The peculiar properties of the Solar System

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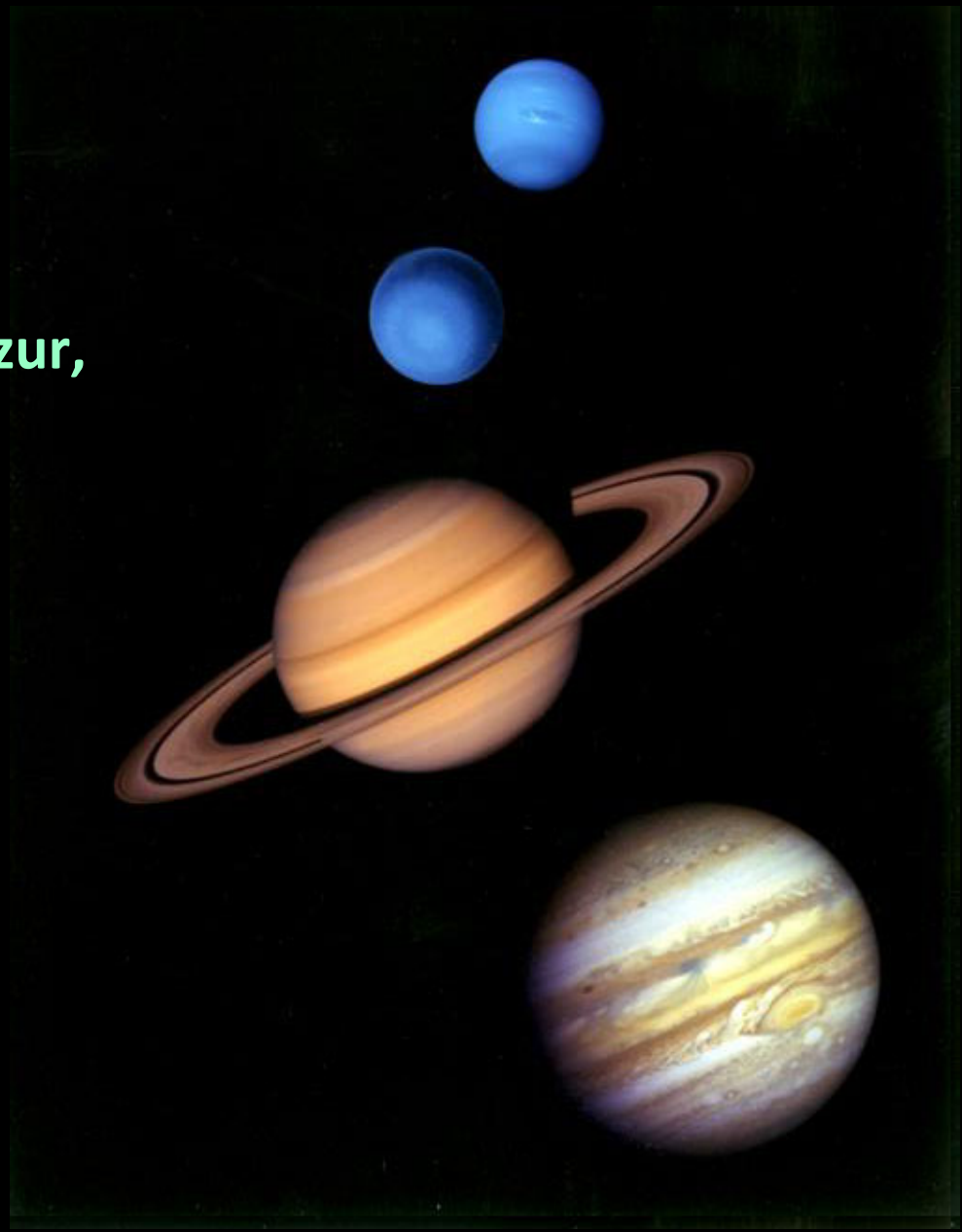

PROJET FINANCÉ PAR L'ANR - PROJECT FUNDED BY THE ANR
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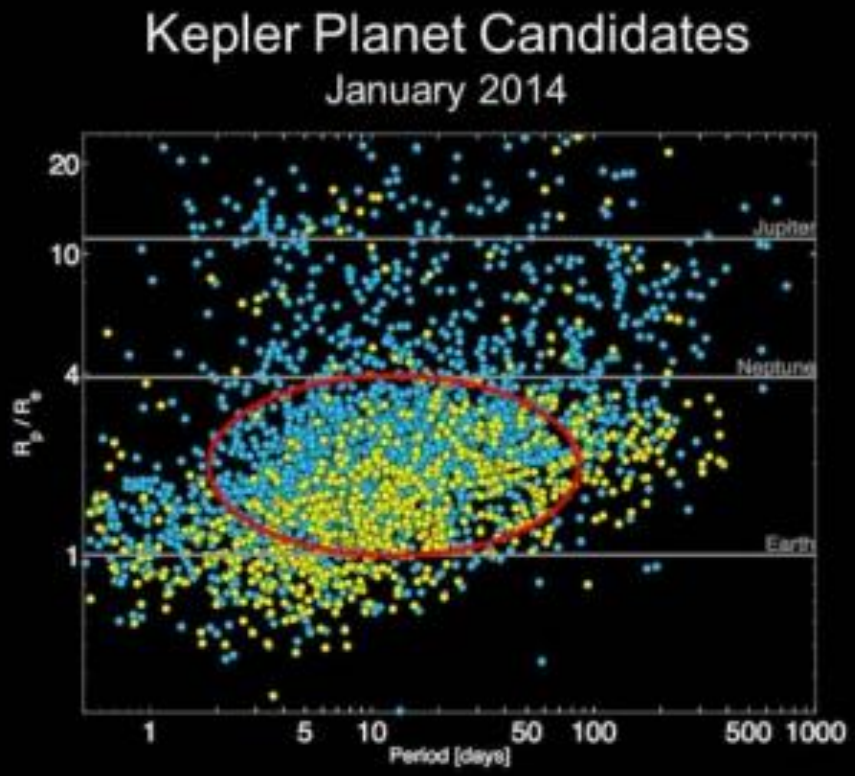
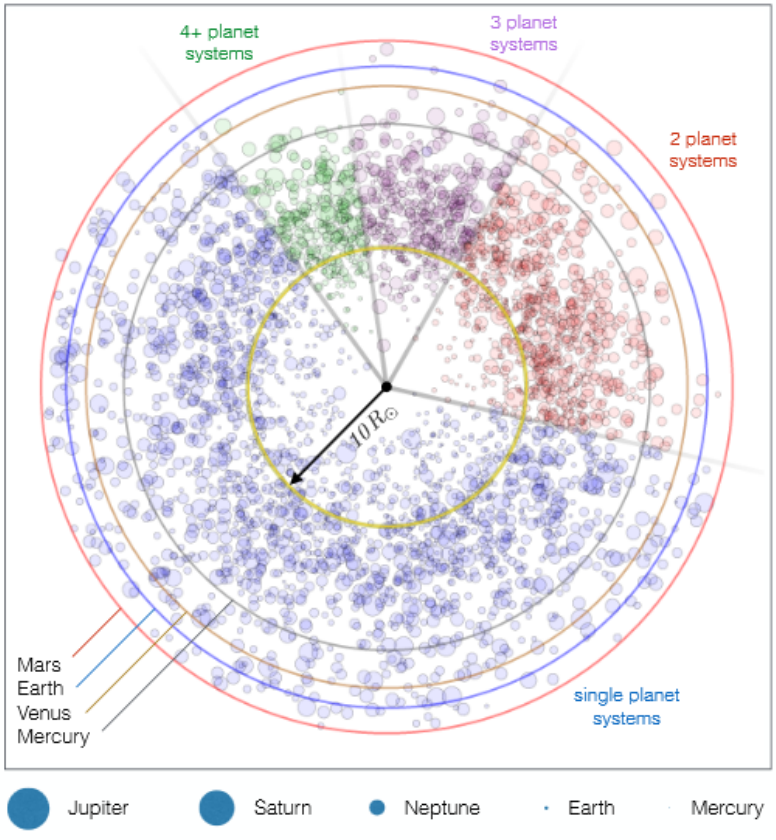


Radial velocity (Mayor et al., 2011) and transit surveys (Howard et al., 2012; Petigura et al., 2013; Fressin et al., 2013) suggest that many (most?) solar-type stars have close-in Super-Earths / Neptune-like (SEN) planets

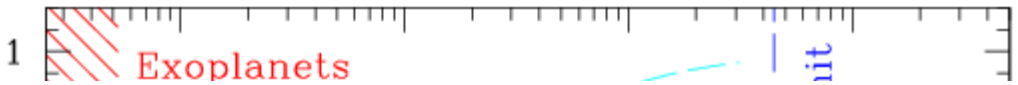
The Solar System is atypical in that our Neptune-like planets are not close-in, but they are beyond Jupiter & Saturn



Batygin and Laughlin, 2015

Our Solar System have giant planets, like probably only ~15% of the other stars, but our giant planets have orbits very different from the extrasolar ones discovered so far.

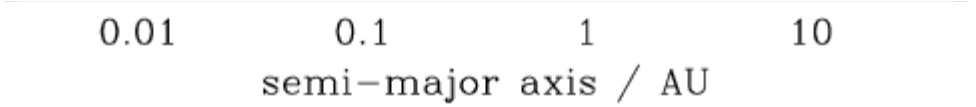
Giant planet orbital distribution



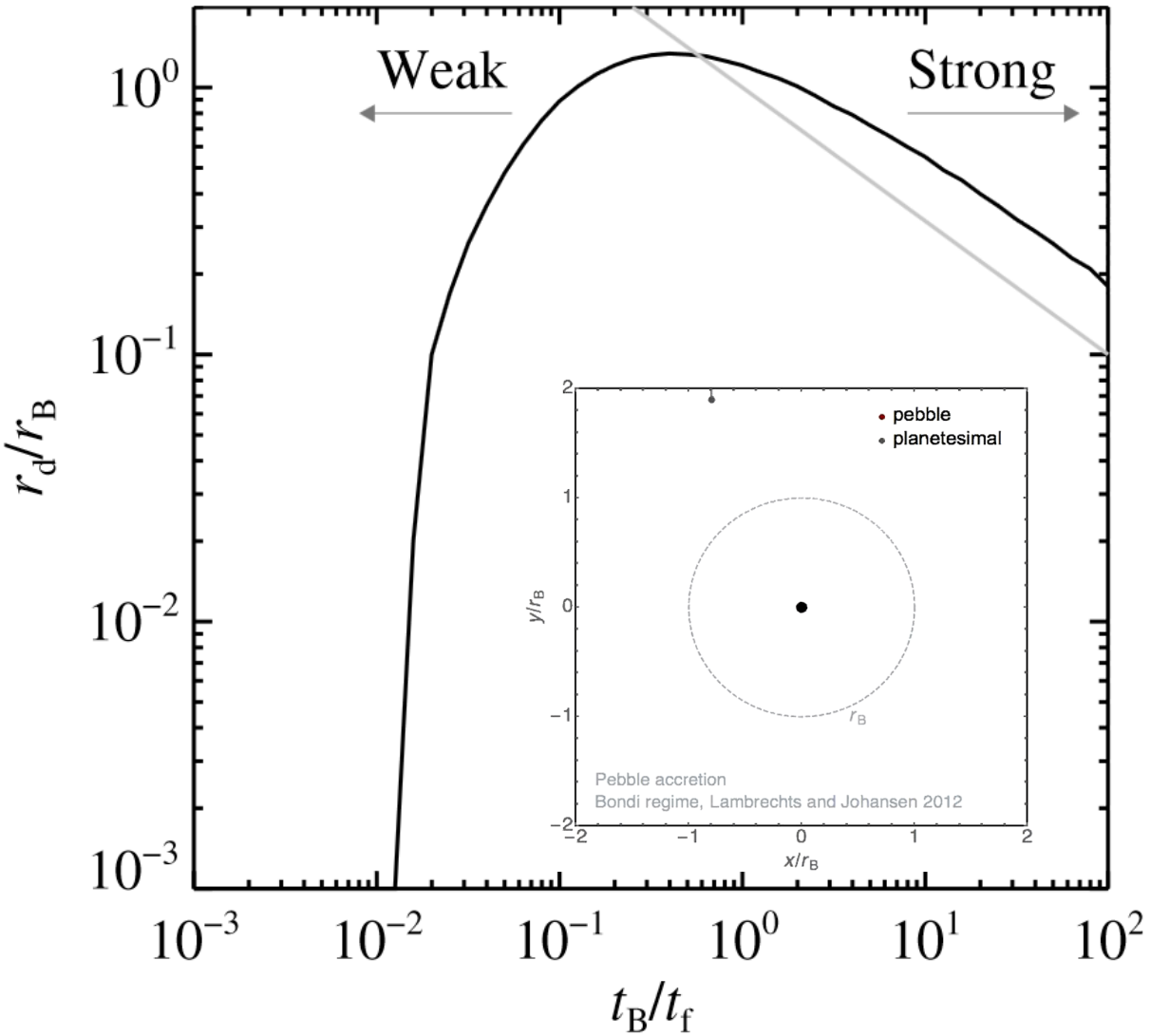
We now know that our Solar System is not typical: 65-80% of solar-type stars have planetary systems different from ours !

We don't know yet from observations if our Solar System represents 10%, 1%, 10^{-4}, 10^{-6} of the planetary systems

We need theory of planet formation/evolution to address this question

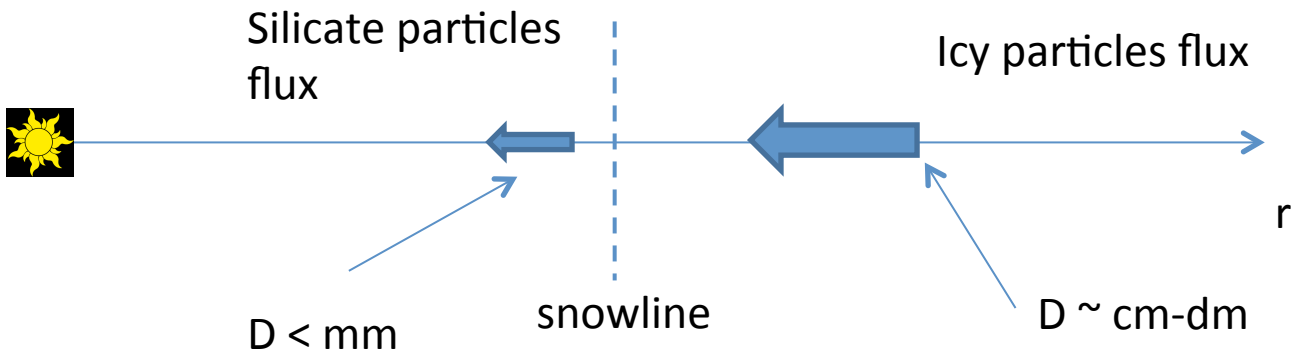


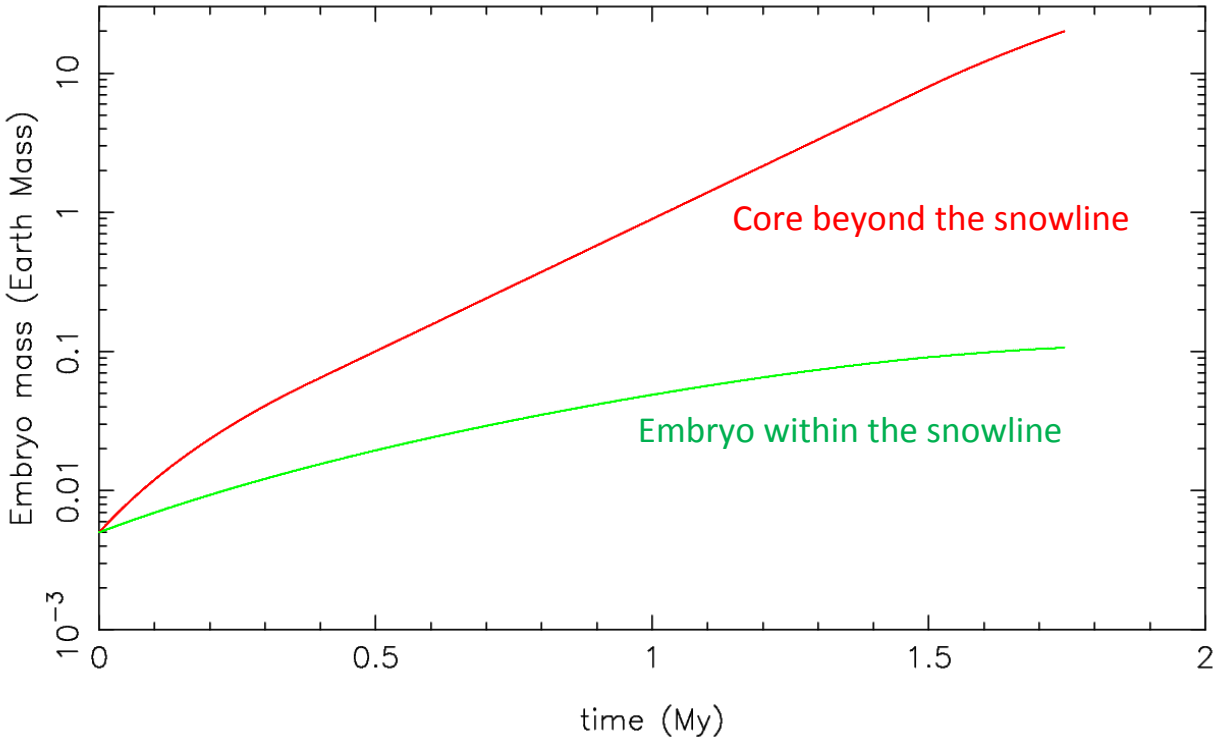
The formation of giant planet cores has remained a mystery for long time, but now we have a new theory that seems to work (Lambrechts et Johansen, 2012, 2014; Johansen et al., 2015)



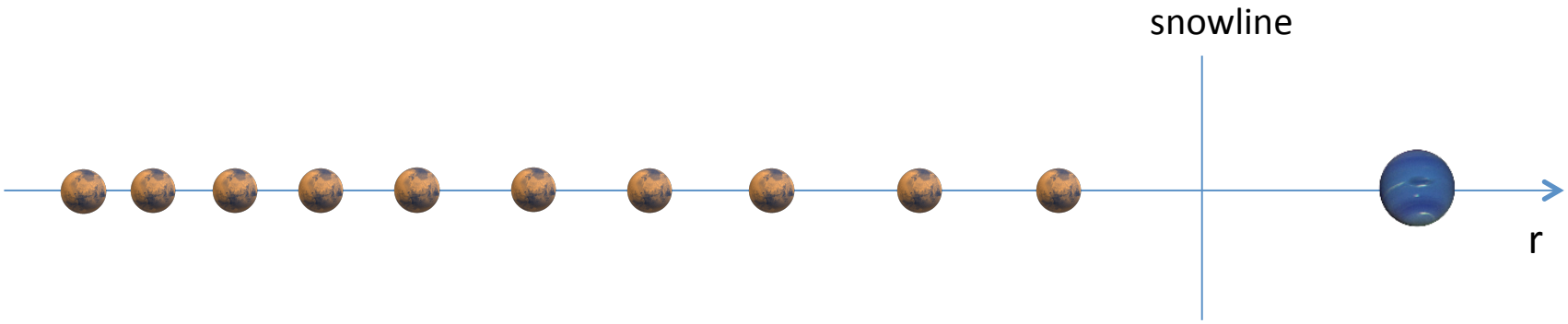
But why giant planet cores formed only in the outer part of the disk?

IDEA



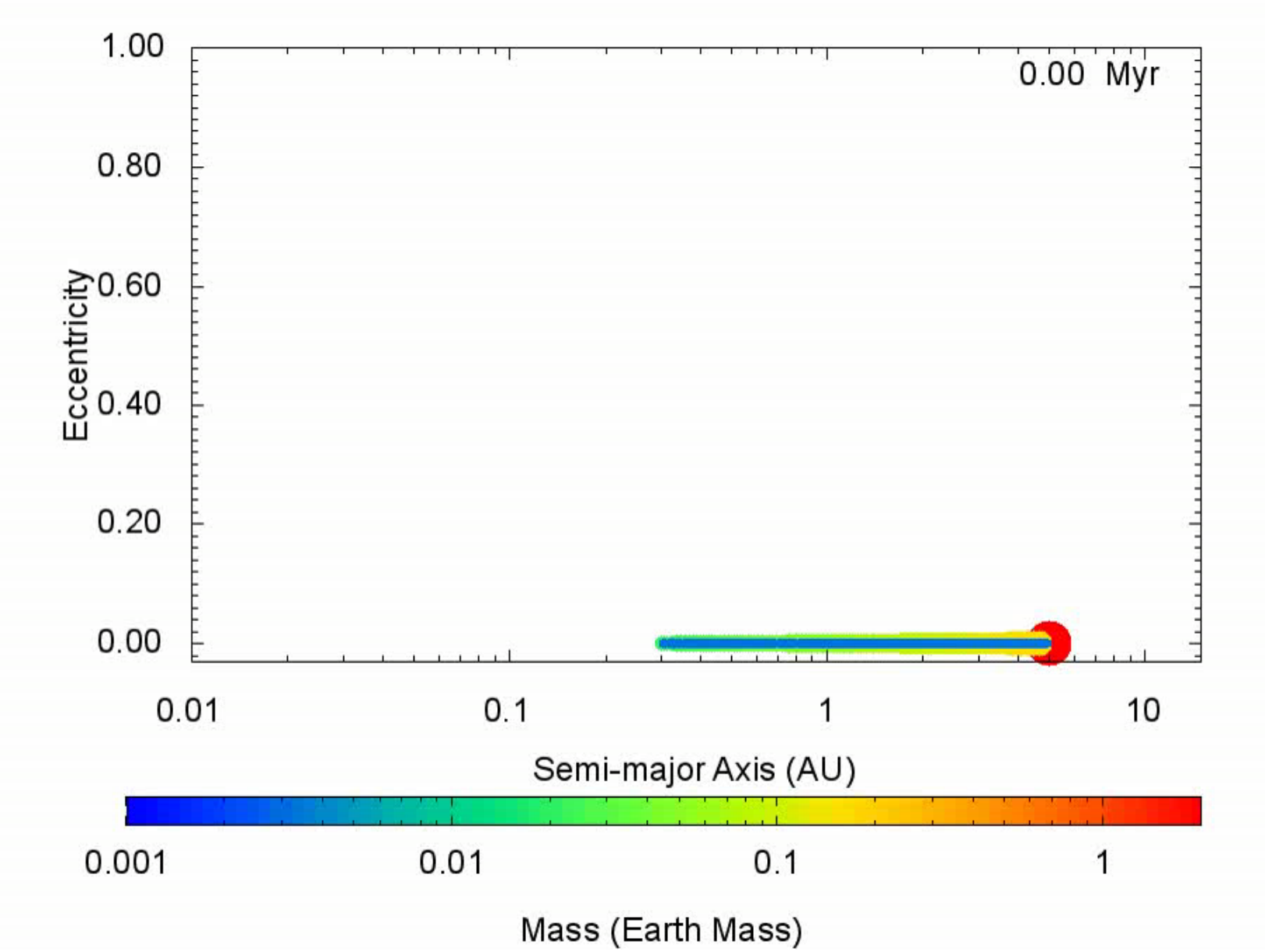


Morbidelli, Lambrechts, Bitsch and Jacobson, Icarus in press



The generic initial structure of a planetary system

The slow inward migration of SENs can prevent the formation of true terrestrial planets



Izidoro et al., 2014

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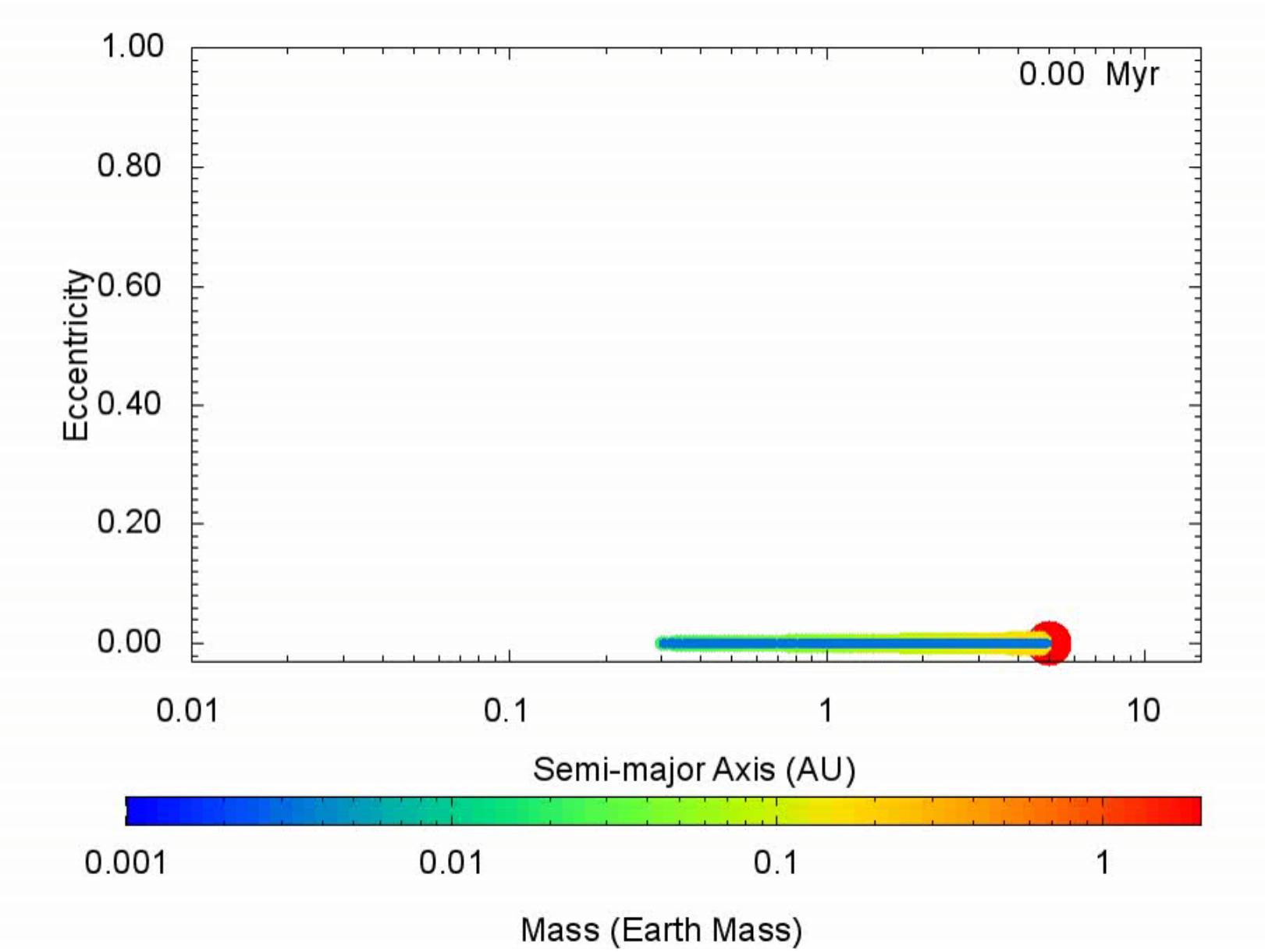
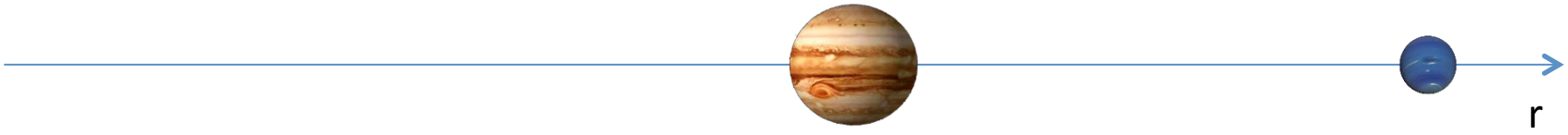


Izidoro et al., 2014

If the innermost SEN becomes a giant planet, results are very different

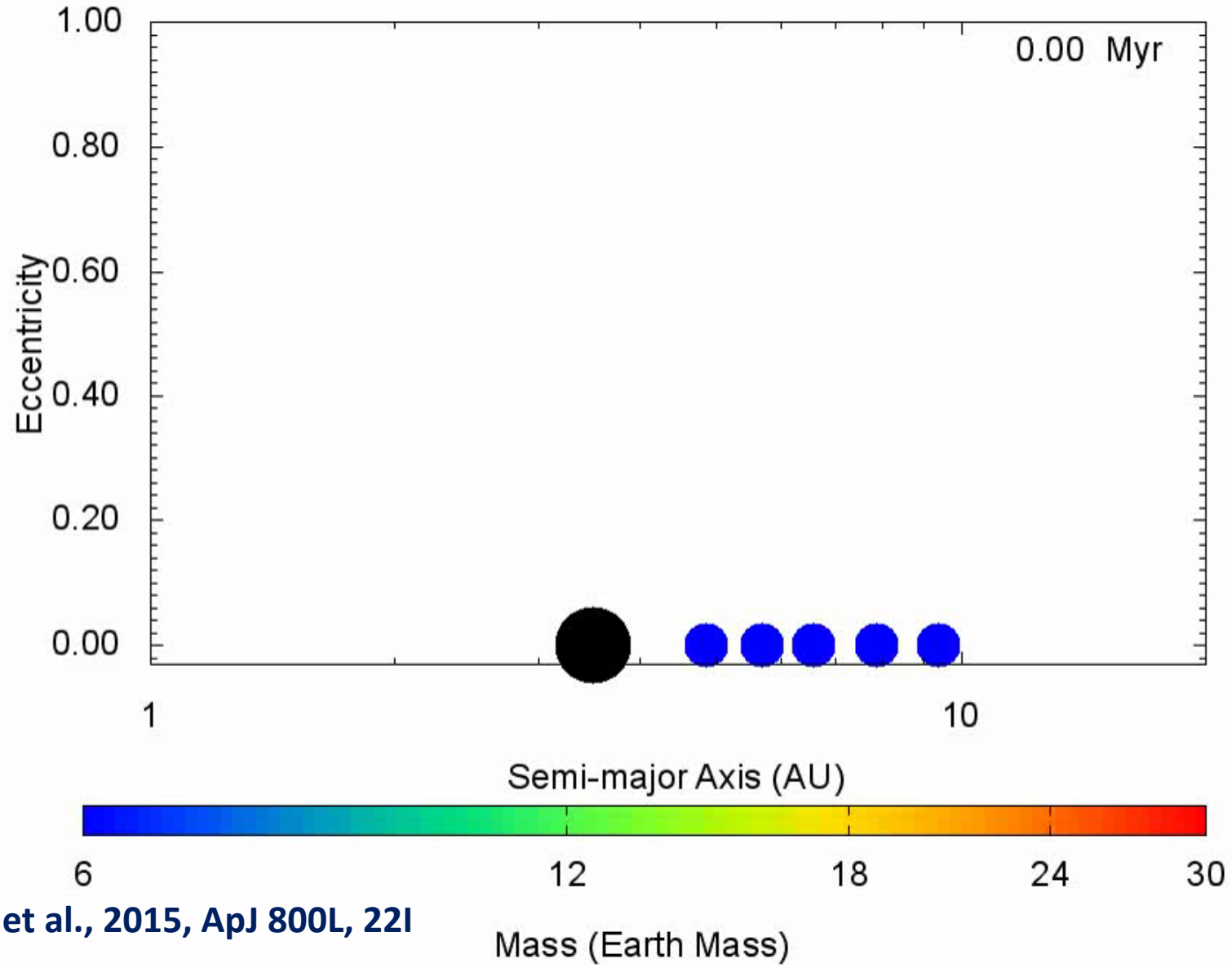
A SEN migrates inwards faster than a giant planet



Thus, SENs tend to approach the giant planet(s)

What happens when a SEN approaches a giant planet? Will it go through its orbit and continue its migration towards the star or will it be blocked?

Giant planets are extremely effective in retaining Super-Earths behind them
(Izidoro, Raymond and Morbidelli, ApJ 800L, 22I)



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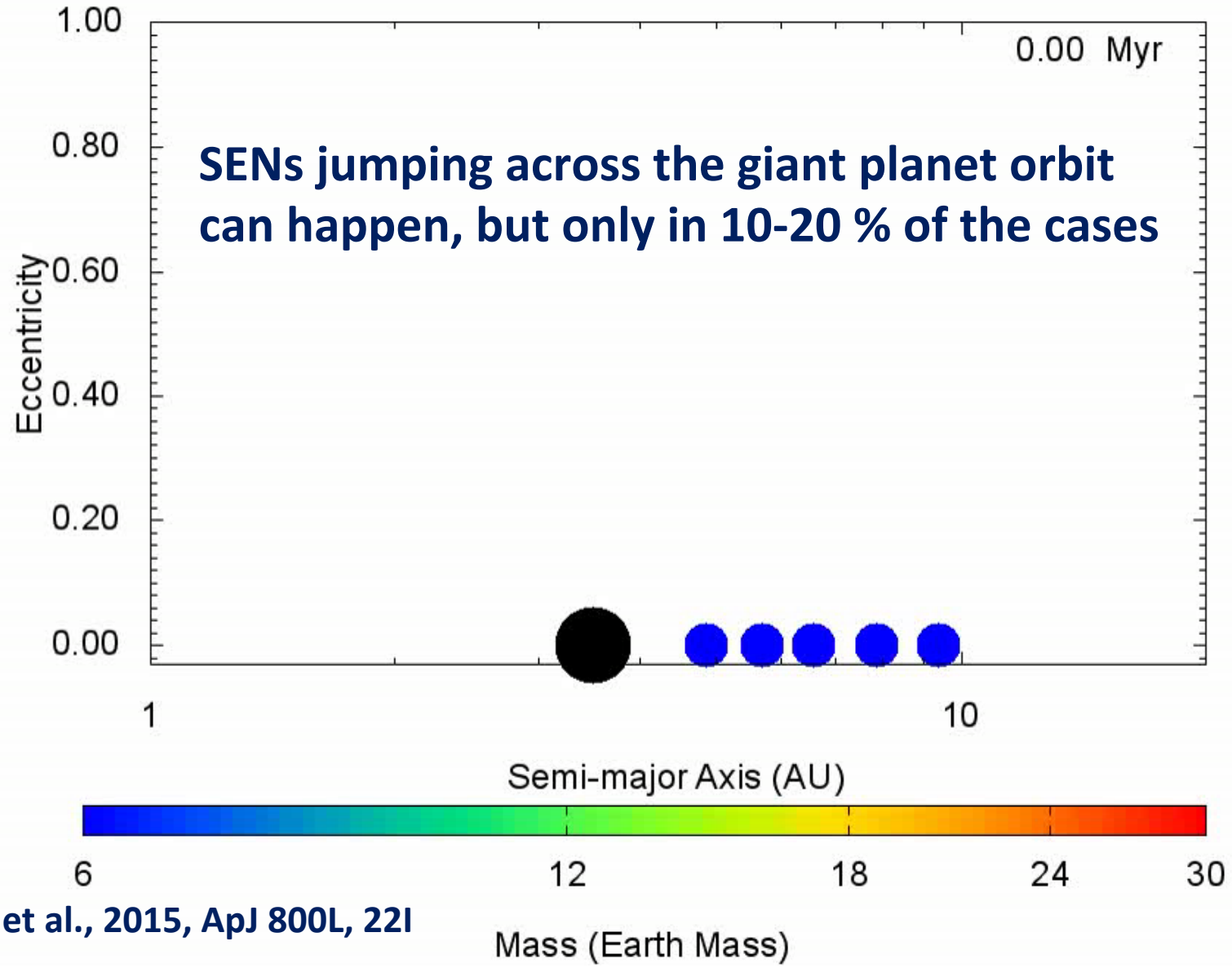


Izidoro et al., 2015, ApJ 800L, 22I

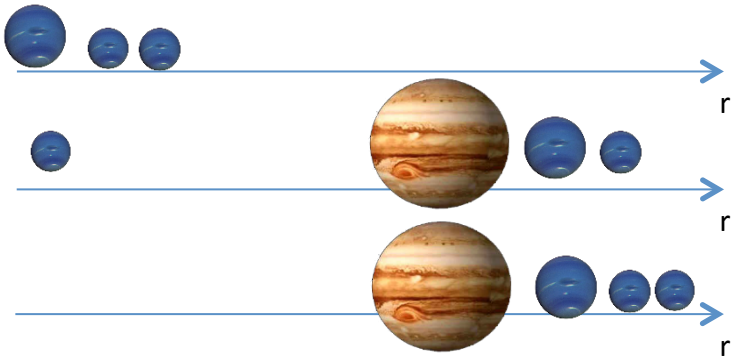
IMPLICATION FOR EXTRASOLAR SYSTEMS

If close-in SENs originated by inward migration and if it is the innermost SEN that is the most likely to become a giant planet then we expect an anti-correlation between close-in SENs and giant planets.

Systems of close-in SENs <-> no giant planets

A single close-in SEN <-> a giant planet further out

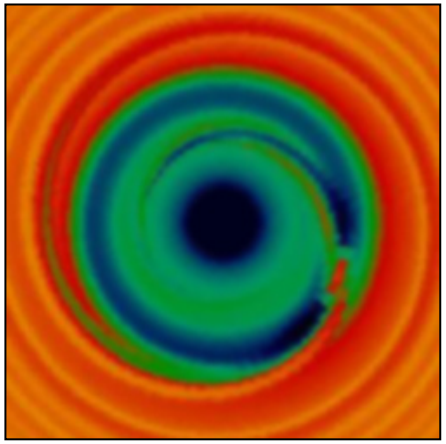
No close-in SENs <-> a giant planet further out



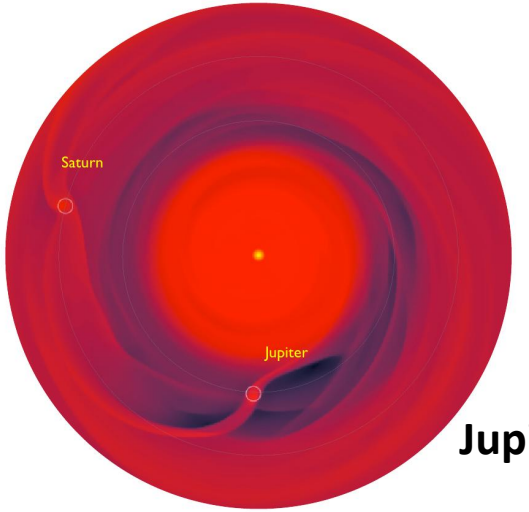
Of course, we expect this correlation not to be 100% true. Some close-in SENs might have formed in-situ, in other cases the giant planet might not have formed from the innermost SEN.

The reliability of this correlation (to be observationally determined) will tell us how often the ifs are valid and therefore it will allow us to infer information on the origin of close-in SENs and formation of giant planets.

In our Solar System we think that Jupiter and Saturn migrated outwards due to their combined interactions with the disk



Jupiter only



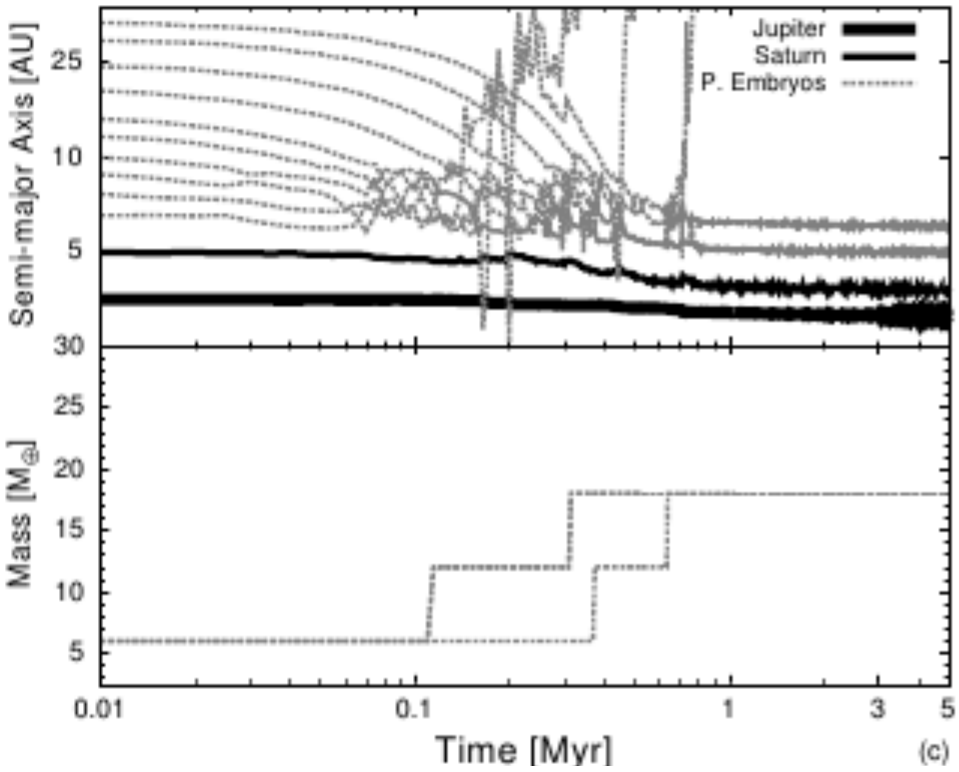
Jupiter and Saturn

Uranus and Neptune did not migrate into the inner Solar System because they have been retained by Jupiter and Saturn

ORIGIN OF URANUS AND SATURN

The large obliquities of Uranus and Neptune indicate that these planets should have experienced giant collisions and this suggests they assembled from several merging embryos.

The dynamical barrier offered by Jupiter and Saturn offers a framework for this to happen

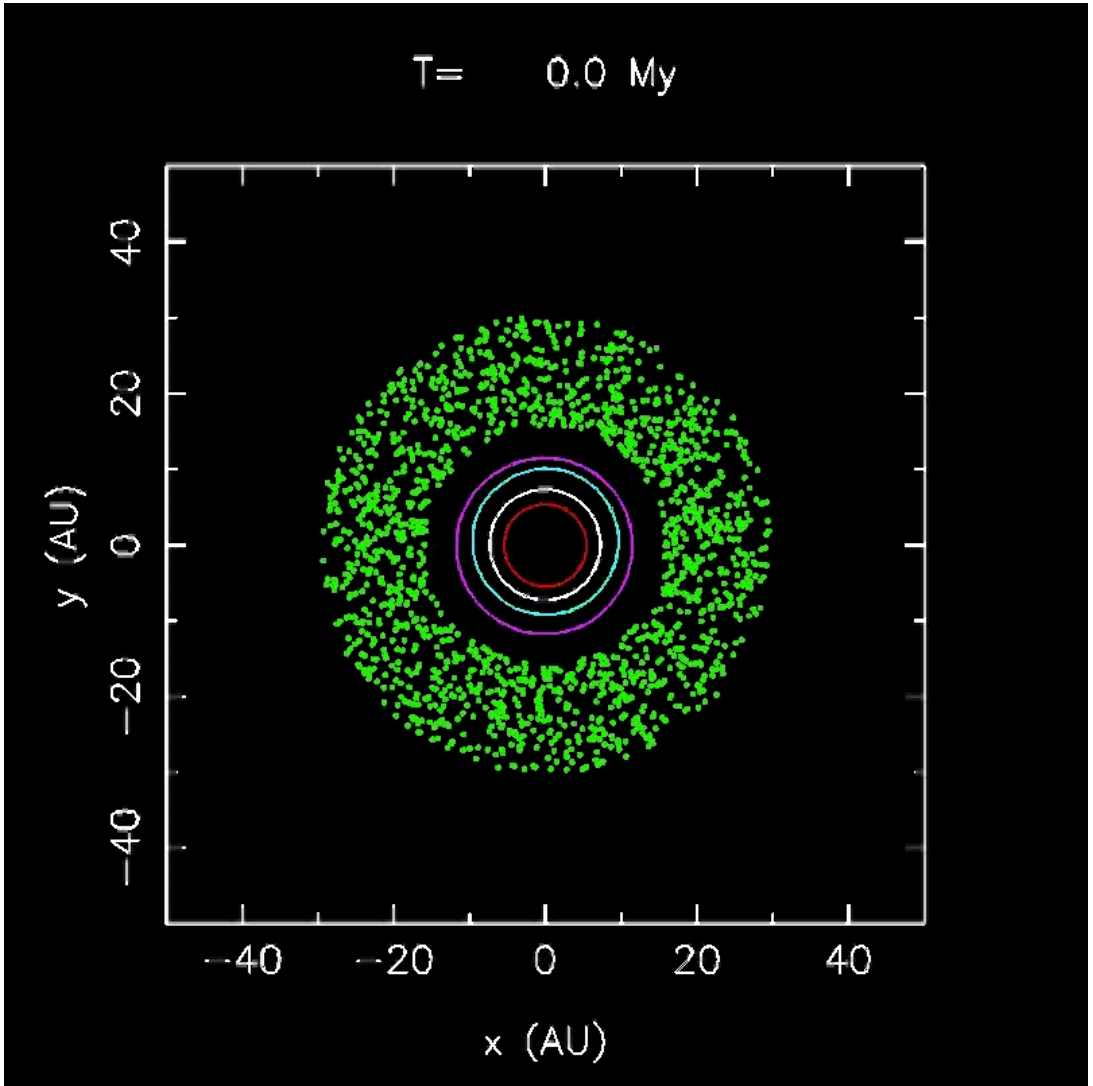


Izidoro et al., MNRAS In press
Jakubik et al., 2012

Giant planets are the key!

- **The formation of big icy planets (SENs) beyond the snowline should be generic…**
- **…as well as their migration into the inner system**
- **If the innermost SEN becomes a gas-giant planet it can offer a dynamical barrier against the migration of the other SENs into the inner disk**
- **The migration of SENs is constrained by the migration of the gas-giant planet**
- **In most extrasolar systems, gas-giant planets migrated down to ~ 1-2 AU**
- **In our system, the mass ratio between Saturn and Jupiter promoted outward migration (distant giant planets). This retained our SENs (Uranus and Neptune) in the outer solar system, thus protecting the "terrestrial planet region".**
- **This allowed the Earth to form…..**

- **The large eccentricities of the extrasolar gas-giant planets are believed to be the consequence of past orbital instability**
- **The Solar System passed through a giant planet instability as well, but a weak one because our giant planets are relatively low-mass and in addition Jupiter and Saturn, by chance, did not encounter with each other.**



The Nice model:

Tsiganis et al., 2005; Gomes et al., 2005; Morbidelli et al., 2007; Levison et al., 2011; Nesvorny and Morbidelli, 2012

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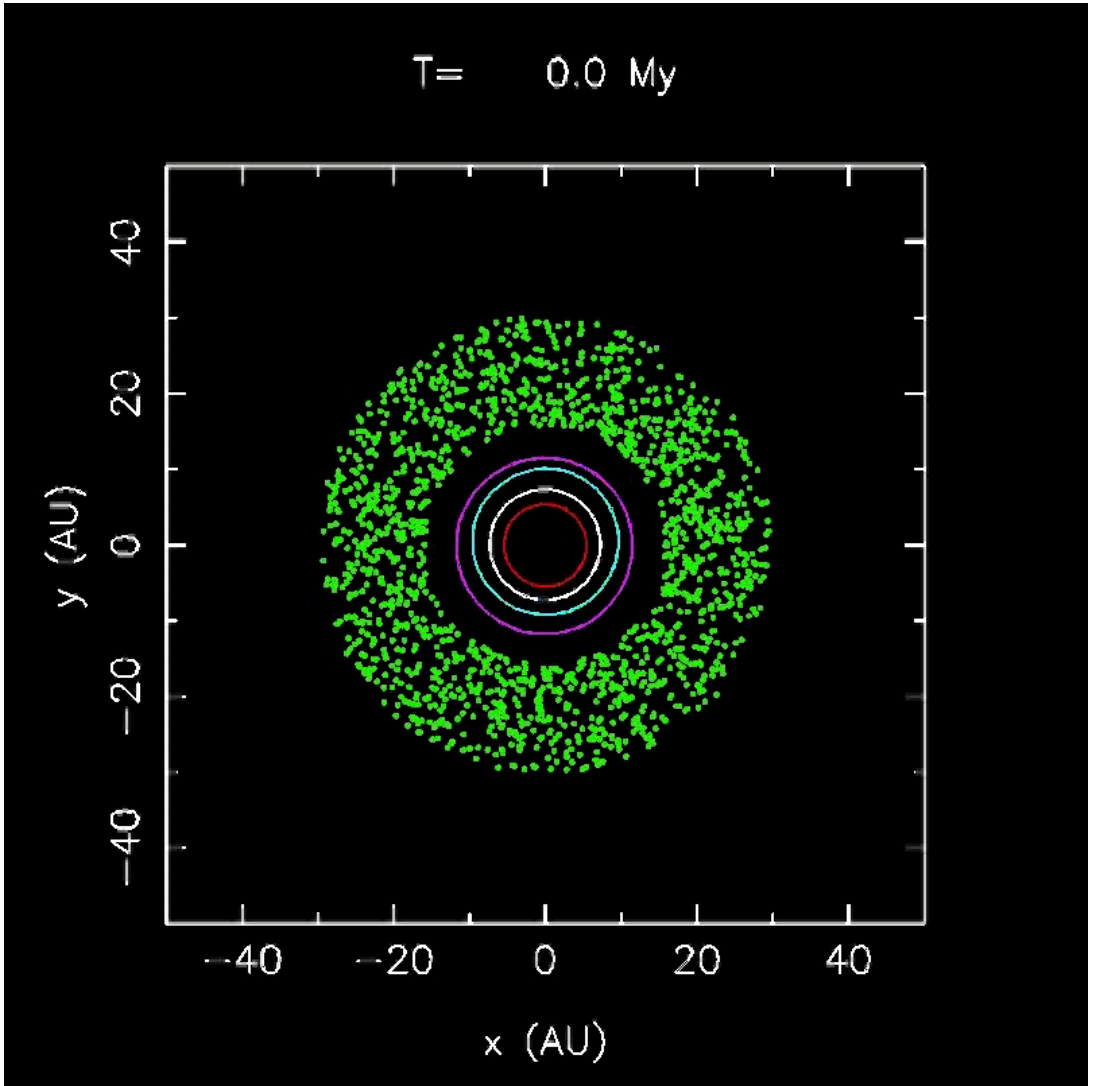

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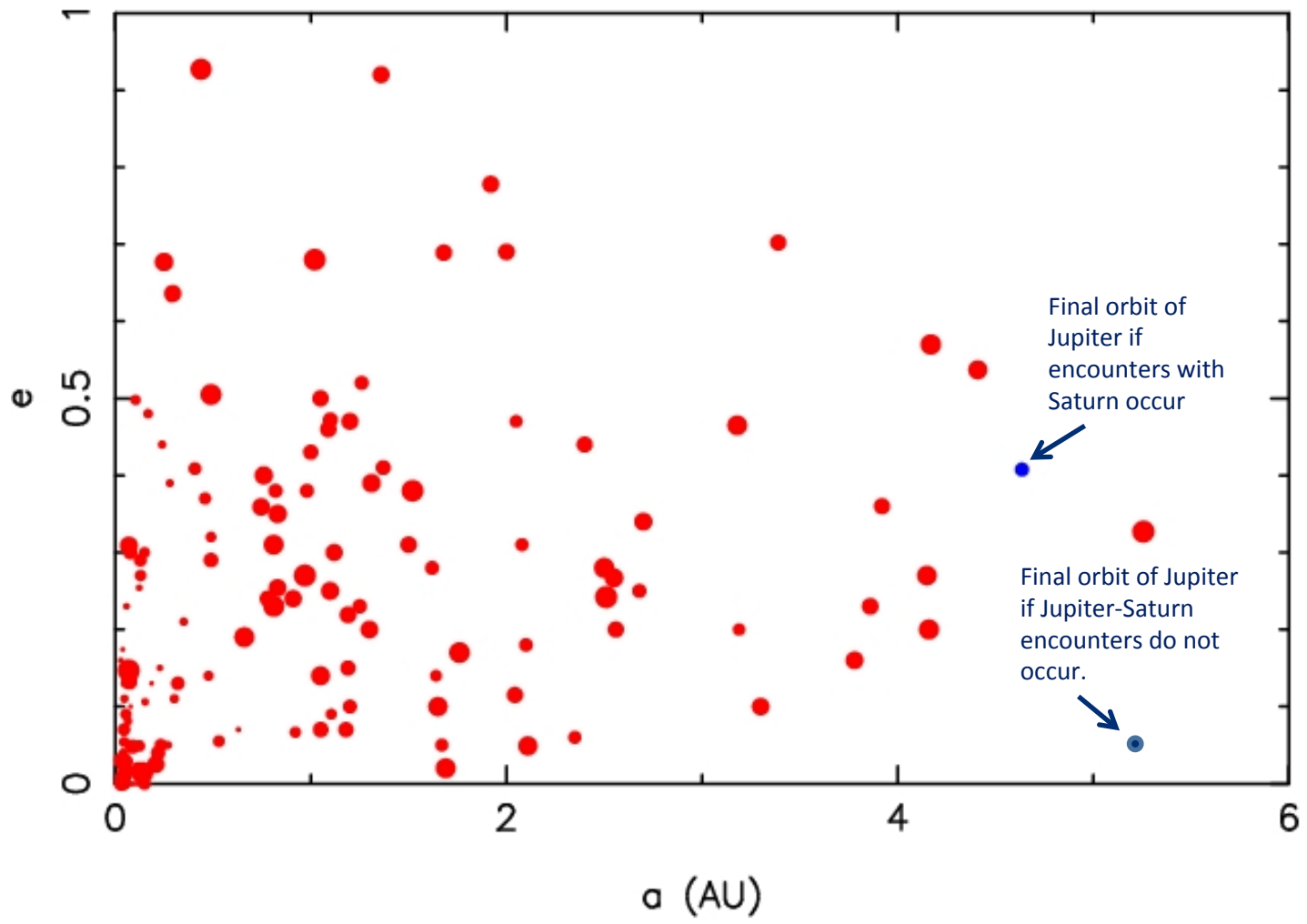
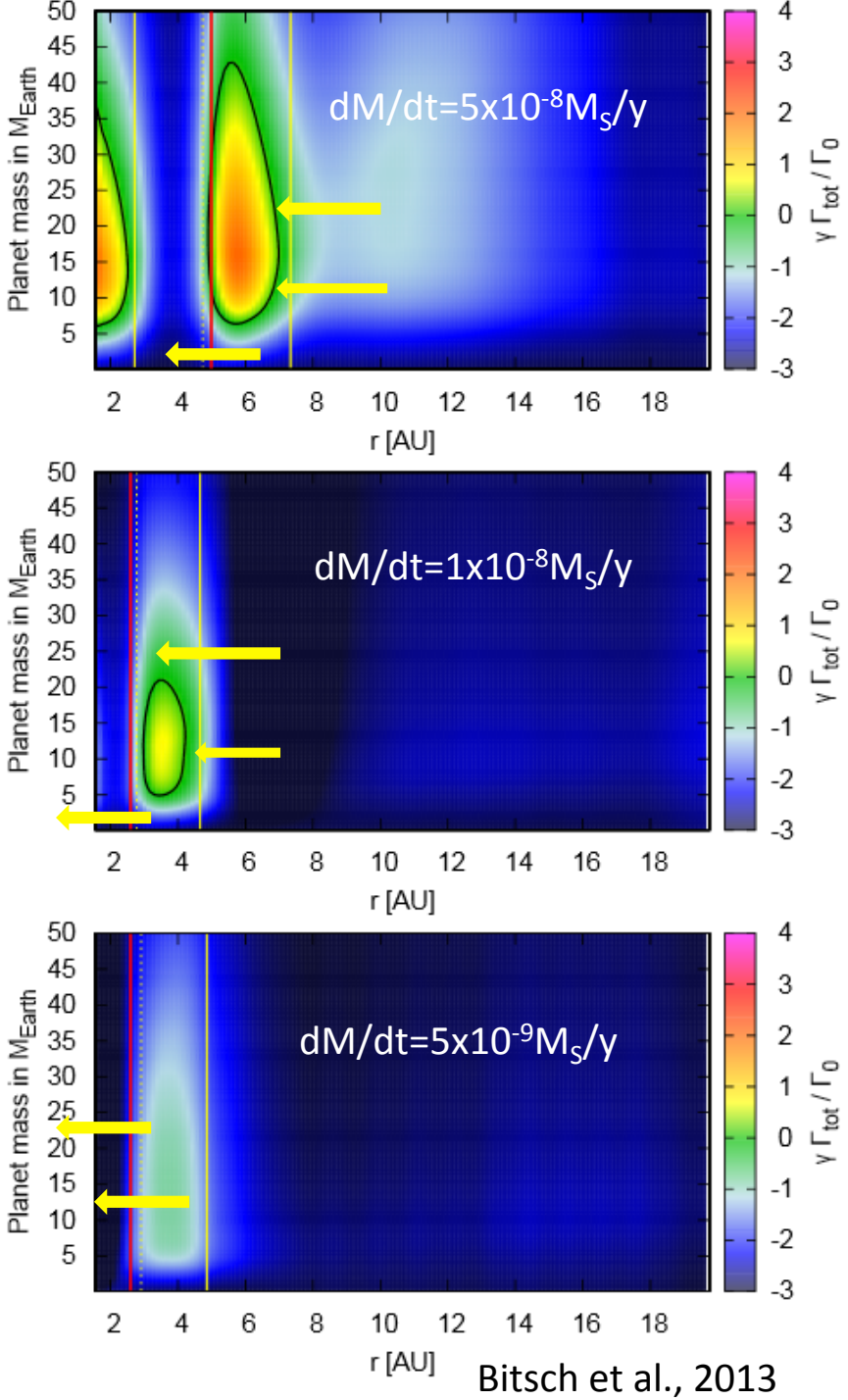

e
0
0.5
1
0
2
4
6
a (AU)
Final orbit of Jupiter if encounters with Saturn occur
Final orbit of Jupiter if Jupiter-Saturn encounters do not occur.

Conclusions

The Three Chances of our Solar System:

1. The innermost core became a giant planet
2. The mass ratio between Jupiter and Saturn prevented these planets to come to close to 1 AU
3. The giant planet instability was mild because Jupiter and Saturn avoided mutual encounters

All this suggests that the Solar System must be very a-typical



Bitsch et al., 2013

Outward migration regions work only for a limited mass-range of SENs and disappear as the disk evolves to a smaller accretion rate

All SENs should migrate from the outer disk to the inner disk, eventually.