Planet Formation During the Migration Episode of a Giant Planet

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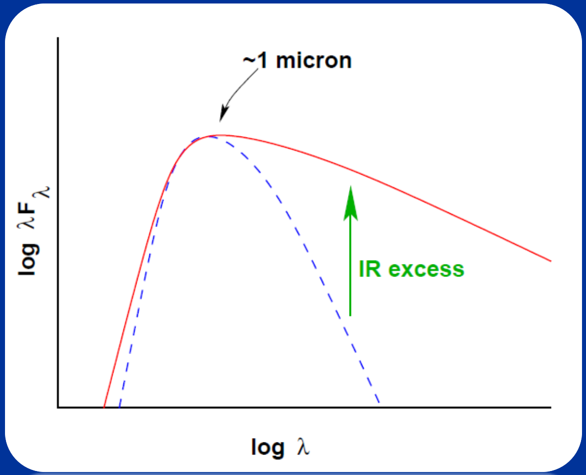
Introduction: nebular hypothesis ...

1755: the idea of a solar nebula by Kant:
An early universe evenly filled with thin gas
Gravitationally unstable → large dense clumps
These clumps rotate → falltened disks

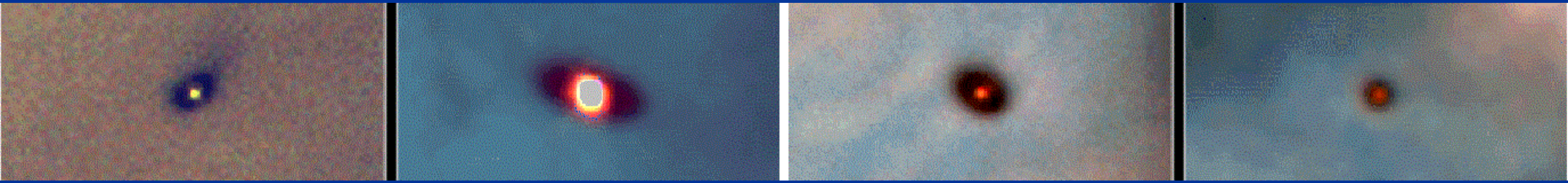
Telescopes were unable to observe such disks

Indirect evidence:
✓ T Tauris stars have „Infrared excesses"



The amount of infrared radiation they emit is too large to be consistent with their output at visible wavelengths

Direct evidence:
views of proplyds in the Orion nebula: T-Tauri Star + 2x – 8x Solar System diameter



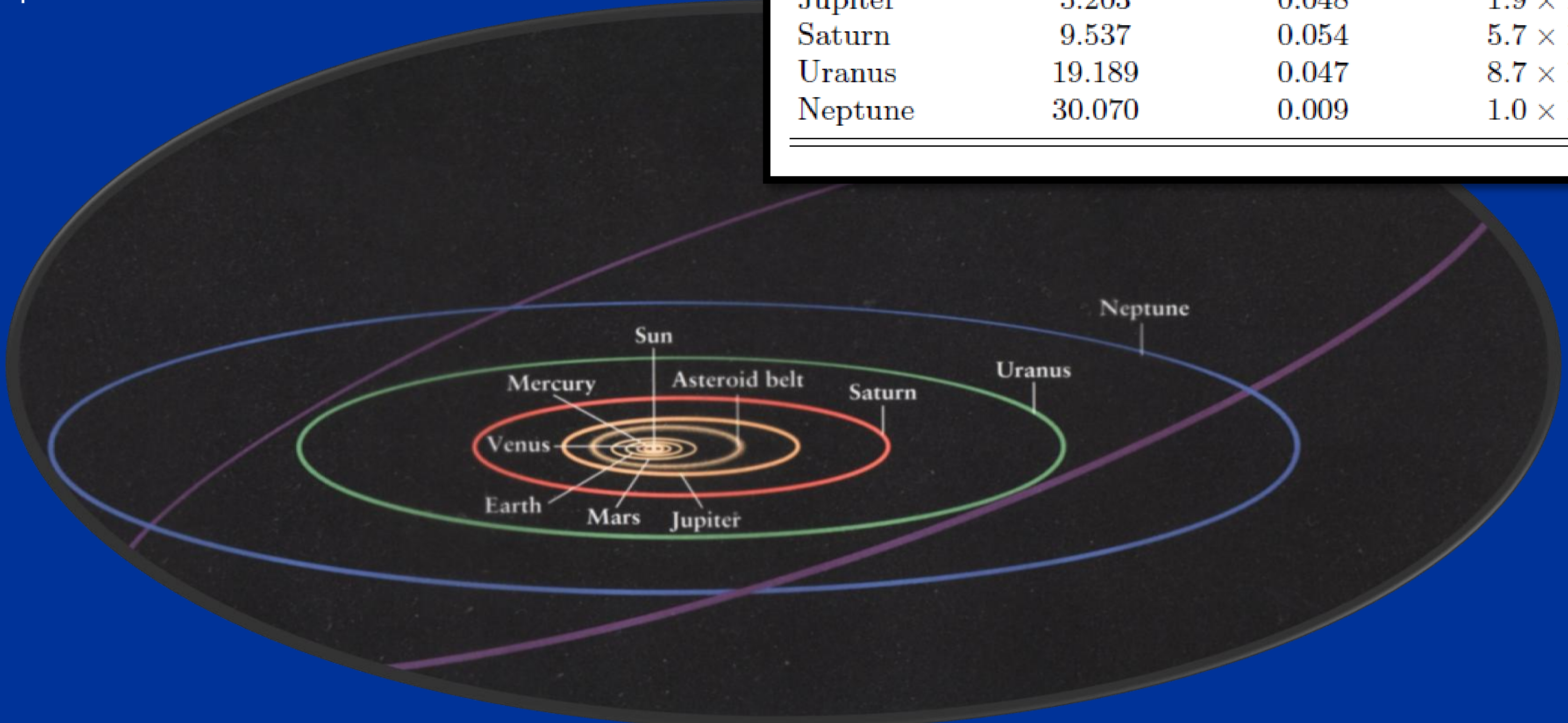
Solar System Observations: *Architecture*

- 2 gas giants (J & S)
- 2 ice giants (U& N)
- 2 larger rocky planets (E & V)
- 2 smaller rocky planets (M & M)

All planets have small e and *i*

TABLE I Basic properties of planets in the Solar System

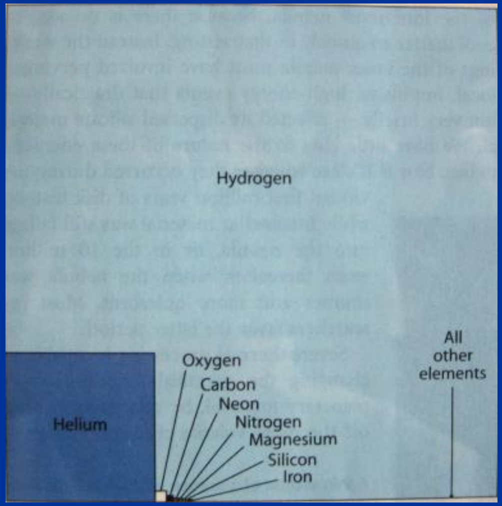
	a/AU	e	M_p/g
Mercury	0.387	0.206	3.3×10^{26}
Venus	0.723	0.007	4.9×10^{27}
Earth	1.000	0.017	6.0×10^{27}
Mars	1.524	0.093	6.4×10^{26}
Jupiter	5.203	0.048	1.9×10^{30}
Saturn	9.537	0.054	5.7×10^{29}
Uranus	19.189	0.047	8.7×10^{28}
Neptune	30.070	0.009	1.0×10^{29}



Solar System Observations:
Mass and angular momentum

The mass of the Sun is ≈ 10^{33} g: 73% H, 25% He, 2% „metals"

Most of the heavy elements are in the Sun (20 Jupiter)



The import of this trivial observation

→ Planet formation is not efficient

Most of the angular momentum is in the planets:

$$L_{\mathrm{Sun}} \approx k^2 M_{\mathrm{Sun}} R_{\mathrm{Sun}}^2 \Omega \approx 3\times 10^{48}$$
$$L_J = M_J \sqrt{G M_{\mathrm{Sun}} a} = 2\times 10^{50}$$

→ Mass and angular momentum have been partitioned

Solar System Observations:
Minimum Mass Solar Nebula

From the observed masses and composition of the planets

→ Lower limit of the gas component

Assumption: the relative abundance in the elements in the nebula is very similar to that of the Sun

Procedure:
1. Start from the known mass of heavy elements (eg. Iron) in each planet, and augment this mass with enough H and He to get a mixture with Solar composition.
2. Divide the Solar System into annuli, with one planet per annulus. Distribute the mixture for each planet uniformly across the annuli to get the characteristic gas surface density at the location of the planet.

→ $$\Sigma \propto r^{-\frac{3}{2}} \quad \left(\Sigma = 1.7 \times 10^{3} r^{-\frac{3}{2}} \, \mathrm{g cm}^{-2} \right)$$

Up to 30 AU → 0.01 M_{Sun}

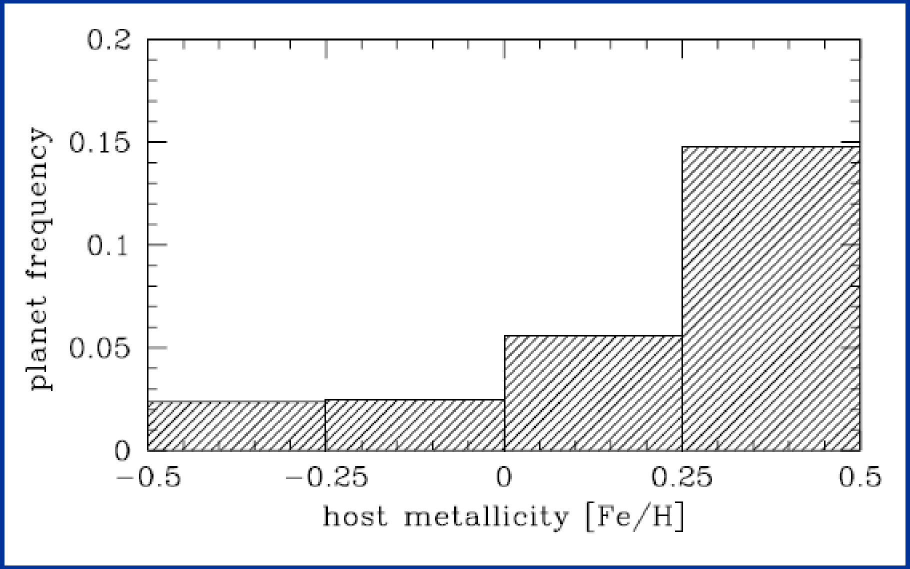
Most theoretical models of disks, in fact, predict $\Sigma \propto r^{-1}$

Exosystem Observations:
Frequency

The giant planet frequency within 5 AU is ≈ 7% (lower limit)

The hot Jupiter frequency ($a \approx 0.1$ AU) is ≈ 1%

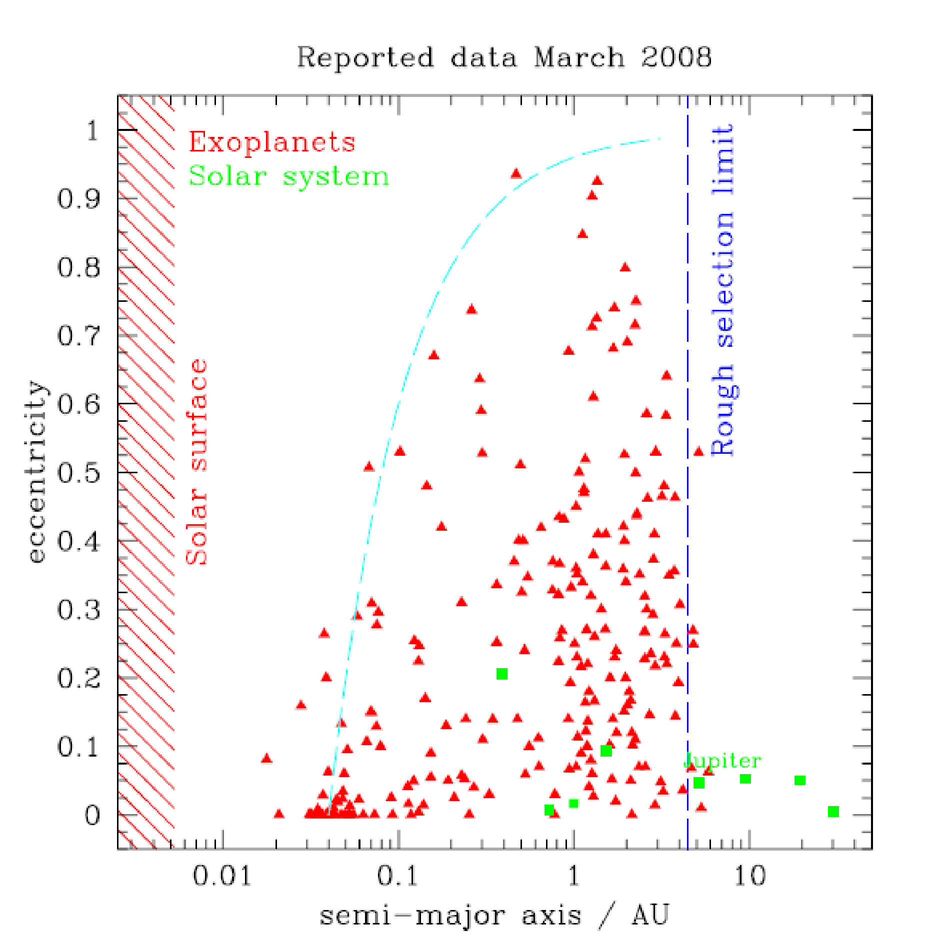
Planet frequency rises with host metallicity



Exosystem Observations:
Distribution in semimajor axis - eccentricty

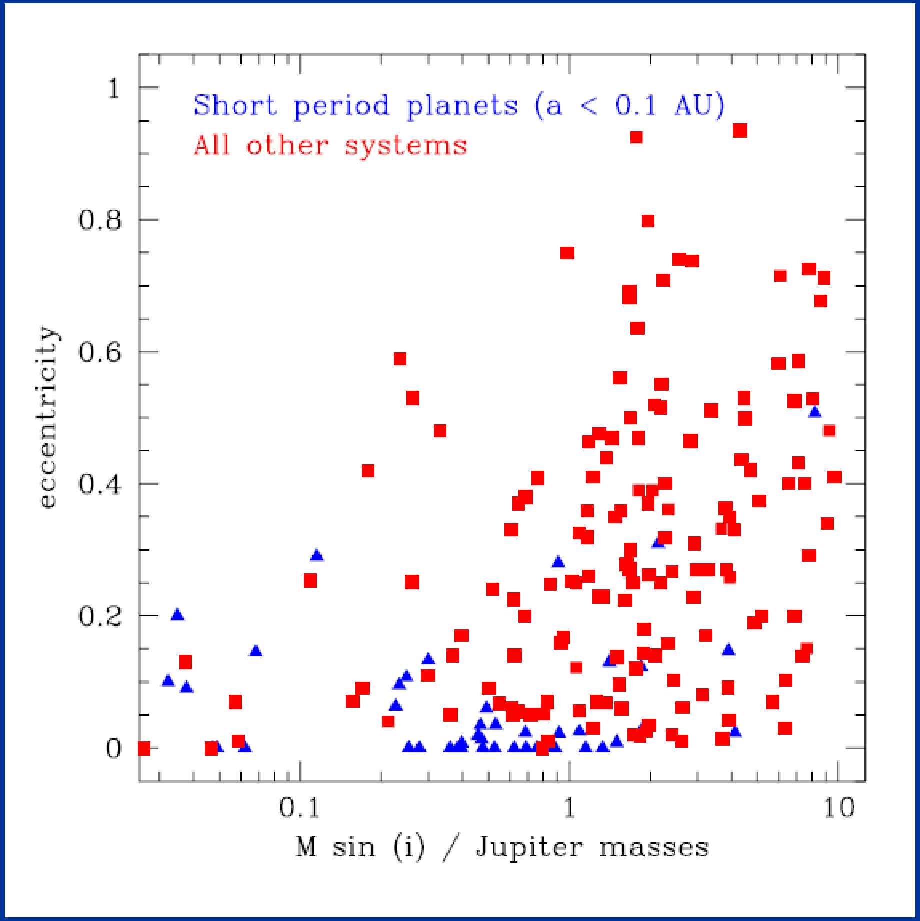
From radial surveys:
- minimum mass
- semimajor axis
- eccentricity
- longitude of pericenter

Eccentiric orbits are common beyond the tidal circularization
<e> = 0.28



Exosystem Observations:
Distribution in mass - eccentricty

No strong correlation of eccentricity with mass

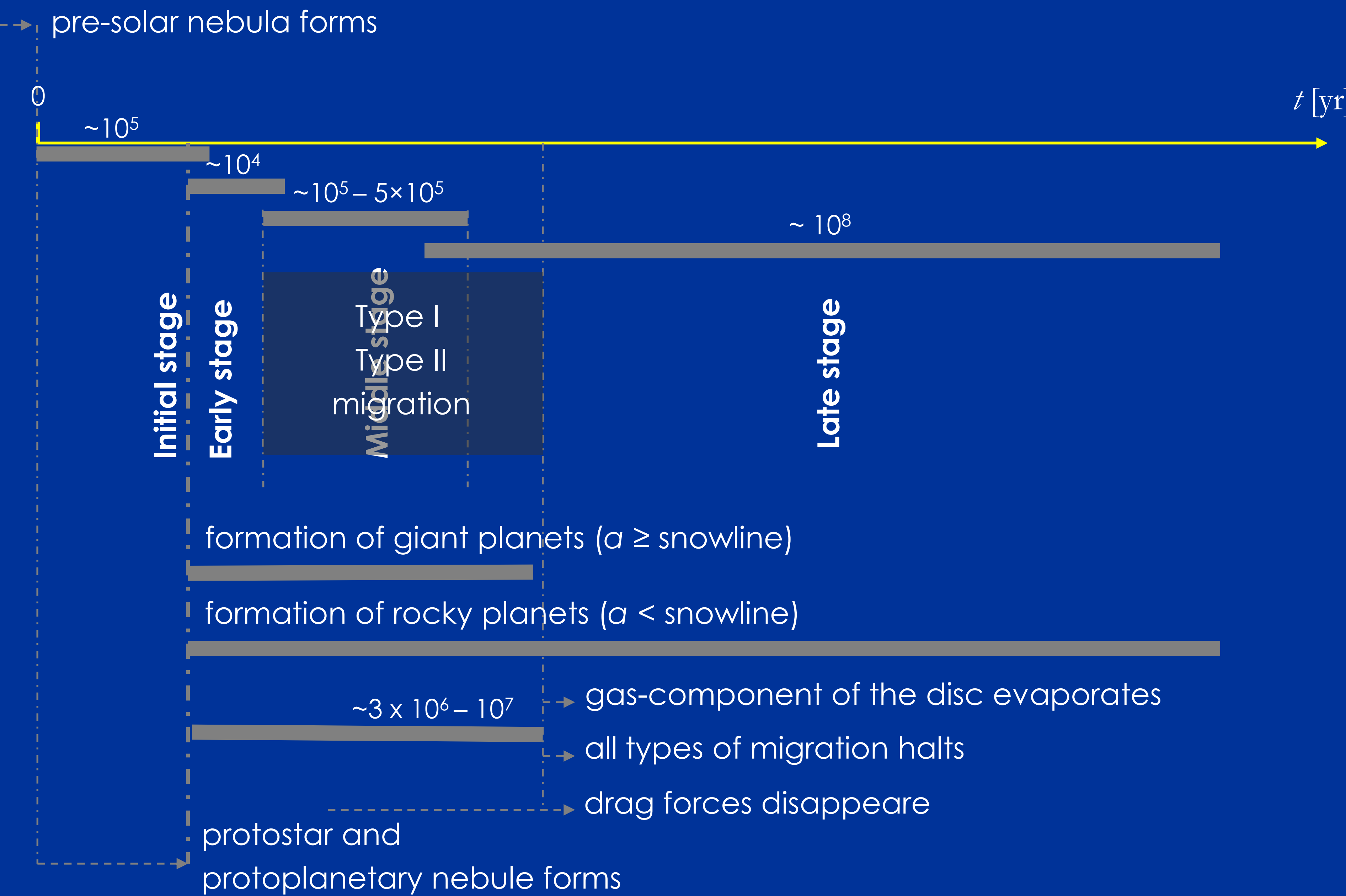


Planetesimal Hypothesis

Name	Description	Consequence
Initial stage (condensation→ grain)	The last stage of star formation (the star is between a protostar and main-squence star, i.e. a *T−Tauri* star); the circumstellar disk created, its composition is similiar to that of the star.	→ planets revolve in the same plane
Early stage (grain→ planetesimal)	The disk cools, the condensation of *dust grains* starts (silicates, iron, etc.), in the outer region ice forms; the grains coagulate into ~1-10 km size objects, the so-called *planetesimals*	→ composition of planets: Earth-type close to the star, gas-giants further out
Middle stage (planetesimal→ protoplanet)	The condensated dustmaterial, the planetesimals collide with each other building larger, a few 1000 km size objects (Moon-size), the *protoplanets*.	→ continouos size distribution
Last stage (protoplanet→ planet)	The few dozens *protoplanets* on a ~10^8 million year timescale undergo giant impacts resulting in a few terrestrial planets on well-spaced, nearly circular and low inclined orbits	→ late heavy bombardment (craters)

The planet formation is not as sequential as above, rather they occur simultaneously!

Planetesimal Hypothesis: Timeline



Planetesimal Hypothesis: Forces

Forces

Gravitation

$$\mathbf{F} = G\frac{m_1 m_2}{r^3}\mathbf{r}$$

Radiation

$$\mathbf{F}_{\mathrm{rad}} = Q_{\mathrm{pr}}\frac{L_* A}{4\pi c r^2}\hat{\mathbf{r}}$$

Poynting Robertson Drag

$$\mathbf{F}_{\mathrm{prd}} = Q_{\mathrm{pr}}\frac{L_* A}{4\pi c r^2}\left[\left(1-\frac{2v_r}{c}\right)\mathbf{r} - \frac{v_\vartheta}{c}\vartheta\right]$$

The Yarkovski-effect

$$\mathbf{F}_{\mathrm{Y}} = \frac{8}{3}\pi R^2\frac{\sigma T^4}{c}\frac{\Delta T}{T}\cos\psi$$

Gas Drag

$$\mathbf{F}_{\mathrm{D}} = -\frac{1}{2}C_{\mathrm{d}}\rho v^2 A\hat{\mathbf{v}}$$

Type I migration

$$\mathbf{F}_{\mathrm{TypeI}} = -m\left(\frac{v}{t_{\mathrm{m}}} + 2\left[\frac{(\mathbf{vr})\mathbf{r}}{r^2 t_{\mathrm{e}}} + \frac{(\mathbf{vk})\mathbf{k}}{t_{\mathrm{i}}}\right]\right)$$

Type II migration

$$\mathbf{F}_{\mathrm{TypeII}} = -\frac{m}{\tau_v}\left(\frac{v}{2} + 50\left[\frac{(\mathbf{vr})\mathbf{r}}{r^2} + (\mathbf{vk})\mathbf{k}\right]\right)$$

The Quest For Initial Conditions

To model the formation process from the early/middle stage one needs the following basic ingredients:

1. a central star
2. one or two migrating giant planets
3. a disk of protoplanets embedded in a swarm of planetesimals
4. the nebula

1. The central star is a T – Tauri star at this stage. Its mass, radius and luminosity are the most important parameters.
2. Giant planets form beyond the snowline (>2 AU), their initial mass > 100 M_E, initialy they orbit an a nearly circular, low inclination orbit
3. Next slide ...

The Quest For Initial Conditions

3. a disk of protoplanets embedded in a swarm of planetesimals:

   Due to the huge number of planetesimals, the treatment of a realistic planetesimal disk (every body interacting) is well beyond the present computer capability.

⇨ *N+N'* approach: *N* protoplanets embedded in a disk of *N'* „super-planetesimals", particles that represent a much larger number of real planetesimals ($\sim 10^5$-10^6).

The giant and the protoplanets feel the gravitational forces, whereas the super-planetesimals feel the star, the protoplanets and the giant, but do not feel each other, i.e. they are non self-interacting.
Super-planetesimals alone experience gas-drag

The Quest For Initial Conditions

4. the nebula: based on the Minimum Mass Solar Nebula

The surface density of solids:

$$\Sigma_S = f_{neb} f_{ice} \Sigma_1 r^{-\beta} = \begin{cases} 3\times 1.0\times 7\cdot r^{-\frac{3}{2}}, \text{if } r < \text{snowline} \\ 3\times 4.2\times 7\cdot r^{-\frac{3}{2}}, \text{if } r \geq \text{snowline} \end{cases}, \quad [\text{gcm}^{-2}]$$

where f_{neb} is a nebular mass scaling factor (order of unity)

f_{ice} is the ice condensation coefficient(≈ 1 if r < snowline, ≈ 4 otherwise)

Σ_1 is the surface density at 1 AU (~ 7 gcm^{-2})

The volume density of gas:

$$\rho_{gas} = f_{neb} \rho_1 r^{-\gamma} \exp\left(\frac{z^2}{h^2}\right),$$

where $\rho_1 = 2.0\times 10^{-9} (f_{gas}/240)(\Sigma_1/10) \quad [\text{gcm}^{-3}]$, f_{gas} is the gas to dust ratio (≈160)

ρ_1 is the density of gas at 1 AU (≈ 10^{-9} gcm^{-3})

z is the height from the midplane, *h* is the disk's scale height

The Quest For Initial Conditions

Example: The number of protoplanets and super-planetesimals:

$$m_{\text{solid}} = \int_0^{2\pi} d\varphi \int_{\text{diskinneredge}}^{\text{diskouteredge}} \Sigma_S \, dr = 2\pi \int f_{\text{neb}} f_{\text{ice}} \Sigma_1 r^{-\frac{3}{2}} dr =$$

$$2\pi f_{\text{neb}} \Sigma_1 \left[1 \times \int_{\text{diskinneredge}}^{\text{snowline}} r^{-1.5} dr + 4.2 \times \int_{\text{snowline}}^{\text{diskouteredge}} r^{-1.5} dr \right] = 2\pi f_{\text{neb}} \Sigma_1 \left\{ \sqrt{r}\Big|_{0.4}^{2.7} + 4.2\sqrt{r}\Big|_{2.7}^{4.0} \right\} = 24.8\,\mathrm{M}_\oplus$$

Assumption: 1. $m_{\text{protoplanet}} = \begin{cases} 0.025 M_\oplus, \text{if } a < \text{snowline (2.7 AU)} \\ 0.1 M_\oplus, \text{if } a \geq \text{snowline (2.7 AU)} \end{cases}$

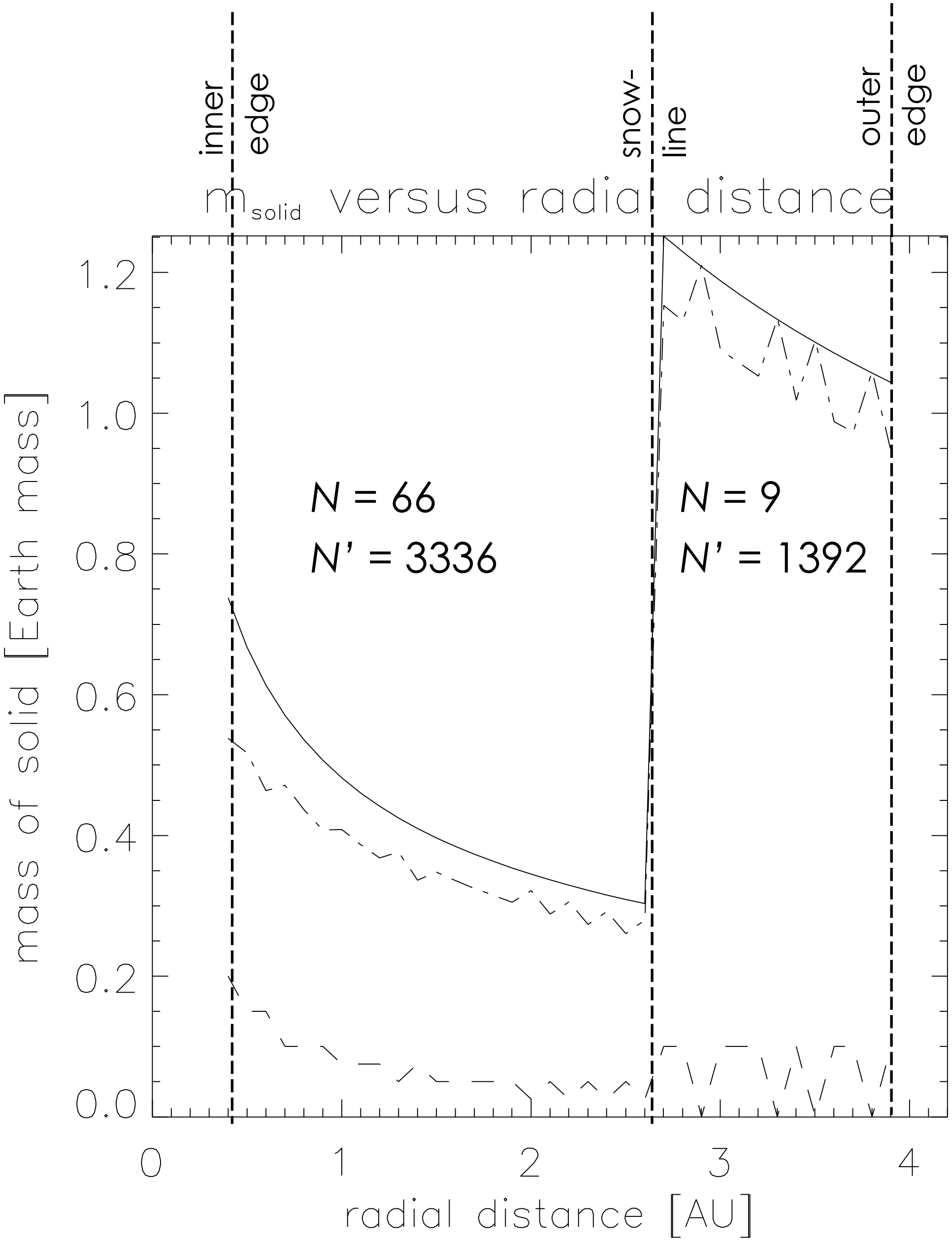
2. the radial spacing between protoplanets are 8 mutual Hill radii.

$N = 75$ $\quad \sum_{i=1}^{N} m_{\text{protoplanet}} = 2{,}55 M_\oplus$

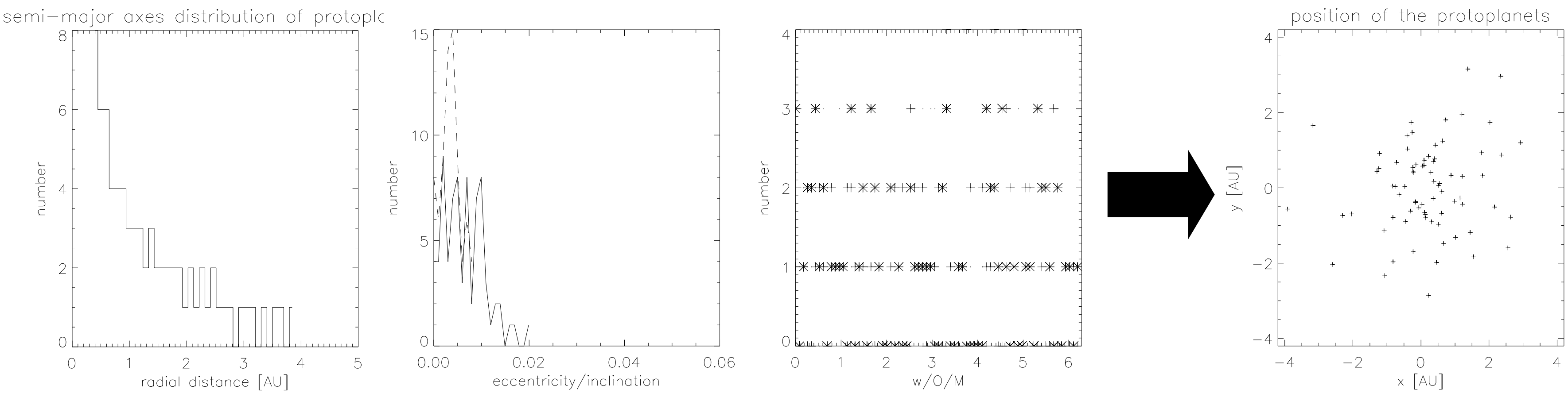
Eccentricities and inclinations are randomized form a Rayleigh distribution with rms values of 0.01 and 0.005, respectively.
The remaining orbital elements are randomized uniformly within their range, i.e. [0, 360] degree.

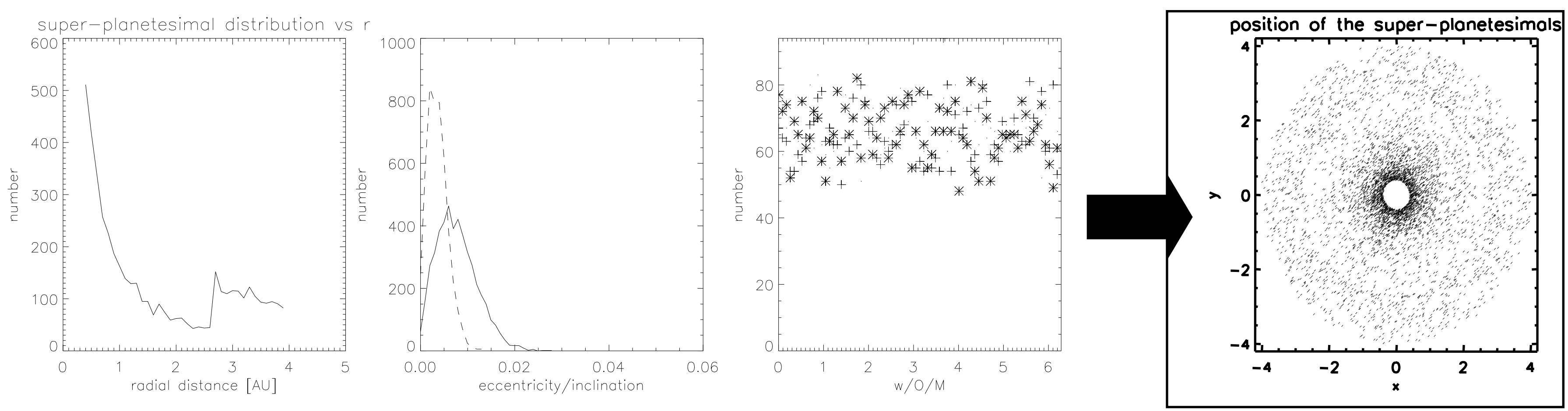
$\sum m_{\text{super-planetesimal}} = m_{\text{solid}} - 2{,}55 = 22{,}25 M_\oplus$ $\quad N' = 4728$

The Quest For Initial Conditions

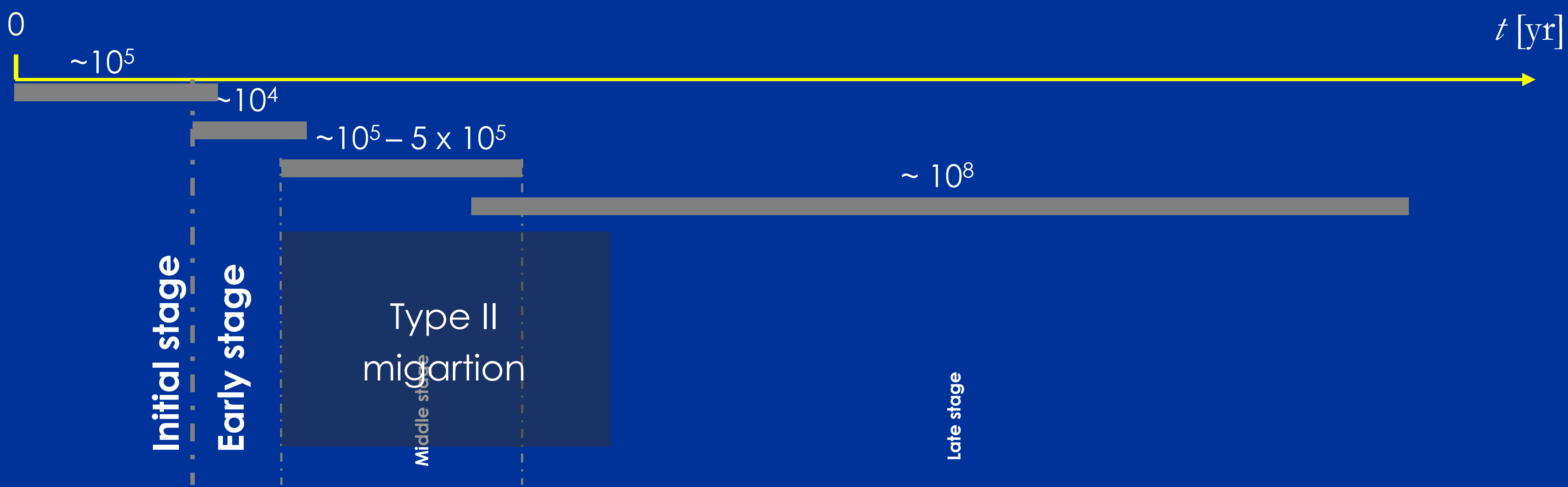


The Quest For Initial Conditions





Timing and effect of migration



Observation: hot Jupiters ($a \leq 0.1$ AU) ~20% of exoplanets : ↔ theory → migration

Q: What effet has the migartion of the giant on the formation of the inner planets

Armitage (2003)	Assumption: the migration complety cleared the inner disk. Resupply of solid material by advection and diffusion is inefficient; Terrestrial planet formation is unlikely
Mandell & Sigurdsson (2003)	Assumption: fully formed inner planetary system. Migration through this system results in 1) excitaion, 2) encounters, 3) ejection, but 1-4% could still possess a planet in the HZ
Raymond et al. (2004)	Assumption: fast migration, the inner disk is not cleared. The presence of a hot Jupiter do not influence terrestrial planet formation, planets in the HZ are commonplace

N + *N*' model, Type II migration

Ingredients of the base model (Fogg & Nelson 2005)

1. Central body (1 M_{Sun}), 1 giant, *N* protoplanets
2. *N*' super-planetesimal
3. Type II migartion of the giant (predefined rate) from 5 AU down to 0.1 AU
4. Super-planetesimals feel drag force
5. Steady-state gas disk
6. Collision

} Base model (B0)

Extension 1 to B0 (Fogg & Nelson 2007a):

- The *N* + *N*' body code is linked to a viscously evolving gas disk

} B1 model

Extension 2 to B0 (Fogg & Nelson 2007b):

- Type I migration of protoplanets

} B2 model

Disks with different age

We have seen that different assumptions on the effect of migartion have lead to completley Different outcomes:

1. Armitage: Terrestrial planets are unlikely
2. Mandell & Sigurdsson : Terrestrial planets are rare
3. Raymond et al. : Terrestrial planets are typical

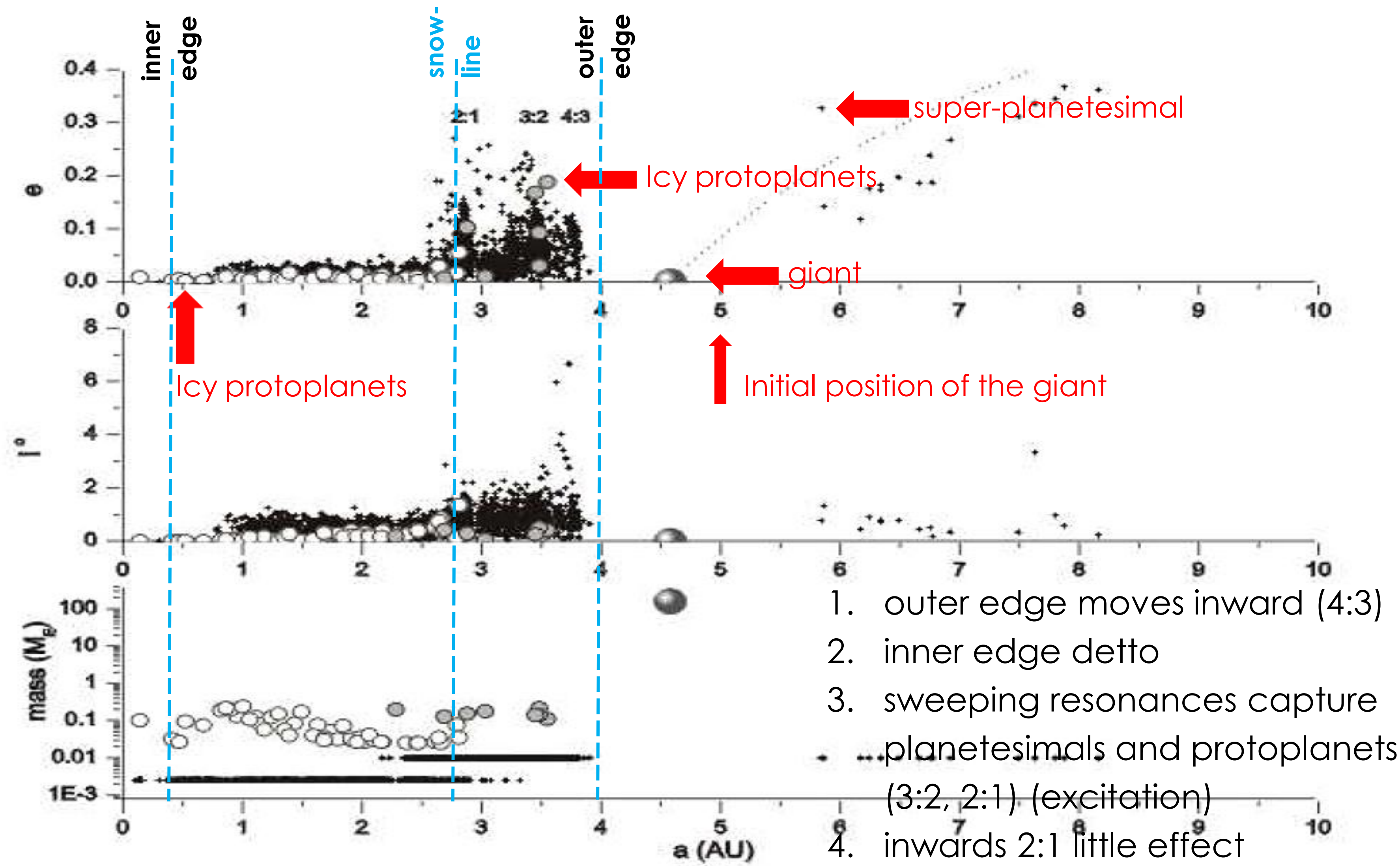
The timing of the migration: the inner disk has different „age”. i.e. the coagulation of the solids have reached different levels and the density of the gas component have more or less decreased

Therefore the B0, B1 and B2 models have simulated for
0.1,   (Scenario I)
0.25,   (Scenario II)
0.5,   (Scenario III)
1.0,   (Scenario IV)
3.0   (Scenario V)
million years before the migartion episode

B0 model

Scenario I at 20 000 years after the start of migration

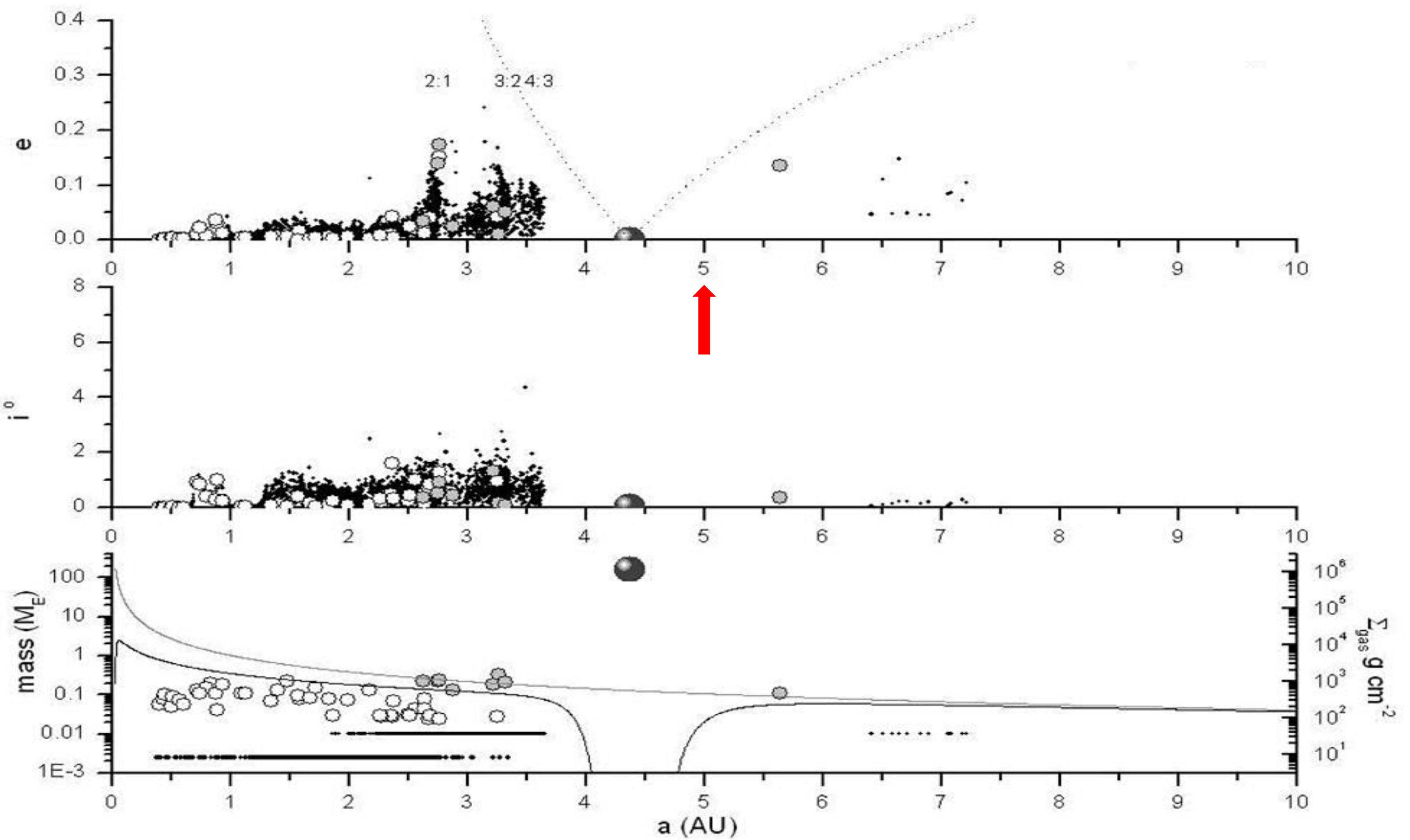
T = 120 000 years



1. outer edge moves inward (4:3)
2. inner edge detto
3. sweeping resonances capture planetesimals and protoplanets (3:2, 2:1) (excitation)
4. inwards 2:1 little effect

B1 model

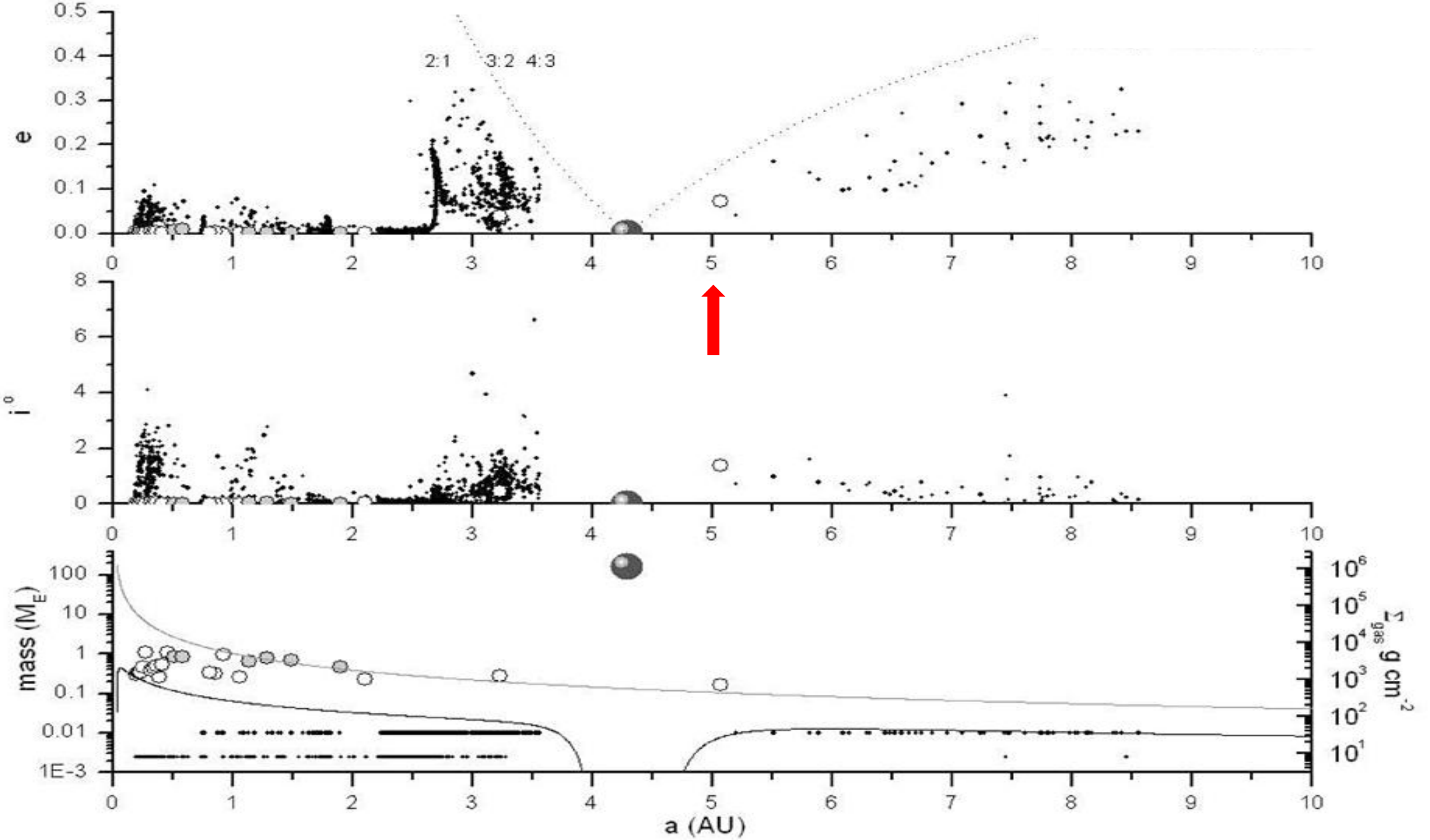
Scenario I at 20 000 years after the start of migration T = 120 000 years



B2 model

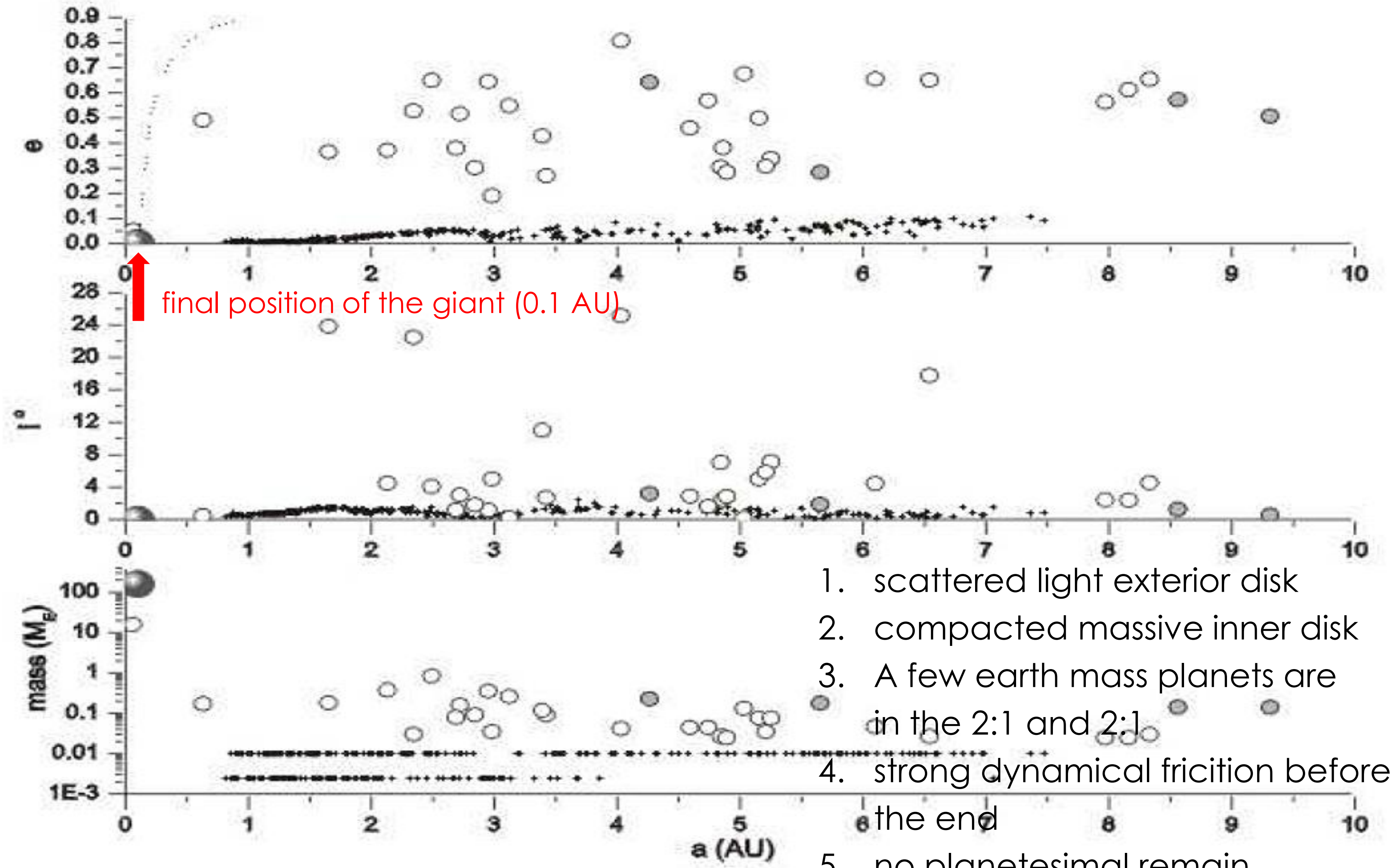
Scenario IV at 20 000 years after the start of migration

T = 1 020 000 years



B0 model

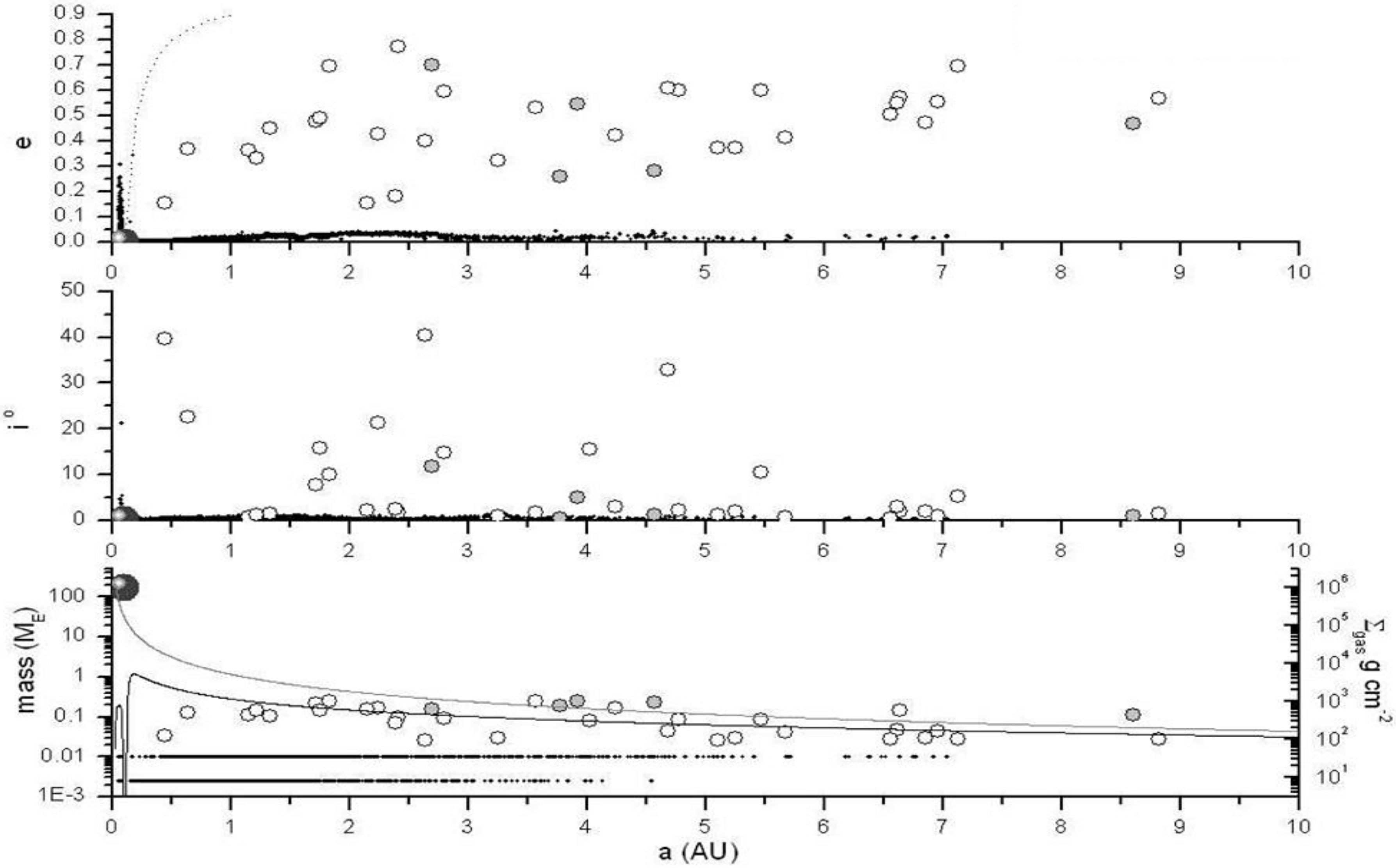
Scenario I at 170 000 years after the start of migration T = 270 000 years



1. scattered light exterior disk
2. compacted massive inner disk
3. A few earth mass planets are in the 2:1 and 2:1
4. strong dynamical fricition before the end
5. no planetesimal remain

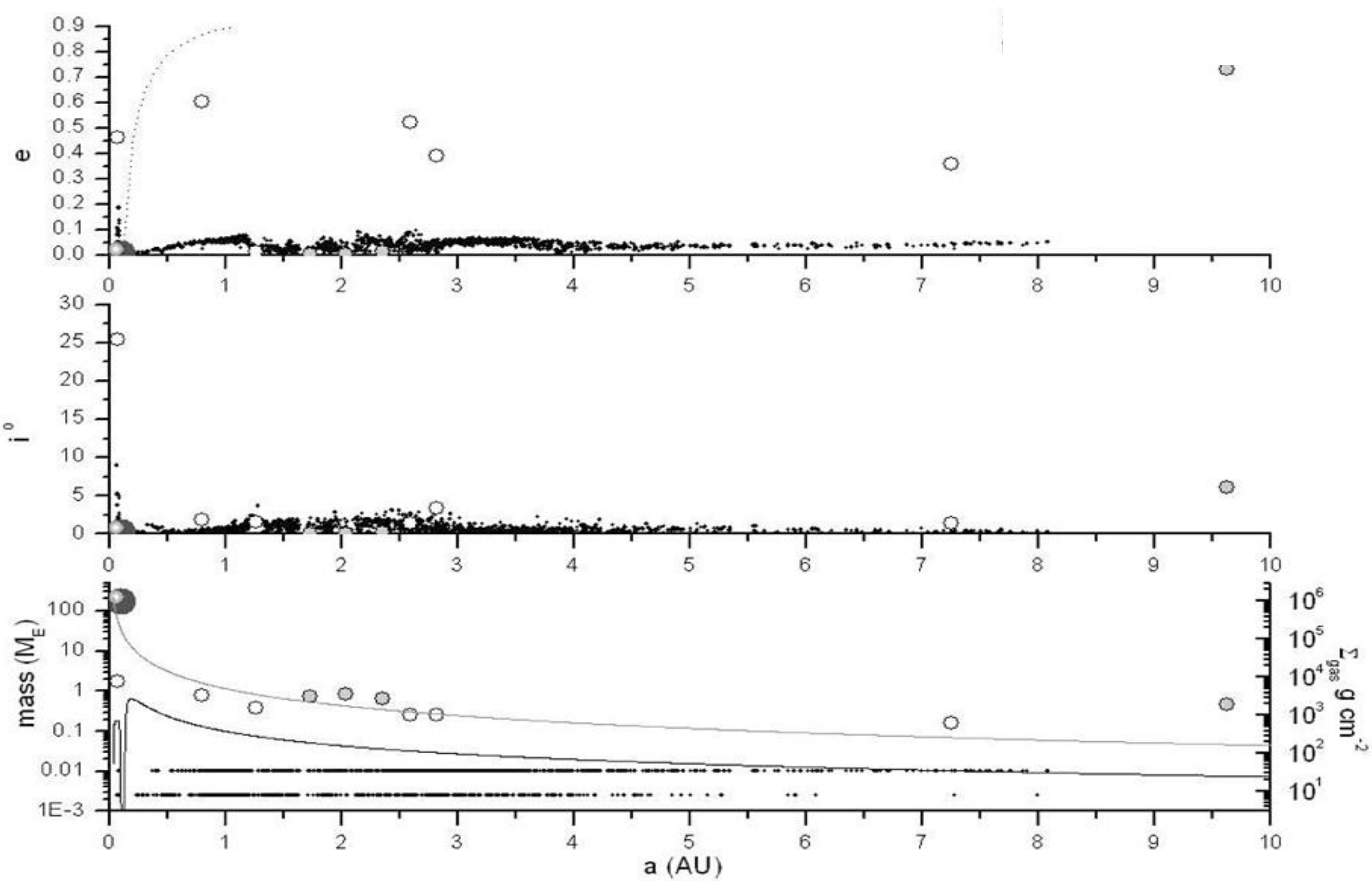
B1 model

Scenario I at 114 000 years after the start of migration T = 214 000 years



B2 model

Scenario IV at 152 000 years after the start of migration T = 1 152 500 years



Summary of the observed behavior

The character of the planetary systems vary systematically with the age of the disk. However, all scenarios have common behavioral features in common:

1. **Shepherding:** planetesimals random velocities continously damped by gas drag, they are moving inward, ahead of the giant (at the 4:3 resonance). Protoplanets are weakly coupled by dynamical friciton to planetesimals, therefore they also exhibit shepherding.

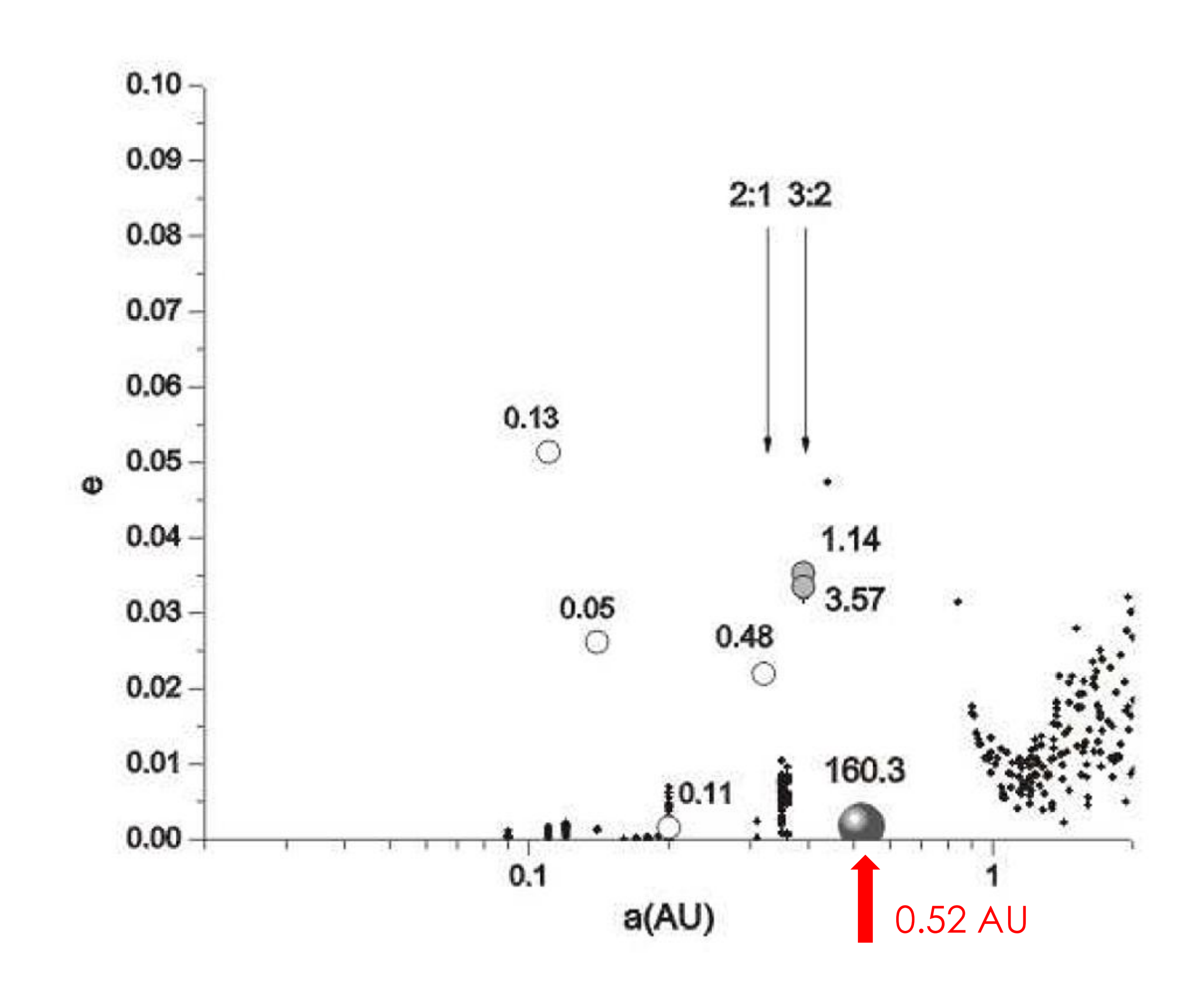
2. **Resonant capture:** first order resonances with the giant capture an increasing amount of mass as they are sweeping inward. This results in compacting.

3. **Acceleration of planetary growth interior to the giant:** accretion speeds up inside 0.1 AU: in a few 1000 years typically 1-3 terrestrial planets with 1 – 10 earth masses (hot Neptune) are the end result.

4. **Formation of a scattered exterior disk:** eccentricity excitation by resonances causes close encounters with the giant. These bodies are either ejected from the system or become part of the exterior disk.

B0 model

Scenario I at 160 000 years after the start of migration



Blow up of the interior region (0 – 2 AU, log horizontal axis):
A total of 15 earth masses:
2/3 in planetesimals
1/3 in protoplanets
2 protoplanets in 3:2
1 protoplanet in 2:1

Summary

1. Migration of a giant planet through an inner disk partitions the mass of that disk into internal and external remnants. The mass of the interior and exterior disk depends on the age of the disk. The concept that giant planet migration would eliminate all the mass in its swept zone is not supported by the results. The inner part clears completly if the giant moves inside 0.05 AU.
2. Hot Neptunes and lesser massive terrestrial planets ($1\ M_E < m < 15\ M_E$) are a possible by-product of type II migration, if the giant stops at $a \geq 0.1$ AU.
3. The results indicate that eventual accumulation of a number of terrestrial planets orbiting exterior to the giant, including the habitable zone. Hot Jupiter systems may host Earth-like planets.

Thank you