The dynamical origins of giant planet eccentricities

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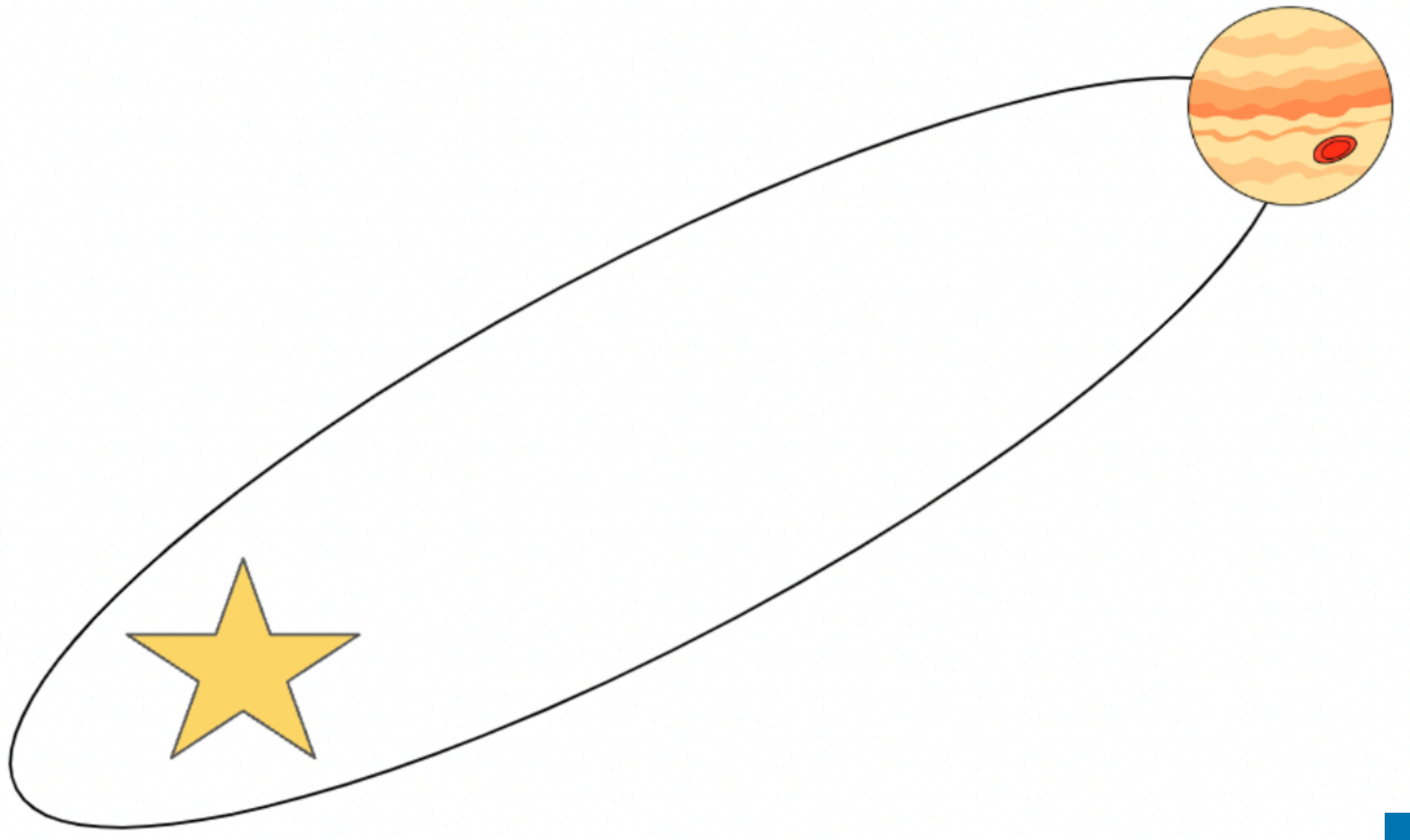

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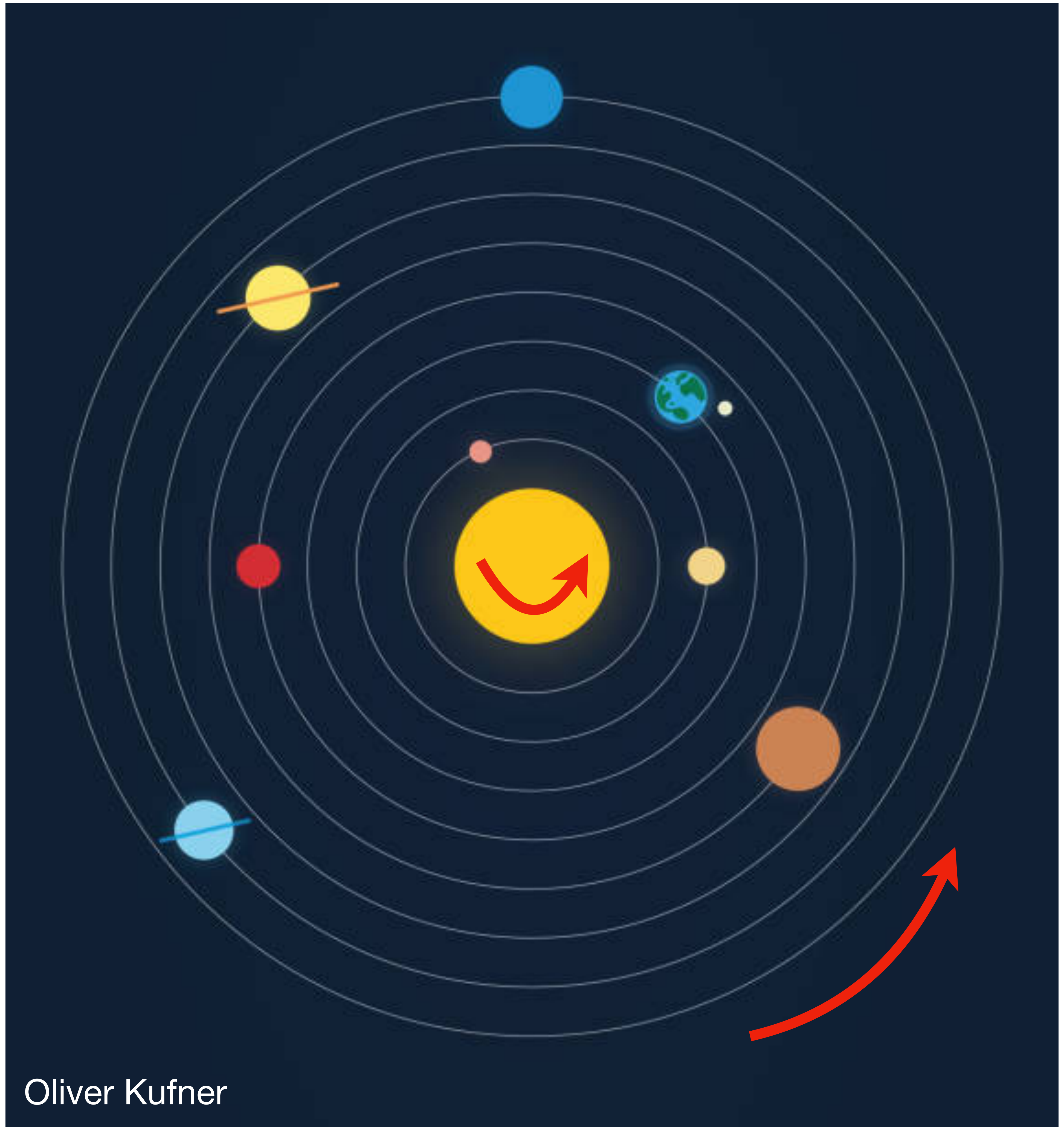
The Solar System



- Nearly circular orbits (low eccentricities)

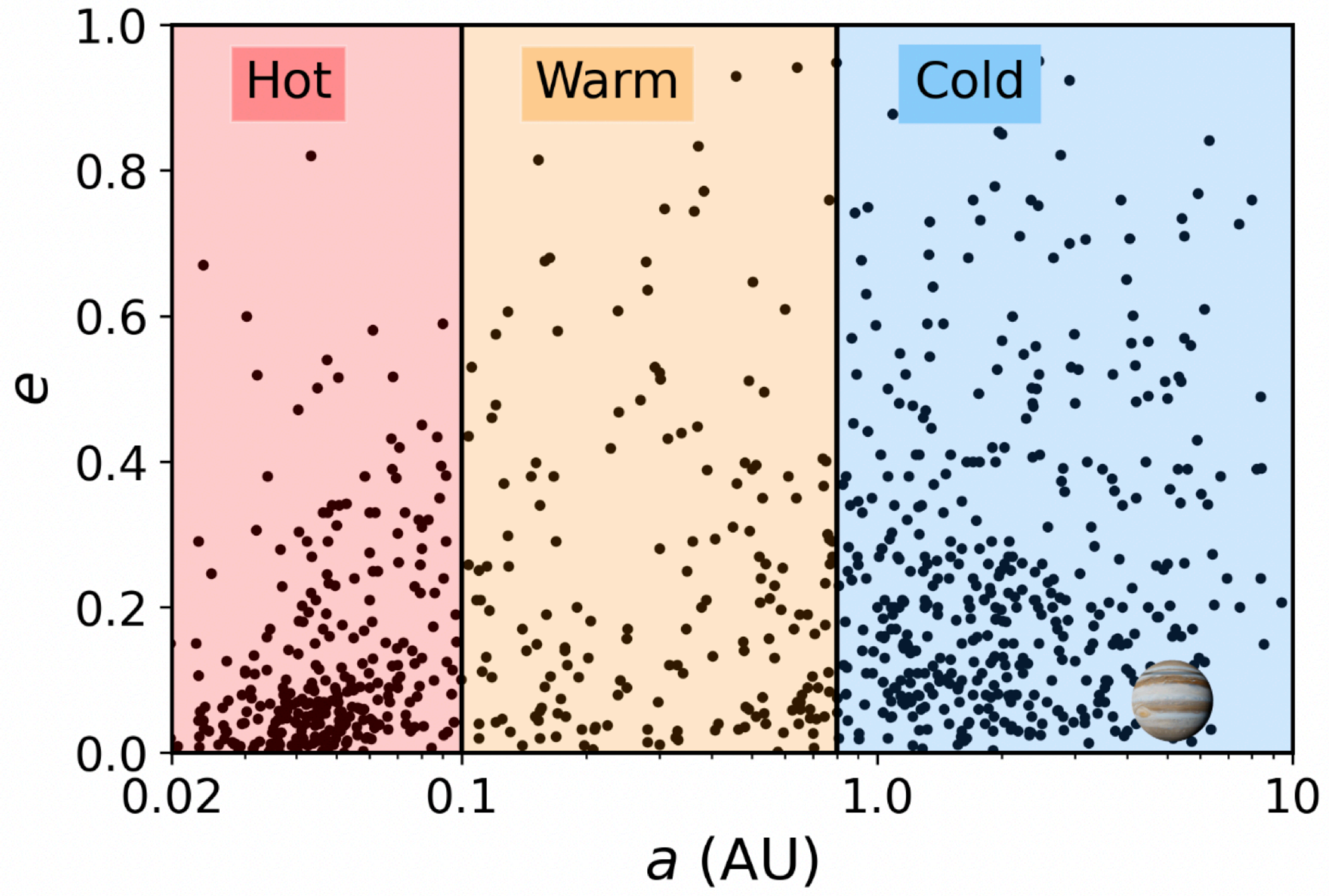
- Nearly coplanar orbits

- Orbital motion in the same direction as stellar spin

- Gas giants at large distances

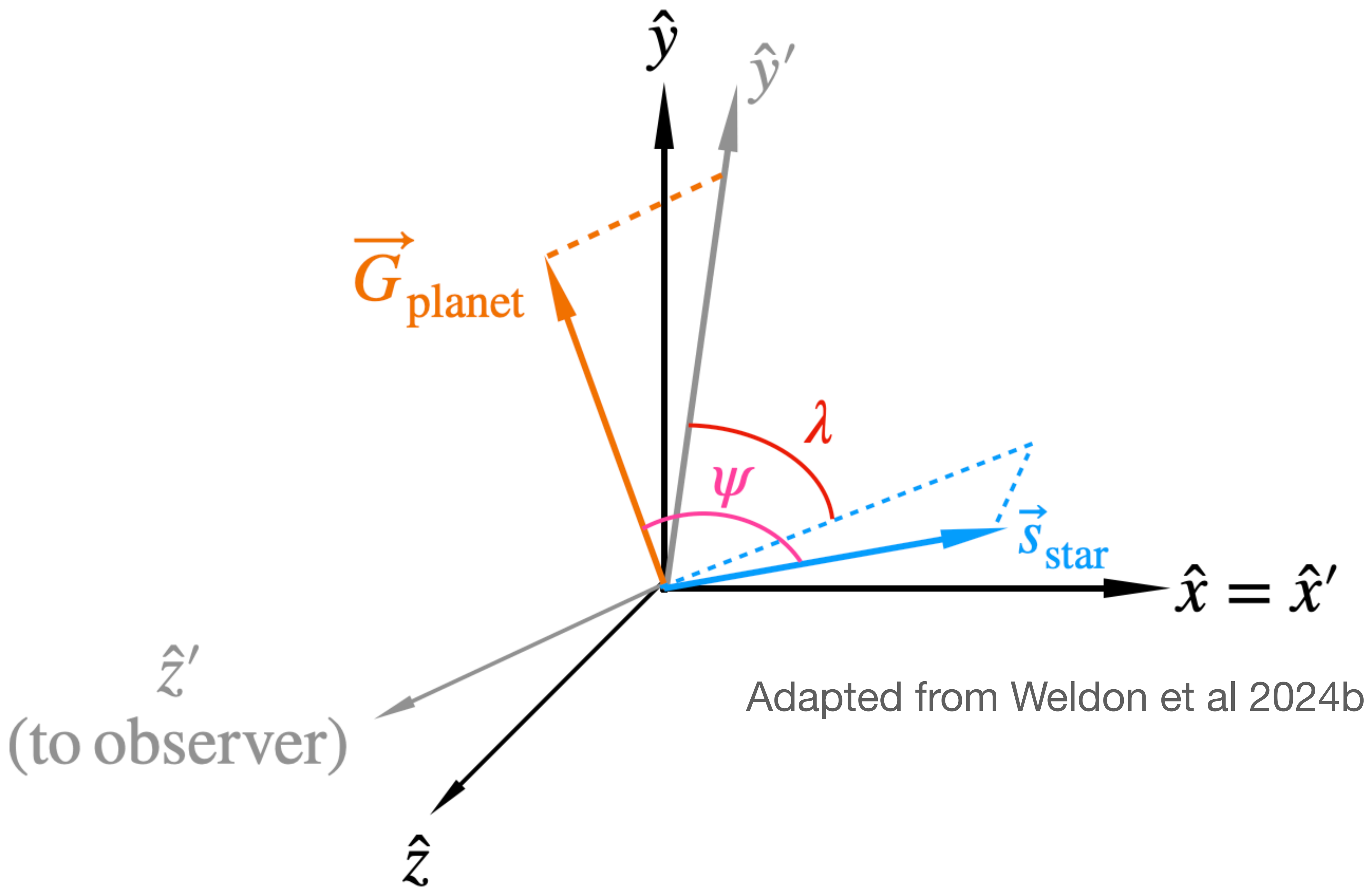
Surprises in the extrasolar giant population

Close-in giants and high eccentricities!



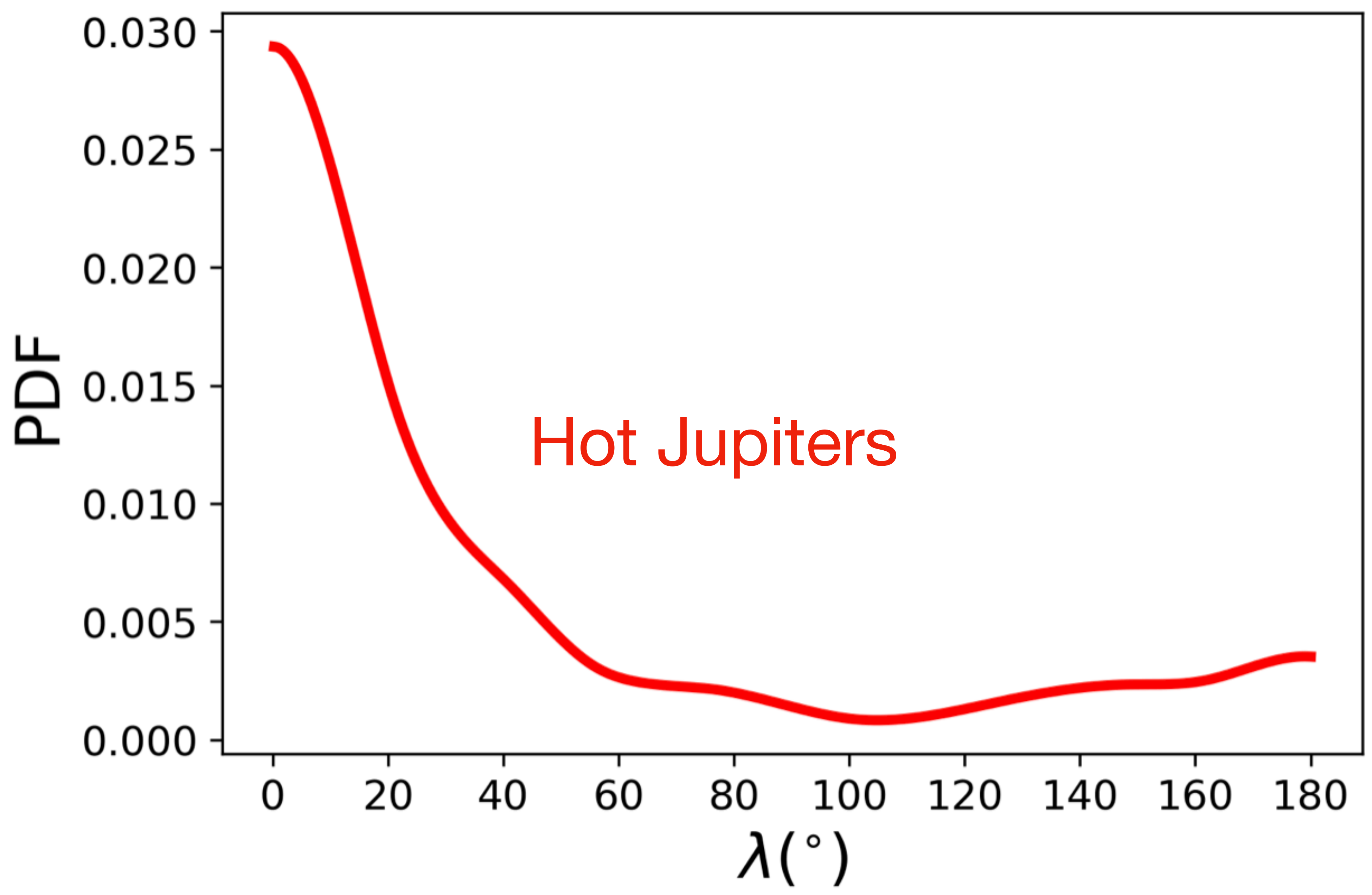
Adapted from Weldon et al 2024b; Data from NASA Exoplanet Archive

Surprises in the extrasolar giant population



Adapted from Weldon et al 2024b

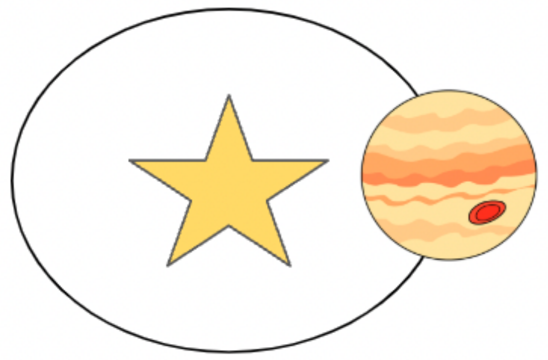
High stellar obliquities, including retrograde motion!



Adapted from Naoz et al. 2012, Wright et al. 2011

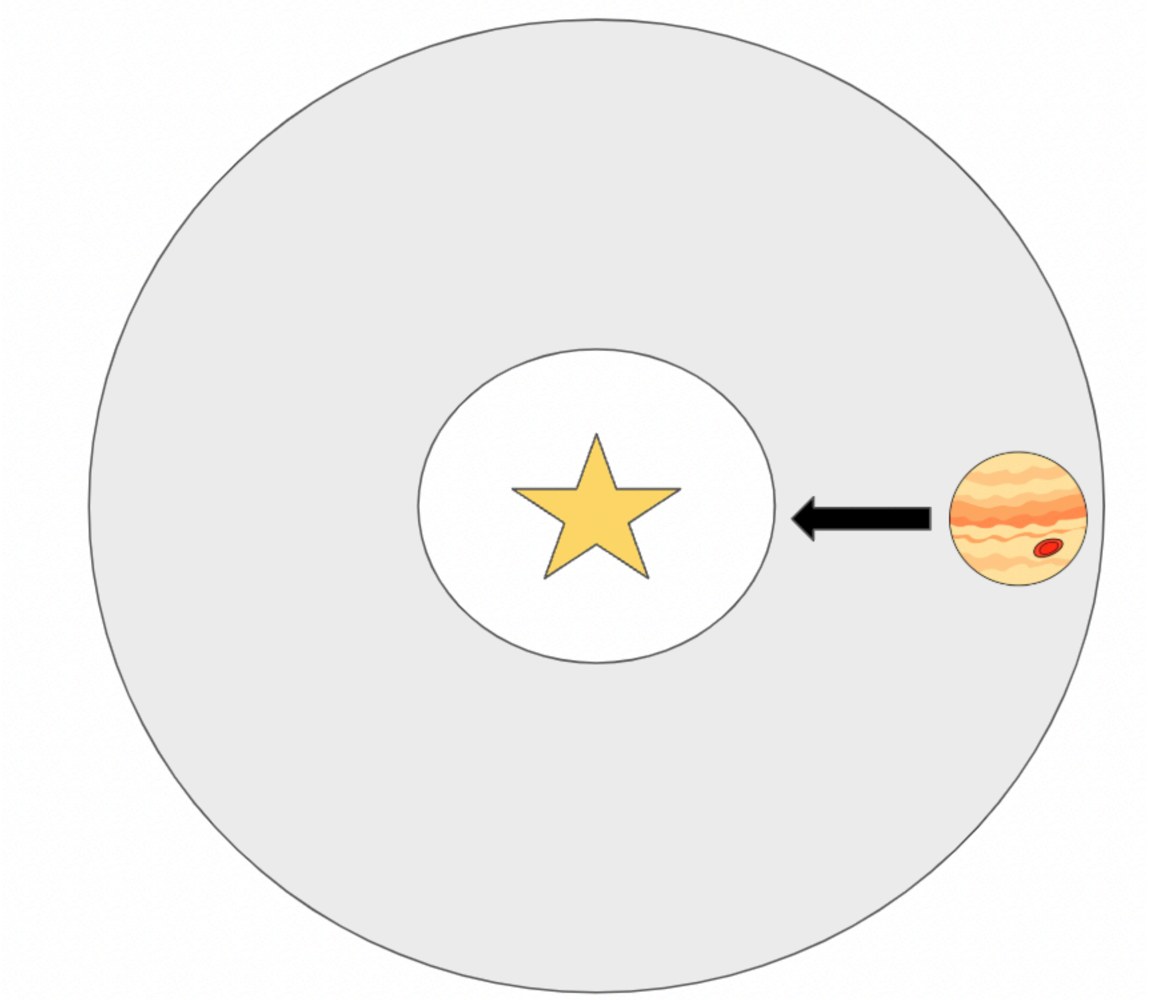
Proposed hot Jupiter formation channels

In situ formation



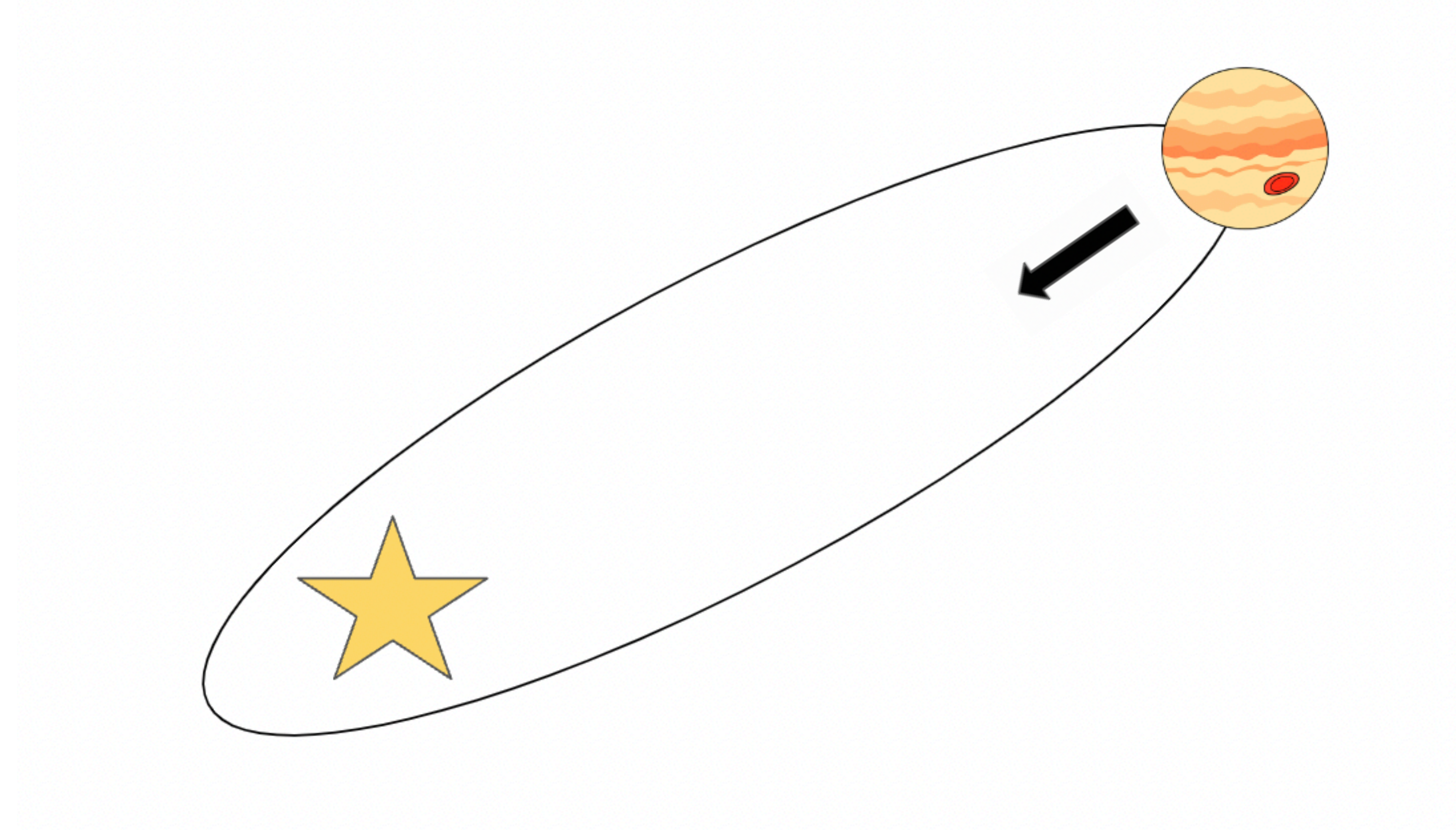
Requires enhanced solid material near star (e.g., Batygin et al 2016, Boley et al 2016)

Disk migration



Torques between cold Jupiter and gaseous disk (e.g., Goldreich & Tremaine 1980, Lin & Papaloizou 1986)

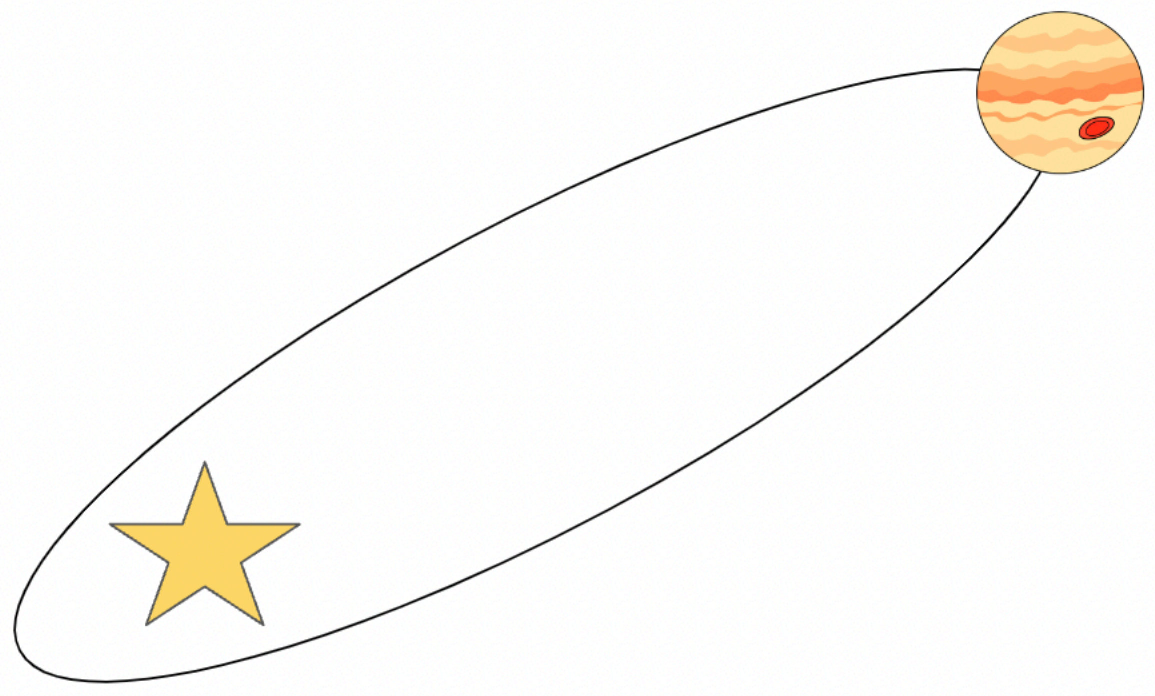
High-eccentricity migration



Eccentricities may be generated by:

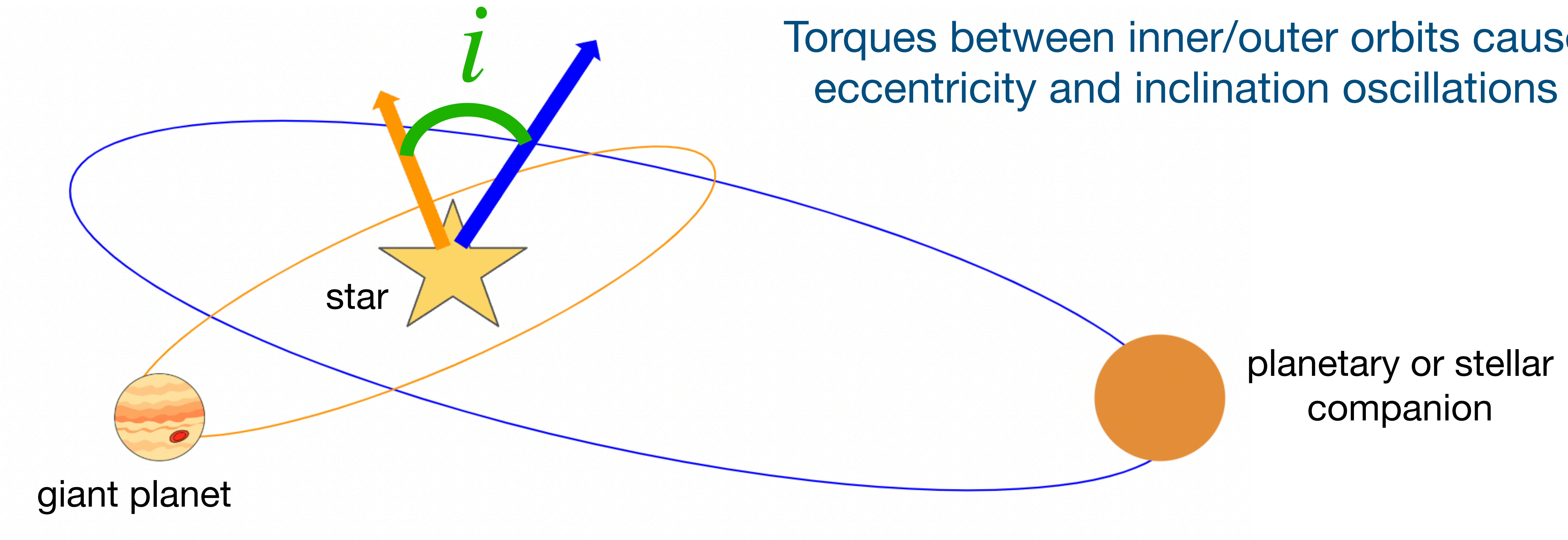
- Planet-planet scattering (e.g., Rasio & Ford 1996, Jurić & Tremaine 2007, Chatterjee et al 2008, Nagasawa et al 2008)
- Multi-planet secular (long-timescale) chaos (e.g., Wu & Lithwick 2011, Teyssandier et al 2019)
- **Secular perturbations from a distant planet or star; the Eccentric Kozai-Lidov (EKL) mechanism** (e.g., Kozai 1962, Lidov 1962, Naoz 2016)

I. Analytical models for EKL-driven eccentricity evolution



Eccentric Kozai-Lidov (EKL) mechanism acts in hierarchical three-body systems, where secular approximation (averaging over orbital periods) can be applied

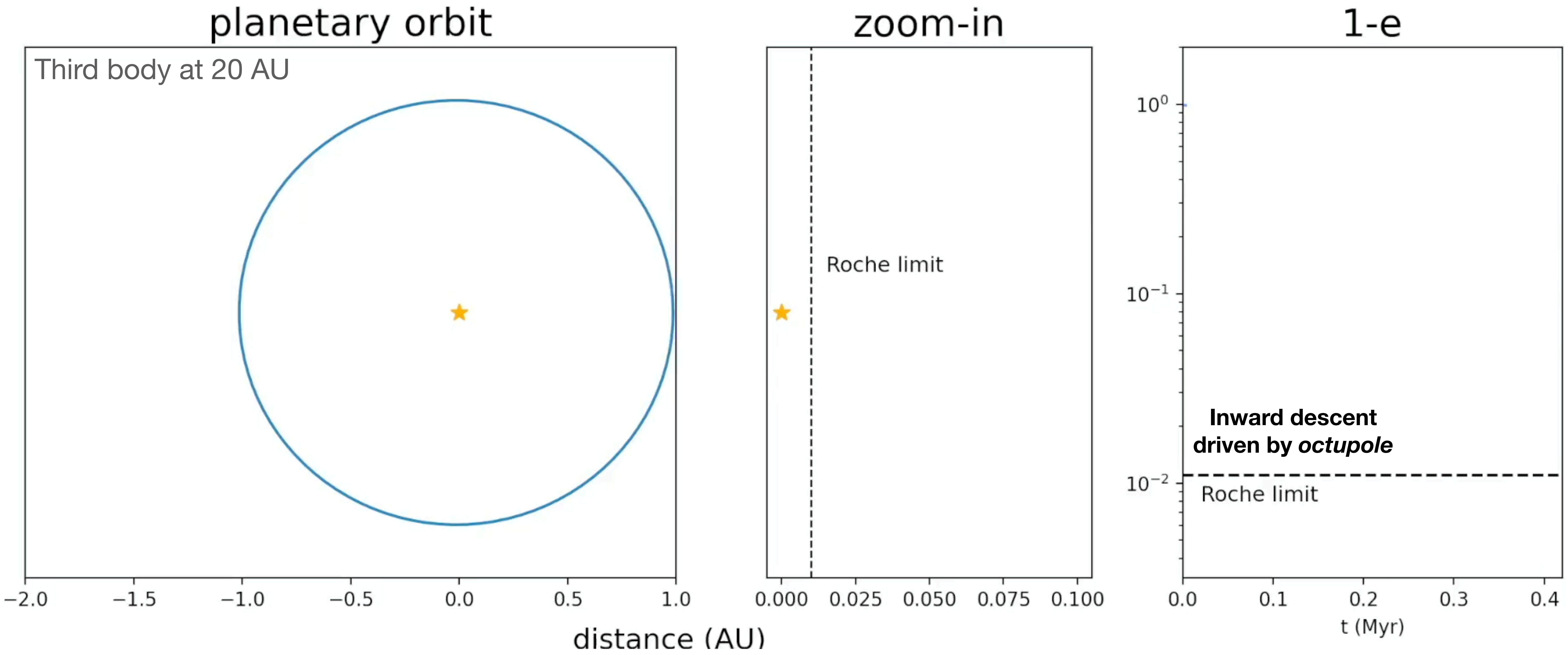
(see Naoz 2016 for review)



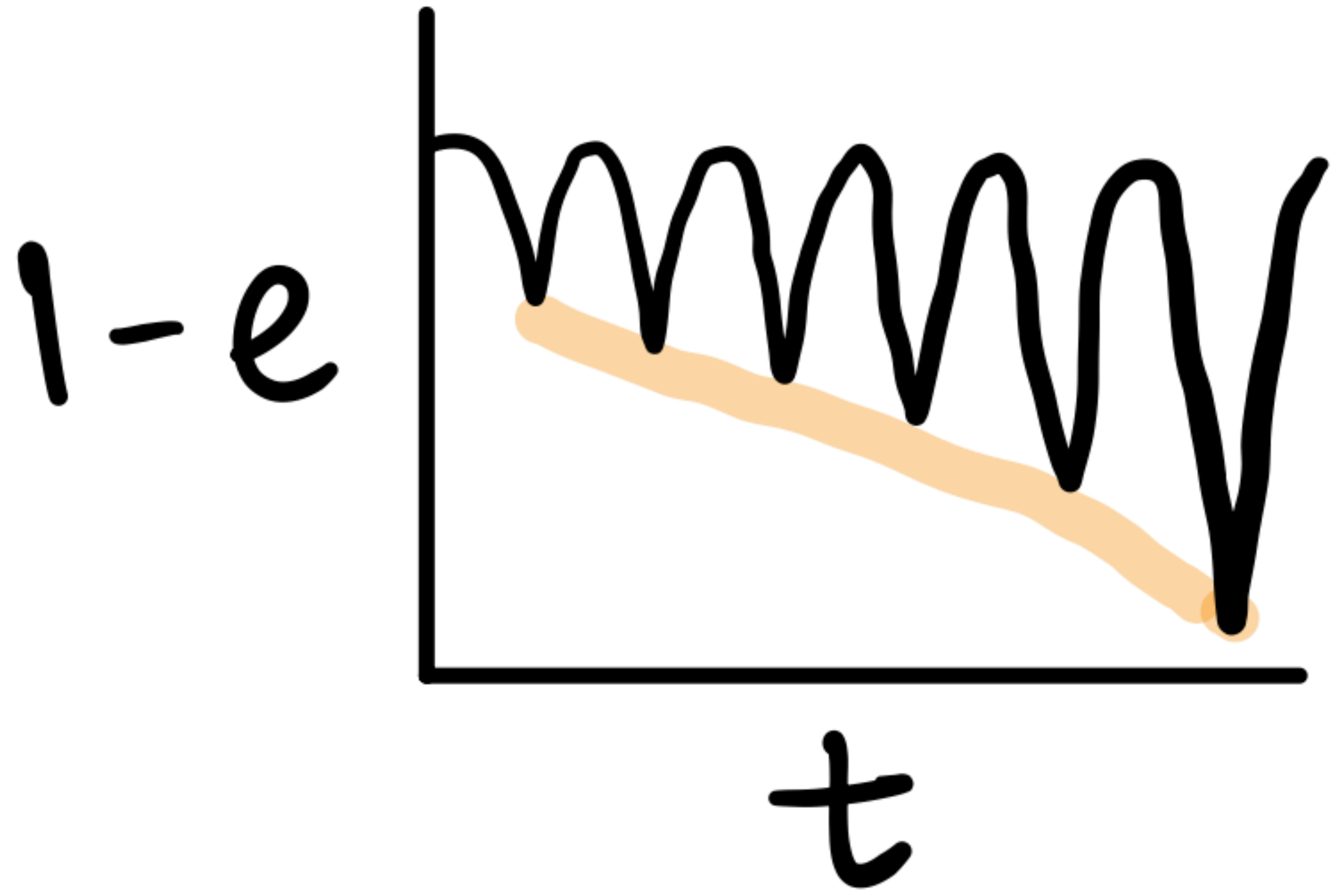
Torques between inner/outer orbits cause eccentricity and inclination oscillations

Diagram not to scale

Simulation of EKL eccentricity evolution



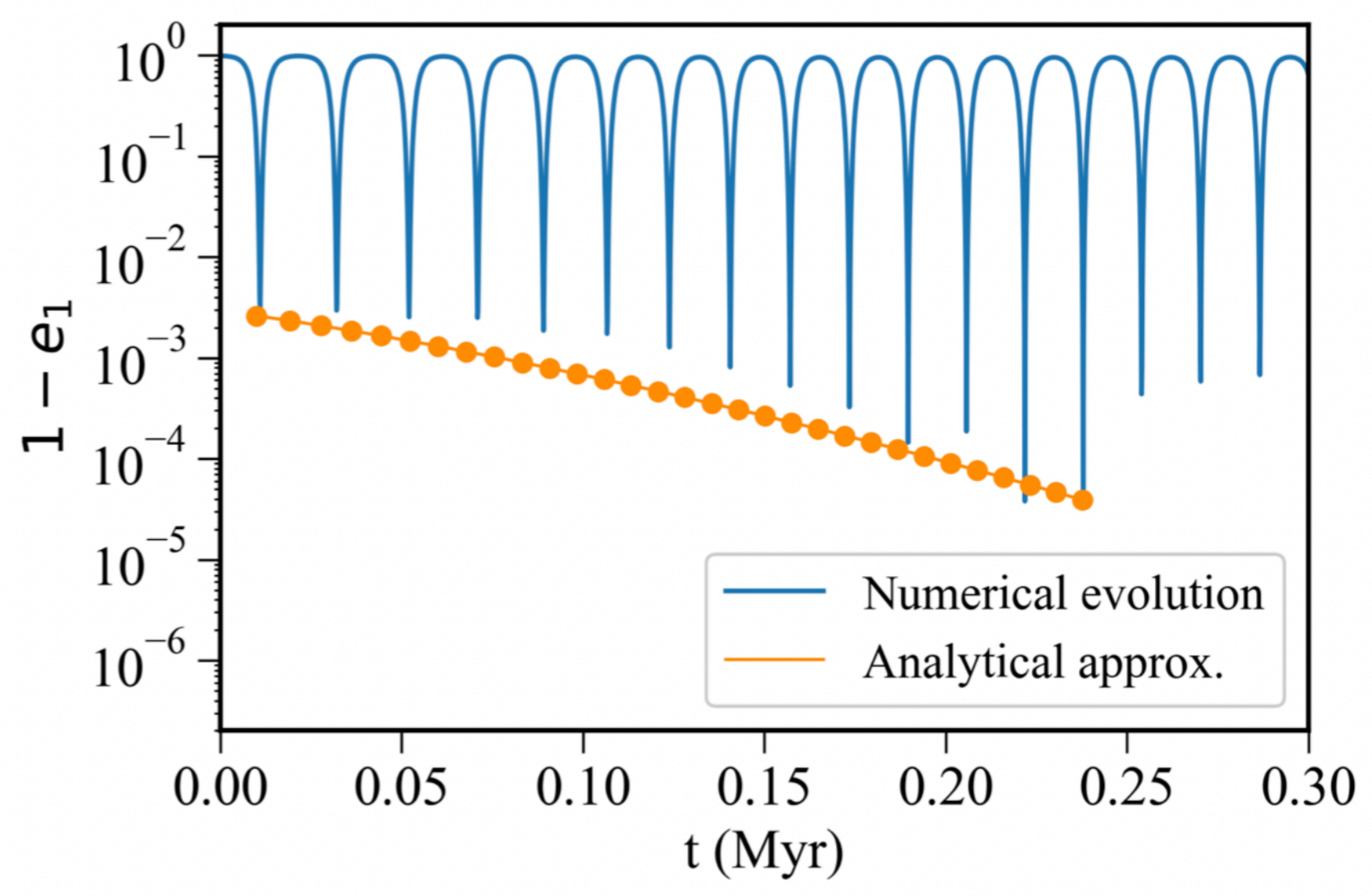
We seek an analytical model for the form and timescale of the octupole-level eccentricity evolution, tracing the pericenter descent down to a close-encounter distance



Analytical models for the EKL-driven descent

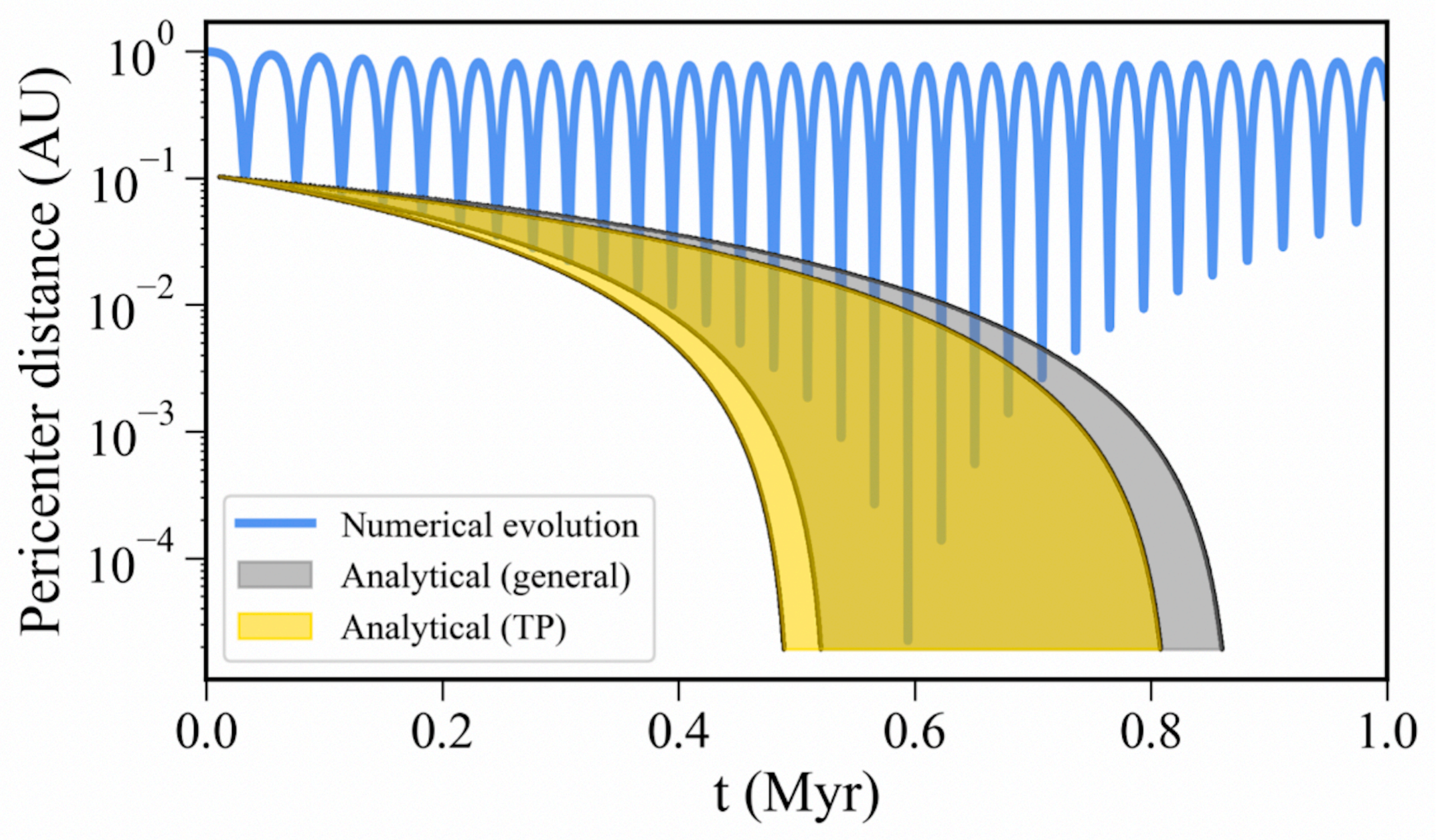
Step-wise approximation

Test particle limit: $m_p \to 0$



Envelope approximation

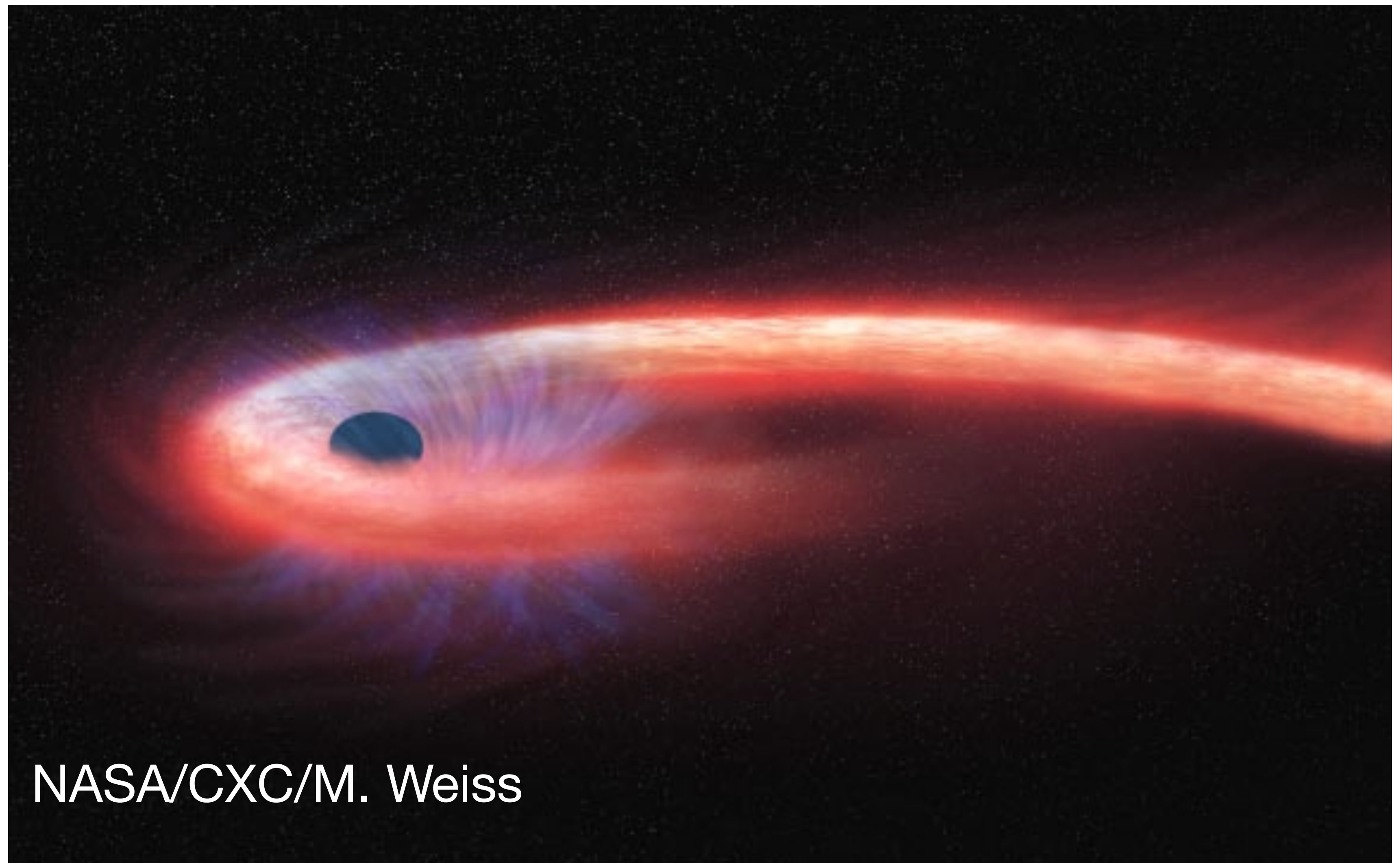
Test particle and general cases



Weldon et al. 2024a

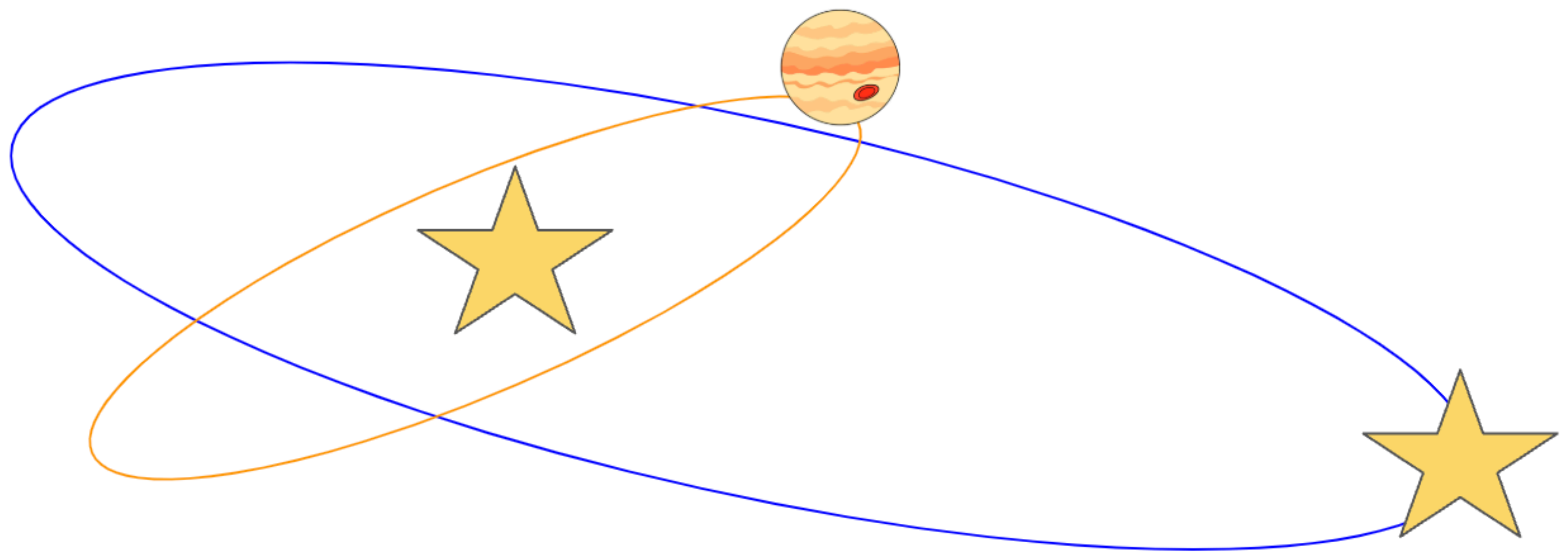
These novel analytical models are applicable to many other astrophysical settings in which EKL drives the eccentricity to large values:

- Asteroids
- Small planets
- Stellar mergers
- Compact object mergers
- Extreme-mass-ratio inspirals
- Tidal disruption events

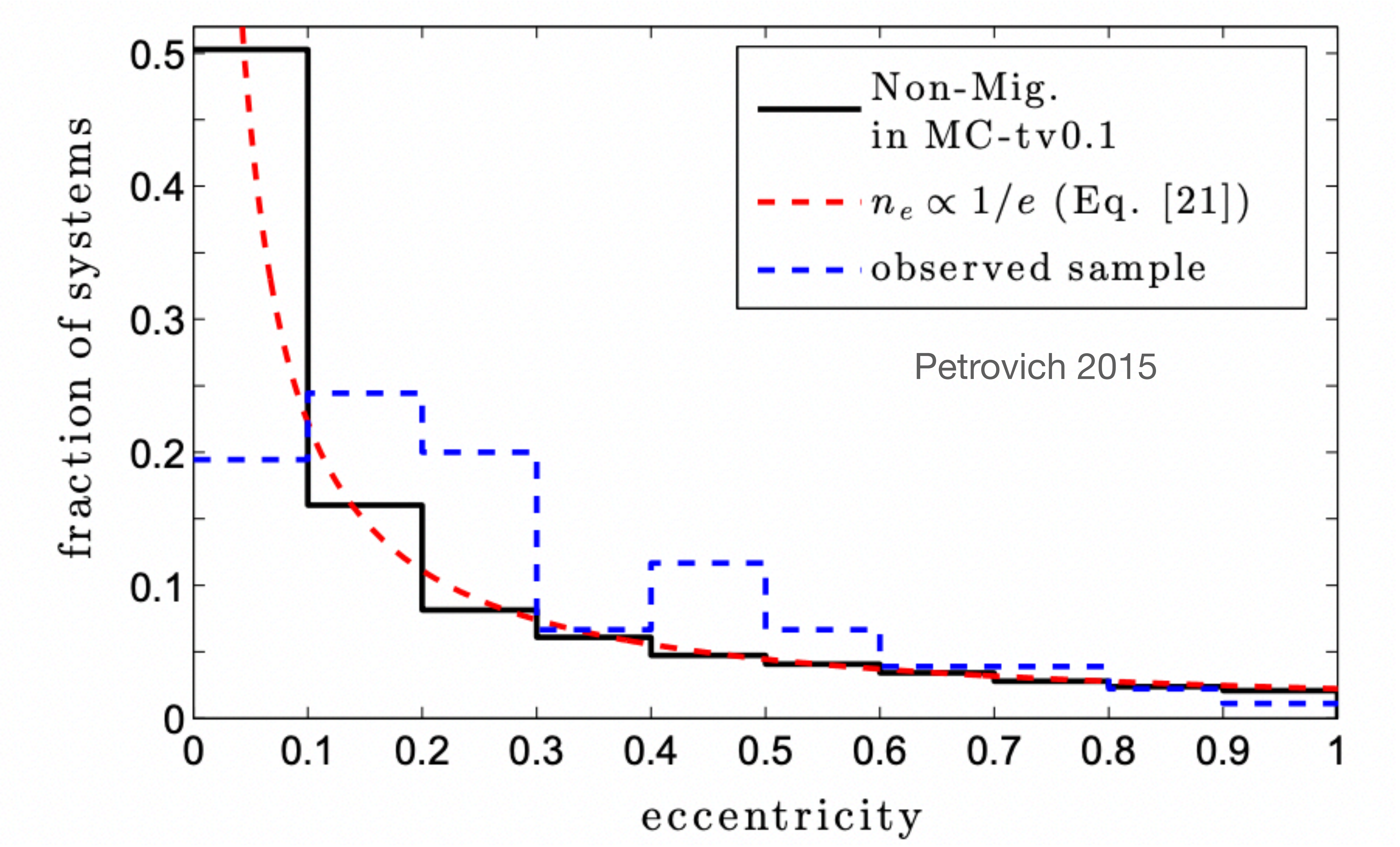


NASA/CXC/M. Weiss

II. Cold Jupiter eccentricity distribution from the stellar EKL mechanism



The dominant mechanism for hot Jupiter formation should leave its signature on the eccentricity distribution of cold Jupiters

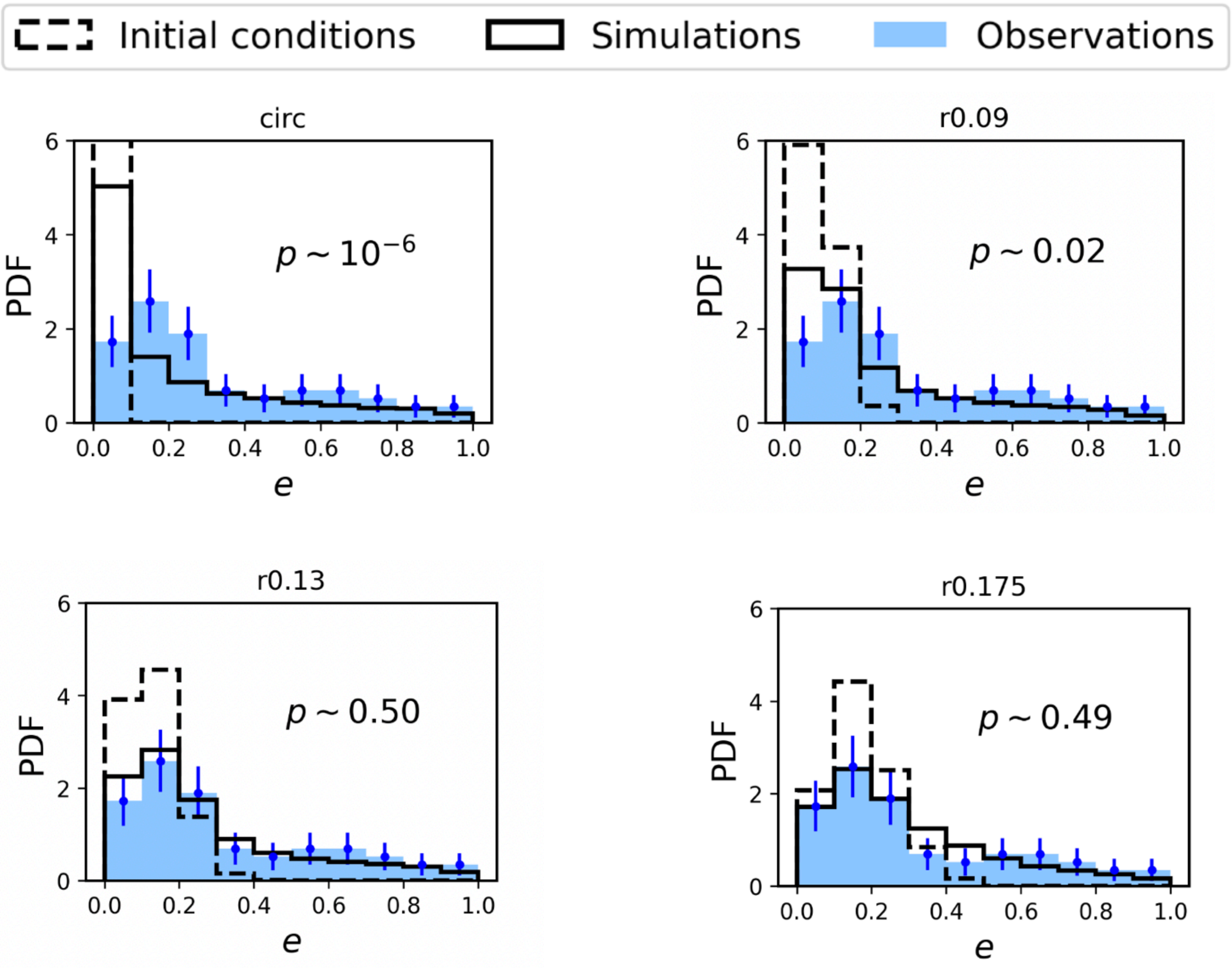


Previous studies find a mismatch between EKL predictions and observations, suggesting this process plays only a minor role

(e.g., Takeda & Radio 2005, Petrovich 2015)

Population synthesis setup

- Cold (0.8-6 au) giant planets (0.3-10 M_J) in isotropically oriented FGK stellar binaries (50-1500 au) with uniform binary eccentricity distribution
- Evolve systems in a hierarchical three-body code for 10 Gyr with EKL, general relativity, tides, stellar evolution
- Compute the time-averaged eccentricity distribution of the cold planets
- We test various initial eccentricity distributions for the planets, considering **planet-planet scattering acts on ~Myr timescales before EKL acts on ~Myr-Gyr timescales**



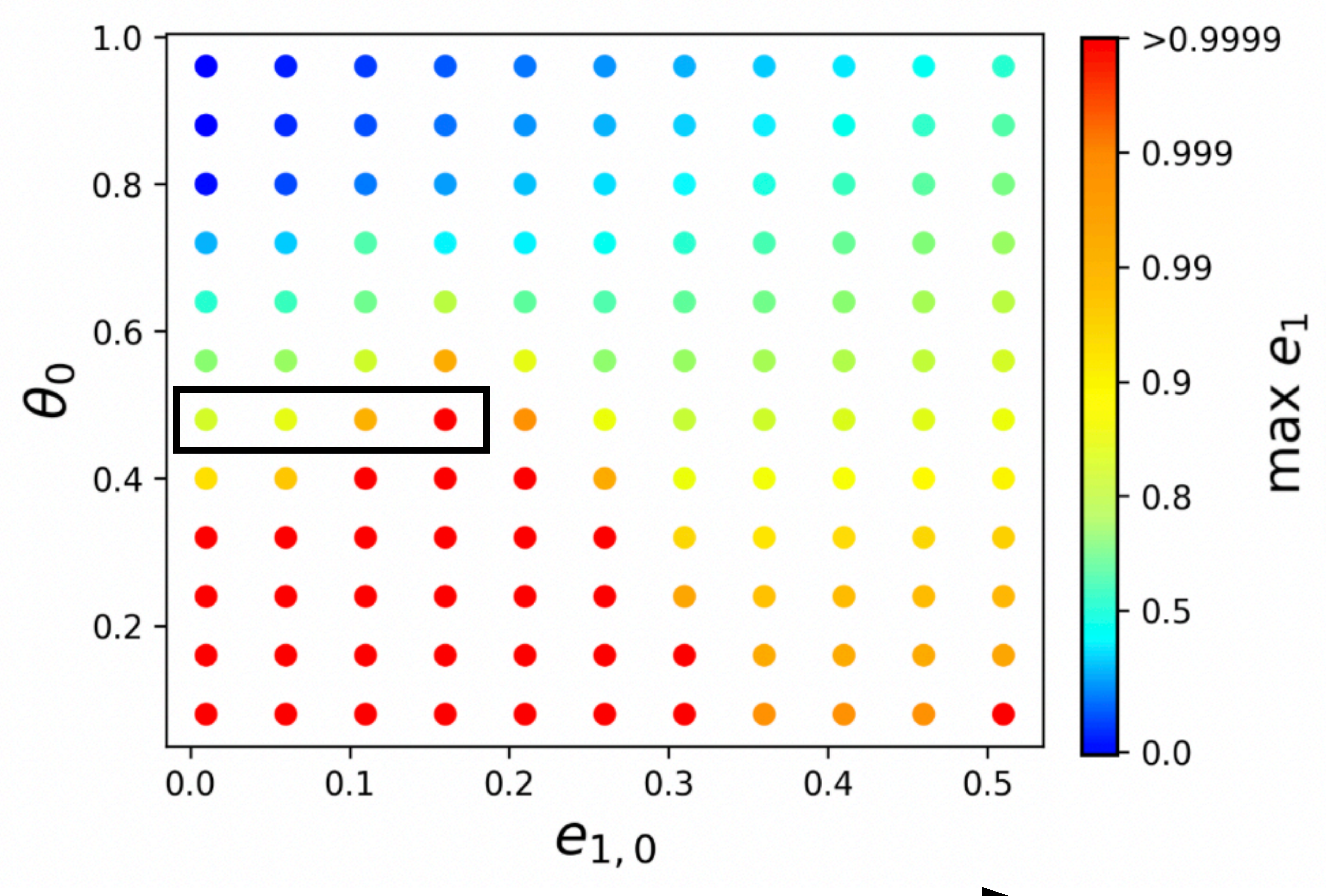
Weldon et al. 2024b

Simulated and observed eccentricities are consistent for initial distributions with means of ~0.1-0.2

Small initial eccentricities can lead to more extreme EKL behavior

Lower inclination

$\theta = \cos i$



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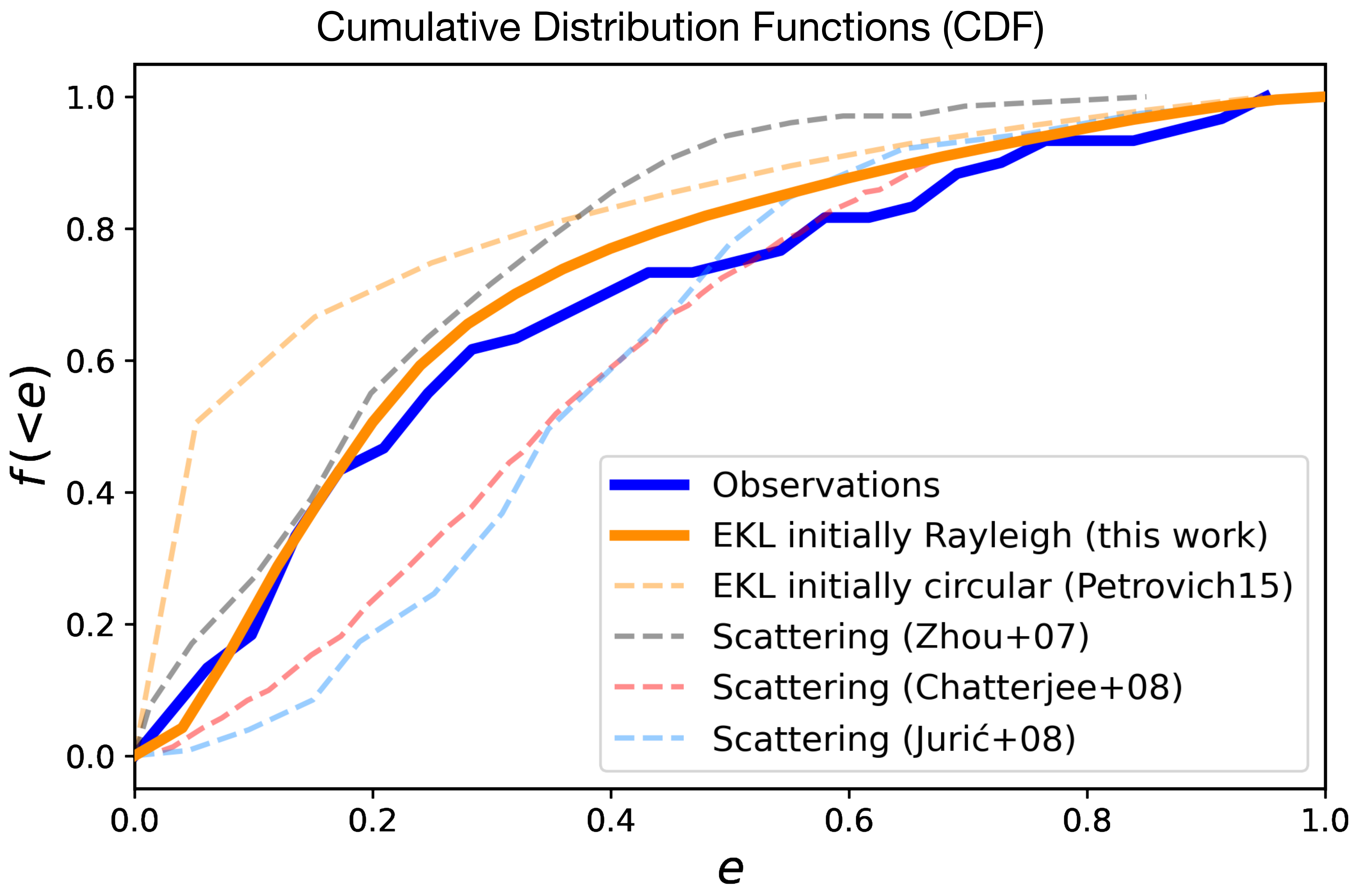
Higher initial eccentricity

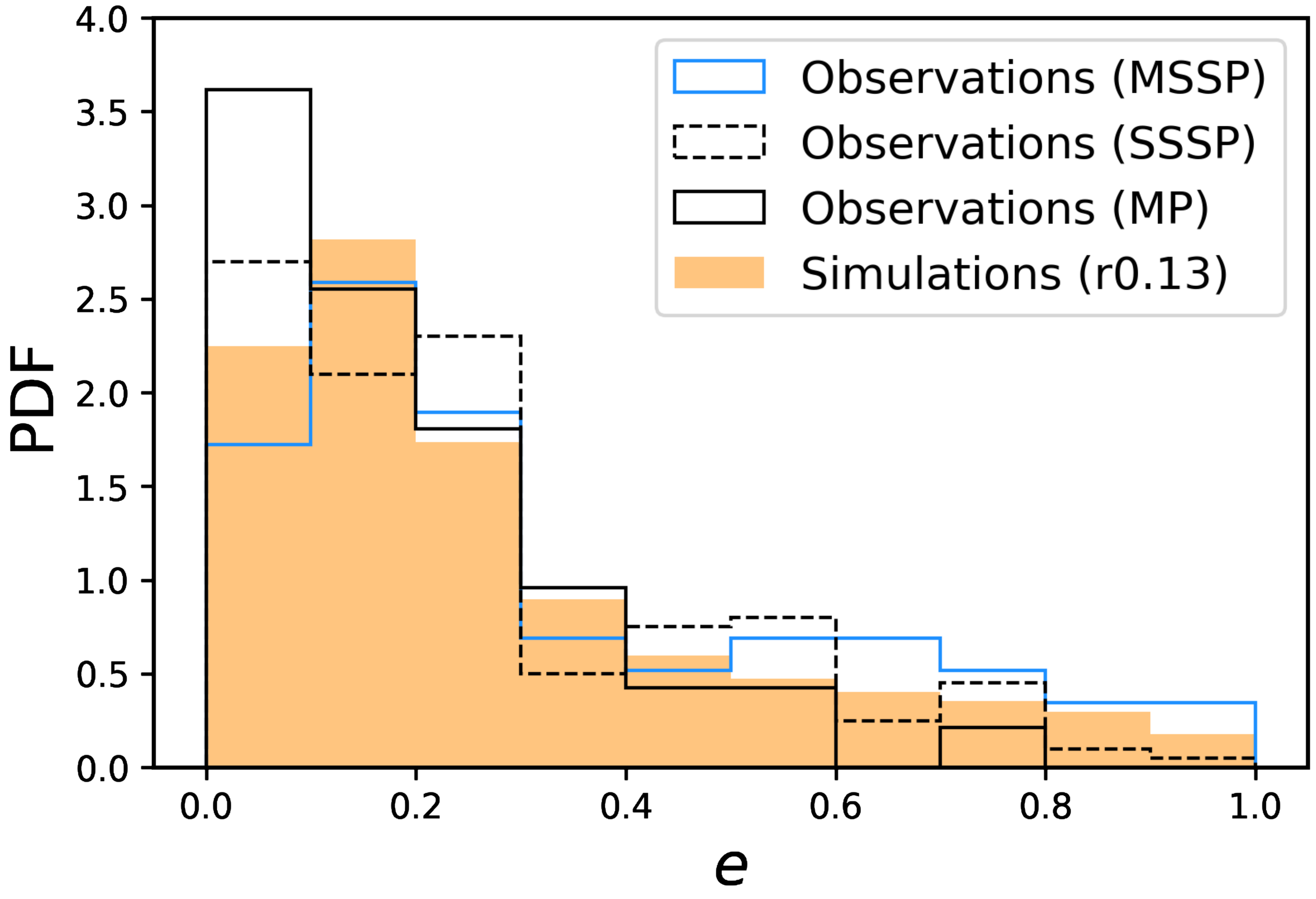
Comparison with previous studies



Weldon et al. 2024b

EKL from stellar companions may be more dominant at driving cold Jupiter eccentricities and forming hot Jupiters than previously claimed

Stellar and planetary multiplicity



Weldon et al. 2024b

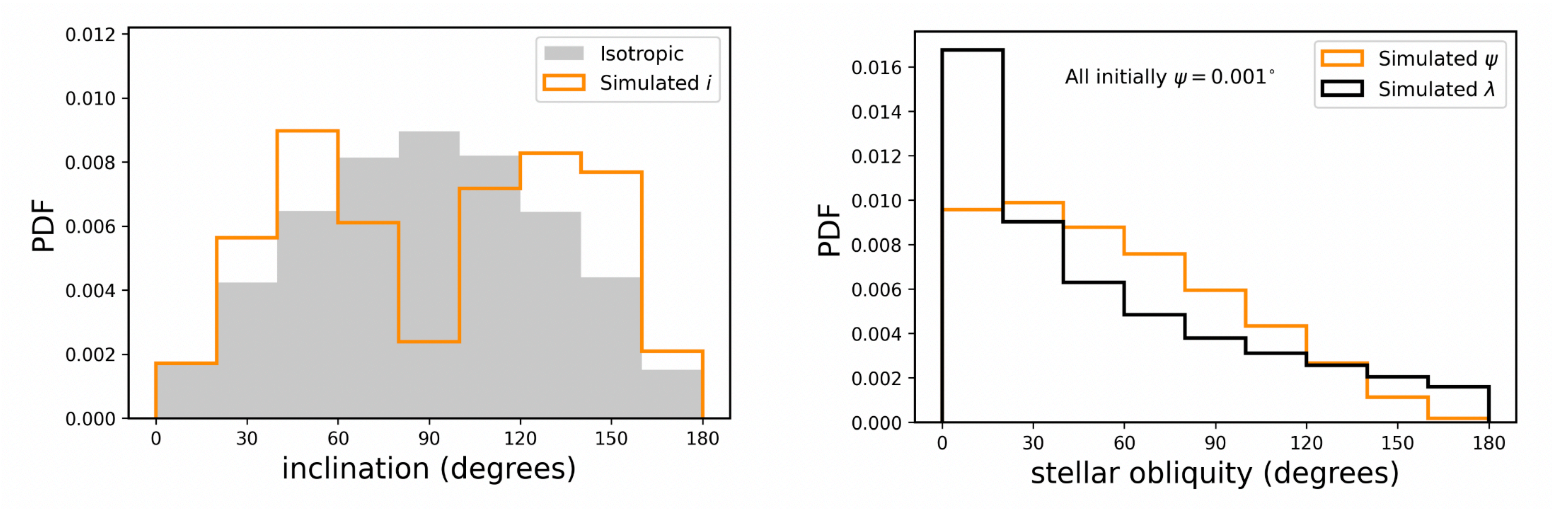
MSSP = multi-star, single-planet ($N = 58$)

SSSP = single-star, single-planet ($N = 200$)

MP = multiple (giant) planets ($N = 94$)

Single-star systems have lower eccentricities than multi-star systems, *but may have some undetected companions; future observations can test this result*

Predictions for mutual inclinations and stellar obliquities of cold Jupiters



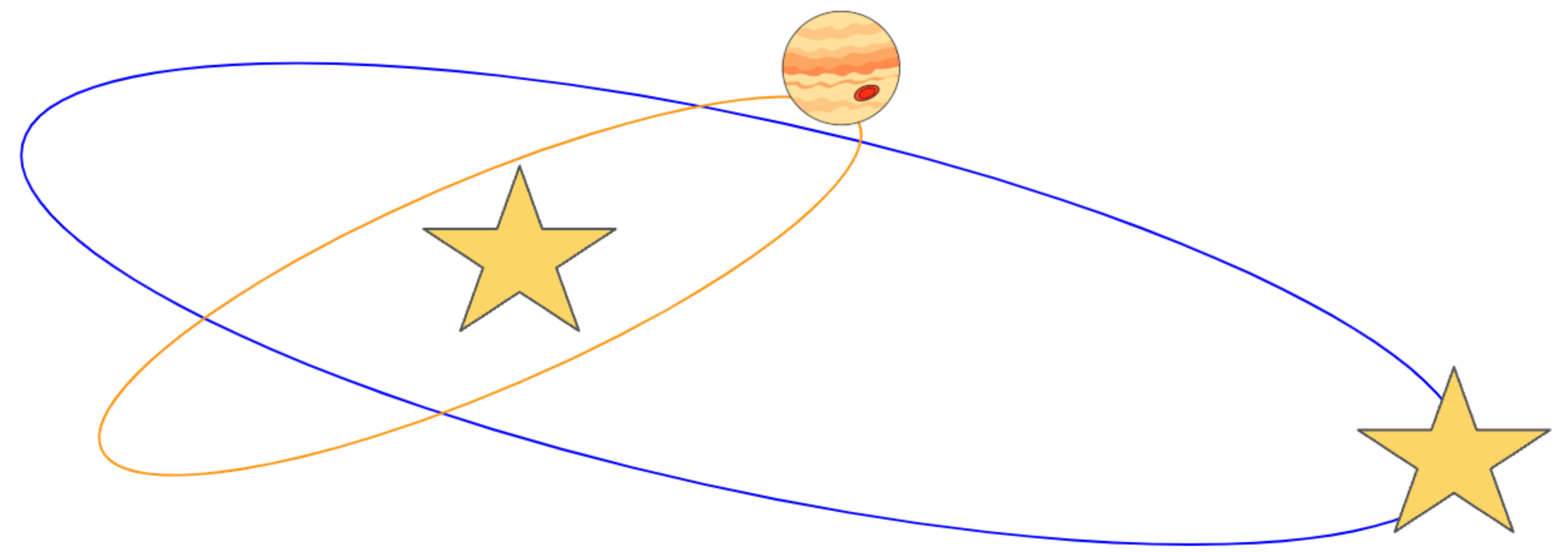
Adapted from Weldon et al. 2024b

Conclusions

- The existence of hot Jupiters and the eccentricities of cold Jupiters may be explained by high-eccentricity migration
- The Eccentric Kozai-Lidov (EKL) mechanism can generate eccentricity and inclination oscillations
- We obtain new analytical approximations for the octupole-level EKL eccentricity evolution, tracing the overall inward descent of a planet with a distant companion
- We find that EKL in stellar binaries can produce a cold Jupiter eccentricity distribution consistent with observations, suggesting that this mechanism may play an important role in forming hot Jupiters

Analytical EKL
Published in ApJ

Cold Jupiter eccentricities
Accepted to ApJ Letters



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Thank you!