On the combined action of disc migration and planet-planet scattering in the formation of giant planetary systems

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Planetary System Architecture

- Observations: the orbits of extrasolar systems are more various than the circular and coplanar ones of the Solar system
- The search of Earth-like planets in the RV-detected planetary systems calls for a good understanding of giant planetary system architecture
- Limits of the observational methods: free parameters in the dynamical studies of the detected systems, especially the inclinations
- Idea : To resort to formation theories to have additional information about giant planetary systems

Late-stage formation of giant planetary systems

- **During** the disc phase: **Giant planet migration** (Type II)
  (e.g. Lin & Papaloizou 1986a, Kley 2000, Nelson et al. 2000)
  => eccentricity and inclination excitations
  (e.g. Thommes & Lissauer 2003, Libert & Tsiganis 2009, Teyssandier & Terquem 2014)

- **After** the disc phase: **Planet-planet scattering**
  (e.g. Weidenschilling & Marzari 1996, Ford & Rasio 2008, Juric & Tremaine 2008, Chatterjee et al. 2008)
  => eccentricity and inclination excitations
  + Initial conditions problem

- **Combined action** of both previous mechanisms:
  Planet-planet interactions DURING migration in the protoplanetary disc
  (e.g. Adams & Laughlin 2003, Matsumara et al. 2010, Libert & Tsiganis 2011)
  No inclination damping

Our work

Generalization of *Libert & Tsiganis 2011*

- 11 000 simulations of 3 giant planet systems in the late stage of the disc (SYMBA, 2×10^5 computational hours)
- planets with mass in [1, 10] M_{Jup}, initially outside the snowline, on quasi-circular and coplanar orbits
- different initial system configurations, planetary mass ratios, disc masses
- τ_{II}=viscous accretion timescale x max (1 , M_p / local disc mass) *(Baruteau et al. 2013)* for the outer planet only
- exponential decrease of the disc mass, with a dispersal time of ~1 Myr

- **eccentricity and inclination damping formulae** provided by the 3D hydrodynamical simulations of *Bitsch et al. 2013*

ECC

$$\mathcal{F}_e(i_P) = -\frac{M_{\rm disc}}{0.01\, M_\star}\left(a(i_P + i_D)^{-2b} + c\, i_P^{-2d}\right)^{-1/2}$$

$$\mathcal{G}_e(i_P, M_P, e_P) = 12.65\,\frac{M_P M_{\rm disc}}{M_\star^2}\, e_P\, \exp\left(-\left(\frac{(i_P/1^\circ)}{\tilde{M}_p}\right)^2\right)$$

$$\begin{aligned}
a_e(M_P, e_P) &= 80\, e_P^{-2}\, \exp\left(-e_P^2 \tilde{M}_p/0.26\right) 15^{\tilde{M}_p}\left(20 + 11\tilde{M}_p - \tilde{M}_p^2\right)\\
b_e(M_P) &= 0.3\tilde{M}_p\\
c_e(M_P) &= 450 + 2^{\tilde{M}_p}\\
d_e(M_P) &= -1.4 + \sqrt{\tilde{M}_p}/6.
\end{aligned}$$

INCL

$$\begin{aligned}
a_i(M_P, e_P) &= 1.5\times 10^4 (2 - 3e_P)\tilde{M}_p^3\\
b_i(M_P, e_P) &= 1 + \tilde{M}_p e_P^2/10\\
c_i(M_P, e_P) &= 1.2\times 10^6 / \left[(2 - 3e_P)\left(5 + e_P^2\left(\tilde{M}_p + 2\right)^3\right)\right]\\
d_i(e_P) &= -3 + 2e_P\\
g_i(M_P, e_P) &= \sqrt{3\tilde{M}_p/(e_P + 0.001)} \times 1^\circ\\
\mathcal{F}_i(M_P, e_P, i_P) &= -\frac{M_{\rm disc}}{0.01\, M_\star}\left[a_i\left(\frac{i_P}{1^\circ}\right)^{-2b_i}\exp(-(i_P/g_i)^2/2)\right.\\
&\quad \left. + c_i\left(\frac{i_P}{40^\circ}\right)^{-2d_i}\right]^{-1/2}.
\end{aligned}$$

Valid for $e<0.6$ and mass in [1, 10] M_{Jup}

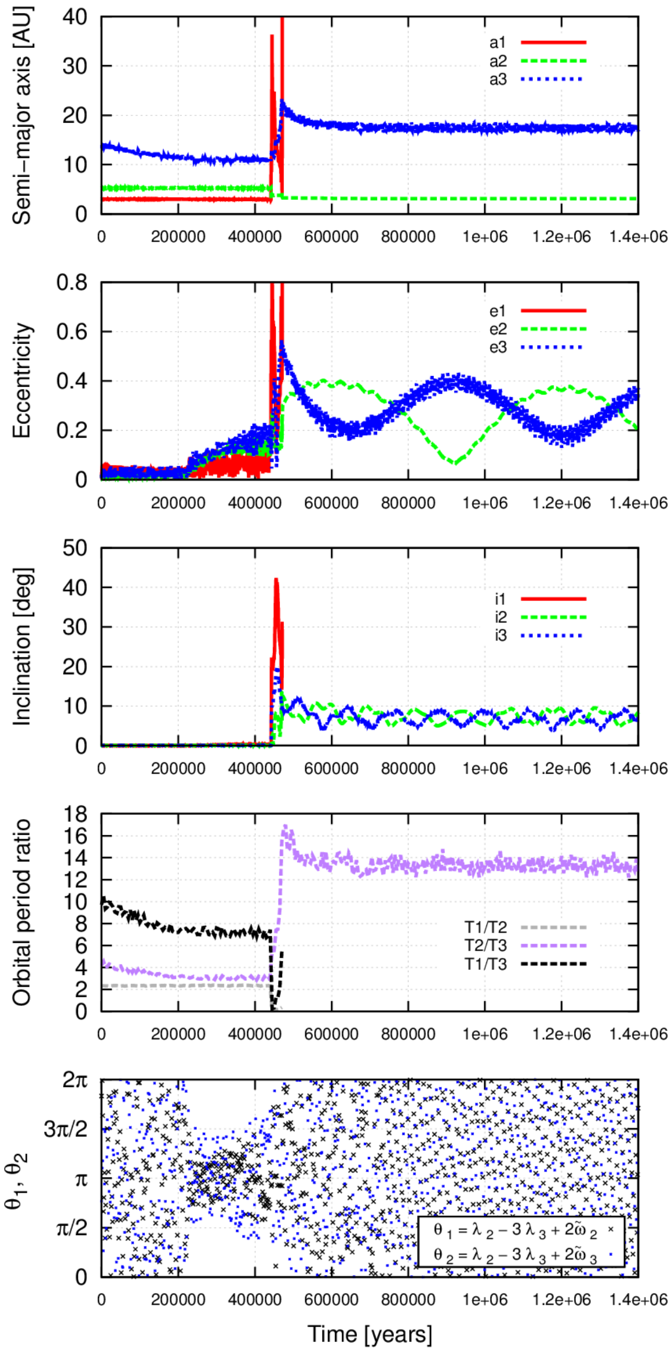
Strong damping !

de/dt=0.001/orbit, i.e. the planet will lose ~0.085 in ecc in 10^4 yrs

di/dt=0.01°/orbit, i.e. the planet will lose ~8.5° of incl in 10^4 yrs

Goals

- Impact of the eccentricity and inclination damping on the final system configurations (a – e – i)
- Dynamical mechanisms producing inclination increase
- Mean-motion resonance captures during the gas phase



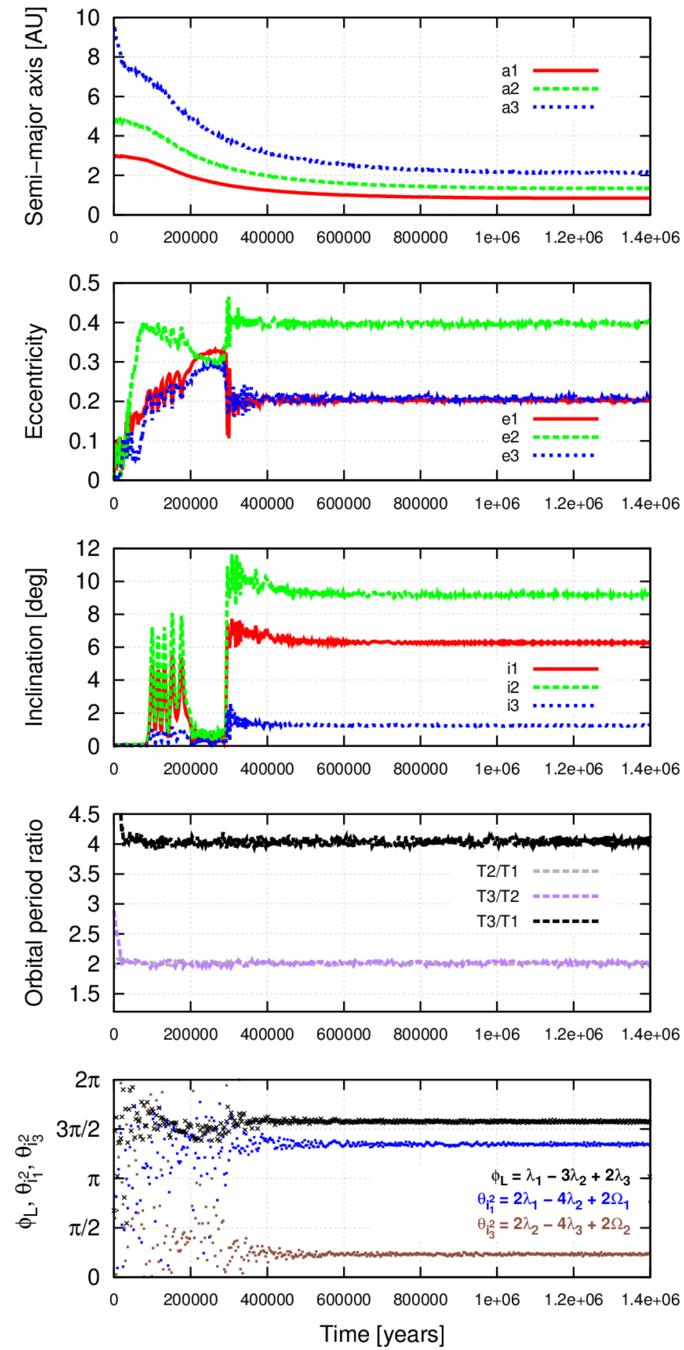
Dynamical mechanisms for inclination increase

Planet-planet scattering during the gas phase

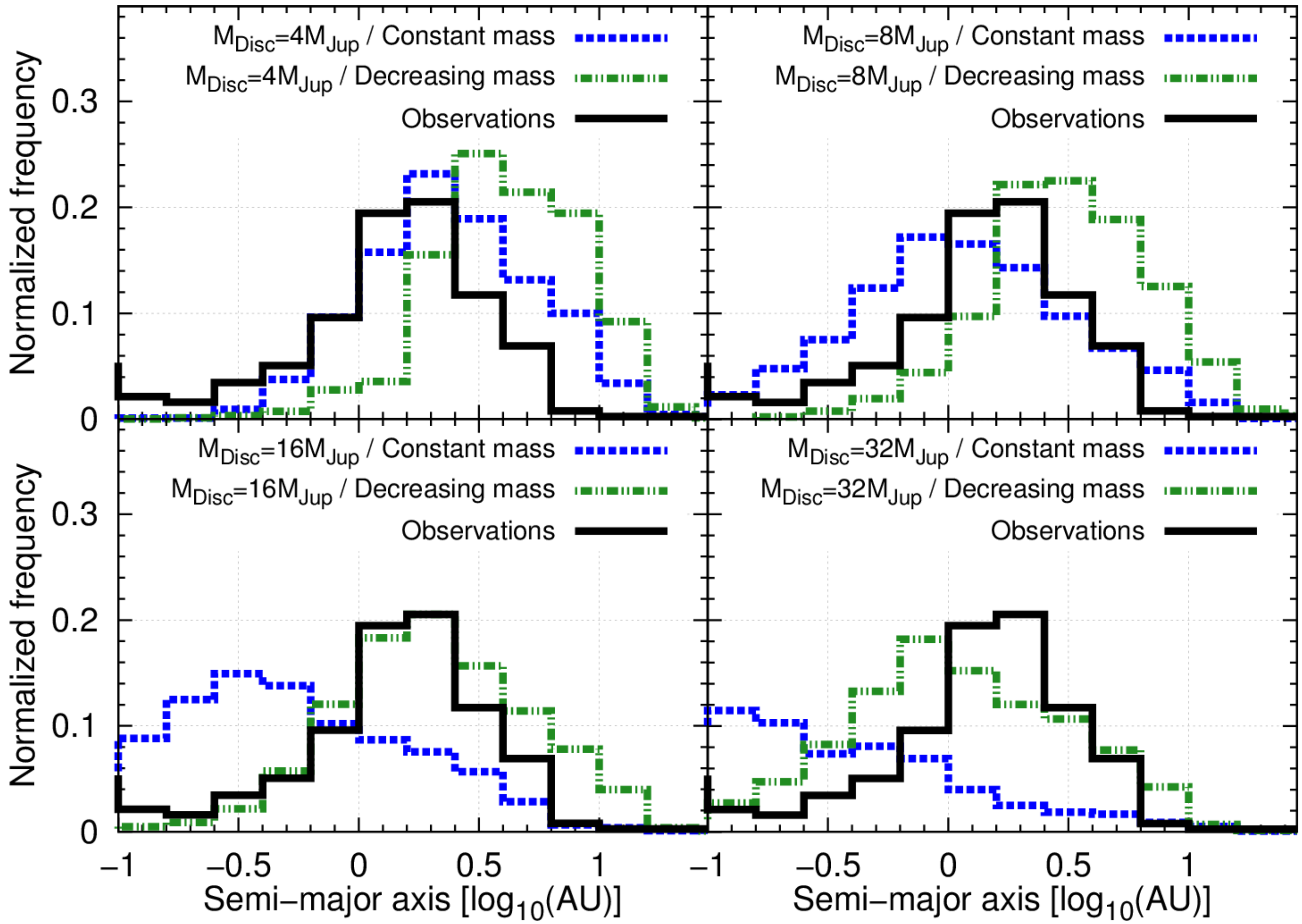
- 1:3 MMR capture for the outer planets
- Subsequent increase of the eccentricities
- When the inner pair approaches the 3:7 commensurability, destabilization of the whole system
- Ejection of the inner less massive body
- Remaining planets in inclined orbits with large eccentricity variations and large orbital separation

Three-body resonance

- Capture in a 1:2:4 Laplace resonance
- Subsequent increase of the eccentricities
- When the eccentricities are high enough, inclination-type resonance
- Strong damping: planets back to the midplane
- Exponential decay of the gass disc: inclination-type resonance produces high inclinations maintained for a long time



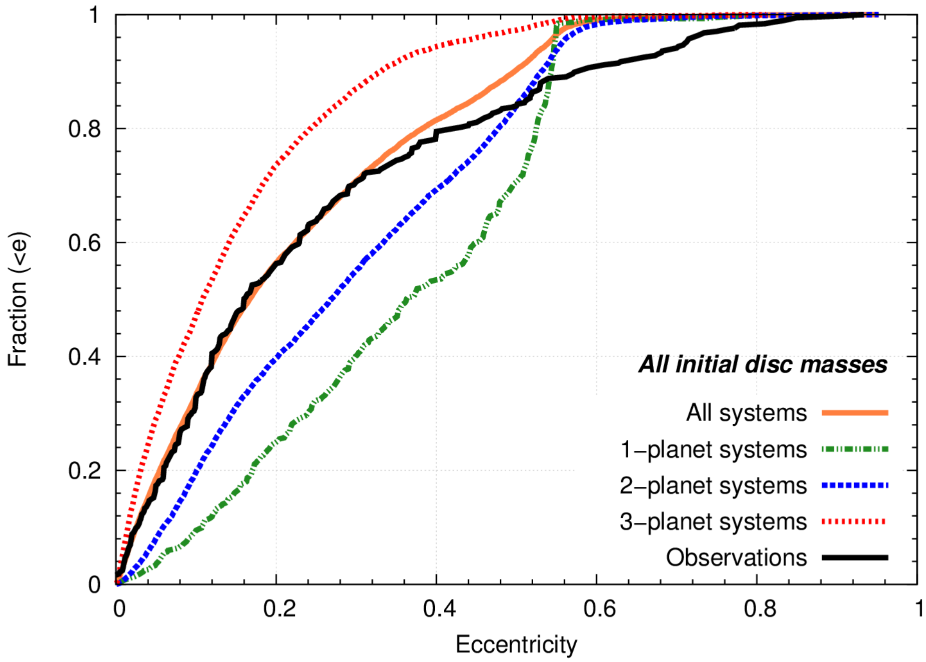
Semi-major axis distribution



Best agreement for 16 M_{Jup}

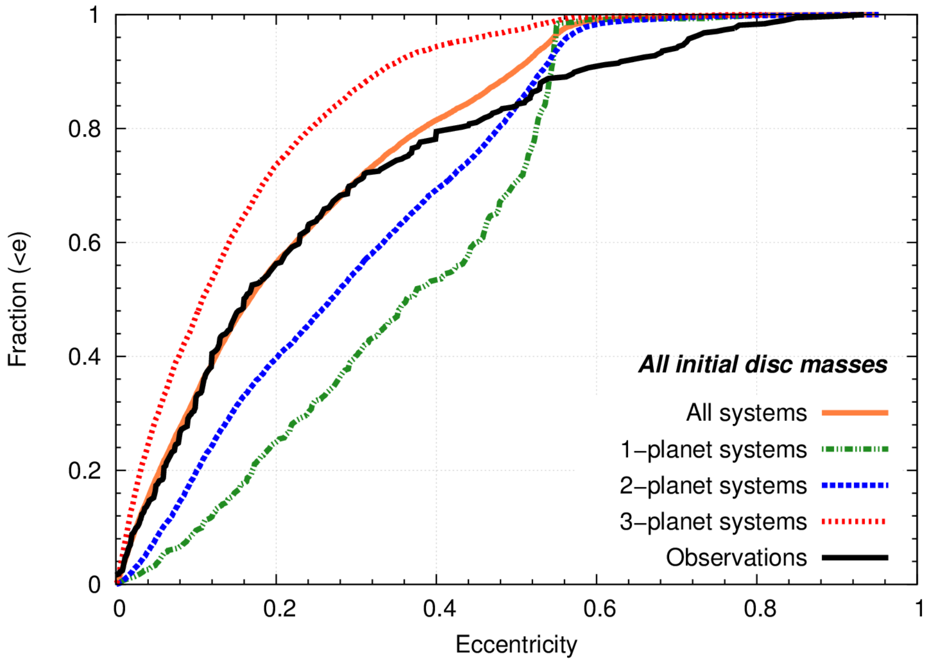
Observations : exoplanets.org

Eccentricity distribution

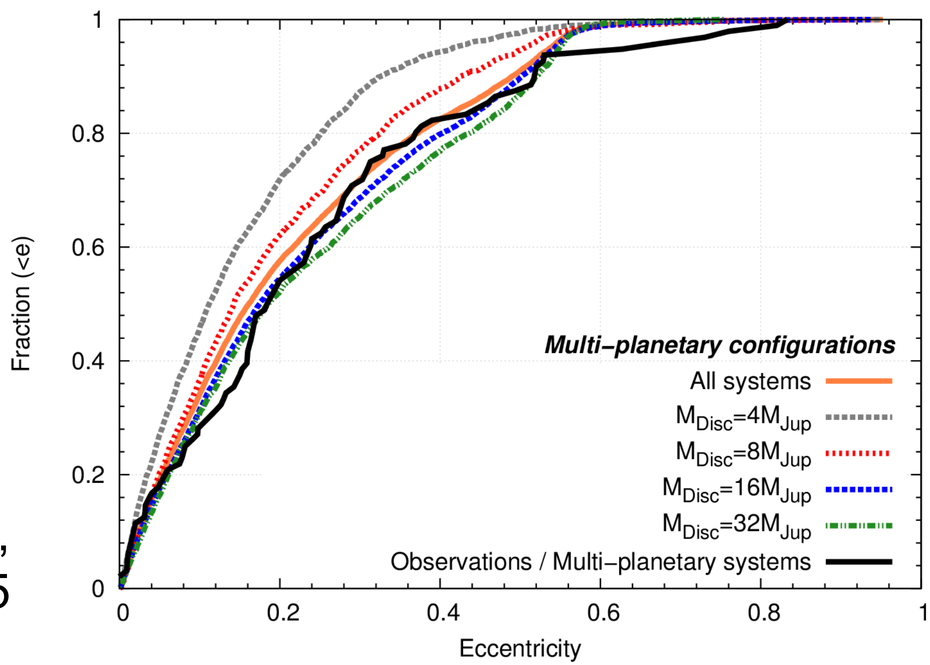


Perfect agreement up to 0.35, lack of highly eccentric orbits

Eccentricity distribution

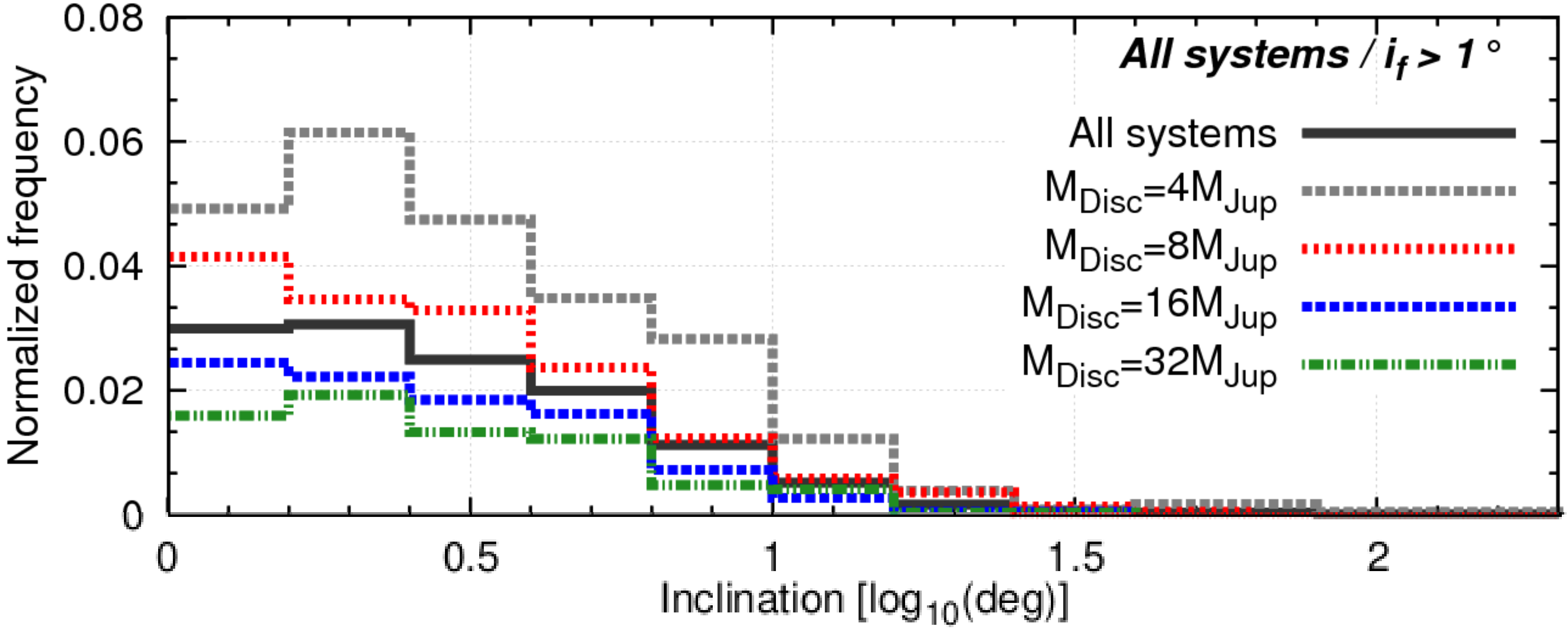


Perfect agreement up to 0.35, lack of highly eccentric orbits



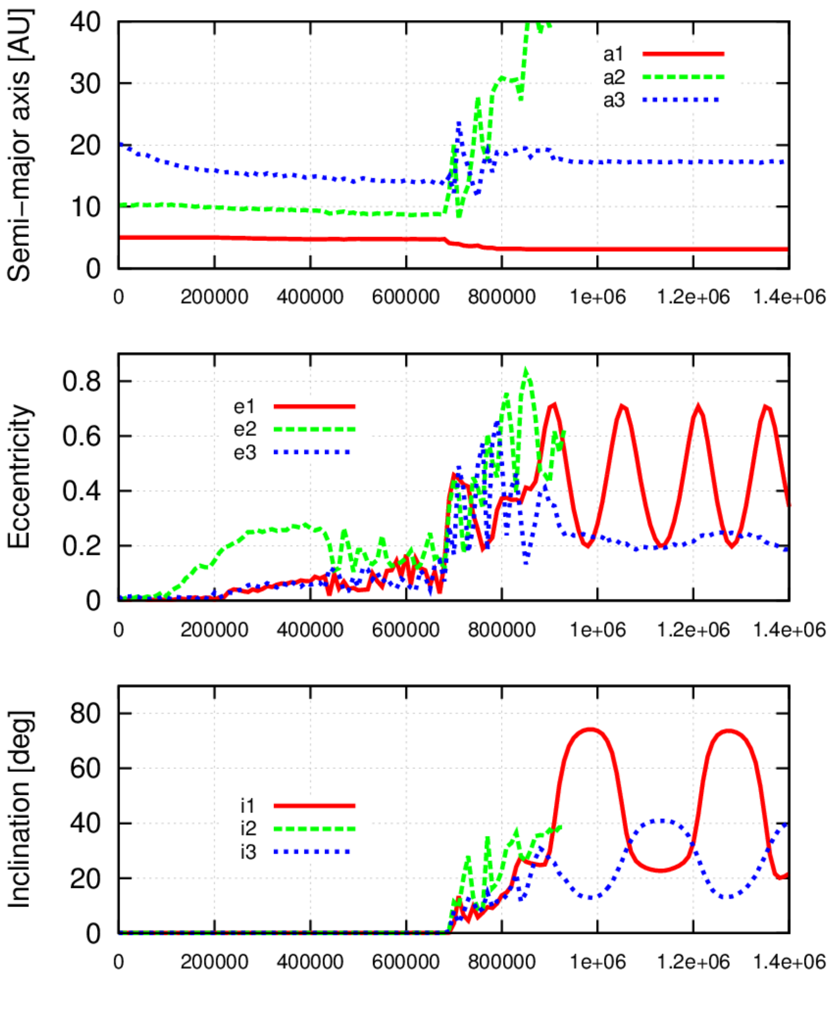
Removing single planet systems, good agreement up to 0.55

Inclination distribution



3% of the systems have mutual inclination > 10°
at the dispersal of the disc

Highly mutually inclined system in a Kozai-resonant state



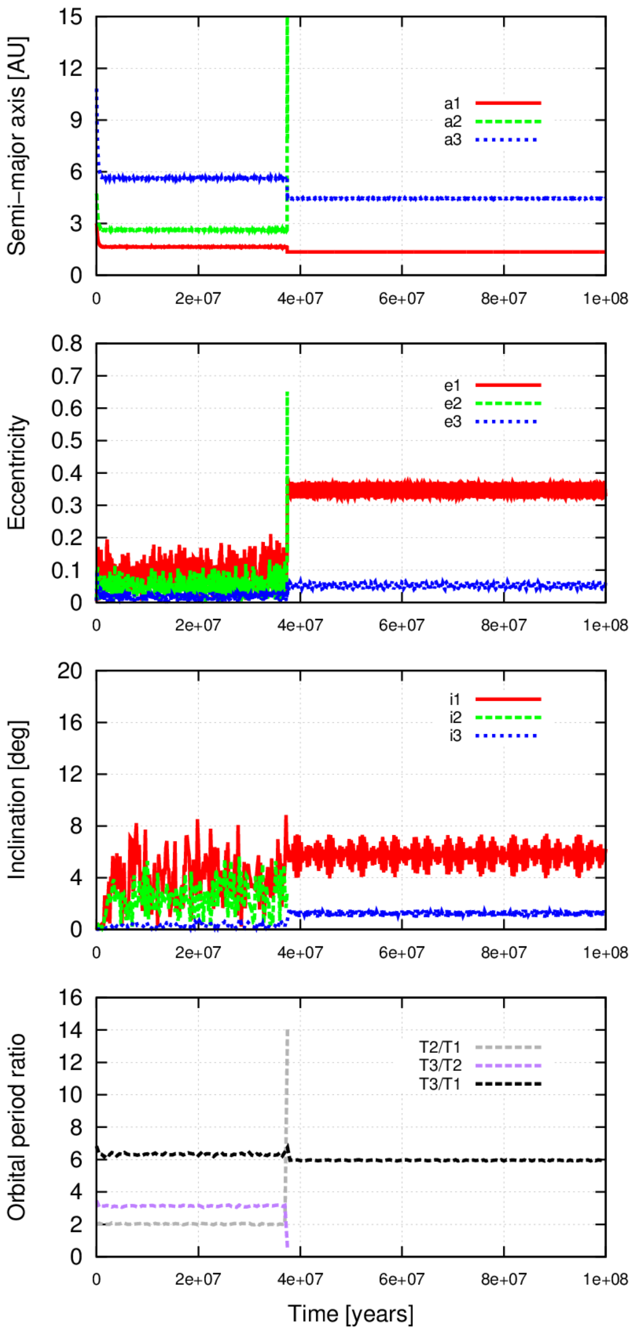
- Capture in a three-body resonance + increase of the eccentricities and inclinations
- Destabilization of the system
- The remaining two-planet system is in a Kozai-resonance state with large eccentricities and inclinations variations of the inner planet + decoupling of the orbital eccentricities (Libert & Tsiganis 2009)

Long-term evolution

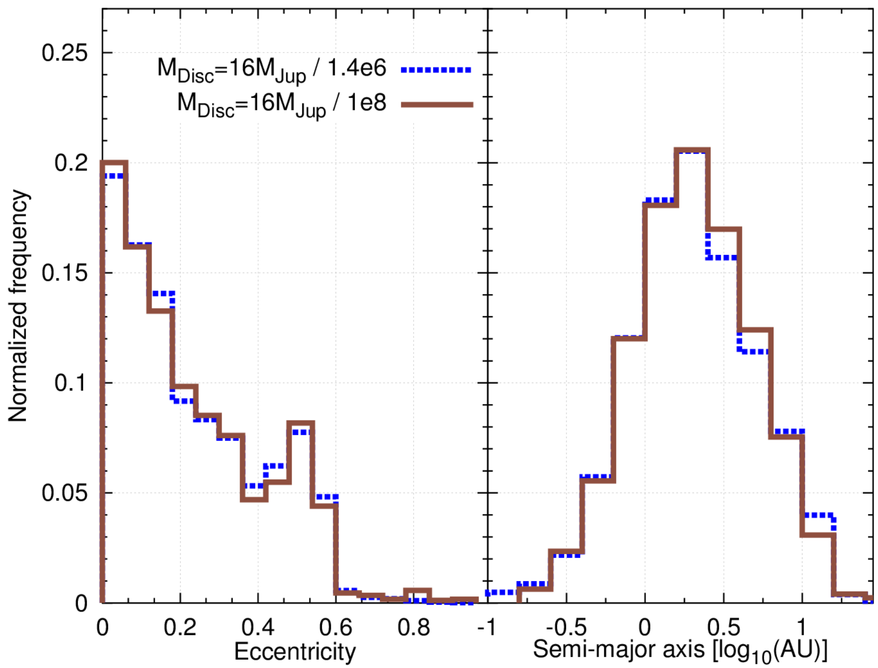
- Orbital adjustements due to planet-planet interactions can occur on a longer timescale AFTER the disc phase

- Number of planets at 1.4d6 and 1d8

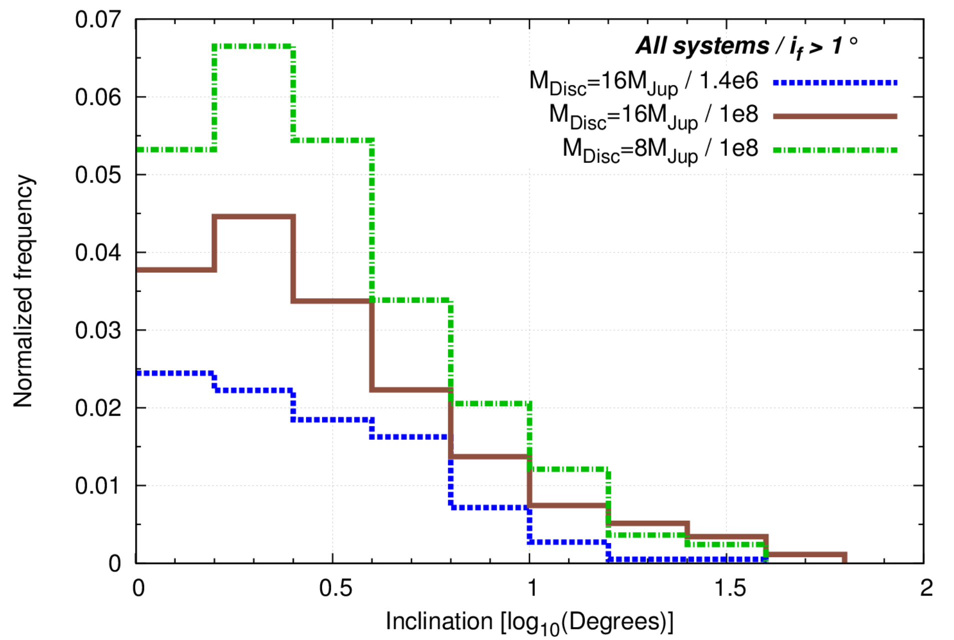
	1 planet	2 planets	3 planets
1.4d6	7%	50%	40%
1d8	12%	53%	32%



- No significant change on the semi-major axis and eccentricity distributions



- Increase of the inclinations



5% of the systems have mutual inclination > 10° on long-time scale

Summary

- Good agreement between our simulations and the observed population of extrasolar systems
- Eccentricities well-diversified at the dispersal of the disc, despite the strong damping exerted by the disc
- Very efficient damping exerted by the disc on the inclinations: most of the planets end up in the midplane
- Inclination-type resonance and planet-planet scattering events during/after the gas phase induce inclination excitation: 5% of highly mutually inclined systems (>10°) in our population
- Future work: study of terrestrial planets in our population of giant planetary systems + their habitability

Thank you for your attention

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