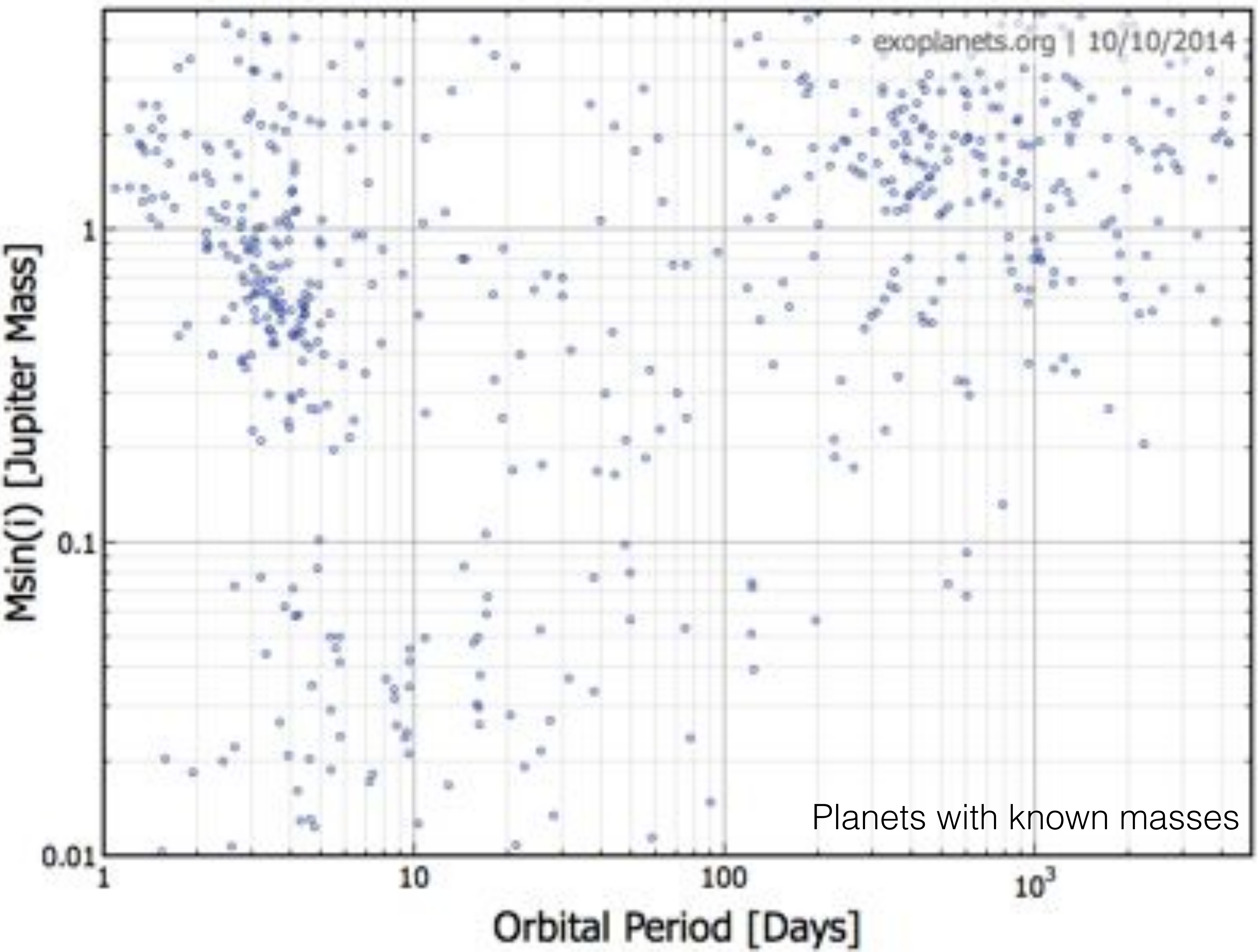
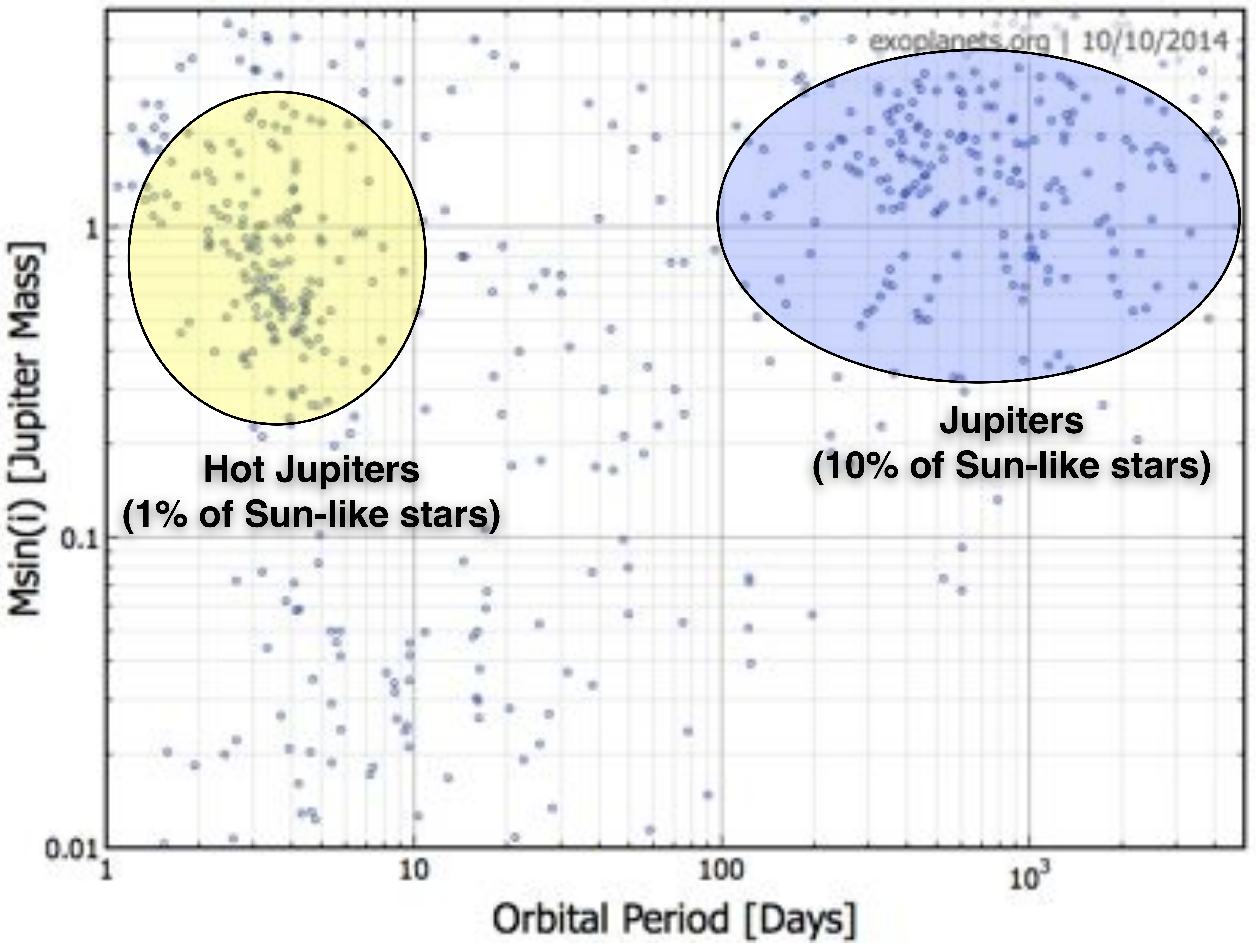
Viewing Solar System Architecture Through an Extrasolar Lens

Konstantin Batygin (Caltech)
Greg Laughlin (UC Santa Cruz)

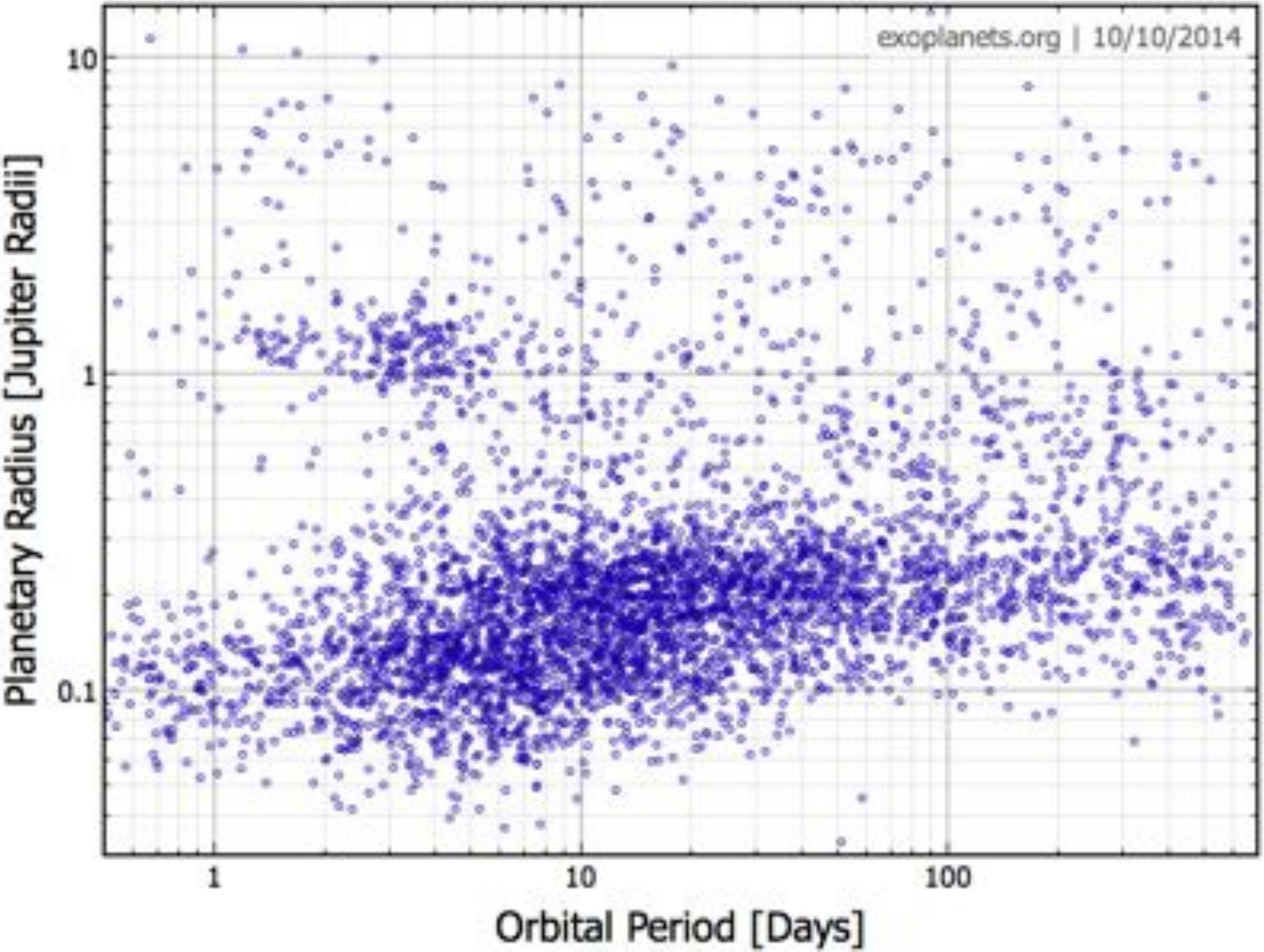


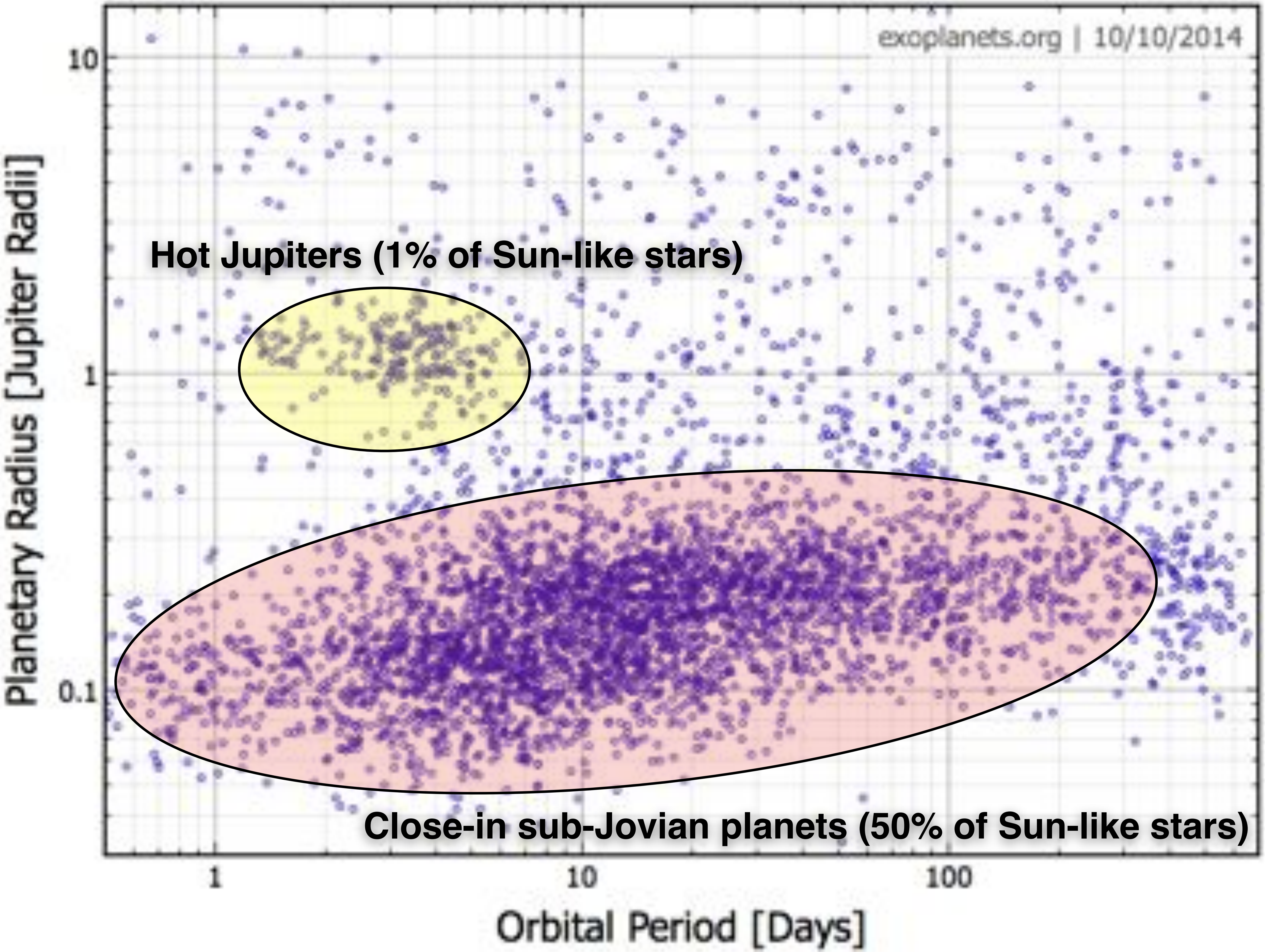
Planets with known masses



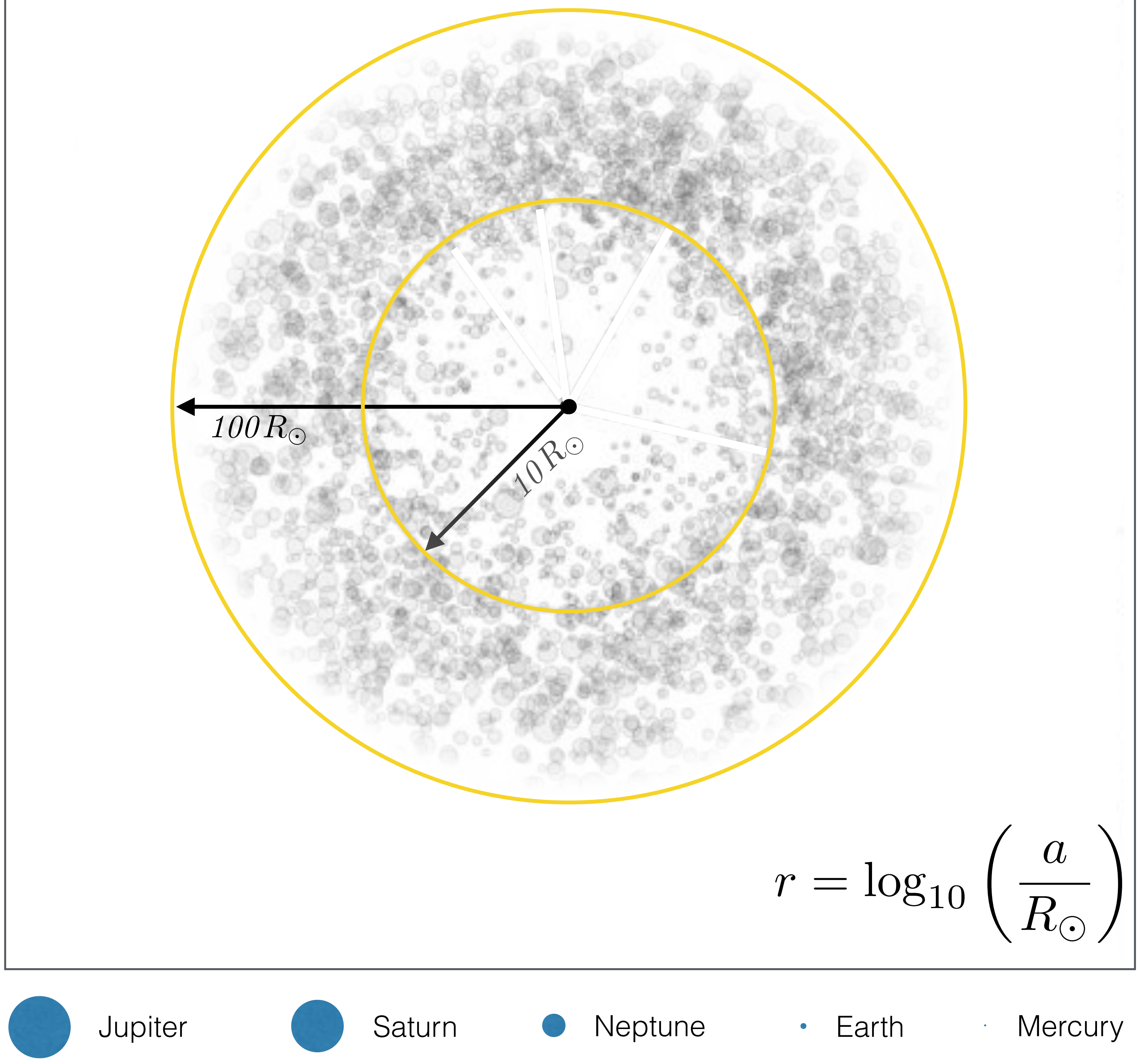
Hot Jupiters
(1% of Sun-like stars)

Jupiters
(10% of Sun-like stars)

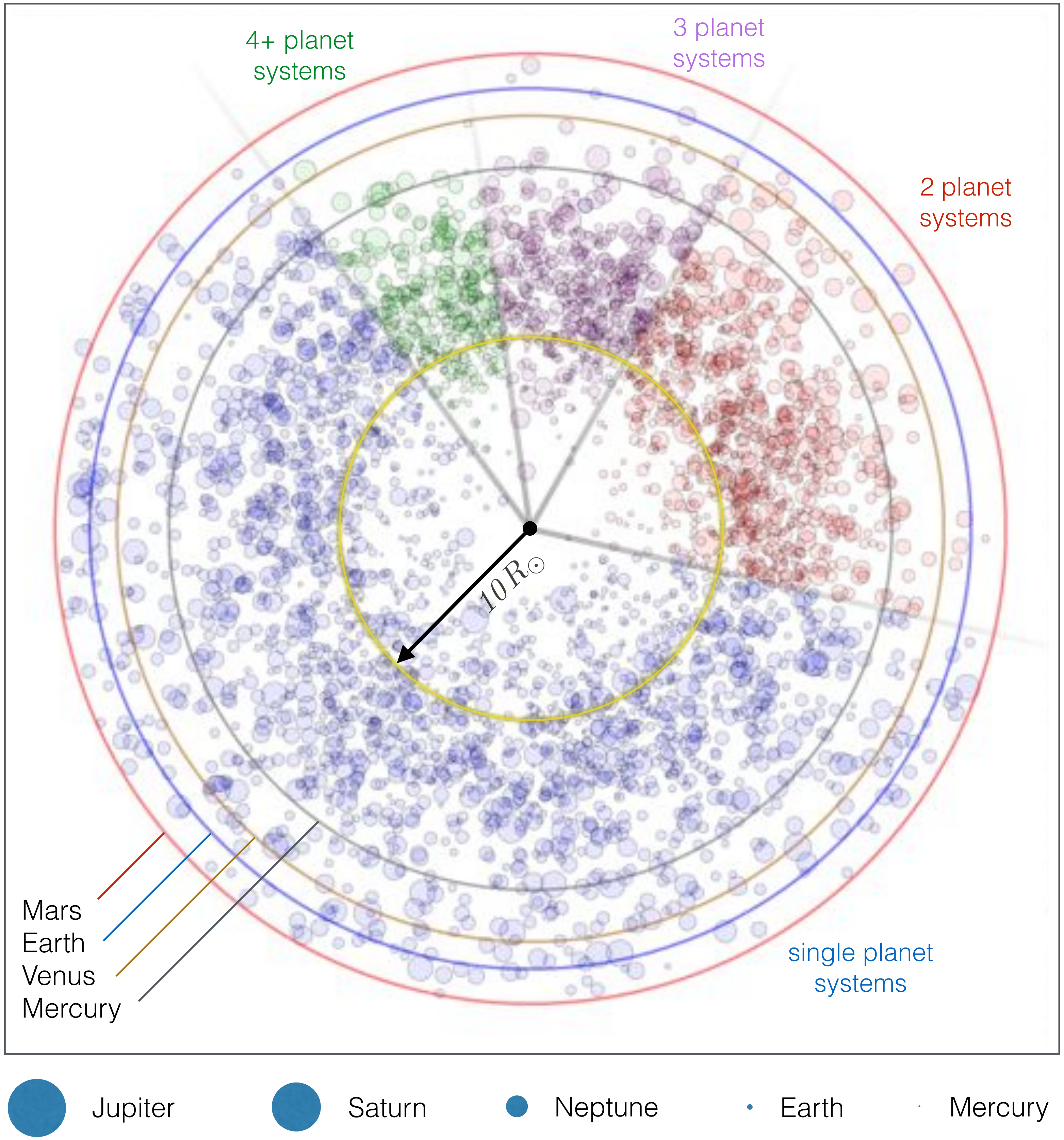

exoplanets.org | 10/10/2014
Planetary Radius [Jupiter Radii]
10
1
0.1
Orbital Period [Days]
1
10
100


exoplanets.org | 10/10/2014
Planetary Radius [Jupiter Radii]
10
1
0.1
1
10
100
Orbital Period [Days]
Hot Jupiters (1% of Sun-like stars)
Close-in sub-Jovian planets (50% of Sun-like stars)

Kepler Planet Candidates (sub-Jovian)



$$r = \log_{10}\left(\frac{a}{R_\odot}\right)$$


4+ planet systems
3 planet systems
2 planet systems
single planet systems
10 R⊙
Mars
Earth
Venus
Mercury
Jupiter
Saturn
Neptune
Earth
Mercury

Minimum Mass Solar Nebula

(Hayashi 1981)

$$\Sigma = 1700 \left(\frac{a}{1\mathrm{AU}} \right)^{-1.5} \mathrm{g/cm^2}$$

$f_{\mathrm{dust}} \sim 0.5\%$ $a < 2.7\mathrm{AU}$

$f_{\mathrm{dust}} \sim 1.5\%$ $a > 2.7\mathrm{AU}$

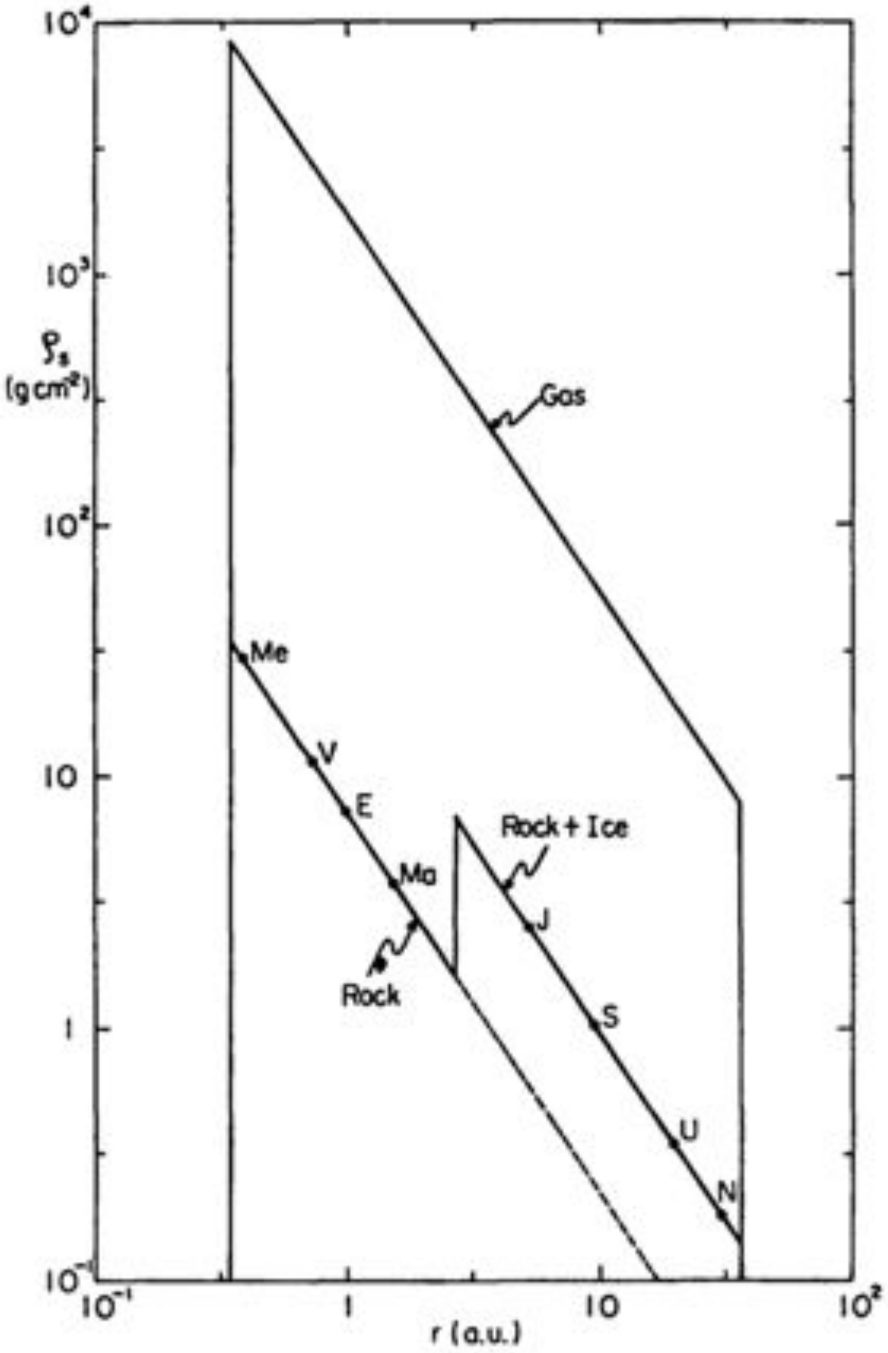


Fig. 1. Surface densities of rocky, icy and gaseous materials in the solar nebula as a function of the distance from the sun.

Minimum Mass Solar Nebula

(Hayashi 1981)

$$\Sigma = 1700 \left(\frac{a}{1\mathrm{AU}}\right)^{-1.5} \mathrm{g/cm^2}$$

$f_{\mathrm{dust}} \sim 0.5\%$ $a < 2.7$AU

$f_{\mathrm{dust}} \sim 1.5\%$ $a > 2.7$AU

Minimum Mass Extrasolar Nebula

(Chiang & Laughlin 2013)

$$\Sigma \sim 10^4 \left(\frac{a}{1\mathrm{AU}}\right)^{-1.6} \mathrm{g/cm^2}$$

$f_{\mathrm{dust}} \sim 0.5\%$

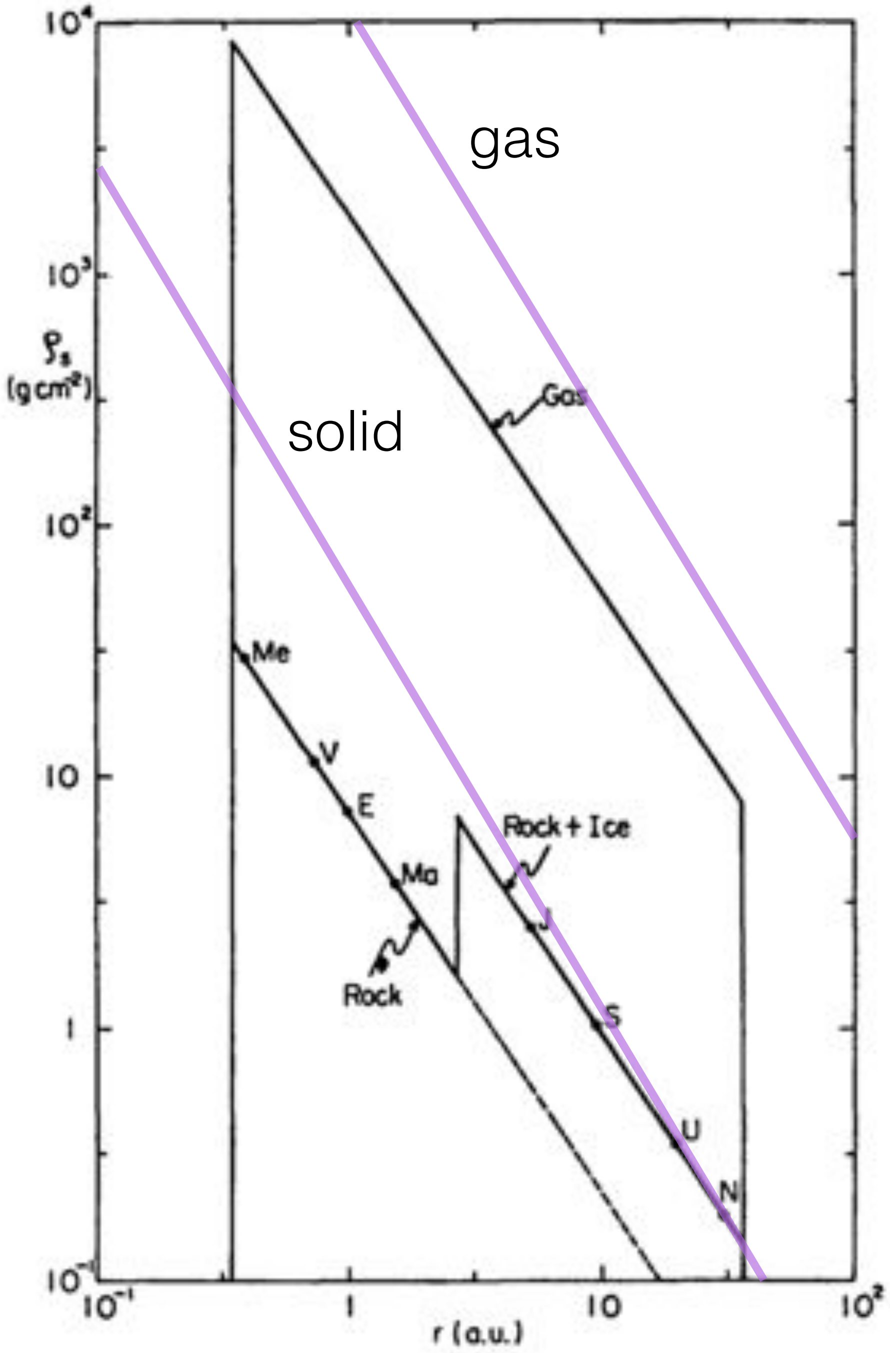
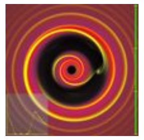


Fig. 1. Surface densities of rocky, icy and gaseous materials in the solar nebula as a function of the distance from the sun.

Relative to other Sun-like, planet-bearing stars, the Solar system’s terrestrial region is severely depleted in mass.

Relative to other Sun-like, planet-bearing stars, the Solar systems’ terrestrial region is severely depleted in mass.

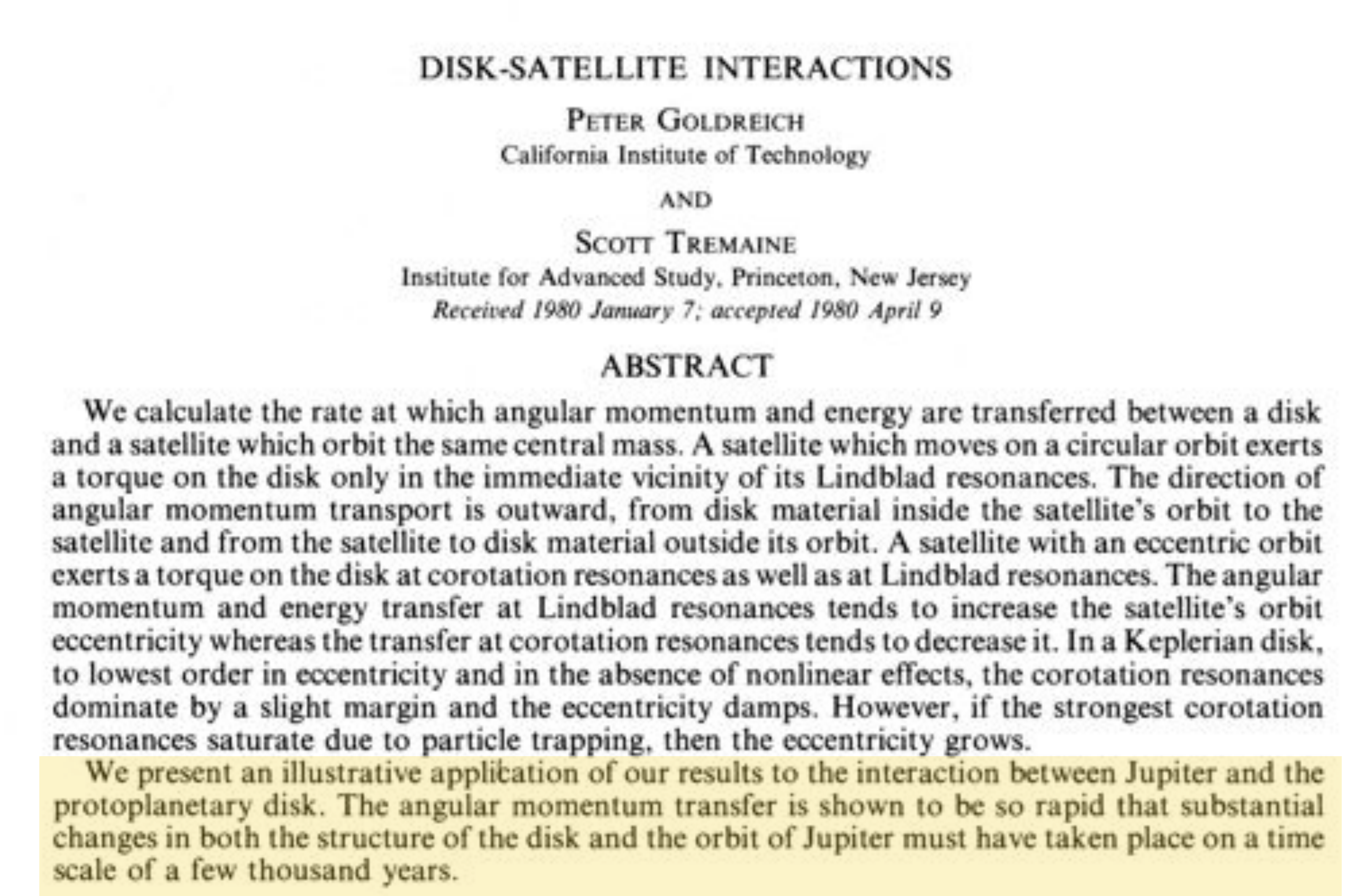
Our proposition:


Long-range (a few AU) migration of Jupiter in the Solar nebula


Orbital excitation of planetesimals by resonant sweeping


Destructive collisional cascade and removal by aerodynamic drift


Resonant shepherding of close-in planets by drifting debris



DISK-SATELLITE INTERACTIONS

PETER GOLDREICH
California Institute of Technology

AND

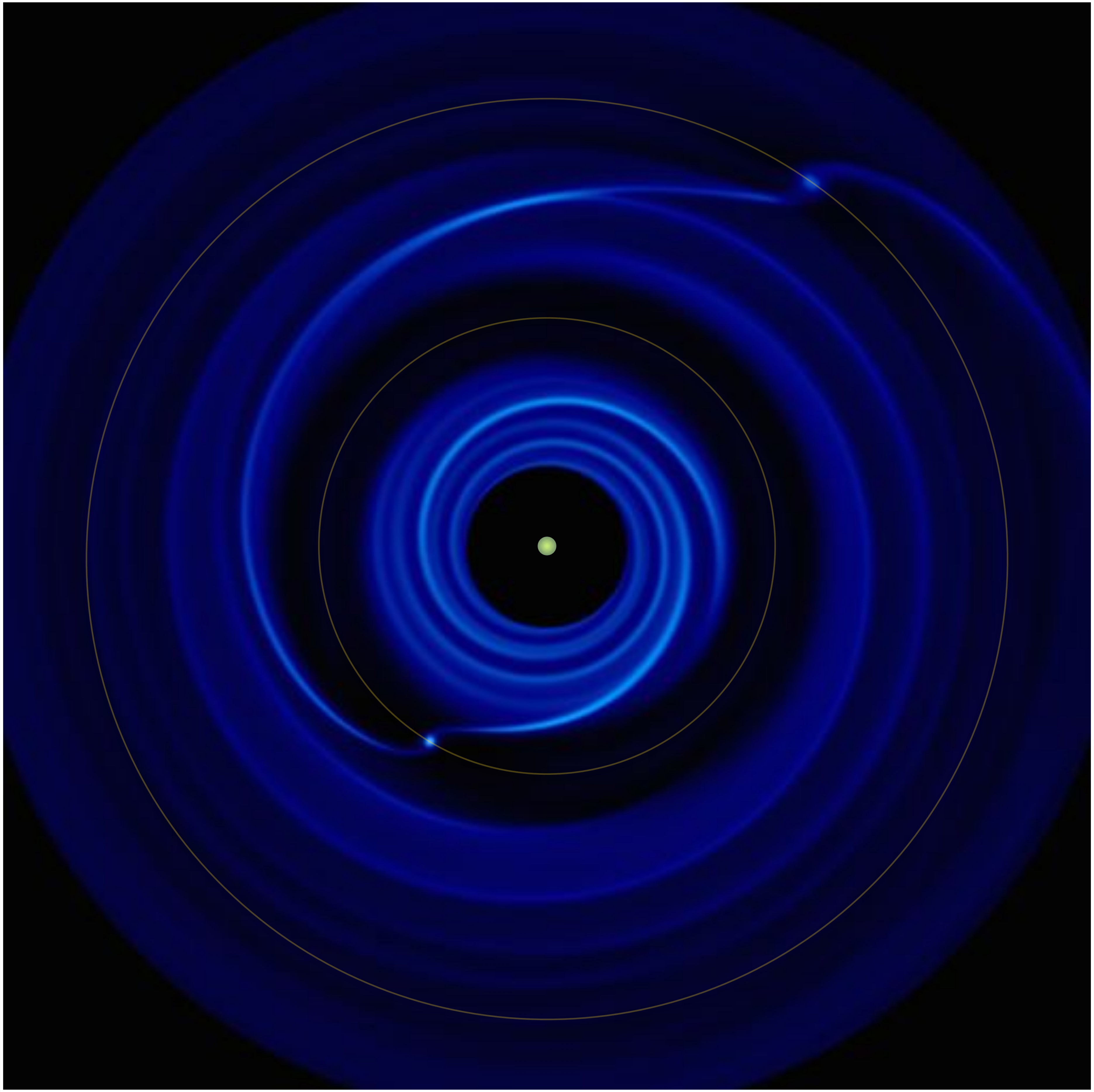
SCOTT TREMAINE
Institute for Advanced Study, Princeton, New Jersey

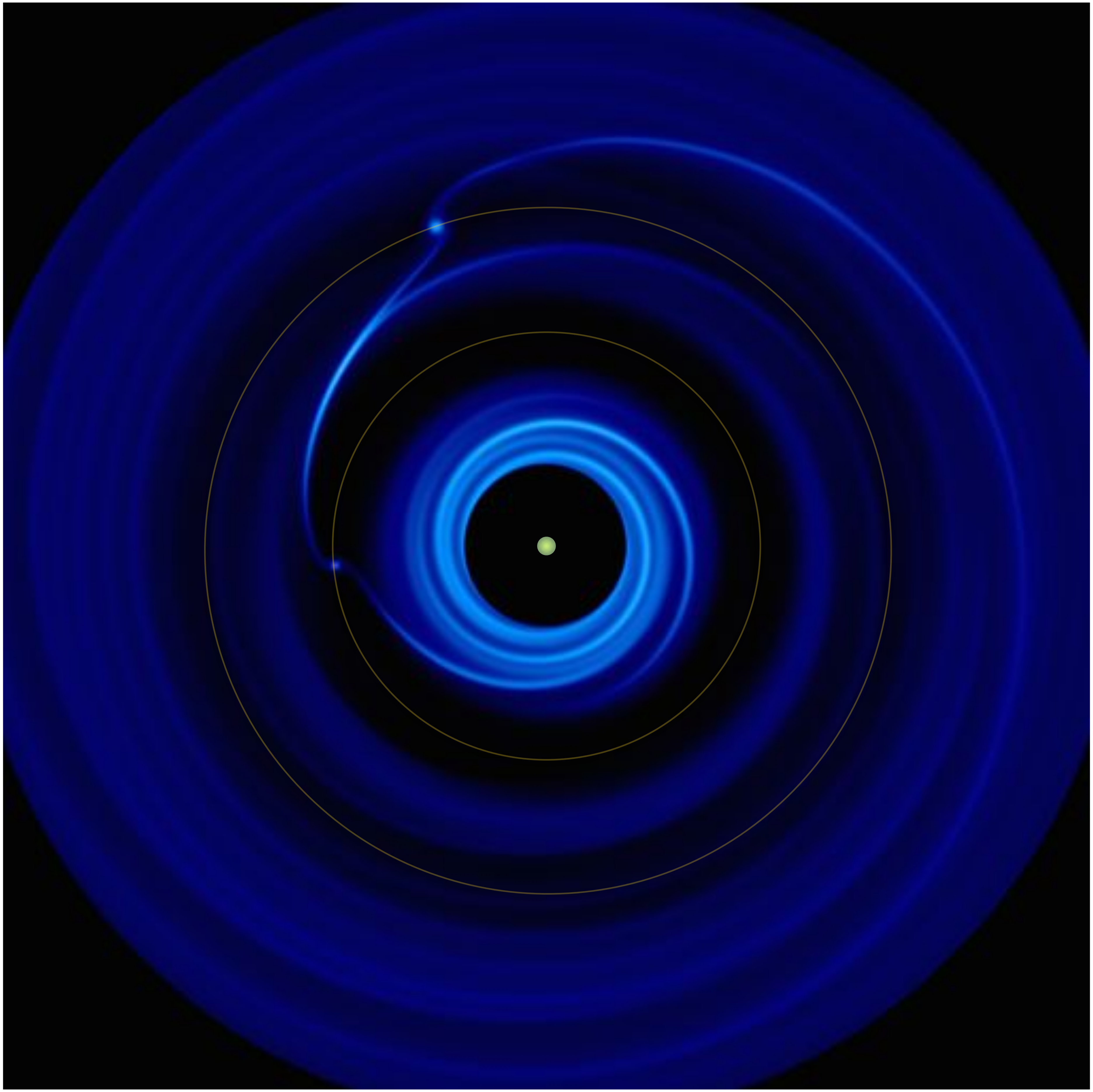
Received 1980 January 7; accepted 1980 April 9

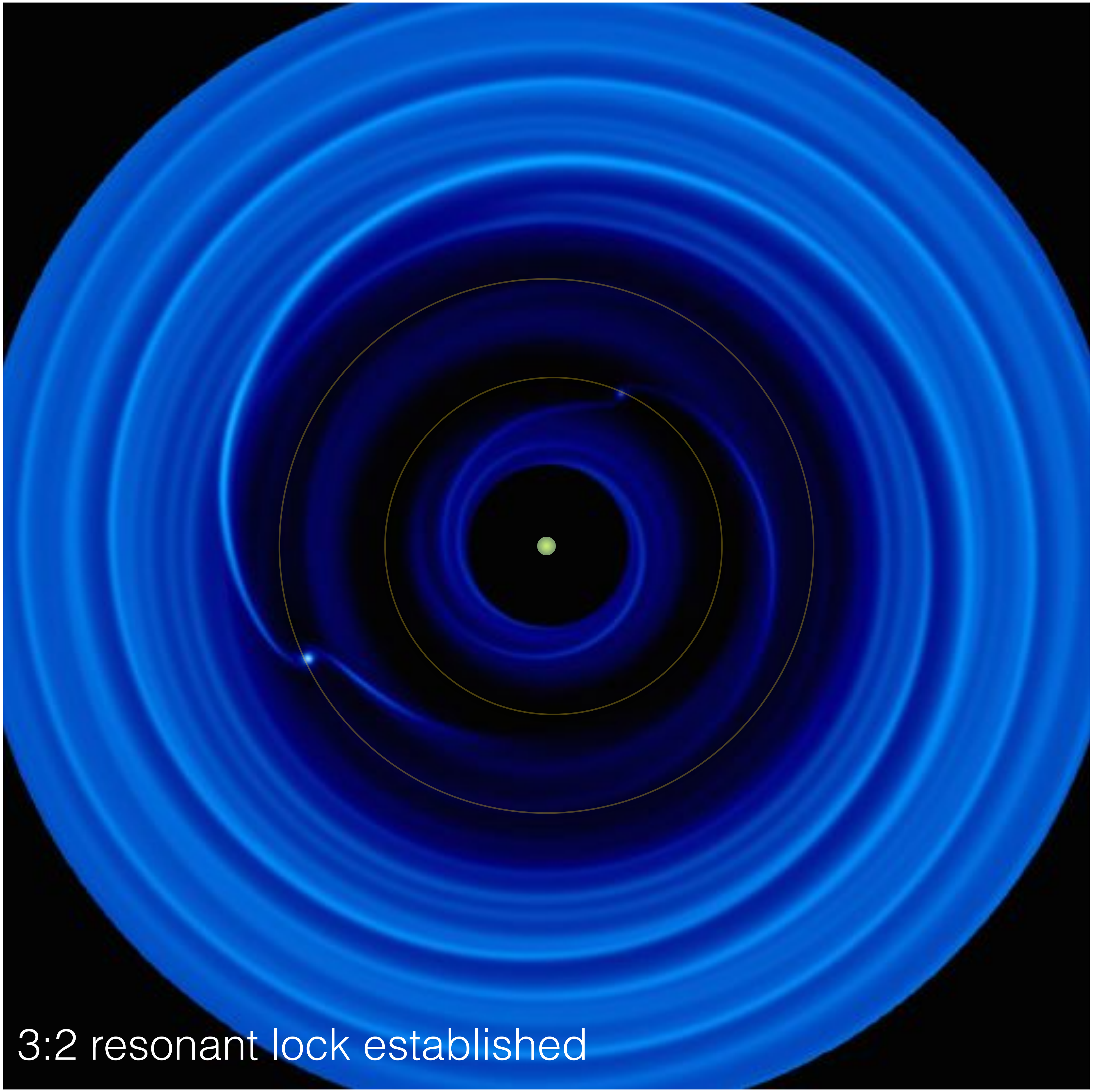
ABSTRACT

We calculate the rate at which angular momentum and energy are transferred between a disk and a satellite which orbit the same central mass. A satellite which moves on a circular orbit exerts a torque on the disk only in the immediate vicinity of its Lindblad resonances. The direction of angular momentum transport is outward, from disk material inside the satellite's orbit to the satellite and from the satellite to disk material outside its orbit. A satellite with an eccentric orbit exerts a torque on the disk at corotation resonances as well as at Lindblad resonances. The angular momentum and energy transfer at Lindblad resonances tends to increase the satellite's orbit eccentricity whereas the transfer at corotation resonances tends to decrease it. In a Keplerian disk, to lowest order in eccentricity and in the absence of nonlinear effects, the corotation resonances dominate by a slight margin and the eccentricity damps. However, if the strongest corotation resonances saturate due to particle trapping, then the eccentricity grows.

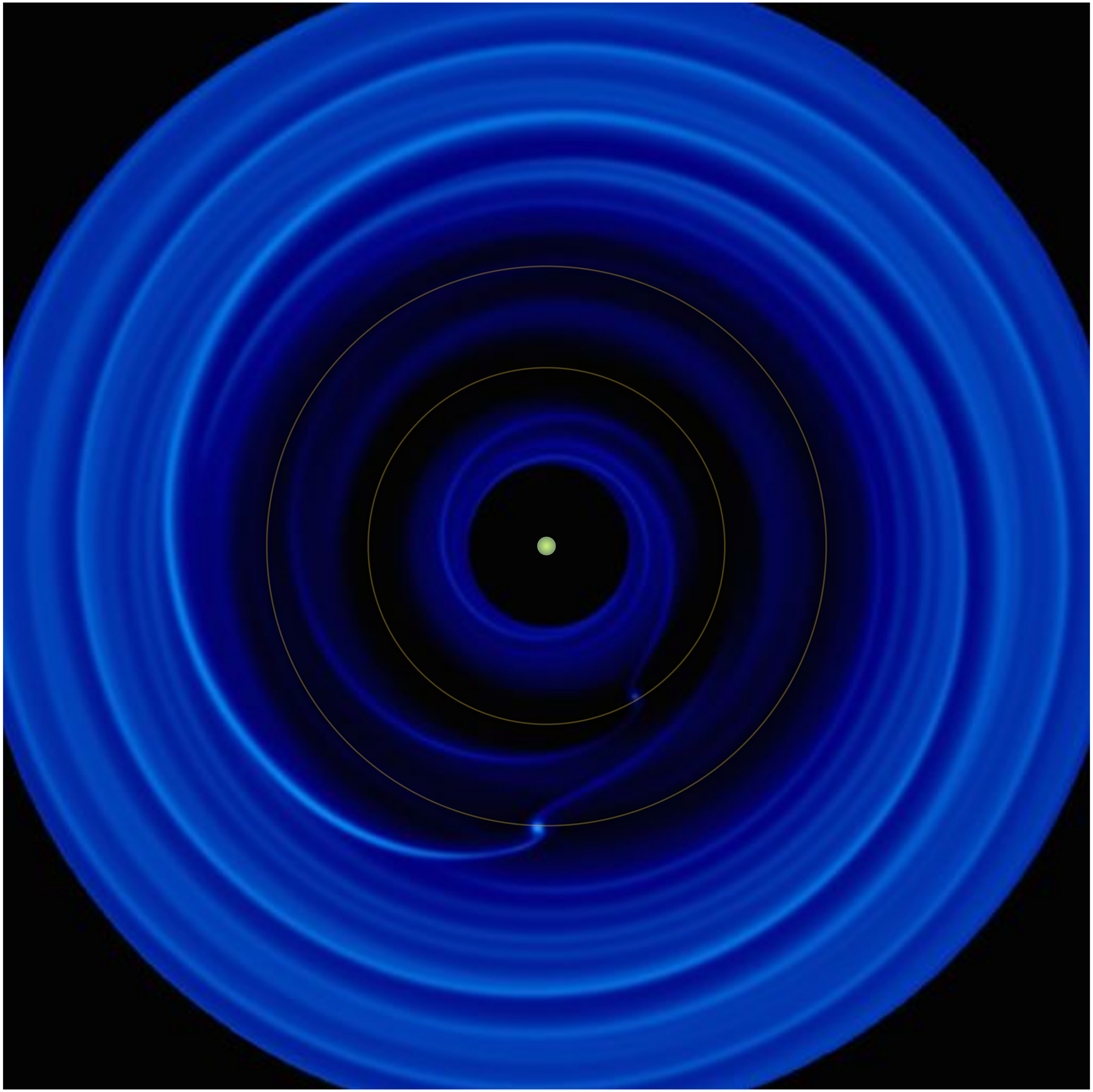
We present an illustrative application of our results to the interaction between Jupiter and the protoplanetary disk. The angular momentum transfer is shown to be so rapid that substantial changes in both the structure of the disk and the orbit of Jupiter must have taken place on a time scale of a few thousand years.

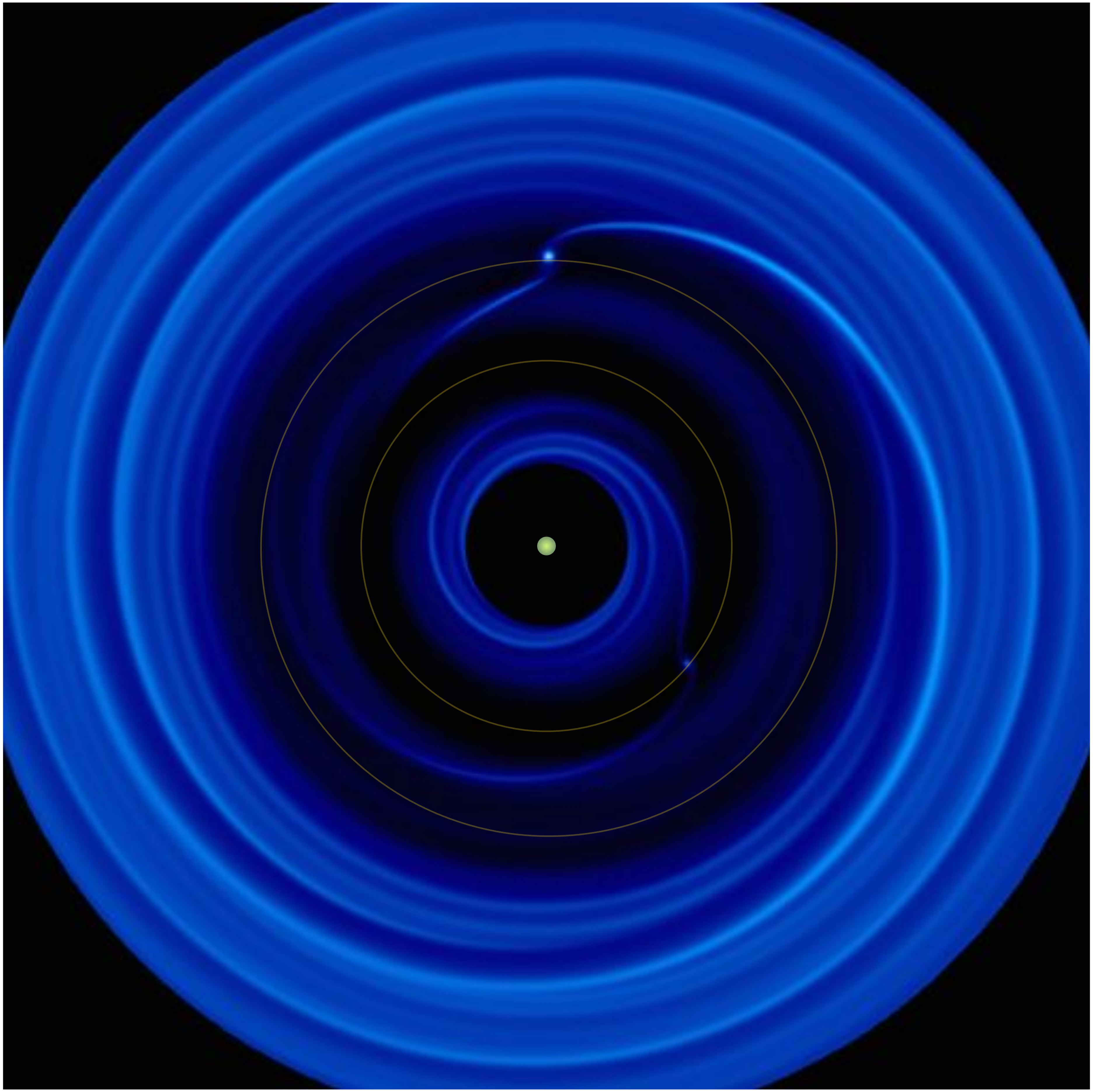


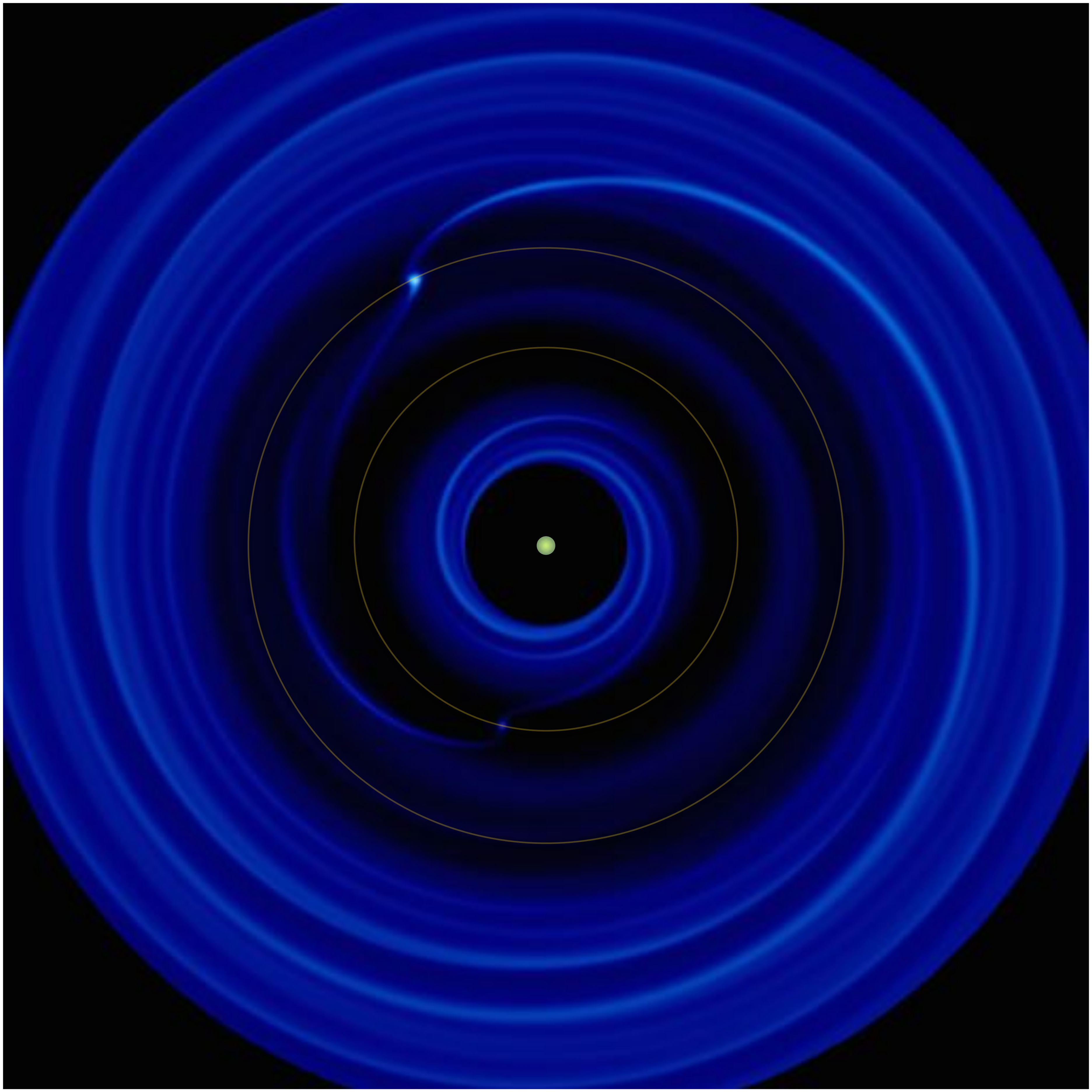




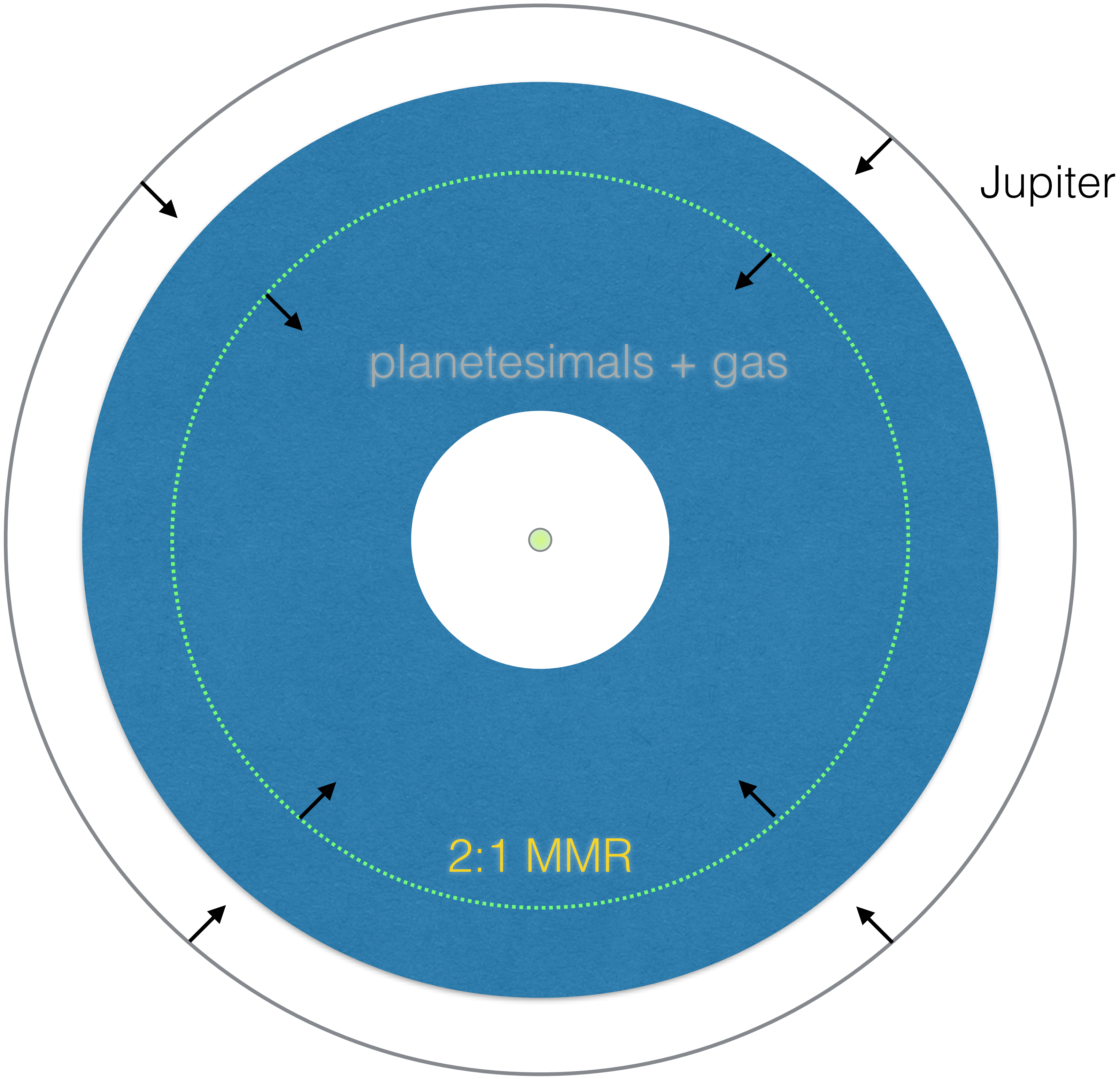
3:2 resonant lock established



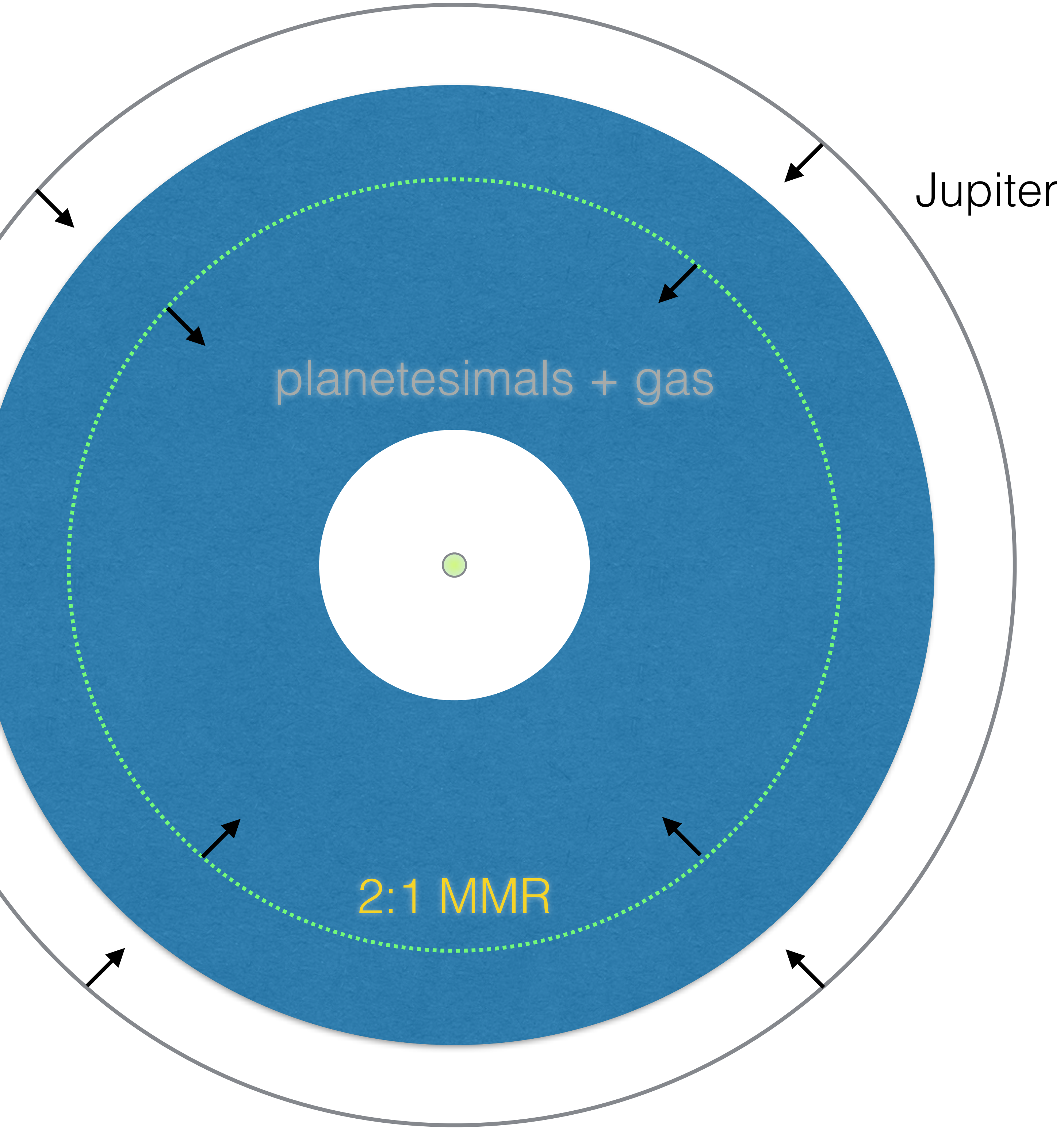




Jupiter’s inward trek resonantly sweeps up planetesimals

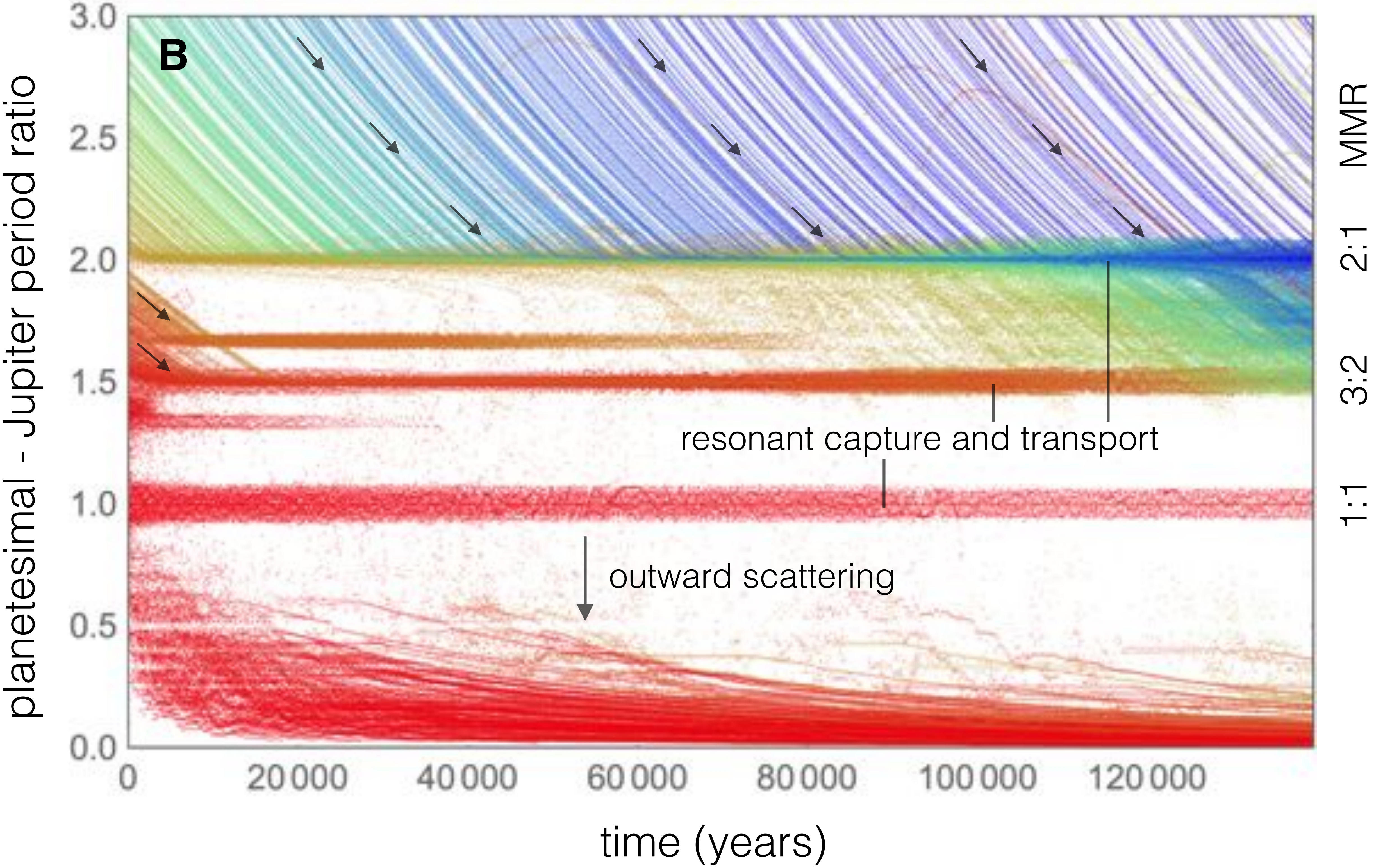


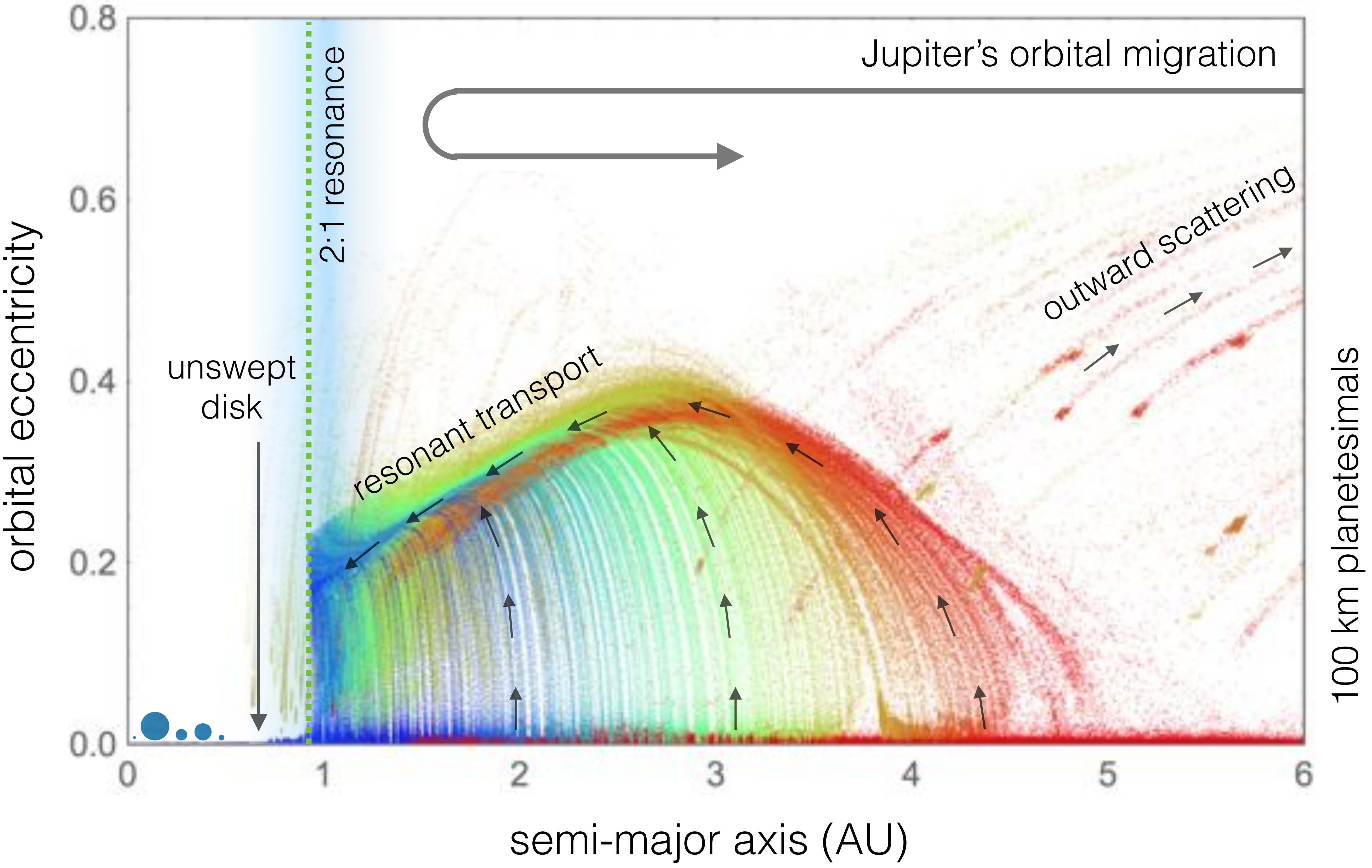
Jupiter's inward trek resonantly sweeps up planetesimals

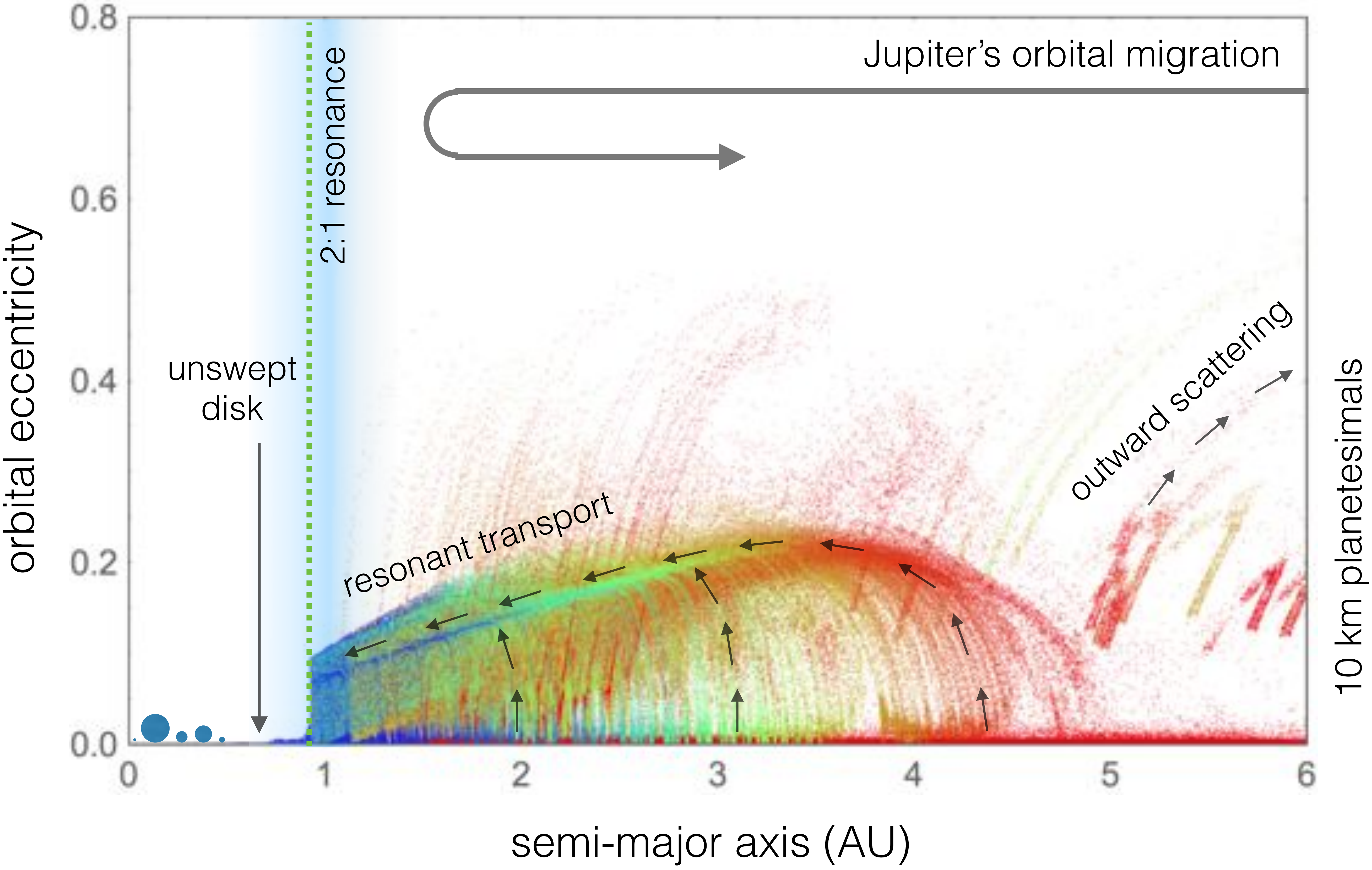


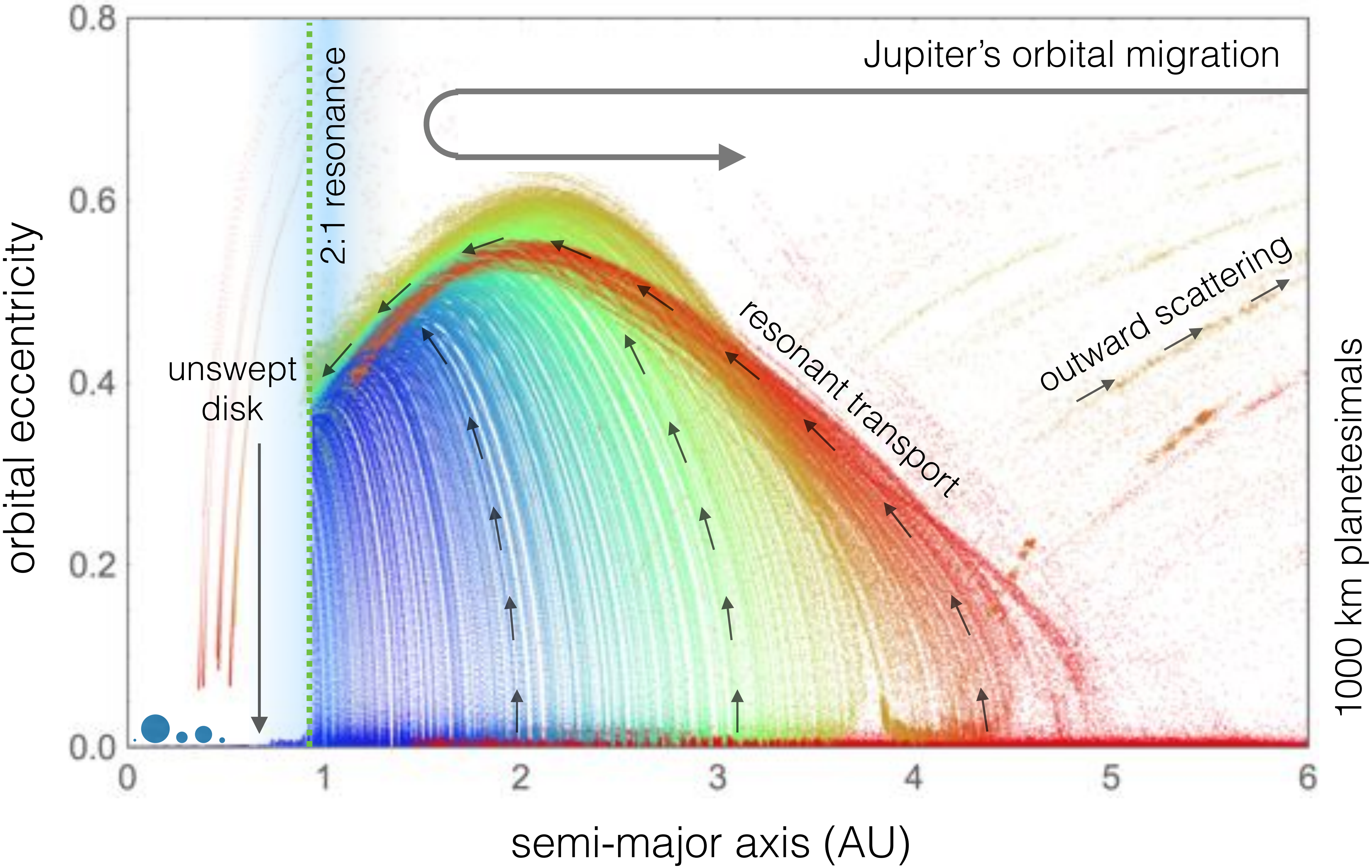
Adiabatic invariance dictates excitation of orbital eccentricity

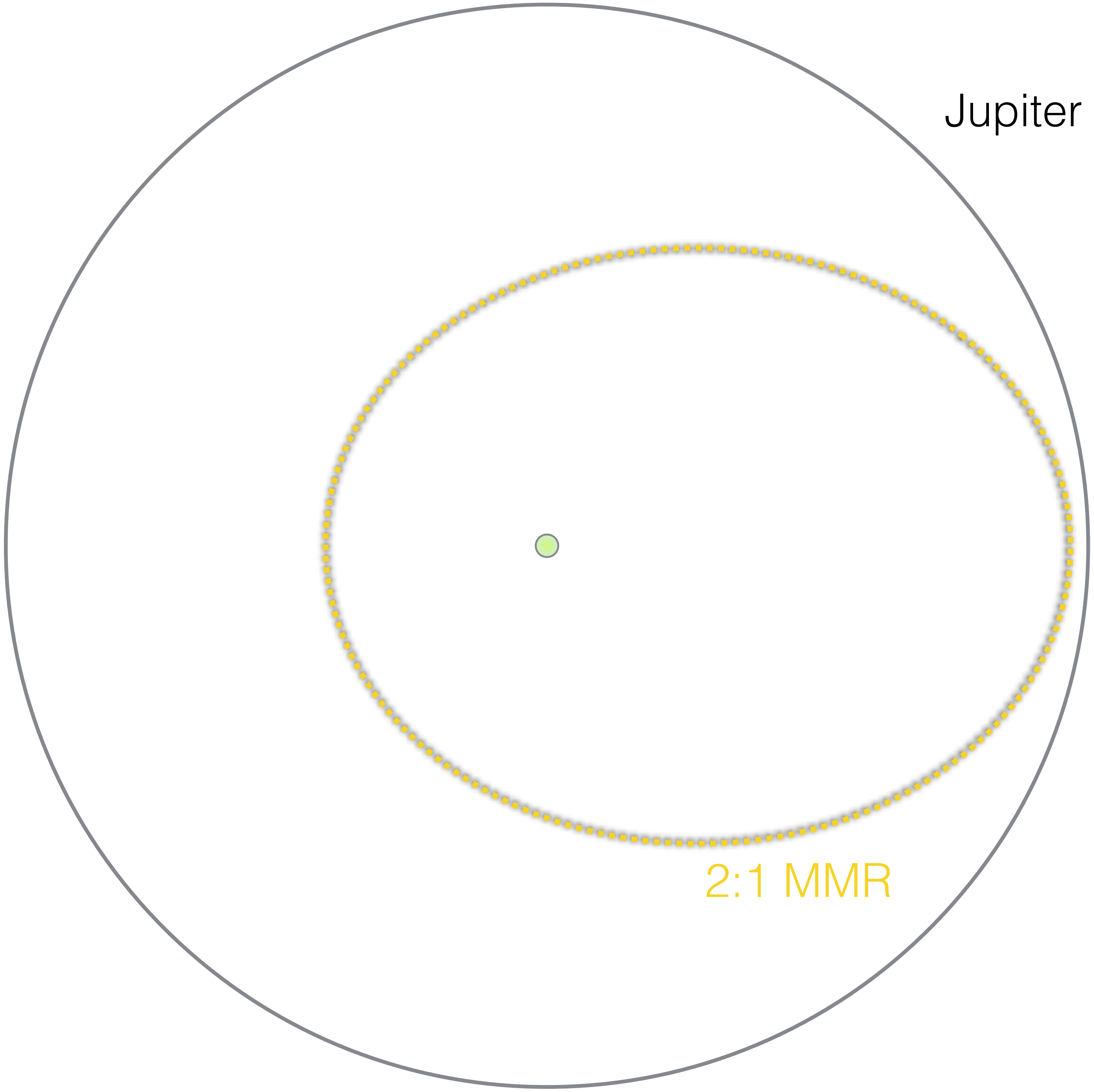
$$\boxed{\sqrt{a}\downarrow\left[1-\sqrt{1-\uparrow e^2}\right] = \mathrm{const.}}$$

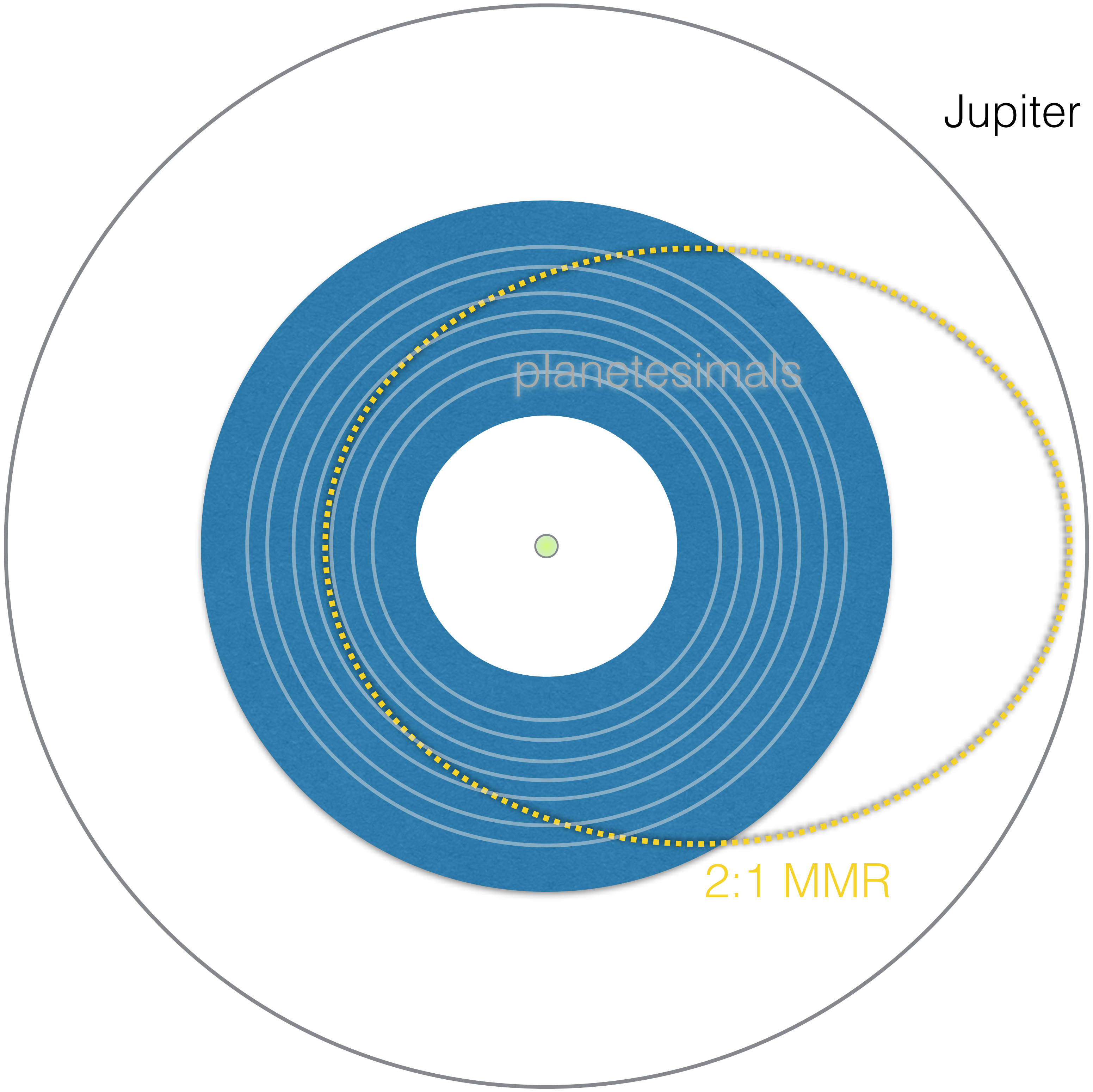

B
planetesimal - Jupiter period ratio
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
20000
40000
60000
80000
100000
120000
time (years)
MMR
2:1
3:2
1:1
resonant capture and transport
outward scattering

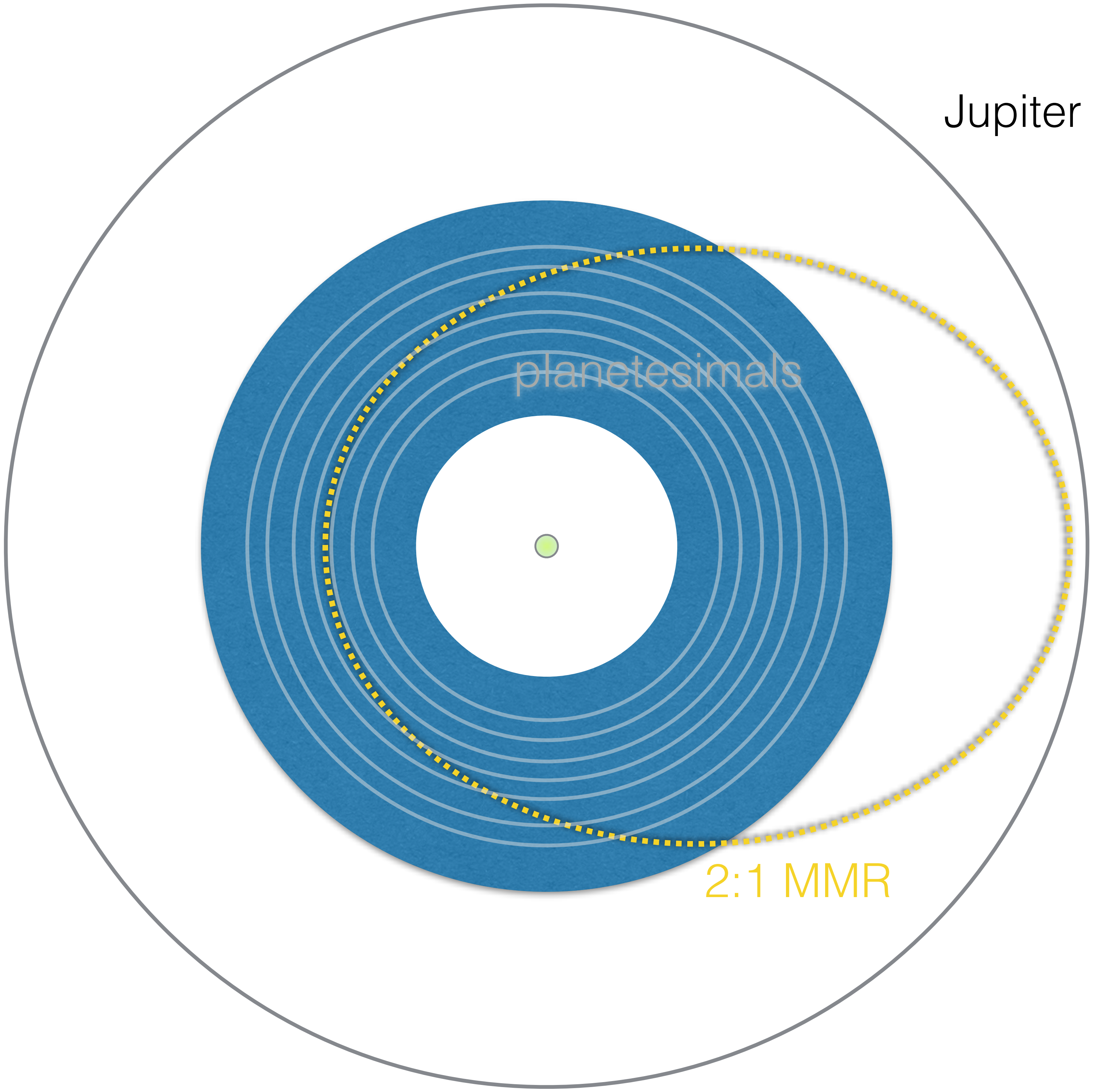

Jupiter's orbital migration
2:1 resonance
unswept disk
resonant transport
outward scattering
100 km planetesimals
orbital eccentricity
semi-major axis (AU)
0.0
0.2
0.4
0.6
0.8
0
1
2
3
4
5
6


Jupiter's orbital migration
2:1 resonance
unswept disk
resonant transport
outward scattering
10 km planetesimals
orbital eccentricity
0.0
0.2
0.4
0.6
0.8
semi-major axis (AU)
0
1
2
3
4
5
6


Jupiter's orbital migration
2:1 resonance
unswept disk
resonant transport
outward scattering
1000 km planetesimals
orbital eccentricity
semi-major axis (AU)
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6


Jupiter
2:1 MMR


Jupiter
planetesimals
2:1 MMR



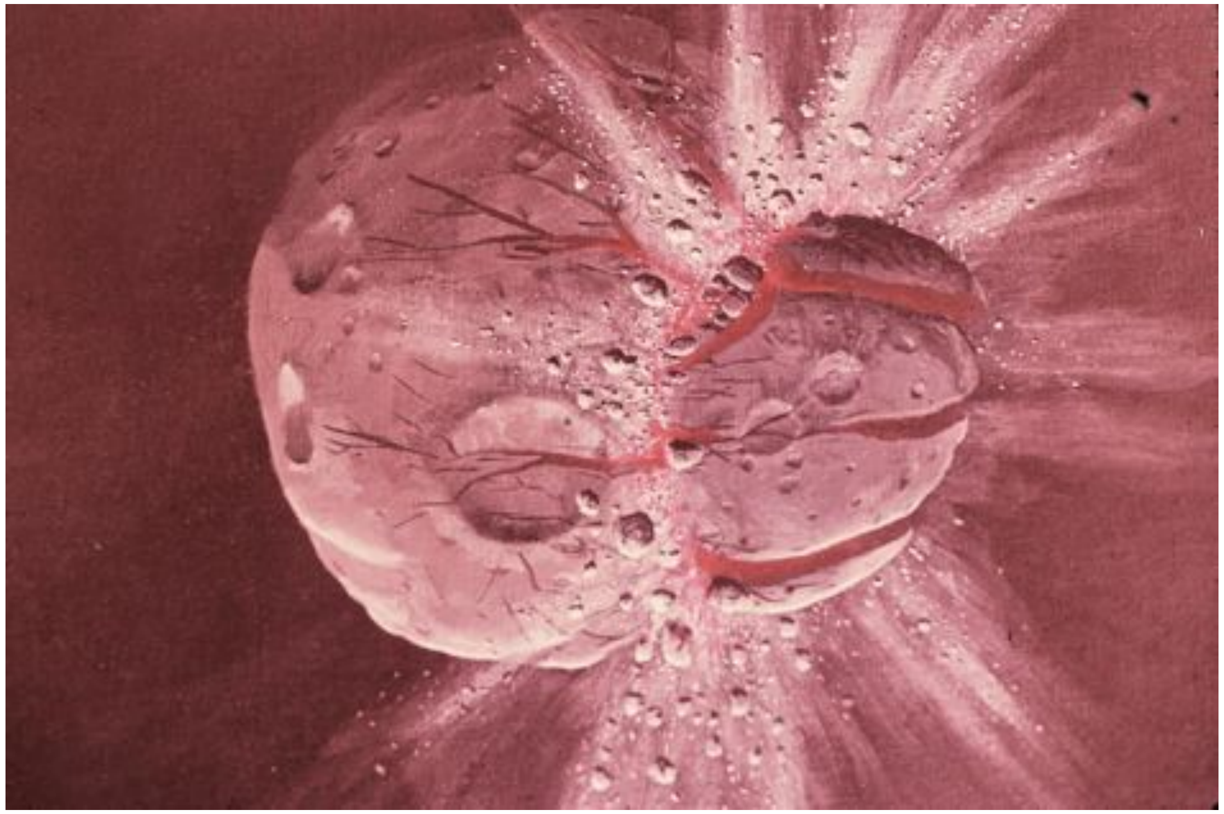
$$\nu \sim n\,\sigma\,v = \frac{M_{\rm tot}/m}{2\pi\langle e\rangle\tan\langle i\rangle a^3}\,\pi s^2 v_{\rm K}\langle e\rangle$$ ~ a collision every ~20 orbits

Collisions can lead to

fragmentation

or

accretion



Collisions are catastrophic if:

$$\left(\frac{m'}{M}\right)\left(\frac{v_{\mathrm{enc}}^2}{2}\right) > \frac{1}{2}\rho\left(\frac{R}{1\,\mathrm{cm}}\right)^{1.36}$$

(Leinhardt & Stewart 2009)

Collisions are catastrophic if:

$$\left(\frac{m'}{M}\right)\left(\frac{\overset{\overset{\sim e\,v_{\mathrm{kep}}}{\downarrow}}{v_{\mathrm{enc}}^2}}{2}\right) > \frac{1}{2}\underset{\underset{3\text{ g/cm}^3\text{ (rock)}}{\uparrow}}{\rho}\left(\frac{\overset{\overset{10,100,1000\text{ km}}{\downarrow}}{R}}{1\,\mathrm{cm}}\right)^{1.36}$$

impactor-target mass ratio of ~10% yields fragmentation!

(Leinhardt & Stewart 2009)

Jupiter’s migration shepherds planetesimals inwards and grinds them down to smaller sizes

Aerodynamics

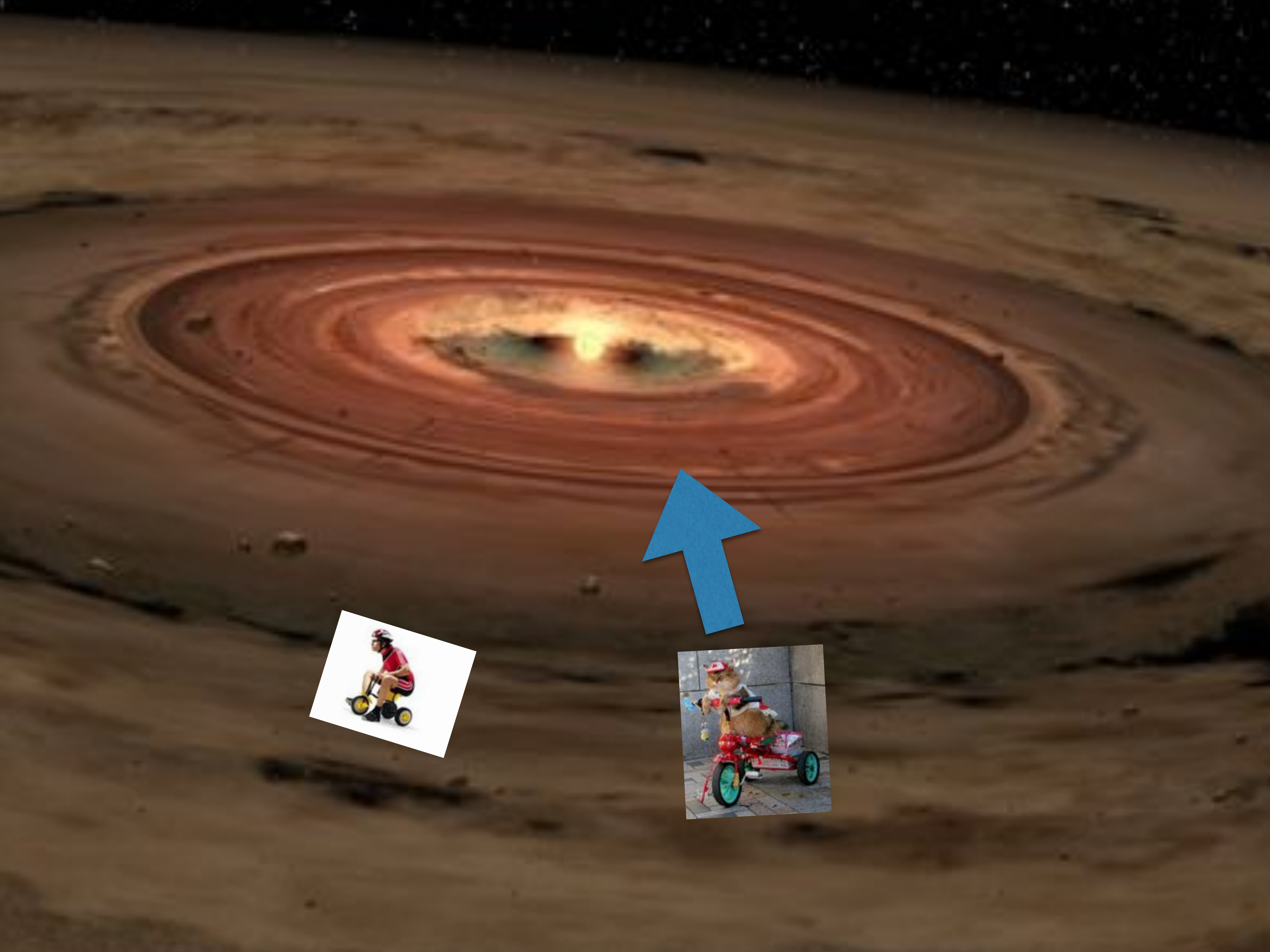
~0.005

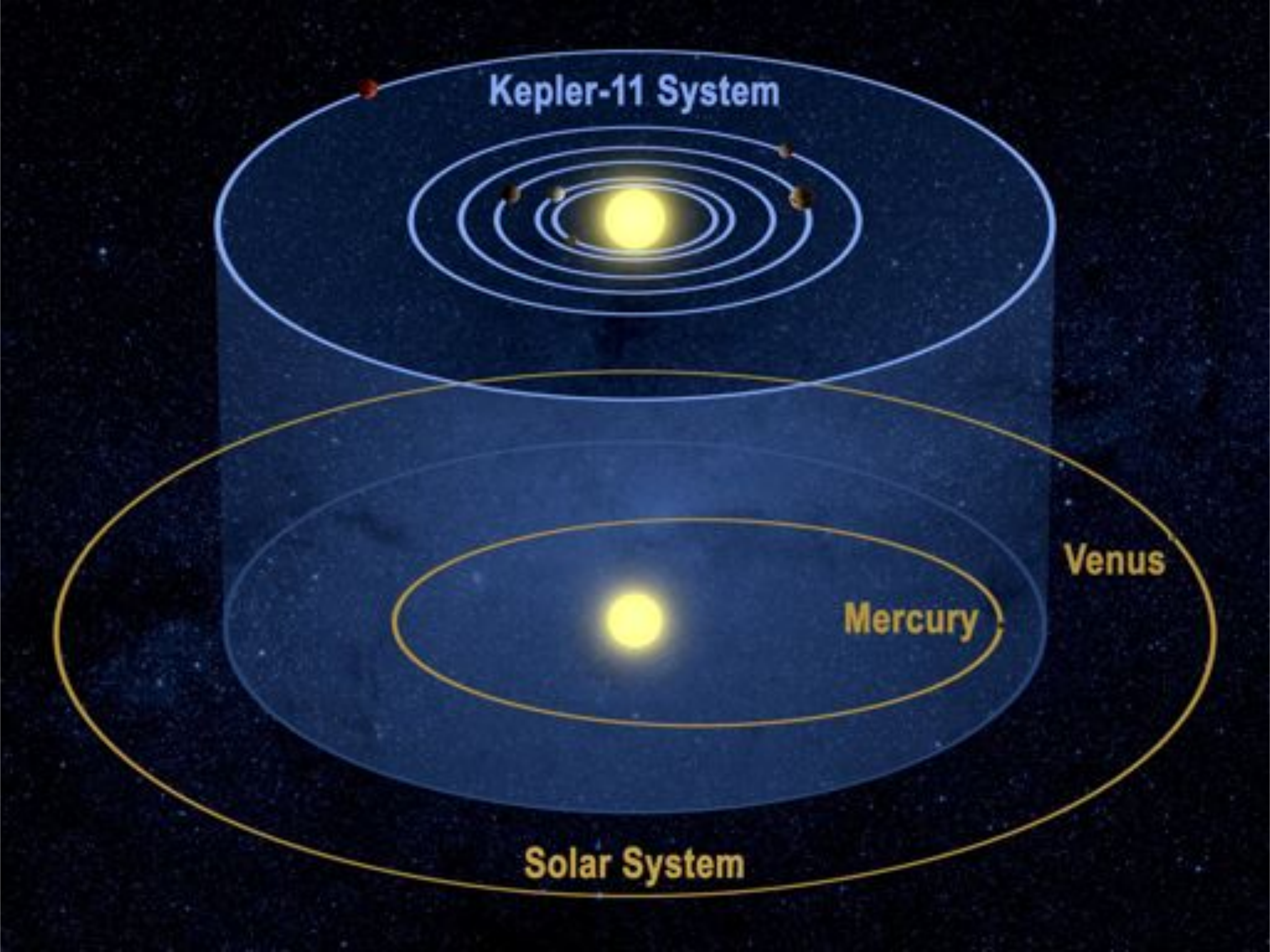
$$\mathbf{v}_{\rm gas} = v_{\rm K}\sqrt{1 - 3\frac{c_{\rm s}^2}{v_{\rm K}^2}}\,\hat{\varphi} = v_{\rm K}(1-\eta)\,\hat{\varphi}$$

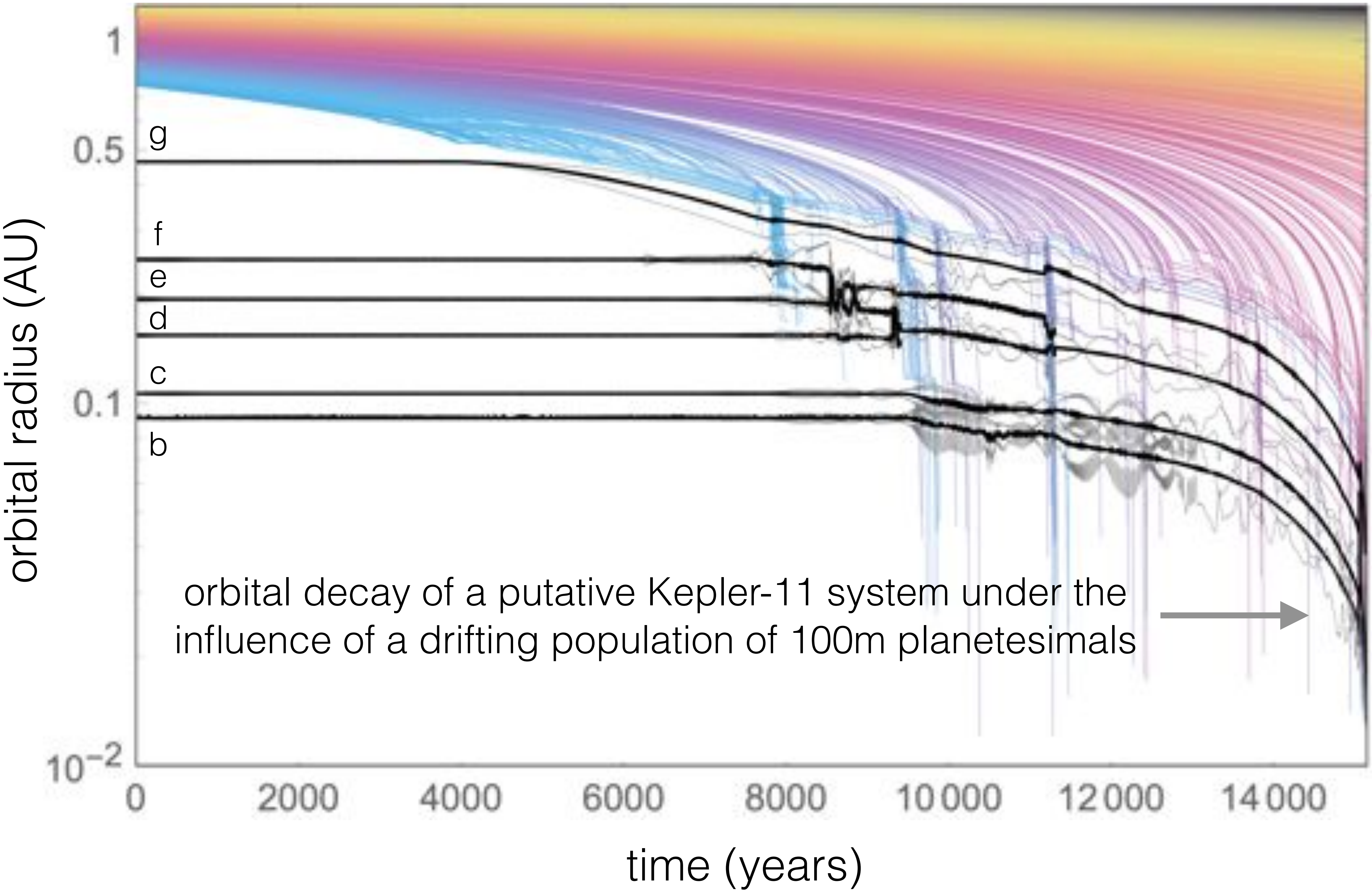
Gas is sub-Keplerian

$$\mathbf{a}_{\rm drag} = -\boxed{\frac{\pi\,\mathcal{C}_{\rm D}}{2m}}\,s^2\rho_{\rm gas}v_{\rm rel}\mathbf{v}_{\rm rel}.$$

small (<1km) planetesimals feel a head-wind

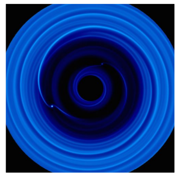



Kepler-11 System
Venus
Mercury
Solar System

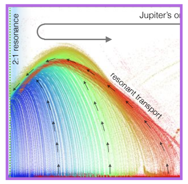


orbital decay of a putative Kepler-11 system under the influence of a drifting population of 100m planetesimals

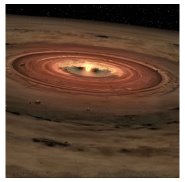
Summary



Jupiter’s current orbit is a consequence of inward-outward migration, facilitated by a resonance with Saturn

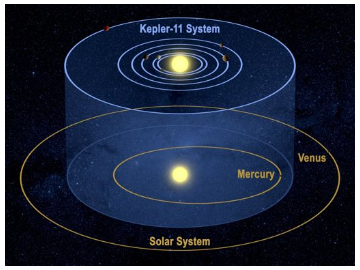


The inward phase of Jupiter’s migration entrained planetesimals into interior resonances and led to orbital excitation

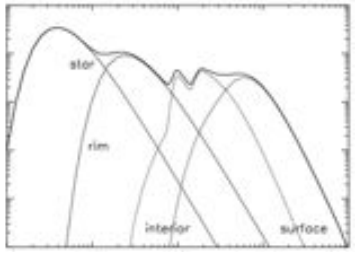


The resulting collisional avalanche generated a debris disk that would have aerodynamically driven any pre-existing short planets into the Sun

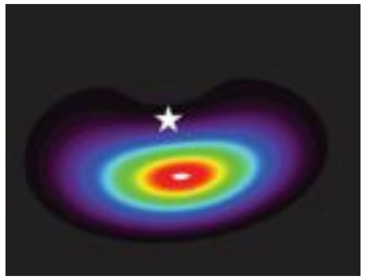
Links with observations



A strong anti-correlation between the existence of multiple close-in planets and giant planets at orbital periods exceeding ~100 days within the same system.



The spectral energy distributions of protoplanetary disks hosting gap-opening planets should exhibit infra-red enhancements.



The morphology of the collisional heating should be strongly a-symmetrical.