La formation des planètes et des exoplanètes

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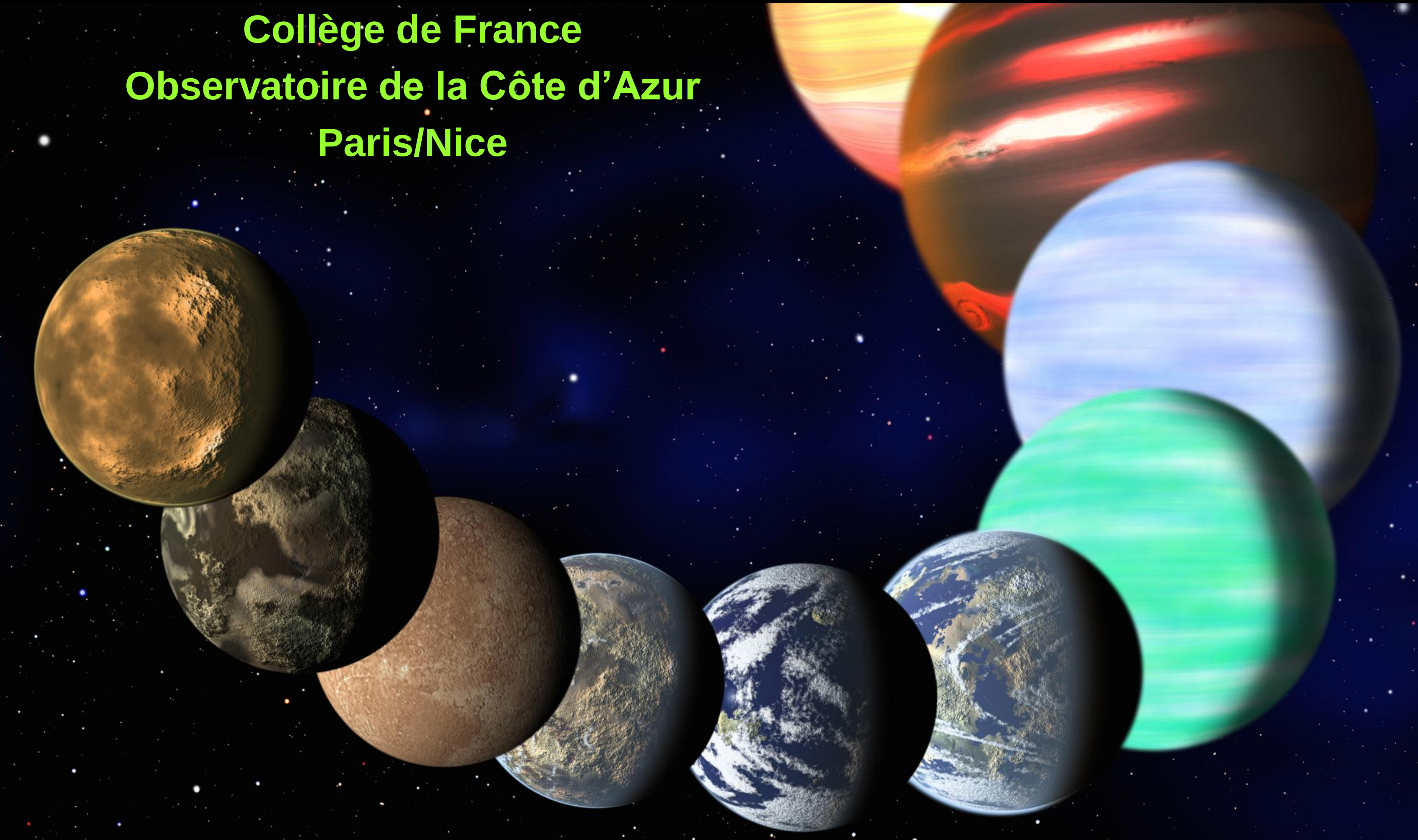
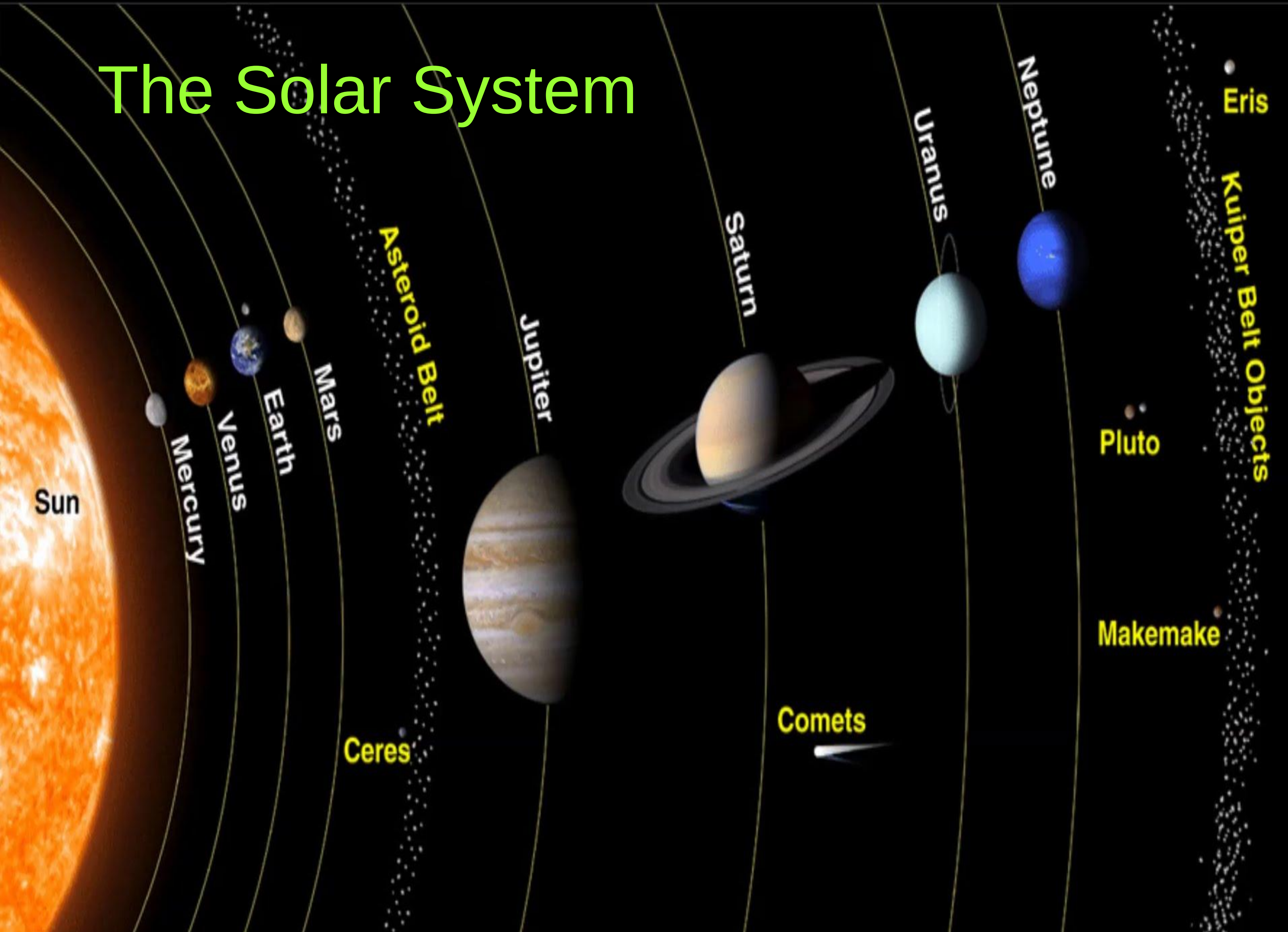
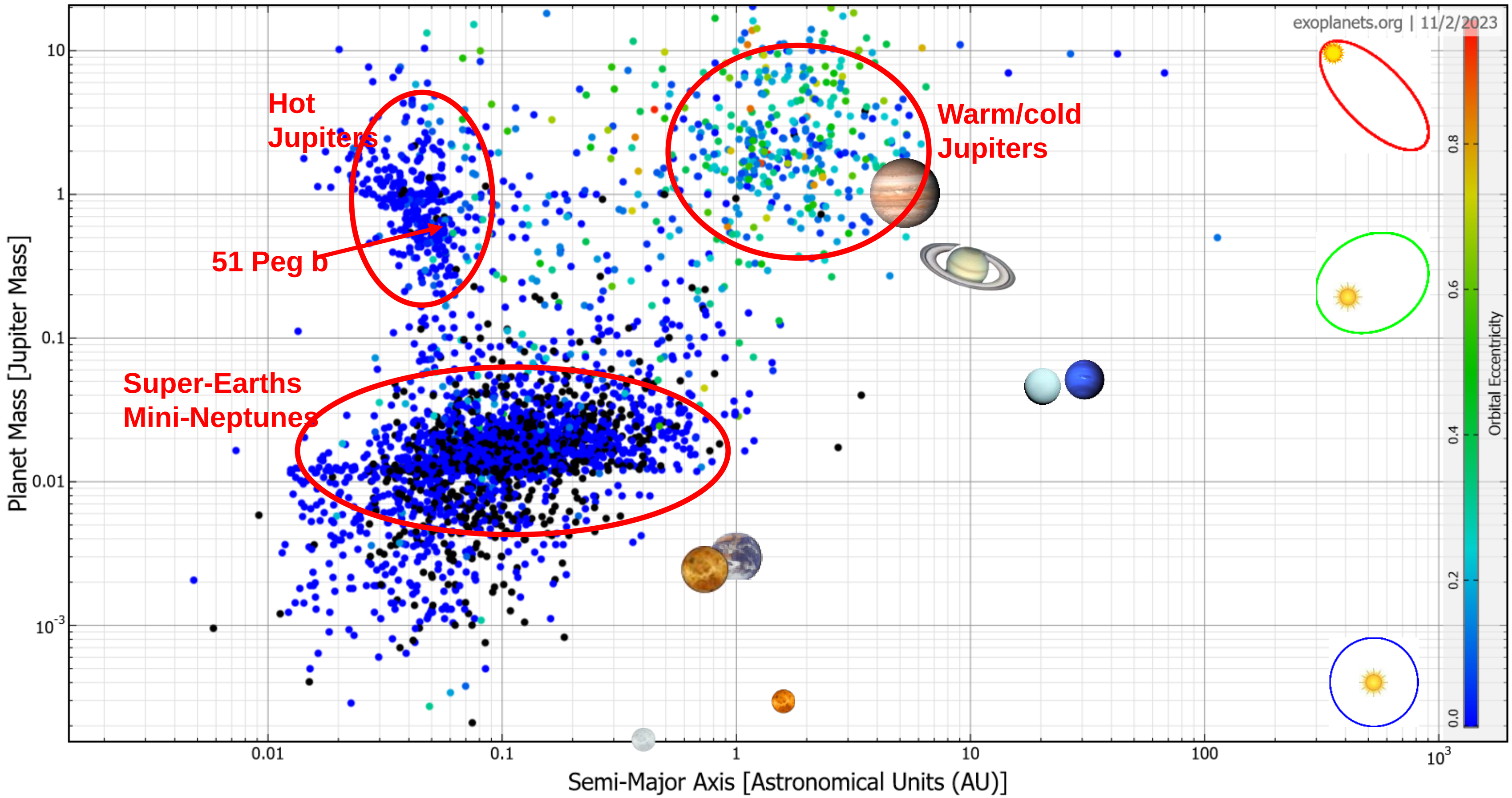


The Solar System



The census of extrasolar planets



Observations tell us that ~50-% of the stars have planets different from those of the Solar System (super-Earths, eccentric Jupiters, hot Jupiters…)

Of all the planets of the Solar System only Jupiter could be observed with our capabilities around other stars

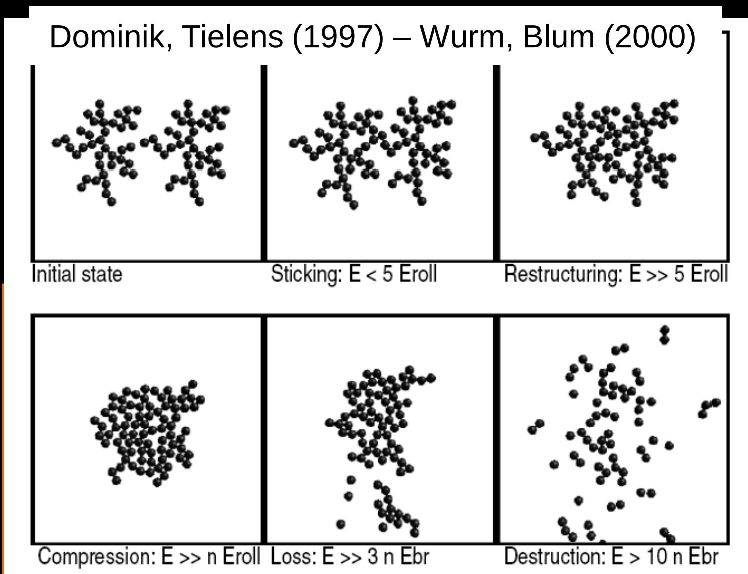
Only ~1% of Solar-type stars seem to have a Jupiter on an orbit « similar » to that of our own Jupiter

Our Solar System is not typical !

Nevertheless, it is interesting to study: the pletora of data we have can help deciphering the processes at work

Why such great diversity of planetary systems?

THREE STEPS TO PLANET ACCRETION:
1) dust growth, sedimentation and drift



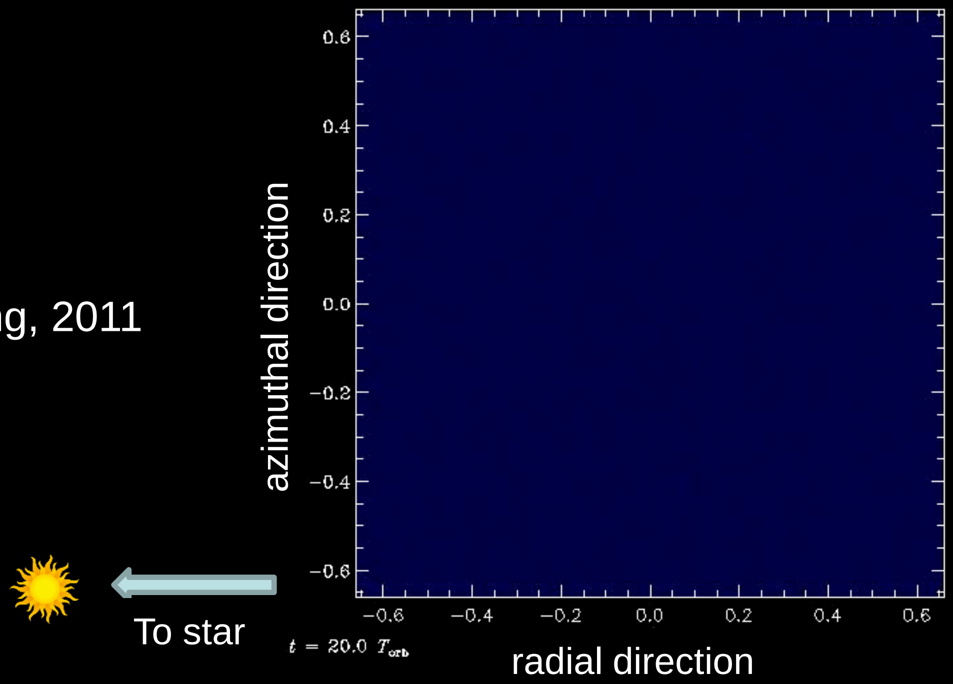
A mm-size bouncing barrier for silicates
For icy particles, better sticking properties -> cm-dm.

Conclusions supported by the analysis of undifferentiated meteorites, showing that planetesimals are aggregates of ~mm-size particles (chondrules, CAIs,….)

THREE STEPS TO PLANET ACCRETION:
2) planetesimal formation

Particle clumping in the disk due to bi-fluid hydrodynamical instabilities, such as the streaming instability

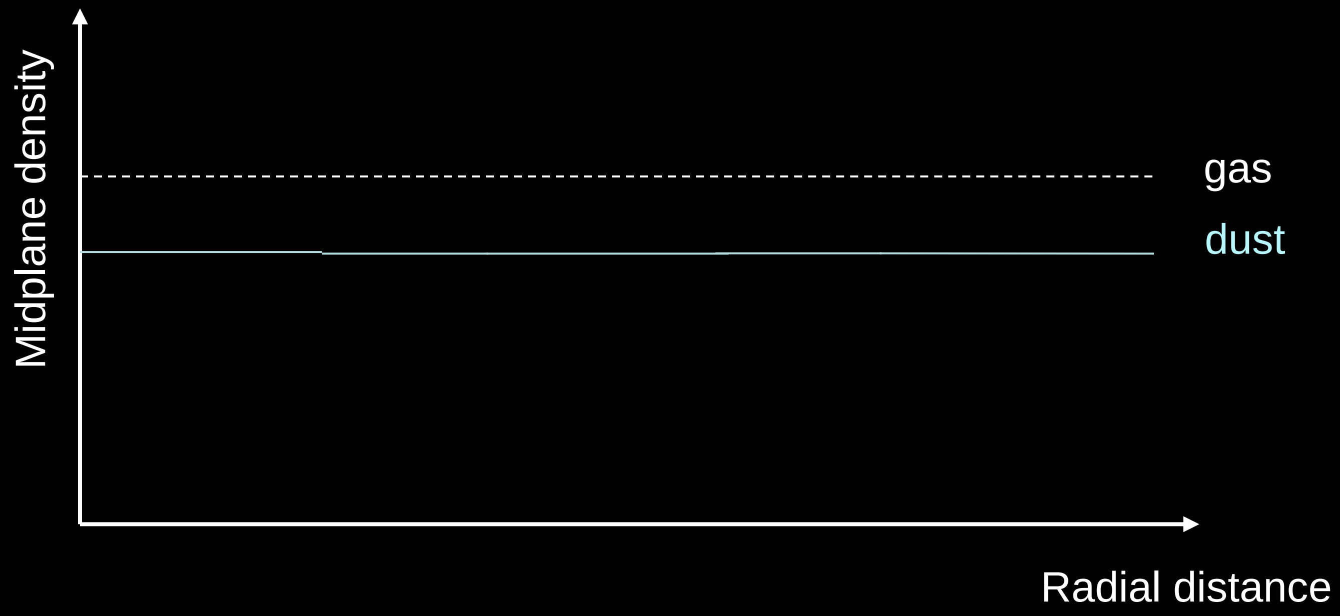
Johansen, Klahr, Henning, 2011



Clumps of particles that are dense-enough can become self-gravitating, and then contract to form a compact planetesimal.
Typical size: 100km (Klahr and Schreiber, 2020)

These instabilities can occur only where the *dust/gas* density ratio on the midplane exceeds unity

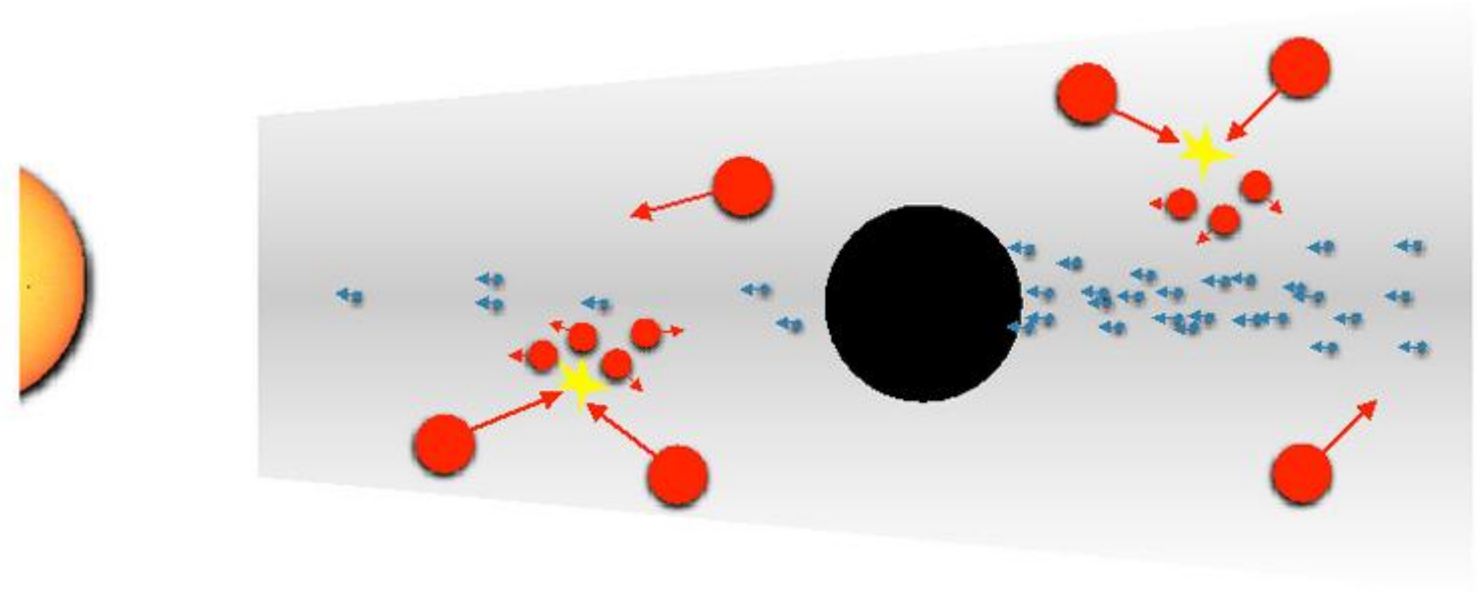
For a disk with solar metallicity and given the limited settling set by the Kelvin-Helmoltz instability (Weidenschilling, 1977), typically *dust density* < *gas density*



- Radial pile-ups possible due to prominent condensation lines (snowline, silicate line,… Stevenson and Lunine, 1988)
- Early planetesimals can only form in rings! (Drazkowska et al., 2016; Morbidelli et al., 2022)
- Only at late times, when gas is photo-evaporated, <u>if some dust is preserved</u>, planetesimals can form everywhere (Carrera et al., 2017)

THREE STEPS TO PLANET ACCRETION: 3) planet formation

- **Mutual Planetesimal collisions protoplanets (Kokubo and Ida, 1996, 1998)**
- **Pebble accretion (Johansen and Lacerda, 2010; Ormel and Klahr, 2010; Murray-Clay et al., 2011; Lambrechts and Johansen, 2012; Ida et al., 2016)**



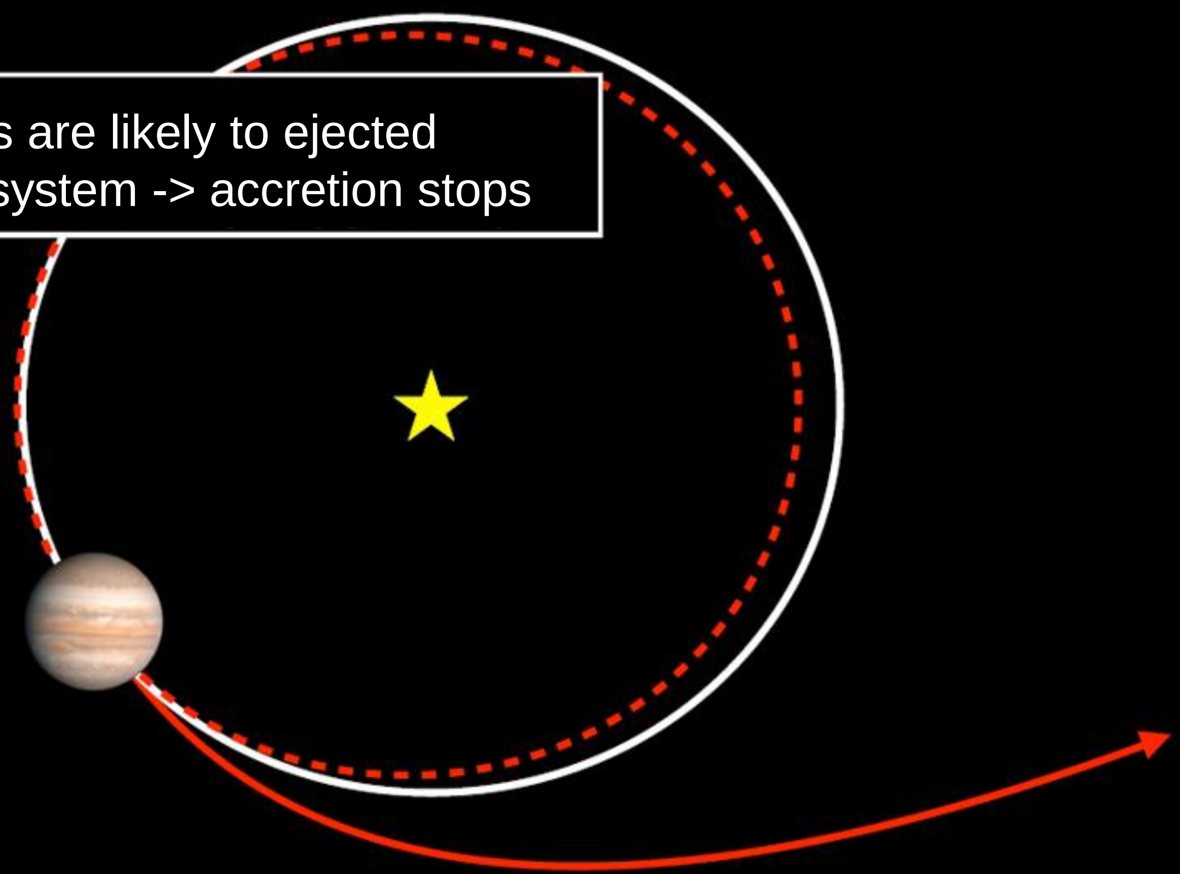
The efficiency of each process depends on the availability of material (planetesimals, pebbles)

LIMITS:

Mutual planetesimal accretion is limited by the Safronov number θ

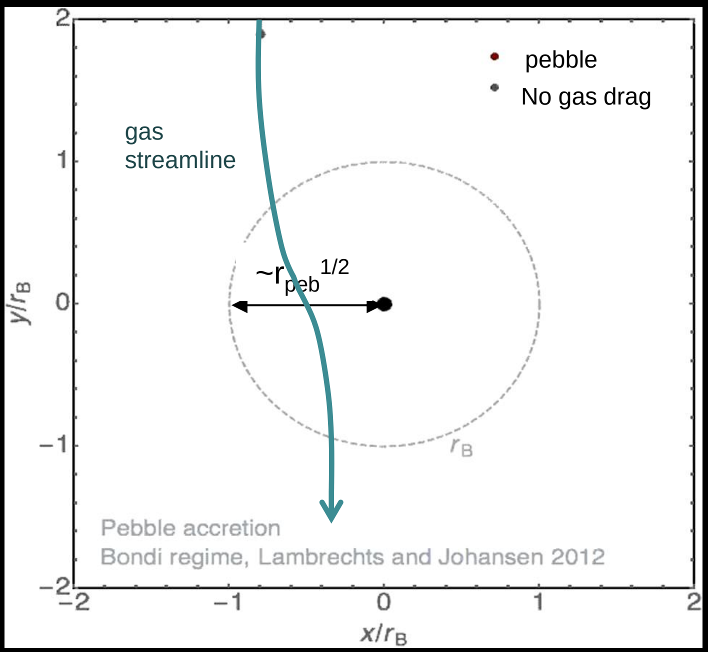
$$\theta \equiv \left(\frac{Gm}{R_p}\right)^{1/2}\left(\frac{r}{GM_\star}\right)^{1/2} \equiv V_{esc}(\text{planet})/V_{esc}(\text{system})$$

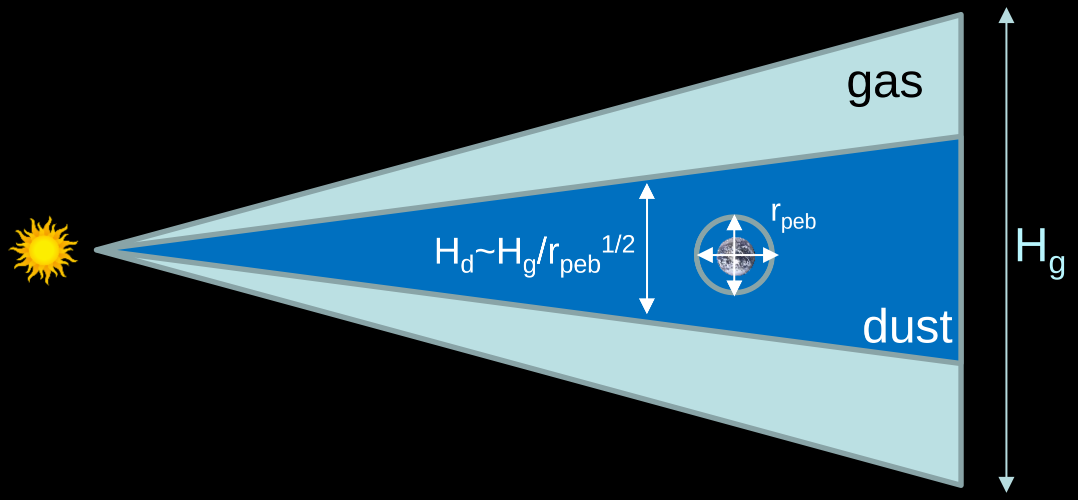
If θ >1, close encounters are likely to ejected planetesimals from the system -> accretion stops



LIMITS:

Pebble accretion for small planets is proportional to $r_{peb}^{3/2}$

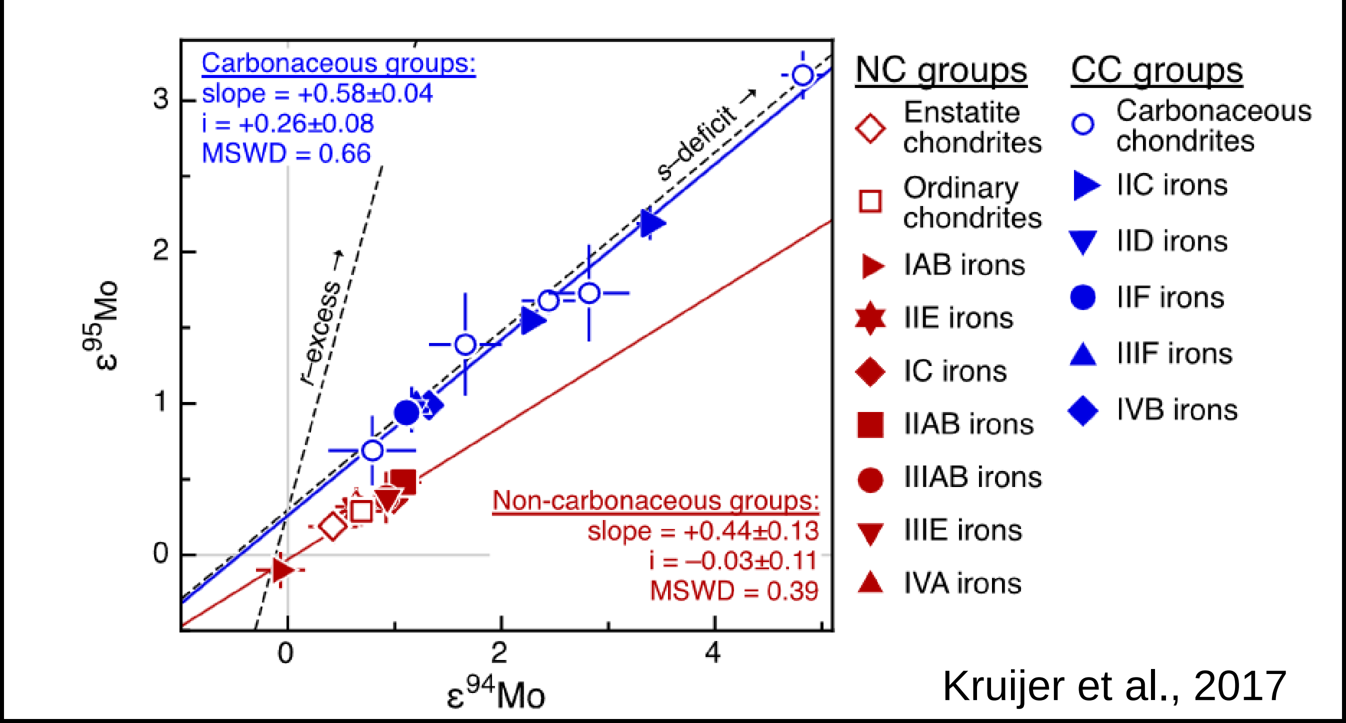




As icy pebbles should be bigger than silicate ones (ice is more sticky) pebble accretion should be more effective in the outer disk, where planetesimal accretion is instead less efficient due to a larger Safronov number

Dust-drift barrier in the Solar system

- The protosolar disk was rapidly divided in two parts, with no passage of dust from the outer to the inner part



Kruijer et al., 2017

This implies that growth in the inner Solar system was material-limited because the region was not replenished by dust drifting from the outer disk.

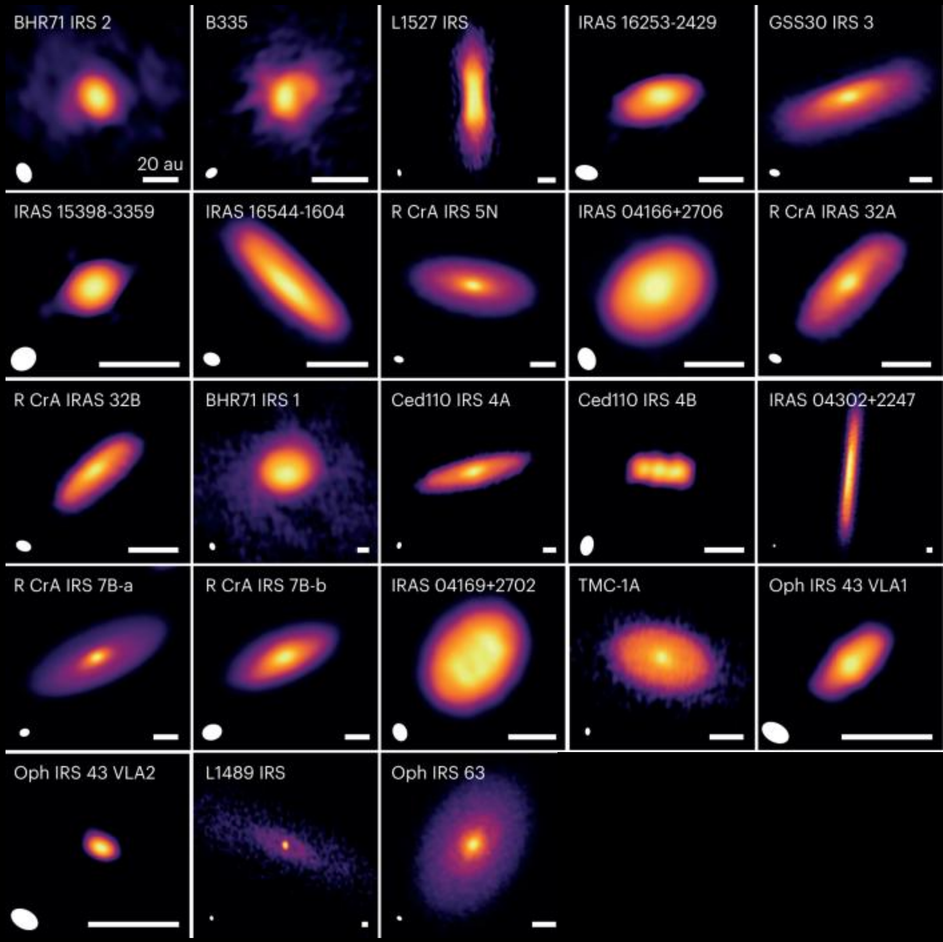
This explains why only Mars-mass bodies formed within the lifetime of the disk

Other systems?

- This division between inner and outer disk is sometimes observed in other disks as well: transitional disks

- In some cases (1 for sure) the barrier is caused by the presence of giant planet(s)

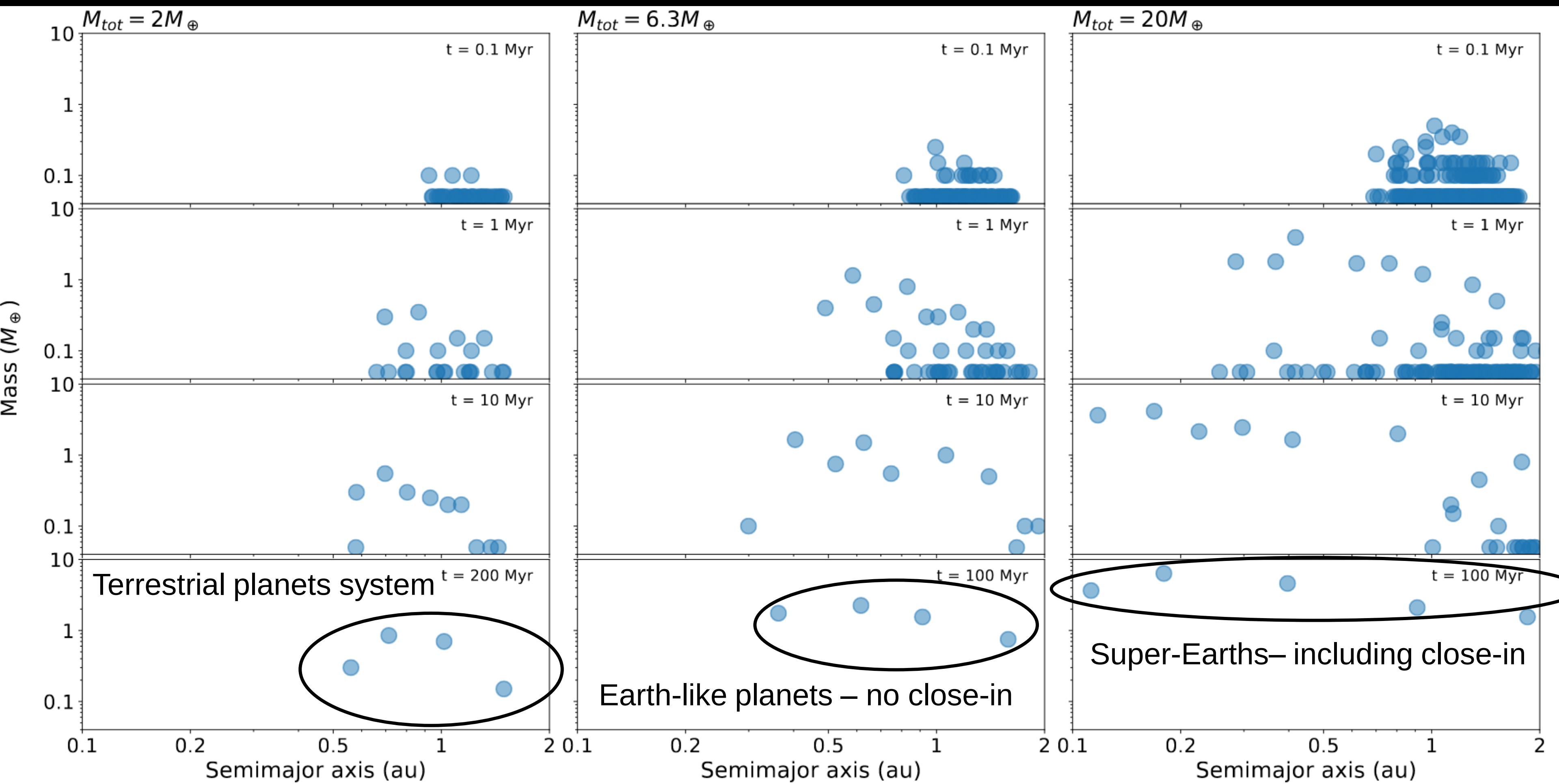
- Not all disks are transition disks



Other systems?

In principle we can imagine that this barrier is not existent in other disks, so that the inner disk has more material available, forming faster bigger planets

Ogihara et al., 2024

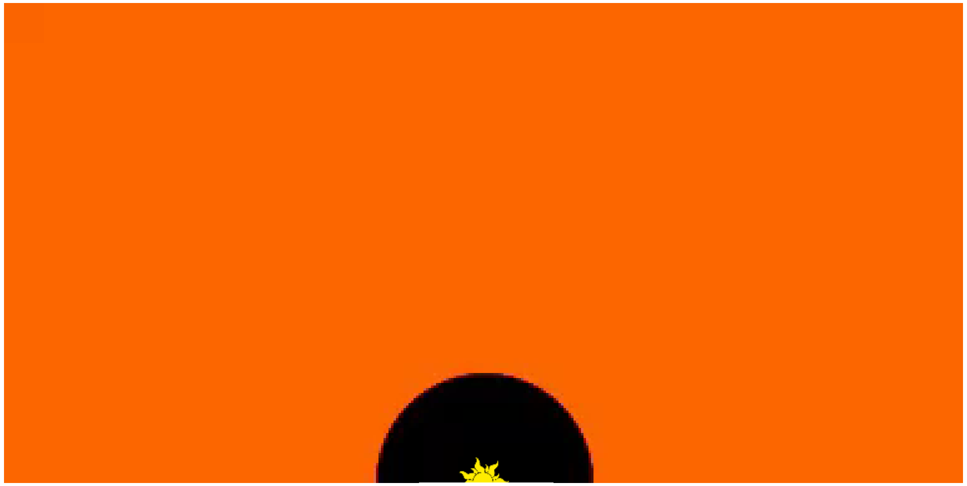


Planet migration

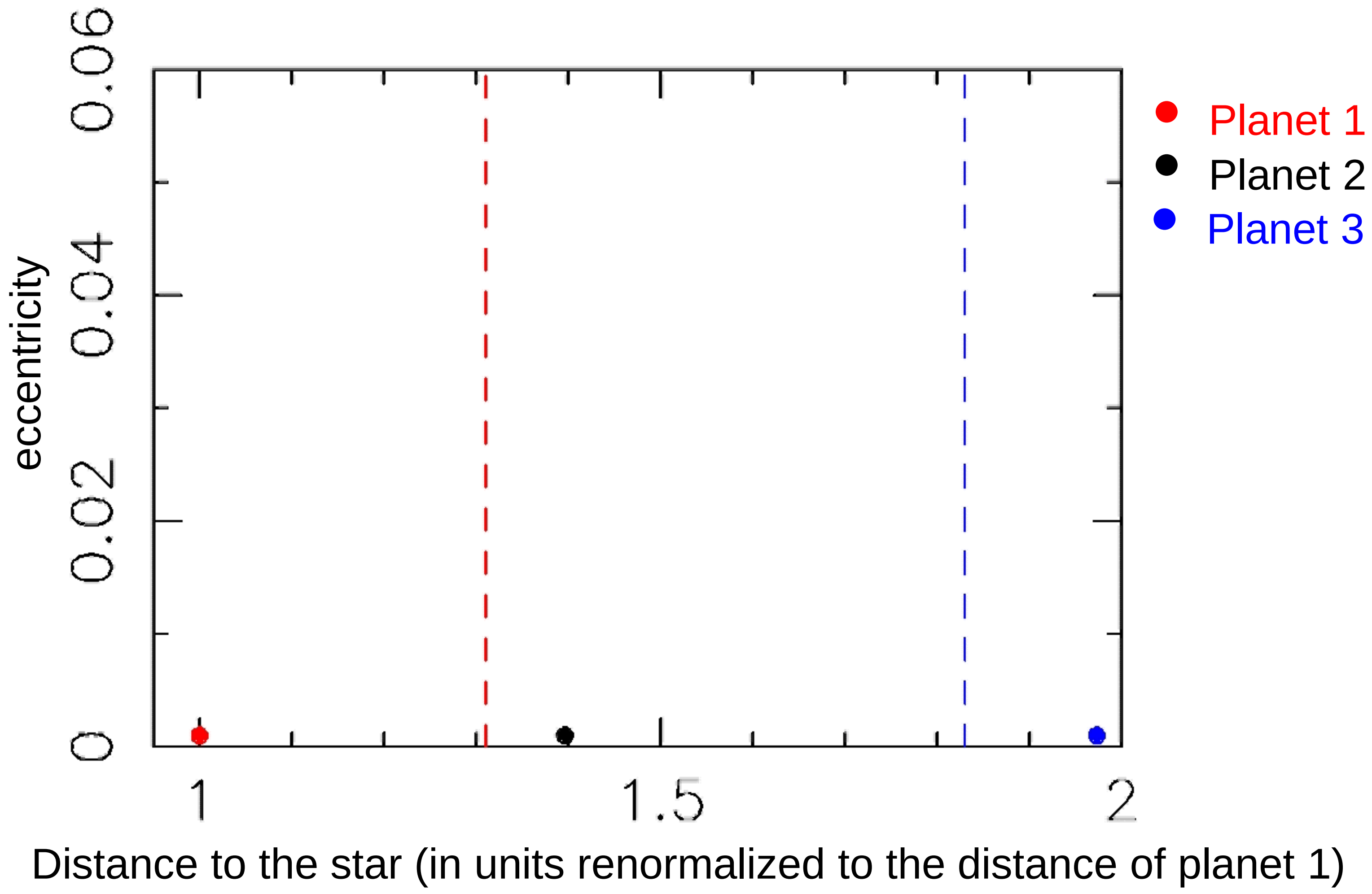
Planets perturb the disk breaking its axial symmetry.

In turn, the axial asymmetry of disks exerts a gravitational torque on the planet, forcing it to migrate

In principle, migration stops only at the inner edge of the disk

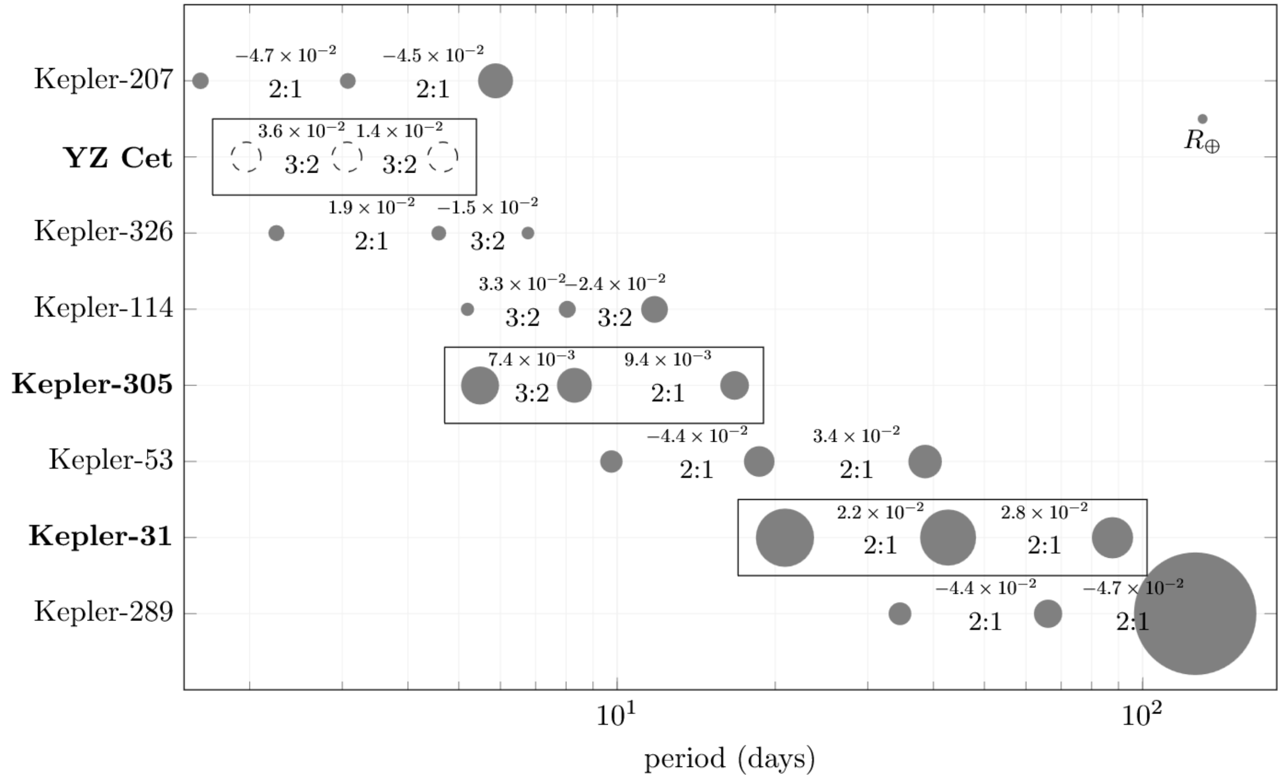


Formation of resonant chains via migration (here 3 planets)

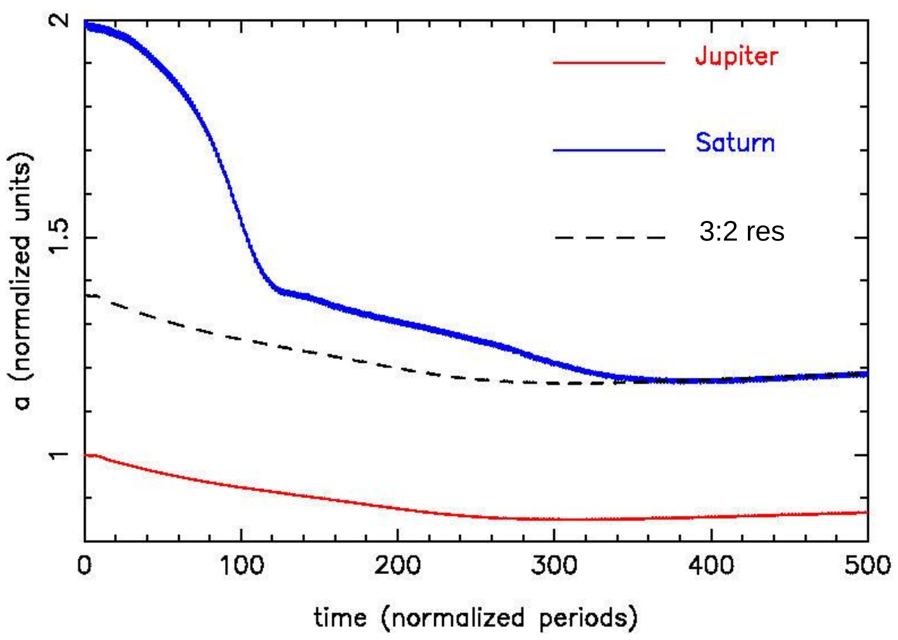


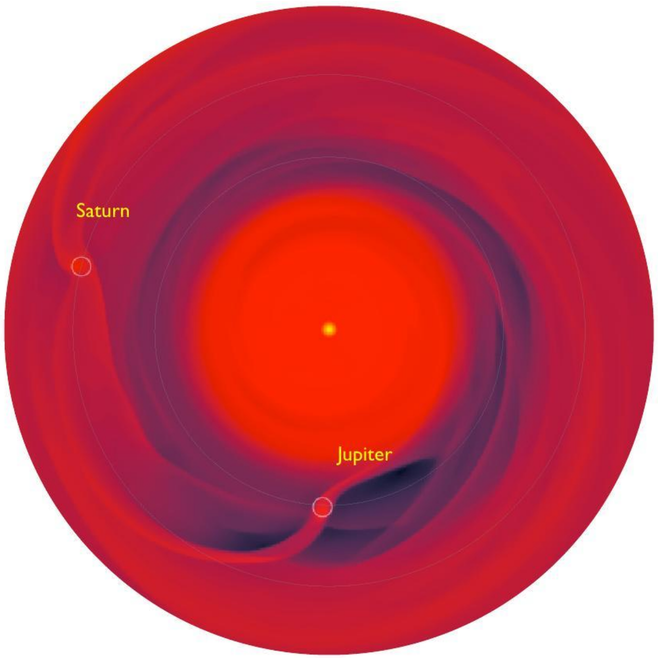
Resonant chains are observed !

They are an uncontroversial proof that planet migration does occur



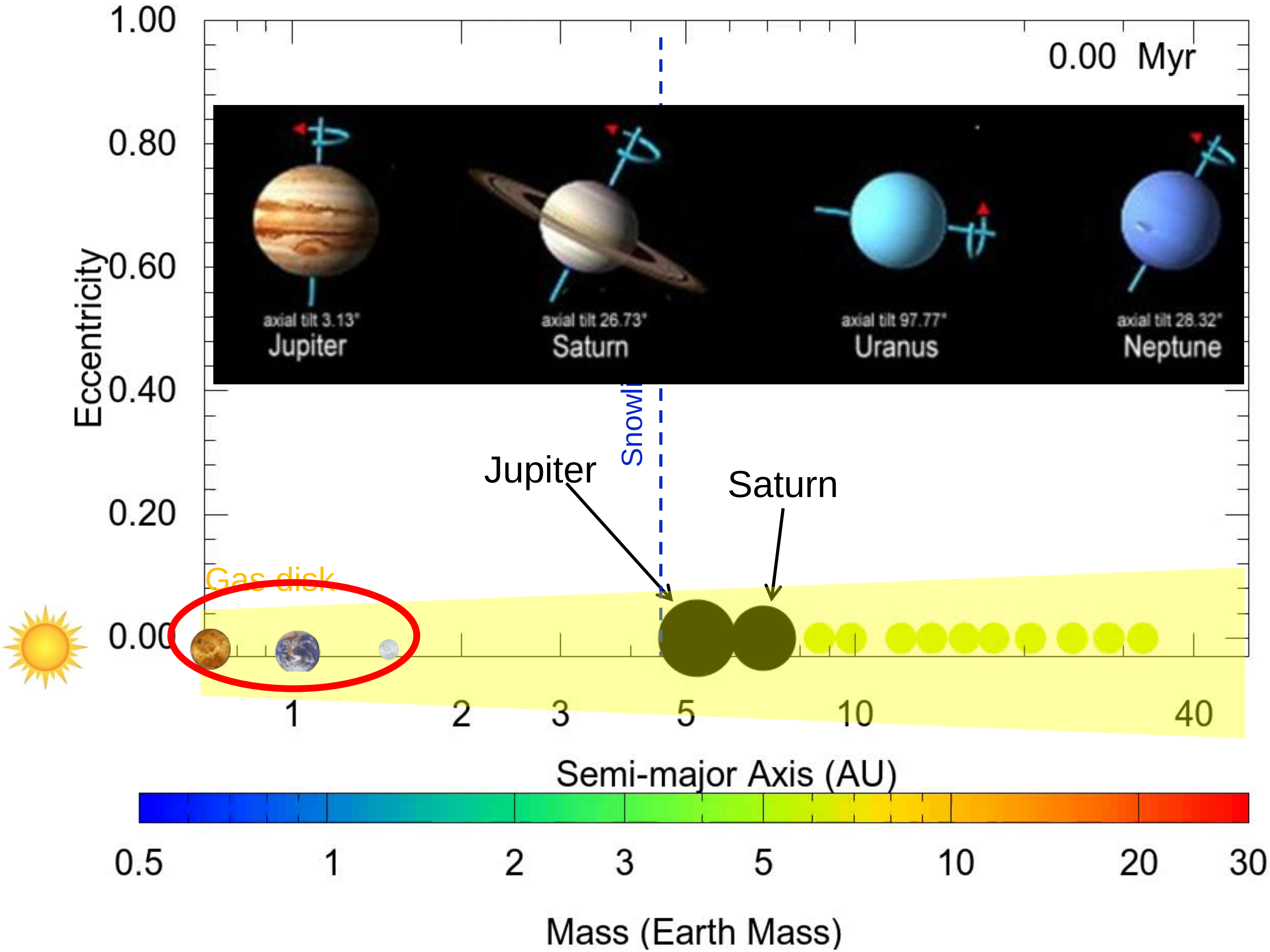
The peculiar case of Jupiter-Saturn dynamics





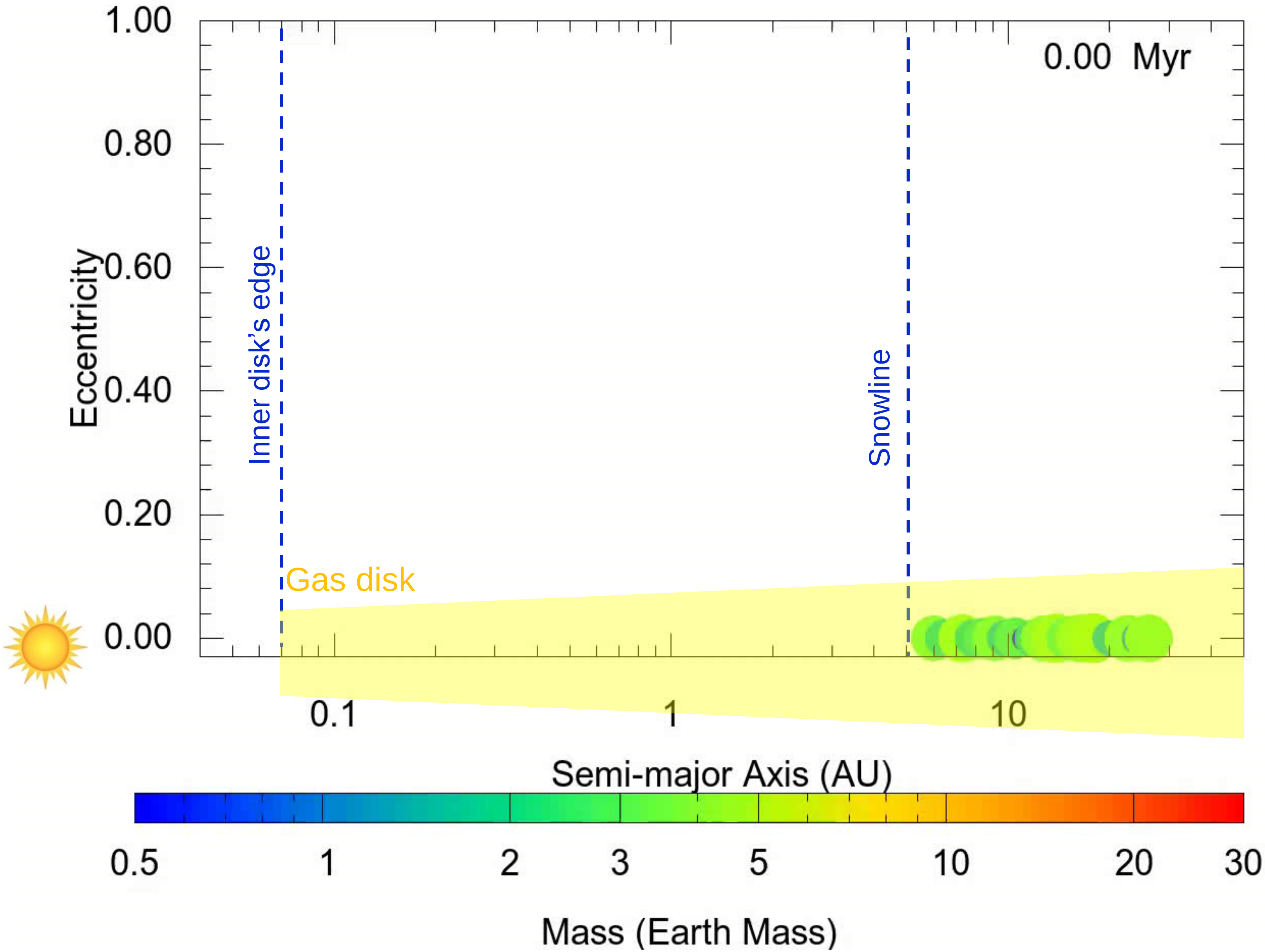
Masset and Snellgrove, 2001; Morbidelli and Crida, 2007; Pierens and Nelson 2008

Examples of migration outcomes: iii) the Solar System case



Izidoro, Morbidelli et al. 2015, A&A, 582

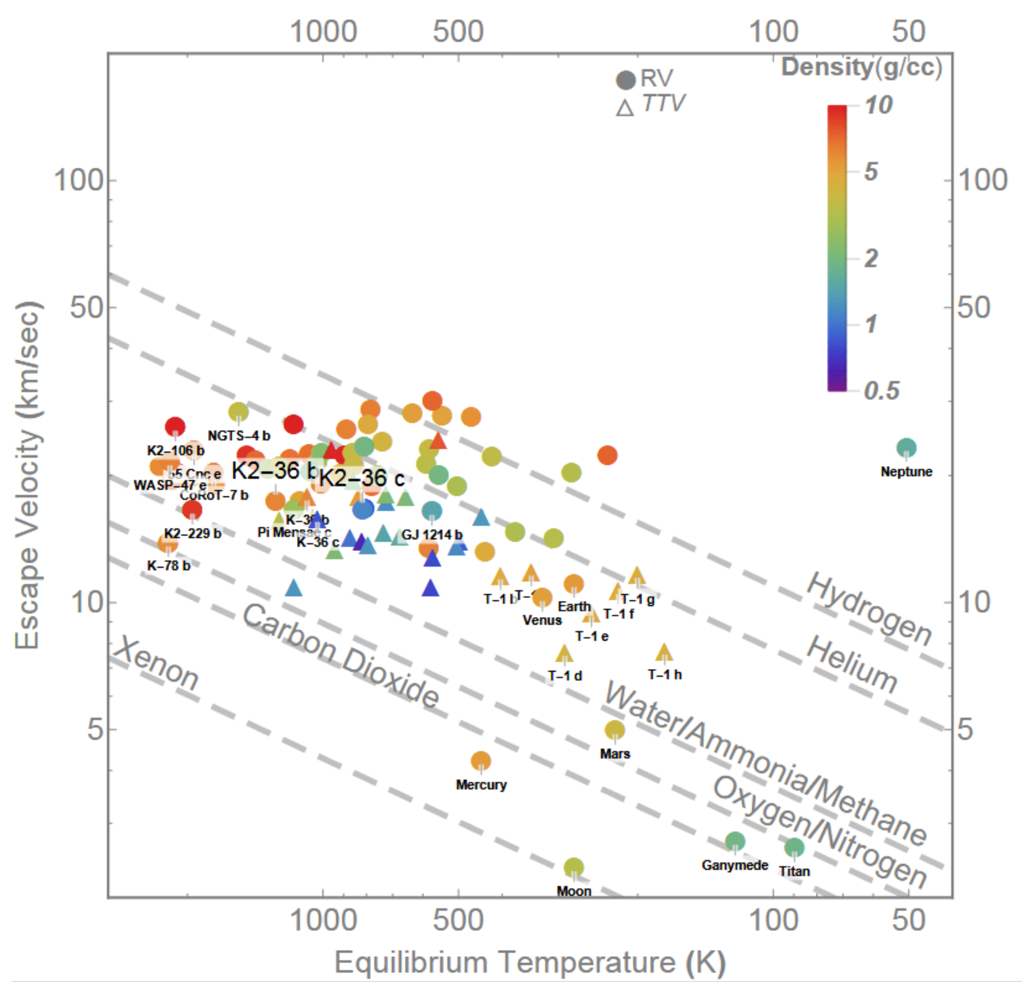
In absence of giant planets migration of icy super-Earths is expected



Izidoro…Morbidelli…Ogihara… 2017 MNRAS 470; Izidoro et al. , 2019 AstroPH

However, icy super-Earths appear rare and mostly only around low-mass stars

Existence of a general obstacle to Type-I migration?



Zeng et al., 2019

Piaulet et al., 2023 (Kepler-138 d)

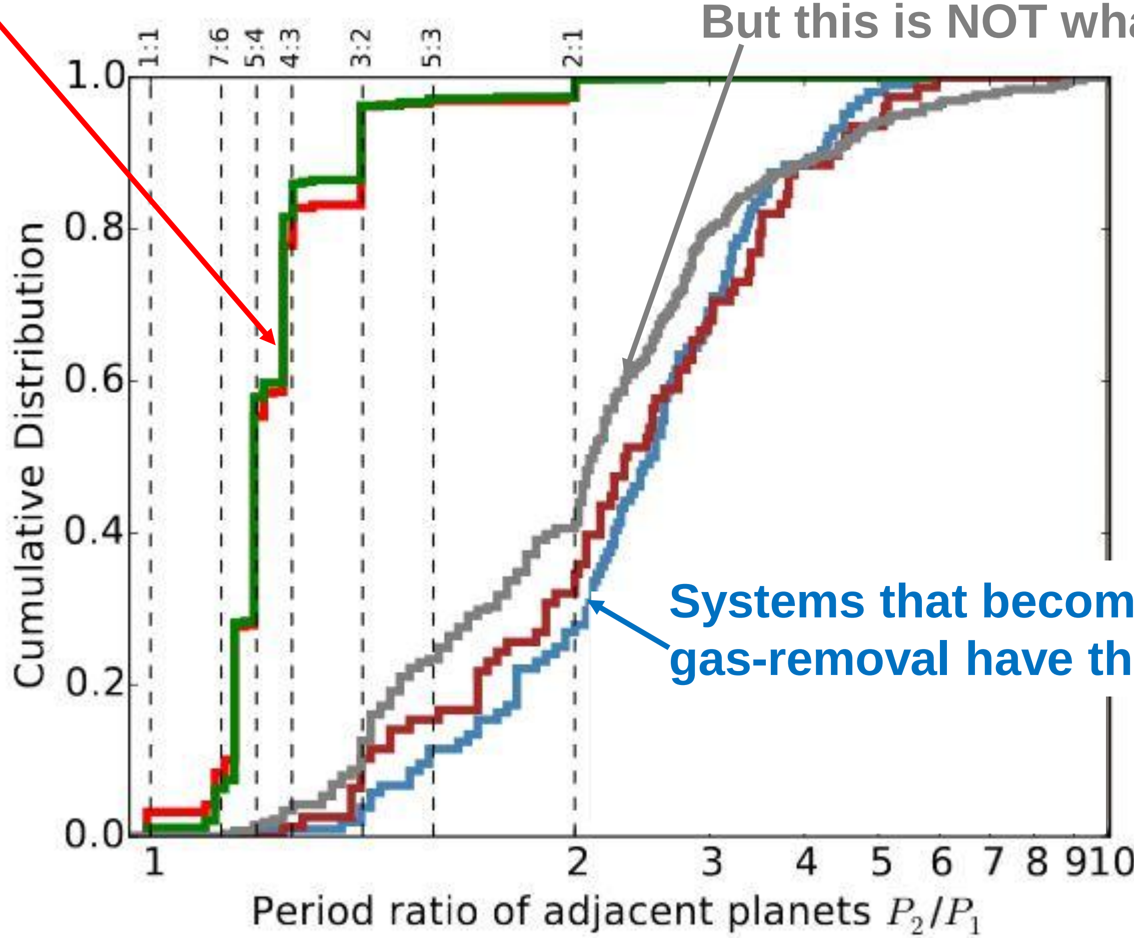
AFTER THE DISAPPEARENCE OF THE PROTOPLANETARY DISK

INSTABILITIES, INSTABILITIES, INSTABILITIES…..

The distribution of period-ratios between adjacent planets reveals that most SE systems eventually become unstable

At the end of migration all super-Earth systems are in mutual resonances (Trappist-1, K60, K80, K2-138…)

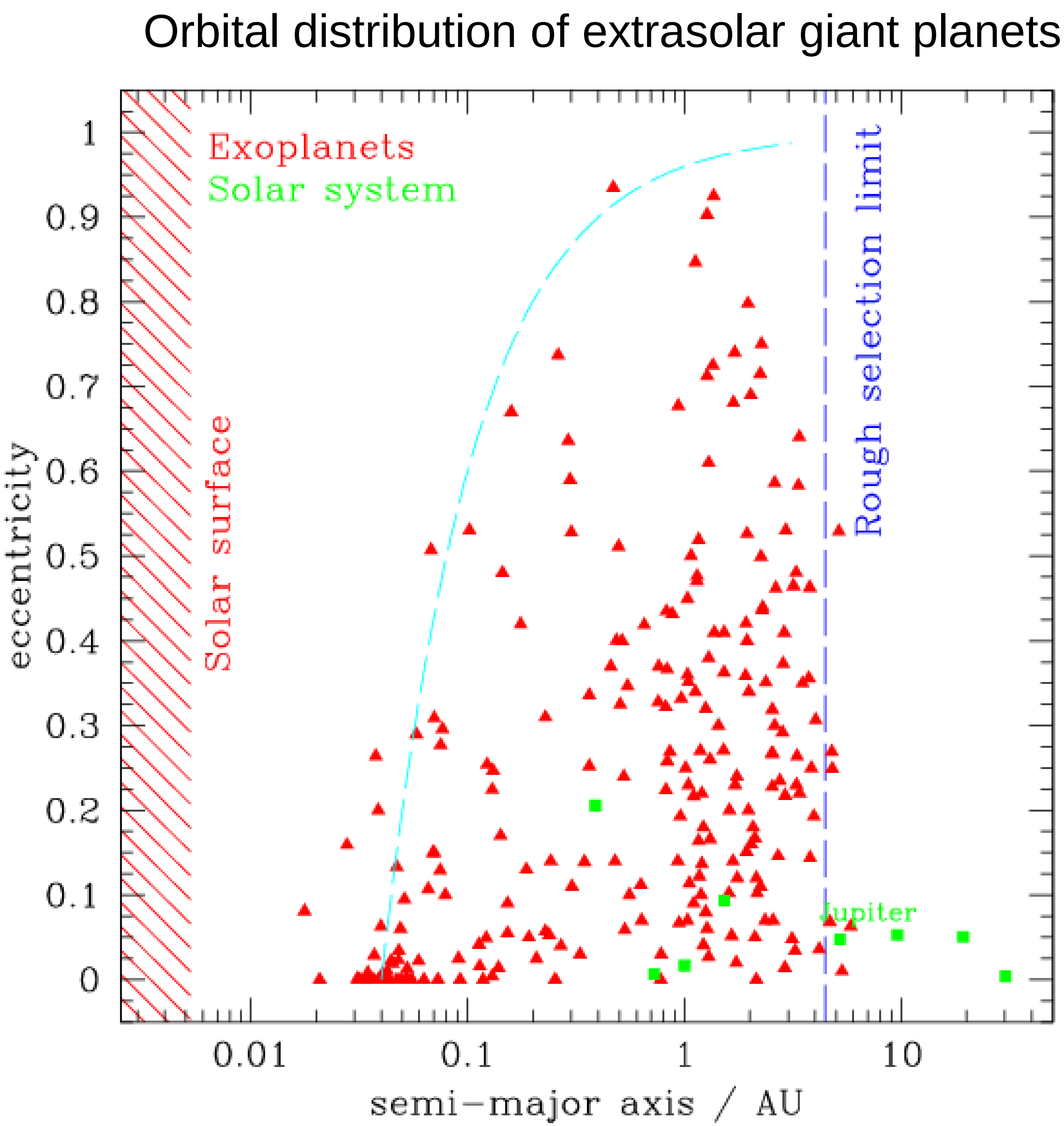
But this is NOT what we observe!



Systems that become unstable after gas-removal have this distribution

Izidoro…Morbidelli…Ogihara… 2017 MNRAS 470; Izidoro ... Morbidelli..., 2021 A&A 650

Dynamical instabilities at the origin of large orbital eccentricities



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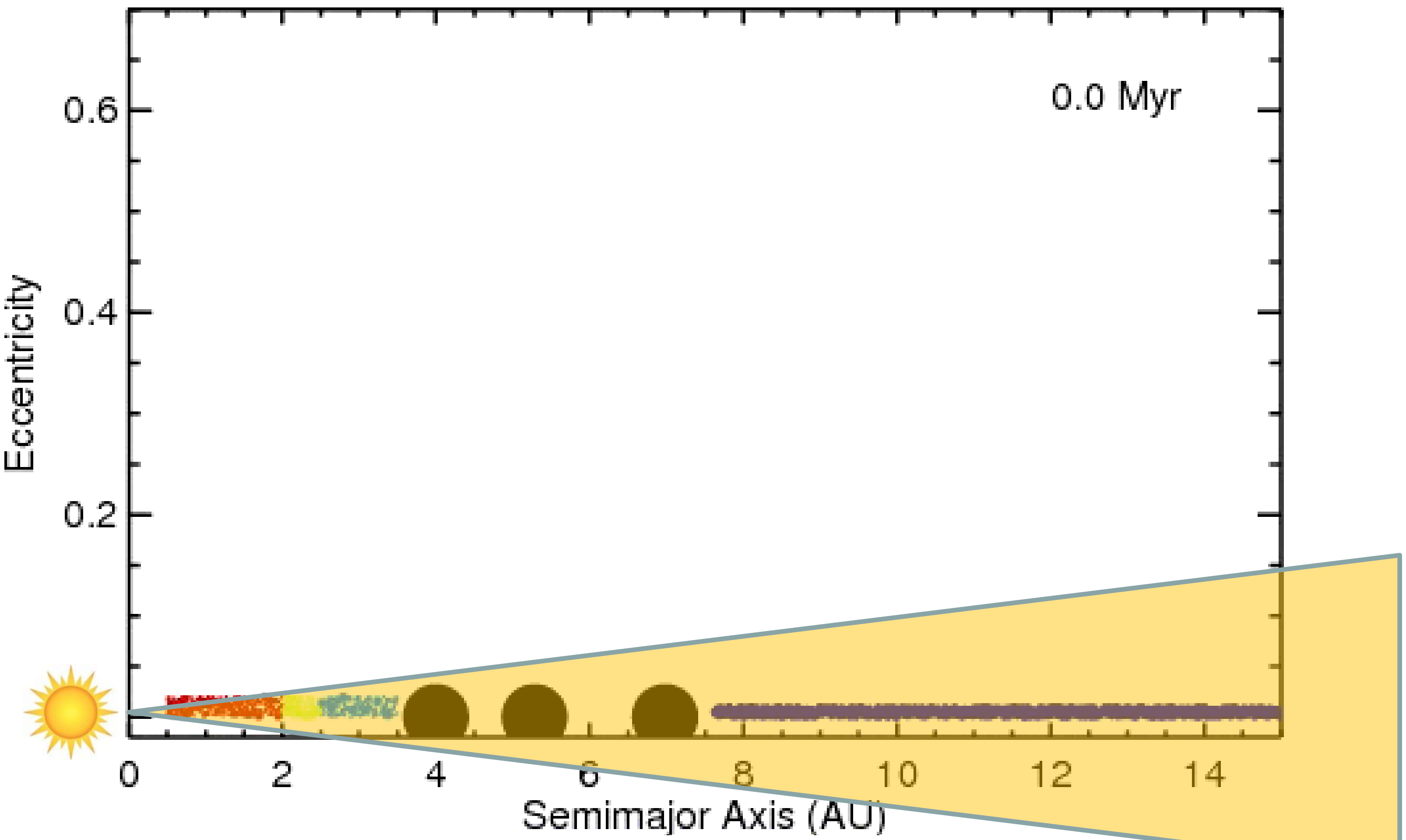

Animation from S. Raymond, LAB, Bordeaux

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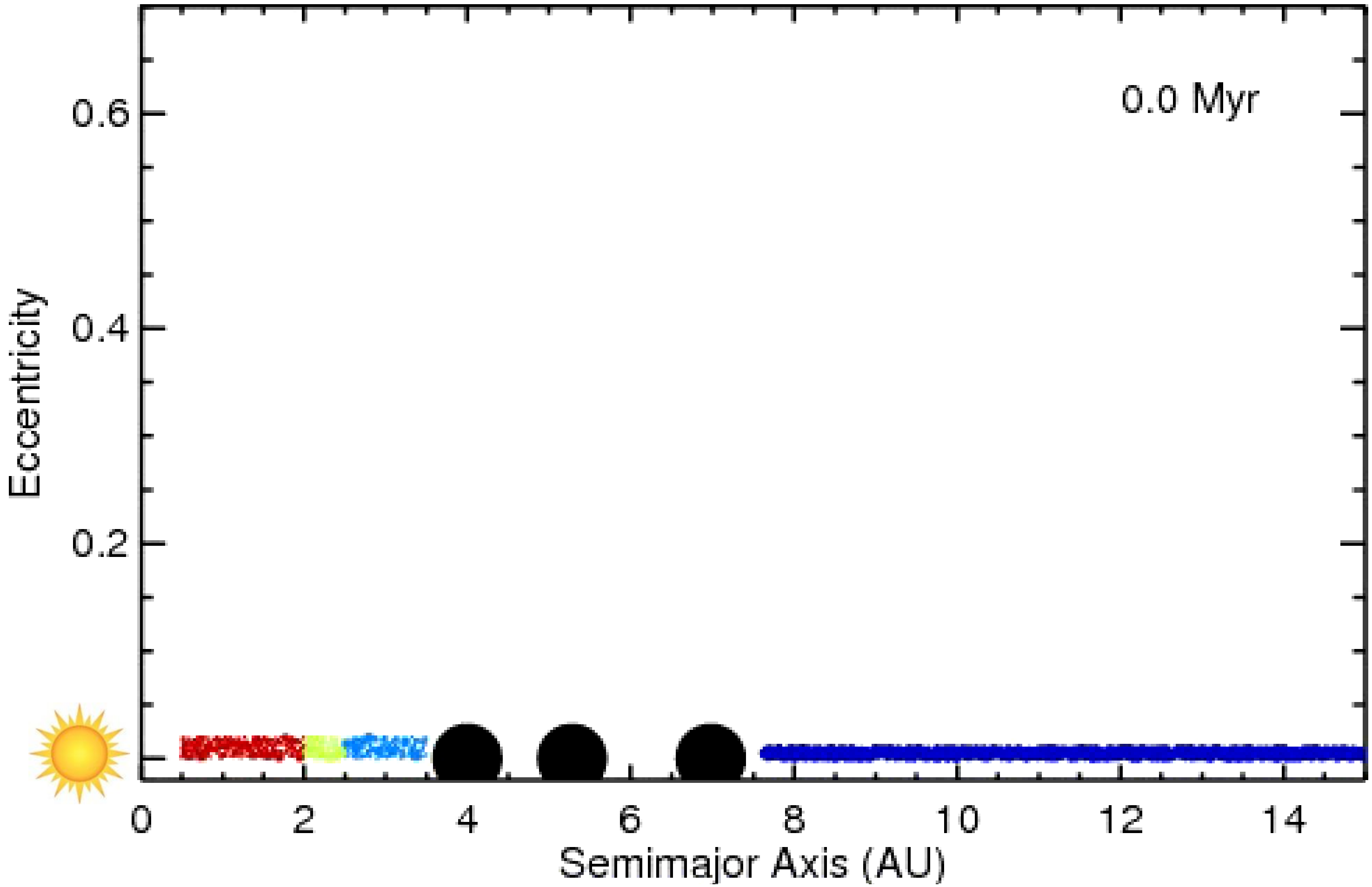
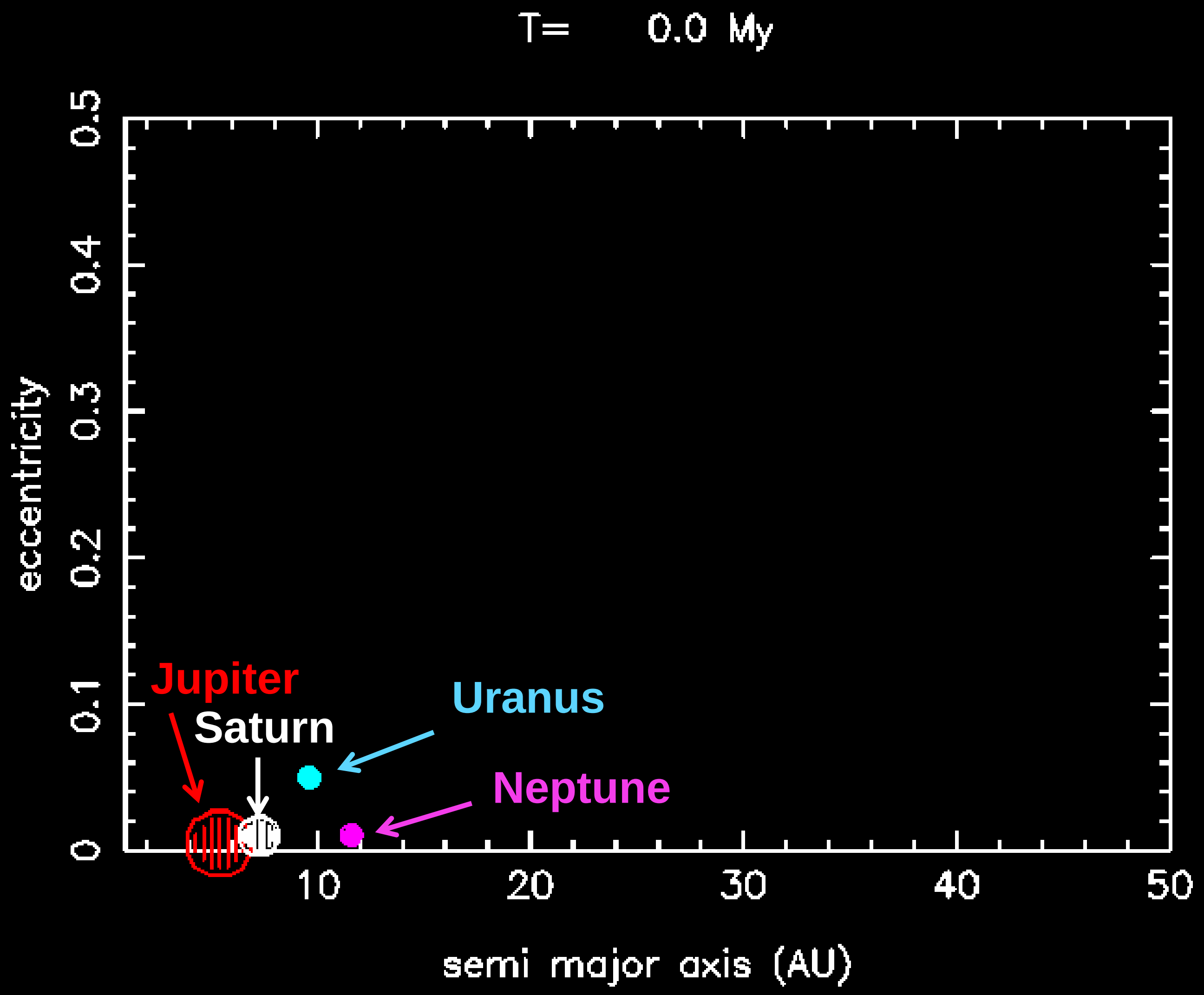


Animation from S. Raymond, LAB, Bordeaux

The giant planet instability of our Solar System: the *Nice* model



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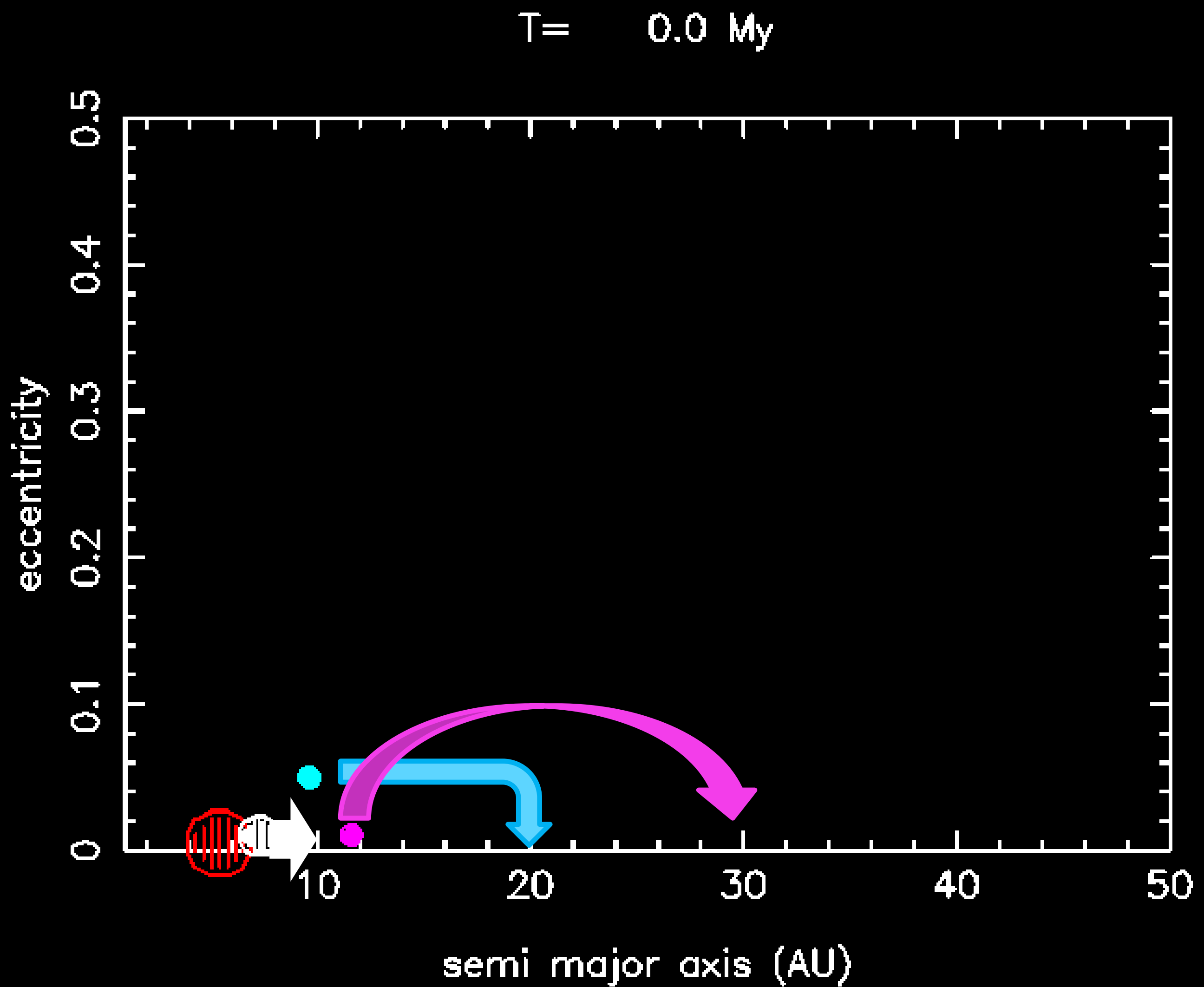
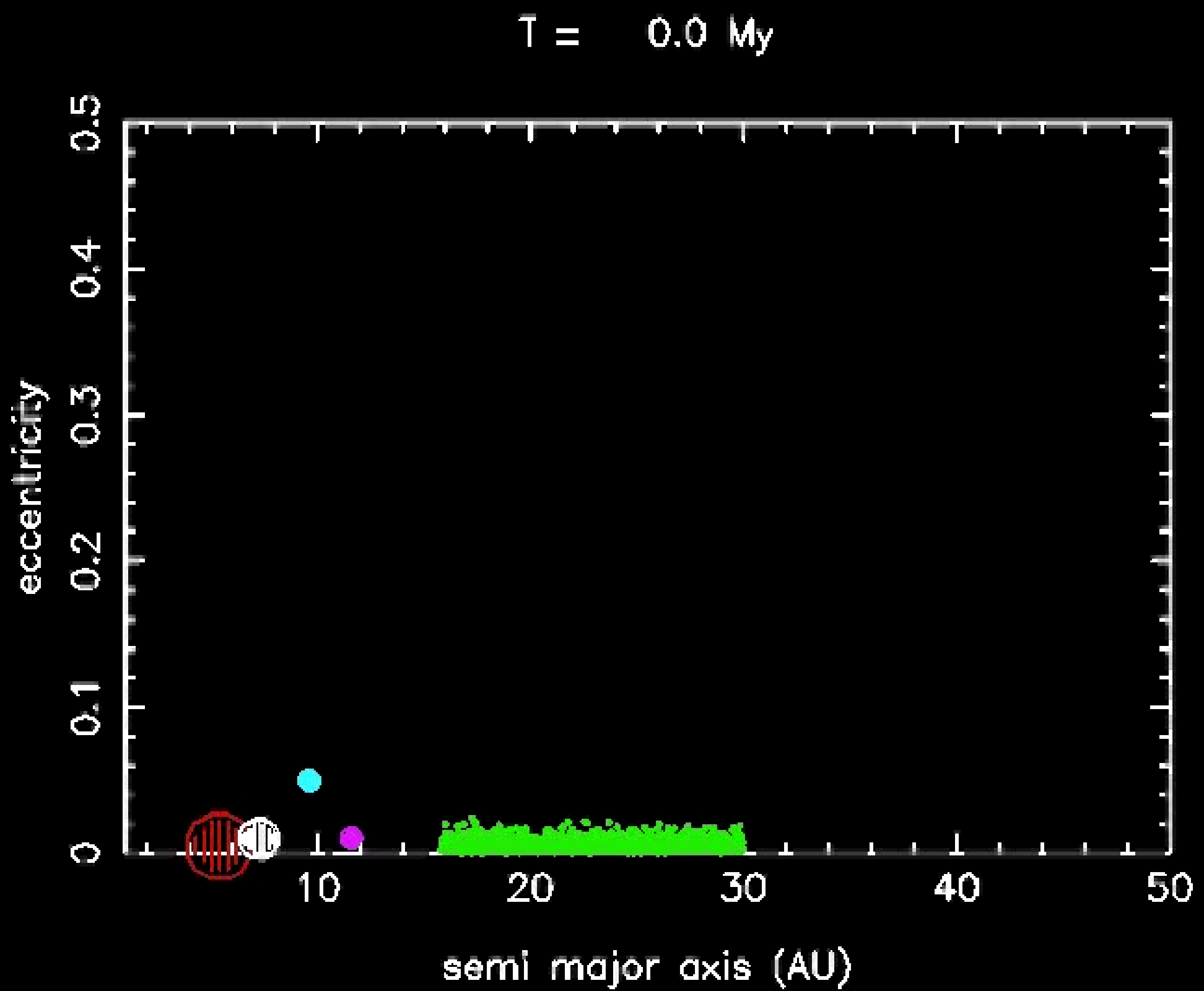


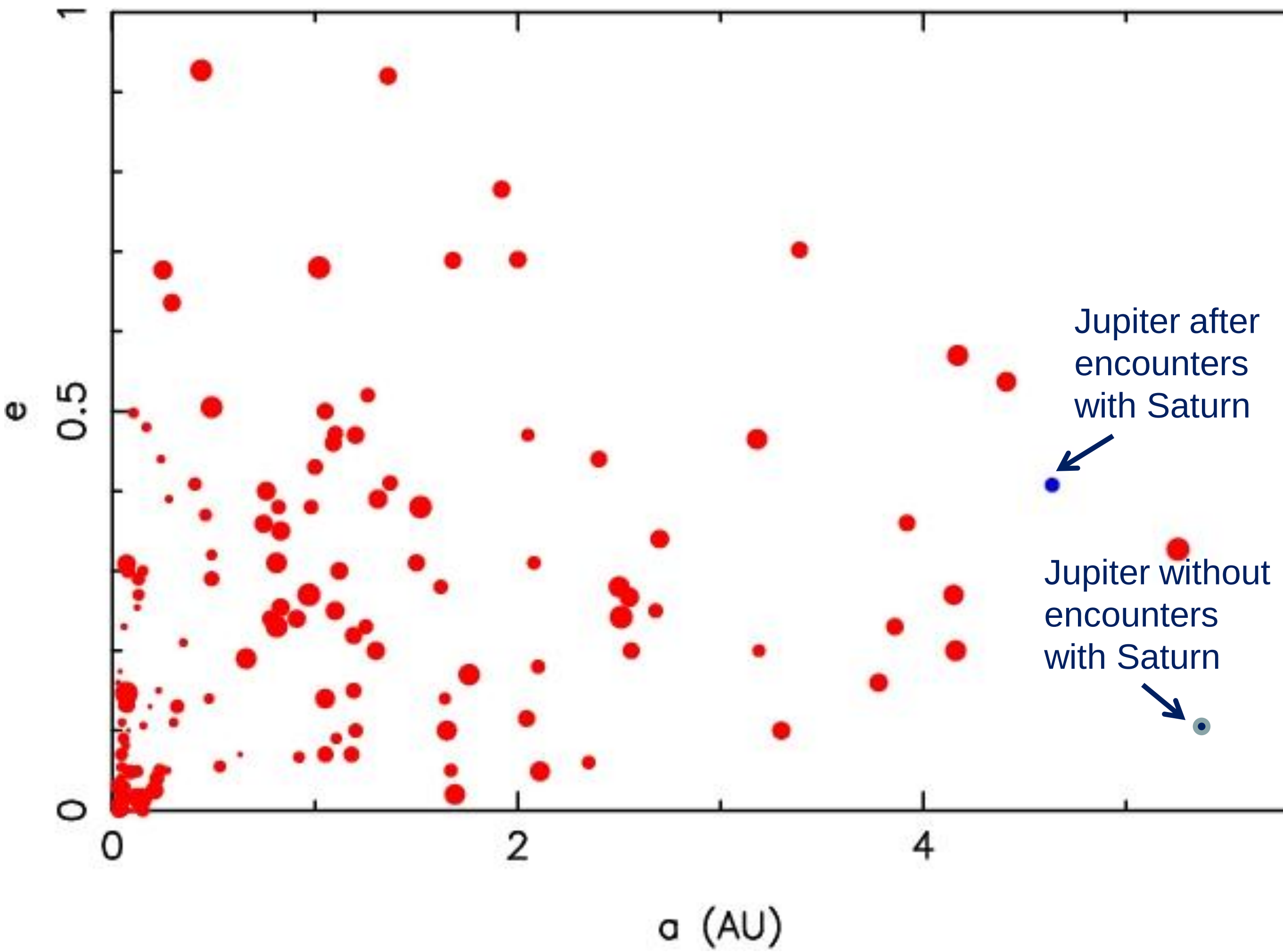
The giant planet instability of our Solar System: the *Nice* model



Morbidelli et al., 2017, AJ, 134; Levison, Morbidelli et al., 2011, AJ 142

The small eccentricities of the giant planets of the Solar System are because Jupiter and Saturn, fortuitously, avoided mutual close encounters

In simulations where these encounters happen, the final eccentricity of Jupiter is similar to typical of those at of extrasolar giant planets.



Conclusions

- **The basic processes ruling planet formation and evolution are the same everywhere:**
  growth by collisions & pebble accretion, migration, orbital instabilities
- **Migration introduces a lot of variability in the final outcomes, with great sensitivity on initial conditions and environment parameters (chaos).**
- ***Recipe to build a solar system*:**
  - **Establishment of a barrier to dust drift, limiting the amount of mass in the inner disk**
  - **The innermost planet beyond the snowline grew to become a giant planet (Jupiter)**
  - **The formation of Saturn followed, blocking Jupiter's migration**
  - **At the instability time the two major planets did not have mutual close encounters**
- **We are not yet able to quantify the likelihood that a planetary system is like ours, but it should be small**
- **We need to live in a system that allowed the formation of a habitable planet, however improbable that is**