PRINCETON UNIVERSITY

# Formation of Hot Jupiters in Systems with Too-Distant Binary Companions

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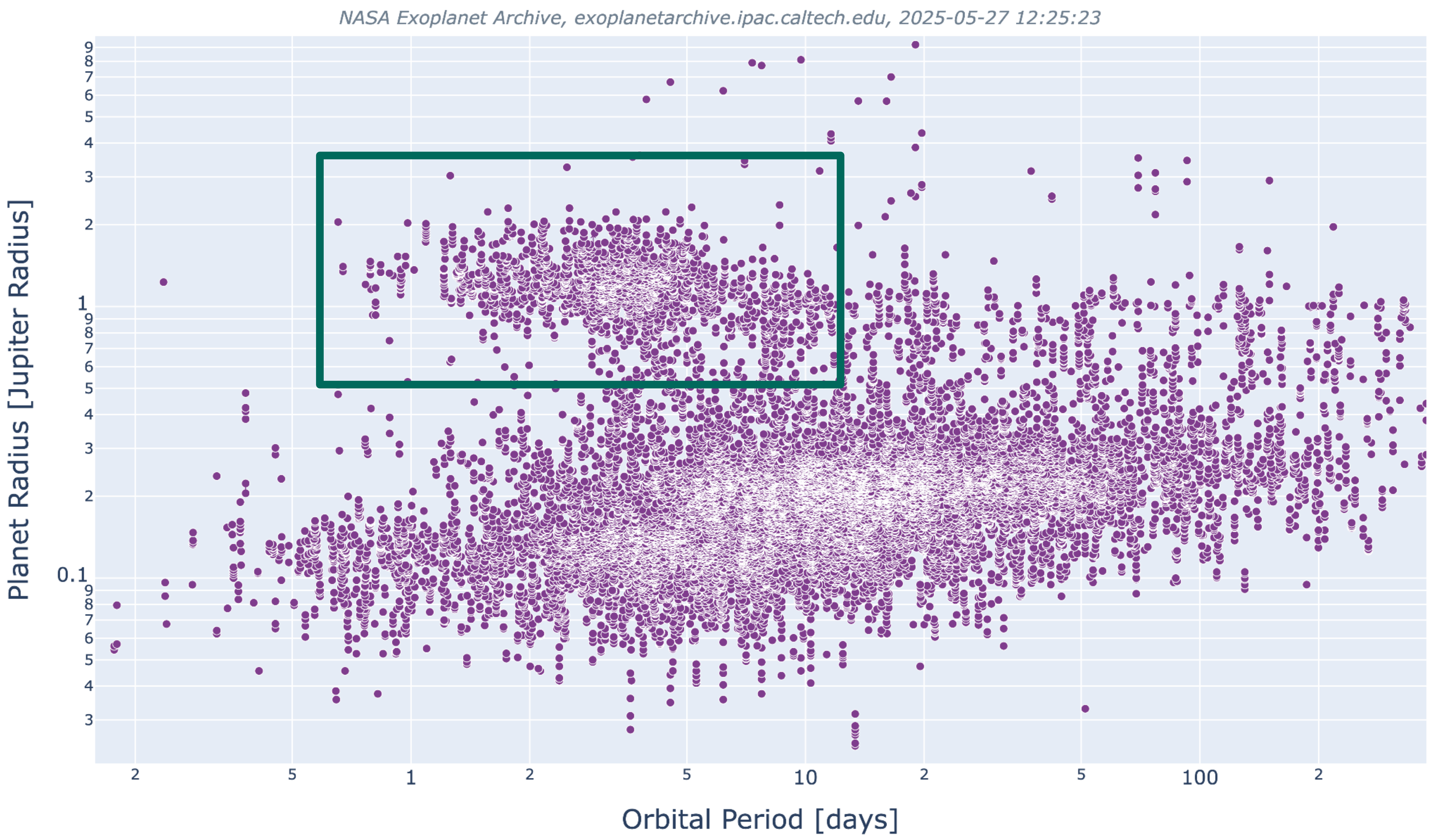
with Eritas Yang and Joshua Winn (Princeton)

Detection and Dynamics of Exoplanets - July 7, 2025

(Eritas Yang)

# Hot Jupiters

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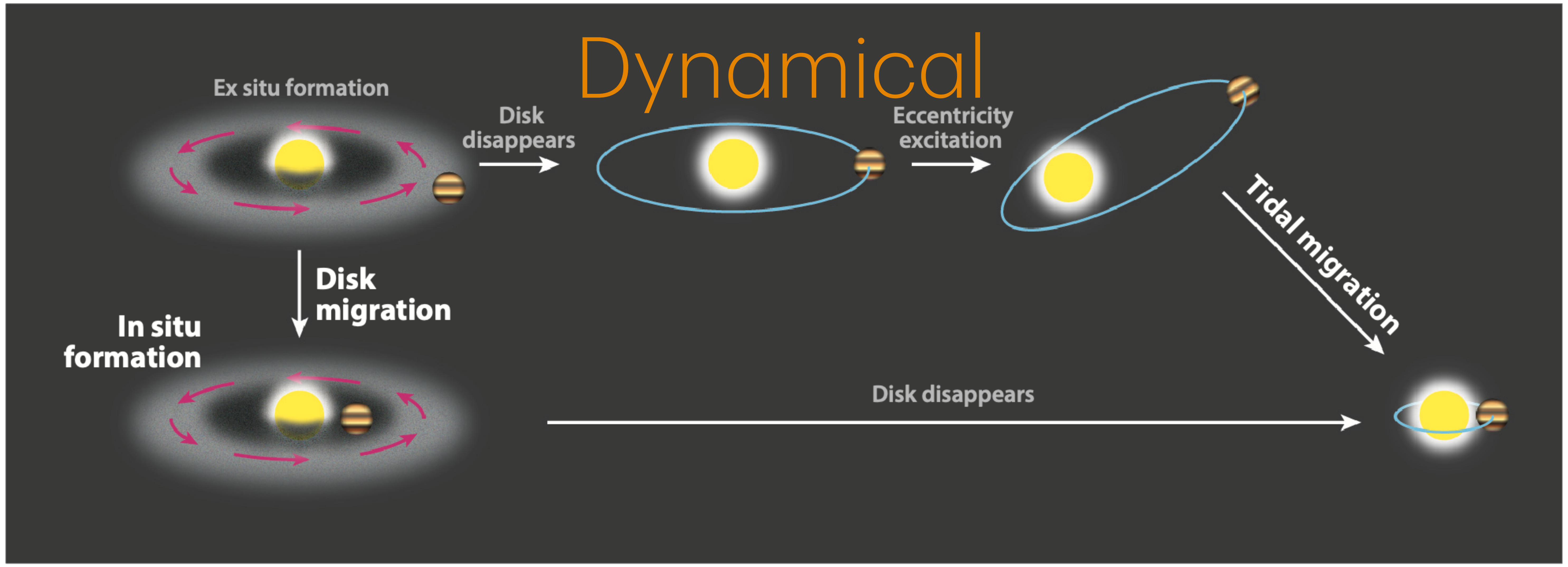
# Hot Jupiters

Quiescent

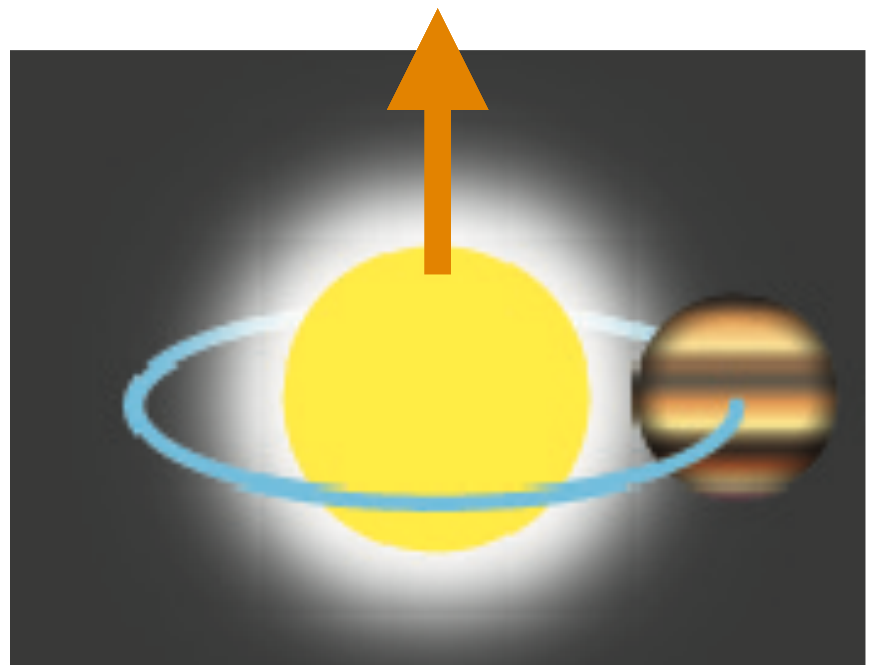



(Dawson+18)

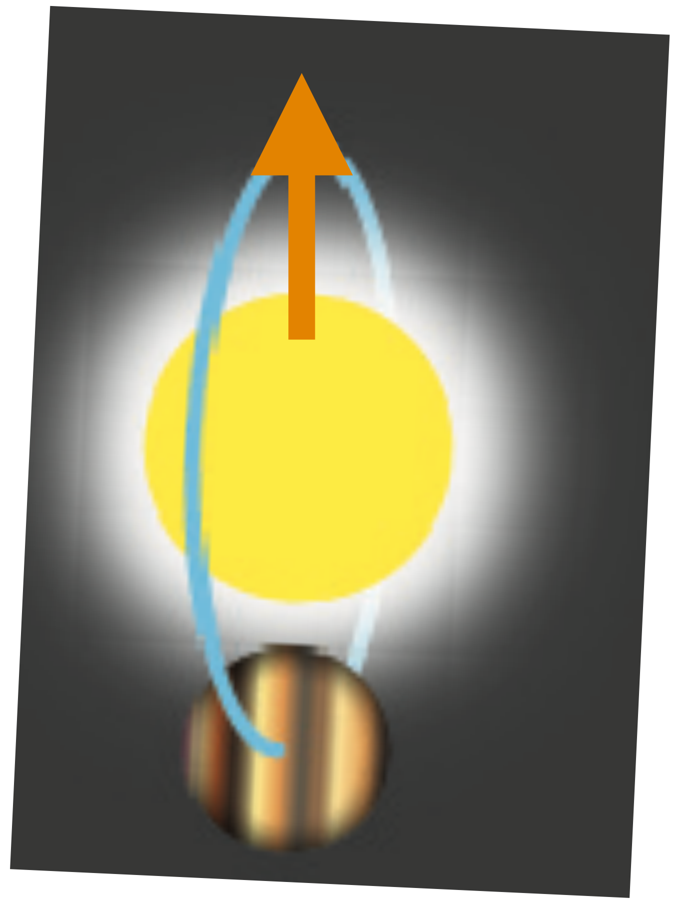
# Hot Jupiters

## The case for Stellar ZLK

- A key diagnostic: stellar ***obliquity***



$\psi = 0^\circ$

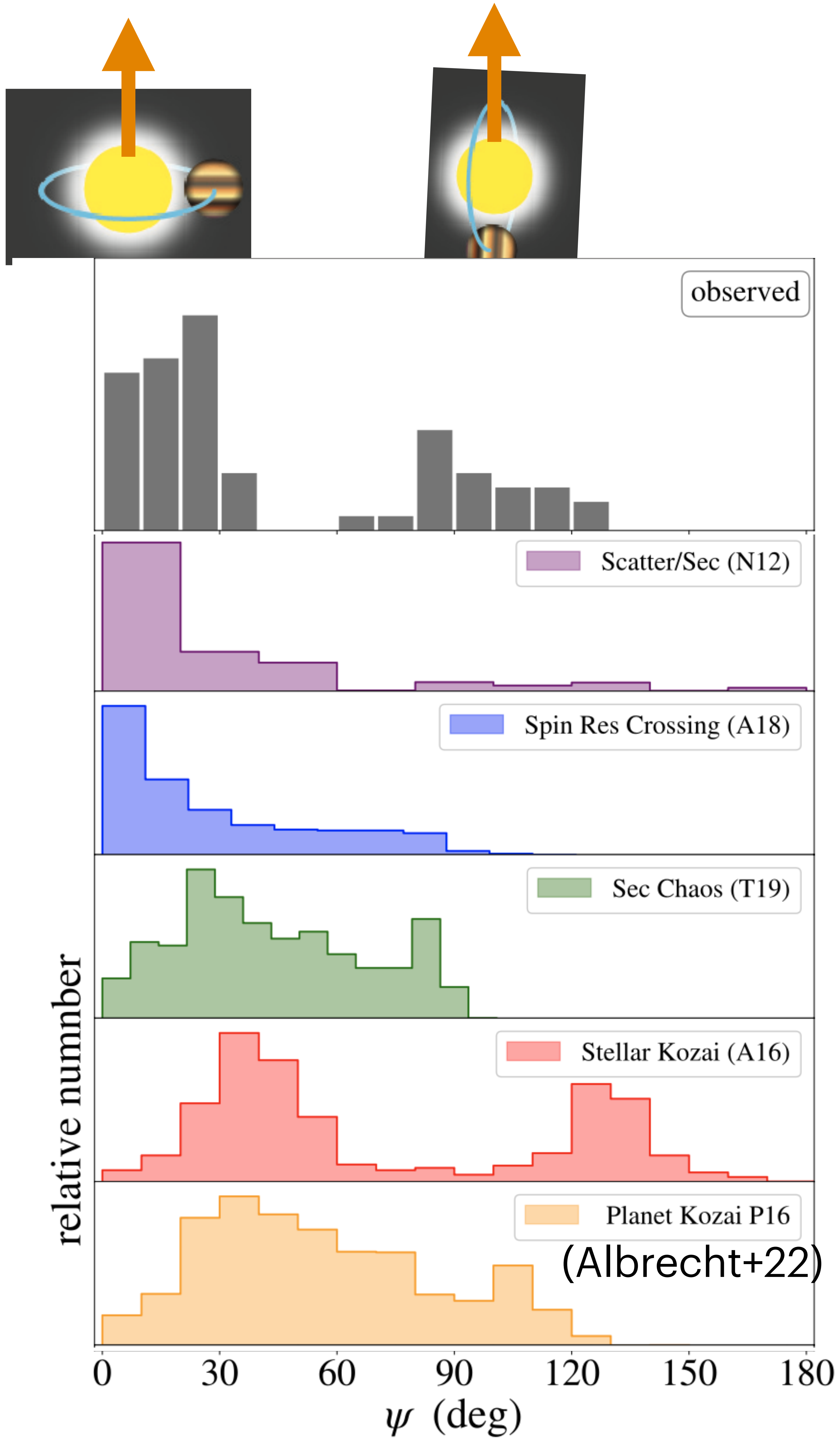


$\psi = 90^\circ$

# Hot Jupiters

## The case for Stellar ZLK

- Many aligned systems: tides or quiescent?
- But many misaligned too! Likely dynamical
  - Stellar von Zeipel-Lidov-Kozai (ZLK; e.g. Wu & Murray 2003) is attractive:
    - Retrograde obliquities!

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# Hot Jupiters

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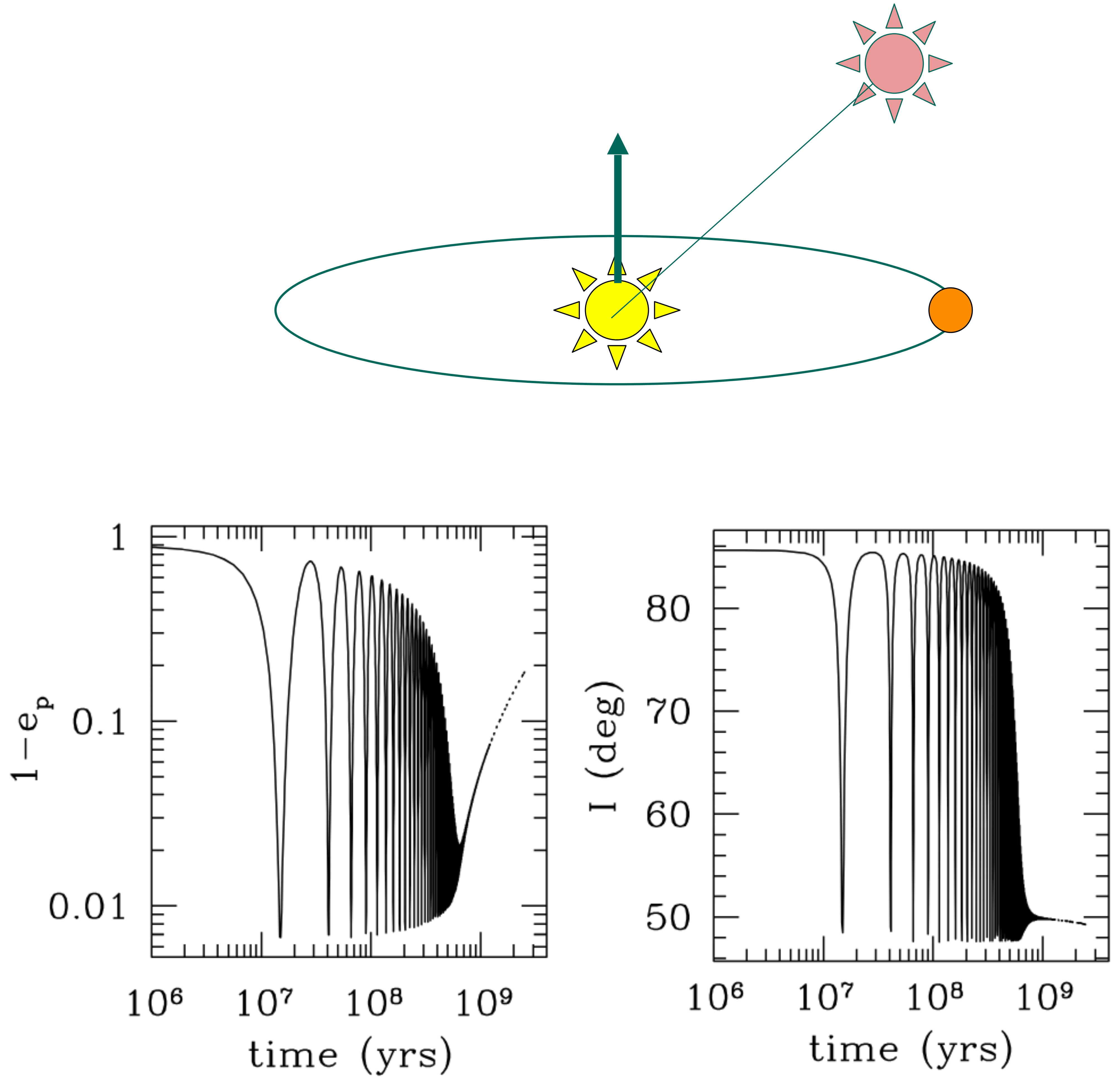


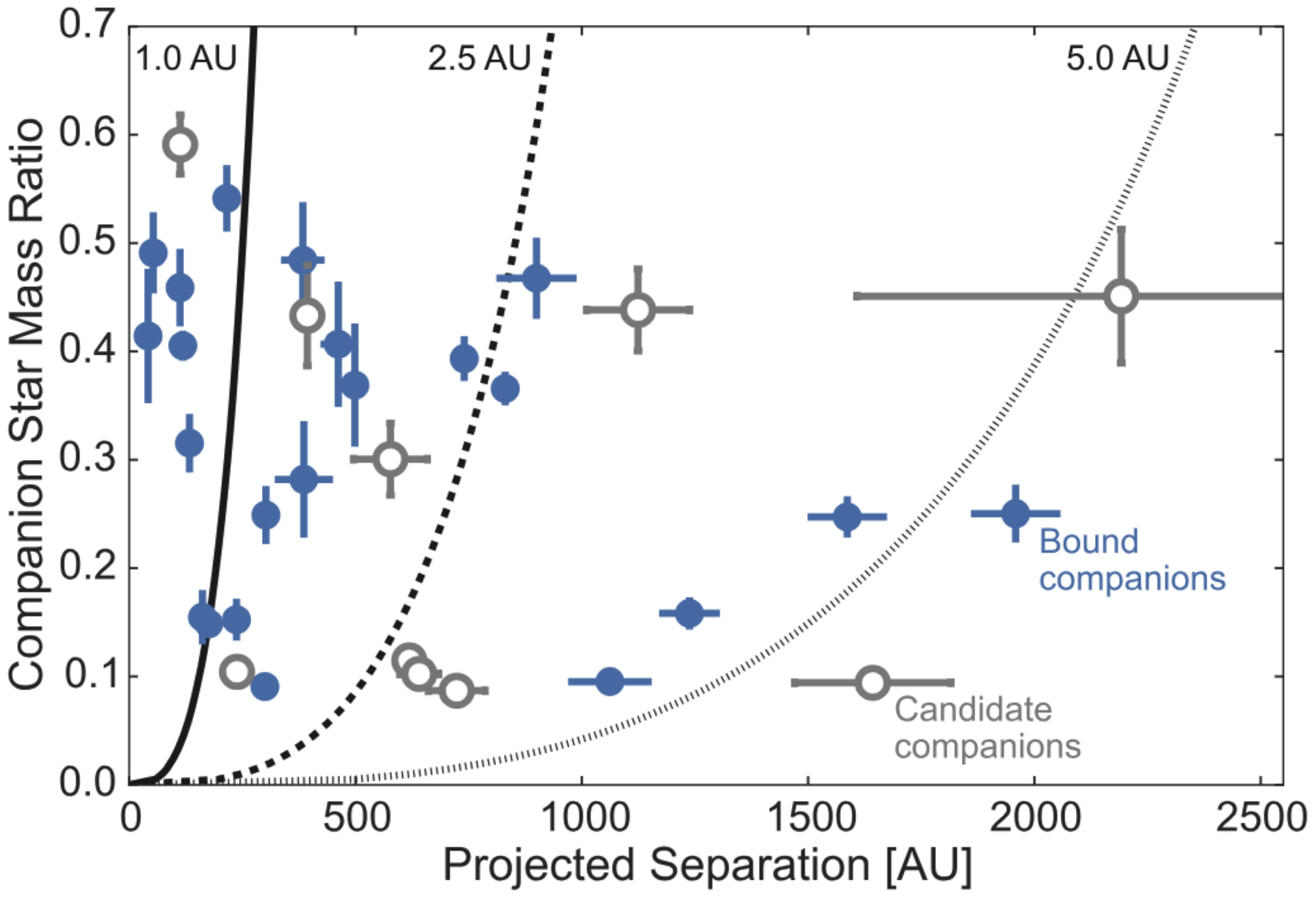
# Stellar ZLK

## The Missing Companions Problem

FRIENDS OF HOT JUPITERS. IV. STELLAR COMPANIONS BEYOND 50 au MIGHT FACILITATE GIANT PLANET FORMATION, BUT MOST ARE UNLIKELY TO CAUSE KOZAI–LIDOV MIGRATION

Henry Ngo, Heather A. Knutson, Sasha Hinkley, Marta Bryan, Justin R. Crepp, Konstantin Batygin, Ian Crossfield, Brad Hansen, Andrew W. Howard, John A. Johnson ▾ Show full author list






We determine that less than 20% of hot Jupiters have stellar companions capable of inducing Kozai–Lidov oscillations assuming initial semimajor axes between 1 and 5 au, implying that the enhanced companion occurrence is likely correlated with environments where gas giants can form efficiently.

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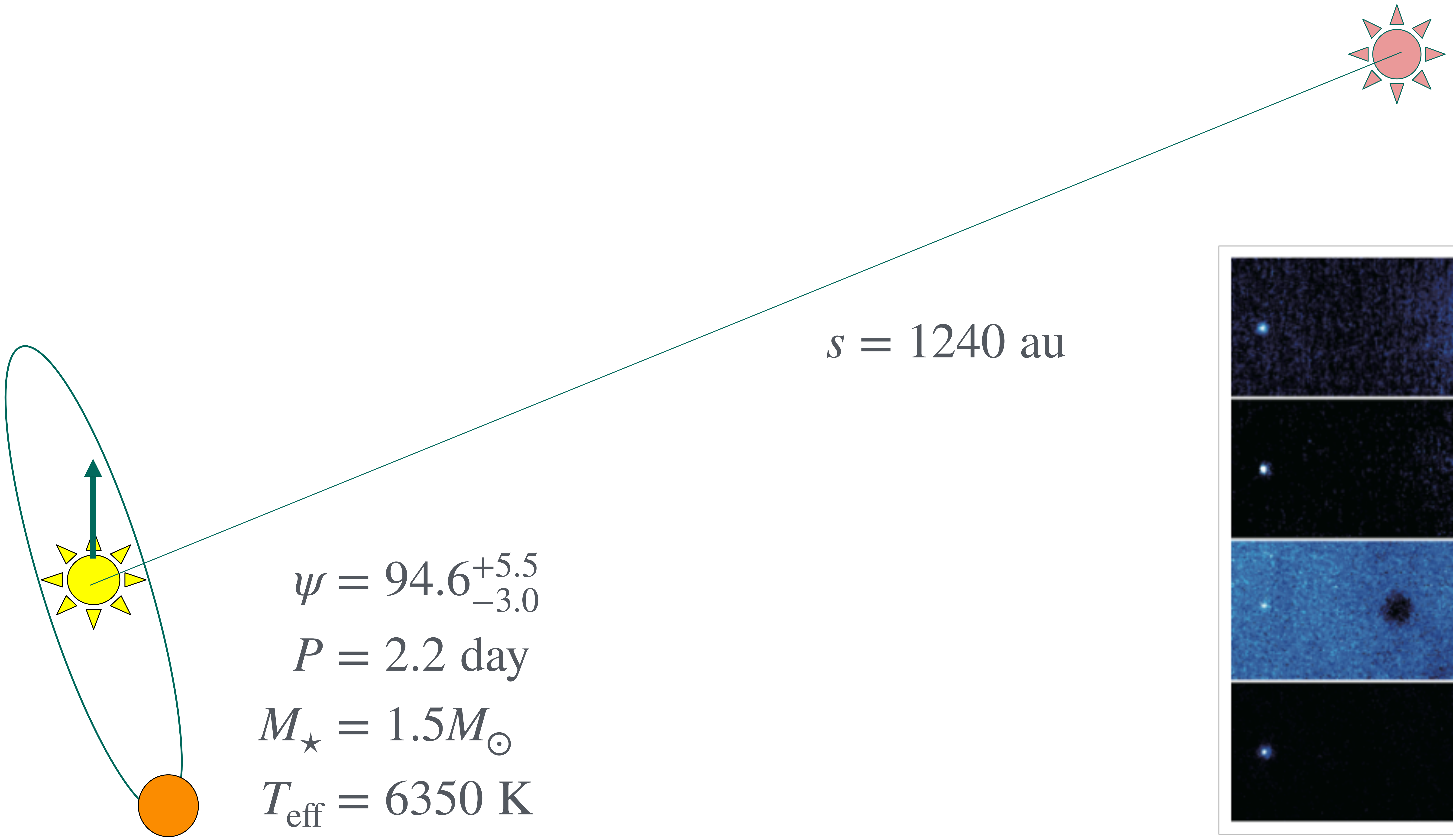
# HAT-P-7

## The Archetypal Missing Companion to HAT-P-7b



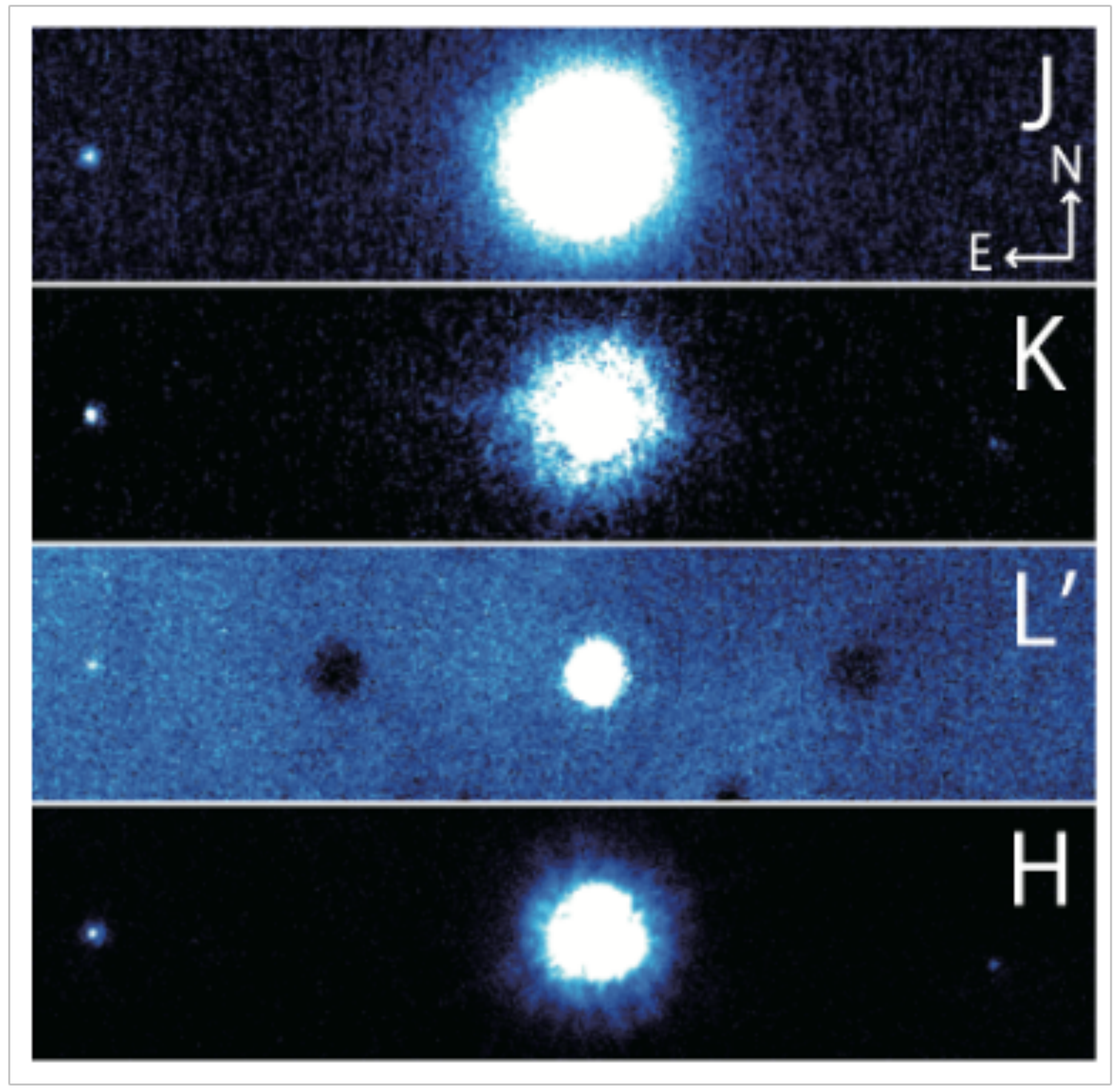
$s = 1240$ au

$\psi = 94.6^{+5.5}_{-3.0}$

$P = 2.2$ day

$M_\star = 1.5 M_\odot$

$T_{\rm eff} = 6350$ K

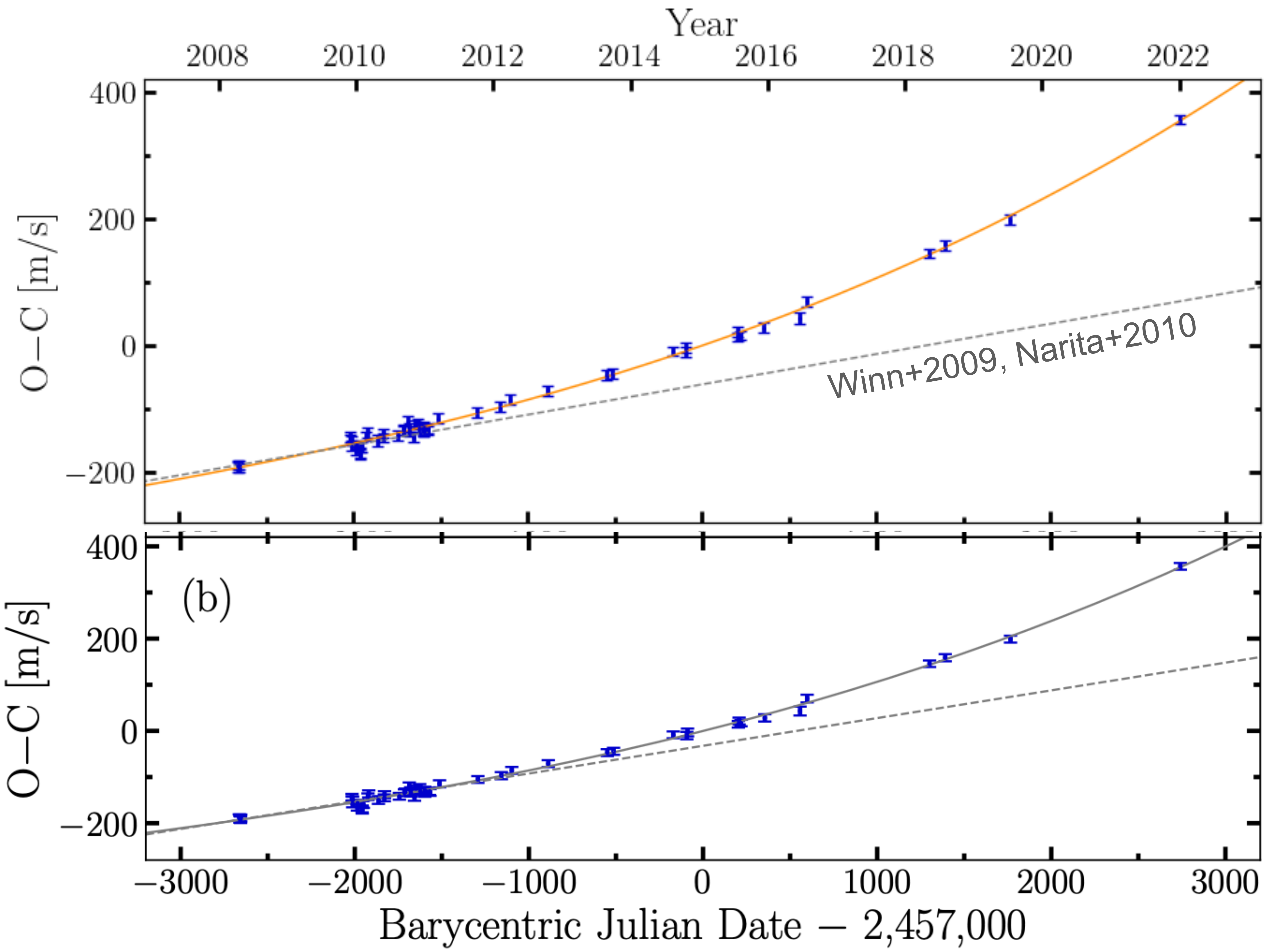



Narita et al. (2012)

# HAT-P-7C: A Star is Discovered!

Radial Velocity

Transit Timing Variations




**An unseen, closer-in companion?**

$m_1 \sin i_1 = 0.19^{+0.11}_{-0.06}\ M_\odot$

$a_1 = 32^{+16}_{-11}$ AU

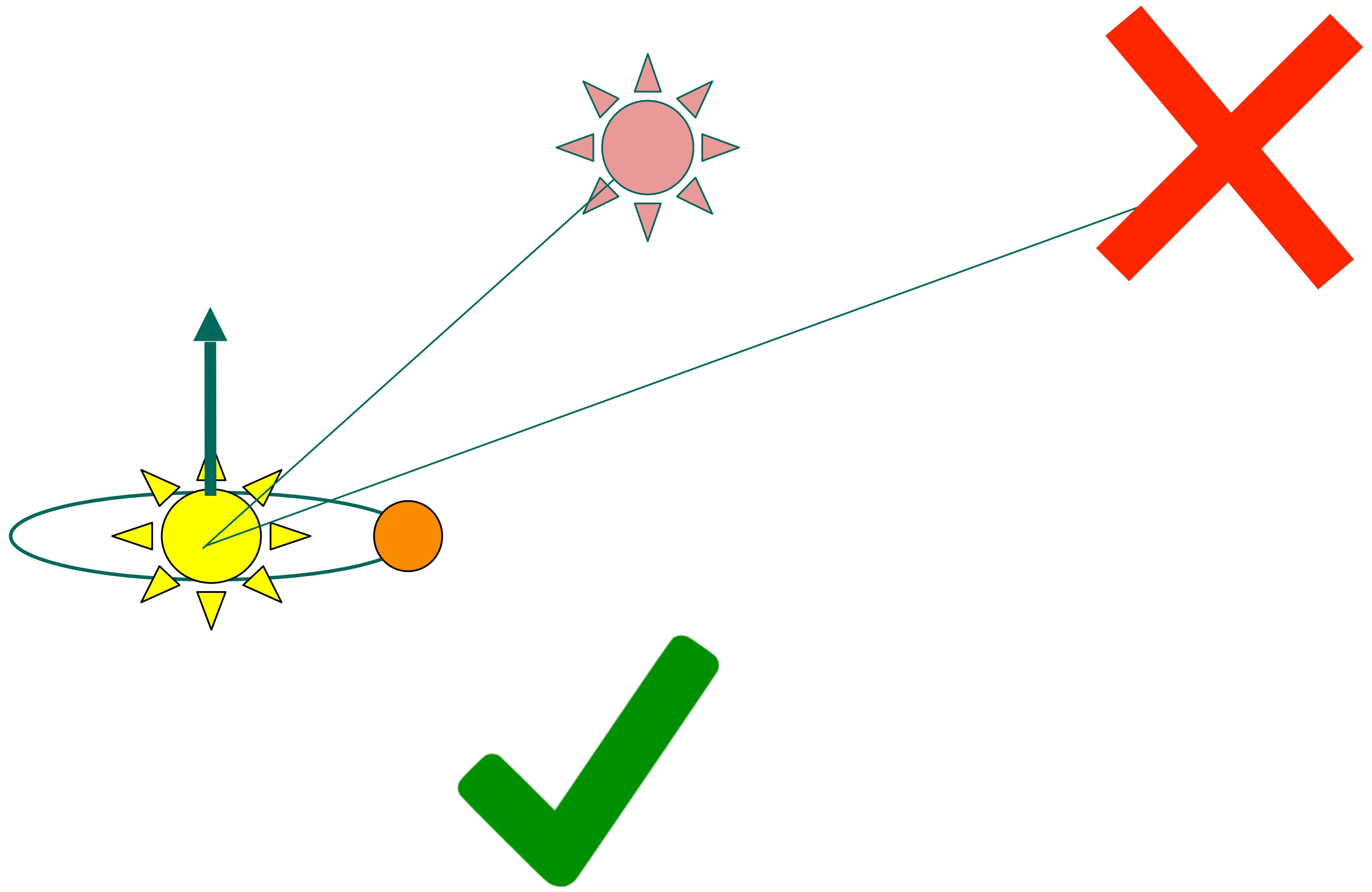
$e_1 = 0.76^{+0.12}_{-0.26}$

# HAT-P-7b: Options for Migration

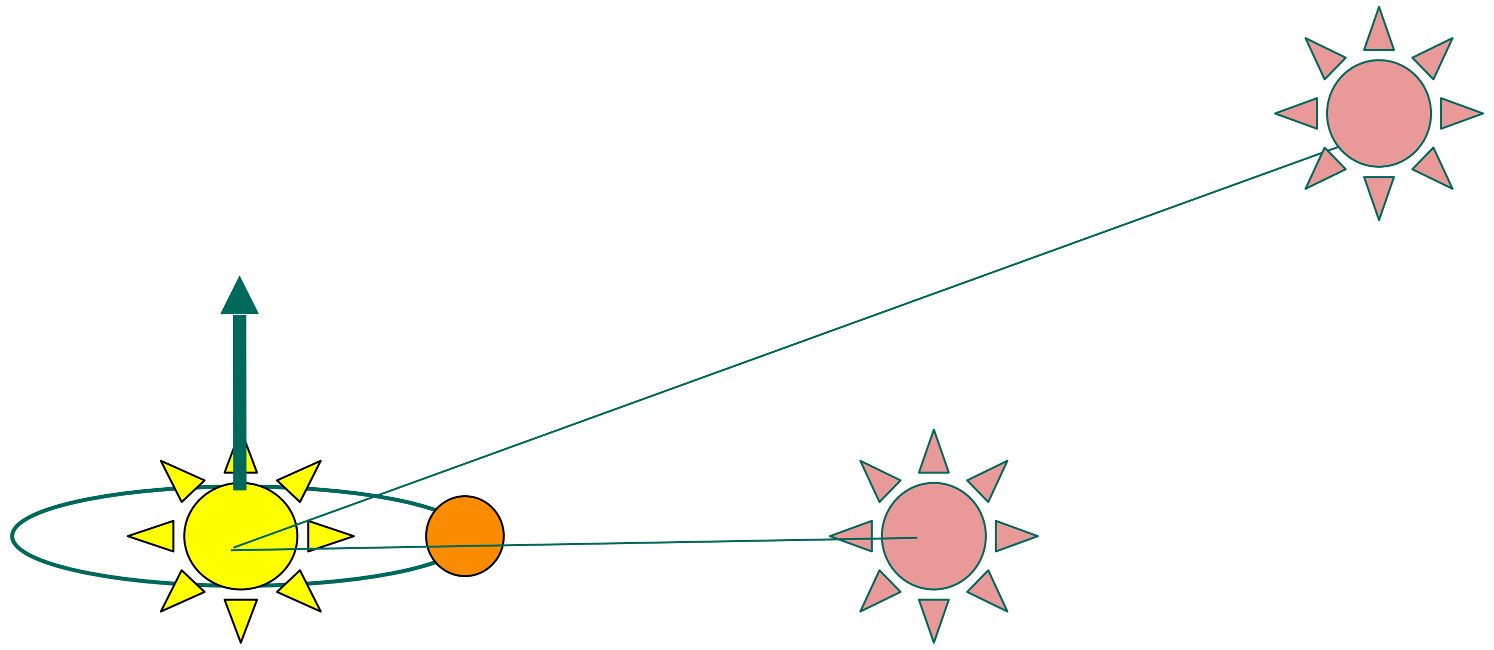
## Two options

(i) Ignore outer star: ZLK with inner star

(requires large misalignment at ~32 AU)



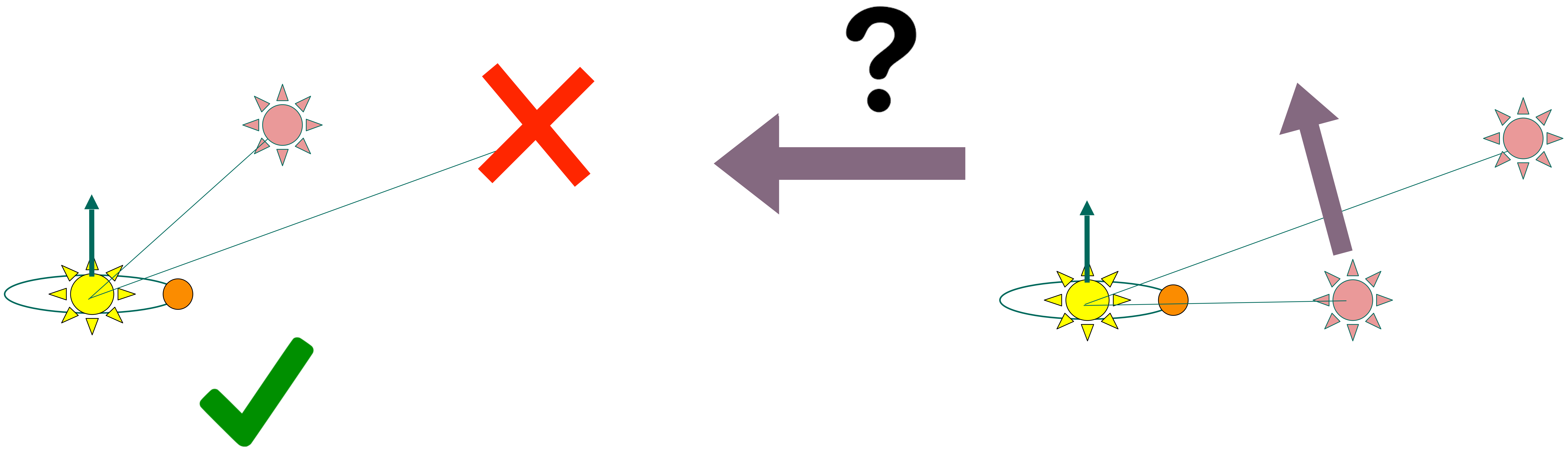
(ii) Dynamics with outer star



# HAT-P-7b: Options for Migration

Triple scenario: (i) naively...

(ii) Dynamics with outer star



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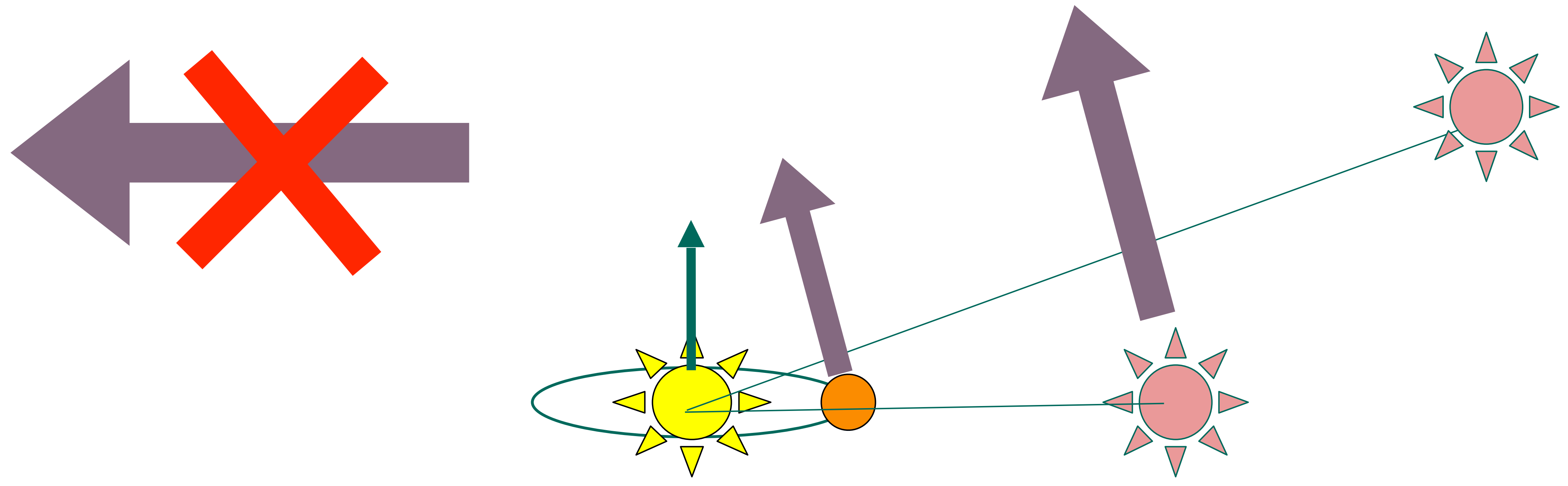
# HAT-P-7b: Options for Migration

## Triple scenario: (i) cannot misalign inner system!

(ii) Dynamics with outer star



$$\frac{\Omega_{12}}{\omega_{p1}} \simeq \frac{m_2}{m_1} \frac{a_1^{9/2}}{a_2^3\, a_p^{3/2}} \sim \mathcal{O}(10^{-3})$$

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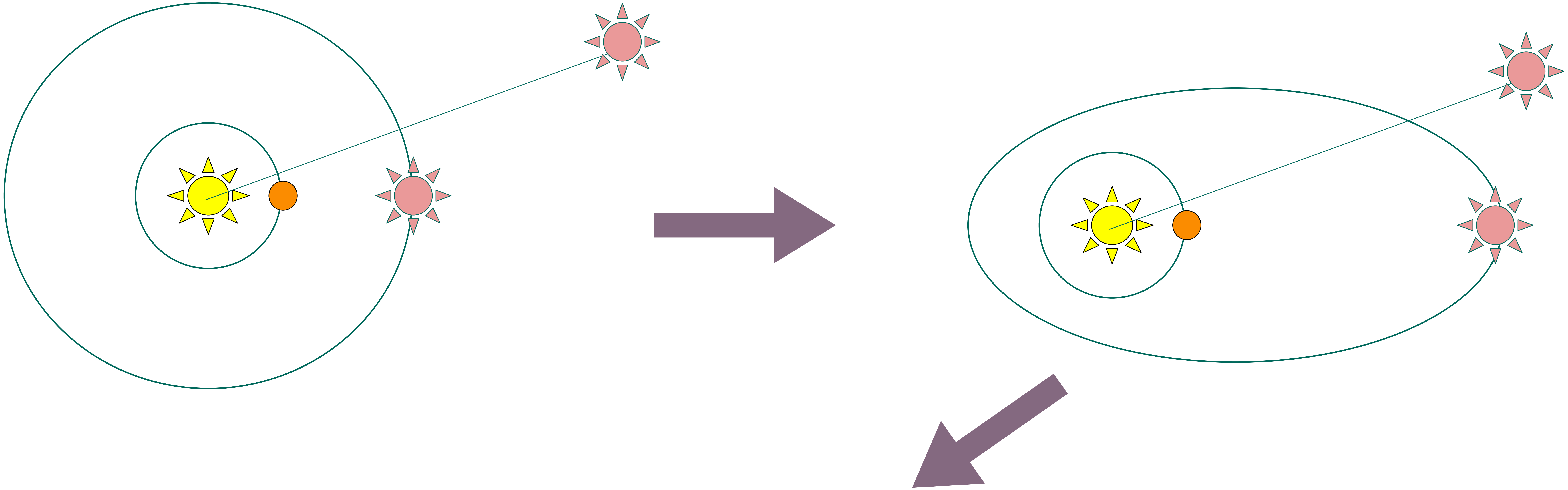
# HAT-P-7b: Options for Migration

## Triple scenario: (ii) outer ZLK + scattering?



Scattering & many ejections?

No! ***Eccentricity Cascade!***

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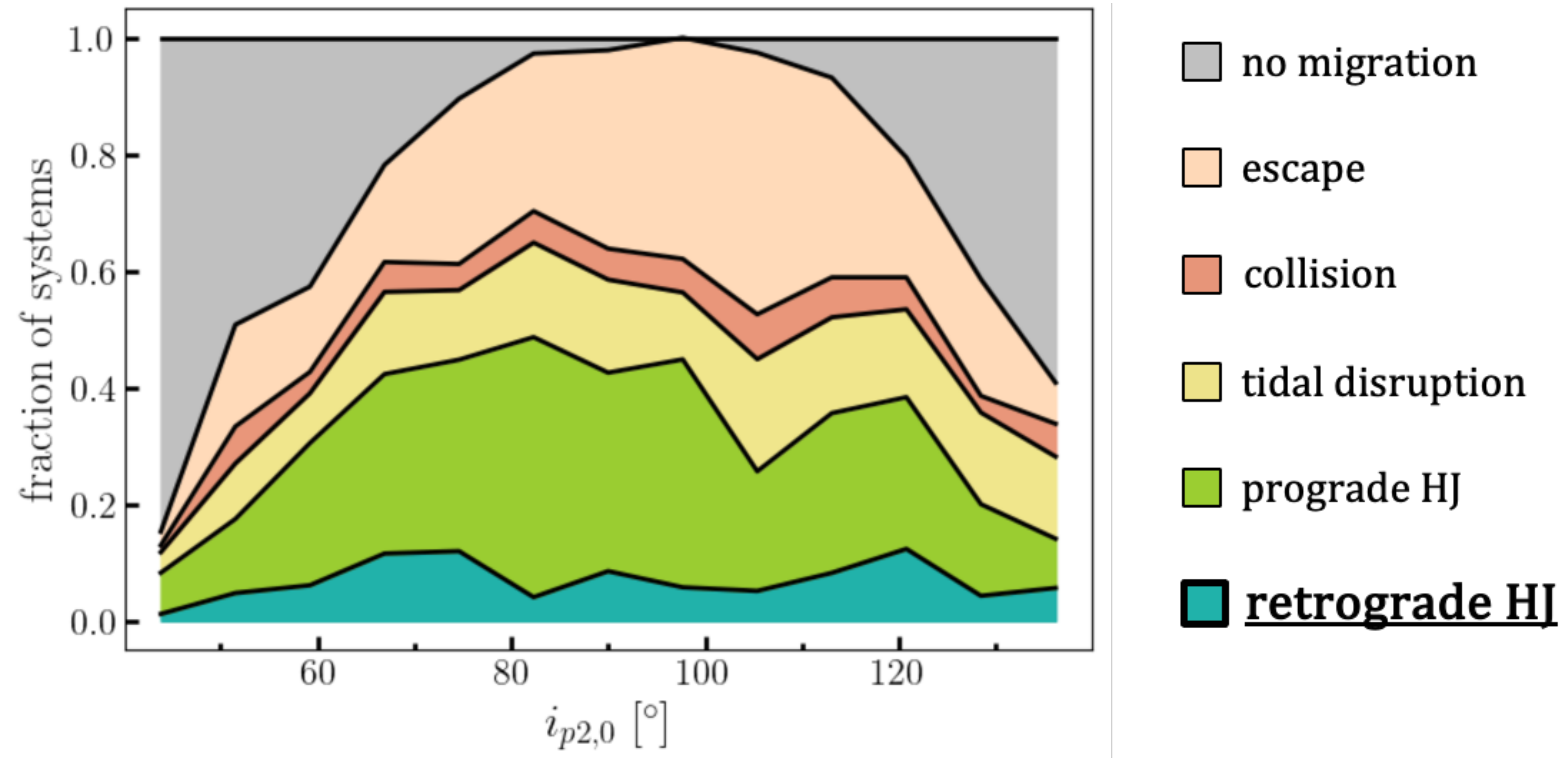
# HAT-P-7b: Options for Migration

## Triple scenario: (ii) outer ZLK + scattering?




Scattering & many ejections?

- EC: > 50% migrate

How does EC avoid lots of scattering?

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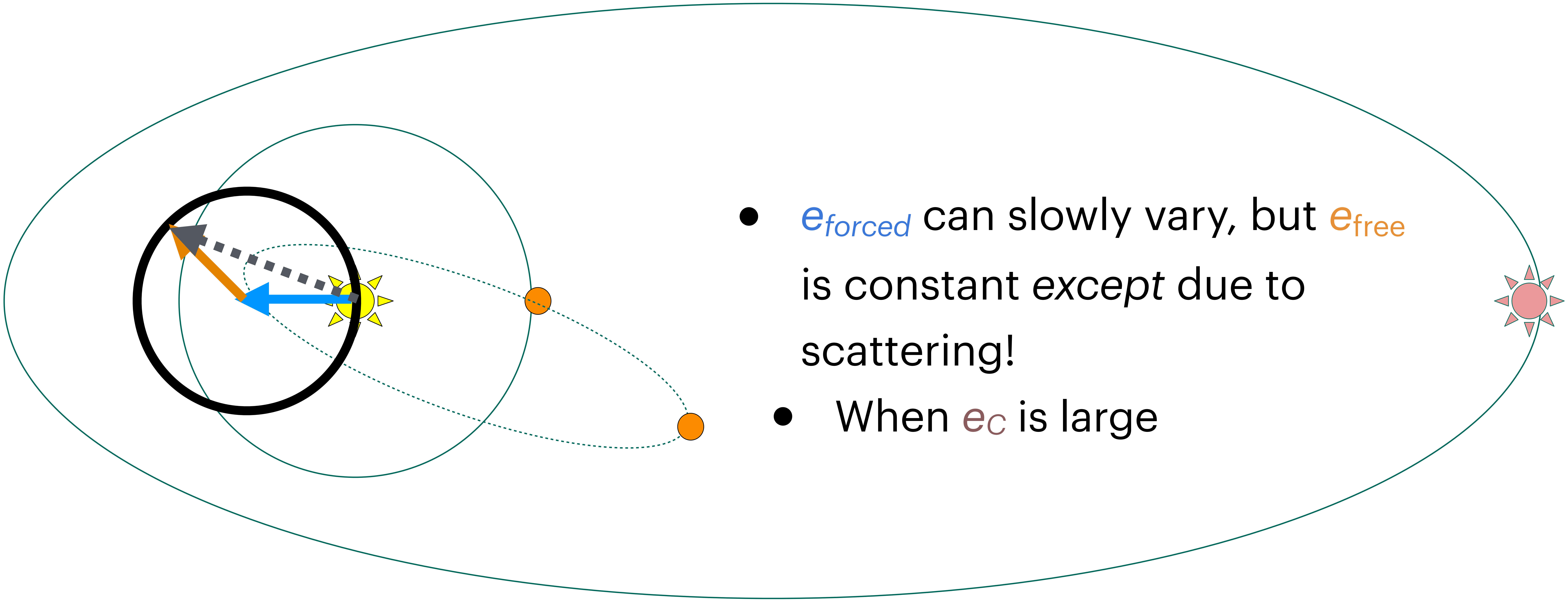
# Eccentricity Cascade

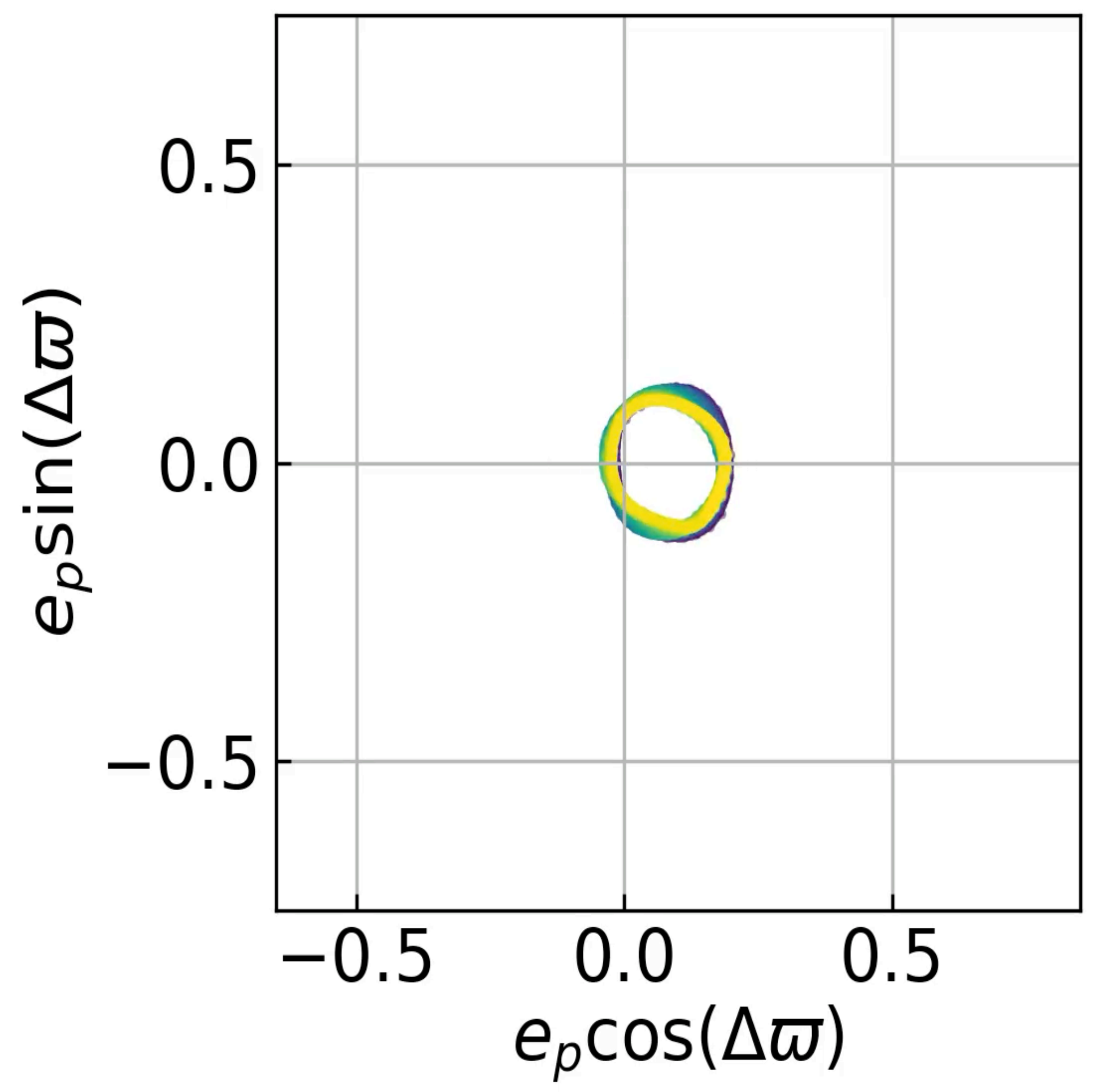
## Digression: Eccentricity Coupling

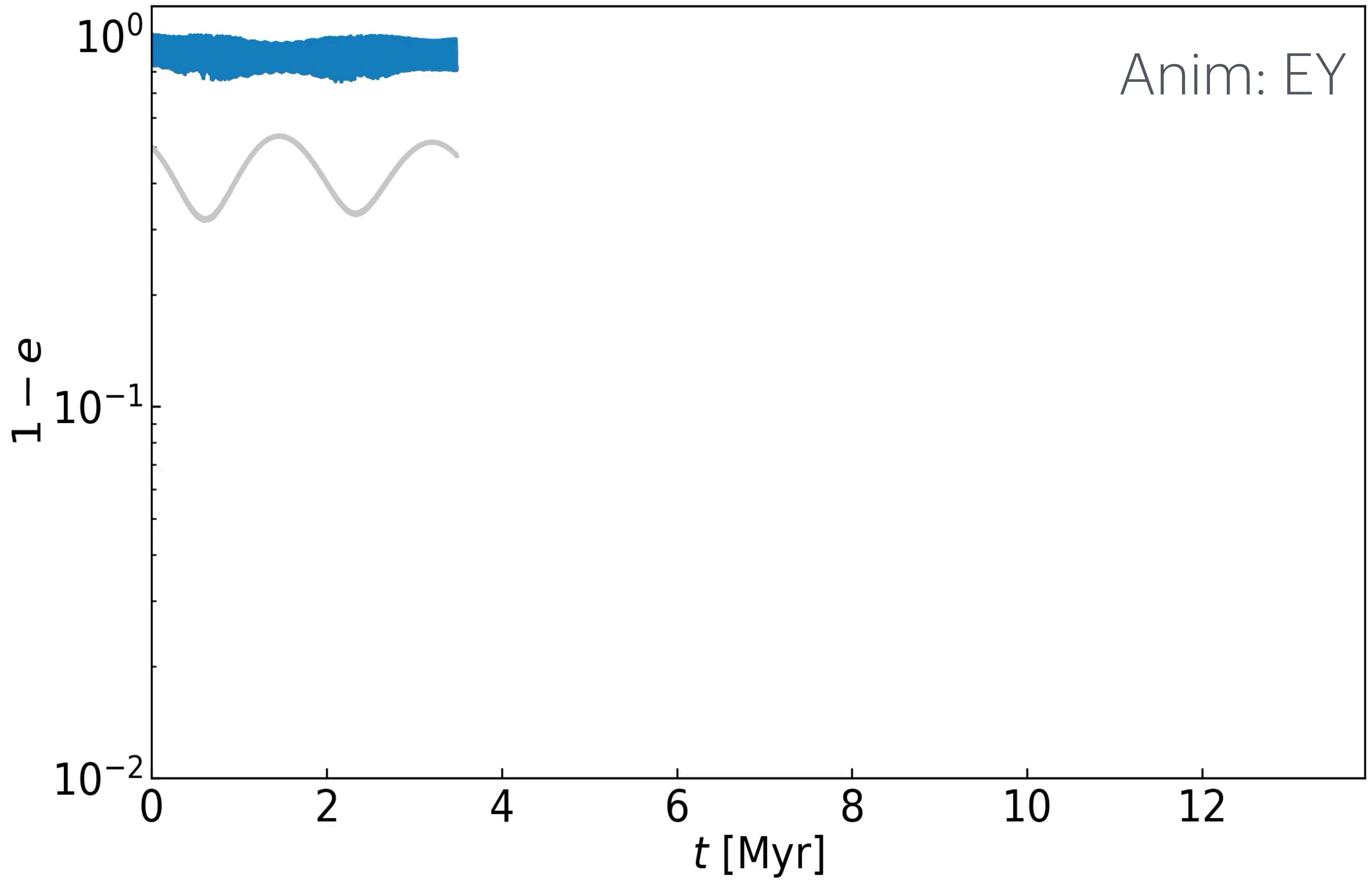


- $e_{forced}$ can slowly vary, but $e_{free}$ is constant *except* due to scattering!
  - When $e_C$ is large

# Eccentricity Cascade

## Triple scenario: (ii) EC = outer ZLK + scattering

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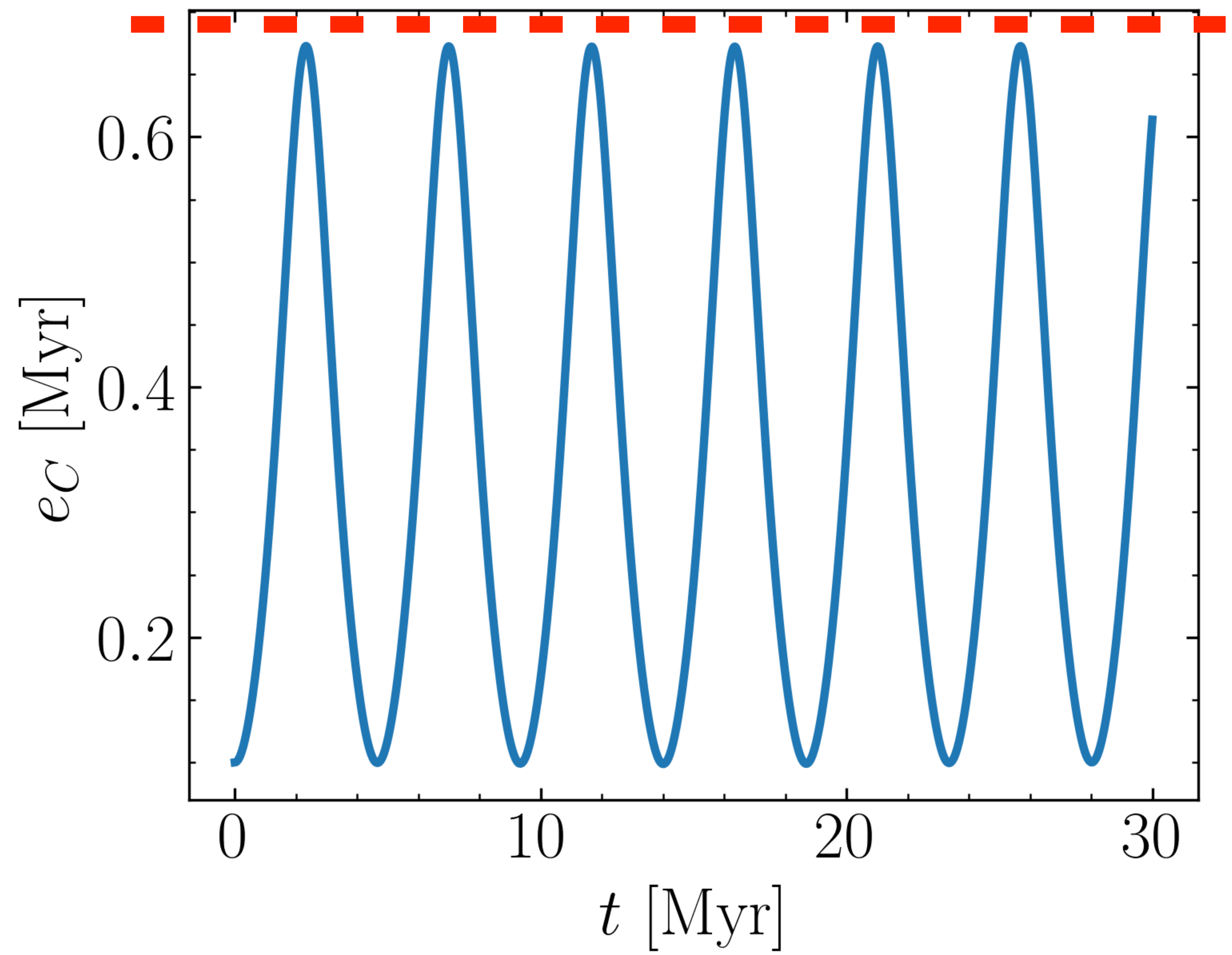
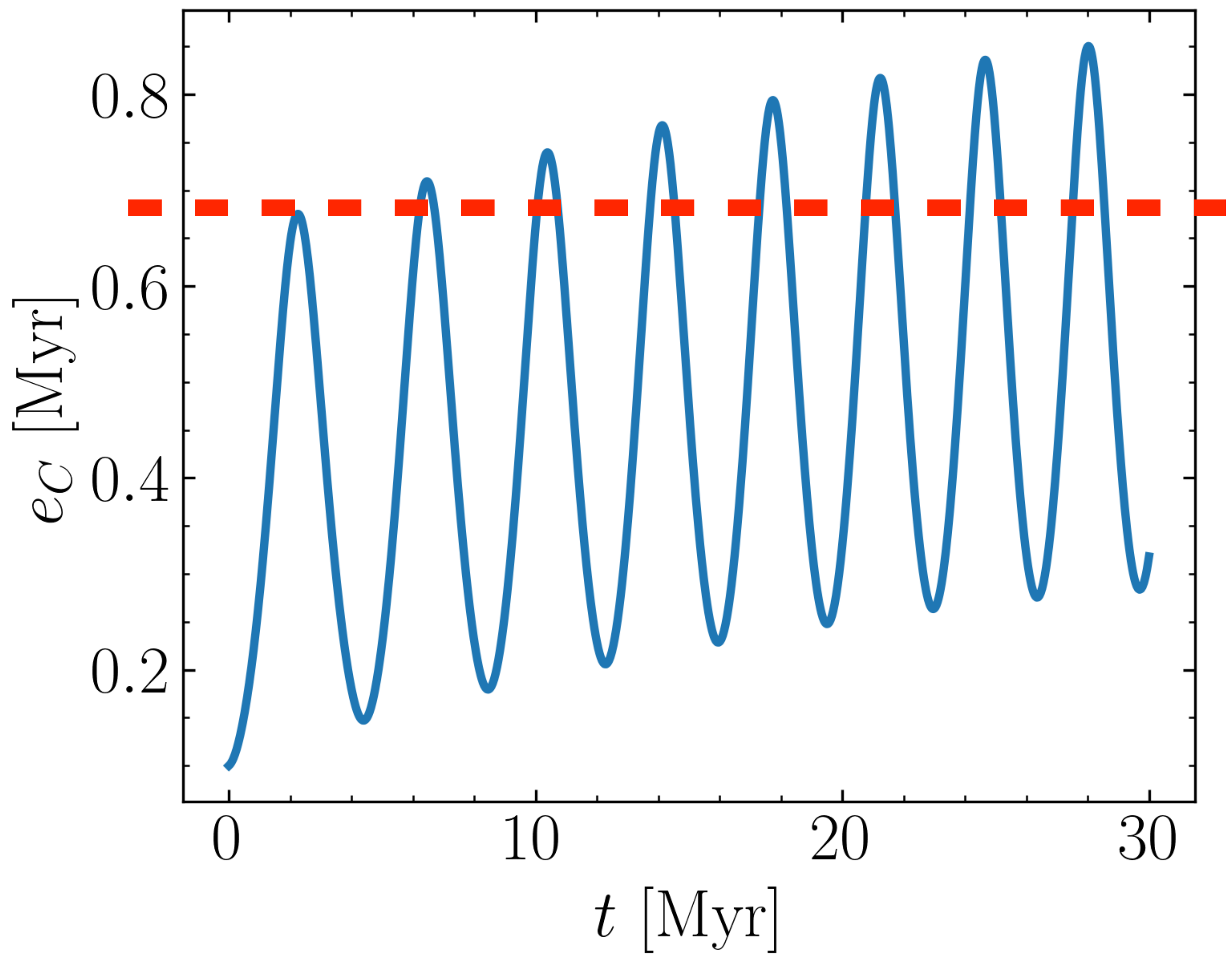
# Eccentricity Cascade

## Triple scenario: (ii) EC = outer ZLK + scattering

Quadrupole-only ZLK




Octupole ZLK: Gradual approach!

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# EC and Circumbinary Stability

## Triple scenario: Onset of the Eccentricity Cascade (YSW in prep)

By analogy to the Chirikov-Taylor standard map, the **instability boundary** lies at...

WIP!!

$$K = \frac{3\pi\zeta(a_1/a_p)^{3/2}}{\sqrt{1+m_1/M_\star}} e^{-2\frac{n_p}{n_1}\left(\cosh^{-1}\left(\frac{1}{e_1}\right)-\sqrt{1-e_1^2}\right)} \gtrsim 0.1$$

$$\zeta = \frac{3\pi^2}{e_1^2(1-e_1^2)^3}\left(\frac{m_1}{M_\star+m_1}\right)^2 .$$

$$\left[\frac{2}{n_p/n_1} + \frac{6(1-e_1^2)^{3/2}}{e_1^2}\right]\left[\frac{6+9e_1^2}{n_p/n_1} + 5(1-e_1^2)^{3/2}\right].$$

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# Summary

YSW25

- Some HJs are probably formed dynamically.
- We identify the Eccentricity Cascade (EC) mechanism to form HJs in stellar triples
  - EC = Stellar ZLK + weak scattering
  - Inspired by our discovery of HAT-P-7C, (0.2 Msun, 28 AU; YSW25)
- We derive analytical boundaries for the EC mechanism based on the circumbinary stability
  - Typically, ~tens of AU companions across a wide mass range