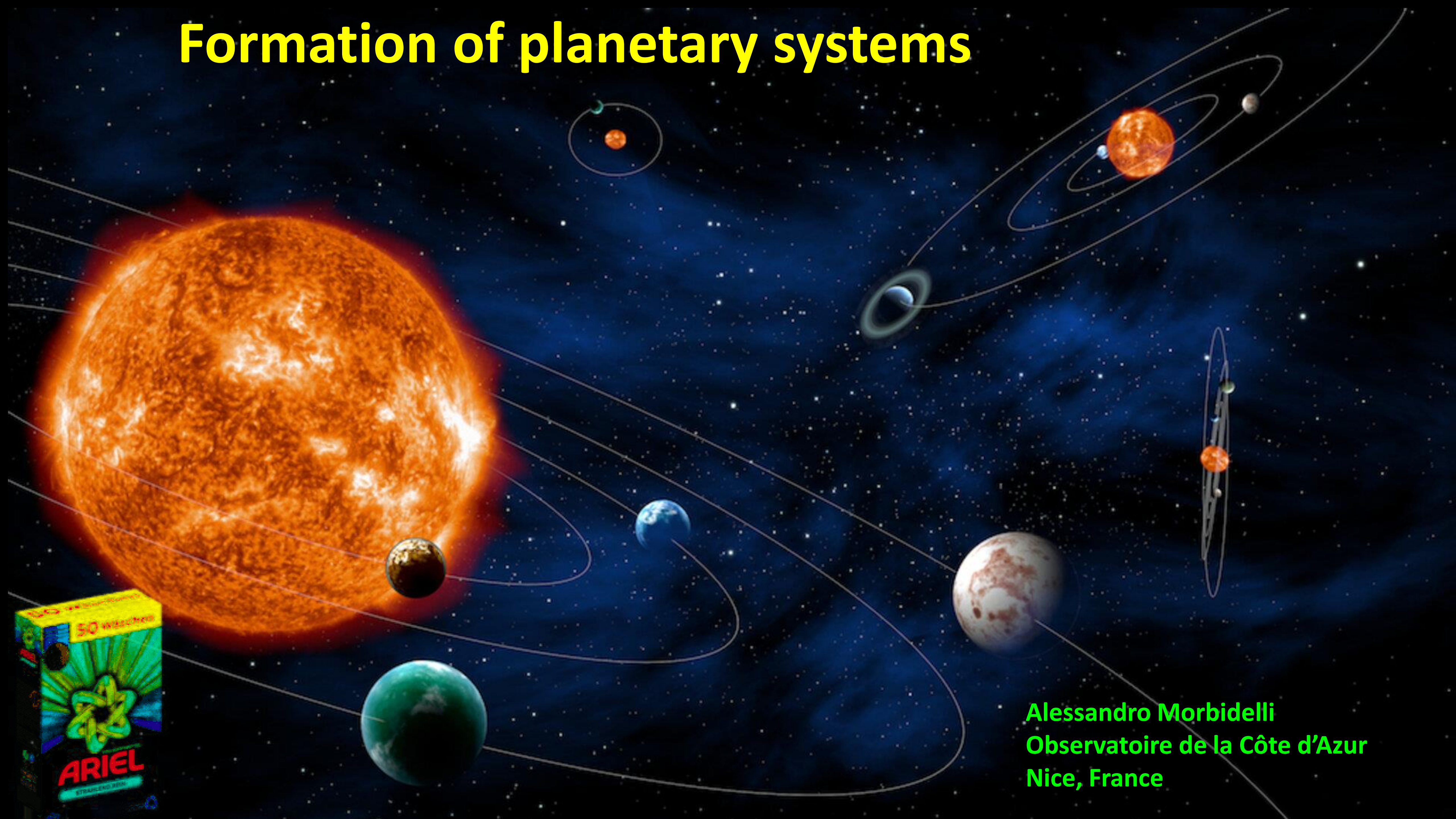
Formation of planetary systems

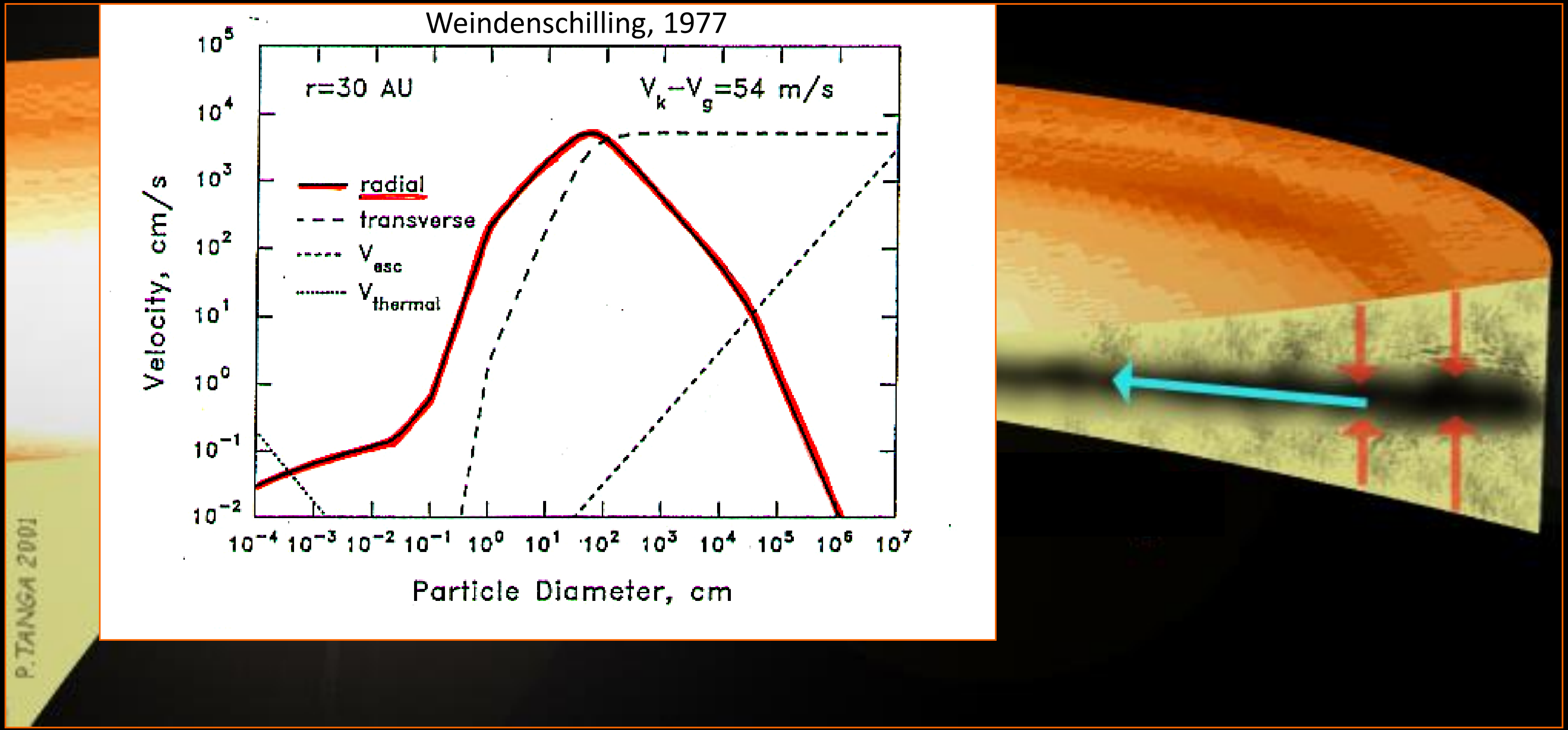


Alessandro Morbidelli
Observatoire de la Côte d'Azur
Nice, France

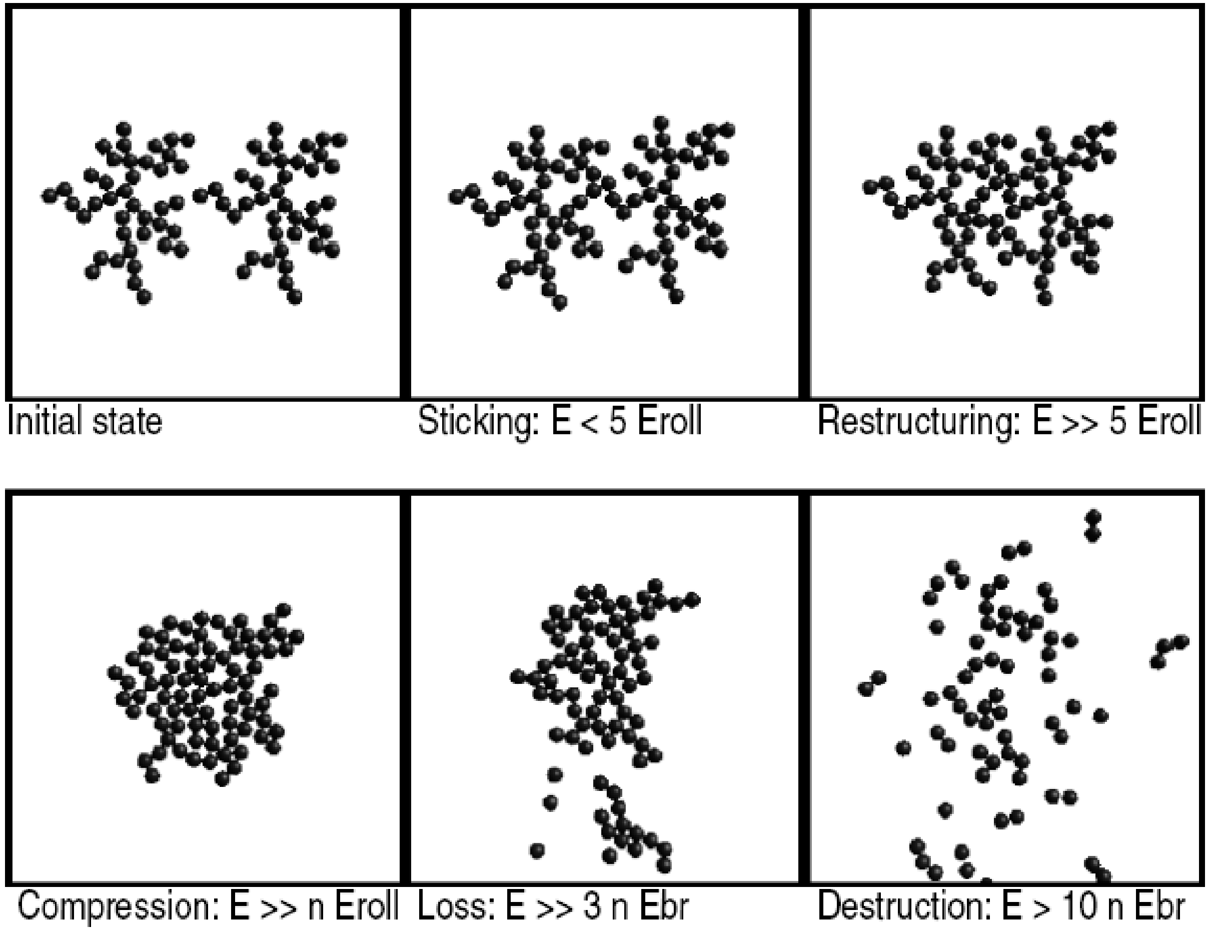
OUTLINE

- Fundamental processes (planetesimal formation, planet formation, migration,….)
- Origin of the most common properties of planetary systems.

THREE STEPS TO PLANET ACCRETION:
1) Dust coagulation, sedimentation and drift



Aggregate-aggregate collisions: results



Dominik, Tielens (1997) – Wurm, Blum (2000)

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

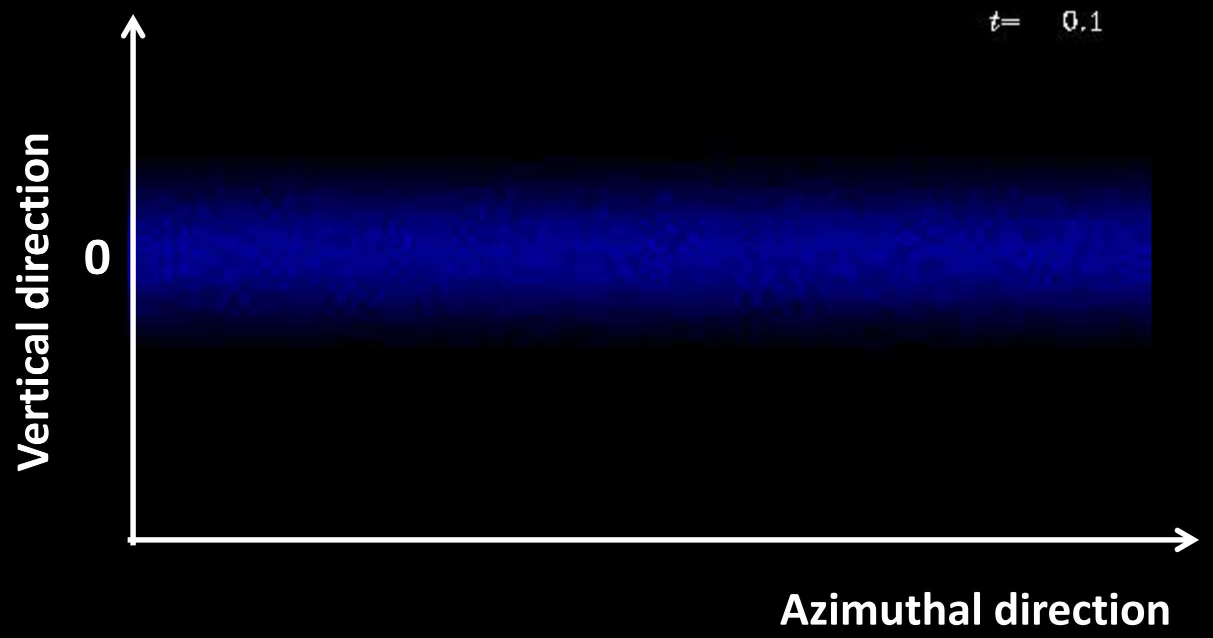
Scenario supported by the analysis of undifferentiated meteorites, which show that planetesimals are aggregates of ~mm-size particles (chondrules, CAIs,….)

THREE STEPS TO PLANET ACCRETION:
2) Planetesimal formation

Particle clumping in the disk due to

1) **Sedimentation on the mid-plane: Kelvin Helmholtz instability (Johansen et al., 2006)**
2) **Radial drift: streaming instability (Youdin and Goodman, 2005)**

Example of clumping due to settling (Johansen et al., 2006)



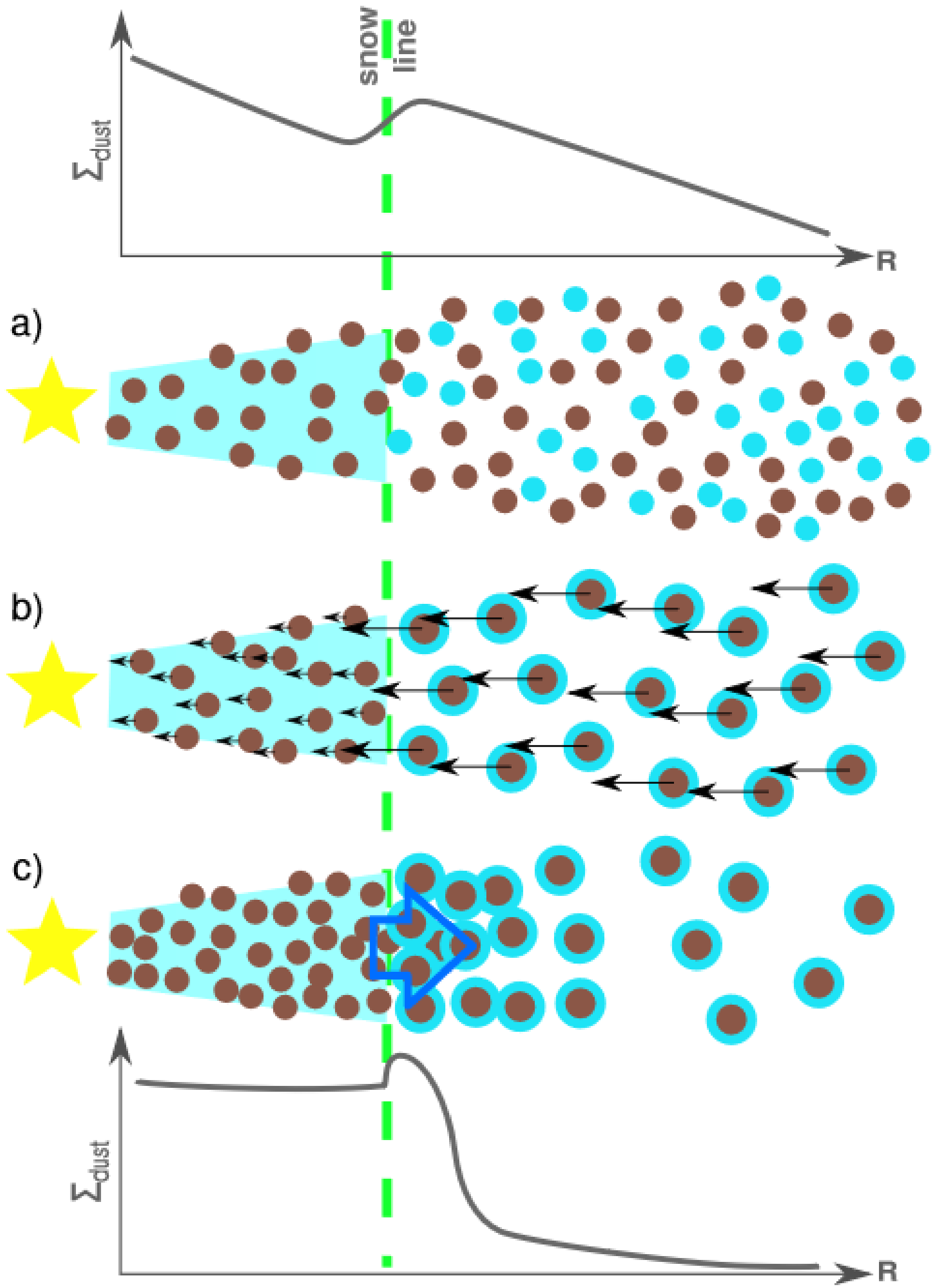
Dust clumps generated in these instabilities can contract under their own gravity and form planetesimals of typical sizes of ~100 km

All problems solved? Not really

The streaming instability can be triggered only if the average particle/gas mass ratio Z is larger than some threshold, typically a few x solar (1%).

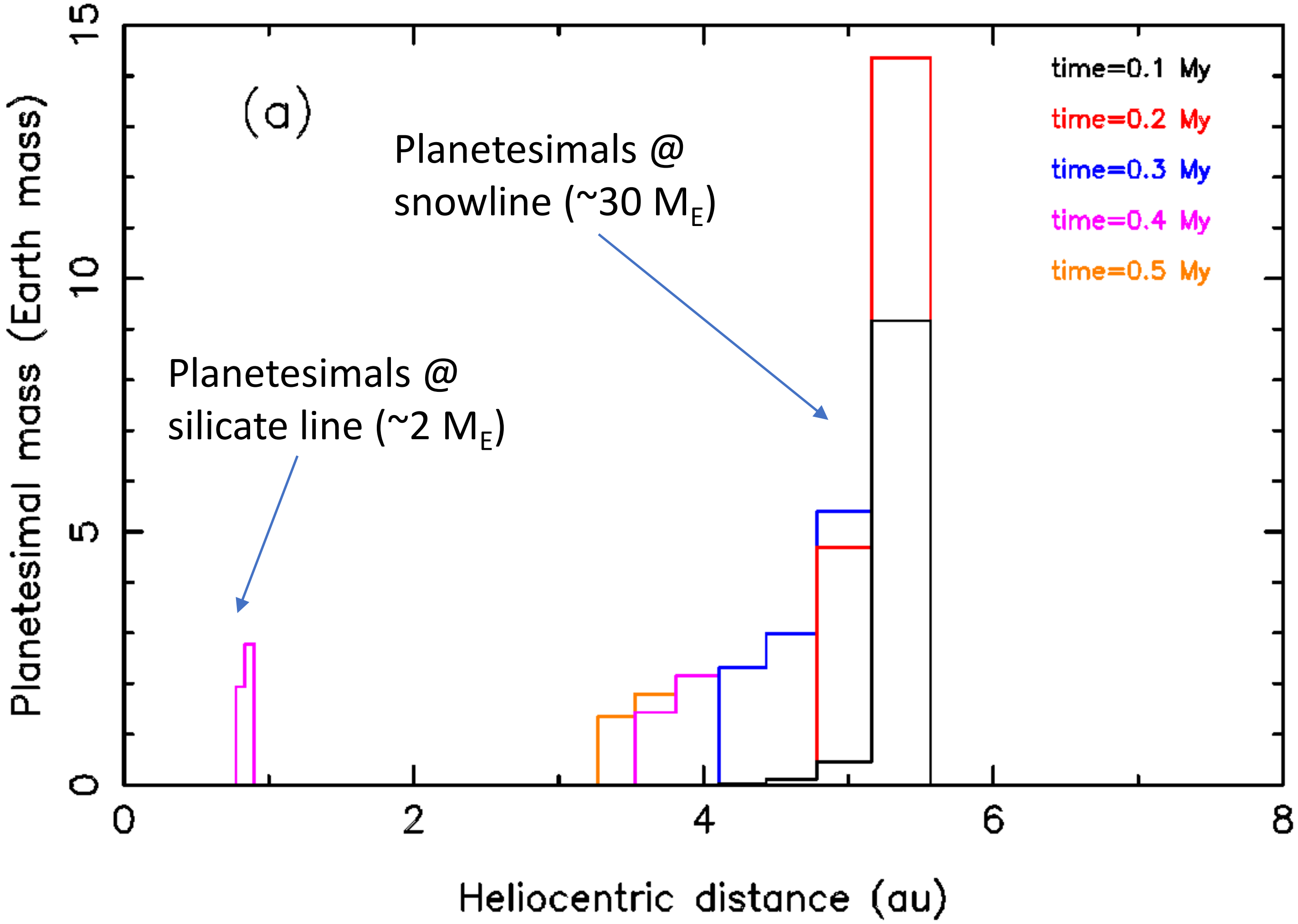
Dust needs to pile-up somewhere in the disk before the streaming instability can operate

Up to recently, solids pile-up has been shown to happen near the snowline (Ida and Guillot, 2016; Schoonenberg and Ormel, 2017; Drazkowska and Alibert, 2017)



This is in sharp contradiction with cosmochemical evidence, showing that early planetesimals formed at least at two distinct locations (iron meteorites CC and NC)

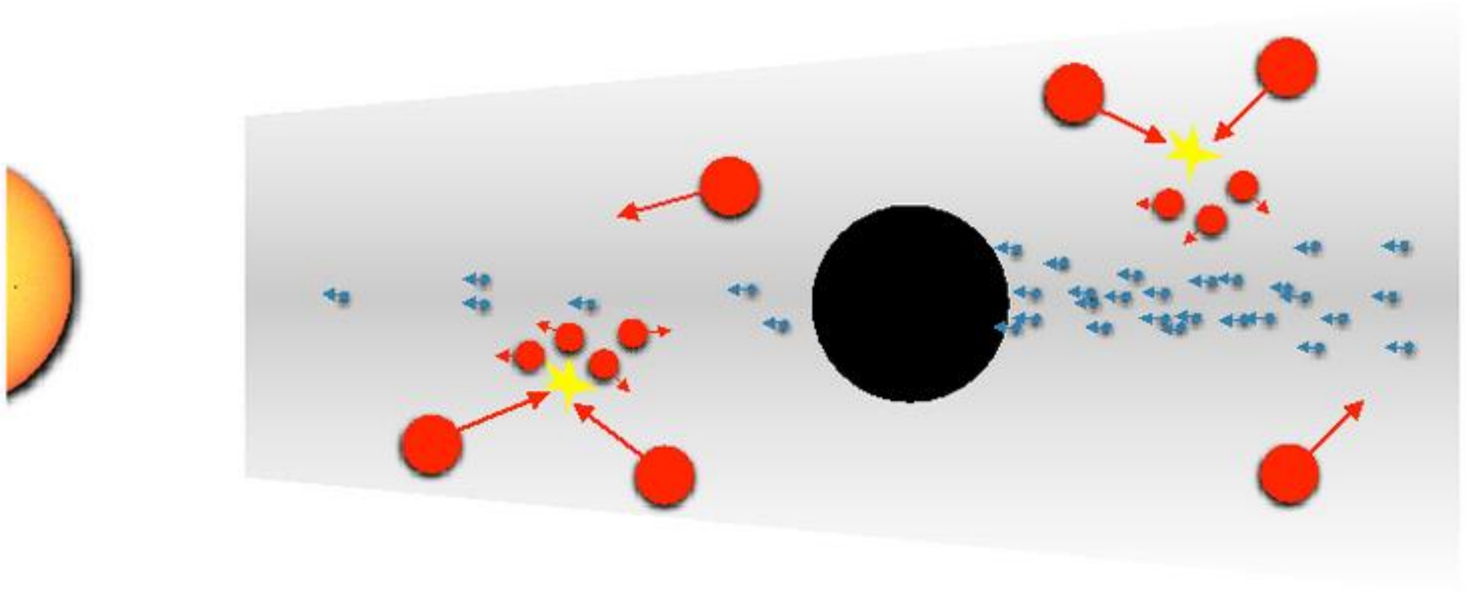
The silicate sublimation line can behave similarly, leading to the formation of a second ring of planetesimals, rocky and near the star



Morbidelli et al., 2022

THREE STEPS TO PLANET ACCRETION:
3) (proto-)planet formation

- **Planetesimals can collide with each other building protoplanets (Kokubo and Ida, 1996, 1998)**
- **The largest planetesimals keep growing by accreting individual dust particles as they drift in the gas (*pebble accretion*: Johansen and Lacerda, 2010; Ormel and Klahr, 2010; Murray-Clay et al., 2011; Lambrechts and Johansen, 2012; Ida et al., 2016)**



The "Safronov number": scattering vs accretion

- Ratio of escape speed from planet's surface to escape speed from system at planet's orbital radius

$$\theta^2 \equiv \left(\frac{Gm}{R_p}\right)\left(\frac{r}{GM_\star}\right) = 10\left(\frac{m}{M_J}\right)\left(\frac{M_\odot}{M_\star}\right)\left(\frac{R_J}{R_p}\right)\left(\frac{r}{5\ \mathrm{AU}}\right),$$

The "Safronov number": scattering vs accretion

- Saf#>1: high-mass or distant planets, scattering is preferred
- Saf#<1: low-mass or close-in planets, accretion is preferred

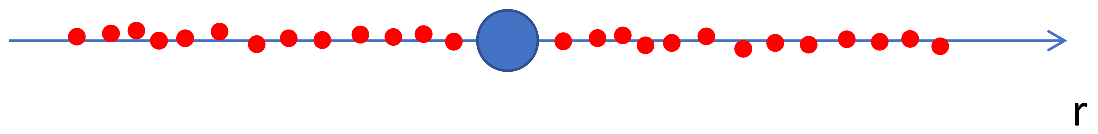
$$\theta^2 \equiv \left(\frac{Gm}{R_p}\right)\left(\frac{r}{GM_\star}\right)$$
$$= 10\left(\frac{m}{M_J}\right)\left(\frac{M_\odot}{M_\star}\right)\left(\frac{R_J}{R_p}\right)\left(\frac{r}{5\ \mathrm{AU}}\right),$$

Even with a large ∑ it is difficult to form bodies more massive than the threshold turning Saf#>1

At 5 AU the escape velocity from the Sun is 19km/s
This is the escape speed from the surface of a planet of a 5 Earth-mass planet

Two big advantages of pebble-accretion over planetesimal-planetesimal accretion:

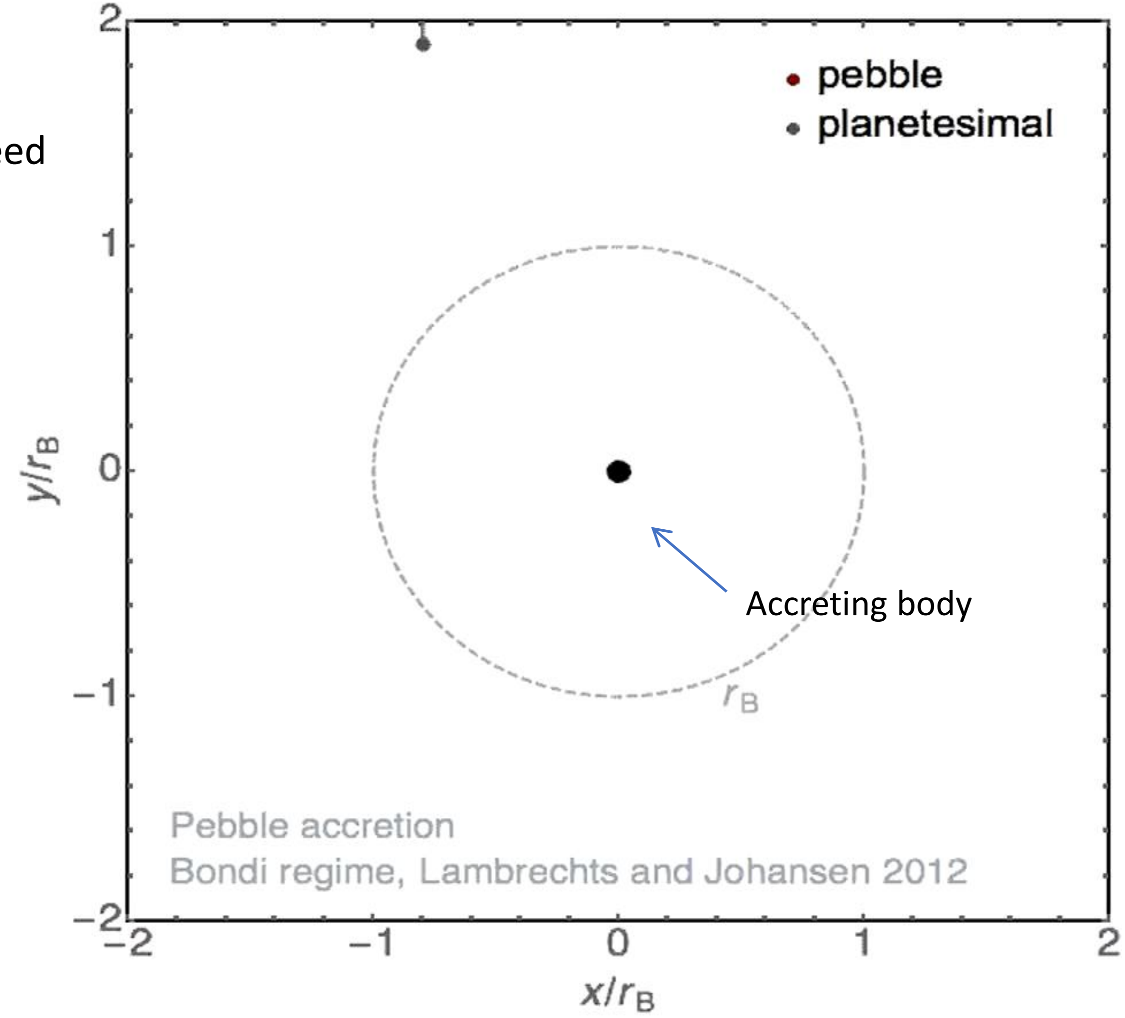
I) No isolation



Two big advantages of pebble-accretion over planetesimal-planetesimal accretion :
II) Larger accretion cross-section

$$r_B = \frac{GM_c}{\Delta v^2}$$

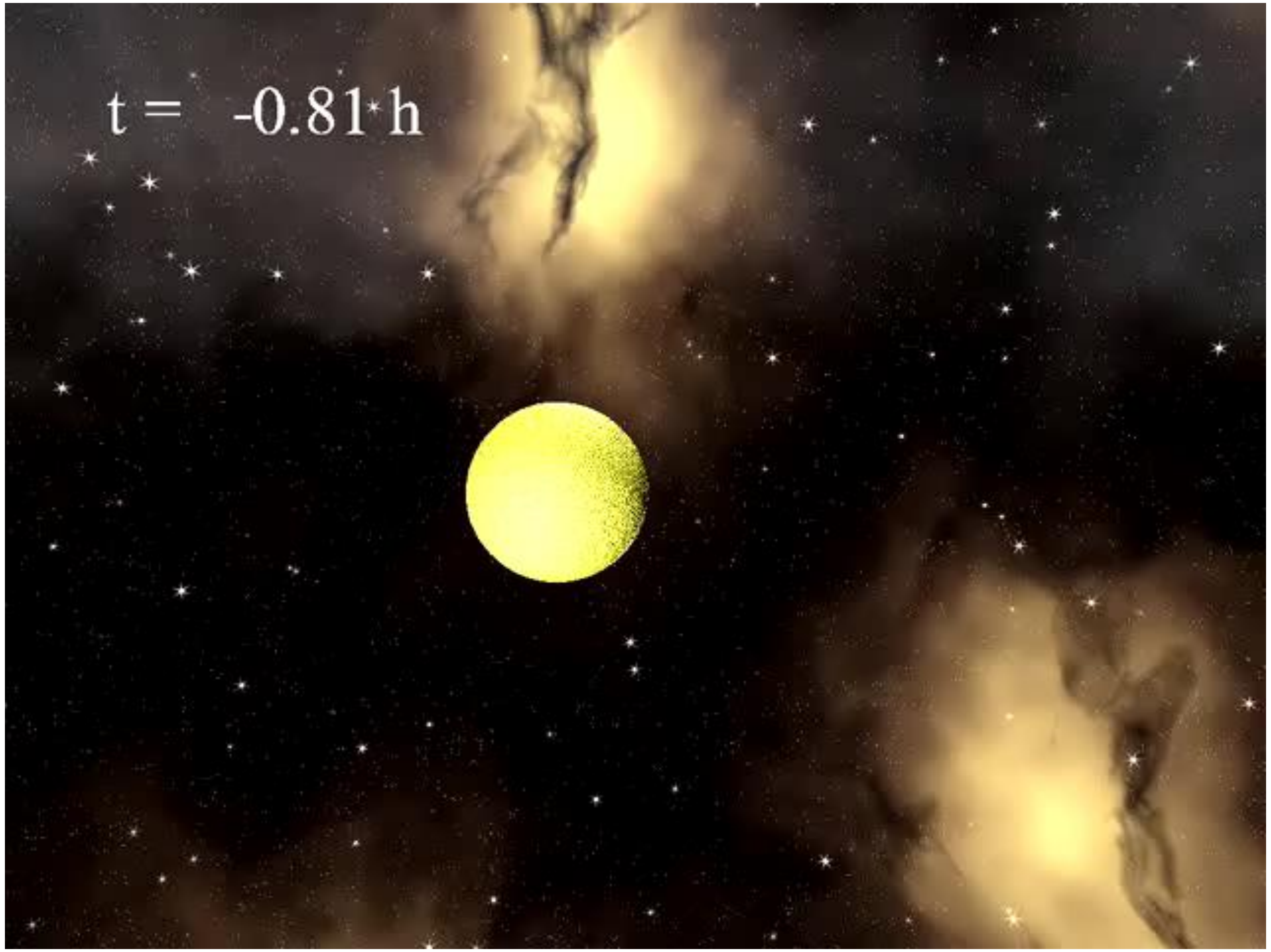
relative speed



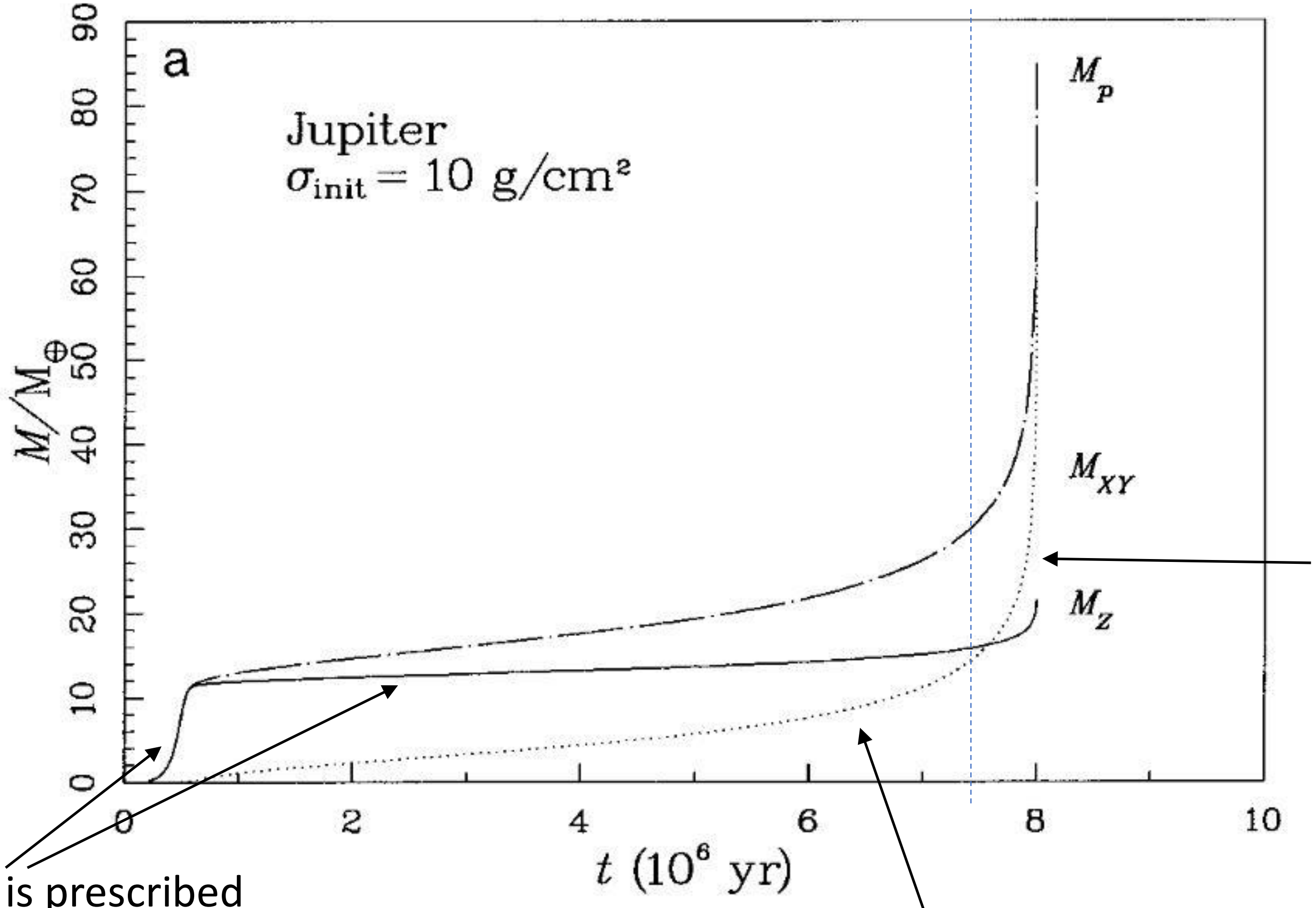
Of course, for pebble-accretion to be effective a large enough flux of pebbles through the disk is needed….

If this is the case, then giant planet cores can form within the disk's lifetime (Lambrechts et al., 2014)

Planet formation by planetesimal/pebble accretion can be complemented by:
I) a phase of giant impacts



Planet formation by planetesimal/pebble accretion can be complemented by: II) accretion of a gas envelope



Pollack et al. (1996)

No hydrostatic equilibrium possible:
runaway gas accretion

Growth of M_c is prescribed

Gas envelope in hydrostatic equilibrium

An alternative giant planet formation mode:
Disk instability

- Requires a region in the disk to be Toomre unstable

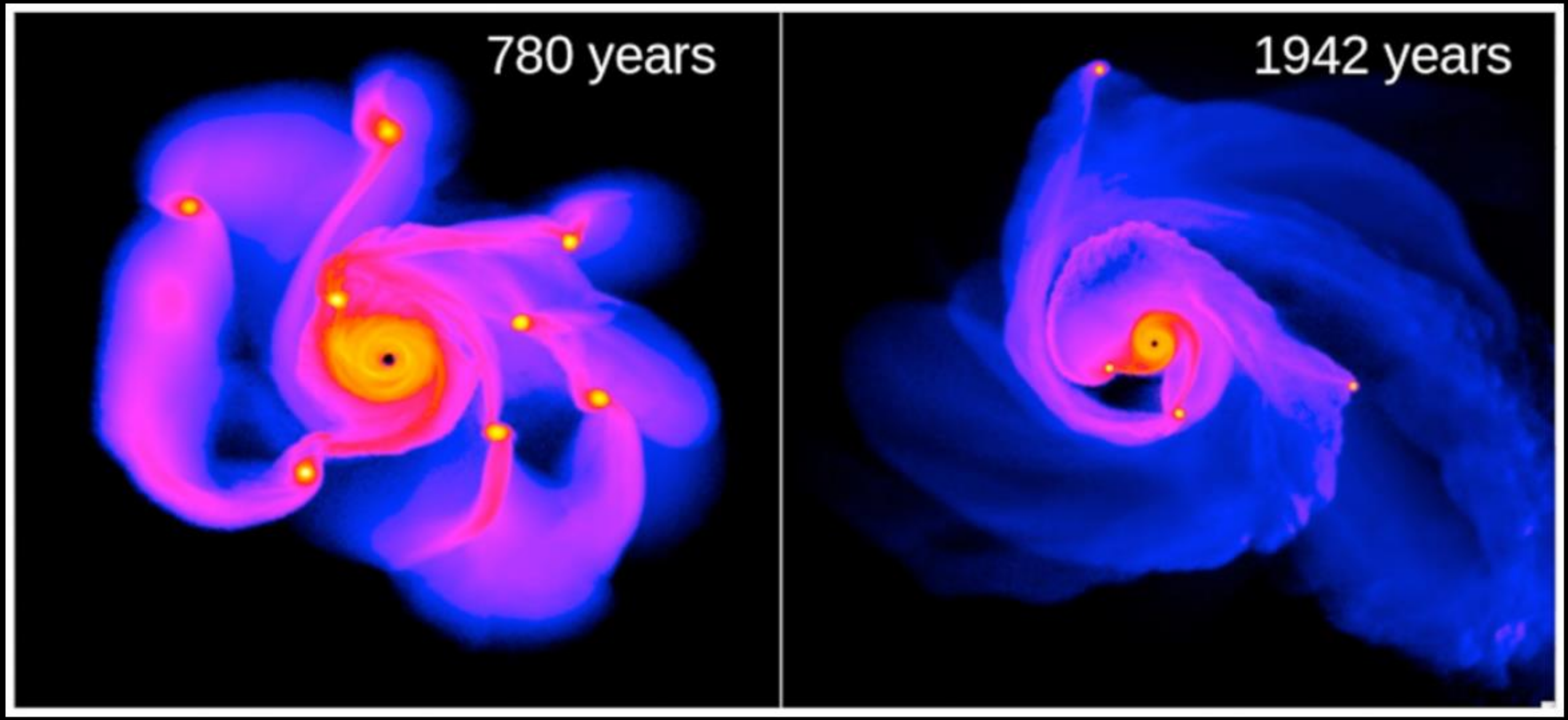
sound speed

orbital frequency

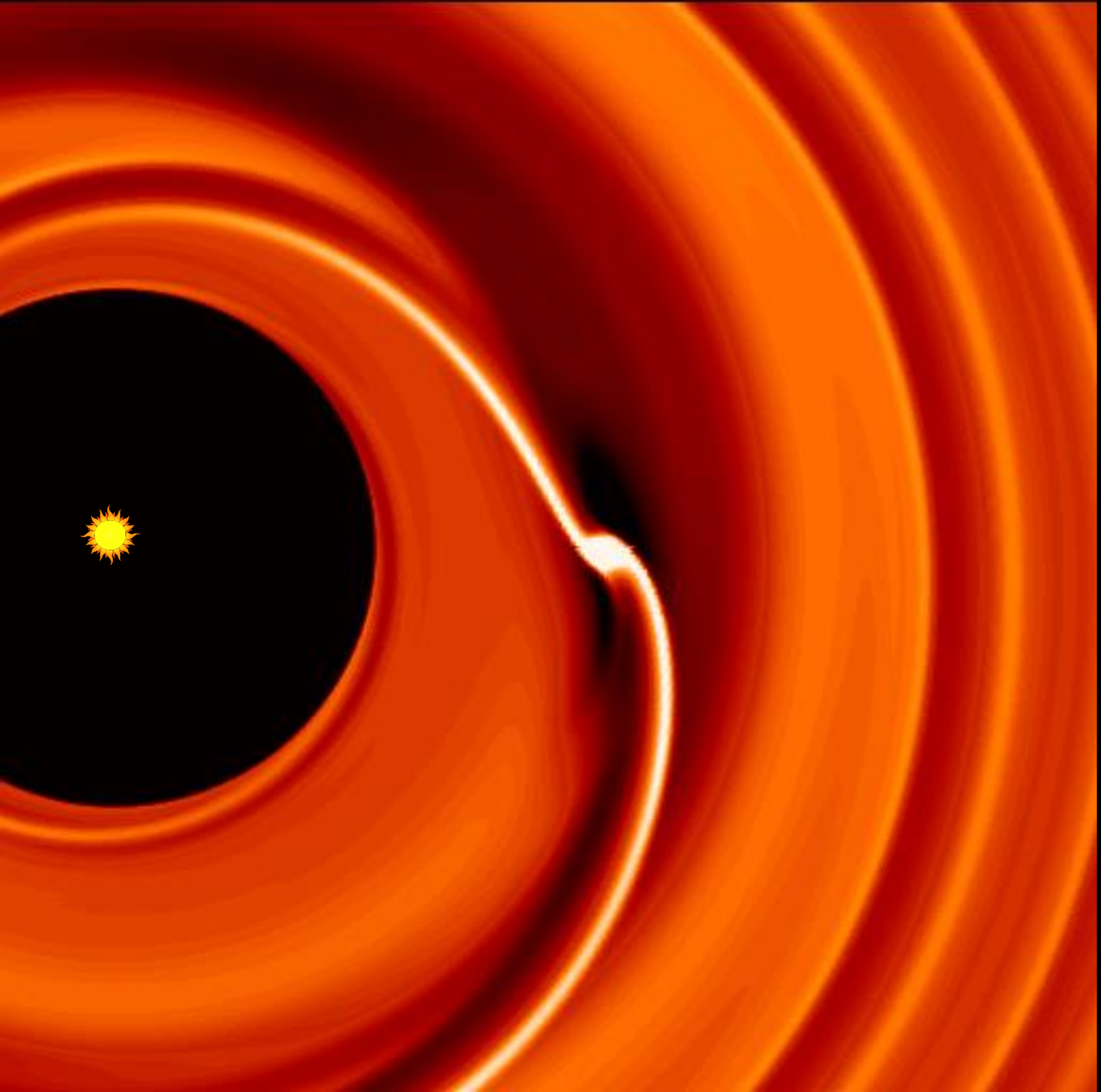
$$\boxed{Q \equiv \frac{c_s \Omega}{\pi G \Sigma} < Q_{\text{crit}} \simeq 1}$$

surface density

An alternative giant planet formation mode:
Disk instability

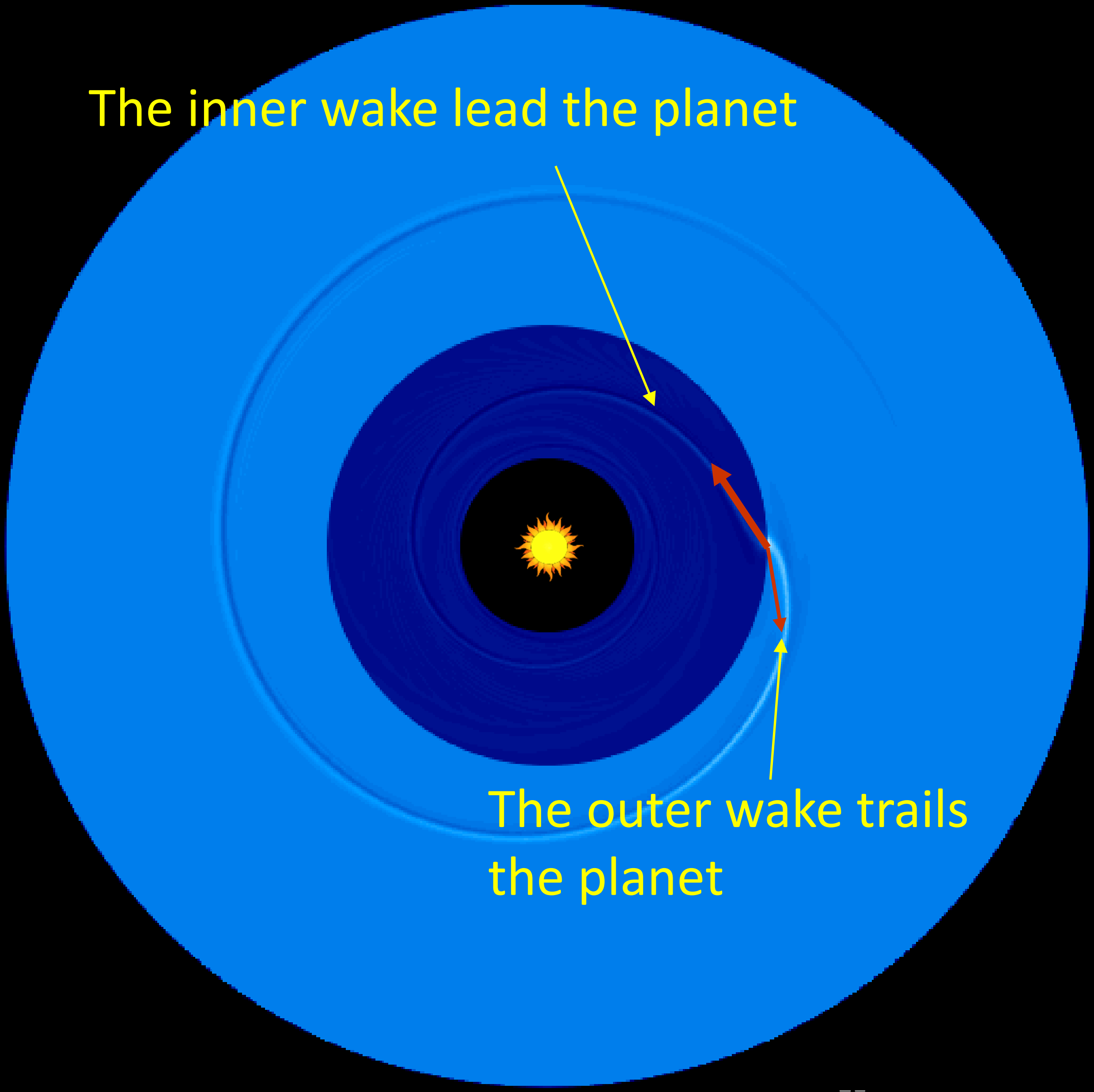


Mayer & Quinn (2016)



Planet Migration

Migration of small planets (Type-I)



The outer wake exerts a negative torque on the planet

The outer wake usually wins: inward migration

The inner wake exerts a positive torque on the planet

Type-I migration in brief

The migration speed is proportional to

→ The planet mass M

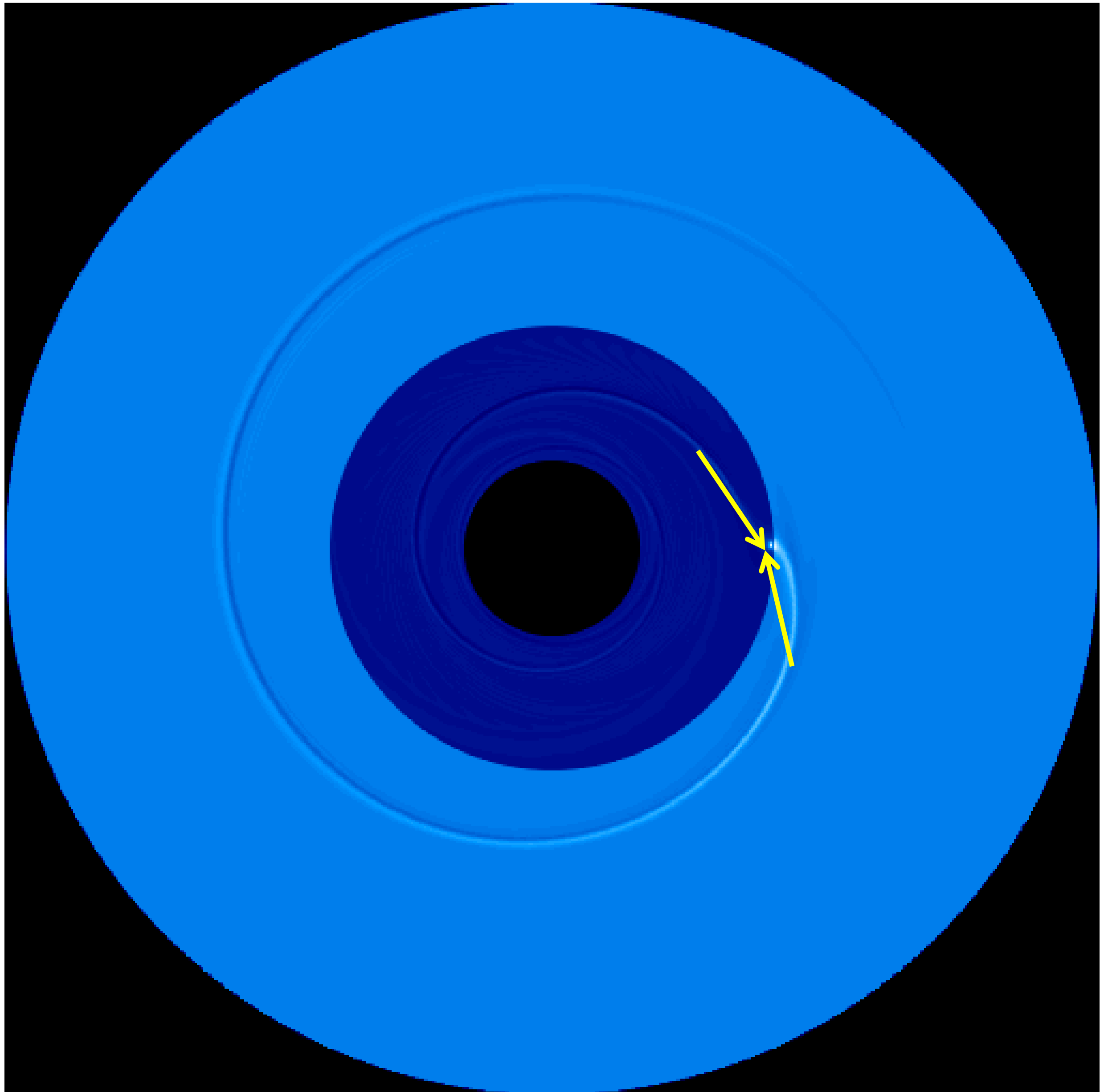
→ The surface density of the disk ∑

→ The inverse square of the disk's aspect ratio: $(r/H)^2$

$dh_p/dt \sim M\,(r/H)^2\,\Sigma\,r$ (h_p is the specific ang. mom. of the planet)
where all quantities are evaluated at the planet's location

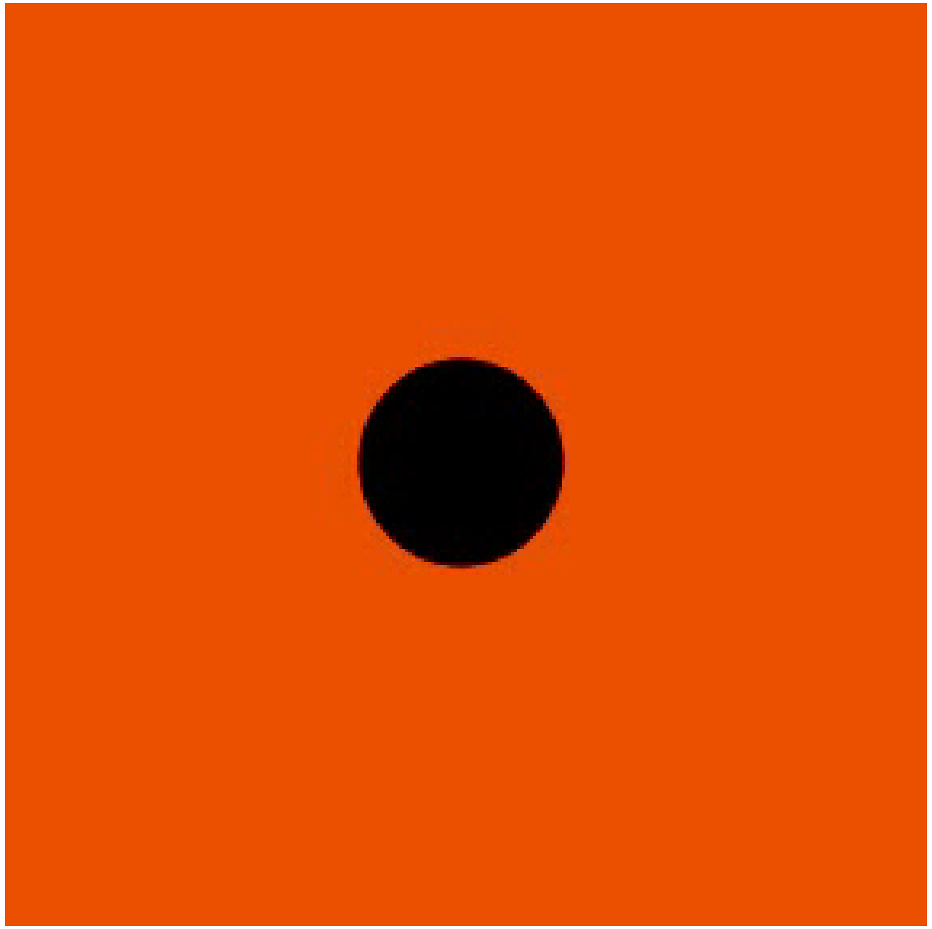
- *The migration speed is independent of the disk's viscosity*

How a massive planet sculpts the disk: gap opening



The planet accelerates the outer disk and pushes it forward and decelerates the inner disk and pushes it inwards. If the force exerted by the planet overcomes the internal (viscous) disk forces, a gap opens

Massive planets and gap opening



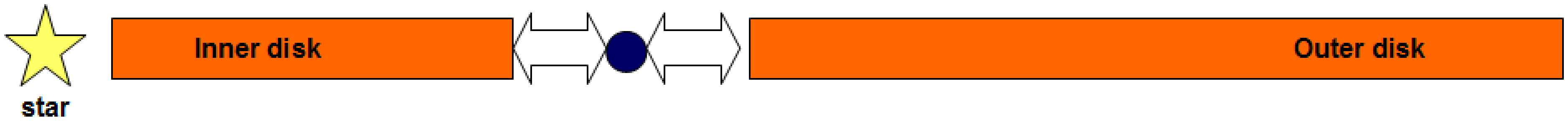
The planet accelerates the outer disk and pushes it forward and decelerates the inner disk and pushes it inwards. If the force exerted by the planet overcomes the internal (viscous) disk forces, a gap opens

The effect of the gap on planet migration

TYPE II MIGRATION

The planet is repelled
→ outwards by the inner disk
→ inwards by the outer disk.

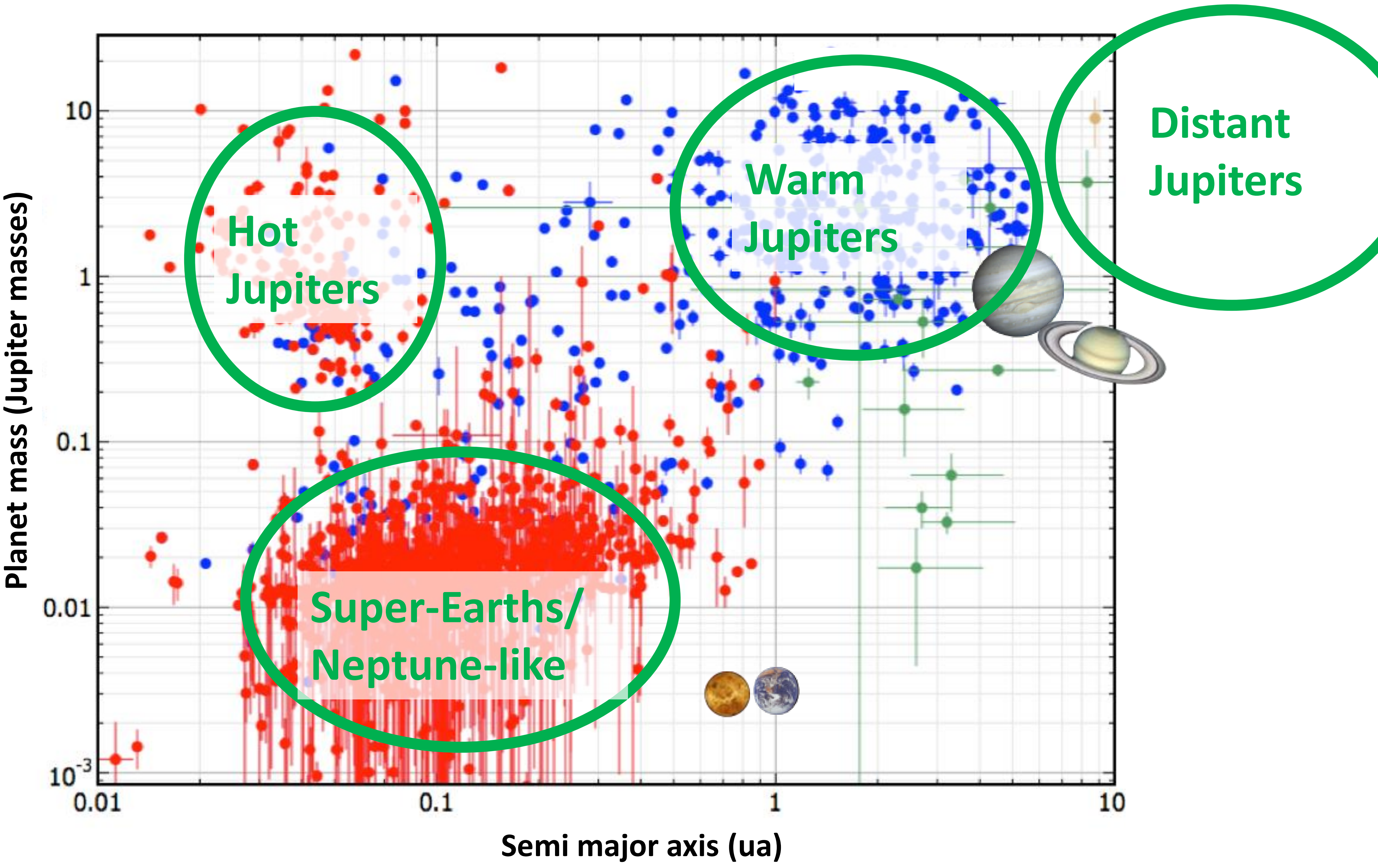
It is locked in the middle of the gap, and can not migrate **with respect to** the gas of the disk anymore.



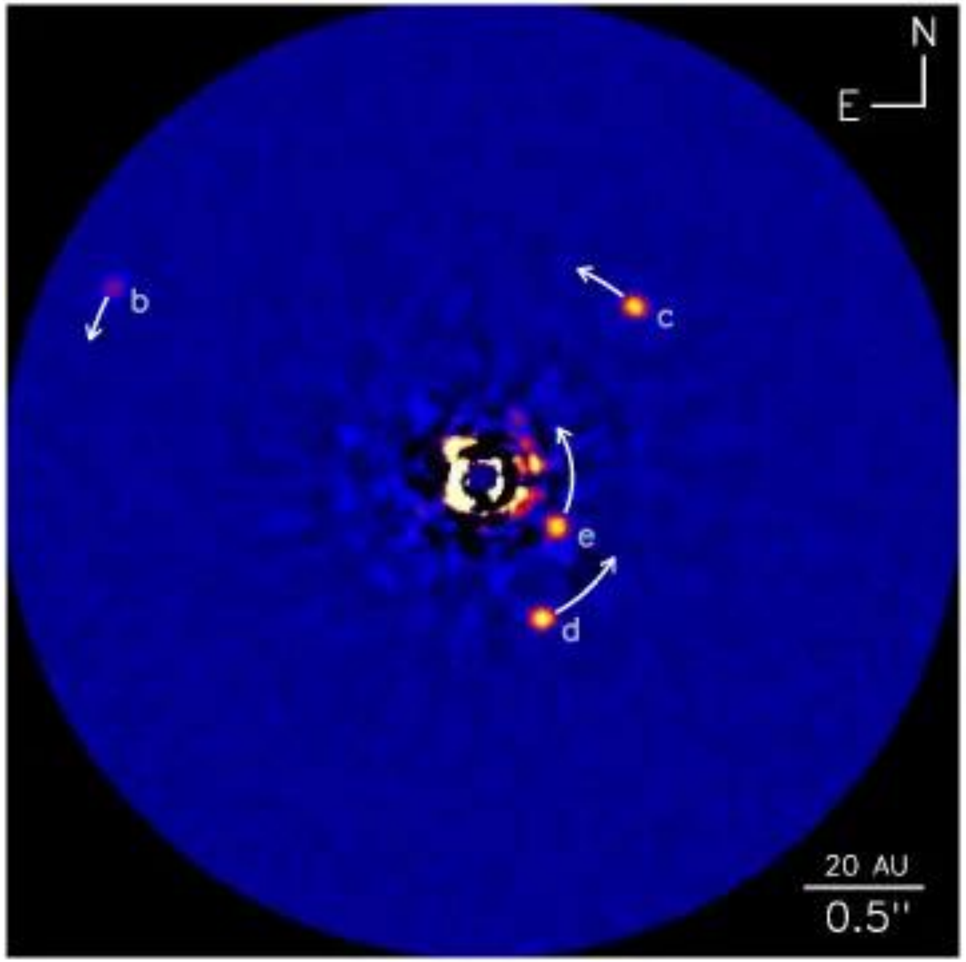
But the disk falls onto the star (accretion), driving the planet inwards.

Hence, the migration rate v_r^{pl} should be equal to v_r^{gas} =-3/2 ν/r (independent of ∑ and M_{pl})

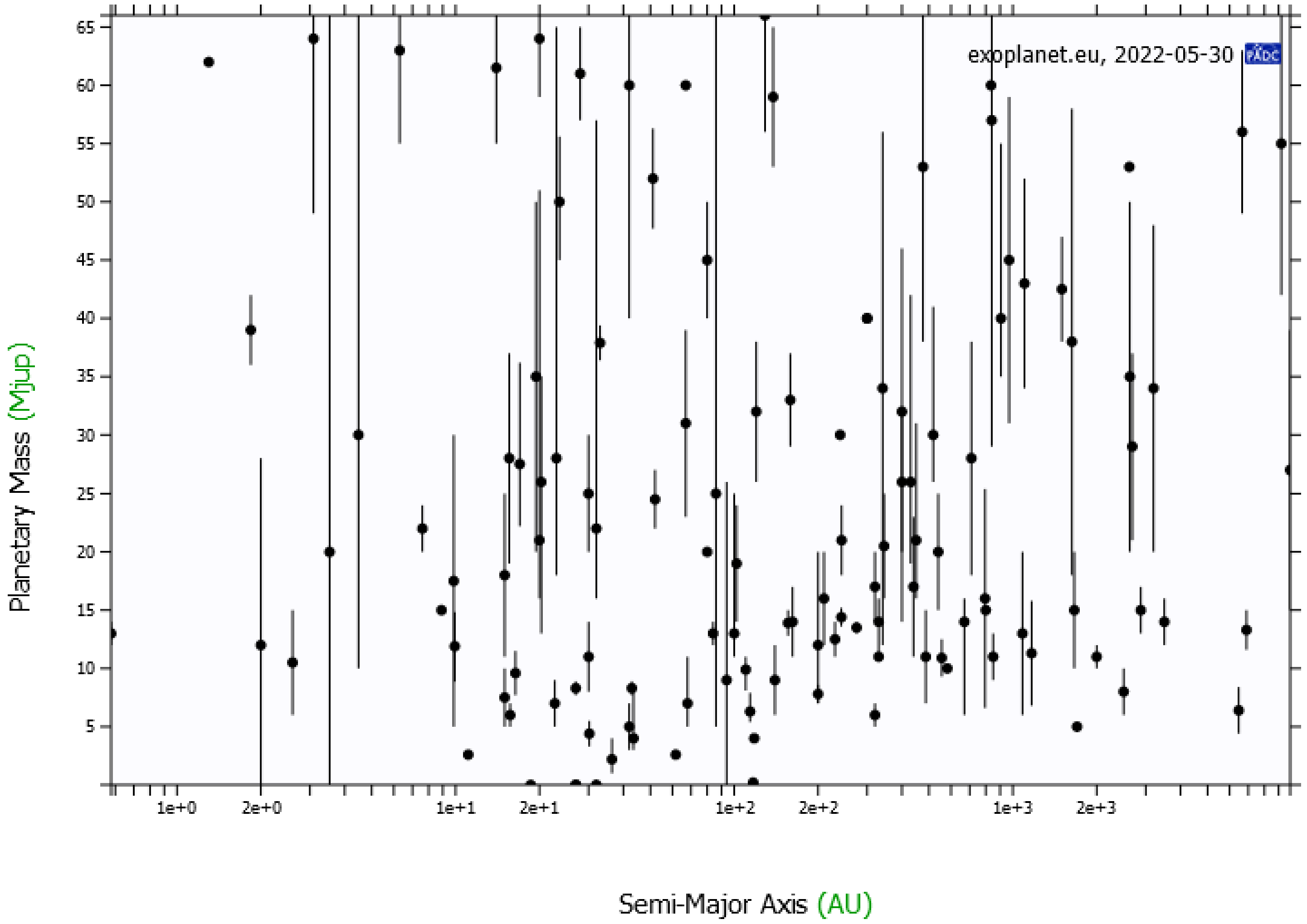
Part II:
Origin and evolution of extrasolar planet systems


Hot
Jupiters
Warm
Jupiters
Distant
Jupiters
Super-Earths/
Neptune-like
10
1
0.1
0.01
10^-3
0.01
0.1
1
10
Planet mass (Jupiter masses)
Semi major axis (ua)

Giant planets

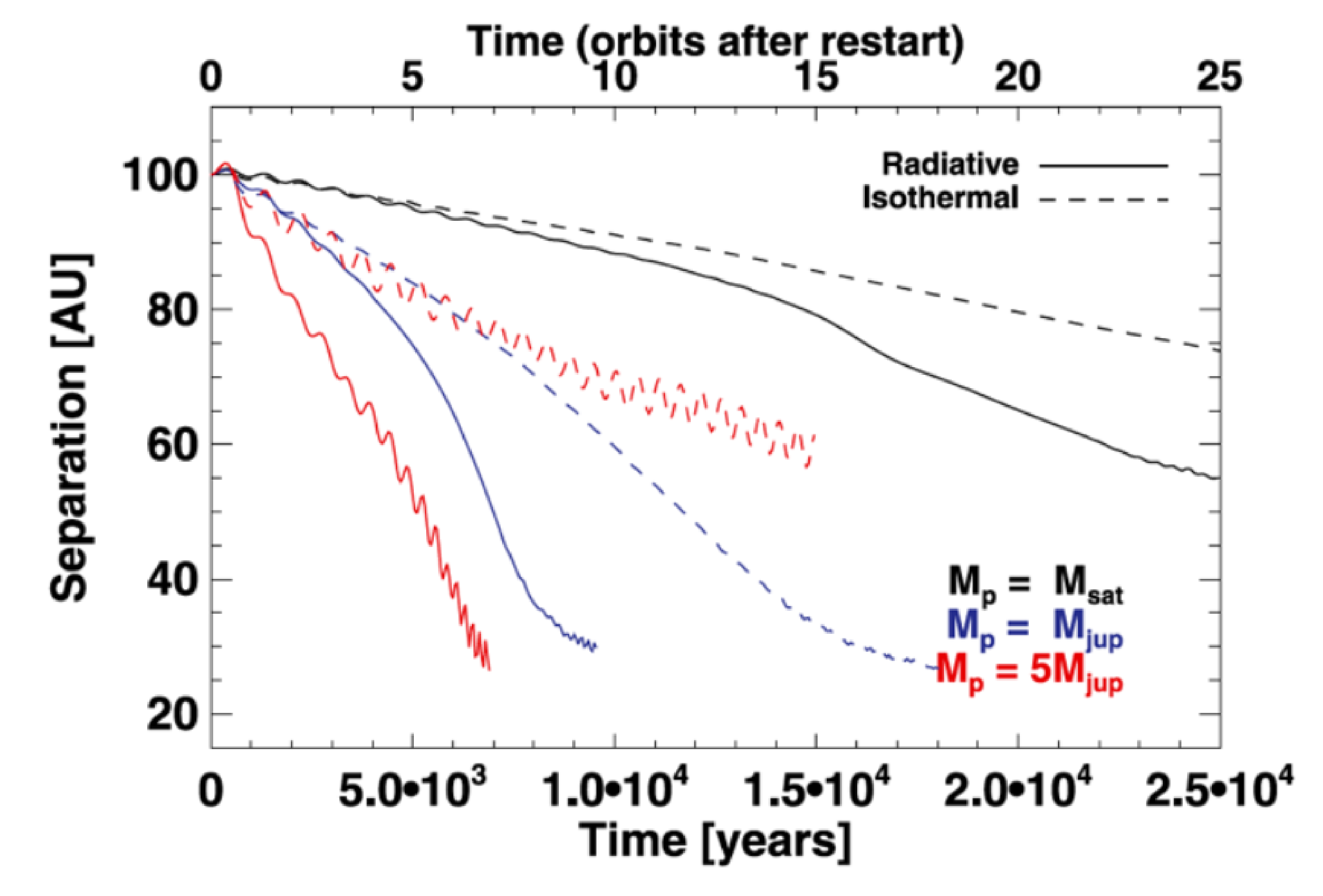


Gravitational instability: the direct imaged “planets” are the best candidates



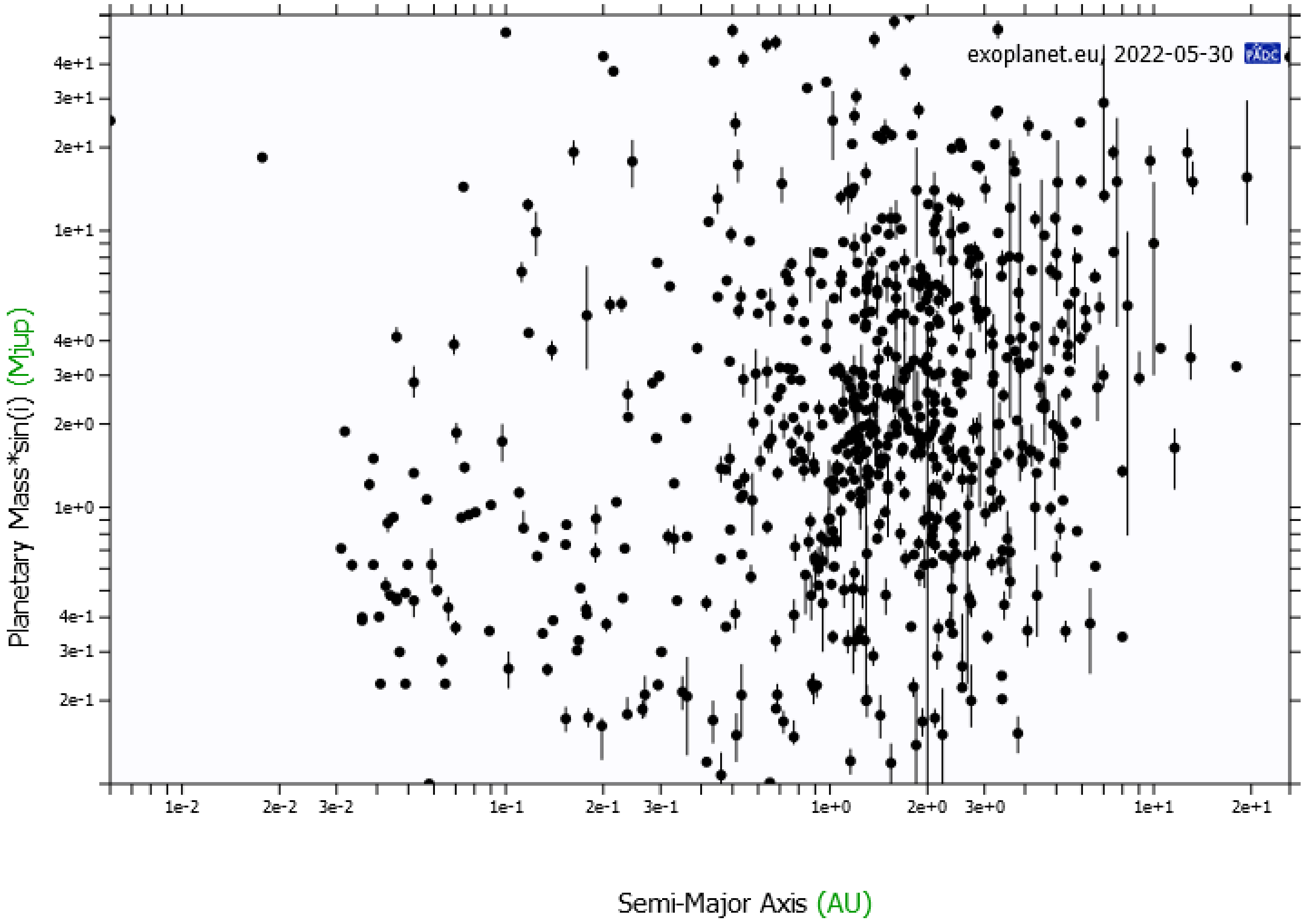
Clumps formed by disk instability migrate inward rapidly

should



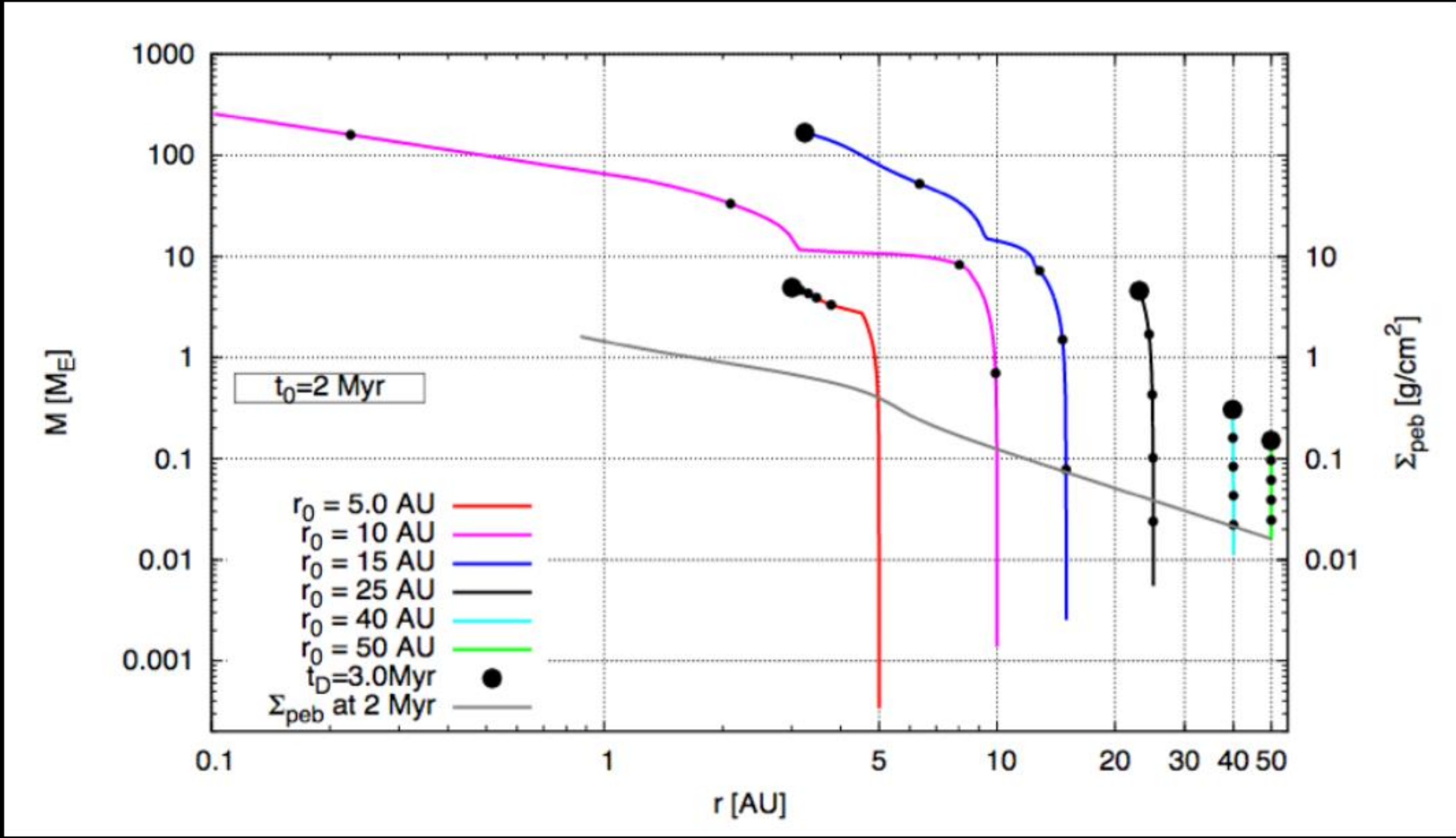
Baruteau et al (2012);
"tidal downsizing hypothesis" by Nayakshin (2010)

Core accretion: all other giant planets are the best candidates



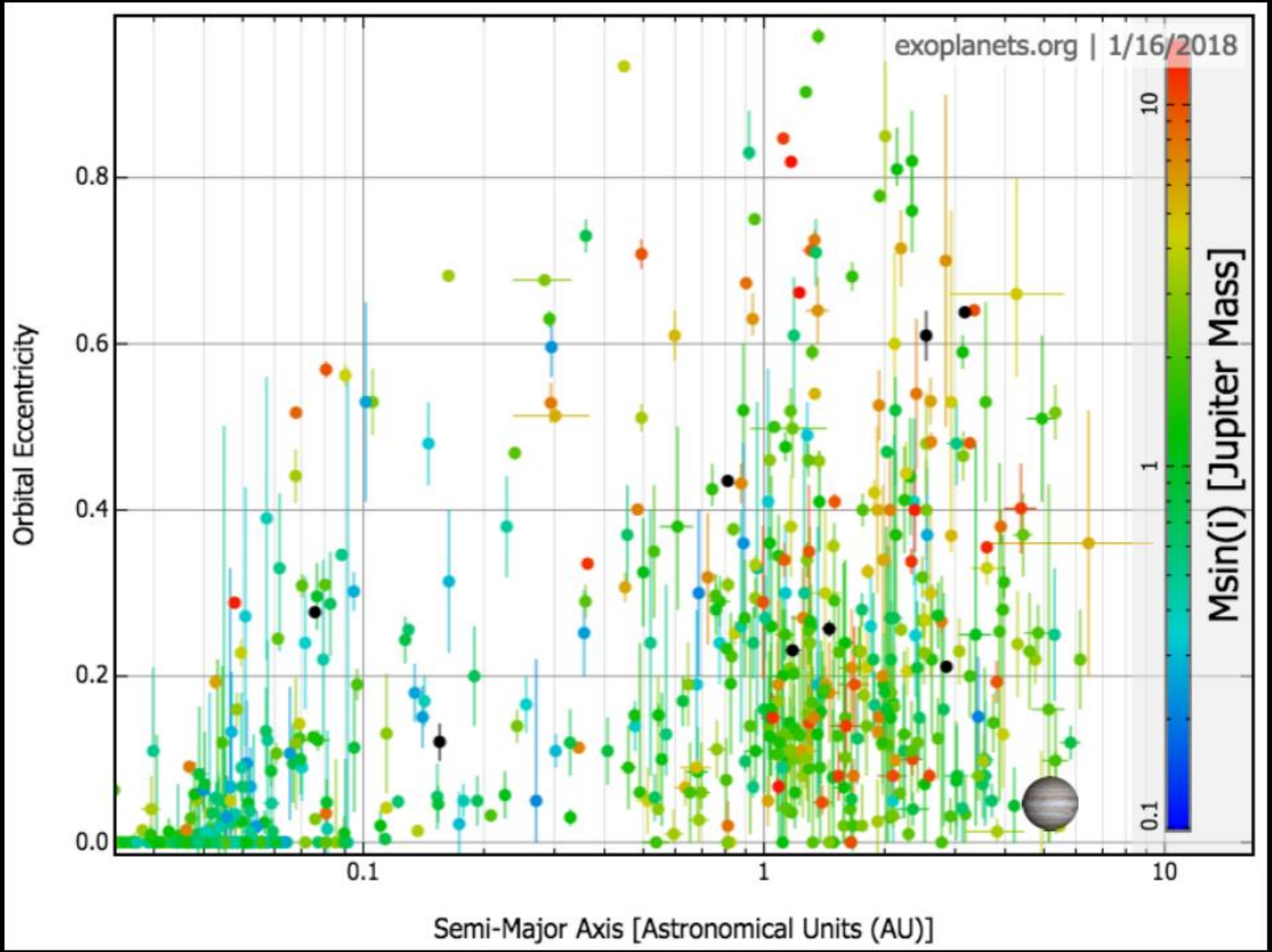
Growth tracks with pebble accretion and migration

Migration remains a main issue



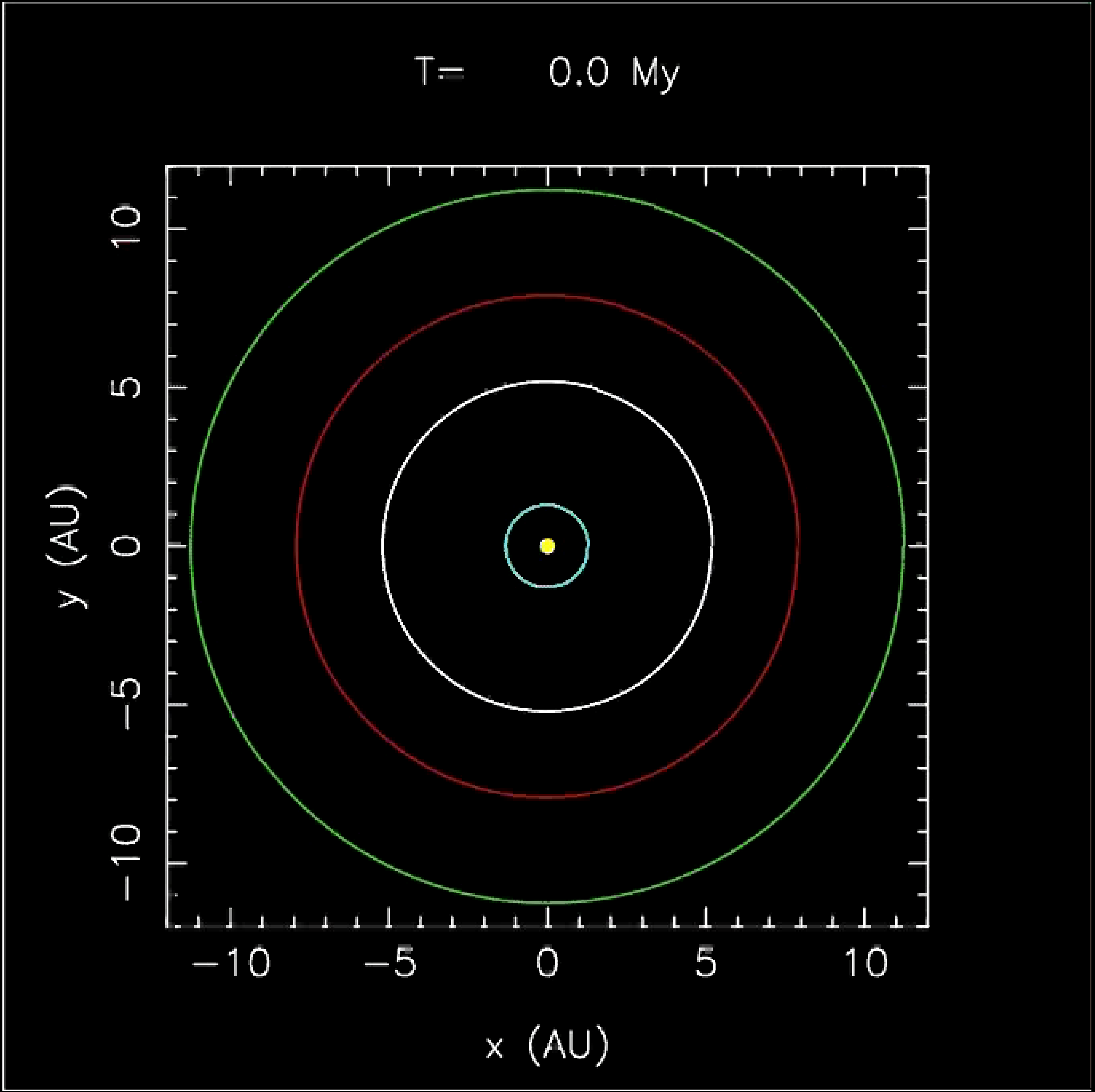
Bitsch et al 2015

Eccentricity distribution (giants)



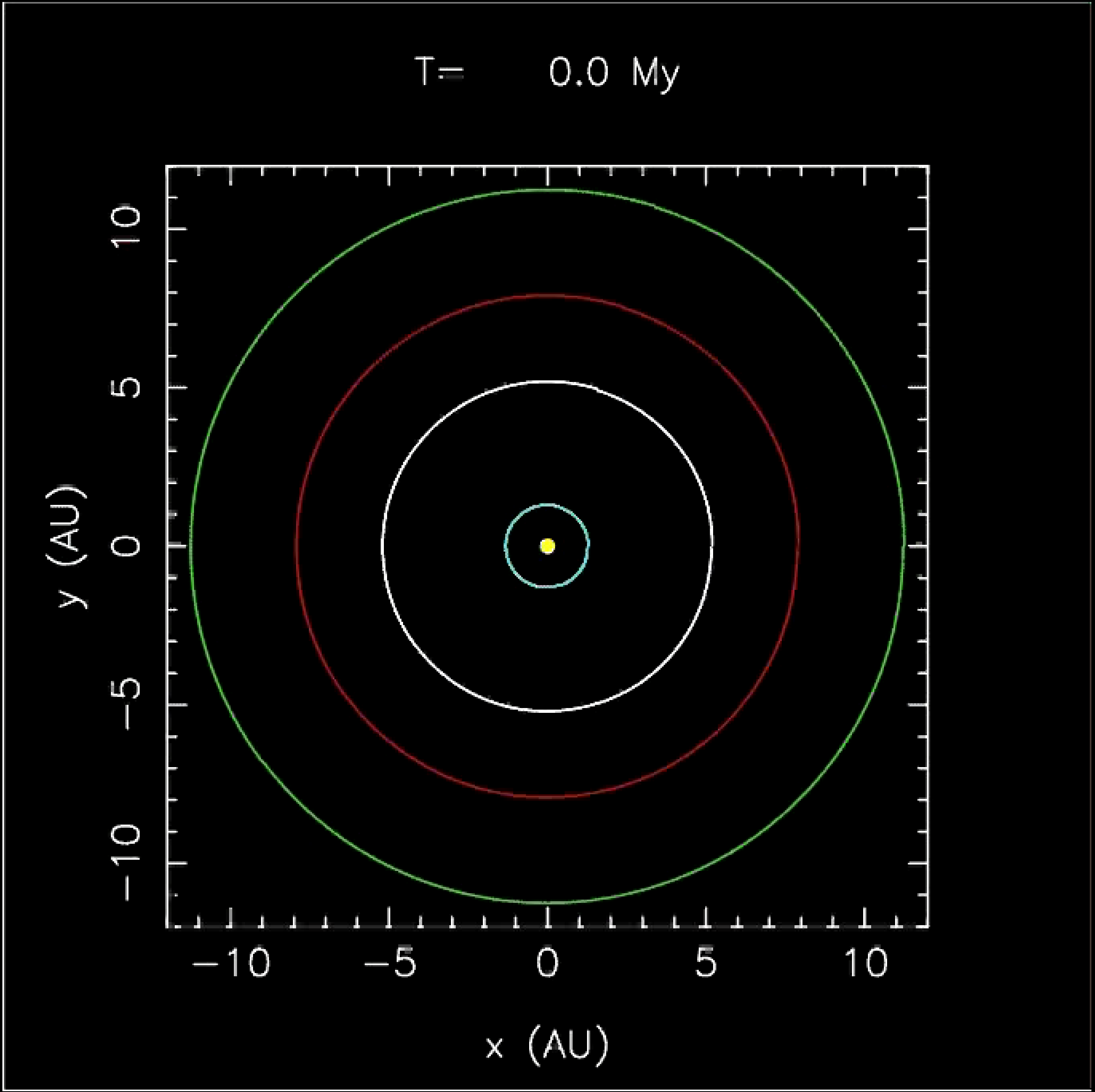
Wright et al 2011

Planet-planet scattering during a giant planet instability is considered to be the best explanation for the eccentricity distribution of the (surviving) planets



Credit: S. Raymond

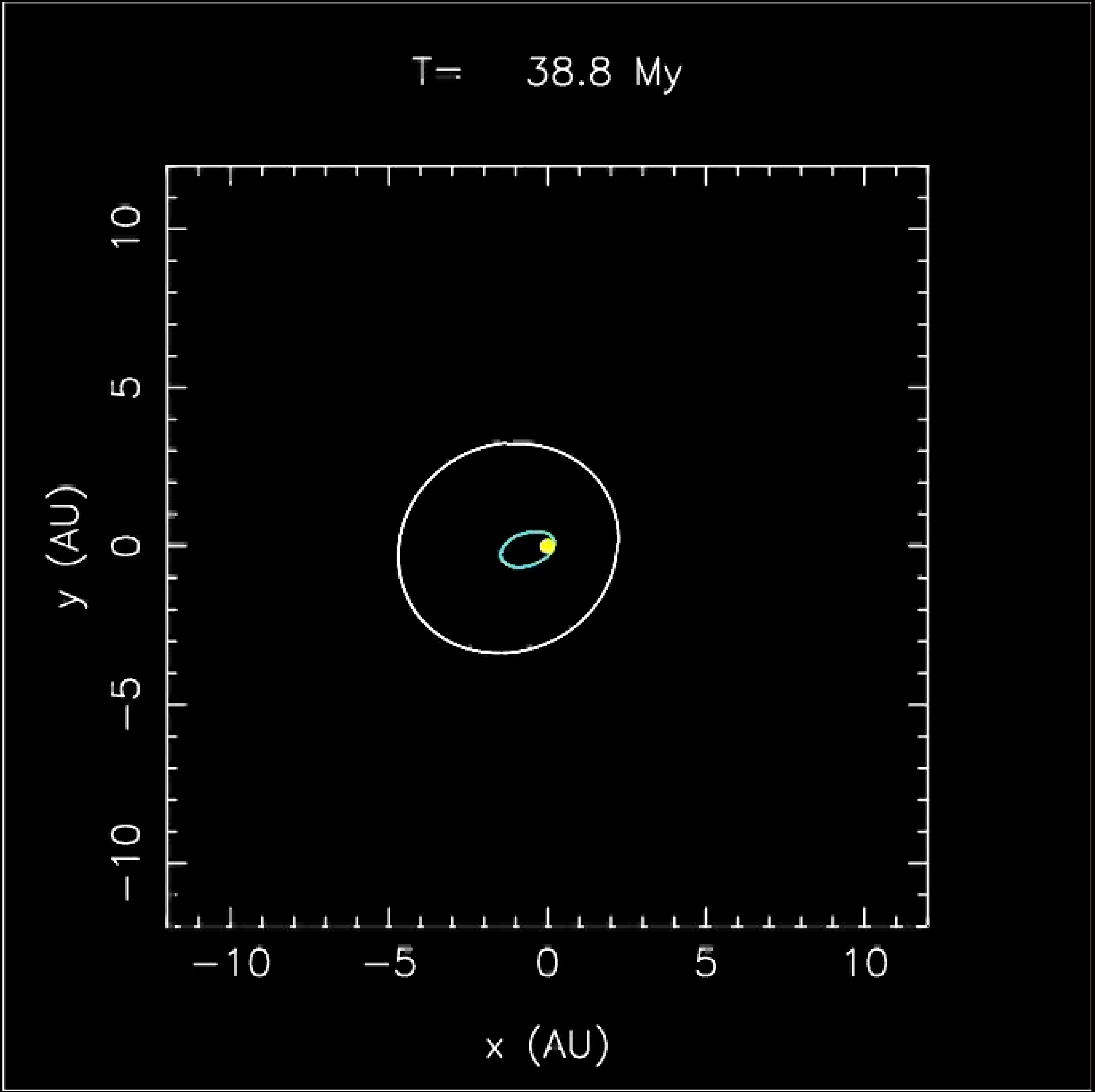
Planet-planet scattering during a giant planet instability is considered to be the best explanation for the eccentricity distribution of the (surviving) planets



Credit: S. Raymond

Planet-planet scattering during a giant planet instability is considered to be the best explanation for the eccentricity distribution of the (surviving) planets

…and also for some distant planets

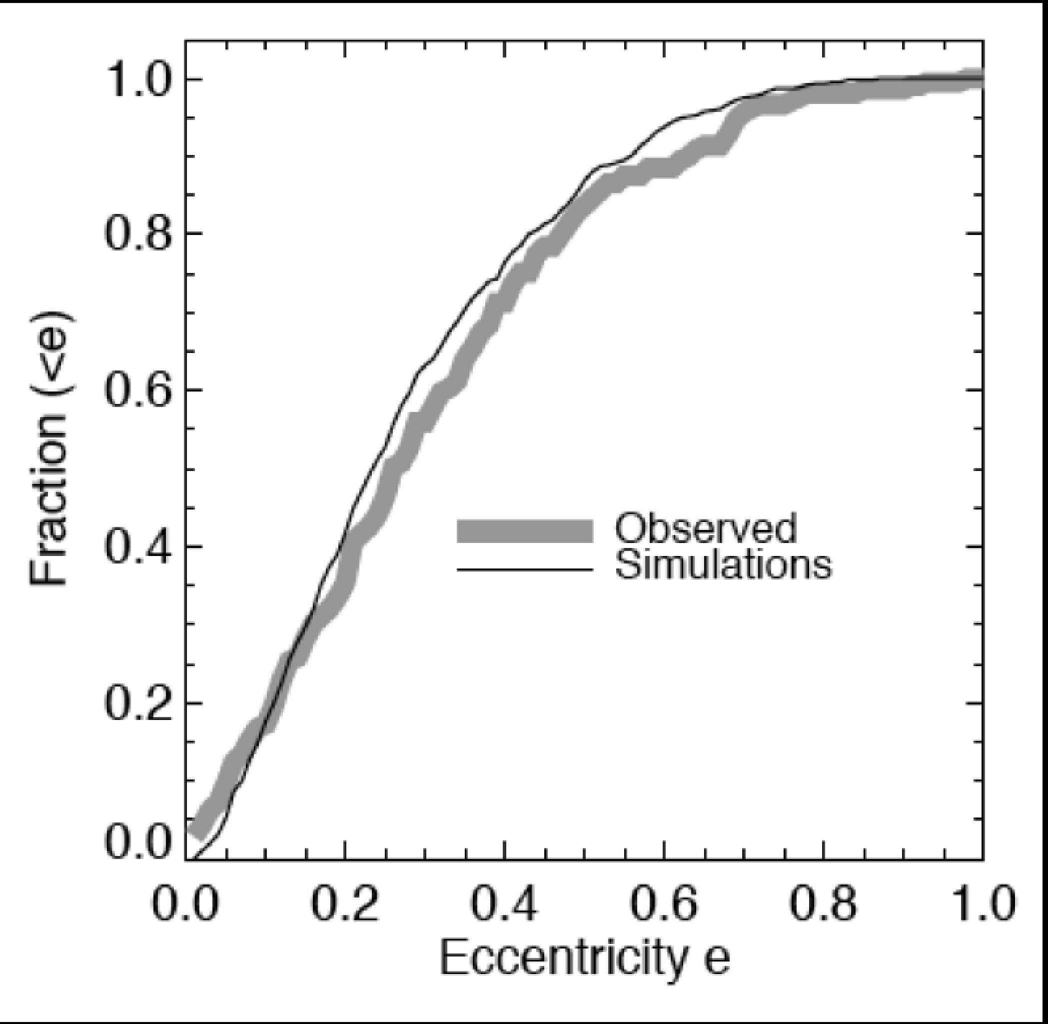


Credit: S. Raymond

Survivors of planet-planet scattering match the eccentricity distribution

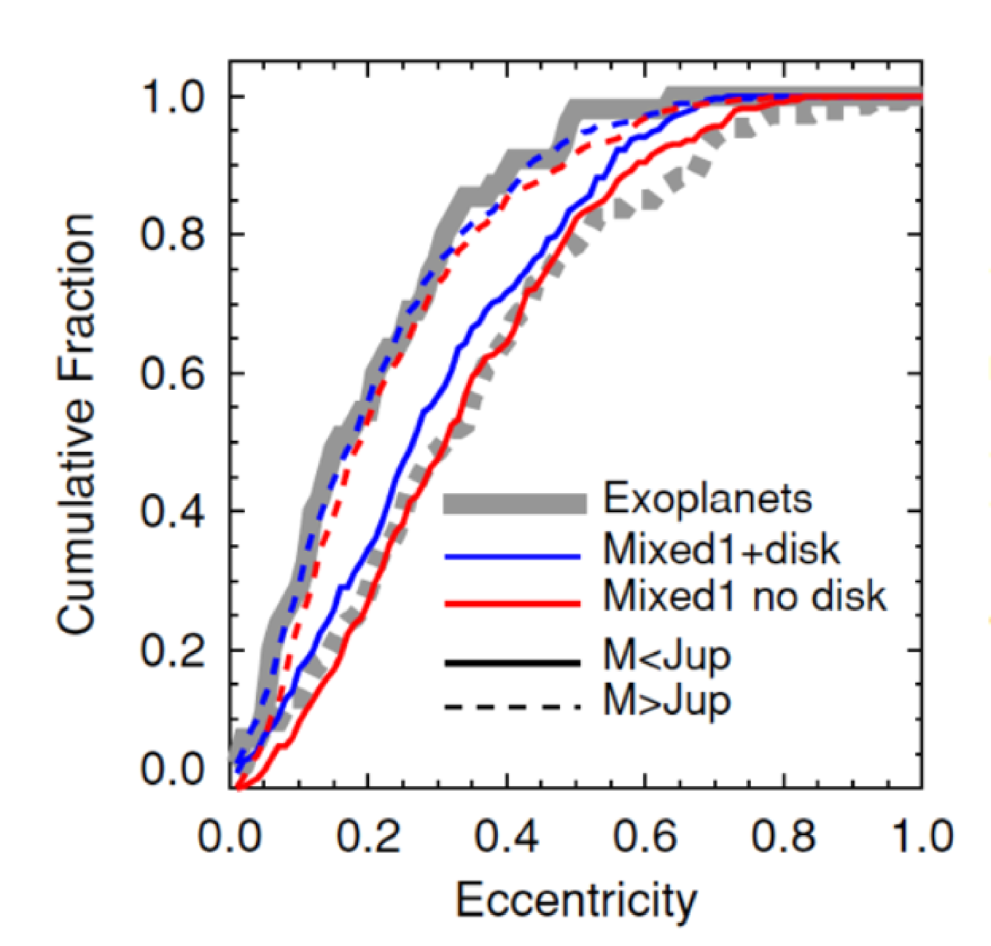
To fit eccentricity distribution, 75-95% of giant exoplanet systems must be survivors of instability

(Juric & Tremaine 2008; Chatterjee et al 2008; Raymond et al 2010)



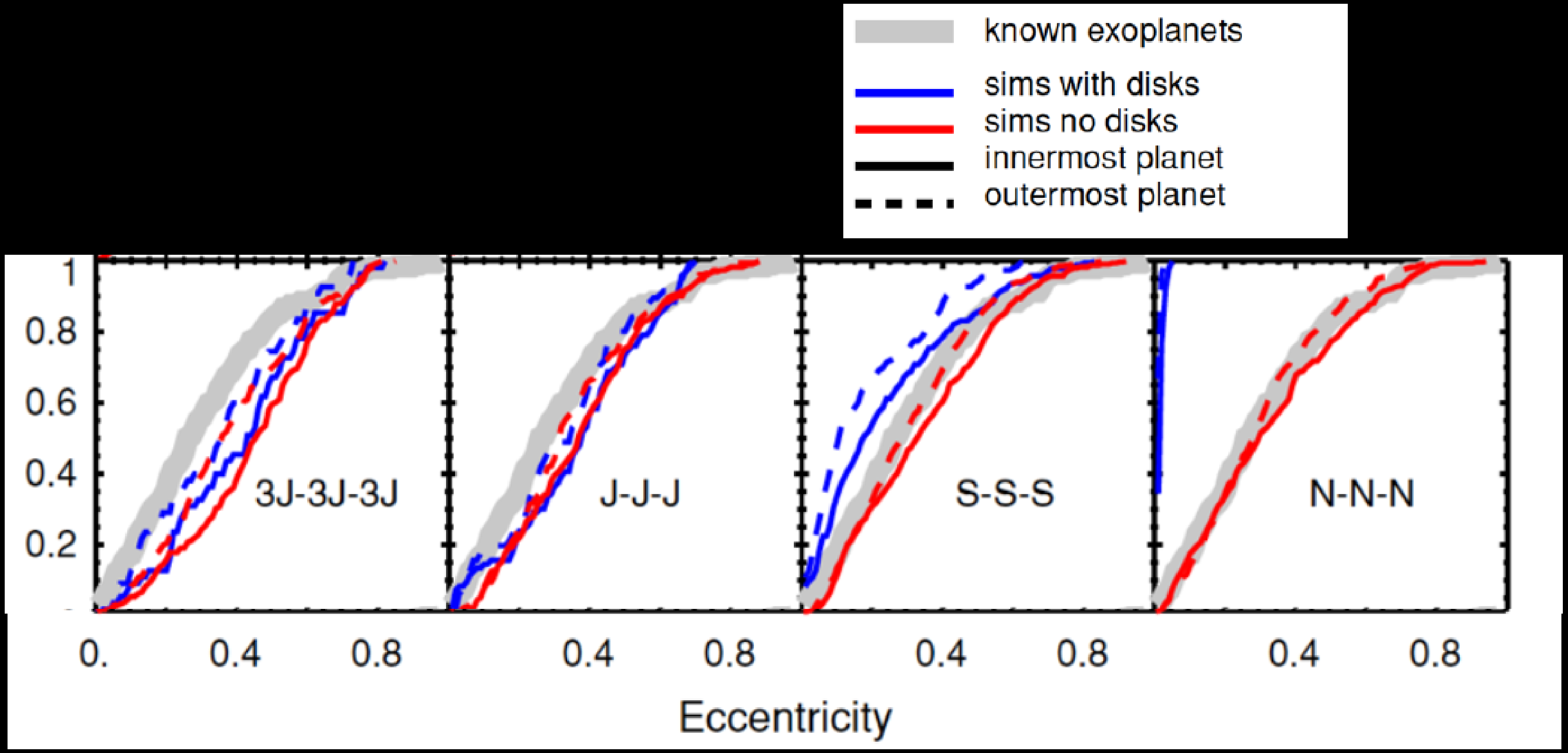
Raymond et al (2009)

Highest-mass planets have highest eccentricities: opposite for planet-planet scattering



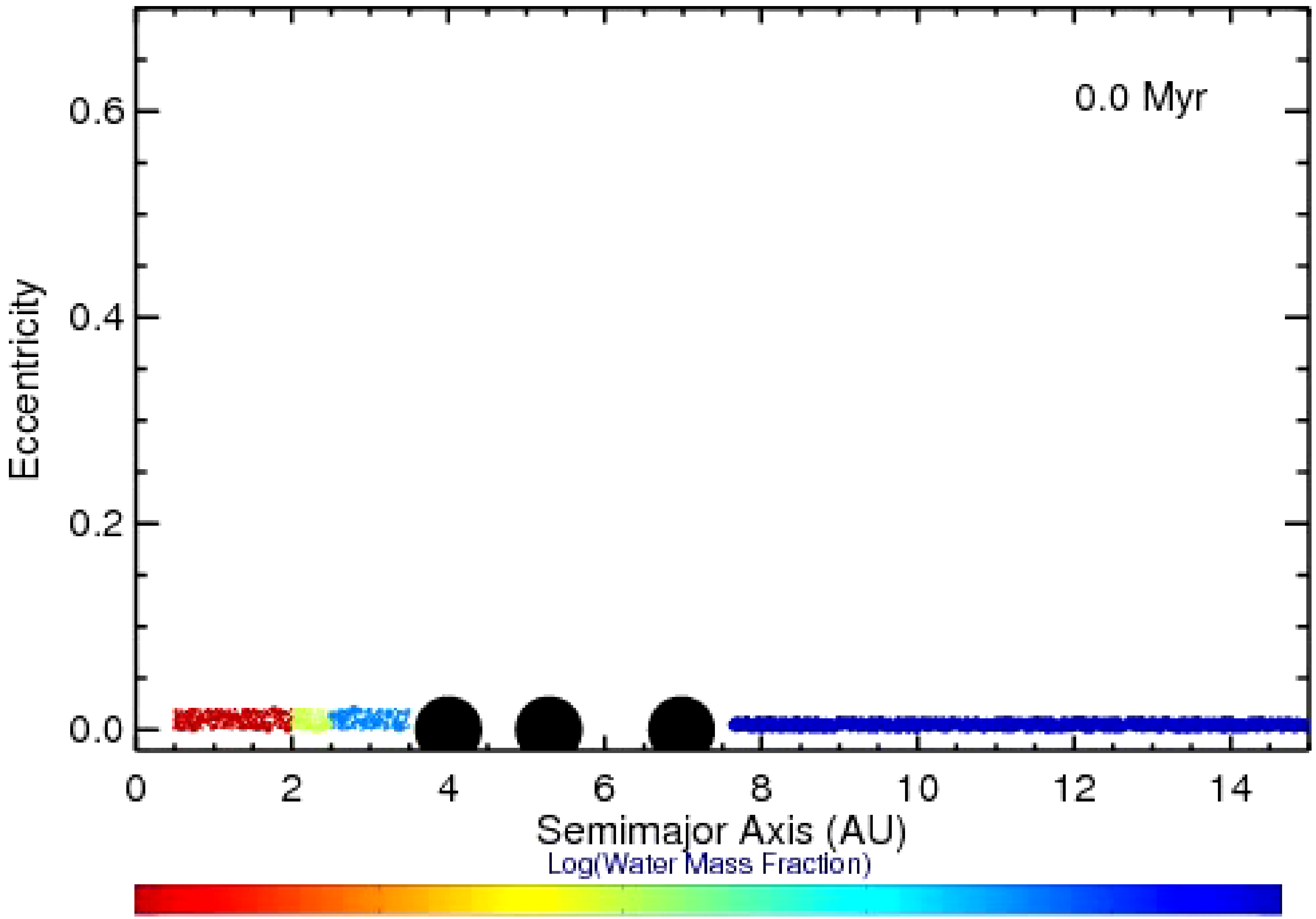
Raymond et al (2010)

Solution: massive planets form in ~equal-mass systems



Raymond et al (2010)

Giant planet scattering is bad for the formation of terrestrial planets

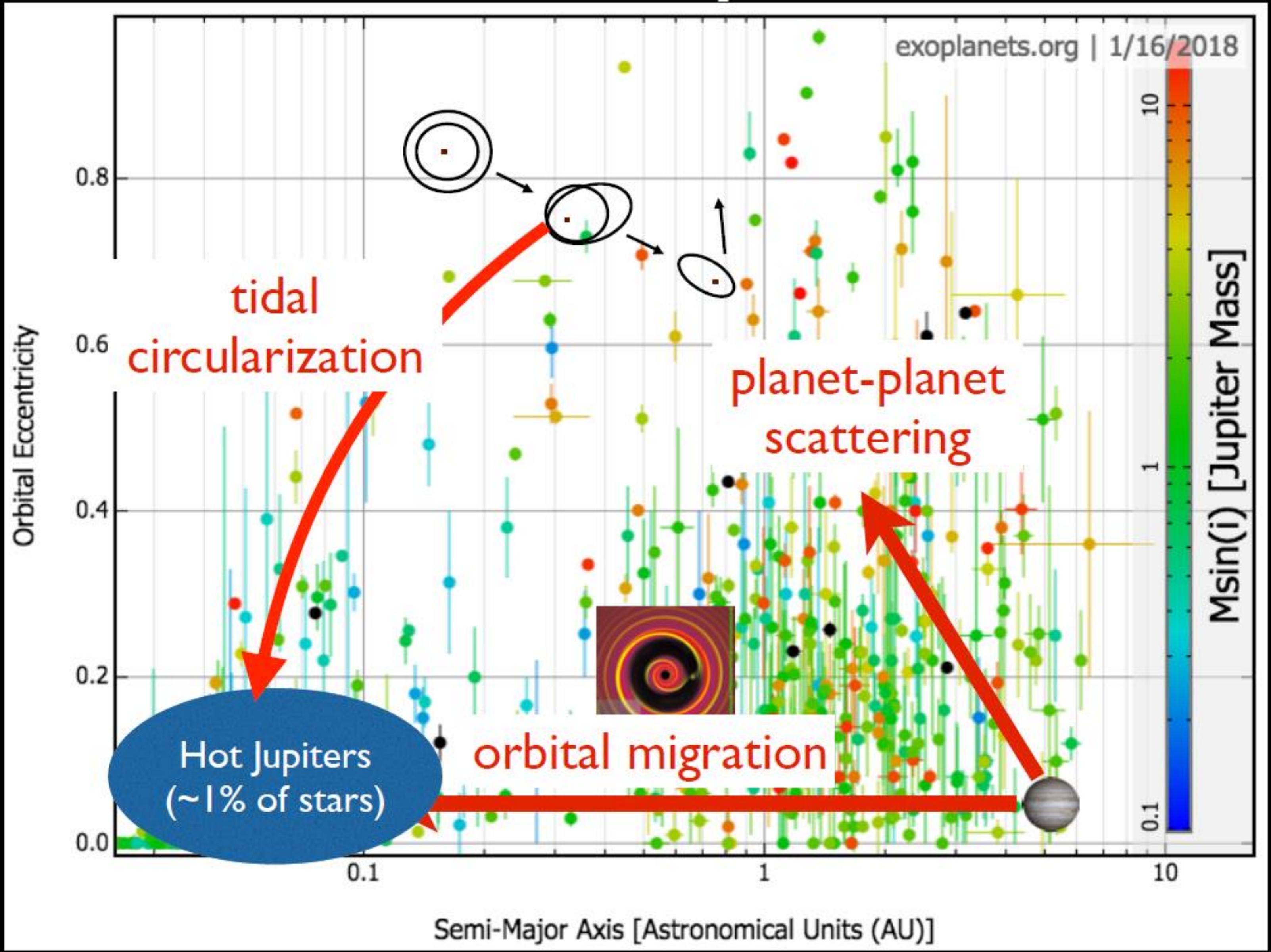


Origins of hot Jupiters

1. Inward migration
2. Tidal circularization of eccentric planets
3. In-situ growth

For details see Dawson & Johnson (2018; Annual Reviews of Astron. & Astrophys.)

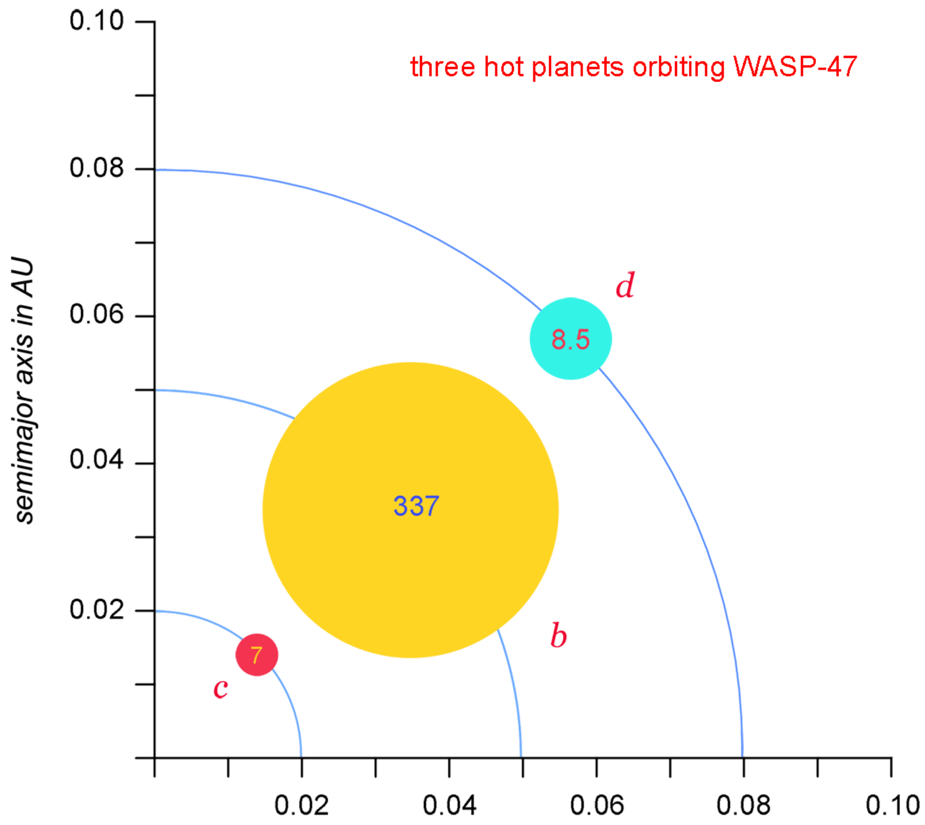
Giant exoplanets



Wright et al 2011

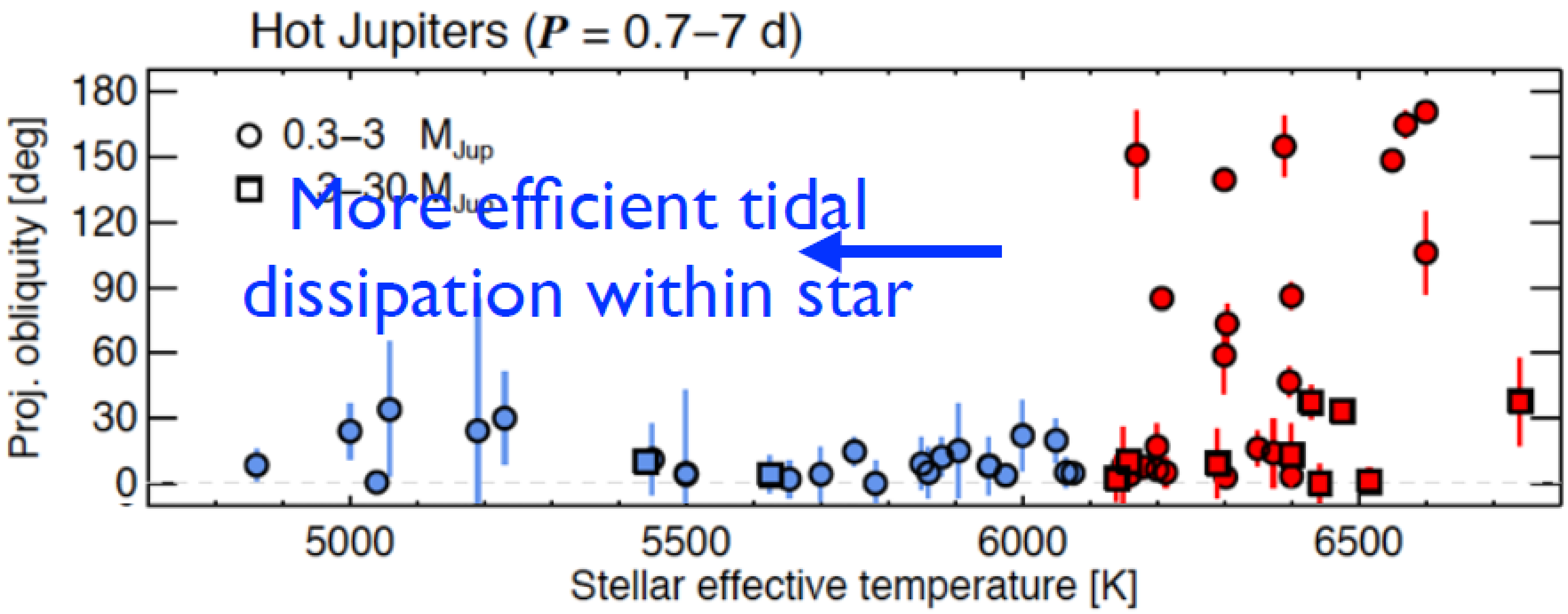
Reasons to prefer planet-planet scattering as the dominant mechanism:

- hot Jupiters rarely reside in multi-planet systems (Wright et al. 2009; Steffen & Agol 2005; Gibson et al. 2009; Latham et al. 2011; Steffen et al. 2012) barring exceptional cases like WASP-47b (Becker et al. 2015; Weiss et al. 2017).

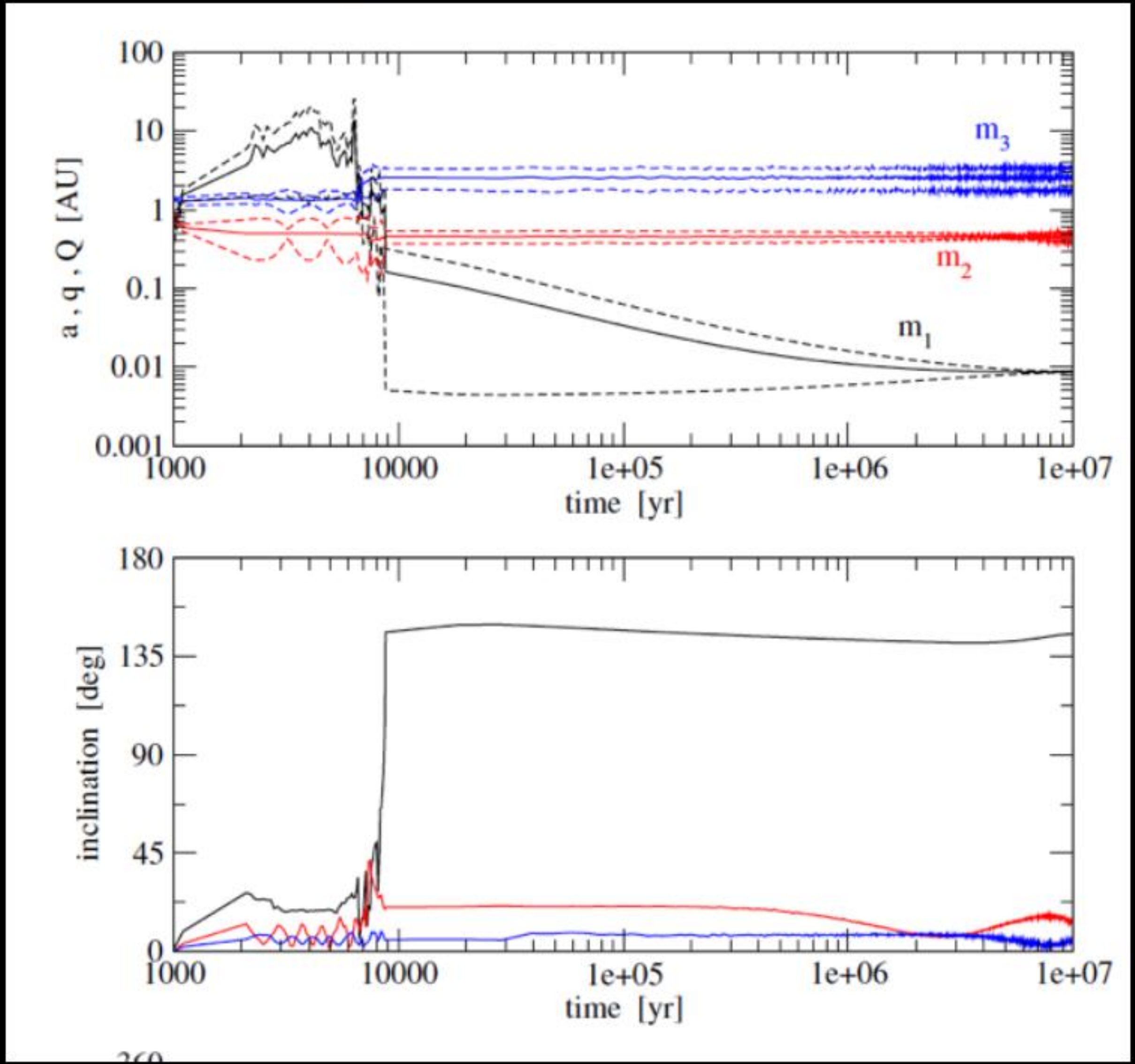


Reasons to prefer planet-planet scattering as the dominant mechanism:

- Many hot Jupiters have high orbital inclinations relative to the stellar equatorial plane



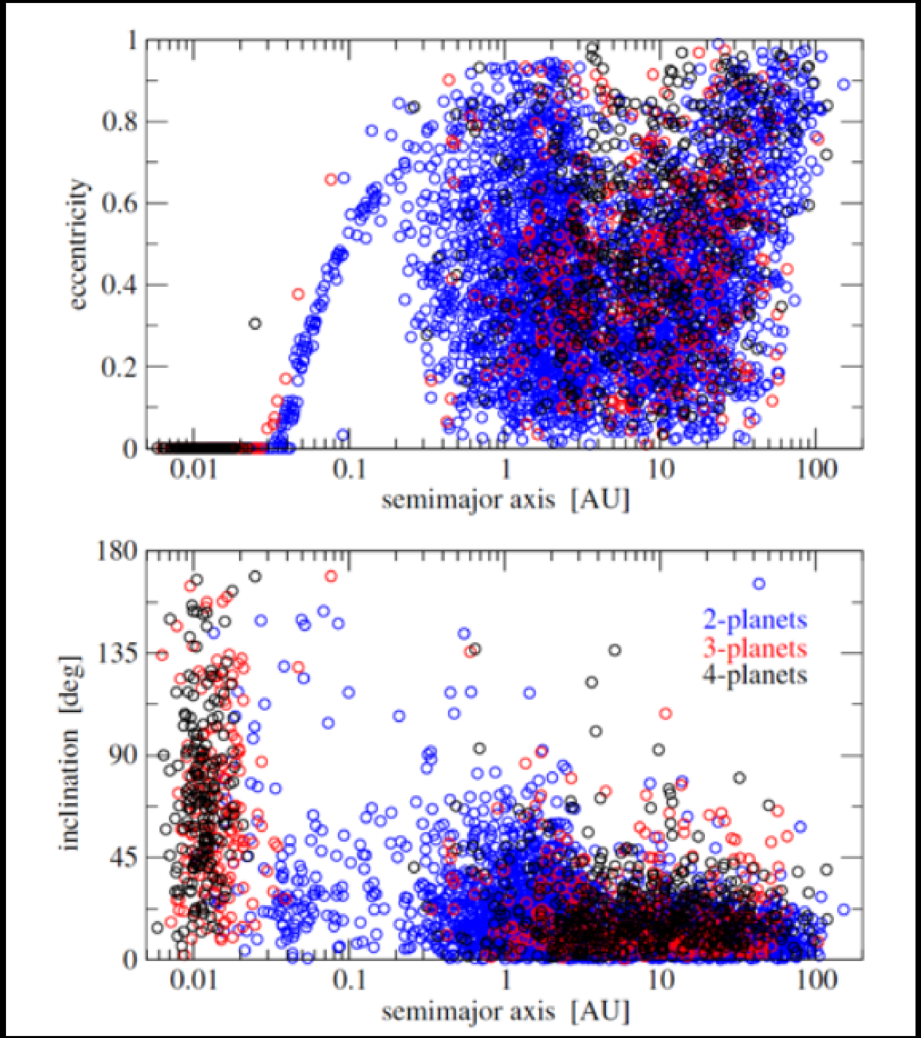
Scattering + tidal friction



Beaugé & Nesvorny (2012)

Pl-pl scattering and tidal circularization

Beaugé & Nesvorny (2012)

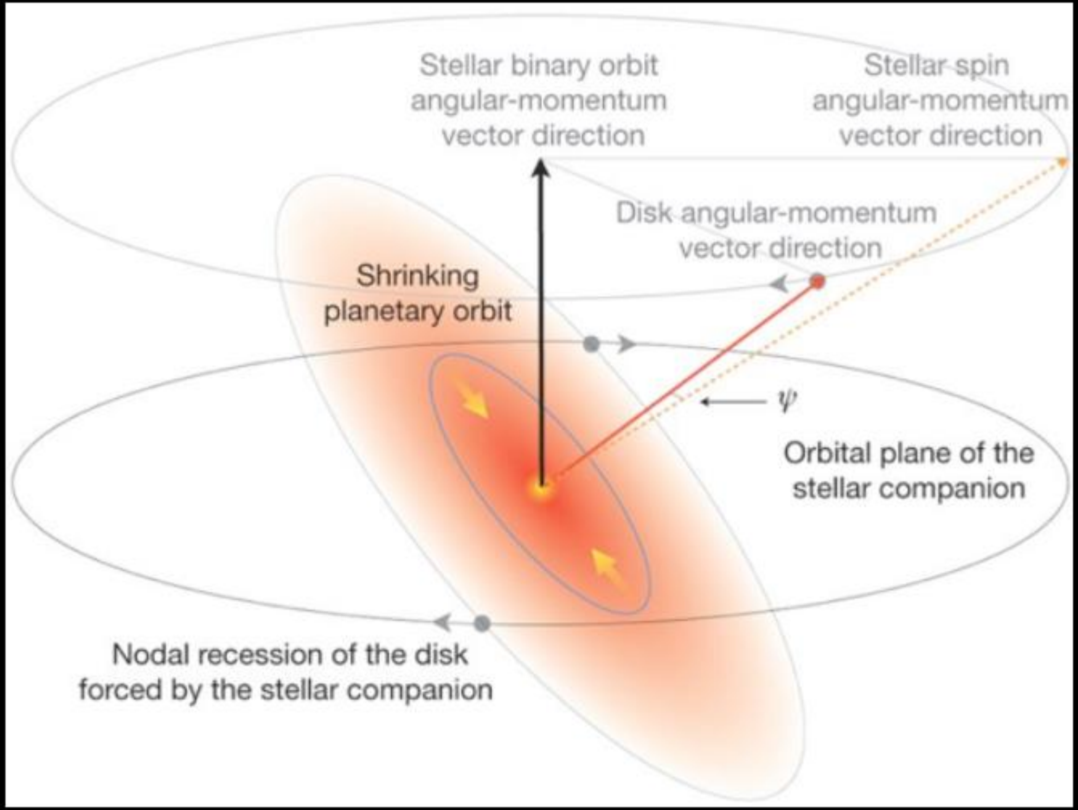


Naturally produces misaligned hot Jupiters from scattering

Other source of eccentricity (e.g., secular chaos, Kozai mechanism) possible
(e.g., Fabrycky & Tremaine 2007; Wu & Lithwick 2011)

Migration

Can only produce misaligned hot Jupiters if the disk itself is tilted with respect to the stellar equator.

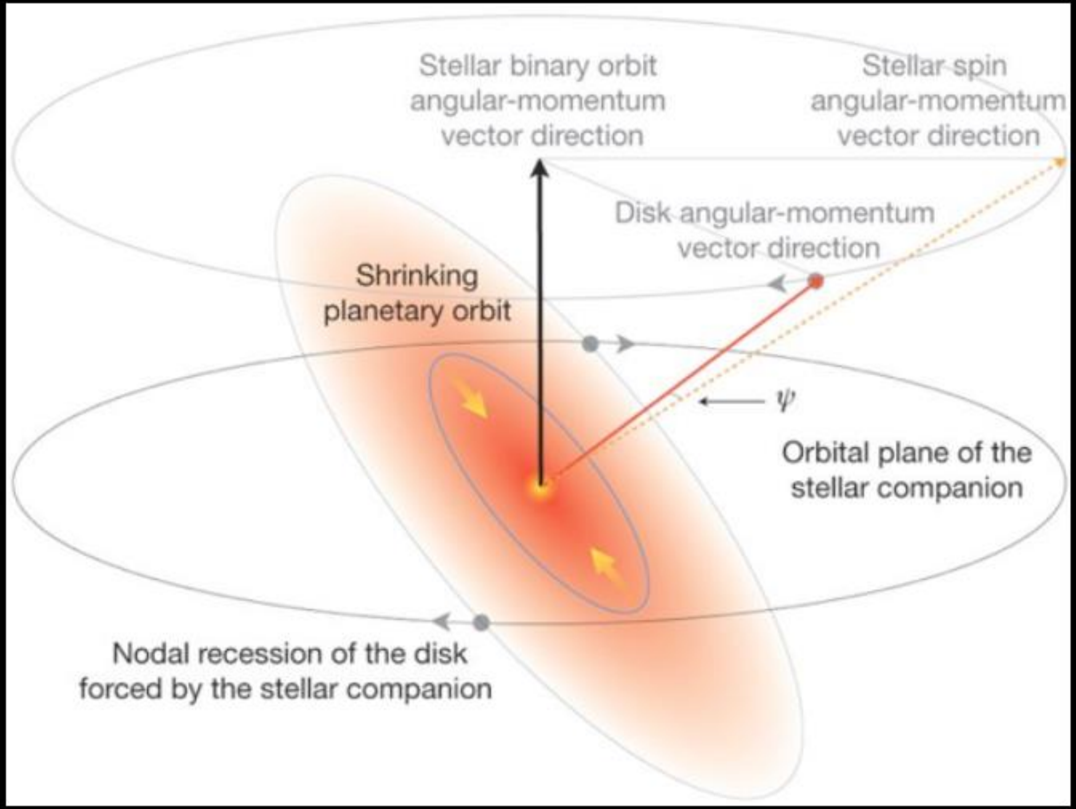


Batygin (2012)

In-situ growth of hot Jupiters?

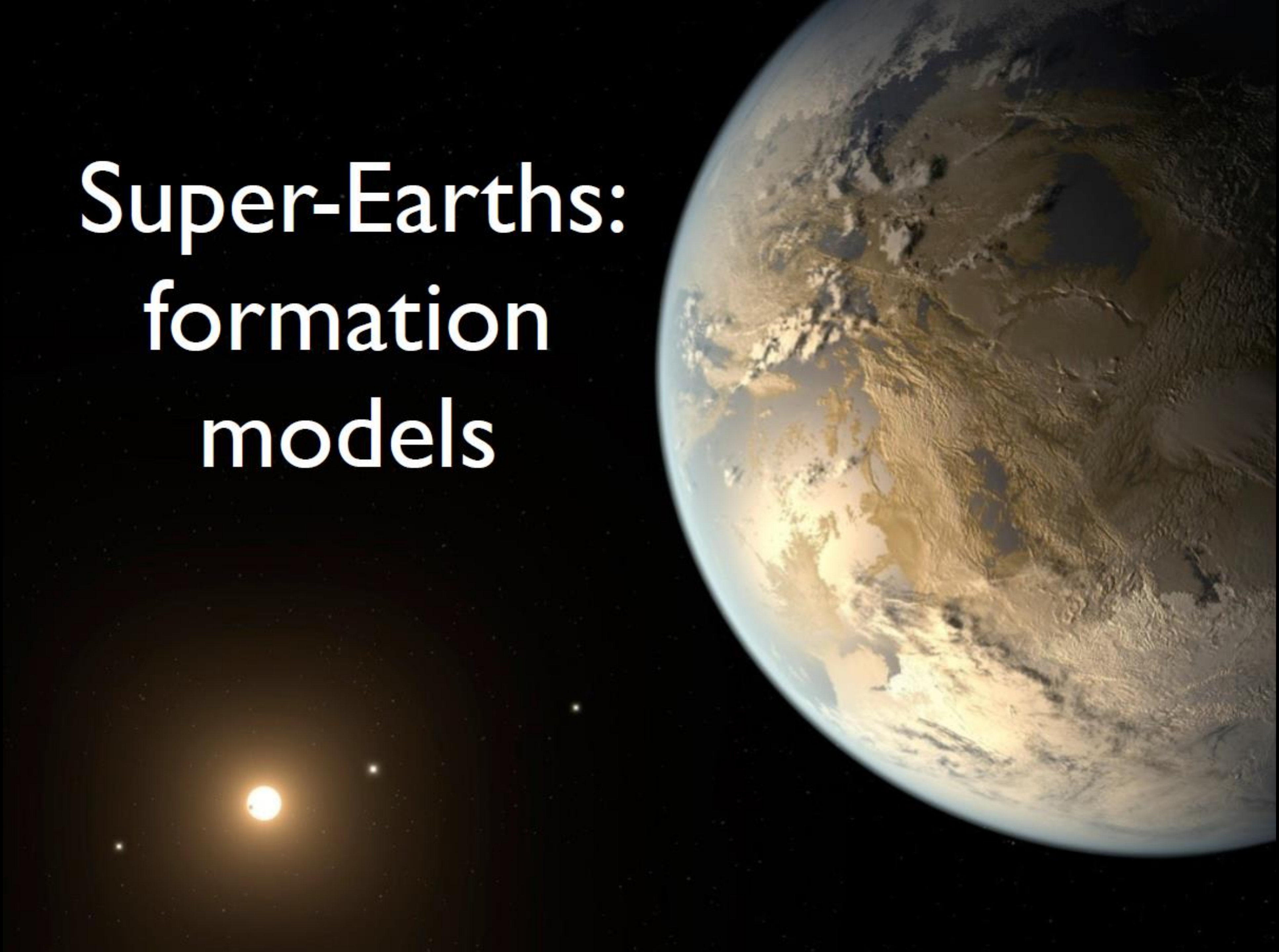
If disks are primordially tilted, why not?

(E.g., early growth of large cores by collisions of fast-growing super-Earths near inner edge of disk)

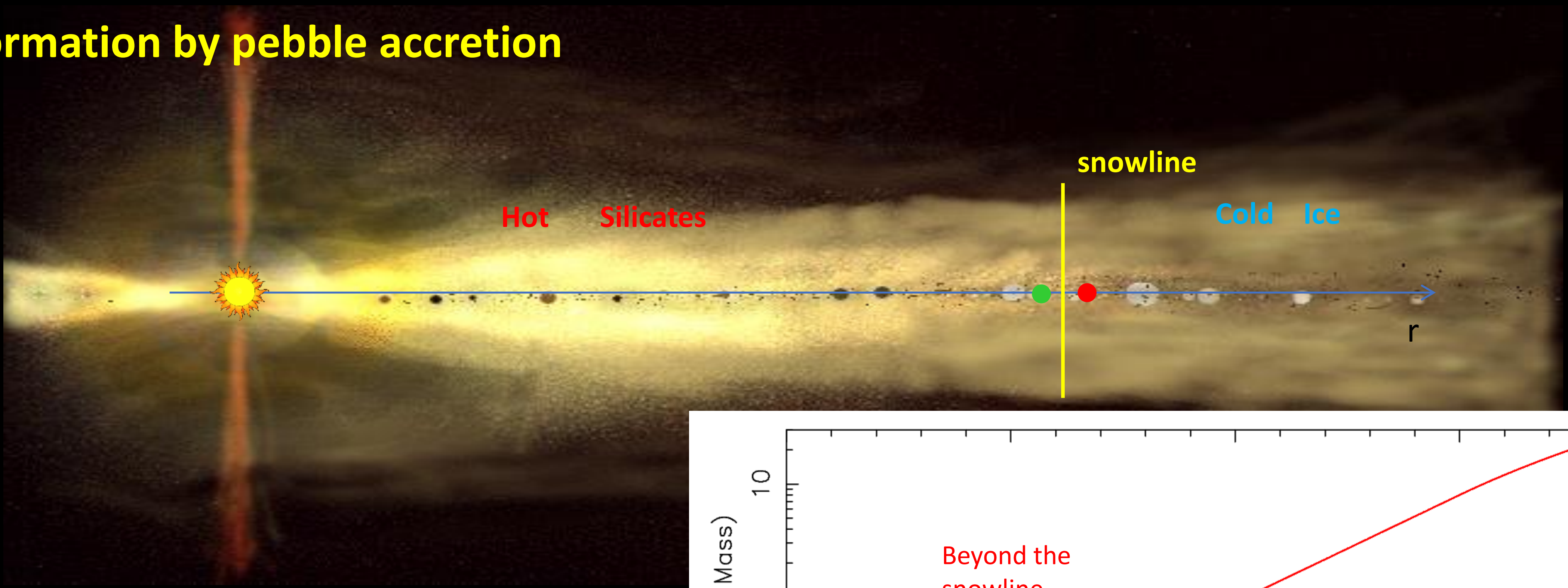


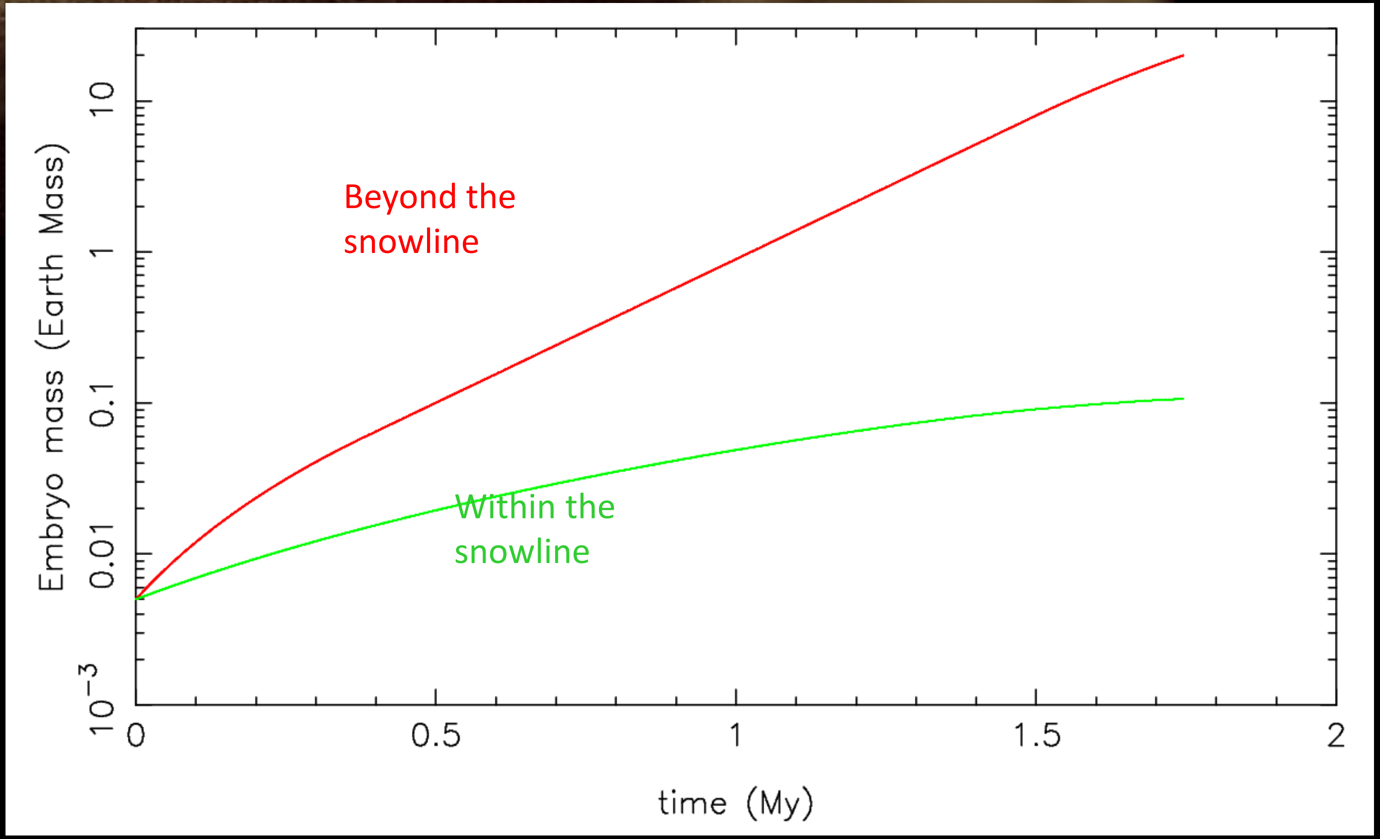
Batygin (2012); Batygin et al (2016)

Super-Earths: formation models



Formation by pebble accretion

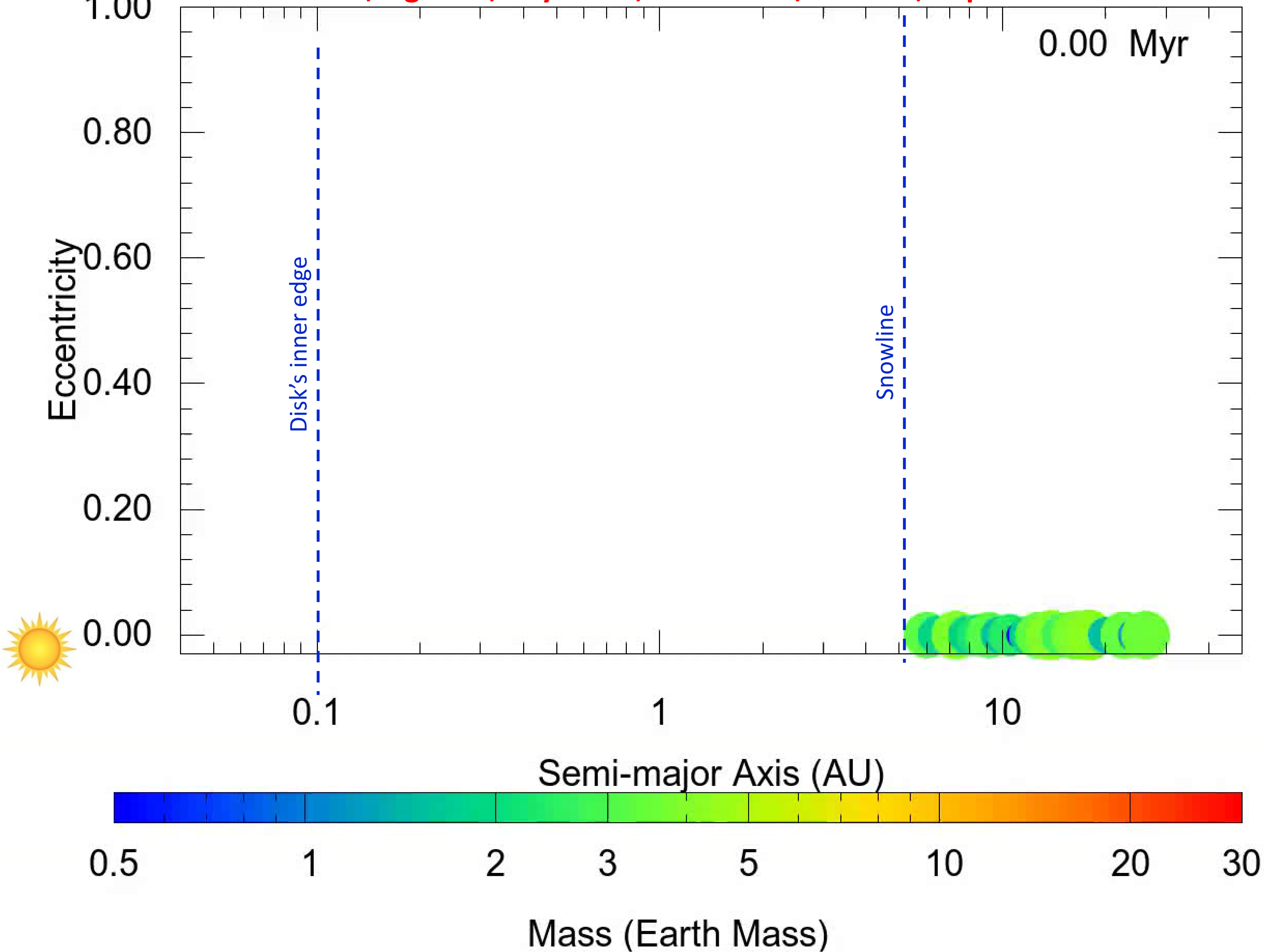




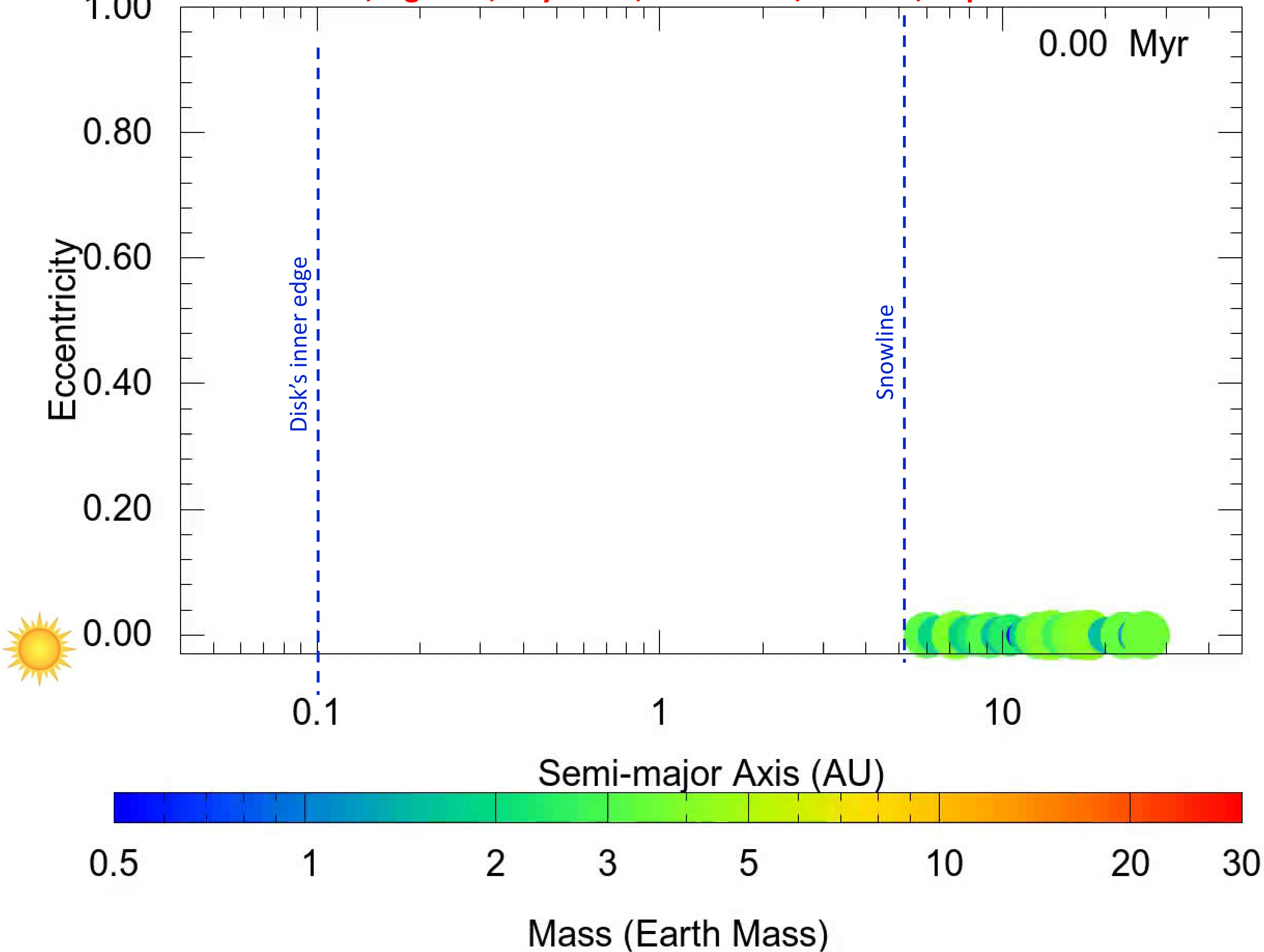
Because Icy-pebbles should be bigger than silicate pebbles, p.a. should produce SE predominantly beyond the SL

Morbidelli et al., 2015
Ida et al., 2016

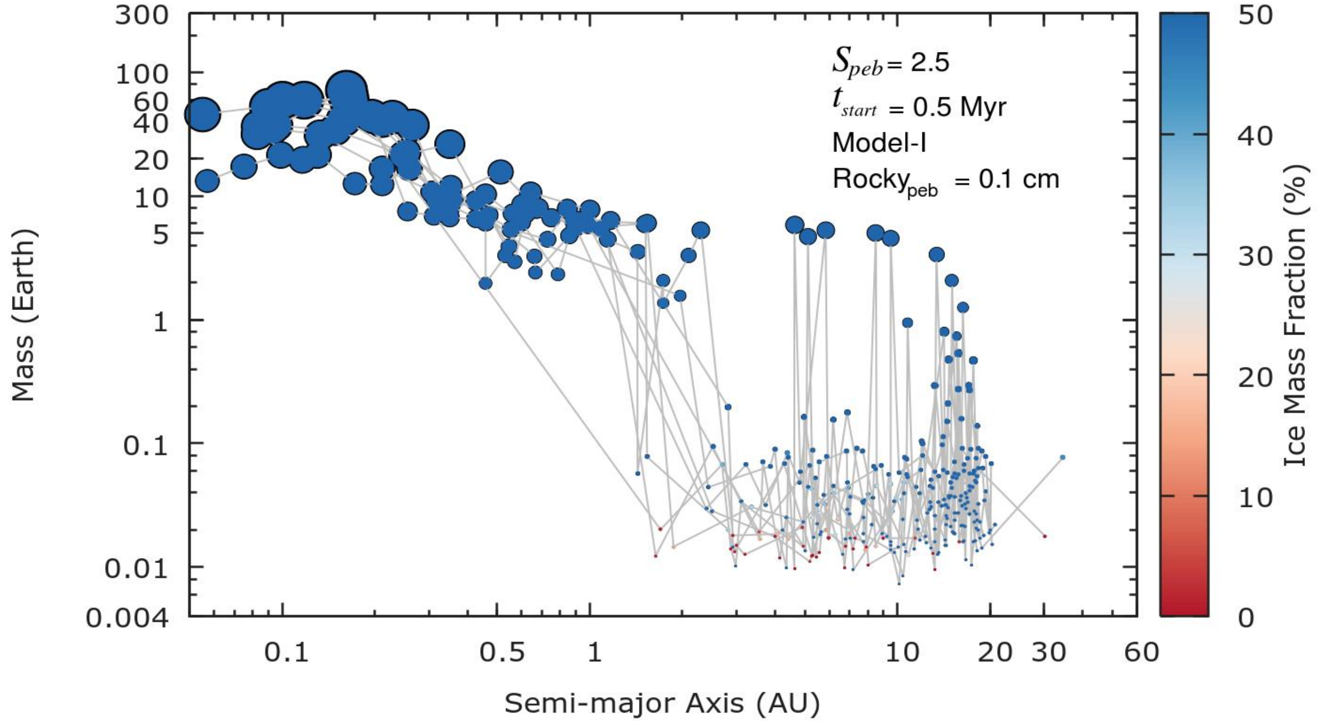
Izidoro, Ogihara, Raymond, Morbidelli, MNRAS, in press



Izidoro, Ogihara, Raymond, Morbidelli, MNRAS, in press

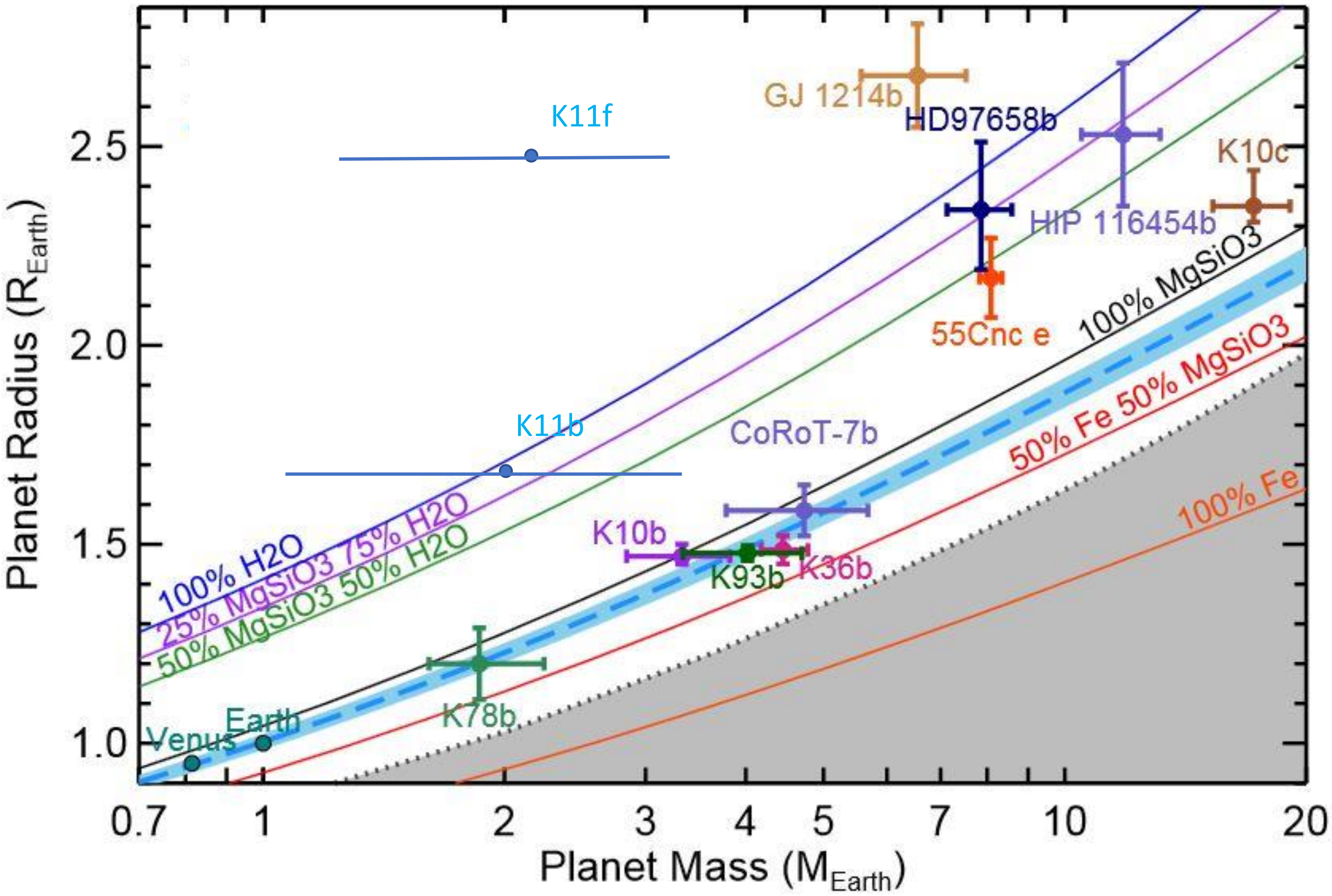


Problem: pebble accretion implies that all super-Earths should be icy.



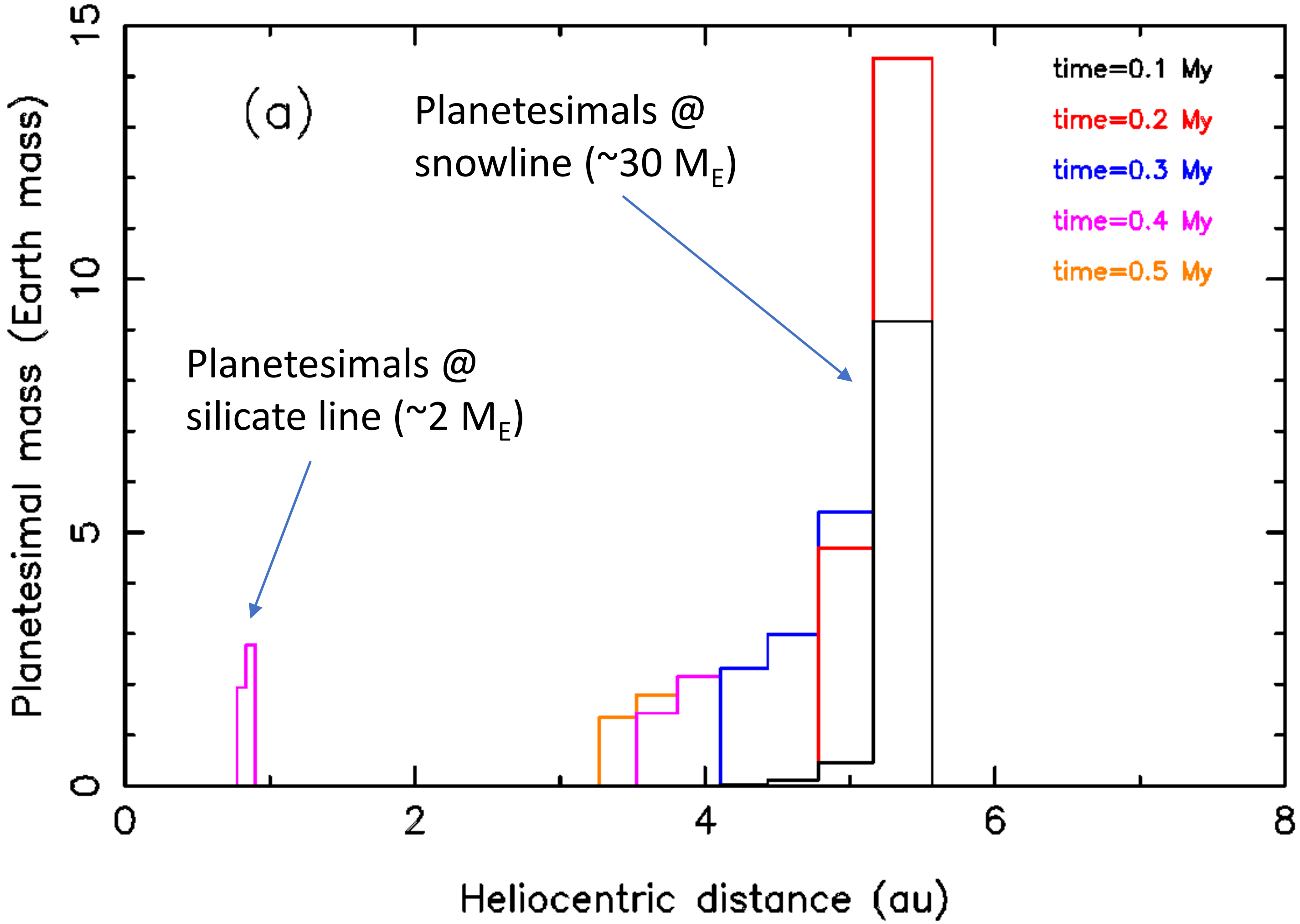
Because icy pebbles are bigger, seeds beyond the SL grow much faster and migrate inwards.

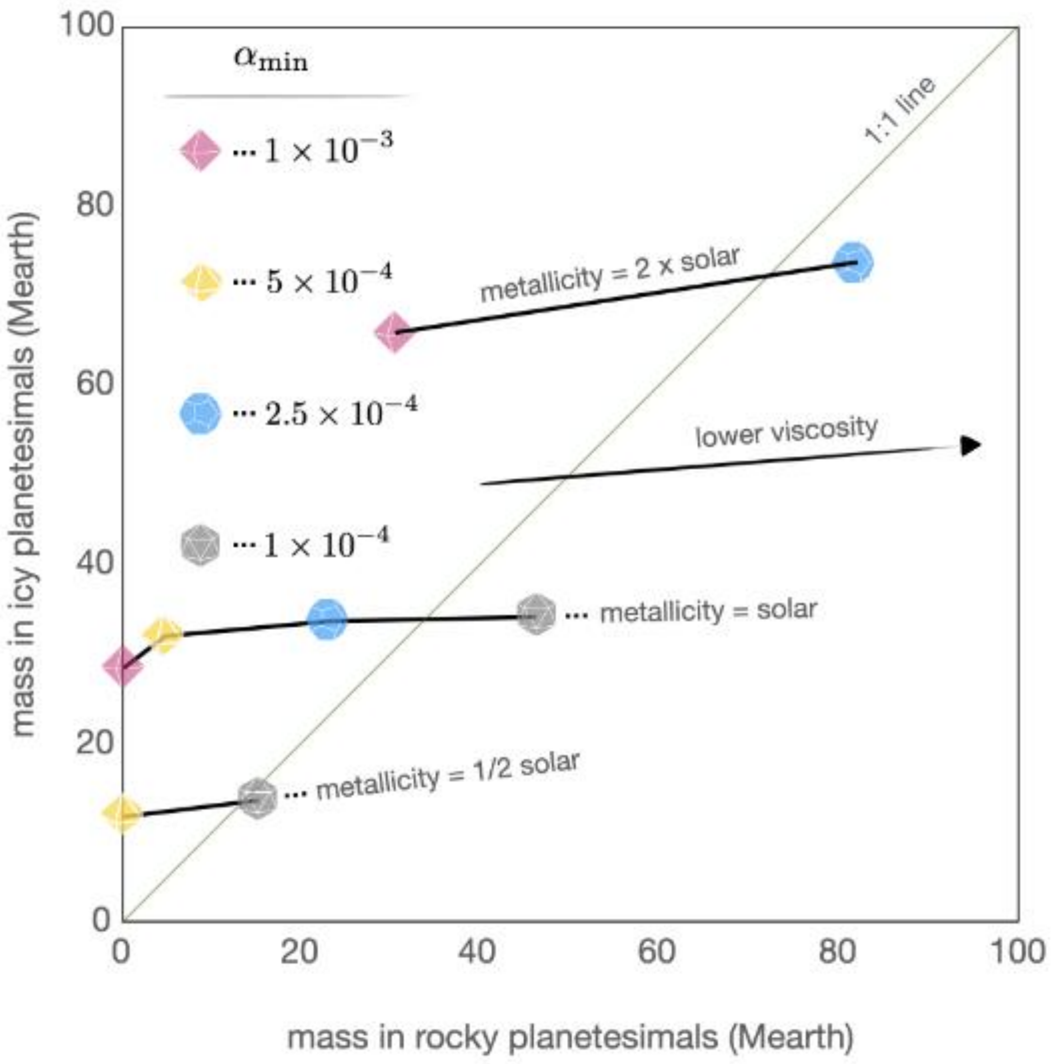
This contrasts with the observation that many Super-Earths are rocky



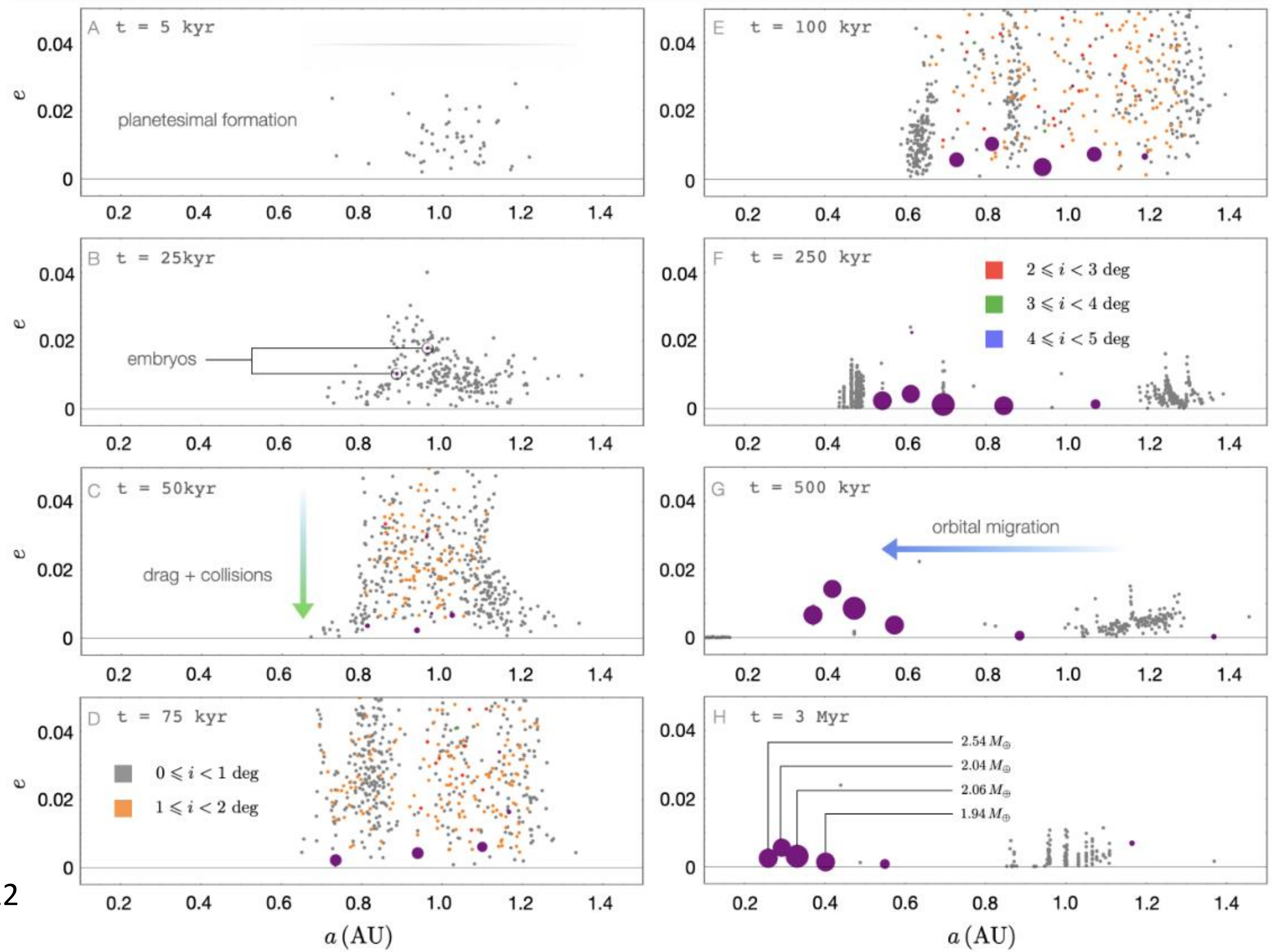
Back to the classic growth model
Two rings of planetesimals and planetesimal-planetesimal collisions

Morbidelli et al., 2022





Back to the classic growth model
Two rings of planetesimals and planetesimal-planetesimal collisions

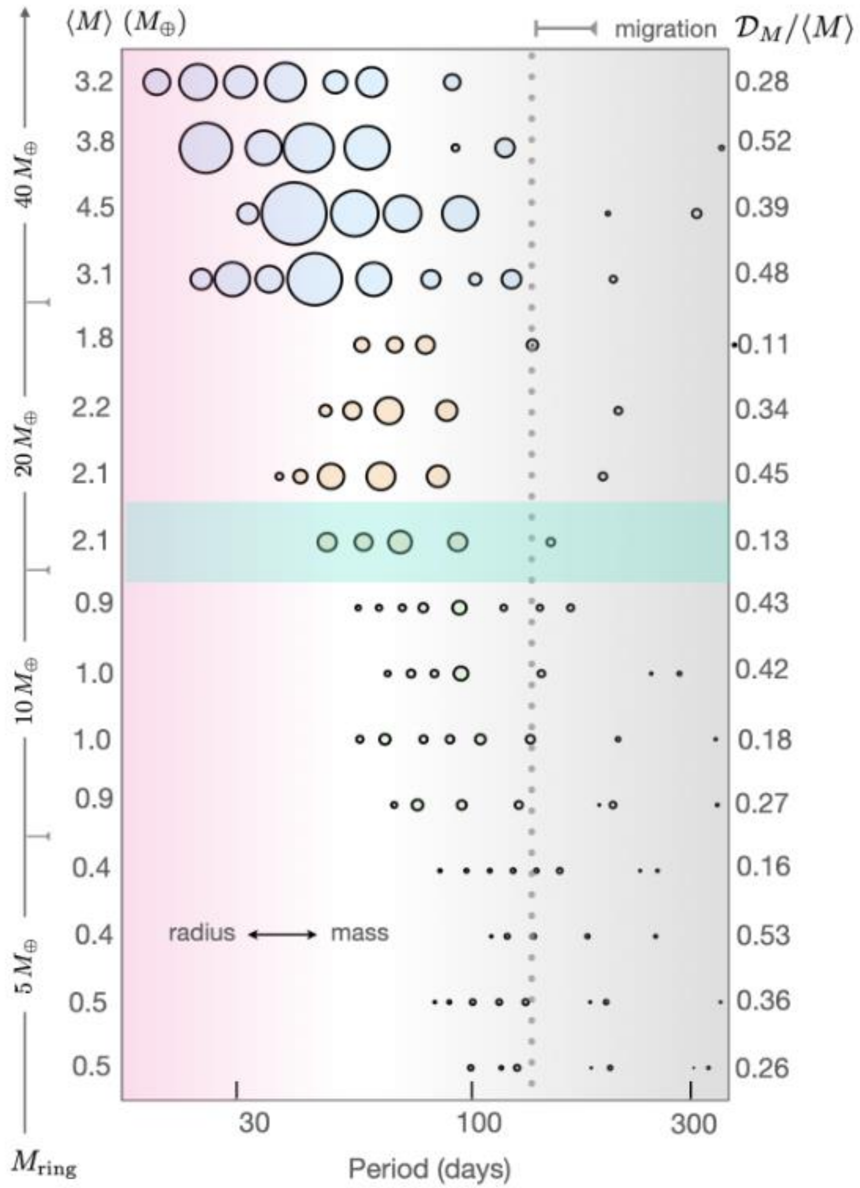


Batygin and Morbidelli, 2022

Back to the classic growth model
Two rings of planetesimals and planetesimal-planetesimal collisions

The advantage is that we reproduce naturally the peas-in-the-pot pattern

Notice the mass-period correlation. Systems with small masses in the rocky ring don't produce planets massive enough to migrate substantially



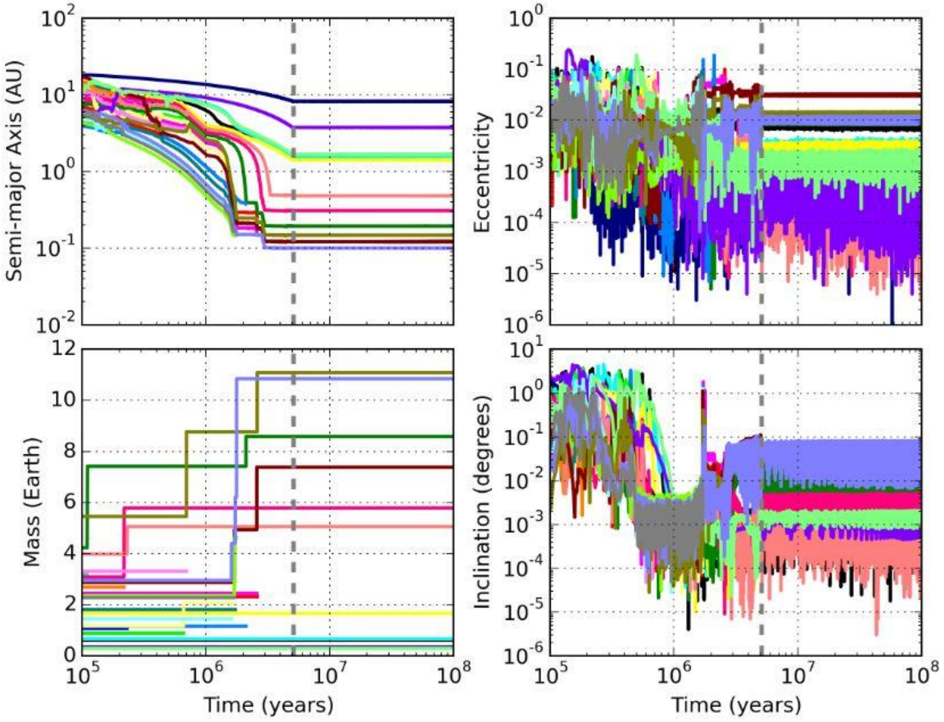
Batygin and Morbidelli, 2022

Take-away points

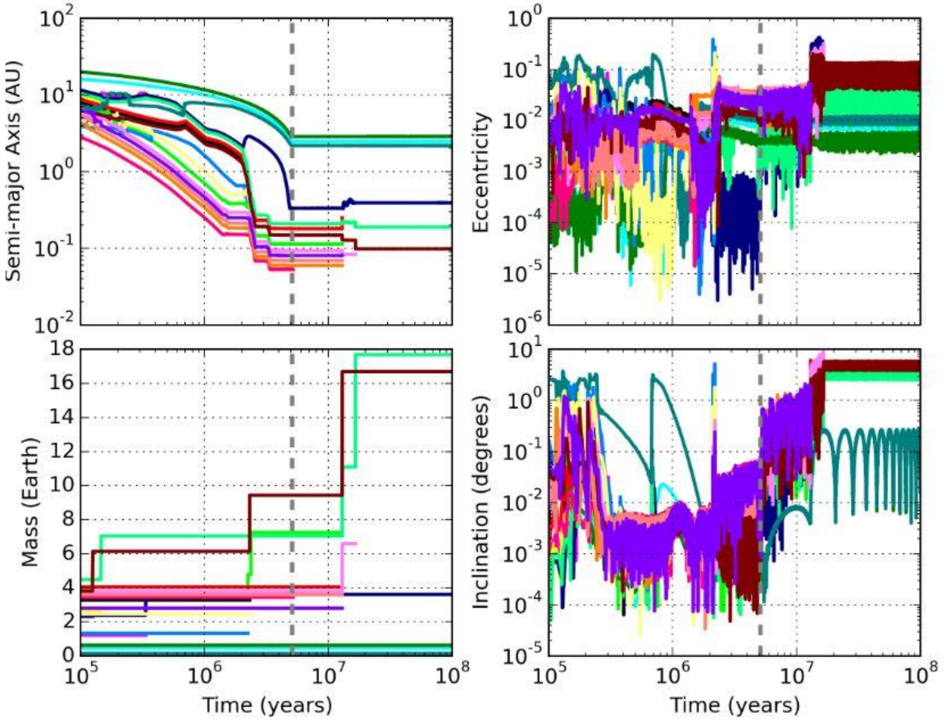
- Hydrodynamical instabilities in the gas-dust disk lead to self gravitating dust clumps which then contract forming planetesimals
- Planetesimal-planetesimal collisions (in the inner part of the disk) and pebble accretion (in the outer part) promote some planetesimals to become solid proto-planets
- Giant impacts among proto-planets and gas accretion may complement the planet formation process
- Planet migration is a pain in the neck for all theorists…..
- Giant planets usually form multi-planet systems of roughly equal mass, don’t migrate much, become unstable after gas removal, so that only few (~1) remain detectable per system
- Scattering and tidal damping should be the main (but not unique!) mechanism to form Hot Jupiters.
- Low-density super-Earths are likely to be failed giant planets which formed at the snowline and migrated to the inner edge of the disk (mini-Neptunes)
- Rocky super-Earths should have formed from mutual collisions in a massive ring of rocky planetesimals. The competition between the accretion and migration timescale leads to the typical peas-in-the-pot pattern
- Both giant planets and super-Earths form within the lifetime of the disk of gas. The terrestrial planets of the solar system don’t fall in this category. Their analog has not been found yet.

Because of migration, all systems form resonant chains at the end of the disk's lifetime.
But after gas-removal ~ 50% of the systems become unstable

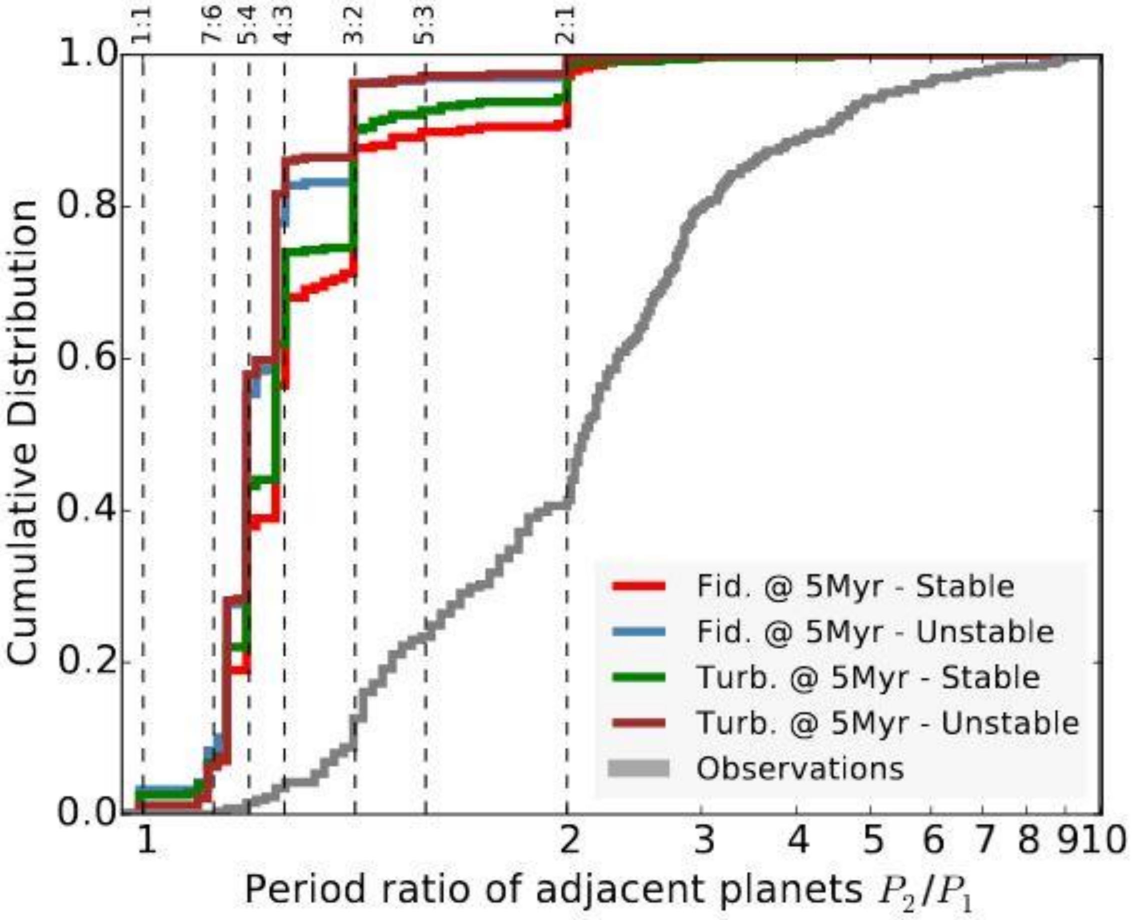
STABLE



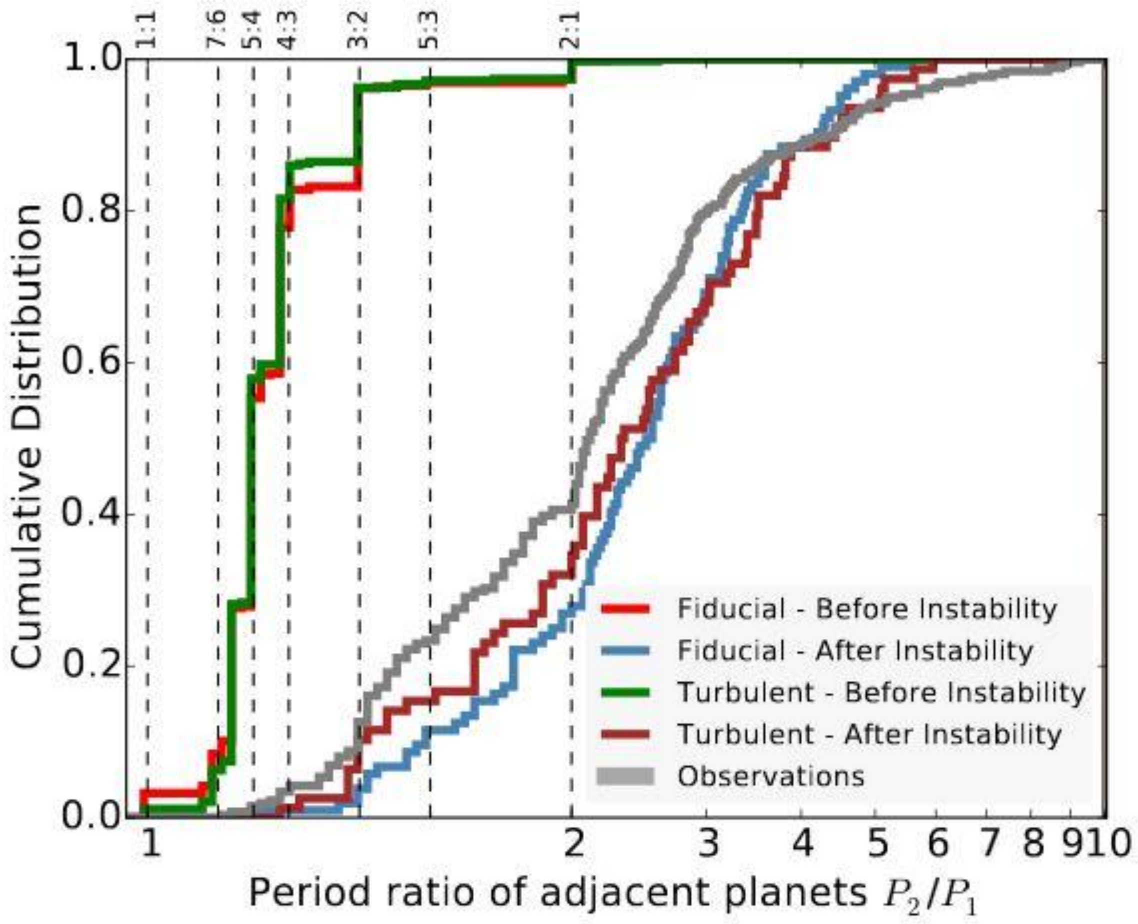
UNSTABLE



Before the instability, stable and unstable systems have statistically the same period-ratio distribution, very different from the one observed



After the instability, systems that went unstable reproduce the observed period-ratio distribution very well.



When we pass our system through a Kepler-survey simulator, reproducing the observed multiplicity distribution requires that 90% of the system became unstable (instead of ~50% as in our simulations – open problem)

NO EVIDENCE FOR SINGLE-PLANET SYSTEMS