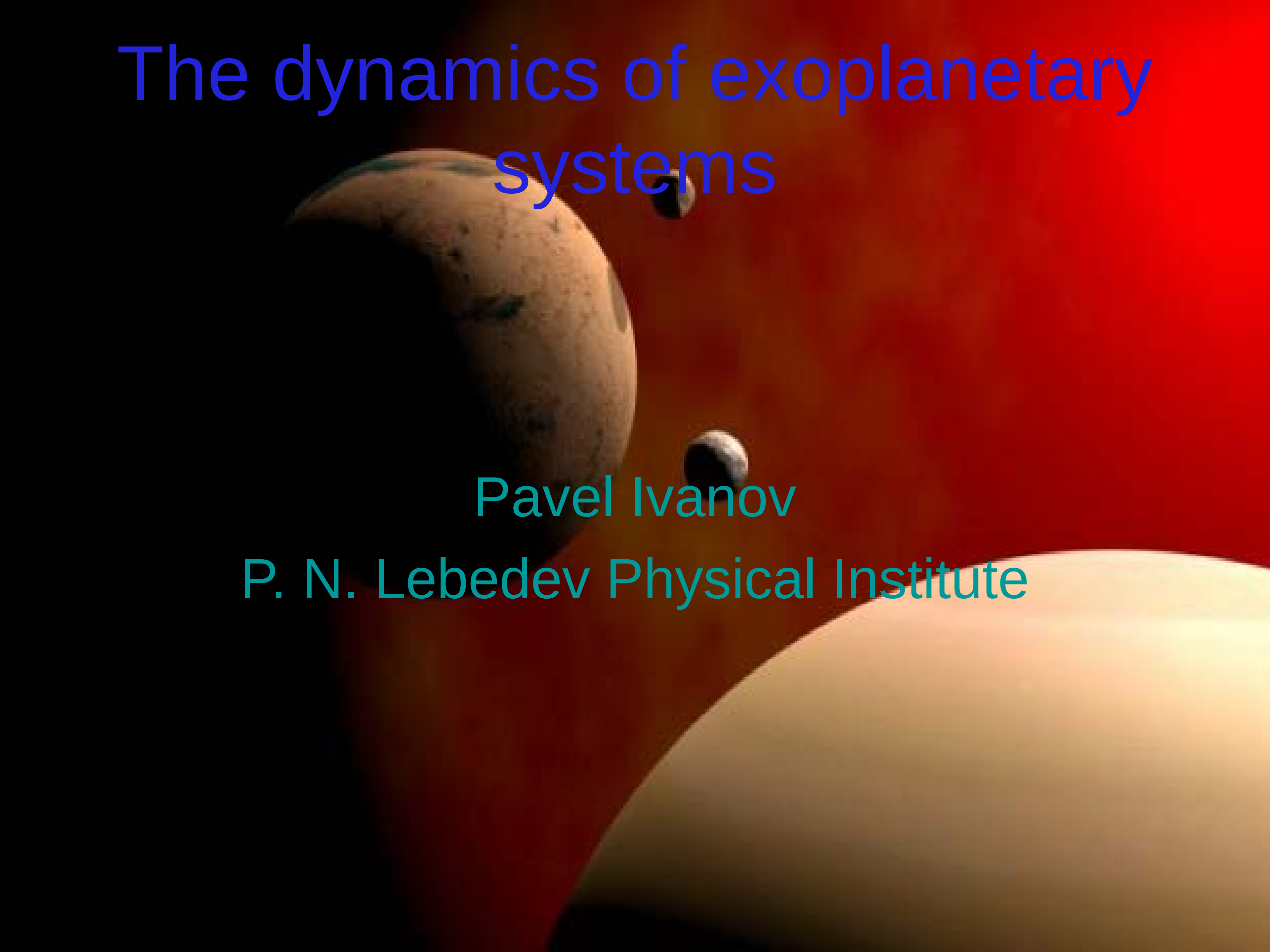

The dynamics of exoplanetary systems

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Observations

3358 planets in 2560 planetary system, including 582 multiple planetary systems, have been confirmed, as of 1 June 2016. The least massive exoplanet is orbiting around a pulsar and has its mass roughly twice the mass of Moon, the most massive planet (which may be, however, classified as a brown dwarf) is about 29 times the mass of Jupiter. Orbital periods – from a few hours to thousands of years, and even to infinity (free floating planets). Eccentiricities – from zero to ~ 1. Many planets with close periods have large orbital inclinations with respect to rotational axes of their host stars, some are even retrograde. Several exoplanetary systems (e.g. Gliese 876, Kepler-223) have planets in mean-motion resonances. There are circumbinary planets, planets interacting with circumstellar debris discs, candidates to exoplanetary systems in other galaxies, etc..

In general, there is a whole zoo of properties of exoplanetary systems, most of them are quite different from what we have in Solar System.

Basic observational techniques

1) Direct imaging

2) Transit method and its extensions

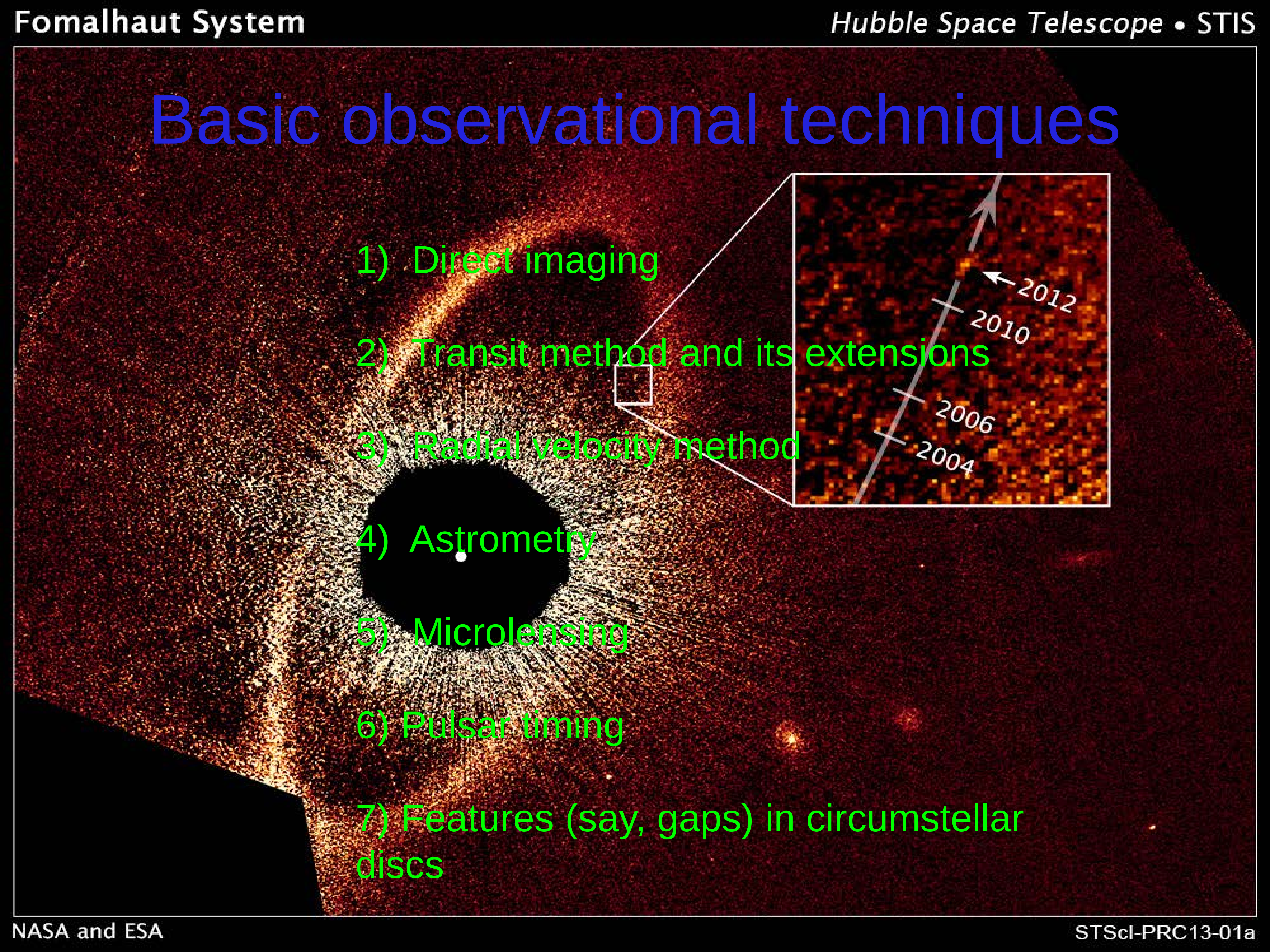
3) Radial velocity method

4) Astrometry

5) Microlensing

6) Pulsar timing

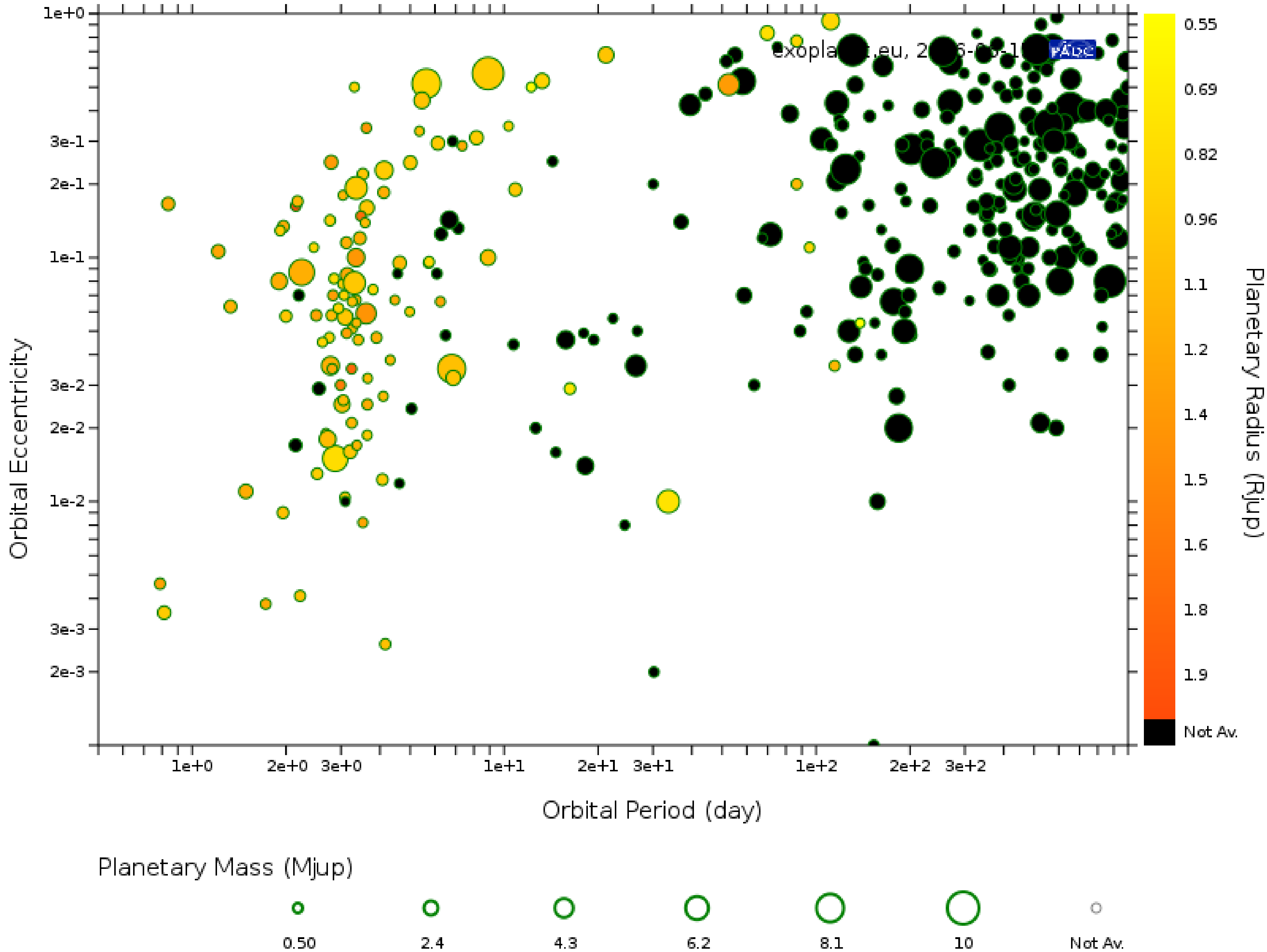
7) Features (say, gaps) in circumstellar discs



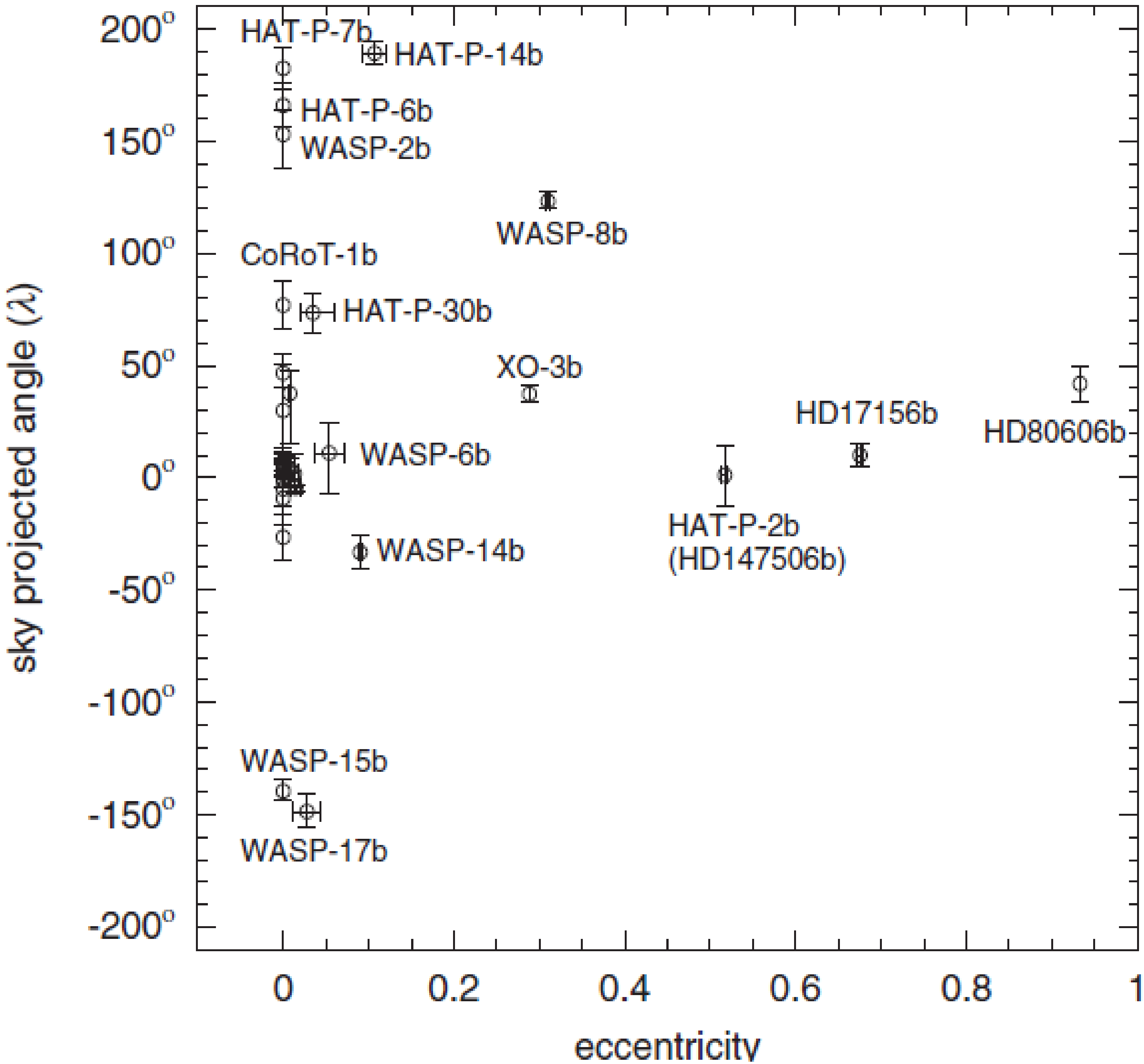
“Hot Jupiters”

One of the most puzzling problems concerning possible formation mechanisms of exoplanetary systems consists in the presence of “Hot Jupiters” - giant gas planets with periods order of a few days. The first exoplanets discovered around a MS star (51 Pegasi b, Mayor & Queloz 1995) is a Hot Jupiter with orbital period ~ 4d. The standard formation mechanisms of gas giants thought to operate in Solar System, where these planets are born outside the so-called 'ice line' with its size ~ a few AU cannot explain their presence.

They have very small eccentricities, some of them have inclined or even retrograde orbits, their host stars typically have larger metallicities.



exoplanet.eu, 2016-06-1
1e+0
3e-1
2e-1
1e-1
3e-2
2e-2
1e-2
3e-3
2e-3
1e+0
2e+0
3e+0
1e+1
2e+1
3e+1
1e+2
2e+2
3e+2
Orbital Eccentricity
Orbital Period (day)
0.55
0.69
0.82
0.96
1.1
1.2
1.4
1.5
1.6
1.8
1.9
Not Av.
Planetary Radius (Rjup)
Planetary Mass (Mjup)
0.50
2.4
4.3
6.2
8.1
10
Not Av.



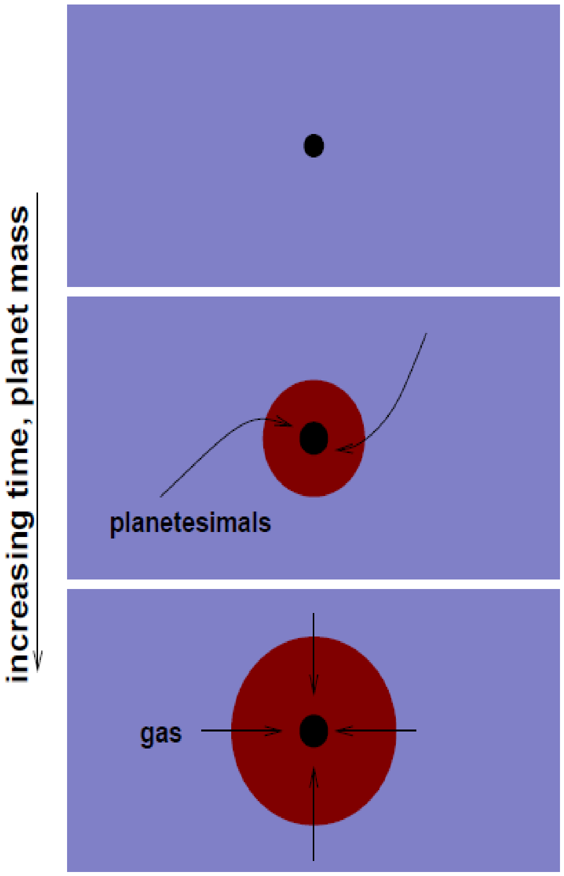
HAT-P-7b
HAT-P-14b
HAT-P-6b
WASP-2b
WASP-8b
CoRoT-1b
HAT-P-30b
XO-3b
HD17156b
HD80606b
WASP-6b
HAT-P-2b
(HD147506b)
WASP-14b
WASP-15b
WASP-17b
sky projected angle (λ)
200°
150°
100°
50°
0°
-50°
-100°
-150°
-200°
0
0.2
0.4
0.6
0.8
1
eccentricity

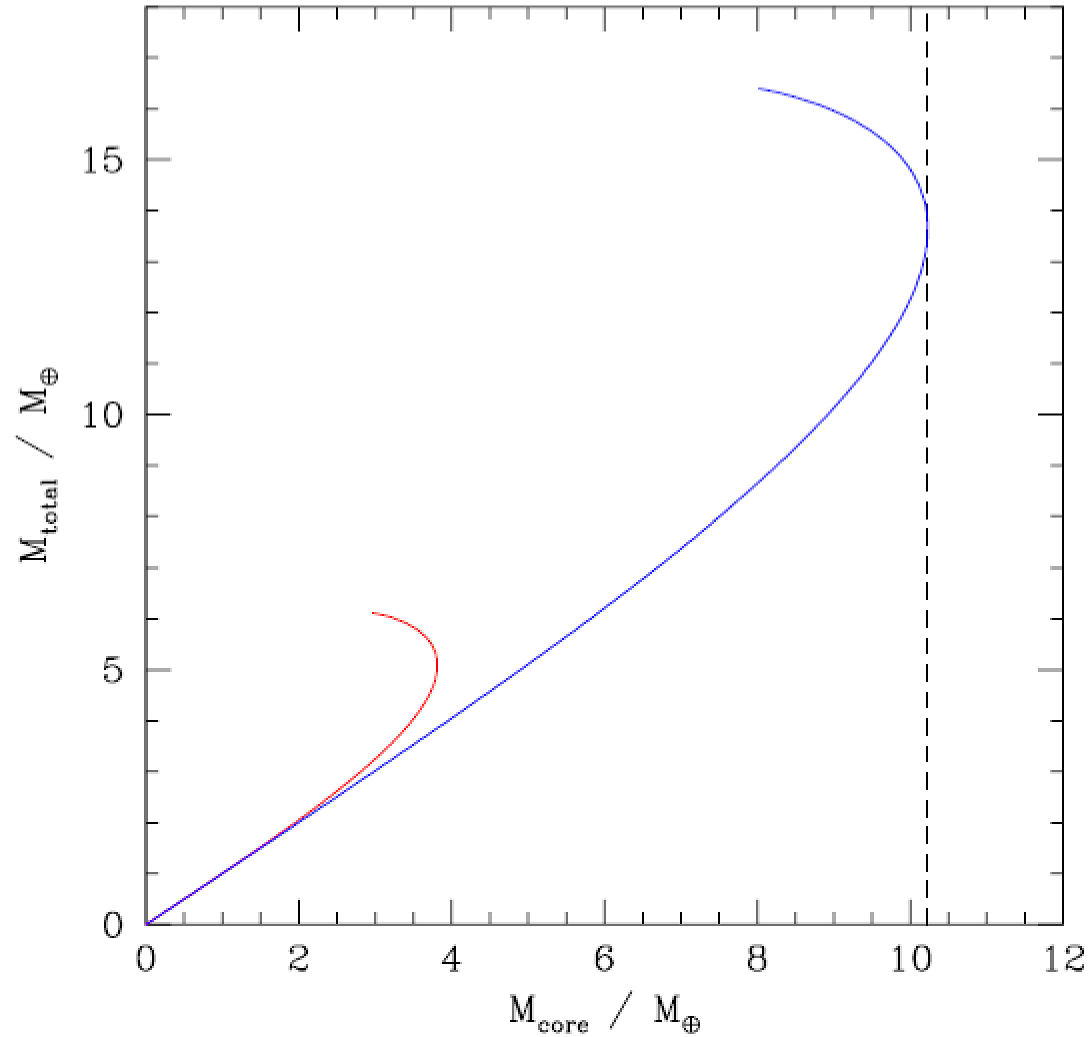
Formation of gas giants

Two possible ways – either so called core formation model or through gravitational instability (may work only for very distant planets).

The core formation model

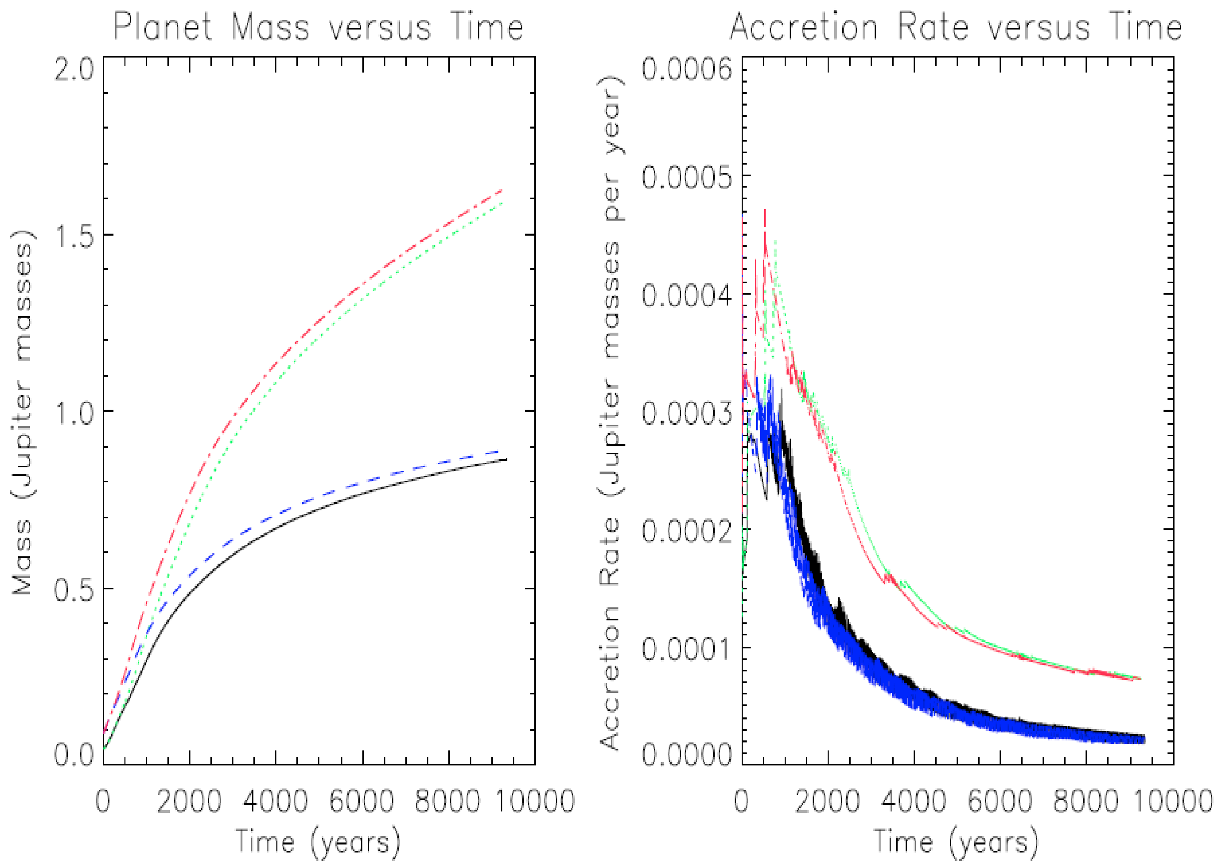
Three main stages
1) formation of "ice" core with mass order of several Earth mass from planetesimals
2) core growth through absorption of planetesimals
3) gas accretion





$$M_t = M_{\rm core} + M_{\rm env}.$$

$$\frac{M_{\rm crit}}{M_\oplus} \approx 12 \left(\frac{\dot{M}_{\rm core}}{10^{-6} \ M_\oplus {\rm yr}^{-1}} \right)^{1/4} \left(\frac{\kappa_R}{1 \ {\rm cm}^2 {\rm g}^{-1}} \right)^{1/4}$$



Papaloizou, Nelson, 2005

sented in Fig. 5. The left hand panel shows the evolution of the planet mass, and the right hand panel shows the accretion rate as a function of time. We considered initial protoplanet masses of $M_{\rm pl} = 15$ and 30 Earth masses, and viscosities with $\alpha = 10^{-3}$ and $\alpha = 5 \times 10^{-3}$. The solid line in Fig. 5 shows the model with $M_{\rm pl} = 15\ M_\oplus$ and $\alpha = 10^{-3}$. The dashed line shows the model with $M_{\rm pl} = 30\ M_\oplus$ and $\alpha = 10^{-3}$. The dotted line shows the model with $M_{\rm pl} = 15\ M_\oplus$ and $\alpha = 5 \times 10^{-3}$, and the dot-dashed line shows the model with $M_{\rm pl} = 30\ M_\oplus$ and $\alpha = 5 \times 10^{-3}$.

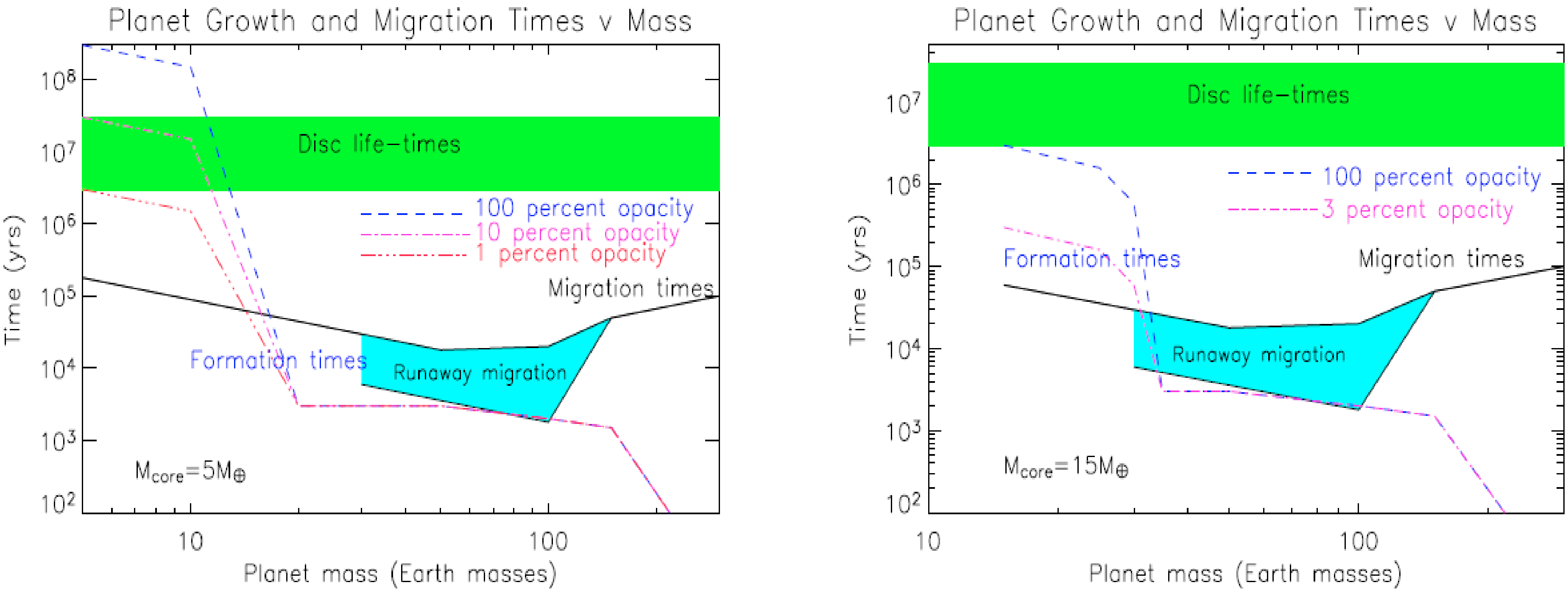


Fig. 15. This diagram provides a schematic representation of the formation and migration time scales of planet models as a function of protoplanet mass for core masses of 5 $M_\oplus$. The range of plausible protostellar disk life-times is indicated by the upper shaded region spanning the times 3×10^6–3×10^7 years. The migration time as a function of planet mass is indicated by the solid line. A shaded region indicating the "danger zone" for rapid type I or runaway migration is also indicated. The growth time of protoplanets as a function of planet mass is given for standard opacity (dashed line), 10 percent opacity (dashed-dotted line), and 1 percent opacity (dashed-dot-dot-dotted line). See text for discussion of this figure.

Gravitational instability

(Armitage, 2014)

The Toomre parameter

$$Q \equiv \frac{c_s \Omega}{\pi G \Sigma} < Q_{\rm crit} \simeq 1$$

$$M_p \sim \pi \Sigma \lambda_{\rm crit}^2 \sim \frac{4\pi c_s^4}{G^2 \Sigma} \sim 5 M_J$$ when $$\Sigma \approx 1.5 \times 10^3 \ \mathrm{gcm}^2.$$

$$Q \propto \frac{c_s^3}{\dot{M}}.$$

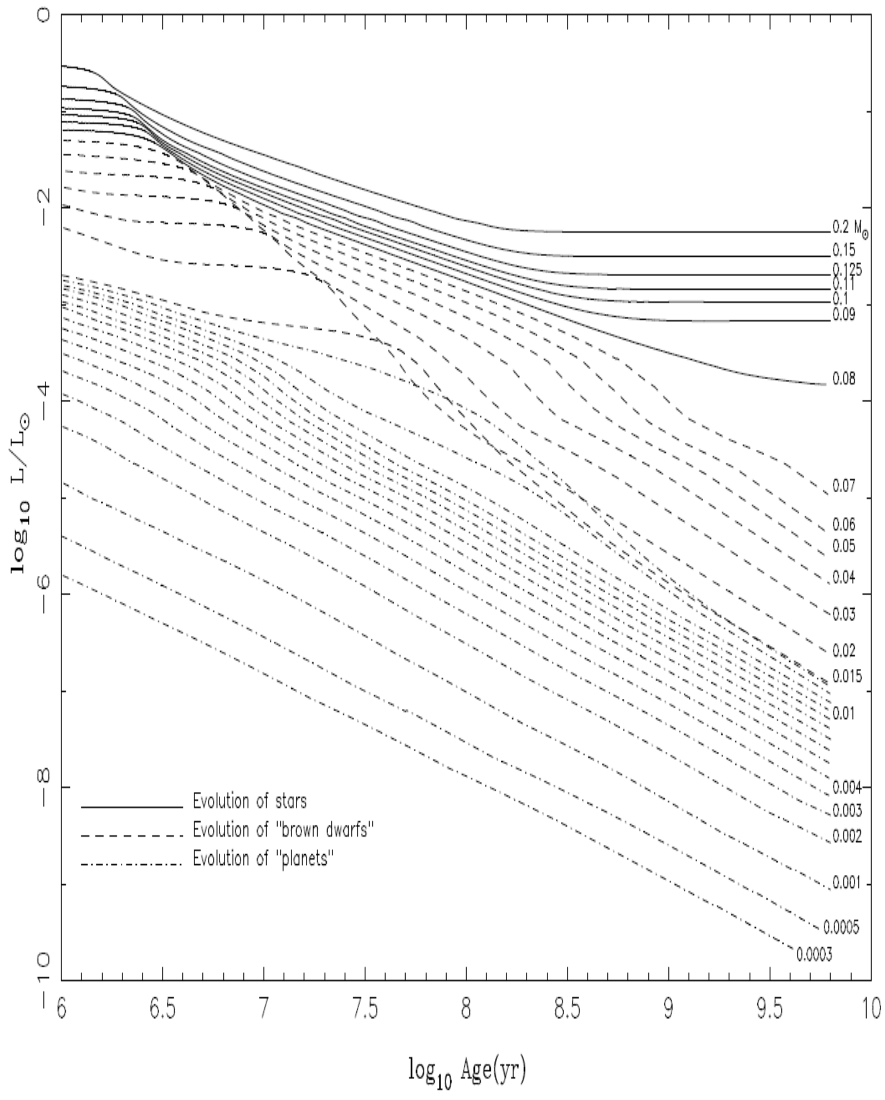
Small Q favour large distances, where sound speed is small

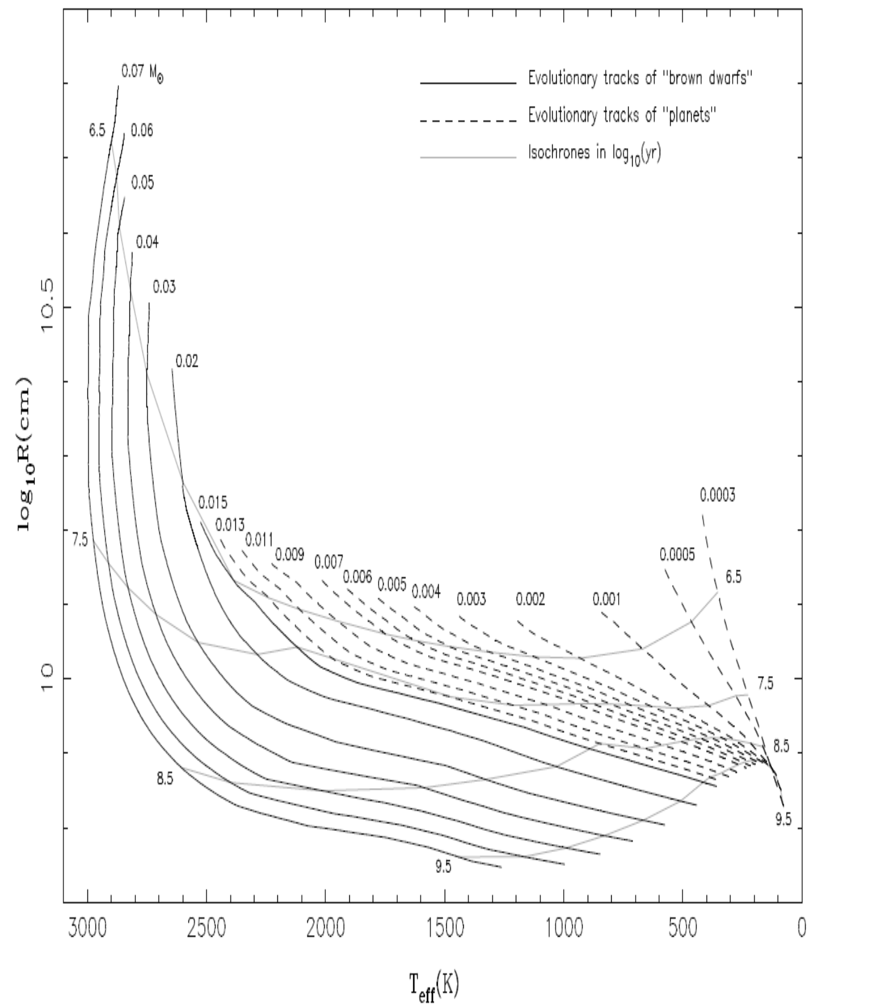
The HR 8799 (Marois et al., 2008) - three massive planets between 24 and 68 AU?

$$t_{\rm cool} = \frac{U}{2\sigma T_{\rm disk}^4}$$

Gammie, 2001

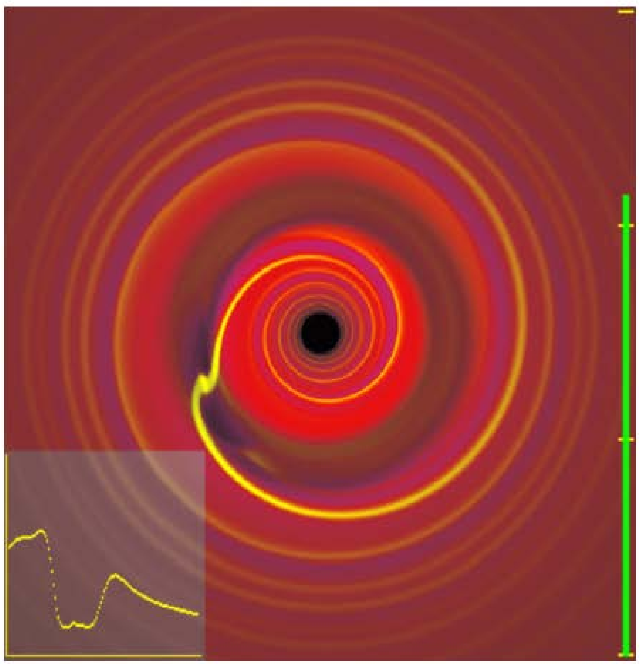
- $t_{\rm cool} \lesssim 3\Omega^{-1}$ — the disk fragments.
- $t_{\rm cool} \gtrsim 3\Omega^{-1}$ — disk reaches a steady state in which heating due to dissipation of gravitational turbulence balances cooling.





Burrows et al, 1997

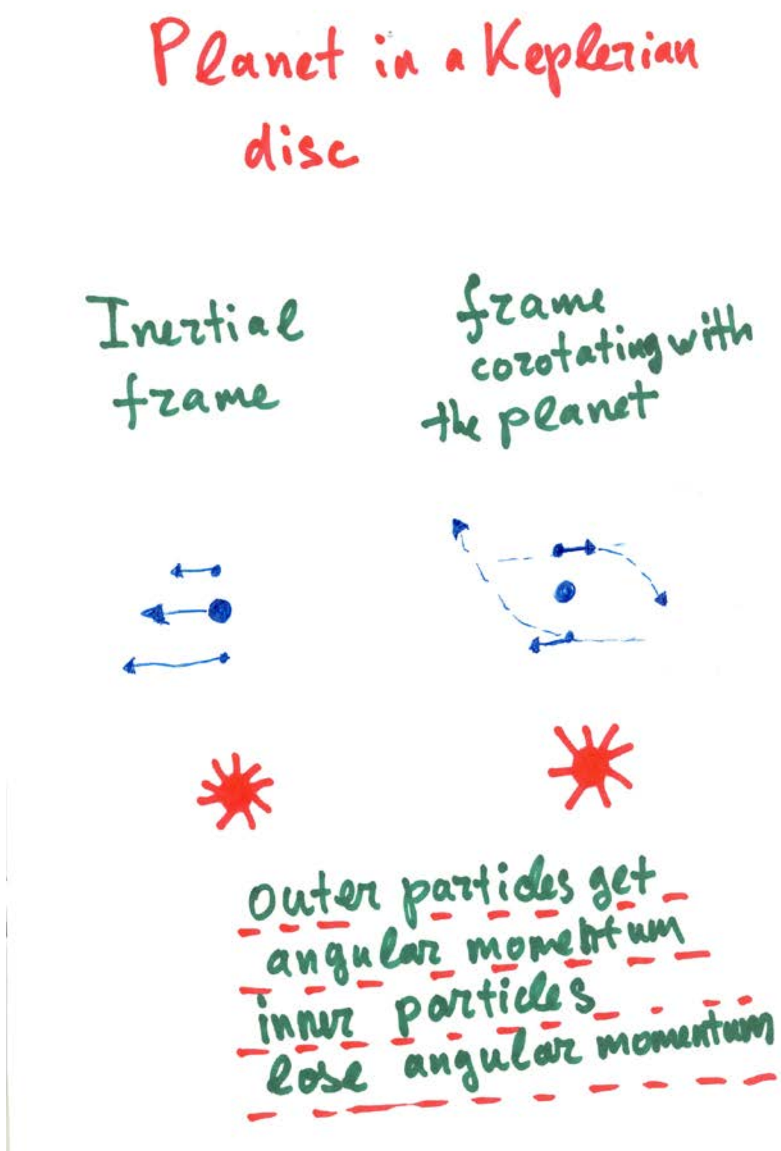
MIGRATION



P. Armitage

ALMA (ESO/NAOJ/NRAO)

Three types of migration



Migration of first type (planet doesn't open a gap in protoplaneraty disc), appropriate for (super) Earth size planets and ice cores of gas giants.

Migration of second type (planet opens a well pronounced gap in the disc), appropriate for planets with masses above Jupiter mass.

Migration of third type (intermediate regime, very fast evolution), appropriate for planets with masses order of Saturn mass.

Resonances in a disc

Imagine a planet in orbit about a star. The rotation frequency of the planet is given by its Keplerian frequency,

$$\Omega_p = \sqrt{\frac{GM_*}{r_p^3}}$$

The, there are special resonant places in the disk. Two types must be distinguished:

1) Corotation resonance located where $\boxed{\Omega = \Omega_p}$

If the disc is Keplerian (i.e., if we neglect gas pressure and self-gravity), then the corot resonance is found at the planet's orbital radius.

2) Lindblad resonances located where $\boxed{m\left(\Omega - \Omega_p\right) = \pm\kappa}$

where *m* is an integer, and the epicyclic frequency is $\kappa^2 = \left(R\frac{d\Omega^2}{dR} + 4\Omega^2\right)$

In the case of a Keplerian potential, it is easy to see that: $\kappa = \Omega$

a) for the + sign (rotation faster than planet): The *inner* Lindblad resonances

b) the - sign (rotation slower than planet): The *outer* Lindblad resonances

The actual position of these resonances can be readily obtained:

$$r_{ILR} = r_p \left(\frac{m}{m-1}\right)^{-2/3} \quad \text{and} \quad r_{OLR} = r_p \left(\frac{m}{m+1}\right)^{-2/3}$$

Type 1

$$\Gamma_L = -(2.34 - 0.1\gamma)\left(\frac{M_p}{M_*}\right)^2\left(\frac{r_p}{h}\right)^2\Sigma r_p^4\Omega^2,$$

$$\Gamma_C = -(0.98 - 0.64\gamma)\left(\frac{M_p}{M_*}\right)^2\left(\frac{r_p}{h}\right)^2\Sigma r_p^4\Omega^2,$$

$$\Sigma \propto r^{-\gamma}$$

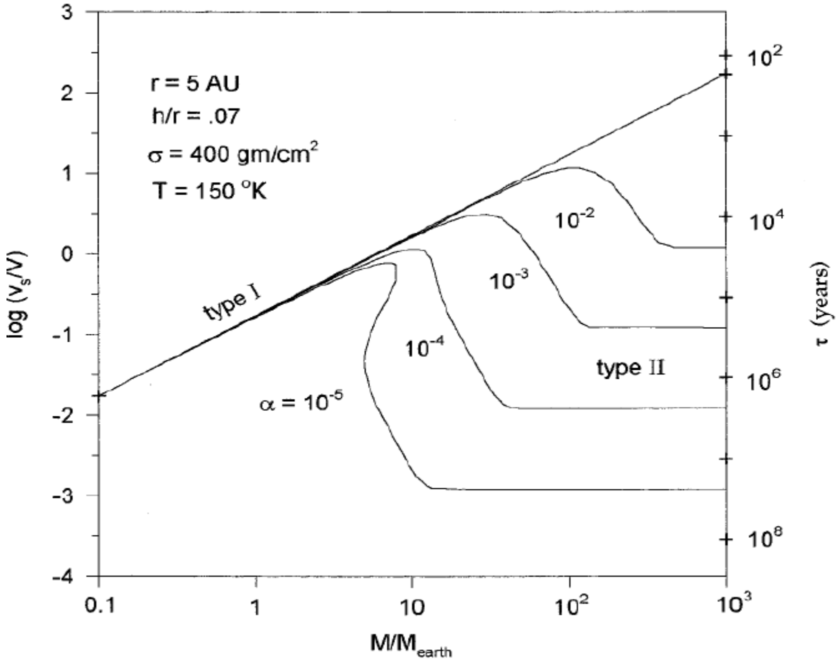
Migration time scale $T_m \sim (M_d/m)(M_p/M_*)^2(r_p/h)^{-2}P_{orb}$

Type 2

$$\frac{M_p}{M_*} \gtrsim (10\pi)^{1/2}\alpha^{1/2}\delta^{1/2}.$$

$$\frac{M_p}{M_*} \gtrsim 3\delta^3$$

δ=h/r



Ward (1997).

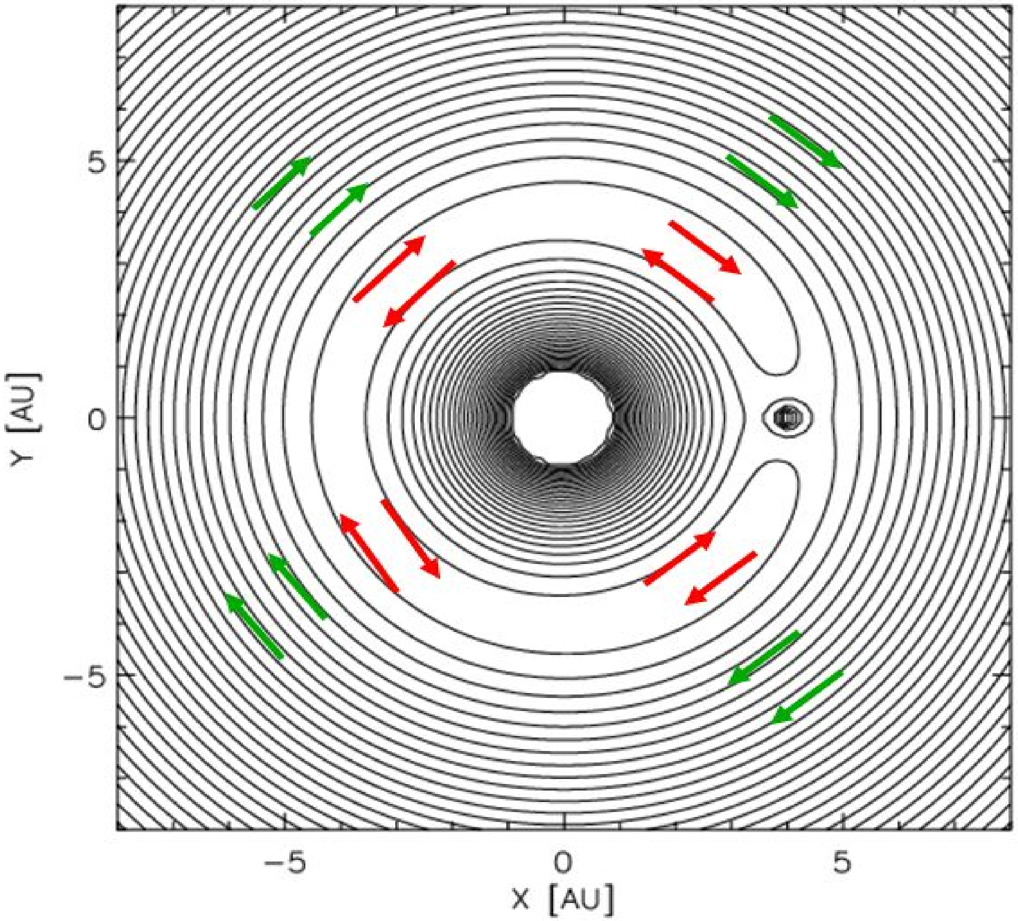
T_m / P_{orb} ~ $\alpha^{-1}\delta^{-2}.$

T_m / P_{orb} $\simeq \frac{M_p}{M_d(r<r_p)}\alpha^{-1}\delta^{-2}$

$M_p > M_d(r < r_p)$

Type III migration

Masset & Papaloizou

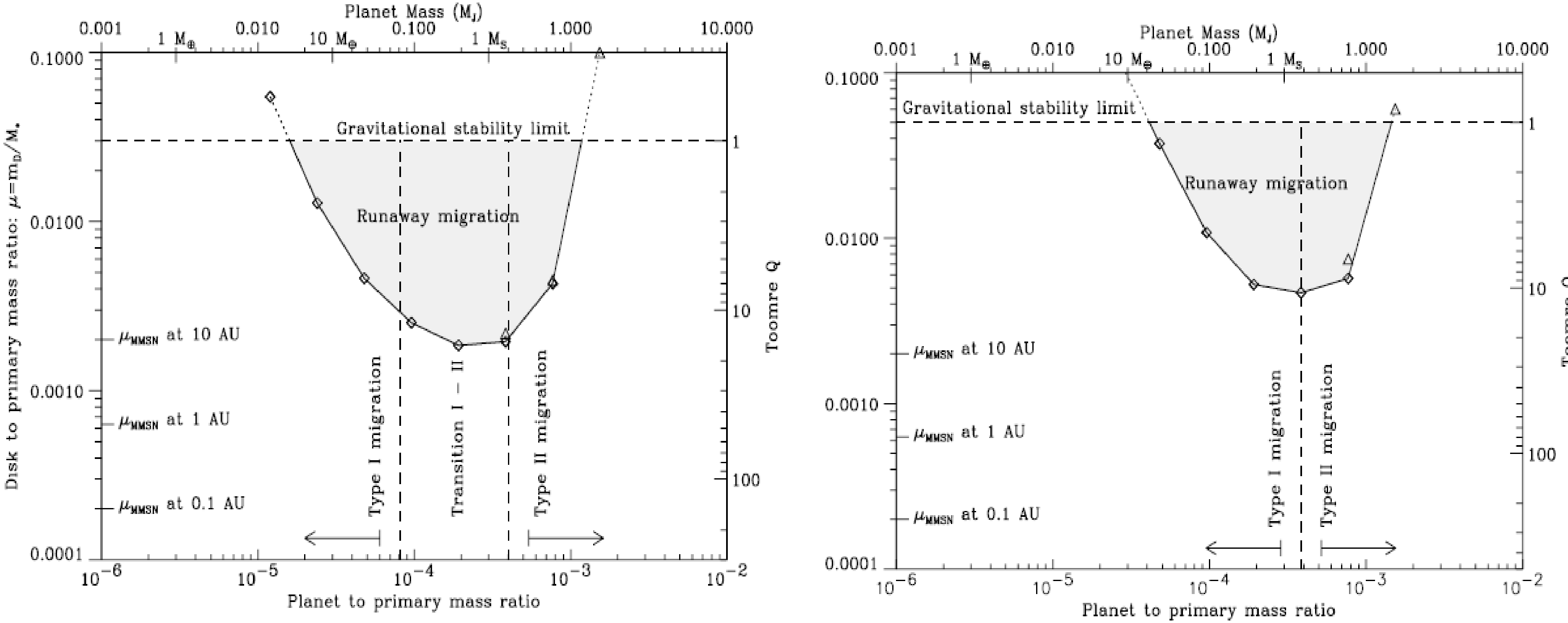


Type III migration takes place when the planet migration time across the co-orbital region is shorter than the libration time.

By the time a parcel has librated to the other fly-by point, it might find itself no longer inside the co-orbital region.

A strong asymmetric horseshoe drag follows.

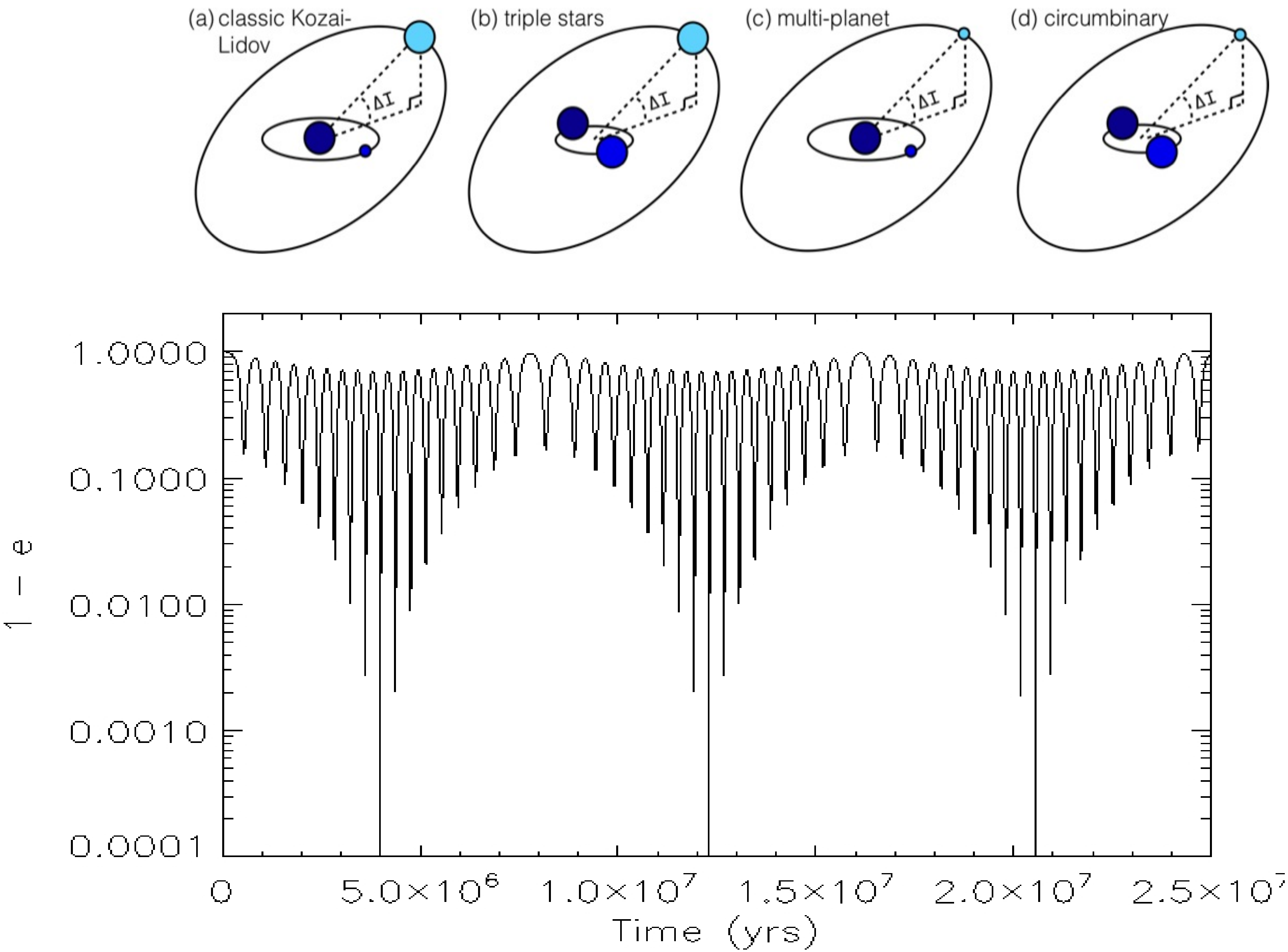
$$a\frac{\Omega_p}{2}(M_p - \delta m)\dot{a} = \Delta\Gamma_{\rm LR} - \frac{\pi a^2\,\delta m}{3x_s}\ddot{a}$$



Planet Mass (M_J)
0.001
1 $M_\oplus$
0.010
10 $M_\oplus$
0.100
1 M_S
1.000
10.000
Gravitational stability limit
Runaway migration
Type I migration
Transition I – II
Type II migration
μ_{MMSN} at 10 AU
μ_{MMSN} at 1 AU
μ_{MMSN} at 0.1 AU
Disk to primary mass ratio: $\mu=m_D/M_*$
Toomre Q
Planet to primary mass ratio

δ=0.03, 0.05

Lidov-Kozai cycles

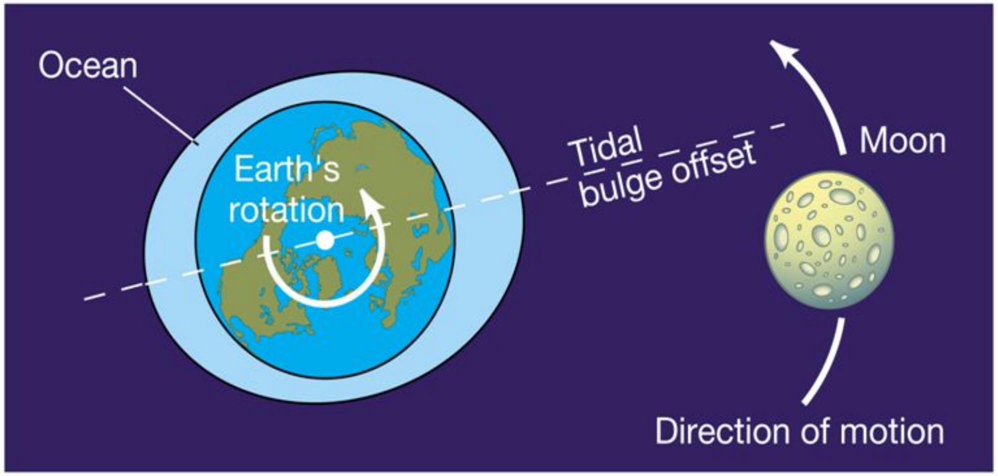


Tides

Two types of tidal interactions are considered: the so-called quasi-stationary tides and dynamic excitations of different normal modes of pulsations of rotating giant planets and stars (dynamic tides). Note that dynamic tides in planets having retrograde motion with respect to stellar rotation are amplified (e.g. Lai, 1997, Ivanov & Papaloizou, 2011). Thus, there is a natural bias towards retrograde orbits in the problem.

Quasi-static tides

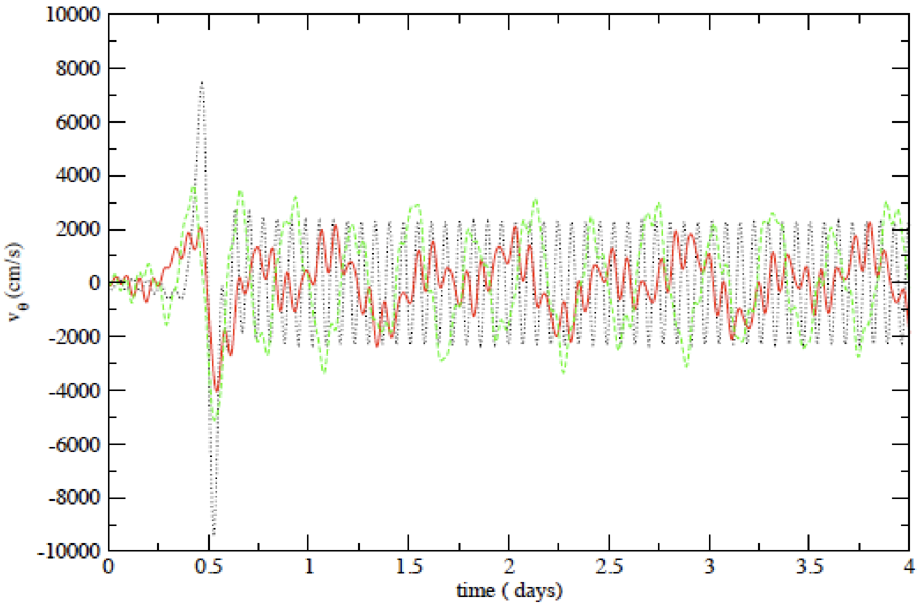
The physics is basically the same as in the Earth-Moon System. The main uncertainty is a value of so-called 'tidal factor' Q defined as the ratio of energy stored in bulge to energy disspated per one forcing period. For EM system it is order of 20. For gas giants/stars it needs to be order 10^5-10^7 to explain observations.



Tidal Bulge: The tidal bulge raised in Earth by the Moon does not point directly at the Moon. Instead, because of the effects of friction, the bulge points slightly "ahead" of the Moon, in the direction of Earth's rotation. (The magnitude of the effect is greatly exaggerated in this diagram.) Because the Moon's gravitational pull on the near-side part of the bulge is greater than the pull on the far side, the overall effect is to decrease Earth's rotation rate.

Dynamic tides

The main idea resonant excitations of various normal modes of planets/stars. Could work both for highly elliptical and quasi-circular orbits. Unlike quasi-static tides, at least in two possible cases main characteristics of the process do not depend on value of dissipation.



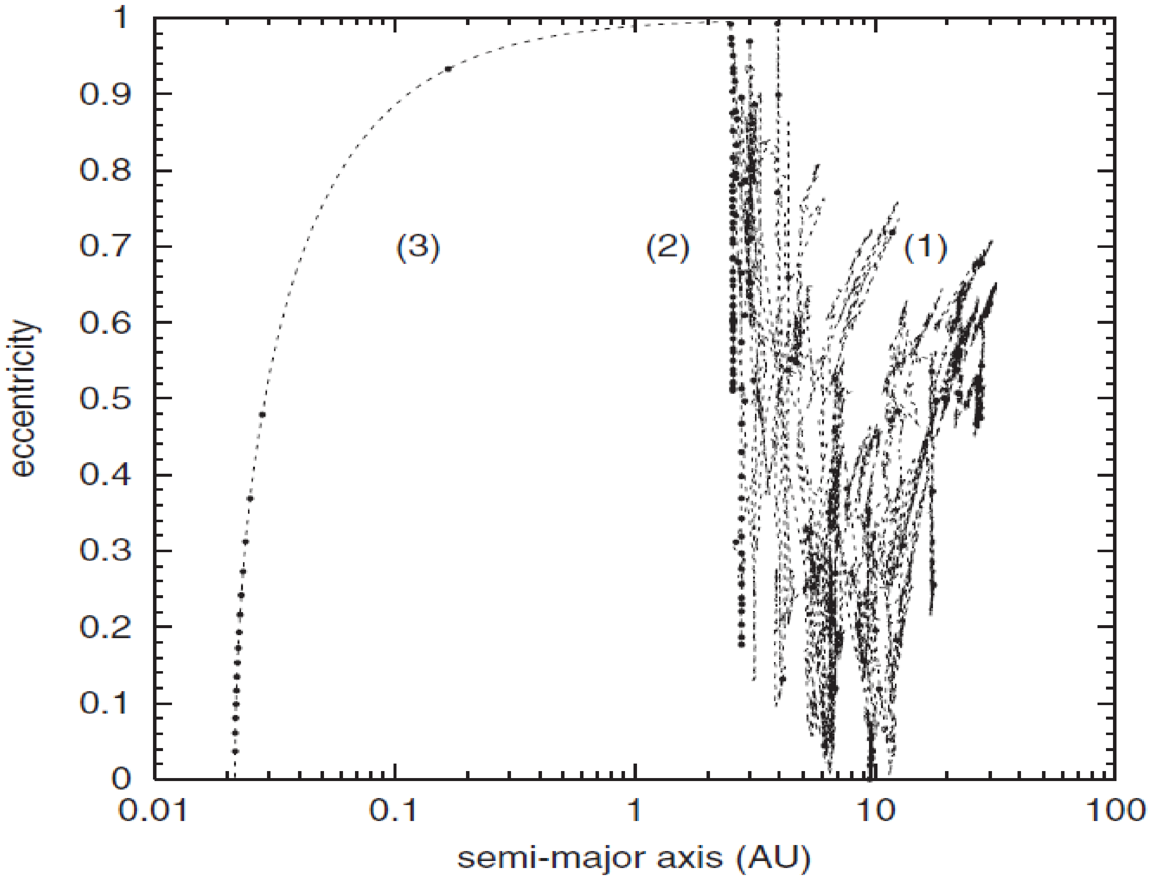
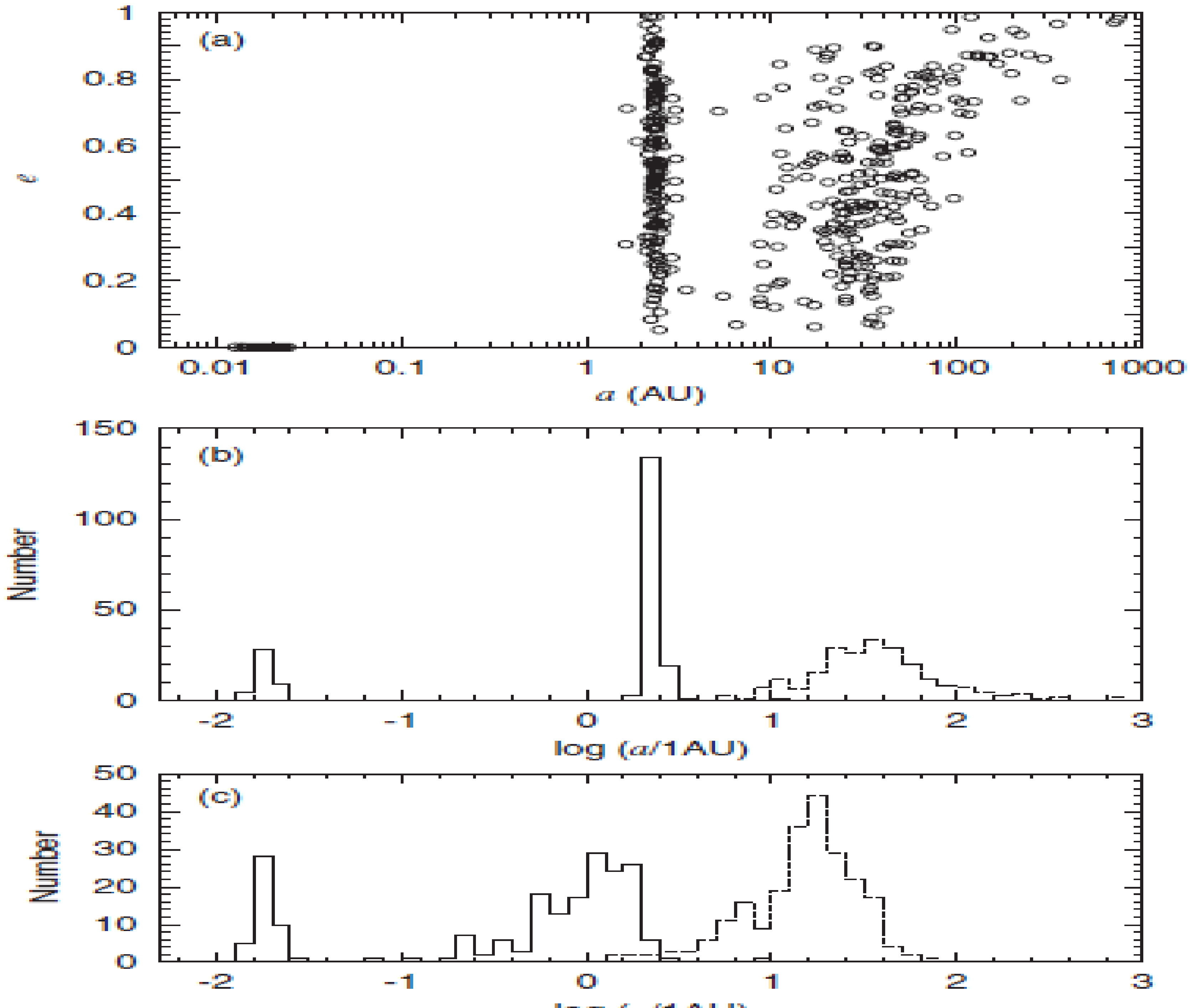


Figure 10. Typical evolution of a close-in planet. Filled circles are plotted every 10^4 yr. Stage (1): orbital crossing phase. Stage (2): secular evolution stage during three planets' interaction. Stage (3): circularization stage.

Nagasawa & Ida 2011


(a)
e
0
0.2
0.4
0.6
0.8
1
0.01
0.1
1
10
100
1000
a (AU)
(b)
Number
0
50
100
150
-2
-1
0
1
2
3
log (a/1AU)
(c)
Number
0
10
20
30
40
50
-2
-1
0
1
2
3

Conclusions

1) Systems of exoplanets demonstrate a lot of intruguing properties totally absent in Solar System, in particular, a phenomenon of presence of Hot Jupiters.

2) Although there are certain more or less realistic scenarios of the formation of exoplanetary systems, they all have problems. More theoretical work and observations are needed due to rather unexpected richness and complexity of exoplanetary systems.

3) Perhaps, a combination of these scenarios would eventually work. In particular, 'Hot Jupiters' and 'Warm Jupiters' may have been formed differently.

4) Our Solar System looks as an exeption rather than a rule. Note, however, that the ubiquity of similar systems may be underestimated due to observational bias towards systems containg massive objects at close orbits.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