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# Formation of giant planetary systems:

## *Planet-planet interactions during the gas phase*

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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

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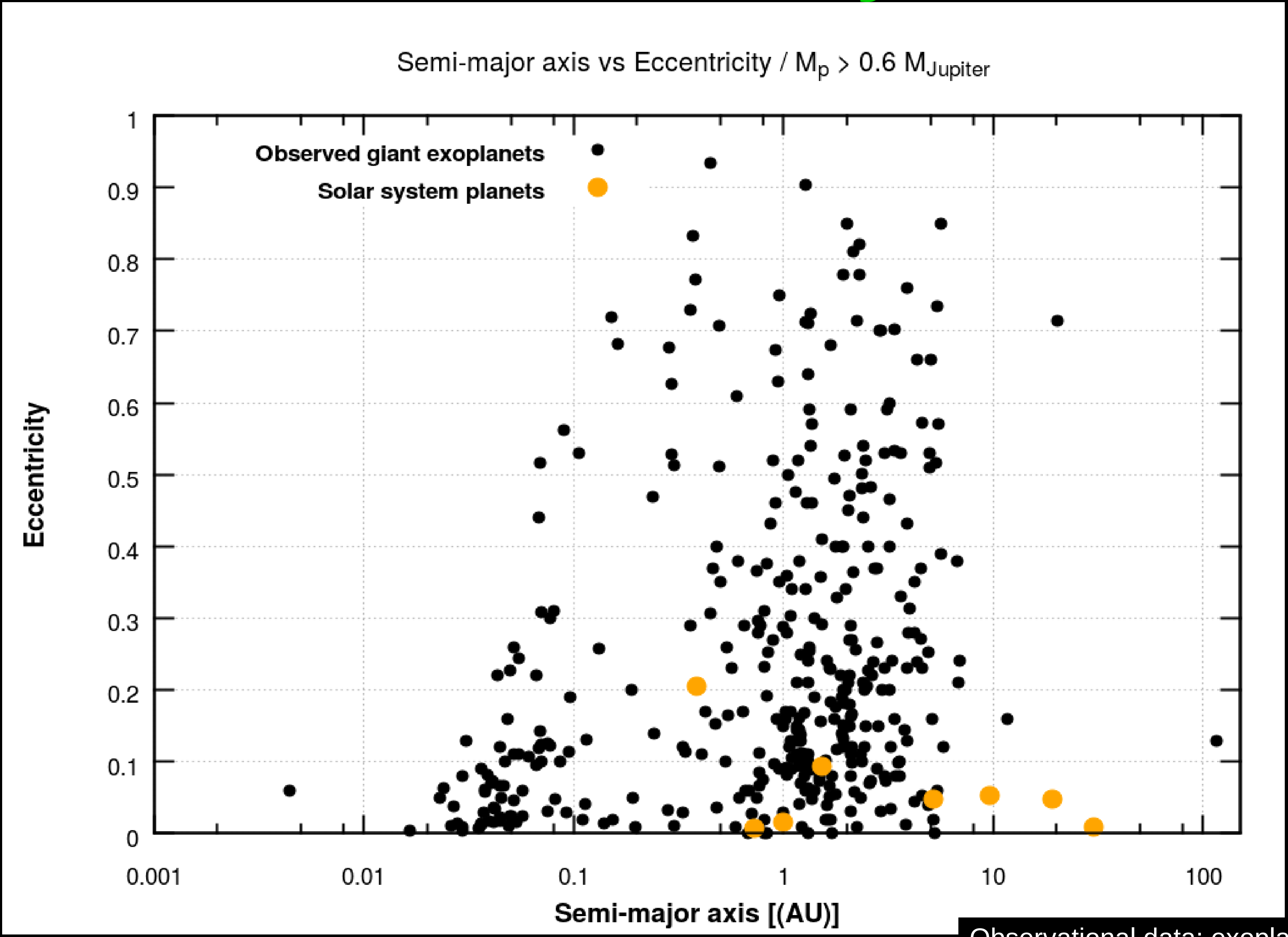
  In particular, **RV-detected giant planets**:

  - Very diversified eccentricities

# Eccentricity




Observational data: exoplanets.org

# Planetary system architecture

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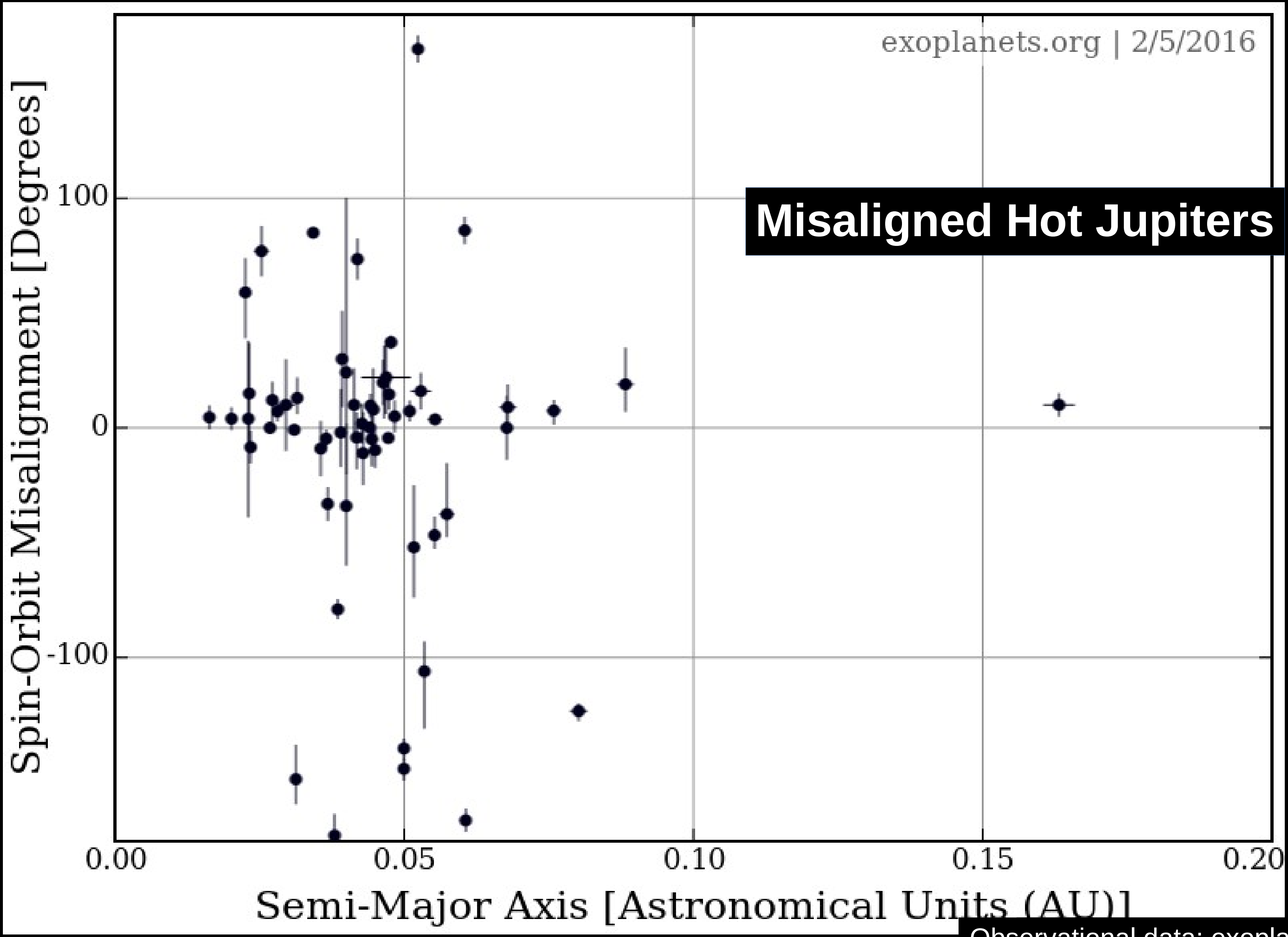
  - Mutual inclinations unknown

# Inclinations: some clues

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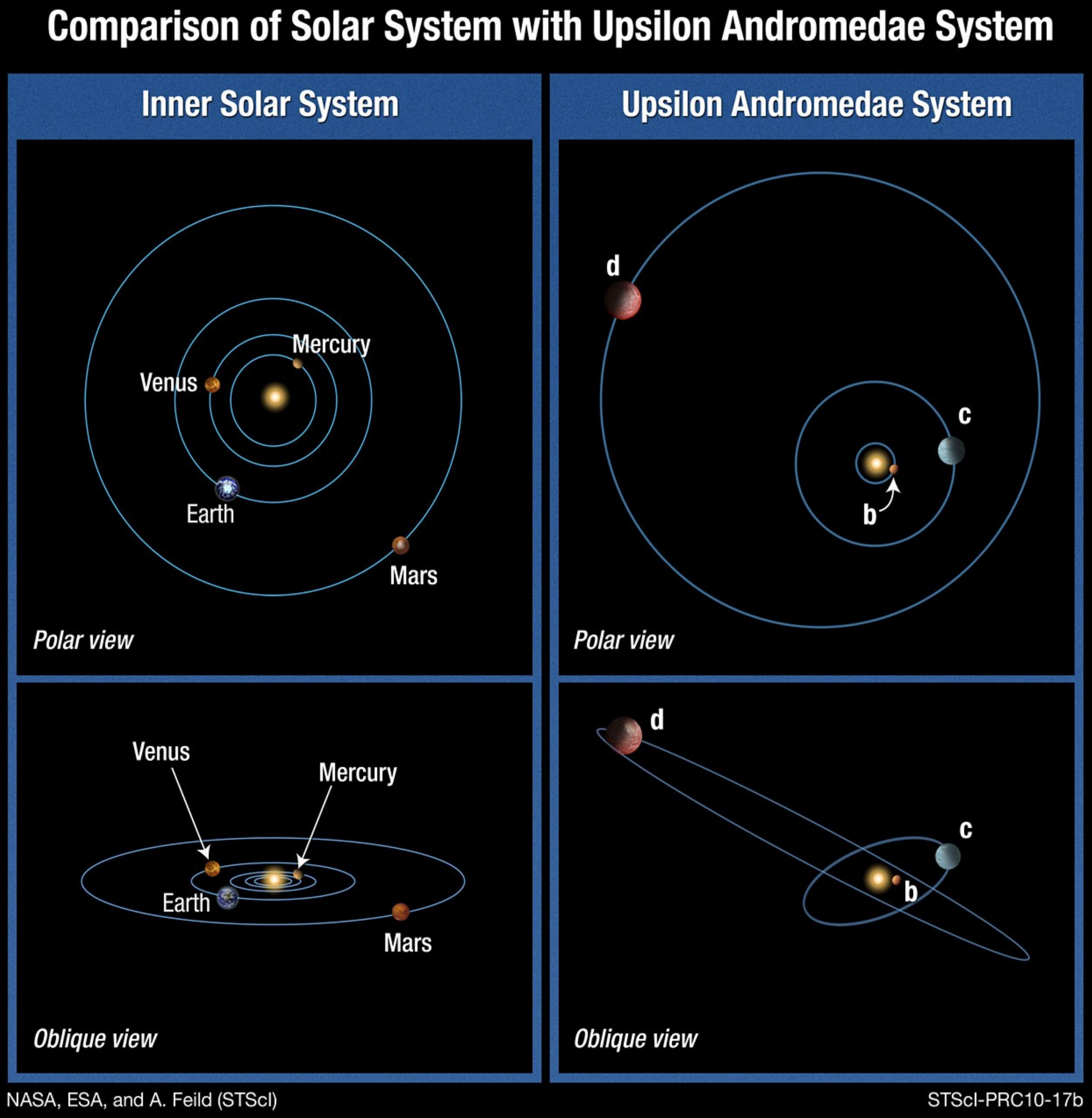
υ **Andromedae System**

Mutual Inclination between c & d orbits **~30º**



# Planetary system architecture

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  In particular, **RV-detected giant planets**:

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- **GOAL:** How to explain the formation of the RV-detected giant planet systems?

# Planet formation

Gas giants form:
- Outside the “snow-line”
- **Circular** and **co-planar** orbits

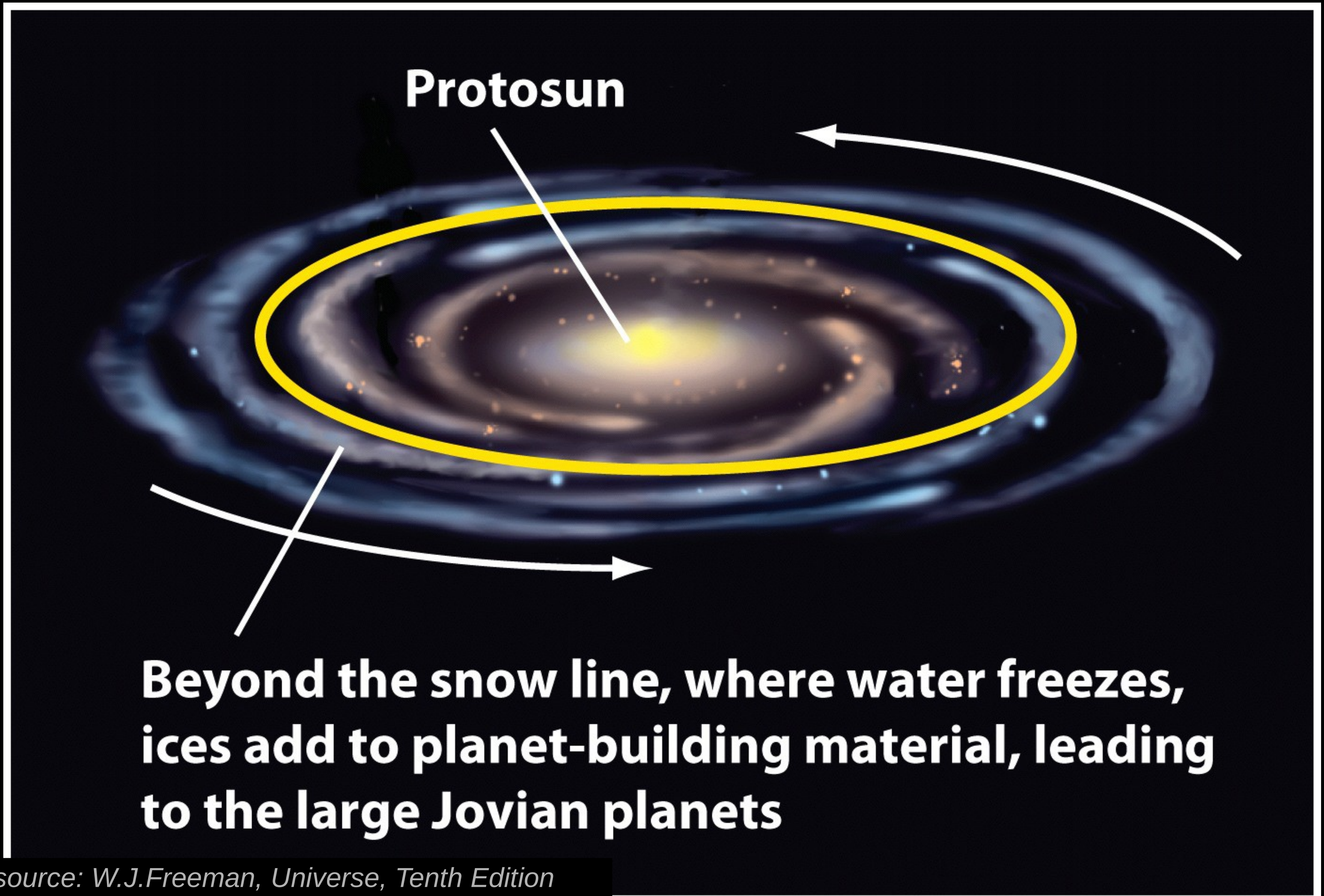



*Image source: W.J.Freeman, Universe, Tenth Edition*

# Late-stage formation of giant planetary systems

- **STAGE I** / 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)*

- **STAGE II** / 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 (*e distribution fits to observations*)

  BUT → 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)*

# Model description

Previous n-body studies

**1st order approximation for eccentricity damping**

$$\frac{\dot{e}}{e} = -K\,\frac{\dot{a}}{a}$$

**No effect of the disc on the Inclinations of the planets**

$$\frac{\dot{I}}{I} = ?$$

# Model description

**Bitsch et al. 2013: 3D Hydrodynamical simulations**

Averaged torques acting on the planet in every orbit

Damping formulae for *e* and *i* *(valid for e<2/3, strong damping)*
Suitable for ***n-body simulations*** → ***in our model***

**ECC**

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

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

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

**INCL**

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

# Model description

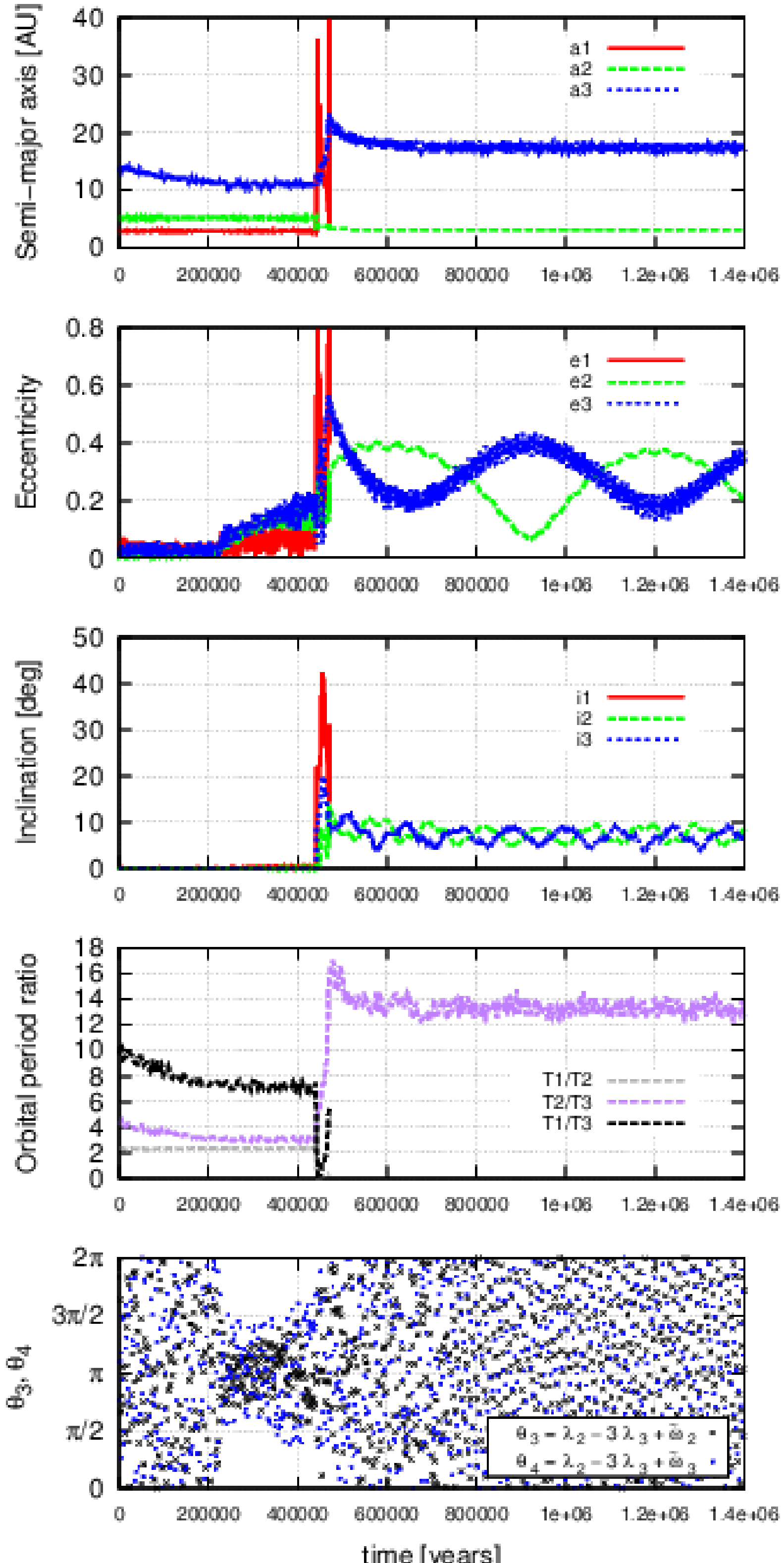
- **11000 simulations of 3 giant planet systems** in the late stage of the disc (SyMBA, 2 x 10^5 computational hours (*CECI clusters*))
- **Type-II migration + improved damping effect** (Bitsch et al. 2013)
- Planets with mass in [1, 10] $M_{Jup}$ initially outside the snowline, on quasi-circular and coplanar orbits
- **Different initial system configurations, planetary mass ratios**, disc masses ( $M_{disc}$ in [4,32] $M_{Jup}$ )
- Exponential decrease of the disc mass, with a dispersal time of ~1 Myr

# Objectives

- Impact of the eccentricity and inclination damping on the final system configurations (a – e – I)

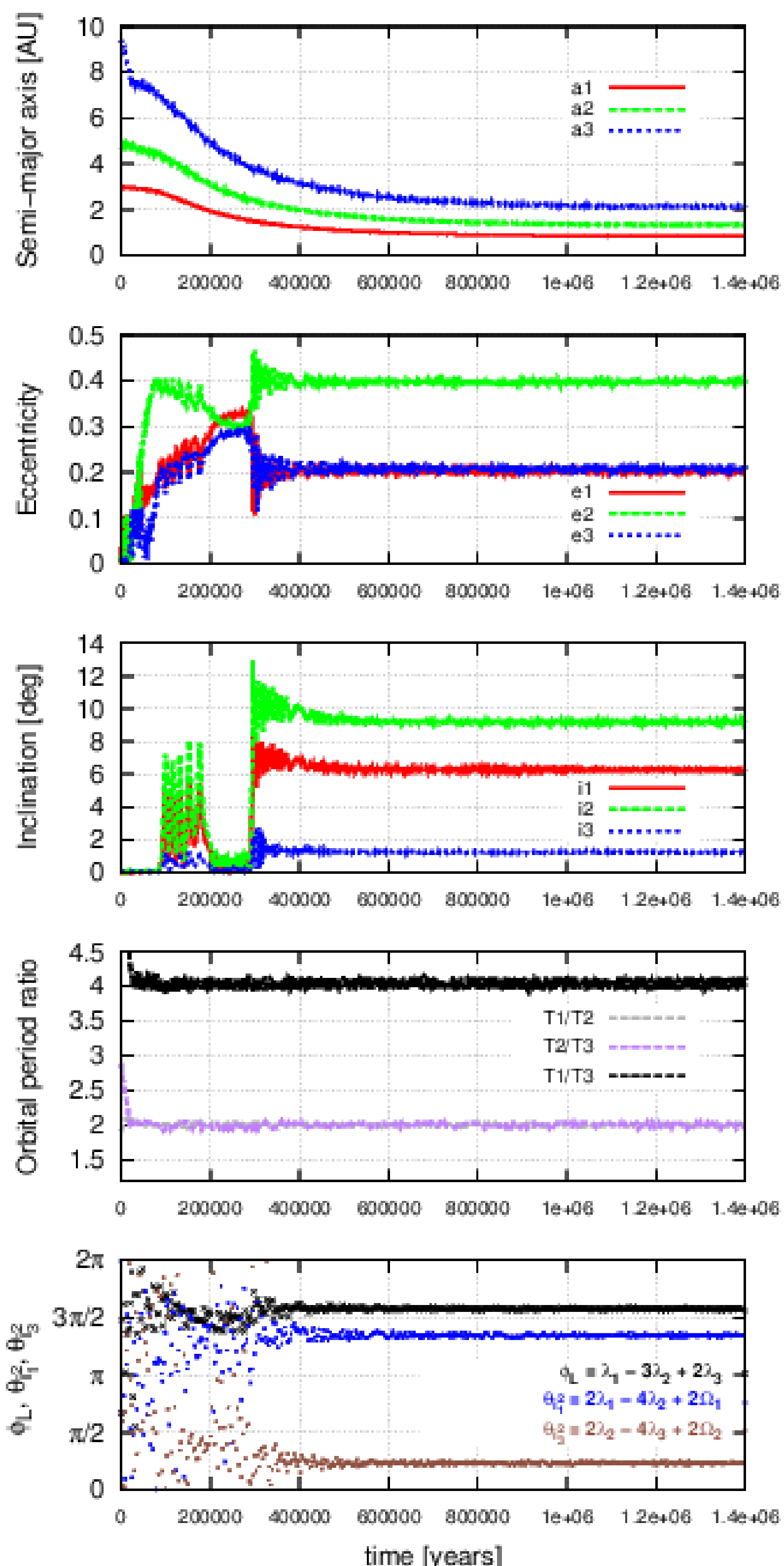
- If non-coplanar systems, identification of dynamical mechanisms producing inclination increase

# Dynamical mechanisms for inclination increase




Planet – planet scattering during the gas phase

- 1:3 MMR capture for the outer planets
- Subsequent increase of 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

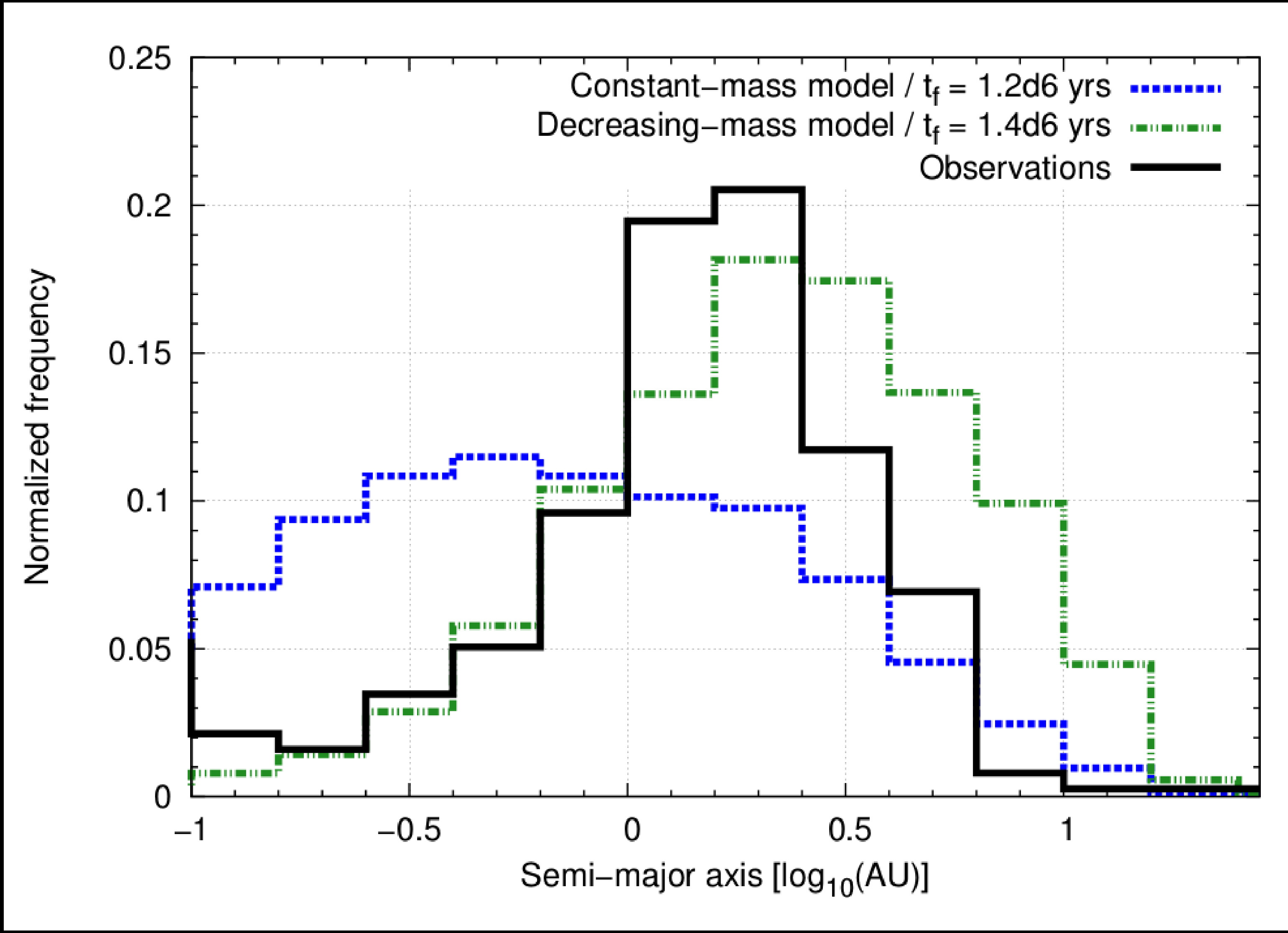



# Dynamical mechanisms for inclination increase

Three-body mean-motion resonance

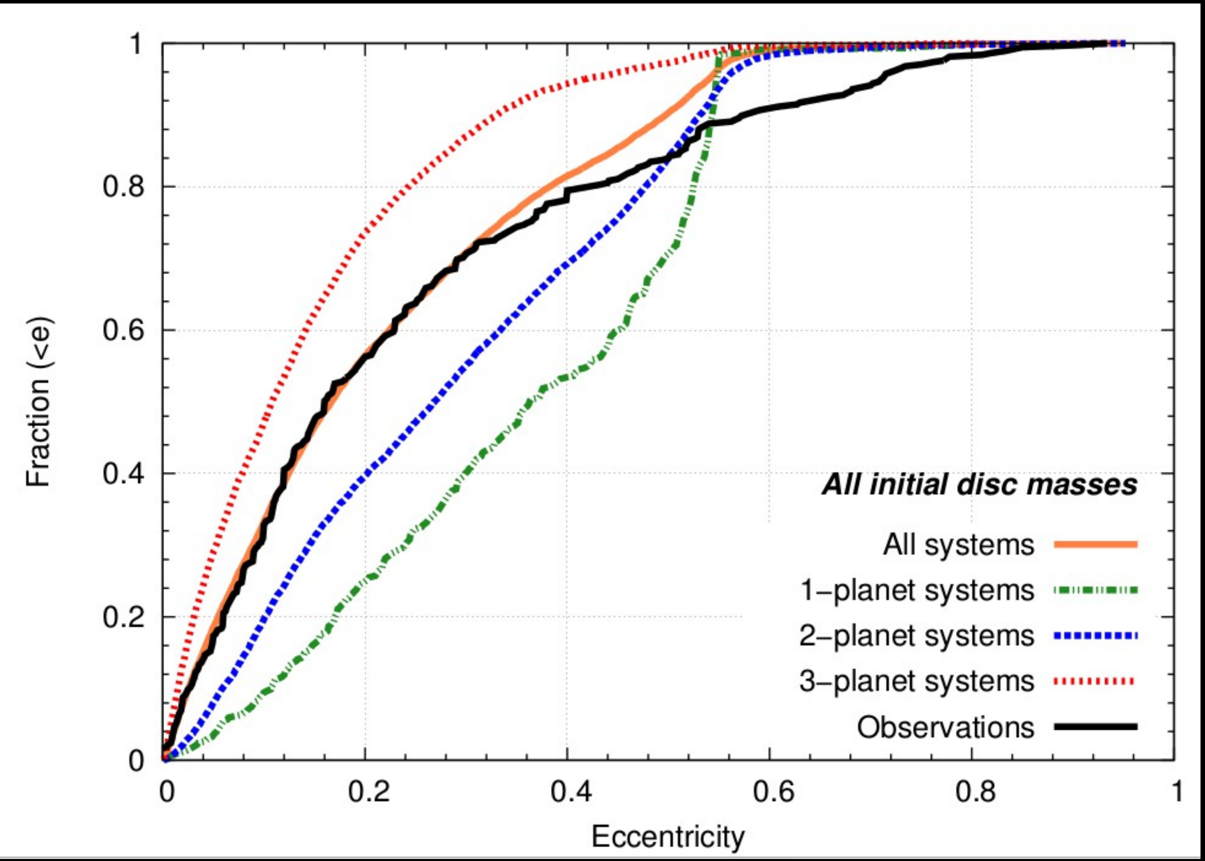
- Capture in a 1:2:4 Laplace resonance
- Subsequent increase of the eccentricities
- When the eccentricities are high enough, inclination-type resonance
- Strong damping: planets back to the midplane
- Exponential decay of the gas disc: inclination-type resonance produces high inclinations maintained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

# Semi-major axis distribution




Observations: exoplanets.org

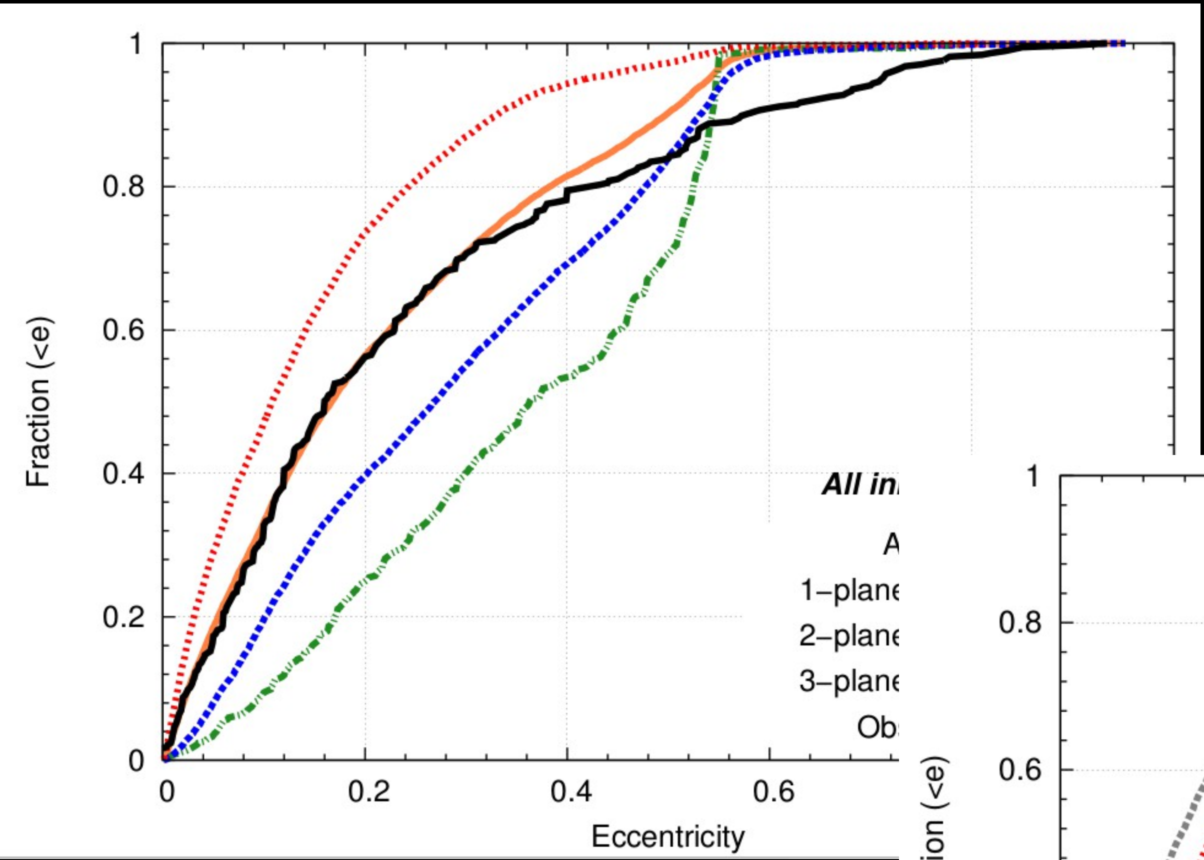
# Eccentricity distribution

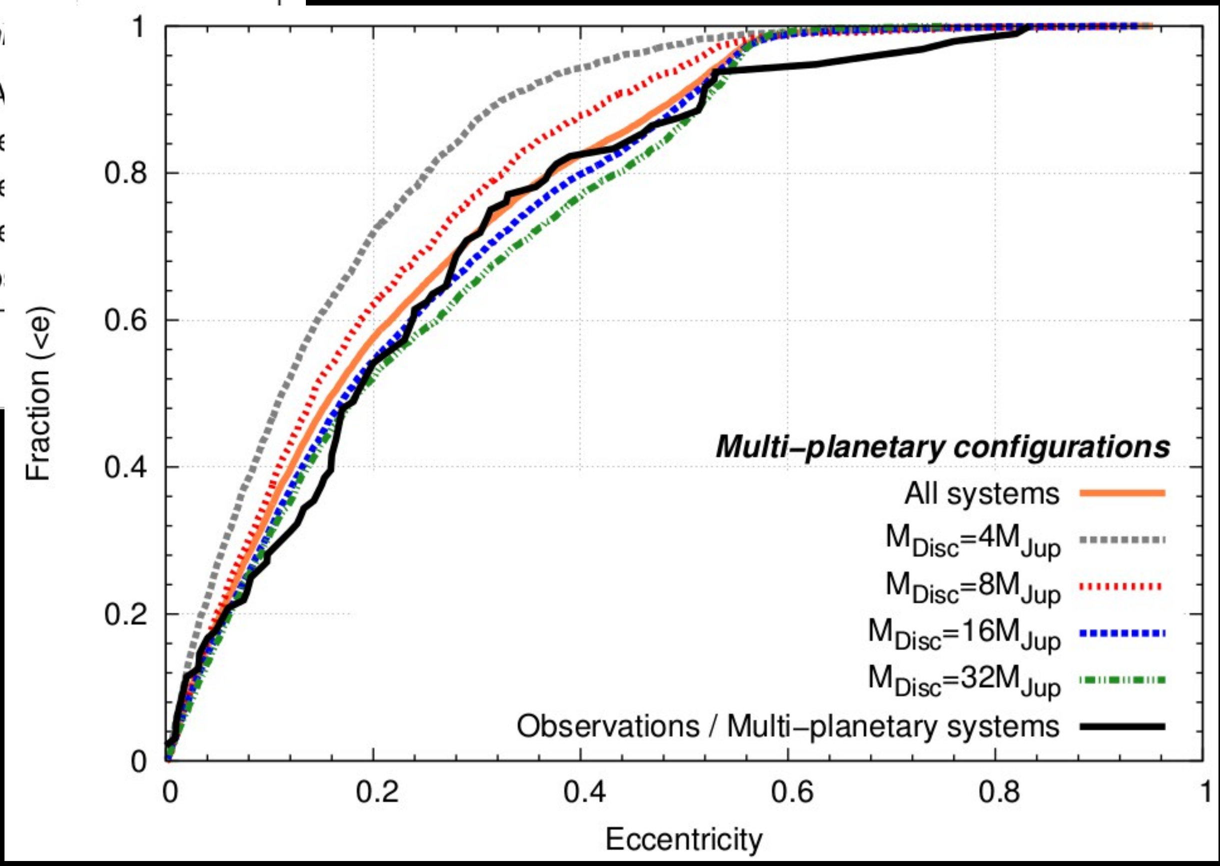



Perfect agreement up to 0.35, lack of highly eccentric orbits

Observations: exoplanets.org

# Eccentricity distribution

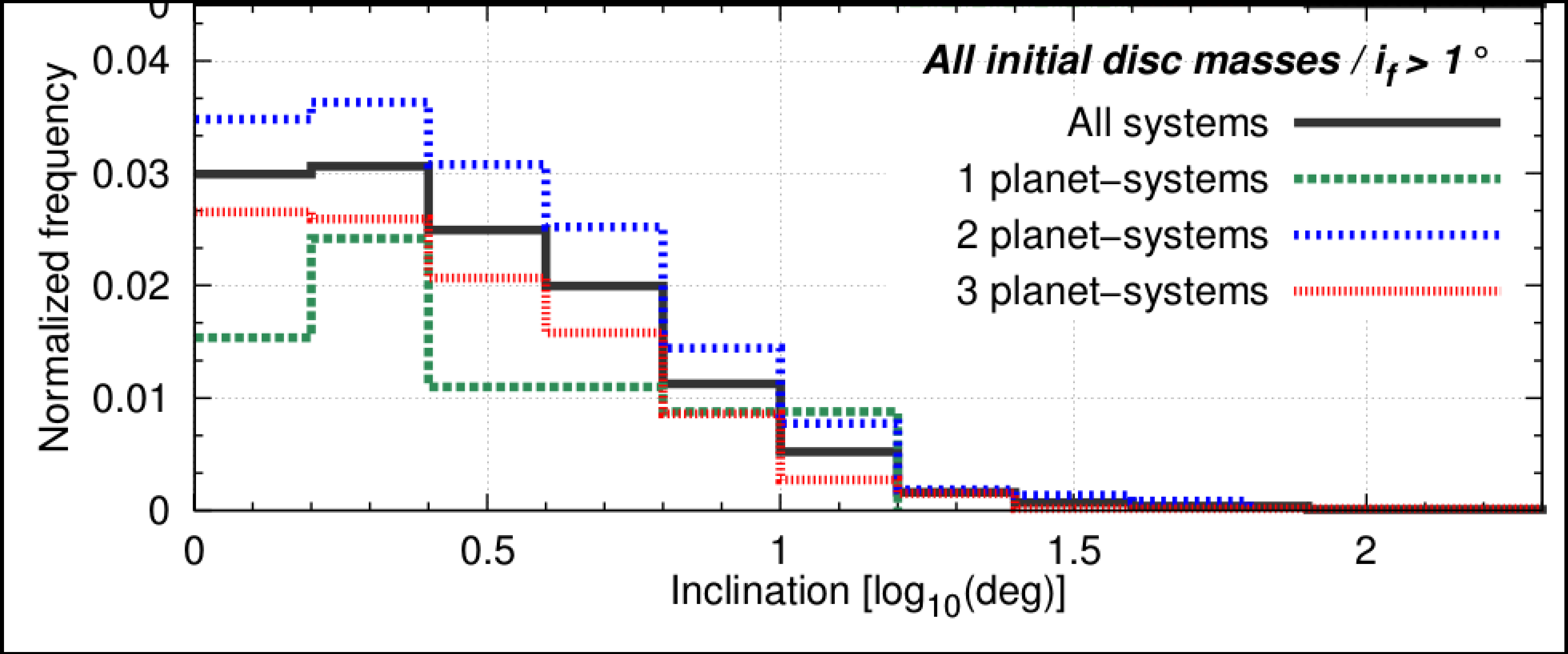



When removing single planet systems, good agreement up to 0.55

Observations: exoplanets.org

# Inclination distribution




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

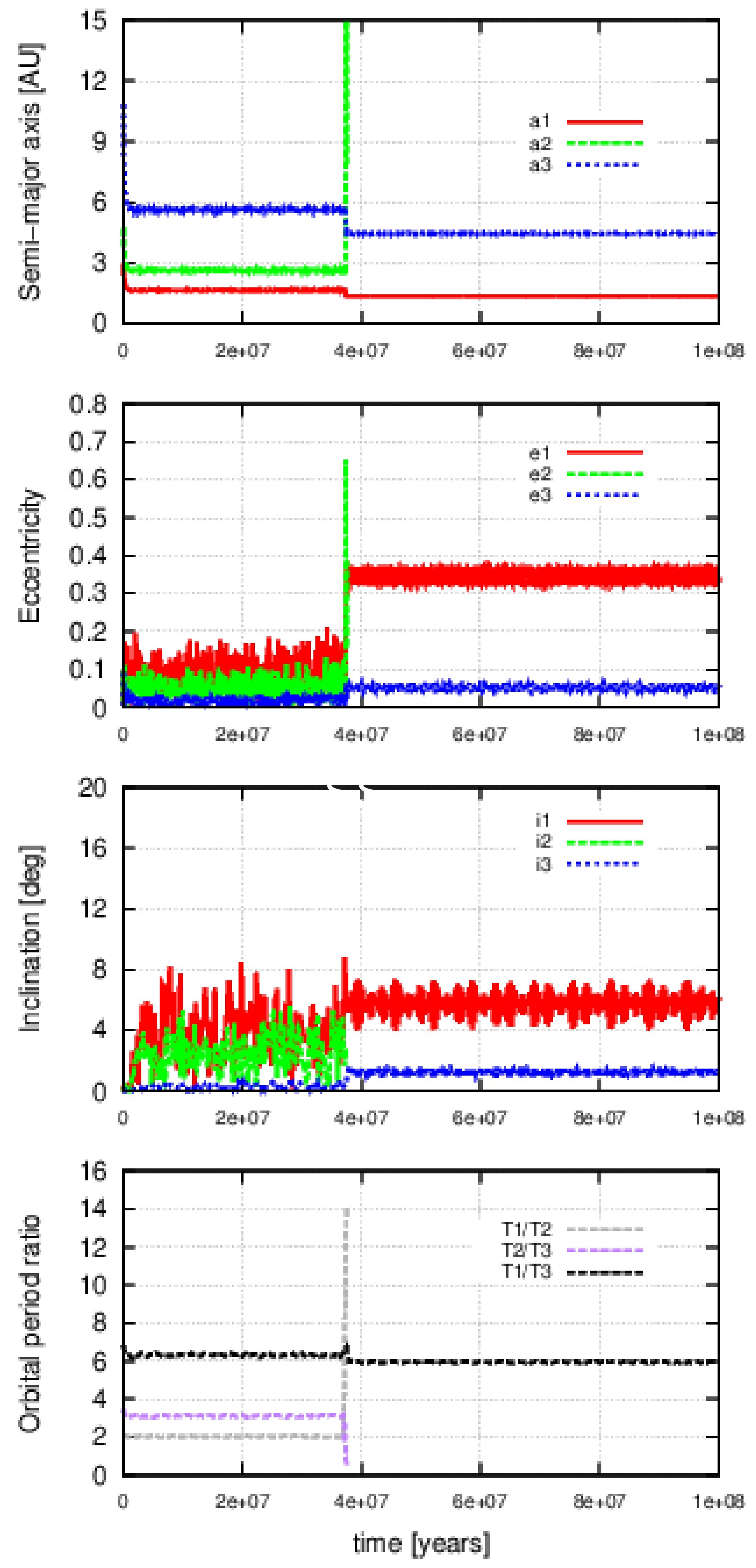
# Long-term evolution

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

- Additional subset
  Integration up to 100 Myrs

- Number of planets at 1.4d6 and 1d8

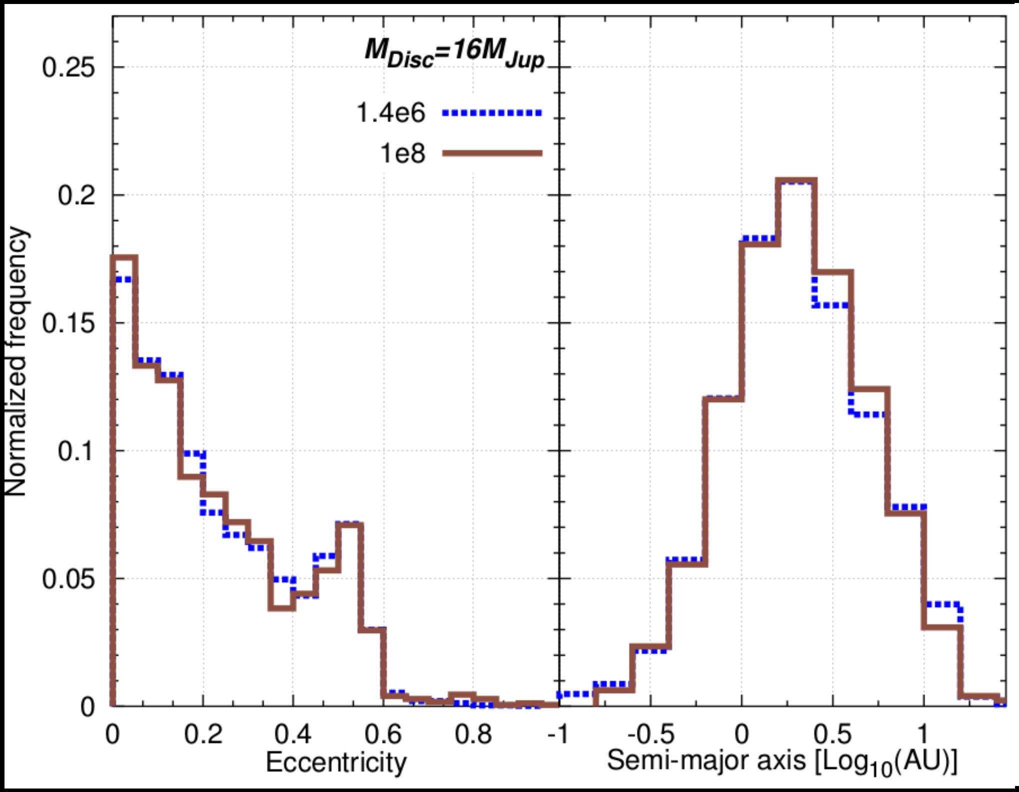
| | 1 planet | 2 planets | 3 planets |
|---|---|---|---|
| 1.4d6 yrs | 7 % | 50 % | 40 % |
| 1d8 yrs | 12 % | 53 % | 32 % |

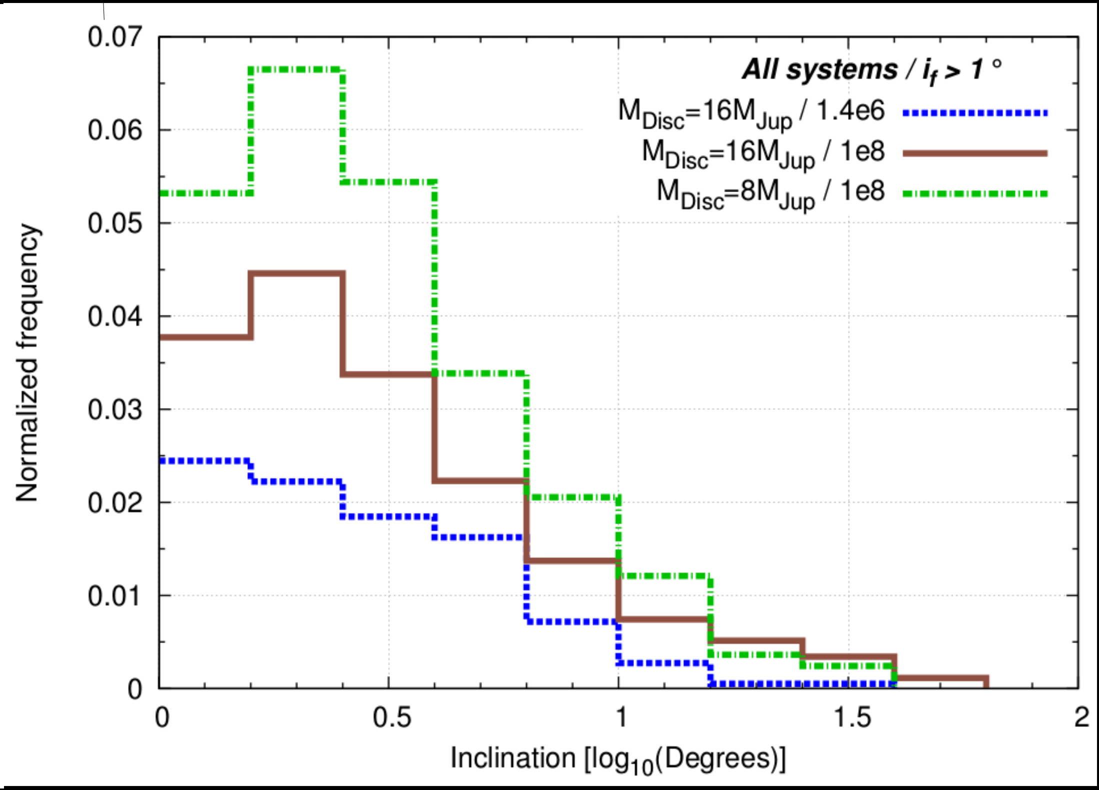


# Long-term evolution

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

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



# Summary

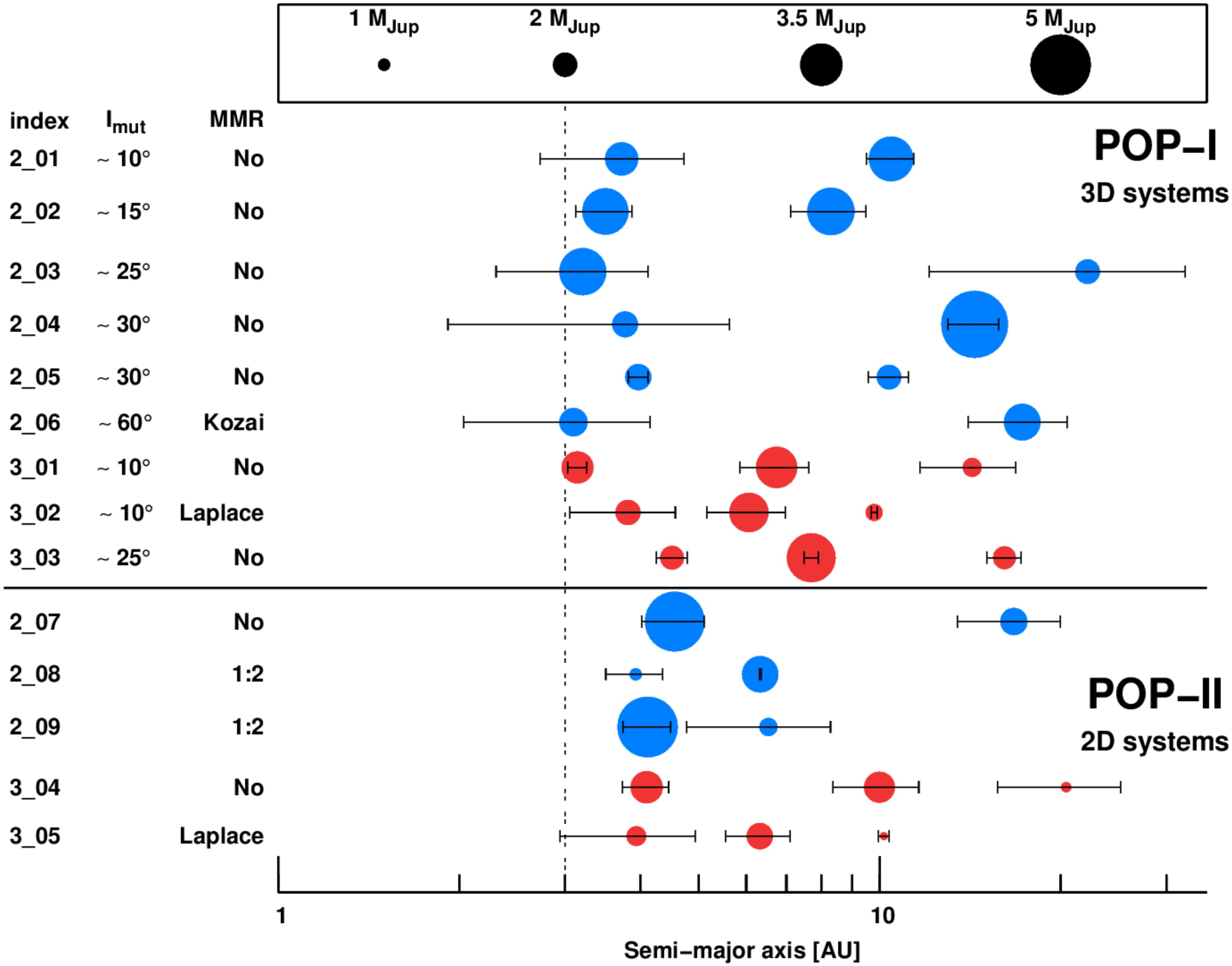
- **Good agreement** between our simulations and the observed population of extrasolar systems
- ***Eccentricities well-diversified*** at the dispersal of the disc, despite the strong damping exerted by the disc
- Very efficient damping exerted by the disc on the inclinations: ***most of the planets 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 observations: percentage of inclined systems could help to discriminate between the formation scenarios

# Next step:
# Terrestrial planet formation

What is the impact of the **eccentric and inclined** giant planet population on the **terrestrial planet formation** process?

# Terrestrial planet formation

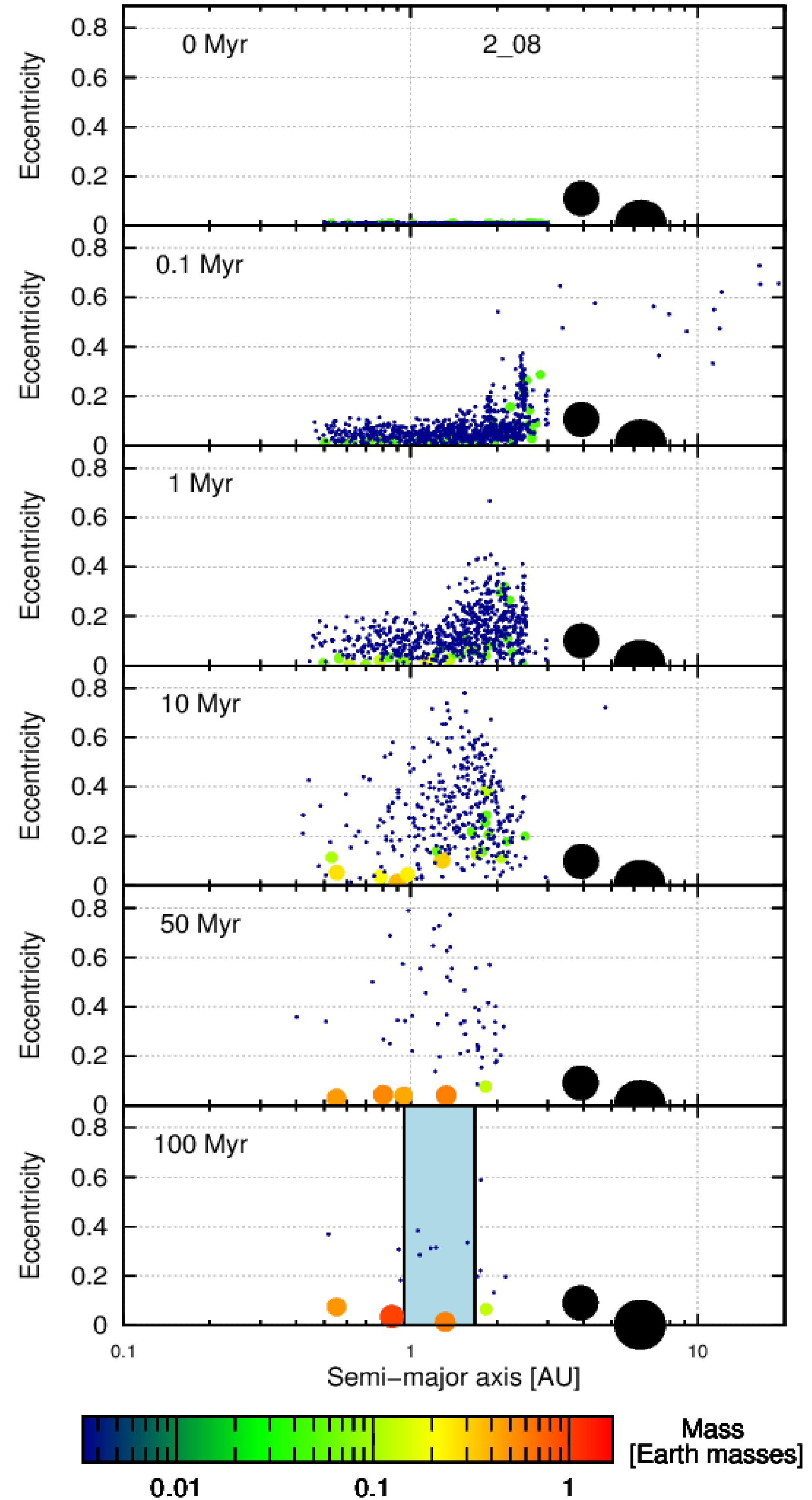
Initial conditions for our simulations



# Terrestrial planet formation

## Preliminary results

- Semi-major axis vs **eccentricity** for a co-planar system (POP-II) initially in a 2:1 MMR
- We have 4 Earth-like planets in near-circular orbits
- One of them inside the habitable zone



# Terrestrial planet formation

## Preliminary results

- Semi-major axis vs **inclination** for a 3D system (POP-I)
- Giants with initial $I_{mut} = 30^o$
- At 100 Myrs, one planet with 0.2 Earth's mass inside the habitable zone with <I>~25$^o$

**Formation of inclined terrestrial planets is possible with the classical accretion theory**

**TO BE CONTINUED**