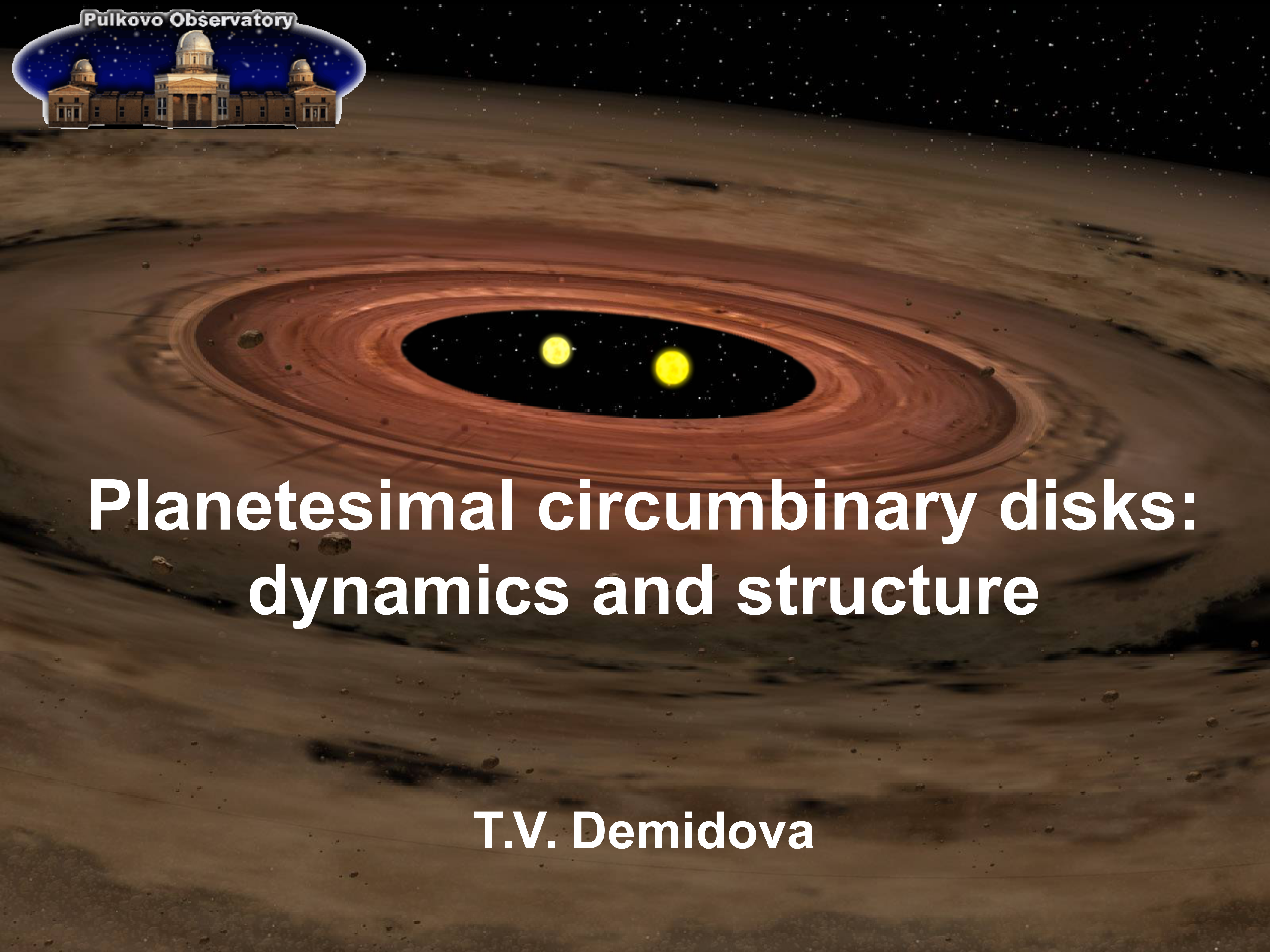
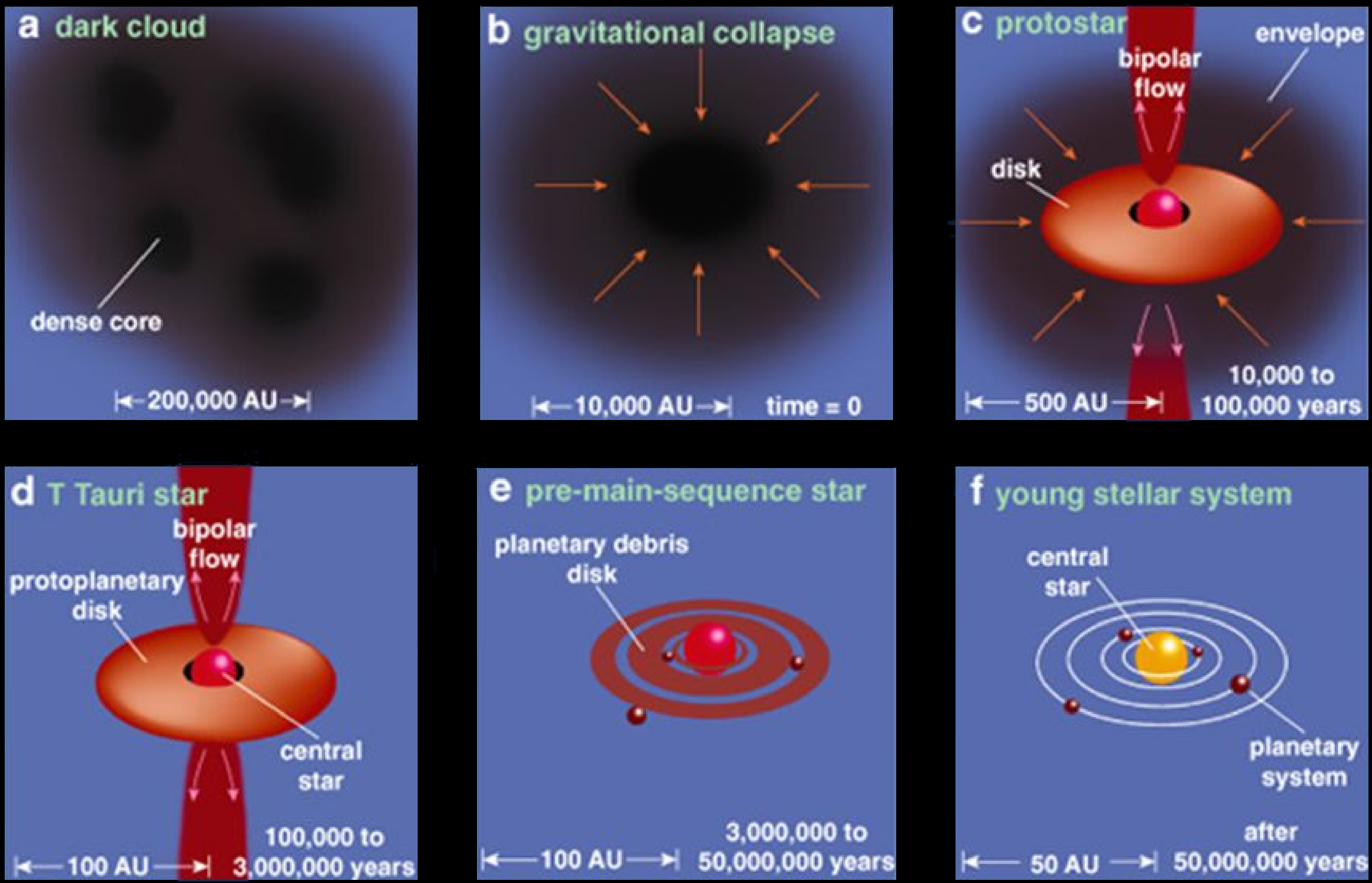


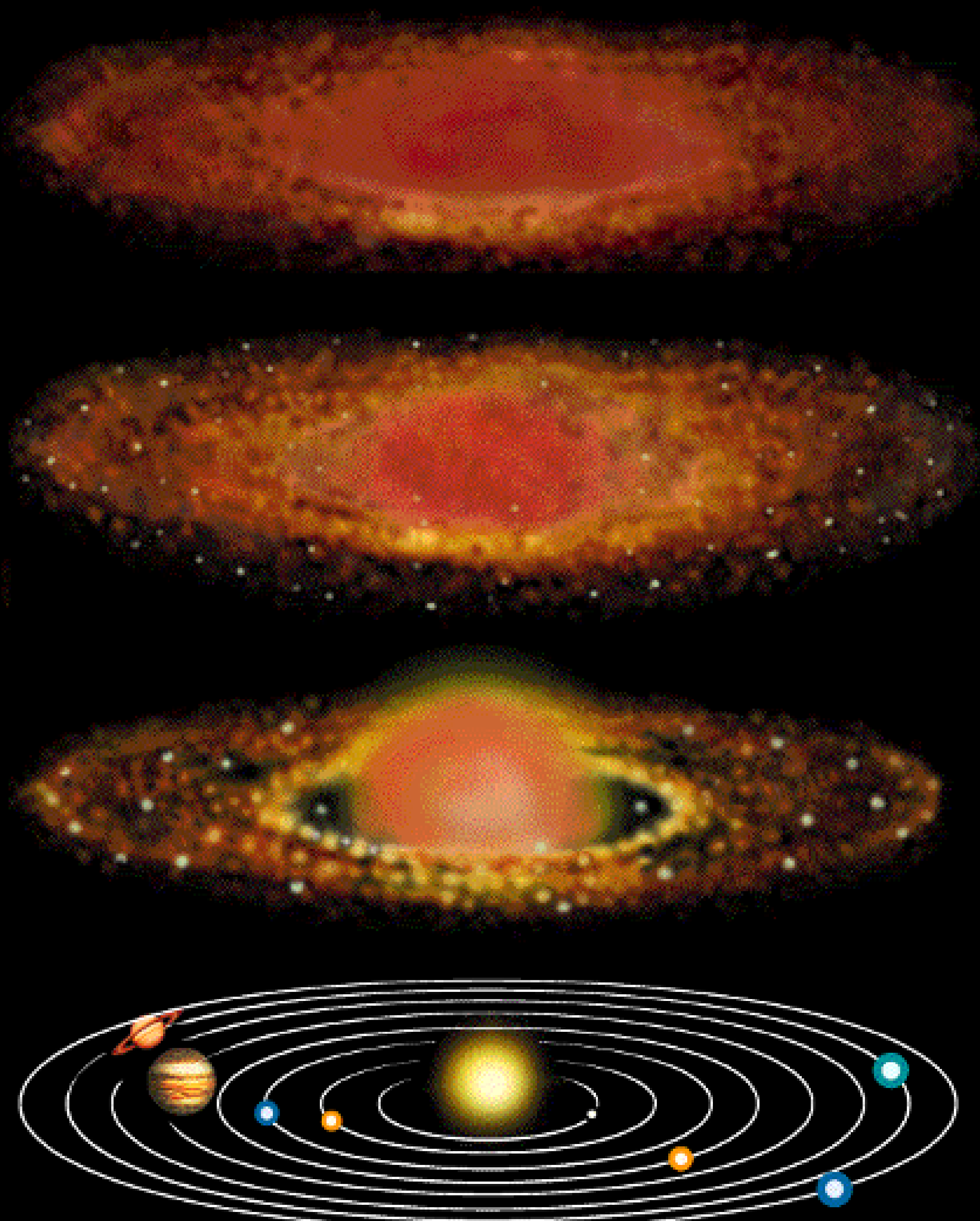
Planetesimal circumbinary disks: dynamics and structure

T.V. Demidova

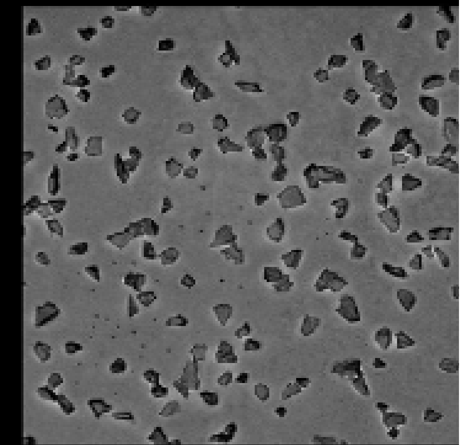
The planet formation scenario



The disk evolution



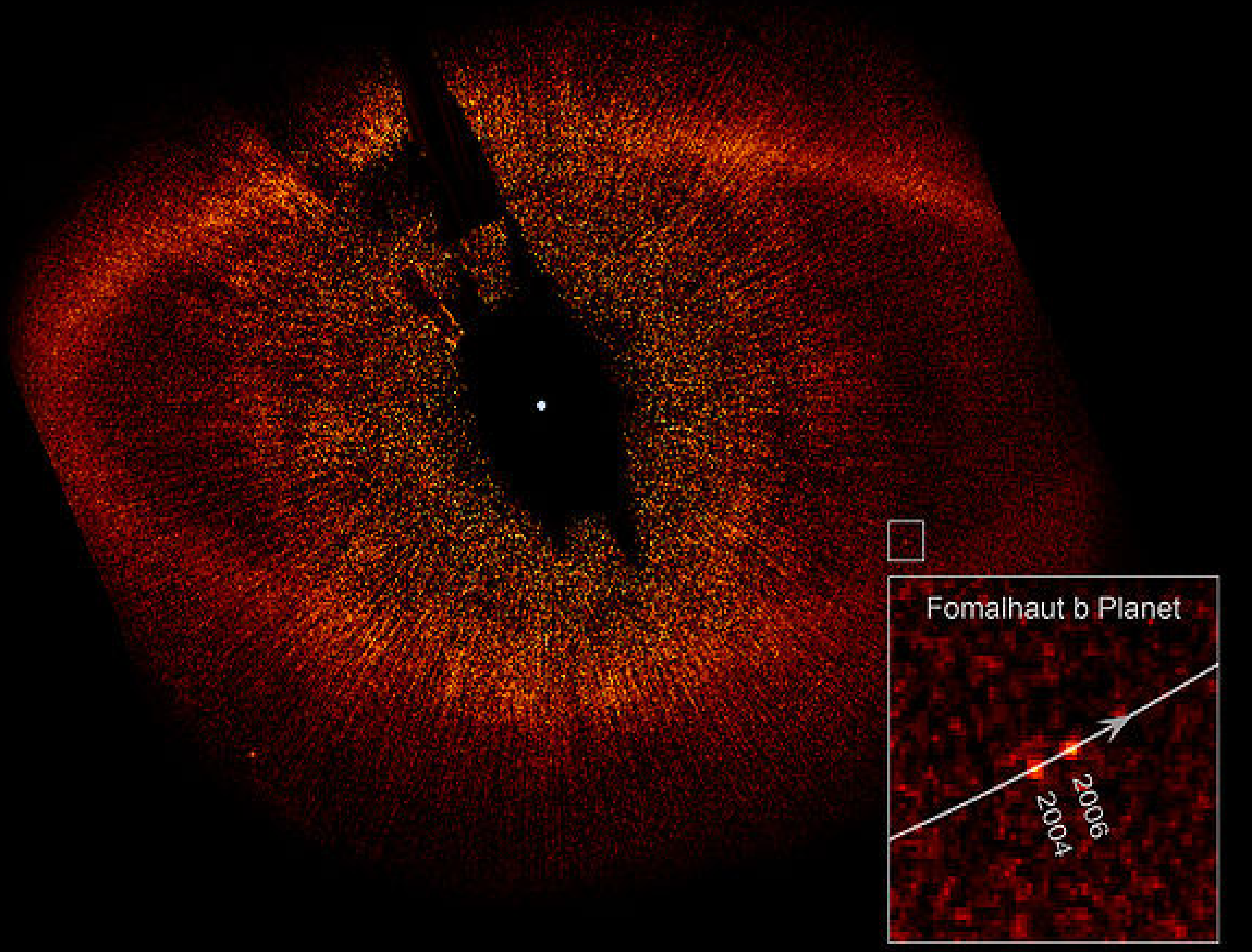
Dust coagulates and settles down



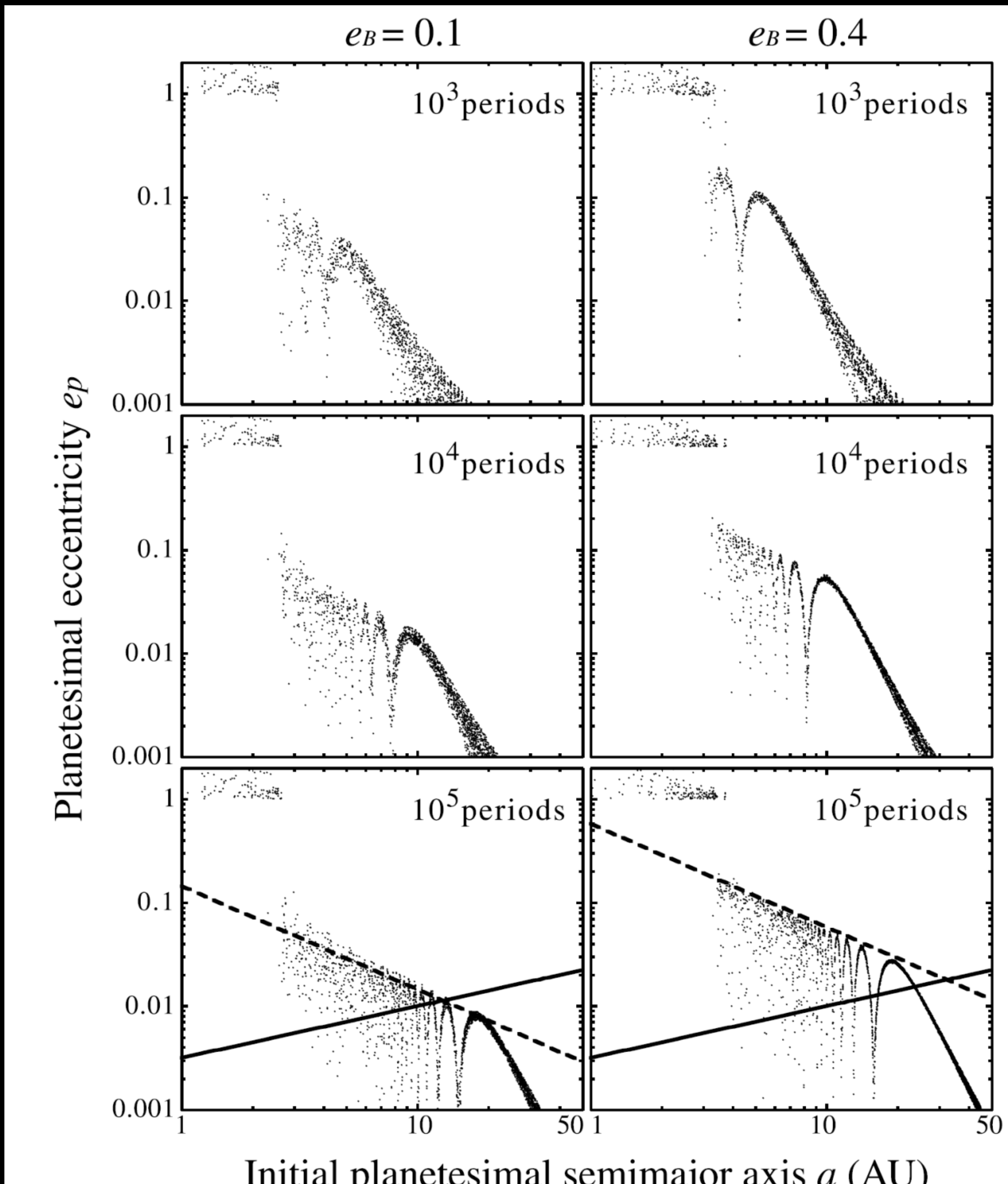
Gas disappears and planetesimals originate

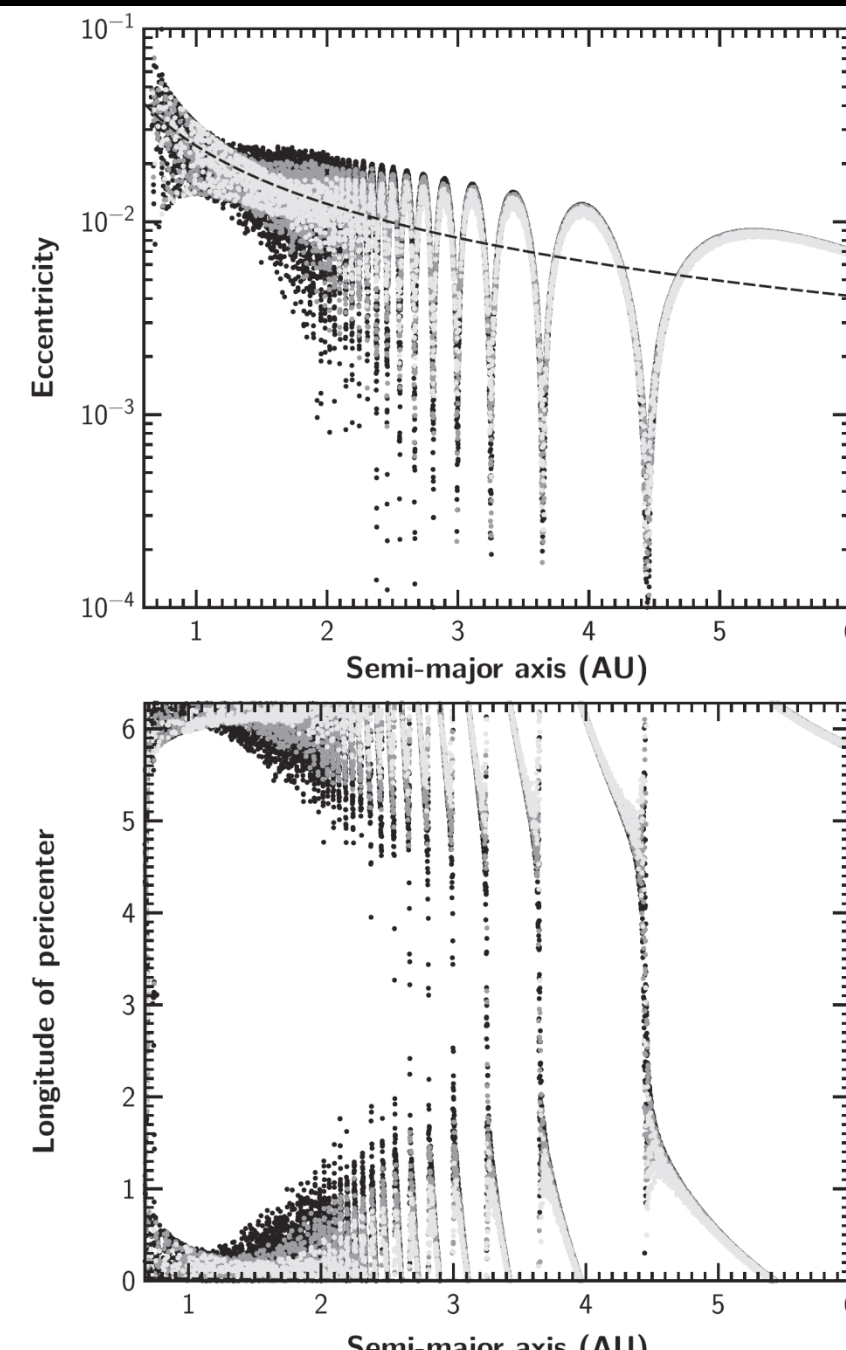
Accretion leads to formation of protoplanets

Planetesimal disk of Fomalhaut (α PsA)

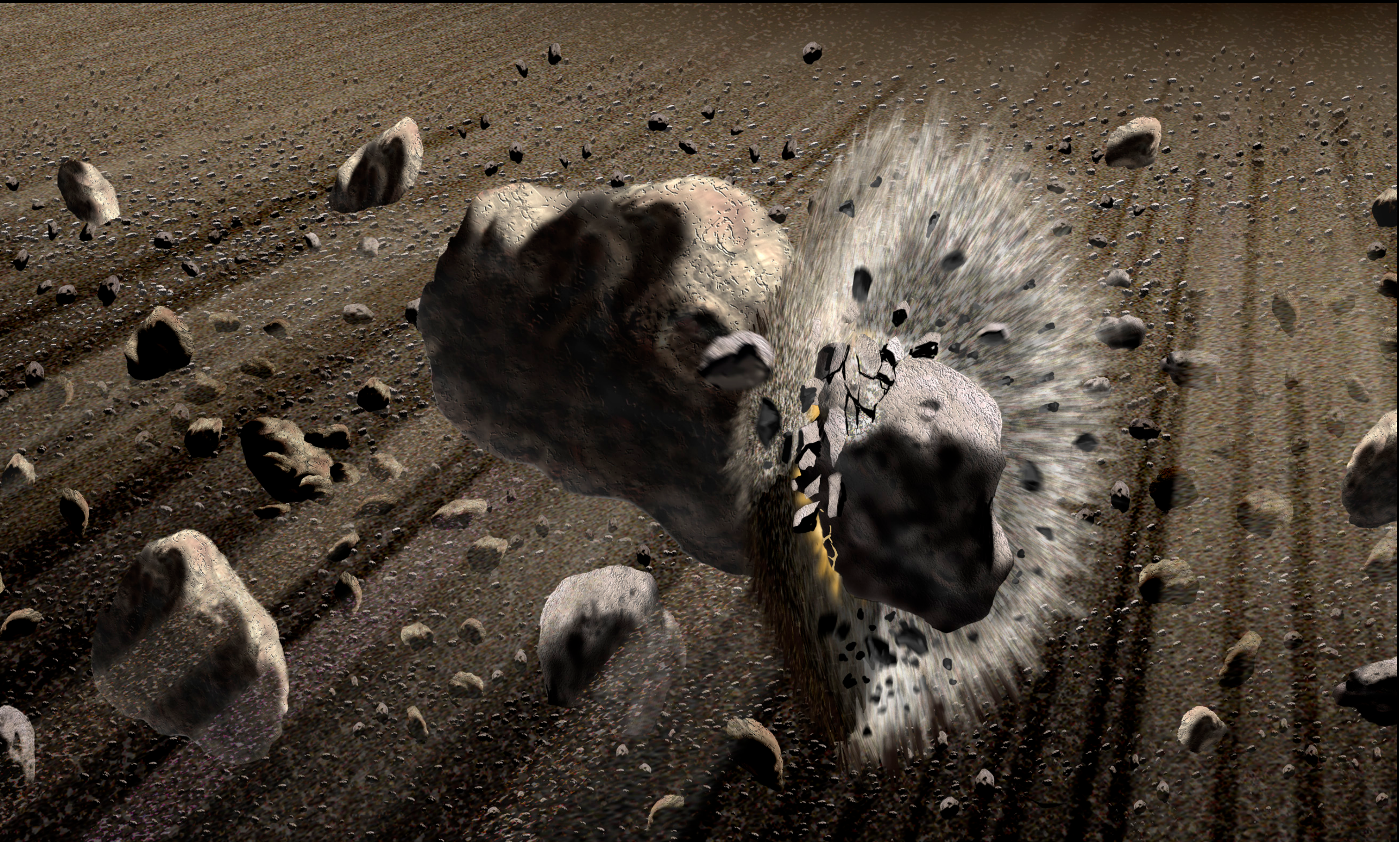


aki & Y. Nakagawa (2004); S. Meschiari (2012)





Stellar binarity may prevent planet formation



Analytical theory

Heppenheimer (1978):

$$e = e_{\max} \left| \sin \frac{ut}{2} \right|,$$

$$\tan \varpi = -\frac{\sin ut}{1 - \cos ut}$$

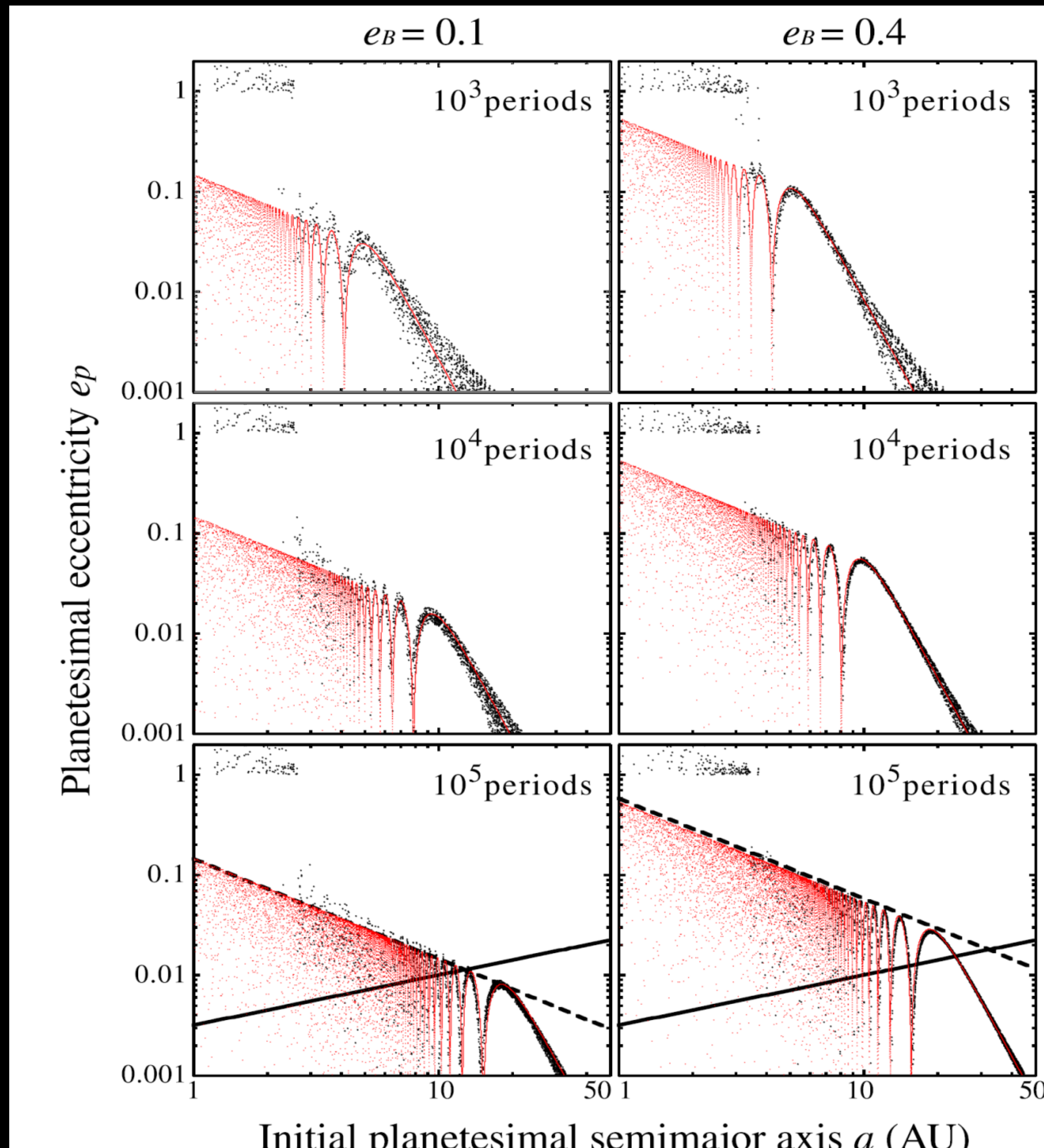
Moriwaki & Nakagawa (2004):

$$u = \frac{3\pi}{2} \frac{m_1 m_2}{(m_1 + m_2)^{3/2}} \frac{a_{\mathrm{b}}^2}{a^{7/2}} \left(1 + \frac{3}{2} e_{\mathrm{b}}^2\right),$$

$$e_{\max} = 2 e_{\mathrm{f}},$$

$$e_{\mathrm{f}} = \frac{5}{4} \frac{(m_1 - m_2)}{(m_1 + m_2)} \frac{a_{\mathrm{b}}}{a} e_{\mathrm{b}} \frac{\left(1 + \frac{3}{4} e_{\mathrm{b}}^2\right)}{\left(1 + \frac{3}{2} e_{\mathrm{b}}^2\right)}.$$

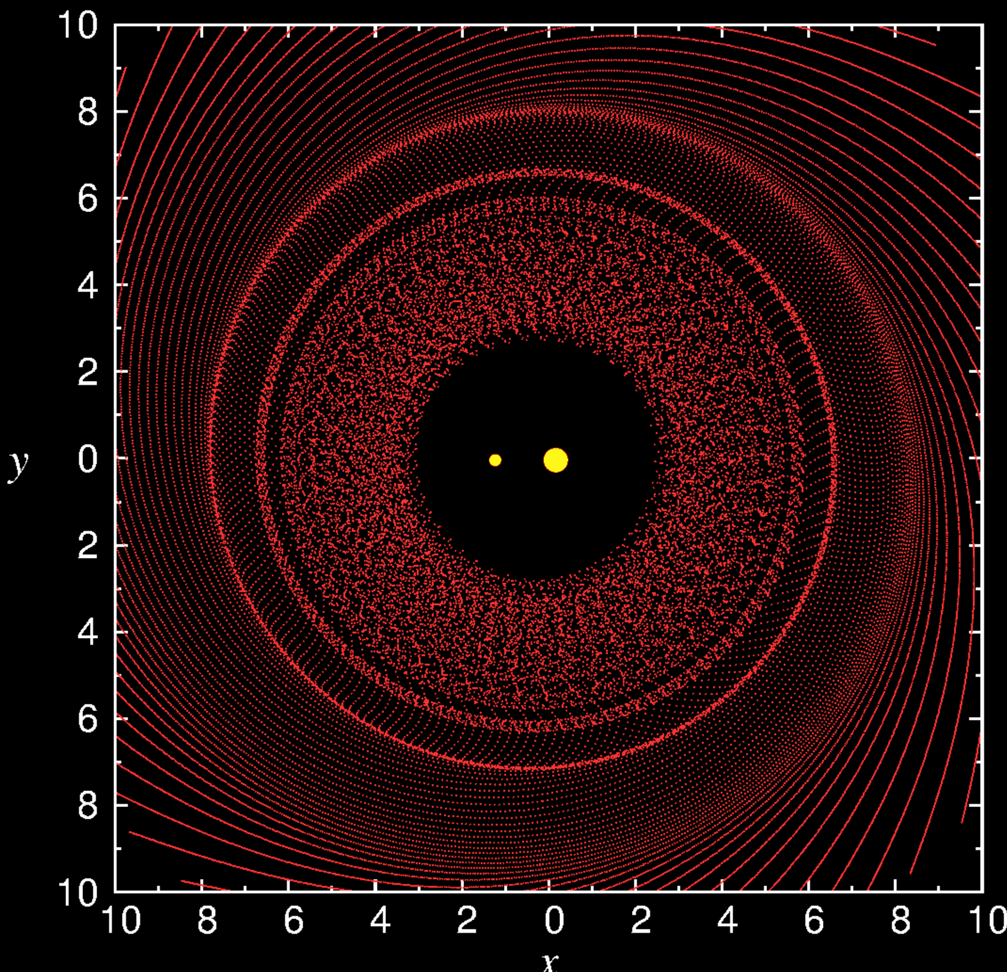
Comparison of numerical experiments and theory



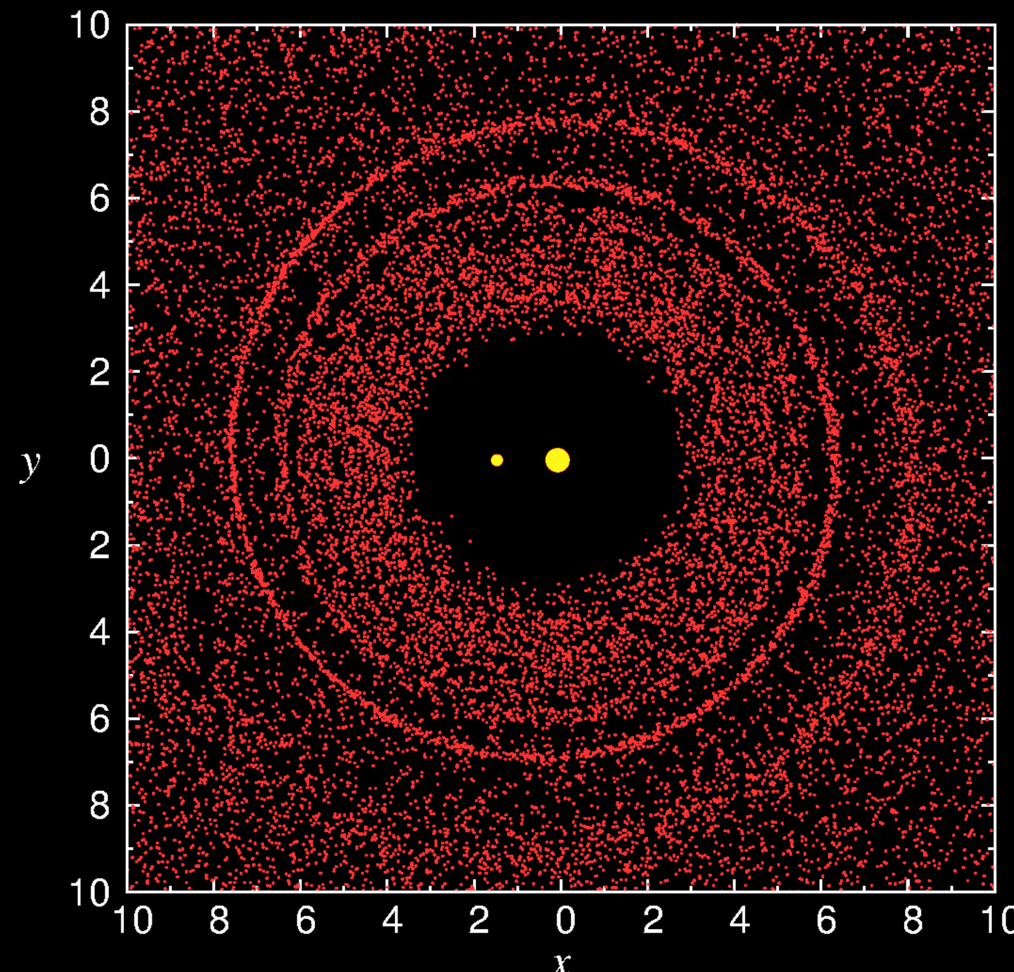
Orbits of planetesimals

Model: $m_1 = M_{\odot}$, $m_2 = 0.2\ M_{\odot}$, $e_b = 0.4$, $a_b = 1$ AU, $t = 10^4$ yr

Calculated in the analytical theory



Computed by the SPH-method

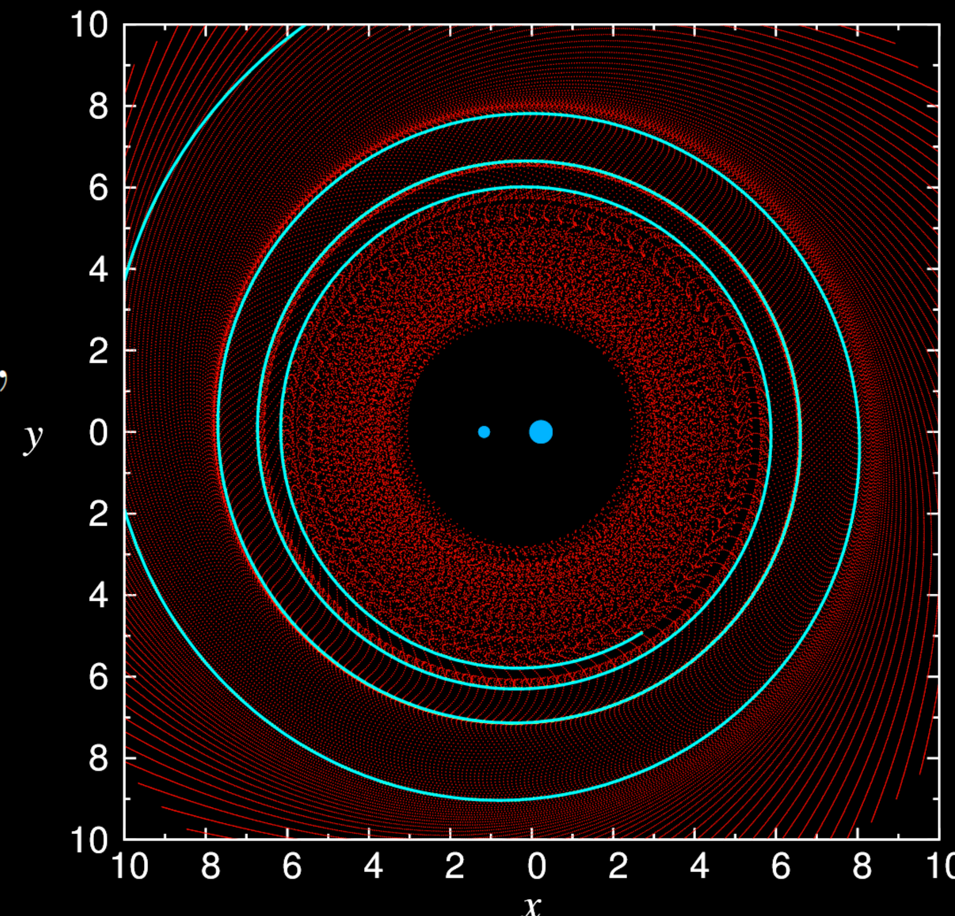


Spiral arm formula

$$r(\theta, t) = \left(\frac{At}{\theta}\right)^{2/7} + B(1 - \cos\theta),$$

$$A = \frac{3\pi}{2}\frac{m_1 m_2}{(m_1 + m_2)^{3/2}} a_{\mathrm{b}}^2 \left(1 + \frac{3}{2}e_{\mathrm{b}}^2\right),$$

$$B = \frac{5}{4}\frac{m_1 - m_2}{m_1 + m_2} a_{\mathrm{b}} e_{\mathrm{b}} \frac{(1 + \frac{3}{4}e_{\mathrm{b}}^2)}{(1 + \frac{3}{2}e_{\mathrm{b}}^2)}.$$



$$T_{\mathrm{s}} = \frac{\pi}{A}(r_{\mathrm{disk}} - 2B)^{7/2} \approx \frac{\pi}{A} r_{\mathrm{disk}}^{7/2}$$

For Kepler-16: $M_1 = 0.69 M_\odot$, $M_2 = 0.20 M_\odot$, $a_b = 0.22$ AU, $e_b = 0.16$, $r_{disk} = 30$ AU, $Ts = 1.1 \cdot 10^7$ yrs.

Gas influence

Model:

$m_1 = M_\odot$

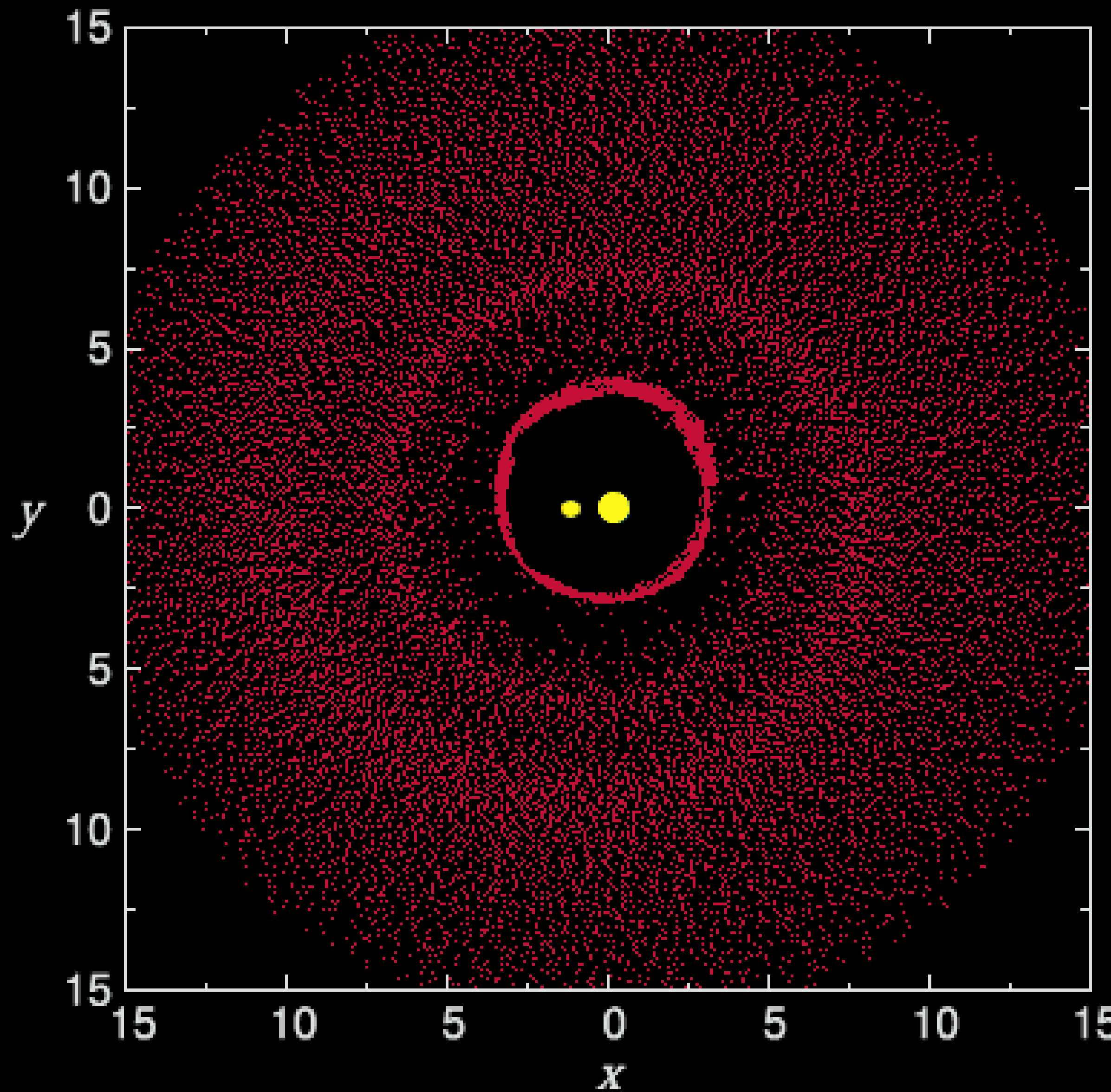
$m_2 = 0.2\ M_\odot$

$e_b = 0.4$

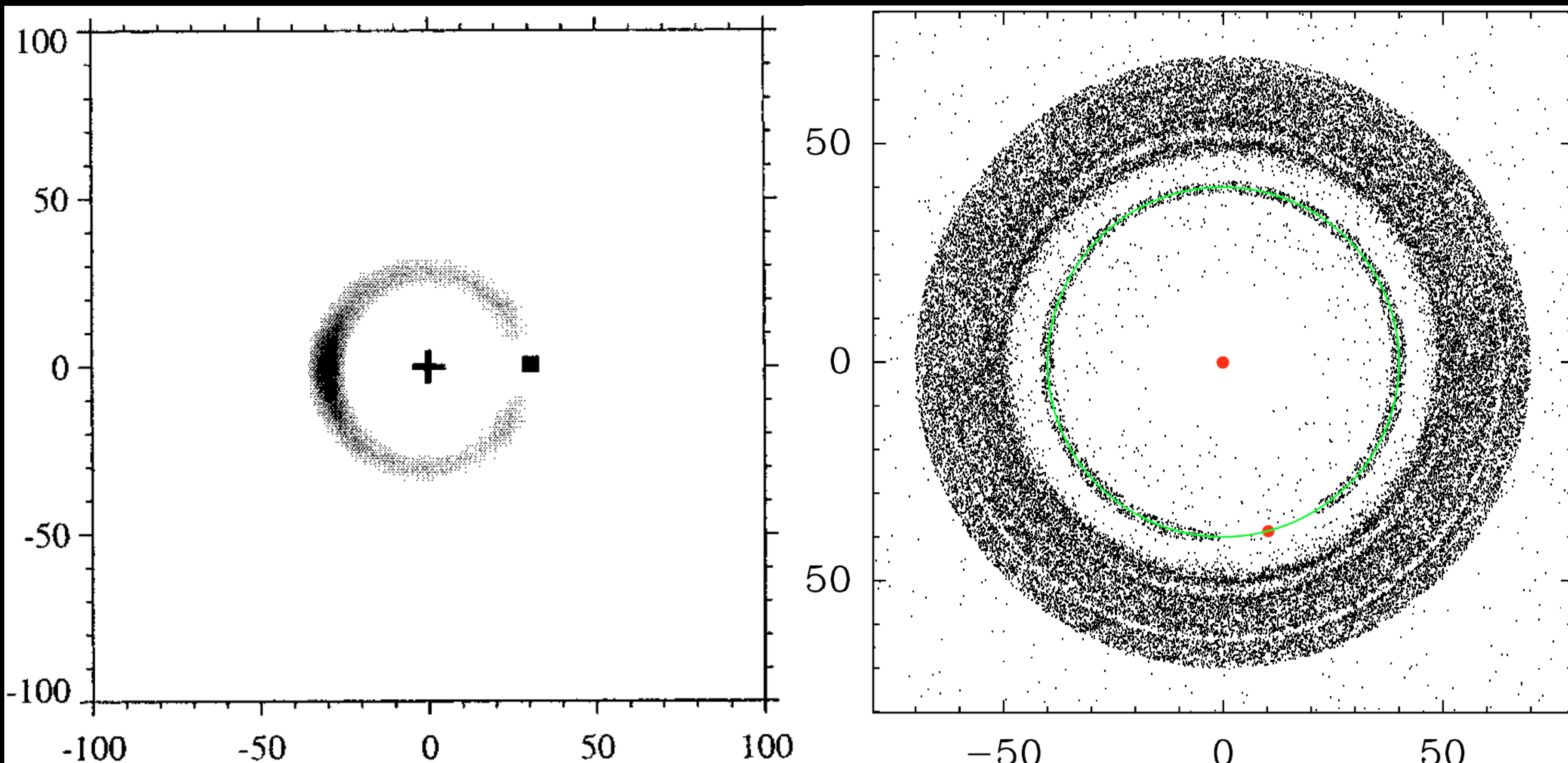
$a_b = 1$ AU

$t = 10^4$ yr

The gas presence slows down the eccentricity pumping and prevents the wave spread.



A ring-like pattern co-orbital with a planet of a single star



Ozernoy et al., 2000; Quillen & Thorndike, 2002; Kuchner & Holman 2003; Reche et al., 2008.

Co-orbital dust rings and Trojans in the Solar system

Dust rings:

co-orbital with the Earth (Jackson & Zook, 1989; Dermott et al., 1994; Reach et al.,1995);

co-orbital with a moon of Neptune (Hubbard et al., 1986; Sicardy, 1991; Sicardy & Dubois, 2003).

Trojan asteroids: Jupiter,

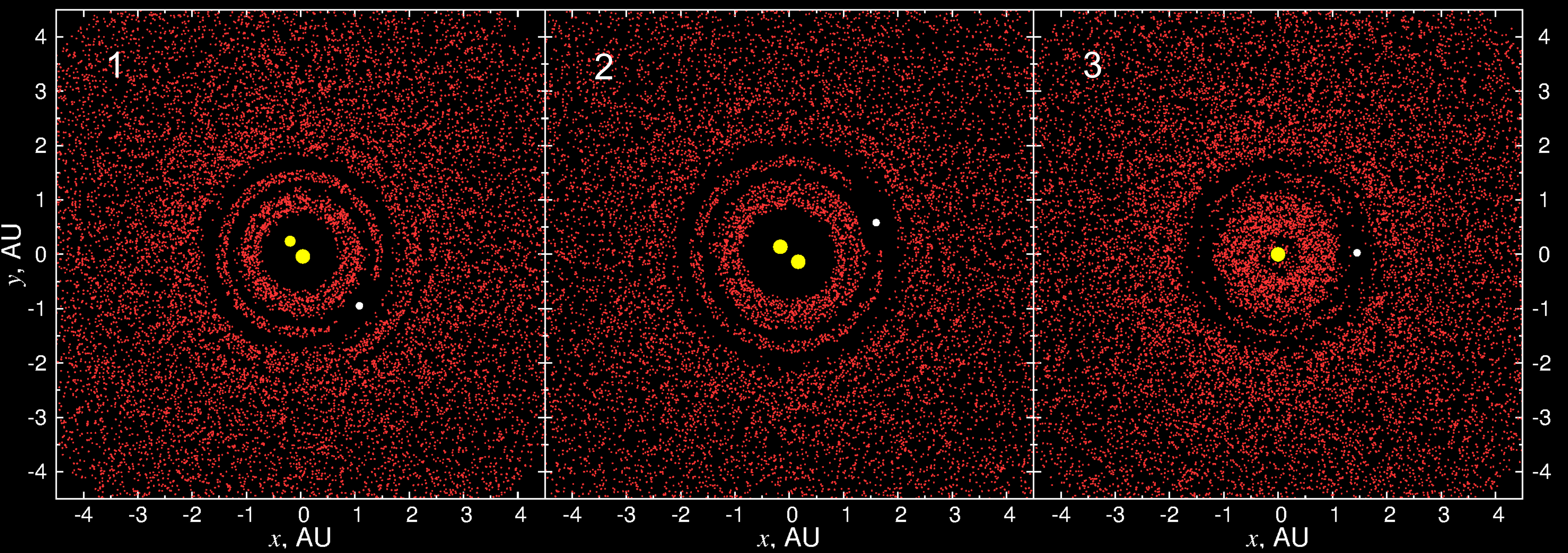
Earth (Connors et al., 2011)

Uranus (Alexandersen et al., 2013)

Mars (Bowell et al., 1990)

Neptune (Sheppard & Trujillo, 2006)

A planet embedded in a debris disk

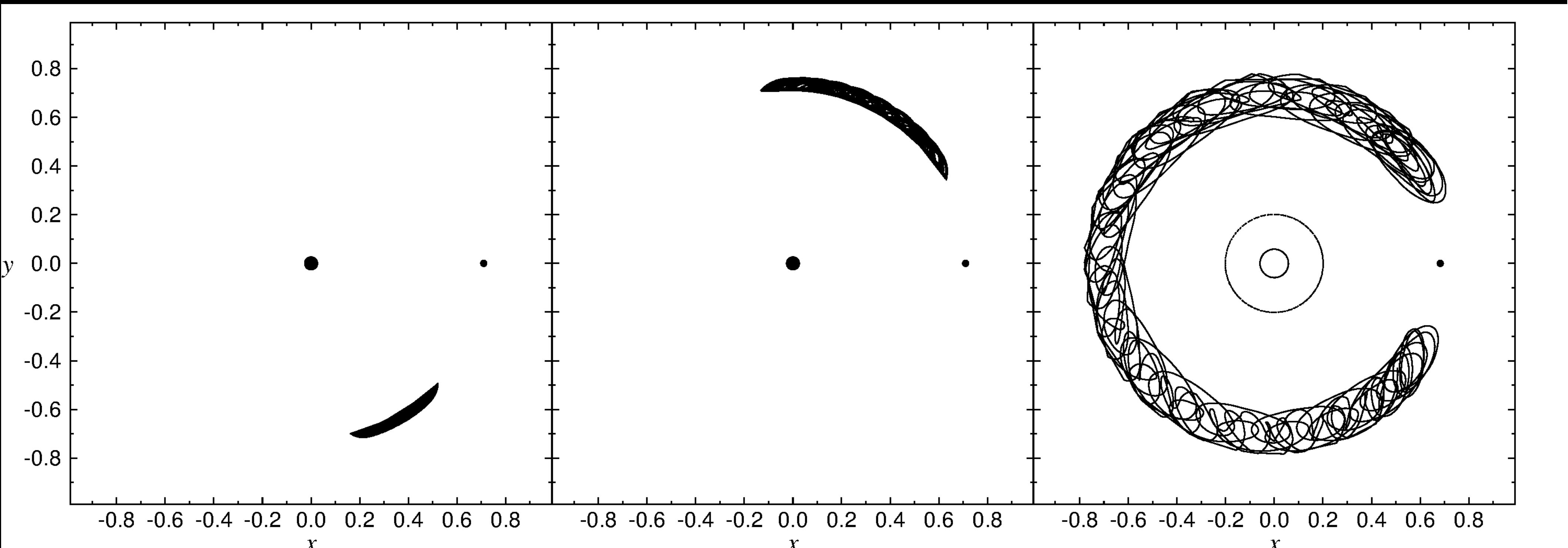


Evolved distributions of planetesimals, 5×10^4 yr.
Model: (1) $M_1 = M_\odot$, $M_2 = 0.2\ M_\odot$; (2) $M_1 = M_2 = M_\odot$;
(3) $M = 1.2\ M_\odot$. Binary period 0.2 yr, planet mass 1 M_J, planet period 1.6 yr.

Planetesimal orbits in the ring

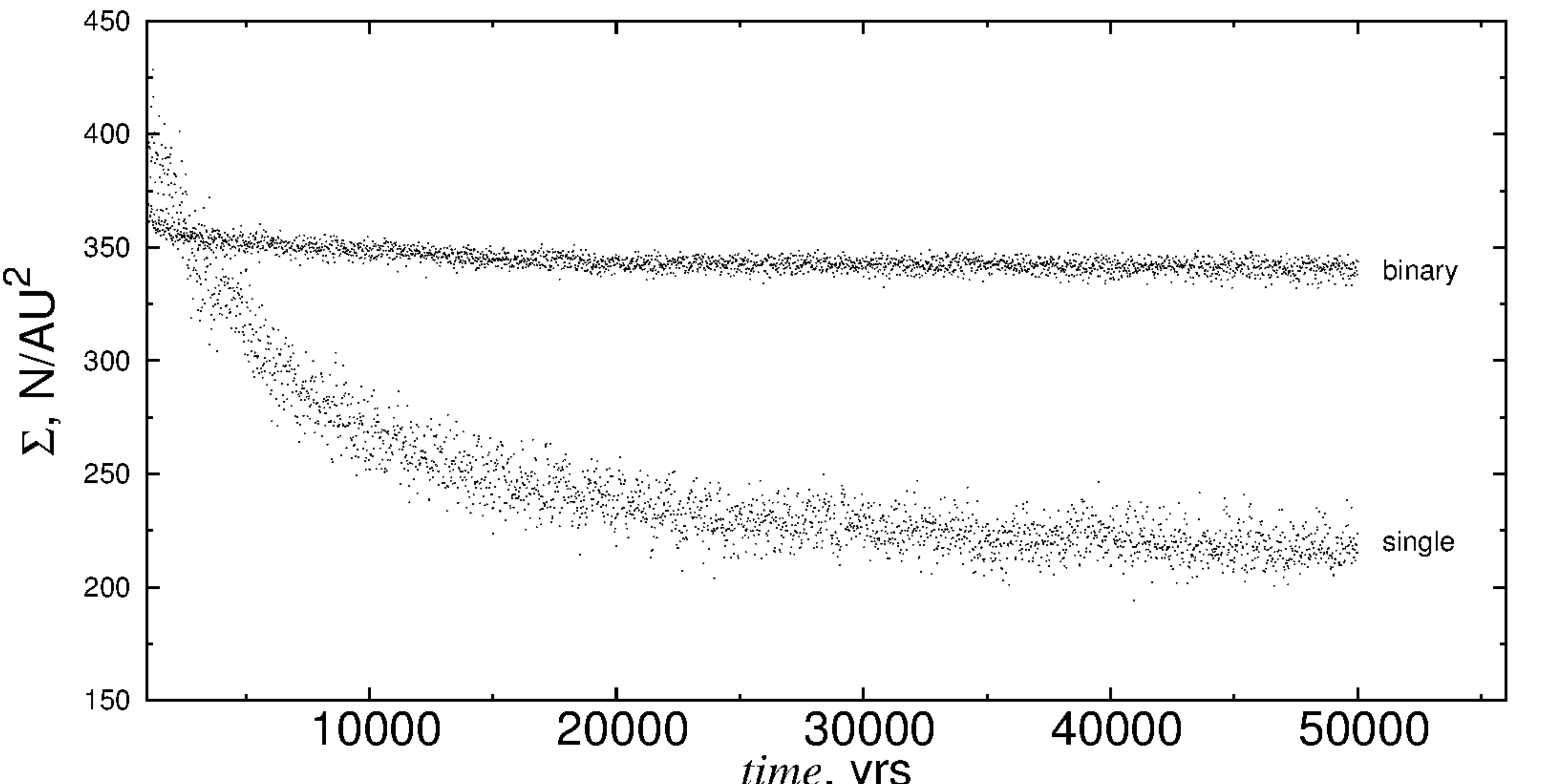
Tagpoles

Horseshoes

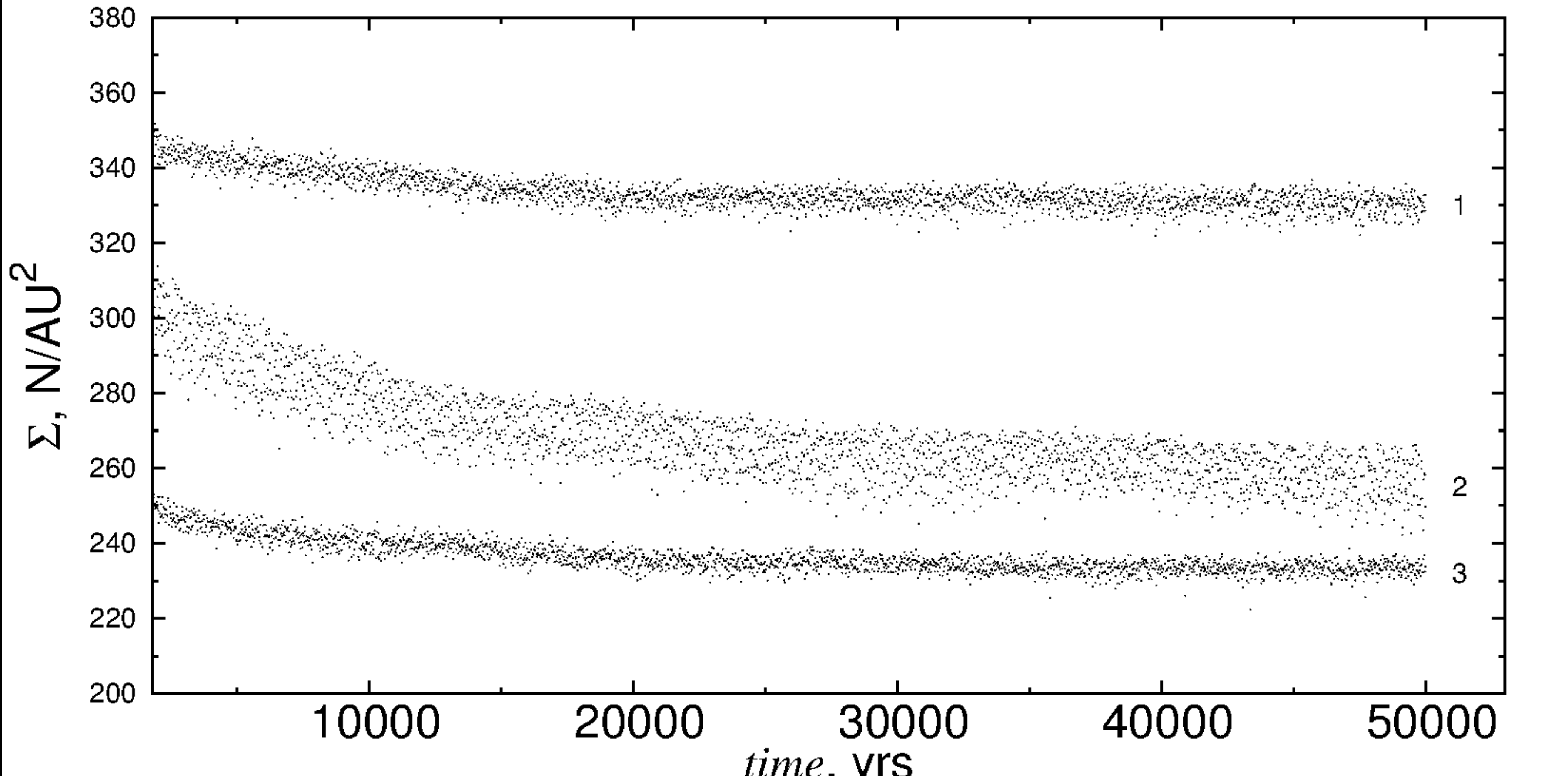


Two kinds of co-orbital orbits may originate for a planet of a single star (Murray & Dermott, 1999): «tadpoles» and «horseshoes». In the circumbinary case, only the horseshoe orbits are observed.

Lifetimes of the ring-like patterns co-orbital with planets



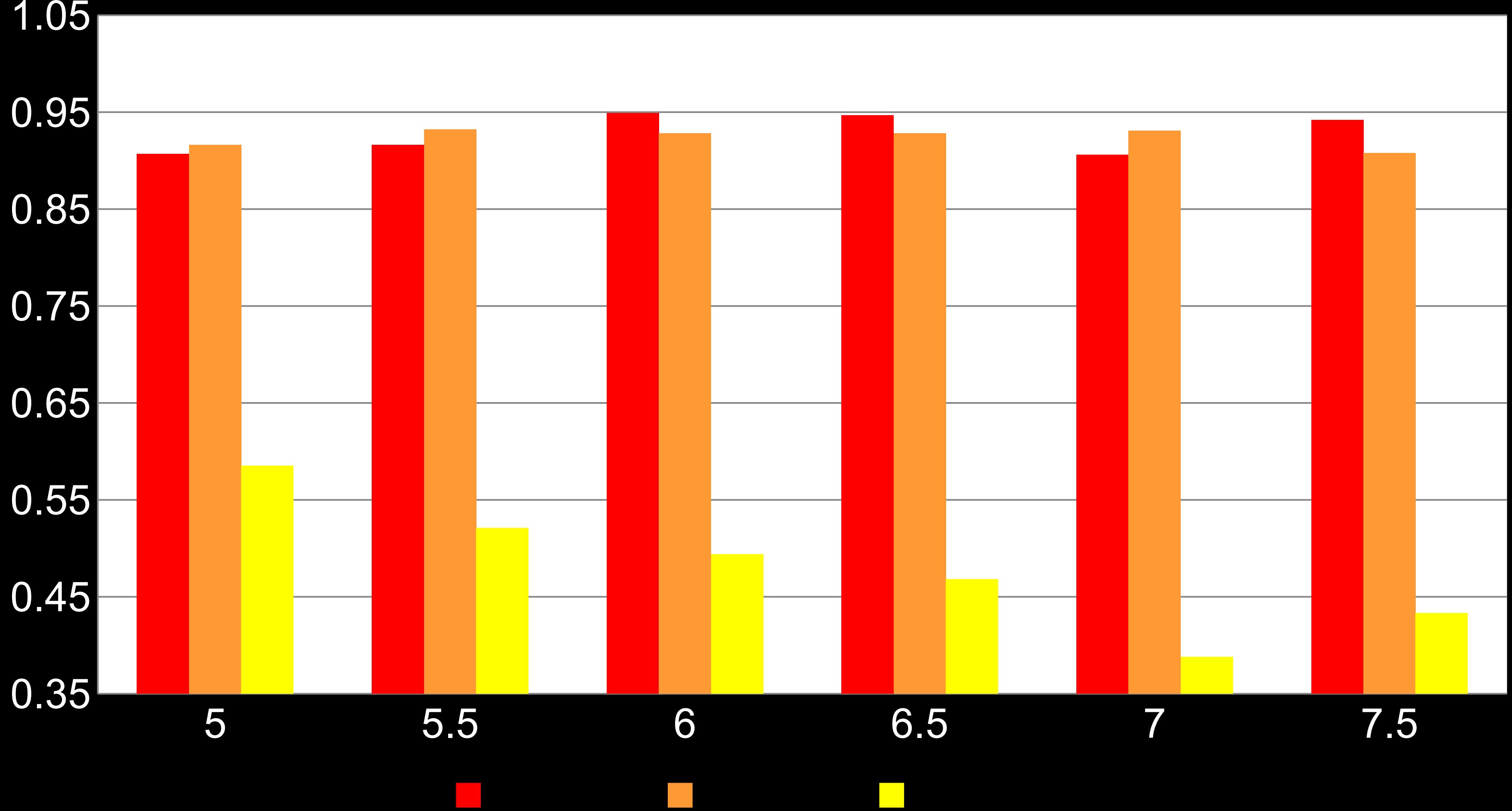
Lifetimes of the ring-like patterns co-orbital with planets



Model parameters: 1. $M_1 = M_\odot$, $M_2 = 0.2\ M_\odot$, $e = 0$;

2. $M_1 = M_\odot$, $M_2 = 0.2\ M_\odot$, $e = 0.1$;

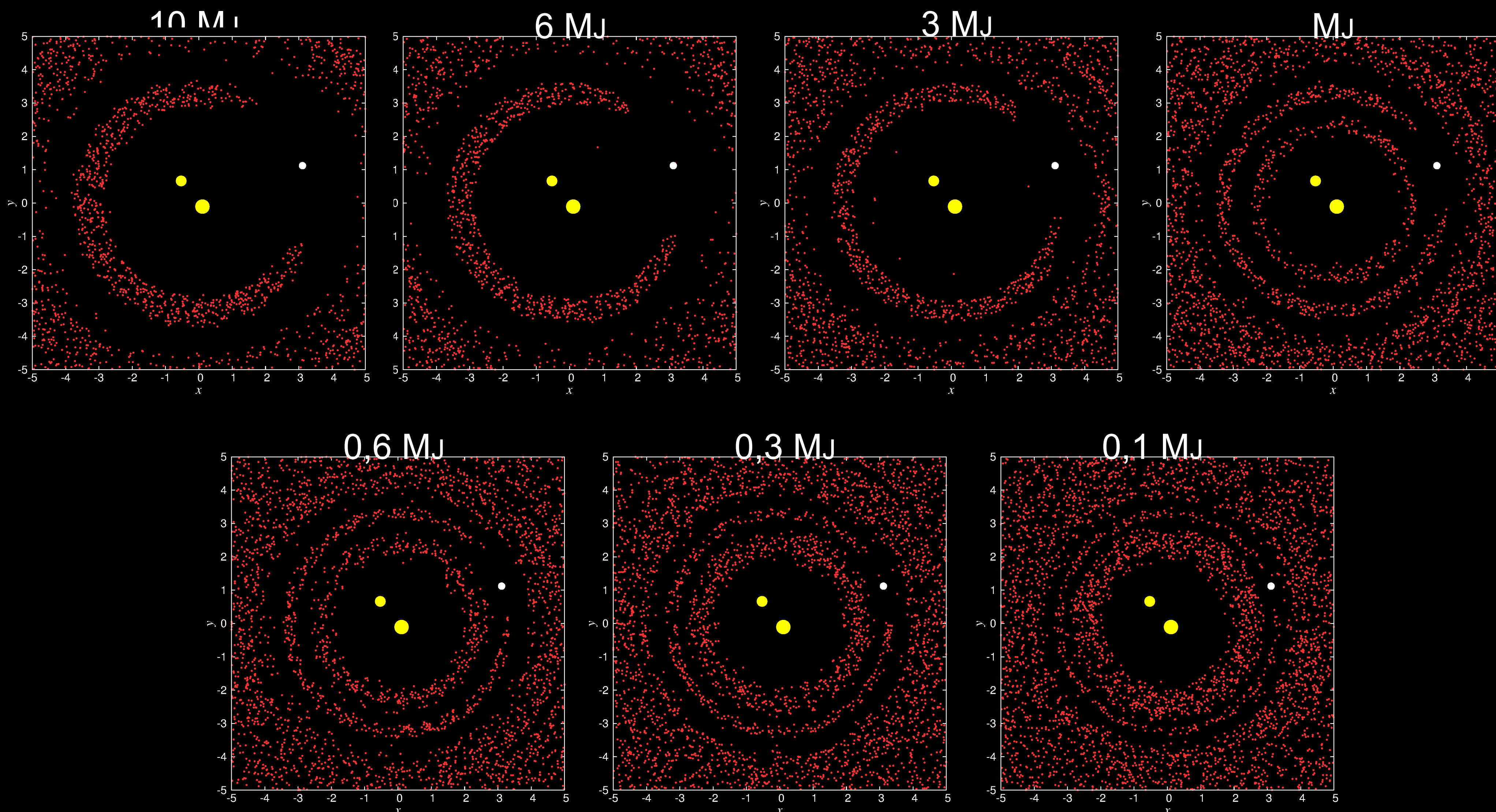
Lifetimes in dependence of the planet position



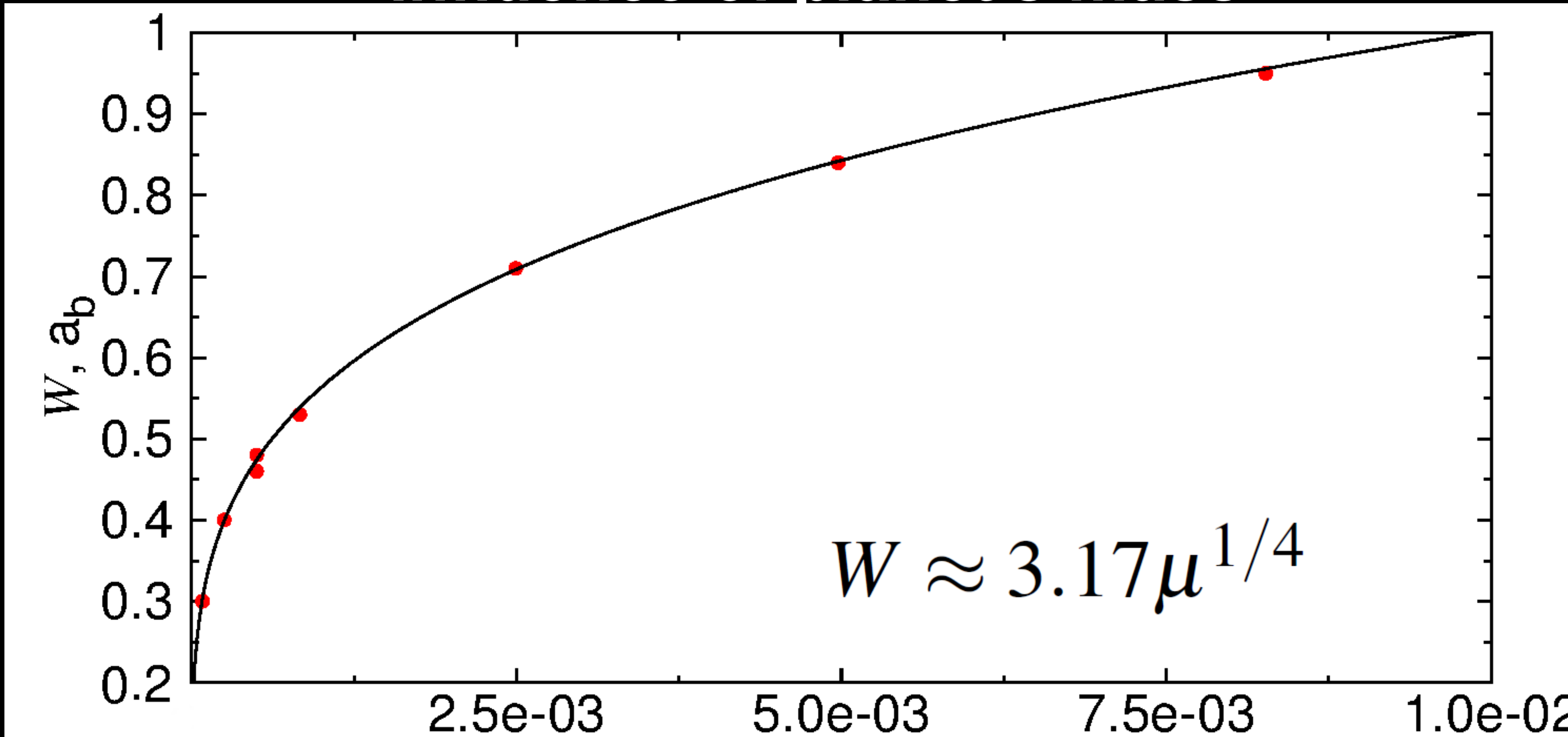
The ratio of final ($t = 50000$ yr) and initial ($t = 1000$ yr) populations of the co-orbital ring. Model parameters: (1) $M_1 = M_\odot$, $M_2 = 0.2\ M_\odot$; (2) $M_1 = M_2 = M_\odot$; (3) $M = 1.2\ M_\odot$. Binary period 0.2 yr, planet mass 1 M_J.

Influence of planet's mass

Model: $M_1 = M_\odot$, $M_2 = 0.2\ M_\odot$; binary period 0.2 yr, planet period 1.2 yr.



Influence of planet's mass



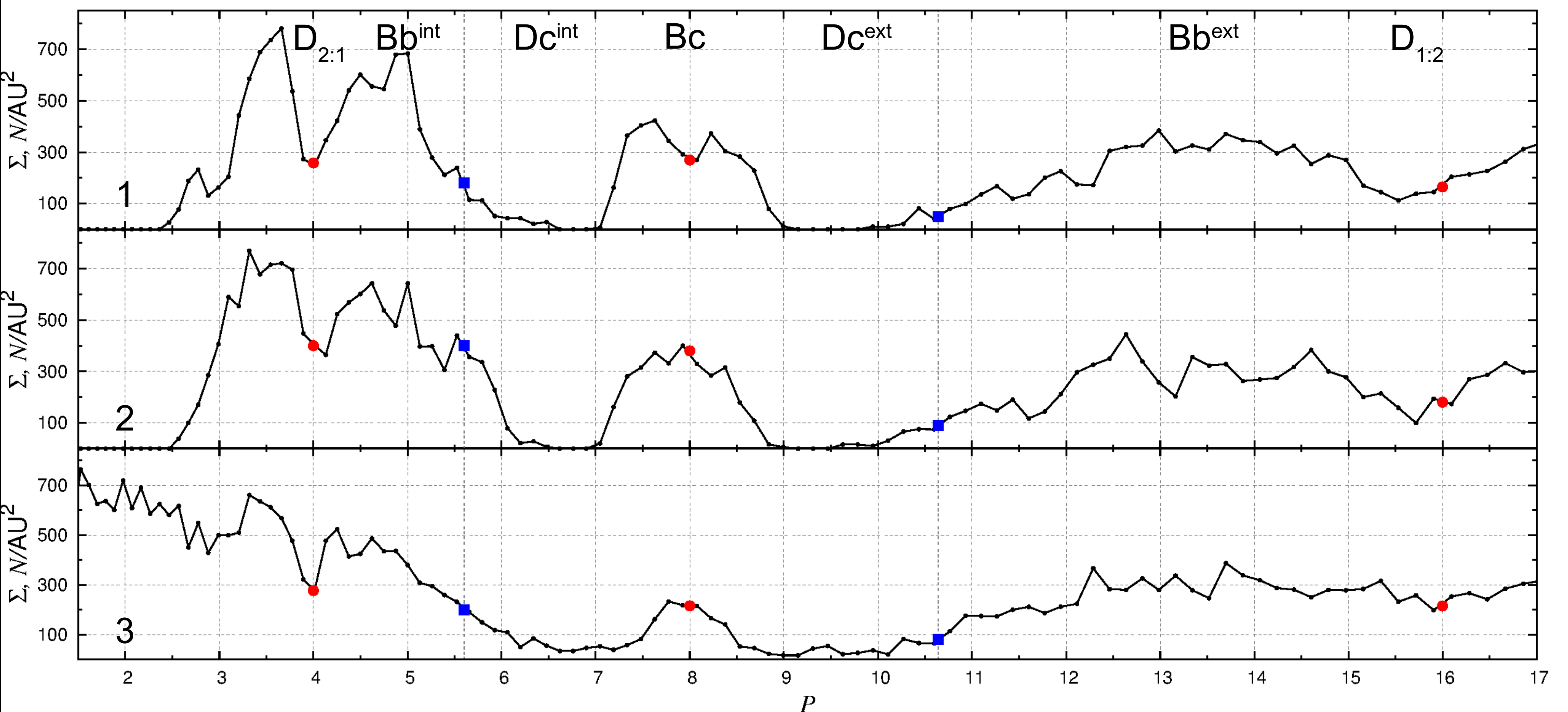
Survivability of the co-orbital ring							
m_p	10 M_J	6 M_J	3 M_J	M_J	0.6 M_J	0.3 M_J	0.1 M_J
$\Sigma(5\cdot10^4)/\Sigma(10^3)$	0.936	0.959	0.950	0.949	0.916	0.901	0.712

A planet is an astronomical object orbiting a star or a stellar remnant that

- is massive enough to be rounded by its own gravity,
- is not massive enough to cause thermonuclear fusion,
- has cleared its neighboring region of planetesimals.

IAU 2006 General Assembly: Result of the IAU Resolution votes.
International Astronomical Union (2006)

Multi-lane signatures of planets in planetesimal disks



The local surface density as a function of the planet's orbital period.
Model: (1) $M_1 = M_\odot$, $M_2 = 0.2\ M_\odot$; (2) $M_1 = M_2 = M_\odot$;
(3) $M = 1.2\ M_\odot$. Binary period 0.2 yr, planet mass 1 M_J, planet period 1.6 yr.

Definition of lanes

The seven-lane complex can be detected: $D_{2:1}$ - Bb^{int} - Dc^{int} - Bc - Dc^{ext} - Bb^{ext} - $D_{1:2}$

Bc is the bright central (or bright co-orbital) lane;

Dc^{int} and **Dc^{ext}** are two components of the broader Wisdom gap, dark central (or dark coorbital), internal and external.

Half-width of the chaotic band around the orbit of a planet (Wisdom, 1980):

$$\Delta a_{\mathrm{Wisdom}} \approx 1.57 \mu^{2/7} a_{\mathrm{p}}$$

$D_{2:1}$ and **$D_{1:2}$** are the dark lanes at resonances 2:1 and 1:2 with the planet;

Bb^{int} is the bright lane (bright barrier) between **$D_{2:1}$** and **Dc^{int}**

Bb^{ext} is the bright lane between **Dc^{ext}** and **$D_{1:2}$**

Demidova & Shevchenko (2016); Tabeshian & Wiegert (2016).

Multi-lane signature in dependence on planet's location

Model:

$M_1 = M_\odot$

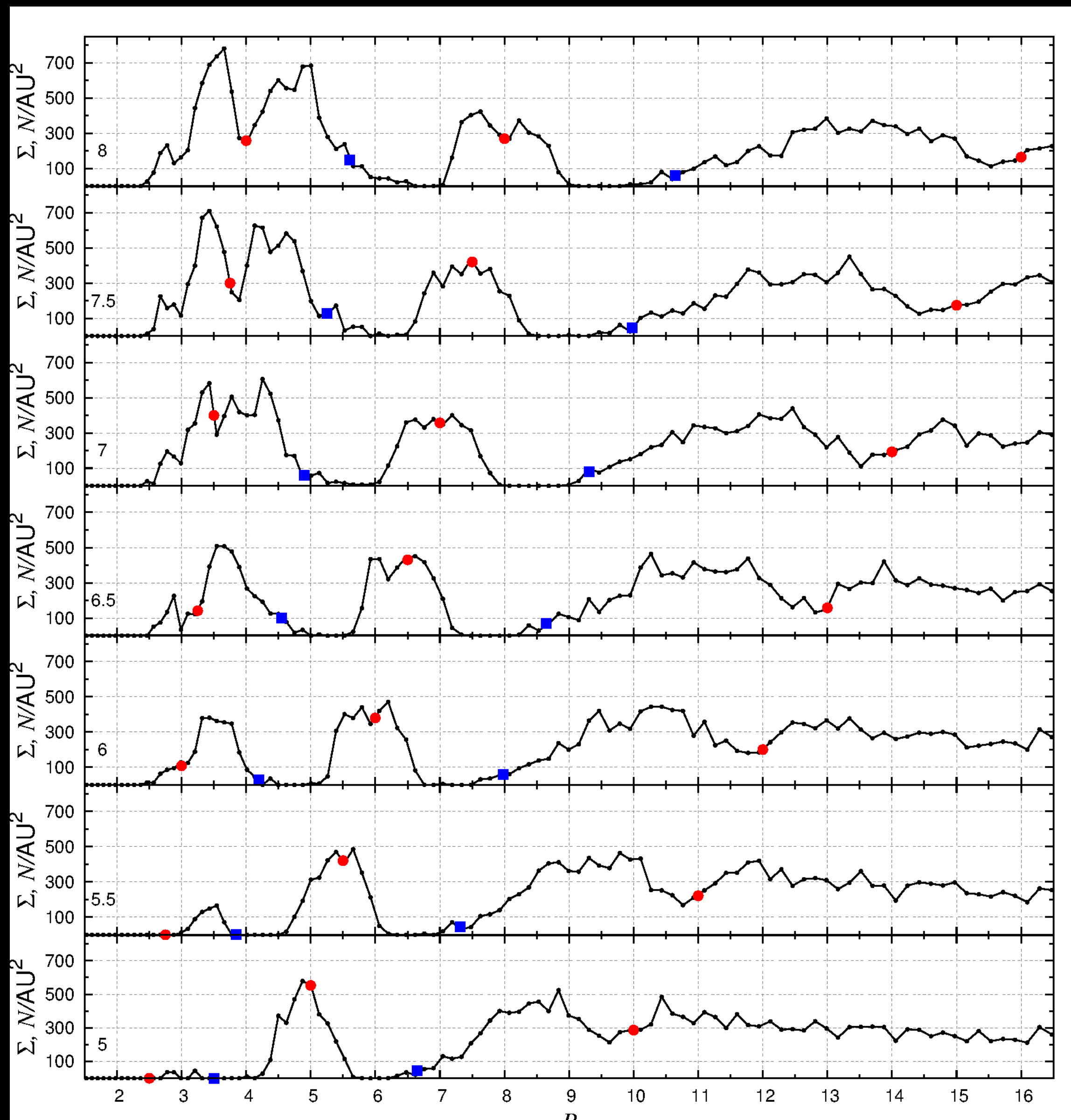
$M_2 = 0.2\ M_\odot$

$e_b = 0$

$P_b = 0.2$ yr

$M_p = 1\ M_J$

$e_p = 0$



Multi-lane – three-lane transfiguration

A three-lane pattern can arise, instead of the generic seven-lane pattern, in two cases:

(1) just because the 2:1 and 1:2 resonances are not prominent;

(2) if the $D_{2:1}$ and $D_{1:2}$ lanes overlap, respectively, with the Dc^{int} and Dc^{ext} lanes (thus, the «bright barriers» Bb vanish).

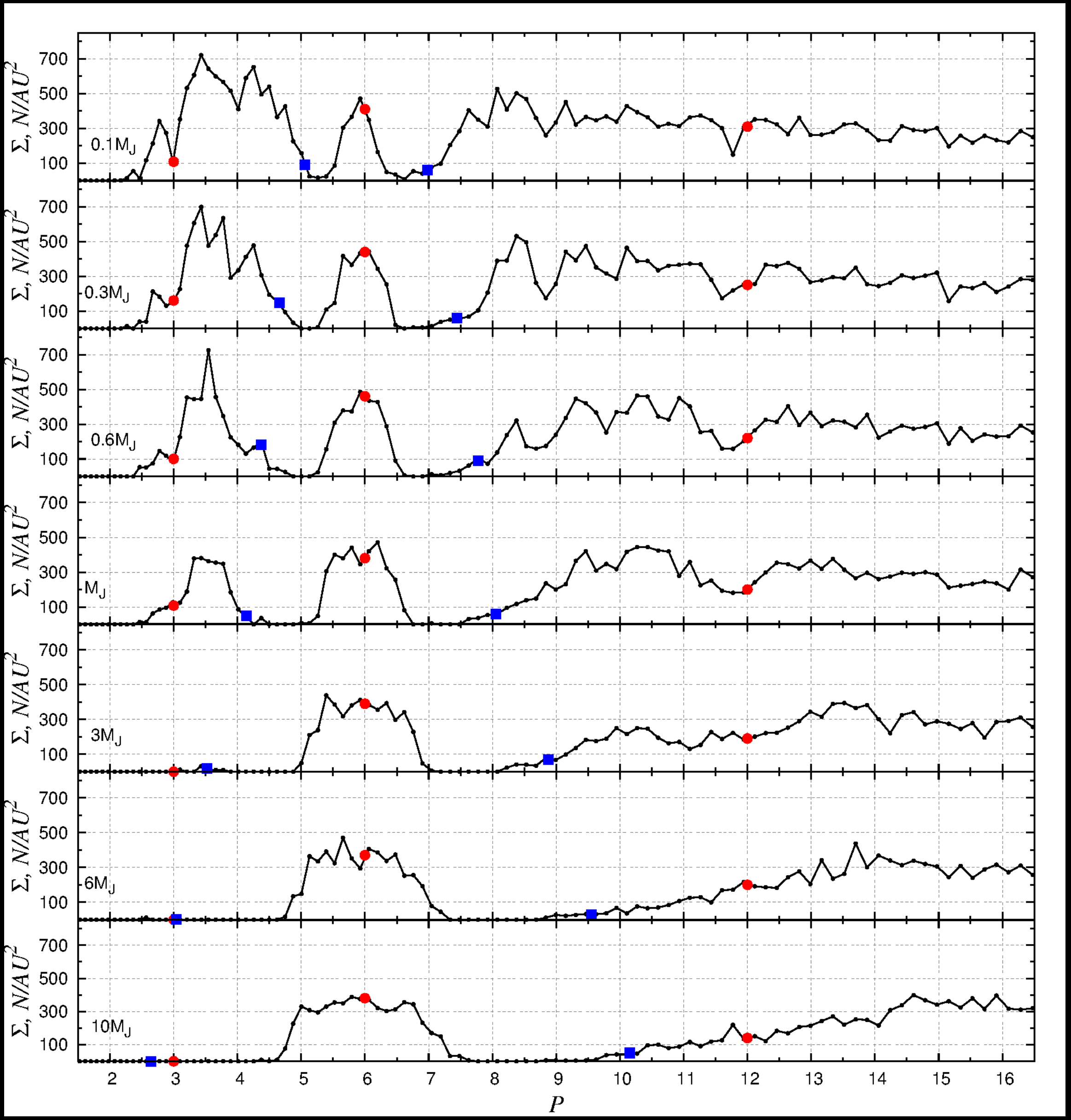
$$1 - 1.57\mu^{2/7} = 2^{-2/3} \qquad 1 + 1.57\mu^{2/7} = 2^{2/3}$$

The critical μ ~ 0.01

At such values one expects the degeneration of the seven-lane complex into the three-lane one.

Multi-lane signature in dependence on planet's mass

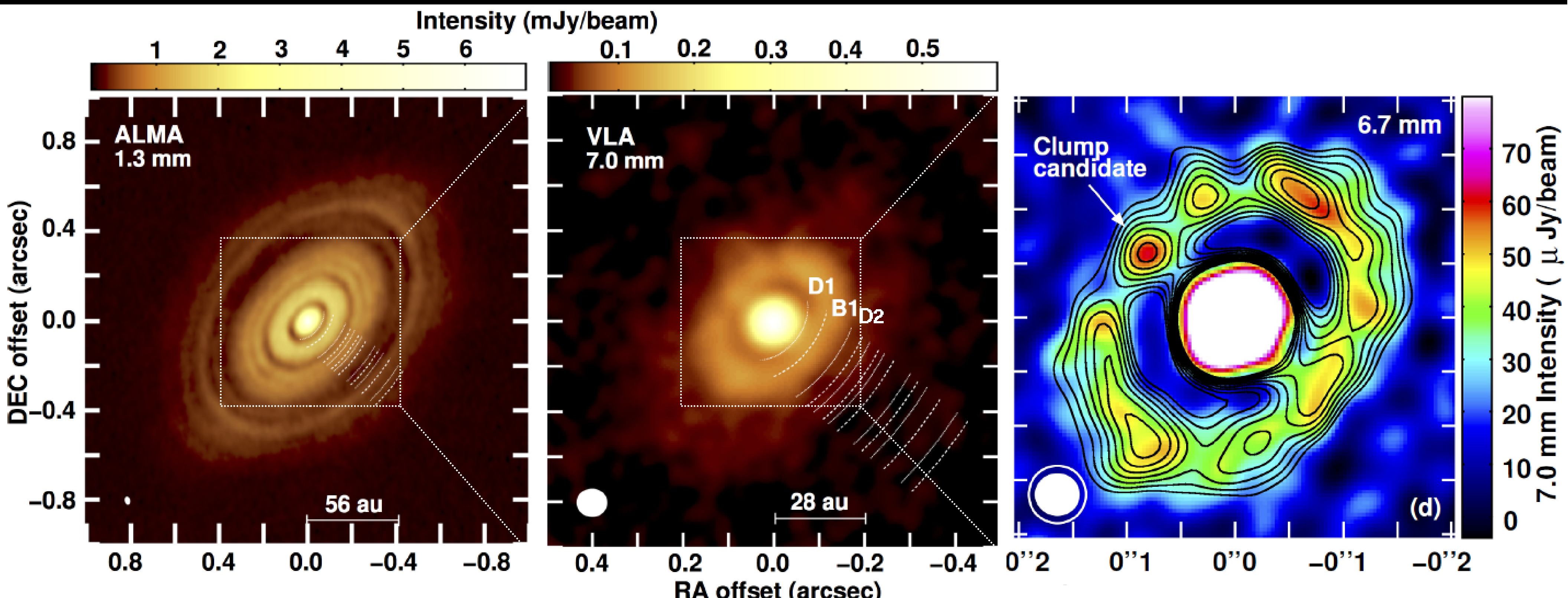
Model:
$M_1 = M_\odot$
$M_2 = 0.2\ M_\odot$
$e_b = 0$
$P_b = 0.2$ yr
$P_p = 1.2$ yr
$e_p = 0$



μ = 8e-5
μ = 2.5e-4
μ = 5e-4
μ = 8e-4
μ = 0.002
μ = 0.005
μ = 0.008

Formation of a planet in the HL Tau disk

(Carrasco-Gonzalez et al., 2016).



The HL Tau disk

Dark ring-like features **D1** and **D2** are situated at radii **0.63** and **1.60** (if the radius of the main bright feature **B1**, that with a planet-like «clump», is set to **1**). These locations correspond to mean motion resonances **2:1** and **1:2** with the clump. Therefore, they correspond to the $D_{2:1}$ and $D_{1:2}$ lanes in our models.

If the dust mass in the clump is **3-8** M_E (Carrasco-Gonzalez et al. 2016) and the dust-to-gas ratio equal to the standard value **1:100**, then the **«clump»** mass is **1-3** M_J. The mass of **HL Tau** star is **0.55** $M_\odot$ (Beckwith et al. 1990). The mass parameter of the star-clump system is **μ = 0.002- 0.006.**

The generic seven-lane pattern degenerates to the three-lane one

Conclusions

If a stellar binary with a planetesimal disk is eccentric and its components have unequal masses, then a spiral density wave is generated in the disk.

• The emerging spiral pattern is a modified «lituus» (a shifted power-law spiral).

• The timescale for the secular wave propagation can be greater than the lifetime of the gas-rich disk.

• The ring pattern co-orbital with the planet is more survivable, if the parent star is double.

• Emerging planets generate three-lane and multi-lane signatures in planetesimal disks.