Origin of Hot Jupiters: Secular Chaos

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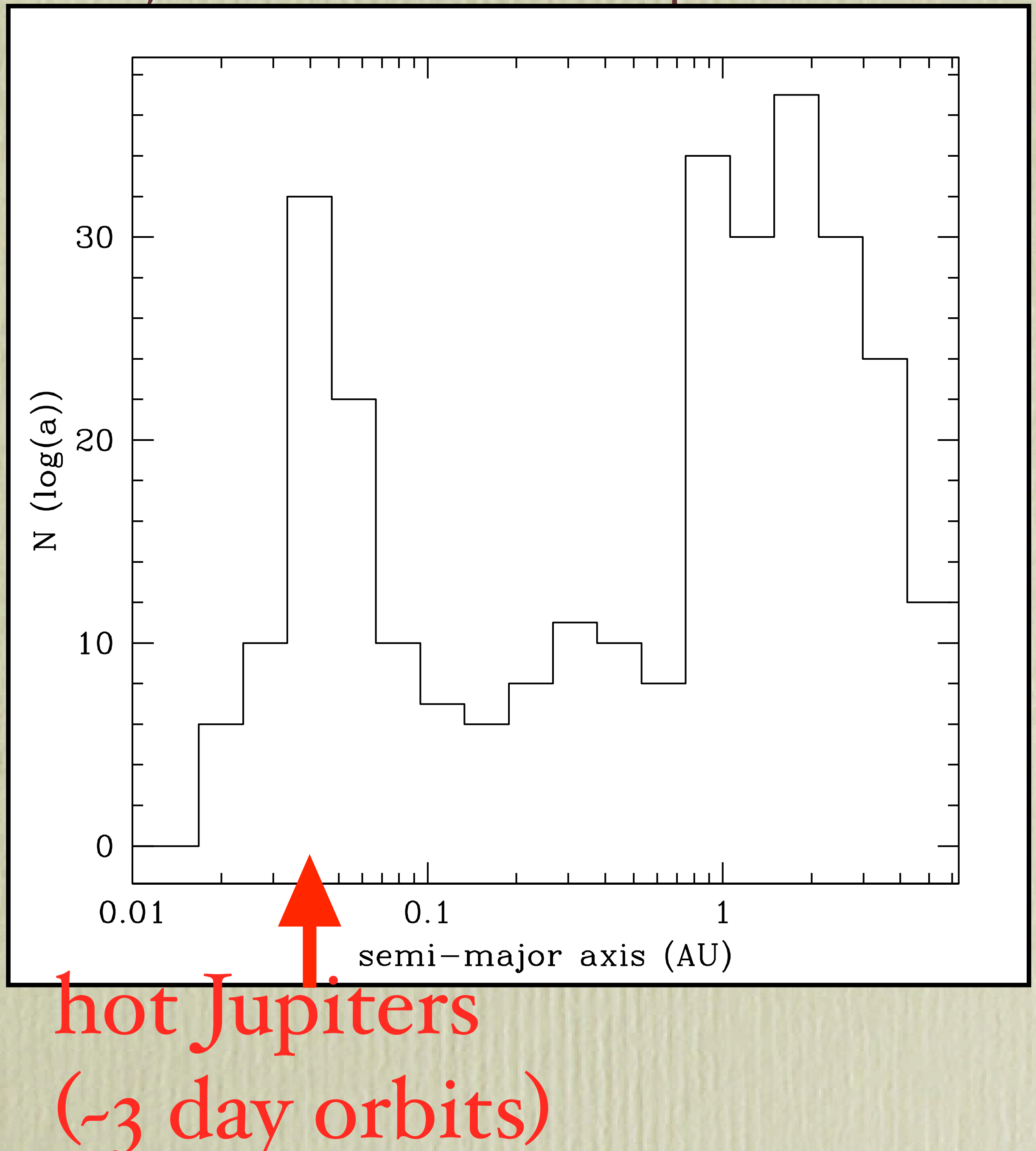
Hot Jupiters

Semi-major axis distribution of planets > 0.1 M_Jup



- ~ 1% of FGK stars have hot Jupiters
- How did Jupiters migrate from >1 AU to < 0.1AU?

A New Migration Mechanism: Secular Chaos

(Wu & Lithwick 2011)

- Start with a few Jupiters beyond an AU, on widely-spaced, mildly eccentric & inclined orbits

- focus on secular (i.e. orbit-averaged) interactions. Okay if no close encounters or strong resonances.

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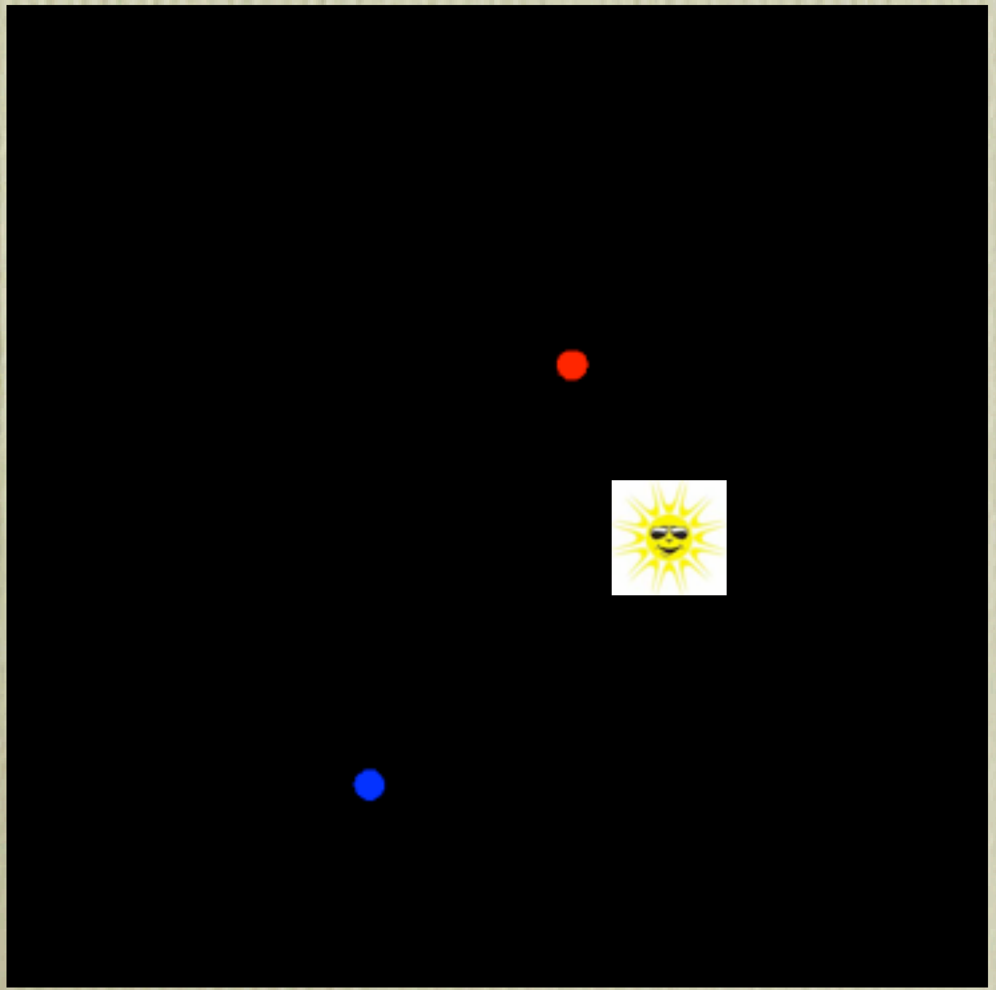

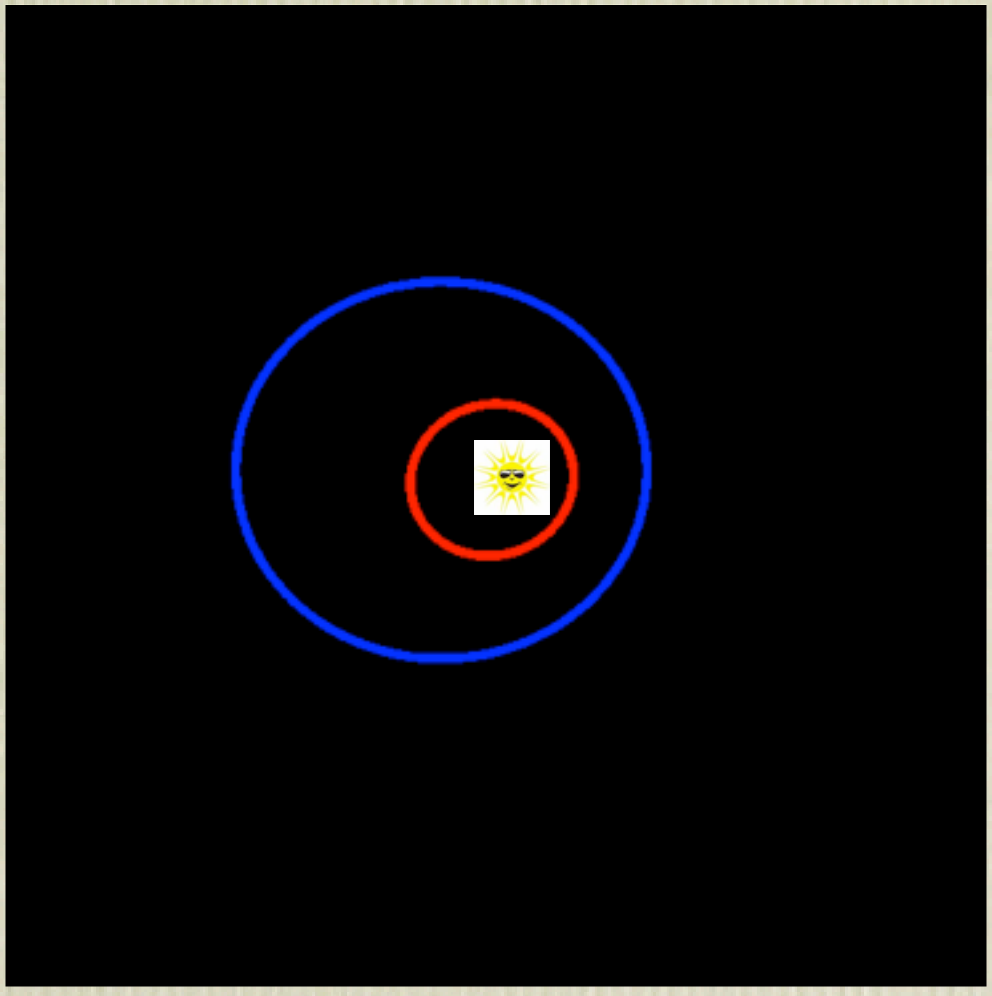

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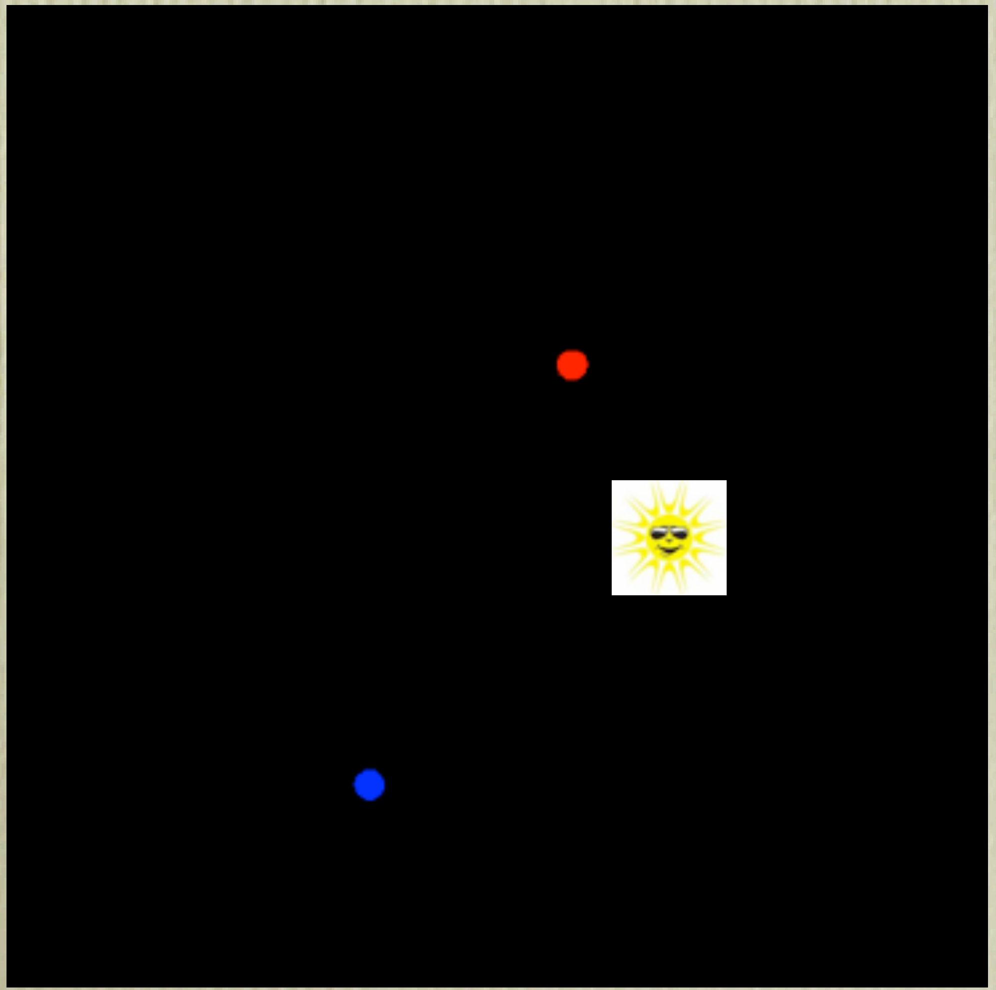
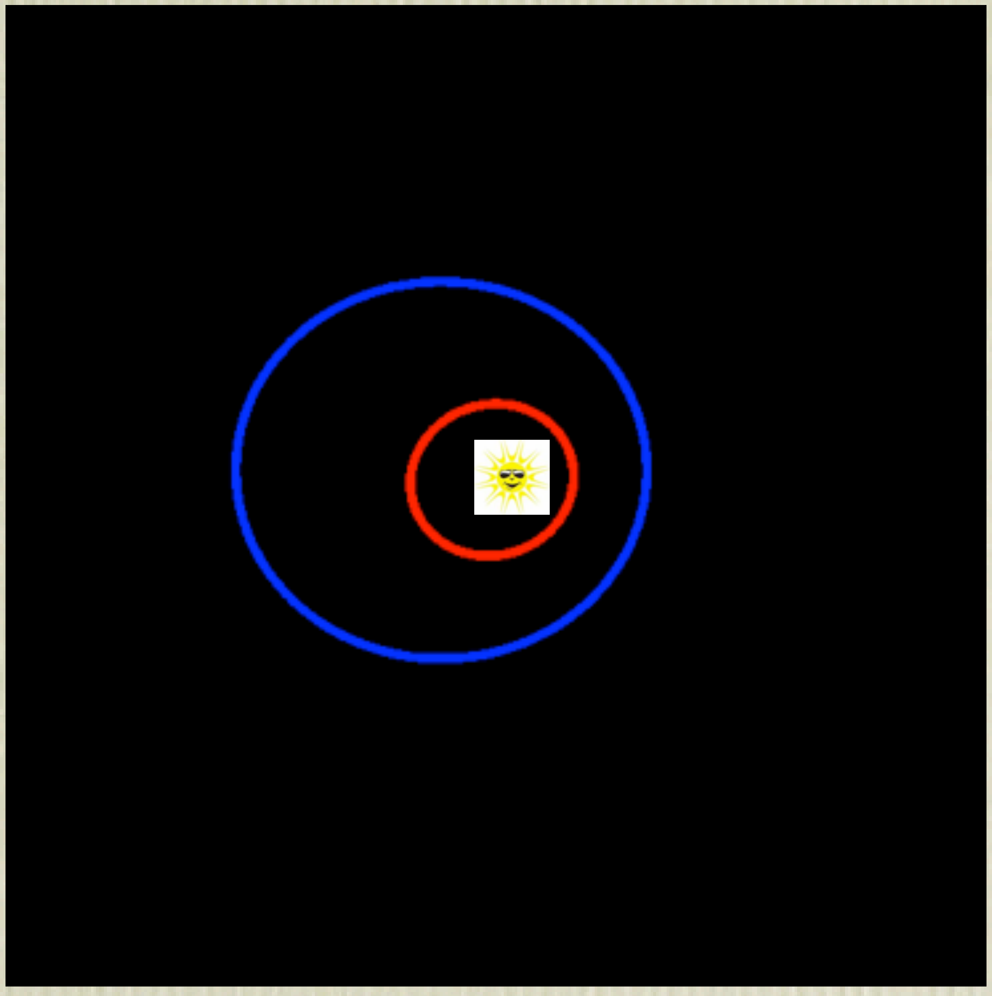
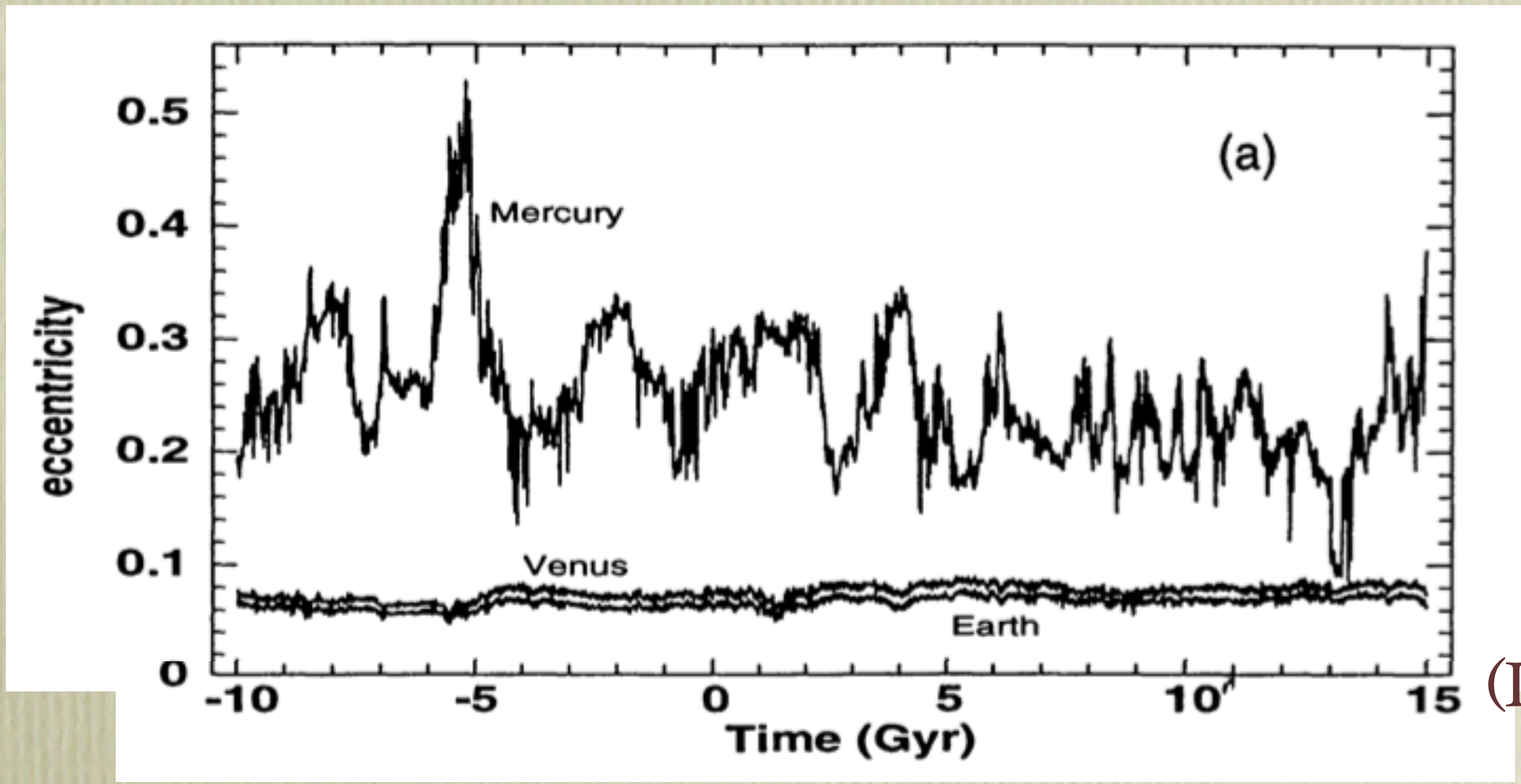




A New Migration Mechanism: Secular Chaos

- secular interactions can lead to chaos

- e.g., terrestrial planets' orbits driven by secular chaos

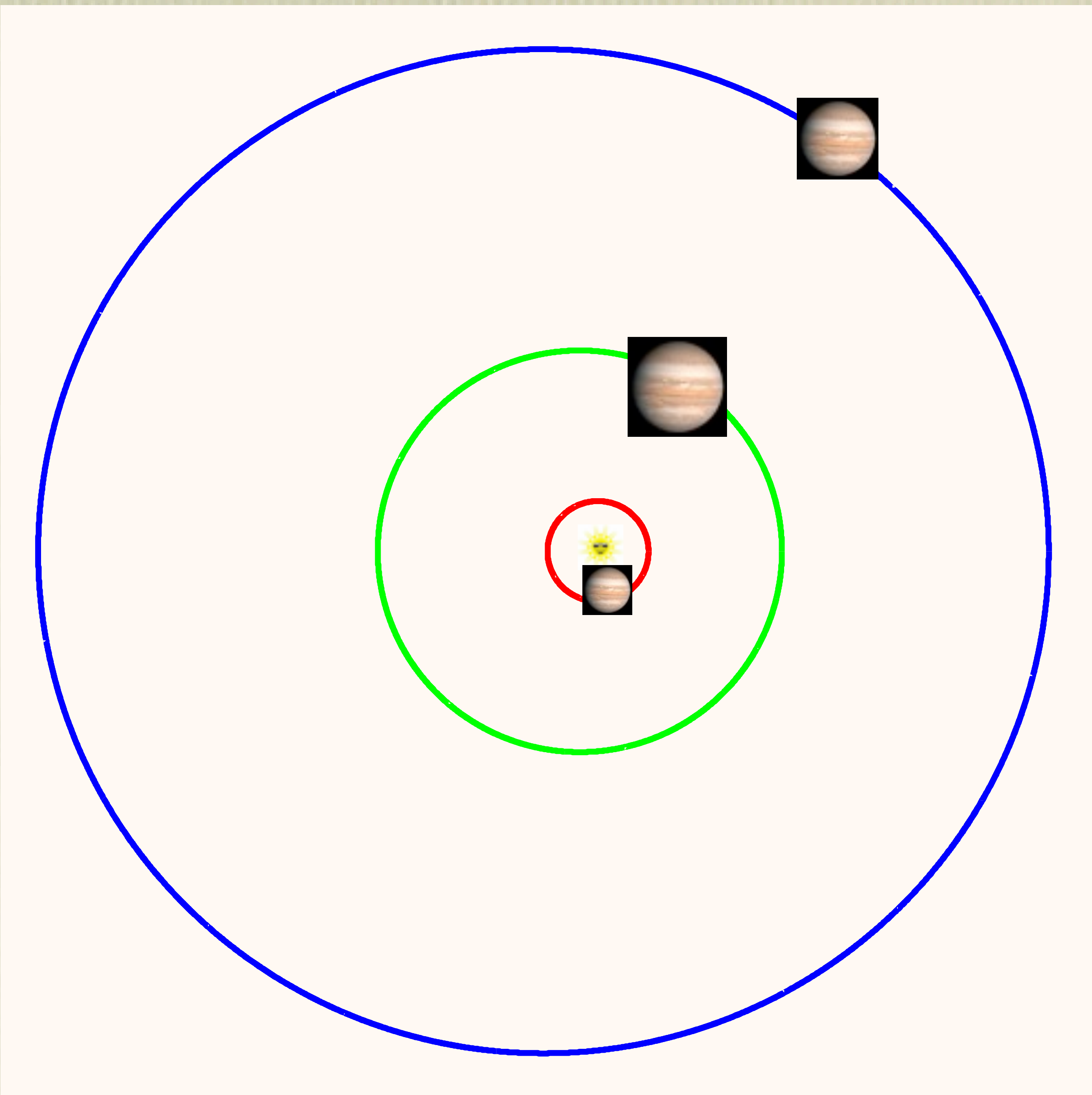


(Laskar '96)

An Example N-body Simulation

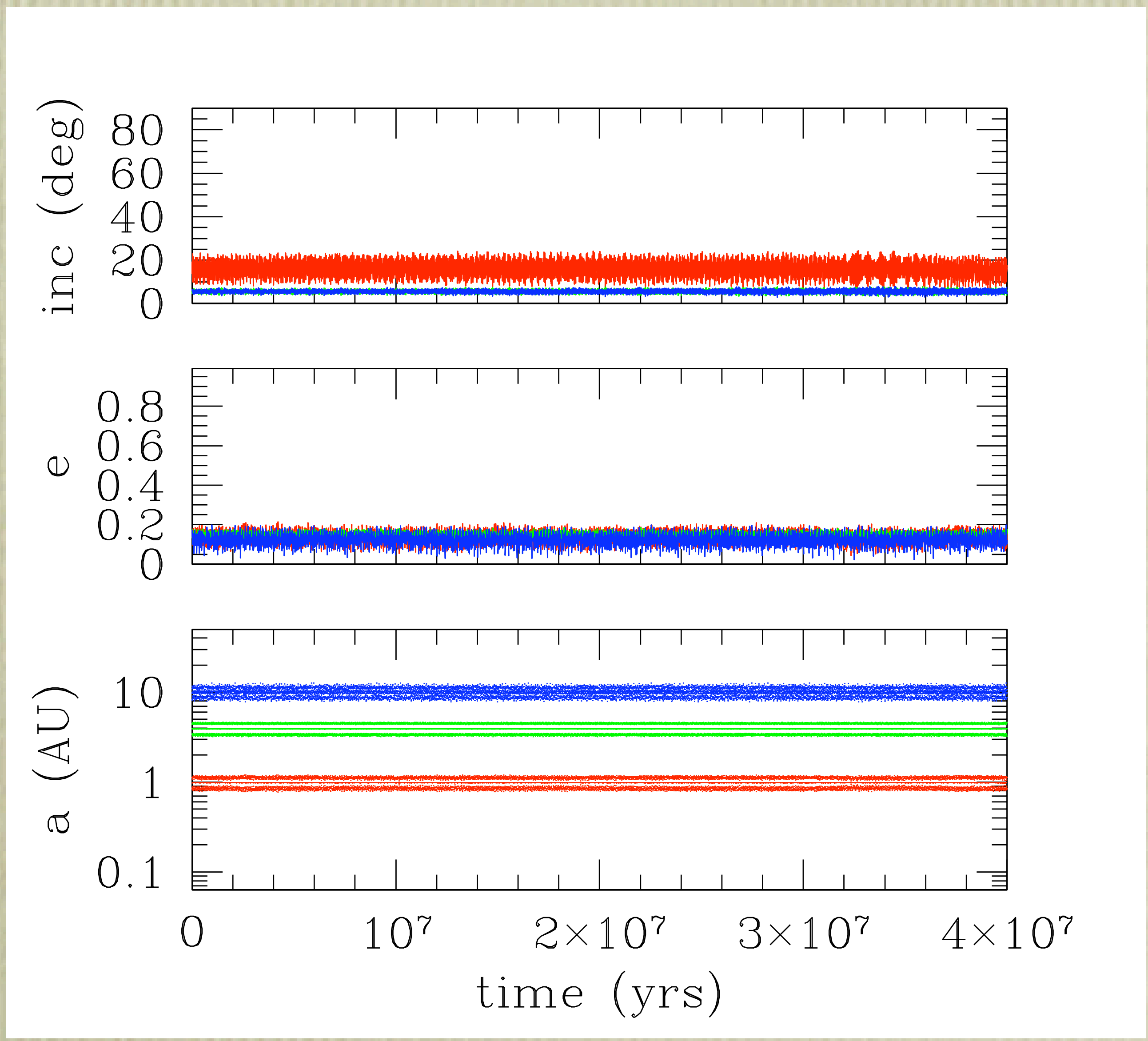
- Initial conditions:

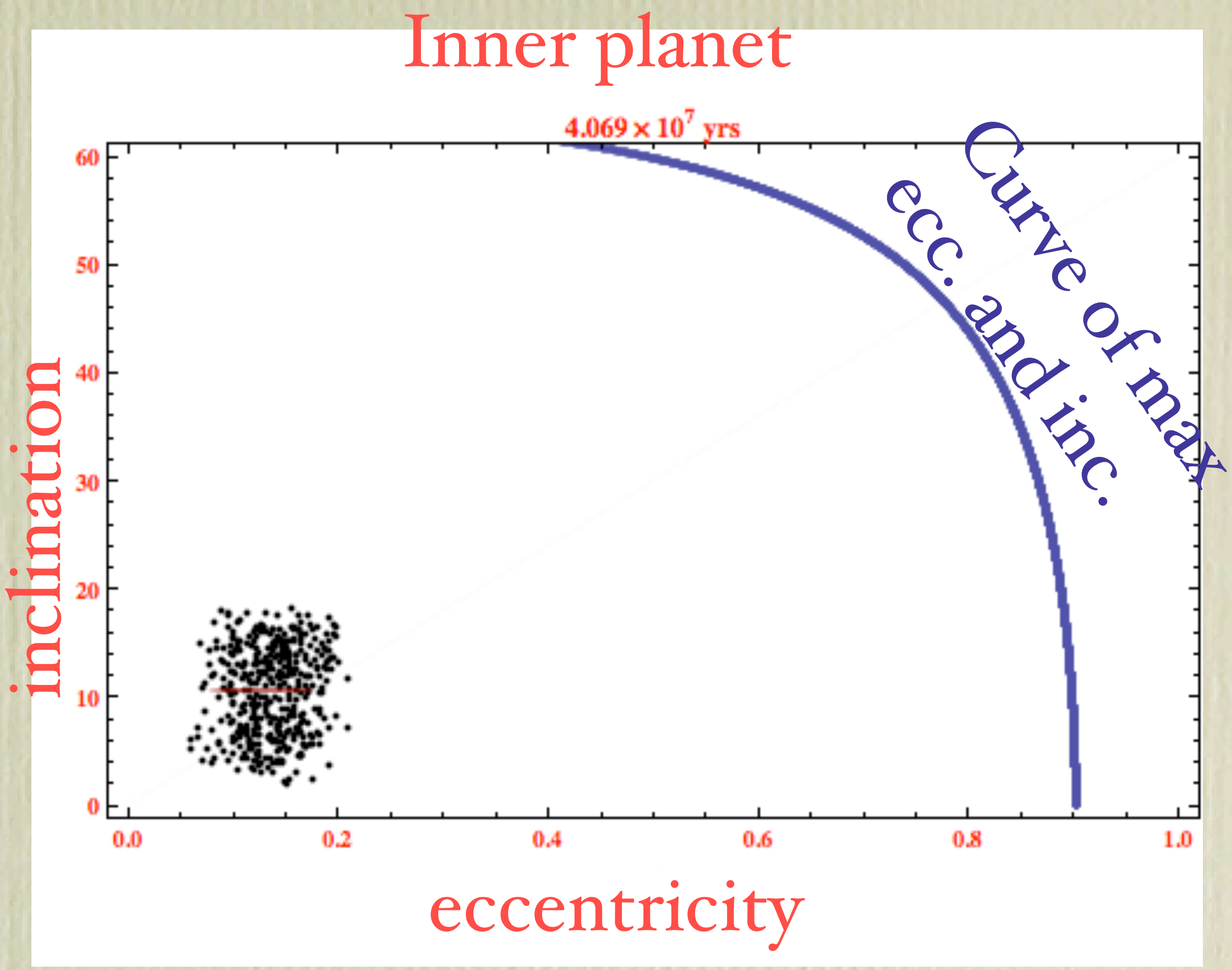
a(AU)	*ecc.*	*inc. (deg)*	*mass (Mjup)*
1	0.12	10	0.5
4	0.12	5	10
10	0.12	5	5



Secular Instability

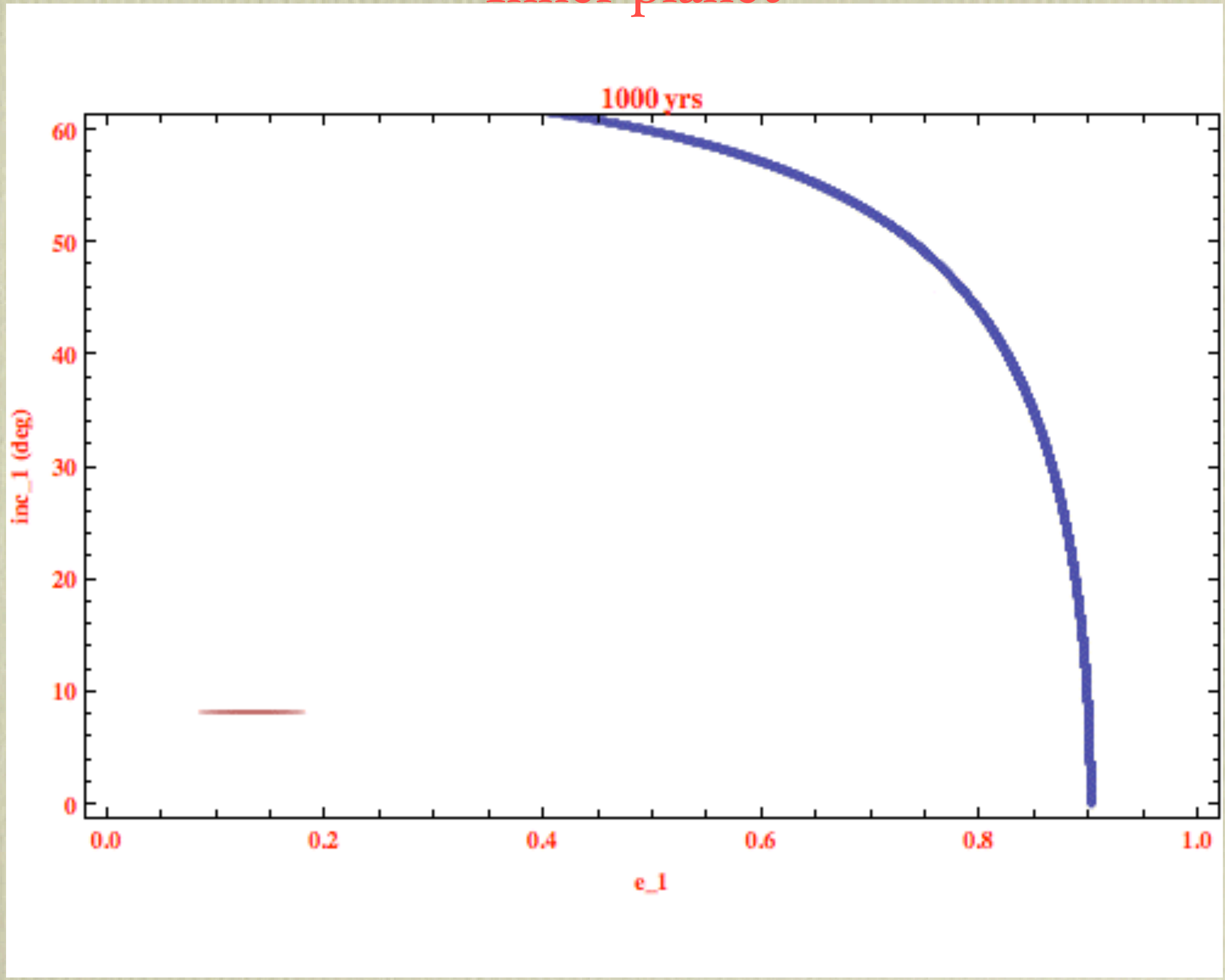
Nothing happens for a long time...





Secular Instability

Inner planet



- Inner planet can reach high eccentricities & inclinations, given enough time

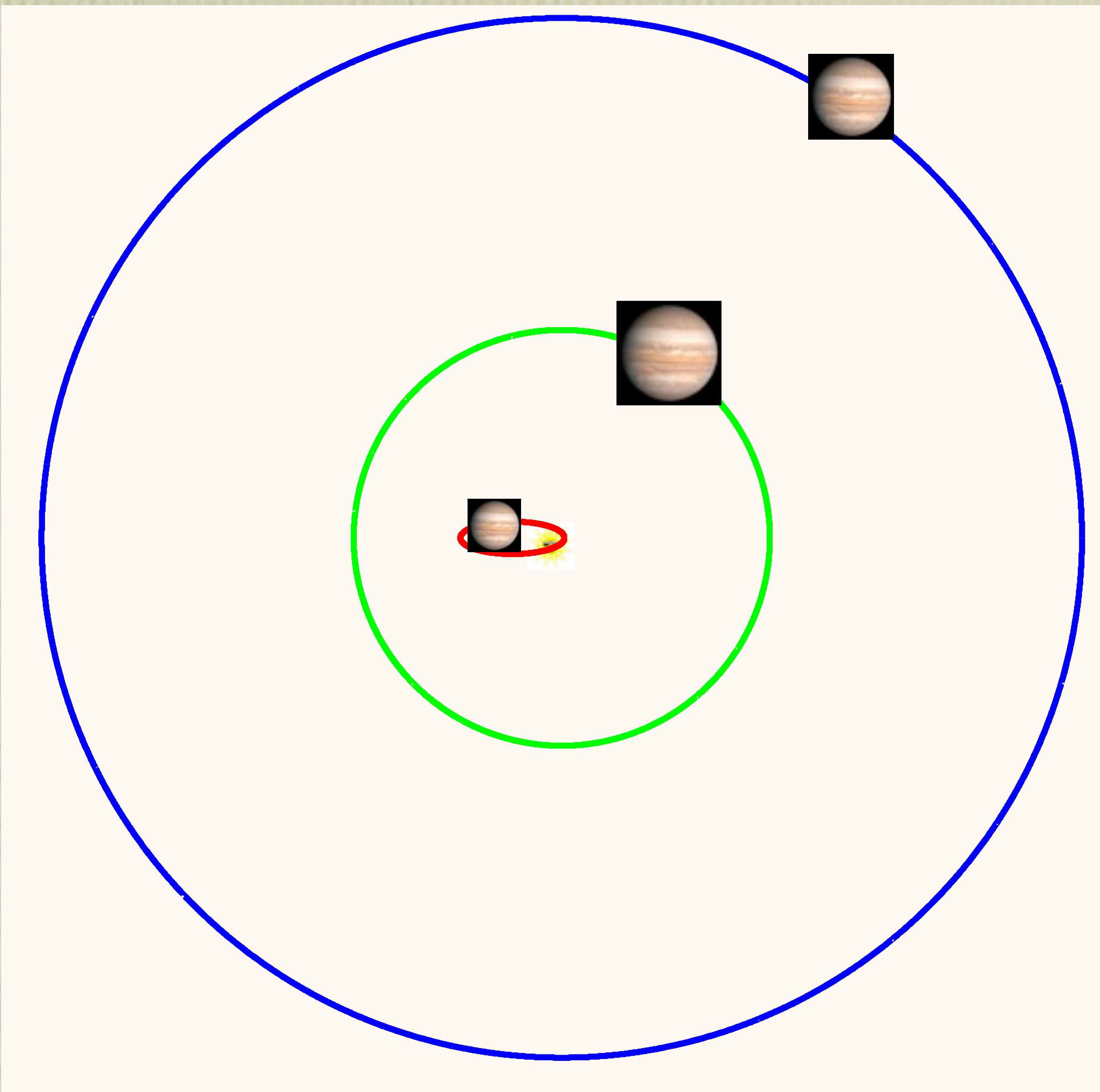
Secular Instability

When inner planet acquires high e,

- pericenter approaches star

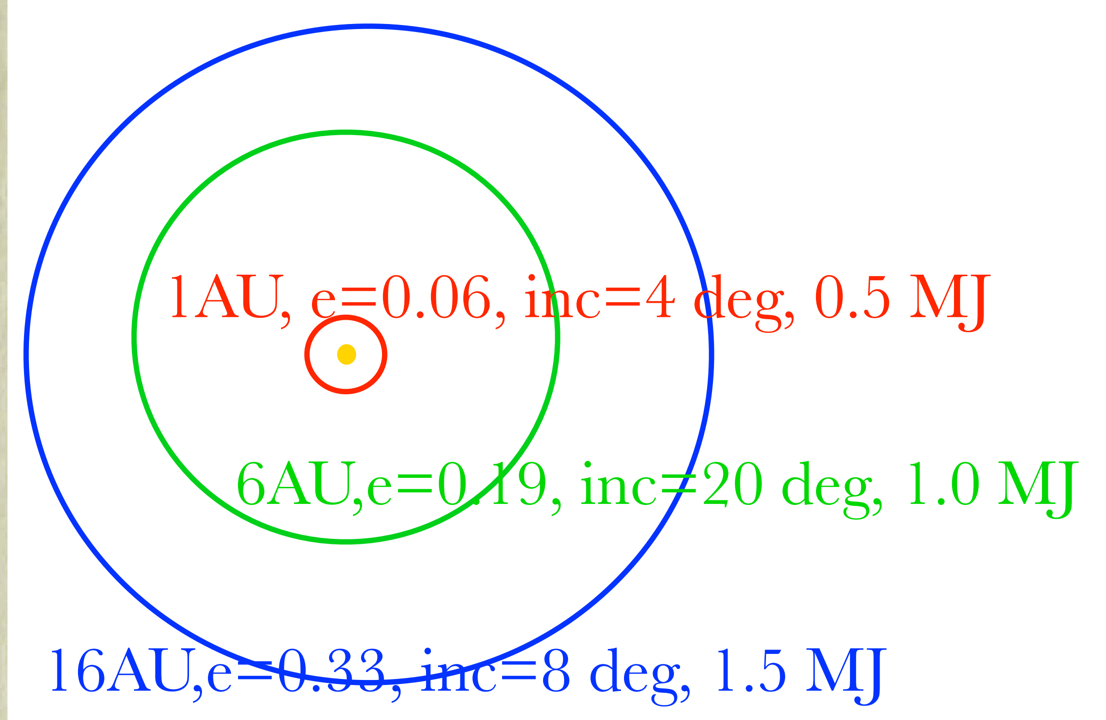
- tides raised by star can circularize planet
$\Rightarrow$ hot Jupiter

- Inner planet has smallest "inertia" $\Rightarrow$ most likely to be excited

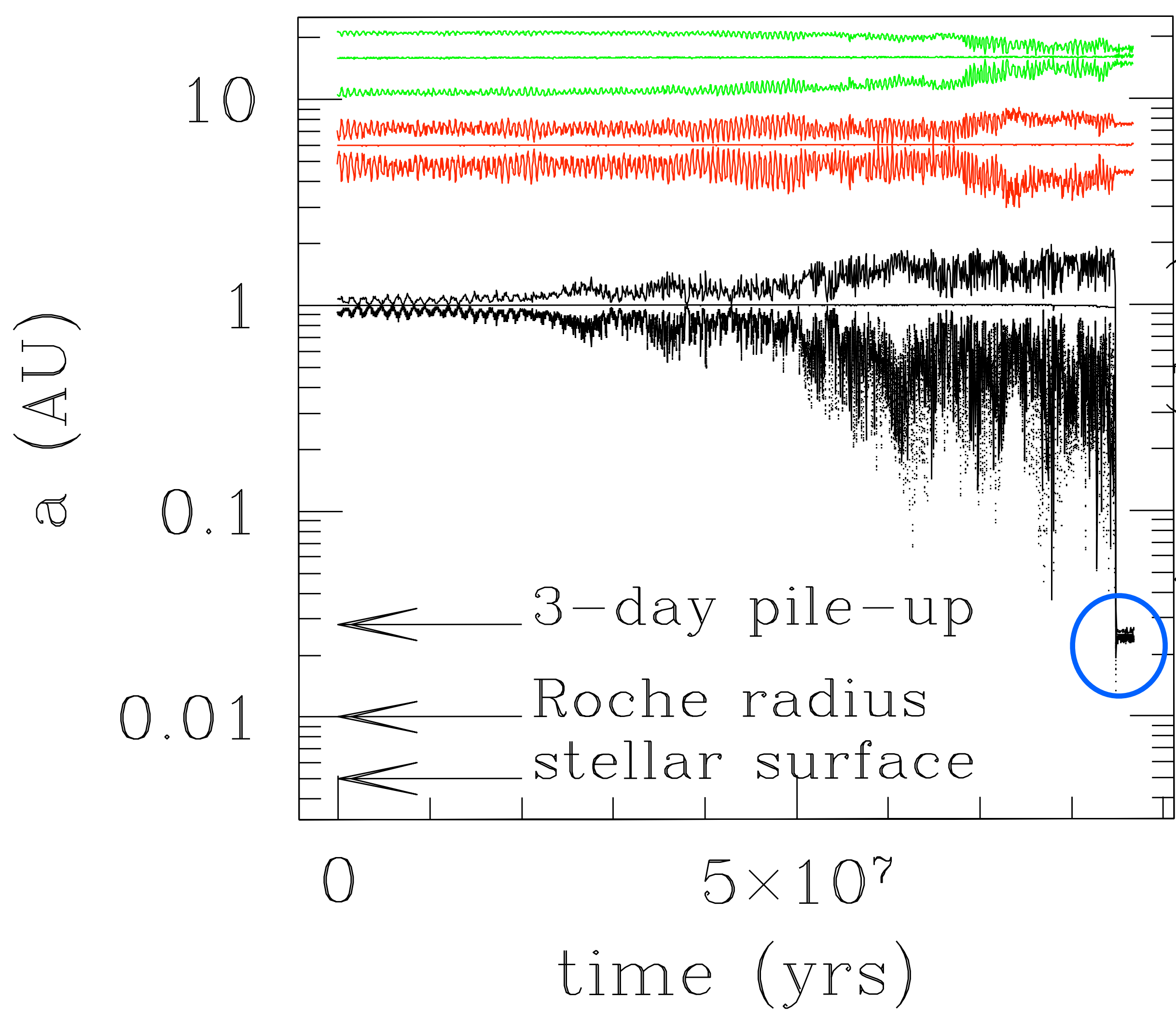


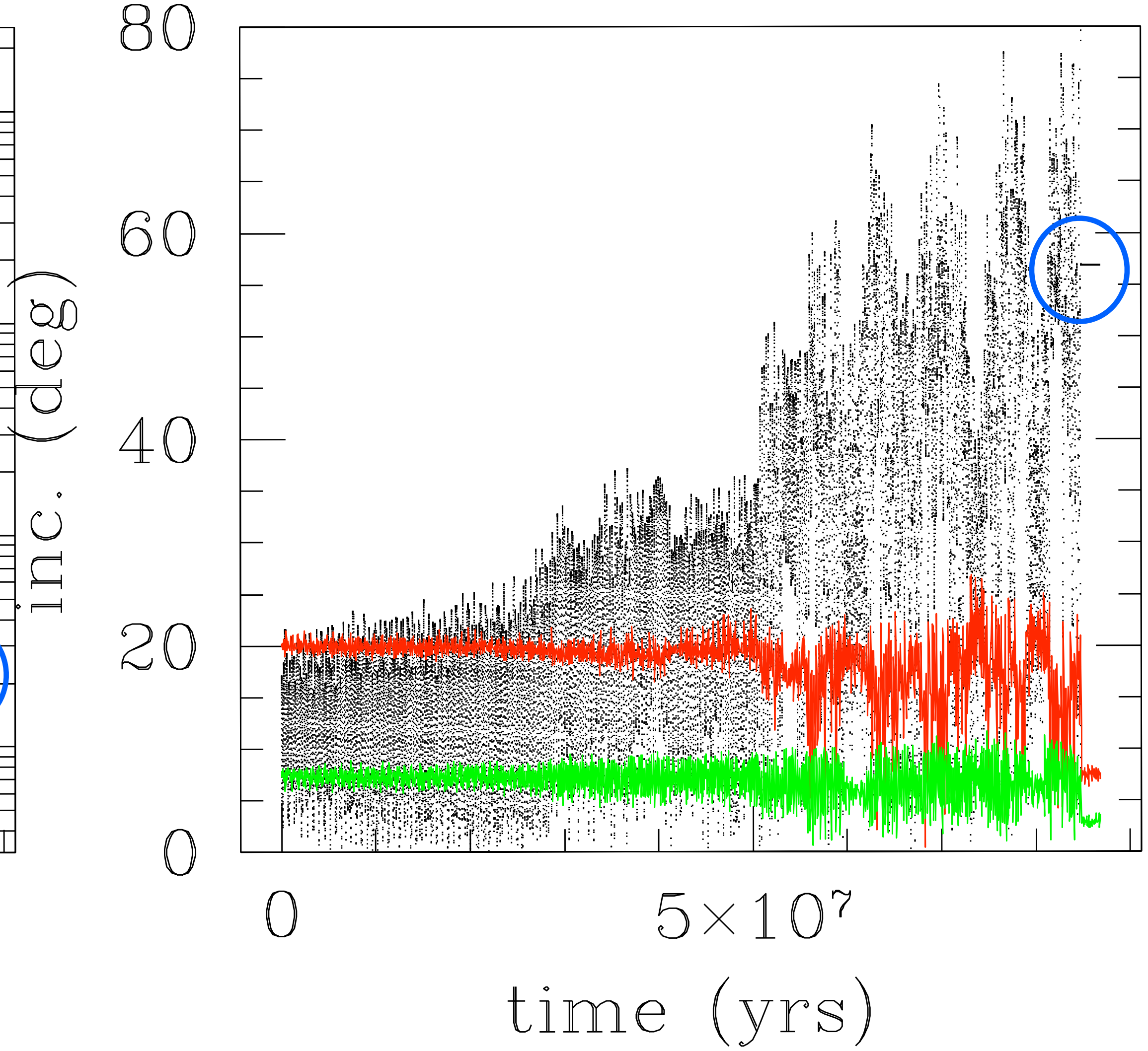
- Note also: remaining planets "cooled"

Another system (with tides & GR)

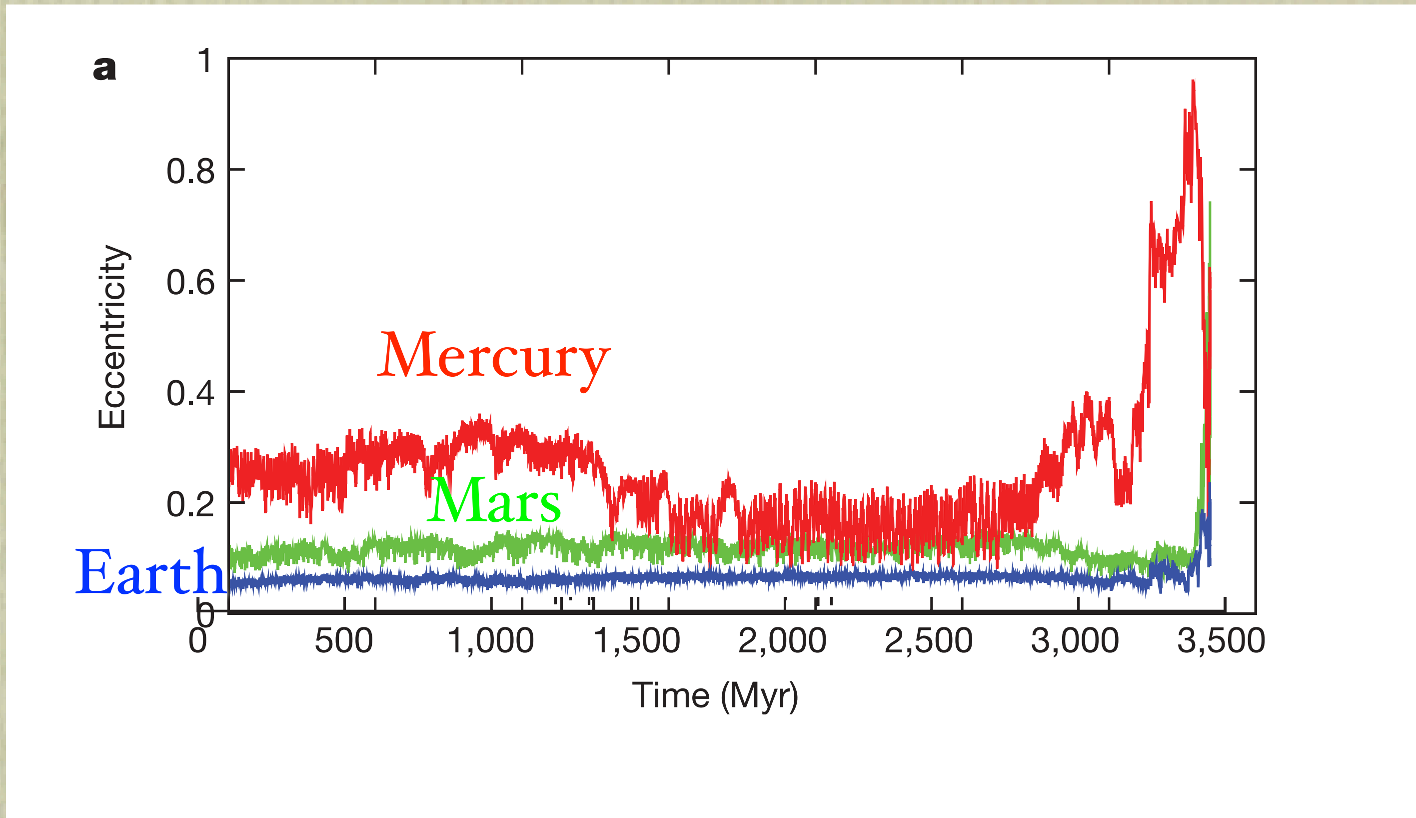


constant a ⇒ secular



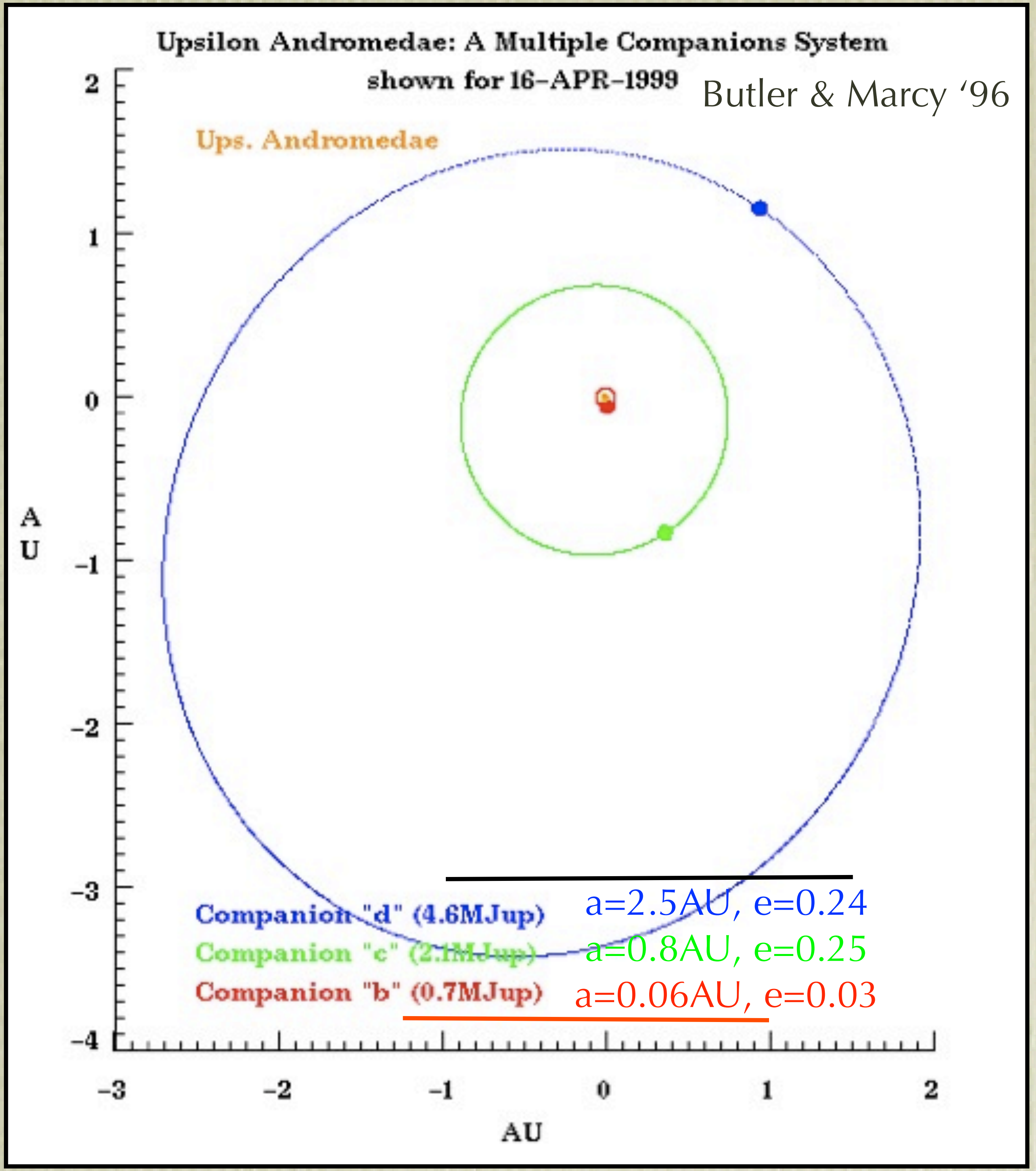


Similar to Mercury's orbital chaos



(Laskar & Gastineau `09)

Has it really happened?



Michtchenko & Malhotra '04
Migaszewski & Gozdziewski '08,'09

Comparison with Observations

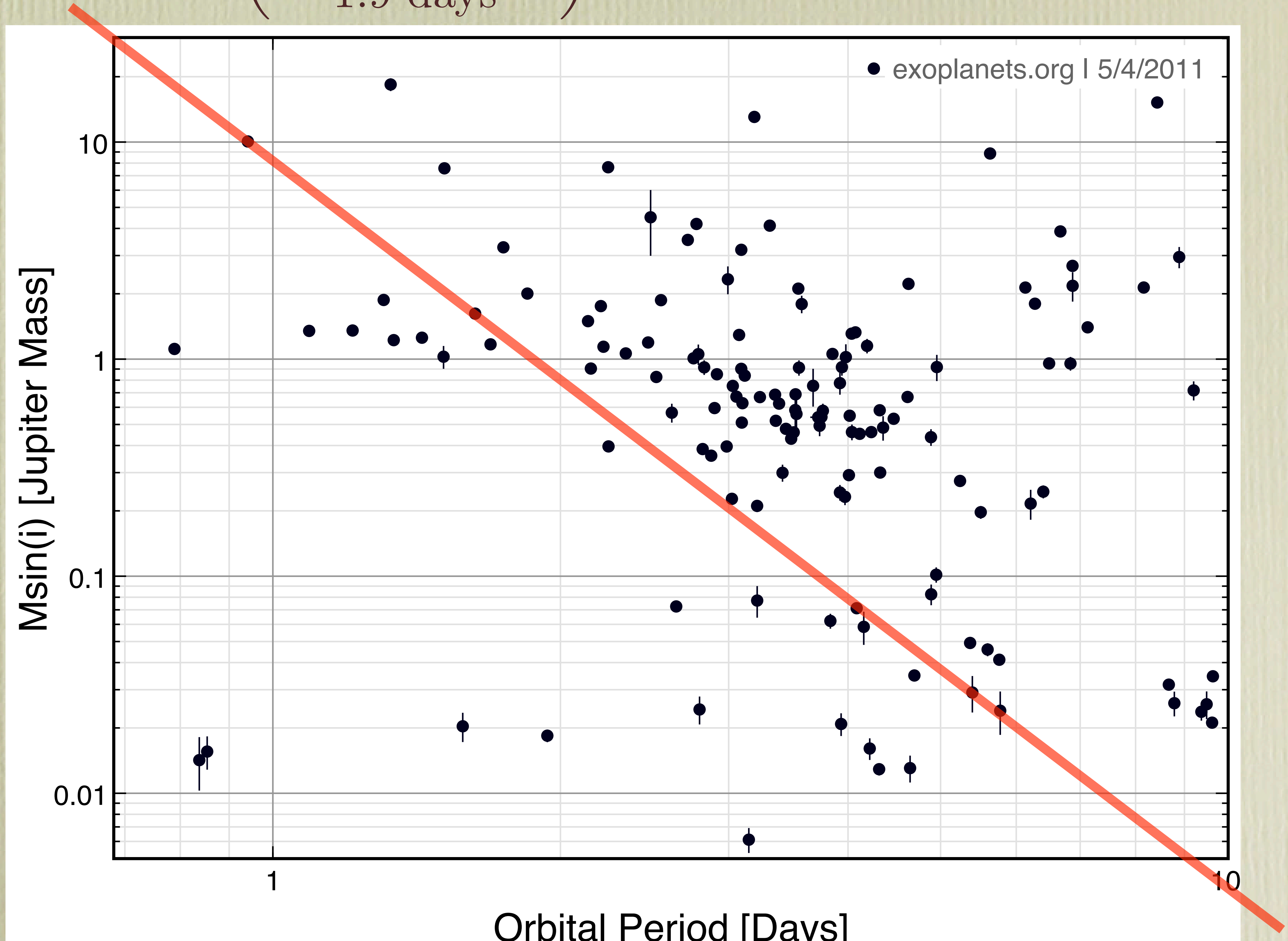
observation		explanation
3-day pile-up	✓	gradual e-growth (timescale > 10^6 yrs) + tidal dissipation
range of stellar obliquities (R-M)	✓	excite both e and i
lack of close companions	✓	predict: no TTV for hot Jupiters more Jupiters beyond a few AU
Masses lower than average	✓	easier to excite low mass planets

Also predict that fraction of hot Jupiters increases with stellar age ⇒ no hot Jupiter around T Tauri observation

	secular chaos	disk migration	Kozai migration	planet scattering	
3-day pile-up	✓	✗?	✓	✗	
range of stellar obliquities (R-M)	✓	✗?	✓	✓	
lack of close companions	✓	✗	✓	✓	
Masses lower than average	✓	?	✗	✗	
			Also, cannot produce frequency of hot Jupiters (Wu et al.)	Also, initial conditions are artificial	

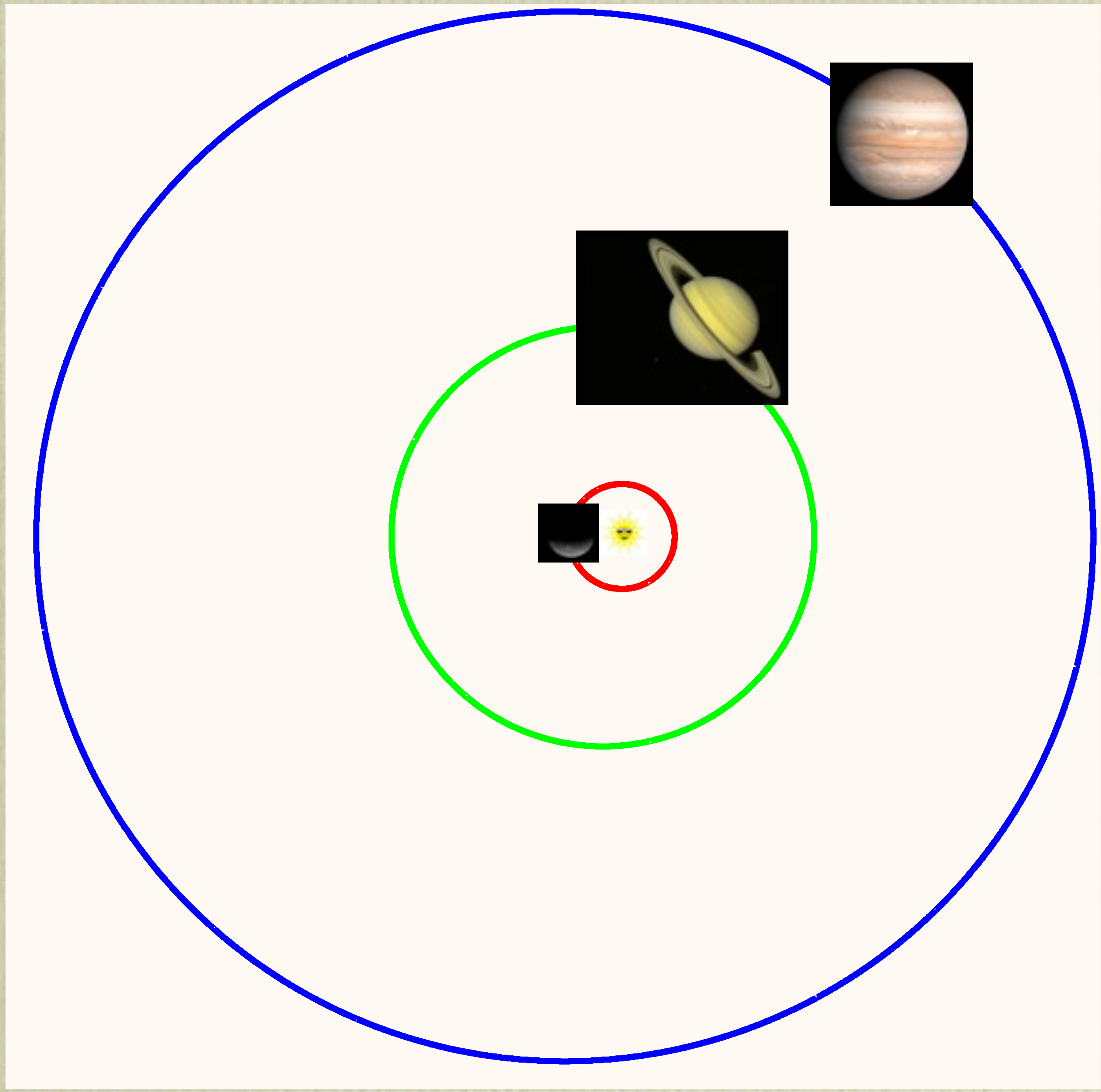
Secular chaos predicts

$$M \simeq M_J \left(\frac{\text{orbital period}}{1.9 \text{ days}} \right)^{-10/3}$$



Theory of Secular Chaos (Lithwick & Wu 2011)

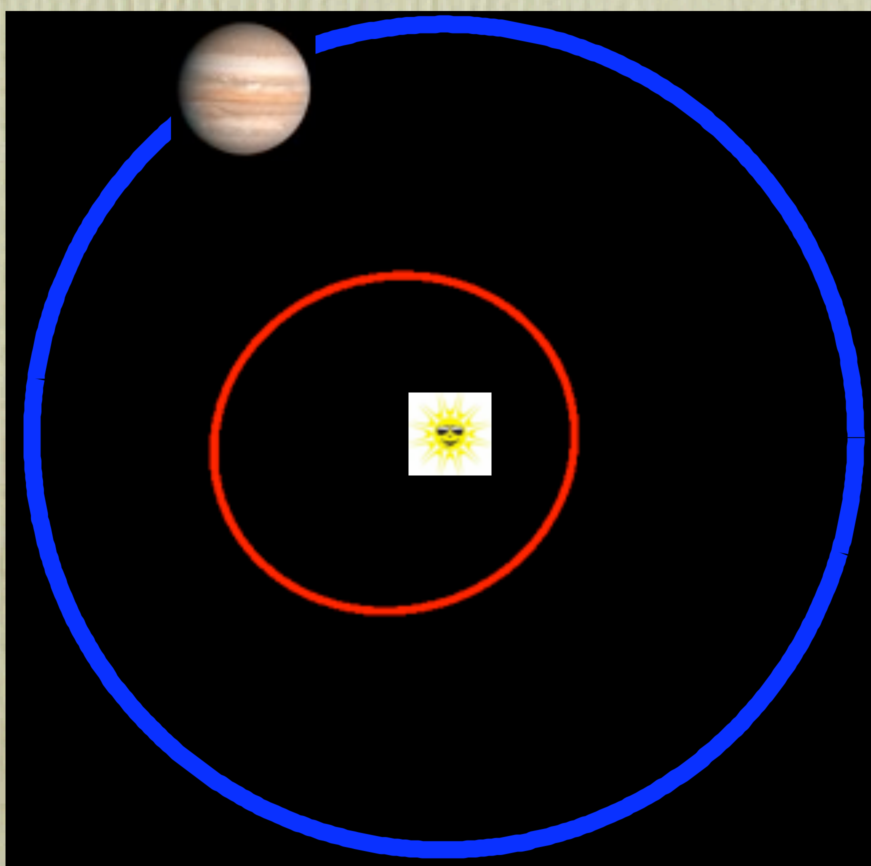
Simple example of instability: two massive & one massless planet ("Jupiter", "Saturn", and "Mercury"). Assume coplanar.



I. Circular Jupiter, no Saturn

$\Rightarrow$ Mercury precesses at const. rate, with const. eccentricity

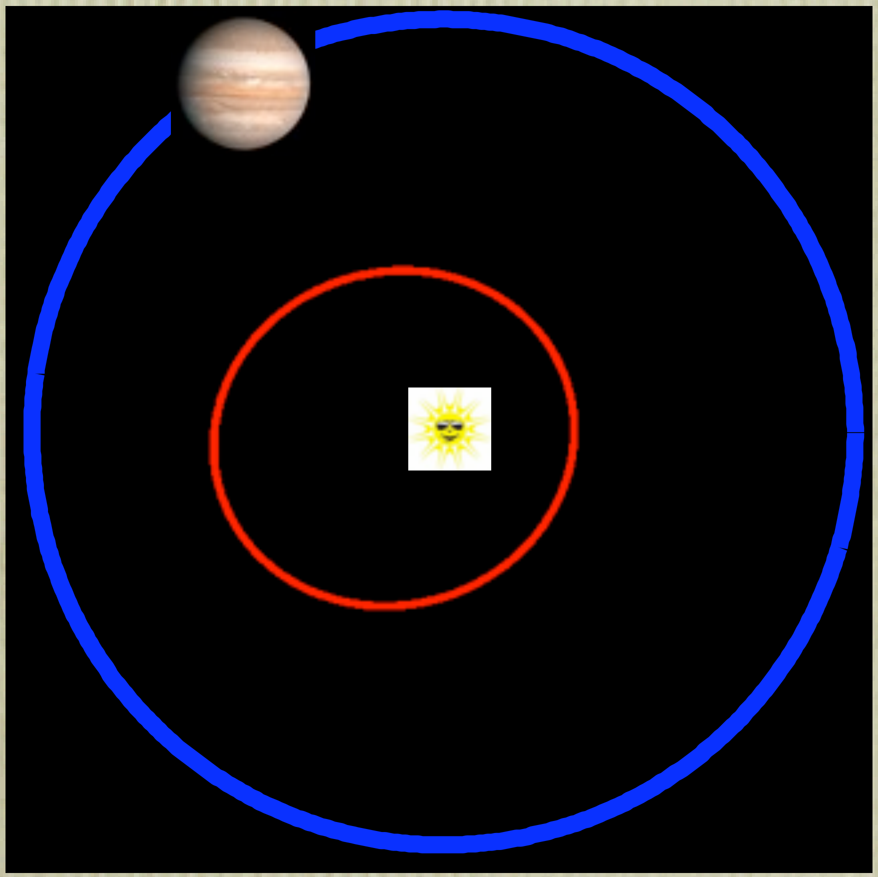
$$\text{precession time / orbital time} \sim \frac{M_\odot}{M_J}\frac{a_J^3}{a_M^3} \sim 10^6$$

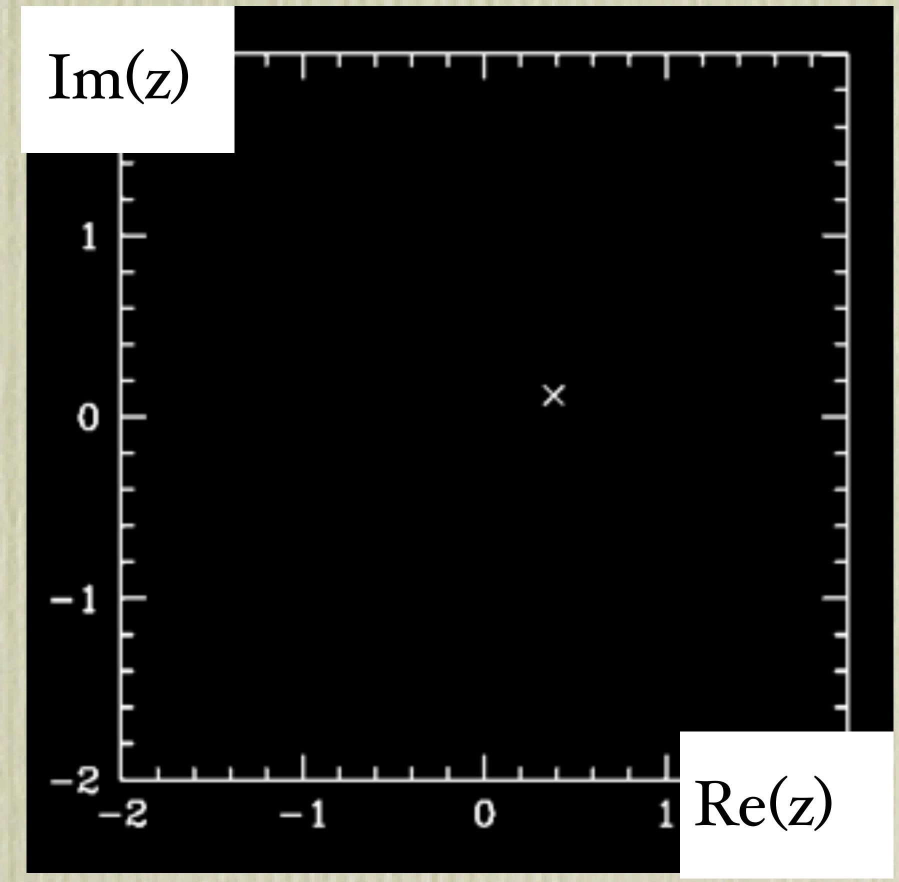


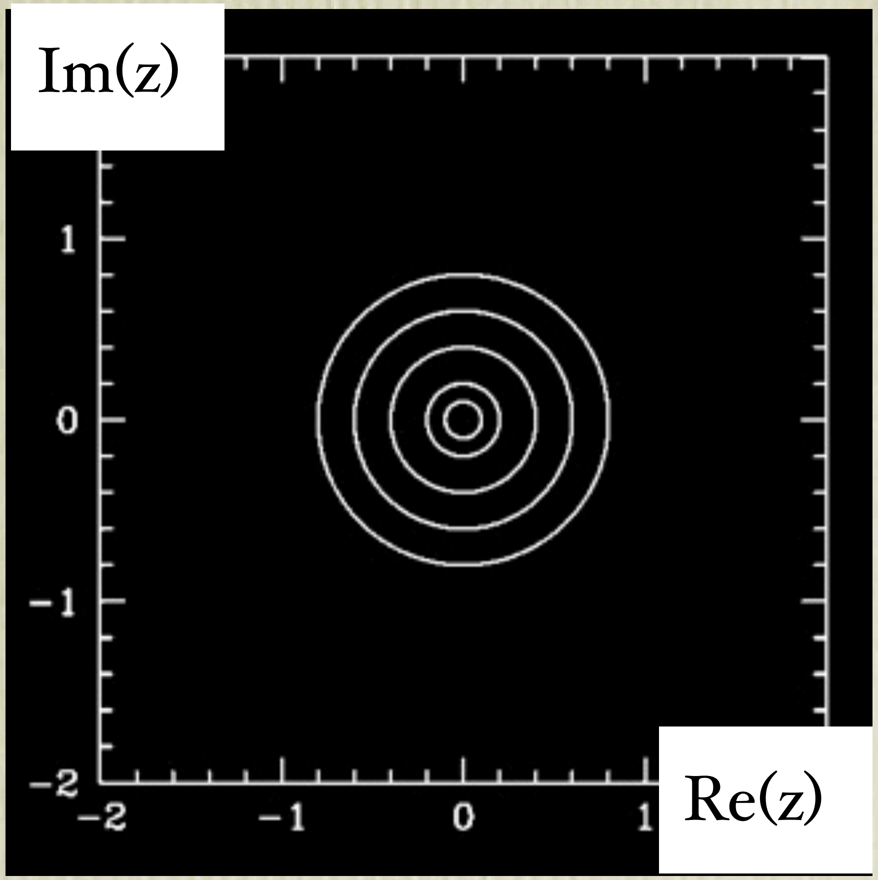
1. Circular Jupiter, no Saturn

⇒ Mercury precesses at const. rate, with const. eccentricity

$$z \equiv \underbrace{e}_{\text{eccentricity}} \cdot e^{i\underbrace{\varpi}_{\text{peri. angle}}}$$







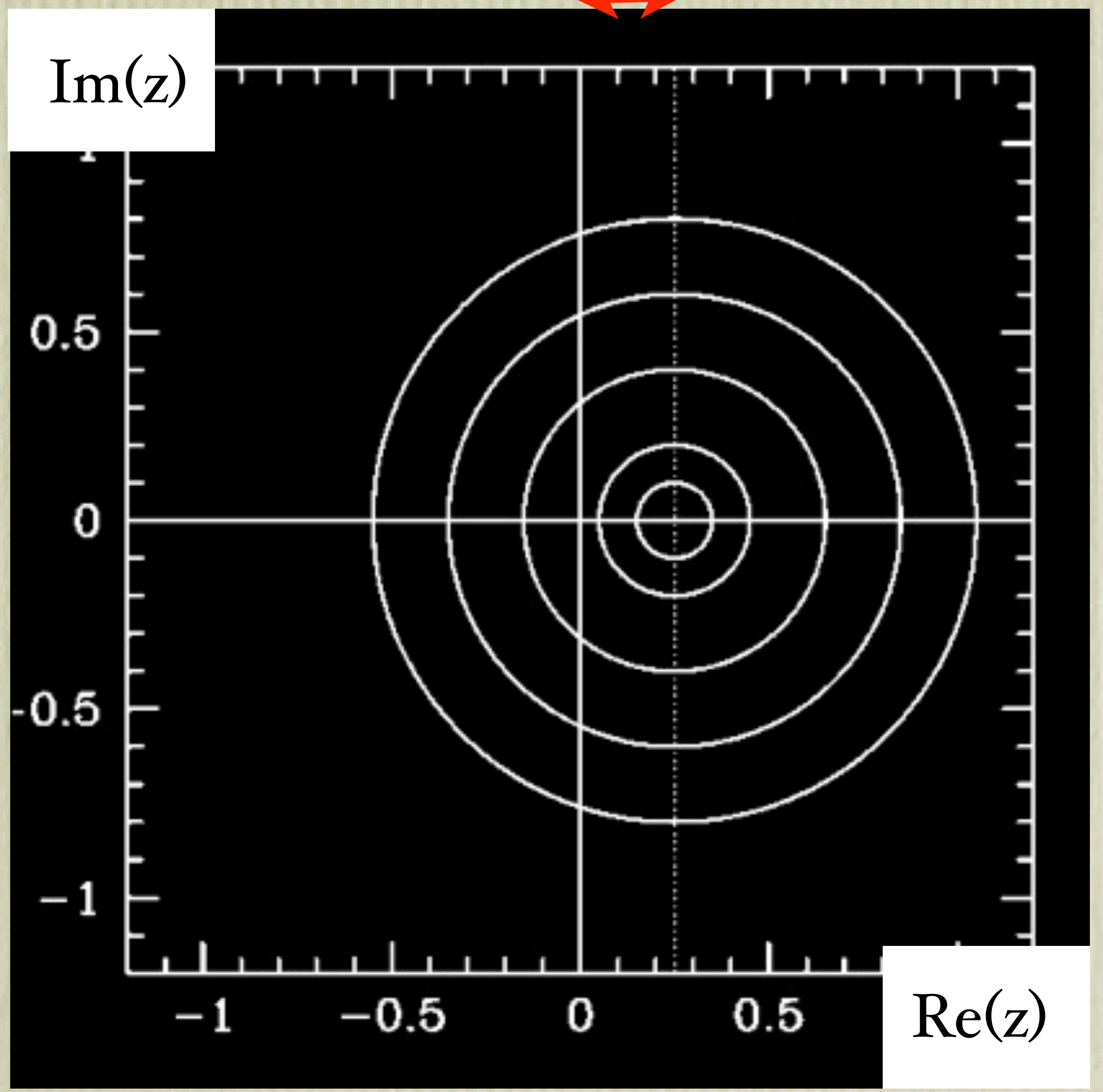
2. Eccentric Jupiter: $$\frac{d}{dt}z = i(z - \epsilon_J)$$

~Jupiter's eccentricity × a_M/a_J

solution: $$z = \underbrace{Ce^{it}}_{\text{free}} + \underbrace{\epsilon_J}_{\text{forced}}$$

(Time in units of the free secular precession freq.)

ϵ_J

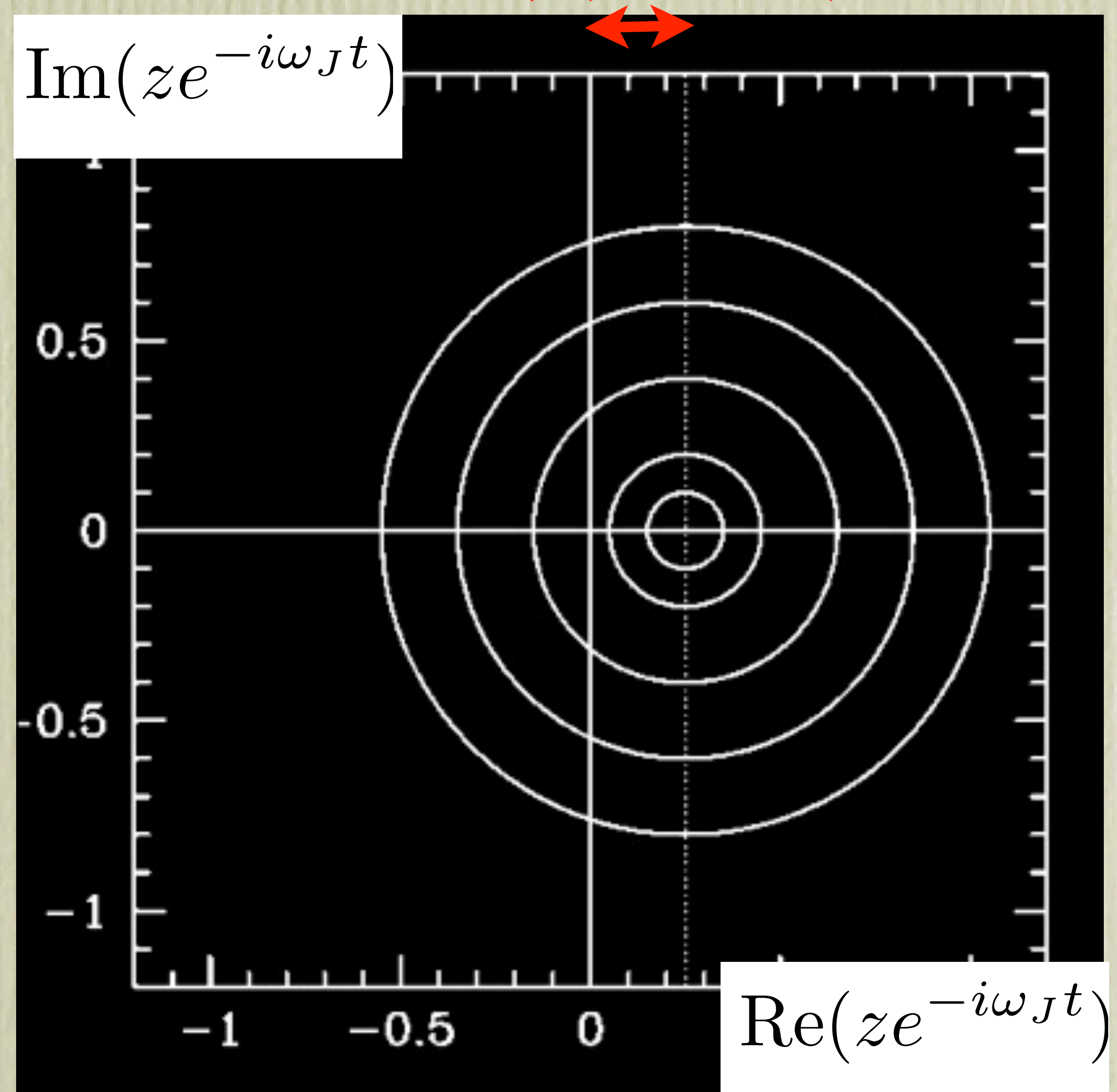


3. Eccentric Precessing Jupiter: $$\frac{d}{dt}z = i(z - \epsilon_J e^{i\omega_J t})$$

Jupiter's precession frequency

solution: $$z = Ce^{it} + \frac{\epsilon_J}{1-\omega_J}e^{i\omega_J t}$$

$\epsilon_J/(1-\omega_J)$

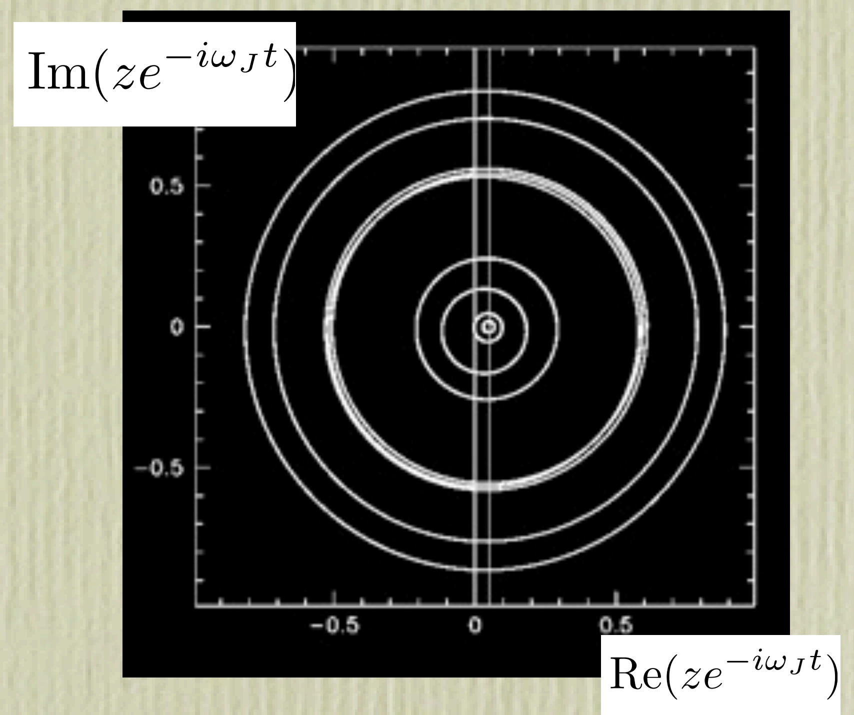


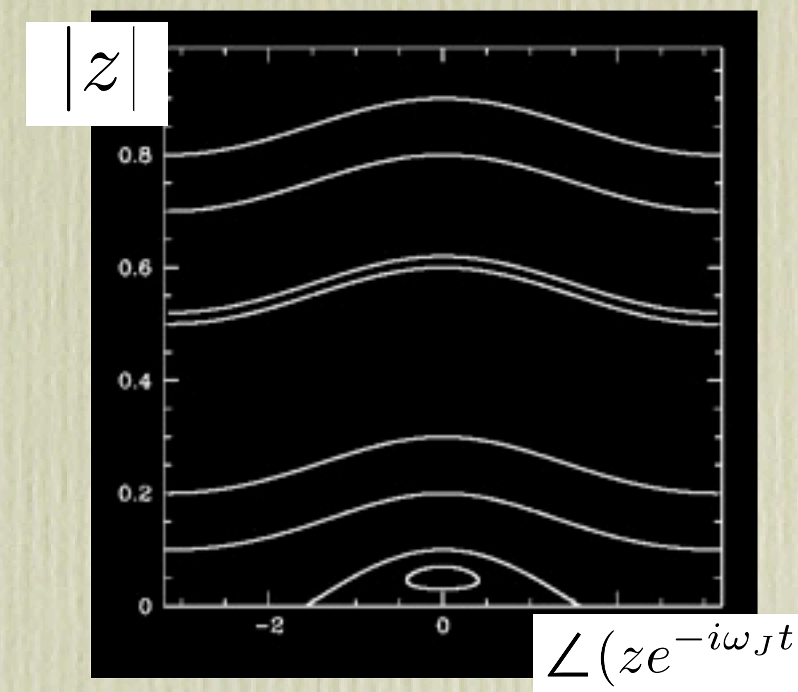
4. Eccentric Precessing Jupiter & Nonlinear Mercury

$$\frac{d}{dt}z = i\left[\left(1 - \frac{|z|^2}{2}\right) z - \epsilon_J e^{i\omega_J t}\right]$$

$\epsilon_J = 0.01, \ \omega_J = 0.8$

Linear:





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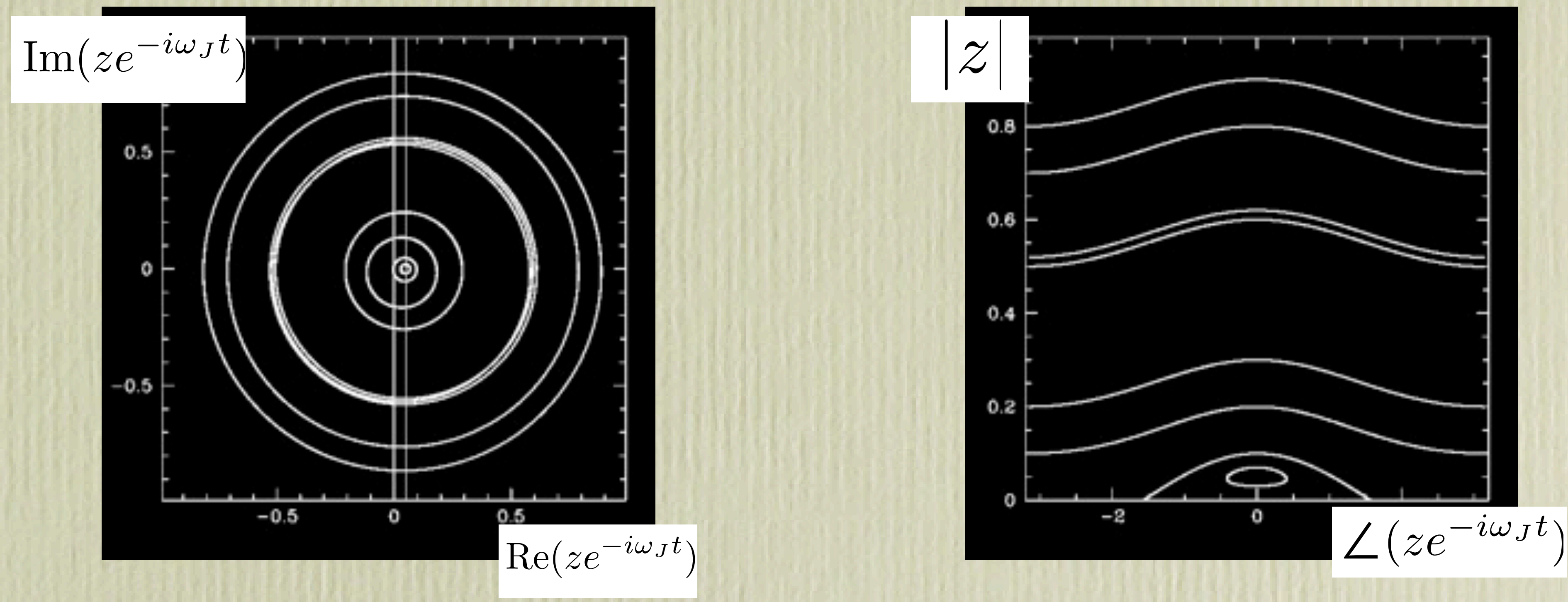
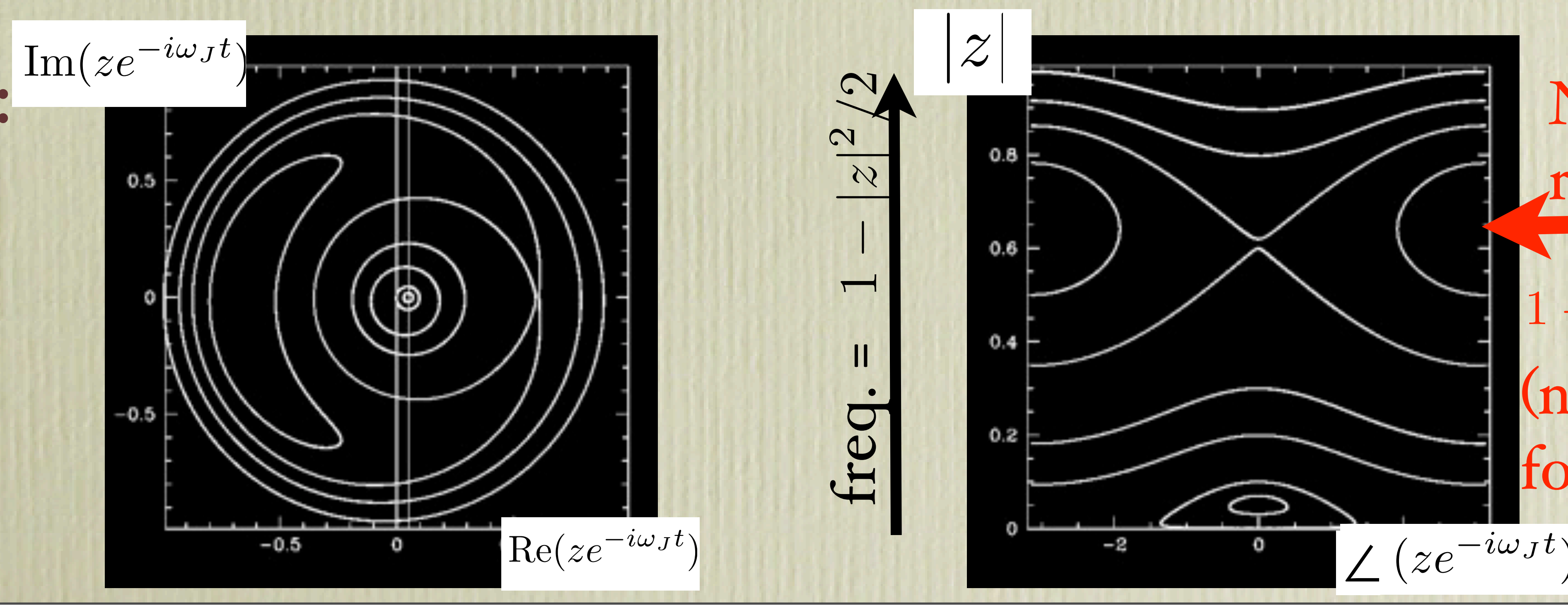


Nonlinear:



Nonlinear resonance

$1 - |z|^2/2 \simeq \omega_J$

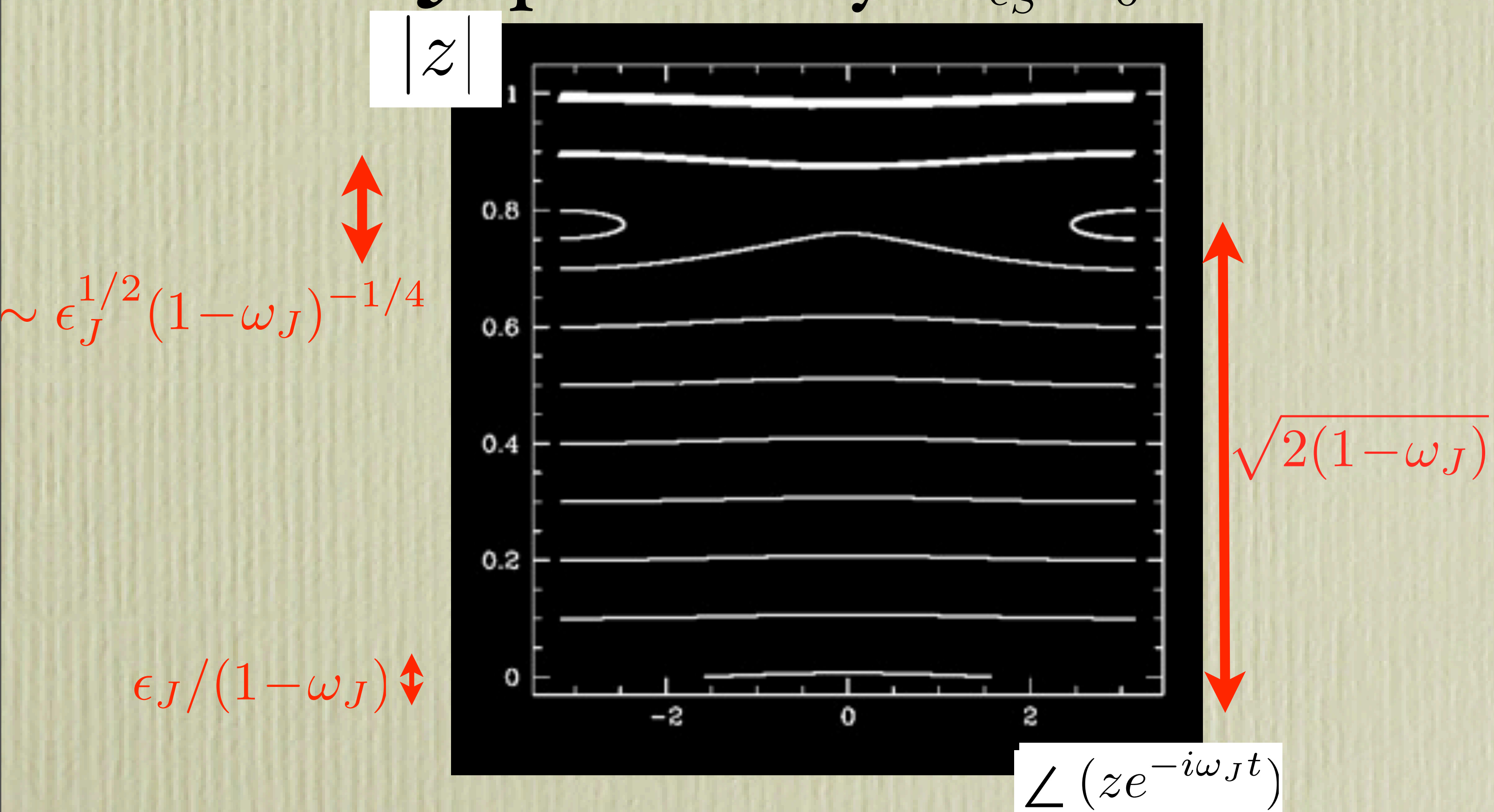
(nonlin freq = forc. freq.)

5. Eccentric Precessing Jupiter & Saturn & Nonlinear Mercury

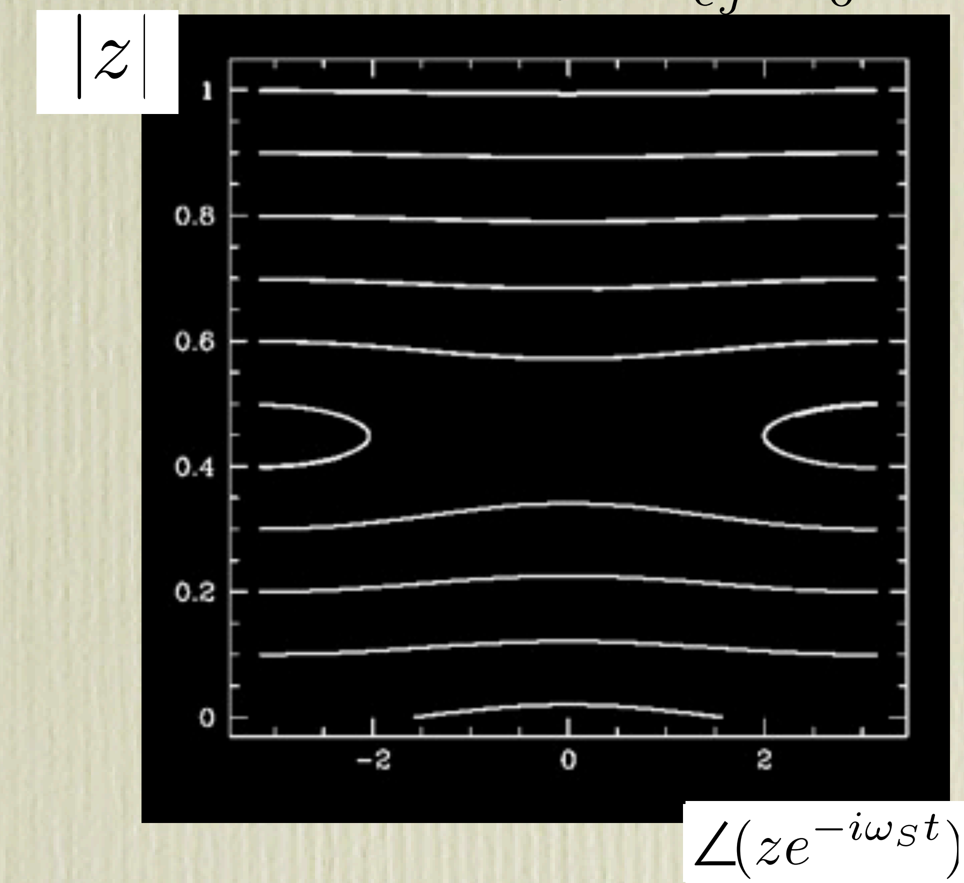
$$\frac{d}{dt}z = i\left[(1-\frac{|z|^2}{2})z - \epsilon_J e^{i\omega_J t} - \epsilon_S e^{i\omega_S t}\right]$$

Case 1: nonoverlapping resonances

Jupiter only ($\epsilon_J = .001$, $\omega_J = .7$, $\epsilon_S = 0$)



Saturn only ($\epsilon_S = .001$, $\omega_S = .9$, $\epsilon_J = 0$)



$$\frac{d}{dt}z = i\left[(1-\frac{|z|^2}{2})z - \epsilon_J e^{i\omega_J t} - \epsilon_S e^{i\omega_S t}\right]$$

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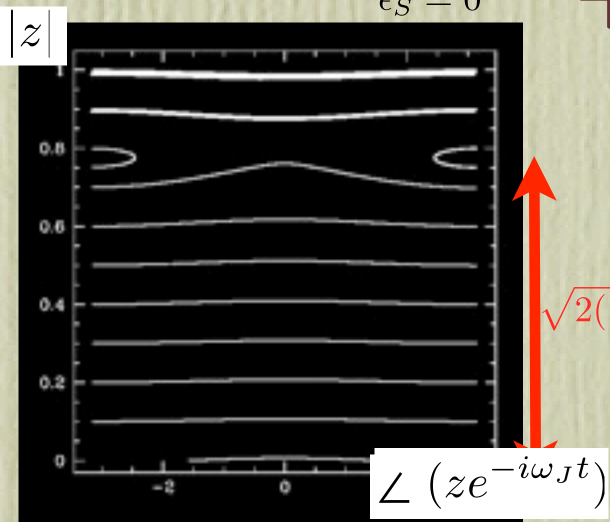

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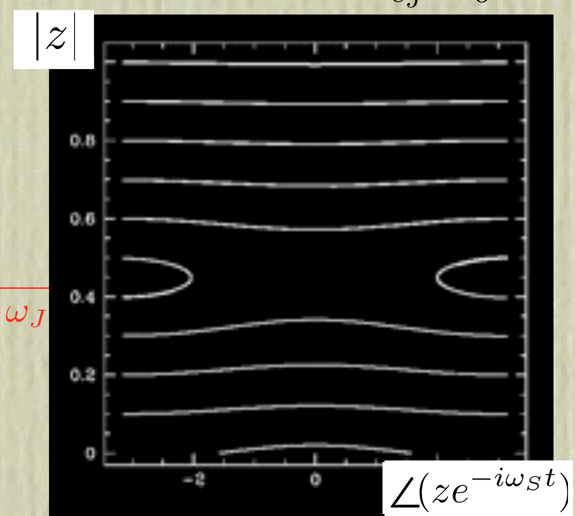


=

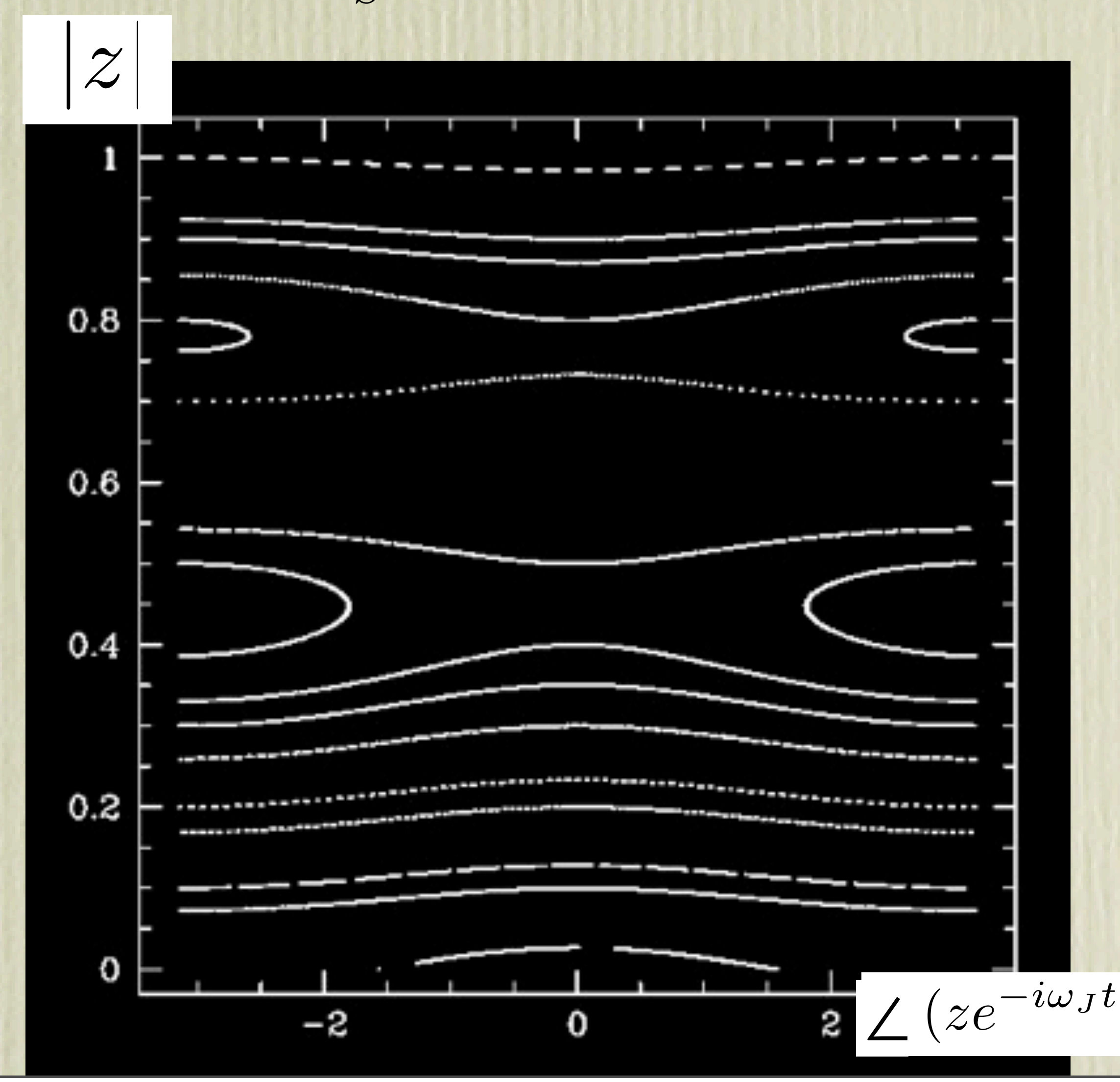
Jupiter & Saturn together

$\epsilon_J = .001$

$\epsilon_S = .001$

$\omega_J = .7$

$\omega_S = .9$

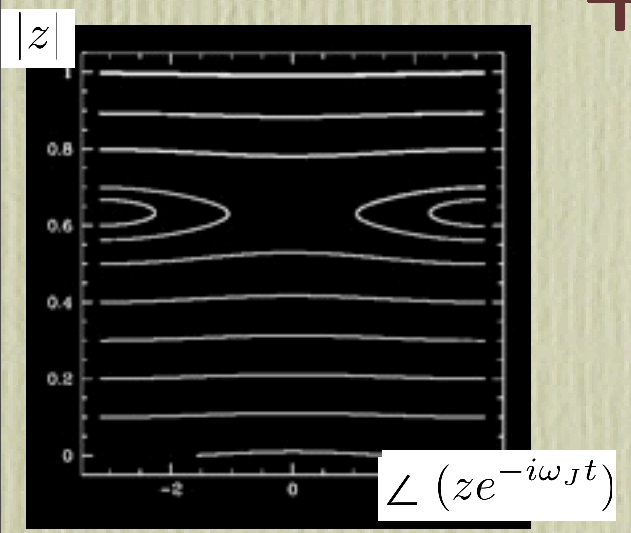


(surface of section, plotted when $e^{it(\omega_J - \omega_S)} = 1$)

$$\frac{d}{dt}z = i\left[(1-\frac{|z|^2}{2})z - \epsilon_J e^{i\omega_J t} - \epsilon_S e^{i\omega_S t}\right]$$

Case 2: overlapping resonances

Jupiter only



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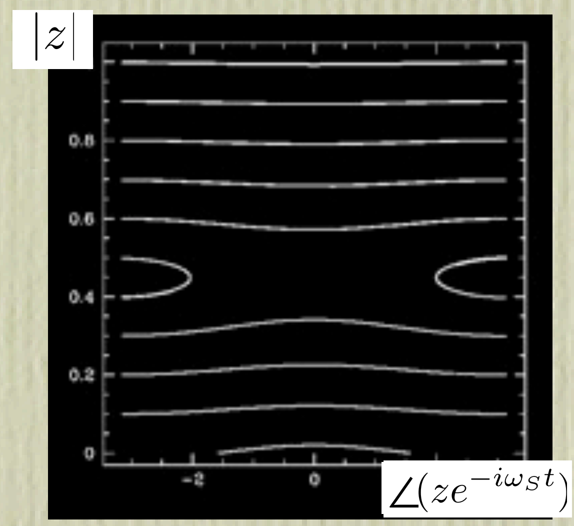
Saturn only



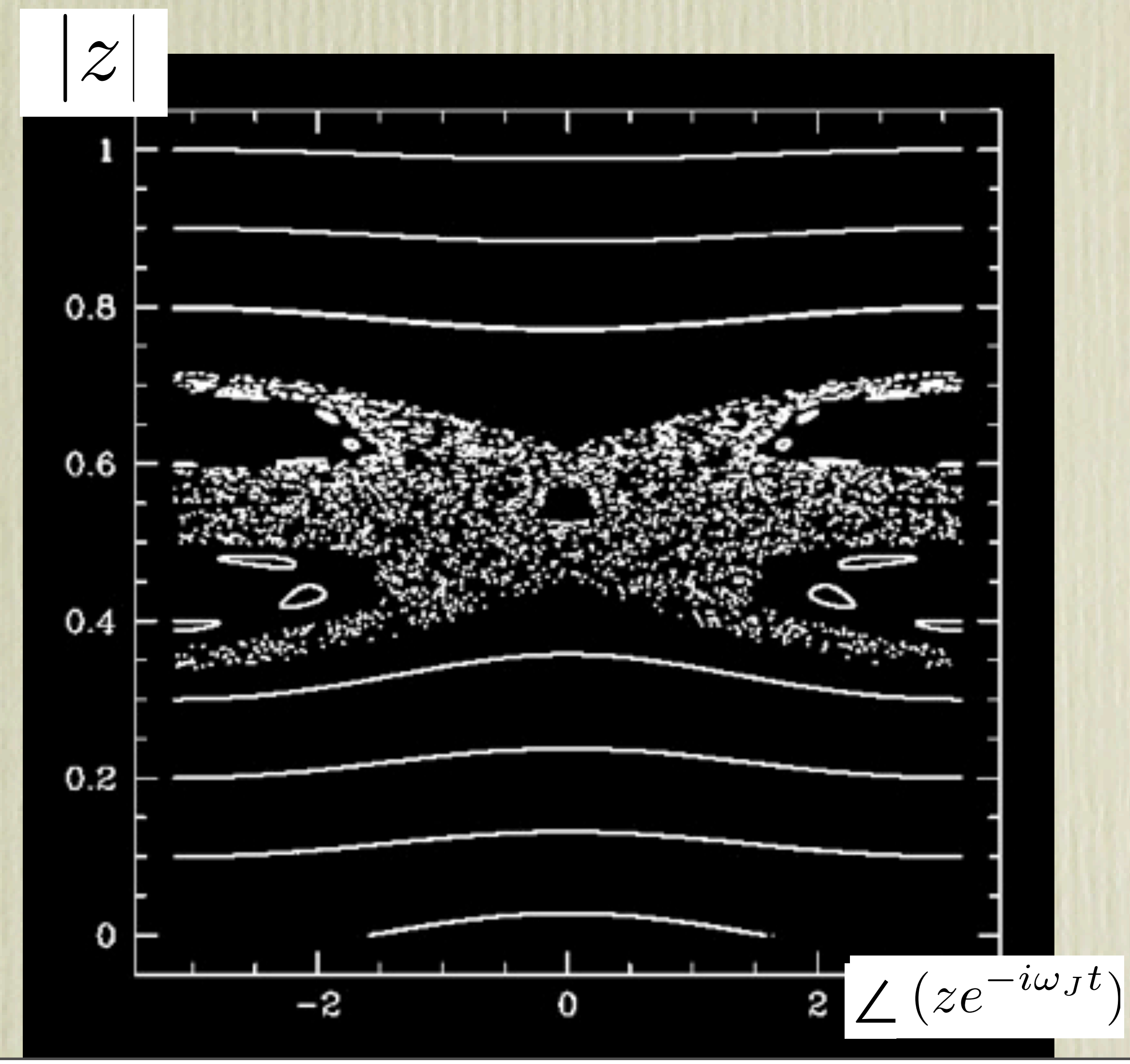
= Jupiter & Saturn together

$\epsilon_J = .001$

$\epsilon_S = .001$

$\cancel{\omega_J = .7} \rightarrow \omega_J = .8$

$\omega_S = .9$



(surface of section, plotted when $e^{it(\omega_J - \omega_S)} = 1$)

Inclination

Mercury perturbed by eccentric Jupiter and inclined Venus:

$$\sigma \equiv ie^{i\Omega}$$

Mercury's inclination

orientation of inclined orbital plane ("longitude of ascending node")

$$\frac{d}{dt}z = i[(1 - \tfrac{|z|^2}{2} - 2|\sigma|^2)z + \tfrac{5}{2}\, z^*\sigma^2 - \epsilon_J e^{i\omega_J t}]$$

$$\frac{d}{dt}\sigma = i[(-1 + \tfrac{|\sigma|^2}{2} - 2|z|^2)\sigma + \tfrac{5}{2}\,\sigma^* z^2 - i_{\mathrm{V}}\, e^{i\omega_{\mathrm{V}} t}]$$

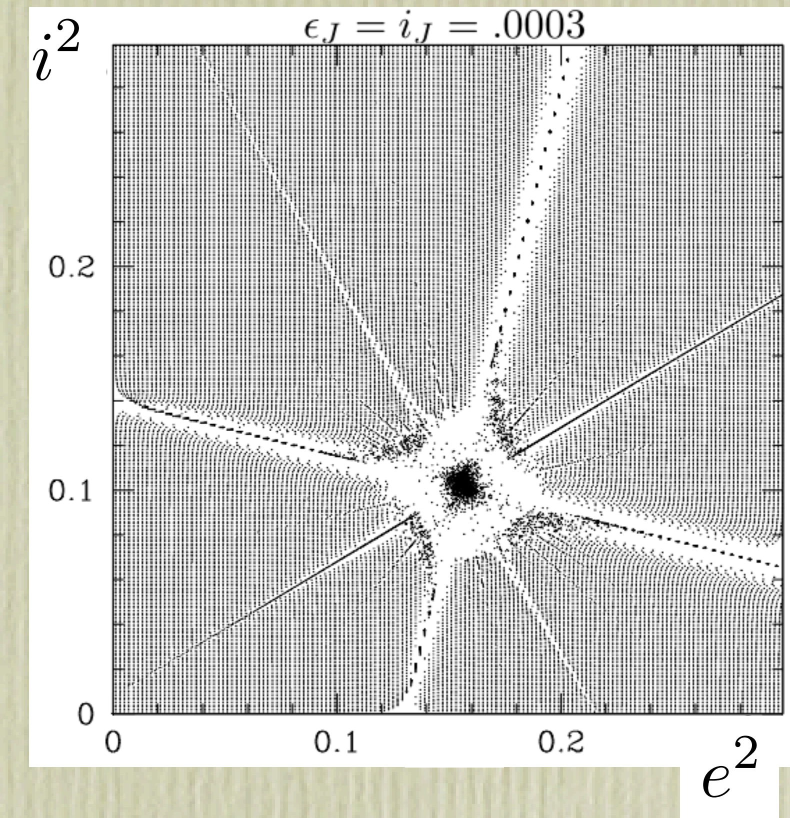
(some terms omitted)

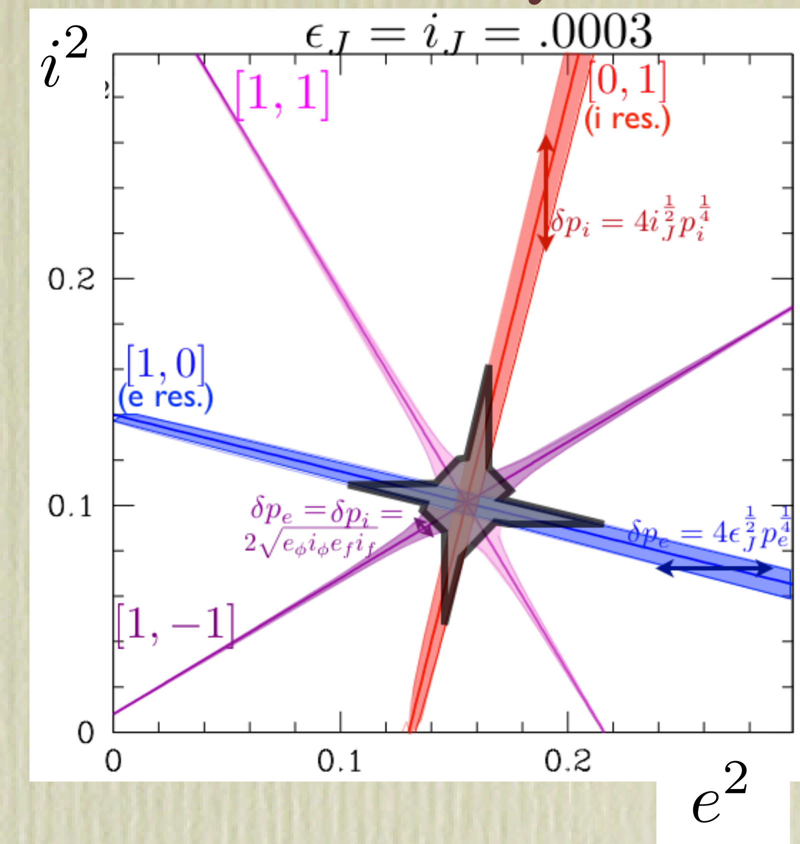
Inclination

Simulation

Theory

low forcing:





true forcing: