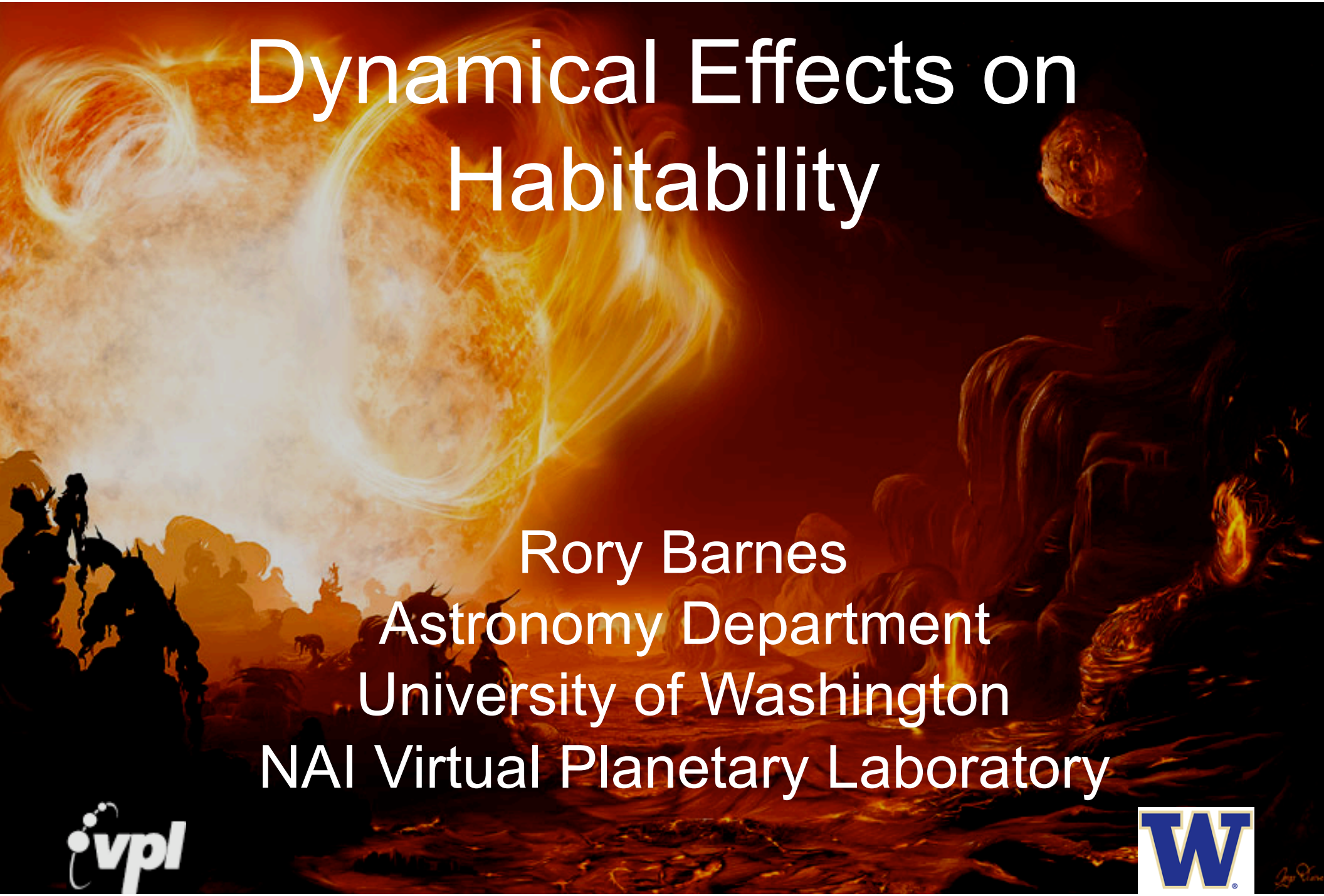

Dynamical Effects on Habitability

Rory Barnes
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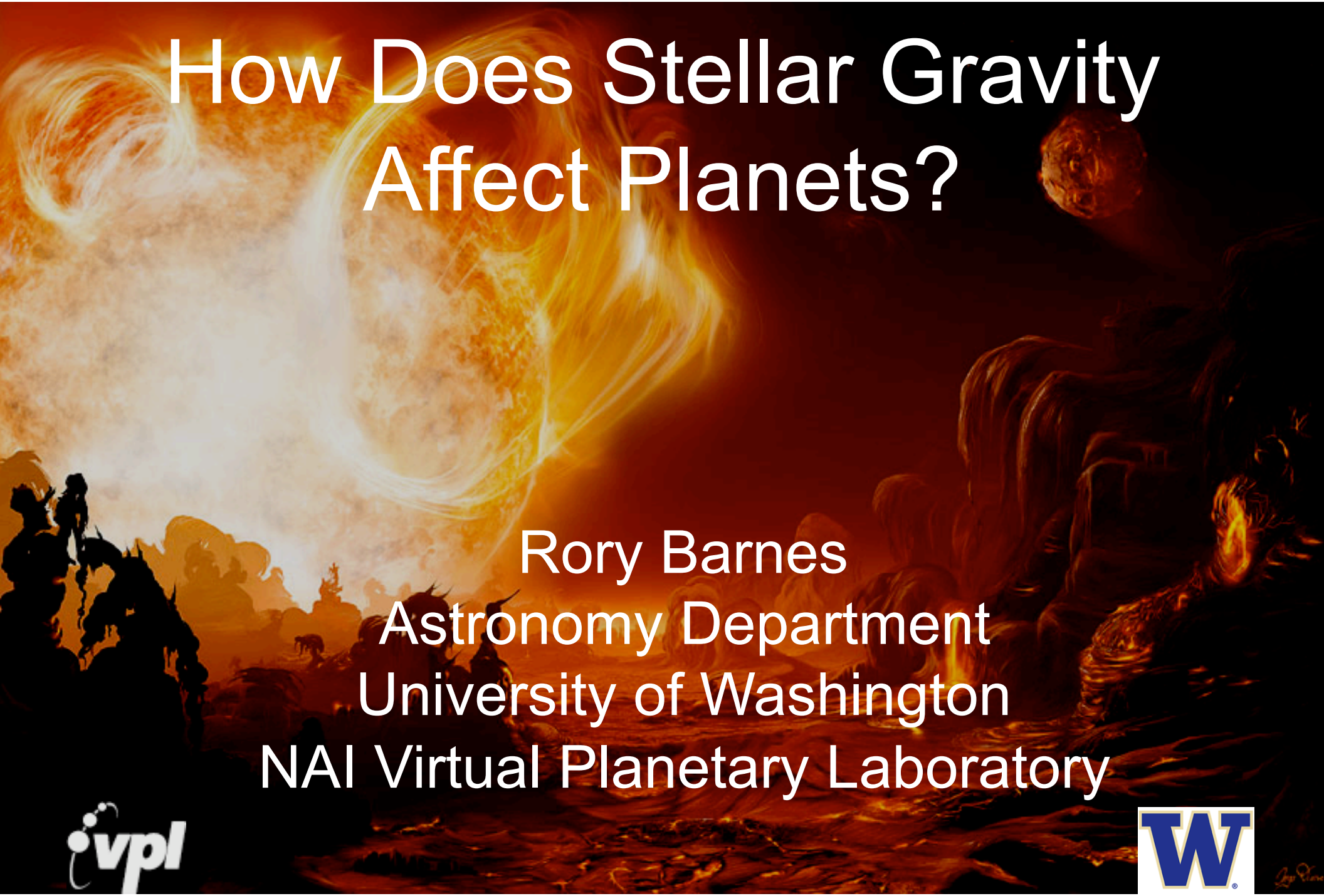
University of Washington
NAI Virtual Planetary Laboratory

How Does Stellar Gravity Affect Planets?

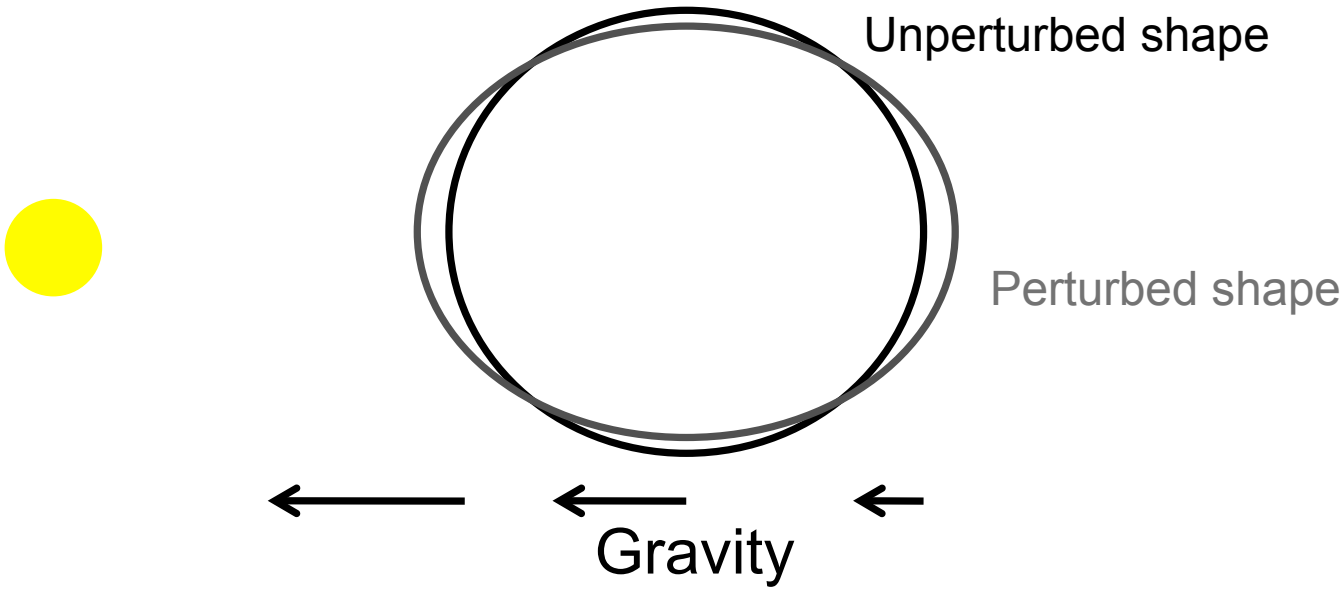
Rory Barnes
Astronomy Department
University of Washington
NAI Virtual Planetary Laboratory



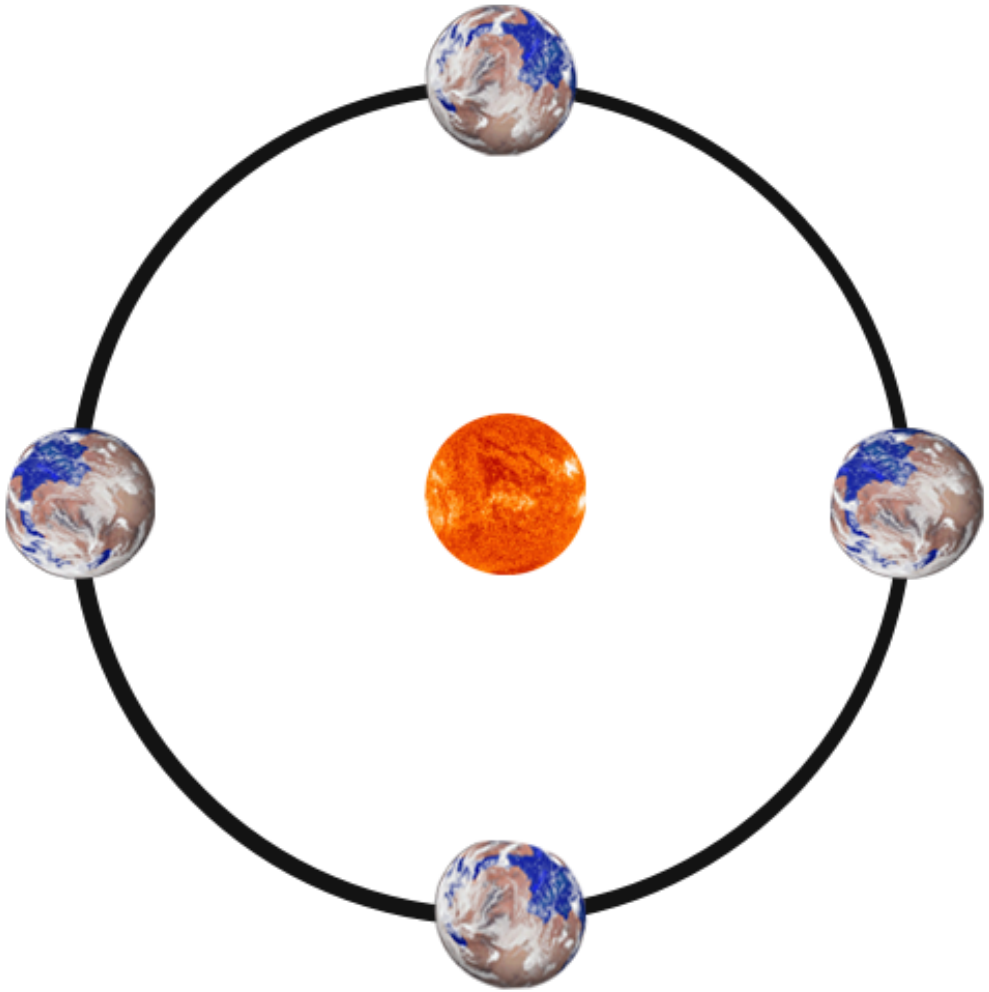
Tides

Close to a star, a planet feels a gravitational gradient

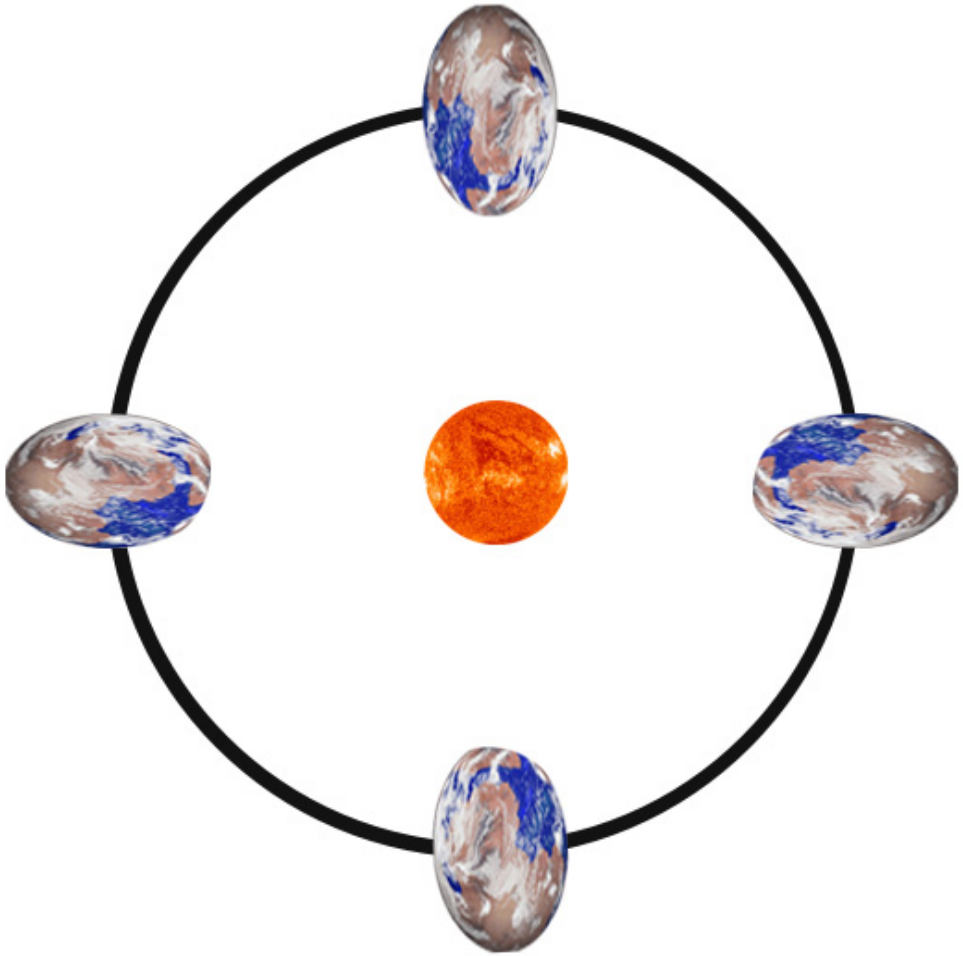
The planet resists, but it's shape is perturbed



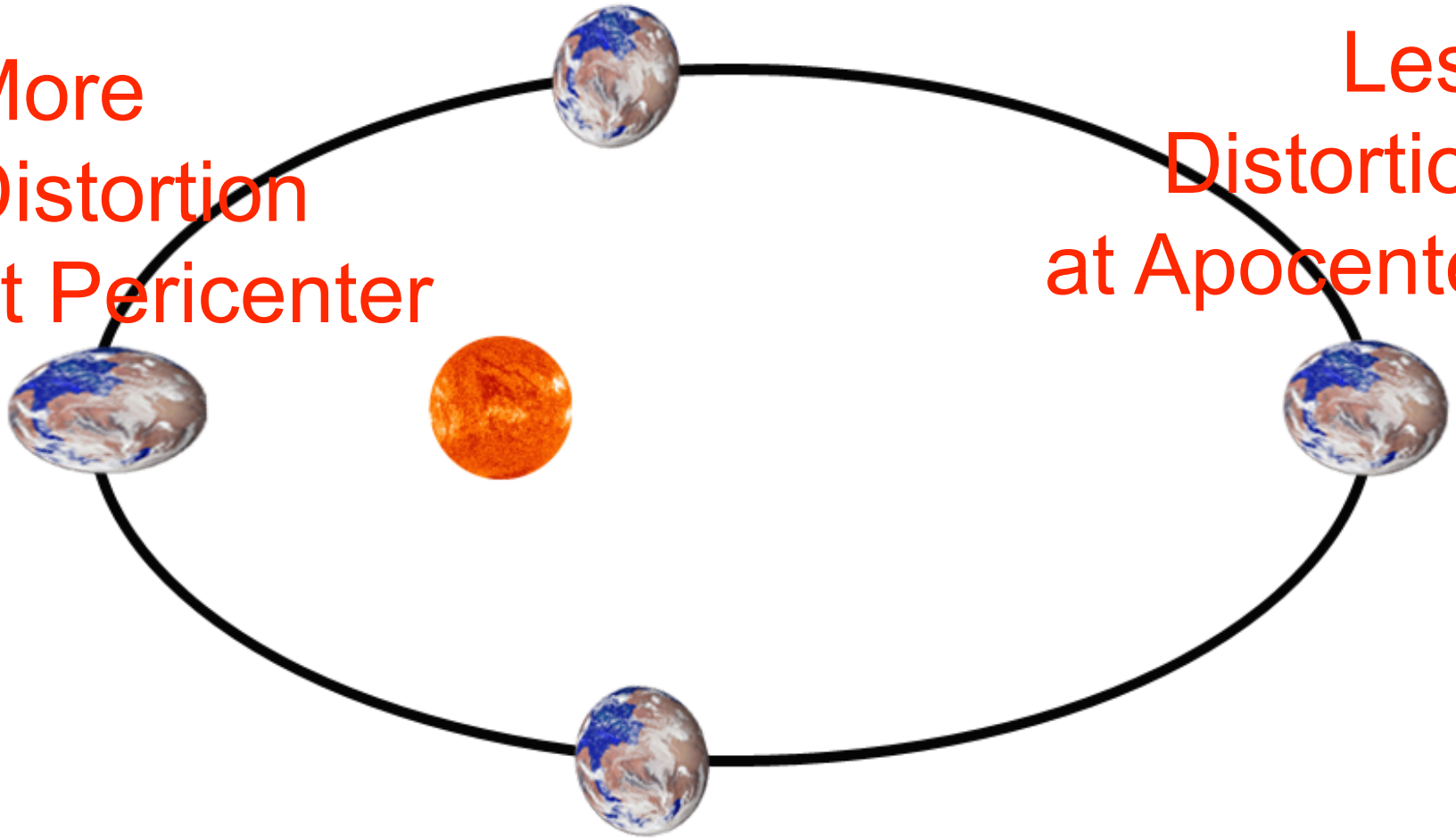
An Orbit with No Tides



An Orbit with Tides

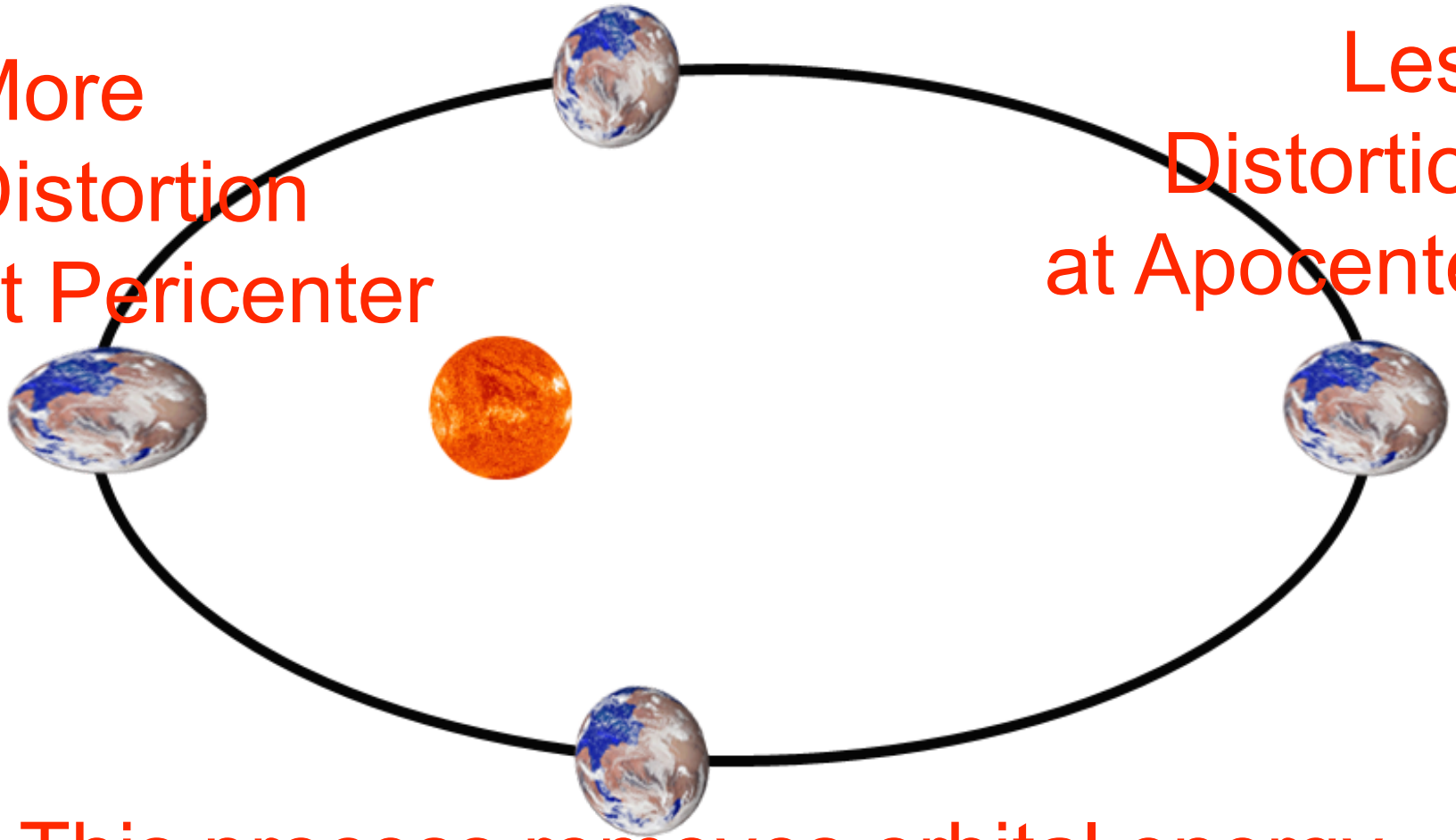


Effect of Eccentricity



Planet changes shape during orbit!

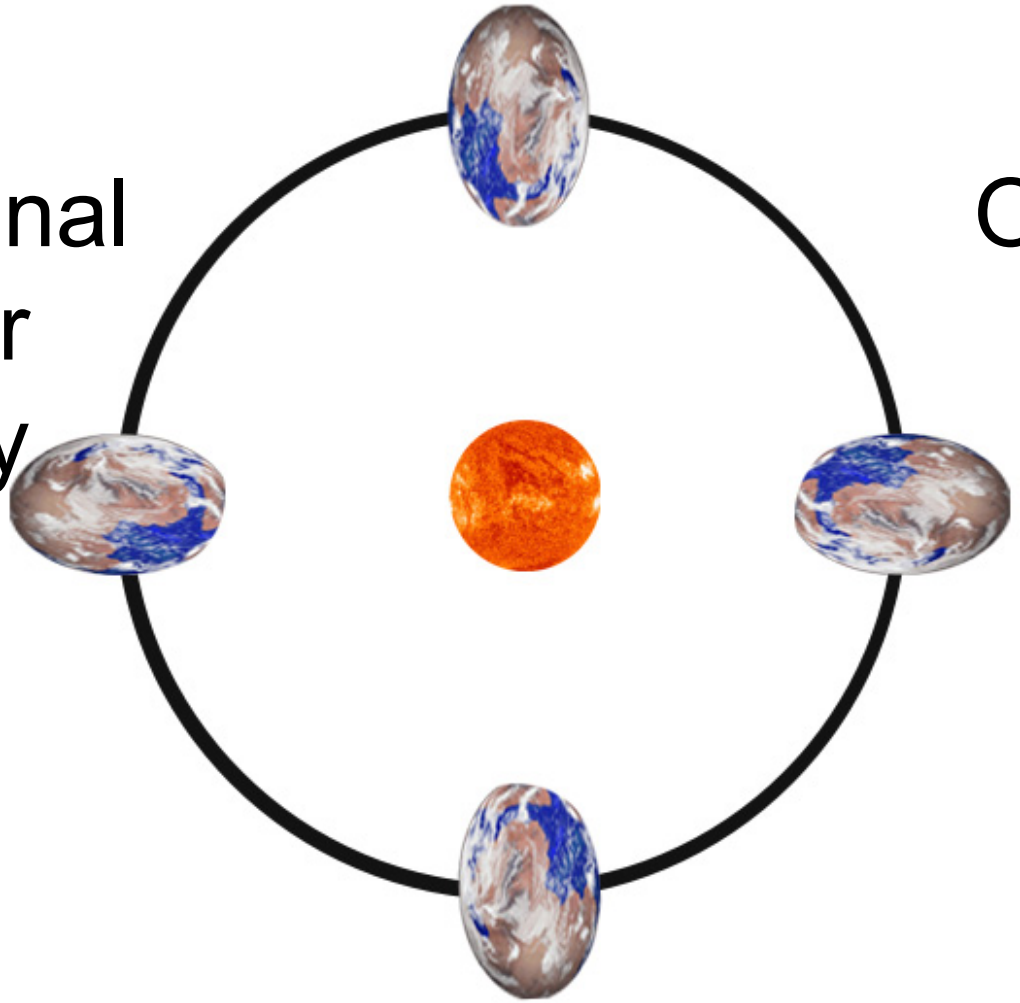
Tidal Heating



This process removes orbital energy
=> The orbit decays

Rotation is Controlled by Bulge

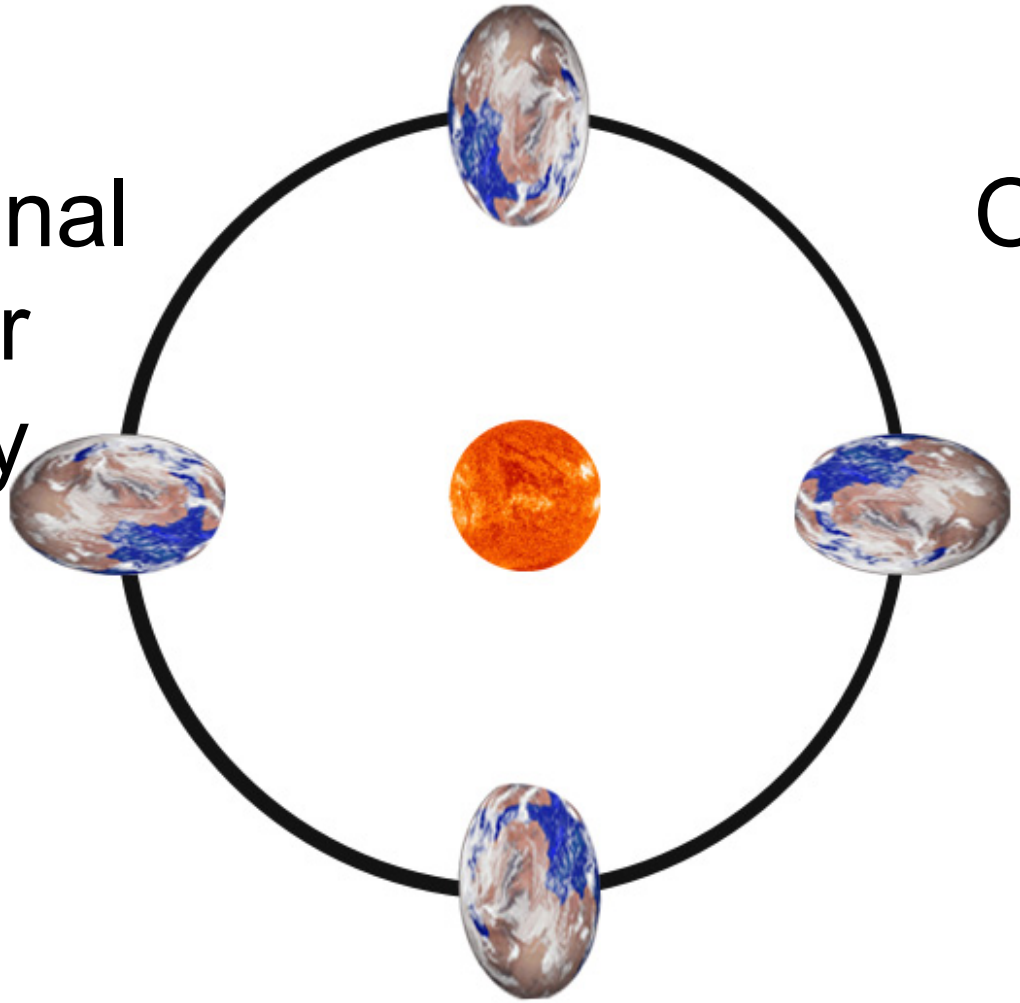
Rotational Angular Velocity Ω



Orbital Angular Velocity n

Rotation is Controlled by Bulge

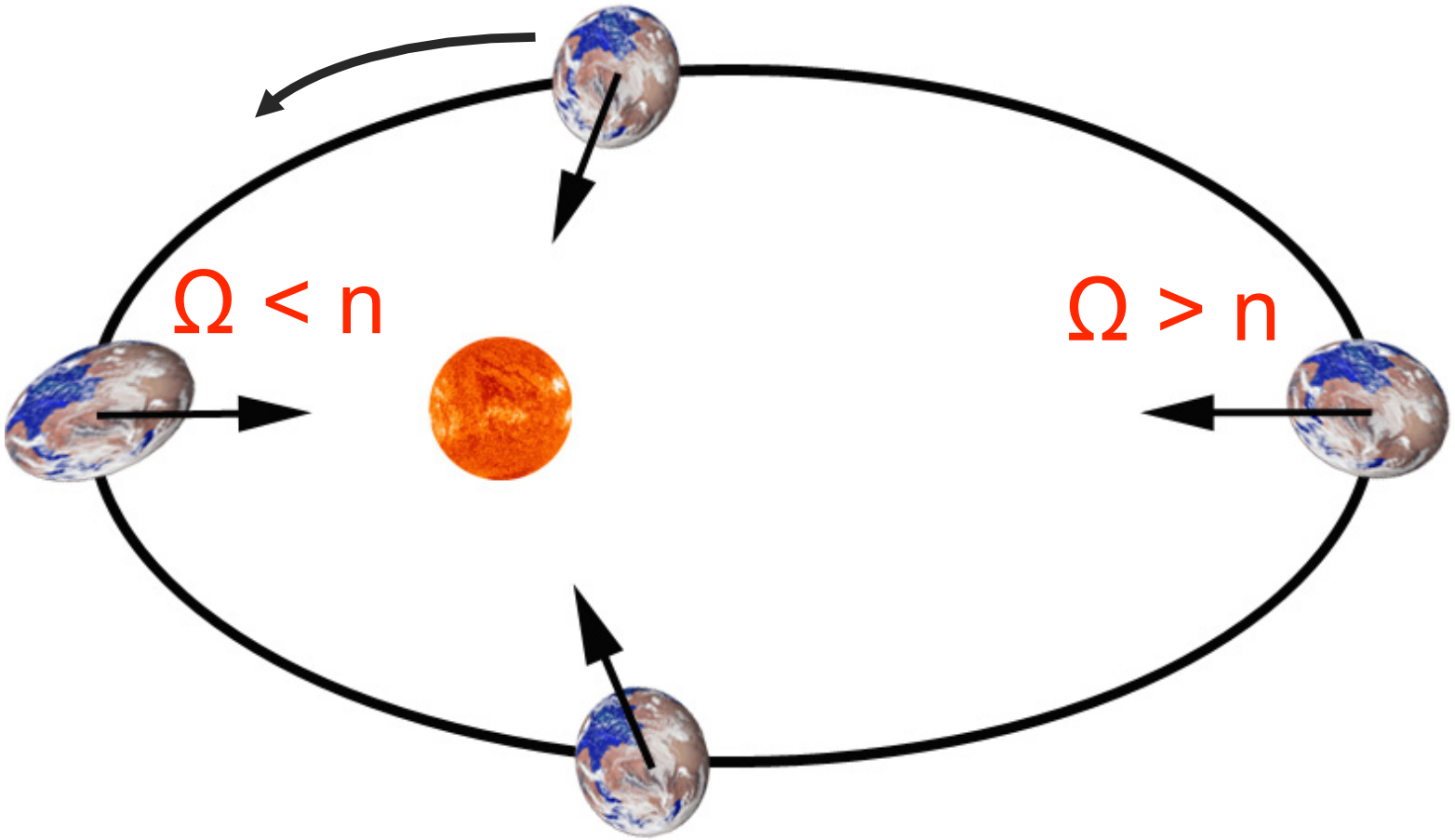
Rotational Angular Velocity Ω



Orbital Angular Velocity n

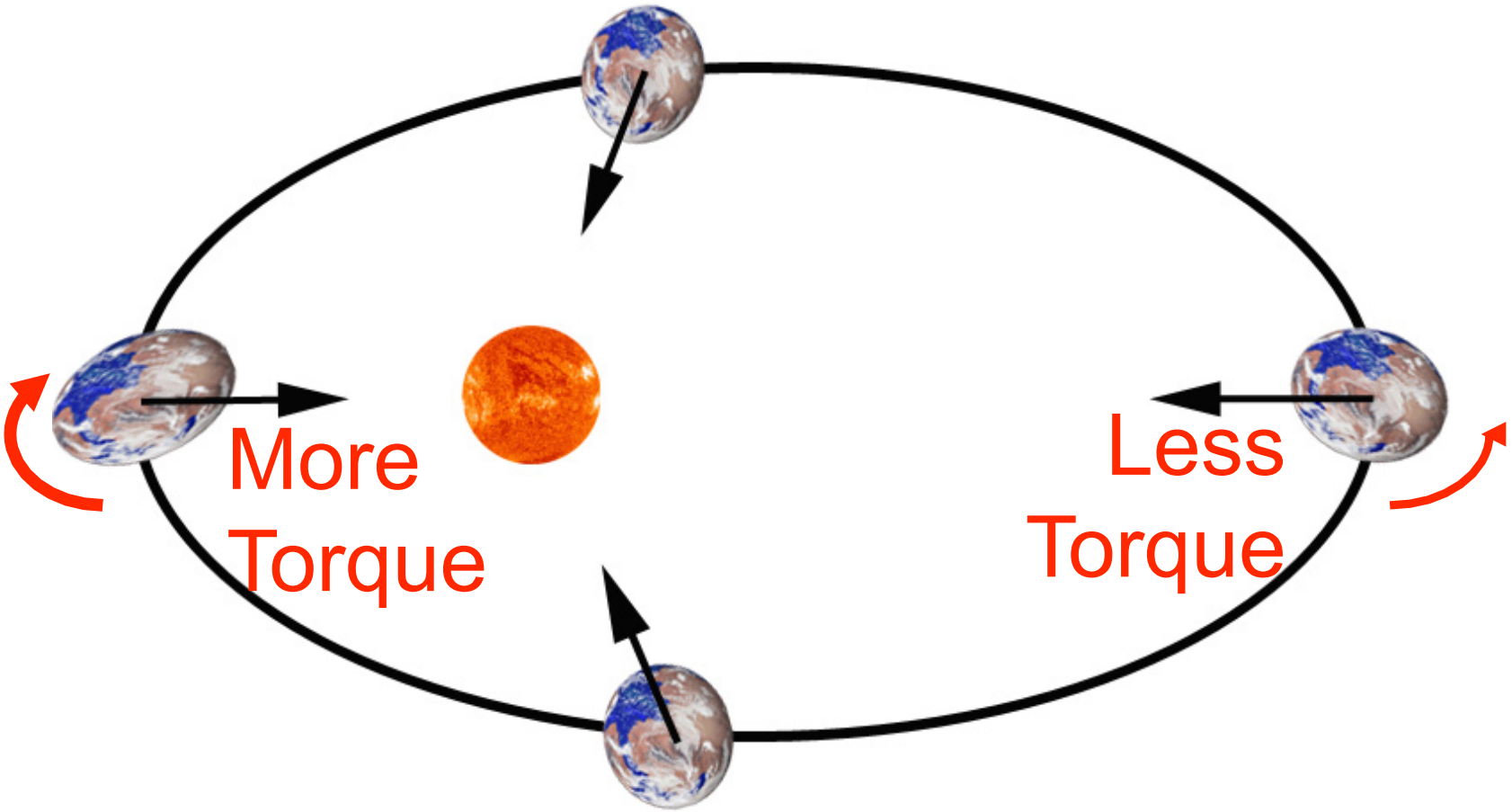
Circular orbit => Synchronous Rotation

Tidal Locking



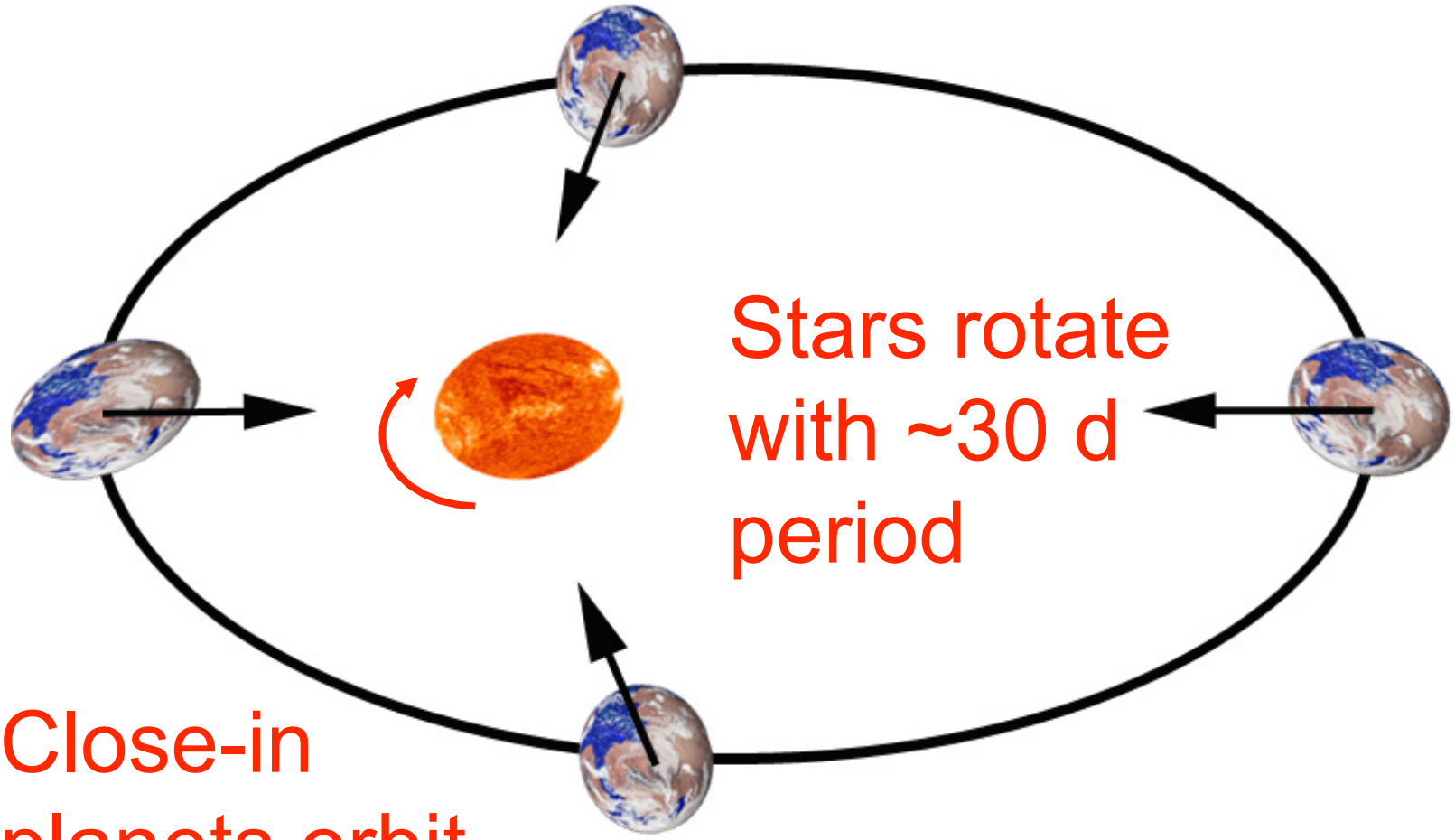
At peri, the planet rotates slower than it orbits
At apo, it rotates faster

Tidal Locking



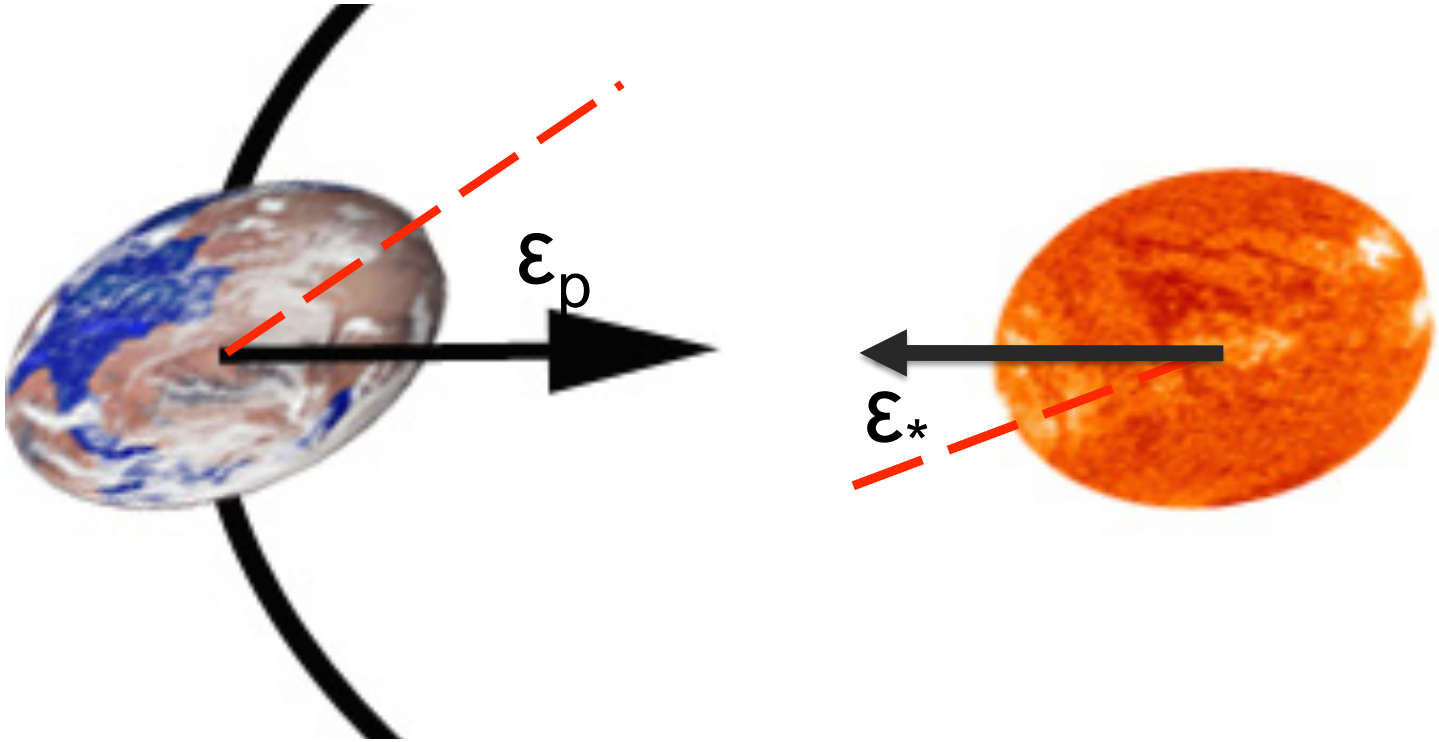
Tidal locking = Rotation controlled by bulge
Rotation is faster than synchronous (e>0)

The Star is Torqued Too



The Magnitude of Tidal Evolution

The bulges lag the pertruber by angle ε

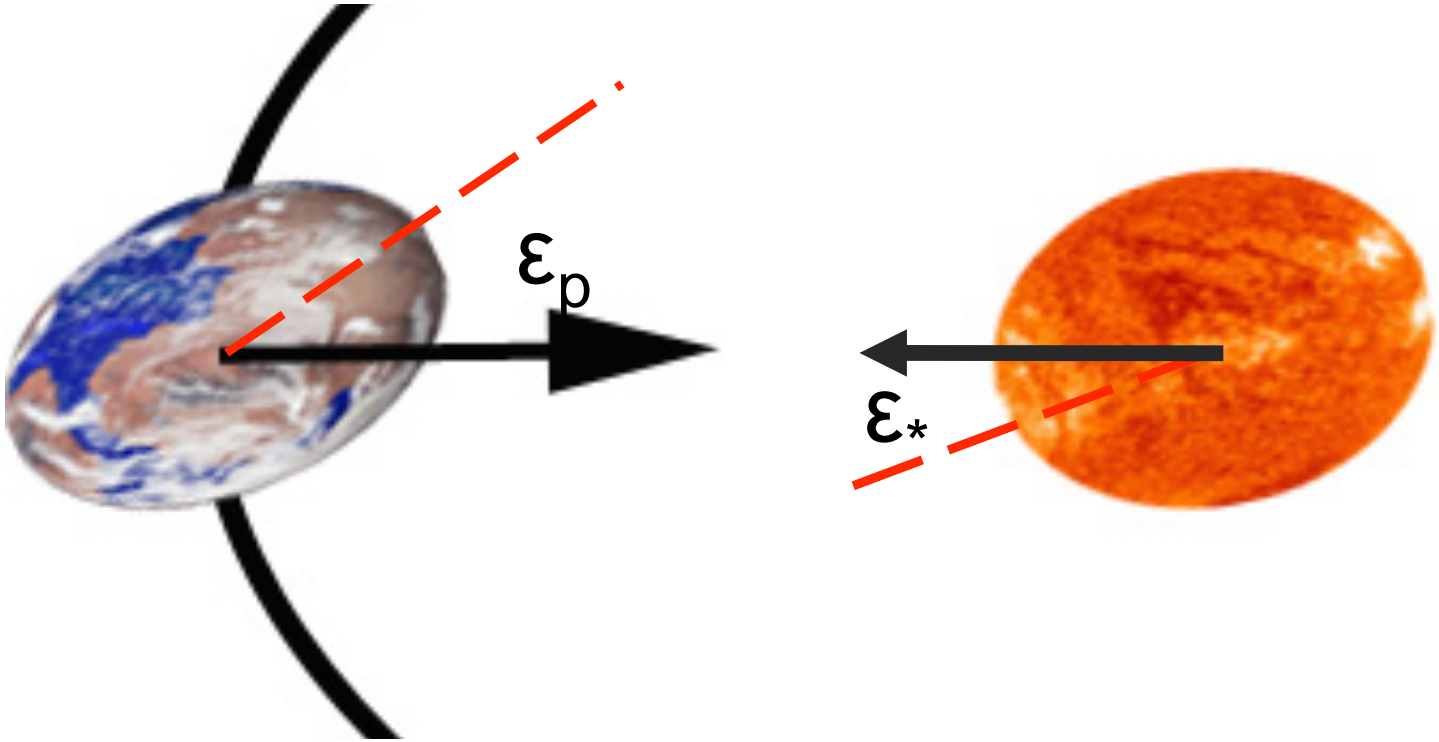


ε depends on internal structure

This is a poor approximation!

The Magnitude of the Tidal Evolution

Usually we talk about “tidal Q” = 1/ε



$Q_{terrestrial} \sim 100$

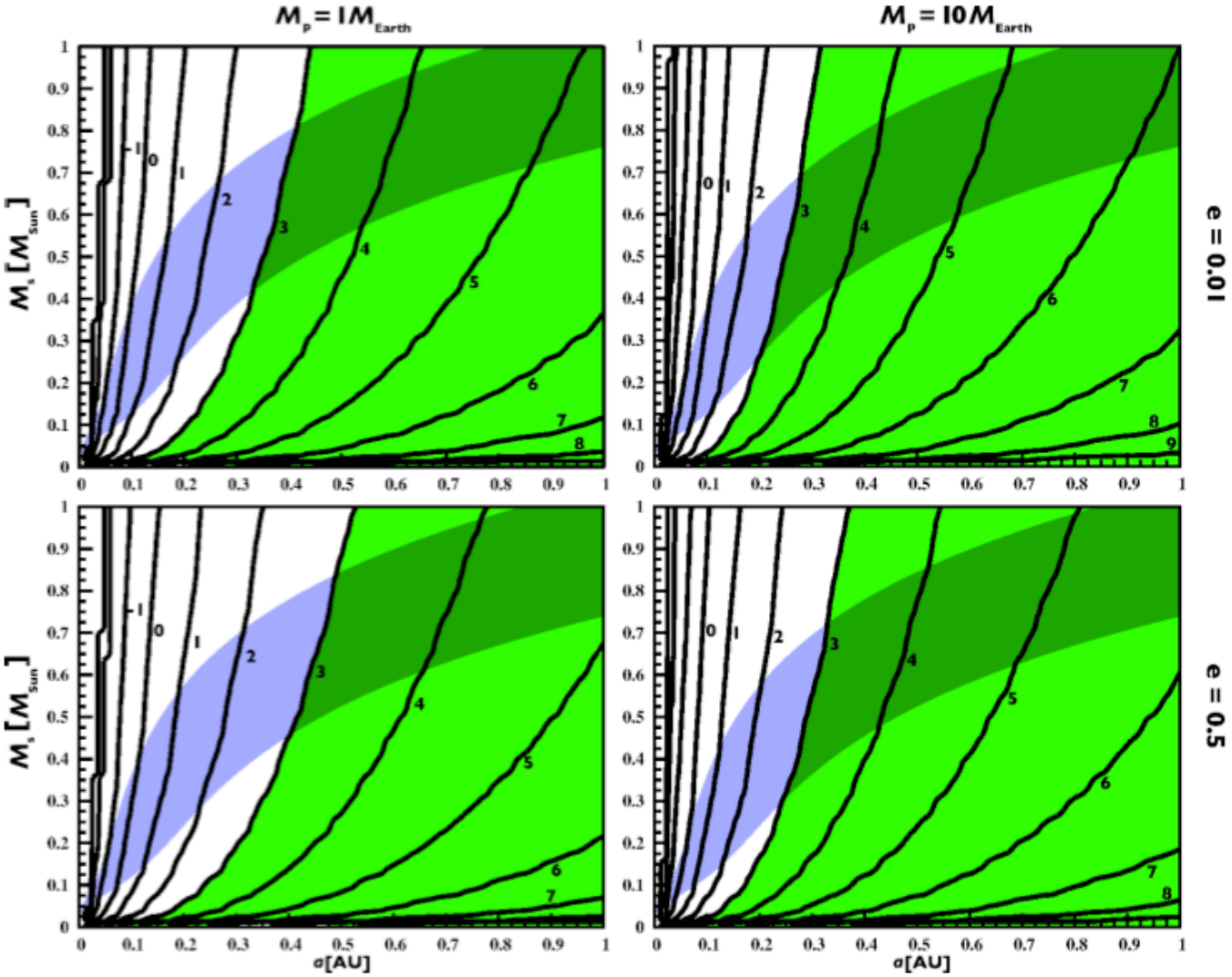
$Q_* \sim 10^6$

Initial Conditions to Tidal Locking

Rotation (rate and tilt) set at last major impact
Obliquities driven to 0 or π
Rotation rate driven to equilibrium
    (synchronous if e=0)
When these conditions are met, the planet is
    “tidally locked” (planetary rotation irrelevant)
Further evolution requires e ≠ 0, or tides raised
    on the star

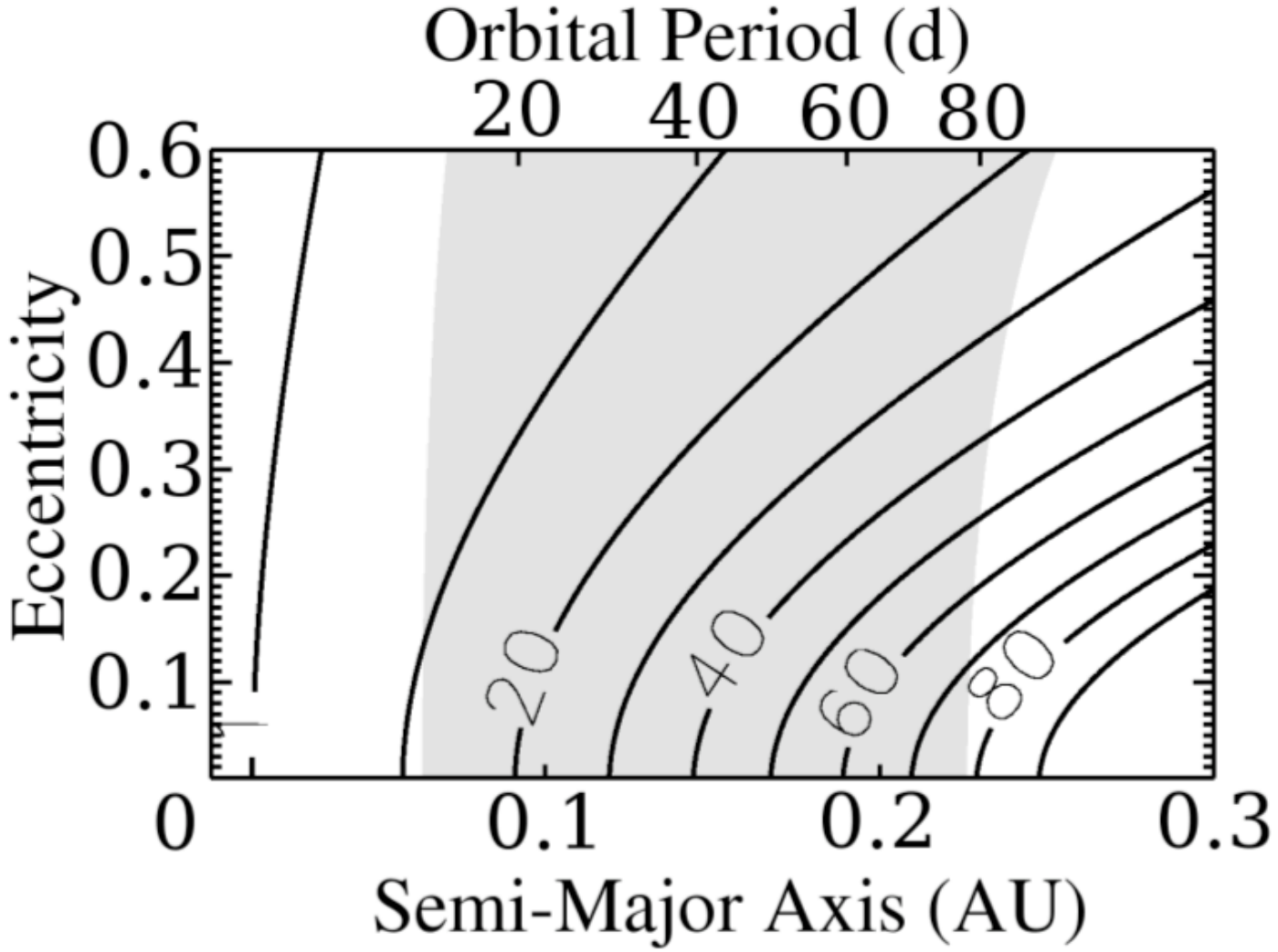
Obliquities →0 (or π)

Time (Gyr) to go from 23.5 to 5 degrees



Heller, Leconte & Barnes, in prep

Equilibrium Rotation Periods (10 M_E, 0.25 M_S)



Barnes *et al.* (2010)

Orbital Evolution

Energy dissipated => *a* decreases

Ang. mom. transferred => e decreases

Assume bulge modeled by linear superposition of spherical harmonics

Assume ε is (in)dependent of frequency

Calculate gravitational forces between bulges

Transform into orbital elements to obtain rates of change of *a* and *e*

Tidal Evolution

Energy dissipated => *a* decreases
Ang. mom. transferred => e decreases

Lots of dubious assumptions
&
Lots of math

$$\frac{da}{dt} = -\left(\frac{63}{2}\frac{\sqrt{GM_*^3}R_p^5}{m_p Q_p'}e^2 + \frac{9}{2}\frac{\sqrt{G/M_*}R_*^5 m_p}{Q_*'}\left[1+\frac{57}{4}e^2\right]\right)a^{-11/2}$$

$$\frac{de}{dt} = -\left(\frac{63}{4}\frac{\sqrt{GM_*^3}R_p^5}{m_p Q_p'} + \frac{225}{16}\frac{\sqrt{G/M_*}R_*^5 m_p}{Q_*'}\right)a^{-13/2}e$$

Tidal Evolution

Tide raised on star

Tide raised on planet

$$\frac{da}{dt} = -\left(\frac{63}{2}\frac{\sqrt{GM_*^3}R_p^5}{m_p Q'_p}e^2 + \frac{9}{2}\frac{\sqrt{G/M_*}R_*^5 m_p}{Q'_*}\left[1+\frac{57}{4}e^2\right]\right)a^{-11/2}$$

$$\frac{de}{dt} = -\left(\frac{63}{4}\frac{\sqrt{GM_*^3}R_p^5}{m_p Q'_p} + \frac{225}{16}\frac{\sqrt{G/M_*}R_*^5 m_p}{Q'_*}\right)a^{-13/2}e$$

Tidal Evolution

Tide raised on star

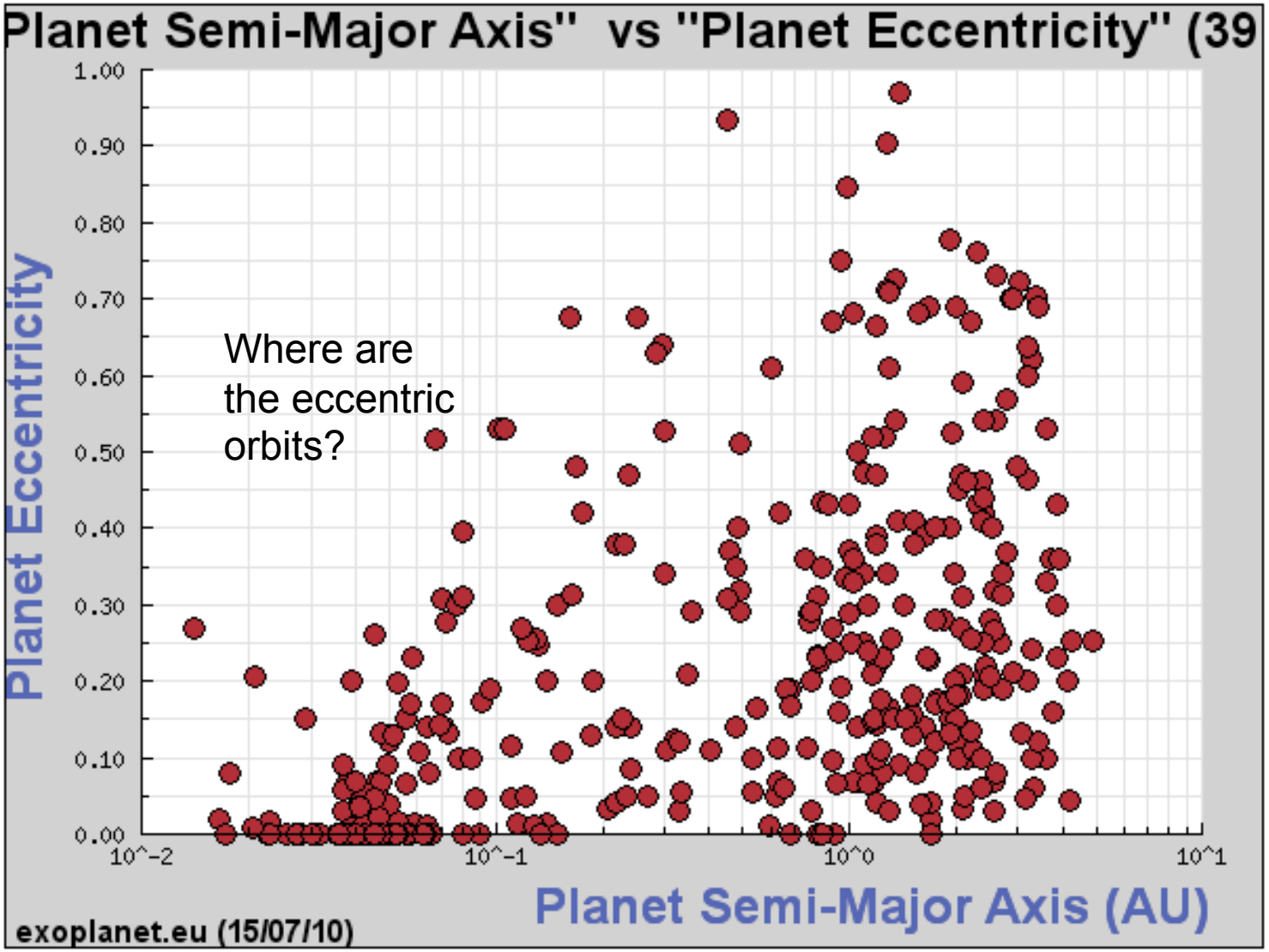
Tide raised on planet

$$\frac{da}{dt} = -\left(\frac{63}{2}\frac{\sqrt{GM_*^3}R_p^5}{m_p Q'_p}e^2 + \frac{9}{2}\frac{\sqrt{G/M_*}R_*^5 m_p}{Q'_*}\left[1 + \frac{57}{4}e^2\right]\right)a^{-11/2}$$

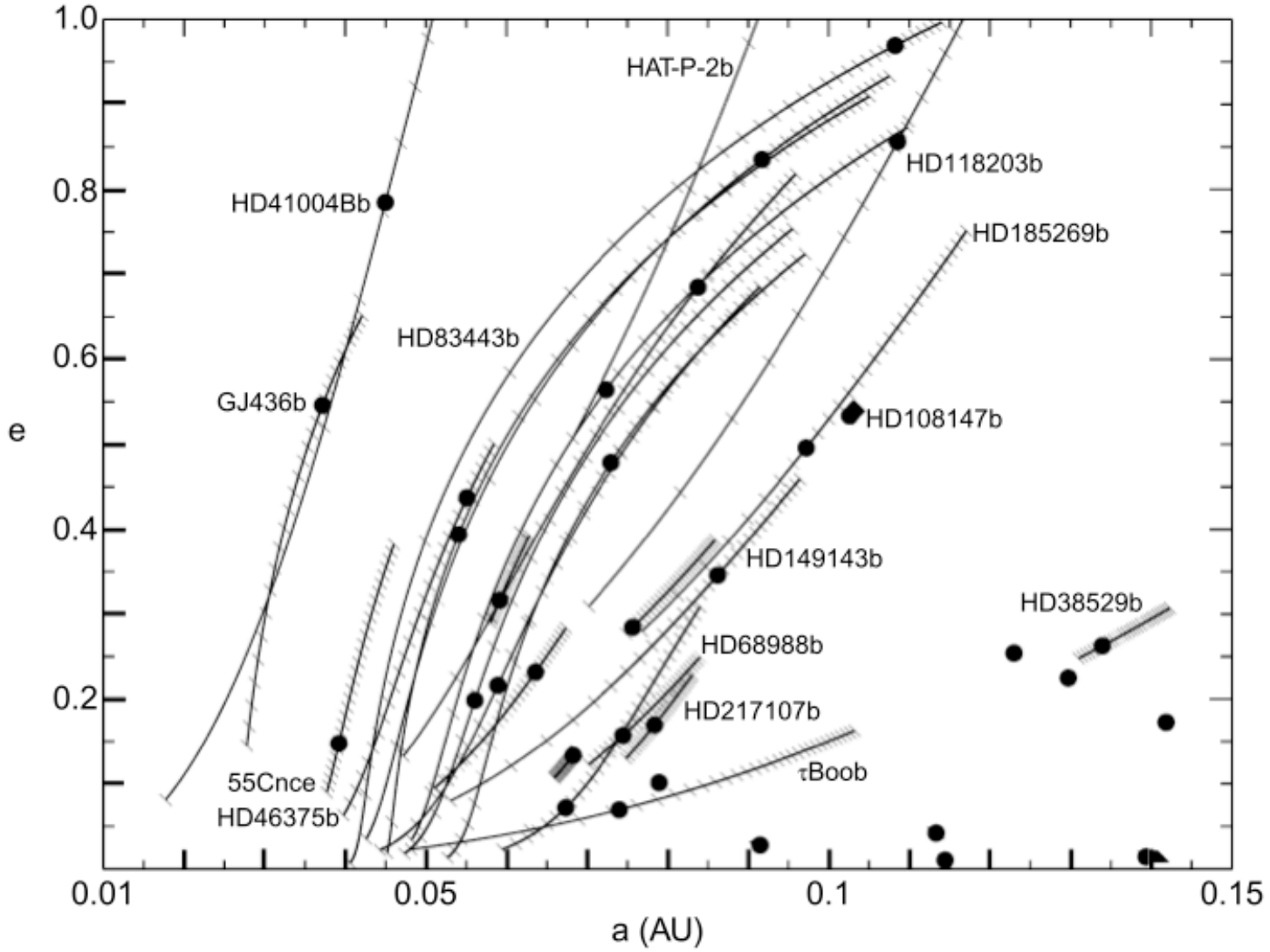
$$\frac{de}{dt} = -\left(\frac{63}{4}\frac{\sqrt{GM_*^3}R_p^5}{m_p Q'_p} + \frac{225}{16}\frac{\sqrt{G/M_*}R_*^5 m_p}{Q'_*}\right)a^{-13/2}e$$

Strong dependence on *a*

Hot Jupiters have Circular Orbits

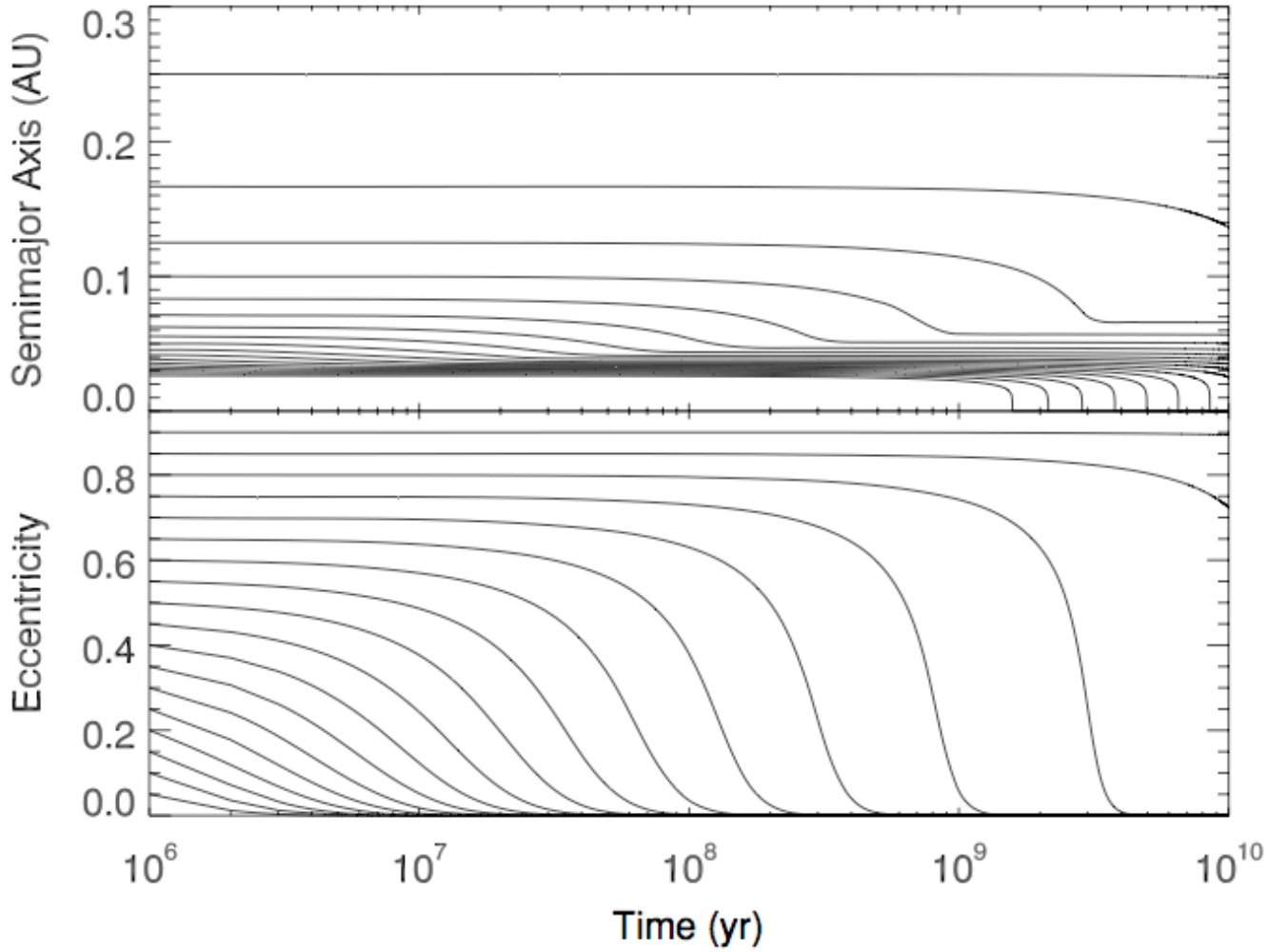


Tidal Evolution of Exoplanets



Jackson, Greenberg & Barnes (2008)

Tidal Destruction of Planets

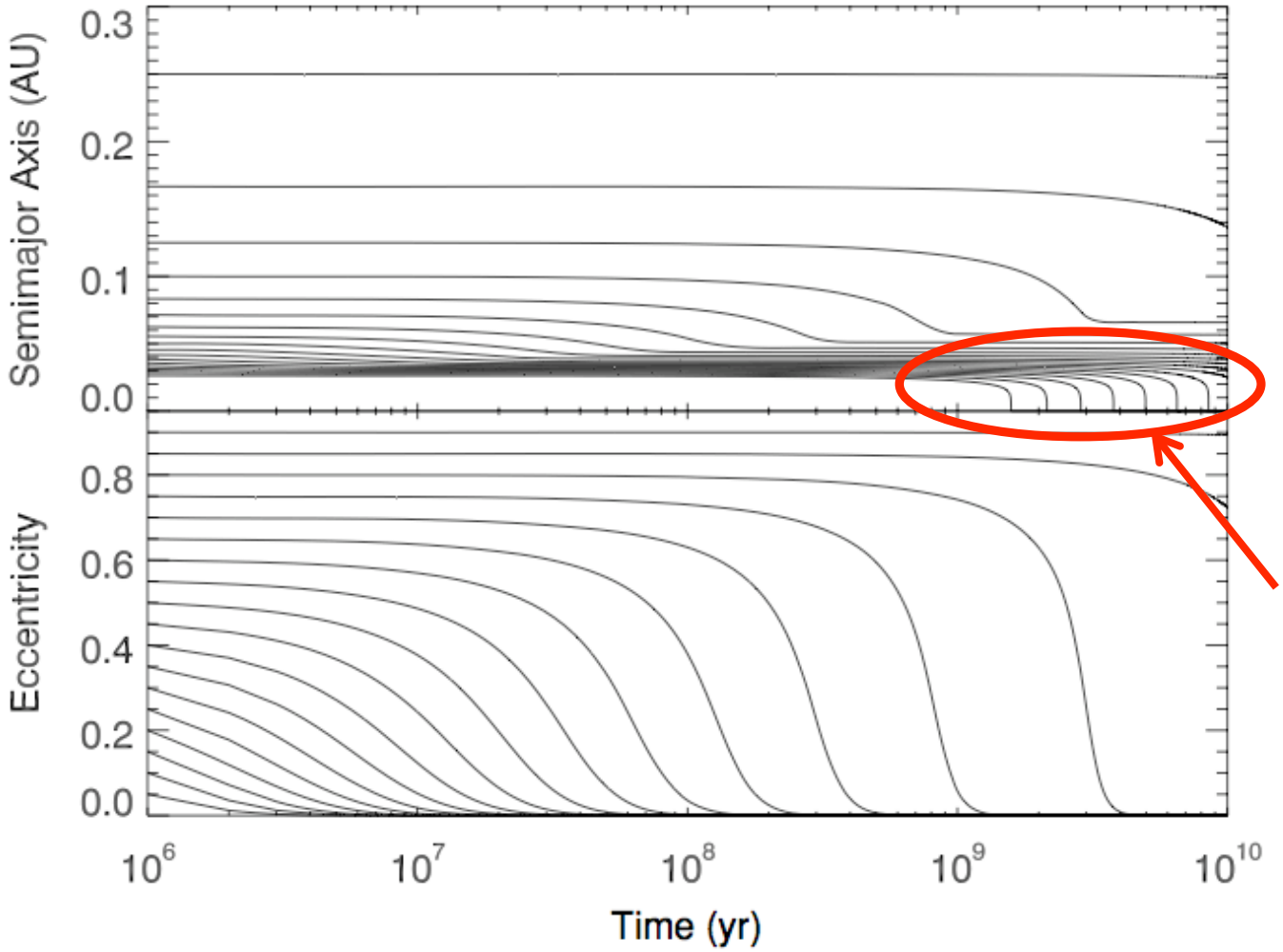


5 M_{Earth}
1 M_{sun}

Initial peri
@ 0.25AU

Raymond, Barnes & Mandell (2008)

Tidal Destruction of Planets

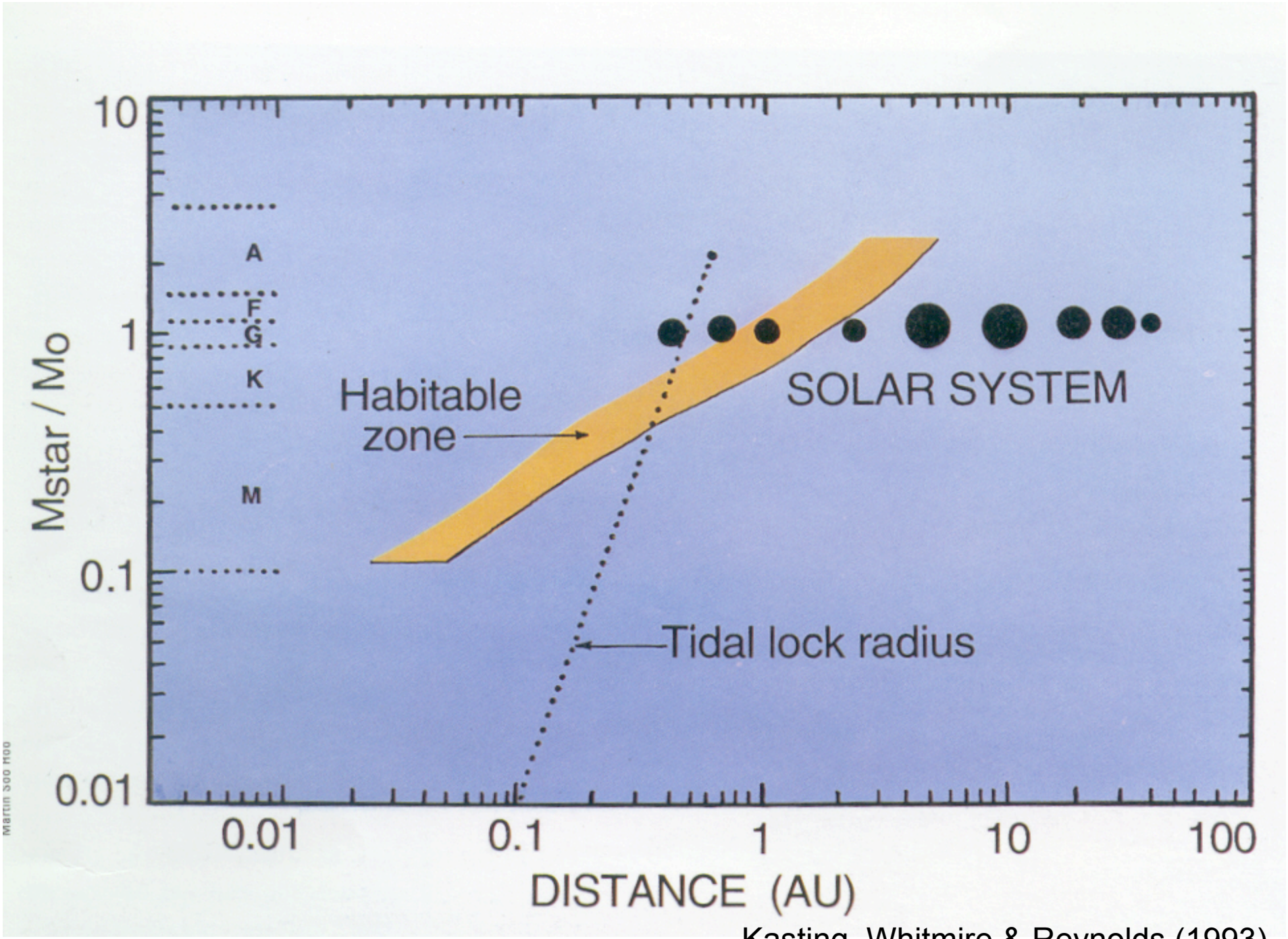


5 M_{Earth}
1 M_{sun}

Initial peri
@ 0.25AU

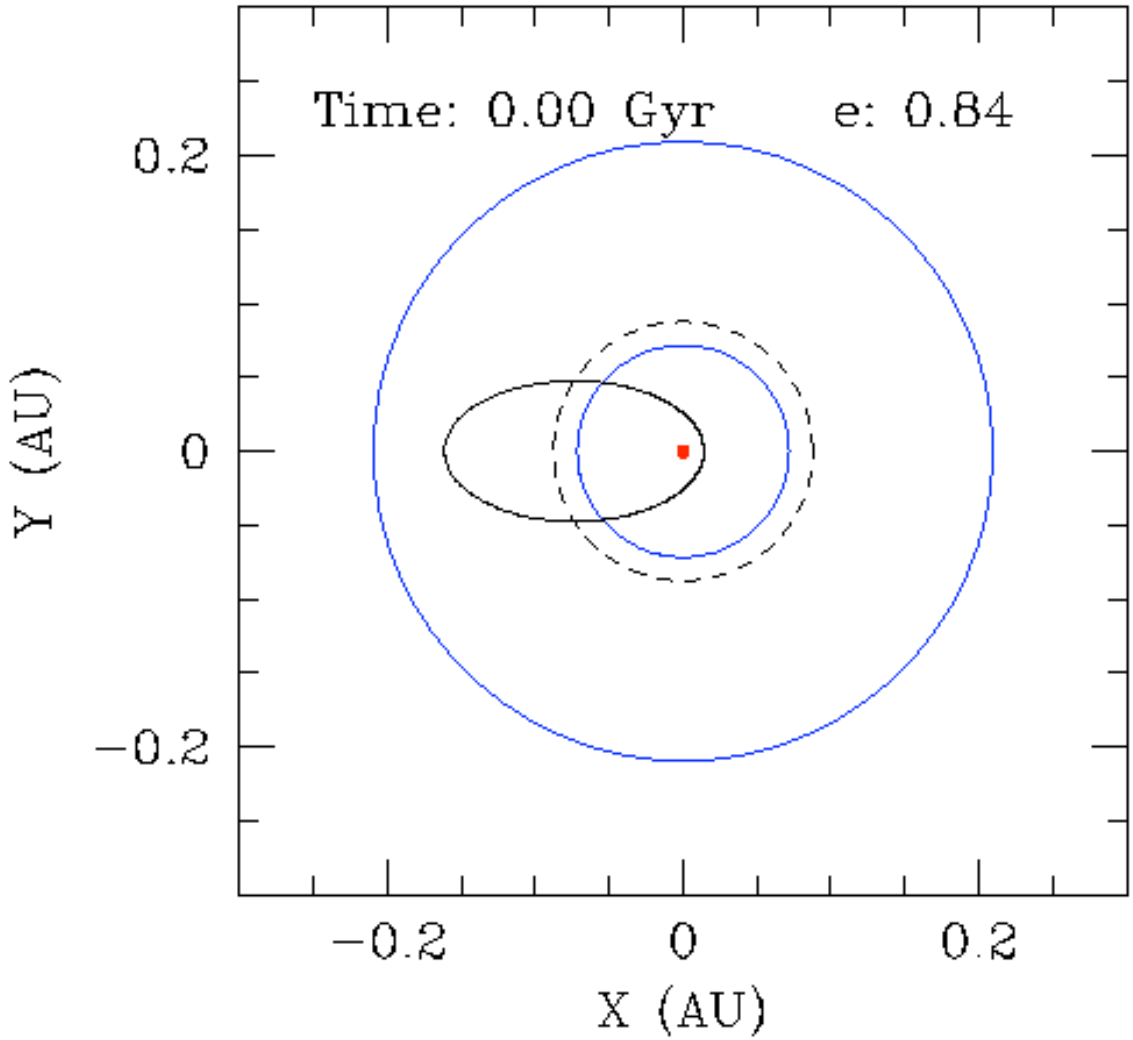
These planets are destroyed!

Ryamond, Barnes & Mandell (2008)



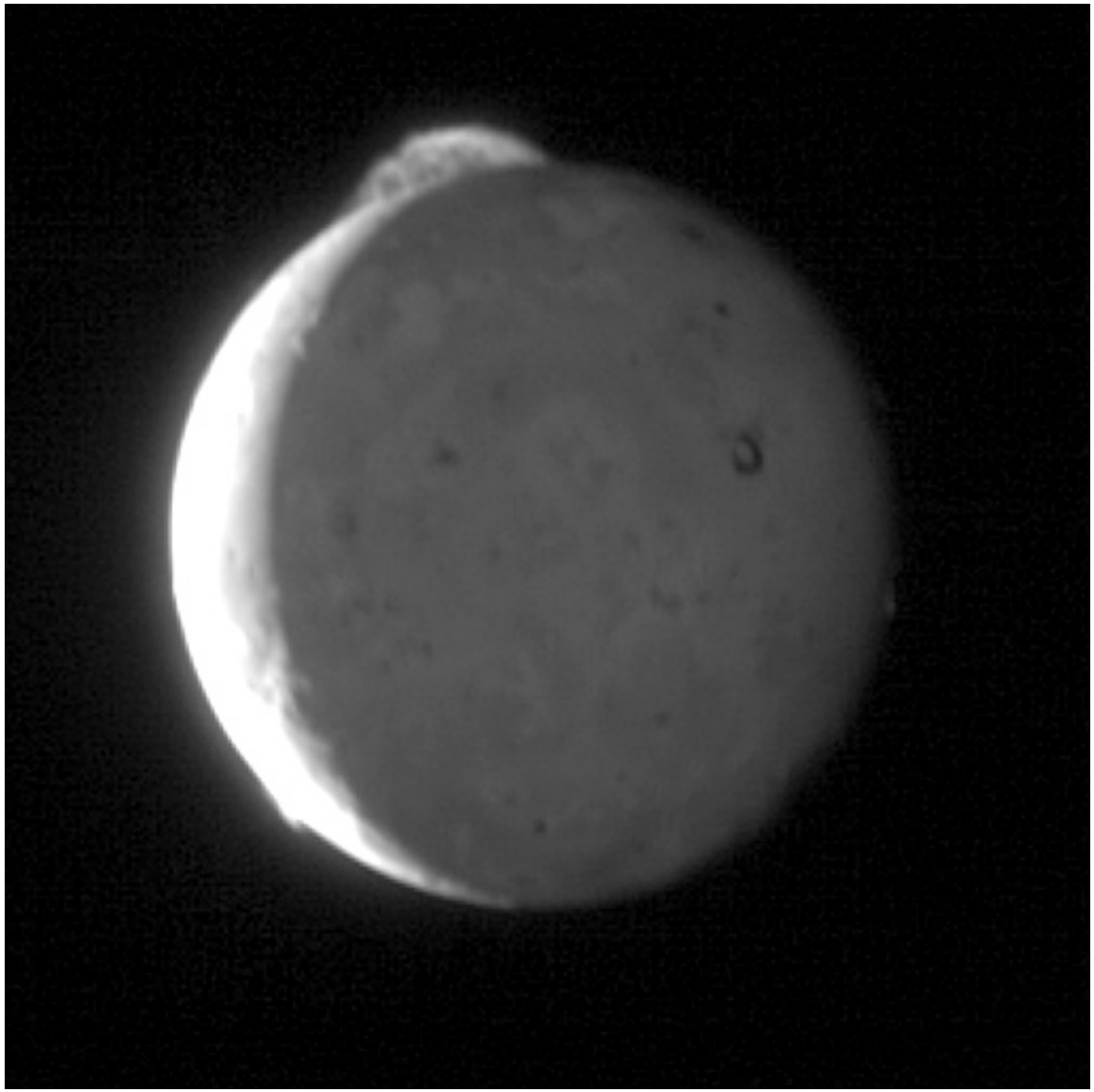
Kasting, Whitmire & Reynolds (1993)

10 M_E Planet Orbiting a 0.15 M_S Star

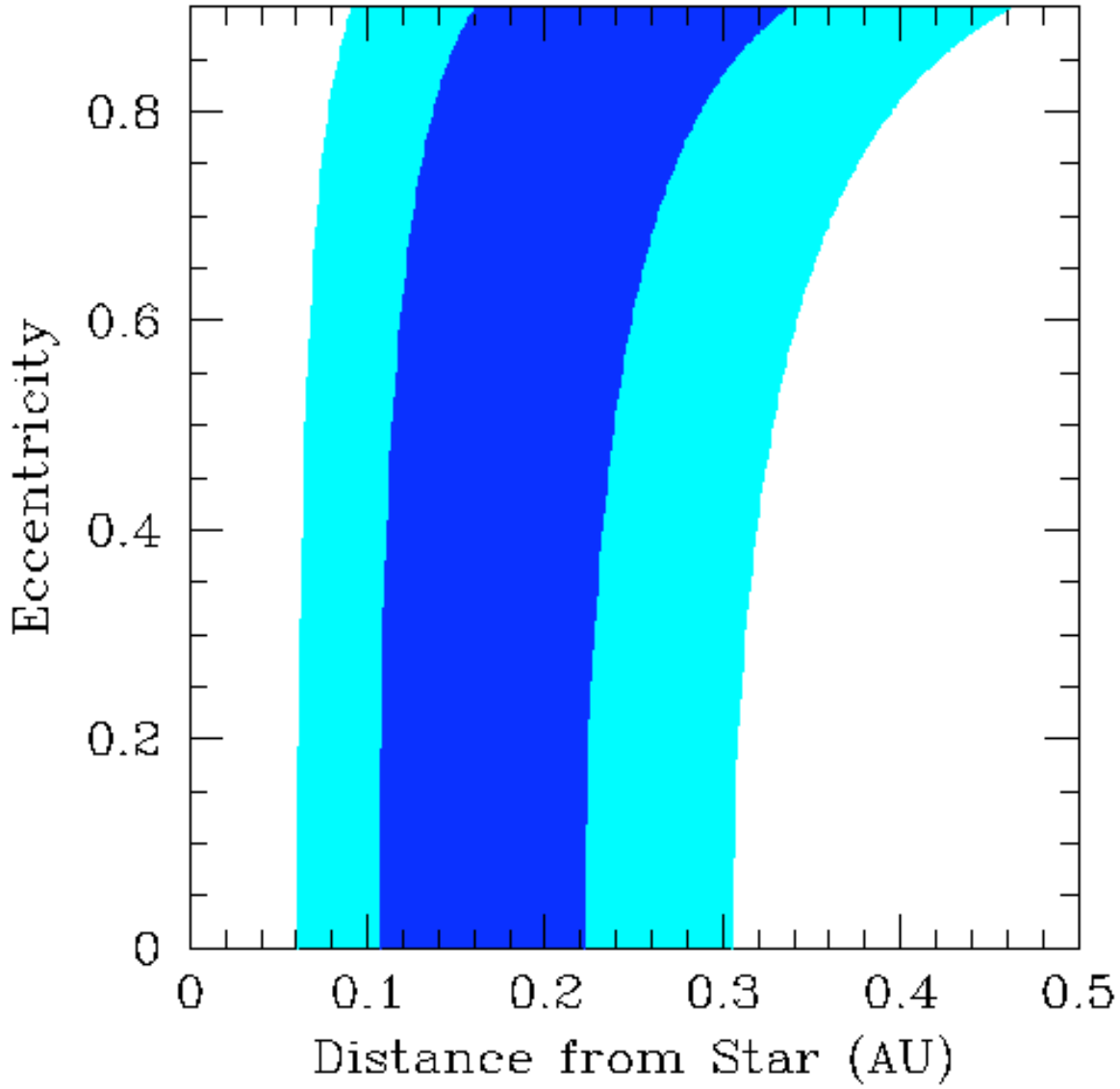


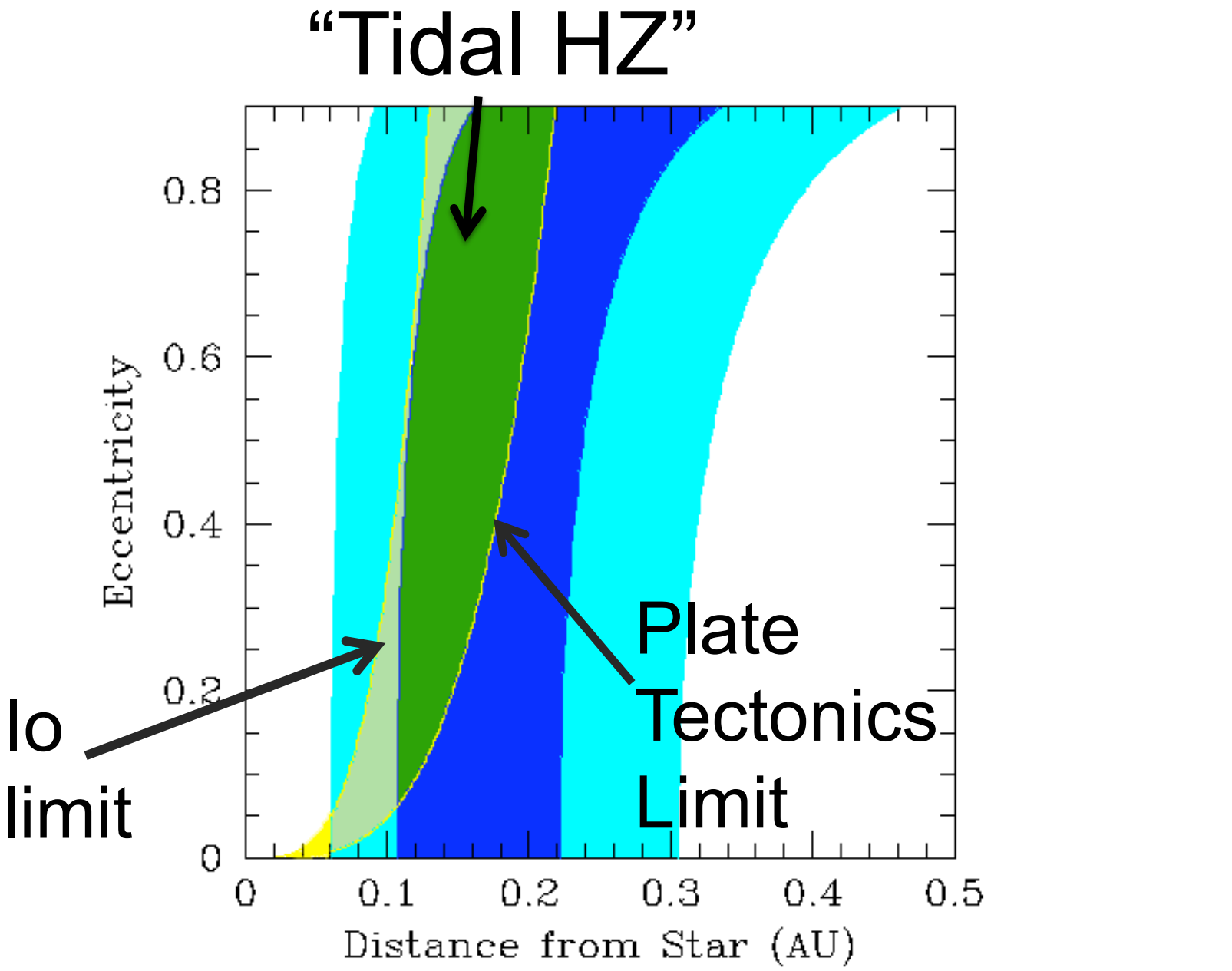
Barnes *et al.* (2008)

Tidal Heating also Important!

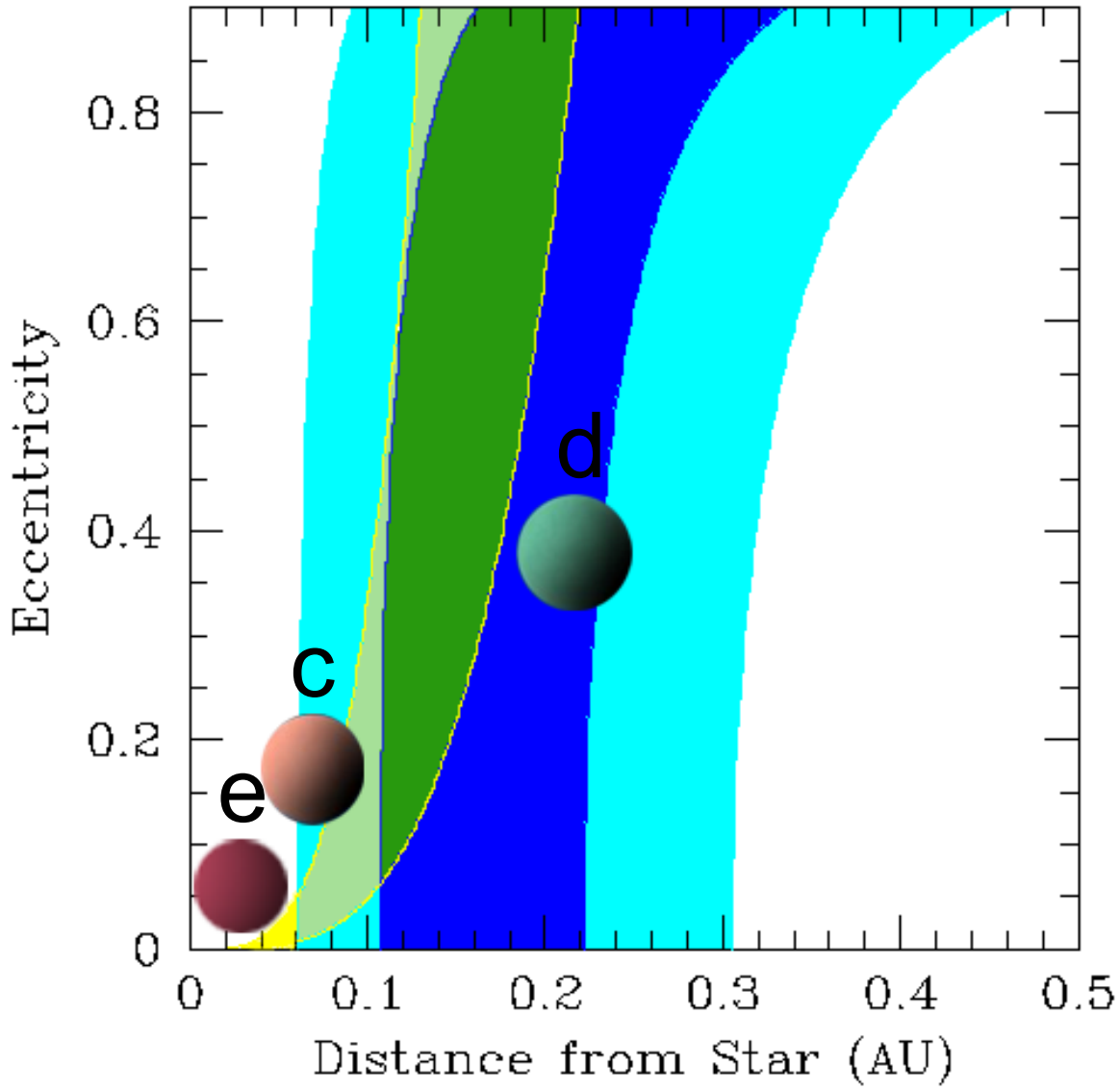


Gl 581

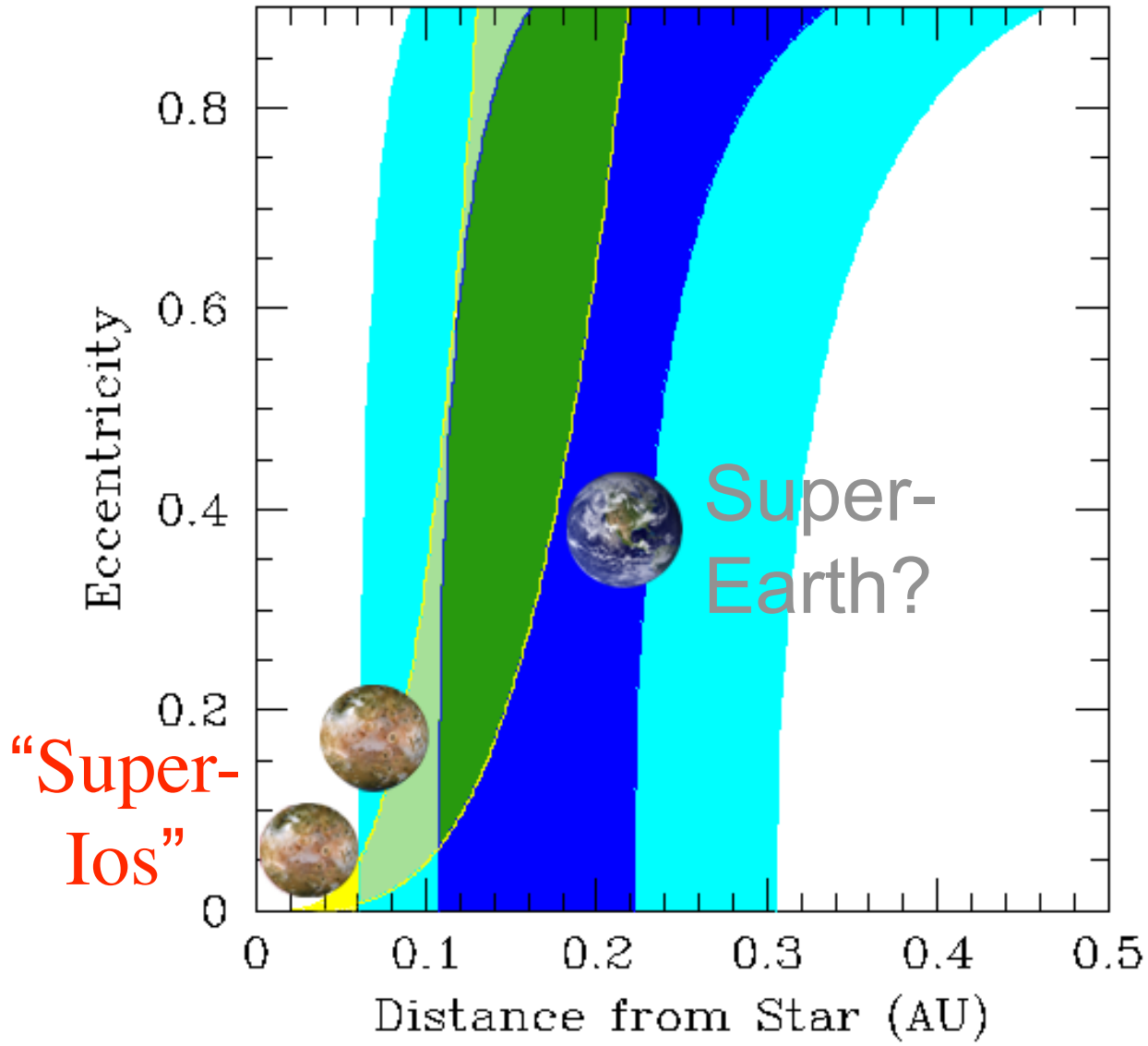

Eccentricity
0
0.2
0.4
0.6
0.8
0
0.1
0.2
0.3
0.4
0.5
Distance from Star (AU)



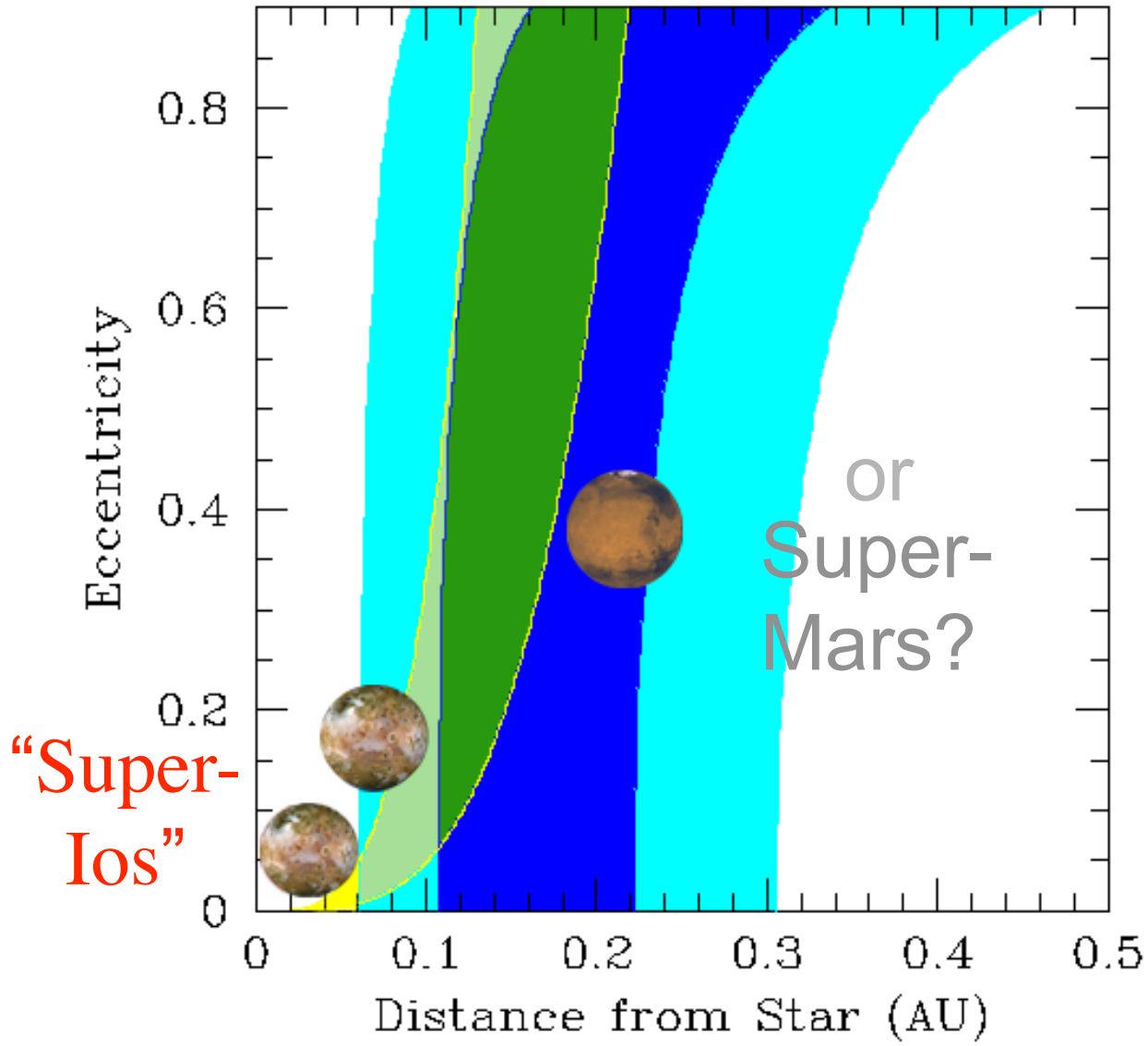
Barnes *et al.* (2009)



Barnes *et al.* (2009)



Barnes *et al.* (2009)



Barnes *et al.* (2009)

Summary

Planets close to their star have their shapes distorted by tides

Evolution driven by misalignment between bulge and perturber

Tides initially drive rotation rate toward orbital period and obliquity to zero or π

After tidal locking, orbits may continue to evolve: *a* and *e* decay

Planets may exit the HZ due to tides

Planets may merge with their star

Tidal heating accompanies eccentric orbits

Super-Ios, Tidal HZ