Terrestrial Planetformation in Binary Star Systems

Prestellar Phase

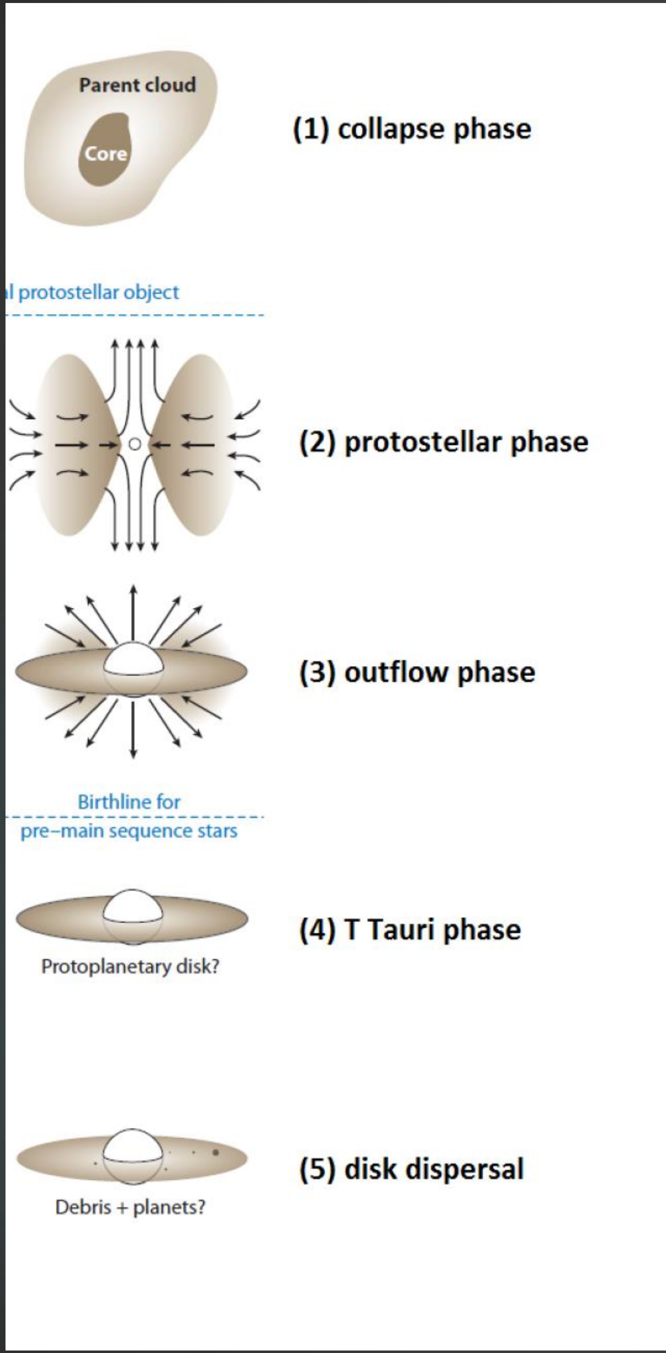
t=0

Protostellar Phase

t <0.03Myr

t ~ 0.2 Myr

t~10Myrs



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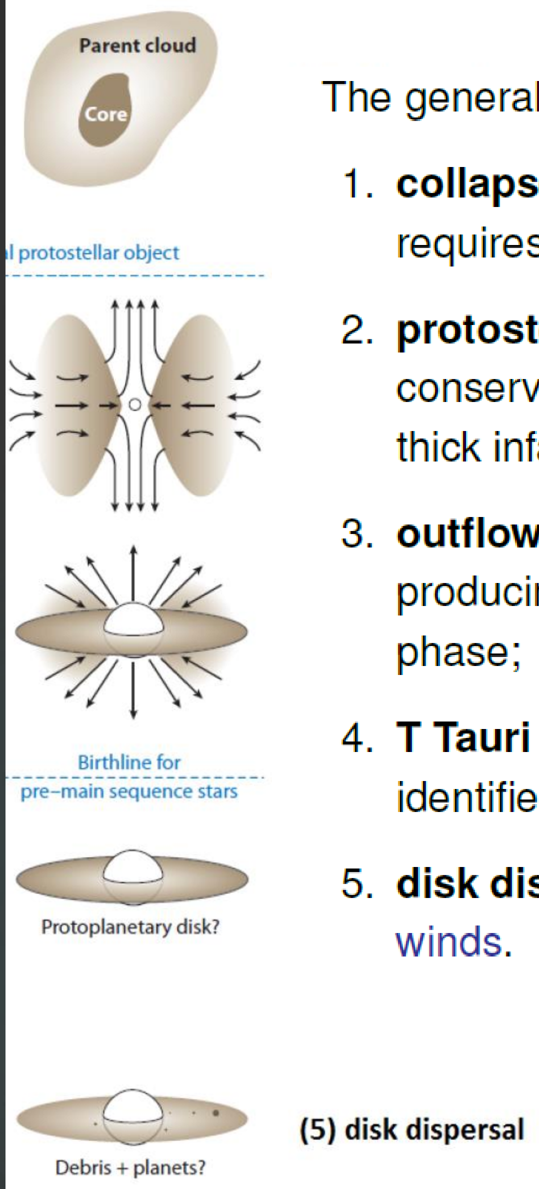

The generally accepted paradigm of low mass star formation (Shu et al. 1987) is as follows:

1. **collapse phase**: giant molecular clouds must contract to form molecular cores. This contraction requires *ambipolar diffusion* to first carry away the magnetic fields which help hold the cloud up;
2. **protostellar phase**: the rapid inside-out gravitational collapse of molecular cloud cores conserves angular momentum, producing a protostar surrounded by a disk and an optically thick infalling envelope;
3. **outflow phase**: a strong stellar wind breaks out at the rotational poles, reversing the infall and producing bipolar outflows. This phase seems to be intimately connected with the disk formation phase;
4. **T Tauri phase**: the newly formed star/disk system becomes optically visible and the protostar is identified as a T Tauri star;
5. **disk dispersal phase**: the final stage is the clearing of the disk, via photoevaporation and stellar winds.

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Protostellar Phase

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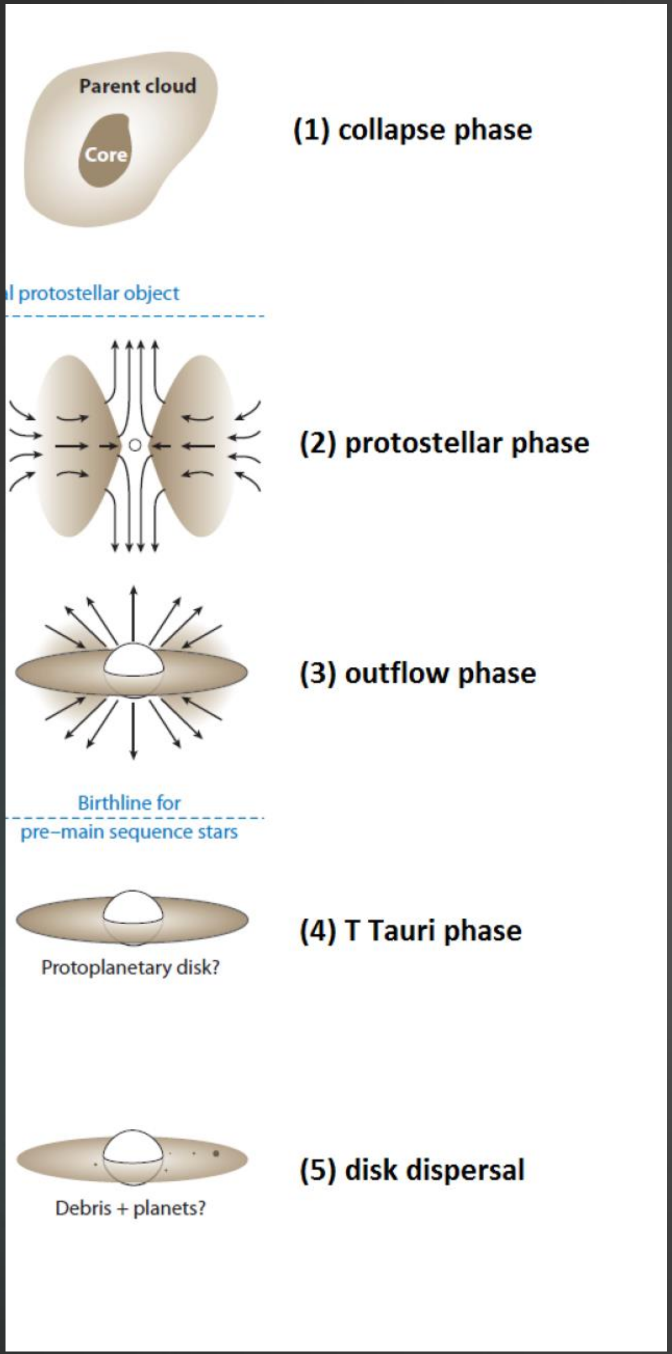
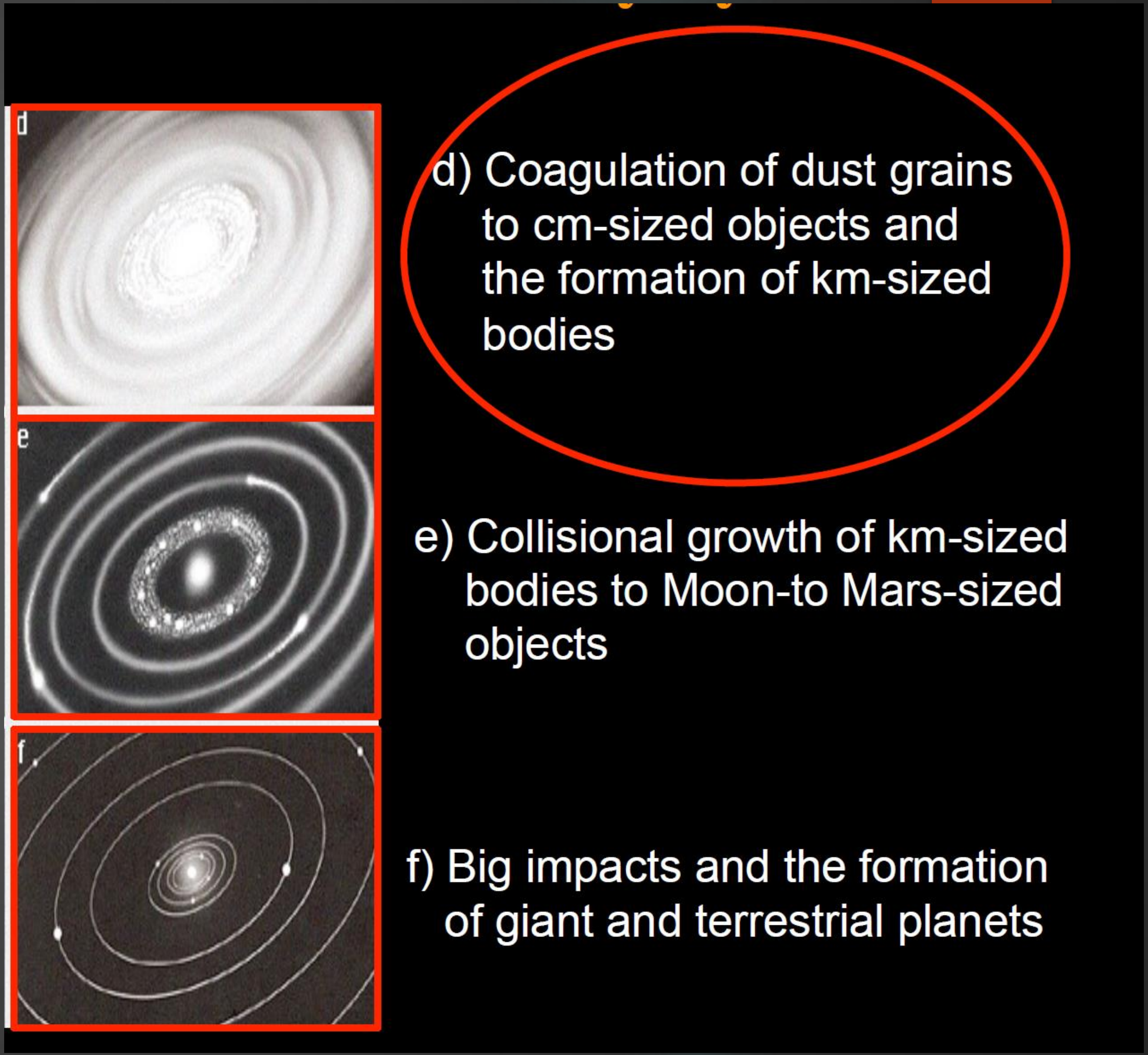
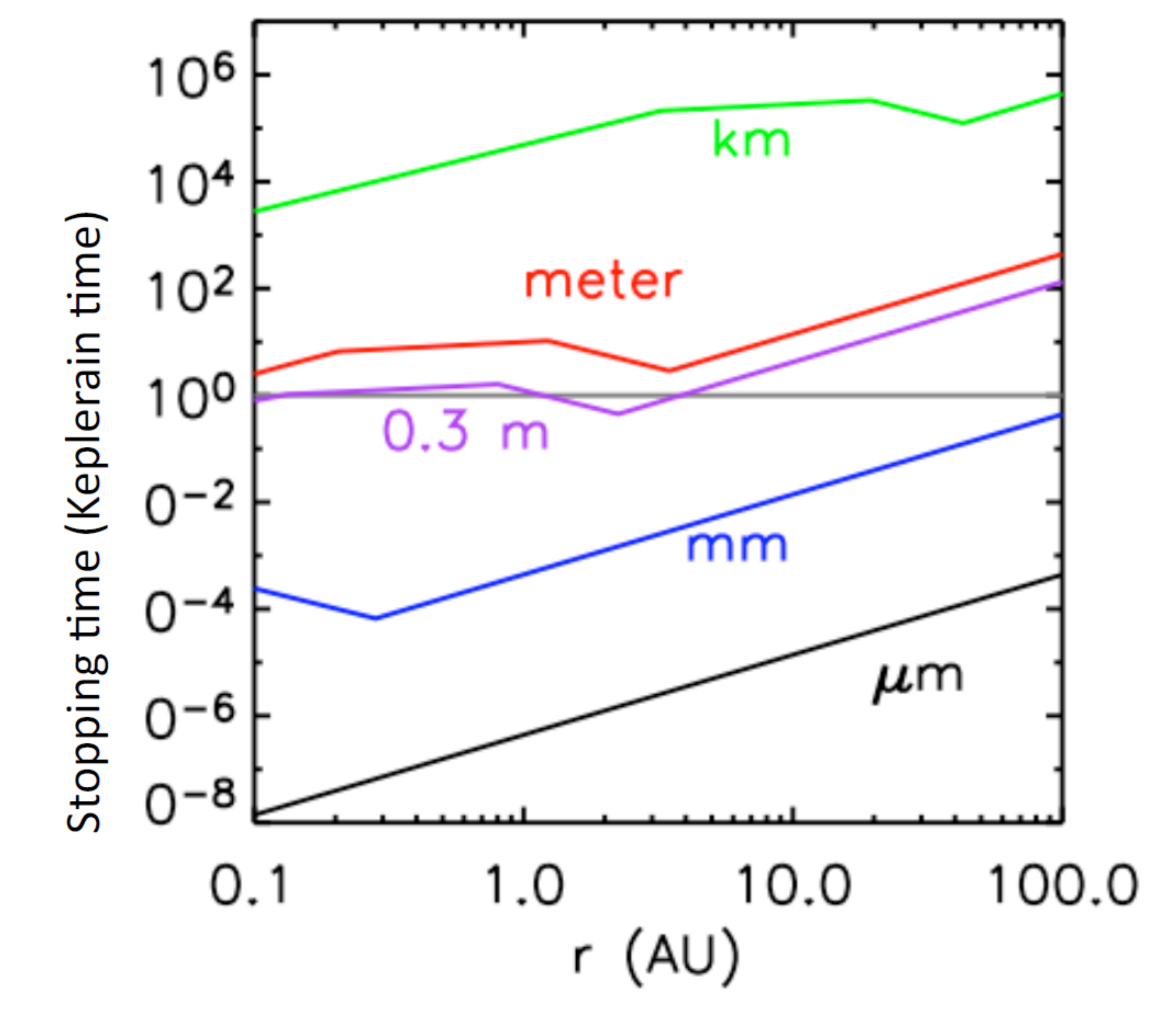
t~10Myrs





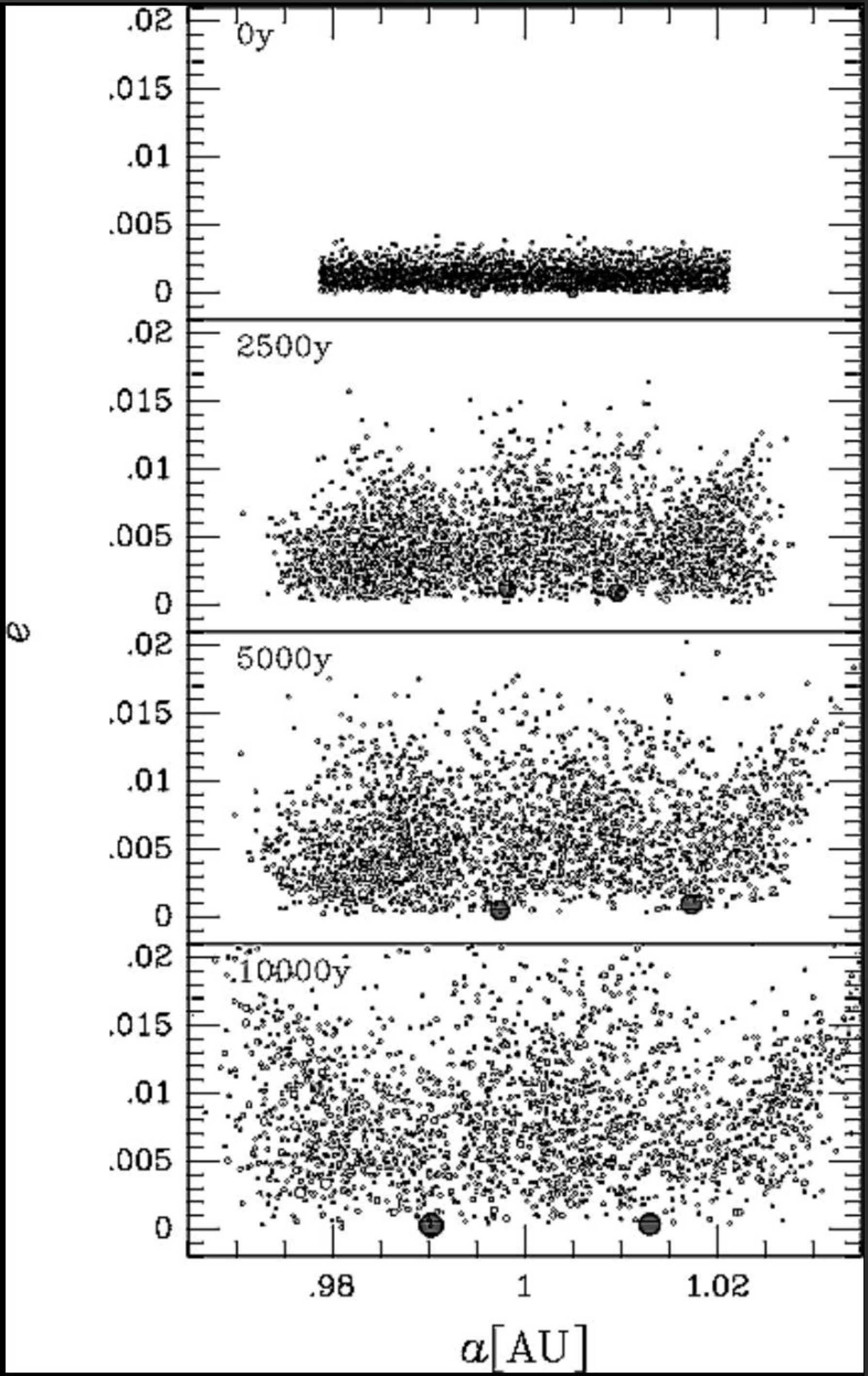
Interactions of solids with gas

- Small grains are strongly coupled to the gas
- Solid/gas coupling weakens as the object grows
- Large objects interact through their mutual gravitational forces



Planetary embryos are formed in ~10,000 y, separated by a few mutual Hill radii.

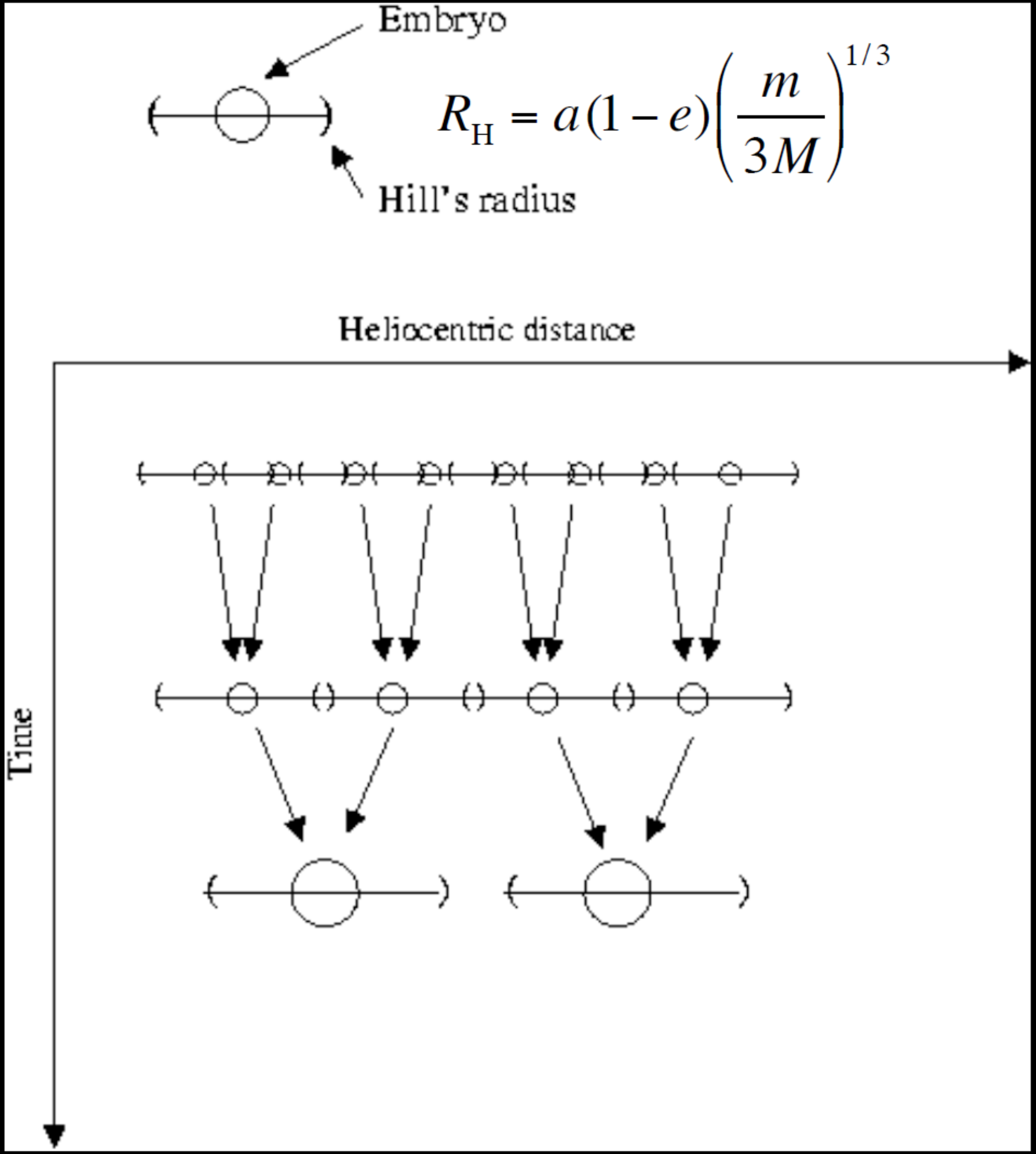
Accretion of embryos is a local process.



Ida and Makino (1993)

Kokubo and Ida (1995, 1996, 1998)

Runaway Growth



i) The semimajor axes of runaway-growing bodies increase linearly with their masses.

ii) The Hill's radius increases as the cube root of the mass.

iii) The runaway growth ends by forming a system of planetary embryos, separated by a few mutual Hill radii

Core-Accretion Model

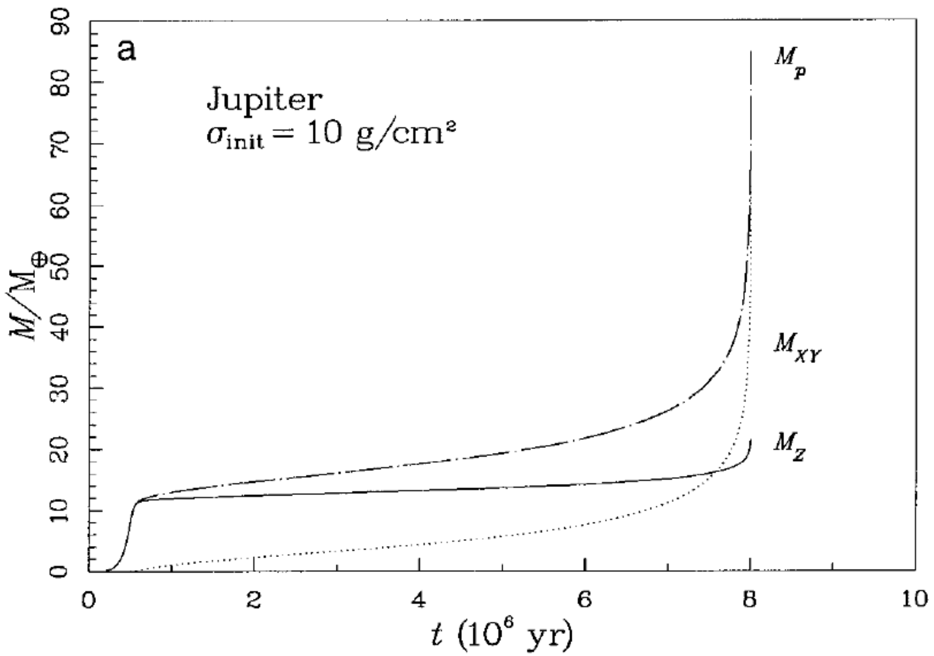
(Gas-giant Planets)

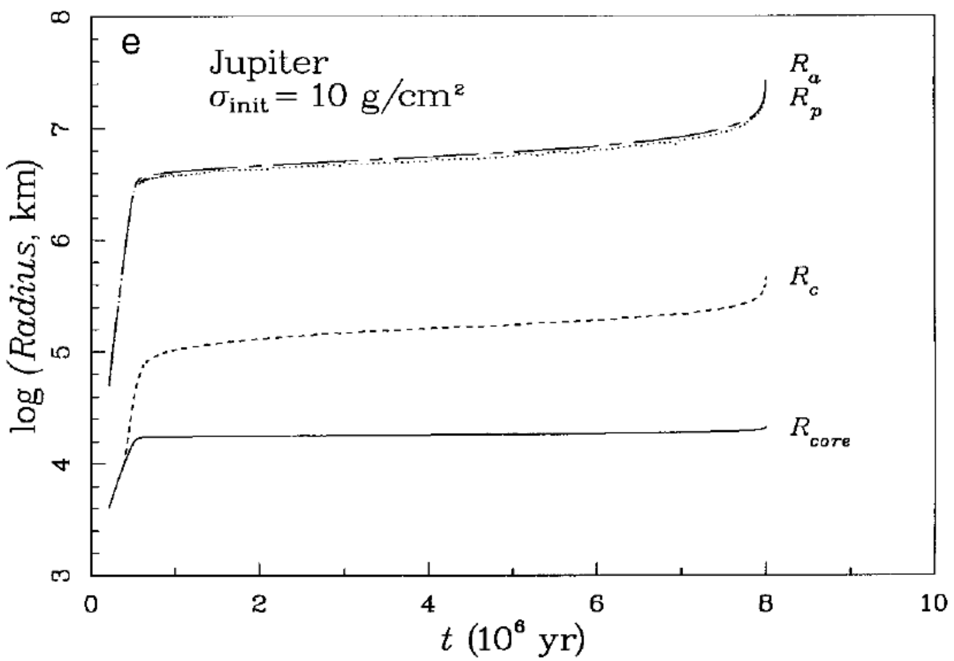
(Pollack et al. 1996)

- Farther out in the protoplanetary disk where the temperature of the gas is lower, the density of solids is enhanced with rocky and icy planetesimals.
- Such an enhancement of the solid density may cause collisional accumulation of solids and results in runaway growth to a mass of approximately10 Earth-masses in ~1 million years.
- These bodies may accrete gas (equivalent to 100 Earth-masses) from the disk within approximately 10 million years and form gas-giant planets.
- The gas collapses and forms a thick envelope.

Core Growth

Planetesimals grow to 10 Earth-masses. At that time they start accreting gas and grow to several hundred Earth. The envelope collapses under its own gravity and forms the final size of the planet.





(Pollack et al 1996)

Problems

- Collisional accumulation of planetesimals;

  ~ Half-million years

- Accretion of gas and formation of envelope

  6-8 million years

HOWEVER

- Lifetime of planet forming disk

  In average no more than 3 million years

Formation of Giant Planets

< 10 Myr

> 1000 years

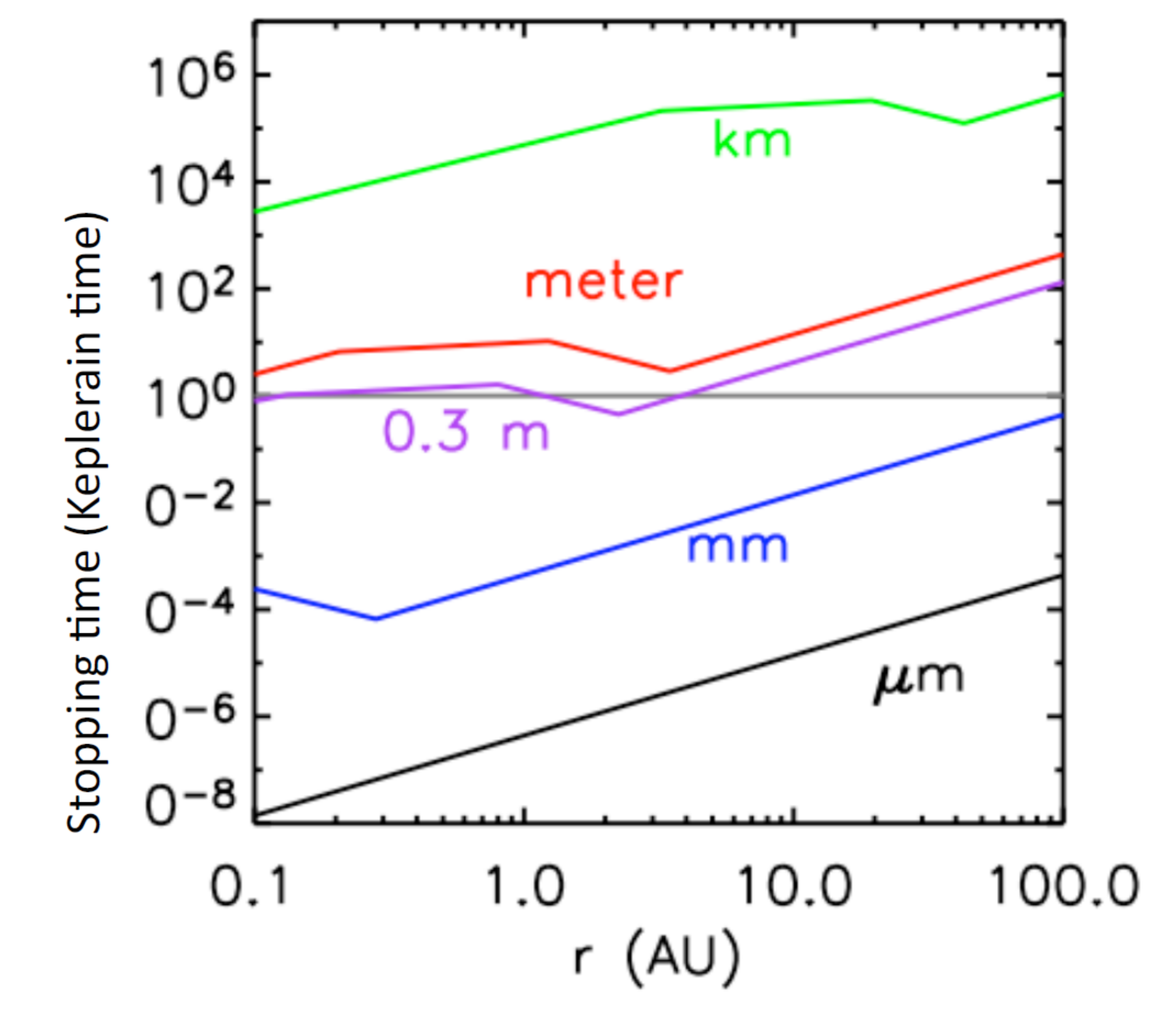
Cores of Gas-giants

Disk Instability

Gas-giant Planets

Interactions of solids with gas

- Small grains are strongly coupled to the gas
- Solid/gas coupling weakens as the object grows
- Large objects interact through their mutual gravitational forces



Disc-protoplanet interaction

Influence of circumprimary radiative discs on self-gravitating protoplanetary bodies in binary star systems

M. Gyergyovits[1], S. Eggl[1,2], E. Pilat-Lohinger[1,4], and Ch. Theis[3]

Aims. We present our 2D hydrodynamical GPU-CPU code and study the interaction of several thousands of self-gravitating particles with a viscous and radiative circumprimary disc within a binary star system. To our knowledge this program is the only one at the moment that is capable to handle this many particles and to calculate their influence on each other and on the disc.

The application of our code using various models shows the differences for planetary formation, when taking into account

(i) binary – disc interactions;
(ii) binary – protoplanet interaction;
(iii) binary – protoplanet – disc interactions.

Table 1. Initial conditions for the simulations.

Primary mass (M_1)	1.4 $M_\odot$
Secondary mass (M_2)	0.4 $M_\odot$
Semi-major axis ($a_{\rm bin}$)	20 au
Eccentricity ($e_{\rm bin}$)	0.4
Disc mass ($M_{\rm d}$)	0.01 $M_\odot$
Viscosity (α)	5×10^{-3}
Adiabatic index (γ)	7/5
Mean-molecular weight (μ)	2.35
Initial density profile (Σ)	$\propto r^{-1}$
Initial temperature profile (T)	$\propto r^{-1}$
Initial disc aspect ratio (H/r)	0.05
Grid ($N_r \times N_\phi$)	254×576
Computational domain ($r_{\rm min} - r_{\rm max}$)	0.5–8 au
Protoplanet mass ($M_{\rm p}$)	~0.016 $M_\oplus$
Number of protoplanets ($N_{\rm p}$)	2048

reference model: here we included only the binary-disc interaction.

model a1: several thousand self-gravitating protoplanets distort the disc gravitationally but no back-reaction from the disc on the particles is considered. At the same time, the disc and the bodies move under the gravitational influence of the binary star.

model a2: the same initial conditions as model a1 are used except for a higher smoothing parameter when calculating the particle – particle forces.

model b1: the full gravitational interaction between particles, the disc and the binary star is taken into account.

model b2: we recalculated the reference model for 50 000 yr, reset disc mass to its initial value, and then inserted particles in the disc taking into account the full gravitational interaction between particles, the disc and the binary star.

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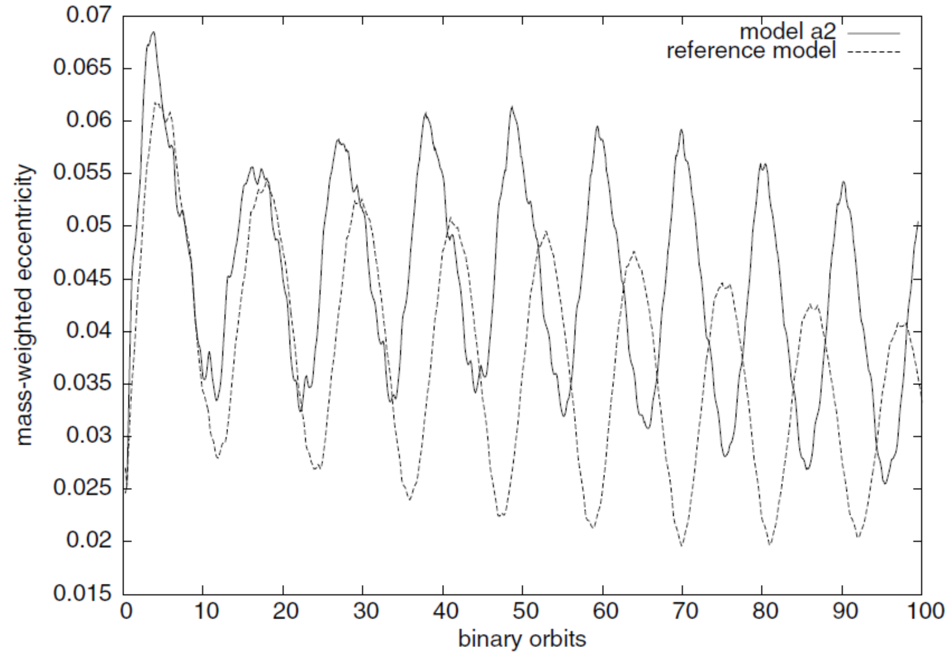


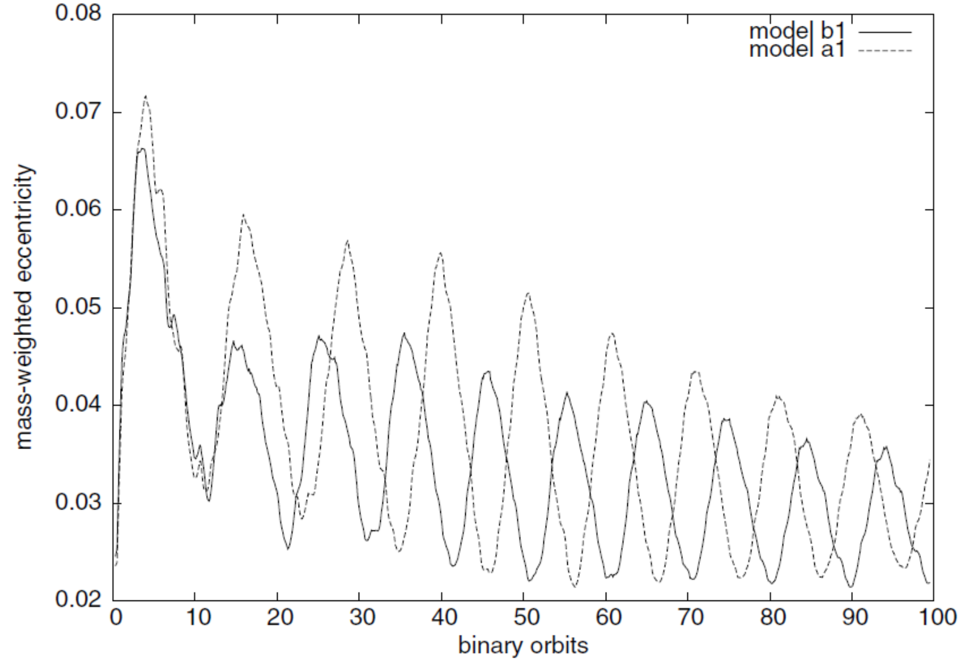


Fig. 1. Time evolution of the mass-weighted eccentricity for a disc without particles (reference model) and model a2 (*upper plot*), and models a1 and b1 (*lower plot*). Time is given in terms of binary orbits, where one orbit corresponds to 66.7 yr. See Sect. 3.1 for details.

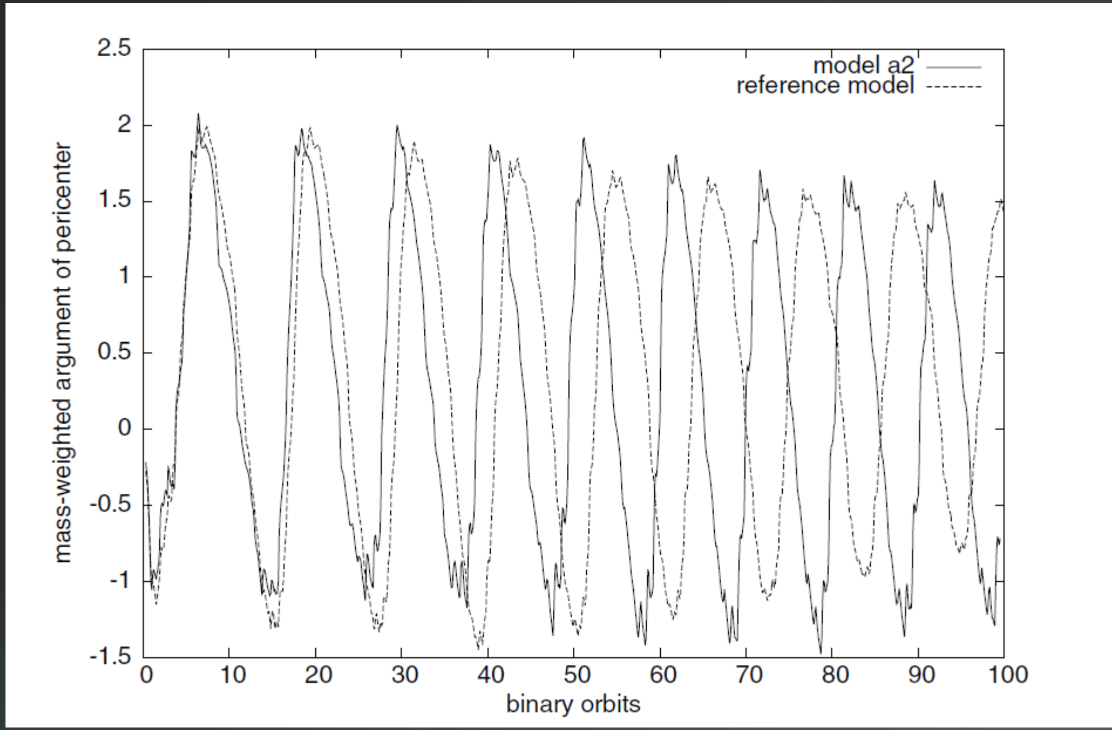
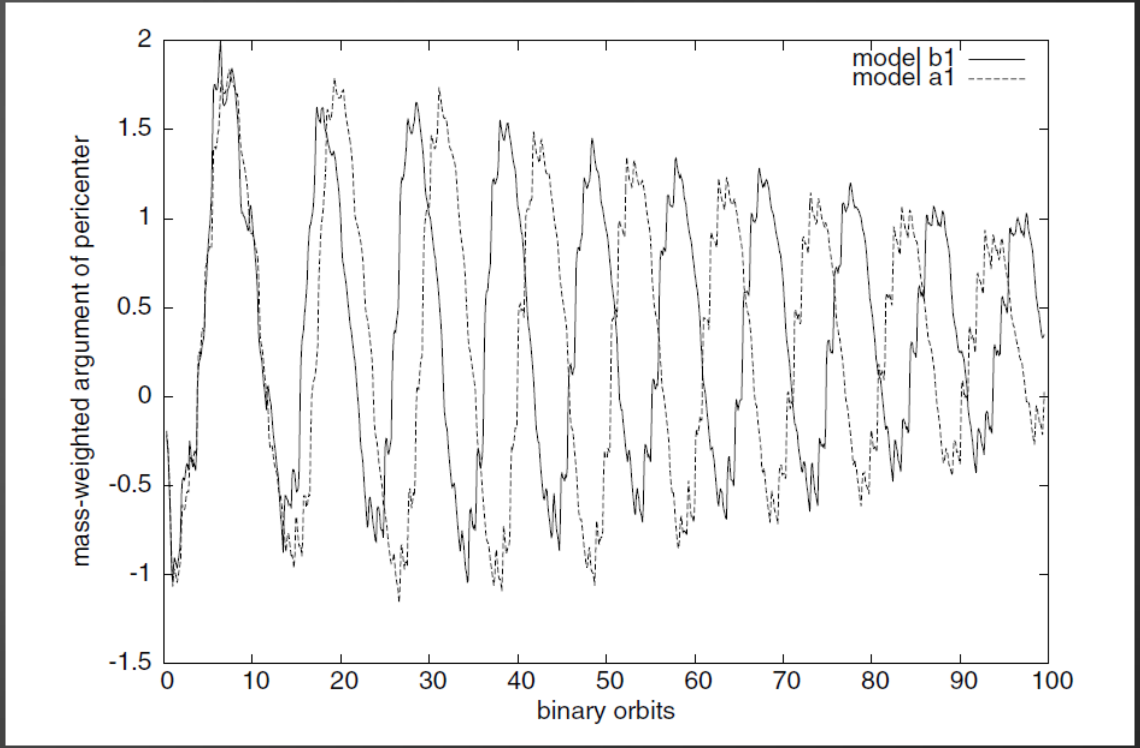


Fig. 2. Time evolution of the mass-weighted argument of the pericenter for a disc without particles (reference model) and model a2 (*upper plot*), and models a1 and b1 (*lower plot*). Time is given in terms of binary orbits, where one orbit corresponds to 66.7 yr.



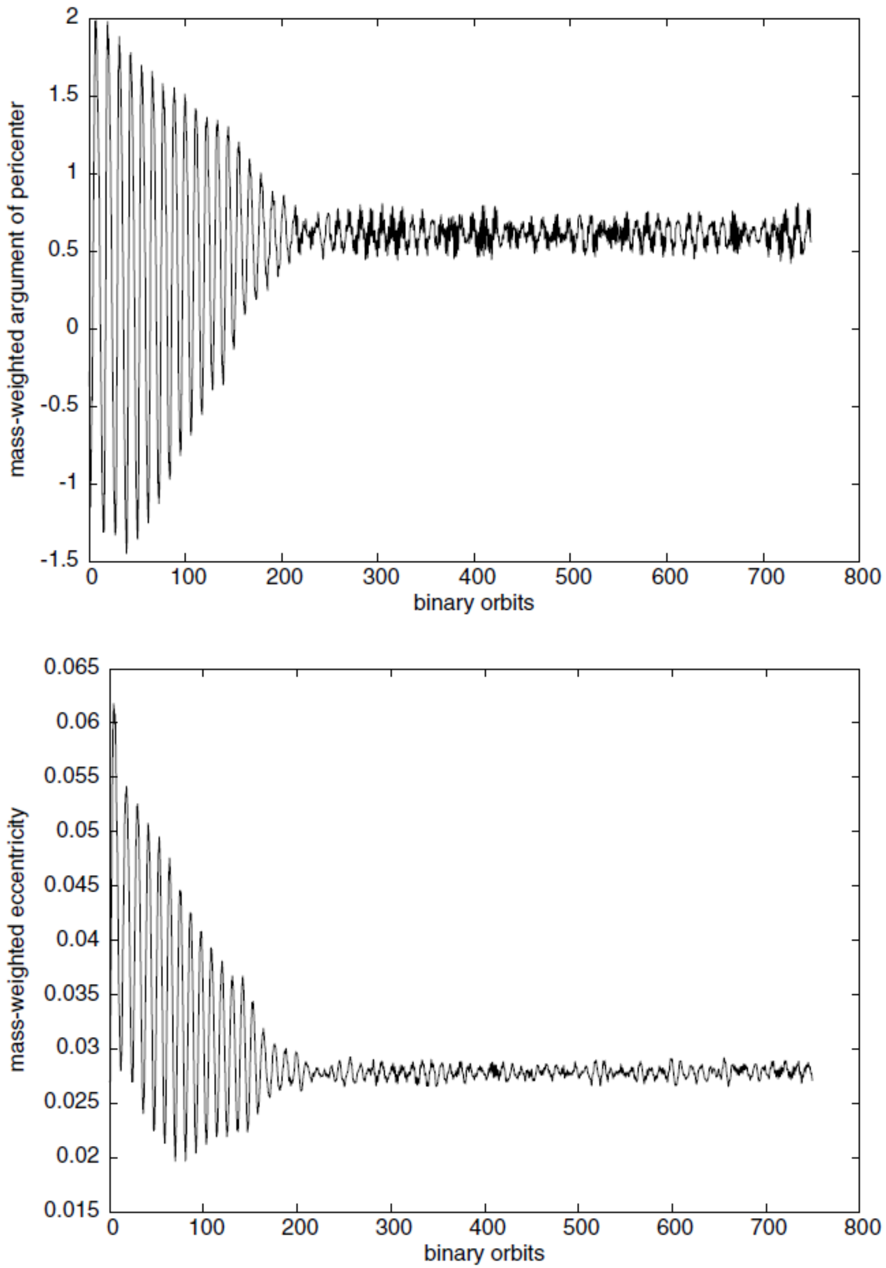


Fig. 3. Time evolution of mass-weighted argument of the pericenter for a disc without particles (*upper plot*) and of mass-weighted eccentricity (*lower plot*) for 50 000 yr after applying a running window average. Time is given in terms of binary orbits, where each orbit corresponds to 66.7 yr. We find transition from circulation to oscillation within 200 binary orbits for $\varpi_{\rm mw}$ and a subsequent oscillation around ≈0.6 rad. A damped oscillation is visible for $e_{\rm mw}$, reaching a value around ≈0.0275.

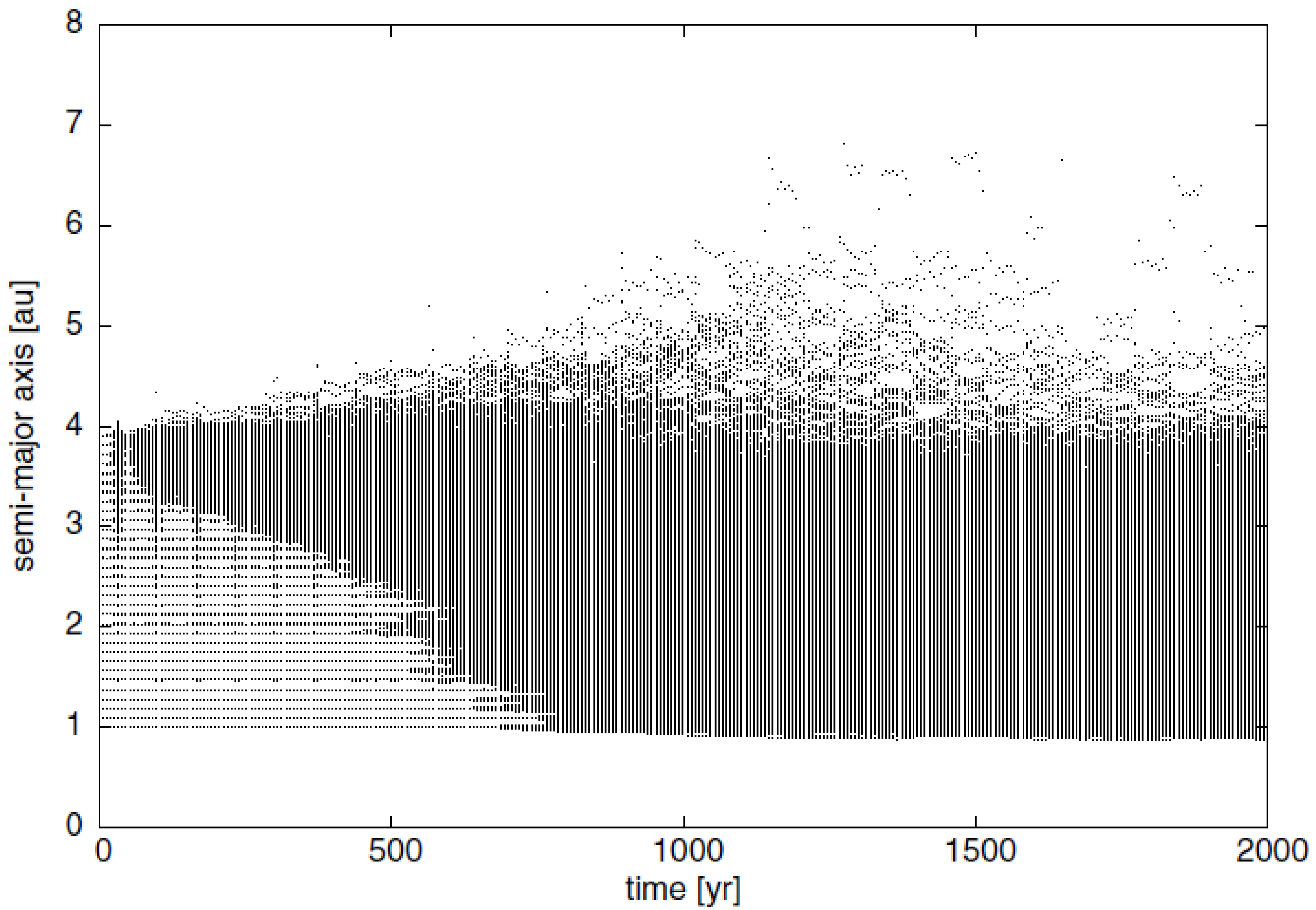


Fig. 4. Time evolution of the particle semi-major axis influenced by the disc (model b1). We find a transition from ordered motion close to the initial positions on the grid (left lower corner) to a distribution of semi-major axes that spreads across the whole stable region of the disc within 900 yr.

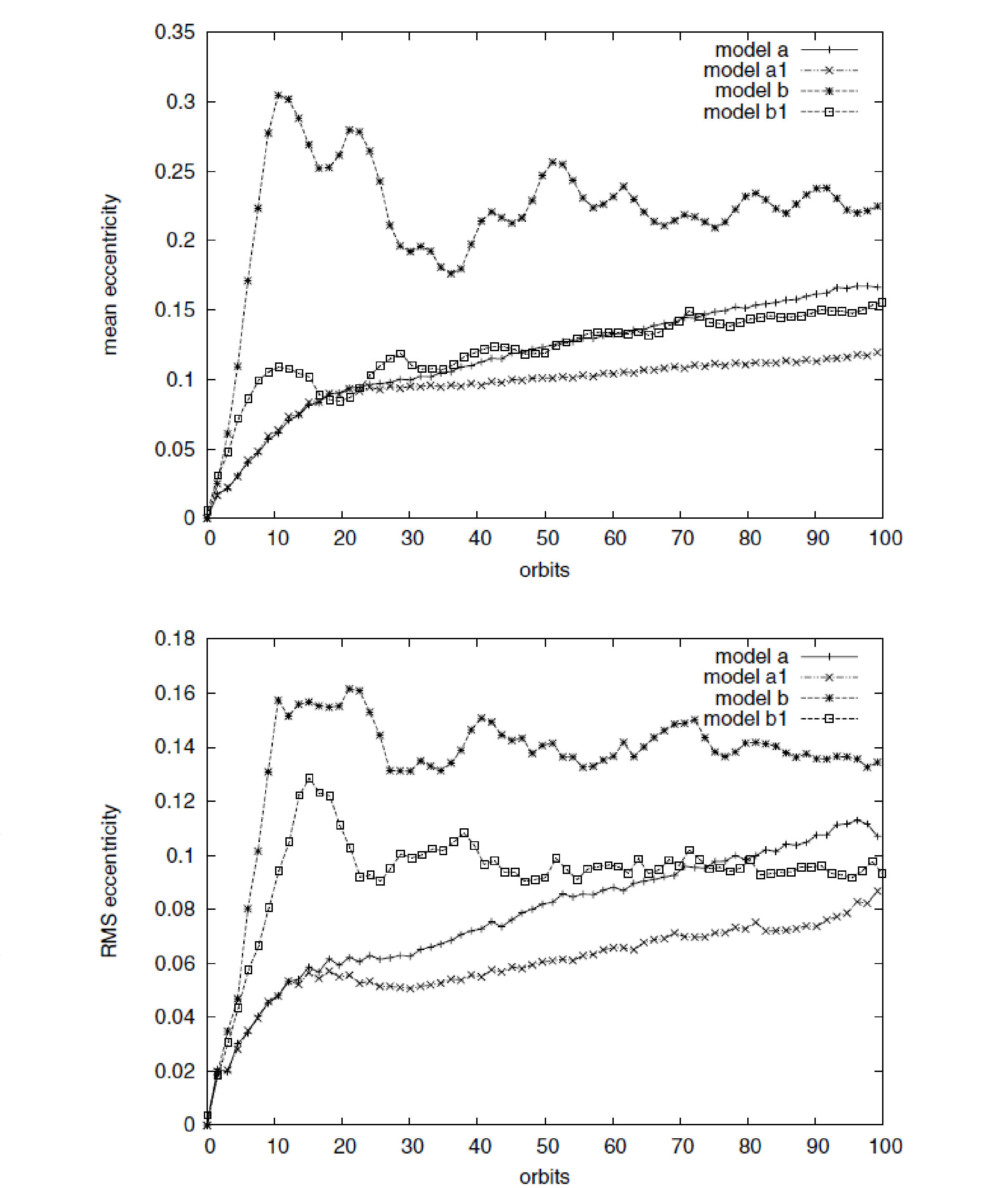


Fig. 5. Evolution of protoplanet mean (*upper plot*) and root mean square eccentricity (*lower plot*) for all four models. Highest values in both plots are reached by model b, whereas model b1 shows a similar behaviour as model a, and the lowest values are reached by model a1.

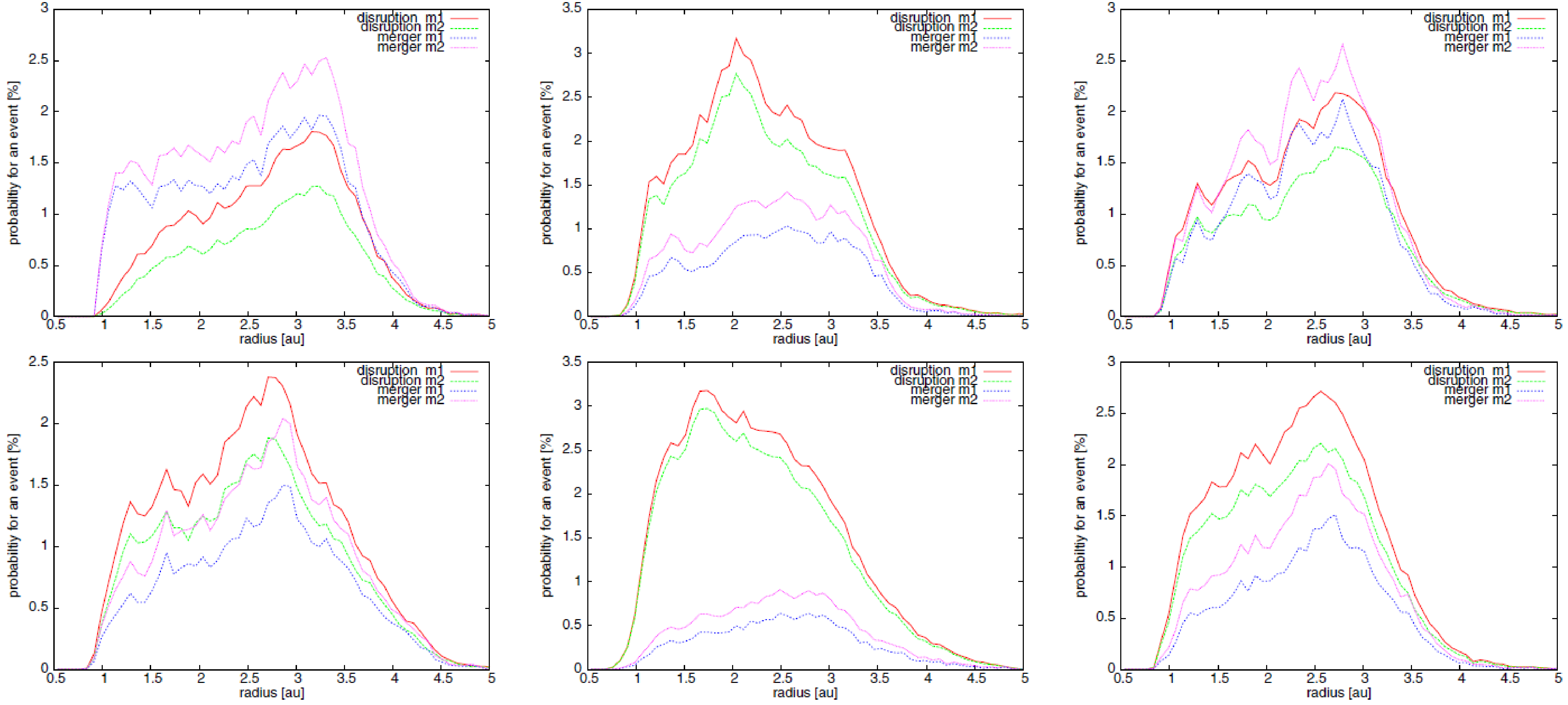
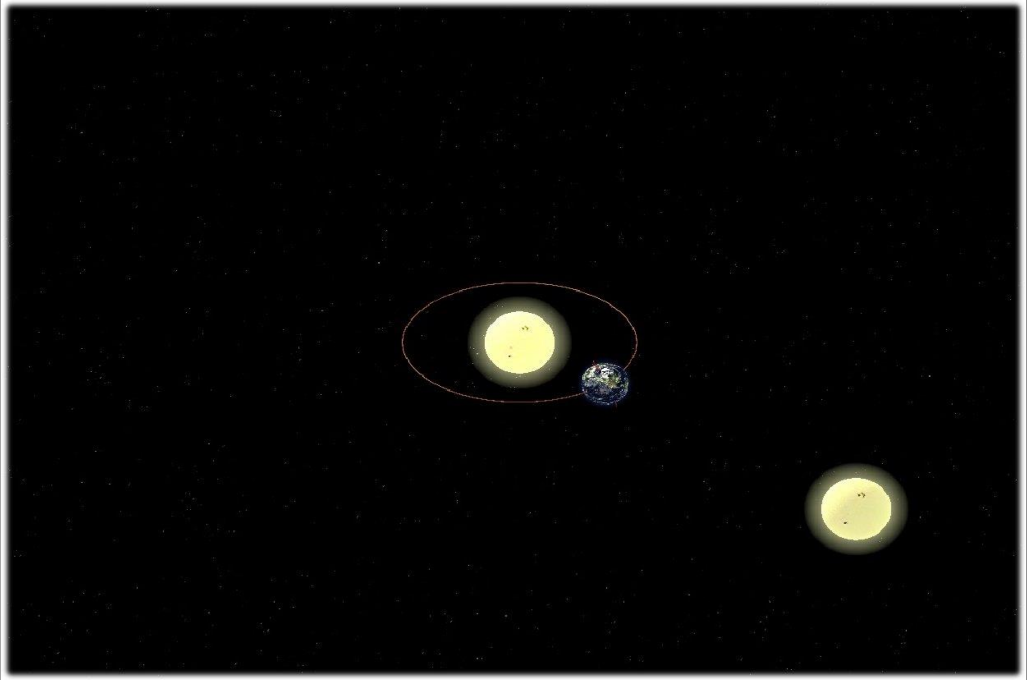


Fig. 6. Collision probabilities for 30–40 orbital periods for model a1 (*upper left*), model b1 (*upper middle*), and model b2 (*upper right*) as well as for 50–60 orbits for model a1 (*lower left*), model b1 (*lower right*), and model b2 (*lower right*). We show the plot radius (in au) versus the probability for an event (in percent) for disruption and merging for methods m1 and m2 (explained in the text).

Specific Problems in Binary Stars:

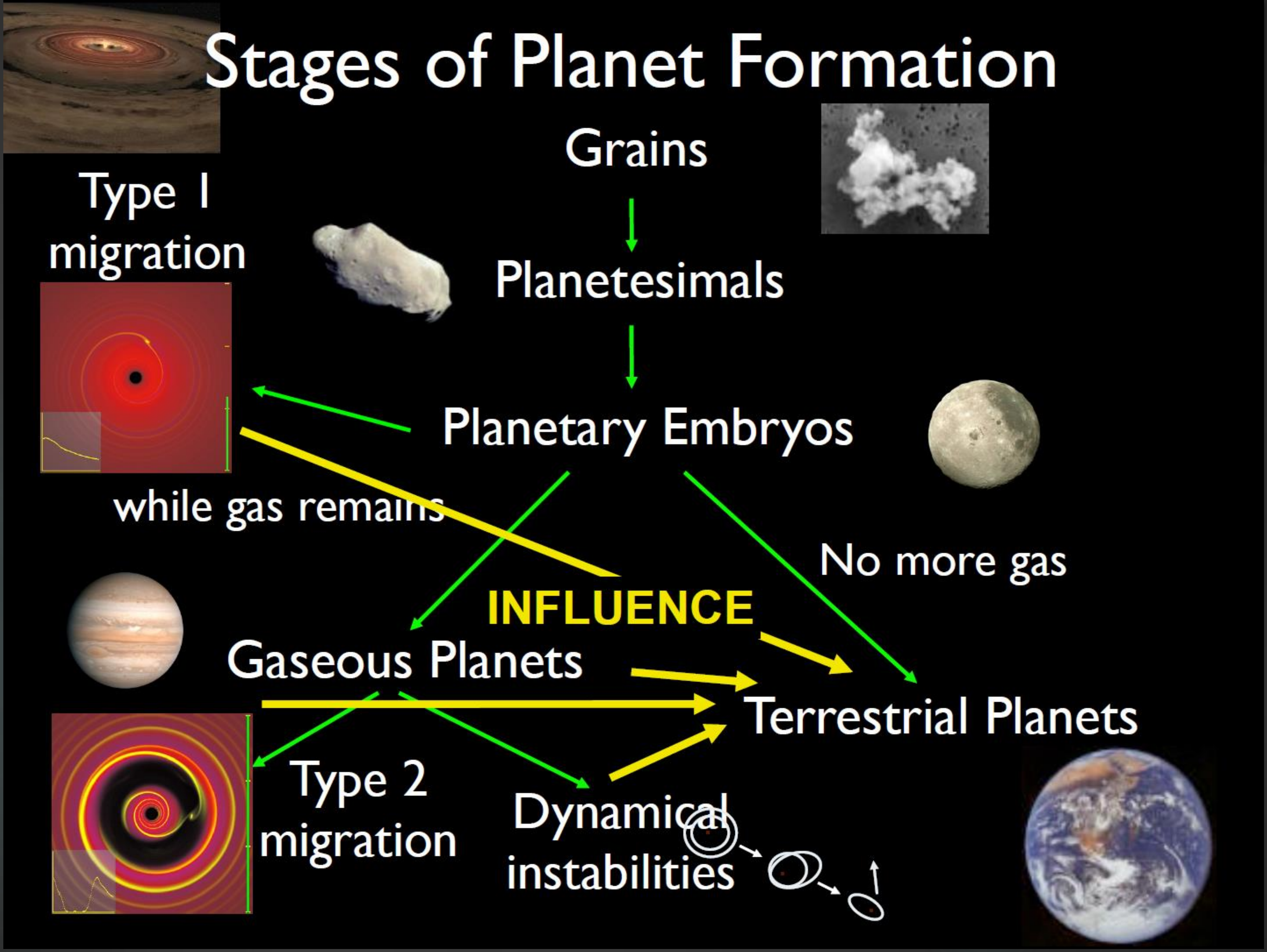


Disk is truncated →

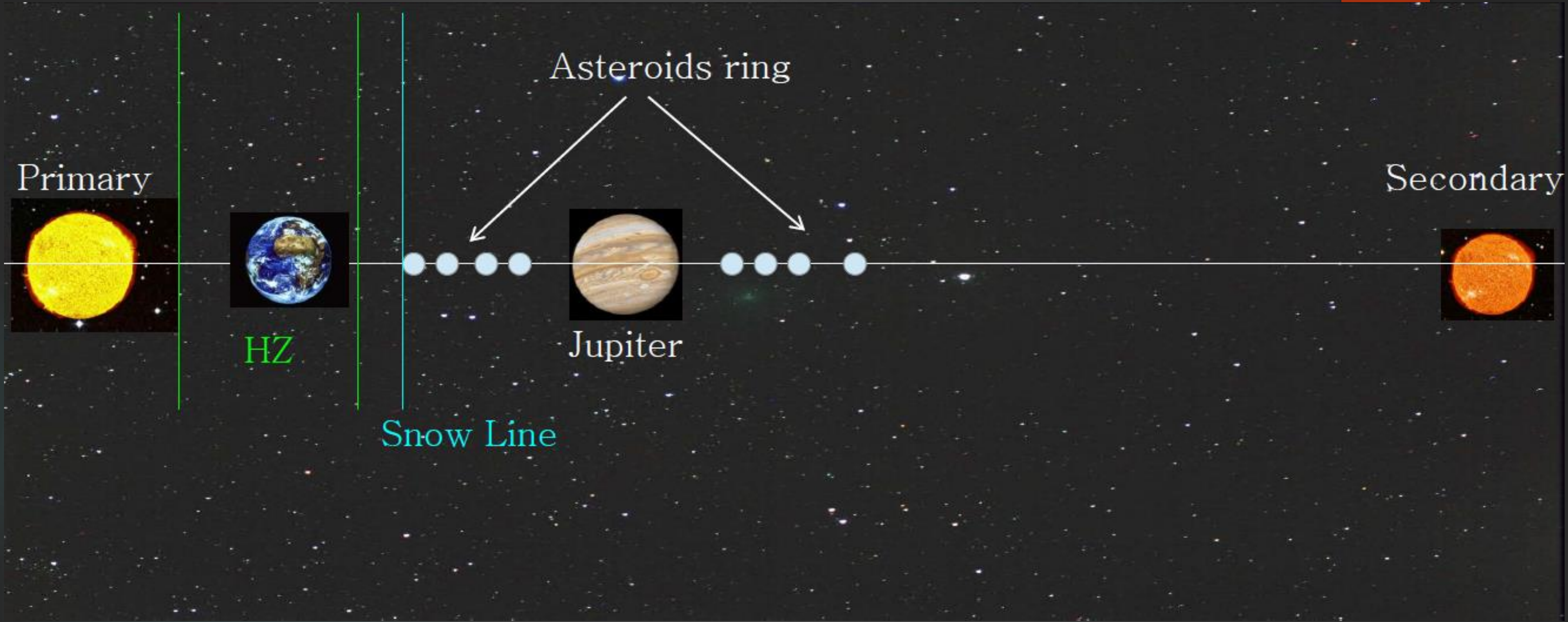
shorter lifetime of the disk

Secondary star causes a periodic perturbation →

influence on planet formation



Stages of Planet Formation
Grains
Planetesimals
Planetary Embryos
Type 1 migration
while gas remains
No more gas
INFLUENCE
Gaseous Planets
Terrestrial Planets
Type 2 migration
Dynamical instabilities



Asteroids ring
Primary
Secondary
HZ
Jupiter
Snow Line

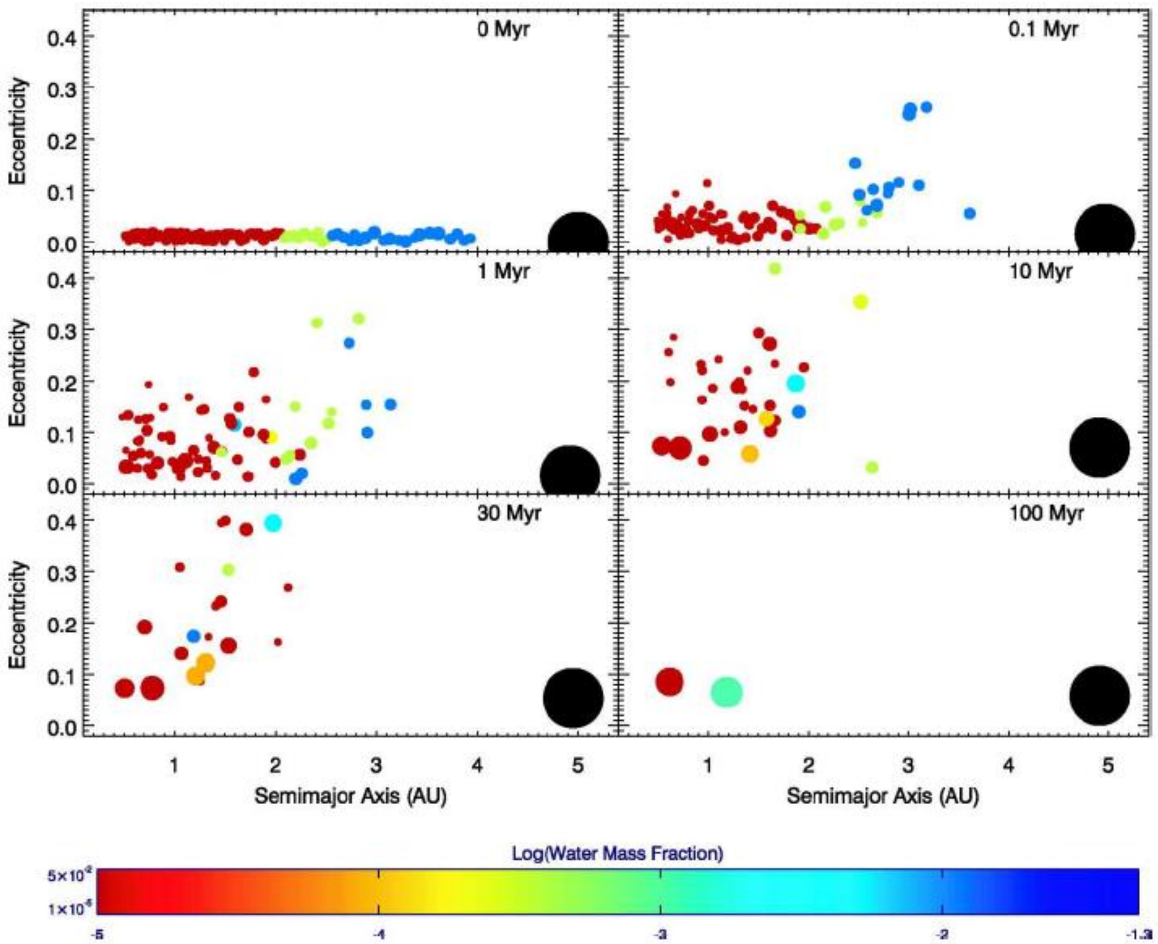


Figure 4.2 Snapshots of terrestrial planet formation in a tight binary where the secondary star (of $0.5M_{\odot}$) is at 30 au in an eccentric orbit with $e_B = 0.2$. The evolution of the protoplanetary disc is shown for certain times which display the gravitational interaction in the system until two terrestrial planets have formed after 100 Myrs. The black circle indicates a Jupiter-sized planet. (This figure is taken from Haghighipour and Raymond (2007)).

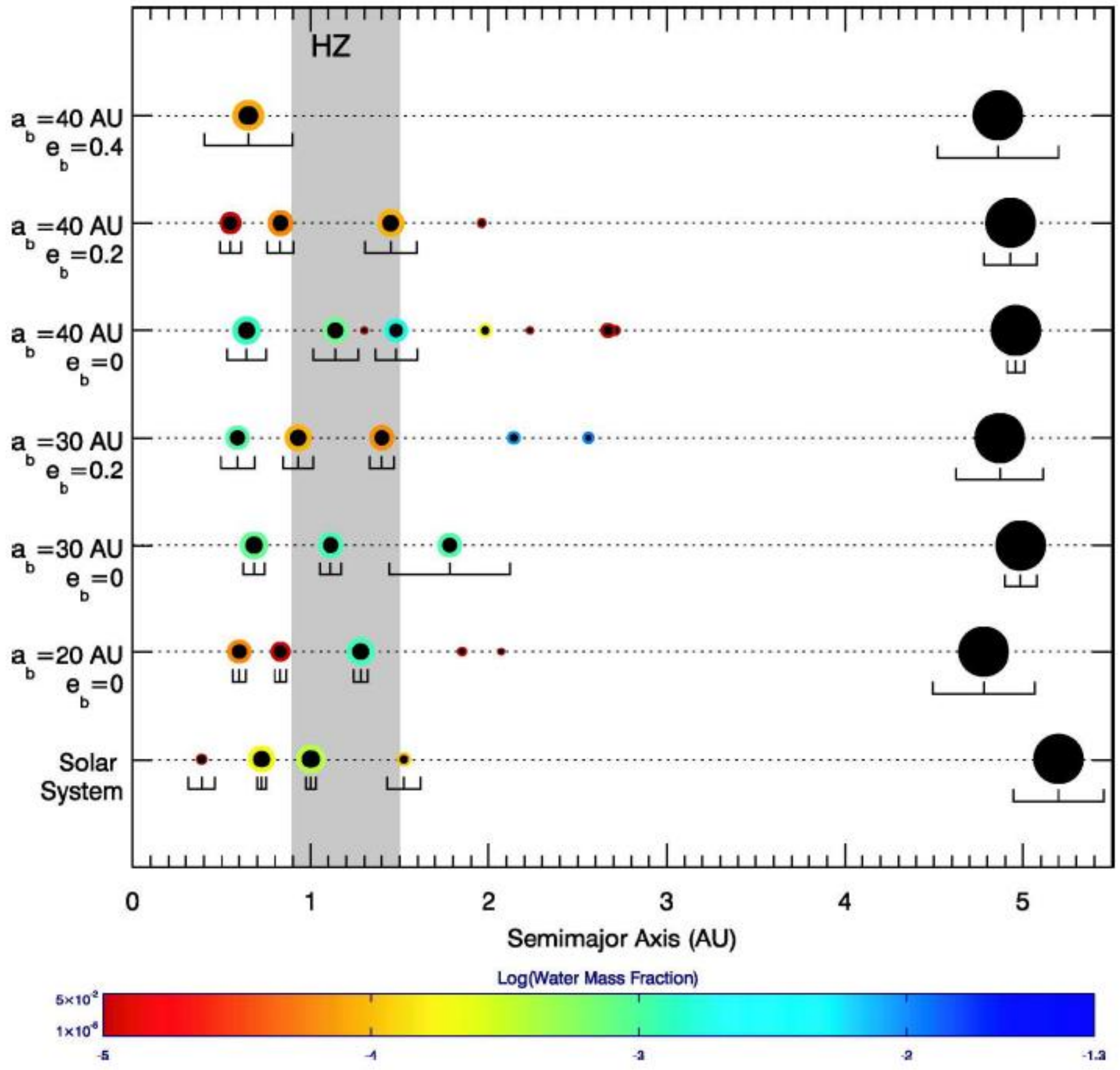


Figure 4.3 .

Planetary systems formed due to core accretion in tight equal-mass binary stars.(This figure is taken from Haghighipour and Raymond (2007)).

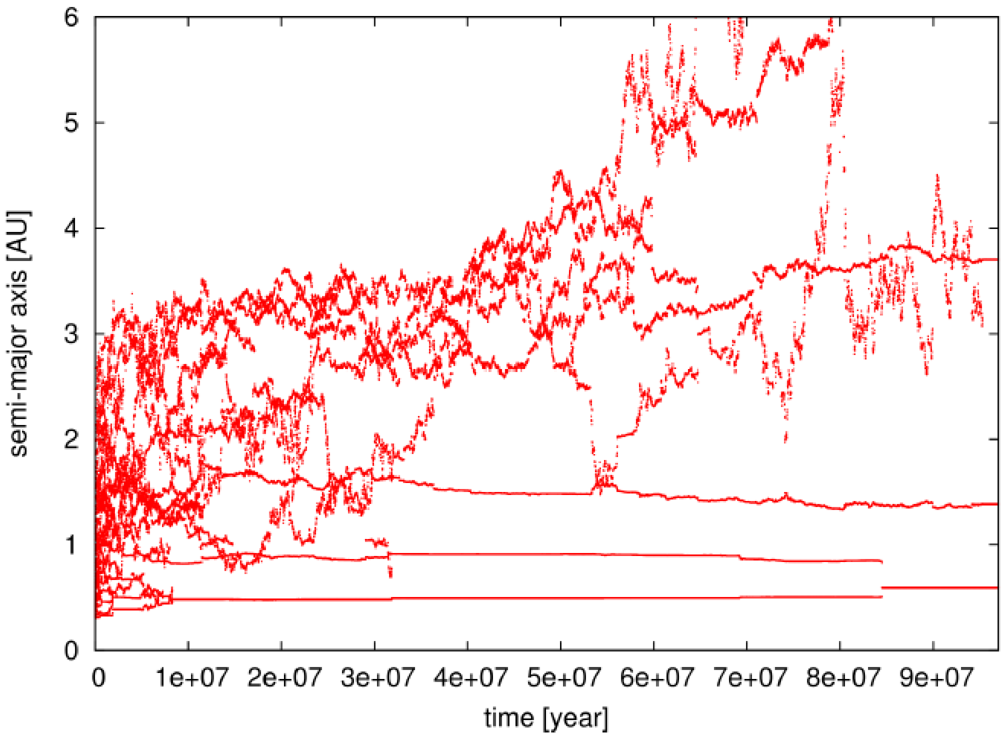
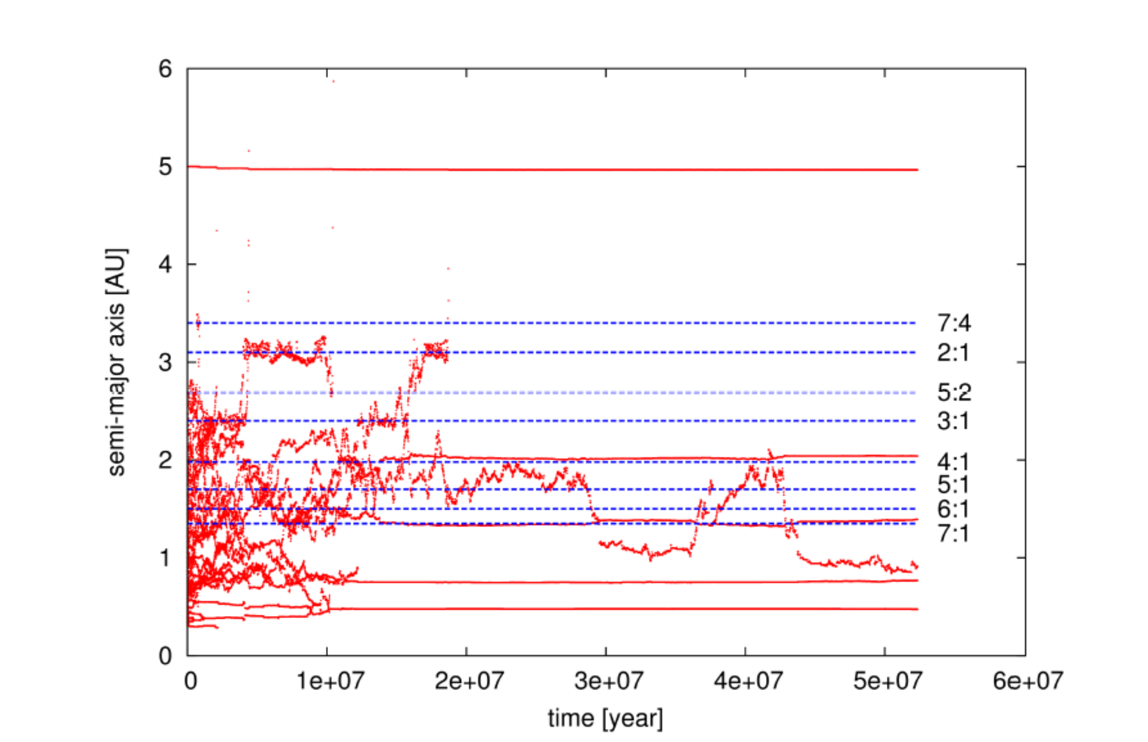


Figure 4.4 Time evolution of embryo semi-major axes in a binary system with parameters $(a_B, e_B) = (100, 0.01)$ in the absence of a giant planet. By mutual interactions the initial population is expanding on average to larger semi-major axes.



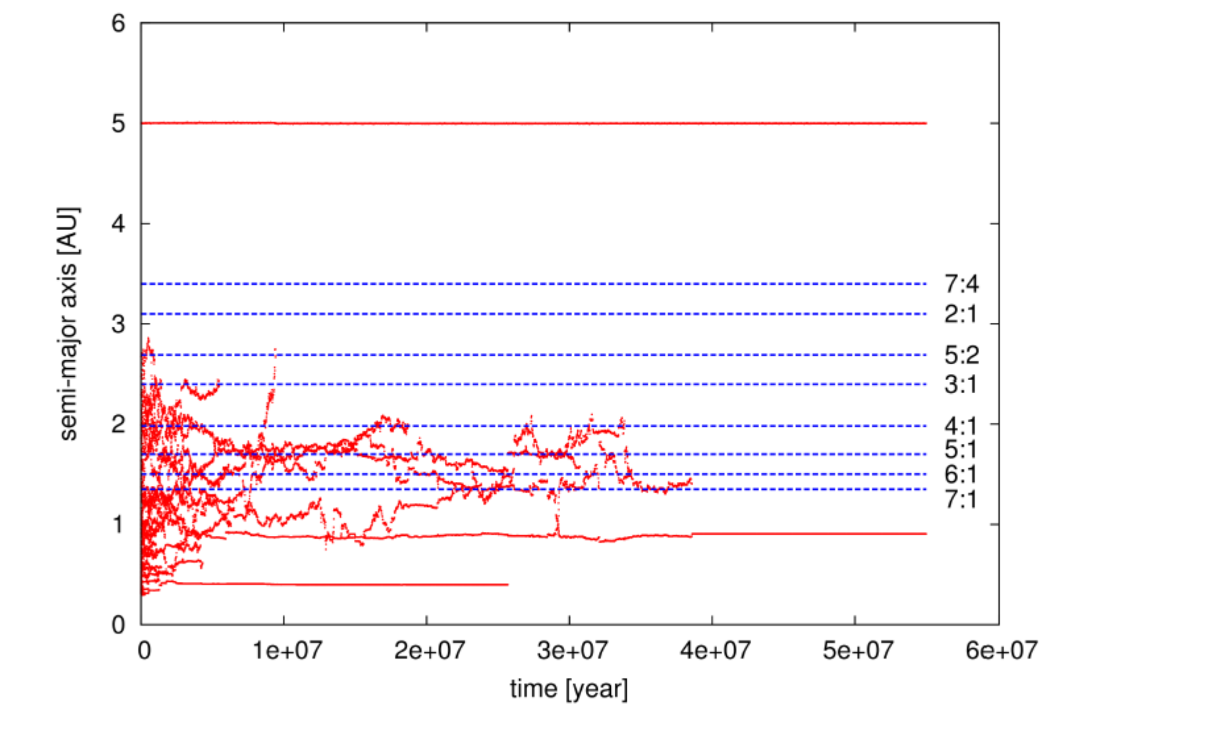


Figure 4.5 Time evolution of embryo semi-major axes in a binary system with parameters $(a_B, e_B) = (100, 0.01)$ (*top*) and $(100, 0.6)$ (*bottom*). Horizontal lines indicate mean motion resonances with the giant planet at 5 au.

Habitable terrestrial planet formation

- ***Aim of simulations***: parameter study to reveal in which systems can form habitable terrestrial planets
- Effects of the ***disk*** and a ***giant planet*** are also considered
- Initial conditions for the binary system:

binary [M_{Sol}]	a_{bin} [AU]	e_{bin}	i_{bin}
G-G [1.0-1.0]	25	0	0°
G-K [1.0-0.7]	50	0.2	5°
G-M [1.0-0.4]	75	0.4	15°
G-F[1.0-1.3]	100	0.6	
G-A[1.0-1.5]			

  - And all combinations when the disks are around stars with masses 0.7, 0.4, and 1.3 M_{Sol}

Habitable terrestrial planet formation

- Initial conditions for disk: based on the Minimum Mass Solar Nebula standard values
  - For the gas component

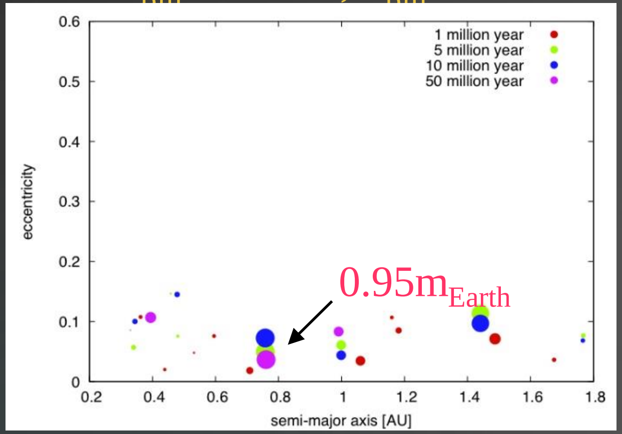
    $\Sigma(r) = 1.7 \times 10^3 \, (r/AU)^{-p} \, gcm^{-2}$, p = 1, 0.5, 1.5
  - For the solid component:

    $\Sigma(r) = 7.1 \times (r/AU)^{-p} \, gcm^{-2}$, p = 1, 0.5, 1.5
- Initial conditions for N-body: two stars, a giant planet and a swarm of isolated embryos up to the snowline meaning ~50 gravitationally interacting bodies

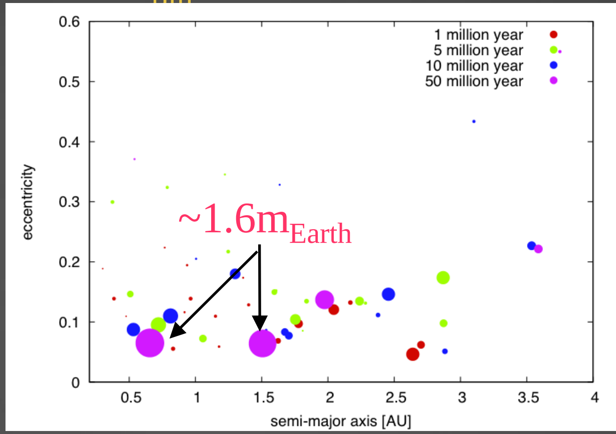
Results:

- Simulations **without giant planet**

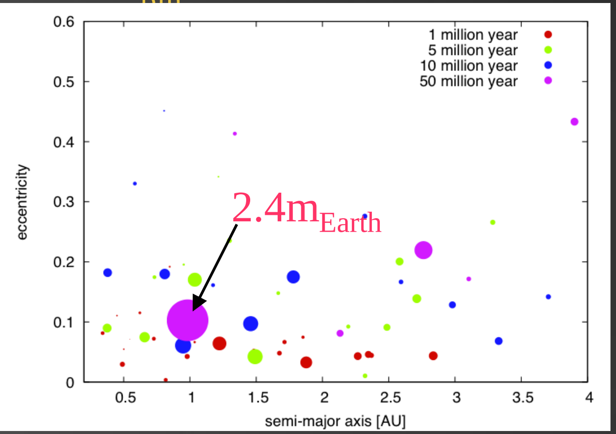
a_{bin} = 25AU, e_{bin} = 0.2



a_{bin} = 50AU

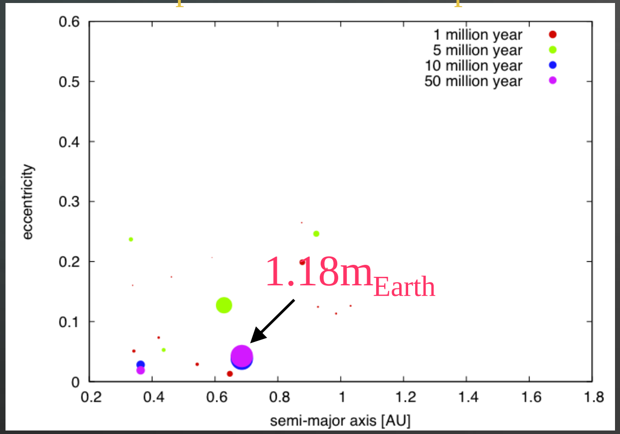


a_{bin} = 100AU

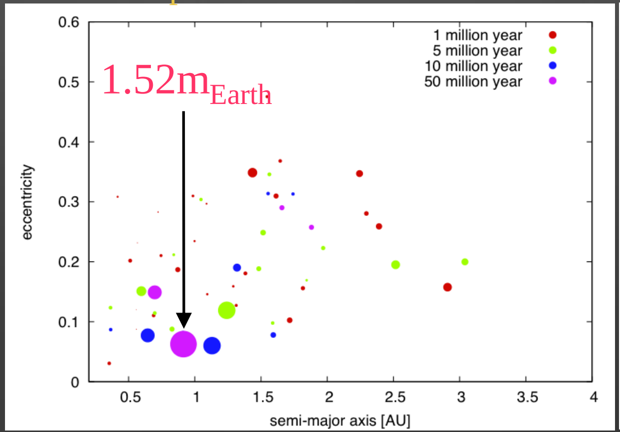


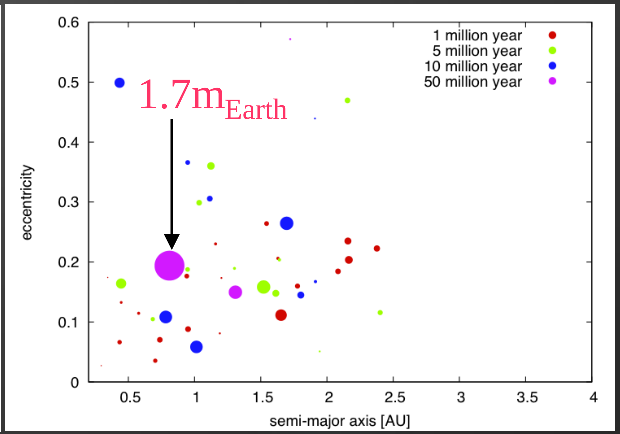
- Simulations **with a non-migrating giant planet**

a_p = 2.5 AU, e_p = 0.05



a_p = 5 AU



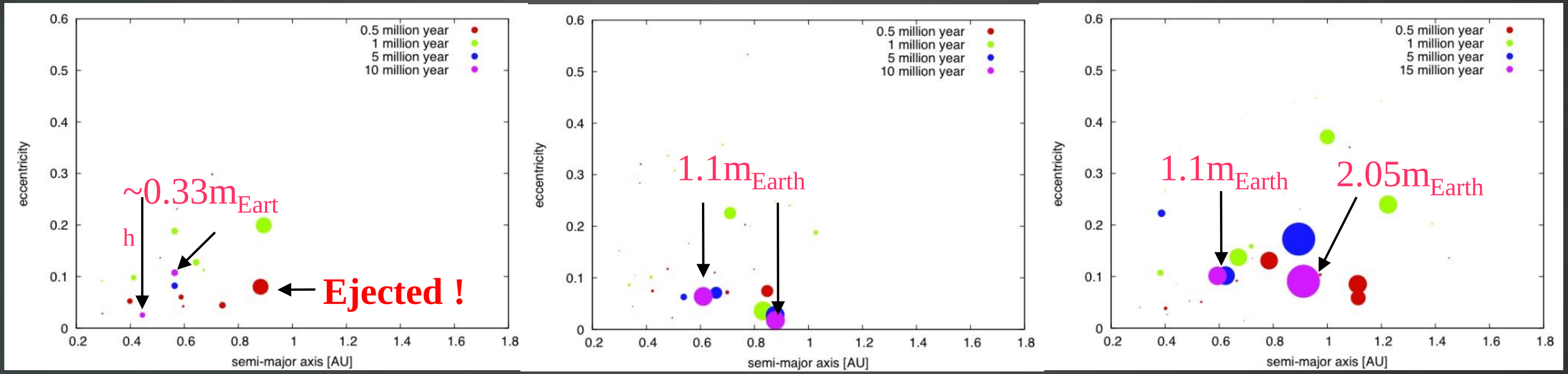


Results

- Simulations **with a migrating giant planet**
  - Migration lasted 10^5 years and was gradually switched off mimicking the disk's dispersal

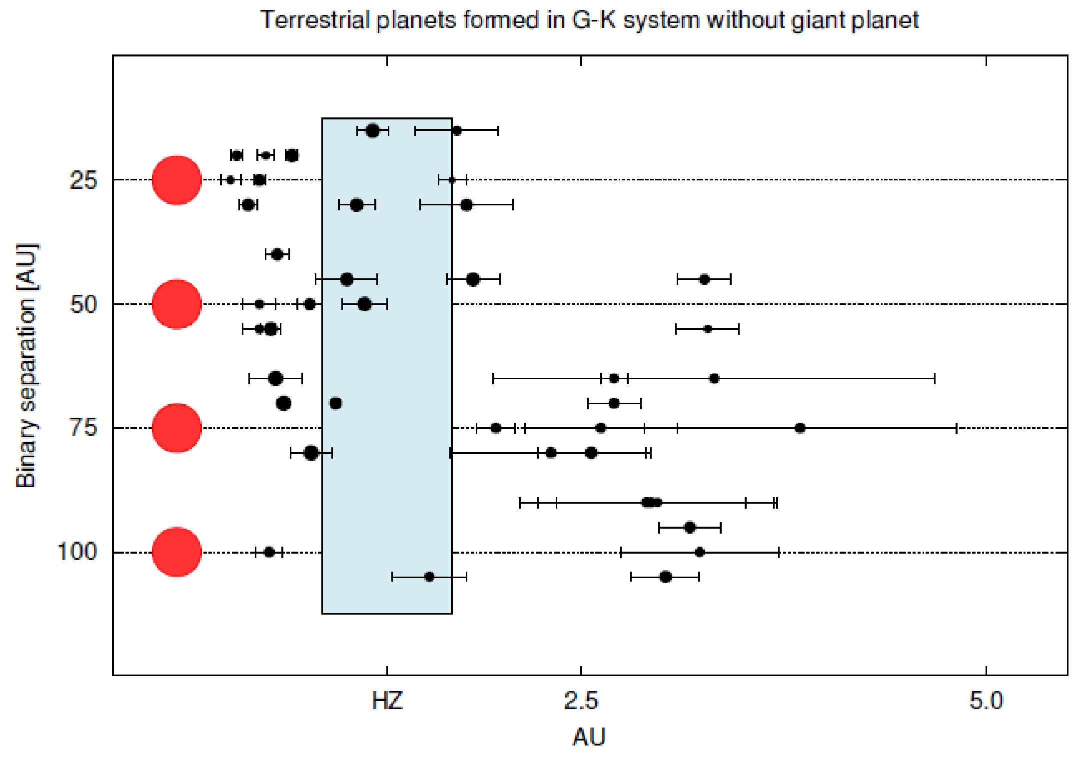
a_{bin}= 25AU, e_{bin}= 0.2 a_{bin}= 50AU a_{bin}= 100AU

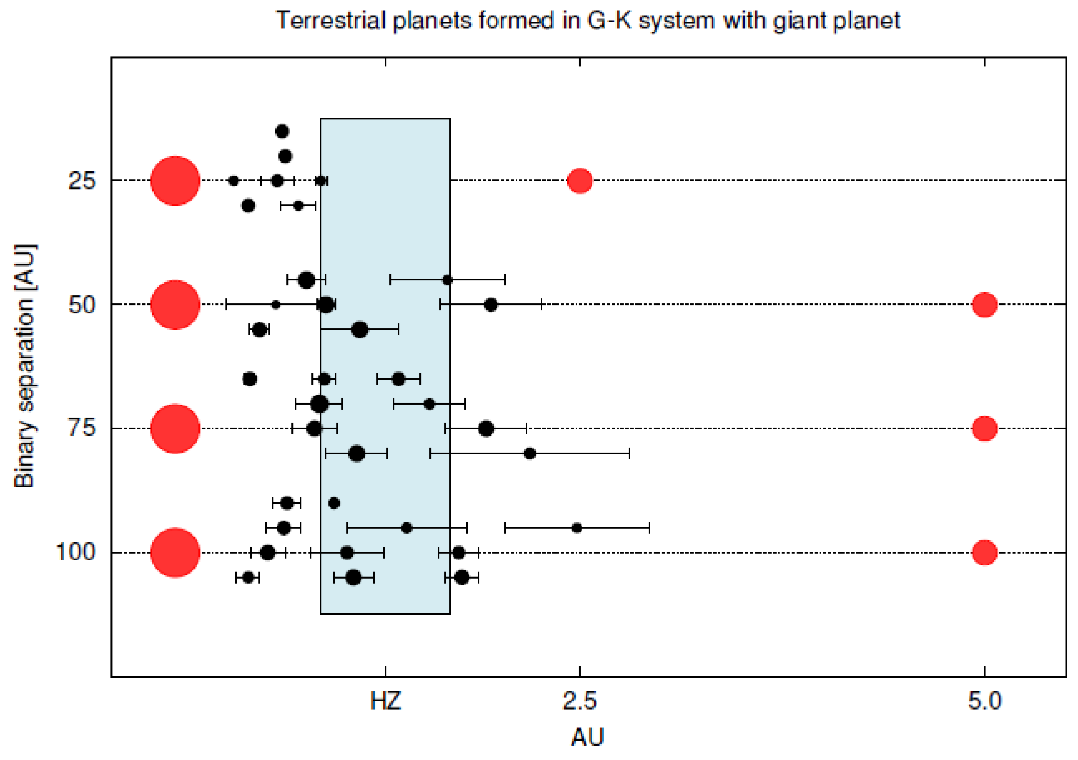
a_{start} = 3.5AU, a_{stop} = 1.6AU a_{start} = 5AU, a_{stop} = 2AU



- Terrestrial planet formation happened within 10 million years!
- Migration of the giant planet helps terrestrial planet formation

- Terrestrial planets were formed in all N-body simulations, the planetary masses are in the range 0.4–2.4 m_{Earth}
  → ***it is a robust phenomenon***
- In the absence of a giant planet, ***more massive planets*** can be formed
- The giant planet ***scatters gravitationall***y the initial embryo population resulting in ***faster formation*** of terrestrial planets
- ***Migration*** of the already formed giant planet makes terrestrial formation ***faster***


Terrestrial planets formed in G-K system without giant planet
Binary separation [AU]
25
50
75
100
HZ
2.5
5.0
AU


Terrestrial planets formed in G-K system with giant planet
Binary separation [AU]
25
50
75
100
HZ
2.5
5.0
AU

We do not know whether planets form wet

If they form dry

then the water has to transported to the planet