Skylar D'Angiolillo
PhD Student

ORBITAL DYNAMICS AS A HABITABILITY DIAGNOSTIC FOR NEARBY PLANETARY SYSTEMS

Skylar D'Angiolillo[1] | Stephen Kane[1] | Zhexing Li[1]

[1] University of California Riverside, Department of Earth and Planetary Sciences, Riverside, CA

sdang049@ucr.edu | AbSciCon 2026 | University of California, Riverside

Check out Kane et al. (2025) for more info on the Eta Cas system!

INTRODUCTION & BACKGROUND

Why Orbital Stability Matters

Long-term habitability requires orbital stability — without it, no planet can maintain the conditions necessary for liquid surface water.

Eccentricity excitation drives large insolation flux variations, potentially triggering runaway greenhouse or snowball states.

Stellar companions (binaries) perturb planetary orbits, constraining the regions where habitable orbits can persist.

Giant planet architecture shapes terrestrial planet distributions through resonant and secular interactions.

⬡ ETA CASSIOPEIAE SYSTEM ⬡

SYSTEM OVERVIEW & MOTIVATION

System Parameters from Giovinazzi et al. (2025) :

Mass of Primary Star	Mass of Secondary Star	Orbital Period	Semimajor Axis	Eccentricity	Argument of Periastron
1.0258 $M_\odot$	0.5487 $M_\odot$	472.2 yr	70.55 au	0.49416	88.34°

Eta Cassiopeiae is a nearby (5.92 pc) binary star system with no known planets [3]. It is of astrobiological interest because:

- **Wealth of Radial Velocity (RV)** data has been collected on this system (945 RV measurements over ~30 years).
- **Binary star** systems are abundant in the universe and understanding how their gravitational interactions shape the habitable zone is crucial.
- **Combined RV and Dynamical** approaches can be used to demonstrate if / where different types of planets (giant and terrestrial) may be present in the system.

Eta Cassiopeiae A Habitable Zone Boundaries [4] :

Conservative HZ (Runaway Greenhouse to Maximum Greenhouse):
0.968 au --1.710 au
Optimistic HZ (Recent Venus to Early Mars):
0.764au --1.803 au

METHODS & SIMULATIONS

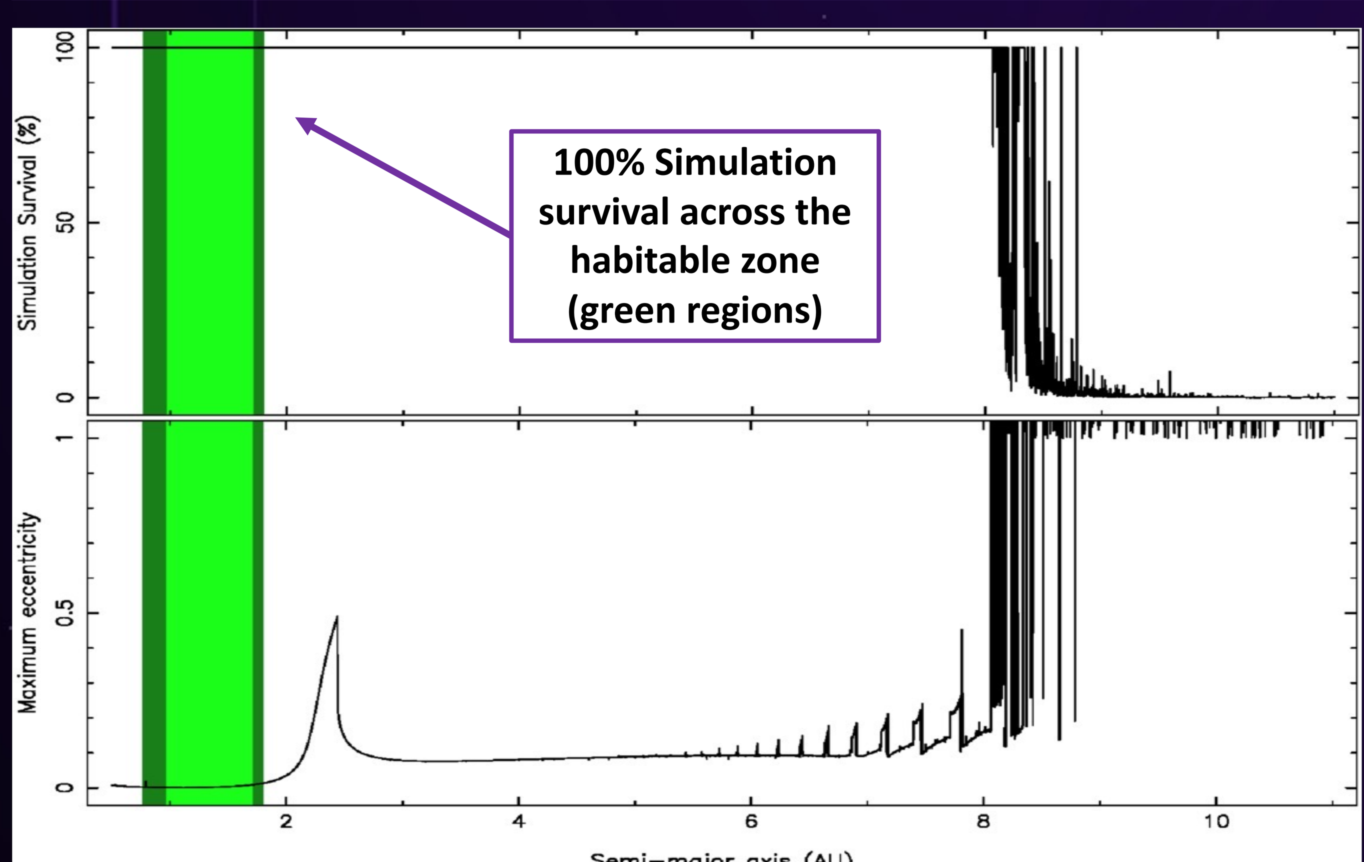
Radial Velocity Data Search (RVSEARCH) [2,8]

- **Orbital Period Range:** 1 - ~50,000 days
- **False Alarm Probability Threshold:** 0.01% (statistically significant)

N-body Injection – Recovery (REBOUND + WHFast) [6,7]

- **7001 Simulations:** semimajor axis 0.5 – 11.0 au (0.0015 au steps)
- **Integration:** 10 Myr | Timestep: 5 days | Orbital elements recorded every 100 years

RESULTS – ETA CASSIOPEIAE



⬡ The Habitable zone of Eta Cassiopeiae is dynamically stable and can host an Earth-mass planet! ⬡

RV Search: No significant periodic signals detected → giant planets excluded out to 8 au [4].

Injection - Recovery Simulations: The habitable zone is stable and can host an Earth-mass planet, but orbits destabilize beyond 8 au [4].

⬡ GJ 3293 SYSTEM ⬡

MOTIVATION – WHY GJ 3293?

GJ 3293 is a nearby M-dwarf (M2.5V, ~ 0.42 $M_\odot$) hosting at least four companions detected via RV [1]. It is of astrobiological interest because:

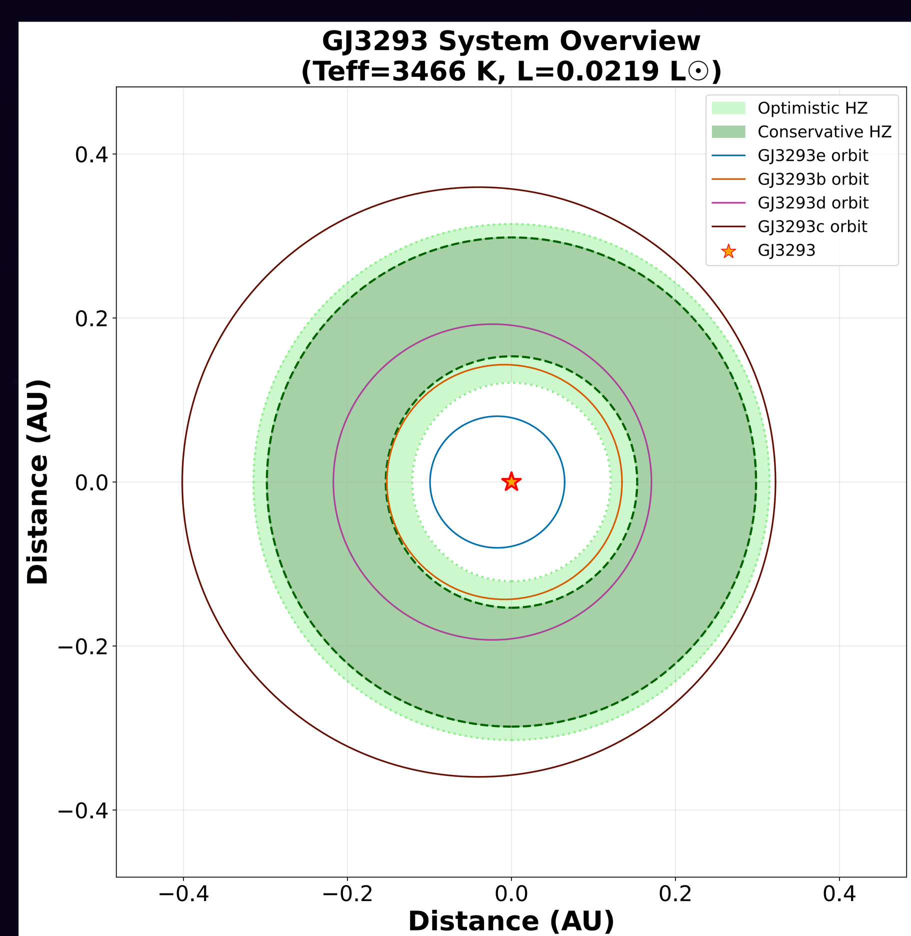
- Minimum mass measurements derived from radial velocity data places planet d on the cusp of terrestrial / mini-Neptune mass.
- The habitable zone (HZ) of this M-dwarf hosts planets b & d.
- Varying the inclination of these planets affects system stability, allowing us to derive the most probable planetary mass estimates.
- Direct Imaging Target for Habitable Worlds Observatory (Planet d has a 9.7 milli-arcsec angular separation)

SYSTEM OVERVIEW – GJ 3293

Planetary Parameters from Astudillo-Defru et al. (2017) :

Planet (GJ 3293)	Minimum Mass ($M_\oplus$)	Semimajor Axis (au)	Eccentricity
e	3.28	0.08208	0.21
b	23.54	0.14339	0.06
d	7.60	0.19394	0.12
c	21.09	0.36175	0.11

Overview of the GJ 3293 system where the conservative and optimistic habitable zones are represented by the dark green and light green shaded regions, respectively, and the orbits of the four known planets are each represented by an annulus.



GJ 3293 Habitable Zone Boundaries [5]:

Conservative HZ (Runaway Greenhouse to Maximum Greenhouse):
0.1533 au -- 0.2983 au
Optimistic HZ (Recent Venus to Early Mars):
0.1210 au -- 0.3146 au

METHODS & ONGOING INVESTIGATIONS

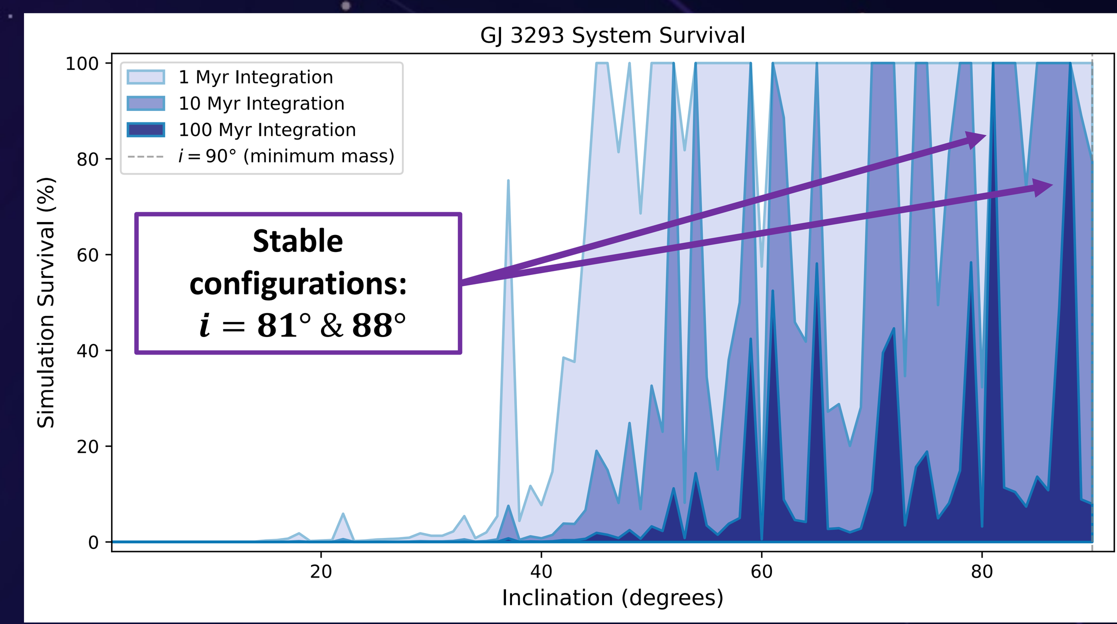
Inclination Sweep (REBOUND + WHFast) [6,7]

- **Mass Scaling :** True mass of each planet scaled as $\frac{M_{min}}{\sin(i)}$, swept from $1° - 90°$, in $1°$ increments
- **Integration:** 100 Myr | Timestep = 0.4 days | Orbital elements recorded at 100,000 output steps
- **Ejection Criteria:** Planet leaves the system ($e \geq 1$ or $a \geq 100$ au) or planet falls into gravity well of host star ($a \leq 0.003$ au)

Injection – Recovery (REBOUND + WHFast) [6,7]

- **2001 simulations:** semimajor axis 0.025 – 1.0 au (0.0004875 au steps)
- **Integration:** 10 Myr | Timestep = 0.2 days | Orbital elements recorded at 100,000 output steps
- **Ejection Criteria:** Planet leaves the system ($e \geq 1$ or $a \geq 100$ au) or planet falls into gravity well of host star ($a \leq 0.003$ au)

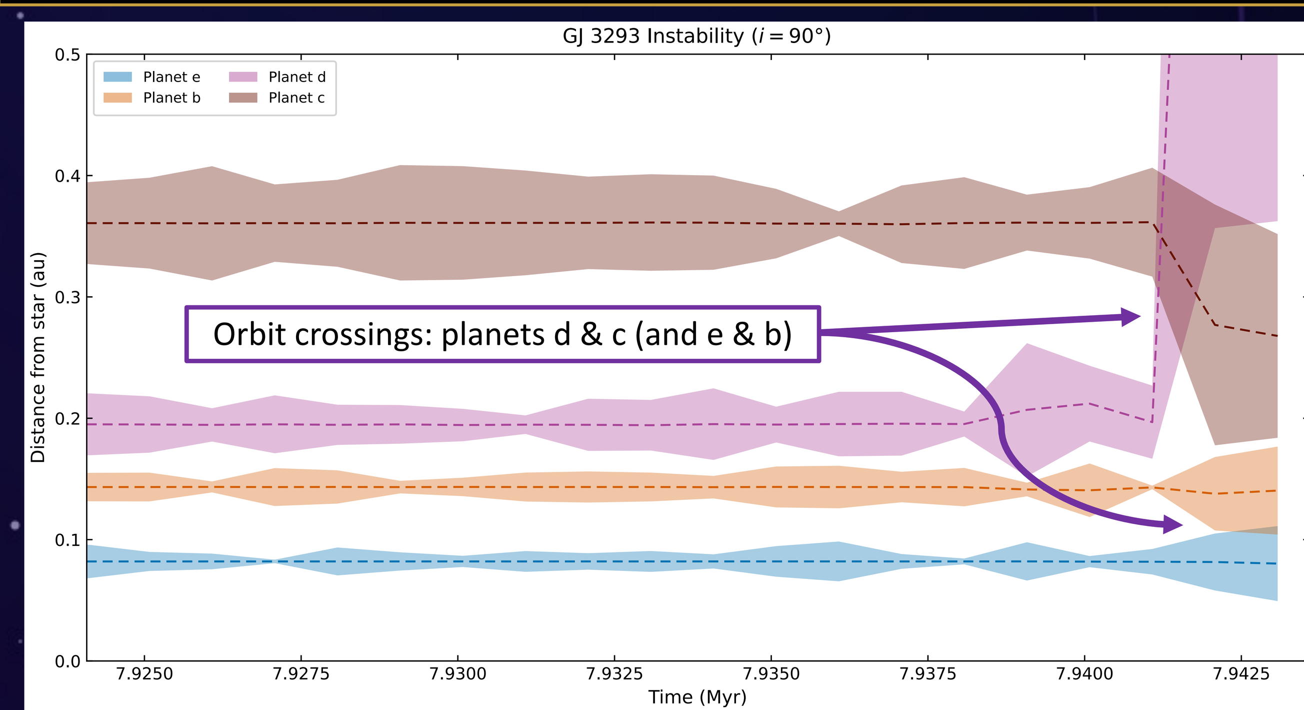
INCLINATION SWEEP RESULTS



Simulation Survival as a function of Inclination

GJ 3293 inclination- sensitive. Nearly all configurations go unstable over 100 Myr, but $i = 81°$ and $i = 88°$ remain stable, implying a true mass for GJ 3293d of 7.695 $M_\oplus$ and 7.605 $M_\oplus$, respectively.

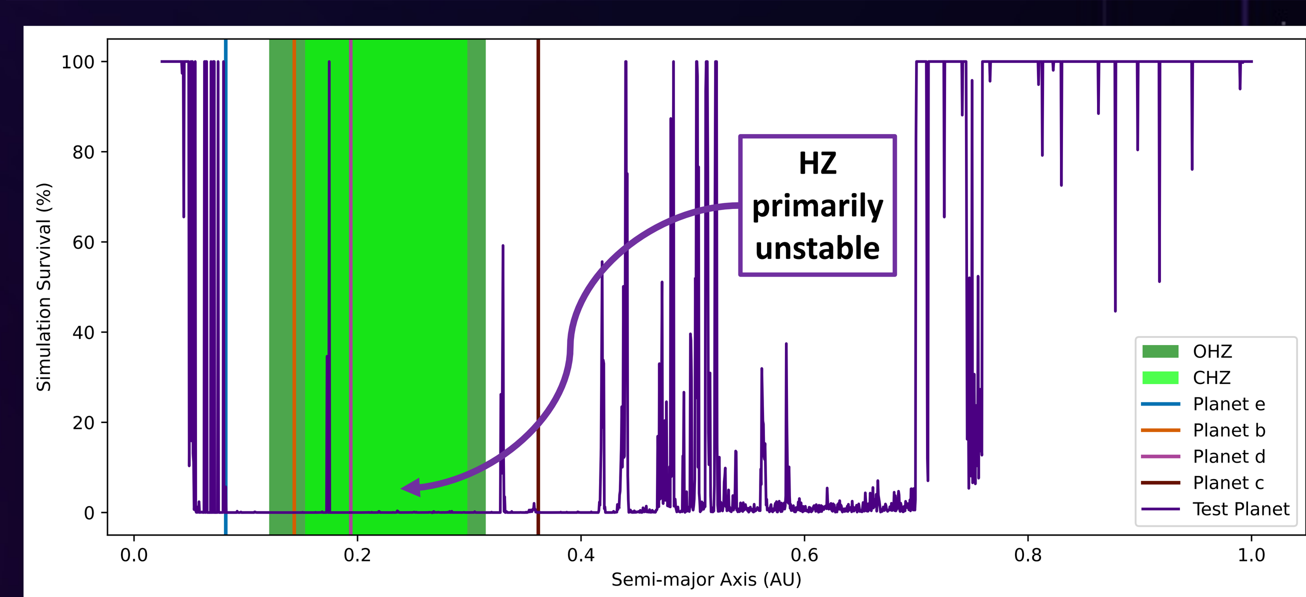
⬡ GJ3293 has a terrestrial planet orbiting entirely within the Habitable Zone! ⬡



Instability at Edge-on Inclination

At $i = 90°$, the system becomes dynamically unstable. In the final timesteps, orbits of planets d & c begin to cross, and planets e & b follow.

INJECTION – RECOVERY RESULTS



Injection-Recovery Uncovers Instabilities in Habitable Zone

The habitable zone is primarily unstable, potentially driven by giant planet GJ 3293b residing within the optimistic habitable zone. Stable orbits exist beyond 0.8 au that can possibly host terrestrial planets.

RESULT SUMMARIES + WHAT'S NEXT?

Eta Cassiopeiae

- RV search and N-body simulations exclude giant planets in this system. The habitable zone remains dynamically stable for Earth-mass planets.
- All work published in Kane et al. (2025).

GJ 3293

- GJ 3293d is a terrestrial planet orbiting completely within the habitable zone. Stable configurations are found at $i = 81°$ and $i = 88°$. Additional terrestrial planets in the HZ are unlikely due to perturbations from surrounding giant planets.
- Next: Search for similar nearby systems that may have viable terrestrial planets, prioritizing targets for upcoming direct imaging missions.

REFERENCES

[1] Astudillo-Defru et al 2017 A&A 602 A88.
[2] Fulton et al 2018 PASP 130 044504.
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