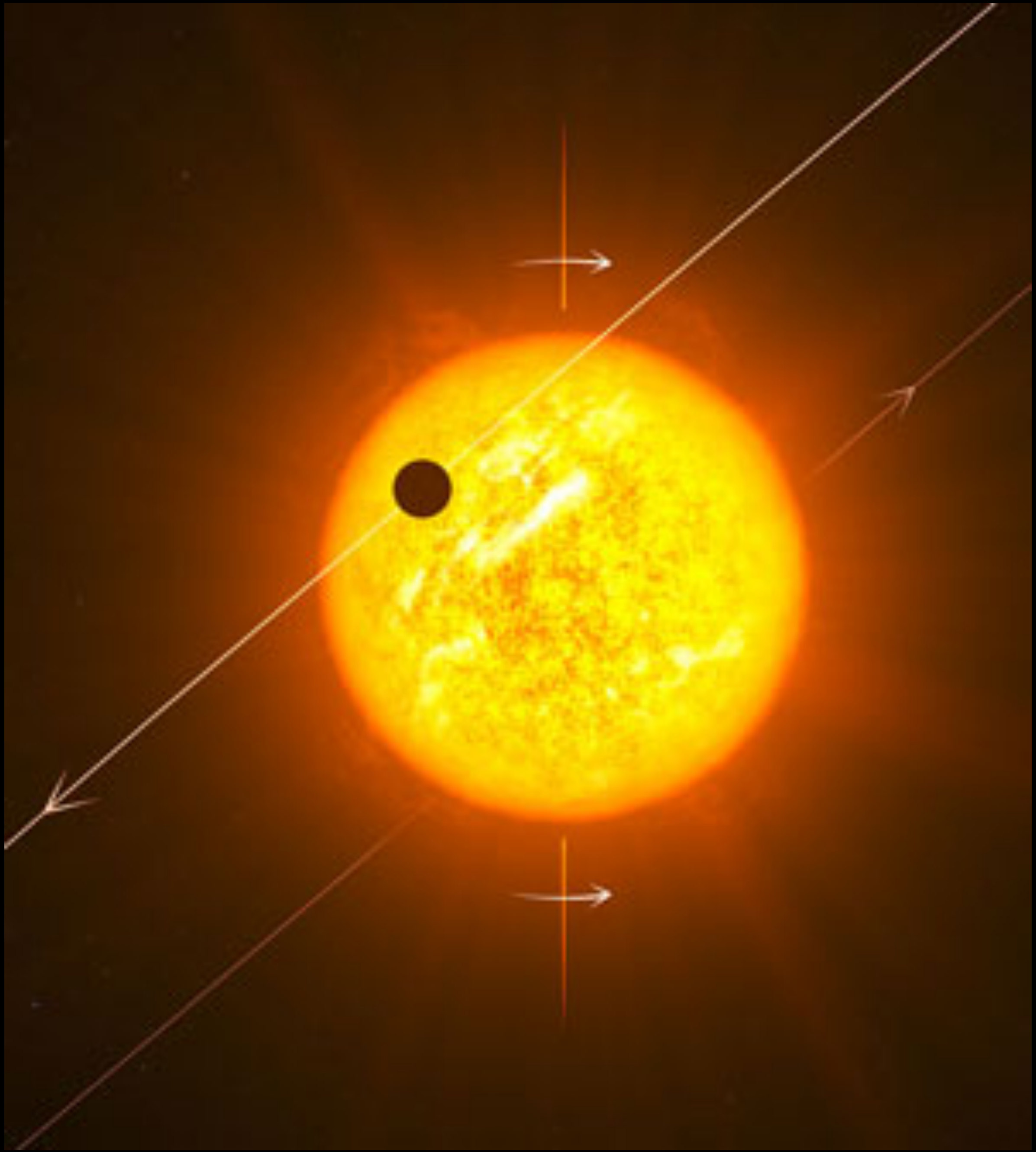
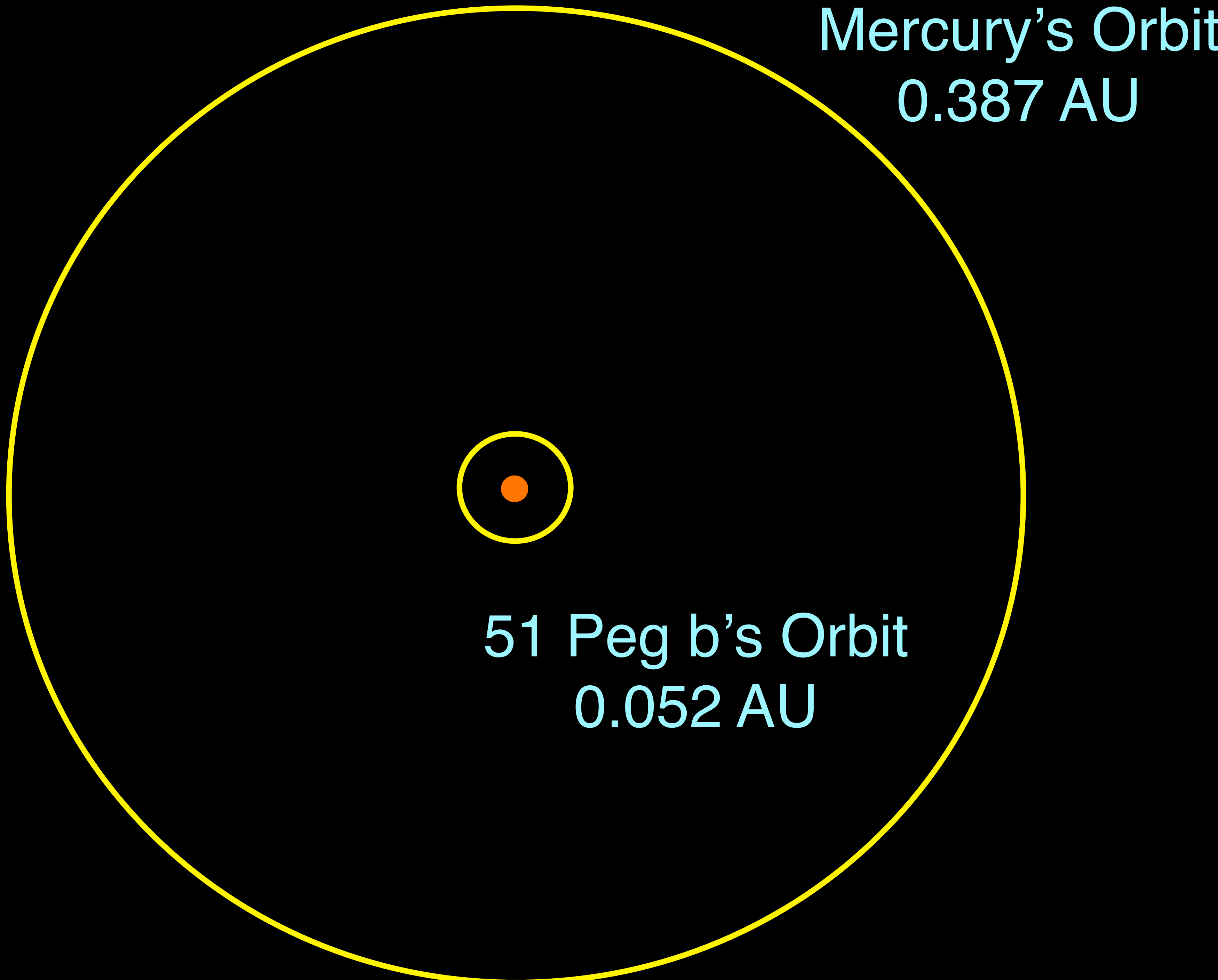
Toward a Grand Unified Theory of the Origin of Hot Jupiters

John Johnson
The Caltech Exolab

NASA Exoplanet Science Institute
California Institute of Technology
NExScI

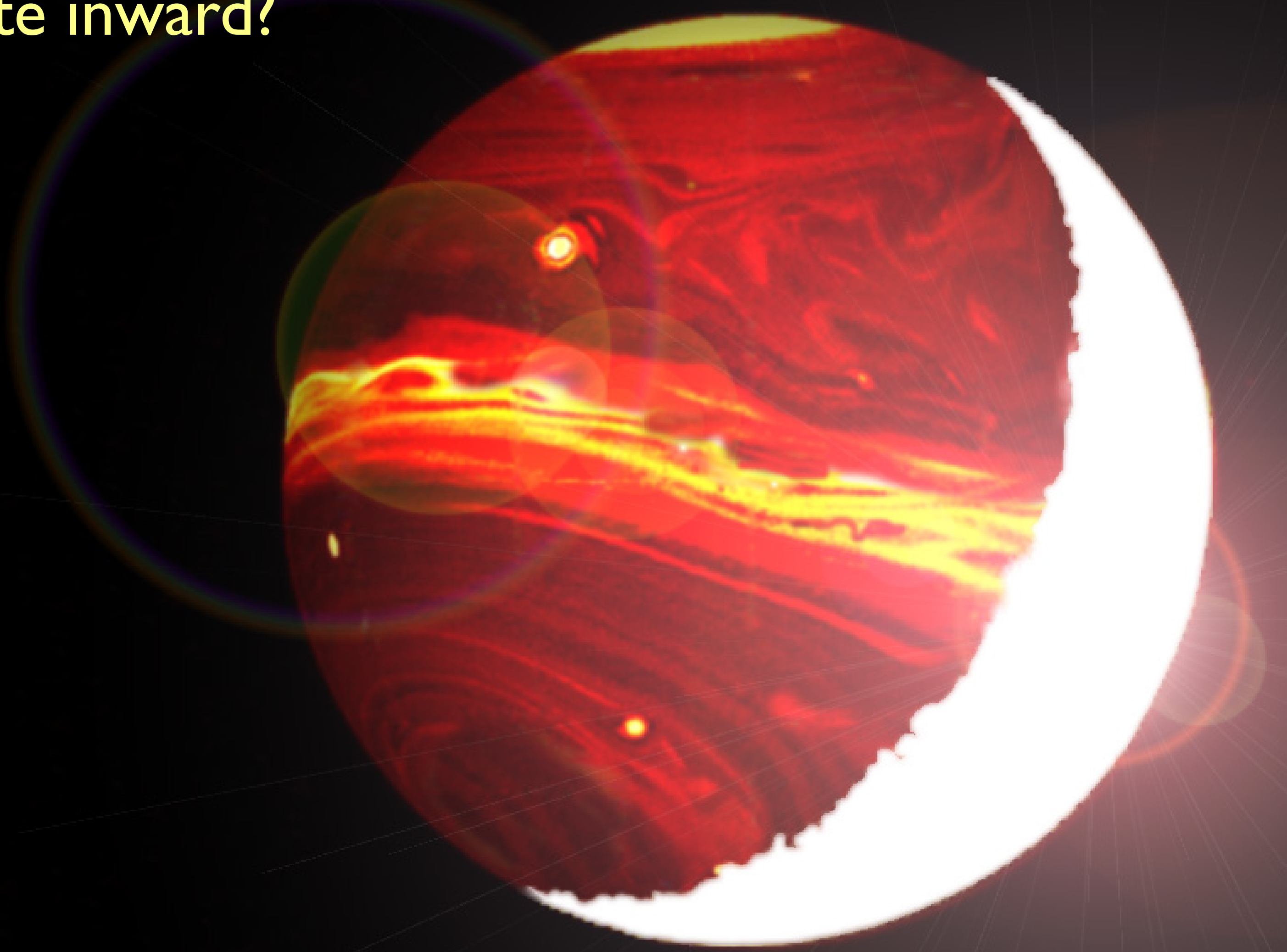
NASA



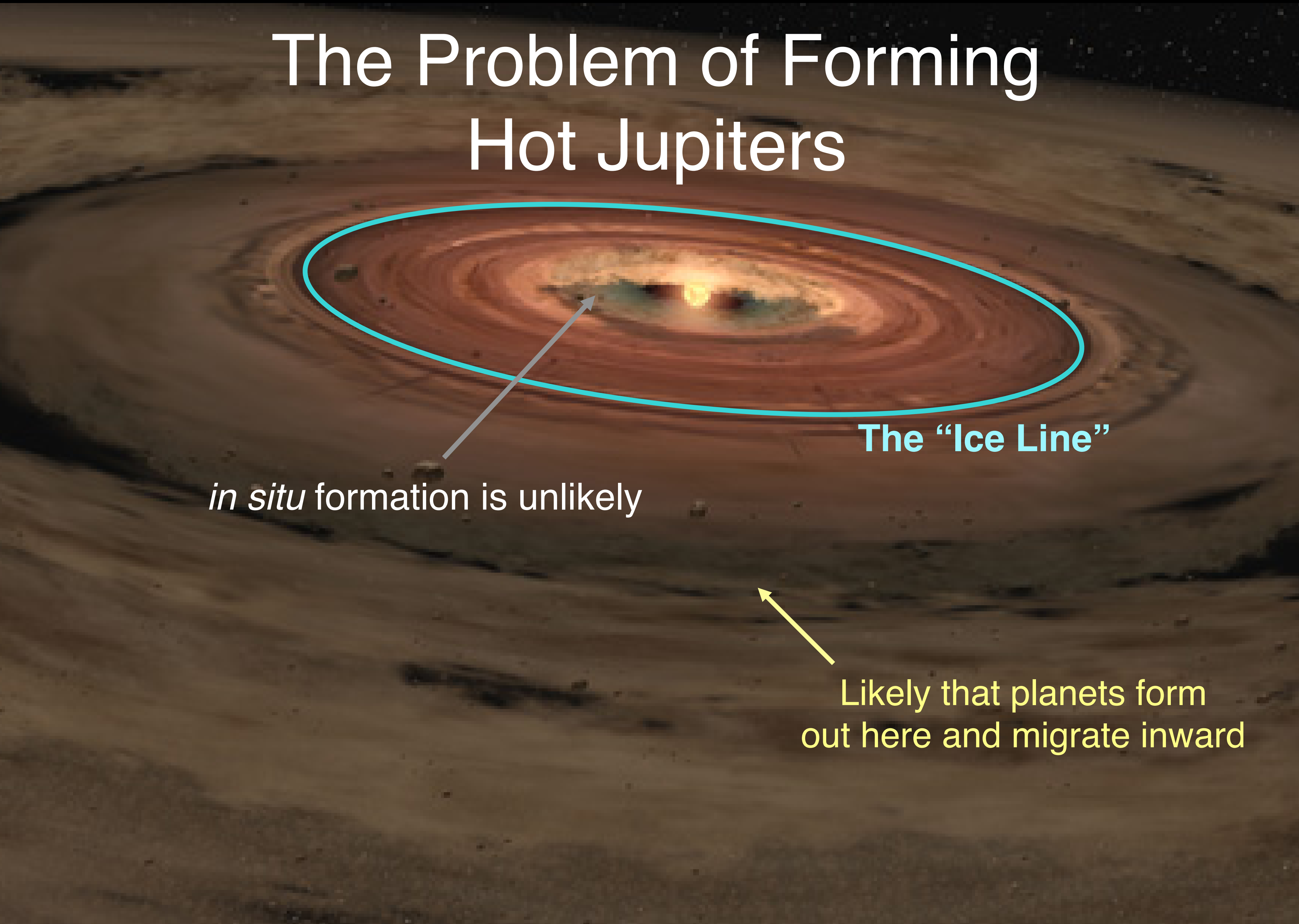

Mercury's Orbit
0.387 AU
51 Peg b's Orbit
0.052 AU

Question:

How did the hot Jupiters migrate inward?



The Problem of Forming Hot Jupiters



Migration Mechanisms

Gentle

- Viscous evolution with the disk

Dynamical/Impulsive

- Perturbation from a passing star
- Planet-planet scattering
- Dynamical relaxation
- Secular chaos
- Kozai cycles with tidal damping

Migration Mechanisms

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- **Kozai cycles with tidal damping**

Kozai Cycles: $(1 - e^2)^{1/2} \cos i_{mutual}$

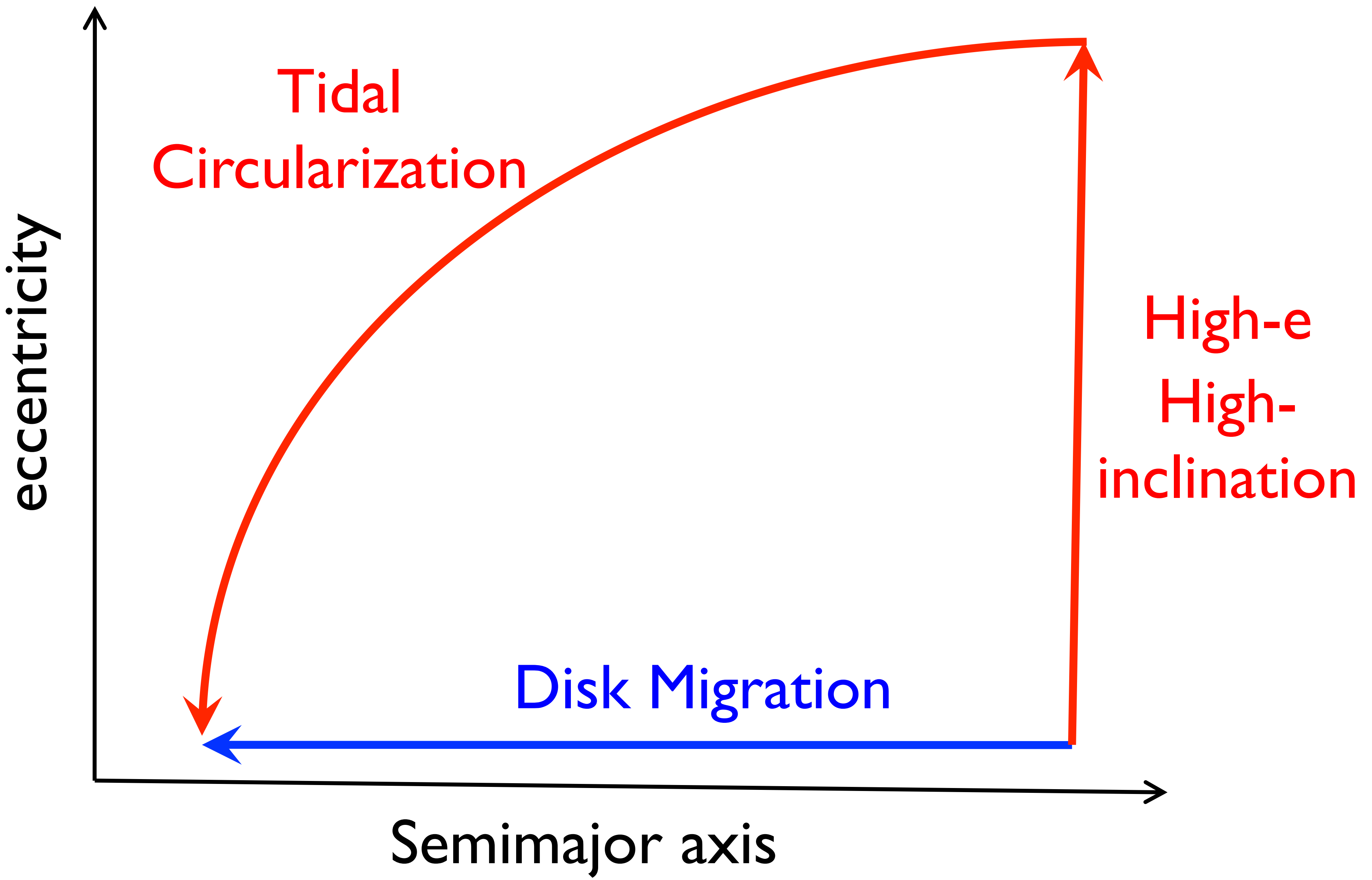
If a planet is perturbed by a mutually inclined outer companion, its orbit will oscillate between

- Circular and inclined

- Eccentric and aligned

Kozai 1962

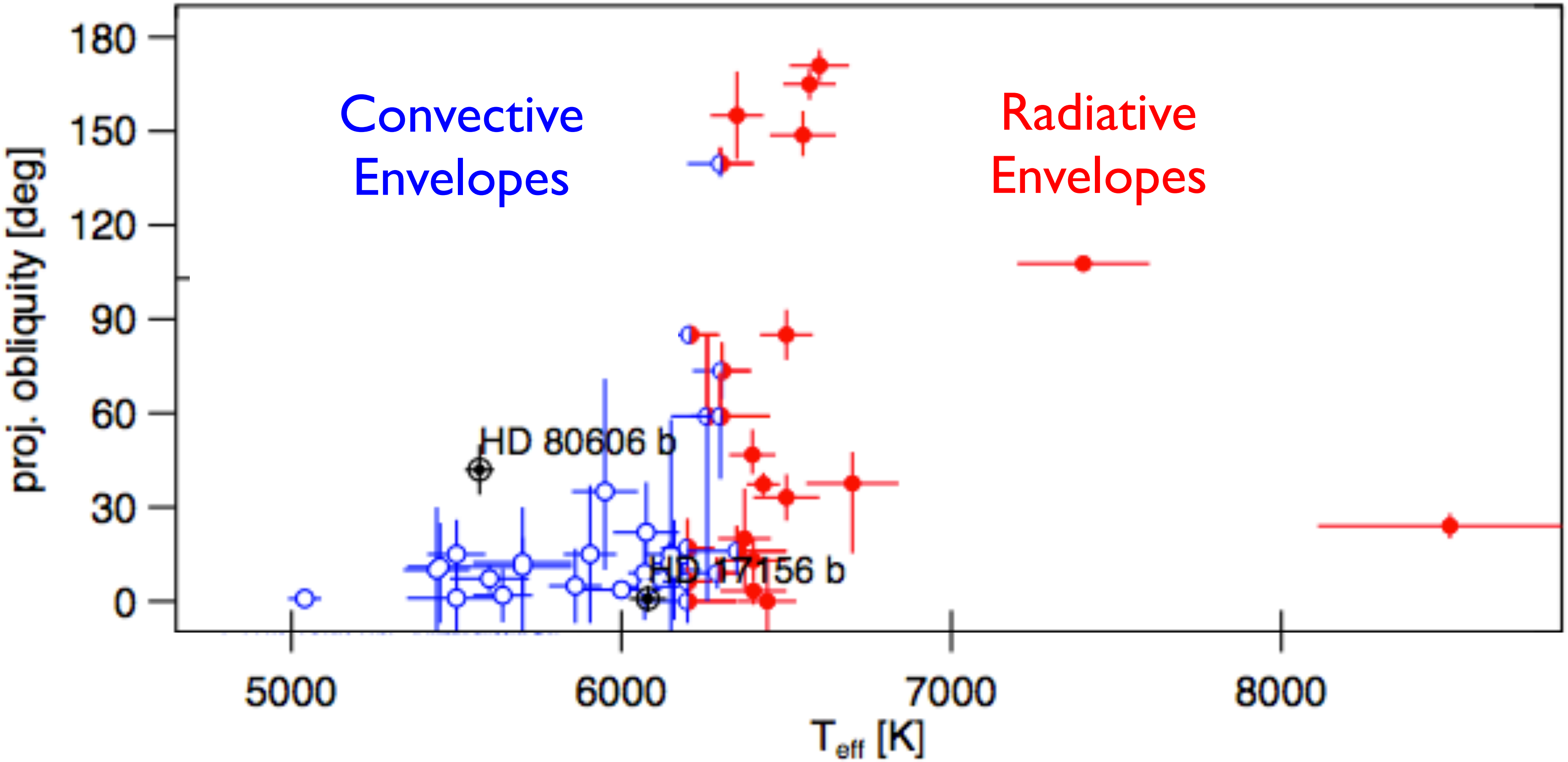
Tidal Damping: When eccentric, the planet loses energy due to tidal friction, leaving the planet on a close, circular orbit.


Tidal
Circularization
High-e
High-
inclination
Disk Migration
eccentricity
Semimajor axis

Hot Stars with Hot Jupiters Have High Obliquities

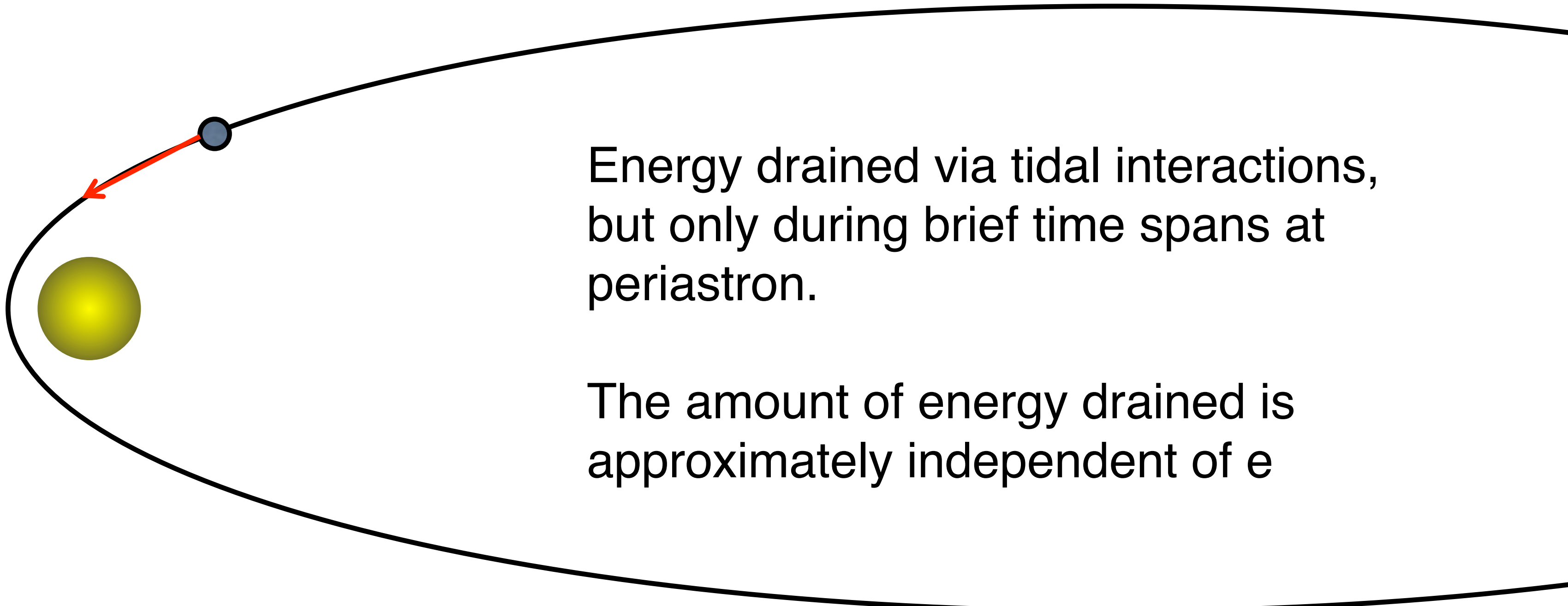
Winn, Fabrycky, Albrecht & Johnson (2010)

Albrecht, Winn, Johnson et al. (2012)



Socrates, Katz, Dong & Tremaine (2012)

$\dot{E} \rightarrow \dot{e}$



Energy drained via tidal interactions, but only during brief time spans at periastron.

The amount of energy drained is approximately independent of e

$\tau \sim e/\dot{e}$

There should exist a population of highly eccentric hot Jupiters.

Aristotle Socrates

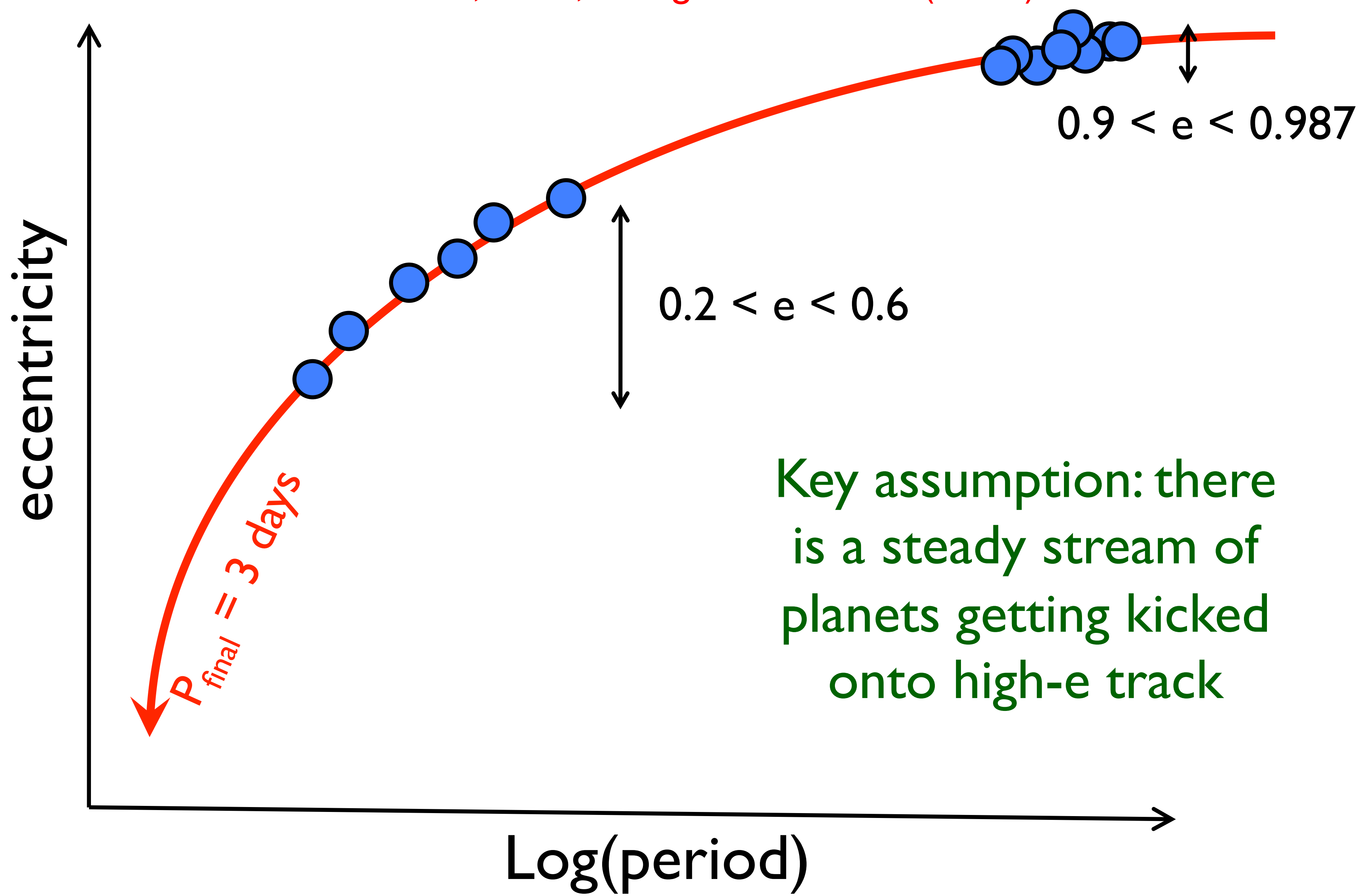
Boaz Katz

Subo Dong

Scott Tremaine

An example population of proto hot Jupiters along a single P_{final} track

Socrates, Katz, Dong & Tremaine (2012)

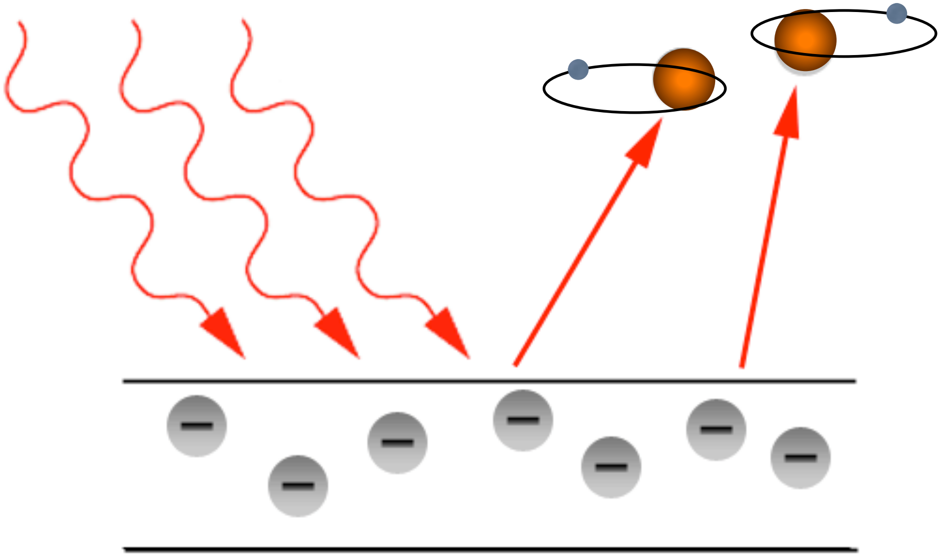


Key assumption: there is a steady stream of planets getting kicked onto high-e track

The Photoeccentric Effect and Proto-Hot-Jupiters

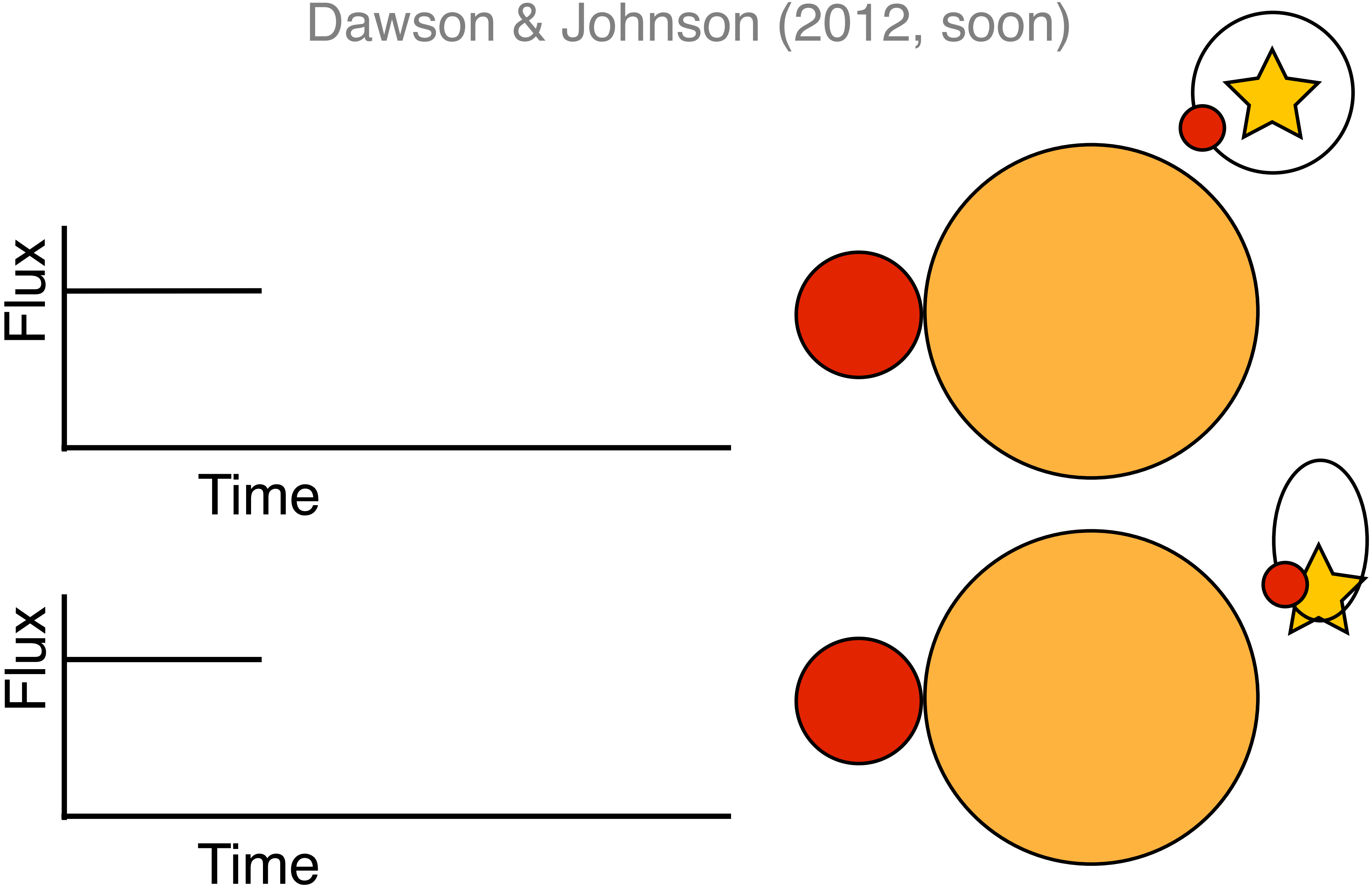
In collaboration with:
Rebekah “Bekki” Dawson (CfA)

The Photoeccentric Effect



The “Photoeccentric” Effect

Dawson & Johnson (2012, soon)



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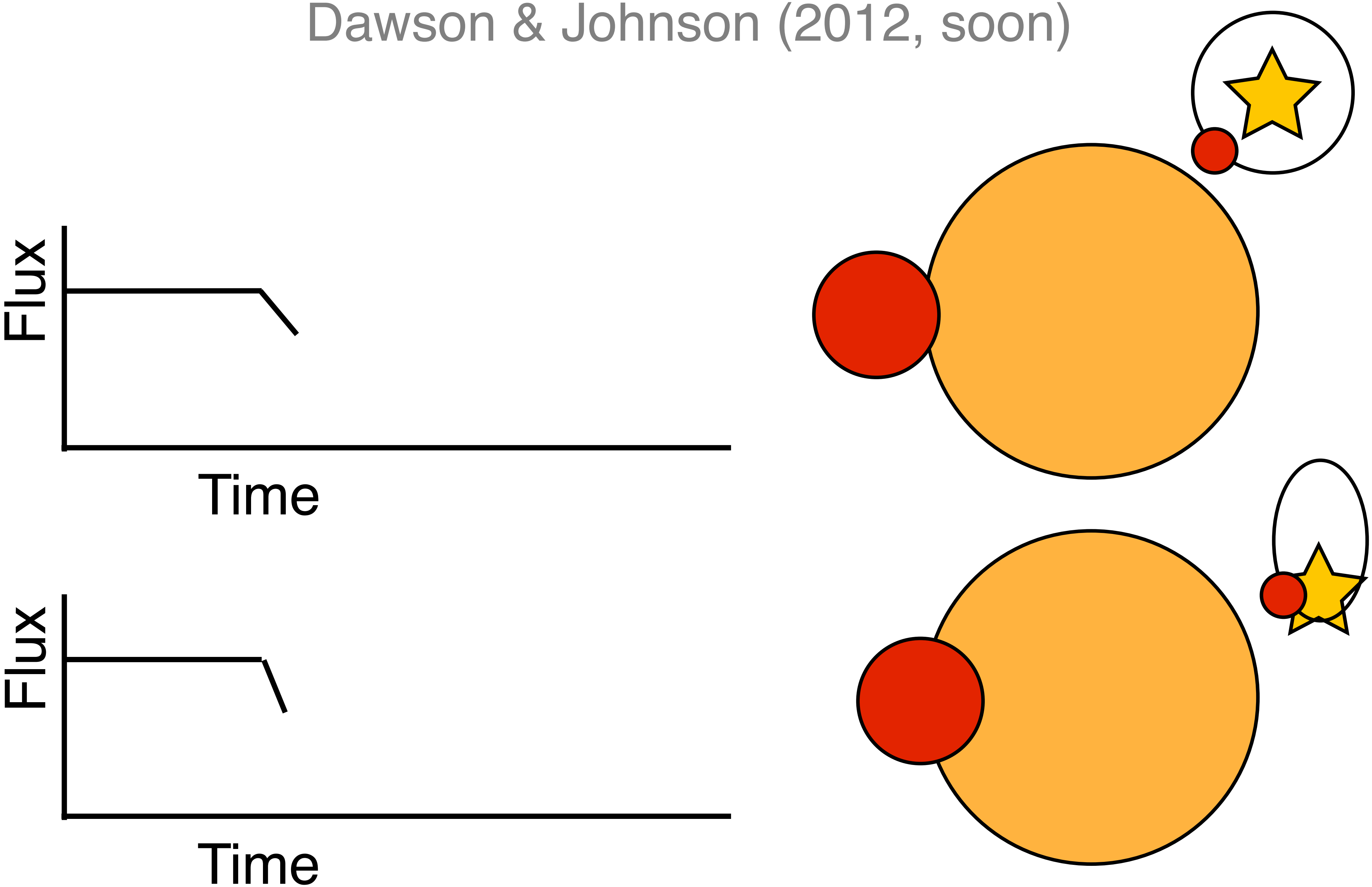

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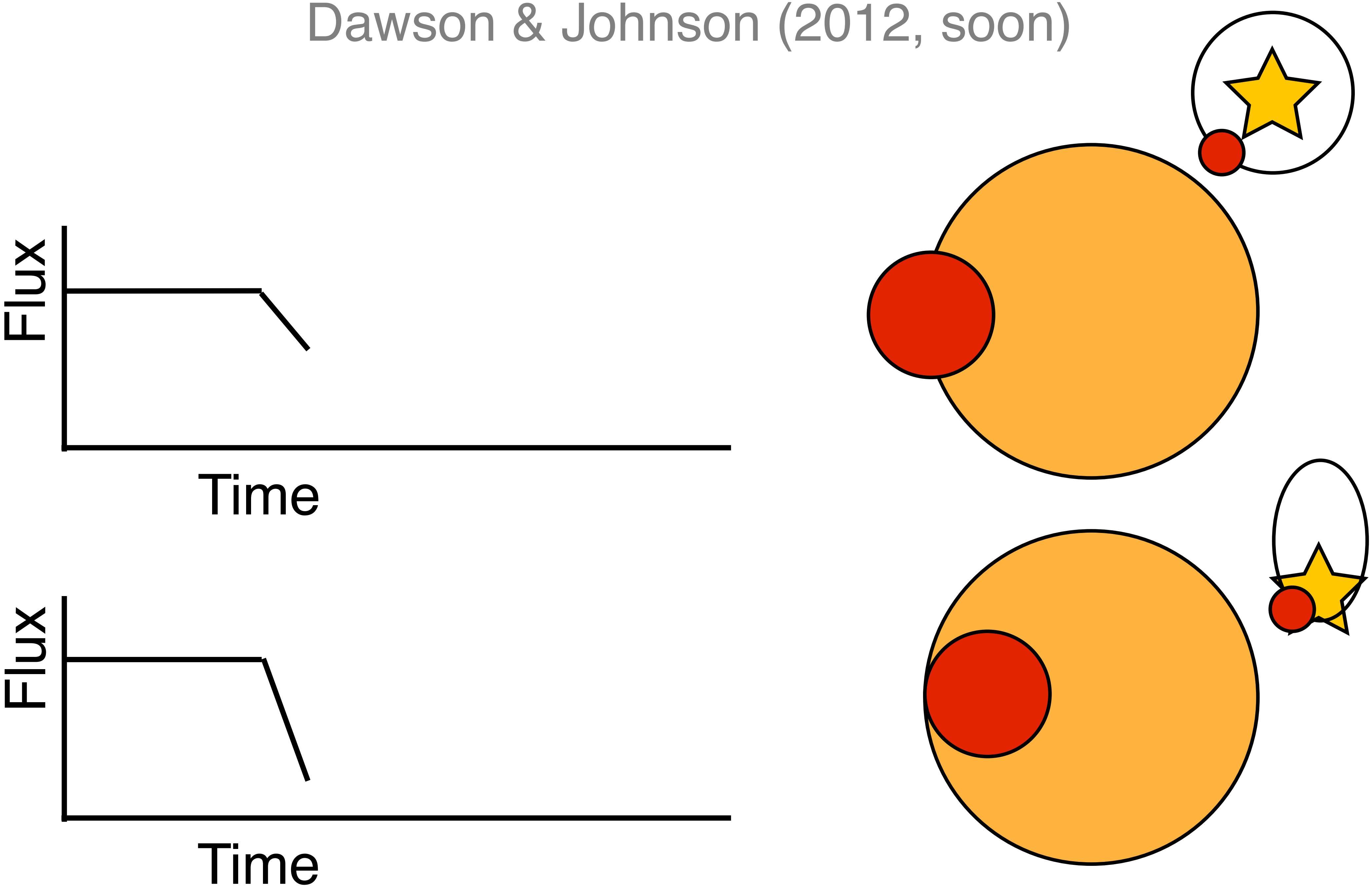

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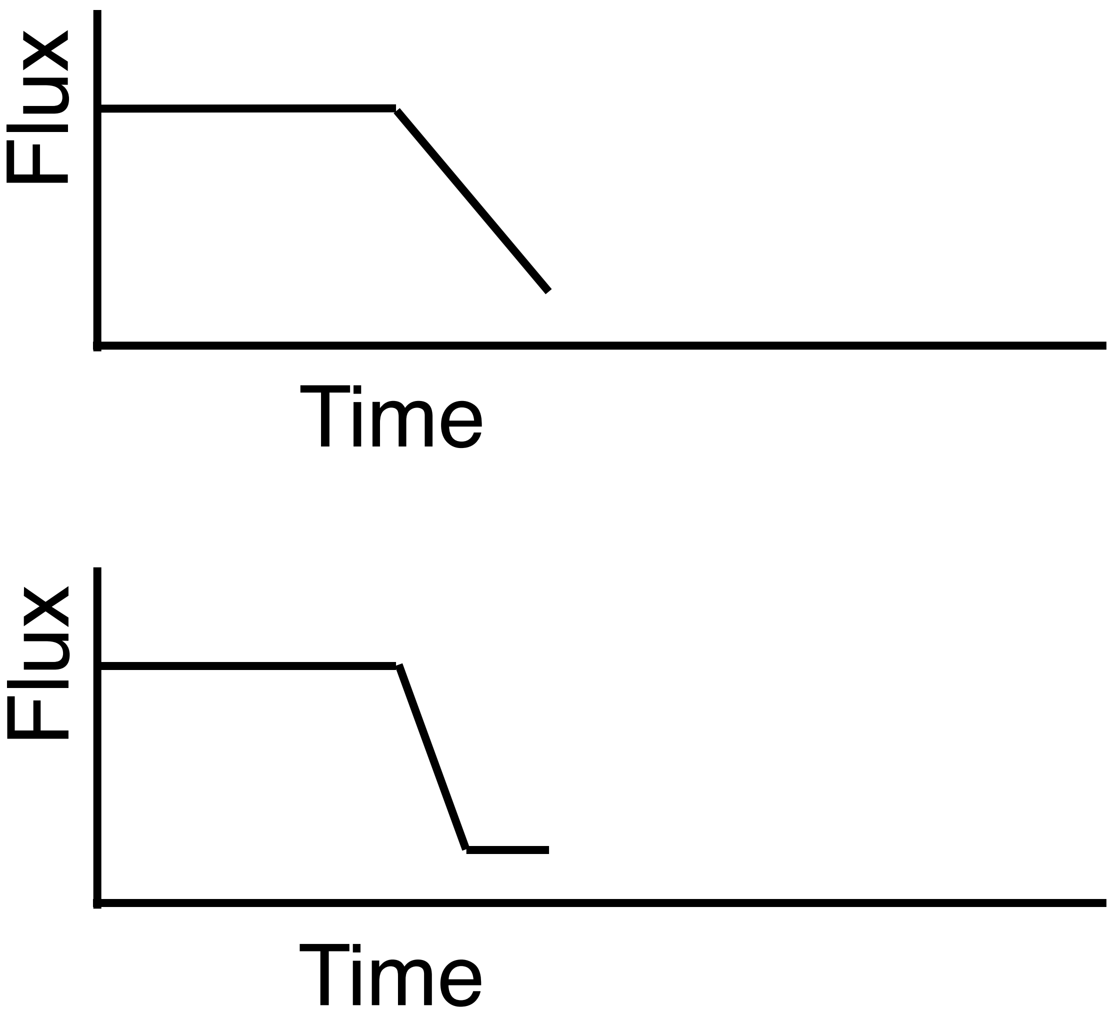

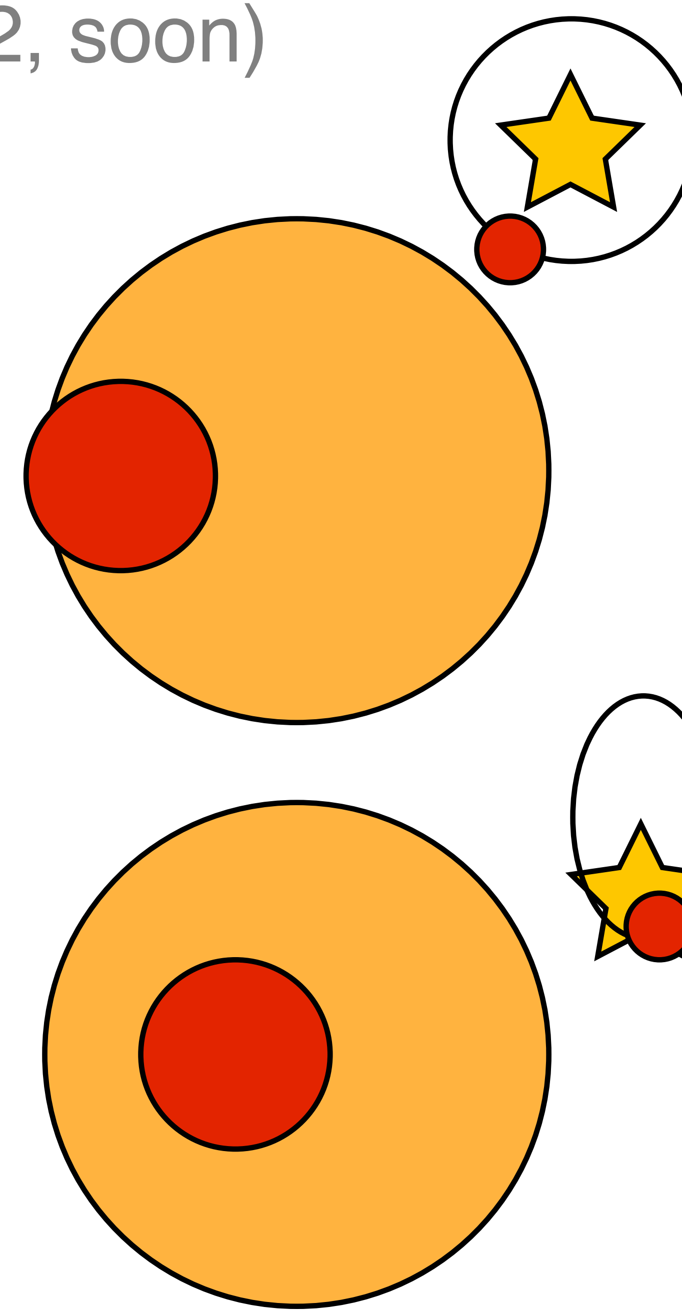

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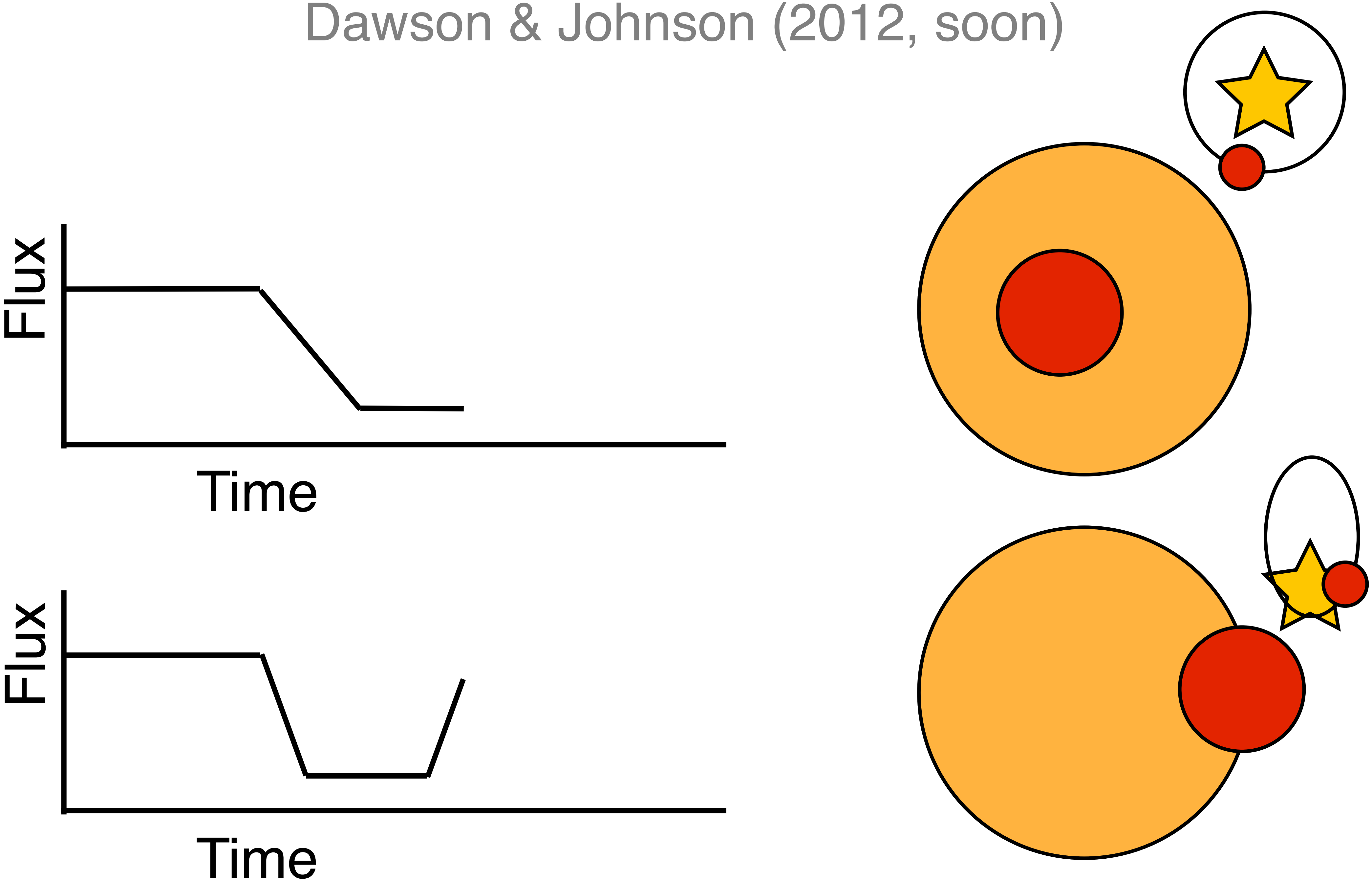
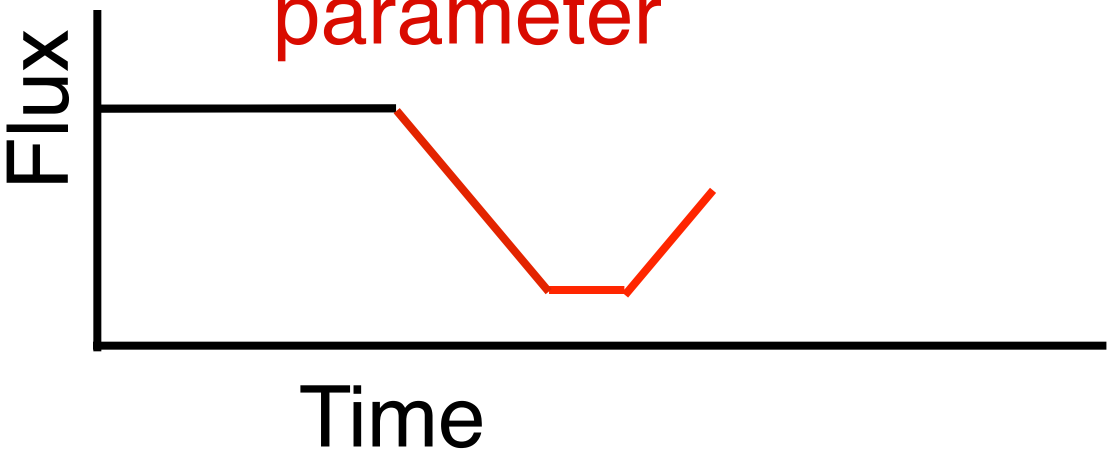
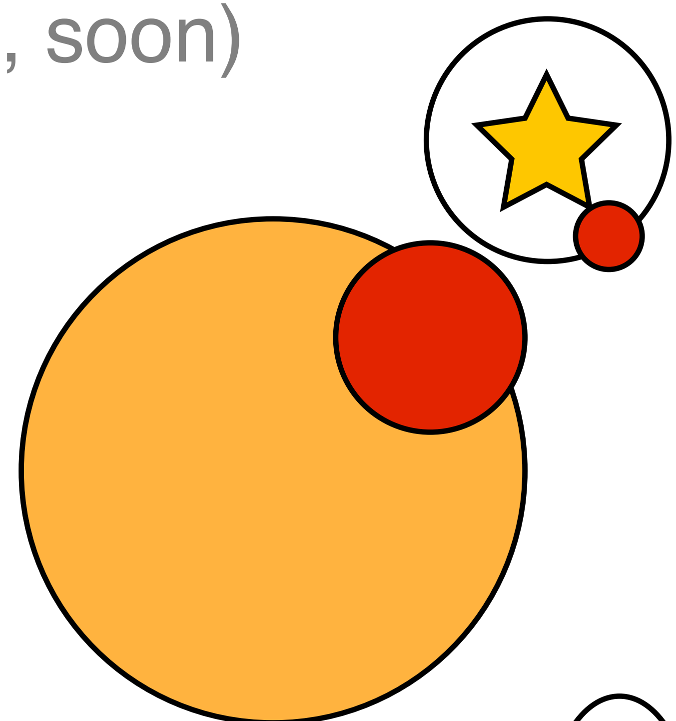


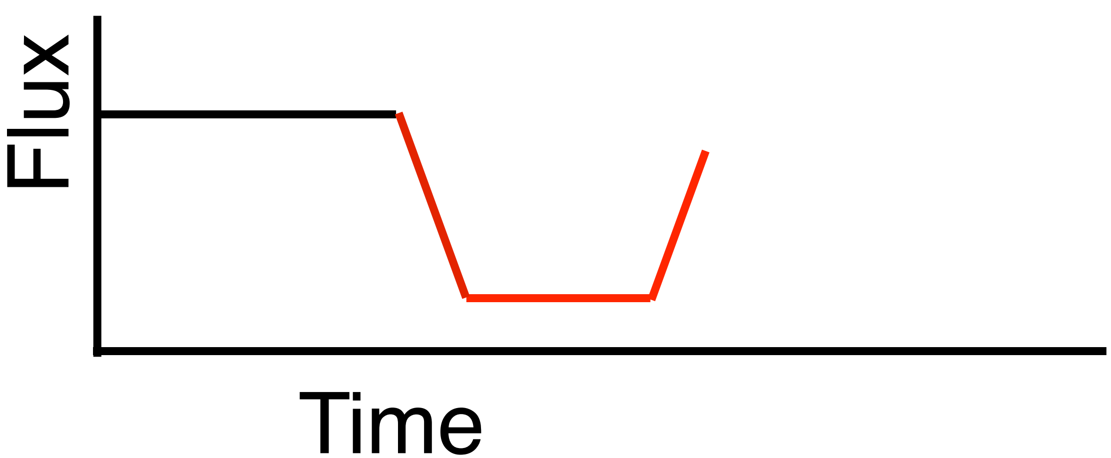
The “Photoeccentric” Effect

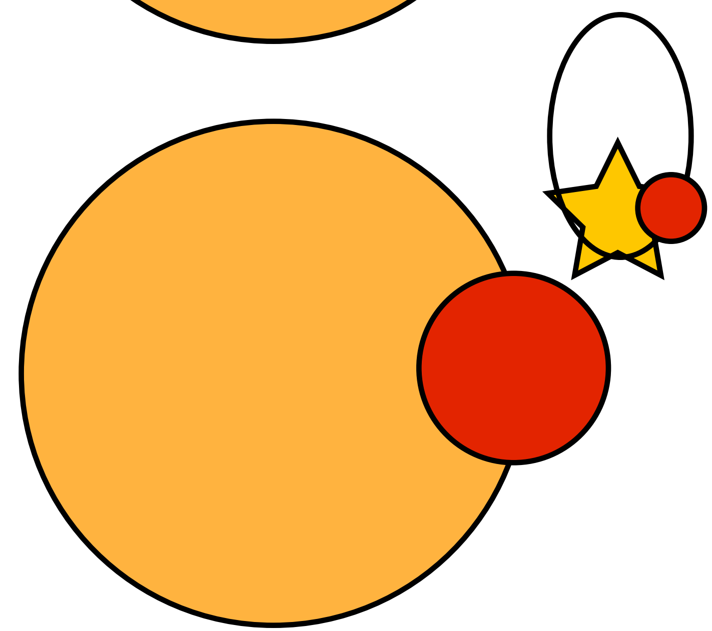
Dawson & Johnson (2012, soon)

Can be distinguished from large impact parameter









Measuring the eccentricity from the light curve

$$\frac{a}{R_\star} g(e,\omega) = \frac{2\delta^{1/4} P}{\pi \sqrt{T_{\rm tot}^2 - T_{\rm full}^2}}$$

derived from light curve quantities

$$\frac{V_{\rm eccentric}}{V_{\rm circular}}$$

$$\frac{1 + e \sin\omega}{\sqrt{1-e^2}}$$

e: eccentricity

ω: periapse angle

Ford, Quinn & Veras (2008)
Kipping 20**
Carter et al. 2008
Winn 2010

Measuring the eccentricity from the light curve

$$\rho_\star \; g(e,\omega)^3 = \rho_{\rm circ}$$

stellar density,
weakly constrained,
perhaps from spectroscopy

$$\frac{1 + e\sin\omega}{\sqrt{1-e^2}}$$

derived from
light curve
quantities

Ford, Quinn & Veras (2008)
Kipping 20**
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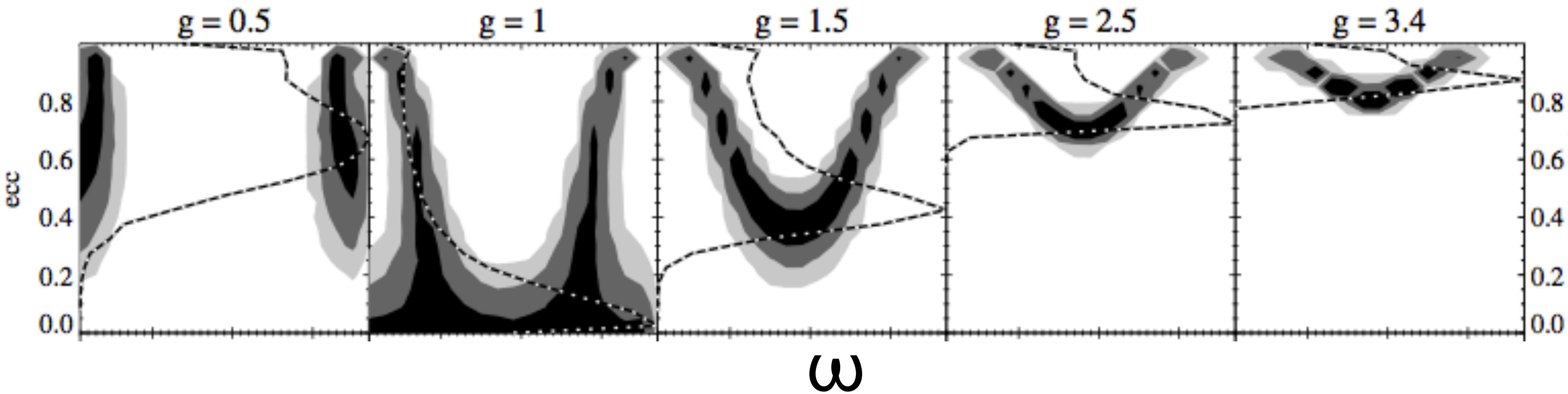
Measuring eccentricity

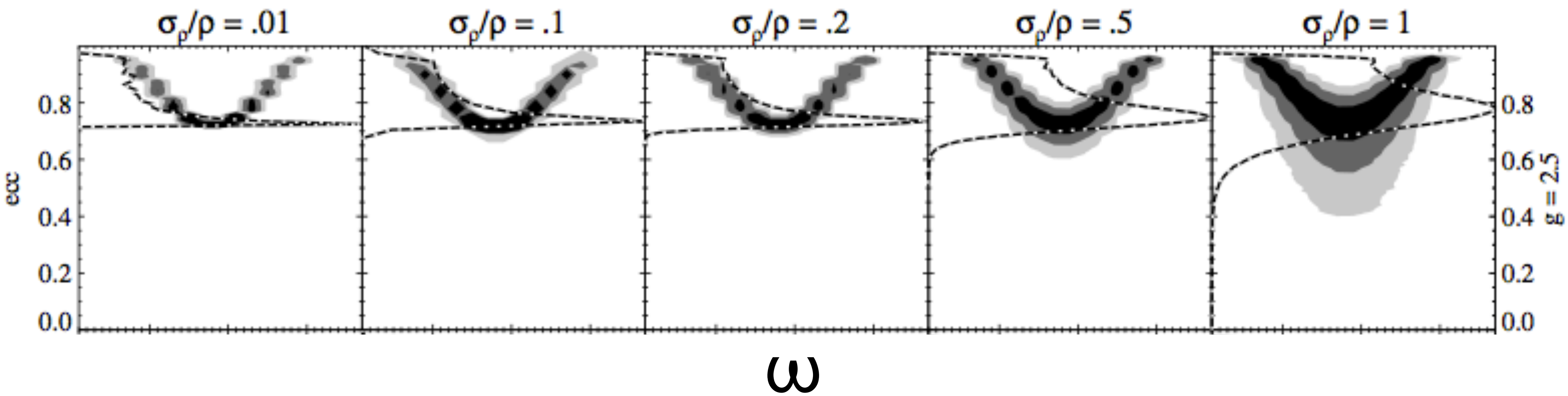
$$\frac{V_{eccentric}}{V_{circular}} \rightarrow$$



Dawson & Johnson (2012)

Tight eccentricity measurement from a loose constraint on stellar density

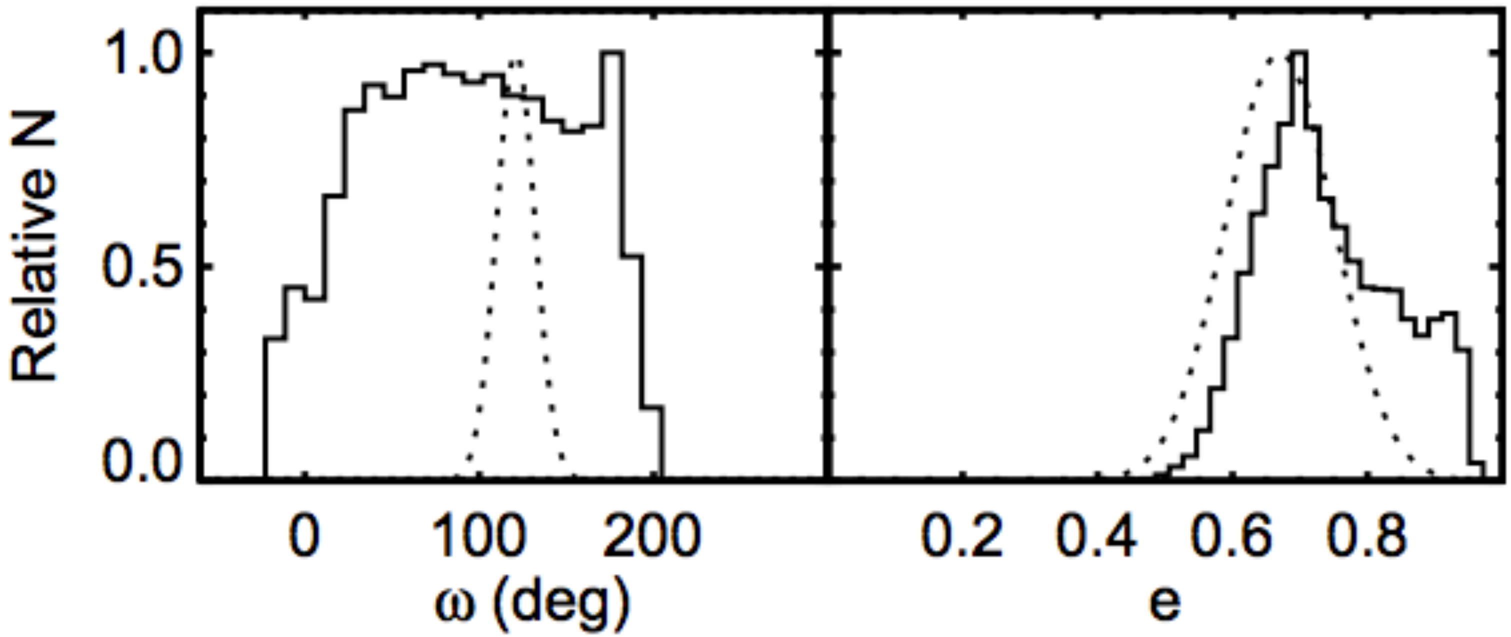
Uncertainty in density →



Dawson & Johnson (2012)

HD 17156 b:
posterior distributions from a light curve

Dawson & Johnson (2012)



Light curve: $e = 0.73^{+0.14}_{-0.09}$

Independently from RV: $e = 0.67 \pm 0.08$ (Fischer et al. 2007)

Testing the high-eccentricity migration mechanism

How many proto-hot-Jupiters should we expect from HEM?

Relative number of highly eccentric to moderately eccentric Jupiters from tidal theory

Normalization Term

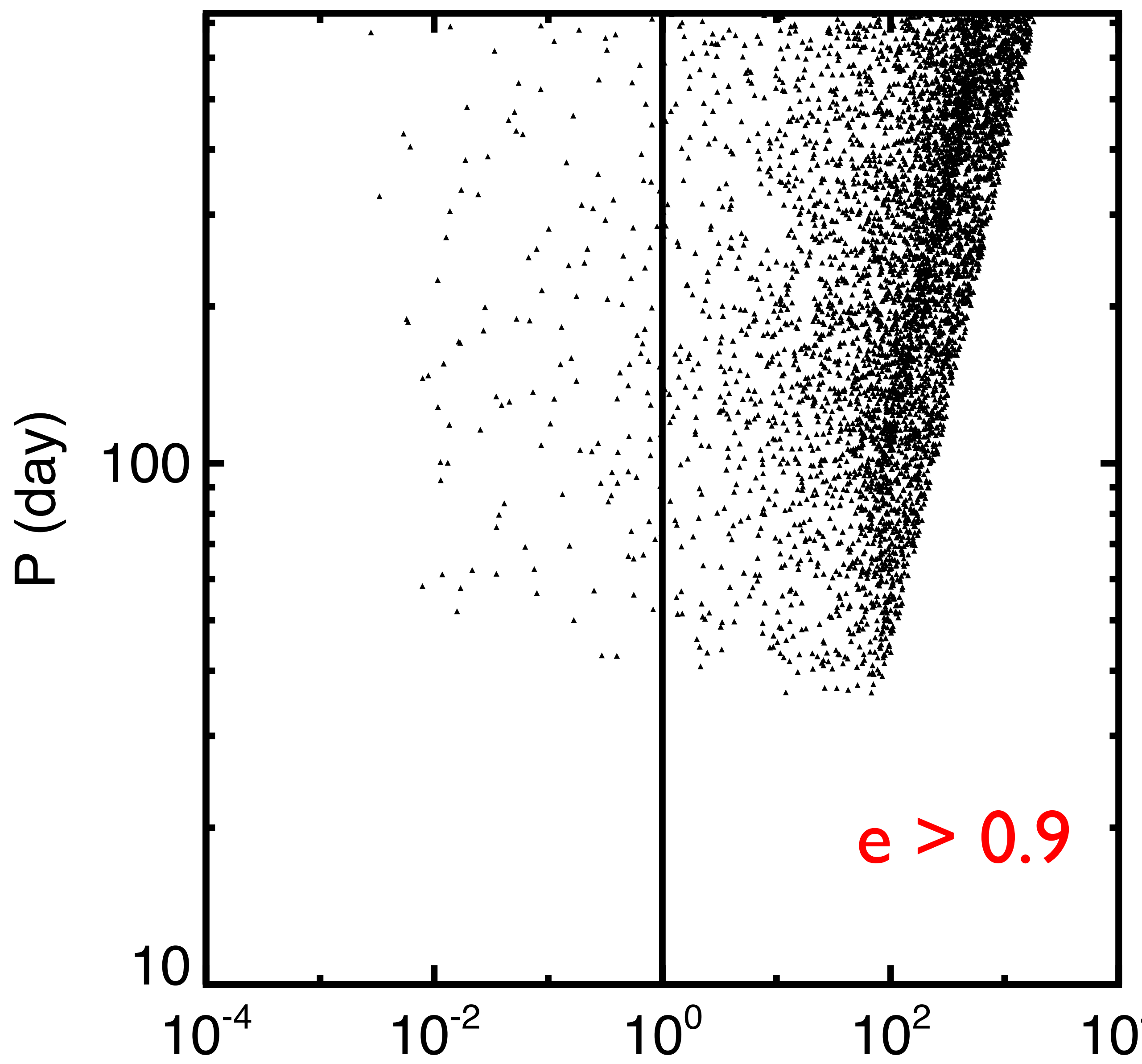
$$N_{\rm pl}(0.9 < e < e_{\rm max}, P_{\rm final}) = \frac{\int_{0.9}^{e_{\rm max}} \frac{1}{|de/dt|} de}{\int_{0.2}^{0.6} \frac{1}{|de/dt|} de} N_{\rm pl}(0.2 < e < 0.6, P_{\rm final}) \frac{N_{\rm HJ,Kep}}{N_{\rm HJ,nonKep}}$$

Expected number of highly eccentric Jupiters in the *Kepler* sample

Observed number of moderately eccentric Jupiters from non-*Kepler* transit surveys

For $P_{\rm final}$ = 3 days, this ratio should be ~unity

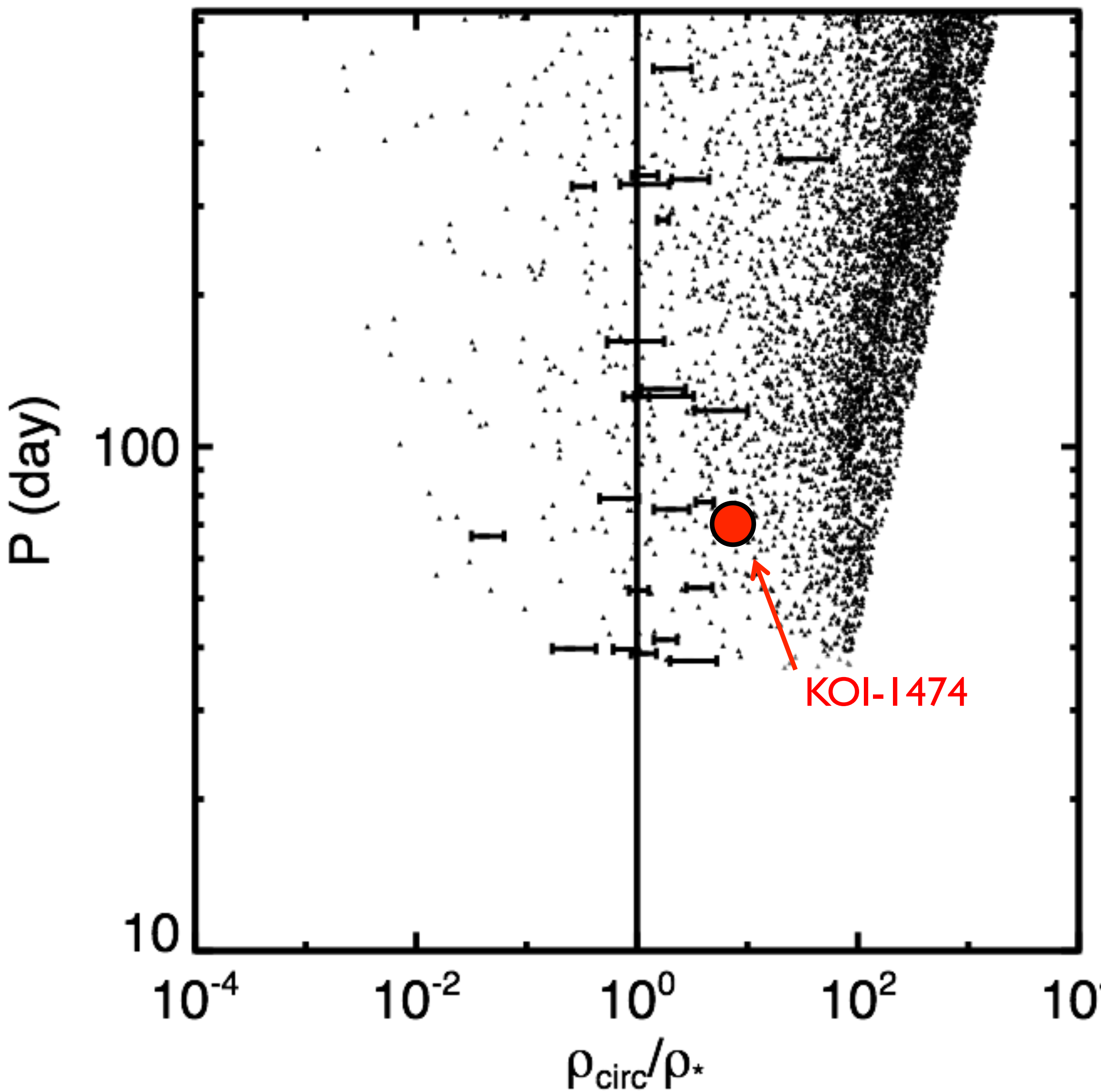
Converting the expected eccentricity distribution into transit observables



Selecting the candidate super-eccentric Jupiters from the *Kepler* sample

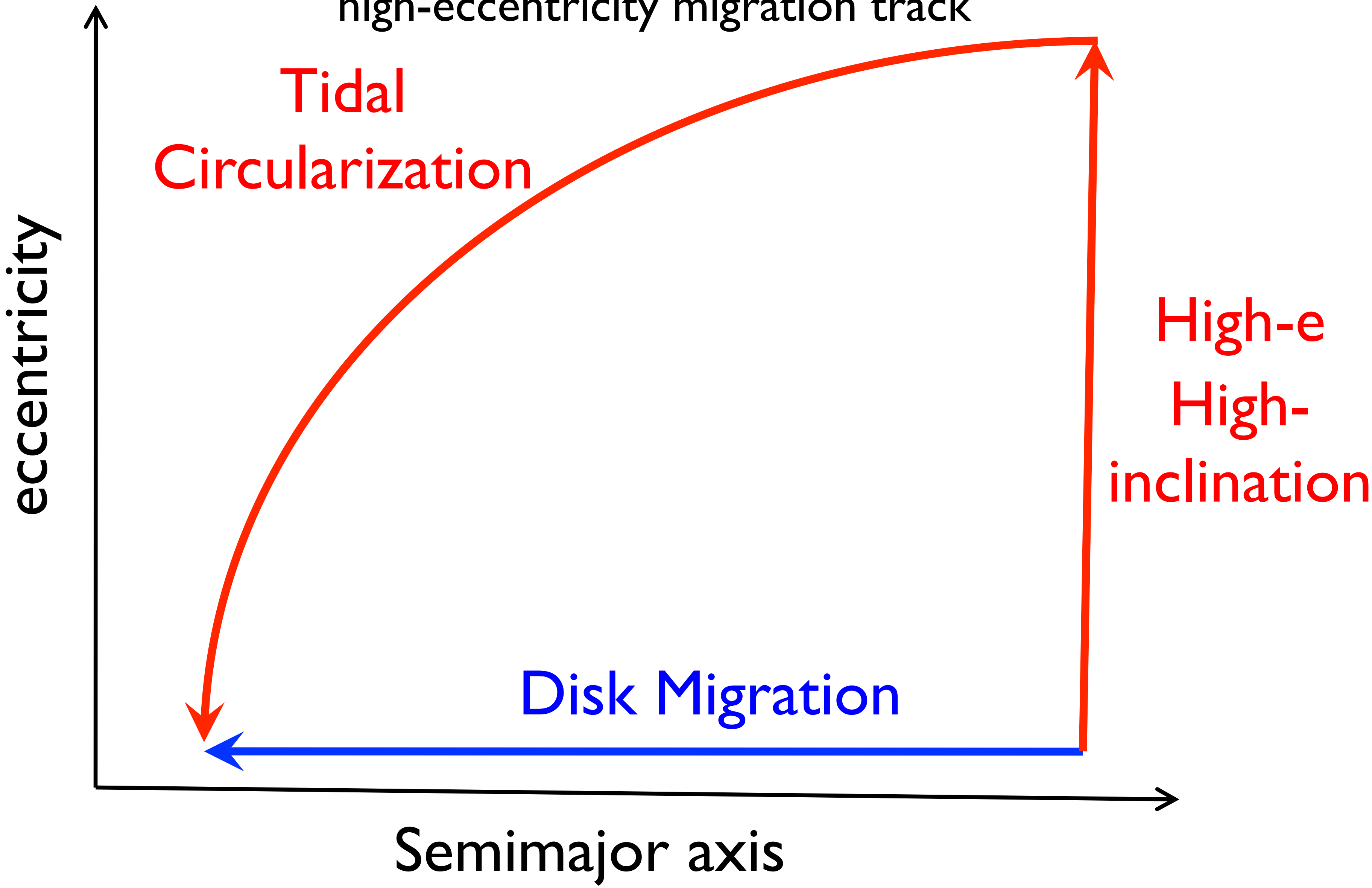
- $4500 < T_{eff} < 6500$ K, $\log g > 4$
- 36 day < P < 2 years
- $R_p > 8\ R_{earth}$

The case of the missing super-eccentric proto hot Jupiters

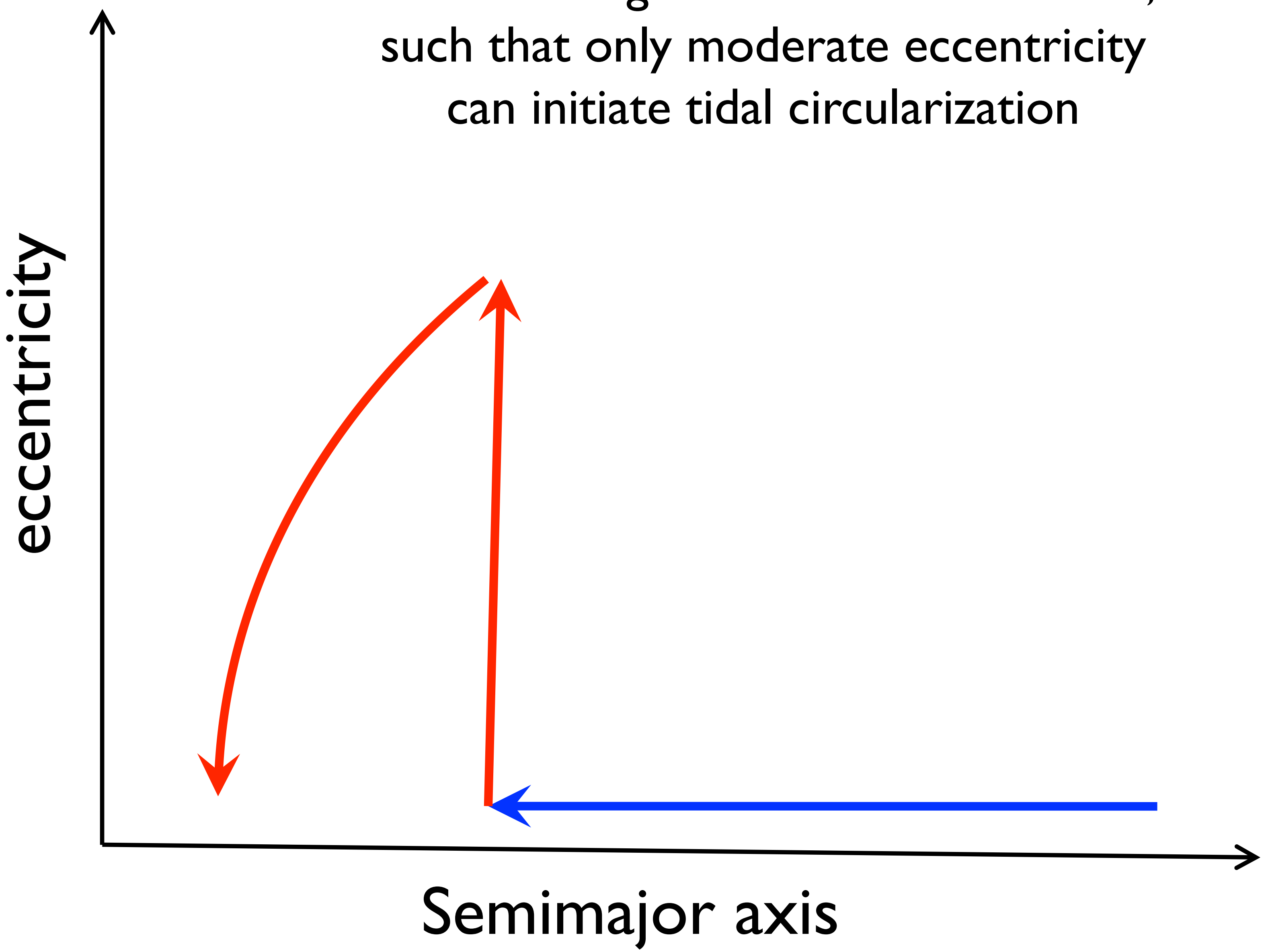


Where are the super-eccentric proto hot Jupiters?

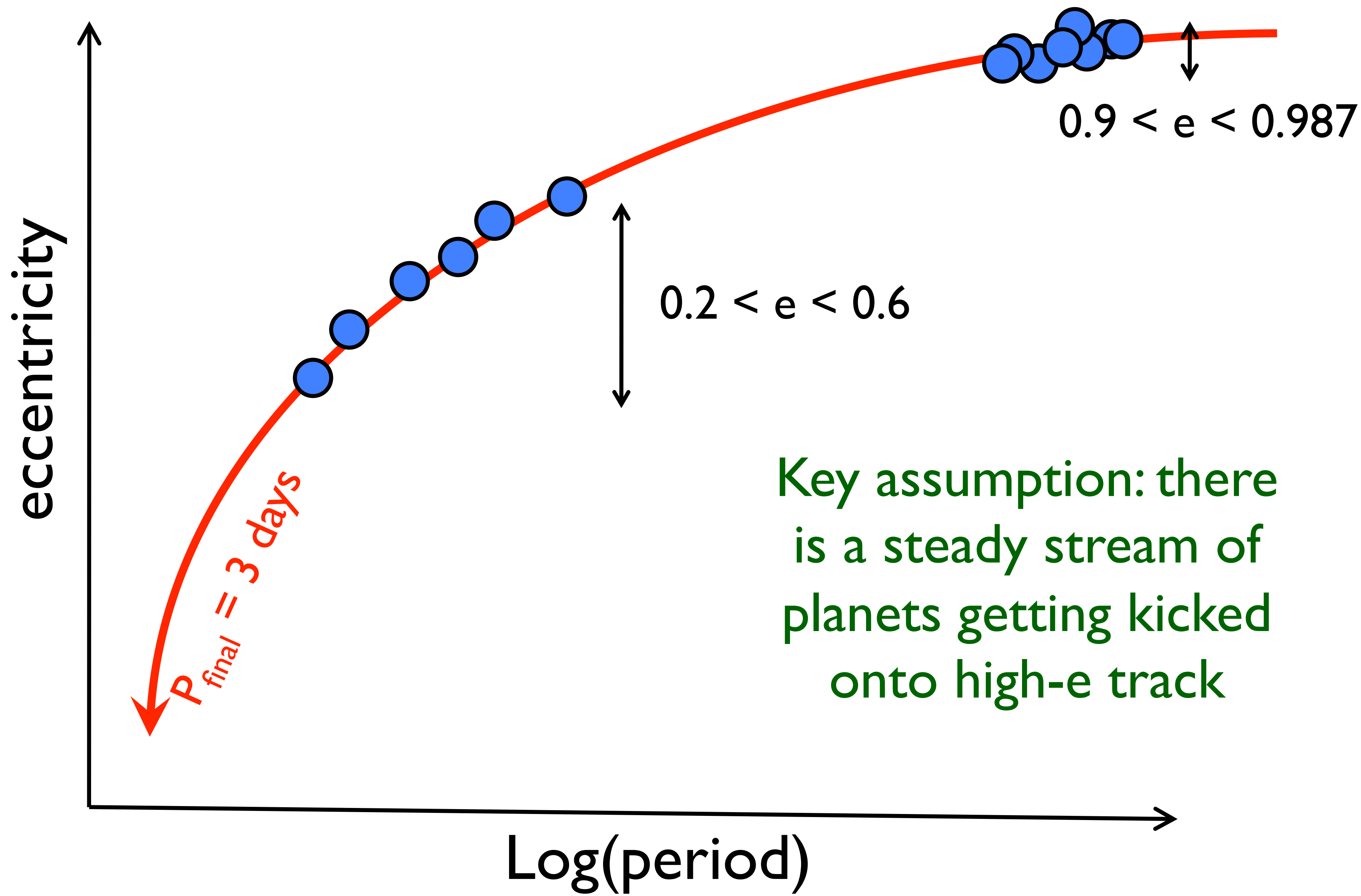
Explanation 1: The moderately eccentric Jupiters didn't travel along the high-eccentricity migration track



Explanation 2: Planets start their eccentric migration closer to the star, such that only moderate eccentricity can initiate tidal circularization



Explanation 3: There is no steady current of hot-Jupiter progenitors



Summary

- Hot Jupiters are rare, but provide a window into the dynamical processes that shape planetary systems
- Hot Jupiters are very frequently misaligned
- There is strong evidence of star-planet tidal-interactions
- However, we don't see a pileup of super-eccentric Jupiters in the *Kepler* sample

Thank you

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