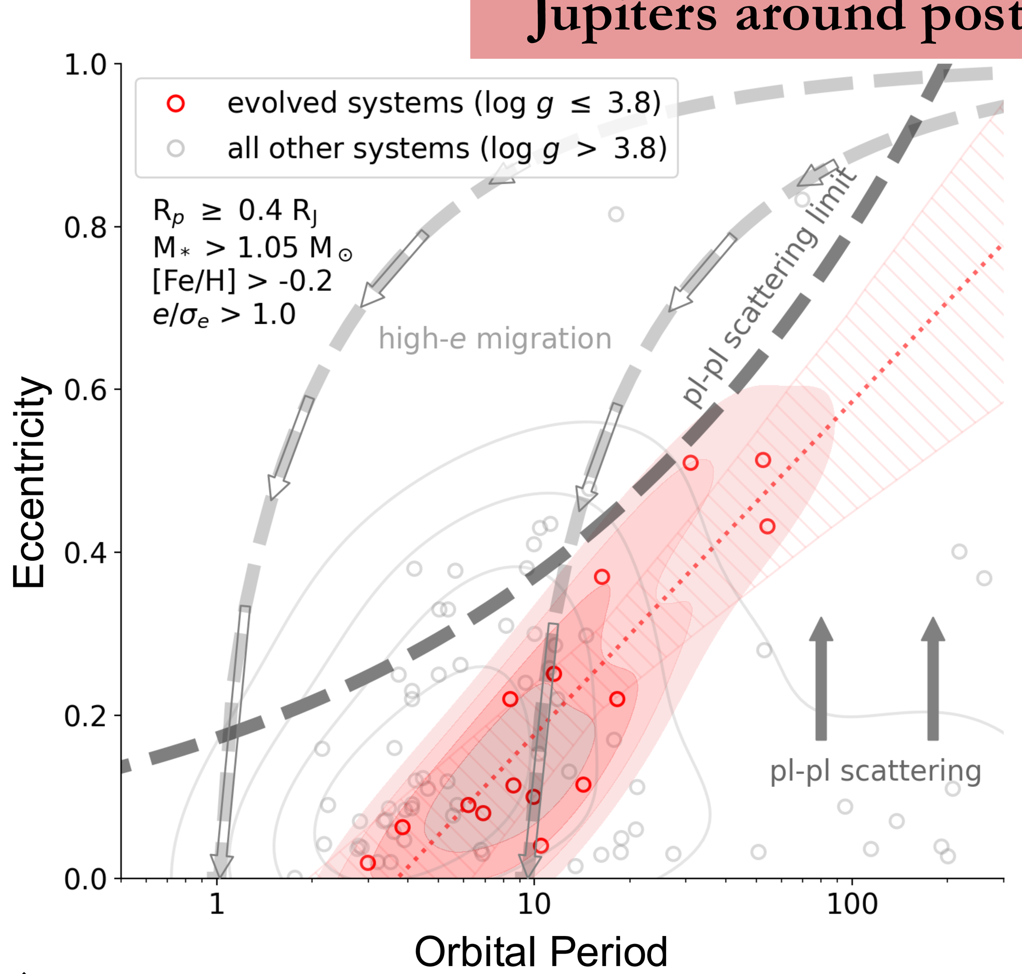

Figure 2: A log-linear relationship between **orbital period and eccentricity** has been observed for Jupiter-sized planets orbiting evolved stars with orbital periods of ~50 days or less [3].

- ❖The combination of planet-planet scattering exciting eccentricities at large orbital periods, and tidally-driven high-eccentricity migration and inspiral damping eccentricities at short periods may be sufficient to explain the unique period-eccentricity relationship [2] (see Figure 2)

It is necessary to model planet-planet dynamics in tandem with stellar evolution to reveal the origin of this evolved planet population feature.

Methodology: Coupling N-body simulations with stellar evolution

REBOUNDx

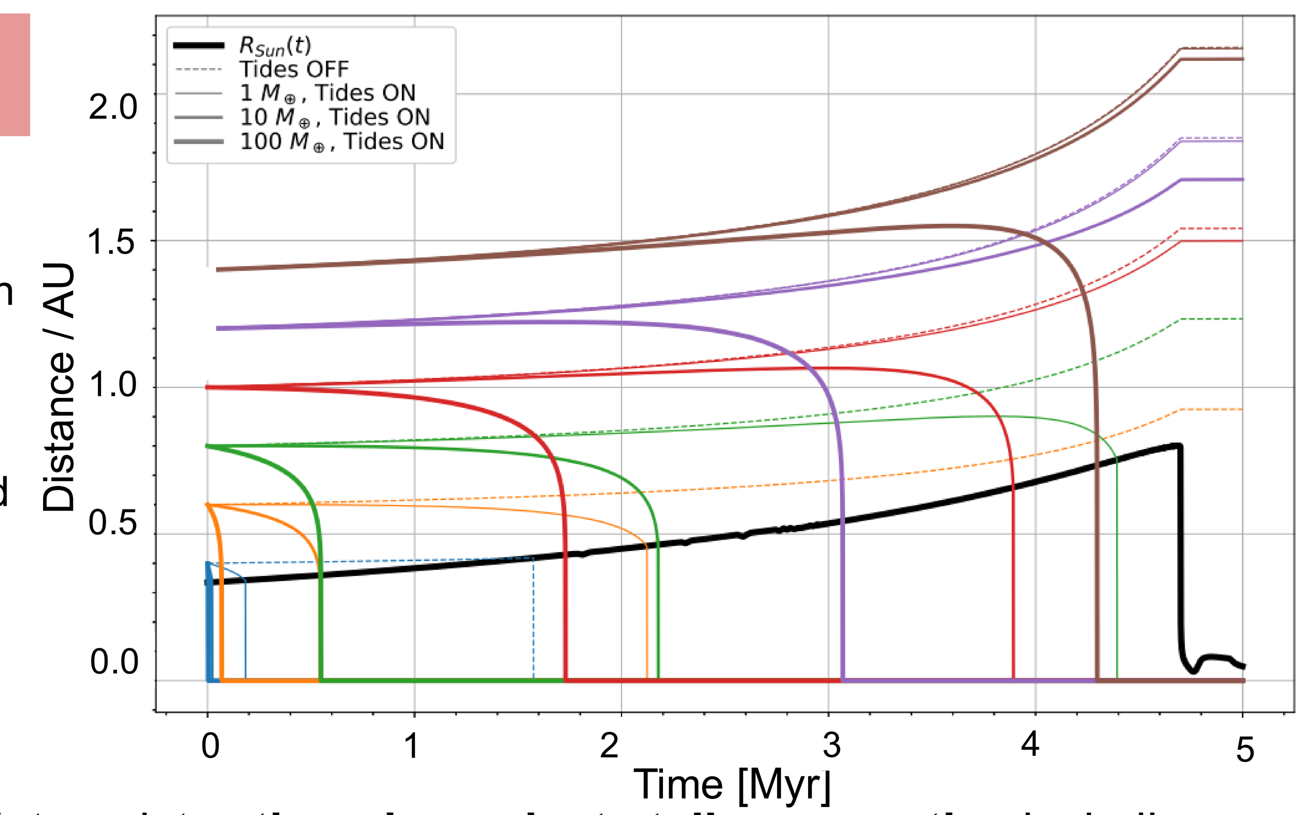

Figure 3: Simulations of orbital evolution in 1-planet systems with and without stellar evolution included (adapted from [5]).

- ❖REBOUNDx interpolates **time-dependent stellar properties** including **mass**, **radius**, and **luminosity** from pre-run stellar evolution tracks at each step in the N-body integration, allowing planet orbits to respond to changes in stellar properties (see Figure 3)
- ❖Equilibrium tides implemented via a **tidal constant time lag (TCTL)** model, dynamical tides not included
- ❖Single planet systems can be run with symplectic, hybrid, or high-order orbit integrators; **close encounters** in multiplanet systems require **hybrid** or **high-order** [6,7]

Evolution of simulated multiplanet systems around early post-MS stars

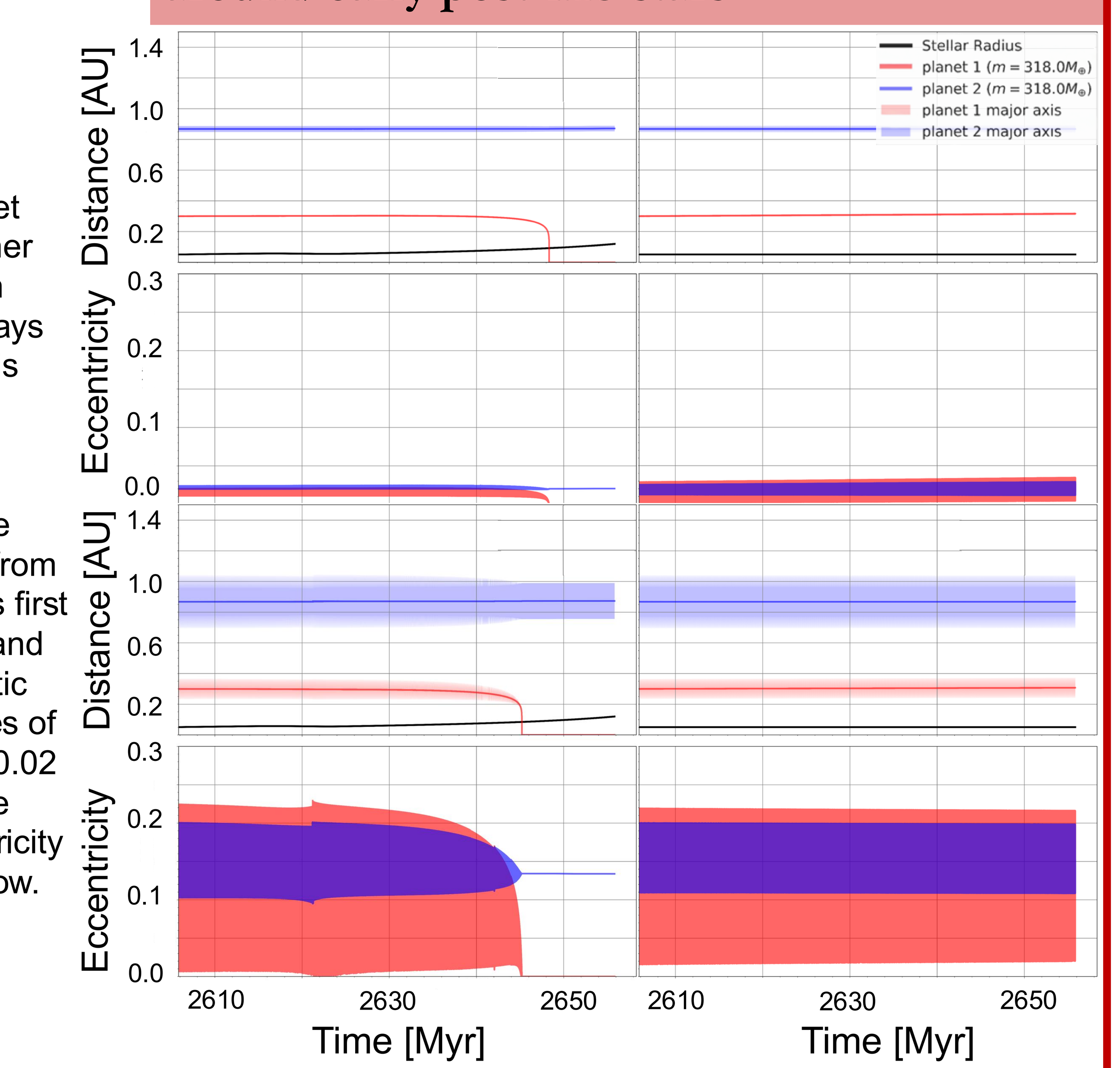

Figure 4: A two planet system where the inner planet is placed at an orbital period of 50 days and the outer planet is placed 13 mutual Hill radii away. The left column shows simulations where the host star is evolving from 10 $R_\odot$ to 25 $R_\odot$ on its first ascent up the RGB, and the right shows a static star. The eccentricities of the both planets are 0.02 in the top row and the outer planet's eccentricity is 0.2 in the bottom row.

- ❖In these simulations, planets are separated by 13 mutual Hill radii, which is the minimum observed separation in multiplanet Hot Jupiter systems [8]
- ❖Eccentricity oscillations have larger amplitudes if the outer planet starts with a higher eccentricity
- ❖These simulations suggest that stellar evolution (tides) can trigger planet inspiral and planets can interact with one another in post-MS to excite eccentricities independently

Evidence is seen for stellar evolution-driven damping but no evidence is seen for stellar evolution-driven planet-planet interaction independently.

Can we reproduce the observed period-eccentricity relationship for planets orbiting post-MS stars?

Tidal force qualitatively retains period-eccentricity relationship

- ❖We can model the future evolution of observed planets transiting post-MS stars using REBOUNDx
- ❖Our simulations suggest several observed post-MS planets will be sengulfed

REBOUNDx simulations reveal that future post-MS system evolution preserves the period-eccentricity relationship

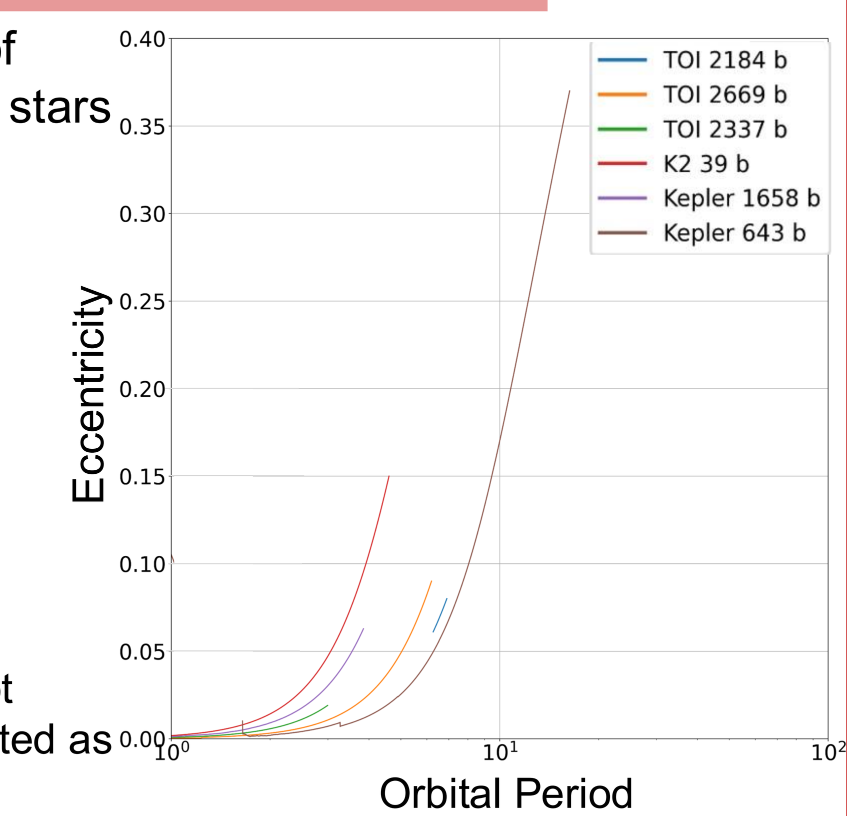

Figure 5: The resulting period-eccentricity evolutionary tracks for several observed Hot Jupiters around post-MS stars when simulated as 1-planet systems with REBOUNDx.

Warm Jupiter scatterings can significantly excite eccentricities!

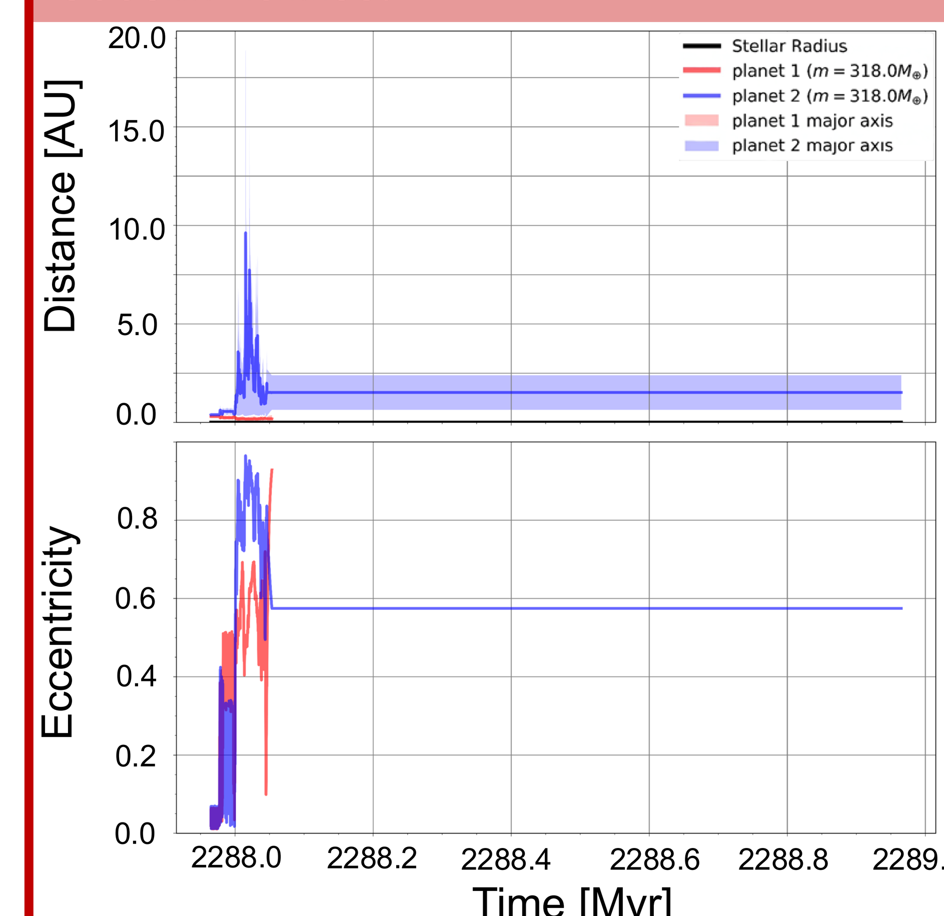

Figure 6: Two planet simulations with an evolving star run with the TRACE integrator. The planets are separated by 3.5 mutual Hill radii - on the edge of dynamical stability. We see significant eccentricity excitation in both planets due to close encounters with each other leading to the inner planet to get engulfed.

- ❖We can excite planet eccentricities through planet-planet scattering, but this is independent of stellar effects
- ❖However, the companion is likely to get scattered, collide with the planet, or get engulfed by the host star – could explain "isolated" Hot Jupiters
- ❖Despite getting excited to an eccentricity of ~ 1, the outer planet survives due to being scattered to 10 AU – the planet is not expected to survive beyond an additional 100 Myr as the star grows

Future work

- ❖Incorporating dynamical tides could explain lack of eccentricities > 0.6
- ❖Unequal mass planets increase scattering potential
- ❖Investigate potential "turnover" of eccentricities beyond 100 days

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